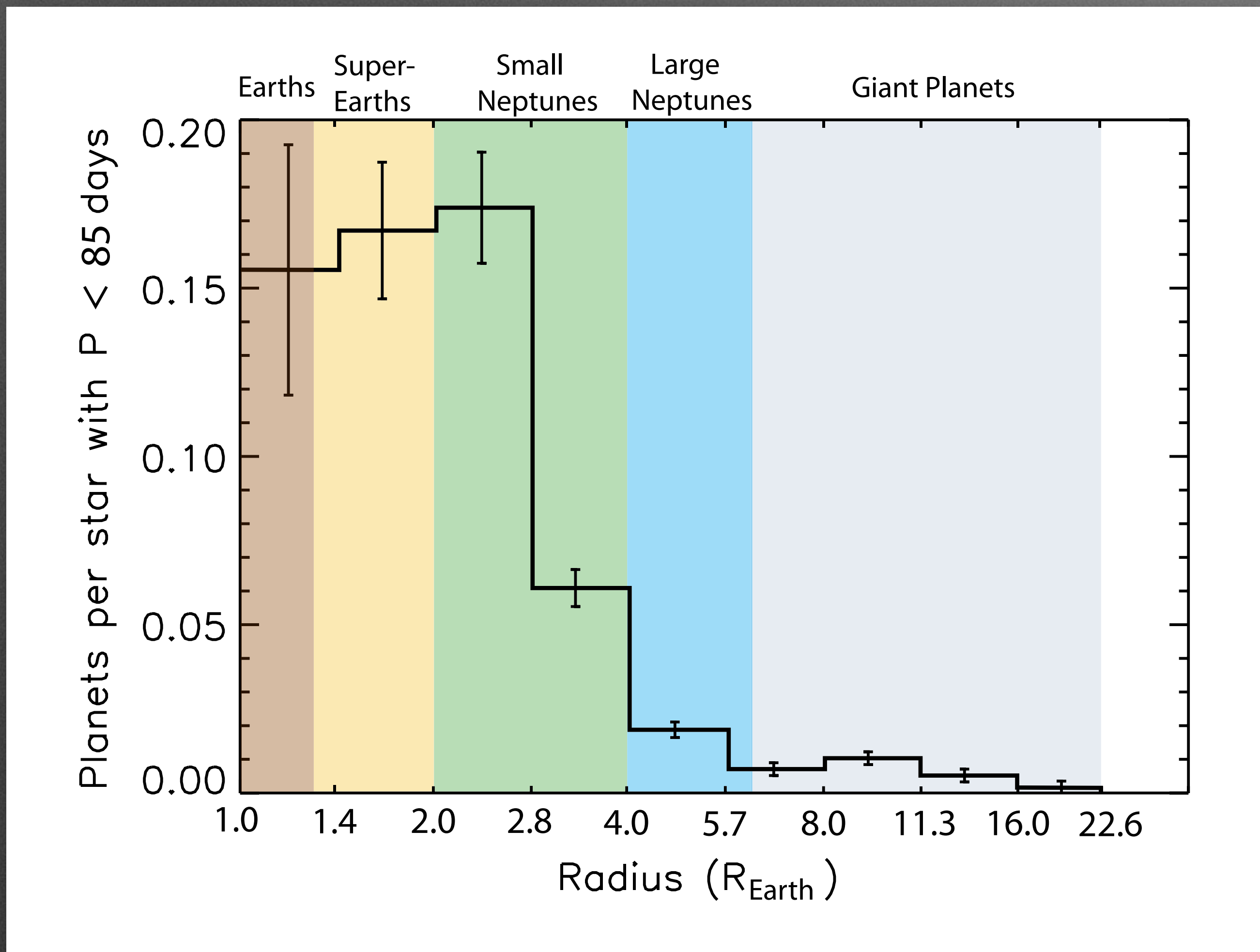
# The California-Kepler Survey. III. A Gap in the Radius Distribution of Small Planets

**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

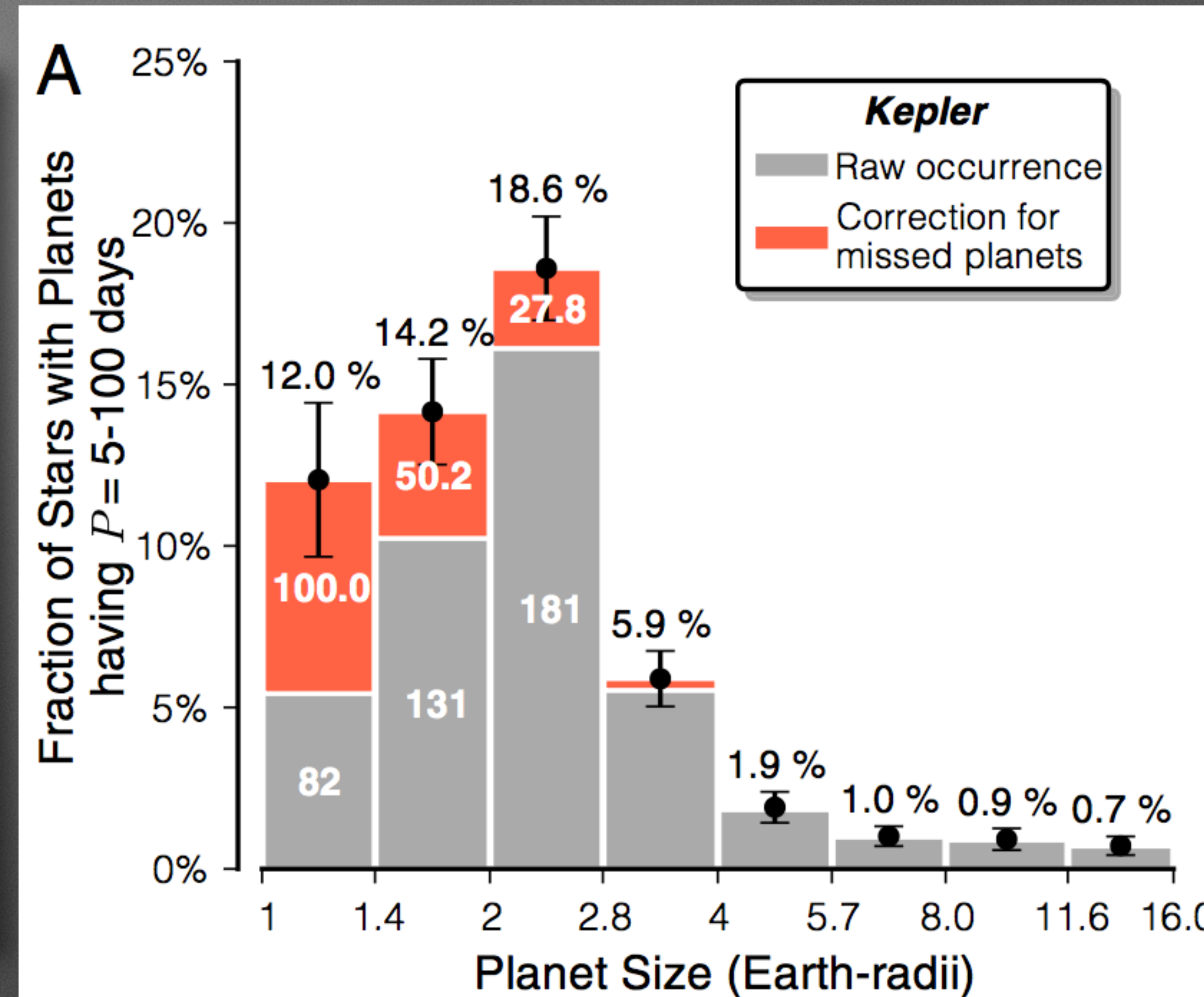
(arXiv:1703.10375)

Petigura, Howard, et al. (submitted)
**CKS I: Spectroscopic Properties of 1305 Planet-Host Stars From Kepler**
(arXiv:1703.10400)

Johnson, Petigura, **Fulton** et al. (submitted)
**CKS II: Precise Physical Properties of 2025 Kepler Planets and Their Host Stars**
(arXiv:1703.10402)




Fressin et al. (2013)

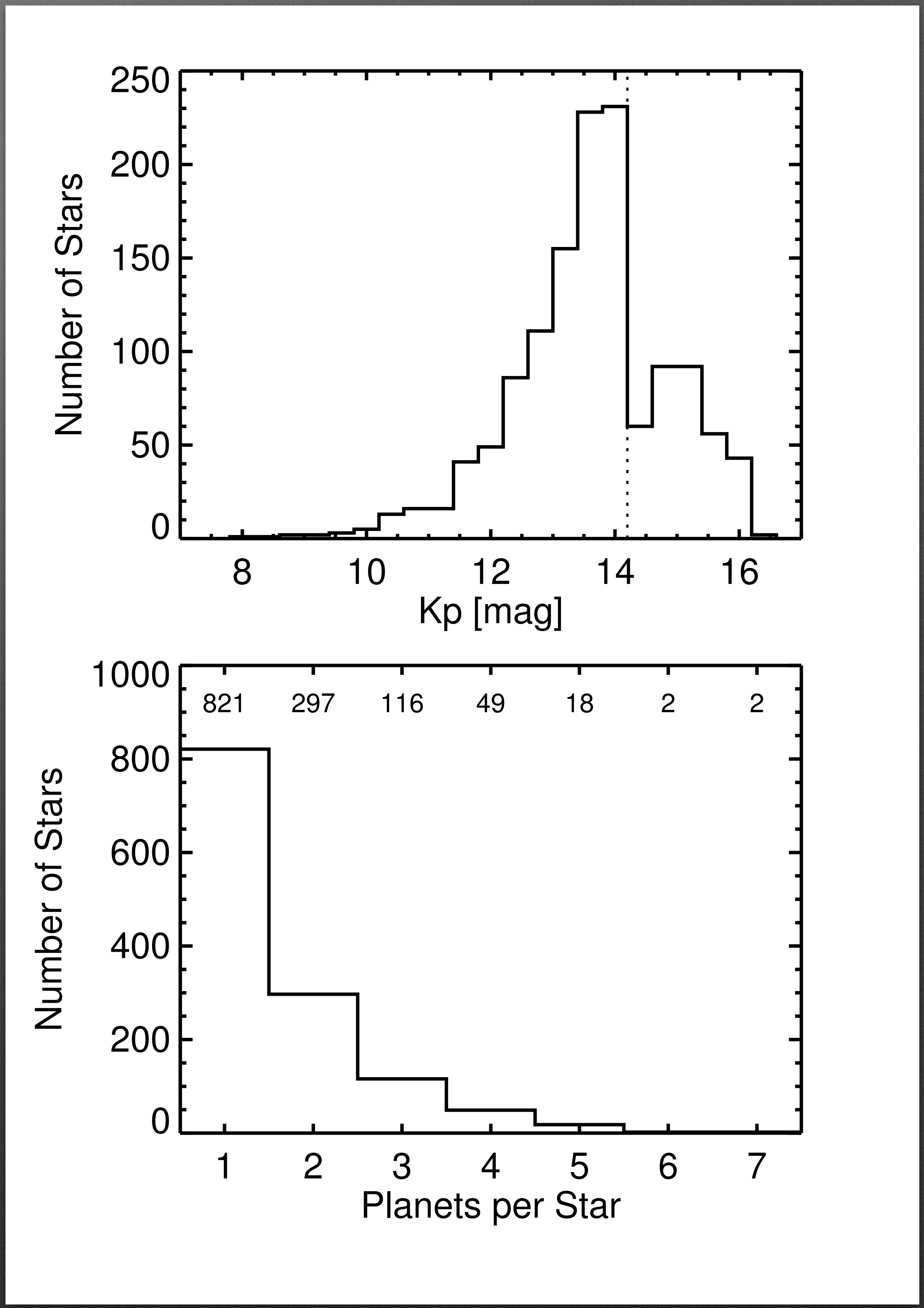



Petigura et al. (2013)

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

# The California-Kepler Survey

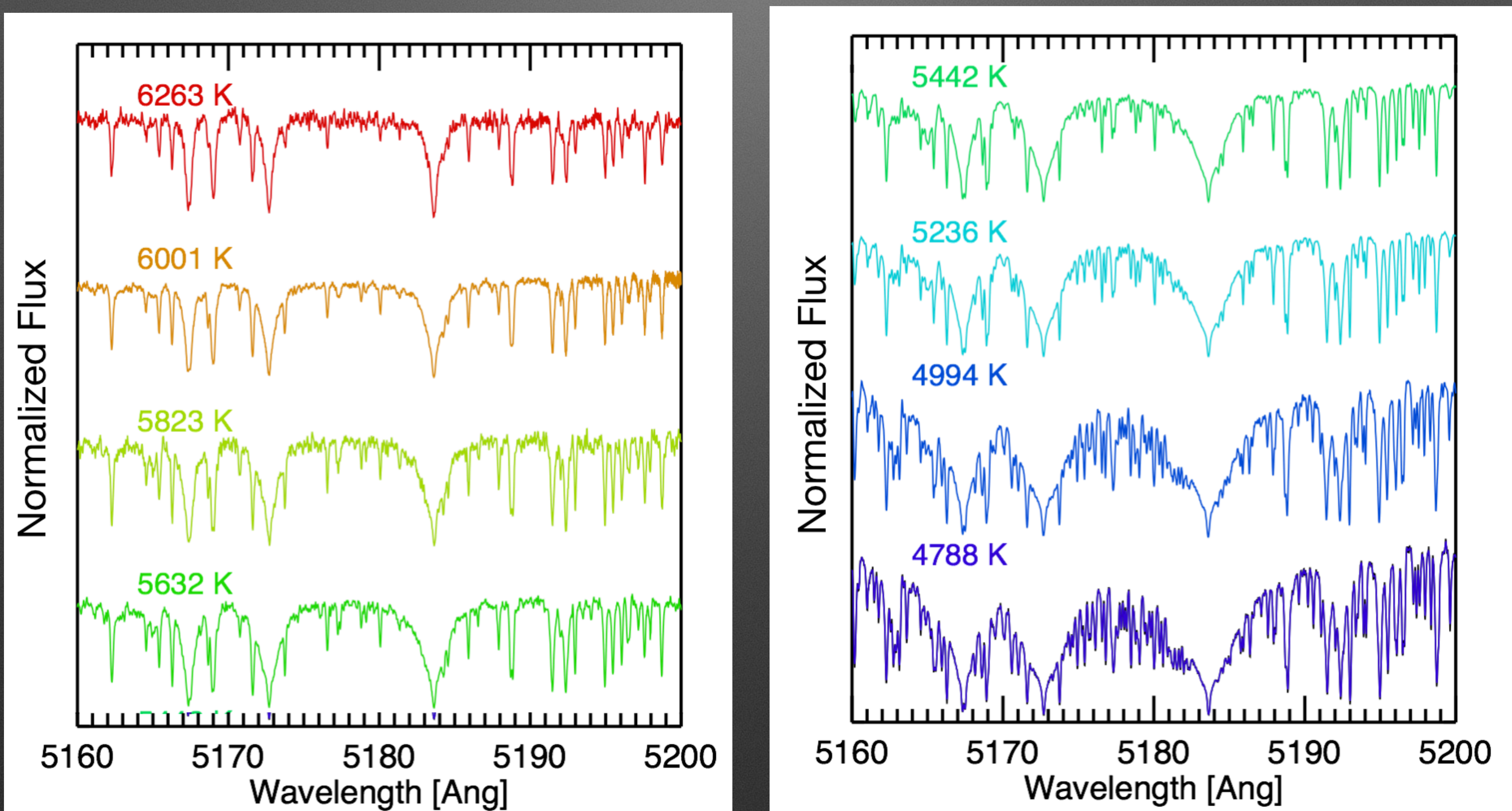
- Led by Andrew Howard, Geoff Marcy, John Johnson
- ~50 Keck nights (2011-2015)
- HIRES spectra of 1305 stars hosting 2075 planet candidates
- Sub-samples:
  - Magnitude limited ($Kp$ < 14.2) ($N_\star$ = 960)
  - Multis ($N_\star$ = 484)
  - USPs ($P$ < 1d) ($N_\star$ = 71)
  - Habitable Zone ($N_\star$ = 127)




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

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

All reduced spectra will be made public




Petigura, Howard et al. (submitted)

# The California-Kepler Survey

BJ Fulton

Aspen 2017

# The California-Kepler Survey

$\sigma T_{eff}$ (Q16) = 156 K

$\sigma T_{eff}$ (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%

# The California-Kepler Survey

$\sigma T_{eff}$ (Q16) = 156 K

$\sigma T_{eff}$ (CKS) = 60 K

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

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

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

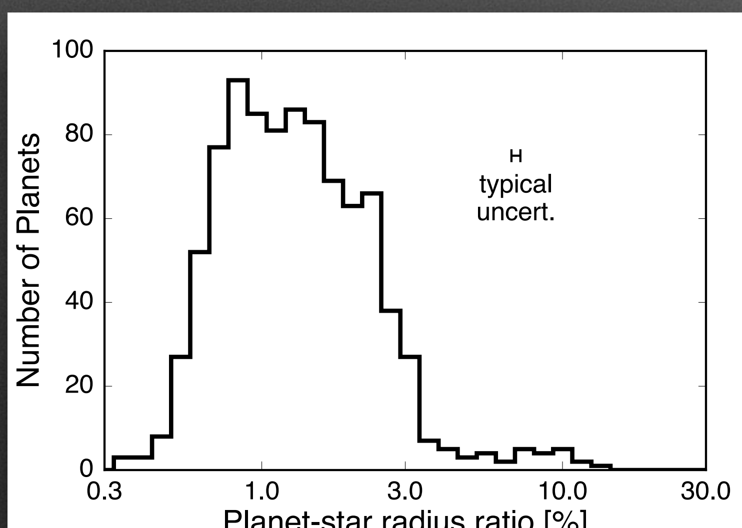
$\sigma M/M$ (CKS) = 5%

$\boxed{\sigma R/R \text{ (Q16)} = 39\% \quad \sigma R/R \text{ (CKS)} = 10\%}$

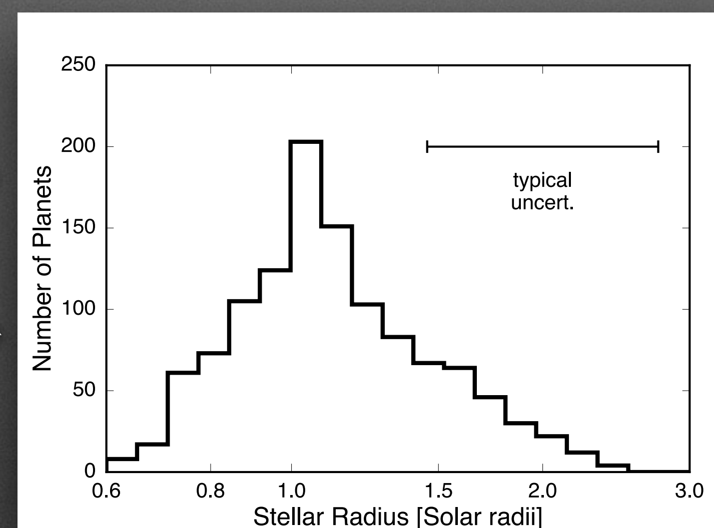
$R_P/R_\star \quad X \quad R_\star \quad = \quad R_P$

$X \quad =$

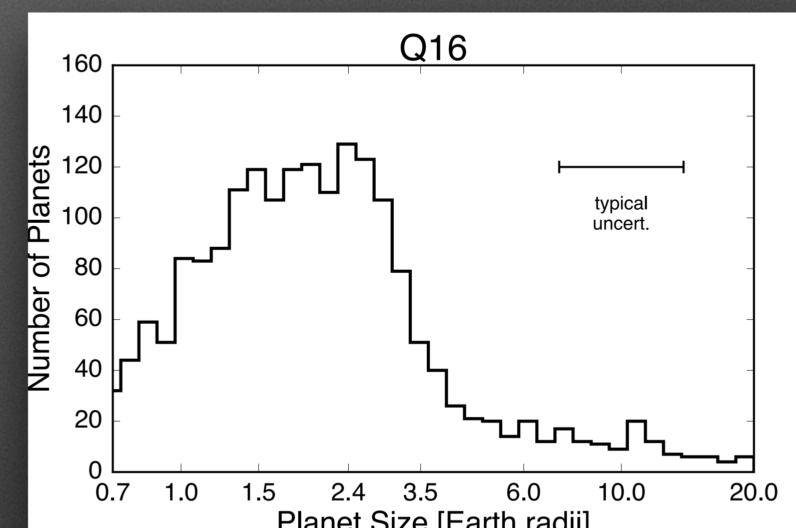
$R_P/R_\star \quad \times \quad R_\star \quad = \quad R_P$




X




=




Transit Depth
Q16

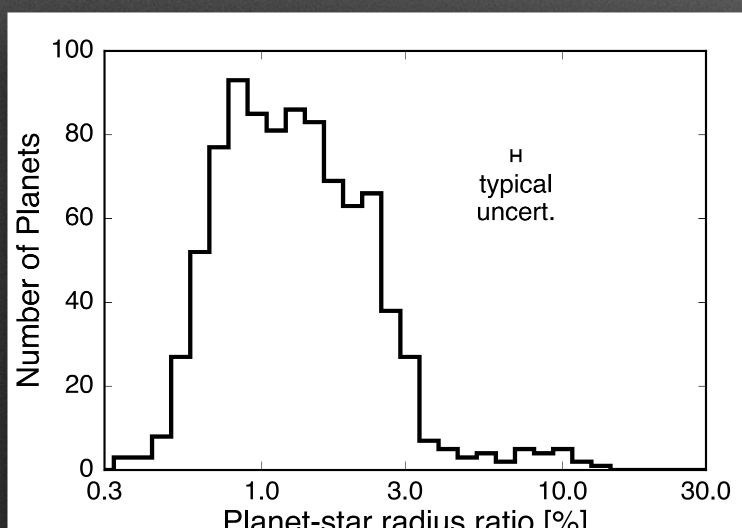
Stellar Radii
Q16

Planet Radii
Q16

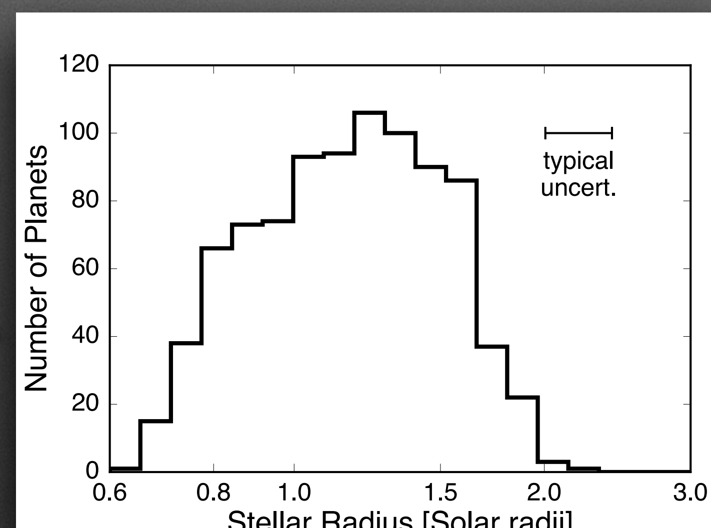


Johnson, Petigura et al. (submitted); Fulton, Petigura, et al. (*submitted*)

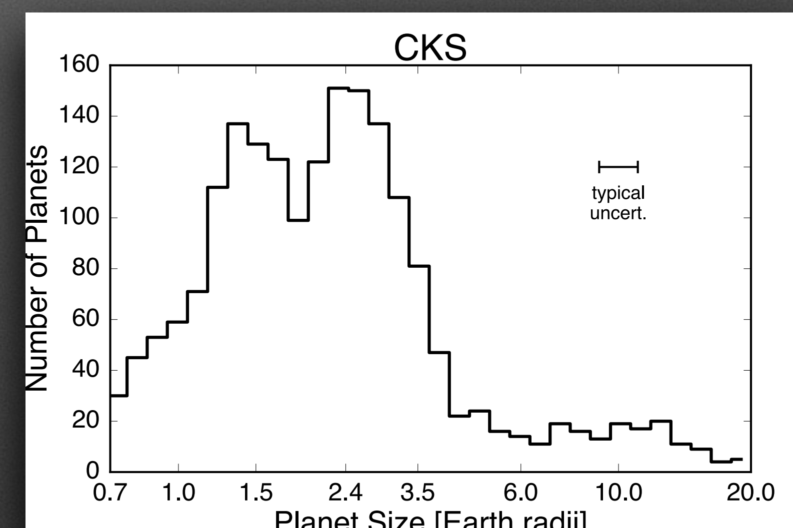
$$R_P/R_\star \quad \times \quad R_\star \quad = \quad R_P$$




X



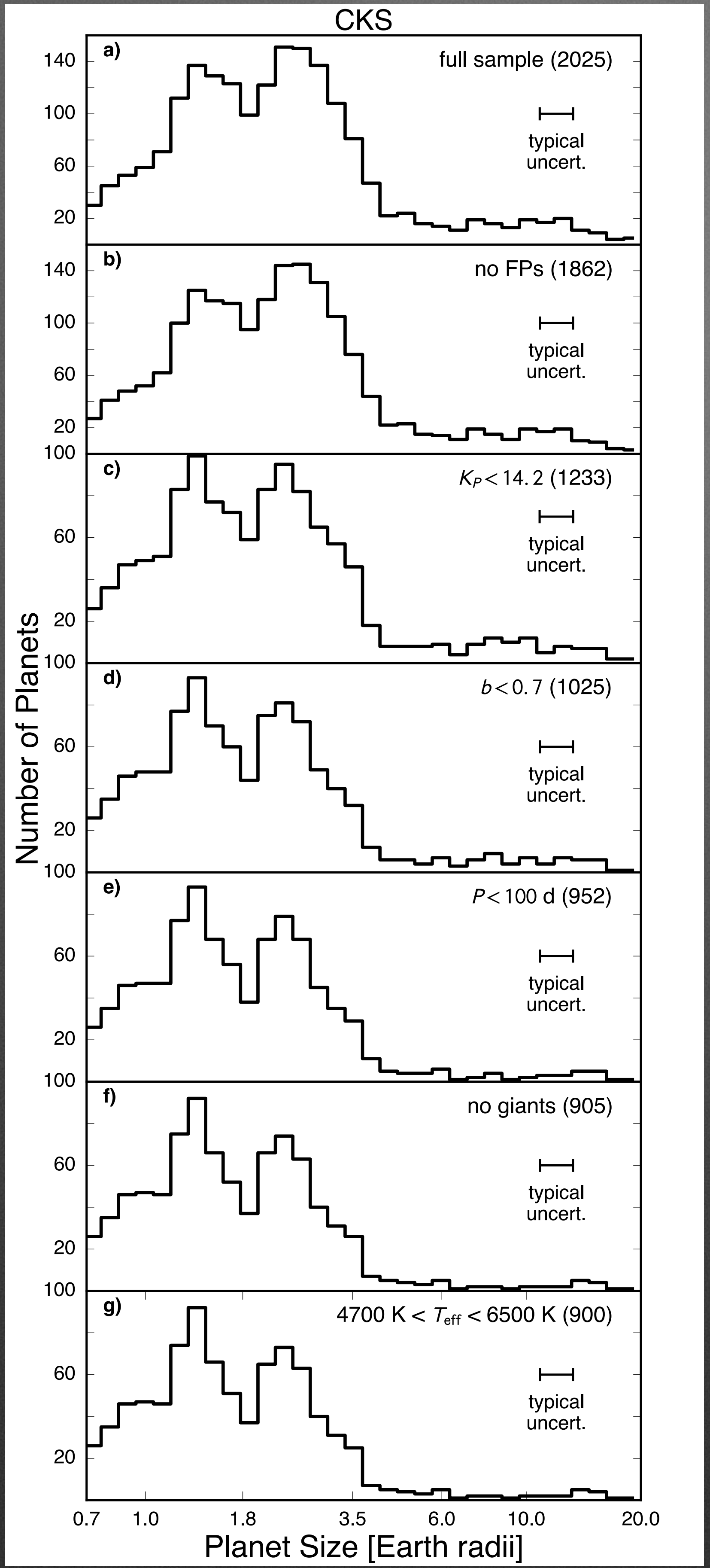

=



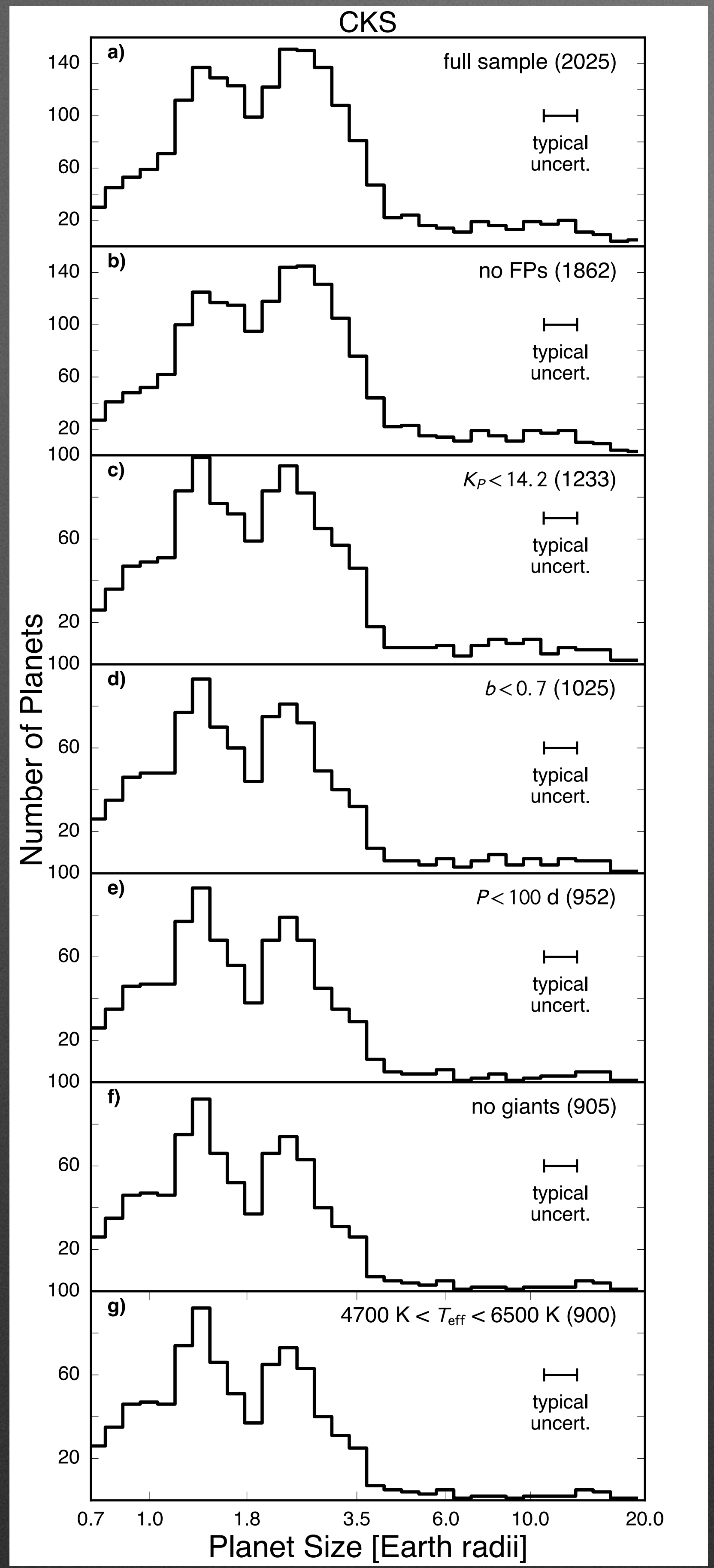

**Transit Depth**
Q16

**Stellar Radii**
~~Q16~~
CKS

**Planet Radii**
~~Q16~~
CKS

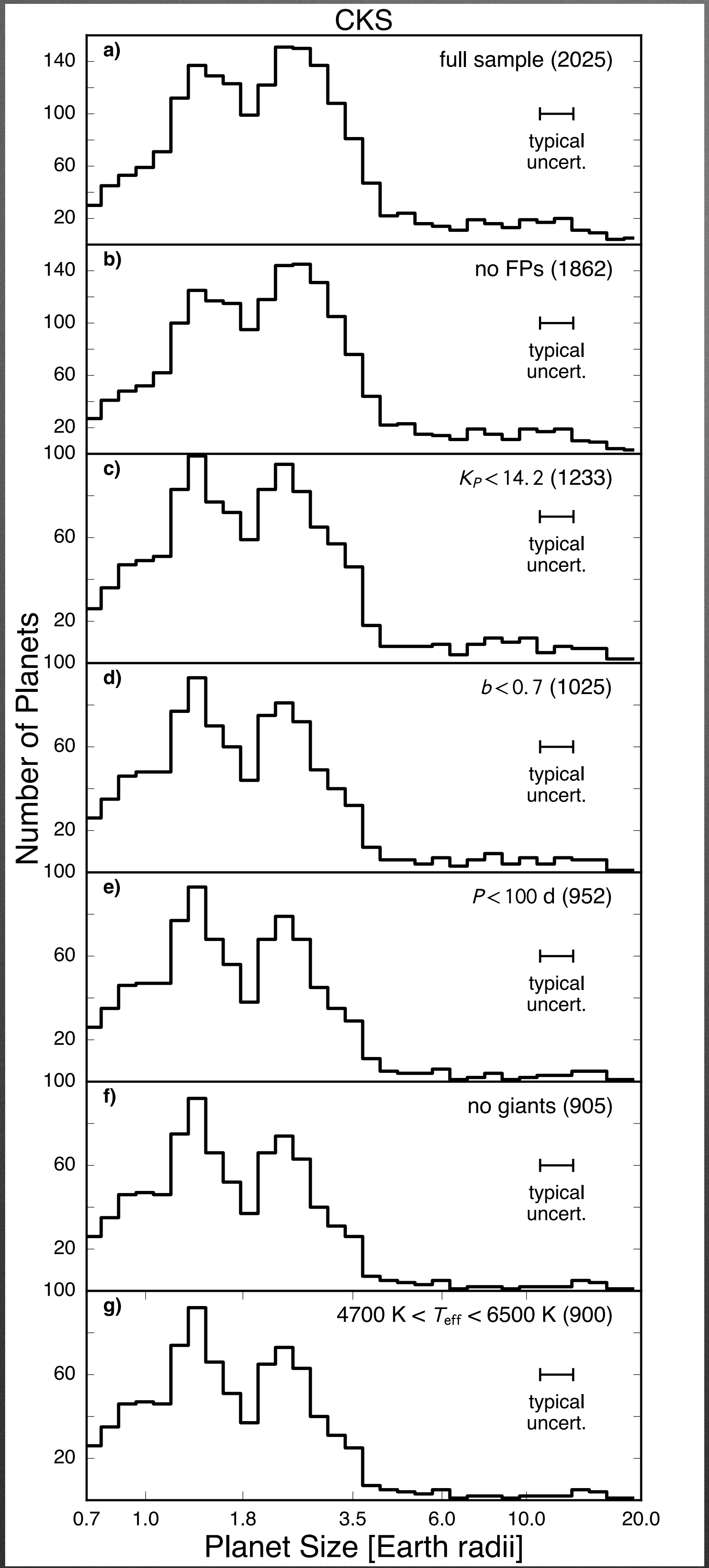



Fulton, Petigura, et al. (*submitted*)




