FORMING AND COMPOSITIONAL DIVERSITY OF ROCKY EXOPLANETS AROUND K-DWARF STARS

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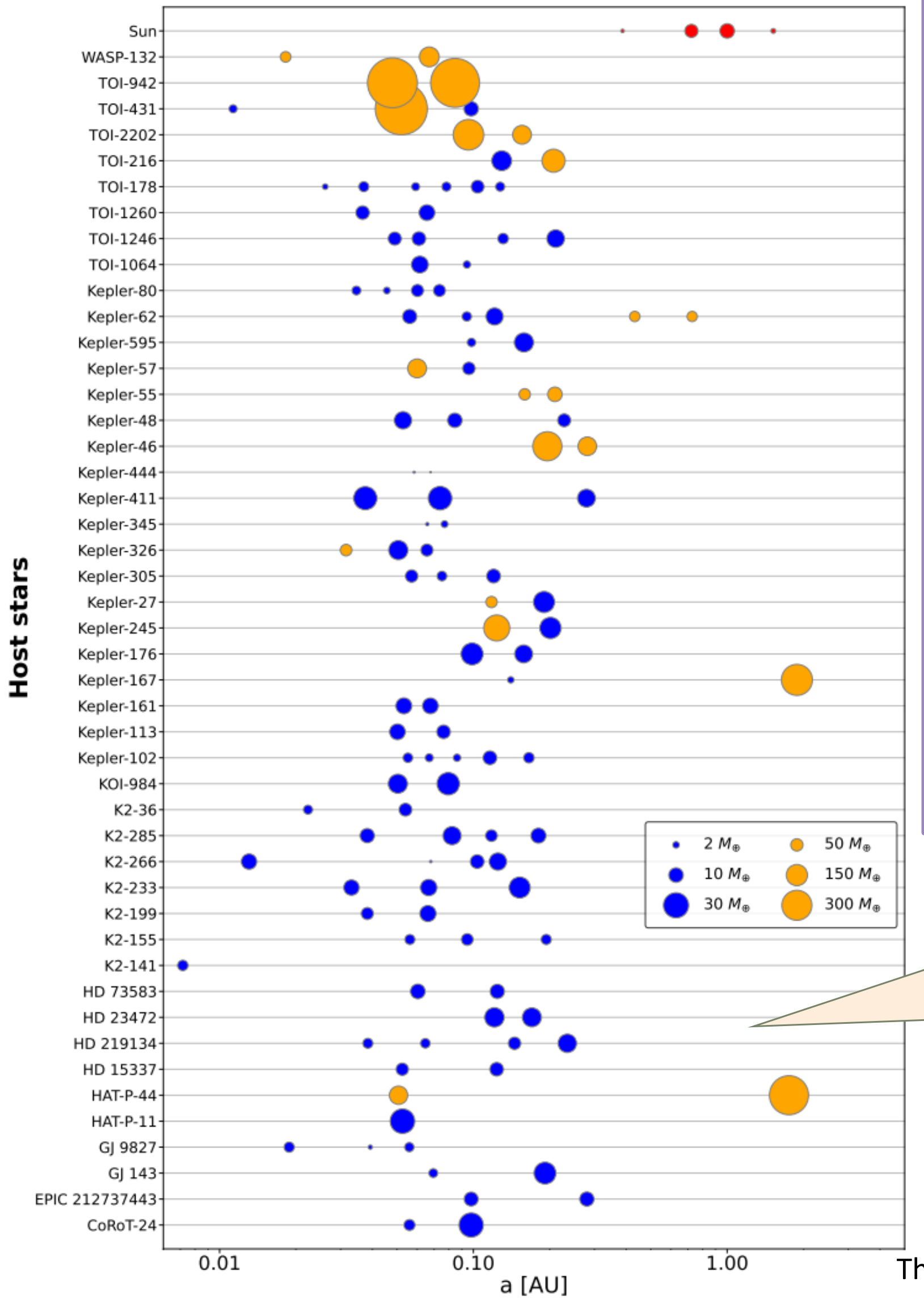
Summary

By employing N-body simulations of planet formation, we reproduced the currently known population of close-in super-Earths around K-dwarf stars[1]. We implemented chemistry into the simulations based on chemical equilibrium in the protoplanetary disk, and developed models of likely basic compositions and radii of rocky exoplanets using the host star's composition as a proxy for planet composition[2].

