Mapping Exoplanet Discoveries to Exoplanet Populations

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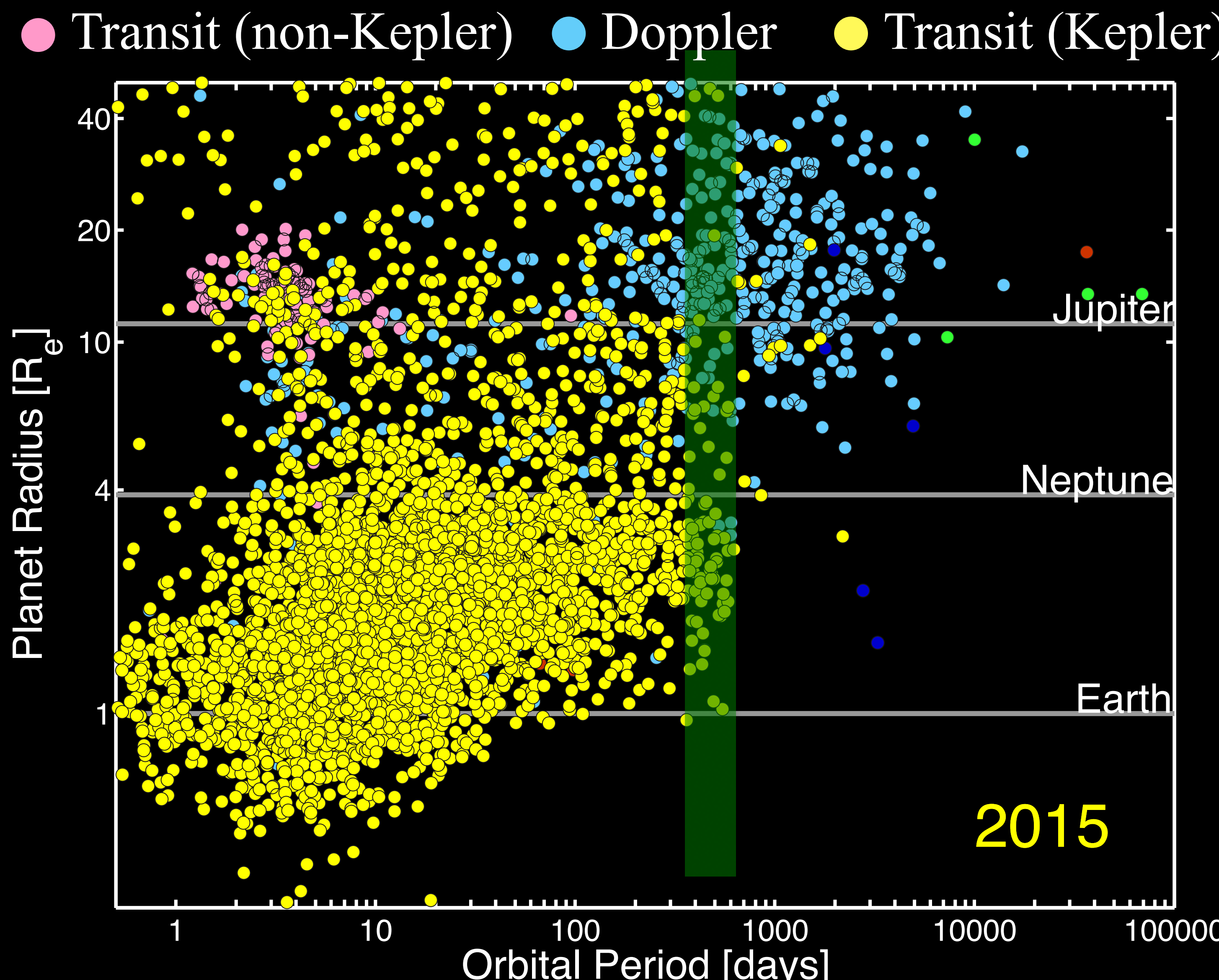
- ✧ Exoplanet Detections
- ✧ De-biasing the Sample
- ✧ Exoplanet Populations
- ✧ Sensitivity Analysis
- ✧ Rocky Planet Populations

Detections

Surveys have produced a statistically significant sample of discoveries orbiting within 1AU down to super-earth sizes.

Exoplanet Discoveries as of Jan 2015

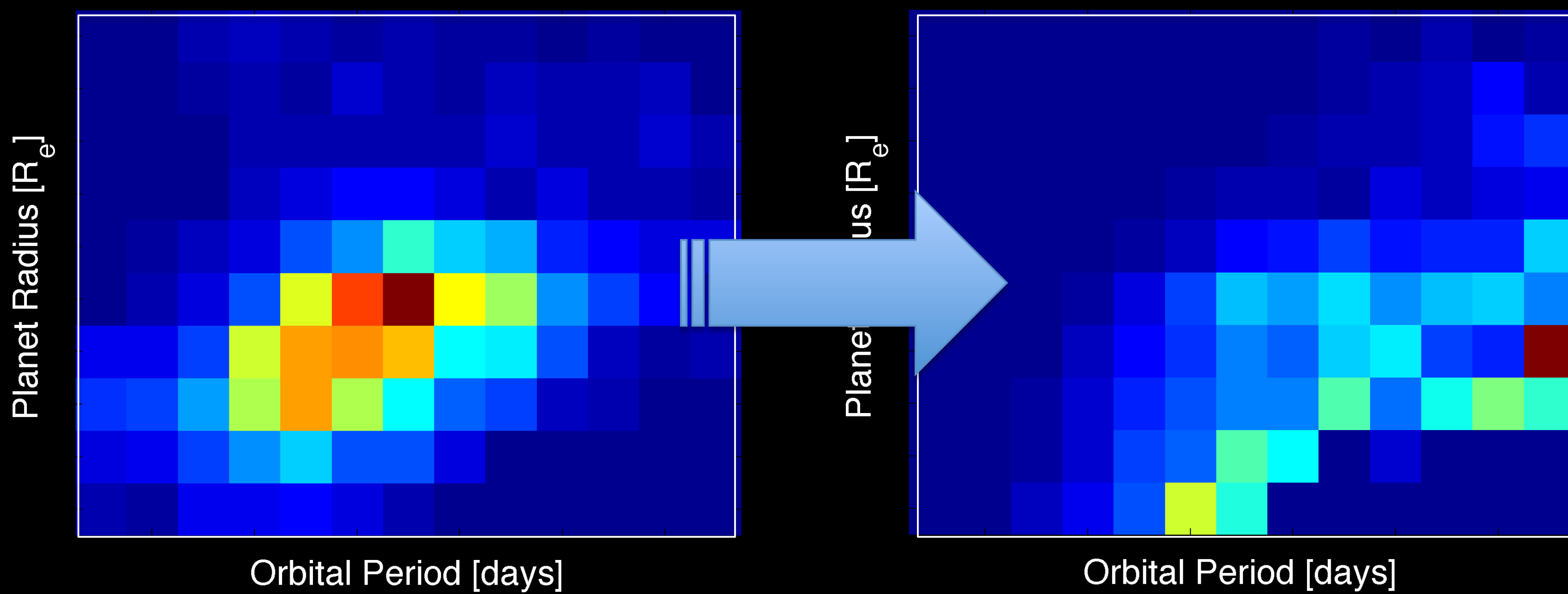


Mullally et al. 2015

Occurrence Rate Products

Using discovery catalogs to derive intrinsic populations requires careful bias corrections.

Transforming and Observed Population into an Intrinsic Population…

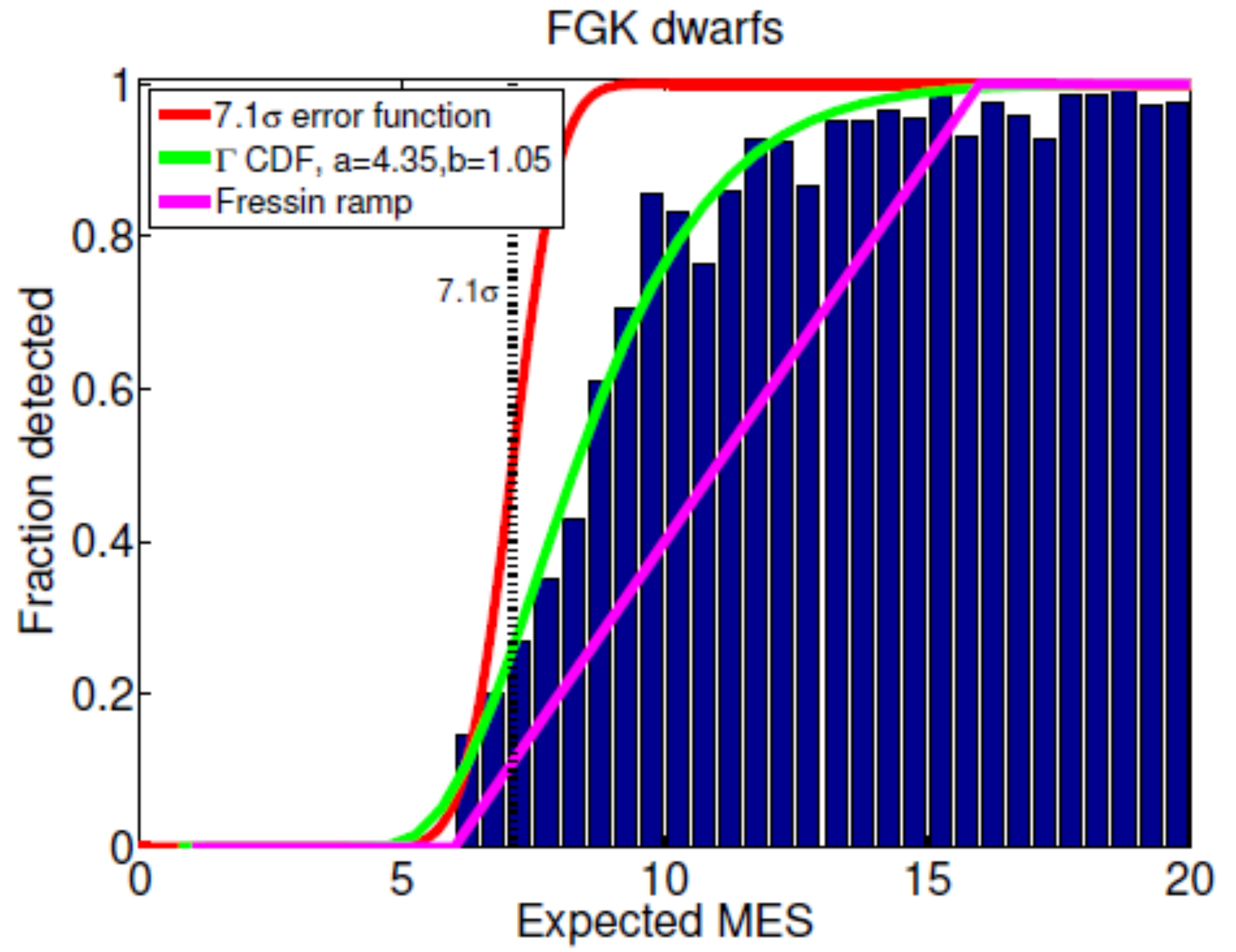


… requires careful bias corrections.

