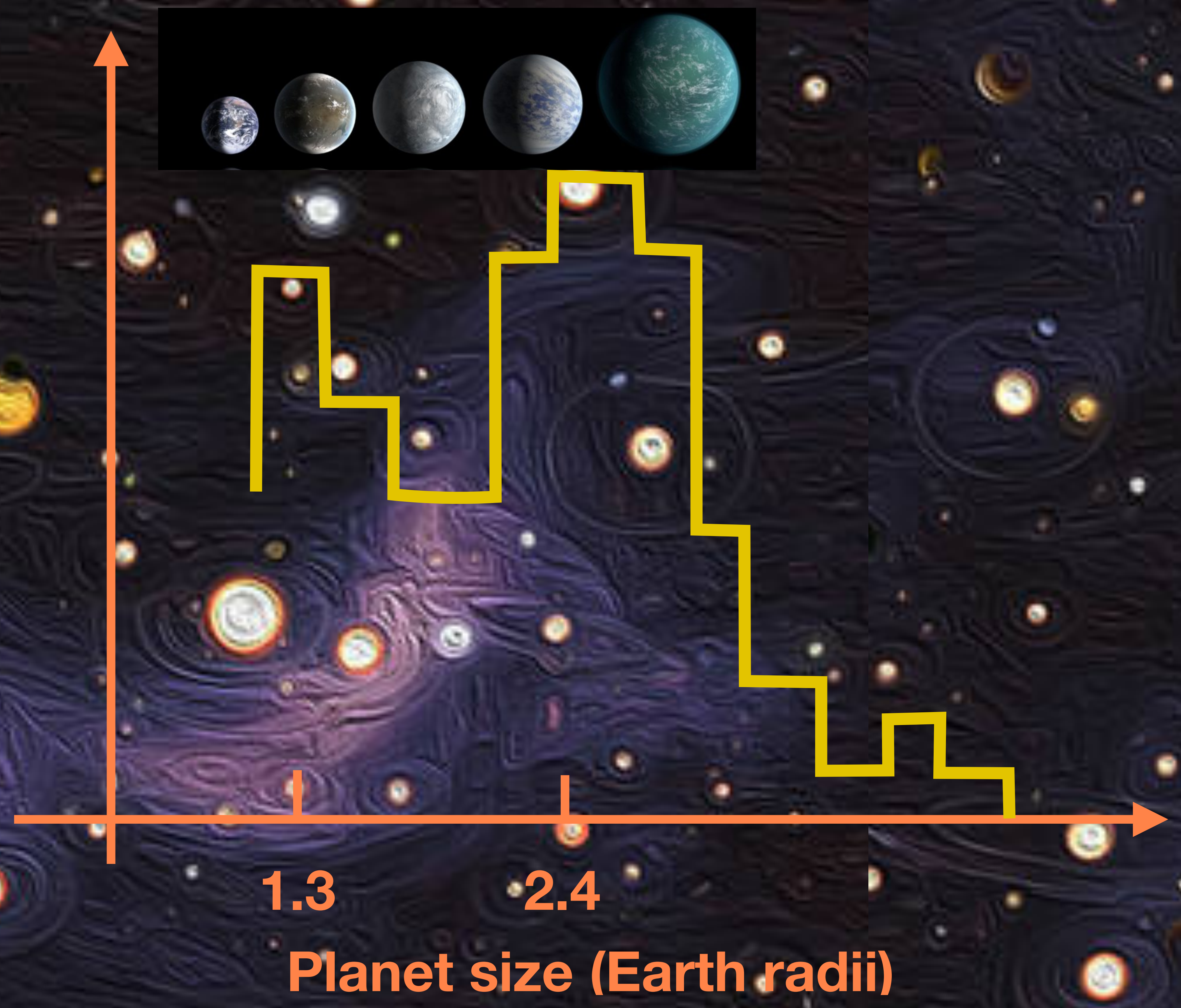
The nature of the Radius Valley: insights from formation models



