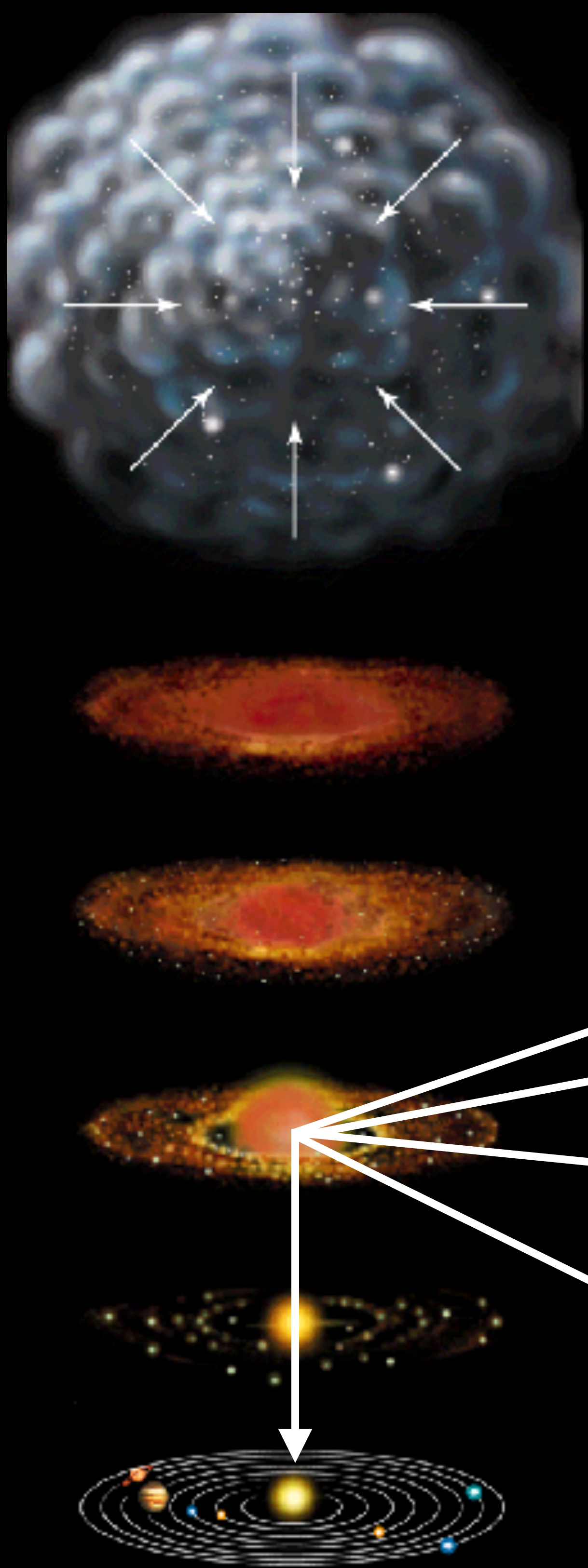
Current and Future of Exoplanet Populations

Is there really a population trend in my dataset?

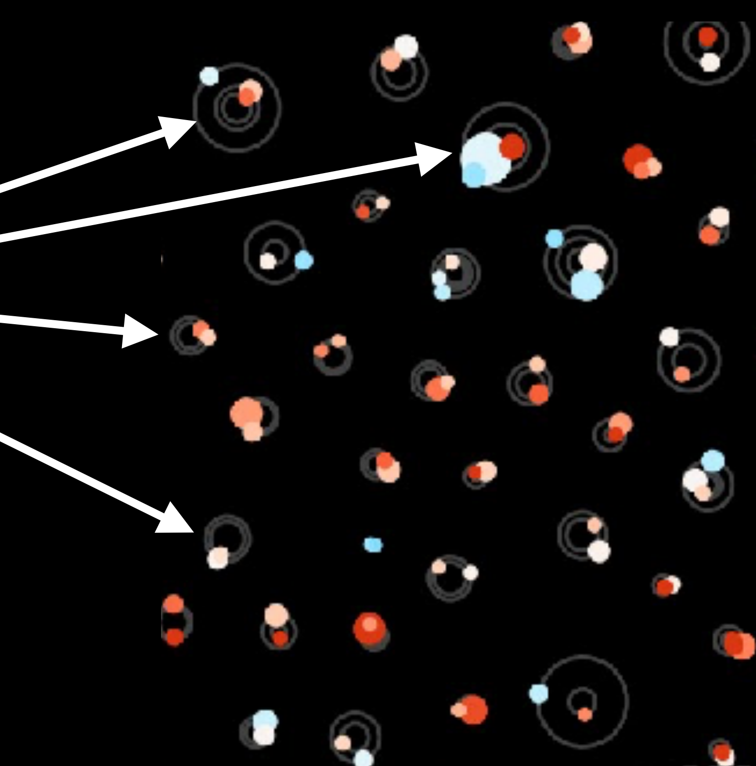
Angie Wolfgang
Penn State
NSF Postdoctoral Fellow

Why Planet Populations?



As physicists, we want to understand how planets form and evolve.

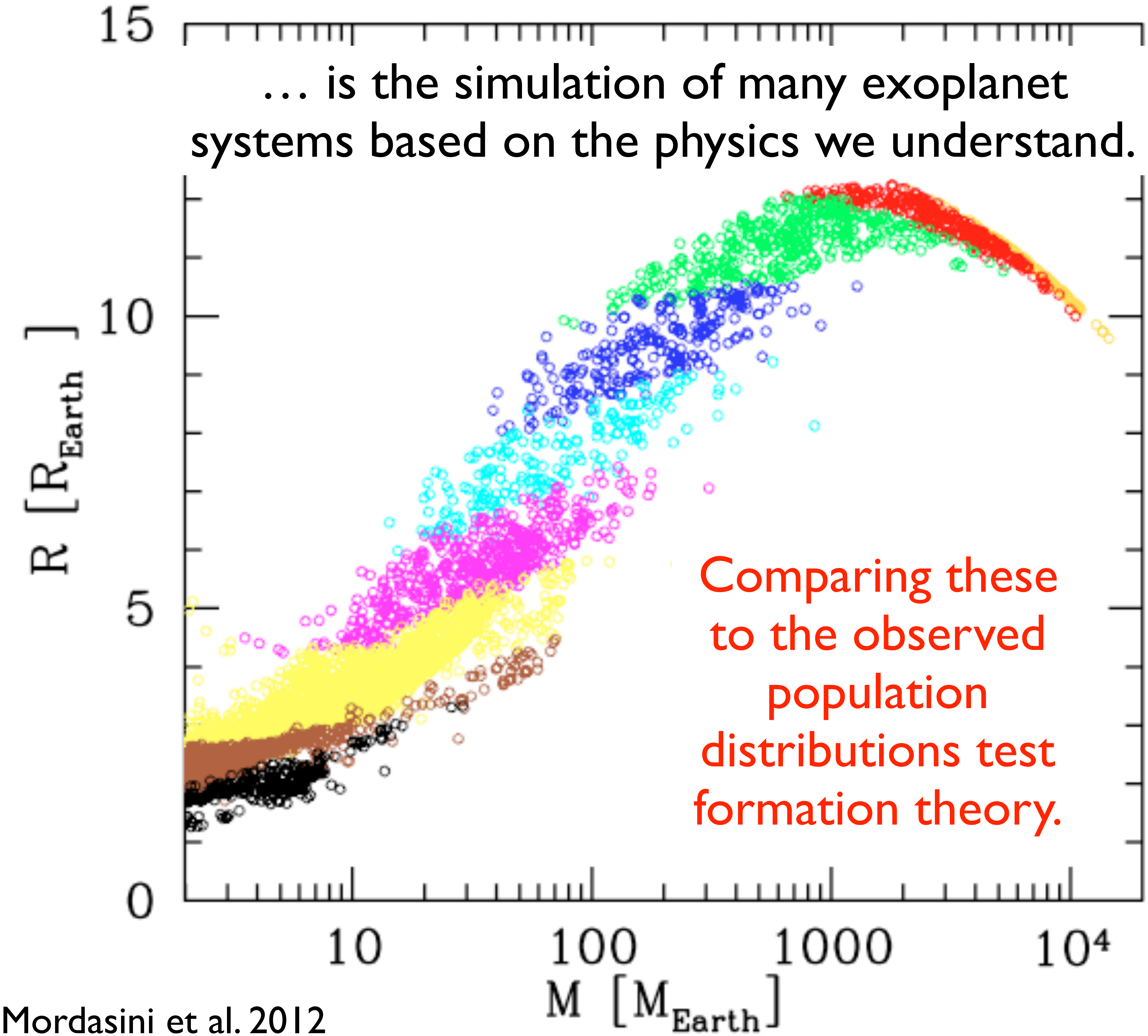
Many physical processes are at work (accretion, migration, photoevaporation) and they are sometimes stochastic (i.e. giant impacts). We need $N_{sys}>1$ to test these theories!



We've been surprised by exoplanets before (existence of hot Jupiters, plethora of sub-Neptunes), so we must map out the diversity of extrasolar systems.

Image credit: astroclock2010.wordpress.com

Planet Population Synthesis

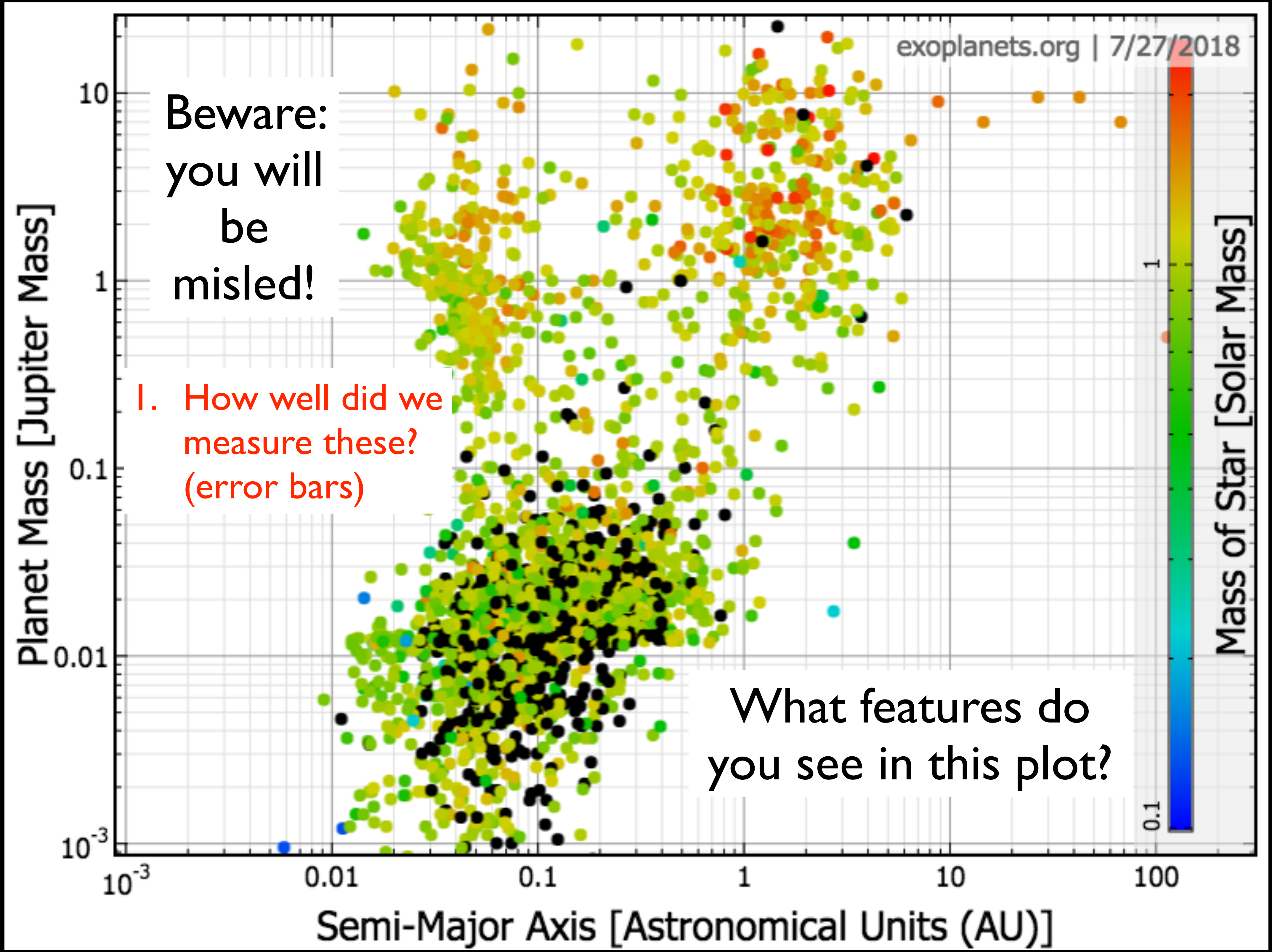


… is the simulation of many exoplanet systems based on the physics we understand.

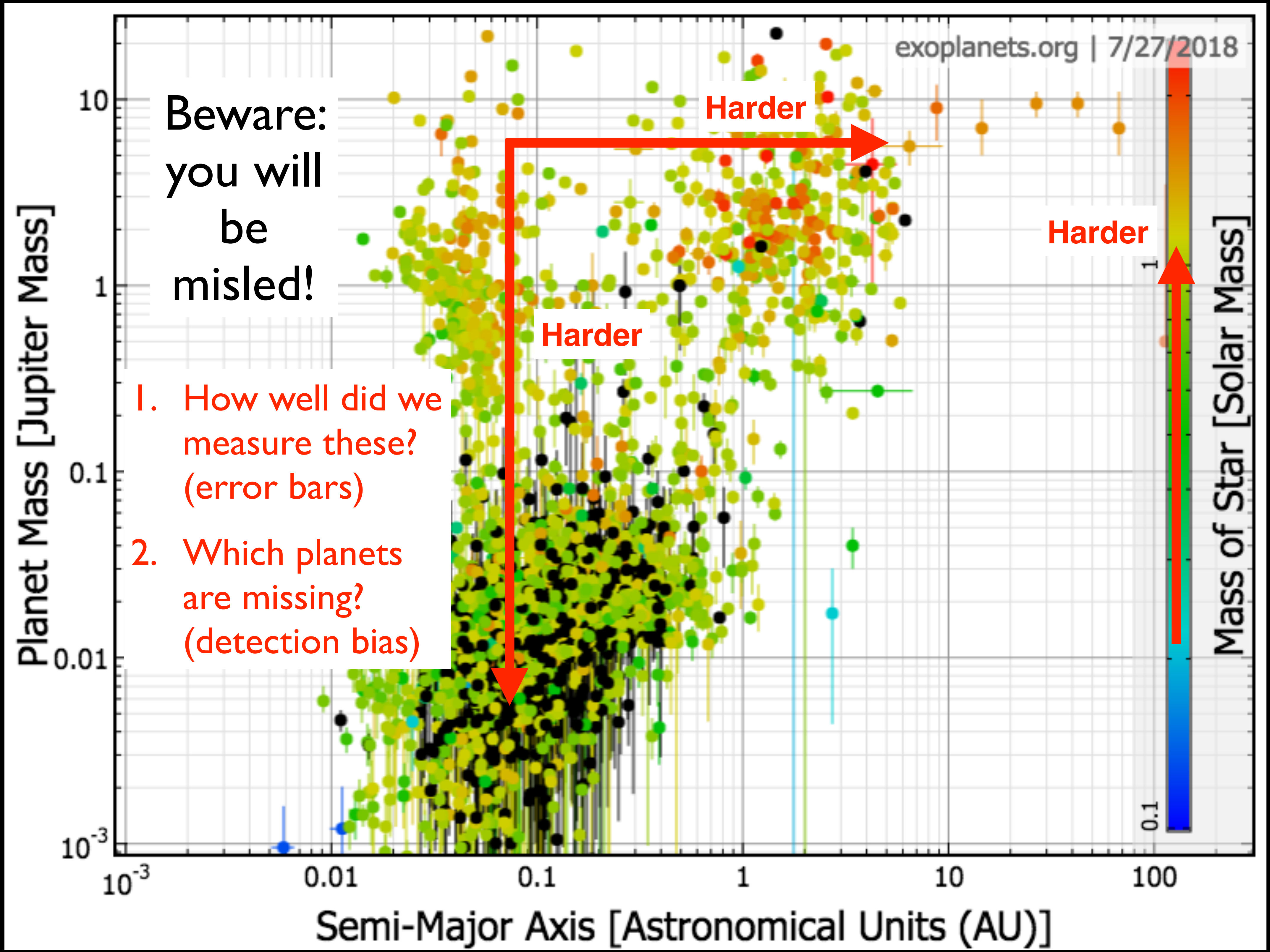
Comparing these to the observed population distributions test formation theory.

