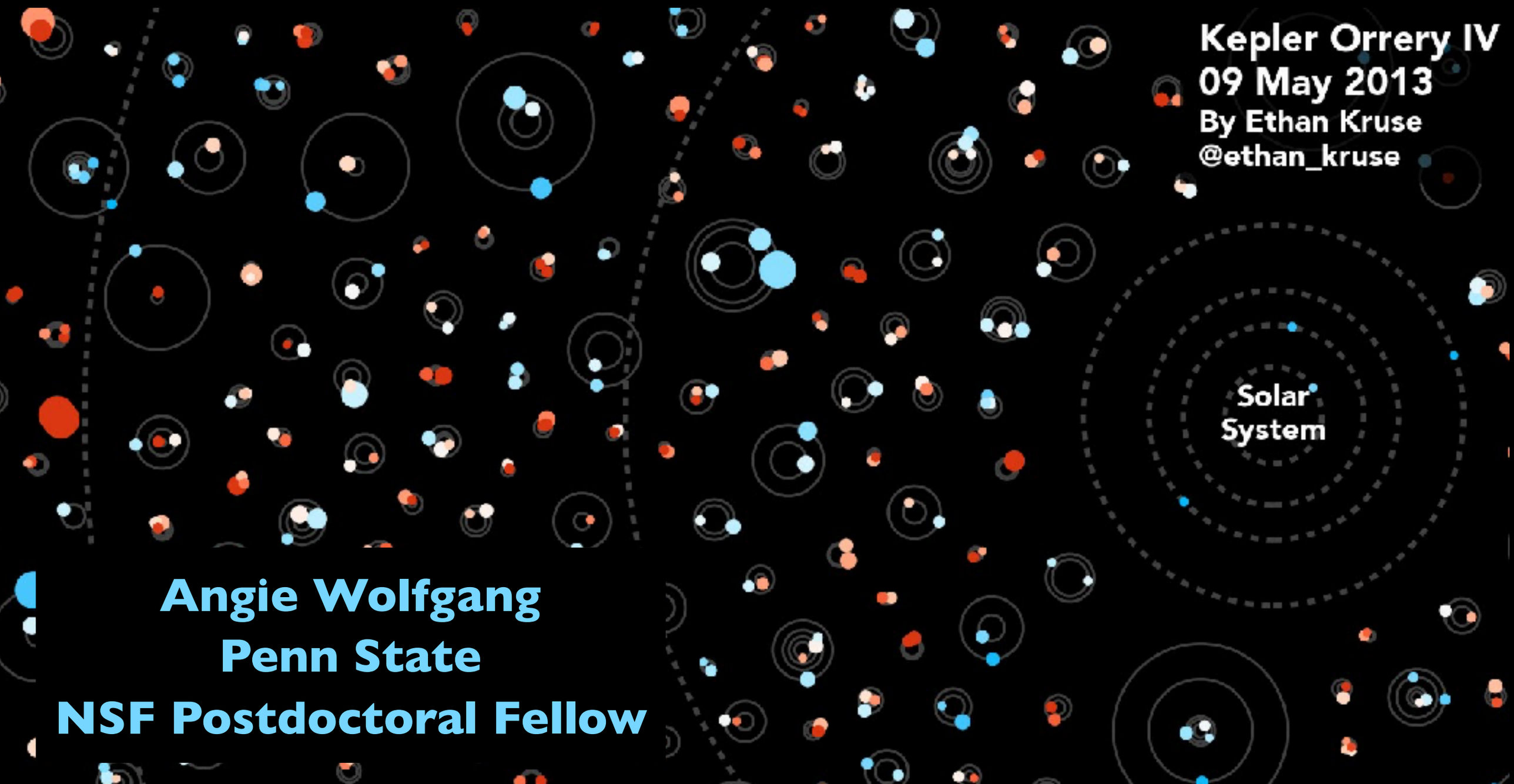
Exoplanetary System Architectures



Angie Wolfgang
Penn State
NSF Postdoctoral Fellow

Architectures: A Rich Problem

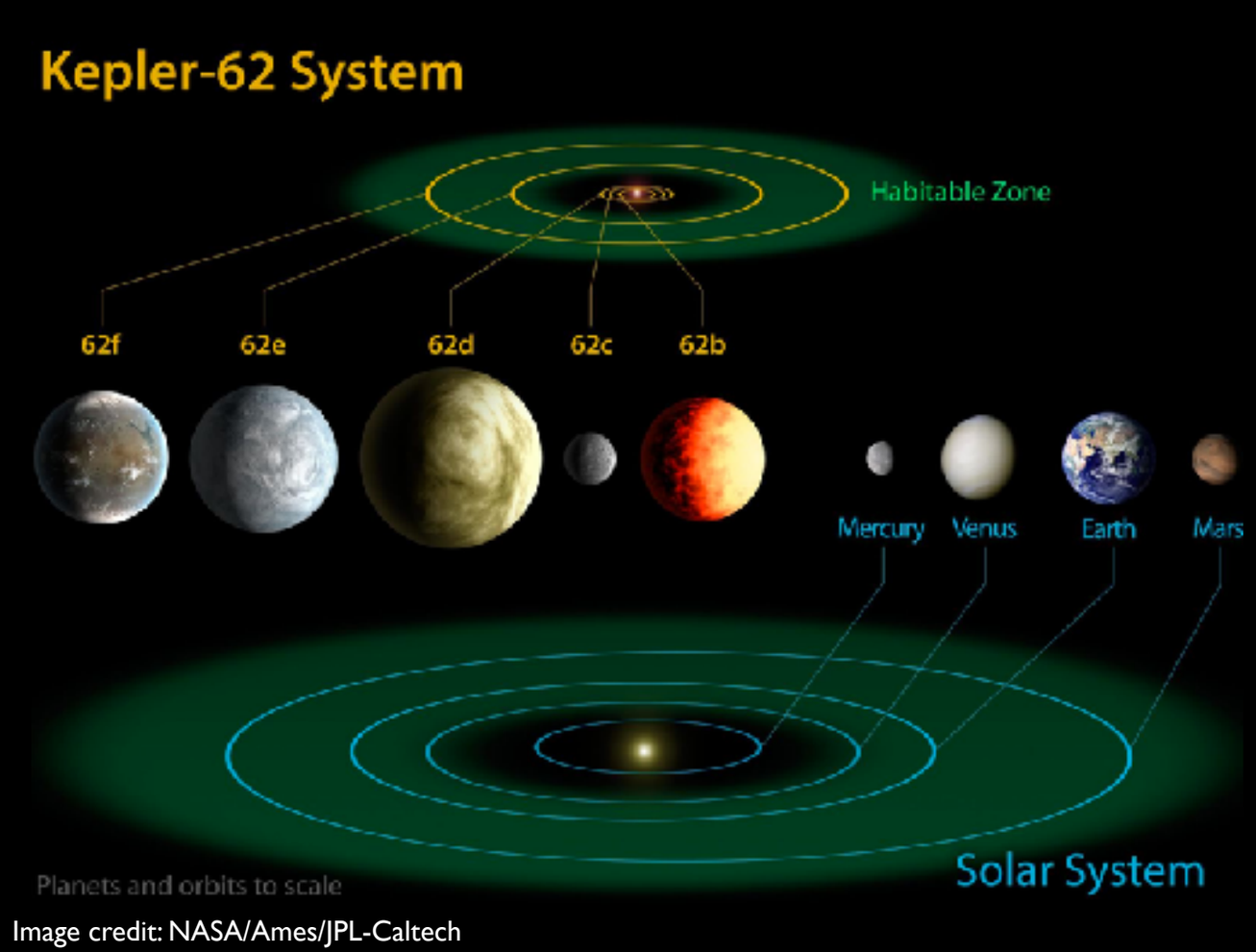
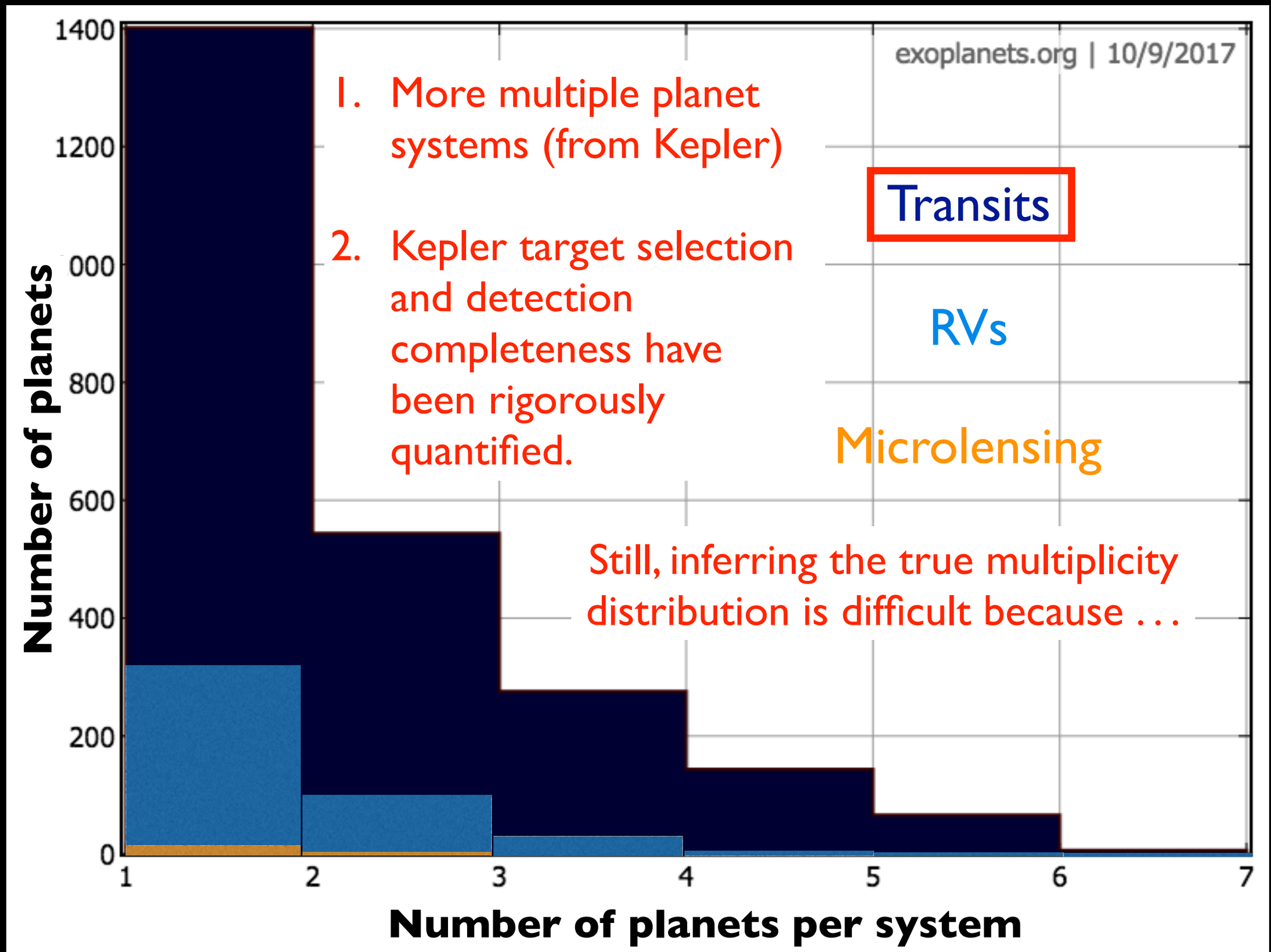


