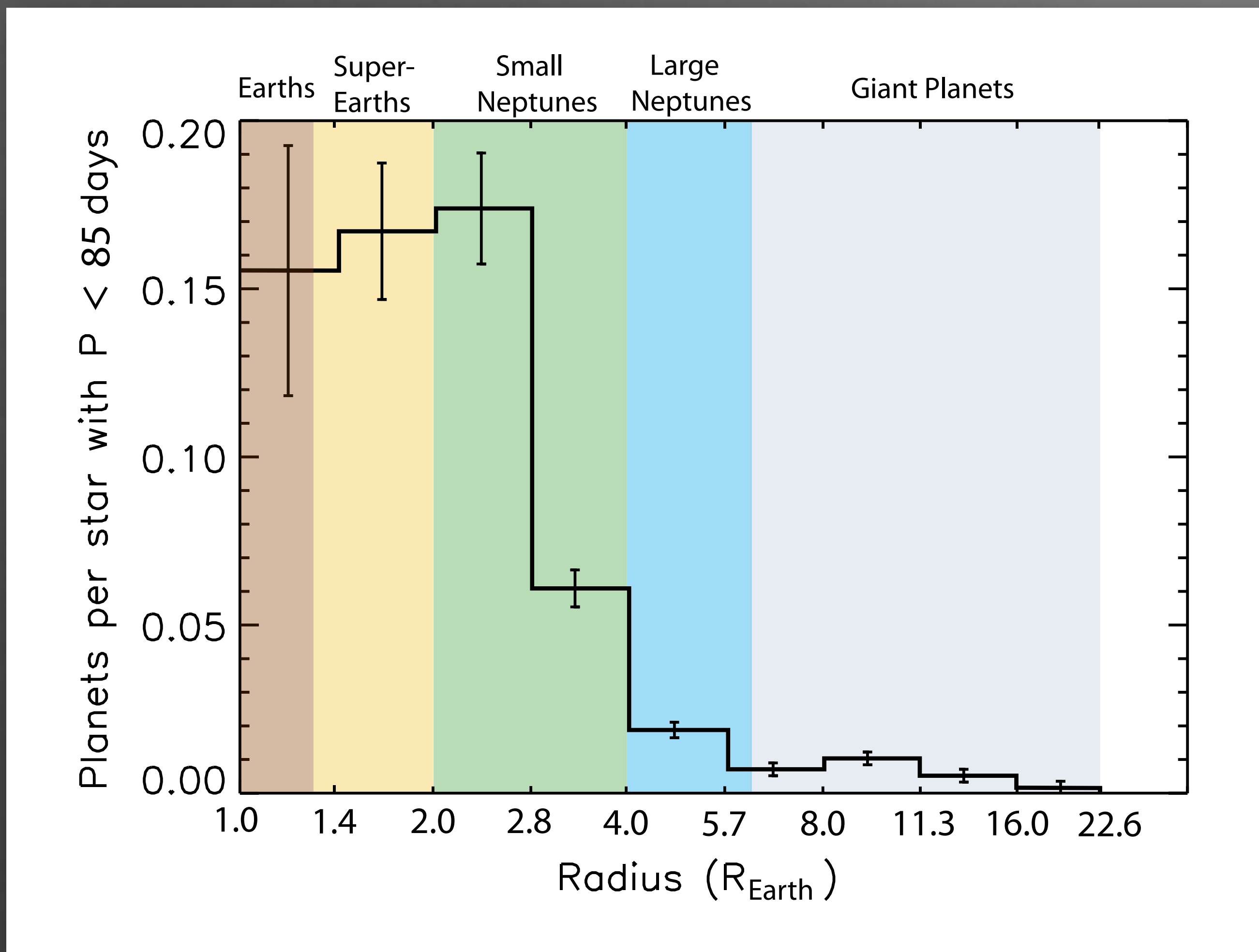
The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets

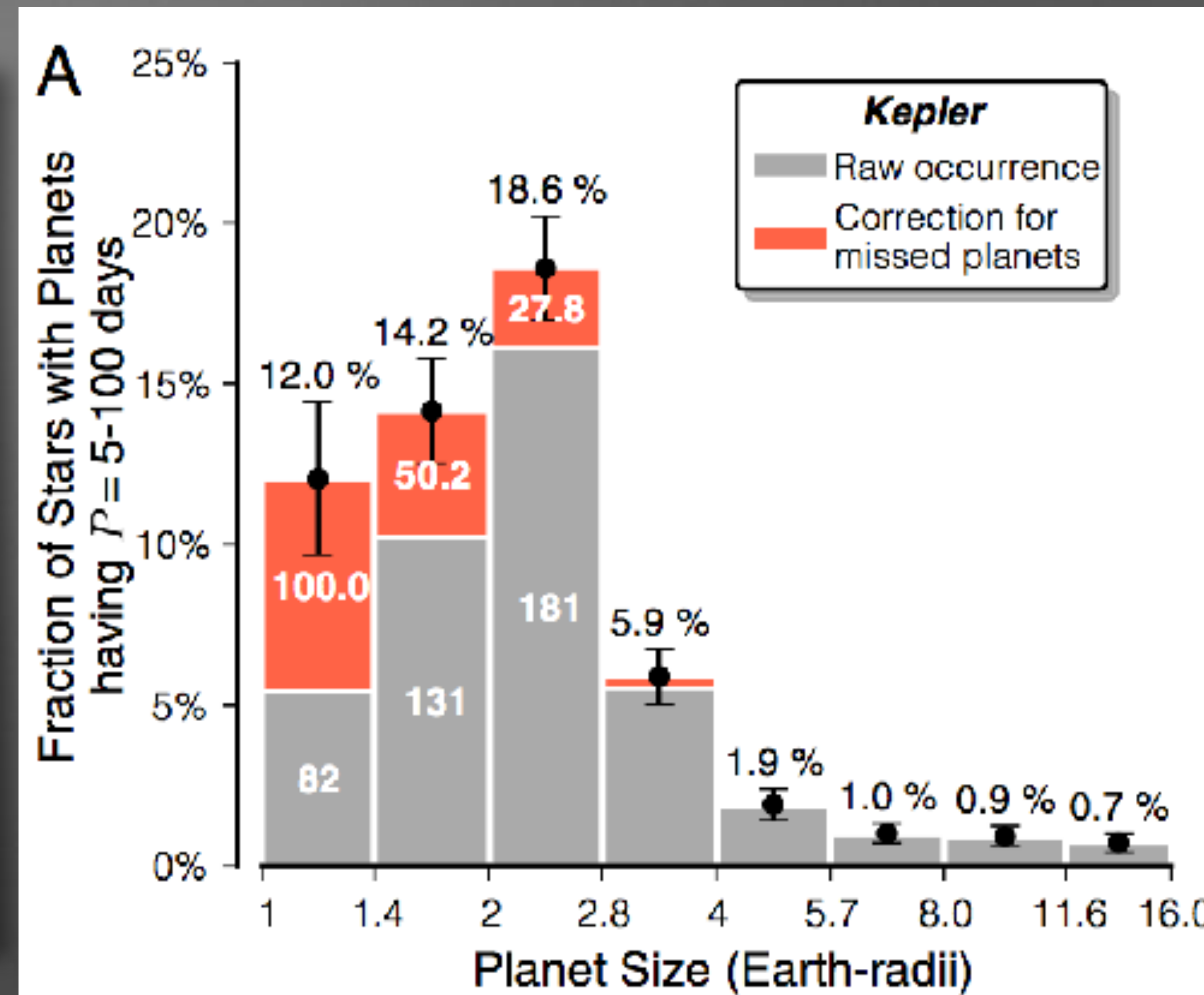
BJ Fulton, Erik Petigura, Andrew Howard, Howard Isaacson, Geoffrey Marcy, Phillip Cargile, Leslie Hebb, Lauren Weiss, John Johnson, Tim Morton, Evan Sinukoff, Ian Crossfield, and Lea Hirsch

Petigura, Howard, et al. (2017)
CKS I: Spectroscopic Properties of 1305 Planet-Host Stars From Kepler

Johnson, Petigura, **Fulton** et al. (2017)
CKS II: Precise Physical Properties of 2025 Kepler Planets and Their Host Stars



Fressin et al. (2013)

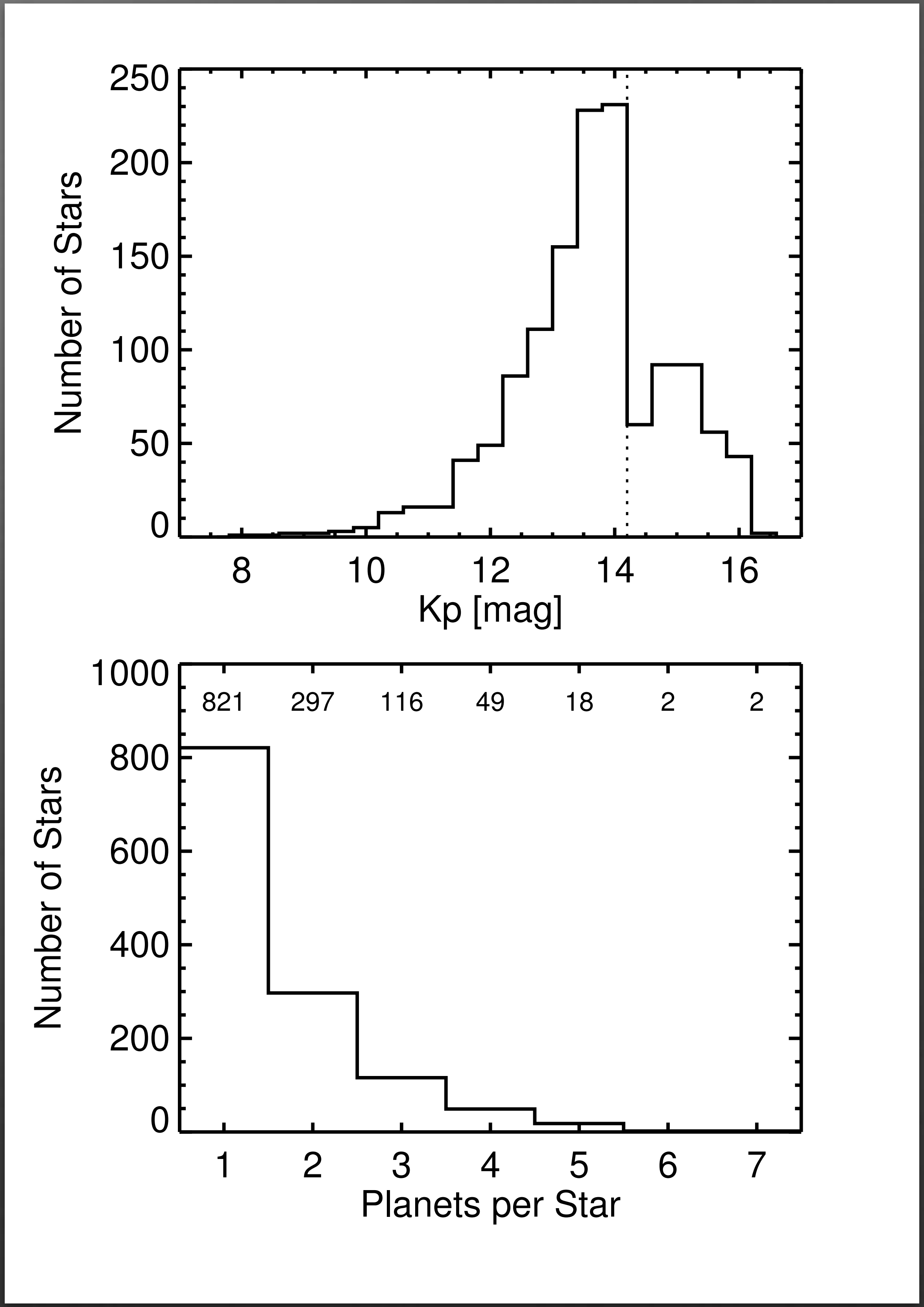


Petigura et al. (2013)

Features in the radius distribution smeared out due to 40% radius errors

The California-Kepler Survey

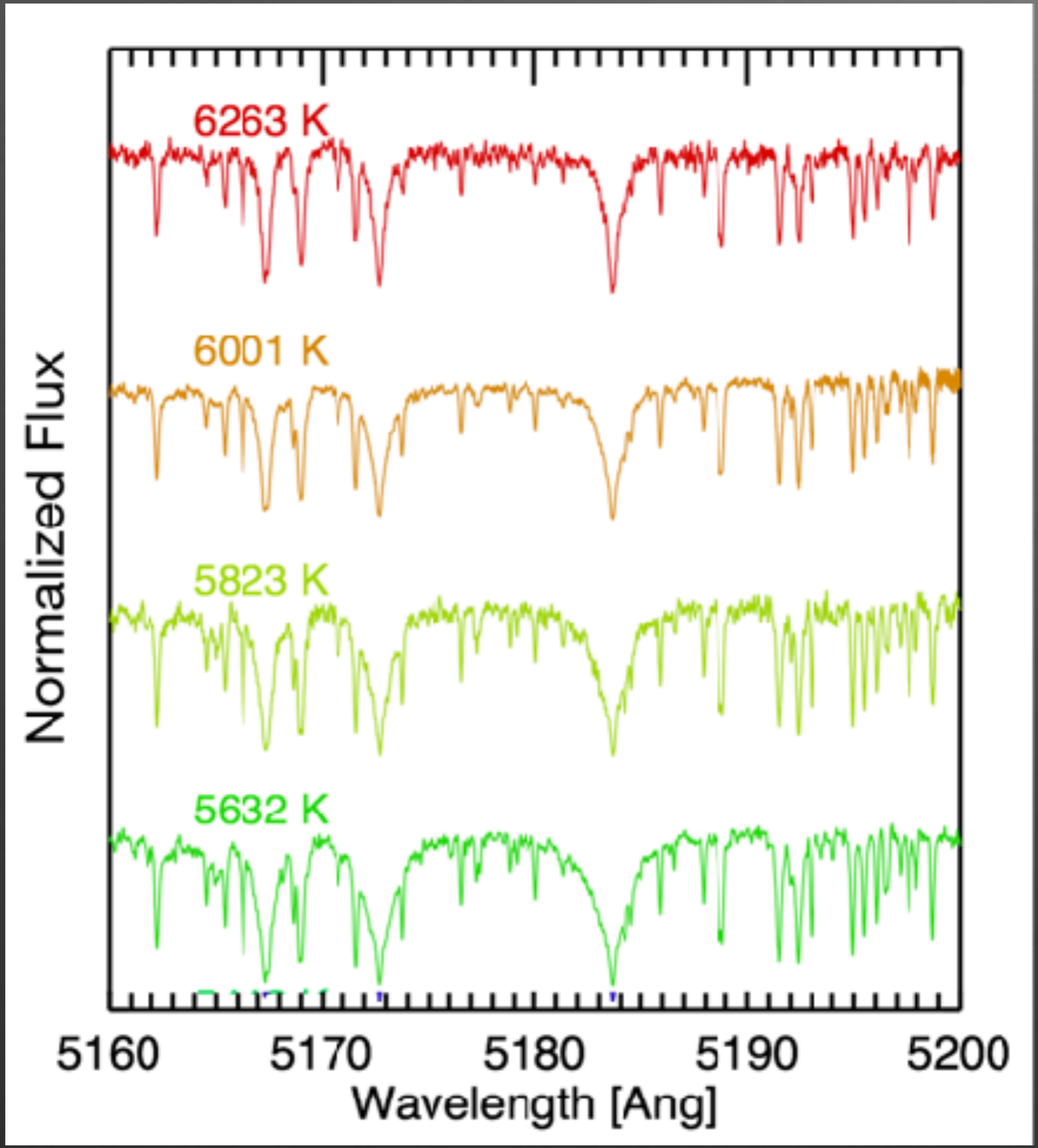
- Led by Andrew Howard, Geoff Marcy, John Johnson
- ~50 Keck nights (2011-2015)
- HIRES spectra of 1305 stars hosting 2025 planet candidates
- Sub-samples:
    - Magnitude limited (*Kp* < 14.2) ($N_\star$ = 960)
    - Multis ($N_\star$ = 484)
    - USPs (*P* < 1d) ($N_\star$ = 71)
    - Habitable Zone ($N_\star$ = 127)

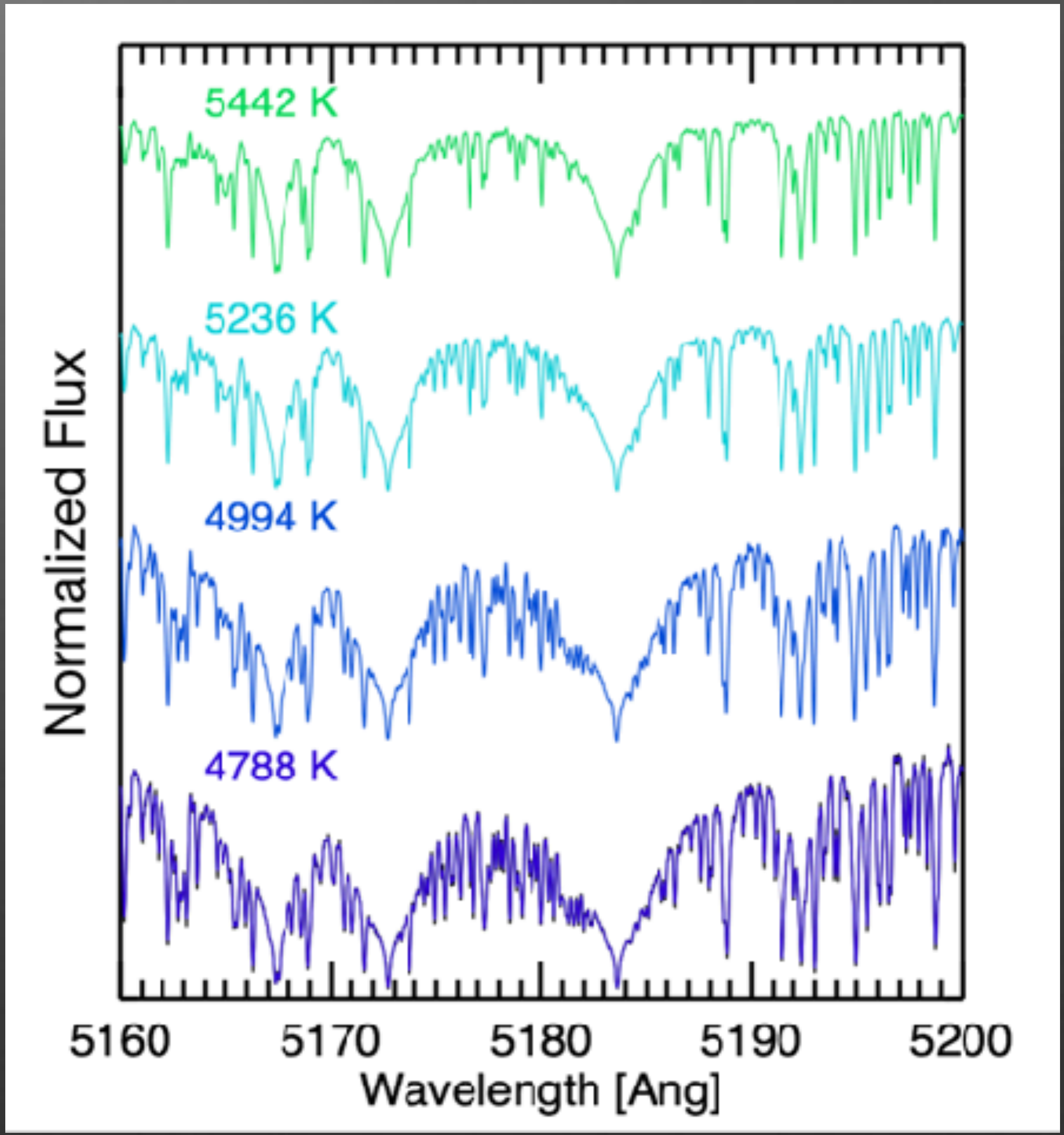


Petigura, Howard, et al. (*2017*)

- **High resolution: *R* ~ 50,000**
  - Enables measurement of vsini
- **High SNR**
  - Precision spectroscopy
  - Searches for faint SB2