A) Introduction



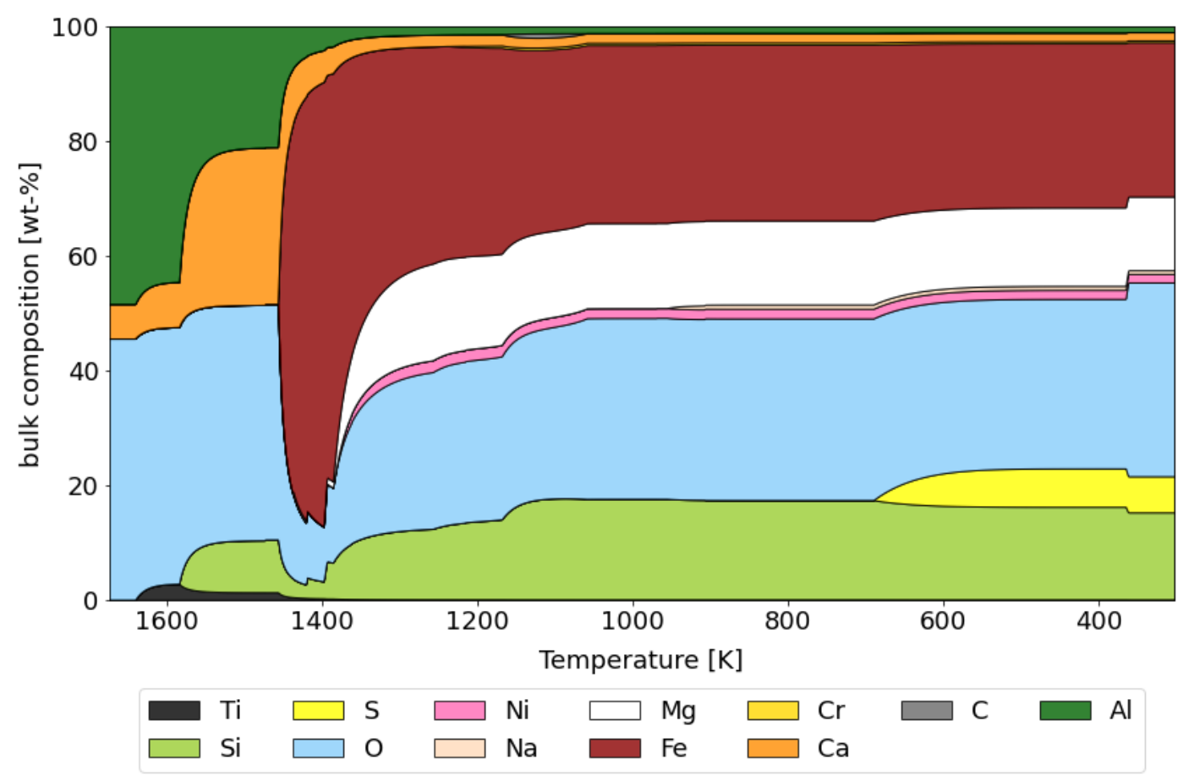
- How multiple close-in super-Earths form around smaller stars is still an open issue.
- So far no studies have specifically focused on planet formation around K-dwarf stars, which are of particular interest in the search for alien life.
- The distribution of known exoplanets on M-R diagram suggests a fascinating variety in their chemical compositions.
- However, interior structures and compositions of rocky exoplanets are inaccessible to observations.

Currently observed population around K dwarfs, stars slightly smaller and colder than our Sun. Compact multi-planet systems of mostly small, dense planets with short periods.