End-to-end Characterization of the Signal Detector Efficiency

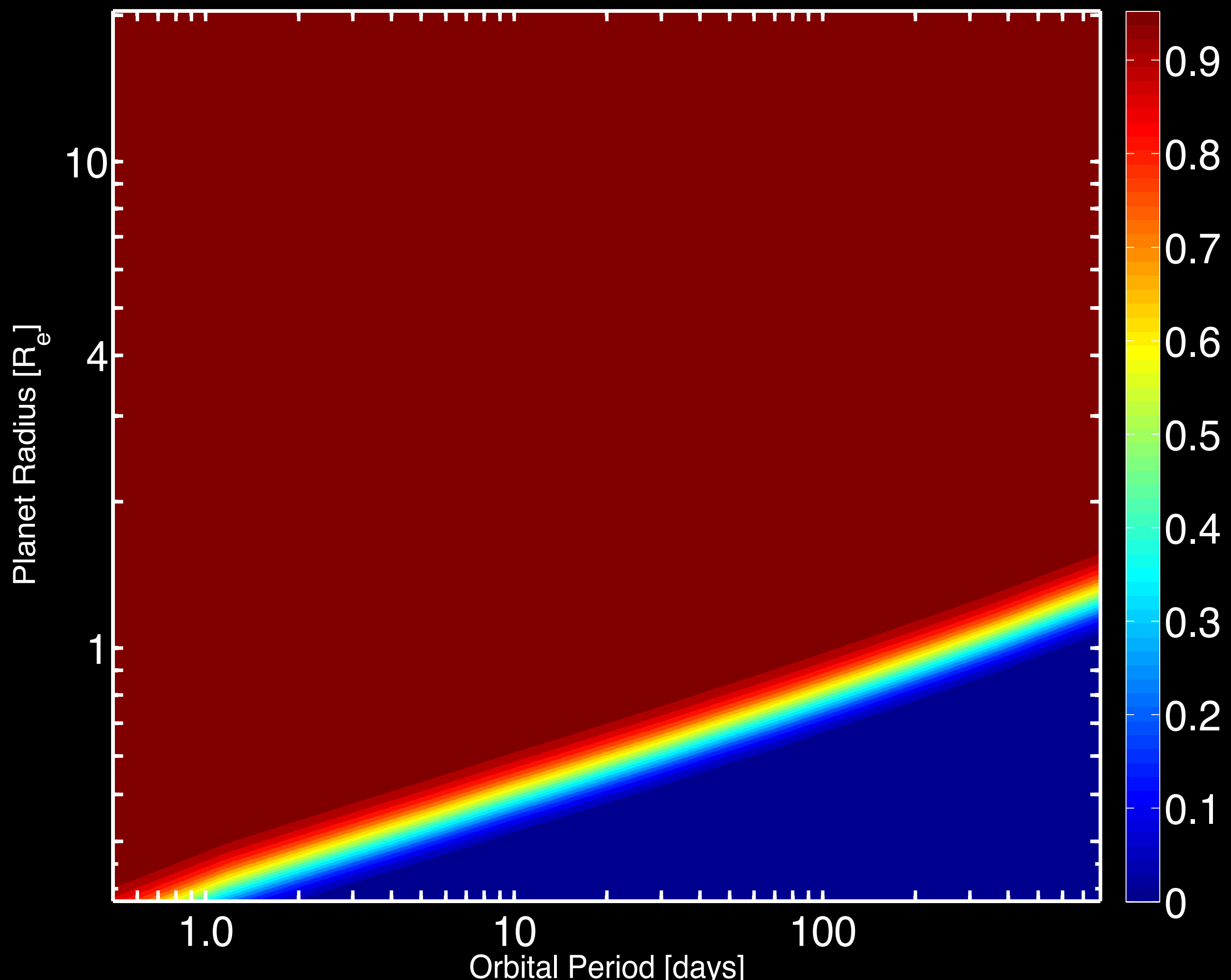
By design, detection efficiency is expected to be a function of MES (SNR) alone.

Quantified via Monte-Carlo transit injection and recovery tests



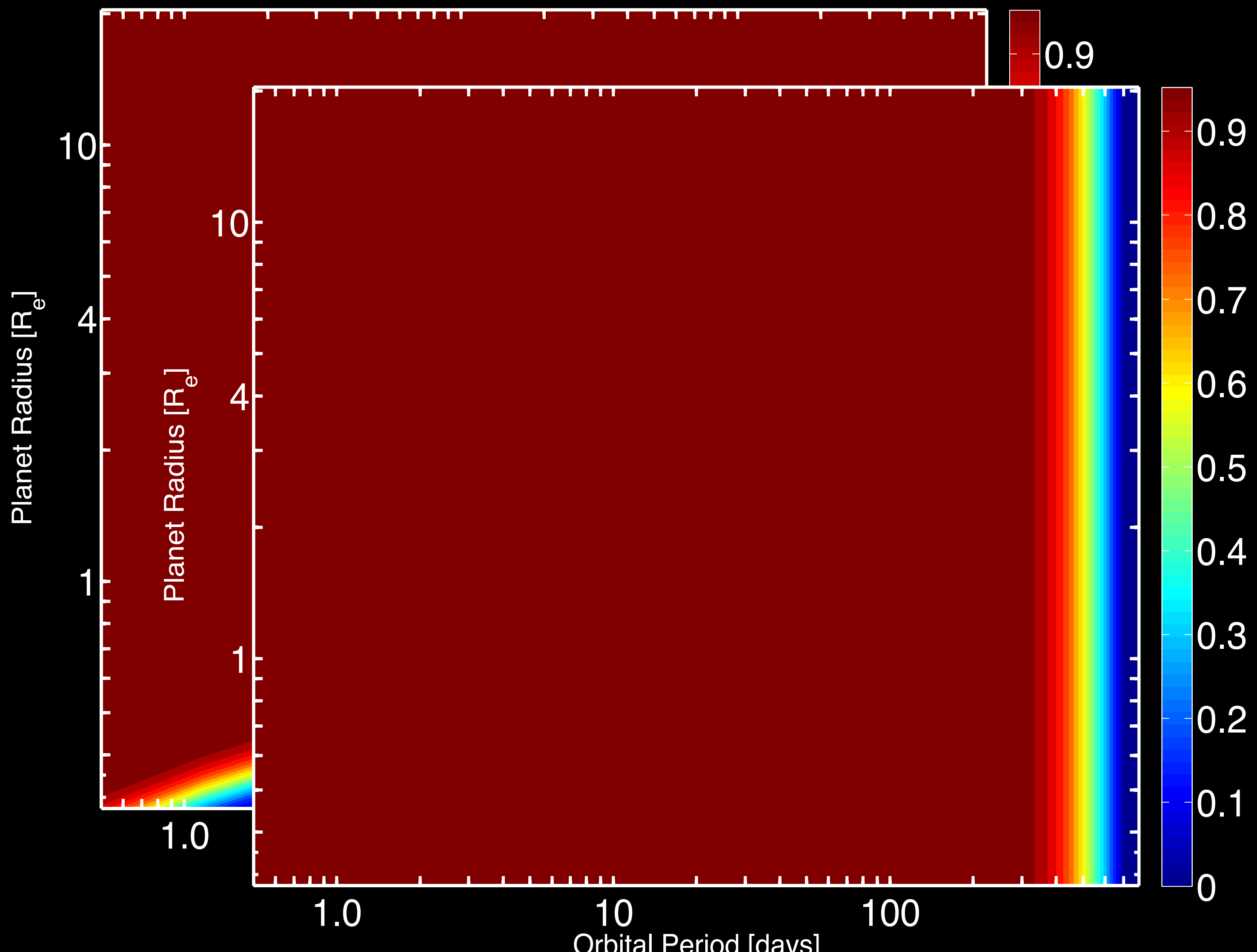
Christiansen et al., submitted

Probability of Detection



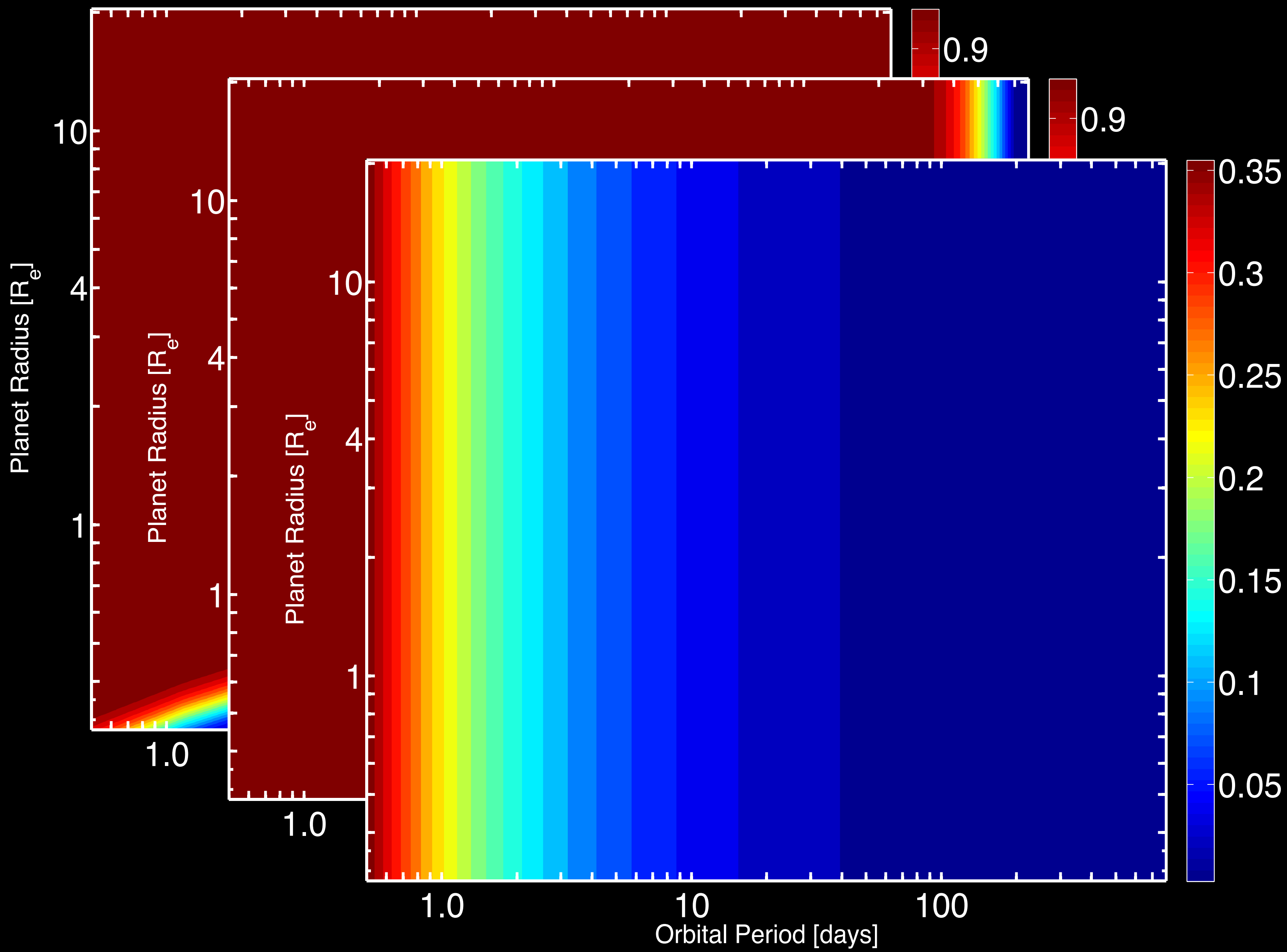
Photometric precision for 14 different durations are available in the Q1-Q16 star properties table at the NASA Exoplanet Archive.

Probability of Seeing 3 Transits

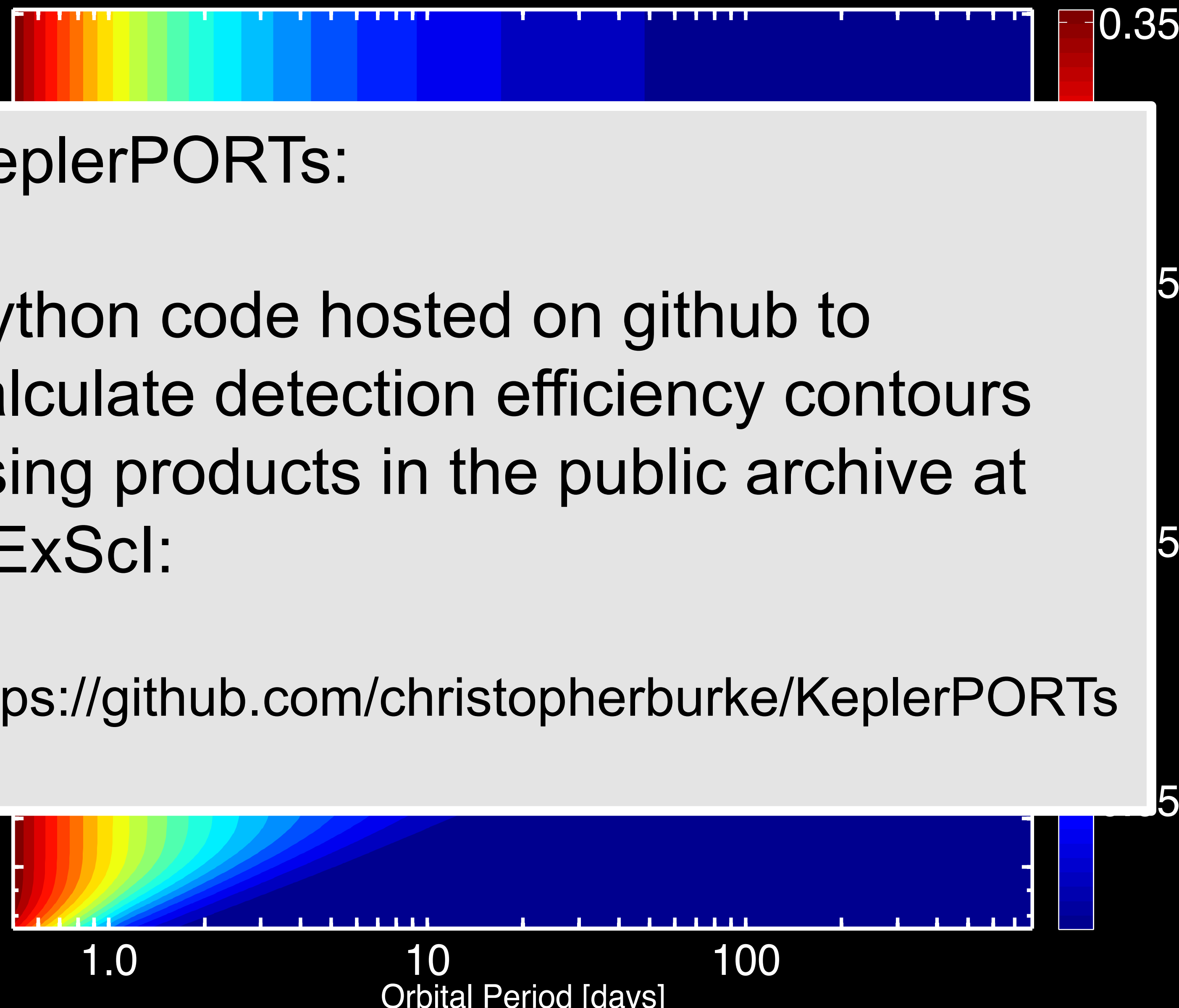


Duty cycle information is now available in the Q1-Q16 star properties table at the NASA Exoplanet Archive.

