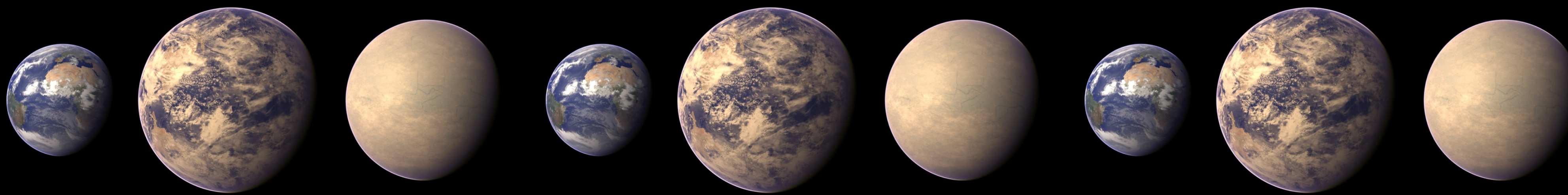
Data-driven Planetary Radii

(and masses, with implications for composition)



Angie Wolfgang
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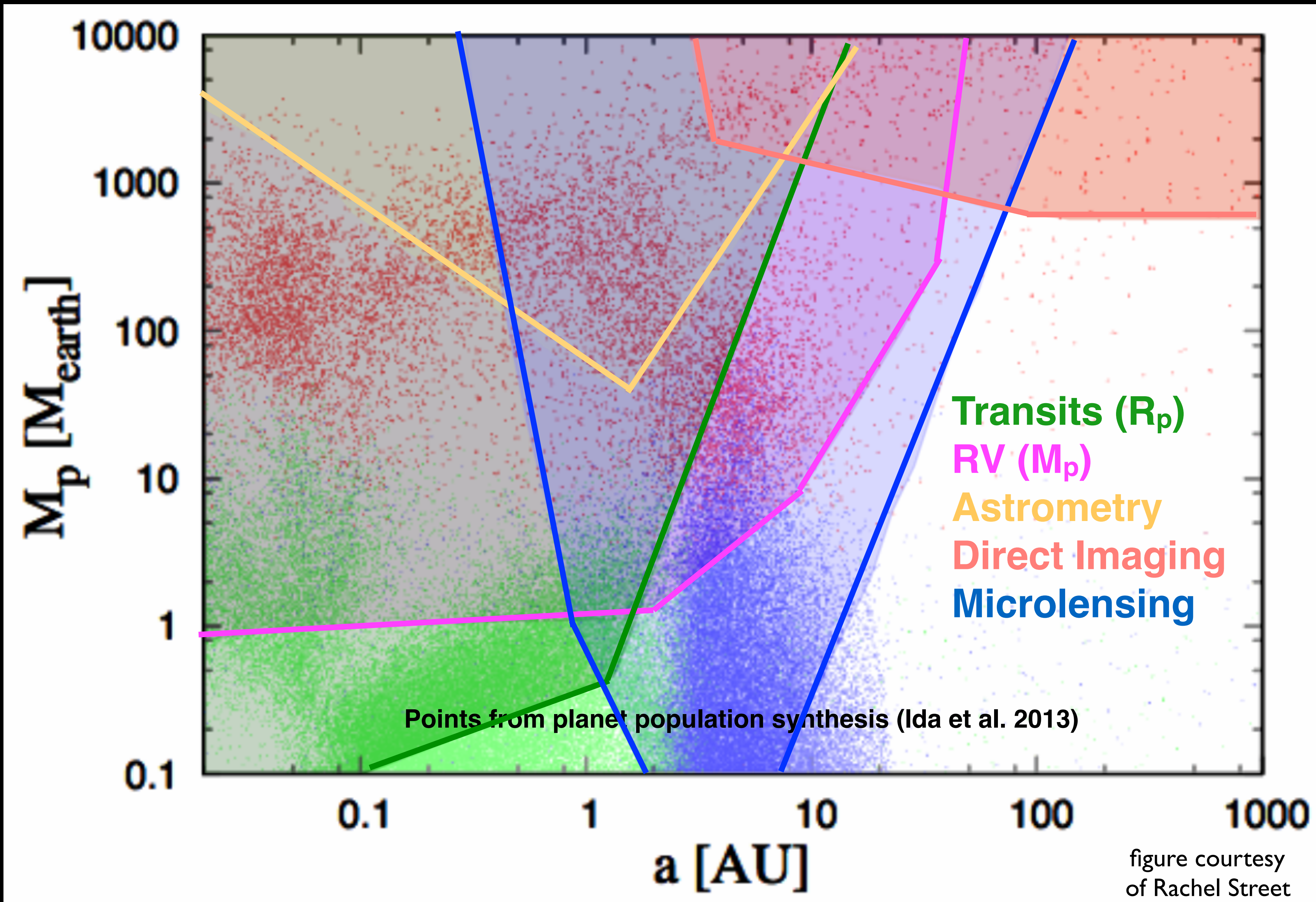
Eric Ford, Daniel Jontof-Hutter, Leslie Rogers, Eric Lopez, Jonathan Fortney,
Bo Ning, Sujit Ghosh, Shubham Kanodia, Jennifer Burt, Johanna Teske, Sharon Wang

Exoplanets: Strength in Numbers



The Current Detections

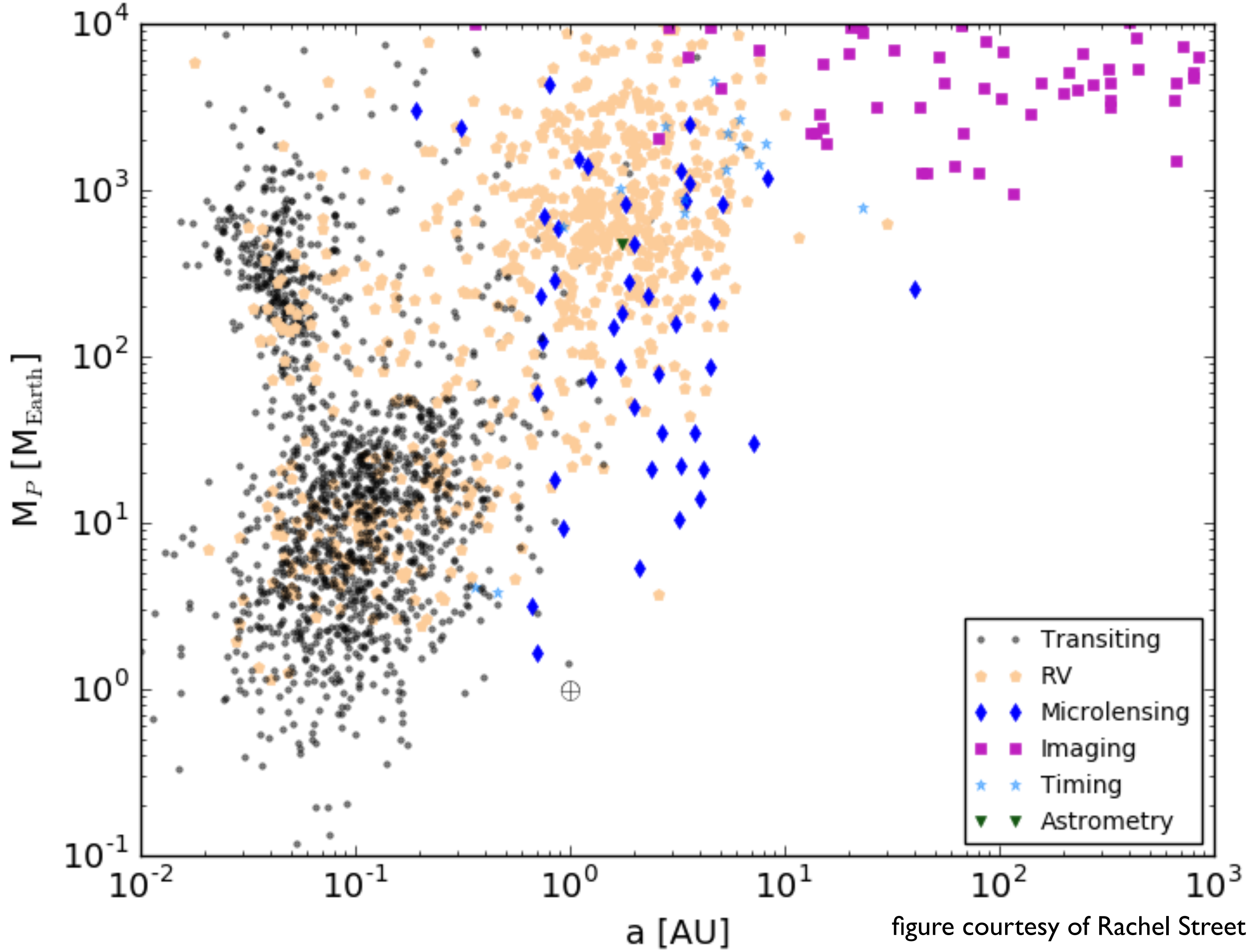


figure courtesy of Rachel Street

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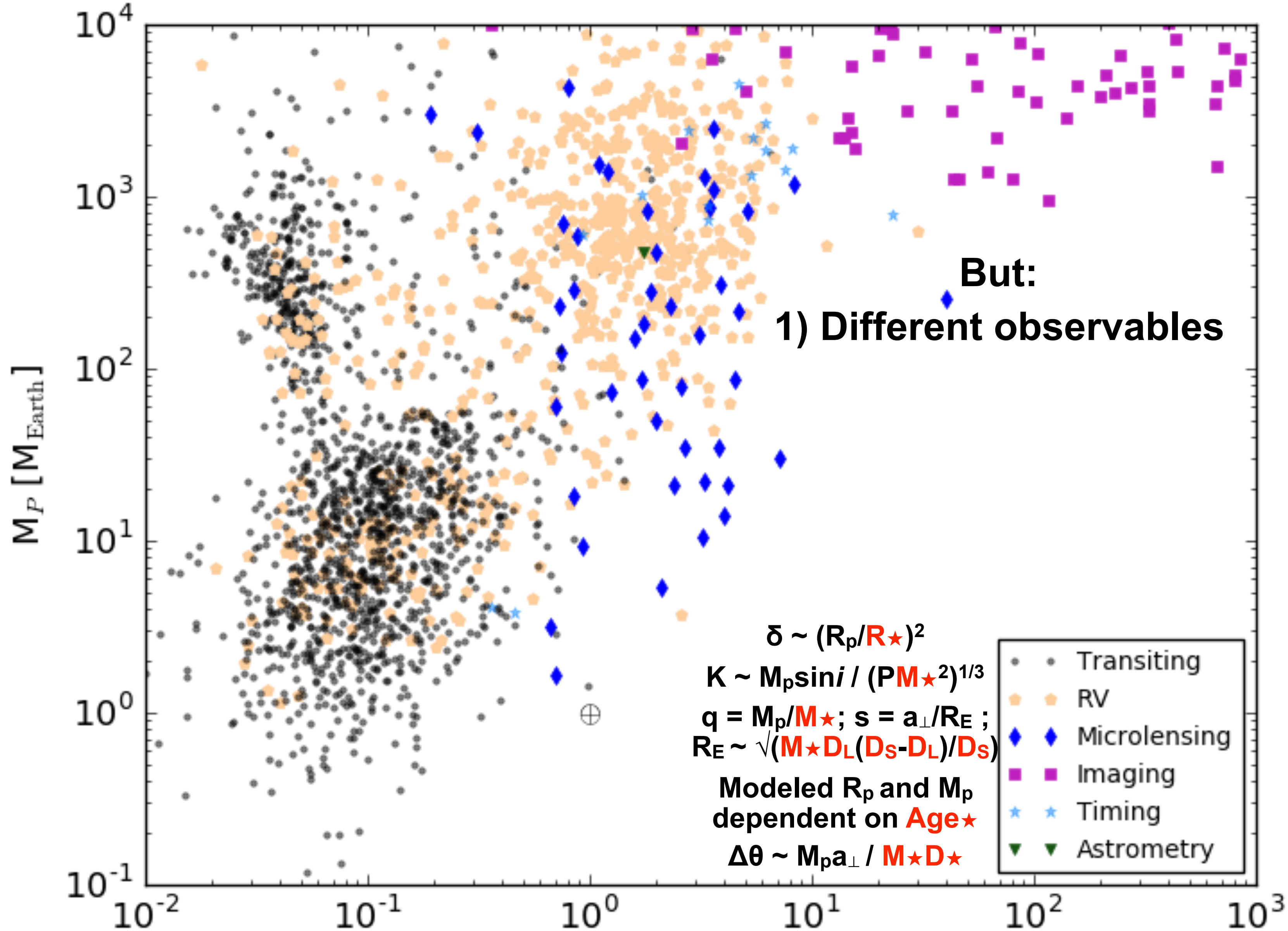

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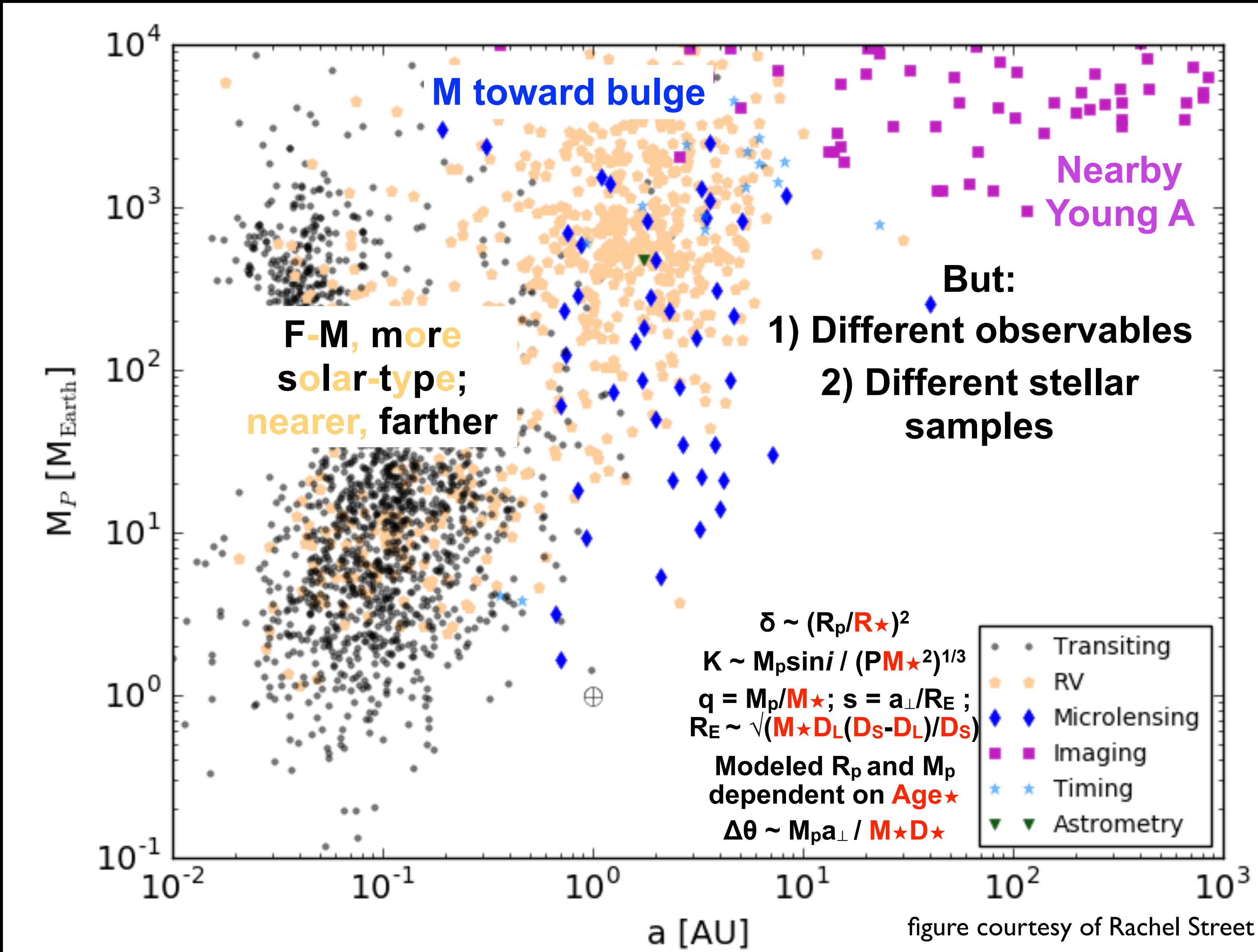