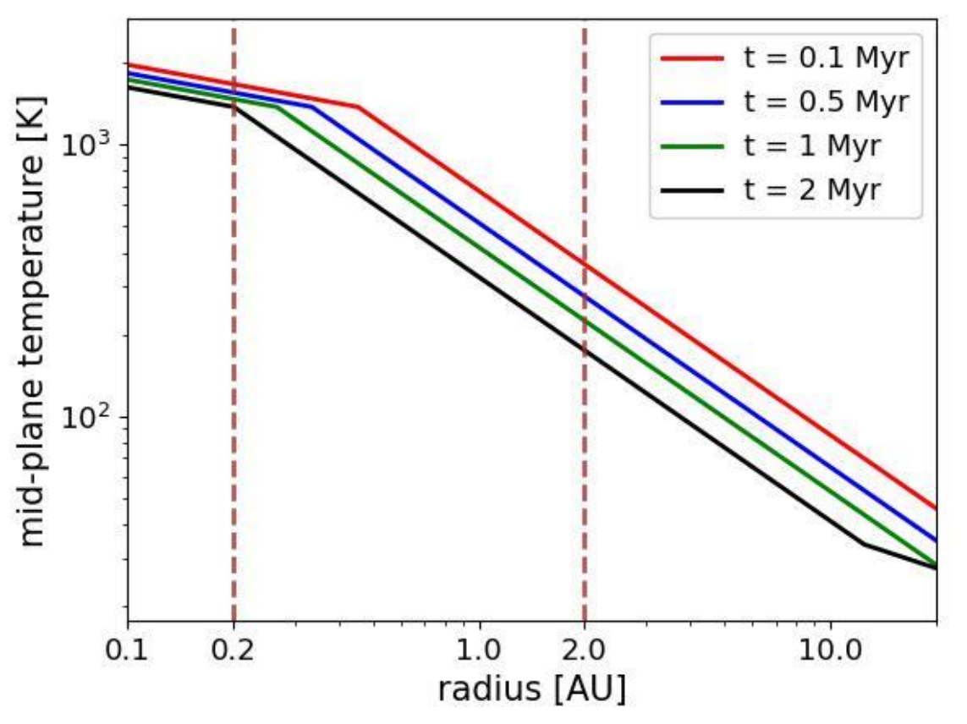
The sample retrieved from https://exoplanetarchive.ipac.caltech.edu/ in Dec. 2022.

B) Methods

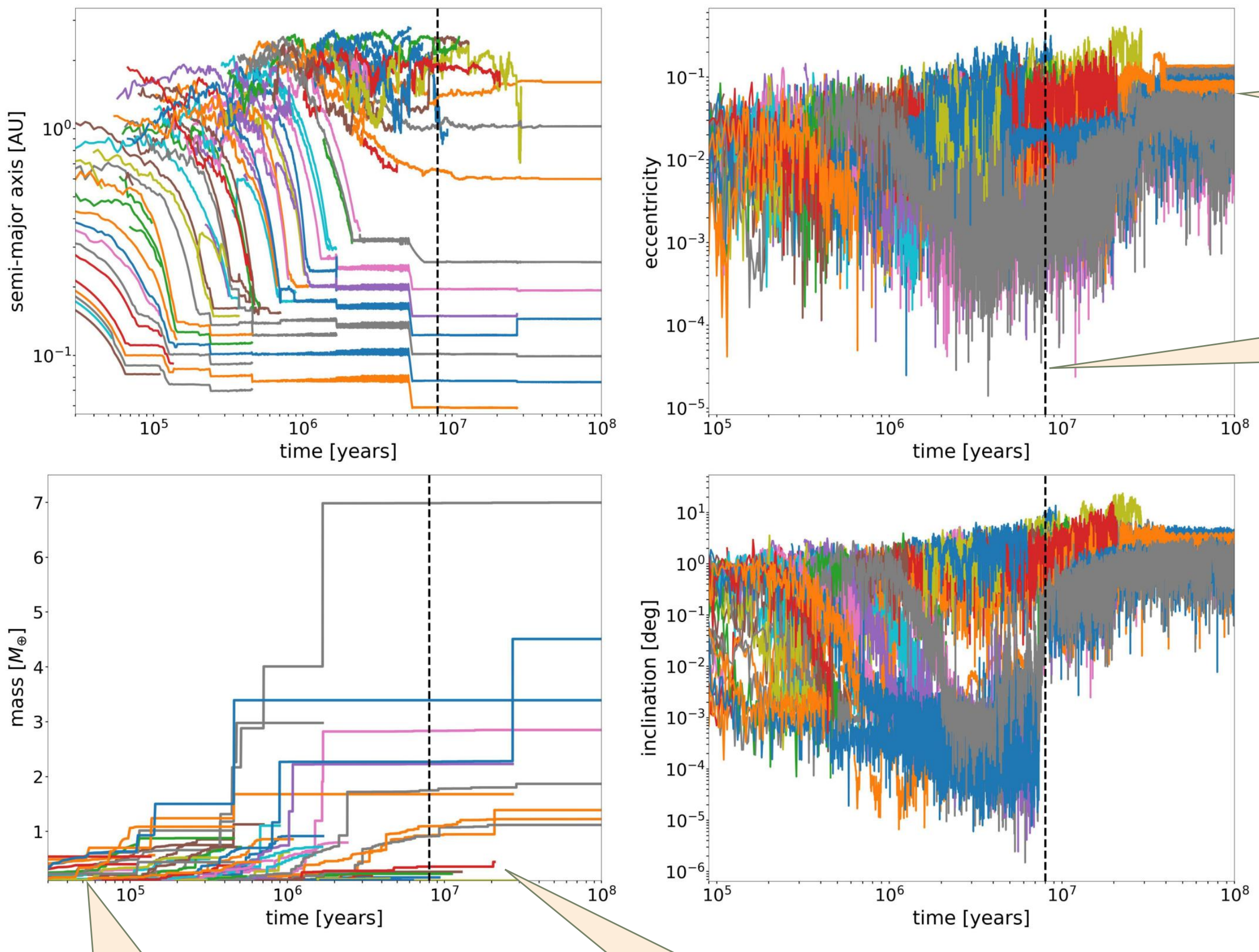
- We performed 48 N-body simulations of planet formation via planetesimal accretion using the GENGA code[5,6] running on GPUs.
- We did not model gas accretion.
- Each simulation began with 12 000 bodies with radii of 200 to 2000 km around 2 different stars with 0.6 and 0.8 M_{Sun}, and we varied the initial disk mass and the solid/gas surface density profile.
- We selected 10 sims that best reproduced the known population, and employed stellar abundances from several K dwarfs[3] with different metallicities.
- Based on the condensation sequence[7] and the T profile of the disk[4], we assigned bulk elemental compositions to planetesimals, and then tracked the accreted rock-forming material (no volatiles).