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

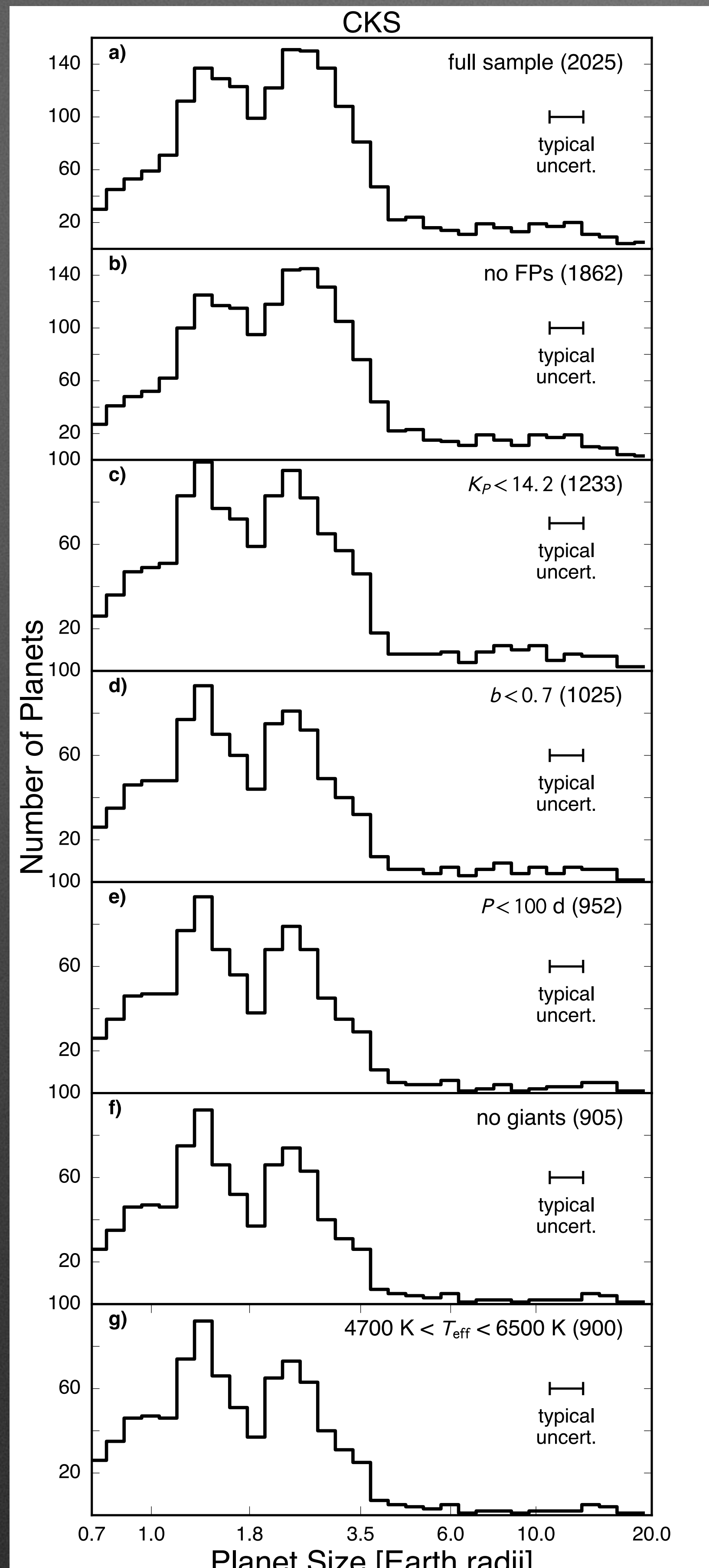
Remove false positives




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

Remove false positives

Keep bright stars (Kp < 14.2)

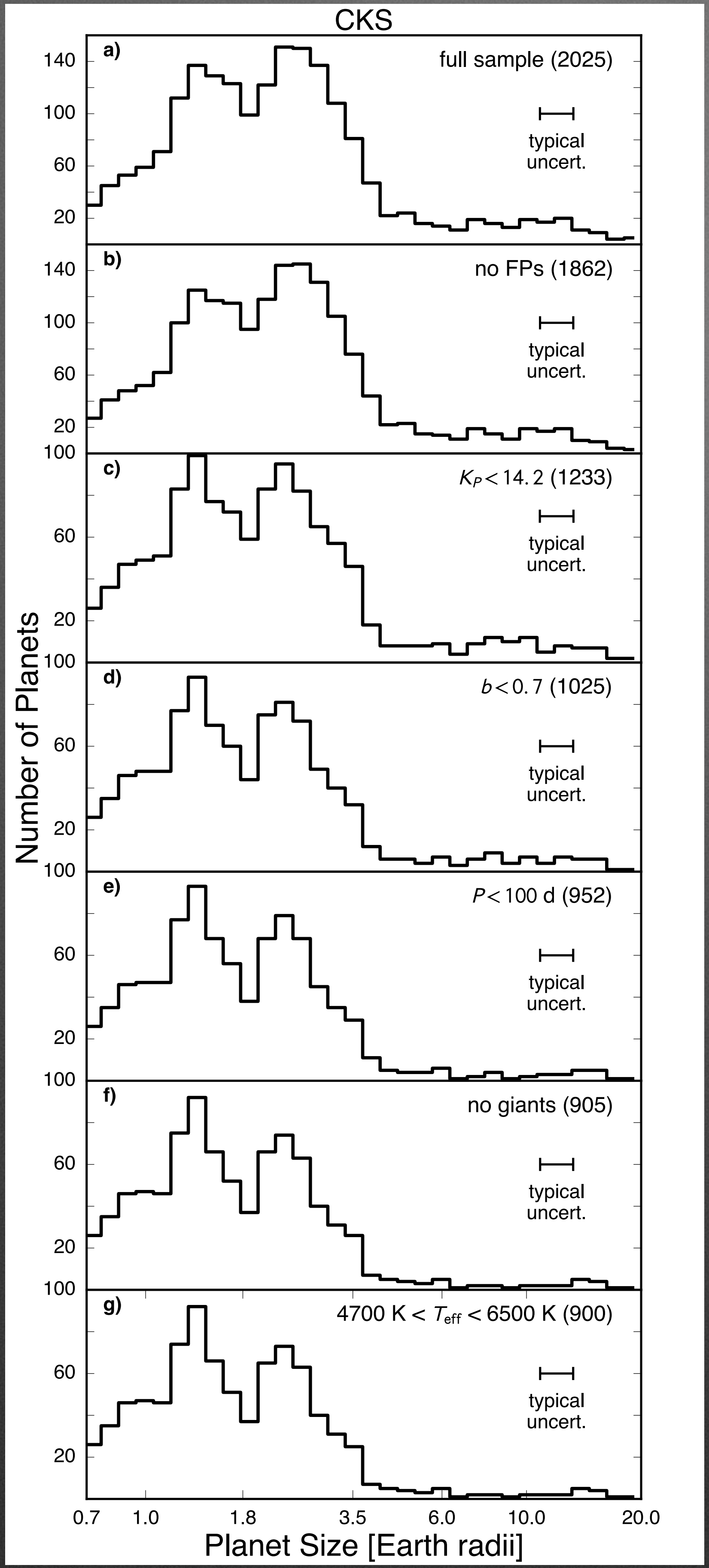



Fulton, Petigura, et al. (*submitted*)

Remove false positives

Keep bright stars
(Kp < 14.2)

Low impact parameters
(b < 0.7)



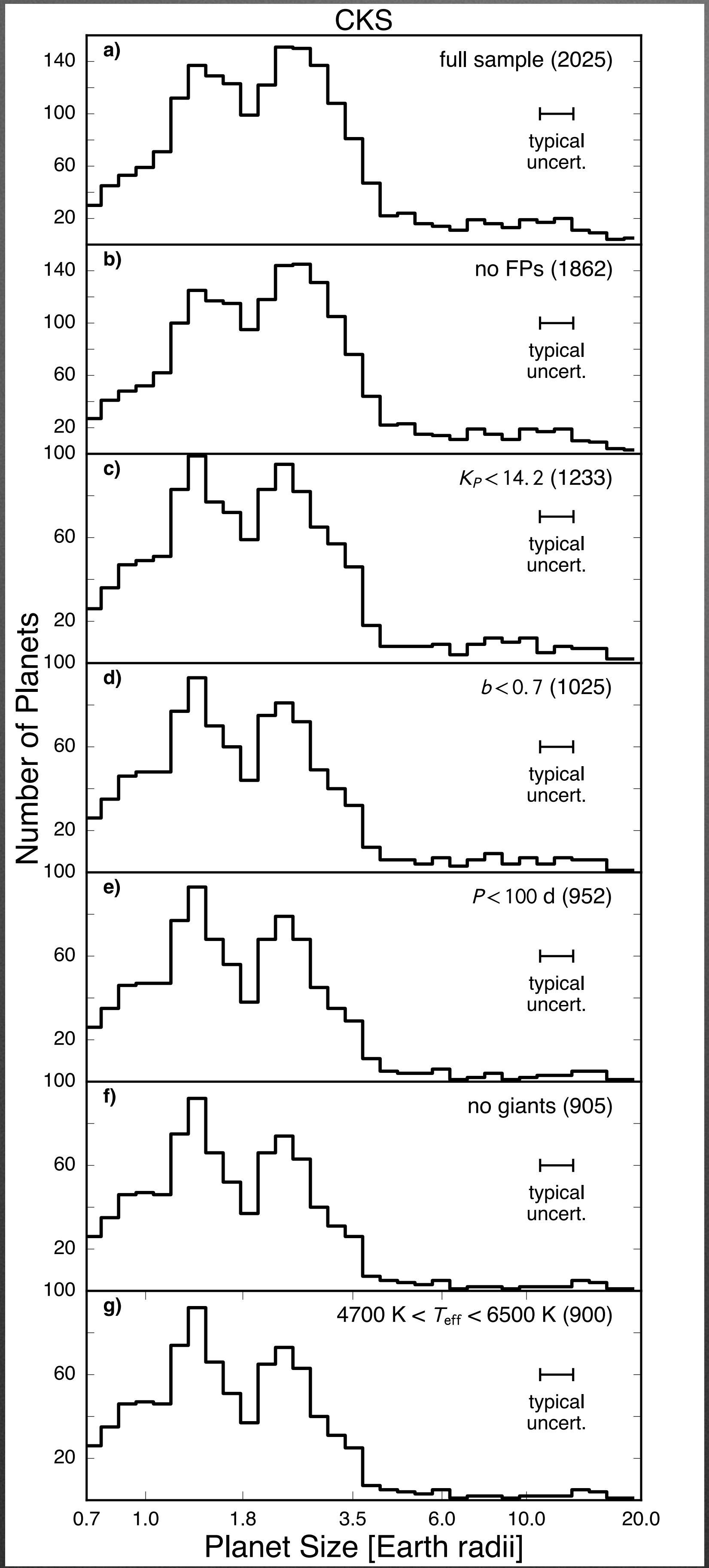

Fulton, Petigura, et al. (*submitted*)

Remove false positives

Keep bright stars (Kp < 14.2)

Low impact parameters (b < 0.7)

Short orbital periods (P < 100 d)




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

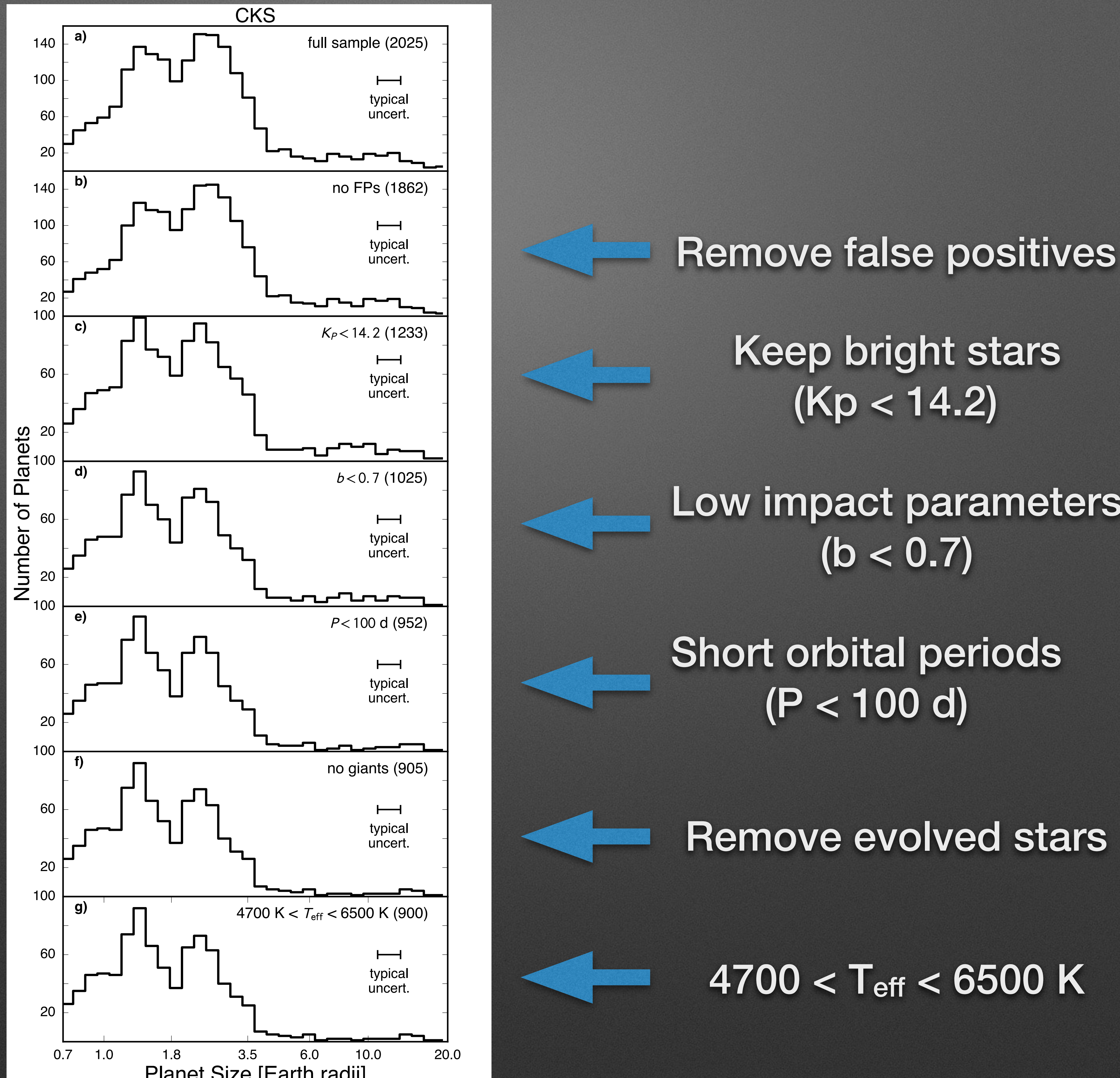
Remove false positives

Keep bright stars (Kp < 14.2)

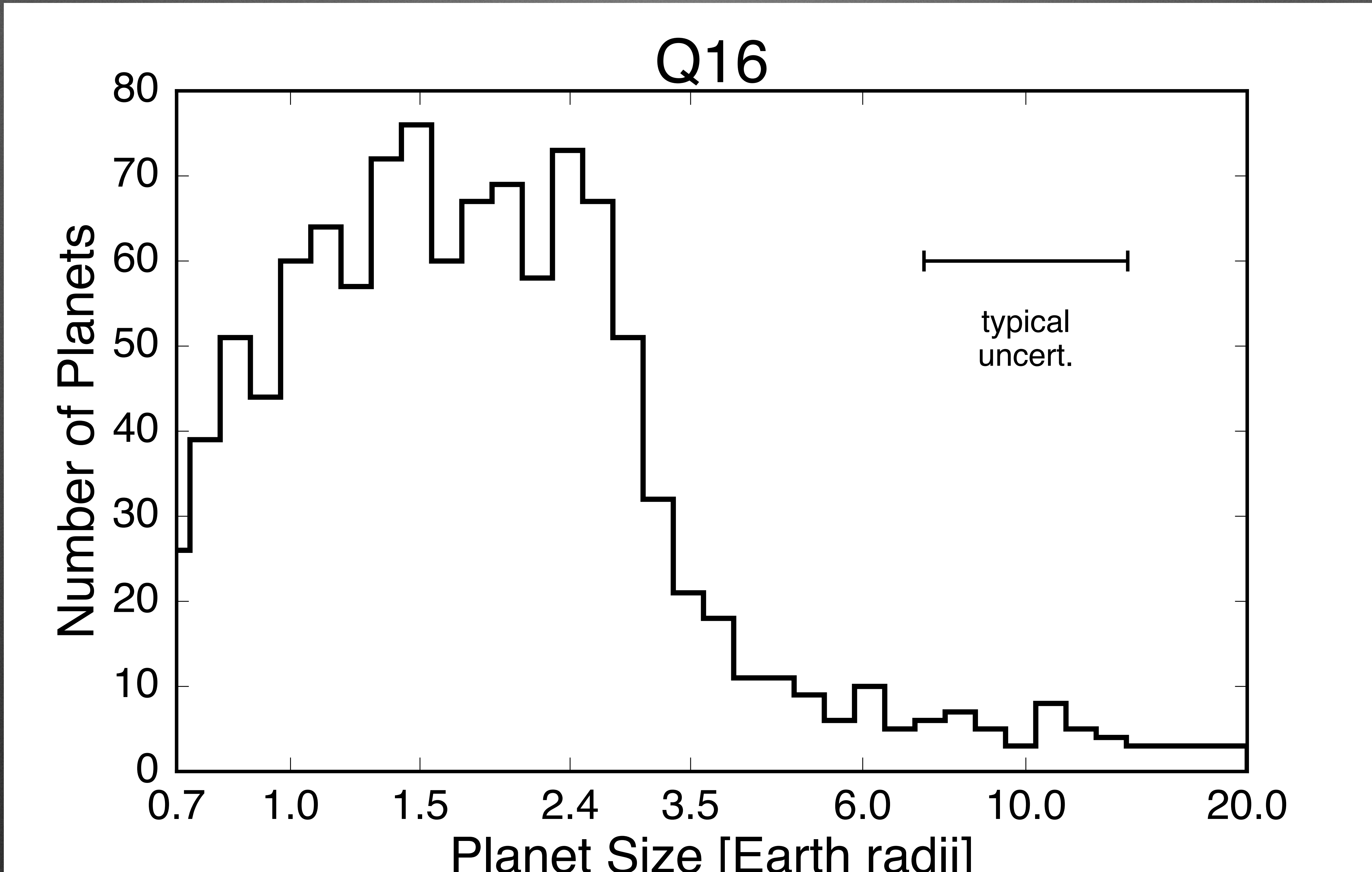
Low impact parameters (b < 0.7)

Short orbital periods (P < 100 d)

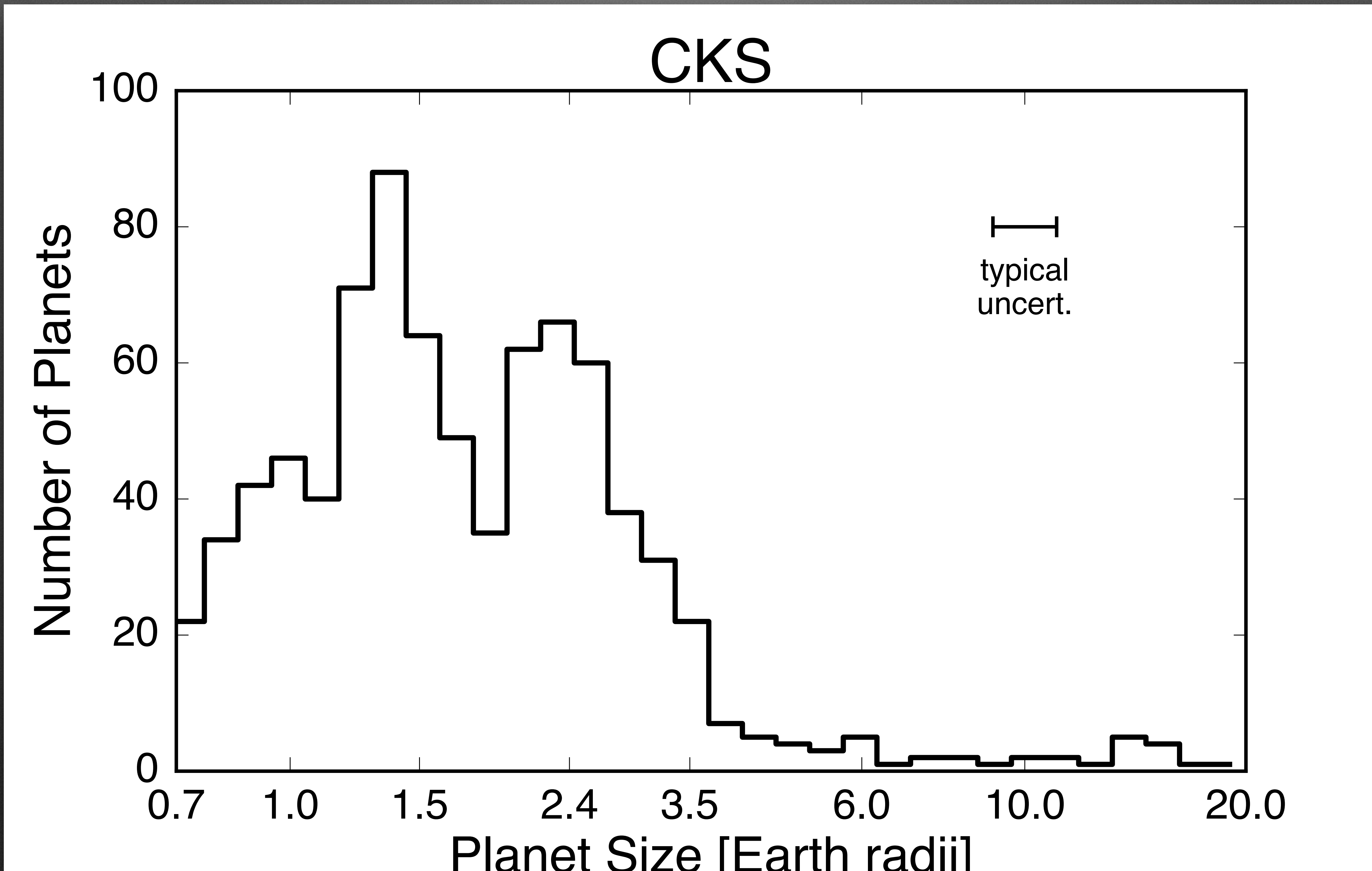
Remove evolved stars



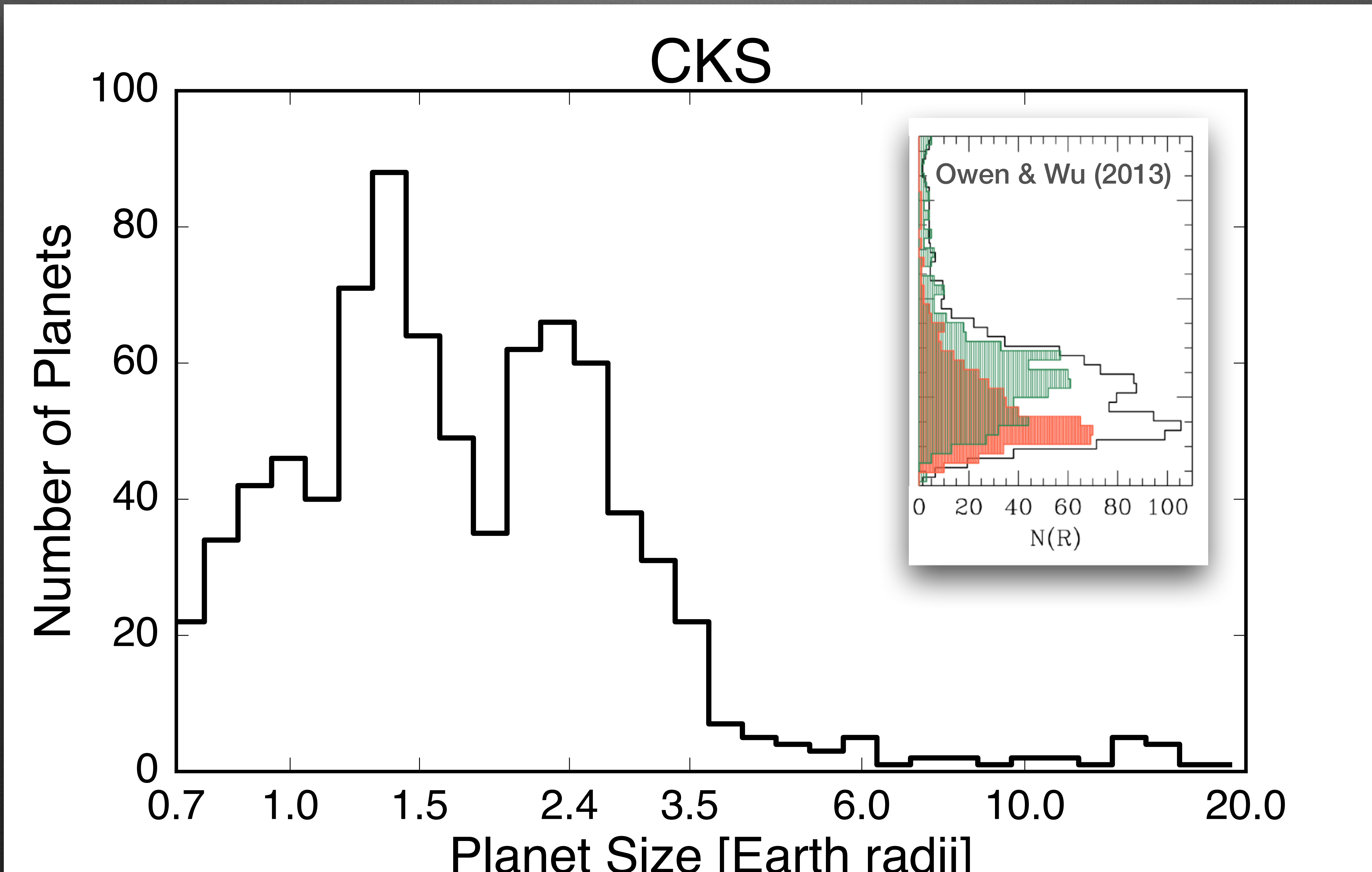

Fulton, Petigura, et al. (*submitted*)




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

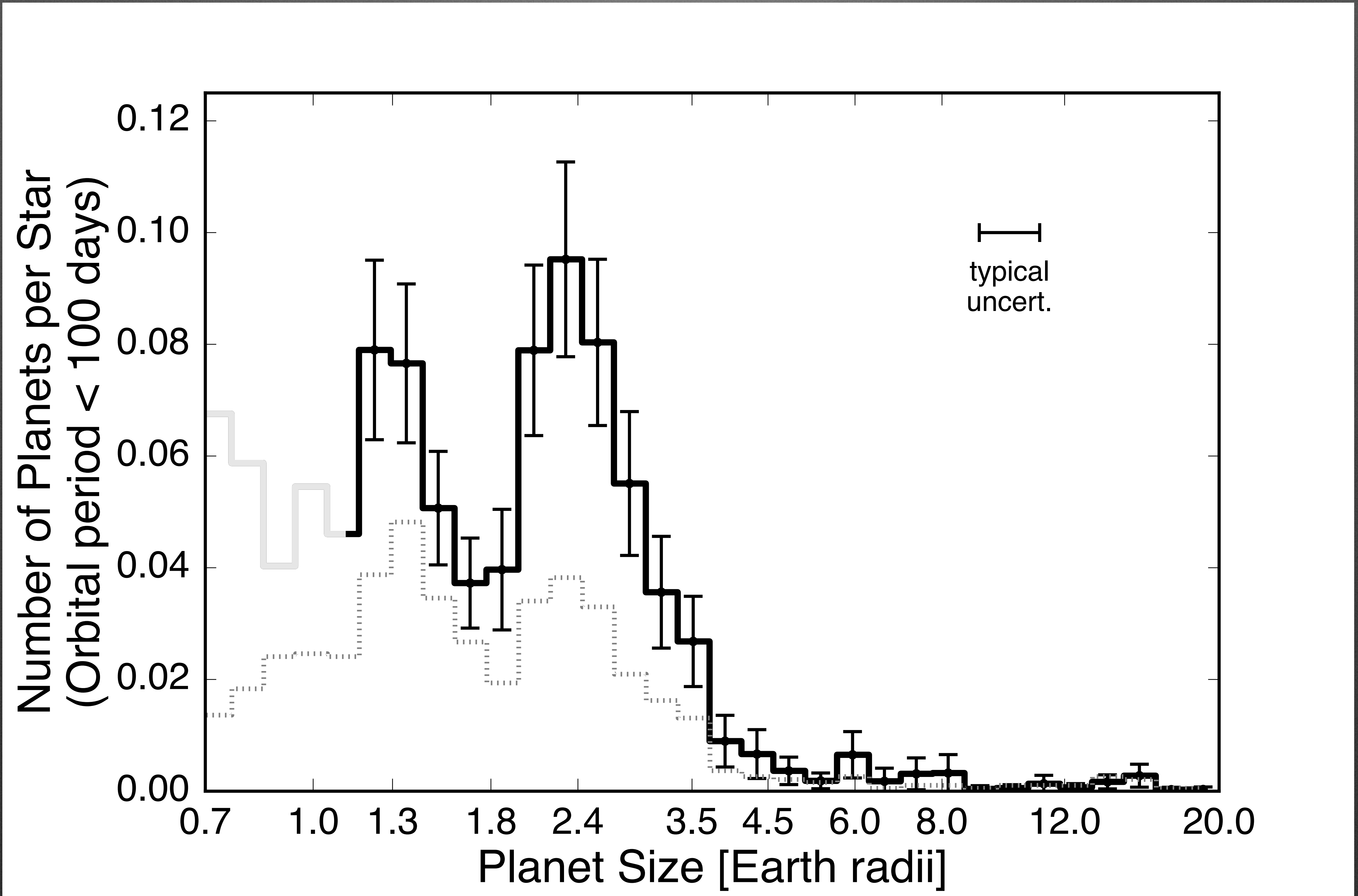



Johnson, Petigura, et al. (*submitted*)




