The Frequency of Exoplanetary Systems

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University of California, Berkeley

Know Thy Star – Know Thy Planet

Pasadena, CA

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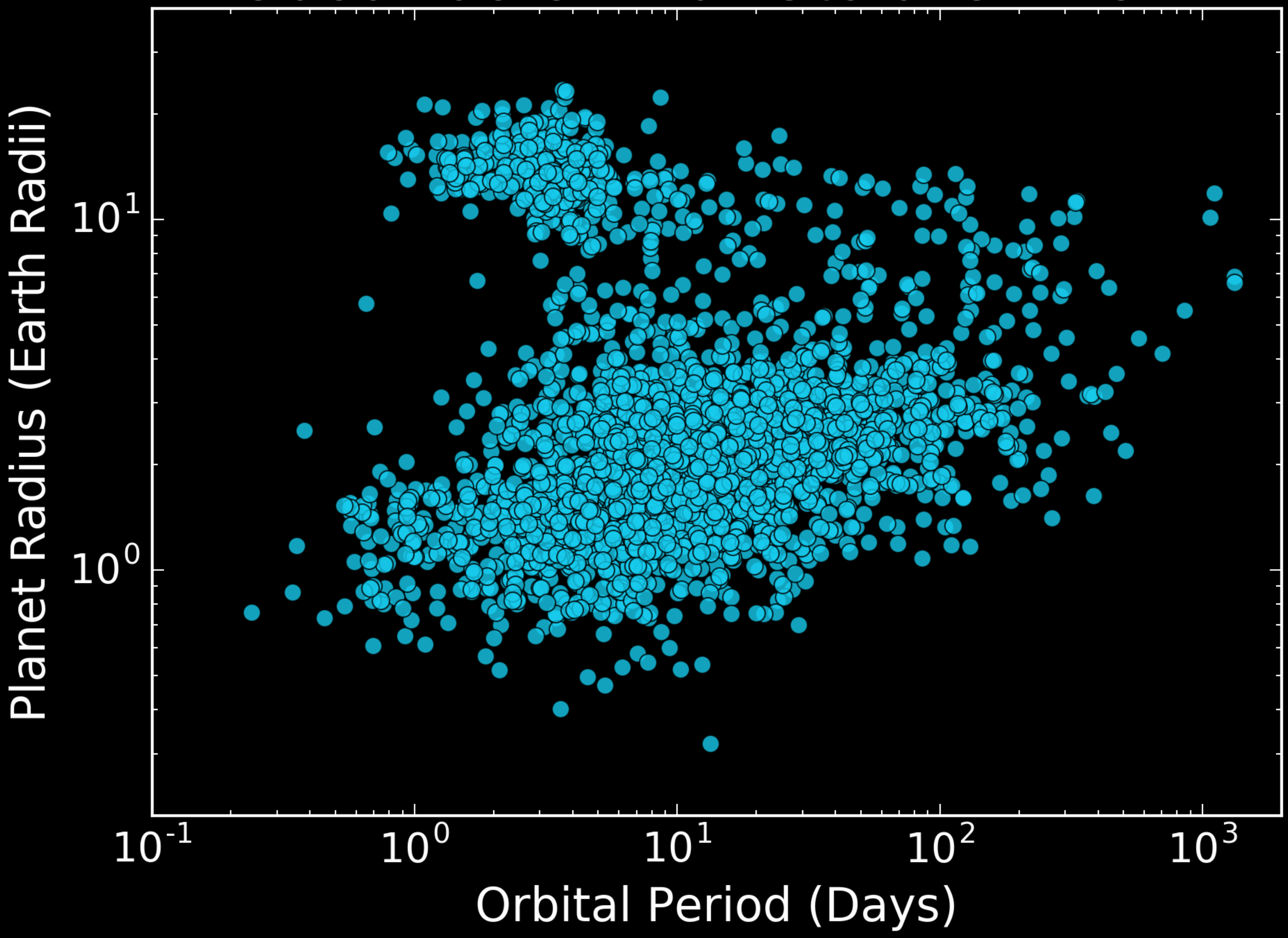
Collaborators: Andrew Vanderburg, Josh Schlieder, Ian Crossfield, Heather Knutson, Elisabeth Newton, David Ciardi, BJ Fulton, Erica Gonzales, Kevin Hardegree-Ullman, Andrew Howard, Howard Isaacson, John Livingston, Erik Petigura, Evan Sinukoff, Mark Everett, Elliott Horch, Steve Howell, Girish Duvvuri, Arturo Martinez, the K2 California Consortium, the HARPS-N Collaboration, & the TESS Minjas

Thousands of Planets are Known



Data from NASA Exoplanet Archive

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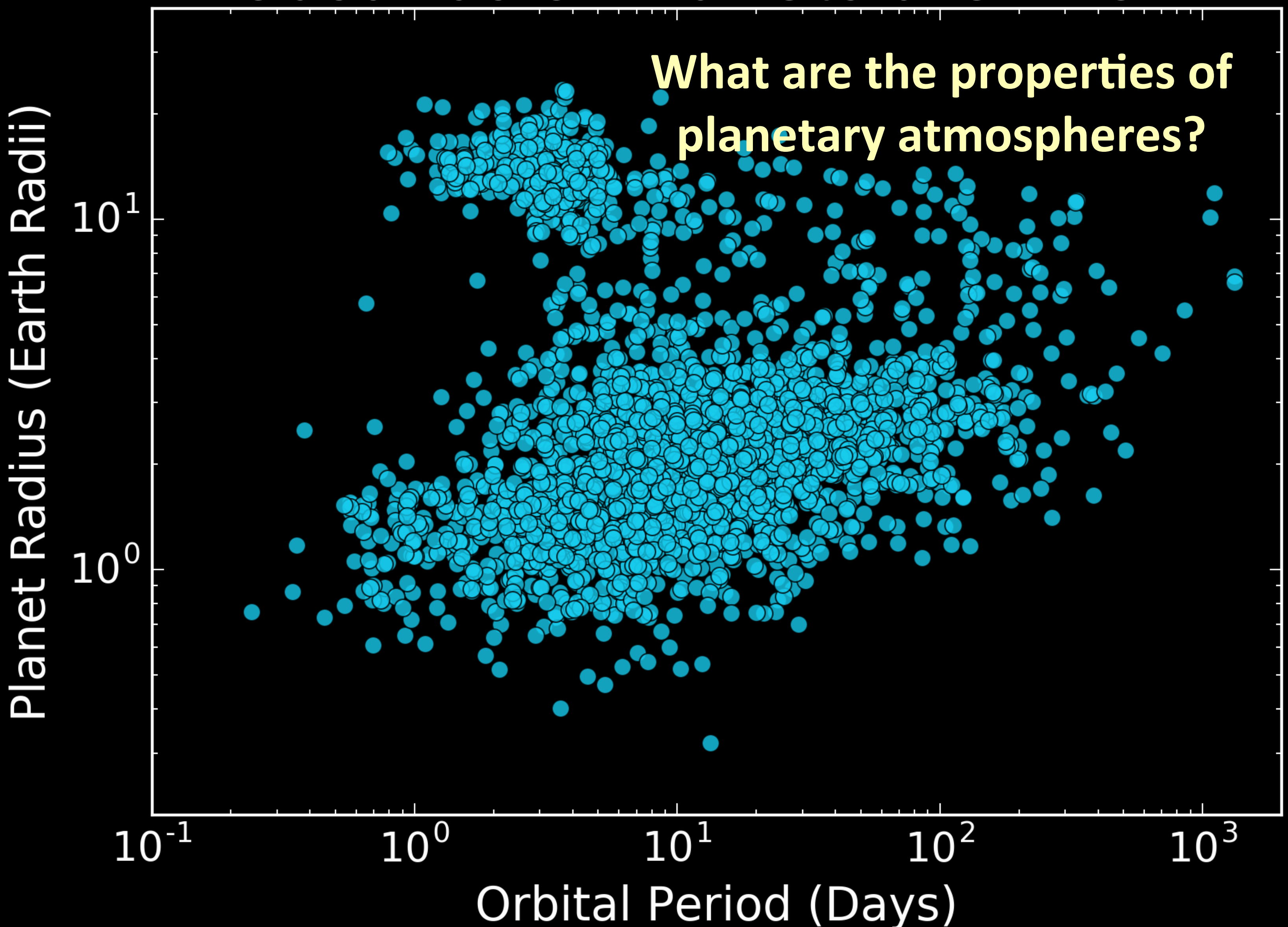

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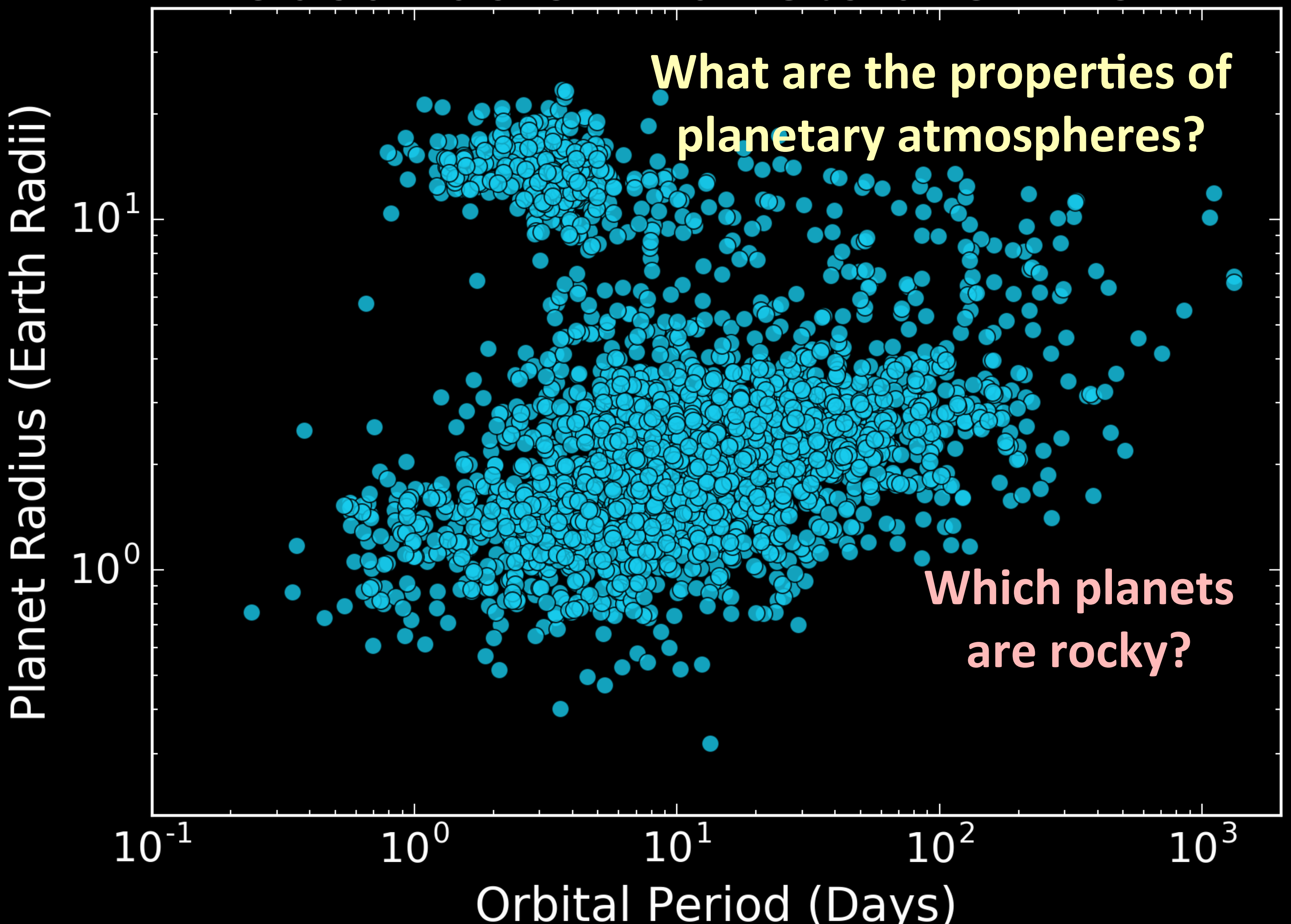

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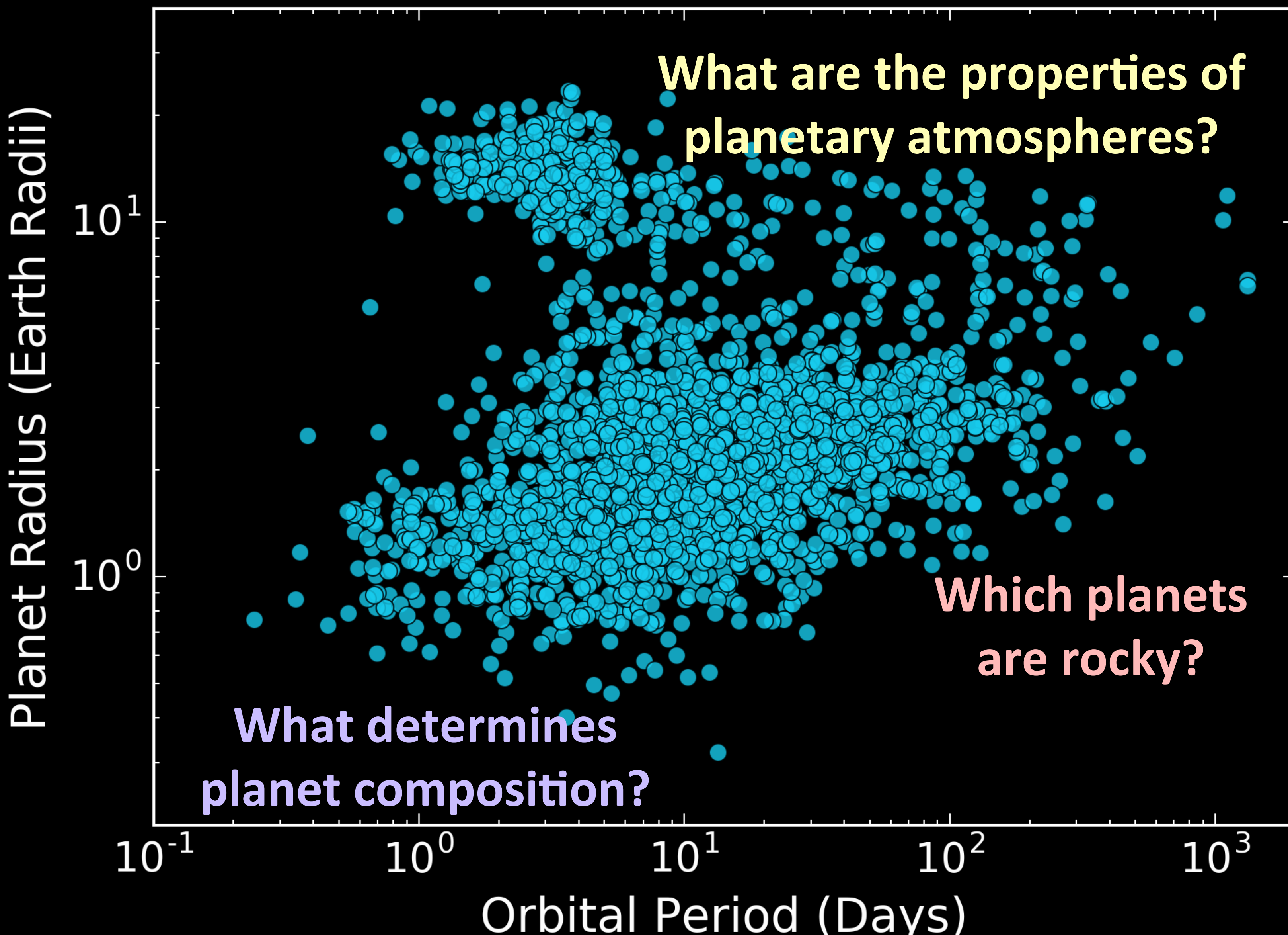

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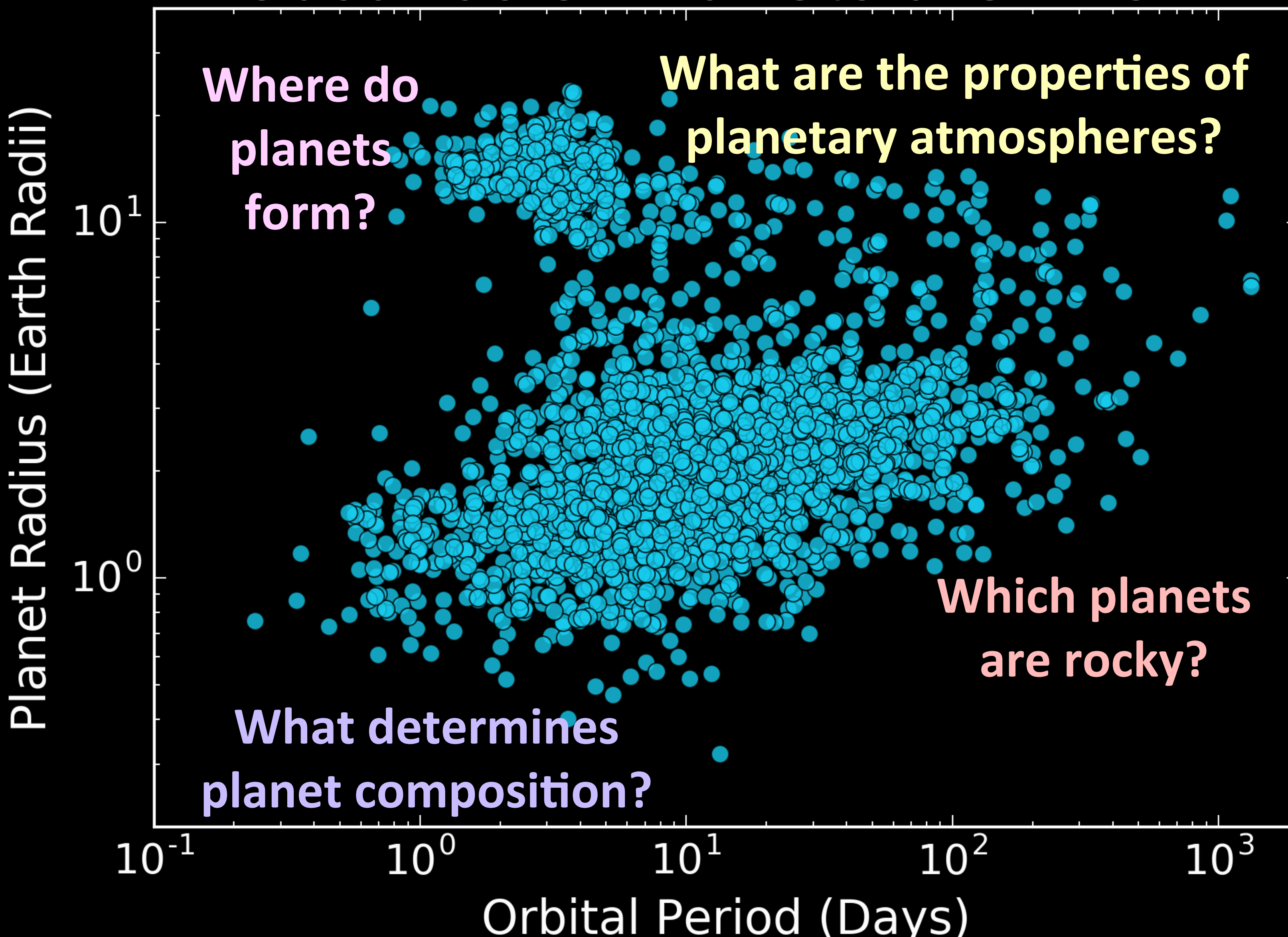

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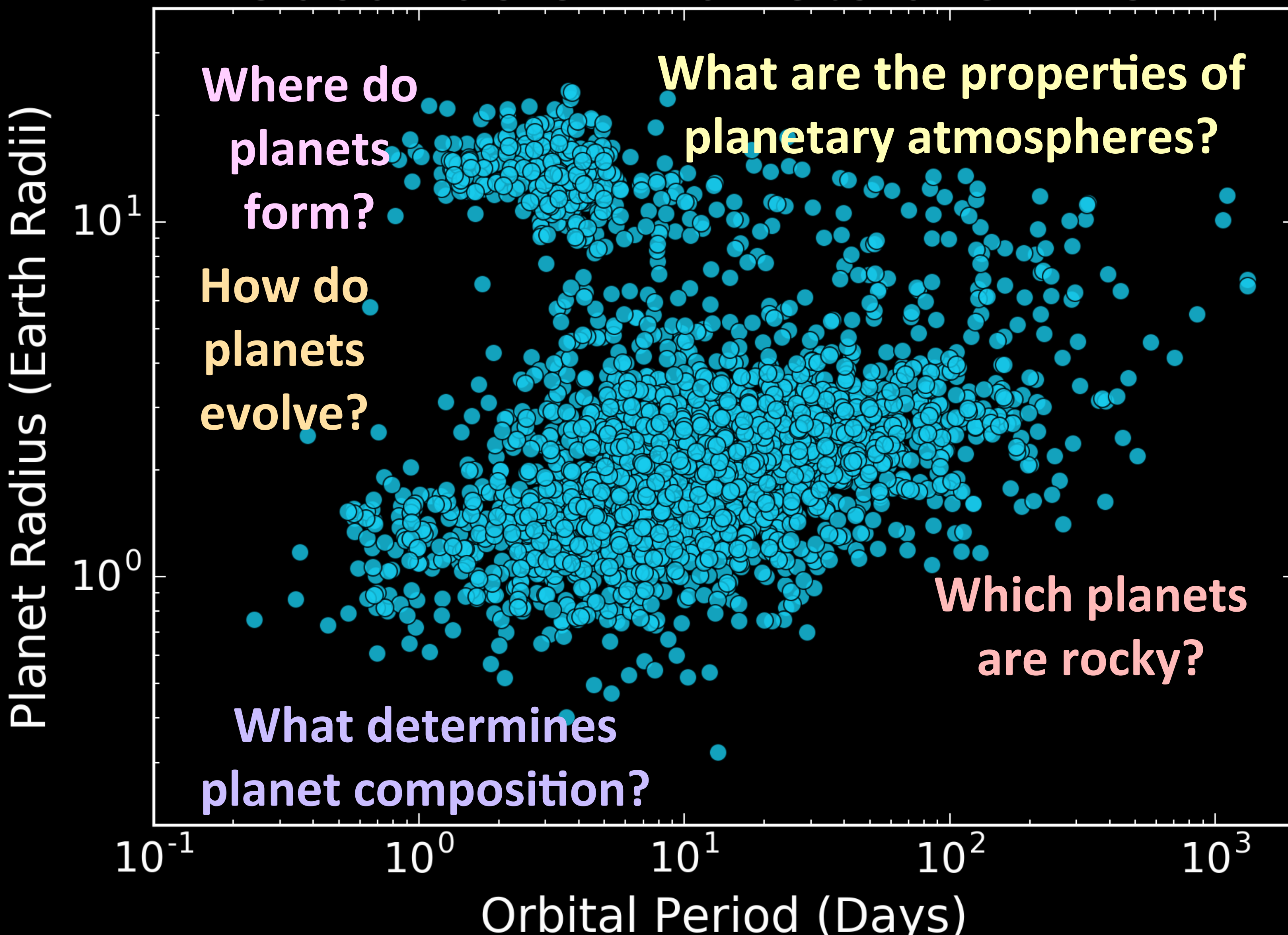

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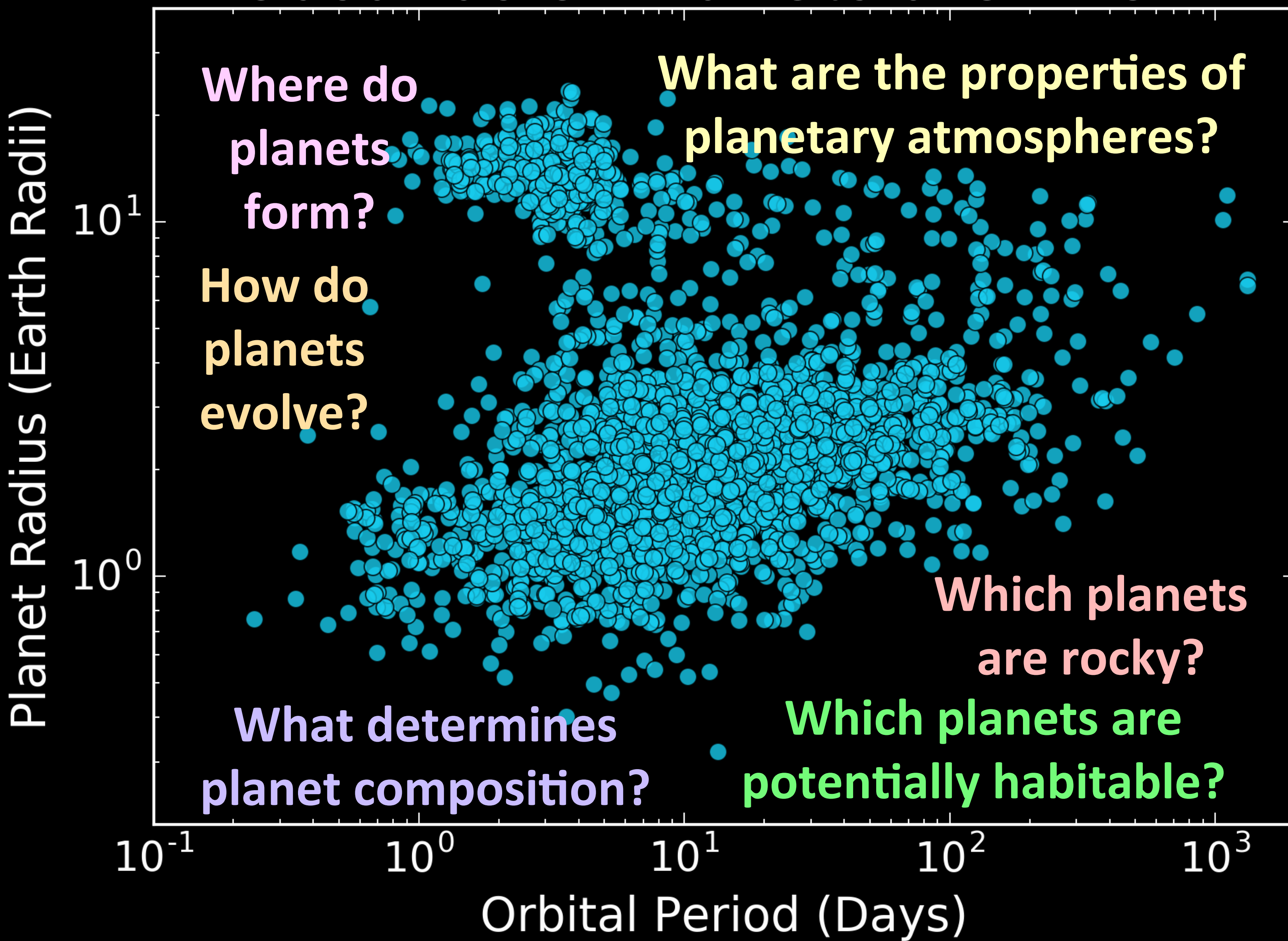


Data from NASA Exoplanet Archive

What do we know about the

structure & evolution of planetary systems?