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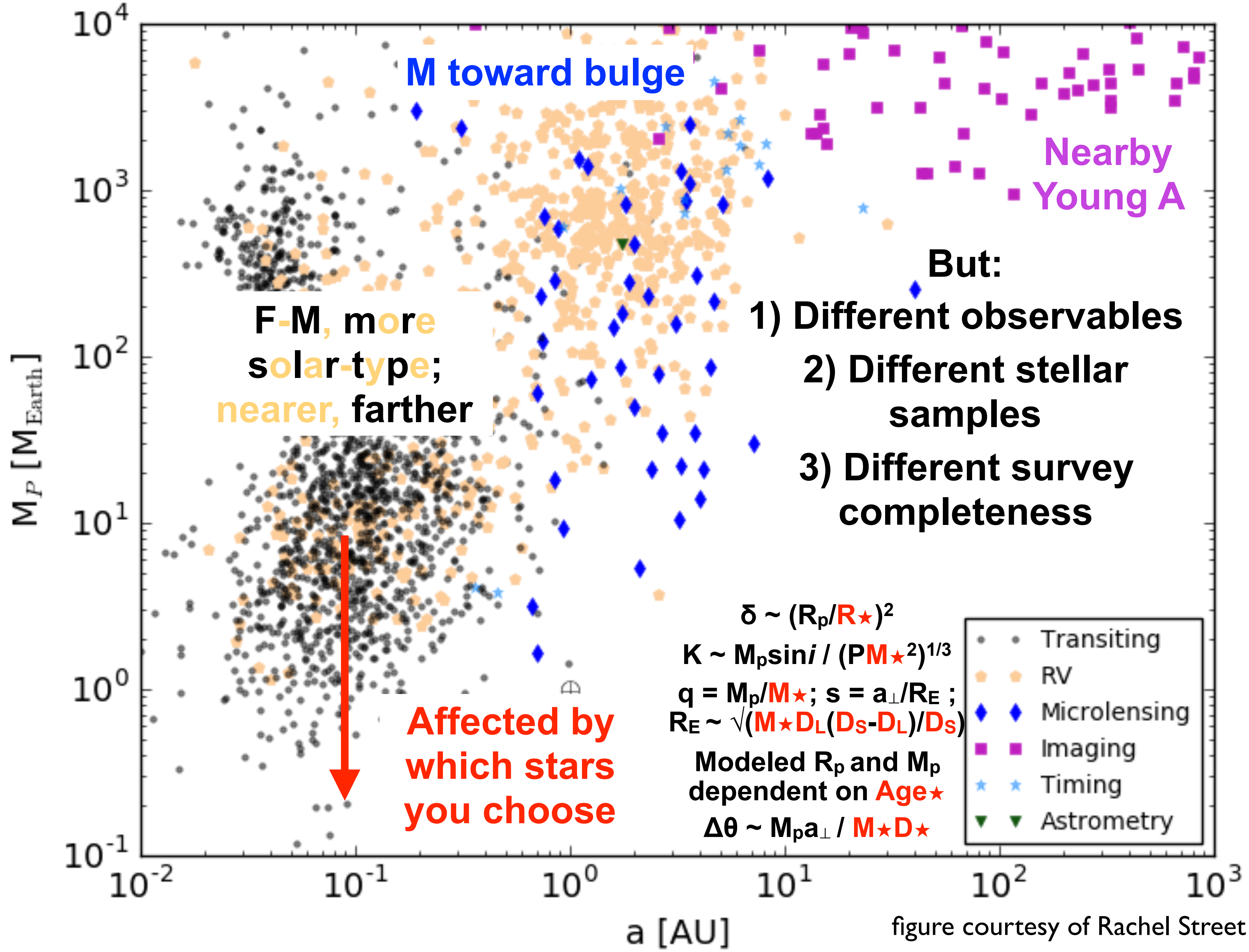

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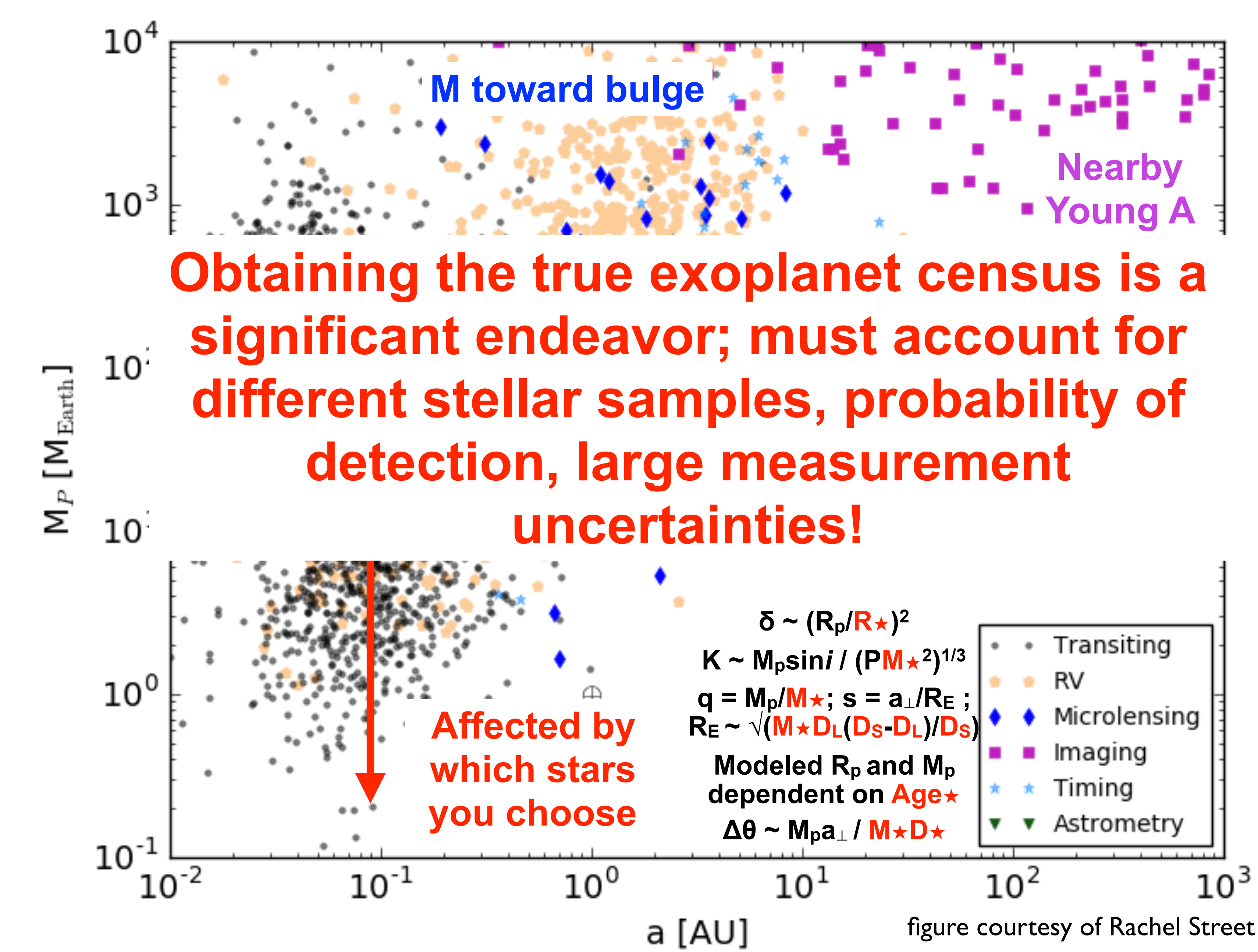

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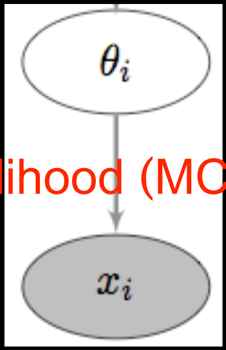
Data is inherently probabilistic

.. so our analysis methodology should be too.

Probabilistic Exoplanet Demographics



Likelihood (MCMC)

Individual Parameters (R_p, M_p, a)

Observables (δ, K, q & s, $\Delta\theta$)

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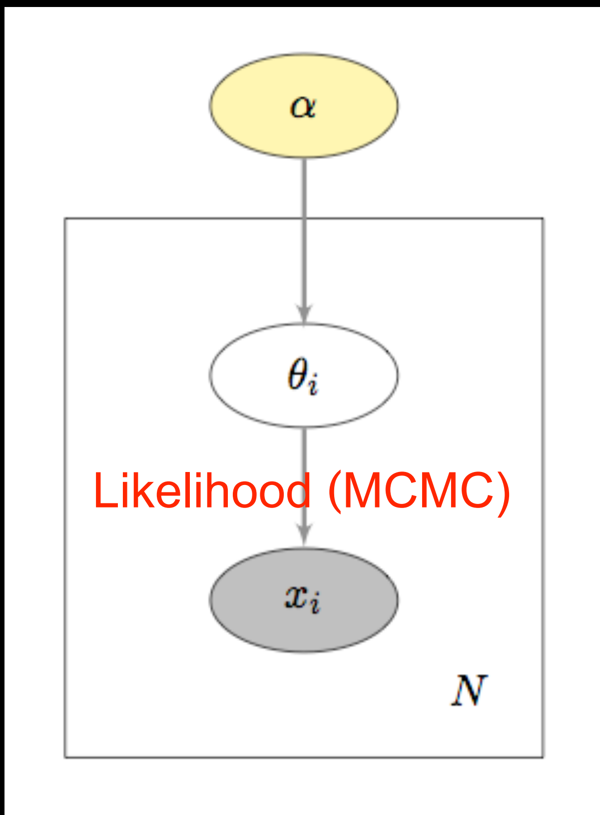

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($dN/dM \sim M^{\alpha}$)

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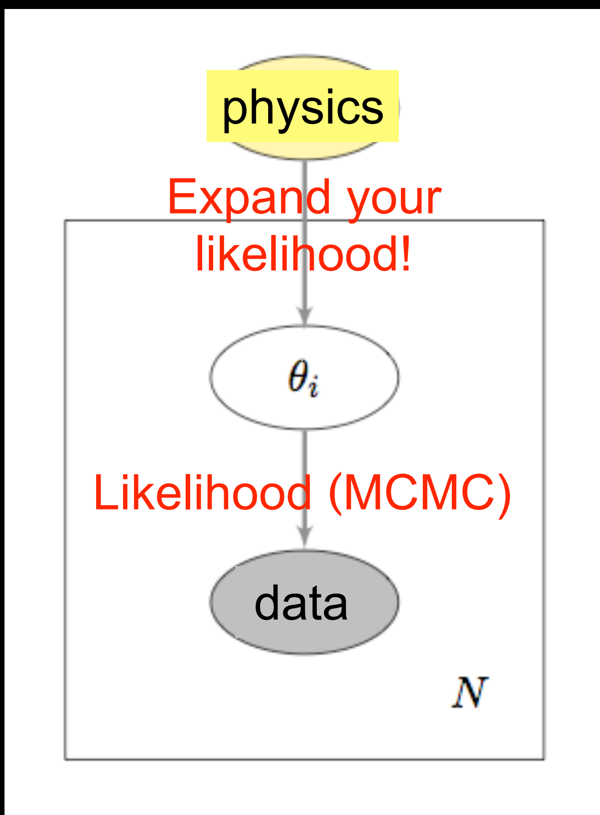

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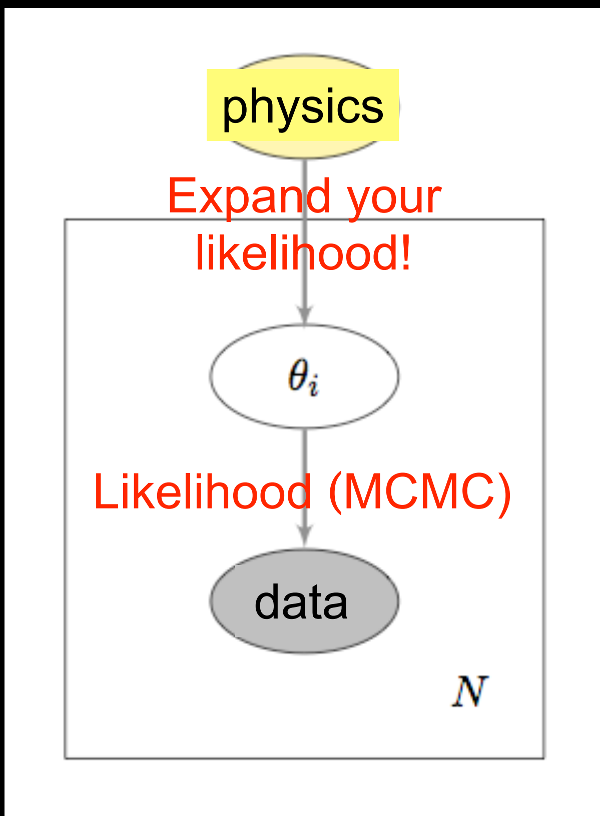

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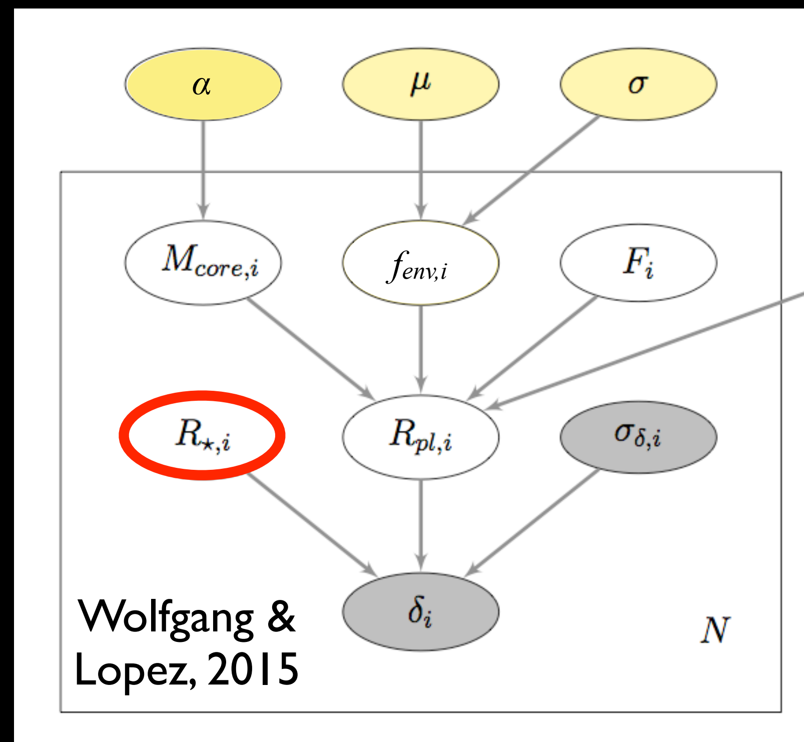
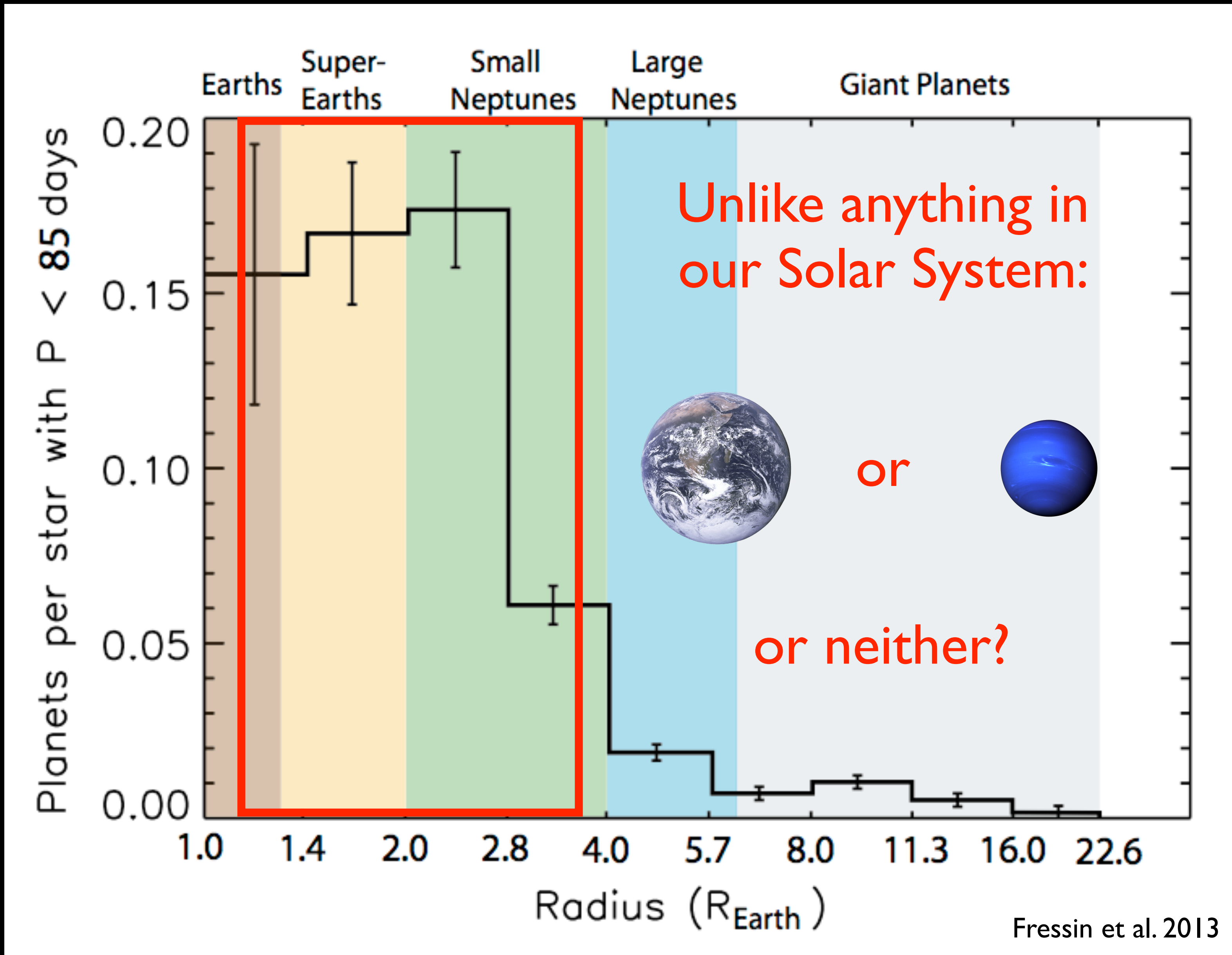


Uncertainty in stellar properties adds to uncertainty in parameters!
This analysis produces error bars that are self-consistent.

