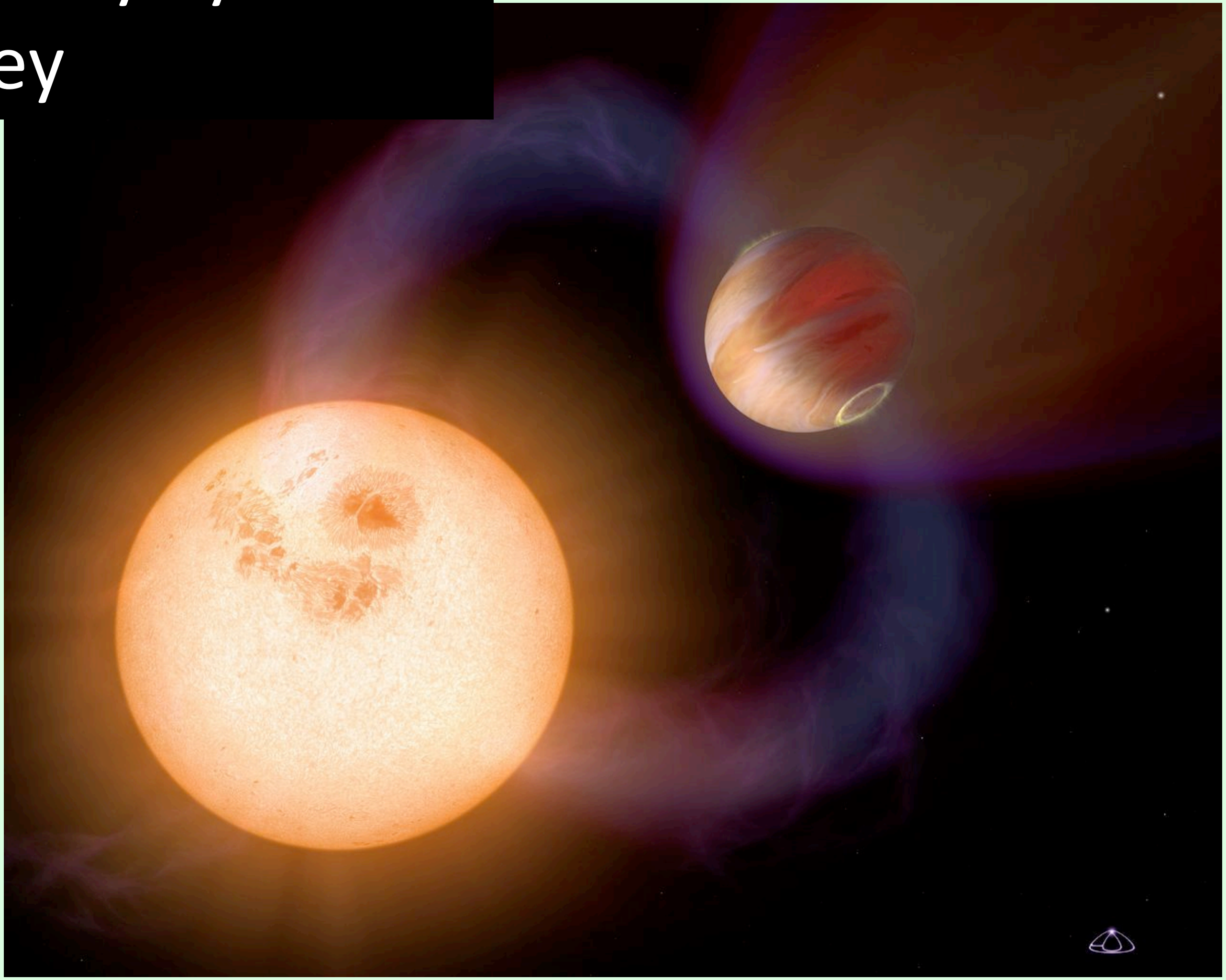
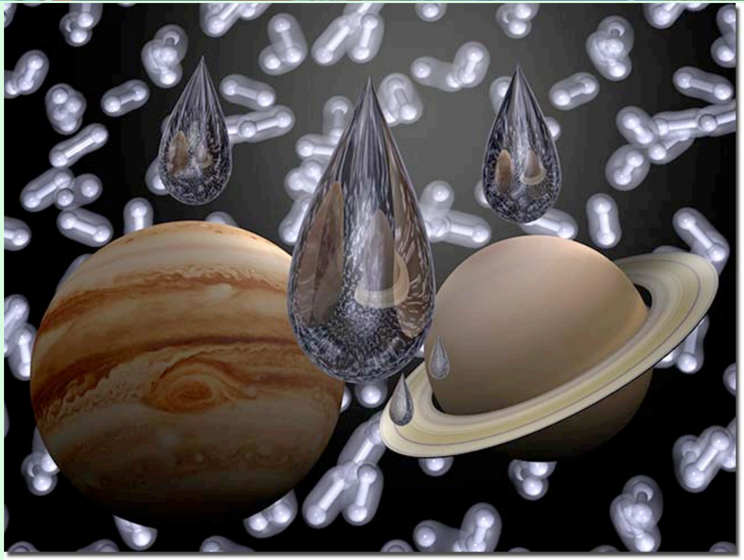
# Astronomy 118
# Physics of Planetary Systems
Jonathan Fortney



**About Me:**

- I grew up near St. Paul, MN
- I got my BS in Physics at Iowa State University, in Ames, IA
- I got my PhD in Planetary Sciences from the University of Arizona, in Tucson, AZ
- I was a postdoc at NASA Ames for 4 years, in Mountain View, CA
- I've been at UCSC for 6+ years
- My wife is a librarian/lawyer for the UC-wide library system, and we have two boys, Finn and Graham, ages 6 and 4
- I am predominantly a theorist and modeler that tries to understand the atmospheres, interiors, and compositions, of planets
- I work about 90% on exoplanets and 10% on solar system planets
- Most of my PhD work was on trying to understand "helium rain" in the deep interior of Saturn



# Astronomy 118
# Physics of Planetary Systems

Professor Jonathan Fortney

Winter Quarter 2012

MWF: 2:00-3:10 p.m., Earth & Marine Sciences B210

This class is designed primarily for physics, astrophysics, and earth & planetary science students in their junior or senior year. Two years of college physics and multivariable calculus are highly recommended as preparation.