Mordasini et al. 2012

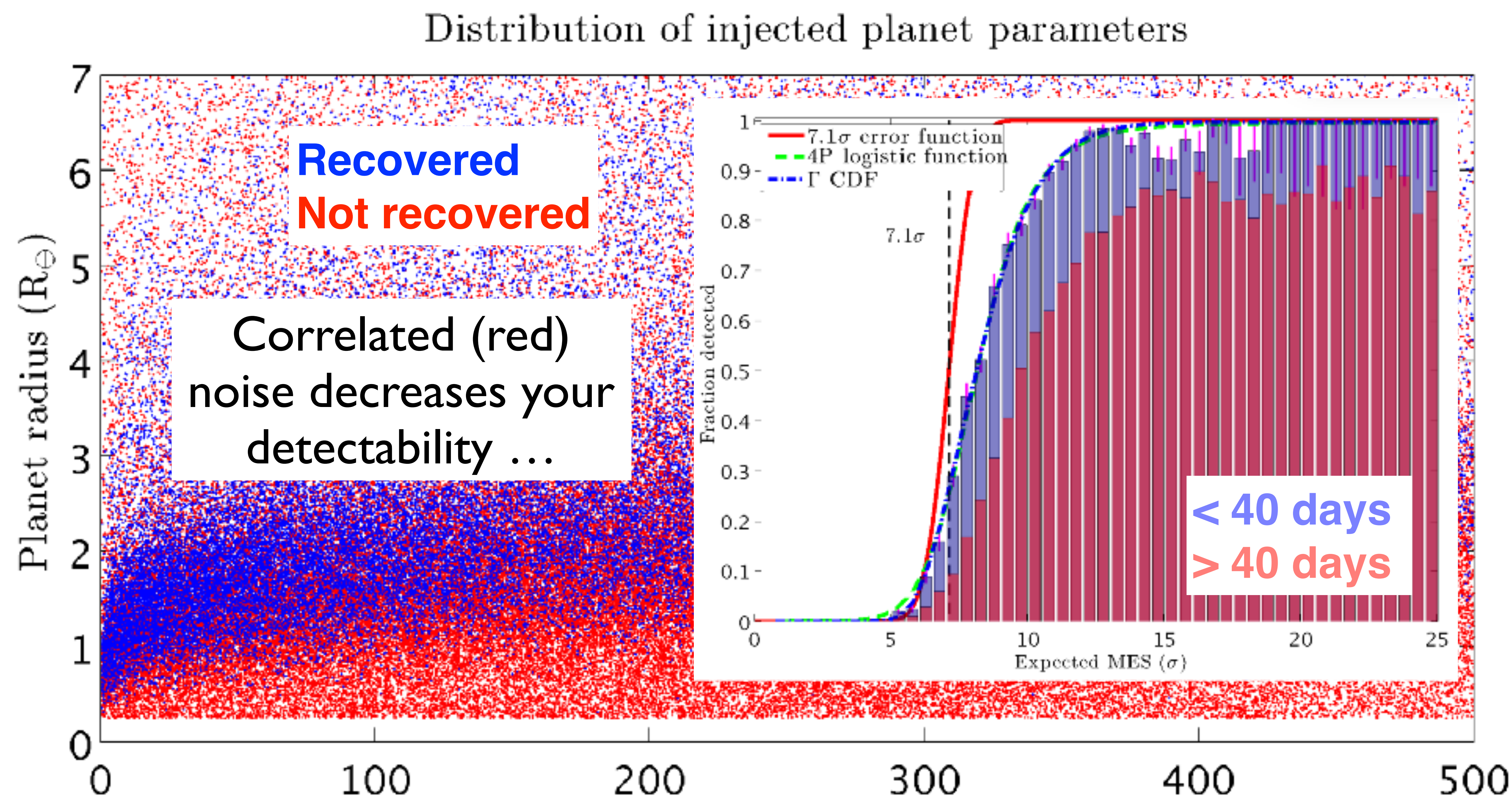
So, what is observed?



So, what is observed?

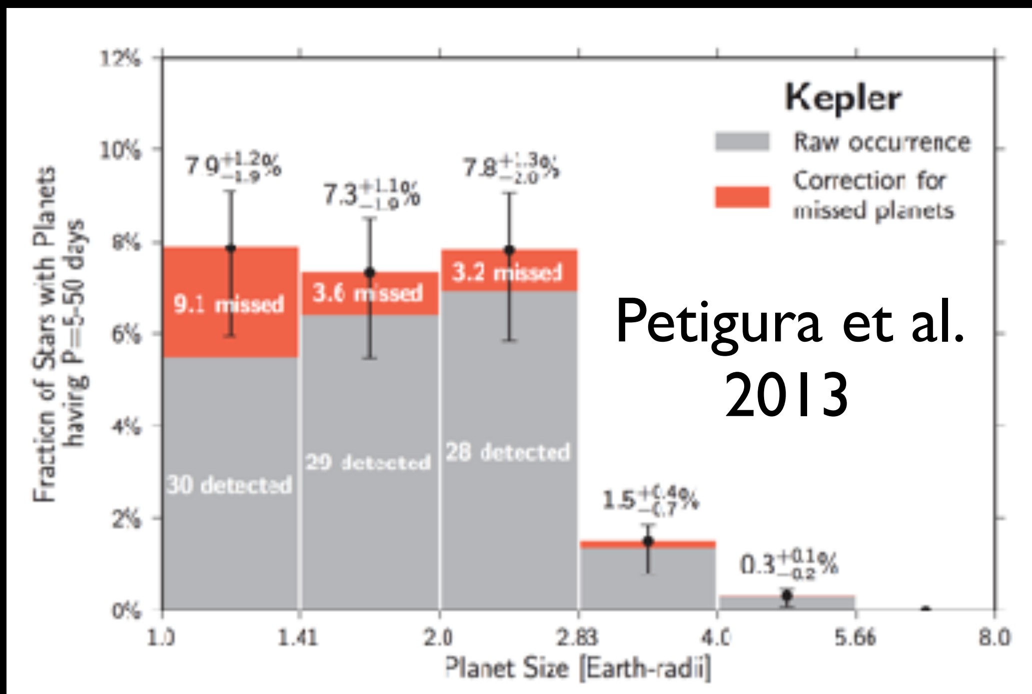


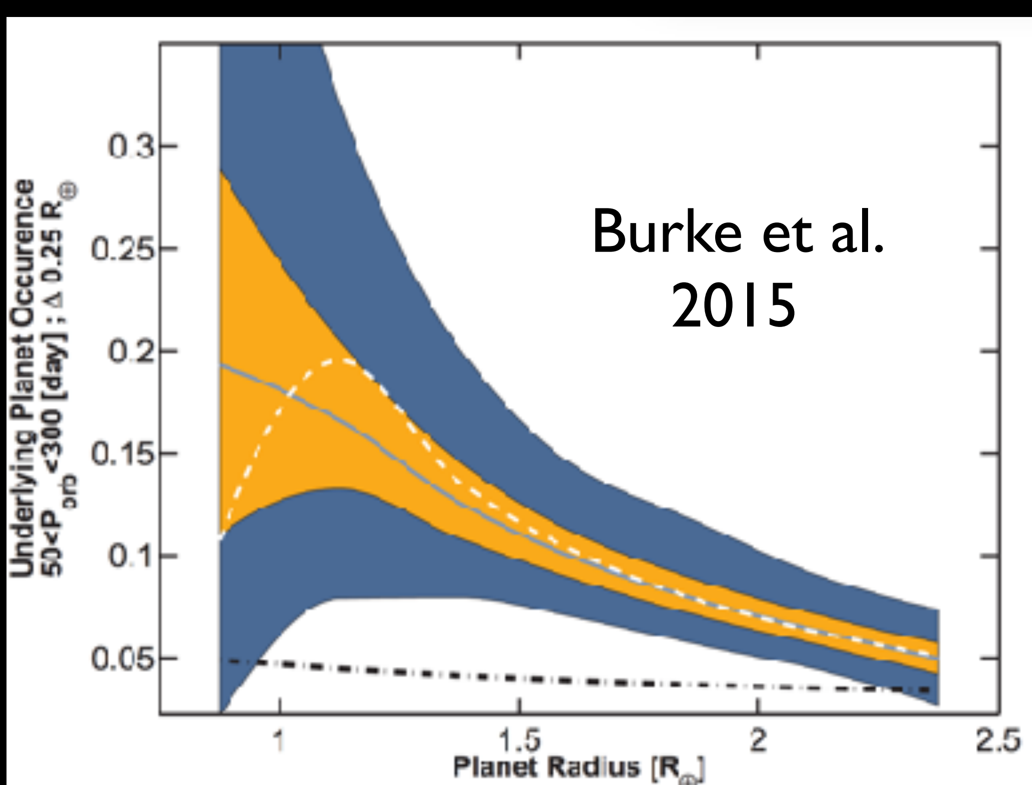
Inject Signals: Do you recover them?

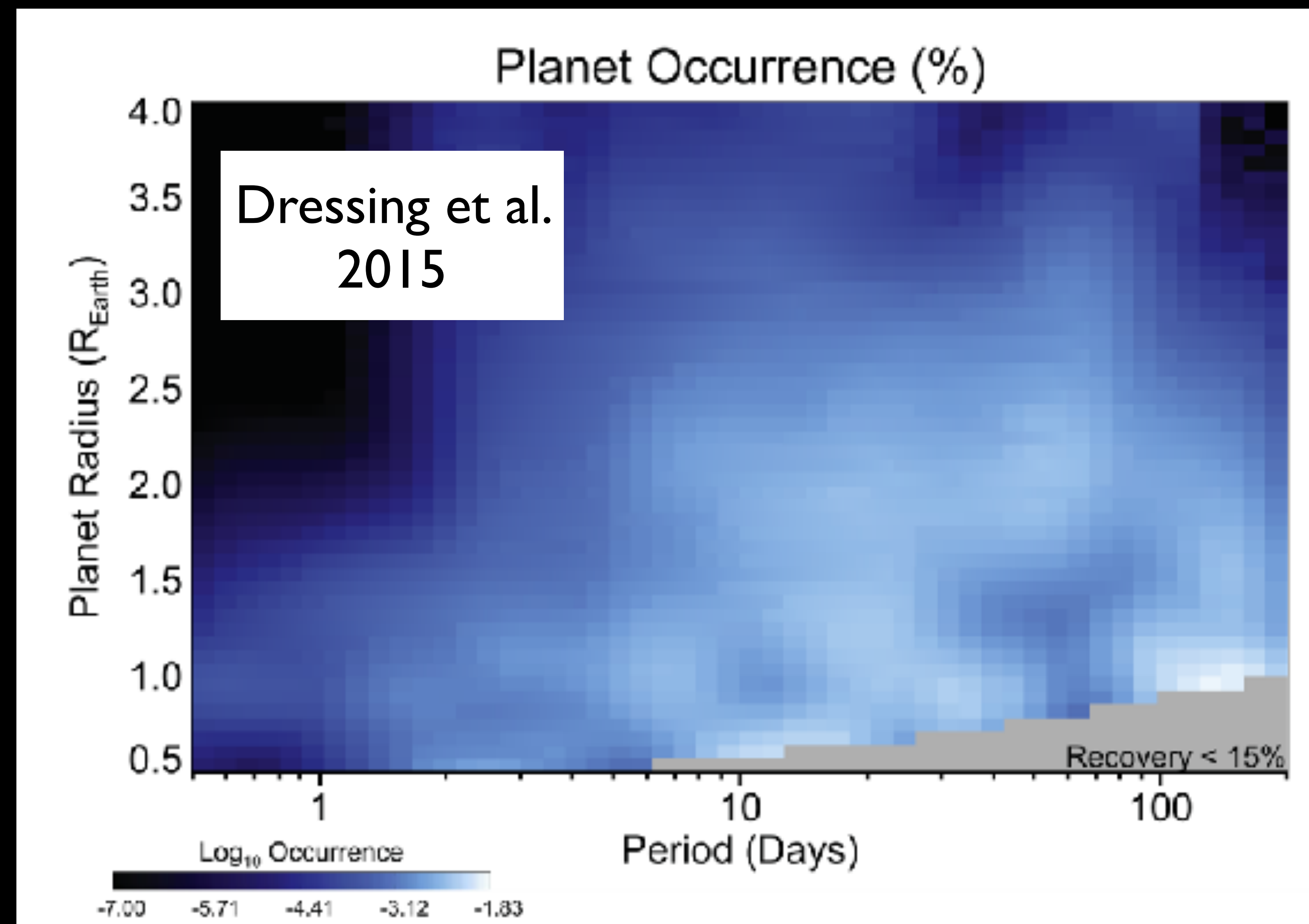


Christiansen et al. 2016

Completeness-corrected Results







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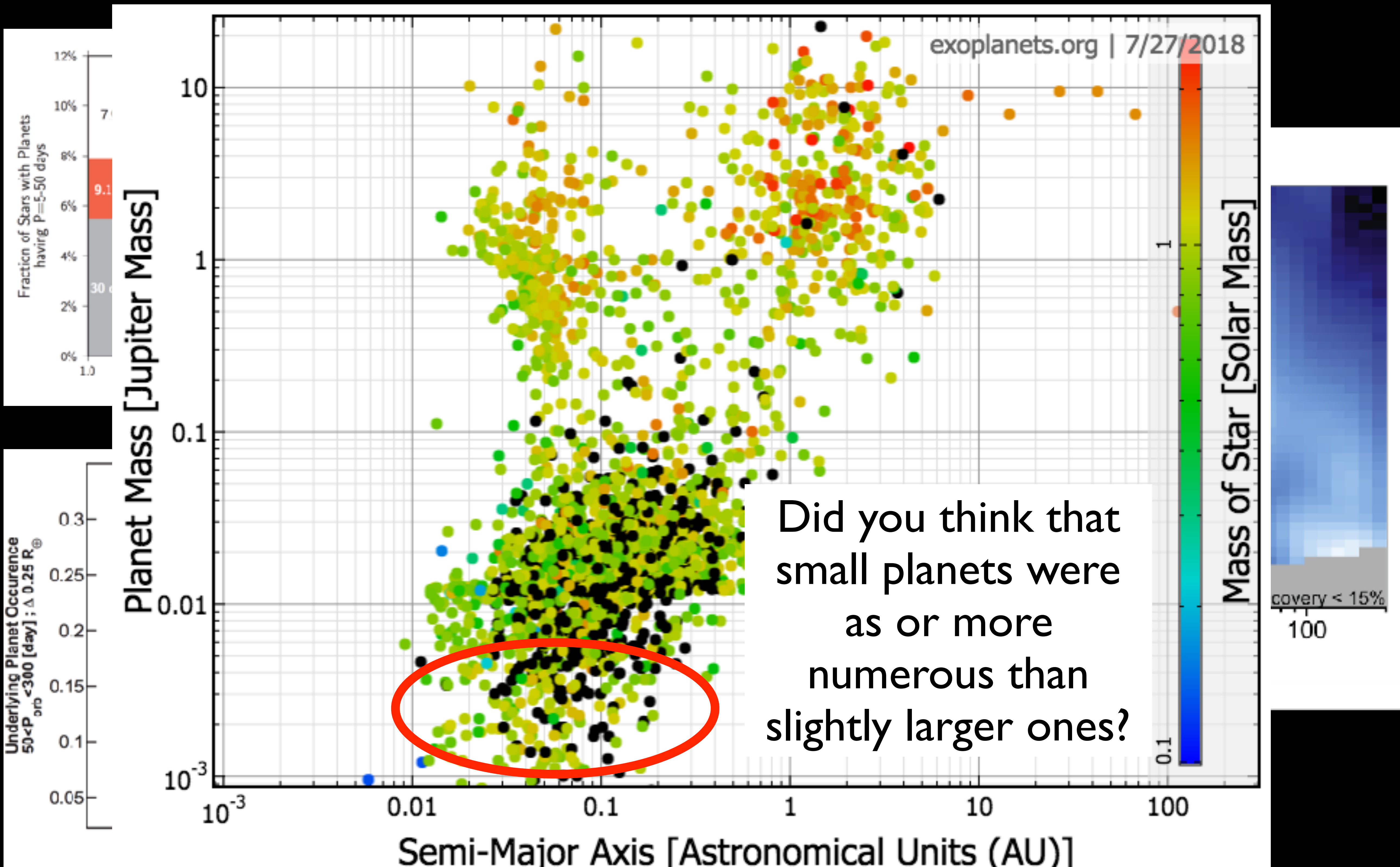


Did you think that small planets were as or more numerous than slightly larger ones?

