Who are *Kepler*'s Sub-Neptunes? Insights from Photo-evaporation

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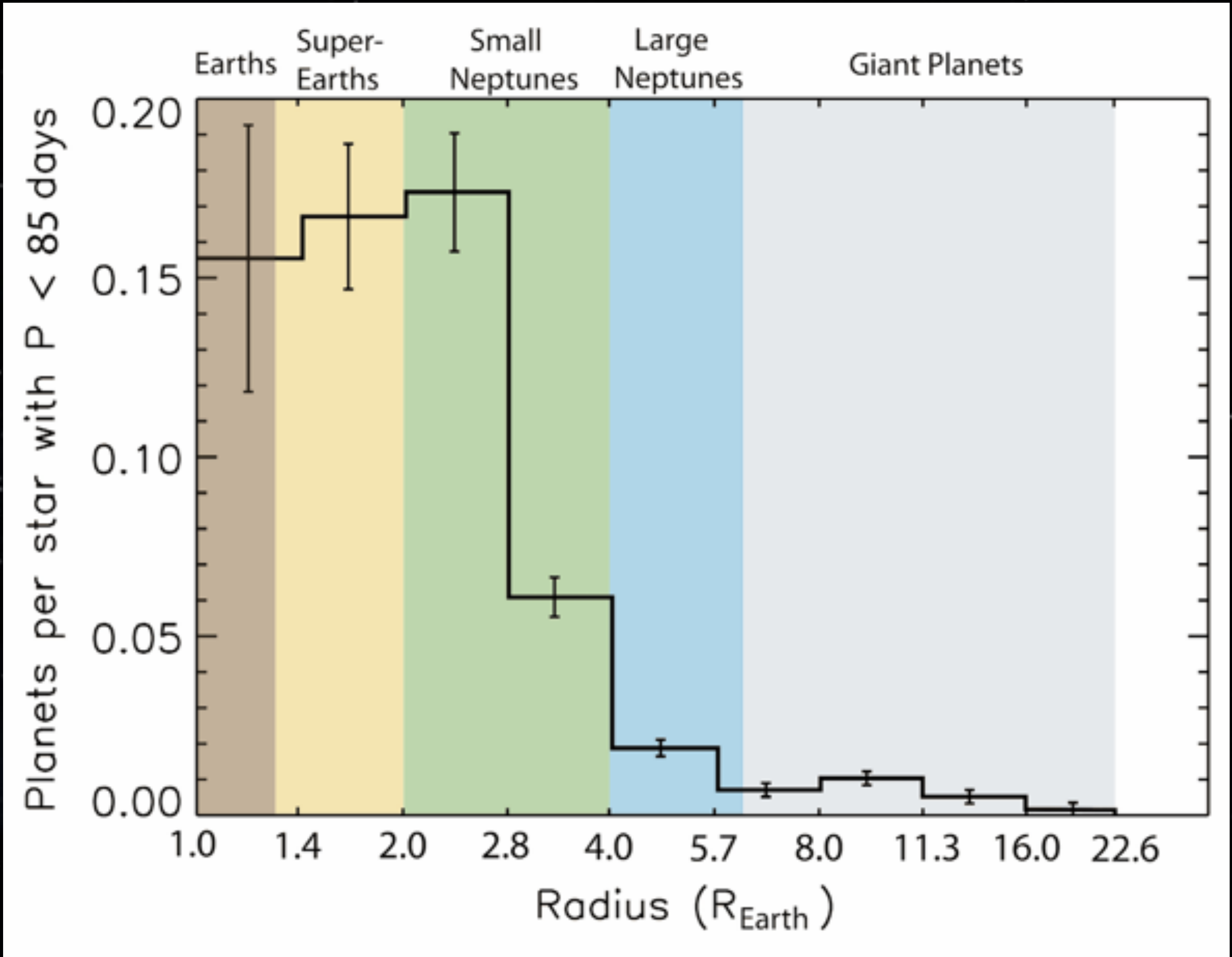
Institute for Astronomy

SEVENTH FRAMEWORK PROGRAMME

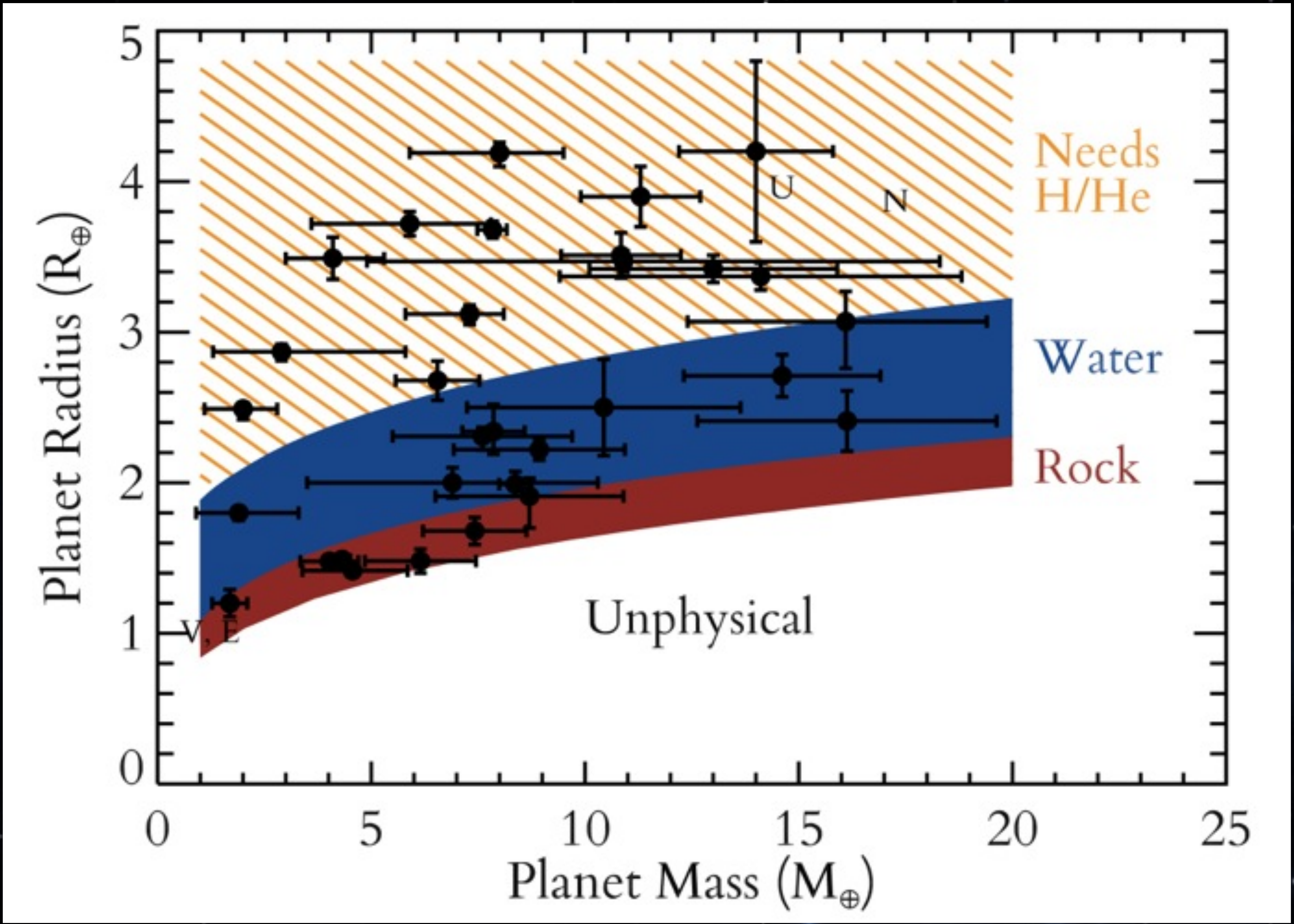
Image Credit: NASA / Tim Pyle

New Classes of Planets



Fressin et al. (2013), also Petigura et al. (2013)

Sub-Neptunes Aren't Rocky

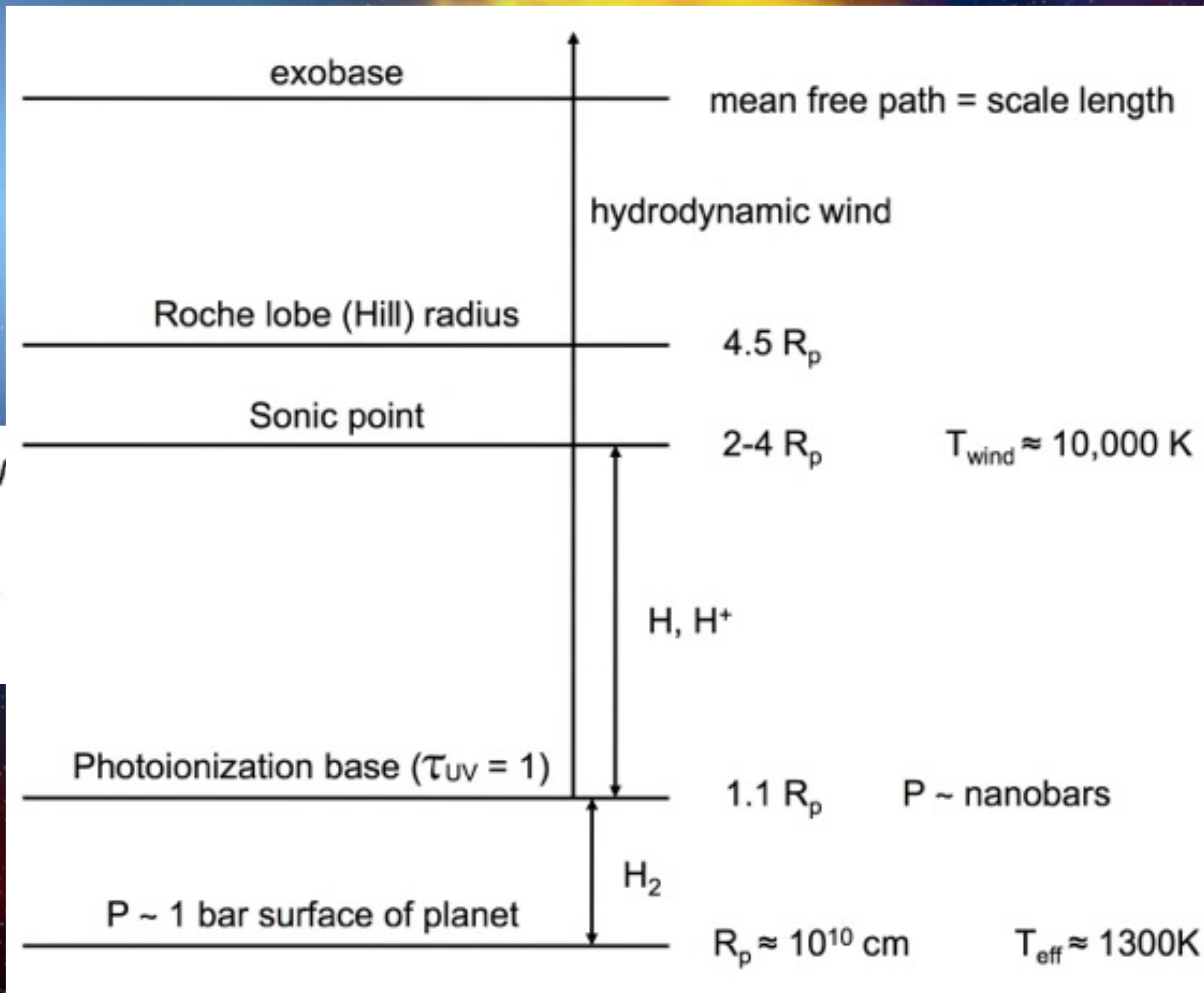


Based on Lopez, Fortney, & Miller (2012)

What are the Sub-Neptunes?

