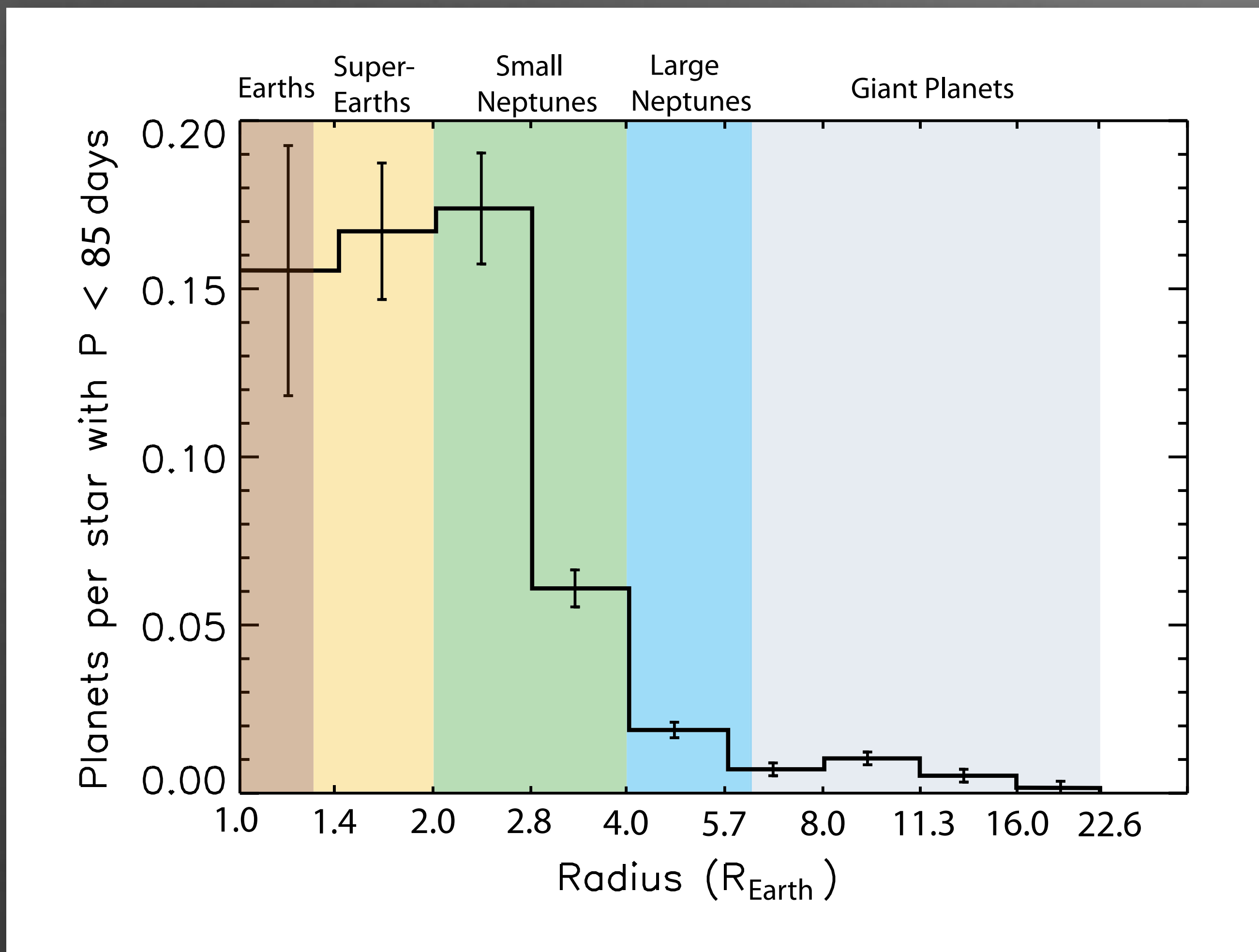
The California-Kepler Survey. III.

A Gap in the Radius Distribution of Small Planets

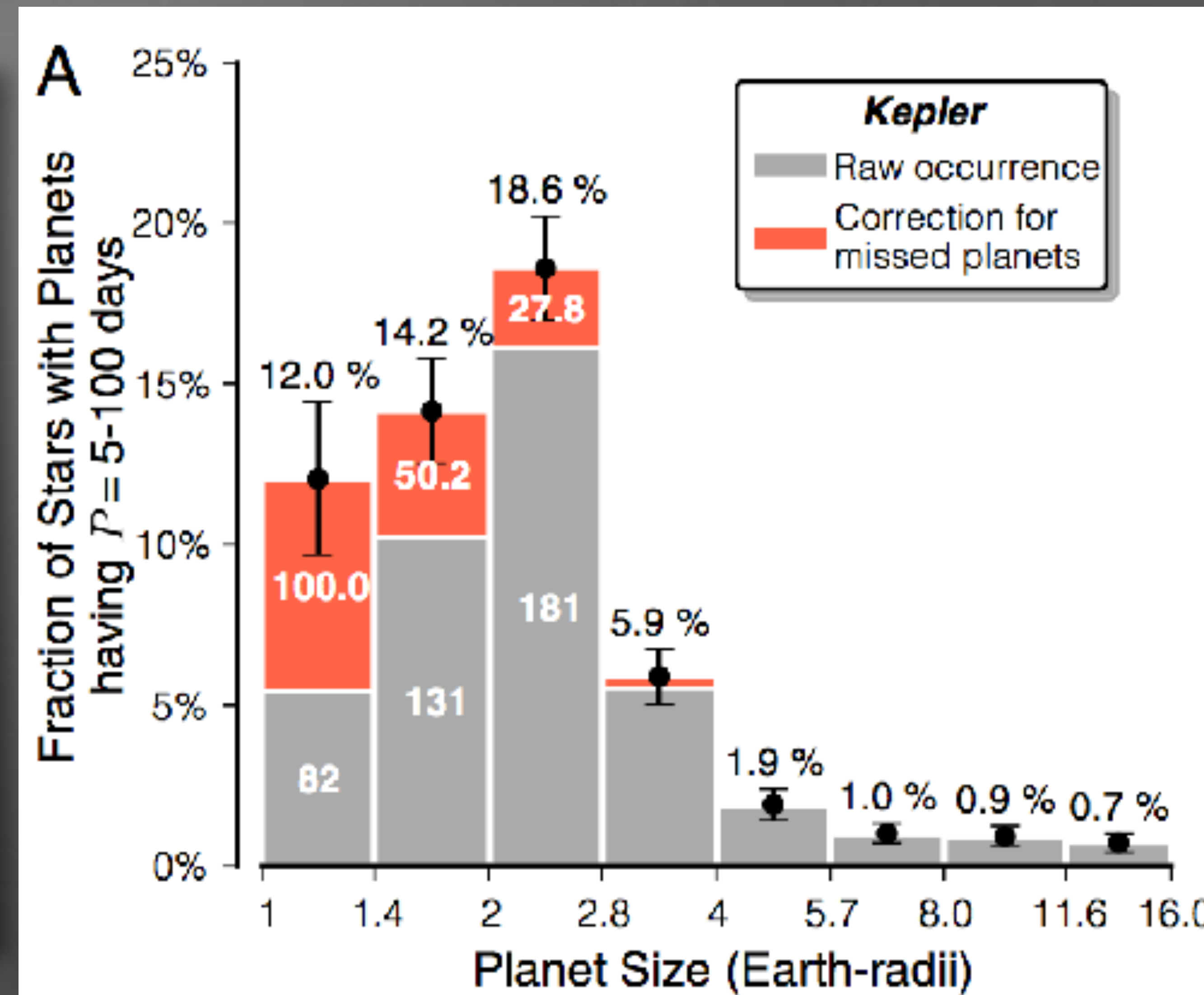
BJ Fulton, Erik Petigura, Andrew Howard, Howard Isaacson, Geoffrey Marcy, Phillip Cargile, Leslie Hebb, Lauren Weiss, John Johnson, Tim Morton, Evan Sinukoff, Ian Crossfield, and Lea Hirsch

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)

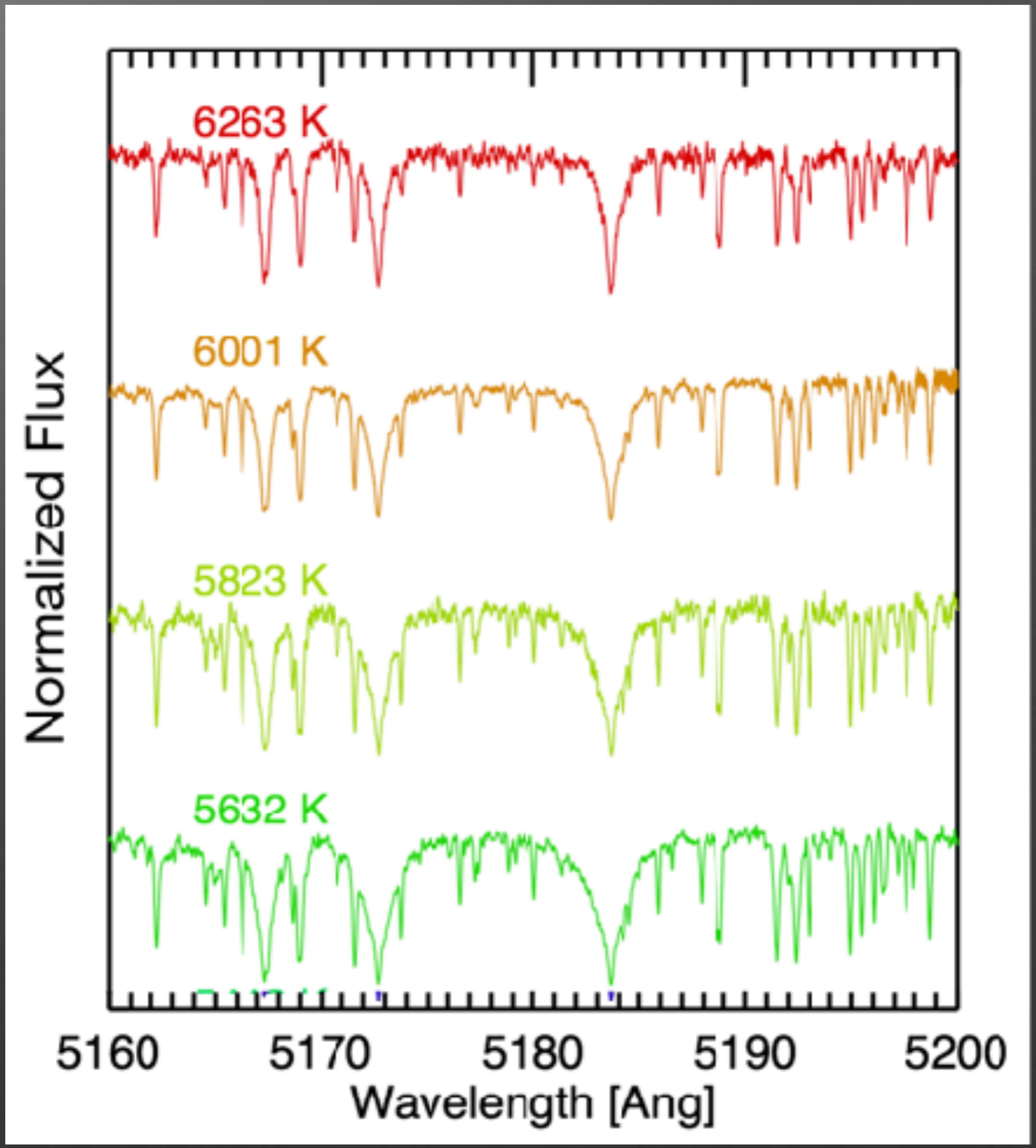


Petigura et al. (2013)

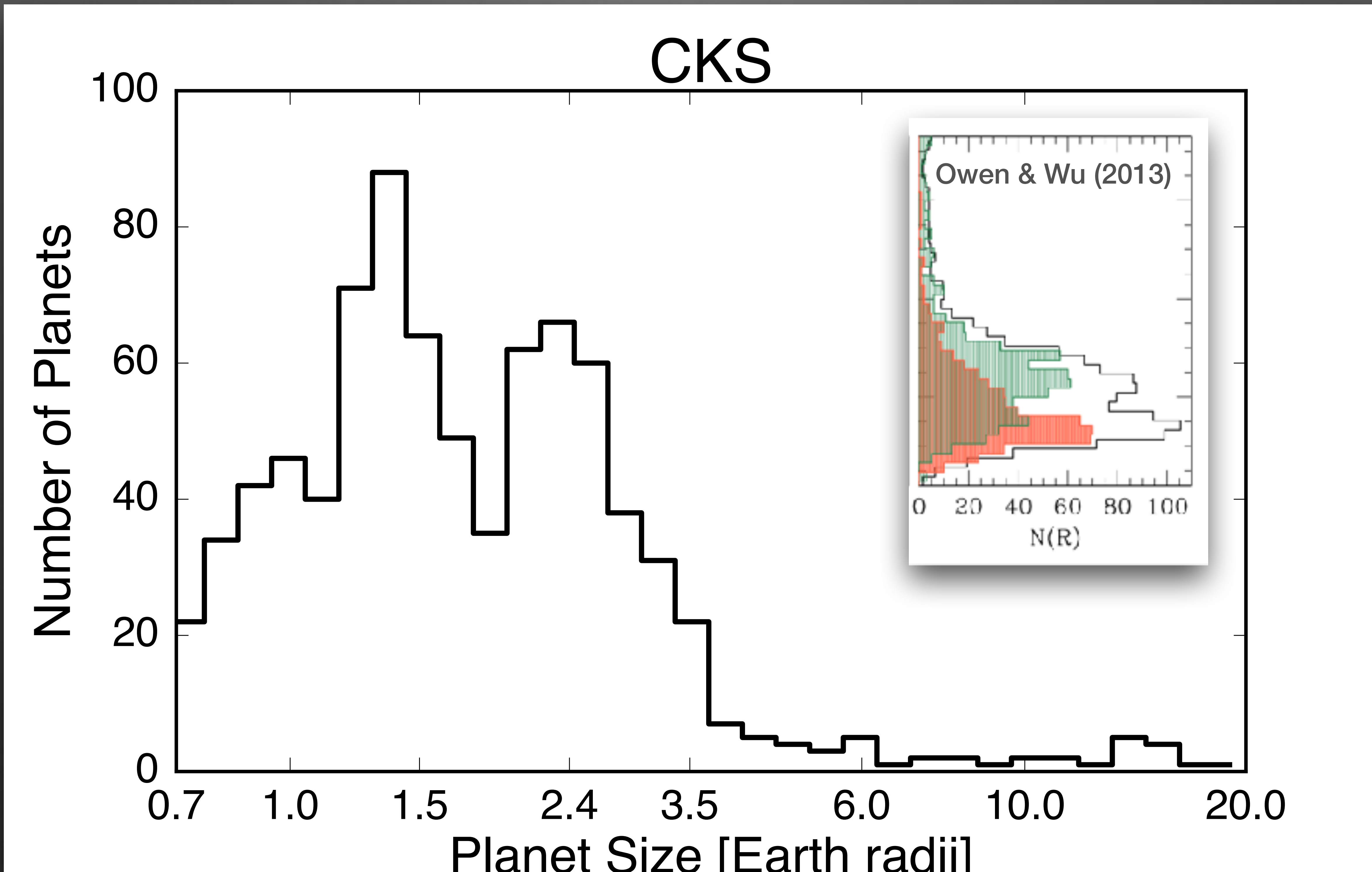
Features in the radius distribution smeared out due to 40% radius errors

The California-Kepler Survey

- Keck/HIRES spectra of 1305 stars hosting 2025 planet candidates
- Core-sample: magnitude limited (Kp < 14.2) ($N_\star$ = 960)
- 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



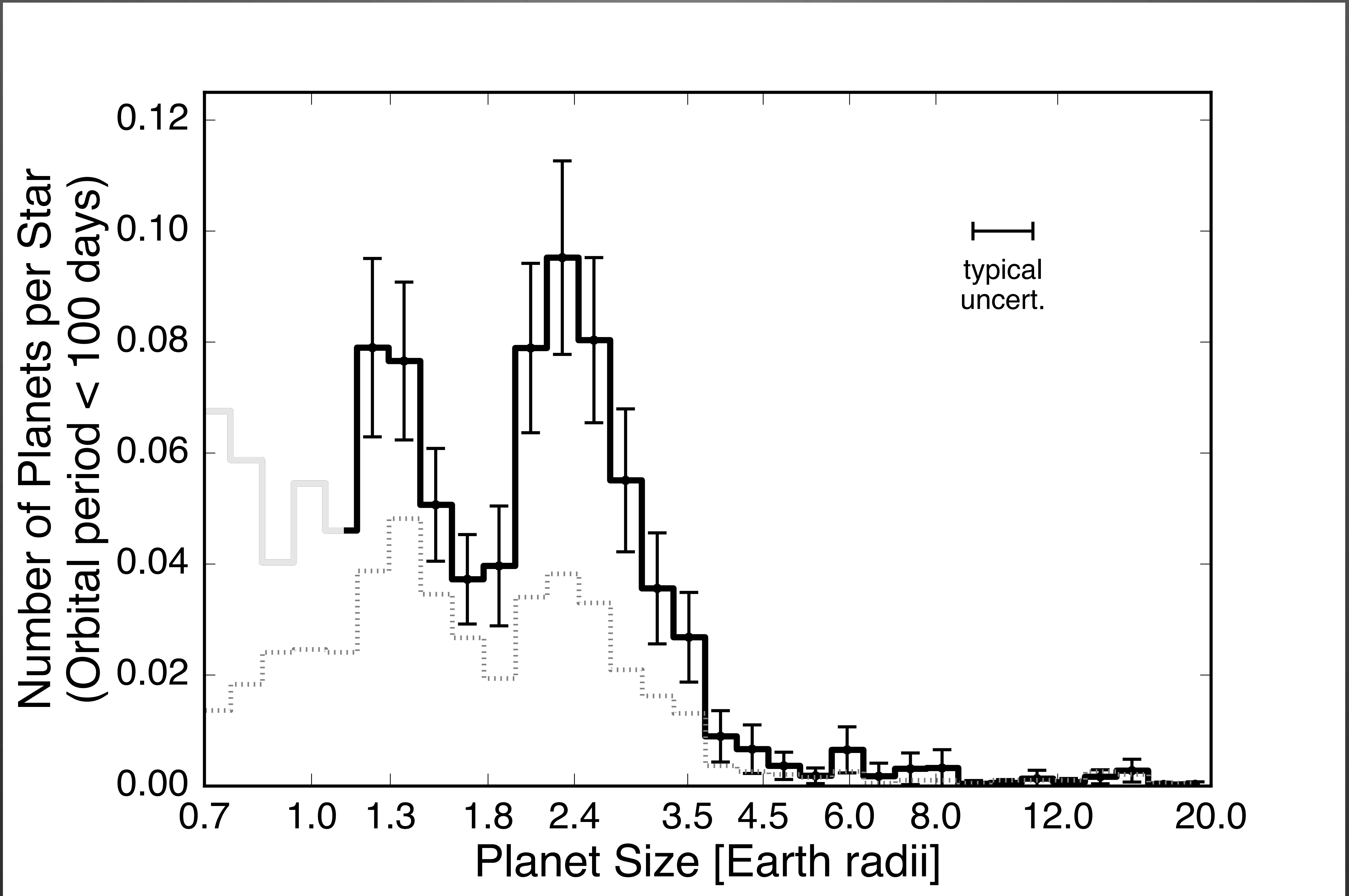
Petigura, Howard, et al. (*2017*)