Different techniques, different biases

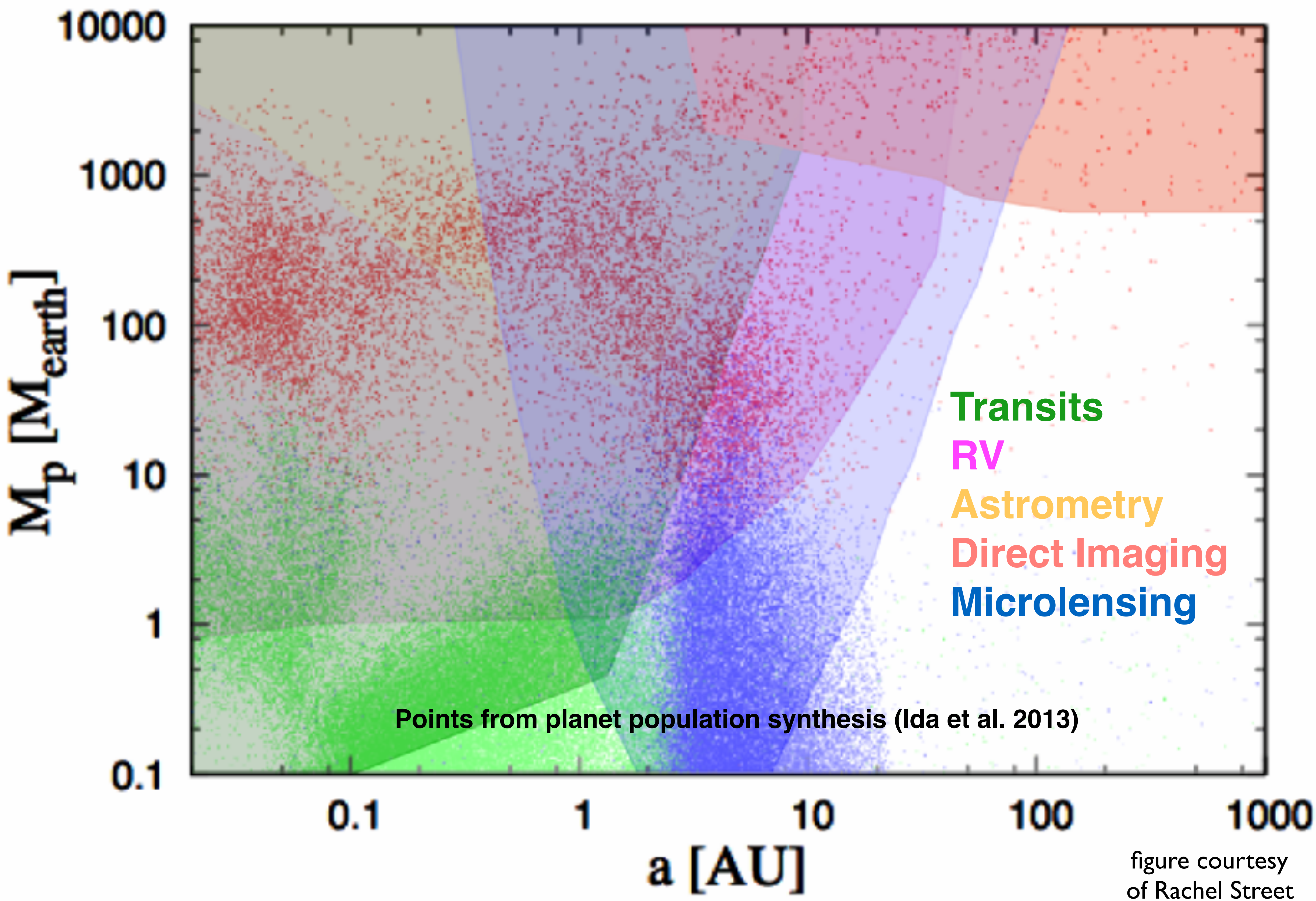
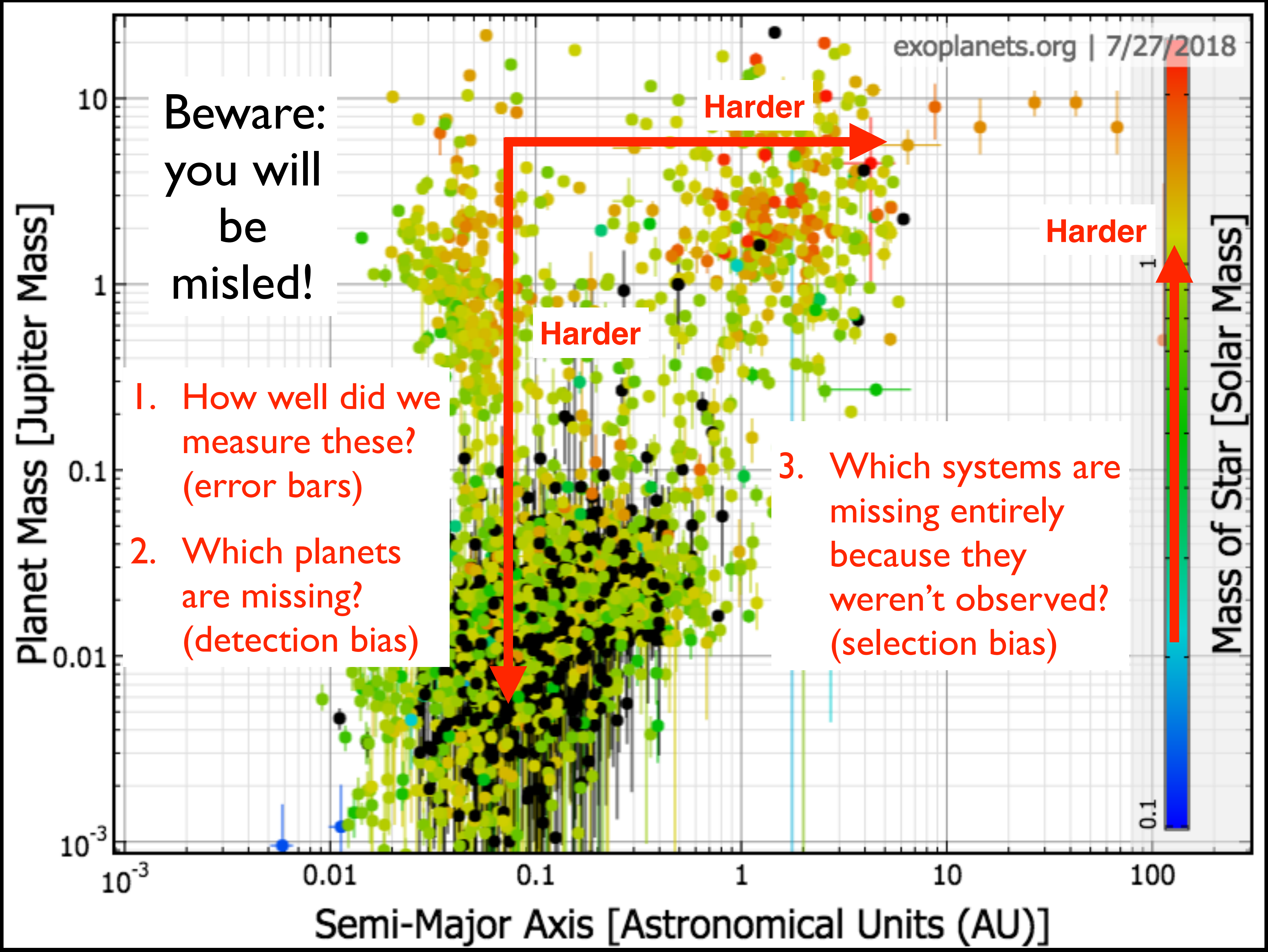
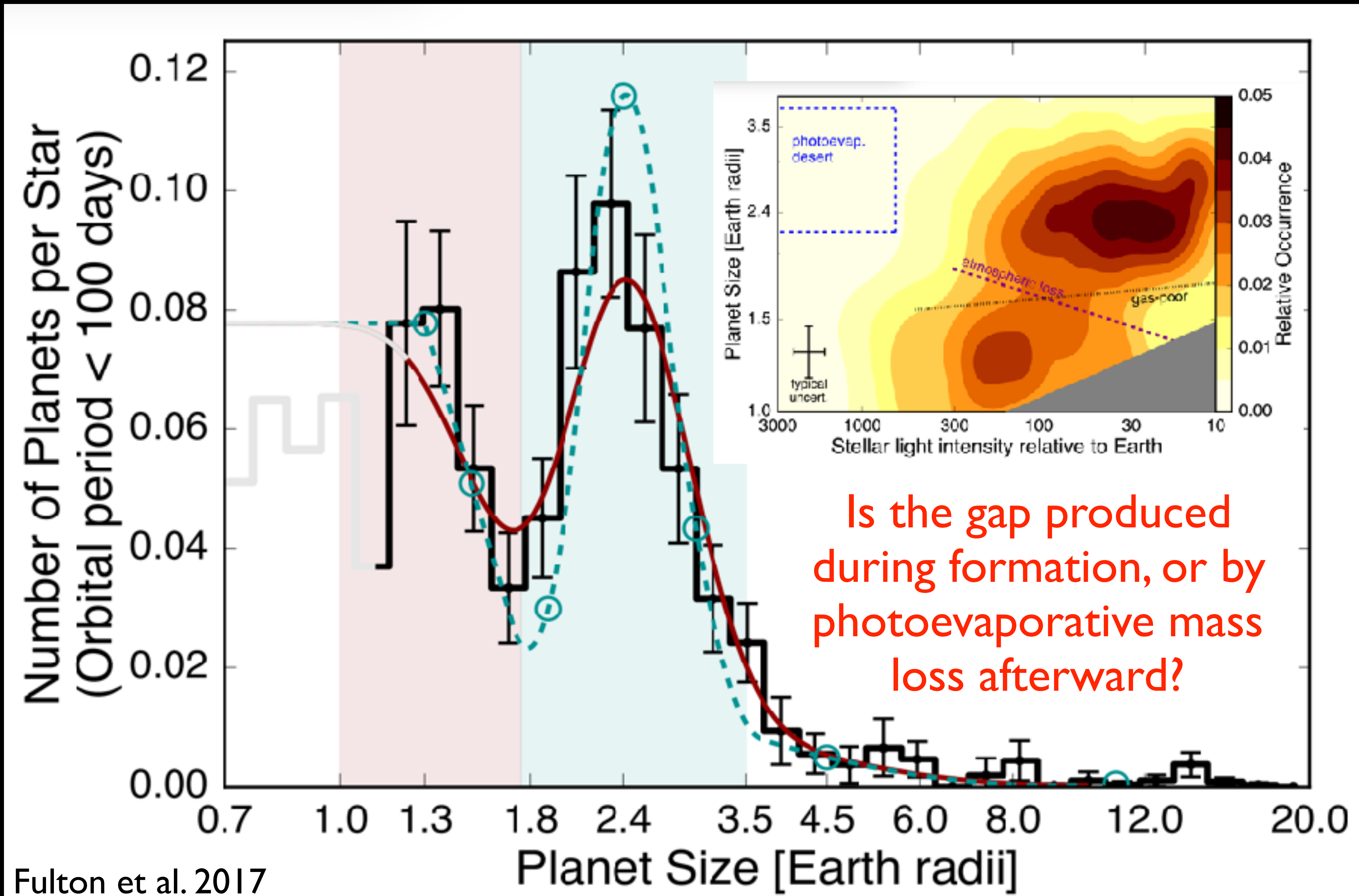


figure courtesy
of Rachel Street

More considerations …



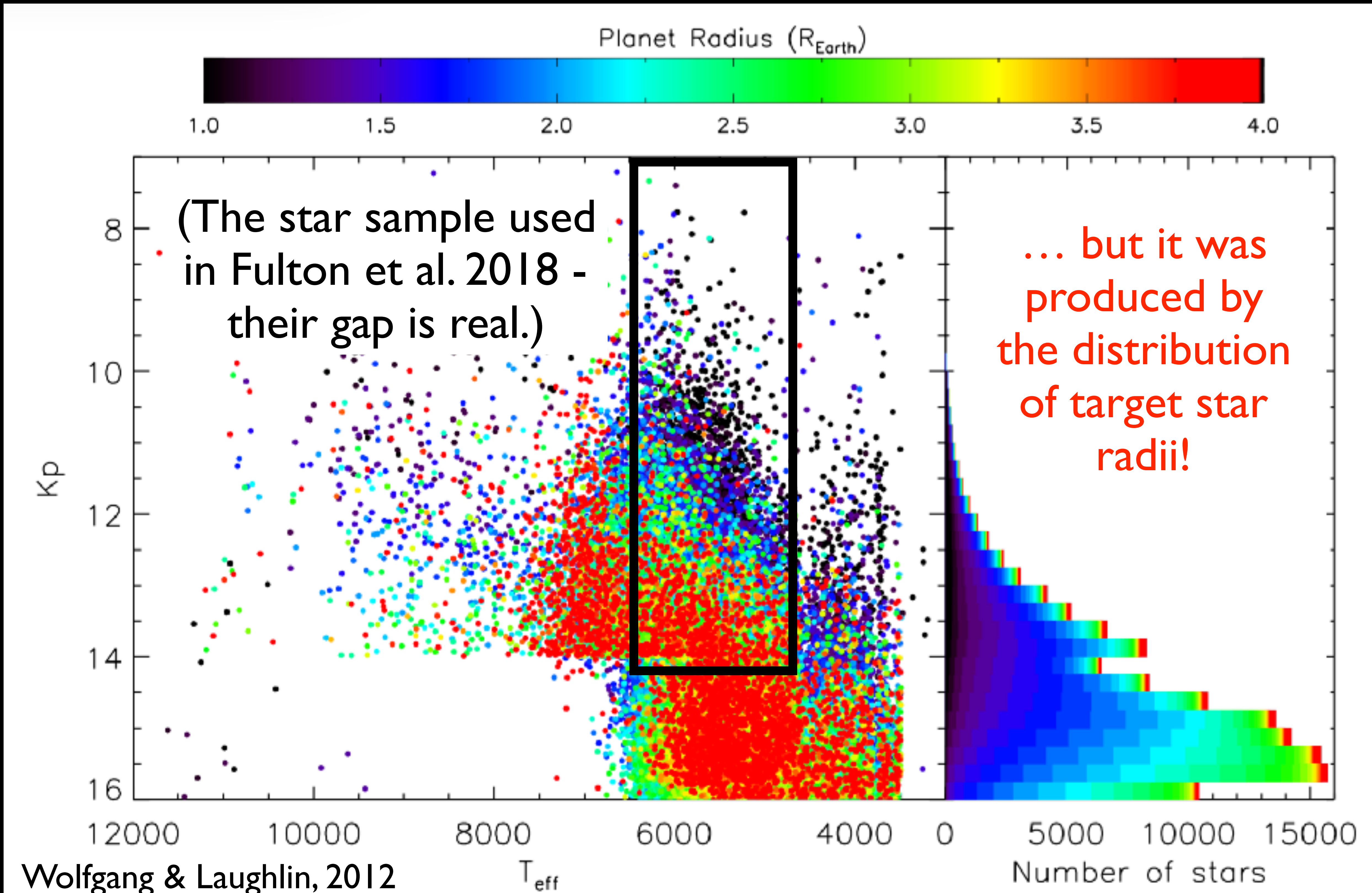
Your target stars are important!



