Modeling the Interior Structures and Thermal History of Super-Puffs

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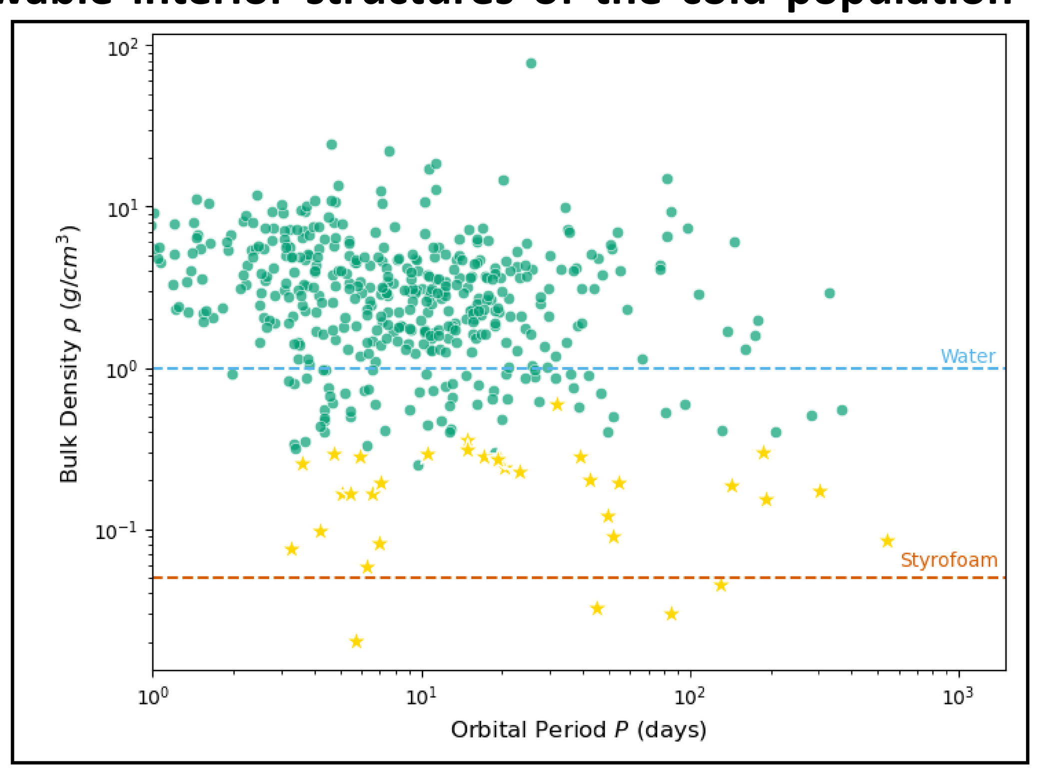
Introduction

- "Super-puffs" are sub-Saturn mass planets which are not consistent with standard mass-radius relations and formation theory due to their low densities. Short orbital period, "hot" super-puffs can often be explained by their proximity to the host star, while "cold" super-puffs require an alternative hypothesis. A variety of novel explanations for this subset has been proposed, including rings [1], hazes [2], and atmospheric outflows [3]. **We aim to identify where non-standard explanations are necessary by determining the allowable interior structures of the cold population** ($S < 100\,S_{\oplus}, P \geq 6.95d$).

Figure 1(right). Bulk density vs orbital period distribution of all known super-puffs . Data sourced from the NASA Exoplanet Archive on 11/24/2025. We define "super-puff" as a planet with:

$$M_p \leq 60 M_{\oplus},$$
$$\rho \leq 0.3 g/cm^3$$



Interior Structure Models

- Using the open-source code PlanetSolver [4], We compute hydrostatic equilibrium solutions for a range of core mass fractions (CMF), as well as atmospheric specific entropy (K) and metallicity (Z). We consider a fully convective H_2-He envelope, and a Vinet EOS describing cores composed of pure Iron, Perovskite, Ice VII, and a terrestrial core of 32.5% Iron, 67.5% Perovskite. We consider $5.5 \leq K \leq 7.0 k_B/baryon$ and Z between 0.1 and 100 × Solar. A set of models is computed for each planet's observed mass, from which solve for the parameters that reproduce the planet's observed radius.