Close-in planetary radii (c. 2013)



What are their compositions?

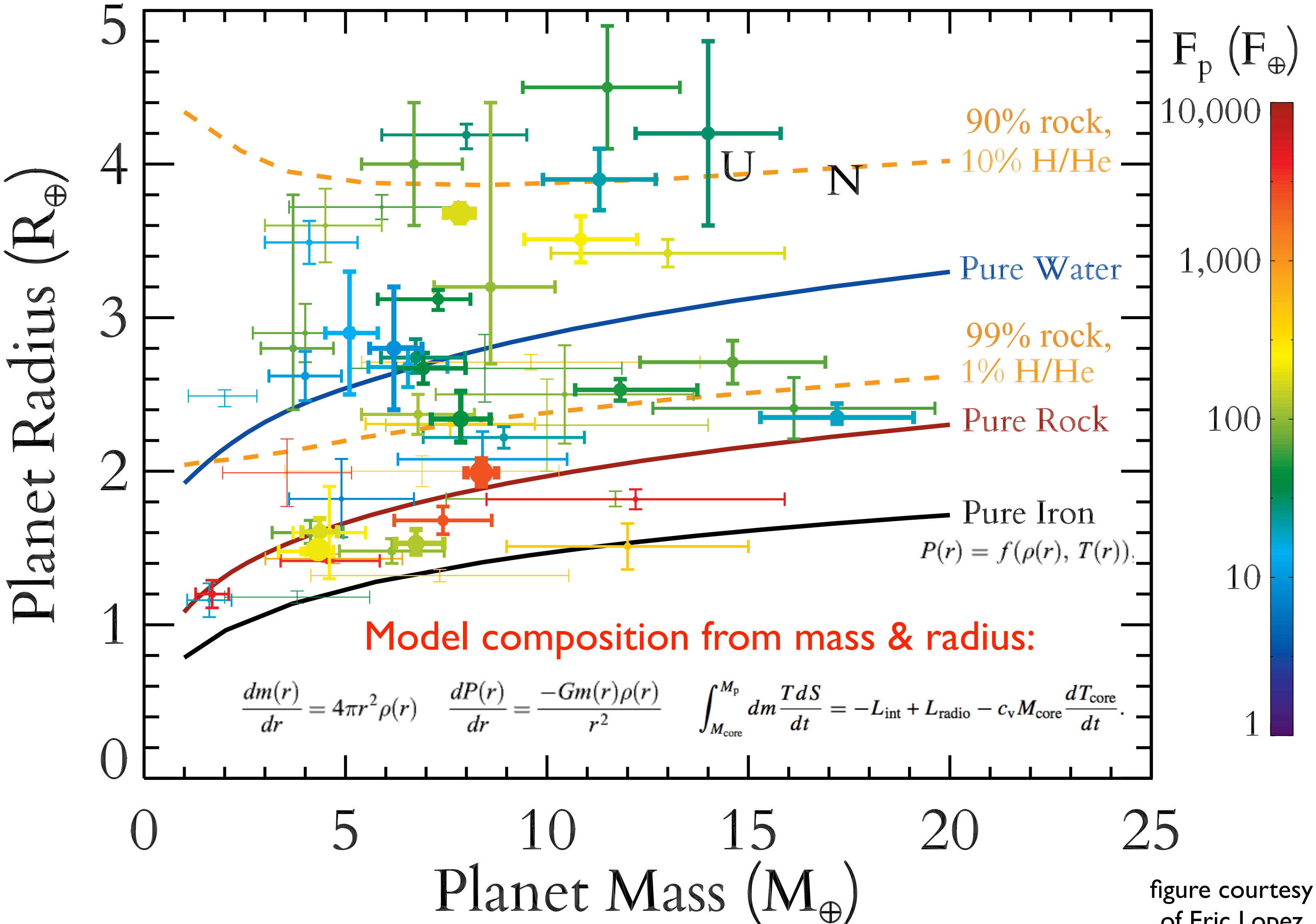


figure courtesy of Eric Lopez

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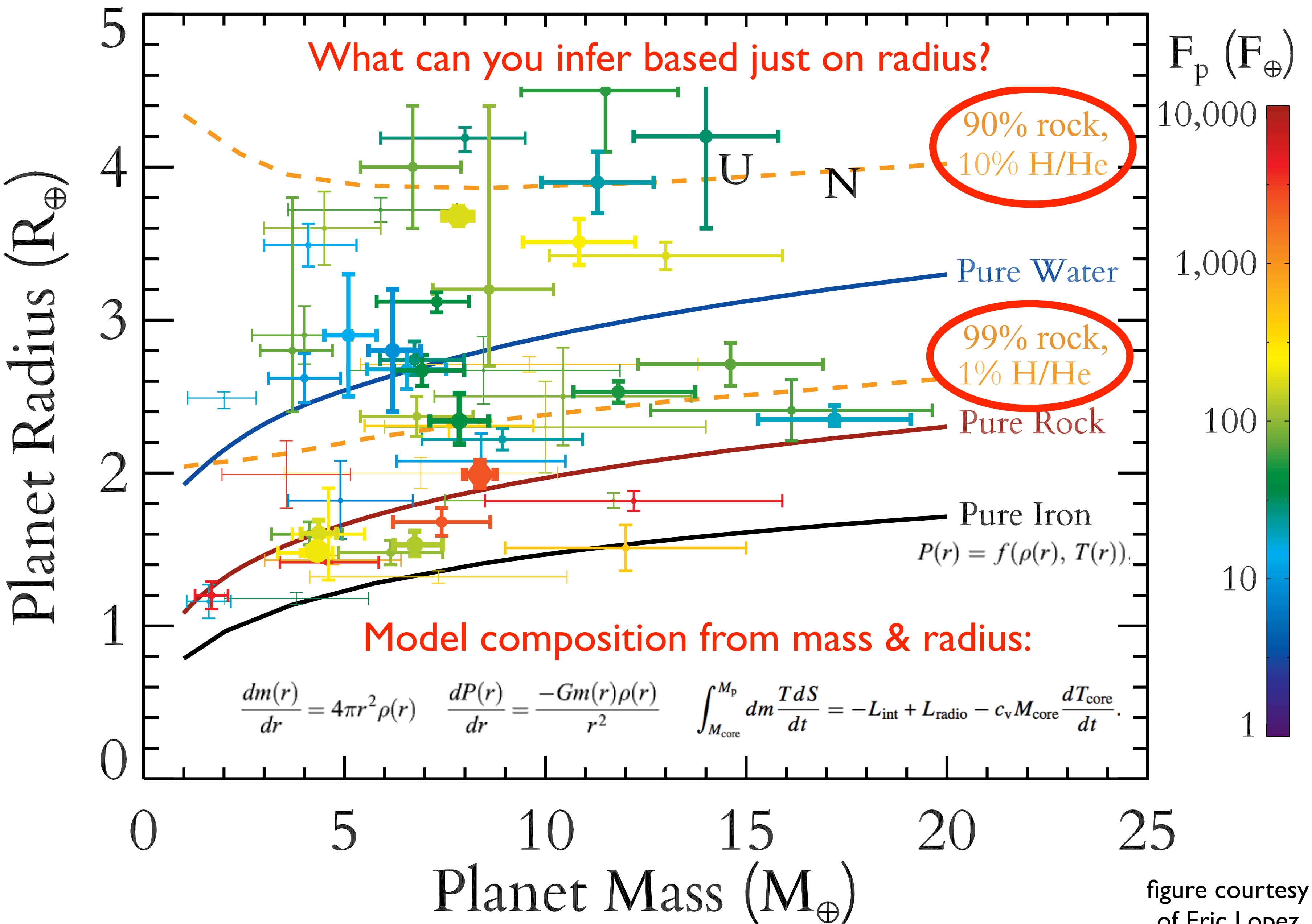

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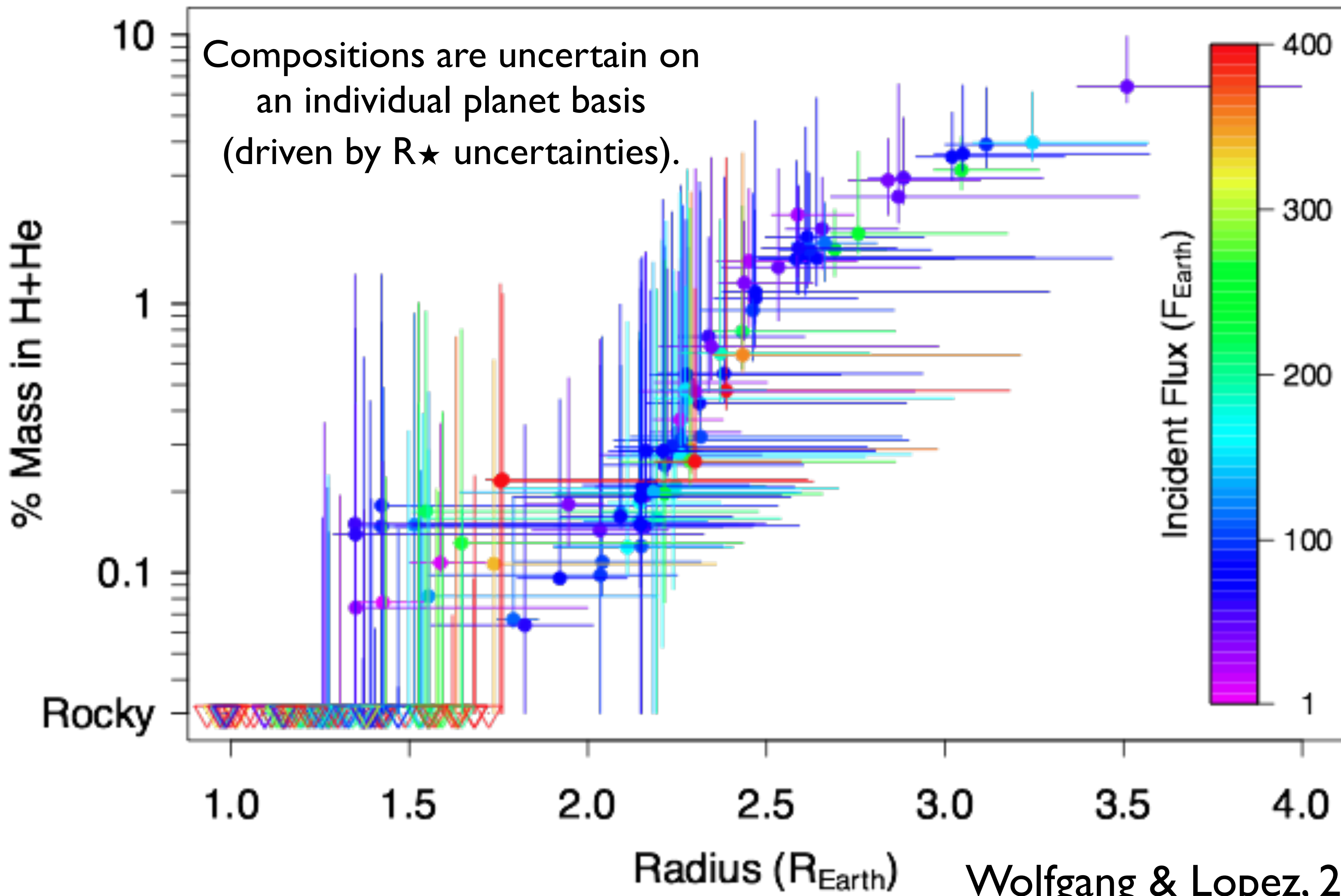
Compositions just from radius



Wolfgang & Lopez, 2015

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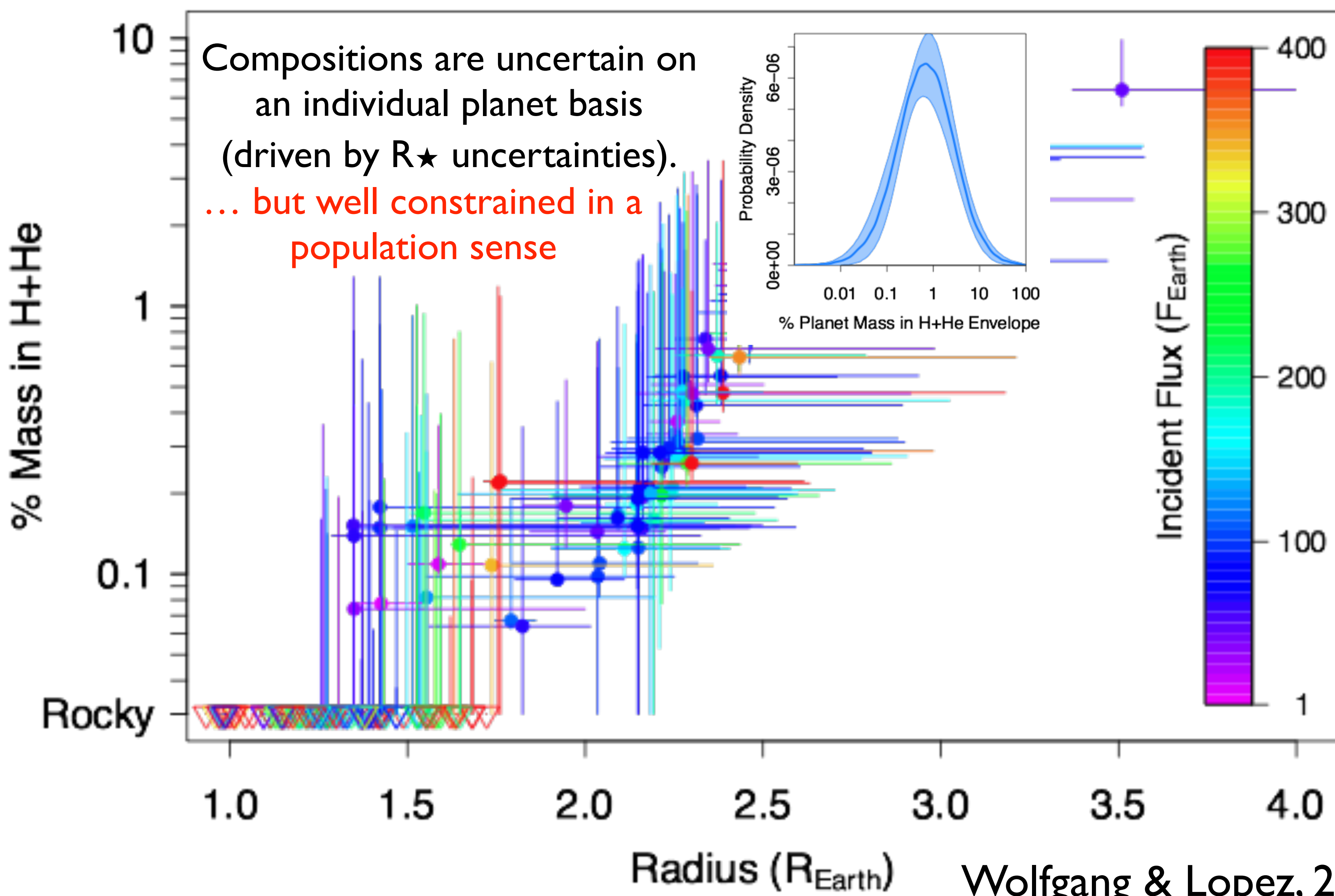