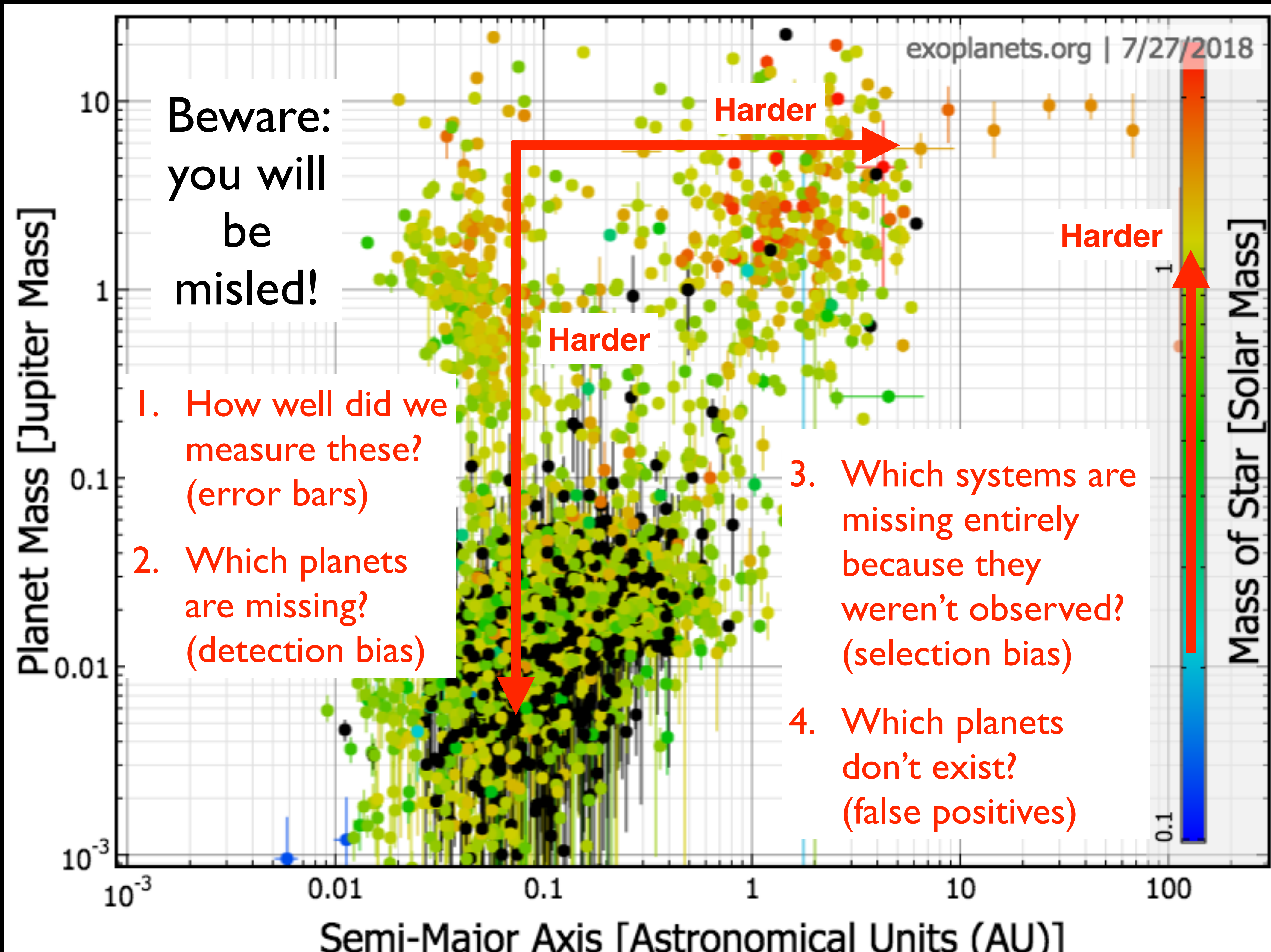
Is the gap produced during formation, or by photoevaporative mass loss afterward?