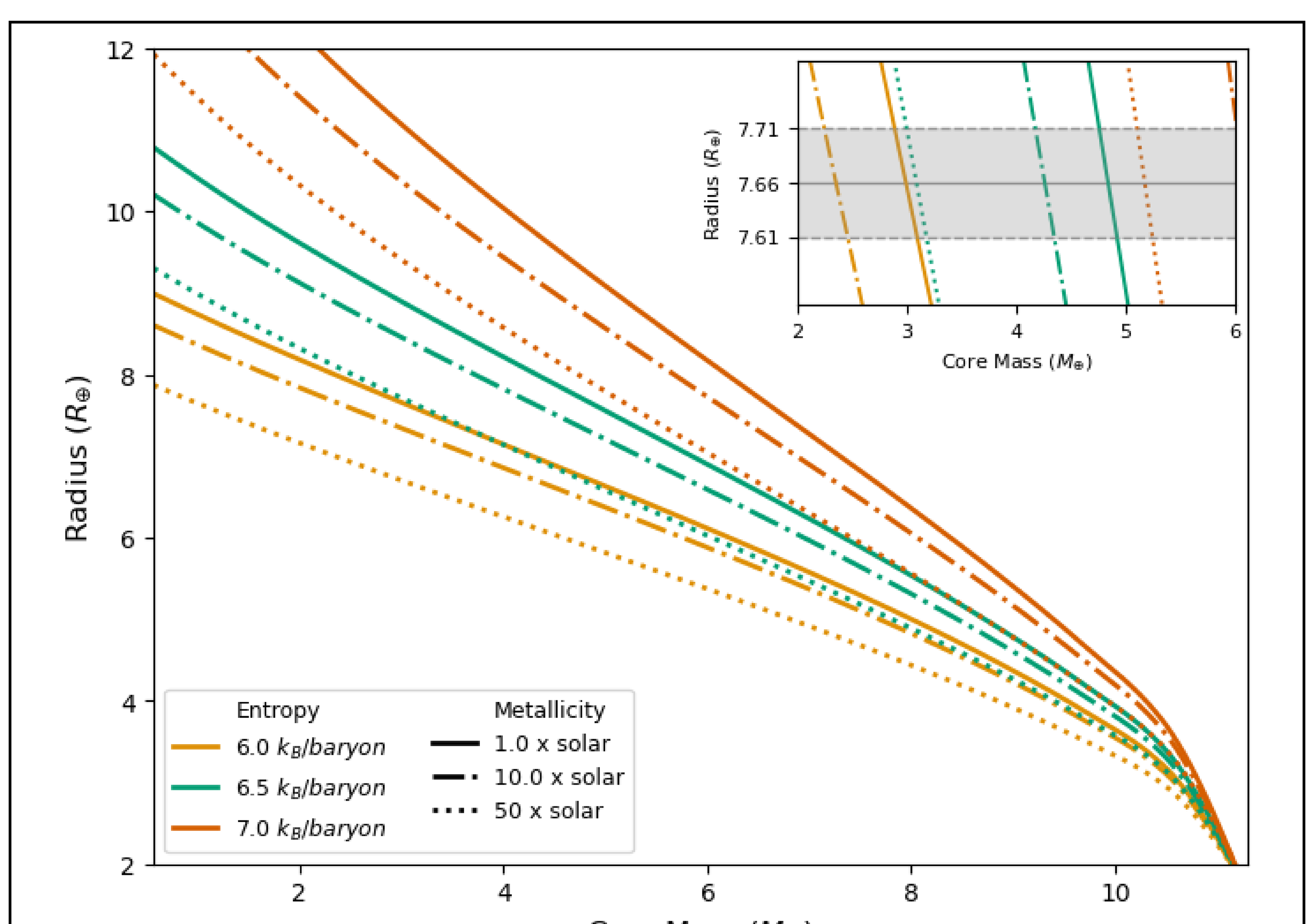