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

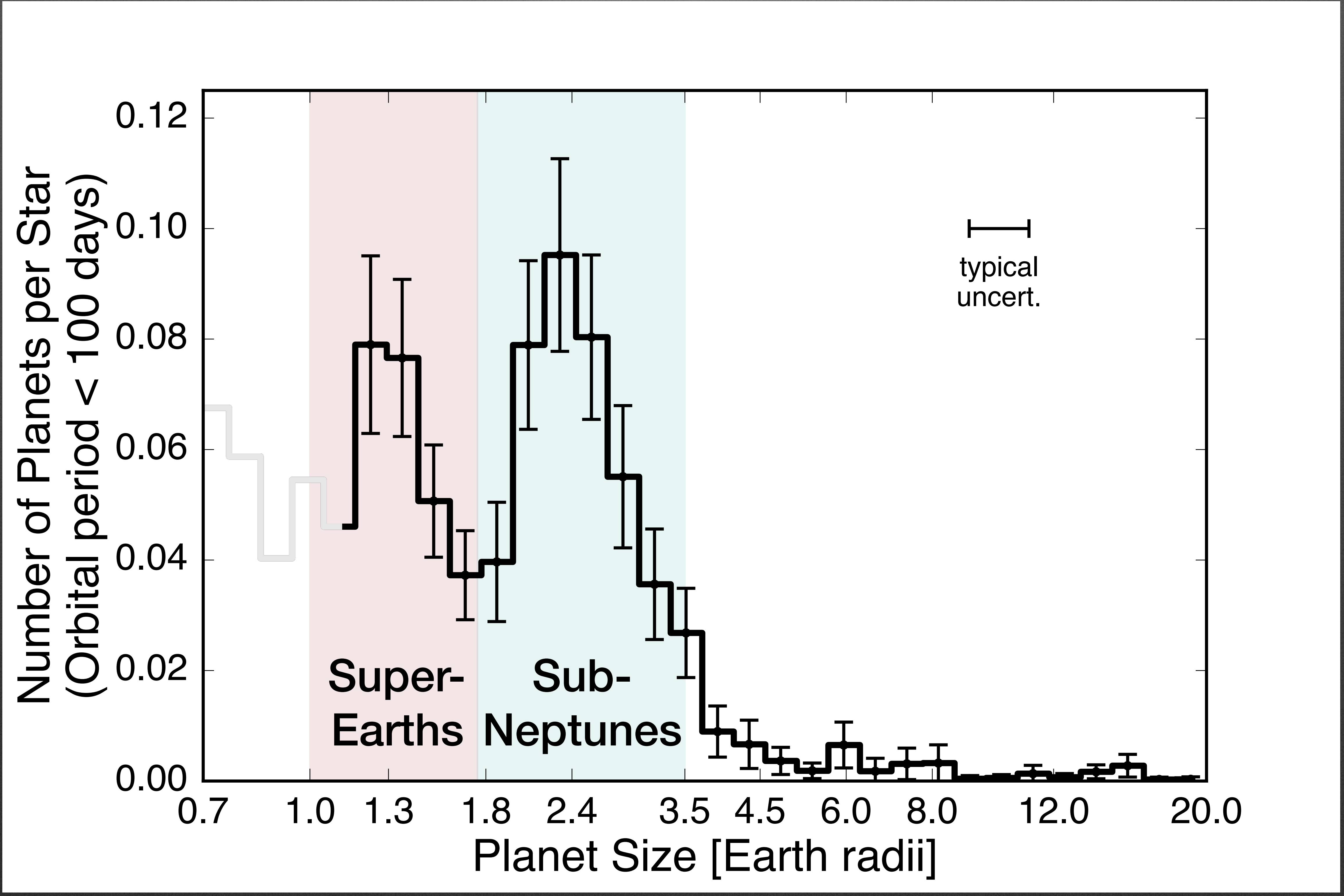
# The Radius Gap






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

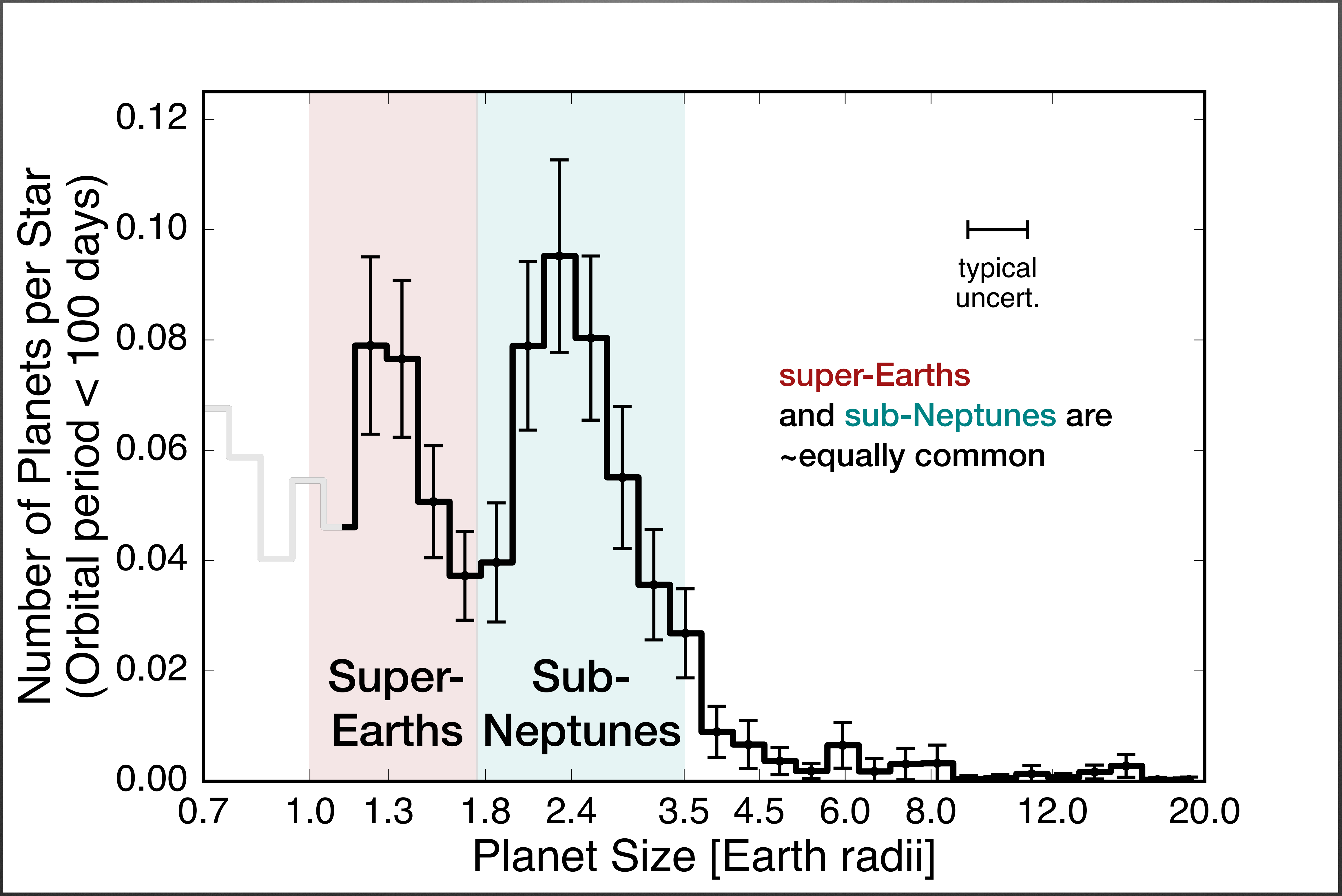
# The Radius Gap






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

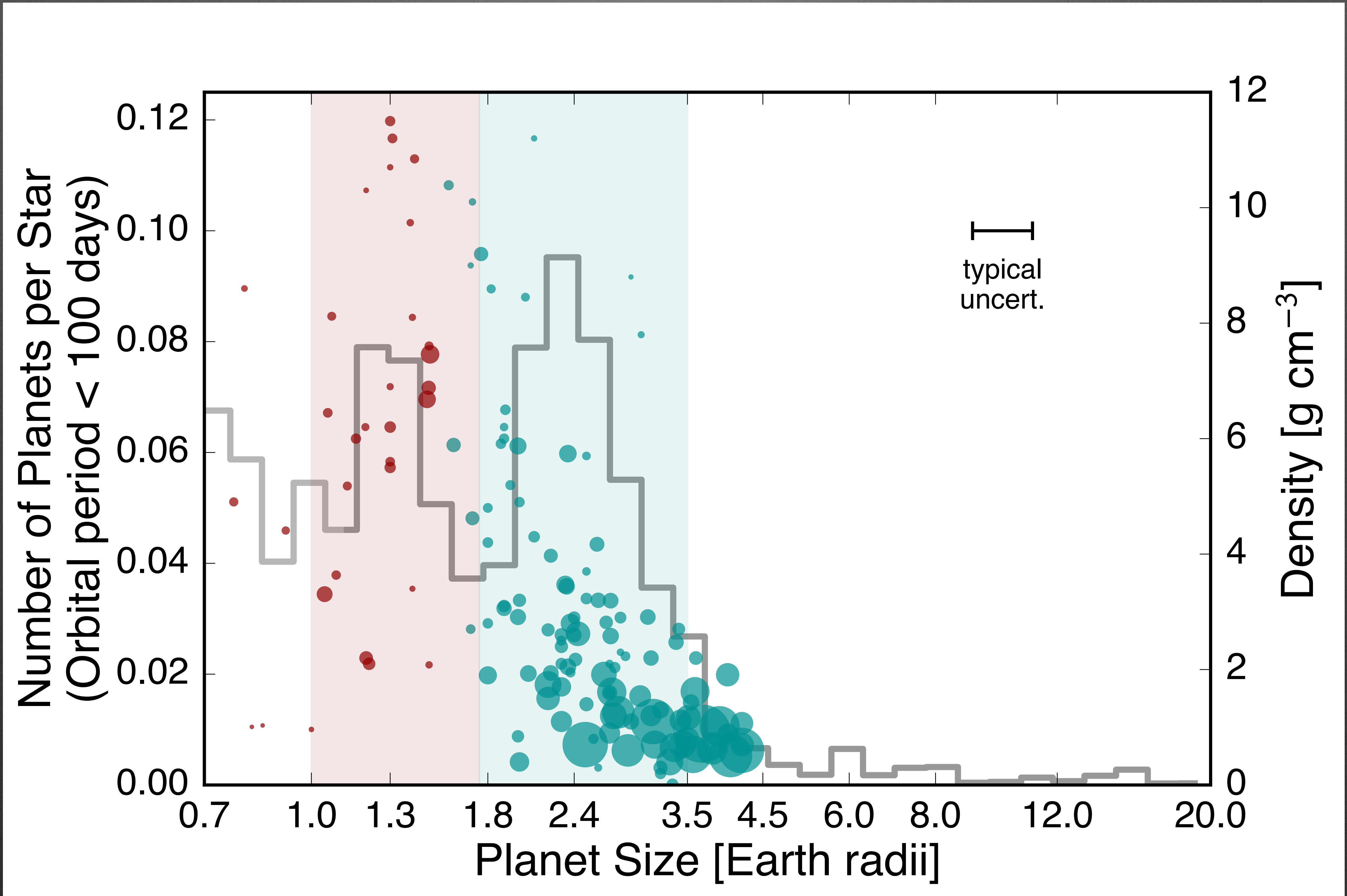
# The Radius Gap





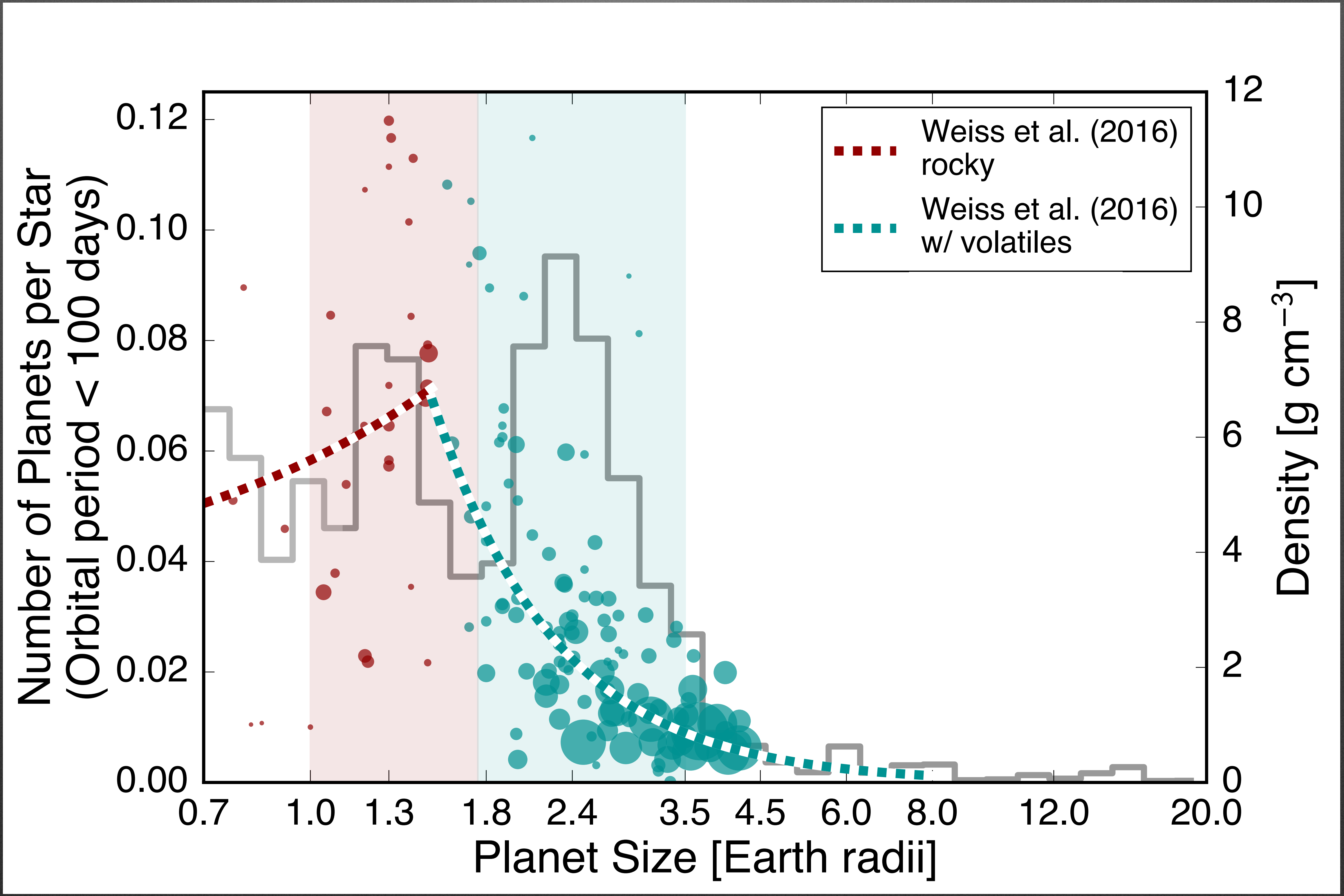

Fulton, Petigura, et al. (*submitted*)

# The Radius Gap




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

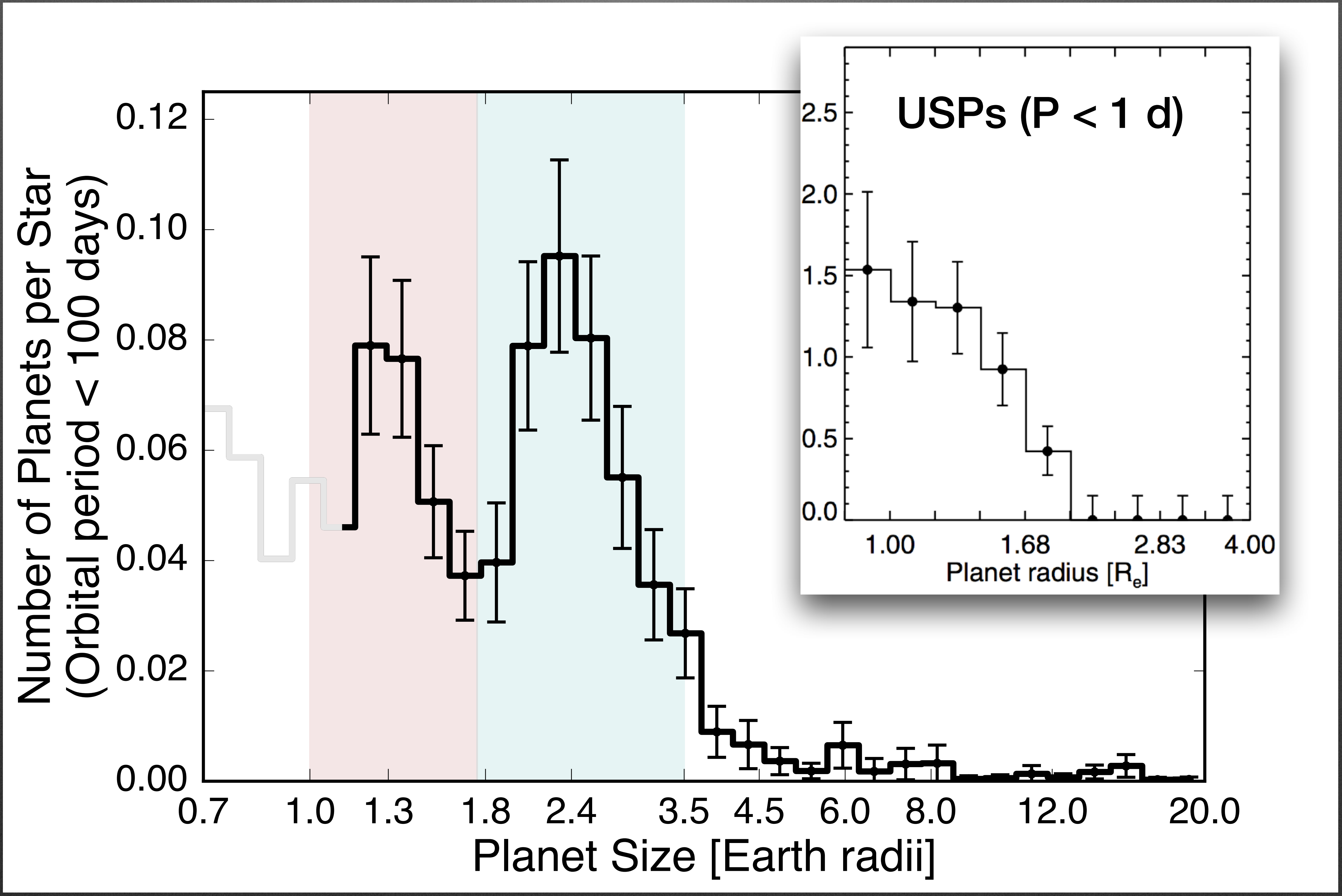
# The Radius Gap






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

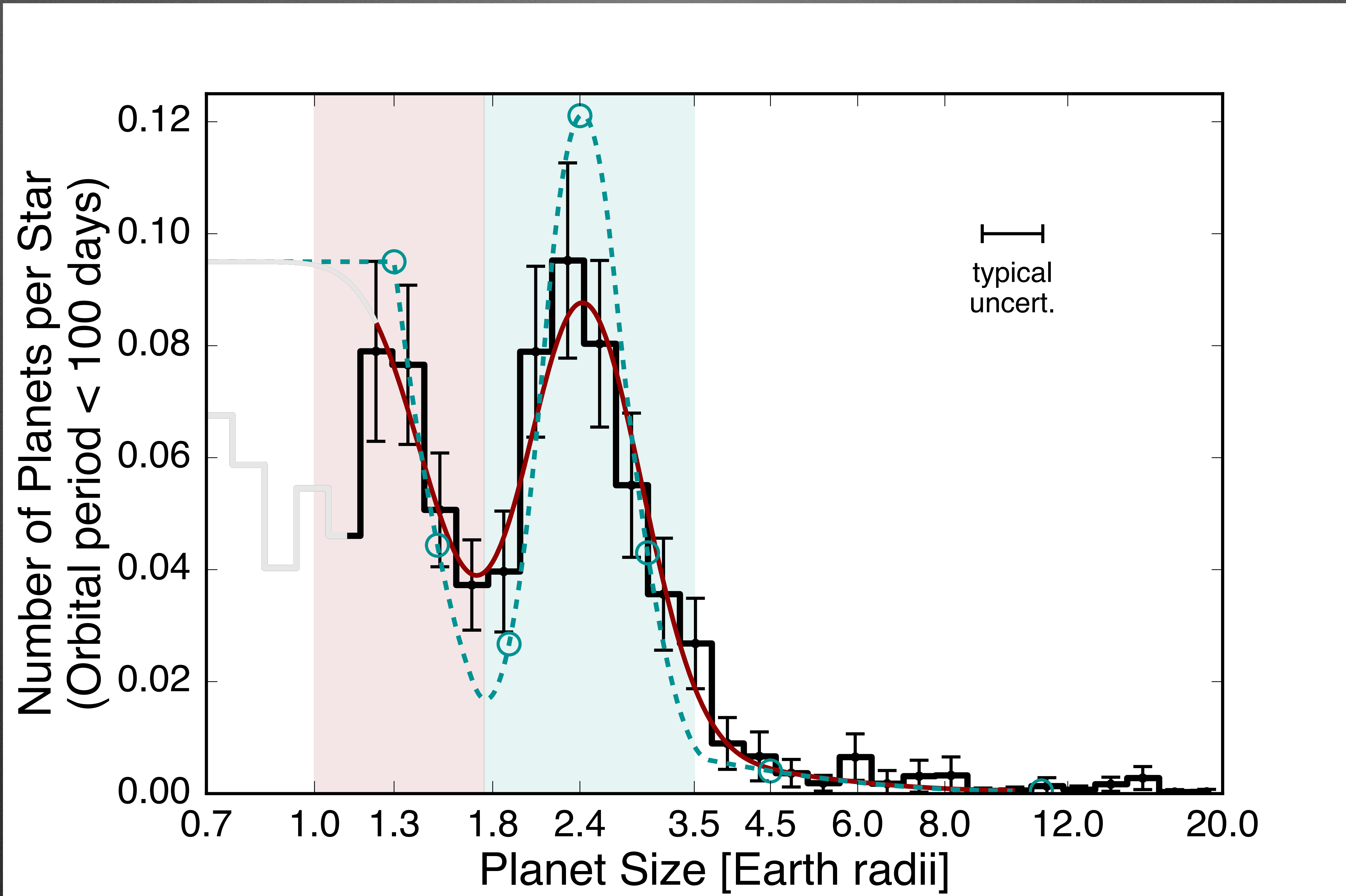
# The Radius Gap






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

# The Radius Gap

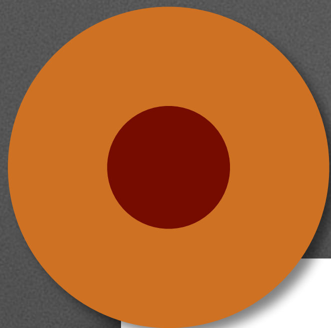


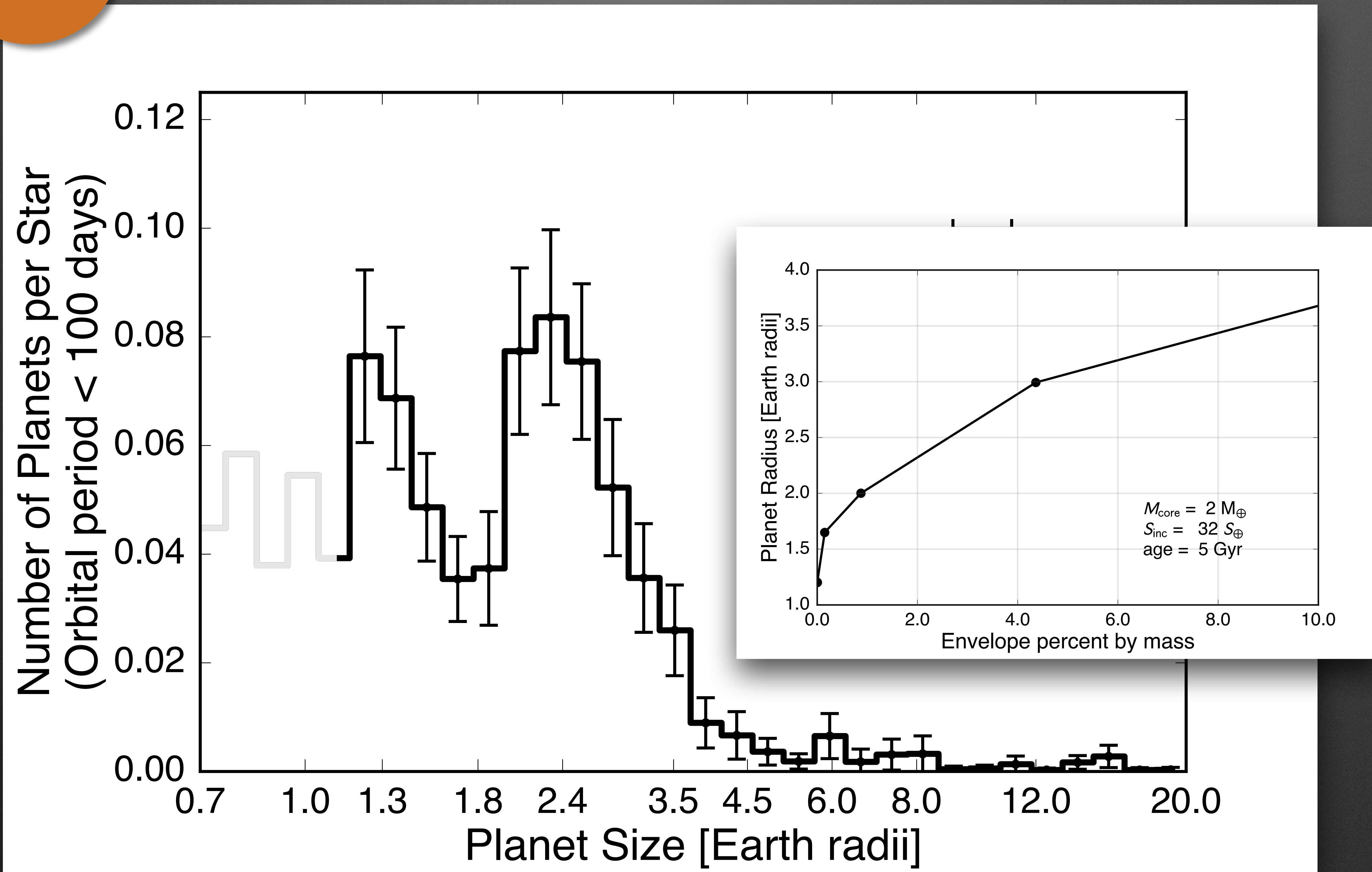



Fulton, Petigura, et al. (*submitted*)

# Plausible Explanations for the Gap

0.3/0.7 $Fe/MgSiO_3$



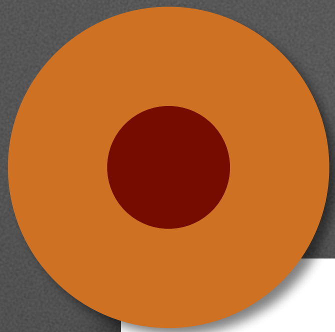


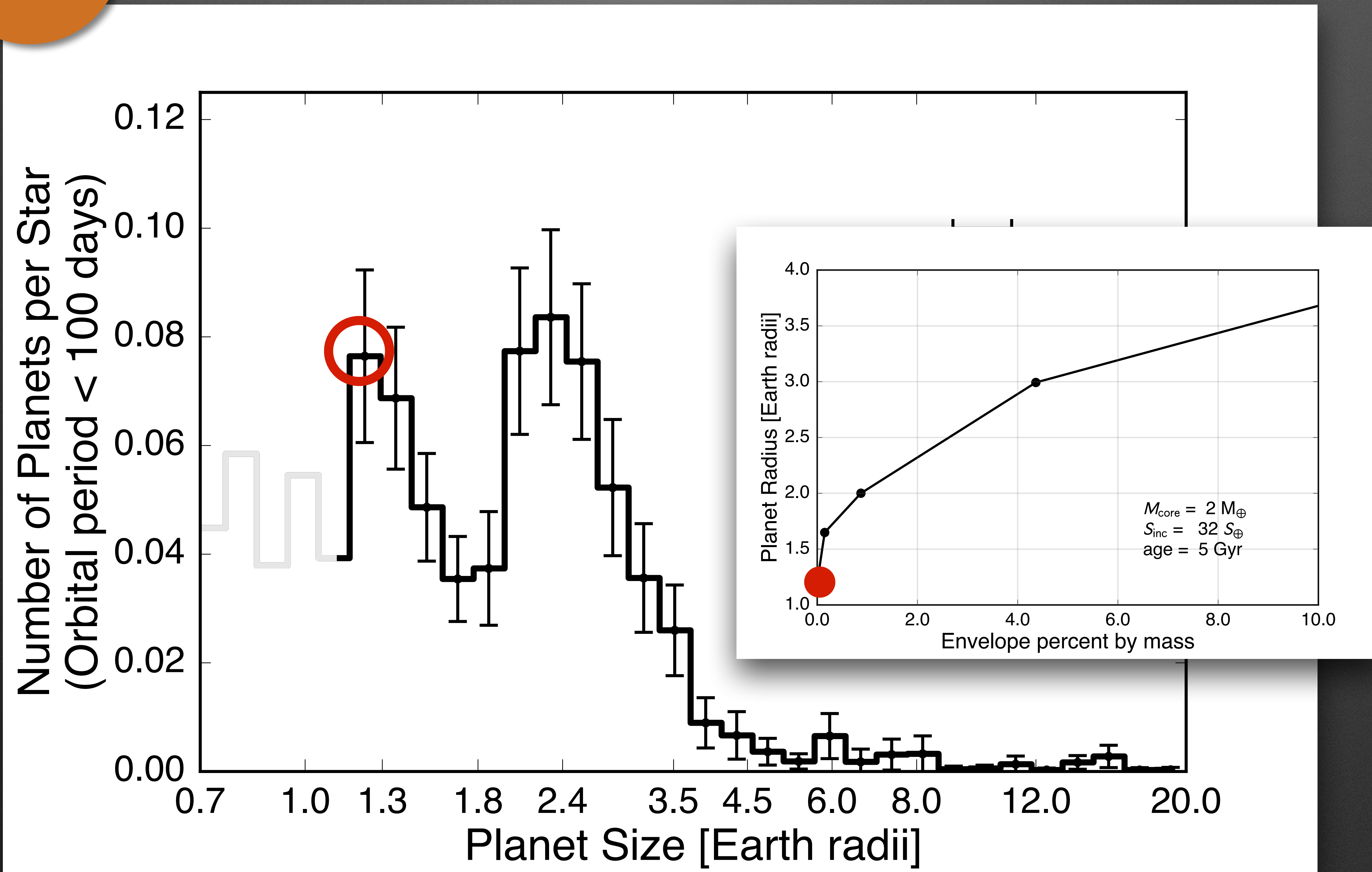

BJ Fulton

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

Aspen 2017

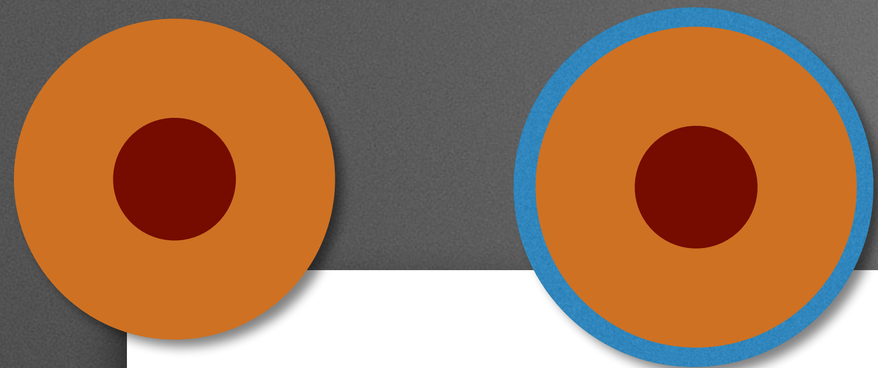
0.3/0.7 $Fe/MgSiO_3$

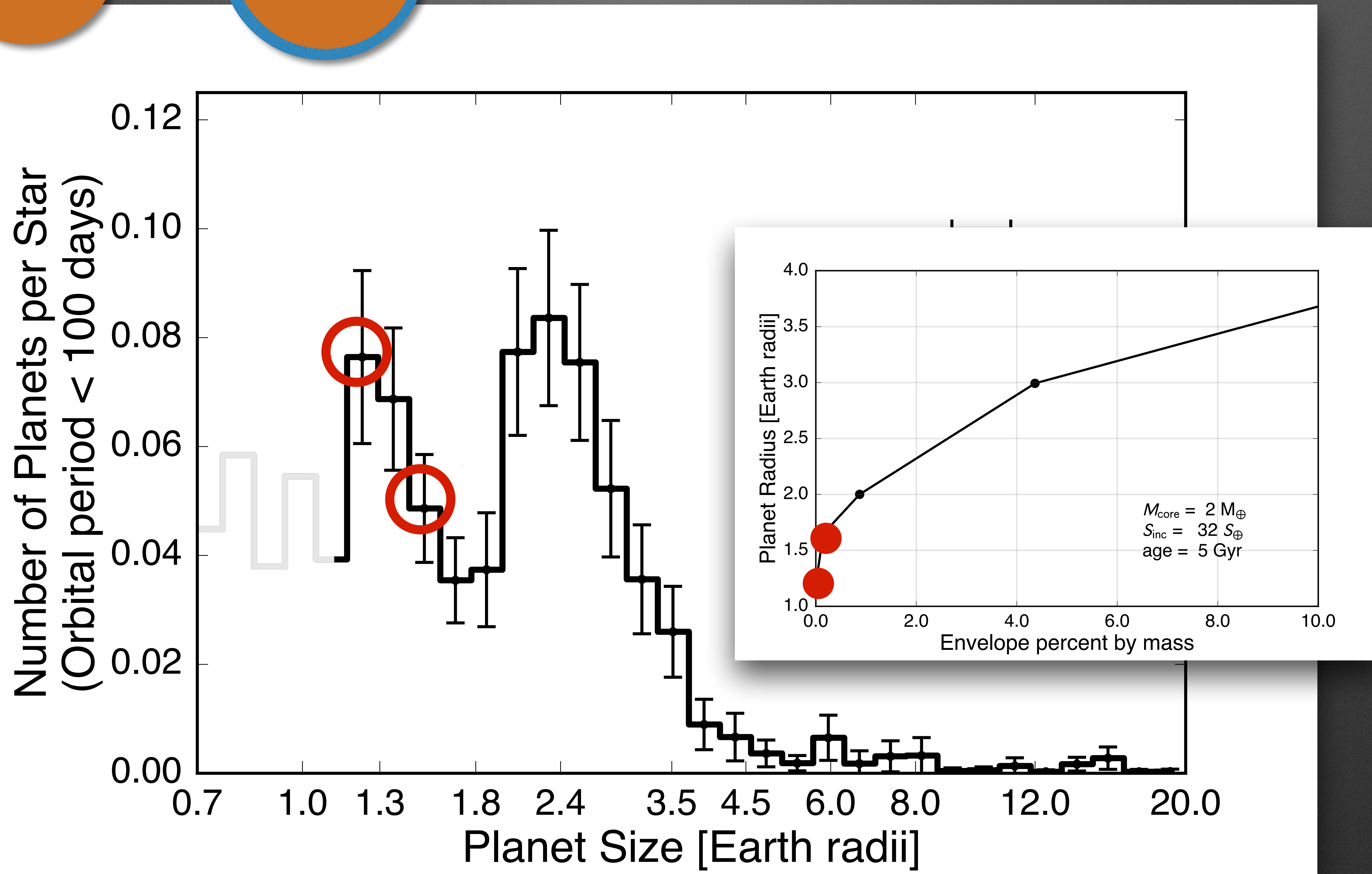






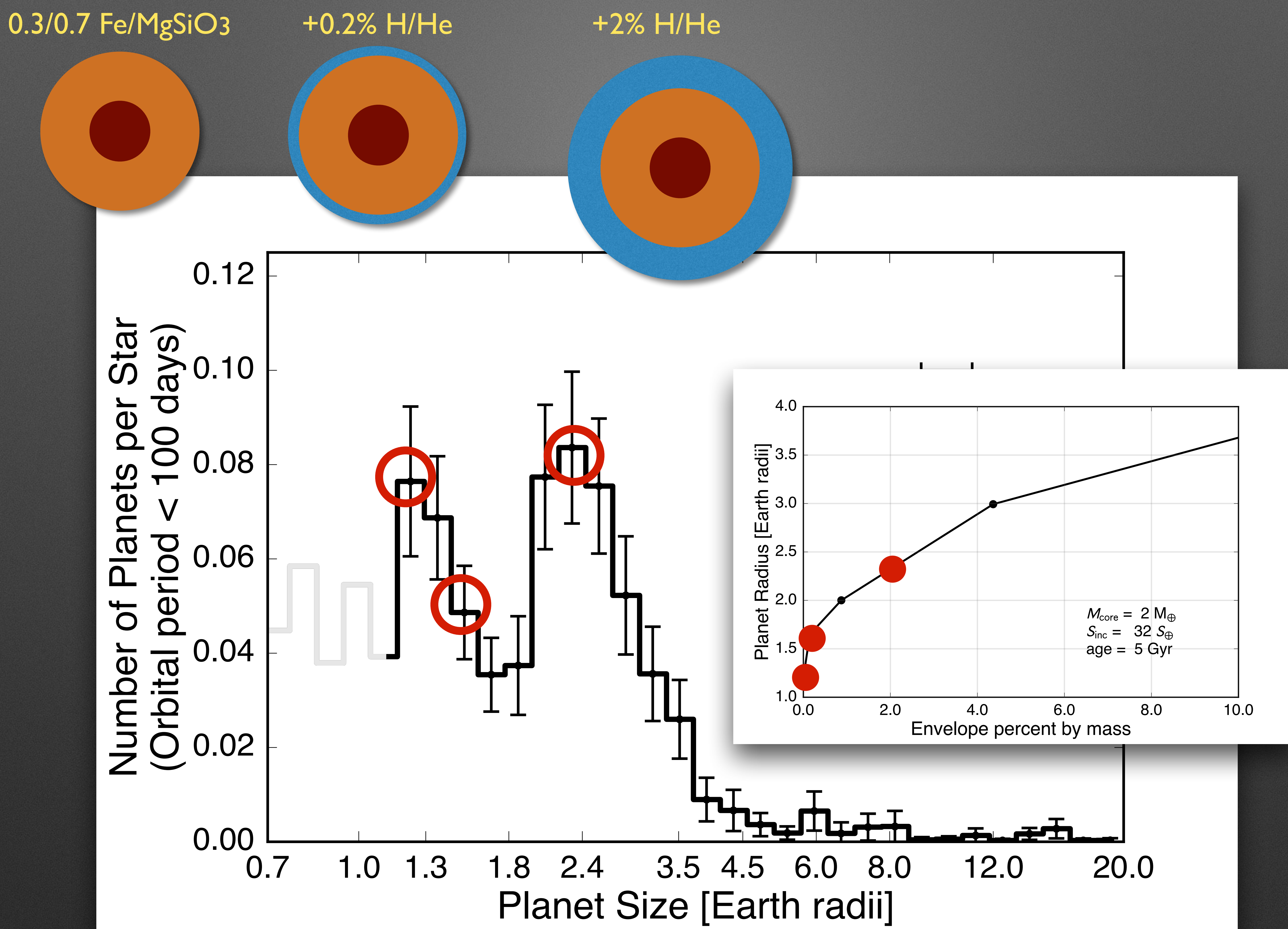

Fulton, Petigura, et al. (*submitted*)