Fulton et al. 2017

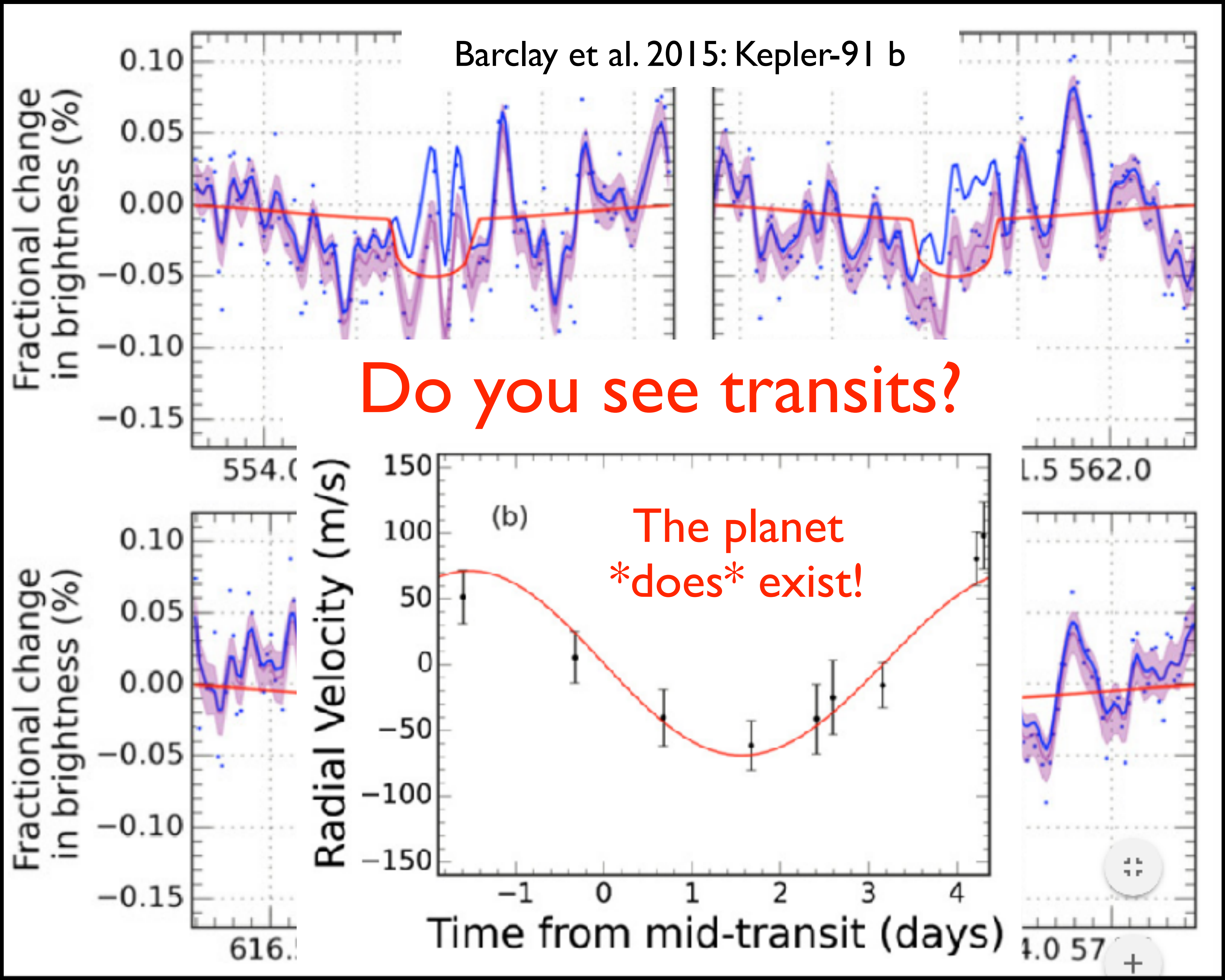
There was a gap before this …



More considerations …



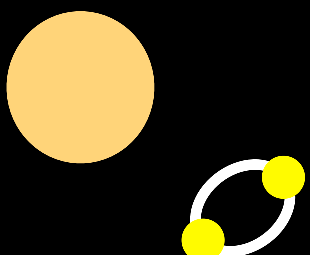
Correlated noise ➜ False alarms

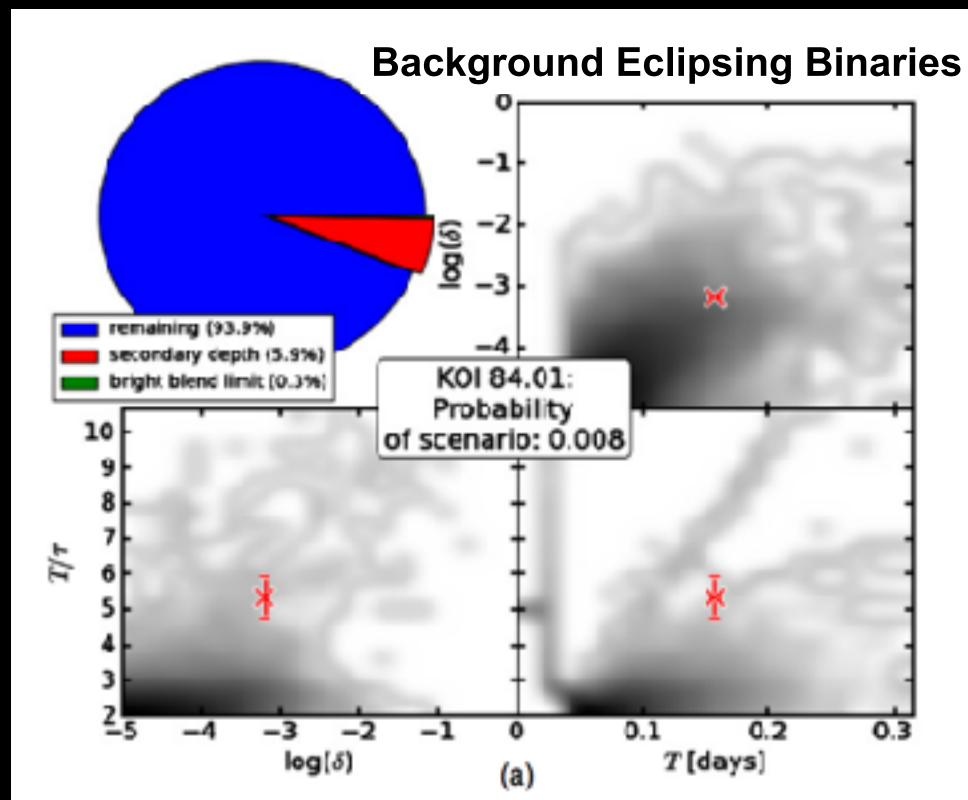


Astrophysical False Positives

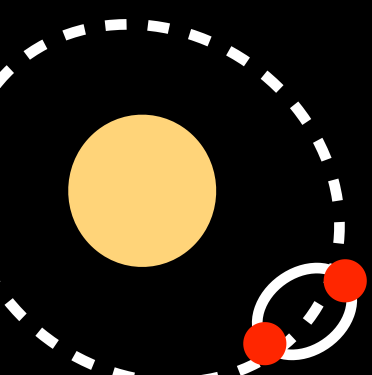
Morton 2012 ➜ VESPA

Background Eclipsing Binaries

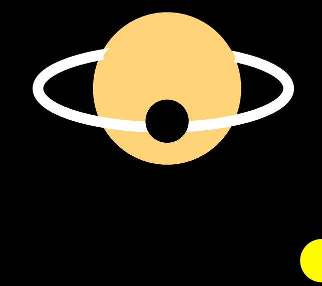




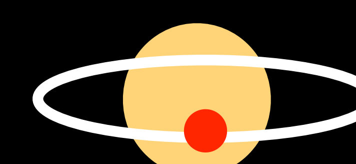
Hierarchical Eclipsing Binaries



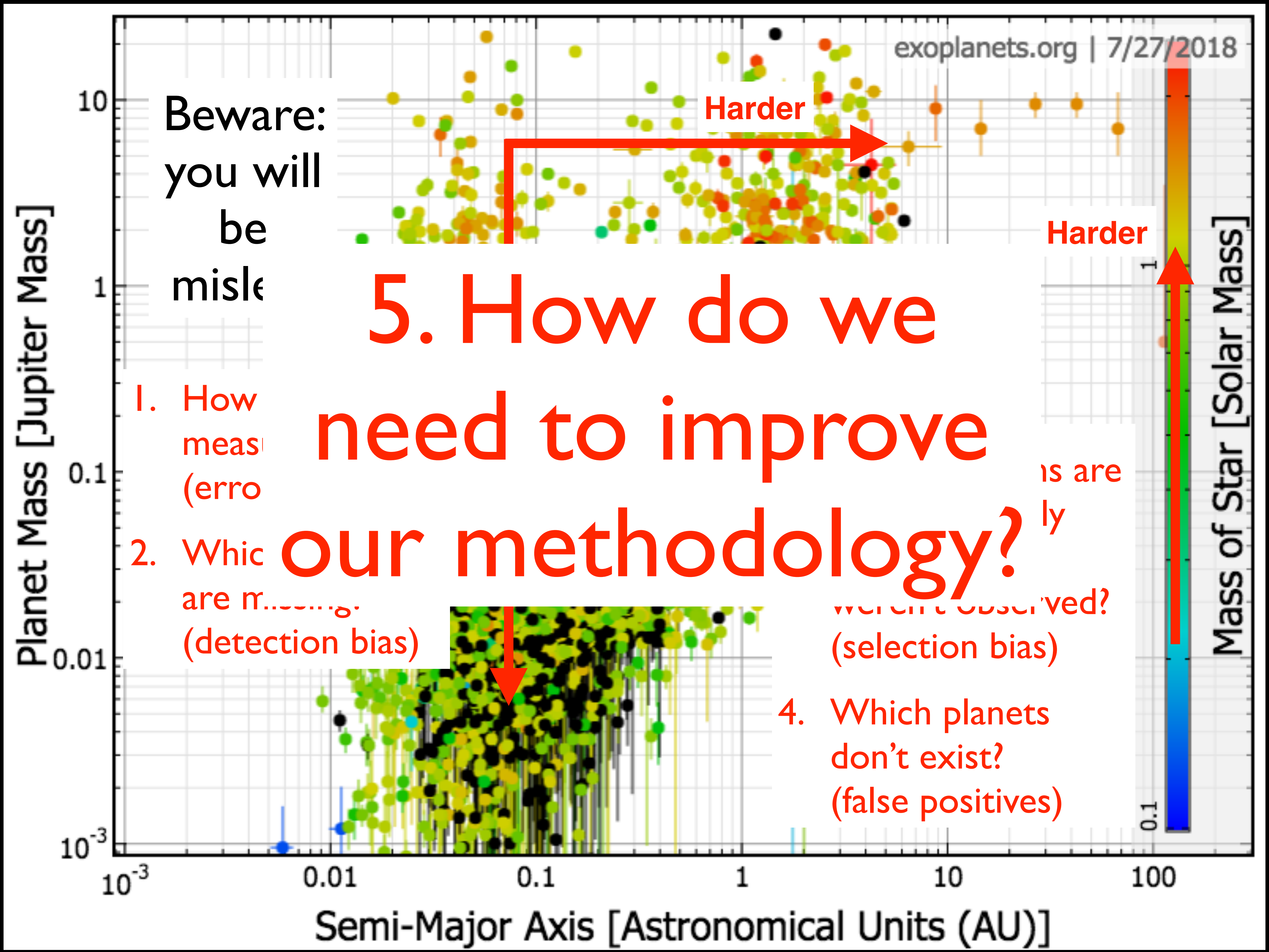
Blended Planets



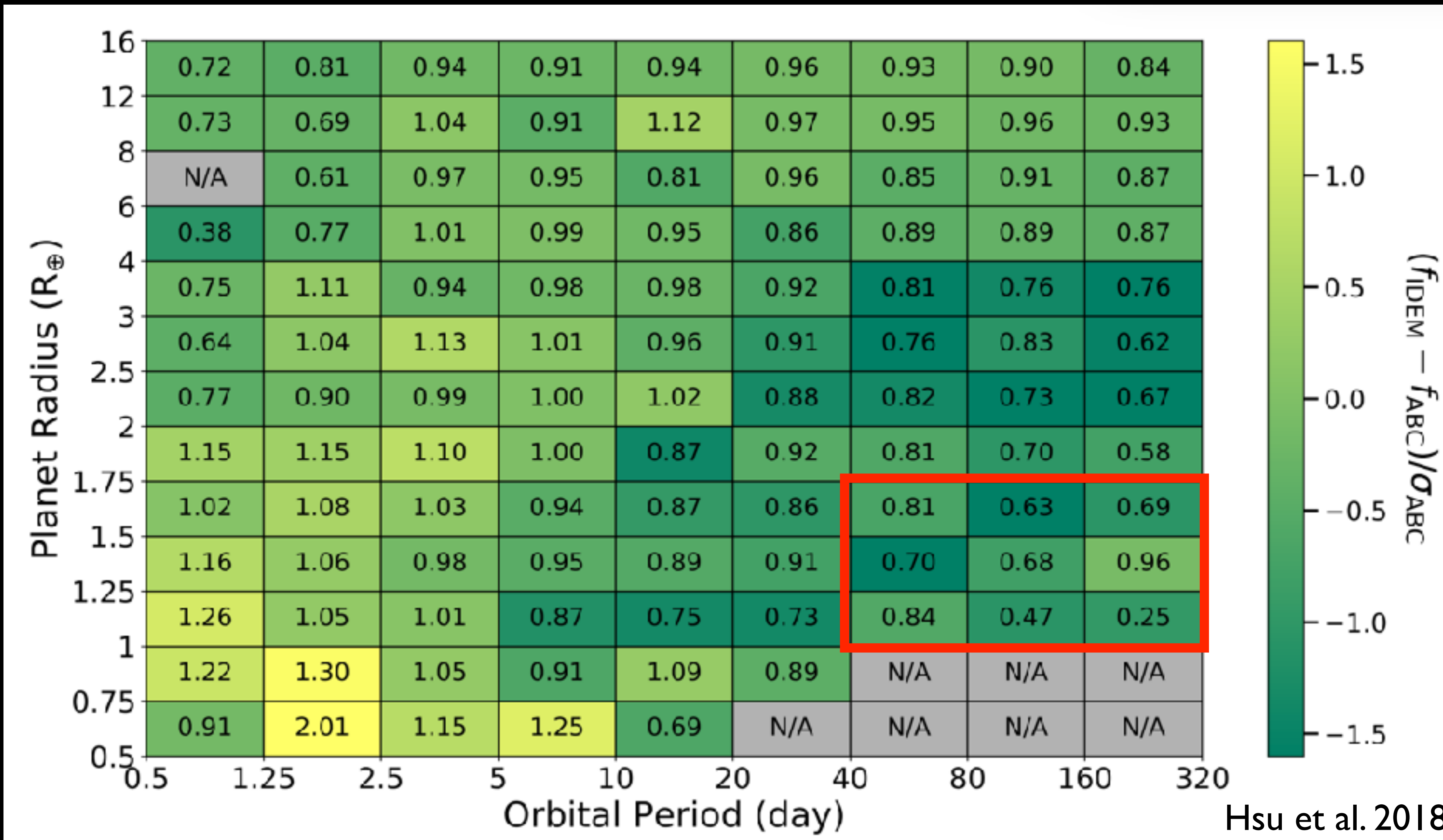
Eclipsing Binaries



More considerations …

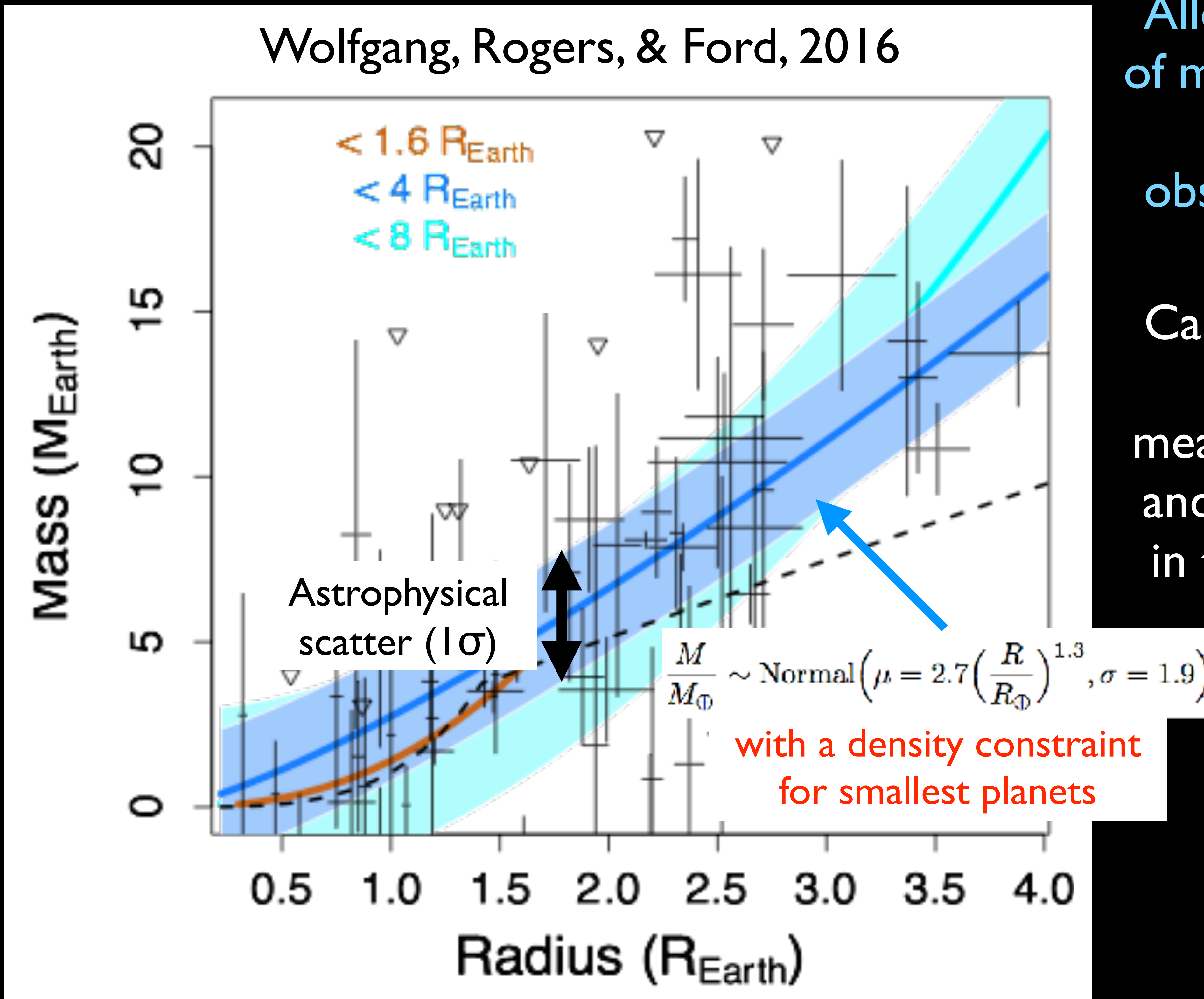


Improved Methods Change Results



Correctly incorporating non-detections in completeness correction changes occurrence rate of Earth-sized planets!

Think Distributions Instead of Lines

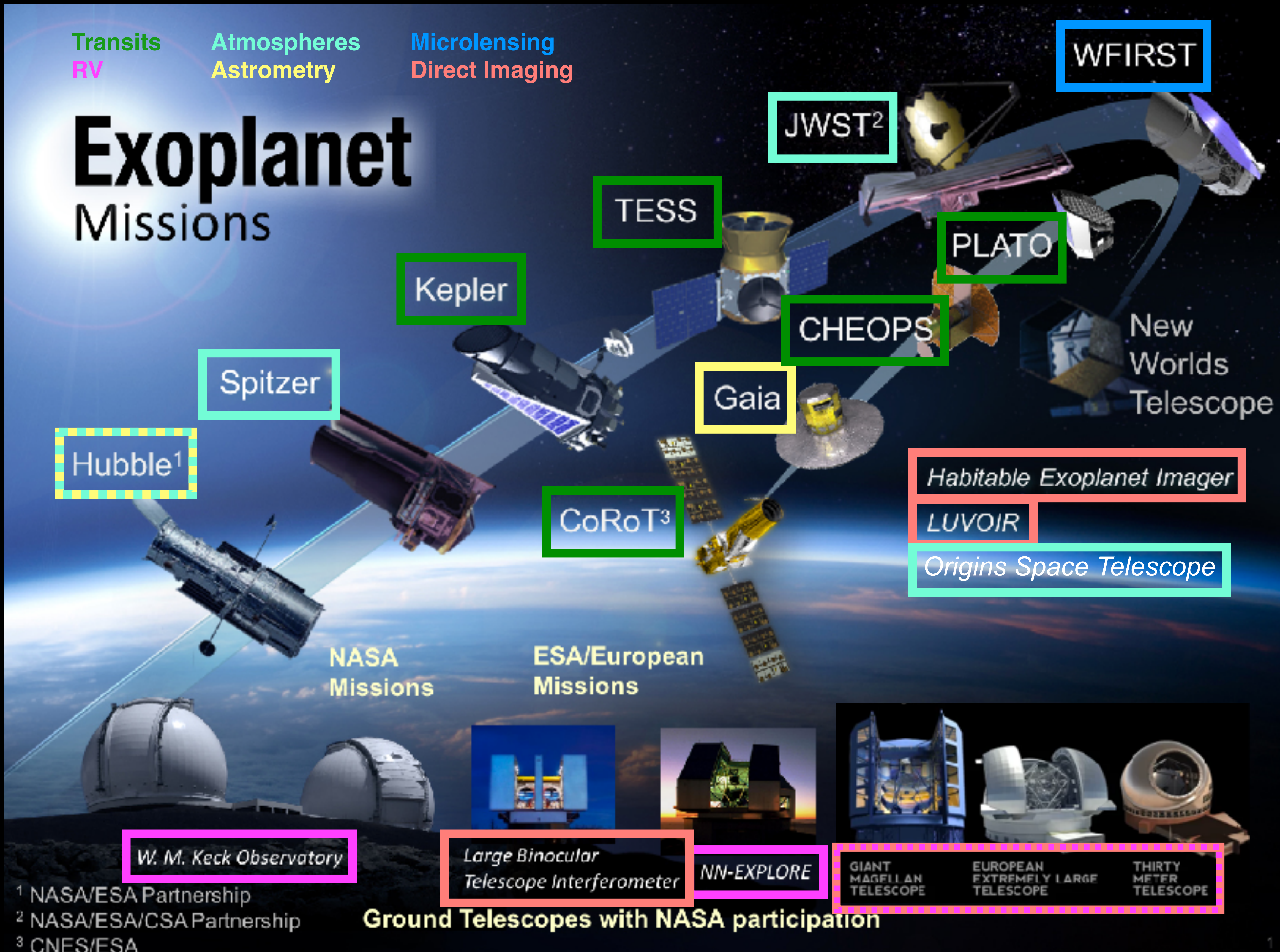


Allows for a distribution of masses at a given radius as is motivated by observations and theory

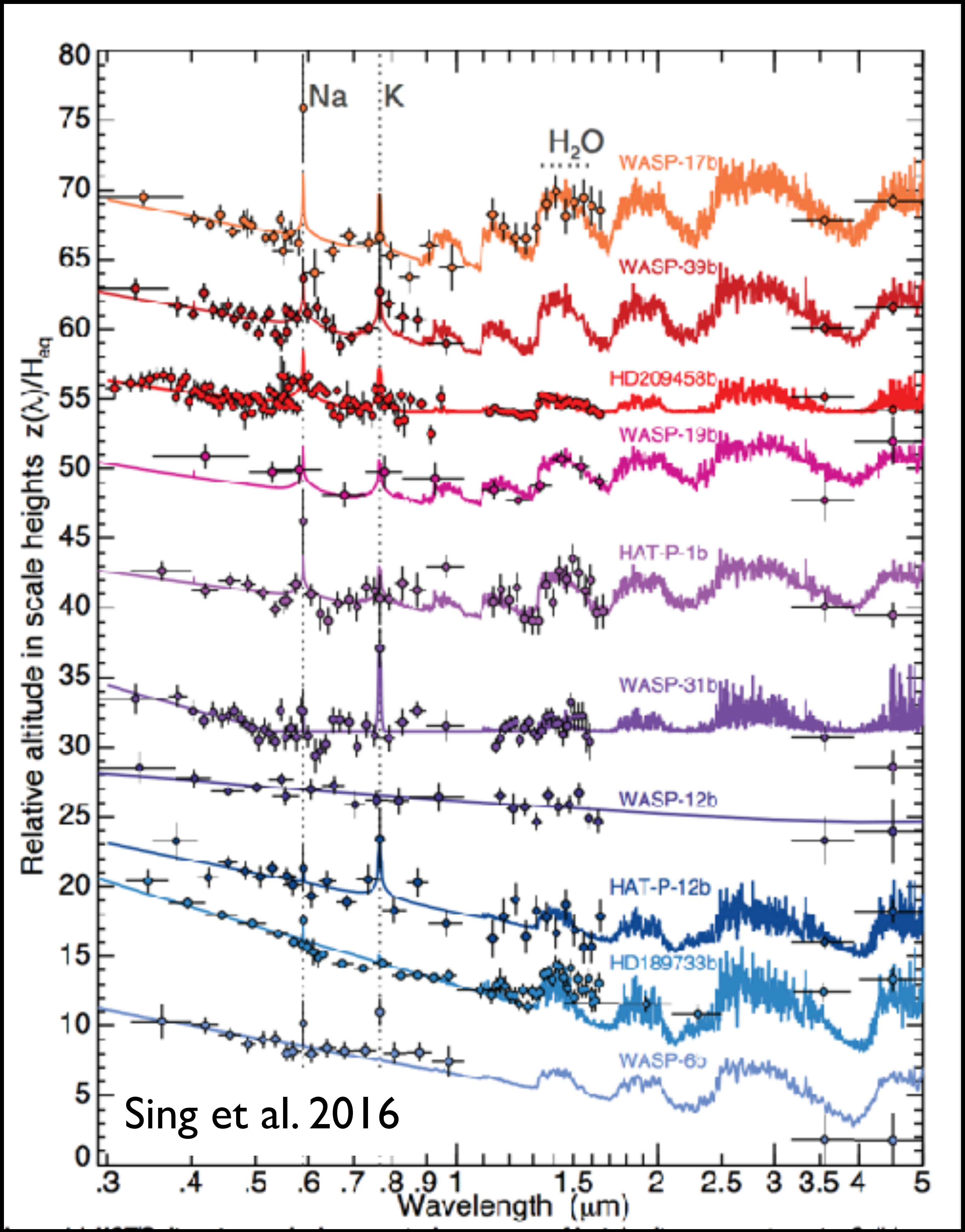
Can distinguish between scatter due to measurement uncertainty and astrophysical scatter in the planet population

Is an empirical description of exoplanet composition distribution.