All spectra and parameters are public
astro.caltech.edu/~howard/cks





Petigura, Howard et al. (2017)

The California-Kepler Survey

σT_{eff} (Q16) = 156 K

σT_{eff} (CKS) = 60 K

$\sigma \log g$ (Q16) = 0.17 dex

$\sigma \log g$ (CKS) = 0.07 dex

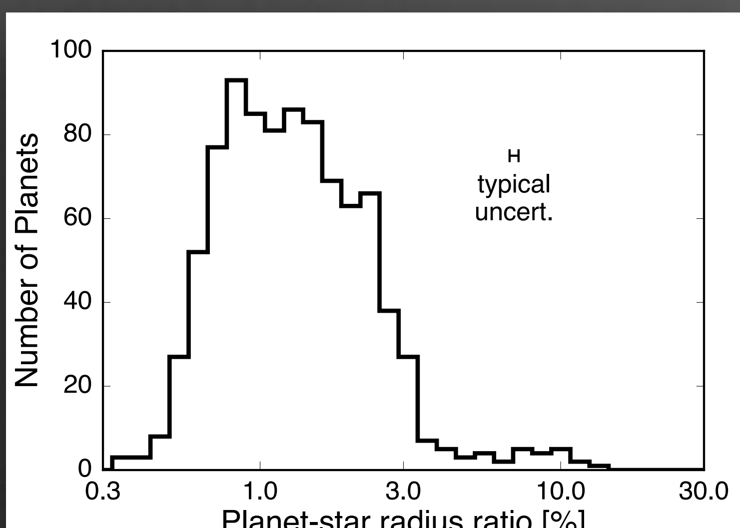
$\sigma M/M$ (Q16) = 14%

$\sigma M/M$ (CKS) = 5%

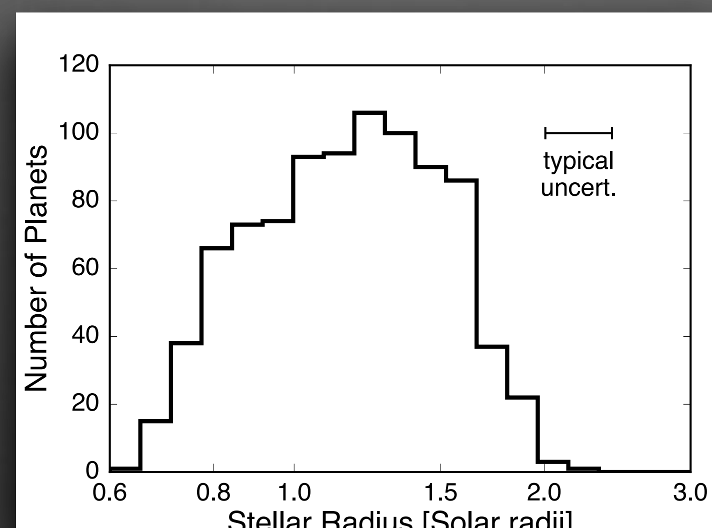
$\sigma R/R$ (Q16) = 39%

$\sigma R/R$ (CKS) = 10%

$$R_P/R_\star \quad \times \quad R_\star \quad = \quad R_P$$



X



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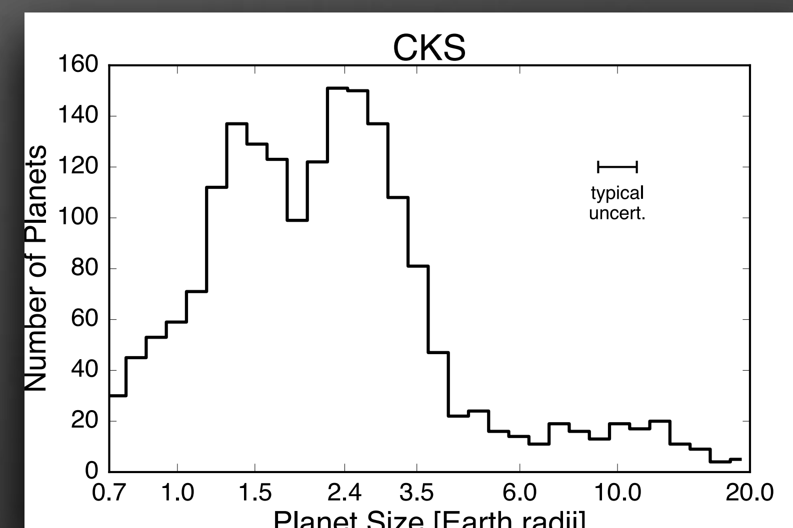


Transit Depth
Q16

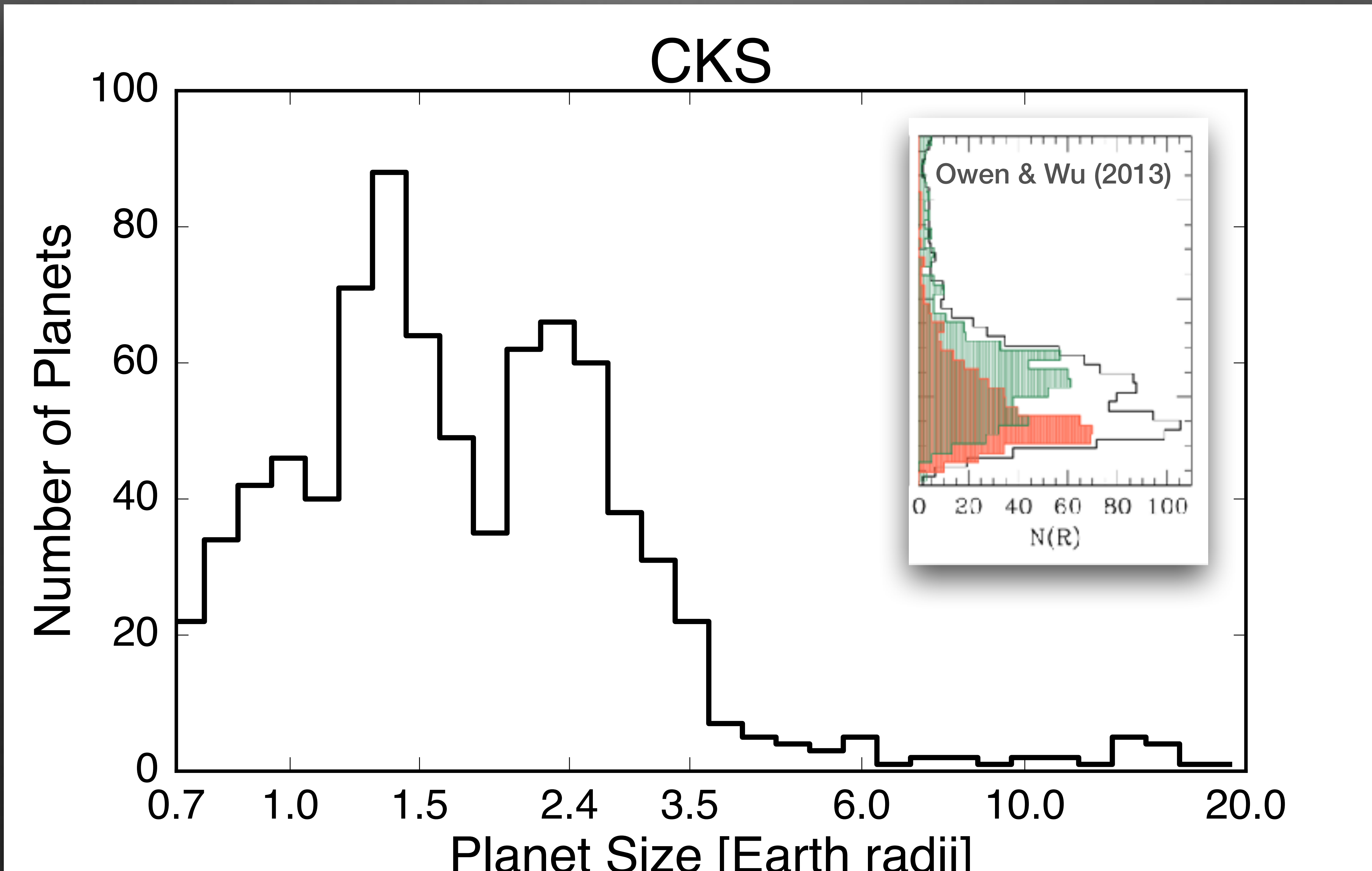
Stellar Radii
~~Q16~~
CKS

Planet Radii
~~Q16~~
CKS

BJ Fulton

Johnson, Petigura, **Fulton** et al. (2017); **Fulton**, Petigura, et al. (2017)

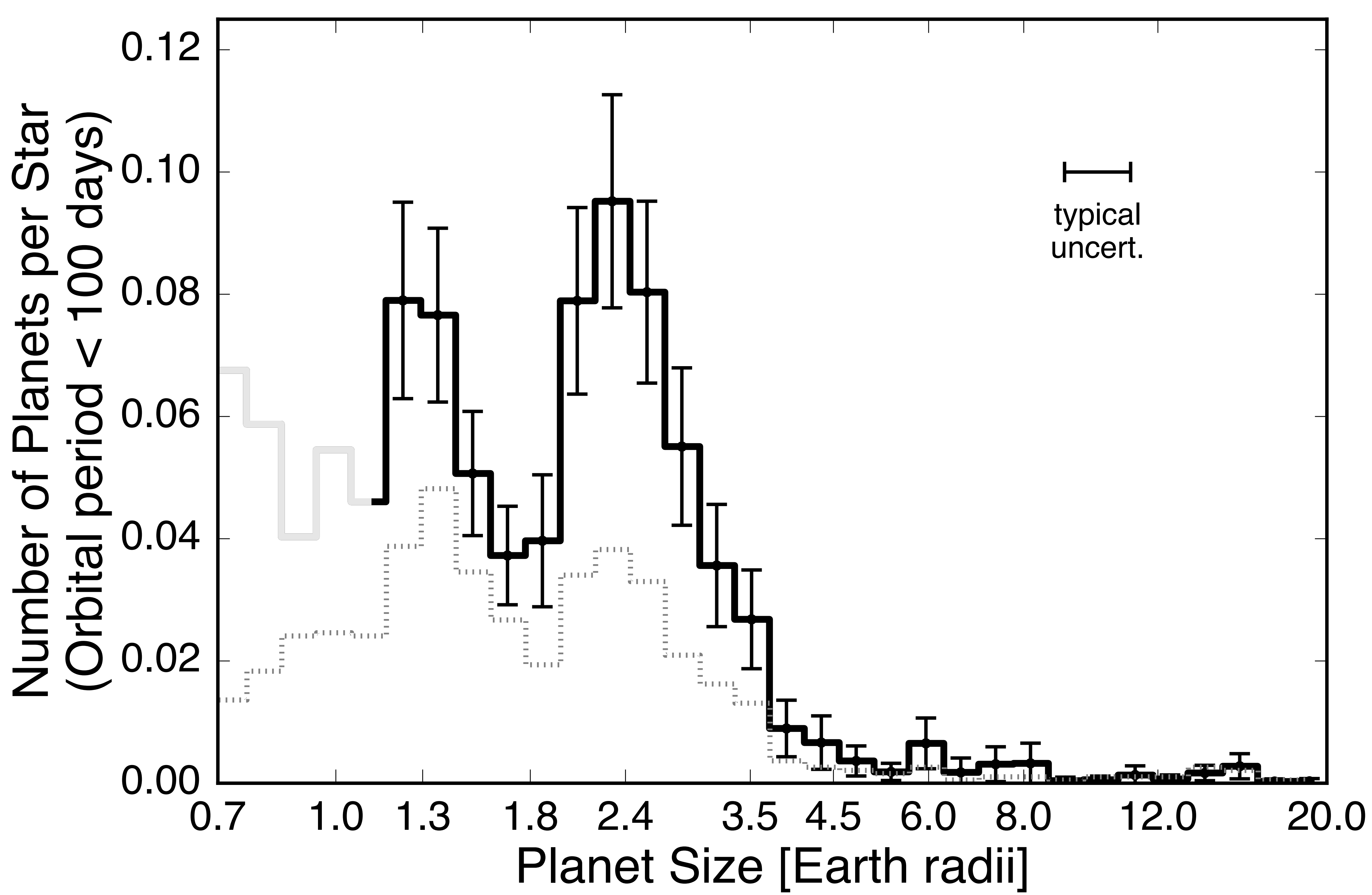
Know Thy Star 2017



Huber et al. (2014); Mullally et al. (2015)

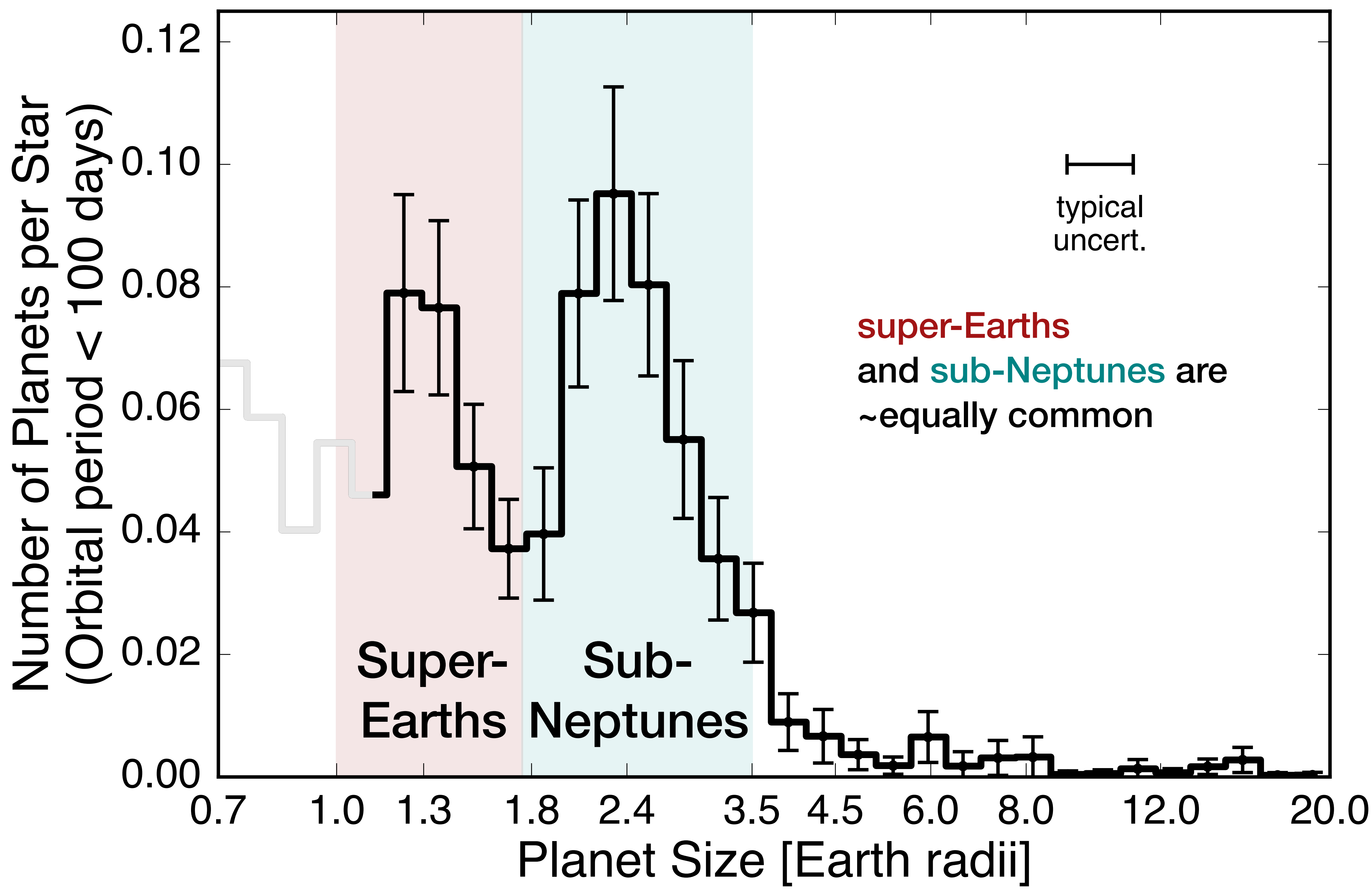
Johnson, Petigura, et al. (*2017*)

The Radius Gap



Fulton, Petigura, et al. (*2017*)