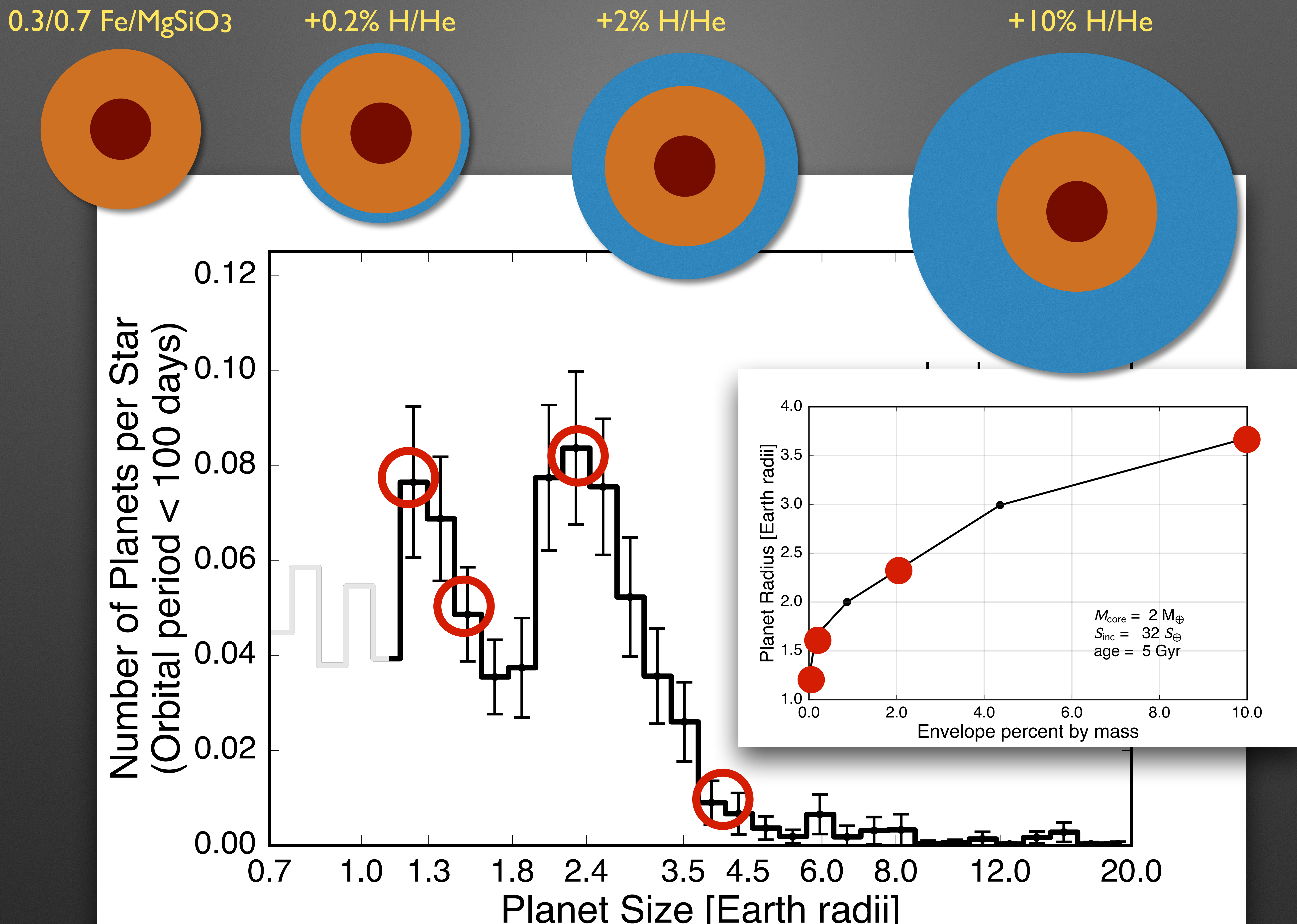




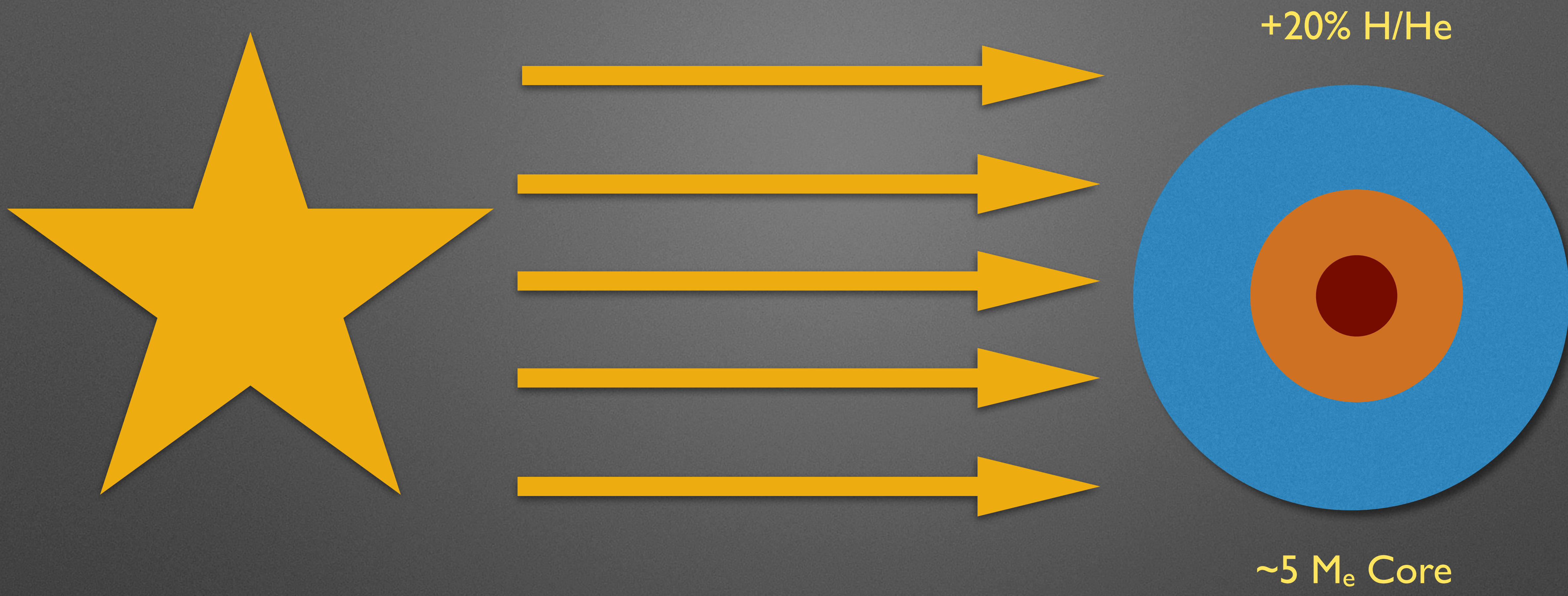

Fulton, Petigura, et al. (*submitted*)

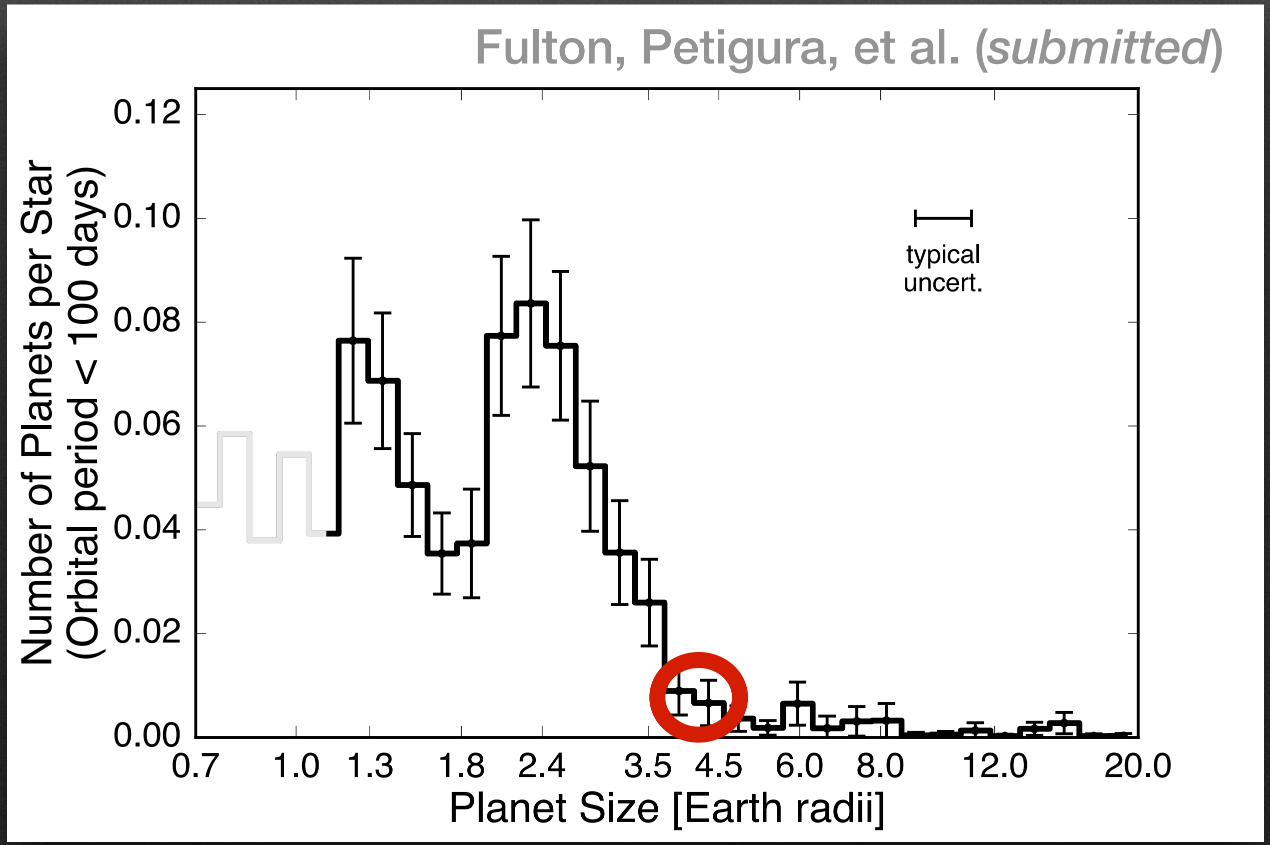

0.3/0.7 Fe/MgSiO3
+0.2% H/He
+2% H/He
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]
Planet Radius [Earth radii]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.0
2.0
4.0
6.0
8.0
10.0
Envelope percent by mass
$M_{core}$ = 2 $M_{\oplus}$
$S_{inc}$ = 32 $S_{\oplus}$
age = 5 Gyr





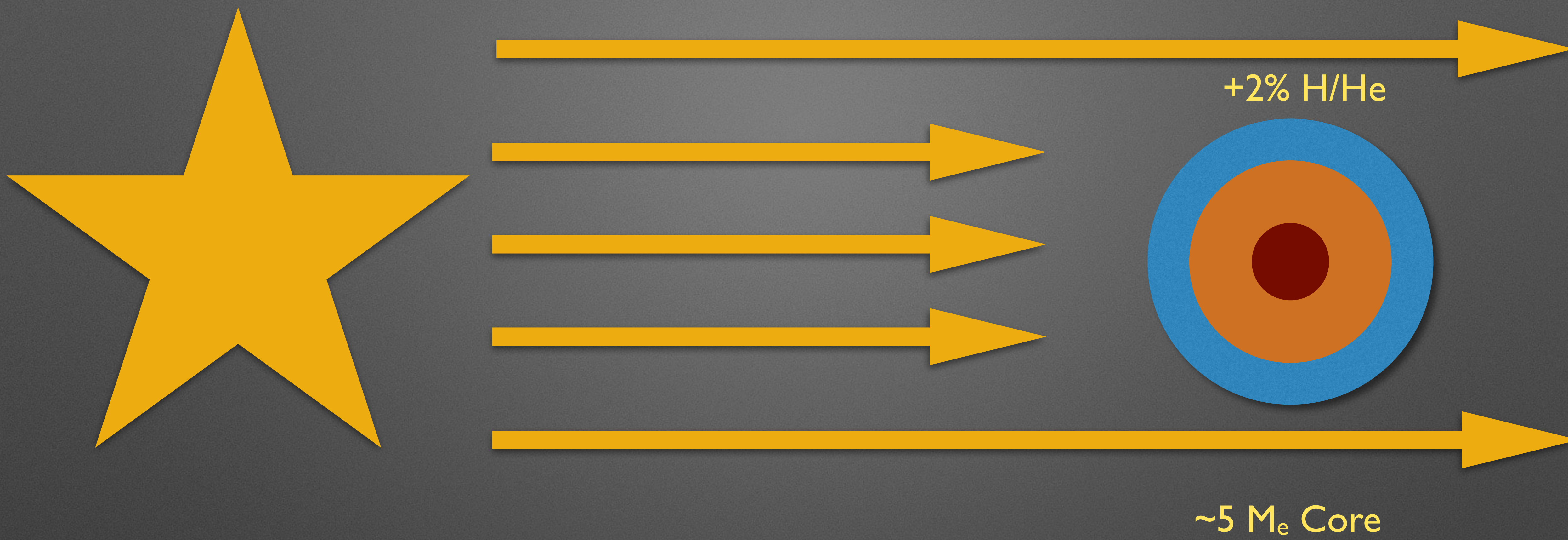

Fulton, Petigura, et al. (*submitted*)

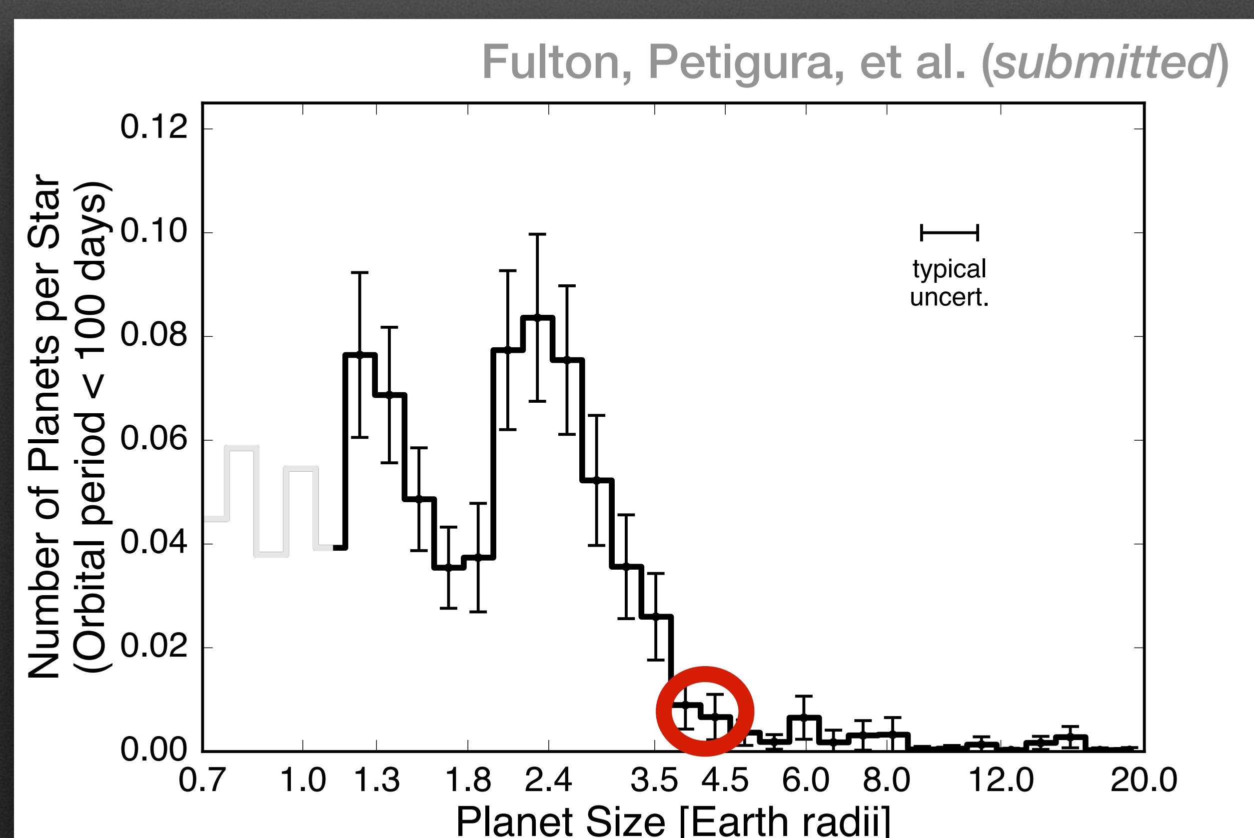


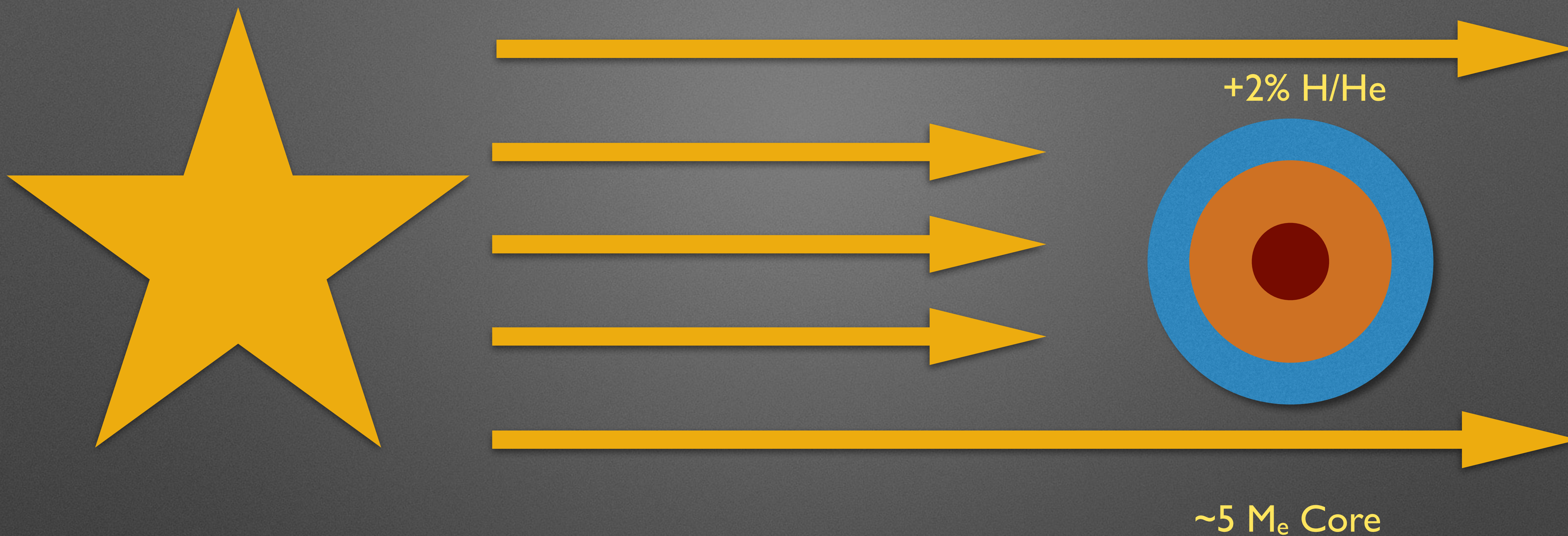



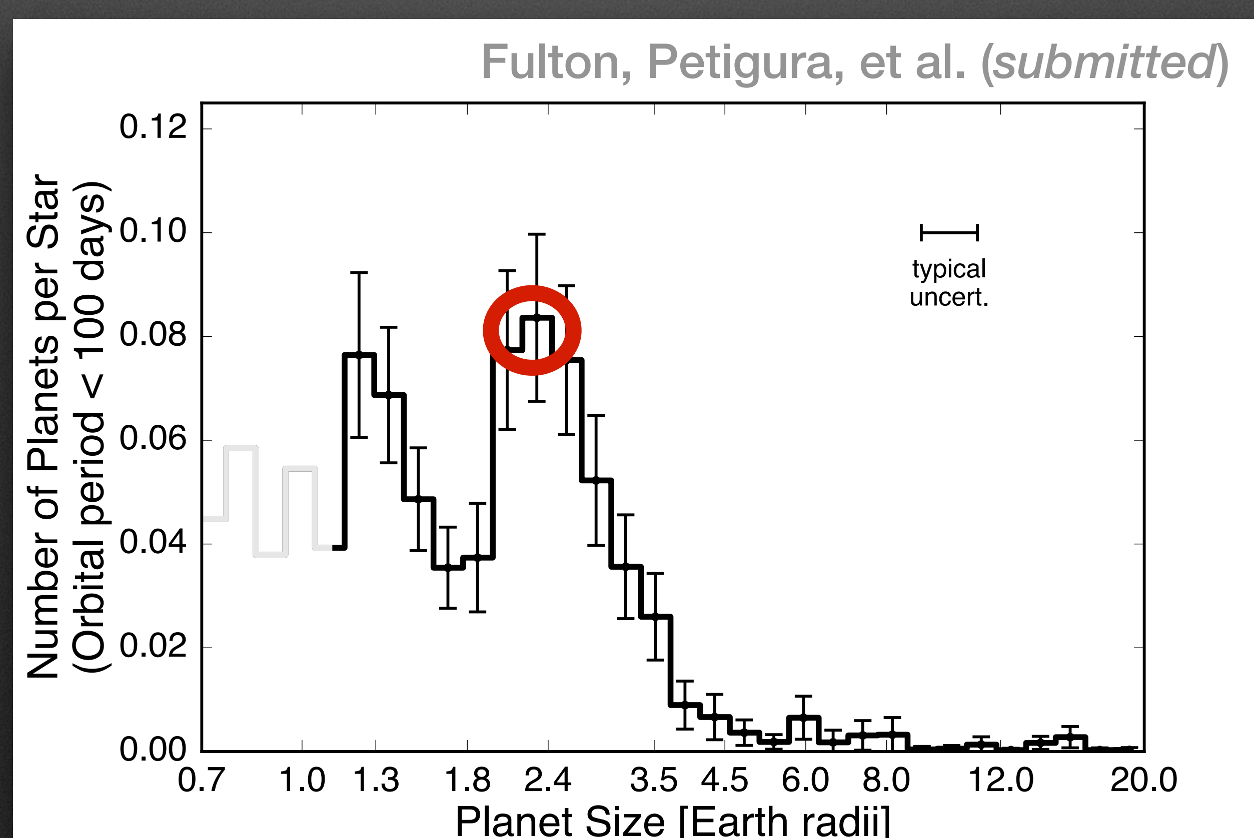

BJ Fulton

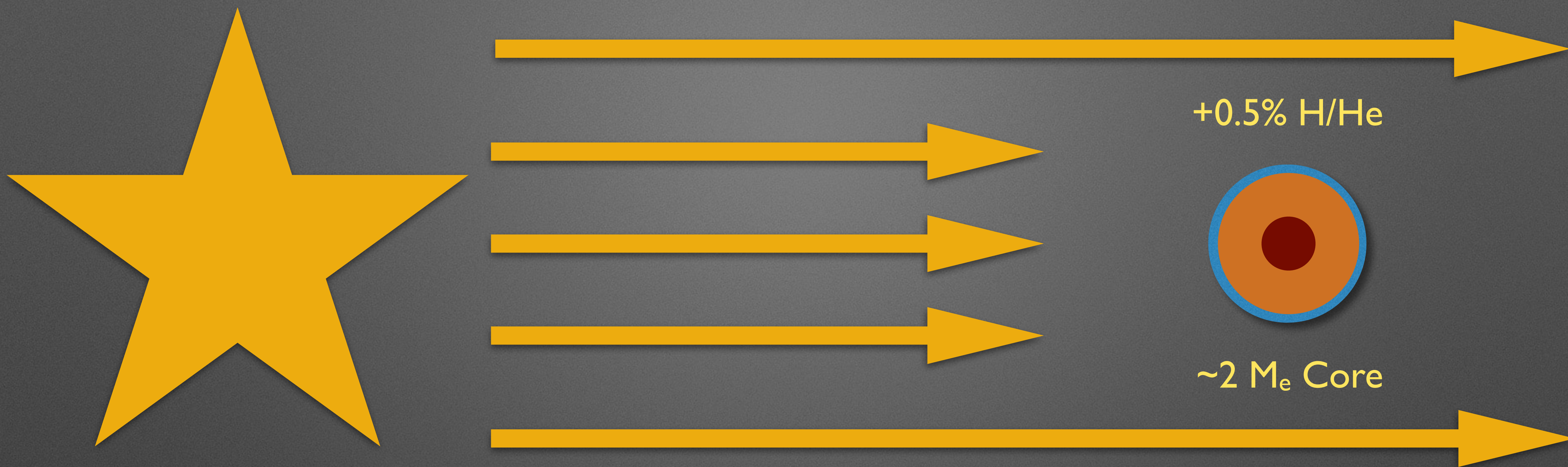
Aspen 2017


+2% H/He
~5 Mₑ Core

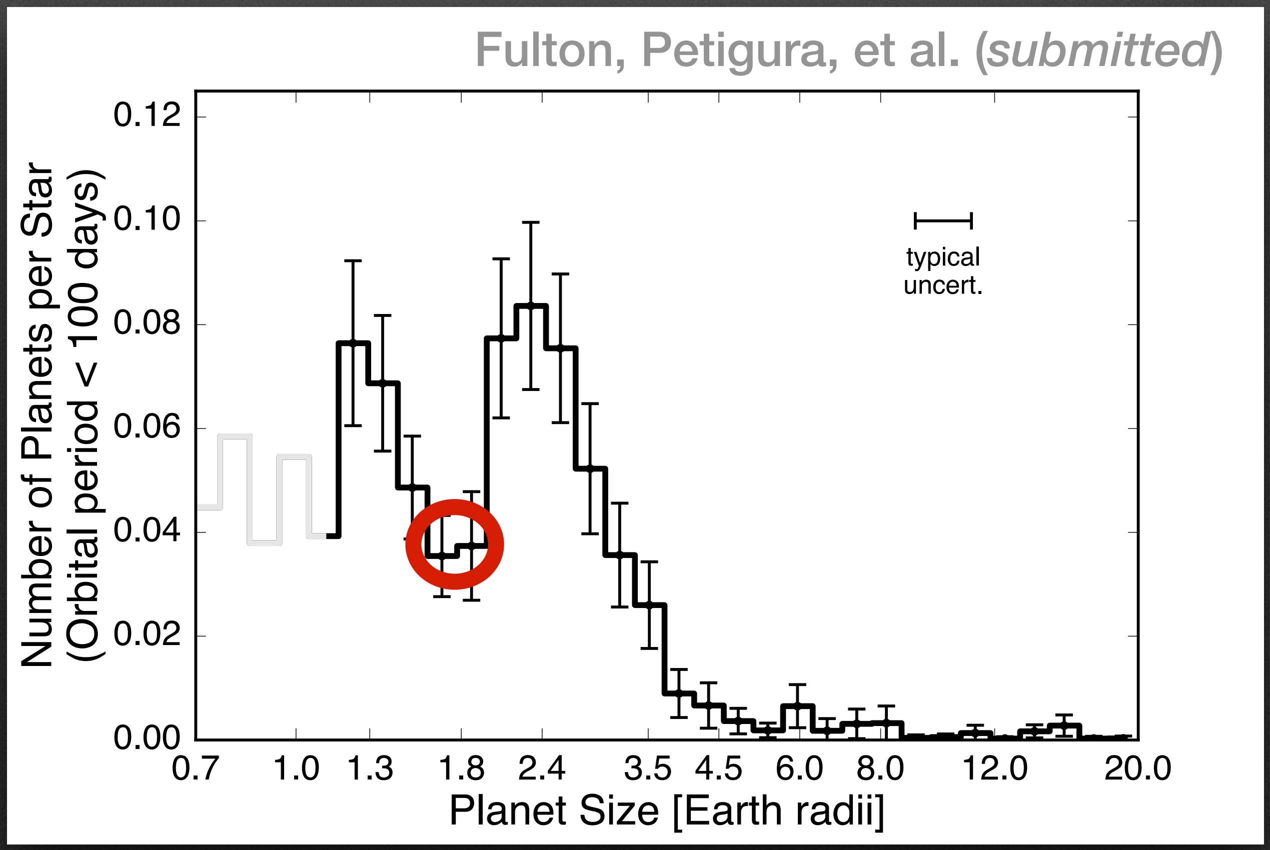

Fulton, Petigura, et al. (*submitted*)
typical
uncert.
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]


+2% H/He
~5 $M_e$ Core

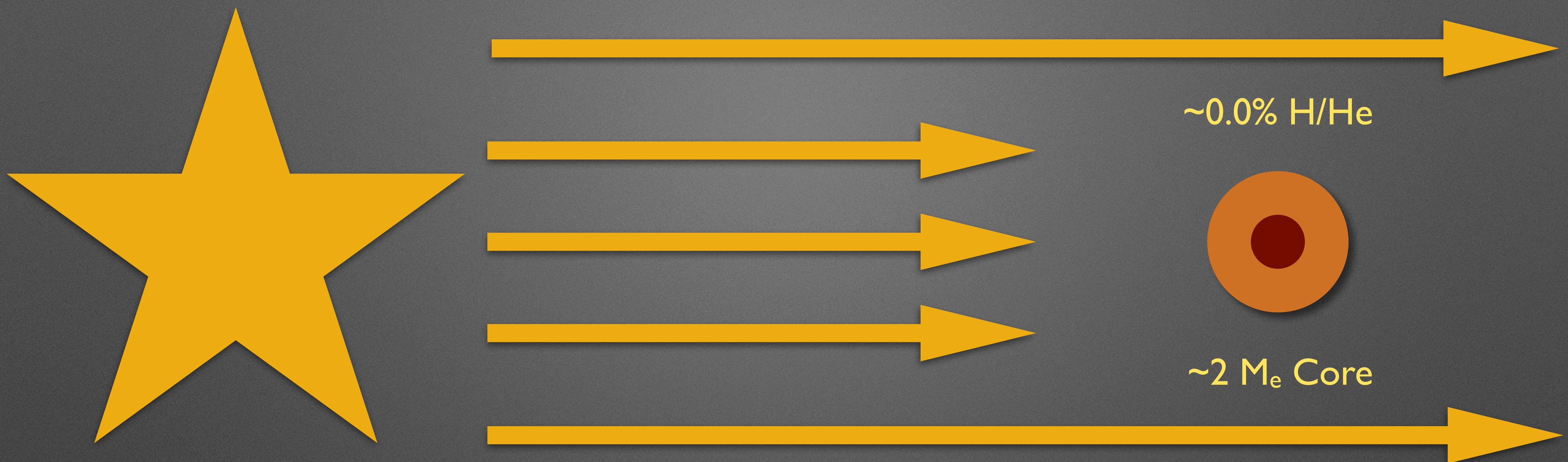

Fulton, Petigura, et al. (*submitted*)
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
typical
uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]

