The Radius Valley as a By-Product of Planet Formation: The Core-Powered Mass-Loss Mechanism

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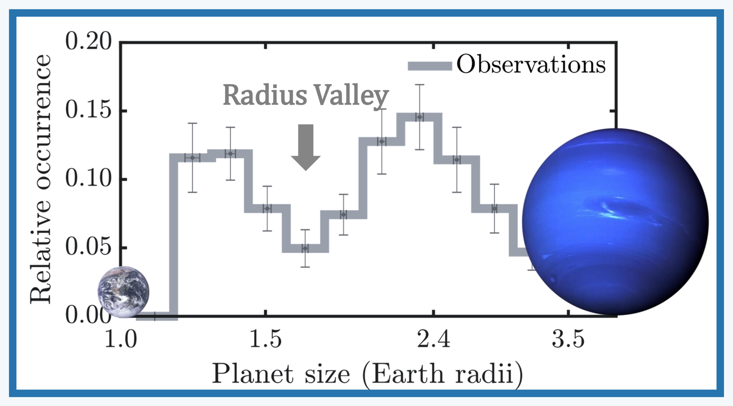
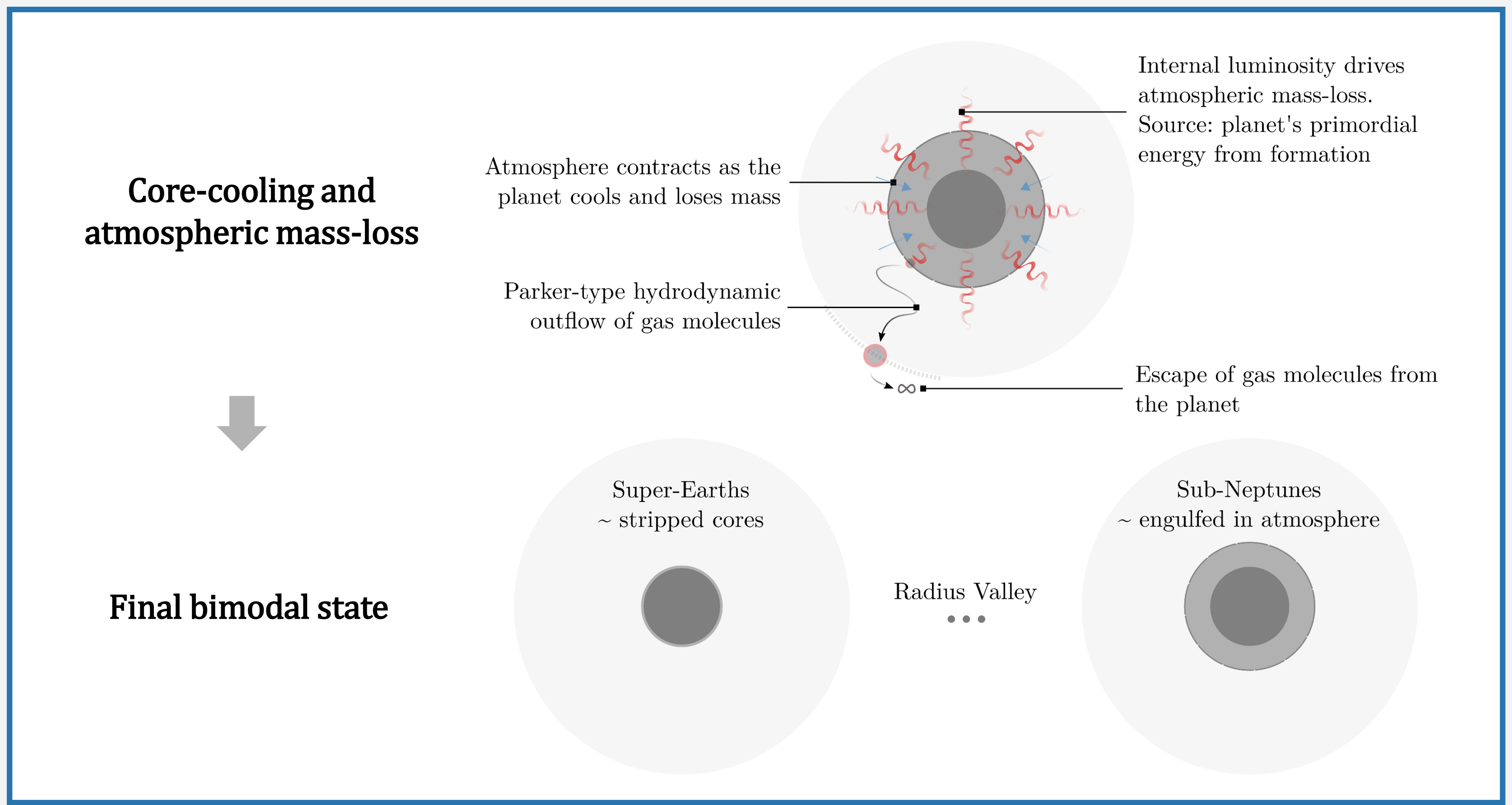
Recent Observations