The Radius Gap

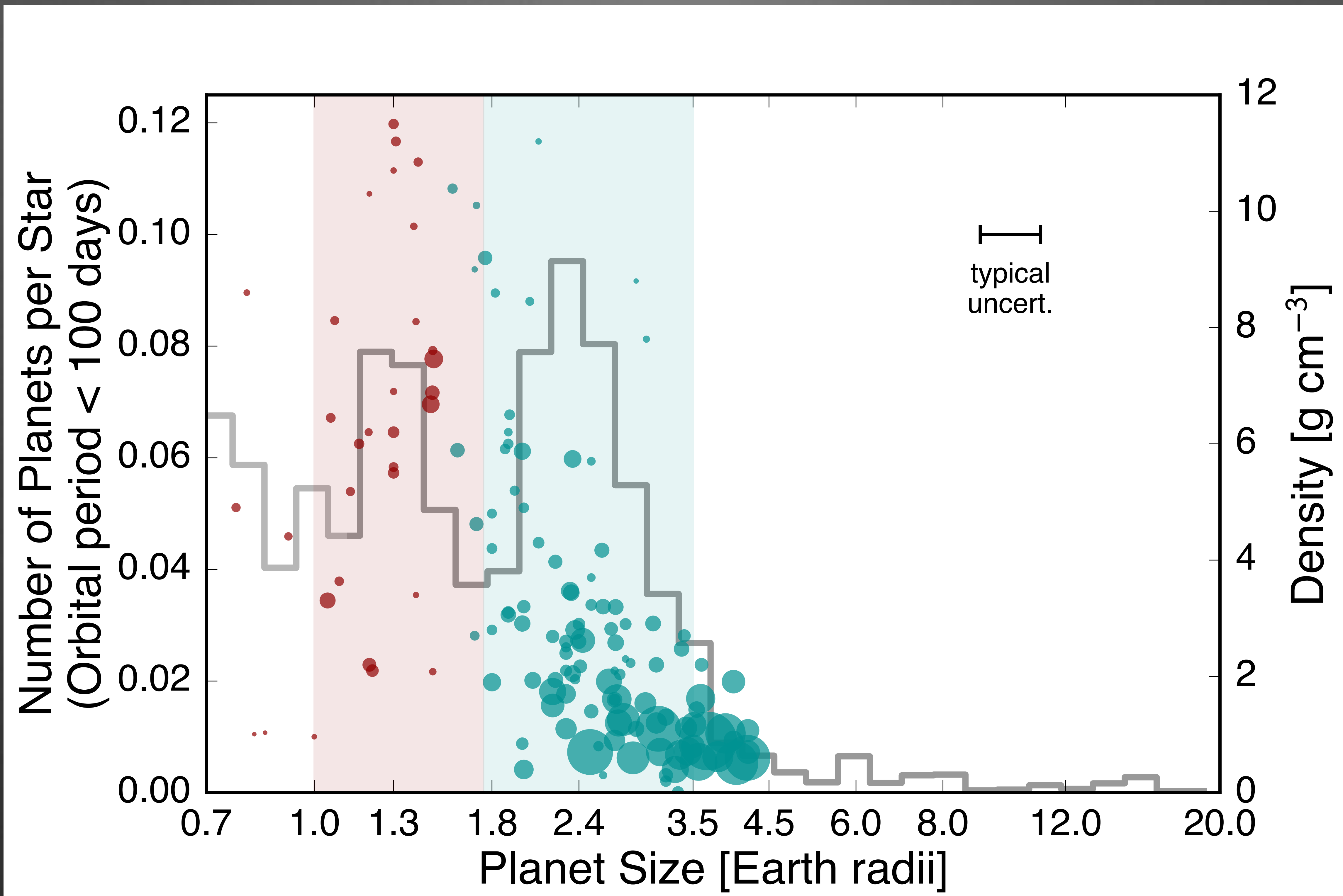


BJ Fulton

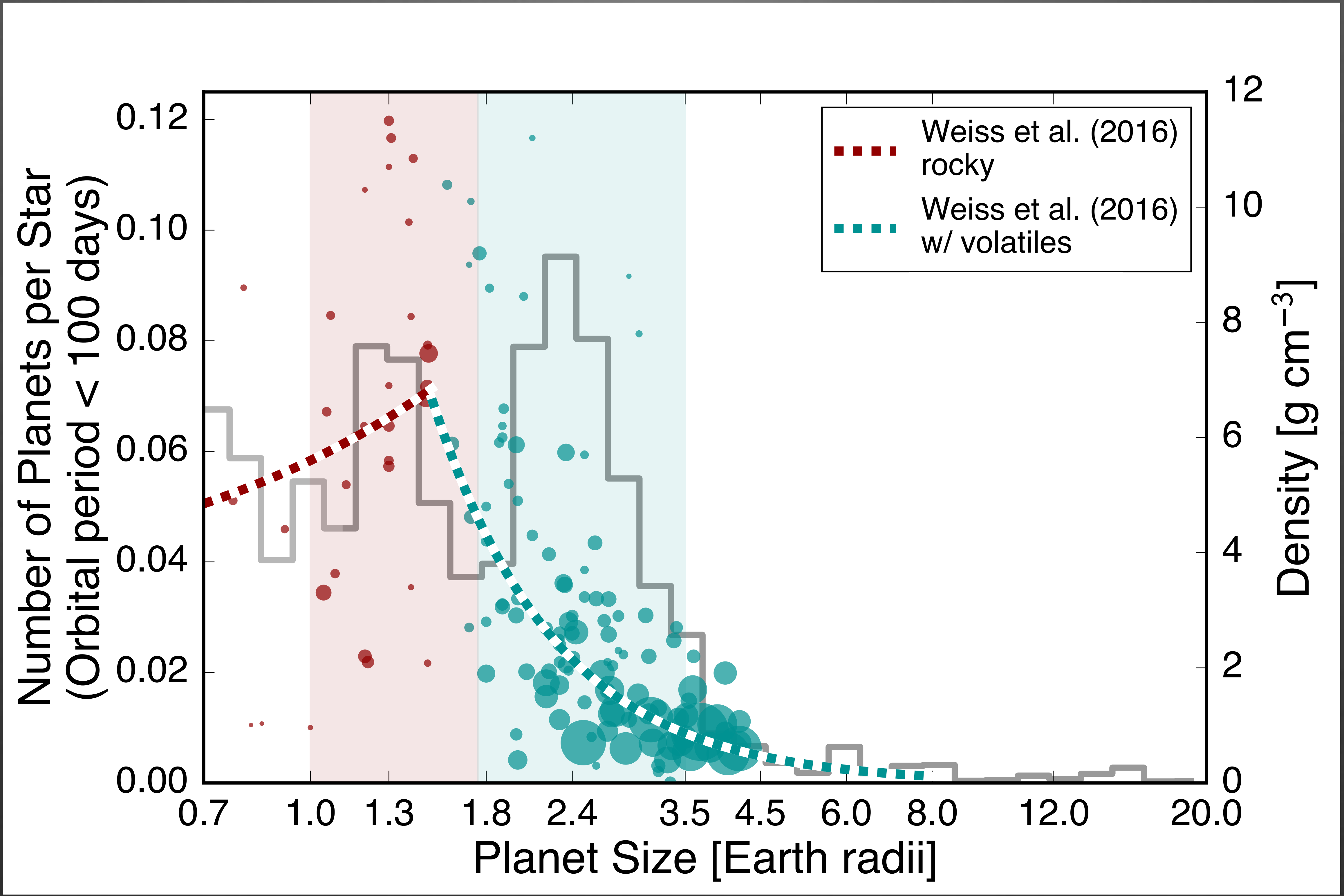
Fulton, Petigura, et al. (*2017*)

Know Thy Star 2017

The Radius Gap



The Radius Gap

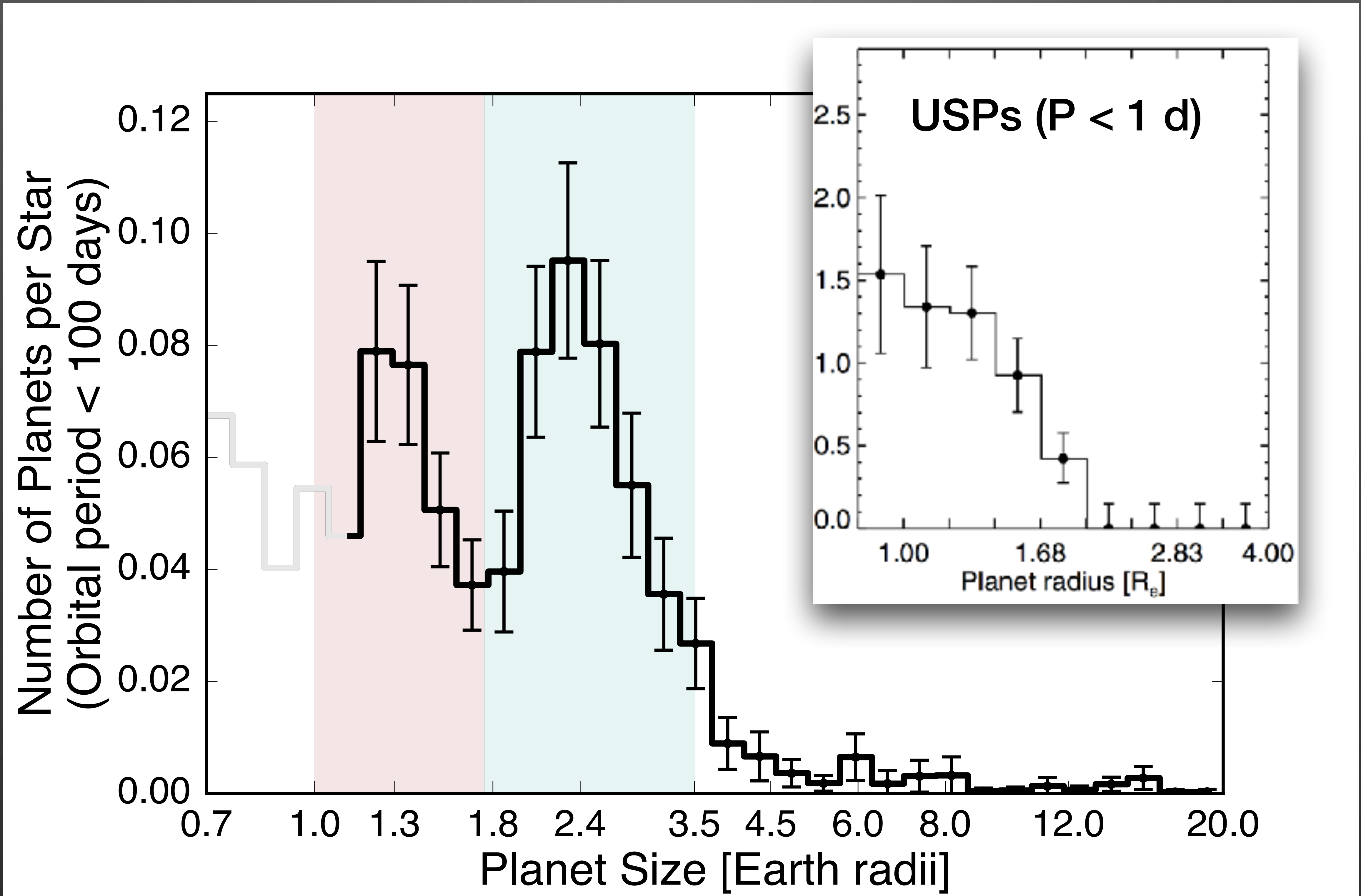


BJ Fulton

Fulton, Petigura, et al. (*2017*)

Know Thy Star 2017

The Radius Gap

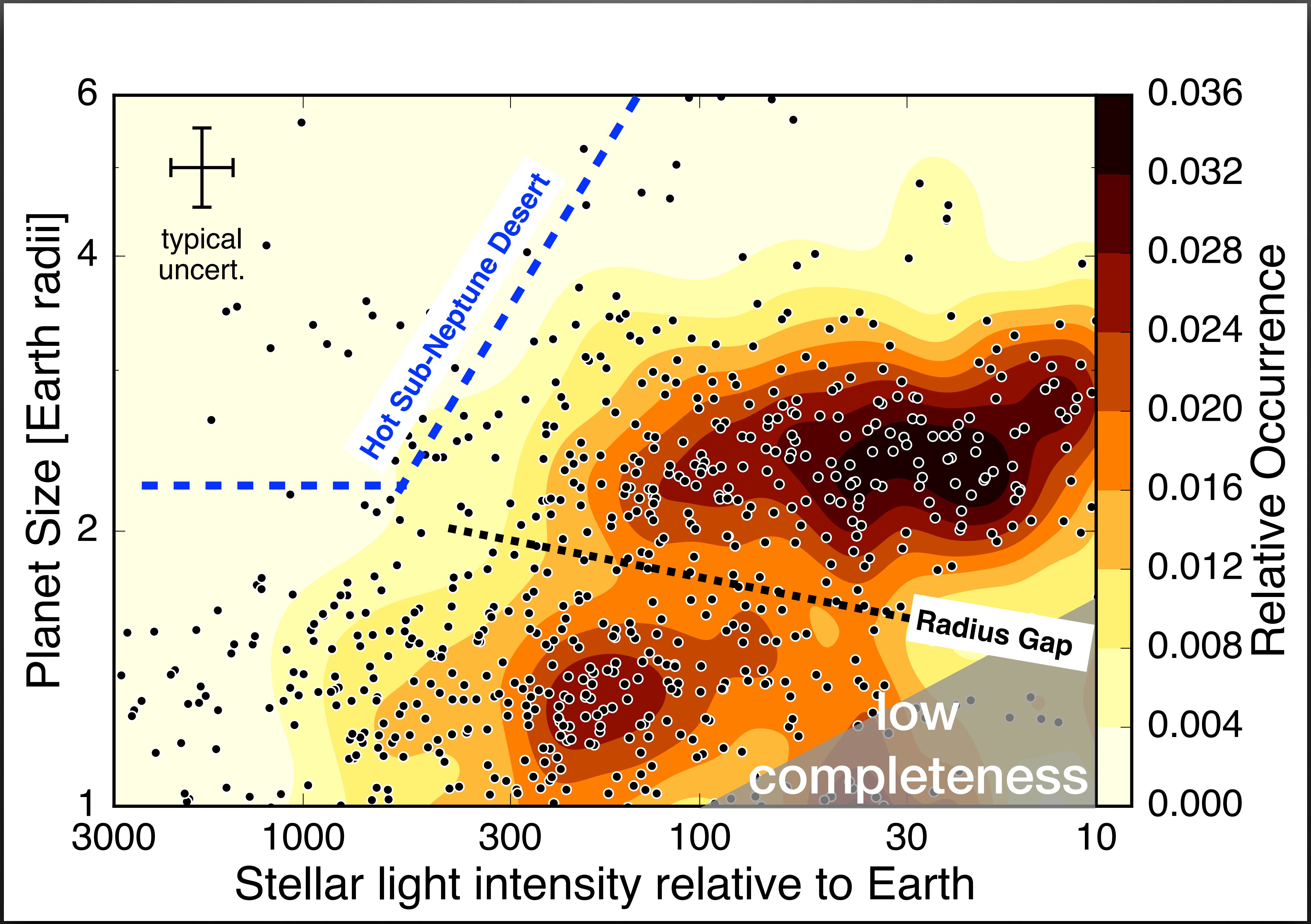


BJ Fulton

Fulton, Petigura, et al. (*2017*)

Know Thy Star 2017

Flux Dependency



Fulton, Petigura, et al. (*2017*)

Flux Dependency

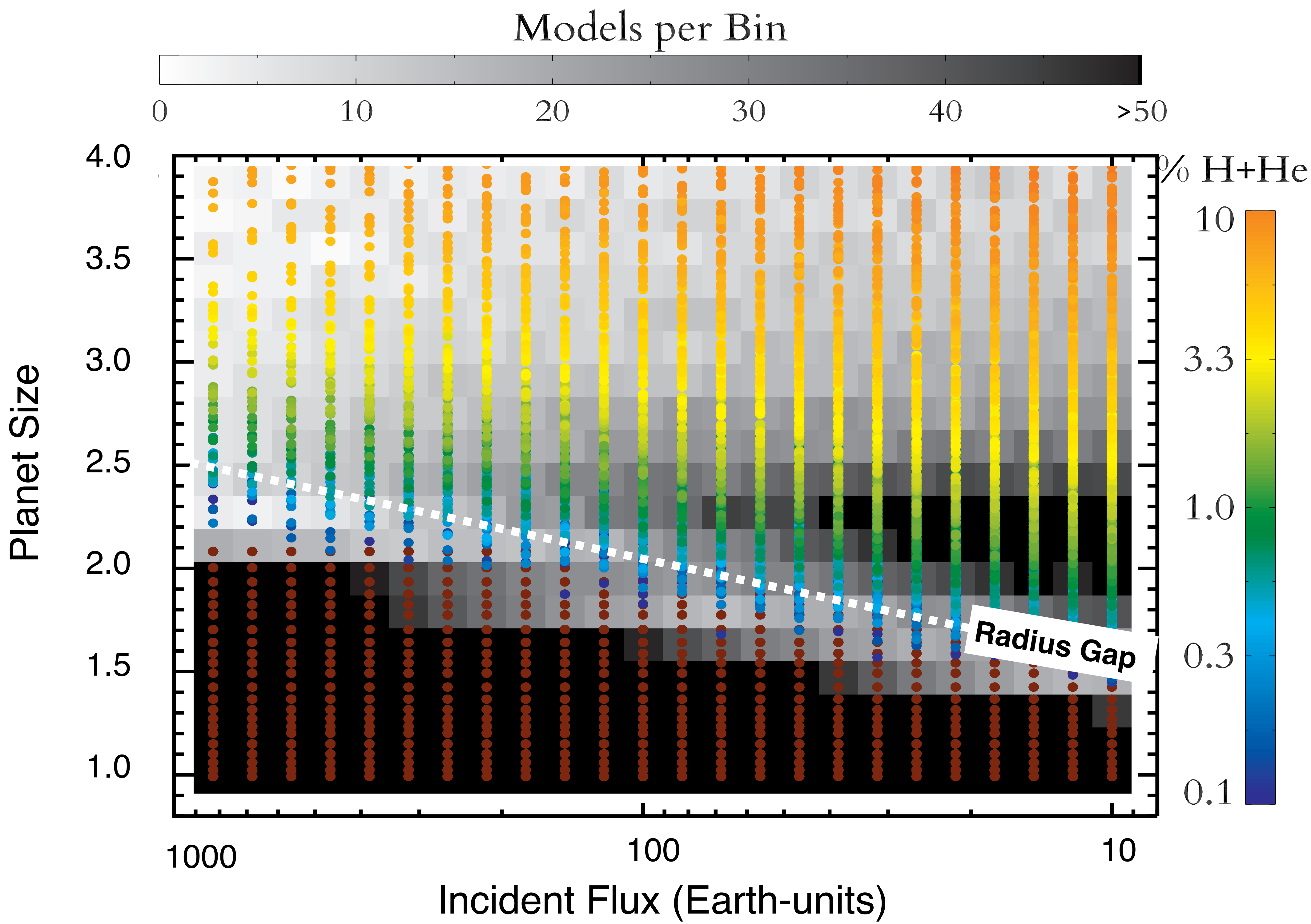
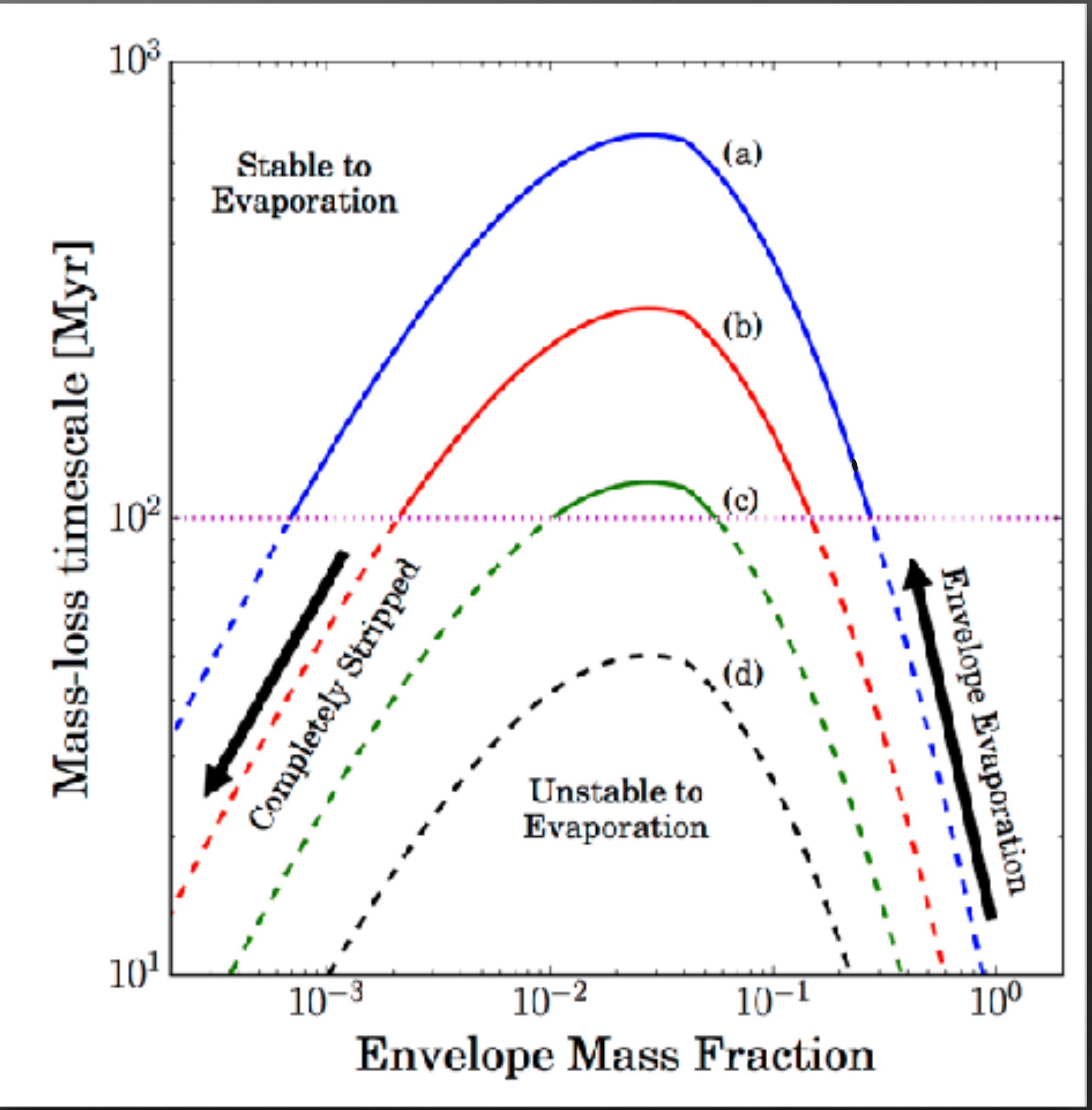


