Precise Demographics of the Kepler Planets

Andrew Howard, Professor of Astronomy, Caltech
10th RESCEU/Planet^2 Symposium - Planet Formation around Snowlines
November 28, 2017

On behalf of:
Geoffrey Marcy, John Johnson, Erik Petigura, Howard Isaacson, Phillip Cargile, Leslie Hebb, BJ Fulton, Lauren Weiss, Tim Morton, Josh Winn, Leslie Rogers, Evan Sinukoff, Lea Hirsch, and Ian Crossfield

Many slides courtesy of E. Petigura

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California-Kepler Survey
Keck/HIRES Spectra of 1305 KOIs

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

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

Fulton, Petigura, Howard, et al. *AJ* (2017)
CKS III: A Gap in the Radius Distribution of Small Planets

Petigura, Marcy, Winn, et al. *AJ* (submitted)
CKS IV: Metal-rich Stars Host a greater Diversity of Planets

Weiss, Marcy, Petigura, et al. *AJ* (submitted; arXiv:1706.06204)
CKS V: Peas in a Pod: Planets in a Kepler Multi-planet System are
Similar in Size and Regularly Spaced

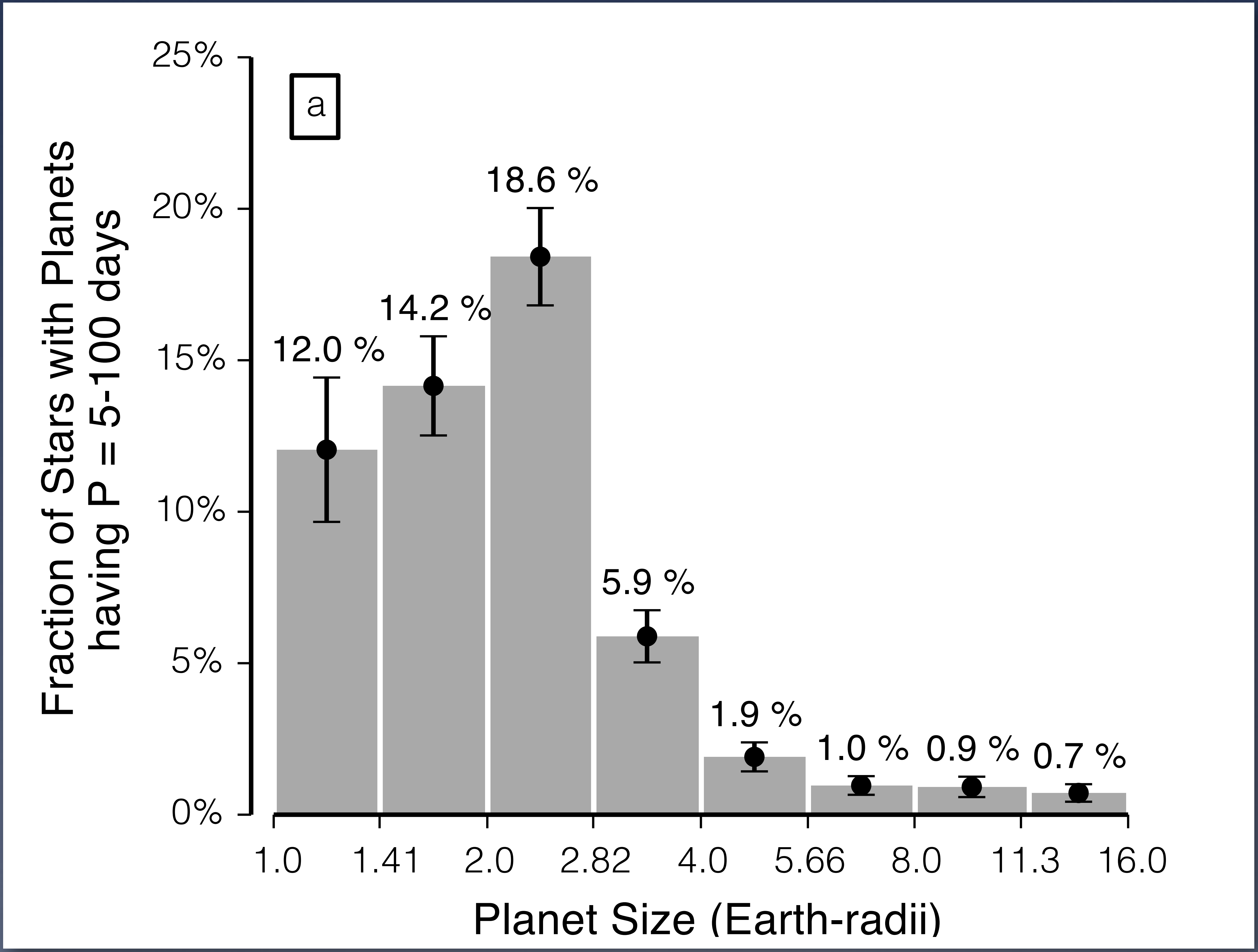
Papers Using CKS Data (to date)

Winn, Sanchis-Ojeda, Rogers, et al. *AJ* (2017)
Absence of a metallicity effect for ultra-short-period planets

Winn, Petigura, Morton, et al. *AJ* (in press, arXiv:1710.04530)
Constraints on Obliquities of Kepler Planet-Hosting Stars

Berger, Howard, Boesgaard *AJ* (submitted)
Identifying Young Kepler Planet Host Stars from Keck-HIRES Spectra of Lithium

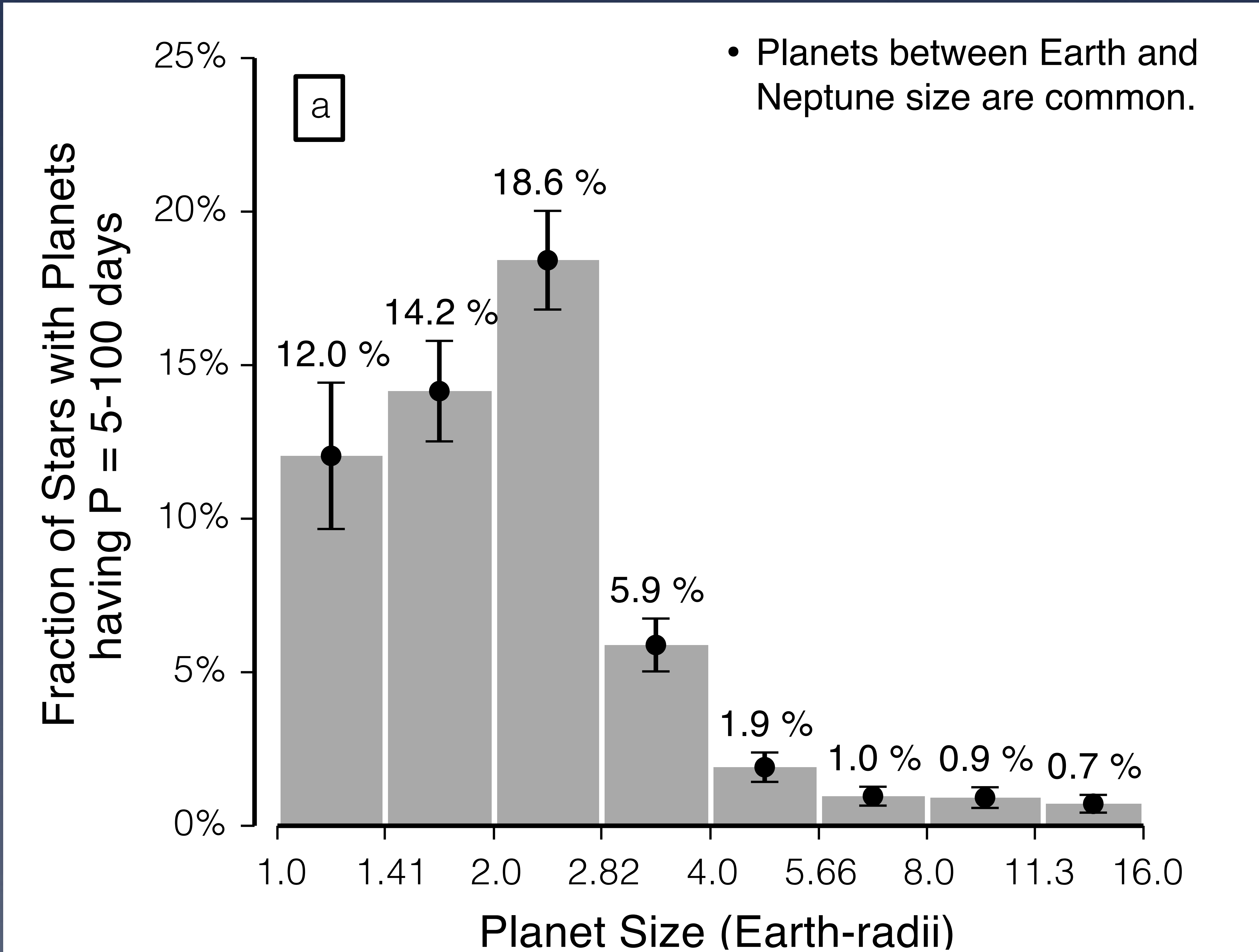
Planet size distribution



Petigura et al. (2013), *PNAS*

Fraction of stars with planets of different sizes

Planet size distribution



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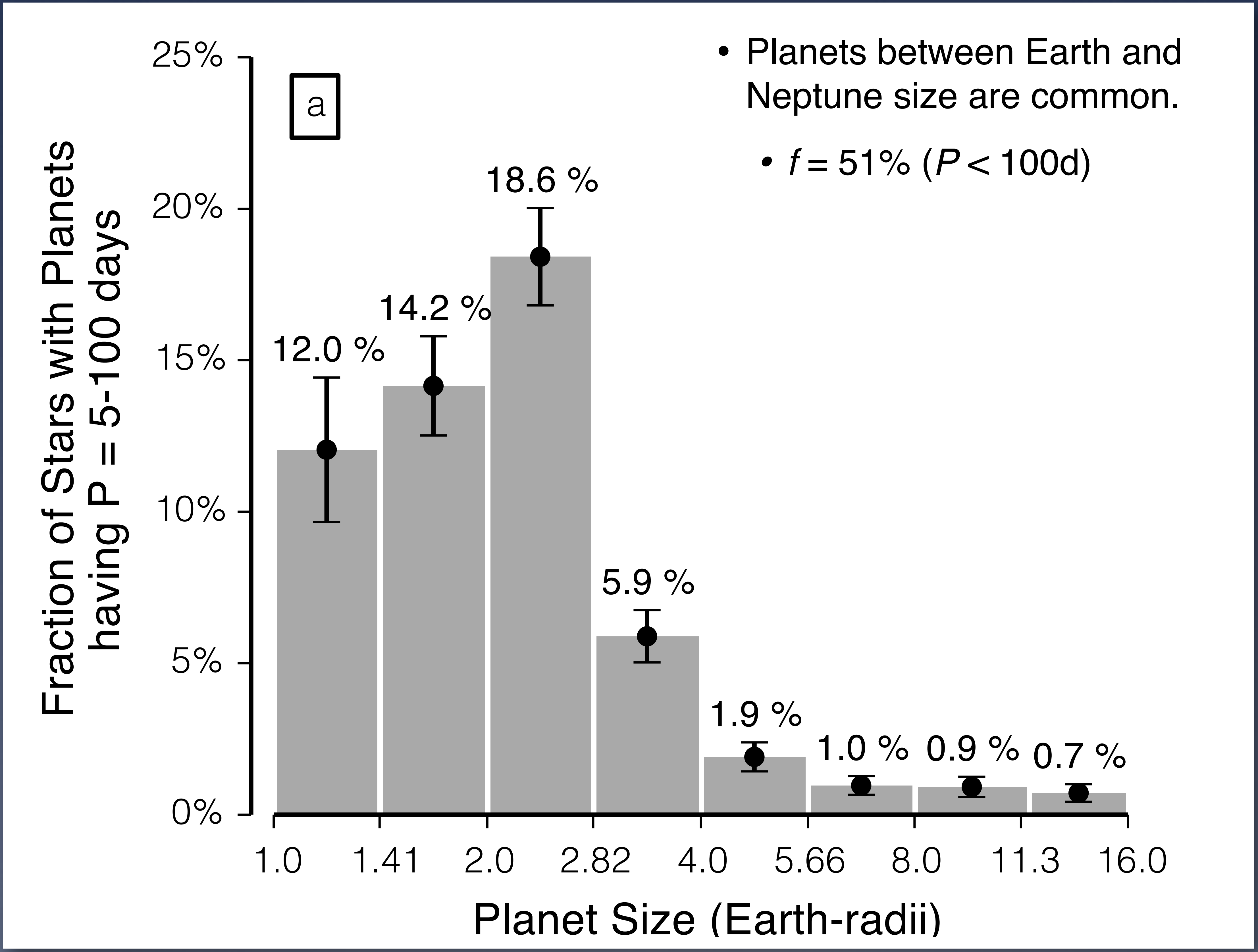
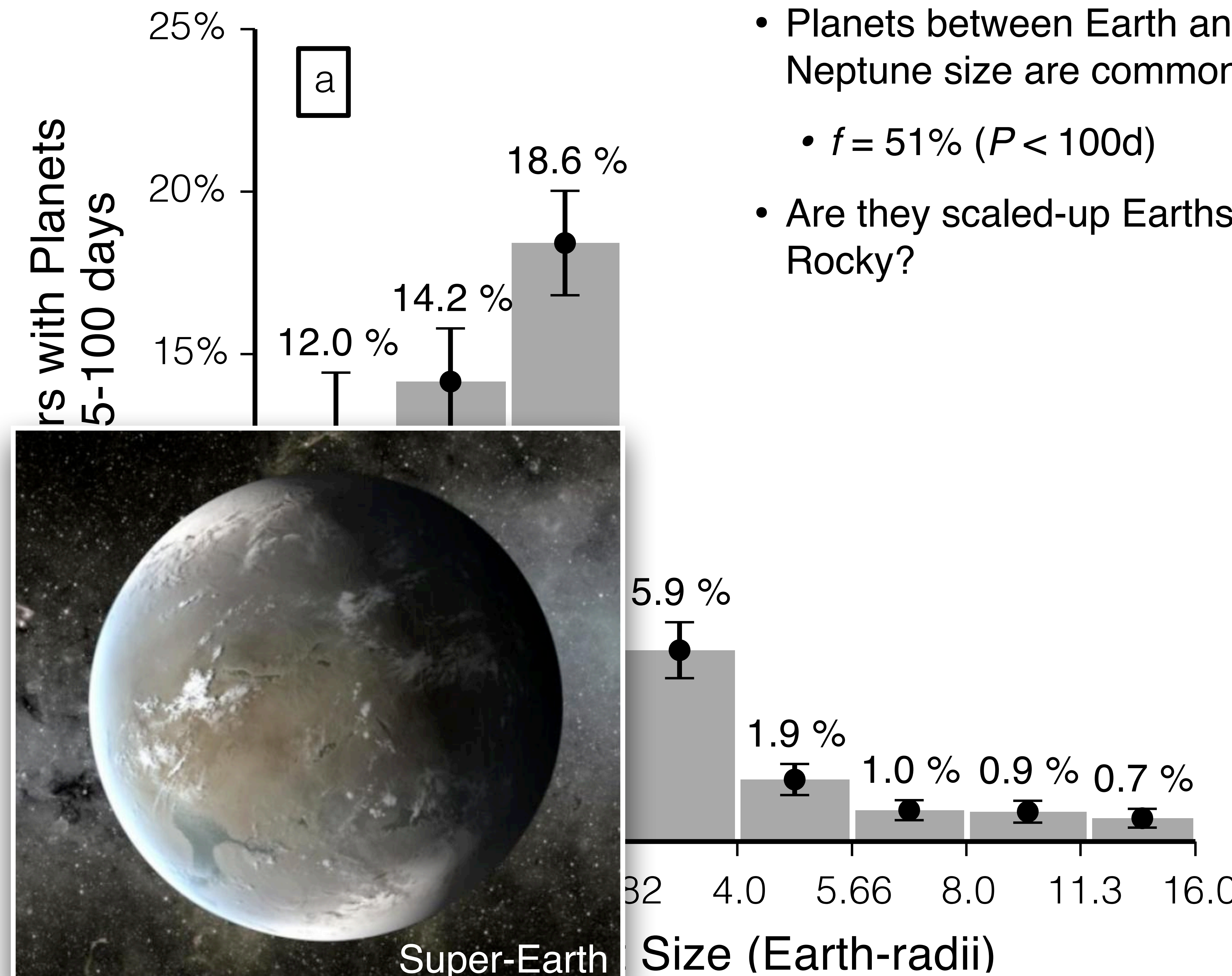
Planet size distribution