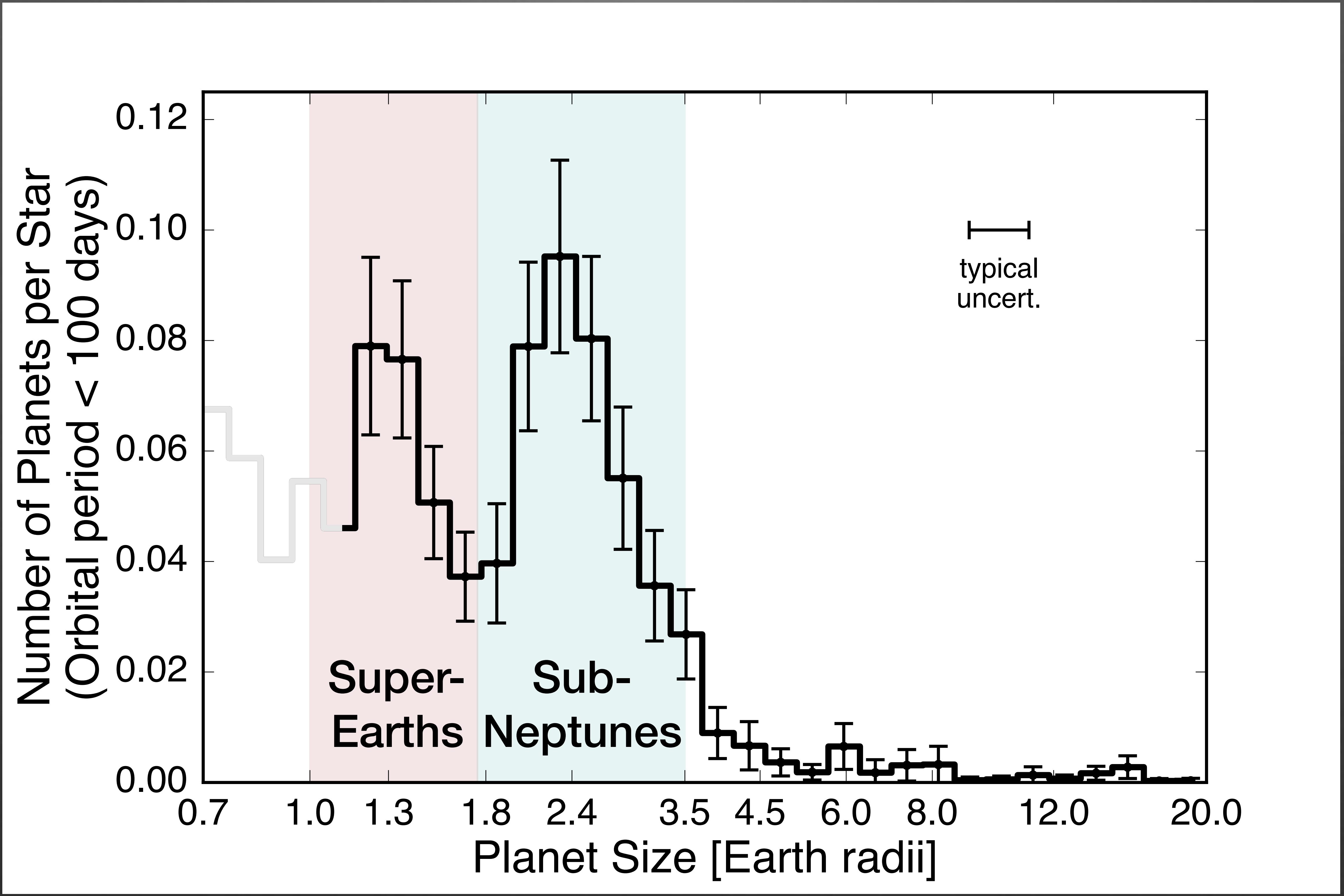
Huber et al. (2014); Mullally et al. (2015)

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

The Radius Gap



The Radius Gap



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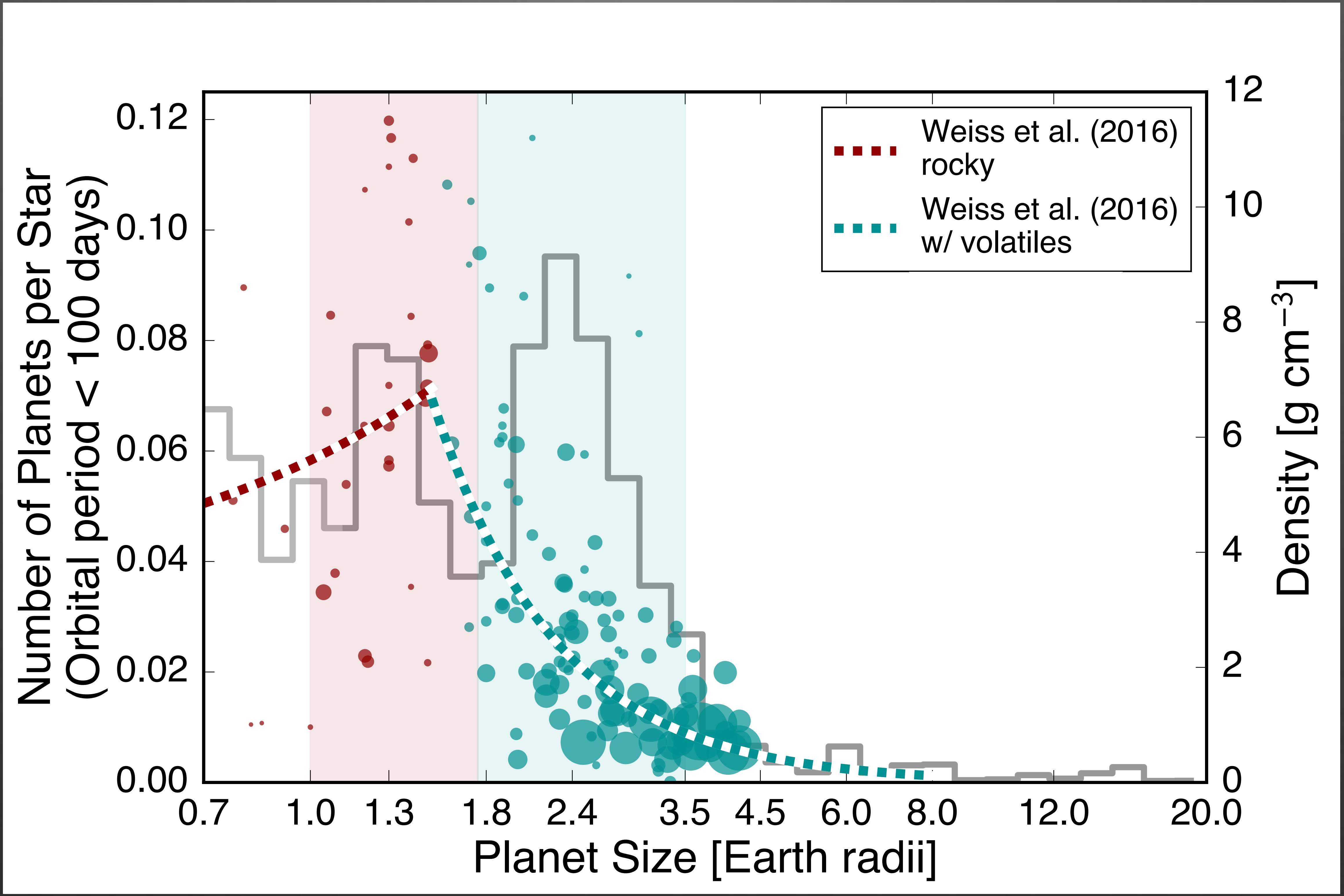
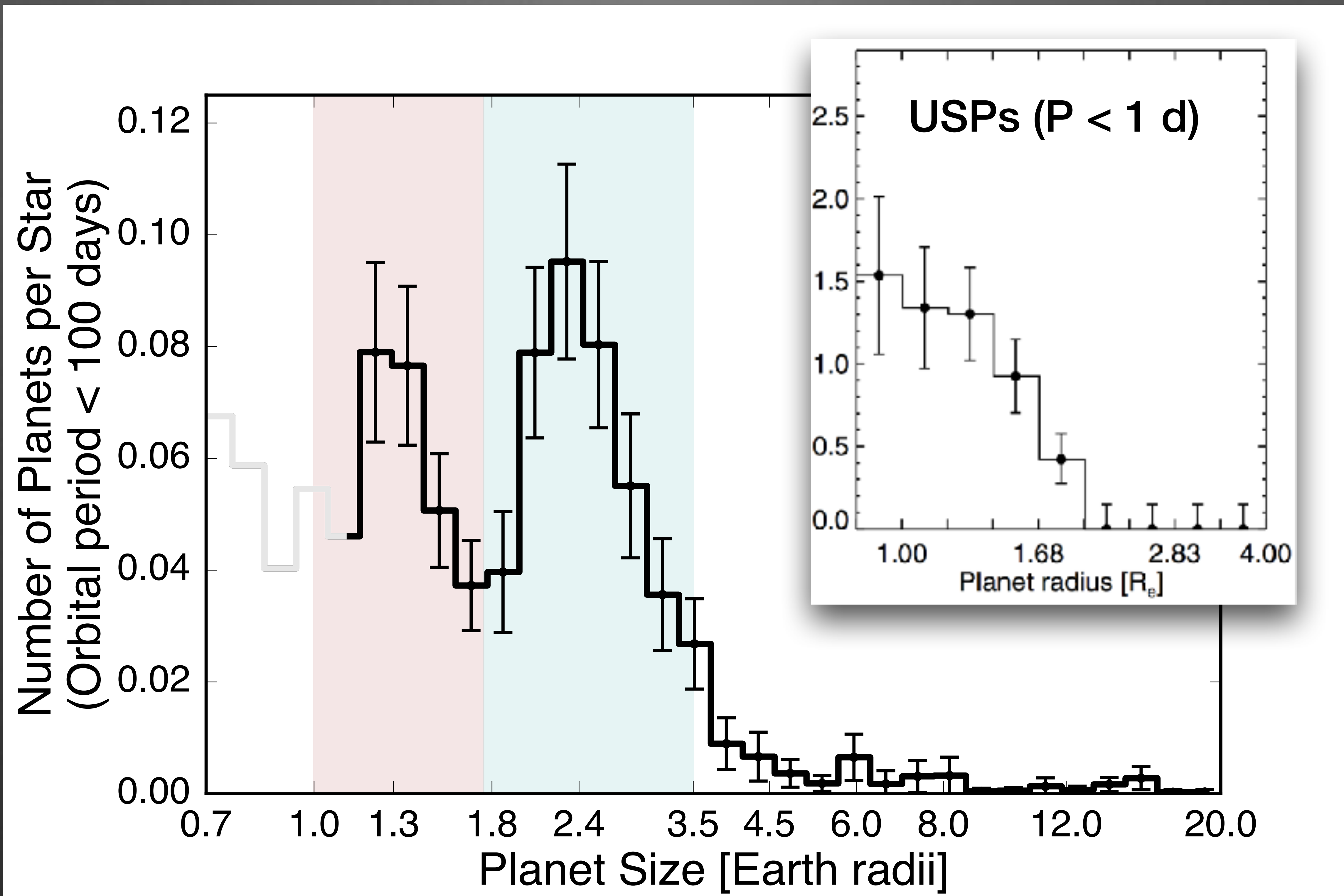
Fulton, Petigura, et al. (*2017*)

ExSoCal 2017

The Radius Gap

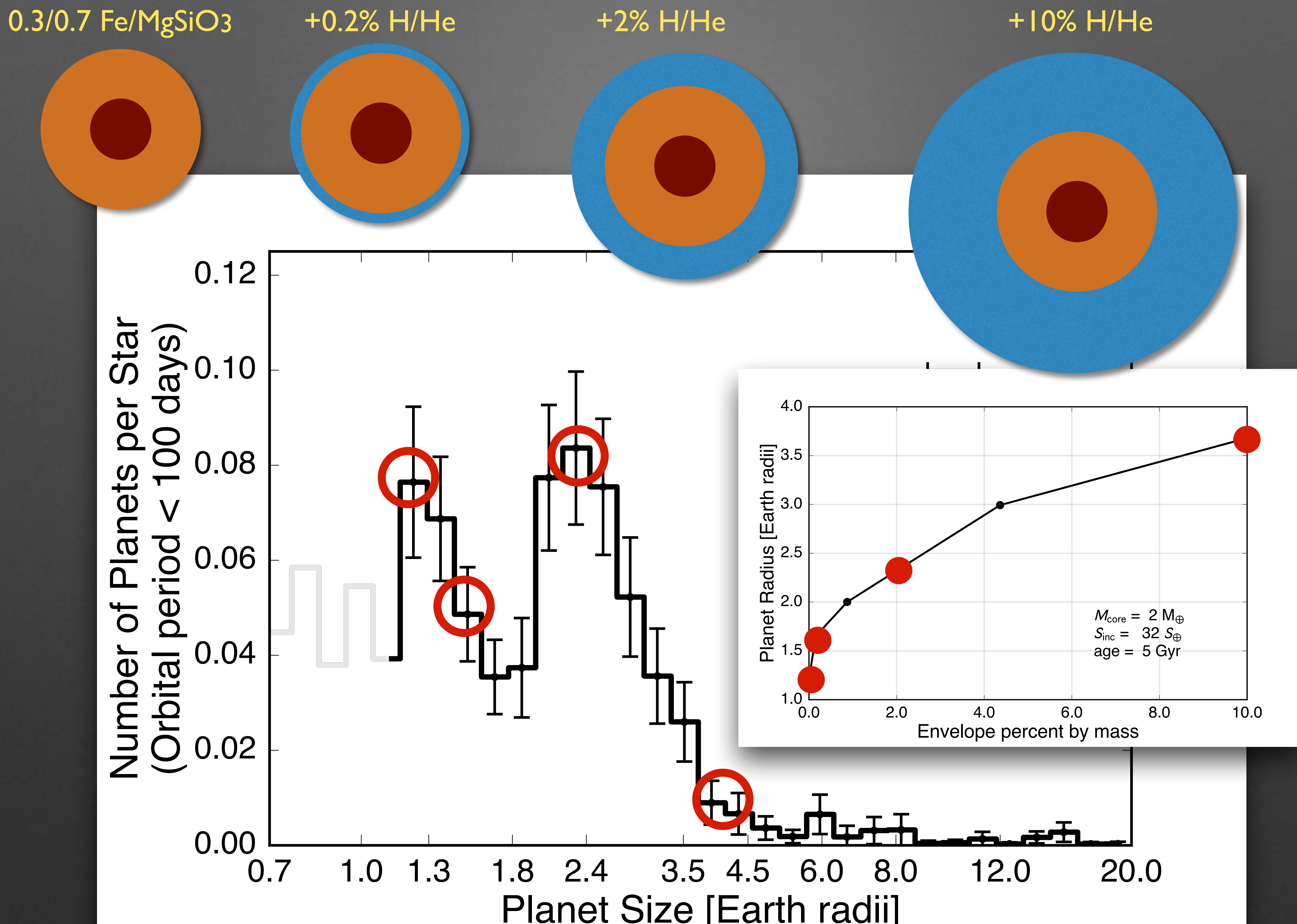


The Radius Gap



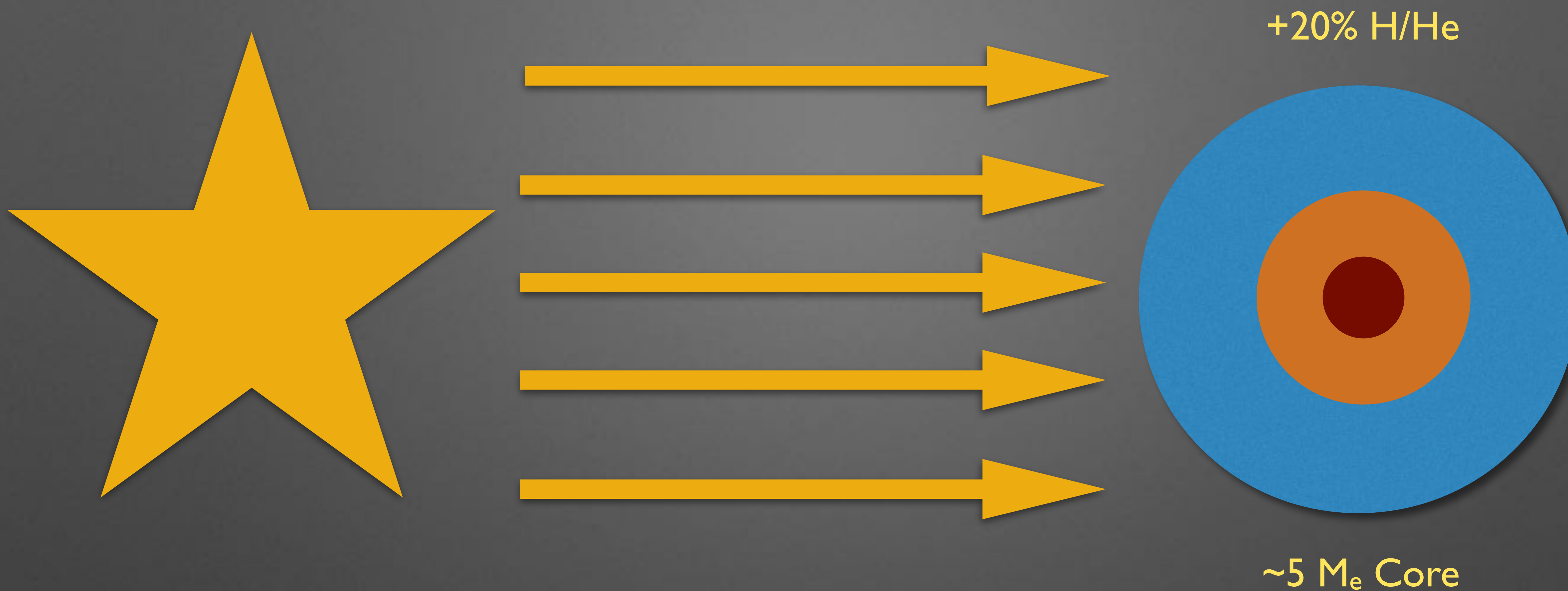
Fulton, Petigura, et al. (*2017*)