Geometric Alignment Probability



Total Detection Efficiency: Kepler-22



KeplerPORTs:

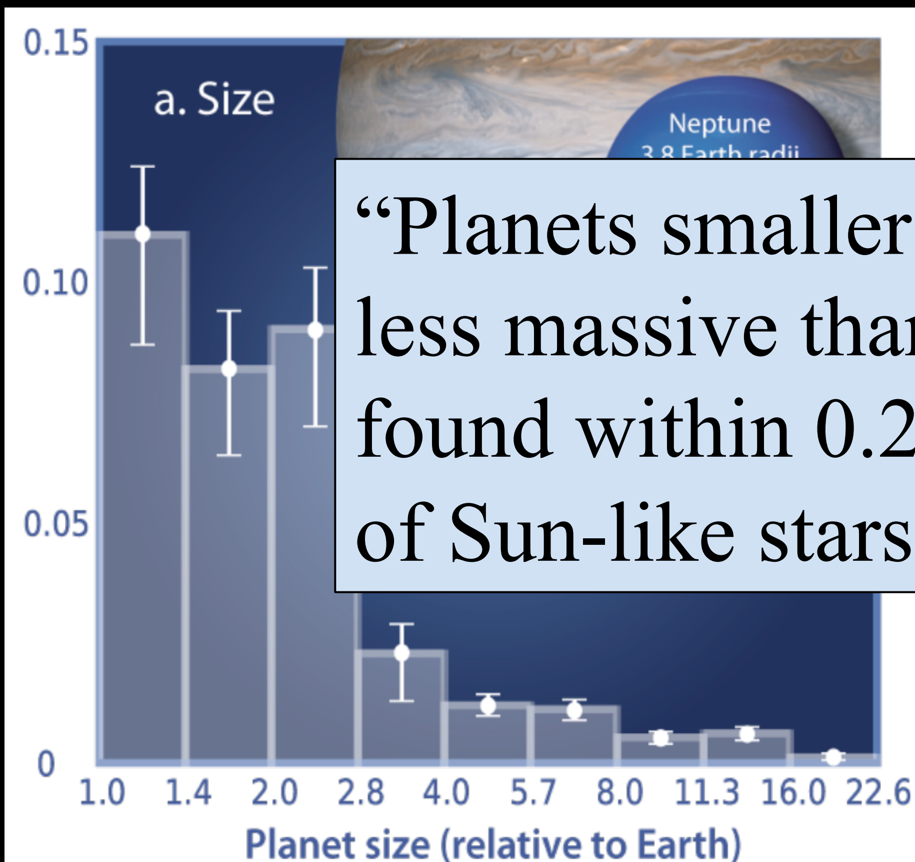
Python code hosted on github to calculate detection efficiency contours using products in the public archive at NExScI:

https://github.com/christopherburke/KeplerPORTs

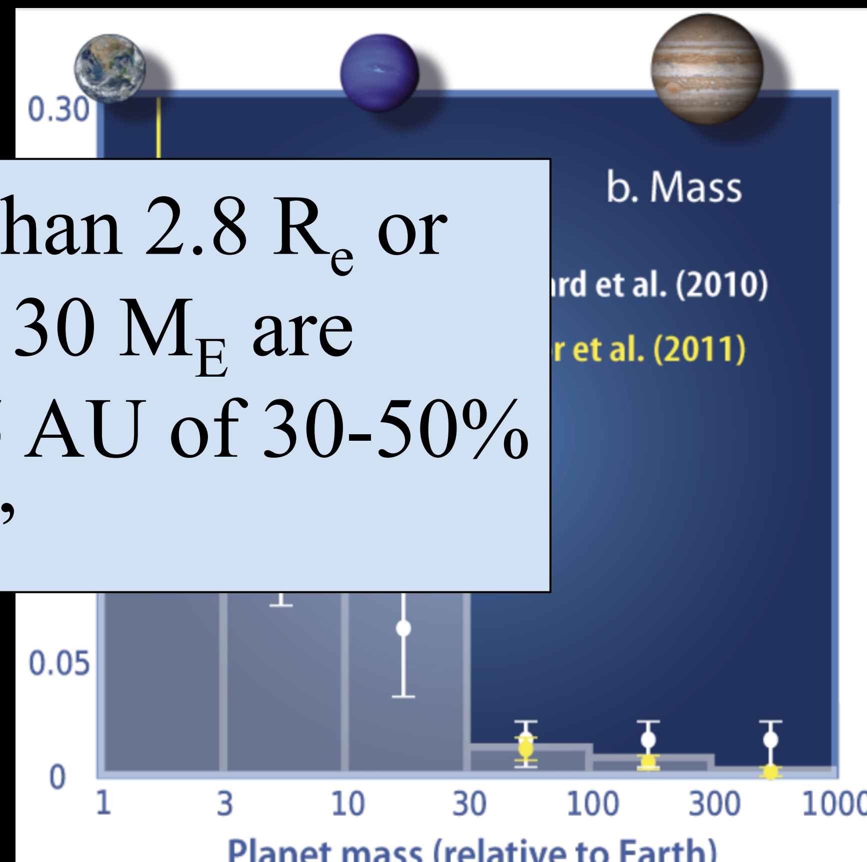
Exoplanet Populations

Doppler, transit, and microlensing surveys have reported on exoplanet occurrence rates.

Both Doppler and Transit surveys report higher frequency of small planets

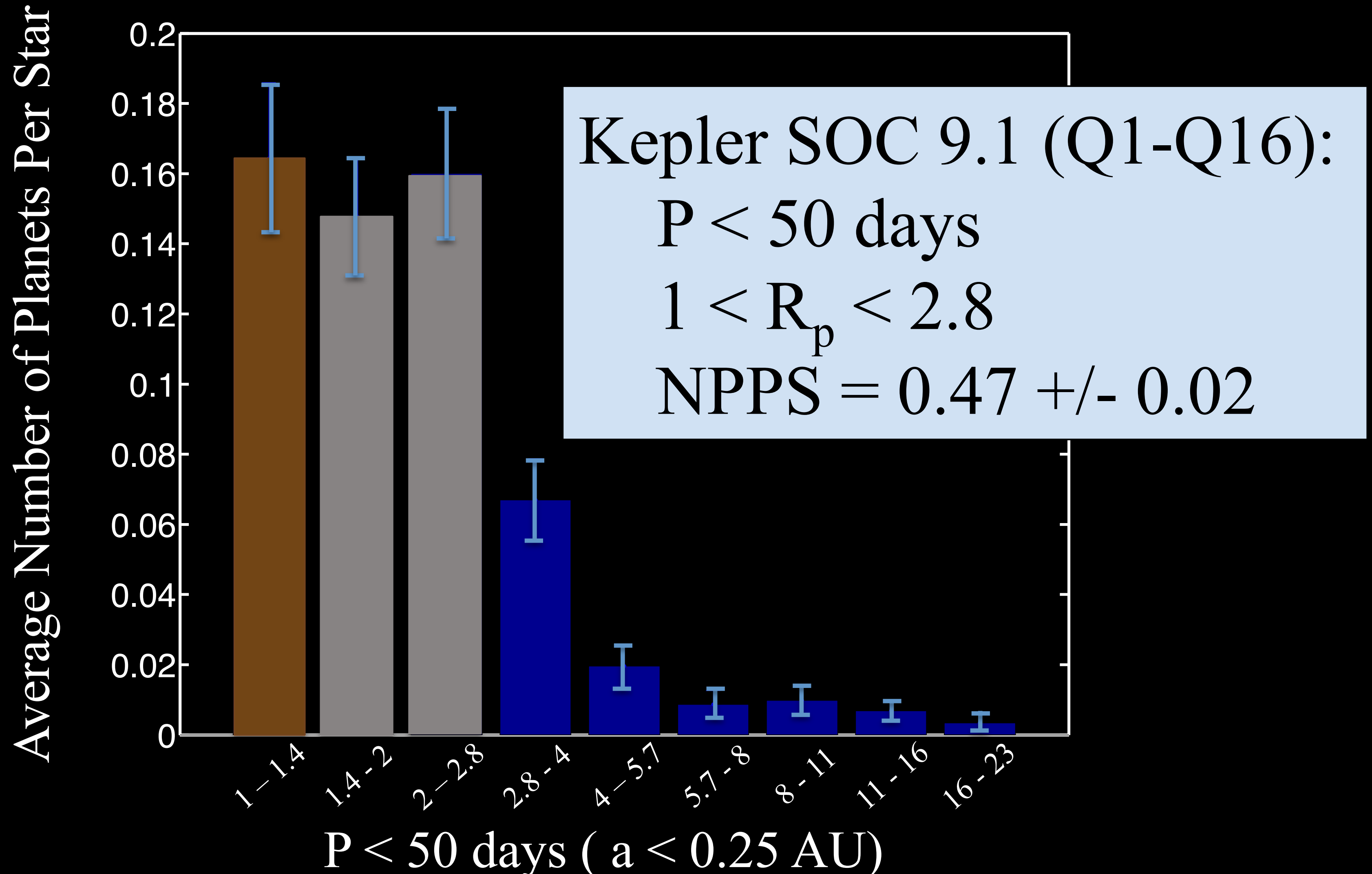


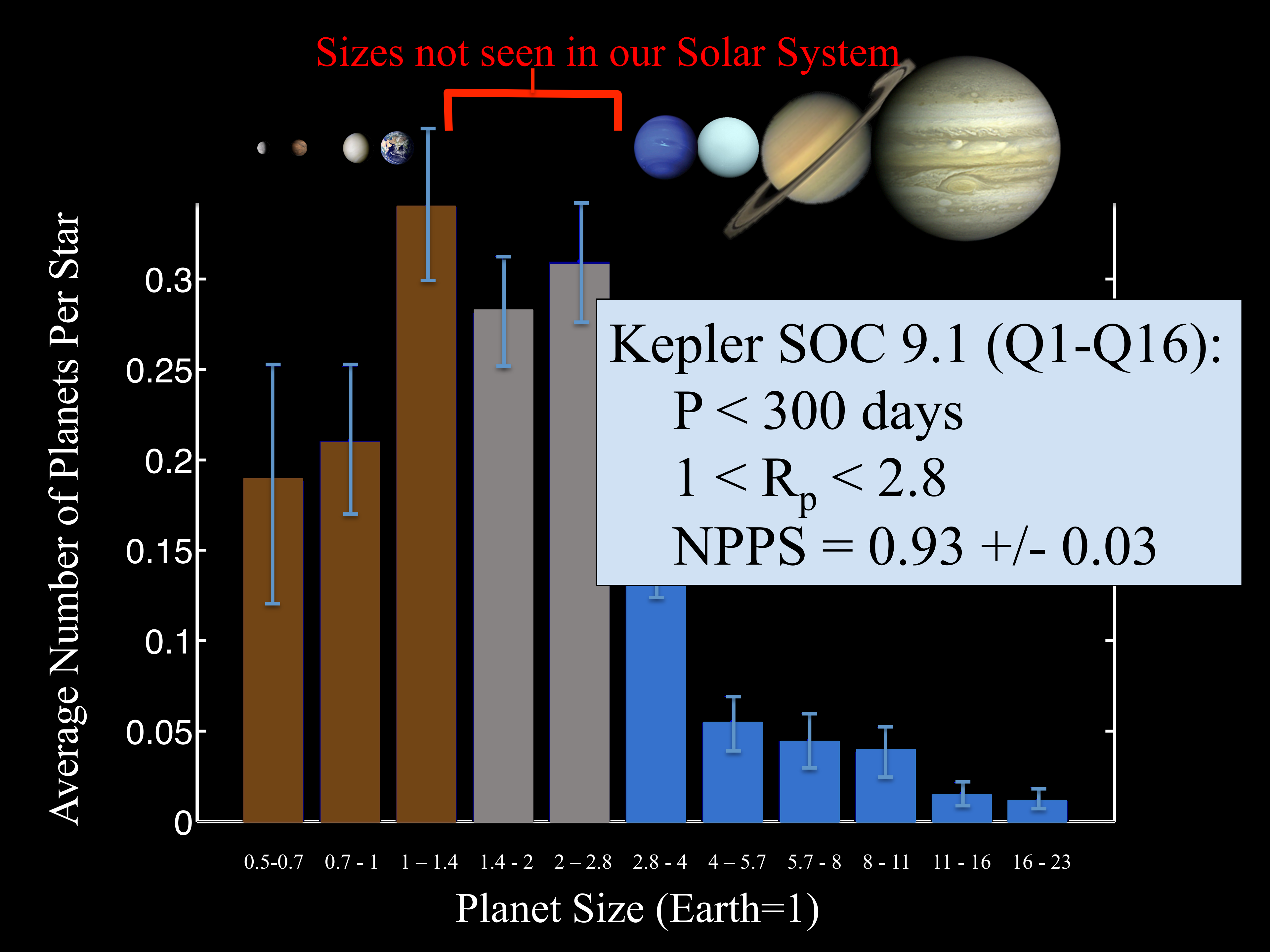
“Planets smaller than 2.8 R_e or less massive than 30 M_E are found within 0.25 AU of 30-50% of Sun-like stars.”