Lessons Learned about Planetary Systems:

Planets are Common

Radial Velocity

8.5 ± 1.3 planets per 100 stars
(P<5.2 yr, M_p>100 M_{Earth})
Cumming+2008

6.5 (+3/-2.3) planets per 100 stars
(P<50 d, 10-30 M_{Earth})
Howard+2010

16.6 ± 4.4 planets per 100 stars
(P<50 d, 3-10 M_{Earth})
Mayor+2011

Transit

Fressin+2013
52 ± 4 planets per 100 stars
(P<85 d, 1.25-22 R_{Earth})

Petigura+2013
26 ± 3 planets per 100 stars
(5-100 d, 1-2 R_{Earth})

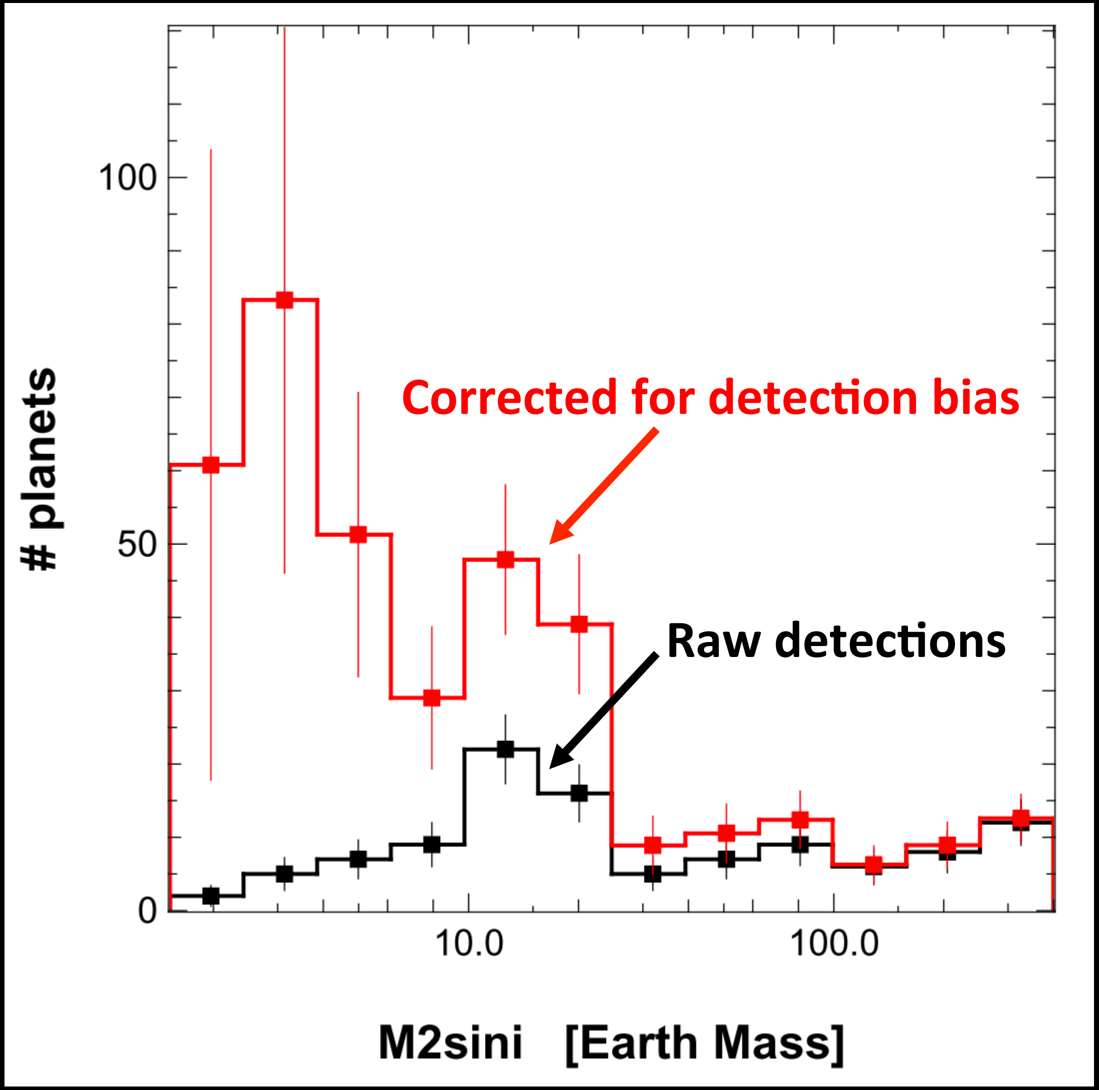
Burke+2015
77 (+113/-43) planets per 100 stars
(50-300 d, 0.75-2.5 R_{Earth})

See also: Youdin 2011; Mayor+2011; Wright+2012; Dong+Zhu 2013; Dressing & Charbonneau 2013, 2015; Morton & Swift 2013; Gaidos 2013, 2014; Mulders+ 2015; Silburt+2015; Clanton & Gaudi+2016

Lessons Learned about Planetary Systems:

Less Massive Planets are More Prevalent

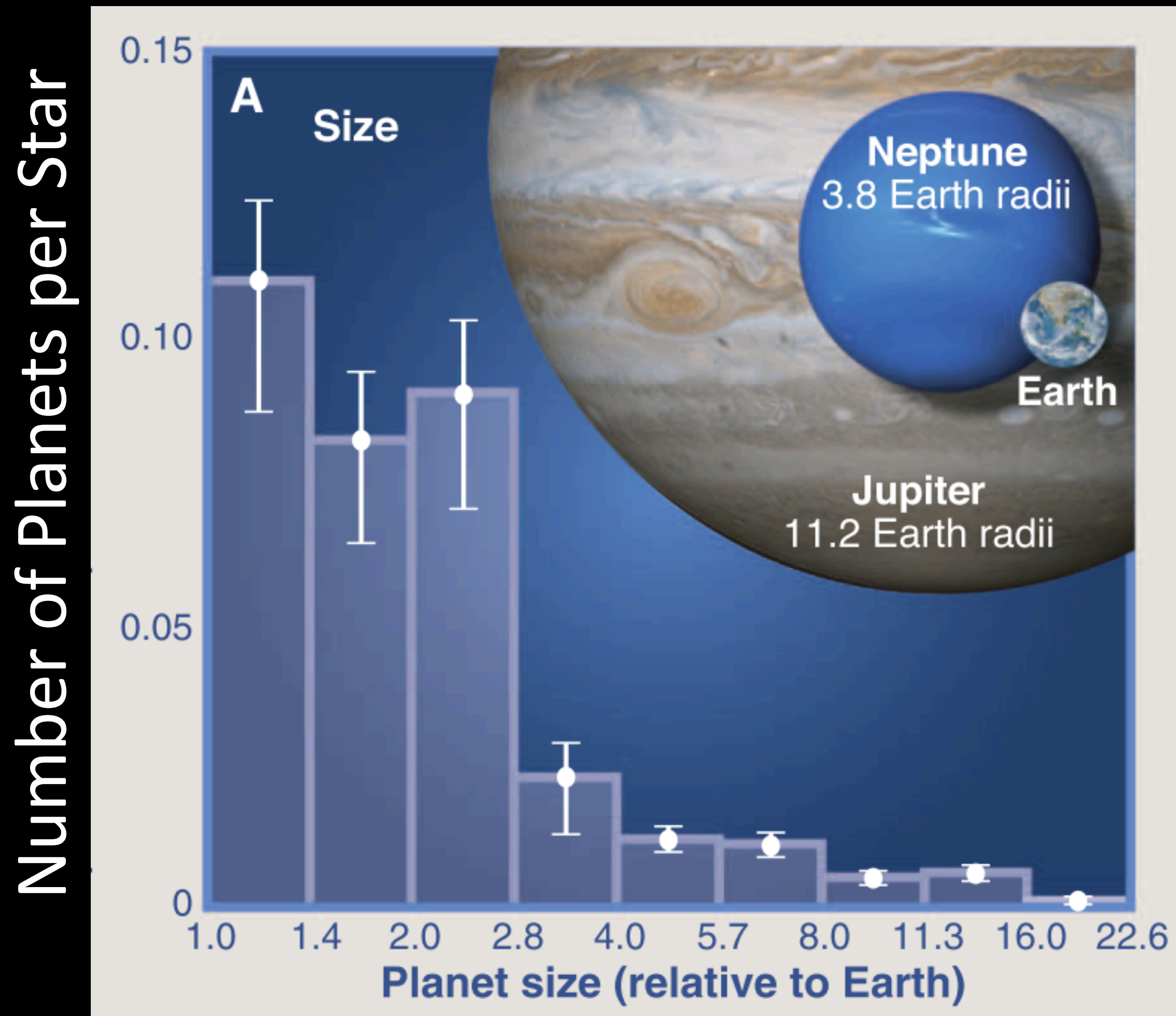
Number of Planets per Star



Mayor et al. 2011

Lessons Learned about Planetary Systems:

Smaller Planets are More Prevalent



Howard 2013, Science, 340, 572

Lessons Learned about Planetary Systems:

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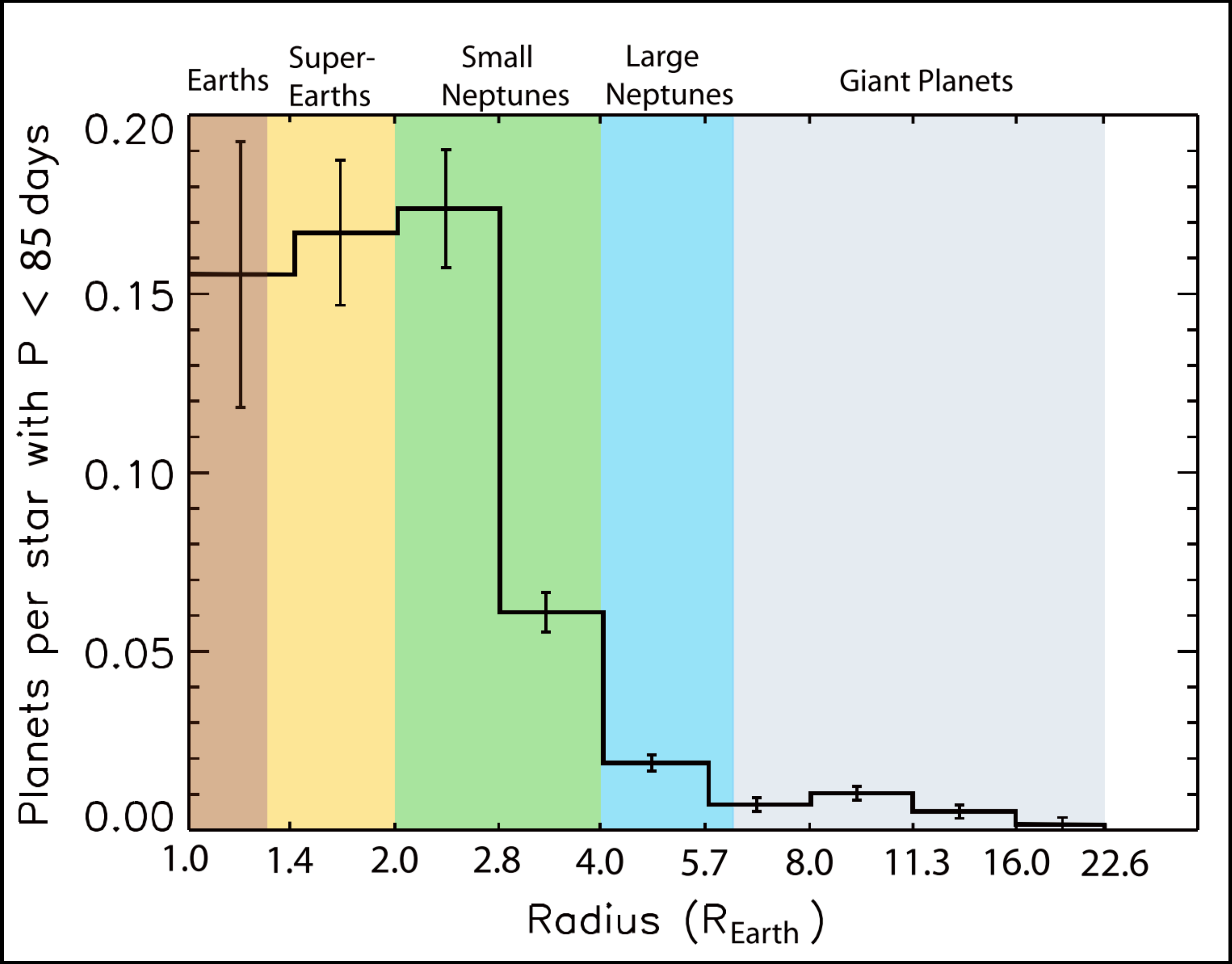
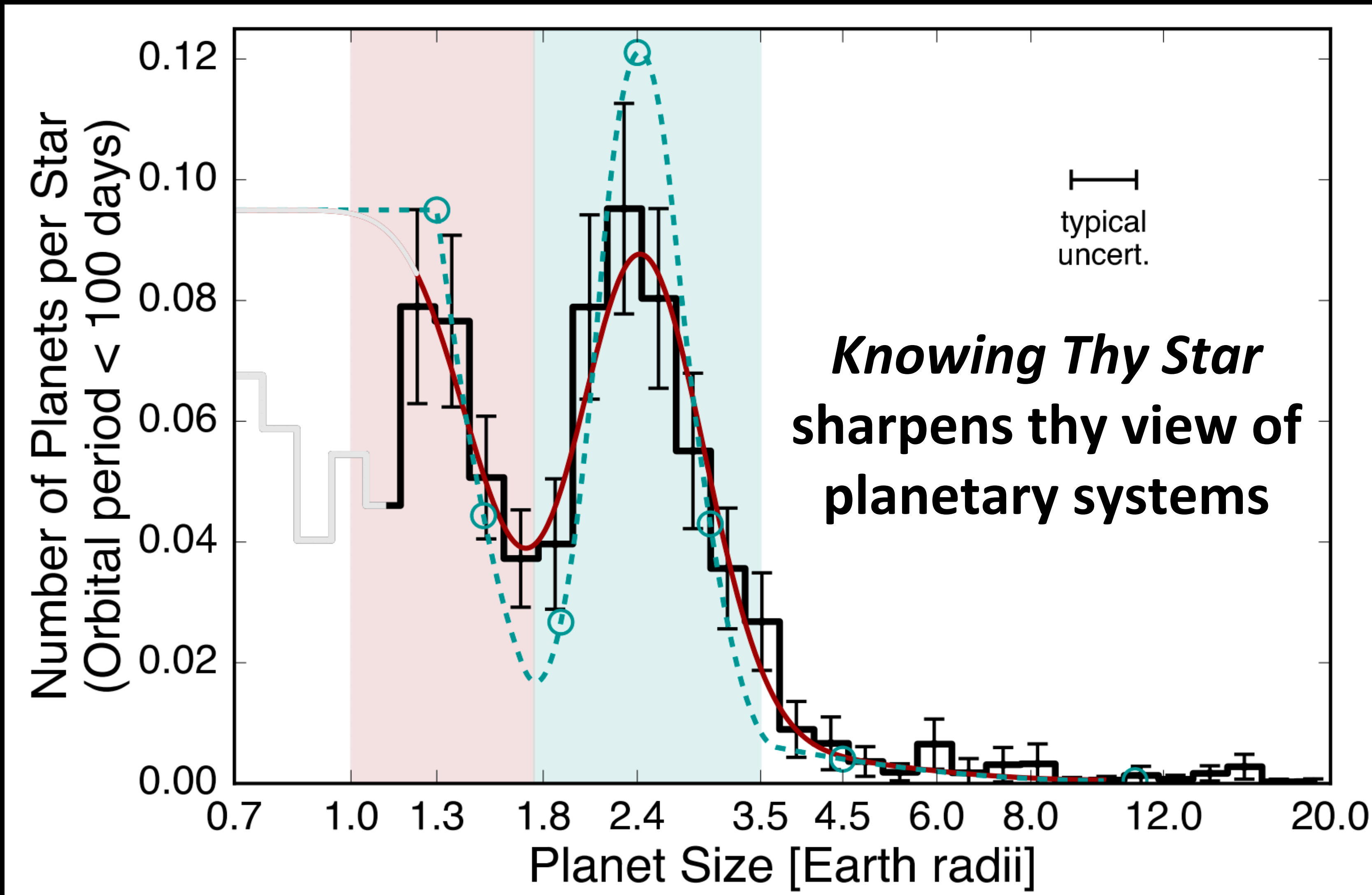
See also: Youdin 2011; Mayor+2011; Dong+Zhu 2013; Dressing & Charbonneau 2013, 2015; Morton & Swift 2013; Gaidos 2013, 2014; Silburt+2015; Clanton & Gaudi+2016



Fressin et al. 2013, ApJ, 766, 81

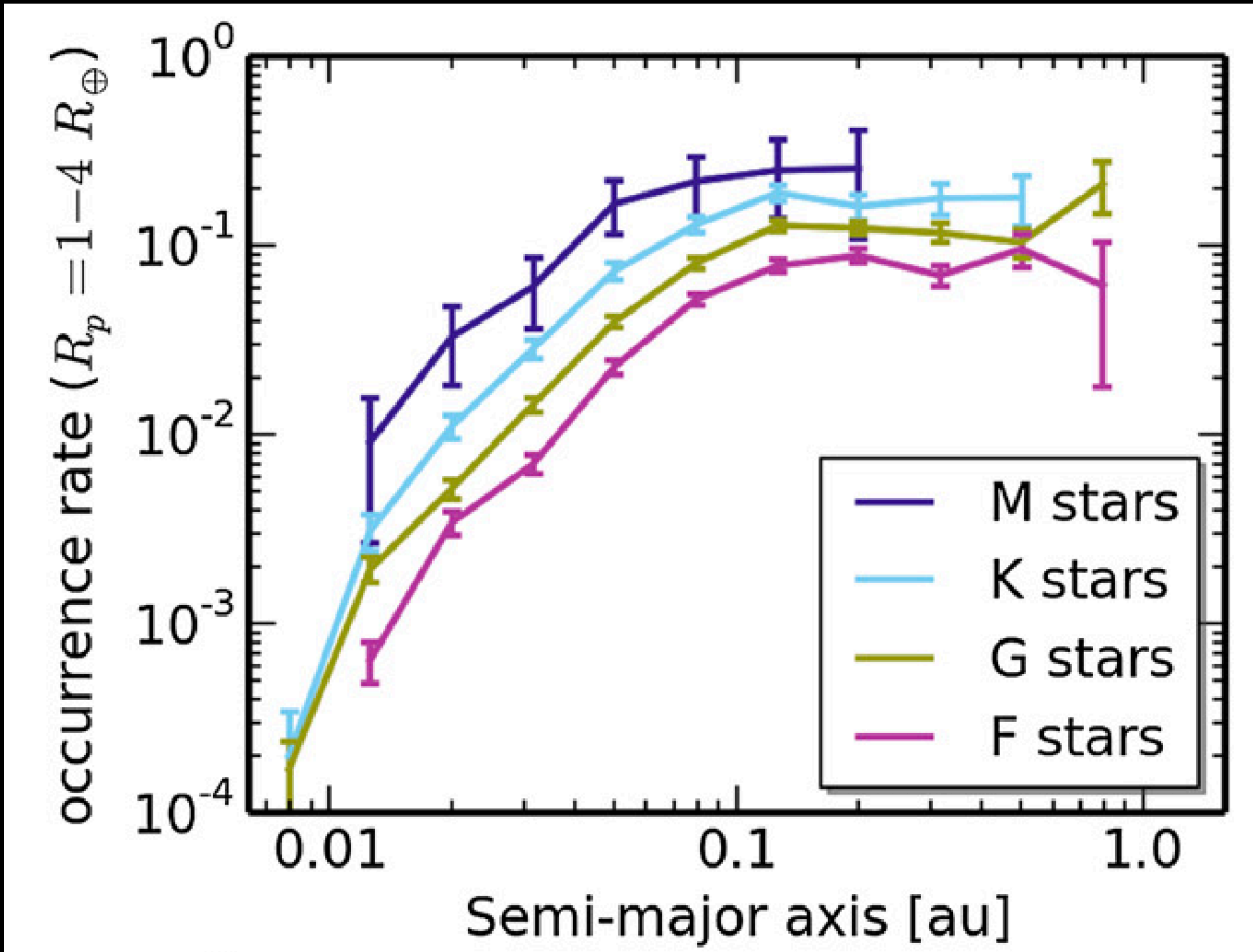
Lessons Learned about Planetary Systems:

There is a Gap in the Radius Distribution of Small Planets



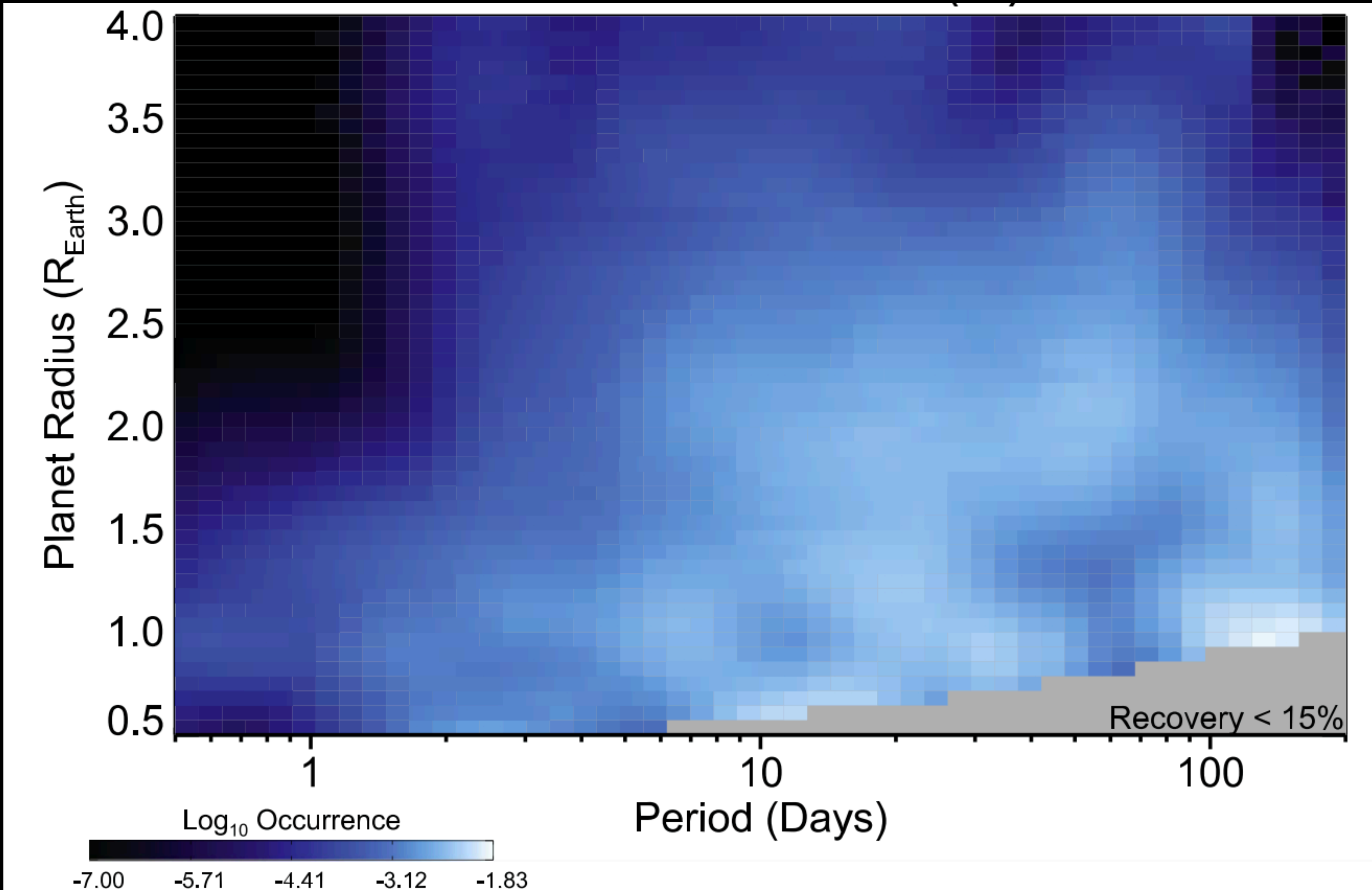
Fulton et al. 2017, accepted to AJ, arXiv:1703.10375