- Most common planets known are 1-4 Earth radii in size
- Lack of small, close-in exoplanets around 1.5-2.0 Earth radii, i.e., a radius `valley' separating a population of super-Earths (smaller planets) and sub-Neptunes (larger planets)
- Compositions?
  - Super-Earths have higher densities → consistent with planets having rocky 'Earth-like' composition
  - Sub-Neptunes have lower densities → consistent with planets engulfed in H/He envelopes



[Based on data from Fulton et al., 2017]

Background: The Core-Powered Mass-Loss Mechanism

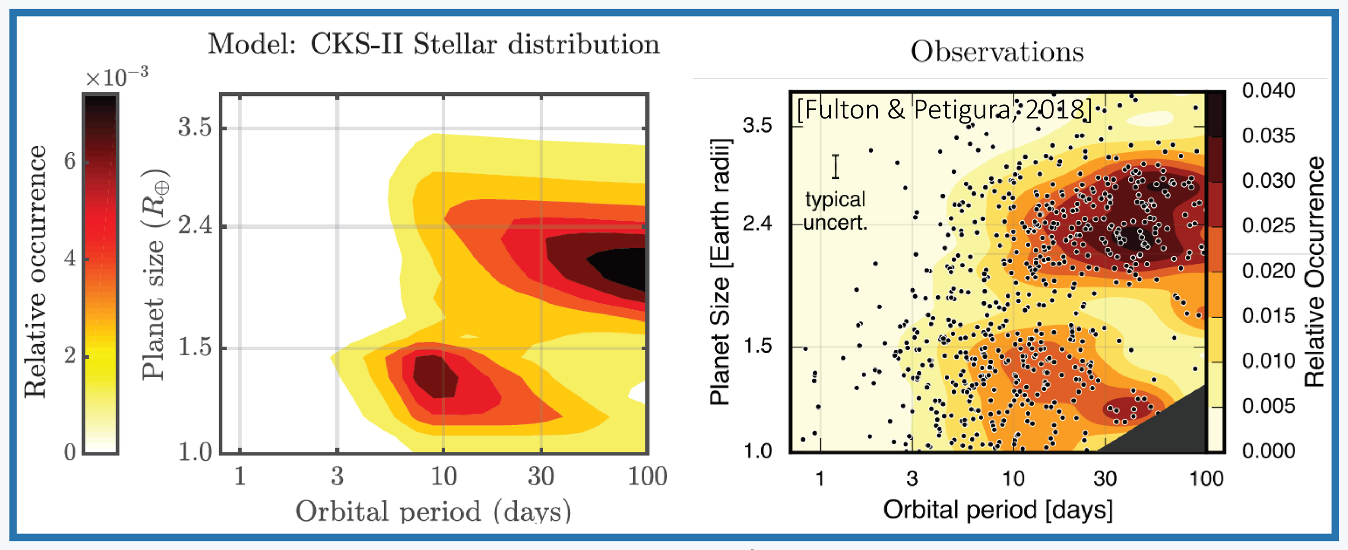


- Final states of a planet:
  - **Sub-Neptune**: if a planet does not has enough internal energy to overcome the gravitational binding energy of its atmosphere OR if a