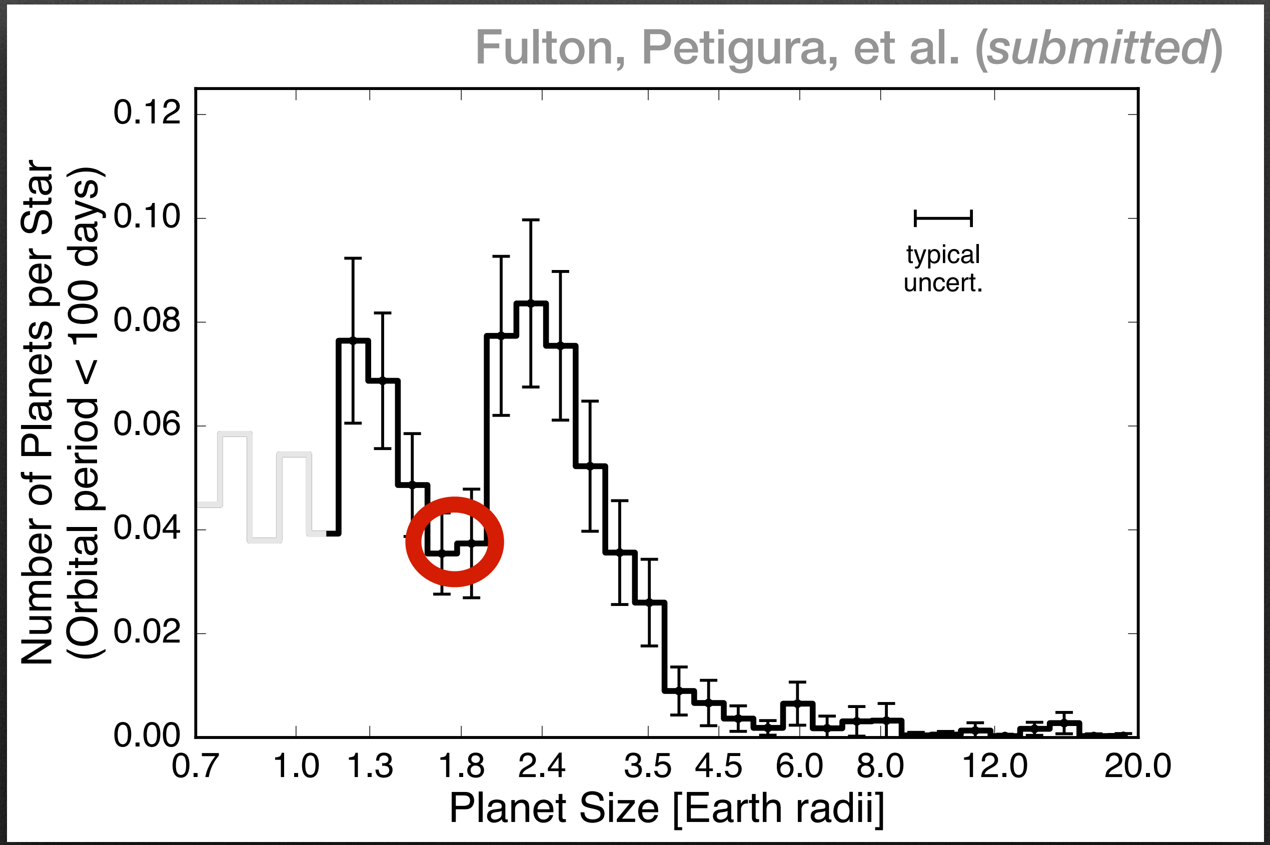


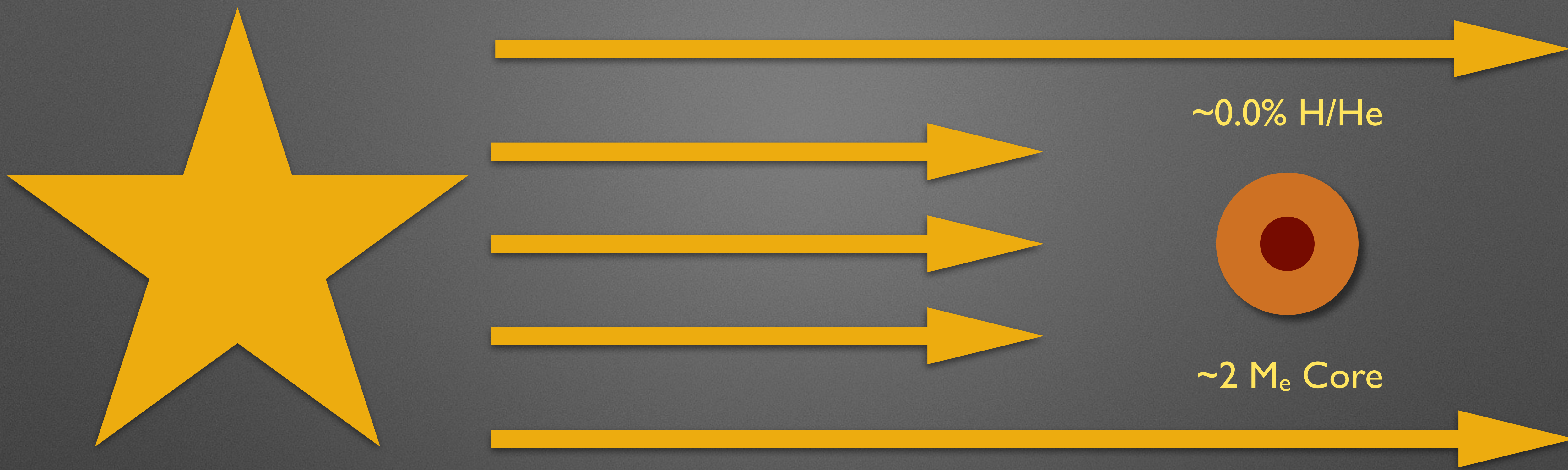
+0.5% H/He
~2 Mₑ Core

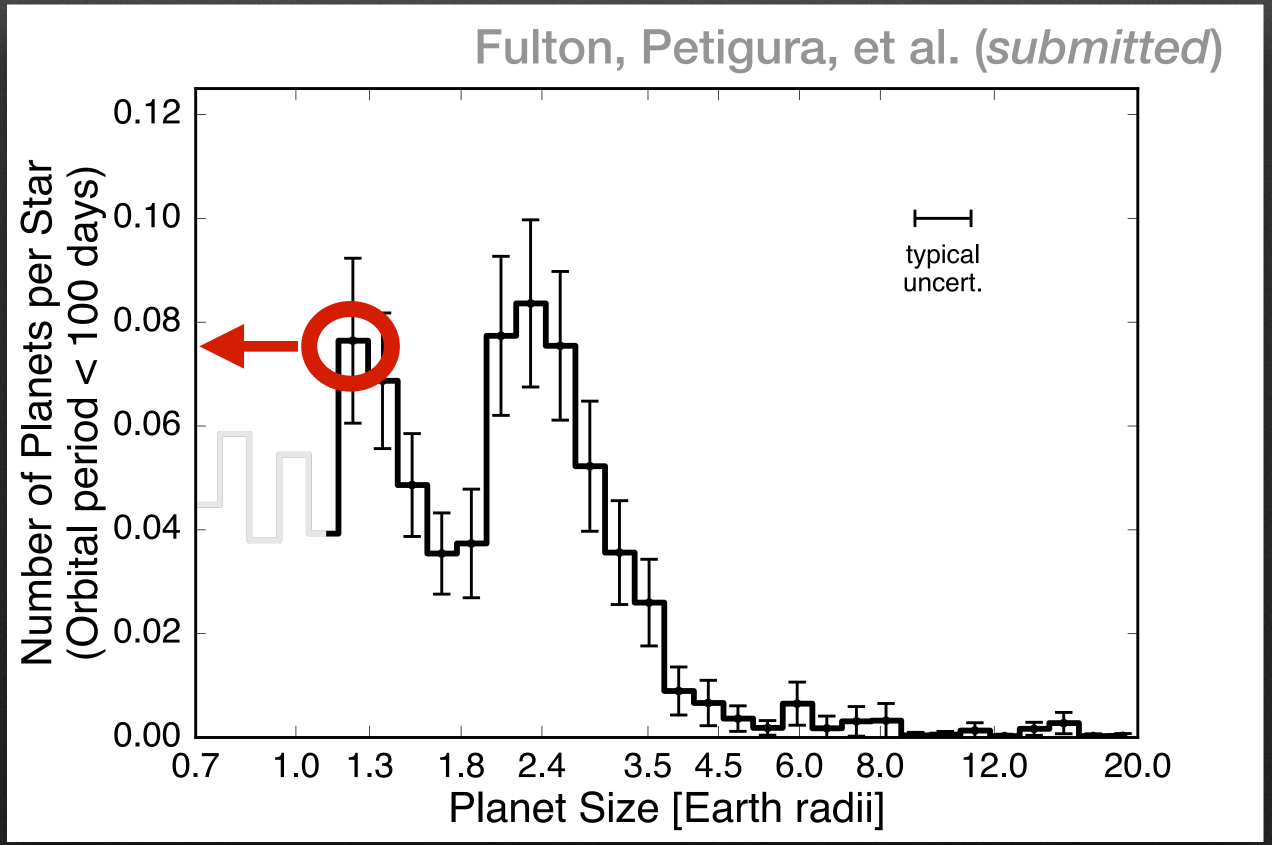



Fulton, Petigura, et al. (*submitted*)
Number of Planets per Star
(Orbital period < 100 days)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
typical
uncert.
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
12.0
20.0
Planet Size [Earth radii]

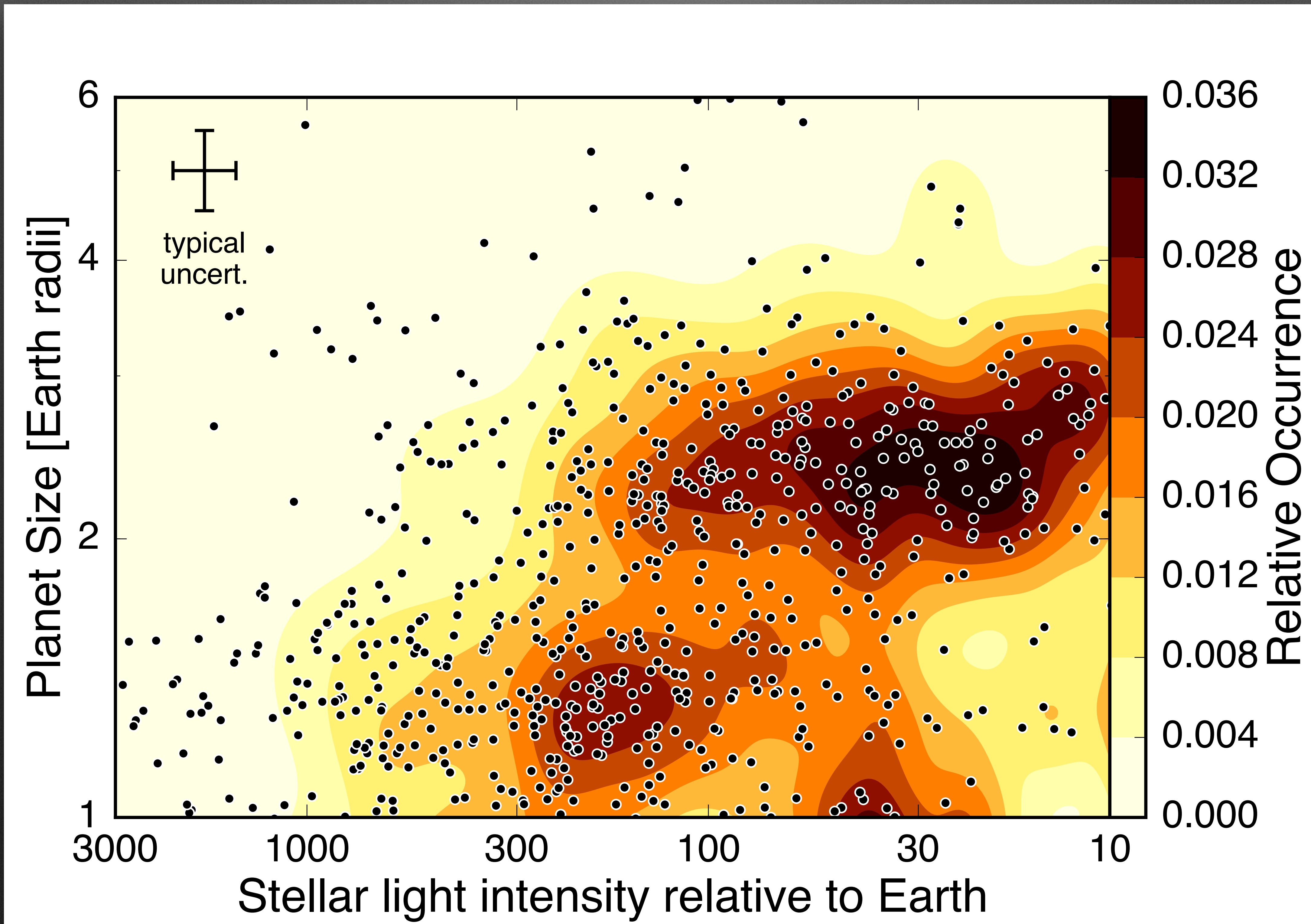

~0.0% H/He
~2 M$_e$ Core


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


~0.0% H/He
~2 $M_e$ Core


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

# Flux Dependency

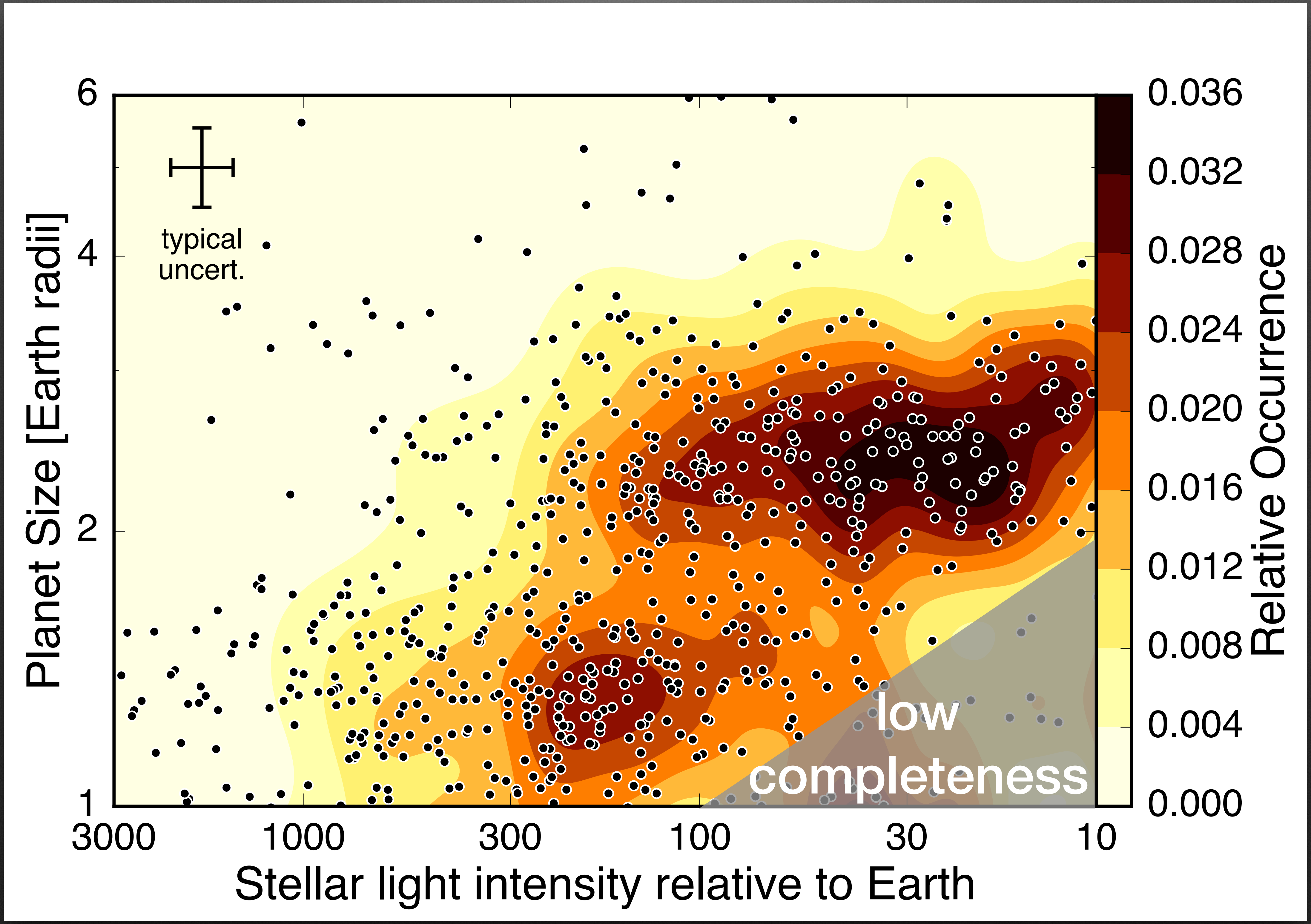



BJ Fulton

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

Aspen 2017

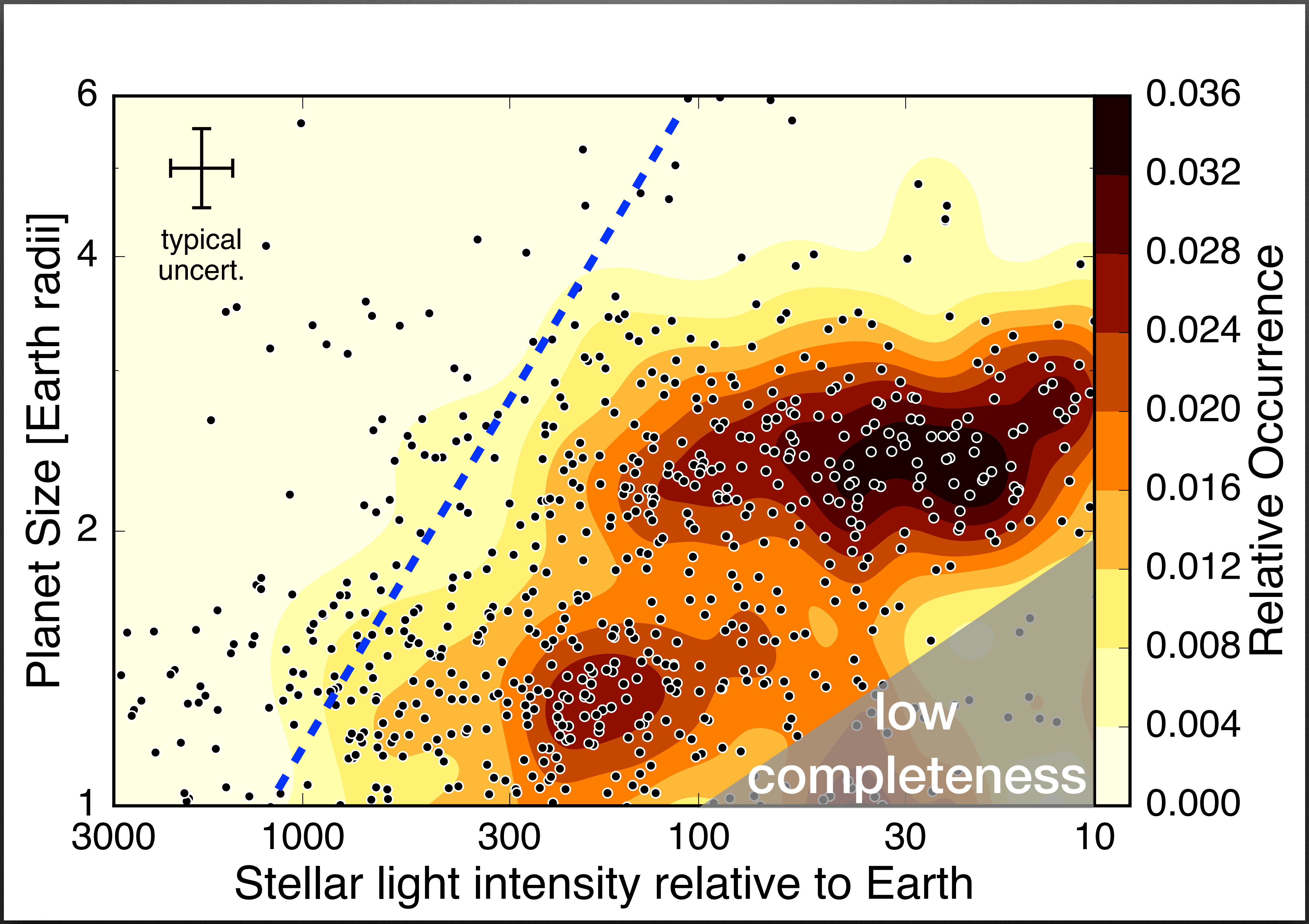
# Flux Dependency



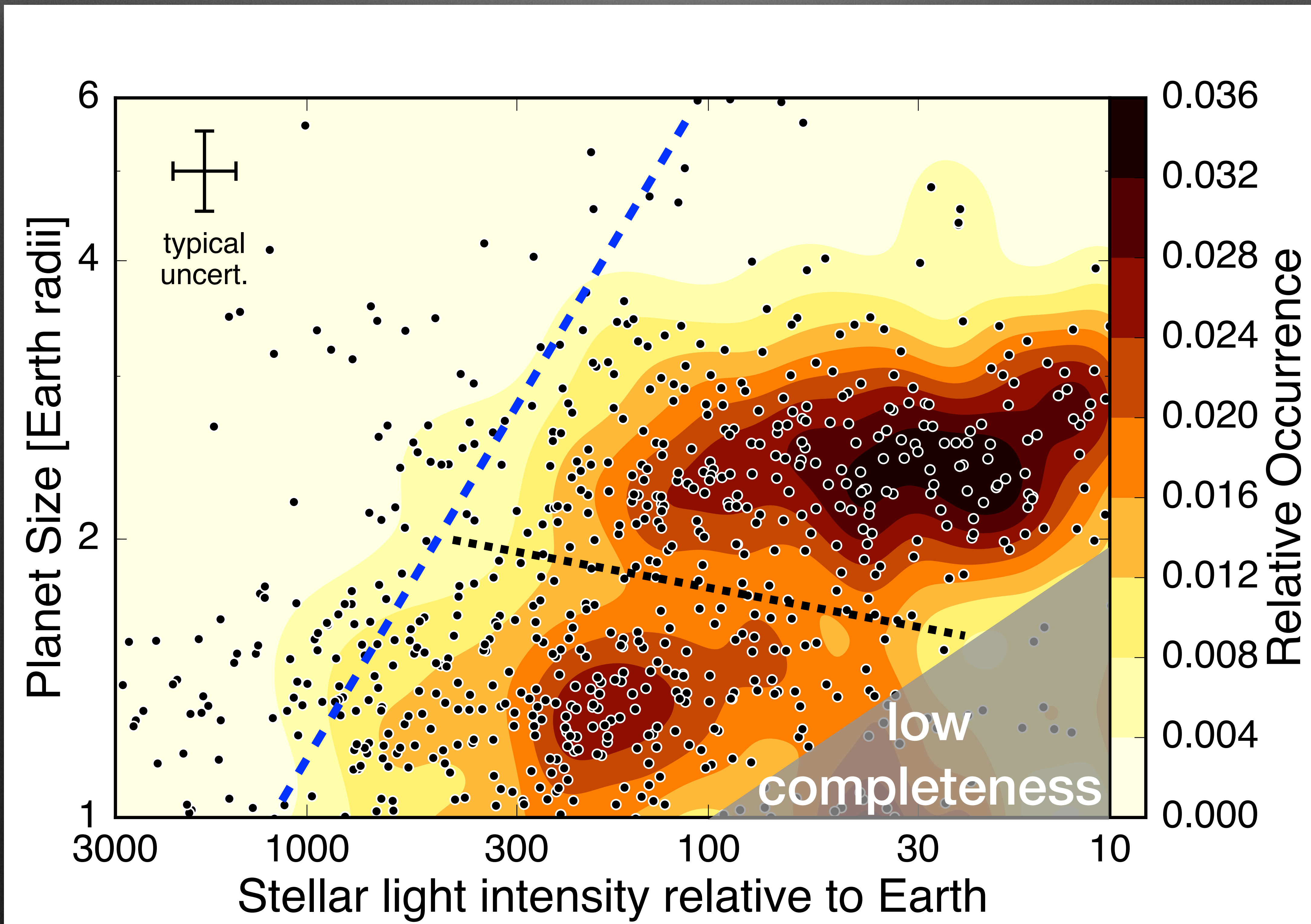



Fulton, Petigura, et al. (*submitted*)

# Flux Dependency



# Flux Dependency

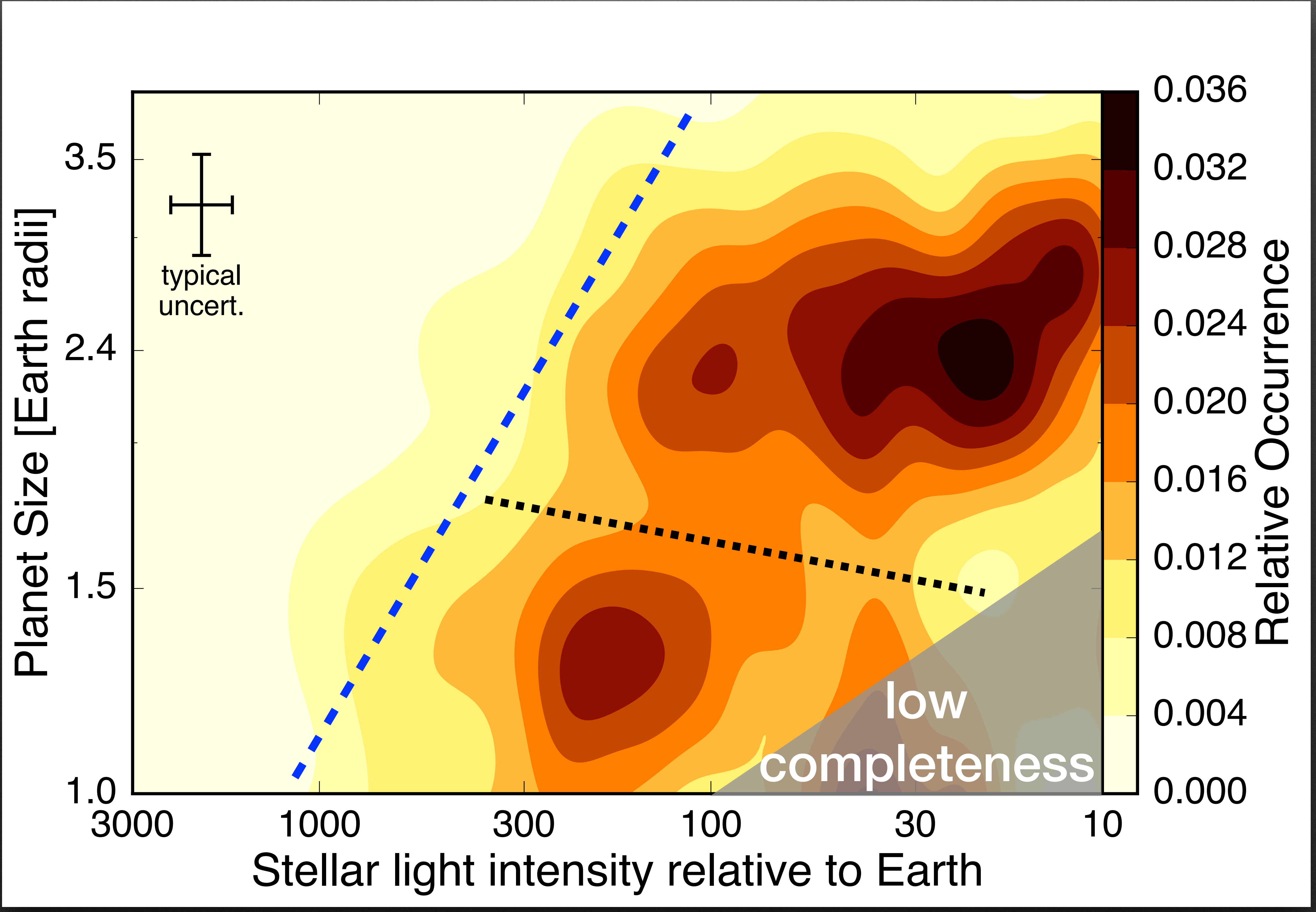



BJ Fulton

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

Aspen 2017

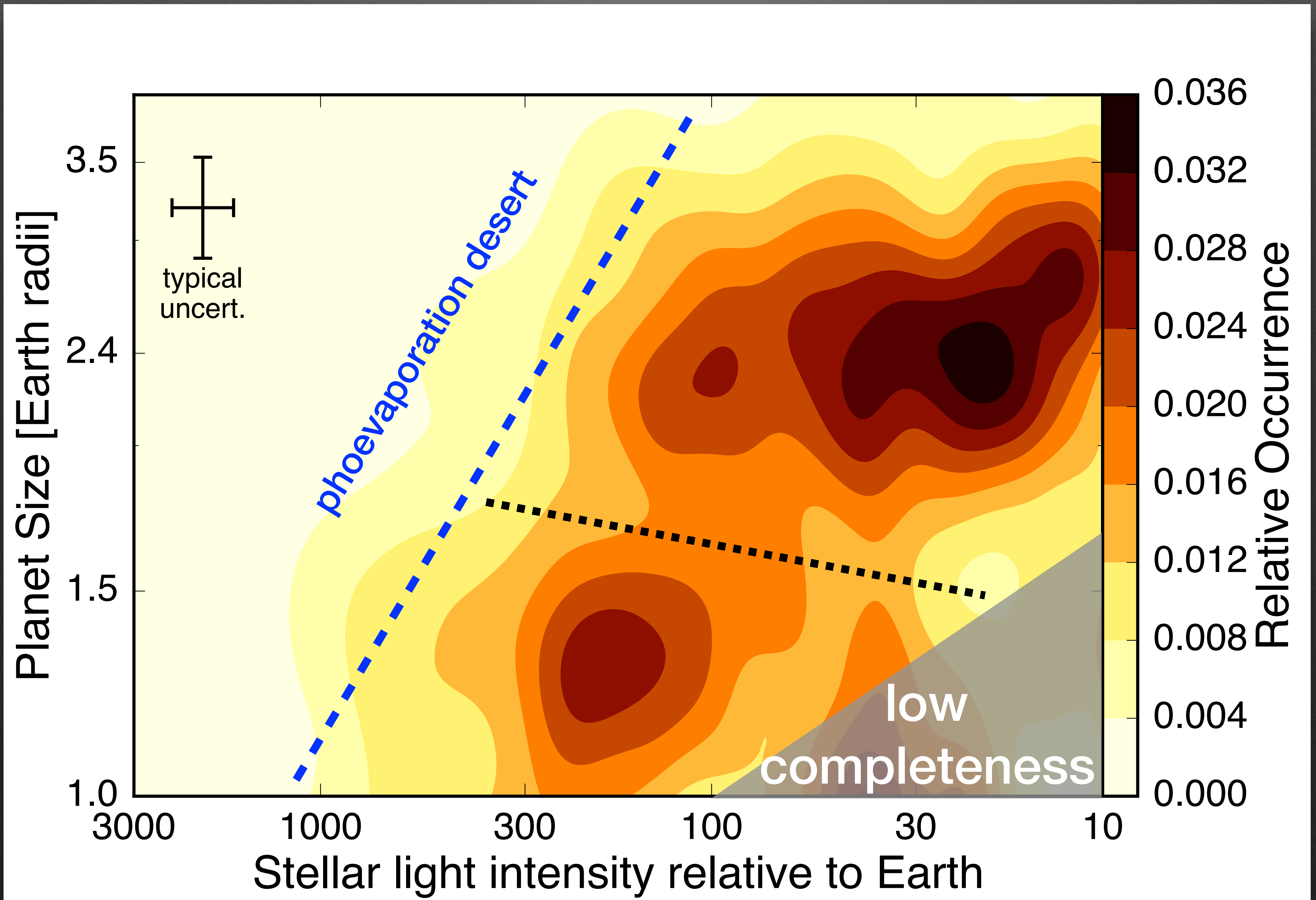
# Flux Dependency






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

# Flux Dependency

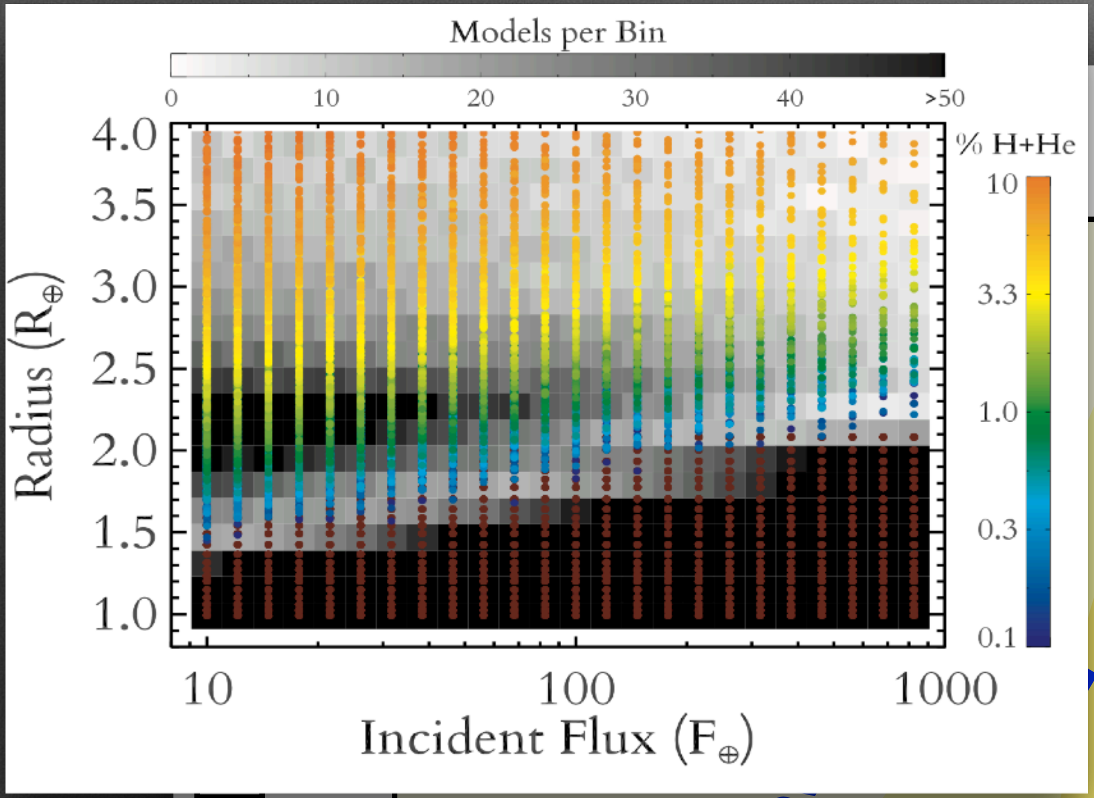


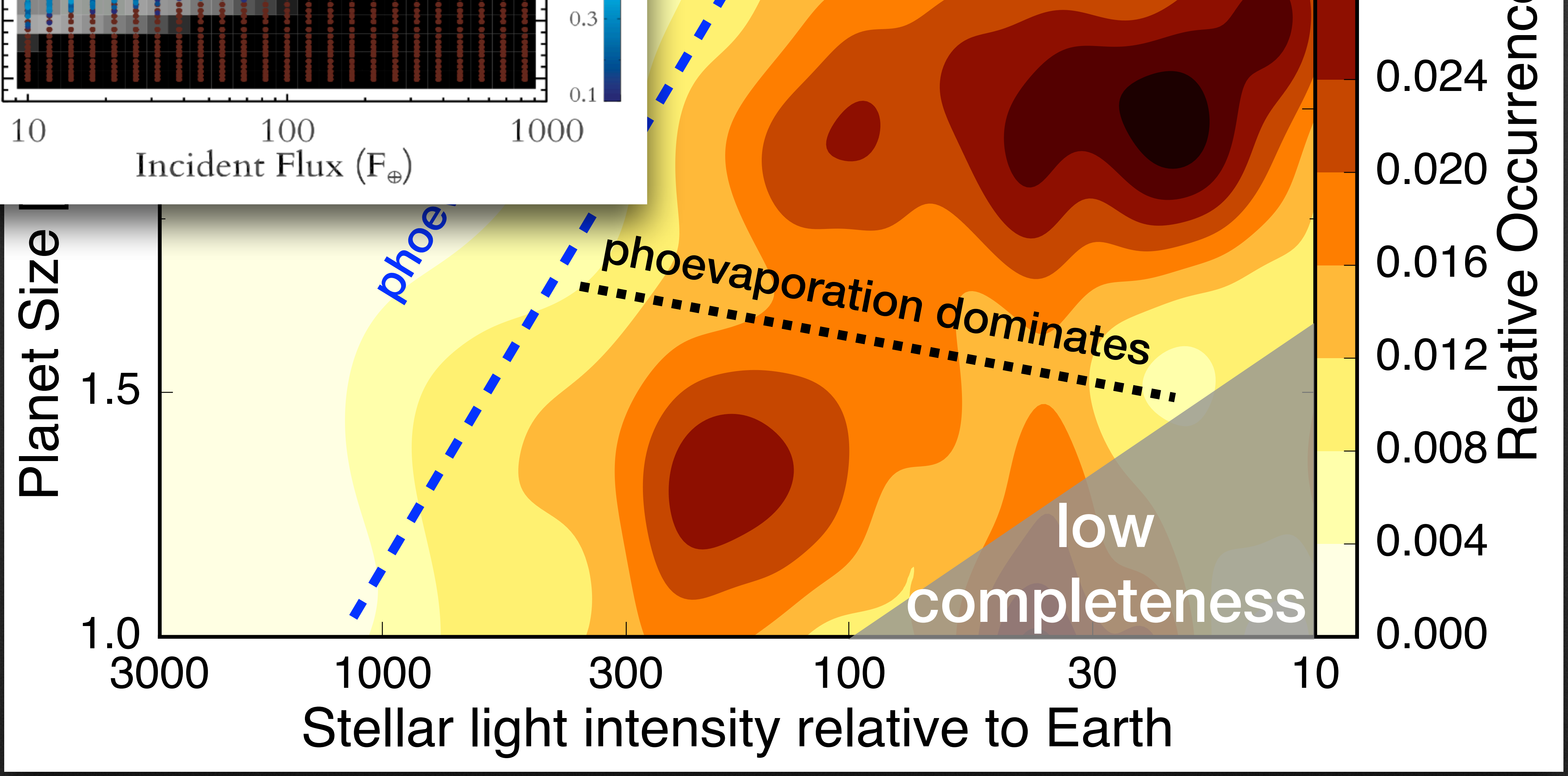



Fulton, Petigura, et al. (*submitted*)

# Flux Dependency

Lopez and Rice (2016)