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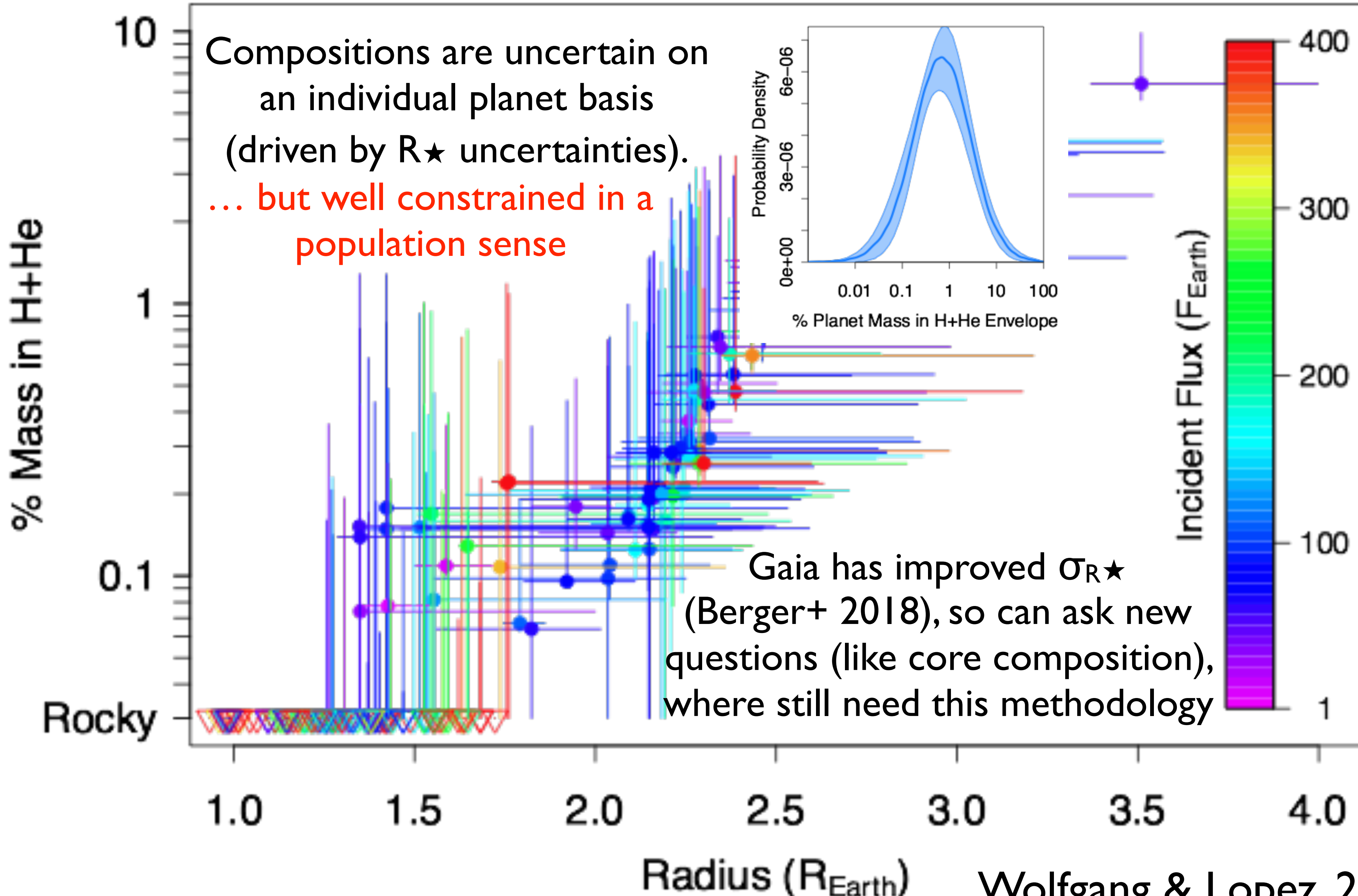

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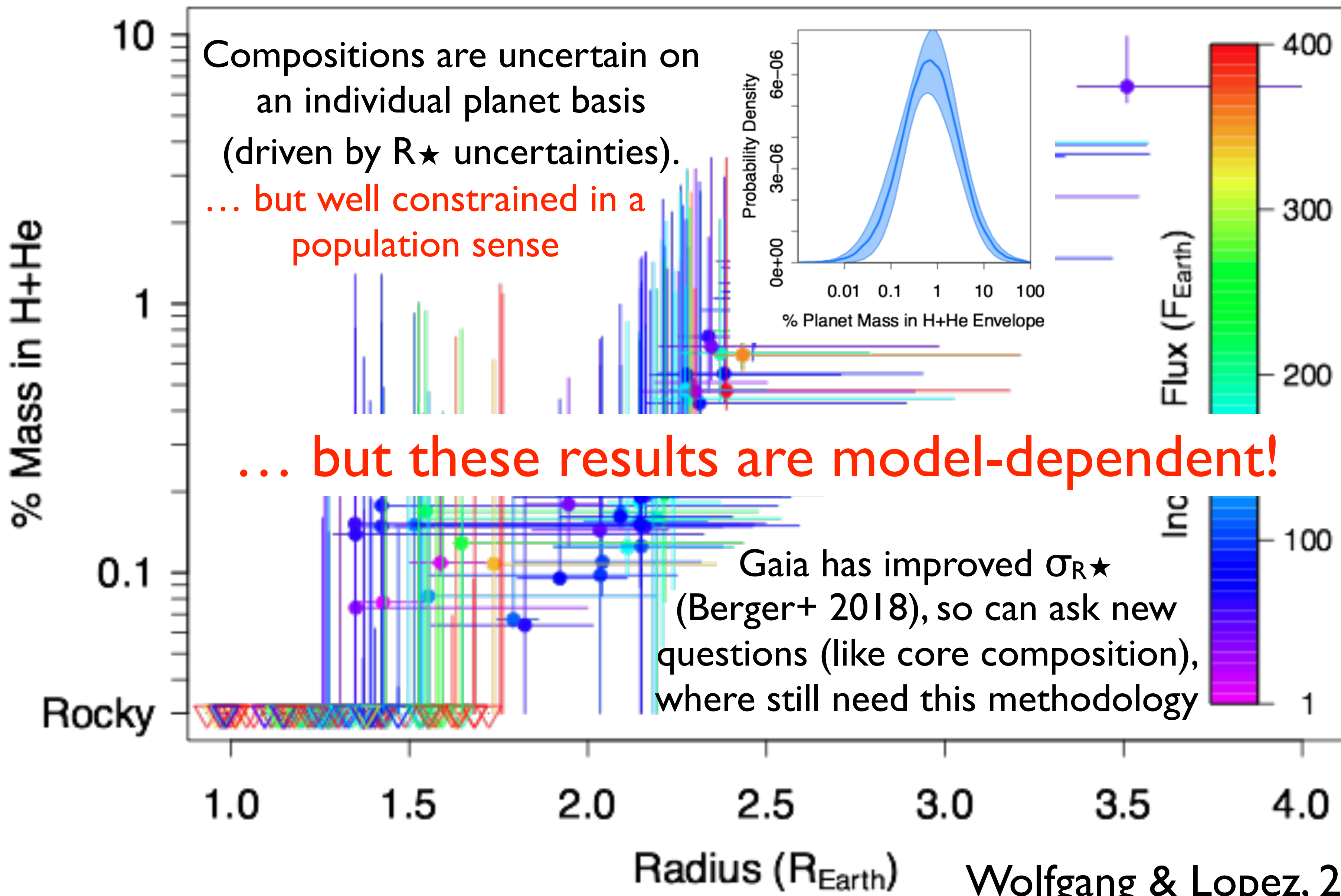


Compositions are uncertain on an individual planet basis (driven by R★ uncertainties).

… but well constrained in a population sense

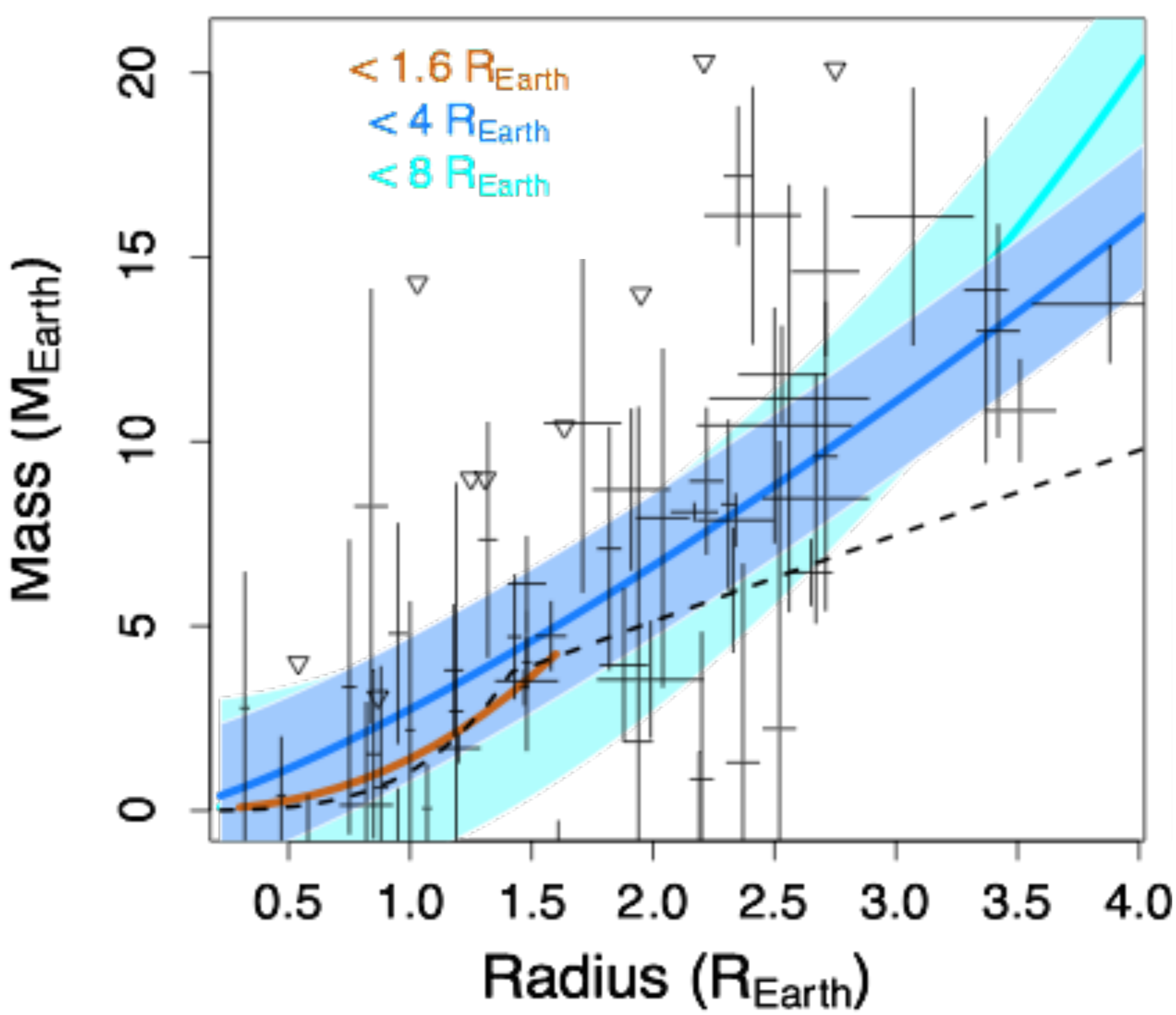
… but these results are model-dependent!

Gaia has improved $\sigma_{R\star}$ (Berger+ 2018), so can ask new questions (like core composition), where still need this methodology

Wolfgang & Lopez, 2015

Data-driven compositions

Wolfgang, Rogers, & Ford, 2016



The M-R relation is an empirical description of exoplanet composition distribution.

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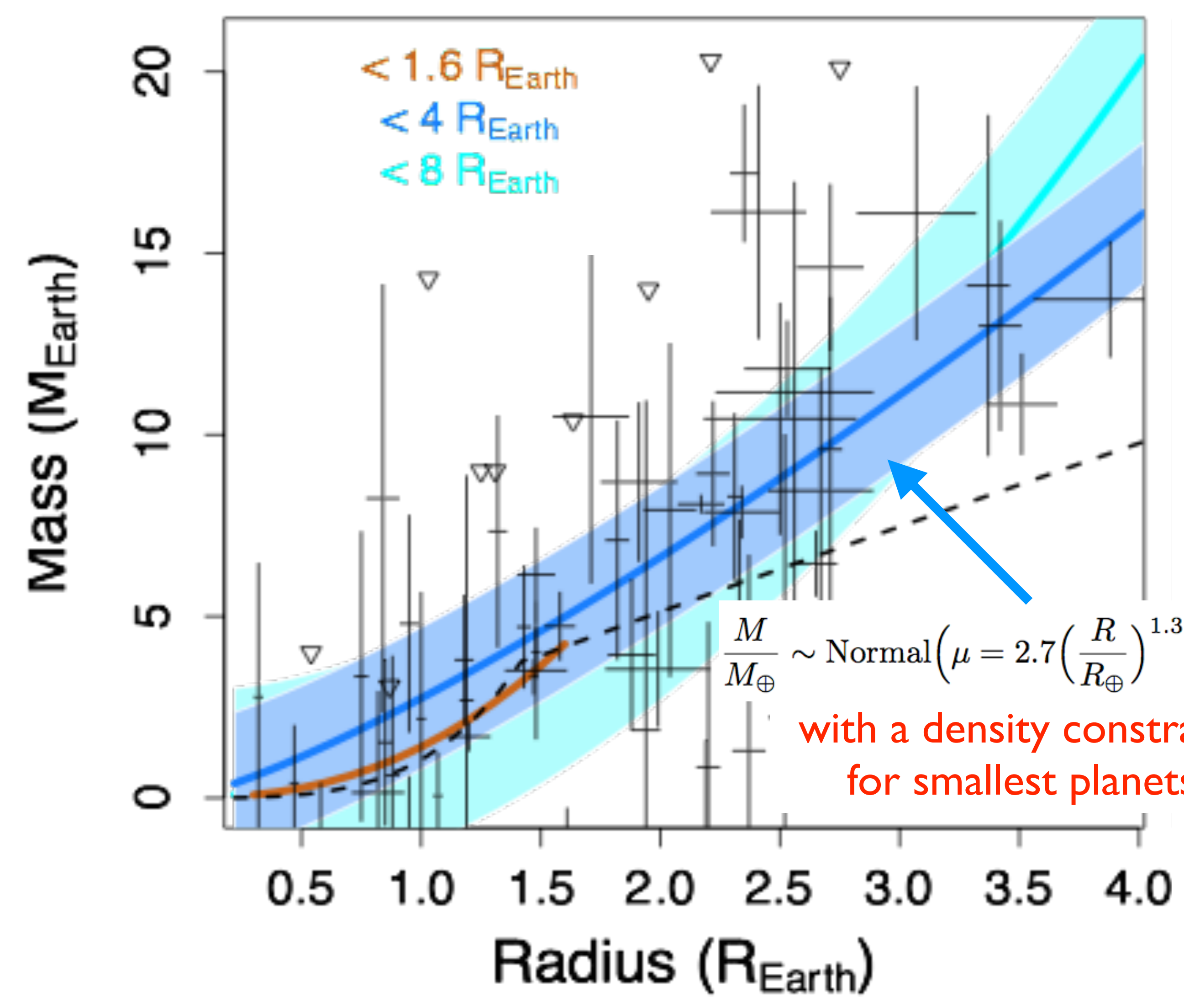

$$\frac{M}{M_\oplus} \sim \mathrm{Normal}\left(\mu = 2.7\left(\frac{R}{R_\oplus}\right)^{1.3}, \sigma = 1.9\right)$$

with a density constraint for smallest planets

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Probabilistic relations allow for a distribution of masses at a given radius as motivated by observations and theory