planet's cooling timescale (t_{cool}) is shorter than its mass-loss timescale (t_{loss}), i.e., if $t_{cool} < t_{loss}$.
  - **Super-Earths**: : if a planet has enough internal energy to overcome the gravitational binding energy of its atmosphere AND if $t_{cool} > t_{loss}$
- **Slope of the Valley** ≡ $t_{cool} = t^B_{loss}$
  - Mass-loss timescale: $t^B_{loss} = \frac{M_{atm}}{4\pi R_s^2 c_s \rho_s} \propto \exp(GM_p/(c_s^2 R_{rcb})) \propto \exp(R_p^3 T_{eq}^{-1} \rho_{c*}^{4/3})$
  - Exponential dependence → valley's slope strongly depends on the terms in the exponent

Results from Gupta & Schlichting, 2019a, 2019b

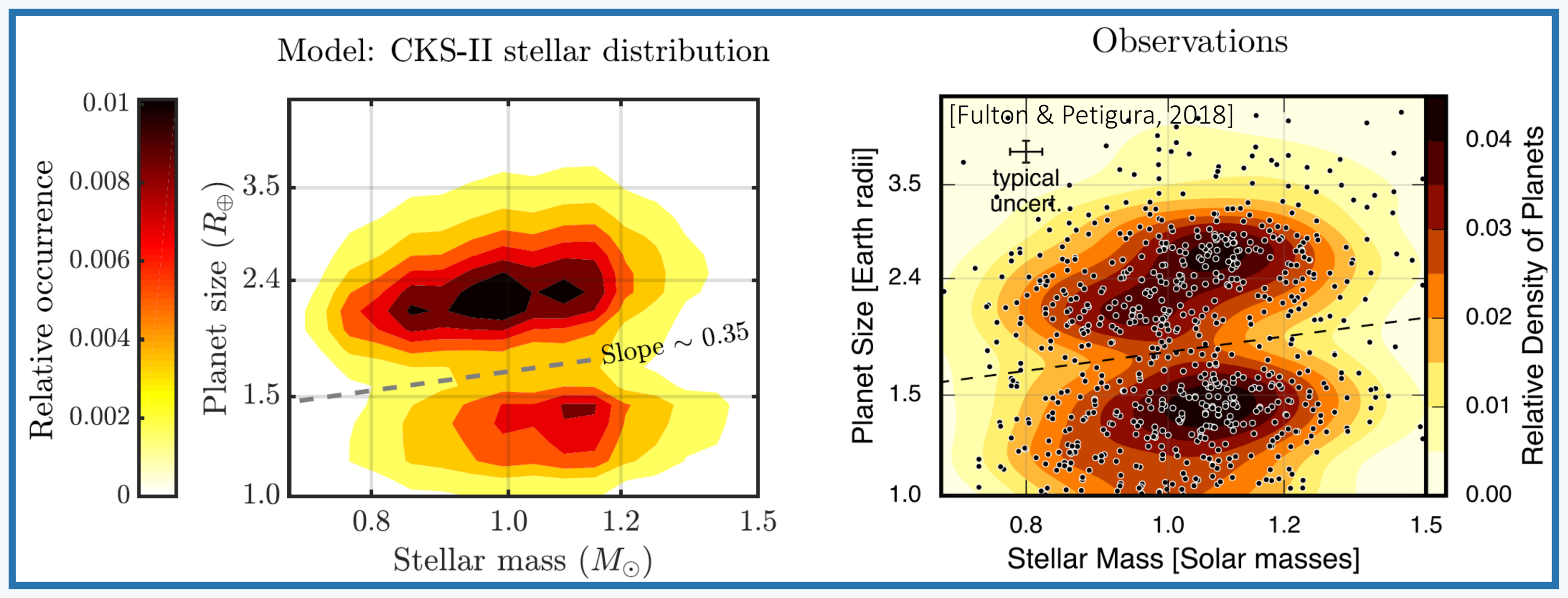
Comparison with observations and trends in planet size distribution with stellar prop.

