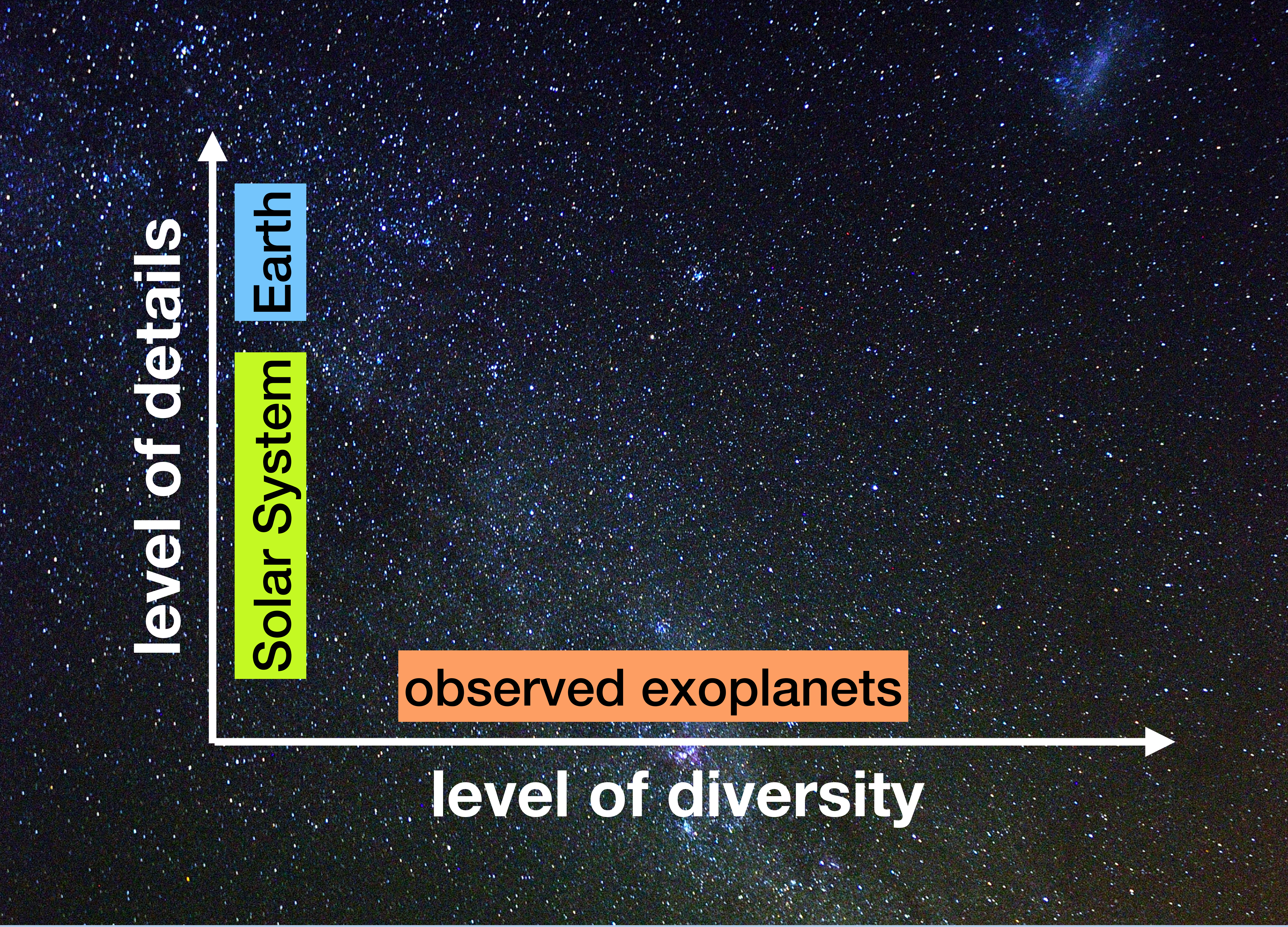
Swiss National Science Foundation

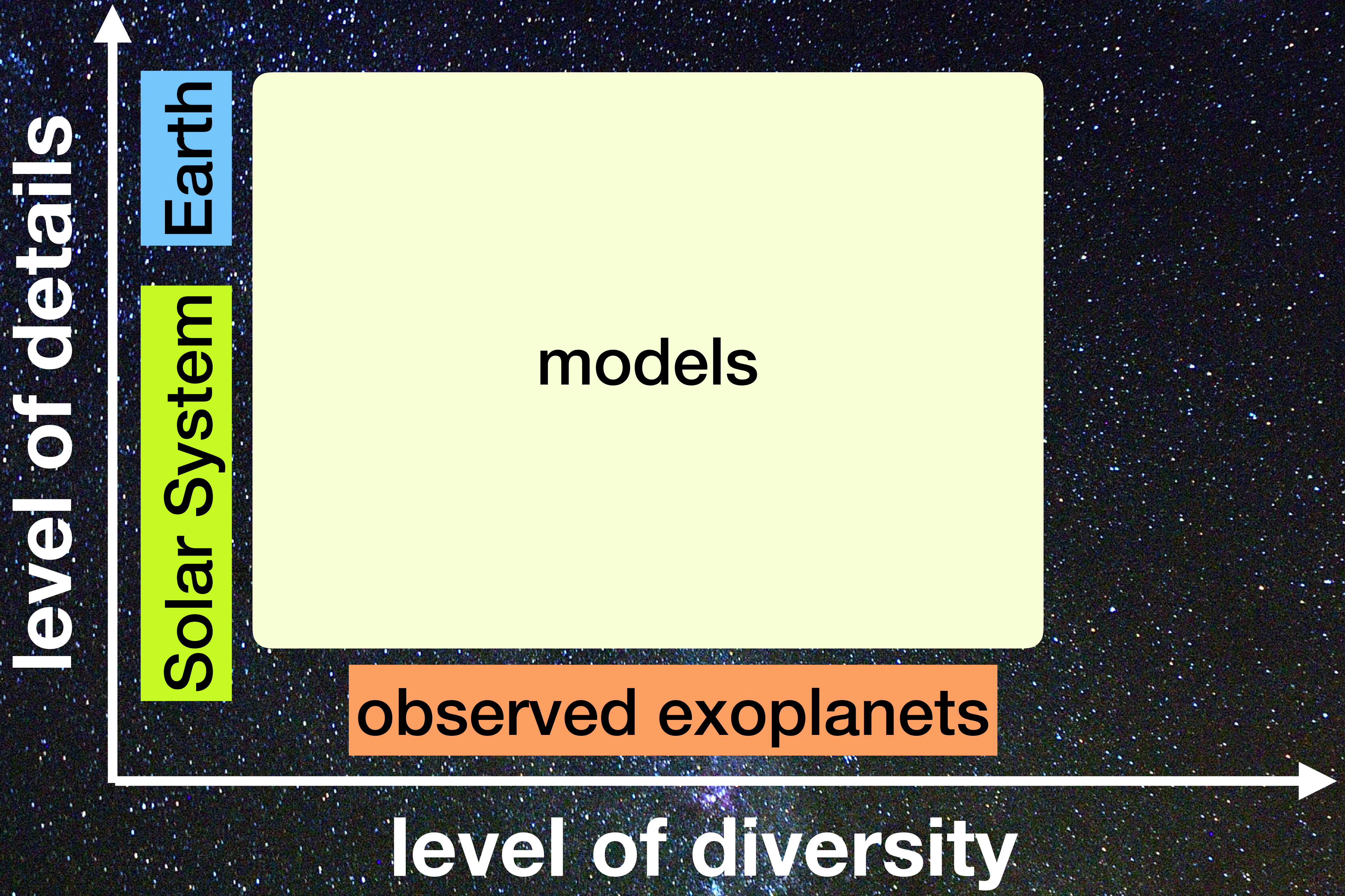
National Centre of Competence in Research

The existing worlds of Trappist-1 & hidden water in terrestrial planets

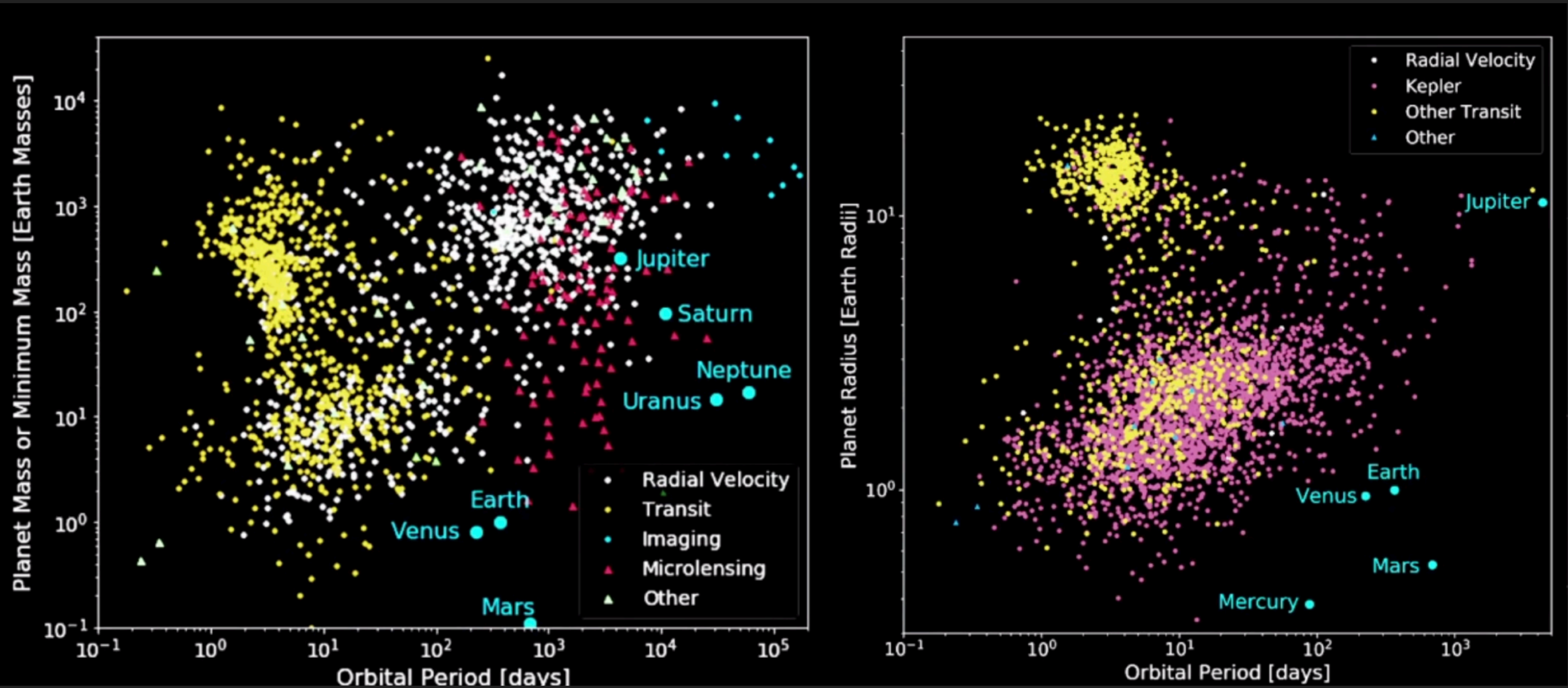
Caroline Dorn

University of Zurich[UZH]


level of details
Earth
Solar System
observed exoplanets
level of diversity

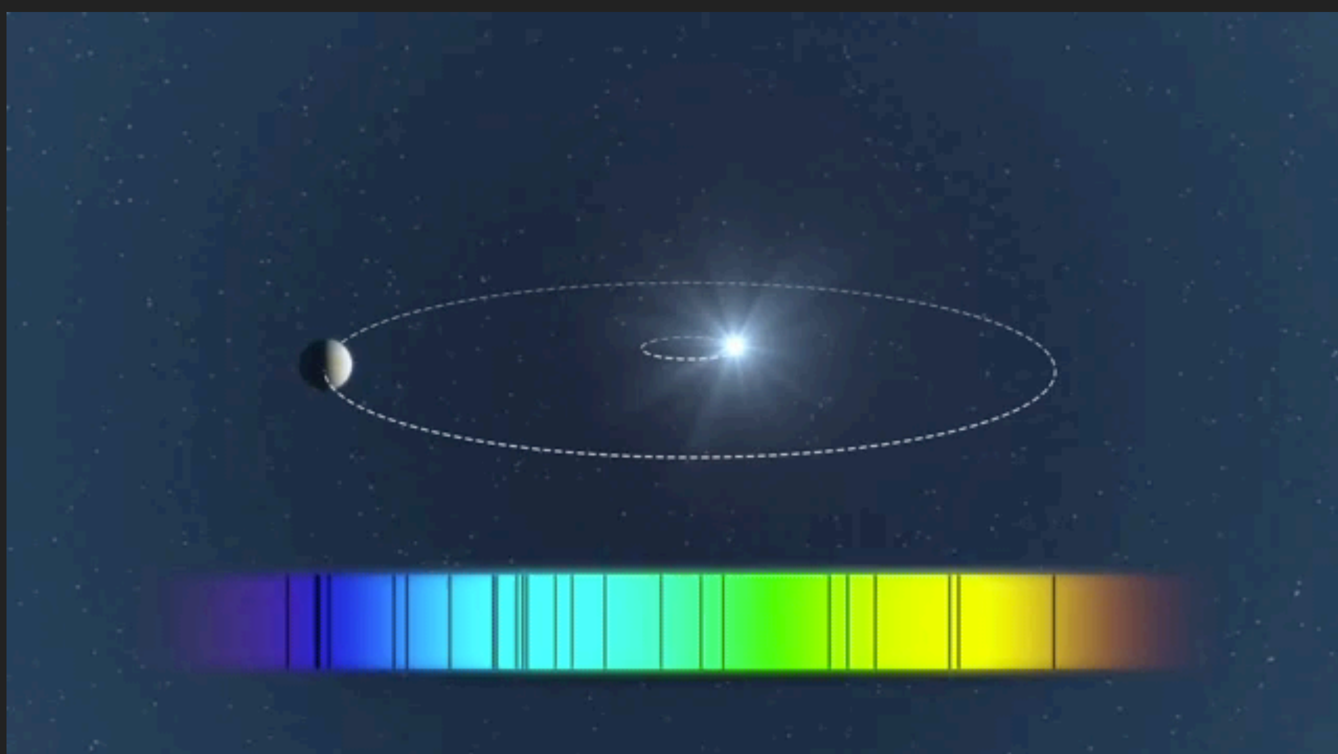

level of details
Earth
Solar System
models
observed exoplanets
level of diversity

THE MOST COMMON PLANETS
SUPER-EARTHS & MINI-NEPTUNES



HOW TO DETECT EXOPLANETS?

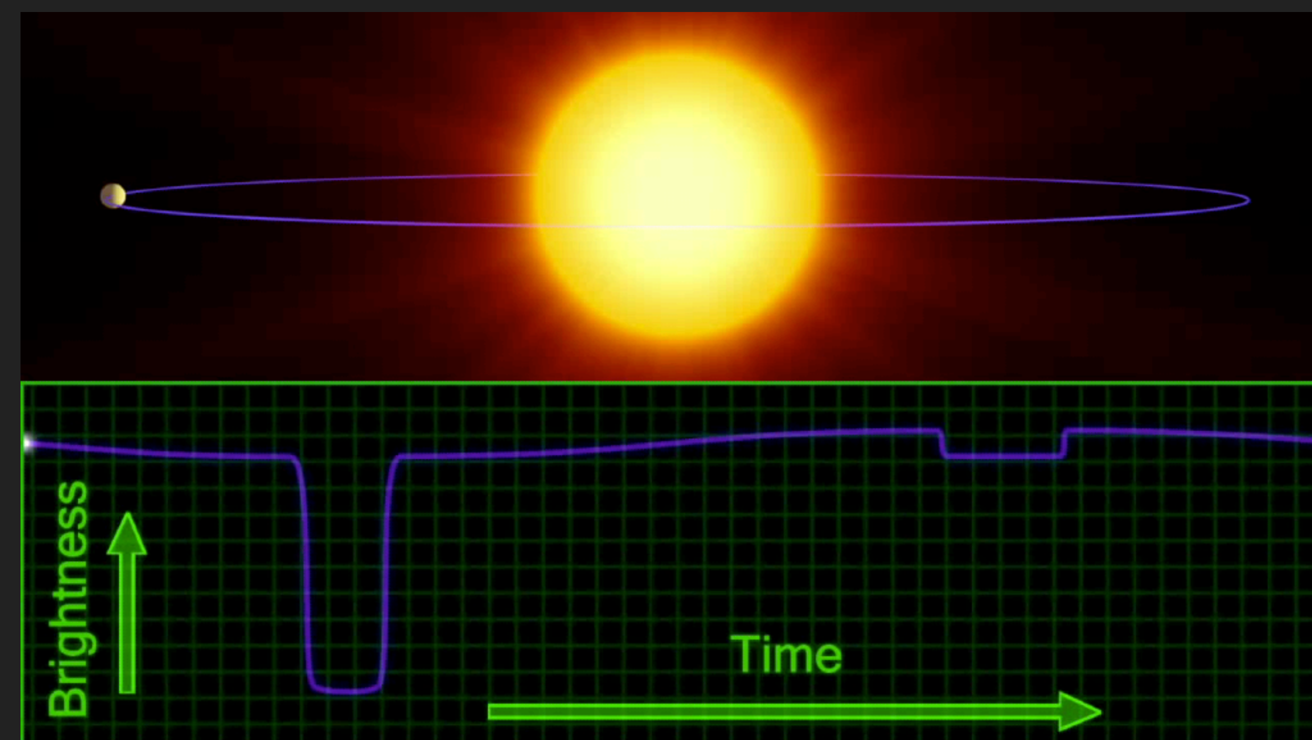
THE RADIAL VELOCITY METHOD
MEASURING STELLAR WOBBLE



> mass of planets

biased towards massive & close-in planets

THE TRANSIT METHOD
MEASURING STELLAR ECLIPSES



> radius of planets

biased towards large & close-in planets, transiting systems

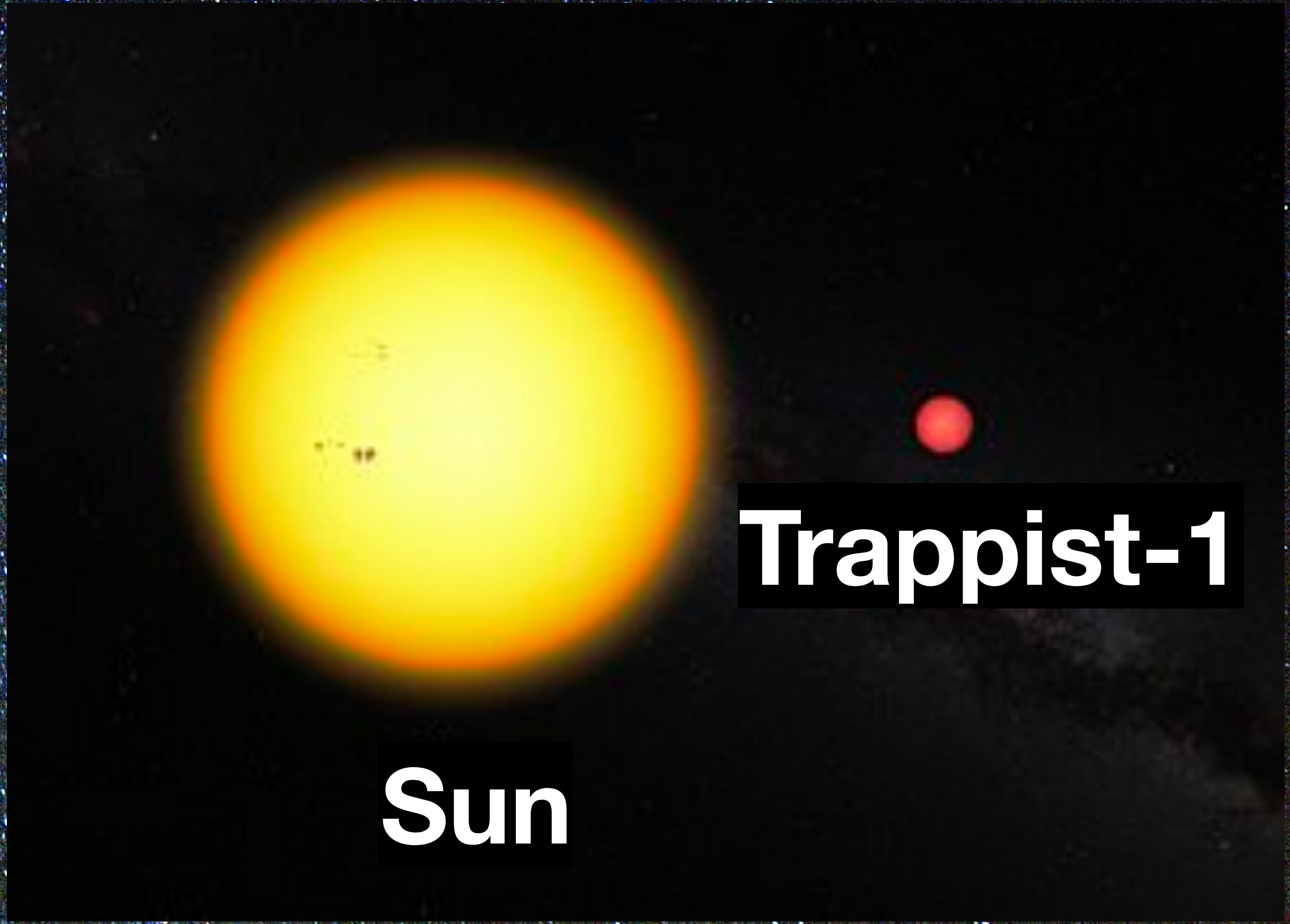
HOW TO DETECT EXOPLANETS?