Planet Occurrence Declines at Short Periods



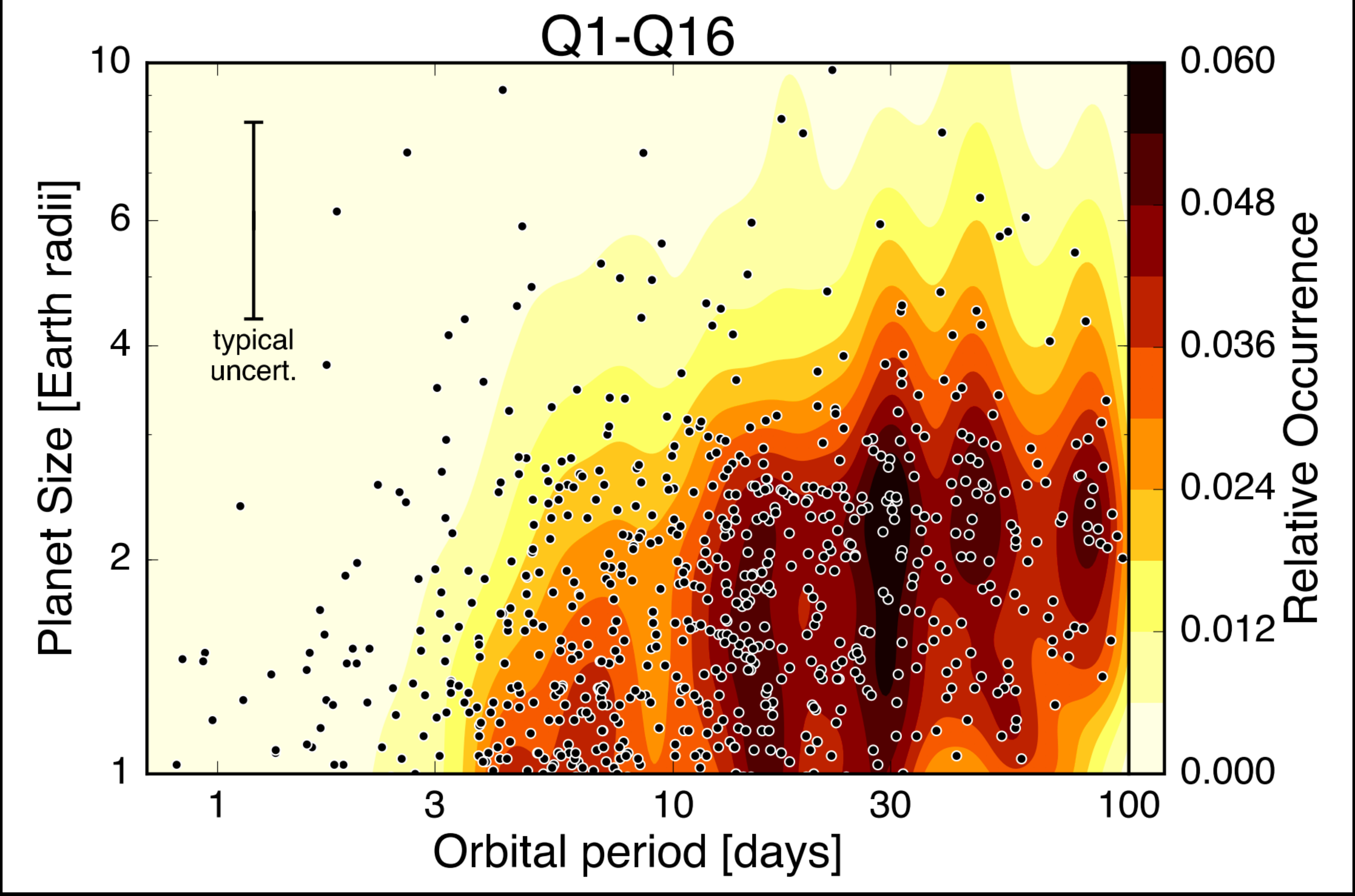
Mulders et al. 2015, ApJ, 798, 112

2-D View of Planet Occurrence for Cool Dwarfs



Dressing & Charbonneau 2015, ApJ, 807, 45

2-D View of Planet Occurrence for FGK Stars



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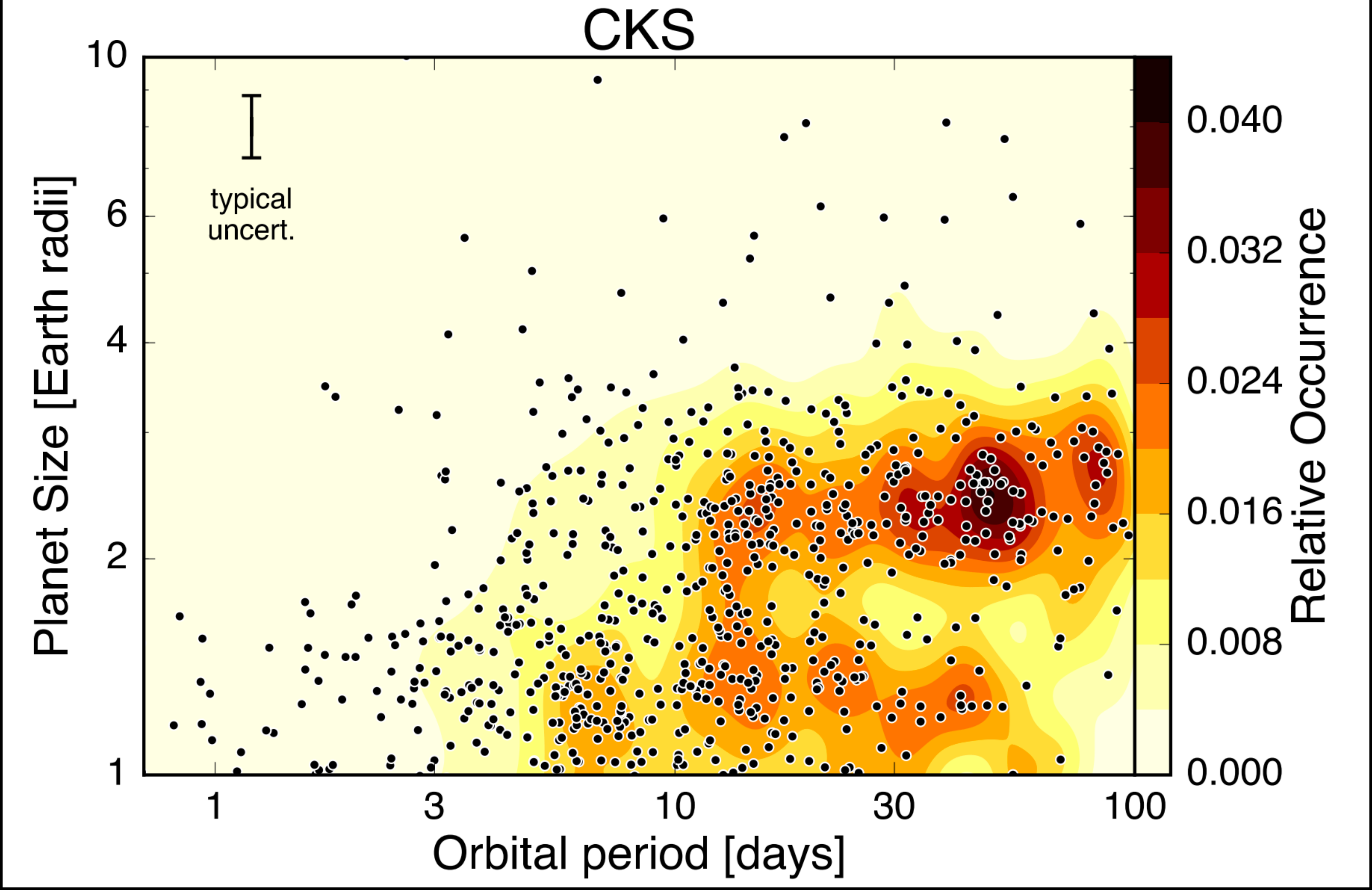
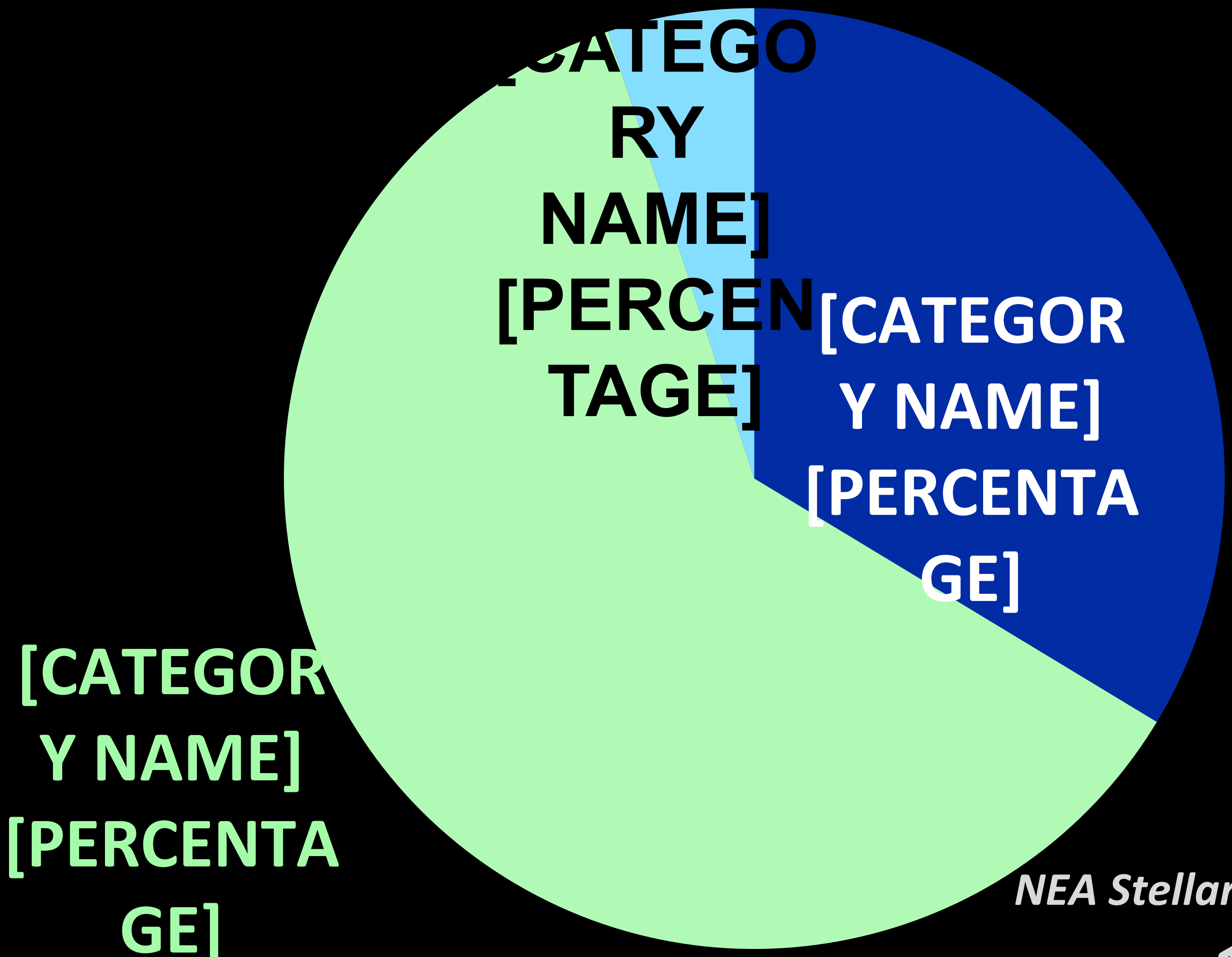


Fulton et al. 2017, accepted to AJ, arXiv:1703.10375

Knowing thy host star

is only the beginning

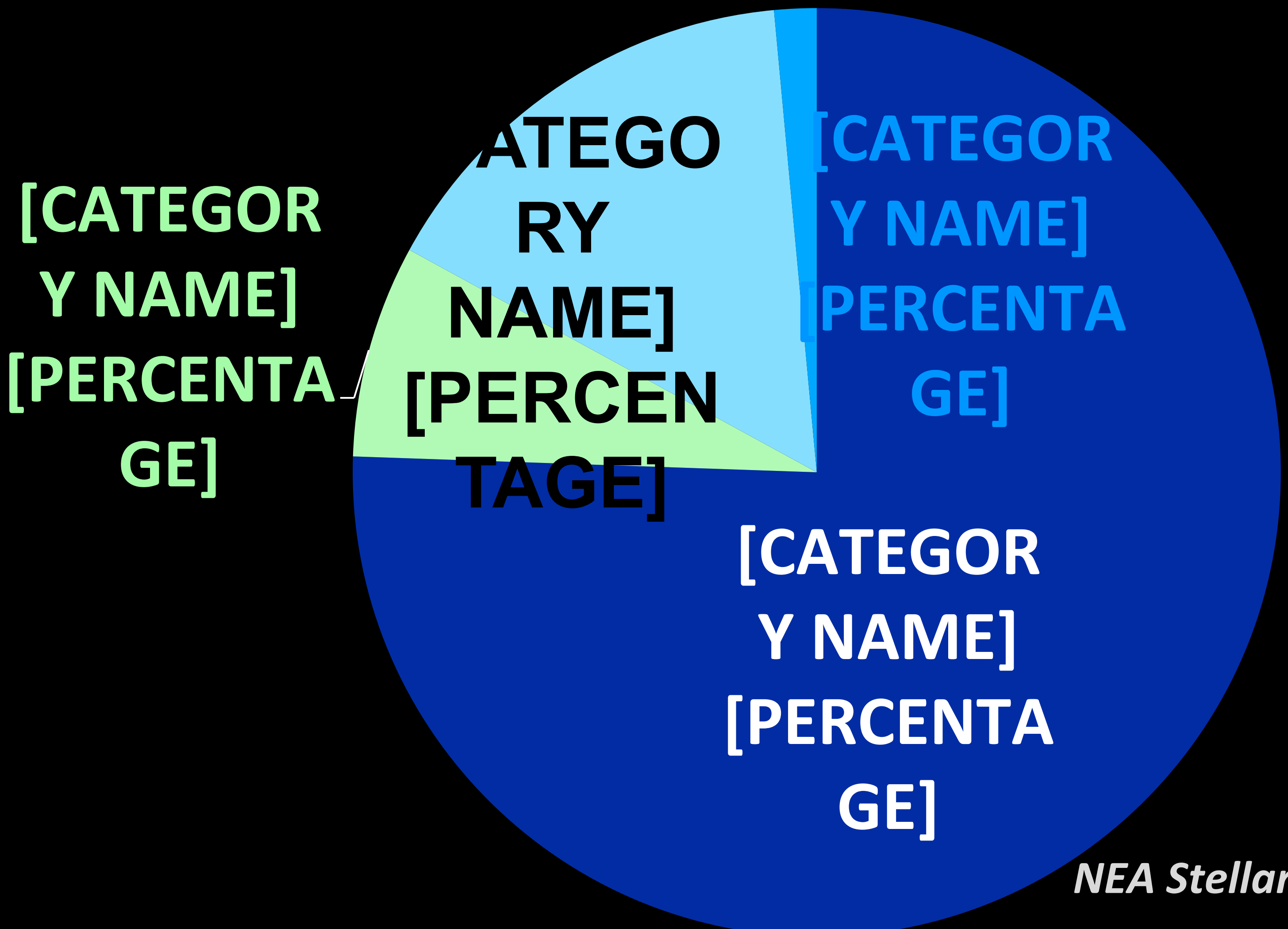
Only 61% of Confirmed Planet Host Stars Targets have Spectroscopic Temperatures



NEA Stellar Properties Table

1649 Stars

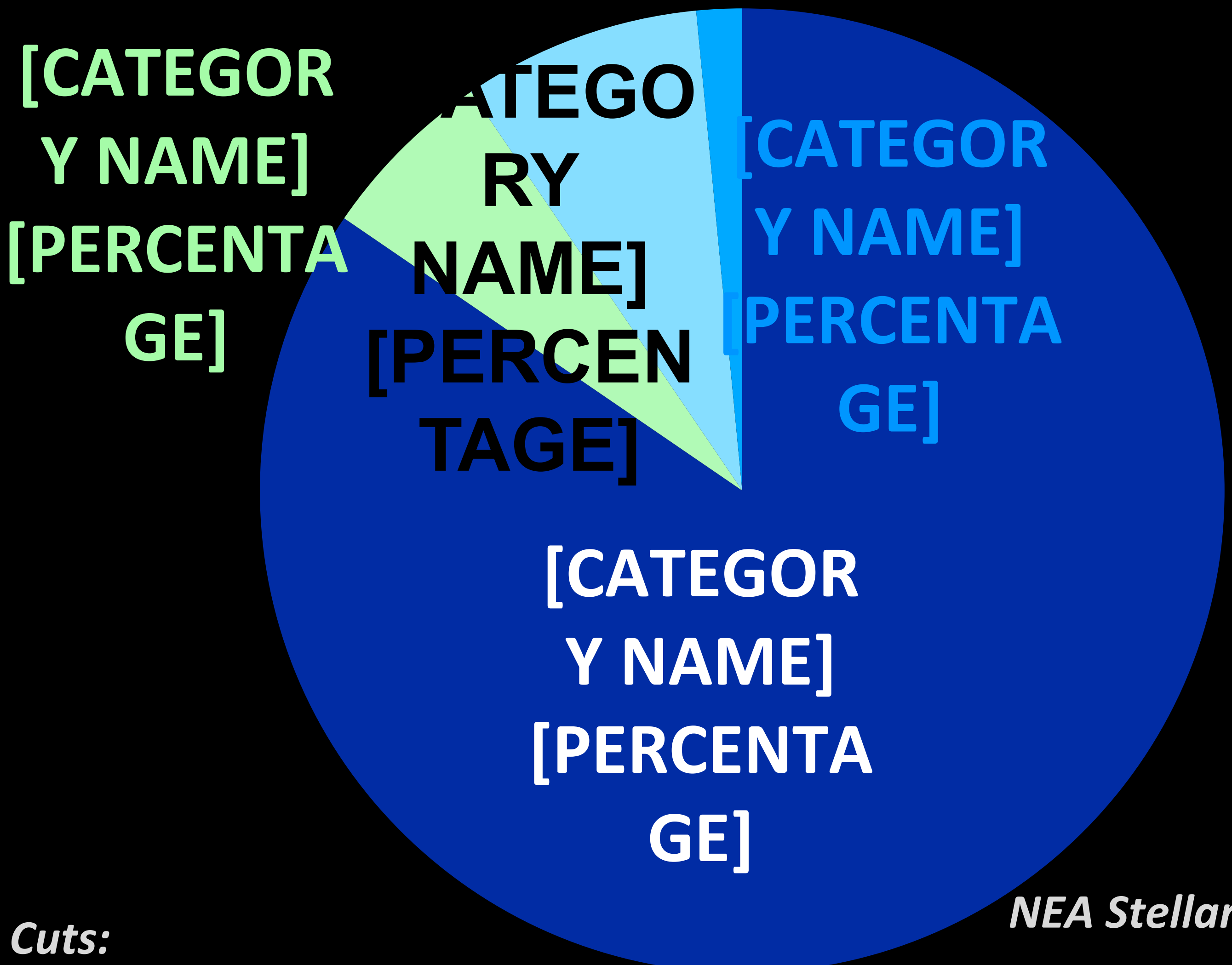
Only 7% of Kepler Targets have Spectroscopic Temperatures



NEA Stellar Properties Table

200,038 Stars

Only 6% of Bright* Dwarfs have Spectroscopic Temperatures



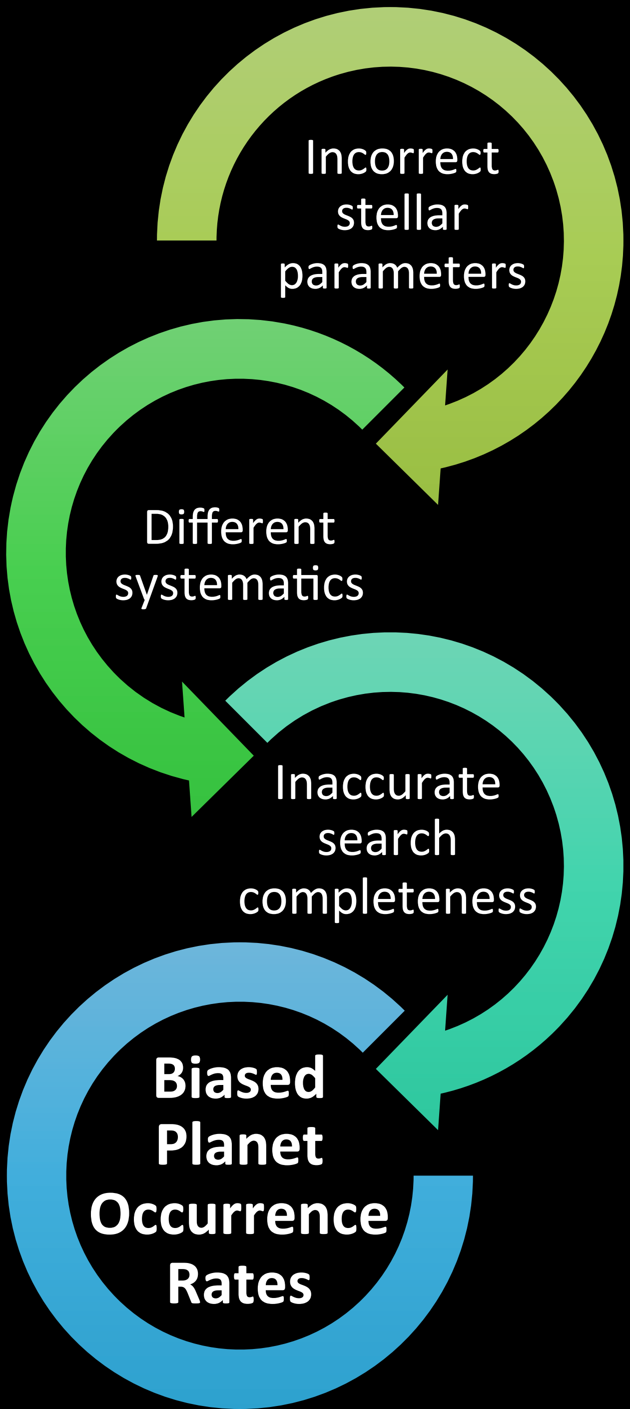
Sample Cuts:

Kp < 15, log (g) > 4, R* < 1.5 Rsun

NEA Stellar Properties Table

70,801 Stars

Why does the disparity matter?



A Case Study:
Do the latest M dwarfs host more planets?