Mean number of planets per star for P < 50 days (a < 0.25 AU)
Image credit: Howard 2013 Science 340 572

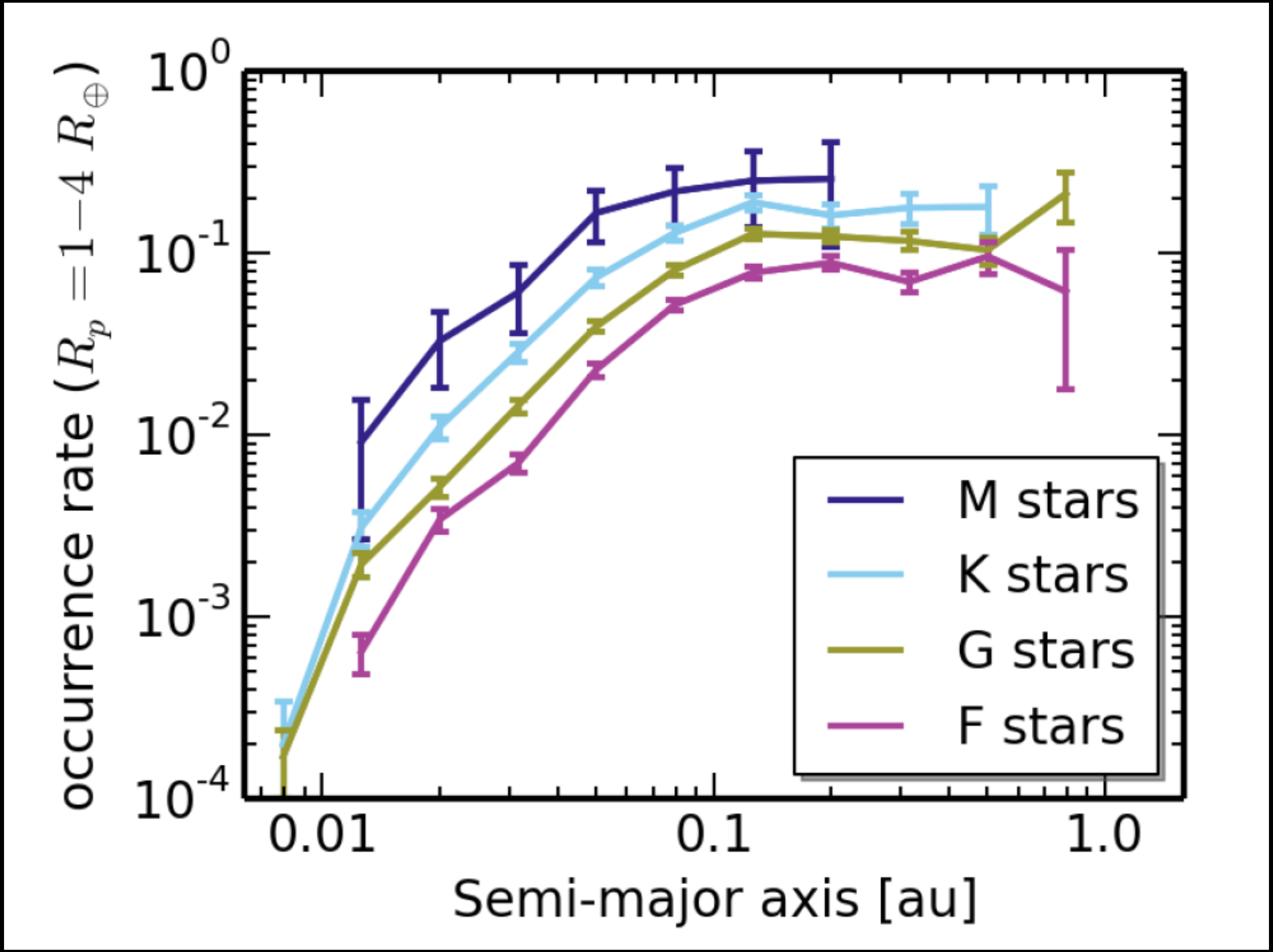
Both Doppler and Transit surveys report higher frequency of small planets





Sizes not seen in our Solar System
Kepler SOC 9.1 (Q1-Q16):
P < 300 days
1 < R_p < 2.8
NPPS = 0.93 +/- 0.03
Average Number of Planets Per Star
0
0.05
0.1
0.15
0.2
0.25
0.3
0.5-0.7
0.7 - 1
1 – 1.4
1.4 - 2
2 – 2.8
2.8 - 4
4 – 5.7
5.7 - 8
8 - 11
11 - 16
16 - 23
Planet Size (Earth=1)

Small planets are more abundant around small stars

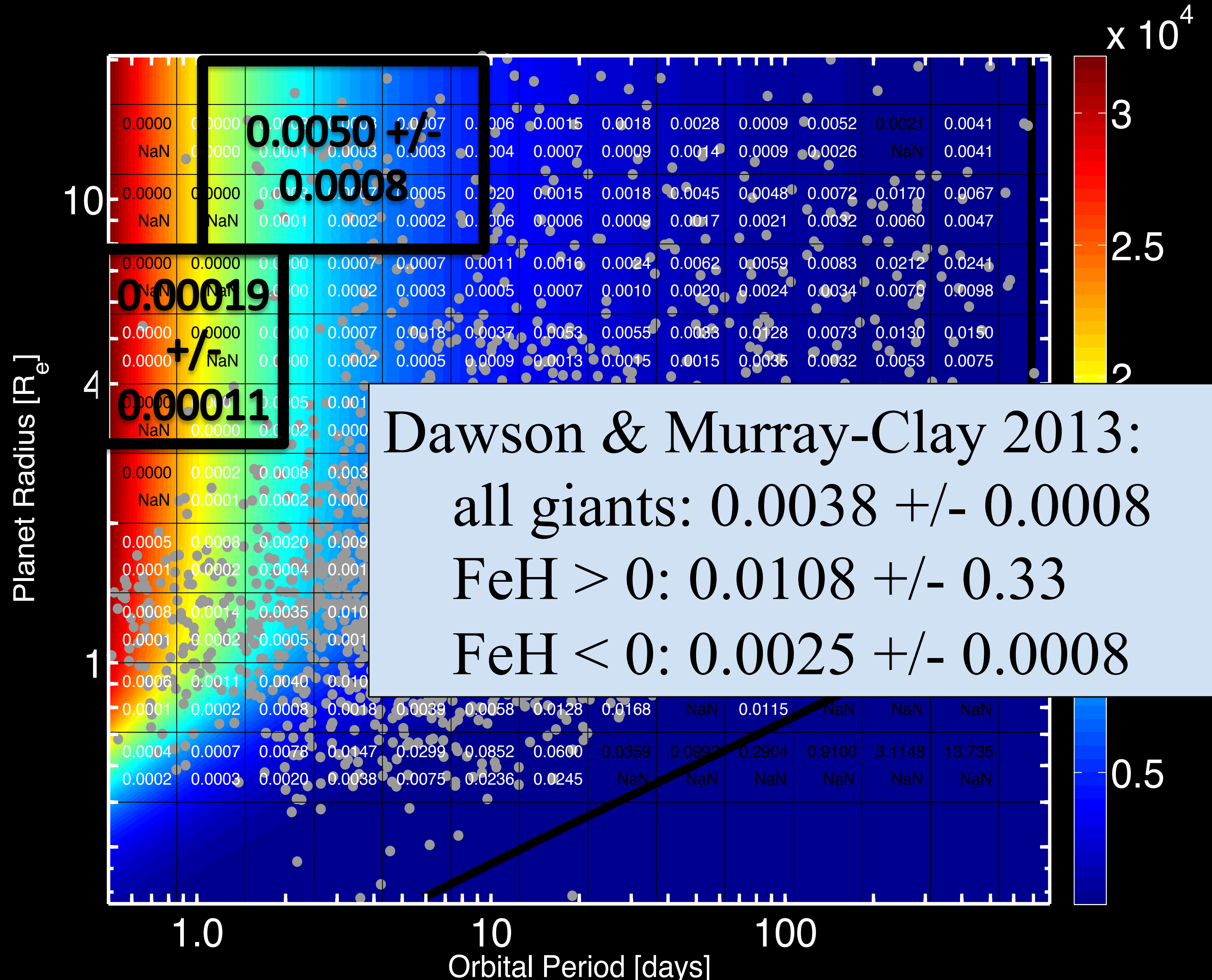


Mulders et al. 2014

Small planets are more adundant around small stars

SpType	1 – 20 Re	1 – 2.5 Re	3 – 4.5 Re
M	1.63 +/- 0.18	1.42 +/- 0.16	No Detections
K	1.47 +/- 0.06	1.07 +/- 0.05	0.16 +/- 0.02
G	1.10 +/- 0.03	0.68 +/- 0.02	0.17 +/- 0.01

For periods ranging from 1 to 300 days

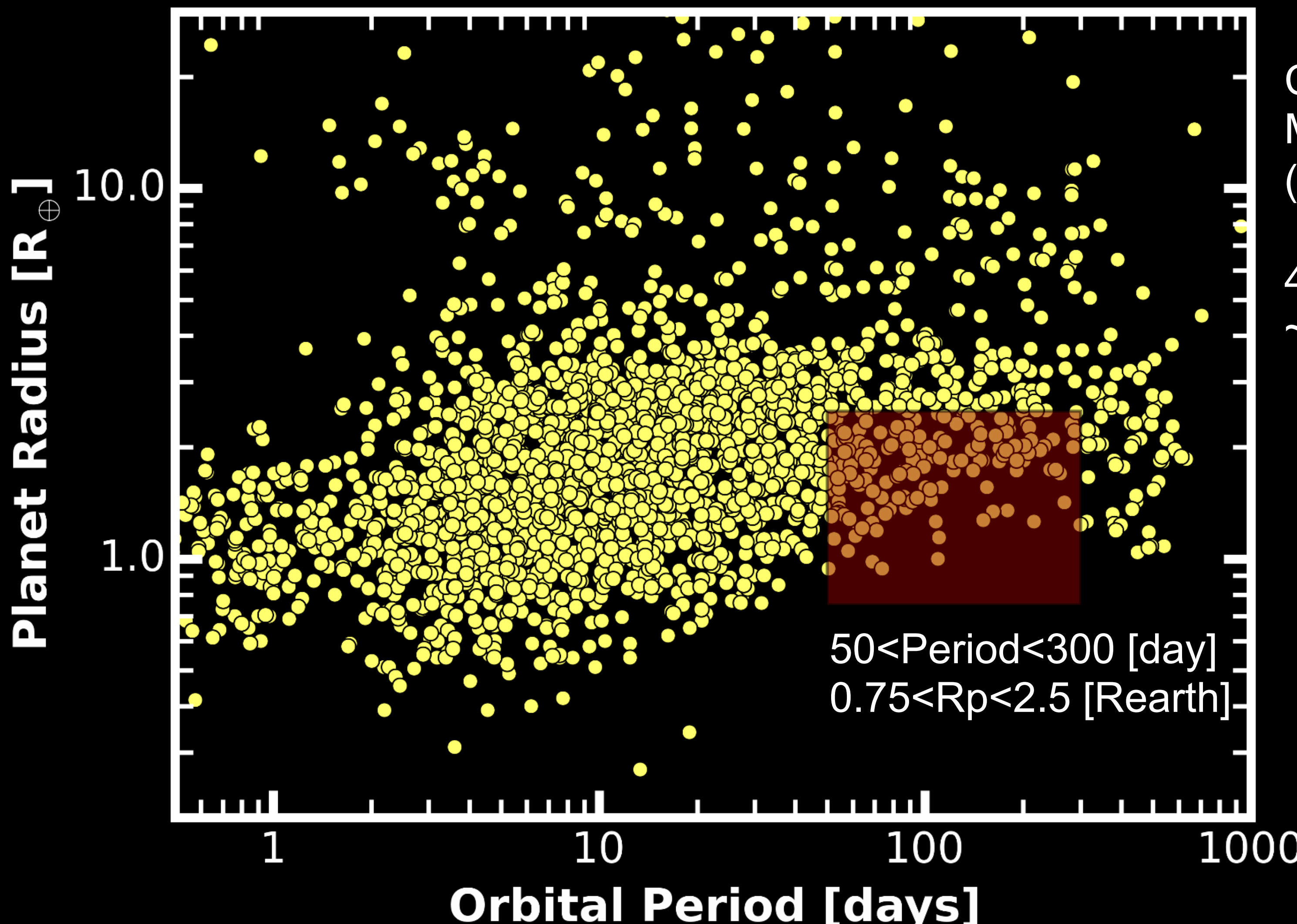


0.0050 +/- 0.0008
0.00019 +/- 0.00011
Dawson & Murray-Clay 2013:
all giants: 0.0038 +/- 0.0008
FeH > 0: 0.0108 +/- 0.33
FeH < 0: 0.0025 +/- 0.0008
Planet Radius [R_e]
Orbital Period [days]
1.0
10
100
10
4
1
x 10^4
3
2.5
2
0.5