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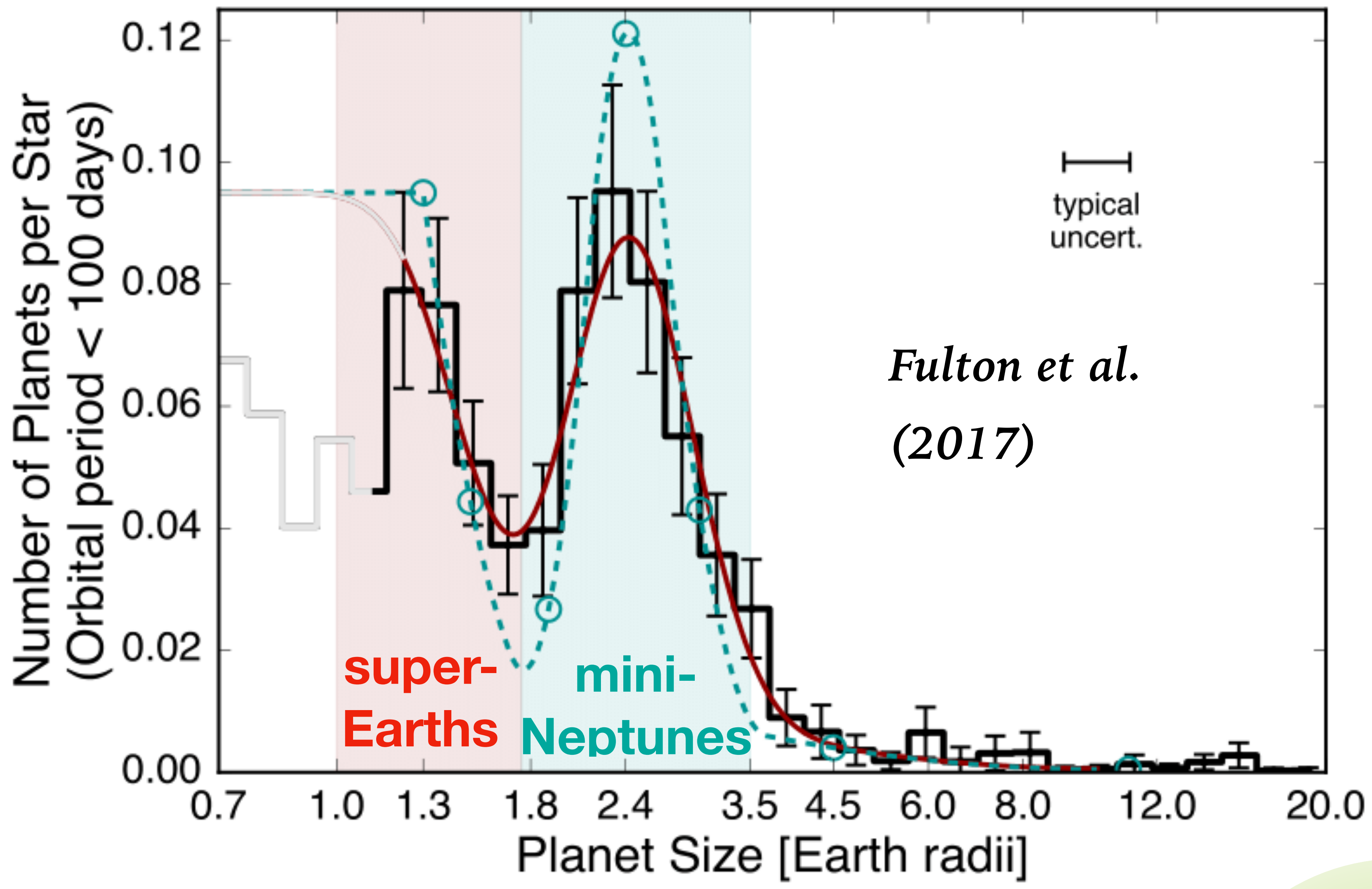