Figure from Lopez+16; see also Owen+13, Lopez+13, Jin+14, Chen+16

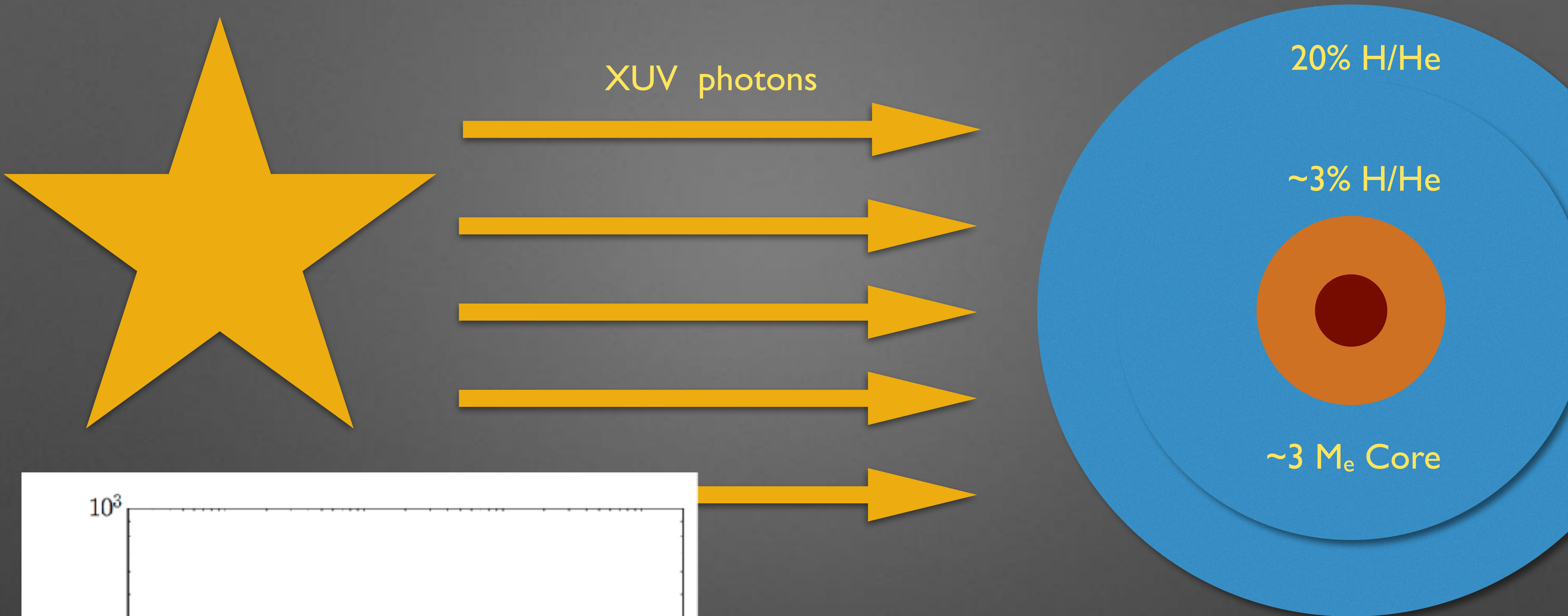
Photo-Evaporation Causes Gap

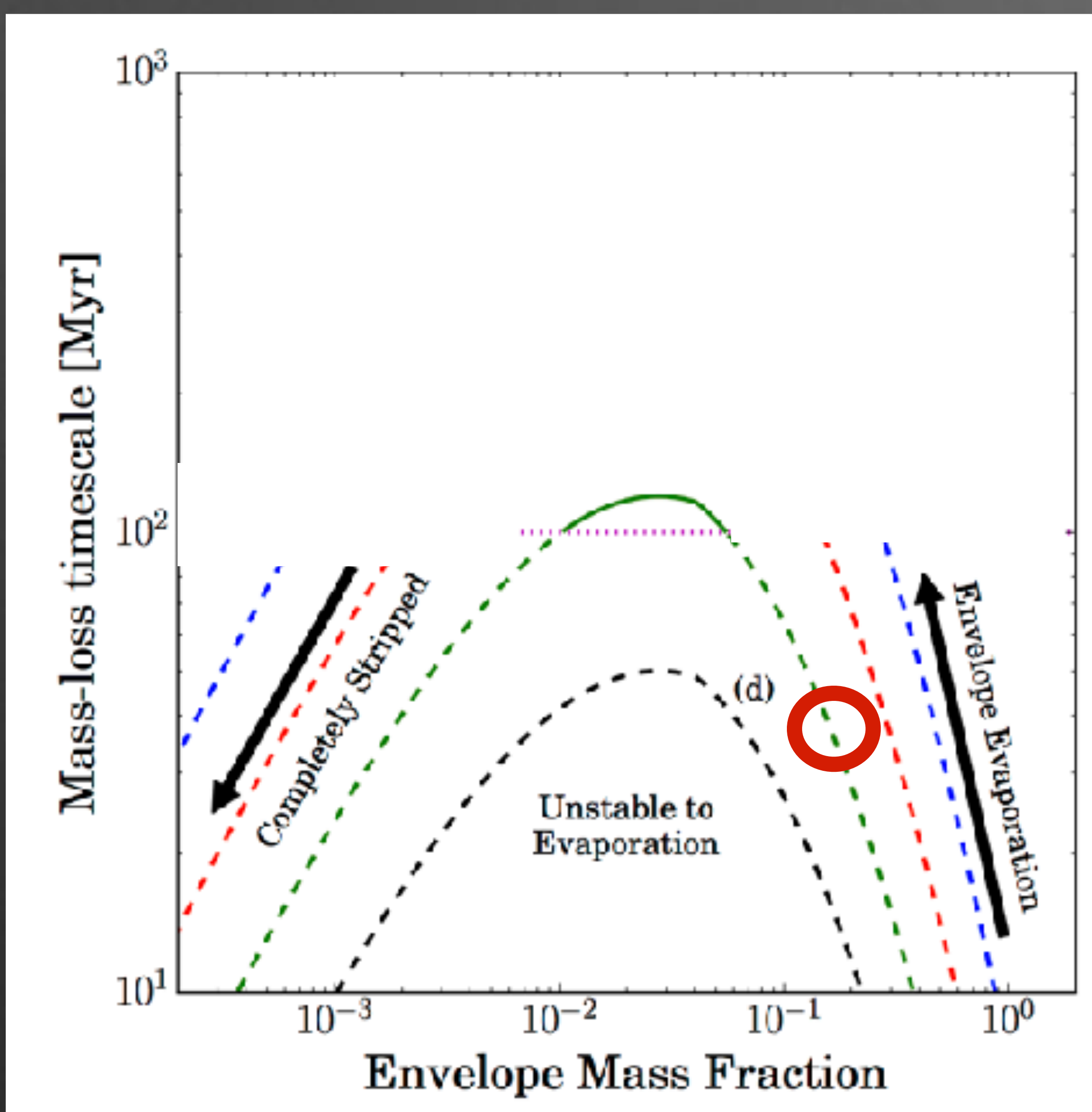
- **Predicted by Theory**
  - Owen & Wu (2013)
  - Lopez & Fortney (2013)
  - Jin et al. (2014)
  - Chen & Rogers (2016)

- **Explanation**
  - High energy XUV photons emitted during star's first 100 Myr erodes envelopes
  - Most sub-Neptunes are ~3% H/He by mass
    - 3% H/He envelopes have longest mass loss timescale
    - Planets are "herded" into two typical sizes

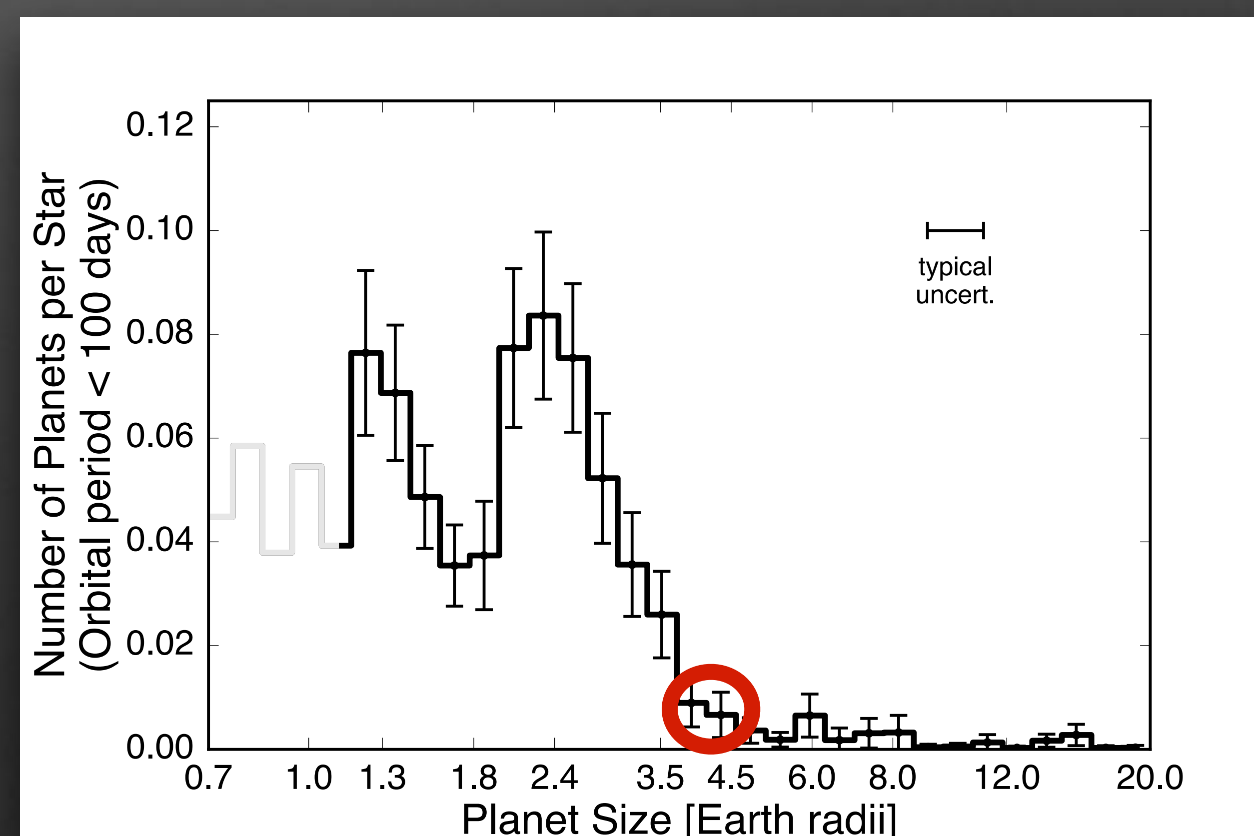


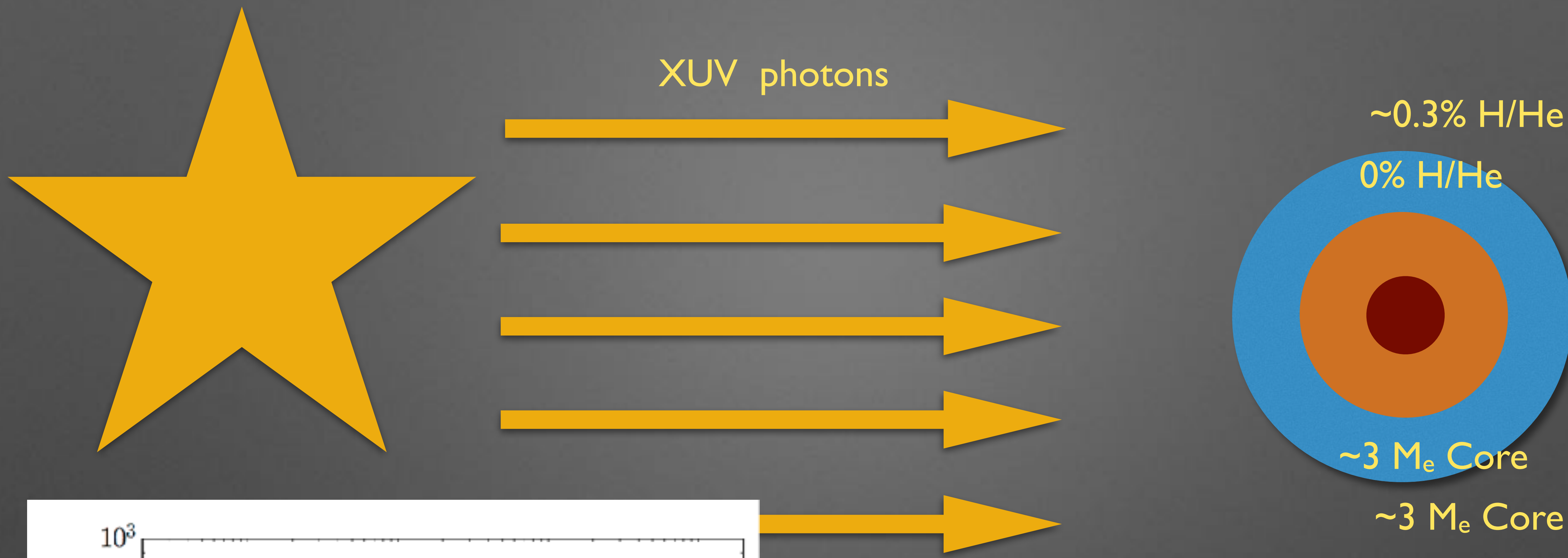
Owen and Wu (2017)

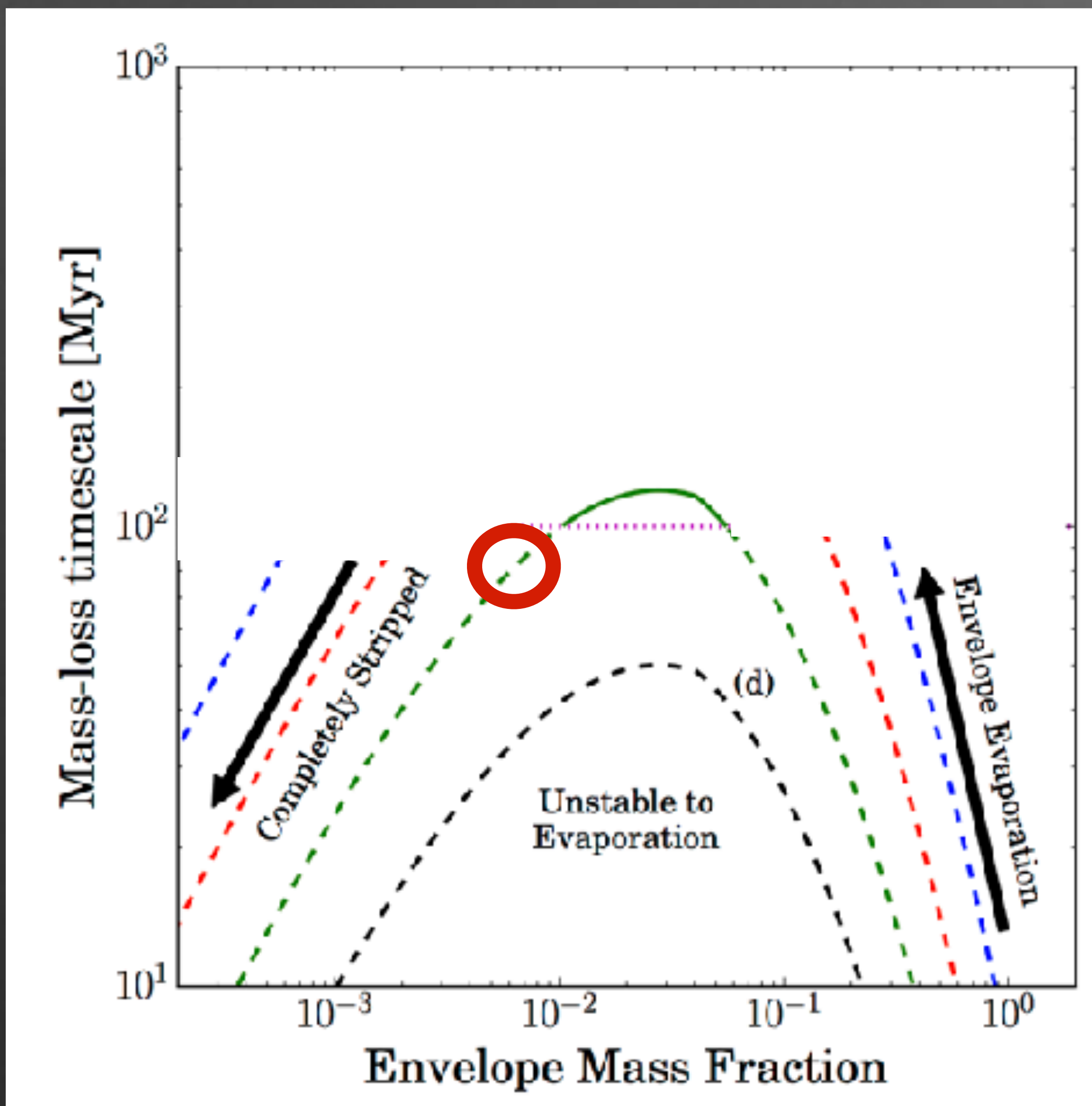

XUV photons
20% H/He
~3% H/He
~3 M_e Core

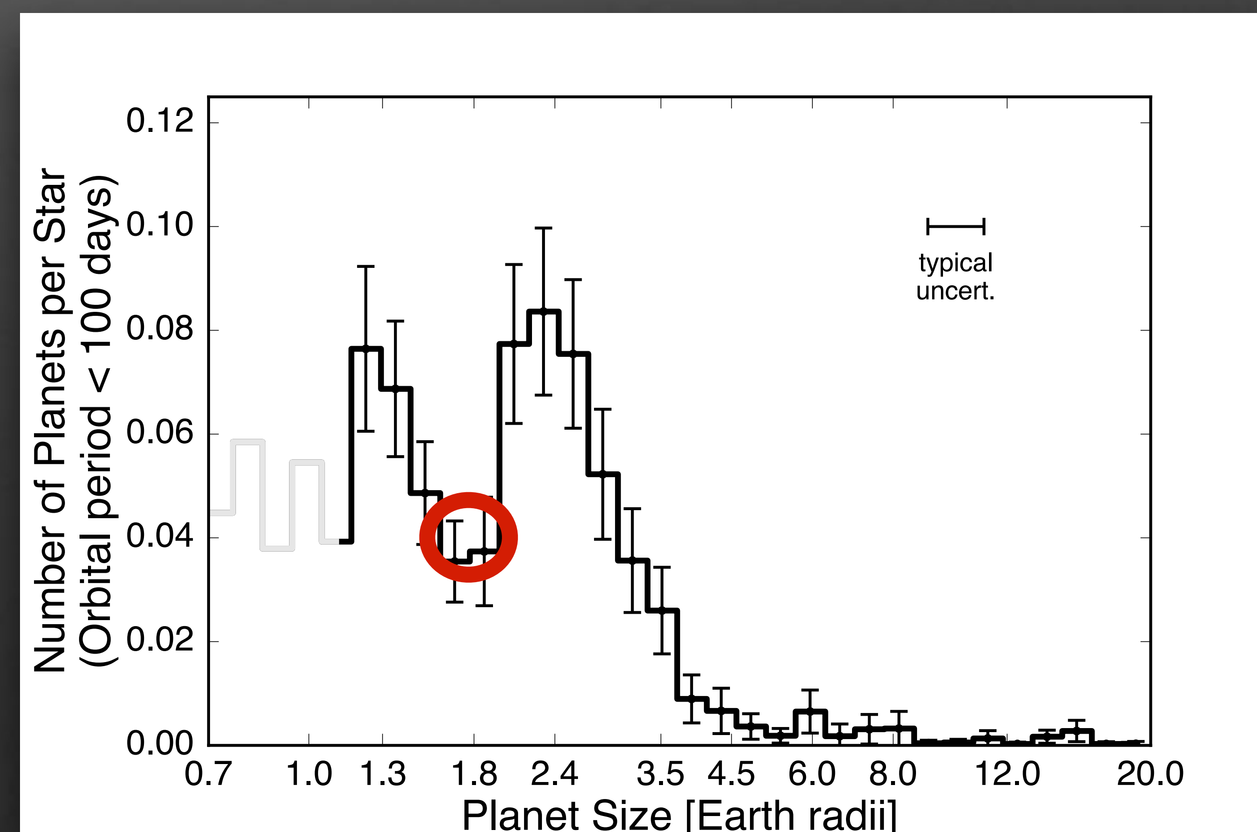

Mass-loss timescale [Myr]
10^3
10^2
10^1
Completely Stripped
(d)
Unstable to Evaporation
Envelope Evaporation
10^{-3}
10^{-2}
10^{-1}
10^0
Envelope Mass Fraction

Oewn & Wu (2017)


Number of Planets per Star (Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
typical uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]