NASA/JPL

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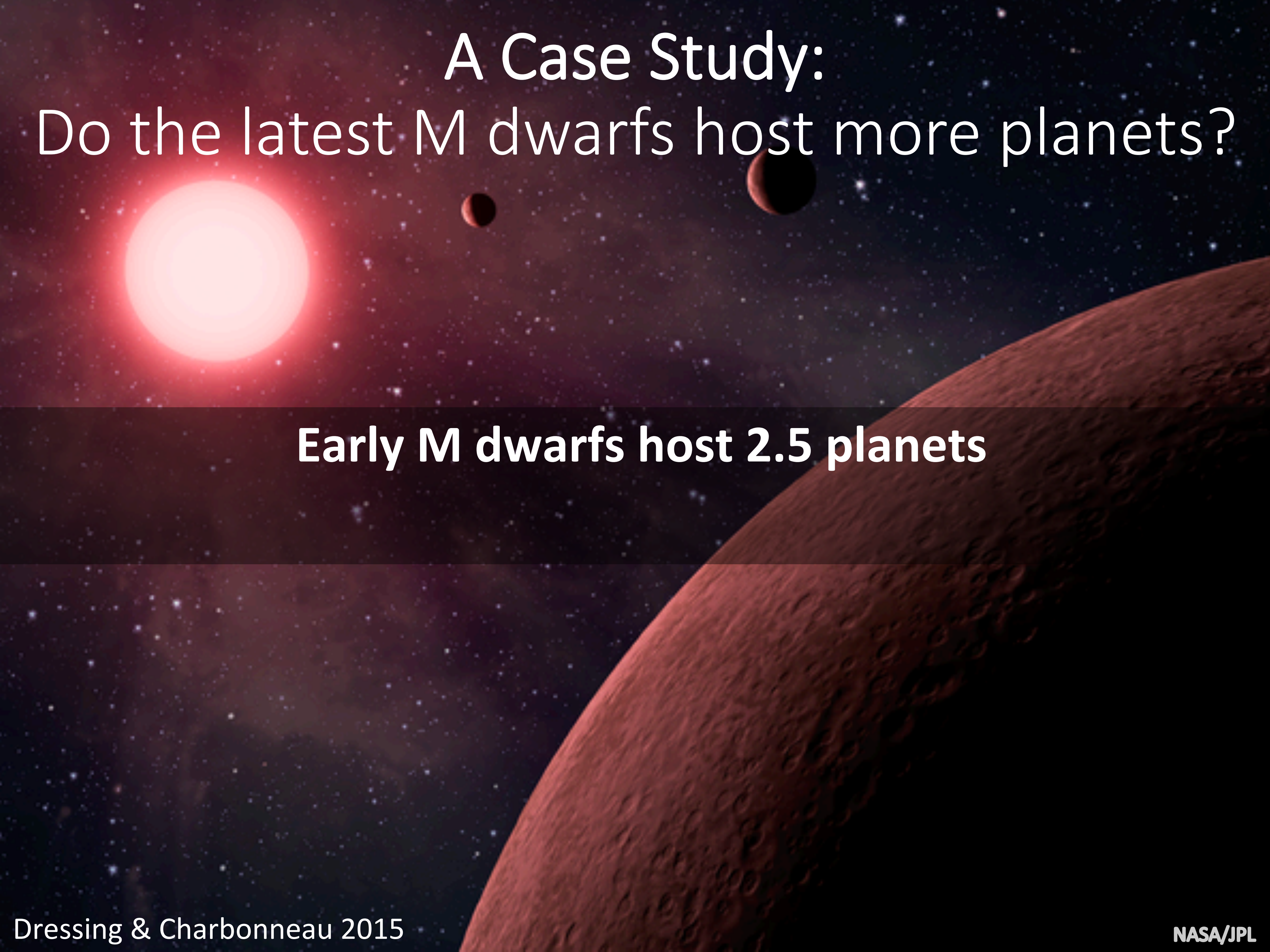
Do the latest M dwarfs host more planets?

Early M dwarfs host 2.5 planets



Dressing & Charbonneau 2015

A Case Study:
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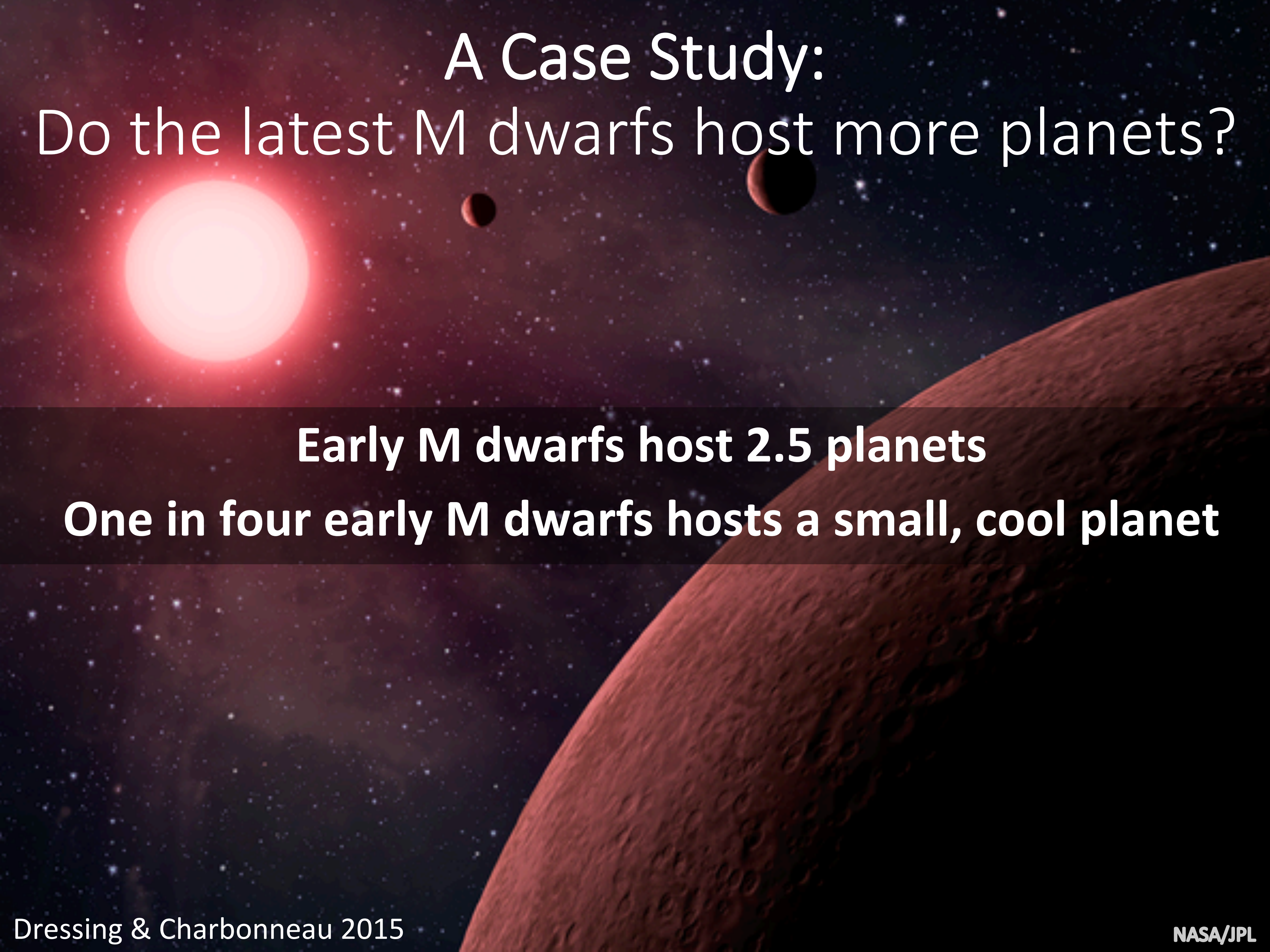
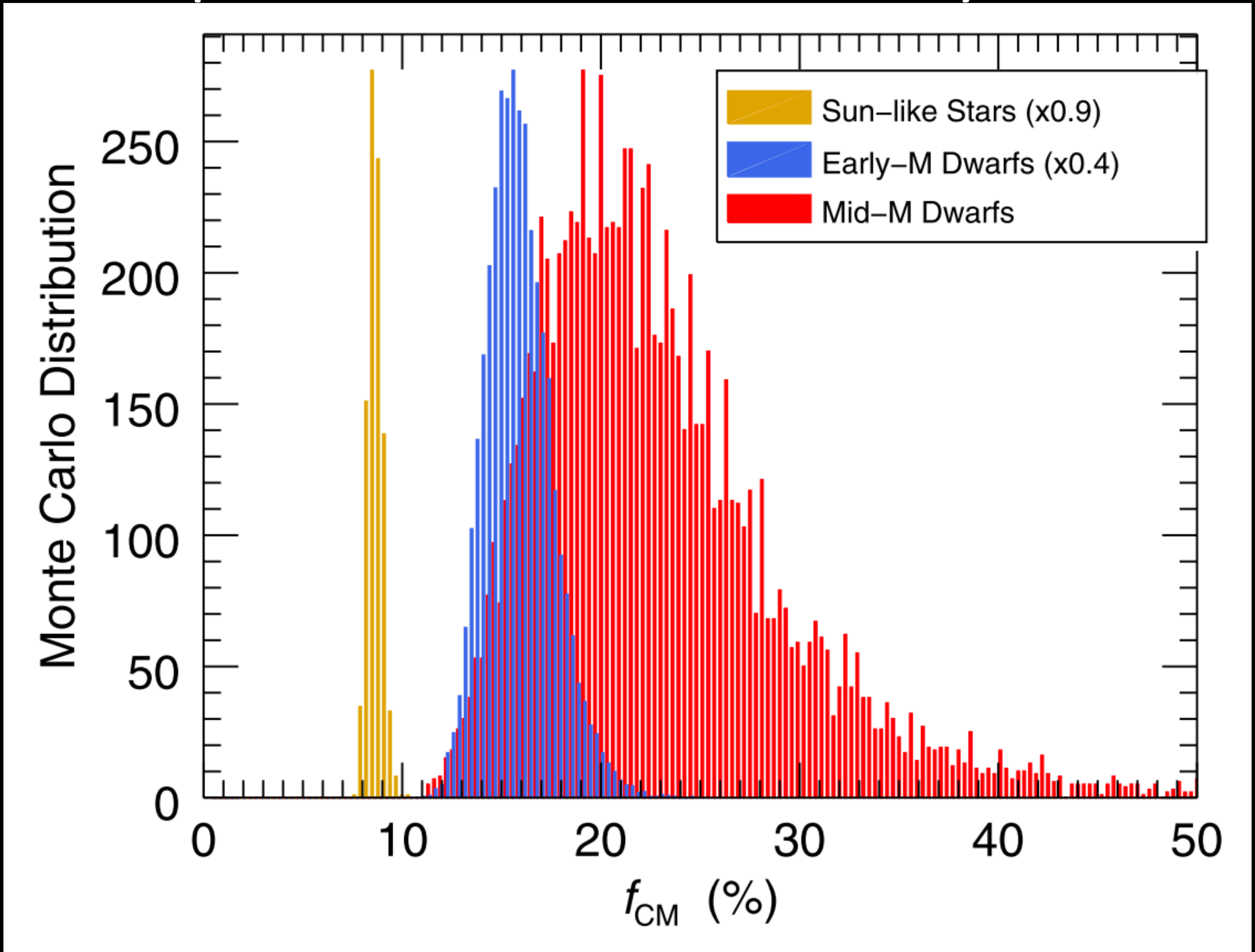


Early M dwarfs host 2.5 planets

One in four early M dwarfs hosts a small, cool planet

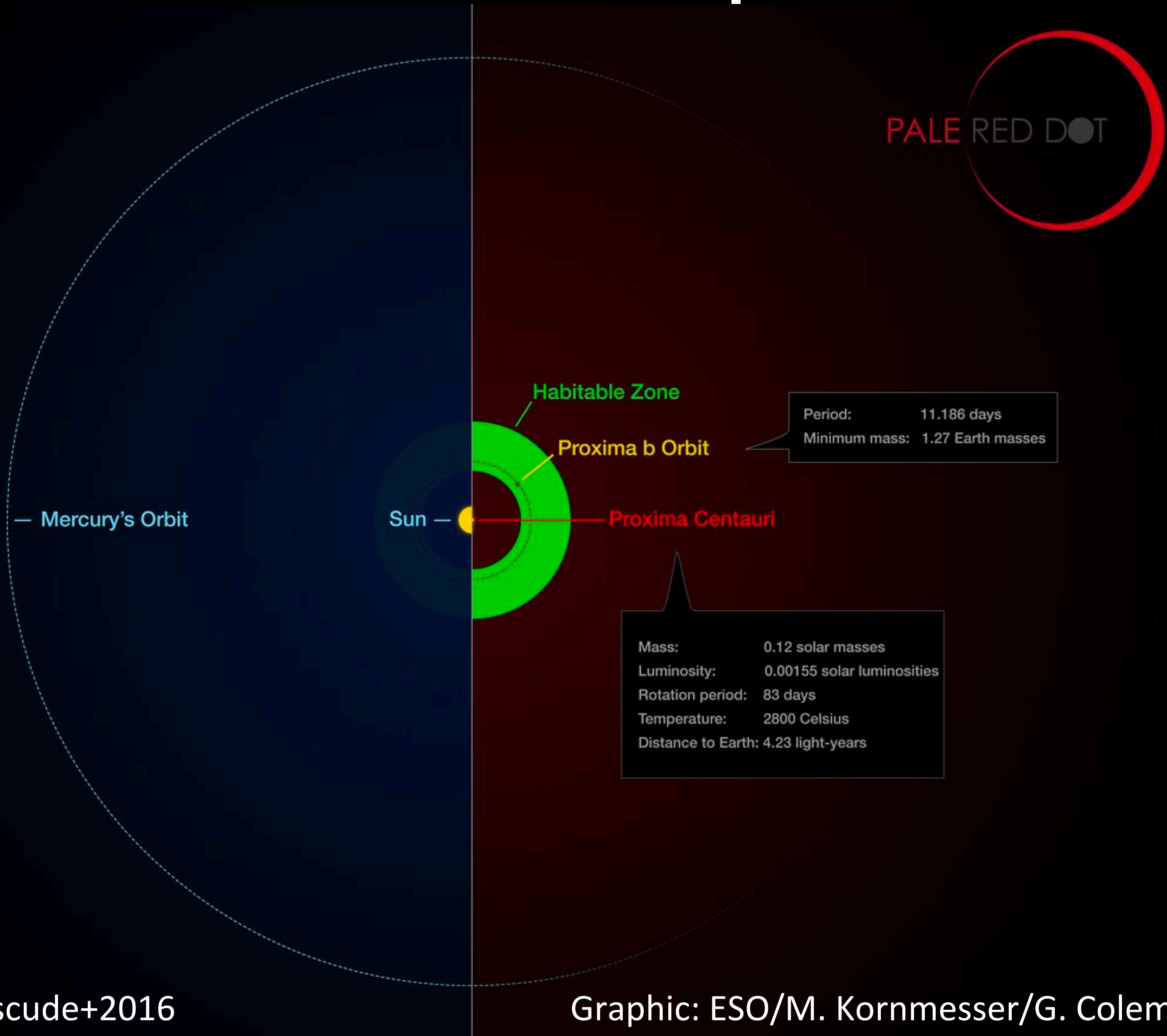
Dressing & Charbonneau 2015

Mid-M Dwarfs Might Harbor More Compact Multi-Planet Systems



Muirhead et al. 2015, ApJ, 801, 18

Proxima Centauri hosts a planet!



Paper: Anglada-Escude+2016

Graphic: ESO/M. Kornmesser/G. Coleman

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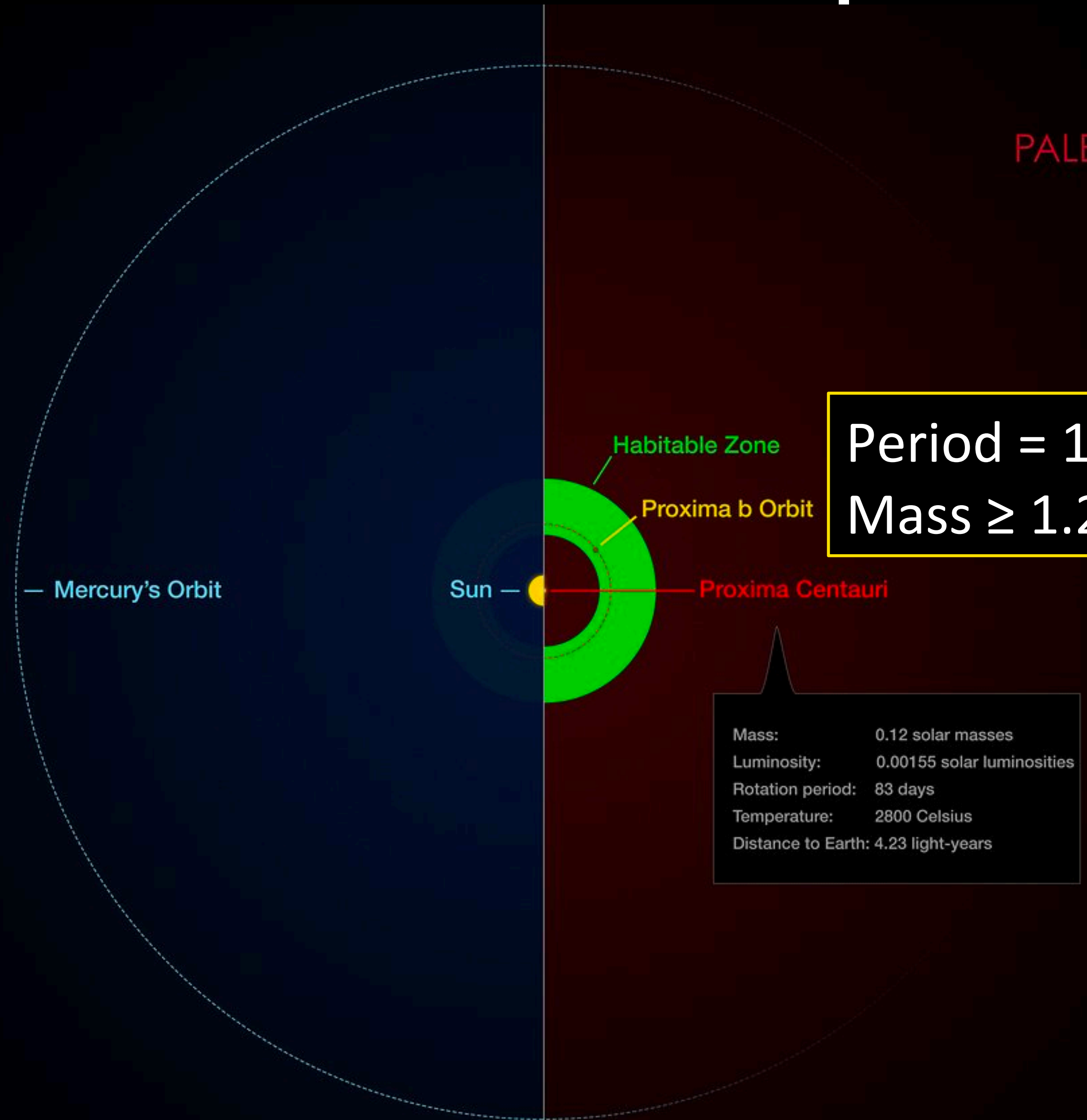

Period = 11.186 days

Mass ≥ 1.27 M_{Earth}

Paper: Anglada-Escude+2016

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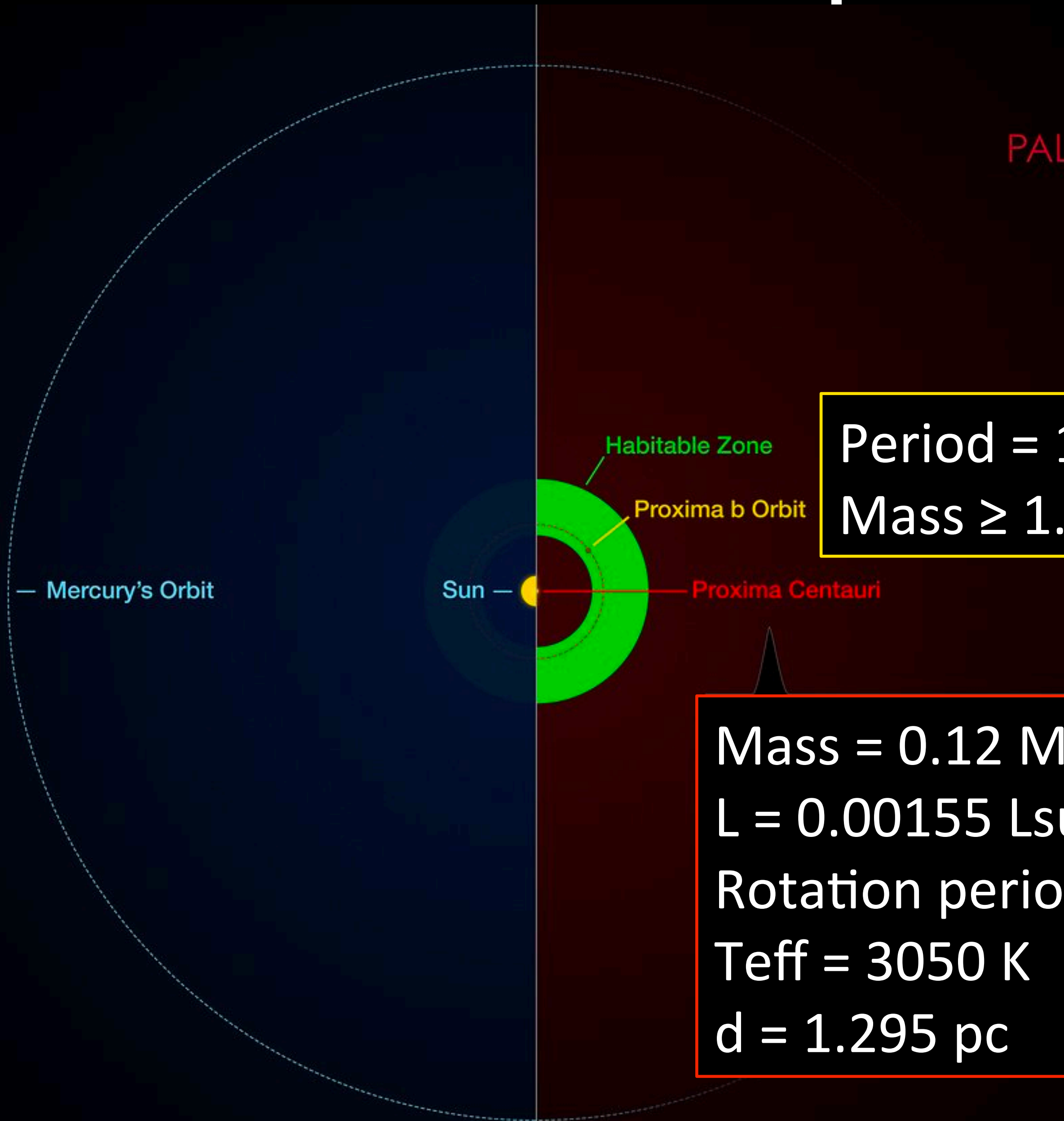

Period = 11.186 days
Mass ≥ 1.27 M_{Earth}

Mass = 0.12 Msun
L = 0.00155 Lsun
Rotation period = 83 d
Teff = 3050 K
d = 1.295 pc

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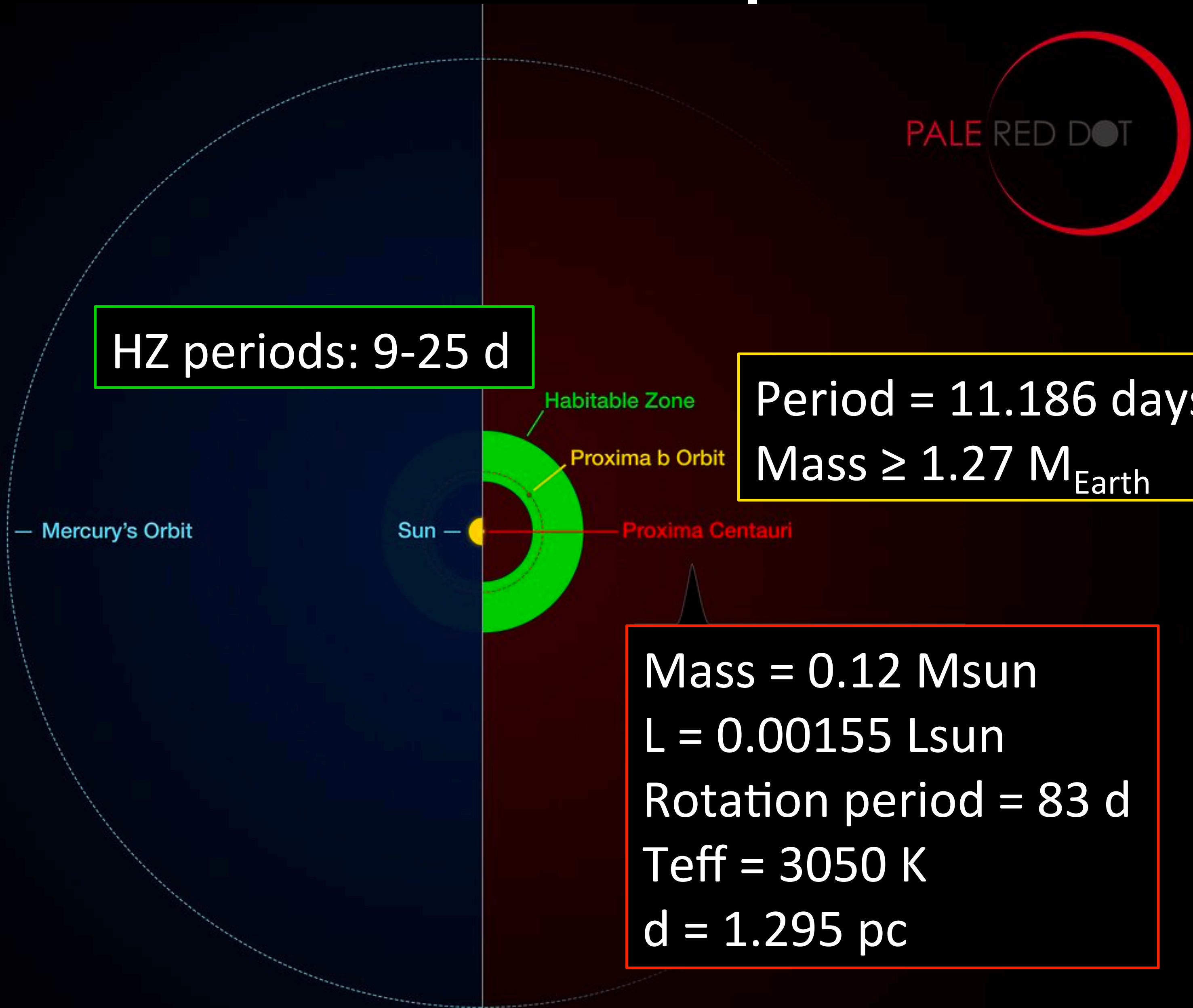