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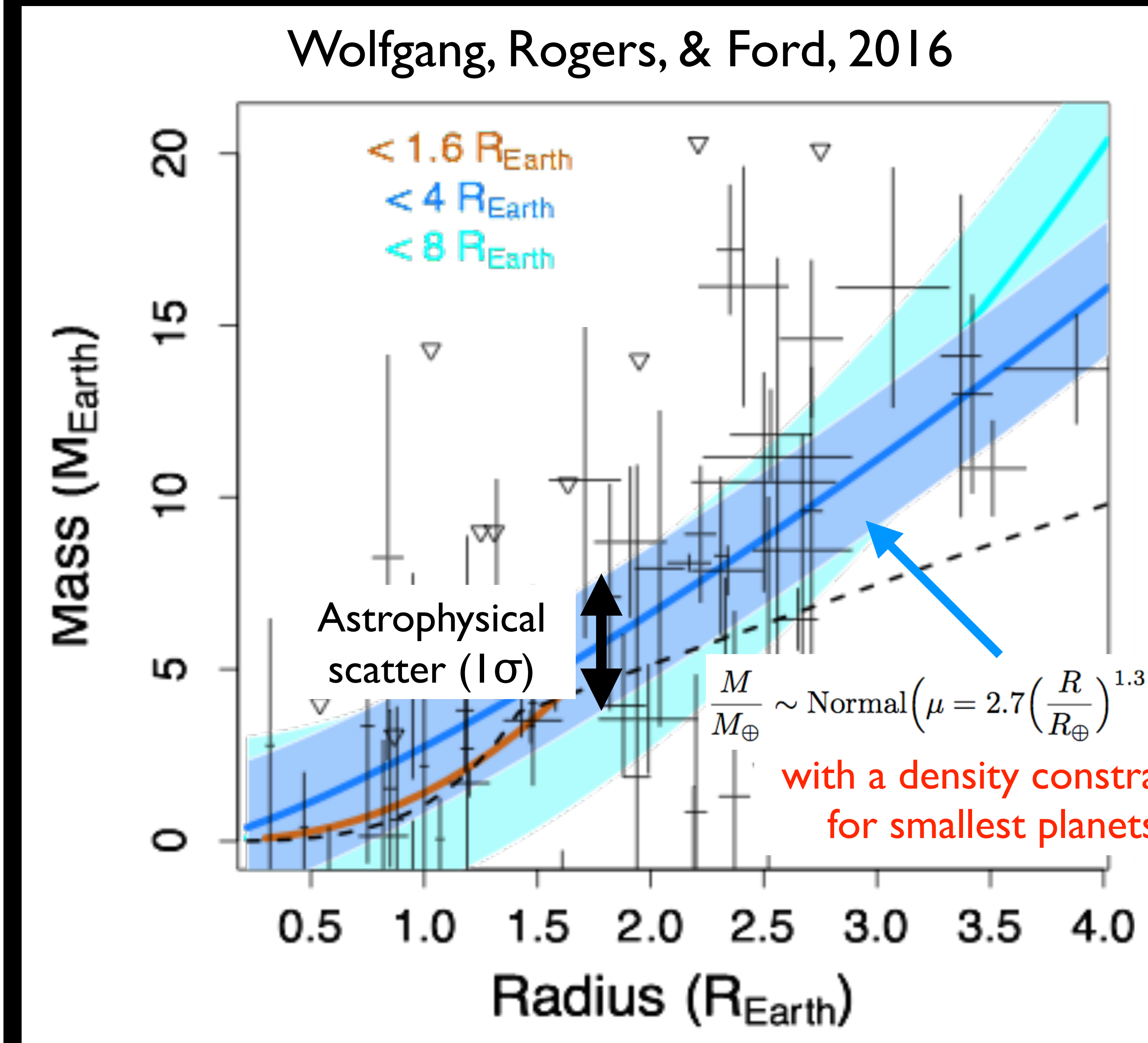

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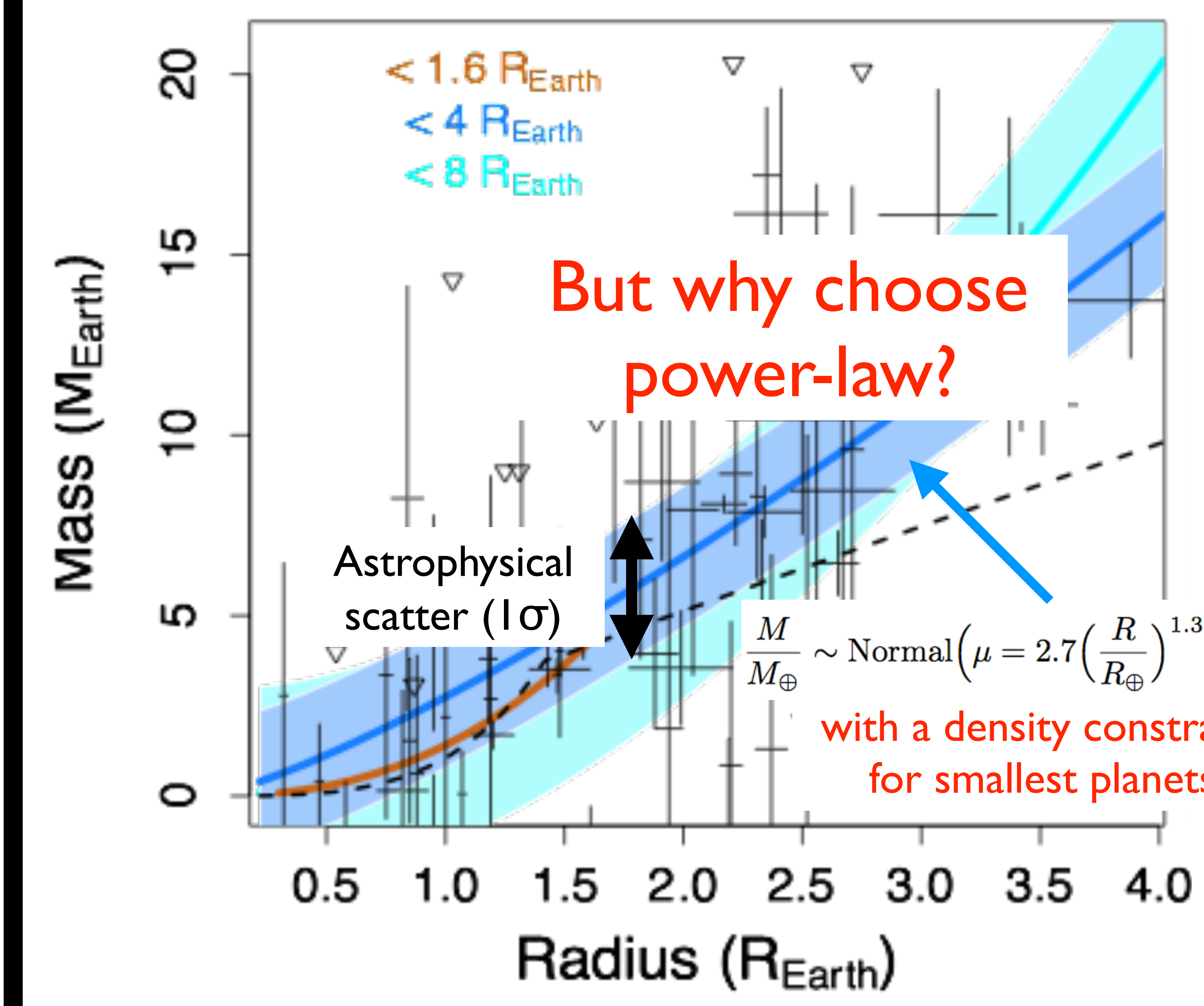

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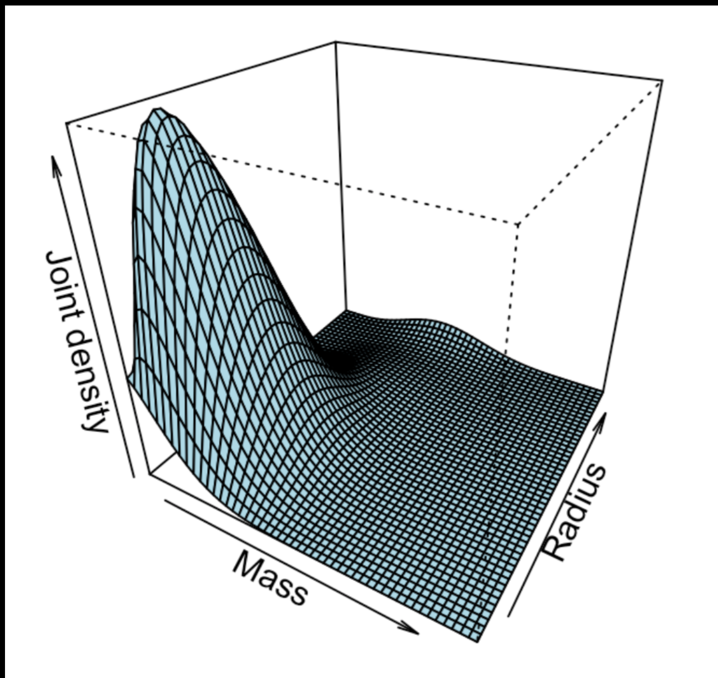
Next-gen M-R: Beyond the Power-Law

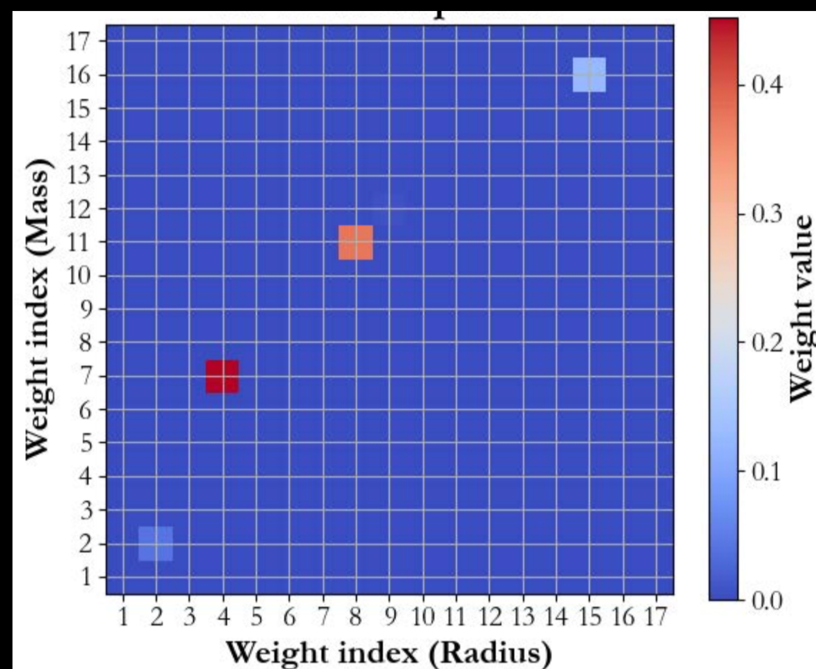
Go nonparametric!! (Ning, Wolfgang & Ghosh, 2018)

1) Define the joint distribution f(m,r) as mixture of basis functions



$$f(m,r|\boldsymbol{w}) = \sum_{k=1}^{N}\sum_{l=1}^{N} w_{kl}\,\frac{B_k(m/M^{\circ}_{\max})}{M^{\circ}_{\max}}\,\frac{B_l(r/R^{\circ}_{\max})}{R^{\circ}_{\max}},$$

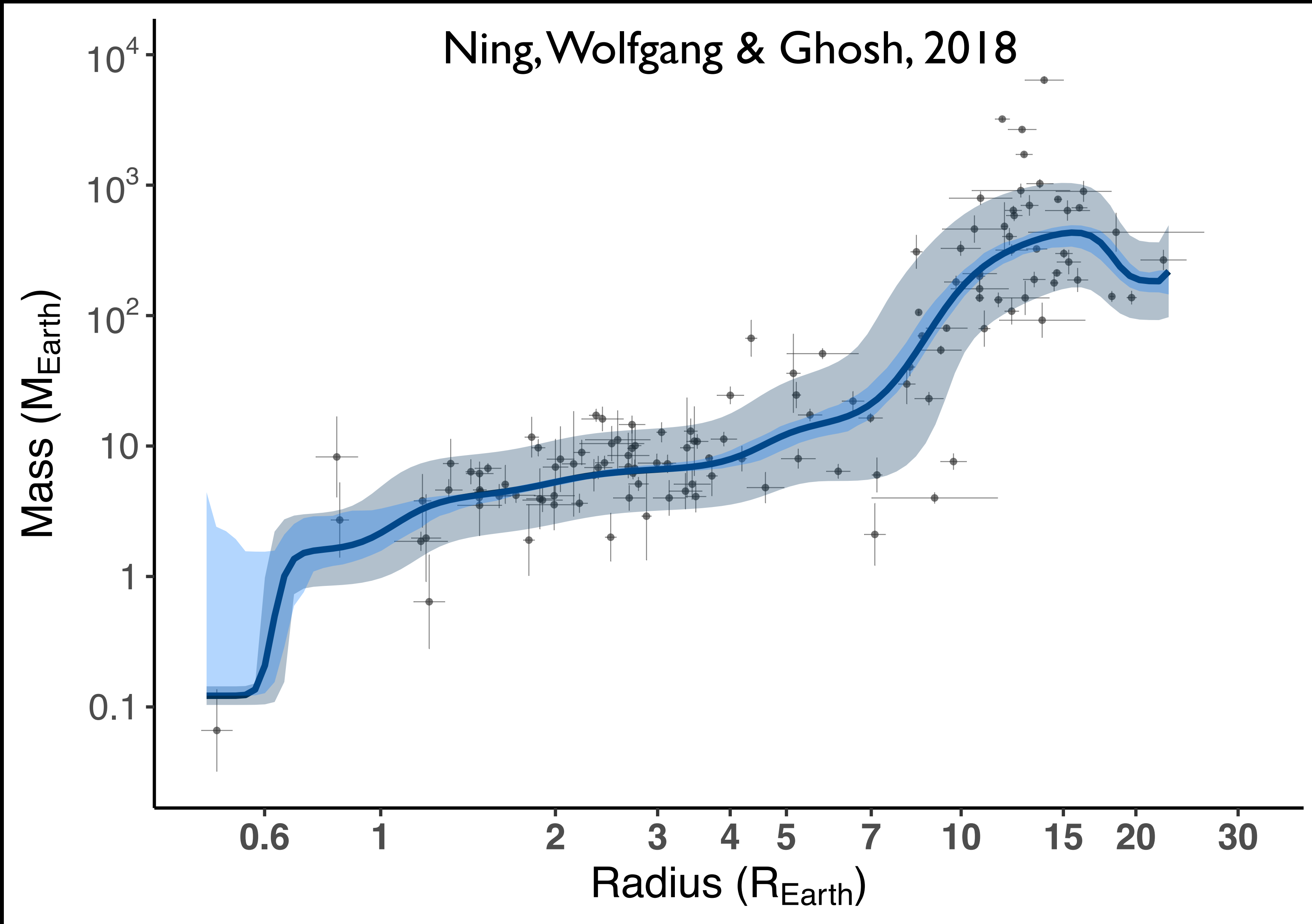
$$B_j(a/A_{\max}) = N\binom{N-1}{j-1}(a/A_{\max})^{j-1}(1-a/A_{\max})^{N-j},$$