Toward the Future



Populations of Exoplanet Atmospheres!

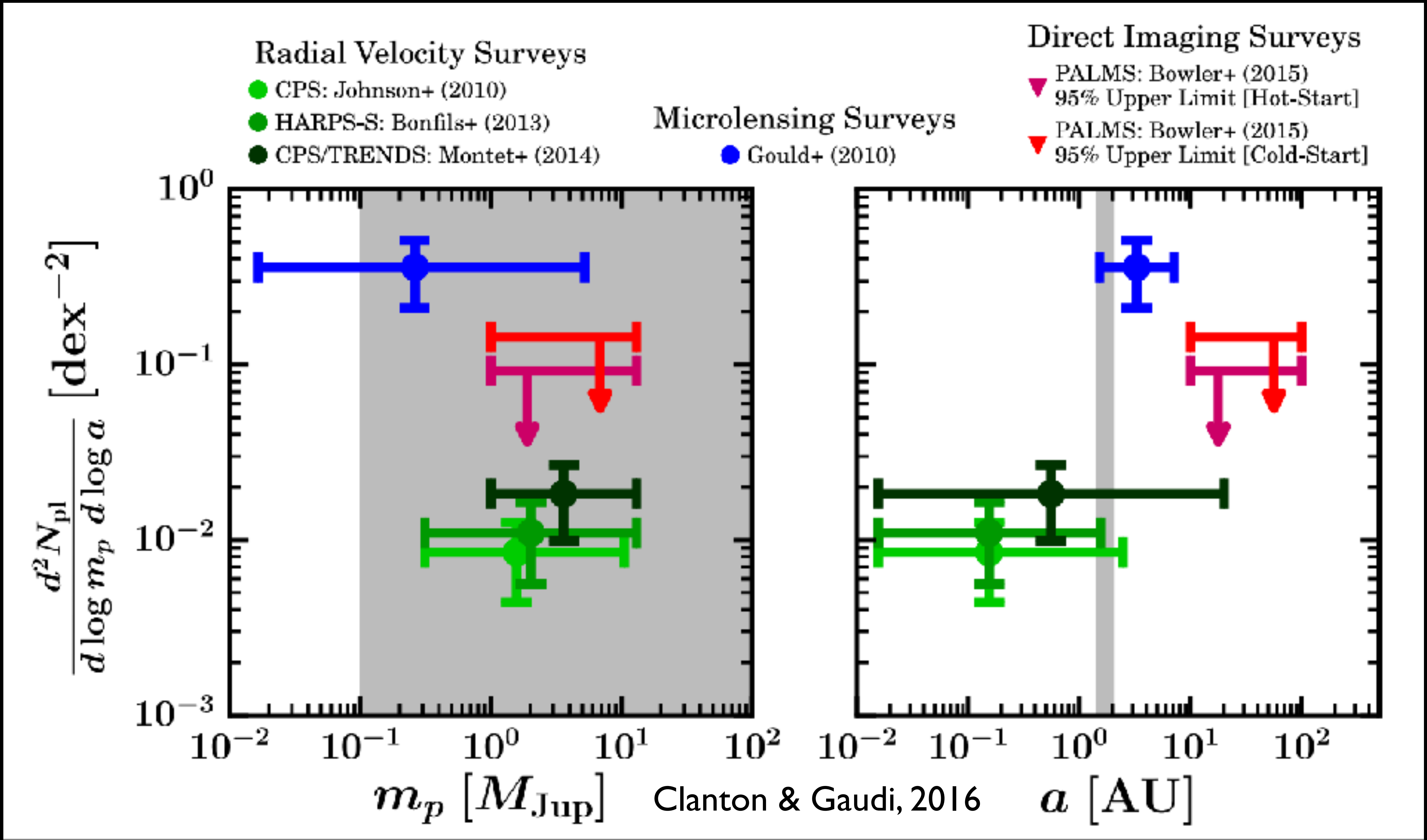


Will need to understand how the choice of targets affects the inference about the population (focus on small, low-density planets ➜ biased toward more low mean molecular weight atmospheres?)

How will the presence of clouds influence our understanding of the population?

Lots to consider for JWST, Origins Space Telescope, …

Synthesizing results from many surveys



Clanton & Gaudi, 2016

First stab: occurrence rate of planets have ~ no dependence on semi-major axis

Future: Full Exoplanet Census

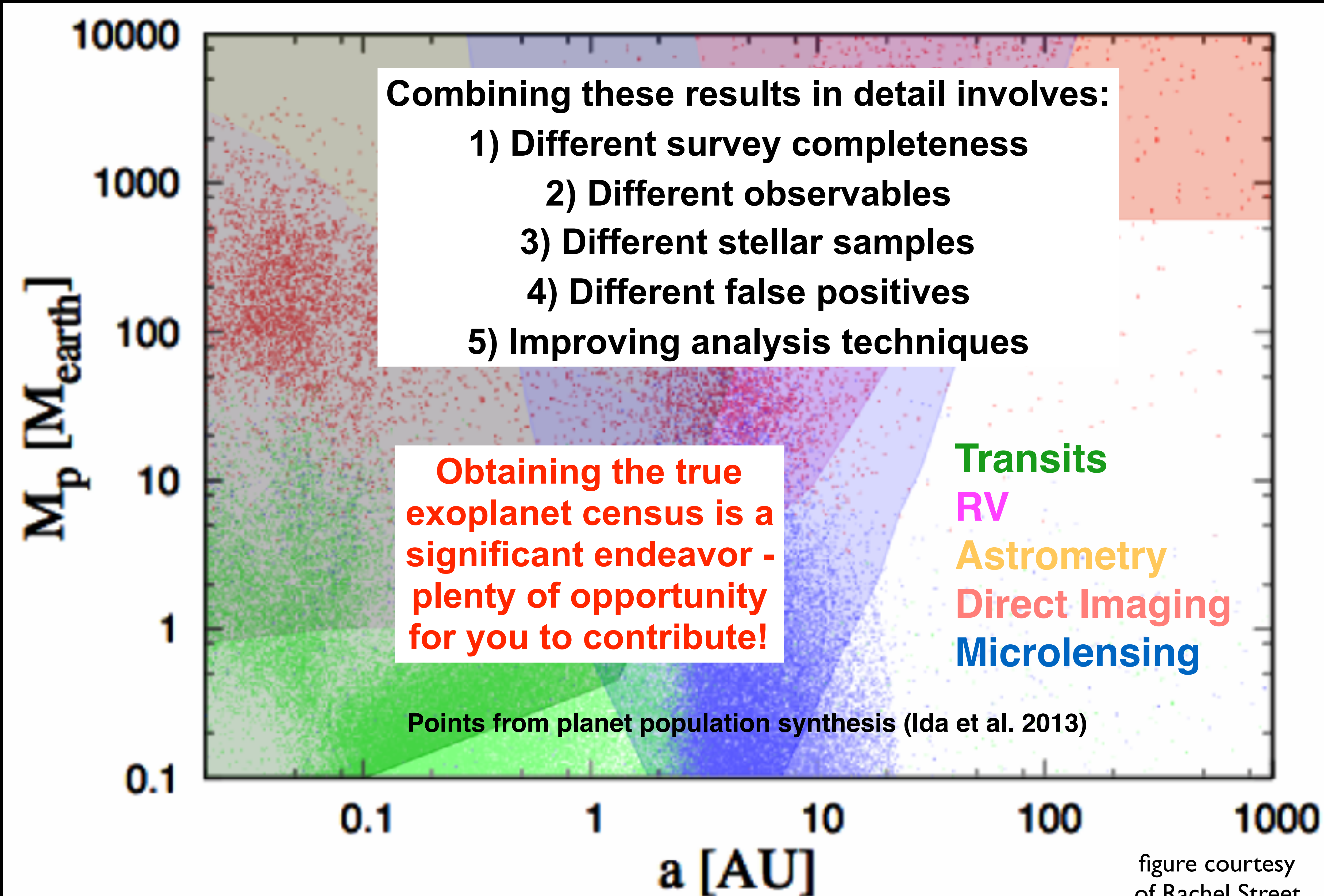


figure courtesy of Rachel Street

Back-up Slides

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Architectures: A Rich Problem

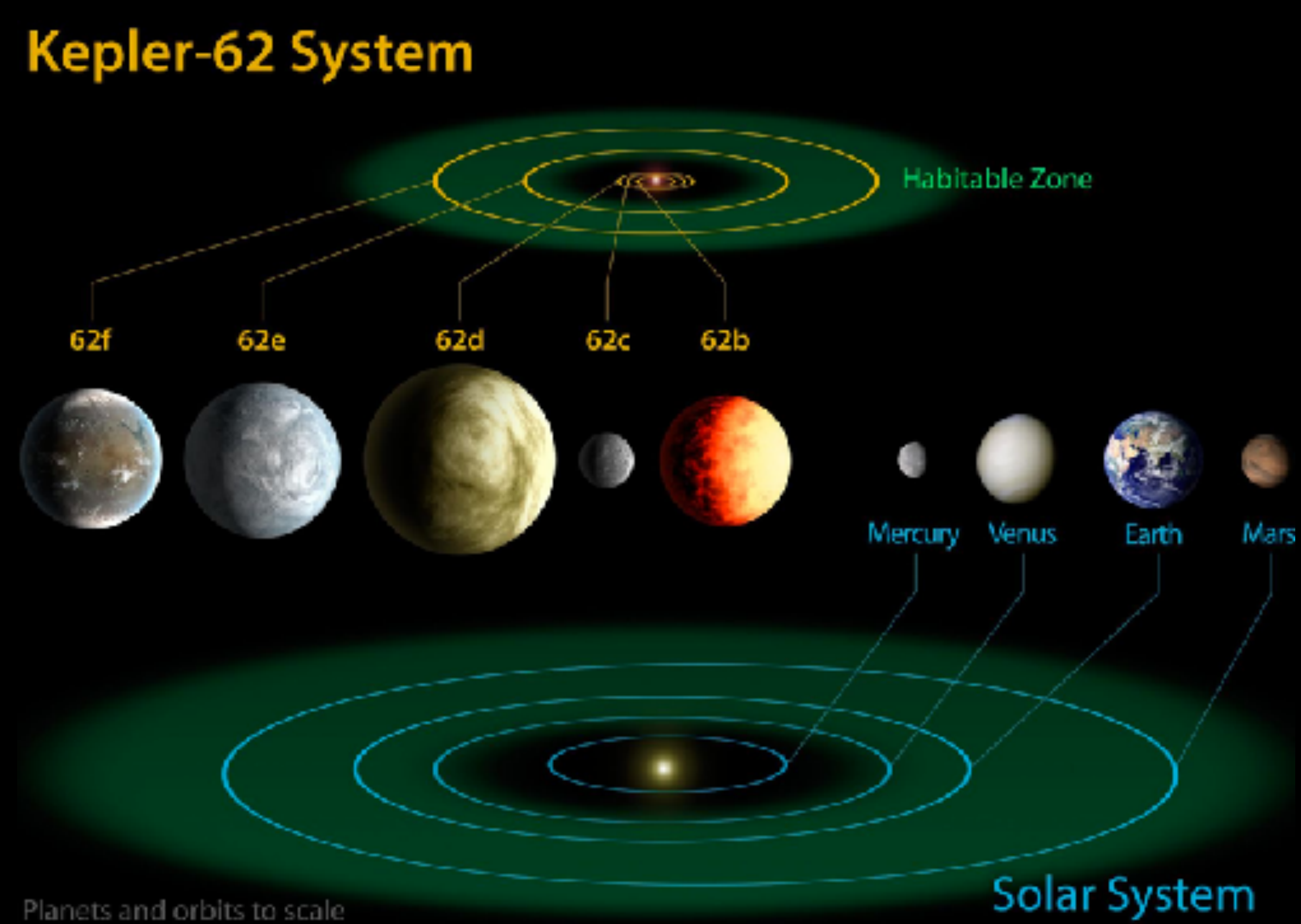
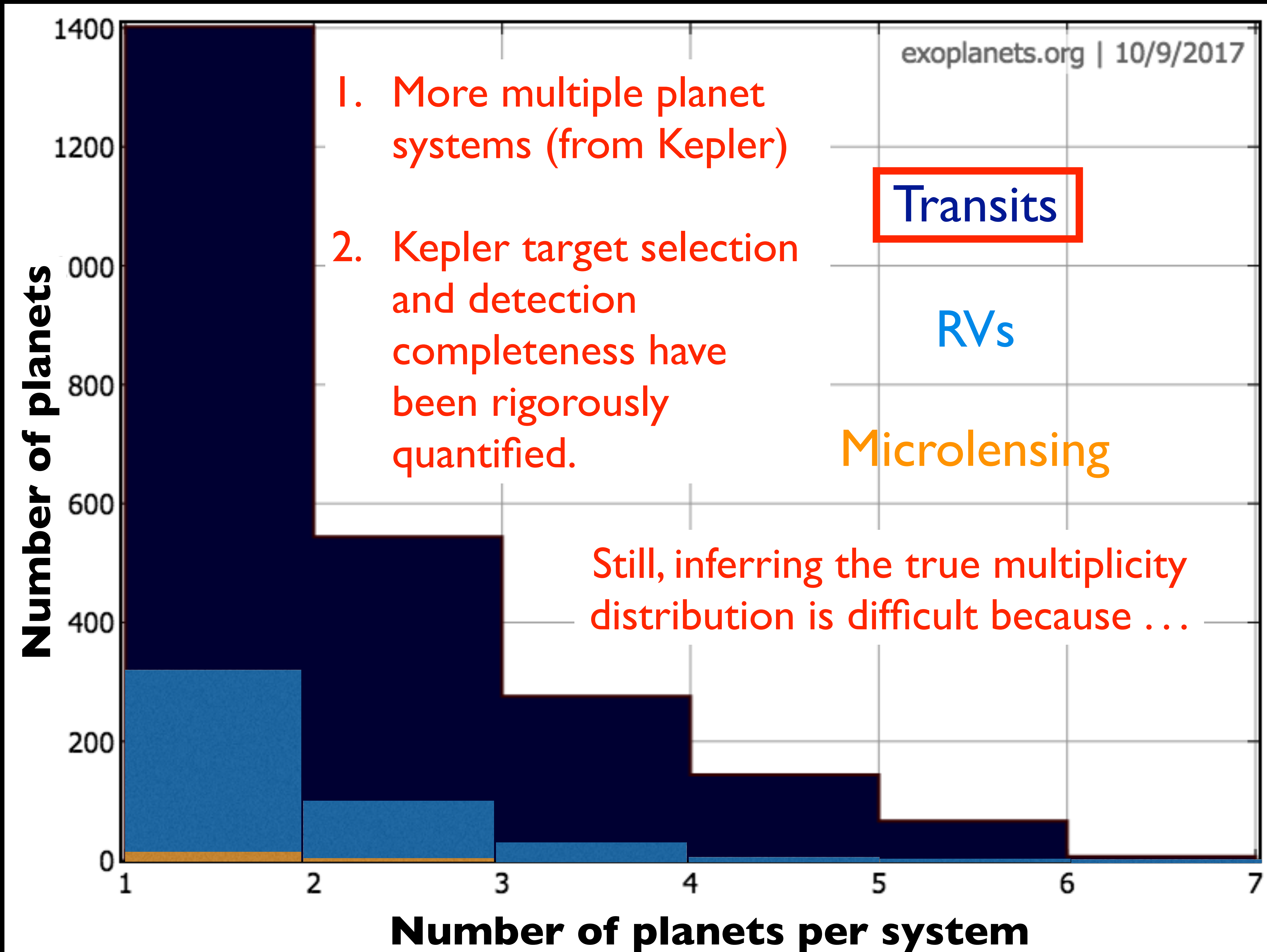