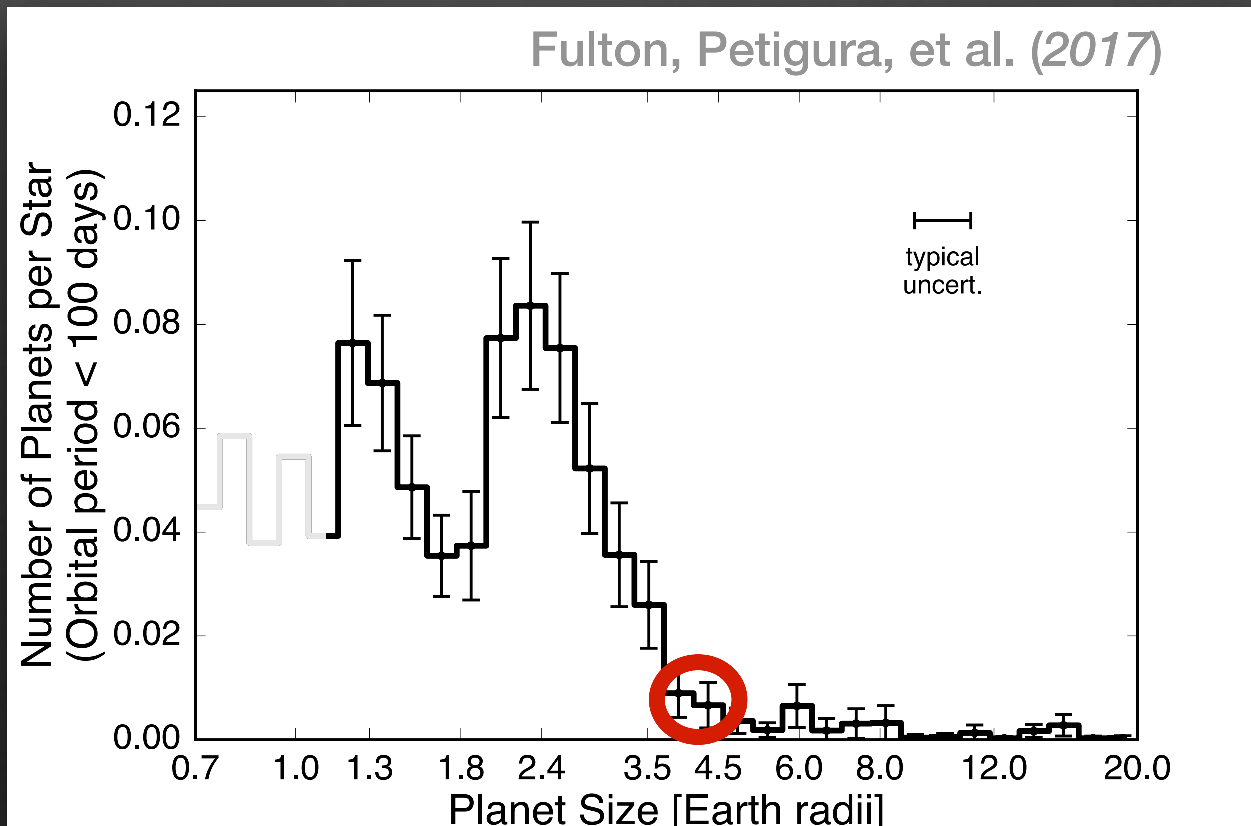
A Plausible Explanation for the Gap



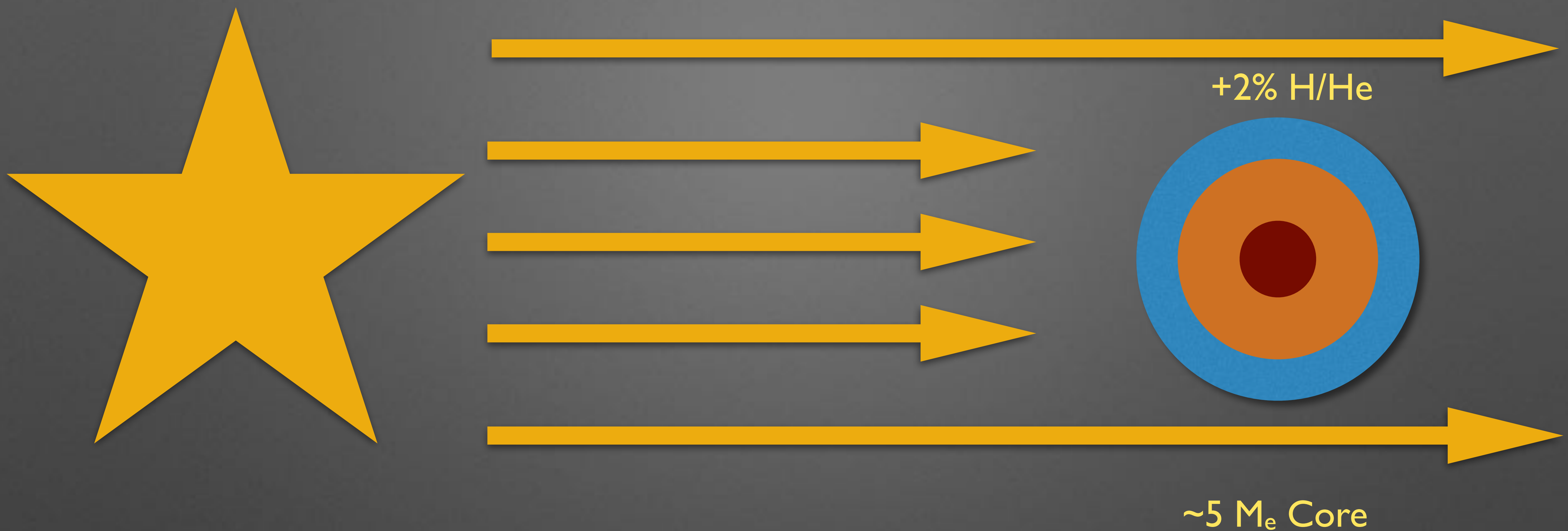
Fulton, Petigura, et al. (*2017*)