Planet size vs. Orbital period



- Good agreement with observations in reproducing the location, slope and shape of the radius valley and relative planetary occurrences
- Results corroborate gravitational compression of planetary cores
- Valley's slope: $t^B_{loss} = t_{cool} \rightarrow t^B_{loss} \propto \exp(R_p^3 T_{eq}^{-1}) \propto \exp(R_p^3 P^{1/3}) \rightarrow d\log(R_p)/d\log(P) = -0.11$
  - Excellent agreement with the observed slope of $-0.09^{+0.02}_{-0.04}$ [5] and $-0.11^{+0.03}_{-0.03}$ [6]
- Since, $t^B_{loss} \propto \exp(R_p^3 \rho_{c*}^{4/3})$: location of the valley depends on planet density as $\rho_{c*}^{-4/9}$
  - For best agreement with observations planet core-densities, $\rho_{c*} \approx$ 5 g cm^{-3}
  - Observed planets can have water/ice content of up to ~ 20% by mass

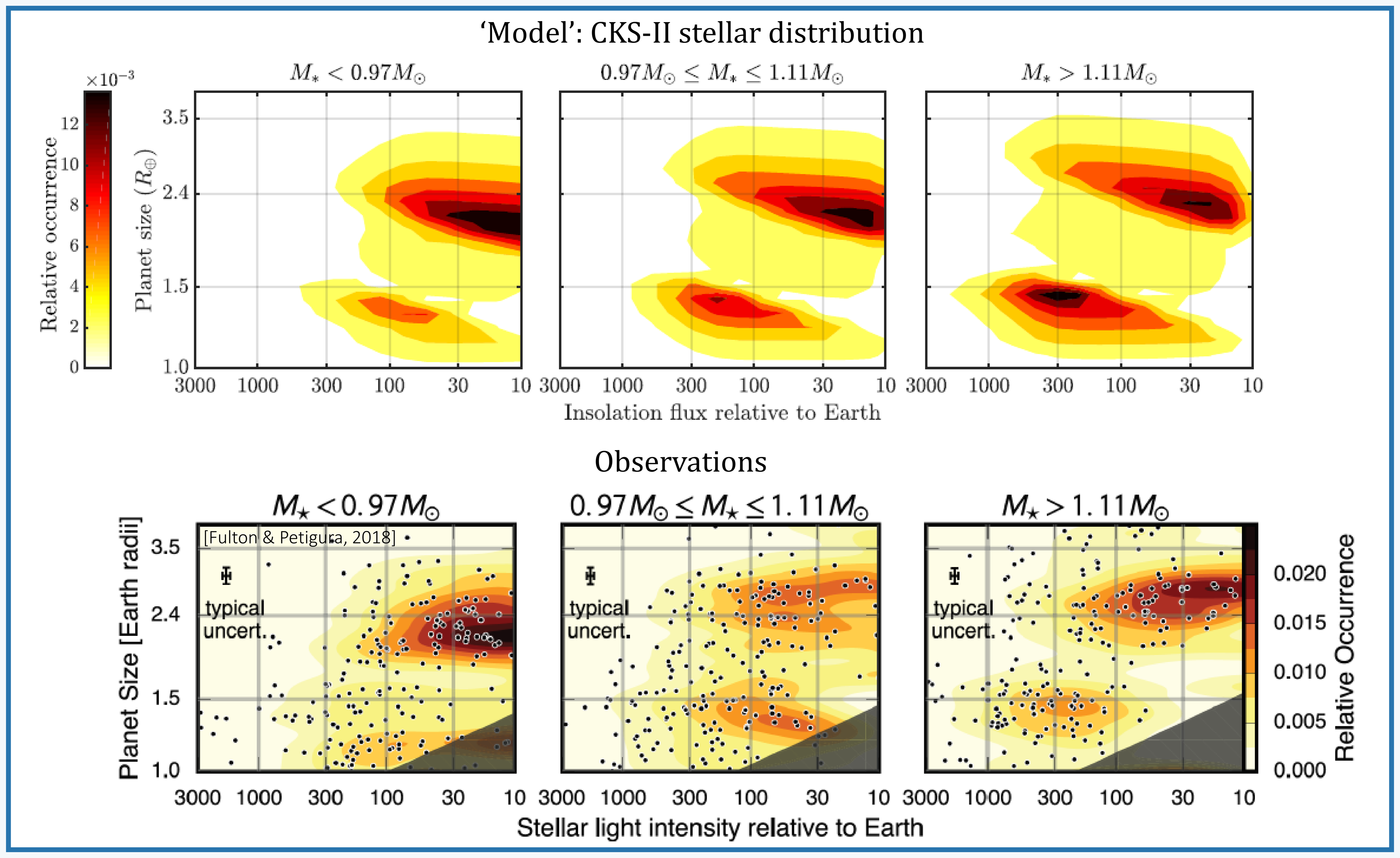
Planet size vs. Stellar mass



- Great agreement with observations.
- The core-powered mass-loss mechanism depends on stellar bolometric luminosity which, in turn, is strongly correlated with stellar mass such that $L_s \propto M_s^\alpha$

- Valley's slope: $t^B_{loss} = t_{cool} \rightarrow t^B_{loss} \propto \exp(R_p^3 T_{eq}^{-1}) \propto \exp(R_p^3 M_s^{-13/12}) \rightarrow d\log(R_p)/d\log(M_s) = (3\alpha - 2)/36$. For CKS-II dataset, $\alpha \approx 5 \rightarrow d\log(R_p)/d\log(M_s) = 0.36$ → consistent with observations [3,7].
  - For observations, as shown in the figure, $d\log(R_p)/d\log(M_s) \sim 0.35$