Sensitivity Analysis

Q1-Q16 (SOC 9.1 codebase) data products are available at the NExSci Archive. Their use is illustrated in Burke et al. 2015: http://arxiv.org/abs/1506.04175

Analyze Small Planets with Intermediate Periods



Catalog:
Mullally et al. (2015)

4200 – 6100 K
~ GK V

Planet Occurrence Methodology

5 Parameter Model

Broken power-law in planet radius

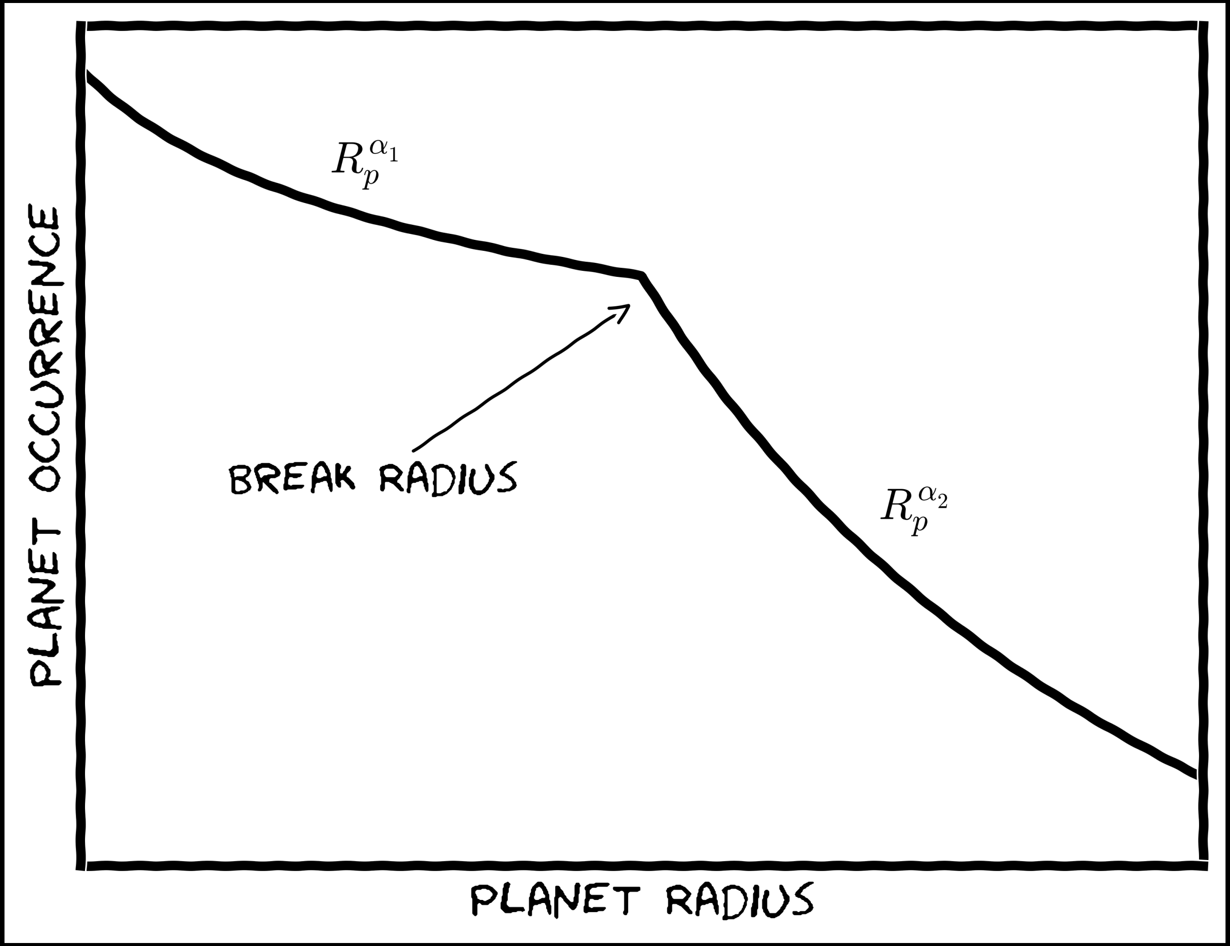
- Rbrk
- α_1
- α_2

power-law in orbital period

- β

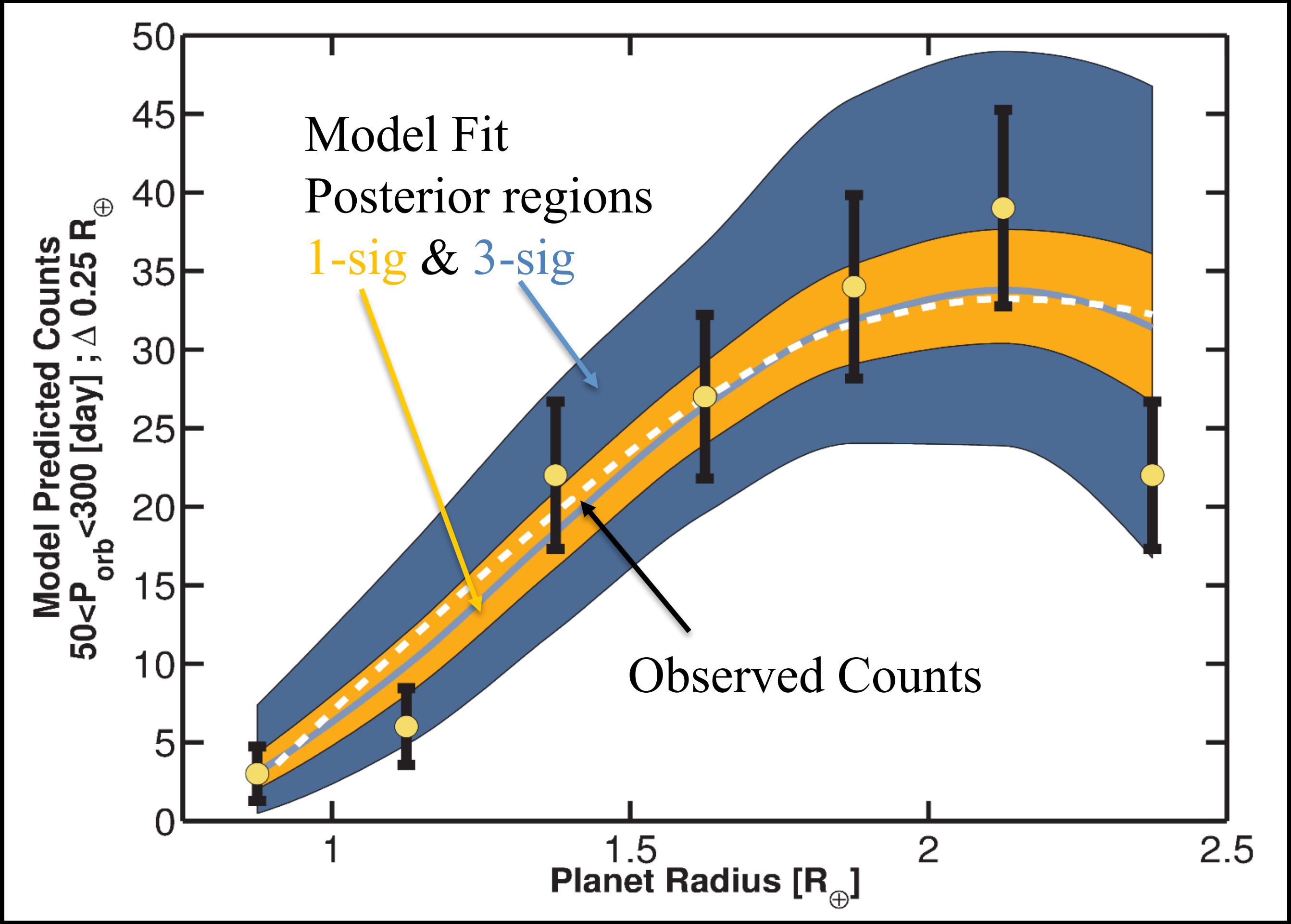
Normalization

- F_o

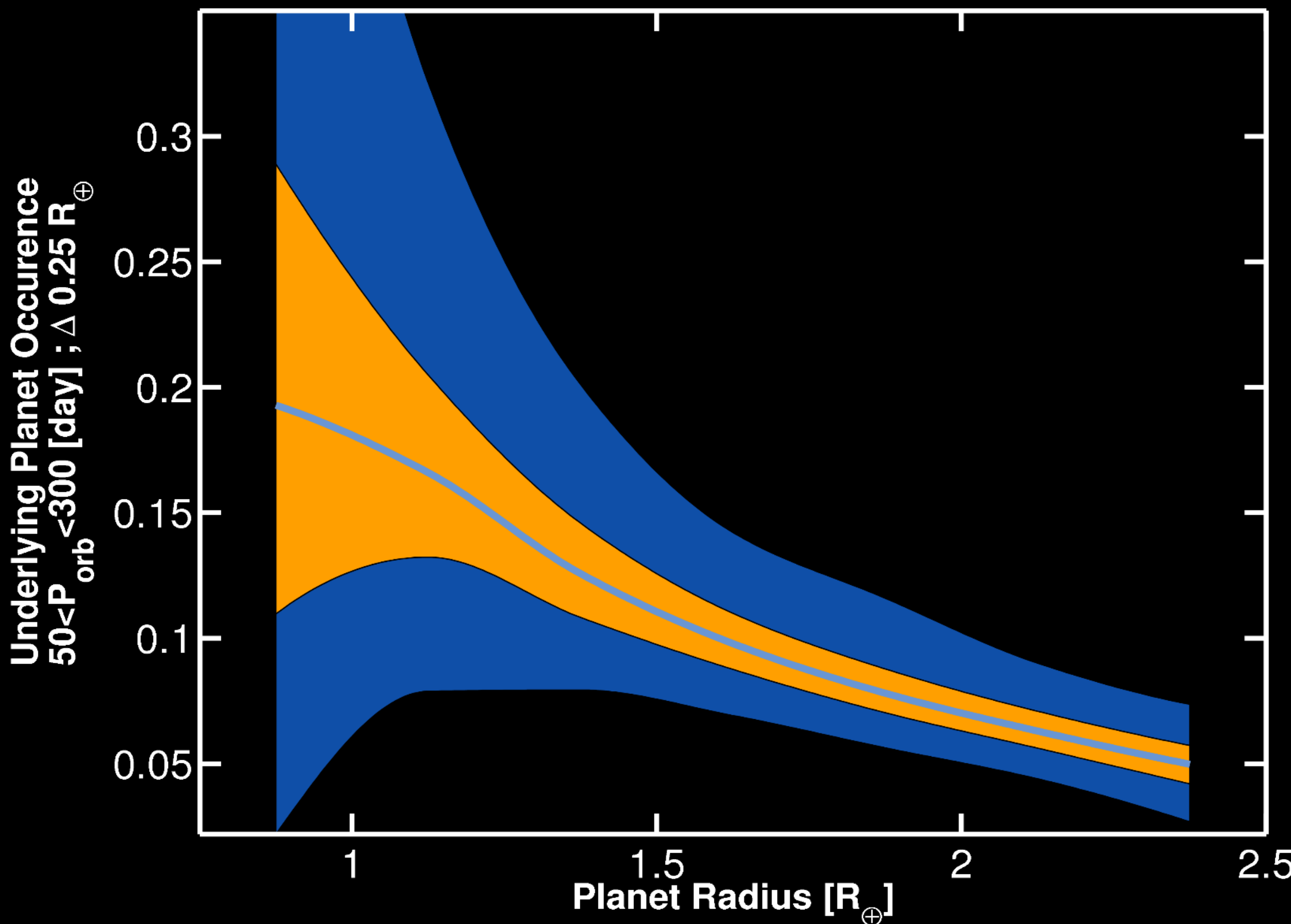


Bayesian Parameter Estimation
MCMC methods; Poisson Likelihood

Intrinsic Planet Distribution & Detection Bias Model Fitting



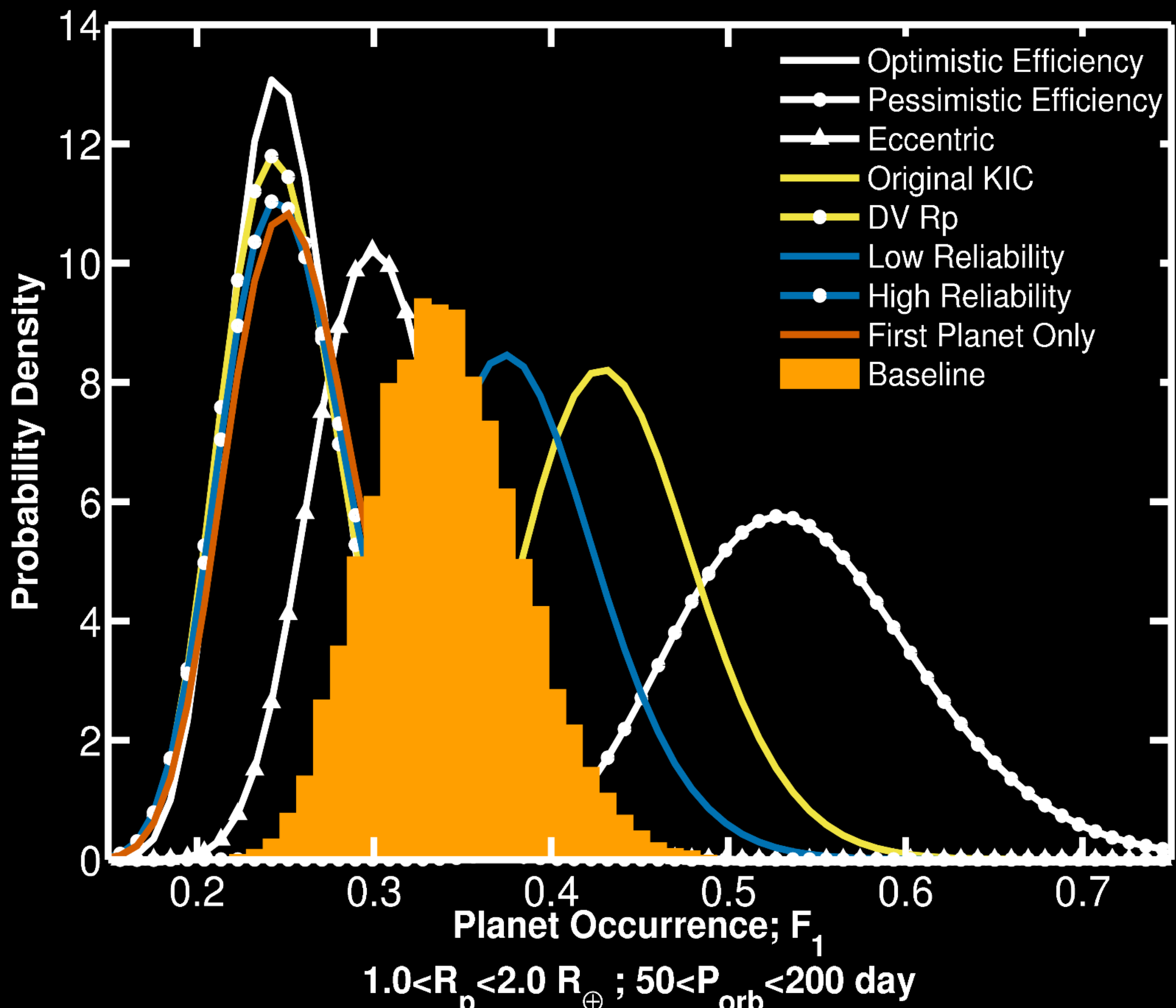
Remove The Detection Bias Component
Intrinsic Planet Distribution



Increasing Planet Occurrence Toward Terrestrial Planets

Average number of planets per star integrated over this phase space: 0.77 +/- 0.12

Systematic Errors > Statistical Errors



Kepler's ExoPop Hack

Dates: October 13, 14, 15
Duration: Three days
Participation: < 25, including project personnel
Core participants:

- Andrew Howard, UH
- Courtney Dressing, Cal Tech
- David Hogg, NYU
- Daniel Foreman-Mackey, UW
- Darin Ragozzine
- Gijs Mulders, UA

Location:

- ARC, Building 232

Small HZ Planets

The challenge is to improve sensitivity, quantify false alarm rate, and compute realistic uncertainties.

Table 2. Occurrence rates of "Earth-like planets"

Type of star	Type of planet	Approx. HZ boundaries* $[S/S_\oplus]$	Occurrence rate [%]	Reference
M	1-10 $M_\oplus$	0.75-2.0	41^{+54}_{-13}	1