HZ periods: 9-25 d

Period = 11.186 days
Mass ≥ 1.27 M_{Earth}

Mass = 0.12 Msun
L = 0.00155 Lsun
Rotation period = 83 d
Teff = 3050 K
d = 1.295 pc

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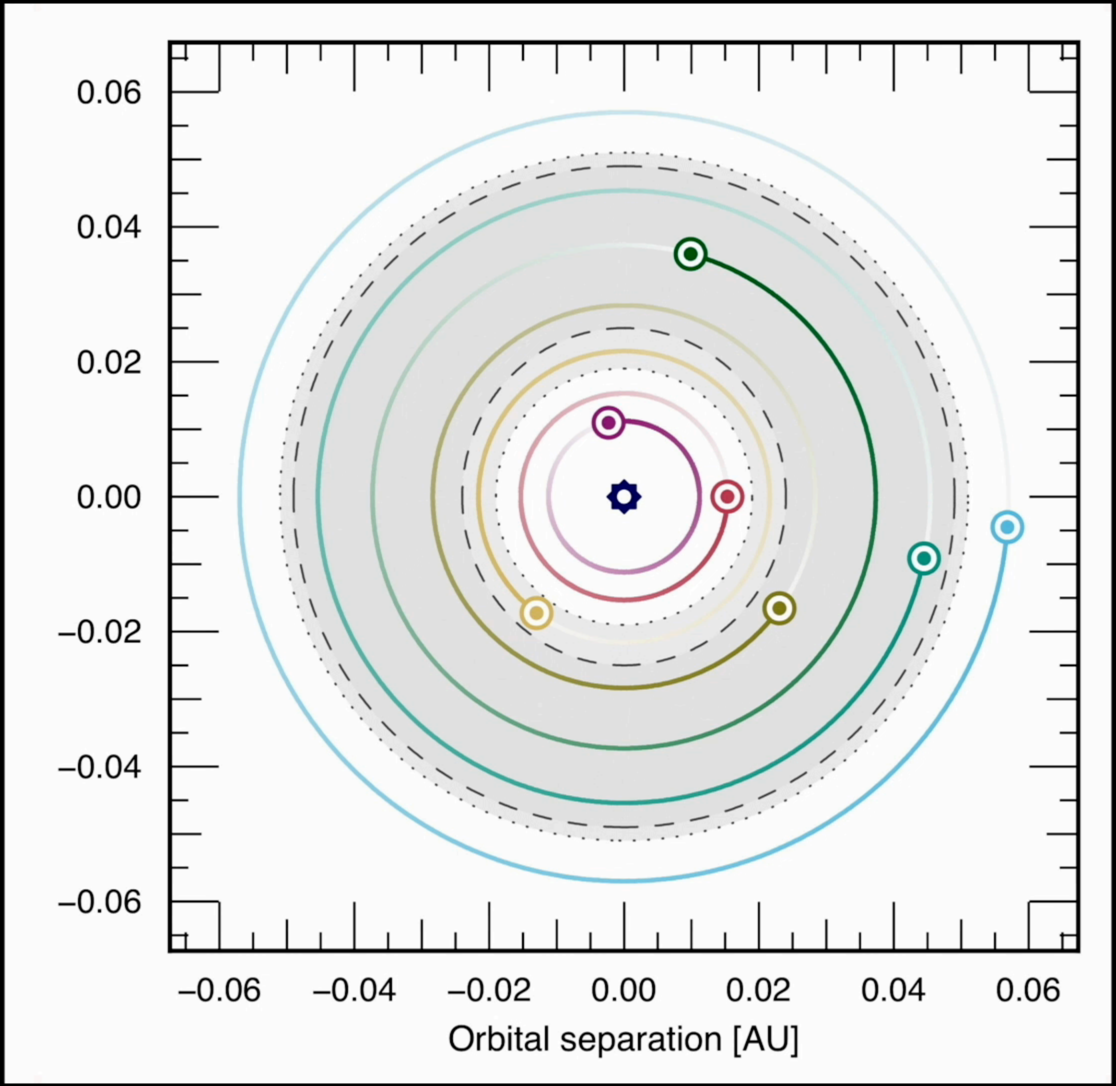
TRAPPIST-1 hosts 7 planets!

Planet b
1.5d
1.1R_{Earth}

Planet c
2.4d
1.1R_{Earth}

Planet d
4.0d
0.8R_{Earth}

Planet e
6.1d
0.9R_{Earth}



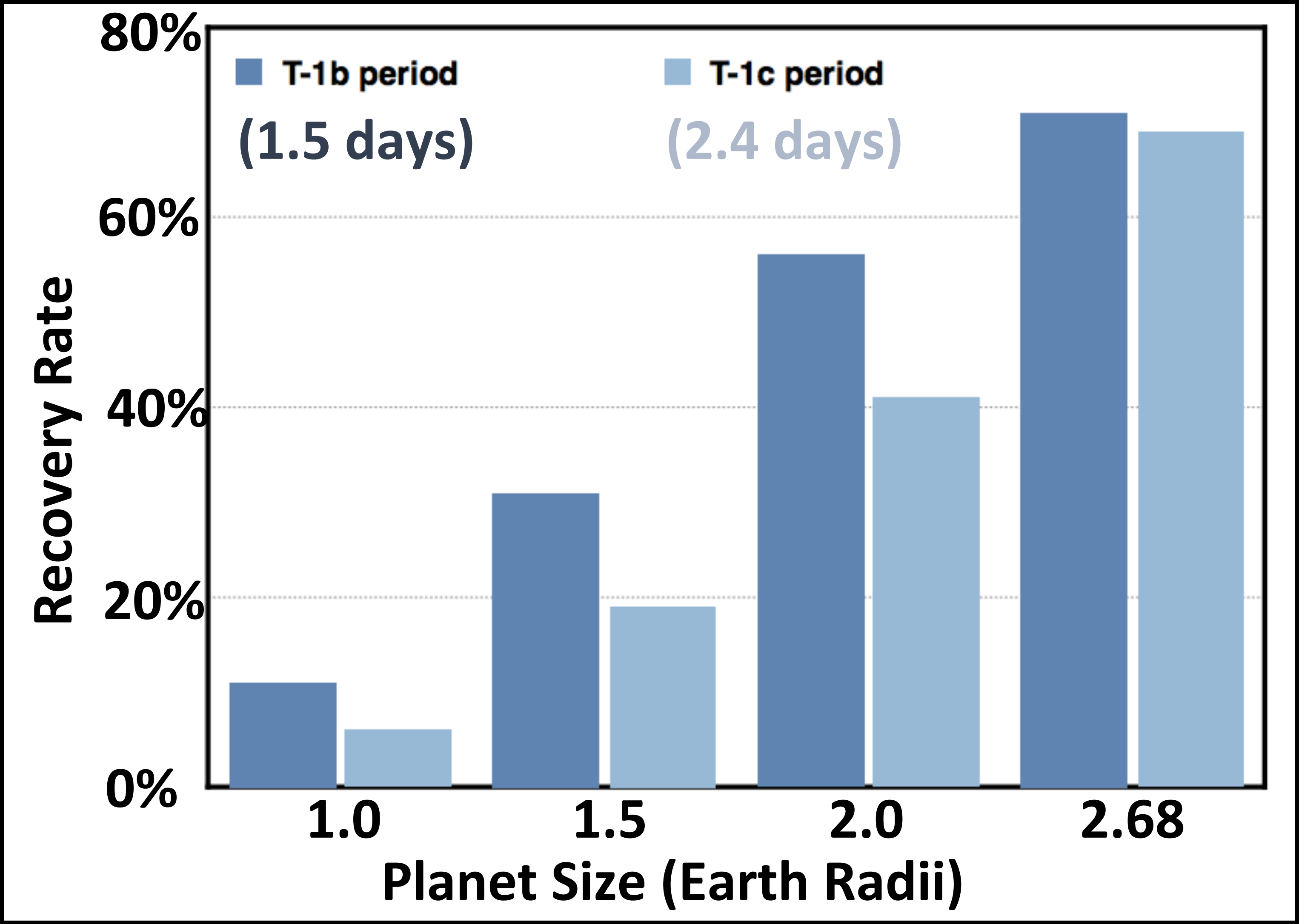
Planet f
9.2d
1.0R_{Earth}

Planet g
12.4d
1.1R_{Earth}

Planet h
18.8d
0.8R_{Earth}

Gillon+2016, 2017

How Common are Planetary Systems Orbiting Late M Dwarfs?



Demory et al. 2016, ApJL, arXiv:1606.08622

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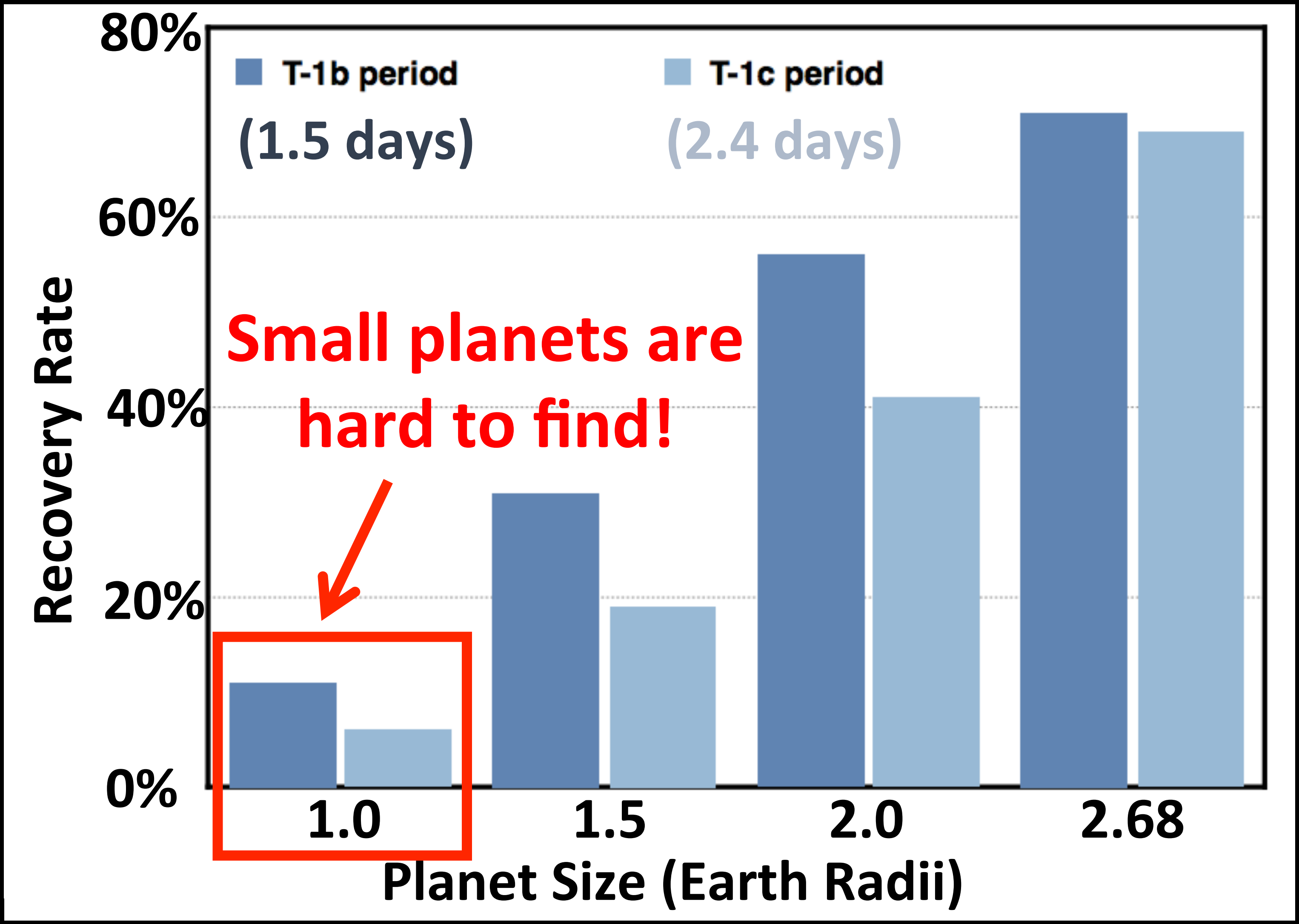

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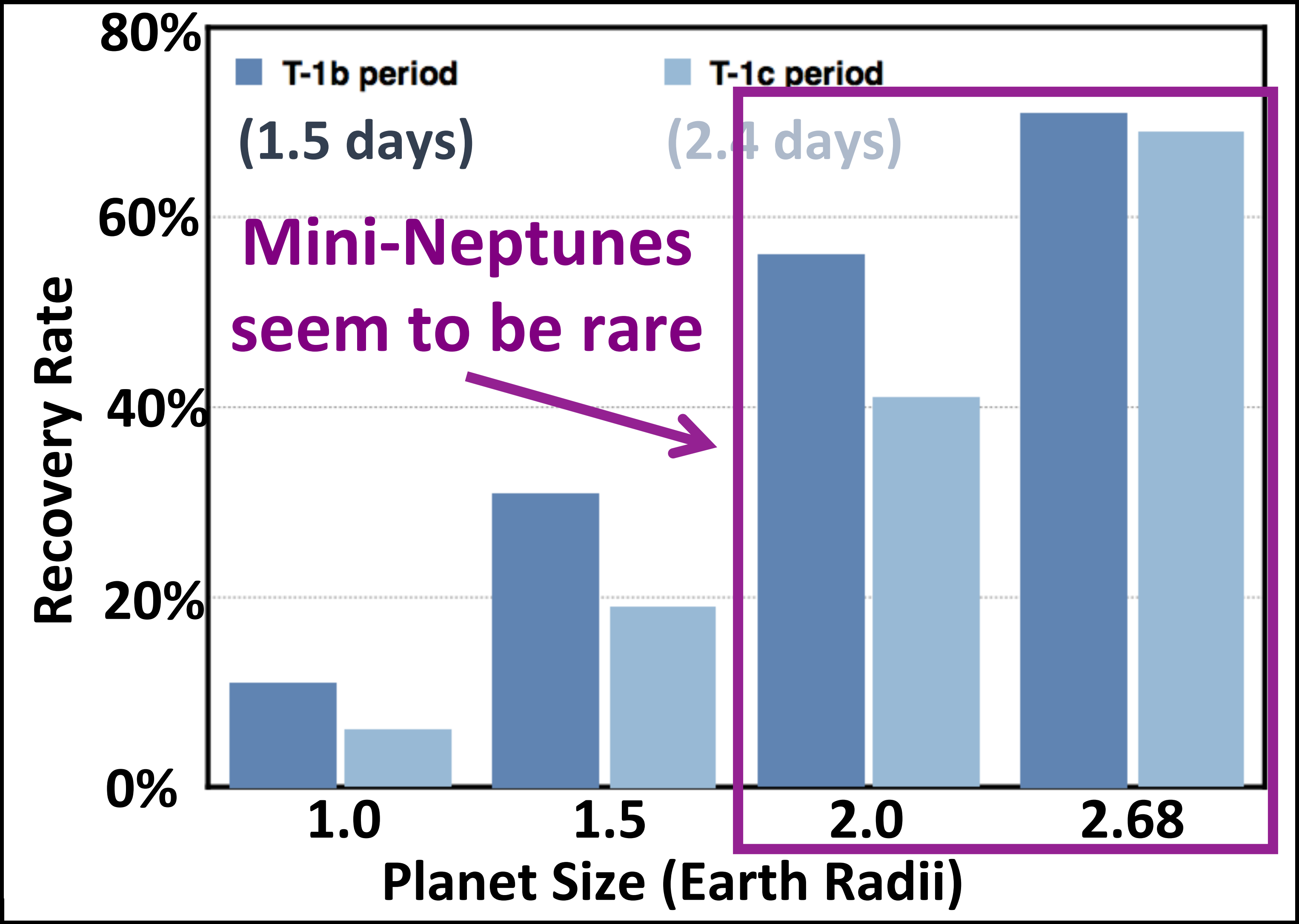
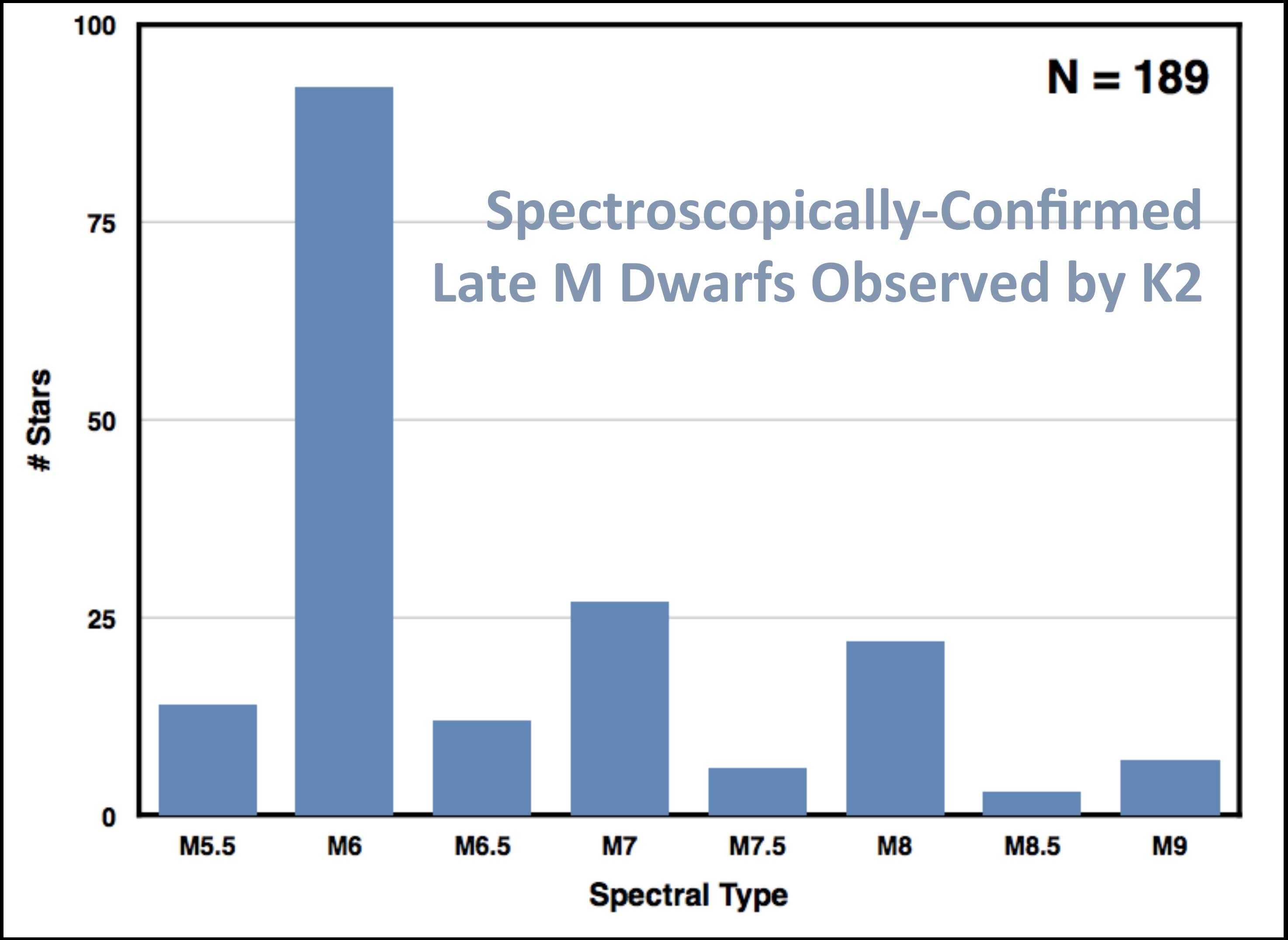


Consistent with Berta-Thompson+ 2013; Dressing + Charbonneau 2013, 2015

Demory et al. 2016, ApJL, arXiv:1606.08622

Studies of Late M Dwarf Planet Occurrence are Limited by Small Stellar Sample Size



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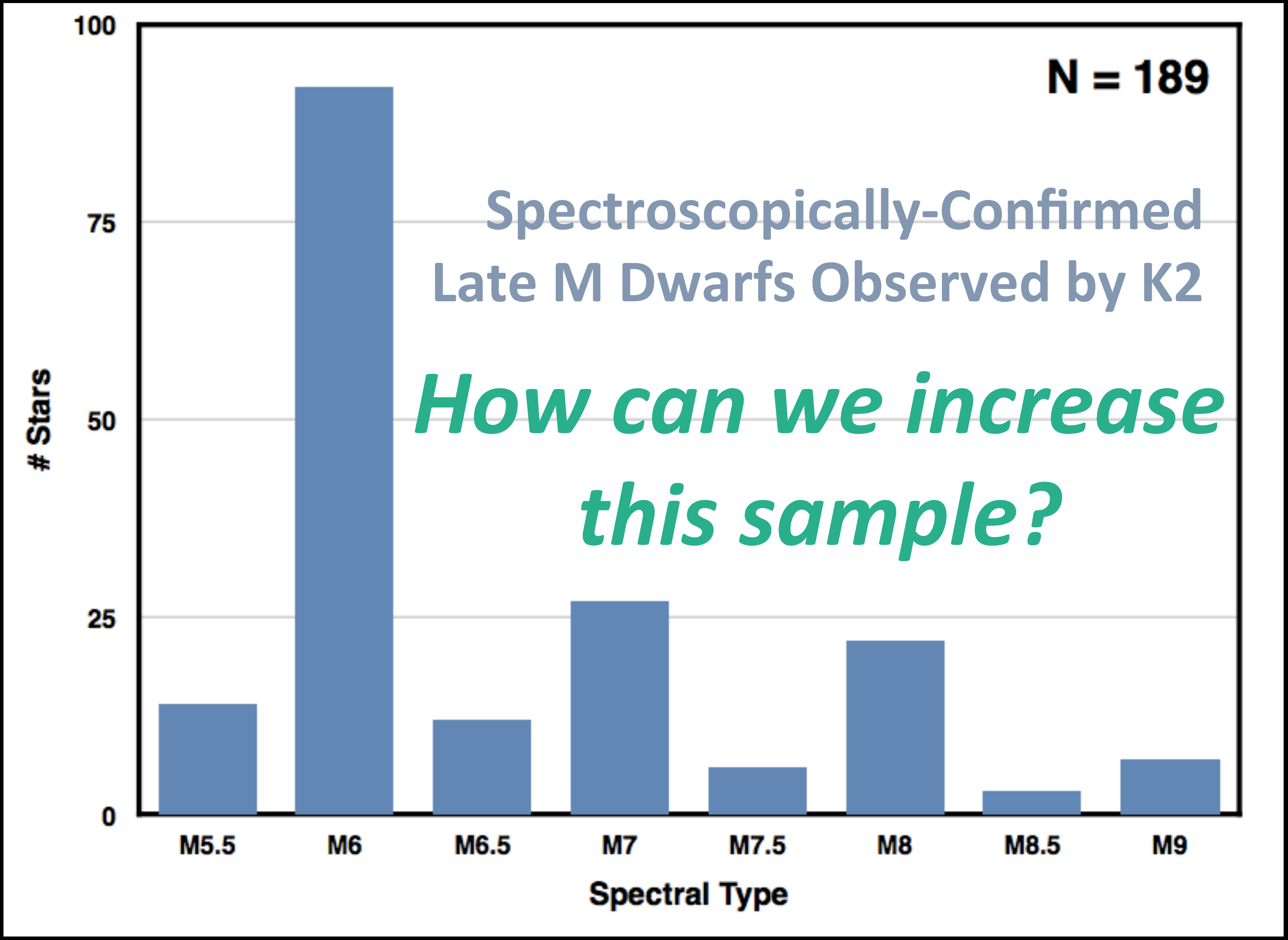