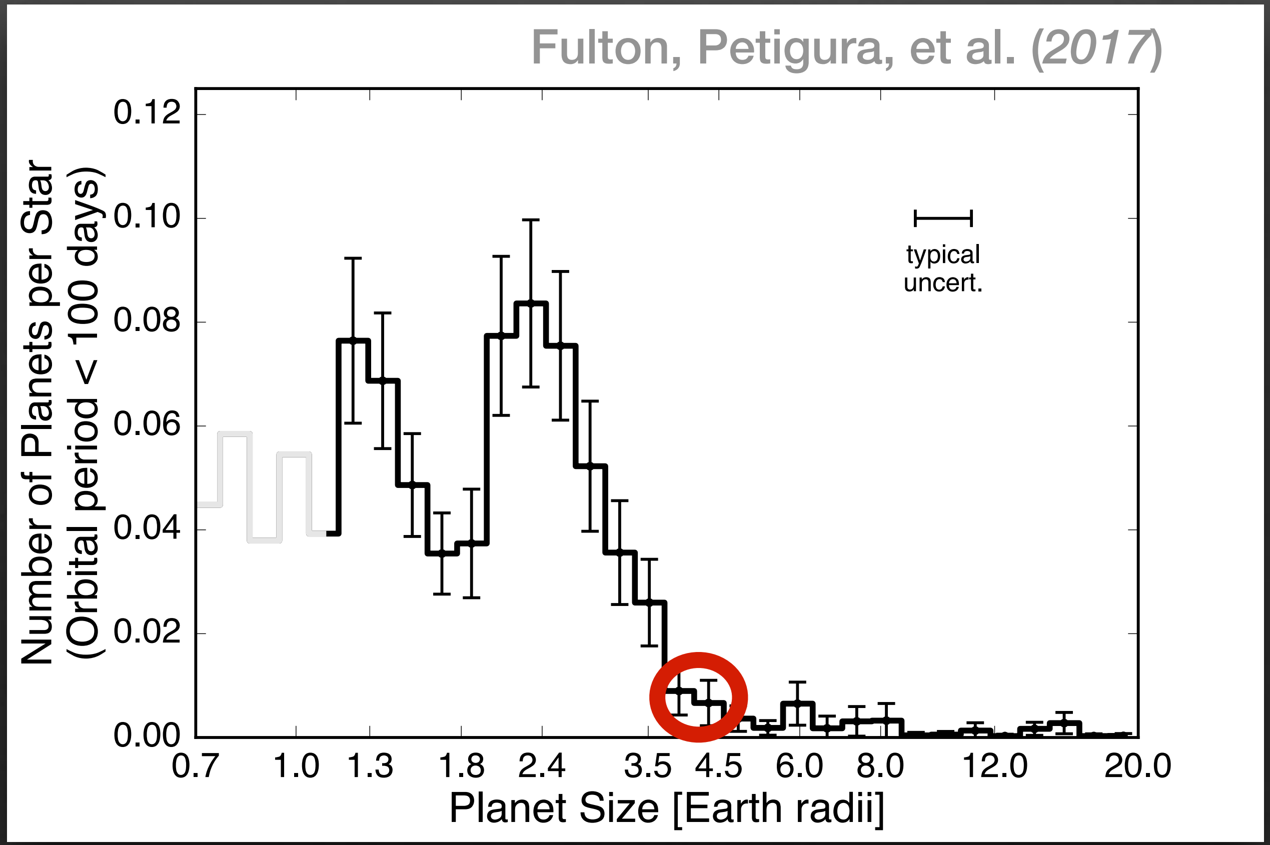
Photoevaporation

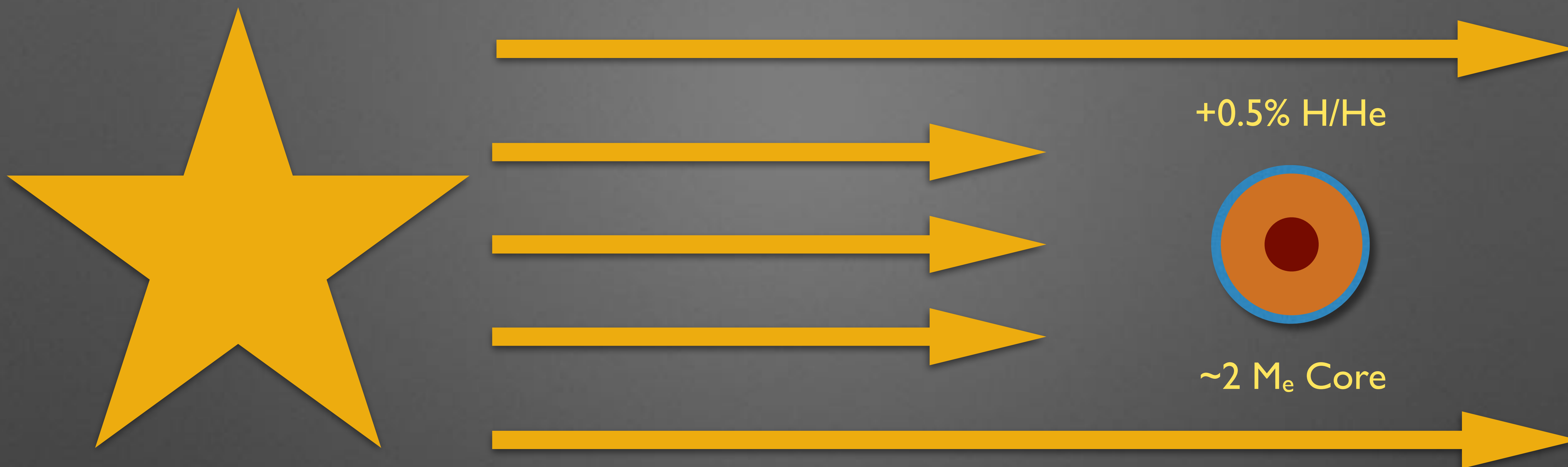


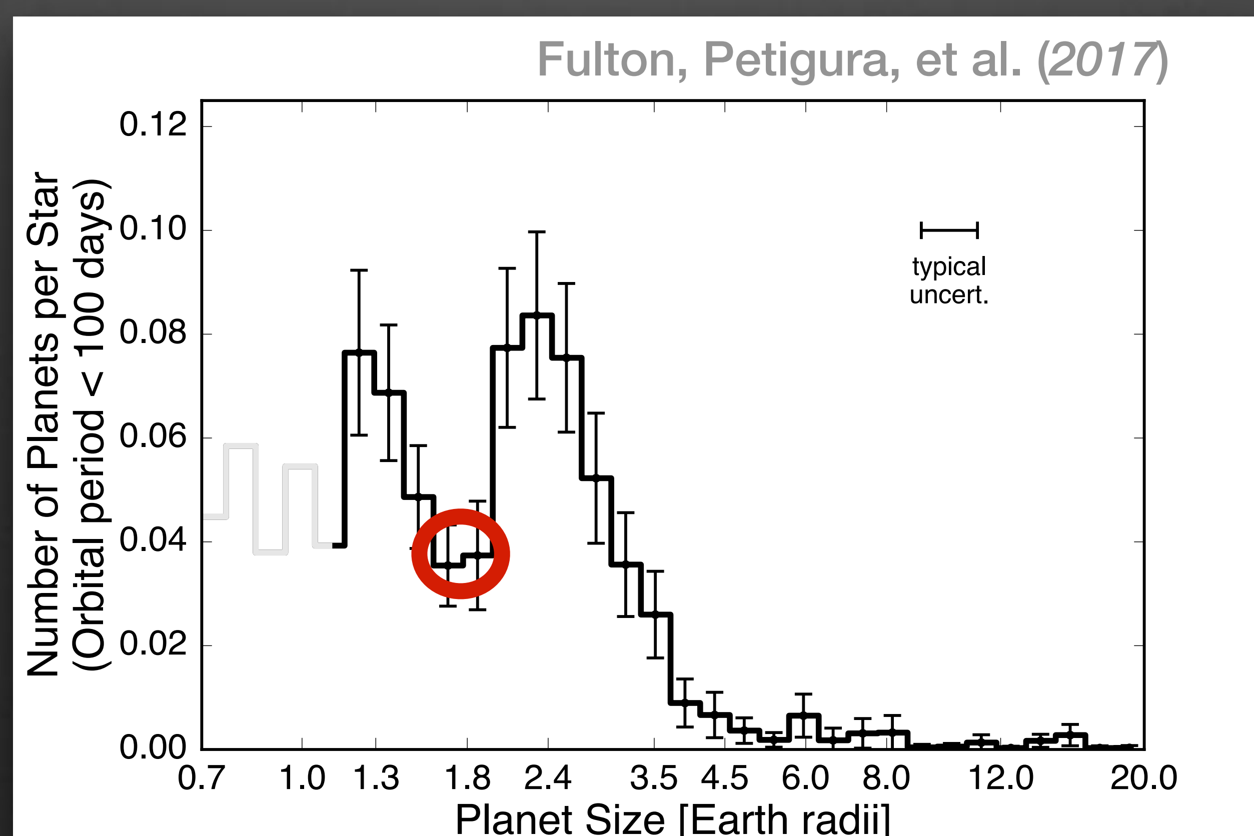


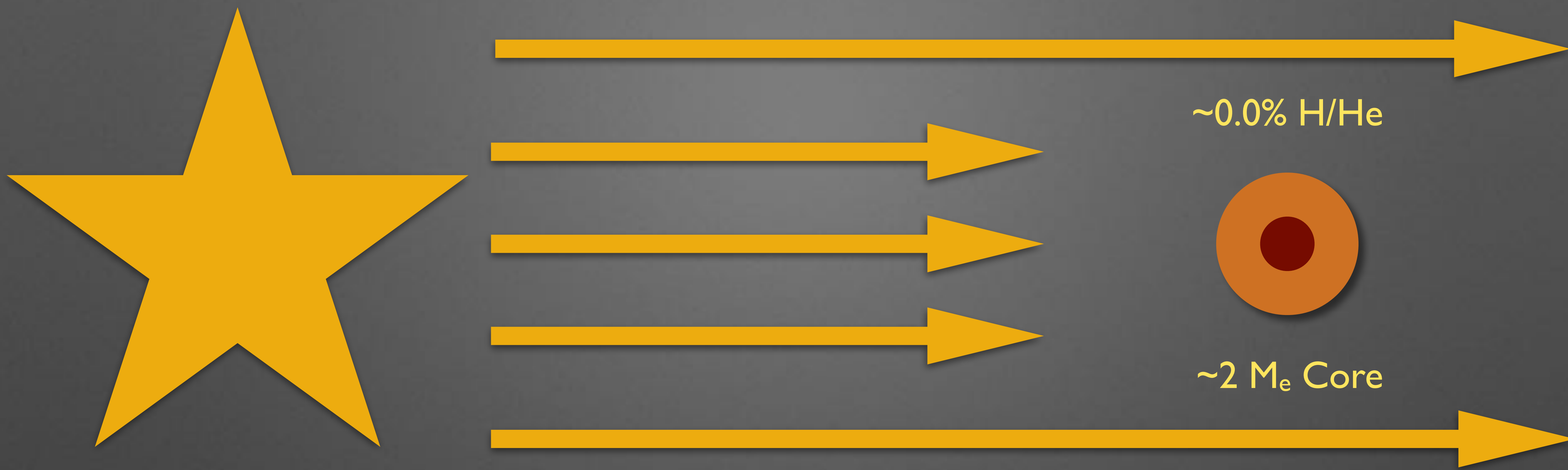
Photoevaporation

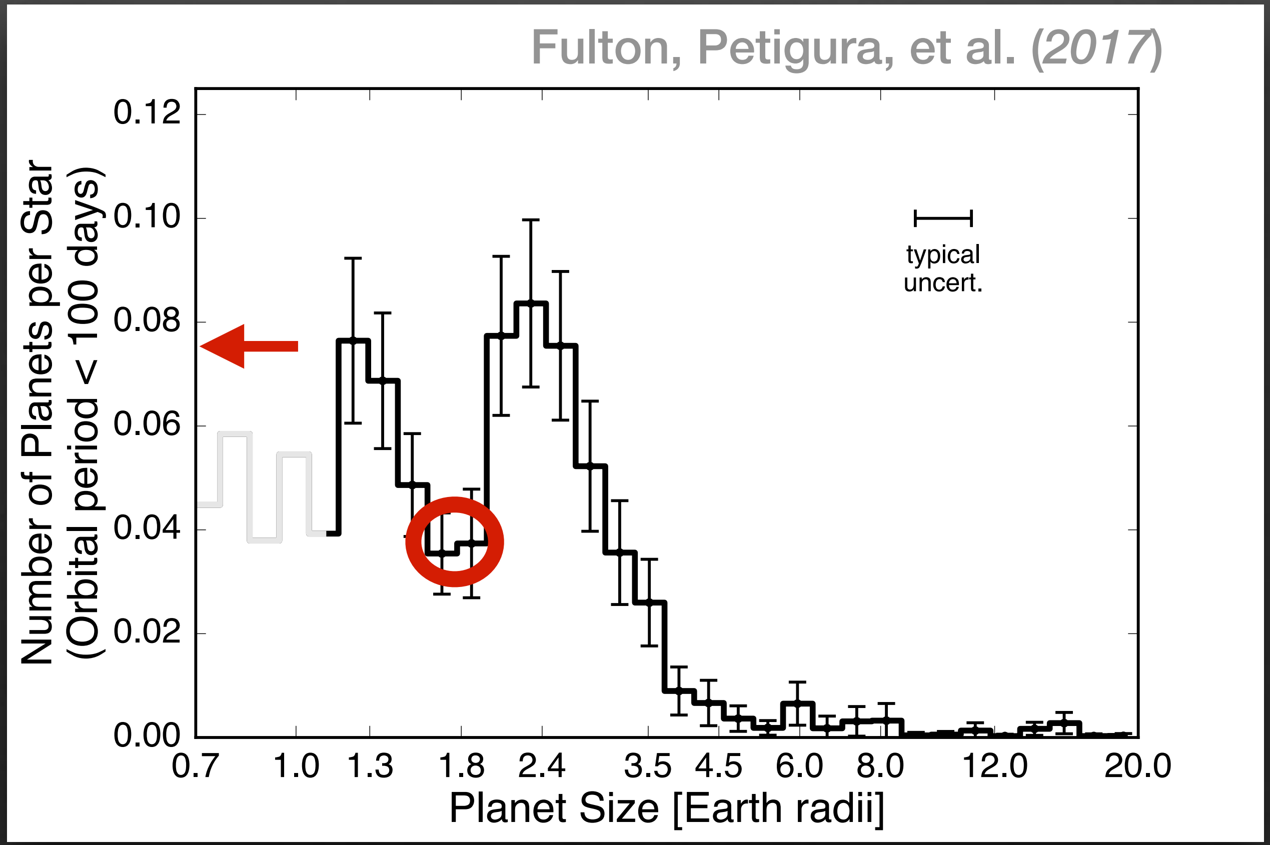





+0.5% H/He
~2 M_e Core


Fulton, Petigura, et al. (*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]


~0.0% H/He
~2 M_e Core


Fulton, Petigura, et al. (2017)
typical
uncert.
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
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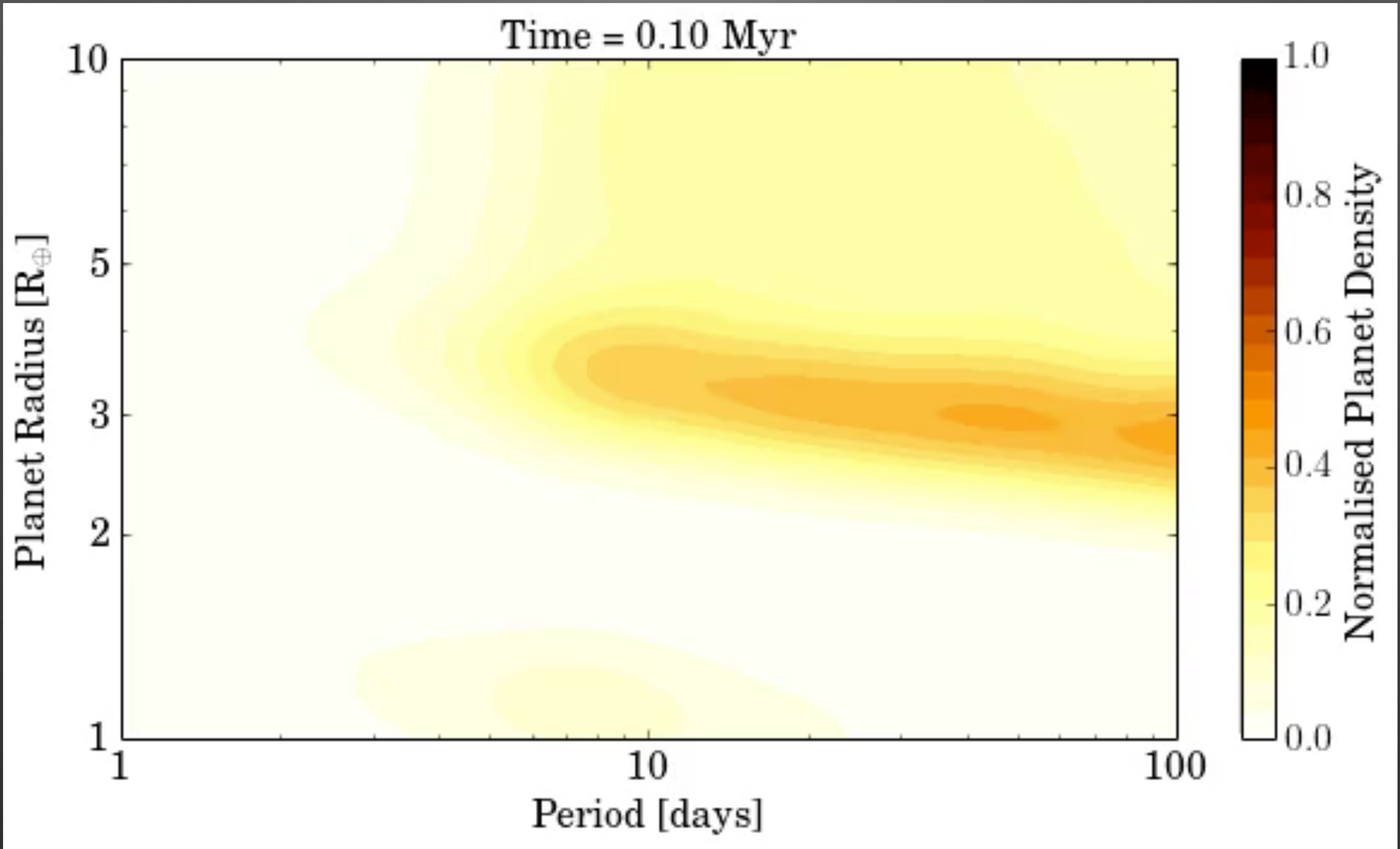
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]

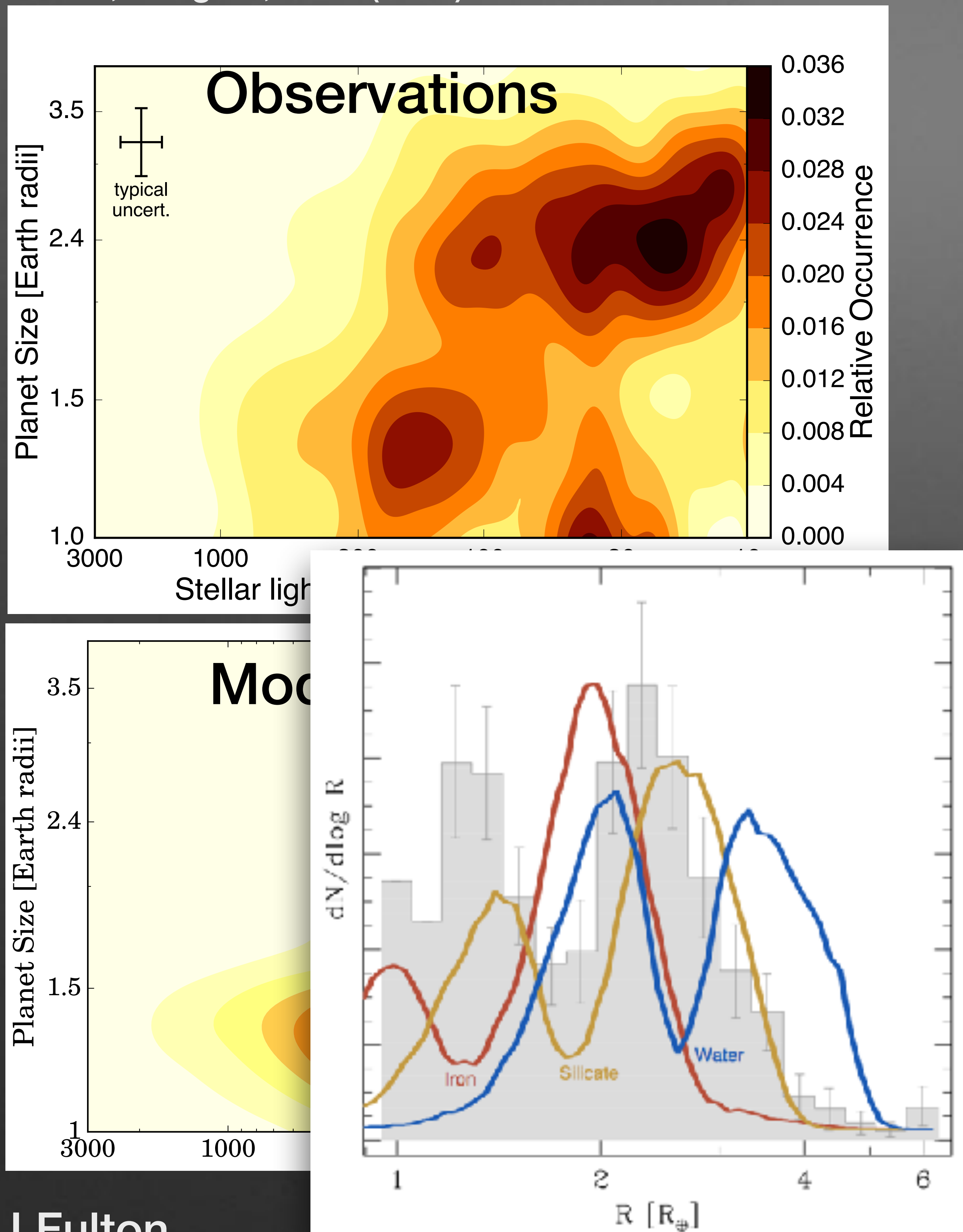
Photoevaporation



Owen & Wu (2017)

Photoevaporation

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

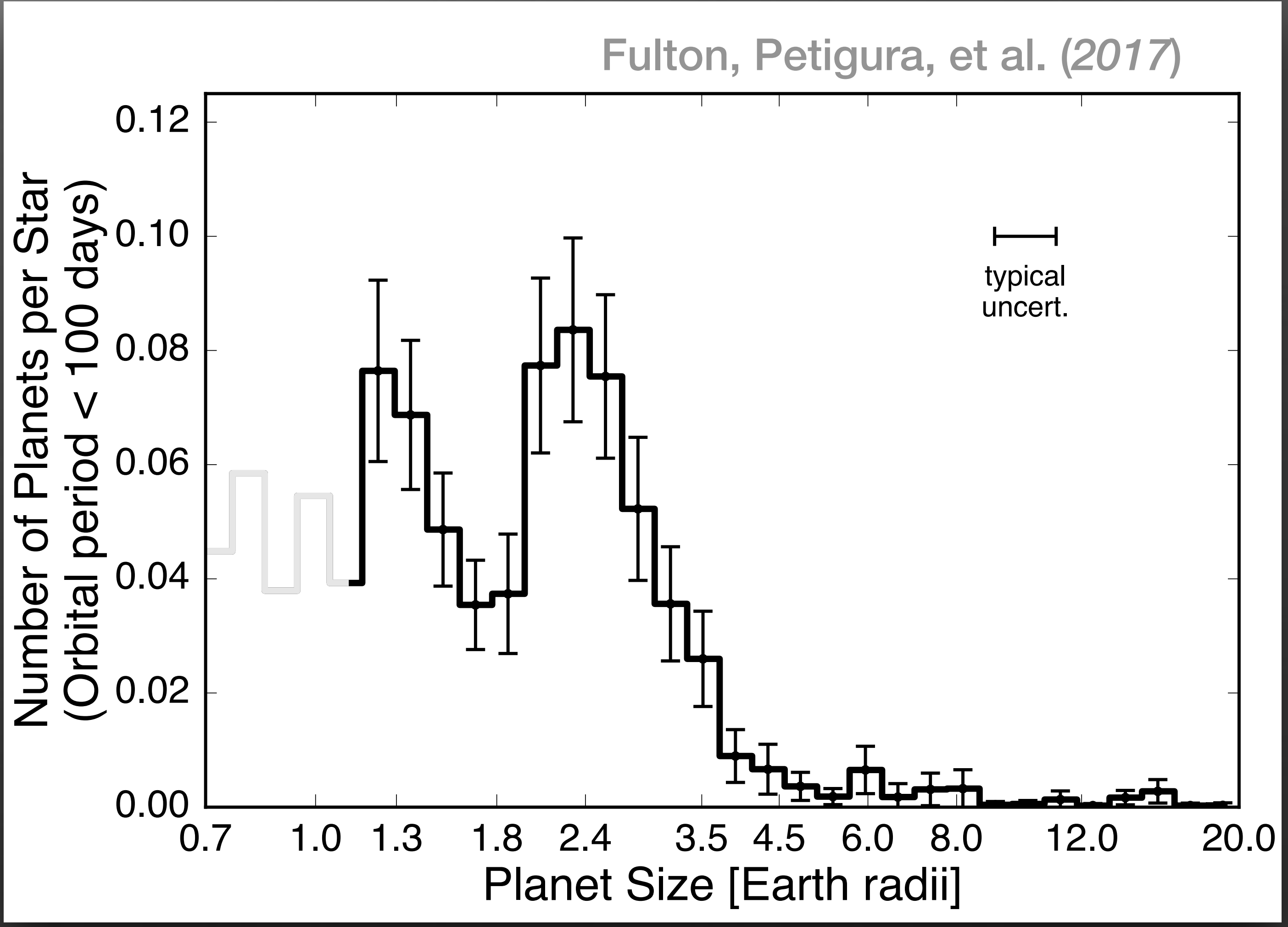


Implications

- Most common core mass is ~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

