Exploring the observational and theorical transition between Super-Earths and Sub-Neptunes around M- and FGK-stars

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Context

Super-Earths and Sub-Neptunes constitute the **dominant population** of exoplanets in our galaxy, with nearly every star likely hosting at least one planet smaller than 4 Rearth, detected at an orbital period of less than 100 days. Recent large-scale surveys by missions like Kepler and TESS, along with ground-based radial velocity monitoring using high-precision spectrometers (ESPRESSO, HARPS, NIRPS...), have enabled **precise characterization** of **185** of these planets (PlanetS Catalog, Otegi et al. 2020 ; Parc et al. 2024). This expanding dataset facilitates demographic studies of planetary parameters and enable a comparison with theoretical models of internal structure, formation, and evolution. We present here the recent work of Parc et al. 2024: *From Super-Earths to Sub-Neptunes: observational constraints and connections to theoretical models.*

Sample & Method

We use the Planets Catalog (https://dace.unige.ch/exoplanets/) to select the well characterized (relative error in mass <25%, in radius <8%) small planets (R < 4 Re) around M-, K- and FG-dwarfs.

We obtain 46, 61 and 72 planets respectively. We explore these samples by using Mass-Radius (M-R) diagrams and by estimating their radius and density distributions with re-sampling and Kernel Density Estimation methods. These allow to take into account uncertainties and the continuous nature of the distributions.

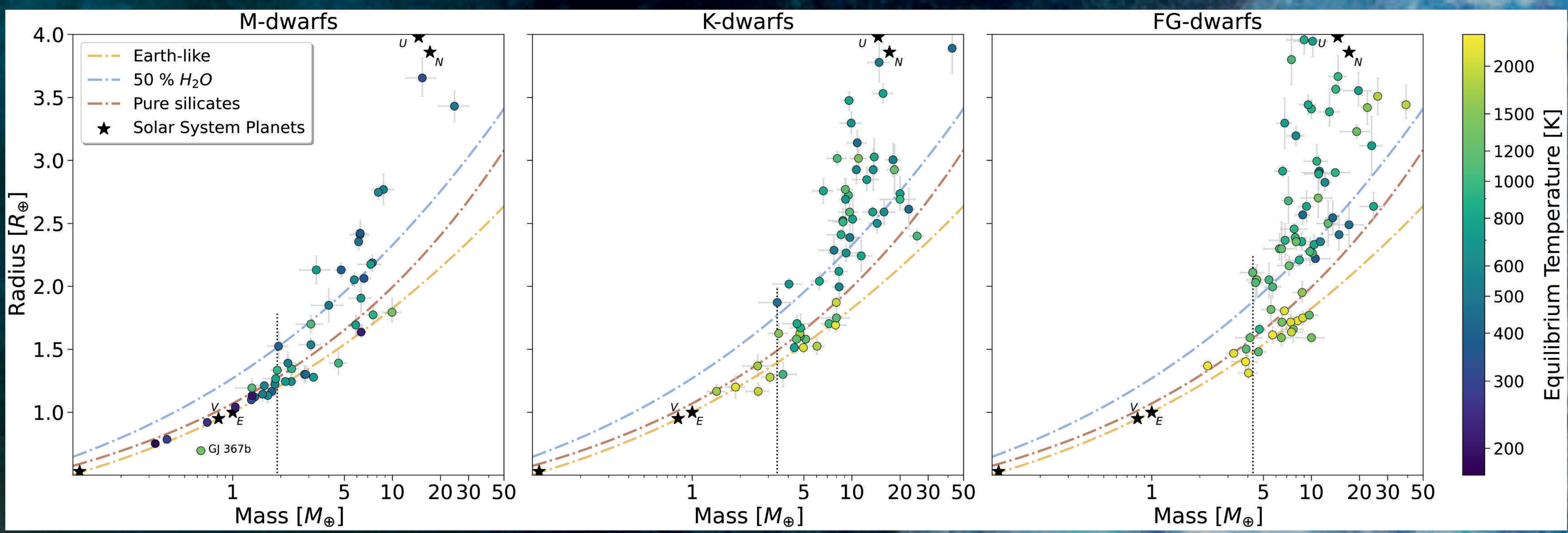

Fig. 1 - Mass-Radius diagram of small planets around M-, K- and FG-dwarfs from the PlanetS catalog colored with the equilibrium temperature of the planet. The composition lines of pure-silicates (brown) from Zeng et al. (2016), Earth-like planets (yellow), and 50% water (blue) from Zeng et al. (2019) are displayed. Vertical dotted lines correspond to the apparent minimum mass of the Sub-Neptunes across spectral types (at 1.9, 3.4 and 4.3 Me for M-, K- and FG-dwarfs).