The course will take an "astronomical" point of view of the science of planetary systems, with less of a focus on the specifics of our solar system. The course is not really an astrobiology class either, but will focus on planets as astronomical objects. This is an exciting time to study planetary systems, as we are now in the midst of a dramatic transformation in our understanding of how our planetary system fits within the galaxy.

**Main Topics:** Star formation, planet formation, exoplanet detection, statistics of known systems, planetary atmospheres, planetary interiors, and habitability. Mostly we will focus on Chapters 1-4, 6-9 in our textbook (see below), and I will also occasionally give out supplementary material to read. You will also do some writing, based on articles I give you to read.

## Schedule of Class

| Week | Day | | | |
|---|---|---|---|---|
| 1 | 1 | M | 6-Jan | |
| | 2 | W | 8-Jan | |
| | 3 | F | 10-Jan | |
| 2 | 4 | M | 13-Jan | |
| | 5 | W | 15-Jan | HW1 |
| | 6 | F | 17-Jan | |
| 3 | Holiday | M | 20-Jan | |
| | 7 | W | 22-Jan | |
| | 8 | F | 24-Jan | |
| 4 | 9 | M | 27-Jan | HW2 |
| | 10 | W | 29-Jan | |
| | 11 | F | 31-Jan | |
| 5 | 12 | M | 3-Feb | |
| | 13 | W | 5-Feb | HW3 |
| | 14 | F | 7-Feb | |
| 6 | 15 | M | 10-Feb | *Midterm* |
| | 16 | W | 12-Feb | |
| | 17 | F | 14-Feb | |
| 7 | Holiday | M | 17-Feb | |
| | 18 | W | 19-Feb | |
| | 19 | F | 21-Feb | HW4 |
| 8 | 20 | M | 24-Feb | |
| | 21 | W | 26-Feb | |
| | 22 | F | 28-Feb | |
| 9 | 23 | M | 3-Mar | HW5 |
| | 24 | W | 5-Mar | |
| | 25 | F | 7-Mar | |
| 10 | 26 | M | 10-Mar | |
| | 27 | W | 12-Mar | |
| | 28 | F | 14-Mar | HW6 |
| 11 | 29 | M | 17-Mar | |

In addition to the midterm, final, and six homework assignments, a quarter project will be required, which is a 10-page review of a current topic in extrasolar or solar system planets.

**Final Exam:** Friday, March 21, 4:00–7:00 p.m.

**Required Textbook:** Caleb Scharf, *Extrasolar Planets and Astrobiology*, 2008.

**Contact info for Professor Fortney:**
Class Web: www.ucolick.org/~jfortney/118.htm
Office hours: Thursdays, 2-3:30 p.m., ISB 275, or by appointment
E-mail: jfortney@ucsc.edu
Phone: 2-7285

**Course Requirements and Grade Fraction:**

| | |
|---|---|
| 1 in-class midterm, open notes/book | 20% |
| 1 final exam, open notes/book | 30% |
| Quarter project | 15% |
| 6 homework sets | 35% |

**Other Issues:**

This class will be graded on a curve, so I cannot estimate what percentage you will need for a given grade. Do your best. I will let you know where you stand as the class progresses.

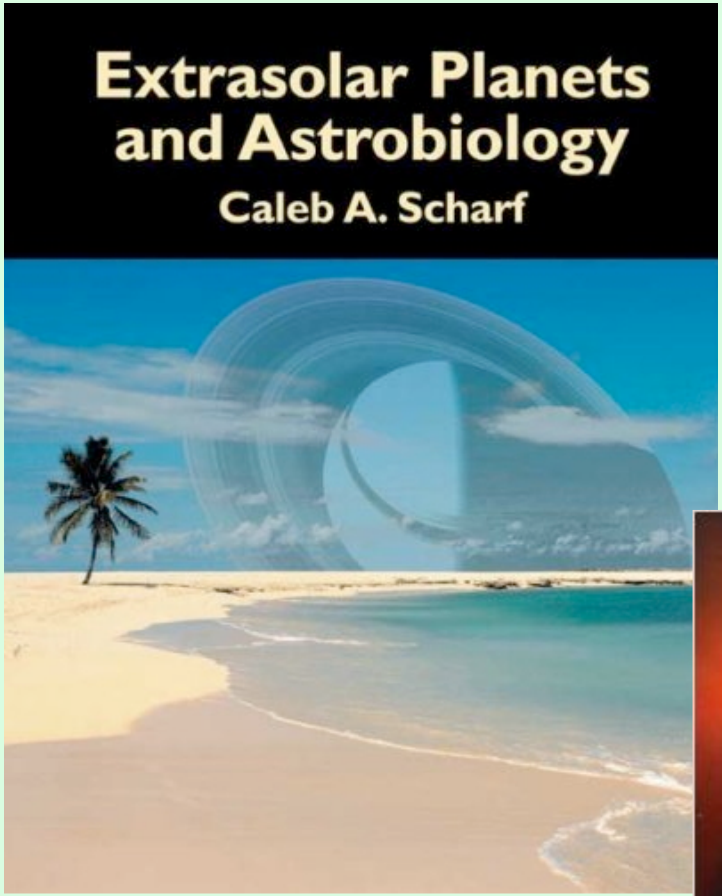
It is OK to work together on homework problems, but you must write up and turn in your own work.