TRANSIT TIMING VARIATIONS

> new planet detections, masses & eccentricities of planets in compact system

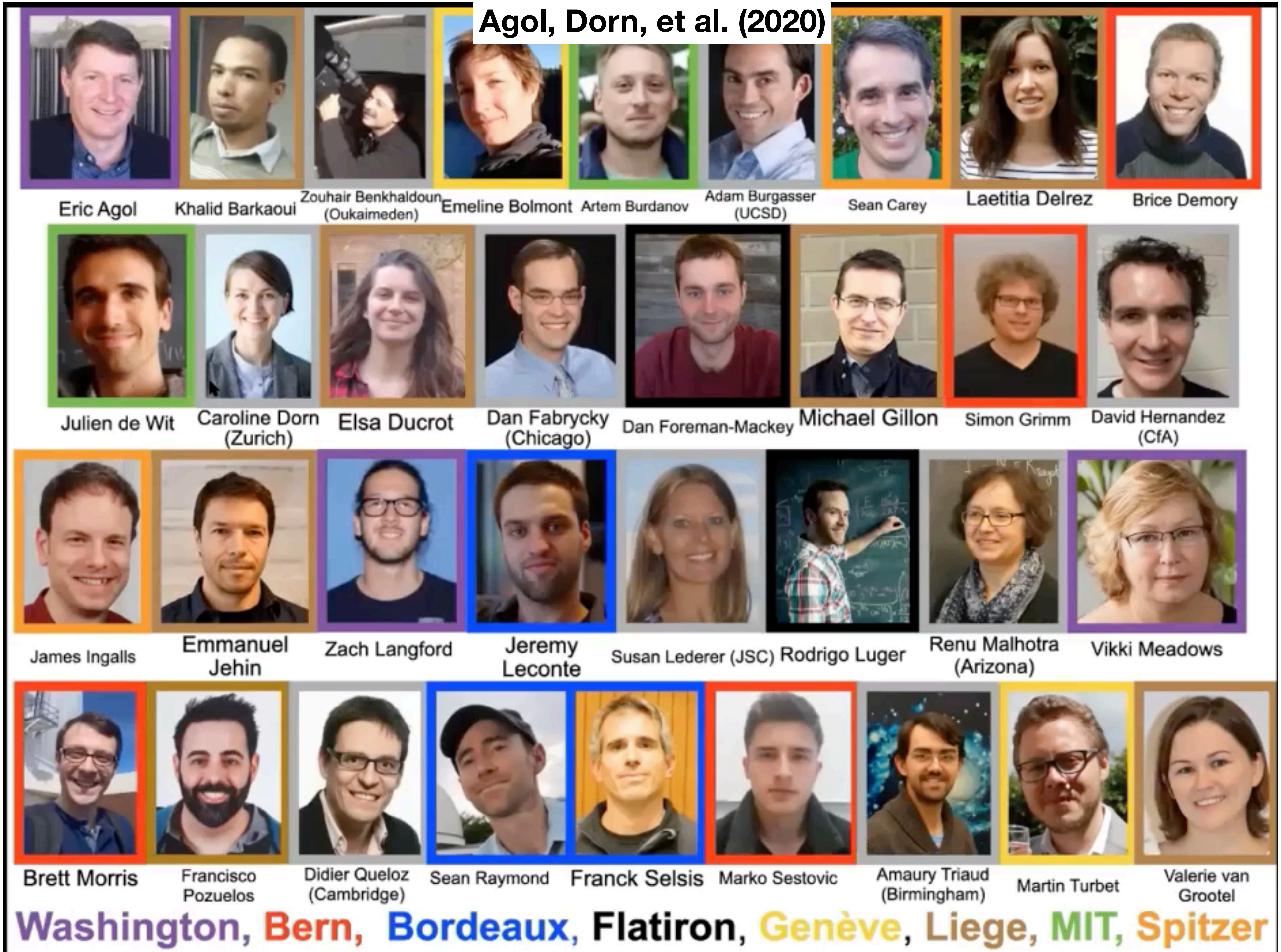
The existing worlds of Trappist-1

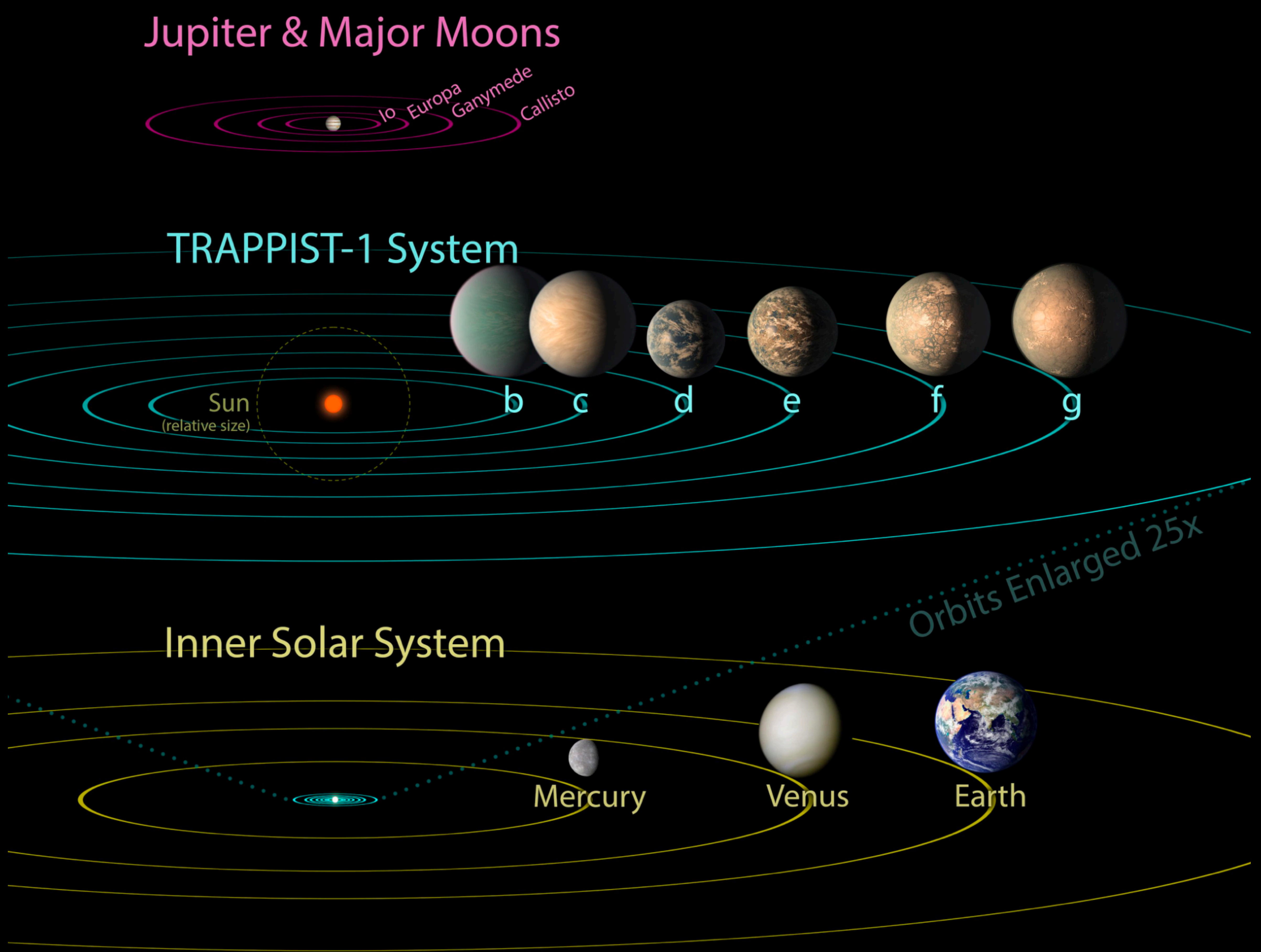
ultra-cool red dwarf star
(44% of Sun's surface temperature,
$R = 0.12\ R_{sun}$,
$M = 0.09\ M_{sun}$)



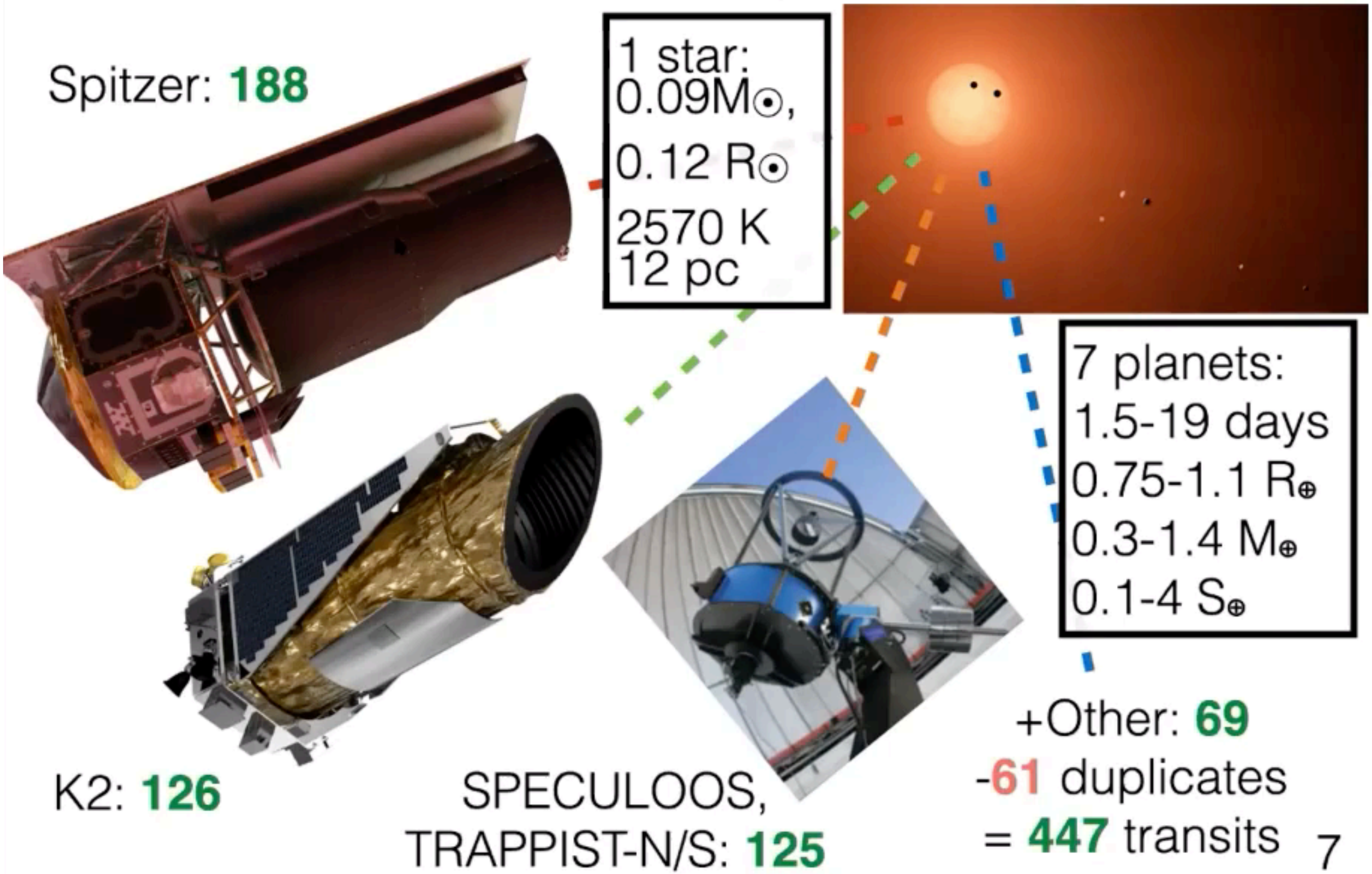
7 Earth-sized planets

incredibly precise planetary M & R


Agol, Dorn, et al. (2020)
Eric Agol
Khalid Barkaoui
Zouhair Benkhaldoun (Oukaimeden)
Emeline Bolmont
Artem Burdanov
Adam Burgasser (UCSD)
Sean Carey
Laetitia Delrez
Brice Demory
Julien de Wit
Caroline Dorn (Zurich)
Elsa Ducrot
Dan Fabrycky (Chicago)
Dan Foreman-Mackey
Michael Gillon
Simon Grimm
David Hernandez (CfA)
James Ingalls
Emmanuel Jehin
Zach Langford
Jeremy Leconte
Susan Lederer (JSC)
Rodrigo Luger
Renu Malhotra (Arizona)
Vikki Meadows
Brett Morris
Francisco Pozuelos
Didier Queloz (Cambridge)
Sean Raymond
Franck Selsis
Marko Sestovic
Amaury Triaud (Birmingham)
Martin Turbet
Valerie van Grootel
Washington, Bern, Bordeaux, Flatiron, Genève, Liege, MIT, Spitzer


Jupiter & Major Moons
Io
Europa
Ganymede
Callisto
TRAPPIST-1 System
Sun
(relative size)
b
c
d
e
f
g
Orbits Enlarged 25x
Inner Solar System
Mercury
Venus
Earth

Transit timing survey



7

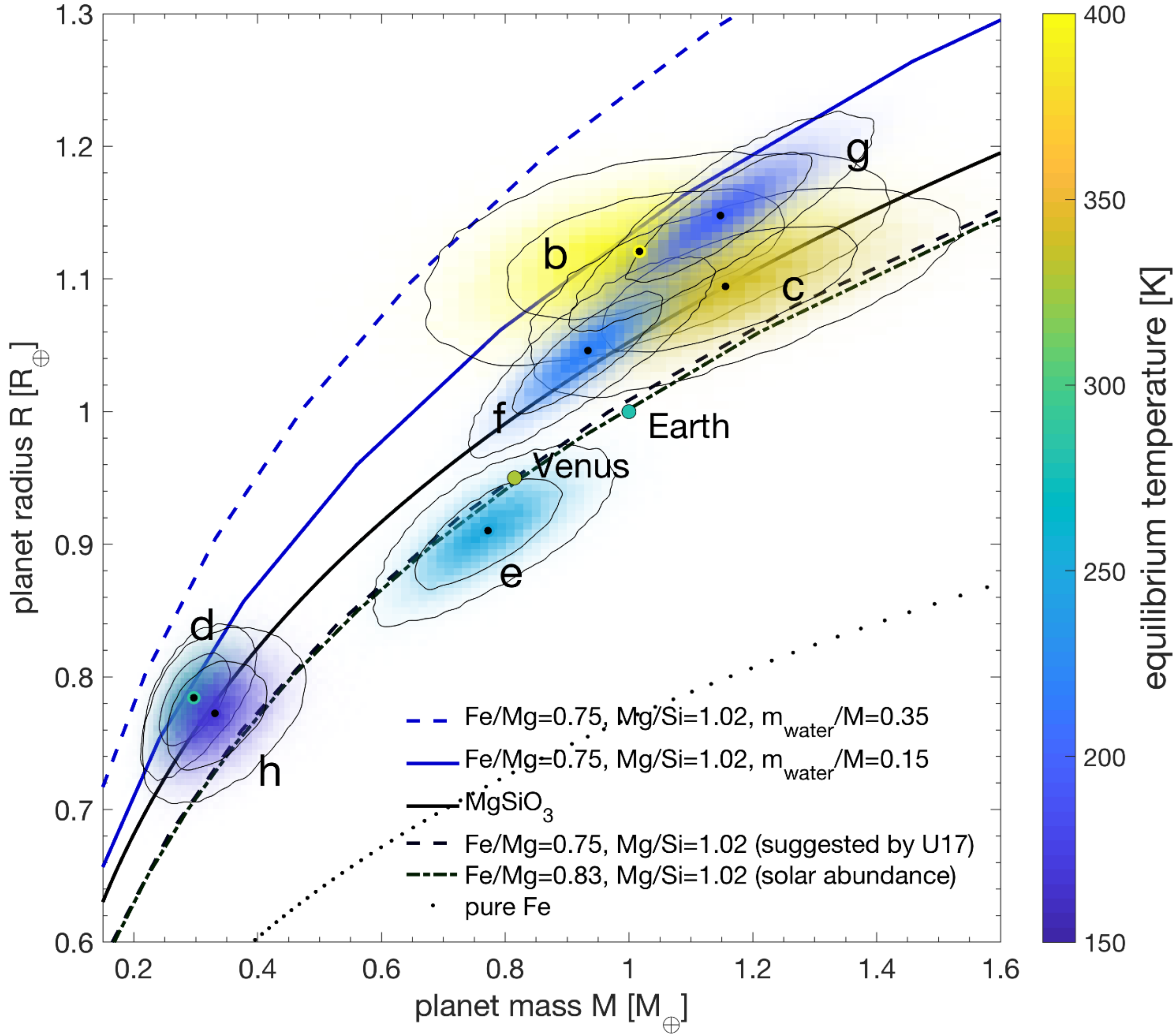
Transit-timing precision

- Signal-to-noise scales as:

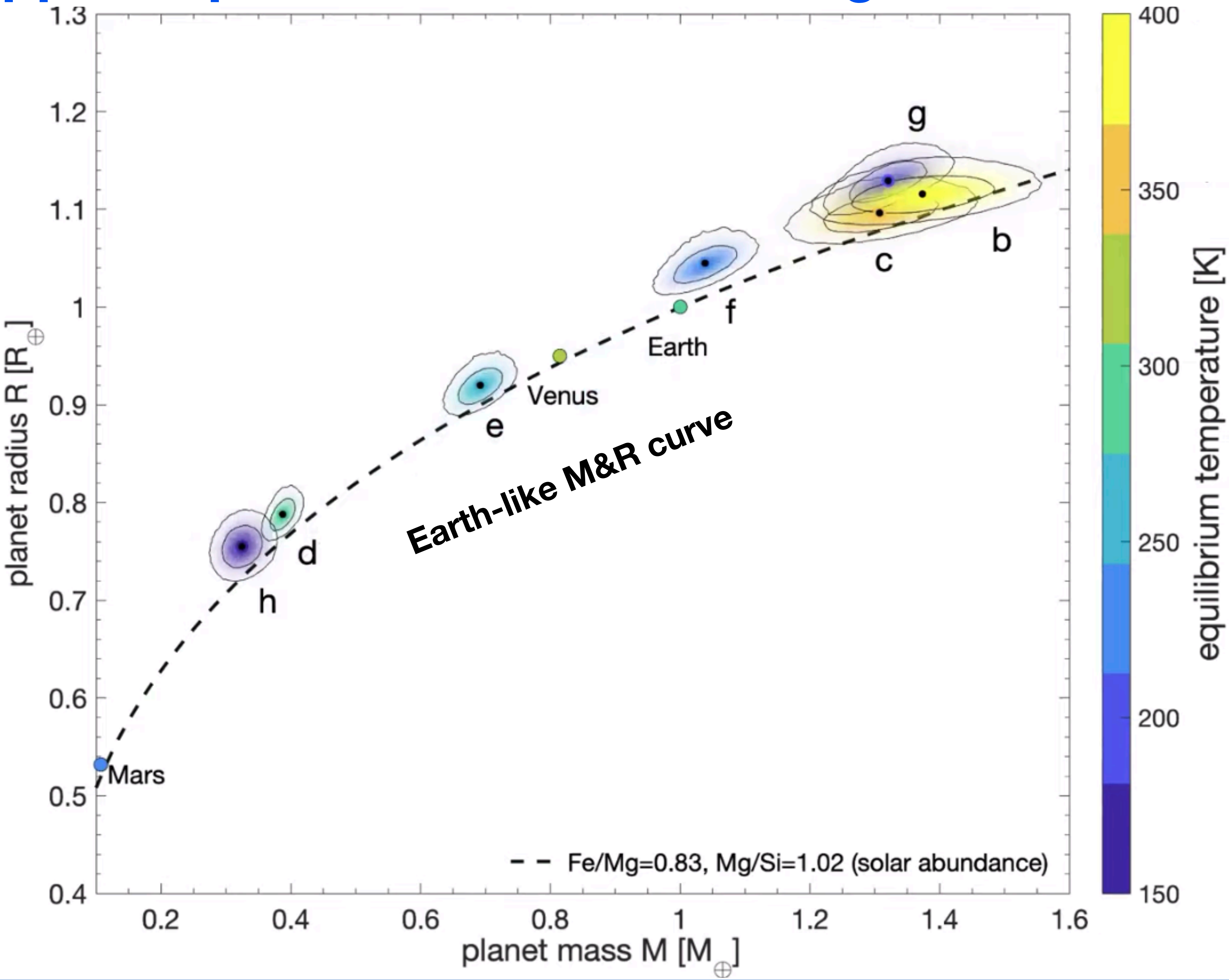
$$S/N \propto \frac{\left(\text{mass of planet}\right)}{\left(\text{mass of star}\right)^{5/6}} \frac{\left(\text{radius of planet}\right)^{3/2}}{\left(\text{radius of star}\right)^{2}} \frac{\left(\text{Orbital period}\right)^{5/6}}{\text{Distance to star}}$$

- The small mass of TRAPPIST-1 increases the signal.
- The small radius of TRAPPIST-1 & close proximity decreases the noise.
- In addition, the short orbital period makes it easier to observe many transits and takes less time to sample the TTV timescale, P_{TTV}.