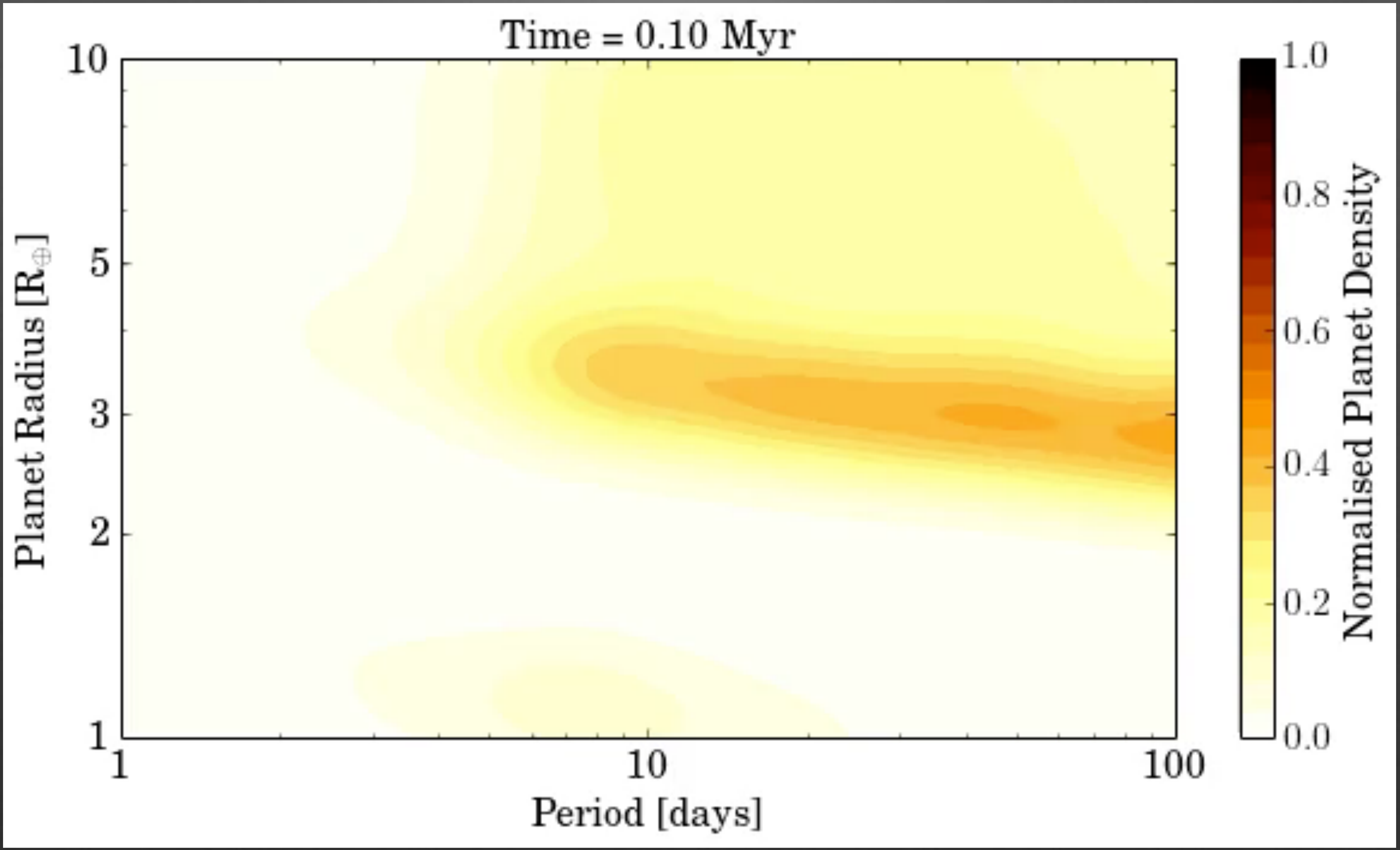

XUV photons
~0.3% H/He
0% H/He
~3 M_e Core
~3 M_e Core


Mass-loss timescale [Myr]
10^3
10^2
10^1
Completely Stripped
Envelope Evaporation
(d)
Unstable to Evaporation
10^{-3}
10^{-2}
10^{-1}
10^0
Envelope Mass Fraction


Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
typical
uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]

Oewn & Wu (2017)

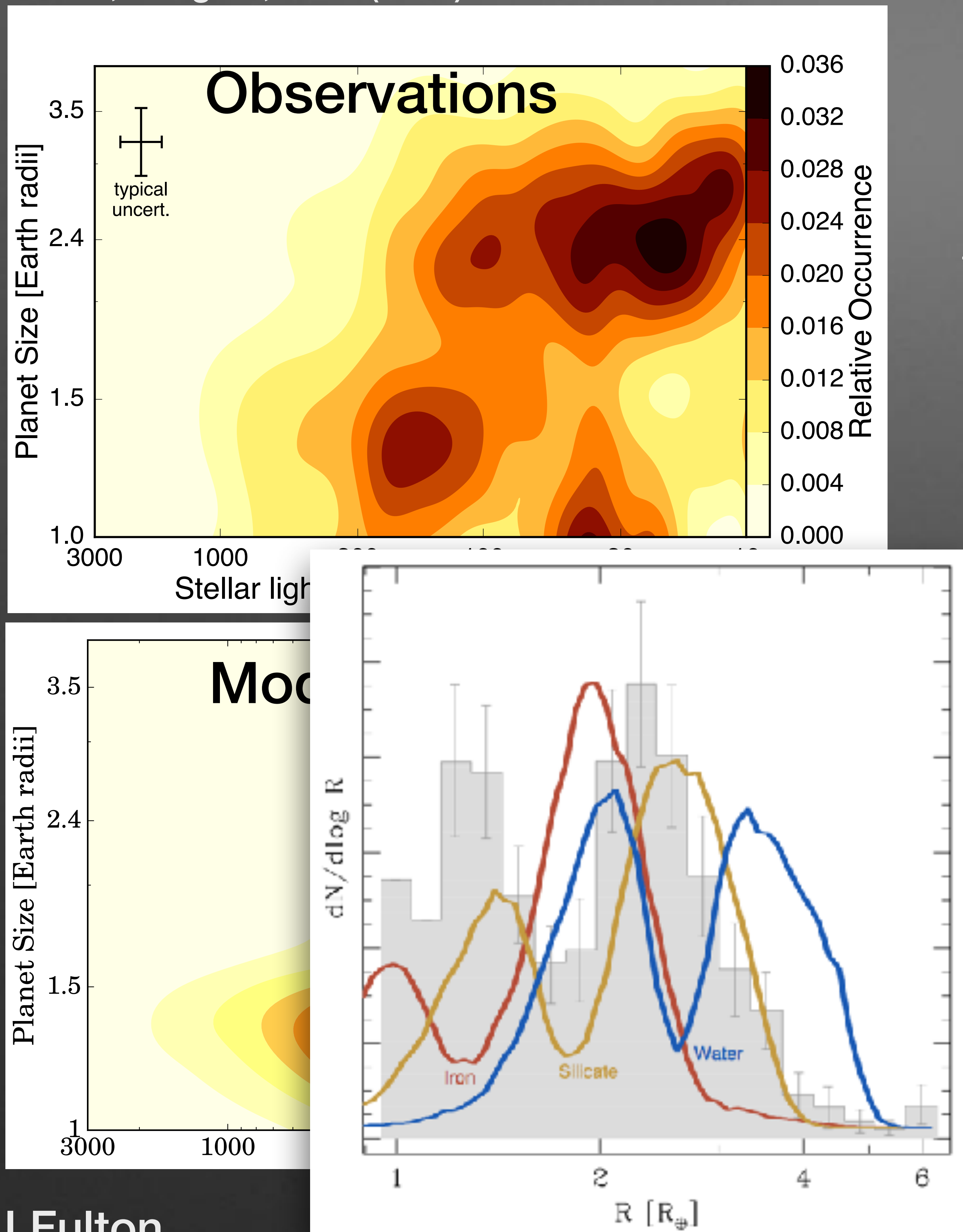
Photoevaporation



Owen & Wu (2017)

Photoevaporation

Fulton, Petigura, et al. (*2017*)

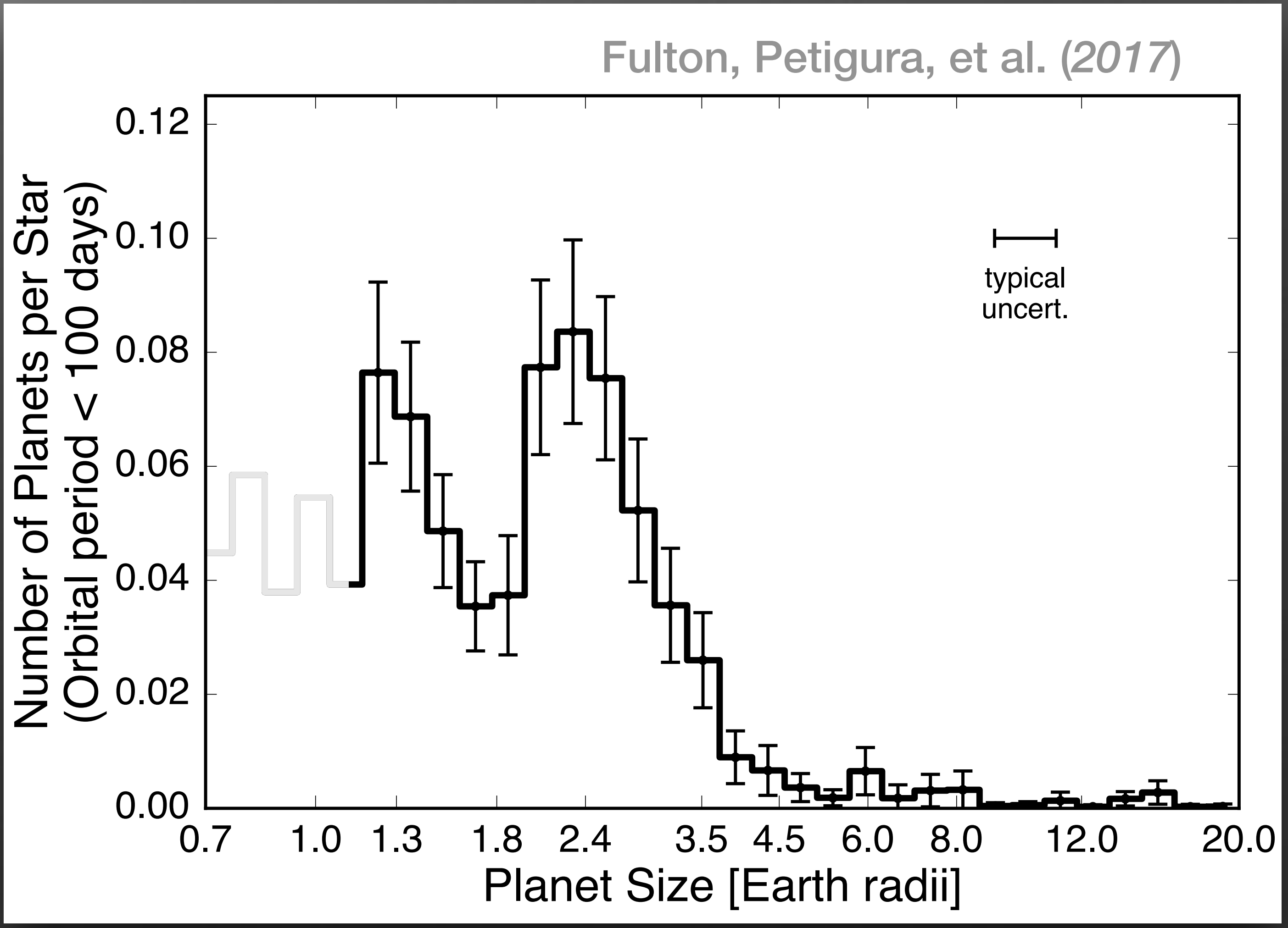


Major Implications

- Maximum core size ~3 Me
- Earth-like composition (water-poor)
- Large scale migration after 100 Myr is uncommon

Summary

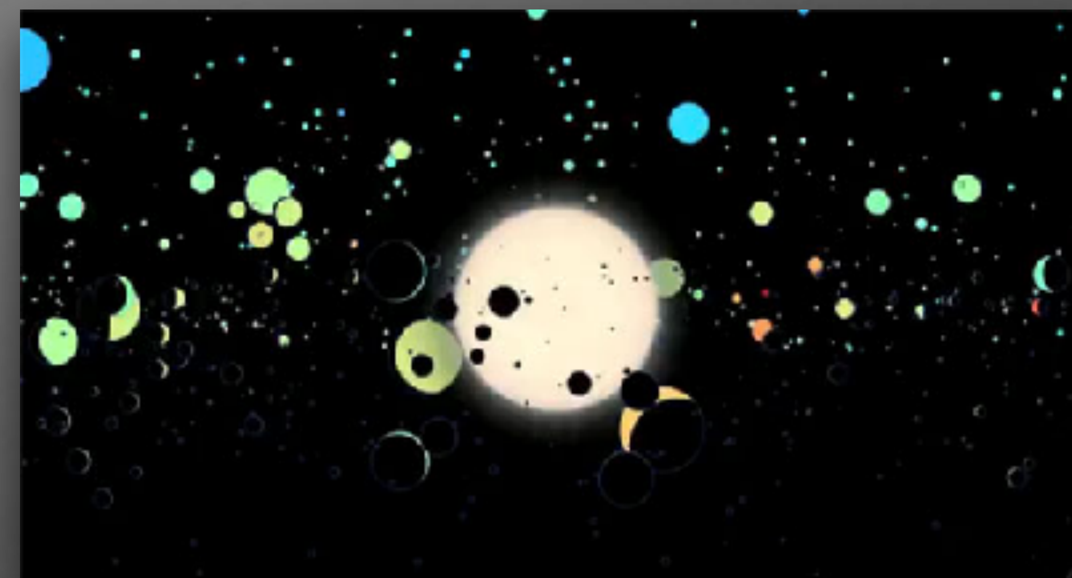
- Precision spectroscopy for 2025 KOIs
- Gap in the radius distribution between 1.5—2.0 R_e
- Two size classes for small planets
- Small, close-in planets are composed of rocky cores with varying amounts of low-density gas



Backup Slides

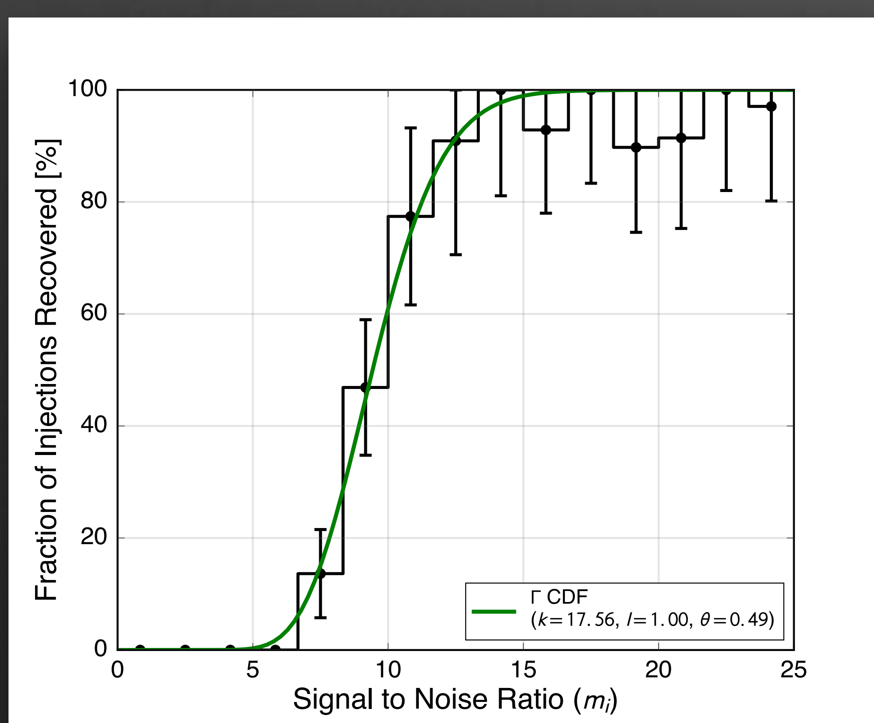
Completeness Corrections

$$w_i = \frac{1}{(p_{\rm det} \cdot p_{\rm tr})}$$



$$m_i = \left(\frac{R_P}{R_{\star,i}}\right)^2 \sqrt{\frac{T_{{\rm obs},i}}{P}} \left(\frac{1}{{\rm CDPP}_{{\rm dur},i}}\right)$$

+



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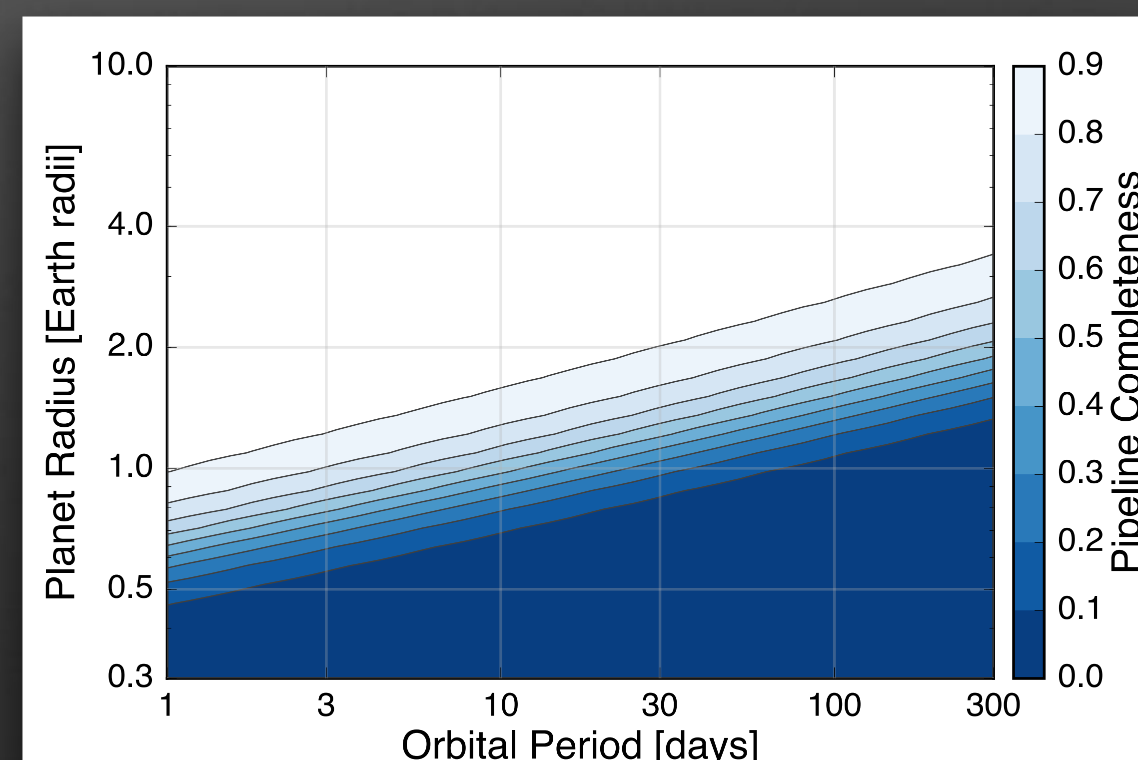
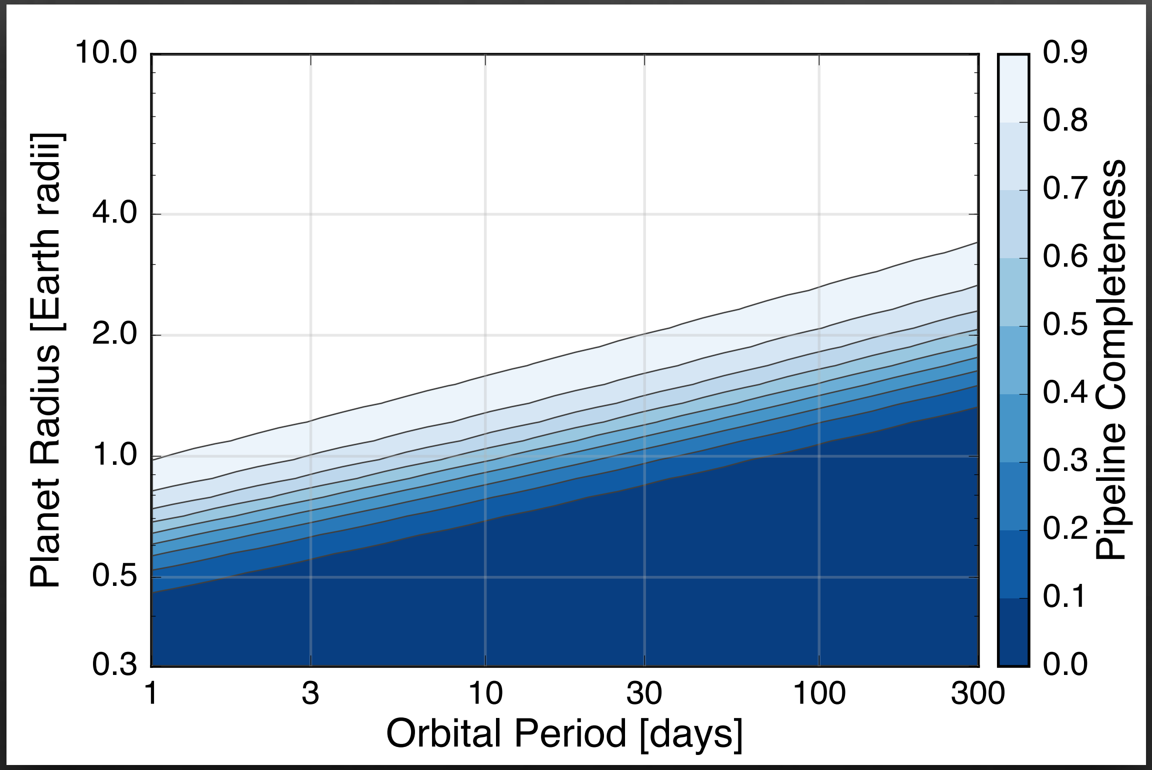


