Transit Surveys

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Starting in September: **NASA Sagan Fellow at Caltech**

Sagan Exoplanet Summer Workshop

July 29, 2015

Our Mission: *Find a* ***transiting Earth-like planet***

Designing transit surveys

Constraining planetary parameters

Accounting for selection effects

Estimating planet occurrence rates

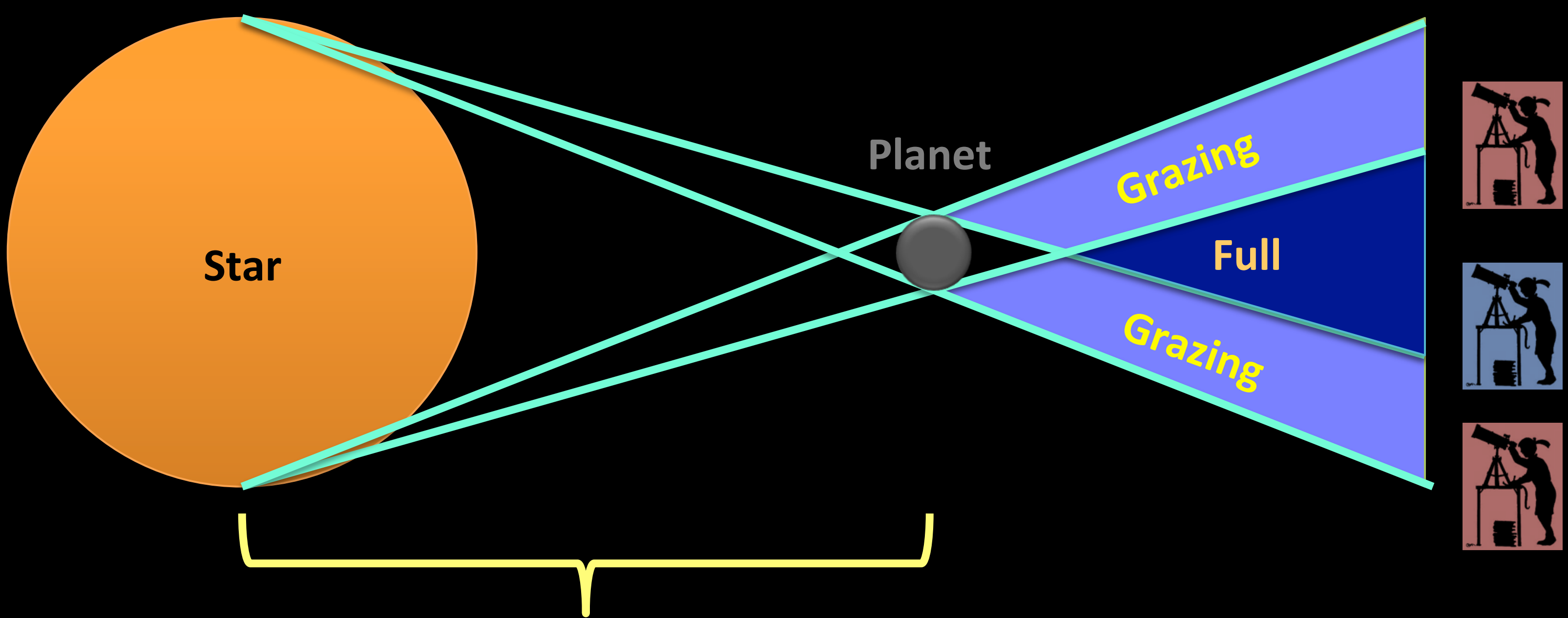
If **1%** of FGK stars harbor **hot Jupiters**
Marcy et al. 2005

then **how many stars** will we need to survey in order to find a single

transiting

hot Jupiter?

Transit Geometry



d = Star-planet separation during transit

Figure based on Winn et al. 2010

Figure based on Murray & Correia 2010

Transit Geometry

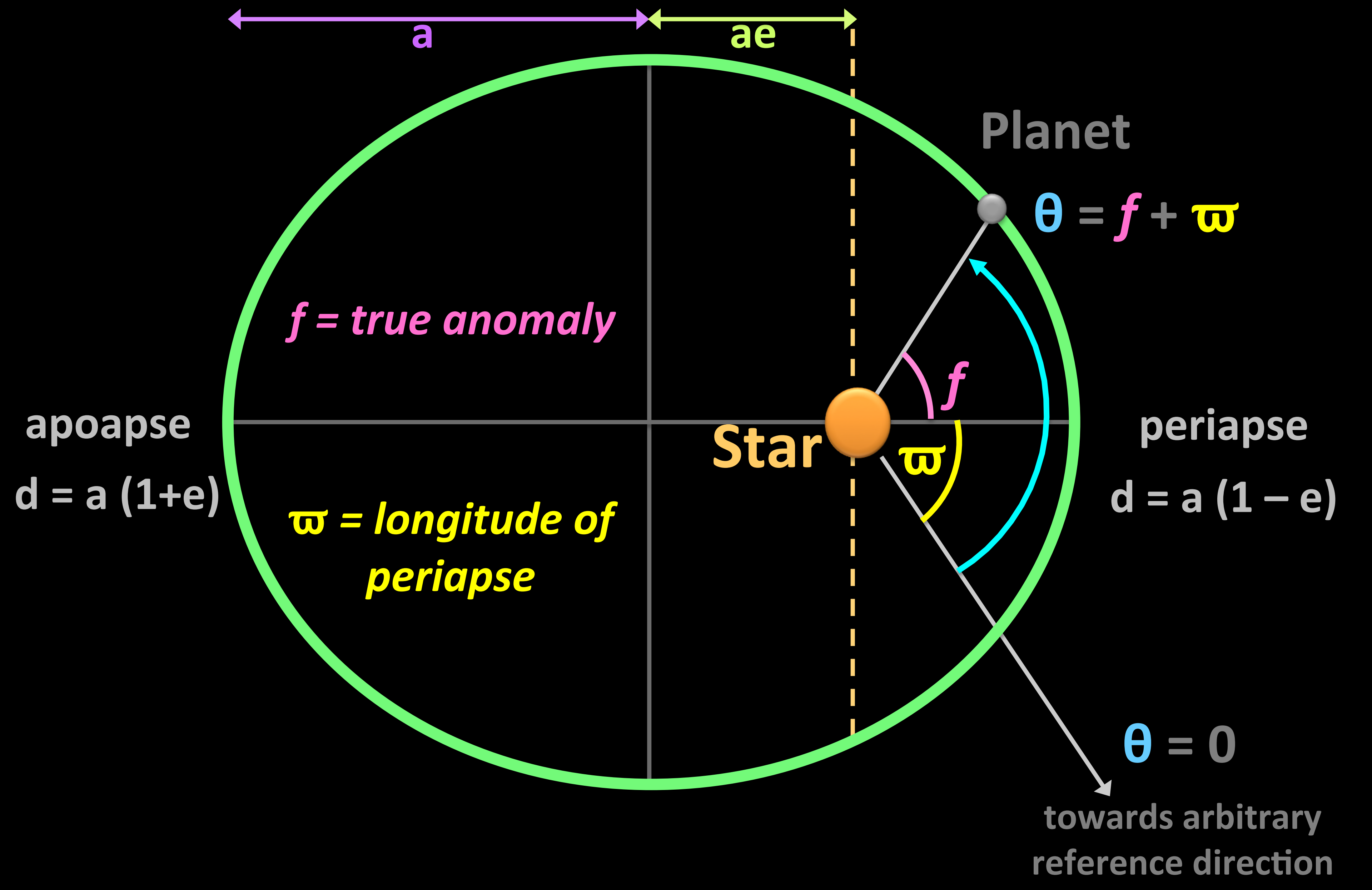
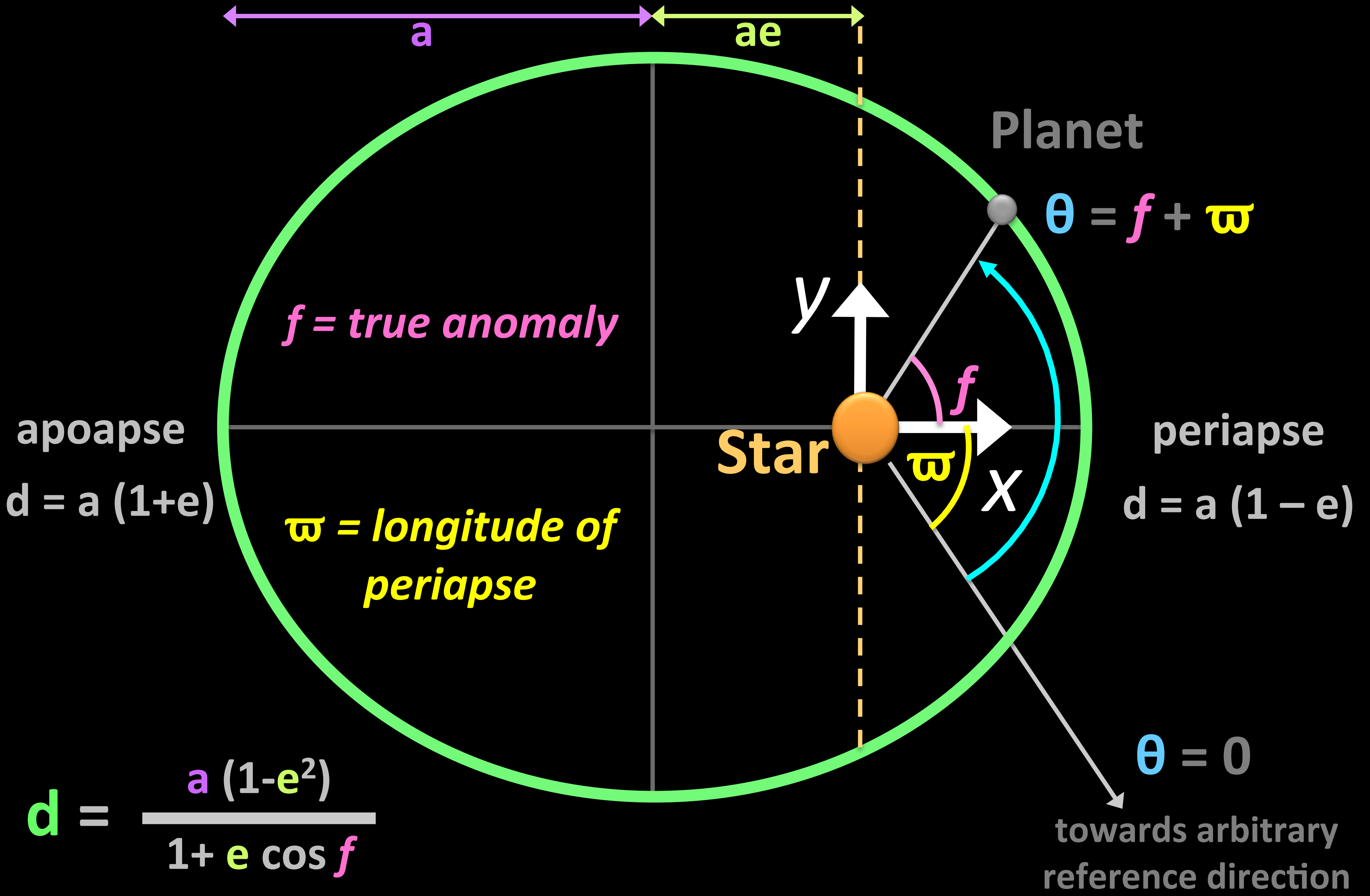


Figure based on Murray & Correia 2010

Transit Geometry



$$d = \frac{a\,(1-e^2)}{1 + e\cos f}$$

$$\text{Transit Probability} = \frac{(R_\star \pm R_p)}{a} \frac{(1 + e \sin \varpi)}{1 - e^2}$$

Easier formula for **circular orbits** *with* **a >> $R_\star$**

$$\text{Transit Probability} = \frac{\text{Stellar Radius}}{\text{Semimajor Axis}}$$

Transit Probability	Sun	Kepler M dwarf	Typical M dwarf
Orbital period = 3.5 days	10%	7%	4%
Insolation = 1 F_{Earth}	0.5%	0.9%	1.4%

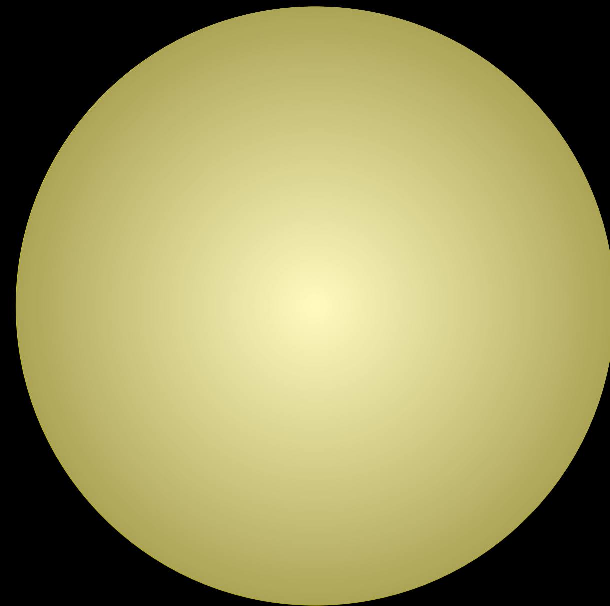
If **1%** of FGK stars harbor **hot Jupiters**

Marcy et al. 2005

and **10%** of those planets transit then

$$N_\star = \frac{1}{0.01} \times \frac{1}{0.1} = \mathbf{1000}\ \textbf{stars}$$

to find a single ***transiting hot Jupiter.***



What precision do we require?

$$\text{Transit Depth} \approx \left(\frac{\text{Planet Radius}}{\text{Stellar Radius}}\right)^2$$

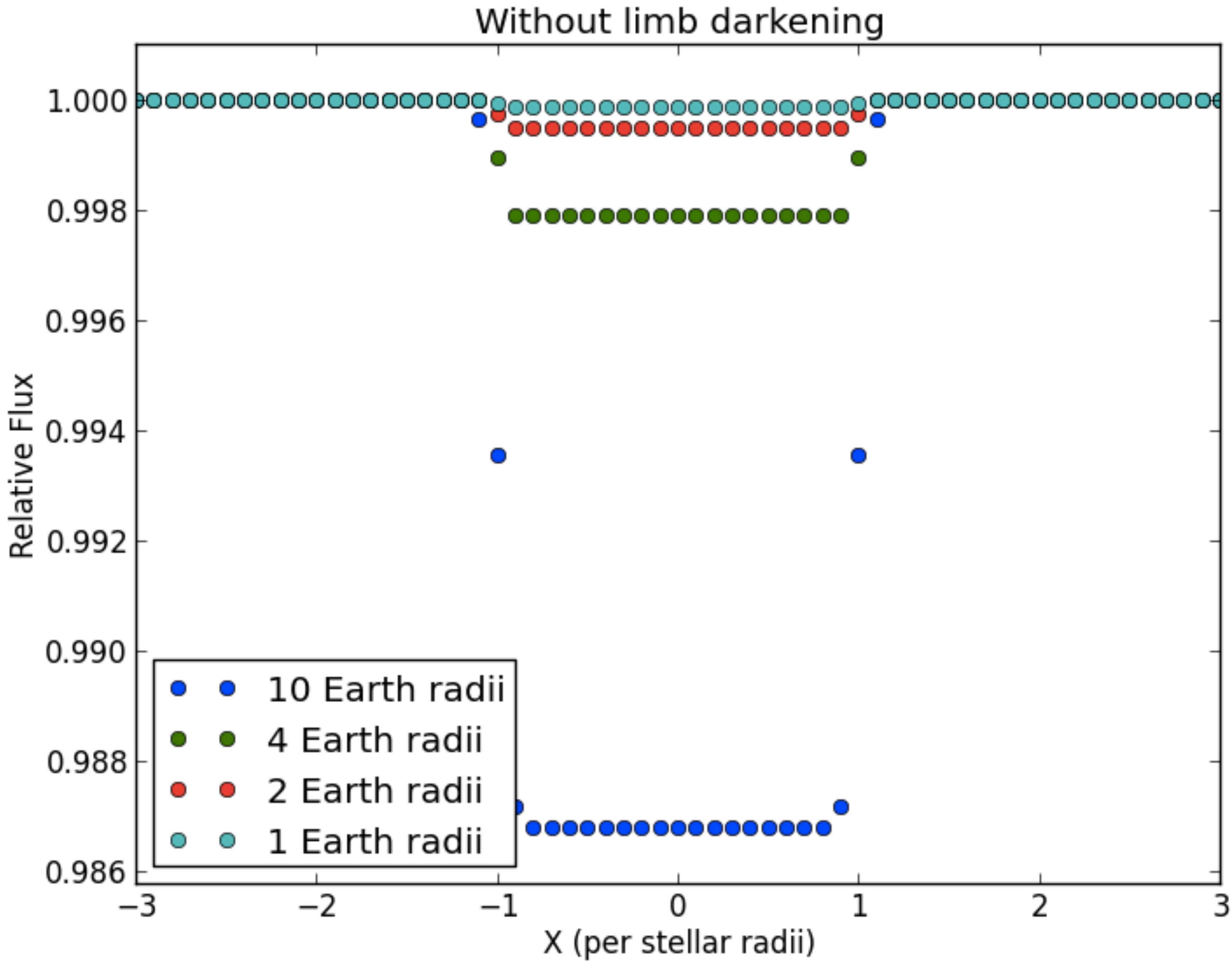


Figure by **Meg Schwab** for the Planet Hunters blog

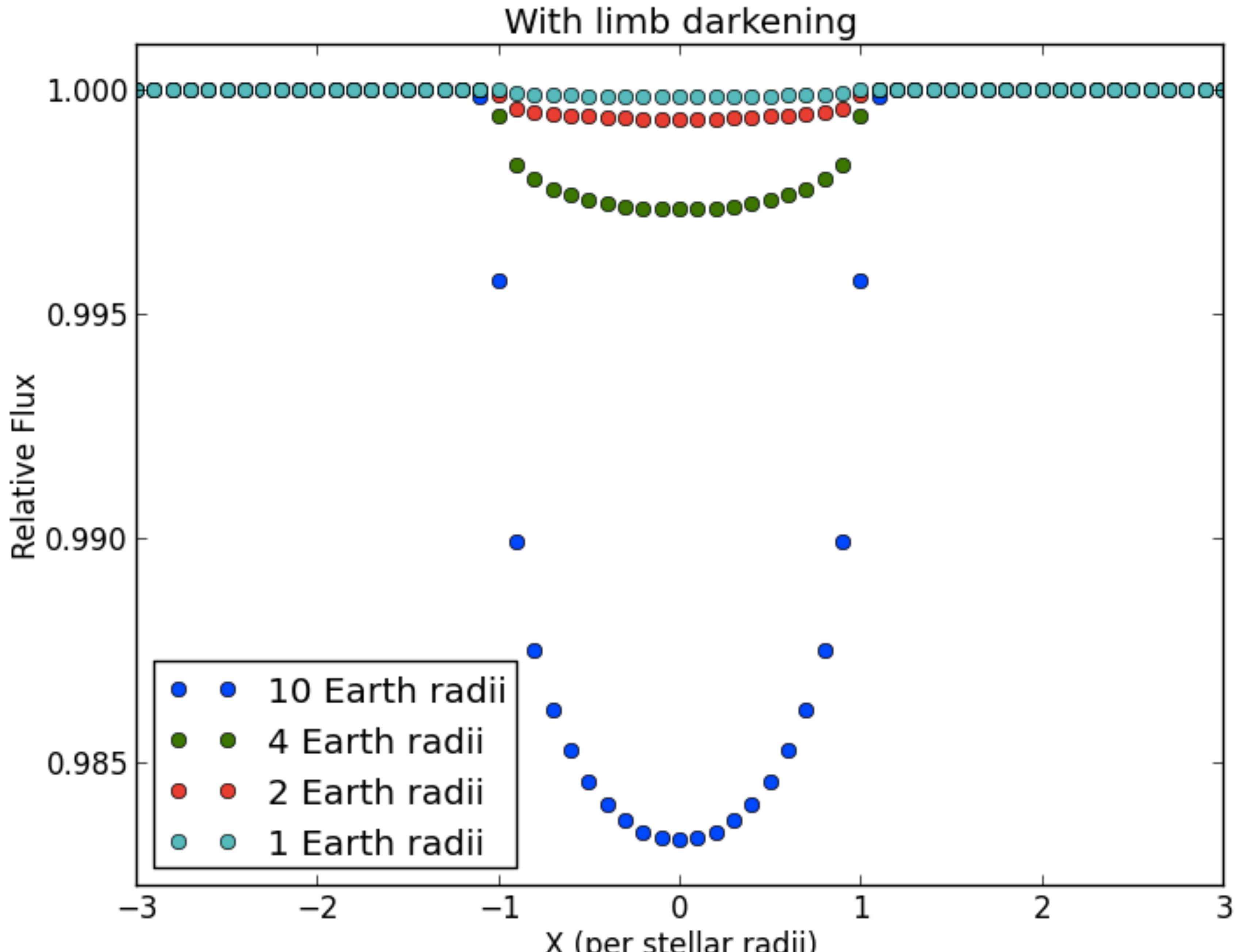
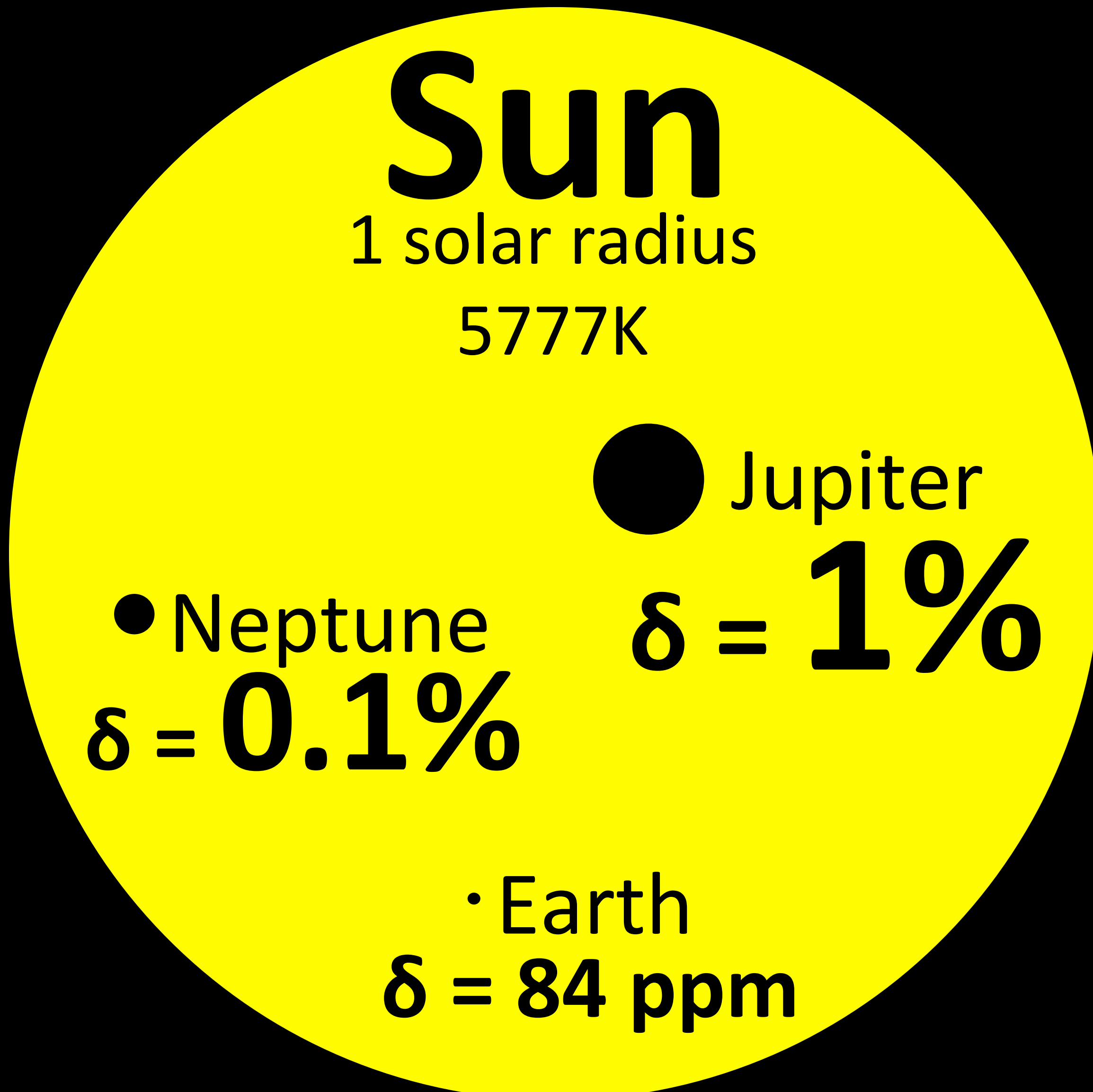
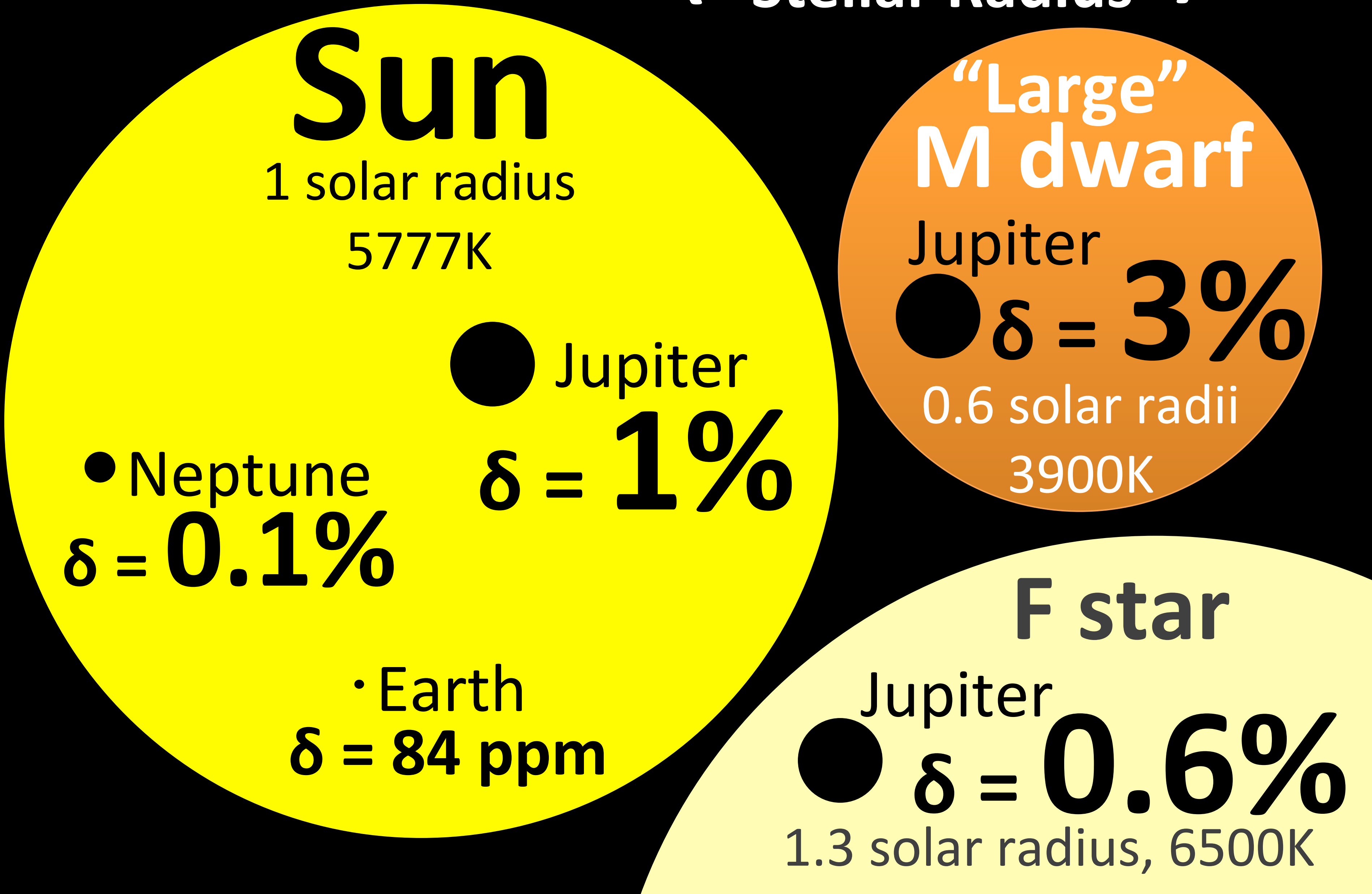


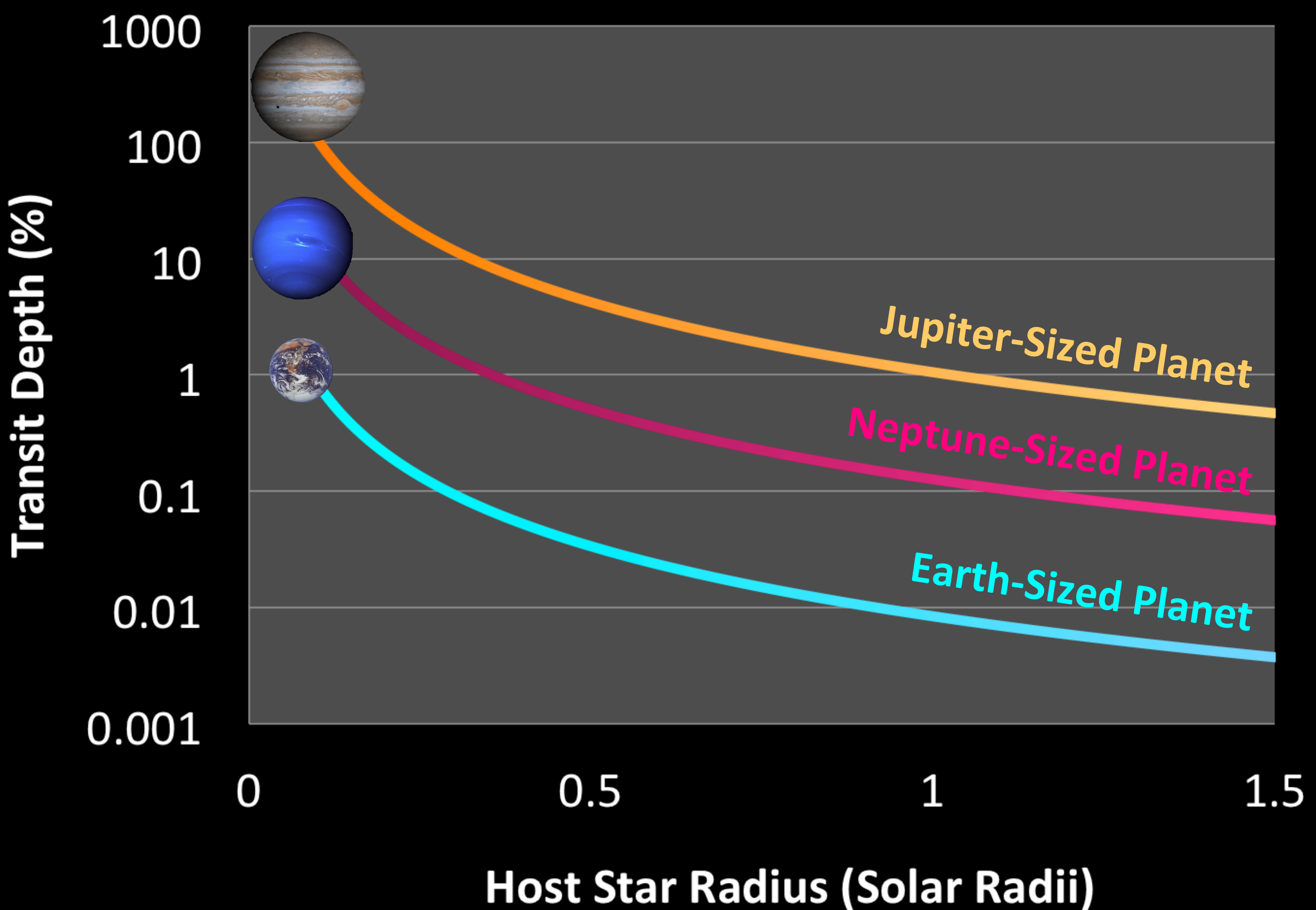
Figure by **Meg Schwab** for the Planet Hunters blog

$$\text{Transit Depth } \delta \approx \left(\frac{\text{Planet Radius}}{\text{Stellar Radius}} \right)^2$$



$$\text{Transit Depth } \delta \approx \left(\frac{\text{Planet Radius}}{\text{Stellar Radius}}\right)^2$$





Transit Depth (%)
1000
100
10
1
0.1
0.01
0.001
0
0.5
1
1.5
Host Star Radius (Solar Radii)
Jupiter-Sized Planet
Neptune-Sized Planet
Earth-Sized Planet

Estimating the Signal-to-Noise Ratio

$$S/N = \frac{C_{\star} \times t}{[(C_{\star} \times t) + (C_{sky} \times t \times n_{pix}) + (RN^2 + (G/2)^2 \times n_{pix}) + (D \times n_{pix} \times t)]^{0.5}}$$

- $C_{\star}$: e⁻ per second from target star
- t: integration time (seconds)
- C_{sky}: e⁻ per second per pixel from sky background
- n_{pix}: number of pixels in aperture
- RN: read noise (e⁻)
- G: Inverse Gain (e⁻/DN)
- D: Dark Current (e⁻/pixel/second)

Bright Star Approximation

e⁻ per second from target star

integration time (seconds)

$$S/N = \frac{C_\star \times t}{[(C_\star \times t) + \cancel{(C_{sky} \times t \times n_{pix})} + \cancel{(RN^2 + (G/2)^2 \times n_{pix})} + \cancel{(D \times n_{pix} \times t)}]^{0.5}}$$

e⁻ per second per pixel from sky background

number of pixels in aperture

read noise (e⁻)

Inverse Gain (e⁻/DN)

Dark Current (e⁻/pixel/second)

Bright Star Approximation

e^- per second from target star

integration time (seconds)

$$S/N \approx (C_\star \times t)^{0.5}$$

Precision for V=10 Star (ppm)	5 sec	60 sec	600 sec
10-cm telescope	2690	780	250
1-meter telescope	270	78	25
5-meter telescope	54	16	5

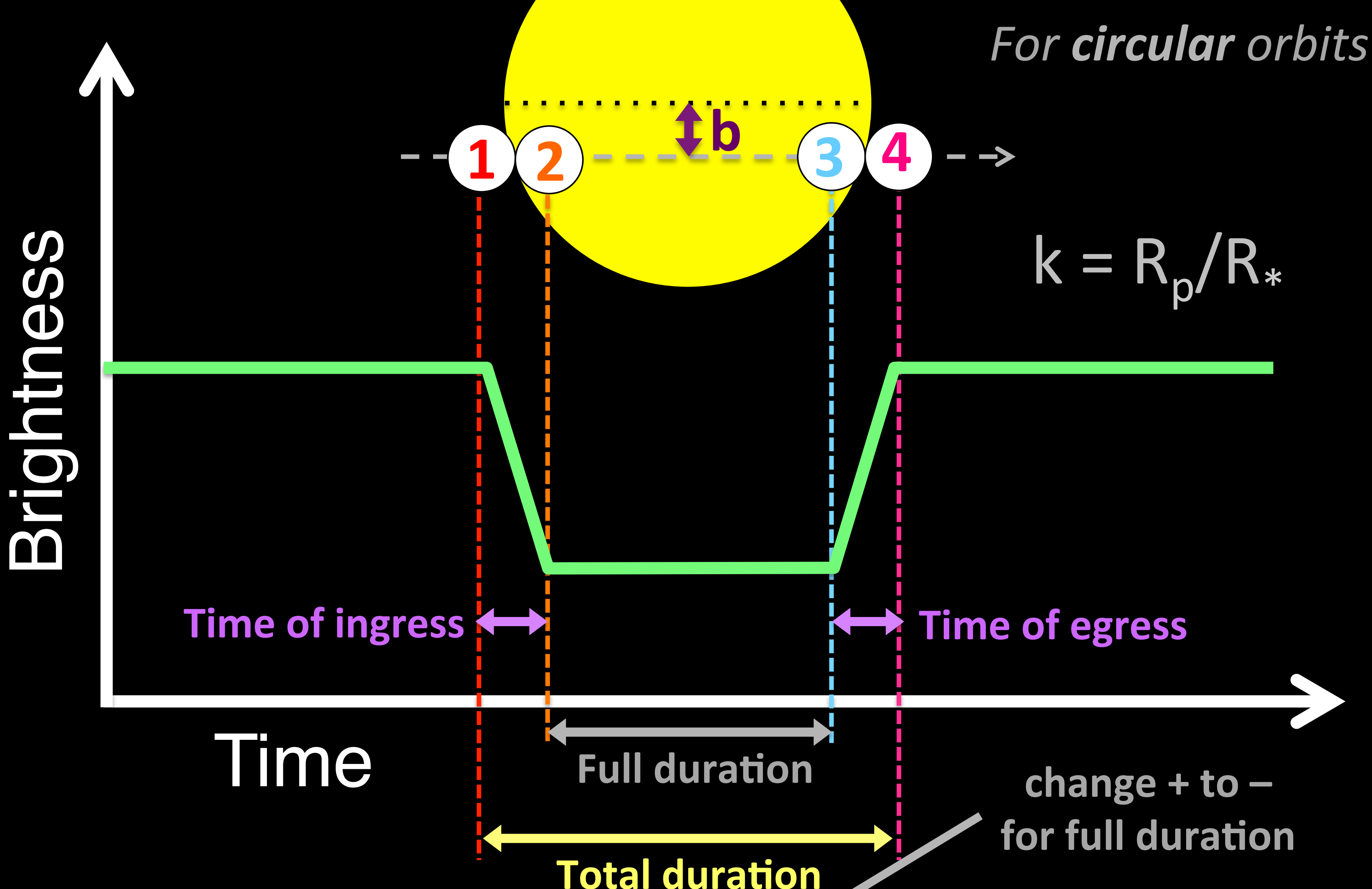
Advantages of Long-Term Monitoring

$$\text{Number of Transits Observed} \approx \frac{\text{Time Coverage}}{\text{Orbital Period}}$$

$$S/N_{multiple} \approx S/N_{single} \times (N_{transits})^{0.5}$$

$$S/N_{multiple} \approx \frac{\delta}{\sigma}\left(\frac{T}{P}\right)^{0.5}$$

What are the relevant timescales?