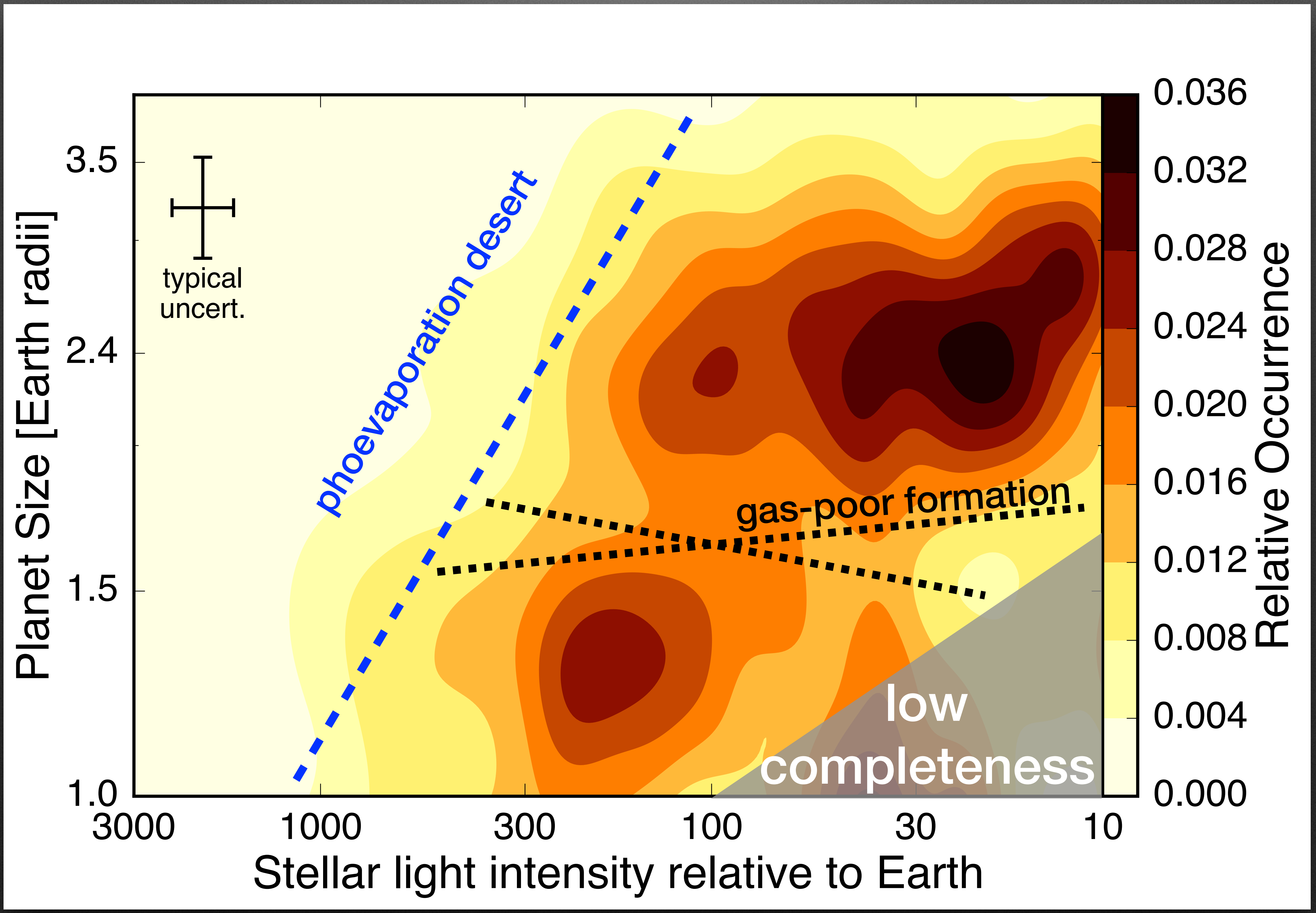





Fulton, Petigura, et al. (*submitted*)

# Flux Dependency

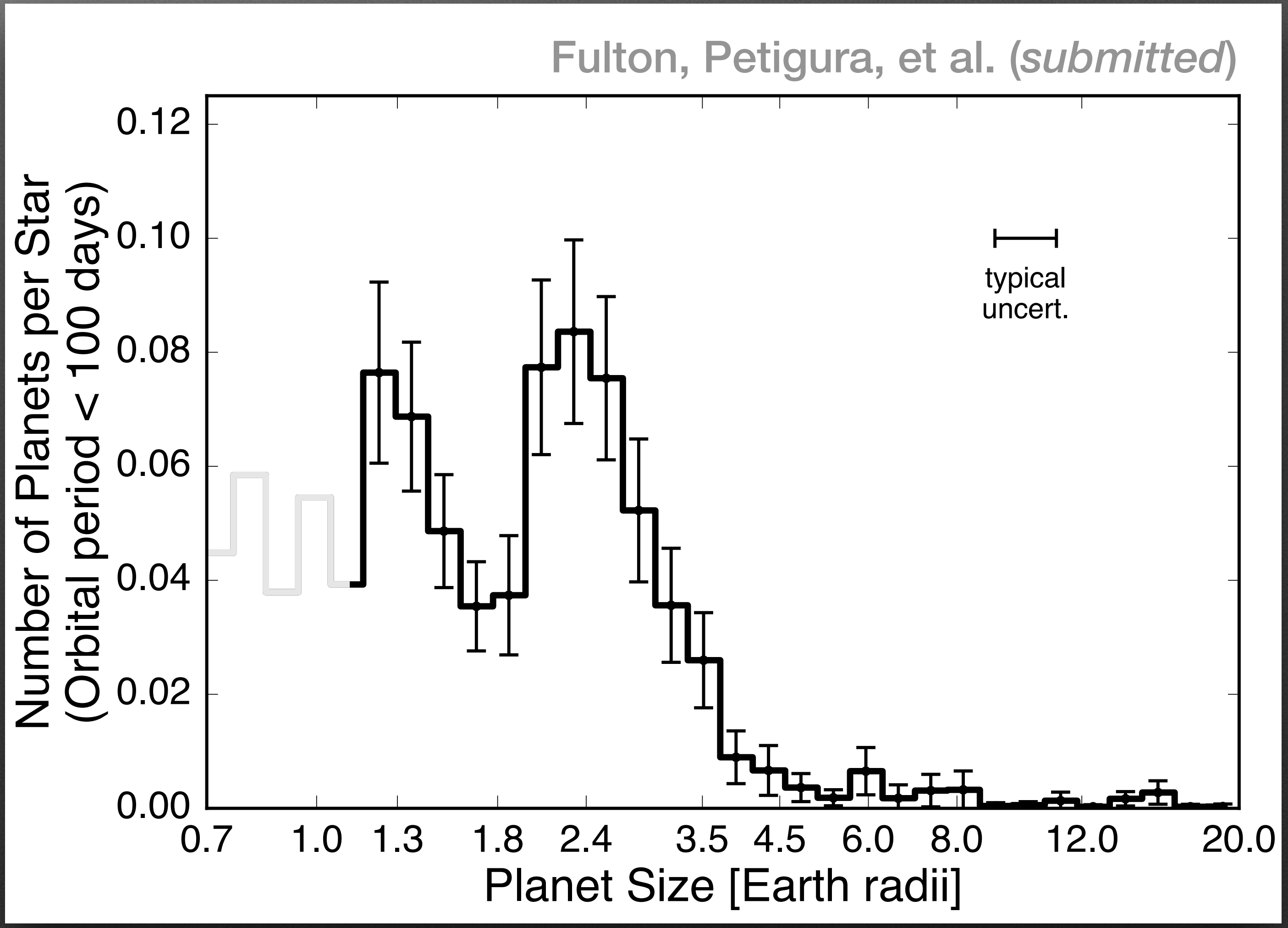





Fulton, Petigura, et al. (*submitted*)

# Summary

- Precision spectroscopy for 2025 KOIs
- This enables the detection of a gap in the radius distribution between 1.5—2.0 $R_e$
- Splits the population of small planets into two size classes with typical radii of either ≤1.3 $R_e$ or 2.4 $R_e$
- Close-in planets smaller than Neptune are composed of rocky cores measuring 1.5 $R_e$ or smaller with varying amounts of low-density gas




CKS I: (arXiv:1703.10400)
CKS II: (arXiv:1703.10402)
**CKS III: (arXiv:1703.10375)**

# Backup Slides

# Completeness Corrections

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

# Completeness Corrections

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

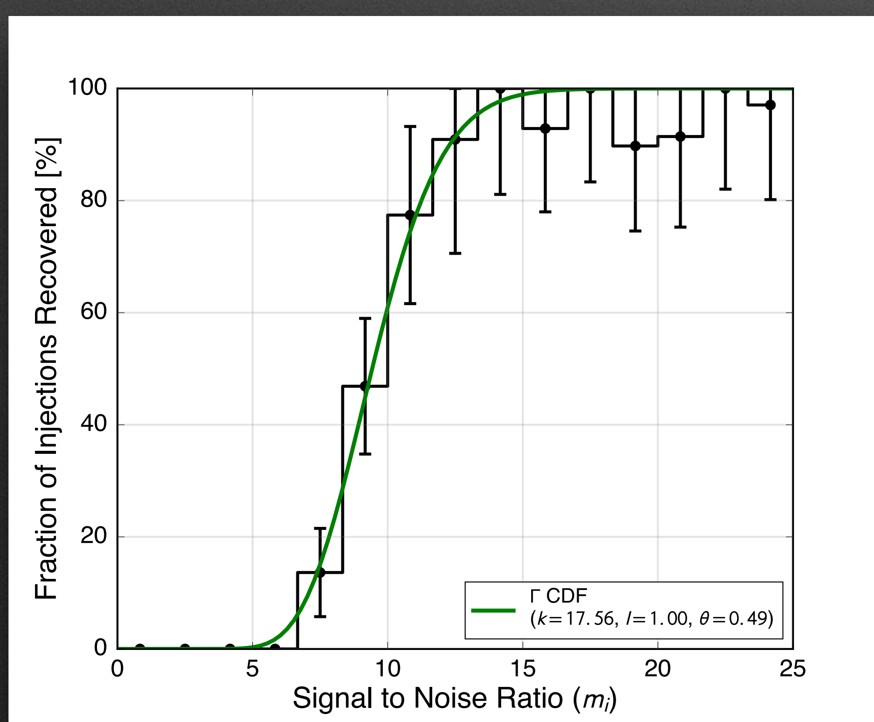
$$m_i = \left(\frac{R_P}{R_{\star,i}}\right)^2 \sqrt{\frac{T_{{\rm obs},i}}{P}} \left(\frac{1}{{\rm CDPP}_{{\rm dur},i}}\right)$$

# Completeness Corrections

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

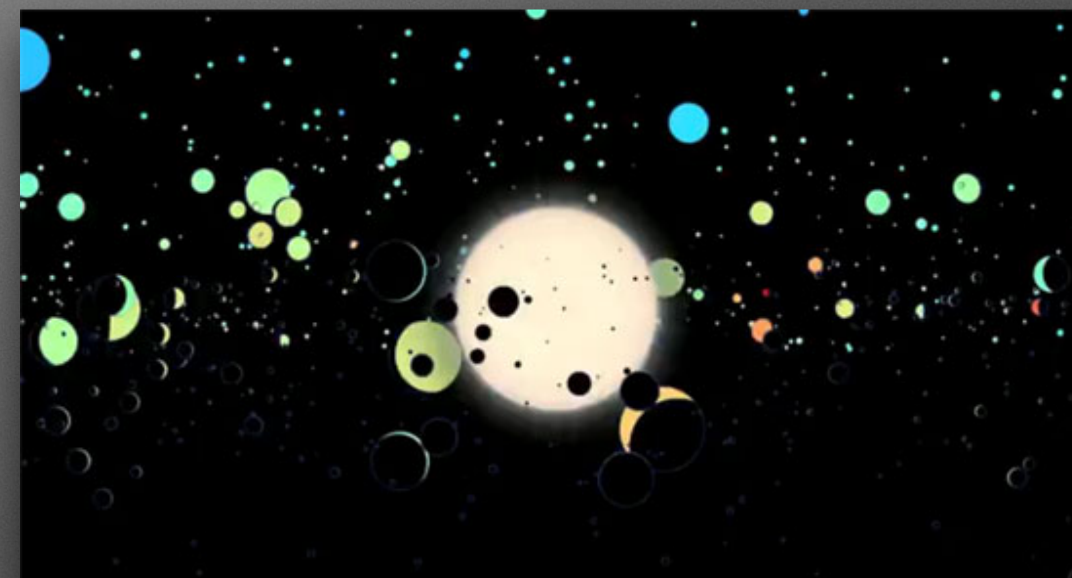
$$m_i = \left(\frac{R_P}{R_{\star,i}}\right)^2 \sqrt{\frac{T_{\mathrm{obs},i}}{P}} \left(\frac{1}{\mathrm{CDPP}_{\mathrm{dur},i}}\right)$$

+



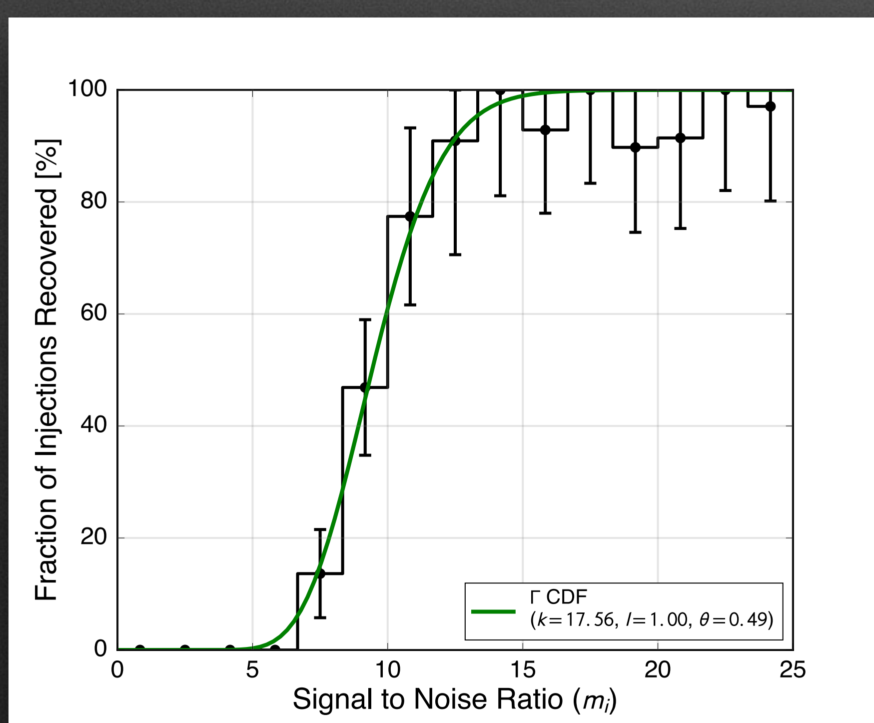
# Completeness Corrections

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

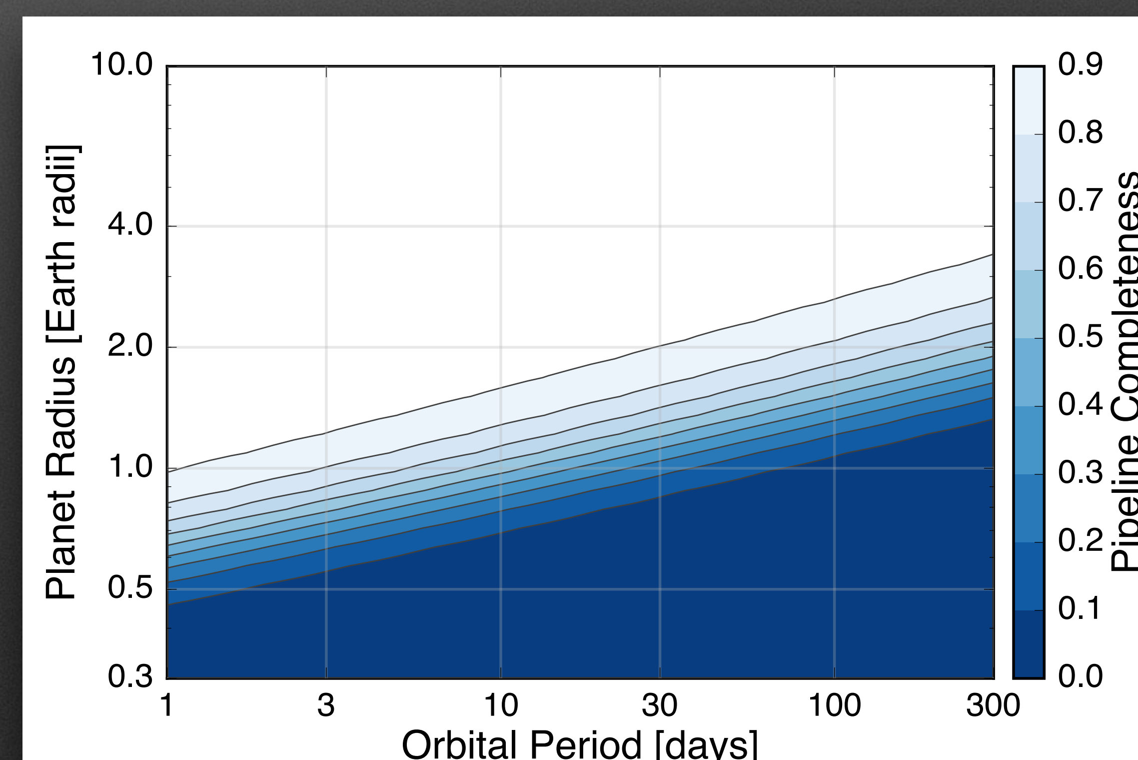


$$m_i = \left(\frac{R_P}{R_{\star,i}}\right)^2 \sqrt{\frac{T_{{\rm obs},i}}{P}} \left(\frac{1}{{\rm CDPP}_{{\rm dur},i}}\right)$$

+




=






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

# Completeness Corrections

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

# Completeness Corrections

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

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

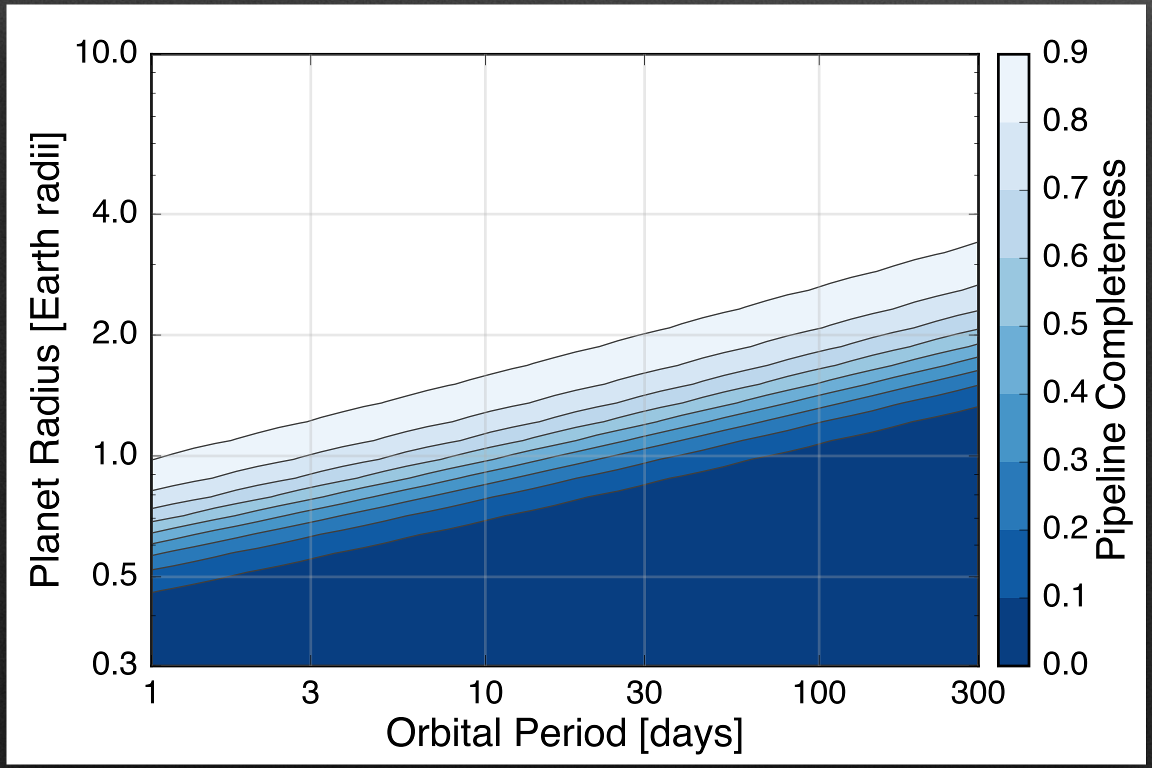
+

# Completeness Corrections

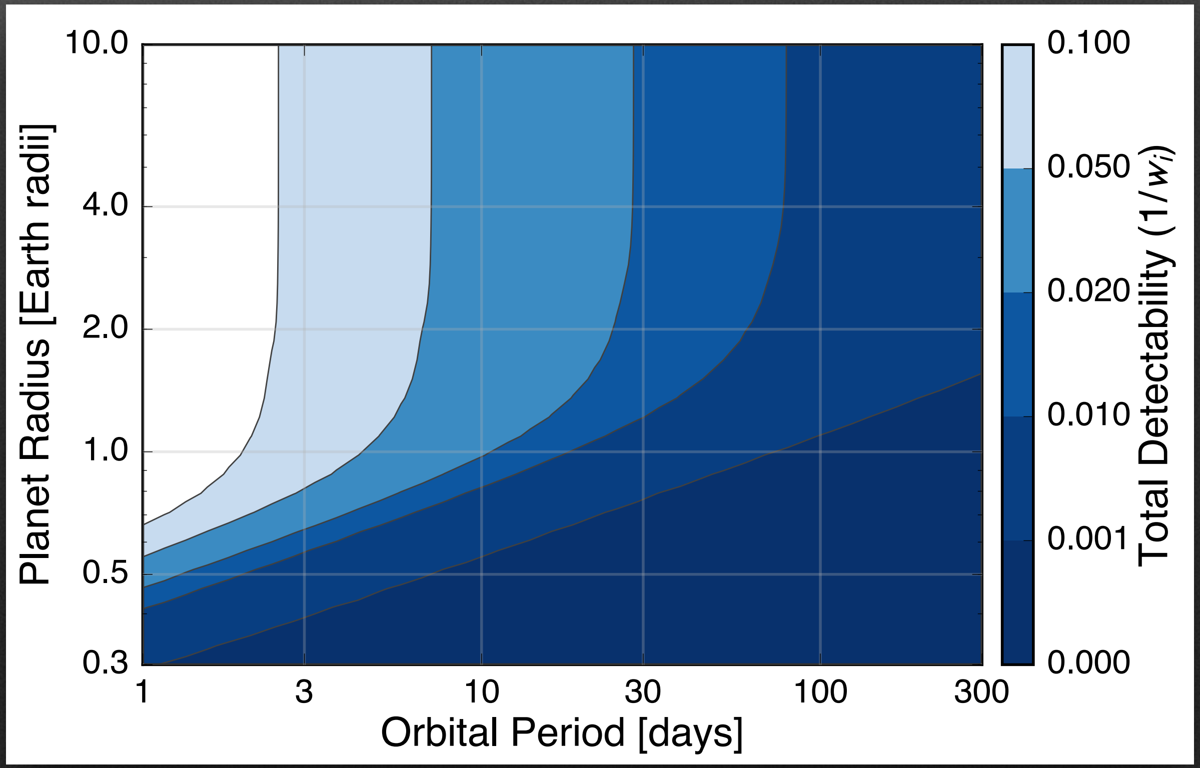
$$w_i = \frac{1}{(p_{\mathrm{det}} \cdot p_{\mathrm{tr}})}$$

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

+




=





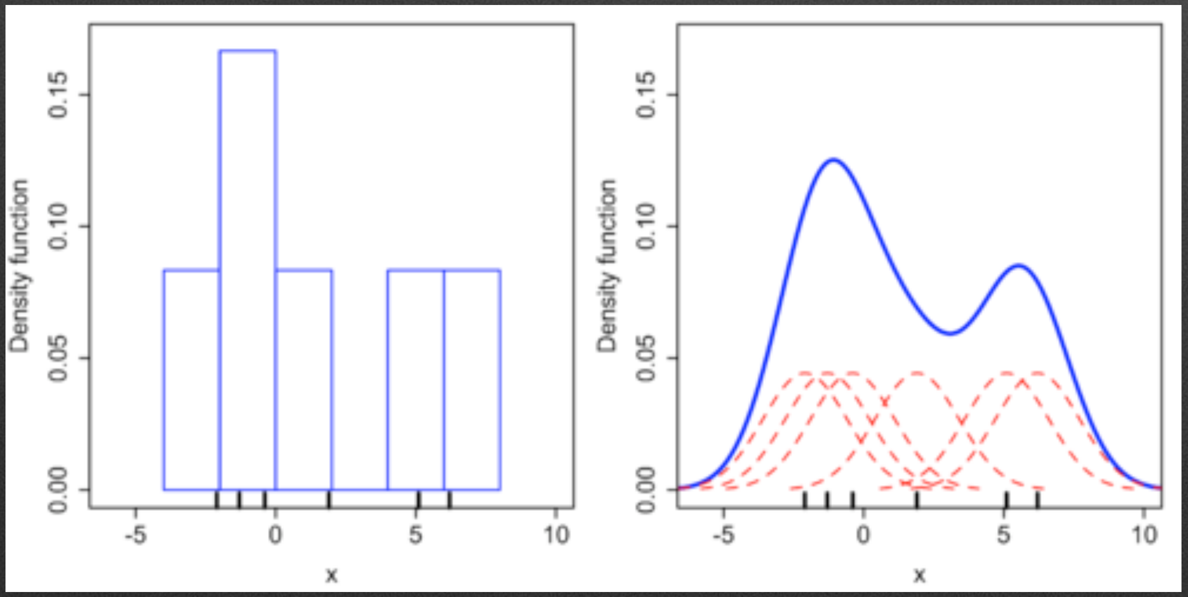

Fulton, Petigura, et al. (*submitted*)

# Completeness Corrections

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

Number of Planets per Star =

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

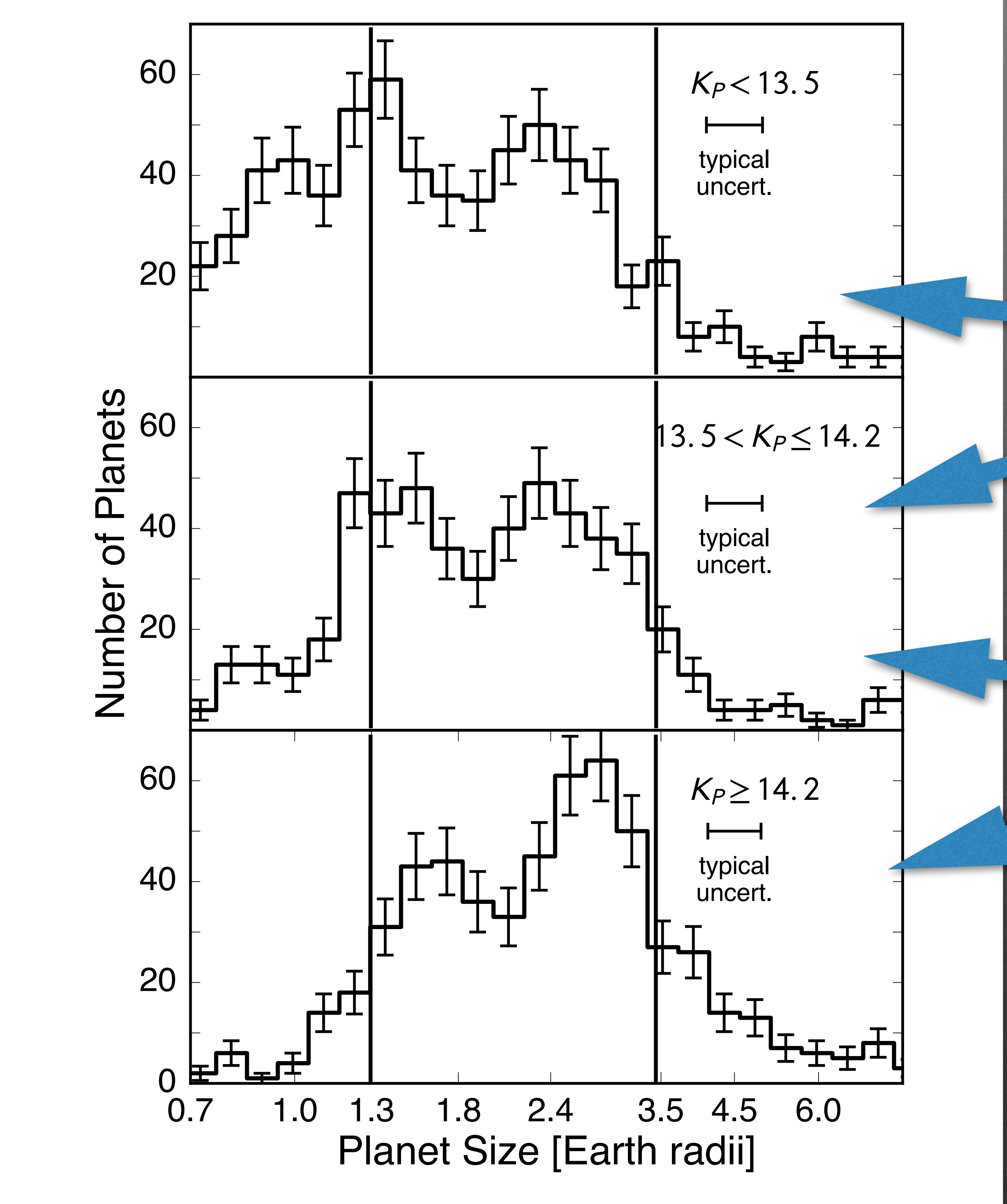



$$\phi(x) = \frac{1}{N_\star} \sum_{i=1}^{n_{\rm pl}} w_i \cdot K(x - x_i, \sigma_{x,i})$$



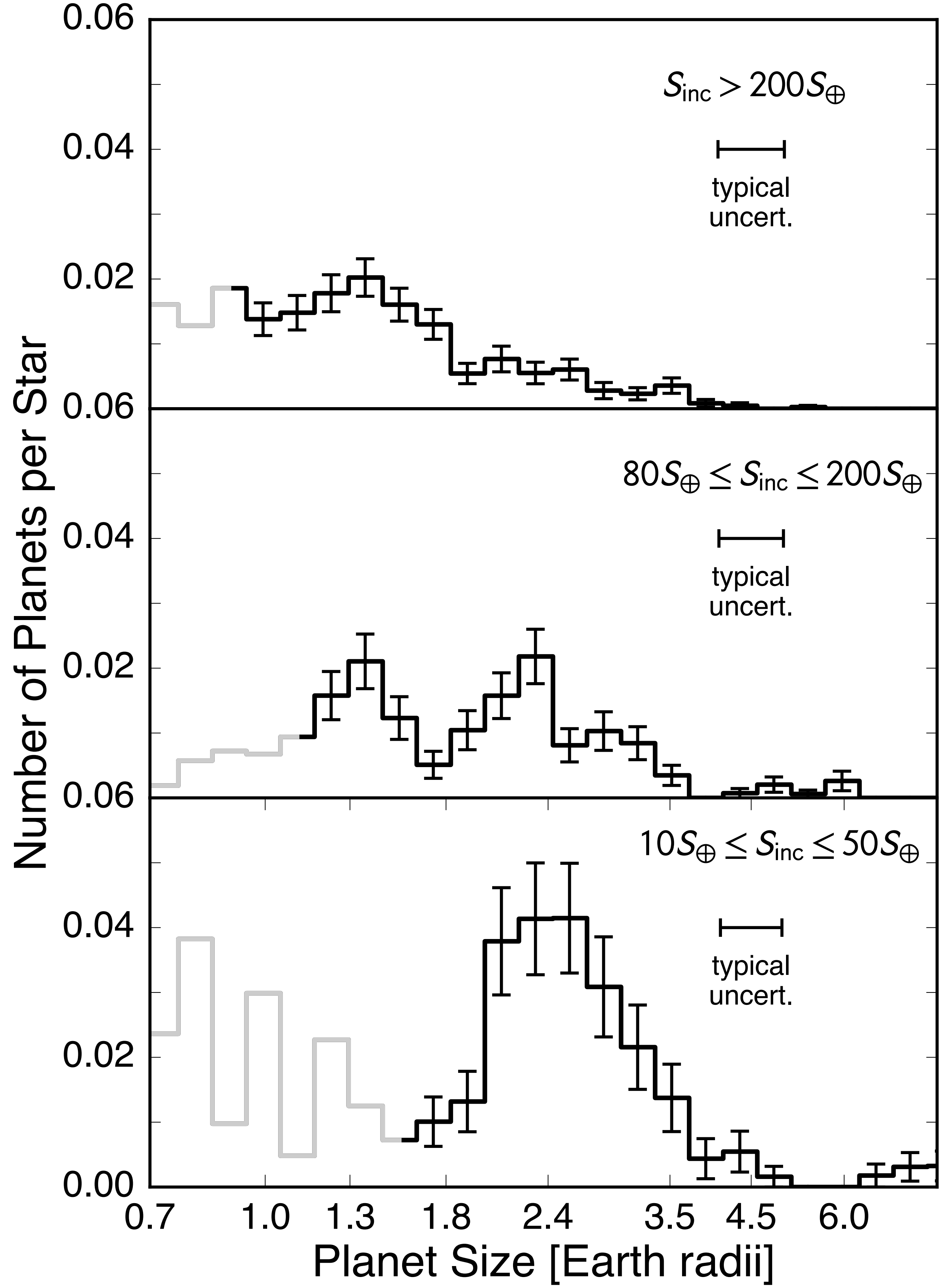
Fulton, Petigura, et al. (*submitted*)

# Magnitude Cuts

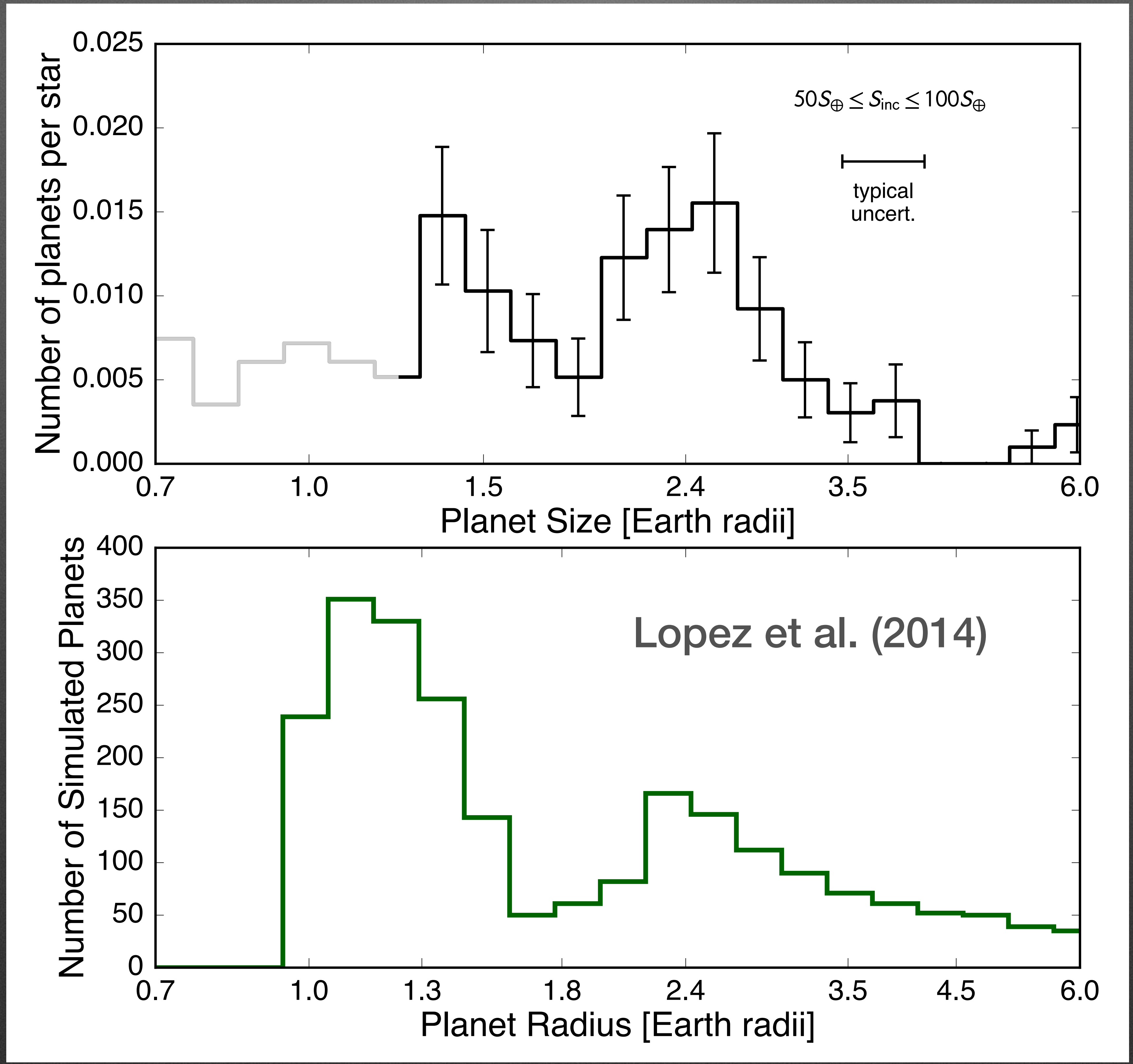



Consistent
(97% confidence)