2) Fit mixture coefficients w to data, then calculate conditional f(m|r)

$$E[M|R=r] = \frac{\int m f(m,r)dm}{\int f(m,r)dm}$$

M-R Relation from Kepler



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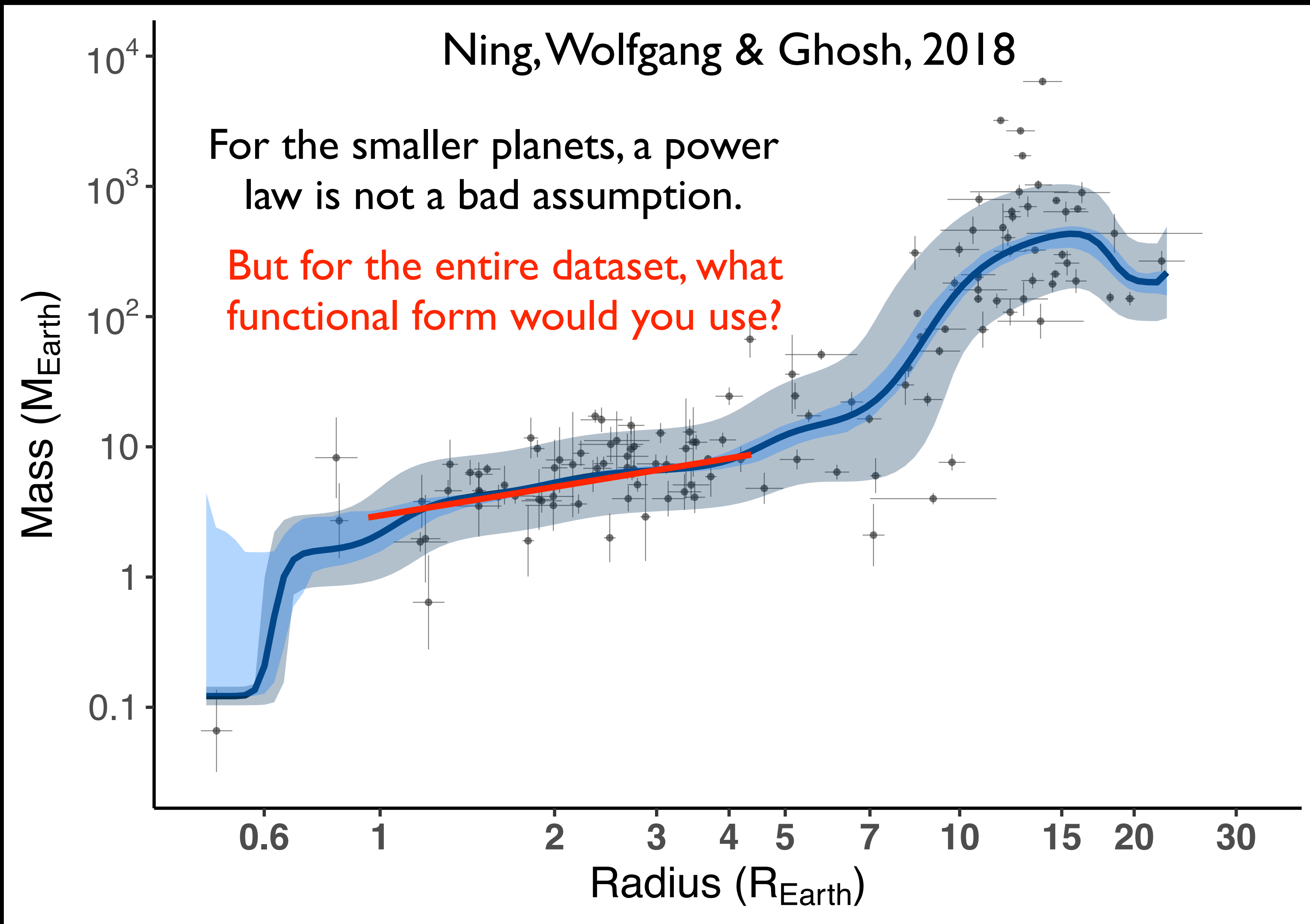

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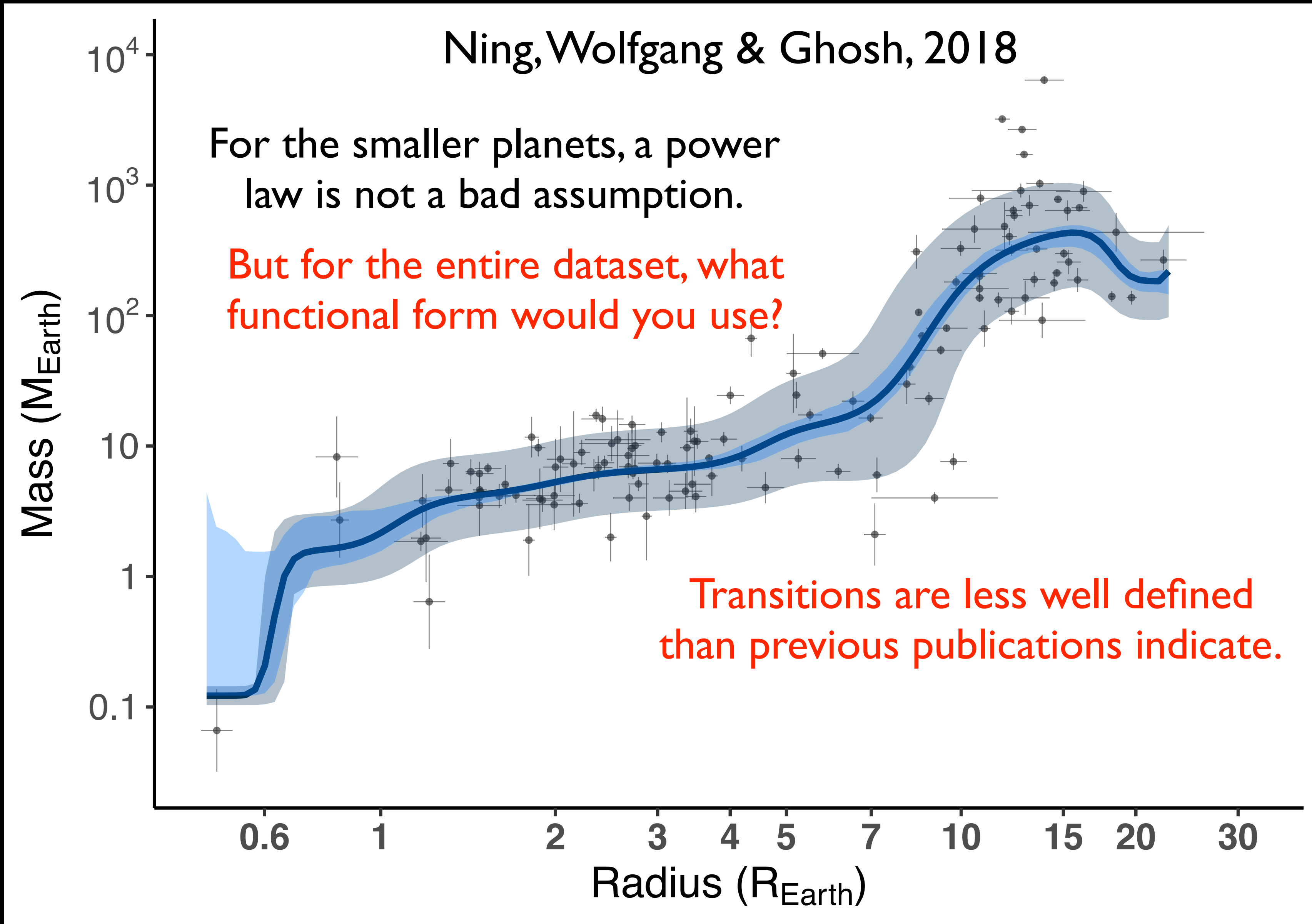

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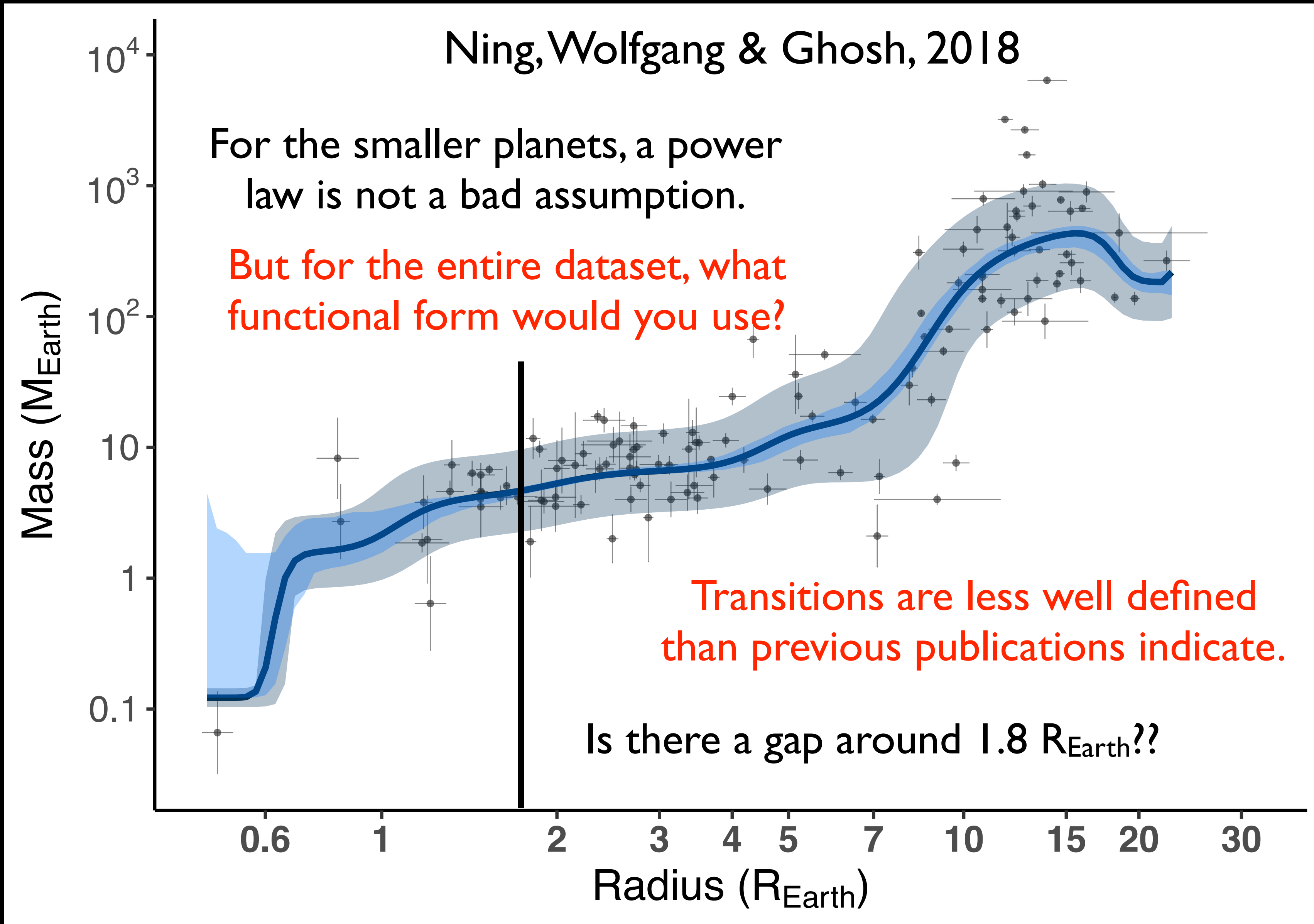
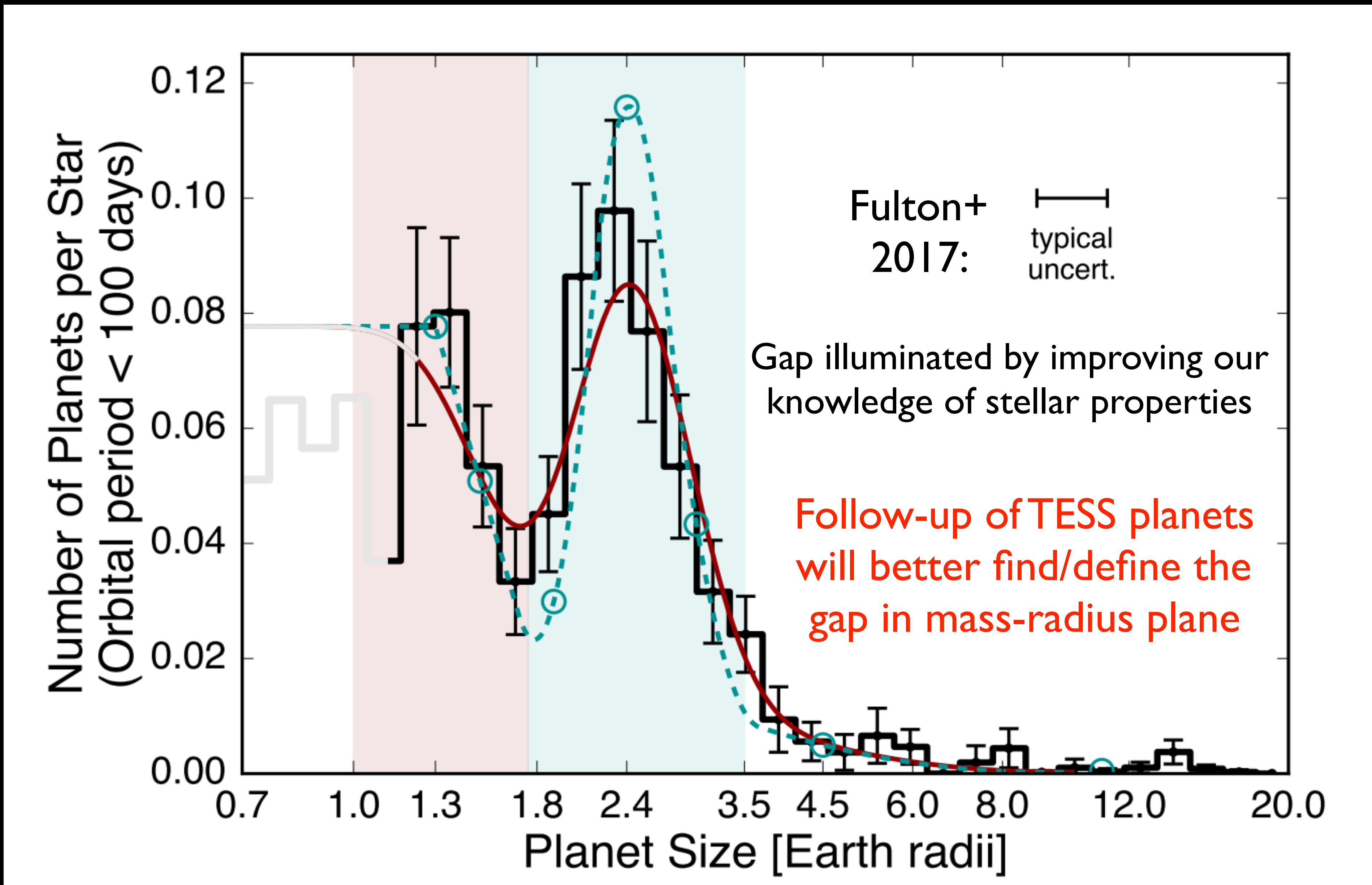
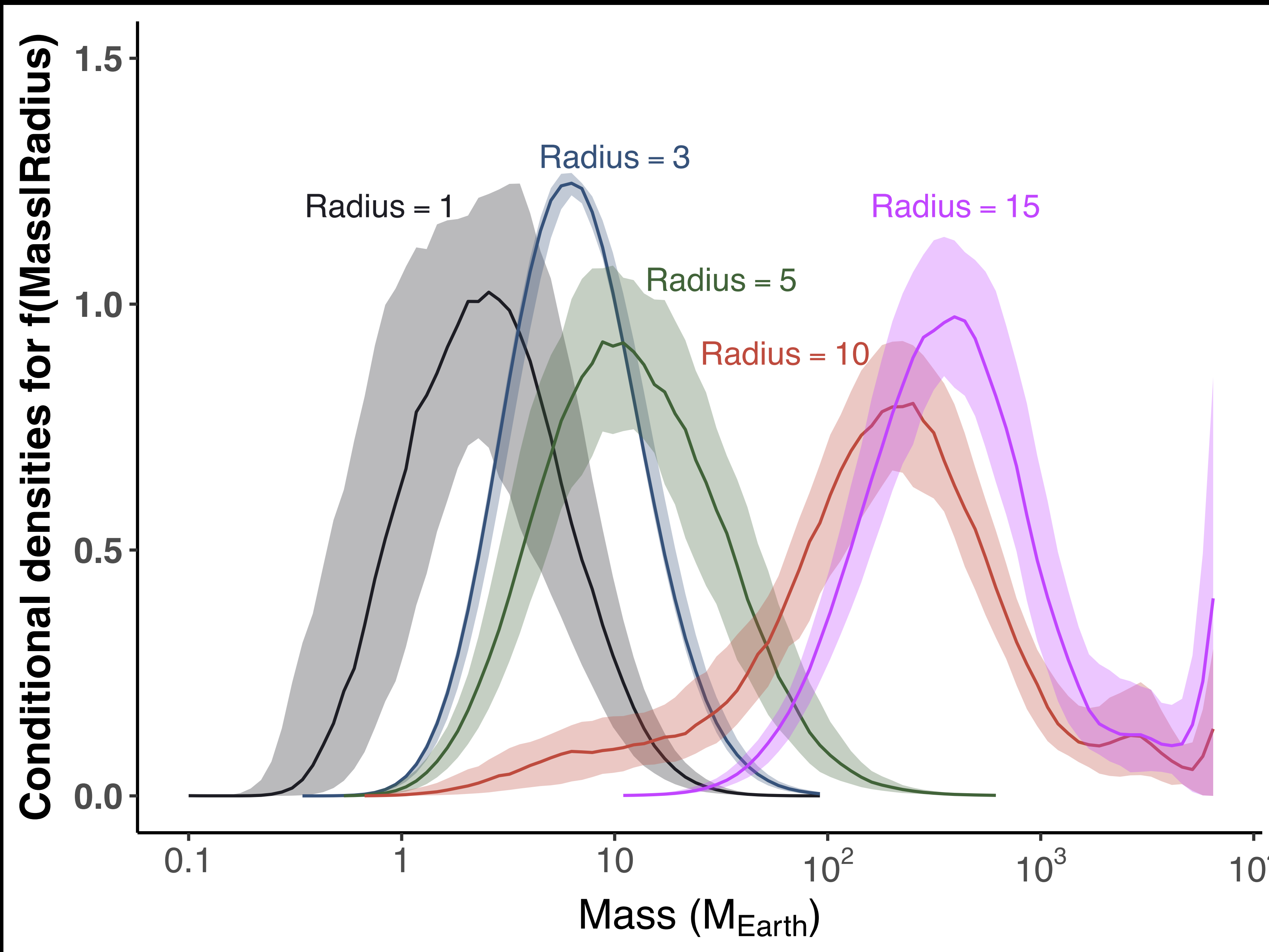