FGK	0.8-2.0 $R_\oplus$	0.3-1.8	$2.8^{+1.9}_{-0.9}$	2
FGK	0.5-2.0 $R_\oplus$	0.8-1.8	34 ± 14	3
M	0.5-1.4 $R_\oplus$	0.46-1.0	15^{+13}_{-6}	4
M	0.5-1.4 $R_\oplus$	0.22-0.80	48^{+12}_{-24}	5
GK	1-2 $R_\oplus$	0.25-4.0	11 ± 4	6
FGK	1-2 $R_\oplus$	0.25-4.0†	$\sim 0.01^\dagger$	7
FGK	1-4 $R_\oplus$	0.35-1.0	$6.4^{+3.4}_{-1.1}$	8
G	0.6-1.7 $R_\oplus$	0.51–1.95	$1.7^{+1.8}_{-0.9}$	9

Note. — References: (1) Bonfils et al. (2013), (2) Catanzarite & Shao (2011), (3) Traub (2012), (4) Dressing & Charbonneau (2013), (5) Kopparapu (2013), (6) Petigura et al. (2013), (7) Schlaufman (2014), (8) Silburt et al. (2014), (9) Foreman-Mackey et al. (2014). In column 3, S refers to the incident flux of starlight on the planet, and $S_\oplus$ to the Earth's insolation. All these works are based on *Kepler* data except (1) which is based on the HARPS Doppler survey, and

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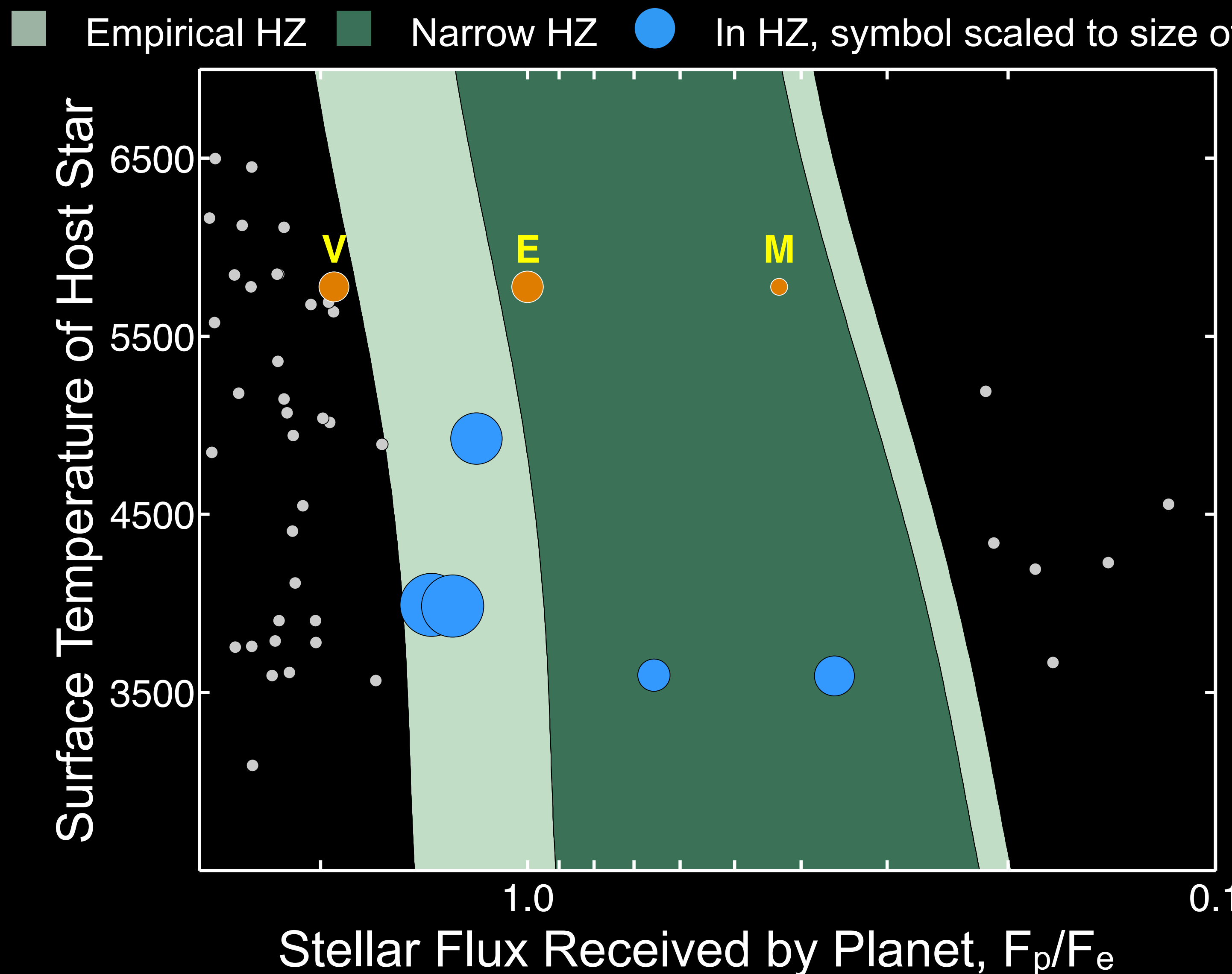
"… the uncertainty is limited for the foreseeable future by our ignorance of the appropriate limits of integration." Winn & Fabrycky 2014 ARAA

ExoPAG SAG-13

SAG-13: *Exoplanet Occurrence Rates and Distributions*

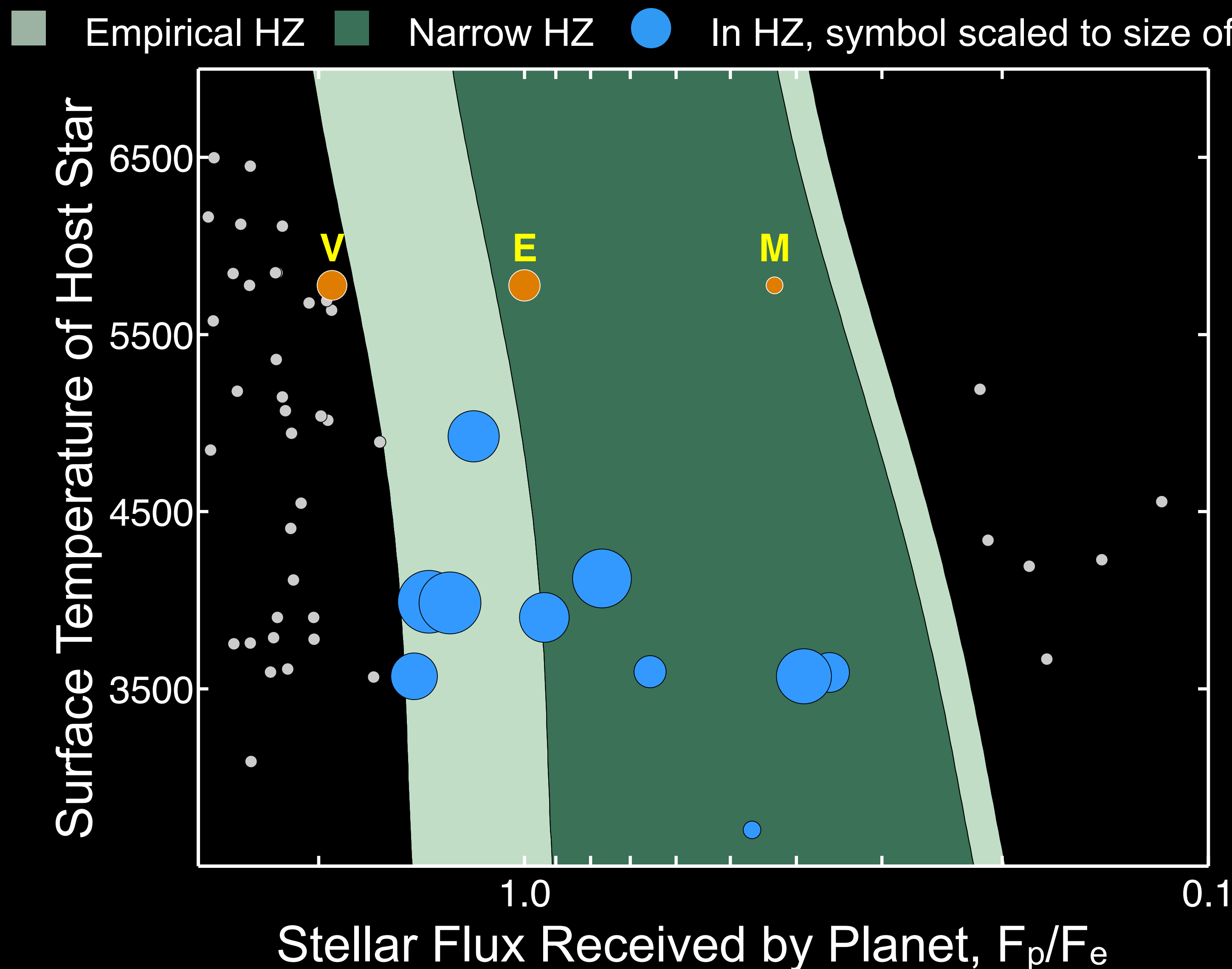
- Chair: Rus Belikov
- Objectives:
  - Establish standard definitions and conventions (e.g. definition of eta-earth, size range for terrestrial planets)
  - Resolve differences between various methodologies
  - Establish baseline measurements for meaningful comparison of planet yield between mission design studies
- Face-to-face meeting to coincide with Kepler Hack Week in October, either day before or day after