Petigura et al. (2013), *PNAS*

Fraction of stars with planets of different sizes

Planet size distribution

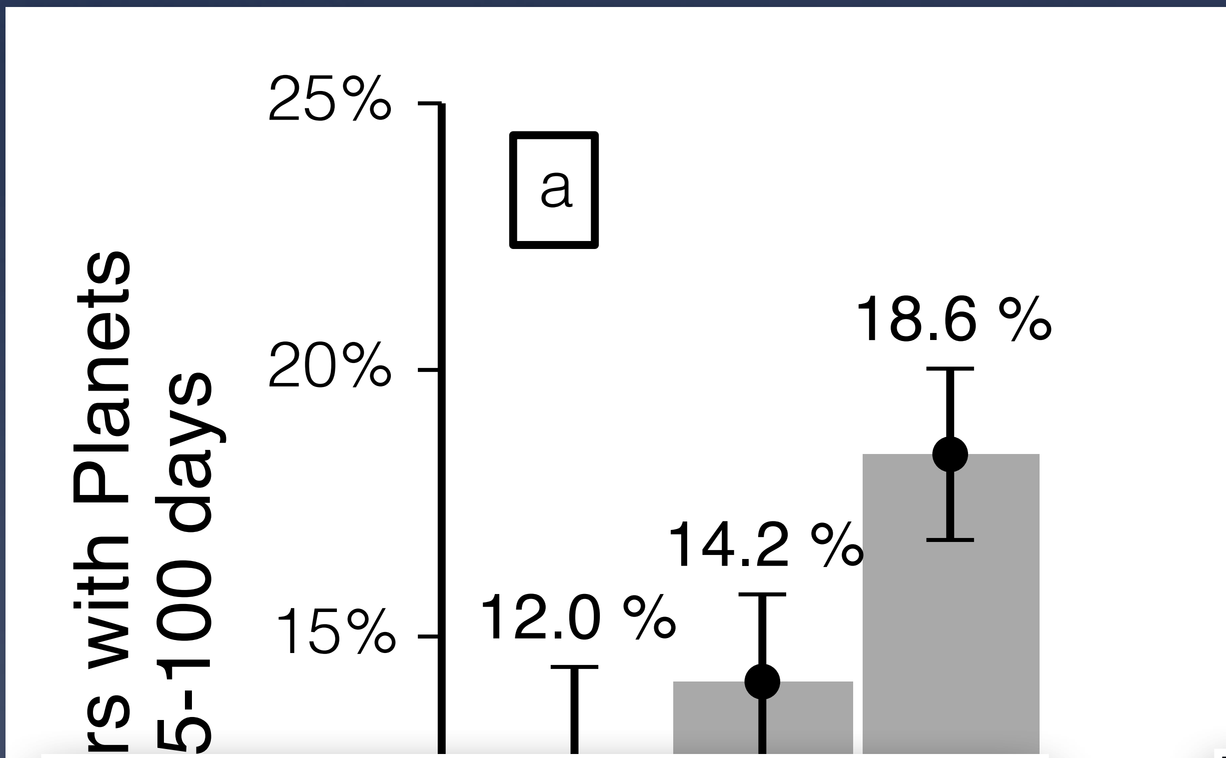


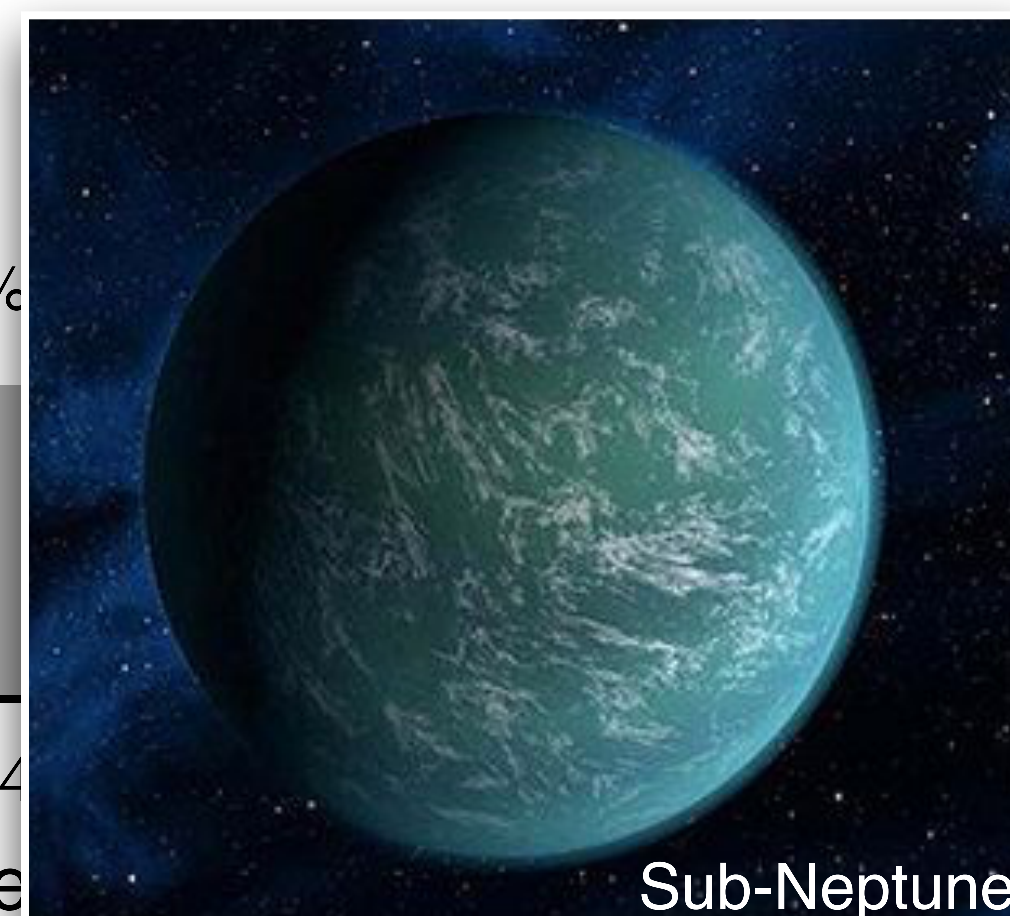
- Planets between Earth and Neptune size are common.
  - $f = 51\%$ ($P < 100$d)
- Are they scaled-up Earths? Rocky?

Petigura et al. (2013), *PNAS*

Fraction of stars with planets of different sizes

Planet size distribution



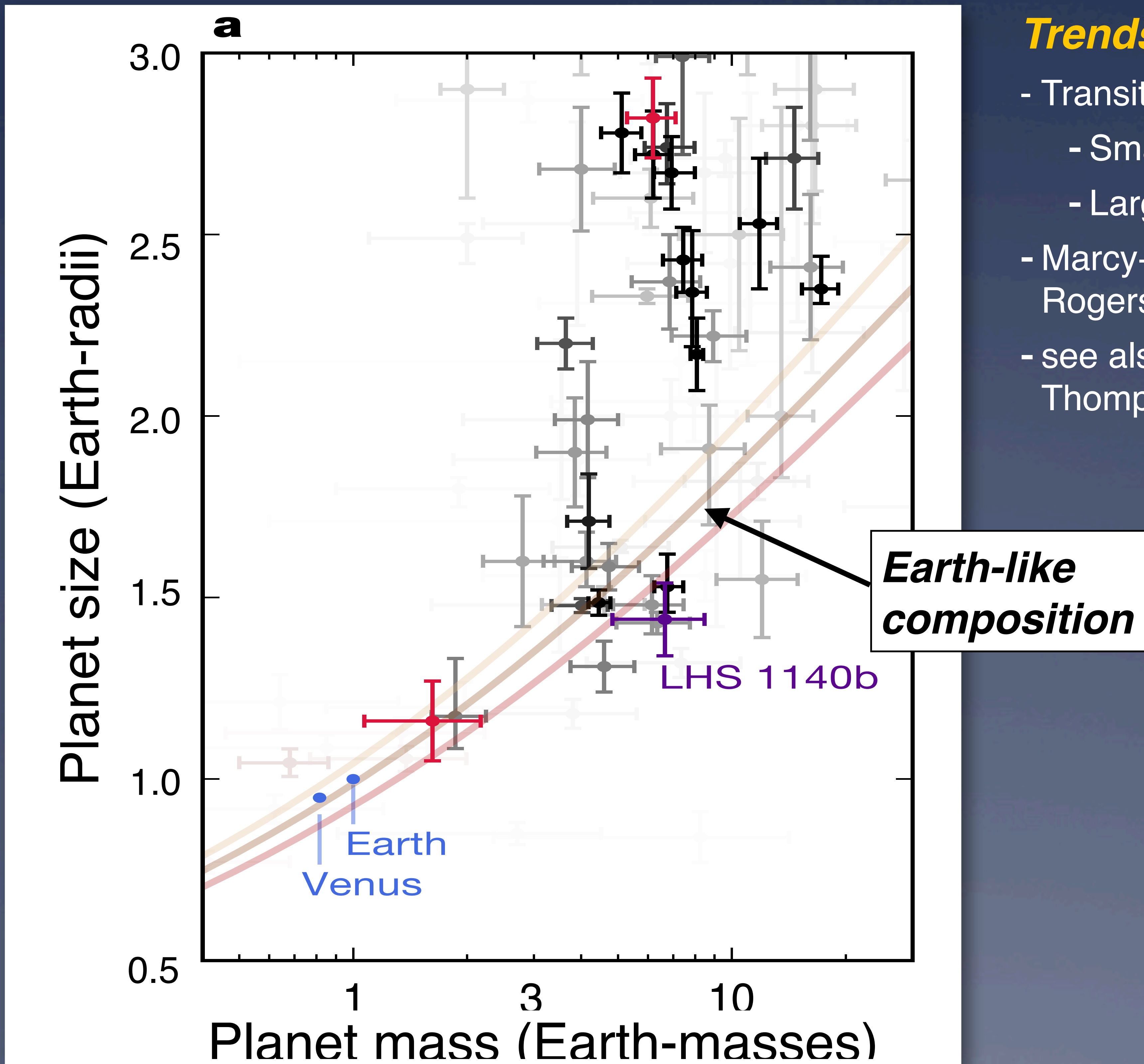


- Planets between Earth and Neptune size are common.
  - $f = 51\%$ ($P < 100$d)
- Are they scaled-up Earths? Rocky?
- ... or scaled-down Neptunes? Gaseous?

Petigura et al. (2013), *PNAS*

Fraction of stars with planets of different sizes

Mass & Radius

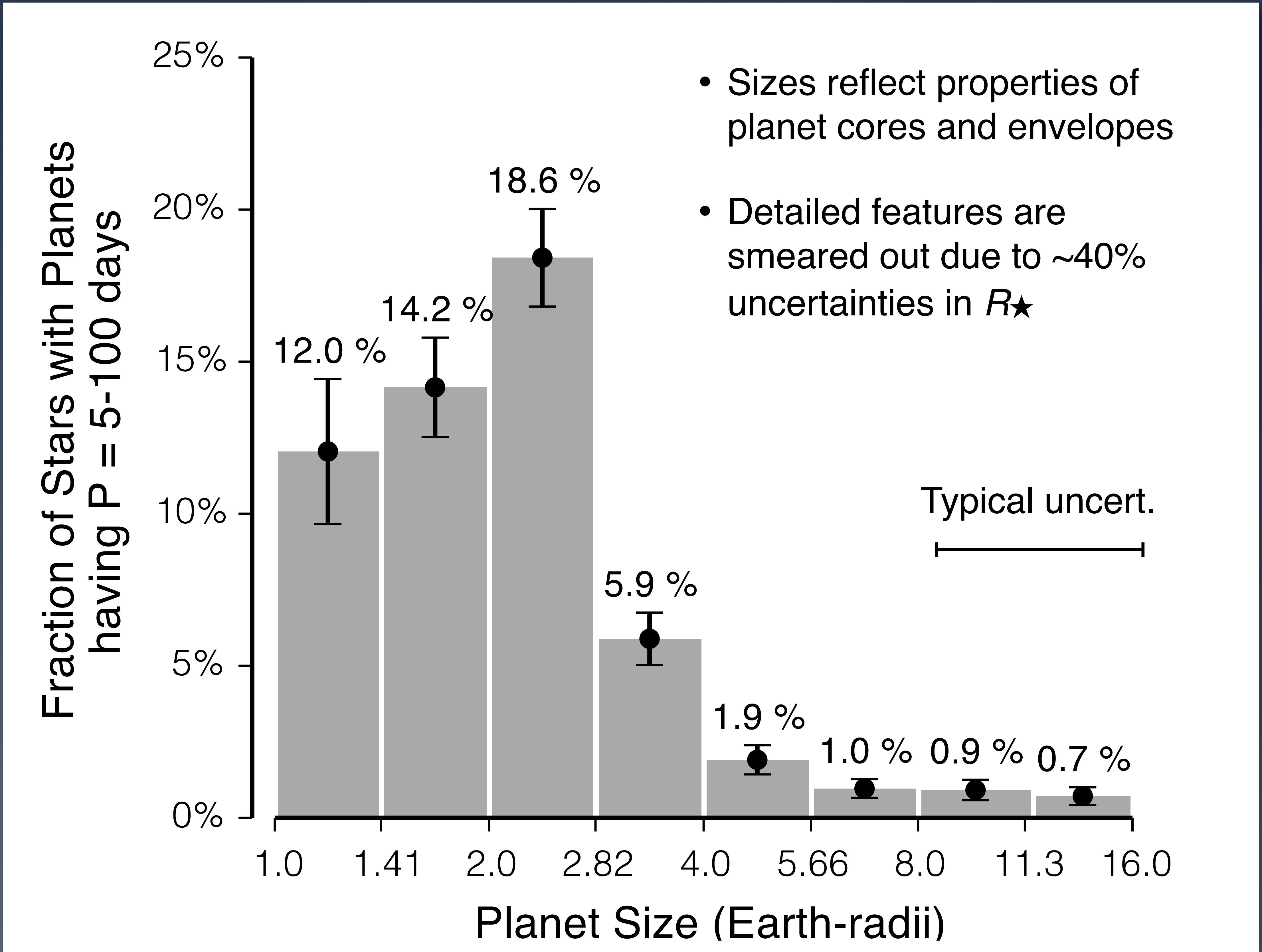


Compilation of planet masses and radii by Dittman+17

Trends for close-in planets

- Transition at ~1.5 R_E
    - Smaller: rocky
    - Larger: thick envelopes
- Marcy+14, Weiss & Marcy 14, Rogers 14
- see also: Dressing+15, Berta-Thompson+15, Wolfgang+16