Predicted composition of rocky bodies based on the cond. seq. computed using *ECCOplanets* code[7] for Kepler-62[3].



C) Dynamical evolution - 100 Myr



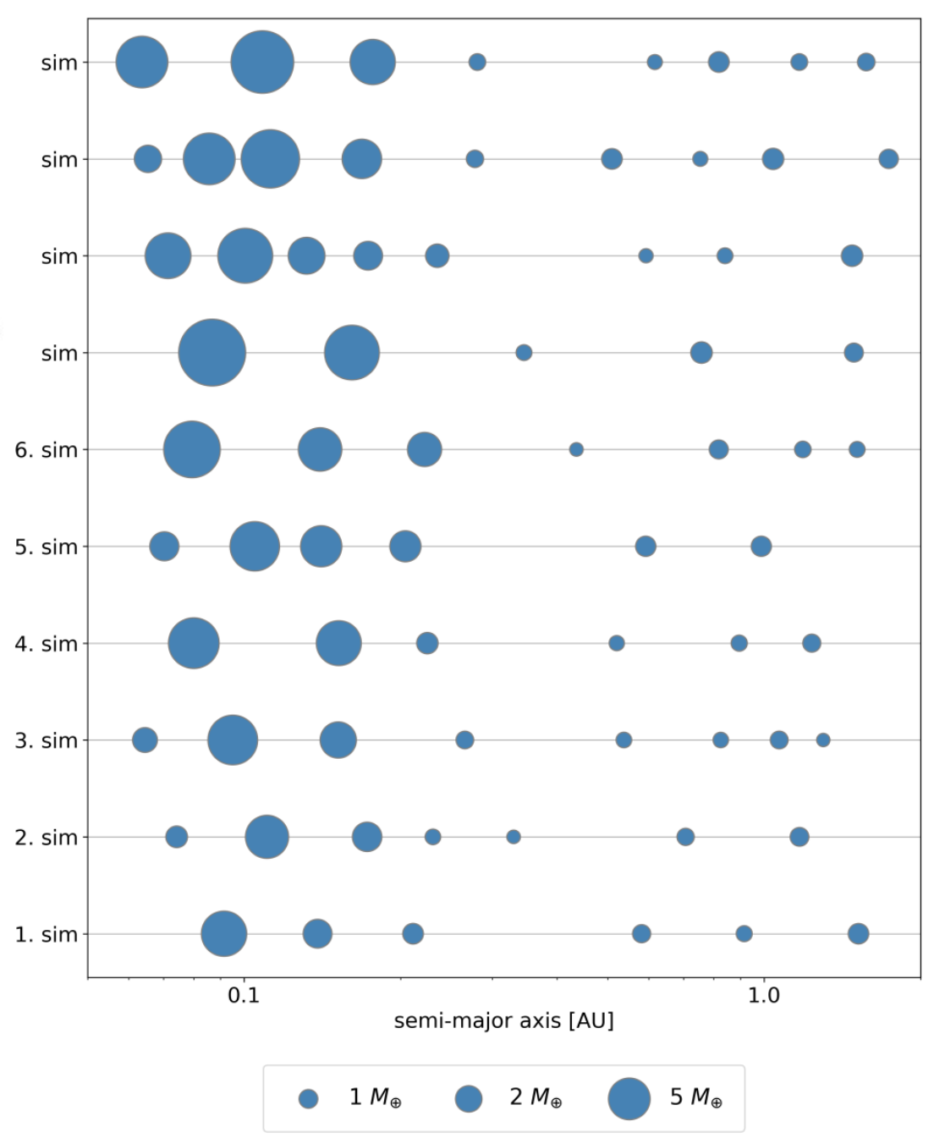
Each color represents an individual object with > 0.1 M_{Earth}.