Small (< 2 R_e) Planets in the HZ: 1 yr



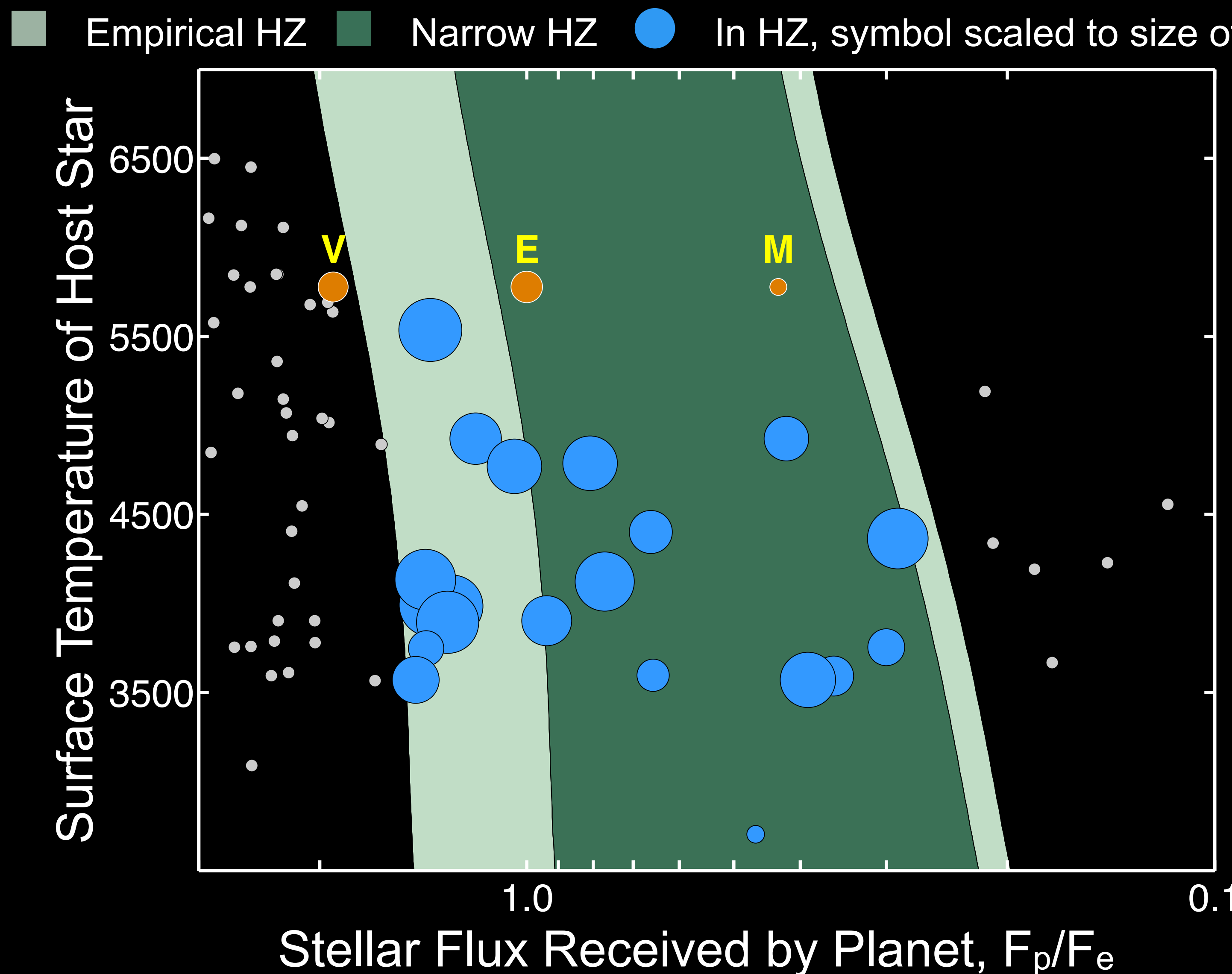
HZ def'n: Kopparapu et al 2013, updated by Leconte et al 2014

Small (< 2 R_e) Planets in the HZ: 2 yr



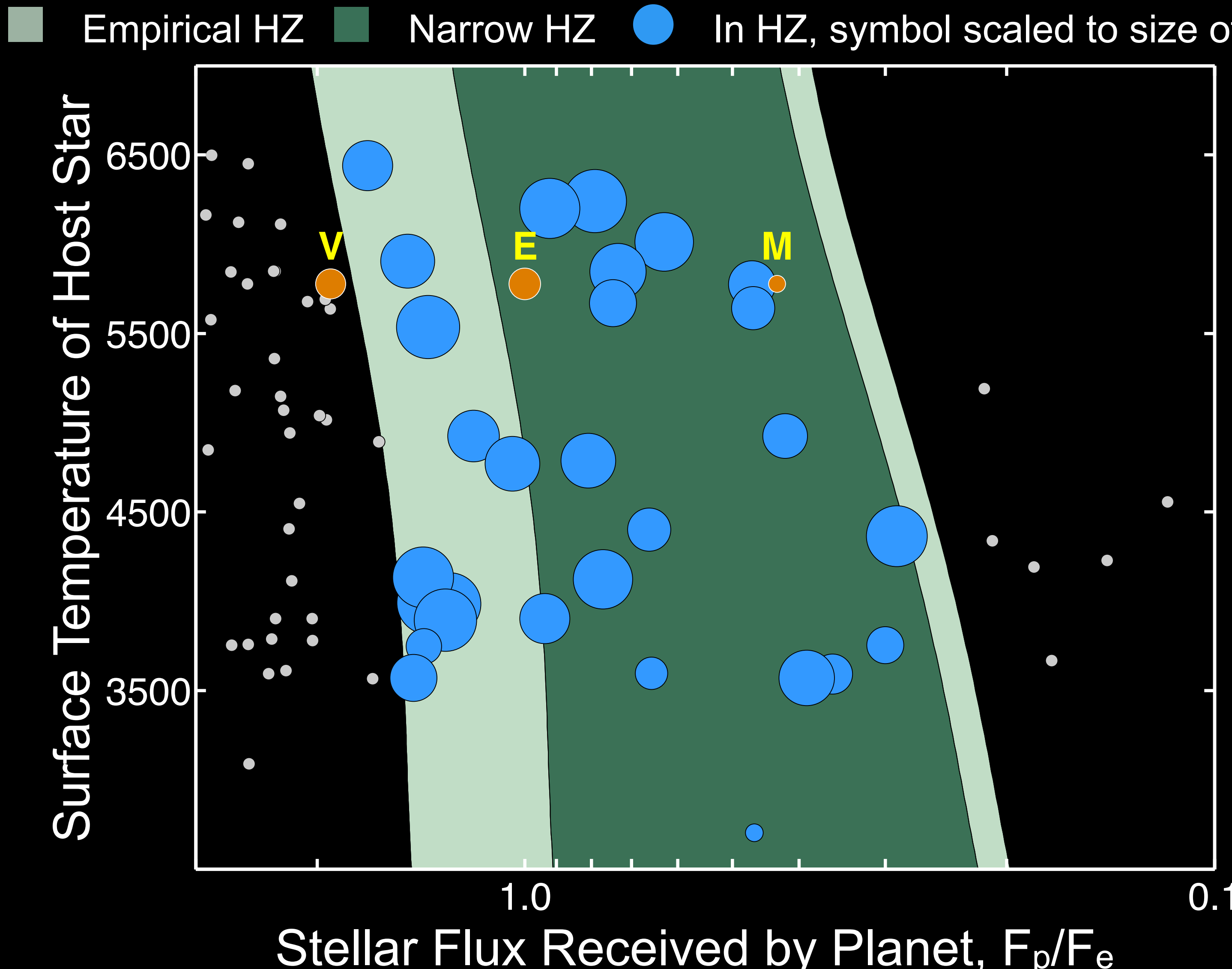
HZ def'n: Kopparapu et al 2013, updated by Leconte et al 2014

Small (< 2 R_e) Planets in the HZ: 3 yr



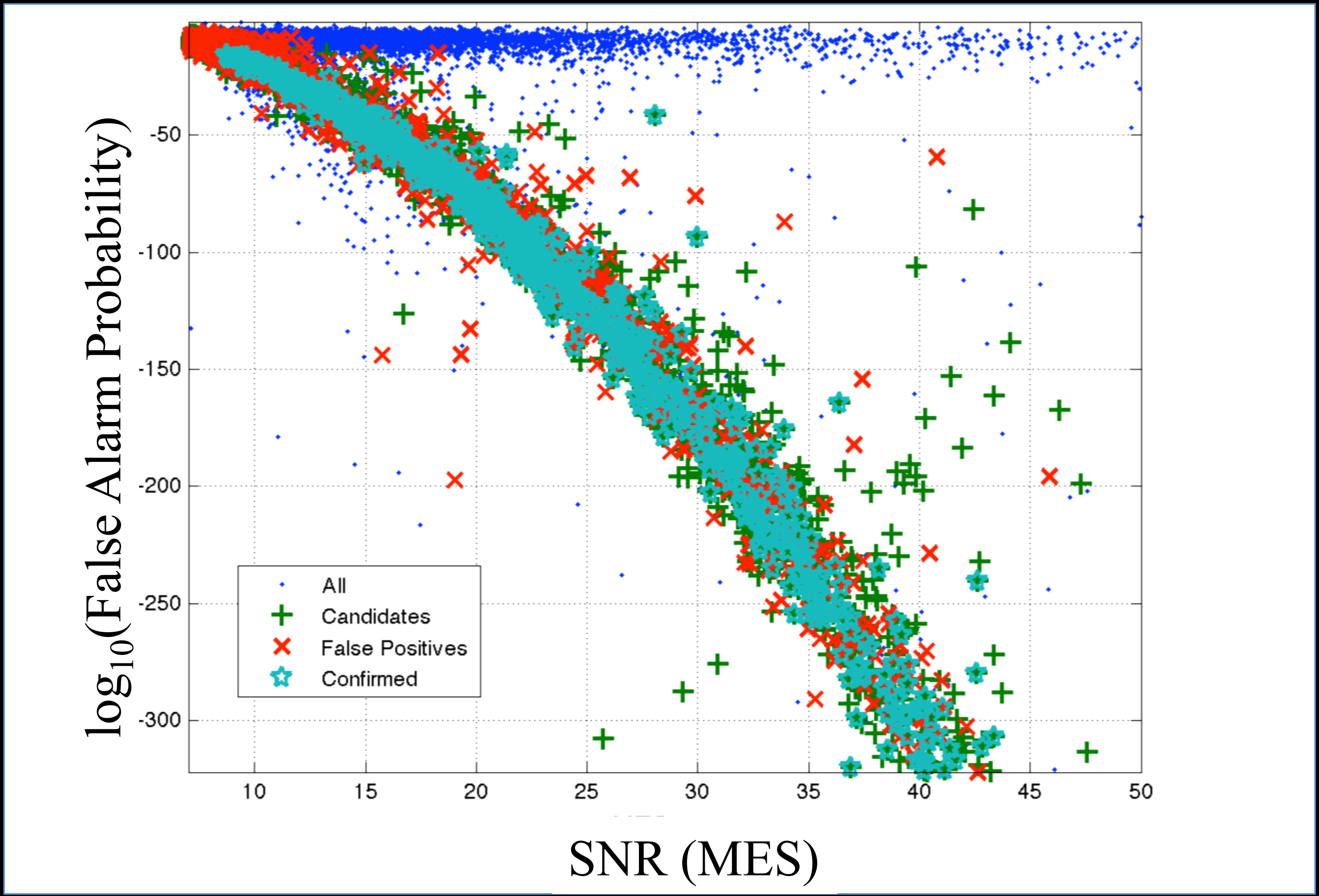
HZ def'n: Kopparapu et al 2013, updated by Leconte et al 2014