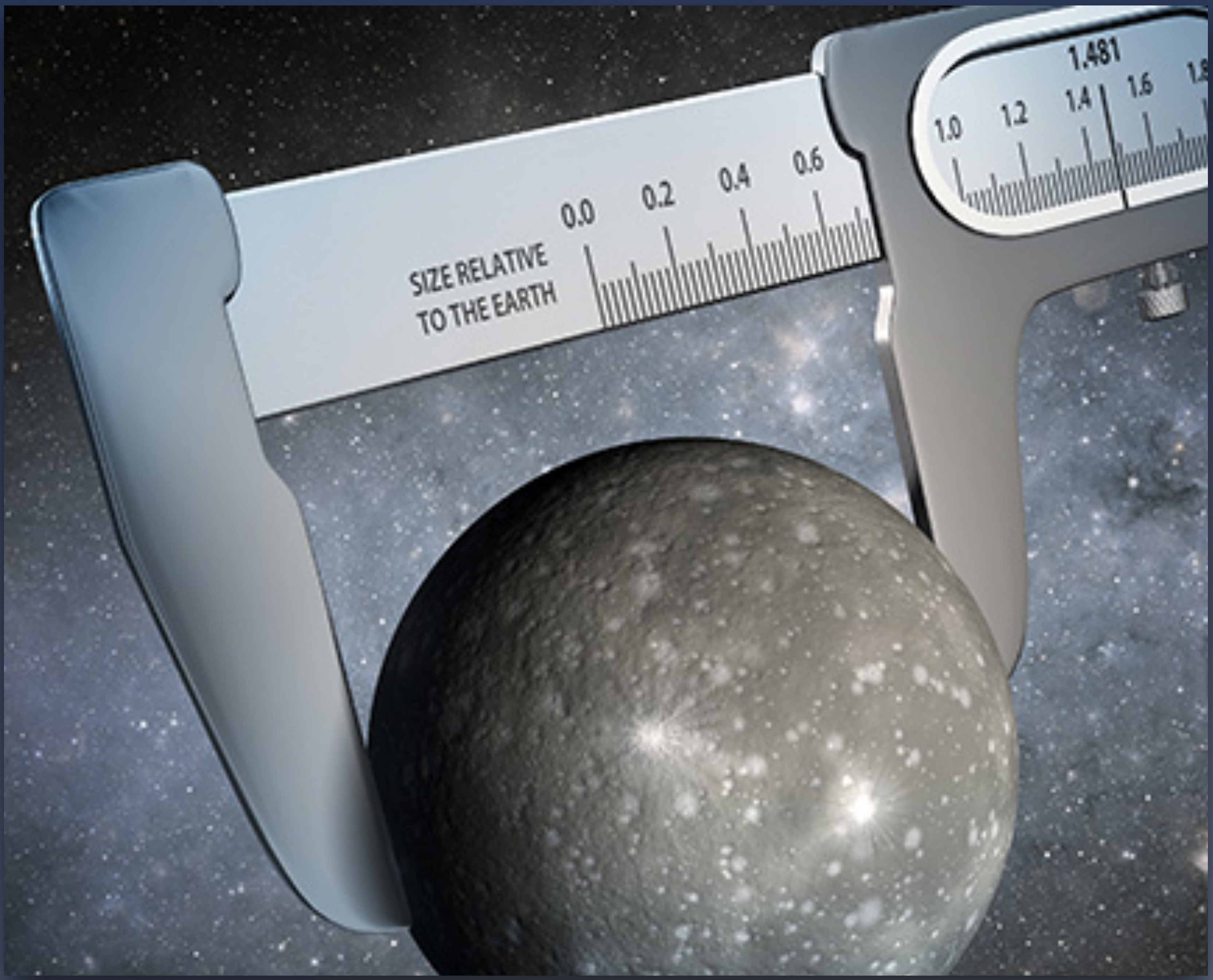
Planet size distribution



Petigura et al. (2013), *PNAS*

Fraction of stars with planets of different sizes

Know Thy Star



e.g. Kepler-93b (Ballard+14); $R_\star$ to ~1%

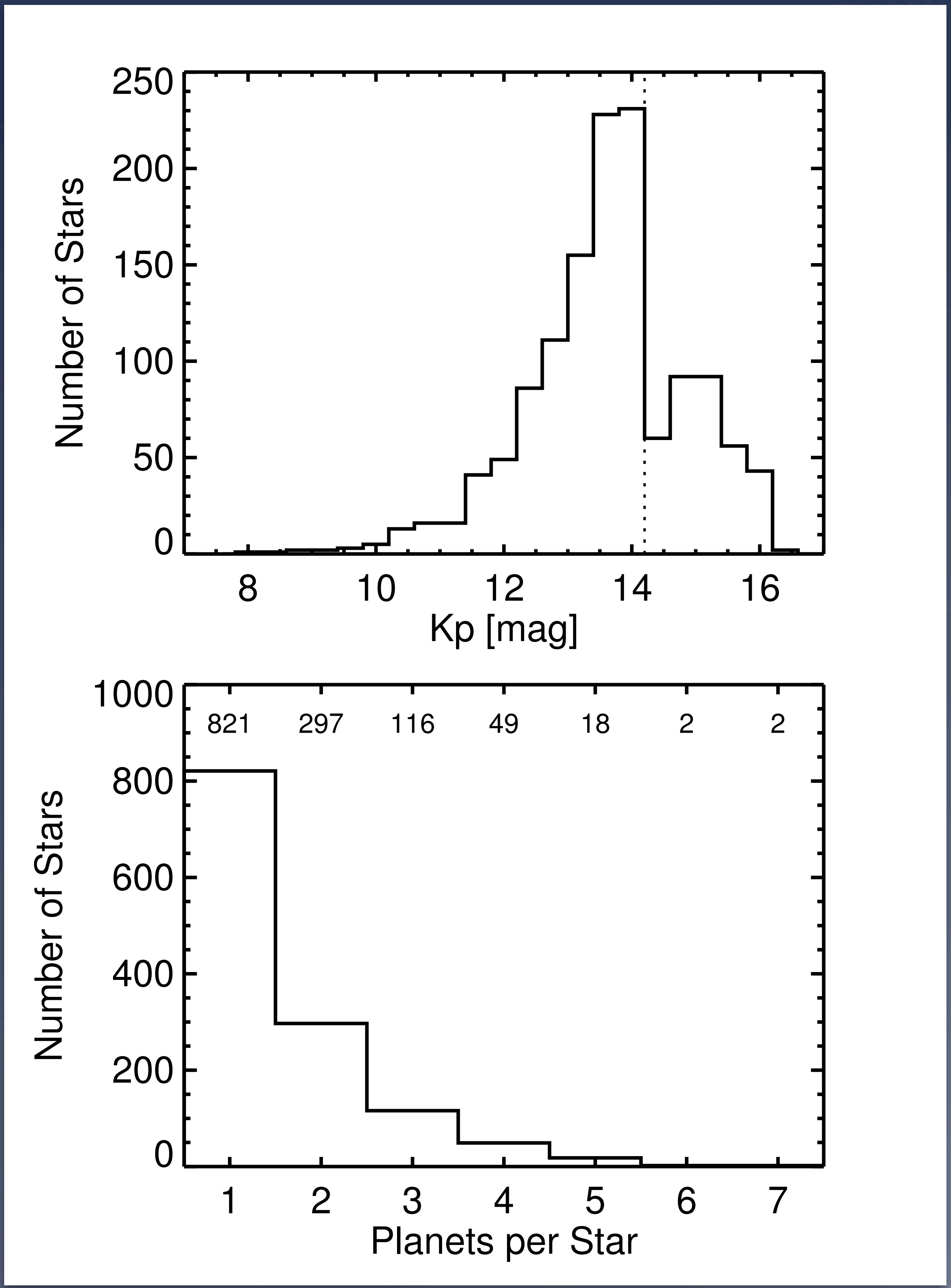
Photometry

- Homogeneous (Huber+14)
- $R_\star$ good to ~40%
- In 2017, majority of planet-hosting stars had photometric constraints only

Spectroscopy

- $R_\star$ as good as ~10%

The California-Kepler Survey

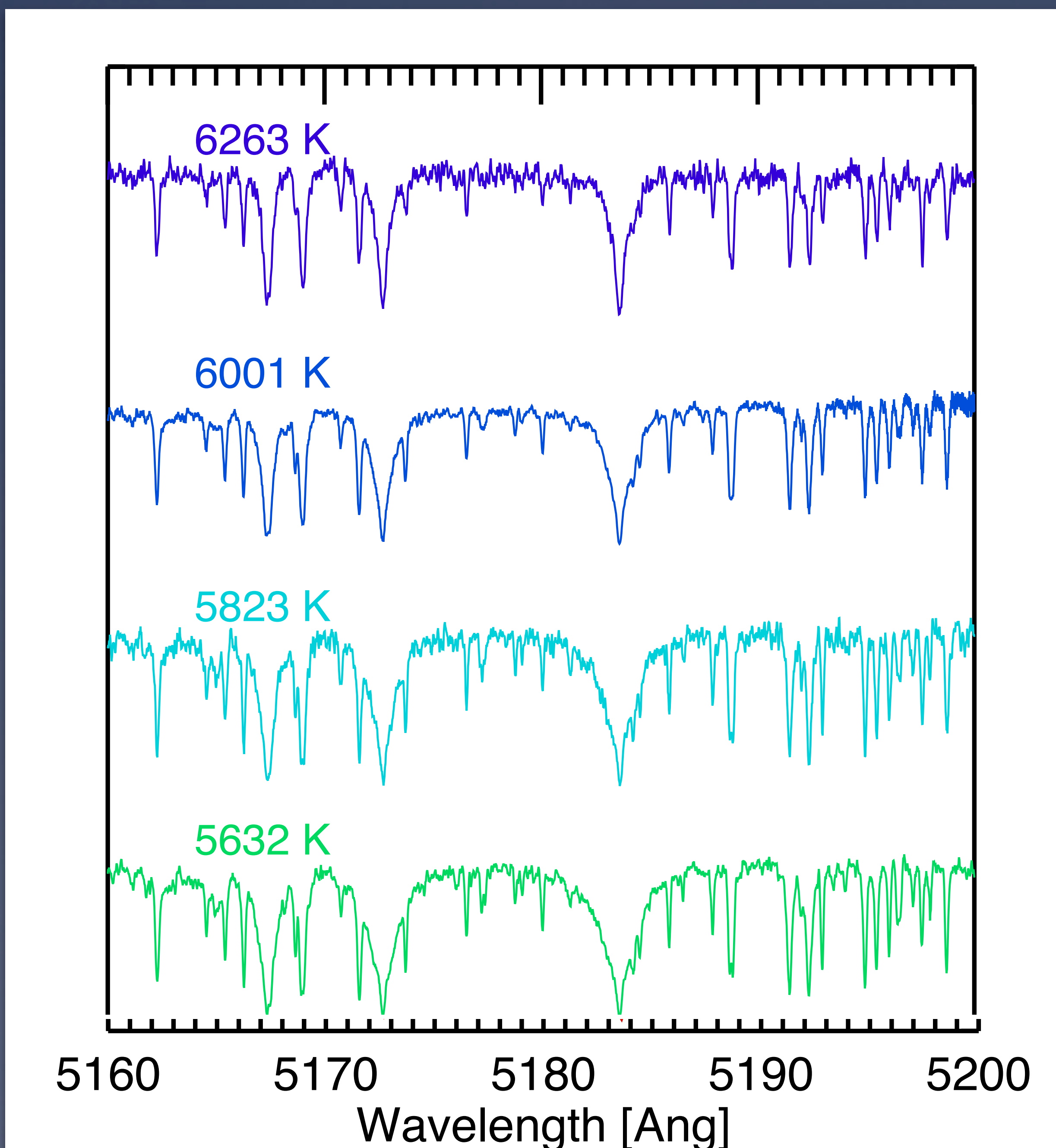


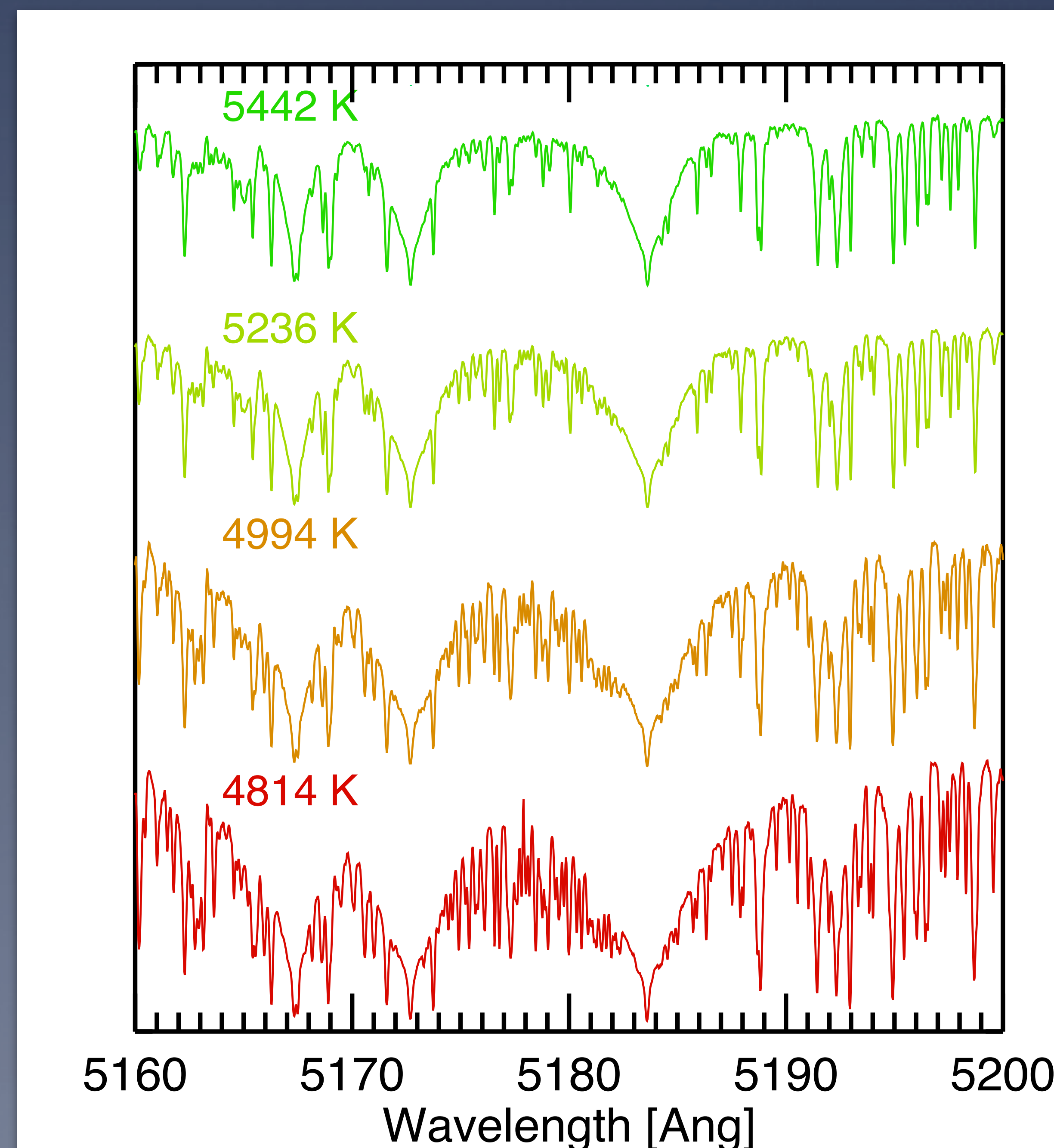
CKS-I: Petigura, Howard et al. (2017)

- PIs: Andrew Howard, Geoff Marcy, John Johnson
- 50 Keck nights (2011–2015)
- HIRES spectra of 1305 stars hosting 2025 planet candidates
- Core sample
  - Magnitude limited ($Kp < 14.2$) ($N_{\star} = 960$)
- Extensions
  - Multi-planet hosts ($N_{\star} = 484$)
  - Ultra-Short Period (USP) ($P < 1$d) ($N_{\star} = 71$)
  - Habitable Zone Planets ($N_{\star} = 127$)

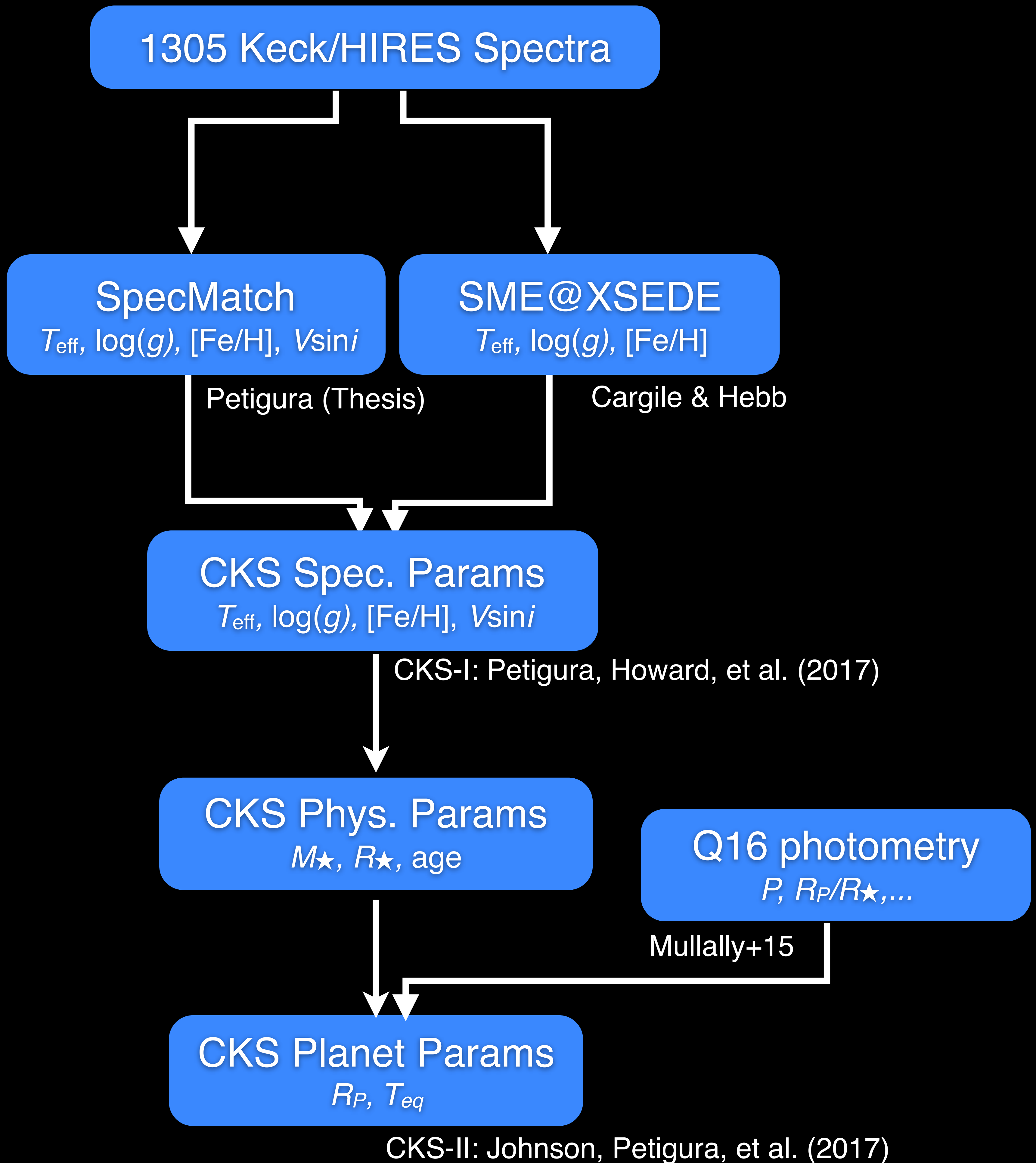
Keck/HIRES Spectra

- R = 60,000
- SNR = 45/pixel
- Precision Teff, logg, [Fe/H]
- Projected rotation *V*sin*i*
- Abundances [Na/H], [Li/H], ...
- Searches for faint SB2
- Absolute RVs (~100m/s)
- ... Your projects! (spectra are public)





CKS-I: Petigura, Howard et al. (2017)

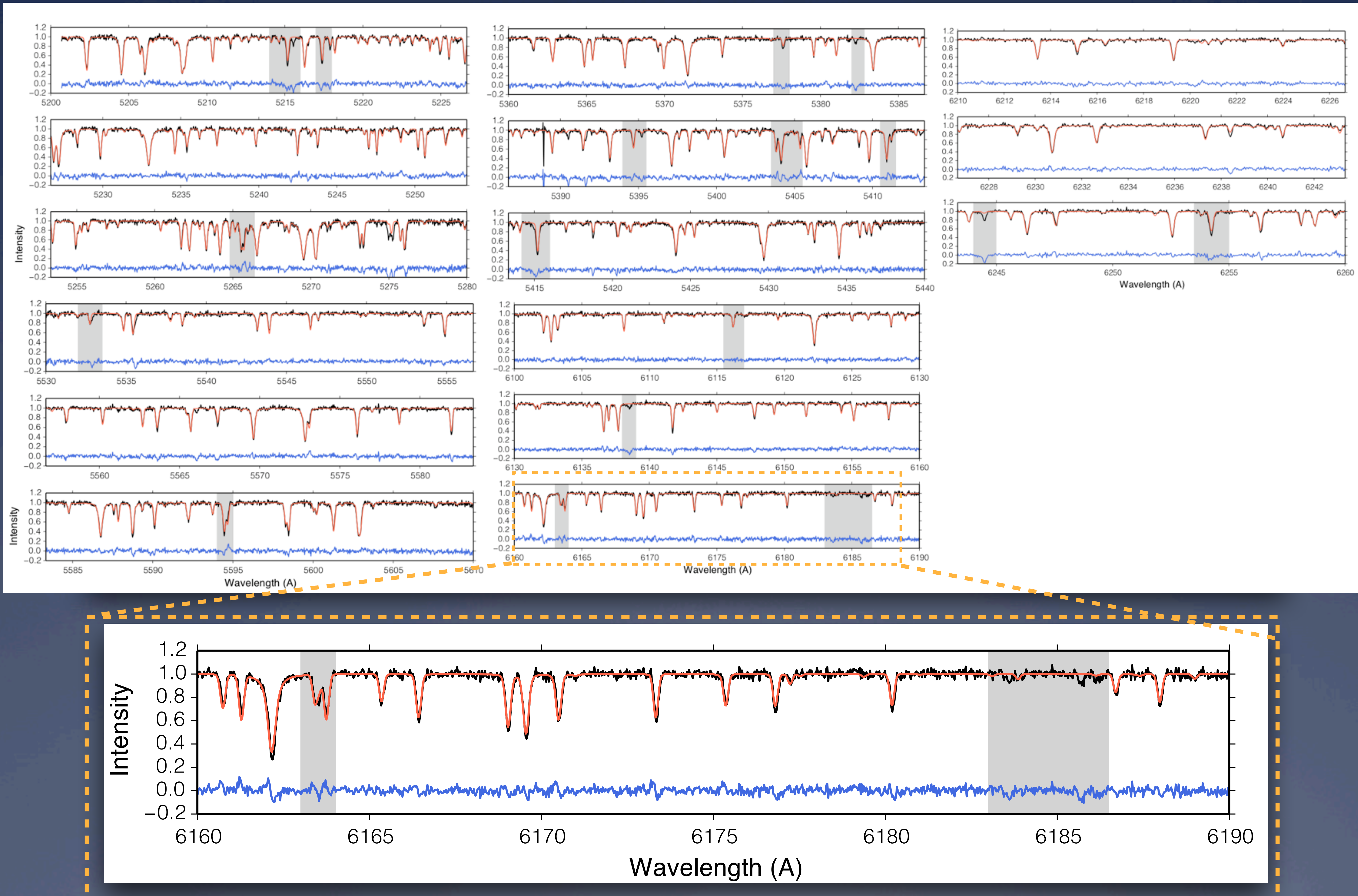


Independently analyze spectra with two spectral codes.