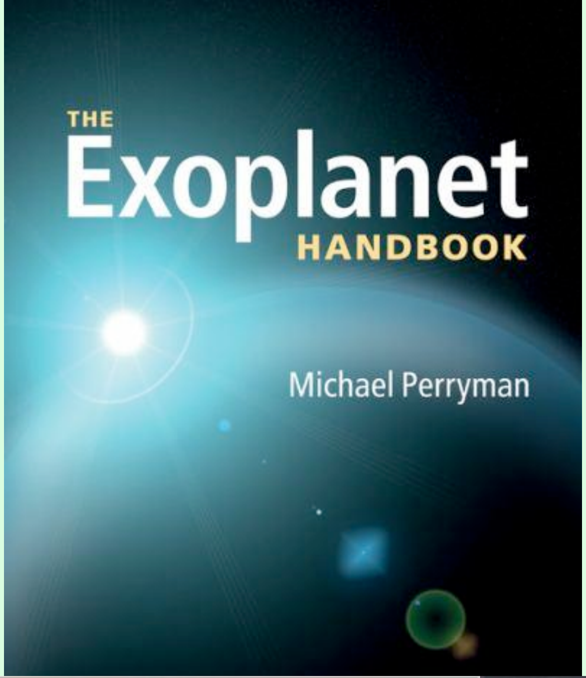
Please the see the "Official University Policy on Academic Integrity for Undergraduate Students" at: http://undergraduate.ucsc.edu/acd_integrity/index.html

## General Course Plan

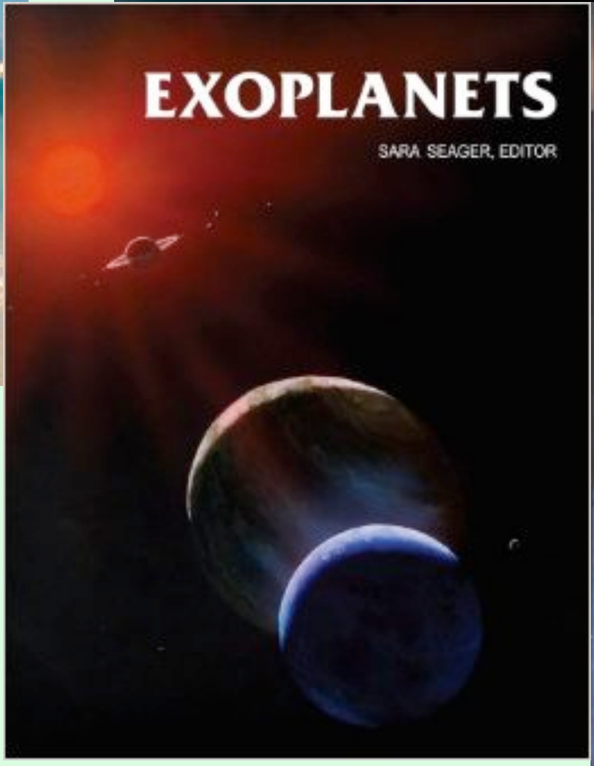
1) Introductory Material
2) Star Formation
3) Planet Formation
4) Exoplanet Detection
5) Atmospheres of Planets
6) Interiors and Surfaces of Planets
7) Habitable Zones