- Are they Scaled up rocky worlds?
- Or small ice giants?
- Do they form in situ?
- Or migrate from beyond the snow-line?

Photo-Evaporation



Murray-Clay, Chiang, & Murray (2008)

Image Credit:
Alfred Vidal-Madjar

Photo-Evaporation

An extended upper atmosphere around the extrasolar planet HD209458b

A. Vidal-Madjar*, A. Lecavelier des Etangs*, J.-M. Désert*,

A giant comet-like cloud of hydrogen escaping the warm Neptune-mass exoplanet GJ 436b

David Ehrenreich[1], Vincent Bourrier[1], Peter J. Wheatley[2], Alain Lecavelier des Etangs[3,4], Guillaume Hébrard[3,4,5], Stéphane Udry[1], Xavier Bonfils[6,7], Xavier Delfosse[6,7], Jean-Michel Désert[8], David K. Sing[9] & Alfred Vidal-Madjar[3,4]

Received 2003 December 23; accepted 2004 February 4; published 2004 March 1

Evaporation of the planet HD 189733b observed in H I Lyman-α

A. Lecavelier des Etangs[1,2], D. Ehrenreich[3], A. Vidal-Madjar[1,2], G. E. Ballester[4], J.-M. Désert[1,2],
R. Ferlet[1,2], G. Hébrard[1,2], D. K. Sing[1,2,5], K.-O. Tchakoumegni[1,2,6], and S. Udry[7]

Photo-Evaporation

HYDRODYNAMIC ESCAPE OF EXO-PLANETARY ATMOSPHERES

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[5]Institute for Geophysics, Astrophysics and Meteorology, University of Graz, Universitätsplatz 5, 8010 Graz, Austria
[6]Department for Astronomy, University of Vienna, Türkenschanzstr. 17, A-1180 Vienna, Austria

The effect of evaporation on the evolution of close-in giant planets

I. Baraffe[1], F. Selsis[2], G. Chabrier[1], T. S. Barman[3], F. Allard[1], P.H. Hauschildt[4] and H. Lammer[5]

Atmospheric escape from hot Jupiters

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[2] Department of Earth and Atmospheric Science, York University, North York, Ontario, Canada

ATMOSPHERIC ESCAPE FROM HOT JUPITERS

Ruth A. Murray-Clay[1,2], Eugene I. Chiang[1], & Norman Murray[3,4]

Accepted to ApJ: *October 29, 2008*

Aeronomy of extra-solar giant planets at small orbital distances

Roger V. Yelle

Department of Planetary Sciences, University of Arizona, Tucson, AZ 85721, USA

Received 20 August 2003; revised 12 February 2004
Available online 24 April 2004

Atmospheric mass loss and evolution of short-period exoplanets: the examples of CoRoT-7b and Kepler-10b

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[2]*Max Planck Institut fuer Astronomie, Koenigstuhl 17, 69117, Heidelberg, Germany*

Birth and fate of hot-Neptune planets

I. Baraffe[1,2], Y. Alibert[3], G. Chabrier[1,2], W. Benz[3]

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Planetary evaporation by UV & X-ray radiation: basic hydrodynamics

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HOW THERMAL EVOLUTION AND MASS-LOSS SCULPT POPULATIONS OF SUPER-EARTHS AND SUB-NEPTUNES: APPLICATION TO THE KEPLER-11 SYSTEM AND BEYOND

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THE ROLE OF CORE MASS IN CONTROLLING EVAPORATION: THE KEPLER RADIUS DISTRIBUTION AND THE KEPLER-36 DENSITY DICHOTOMY

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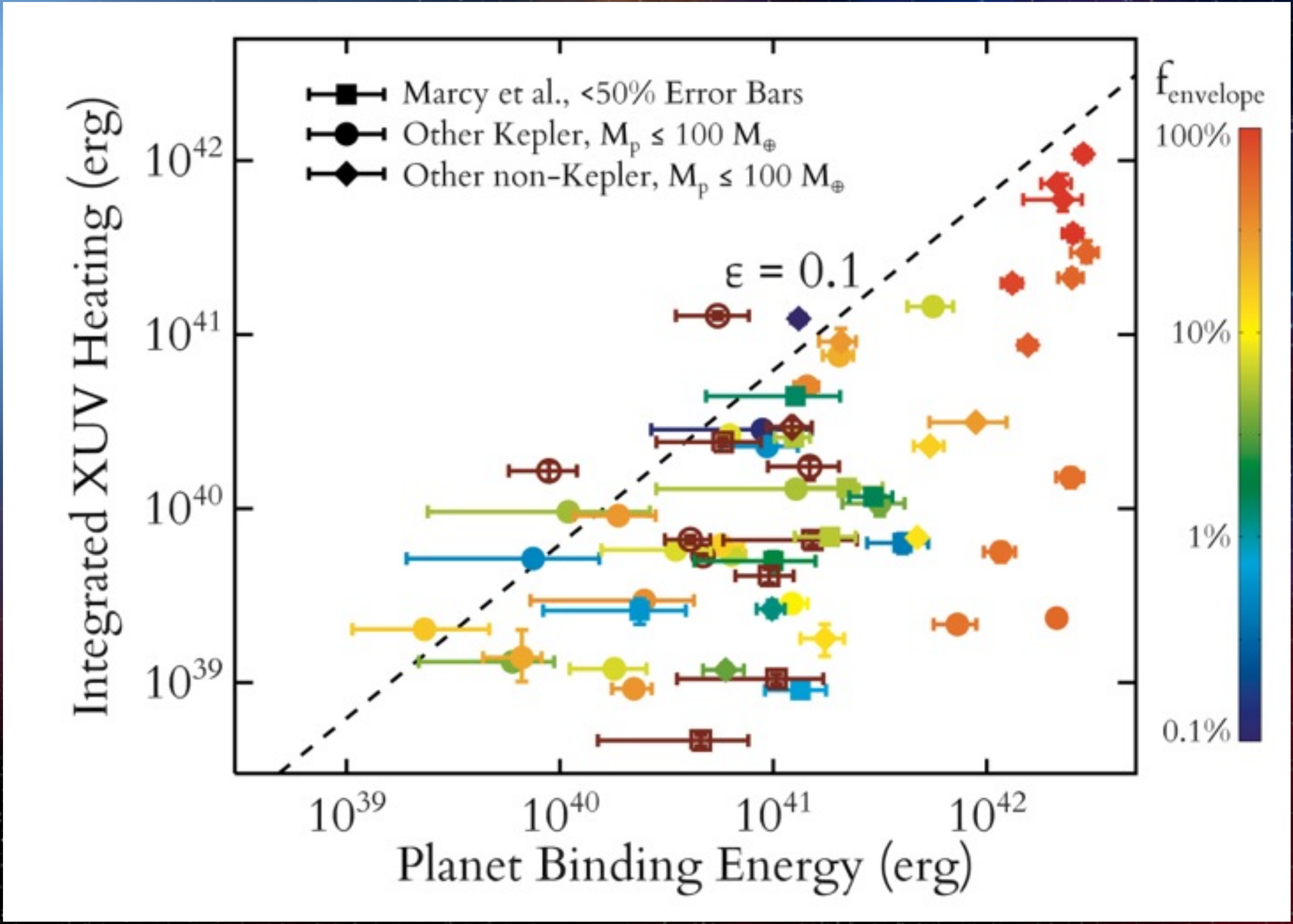
44th Lunar and Planetary Science Conference (2013) **2787.pdf**

THE COSMIC SHORELINE K. J. Zahnle[1] and D. C. Catling[2], [1]MS 245-3, Space Science Division, NASA Ames Research Center, Moffett Field CA 94035 (kevin.j.zahnle@nasa.gov), [2]Dept. Earth and Space Sciences/Astrobiology Program, Box 351310, University of Washington, Seattle WA 98195, USA (dcatling@uw.edu).

Planets Sculpted by Photo-Evaporation



updated from Lopez & Fortney (2014)

Thermal Evolution

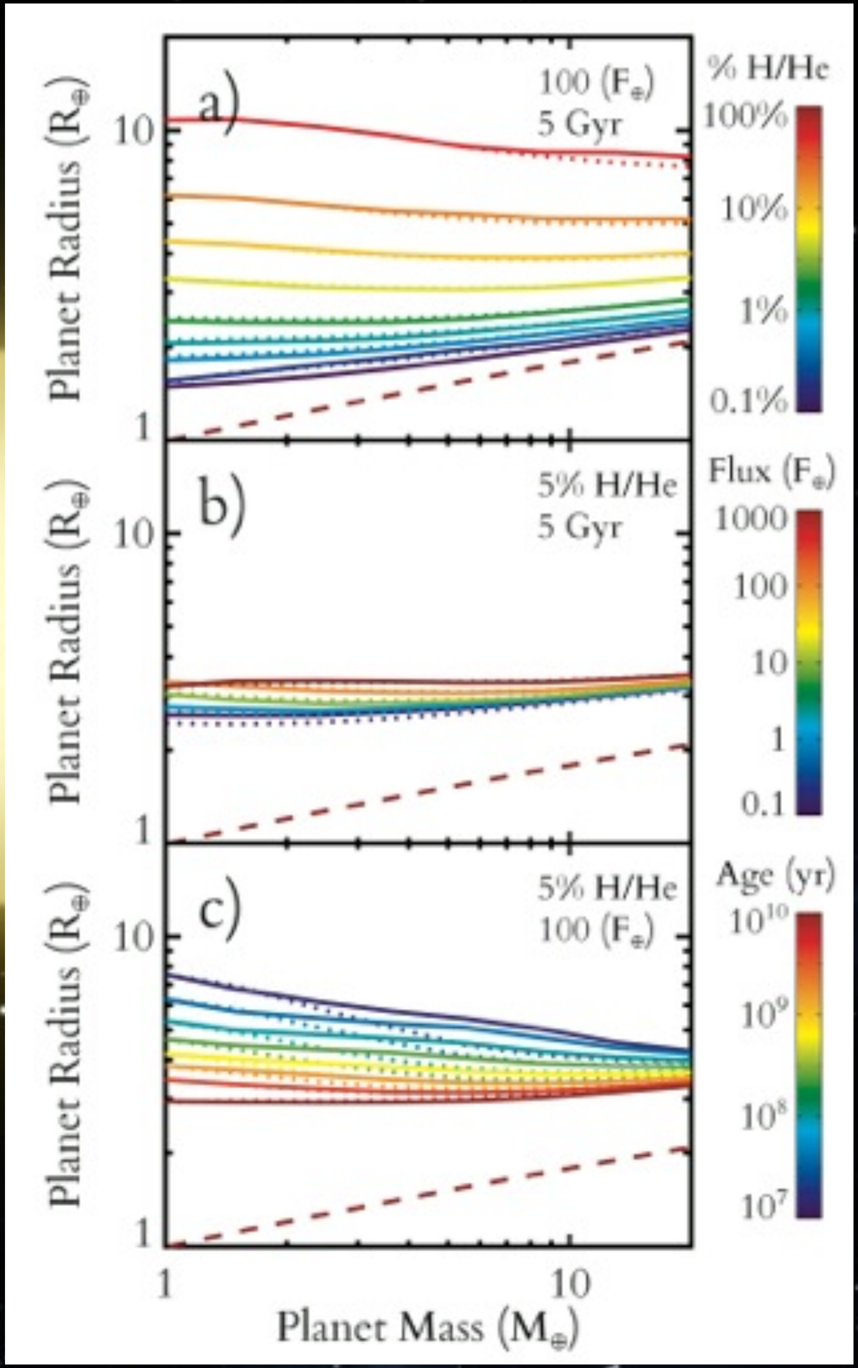
$$\int_{M_{core}}^{M_p} dm \frac{T\,dS}{dt} = -L_{int} + L_{radio} - c_v M_{core} \frac{dT_{core}}{dt}$$

- Models start with large initial entropy from formation then cool and contract.