Not consistent



Number of Planets per Star
Planet Size [Earth radii]
$S_{inc} > 200 S_\oplus$
$80 S_\oplus \leq S_{inc} \leq 200 S_\oplus$
$10 S_\oplus \leq S_{inc} \leq 50 S_\oplus$
typical uncert.
typical uncert.
typical uncert.
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

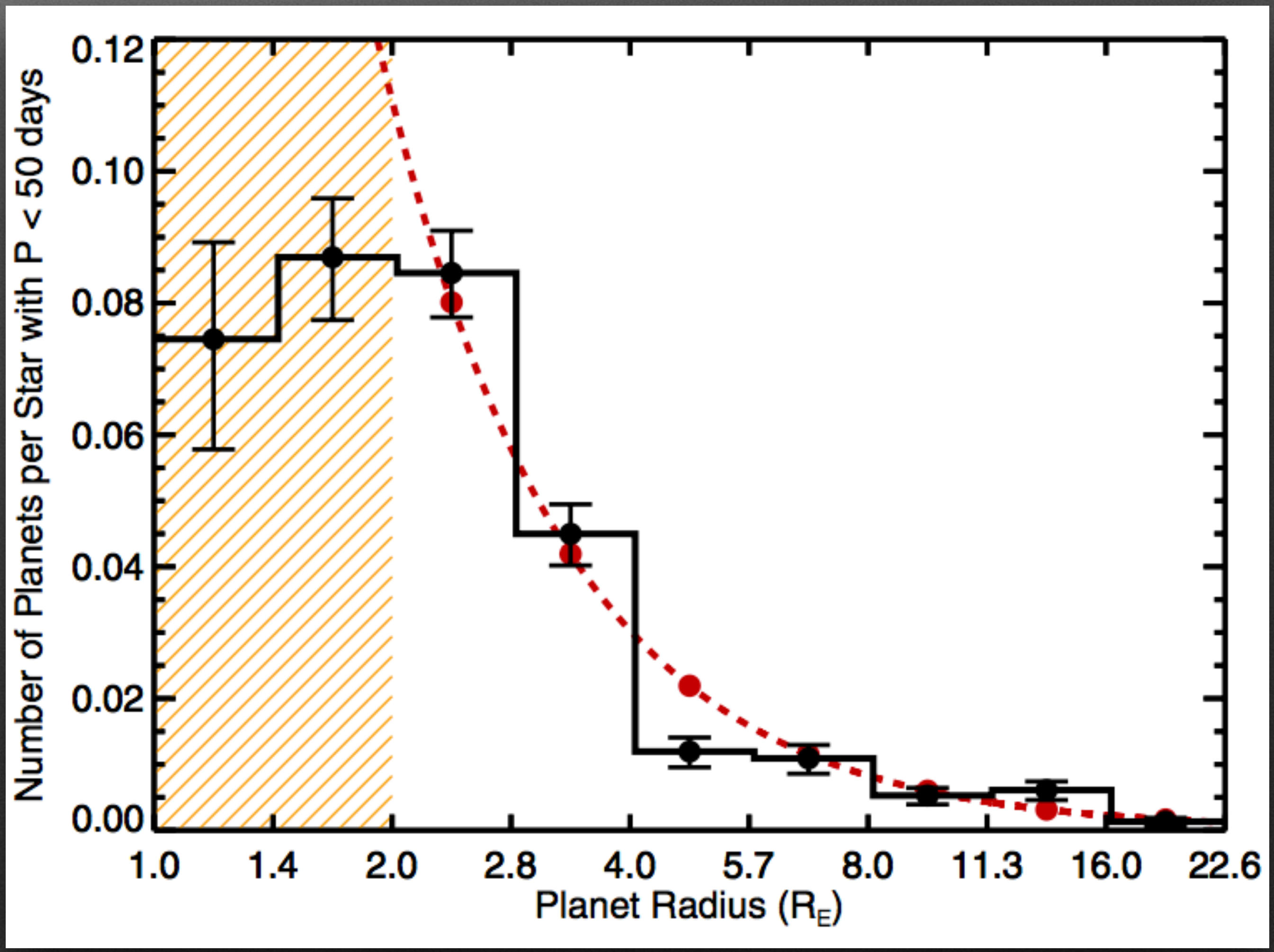


Number of planets per star
0.025
0.020
0.015
0.010
0.005
0.000
$50S_\oplus \leq S_{inc} \leq 100S_\oplus$
typical
uncert.
0.7
1.0
1.5
2.4
3.5
6.0
Planet Size [Earth radii]
Number of Simulated Planets
400
350
300
250
200
150
100
50
0
Lopez et al. (2014)
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
Planet Radius [Earth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

# Previous Occurrence Studies

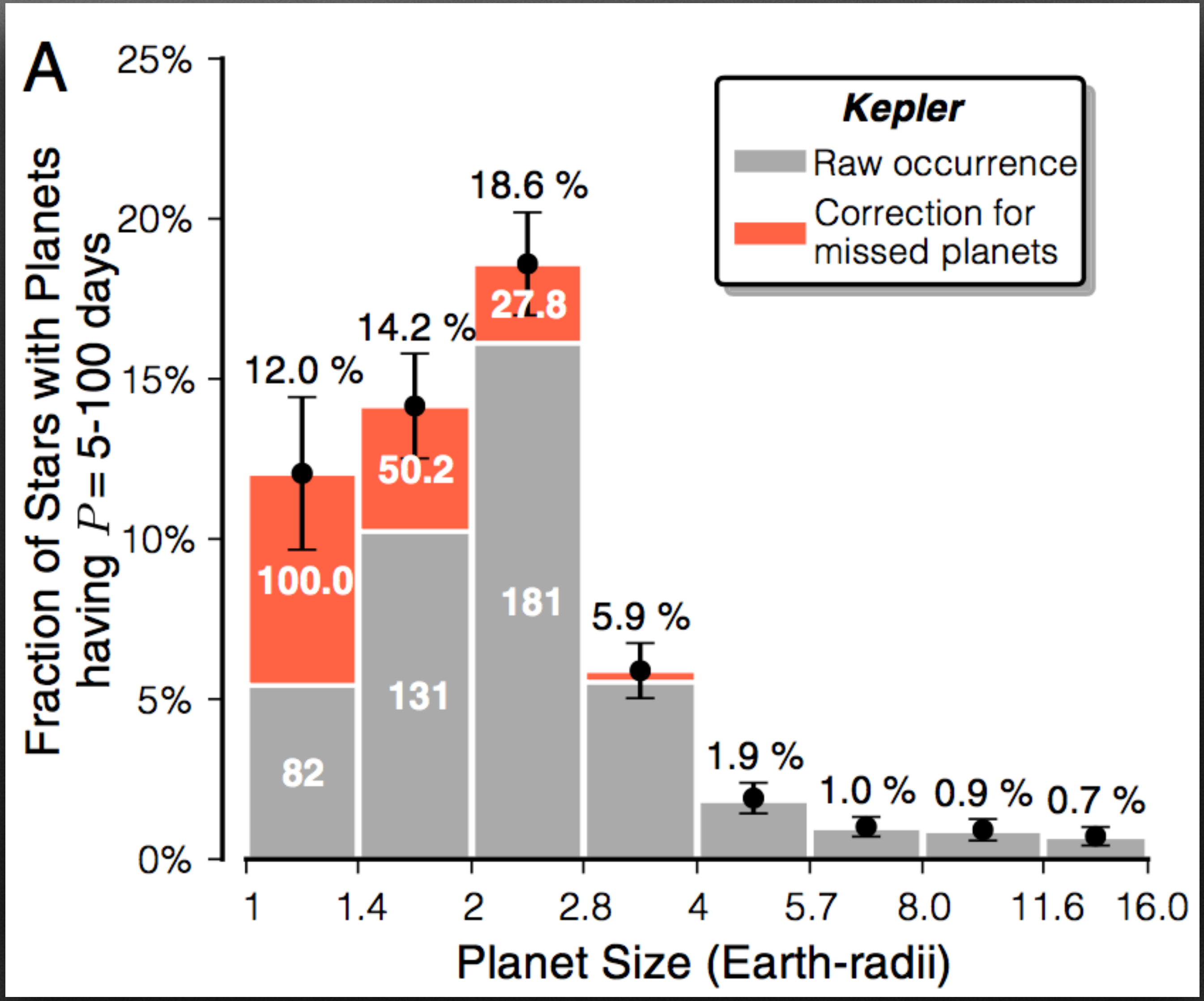
# Previous Occurrence Studies

- Howard et al. (2012)
  *Planet Occurrence Within 0.25 AU of Solar-Type Stars from Kepler*



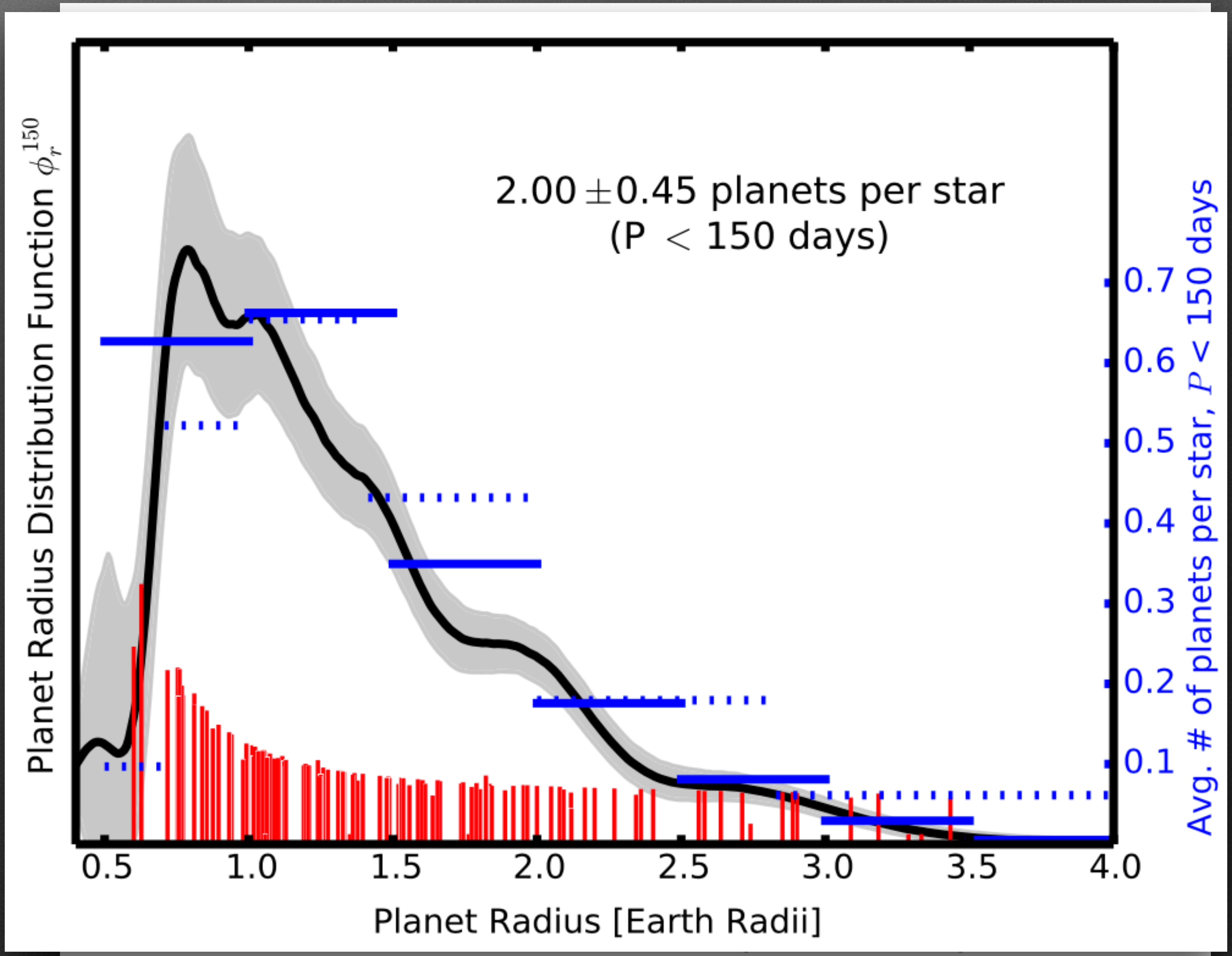
# Previous Occurrence Studies

- 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*



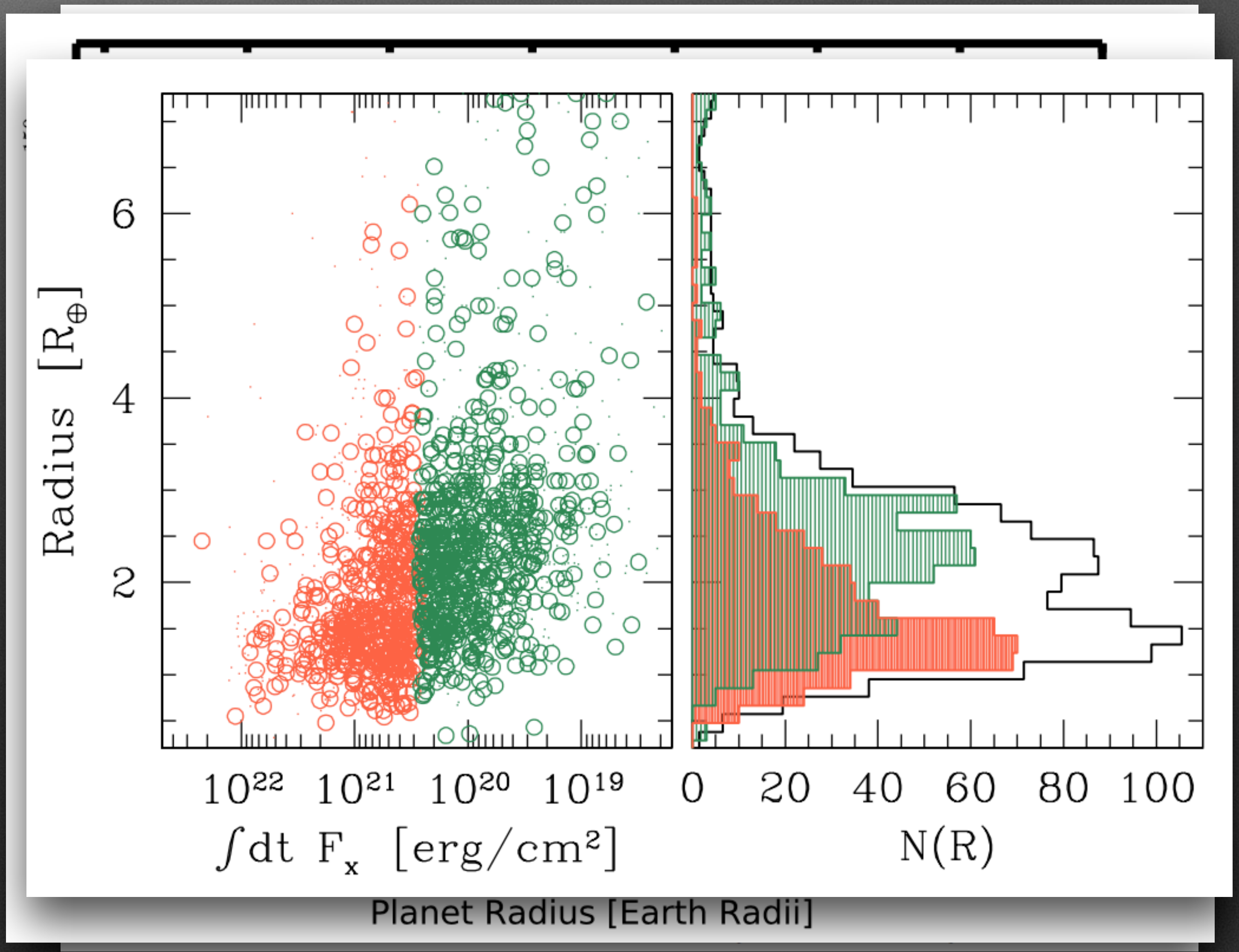
# Previous Occurrence Studies

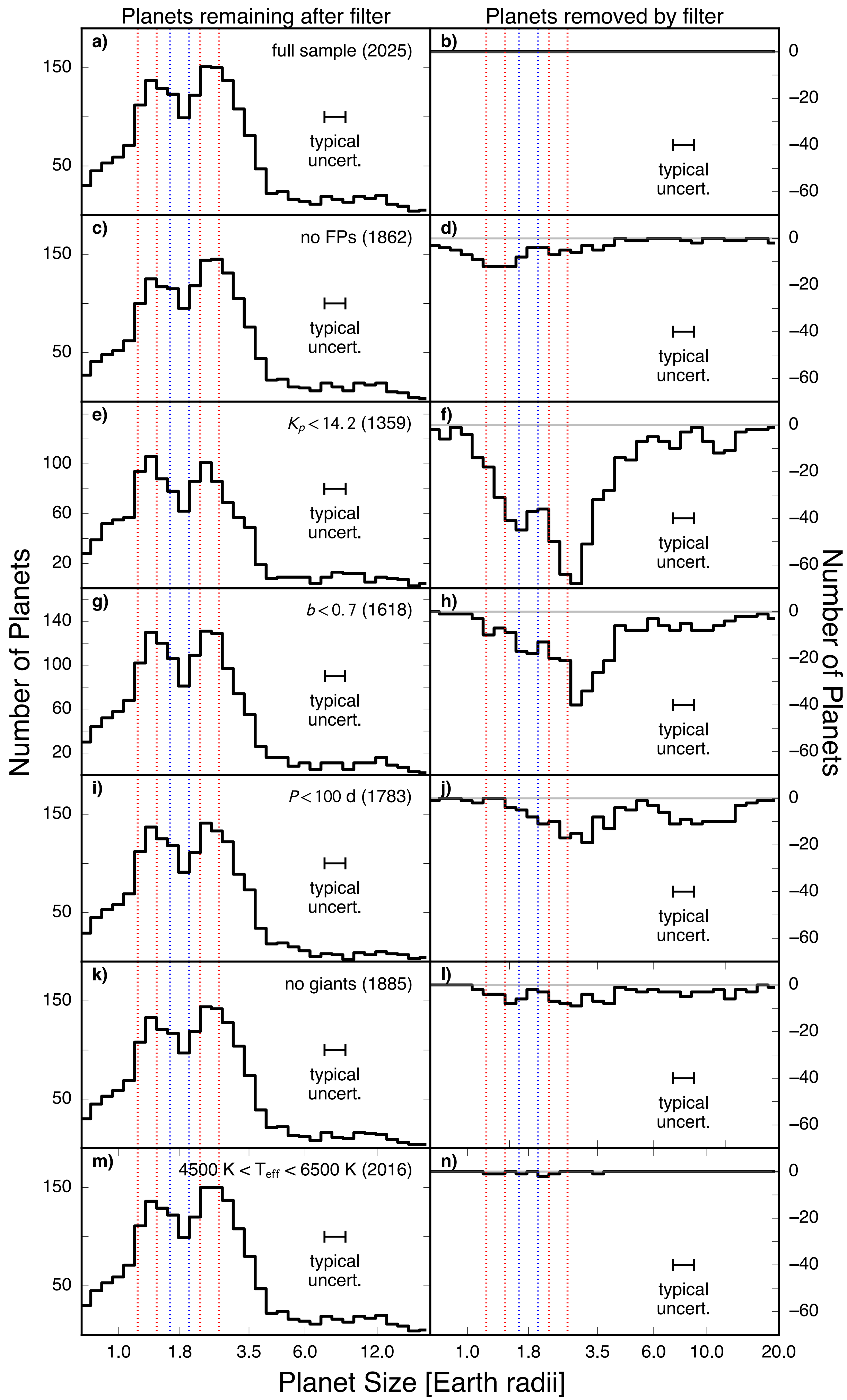
- Howard et al. (2012)
  *Planet Occurrence Within 0.25 AU of Solar-Type Stars from Kepler*
- Petigura et al. (2013)
  *Prevalence of Earth-size planets orbiting Sun-like stars*
- Morton et al. (2014)
  *The Radius Distribution of Planets Around Cool Stars*



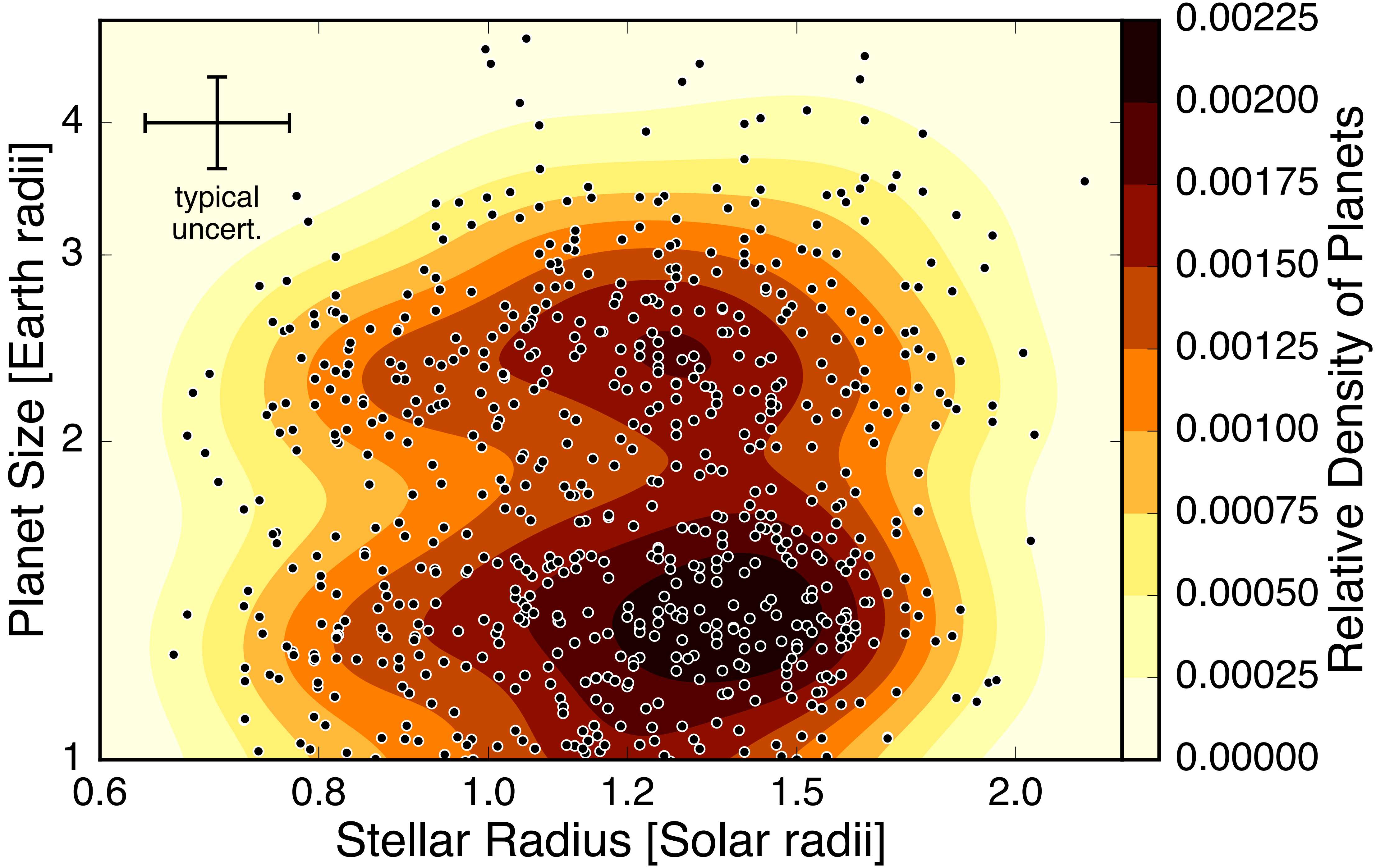
# Previous Occurrence Studies

- 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*

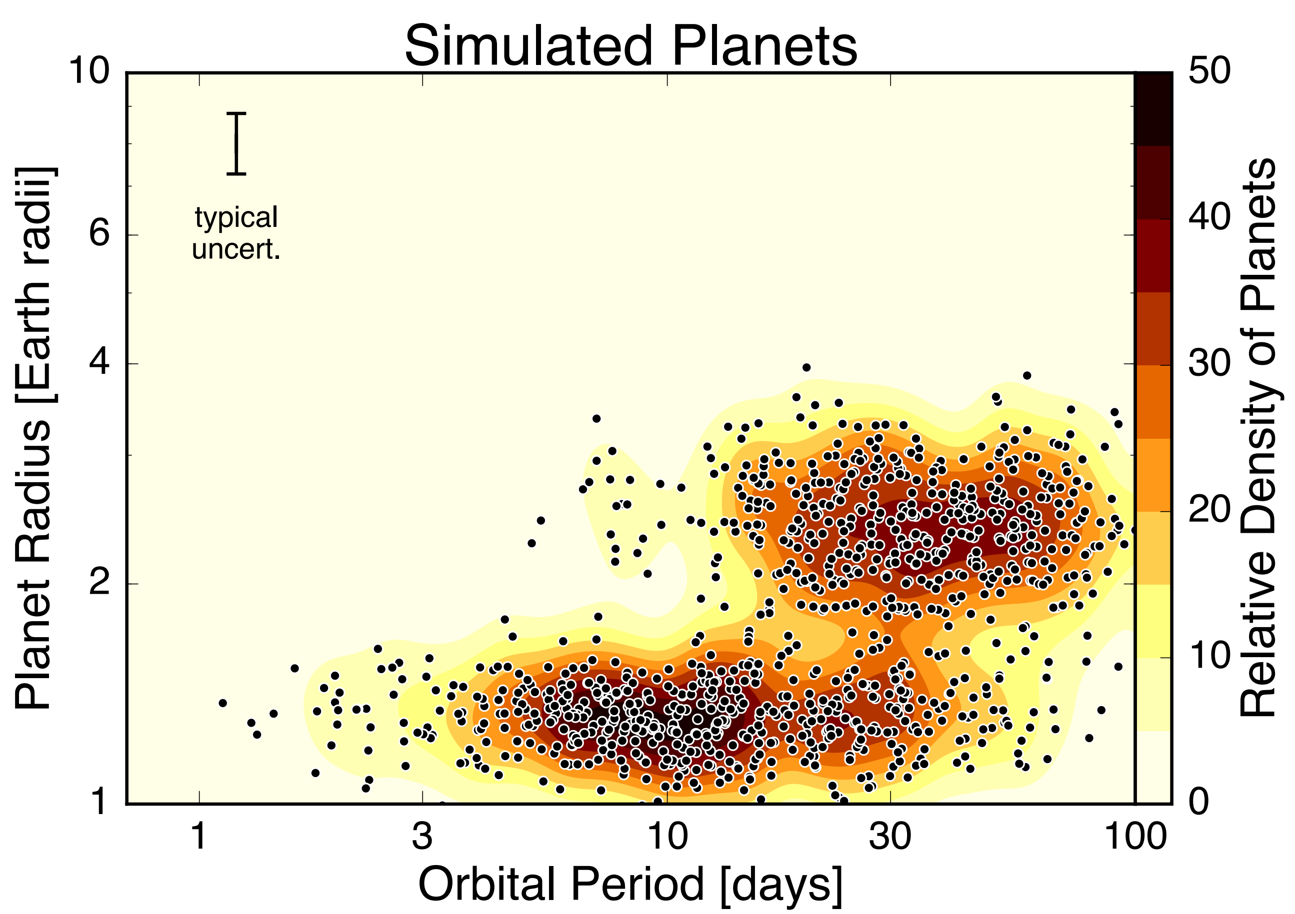


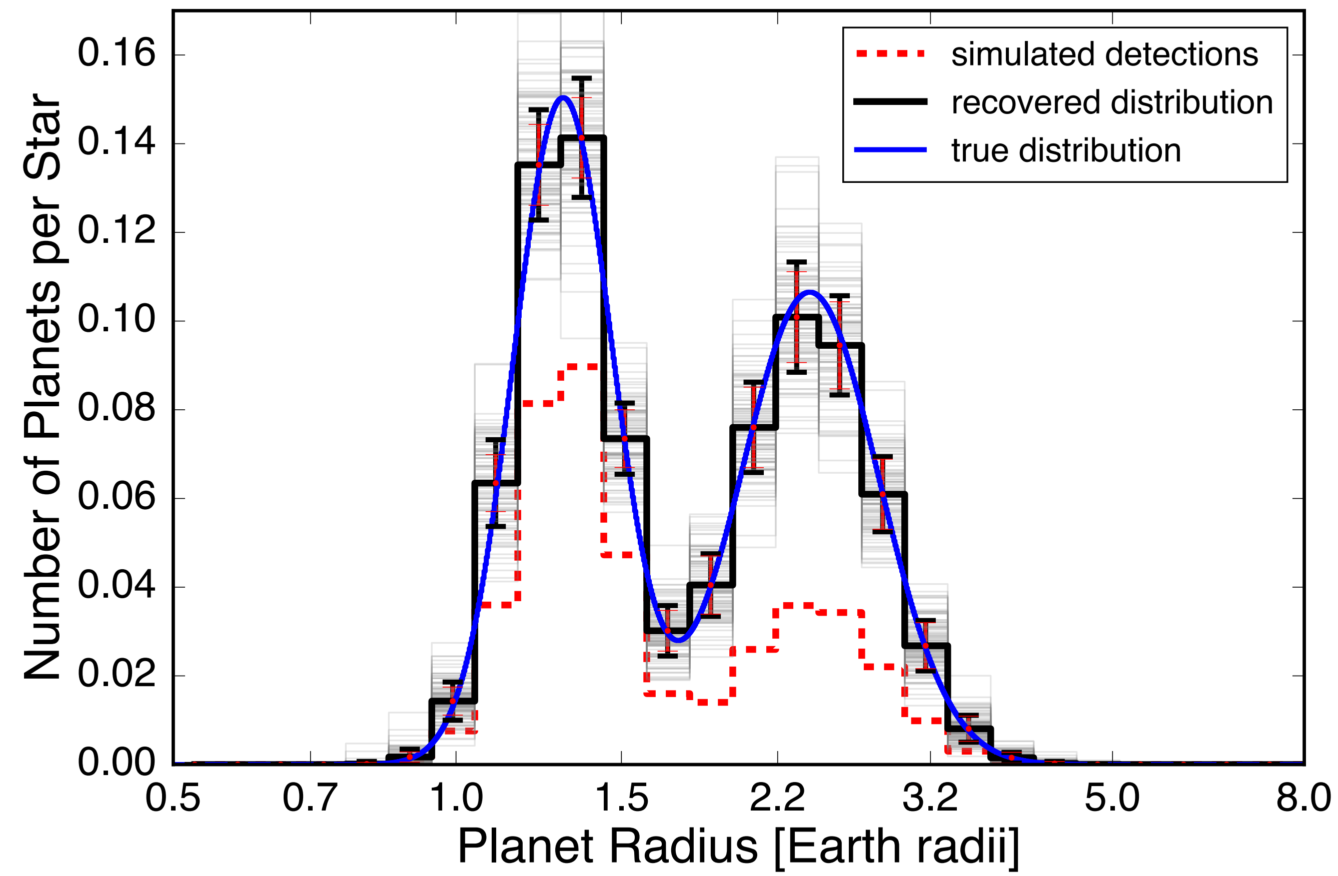


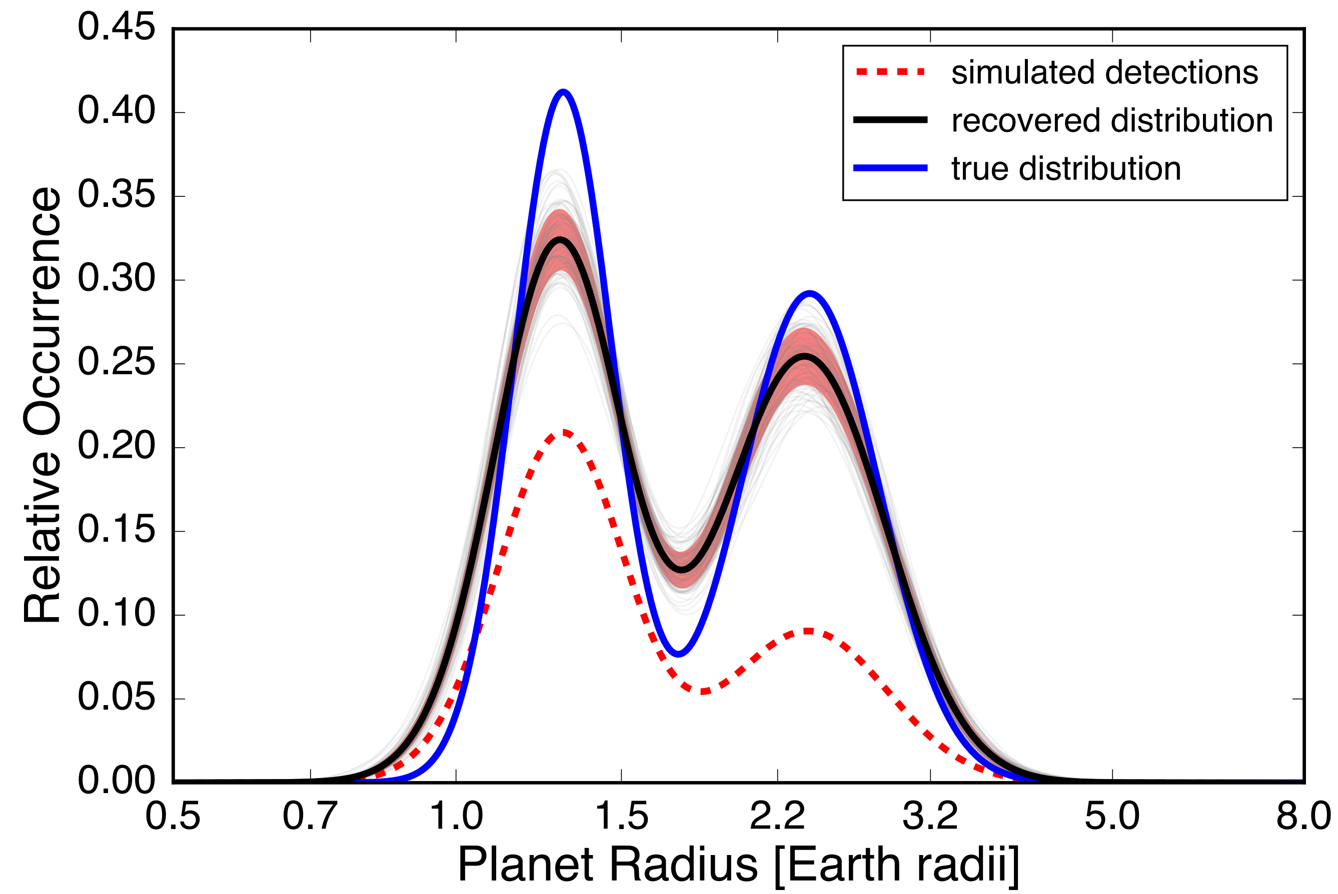
Planets remaining after filter
Planets removed by filter
a) full sample (2025)
b)
c) no FPs (1862)
d)
e) $K_p < 14.2$ (1359)
f)
g) $b < 0.7$ (1618)
h)
i) $P < 100$ d (1783)
j)
k) no giants (1885)
l)
m) 4500 K < $T_{eff}$ < 6500 K (2016)
n)
typical uncert.
Number of Planets
Number of Planets
Planet Size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