Most gas has dissipated within ~ 8 Myr.

Earth-mass planets form quickly, within a few Myr, mostly before the gas disk dispersal.

Planetary bodies orbit their host star, often collide, merge and grow, or get scattered or ejected.

Final simulated population of long-term stable, nonresonant systems



Acknowledgments

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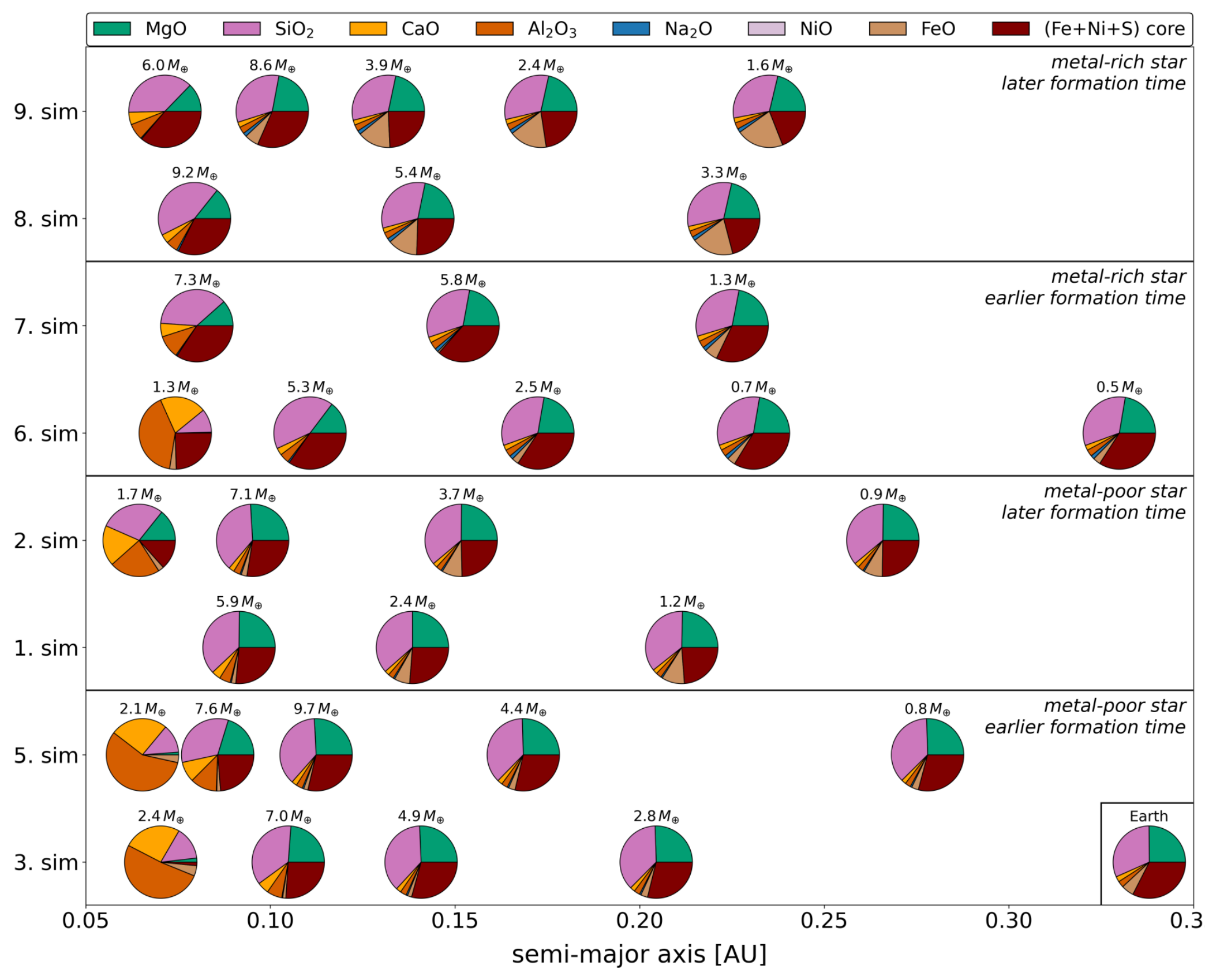
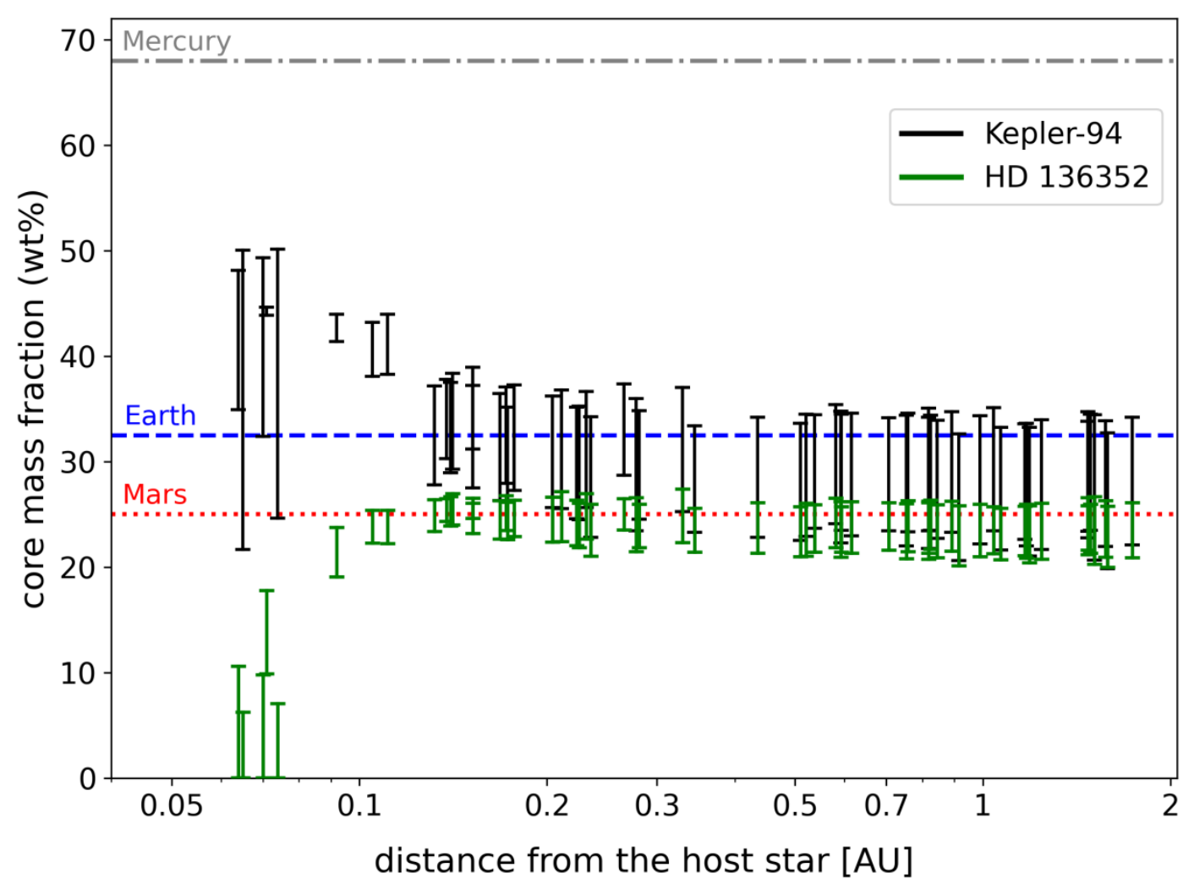
D) Basic composition and internal structure