Combine parameters, identify outliers

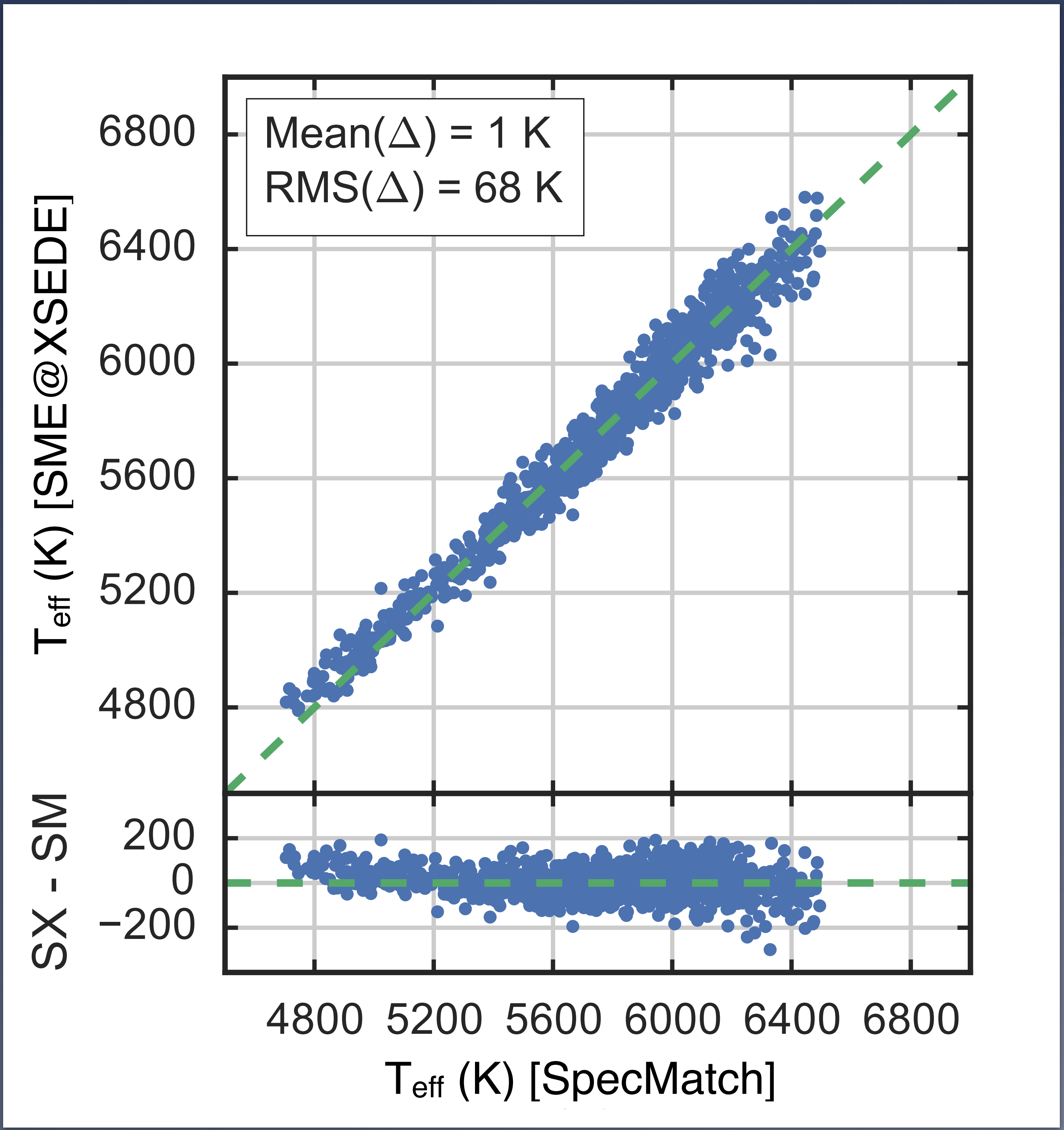
Isochrone modeling
Morton 2015

Re-derive planet properties



Petigura 15 (thesis)

CKS Precision: Effective Temp.



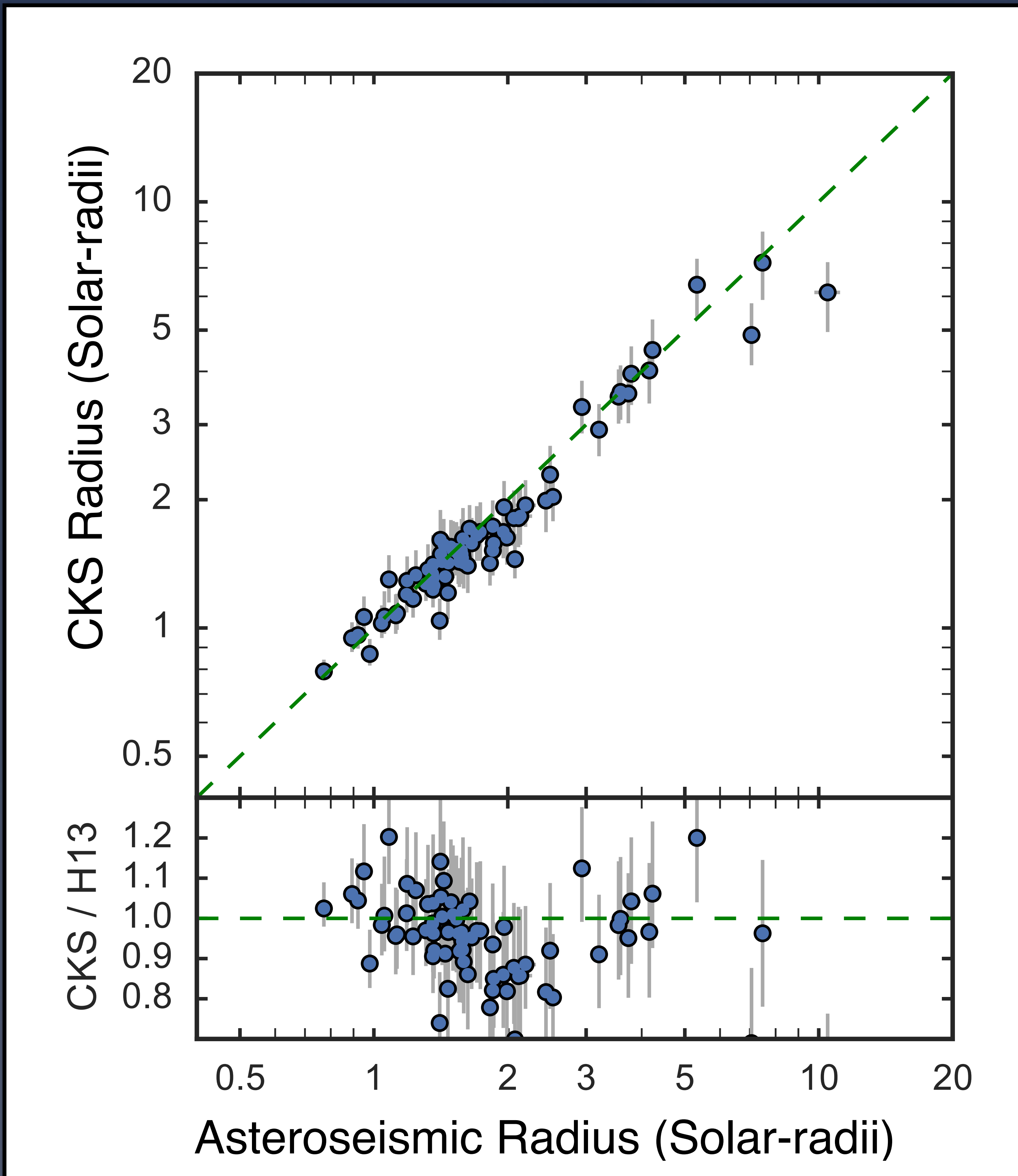
Spectroscopic

- T_{eff} ~ 60 K (vs ~200 K phot.)
- log*g* ~ 0.10 dex
- [Fe/H] ~ 0.04 dex
- vsini ~ 1 km/s

Derived

- $R_\star$ ~ 10% (vs ~40% phot.)
- $M_\star$ ~ 5%
- ages ~ 30%
- distances ~ 10%

CKS Precision: Stellar Radii



CKS-II: Johnson, Petigura, et al. (2017)

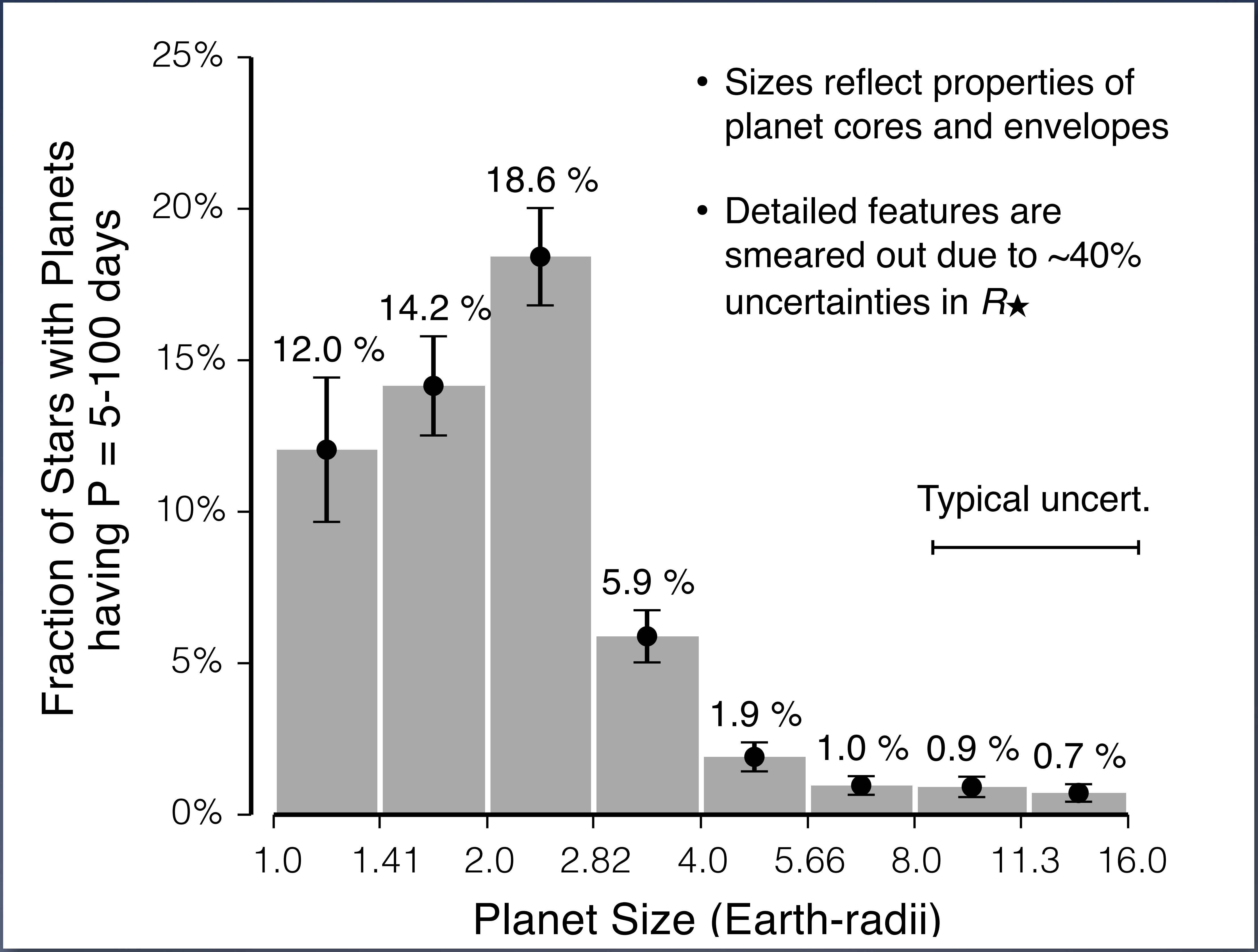
Spectroscopic

- T_{eff} ~ 60 K (vs ~200 K phot.)
- log*g* ~ 0.10 dex
- [Fe/H] ~ 0.04 dex
- vsini ~ 1 km/s

Derived

- $R_\star$ ~ 10% (vs ~40% phot.)
- $M_\star$ ~ 5%
- ages ~ 30%
- distances ~ 10%