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) = 0.10 dex

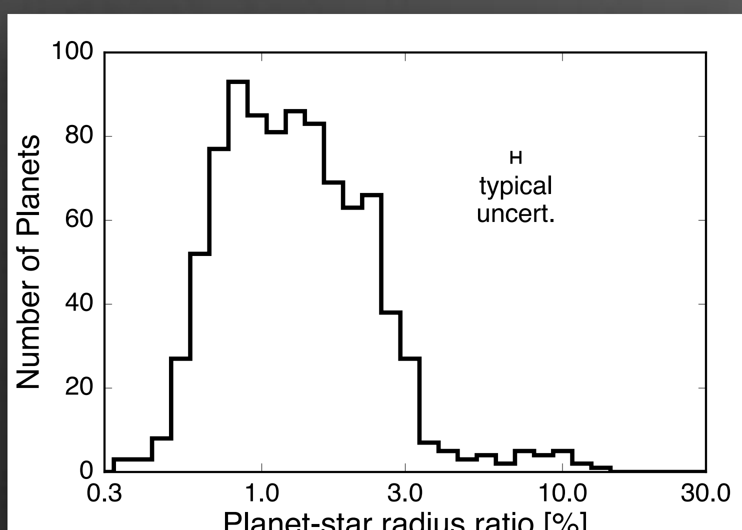
$\sigma M/M$ (Q16) = 14%

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

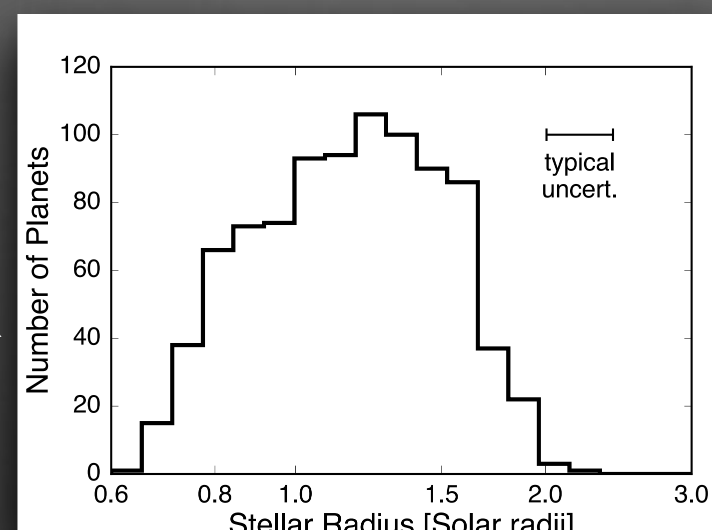
$\sigma R/R$ (Q16) = 39%

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

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



X



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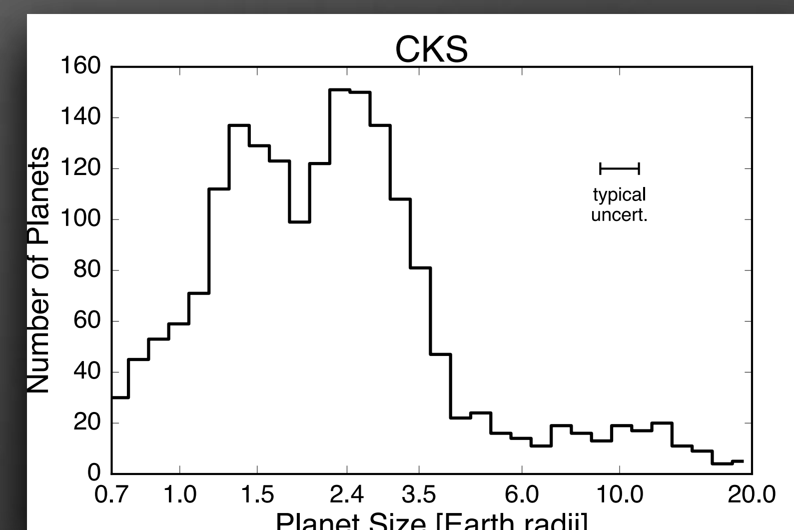
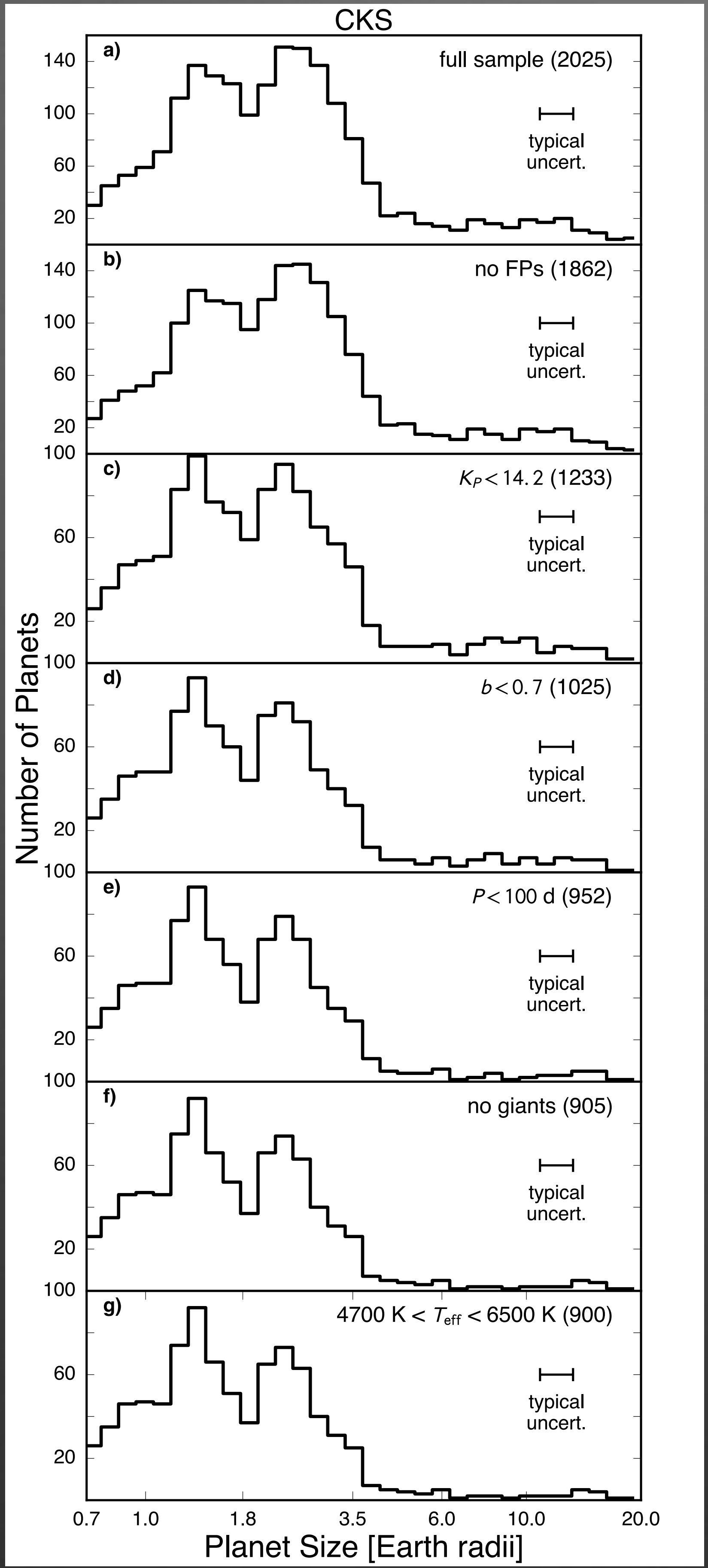


Transit Depth
Q16

Stellar Radii
~~Q16~~
CKS

Planet Radii
~~Q16~~
CKS

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



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

Remove false positives

Keep bright stars
(Kp < 14.2)

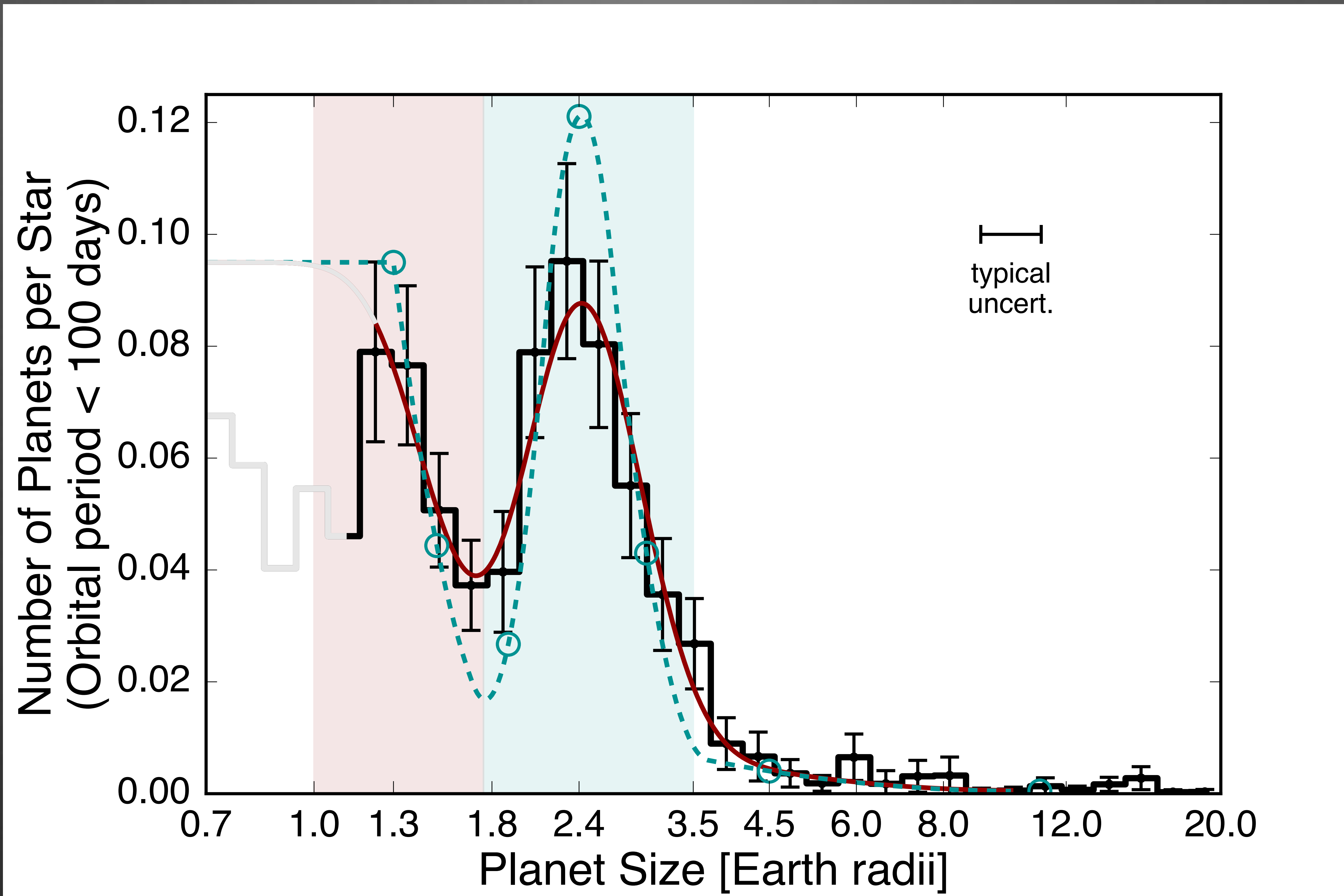
Low impact parameters
(b < 0.7)

Short orbital periods
(P < 100 d)