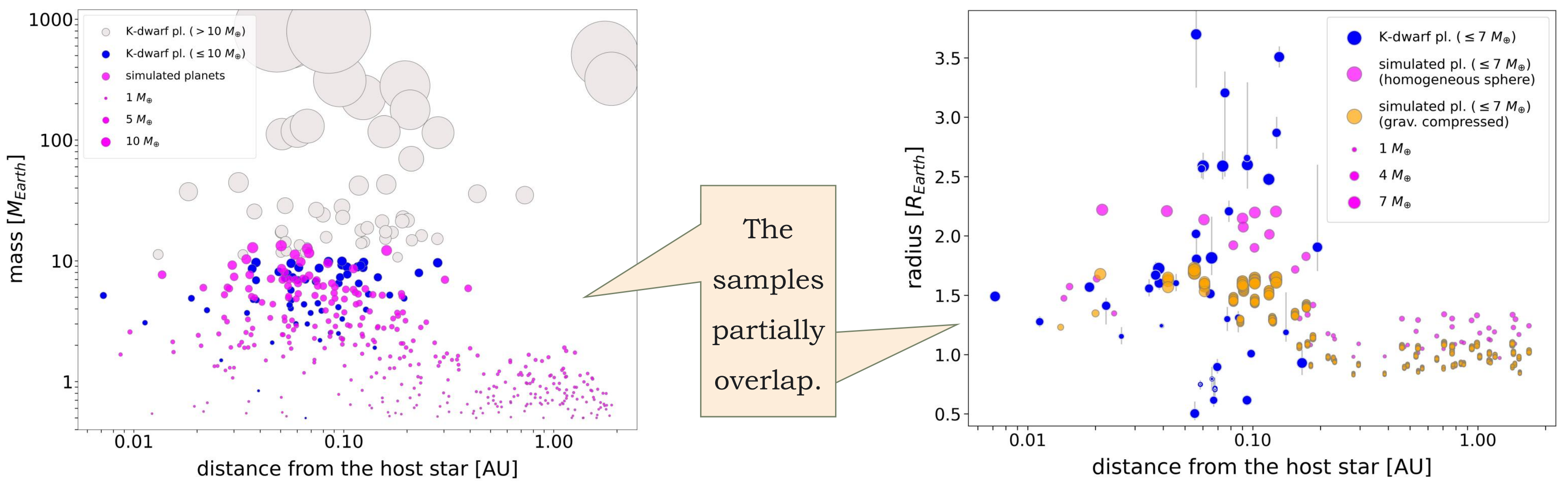
- The basic compositions were computed from bulk elemental compositions using the oxidation sequence: Na_2O-CaO-MgO-Al_2O_3-SiO_2-FeO-NiO-SO_3-CO_2-C-metals[9].
- We selected several stars with the metallicity from -0.33 to 0.33.
- We assumed planetesimal formation times of 0.2 and 0.8 Myr.
- Only planets with a < 0.4 AU are displayed, as more distant planets show minimal further variations.





- We show CMFs (Fe+Ni+S) of the planets around a high (Kepler-94) and a low (HD 136352) metallicity star computed using *ExoPlex* code[8].
- The lower/upper limits correspond to the planetesimal formation times of 0.8/0.2 Myr.
- Higher [M/H] and shorter formation times generally produce larger CMFs and vice versa.