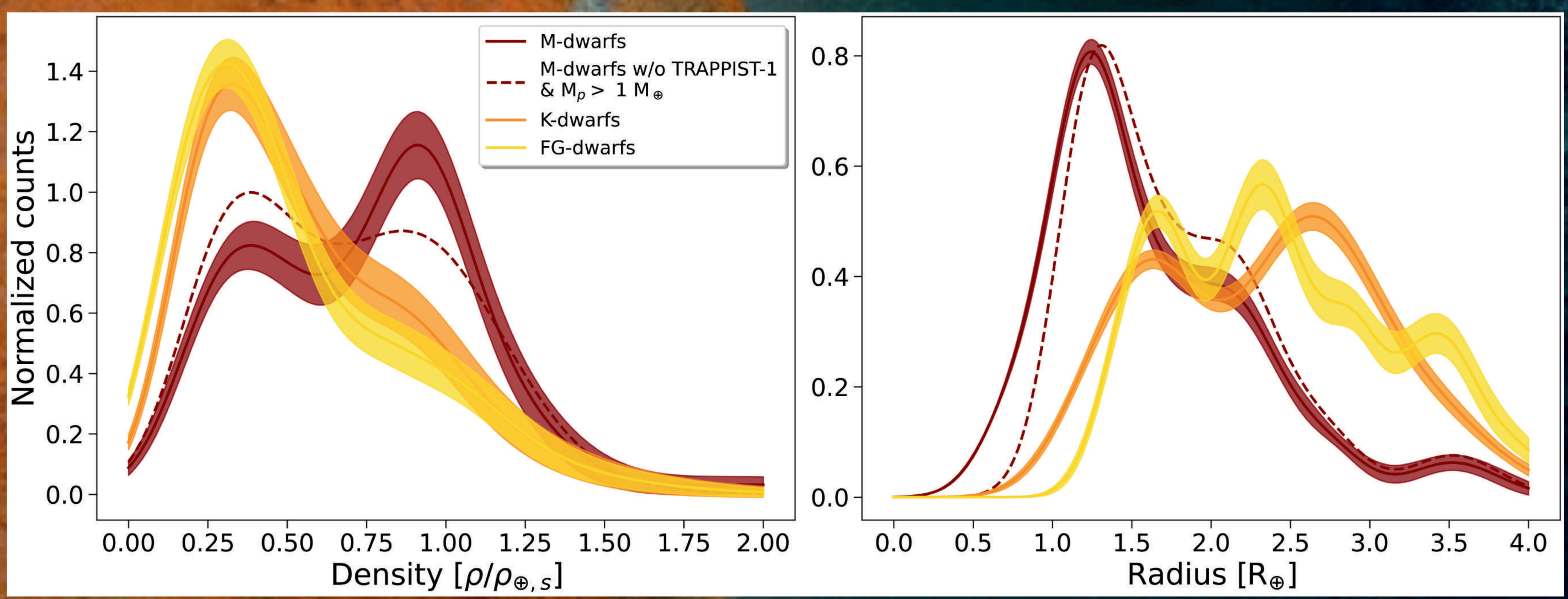

Fig. 2 - Kernel Density Estimates of the density (left) and radius (right) distributions of the small planets orbiting M- (red), K- (orange) and FG-dwarfs (yellow) from the PlanetS catalog. For visibility, only the resulting mean KDE (solid line) of the 10,000 realizations and its standard deviation (filled area) are plotted. The red dashed lines are the density/radius distributions of the sample orbiting M-dwarfs without the TRAPPIST-1 system and planets below 1 Mearth.

M-dwarfs

Focusing on the population of planets around M-dwarfs, the examination of the M-R diagram and KDEs [Fig. 1 & 2] revealed several trends:

- There is a continuous transition of composition in the transition between Super-Earths and Sub-Neptunes around M-dwarfs, ranging from terrestrial to more volatile compositions. This revisits the gap in composition found by Luque & Pallé 2022.

The **50% condensed water** line is **not realistic** for the equilibrium temperature of the planets in the sample. Advanced models of interior and atmosphere (Aguichinine et al 2021 ; Luo et al. 2024) suggest that these planets can possess a water-rich interior, but the Sub-Neptunes in question exhibit a diverse range of compositions **contingent on their level of insolation** [Fig. 3]. Aguichine's model allows for a vapor-water atmosphere, while Luo's model allows for the solubility of water in the inner layers of the planet.

- There is a **dearth of Sub-Neptunes** around M-dwarfs relative to Super-Earths, consistent with occurence rate studies (Ment & Charbonneau 2023).
- The **radius valley** of M-planets is **fading**. The same trend is found theoretically by Venturini et al. (2024) and observationally by Ho et al. (2024).

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M-dwarfs vs FGK-dwarfs

We compare the M-R diagrams and KDEs [Fig. 1 & 2] across different spectral types and find tendencies that can be interpreted in the context of formation and evolution models:

- There is a **scarcity of Sub-Neptunes** around M-dwarfs in contrast to FGK-dwarfs.

That might be attributed to the **intense XUV flux** emanating from M-dwarfs in their youth, potentially leading to heightened atmospheric evaporation from planets in these systems.