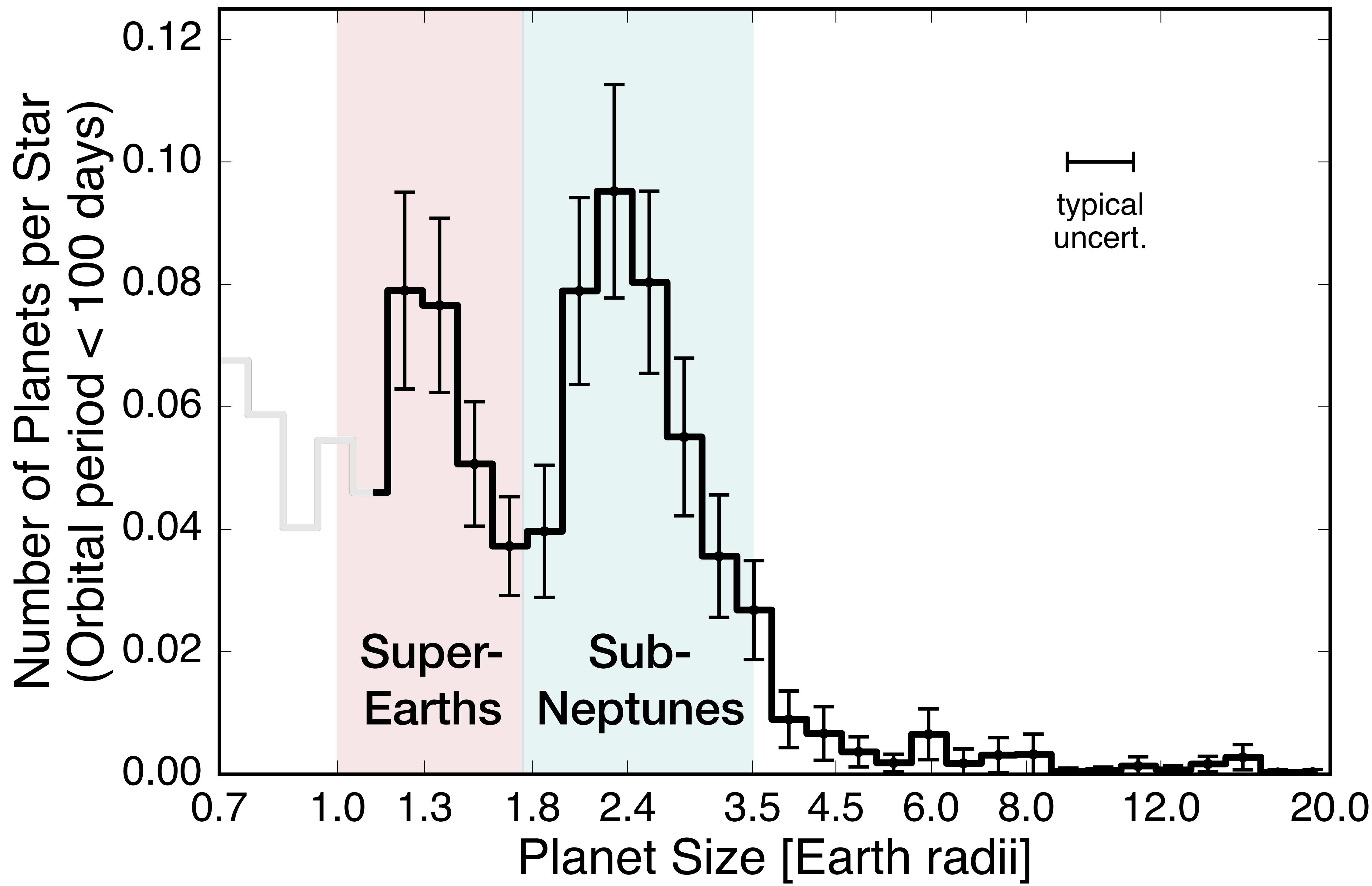
Gap in Planet Radii



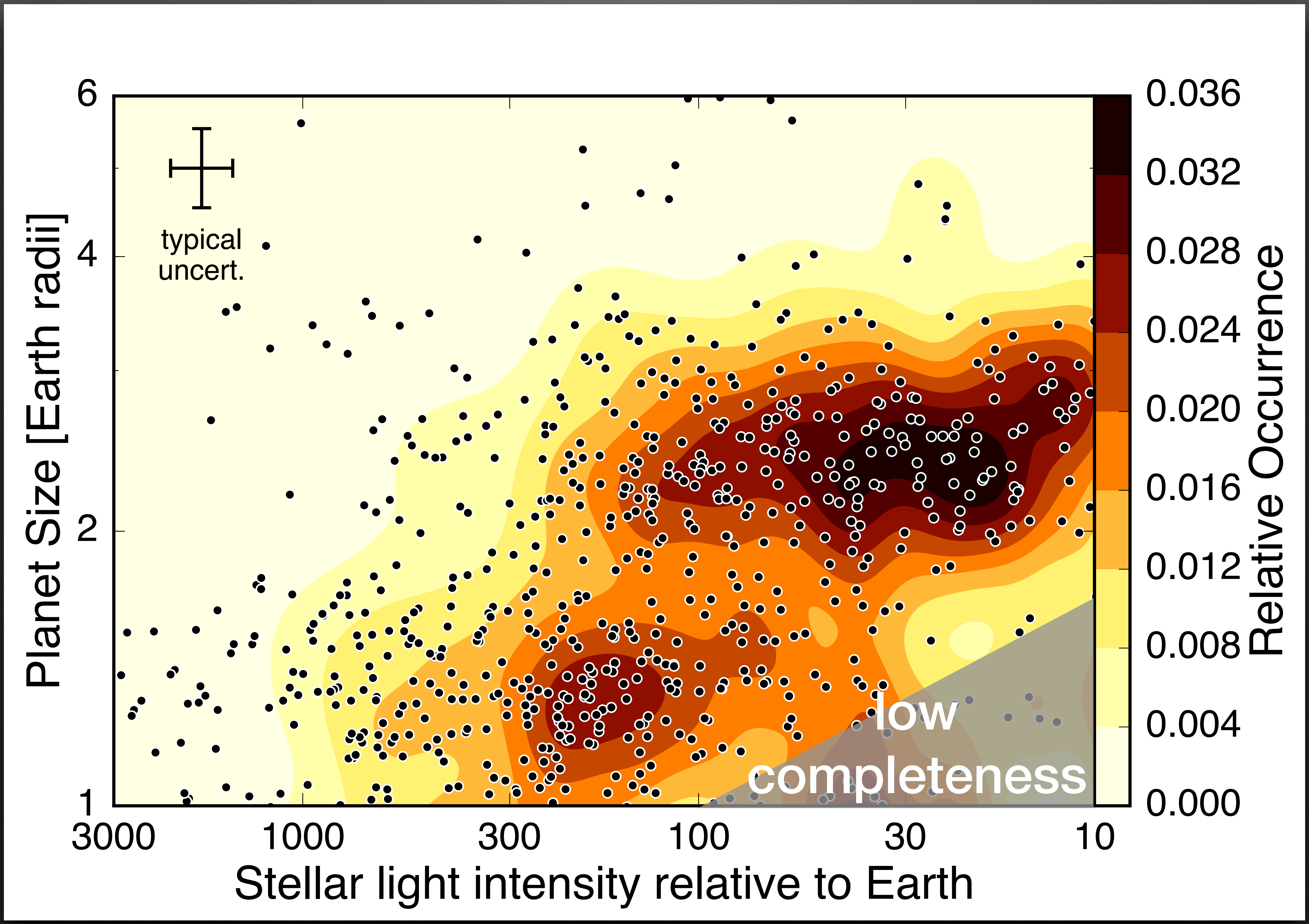
Petigura et al. (2013), *PNAS*

Fraction of stars with planets of different sizes

Gap in Planet Radii

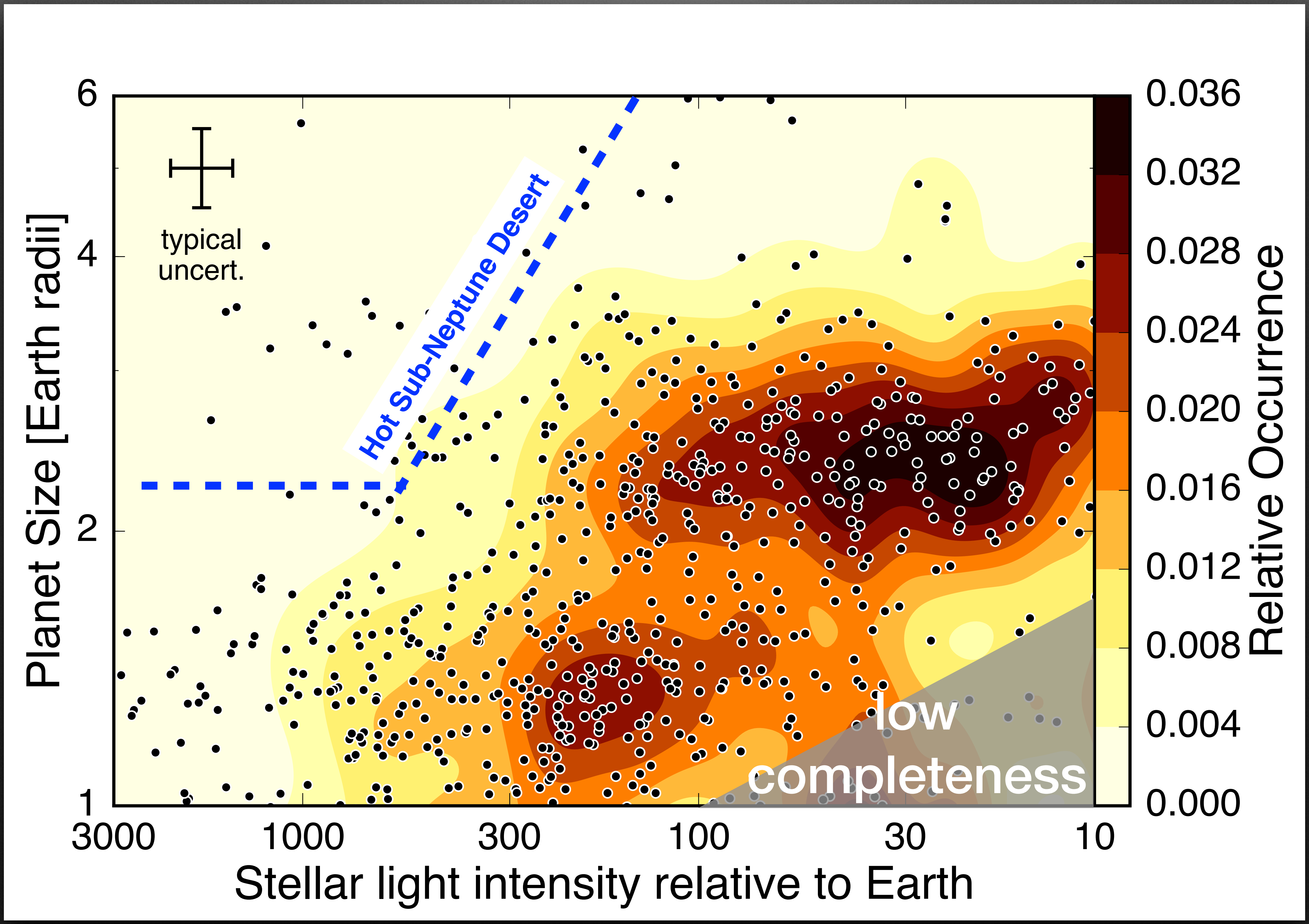


Flux Dependency



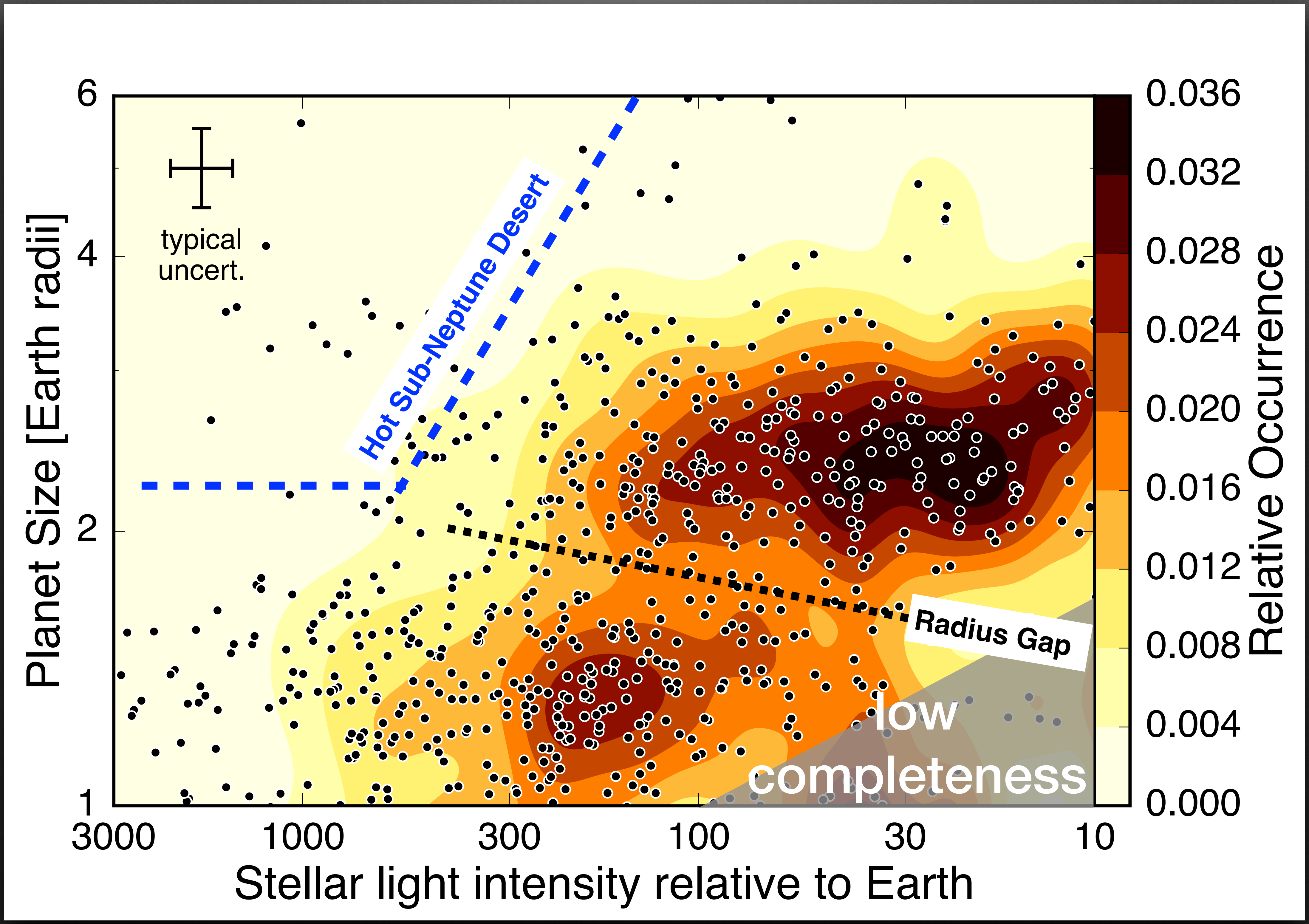
Fulton, Petigura, et al. (*2017*)

Flux Dependency



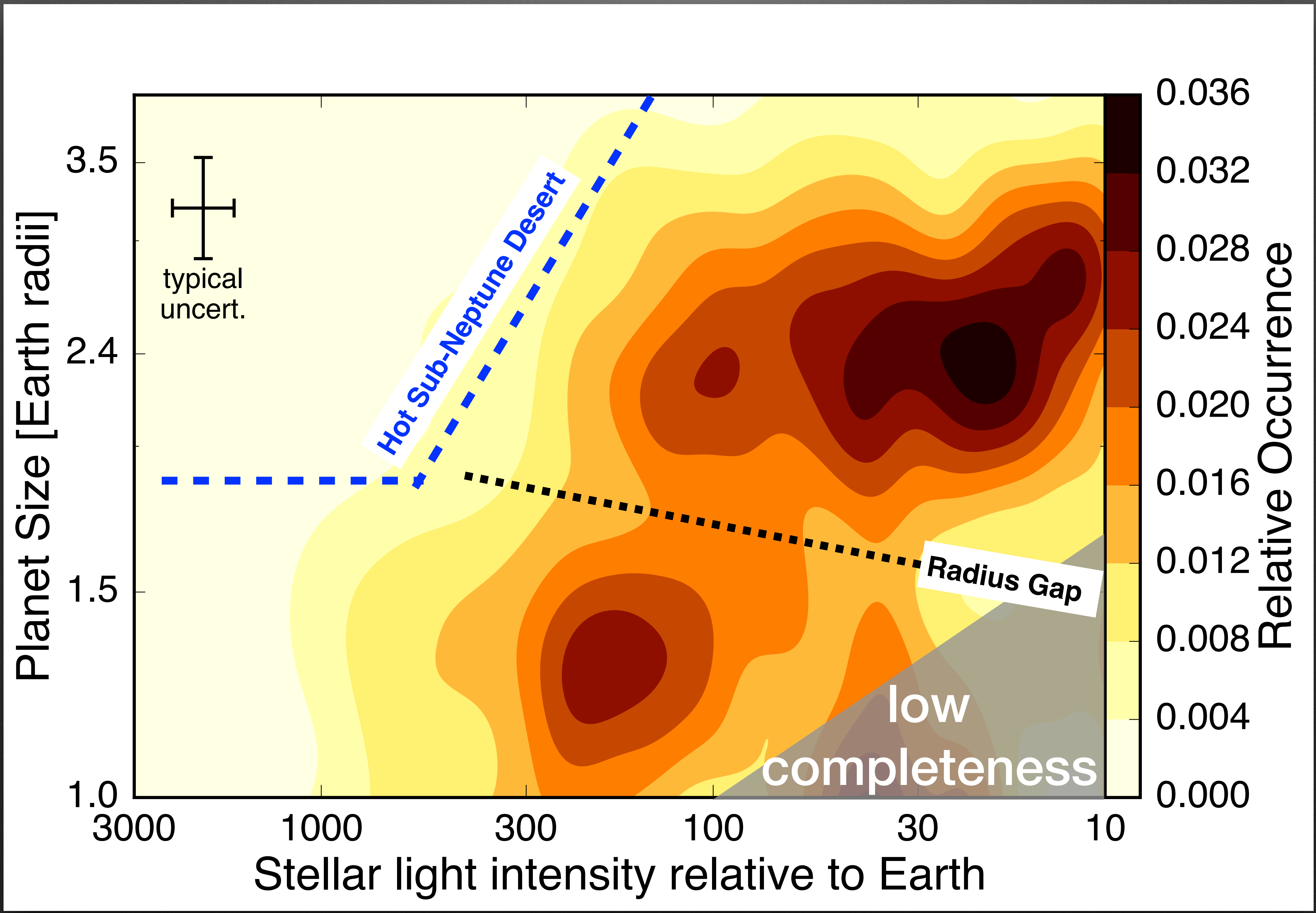
Fulton, Petigura, et al. (*2017*)