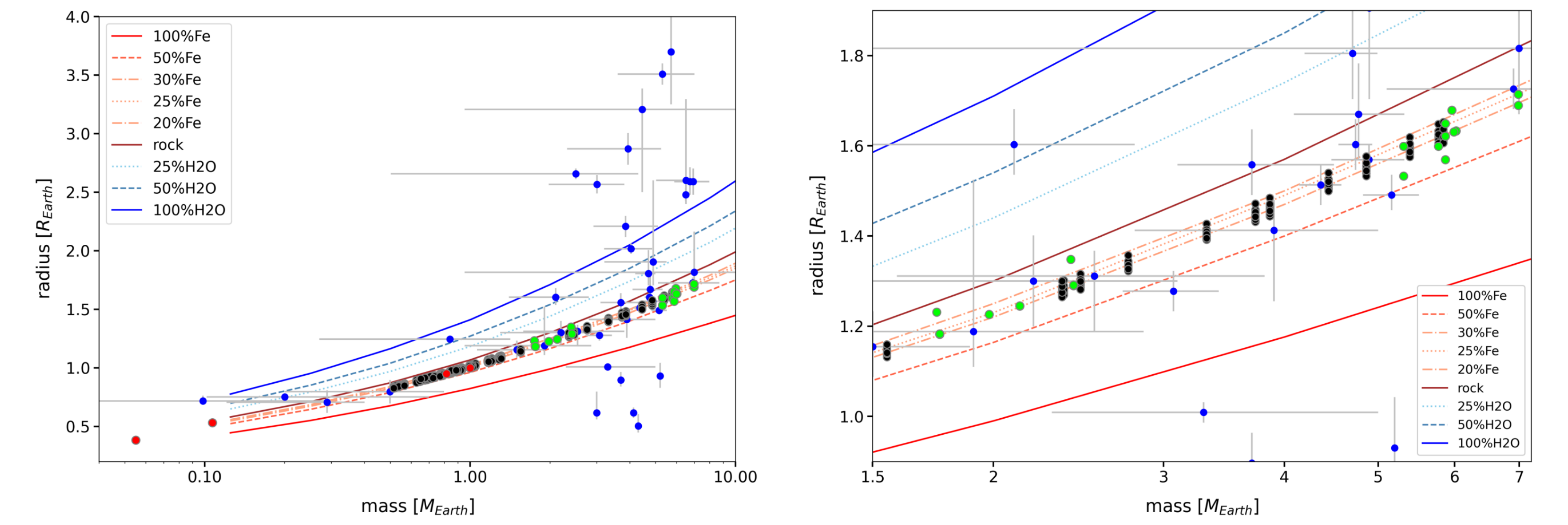
E) Comparison to the observed systems



The samples partially overlap.

On the left: Masses of the simulated planets compared to the observed sample. On the right: Radii of the simulated planets as homogeneous spheres with one preset density from the planet formation simulations, and radii of the simulated planets computed using *ExoPlex*[8], compared to the observed sample. The computed radii are gravitationally compressed based on the compositions. Only planets with masses <= 7 M_{Earth} are considered (so without substantial amounts of accreted gas).

- The majority of planets are compositionally like more or less massive versions of Earth and Venus.
- The Ca- and Al-rich innermost planets almost reach the rock (core-less planets) and 50%Fe curves.



M-R diagram: The simulated planets (in black), the observed K dwarf population (in blue), the terrestrial Solar System planets (in red), and Ca- and Al-rich planets (in green), together with the compositional curves[10]. Only planets with masses <= 7 M_{Earth} are considered.

Conclusions

- We reproduced the main characteristics and architectures of the known K dwarf systems.
- The planets located at:
    - < 0.1 AU have Al/Si and Ca/Si ratios well above the Solar System values
    - > 0.1 AU have similar compositions, and likely structures strongly resembling the Earth
- We formed: Ca- and Al-rich planets, core-less planets, planets with CMFs ranging from very similar to Earth or Mars to very different, but no Mercury-like planets with a huge iron core.
- The largest variations in the planet compositions come from:
    - radial compositional variations in the disk, in the inner regions of the systems
    - differences in the stellar chemical abundances, in the outer regions of the systems

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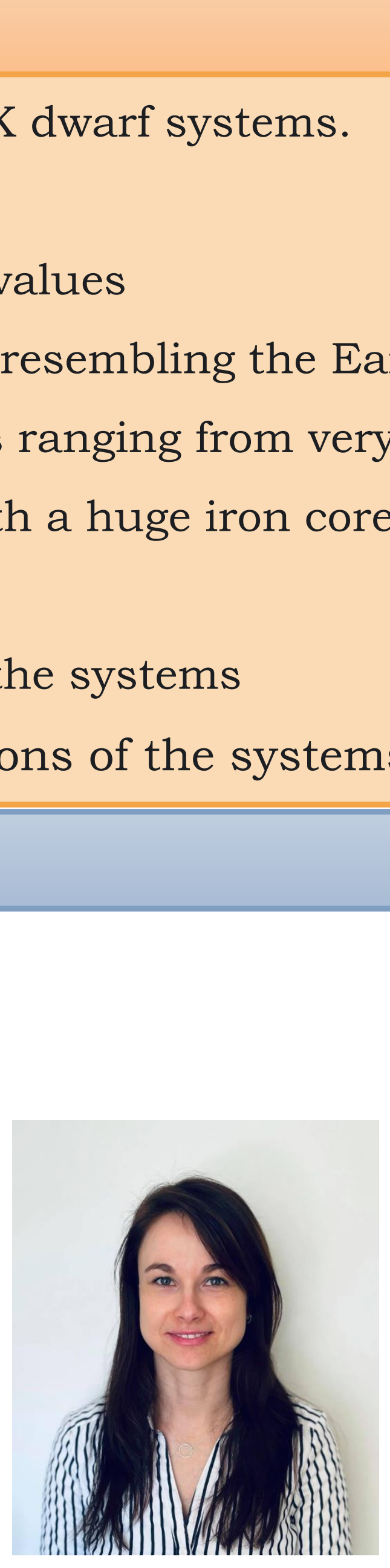

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