Image credit: NASA/Ames/JPL-Caltech

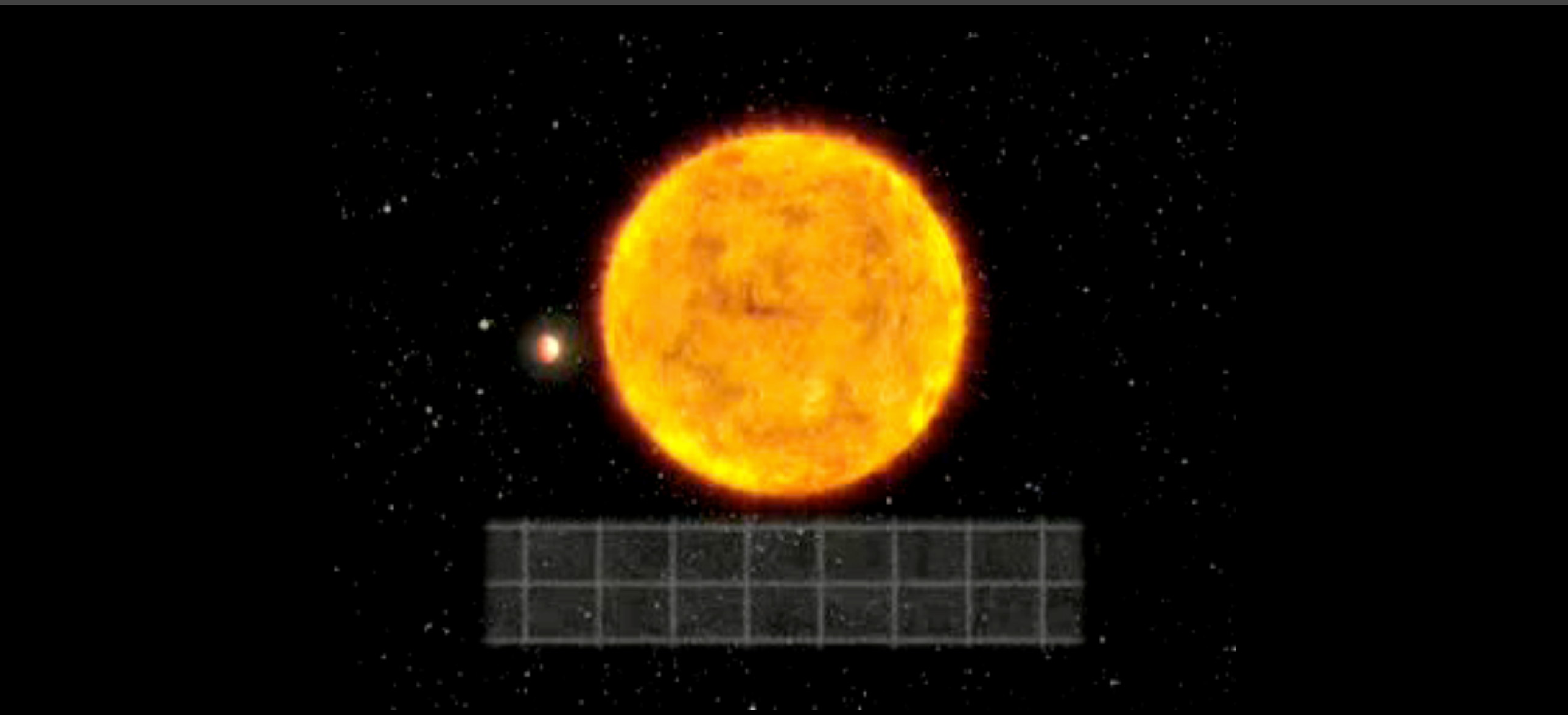
- Multiplicity: number of planets per system
- Spacing: periods & period ratios
- Alignment: inclination differences between planets
- Orbital eccentricities
- Stellar spin & orbital alignment

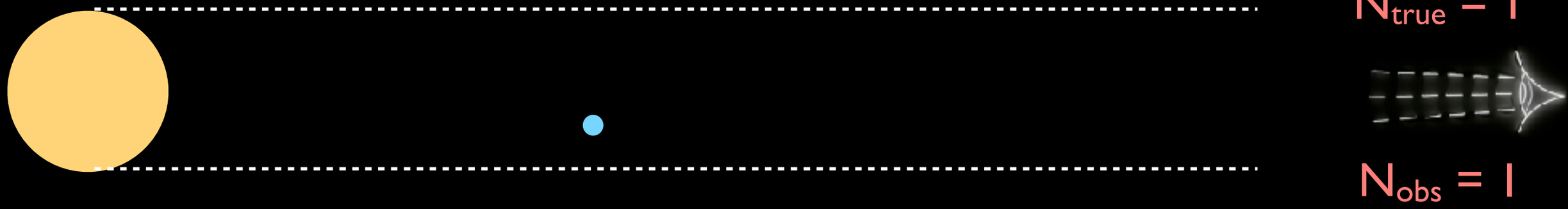
- Dynamics: 3-D orbits with argument of periapse and longitude of ascending node, and changes in all orbital elements
- Orbital elements as a function of host star properties
- Planet size/mass/composition as a function of orbital elements

Observed Multiplicity Distribution



Detections Depend on Inclination!





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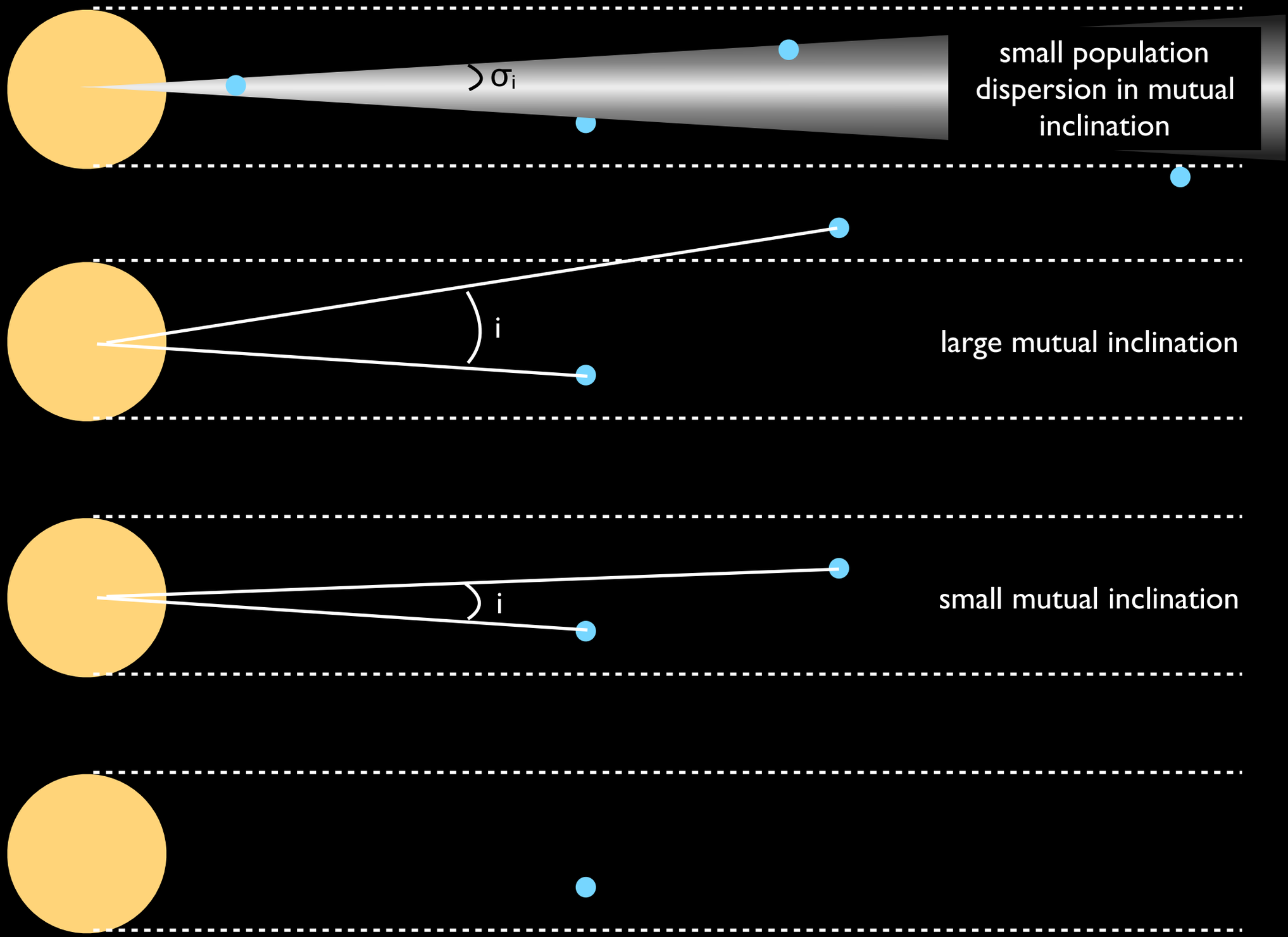