- Core dominates thermal evolution for sub-Neptunes

- At fixed composition, radius independent of mass if planet >1% H/He.

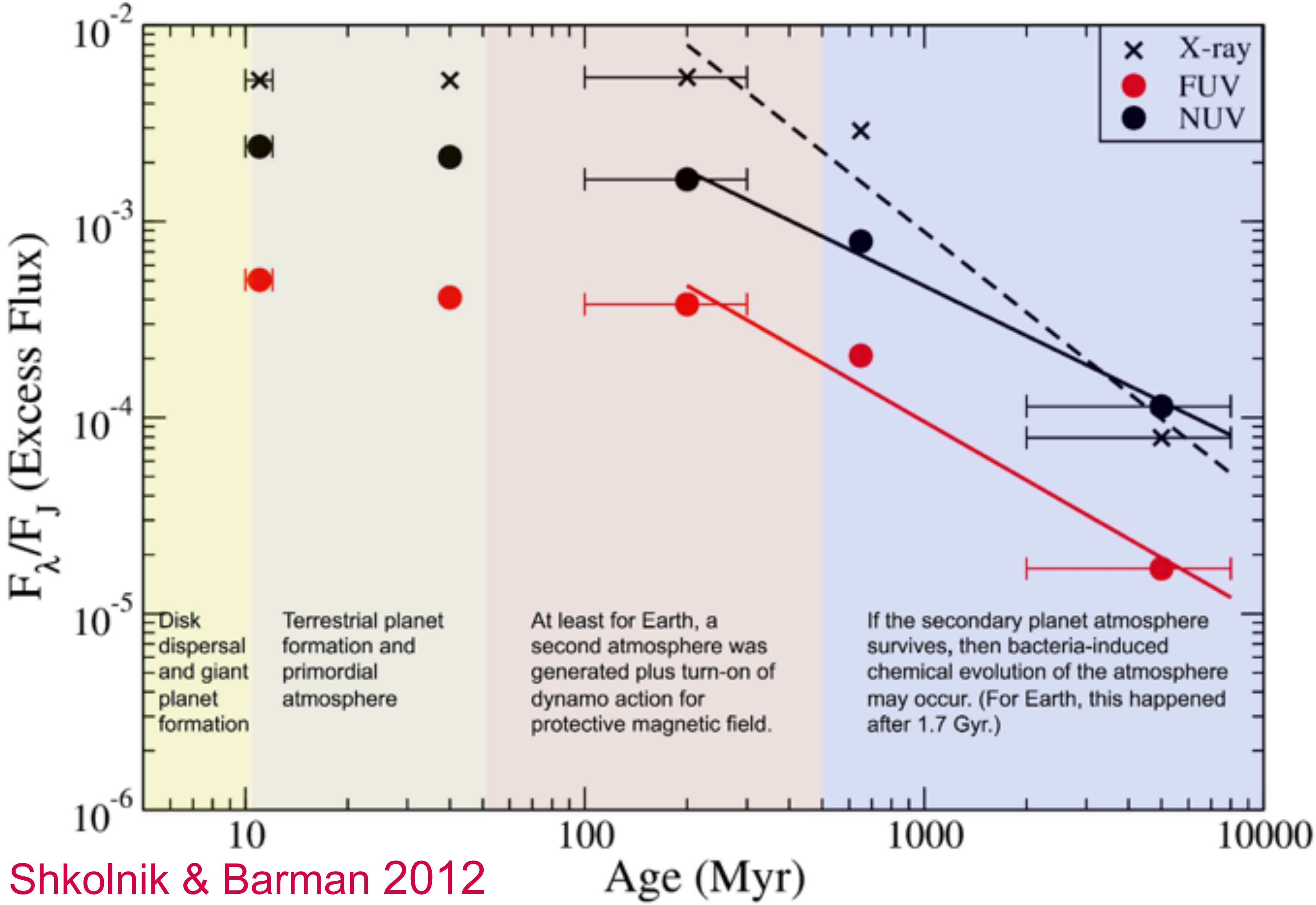
- Lopez & Fortney (2014)



Stellar XUV Fluxes

$$F = 29.7\tau^{-1.23} \text{ ergs s}^{-1} \text{ cm}^{-2}, \quad 1 \text{ Å} < \lambda < 1200 \text{ Å},$$

Ribas et al. 2005



Shkolnik & Barman 2012

Hydrodynamic Escape Rates

- Assume a fraction of all incident XUV energy goes into PdV work.

- H/He atmospheres are especially vulnerable when integrating mass loss history.

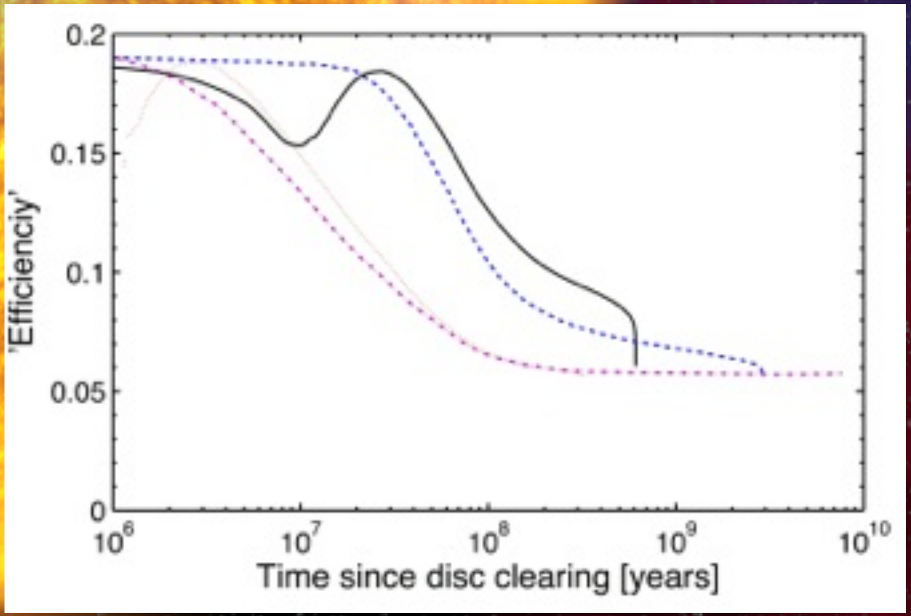
- For planets at ~0.1 AU, mass loss is ~linear with flux, with efficiency ~10%.

$$\dot{M}_{\text{e-lim}} \approx \frac{\epsilon \pi F_{\text{XUV}} R_{\text{XUV}}^3}{G M_{\text{p}} K_{\text{tide}}}$$