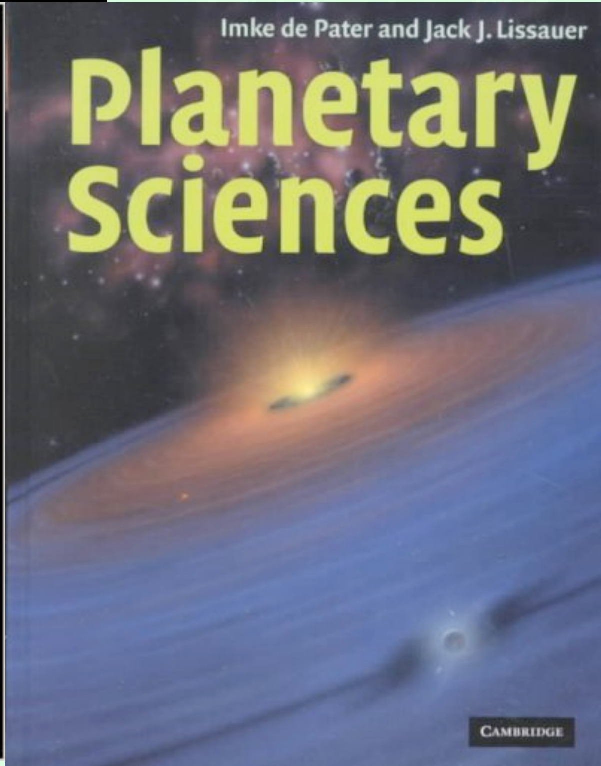
Our Book



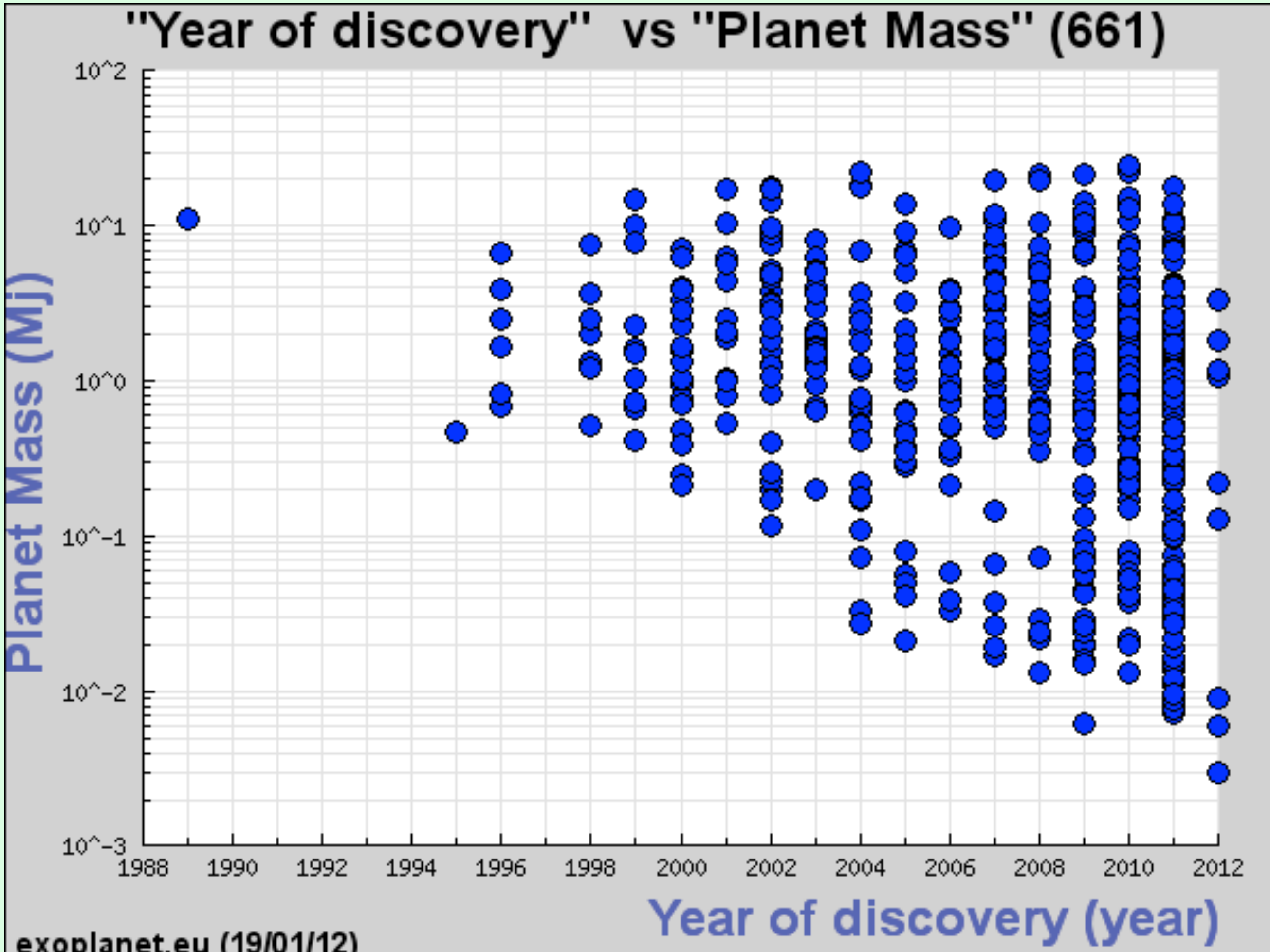

Others will be placed on reserve at the UCSC Science Library