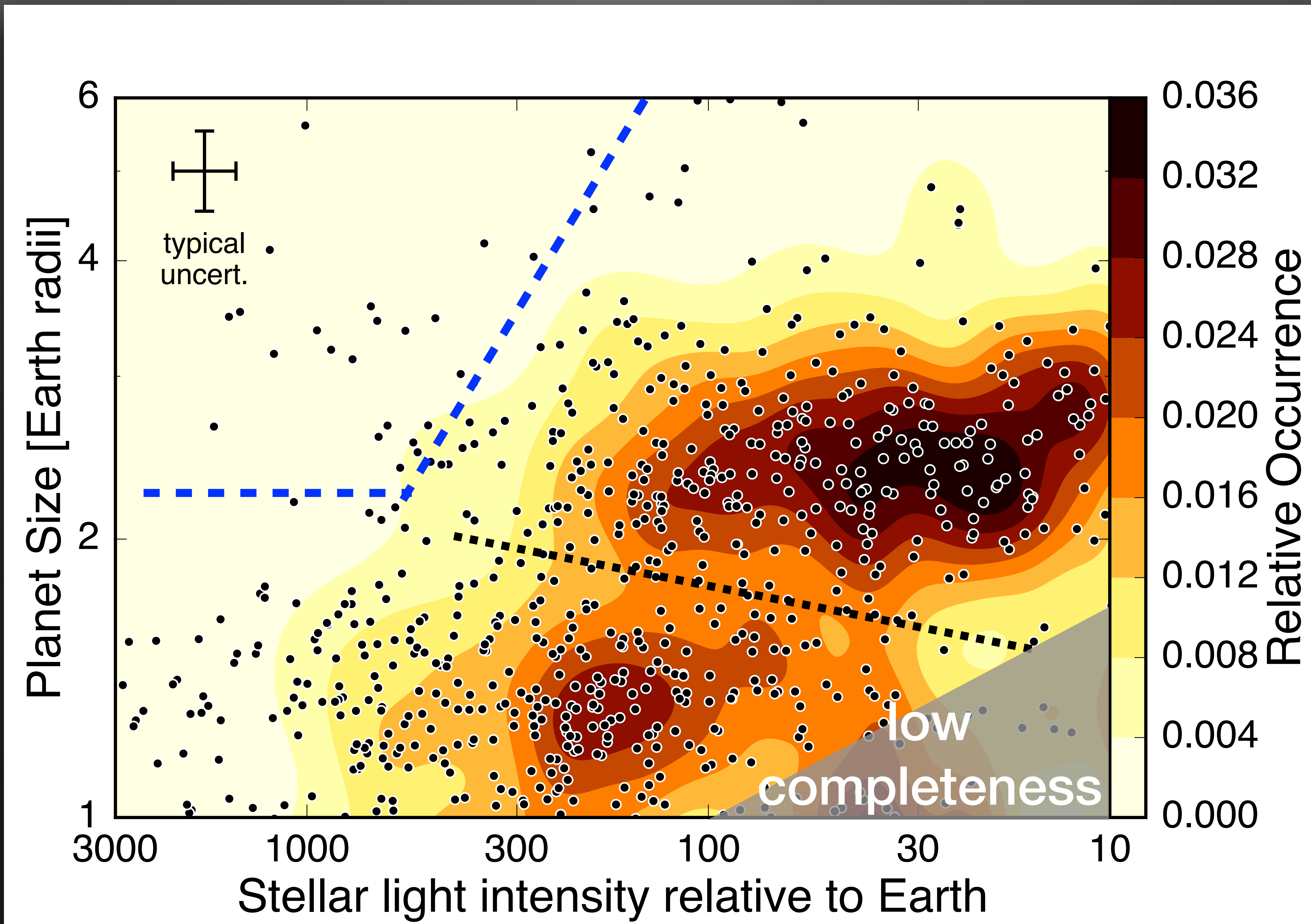
Remove evolved stars

4700 < T_{eff} < 6500 K

The Radius Gap



Flux Dependency



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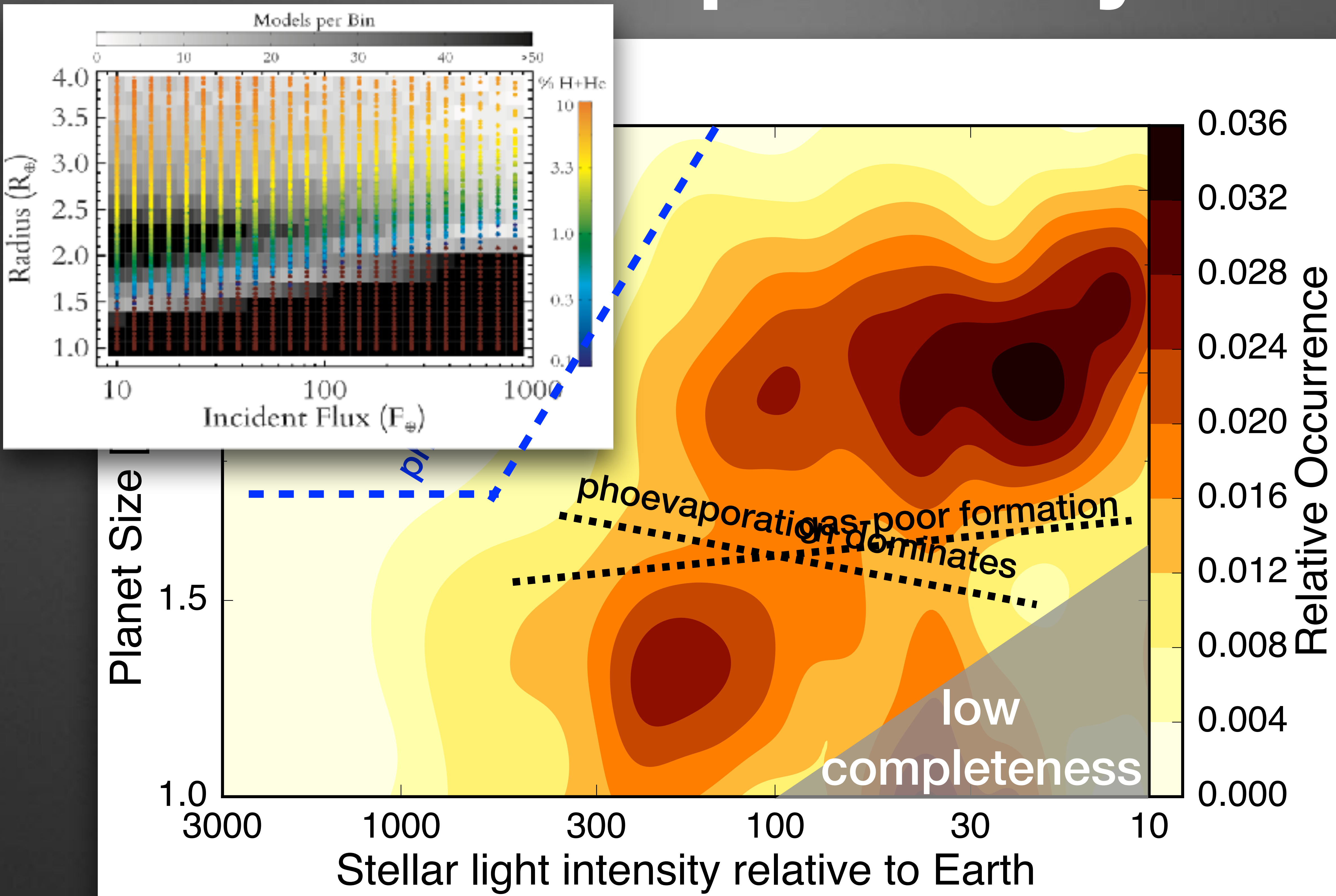
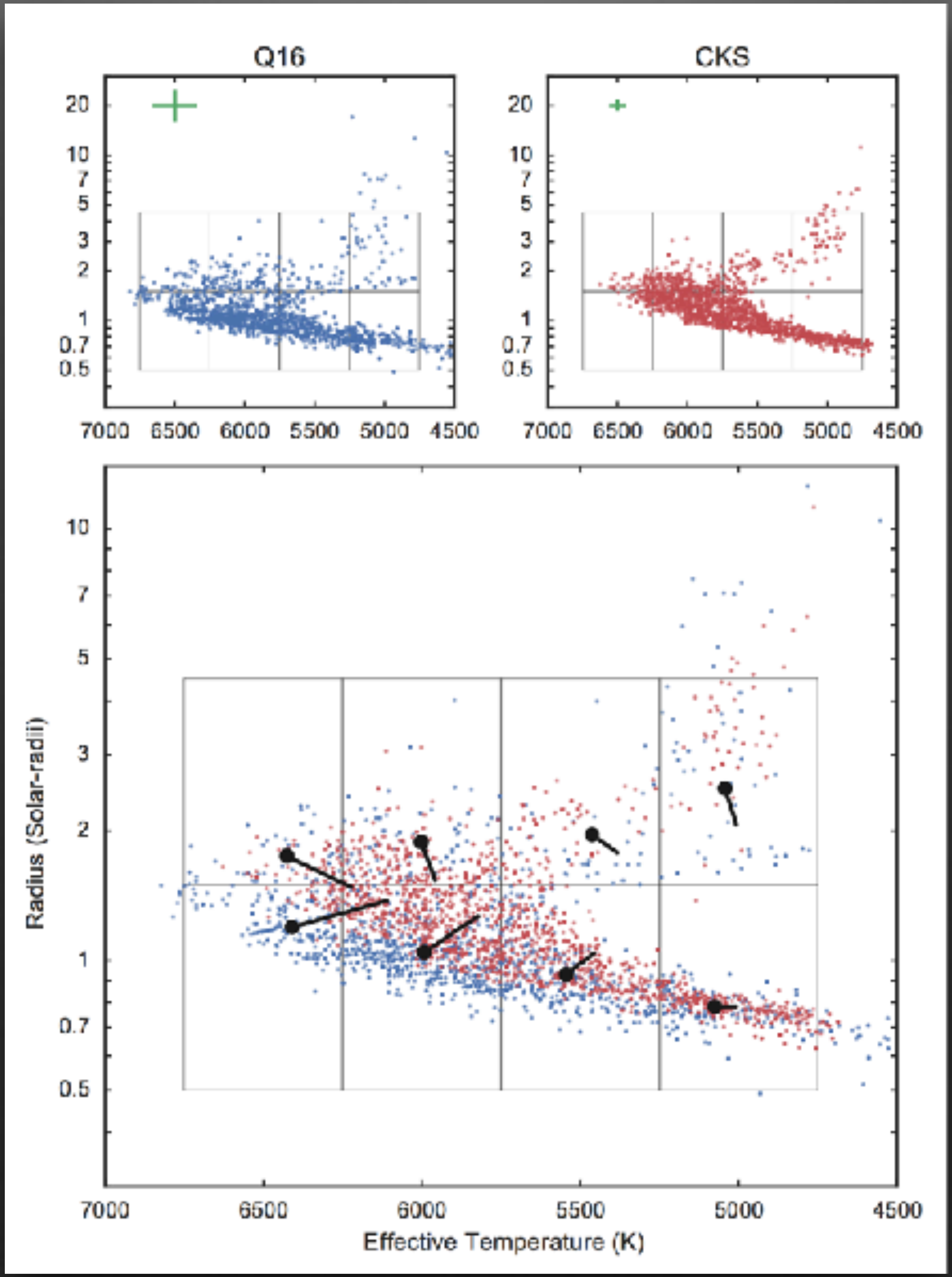
Fulton, Petigura, et al. (*2017*)

Flux Dependency

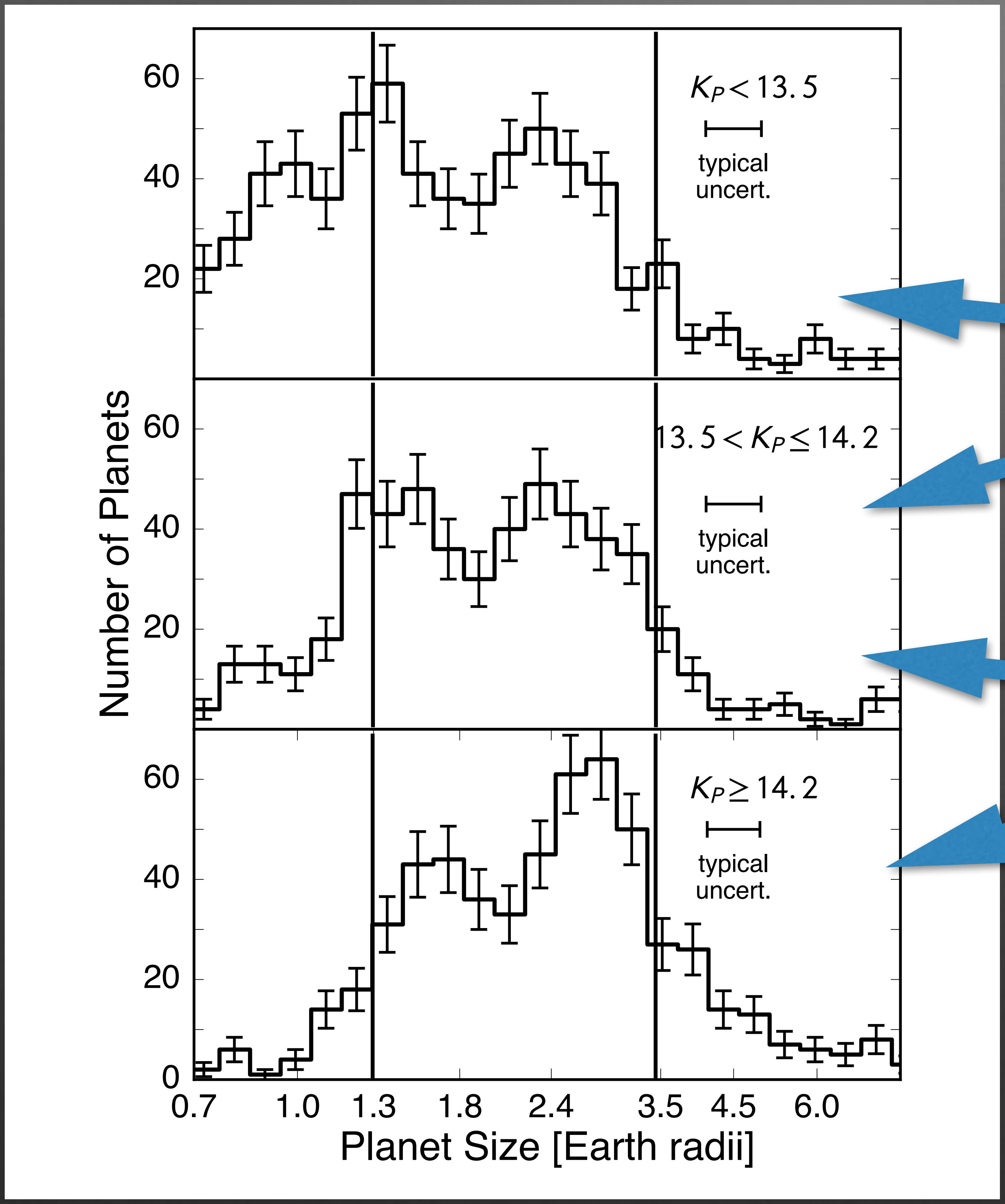
Lopez and Rice (2016)



The California-Kepler Survey



Magnitude Cut



Consistent
(97% confidence)

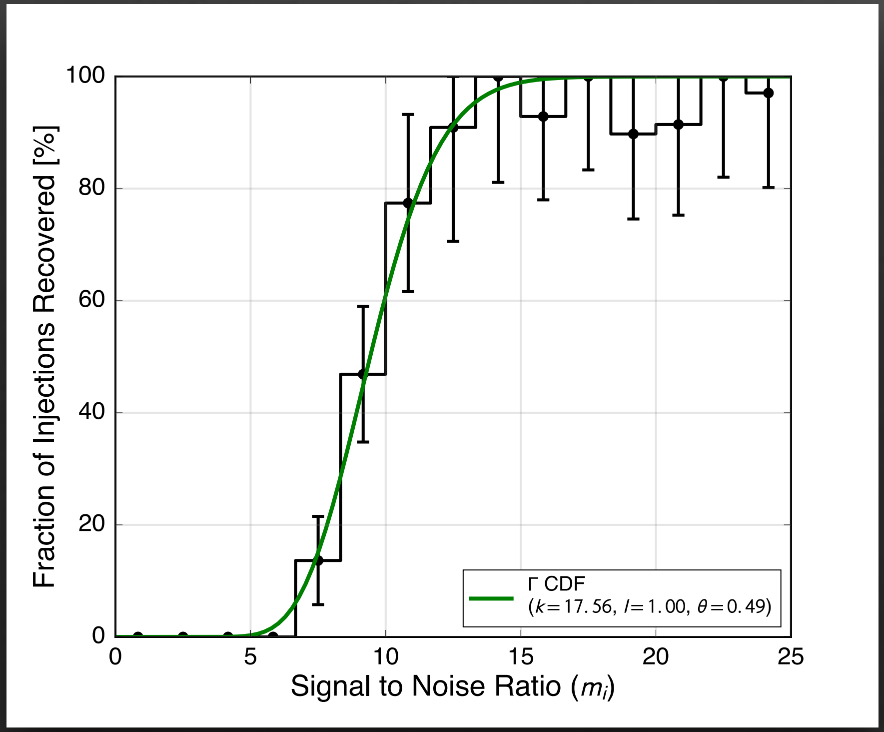
Not consistent

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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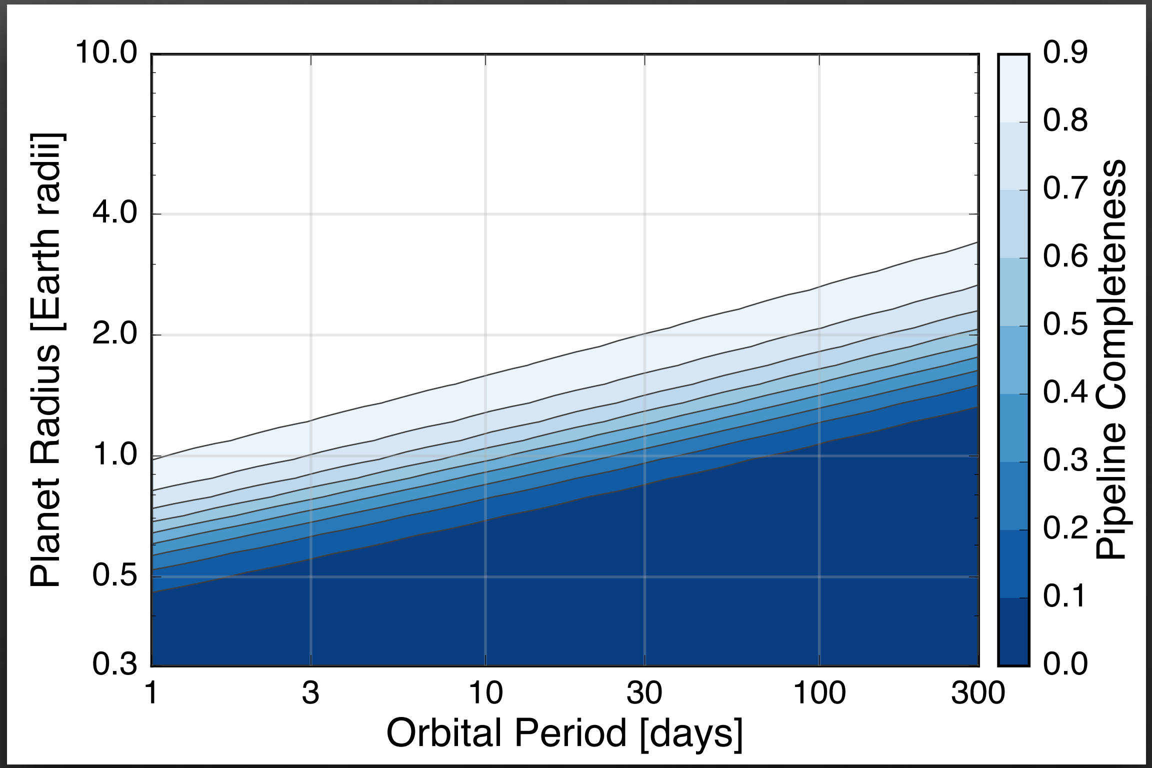


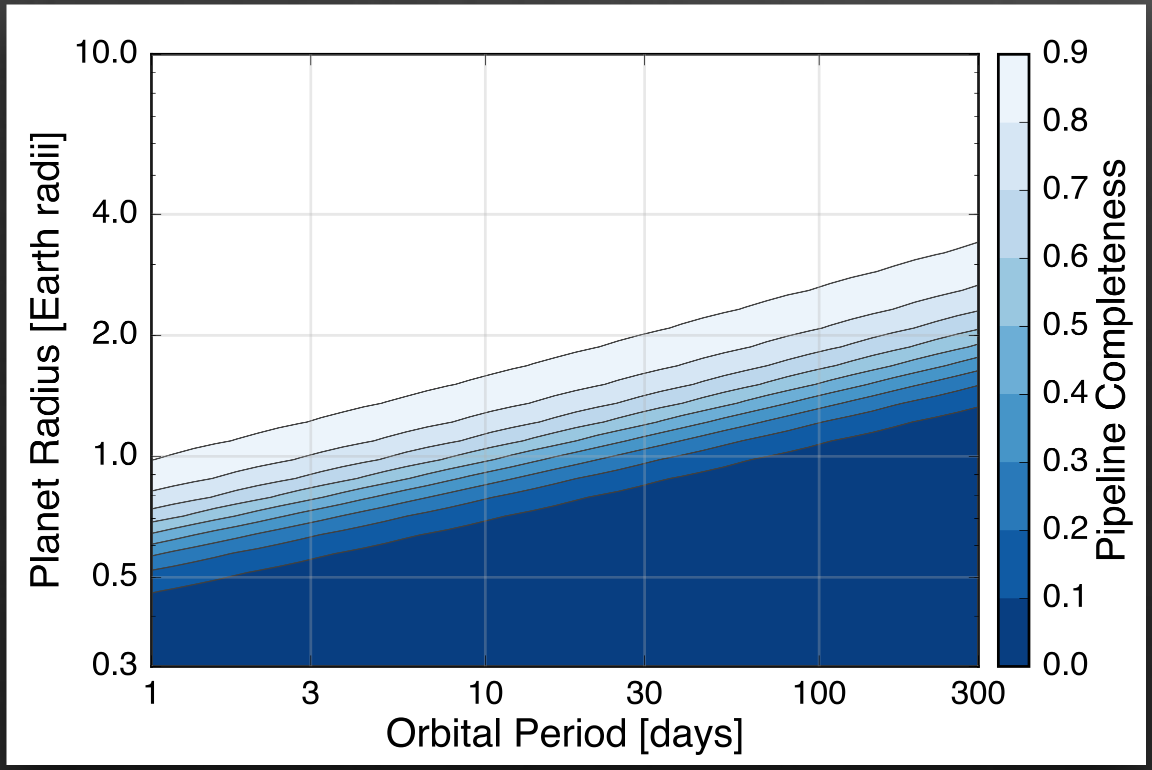
Fulton, Petigura, et al. (*2017*)