Total duration $= \dfrac{P}{\pi} \sin^{-1}\left(\dfrac{R_\star}{a} \dfrac{((1+k)^2 - b^2)^{0.5}}{\sin i} \right)$

Characteristic Timescale:

$$T_0 = \frac{R_\star P}{\pi a} \approx 13\text{ hr}\left(\frac{P}{1\text{ yr}}\frac{\rho_\odot}{\rho_\star}\right)^{1/3}$$

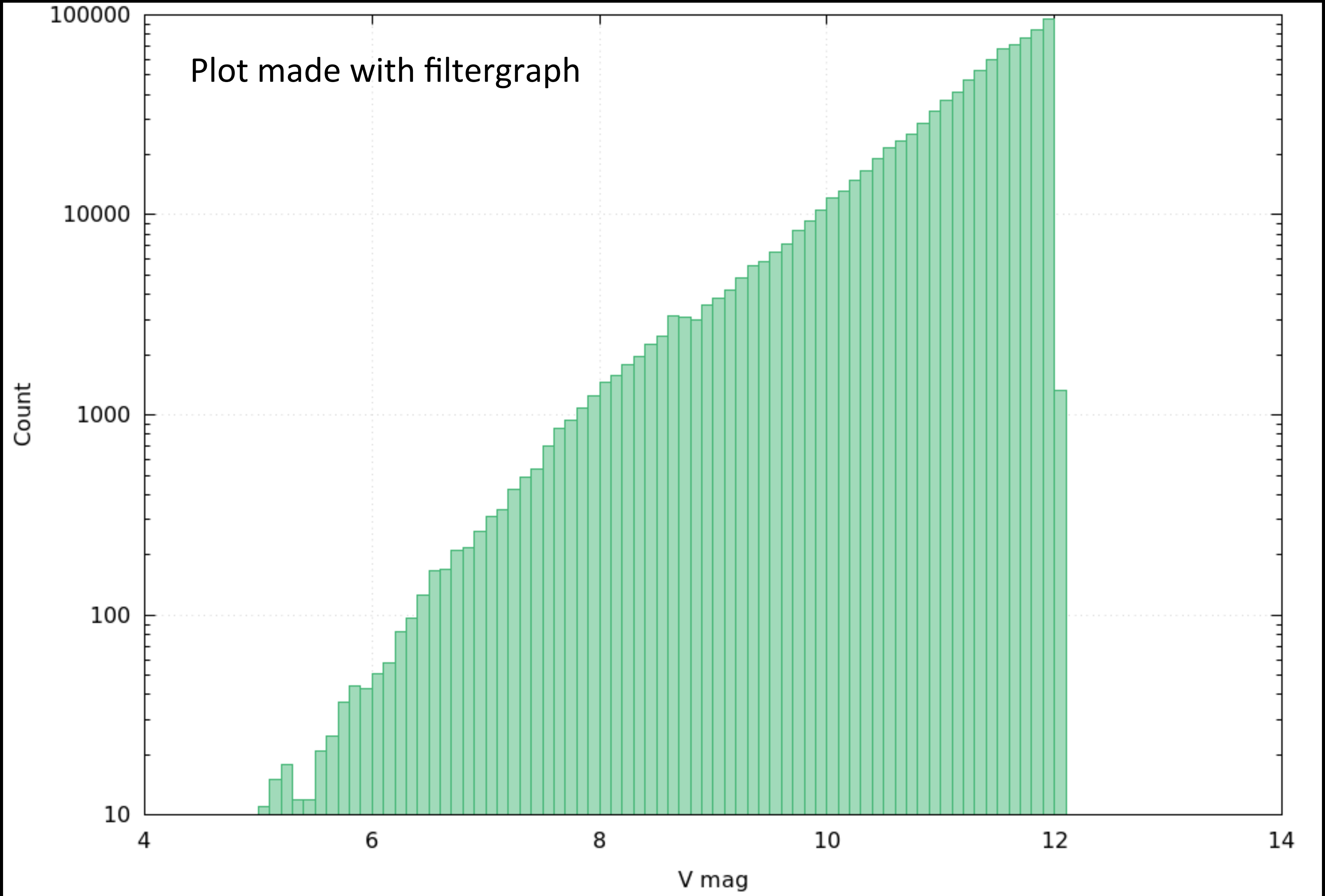
Transit Duration $\approx T_0\ (1-b^2)^{0.5}$

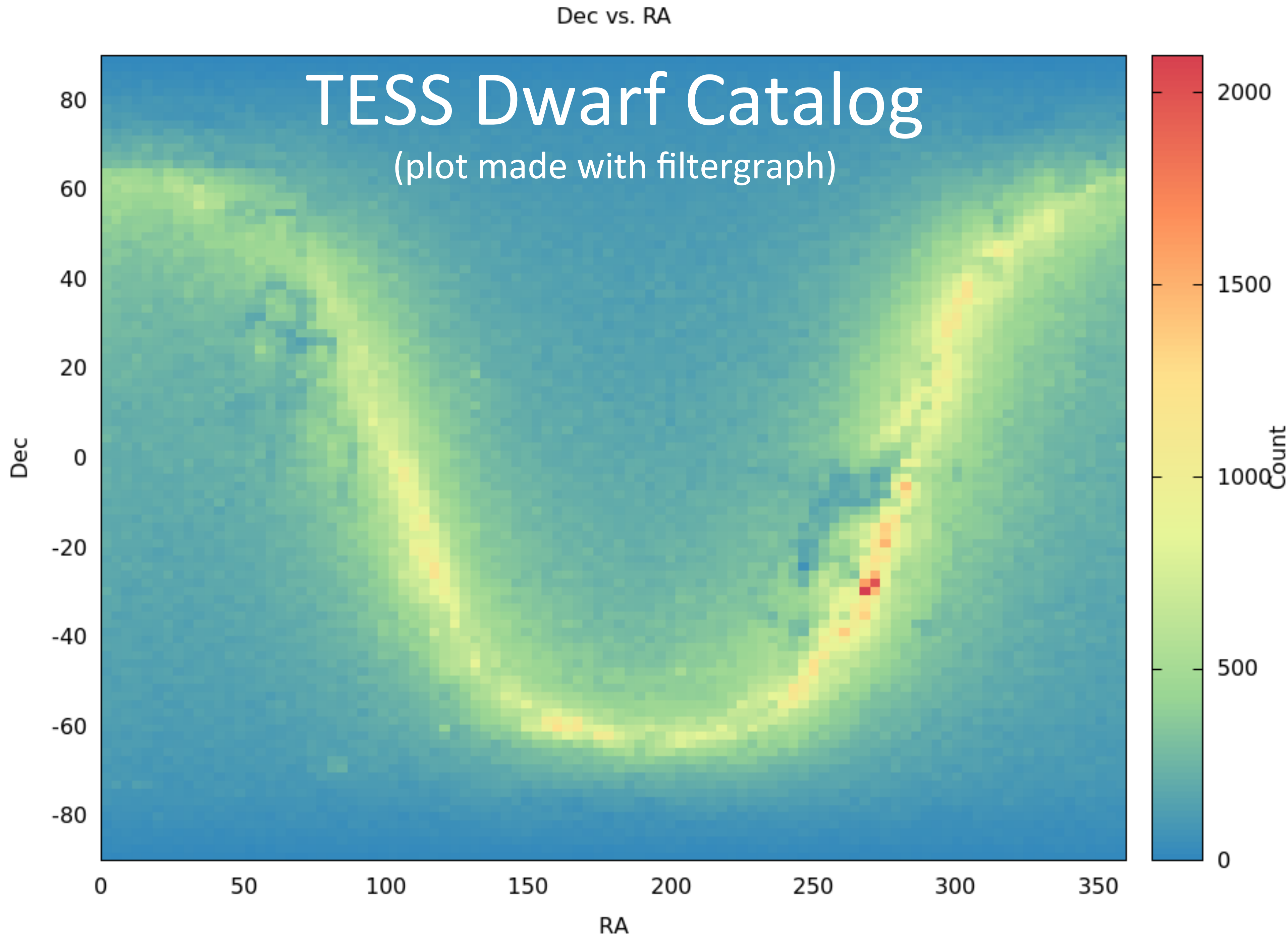
Ingress Duration $\approx T_0\, k(1-b^2)^{-0.5}$

for small planets in circular orbits with a>> $R_\star$ and b << 1-k

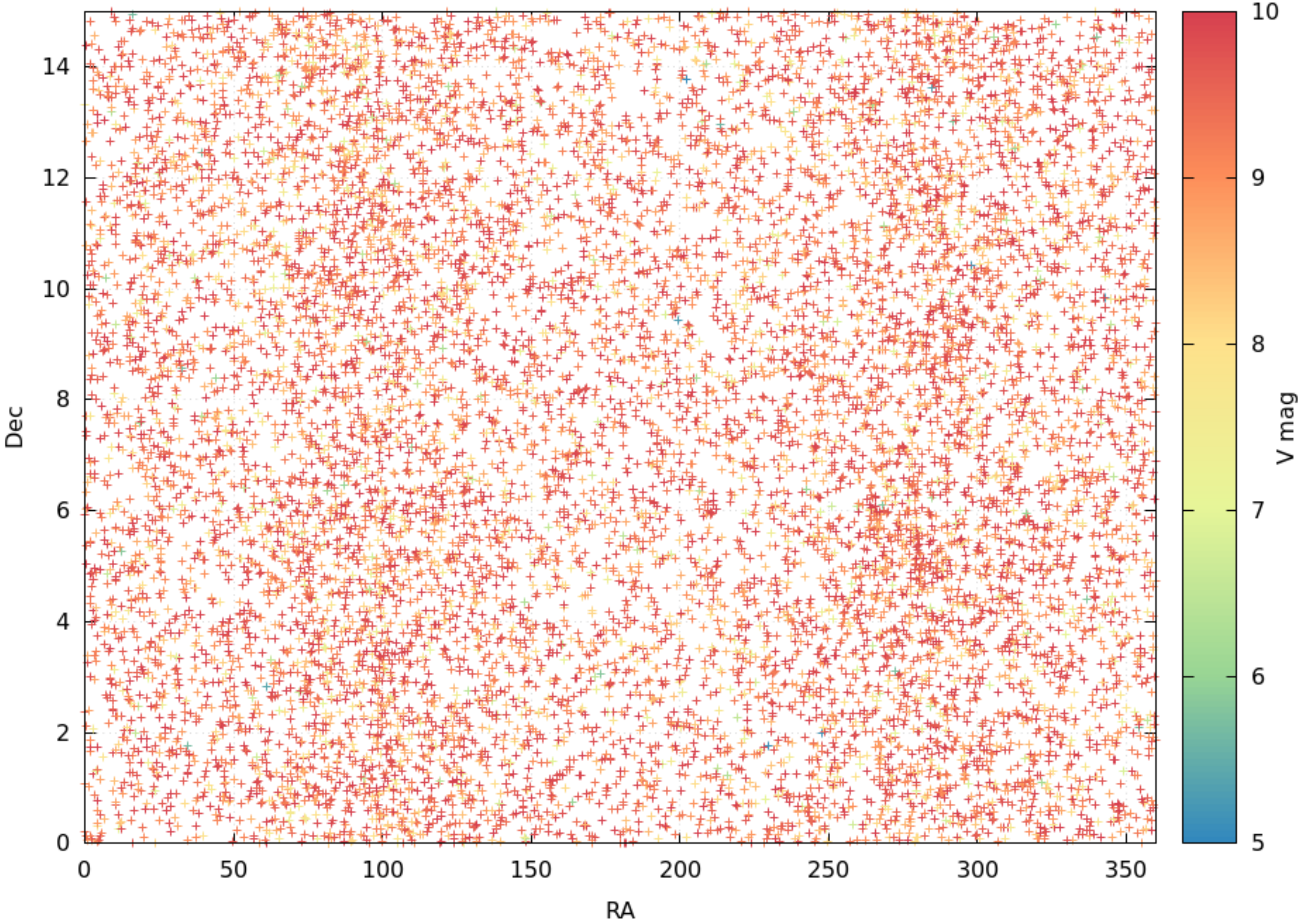
Event Duration for a Jupiter with P = 3.5 days	Late F star	Sun	Early M dwarf
Total Transit (hr)	3	3	2
Transit Ingress (min)	16	17	20

TESS Dwarf Catalog

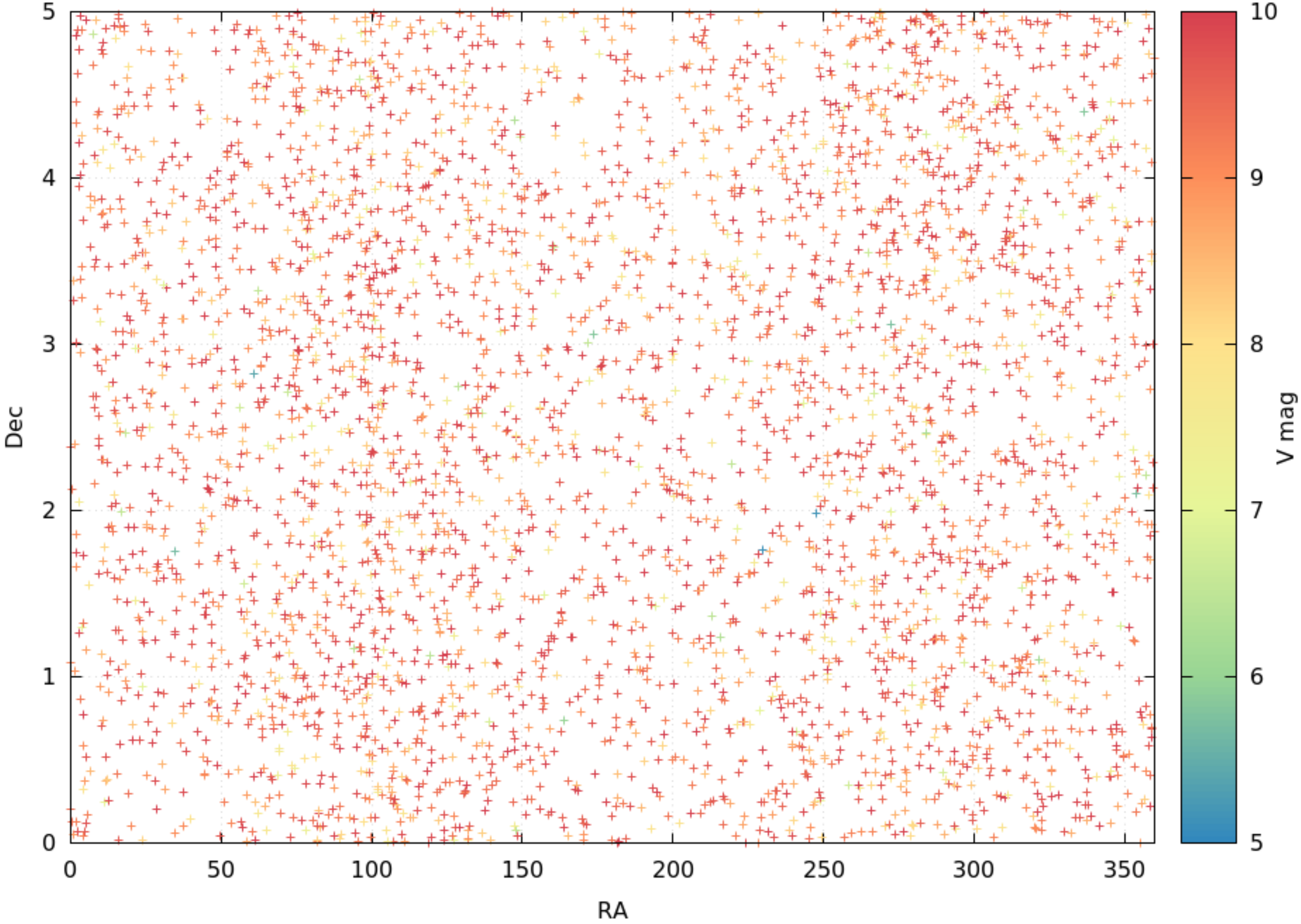



Dec vs. RA
TESS Dwarf Catalog
(plot made with filtergraph)
80
60
40
20
0
-20
-40
-60
-80
Dec
0
50
100
150
200
250
300
350
RA
2000
1500
1000
500
0
Count

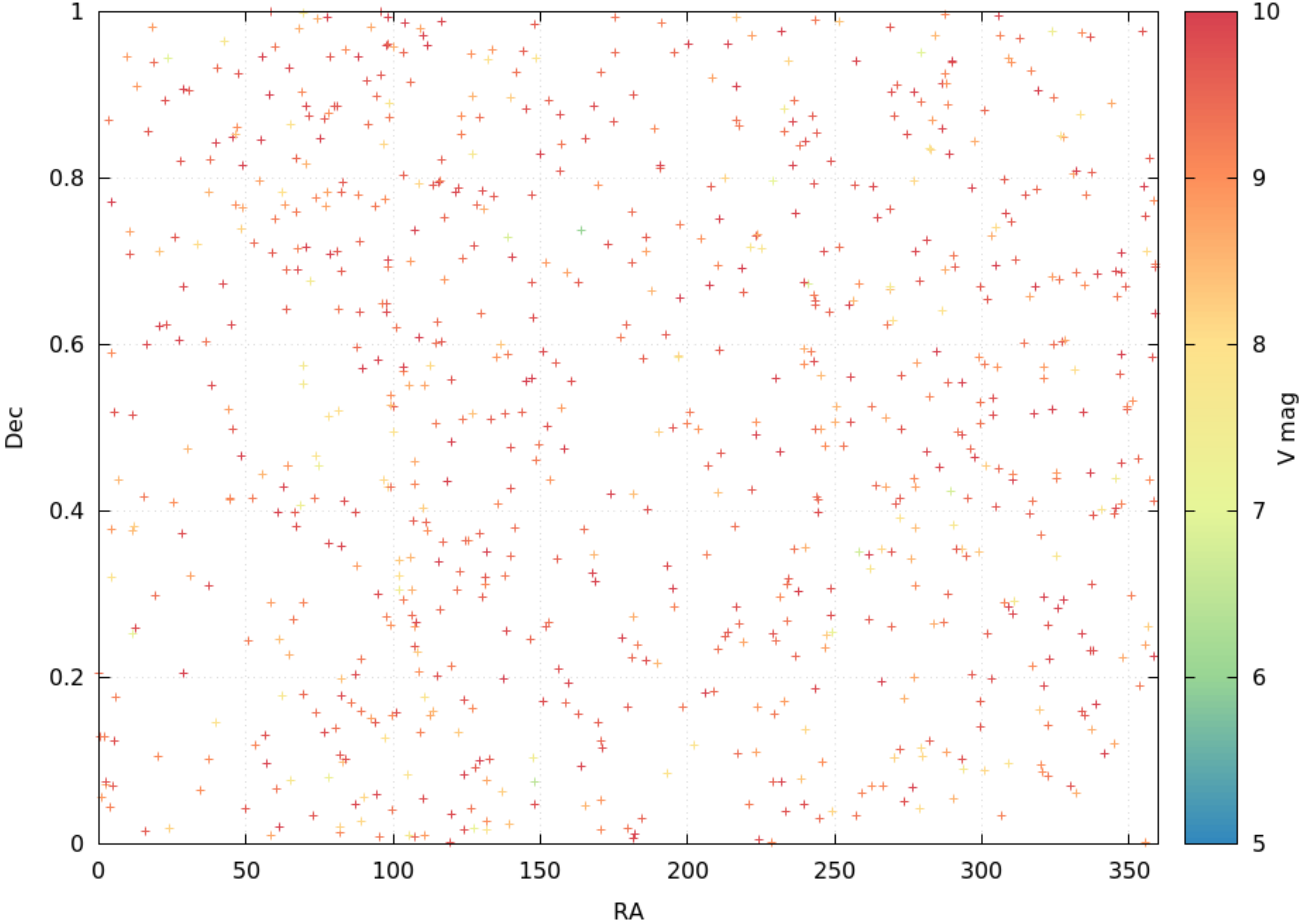
TESS Dwarf Catalog FOV = 15° x 360°



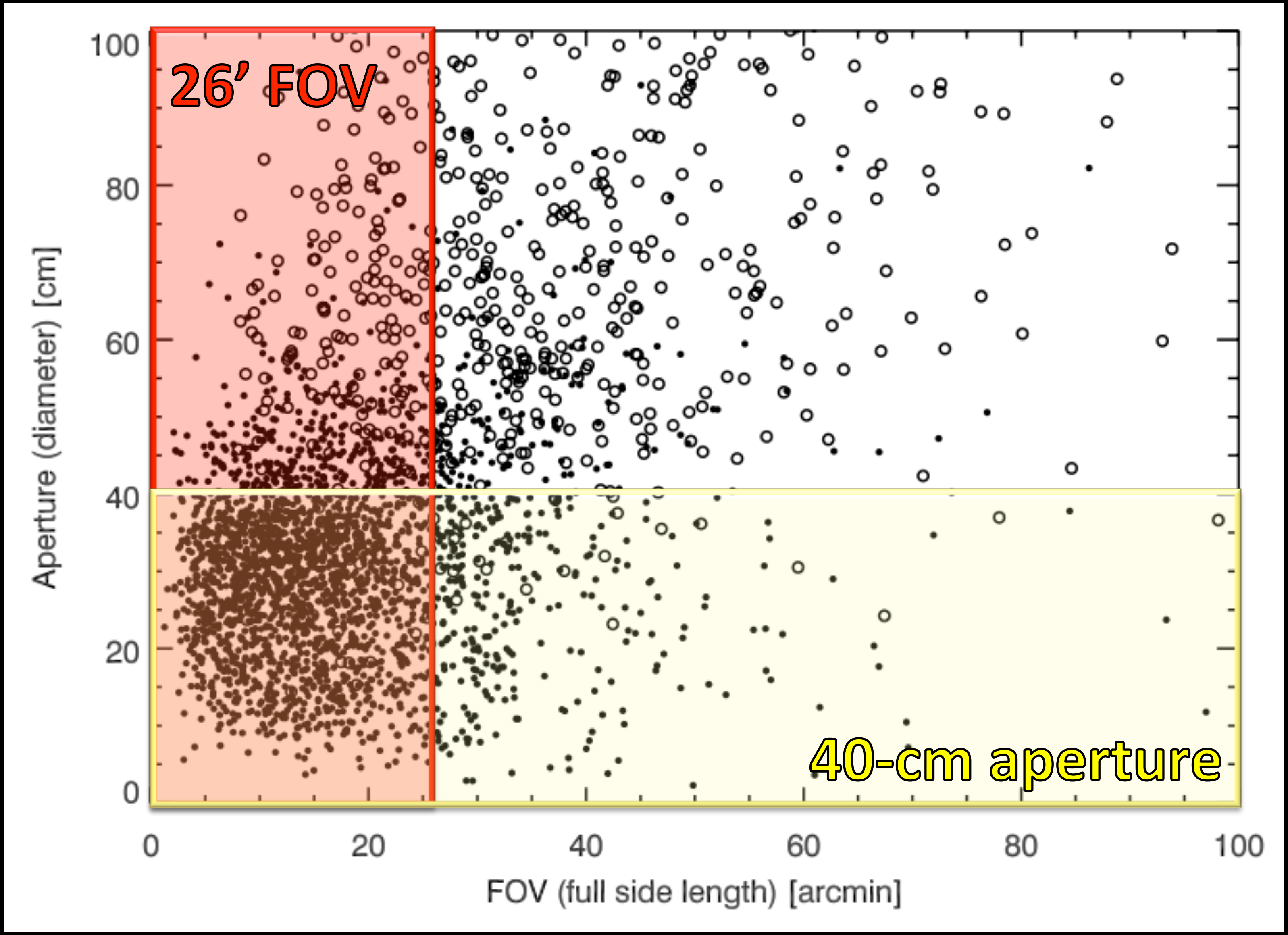
TESS Dwarf Catalog FOV = 5° x 360°



TESS Dwarf Catalog FOV = 1° x 360°



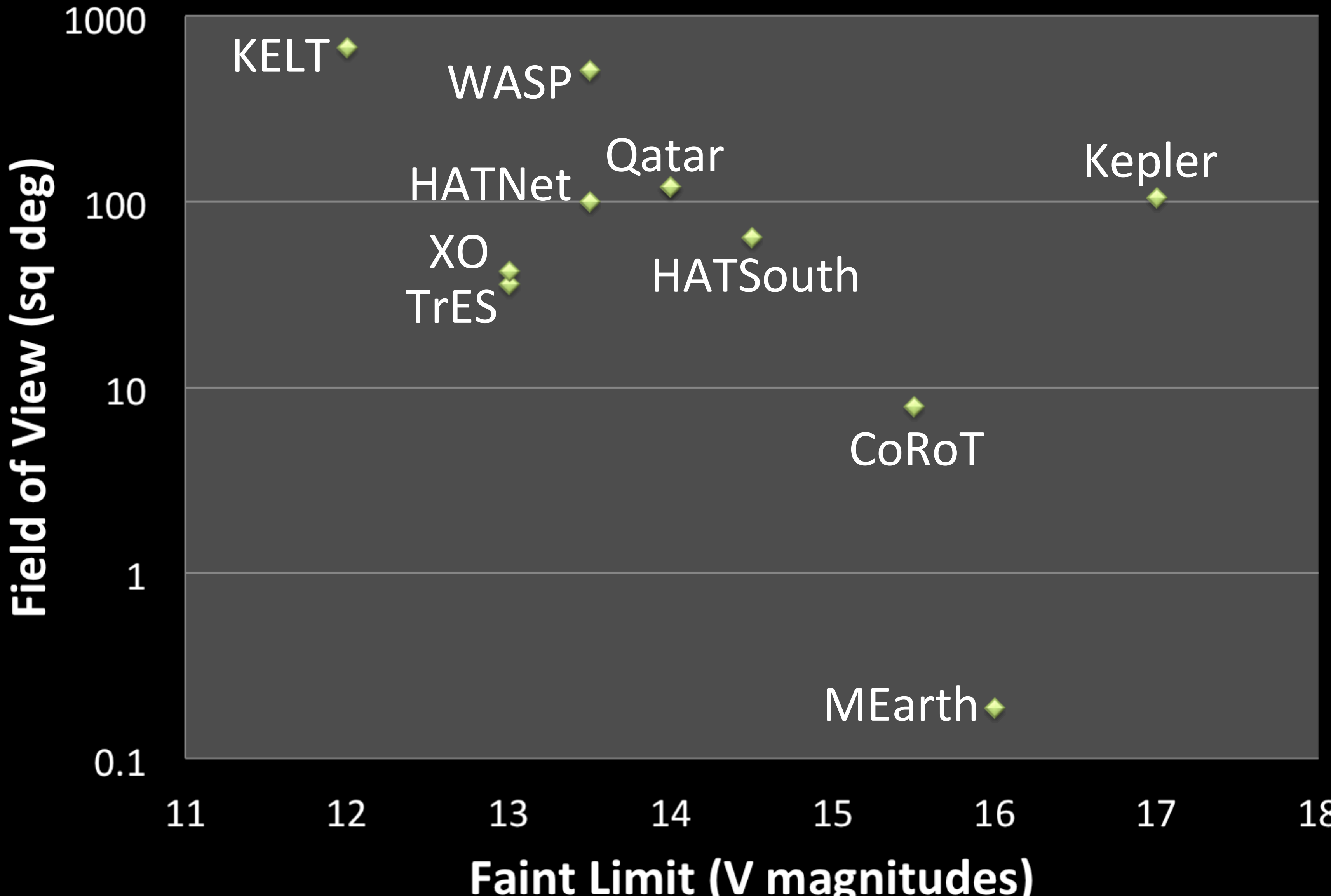
Ideal Survey Design Depends on Stellar Sample



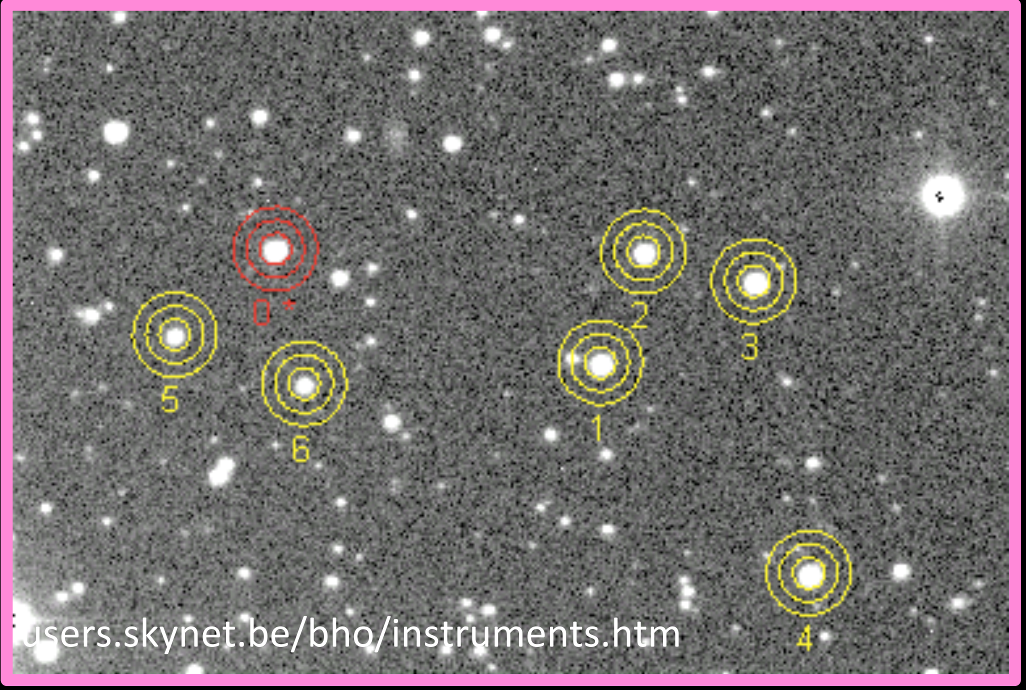
Nutzman & Charbonneau 2008, PASP, 120, 317

MEarth-South telescopes in action (February 2014)

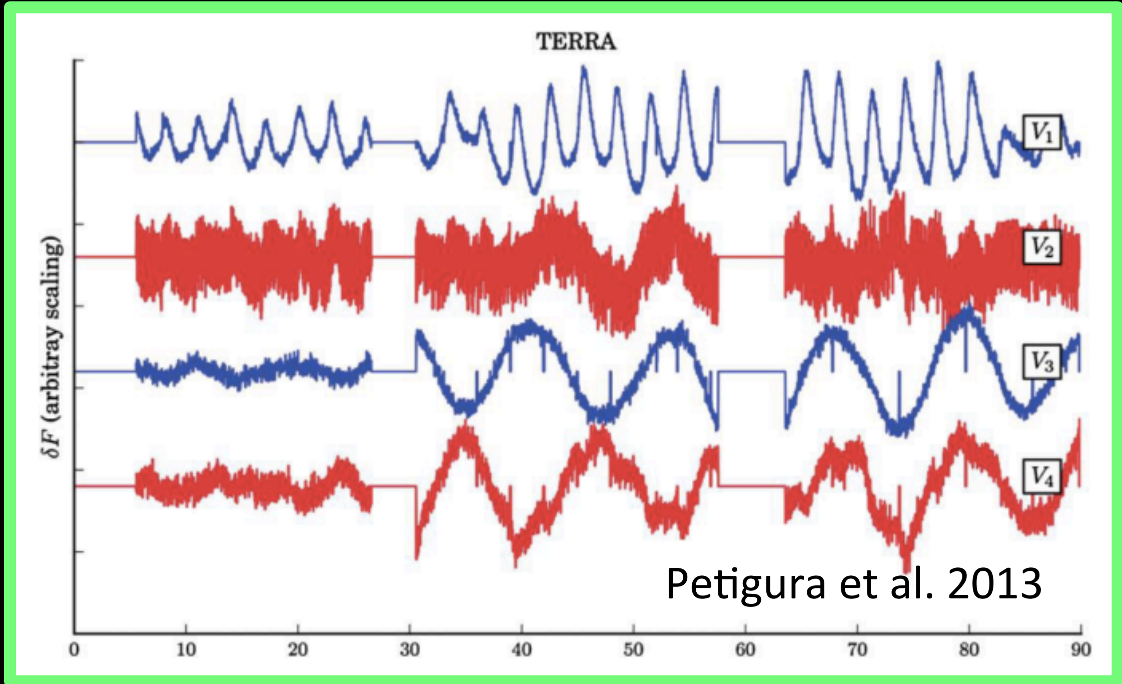
Surveys with smaller FOV are often deeper



Two Possible Approaches to Calibration

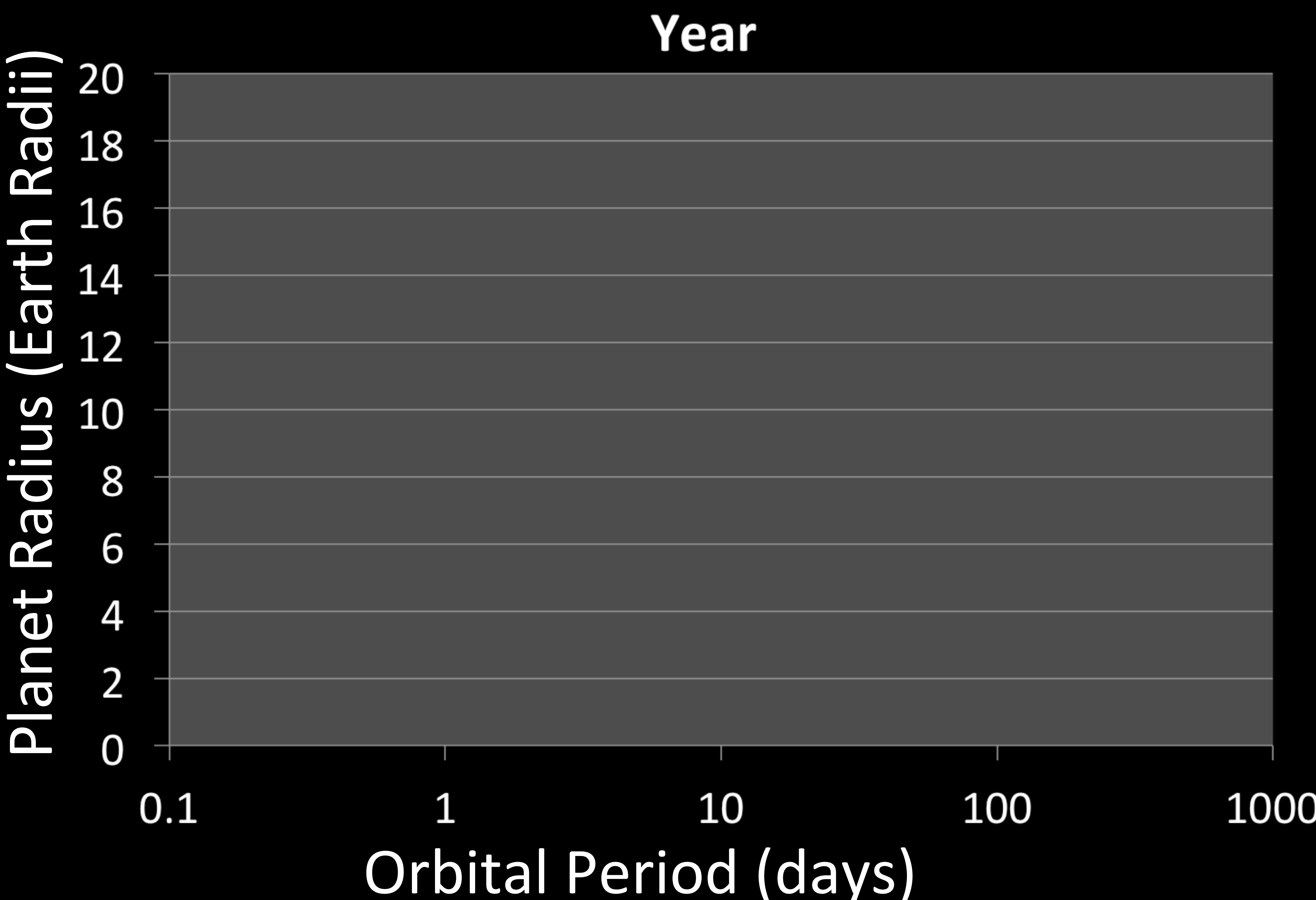


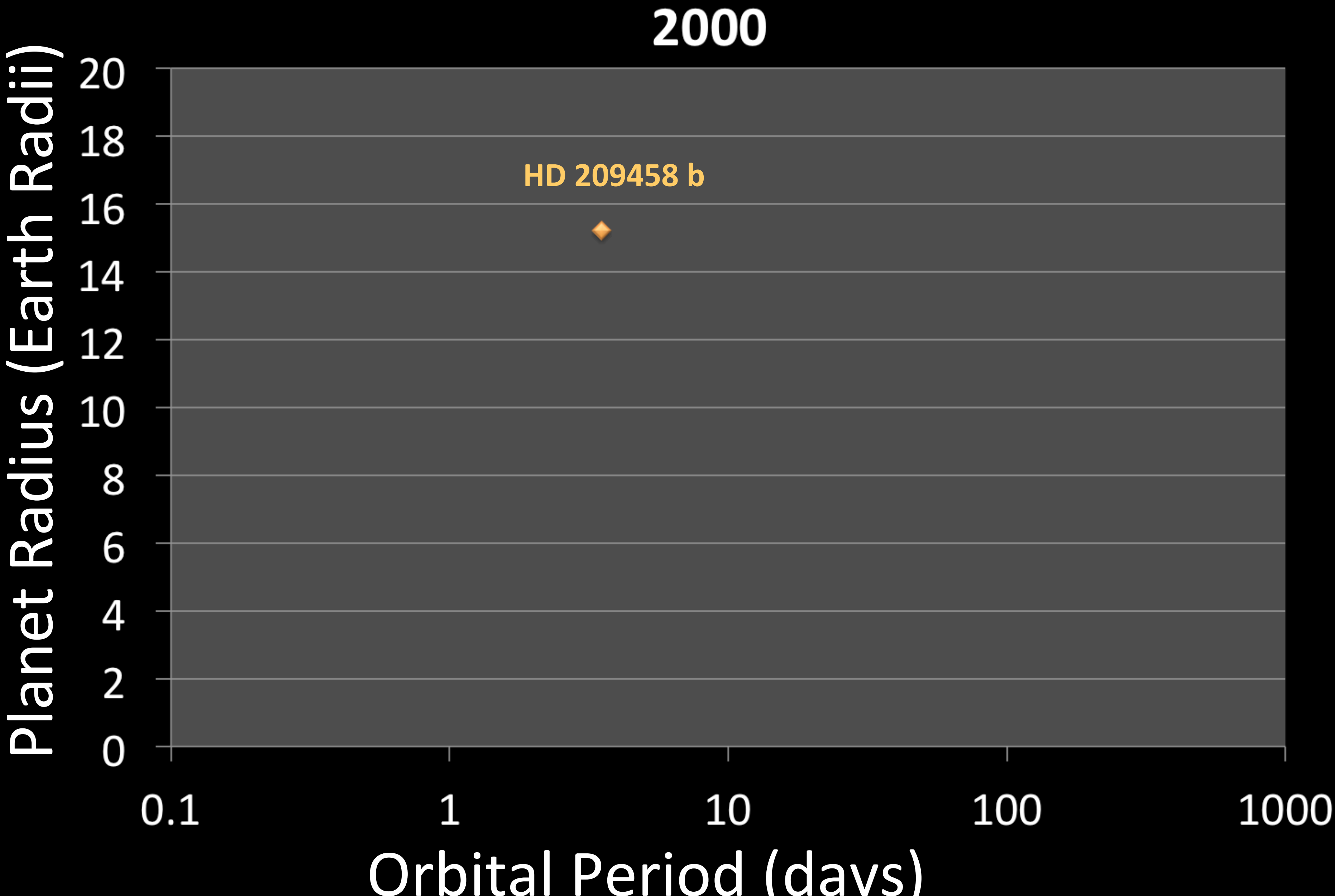
Employing designated reference stars



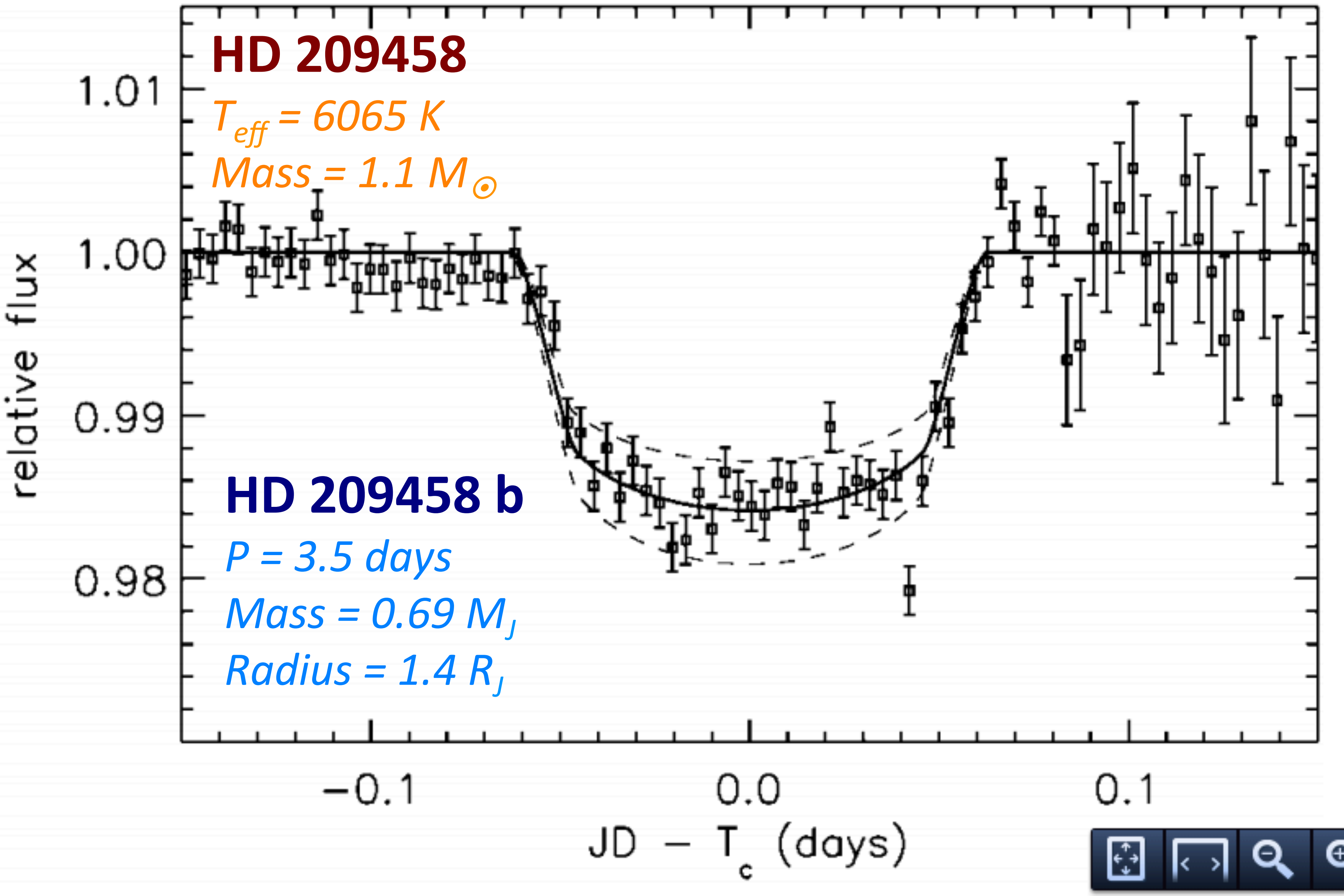
Using the ensemble of science targets

What have we found?