See this gap in radius distribution:



New Predictions for Mass:



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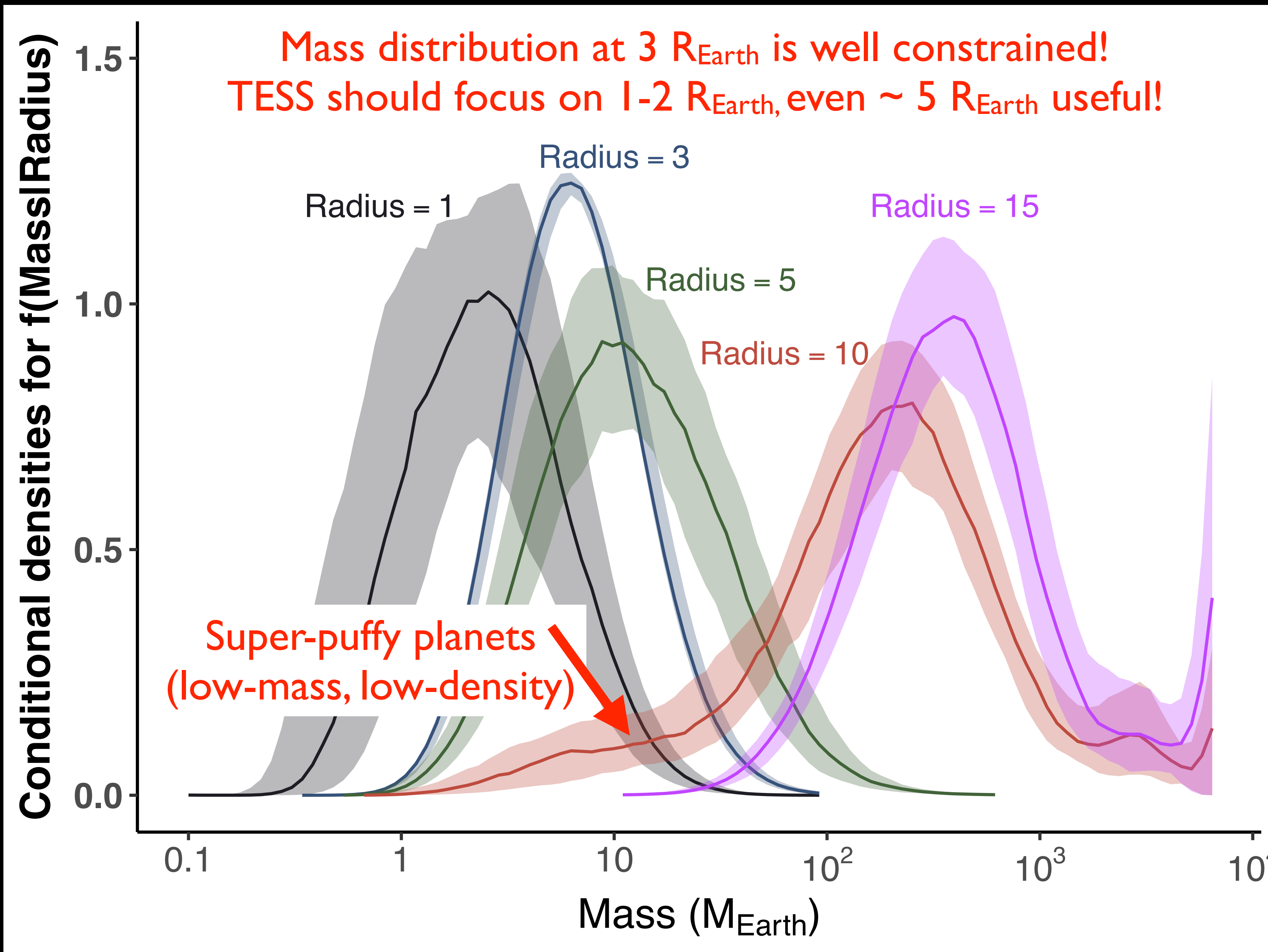

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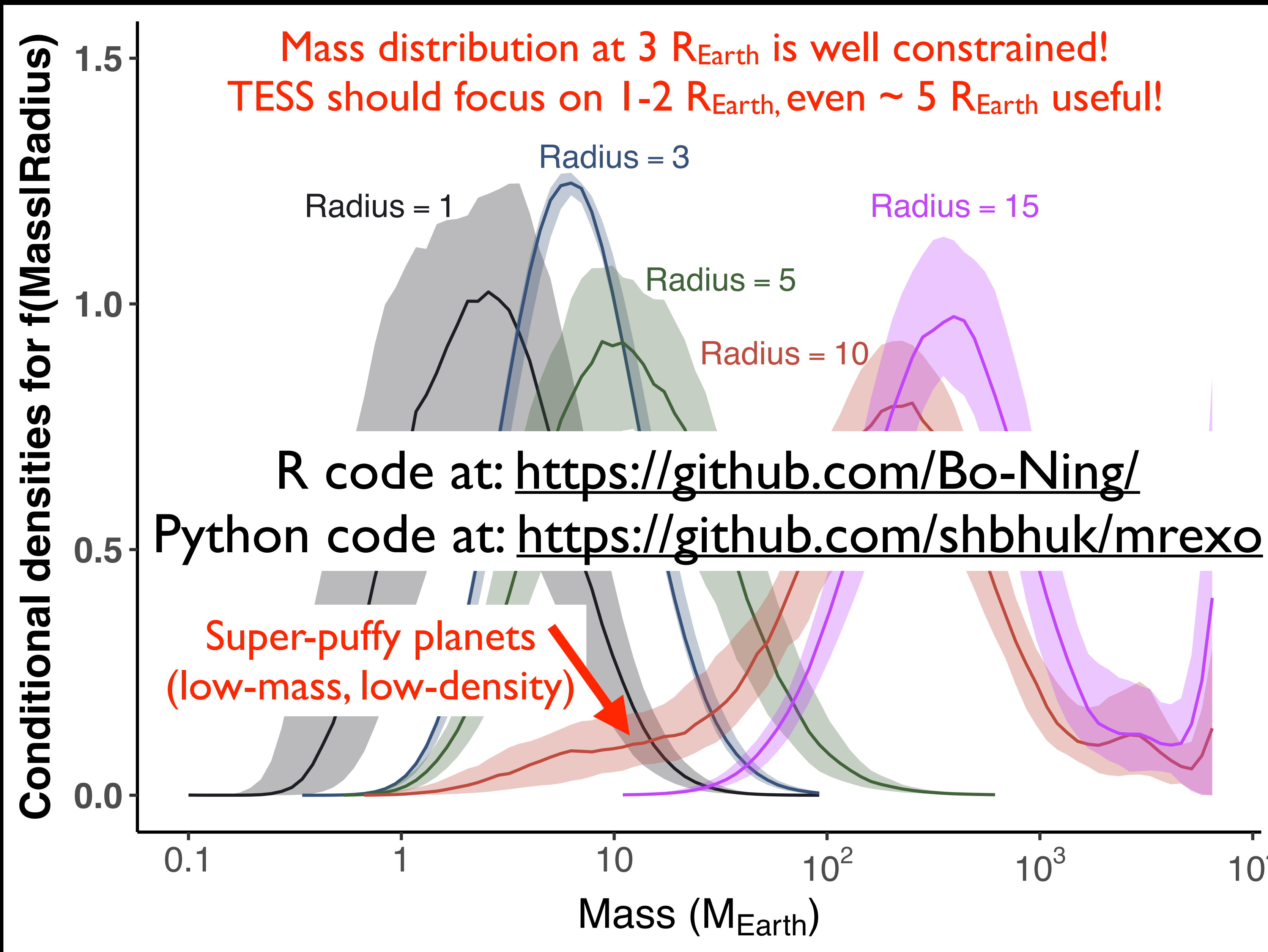
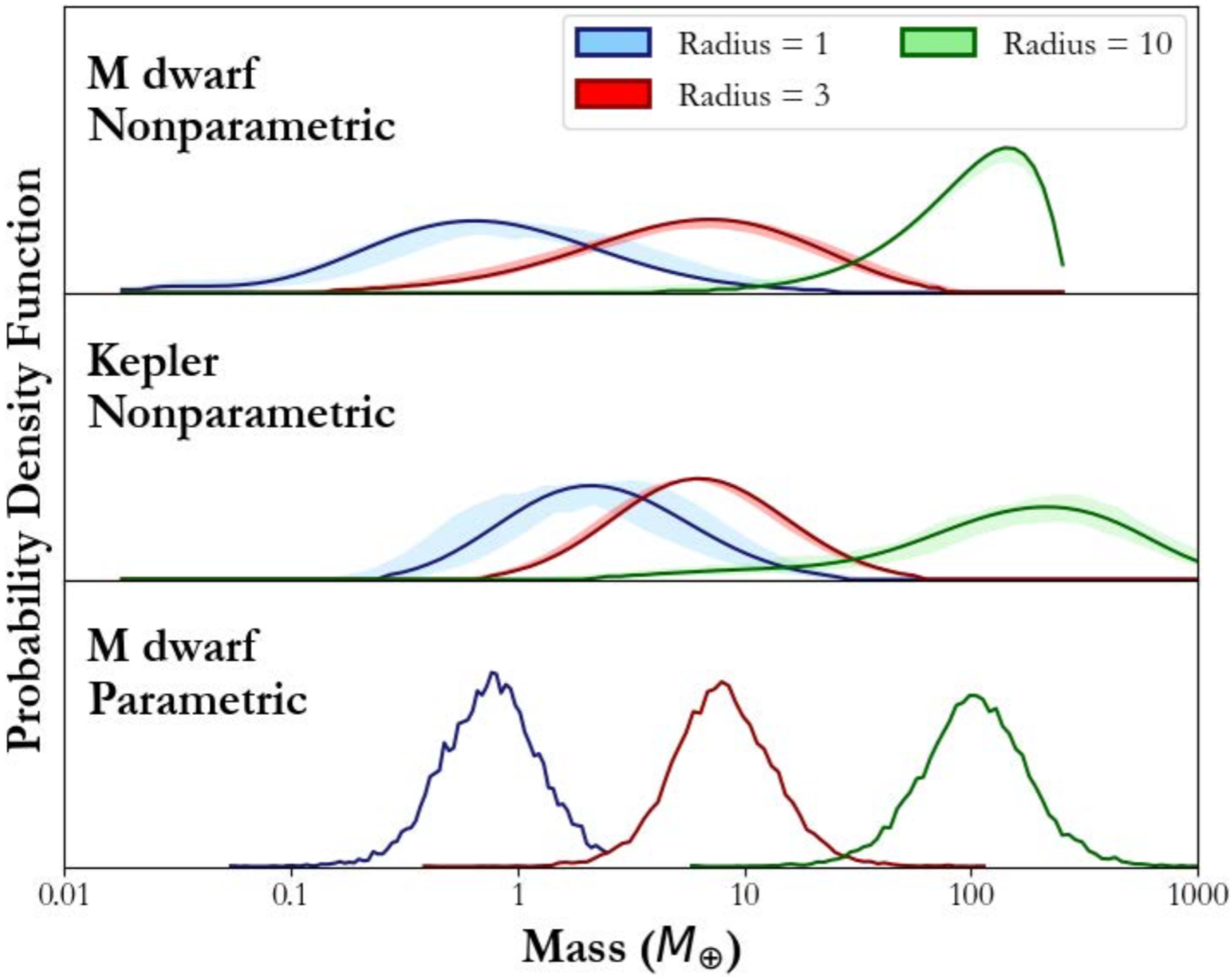


R code at: https://github.com/Bo-Ning/

Python code at: https://github.com/shbhuk/mrexo

As a function of T_{eff} (M-dwarfs)

Kanodia, Wolfgang+, in review; arXiv:1903.00042



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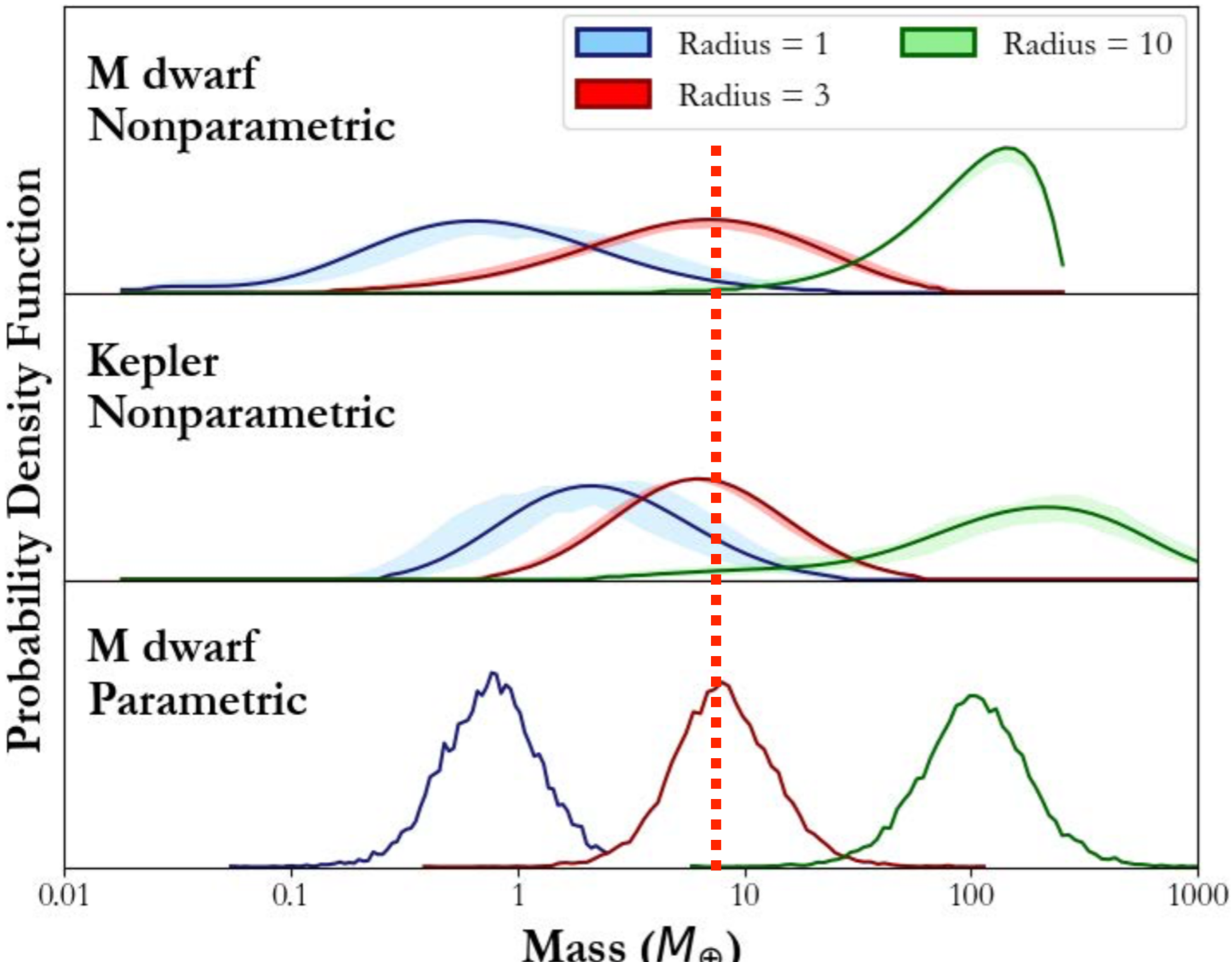