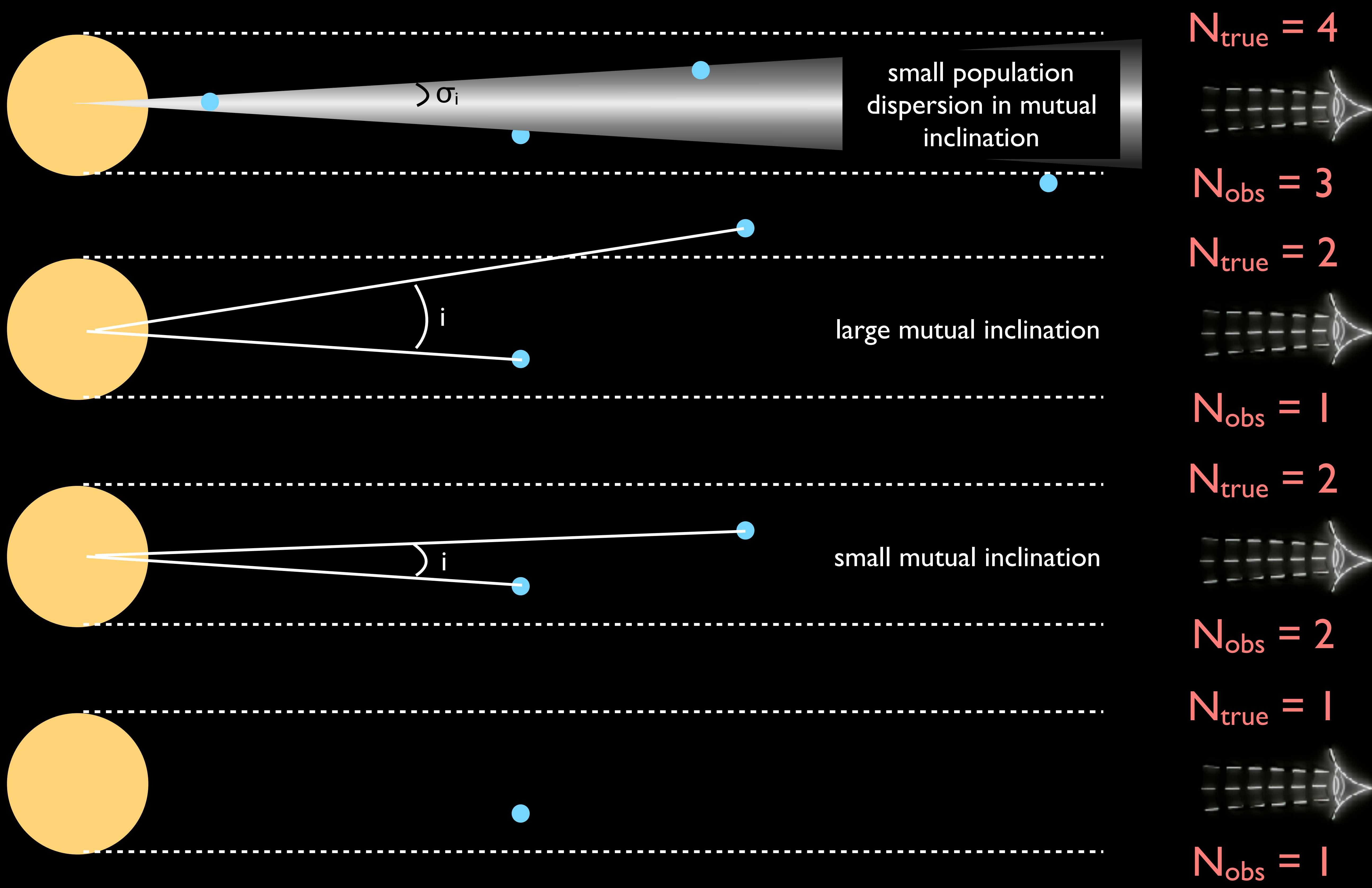
Image credit: NASA/Ames/JPL-Caltech

- 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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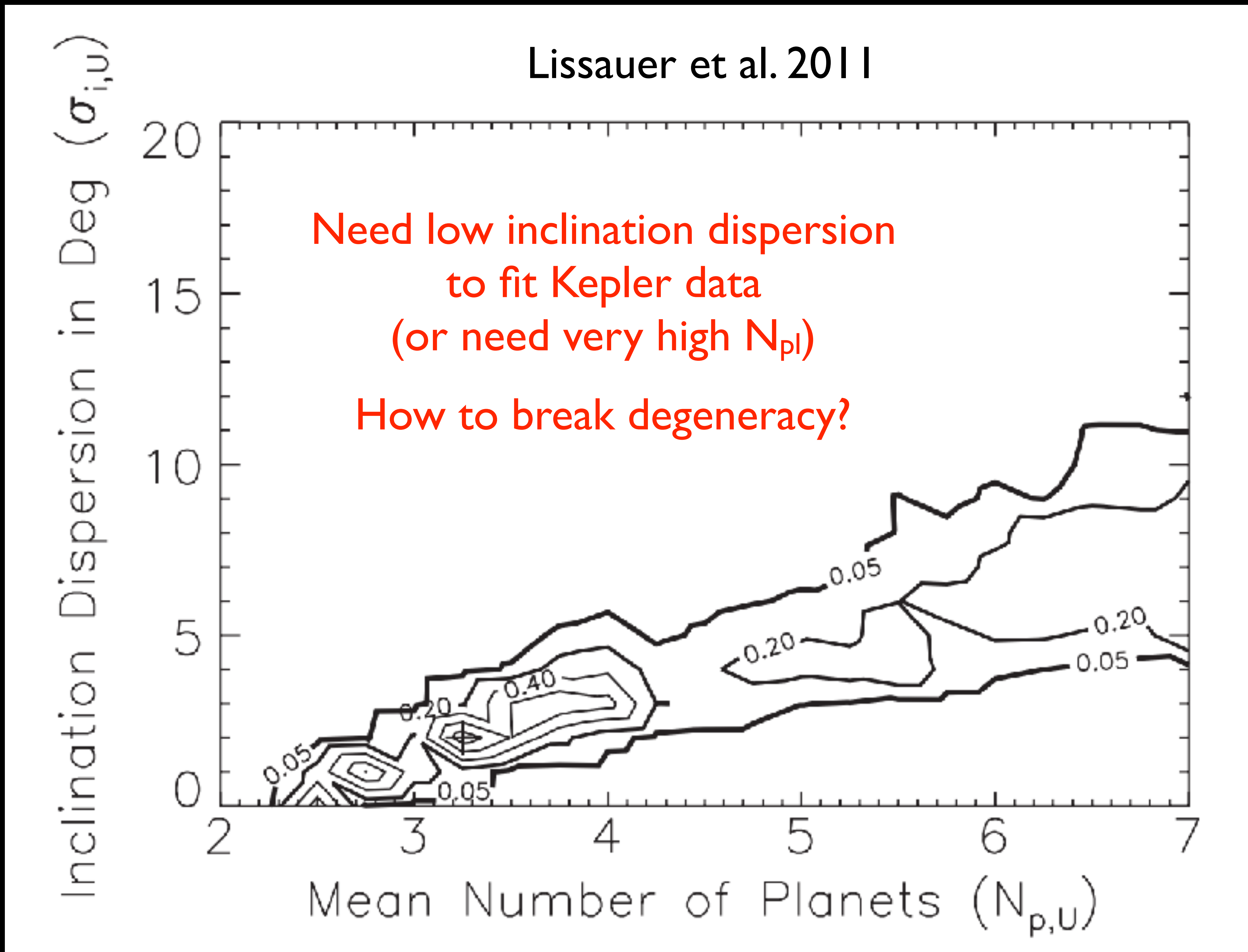
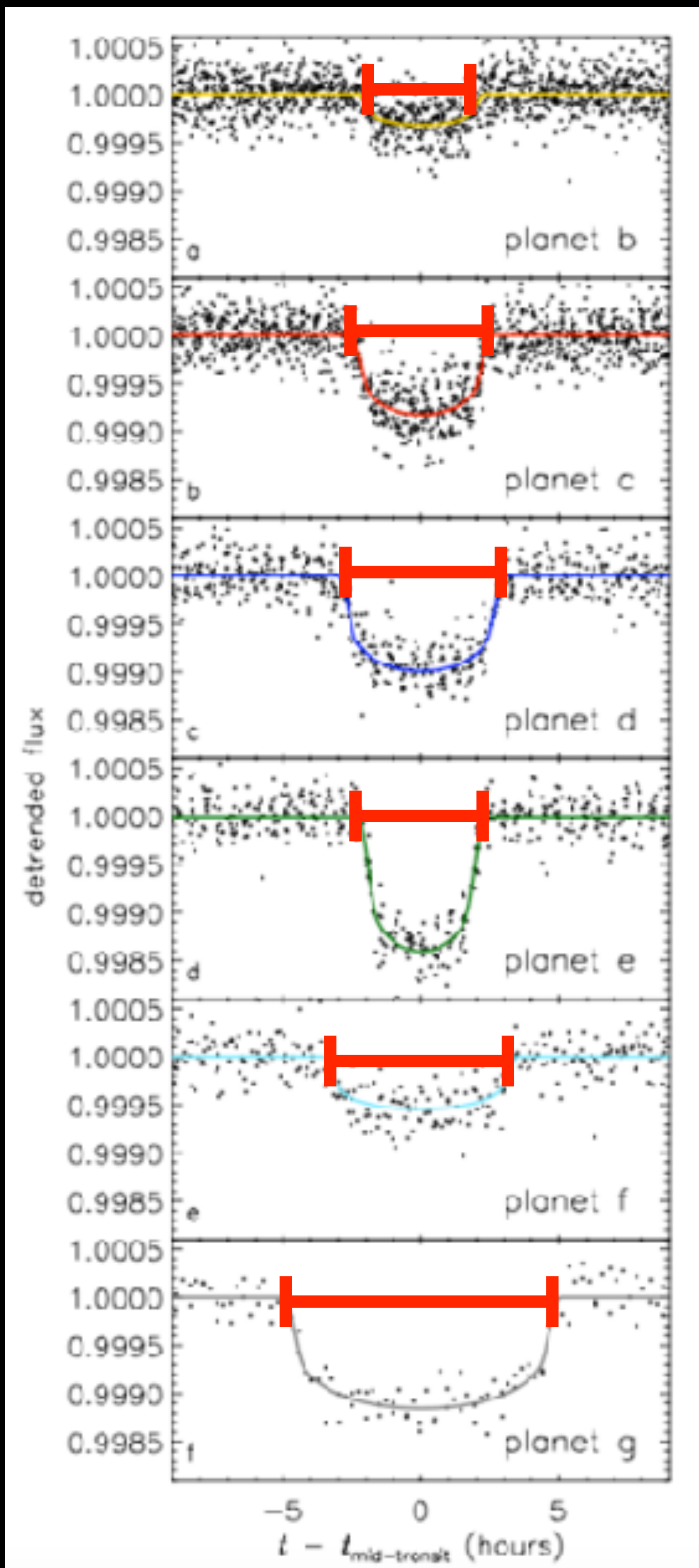


Inclinations from transit durations



innermost planet
(P = 10.3 days)