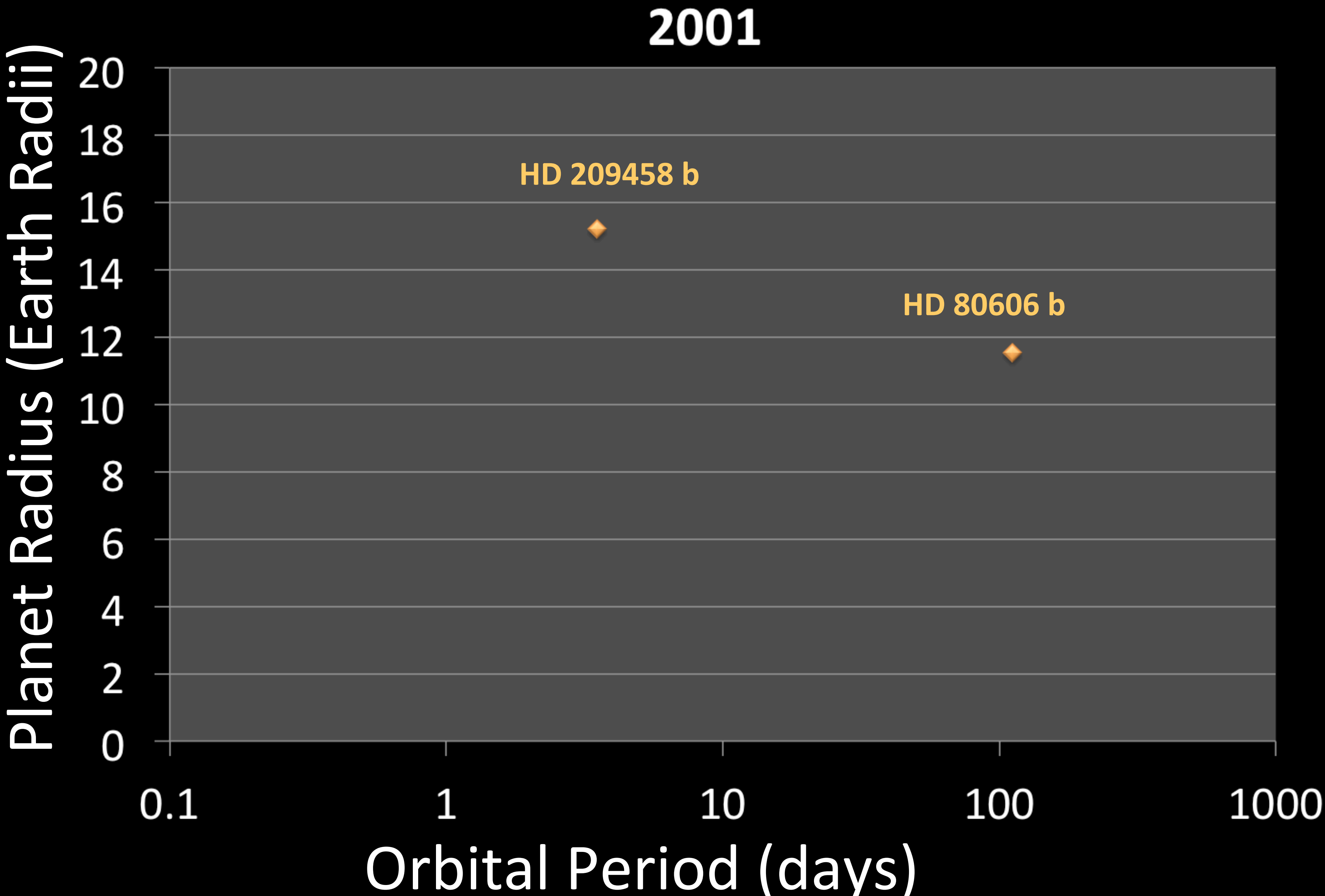

Year
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)

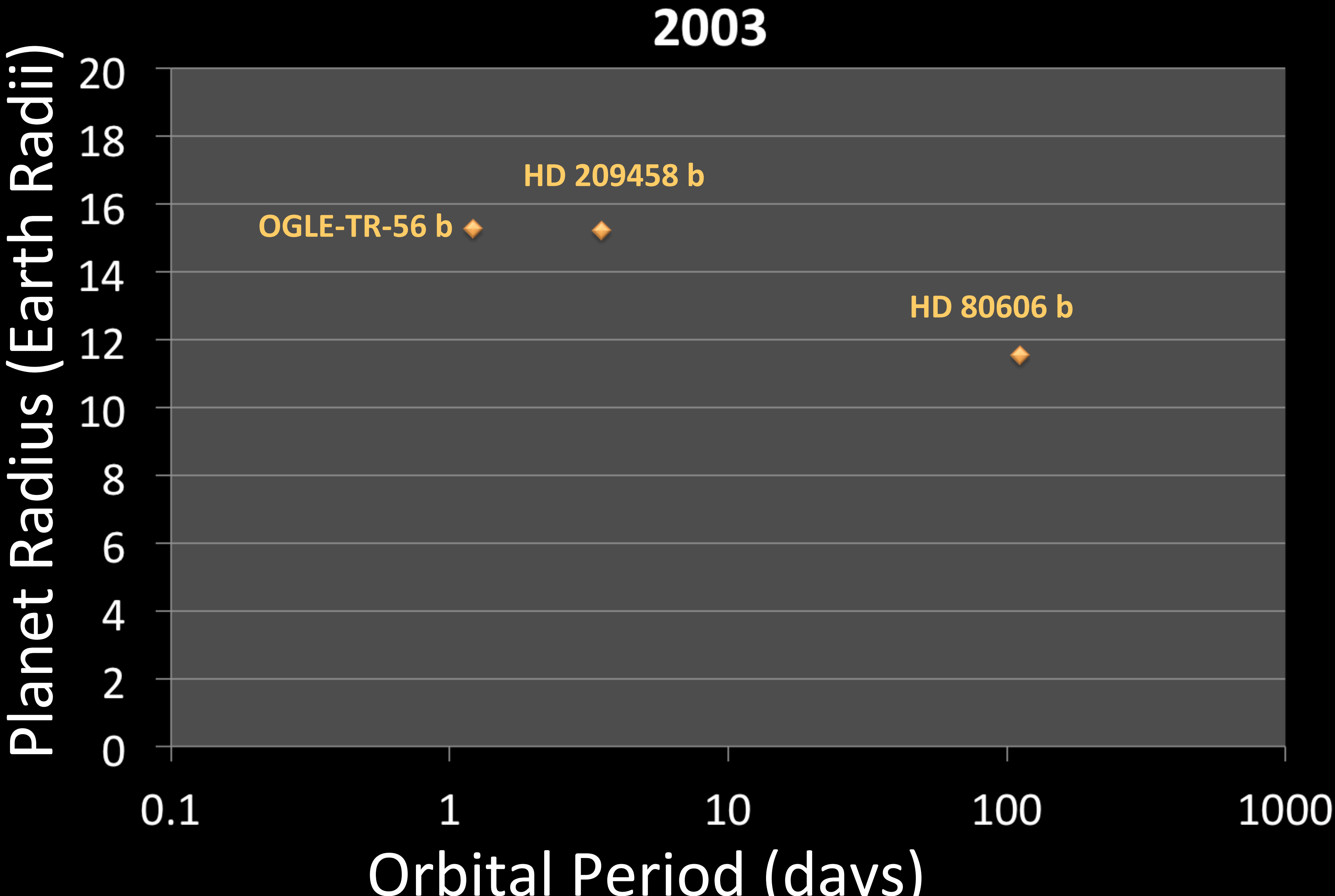


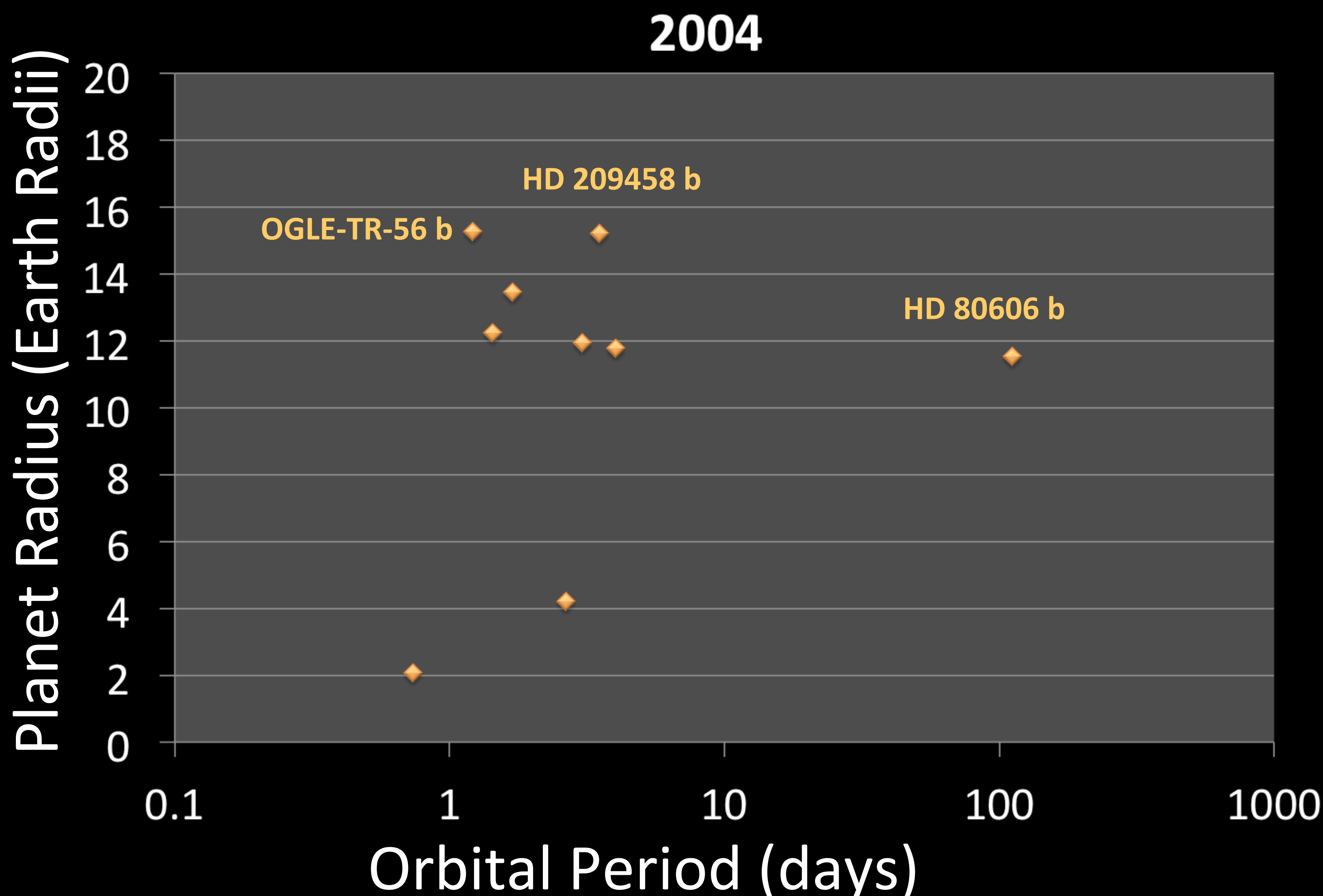
2000
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
HD 209458 b
0.1
1
10
100
1000
Orbital Period (days)

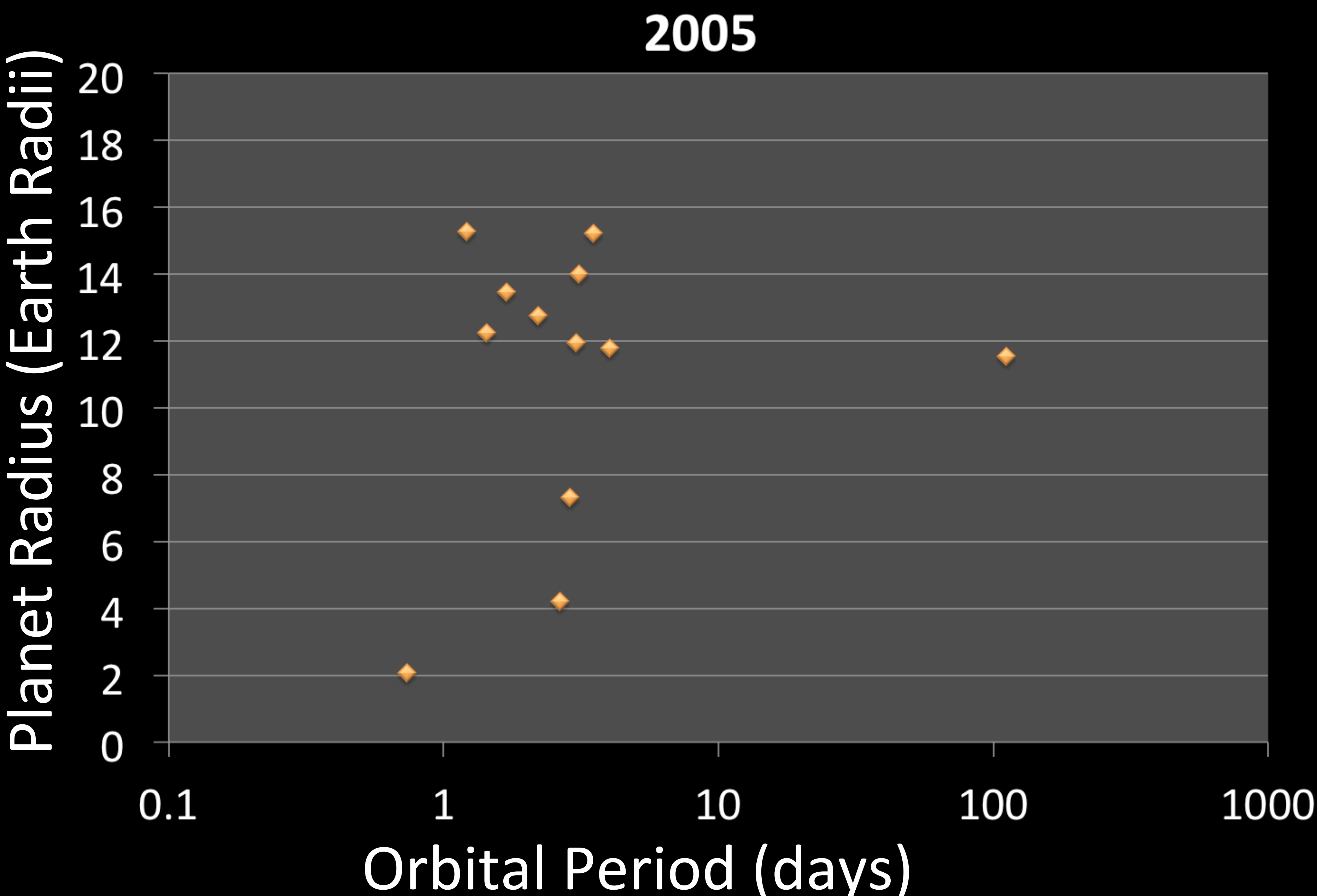


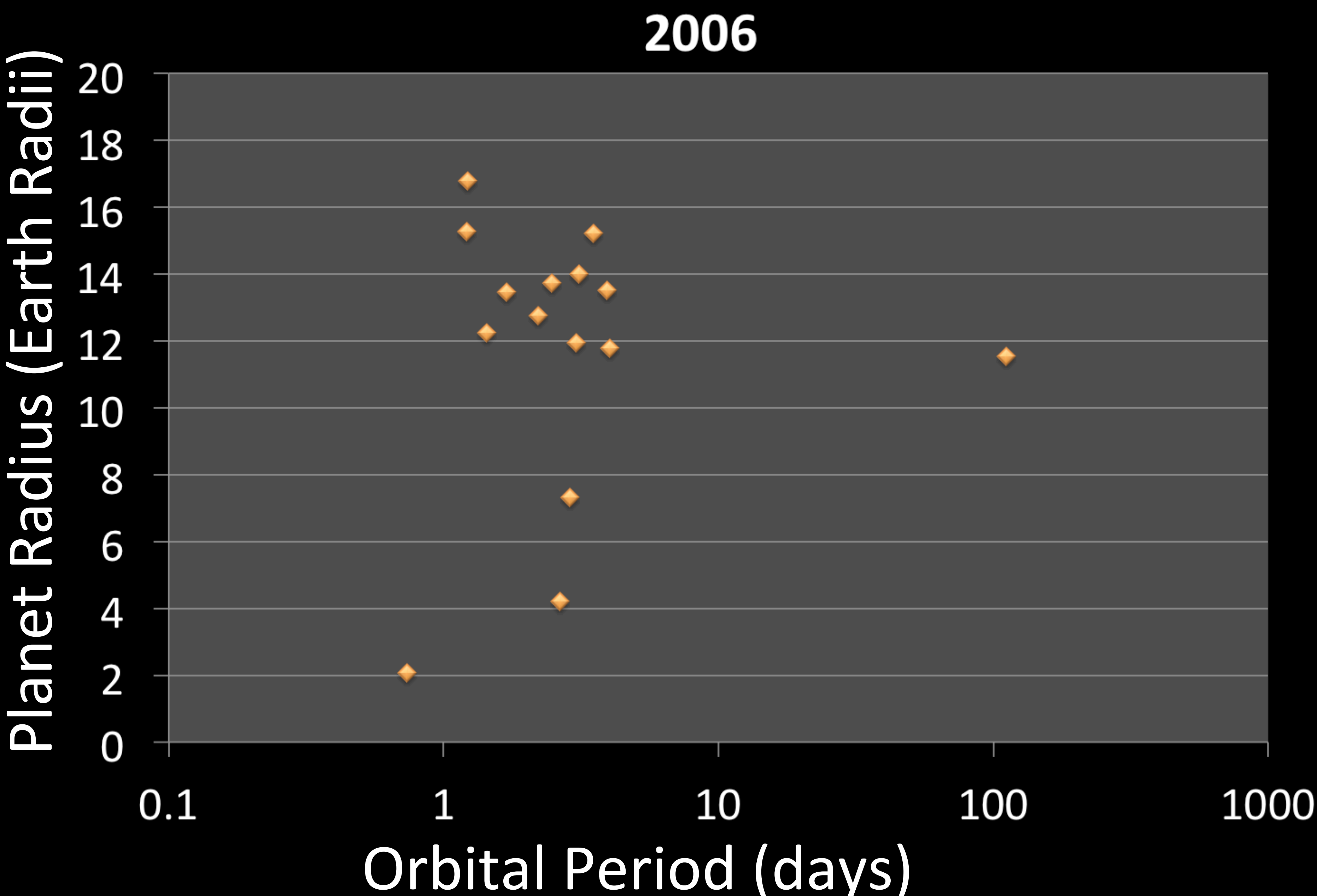
Charbonneau et al. 2000, ApJ, 529, 45

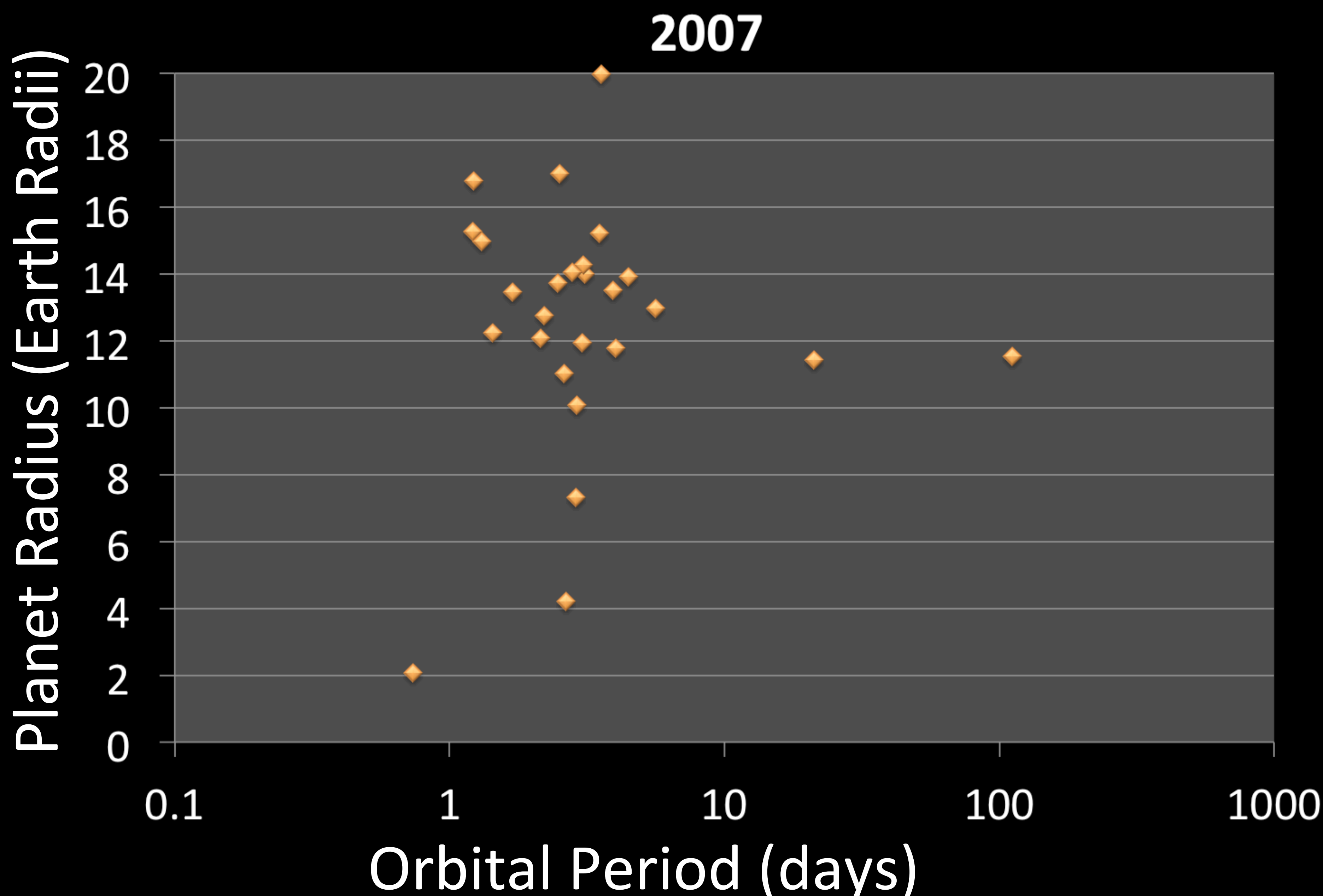

2001
HD 209458 b
HD 80606 b
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000
Orbital Period (days)


2003
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
OGLE-TR-56 b
HD 209458 b
HD 80606 b
0.1
1
10
100
1000
Orbital Period (days)

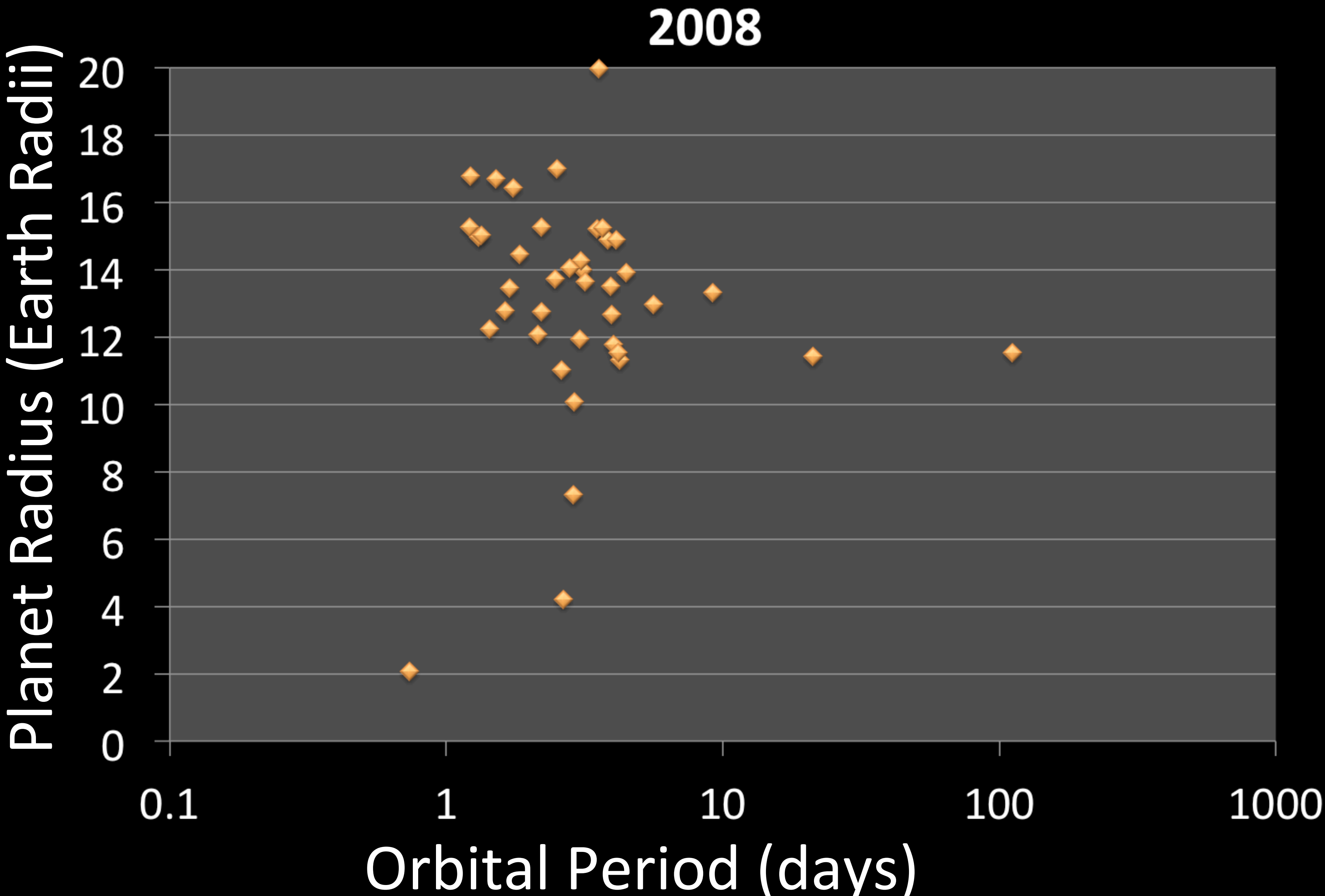

2004
Planet Radius (Earth Radii)
Orbital Period (days)
HD 209458 b
OGLE-TR-56 b
HD 80606 b
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000

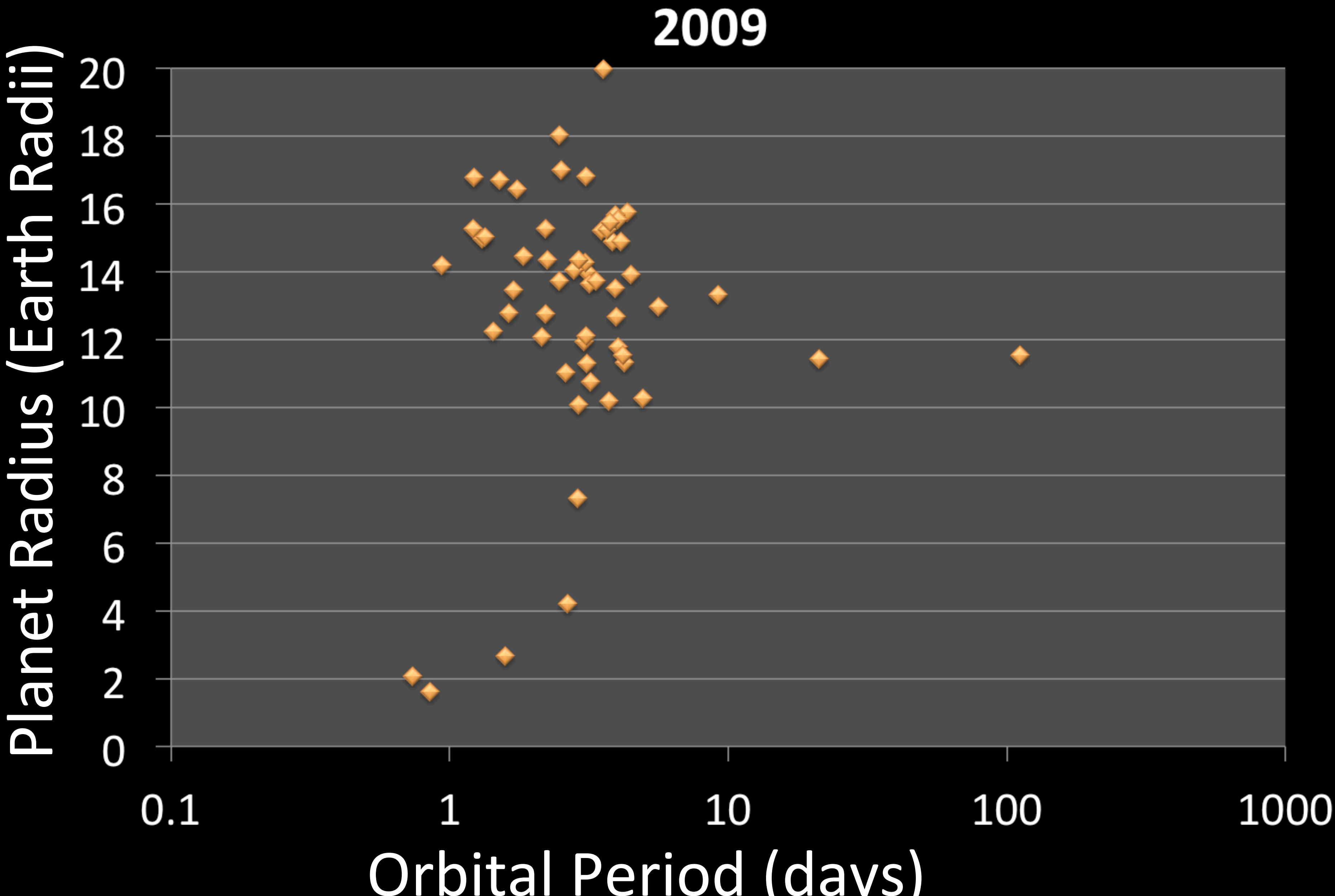

2005
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)

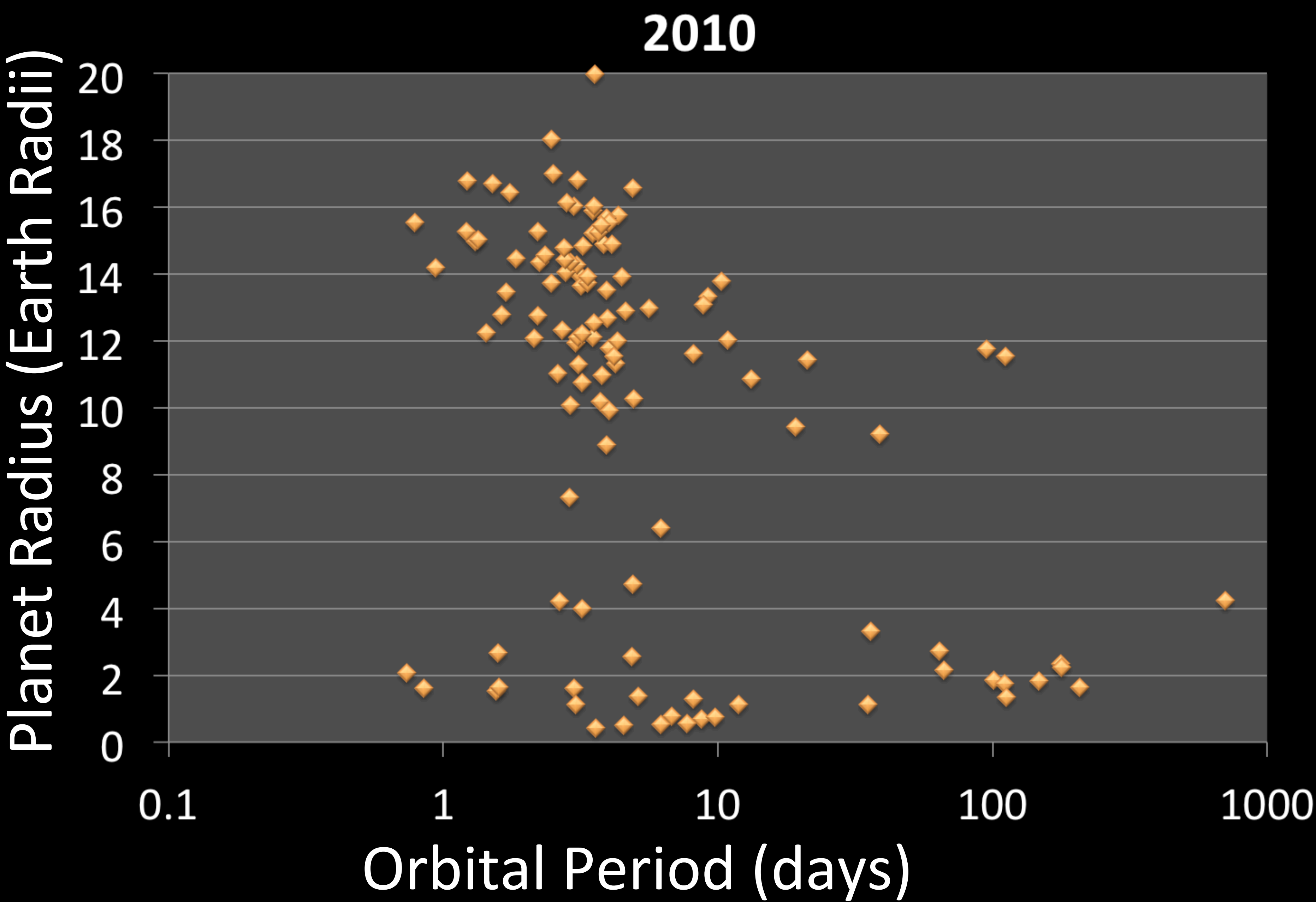

2006
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)



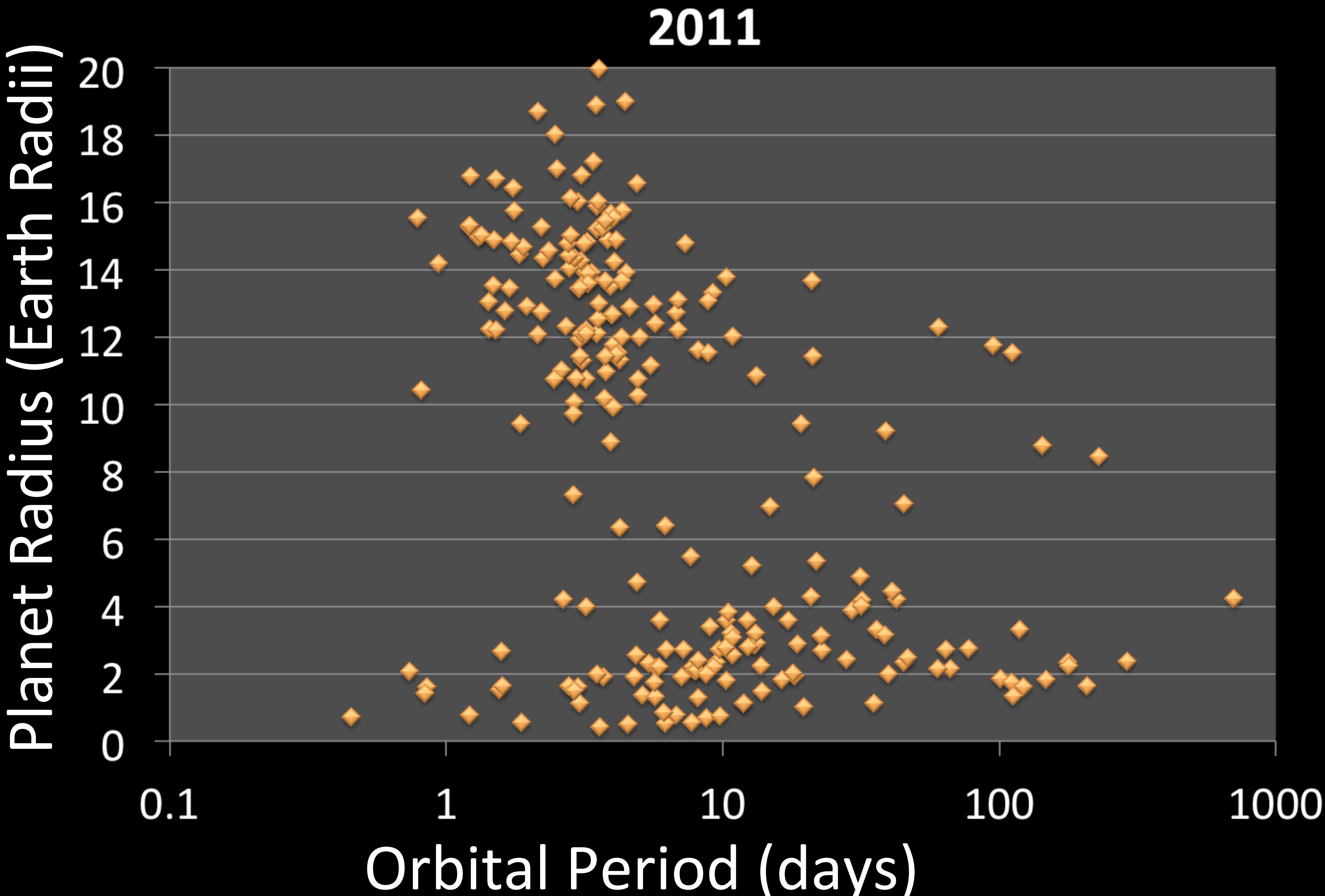
2007
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)

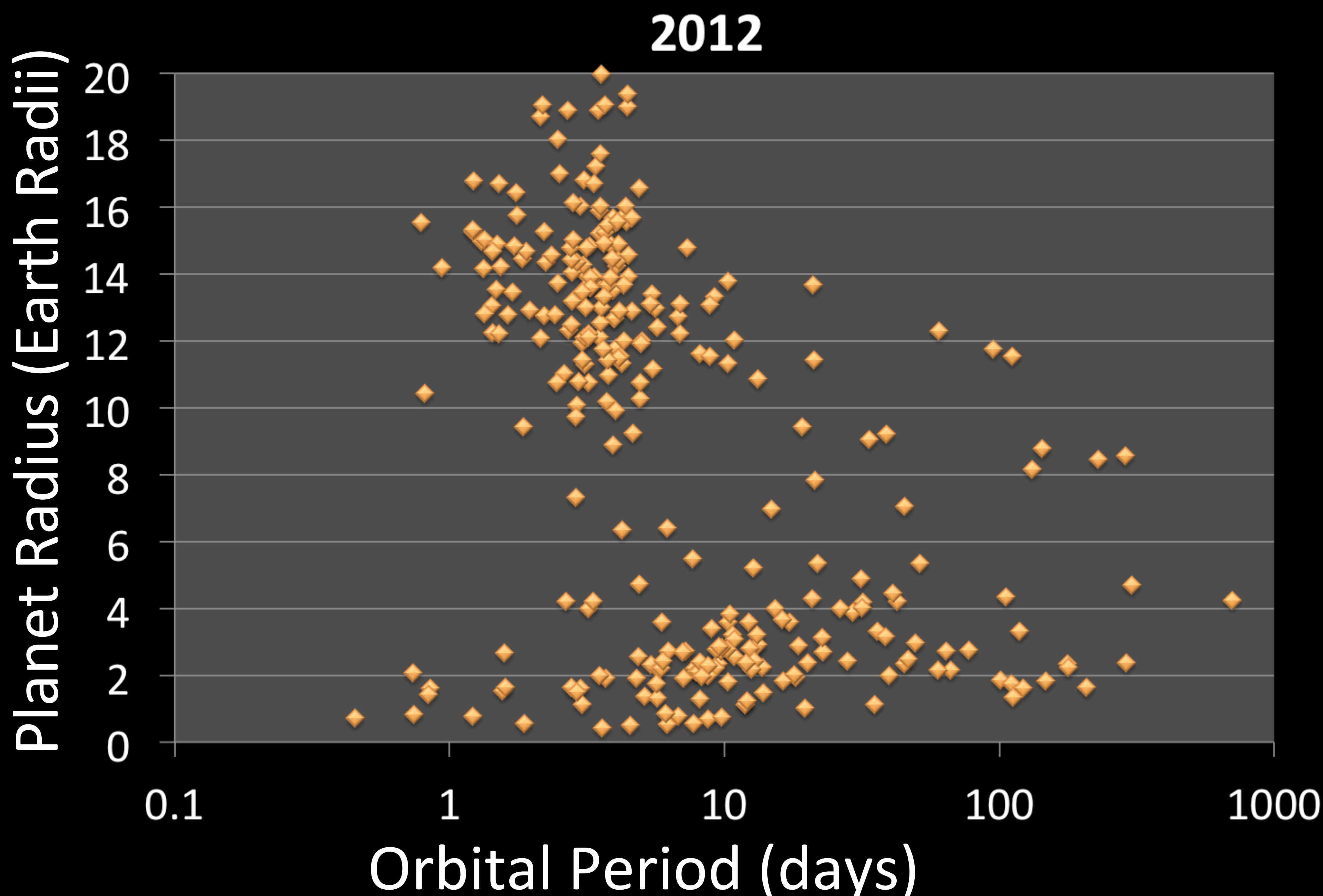

2008
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000
Orbital Period (days)


2009
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)

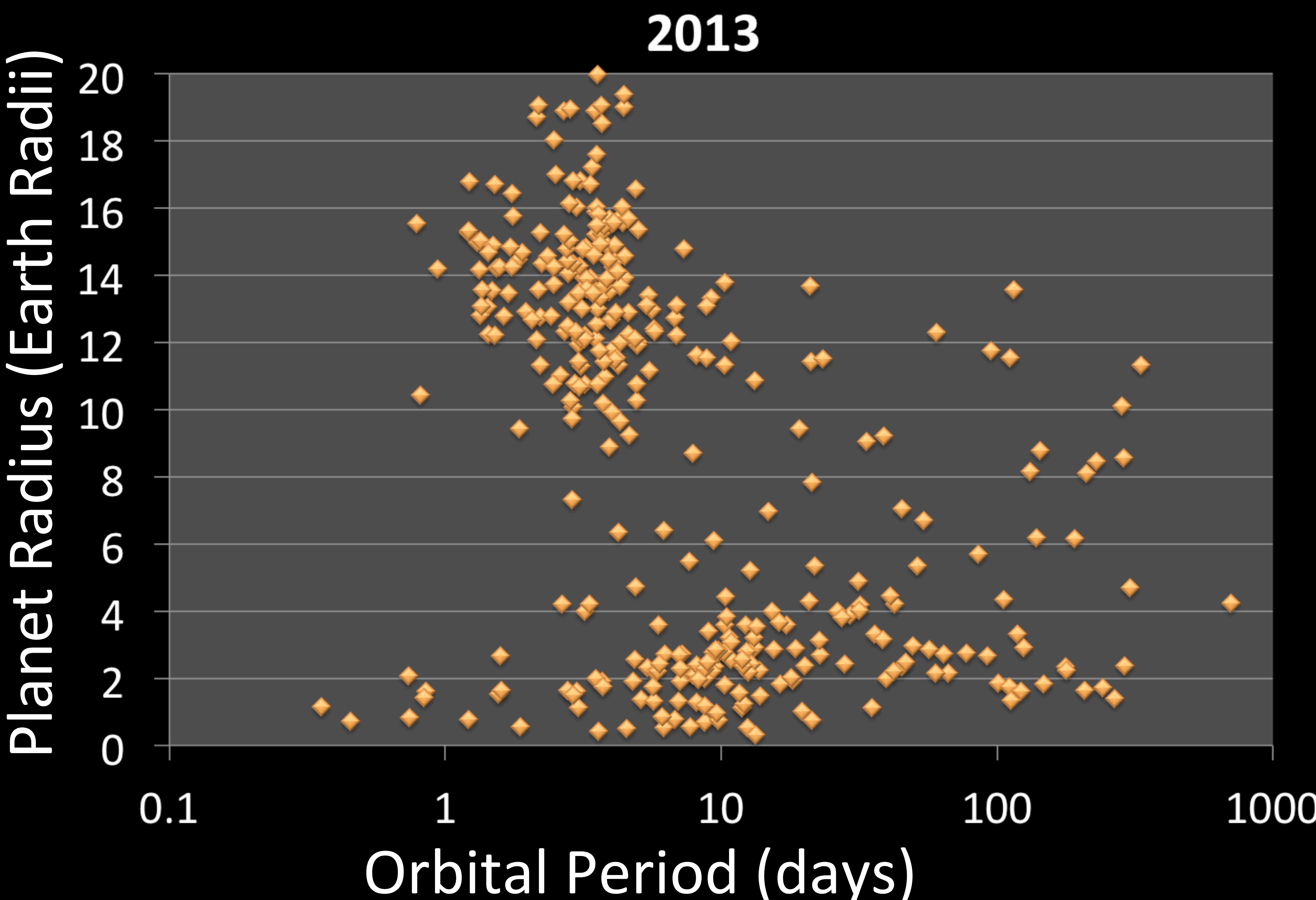


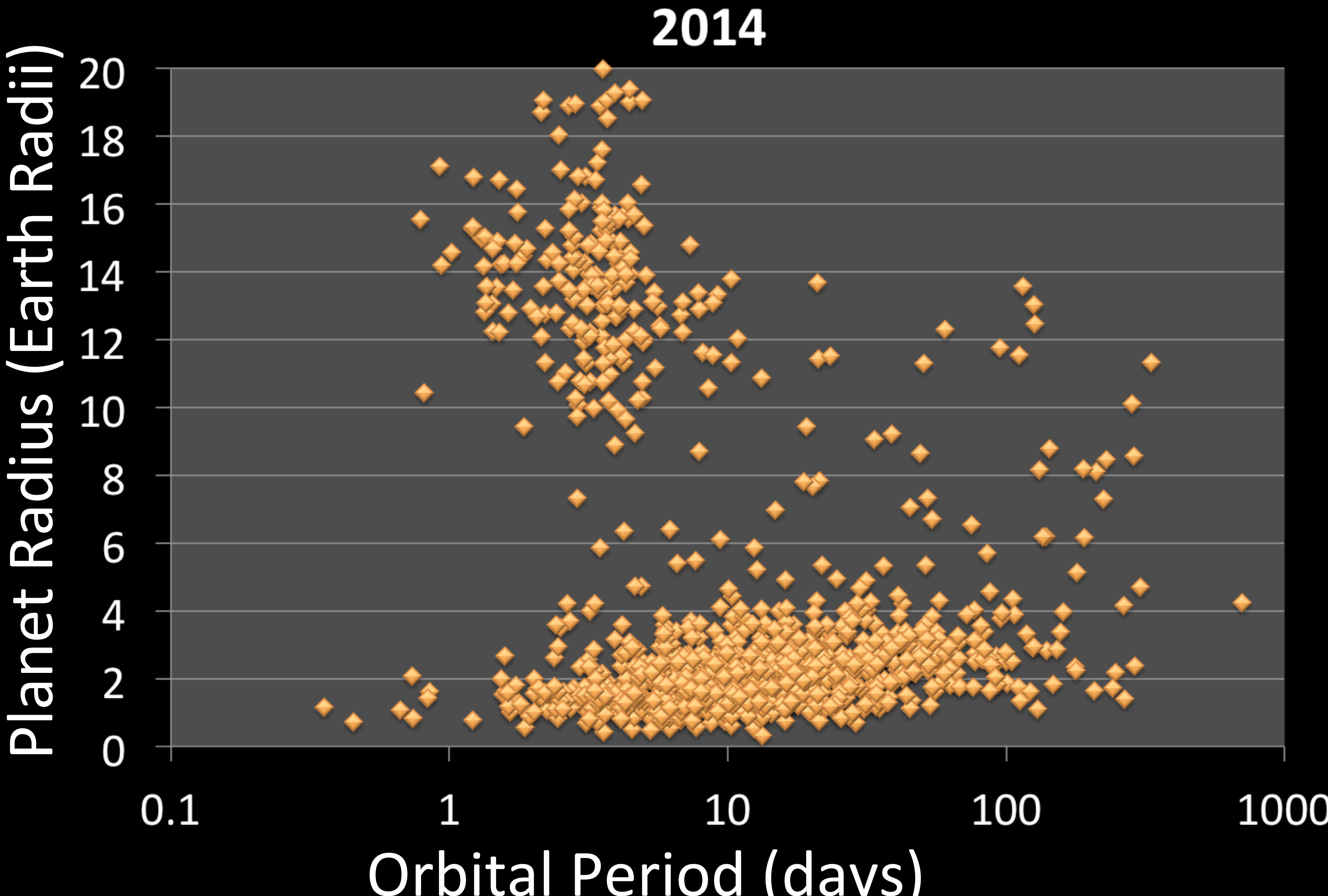
2010
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000
Orbital Period (days)