Flux Dependency



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

Flux Dependency



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Flux Dependency

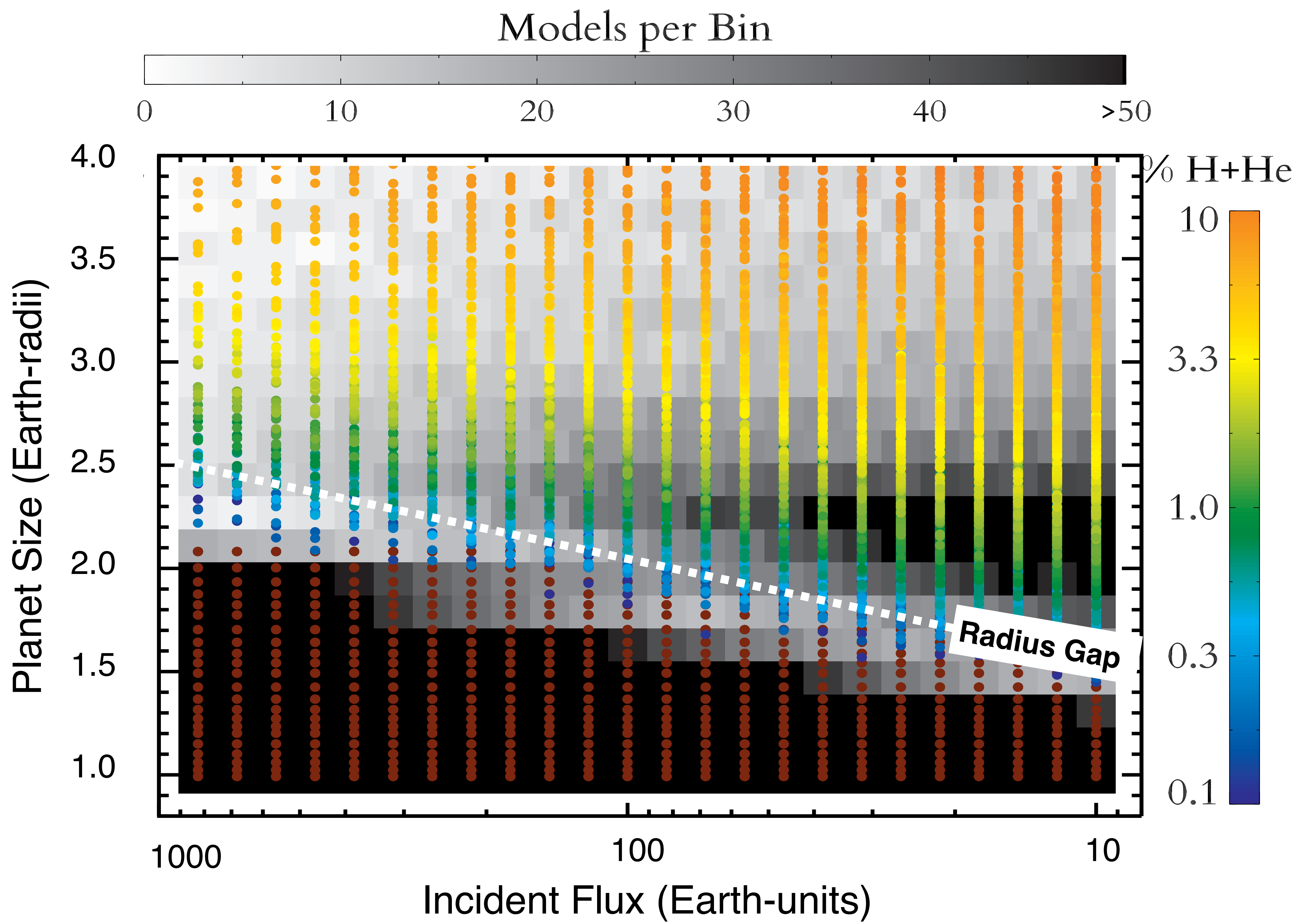
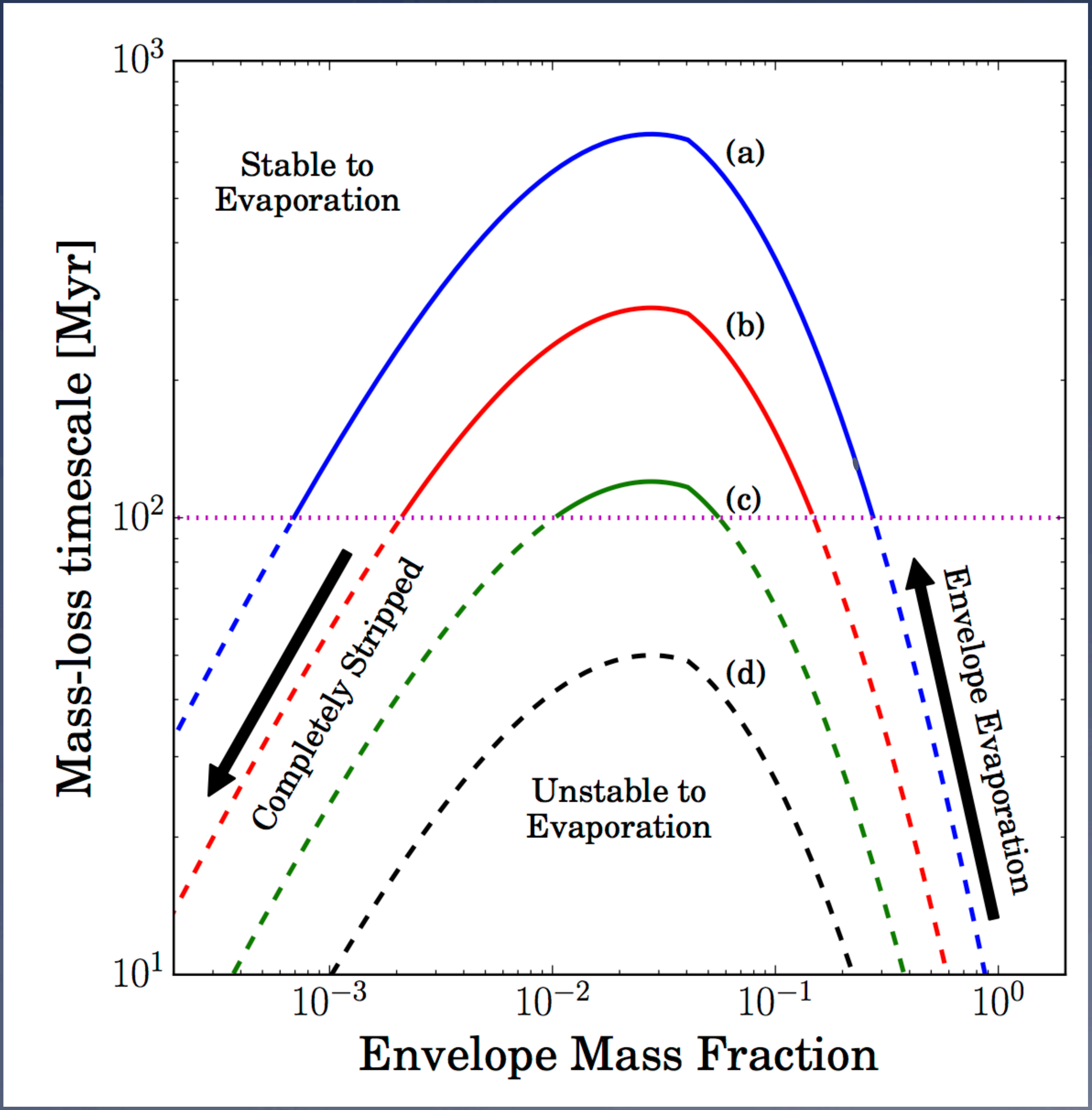


Figure from Lopez+16; see also Owen+13, Lopez+13, Jin+14, Chen+16

Photo-Evaporation Causes Gap



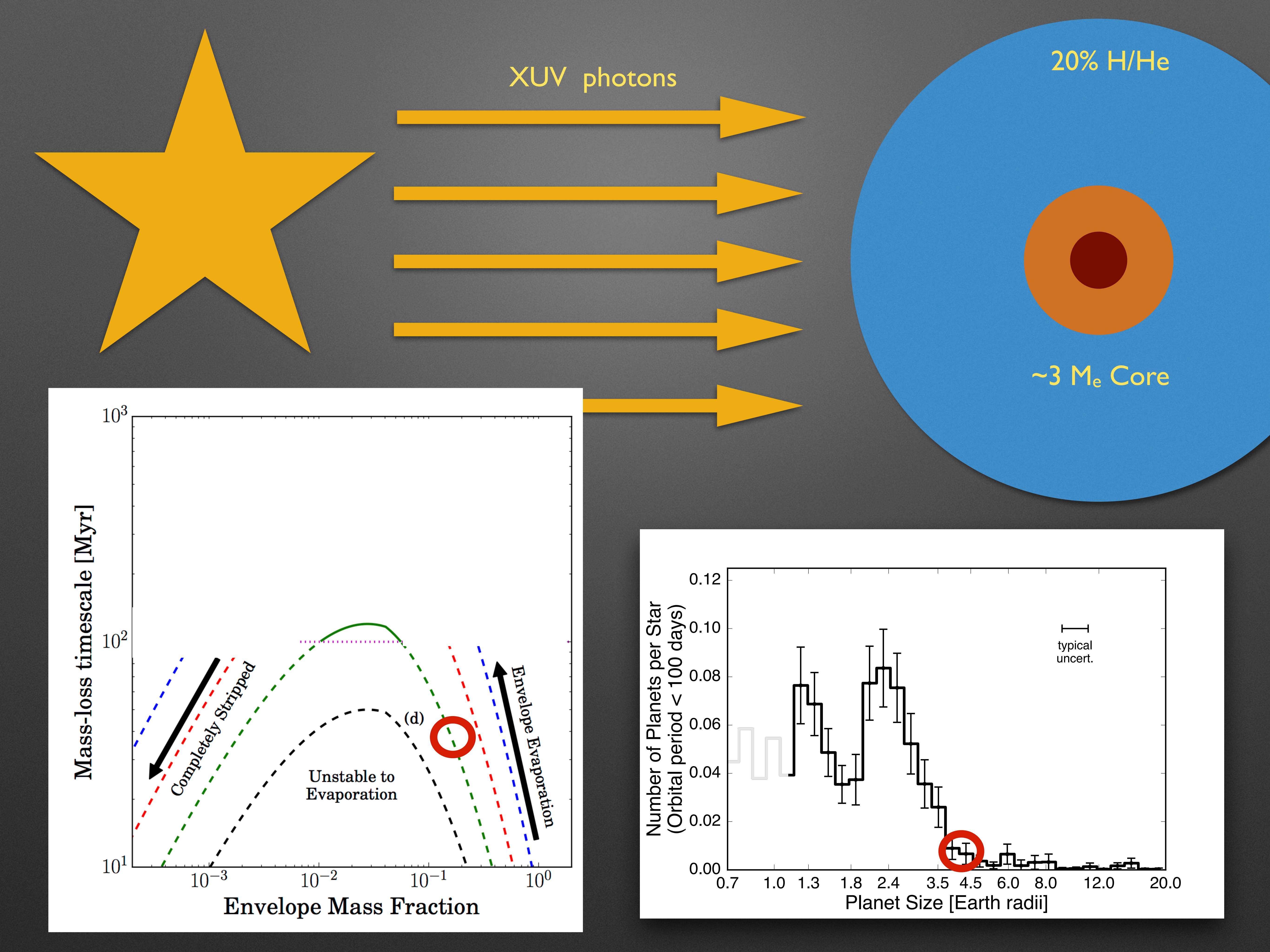
Owen and Wu (2017)

Predicted by Theory

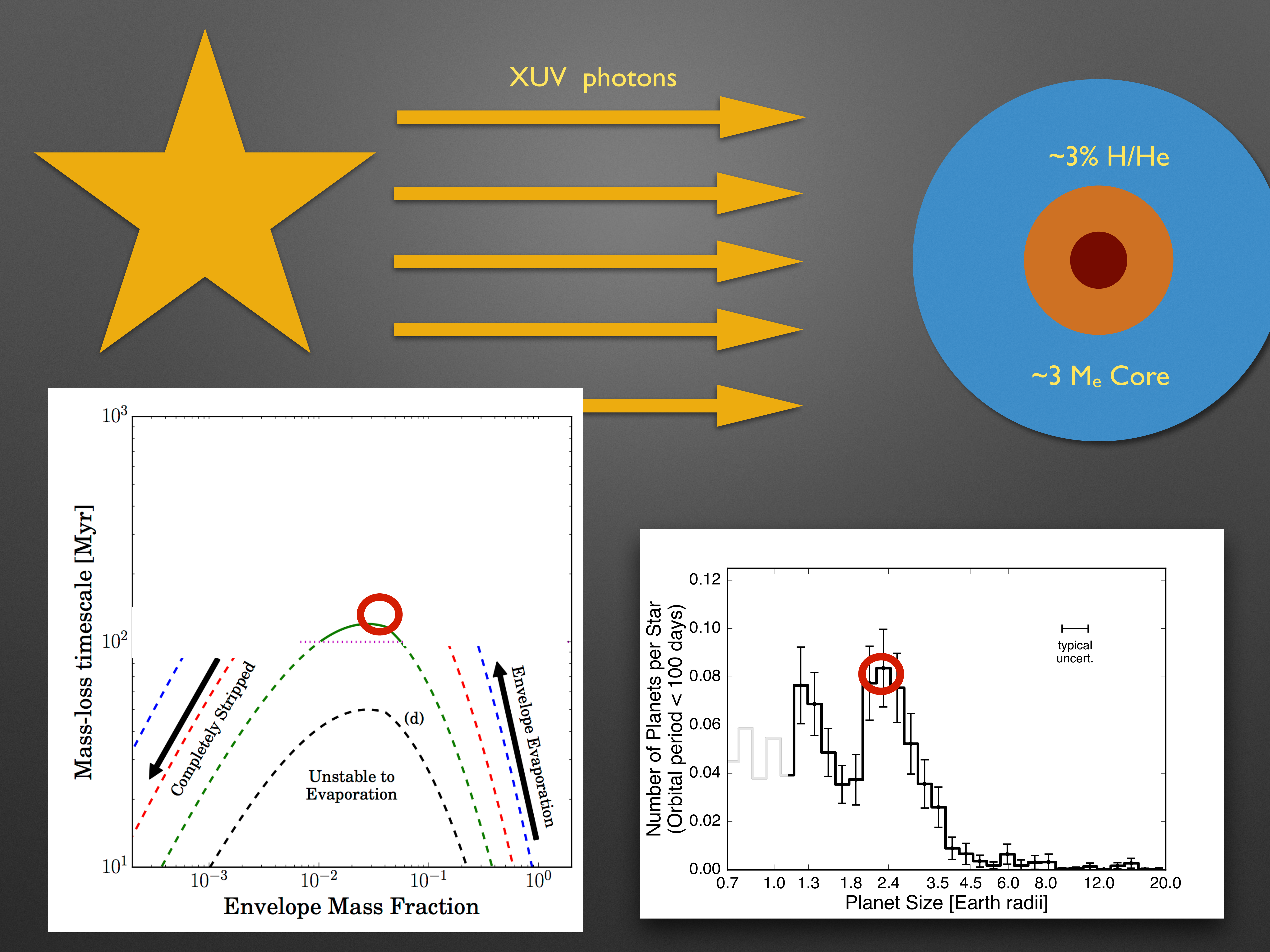
- Owen & Wu (2013)
- Lopez & Fortney (2013)
- Jin et al. (2014)
- Chen & Rogers (2016)