Completeness Corrections

$$w_i = \frac{1}{(p_{\rm det} \cdot p_{\rm tr})}$$

$$p_{\rm tr} = 0.7 R_\star / a$$

+



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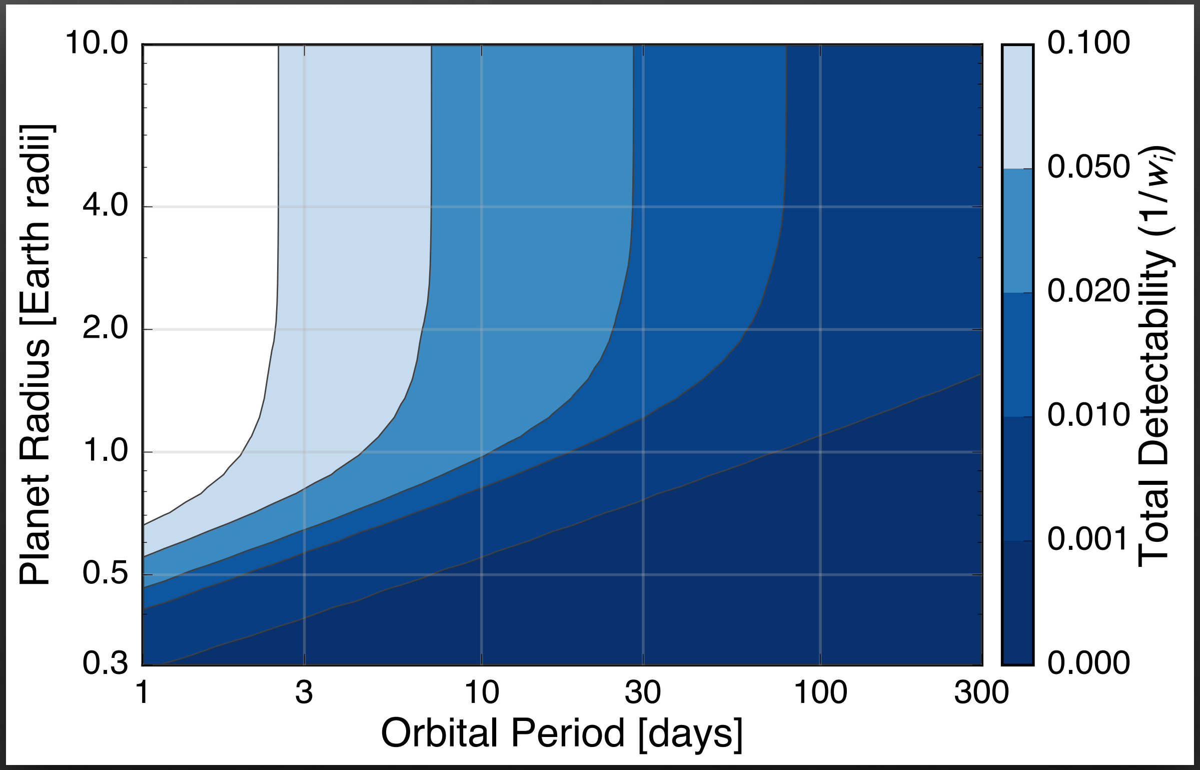
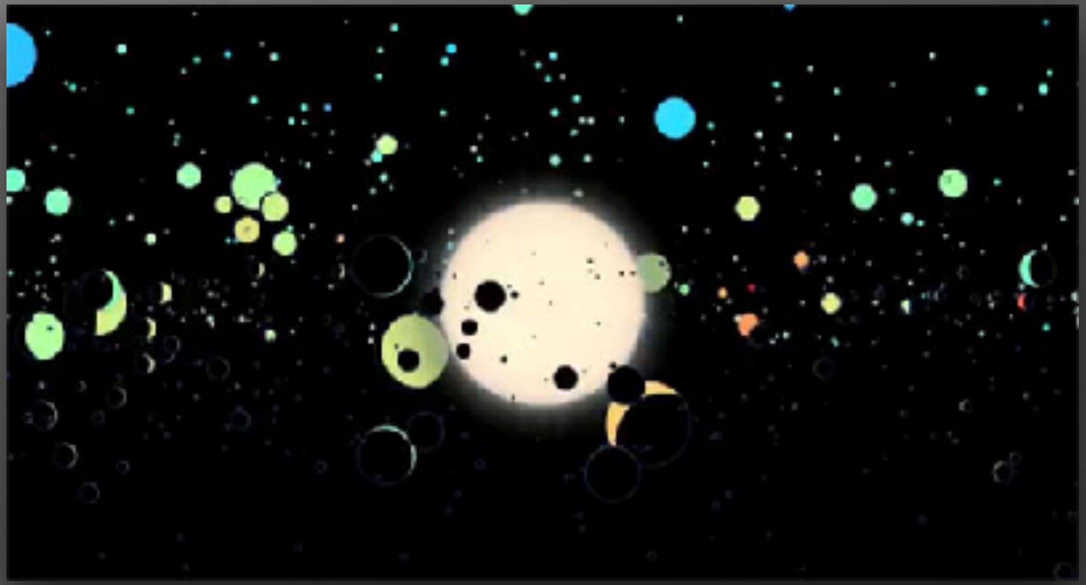


Fulton, Petigura, et al. (*submitted*)

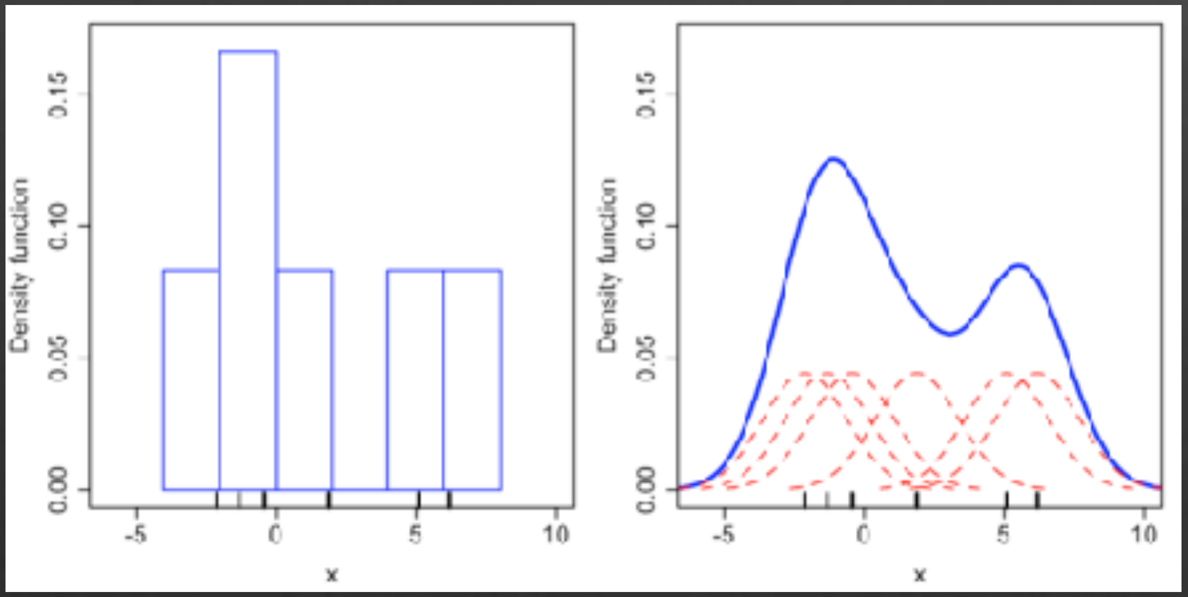
Completeness Corrections

$$w_i = \frac{1}{(p_{\rm det} \cdot p_{\rm tr})}$$



Number of Planets per Star =

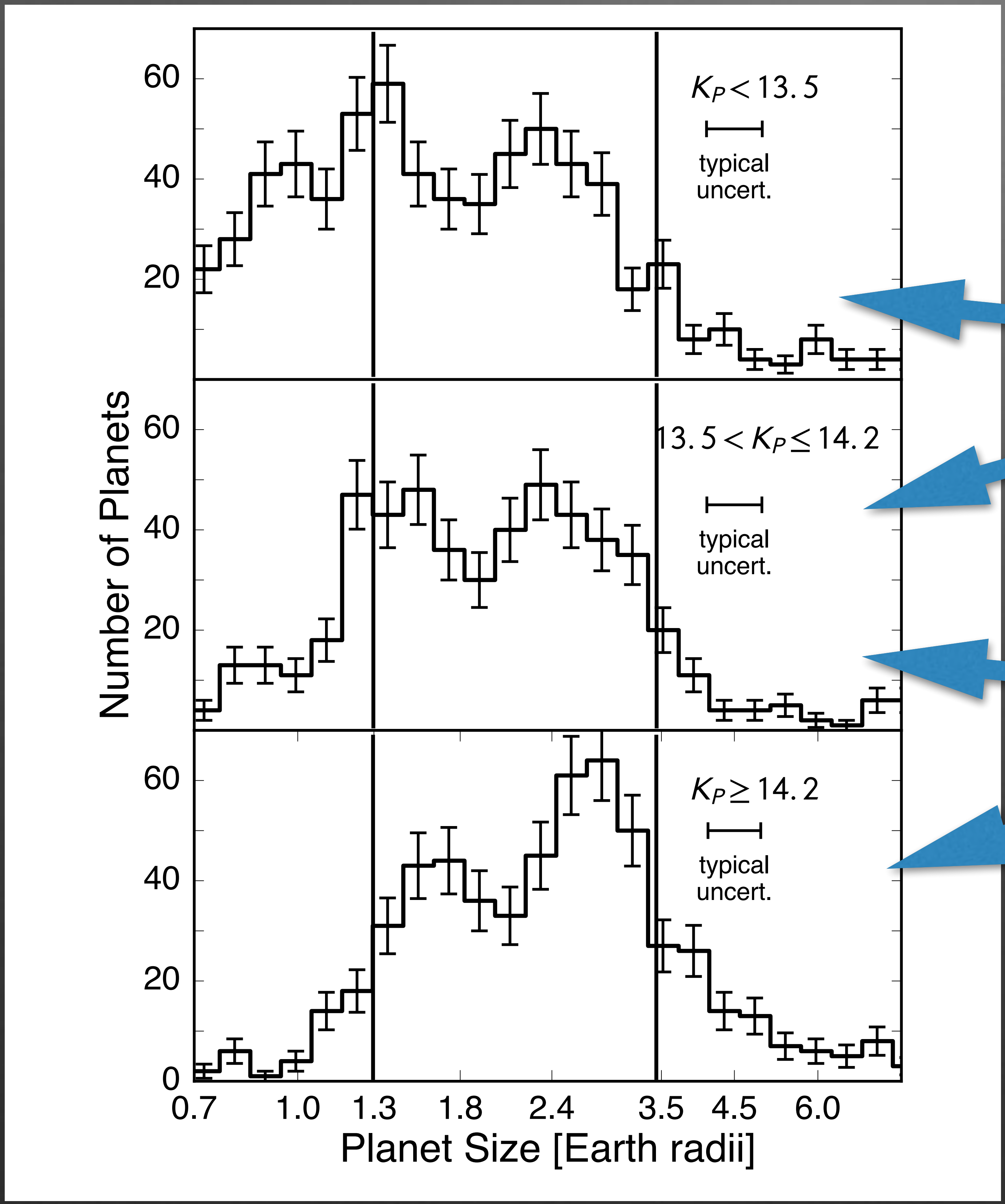
$$f_{\rm bin} = \frac{1}{N_\star} \sum_{i=1}^{n_{\rm pl,bin}} w_i$$



$$\phi(x) = \frac{1}{N_\star} \sum_{i=1}^{n_{\rm pl}} w_i \cdot K(x - x_i, \sigma_{x,i})$$

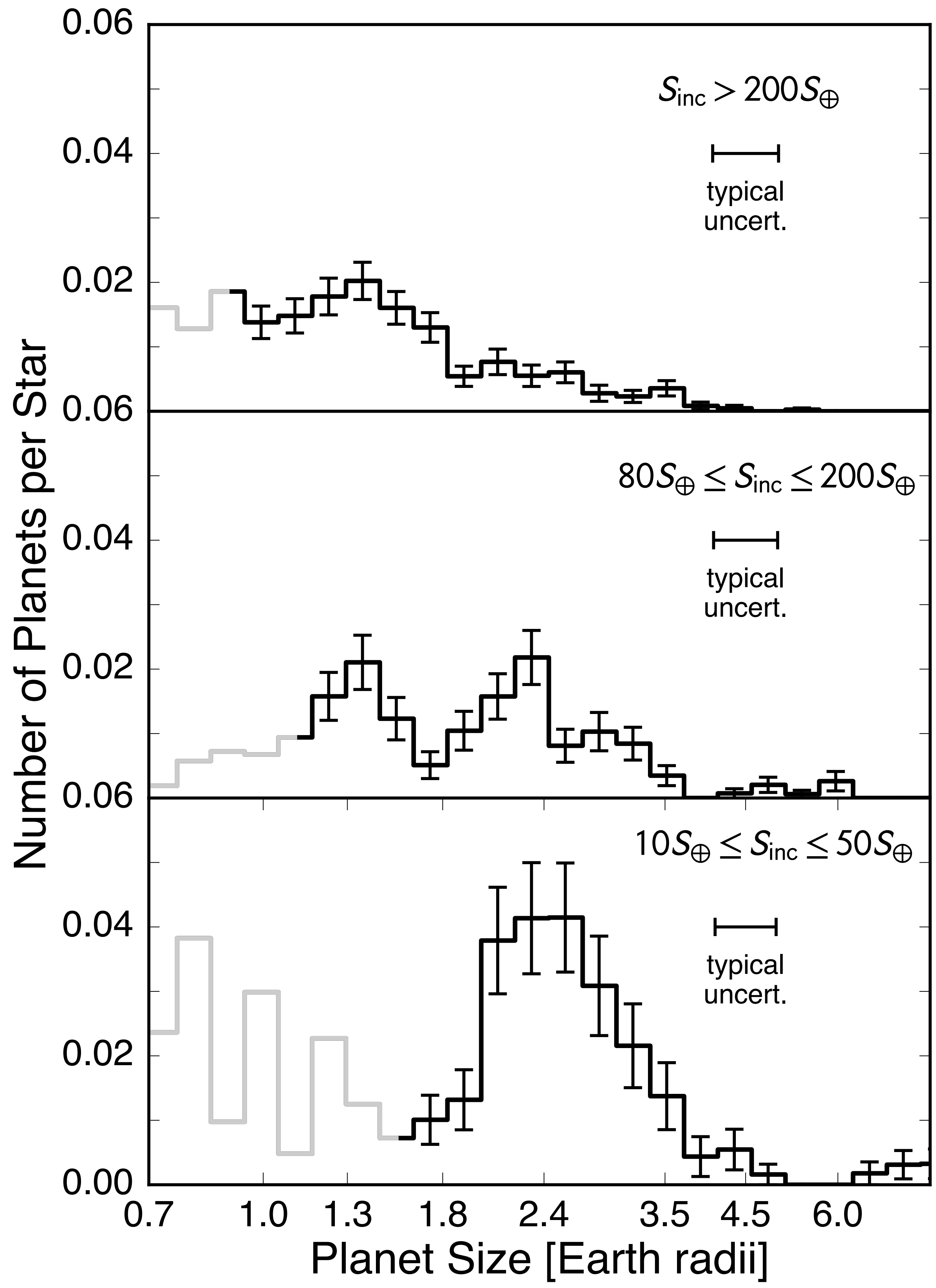
Fulton, Petigura, et al. (*submitted*)

Magnitude Cuts

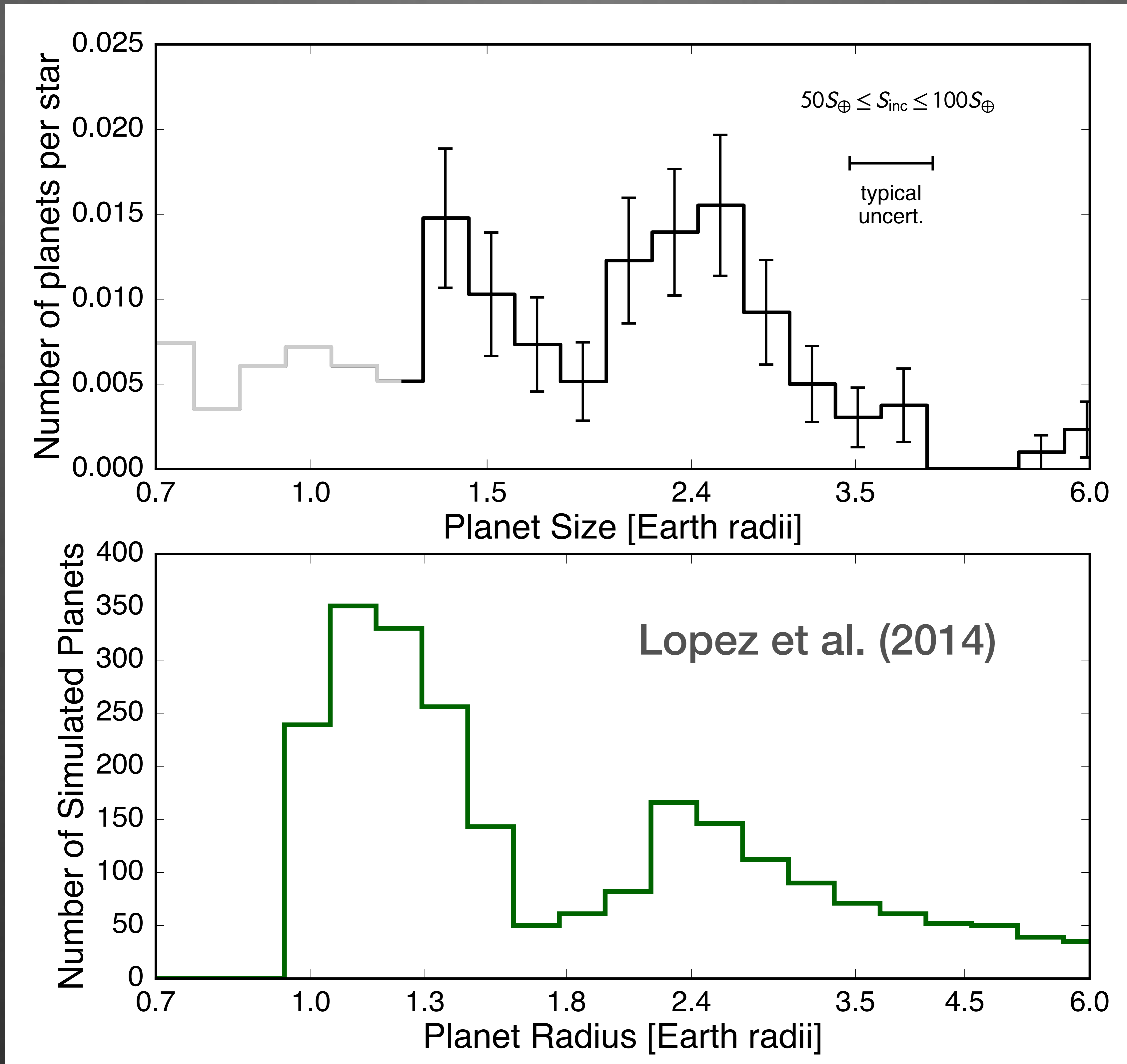


Consistent
(97% confidence)