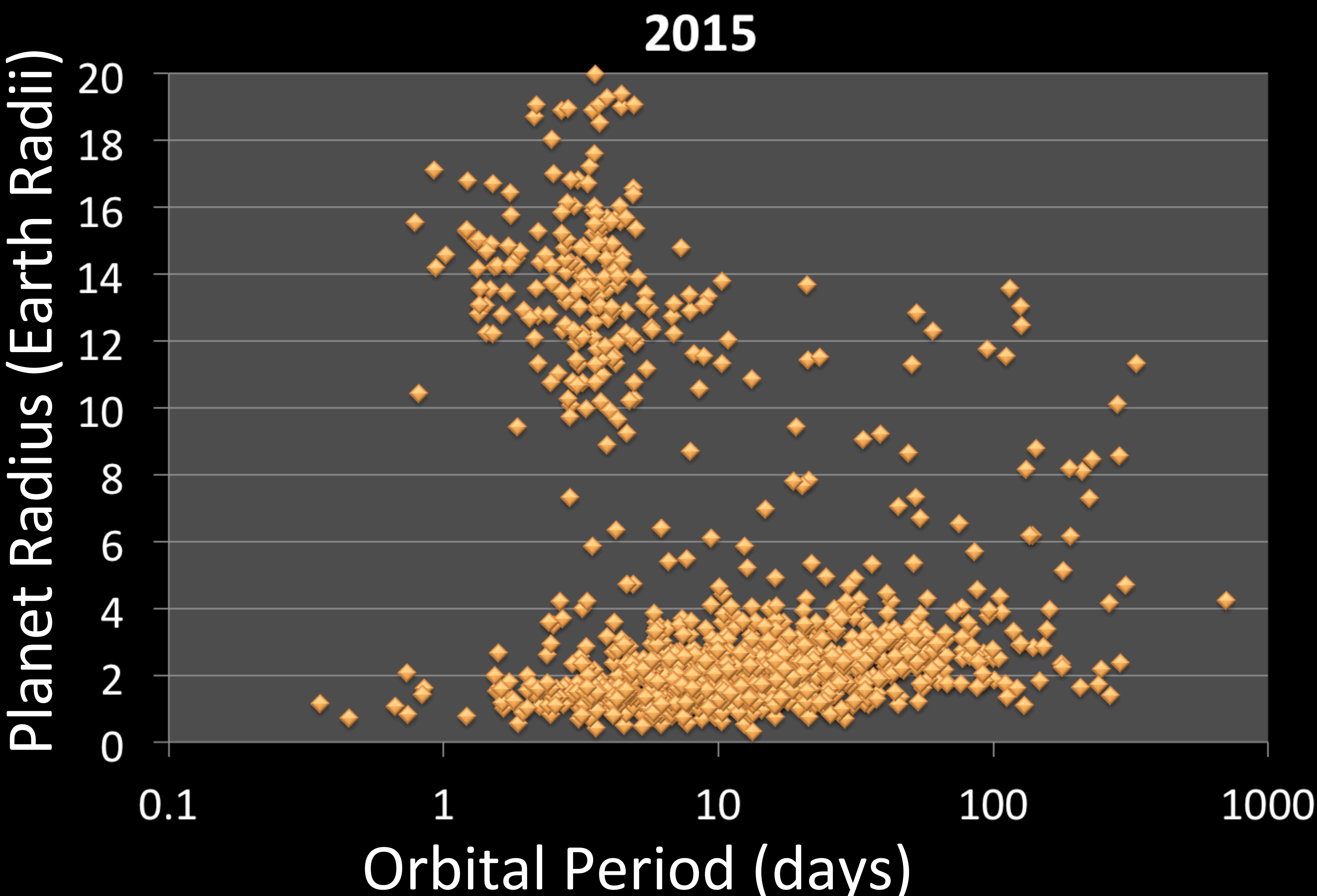

2011
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)



2012
Planet Radius (Earth Radii)
20
18
16
14
12
10
8
6
4
2
0
0.1
1
10
100
1000
Orbital Period (days)


2013
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000
Orbital Period (days)


2014
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000
Orbital Period (days)


2015
Planet Radius (Earth Radii)
0
2
4
6
8
10
12
14
16
18
20
0.1
1
10
100
1000
Orbital Period (days)

Back to the opening question :

How many stars do we need to survey to obtain a **4σ detection** of an **Earth-like planet** transiting a **Sun-like star?**

Case Study: The *Kepler* Mission

Earth – Sun transit depth: **84 ppm**

Required Precision for 4σ detection $= \dfrac{84 \text{ ppm}}{4} =$ **20 ppm**

Noise model

$$20 \text{ ppm} > \sigma = [(\sigma_{shot})^2 + (\sigma_{star})^2 + (\sigma_{meas})^2]^{0.5}$$

If $\sigma_{star} = 10$ ppm and $\sigma_{meas} = 10$ ppm then

$$\sigma_{shot} < (20^2 - (10^2 + 10^2))^{0.5} = 14 \text{ ppm}$$

Case Study: The *Kepler* Mission

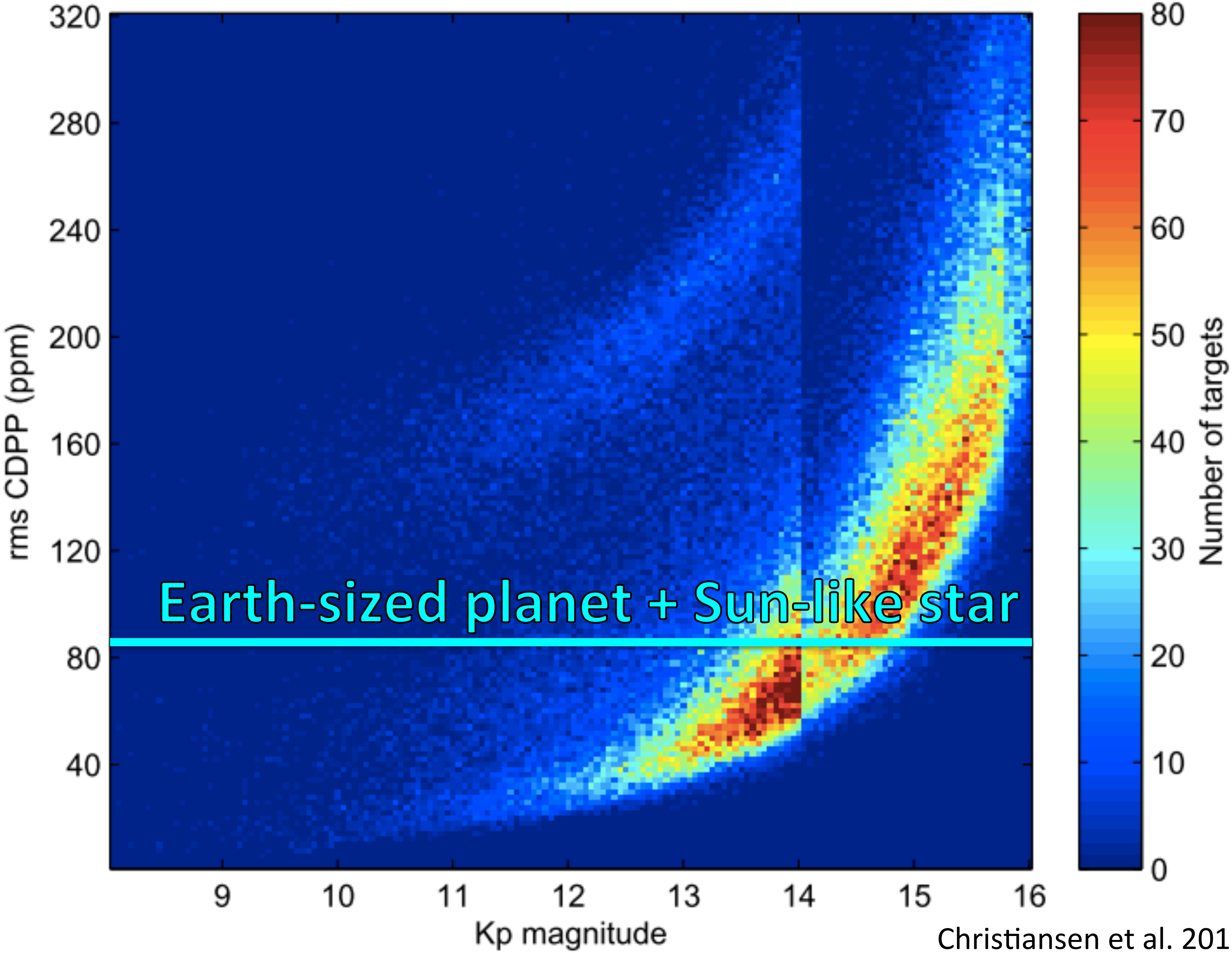
Earth – Sun transit duration: **13 hr**

Mission Requirement: **Detect 84 ppm transit in 6.5 hr**

see Koch et al. 2010, ApJ, 713, 80

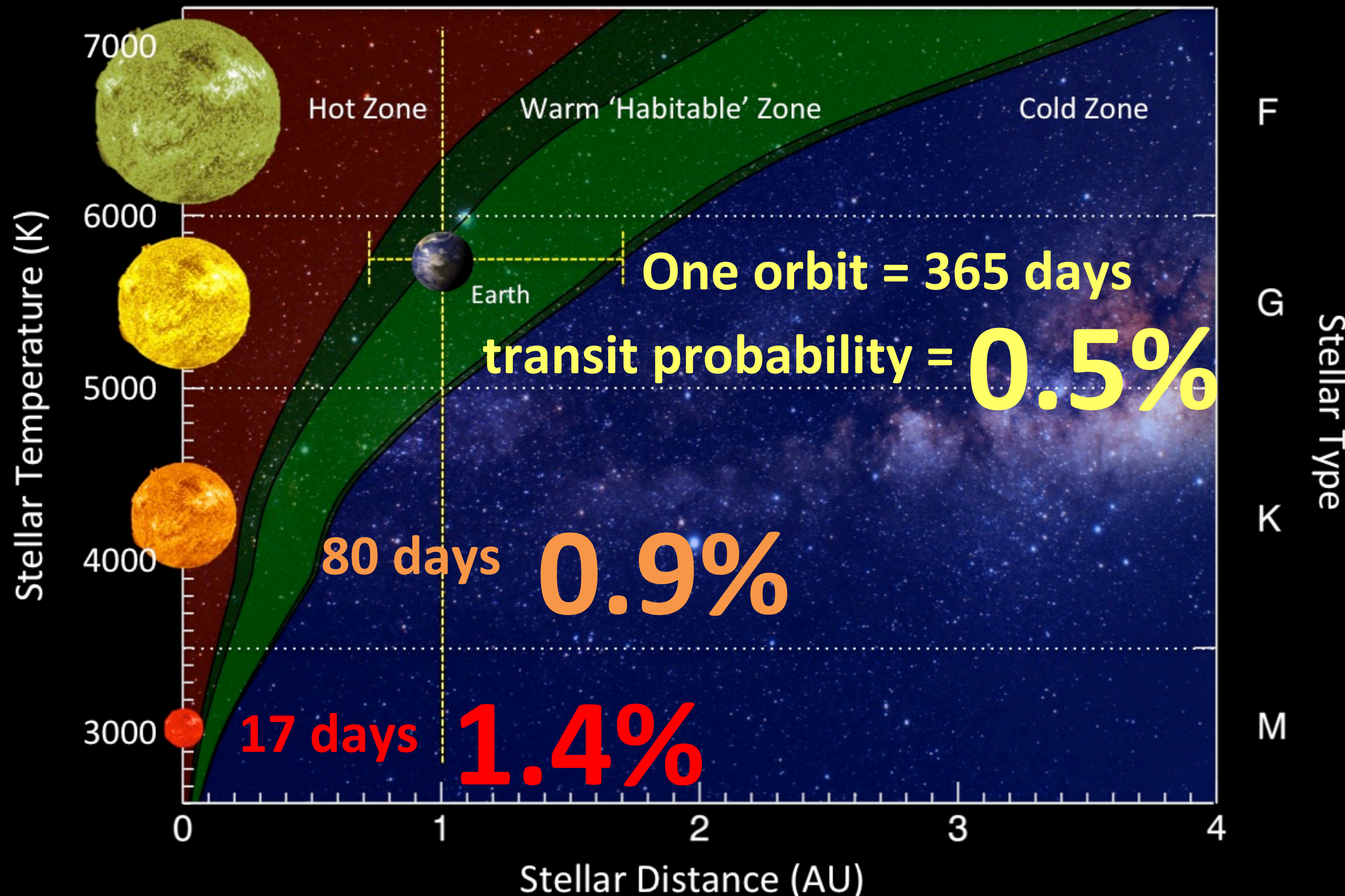
$$\text{Required Number of Photons in 6.5 hr} = \left(\frac{1}{14\ \text{ppm}}\right)^2 = 5 \times 10^9$$

Suggests we should target stars with ***V ≤ 12***



Christiansen et al. 2012

Transit Probabilities for Potentially Habitable Worlds



CREDIT: PHL @ UPR Arecibo

If **5%** of Sun-like V=12 stars harbor **Earth-like planets**

and **0.5%** of those planets transit then

$$N_\star = \frac{1}{0.5} \times \frac{1}{0.005} = 4000 \text{ stars}$$

to find a single

transiting Earth-like planet.

How might we estimate planet occurrence?

Completeness Case Study:

the Kepler M Dwarfs


Most Stars are M Dwarfs


Most Stars are M Dwarfs

Planet Occurrence

Equally Valid Alternative Choice:

Planet occurrence = Fraction of Stars with Planetary Systems

# of Planets = # of Planet Candidates – # of False Positives

$$\text{Planet Occurrence Rate} = \frac{\text{Number of Planets}}{\text{Number of Stars “Searched”}}$$

# of Planets = # of Planet Candidates – # of False Positives

Planet Occurrence Rate = **Number of Planets** / **Number of Stars "Searched"**

Transit detectability depends on **stellar** and **planetary** properties

Which astrophysical phenomena can produce transit-like brightness dips?

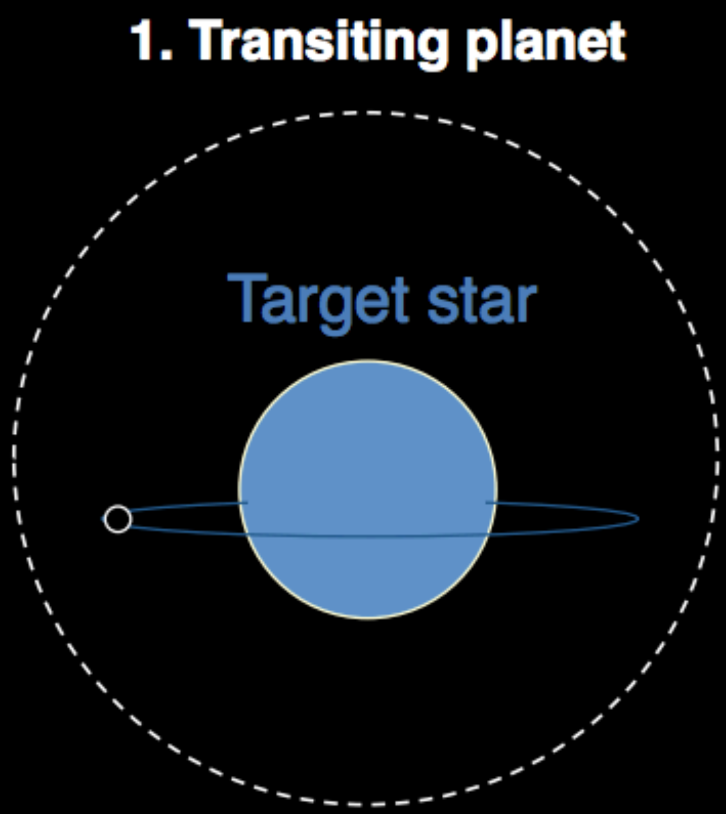
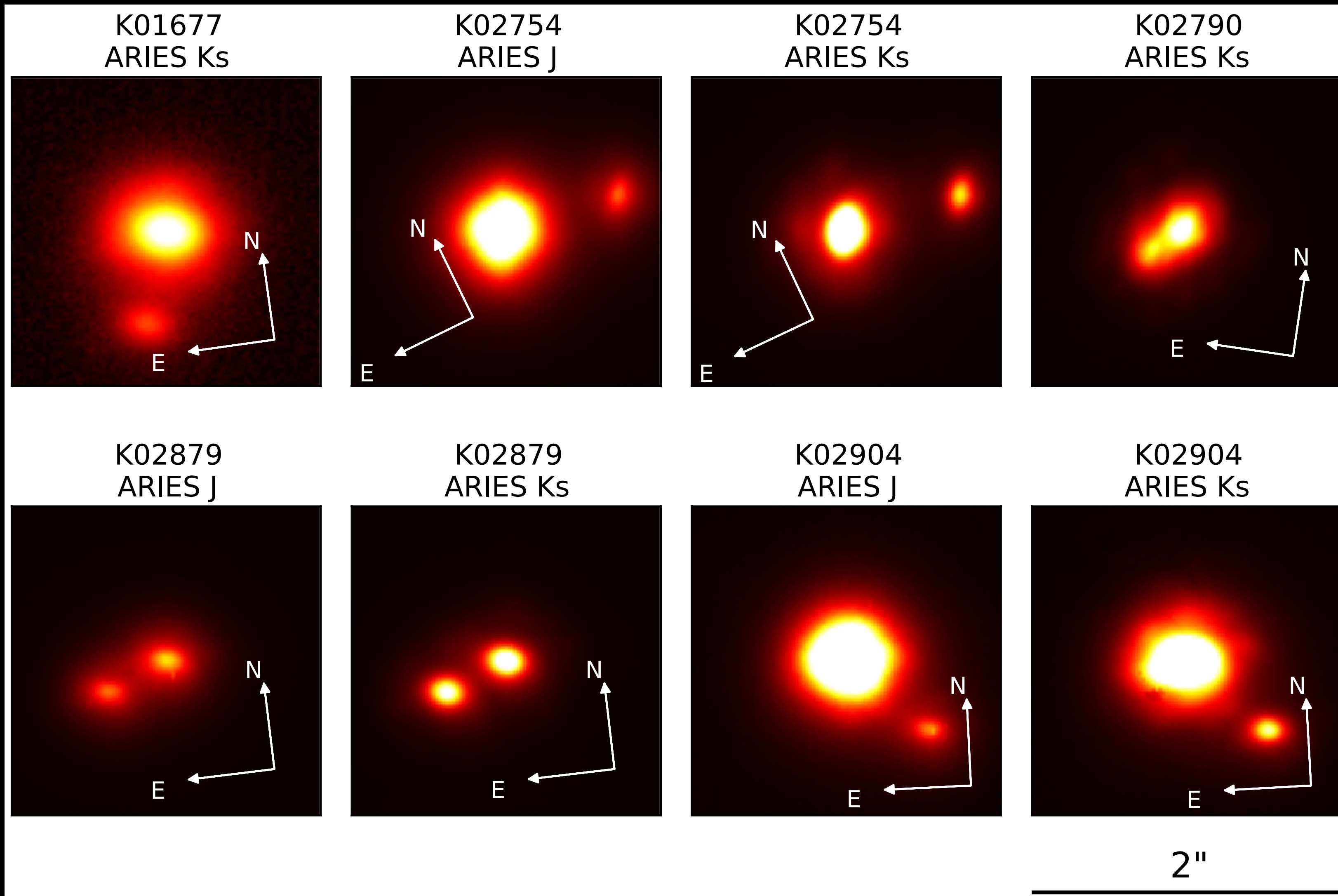


Figure credit: Sarah Ballard

High-Contrast Imaging

One of several ways to identify astrophysical false positives

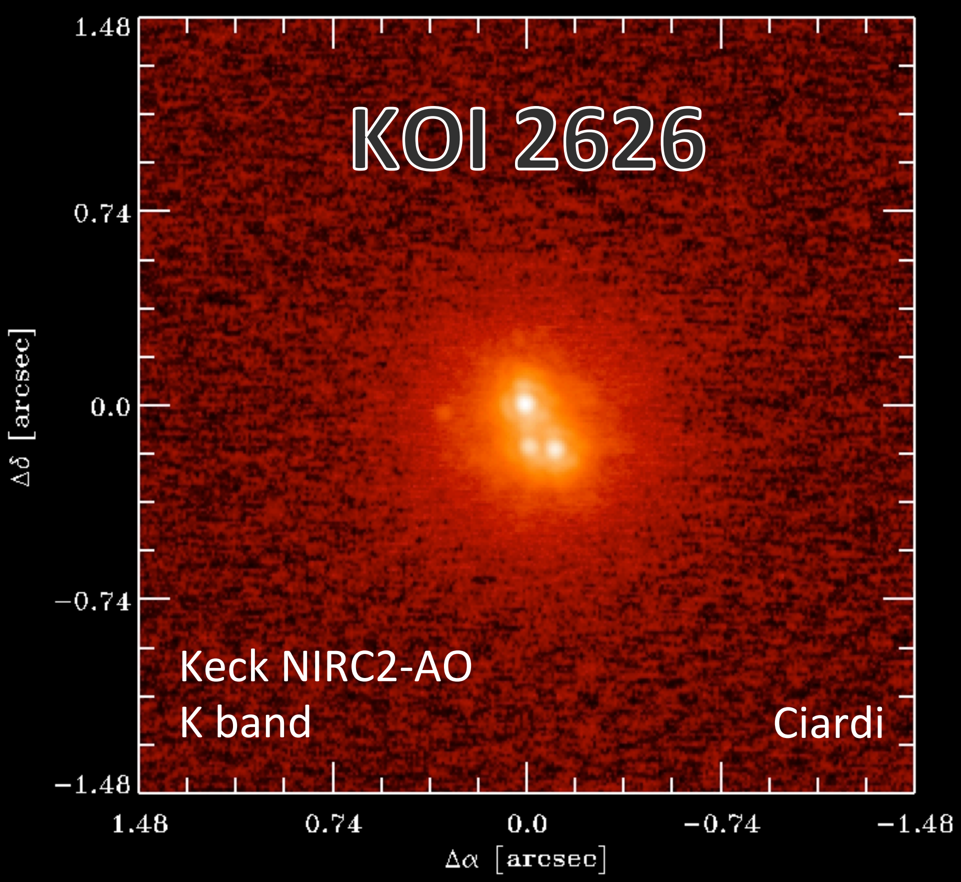
Kepler targets with companions within 1"

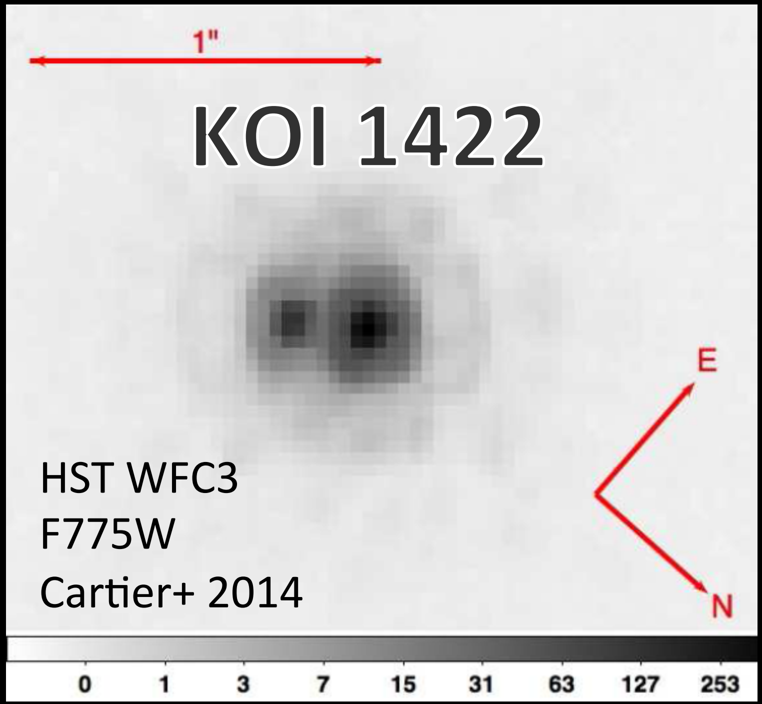


Dressing et al. 2014, AJ, 148, 78

Why High-Resolution Imaging Matters:

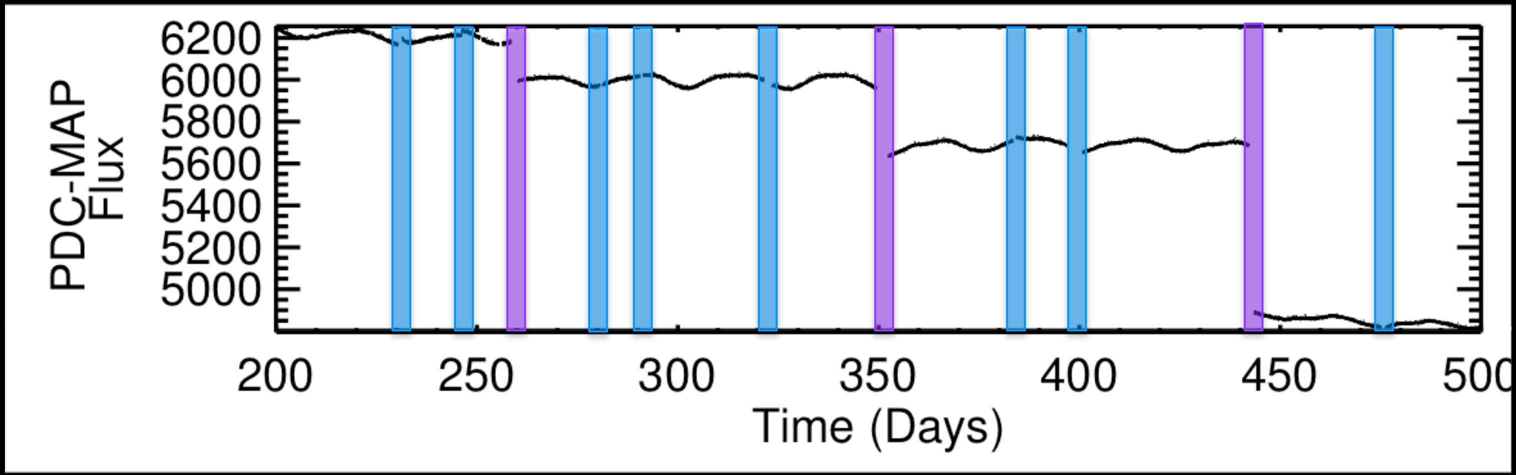
Thwarting the Aspirations of Potentially Habitable M Dwarf Planets





CFOP
Kepler Community Follow-up Observing Program

Searching for Planets Orbiting *Kepler* M Dwarfs

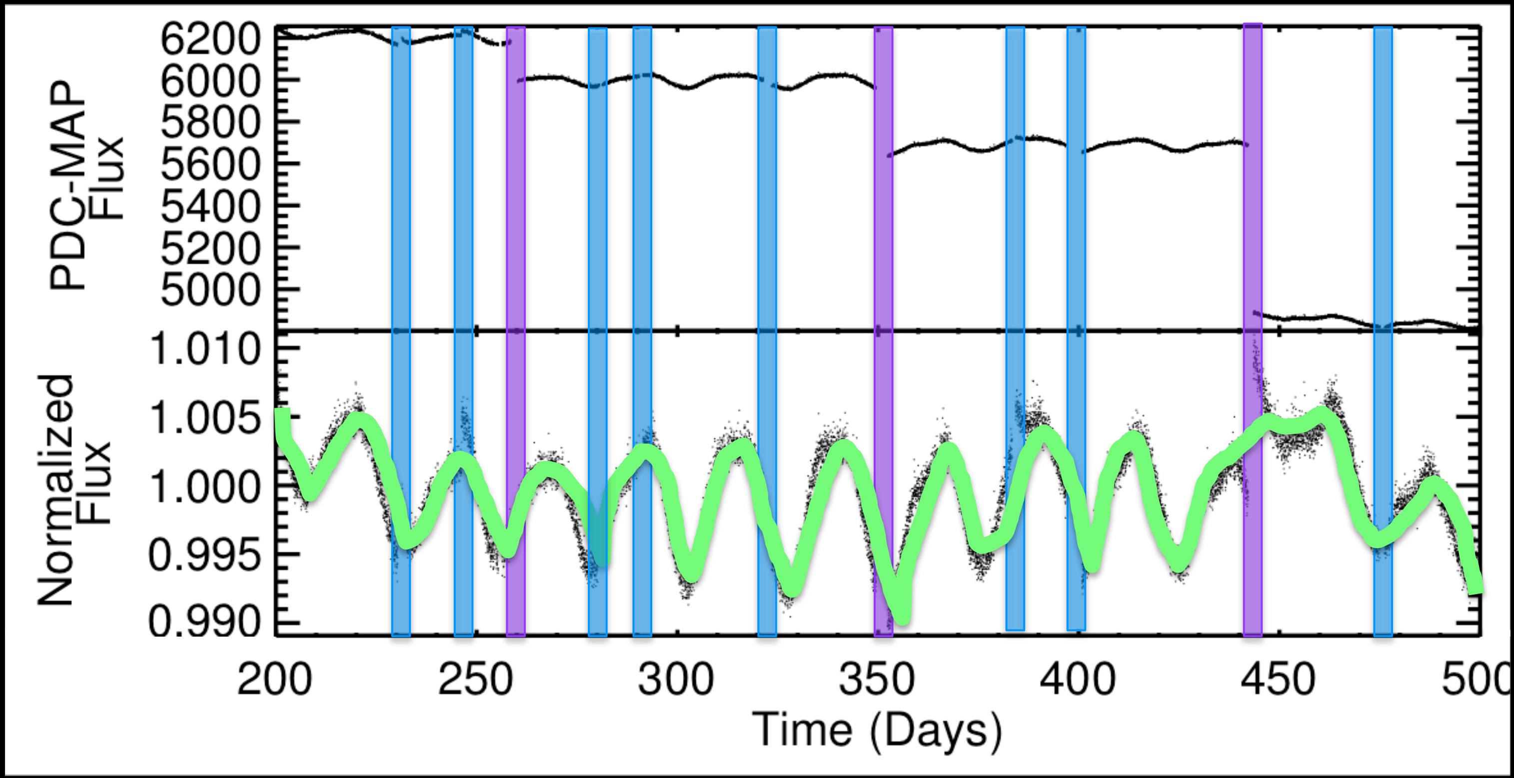


Quarterly Spacecraft Rolls

Data Gaps

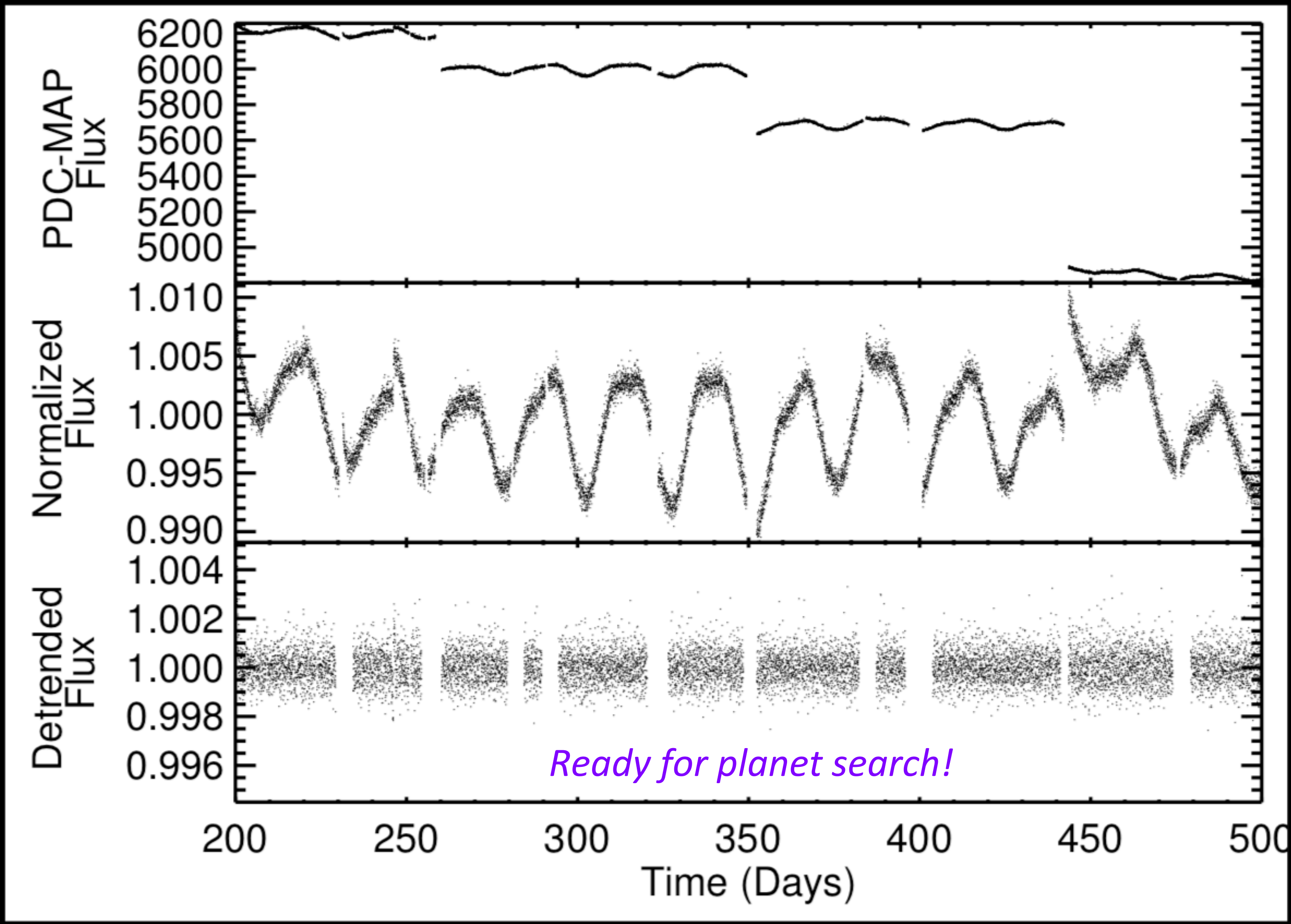
Normalize to remove quarterly offsets

Searching for Planets Orbiting *Kepler* M Dwarfs

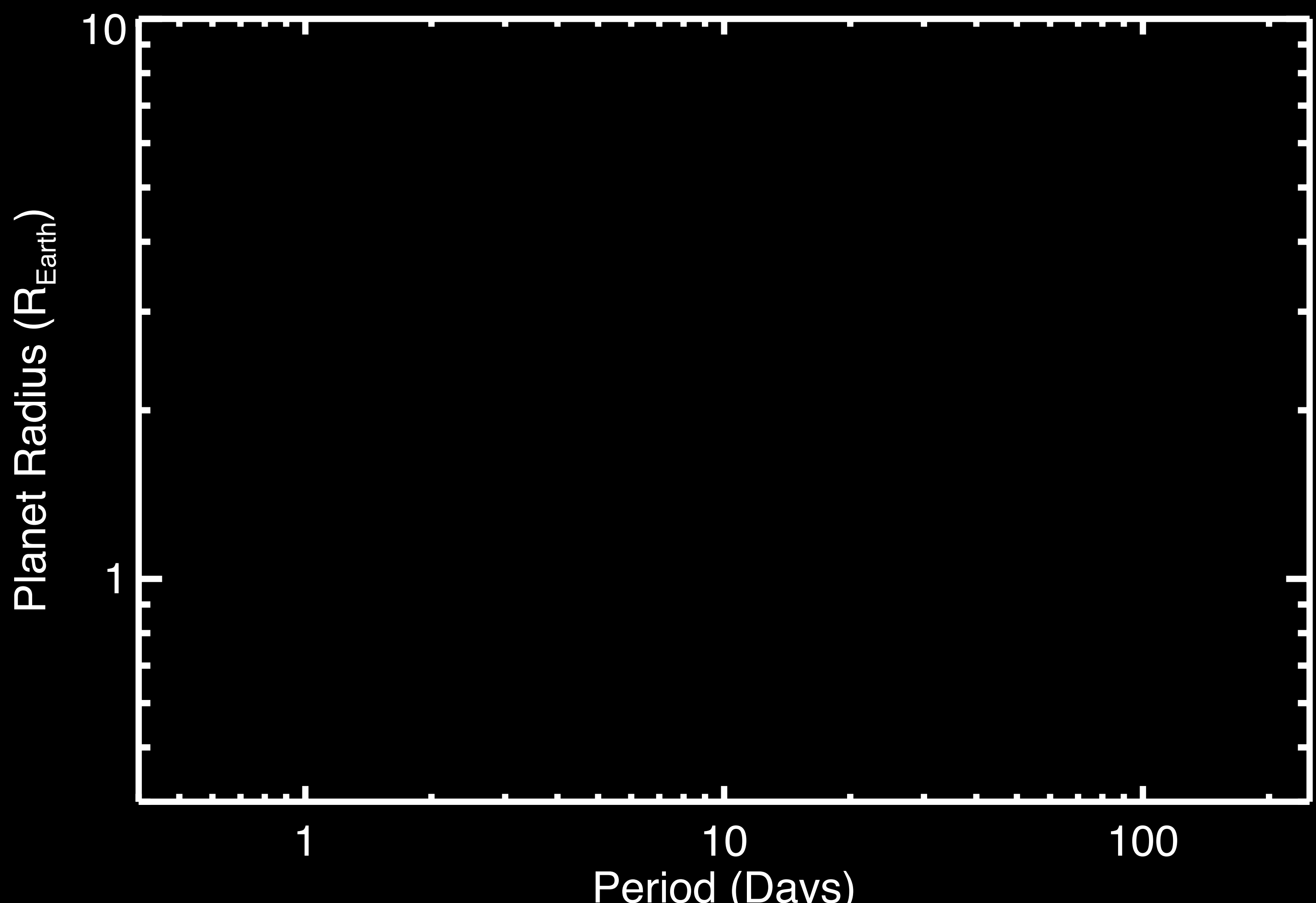


Use median filtering and sigma clipping to remove spots and lingering pointing offsets.

Searching for Planets Orbiting *Kepler* M Dwarfs



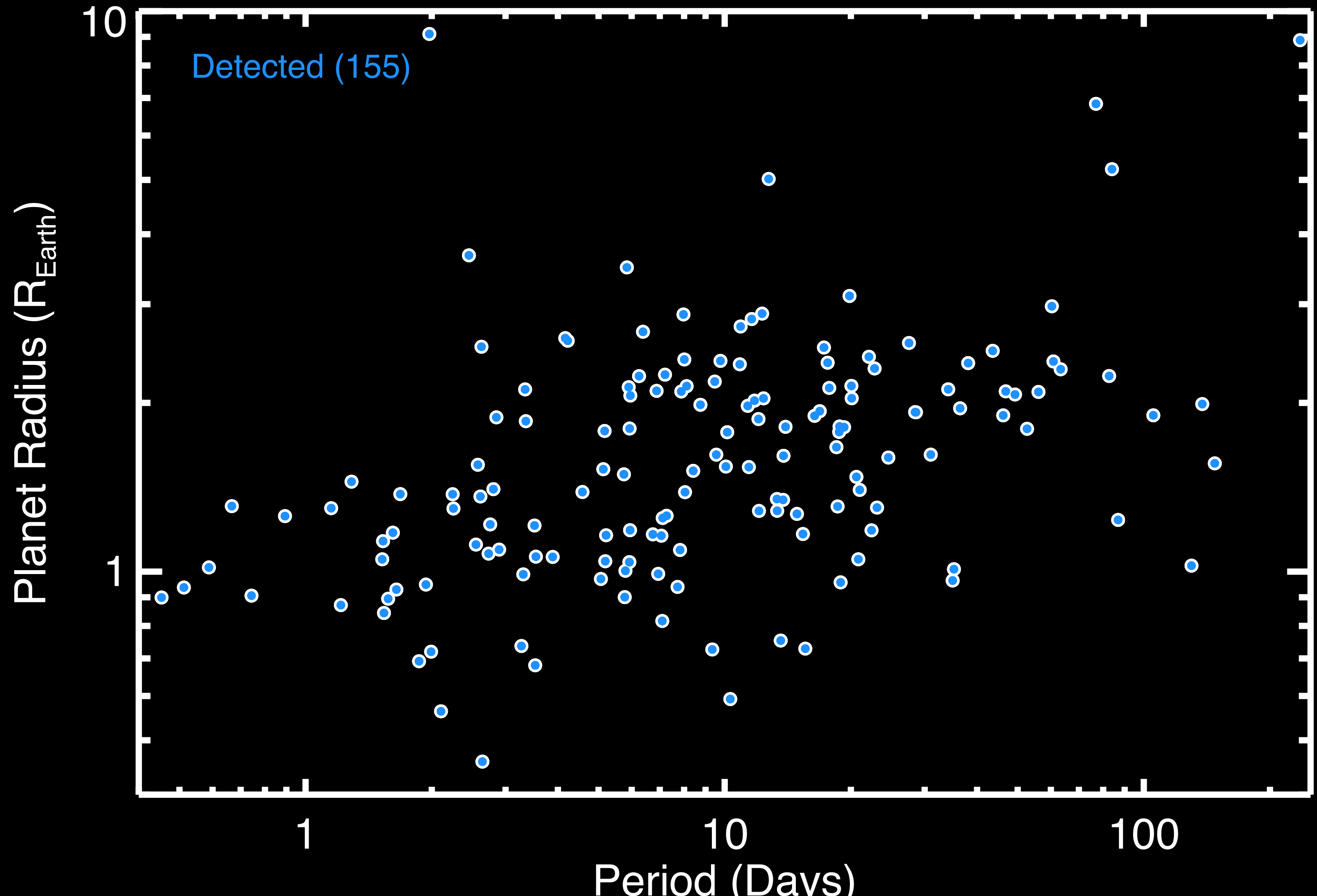
Planet Search Results:



Dressing & Charbonneau 2015, ApJ, 807, 45

Planet Search Results:

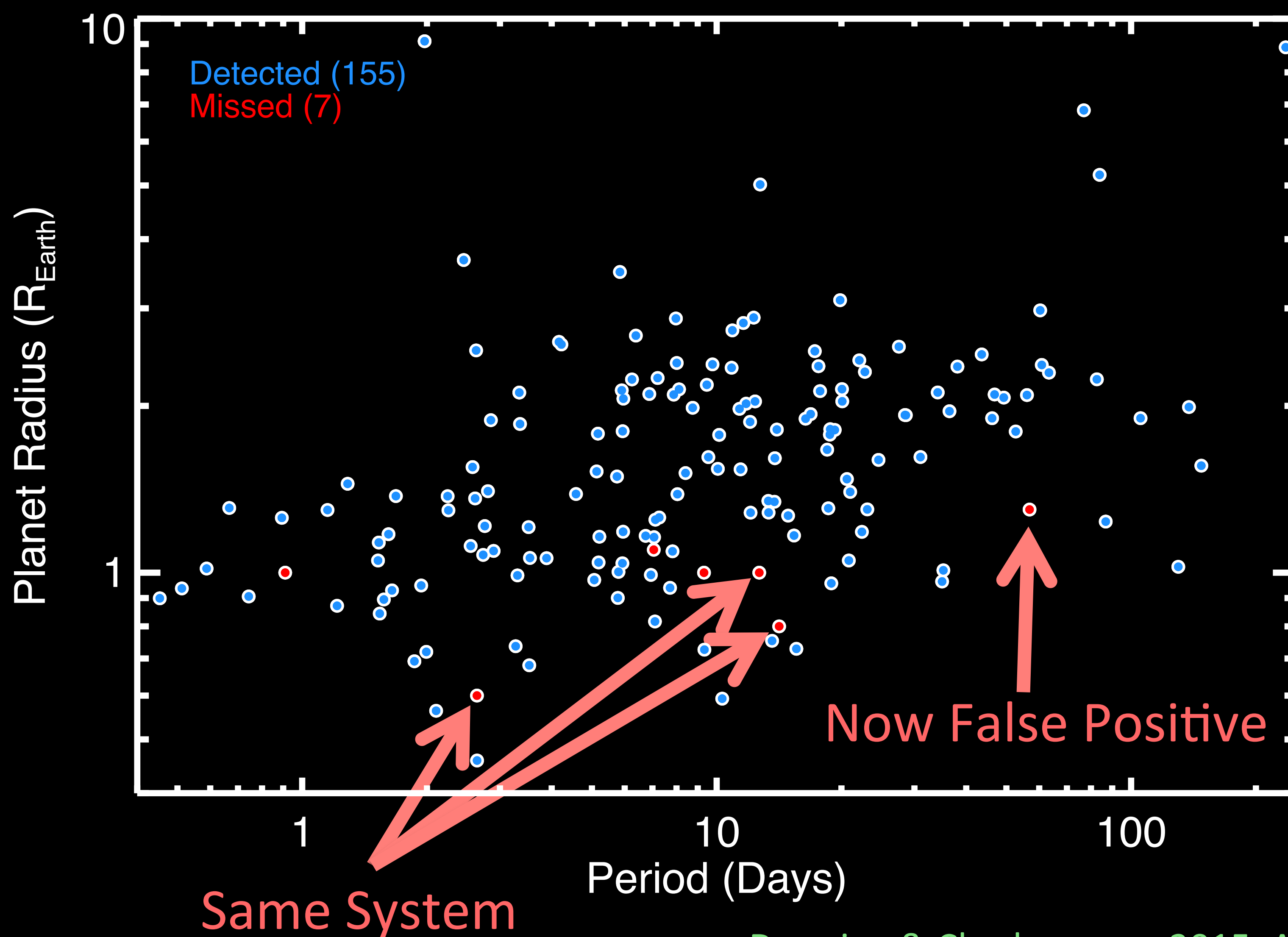
We Detect Most Previously Known Planets



Dressing & Charbonneau 2015, ApJ, 807, 45

Planet Search Results:

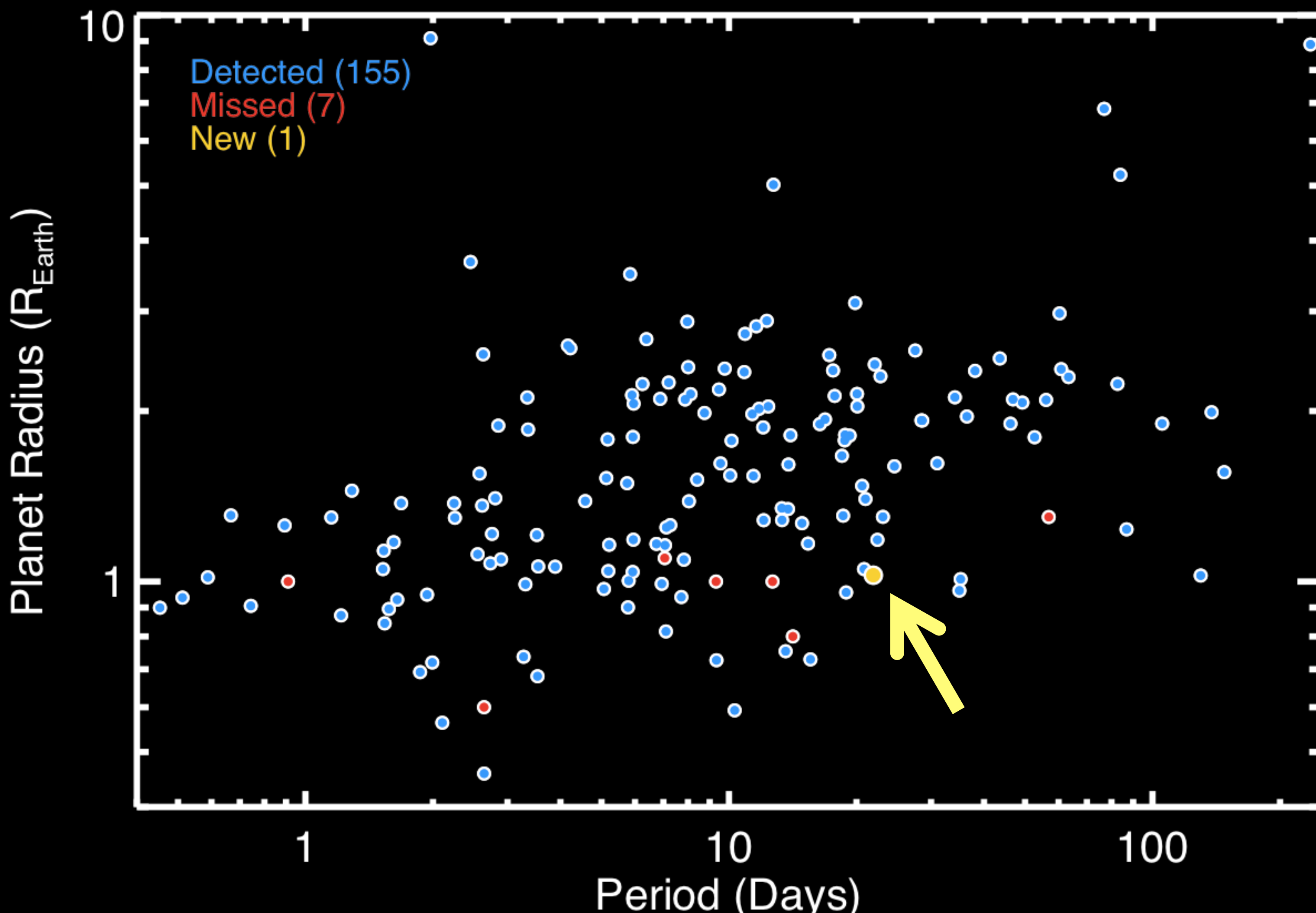
We Miss a Few Tricky Planets *(Some may be false positives)*



Dressing & Charbonneau 2015, ApJ, 807, 45

Planet Search Results:

We Found One New Planet Candidate



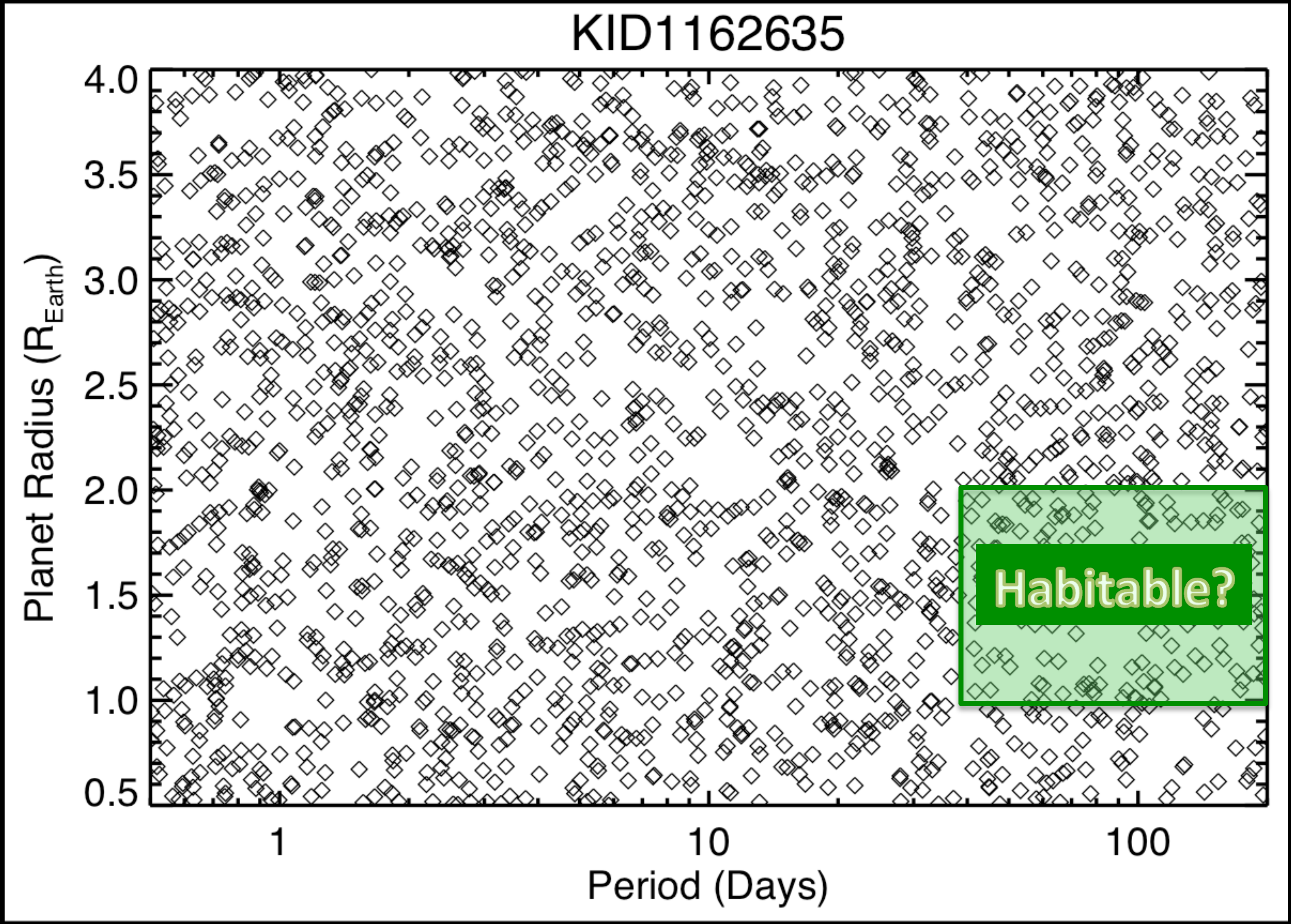
Dressing & Charbonneau 2015, ApJ, 807, 45

$$\textit{Planet Occurrence Rate} = \frac{\text{Number of Planets}}{\text{Number of Stars “Searched”}}$$

Planet Occurrence Rate = **156 Planets** / **Number of Stars "Searched"**

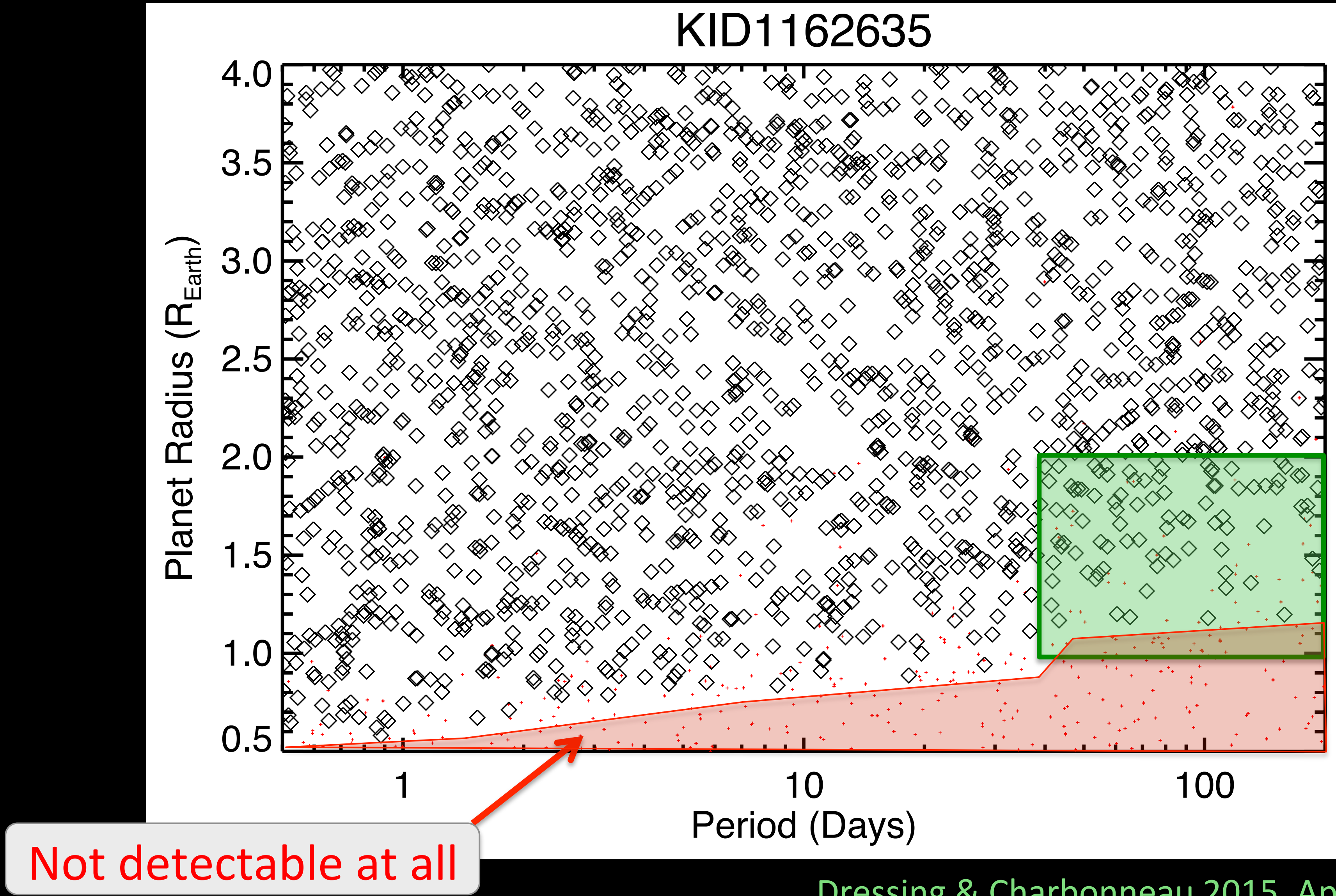
How many stars did we search at each planet radius & orbital period?

Estimating Pipeline Sensitivity



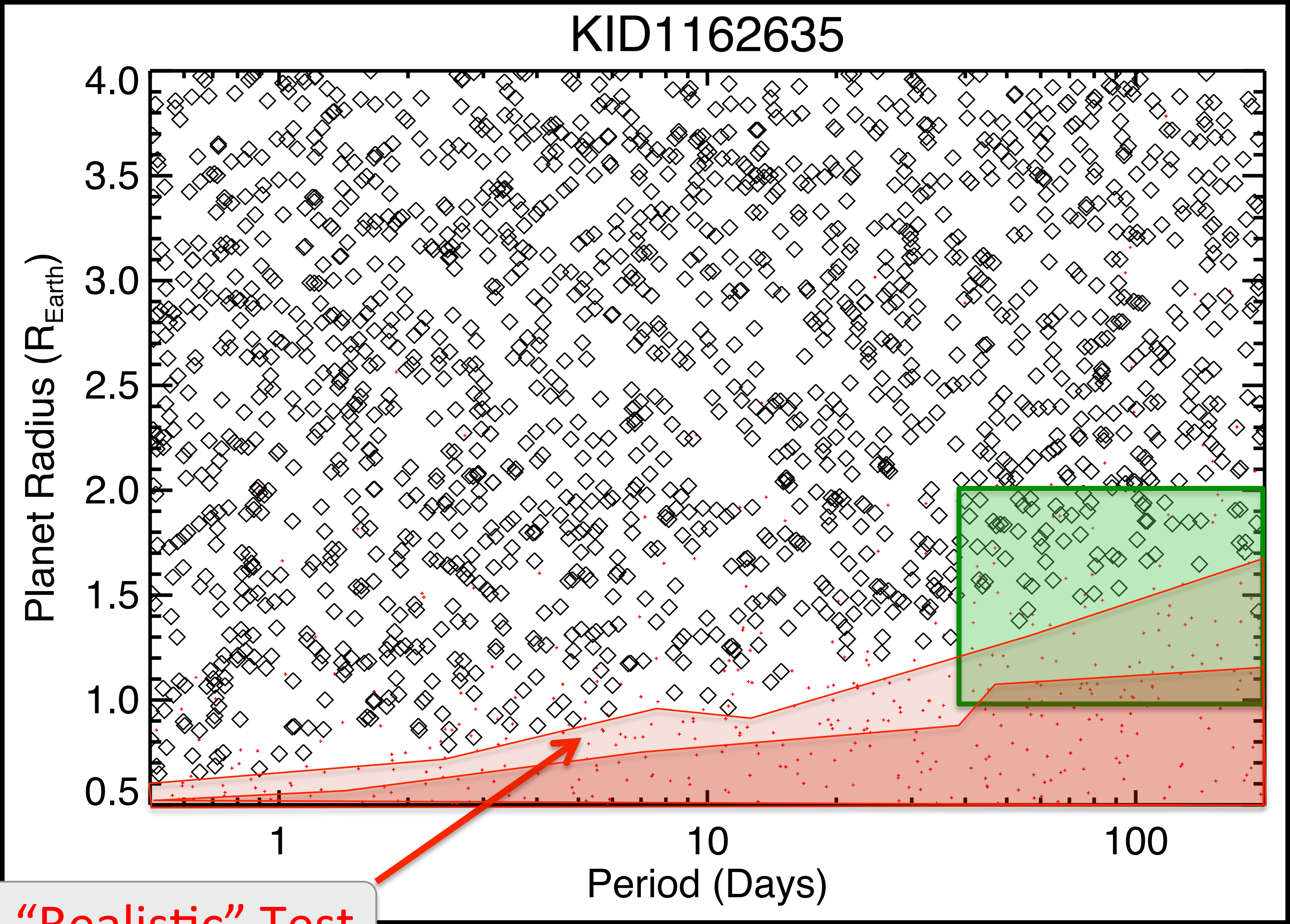
Dressing & Charbonneau 2015, ApJ, 807, 45

Estimating Pipeline Sensitivity



Dressing & Charbonneau 2015, ApJ, 807, 45

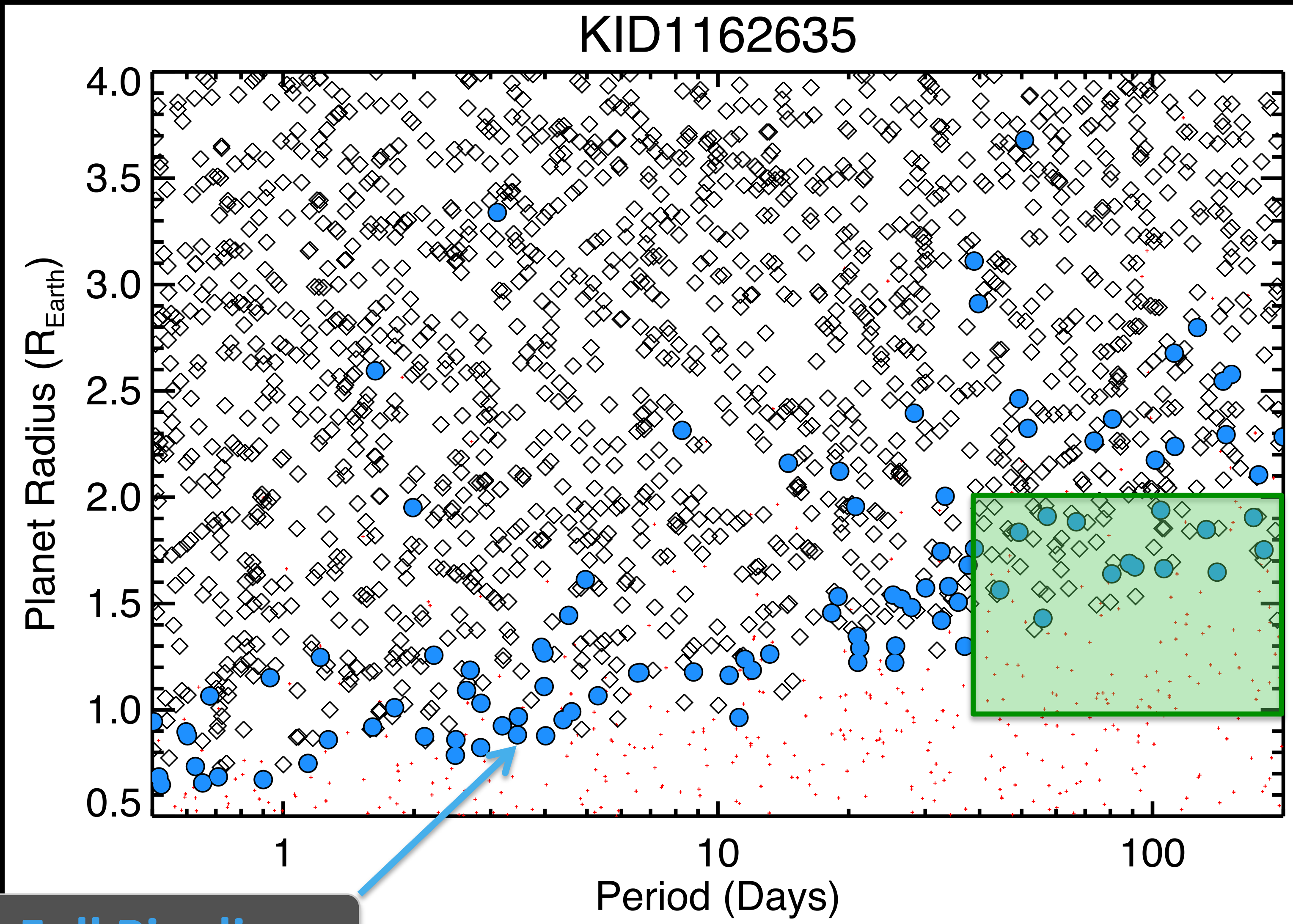
Estimating Pipeline Sensitivity



Failed “Realistic” Test

Dressing & Charbonneau 2015, ApJ, 807, 45

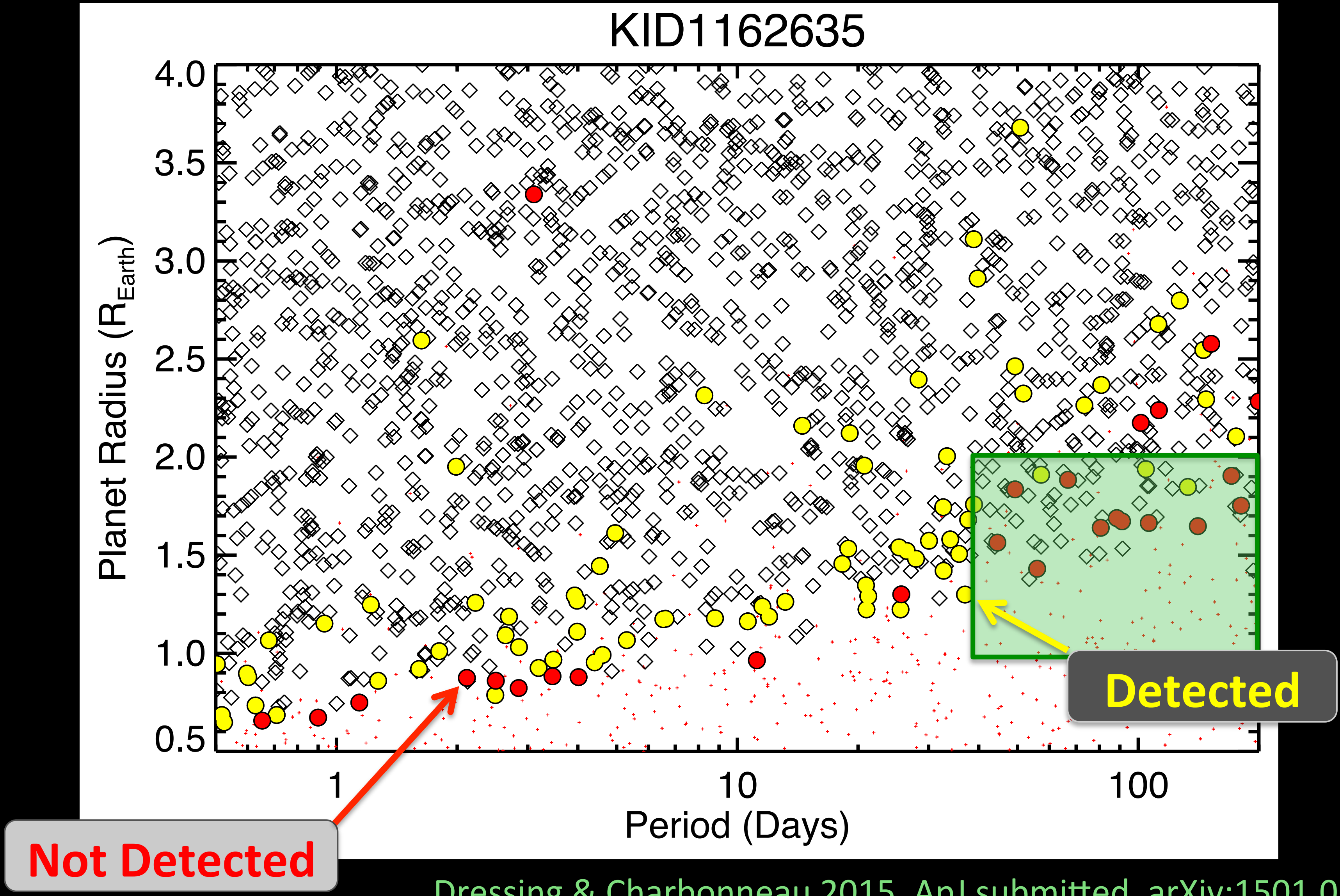
Estimating Pipeline Sensitivity



Ran Full Pipeline

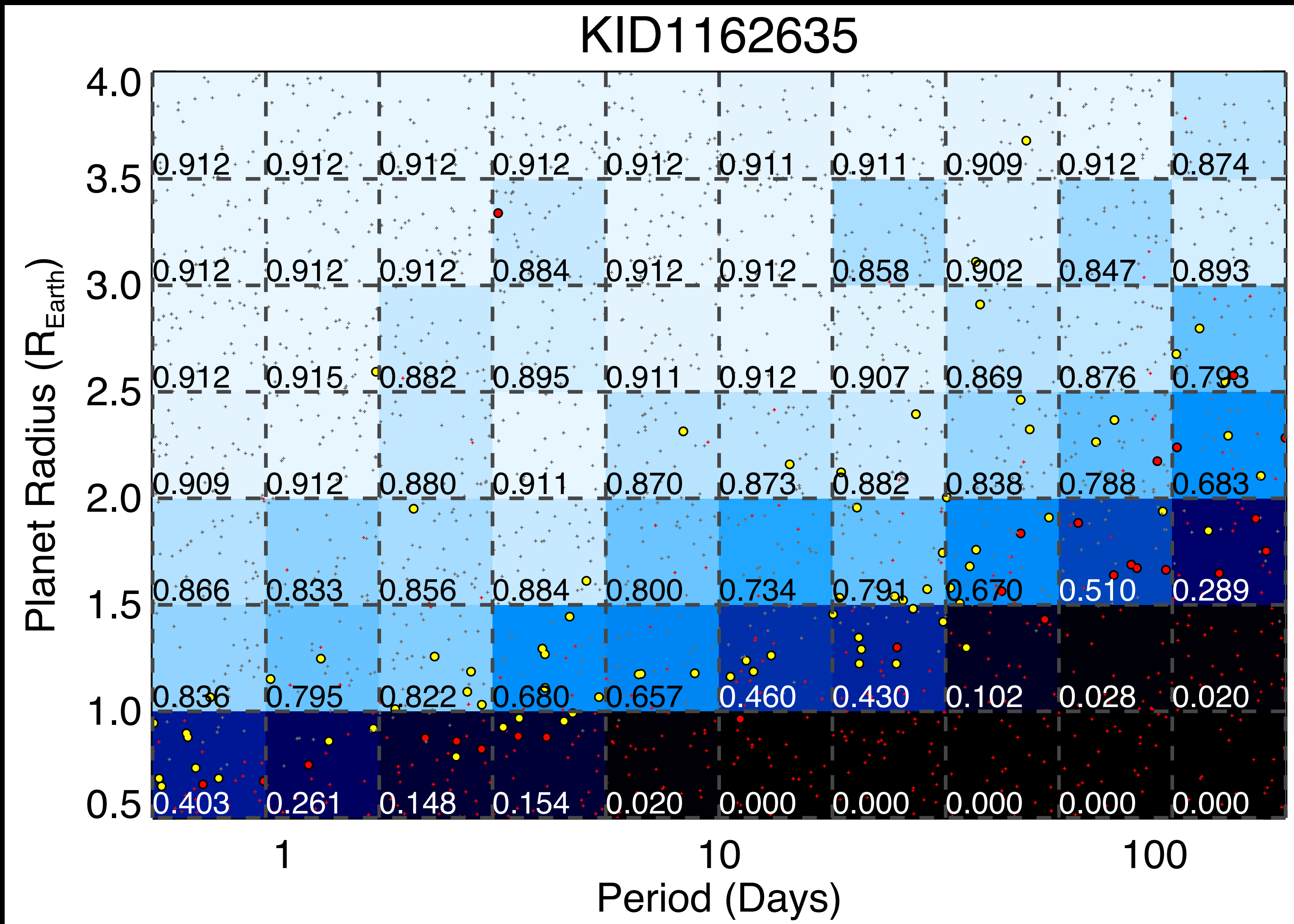
Dressing & Charbonneau 2015, ApJ submitted, arXiv:1501.01623

Estimating Pipeline Sensitivity



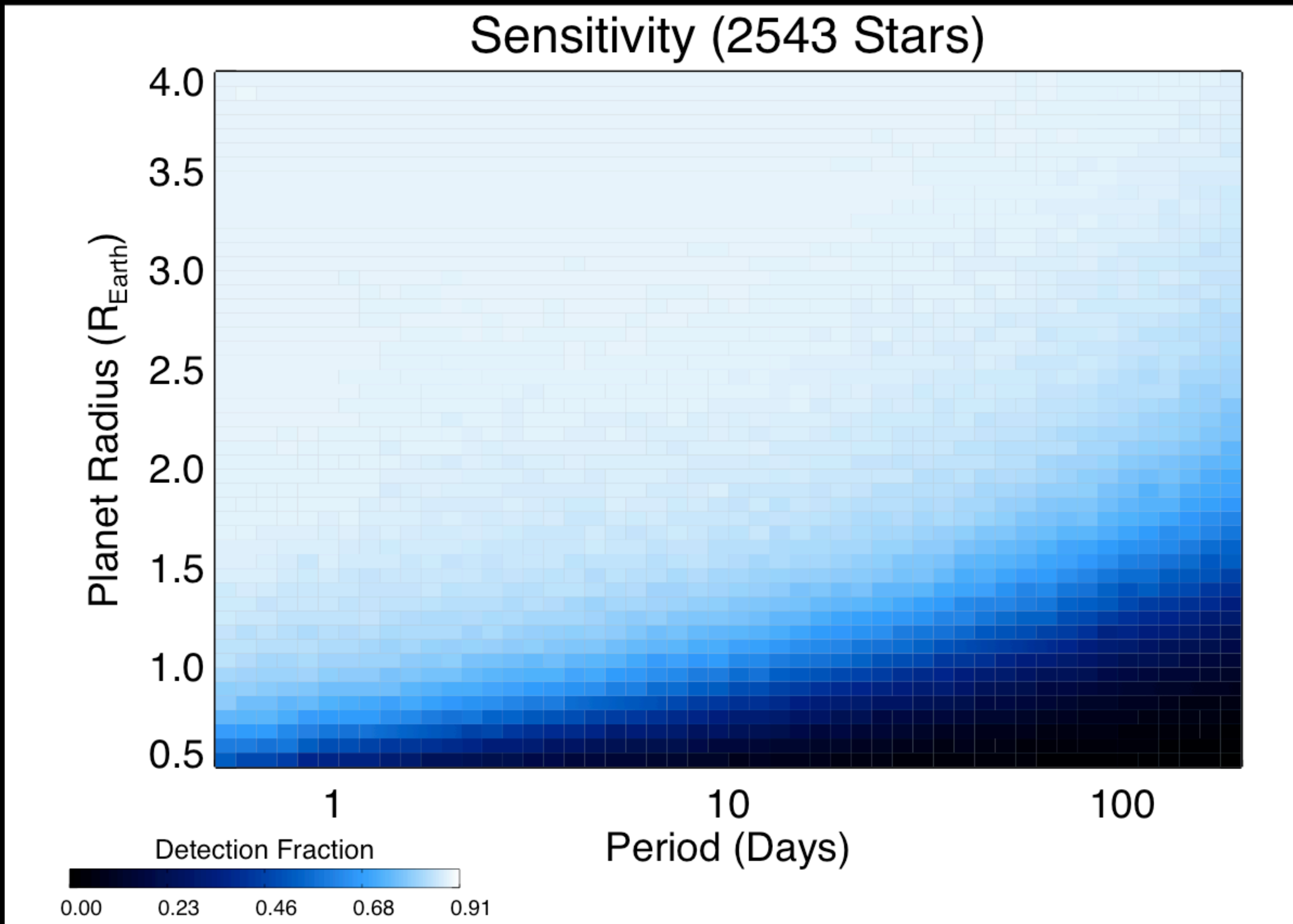
Dressing & Charbonneau 2015, ApJ submitted, arXiv:1501.01623

We Produced Star-by-Star Sensitivity Maps



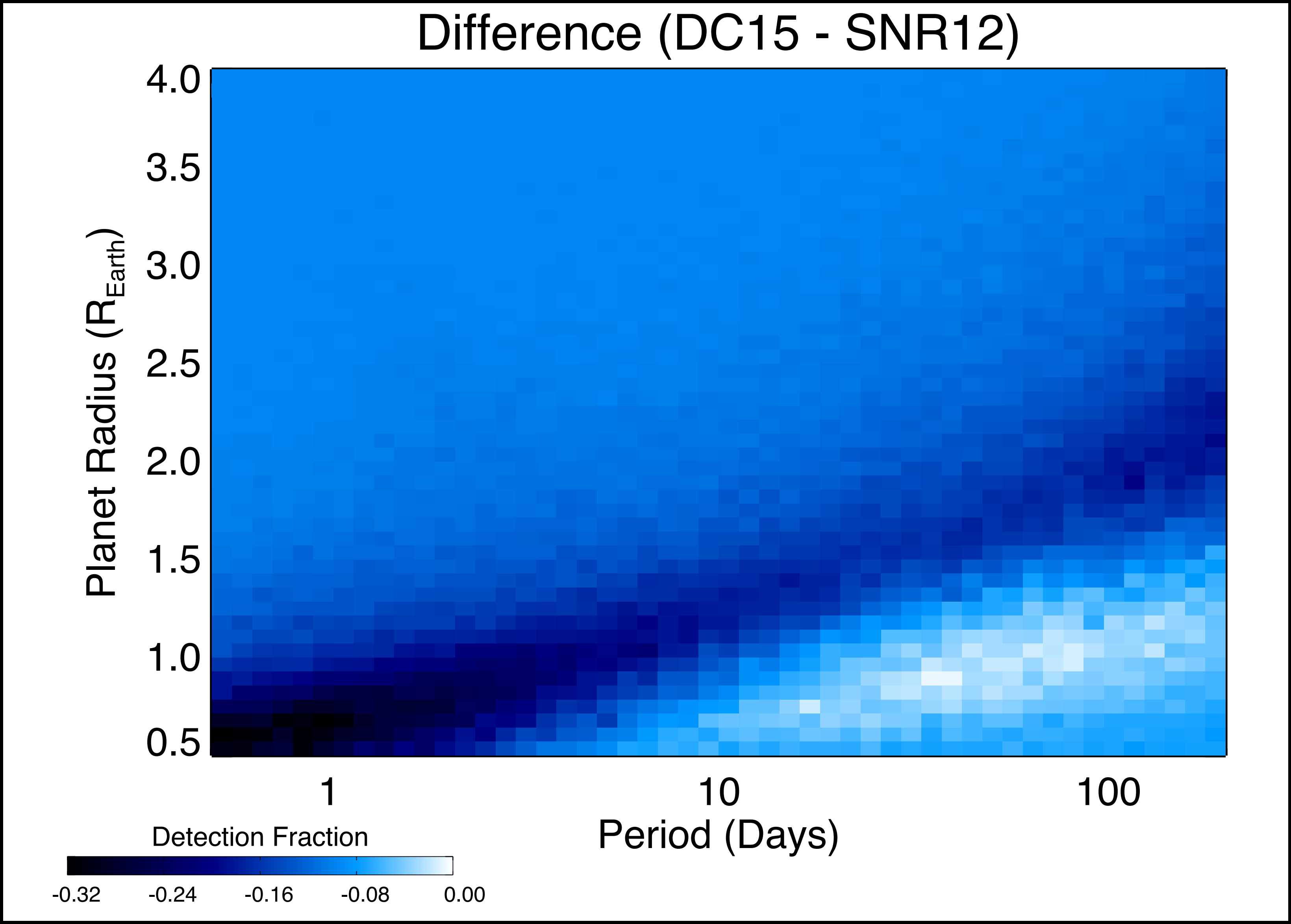
Dressing & Charbonneau 2015, ApJ, 807, 45

Sensitivity to Earth-size Planets Depends Strongly on Orbital Period

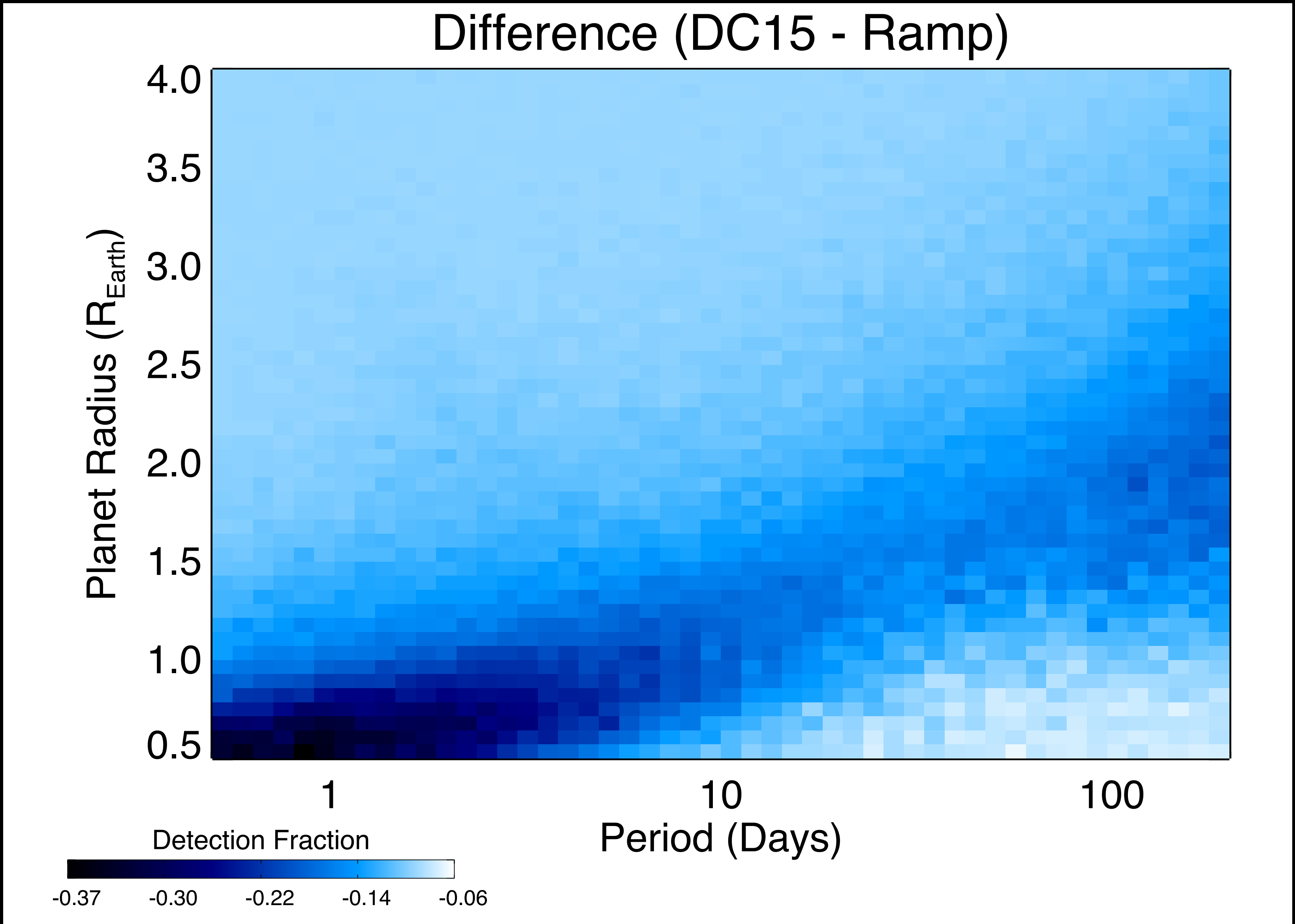


Dressing & Charbonneau 2015, ApJ, 807, 45

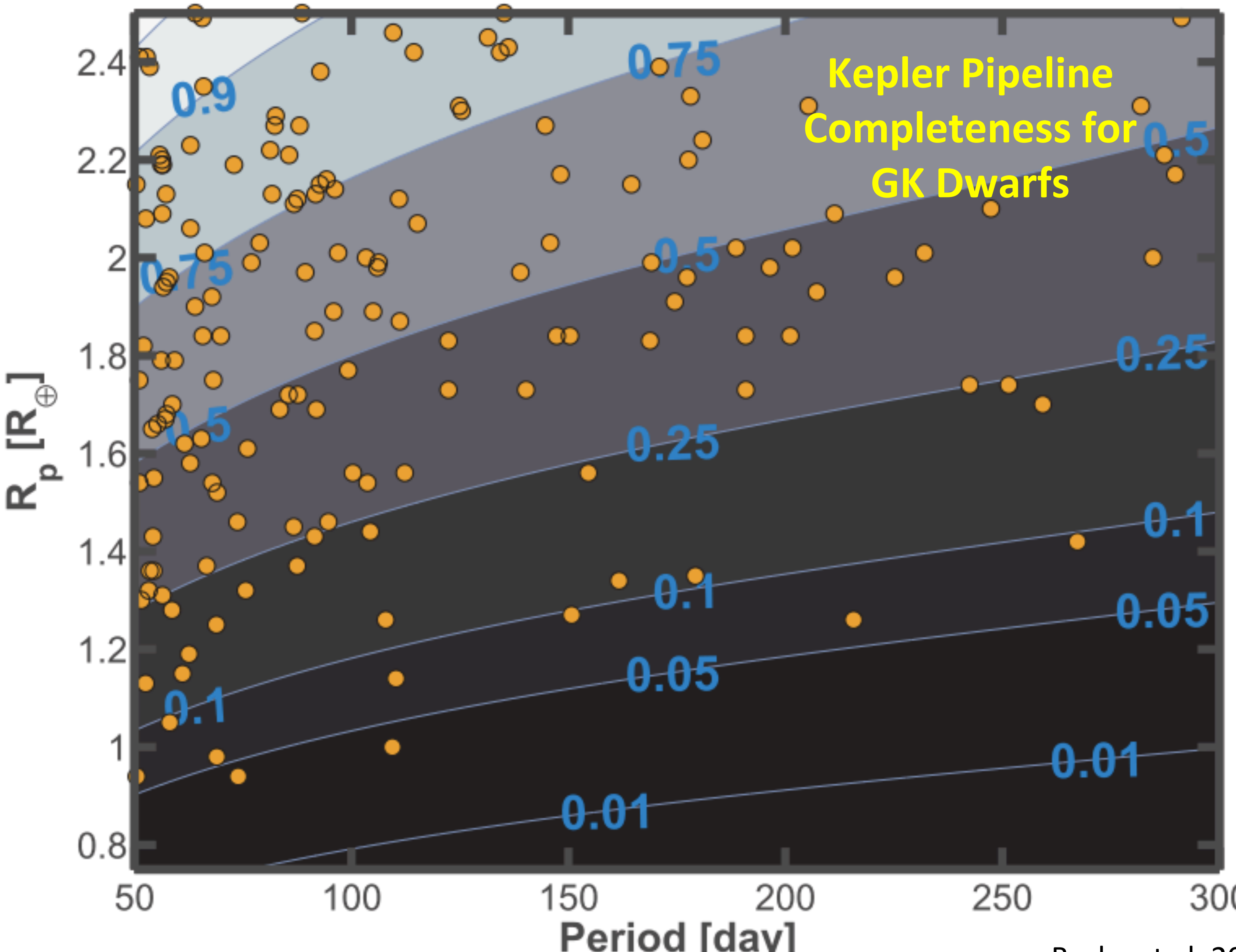
How does our search completeness compare to theoretical predictions?