Small (< 2 R_e) Planets in the HZ: 4 yr



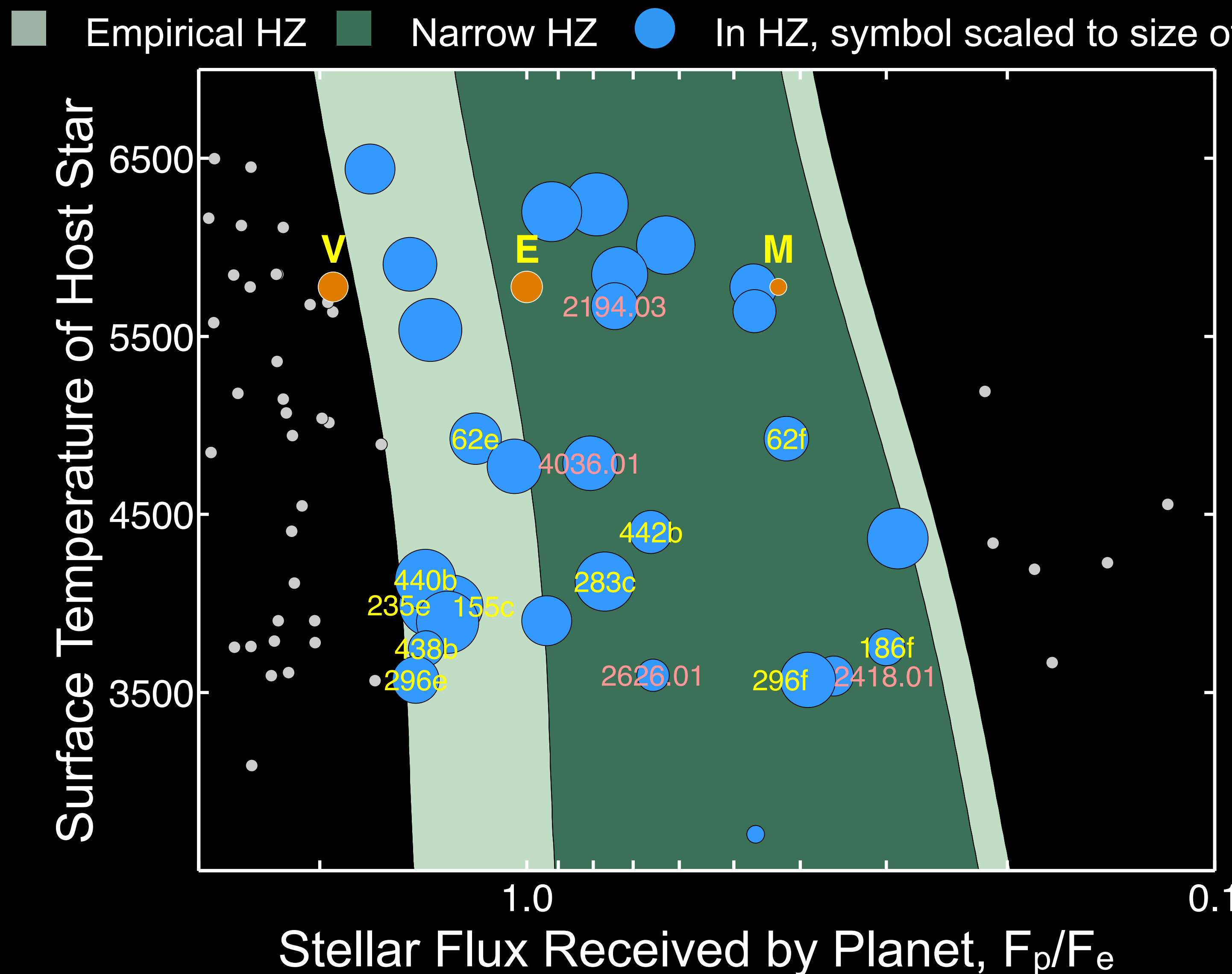
HZ def'n: Kopparapu et al 2013, updated by Leconte et al 2014

Quantifying the False Alarm Rate



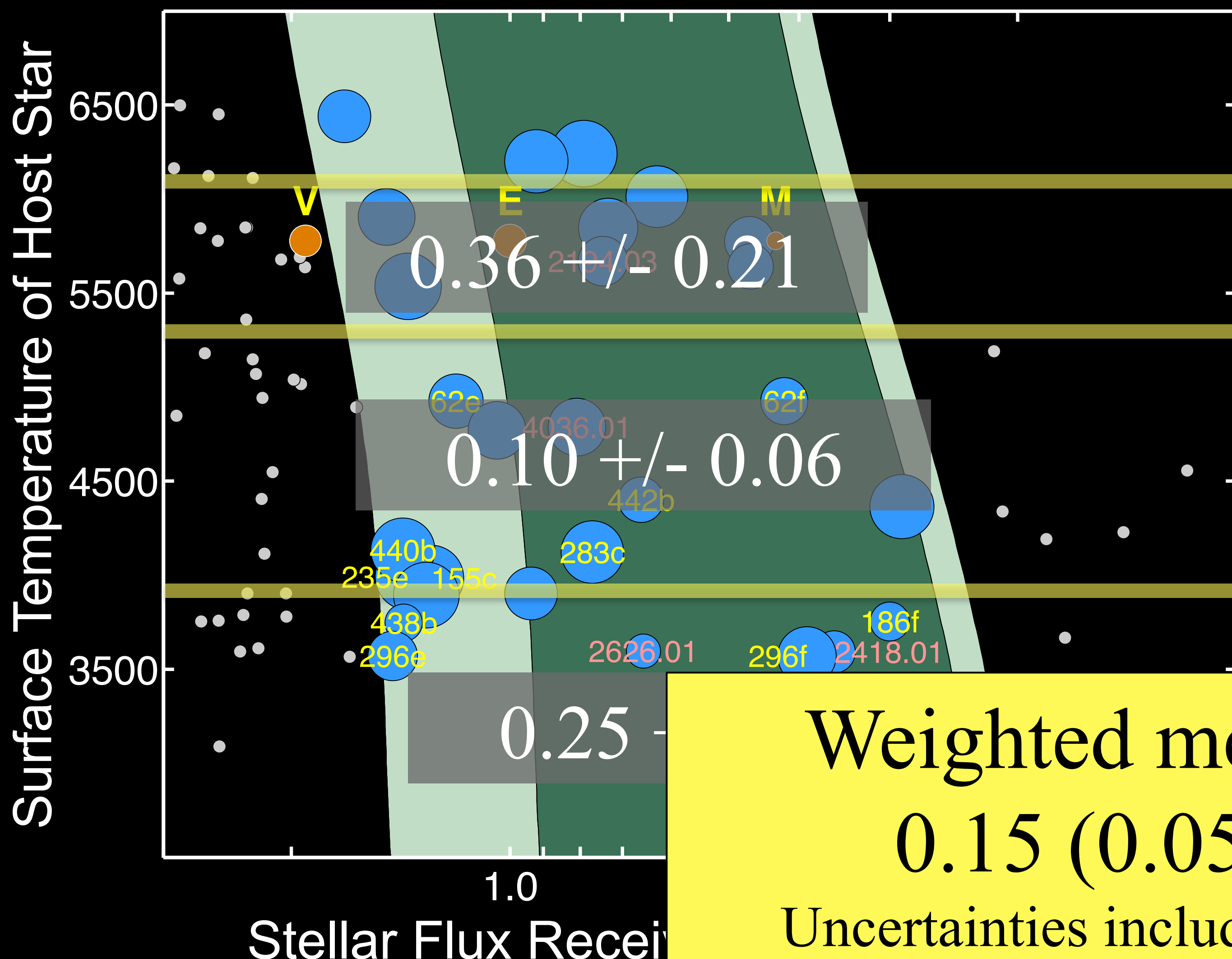
Credit: Shawn Seader, Jon Jenkins

Small (< 2 R_e) Planets in the HZ: 4 yr



HZ def'n: Kopparapu et al 2013, updated by Leconte et al 2014

Small (< 2 R_e) Planets in the HZ: 4 yr

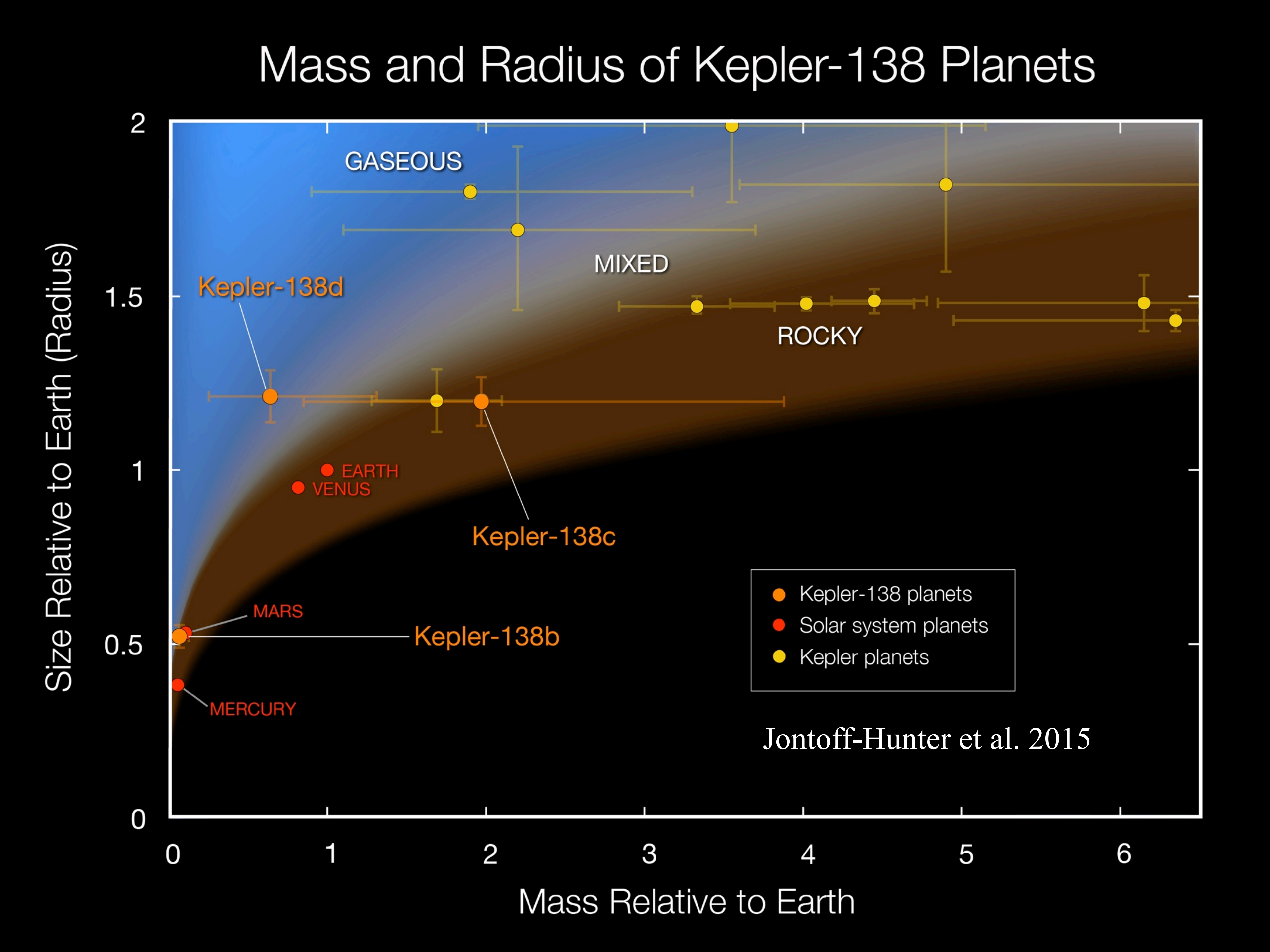


For size range:
1 – 1.6 R_e

Weighted mean:
0.15 (0.05)
Uncertainties include only statistical errors.

Mass-Radius Diagram

We can make statistical inferences about composition using posterior distributions on planet mass from RV campaigns and transit timing analyses.


Mass and Radius of Kepler-138 Planets
GASEOUS
MIXED
ROCKY
Kepler-138d
Kepler-138c
Kepler-138b
EARTH
VENUS
MARS
MERCURY
Kepler-138 planets
Solar system planets
Kepler planets
Jontoff-Hunter et al. 2015
Size Relative to Earth (Radius)
Mass Relative to Earth
0
0.5
1
1.5
2
0
1
2
3
4
5
6

Closing Comments:

- Efforts in the Kepler closeout (9/15 – 9/17) are focused on delivering legacy data products that enable population studies beyond mission closeout. SOC 9.1 products and tools are available.
- At present, systematic errors in Kepler occurrence rates are larger than the statistical errors. Reducing them to <10% is also the focus of the closeout effort.
- Kepler will yield eta-Earth estimates for G, K, and M stars but suffers from small sample sizes for earth-sun analogs.
- Filling in the mass-radius diagram is critical for understanding which planets are most likely to harbor life. Both TTVs and RVs are making important contributions.