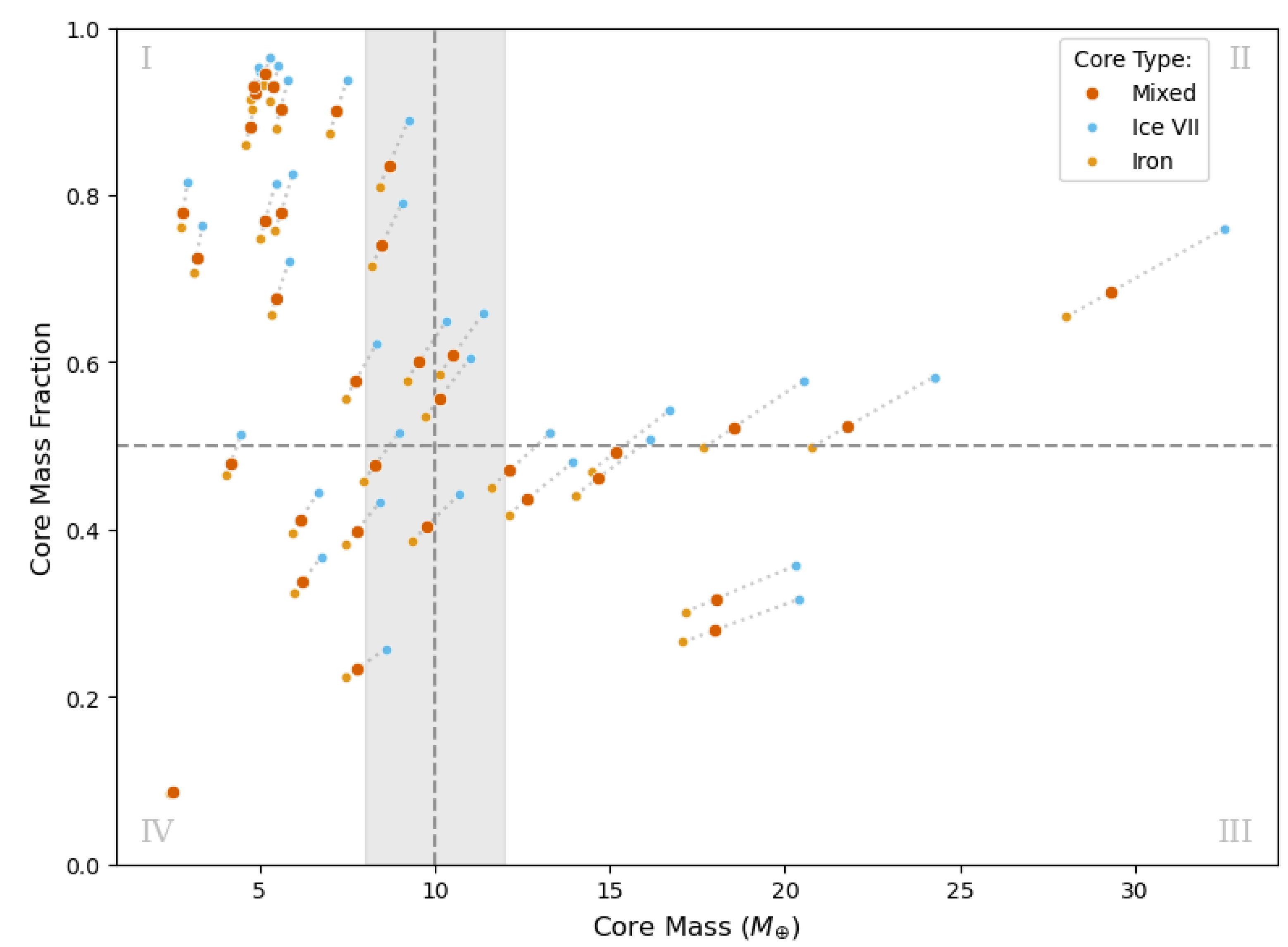