Erkaev et al. 2007

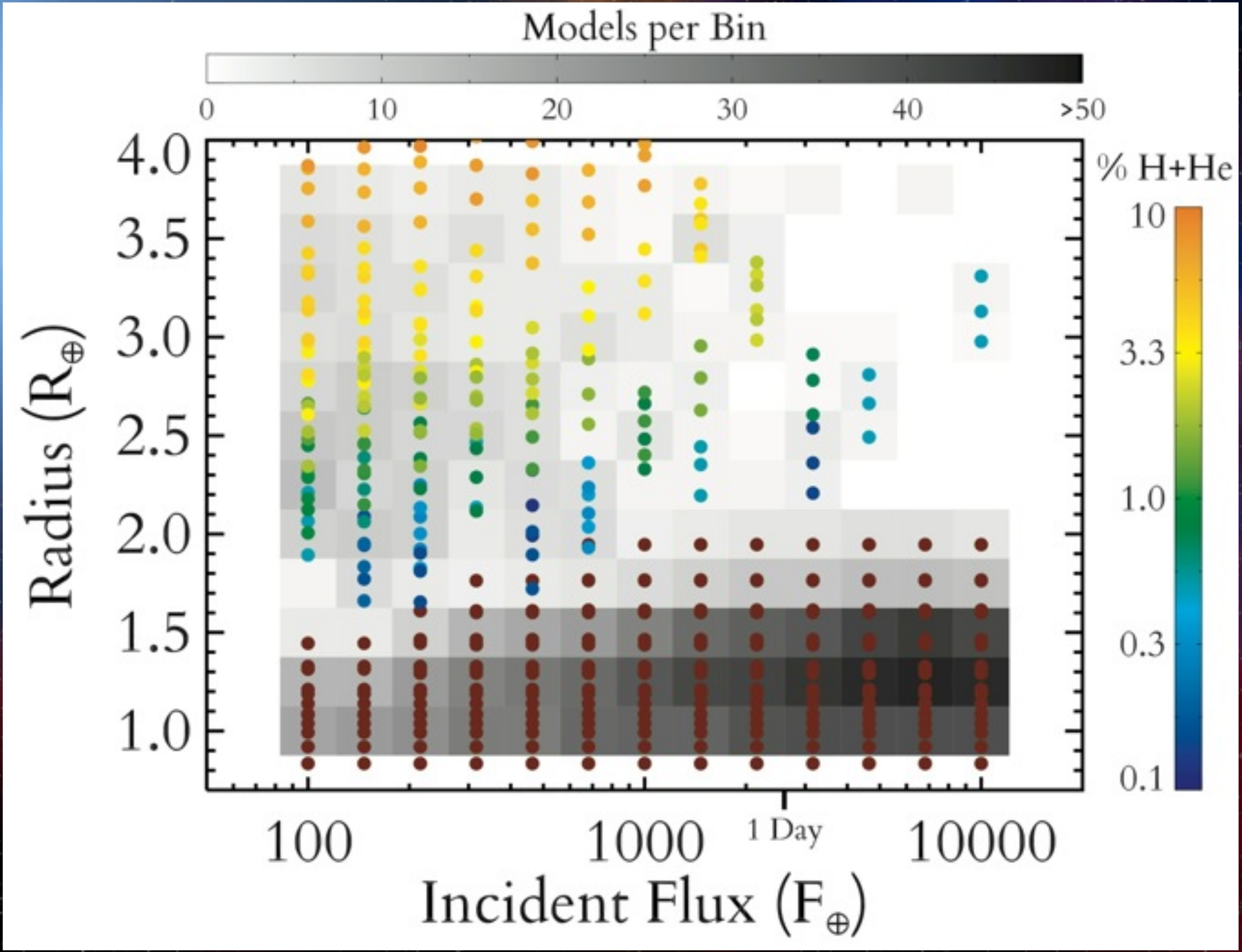
$$\xi \propto Z^{-0.77}$$

Owen & Jackson 2012



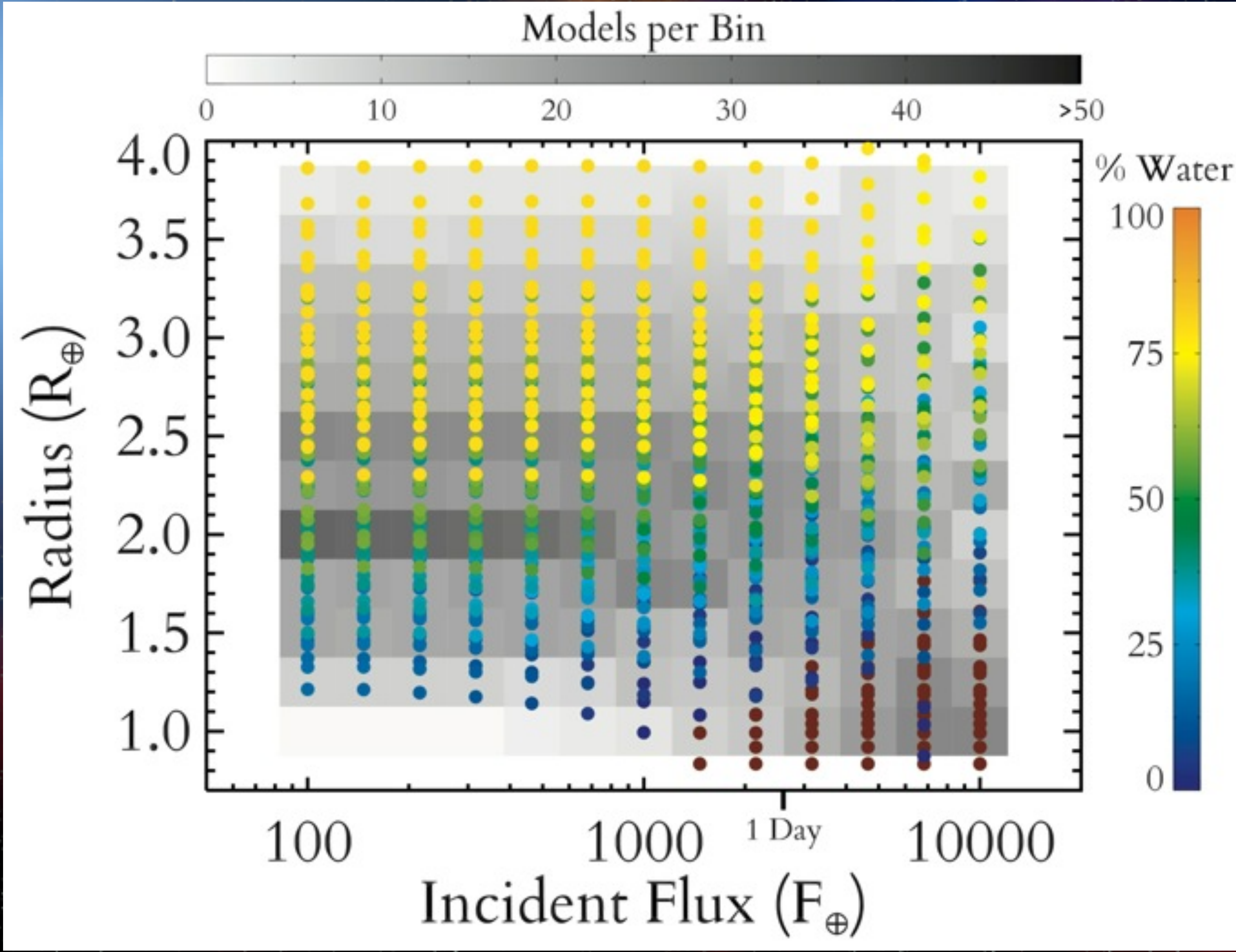
Owen & Wu 2013

The Radius-Flux Distribution



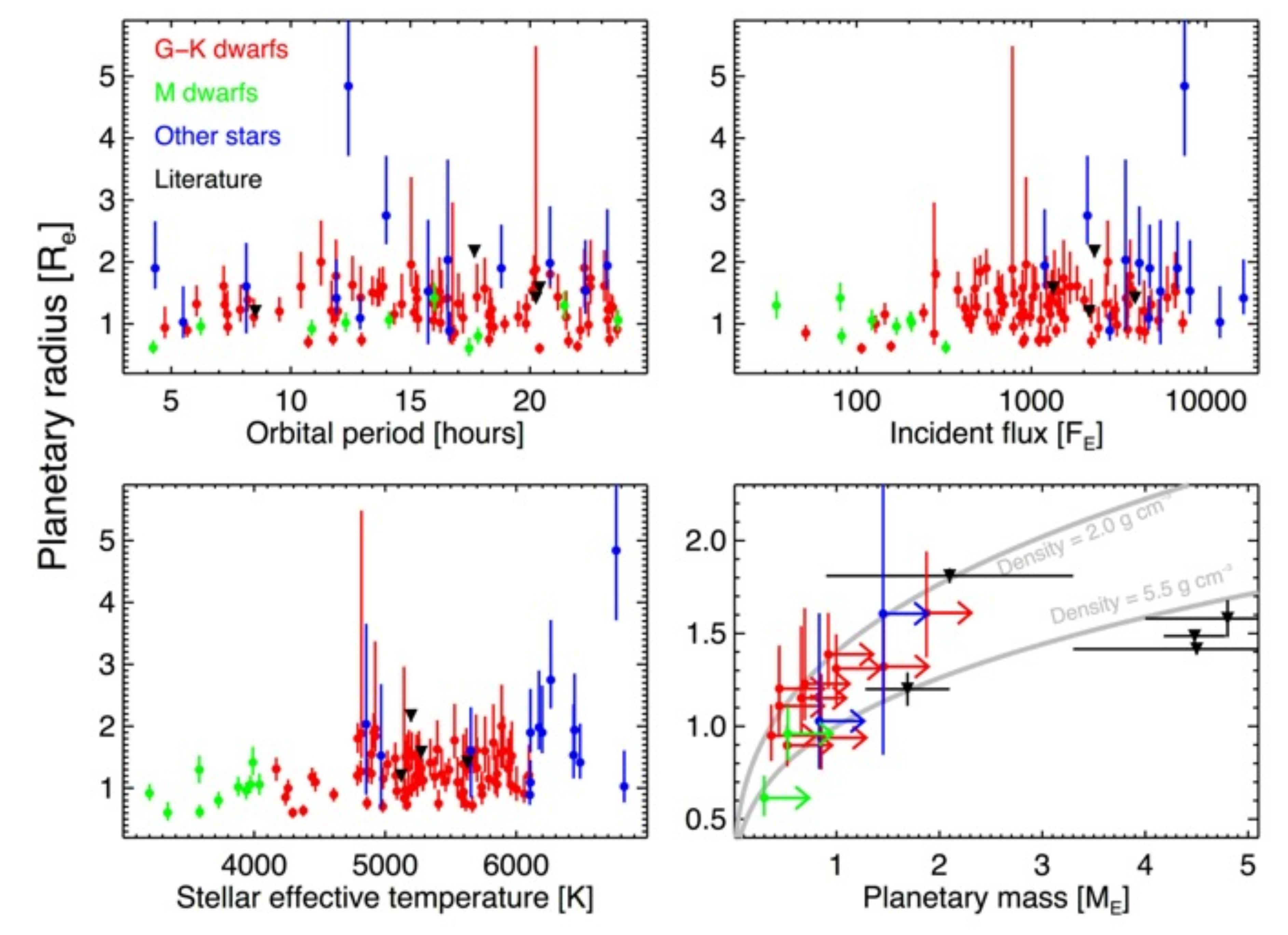
Lopez (in prep)

The Radius-Flux Distribution



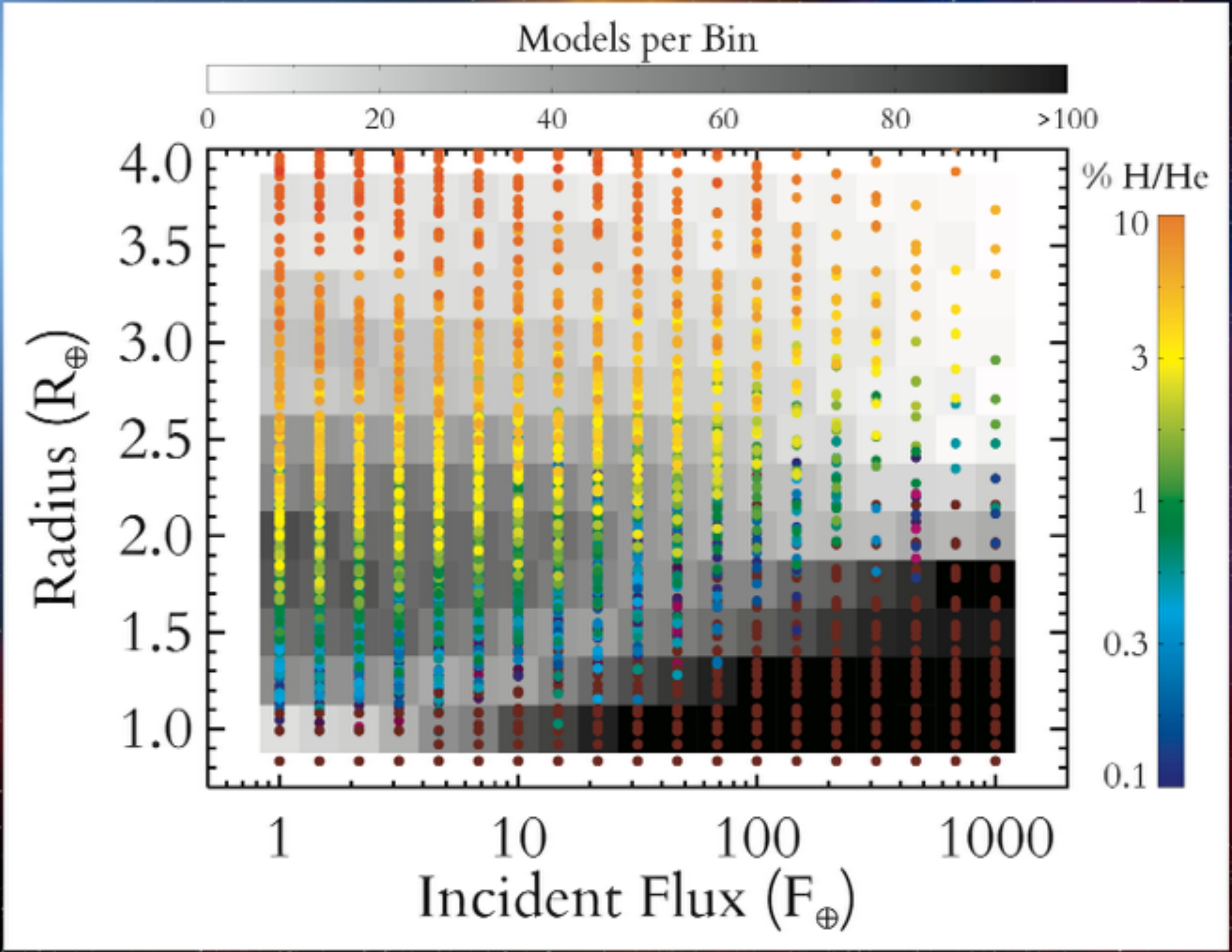
Lopez (in prep)