Not consistent



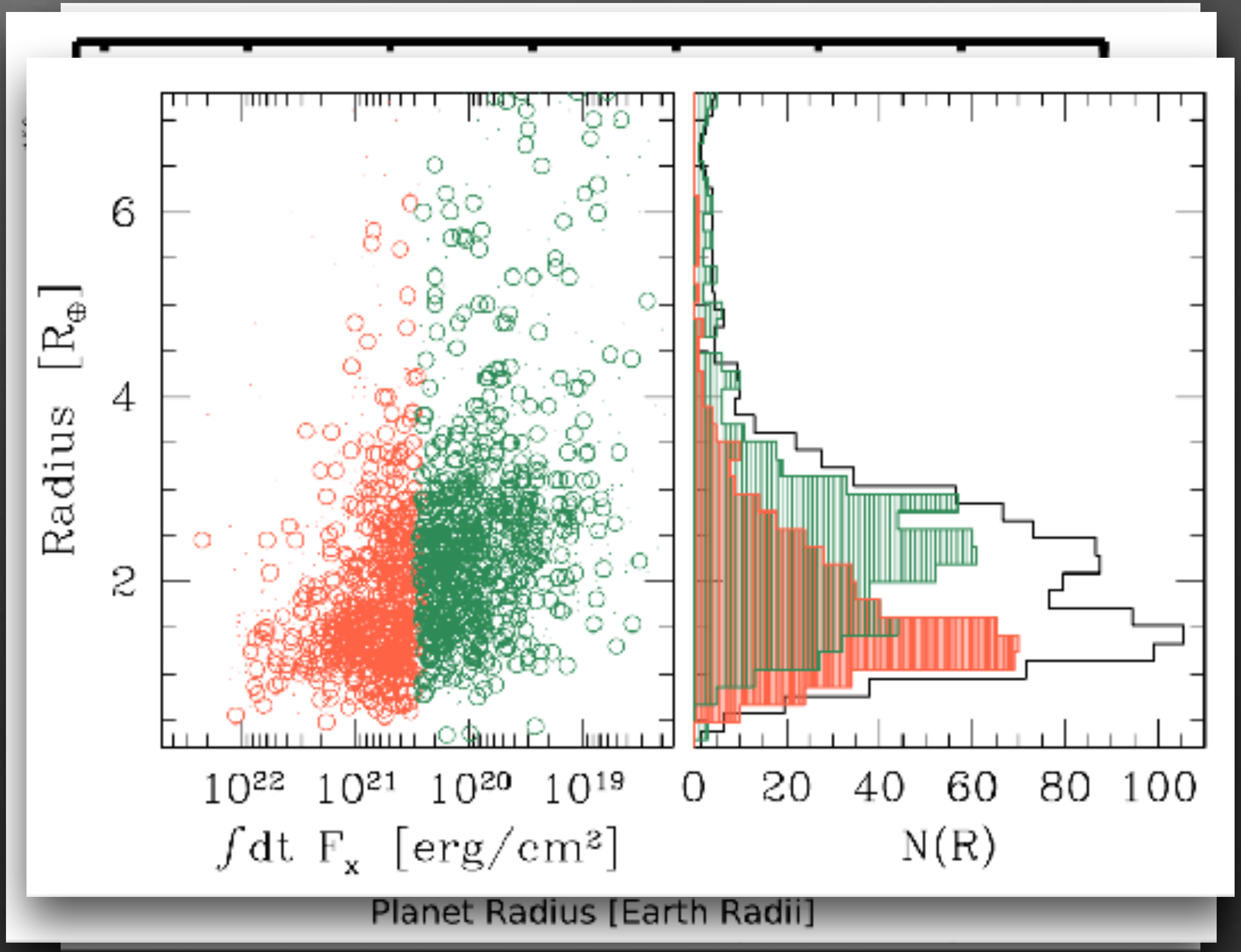
$S_{inc} > 200 S_\oplus$
typical uncert.
$80 S_\oplus \leq S_{inc} \leq 200 S_\oplus$
typical uncert.
$10 S_\oplus \leq S_{inc} \leq 50 S_\oplus$
typical uncert.
Number of Planets per Star
0.06
0.04
0.02
0.06
0.04
0.02
0.06
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
Planet Size [Earth radii]

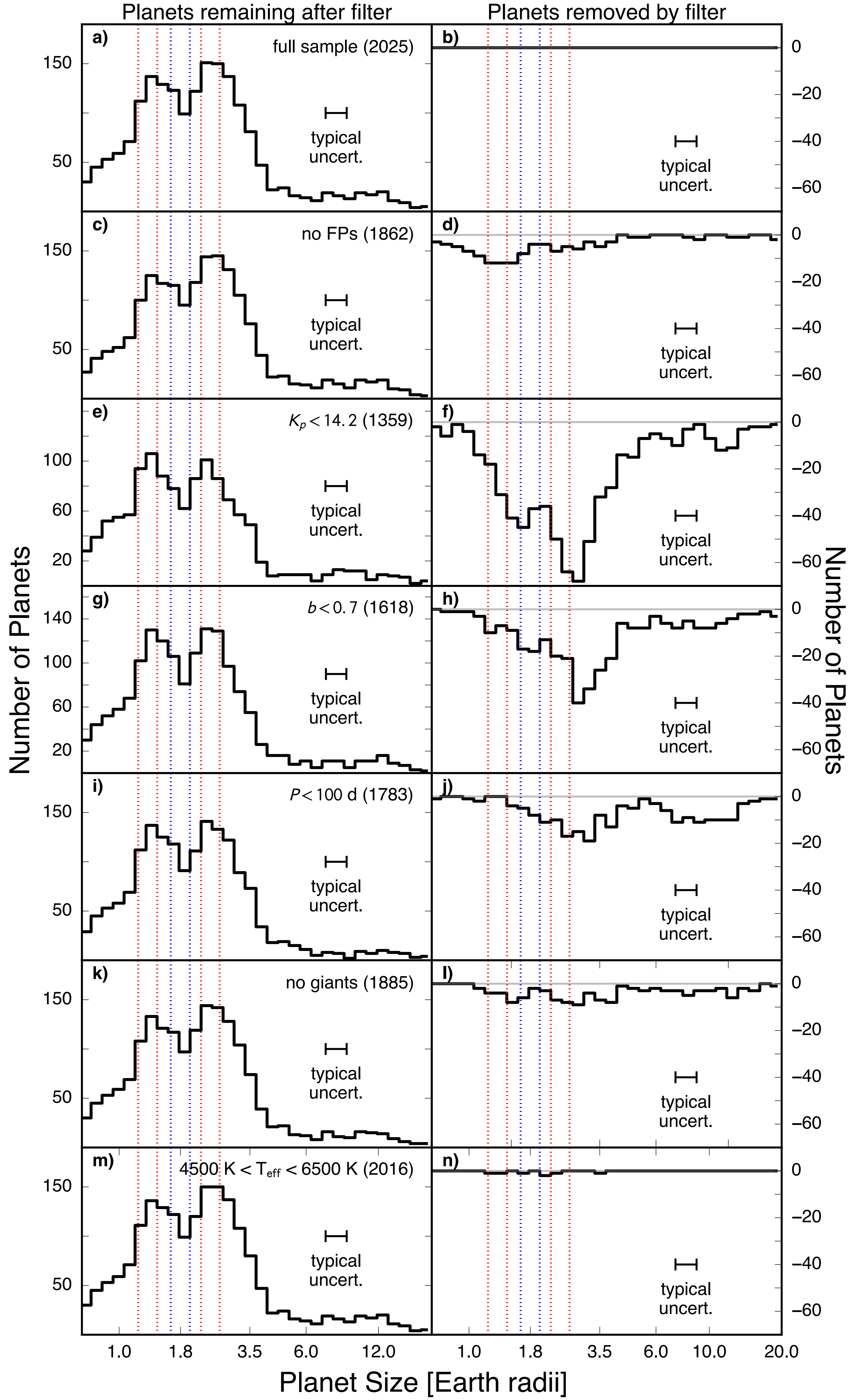


0.025
0.020
0.015
0.010
0.005
0.000
Number of planets per star
$50S_\oplus \le S_{inc} \le 100S_\oplus$
typical
uncert.
0.7
1.0
1.5
2.4
3.5
6.0
Planet Size [Earth radii]
400
350
300
250
200
150
100
50
0
Number of Simulated Planets
Lopez et al. (2014)
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
Planet Radius [Earth radii]

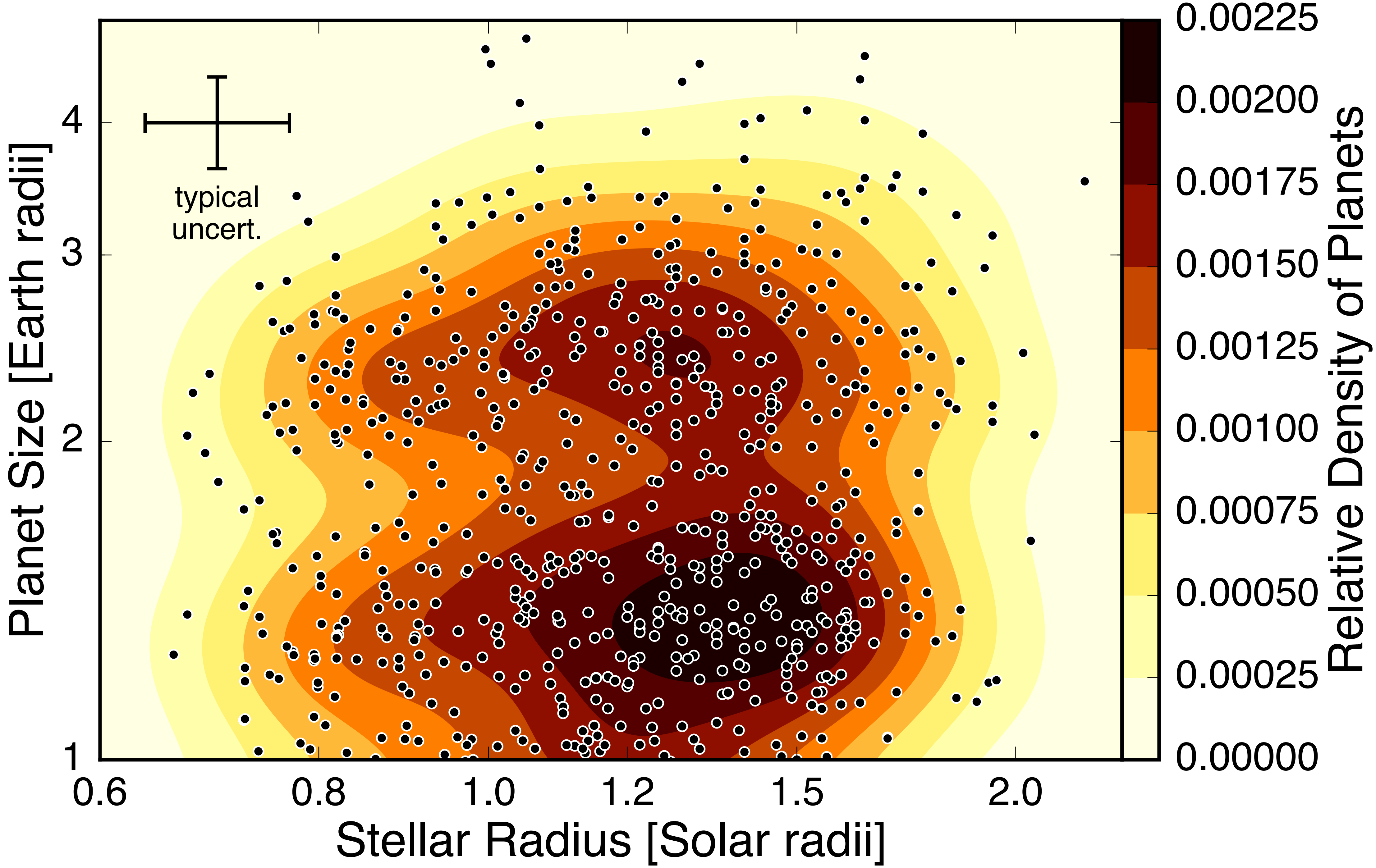
Previous Occurrence Studies

- Howard et al. (2012)
  Planet Occurrence Within 0.25 AU of Solar-Type Stars from Kepler
- Petigura et al. (2013)
  Prevalence of Earth-size planets orbiting Sun-like stars
- Morton et al. (2014)
  The Radius Distribution of Planets Around Cool Stars
- Owen & Wu (2014)
  Kepler Planets: A Tale of Evaporation

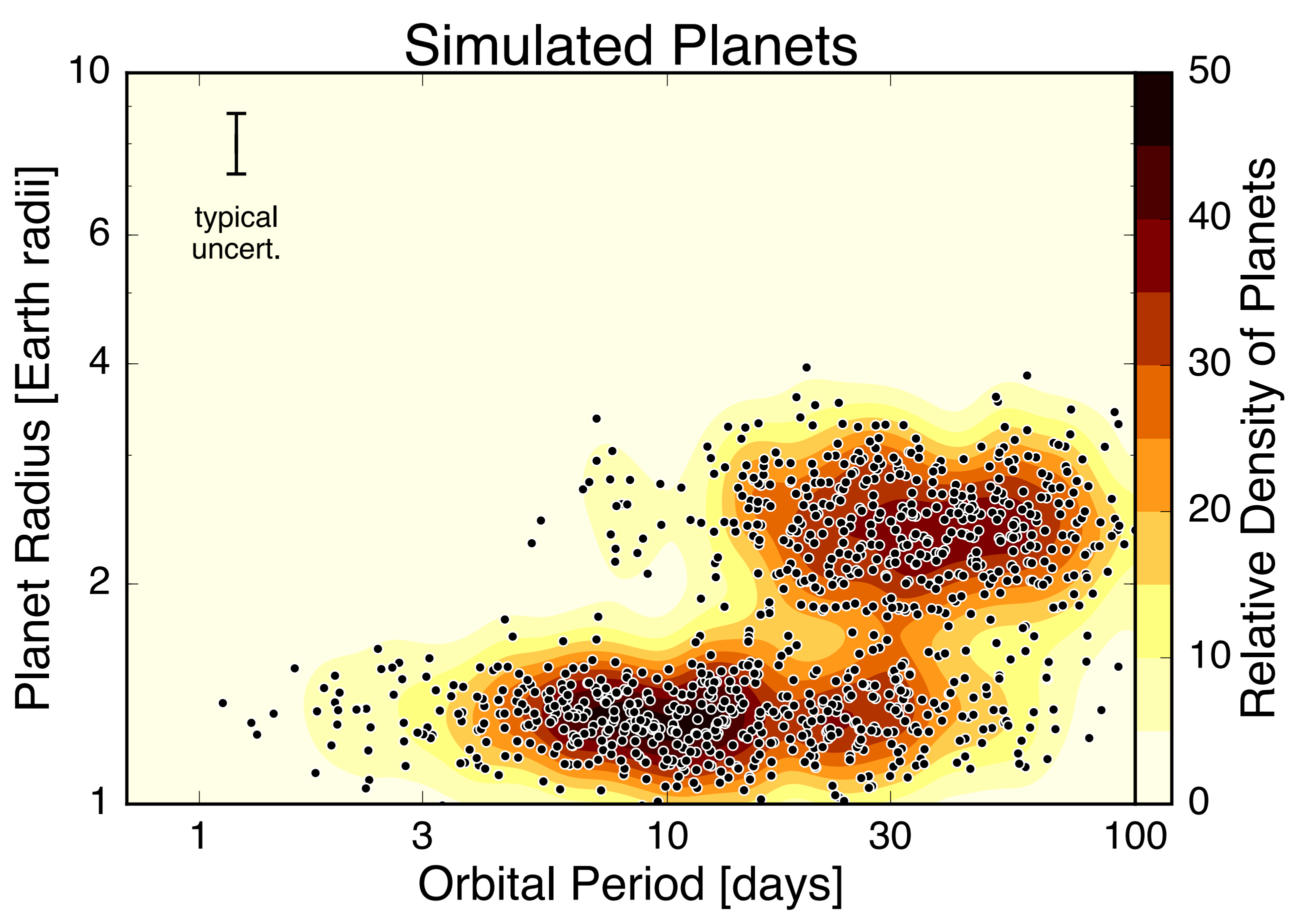




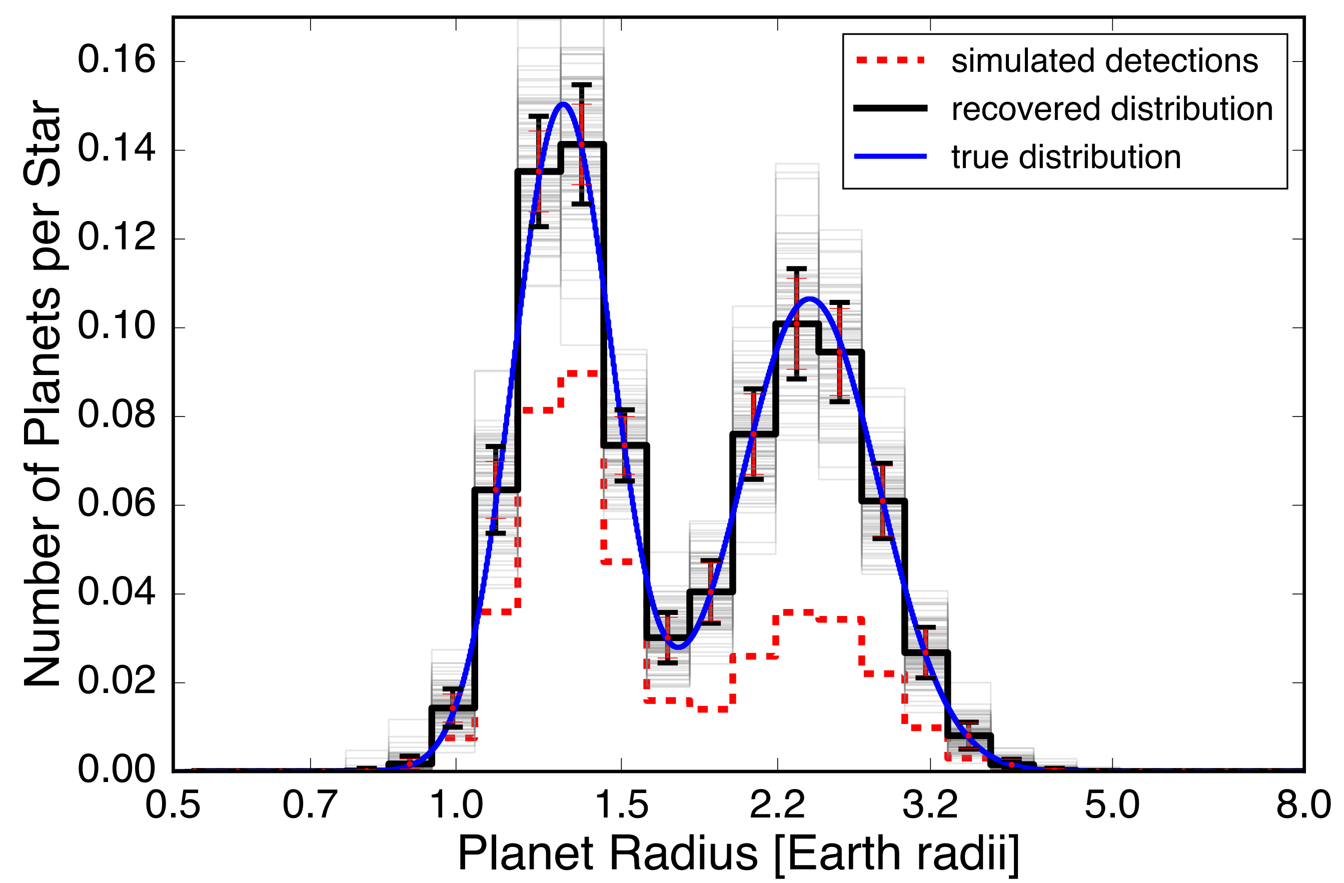
Planets remaining after filter
Planets removed by filter
a) full sample (2025)
b)
c) no FPs (1862)
d)
e) $K_p < 14.2$ (1359)
f)
g) $b < 0.7$ (1618)
h)
i) $P < 100$ d (1783)
j)
k) no giants (1885)
l)
m) 4500 K < T_{eff} < 6500 K (2016)
n)
typical uncert.
Number of Planets
Number of Planets
Planet Size [Earth radii]
1.0
1.8
3.5
6.0
12.0
10.0
20.0
150
50
100
60
20
140
0
−20
−40
−60