Estimates from Grimm et al. 2018



Trappist-1 planets can be fit to single M-R-trend



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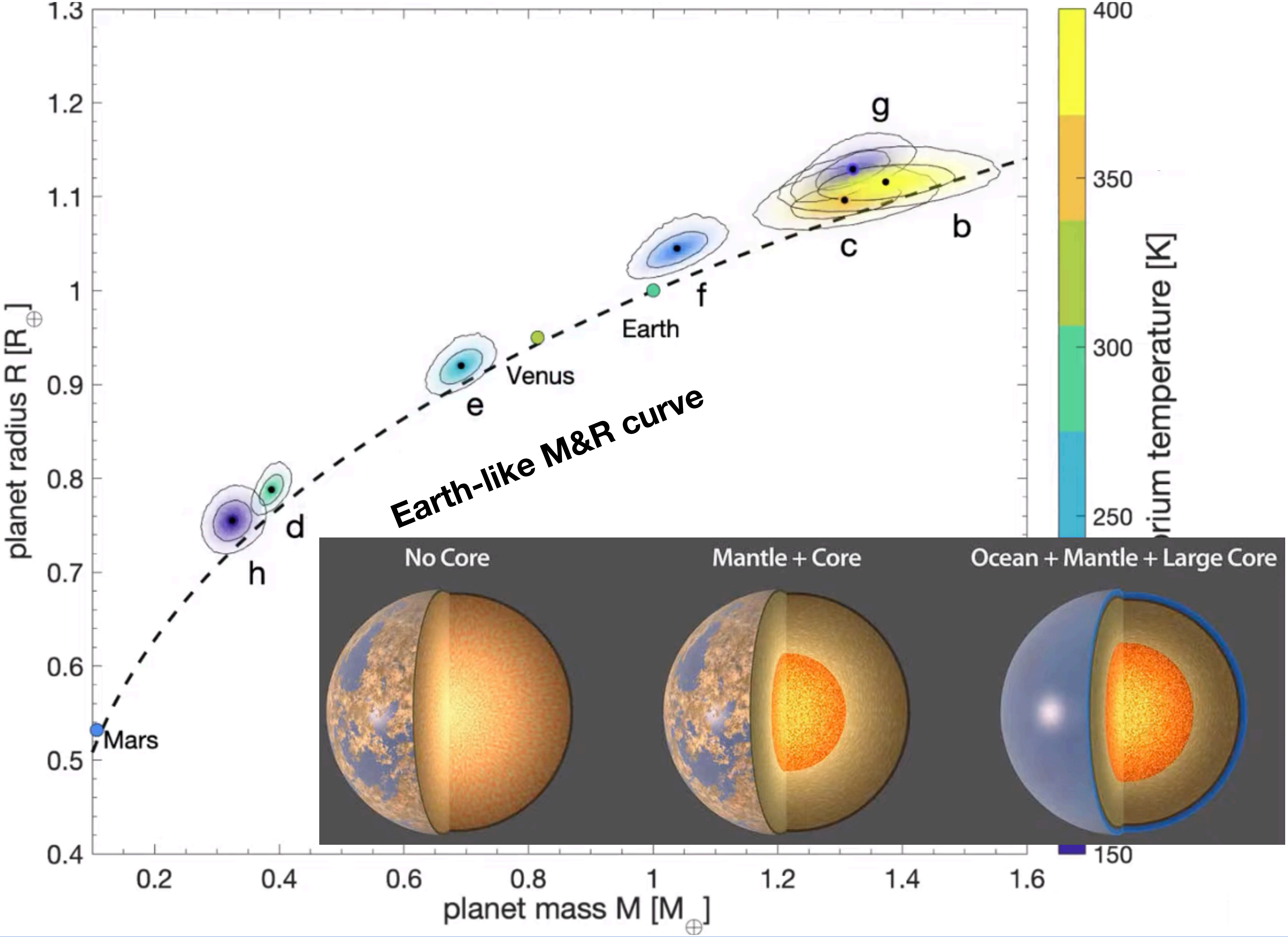
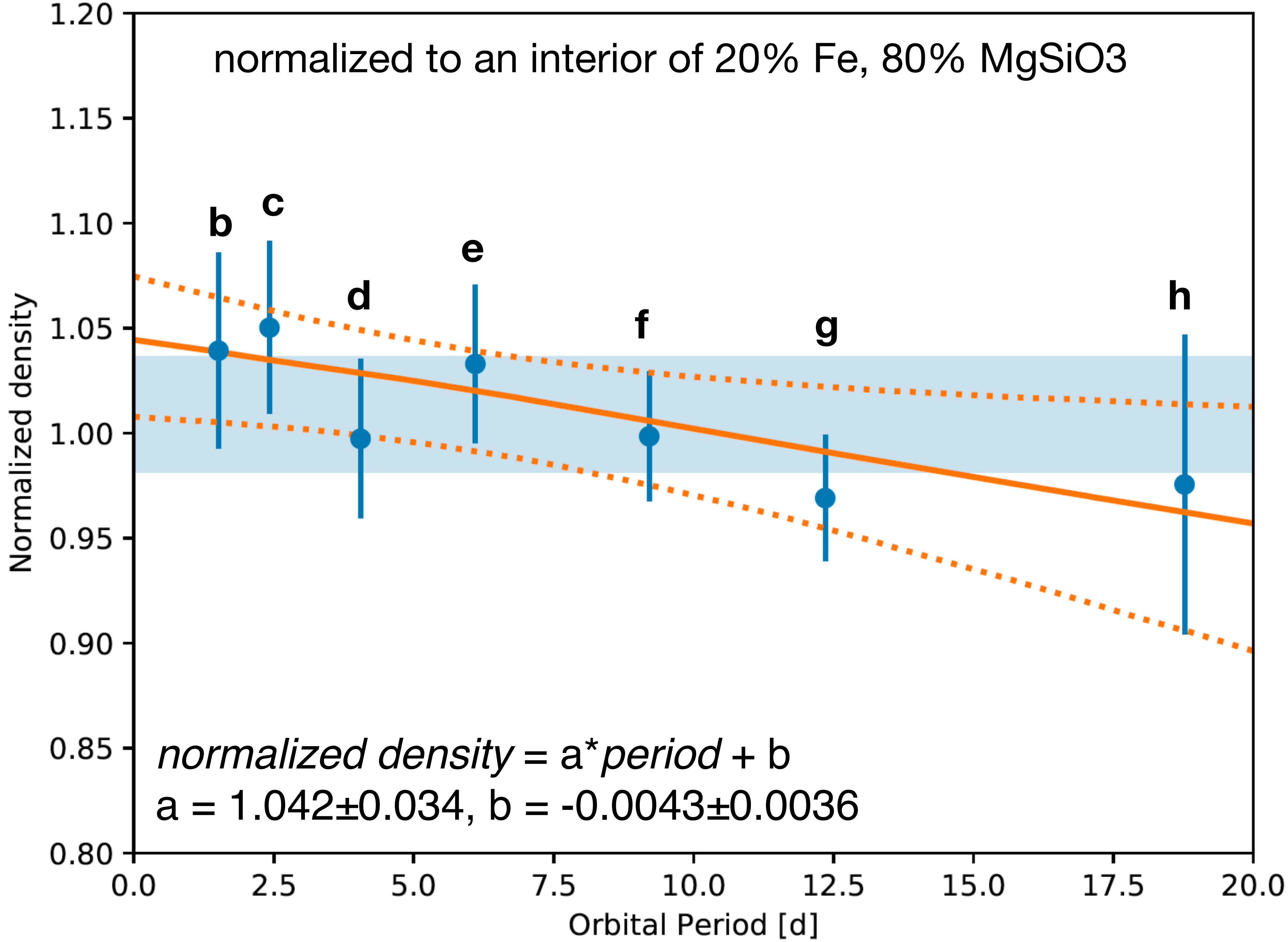
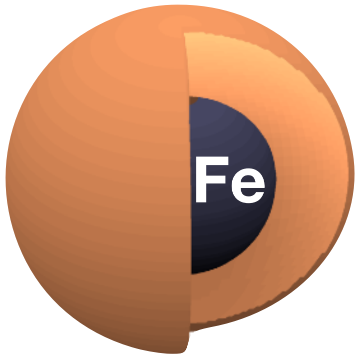
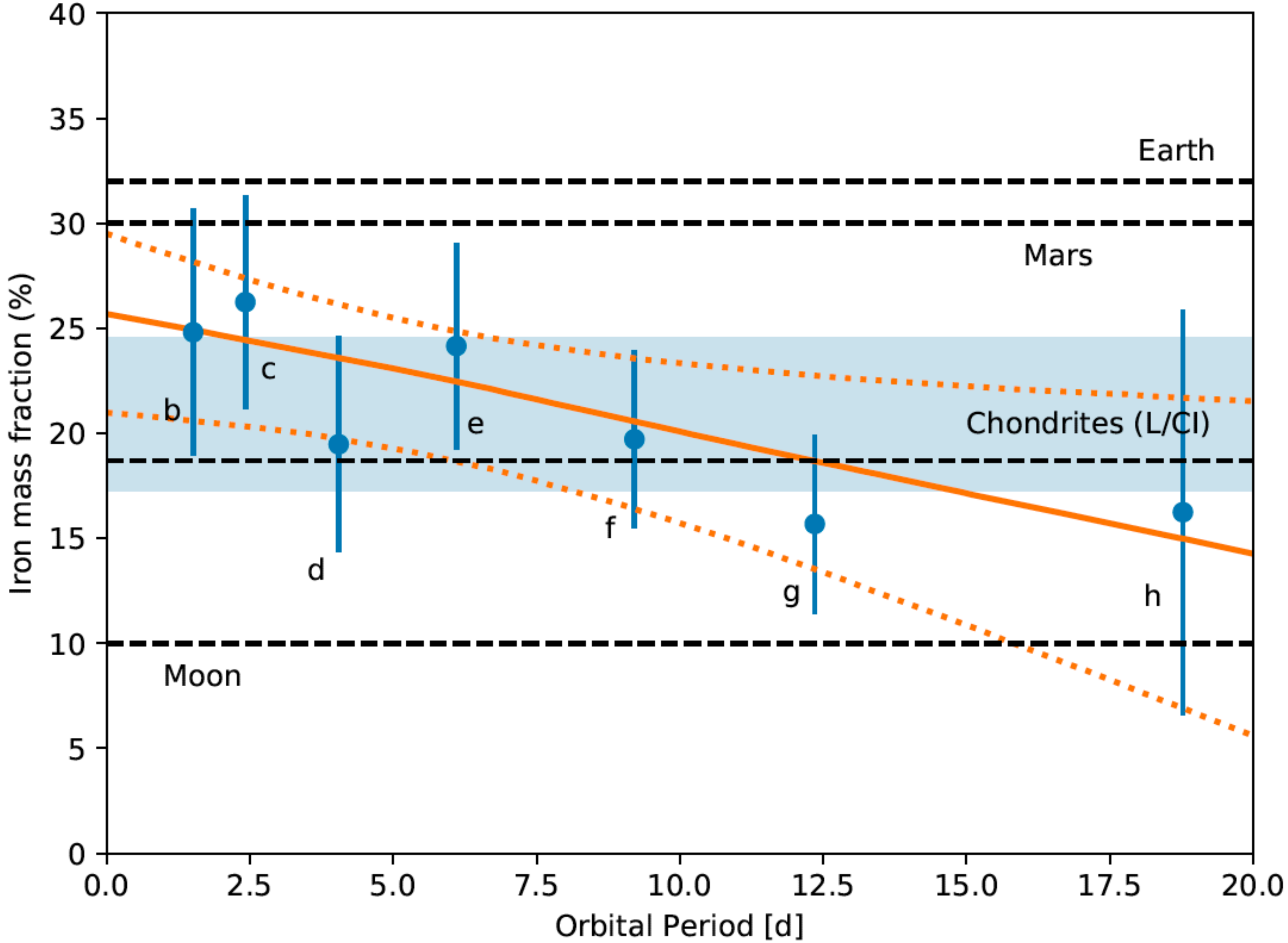



normalized to an interior of 20% Fe, 80% MgSiO3
b
c
d
e
f
g
h
normalized density = a*period + b
a = 1.042±0.034, b = -0.0043±0.0036
Normalized density
Orbital Period [d]
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

Rock composition
-> lower iron content

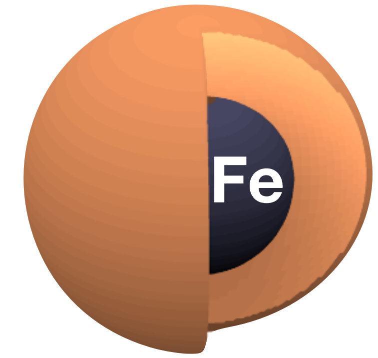


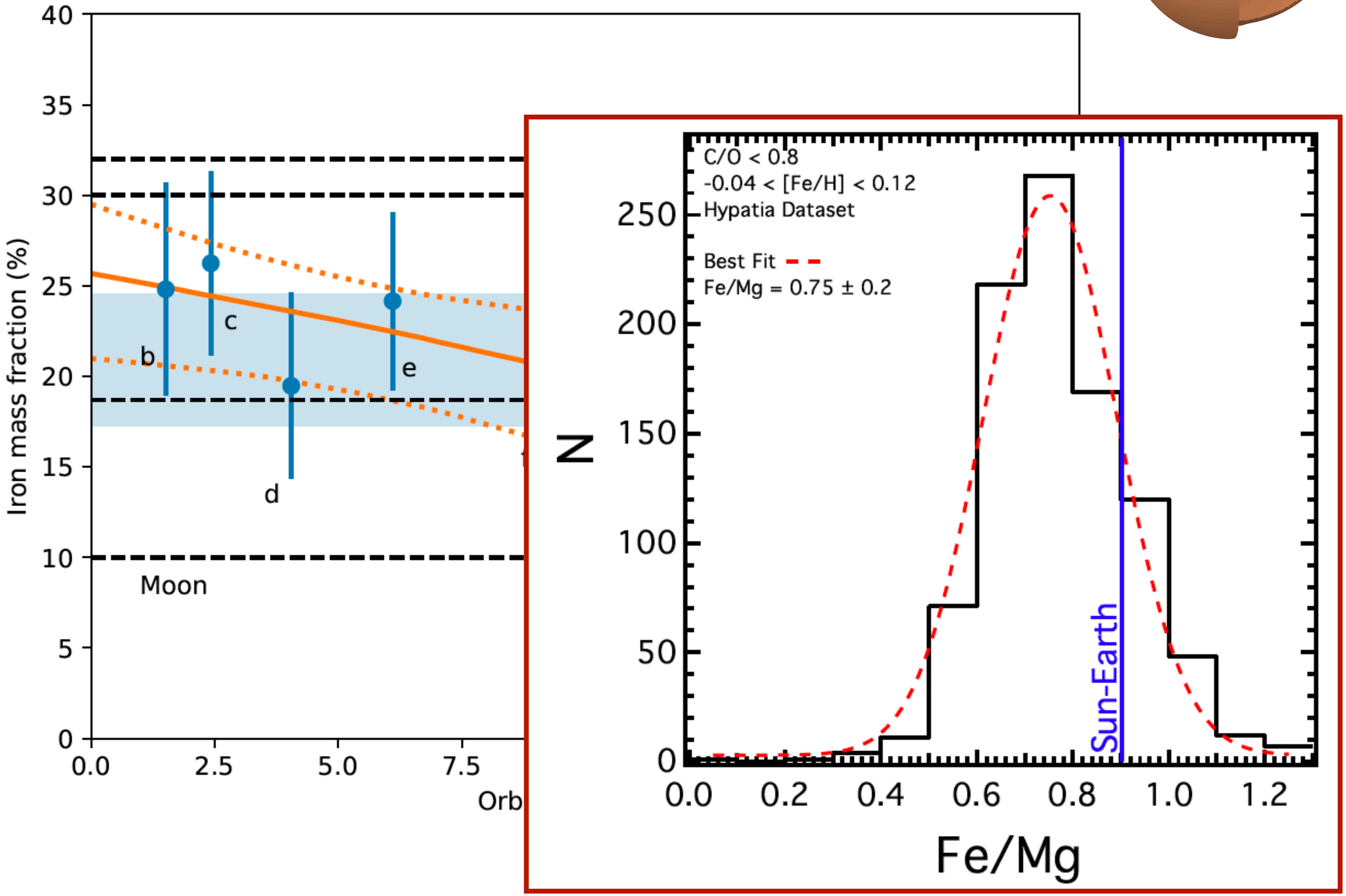


Rock composition

-> lower iron content

low iron content predicted given abundances of stars similar to T1

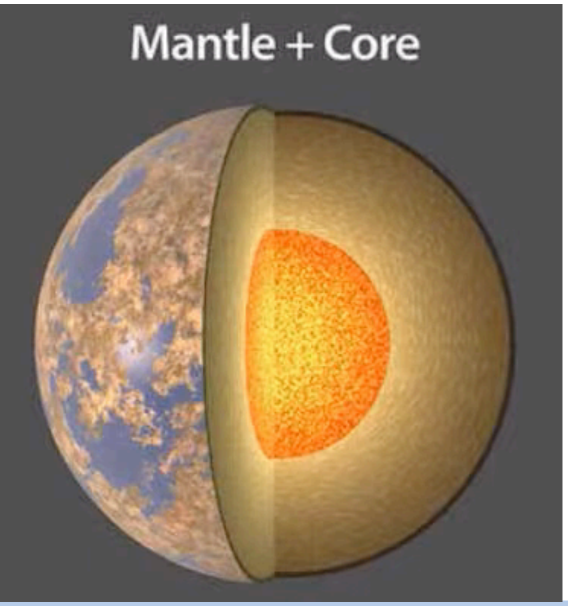


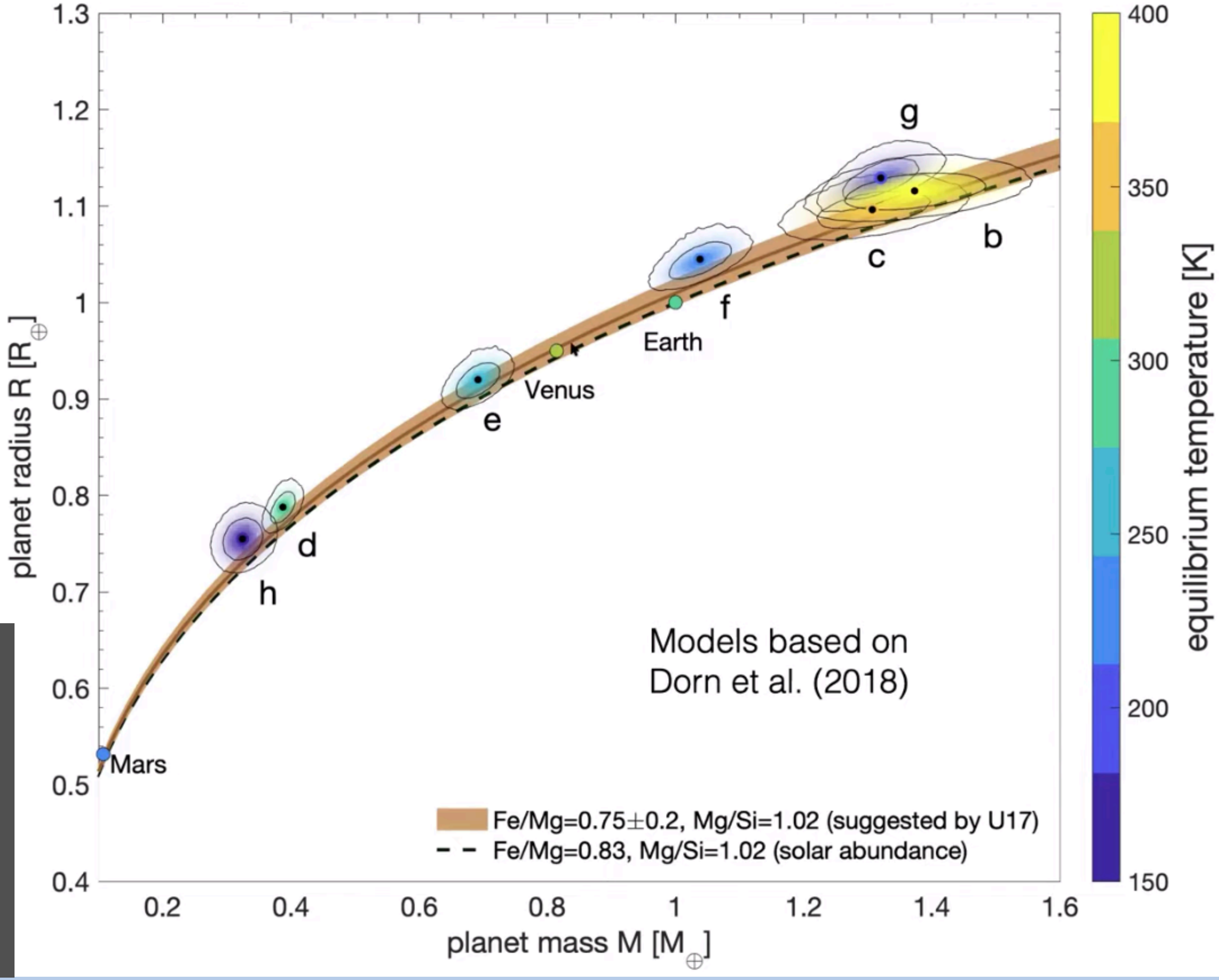


Unterborn et al. (2017)