Figure 2. Interpolated Mass-Radius curves for TOI-1338 b. The inset shows the region near TOI-1338 b's measured radius.

Interior Structure Results

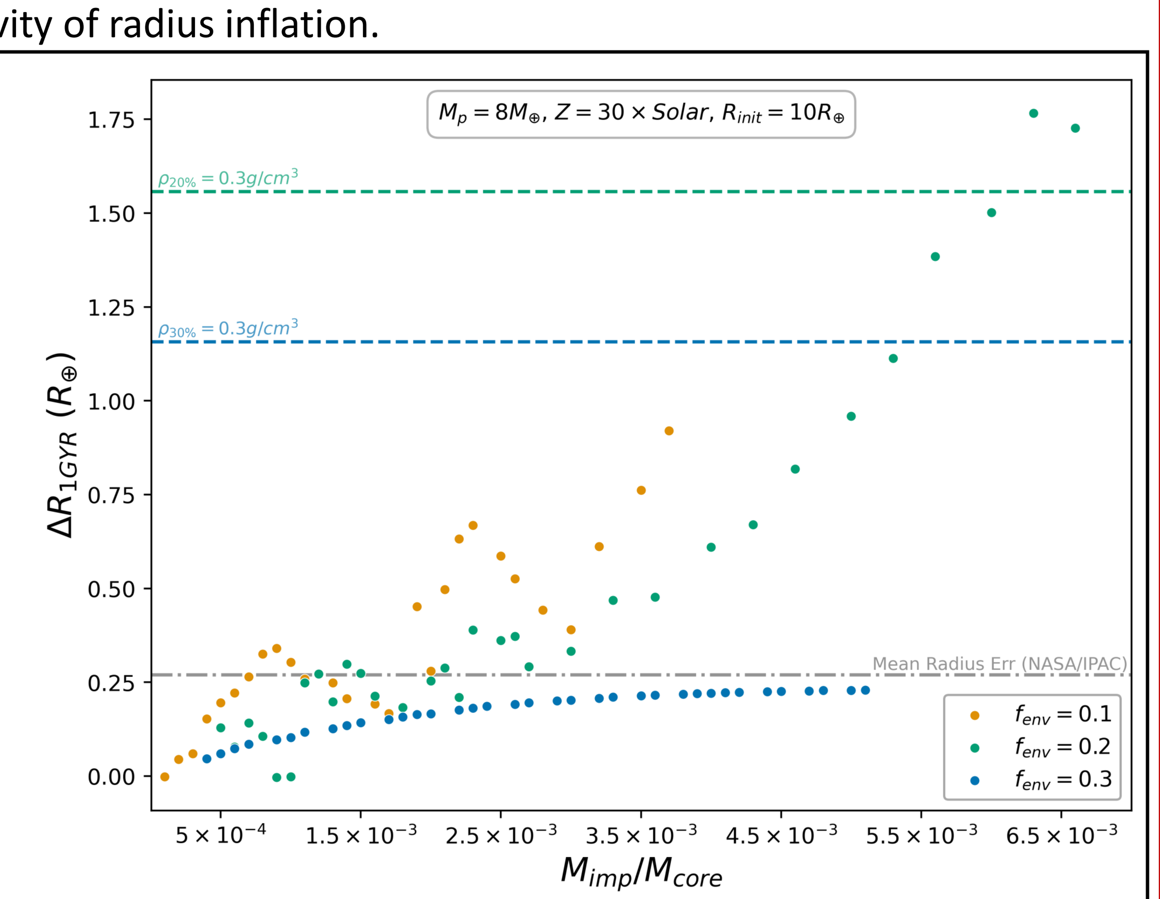
Figure 3. The maximum core mass fraction achieved within the range of typical K and Z. **Quadrant I** contains Planets which can feasibly be explained by standard processes (16 Planets). **Quadrants II & III**: Planets met criteria for runaway accretion (RA), but RA ended prematurely or did not occur (11 Planets). **Quadrant IV** contains Planets with core masses too low to have undergone RA, with too large an atmosphere to be explained by other standard processes. Planets in this quadrant (HIP 41378 f, Kepler-177 c, Kepler-51 d, TOI-1420 b, TOI-1173 A b, WASP-107 b, V1298 Tau b & e) suggest a non-standard explanation is required.



Giant Impact-driven Inflation

- Giant impacts can add heat into planetary atmospheres, potentially causing inflated radii. Standard evolution and cooling models [5] are perturbed to determine whether giant impacts are a viable explanation for super-puff radius inflation. We simulate impact events at 1Gyr according to [6] for a range of impact masses and record the magnitude and longevity of radius inflation.

Figure 4. The maximum radius inflation $\Delta R = R(t) - R_{control}(t)$ achieved with 10%, 20%, and 30% envelope mass fraction models, as a function of impact mass. The dashed lines represent the inflation required to lower the planet's bulk density below $0.3 g/cm^3$.