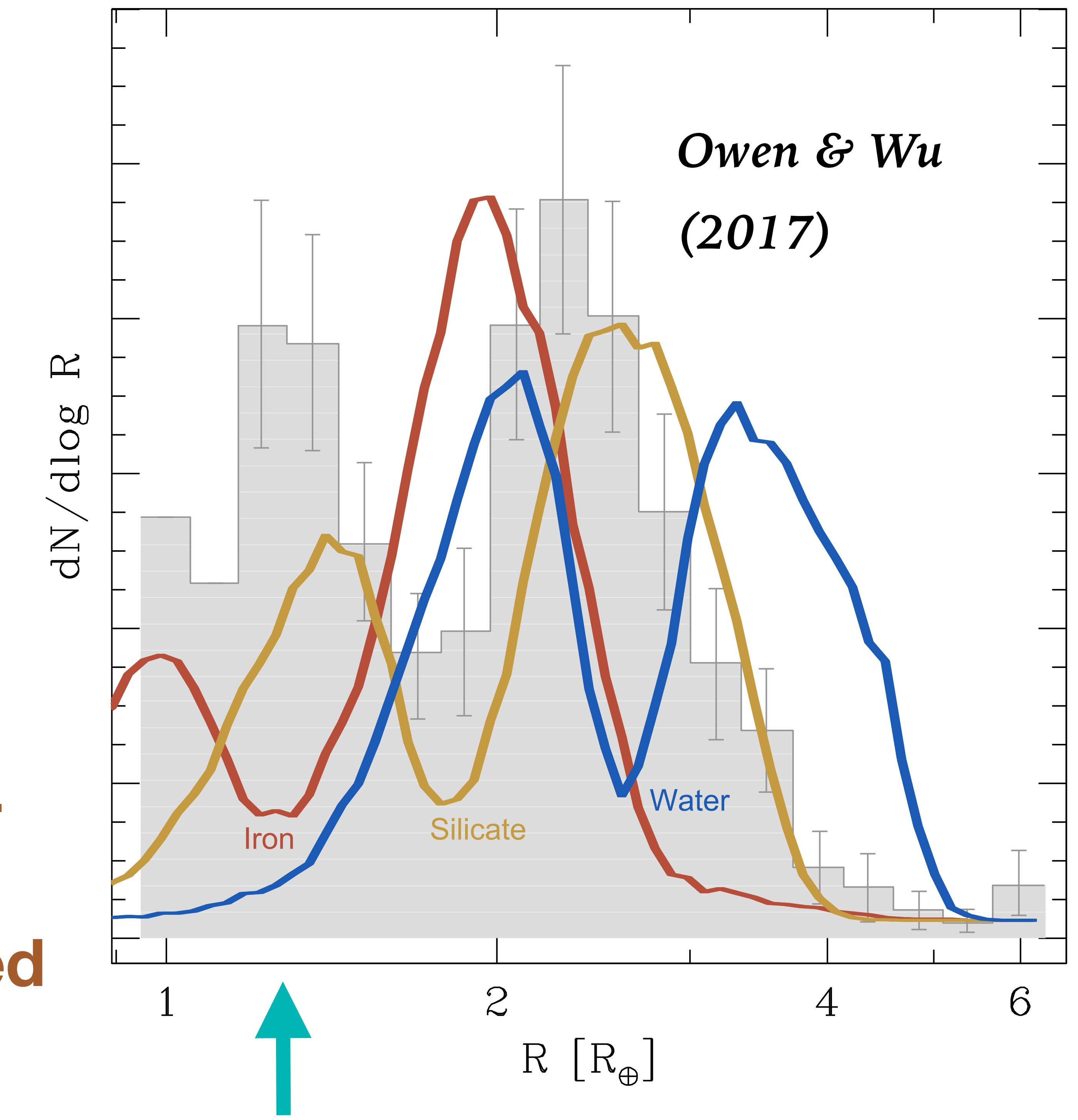