$N_{true} = 4$

$N_{obs} = 3$

$N_{true} = 2$

$N_{obs} = 1$

$N_{true} = 2$

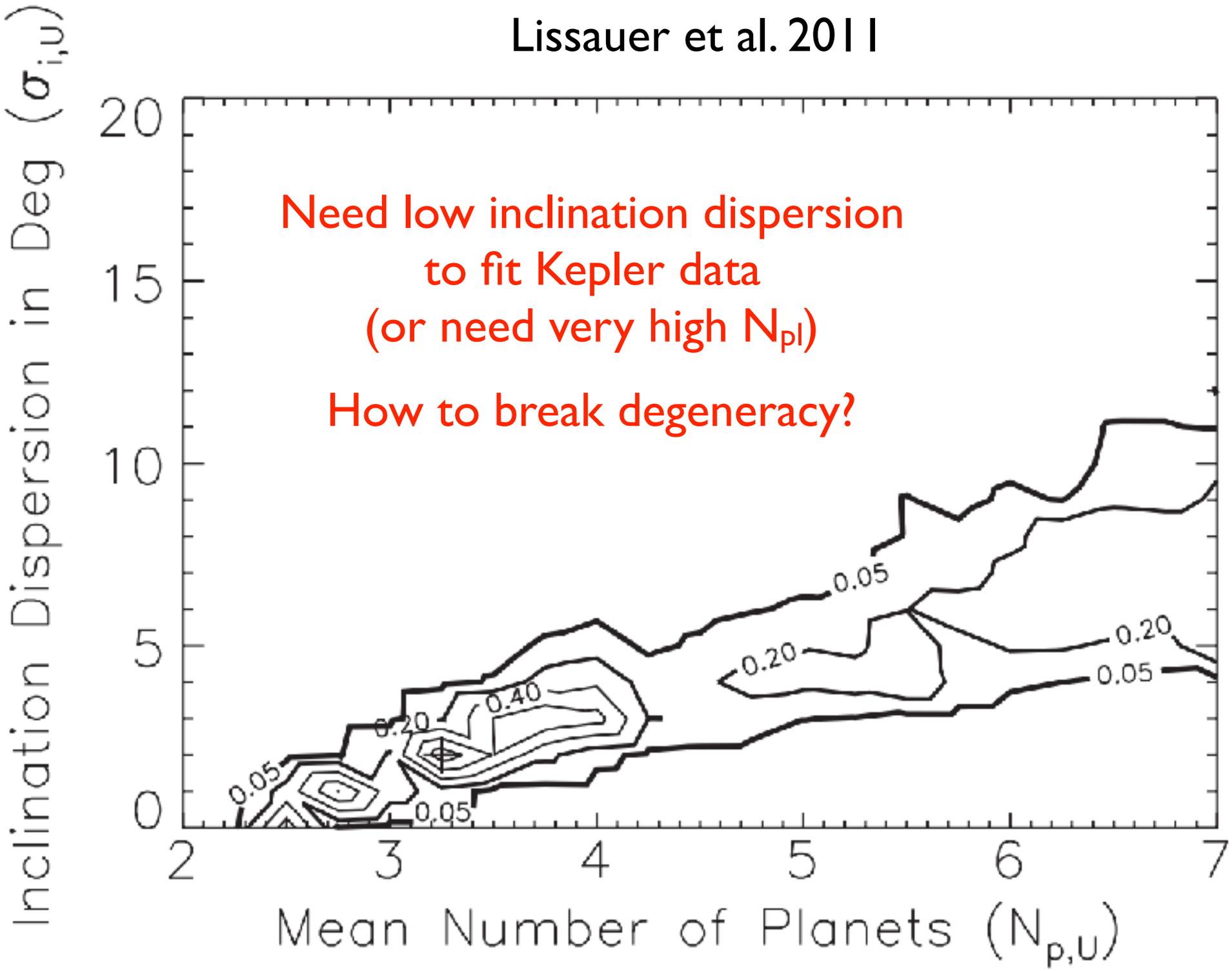
$N_{obs} = 2$

$N_{true} = 1$

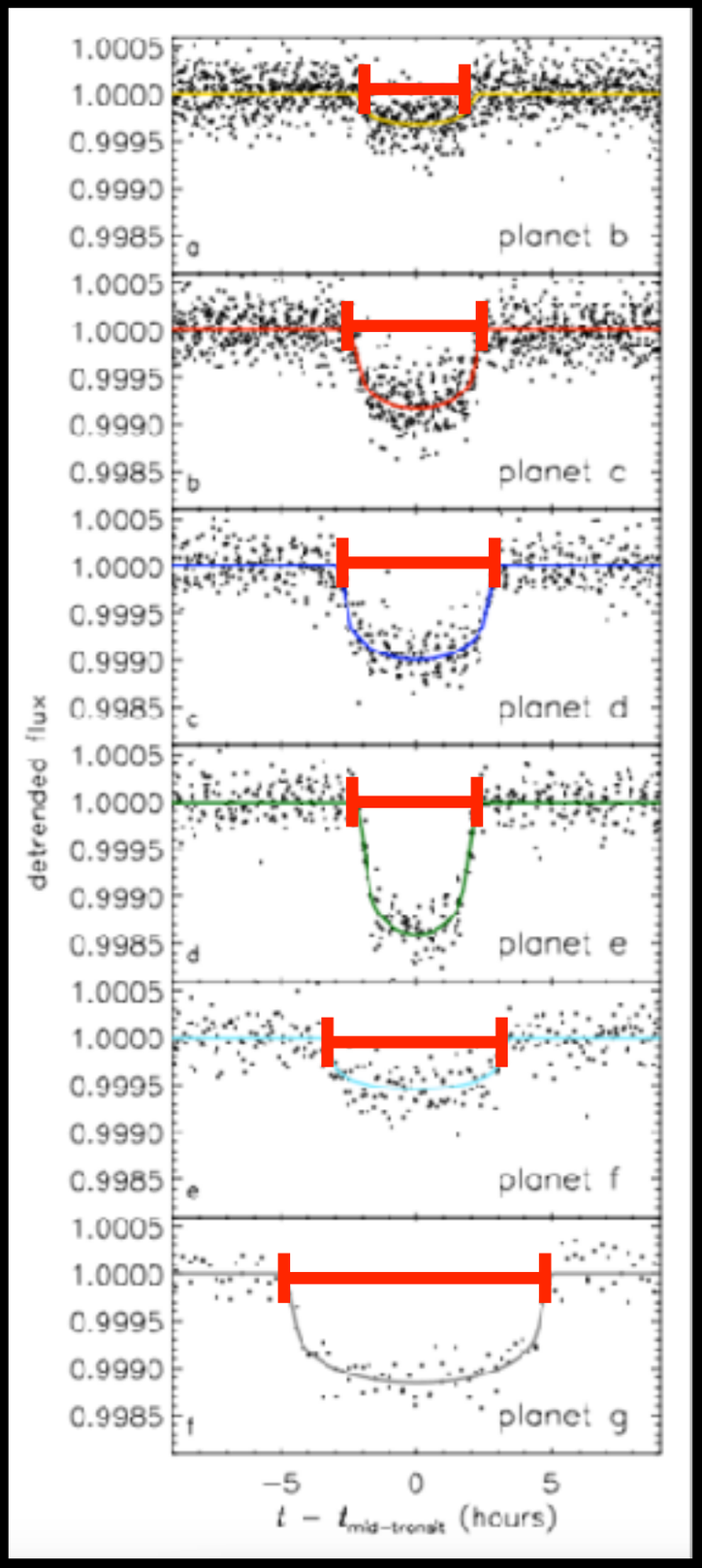
$N_{obs} = 1$

Multiplicity Depends on Inclination!

Lissauer et al. 2011



Inclinations from transit durations



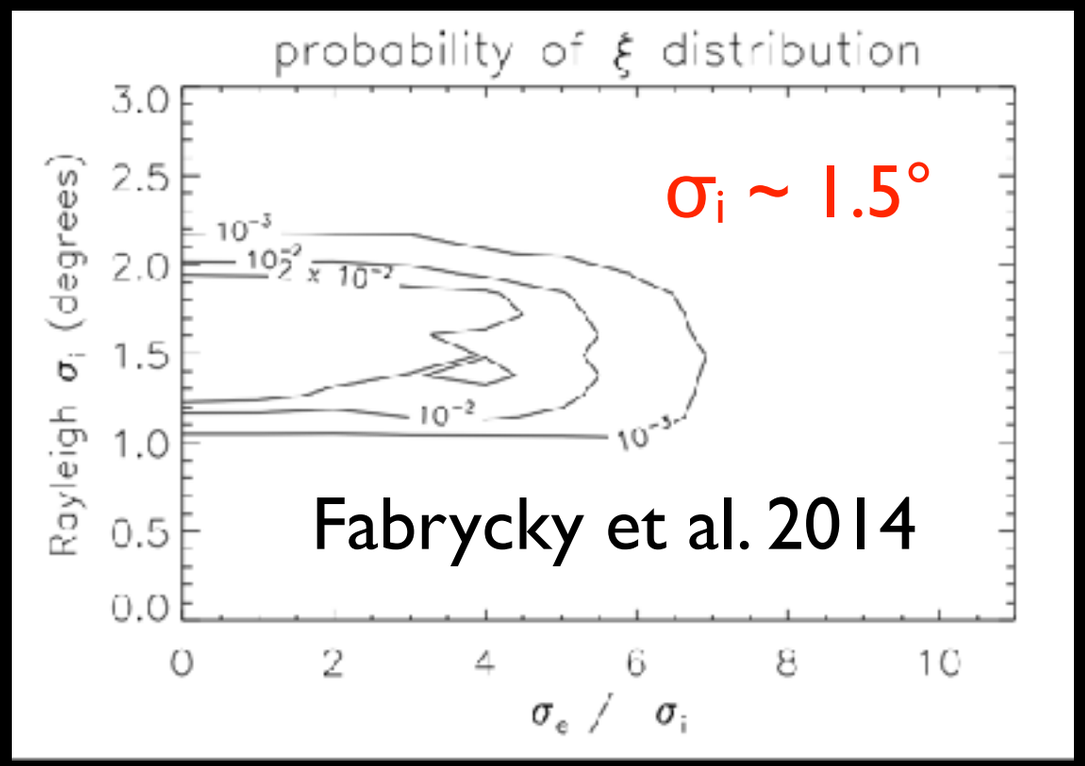
innermost planet
(P = 10.3 days)

$$T_{\rm dur} = \frac{P}{\pi} \arcsin\left(\frac{R_\star}{a} \left[\frac{\left(1+\frac{R_p}{R_\star}\right)^2 - \left(\frac{a}{R_\star}\cos i\right)^2}{1-\cos^2 i} \right]^{1/2} \right)$$

transit duration
increases with period

$$\xi \equiv \frac{T_{\rm dur,in}/P_{\rm in}^{1/3}}{T_{\rm dur,out}/P_{\rm out}^{1/3}}$$

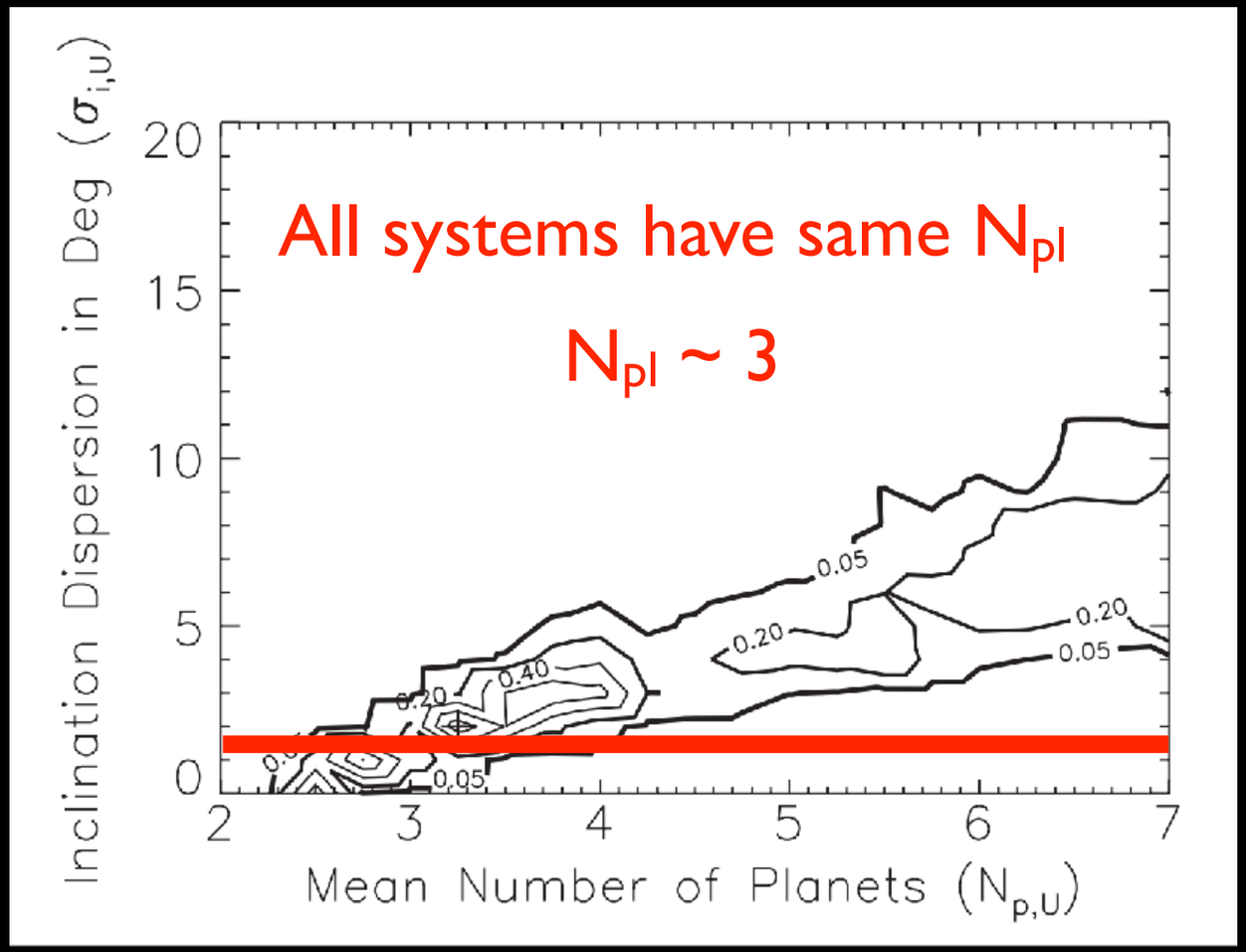
Planet e has
a higher
inclination!!
(eccentricity is a
2nd order
effect)