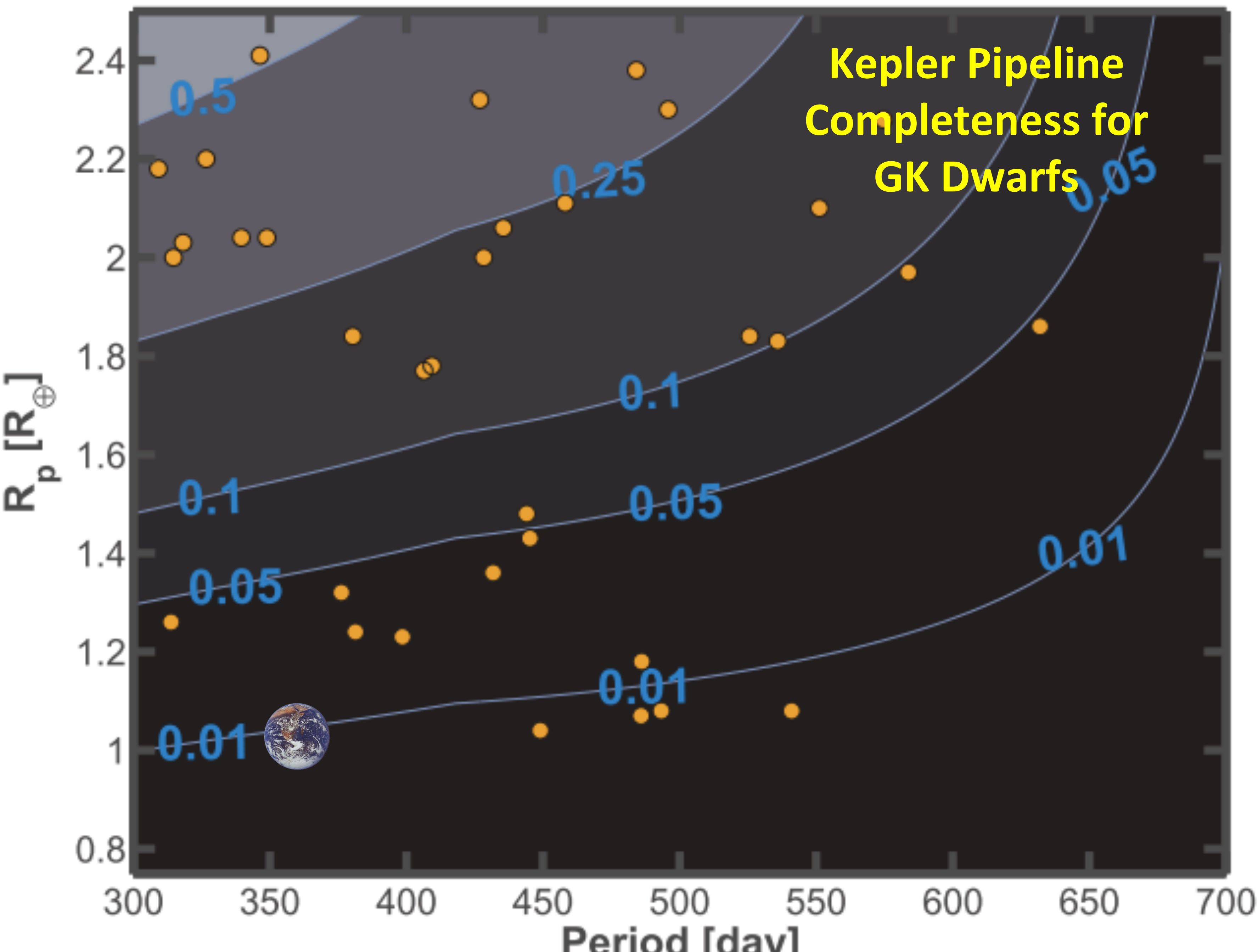
Difference (DC15 - SNR12)
Planet Radius (R_Earth)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
1
10
100
Period (Days)
Detection Fraction
-0.32
-0.24
-0.16
-0.08
0.00



Difference (DC15 - Ramp)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
Planet Radius (R_{Earth})
1
10
100
Period (Days)
Detection Fraction
-0.37
-0.30
-0.22
-0.14
-0.06

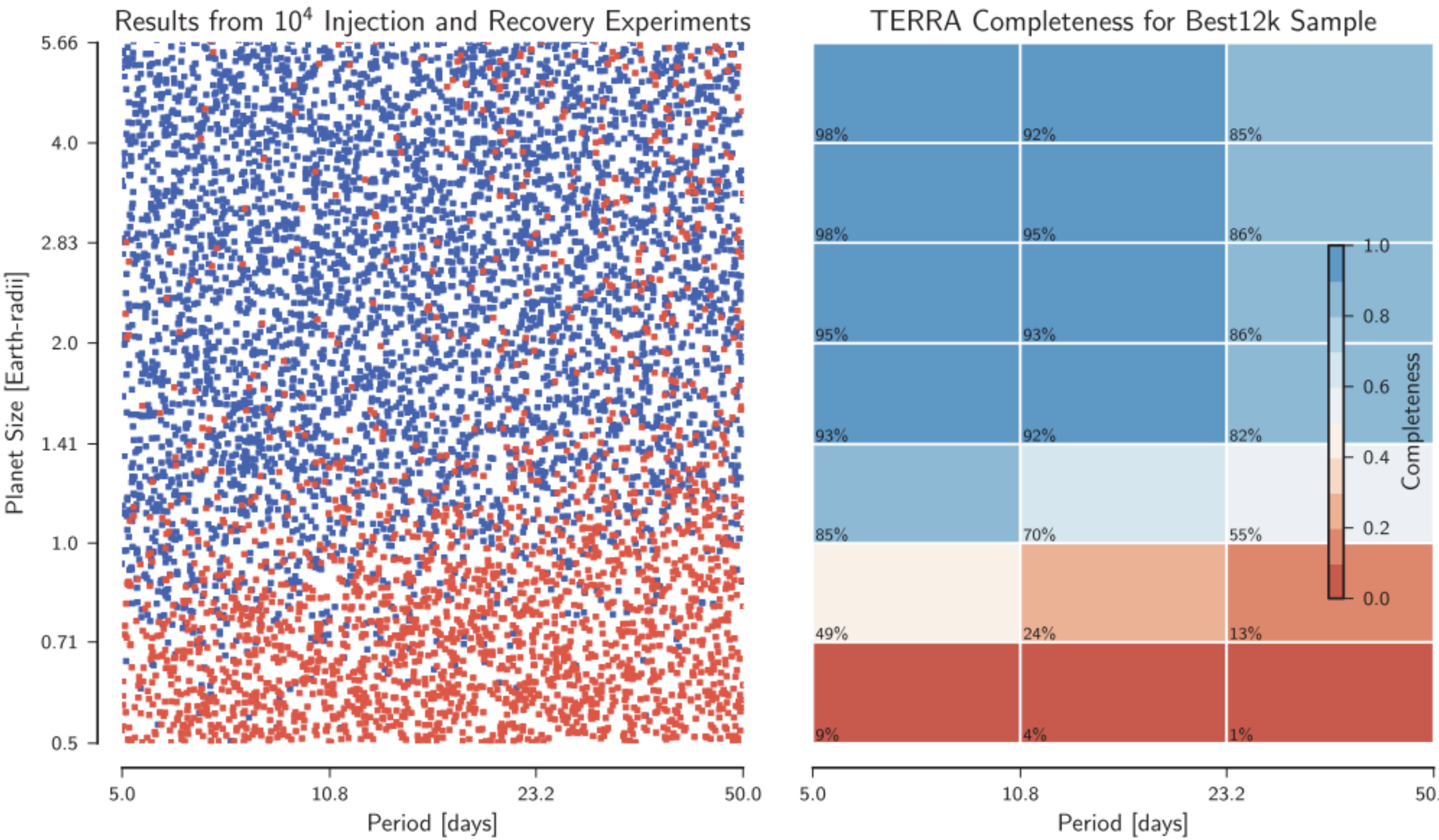


Burke et al. 2015



Burke et al. 2015

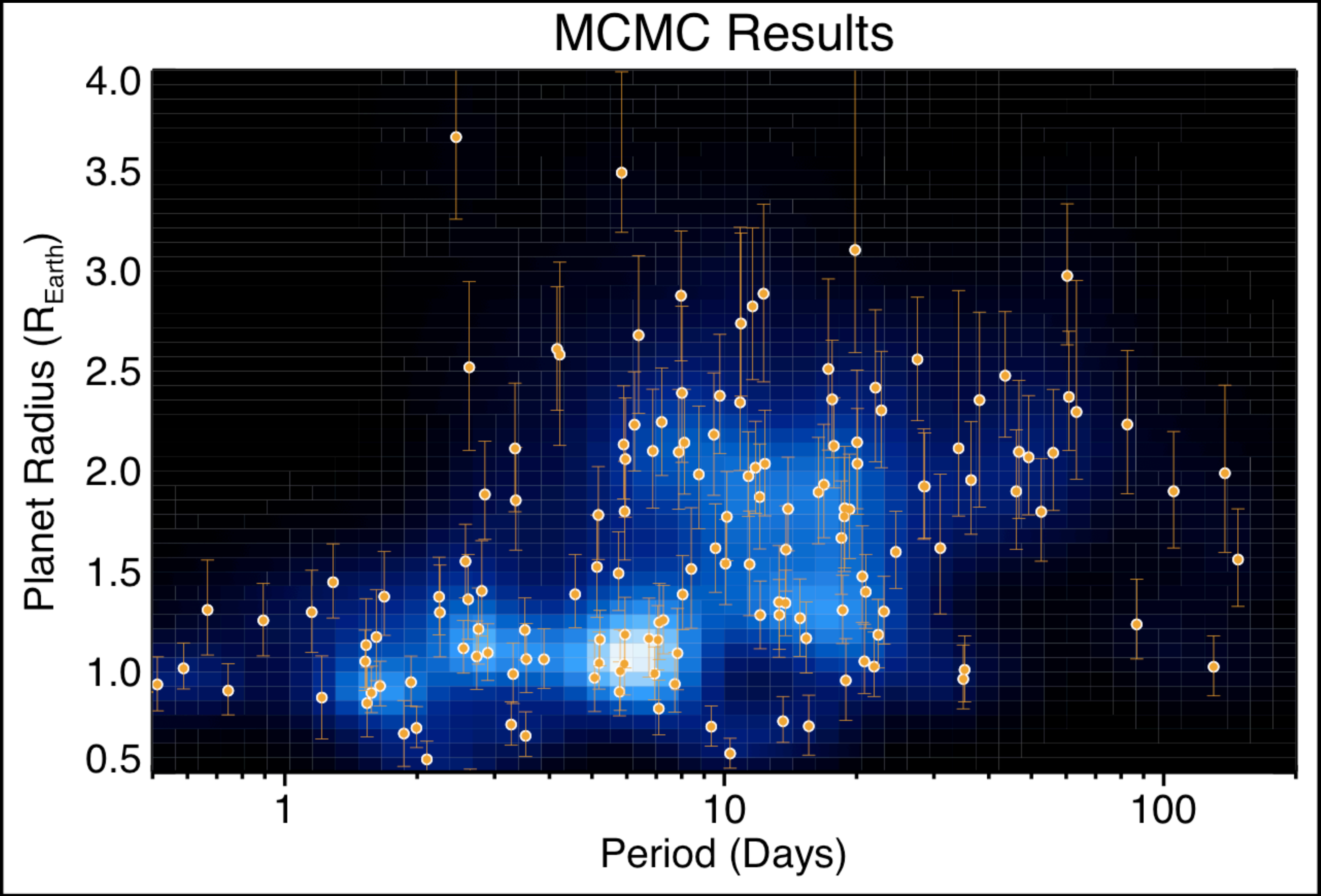
Another view of Completeness for Kepler's FGK Target Stars



Petigura et al. 2013, ApJ, 770, 69

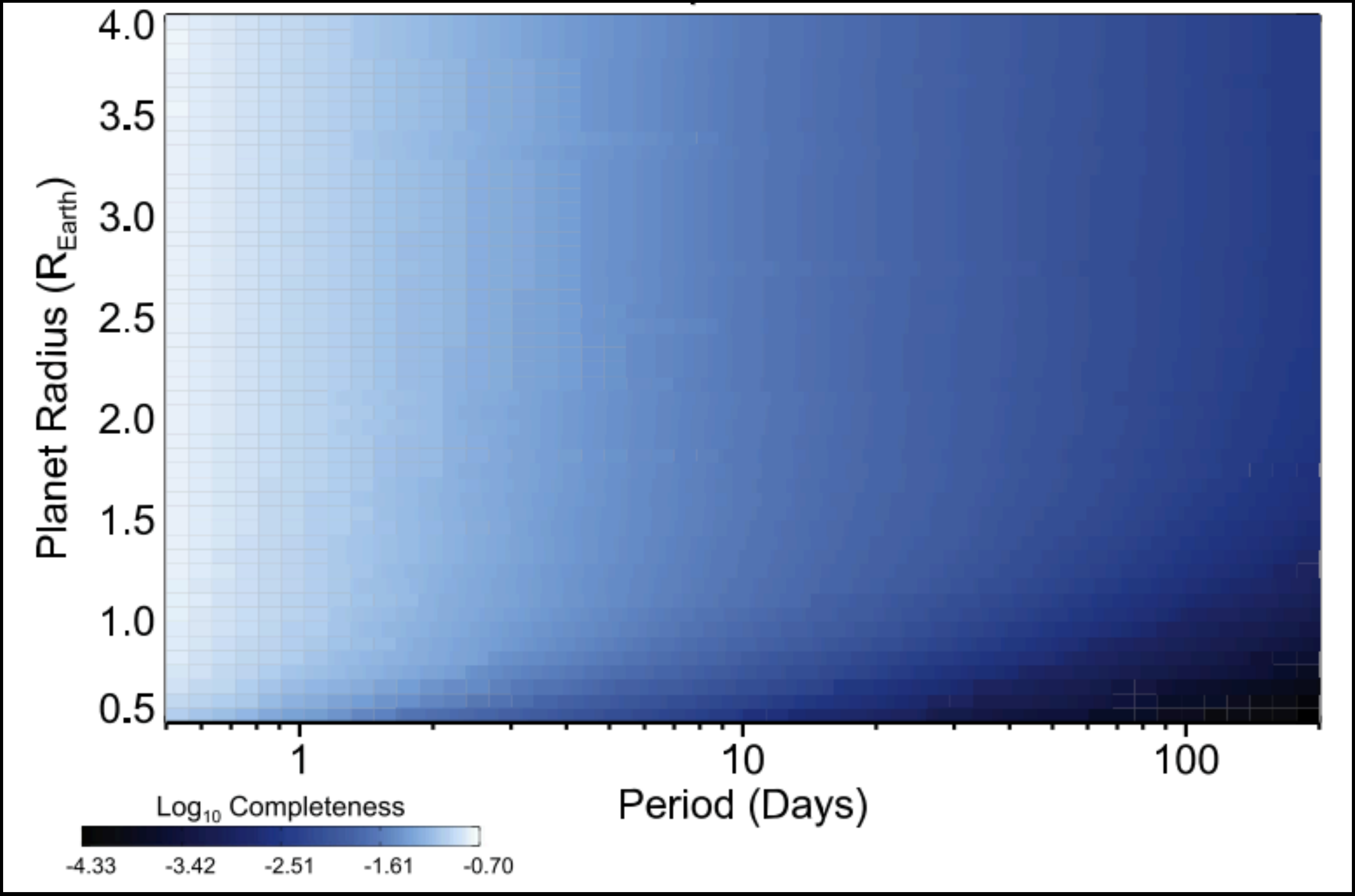
How common are planetary systems orbiting M dwarfs?

Smoothed Population of Planet Candidates



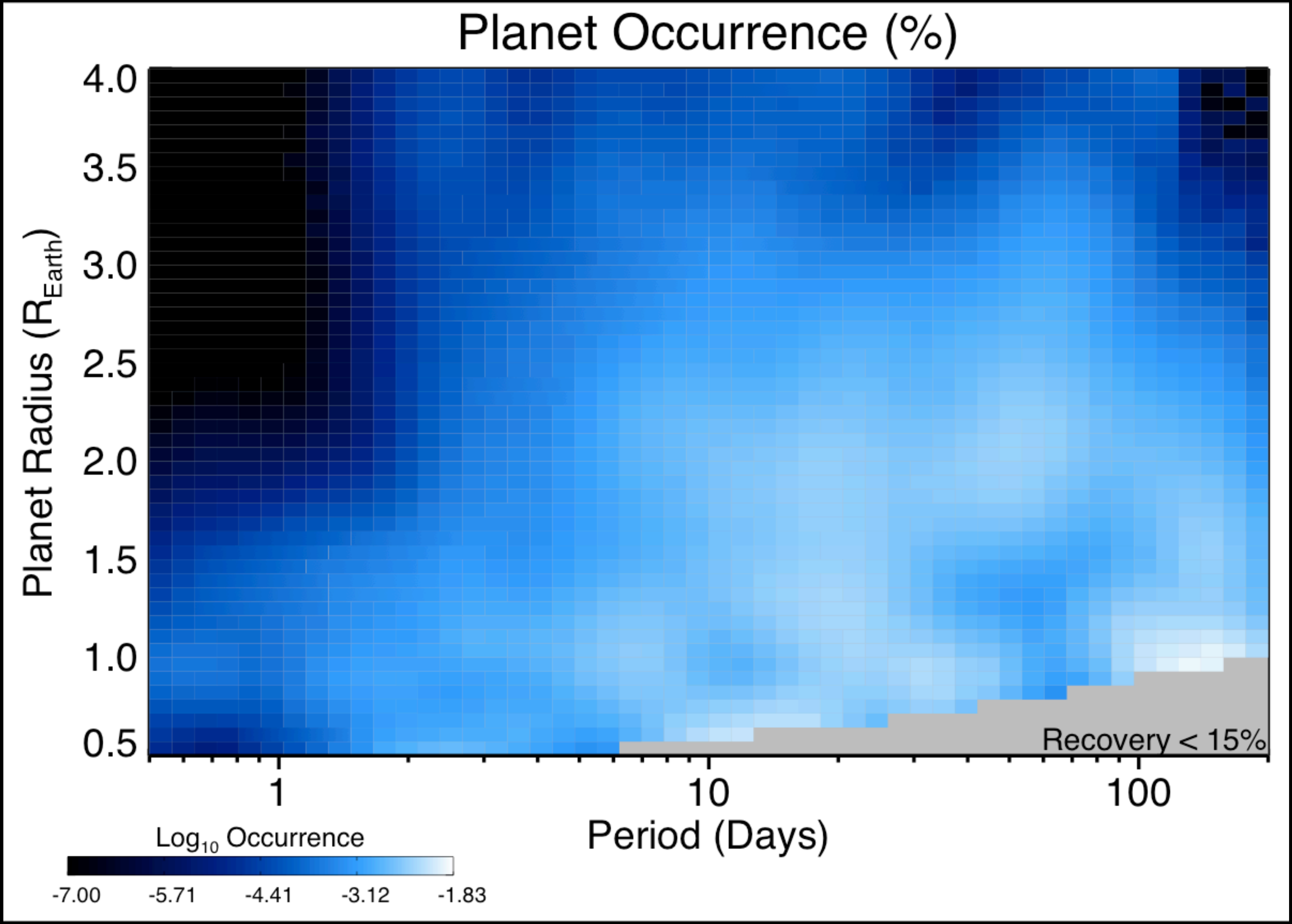
Dressing & Charbonneau 2015, ApJ, 807, 45

Full Search Completeness (Includes Sensitivity & Transit Probability)



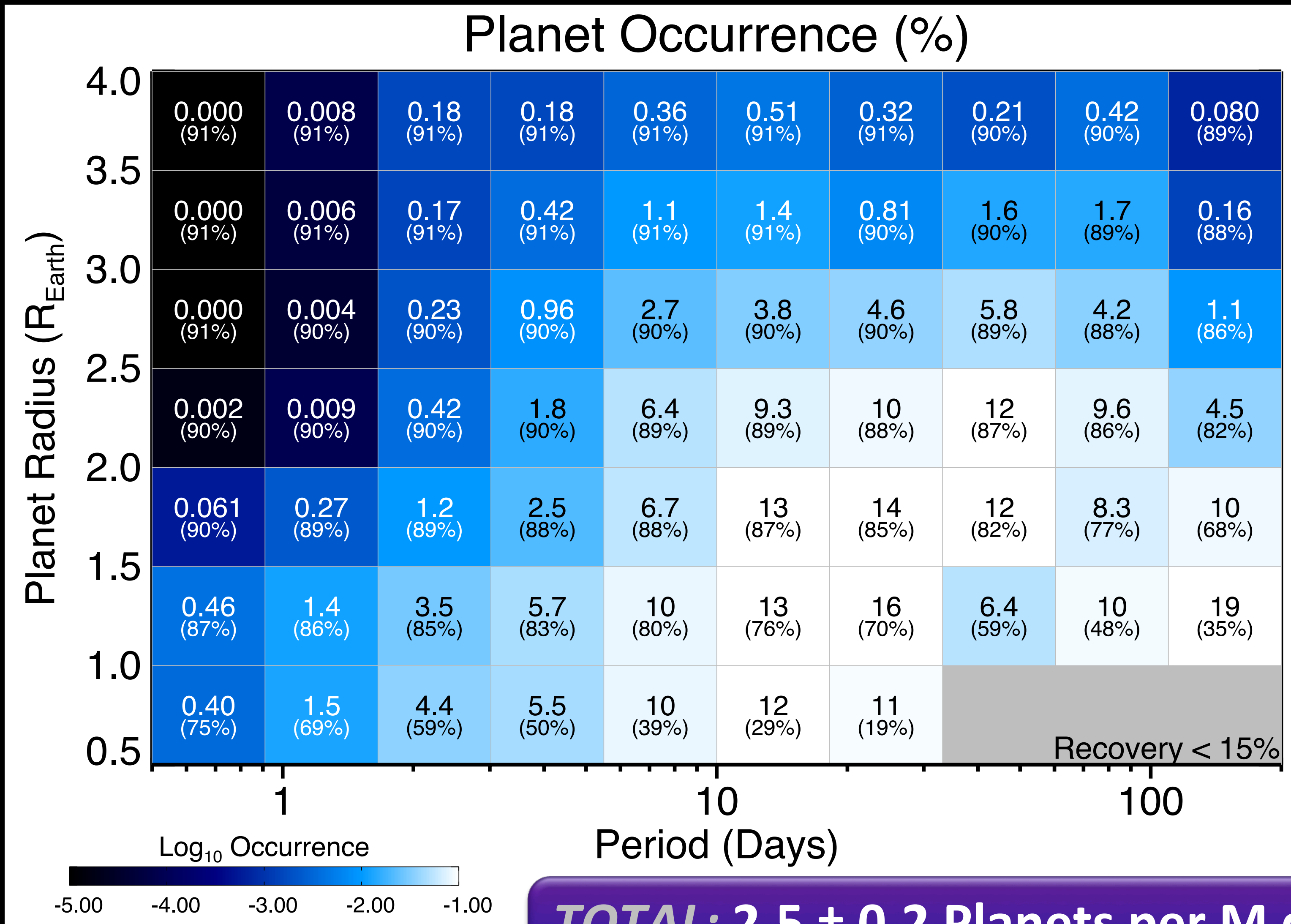
Dressing & Charbonneau 2015, ApJ, 807, 45

Smaller Planets Are More Prevalent



Dressing & Charbonneau 2015, ApJ, 807, 45

Small, Long-Period Planets are Common

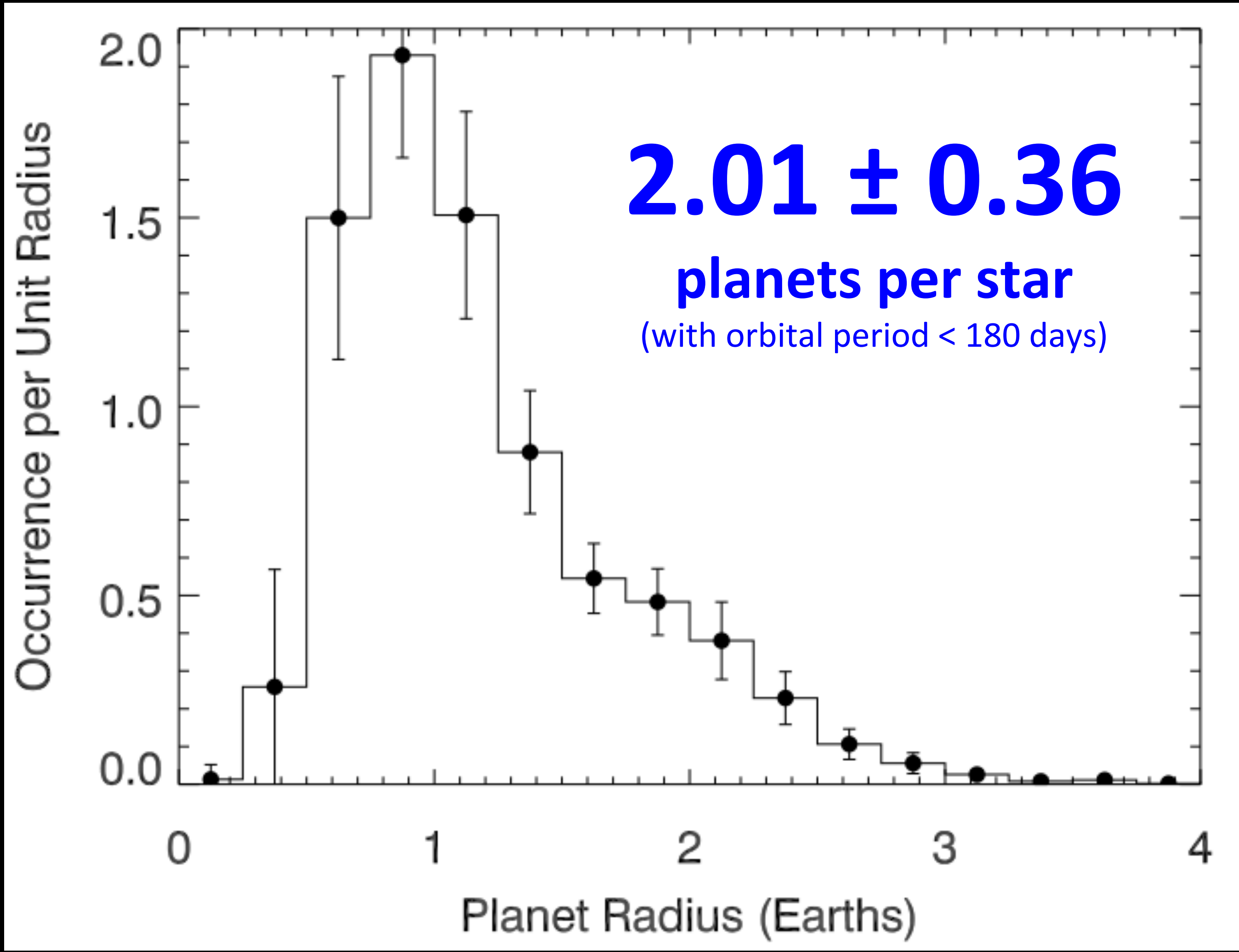


TOTAL: **2.5 ± 0.2 Planets per M dwarf**

with P<200 days, R_p = 1-4 REarth

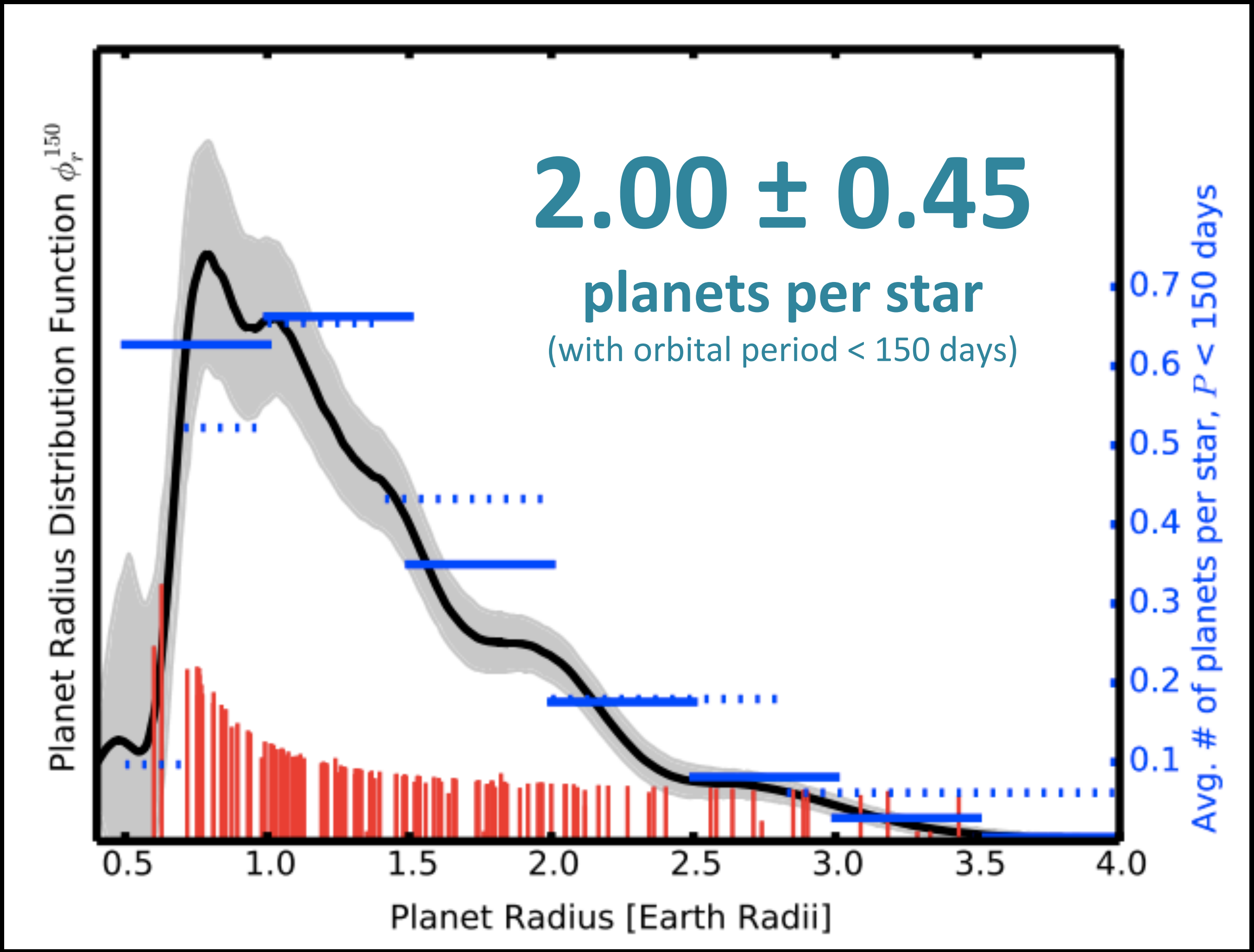
Dressing & Charbonneau 2015, ApJ, 807, 45

Further Evidence for the Commonality of M Dwarf Planetary Systems



Gaidos et al. 2014, MNRAS, 443, 2561

Further Evidence for the Commonality of M Dwarf Planetary Systems

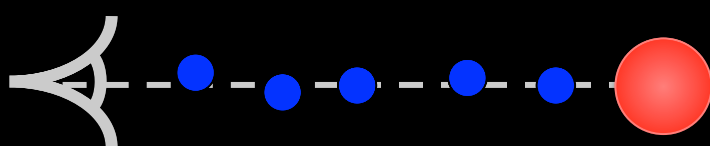


Morton & Swift 2014, ApJ, 791, 10

How flat are exoplanetary systems?

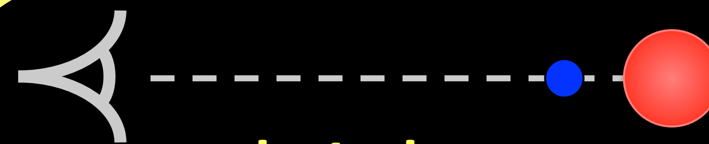
Evidence for Two Populations of M Dwarf Planetary Systems

45% of systems



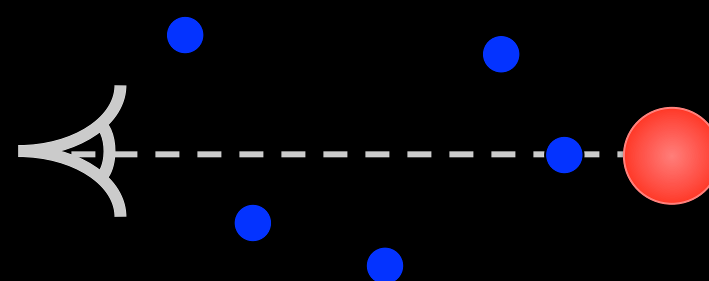
roughly **5 planets** with **coplanar** orbits

55% of systems



only 1 planet

or

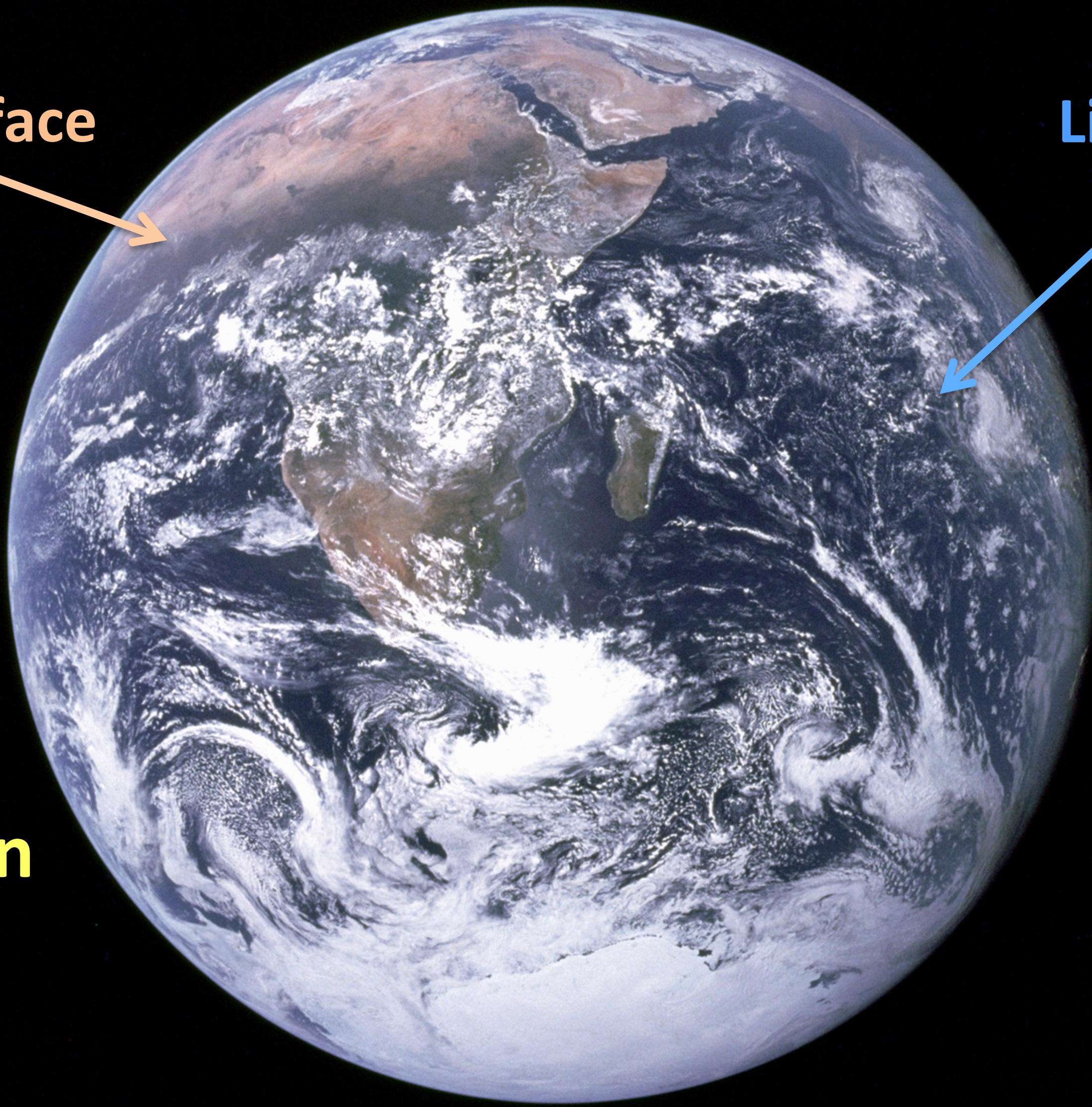


multiple planets with **high mutual inclinations**

Ballard & Johnson 2014, arXiv:1410.4192, submitted to *ApJ*

Are any of these planets habitable?

Rocky Surface



Liquid Water

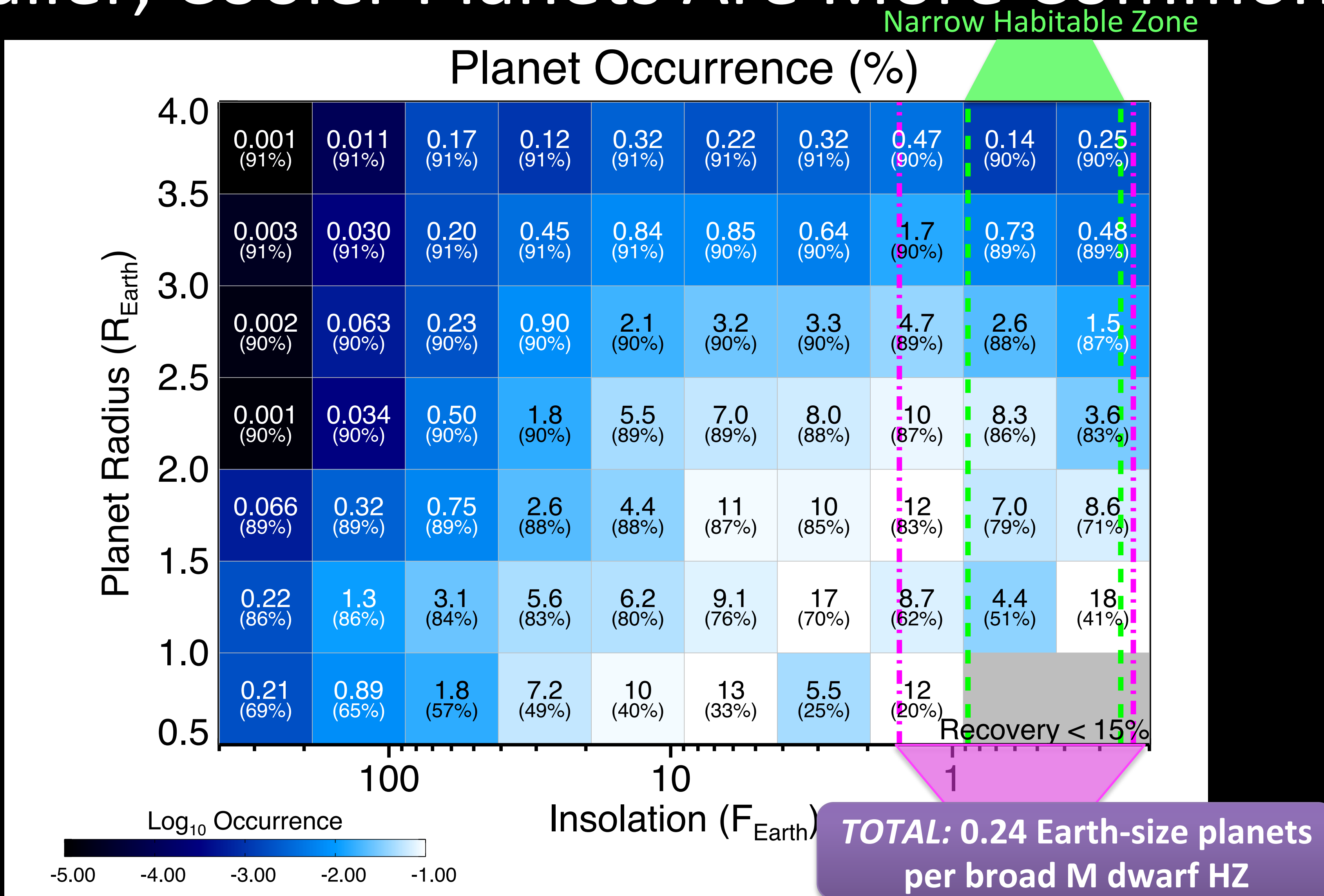
Is there an upper limit on the size of a rocky planet?

Look for planets **smaller than 1.7 Earth Radii**

Look for planets with **temperate climates**

Image credit: NASA/Apollo 17

Smaller, Cooler Planets Are More Common



Dressing & Charbonneau 2015, ApJ, 807, 45


Nearest HZ Earth 2.6 pc
Transiting HZ Earth 11 pc
Green

M Dwarf Planetary Systems are Common

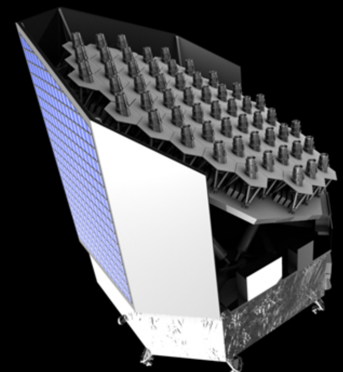
- *Per star:*
  - **0.56** (+0.06/-0.05) **Earth-size planets** with **P<50 days**
  - **0.46** (+0.07/-0.05) **super-Earths** with **P<50 days**
  - **2.5** (± 0.2) **small** (1-4 R_E) **planets** with **P<200 days**

- *Empirical Venus/Mars Habitable Zone:*
  - **0.24** (+0.18/-0.08) **Earth-size planets**
  - **0.21** (+0.11/-0.06) **super-Earths**
  - **11 pc** to nearest **transiting Earth-like planet**

What's Next?