The Observed USPs



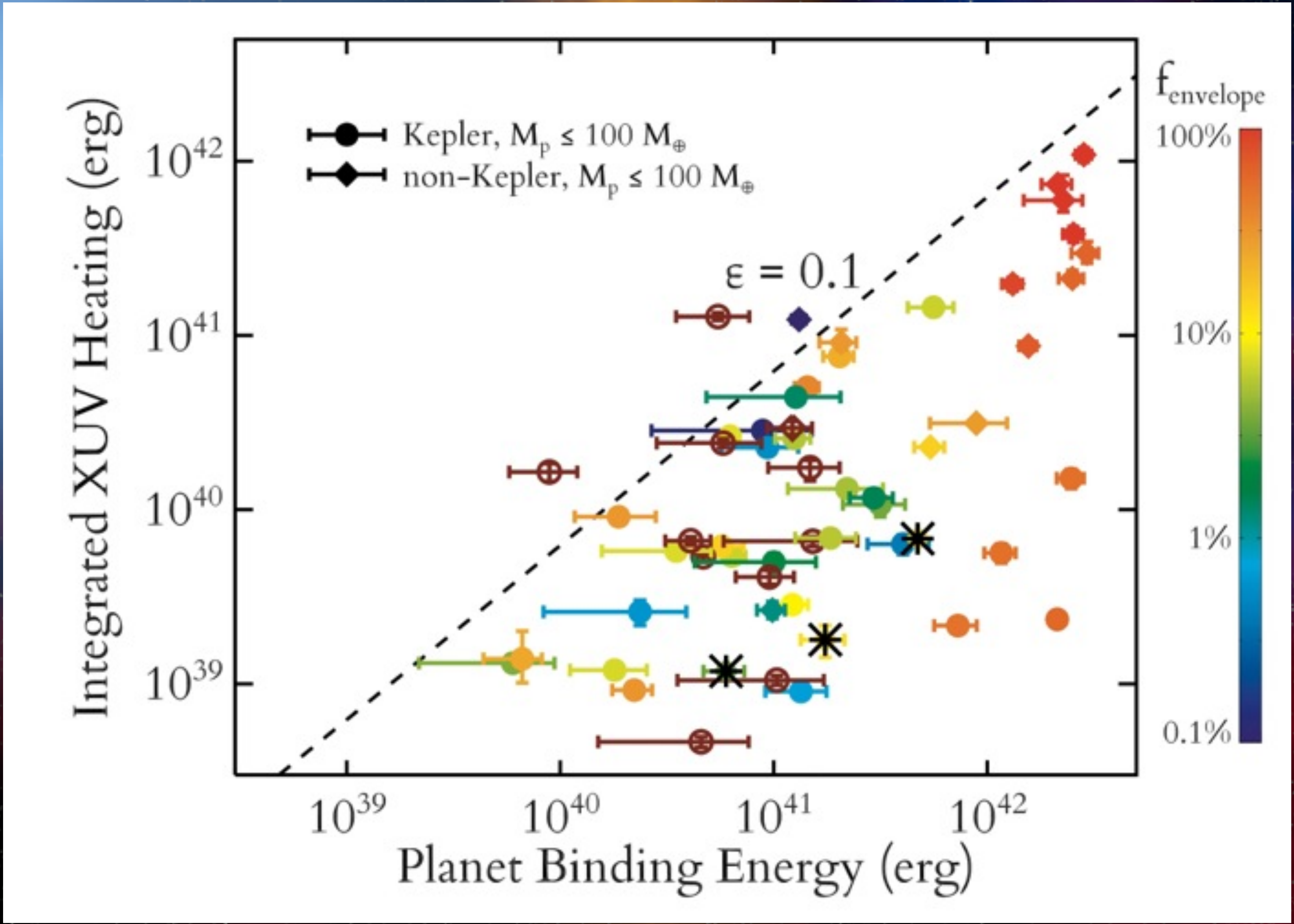
Sanchis-Ojeda et al. (2014)

The Evaporation Valley



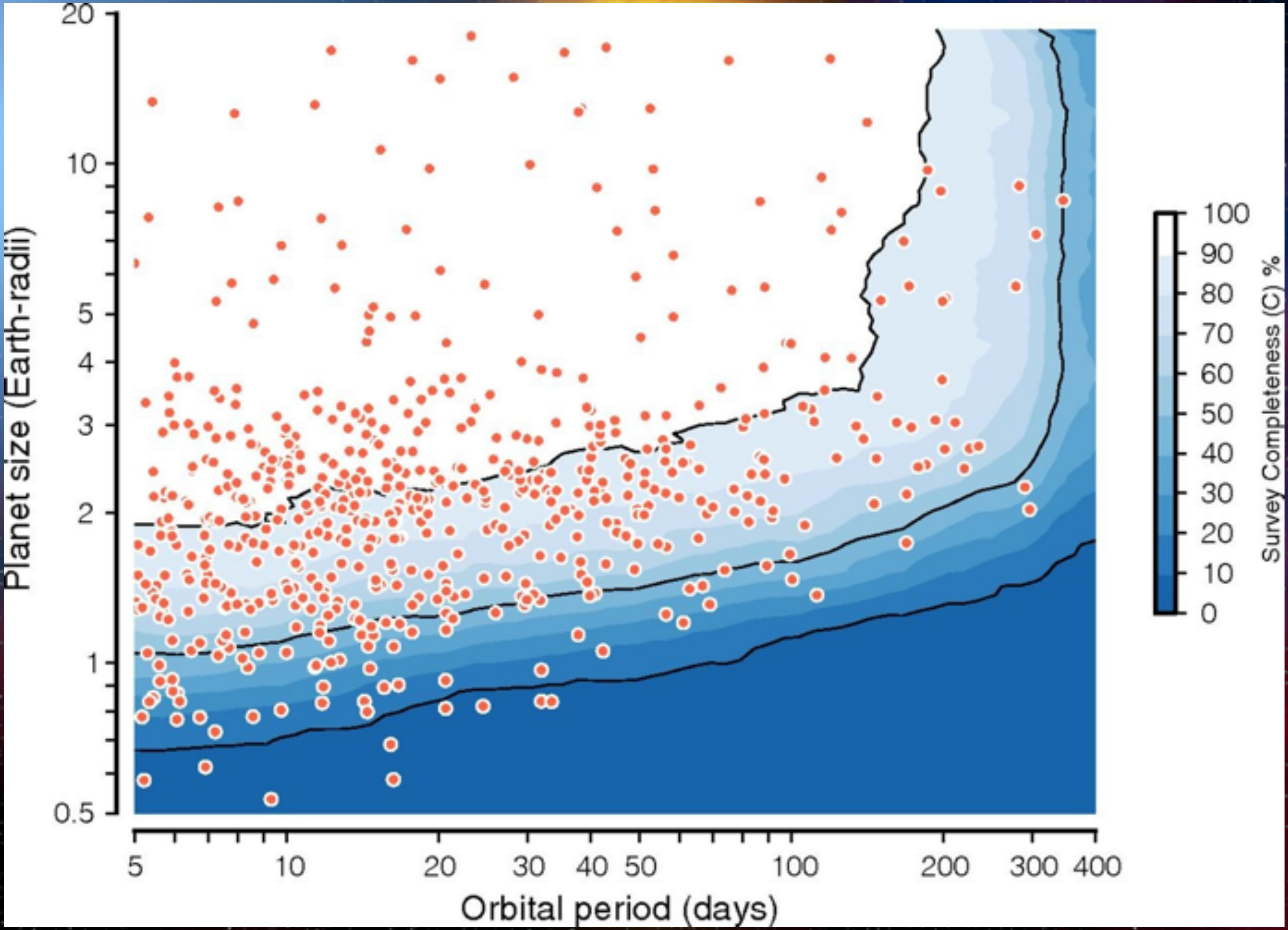
Lopez & Fortney (2013)

What about planets around M Dwarfs?



Modified from Lopez & Fortney (2014)

Over-Estimating Eta-Earth?



Petigura, Howard, & Marcy (2013)

Over-Estimating Eta-Earth?

- Gas Rich sub-Neptunes are ubiquitous.
- Most short-period rocky planets could be the remains of sub-Neptunes.
- Almost all known rocky planets are highly irradiated.
- Earth-like habitable rocky planets could be quite rare.

Conclusions

• *Kepler* has discovered an abundant new population of sub-Neptune sized planets, which must have large volatile envelopes.

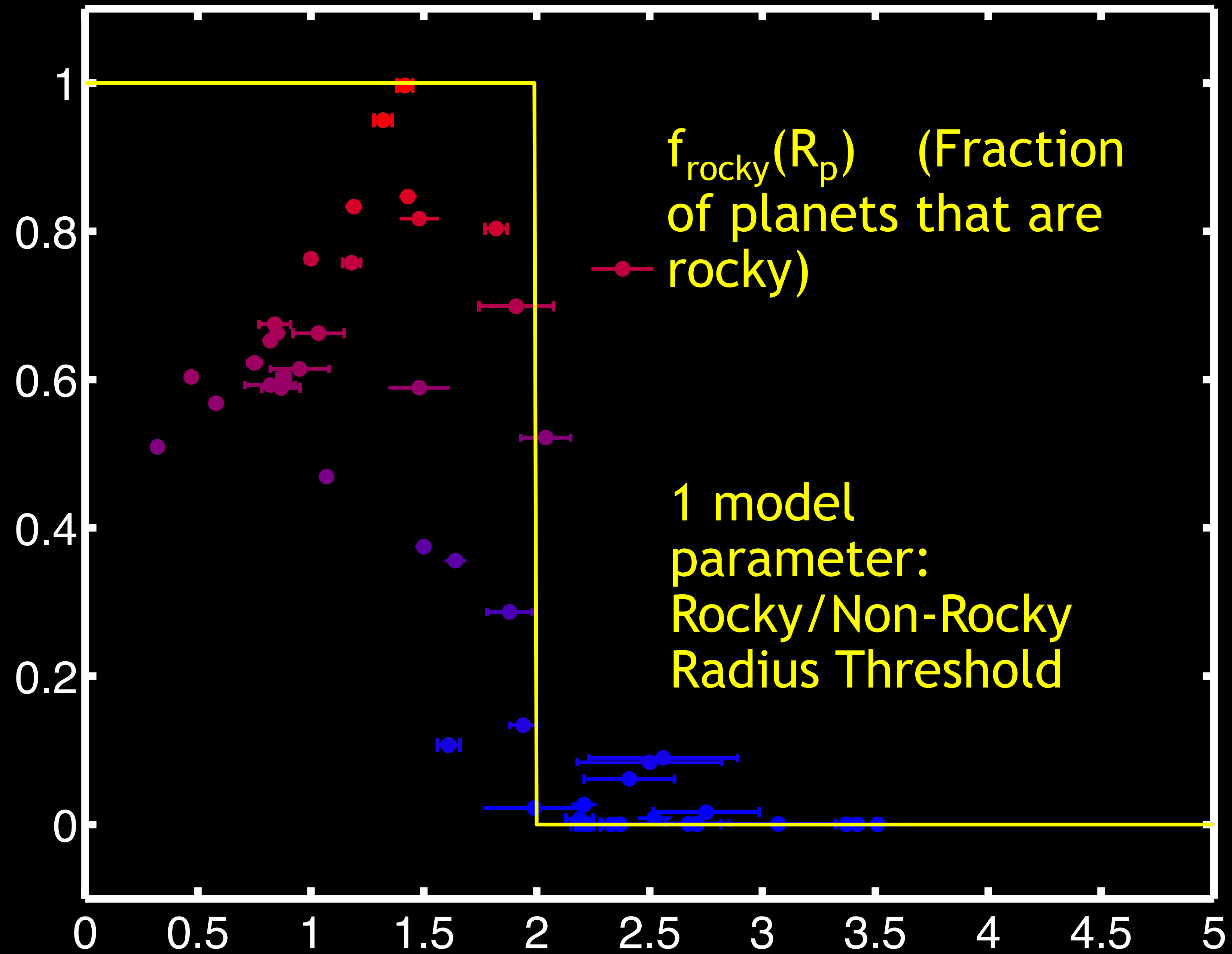
• The present day compositions of sub-Neptunes have been sculpted by photo-evaporation.