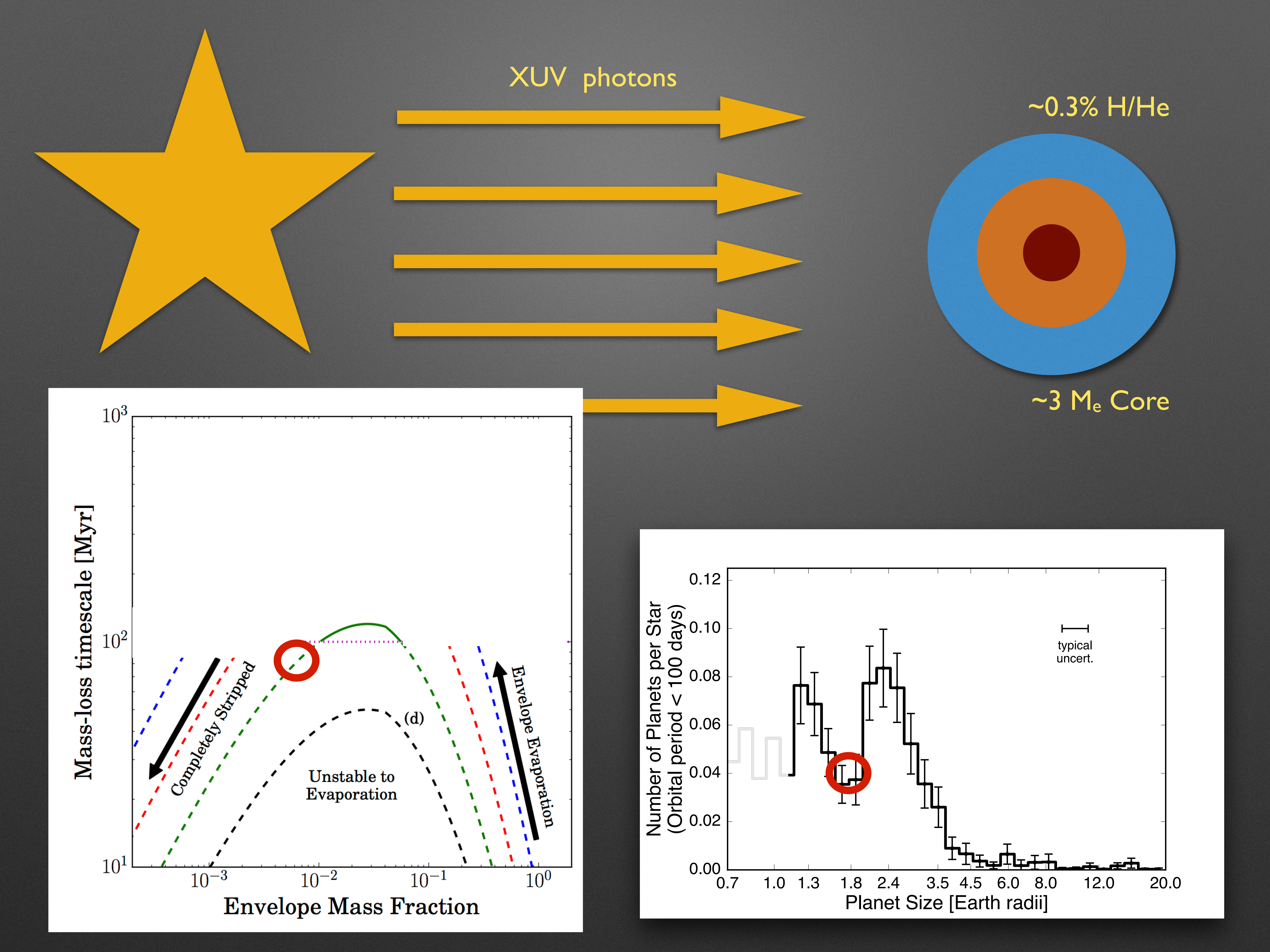
Explanation

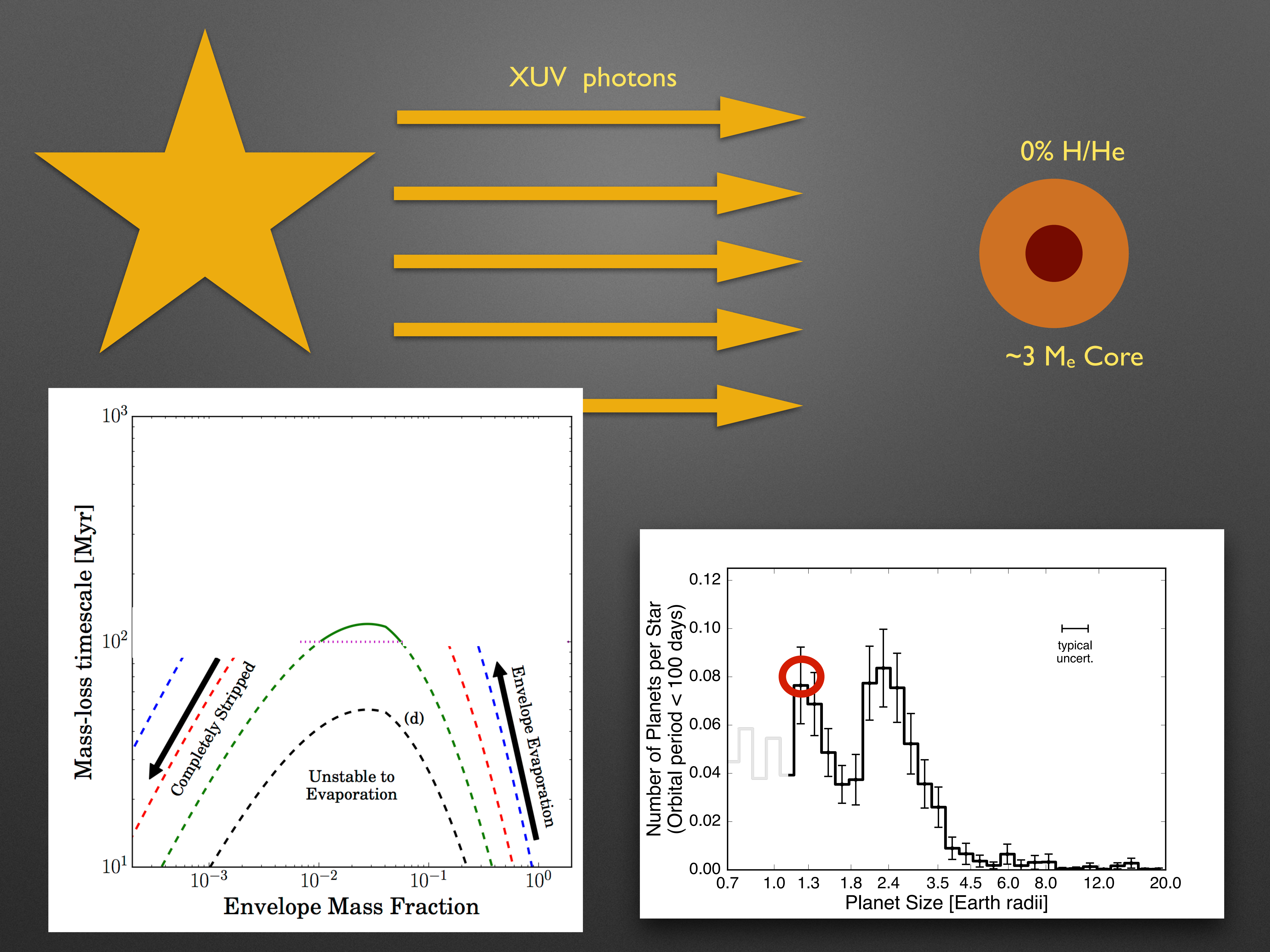
- High energy XUV photons emitted during star's first 100 Myr erodes envelopes
- Most sub-Neptunes are ~3% H/He by mass. Why?
- 3% H/He envelopes have longest mass loss timescale
- Planets are "herded" into two typical sizes



XUV photons
20% H/He
~3 M_e Core
Mass-loss timescale [Myr]
10^3
10^2
10^1
10^{-3}
10^{-2}
10^{-1}
10^0
Envelope Mass Fraction
Completely Stripped
Envelope Evaporation
Unstable to Evaporation
(d)
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
~3% H/He
~3 Me Core
Mass-loss timescale [Myr]
Envelope Mass Fraction
Completely Stripped
Envelope Evaporation
Unstable to Evaporation
(d)
Number of Planets per Star (Orbital period < 100 days)
Planet Size [Earth radii]
typical uncert.

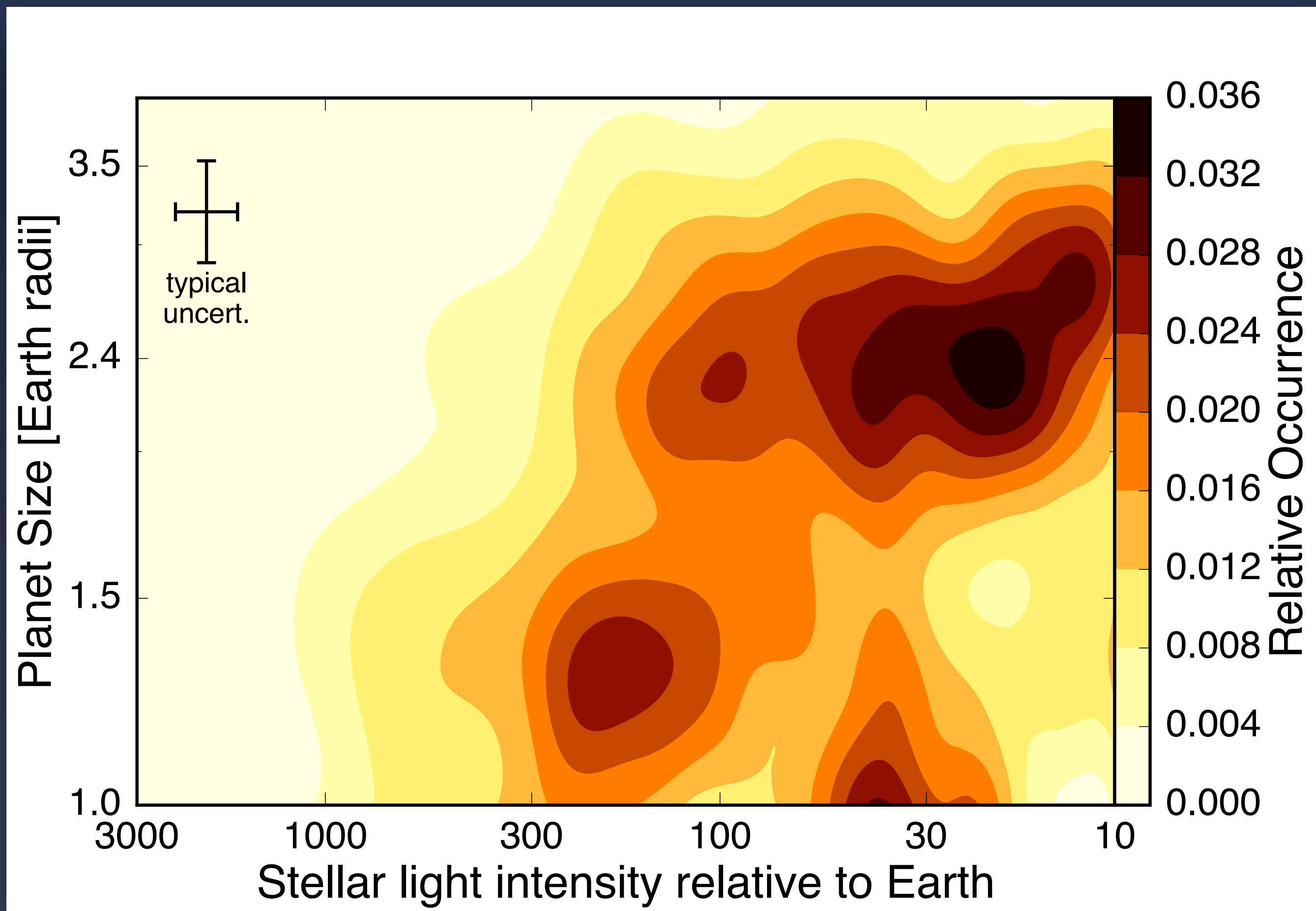

XUV photons
~0.3% H/He
~3 Mₑ Core
Mass-loss timescale [Myr]
Envelope Mass Fraction
10^1
10^2
10^3
10^{-3}
10^{-2}
10^{-1}
10^0
Completely Stripped
Envelope Evaporation
(d)
Unstable to
Evaporation
Number of Planets per Star
(Orbital period < 100 days)
Planet Size [Earth radii]
0.00
0.02
0.04
0.06
0.08
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
typical
uncert.



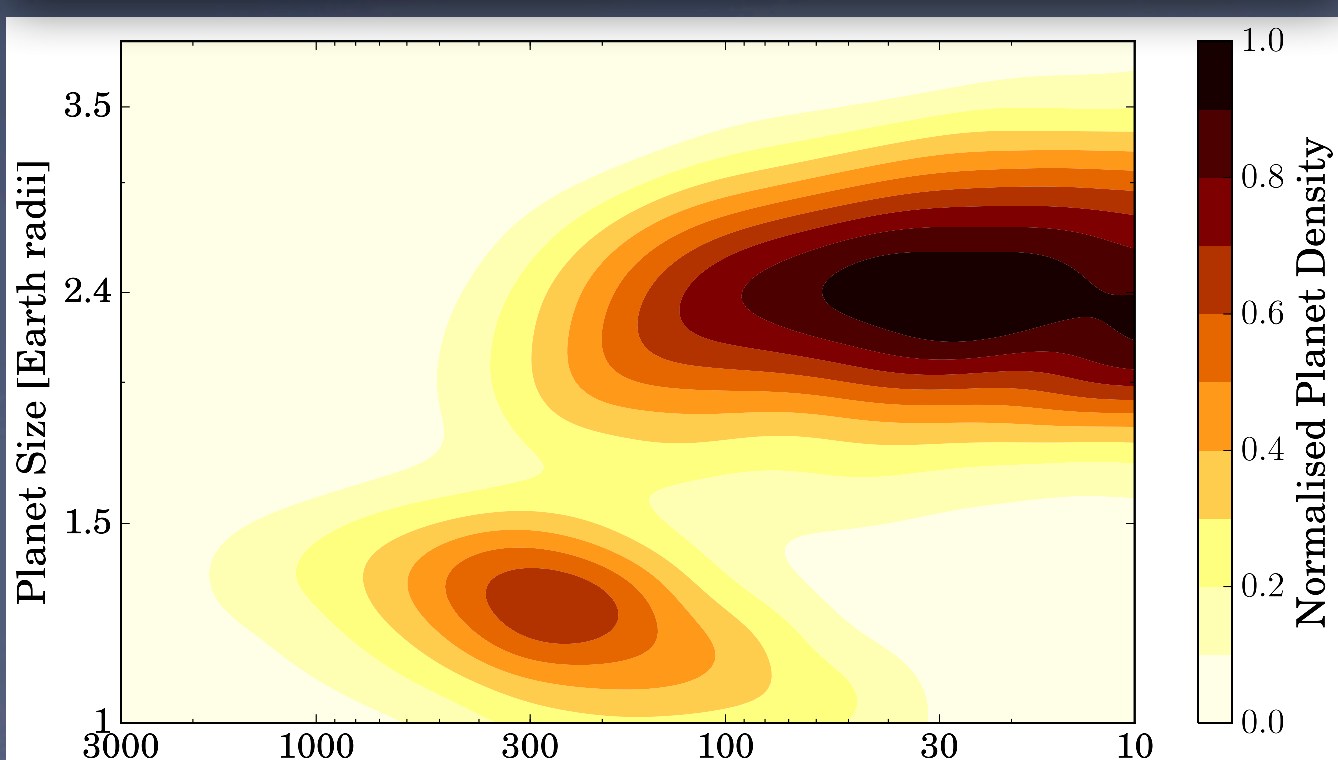
XUV photons
0% H/He
~3 Me Core
Mass-loss timescale [Myr]
Envelope Mass Fraction
Completely Stripped
Envelope Evaporation
Unstable to Evaporation
(d)
Number of Planets per Star
(Orbital period < 100 days)
Planet Size [Earth radii]
typical uncert.

Photo-Evaporation Causes Gap

Fulton, Petigura, et al. (2017)



Owen and Wu (2017)

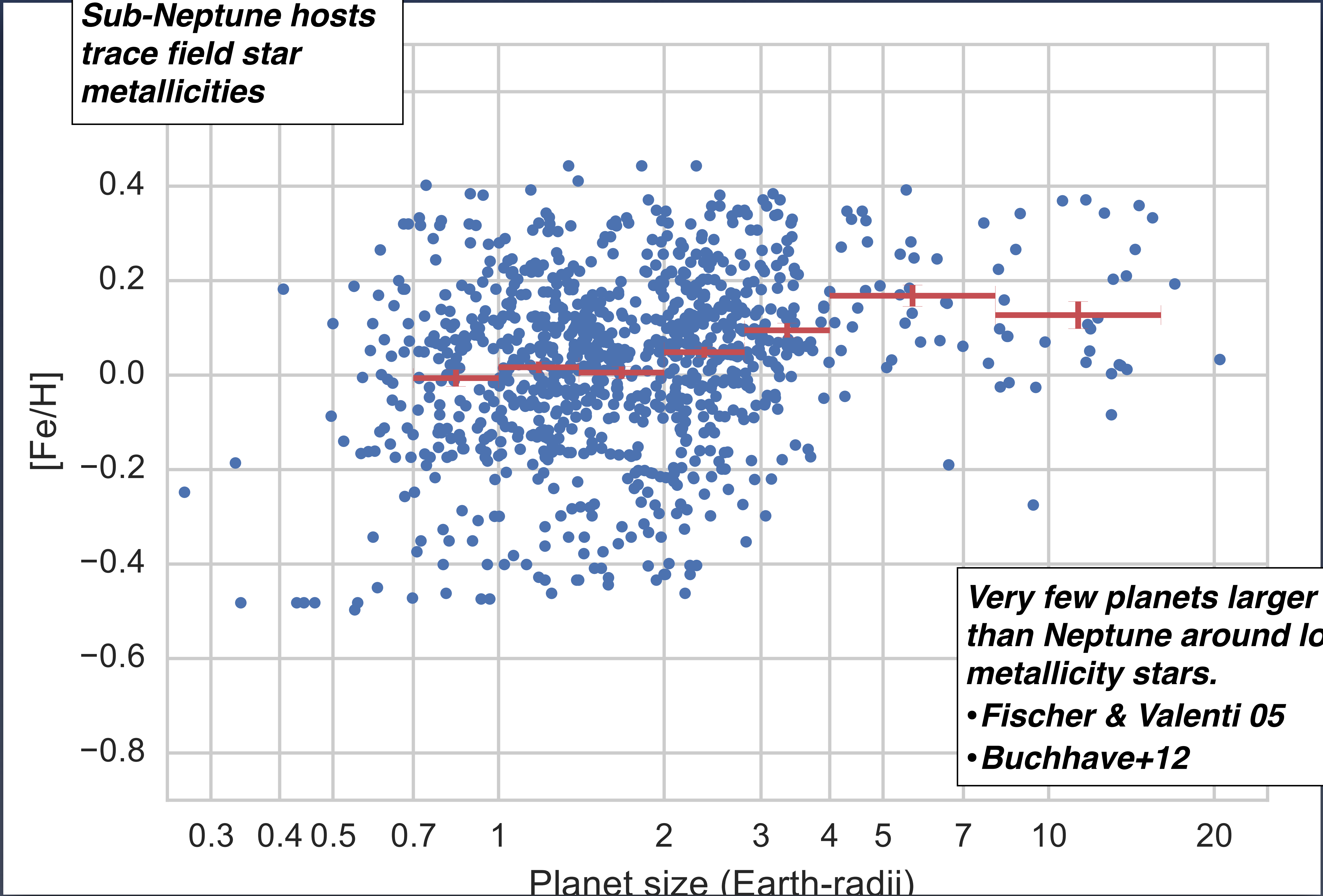


Implications

- Most common core mass is ~3 M_E
- Why are inner solar system planets < 1 M_E?
- Large scale migration after 100 Myr is uncommon
- Planet population should change as a function of stellar mass (different XUV output)

Planet-Metallicity Connection

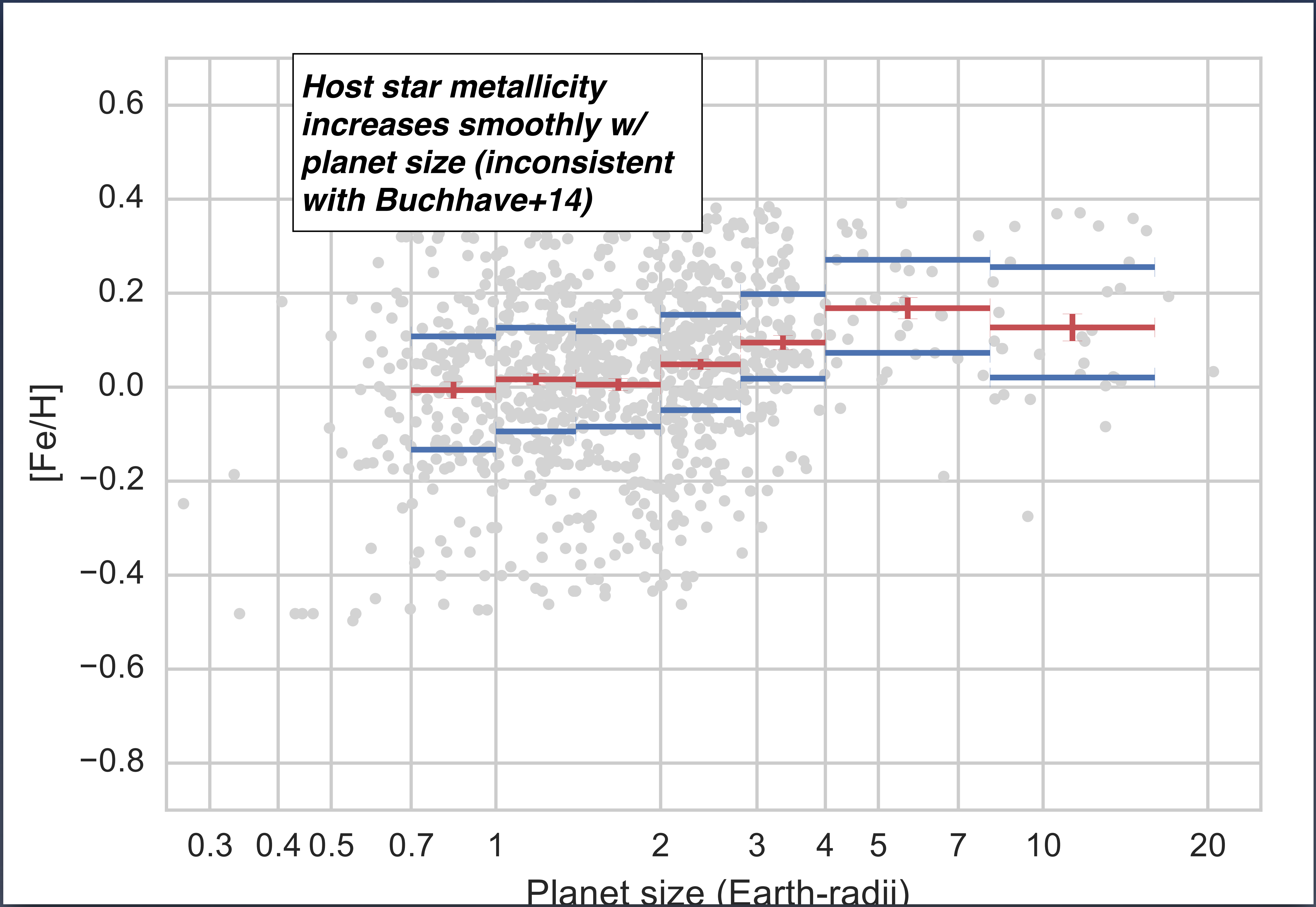
Sub-Neptune hosts trace field star metallicities



Very few planets larger than Neptune around low-metallicity stars.