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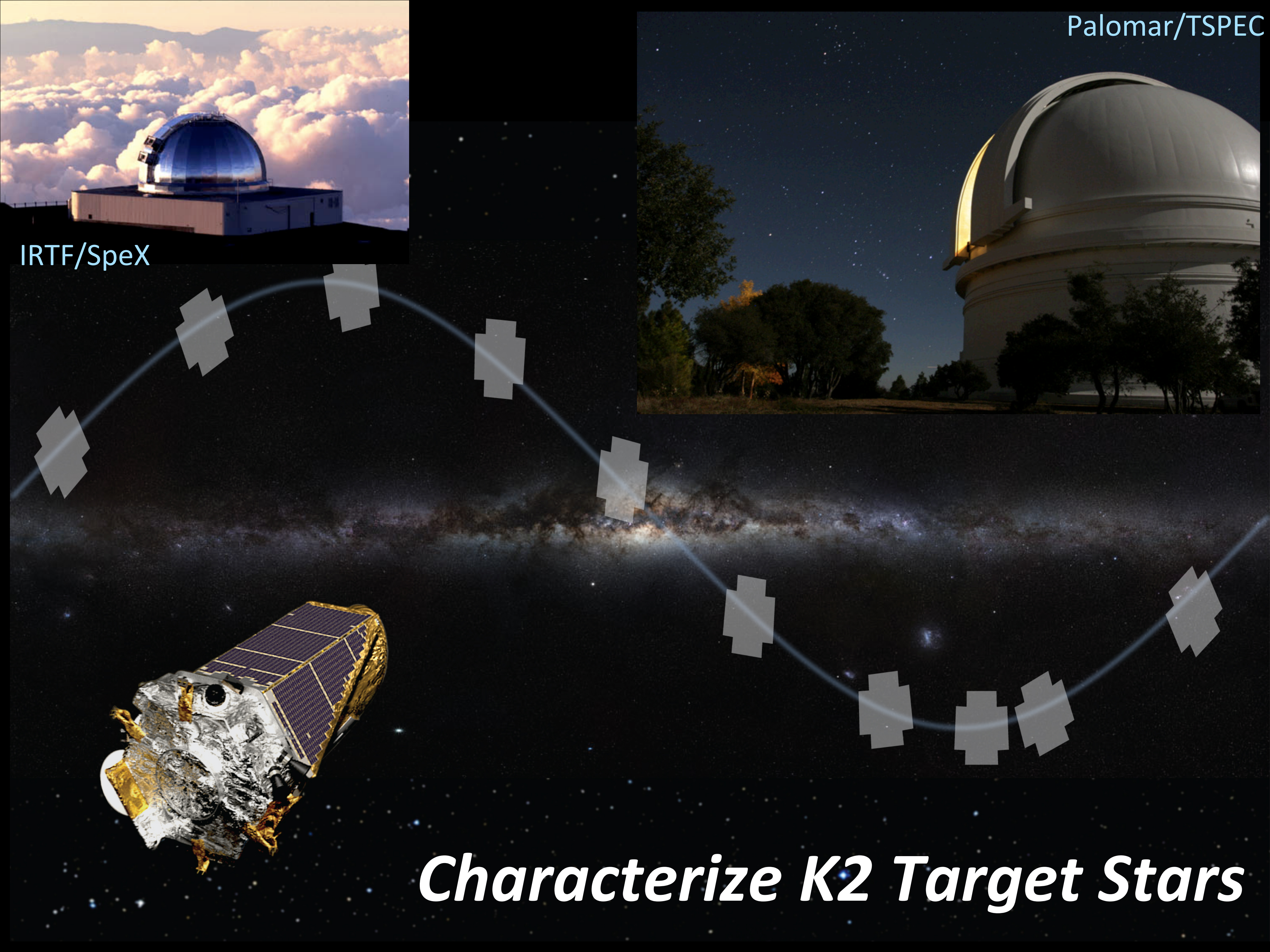
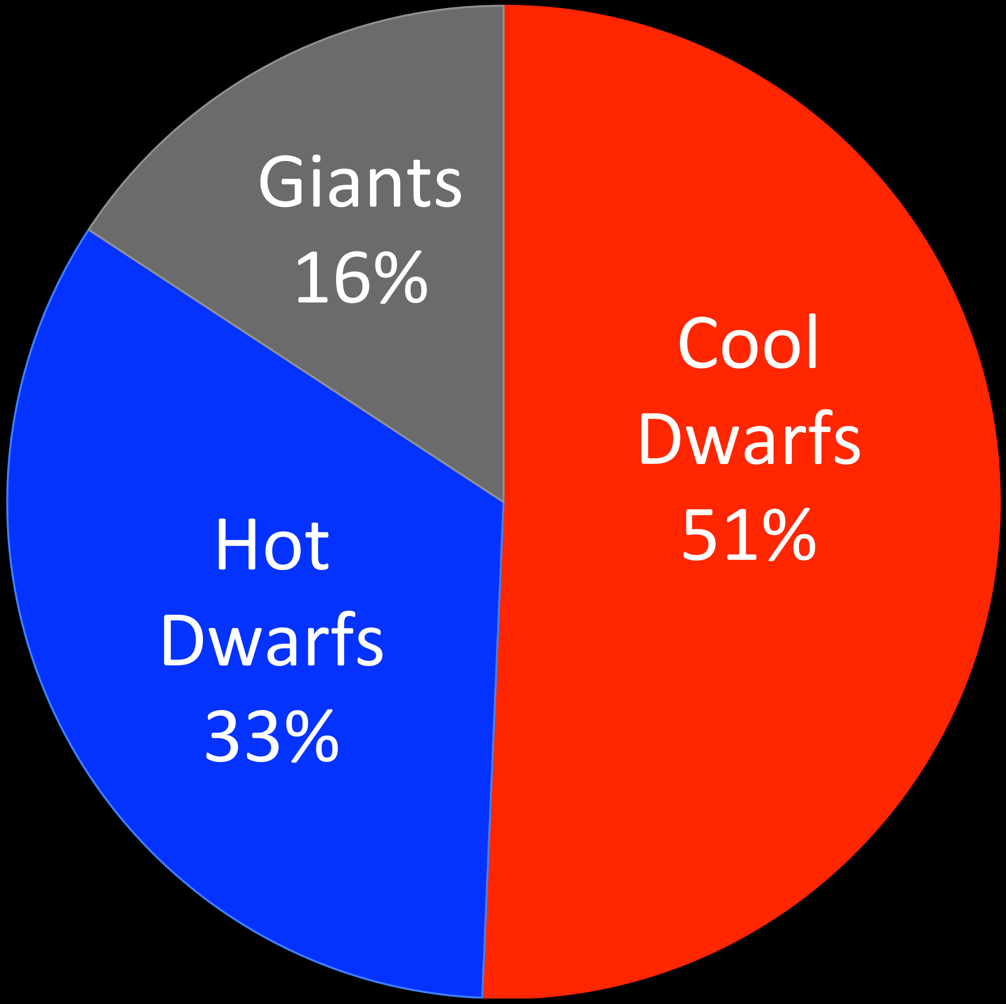
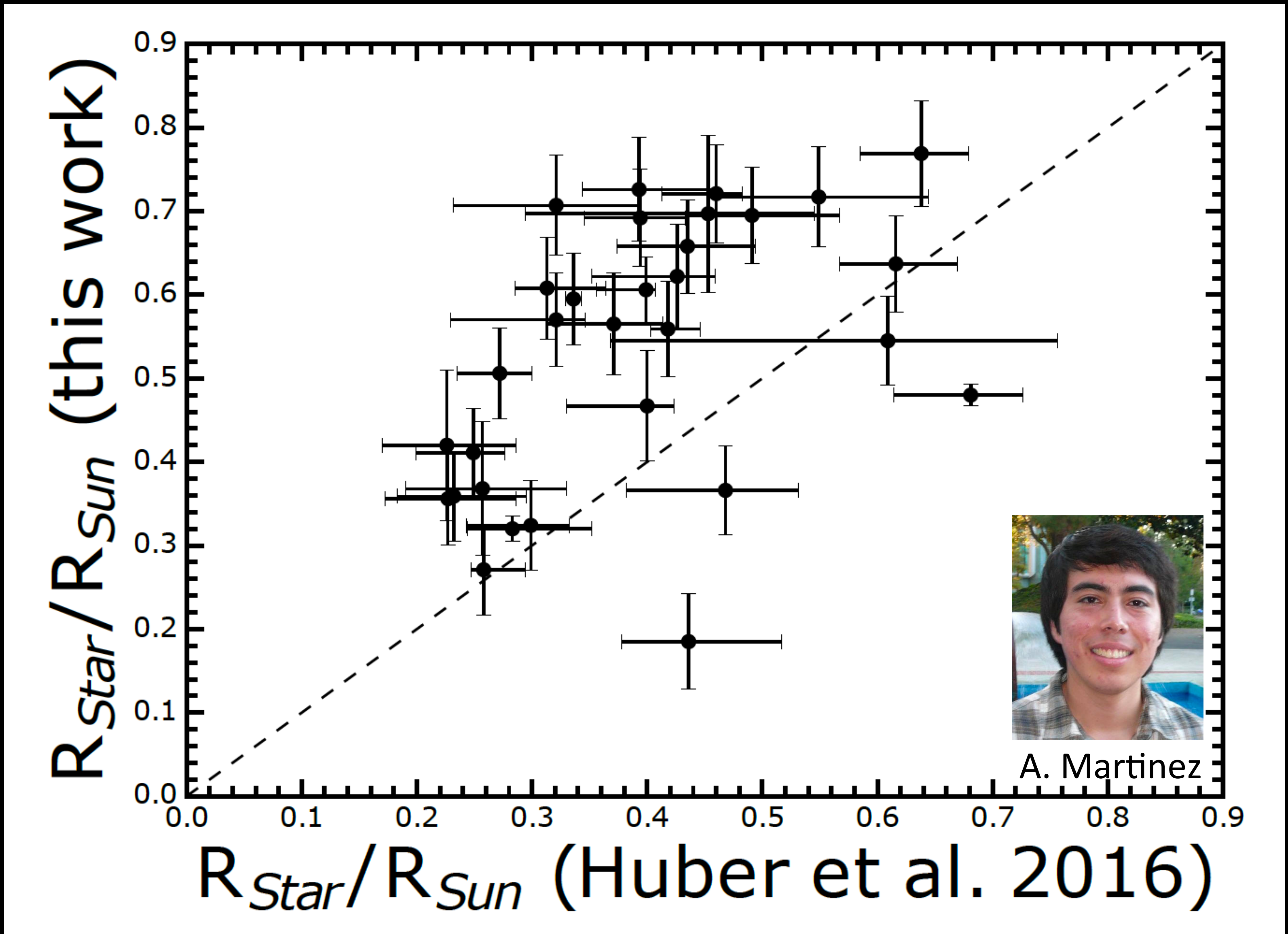

IRTF/SpeX
Palomar/TSPEC
Characterize K2 Target Stars

Only 51% of our initial targets were actually Low-mass Dwarfs



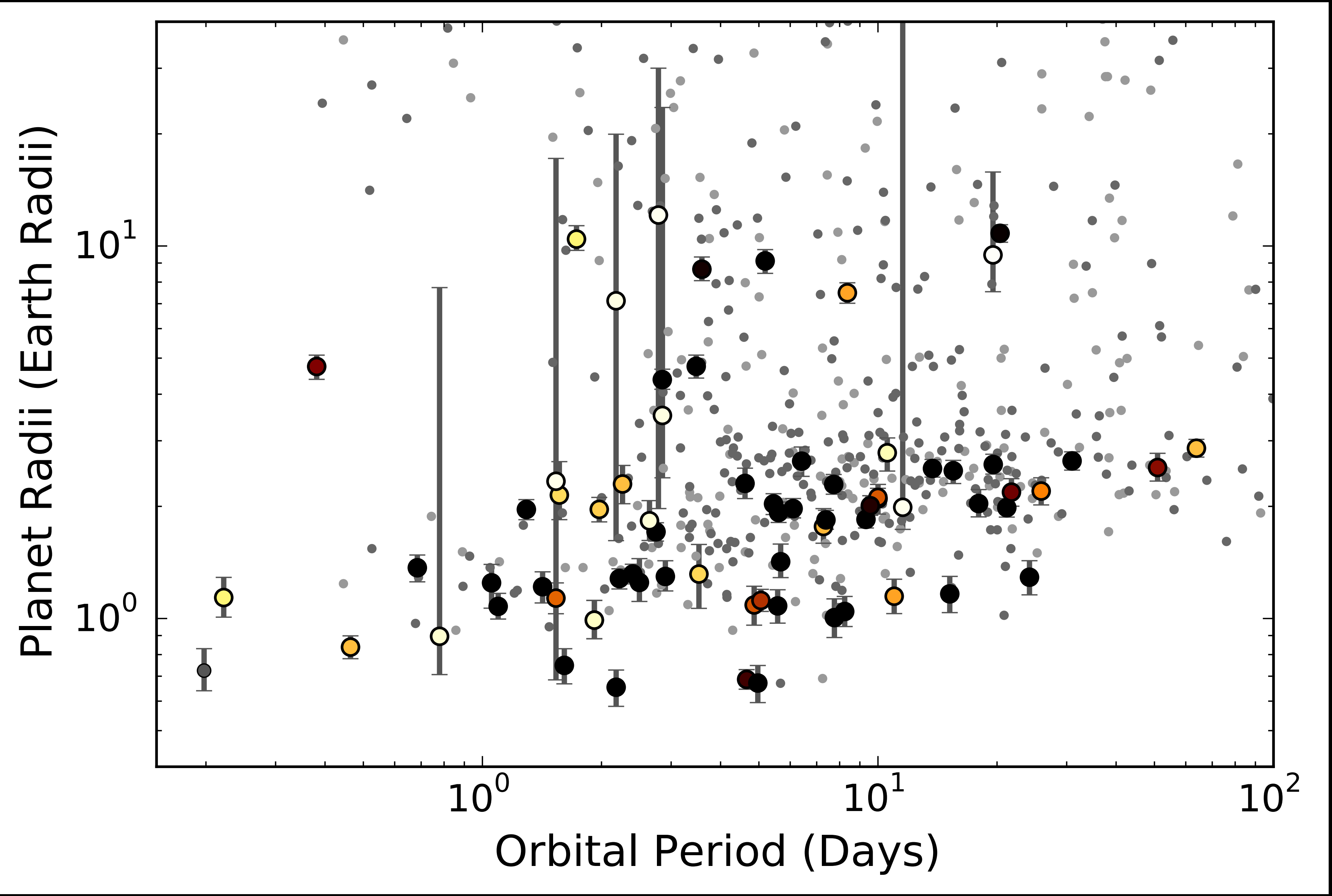
Dressing et al. 2017a, ApJ, 836, 167

Revised Stellar Radii Are Larger



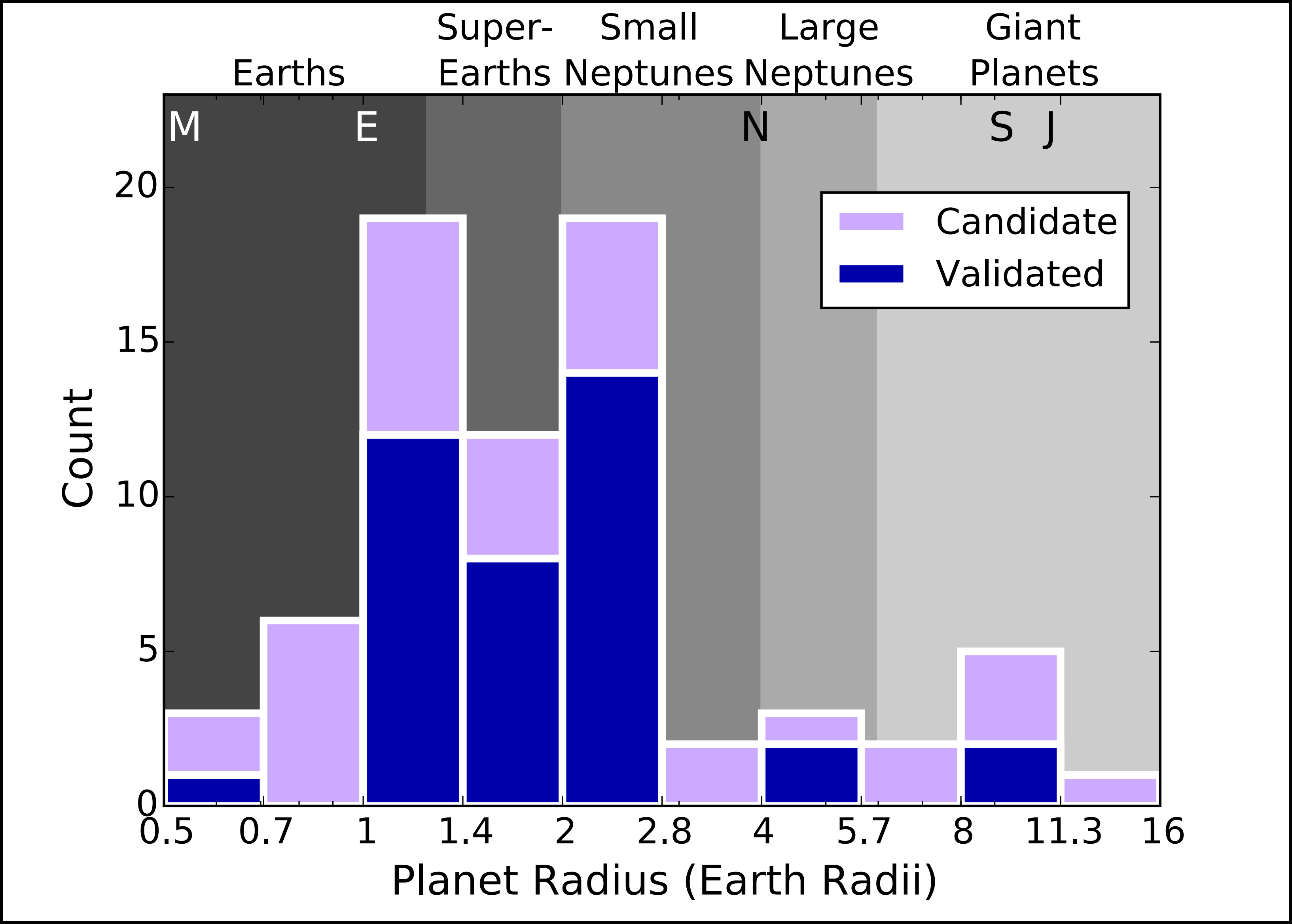
Martinez, Crossfield, Schlieder, Dressing et al. 2017, ApJ, 837, 72

Most of our Planets & Candidates are Small and Hot



Dressing et al. 2017b, accepted to AJ, arXiv:1703.07416

85% are Smaller than Neptune

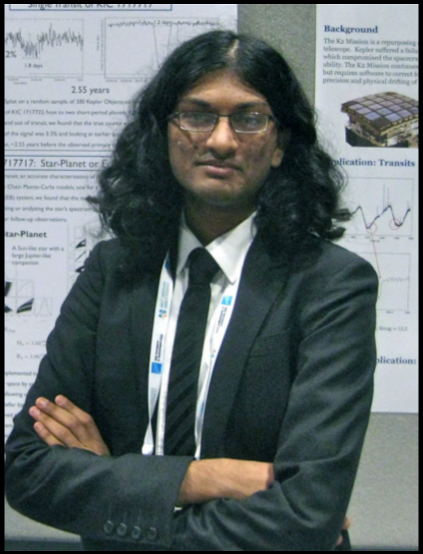


Dressing et al. 2017b, accepted to AJ, arXiv:1703.07416

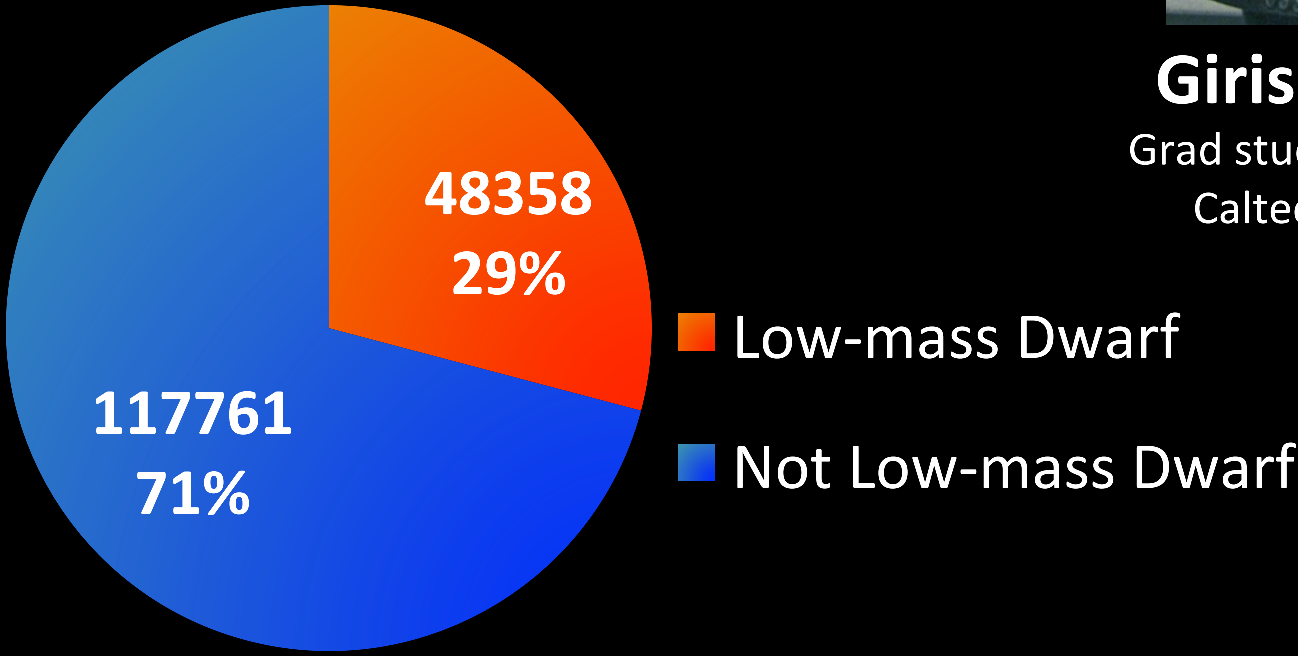
Spectra are Expensive!

How can we classify the full K2 M dwarf sample?