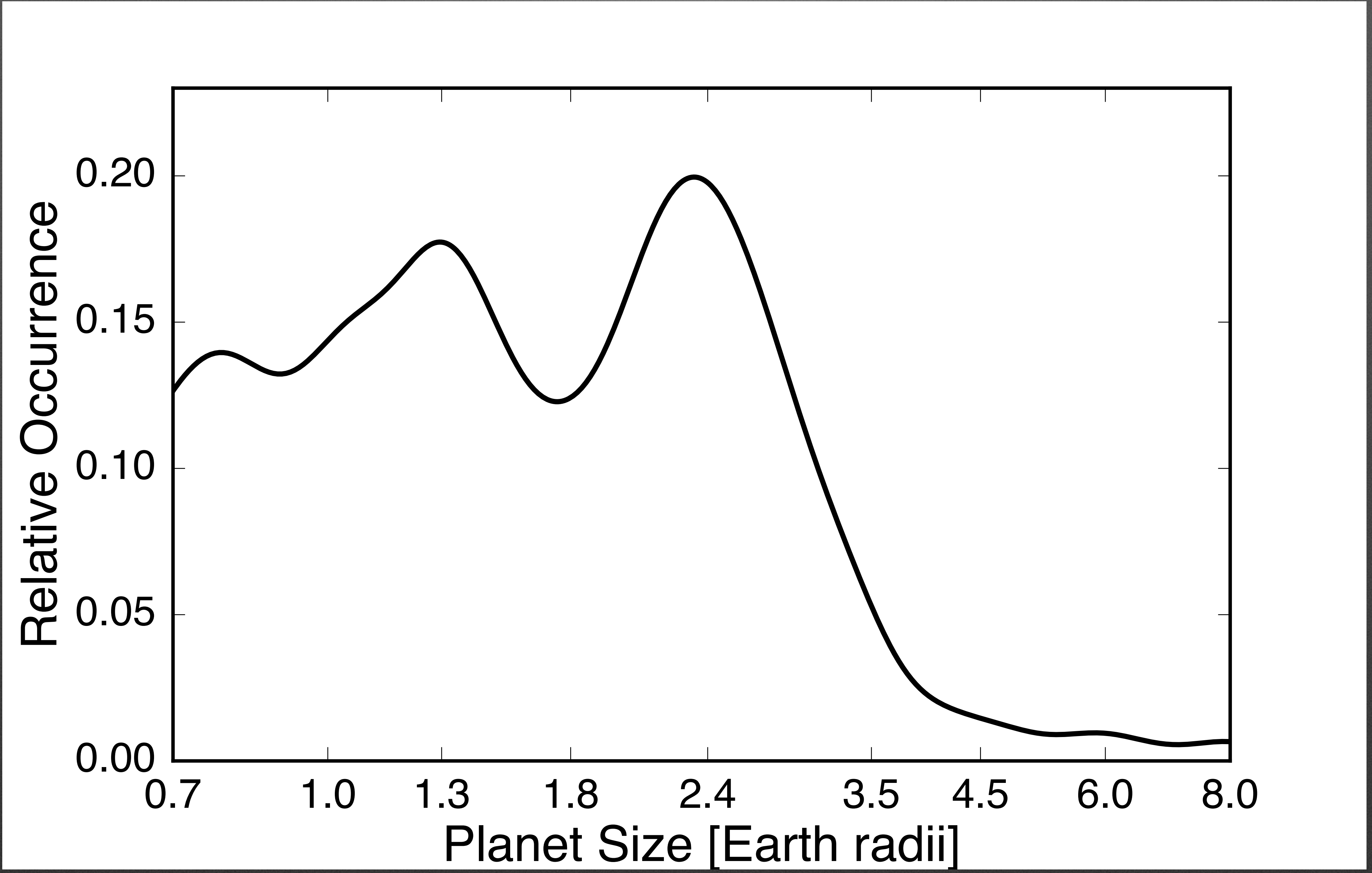


typical
uncert.
Planet Size [Earth radii]
1
2
3
4
Stellar Radius [Solar radii]
0.6
0.8
1.0
1.2
1.5
2.0
Relative Density of Planets
0.00000
0.00025
0.00050
0.00075
0.00100
0.00125
0.00150
0.00175
0.00200
0.00225


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

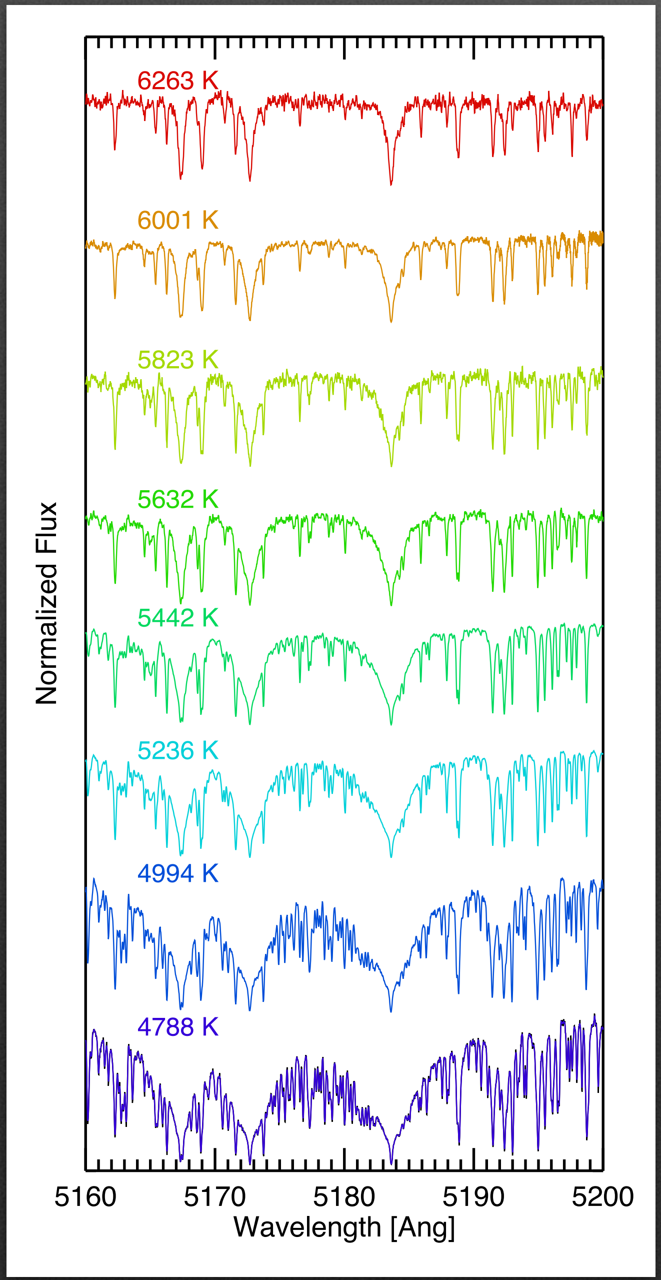

simulated detections
recovered distribution
true distribution
Relative Occurrence
Planet Radius [Earth radii]
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.5
0.7
1.0
1.5
2.2
3.2
5.0
8.0

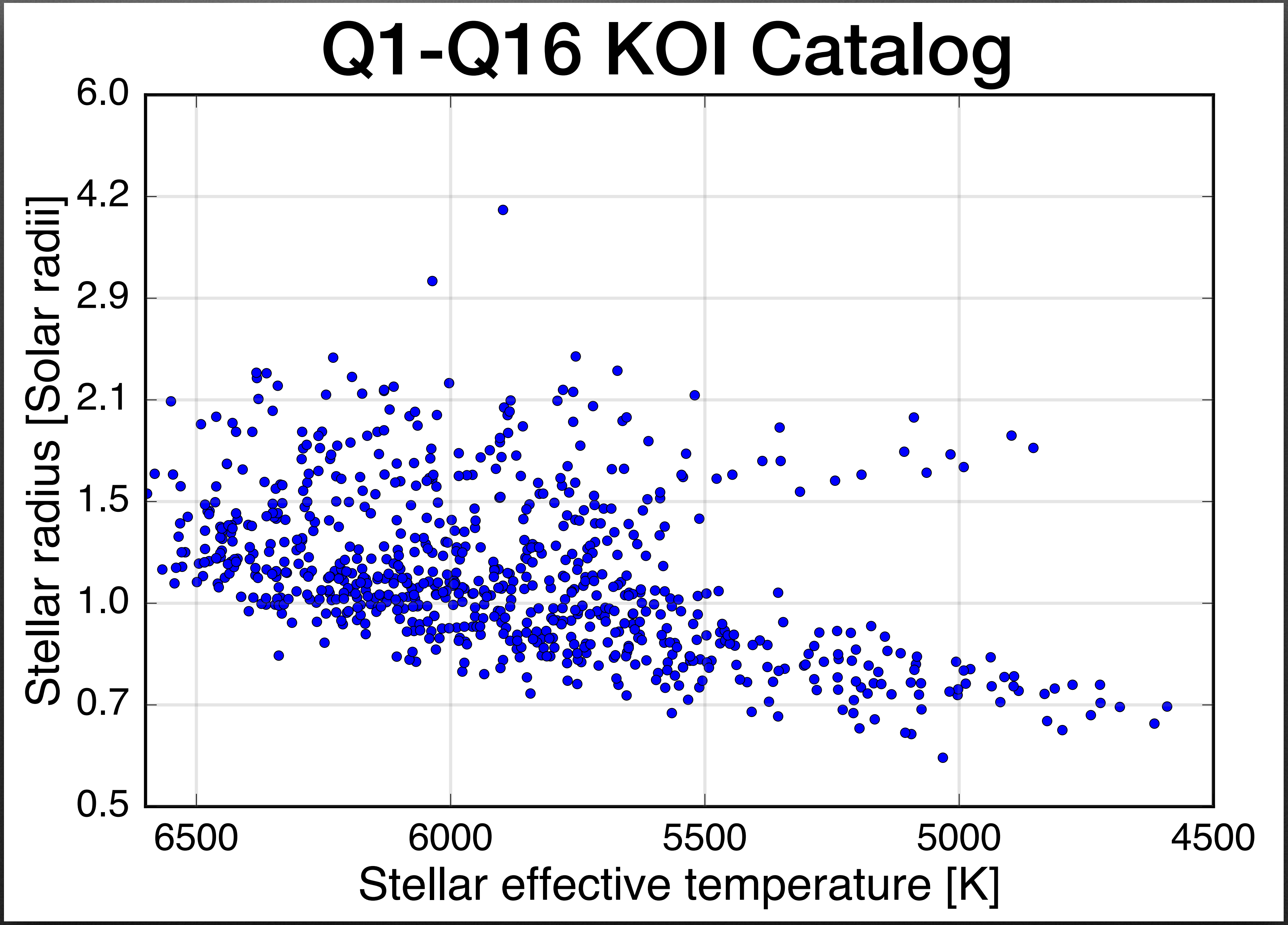


Relative Occurrence
0.00
0.05
0.10
0.15
0.20
0.7
1.0
1.3
1.8
2.4
3.5
4.5
6.0
8.0
Planet Size [Earth radii]

# The California-Kepler Survey

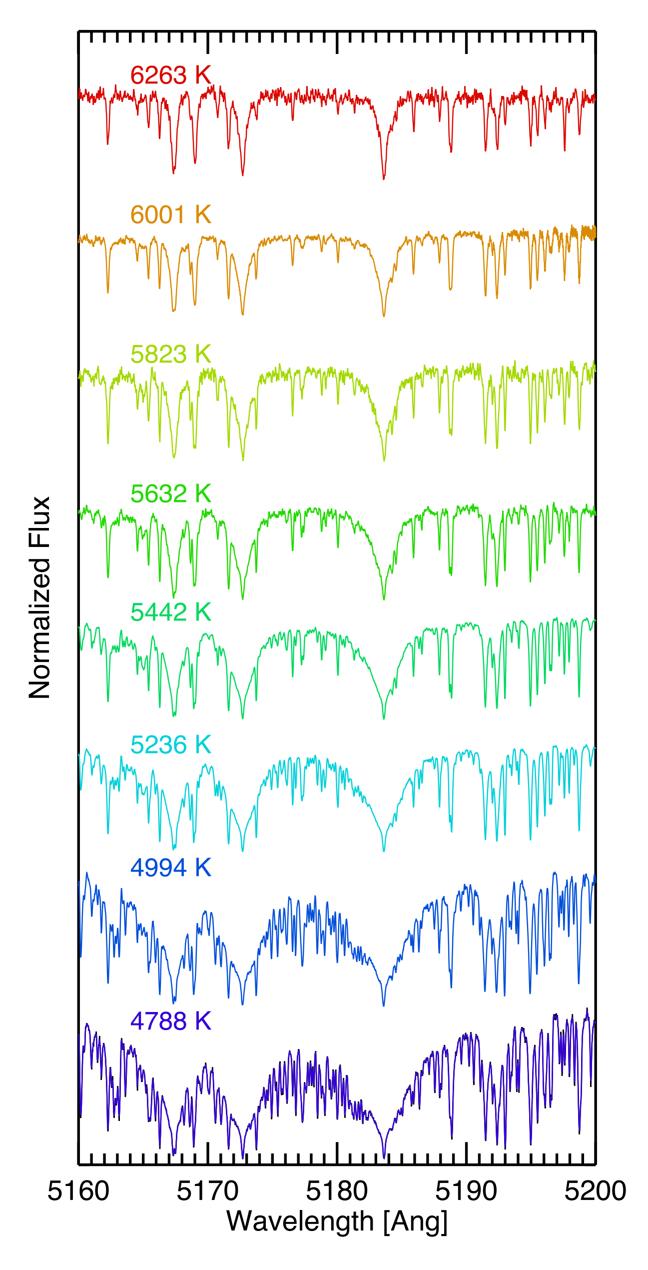
Keck/HIRES spectra for 1305 *Kepler* Objects of Interest

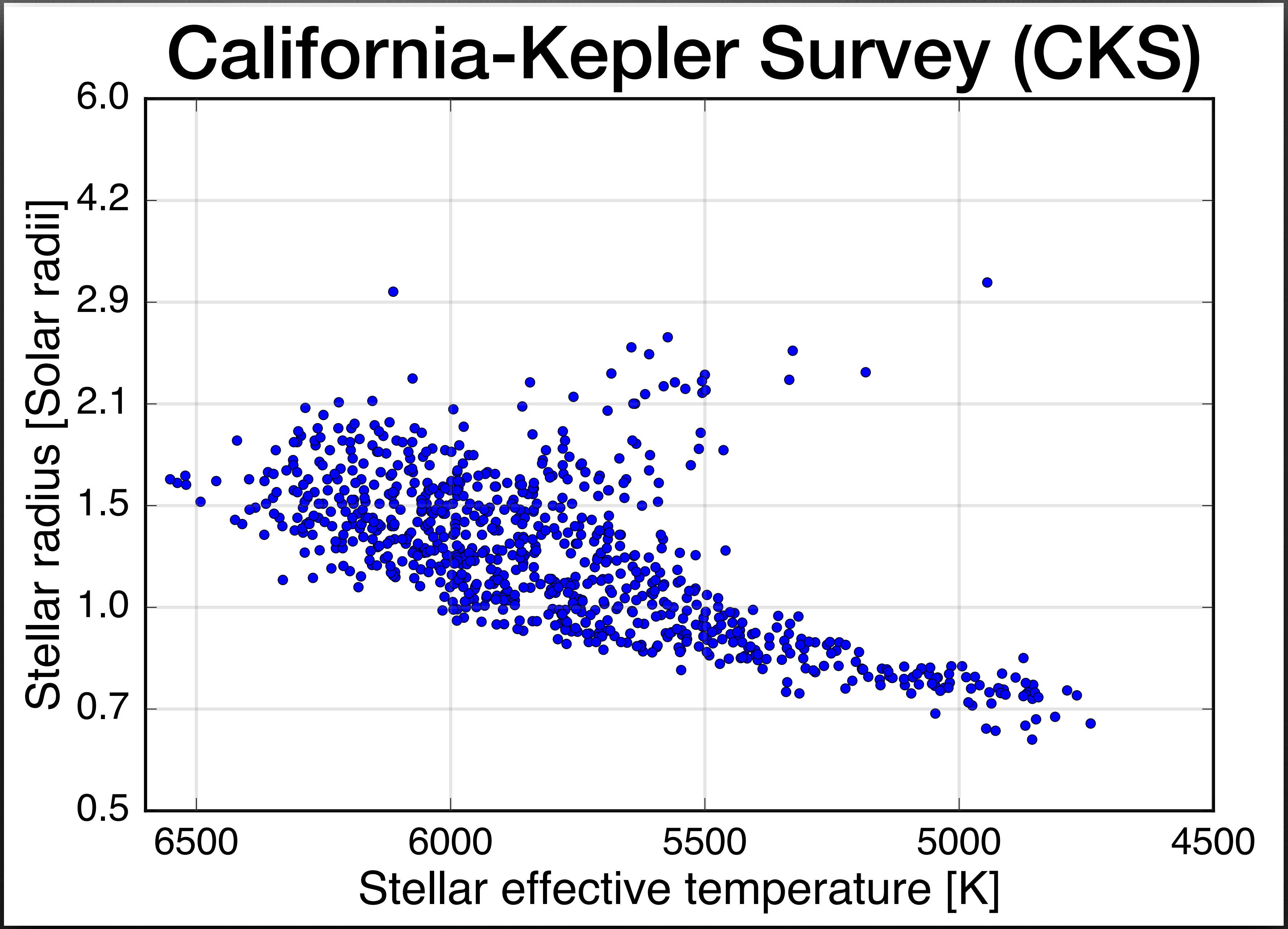


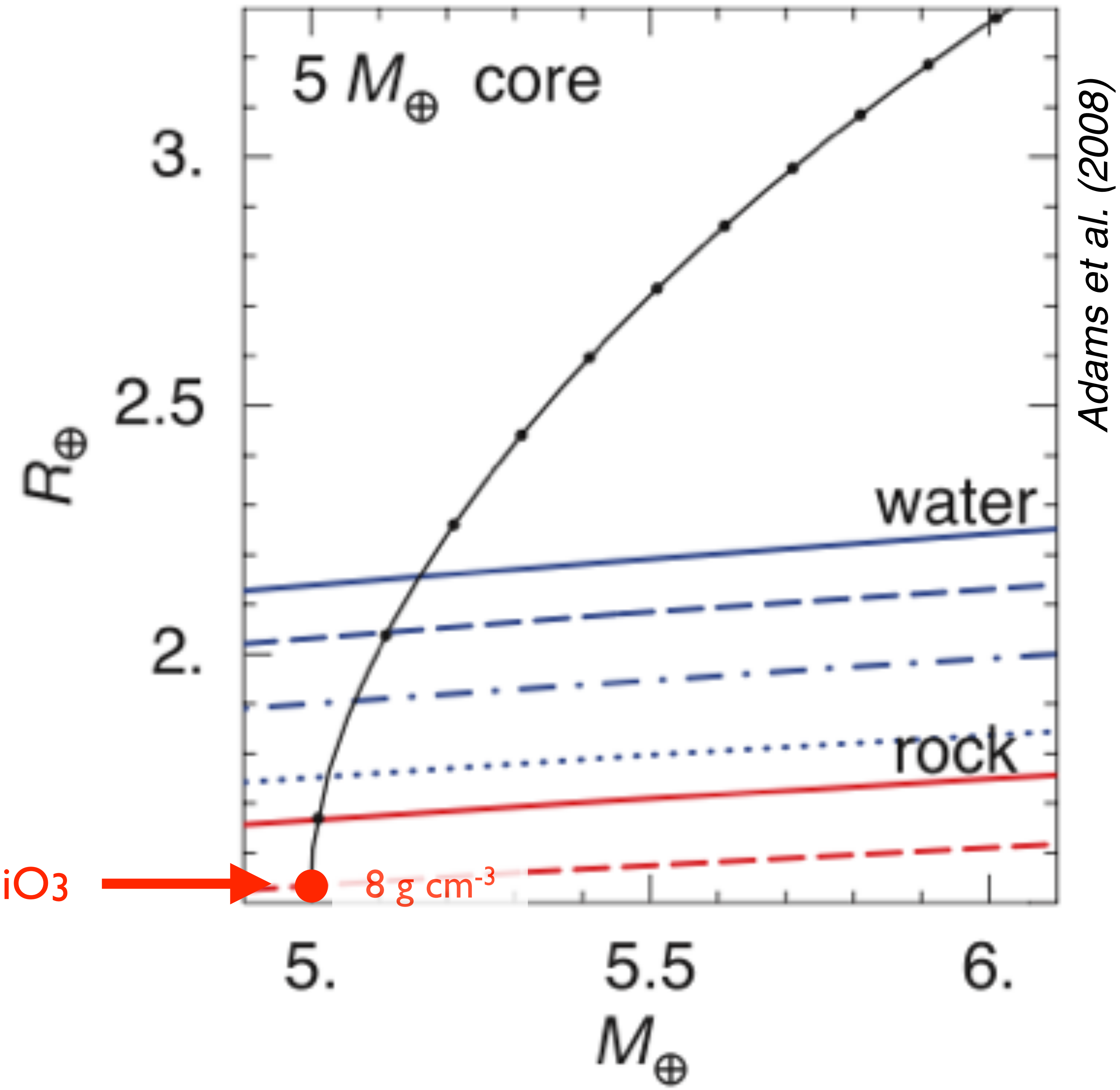
# The California-Kepler Survey

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

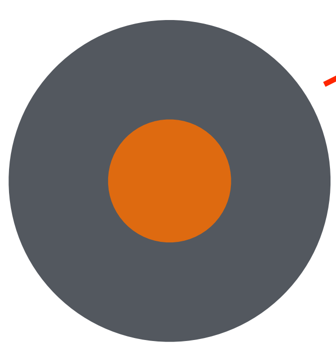


# Adding an Atmosphere

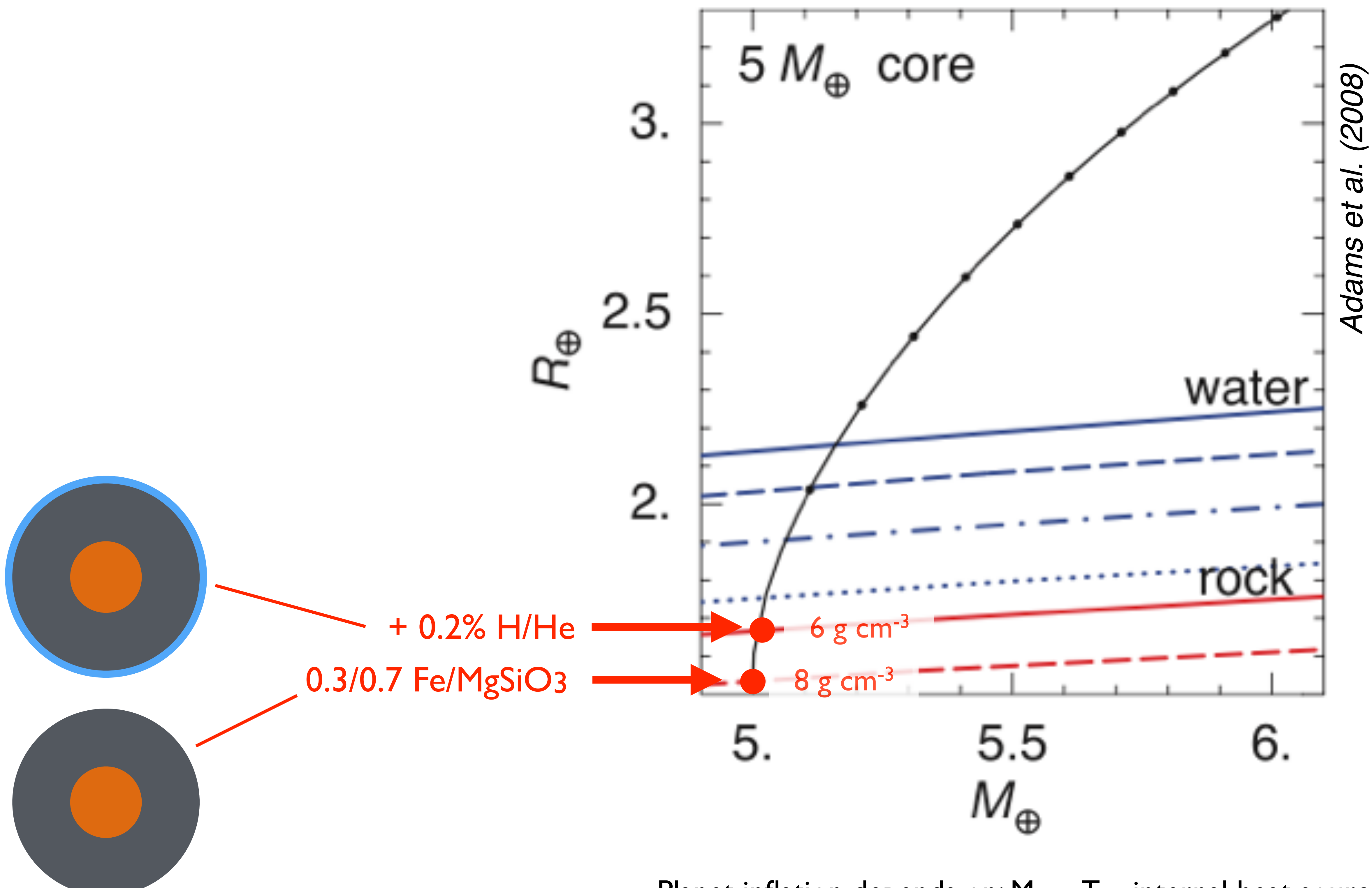



0.3/0.7 Fe/MgSiO3



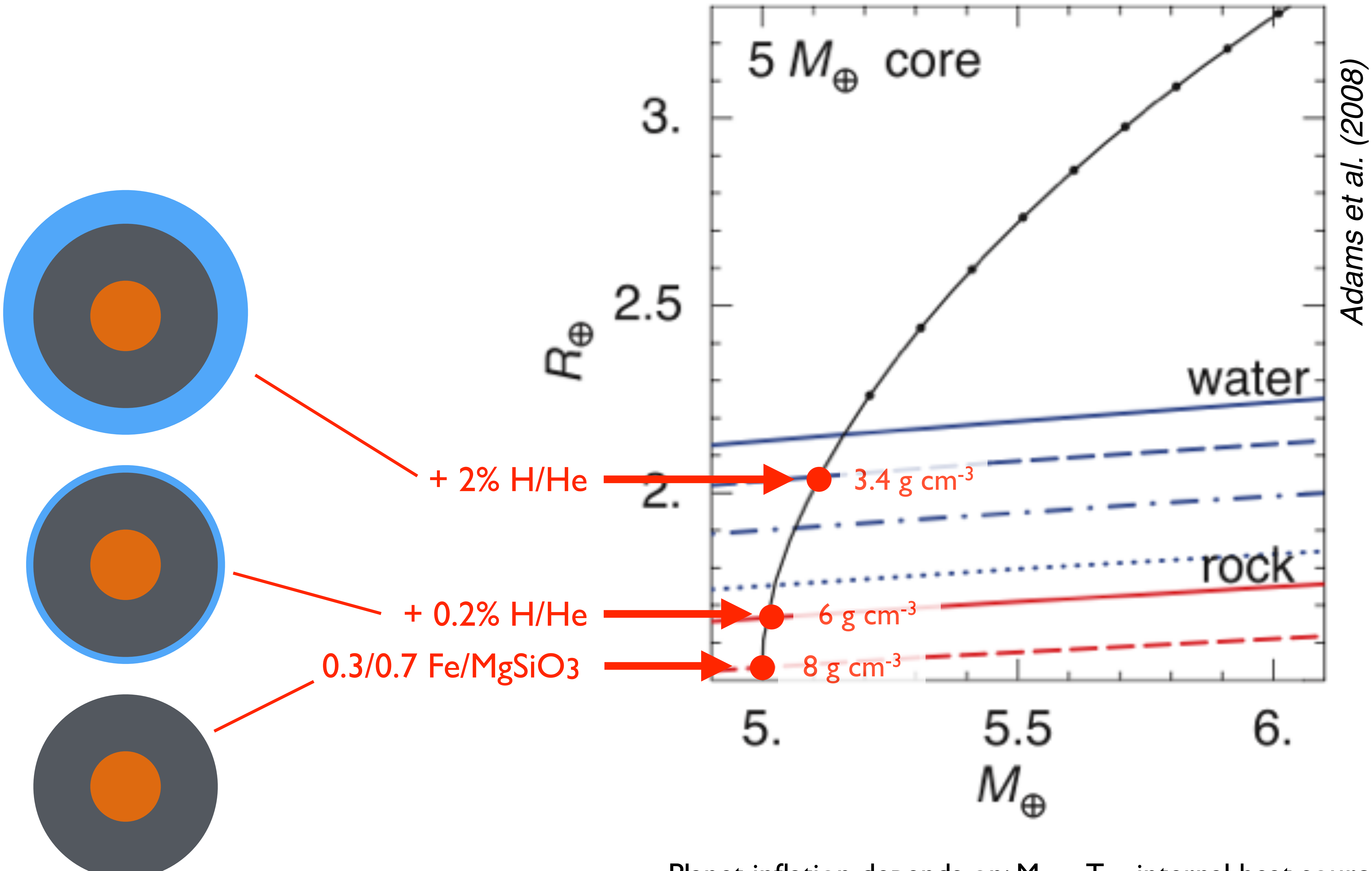
Planet inflation depends on: $M_{core}$, $T_{eff}$, internal heat sources

# Adding an Atmosphere



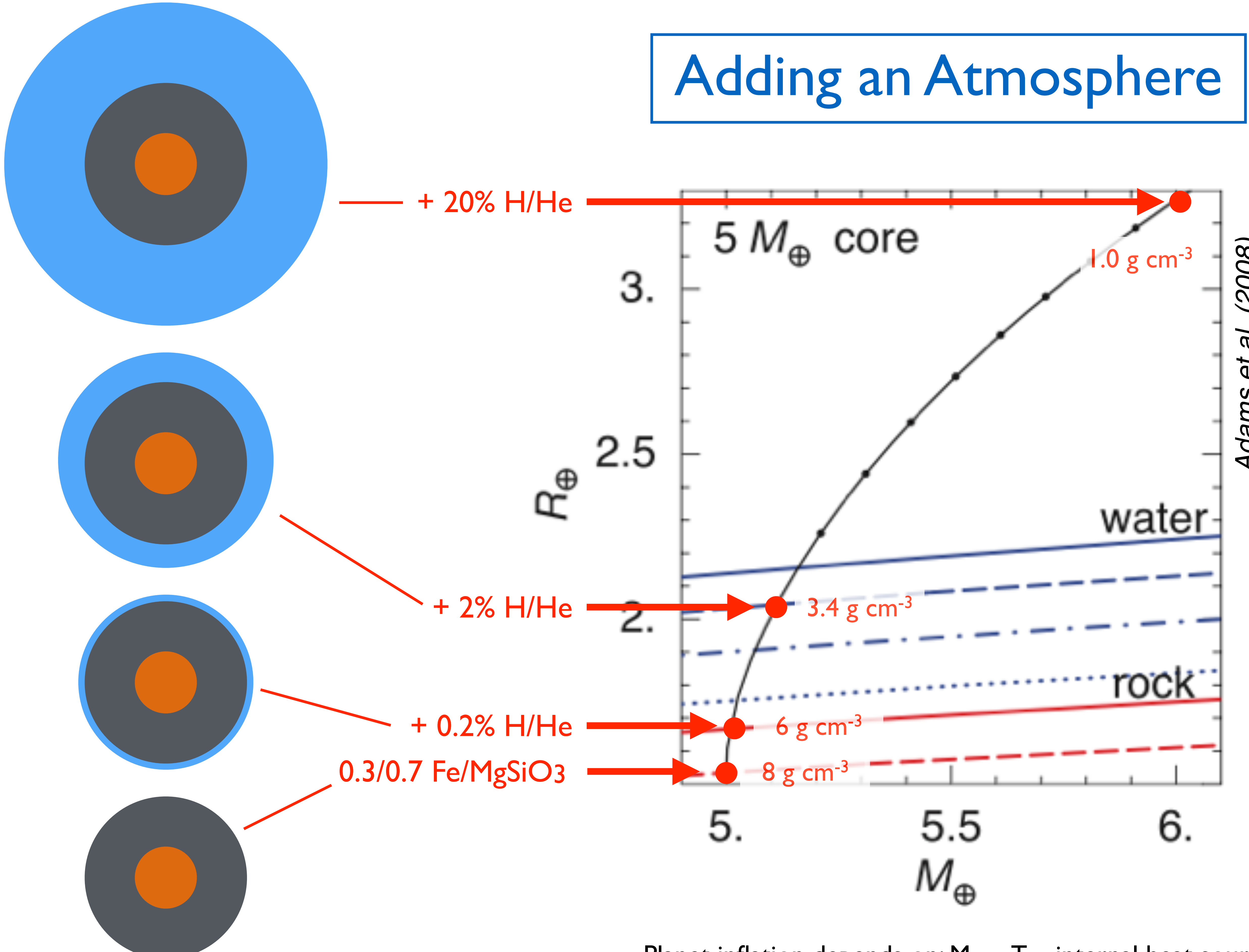

Planet inflation depends on: $M_{core}$, $T_{eff}$, internal heat sources

# Adding an Atmosphere




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

# Adding an Atmosphere




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