Rock composition

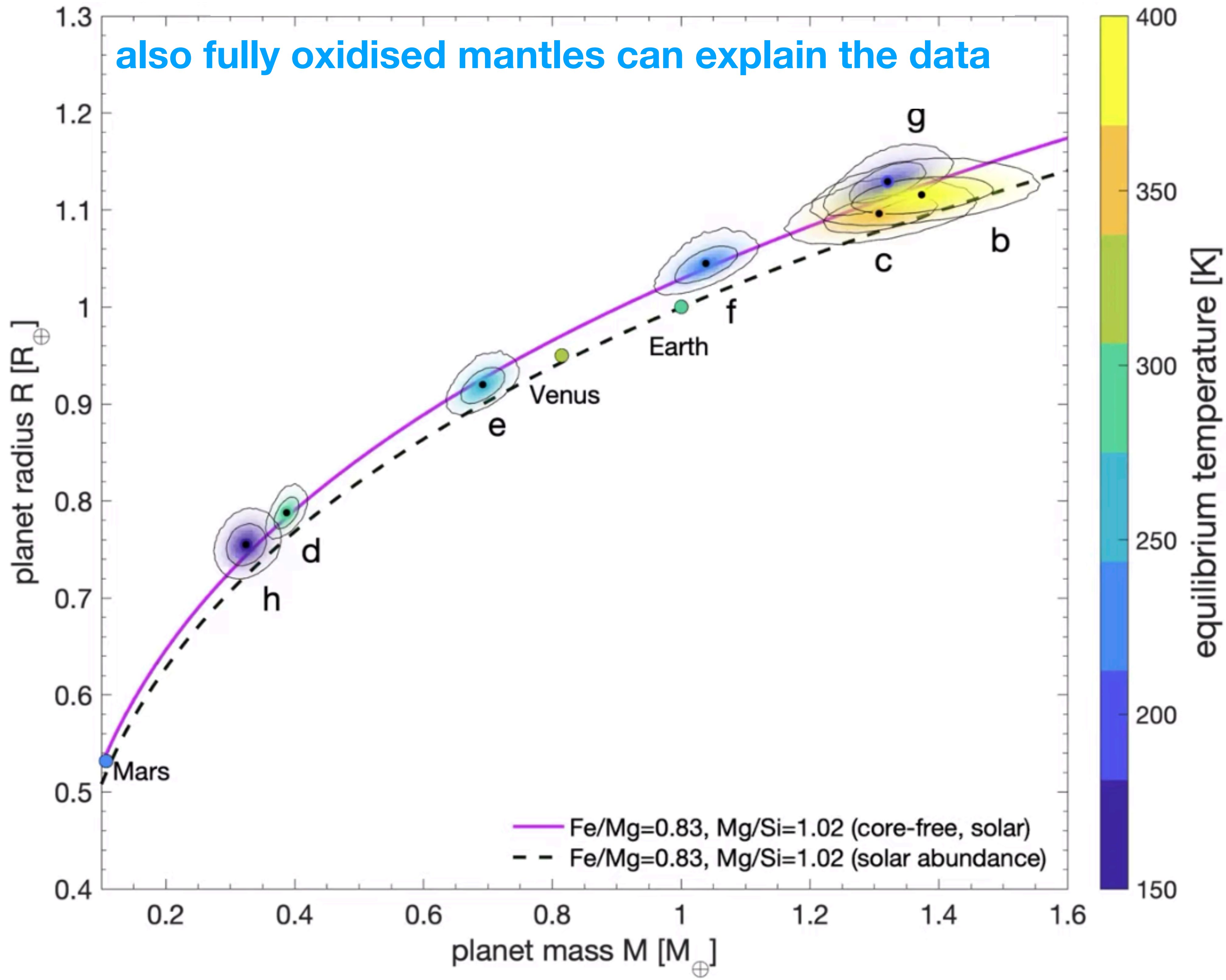
-> lower iron content

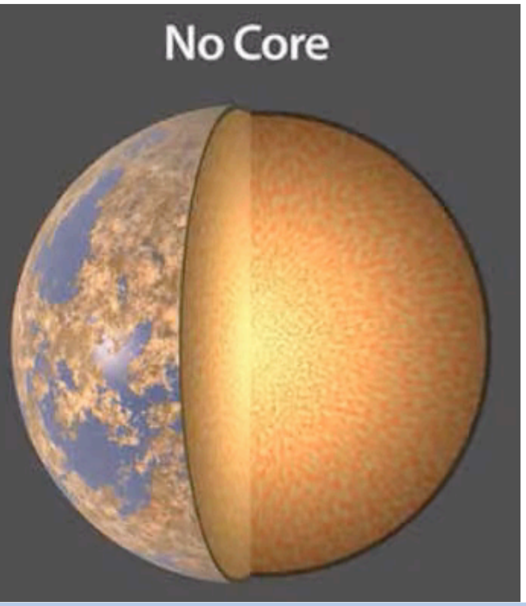




Rock composition

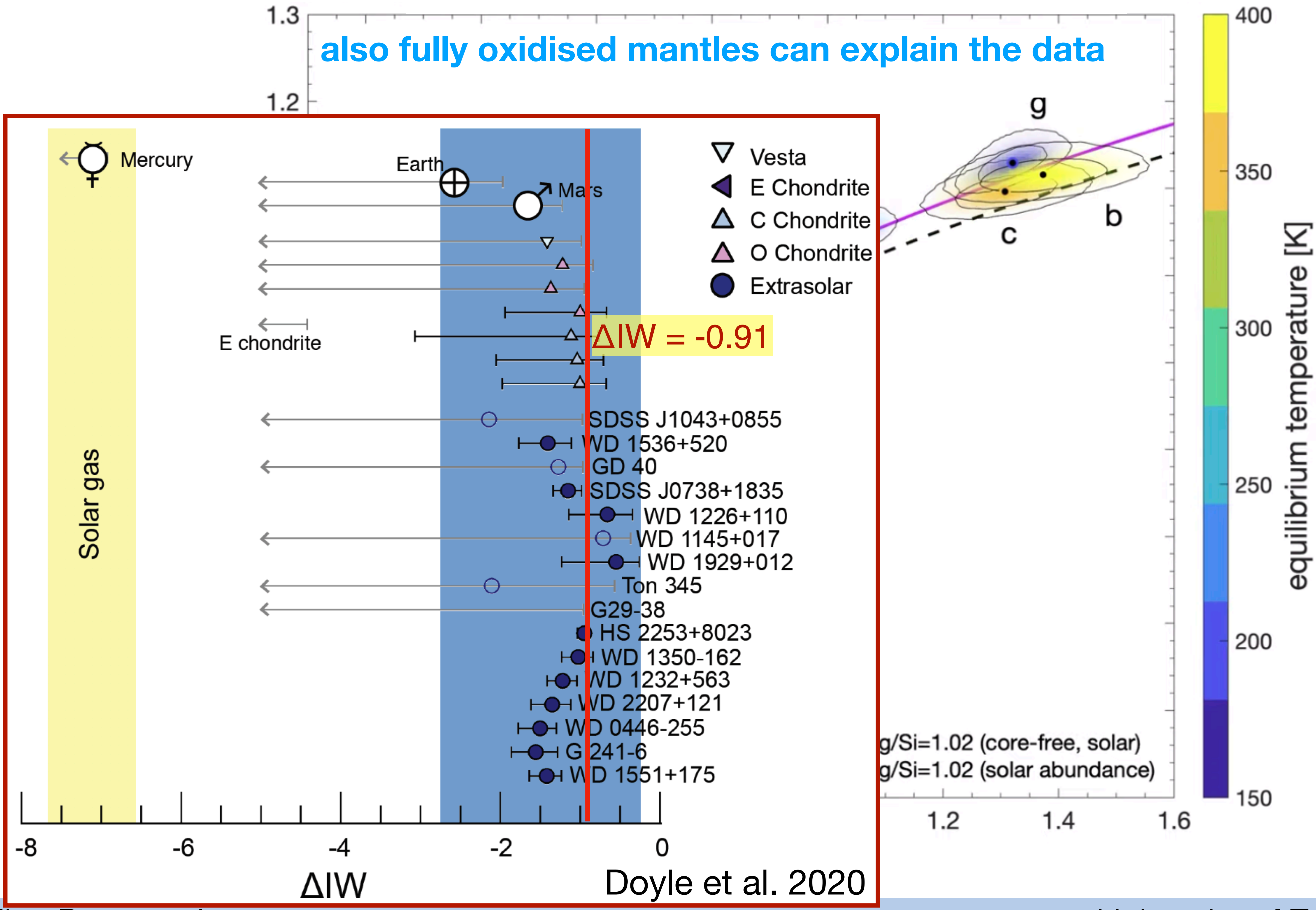
-> higher oxygen content





Rock composition

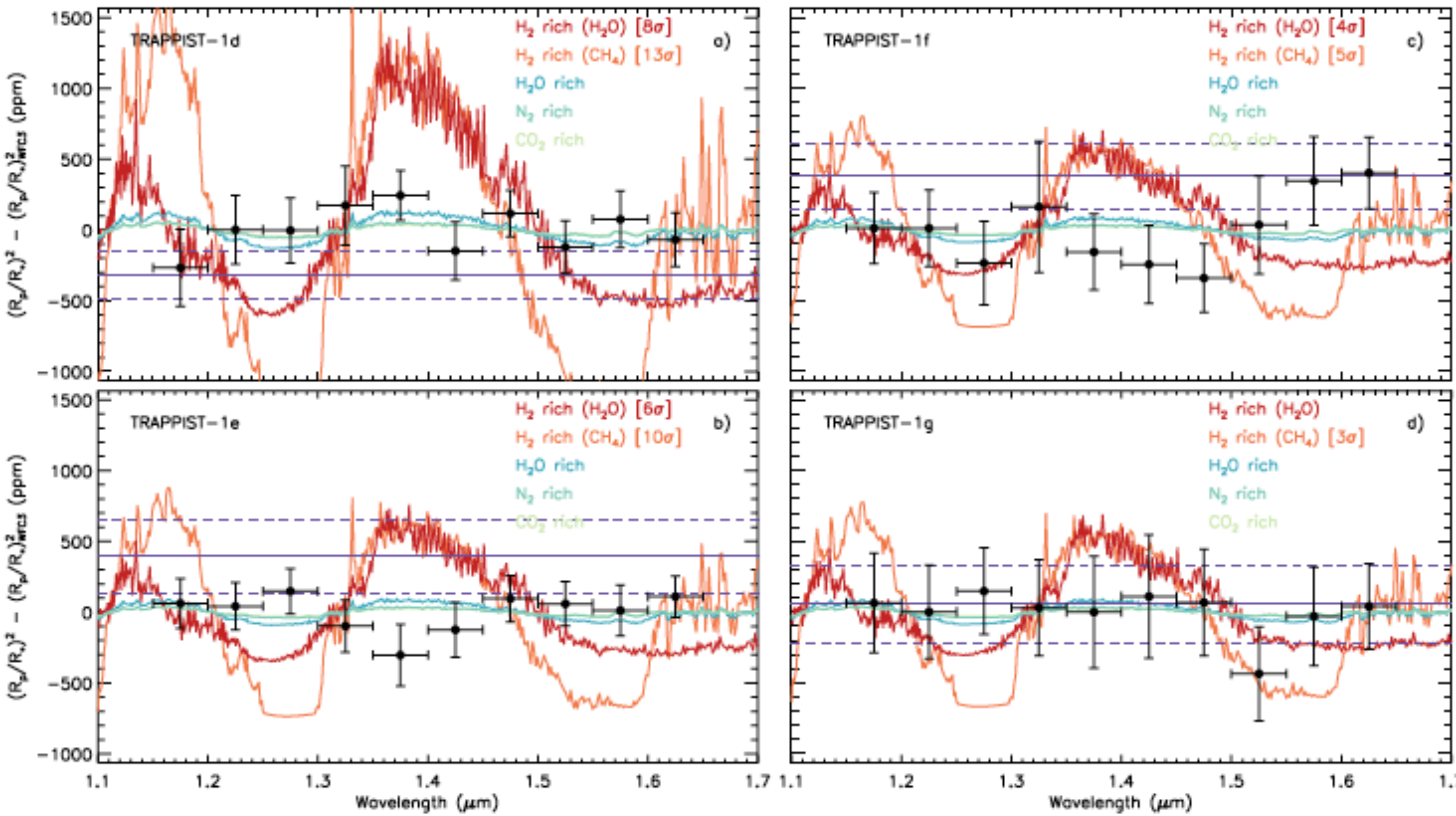
-> higher oxygen content



Volatile abundance (H/He)

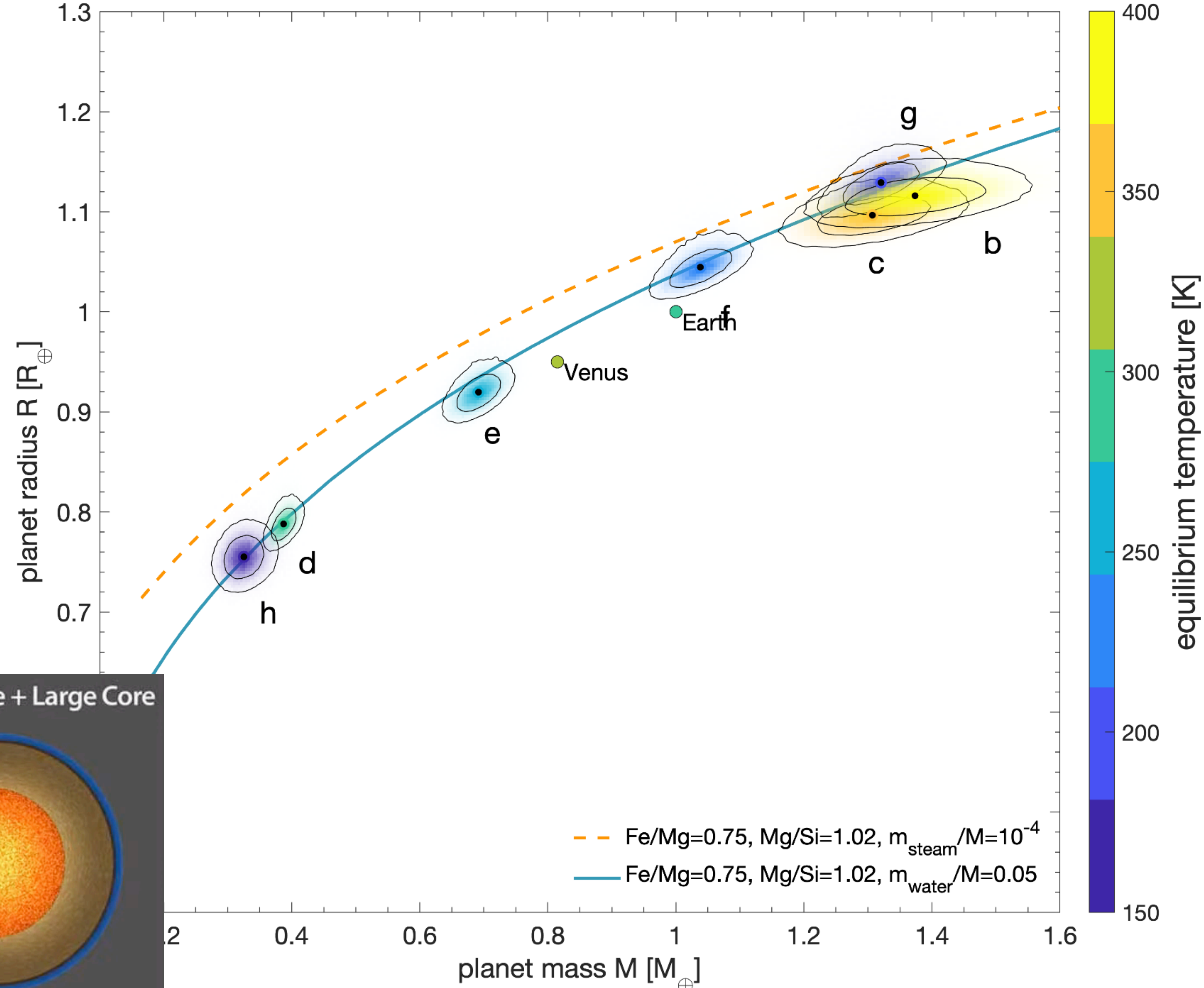
see also Zhang+2018, Moran +2018 Ducrot+2020

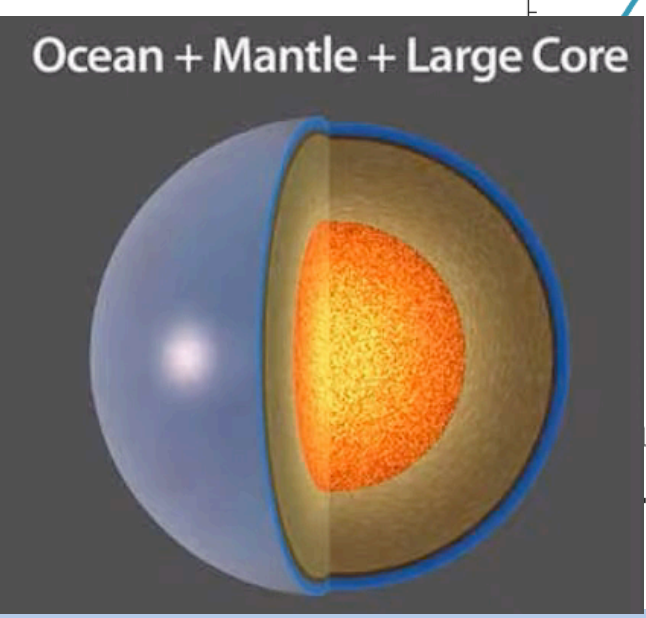
Cloud-free hydrogen-dominated atmospheres are ruled out
for planet b, c, d, e, f, g



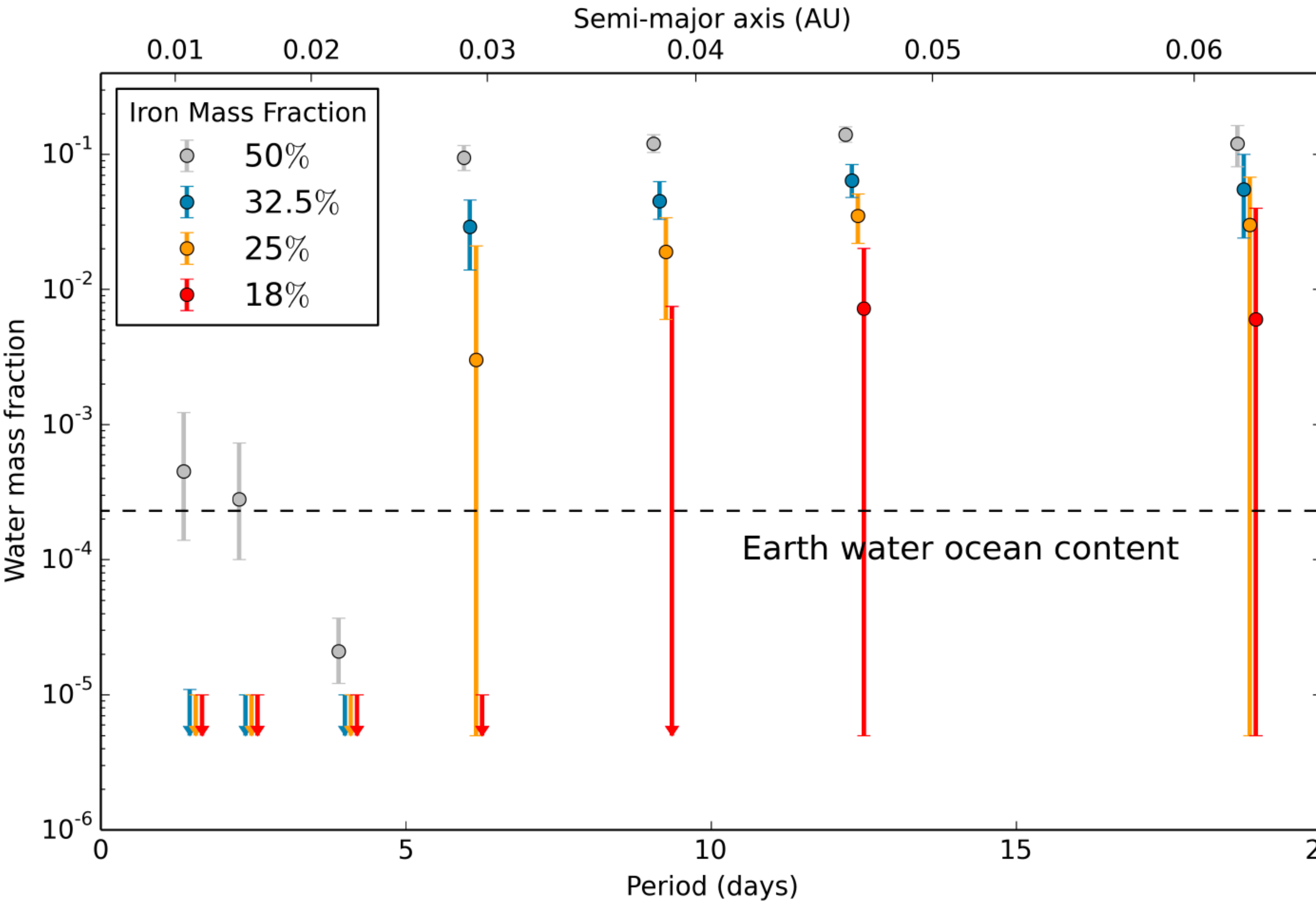
de Wit+(2016, 2018), Wakeford+2018

Volatile abundance (H_2O)