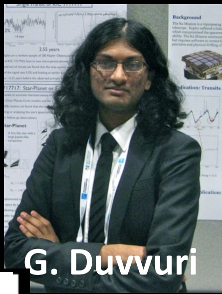
- Trained random forest using spectroscopically-classified stars
- Reported probabilities that individual targets are M dwarfs

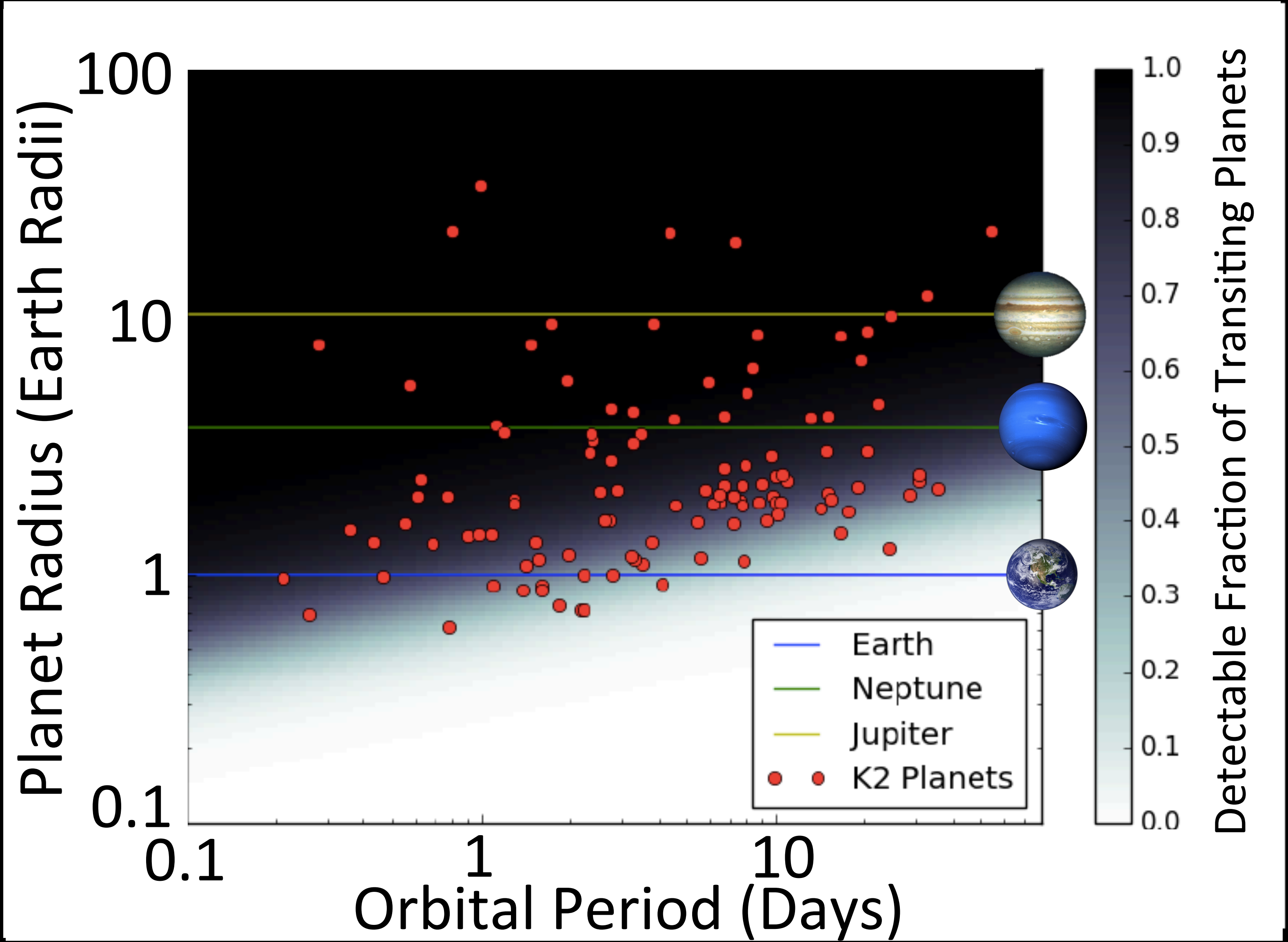


Girish Duvvuri
Grad student at Colorado
Caltech SURF 2016

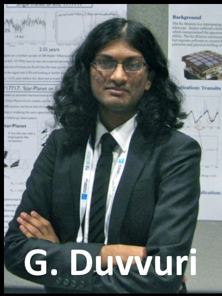


Girish Estimated K2's Sensitivity to Planetary Systems Orbiting M Dwarfs



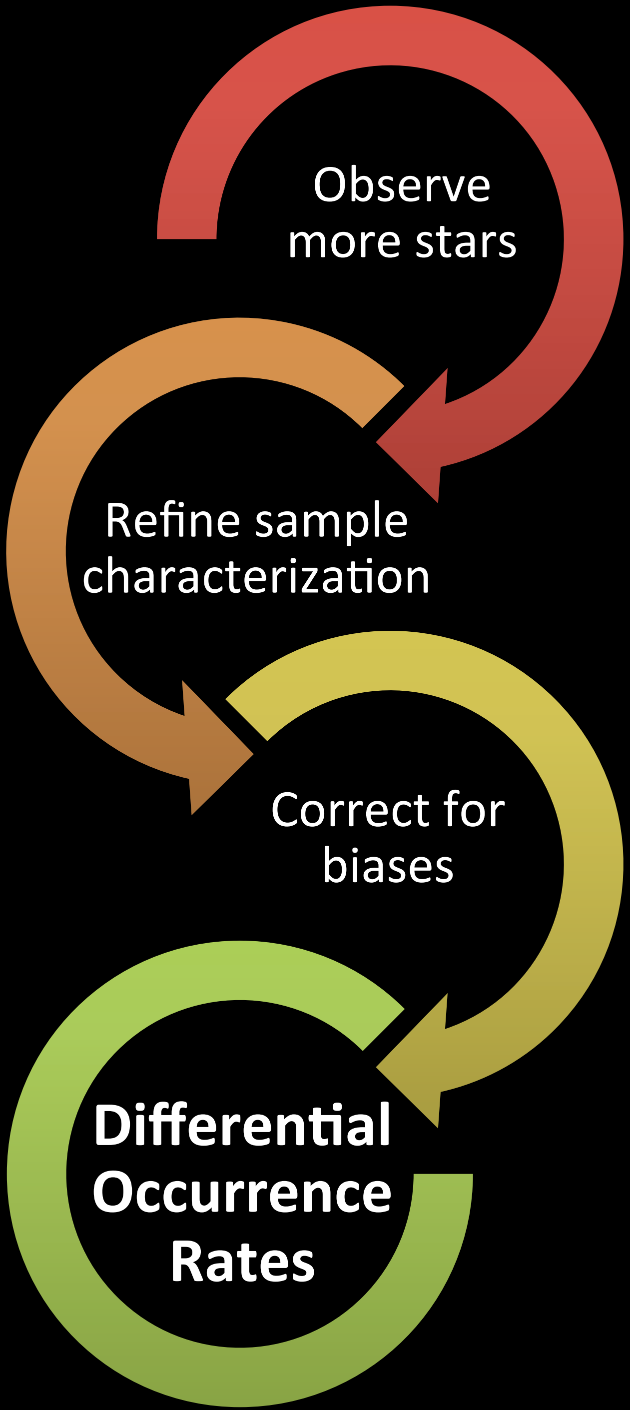


Typical K2 M dwarfs host 1.2 small planets with periods < 50 days

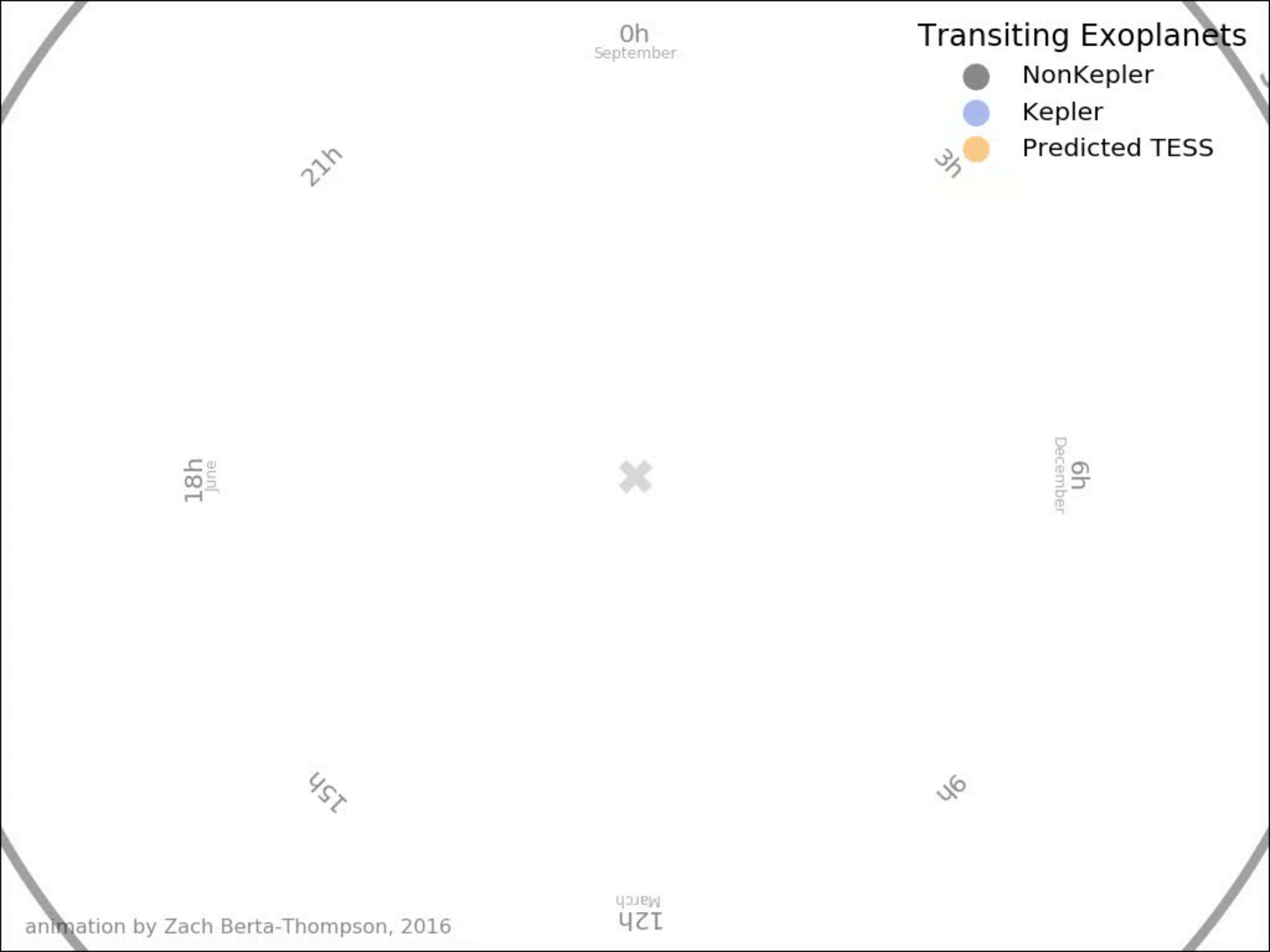


Size Range:	**Period < 10 Days**	**Period 10 – 50 Days**
Smaller than Earth	0.21	0.07
Earth – Neptune	0.35	0.45
Neptune - Jupiter	0.07	0.07

Our Future Steps



TESS will change the landscape


Transiting Exoplanets
NonKepler
Kepler
Predicted TESS
0h
September
3h
21h
18h
June
6h
December
15h
9h
12h
March
animation by Zach Berta-Thompson, 2016

WHICH REAL STARS WILL TESS OBSERVE?

The TESS Input Catalog and Candidate Target List [ver. 20170628]

Keivan G. Stassun[1,2,3], Ryan J. Oelkers[1,2], Joshua Pepper[4,2], Martin Paegert[5,2], Nathan De Lee[6,2], Guillermo Torres[5], David Latham[5], Philip Muirhead[7], Courtney Dressing[8], Barbara Rojas-Ayala[9], Andrew Mann[10], Scott Fleming[11], Al Levine[12], Roberto Silvotti[13], Peter Plavchan[14], and the TESS Target Selection Working Group

arXiv:1706.00495; will be submitted closer to launch

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A CATALOG OF COOL DWARF TARGETS FOR THE TRANSITING EXOPLANET SURVEY SATELLITE

Philip S. Muirhead,[1] Courtney Dressing,[2] Andrew W. Mann,[3,*] Bárbara Rojas-Ayala,[4] Sebastien Lepine,[5] Martin Paegert,[6] Nathan De Lee,[7,8] and Ryan Oelkers[8]

arXiv:1710.00193, submitted to AAS Journals

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$V - J > 2.7$, $T_{eff} \leq 4000$ K

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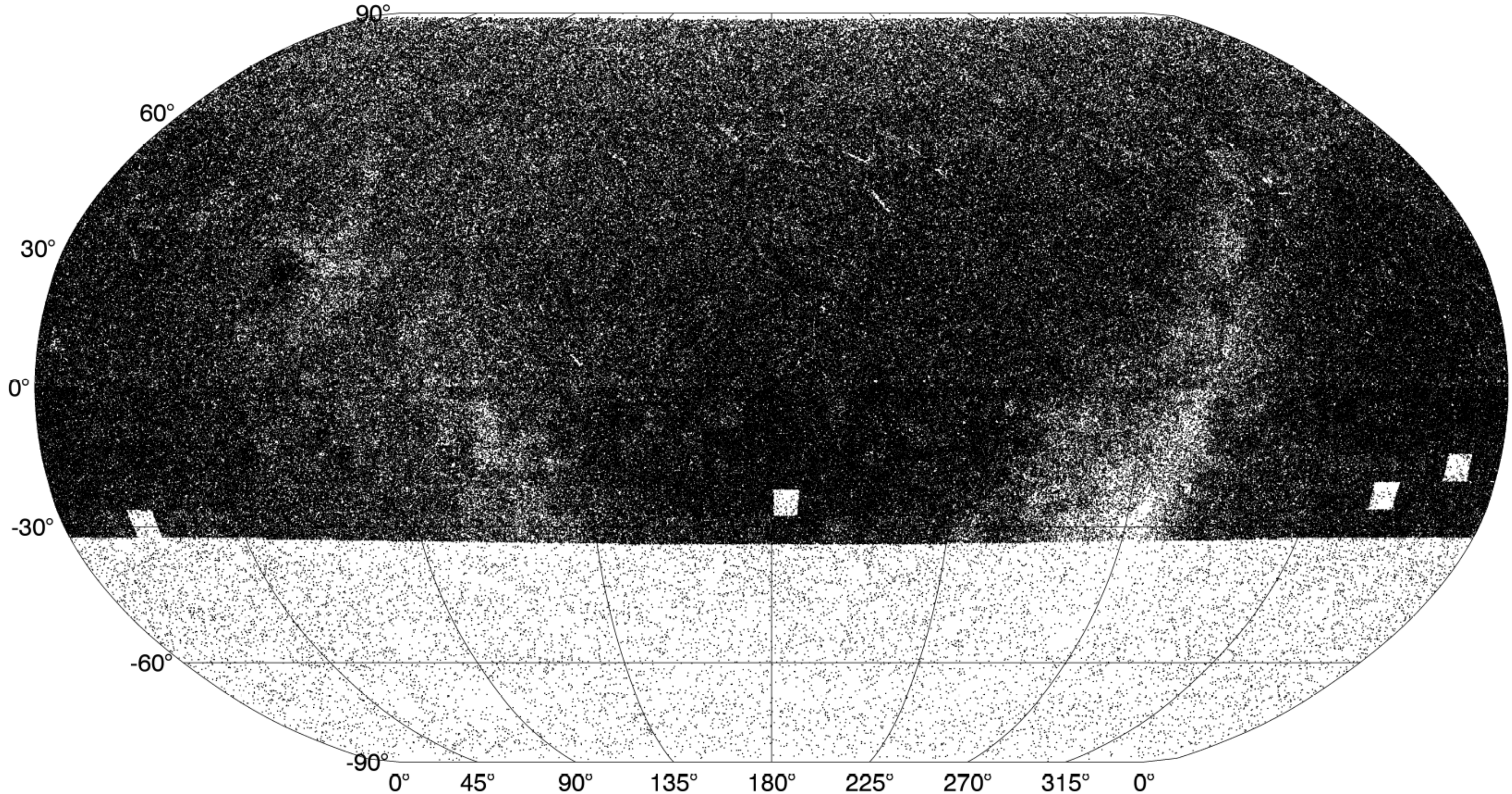
How did we identify cool dwarfs?

- Started with **SUPERBLINK** catalog
  - All-sky
  - High proper motions (> 40 mas/yr)
  - Optical & infrared magnitudes
- Updated V band magnitudes
- Separated dwarfs from giants
- Calculated TESS magnitudes
- Estimated stellar properties
  - T_{eff} from color
  - Mass& radius from M_K (3% errors) or T_{eff} (13% errors)

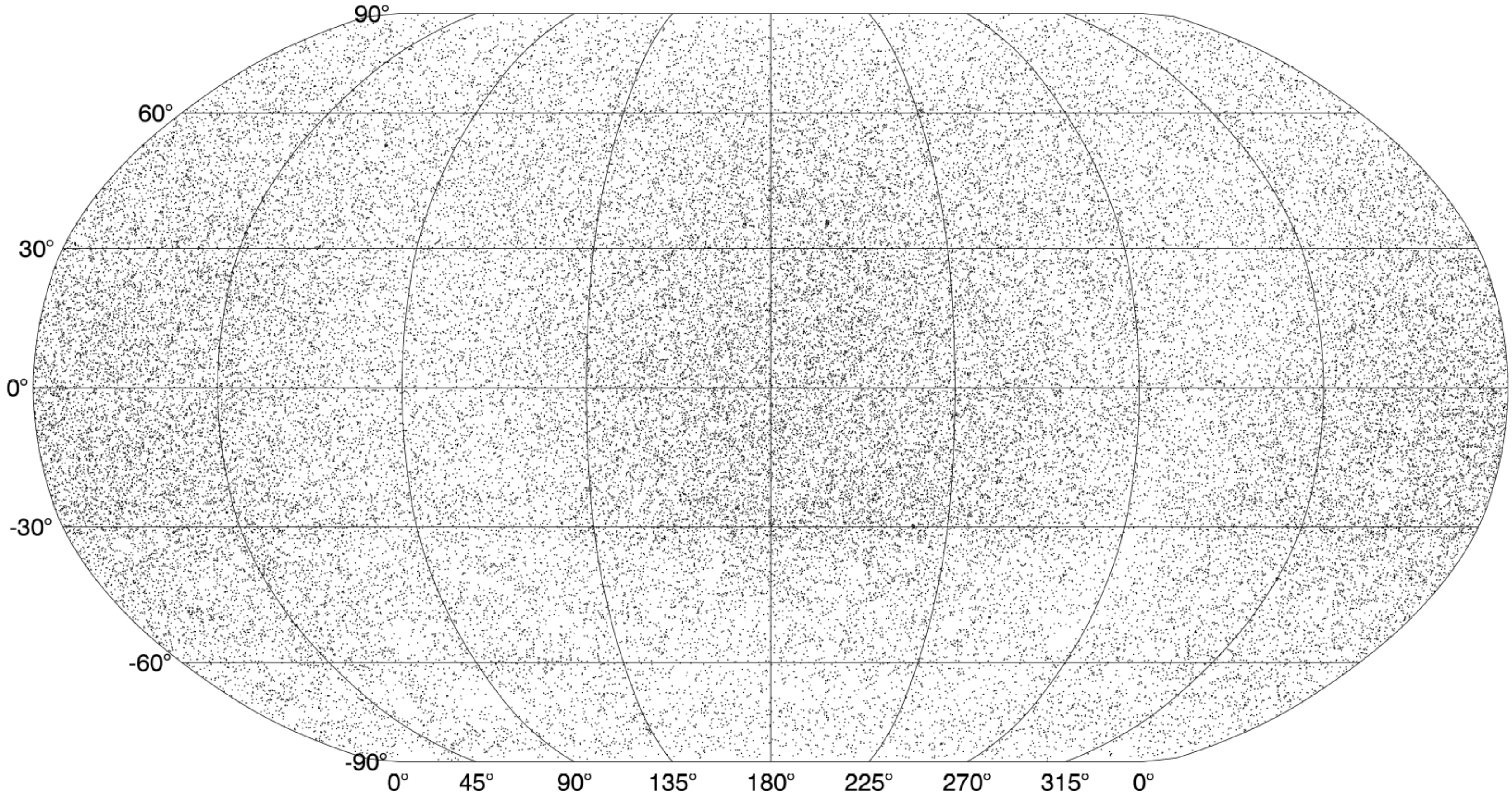
Cool Dwarf Catalog: 1,080,005 stars



Muirhead, Dressing, Mann, et al., *submitted , arXiv:1710.00193*

Only stars with high proper motion

(> 150 mas/yr)



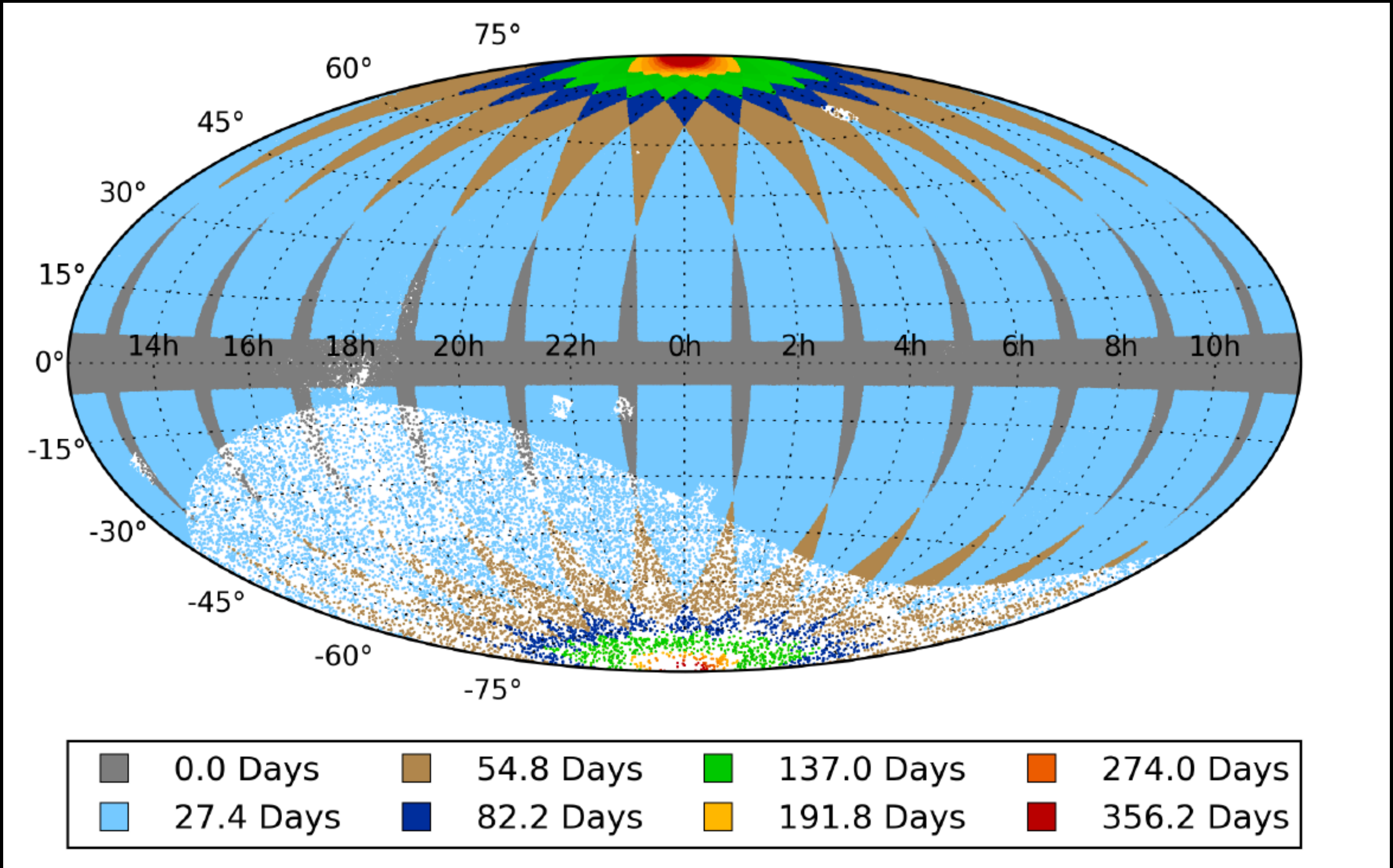
Muirhead, Dressing, Mann, et al., *submitted , arXiv:1710.00193*

How many planets might we find?

How many planets might we find?

Let's look at ALL the cool dwarfs!

How many planets might we find?