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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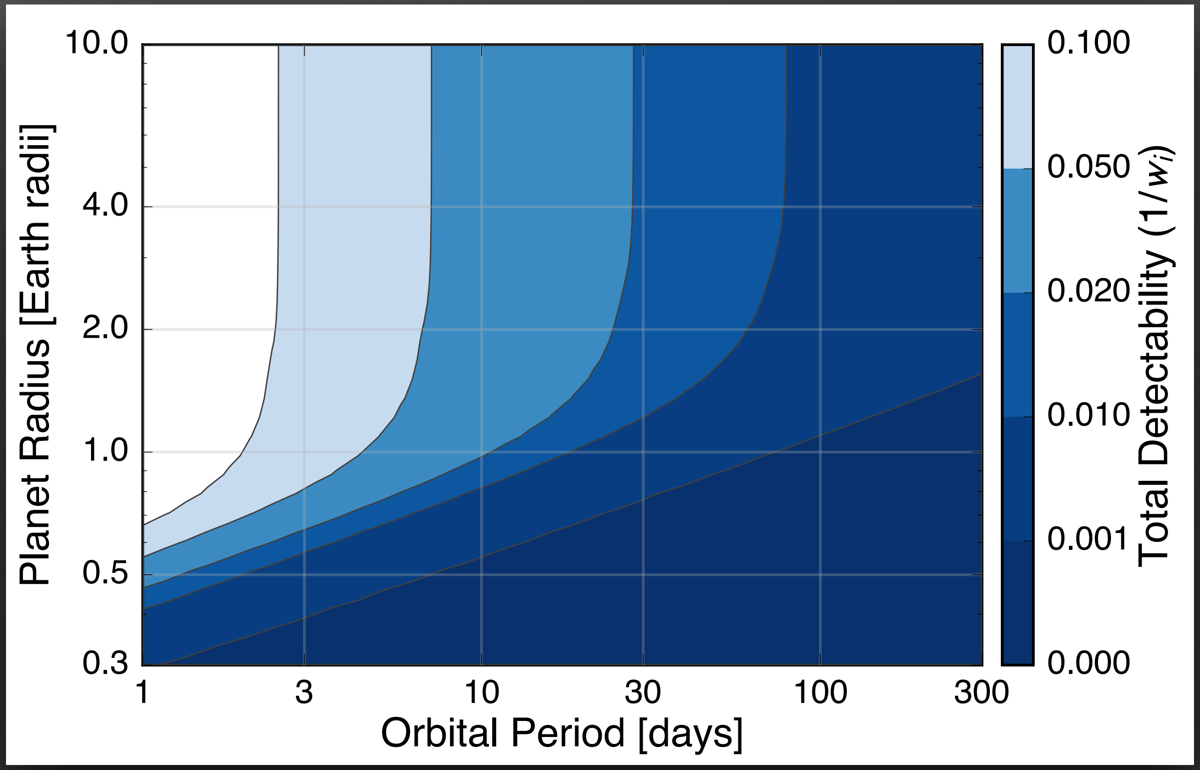
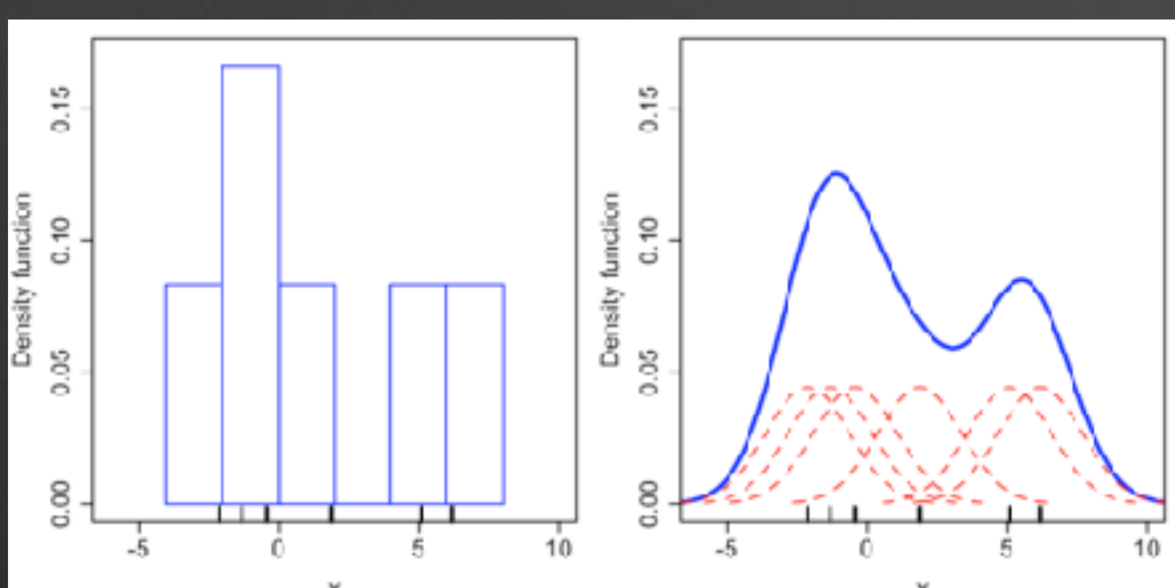


Fulton, Petigura, et al. (*2017*)

Completeness Corrections

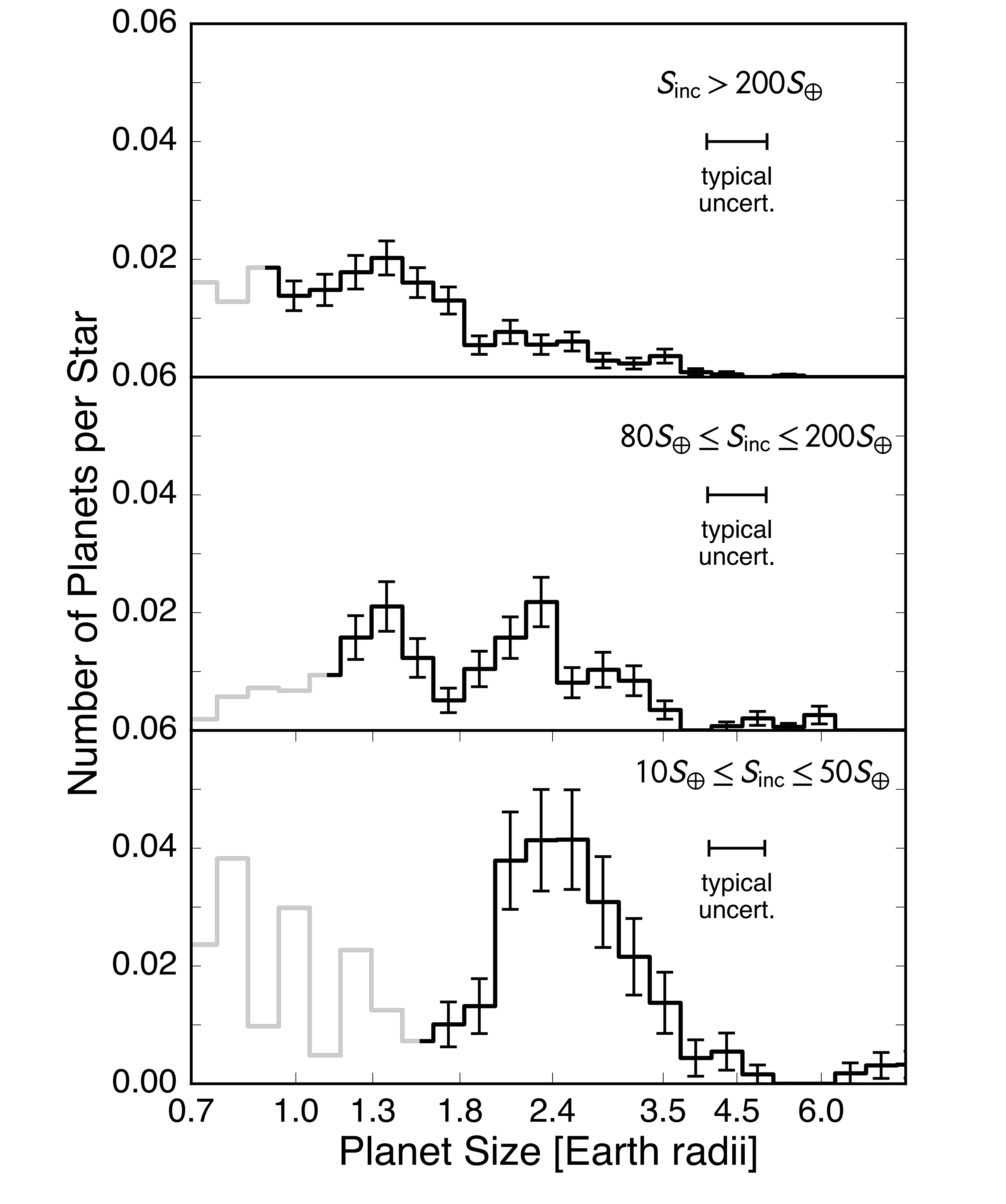
$$w_i = \frac{1}{(p_{\mathrm{det}} \cdot p_{\mathrm{tr}})}$$

Number of Planets per Star = $$f_{\mathrm{bin}} = \frac{1}{N_\star} \sum_{i=1}^{n_{\mathrm{pl,bin}}} w_i$$

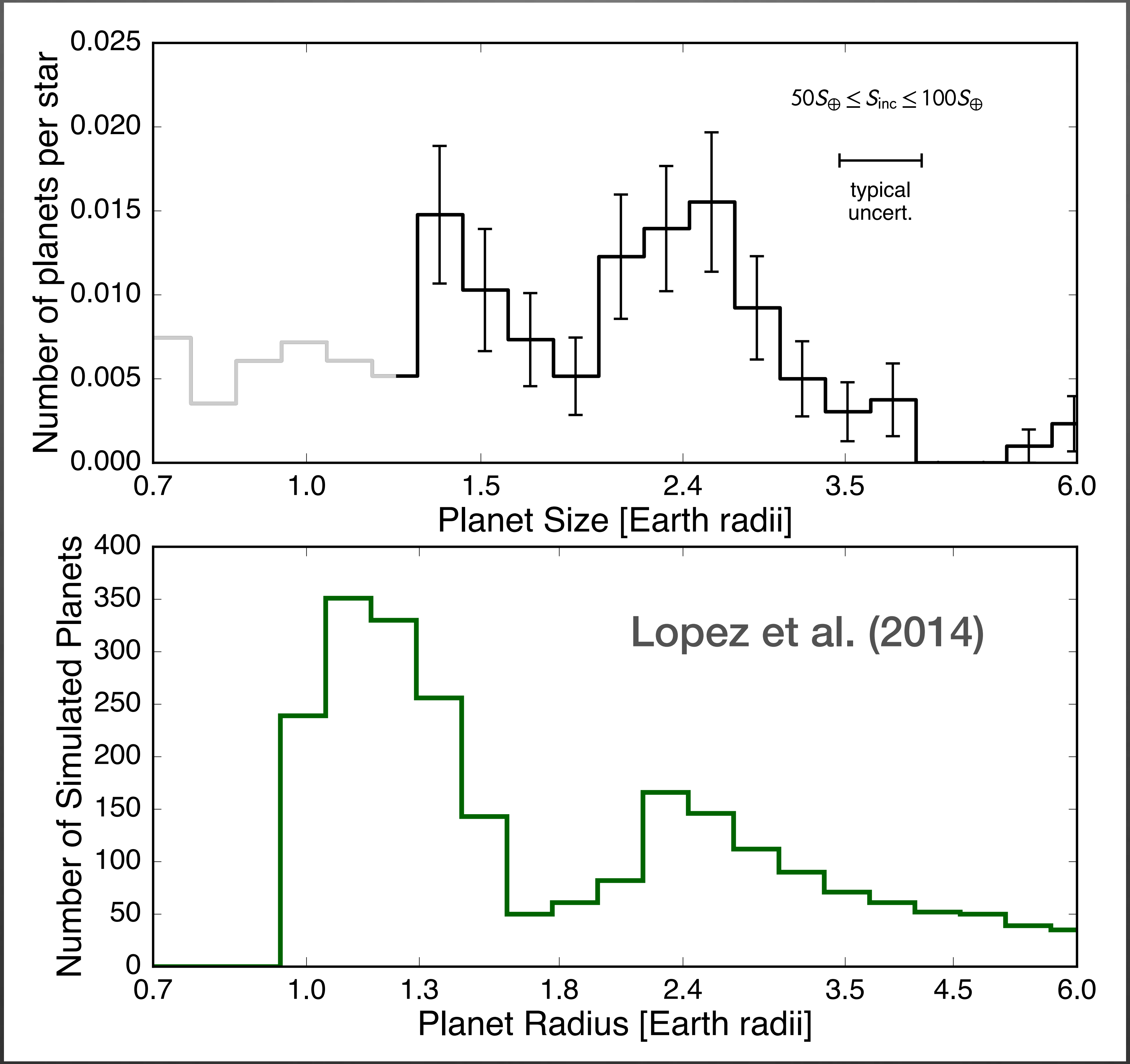


$$\phi(x) = \frac{1}{N_\star} \sum_{i=1}^{n_{\mathrm{pl}}} w_i \cdot K(x - x_i, \sigma_{x,i})$$

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



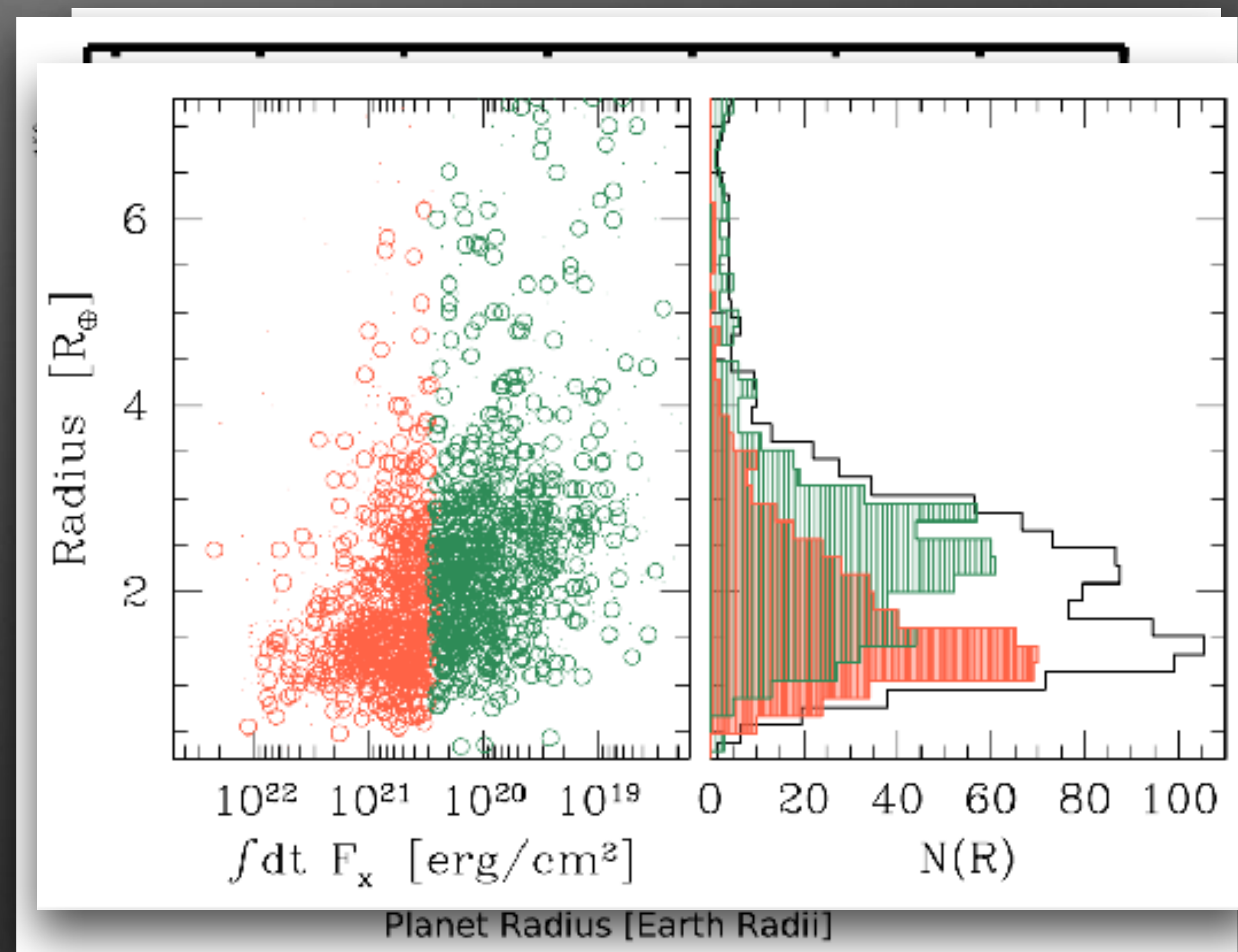
$S_{inc} > 200 S_\oplus$
typical uncert.
$80 S_\oplus \leq S_{inc} \leq 200 S_\oplus$
typical uncert.
$10 S_\oplus \leq S_{inc} \leq 50 S_\oplus$
typical uncert.
0.06
0.04
0.02
0.06
0.04
0.02
0.06
0.04
0.02
0.00
Number of Planets per Star
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
Planet Size [Earth radii]

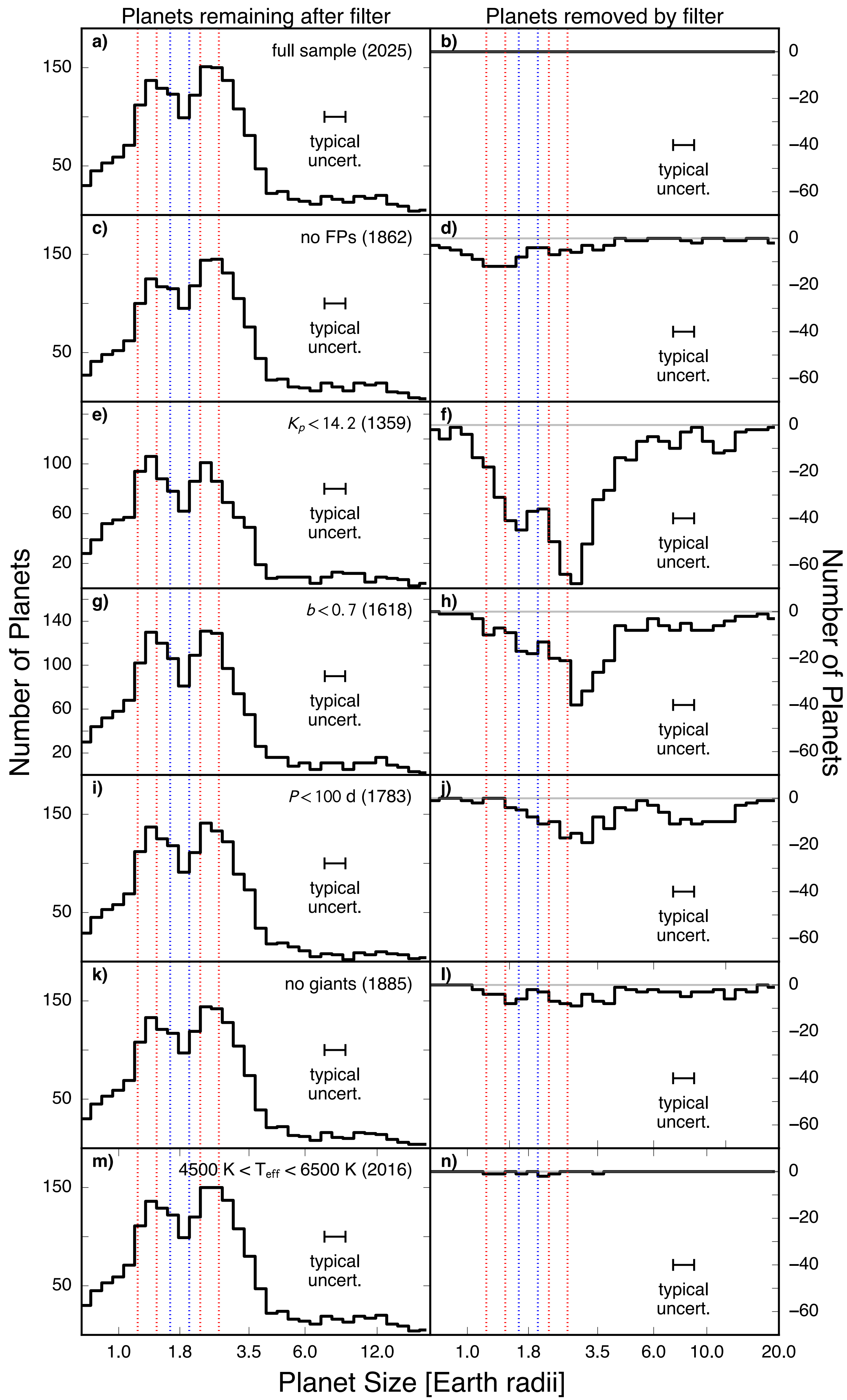


0.025
0.020
0.015
0.010
0.005
0.000
Number of planets per star
$50S_{\oplus} \le S_{\rm inc} \le 100S_{\oplus}$
typical
uncert.
0.7
1.0
1.5
2.4
3.5
6.0
Planet Size [Earth radii]
400
350
300
250
200
150
100
50
0
Number of Simulated Planets
Lopez et al. (2014)
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
Planet Radius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