Results & Conclusions

- We find that **27 of the 35 modeled super-puffs can be explained by standard formation theory or a brief period of runaway accretion**. The remaining eight planets cannot be described by models with less than 50% envelope mass and/or core masses capable of undergoing runaway accretion. The following planets likely require a novel explanation.
  - HIP 41378 f
  - Kepler-51 d
  - Kepler-177 c
  - TOI-1173 A b
  - TOI-1420 b
  - V1298 Tau b and e
  - WASP-107 b
- **We find that planets requiring novel explanations are not concentrated below or near a specific bulk density (see Figure 5 below) and have a wide range of proposed explanations.**
- **Our impact model results indicate observable radius inflation is possible on Gyr timescales, and suggest that further investigation into this explanation is warranted**

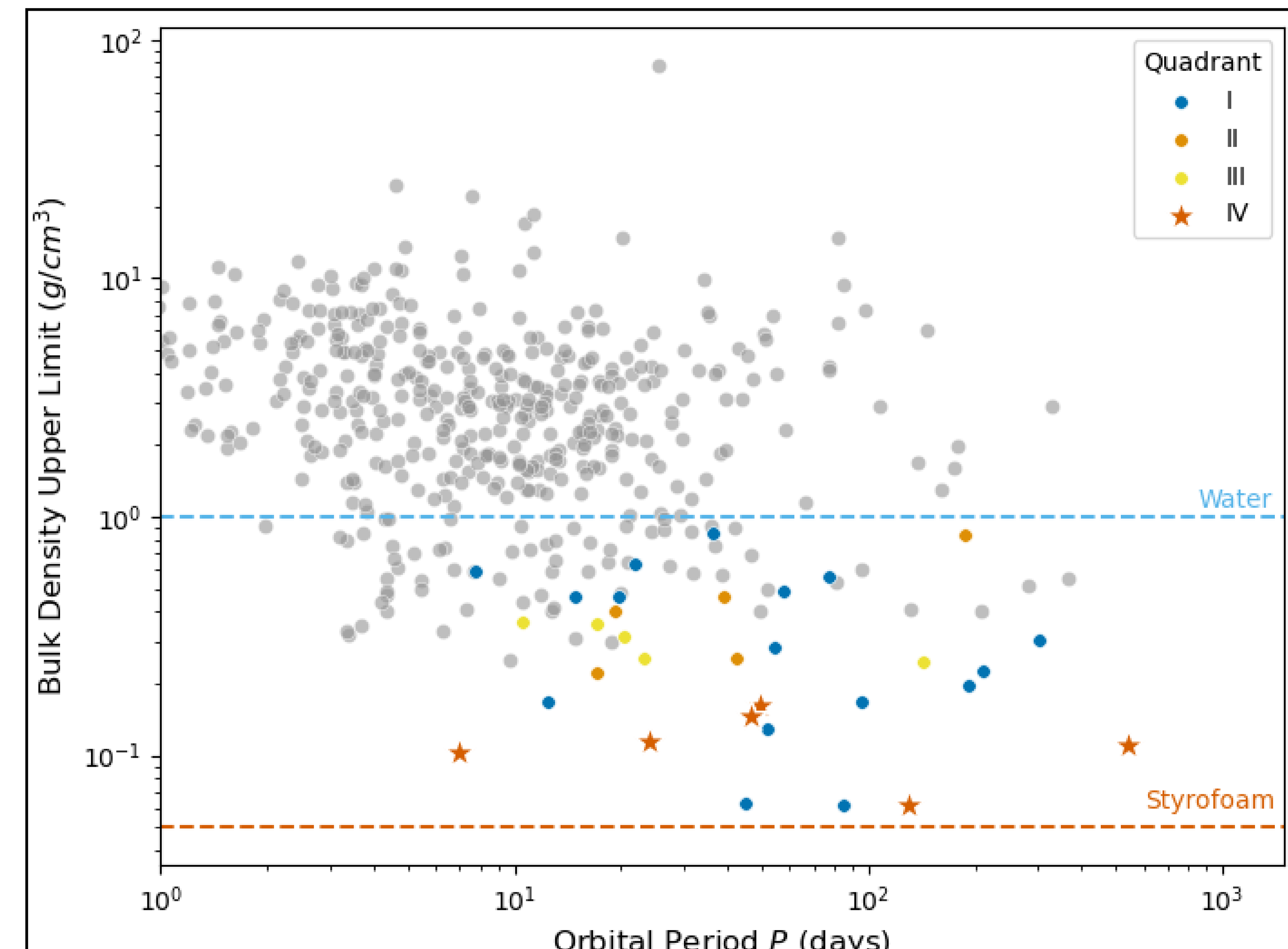


Figure 5. A demographic visual of cold-super puffs, color coded according to the explanation suggested by our results. Quadrant IV planets require non-standard hypotheses.

References

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