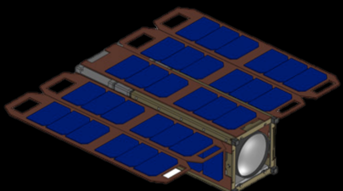
K2

TESS



PLATO

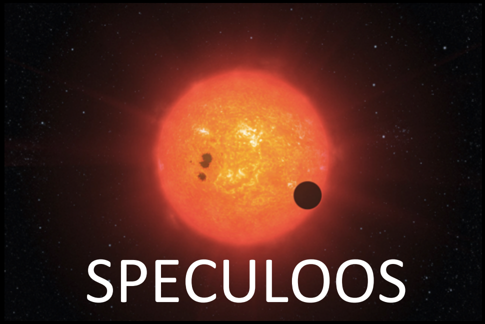
CHEOPS



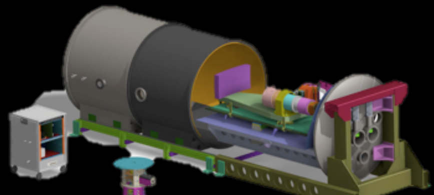
ExoplanetSat

Current & Future Missions Targeting Planets Orbiting Small Stars

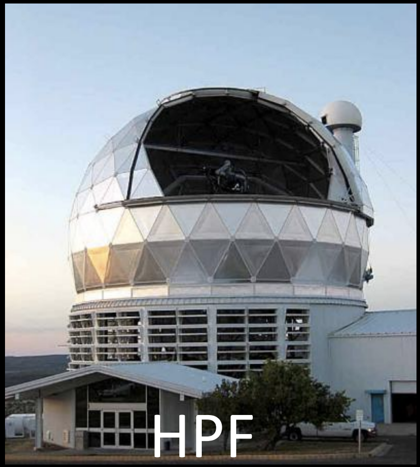
CARMENES



SPECULOOS



SPIRou

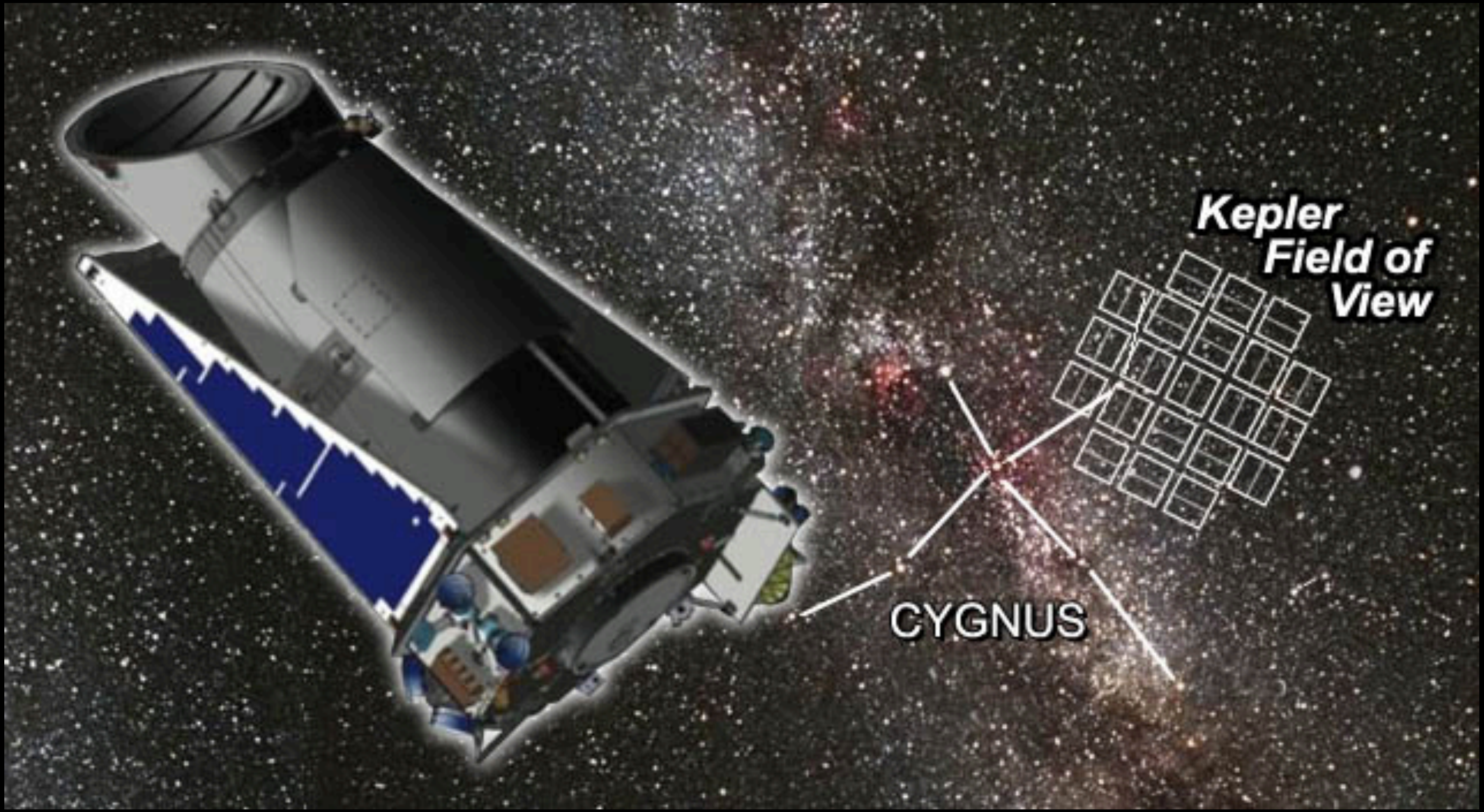


HPF

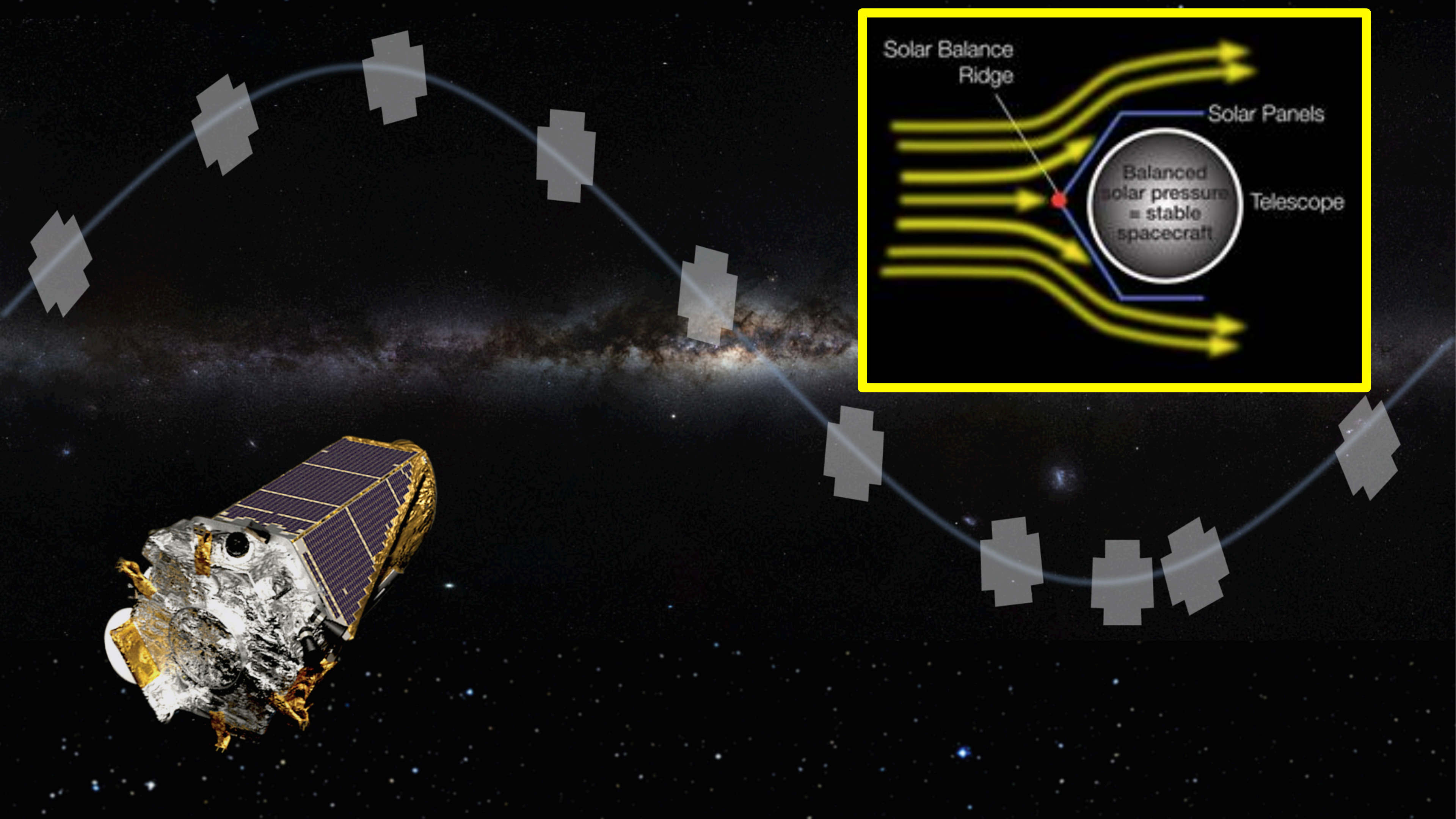
MEarth & MEarth-South

ExTrA

Kepler Stared at One Field



K2 Will Look at Multiple Fields

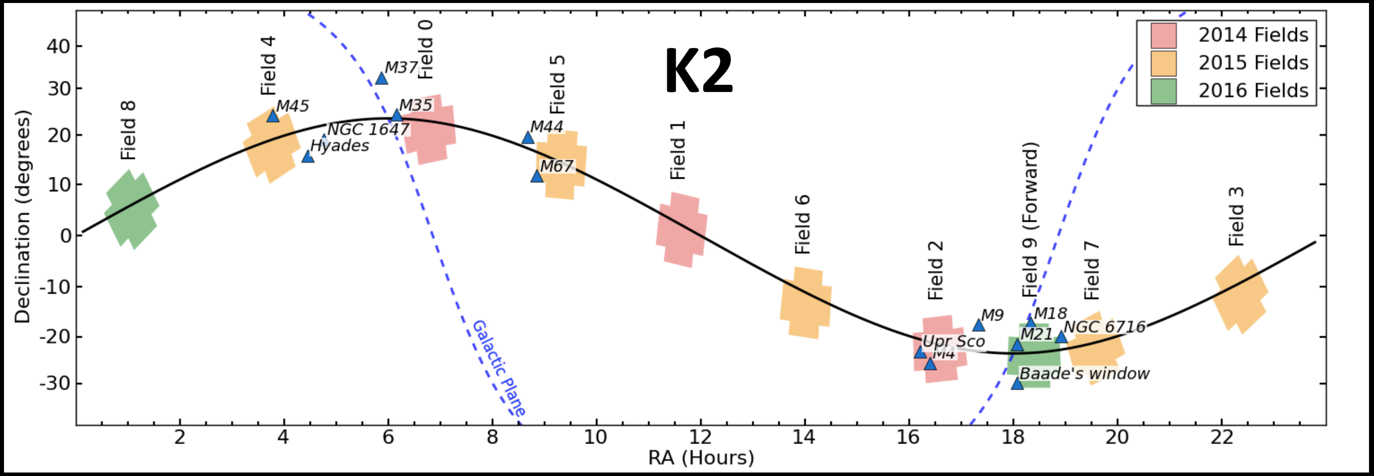


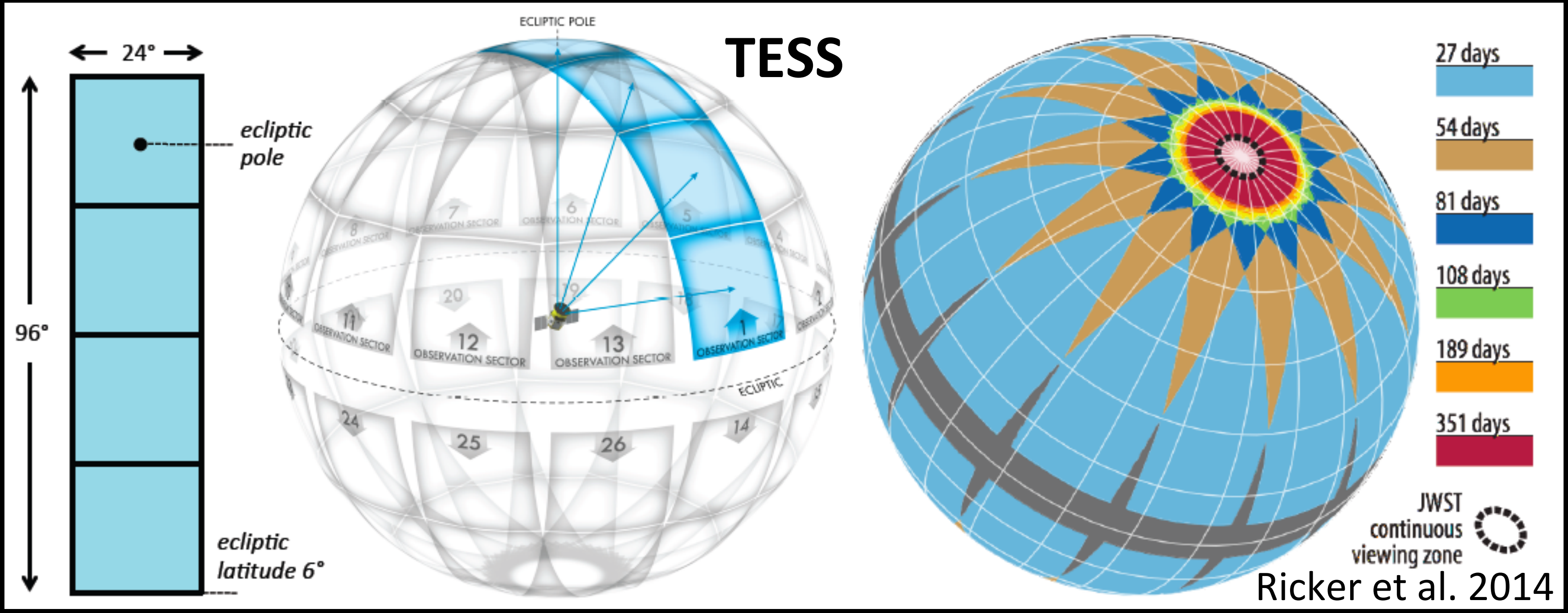
The Transiting Exoplanet Survey Satellite

- Launch in 2017
- Two-year survey
- 90% of sky

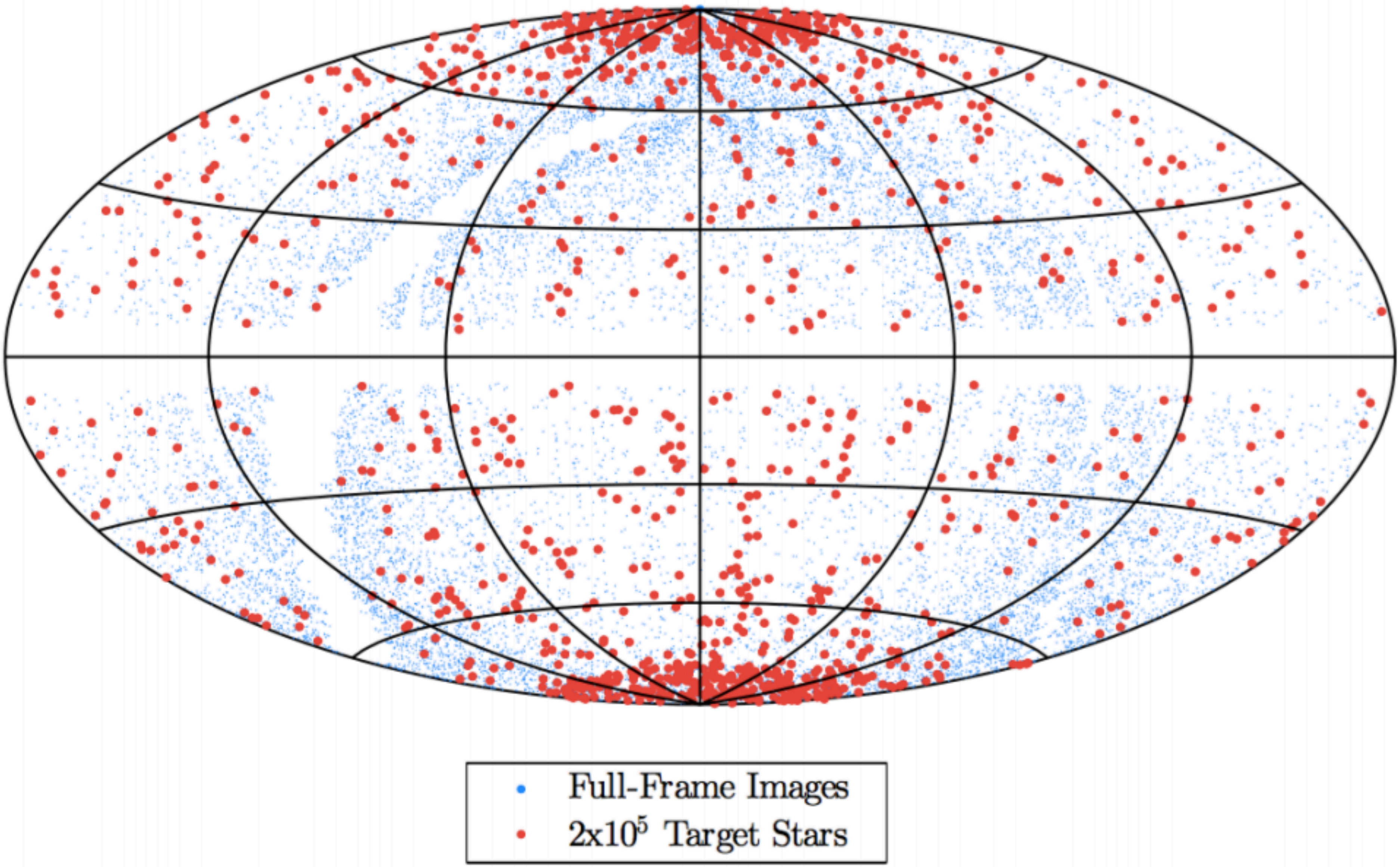
Hundreds of Earth-size planets & super Earths!

K2 & TESS Have Complementary Sky Coverage



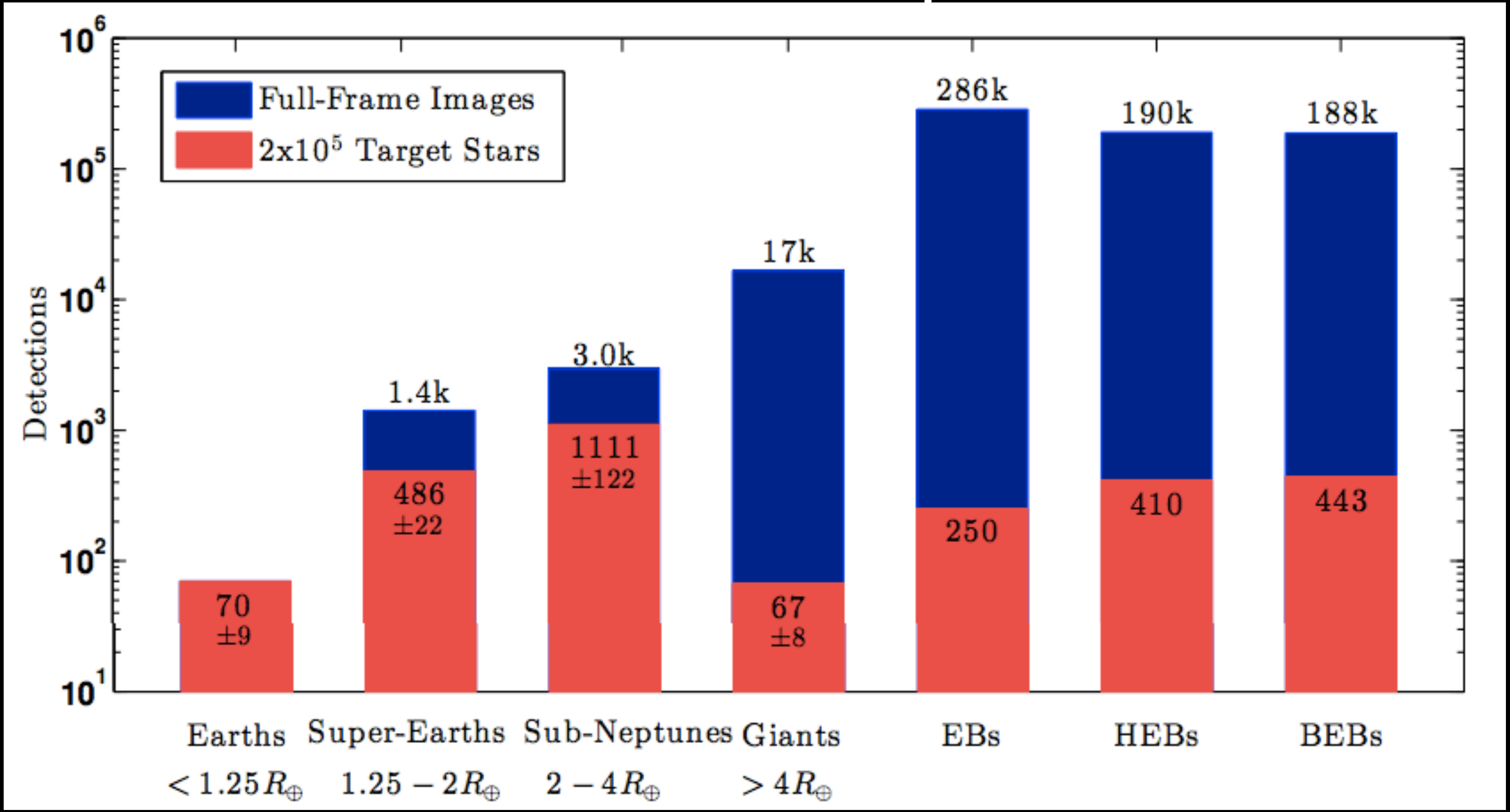


Simulation of TESS Planet Detections



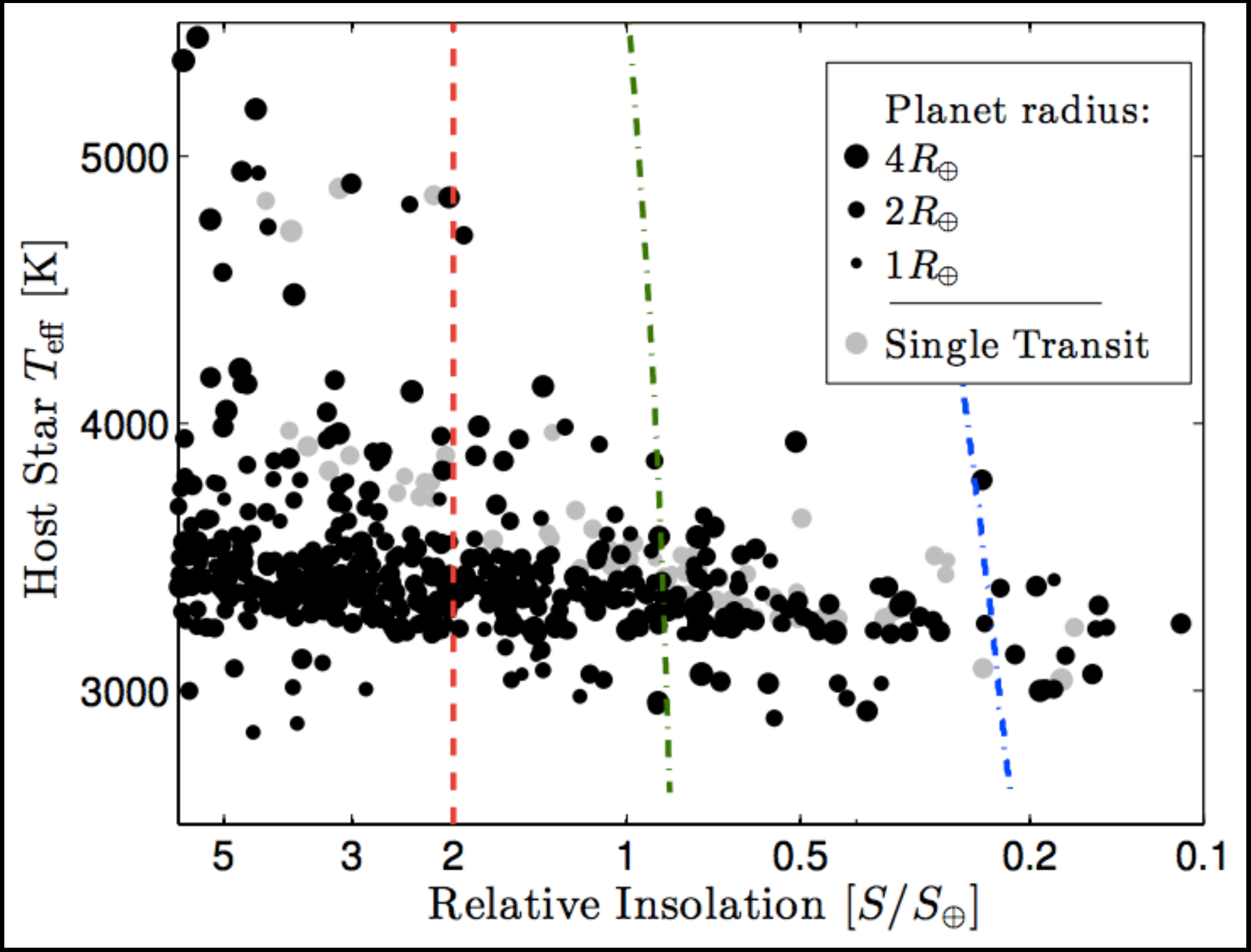
Sullivan et al. 2015, accepted to ApJ, arXiv: 1506.03845

TESS Will Find Dozens of Earth-size Planets and Hundreds of Super-Earths



Sullivan et al. 2015, accepted to ApJ, arXiv: 1506.03845

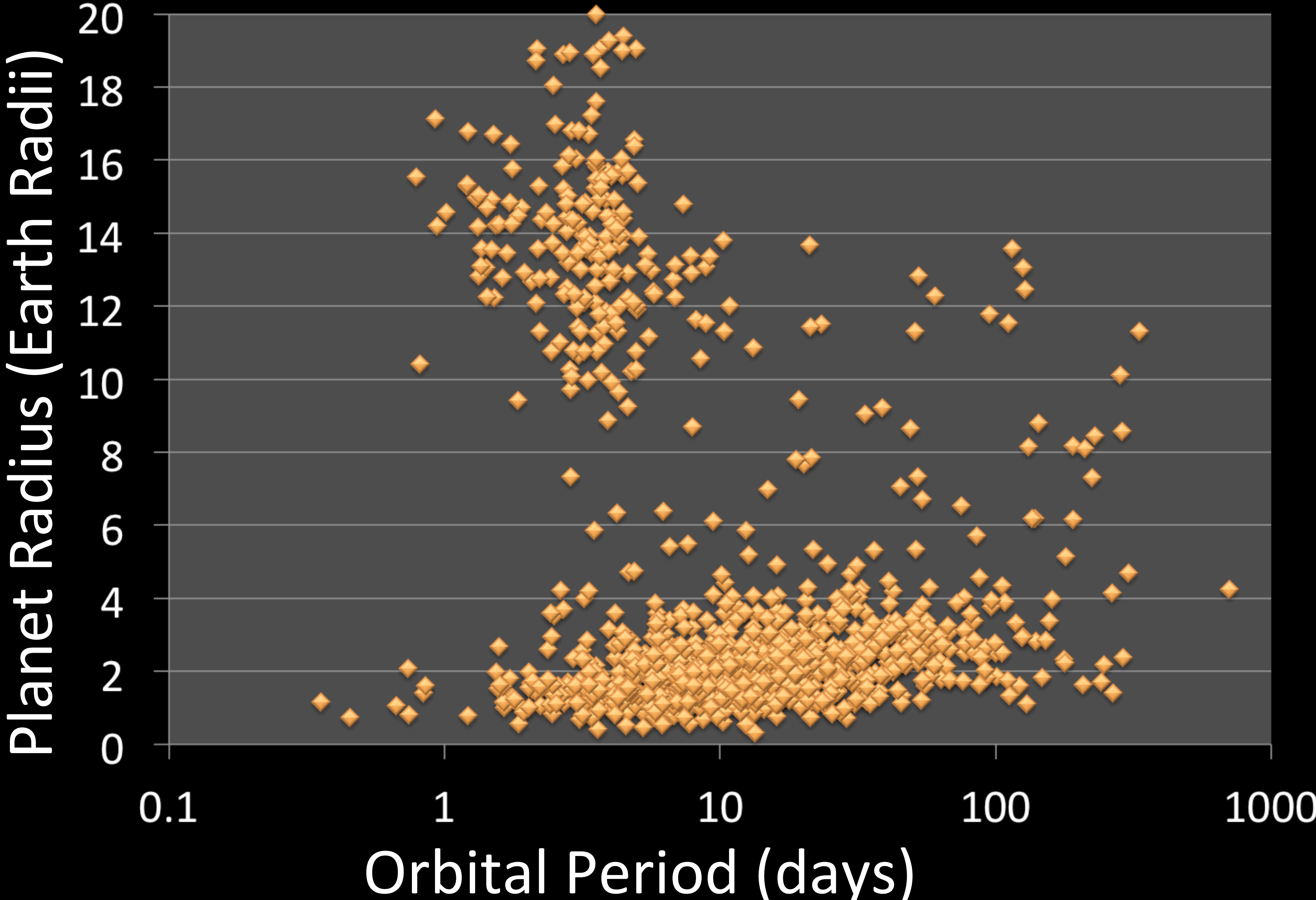
TESS Will Find Some Potentially Habitable Planets Orbiting Cool Stars



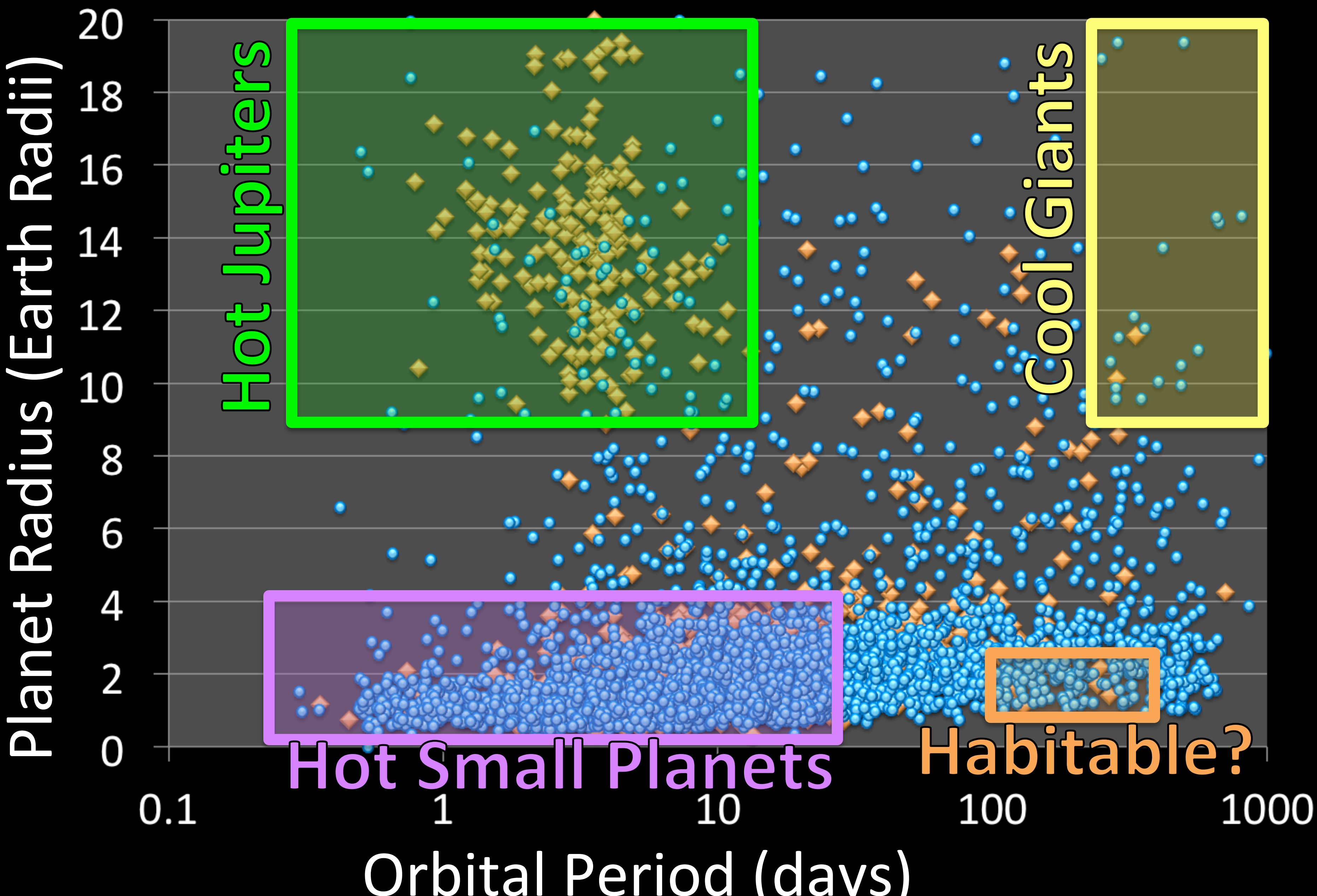
Sullivan et al. 2015, accepted to ApJ, arXiv: 1506.03845

PUTTING EVERYTHING TOGETHER

Confirmed Transiting Planets



Confirmed Transiting Planets & Kepler Candidates



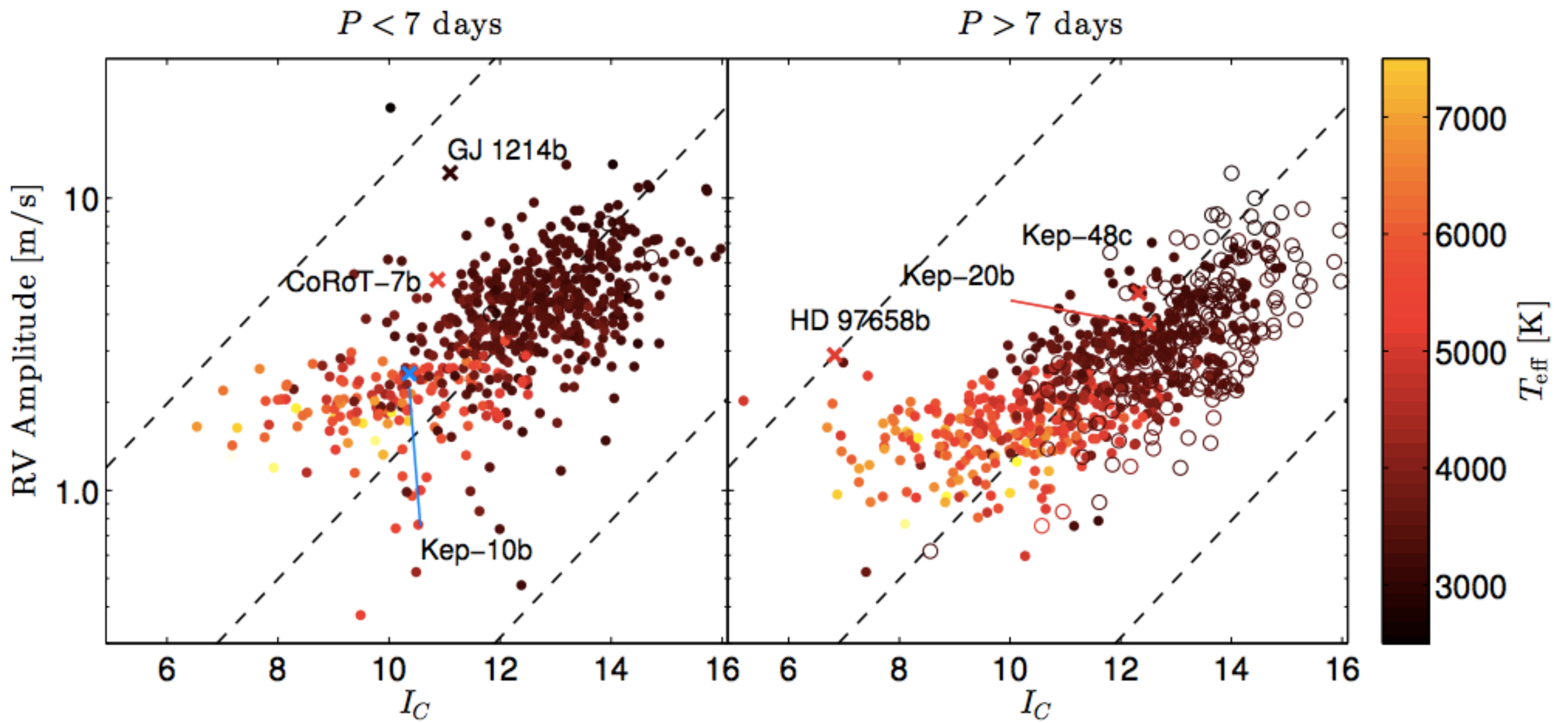
What we've learned so far

- Exoplanetary **systems** are **diverse**
- **Many stars harbor close-in planets** with high transit probabilities
- Transiting planets offer unique laboratories to investigate **atmospheric compositions** and **bulk densities**

The future is **bright.**

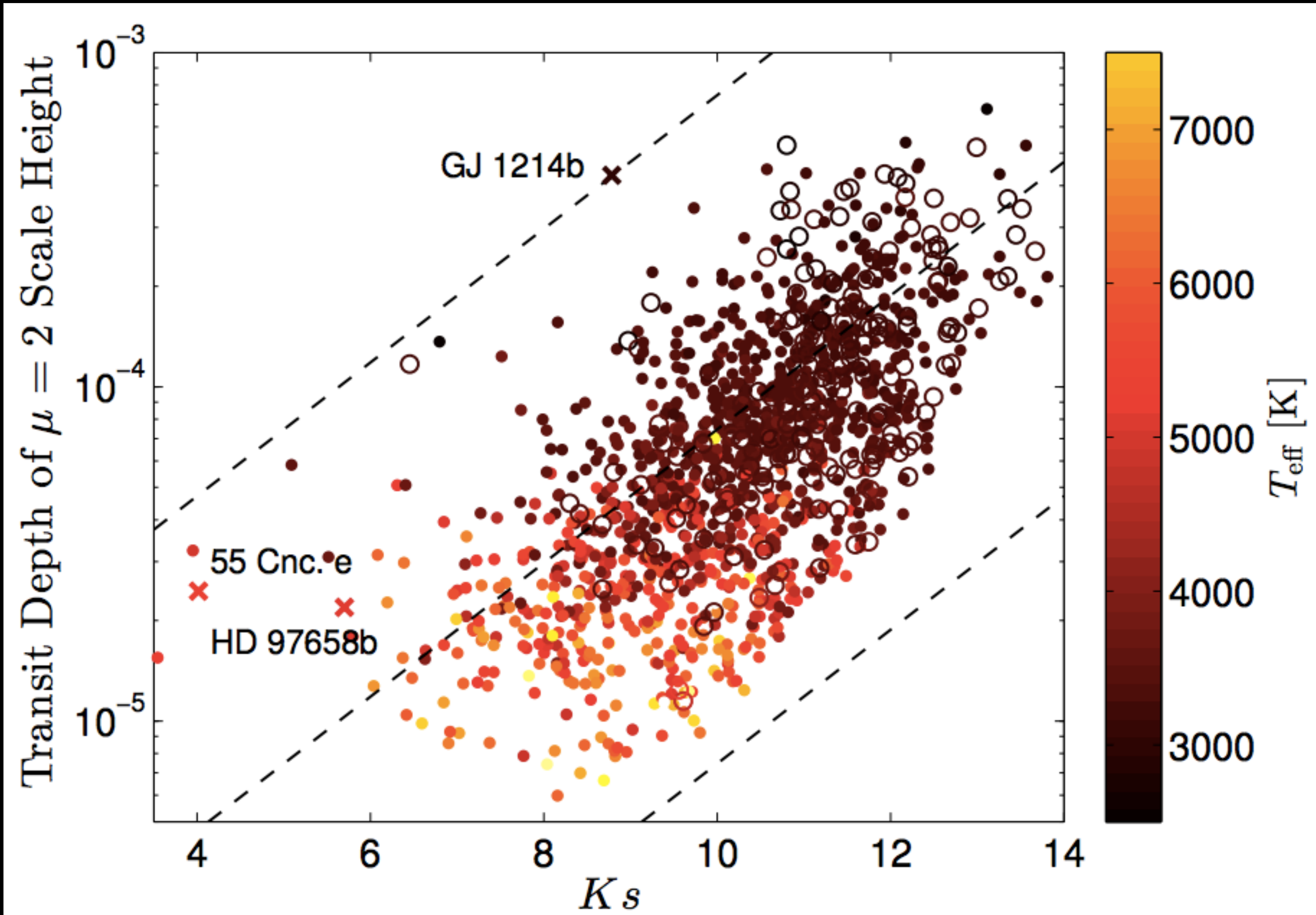
Additional Slides

TESS Detections will be Well-Suited for Mass Measurement

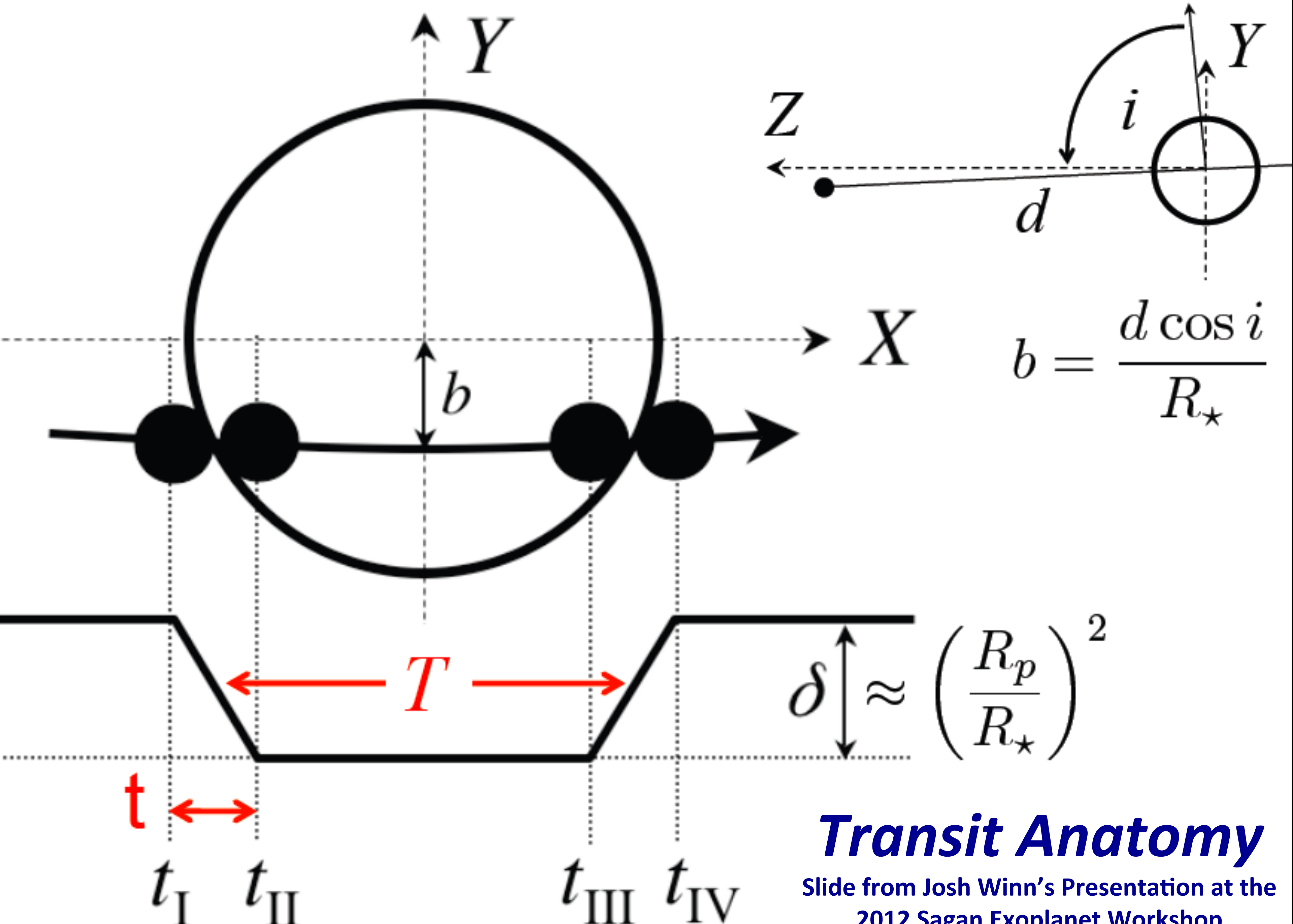


Sullivan et al. 2015, accepted to ApJ, arXiv: 1506.03845

Potential for Studying the Atmospheres of TESS Planets

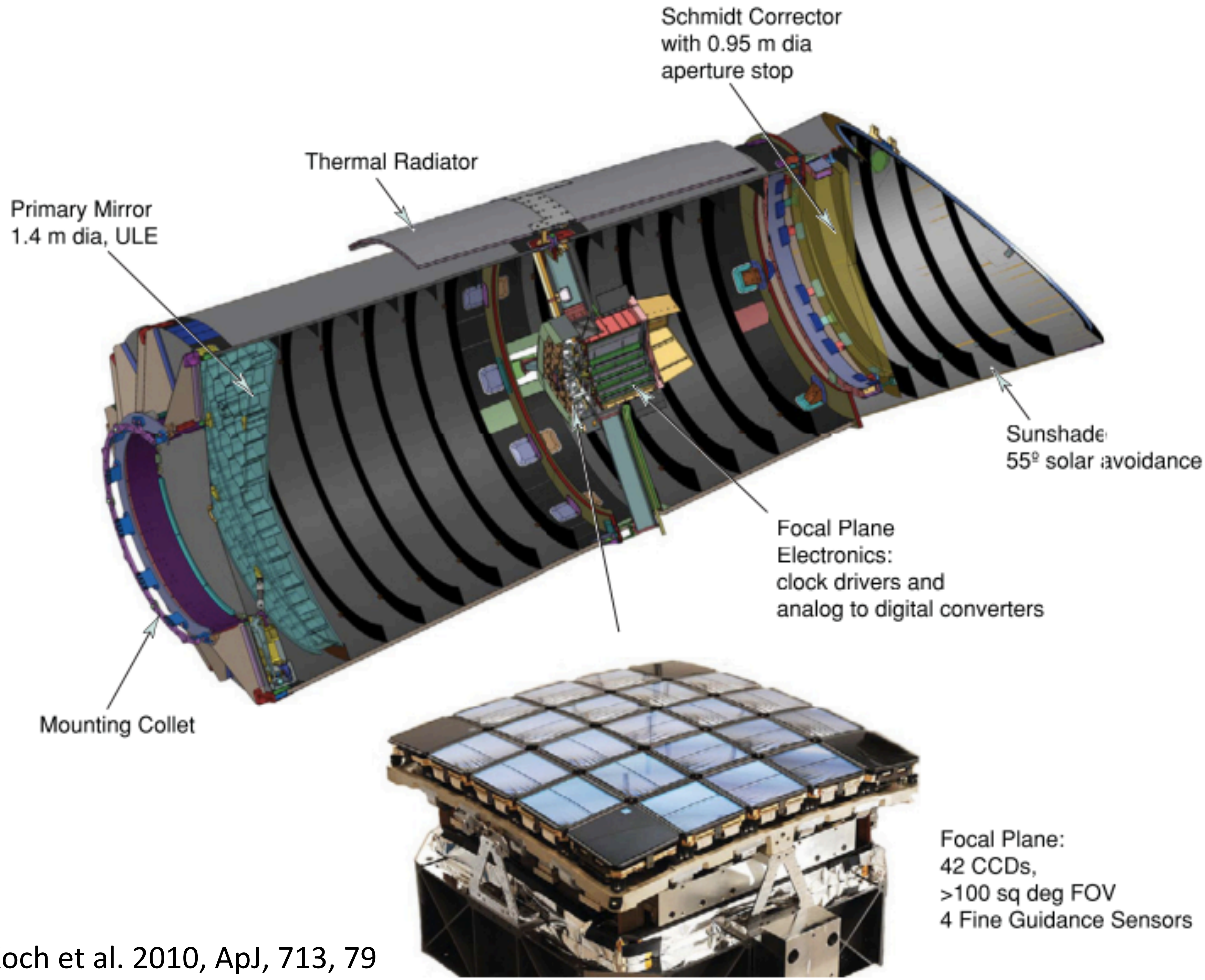


Sullivan et al. 2015, accepted to ApJ, arXiv: 1506.03845



Transit Anatomy

Slide from Josh Winn's Presentation at the 2012 Sagan Exoplanet Workshop



Koch et al. 2010, ApJ, 713, 79

Table 1
Kepler Mission Characteristics

Koch et al. 2010, ApJ, 713, 79

Component	Value	Comment
Optics	Brashear & Tinsley	Manufacturers
Schmidt corrector	0.99 m dia./0.95 m dia. stop	Corning Fused silica
Primary mirror	F1 1.40 m dia., silver coated	Corning ULE®
Central obscuration	23.03%	Due to focal plane and spider
FFLs	2°5 square	Sapphire
PRF	3.14–7.54 pixels, 95% encircled energy diameter	Depends on FOV location
Sunshade	55° sun avoidance	From center of FOV
CCDs	e2v Technologies	Manufacturer
Format	1024 rows × 2200 columns	Two outputs per CCD
Pixel size	27 μm square	Four phases
Plate scale	3.98 arcsec pixel^{-1}	
Full well	1.05×10^6 electrons, typical	Set by parallel clock voltage
Dynamic range	$7 \leqslant Kp \leqslant 17$	Meets photometric precision
Operating temperature	−85 °C	10 mK stability
Controller	Ball Aerospace	Design and manufacturer
Channels	84	Multiplexed into 20 ADCs on five electronic board pairs
CCD integration time	6.02 s	Selectable 2.5–8 s
CCD readout time	0.52 s	Fixed
LC period	1765.80 s	270 integrations + reads
SC period	58.86 s	9 integrations + reads
Maximum LC targets	170,000	Average 32 pixels/target
Maximum SC targets	512	Average 85 pixels/target
Timing accuracy	50 ms	For asteroseismology and transit timing
System	Ball Aerospace	Design, integration, and test
Spectral response	423–897 nm	5% points
FOV	105 deg^2 <10% vignetted	115 deg^2 of non-contiguous active silicon
Pointing jitter	3 mas per 15 minutes	1σ per axis
CDPP (total noise)	20 ppm in 6.5 hr for >90% of FOV	$V = 12$ solar-like star including 10 ppm for stellar variability
Data downlink period	31-day average	<1 day observing gap
Mission length	3.5 years	Baseline. May be extended
Orbital period	372 days by year 3.5	Earth-trailing heliocentric