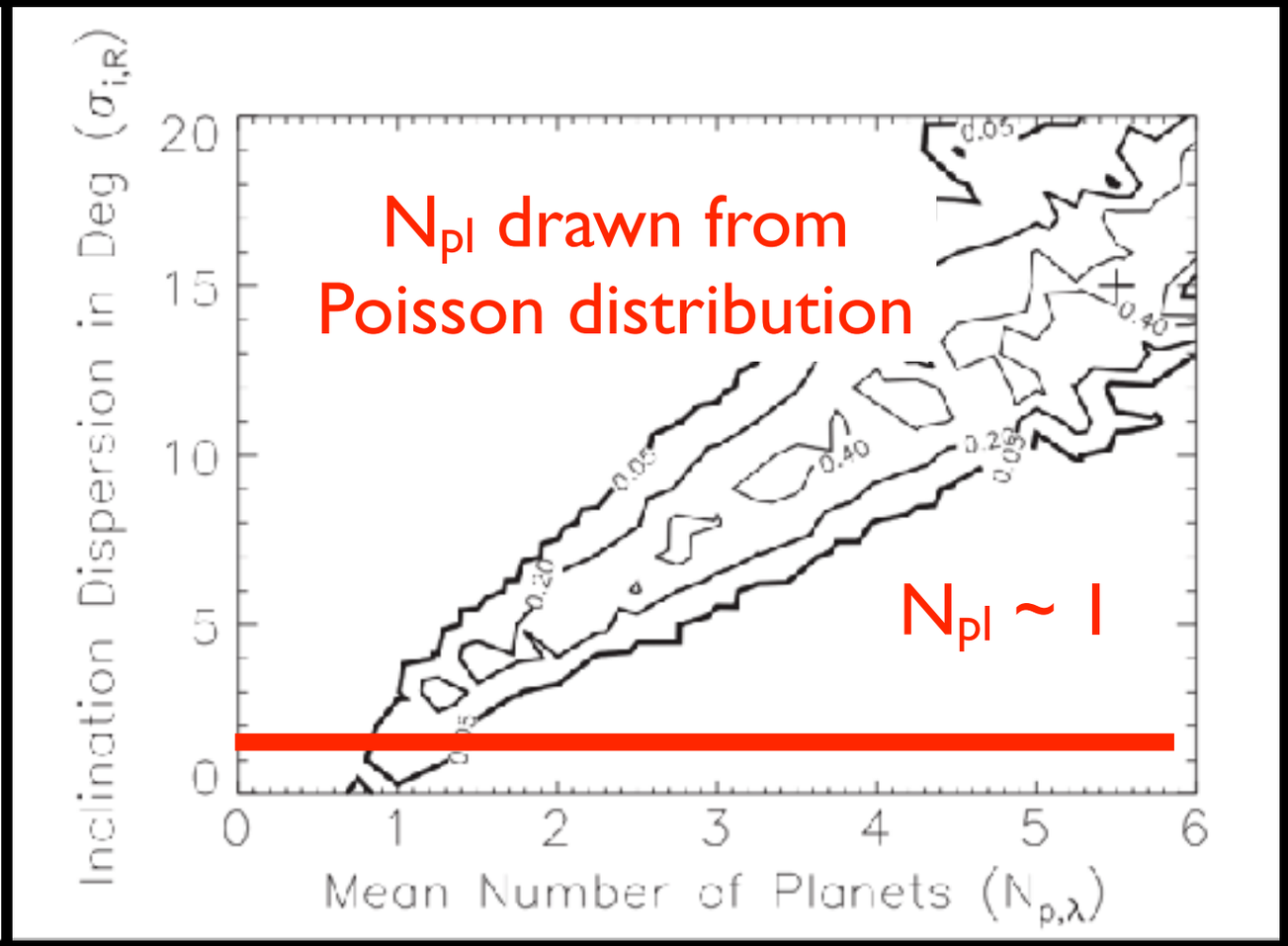


outermost planet
(P = 118 days)

Kepler-11

So, how many planets per system?





Difficult to fit observed multiplicity distribution with one parameterized true multiplicity distribution

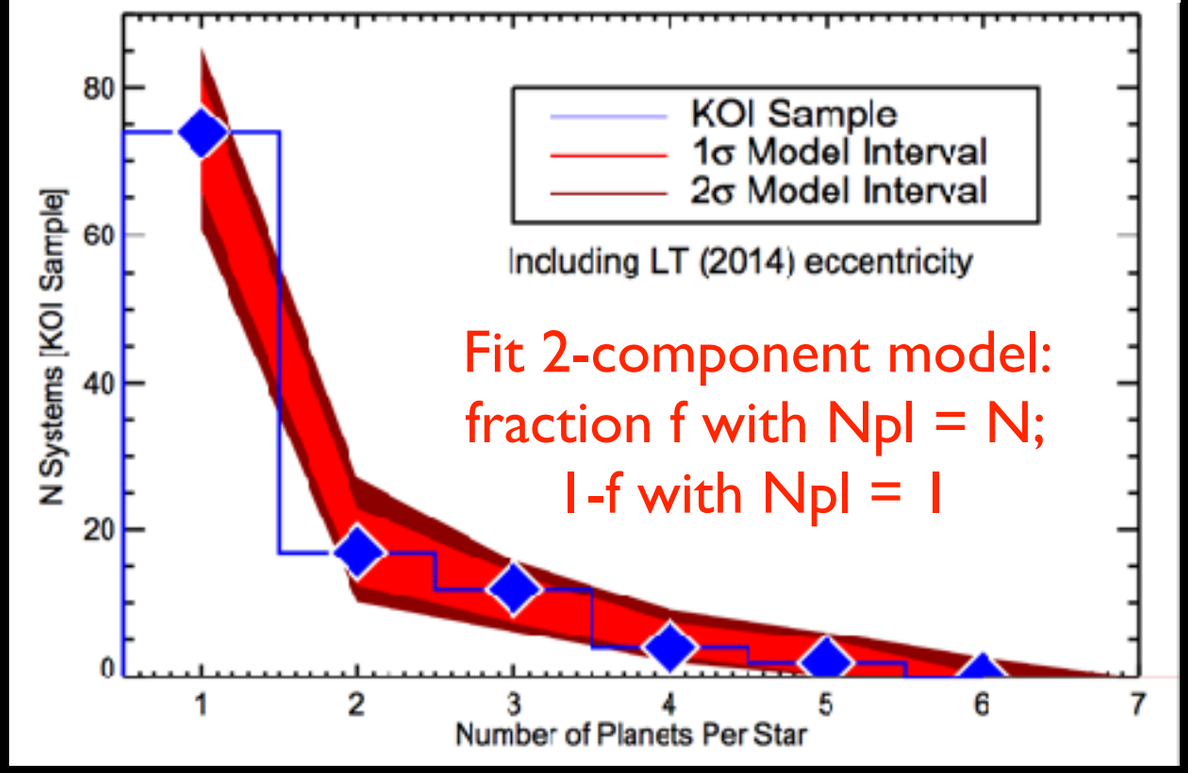
(not an issue with generalized multiplicity distributions: Tremaine & Dong, 2012)

Also: in-situ planet formation underpredicts number of 1-planet systems (Hansen & Murray, 2013)

→ the “Kepler Dichotomy”: need > 1 formation pathway!!

An Opportunity from Knowing the Star

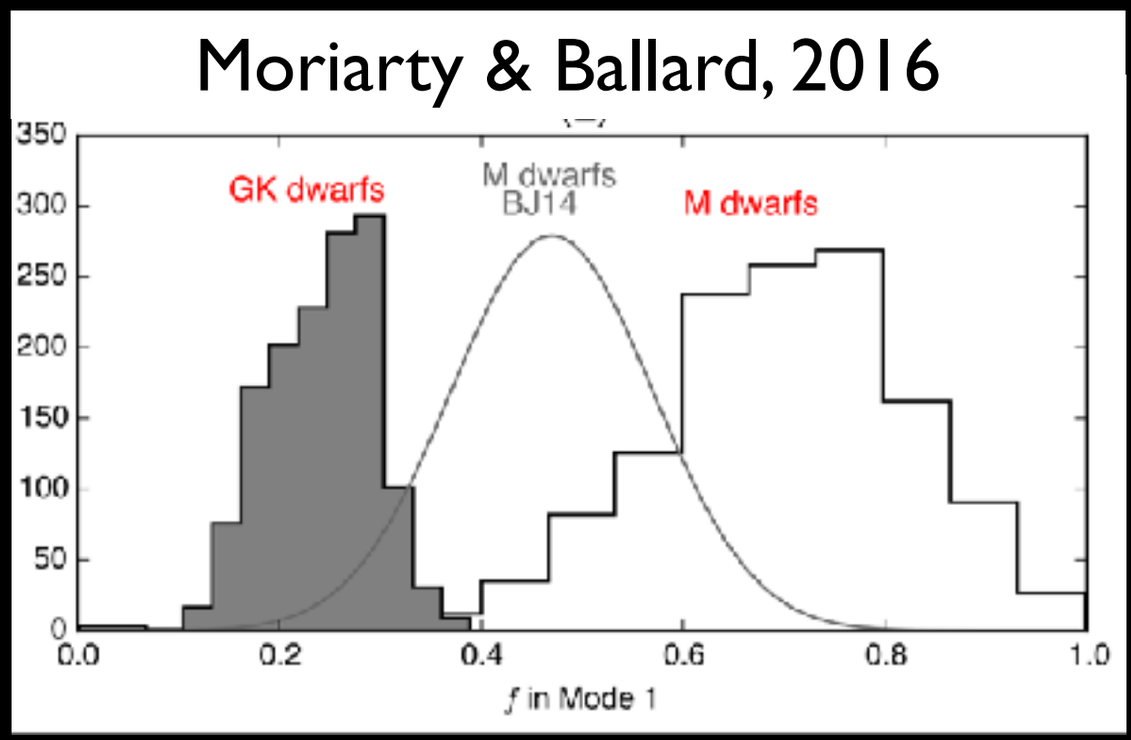
Ballard & Johnson, 2016



Kepler Dichotomy for M-dwarfs:
~ 50% of systems have intrinsically high multiplicity

Kepler Dichotomy for GK-dwarfs:
~ 25% of systems have intrinsically high multiplicity