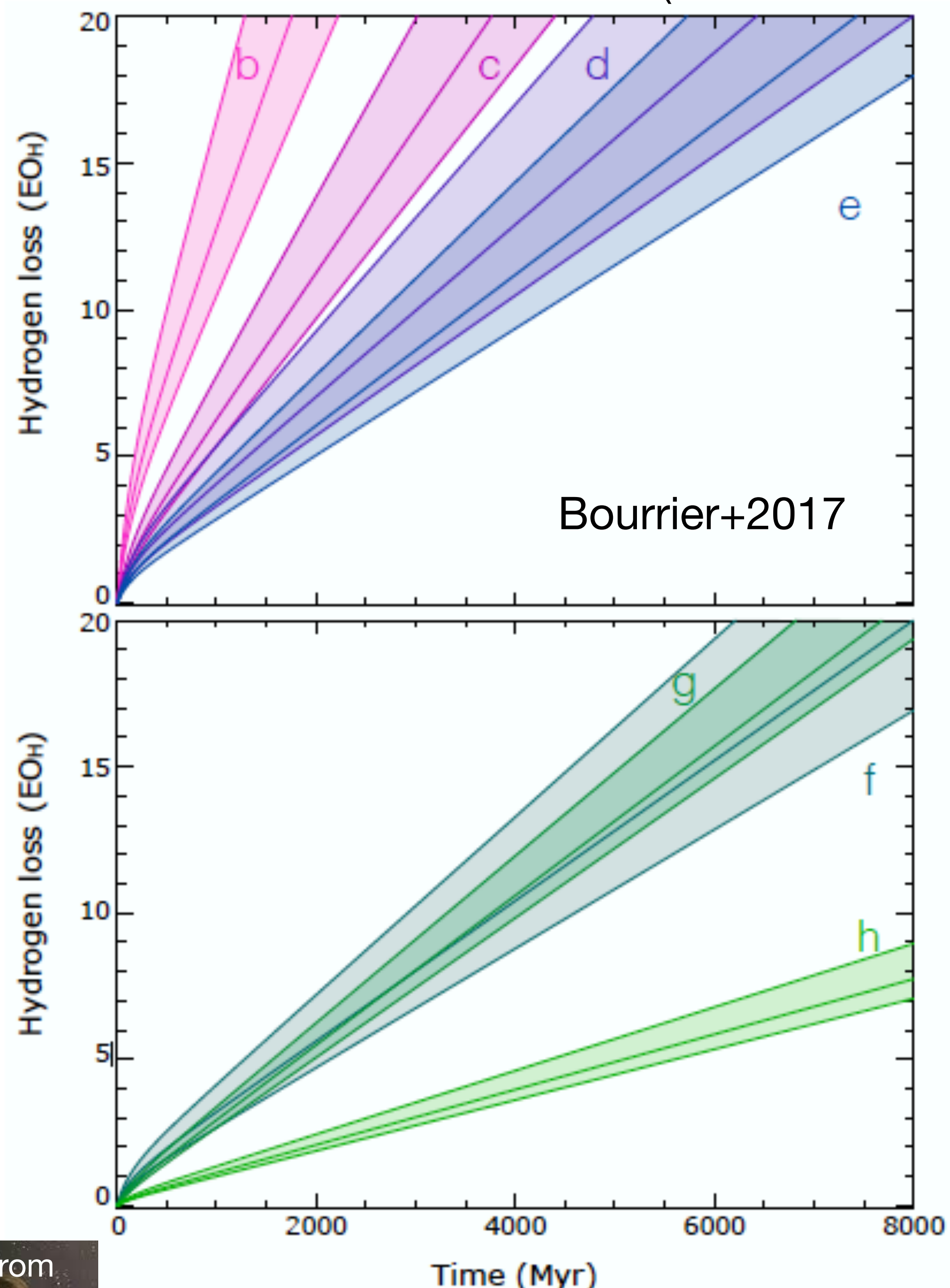
Volatile abundance (H_2O)



Volatile (H_2O) content of TRAPPIST-1 planets *over time*

water loss (evaporative loss)

max. **100 Earth oceans** can be lost (for b:~ 0.023 M_p)



(b) Evolving XUV luminosity

see Bolmont+2017,
Roettenbacher & Kane 2017, Wheatley et al. 2017, Becker et al. 2020,
Peacock et al. 2019, Fleming et al. 2020, Hori & Ogihara 2020

likely *all* planets have lost a significant fraction of their initial atmosphere.. or maybe completely lost it

erosion can remove up to 1-10% of the total planetary mass in volatiles

late water accretion

cometary impactors on the TRAPPIST-1 planets can destroy all planetary atmospheres

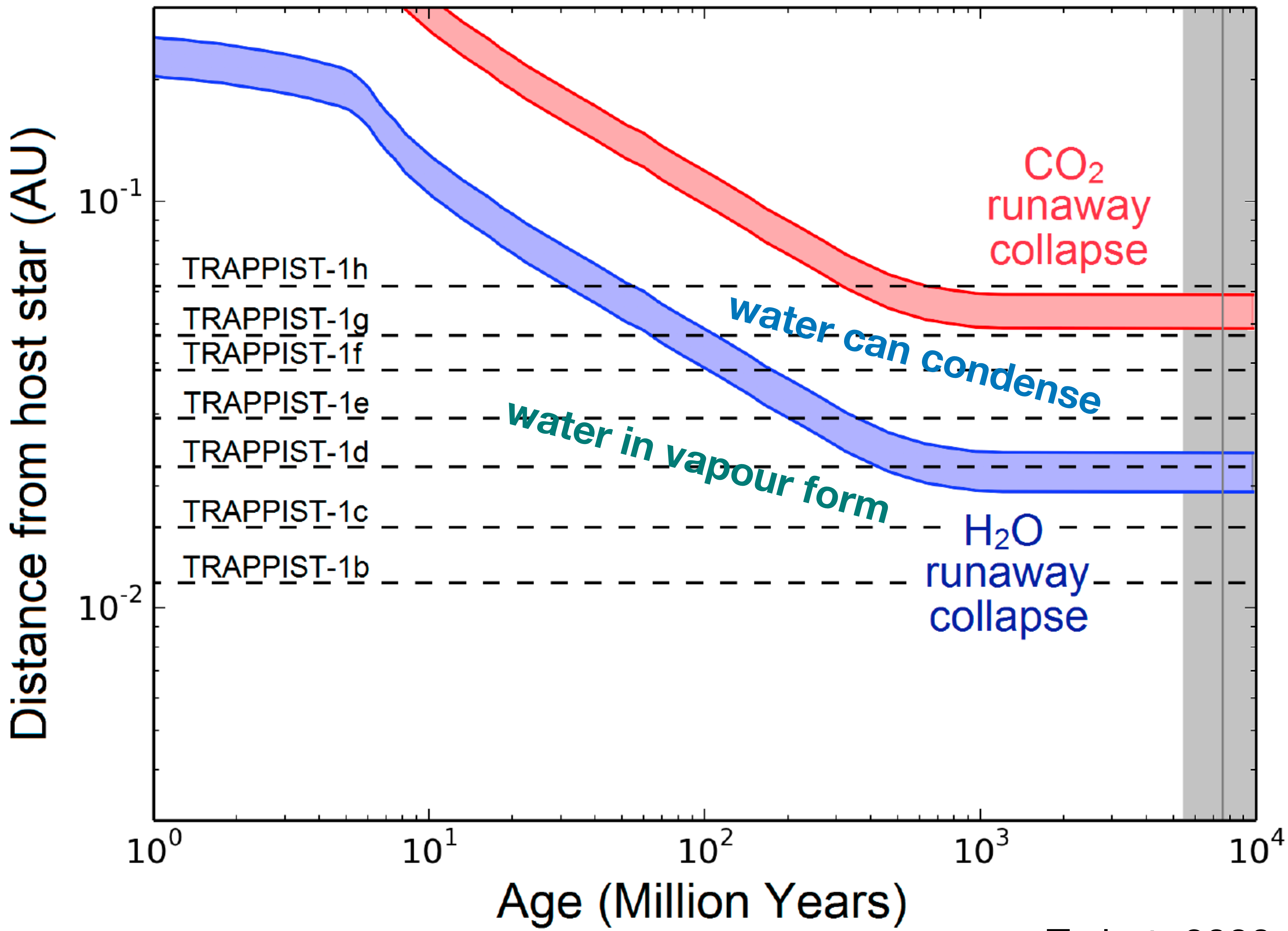
1 Earth ocean of water can be added & thereby rebuild a secondary atmospheres on **planets f, g, h**

Kral+2018, Dencs and Regàly 2019

H_2O oceans / steam atmospheres

in general possible atmosphere species include

H2O, CO2, CH4, N2

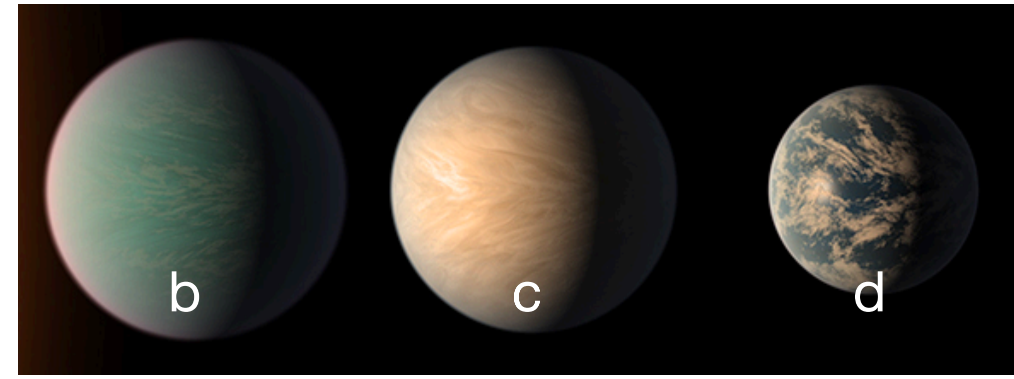


Turbet+2020

see Turbet+2020 for a review

innermost planets:

- if **water steam,** if not lost its limited to $\mathbf{M_{water} < 10^{-5}\ M_p}$
- **planet b, c, (d)** beyond the runaway greenhouse limit

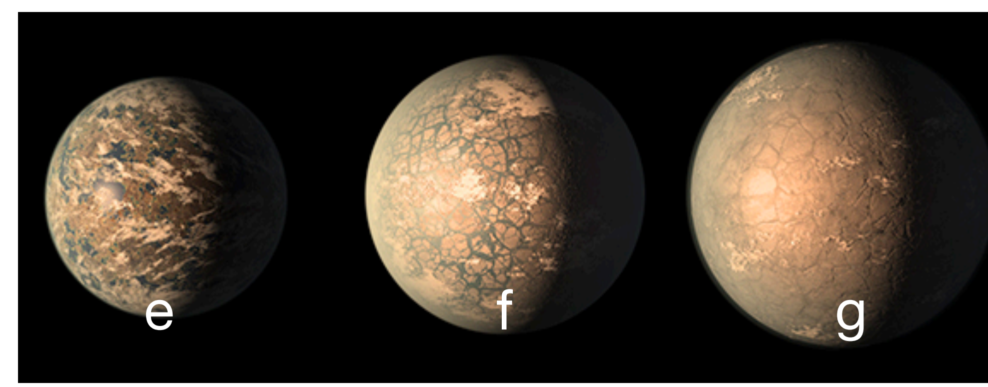


Trappist-1e:

- can sustain **liquid water** on its surface (Turbet+2017, 2020, Grimm+2018)
- if it has a high density, water fraction can be small (i.e., Earth-like)
- high potential for surface habitability

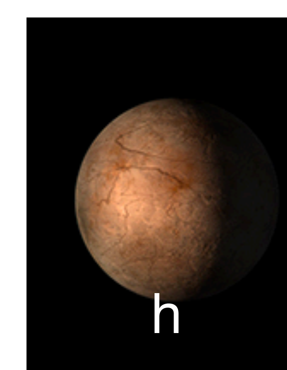
Trappist-1e, f, g:

- can sustain **liquid water** on its surface, with moderate amounts of CO2 needed (Turbet+2017, 2020, Grimm+2018)

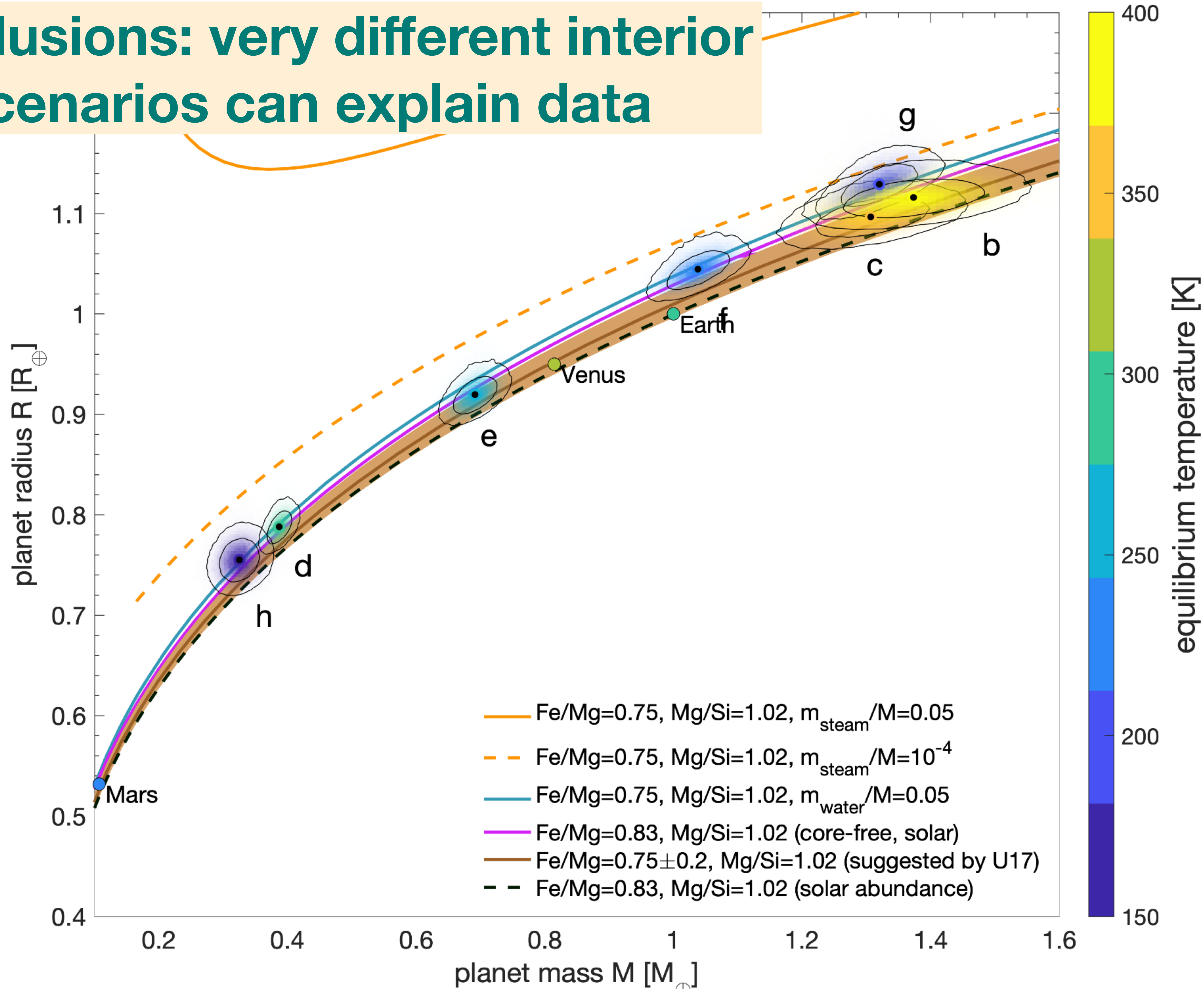


outermost planet:

- **H_2O and CO_2** would be in solid form, (e.g., Turbet+2017, 2020, Wolf+2017)
- possible **CO2 atmosphere in special conditions only**