- Small Sub-Neptunes (1.8 Re < R < 2.8 Re) observed around M-dwarfs exhibit significantly **lower density** compared to their counterparts around FGK-dwarfs.

This may be explained by the fact that M-planets are **richer in ice** than FGK-planets, and **migrated more efficiently** after accreting most of their solids beyond the ice line.

- The **minimum mass of volatile-rich** Sub-Neptunes increases as stellar masses increase.

It may be an effect of **type-I migration** (Paadekooper et al. 2010), but the exact values of minimum mass could still be affected by observational biases. The same effect is reported in formation and evolution models (Burn et al. 2021 ; Venturini et al. 2024) and is also responsible of the fading of the radius valley around M-dwarfs compared to FGKs.

- The **maximum mass** of a planet with a **terrestrial composition** appears **consistent across spectral types**, remaining close to 10 Me.

Pinpointing this value precisely of 10 Me through formation and evolution models poses challenges.

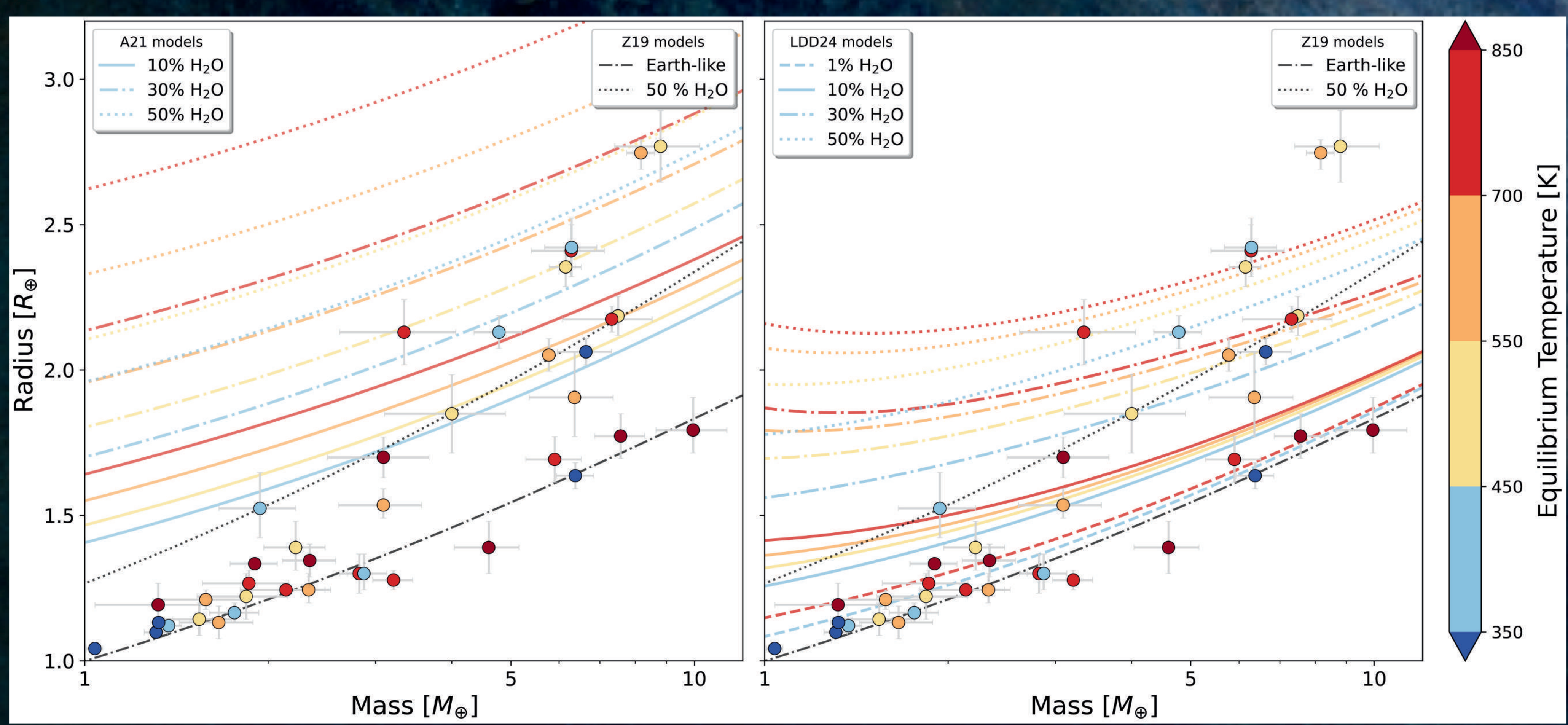

Fig. 3 - Mass-Radius diagrams of small planets orbiting M-dwarfs, focusing on those larger and more massive than Earth, up to 3 Rearth. Composition lines for different Water Mass Fraction (WMF) are displayed for two different internal structure models: from Aguichine et al. (2021) (A21) on the left and from Luo et al. (2024) (LDD24) on the right. The planets and composition lines are colored according to their equilibrium temperature intervals.

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PlanetS National Centre of Competence in Research

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