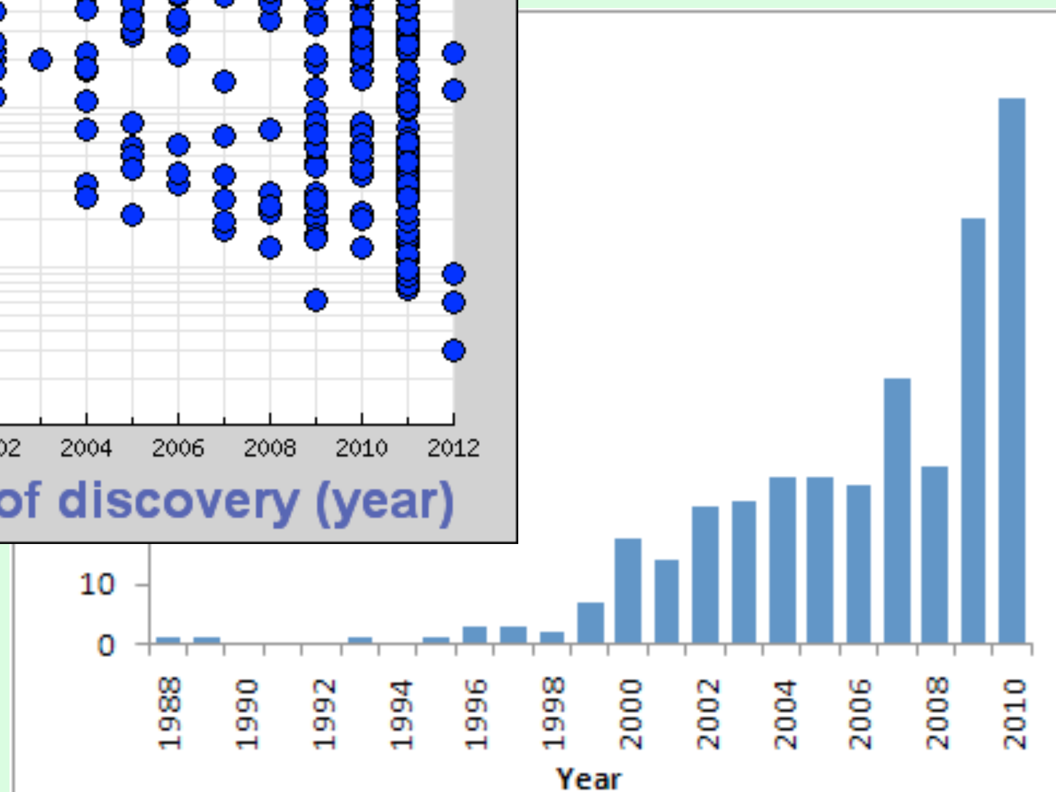


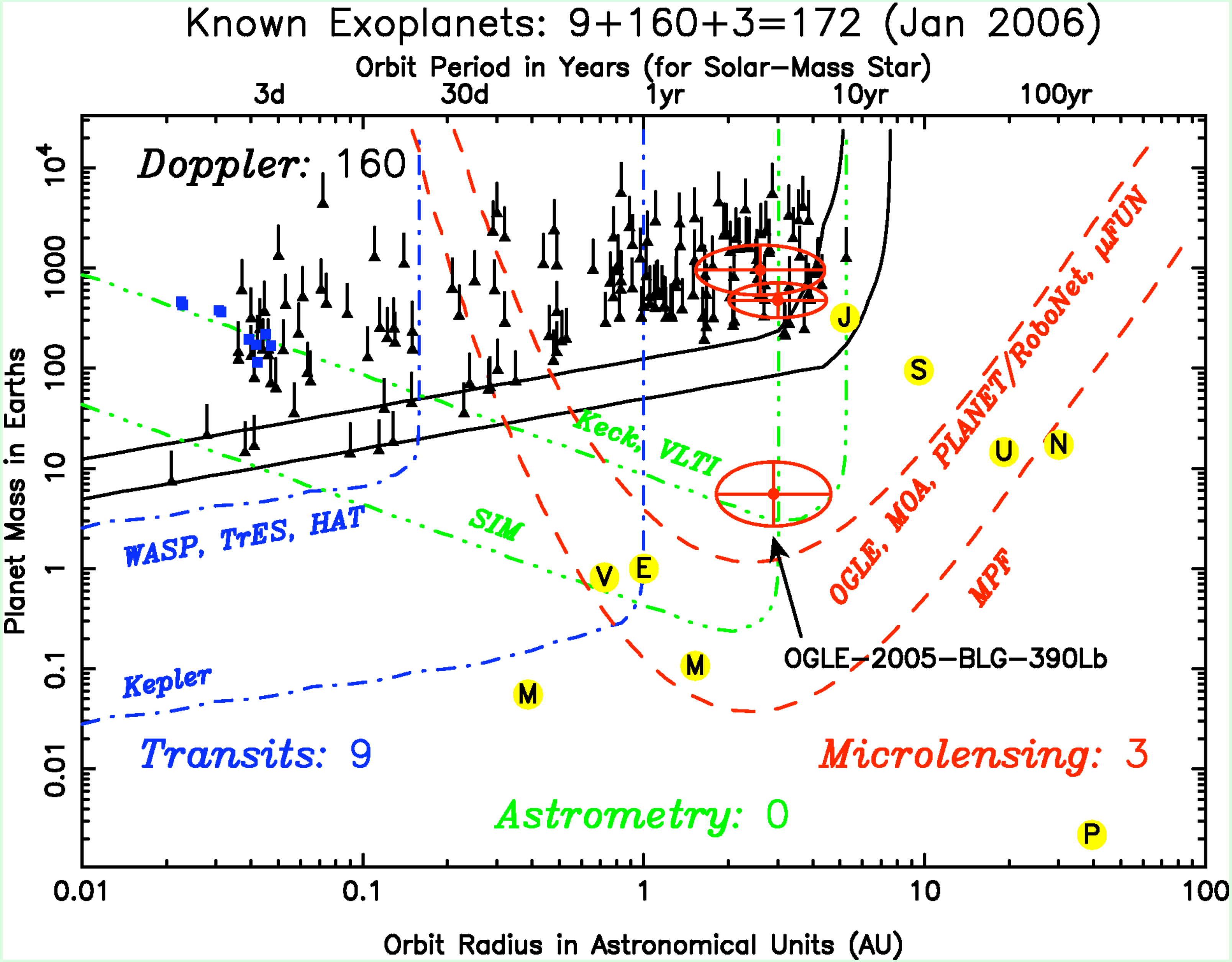



The Shape of Exoplanet Science Today:
Where the Planets are and What We’ve Learned

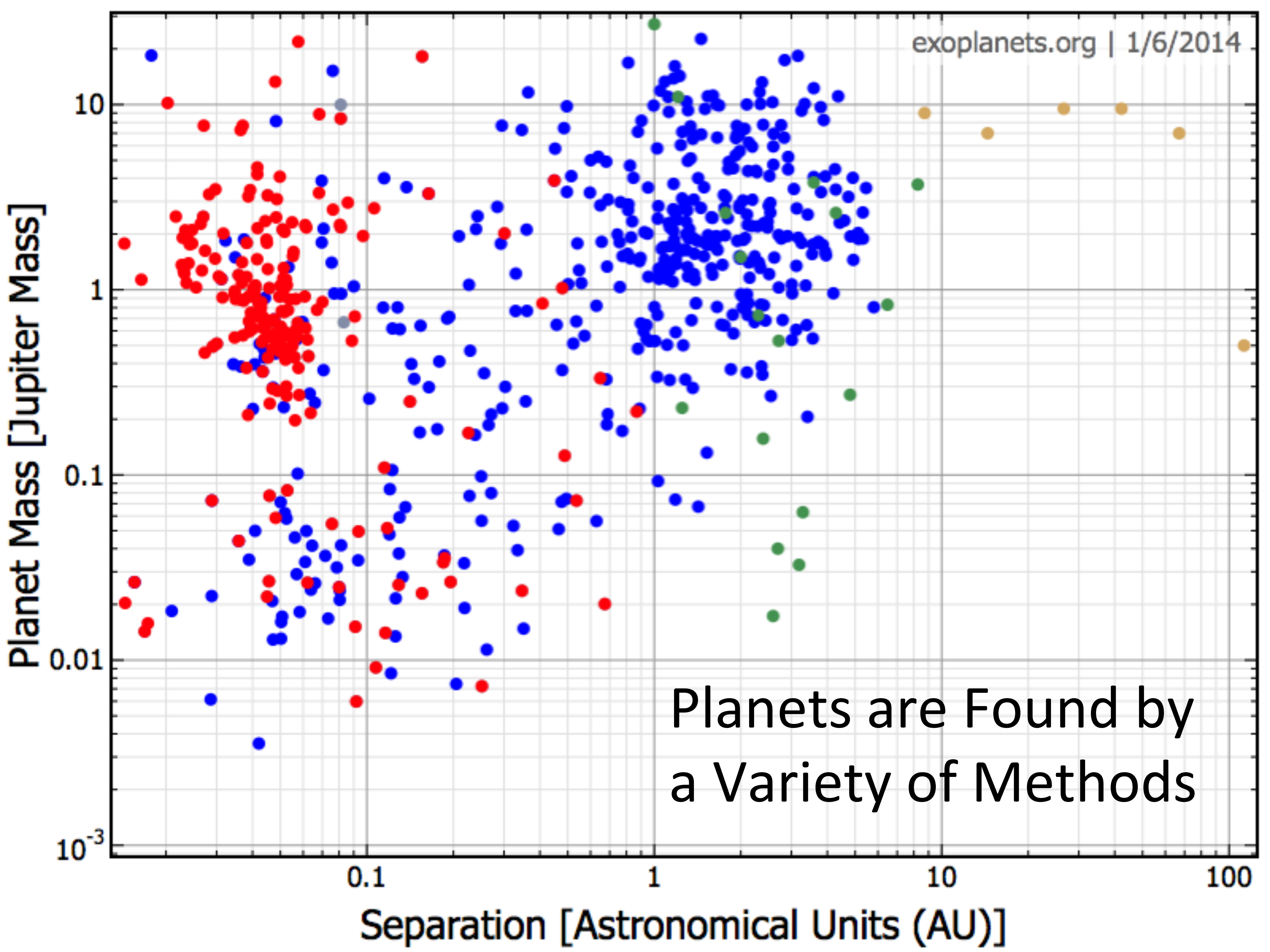
# The "Olden Days" was not very long ago