Conclusions: very different interior scenarios can explain data



FNSNF
Swiss National Science Foundation

PlanetS
National Centre of Competence in Research

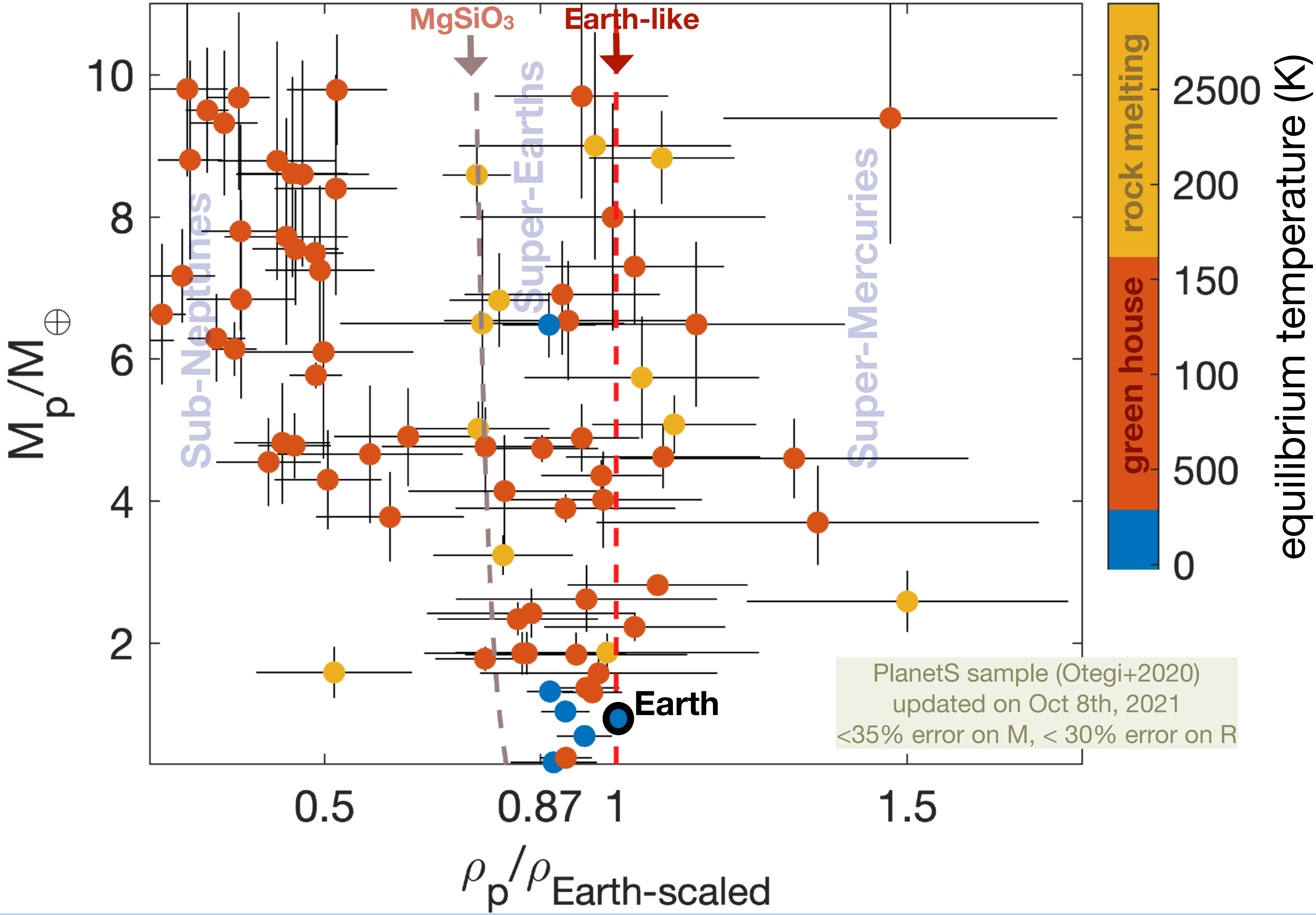
Hidden water in magma ocean exoplanets

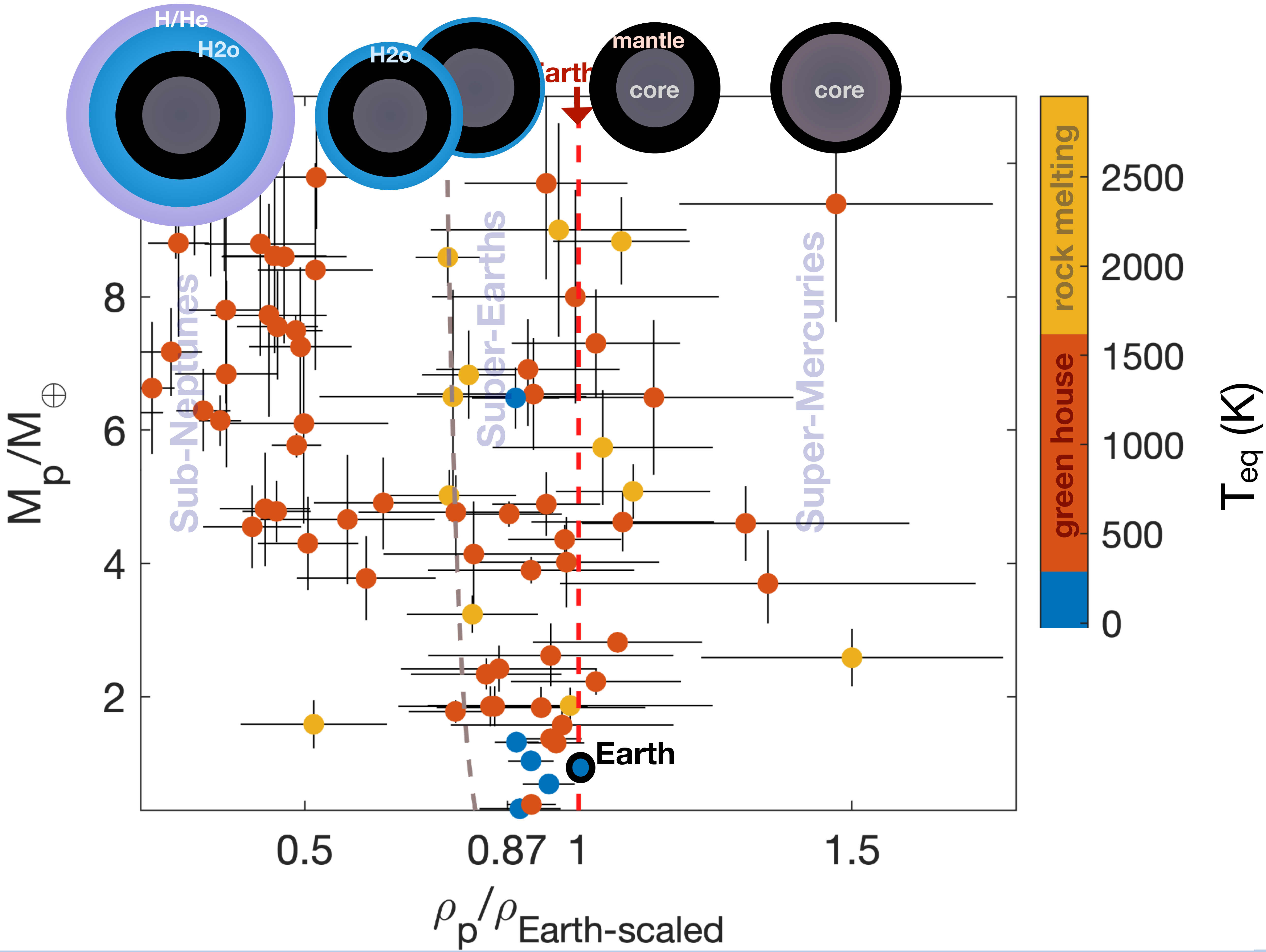
Caroline Dorn, Tim Lichtenberg

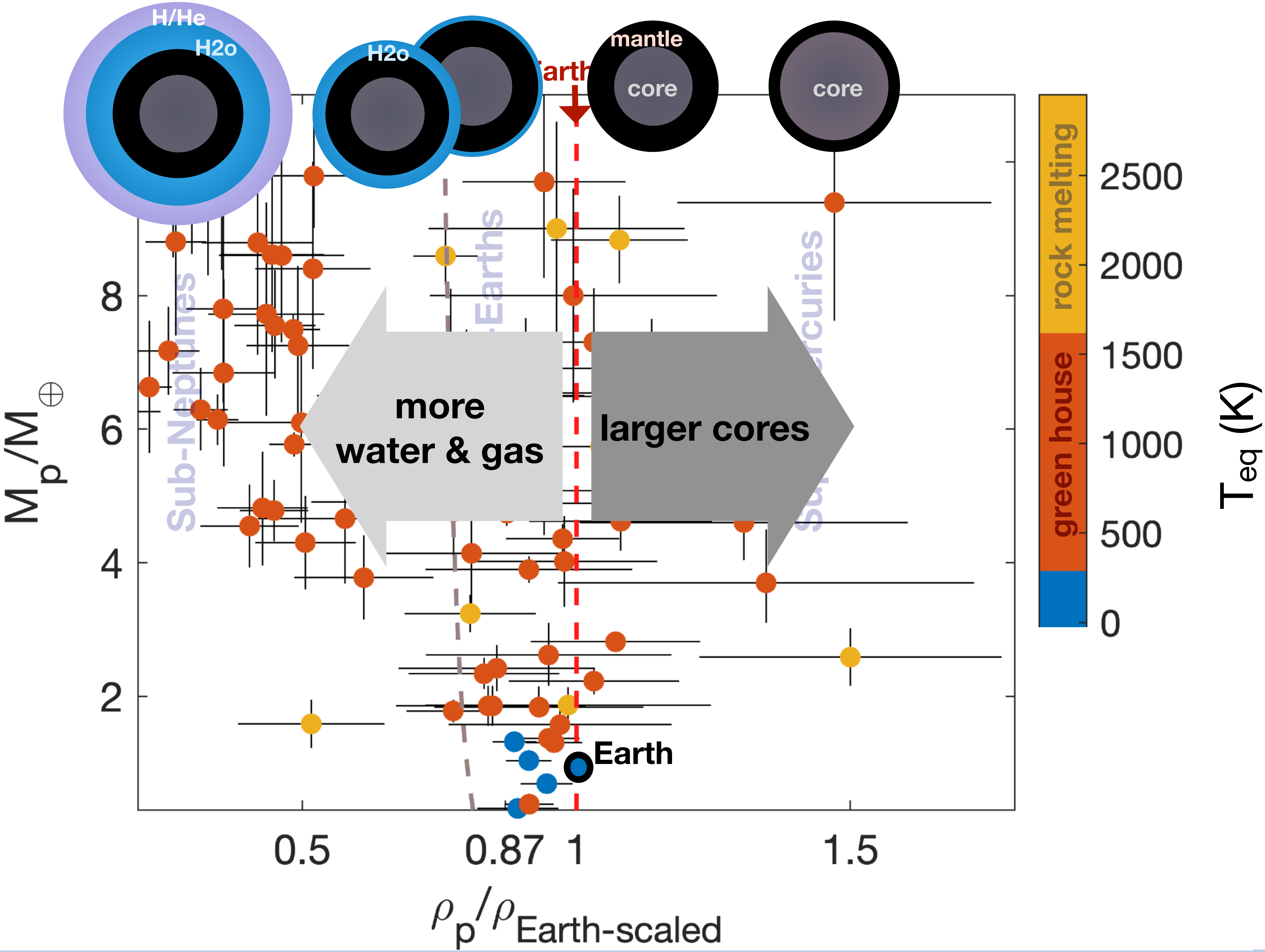
University of Zurich[UZH]

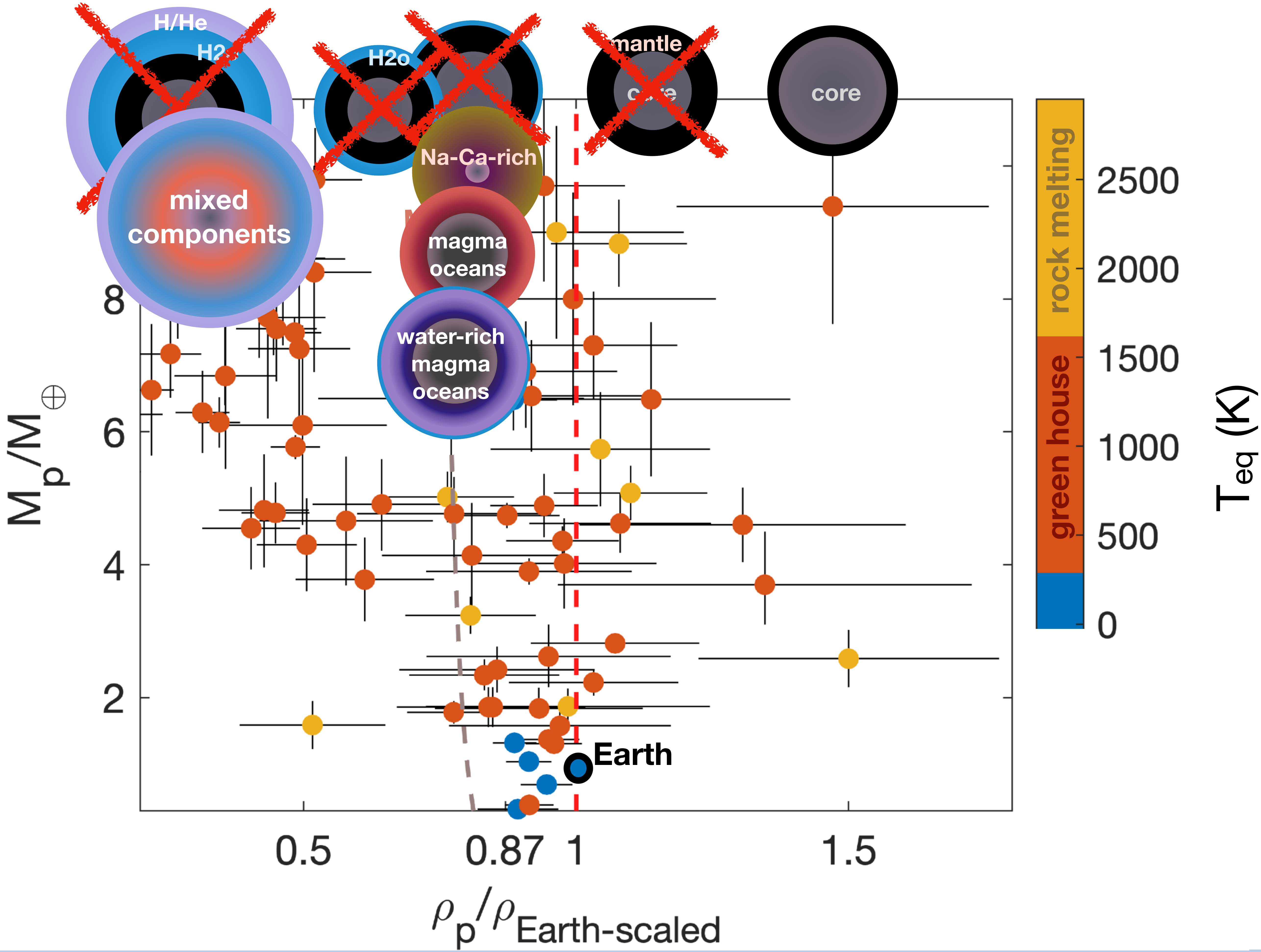
University of Oxford

for uncompressed density: see Plotnykov & Valencia 2020

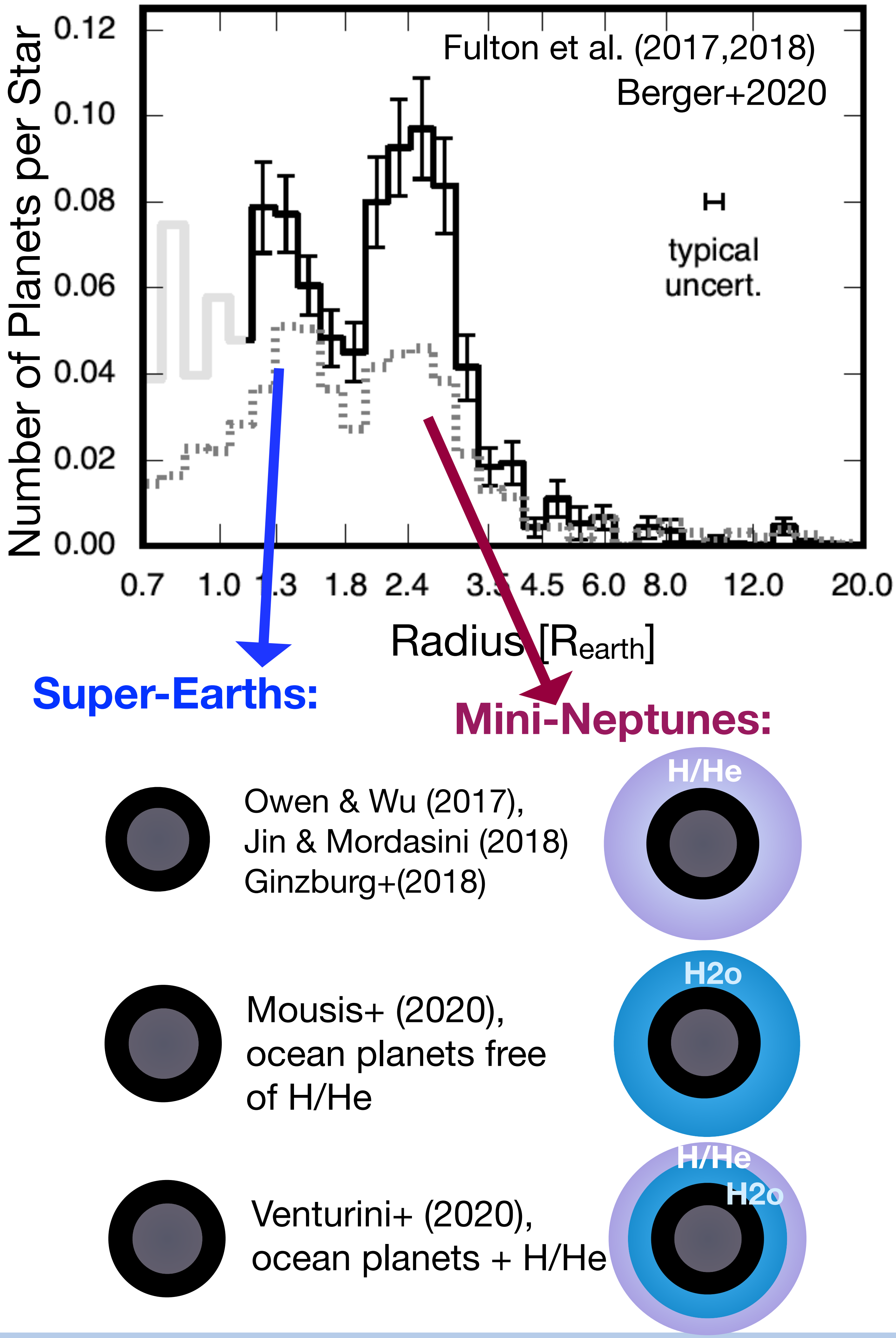



H/He
H2o
H2o
Earth
mantle
core
core
Sub-Neptunes
Super-Earths
Super-Mercuries
Earth
8
6
4
2
0.5
0.87
1
1.5
$M_p/M_\oplus$
$\rho_p/\rho_{\text{Earth-scaled}}$
rock melting
green house
2500
2000
1500
1000
500
0
T_{eq} (K)

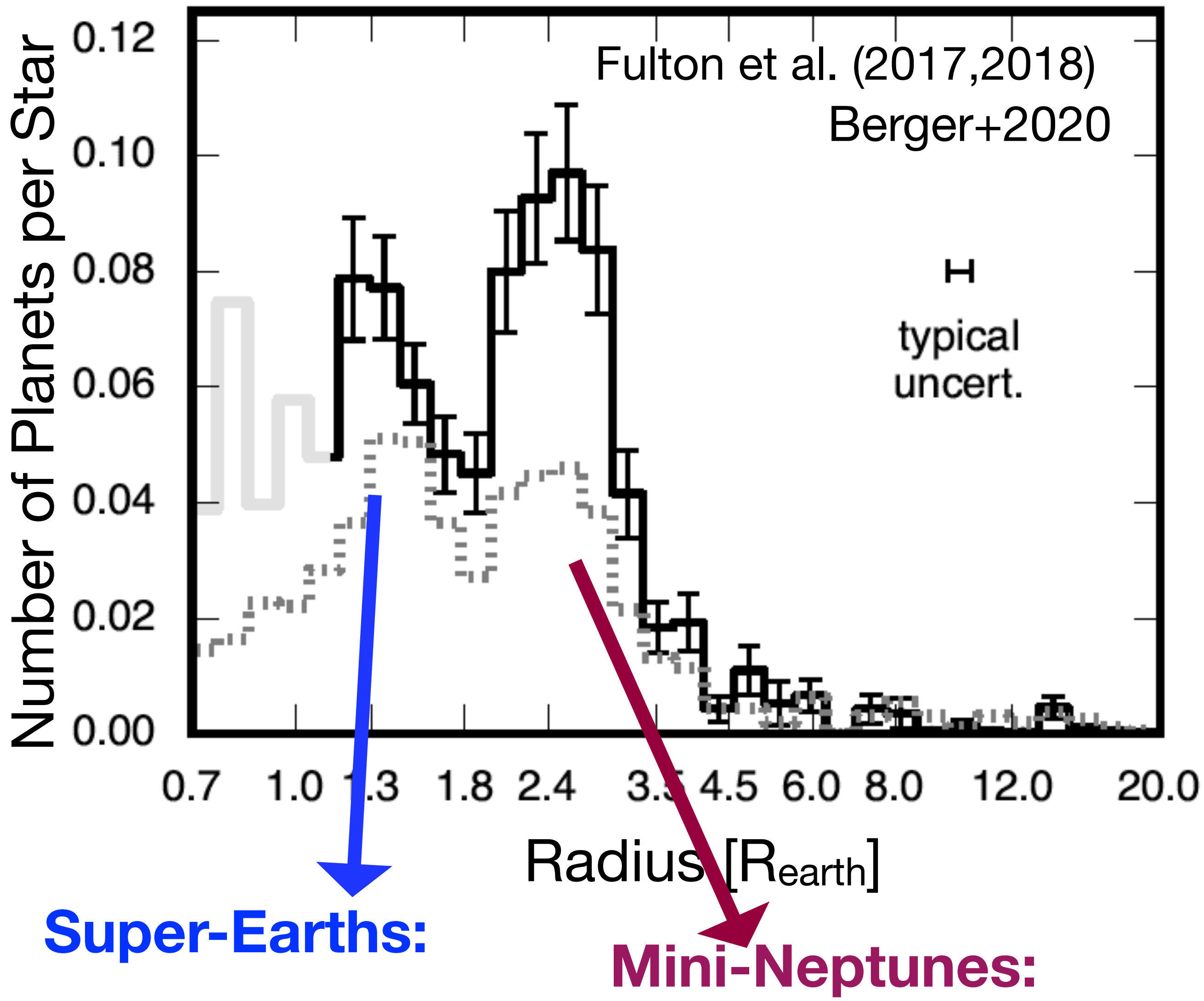

H/He
H2o
H2o
mantle
core
core
more
water & gas
larger cores
Earth
$M_p/M_\oplus$
8
6
4
2
0.5
0.87
1
1.5
$\rho_p/\rho_{Earth\text{-}scaled}$
rock melting
green house
2500
2000
1500
1000
500
0
T_{eq} (K)

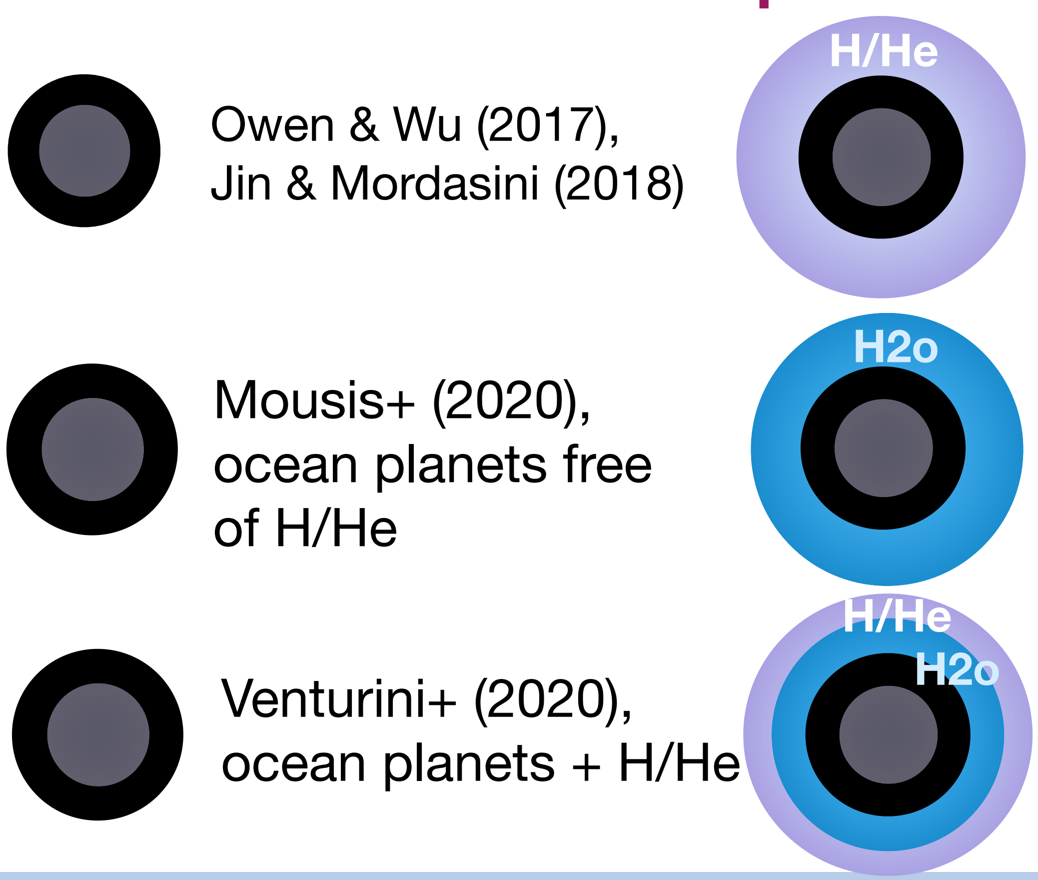


H/He
H2o
H2o
mantle
core
core
mixed components
Na-Ca-rich
magma oceans
water-rich magma oceans
Earth
$M_p/M_\oplus$
$\rho_p/\rho_{\text{Earth-scaled}}$
0.5
0.87
1
1.5
2
4
6
8
rock melting
green house
T_{eq} (K)
0
500
1000
1500
2000
2500