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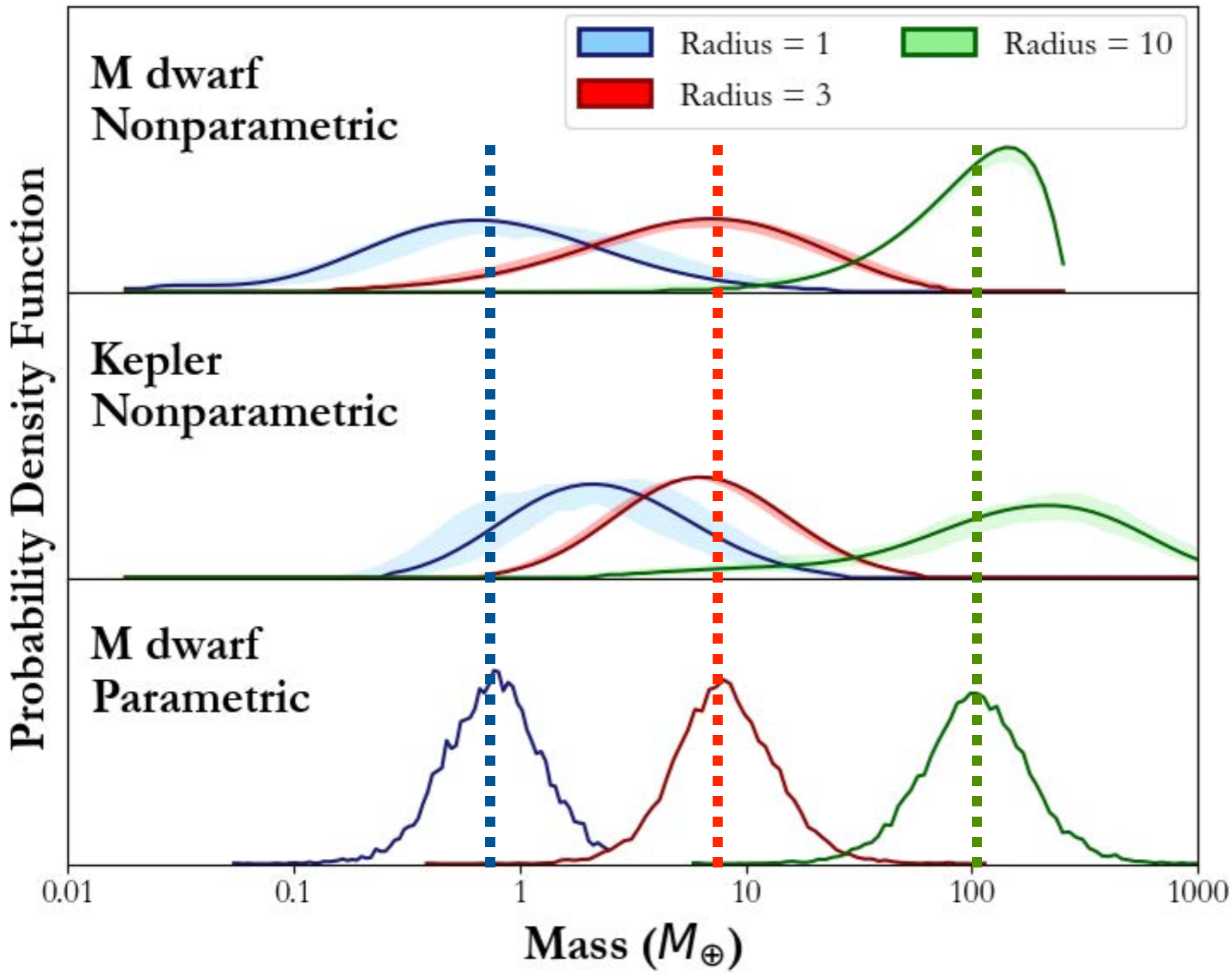

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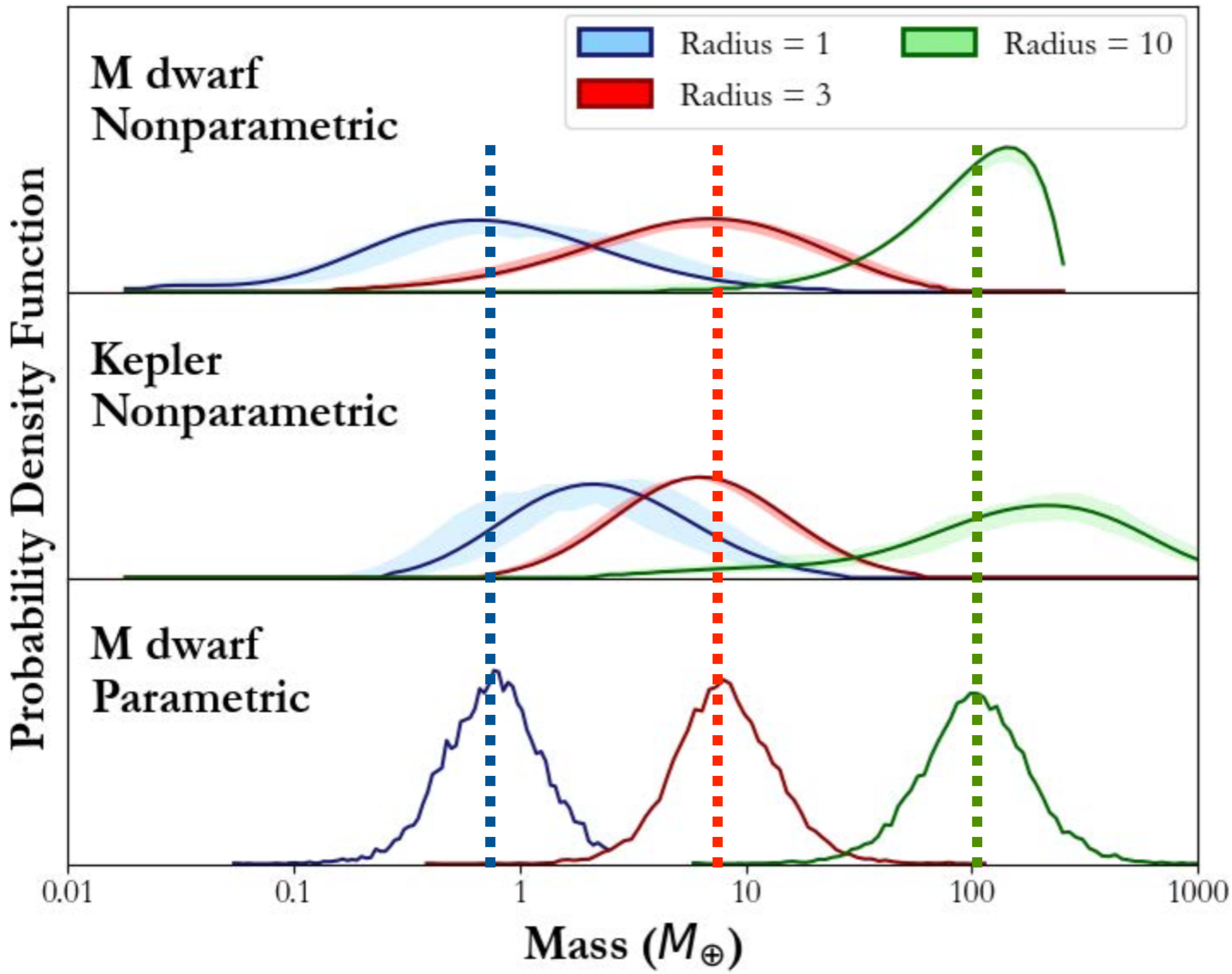

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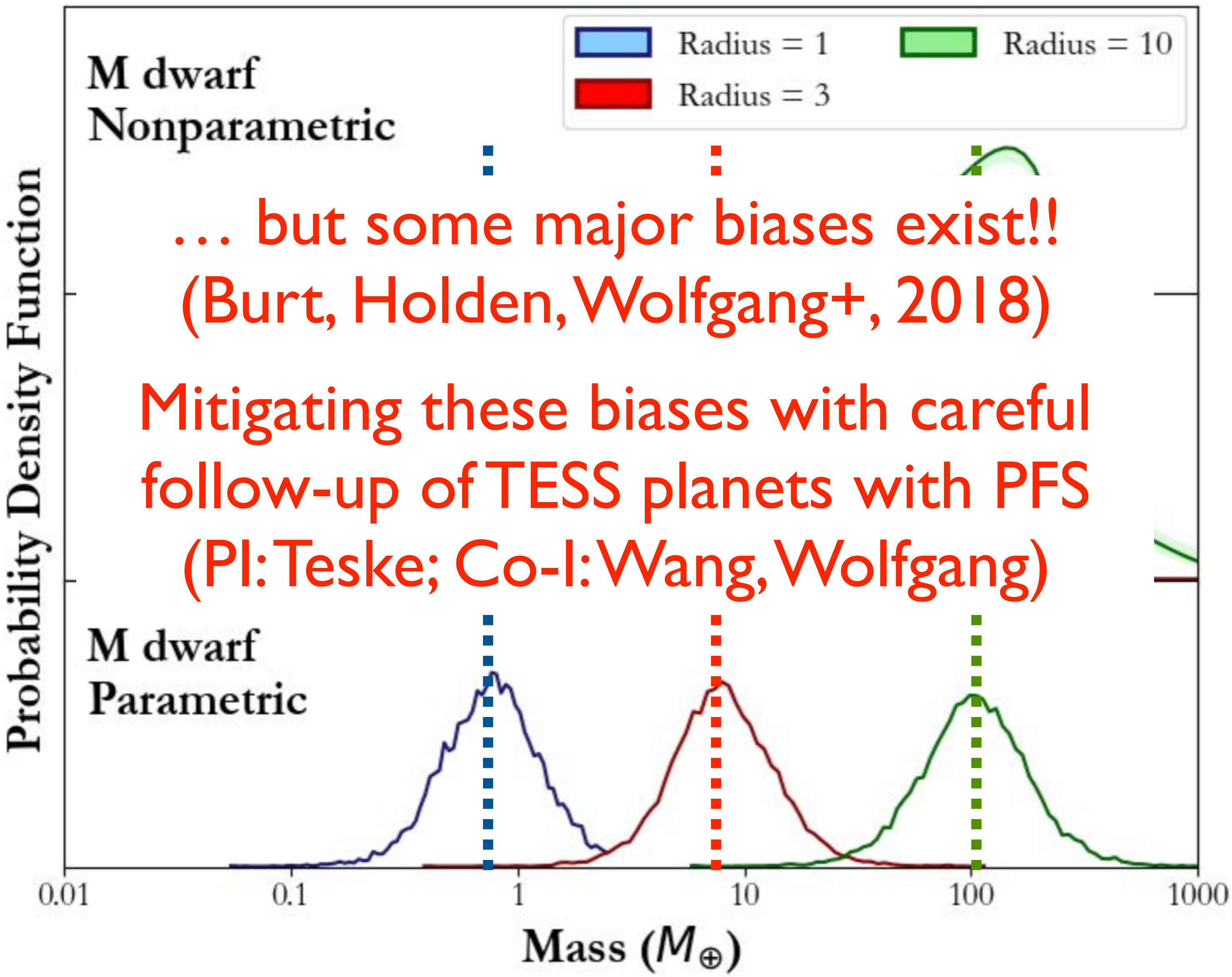

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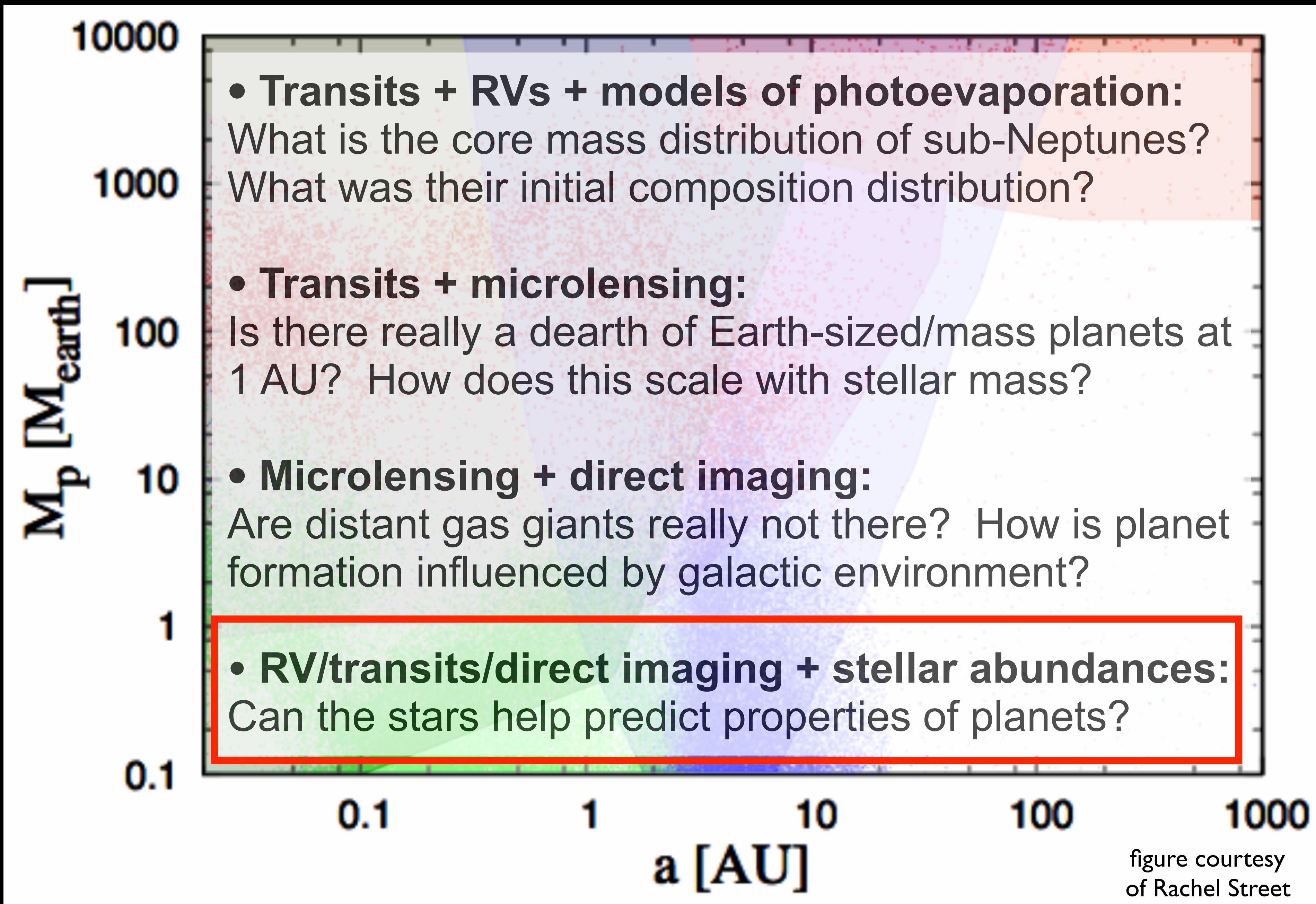
Numerous Future Directions



Summary

Observations of **planet populations are inherently probabilistic**; our analysis of planet demographics should be too.

Composition distribution of Kepler's sub-Neptunes:
the typical 1 < R_{Earth} < 4 planet has ~1% mass in H+He envelope;
95% have envelope fractions between 0.1% and 10 %

The **mass-radius relation** has astrophysical scatter, so that there's a **range of possible masses at a given radius**. The average mass can be modeled as a power law for smaller radii.

The Galactic **exoplanet census** will provide numerous and valuable **constraints on planet formation.** Constructing it requires expertise in **astrostatistics and many Ph.D.s** worth of research.