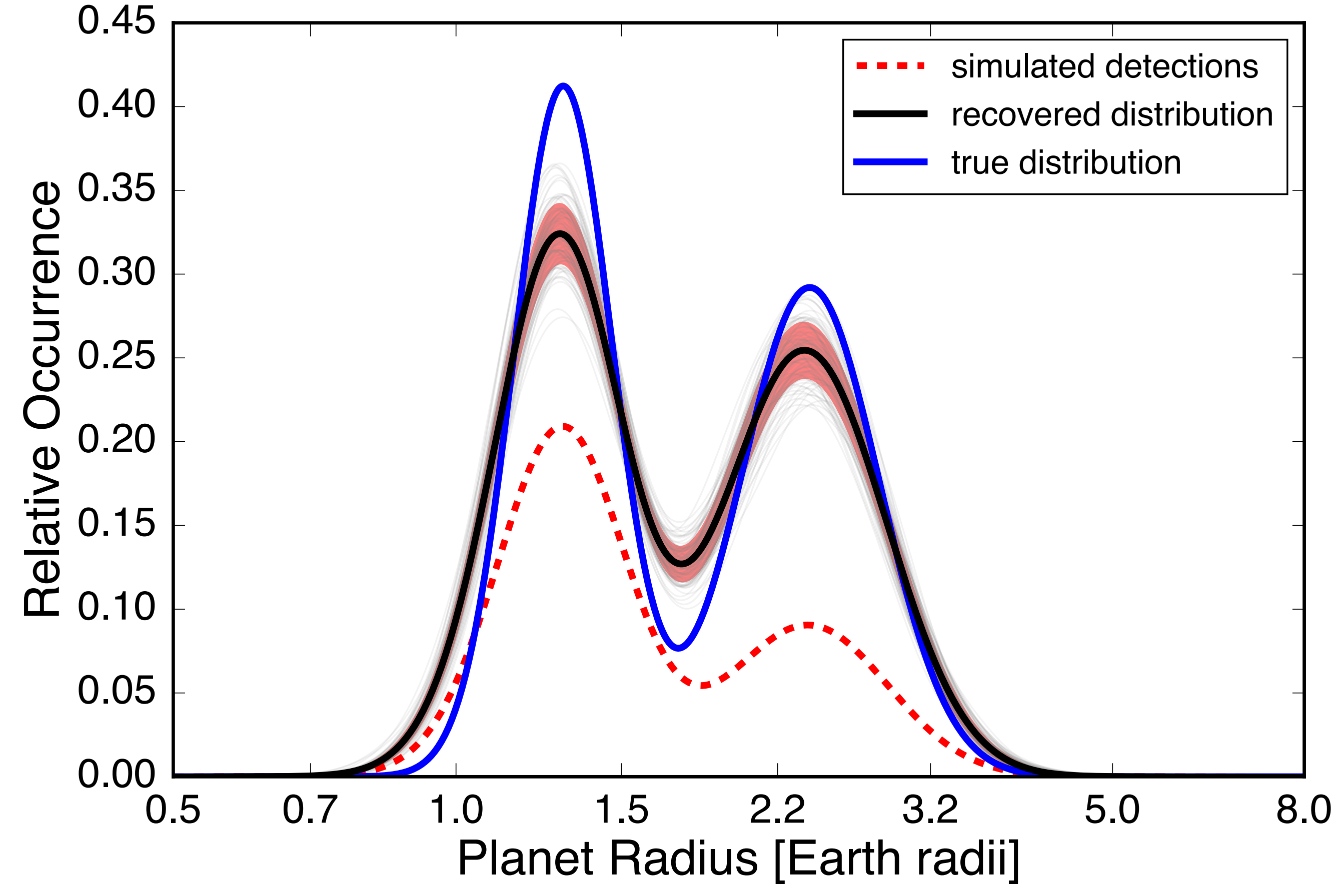
typical
uncert.
4
3
2
1
0.6
0.8
1.0
1.2
1.5
2.0
Planet Size [Earth radii]
Stellar Radius [Solar radii]
0.00225
0.00200
0.00175
0.00150
0.00125
0.00100
0.00075
0.00050
0.00025
0.00000
Relative Density of Planets



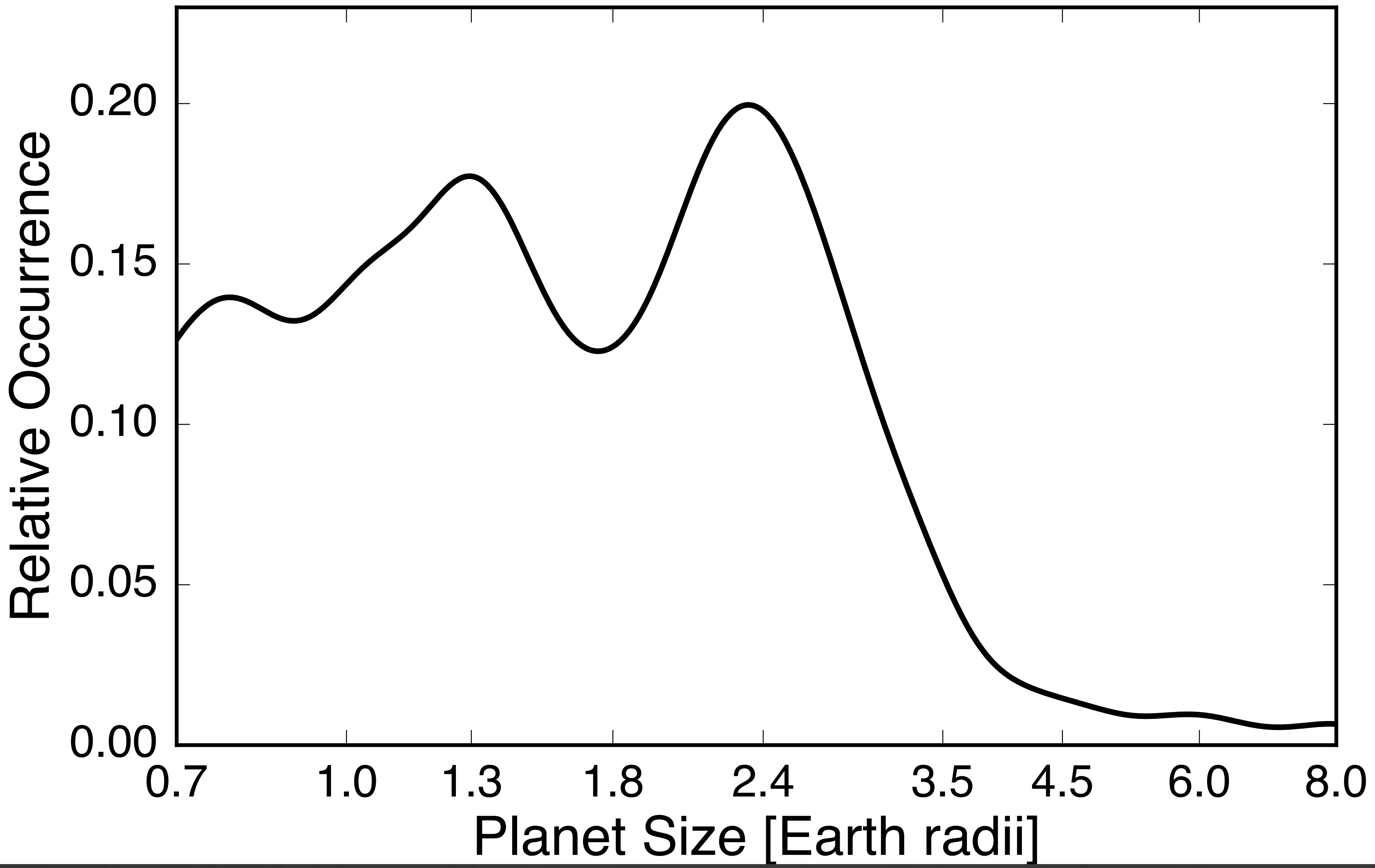
Simulated Planets
typical
uncert.
Planet Radius [Earth radii]
Orbital Period [days]
Relative Density of Planets



simulated detections
recovered distribution
true distribution
Number of Planets per Star
Planet Radius [Earth radii]



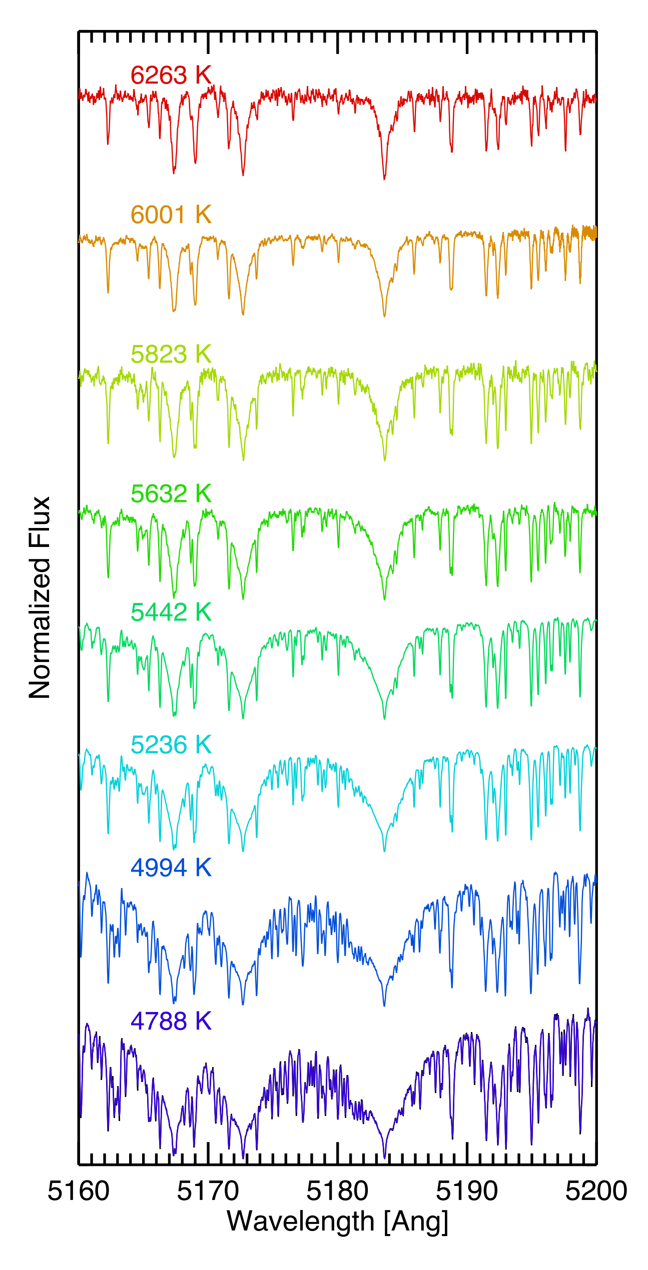
simulated detections
recovered distribution
true distribution
Relative Occurrence
Planet Radius [Earth radii]

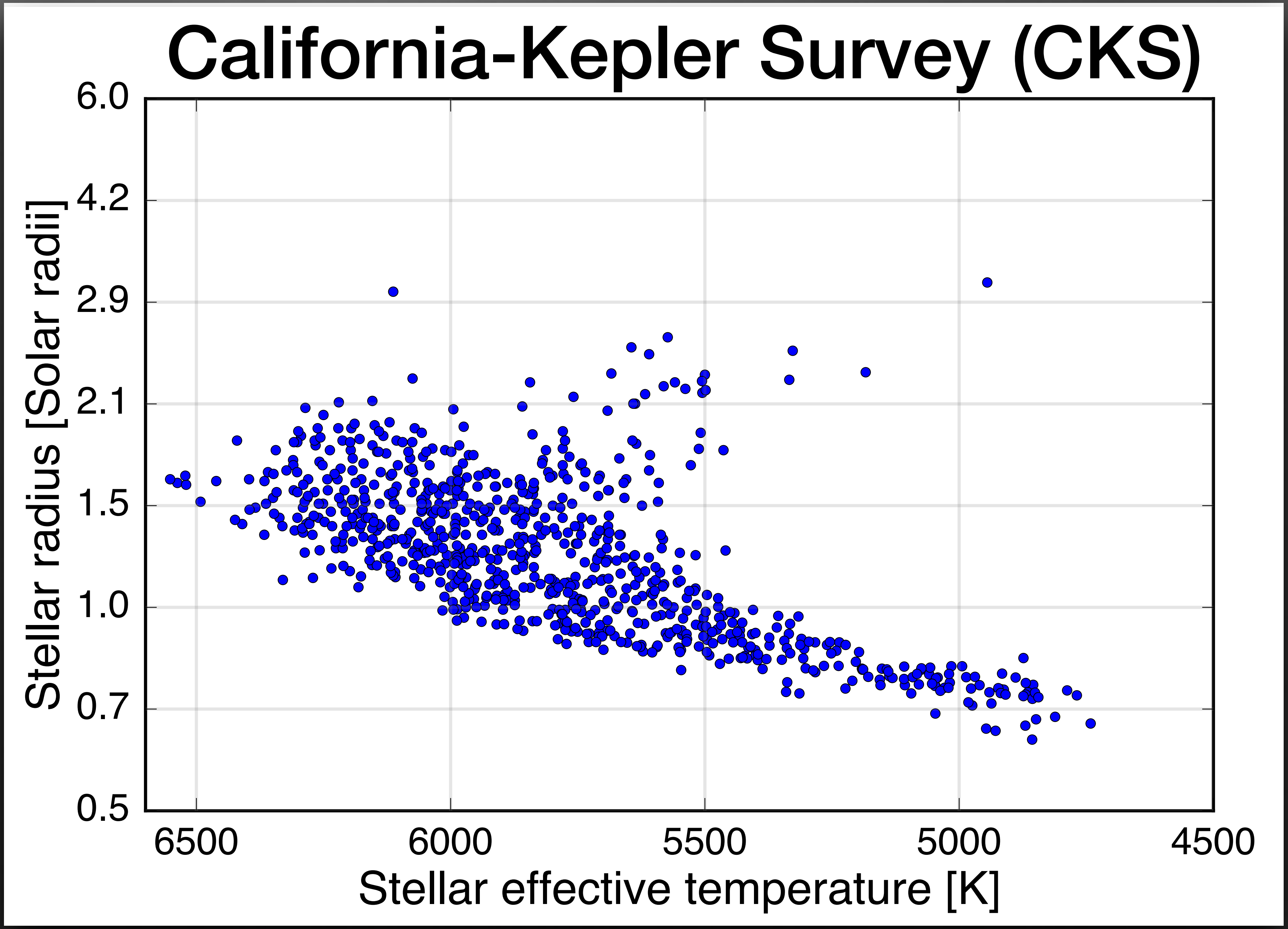


0.20
0.15
0.10
0.05
0.00
Relative Occurrence
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
Planet Size [Earth radii]

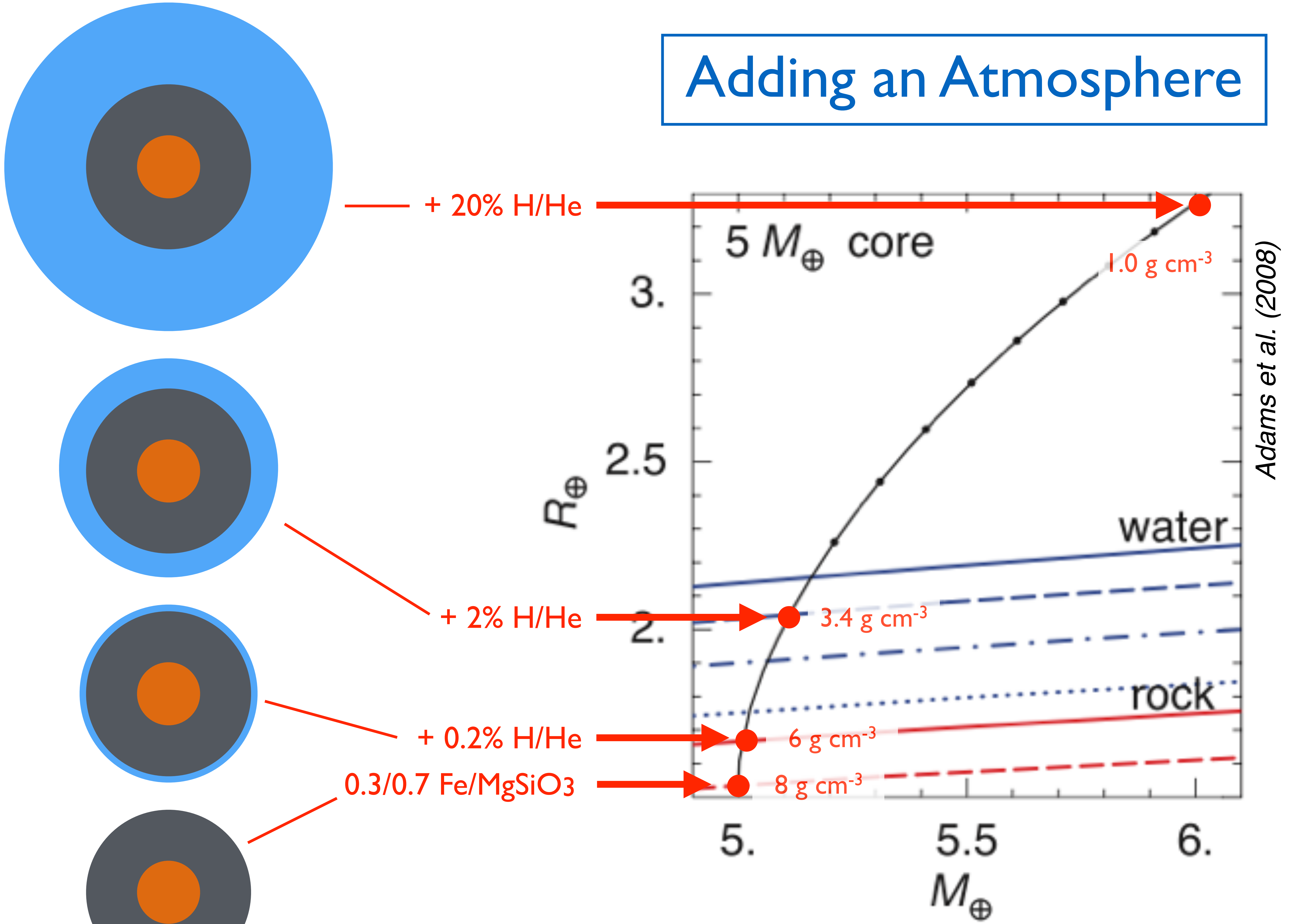
The California-Kepler Survey

Keck/HIRES spectra for 1305 *Kepler* Objects of Interest





Adding an Atmosphere



Planet inflation depends on: M_{core}, T_{eff}, internal heat sources