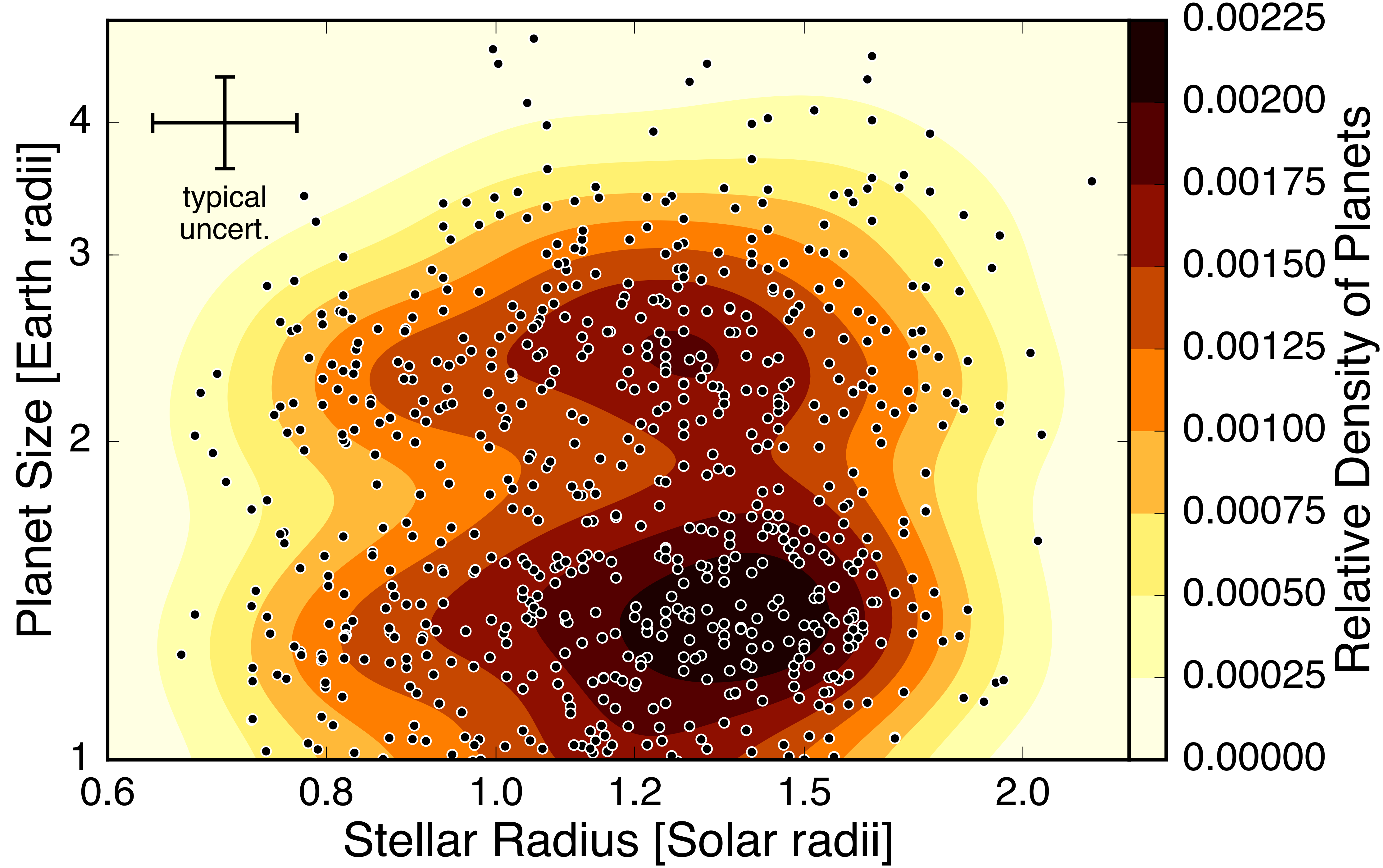
Previous Occurrence Studies

- 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

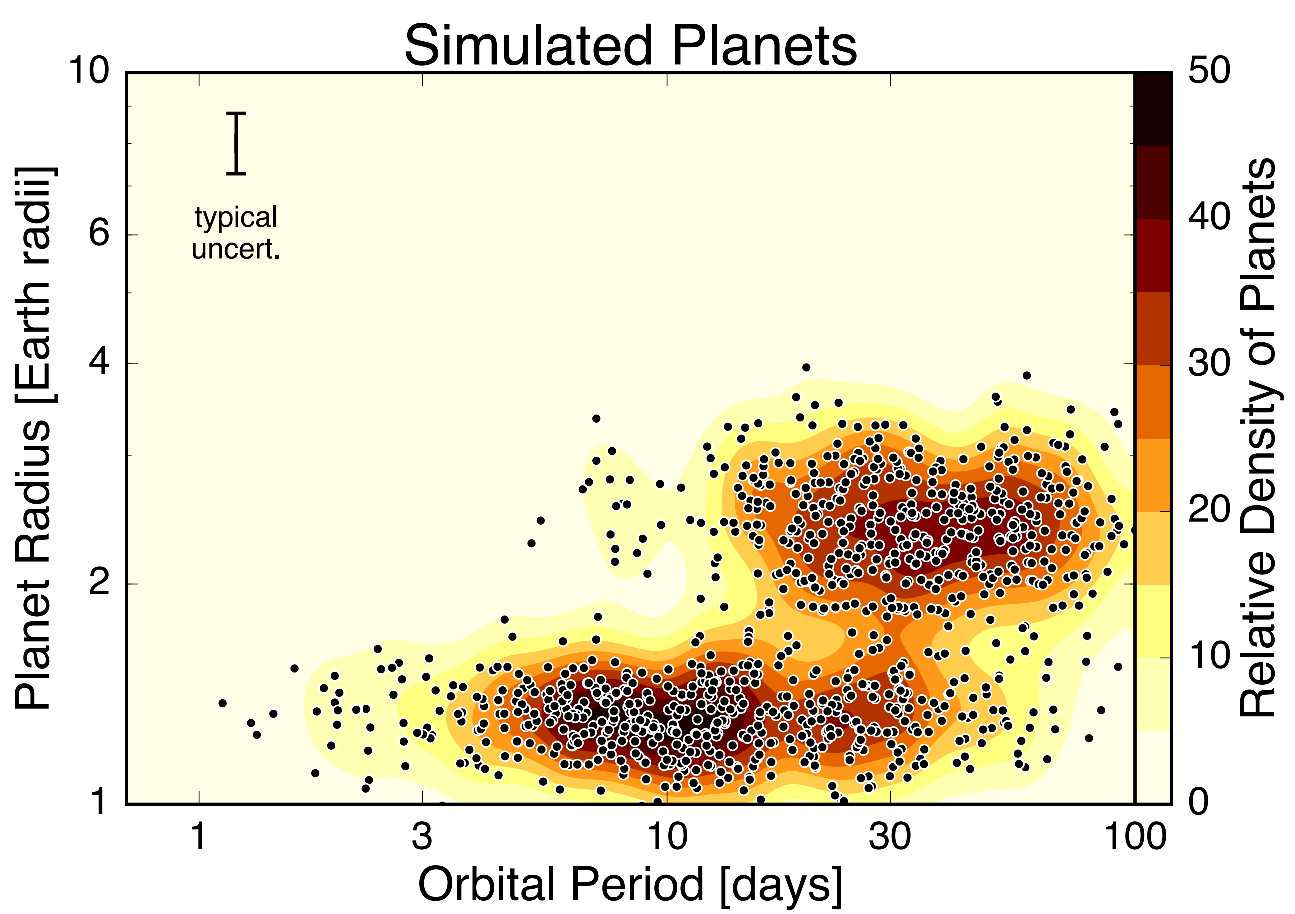


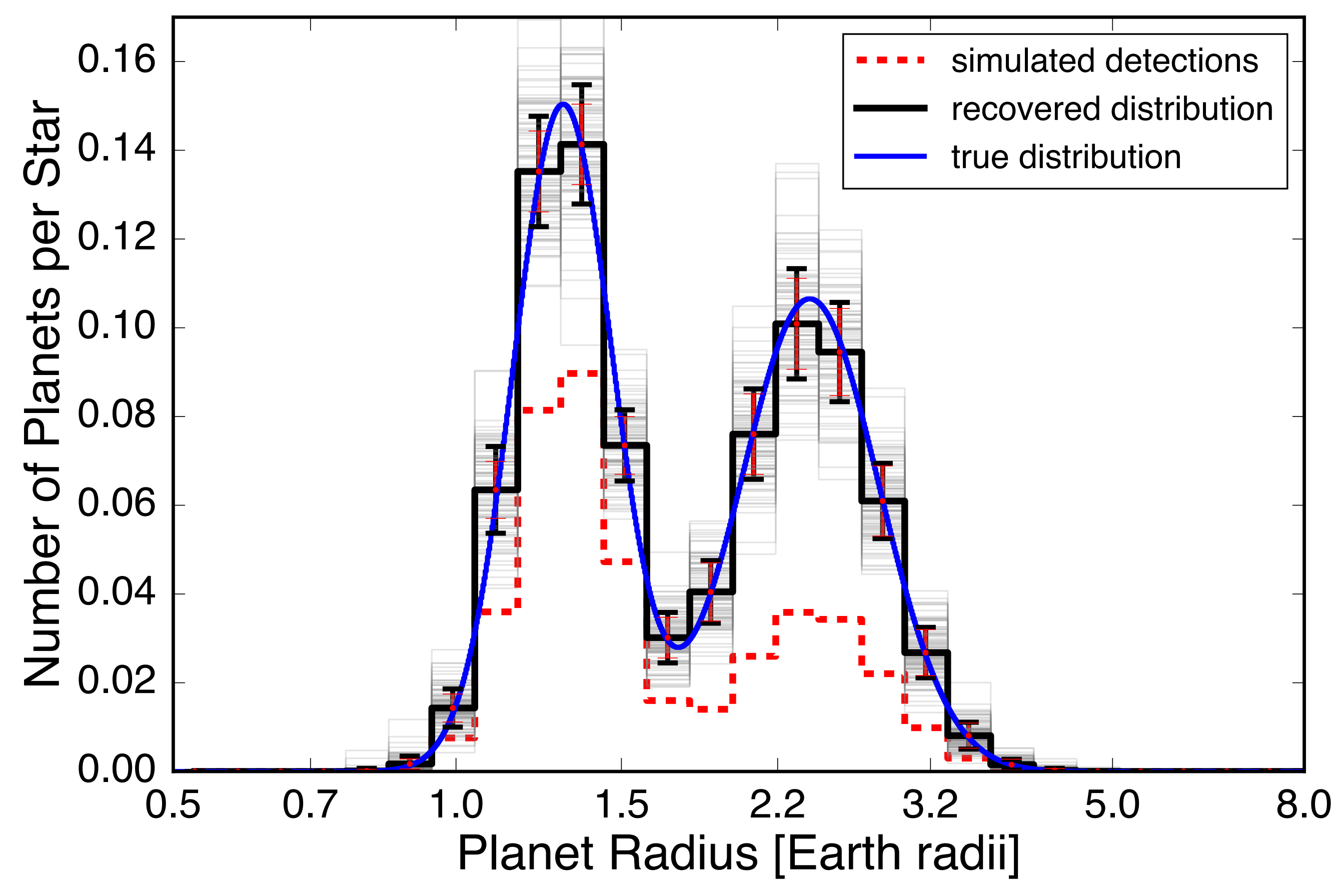


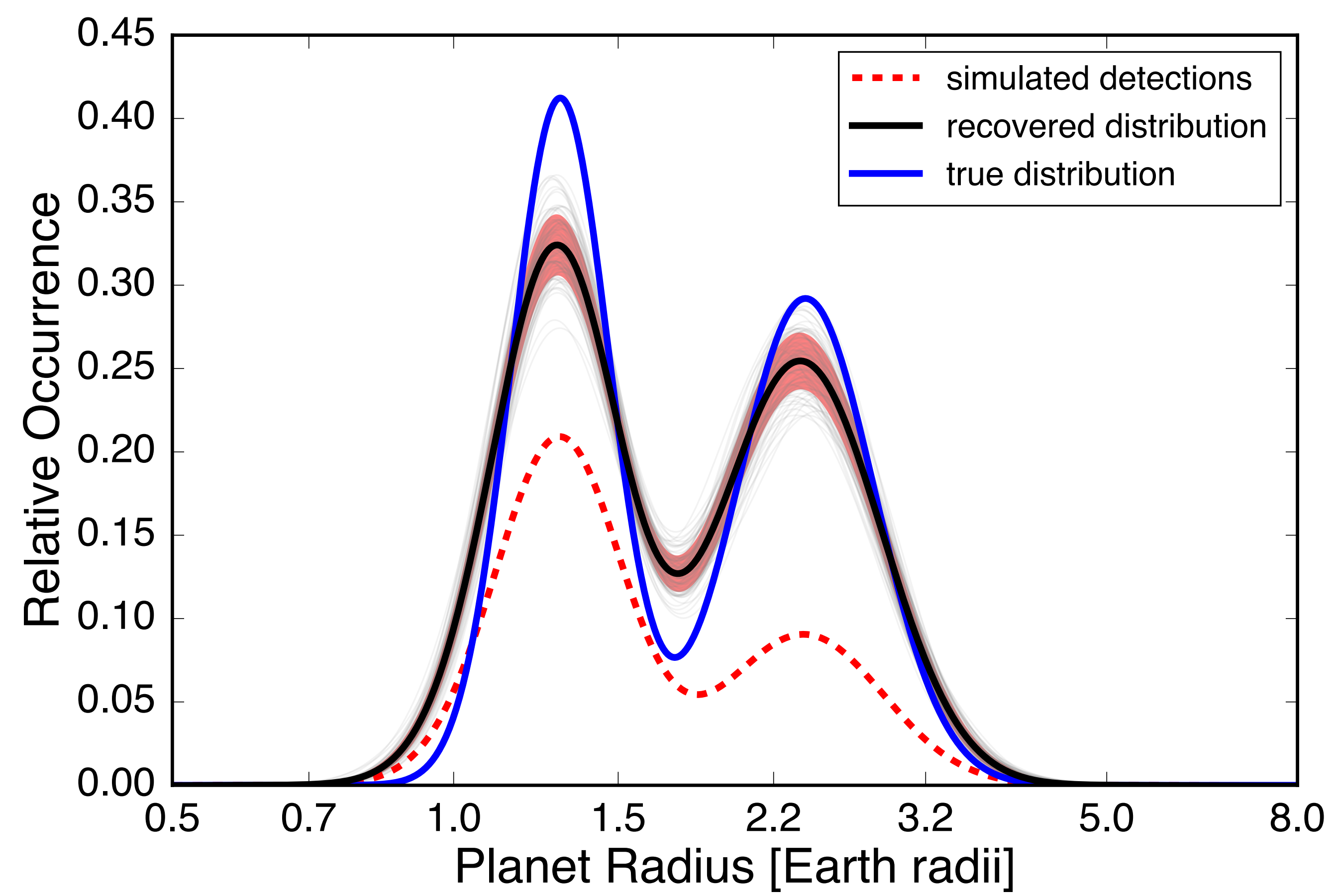
Planets remaining after filter
Planets removed by filter
a)
full sample (2025)
b)
c)
no FPs (1862)
d)
e)
$K_p < 14.2$ (1359)
f)
g)
$b < 0.7$ (1618)
h)
i)
$P < 100$ d (1783)
j)
k)
no giants (1885)
l)
m)
4500 K < T$_{eff}$ < 6500 K (2016)
n)
typical uncert.
Number of Planets
Number of Planets
Planet Size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



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
10
6
4
2
1
1
3
10
30
100
50
40
30
20
10
0


simulated detections
recovered distribution
true distribution
Number of Planets per Star
Planet Radius [Earth radii]
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.5
0.7
1.0
1.5
2.2
3.2
5.0
8.0


simulated detections
recovered distribution
true distribution
Relative Occurrence
Planet Radius [Earth radii]
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.5
0.7
1.0
1.5
2.2
3.2
5.0
8.0