- ***Fischer & Valenti 05***
- ***Buchhave+12***

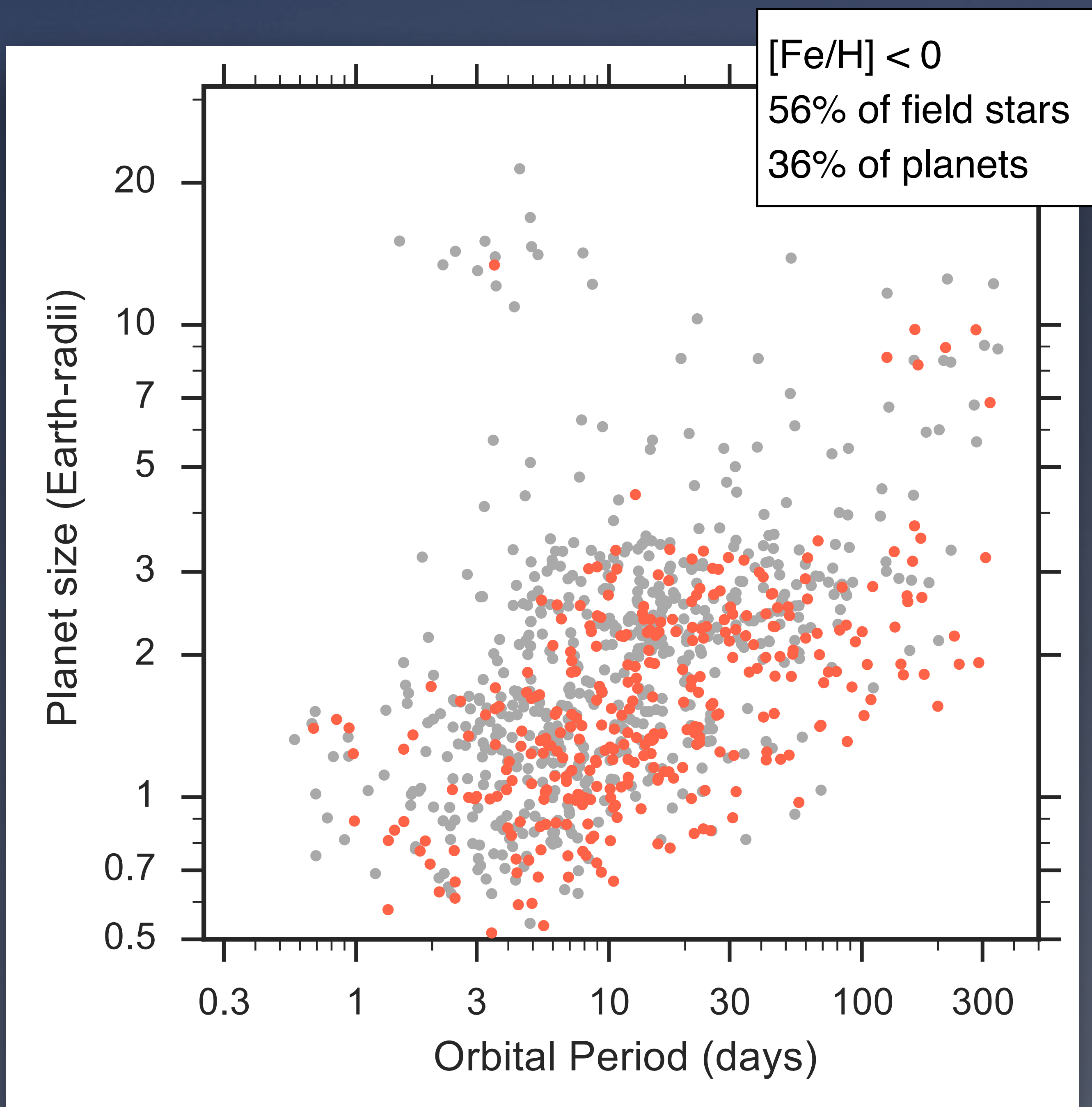
Planet-Metallicity Connection

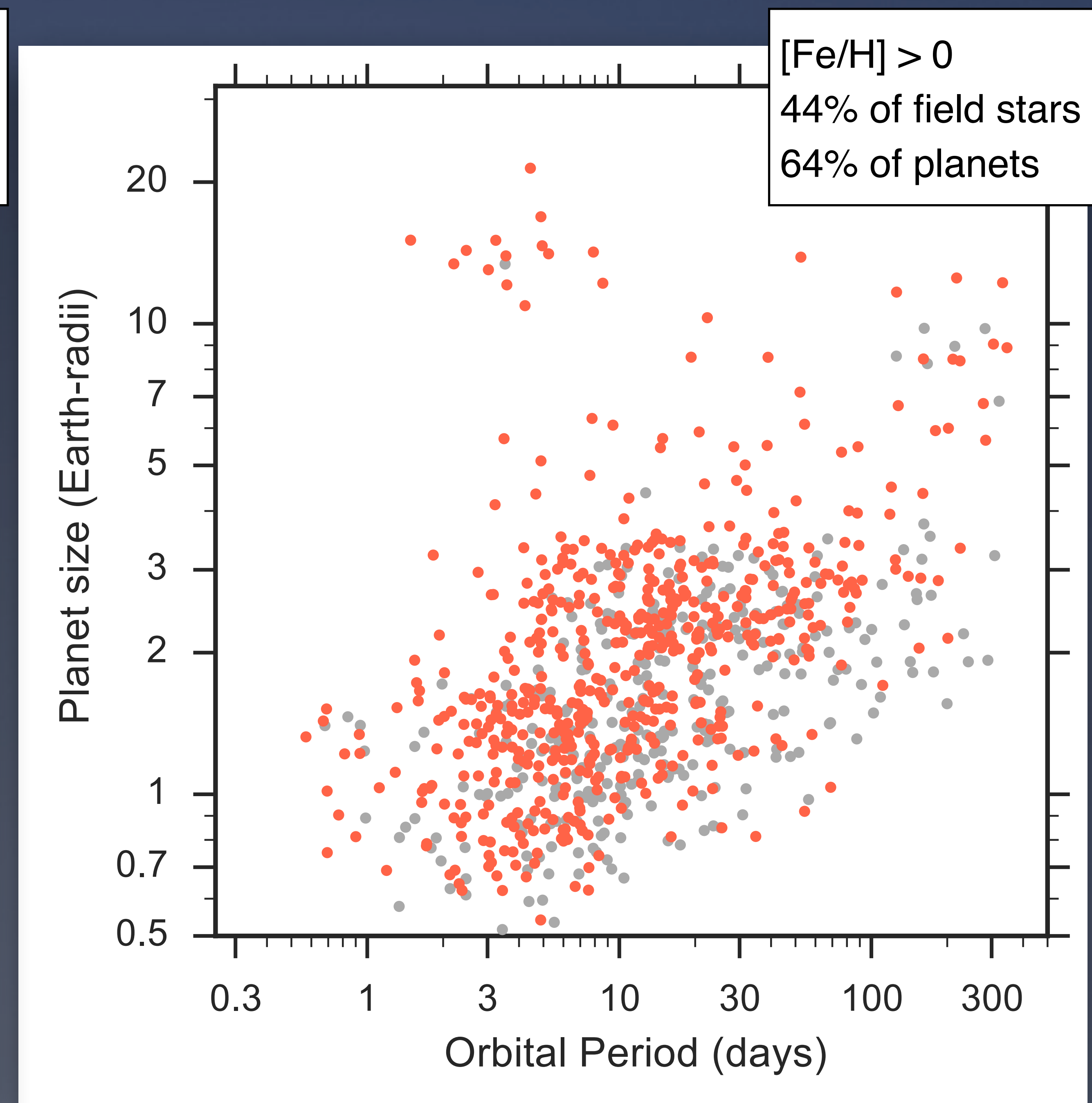


Metal-rich Stars: Diverse Planets

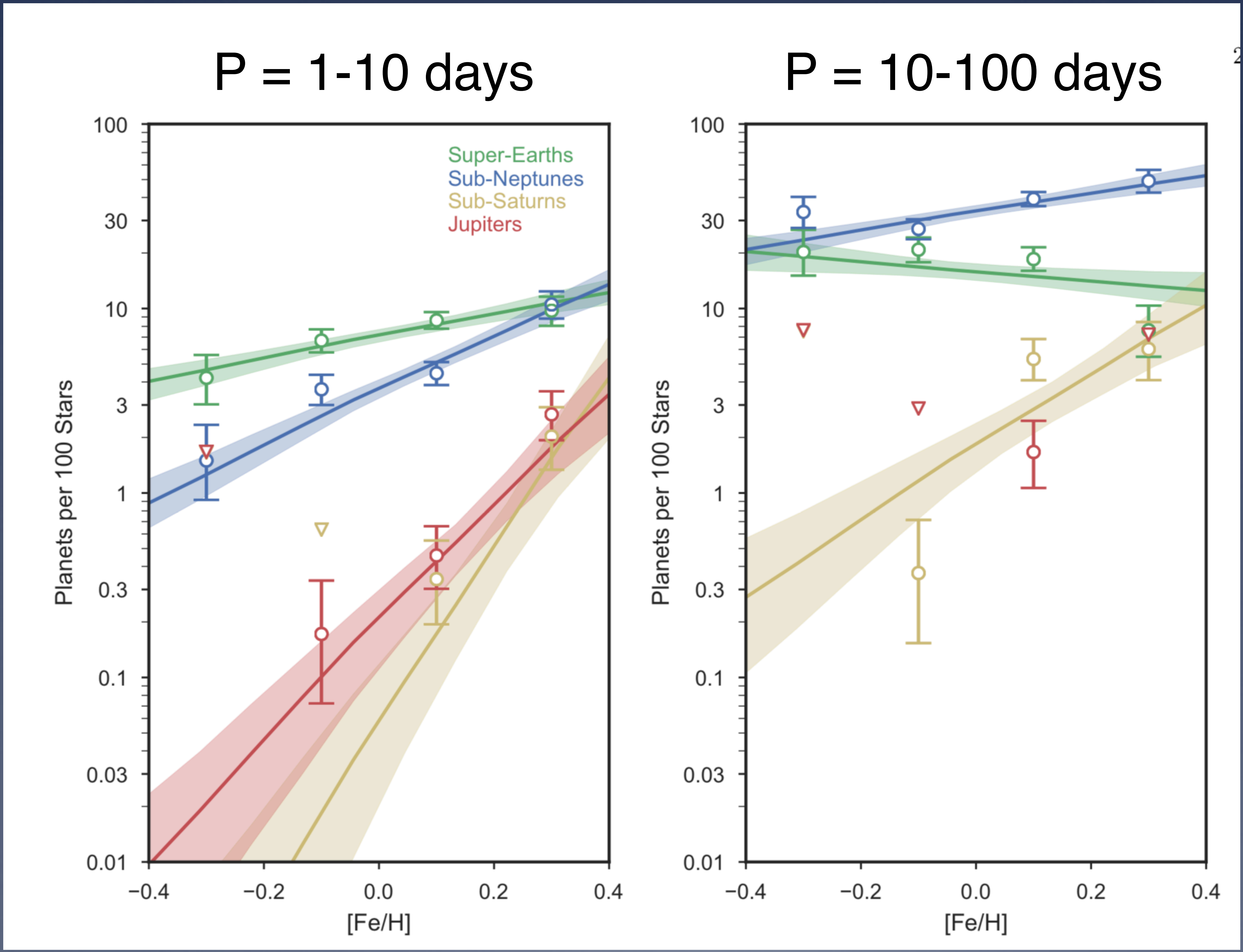
- Very few Hot Jupiters
- Few close-in planets (Mulders+16)
- Few planets larger than Neptune
- Possible exception: cool giants ($P > 100$ d)

- More Hot Jupiters
- More close-in planets (Mulders+16)
- More warm sub-Saturns and Jovians ($P = 10$–100d)

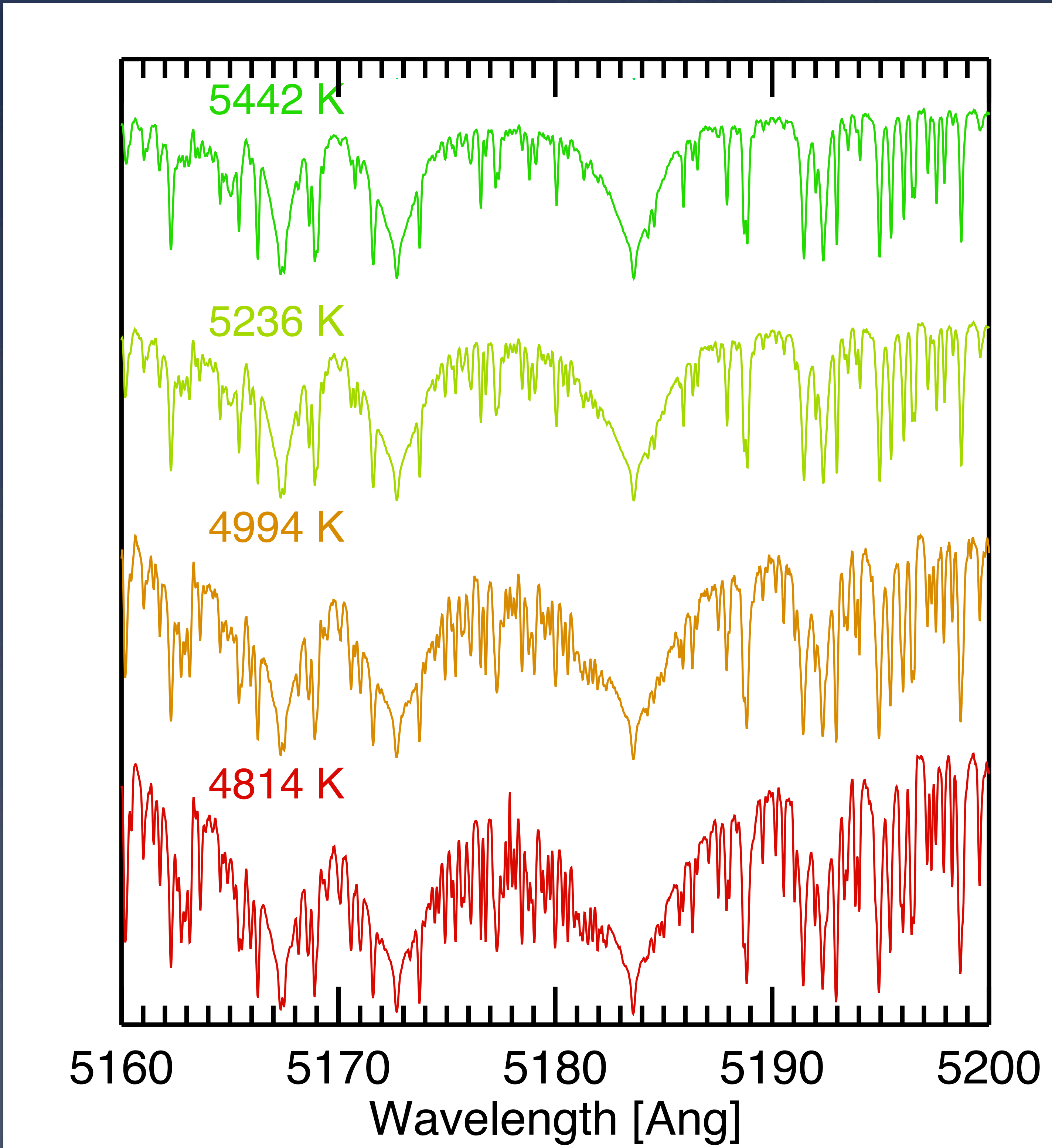




Planet-Metallicity Correlation



The California-Kepler Survey



CKS-I: Petigura, Howard et al. (2017)

Homogeneous

- Keck spectra of 1305 stars hosting 2025 planet candidates

Precision

- Planet radii precise to ~10%

New insights

- Fulton radius gap
- Planet-metallicity connection
- *Kepler* compact multis
- Your projects

Data are public

- Spectra and parameters publicly available on the ExoFOP
- **astro.caltech.edu/~howard/cks/**