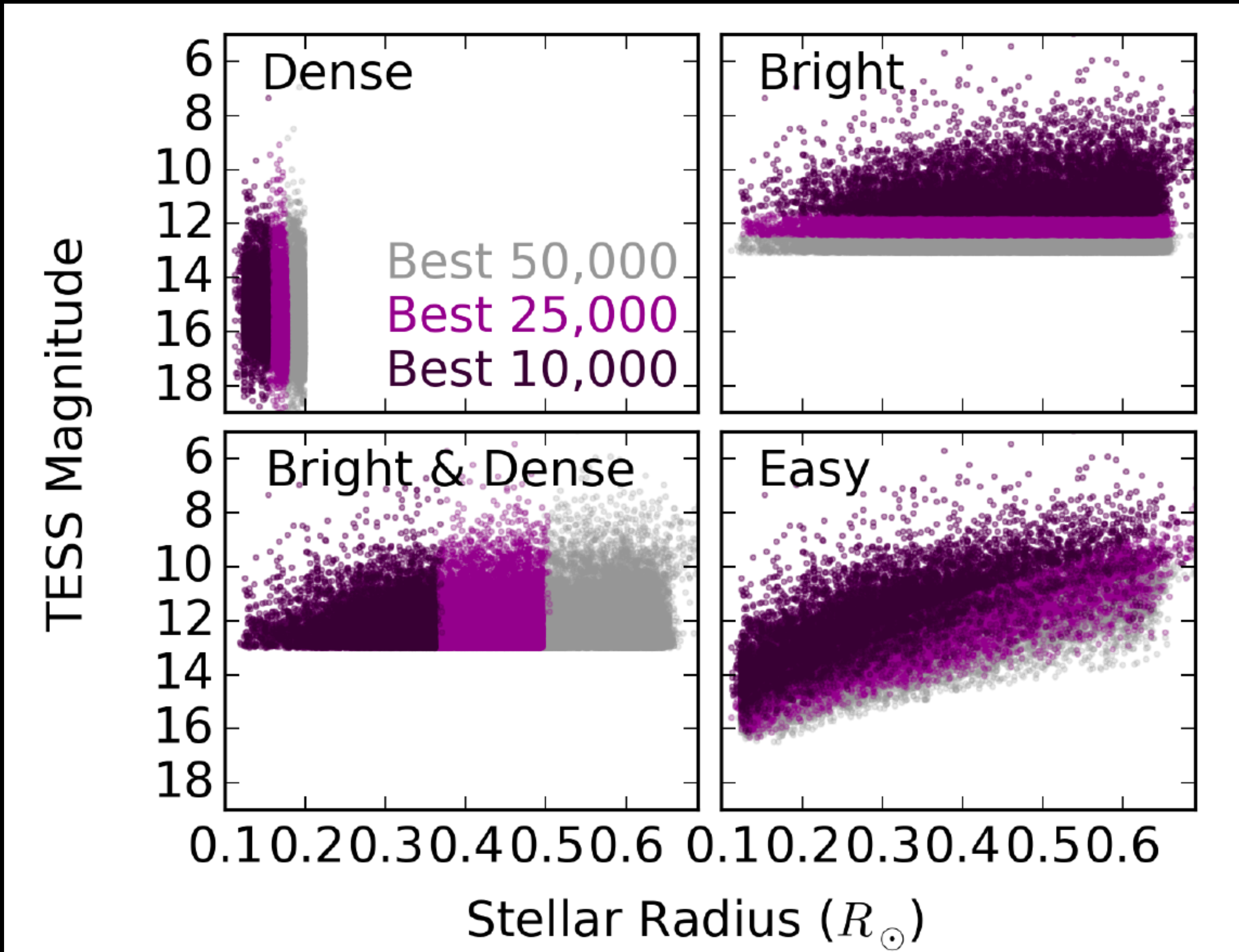


2533 planets with Rp = 0.5 – 4 R_{Earth} & P < 200 days

REALITY CHECK:

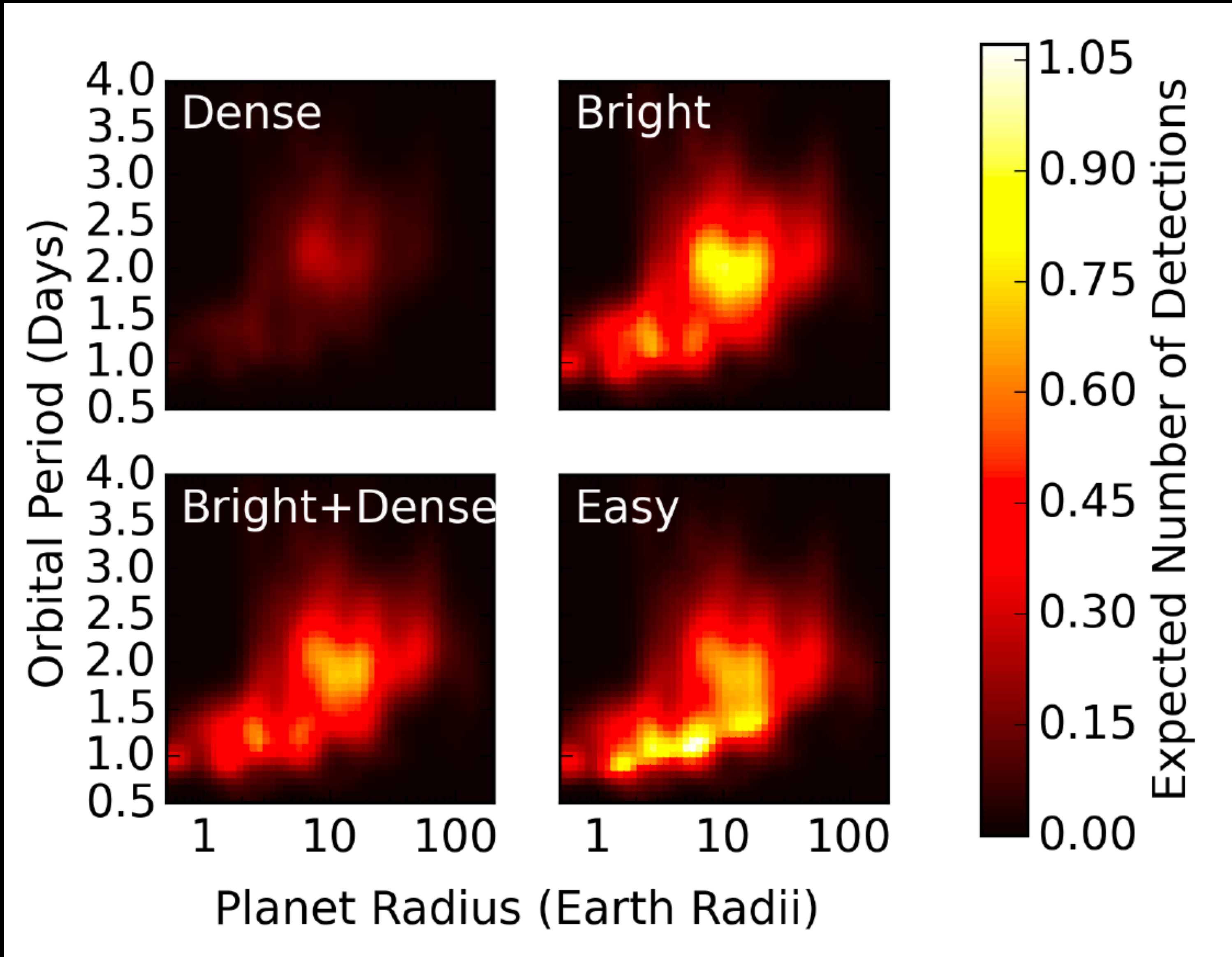
NOT ALL COOL DWARFS WILL BE OBSERVED AT 2-MINUTE CADENCE

Possible Prioritization Schemes



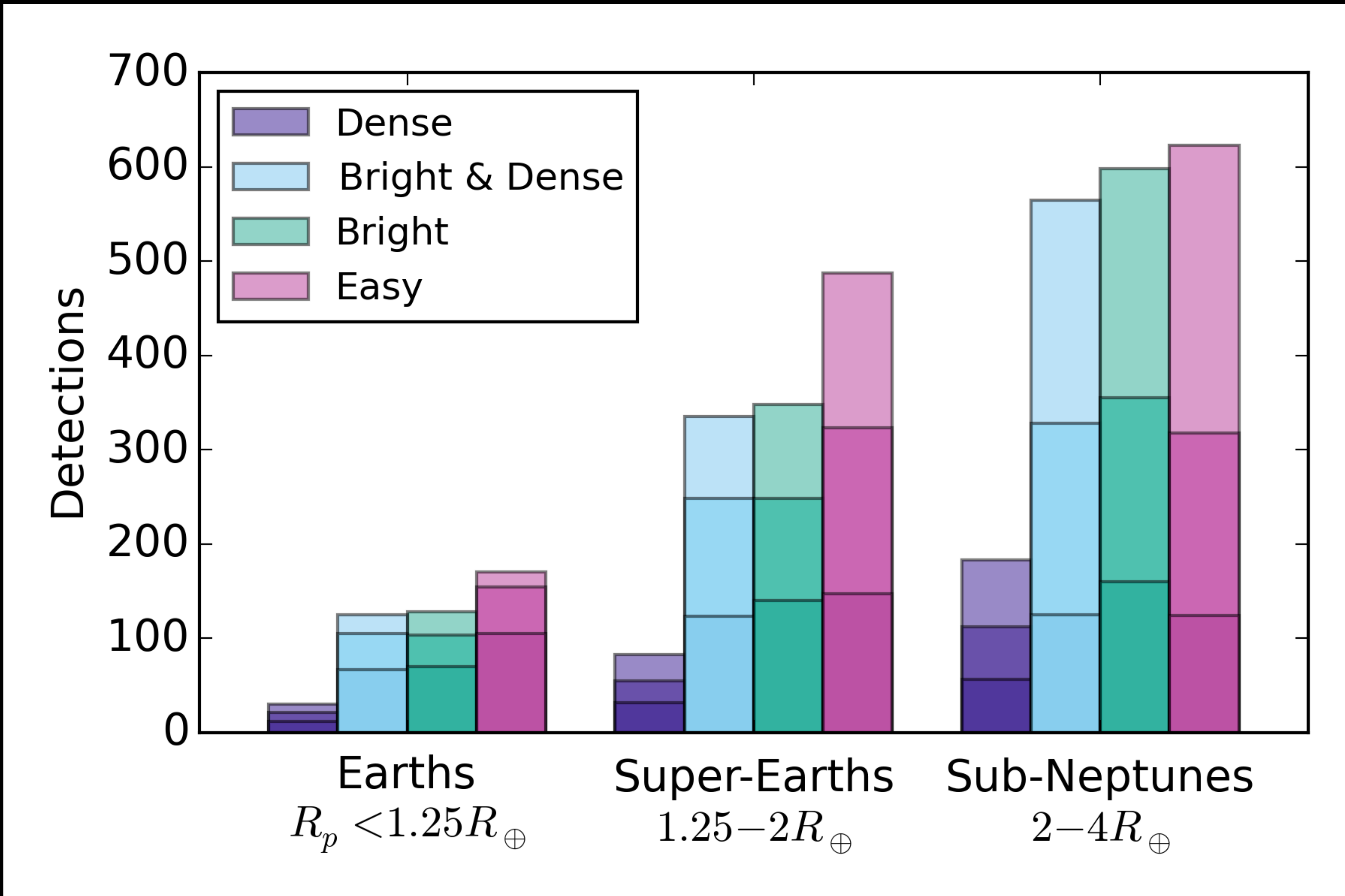
Muirhead, Dressing, Mann, et al., *submitted , arXiv:1710.00193*

The “Easy” Scheme Maximizes Planet Yield



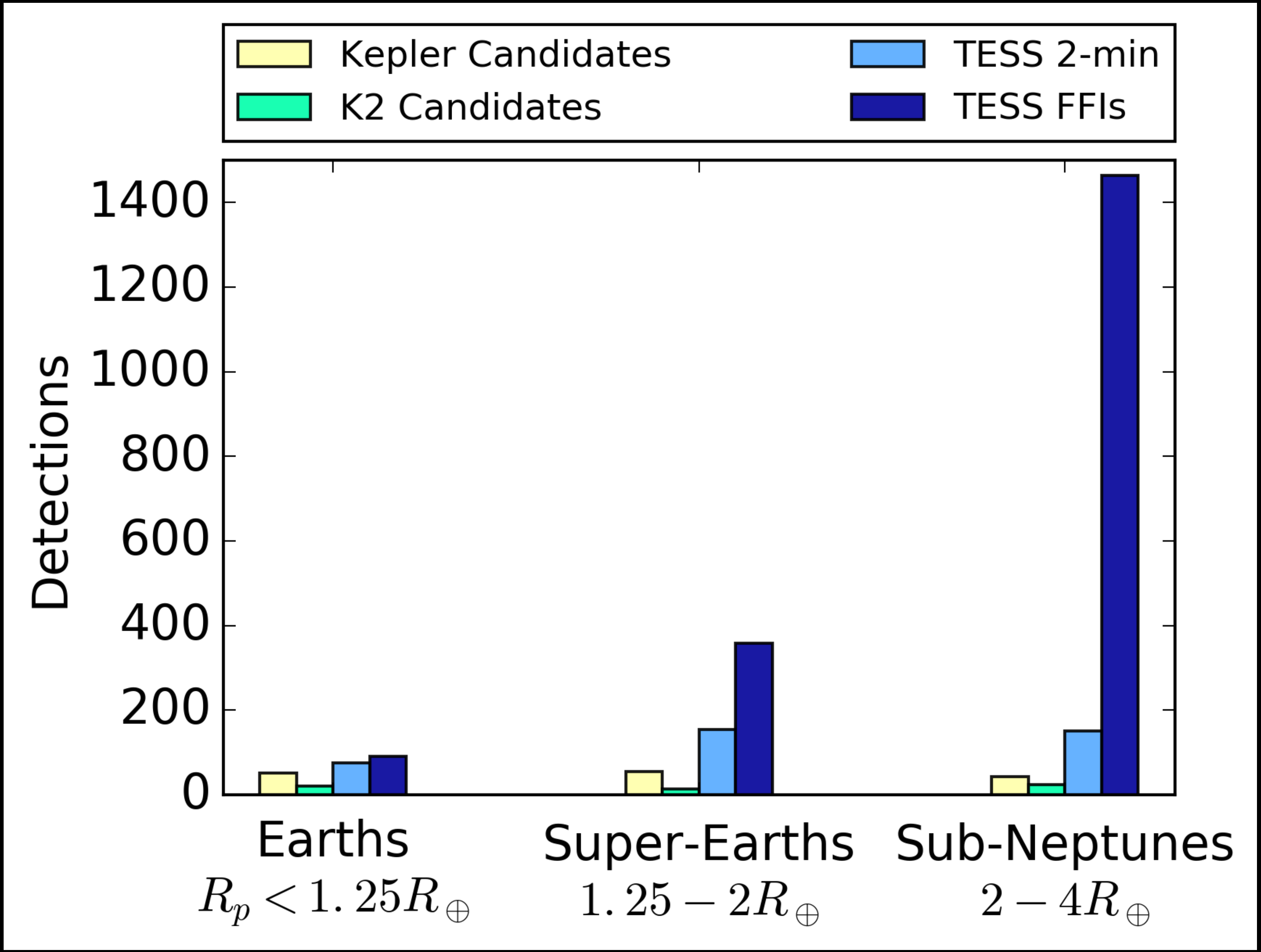
Muirhead, Dressing, Mann, et al., *submitted , arXiv:1710.00193*

The “Easy” Scheme Maximizes Planet Yield

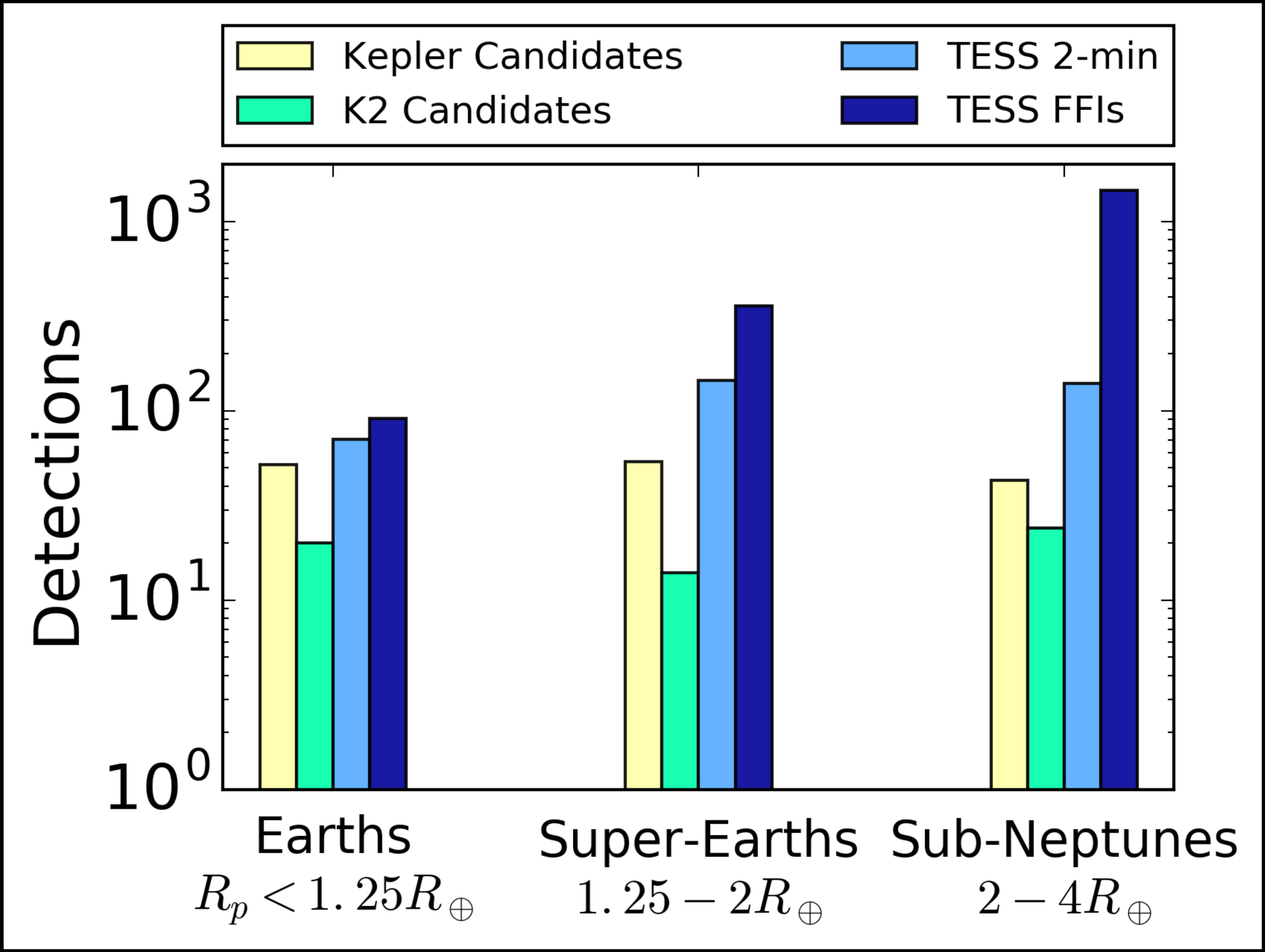


Muirhead, Dressing, Mann, et al., *submitted , arXiv:1710.00193*

The TESS Planet Yield will Dwarf the Kepler & K2 Sample



The TESS Planet Yield will Dwarf the Kepler & K2 Sample



Summary

- Planets are common
- Smaller/less massive planets are more frequent
- Smaller stars have more close-in planets
- Large surveys of diverse stellar populations are required to truly understand planet occurrence

Know all thy stars thou must to know thy planet occurrence rates.

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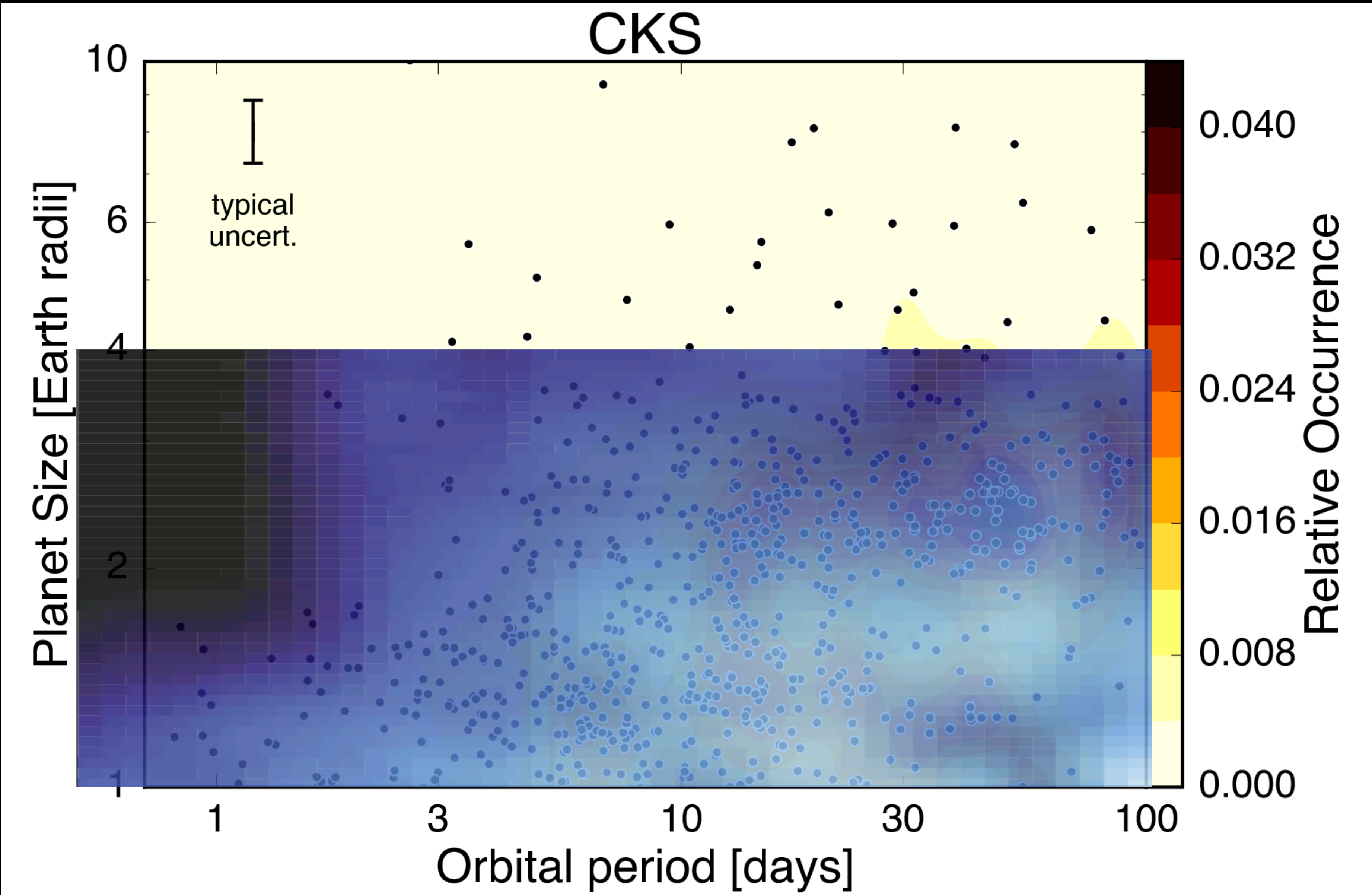
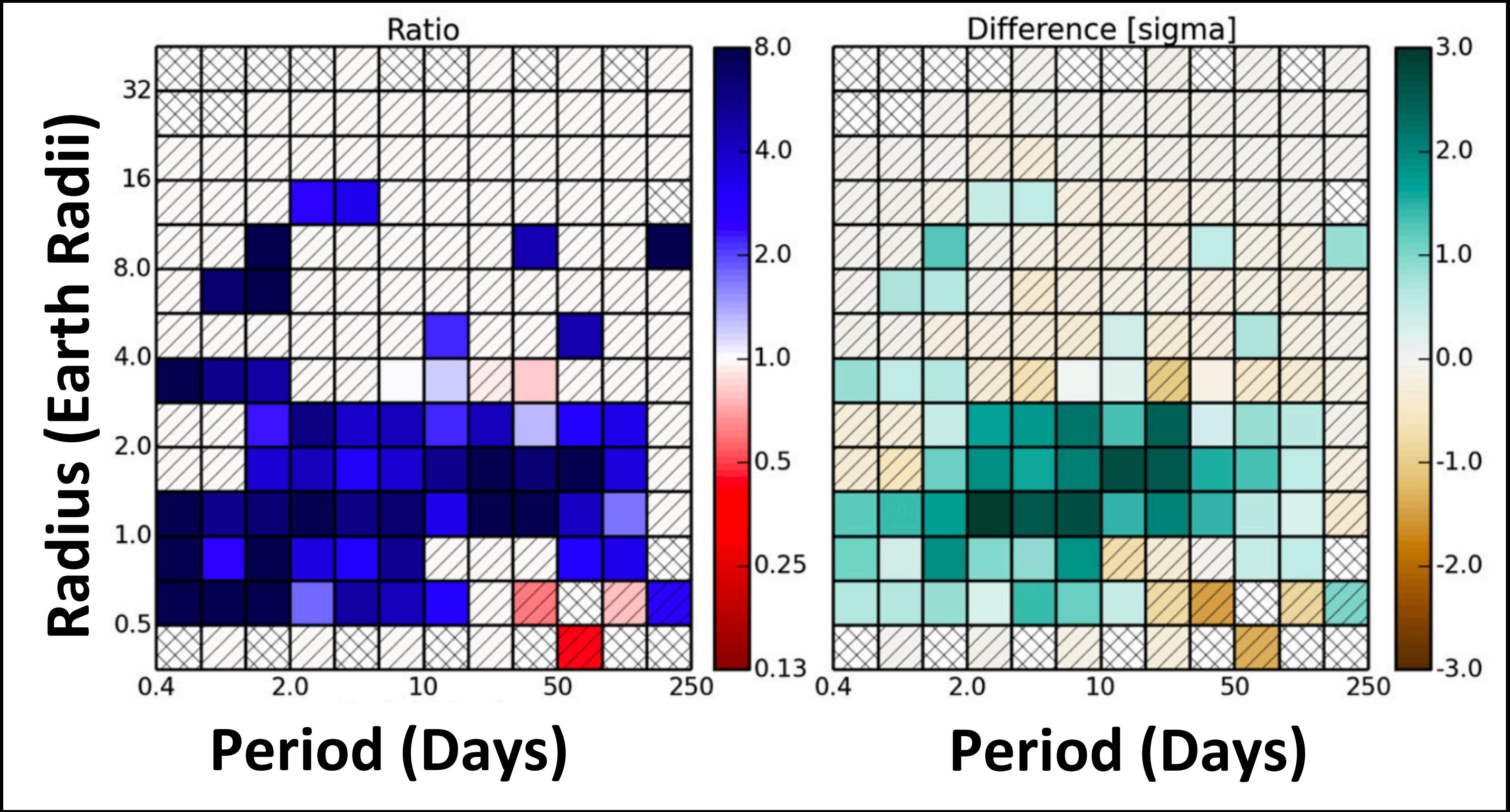
2-D View of Planet Occurrence for FGK Stars



Fulton et al. 2017, accepted to AJ, arXiv:1703.10375

Small Stars Host More Planets



Mulders et al. 2015, ApJ, 798, 112