• The Ultra-Short-Period planets likely formed rocky.

• Likewise, the evaporation valley will help diagnose whether moderate period sub-Neptunes are water-rich.

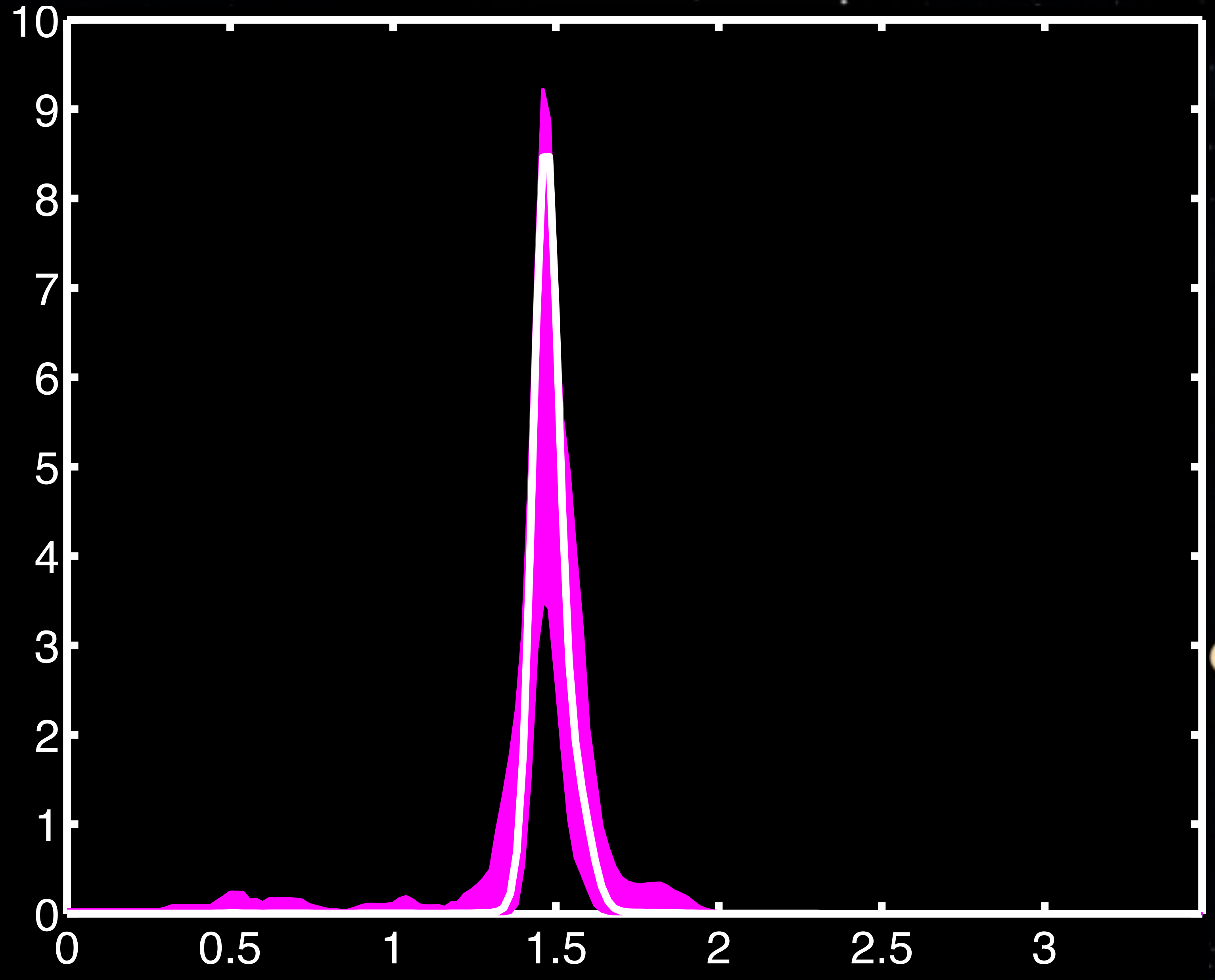
• Photo-evaporation could lead to over-estimates of Eta-Earth

This Agrees with Marcy et al. RV Survey



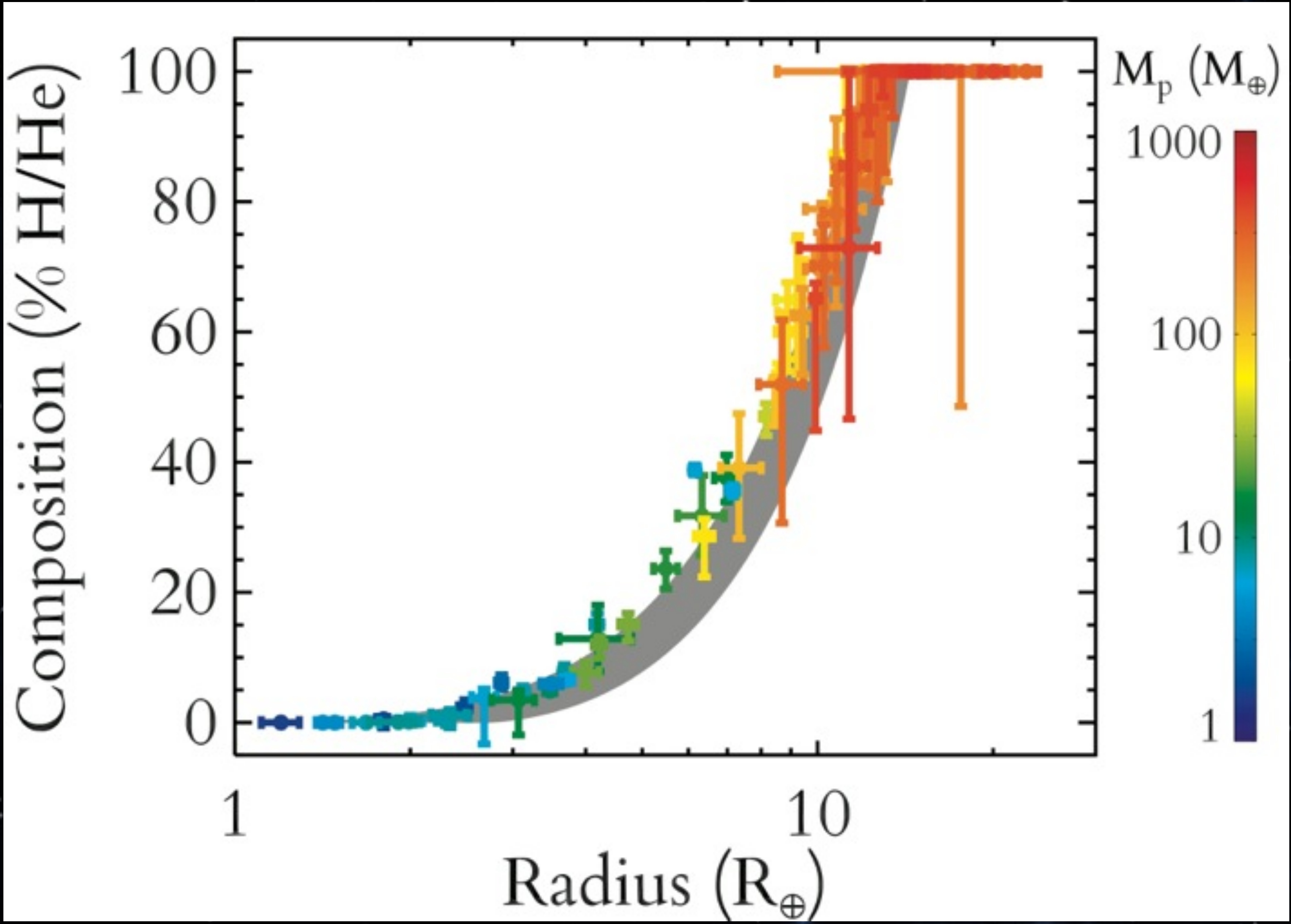
Rogers (2014)

Transition at 1.5 R_{earth}



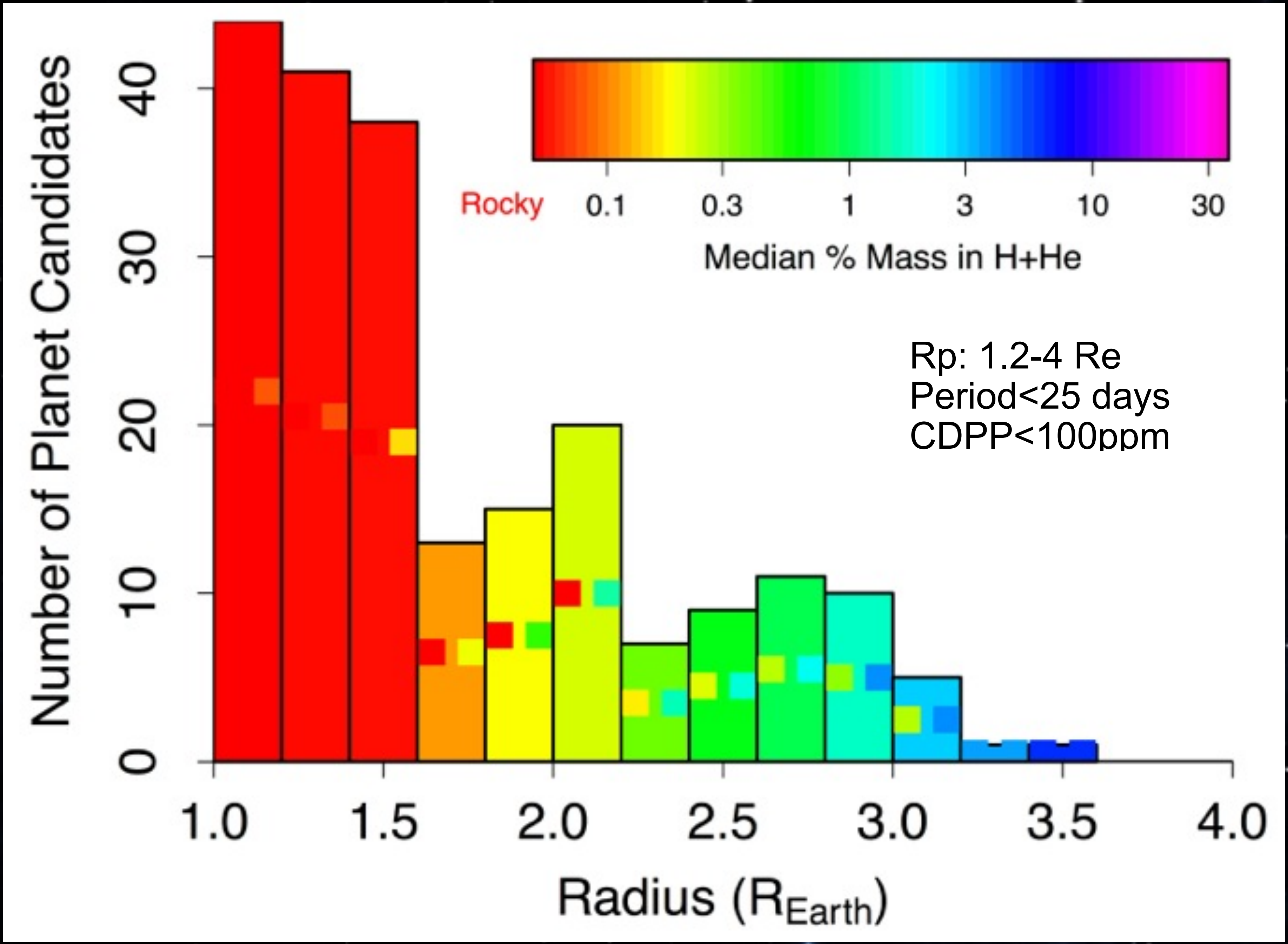
Rogers (2014)