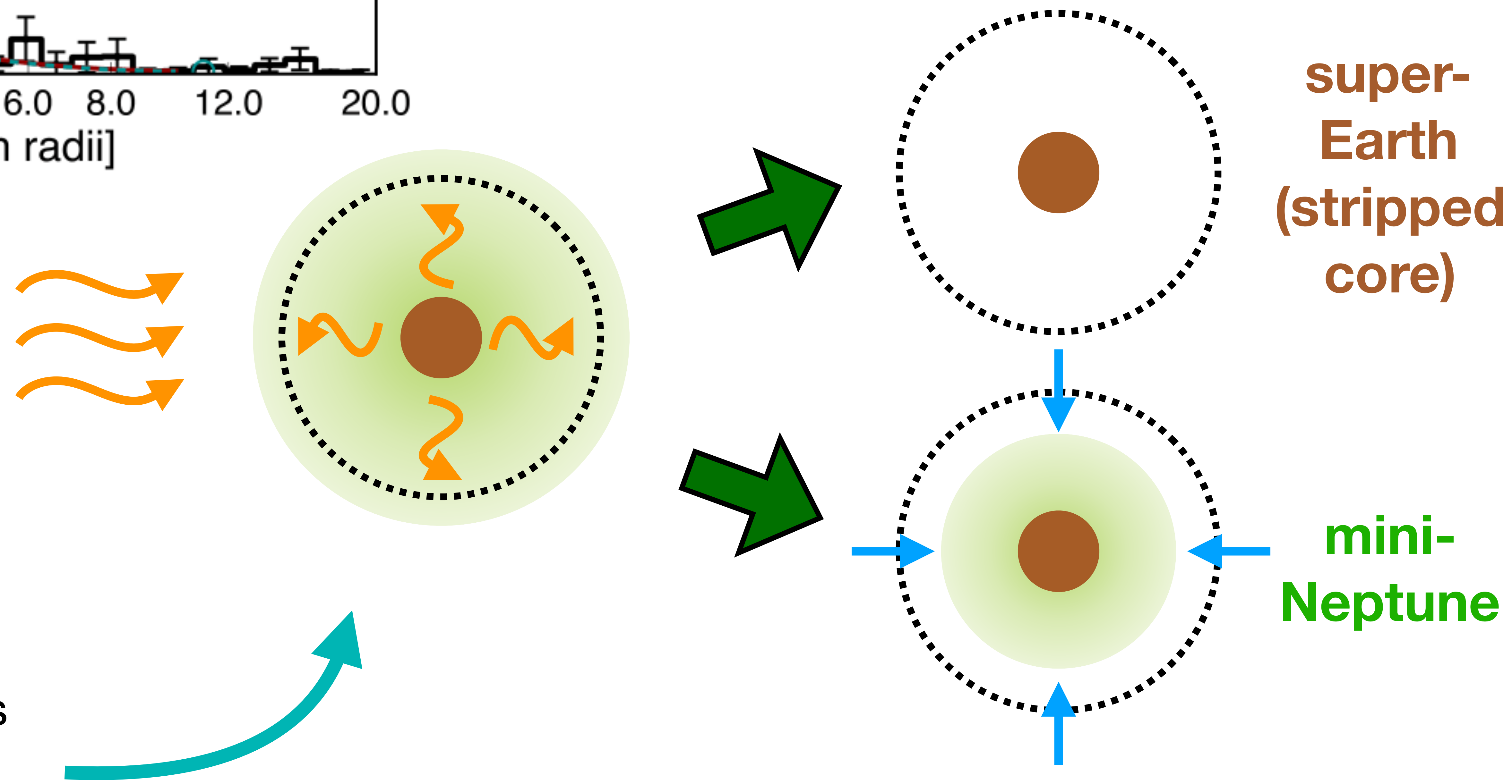
THE RADIUS VALLEY AND THE EVOLUTIONARY INTERPRETATION