Moriarty & Ballard, 2016



Architectures: A Rich Problem

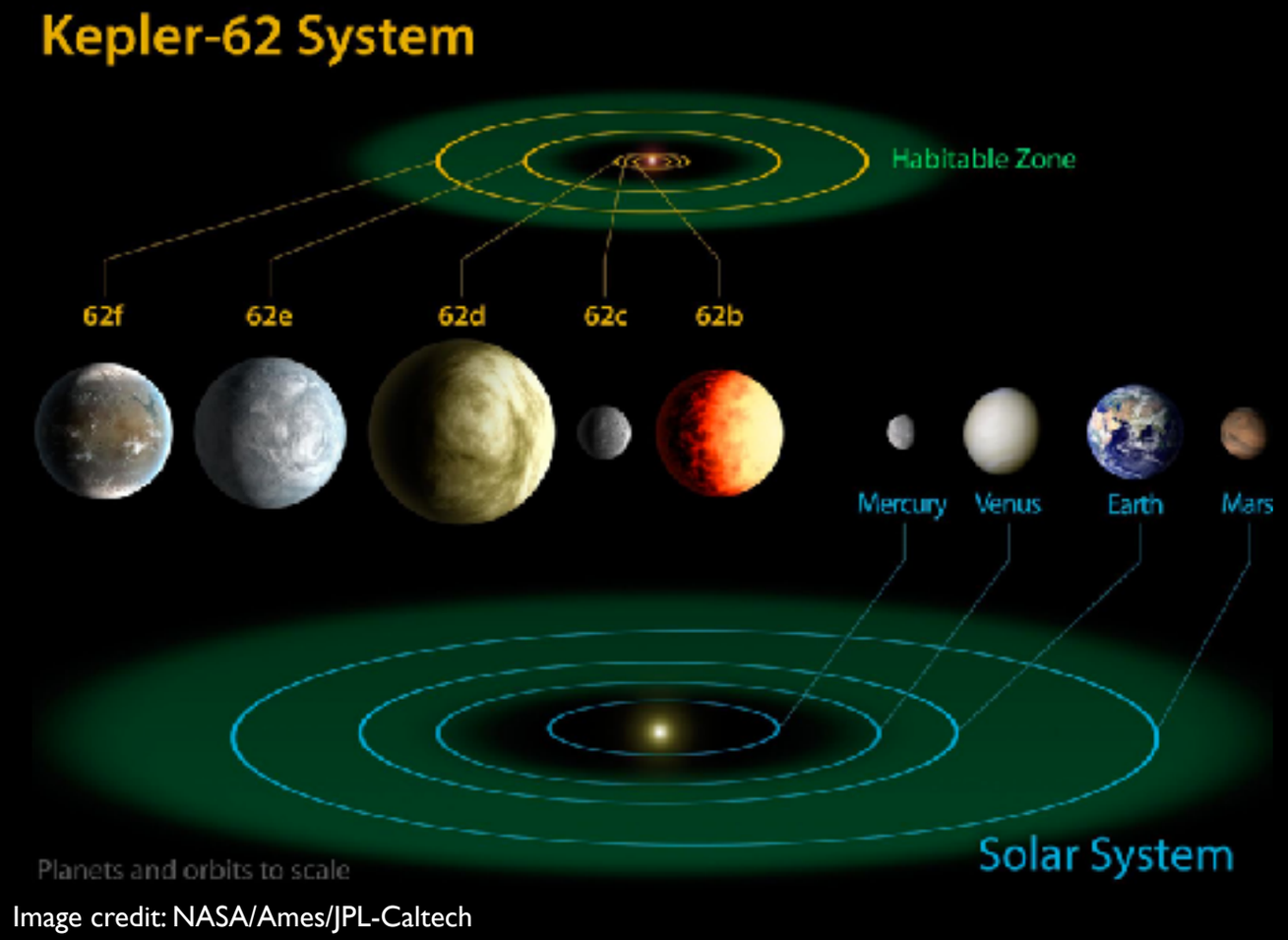


Image credit: NASA/Ames/JPL-Caltech

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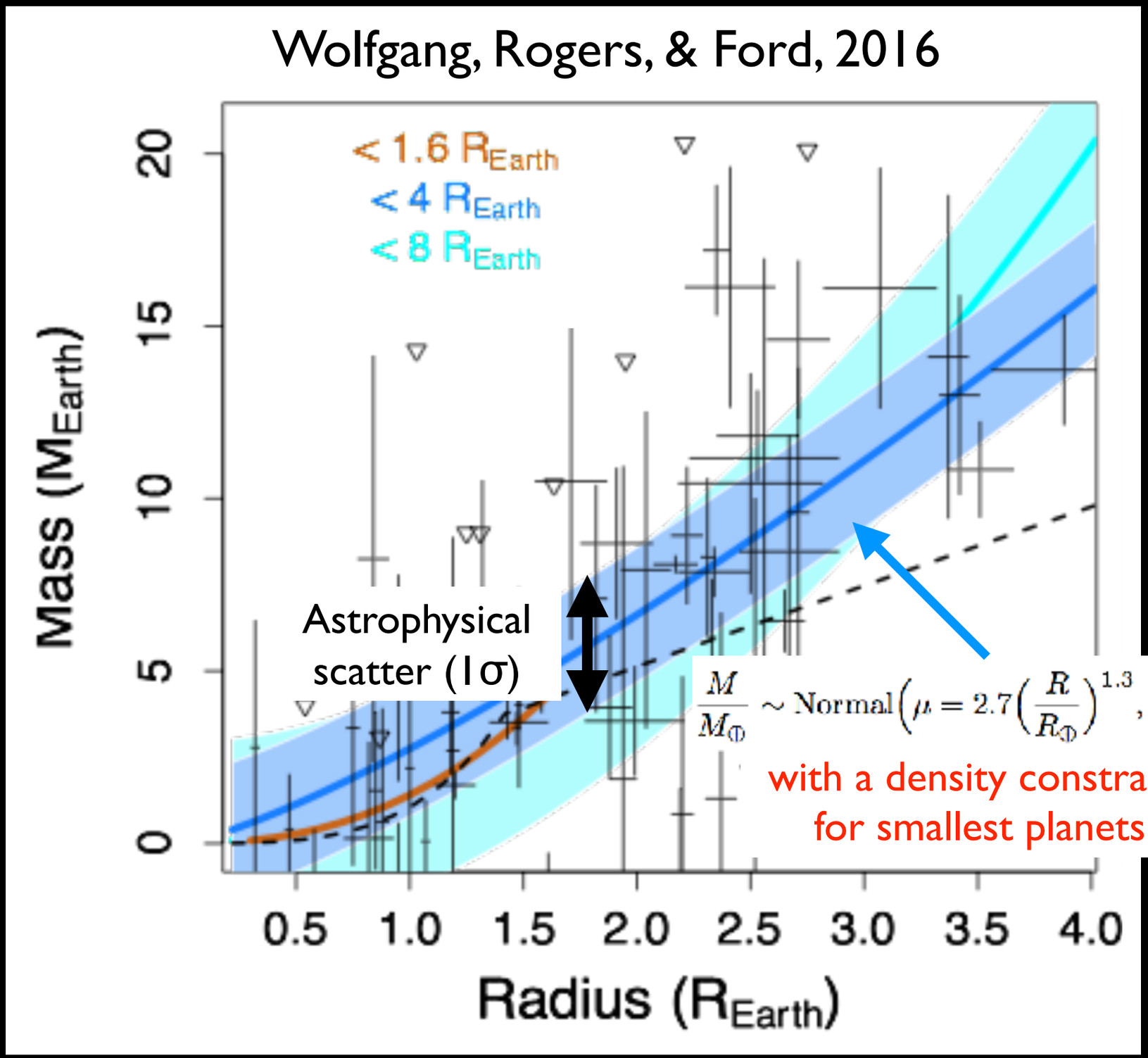
Probabilistic M-R Relation

Wolfgang, Rogers, & Ford, 2016



Allows for a distribution of masses at a given radius as is motivated by observations and theory

Can distinguish between scatter due to measurement uncertainty and astrophysical scatter in the planet population

Is an empirical description of exoplanet composition distribution.

Scatter Due to Orbital Period?

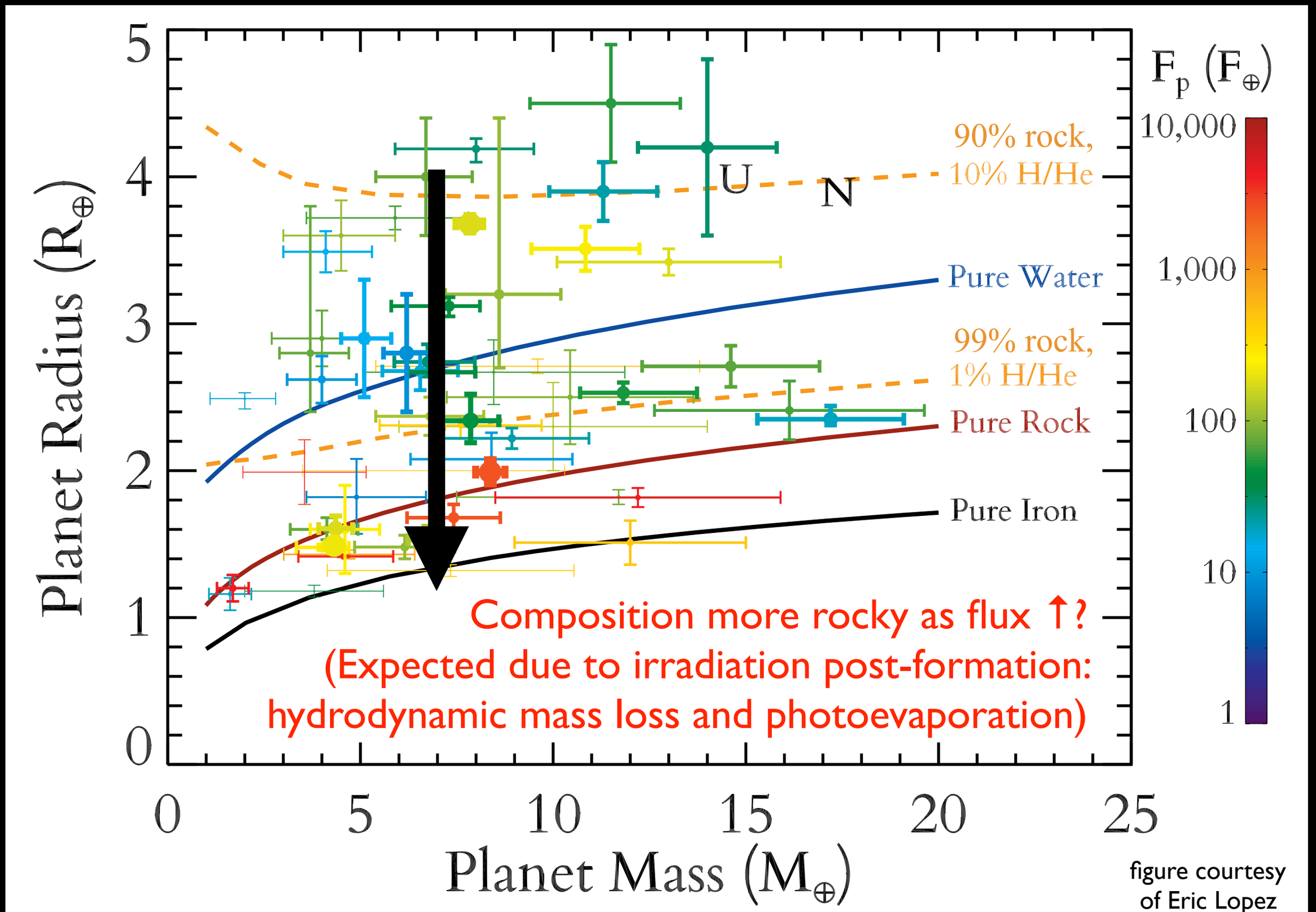
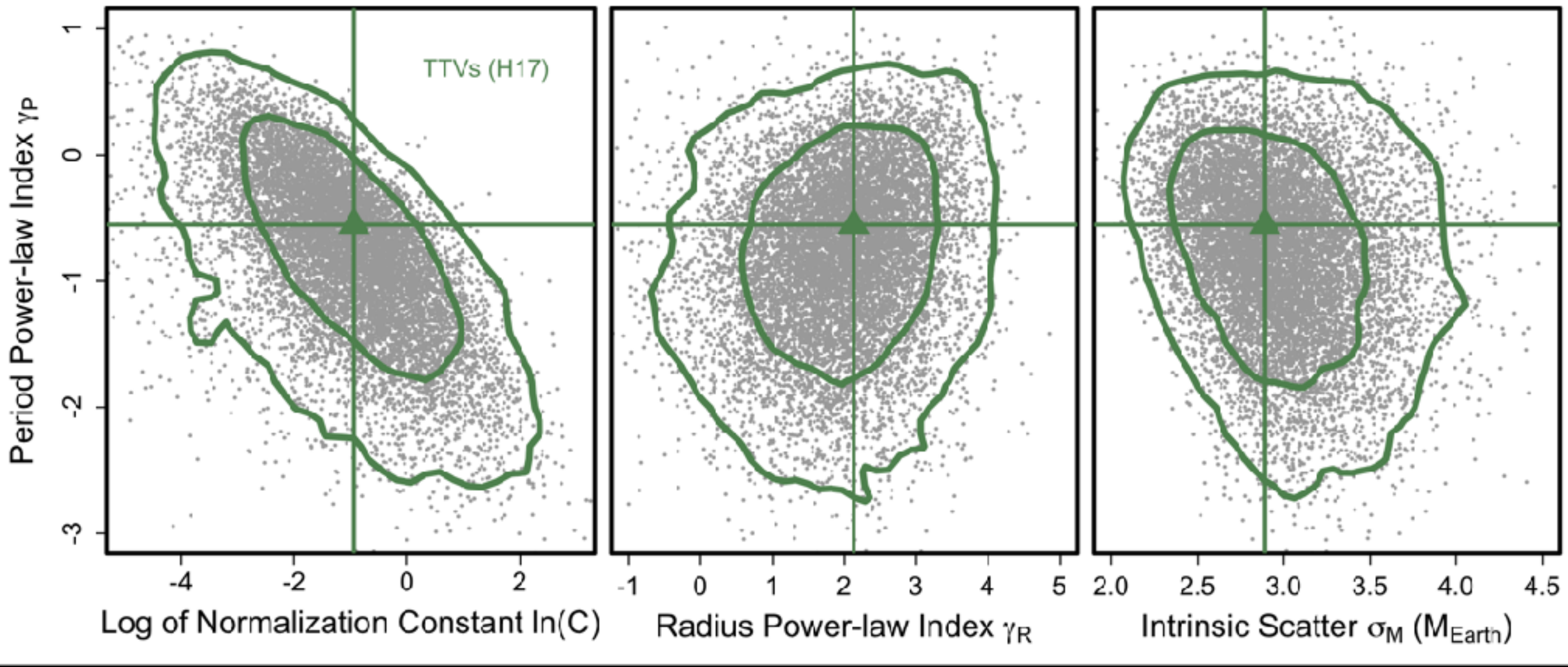