- Physical understanding: more massive/luminous stars → higher planetary equilibrium temperature → more massive cores can get stripped of their atmospheres → valley moves up in planet size
- Photoevaporation predicts a roughly flat radius valley as a function of stellar mass (provided that the orbital period distribution is independent of stellar mass [3])
  - Therefore, a linear correlation between planet and stellar mass has been invoked to understand these observations under photoevaporation [8]
- In contrast to photoevaporation models: Core-powered mass-loss predicts no significant correlation between planet and stellar mass

Planet size vs. Insolation flux, as a function of Stellar mass



- Results show that super-Earth and sub-Neptune populations move to higher insolation flux with increasing stellar mass, since the observed orbital period distribution is roughly independent of stellar mass [3]

Observational Predictions

- No significant, i.e., weaker than linear, correlation between planet and stellar mass
- Slope of the valley is a function of stellar mass, i.e., it depends on the stellar-mass luminosity relation
- Relative abundance of super-Earths to sub-Neptunes changes with age even after the first 500 Myrs
- Existence of giga year old planets in the radius valley which are losing mass

References

[1] Gupta & Schlichting, 2019a, MNRAS, 487, 24. [2] Gupta & Schlichting, 2019b, arXiv: 1907.03732. [3] Fulton & Petigura, 2018, AJ, 156, 264. [4] Fulton et al. 2017, AJ, 154, 109. [5] Van Eylen et al. 2018, MNRAS, 479, 4786. [6] Martinez et al. 2019, ApJ, 875, 29. [7] Johnson et al. 2017, AJ, 154, 108. [8] Wu 2019, ApJ, 874, 91.