1. Most exoplanets discovered so far have **sizes** between Earth and Neptune, and the distribution is **bimodal,** with peaks at ~1.3-1.5 RE ("super-Earths") and ~2.4-2.7 RE ("mini-Neptunes"), and the valley at ~1.8-2 RE. *(Fulton et al. 2017, 2018; Martinez et al 2019, Petigura et al. 2020).*



2. Two types of evolution models can explain the bimodality. The idea is that some heat source (e.g, external: **photoevaporation** or internal: **core-powered mass-loss**) produces atmospheric escape. Some planets will get so hot that will lose their atmospheres completely, but some will retain a thin H-He atmosphere.



3. Both models are able to reproduce the correct size distribution if **planets are rocky** *(Owen & Wu 2017, Gupta & Schlichting 2019)*=> This led to the interpretation that these planets were **formed inside the water ice line.**

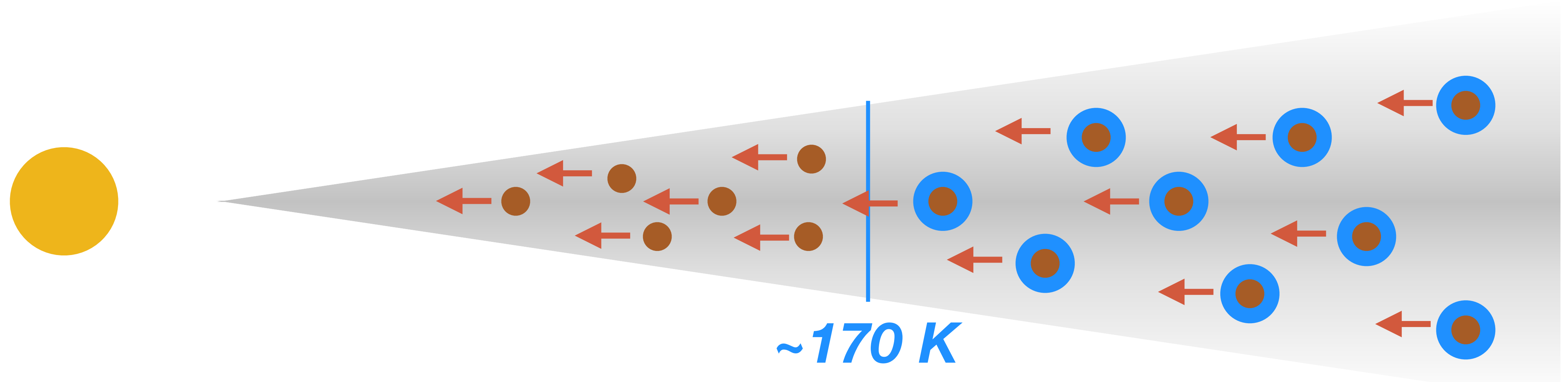
(Owen & Wu, 2017, Jin & Mordasini 2018, Mordasini 2020, Modirrousta-Galain 2020)

4. However, **planet formation** models tend to favour accretion beyond the ice line. Super-Earth mass planets easily undergo Type-I migration, which places **water-rich objects at short orbital periods.** *(e.g, Alibert et al. 2013, Raymond et al. 2018, Bitsch et al. 2019).*

GLOBAL PLANET FORMATION SIMULATIONS WITH PEBBLE ACCRETION

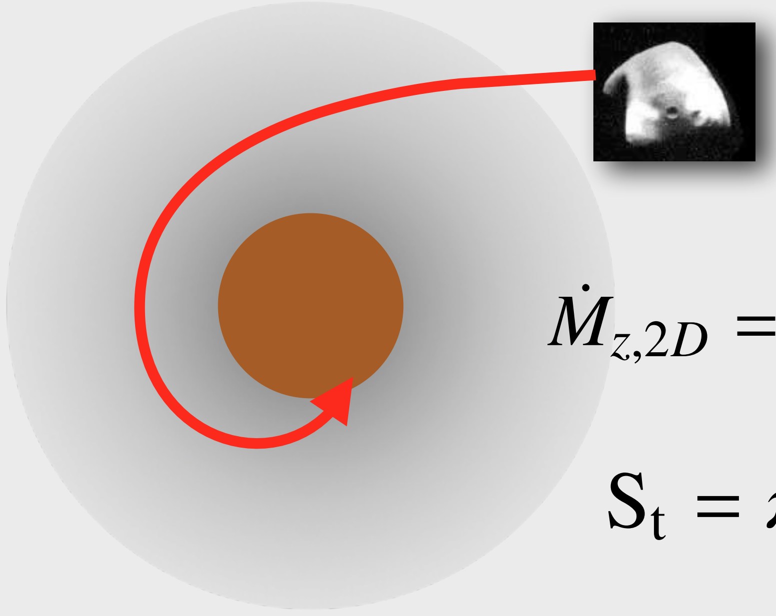
- **1d+1d gas disk** that evolves by viscous accretion and photoevaporation.
- **Dust growth** model of Birnstiel et al. (2012):
  - Dust (pebbles) evolve by growth, fragmentation and drift.
  - 1 dominant size of solid particle.
  - sublimation of ice at the ice line.

  (Guilera et al. 2020: https://arxiv.org/abs/2005.10868
  Venturini et al. 2020: https://arxiv.org/abs/2008.05497)



- A lunar-mass embryo grows by **accreting drifting pebbles** and gas from the disk. **Migration** is considered.