Radius as a Proxy for Composition



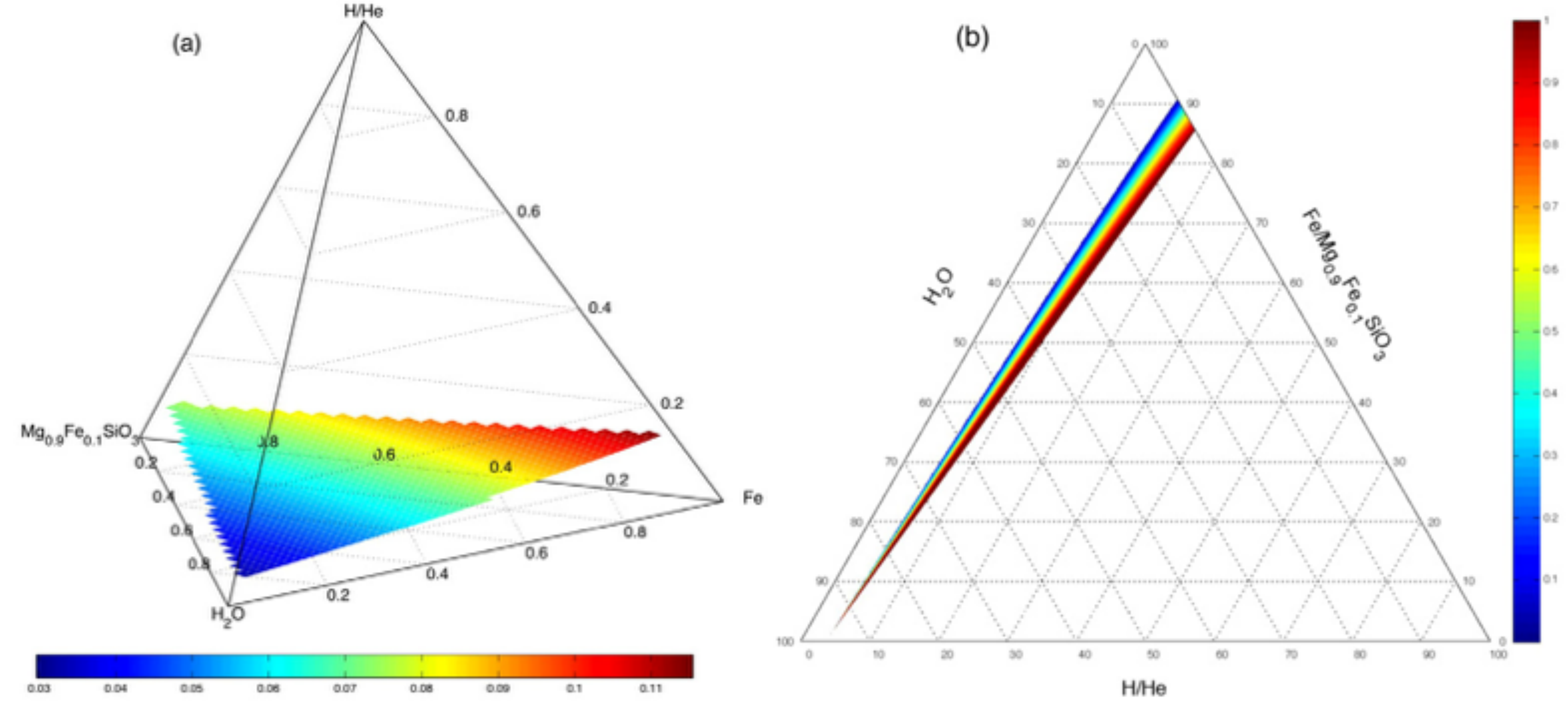
Lopez & Fortney (2014)

The Rocky/Gaseous Transition



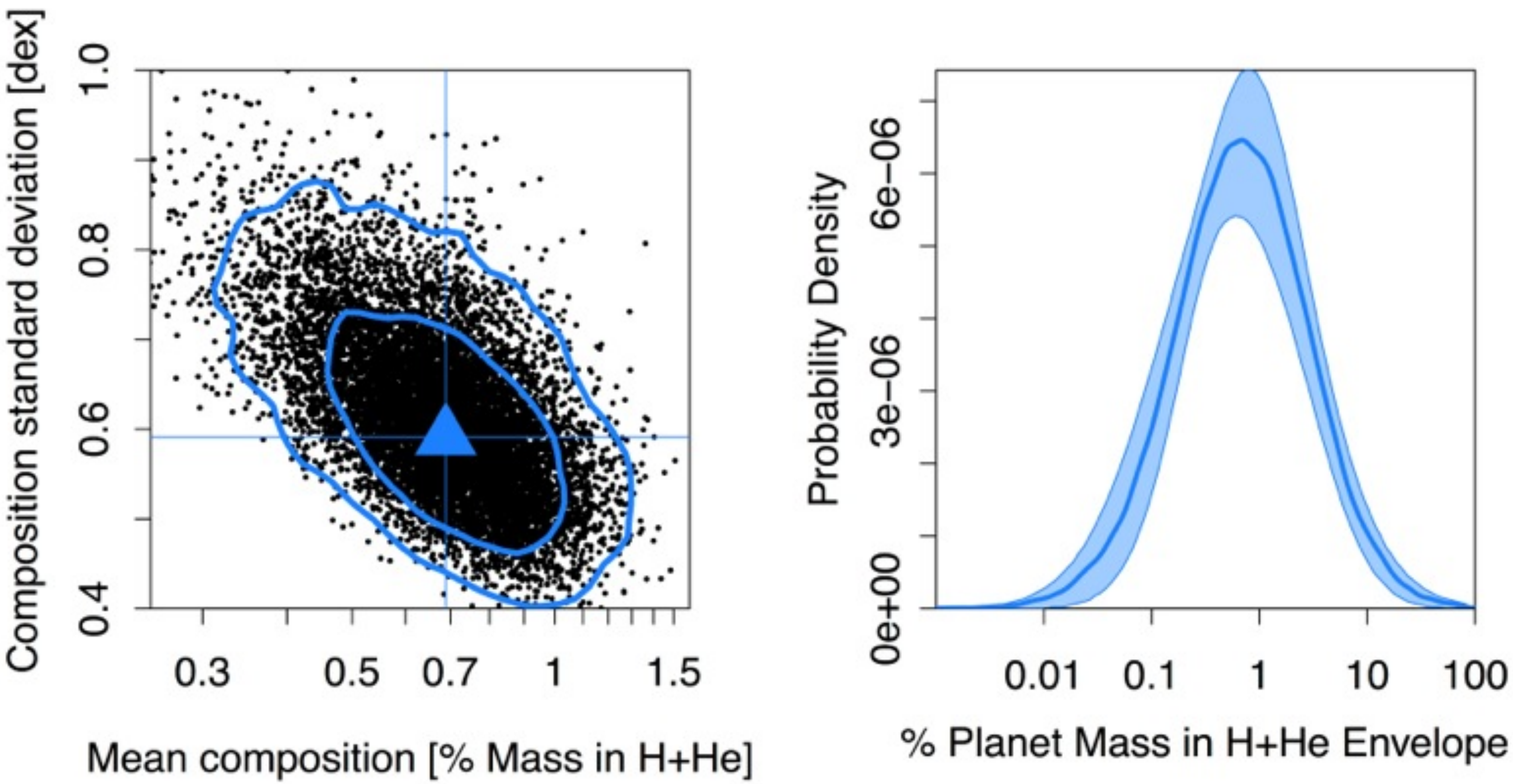
Wolfgang & Lopez (2014)

We've Constrained H+He, what about Water?



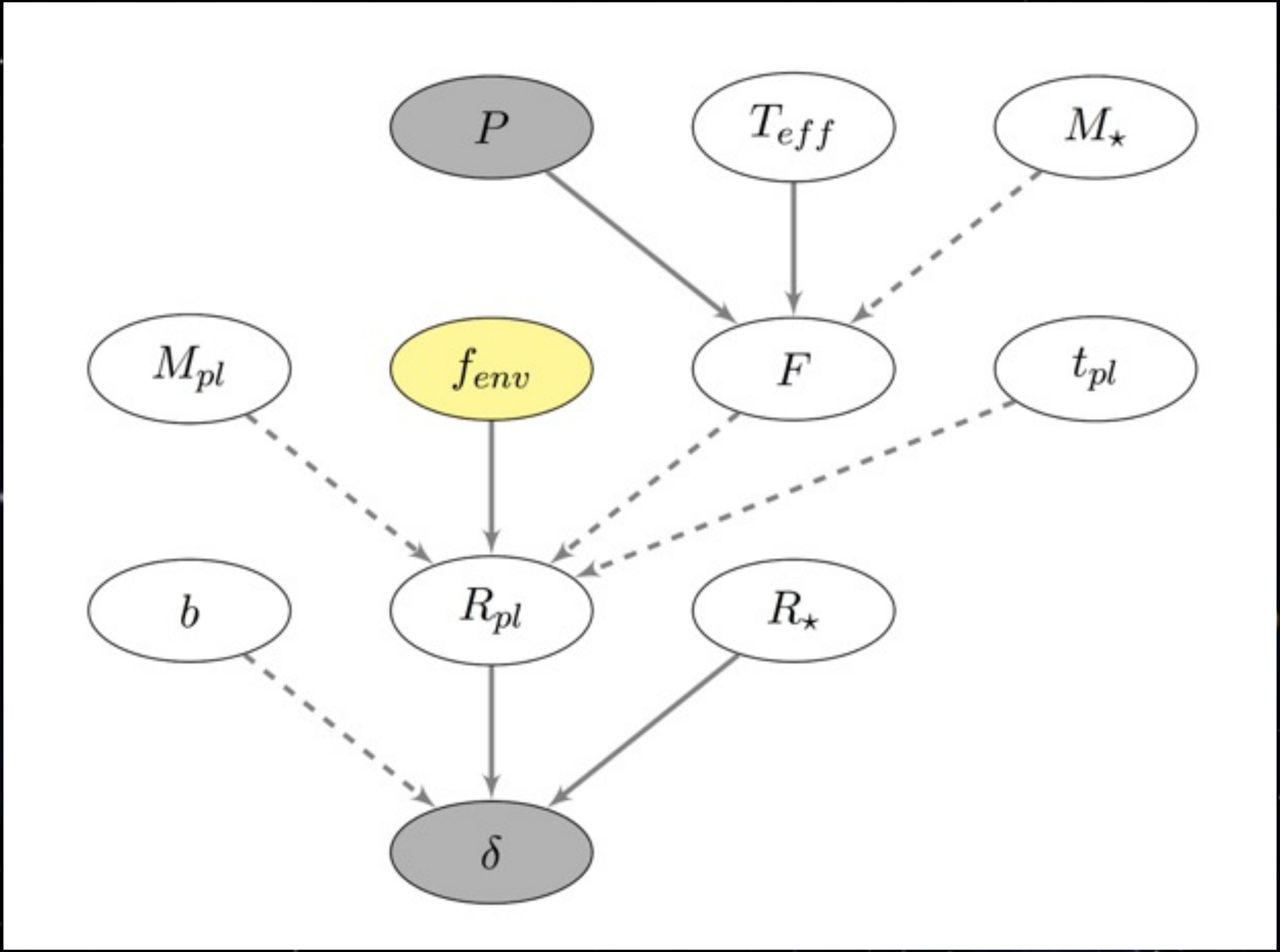
Rogers & Seager (2010)