Fulton et al. (2017,2018)
Berger+2020
typical
uncert.
Number of Planets per Star
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Radius [Rearth]
Super-Earths:
Mini-Neptunes:
H/He
Owen & Wu (2017),
Jin & Mordasini (2018)
Ginzburg+(2018)
H2o
Mousis+ (2020),
ocean planets free
of H/He
H/He
H2o
Venturini+ (2020),
ocean planets + H/He

New view on exoplanets





magma oceans are common!
mantle rock is molten

Kite et al. (2016)
Elkins-Tanton et al. (2008)

magma ocean + primordial H:
water is produced

$$FeO_{silicate} + H_{2,gas} \rightleftharpoons Fe_{metal} + H_2O_{gas}$$

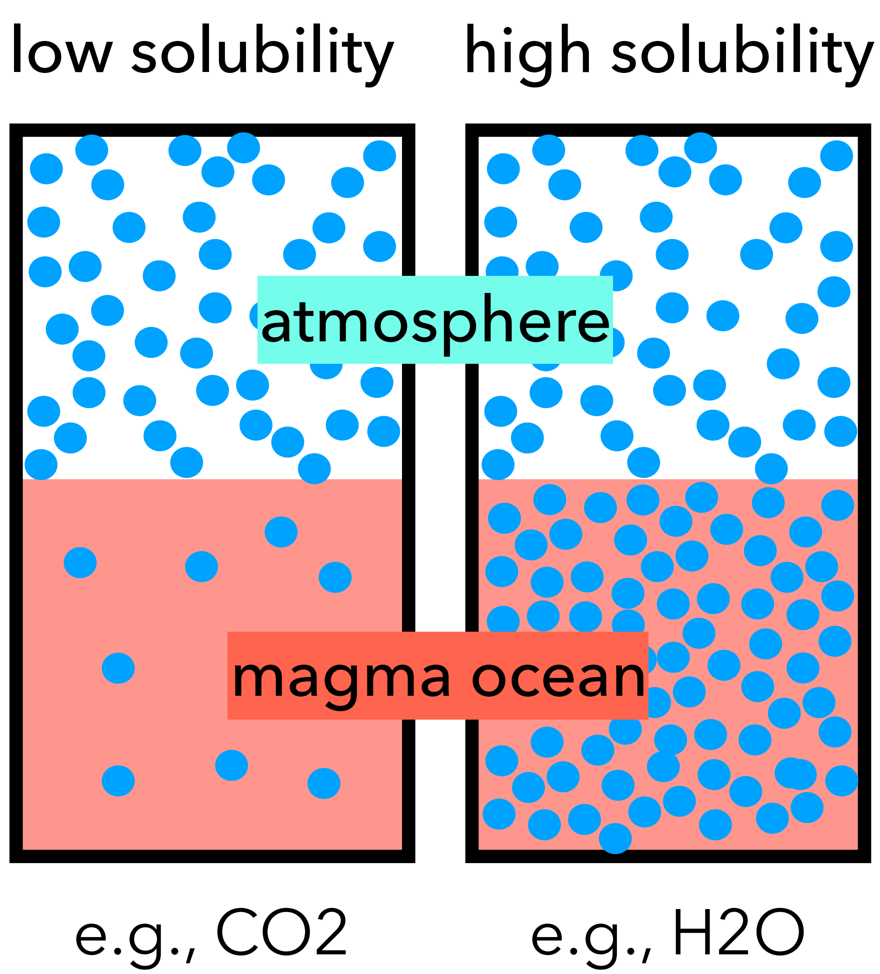
Kite & Schaefer (2021)
Schlichting & Young (arxiv, 2021)
Kimura & Ikoma (2020)

magma ocean + volatiles:
volatiles & magma mix

H2O partitions most efficiently

Olson & Sharp (2019)
Vazan+(2020)
Dorn & Lichtenberg (2021)

New view on exoplanets



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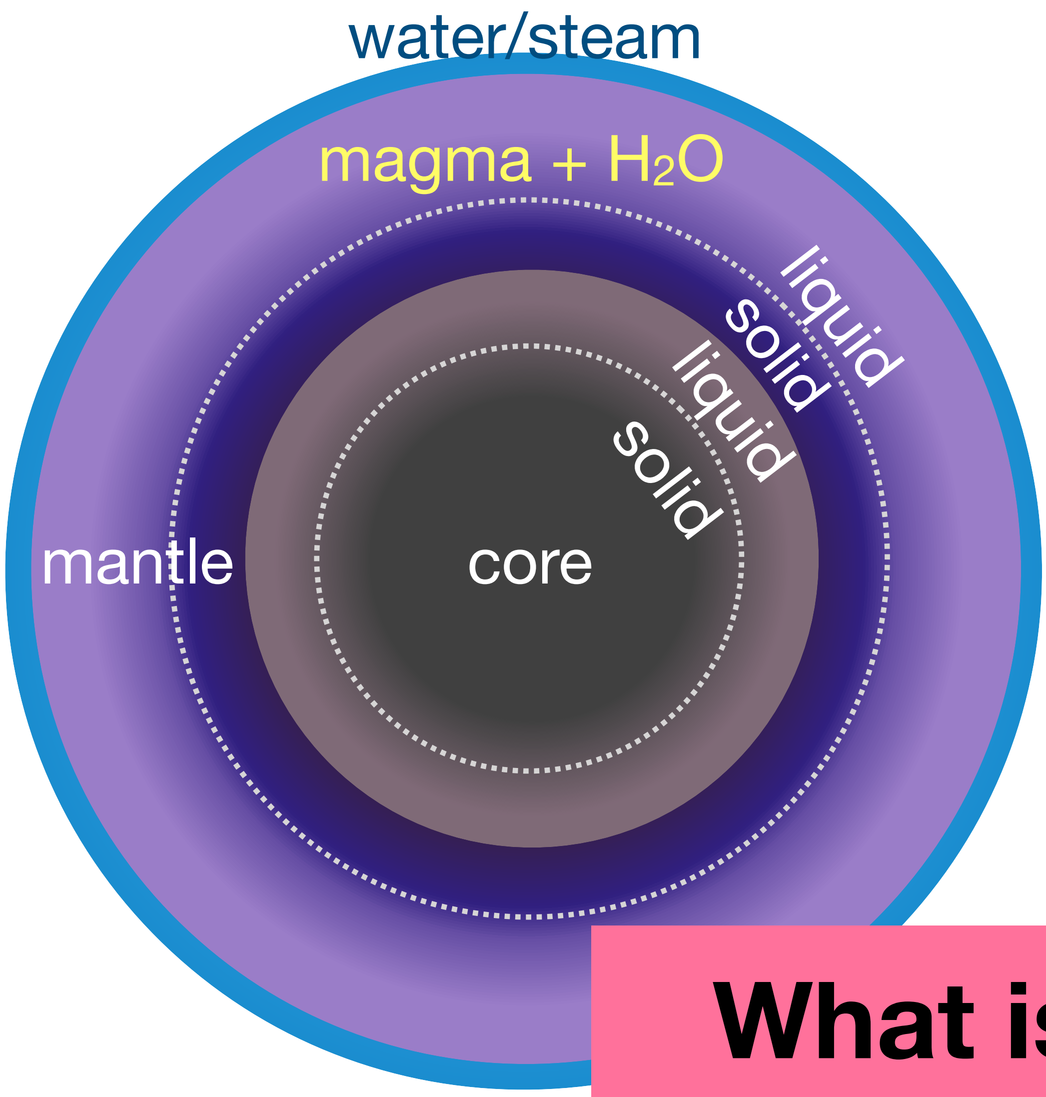
magma ocean + volatiles:
volatiles & magma mix

H2O partitions most efficiently

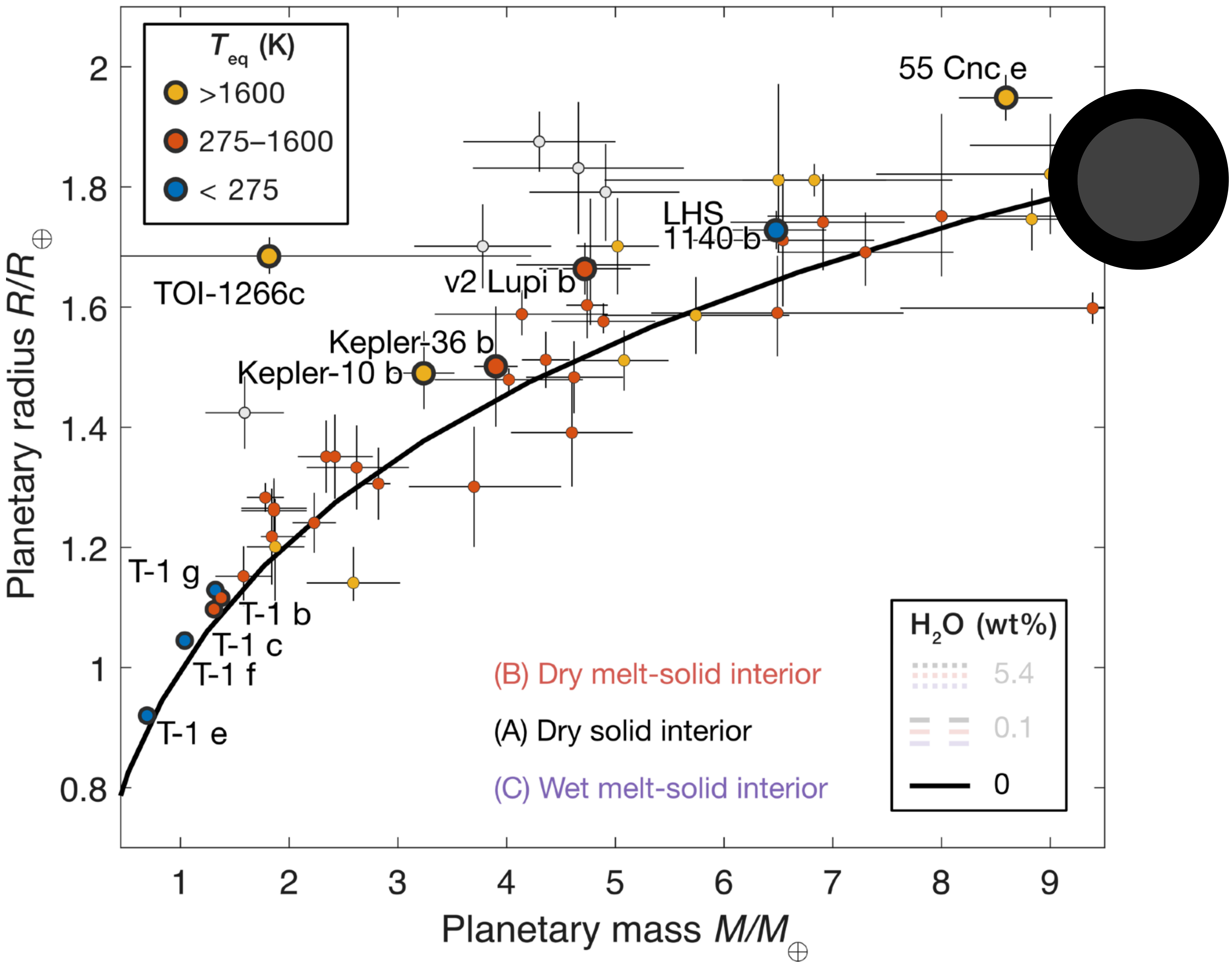
Olson & Sharp (2019)
Vazan+(2020)
Dorn & Lichtenberg (2021)

magma oceans can be huge water reservoirs

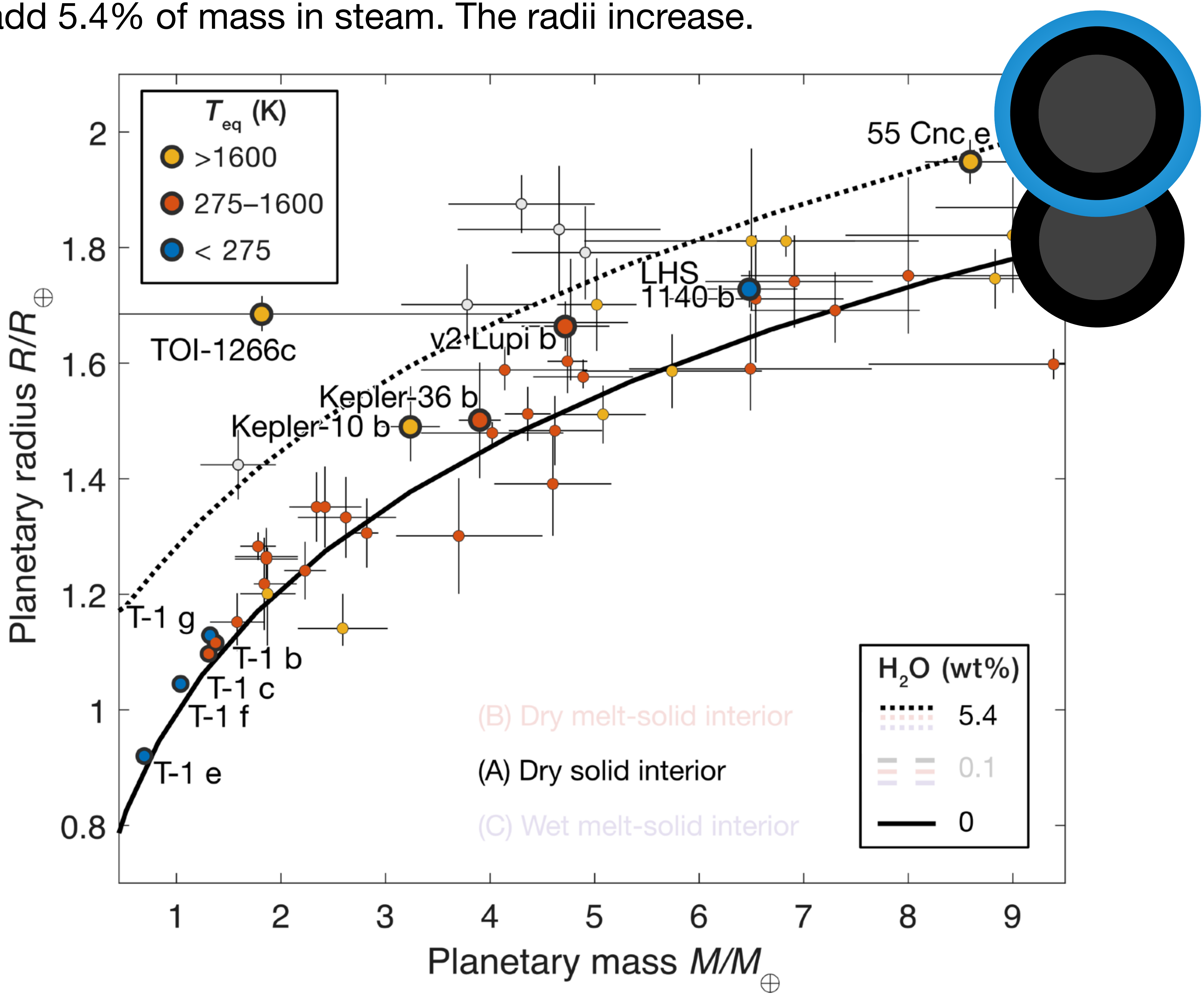


What is the effect on R of deep water reservoirs ?

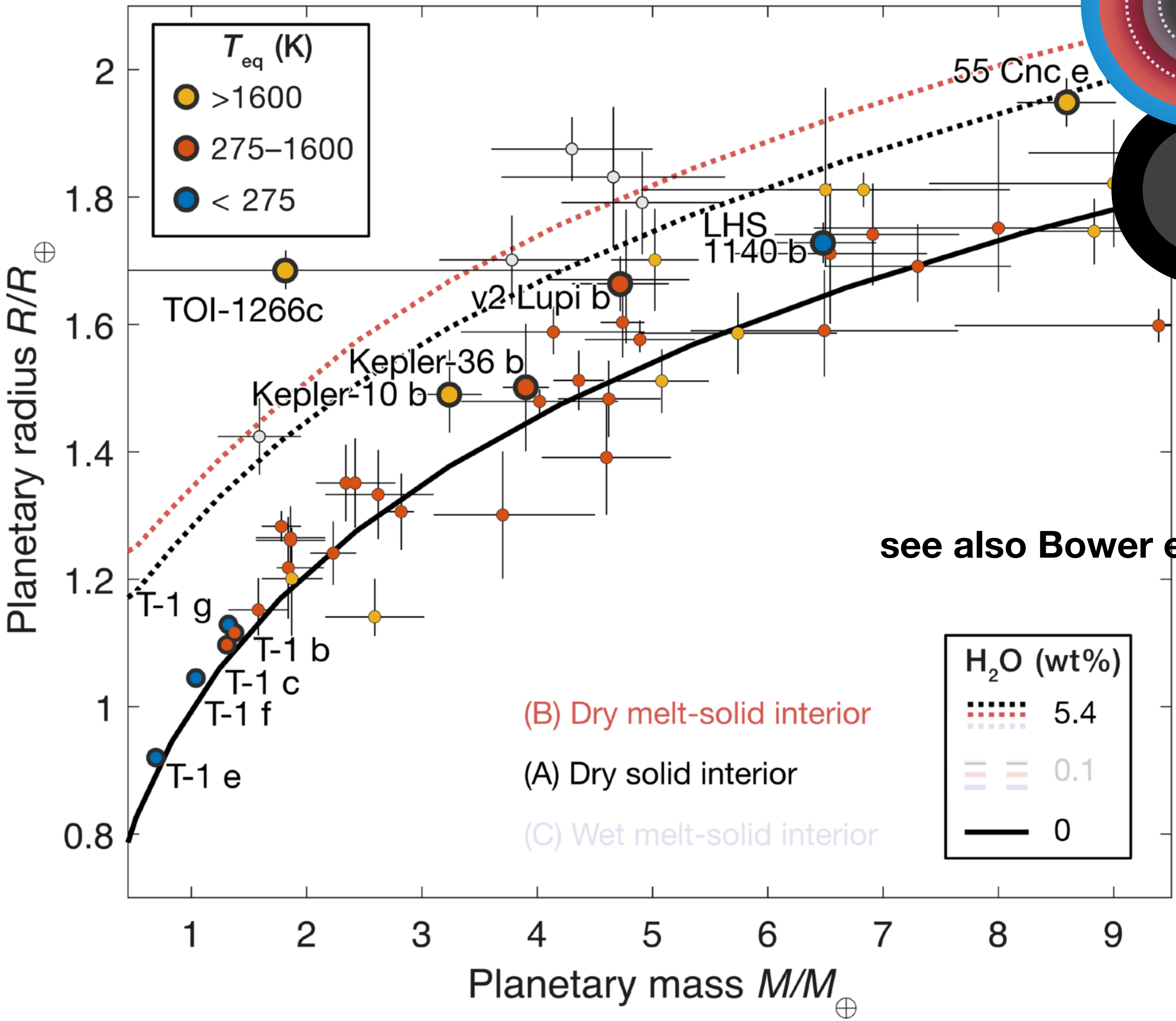
Here I plot a curve for an Earth-like composition, a purely rocky and cold interior.

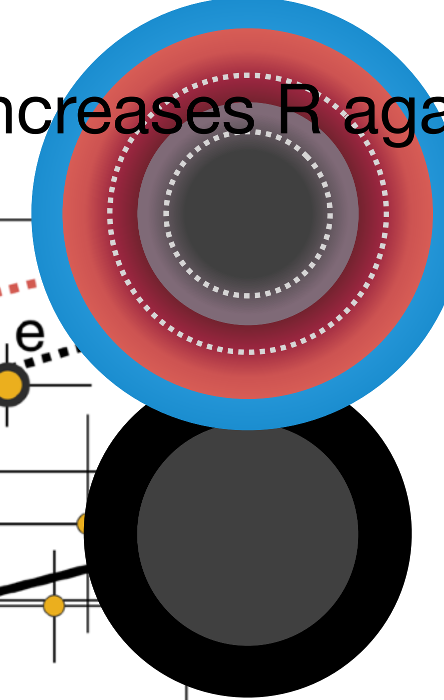


Now I add 5.4% of mass in steam. The radii increase.