figure courtesy of Eric Lopez

Allow a Period Dependence:

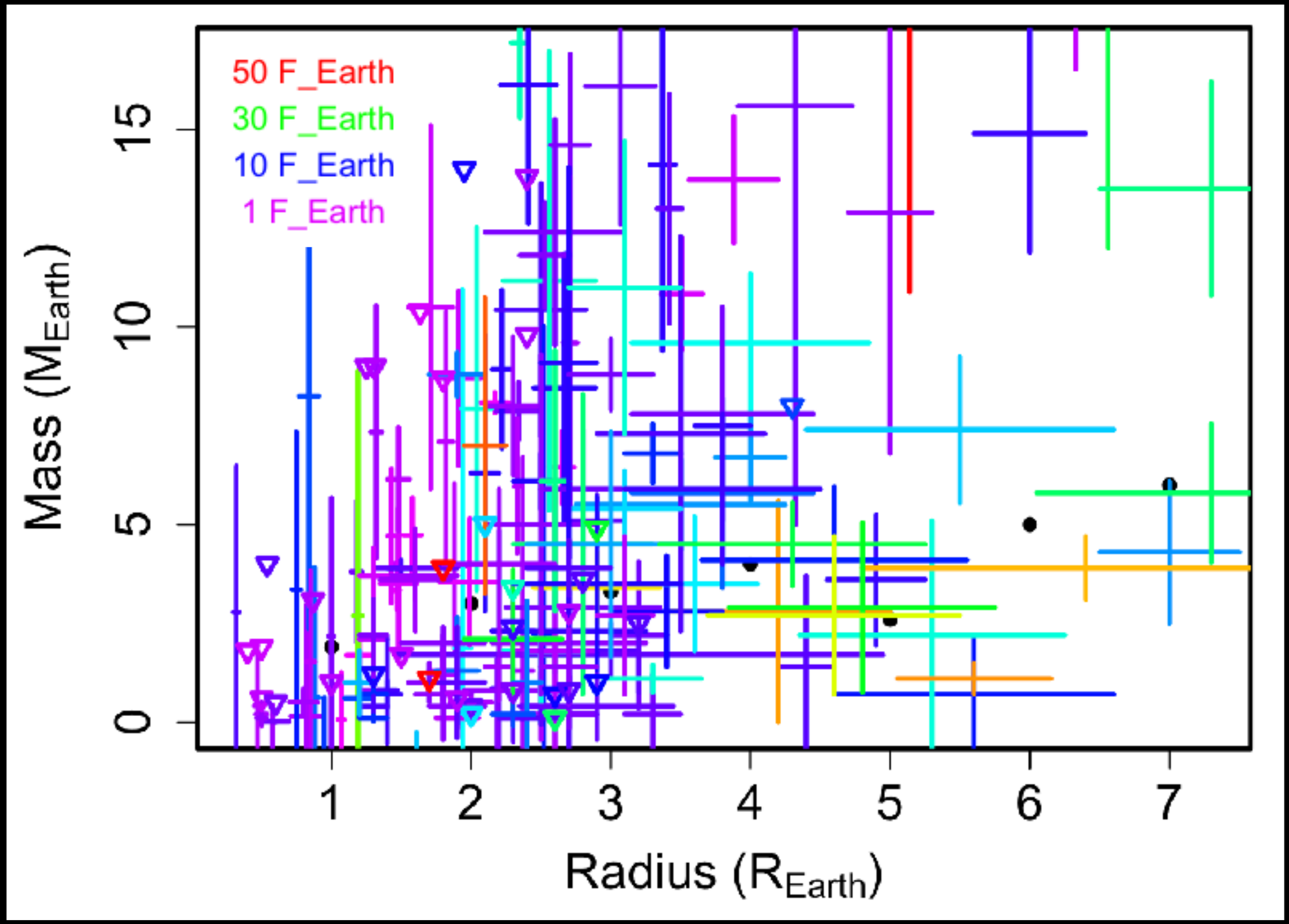
$$\frac{M}{M_\oplus} \sim \text{Normal}\left(\mu = C\left(\frac{R}{R_\oplus}\right)^{\gamma_R}\left(\frac{P}{P_\oplus}\right)^{\gamma_P}, \sigma = \sigma_M\right)$$

Wolfgang, Jontof-Hutter, & Ford, in prep.



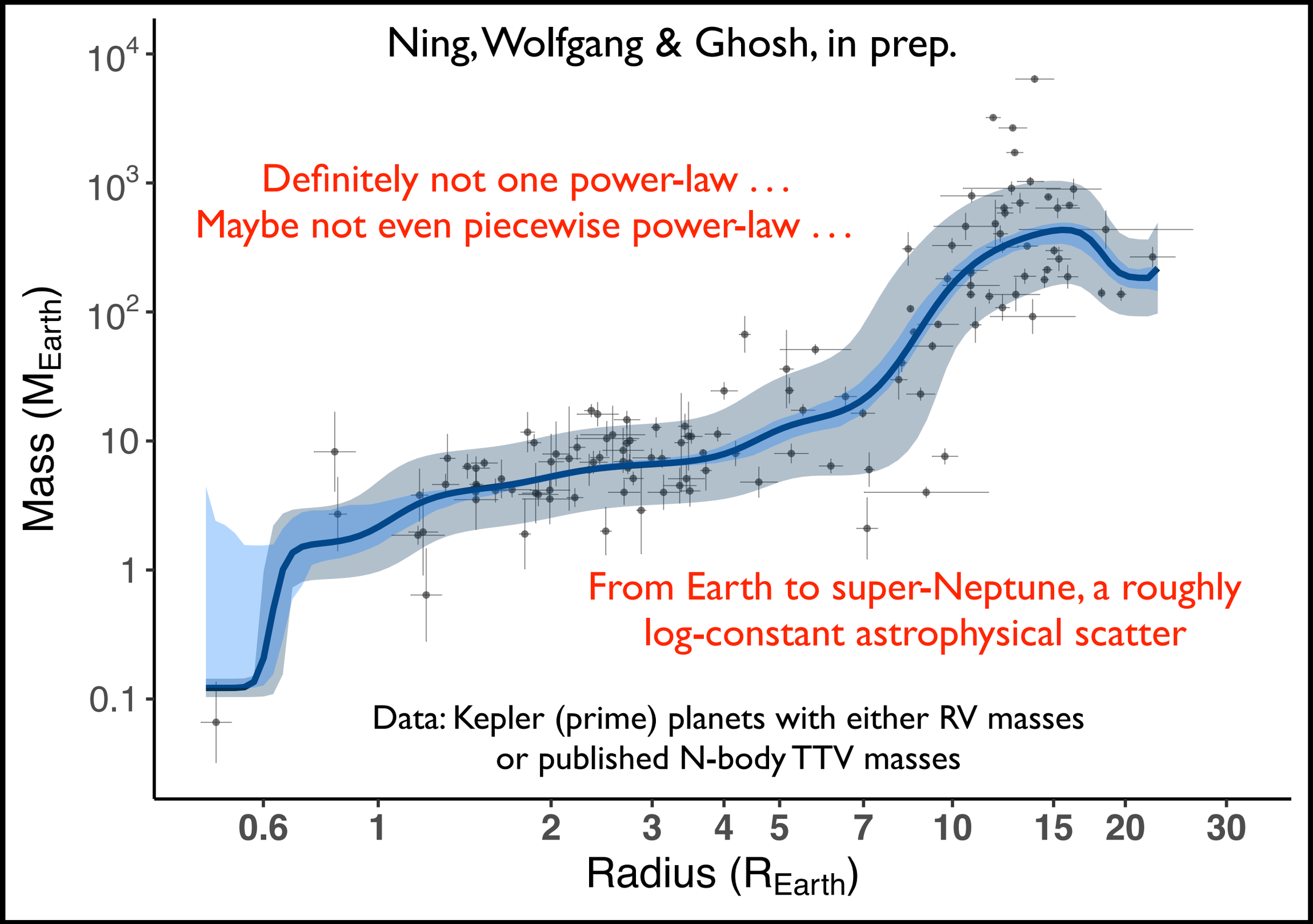
Marginally negative γ_P → decreasing average mass at longer periods; note that the astrophysical scatter is larger now …

Data Don't Suggest a Power-Law



How can we still predict planet masses with this?!