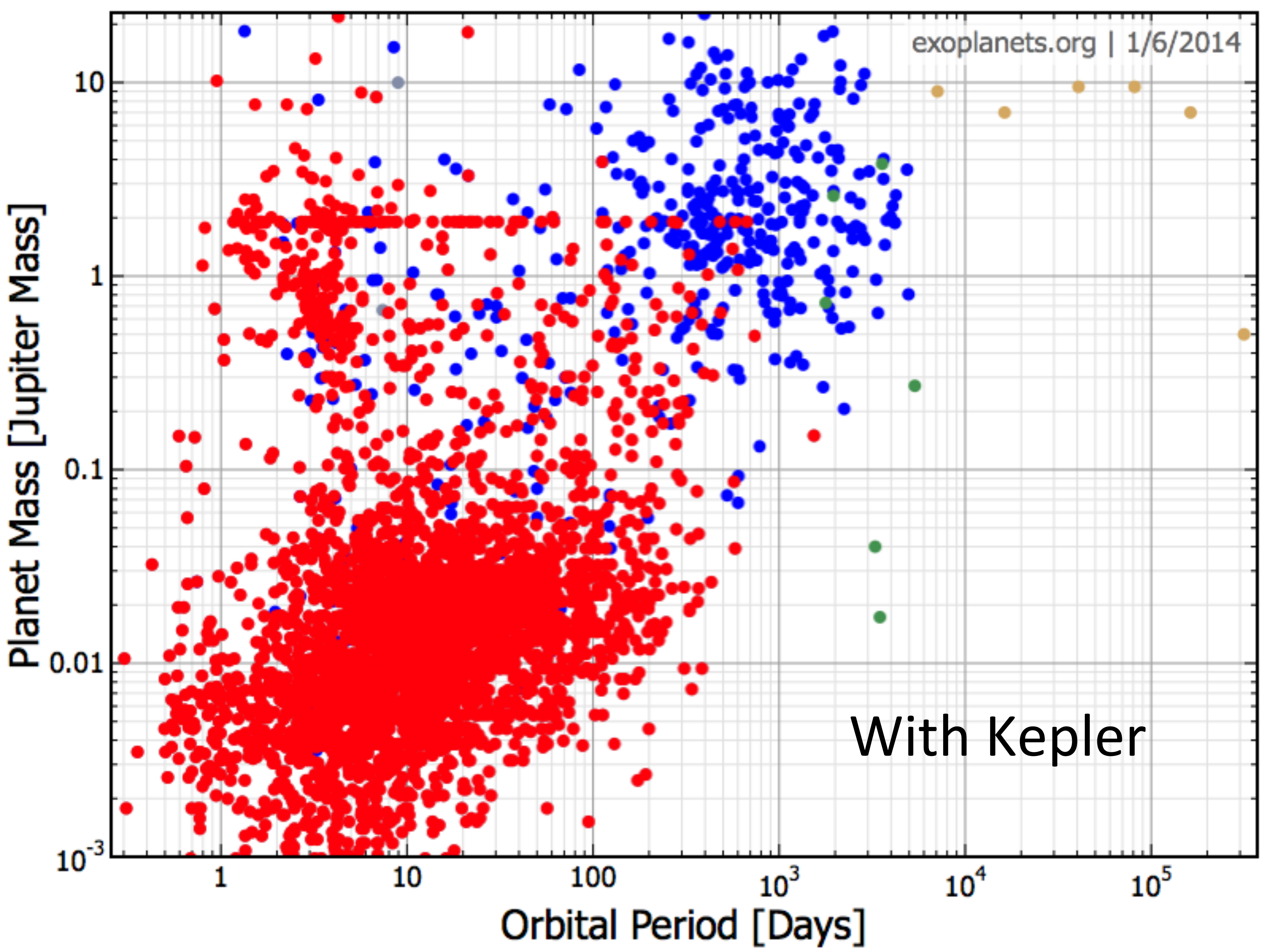


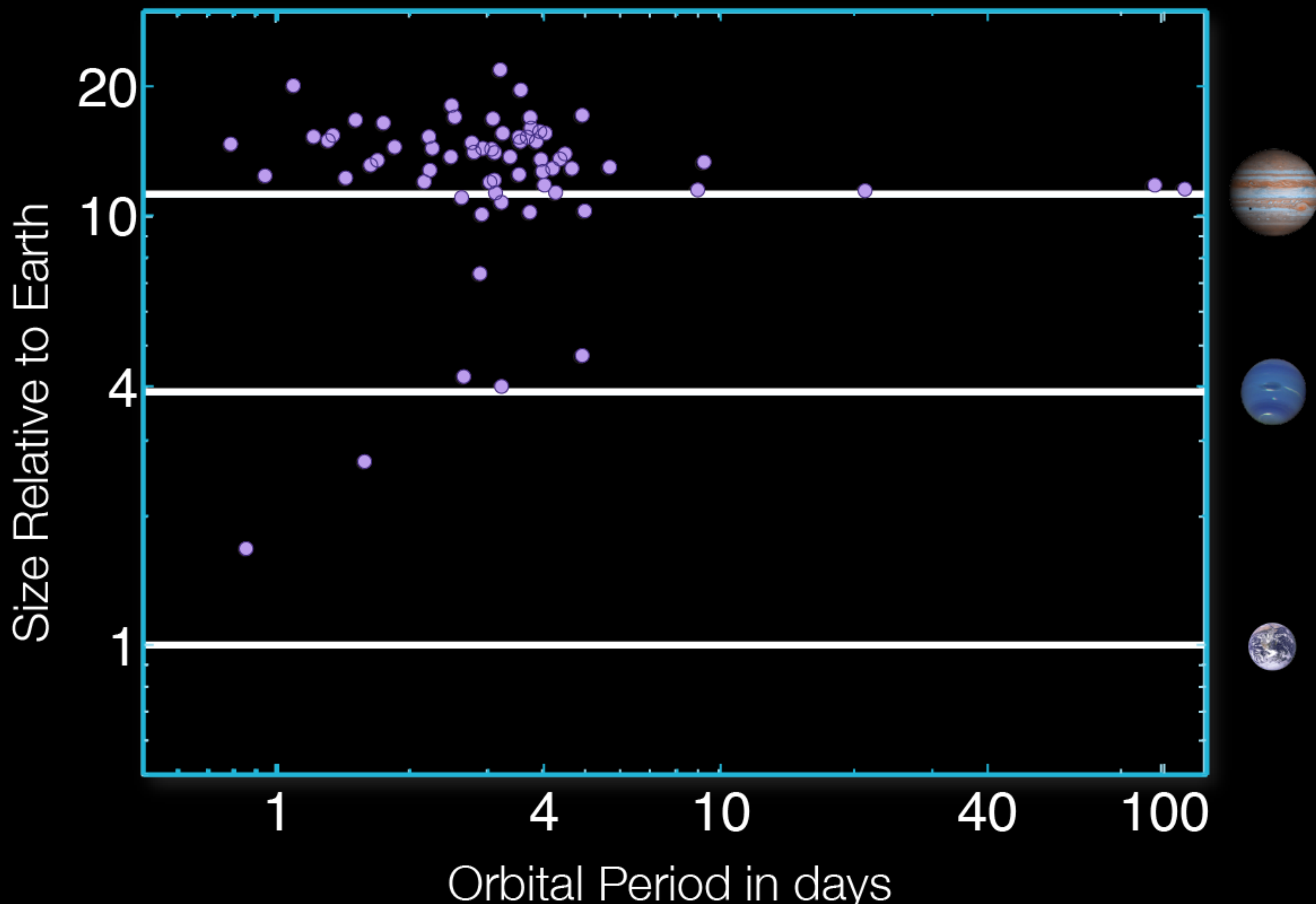


Known Exoplanets: 9+160+3=172 (Jan 2006)
Orbit Period in Years (for Solar-Mass Star)
3d
30d
1yr
10yr
100yr
Doppler: 160
Transits: 9
Astrometry: 0
Microlensing: 3
WASP, TrES, HAT
Kepler
Keck, VLTI
SIM
OGLE, MOA, PLANET/RoboNet, μFUN
MPF
OGLE-2005-BLG-390Lb
J
S
U
N
V
E
M
M
P
Planet Mass in Earths
$10^4$
1000
100
10
1
0.1
0.01
0.01
0.1
1
10
100
Orbit Radius in Astronomical Units (AU)