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

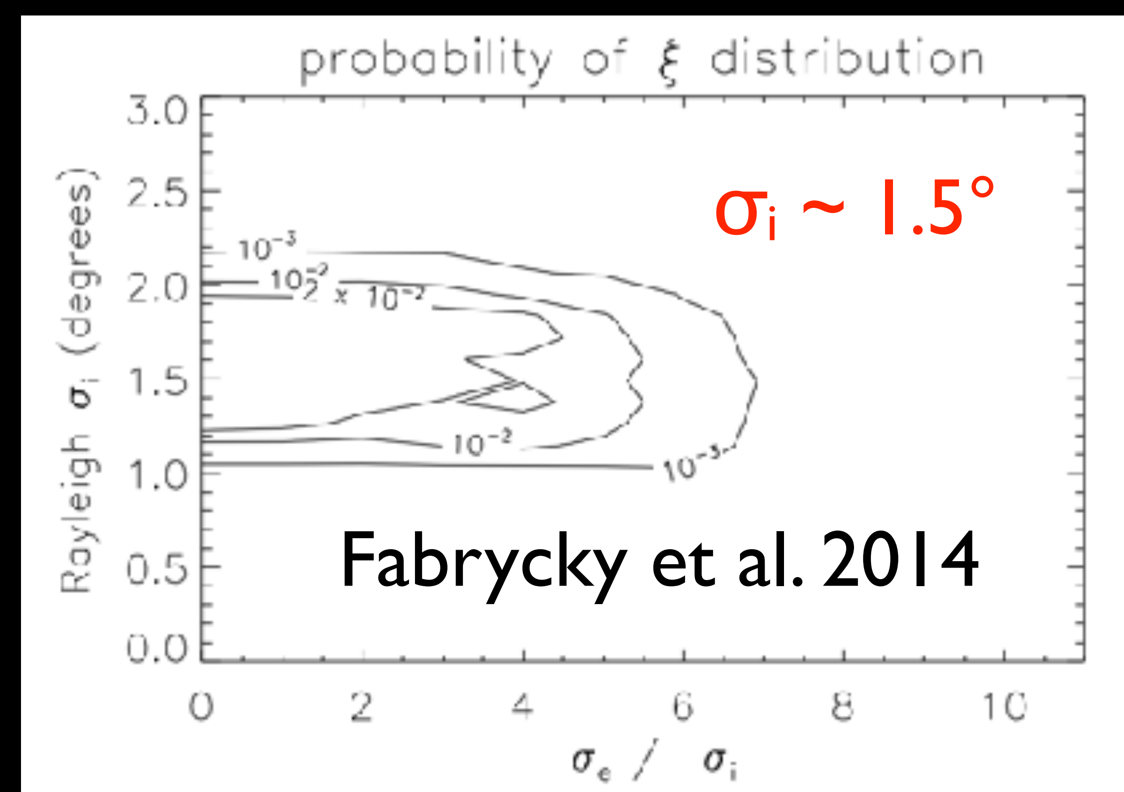
transit duration increases with period

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

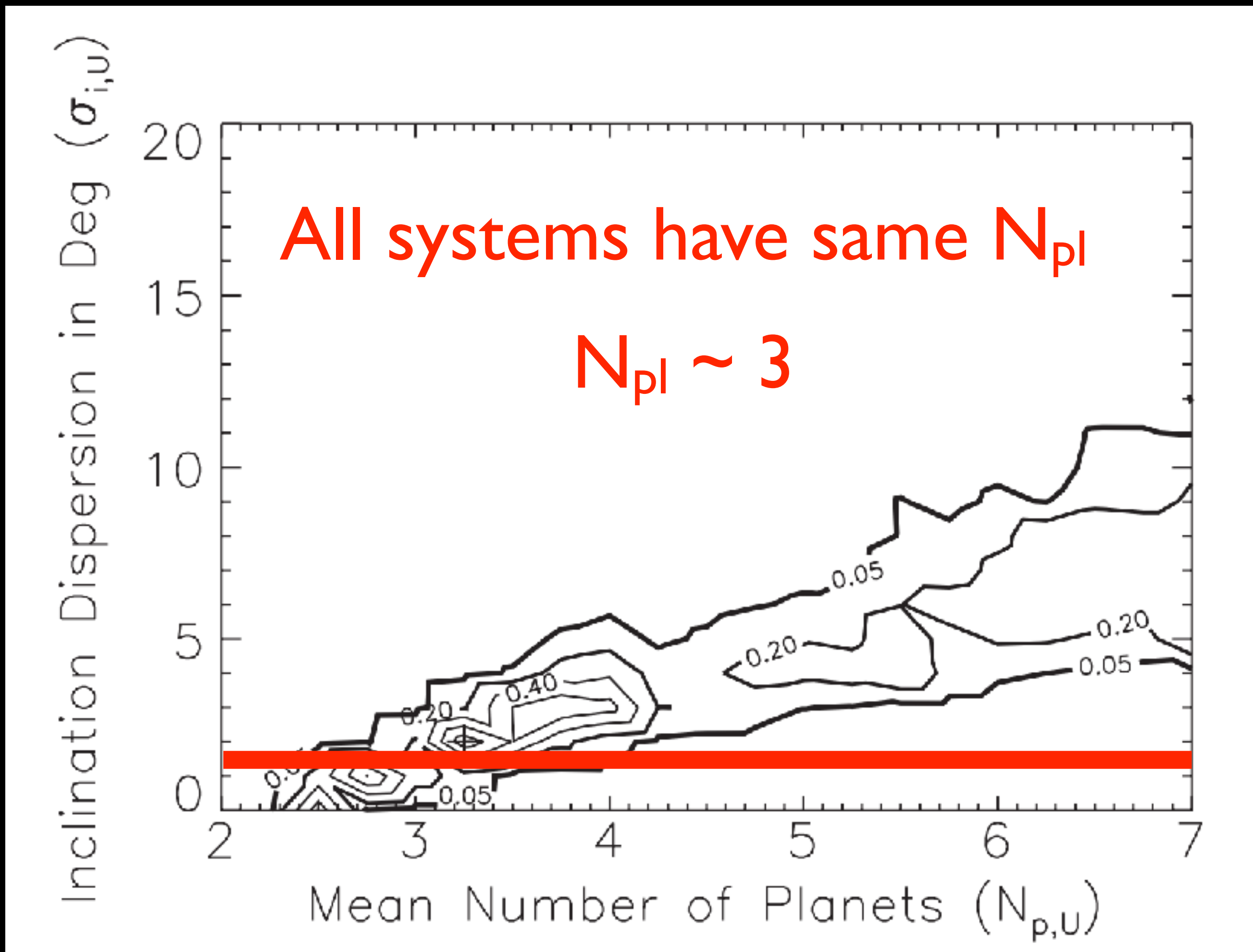
Planet e has a higher inclination!!
(eccentricity is a 2nd order effect)

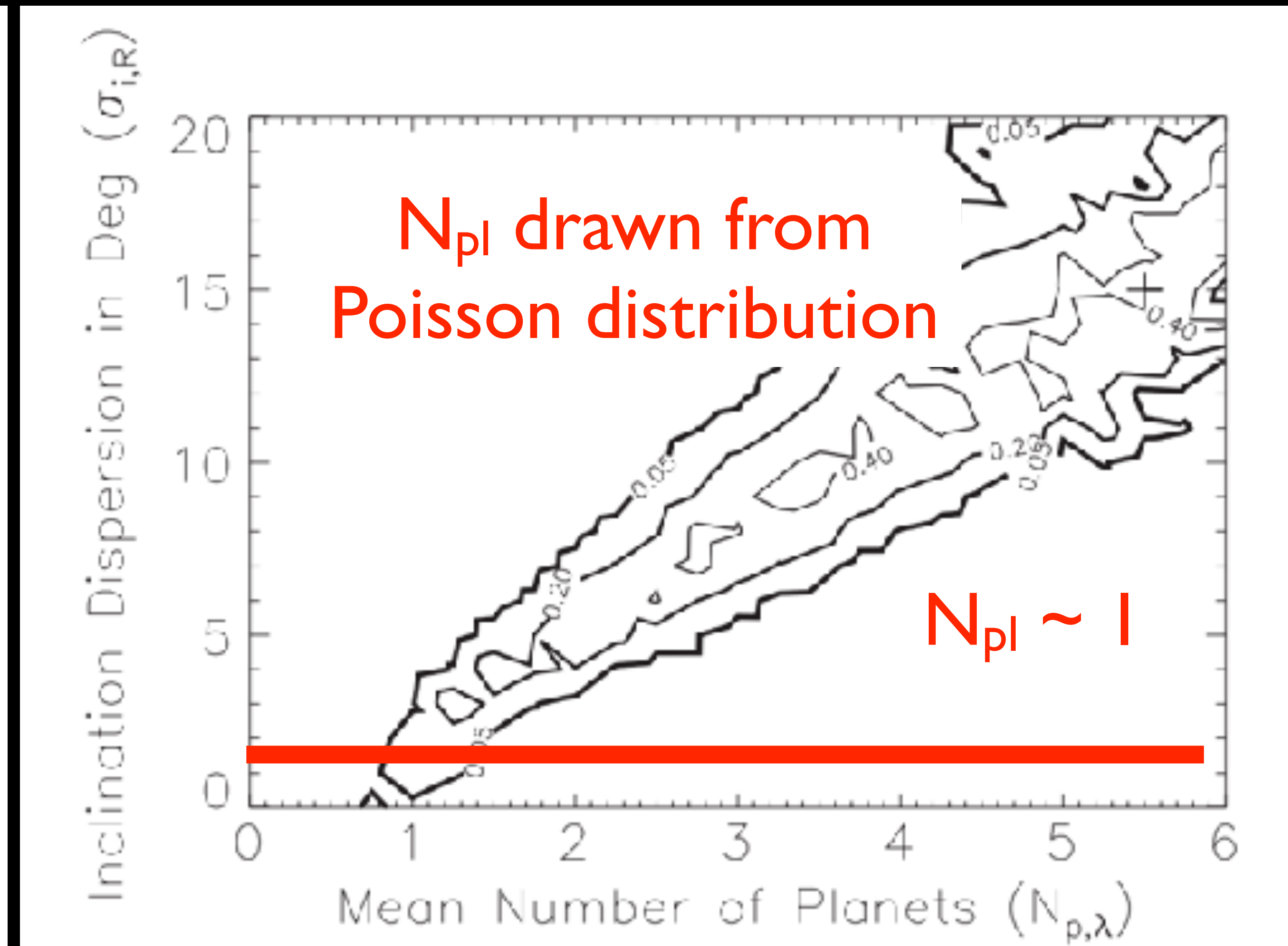
outermost planet
(P = 118 days)

Kepler-11



So, how many planets per system?





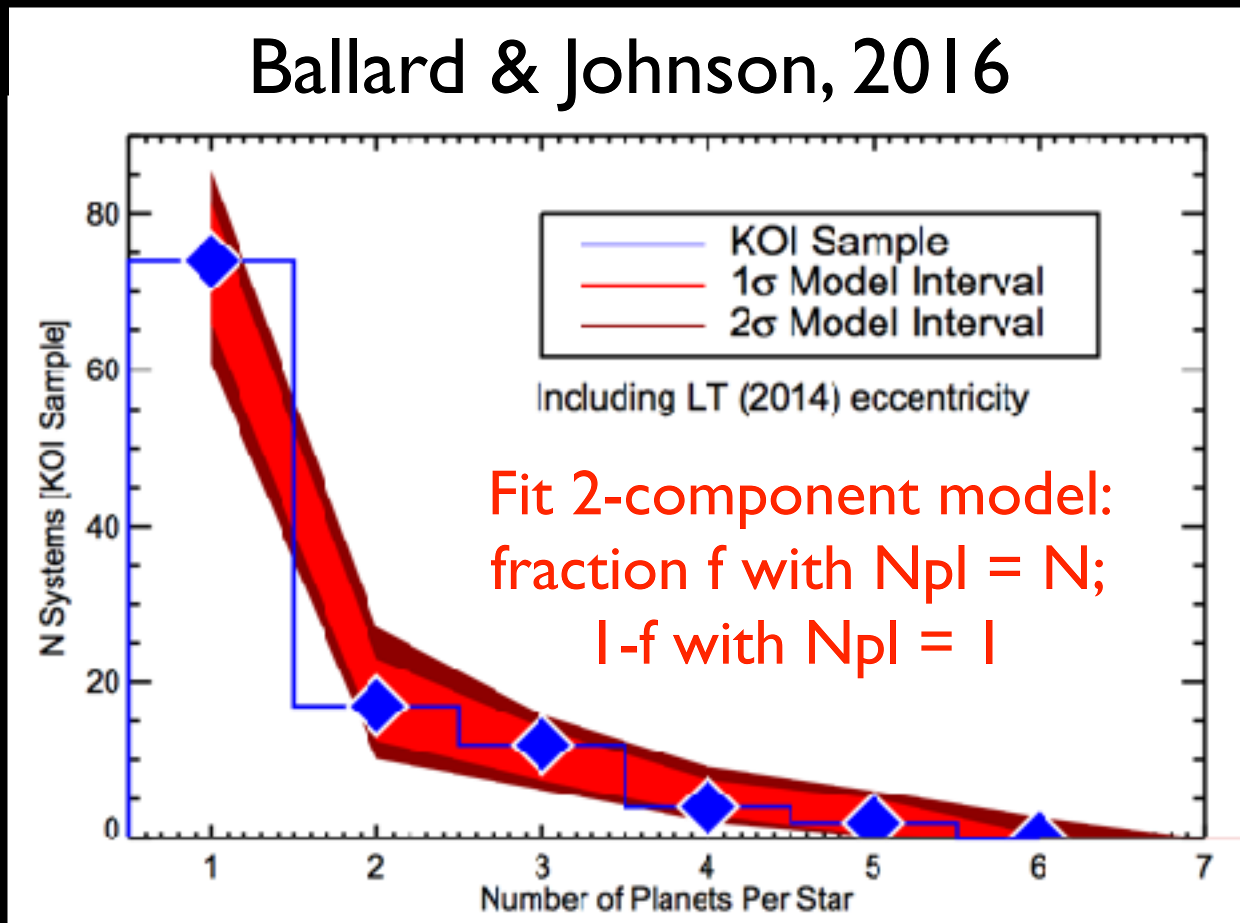
Difficult to fit observed multiplicity distribution with one parameterized true multiplicity distribution

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

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

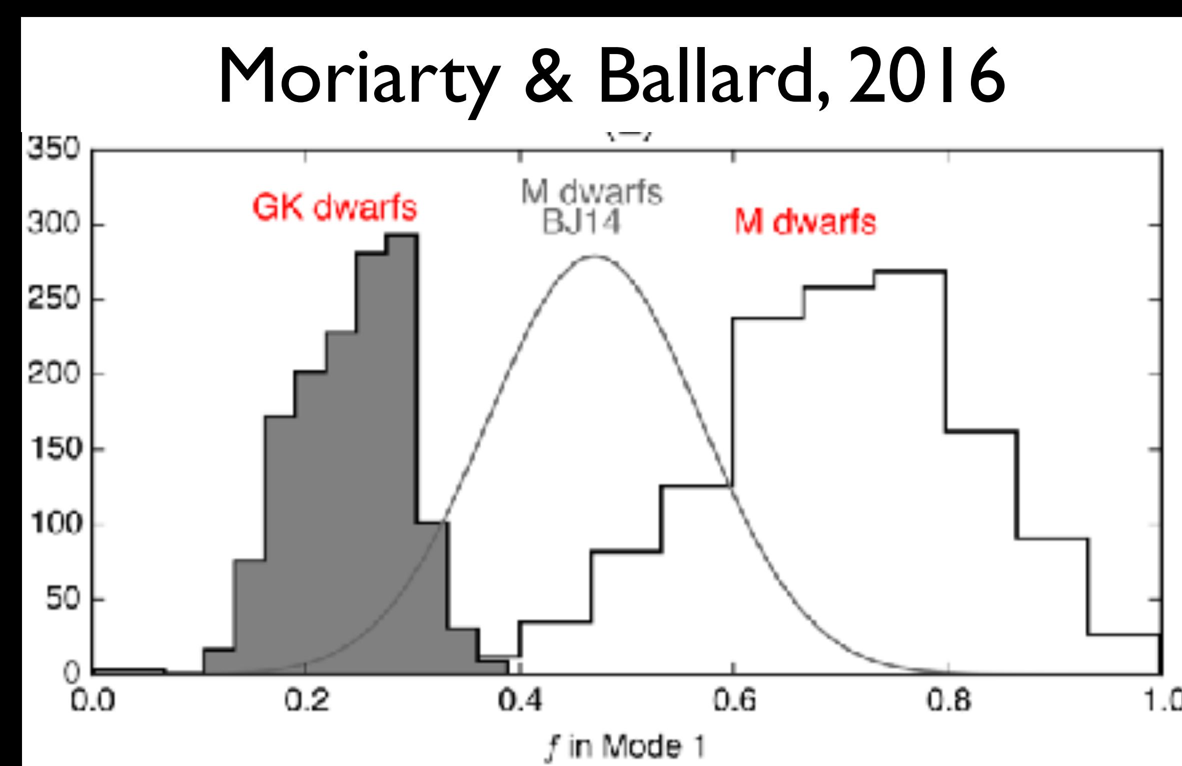
→ the “Kepler Dichotomy”: need > 1 formation pathway!!

An Opportunity from Knowing the Star



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

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



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.