If Dry, sub-Neptunes are Typically ~1% H+He



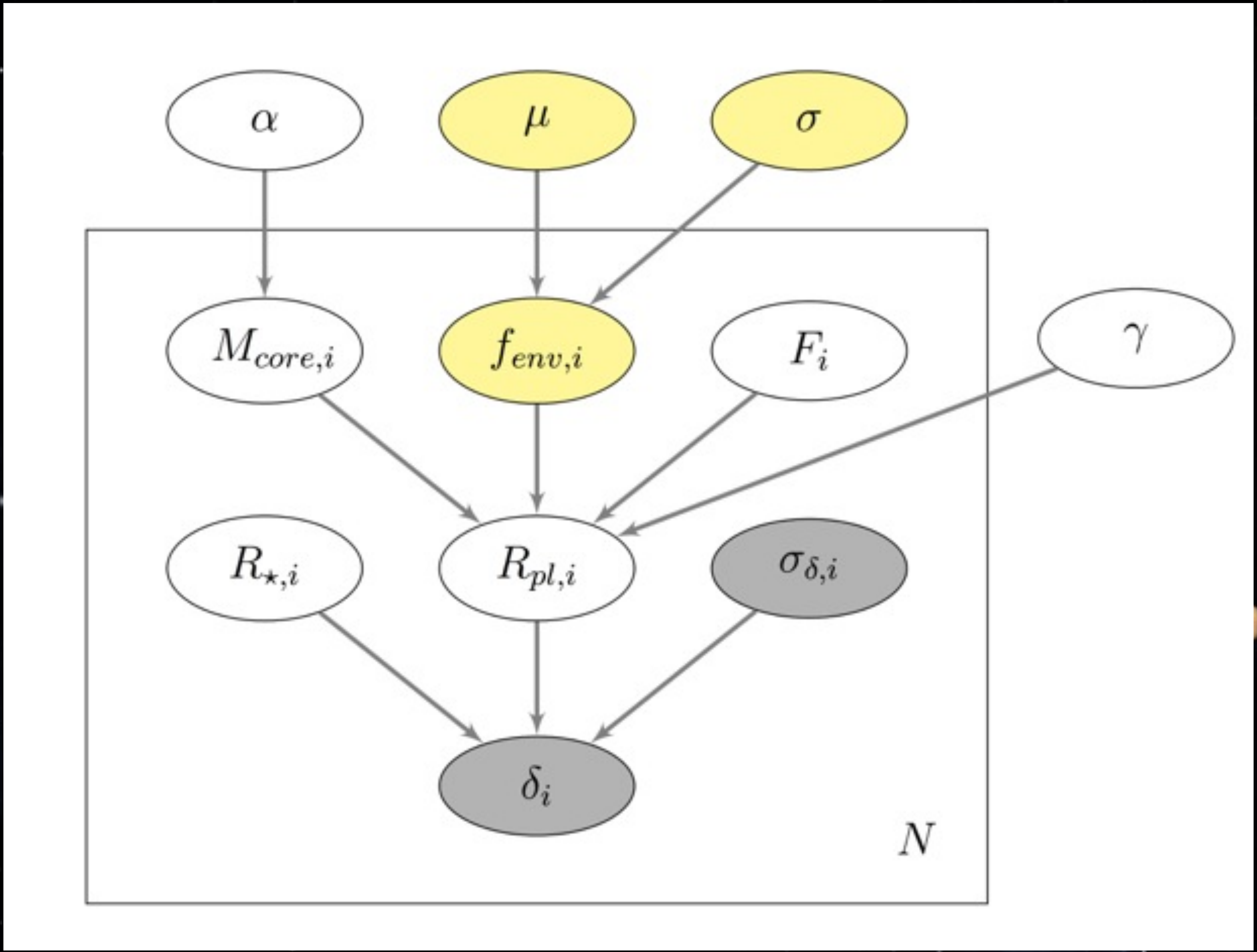
Wolfgang & Lopez (2014)

How We Find Composition



Wolfgang & Lopez (2014)

The Hierarchical Part



Wolfgang & Lopez (2014)

The Details of Our Priors

$$\delta_i|\sigma_{\delta,i}, R_{pl,i}, R_{\star,i}, M_{core,i}, f_{env,i}, F_i, \alpha, \mu, \sigma, \gamma \sim \text{Normal}\left(\delta_i \middle| (R_{pl,i}/R_{\star,i})^2, \sigma_{\delta,i}^2\right)$$

$$R_{pl,i}|M_{core,i}, f_{env,i}, F_i, \alpha, \mu, \sigma, \gamma = g(M_{core,i}, f_{env,i}, F_i, \gamma)$$

$$R_{\star,i} \sim \text{Gamma}\left(R_{\star,i} \middle| a_i, b_i\right) \approx \int \mathcal{L}(R_{\star,i}, M_{\star,i}, T_{eff,i}, [Fe/H]_i)\ \mathrm{d}M_{\star,i}\ \mathrm{d}T_{eff,i}\ \mathrm{d}[Fe/H]_i$$

$$f_{env,i}|\mu, \sigma \sim \text{LogNormal}\left(f_{env,i} \middle| \mu, \sigma\right)$$

$$M_{core,i}|\alpha \sim \text{Pareto}\left(M_{core,i} \middle| -(\alpha+1), 0.5\right)$$

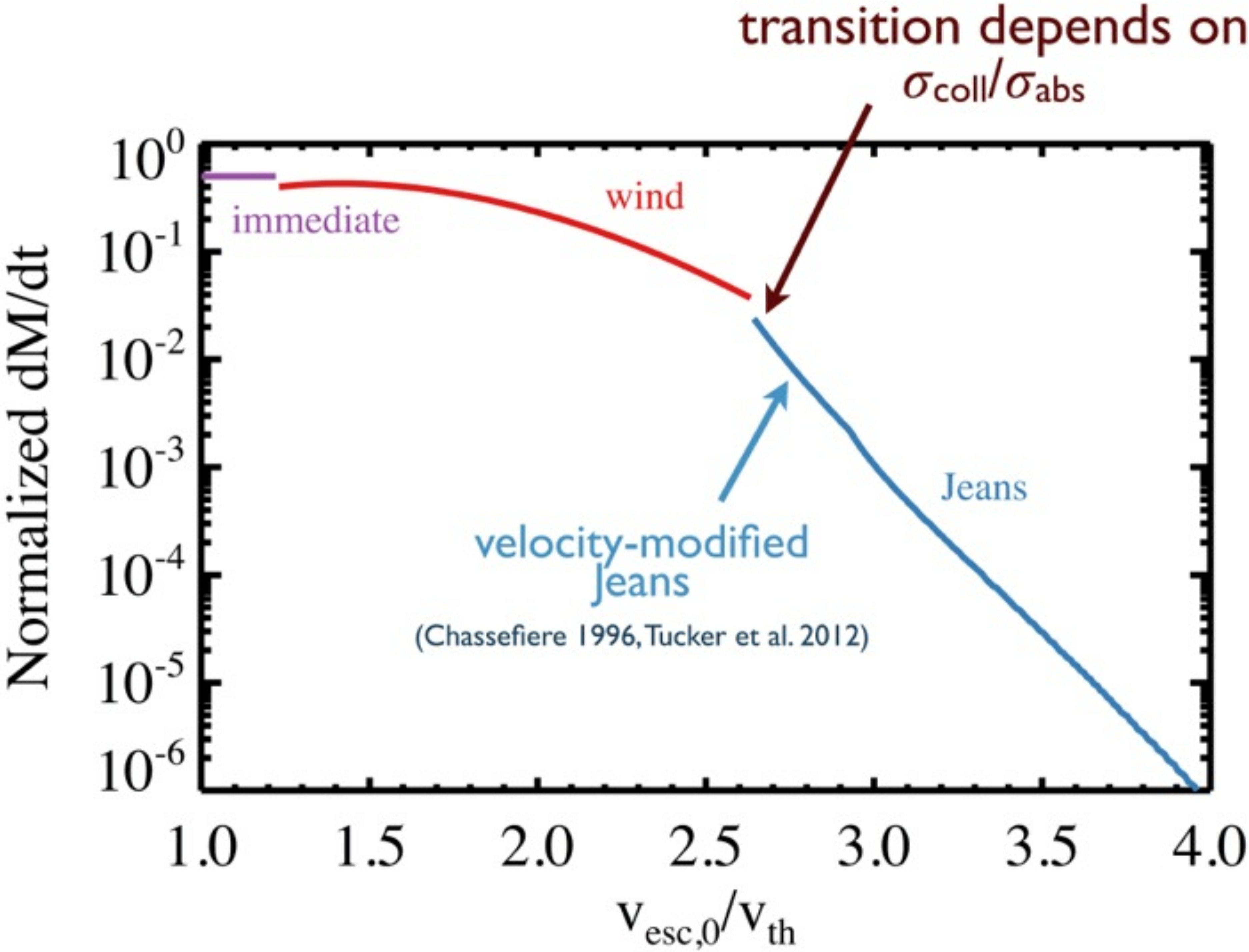
$$\mu \sim \text{Uniform}(-3.5, -1)$$

$$log(\sigma^2) \sim \text{Uniform}(-4, 2)$$

$$\gamma \sim \text{Uniform}(1, 4)$$

$$-(\alpha+1) \sim \text{Beta}(-(\alpha+1)|2, 2)$$

Wolfgang & Lopez (2014)



Courtesy of Ruth Murray-Clay