Table 1
Detector Properties Summary

Parameter	Where Measured	Minimum	Maximum	Median
Read noise (e^- read^{-1})	Flight	81	307 [149][a]	95
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Gain (e^- DN^{-1})	Ground	94	120	112
Saturation (Kepler Mag)[b]	Flight	11.6	10.3	11.3
PRNU[c] (%)	Ground	0.82	1.20	0.96
LDE undershoot (%)	Flight	0.08	1.92	0.34

THE ASTROPHYSICAL JOURNAL LETTERS, 713:L92–L96, 2010 April 20

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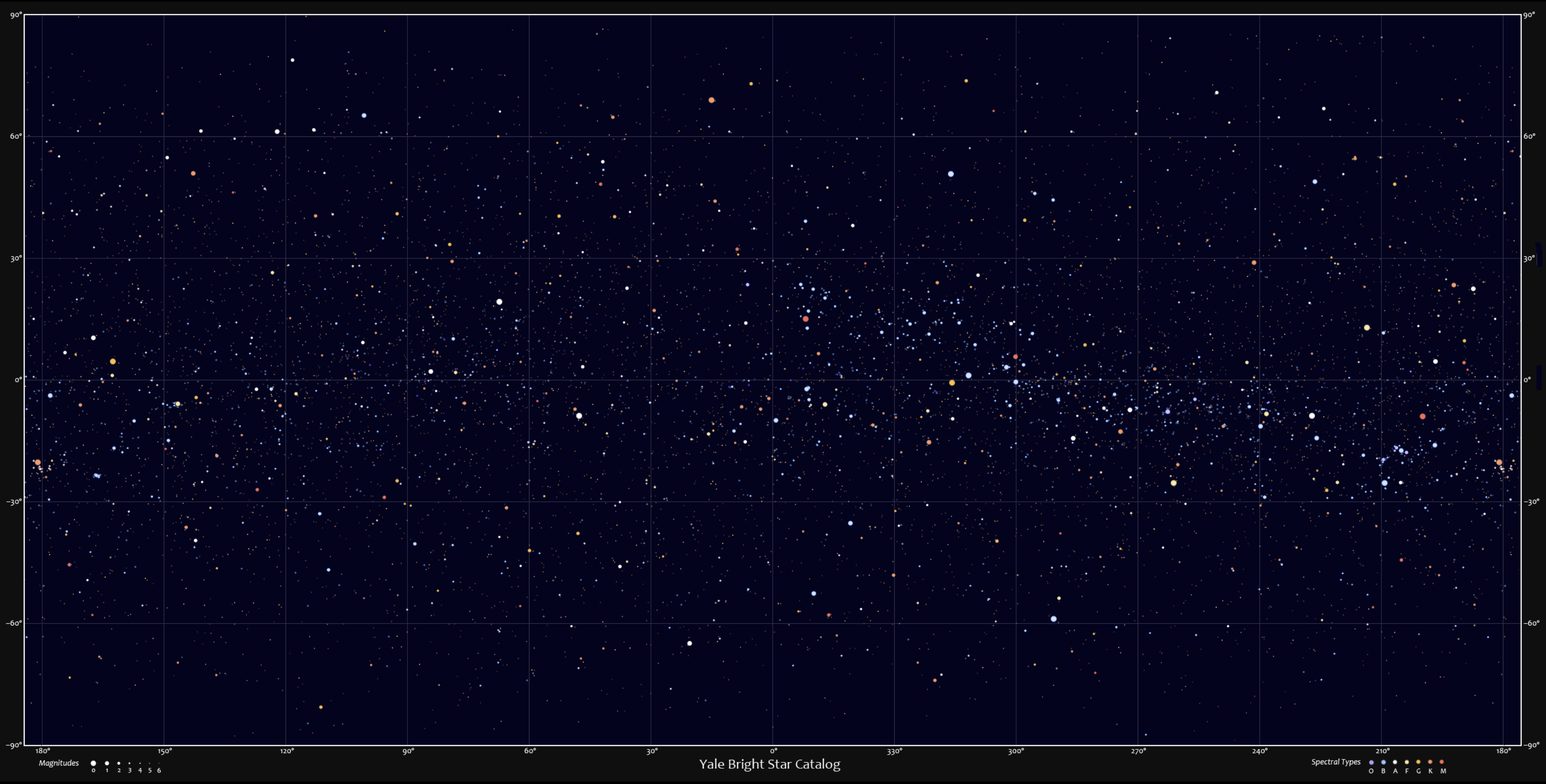
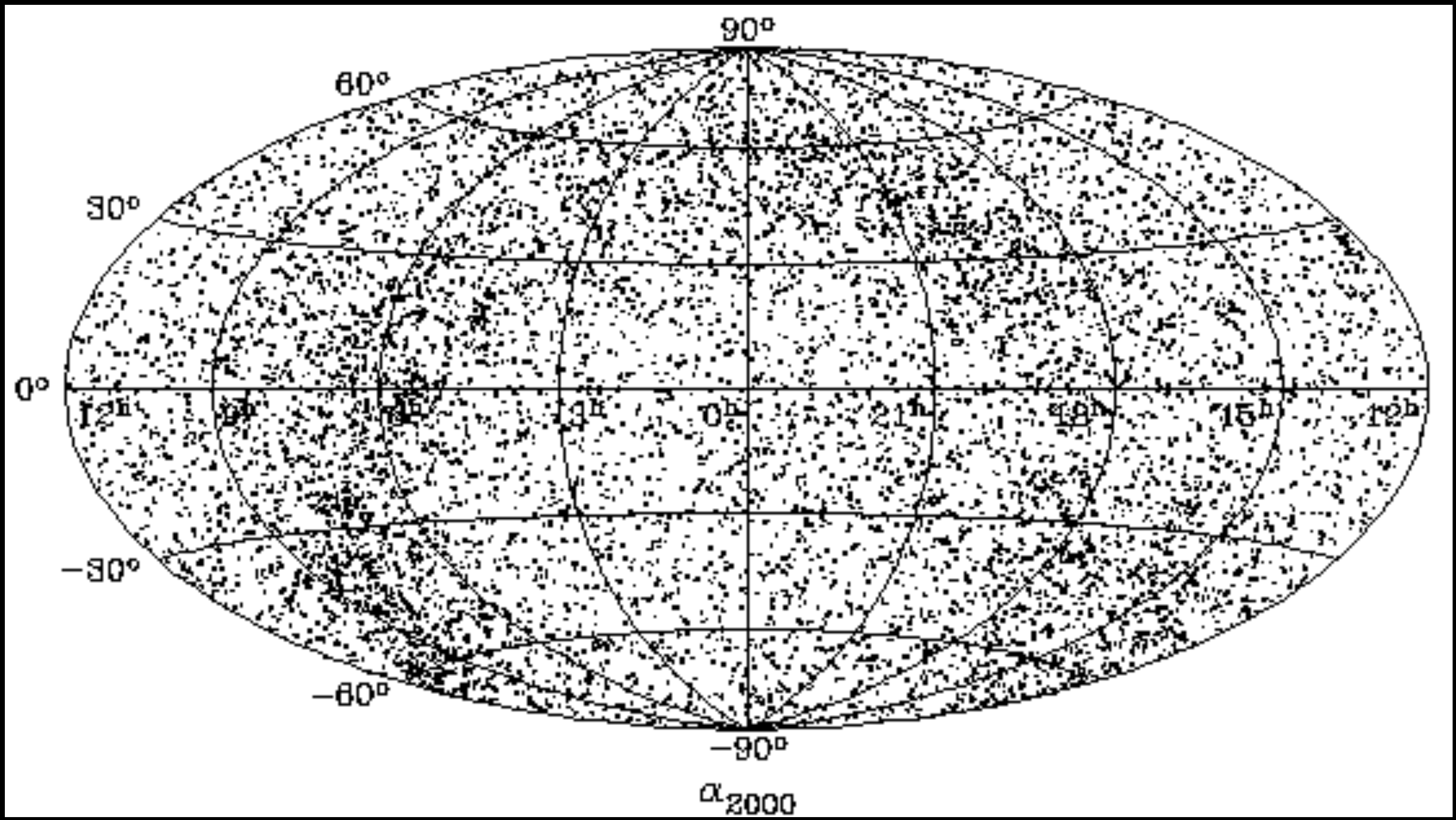
Caldwell et al. 2010, ApJL, 713, 92

Yale Bright Star Catalog



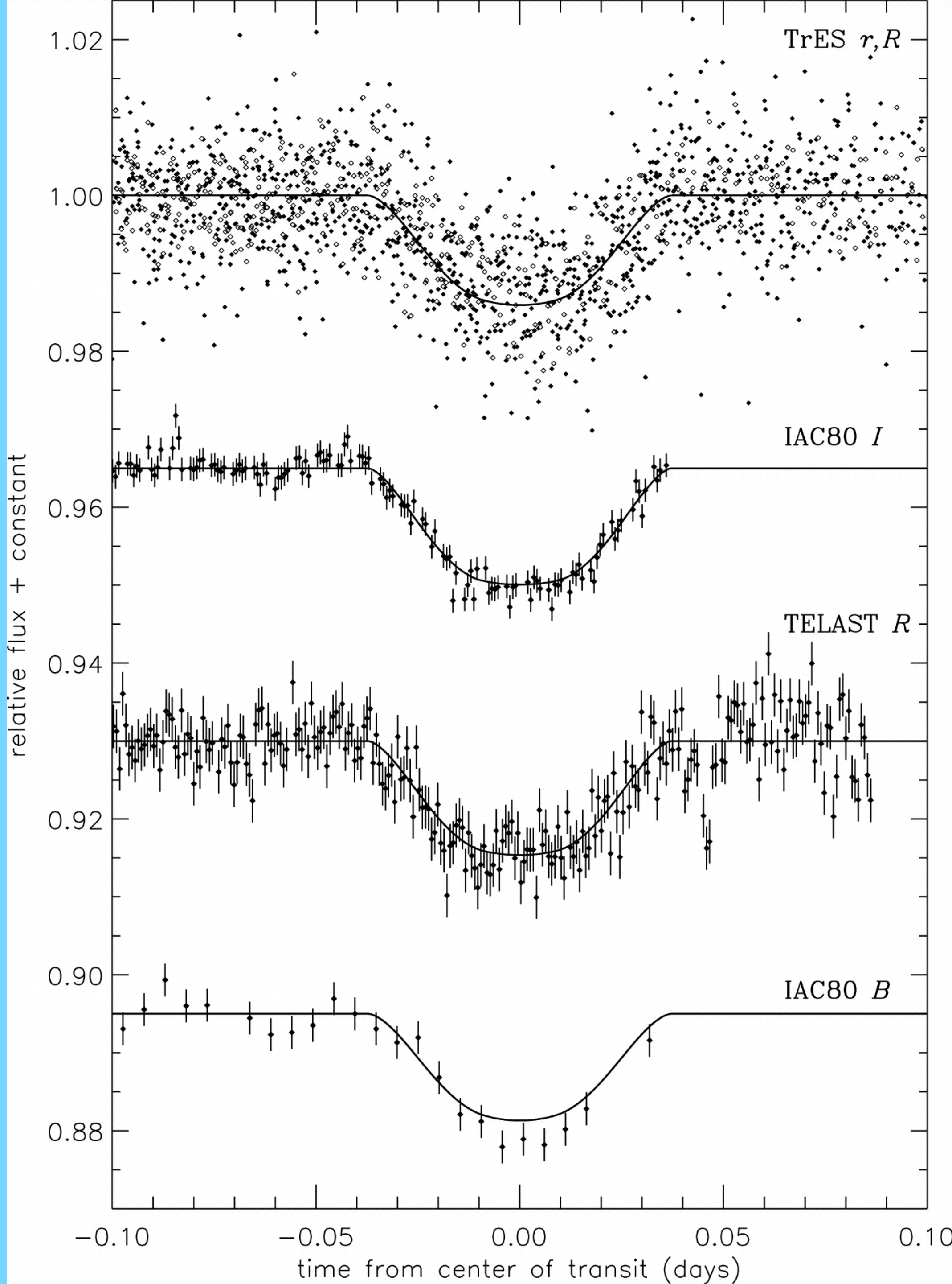
Yale Bright Star Catalog



TrES-2b

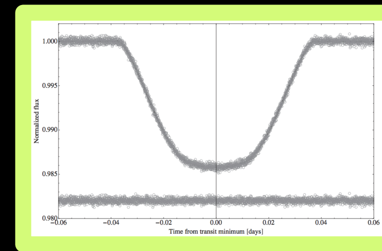
Light Curves from Discovery Paper

O'Donovan et al. 2006, ApJ, 651, 61



Kepler Light Curve (Short Cadence Data)

Kipping & Bakos 2011, ApJ, 733, 36



the Star

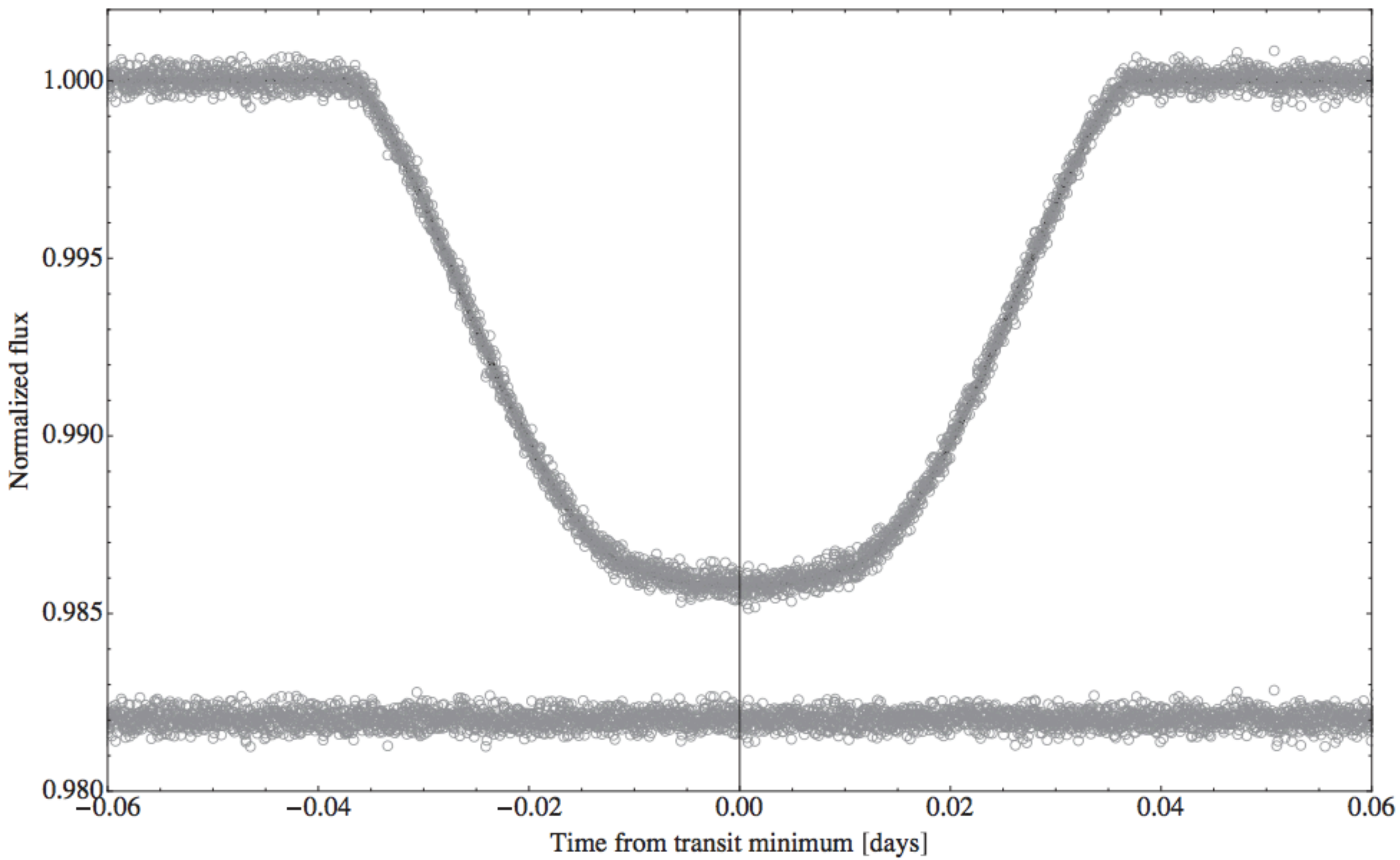
V = 11.4
Mass = 0.98 $R_\odot$
Radius = 1.0 $M_\odot$
Teff = 5850 K

the Planet

Radius = 1.2 R_J
Mass = 1.2 M_J
P = 2.5 days

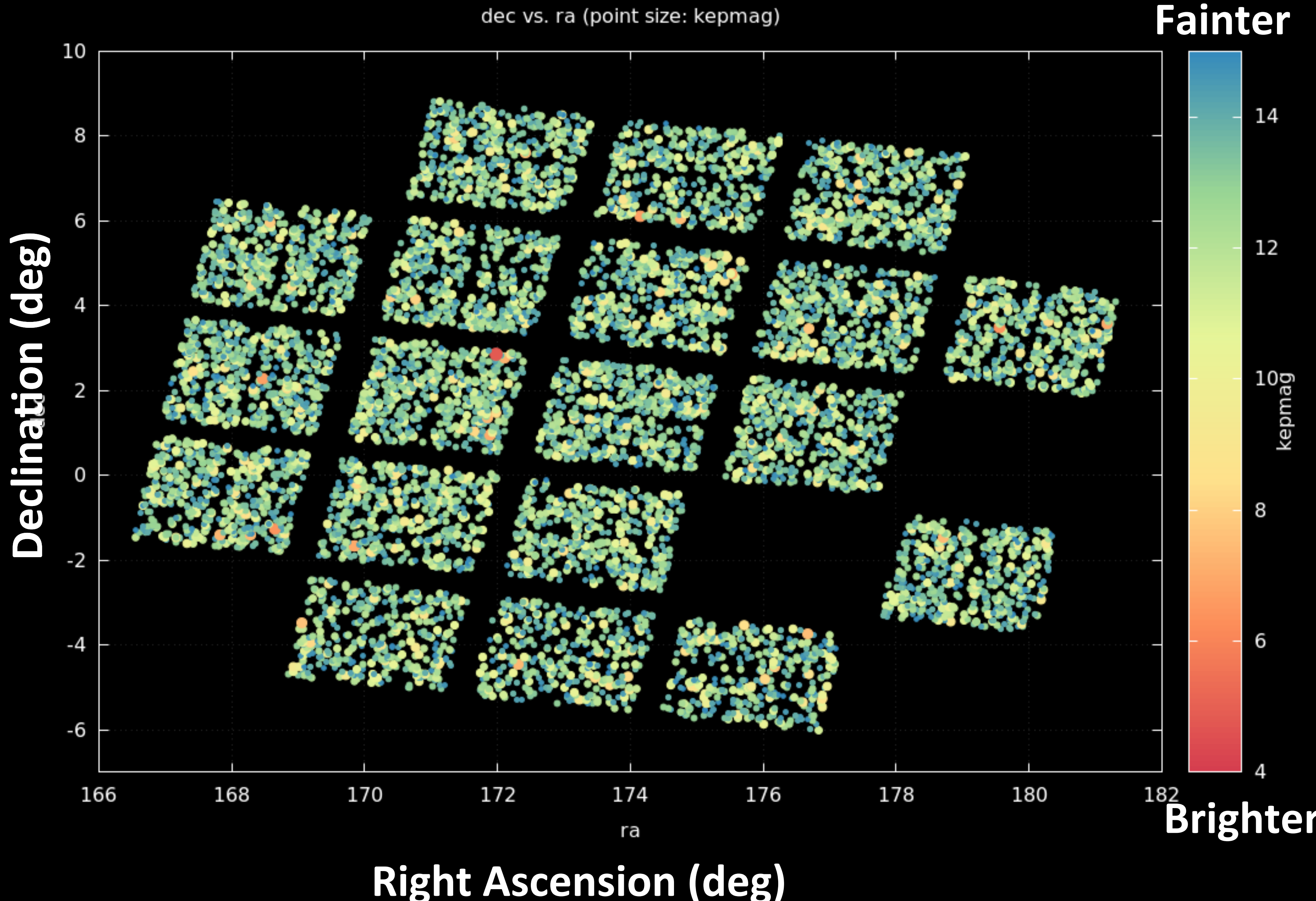
Kepler Light Curve (Short Cadence Data)

TrES-2b

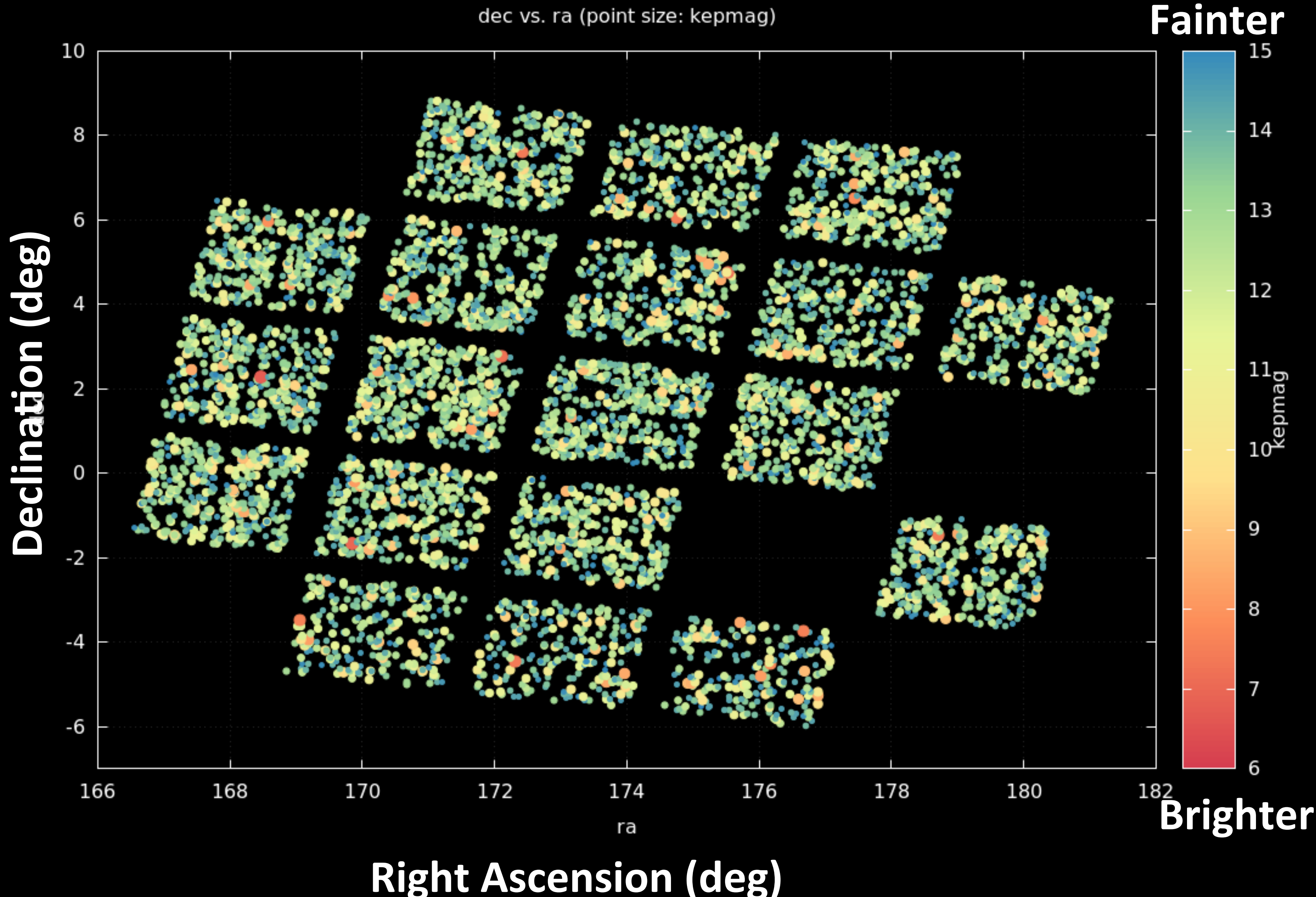


Kipping & Bakos 2011, ApJ, 733, 36

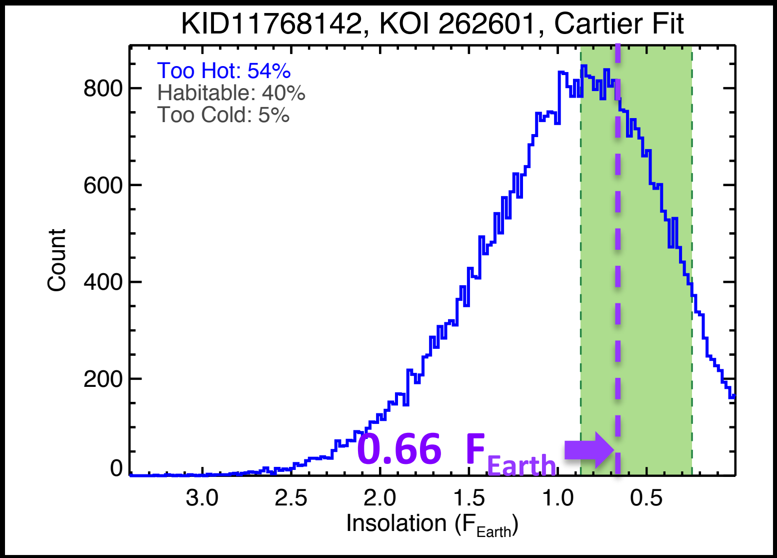
A Patch of Sky: All Stars with Kepmag < 15

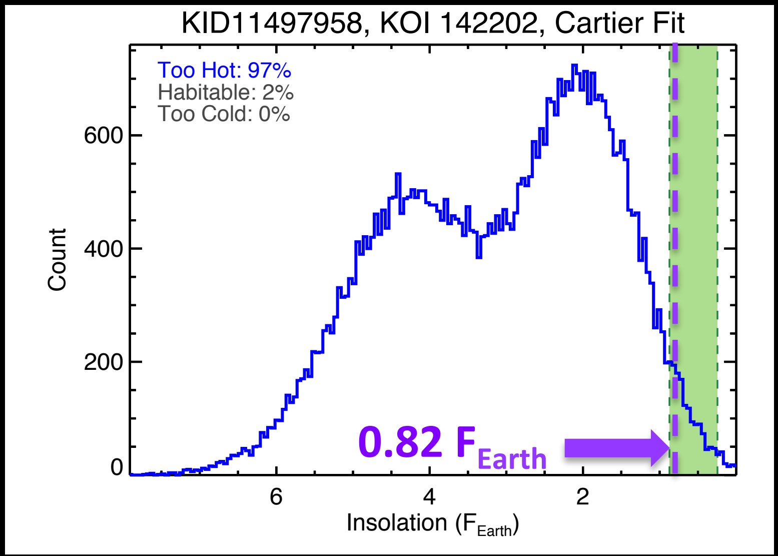


A Patch of Sky: Dwarf Stars with Kepmag < 15



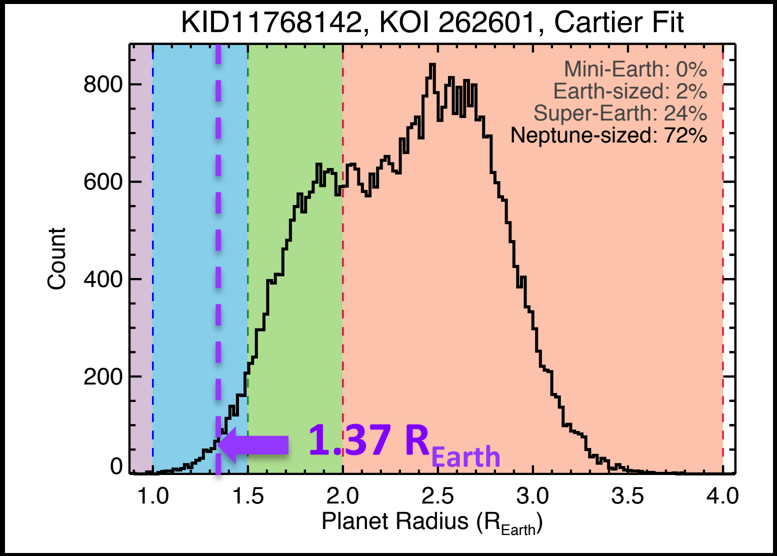
Revised Properties After Imaging

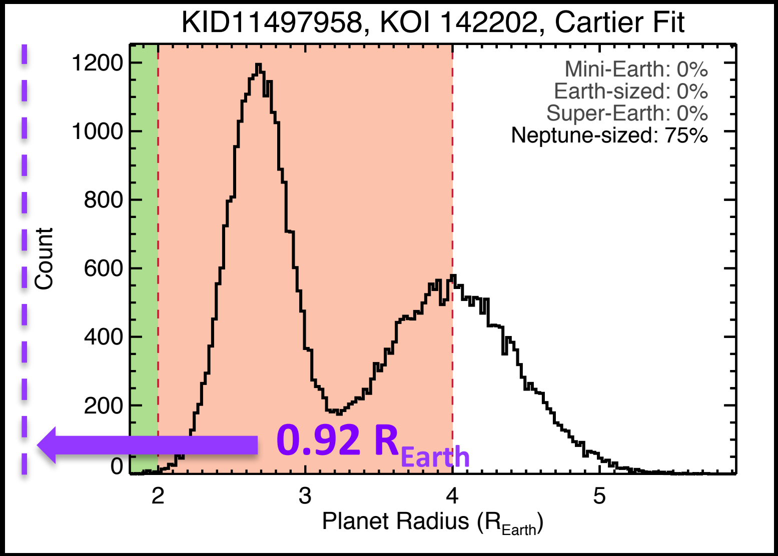




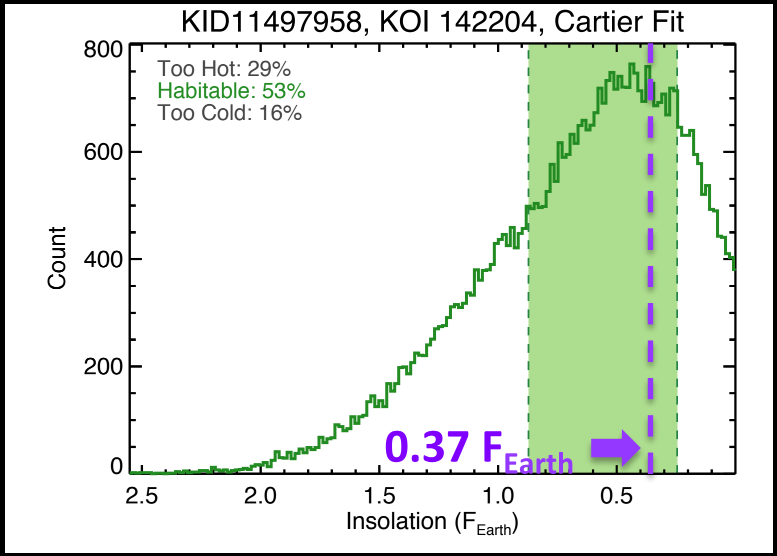
KOI 2626.01

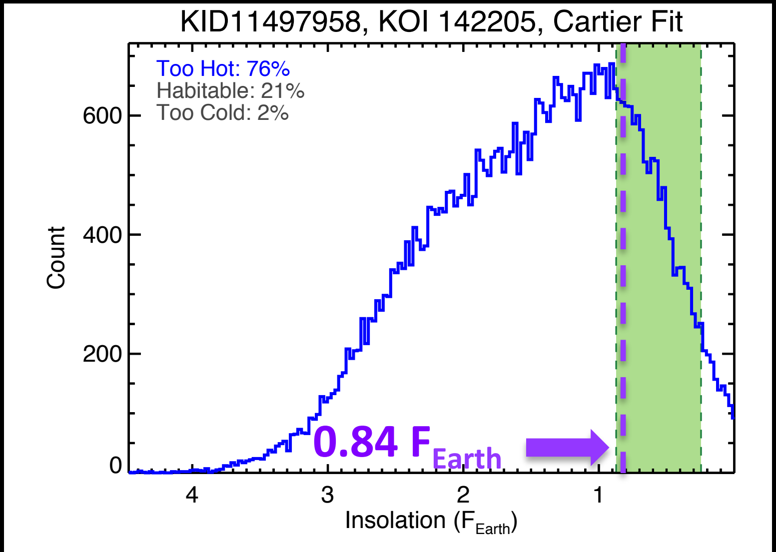
KOI 1422.02





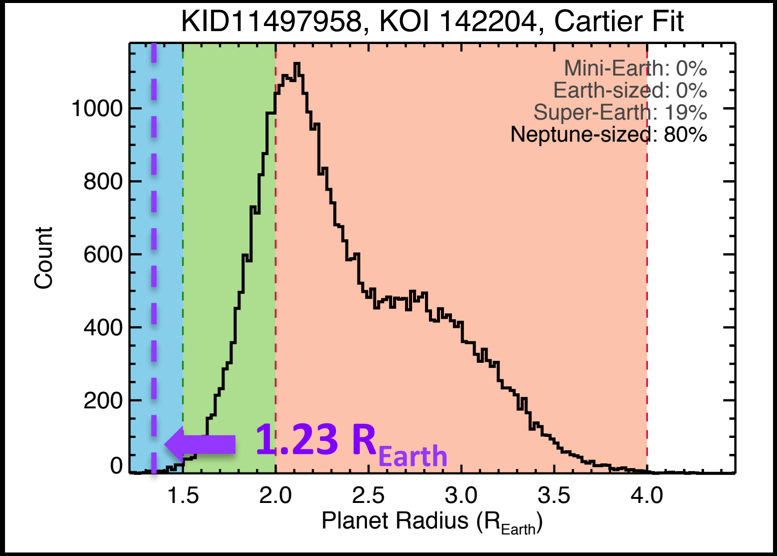
Revised Properties After Imaging

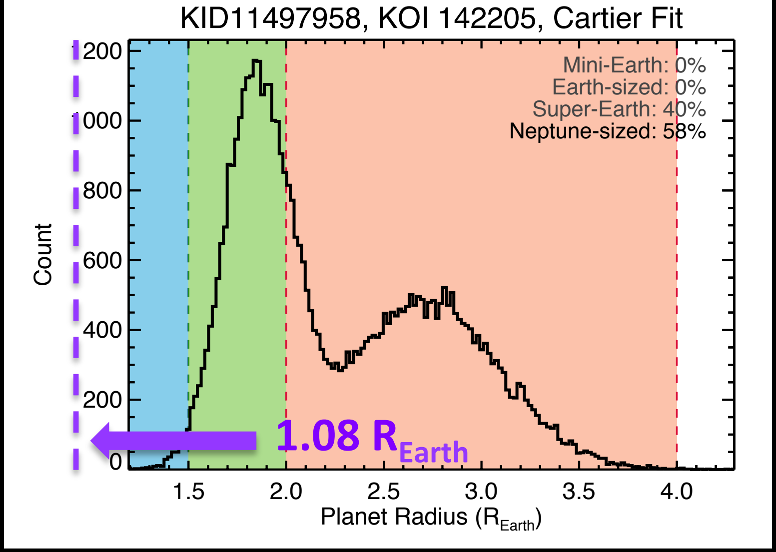




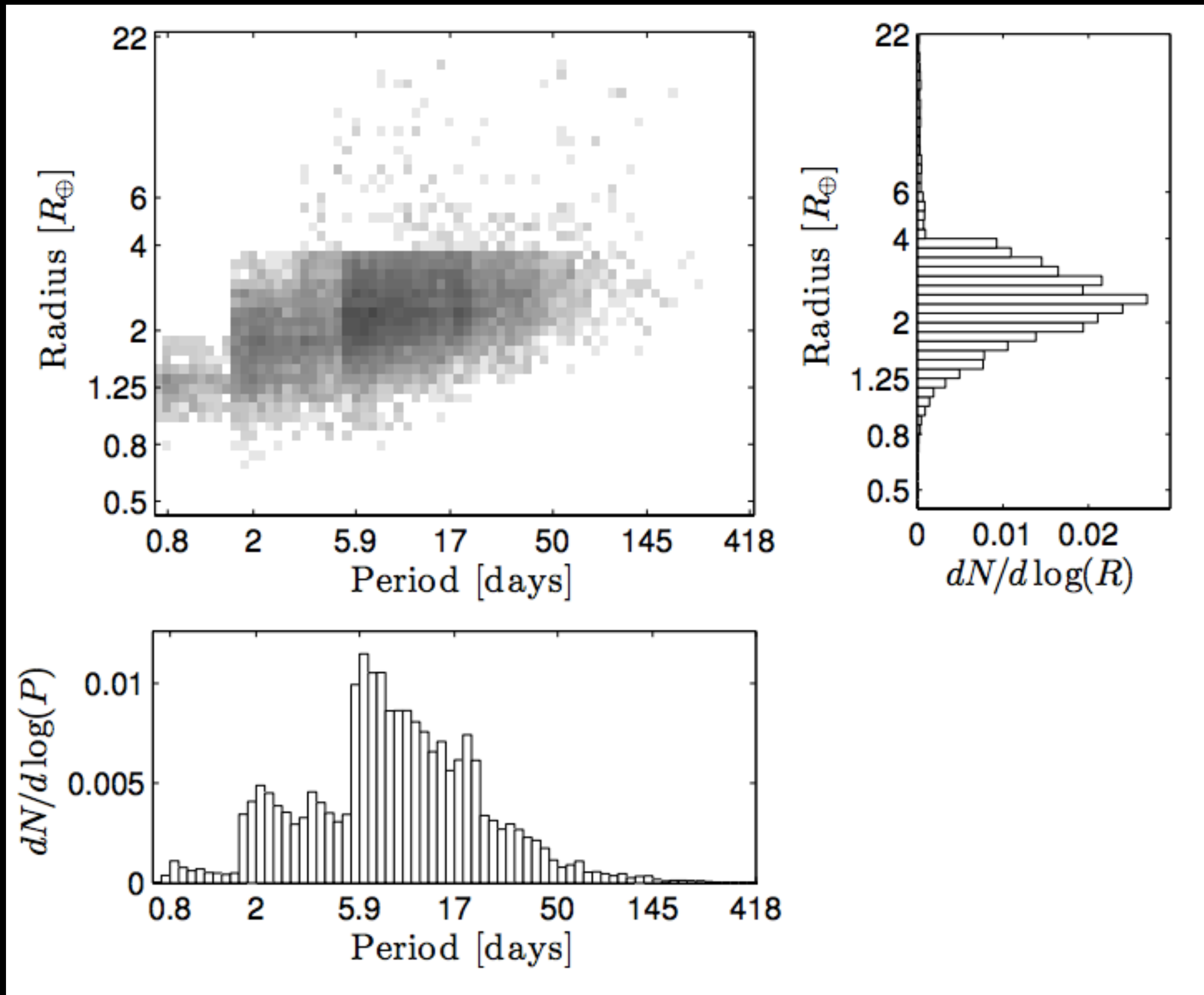
KOI 1422.04

KOI 1422.05





Most TESS Planets will have Short Periods



Sullivan et al. 2015, accepted to ApJ, arXiv: 1506.03845