Beyond the Power Law:



Future Architectures with Full Exoplanet Census

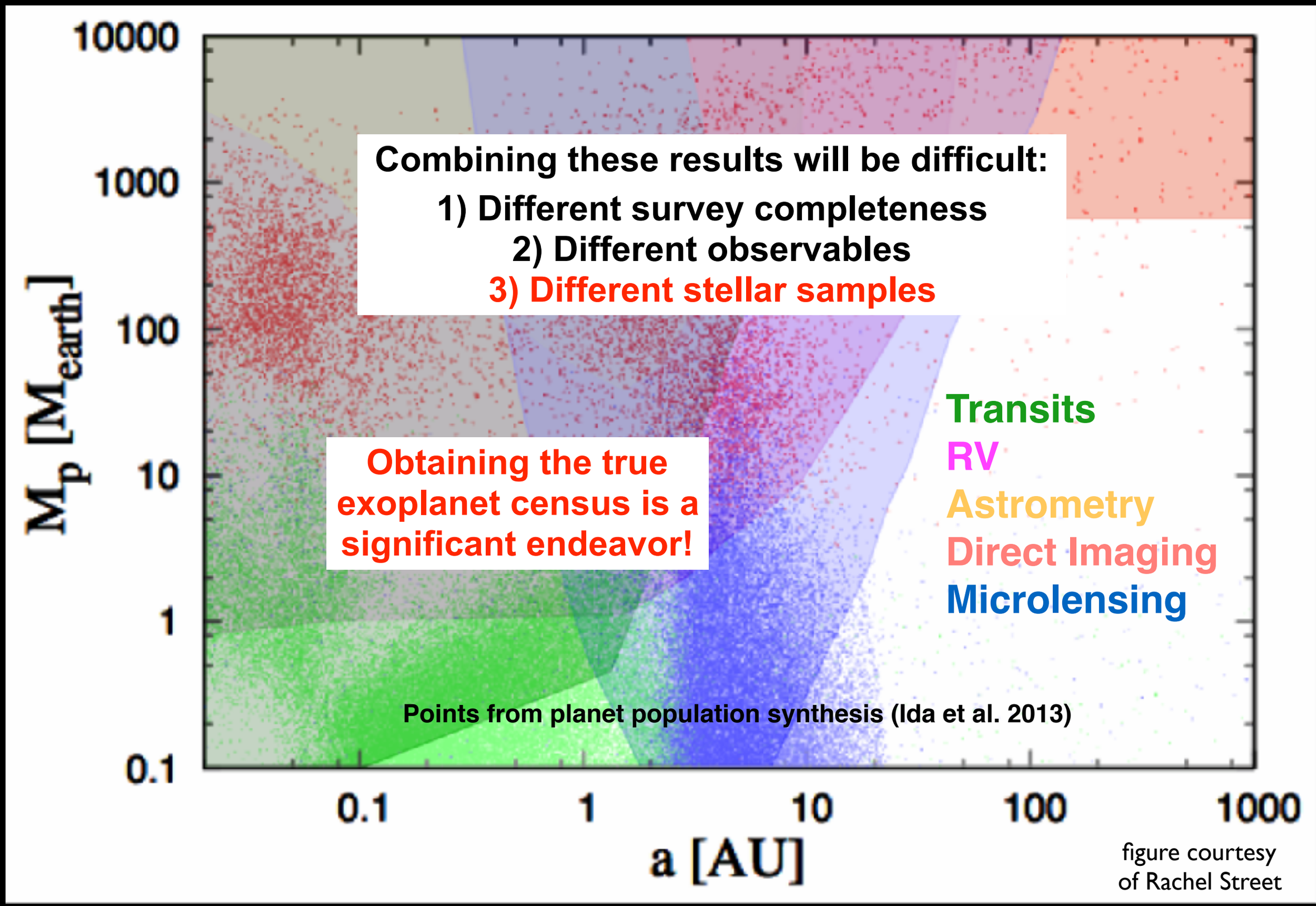


figure courtesy of Rachel Street

Summary

Exoplanetary system **architectures is a rich area of study**, with many interesting questions to pursue.

The true multiplicity distribution depends on the mutual inclination distribution. **Average number of planets per star vary from 1 to 5.**

In-situ planet population synthesis **requires at least two formation pathways** to fit the observed multiplicity distribution; the **fraction** of stars in each pathway **differs for different stellar types.**

We are just starting to probe **planet compositions** as a function of orbital architectures: **weak dependence on period.**

Obtaining a **full exoplanet census** will produce many exciting new directions for studies on system architectures.

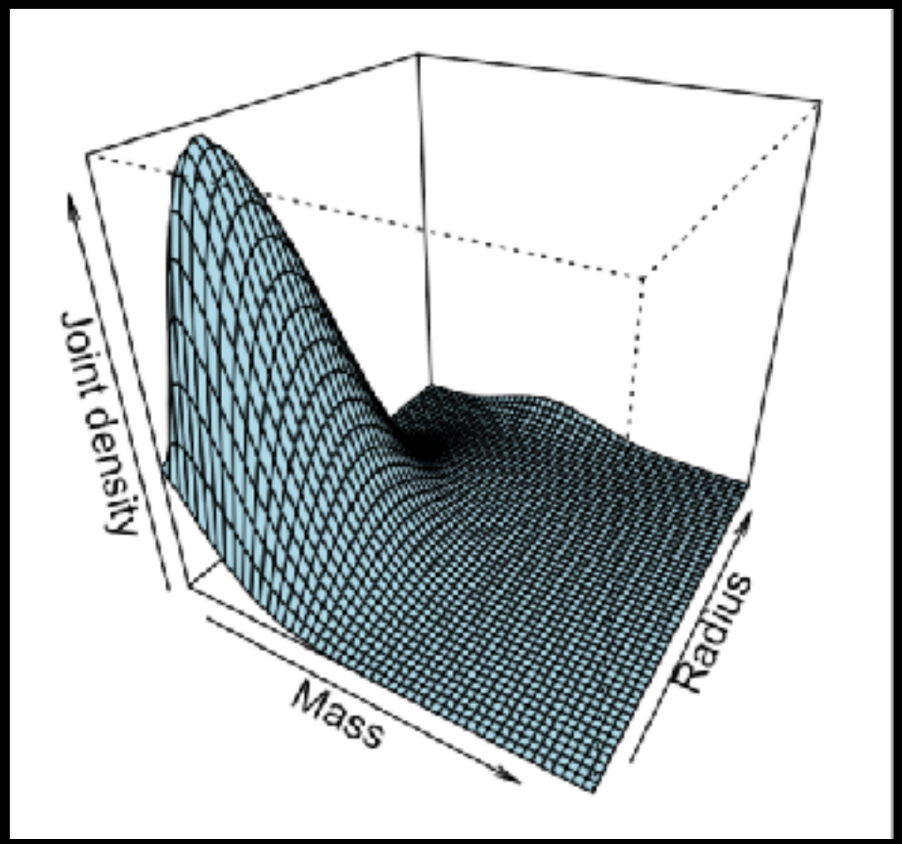
Back-up Slides

Intentionally left blank . . .

Beyond the Power-Law

Go nonparametric!! (Ning, Wolfgang & Ghosh, in prep.)

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



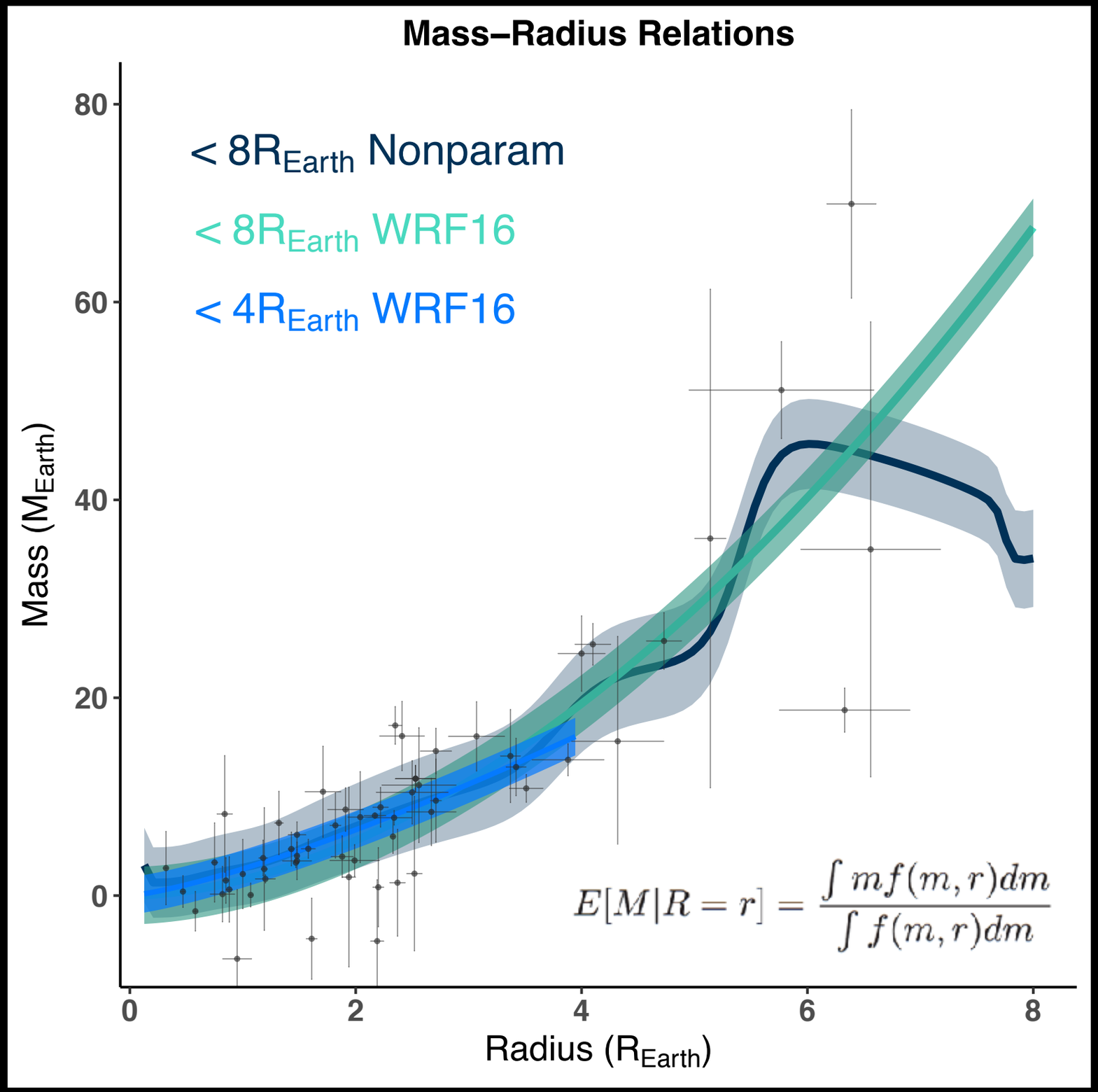
$$f(m,r|\boldsymbol{w}) = \sum_{k=1}^{N}\sum_{l=1}^{N} w_{kl}\frac{B_k(m/M^{\circ}_{\max})}{M^{\circ}_{\max}}\frac{B_l(r/R^{\circ}_{\max})}{R^{\circ}_{\max}}$$