Pebble accretion



$$\dot{M}_{z,2D} = 2\left(\frac{S_t}{0.1}\right)^{2/3} R_H v_H \Sigma_P$$

$$S_t = \pi \rho_d \bar{r}_d / 2\Sigma_g$$

- Beyond the water ice line the pebbles are more sticky and have therefore larger sizes. The larger the pebble sizes, the larger its Stokes number (St), and the more effective is the core growth (see Eqs.) => Beyond the ice line the cores grow more massive (also because the pebble isolation mass is larger.)

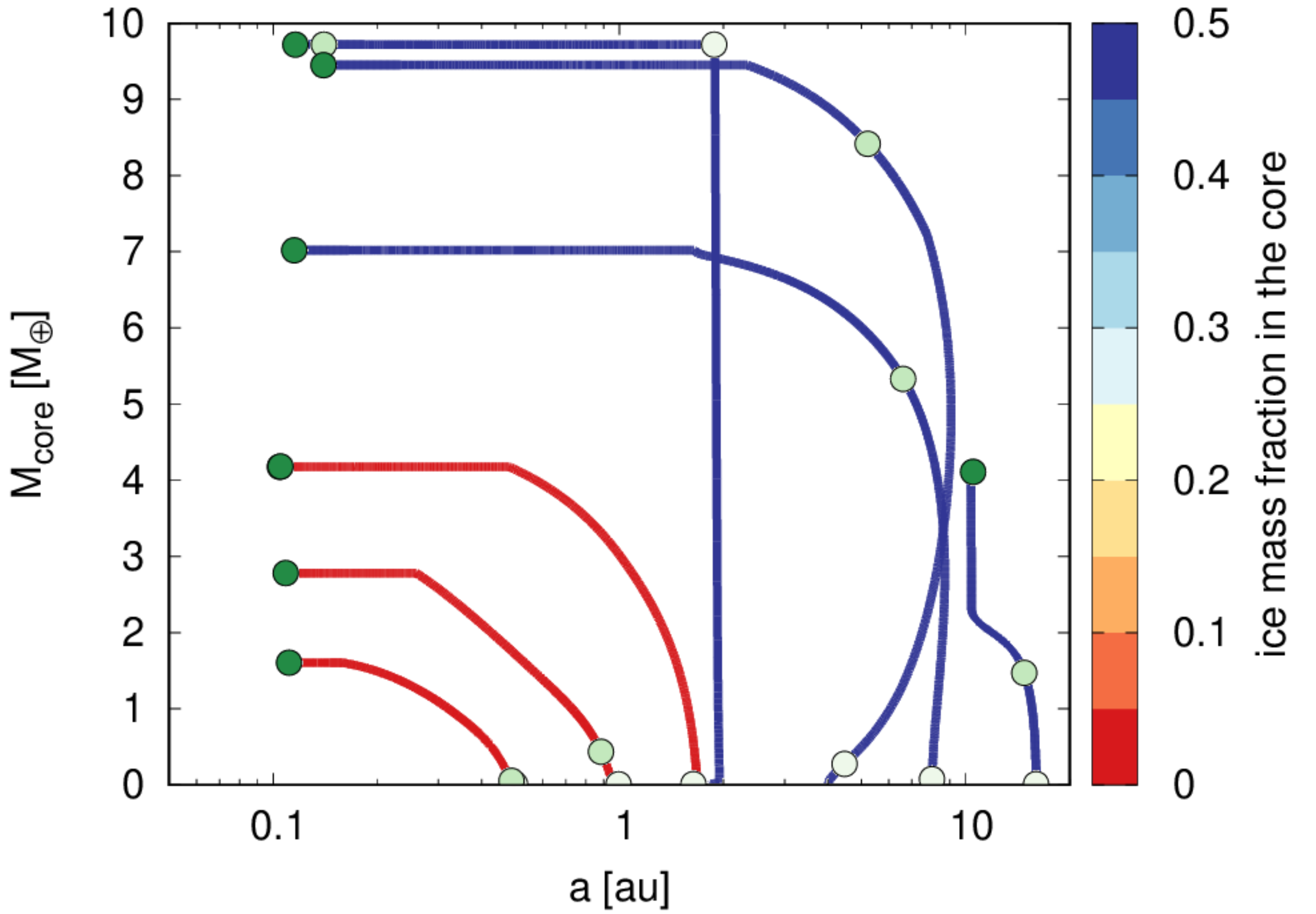