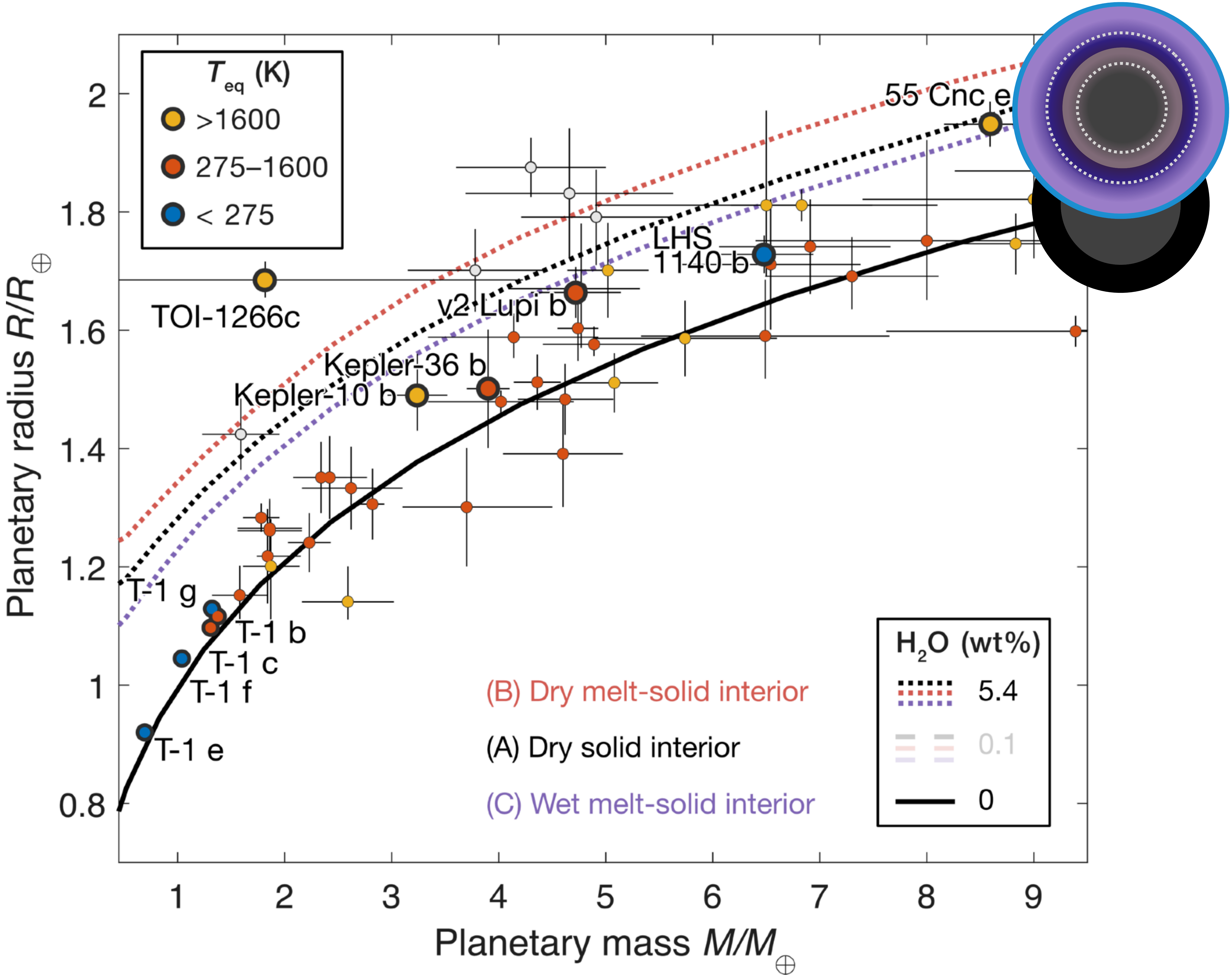
Now the surface rocks must be molten underneath the steam. This increases R again.



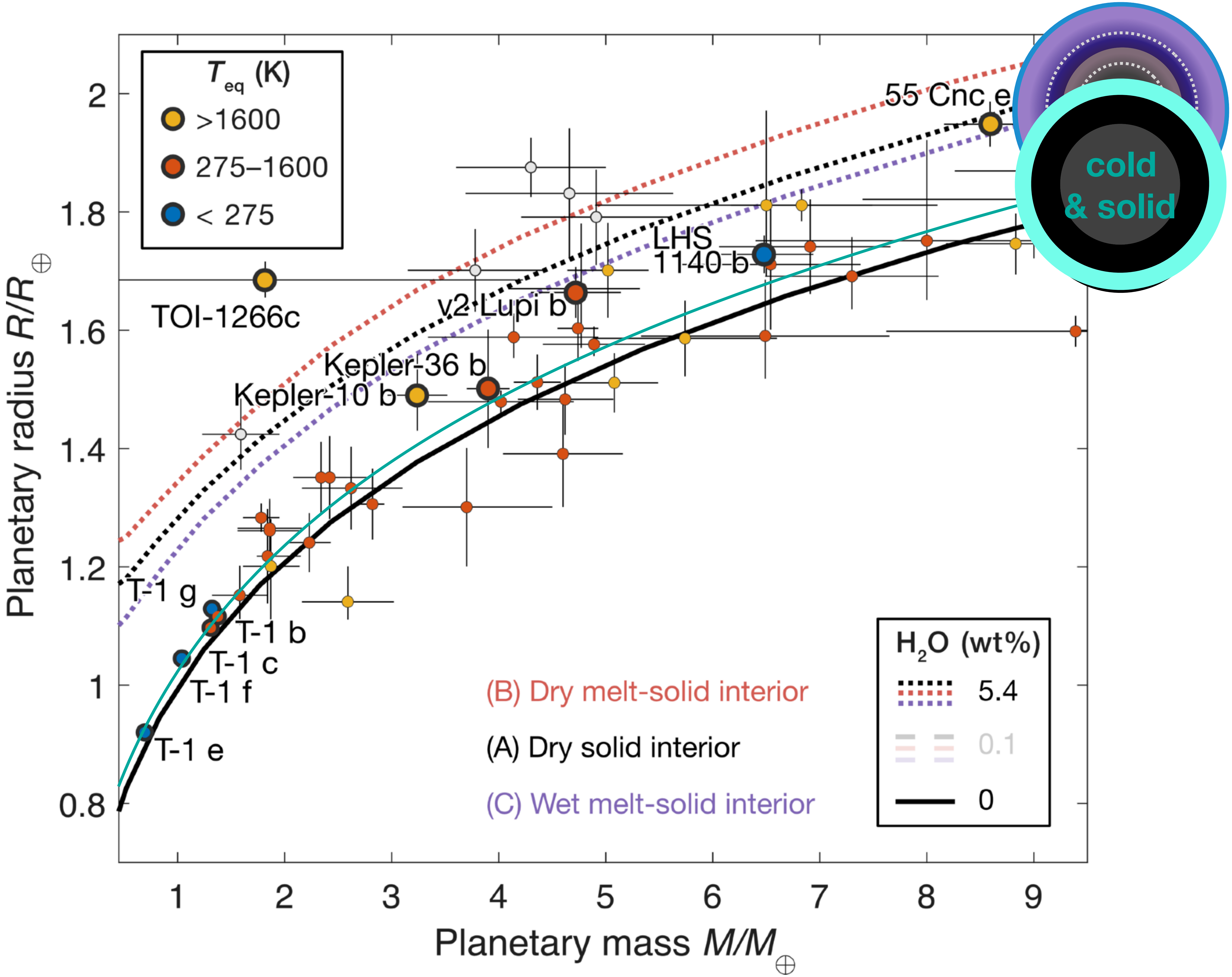


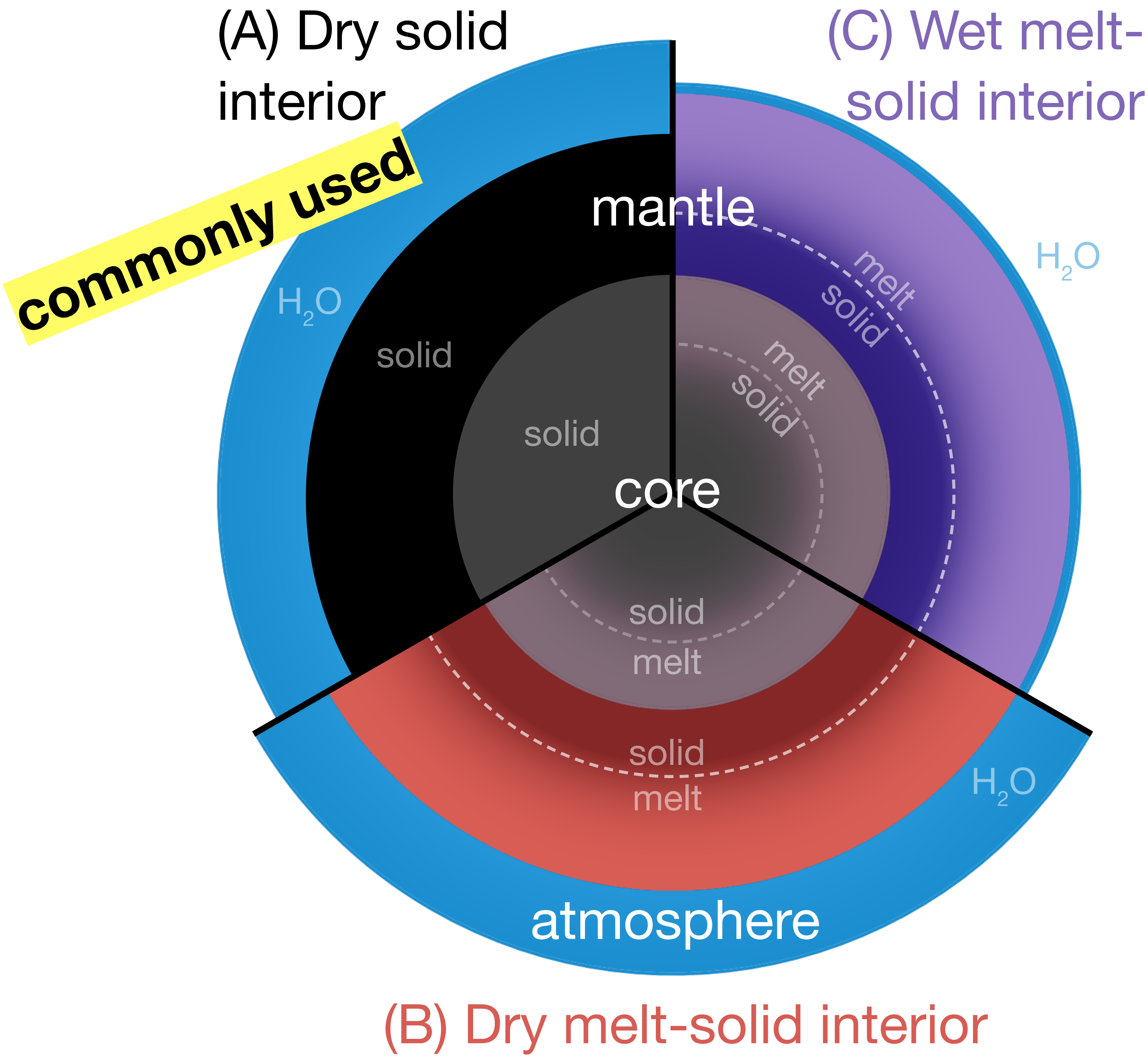
see also Bower et al. 2019

But the water will dissolve into the interior. This decreases R for the purple model.



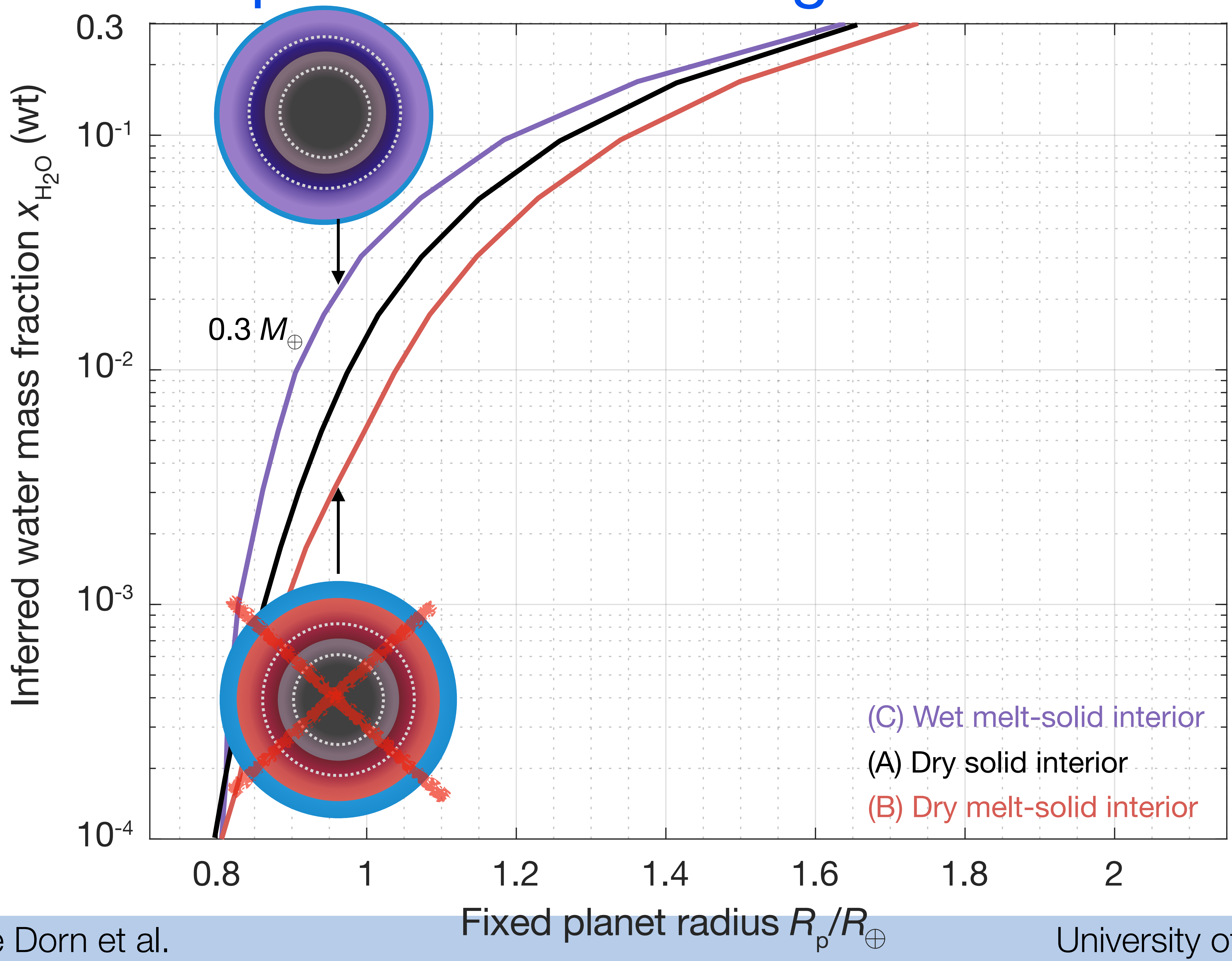
For comparison: Here a M-R curve for a cold interior with water in form of ice.




(A) Dry solid interior
commonly used
(C) Wet melt-solid interior
mantle
H2O
melt
solid
melt
solid
solid
solid
core
solid
melt
solid
melt
H2O
H2O
atmosphere
(B) Dry melt-solid interior

Effect on inferred water budgets?

up to 1 order of magnitude differences



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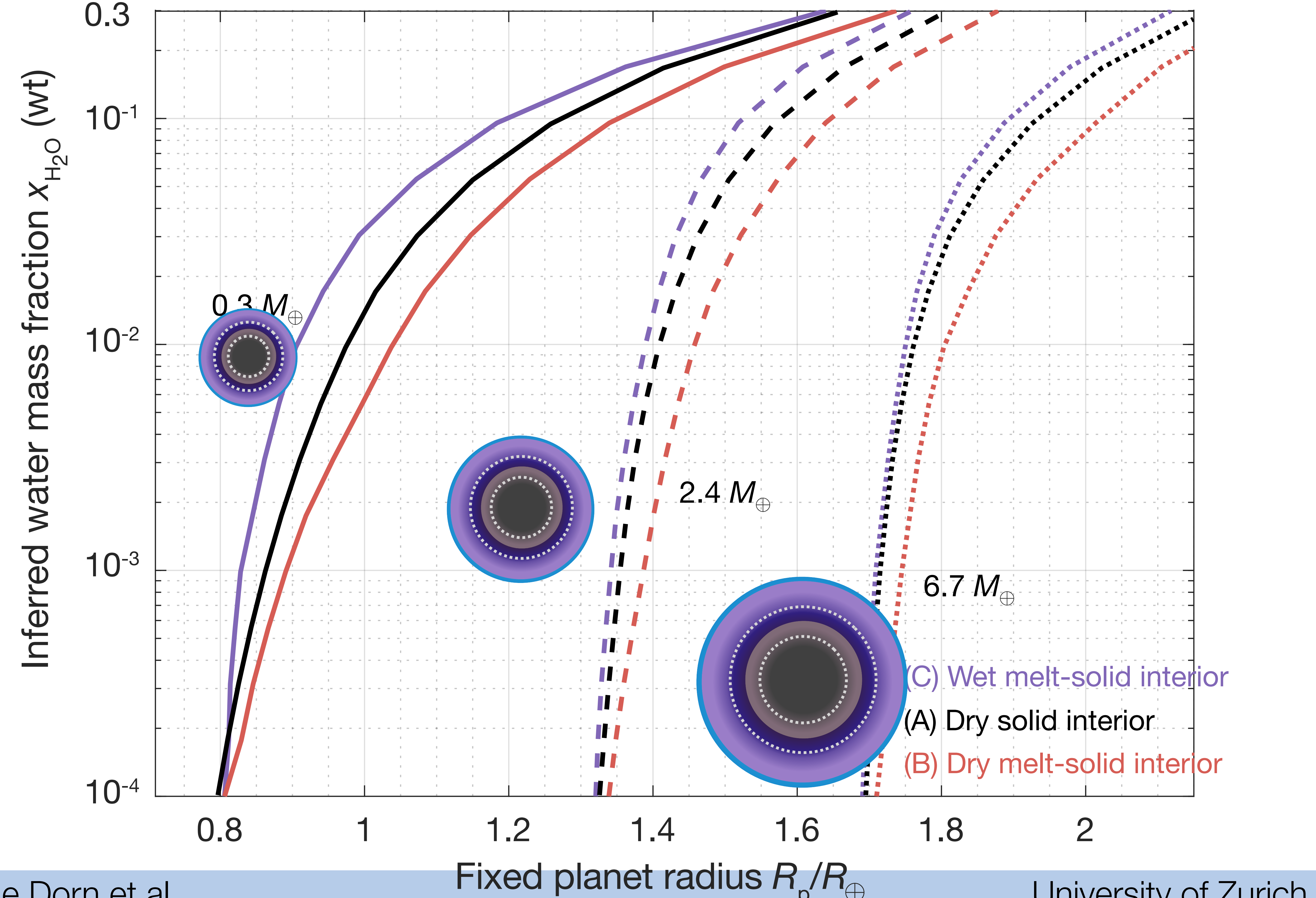
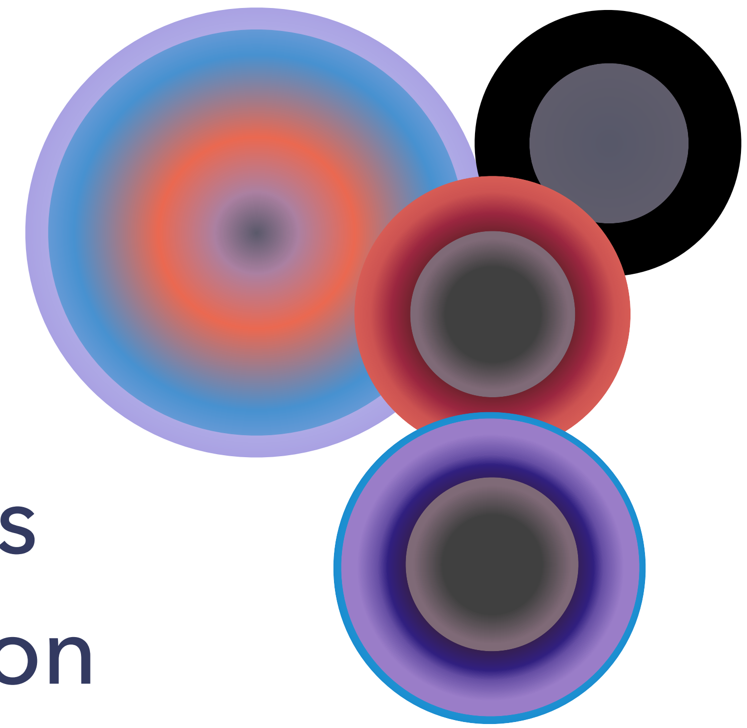


Conclusions



interior characterization **is key:**

- to understand compositions & interiors
- they link to planet formation & evolution

interior characterization **is challenging:**

- data are sparse and carry limited information
- diversity of exoplanets exceed the one in the SS
- models have limited accuracy

2 papers discussed today:

Agol, Dorn, et al. (2020), Planetary Sciences Journal

Dorn & Lichtenberg (2021), Astrophysical Journal Letters