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

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

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

Benchmark to Previous Result

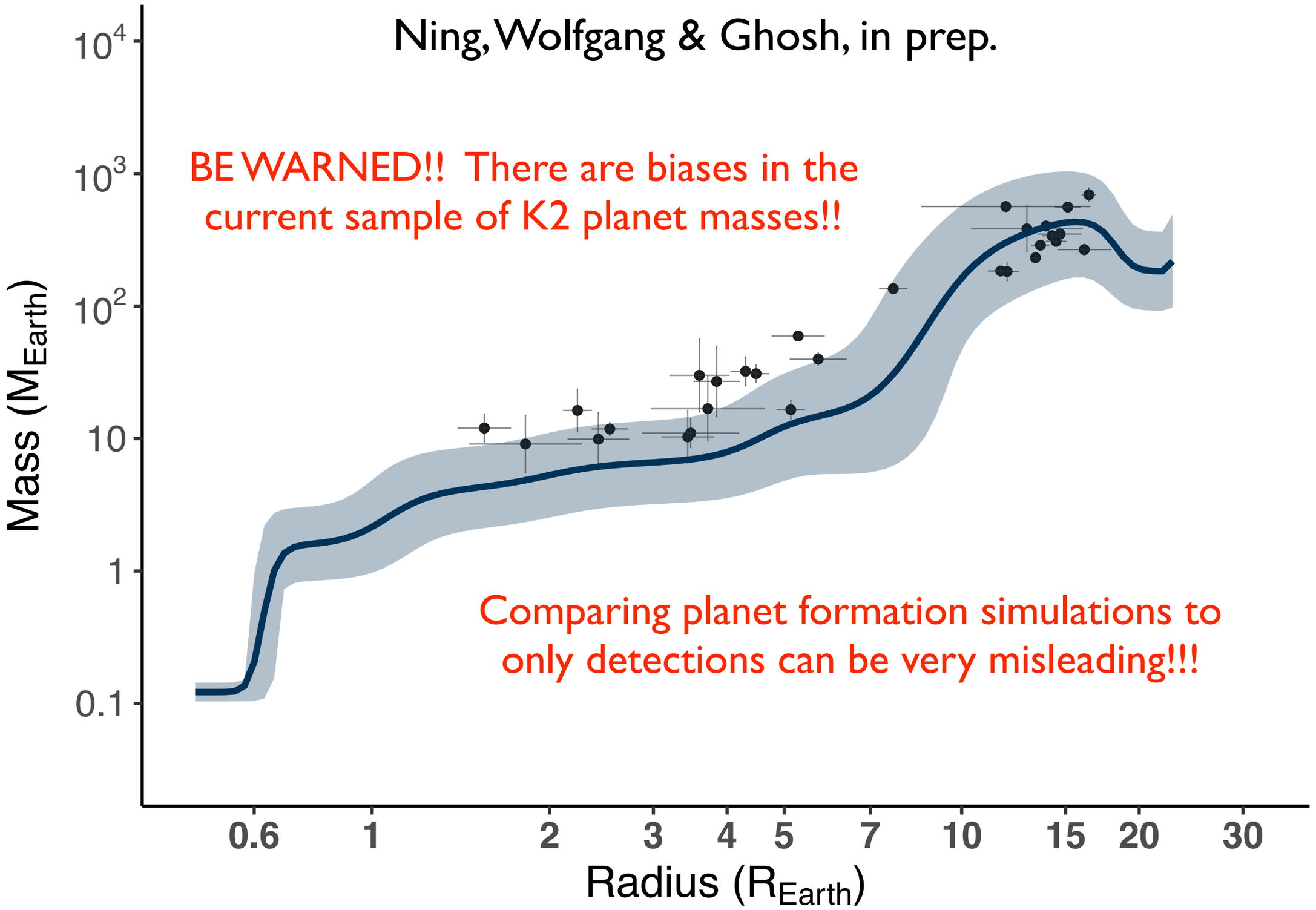


The power law was not a bad assumption for small planets, given the current data.

What about K2 (Zombie Kepler)?

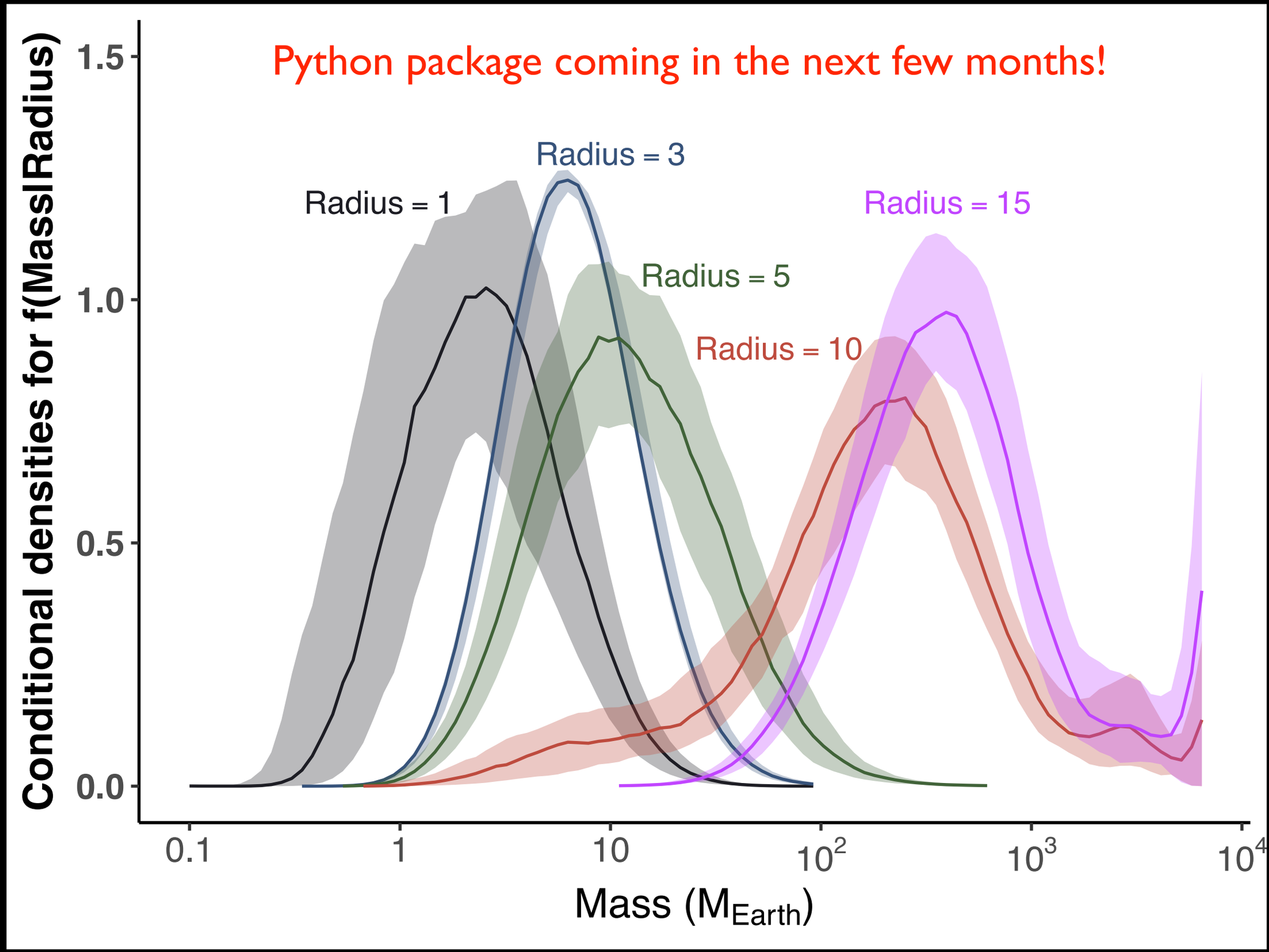
Ning, Wolfgang & Ghosh, in prep.

BE WARNED!! There are biases in the current sample of K2 planet masses!!

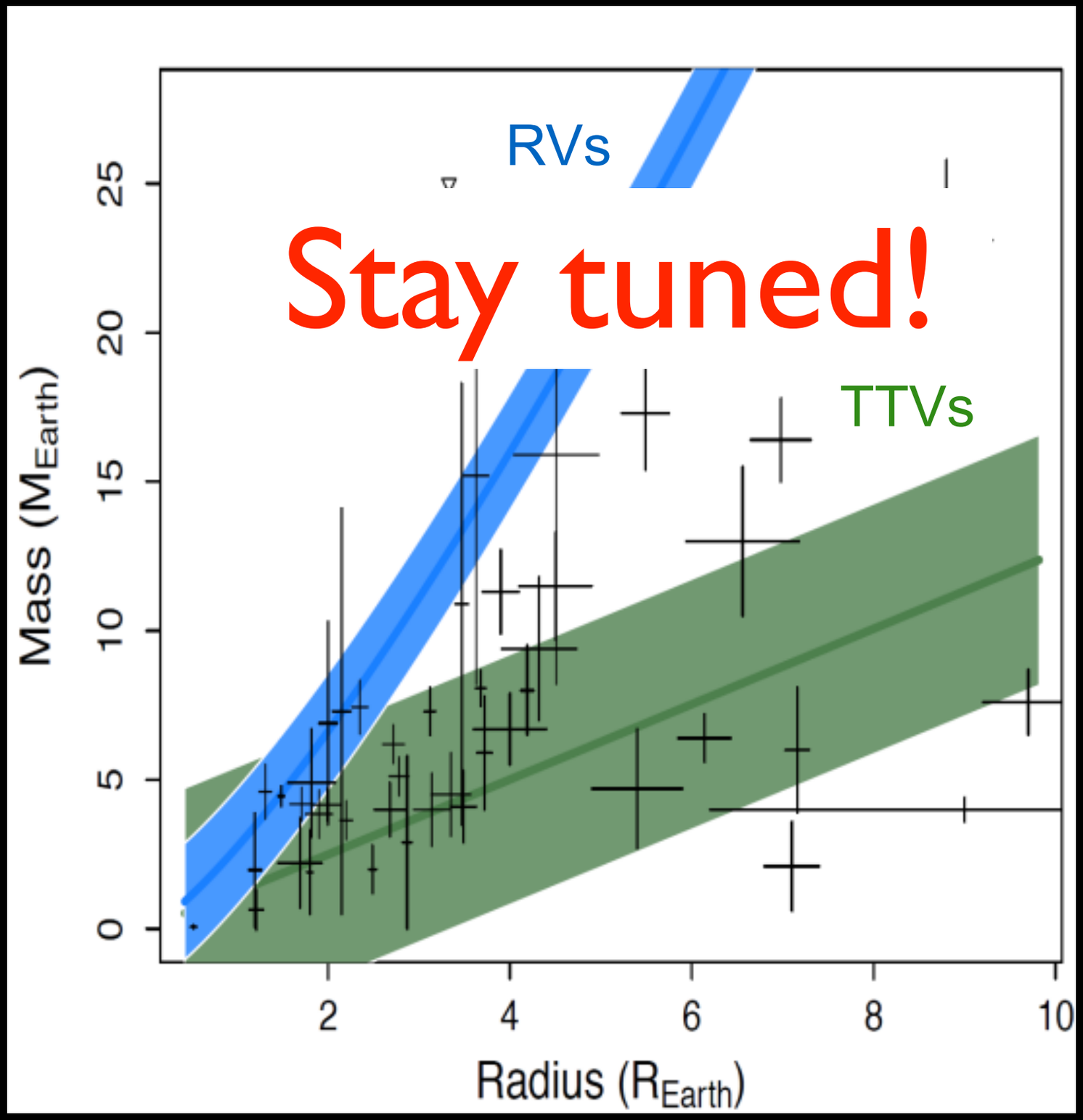


Comparing planet formation simulations to only detections can be very misleading!!!

New Predictions for Mass:



Multiple populations?



Different mass measurement methods will give you different answers!

TTV planets tend to be less dense . . .

selection effect or astrophysical?

(Easier to measure higher mass planets with RVs; easier to measure larger planets with TTVs)