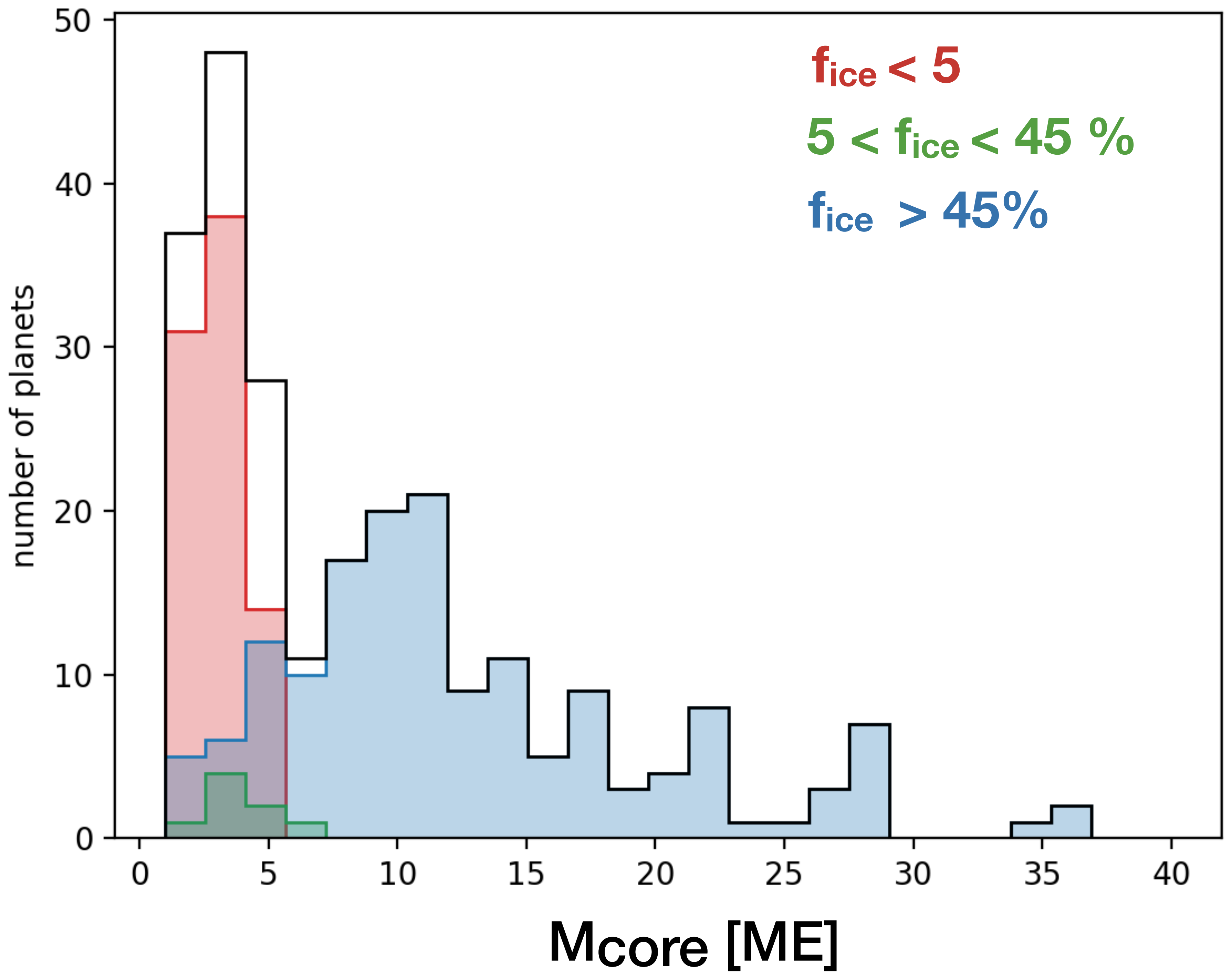
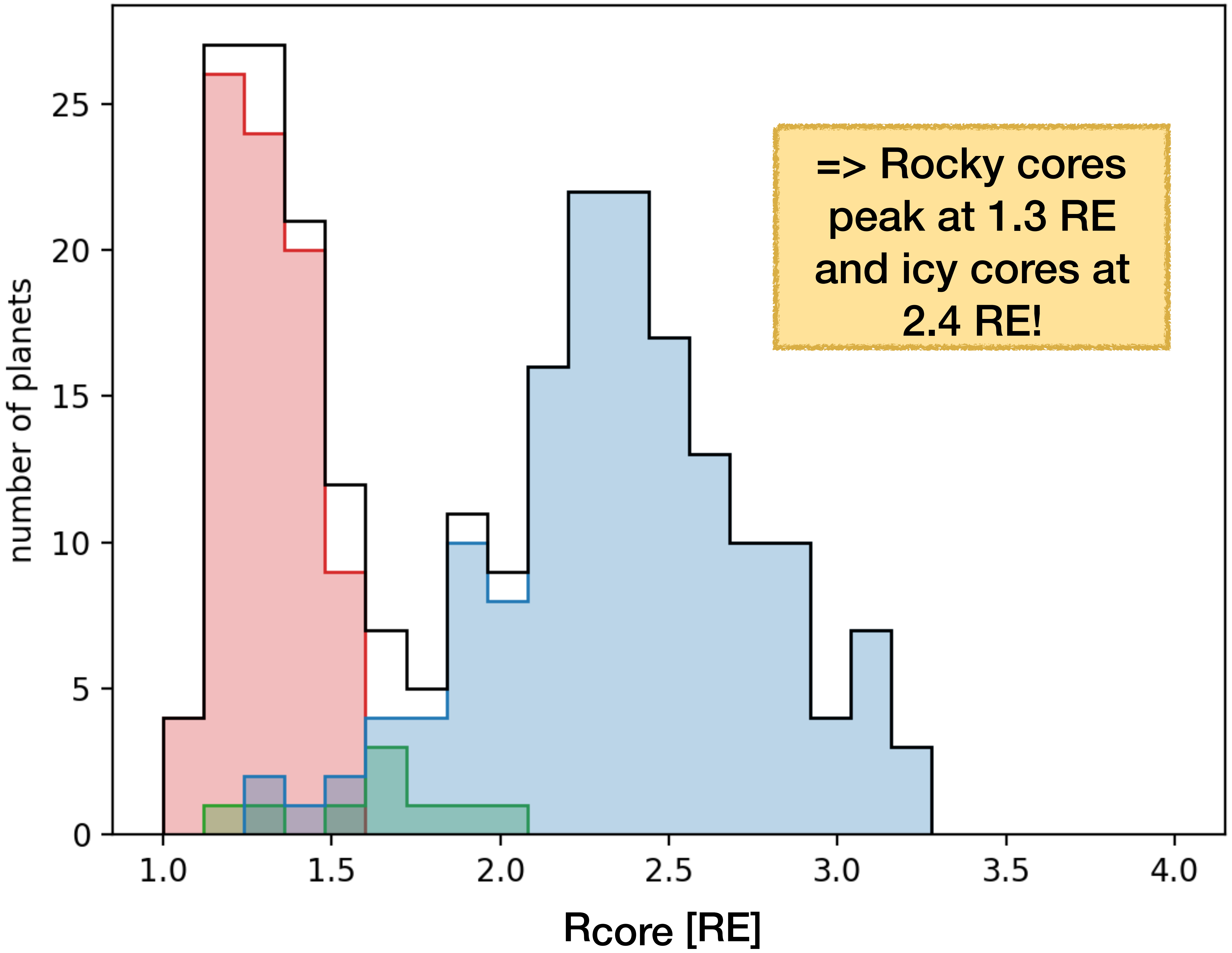


Fig. 1: Formation tracks for seven embryos starting their growth inside (red) or outside the water ice line. The icy cores grow to larger masses.

CORE MASSES AND RADII AFTER FORMATION

The figures show the result of the distributions of core masses and core radii of 665 planet formation simulations, spanning a large range in initial disk metallicity, initial embryo location, and initial disk mass and profile. Only the planets that finish with orbital period <100 days are shown.





- **When the presence of the gaseous envelopes is neglected, the bimodal mass distribution of the rocky and icy cores originating from formation yields the correct radii bimodality observed by *Kepler* => This suggest that some process that inhibits gas accretion or that removes gas after accreted could be at operation.**
- **More details at: https://arxiv.org/abs/2008.05513, https://arxiv.org/abs/2008.05497**