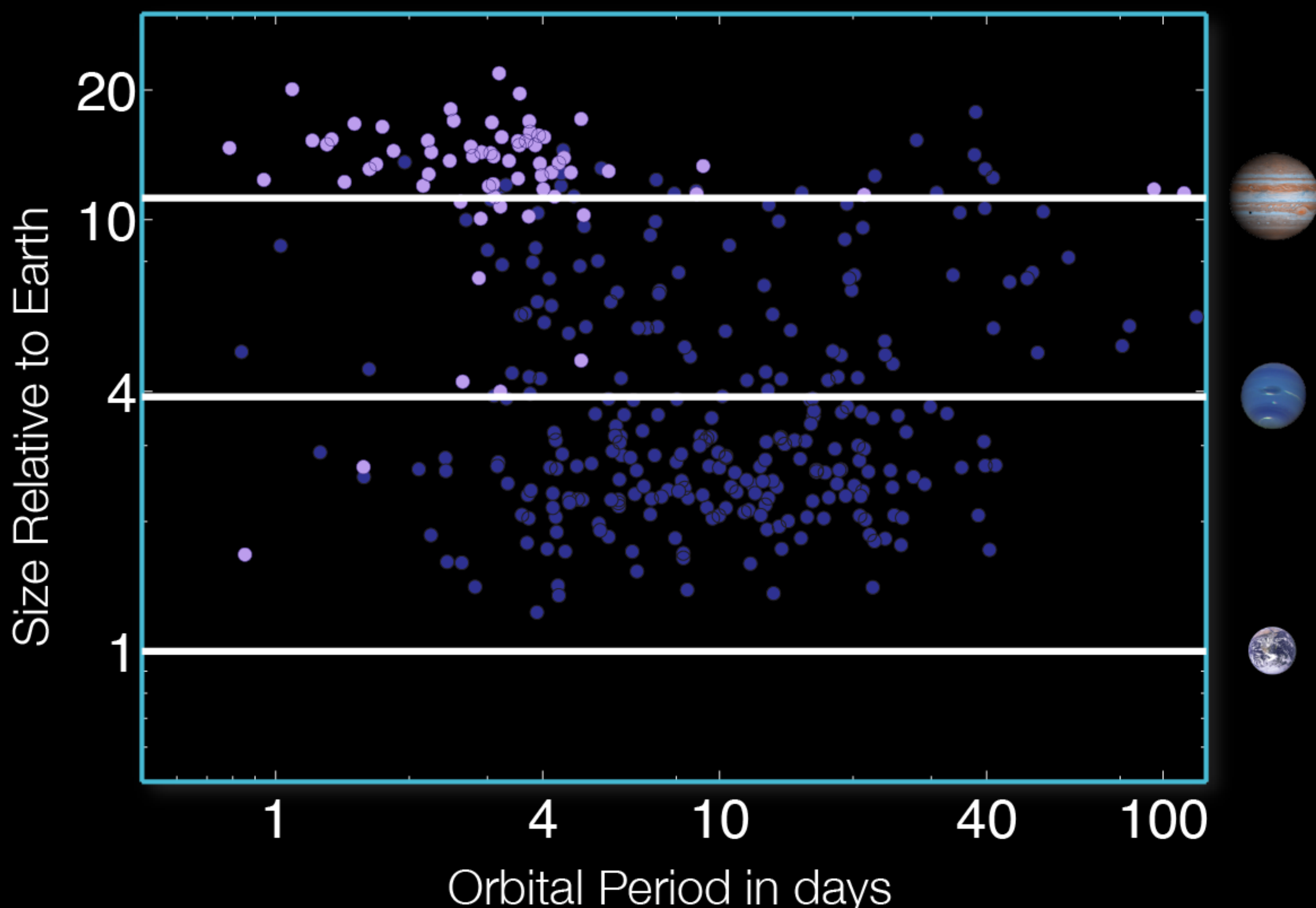

exoplanets.org | 1/6/2014
Planets are Found by a Variety of Methods
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
$10^{-3}$
0.1
1
10
100
Separation [Astronomical Units (AU)]


exoplanets.org | 1/6/2014
With Kepler
Planet Mass [Jupiter Mass]
Orbital Period [Days]
10
1
0.1
0.01
10-3
1
10
100
10^3
10^4
10^5

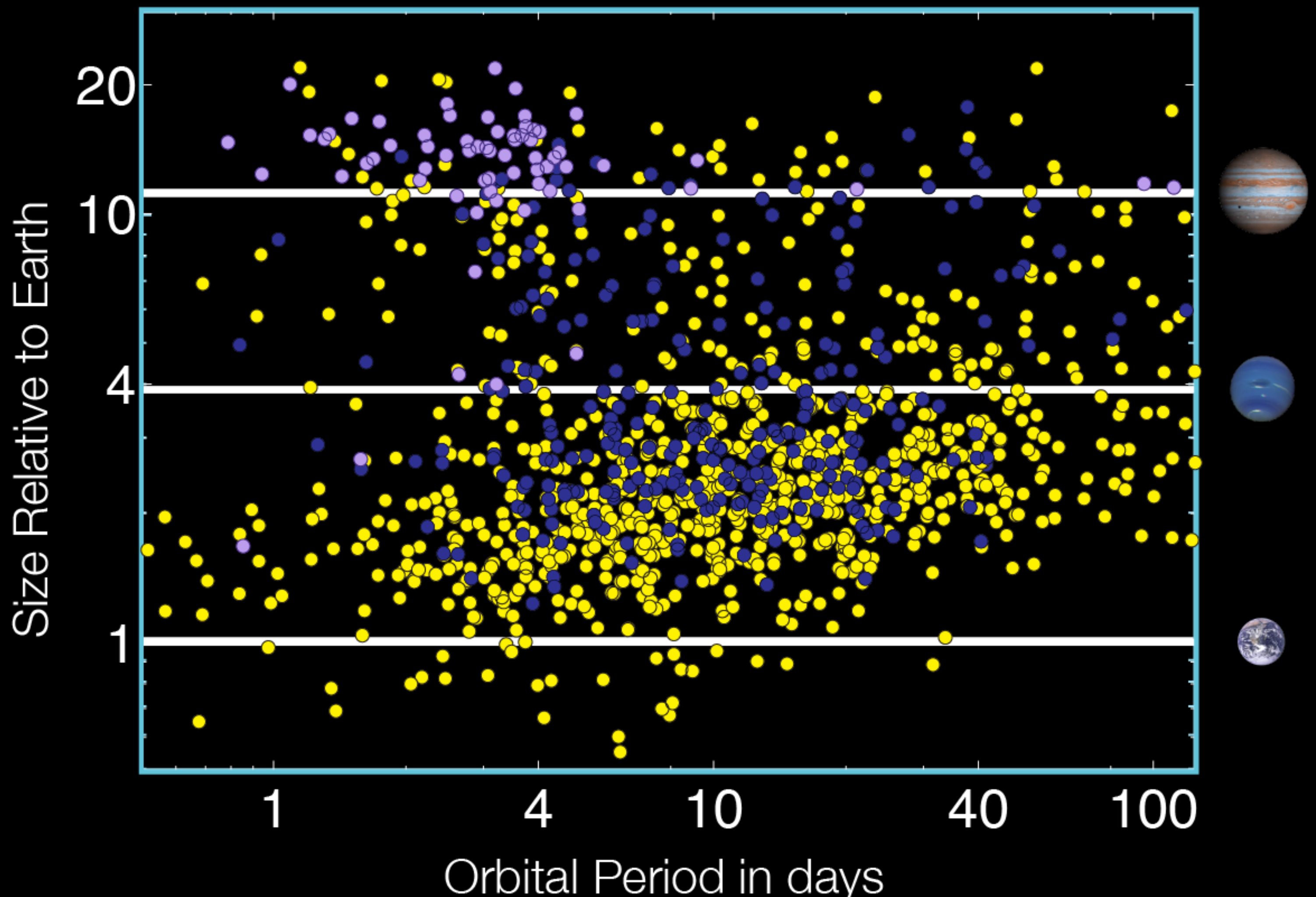
# Pre-Kepler Transiting Planets - 2009



# Kepler Candidates as of June 2010

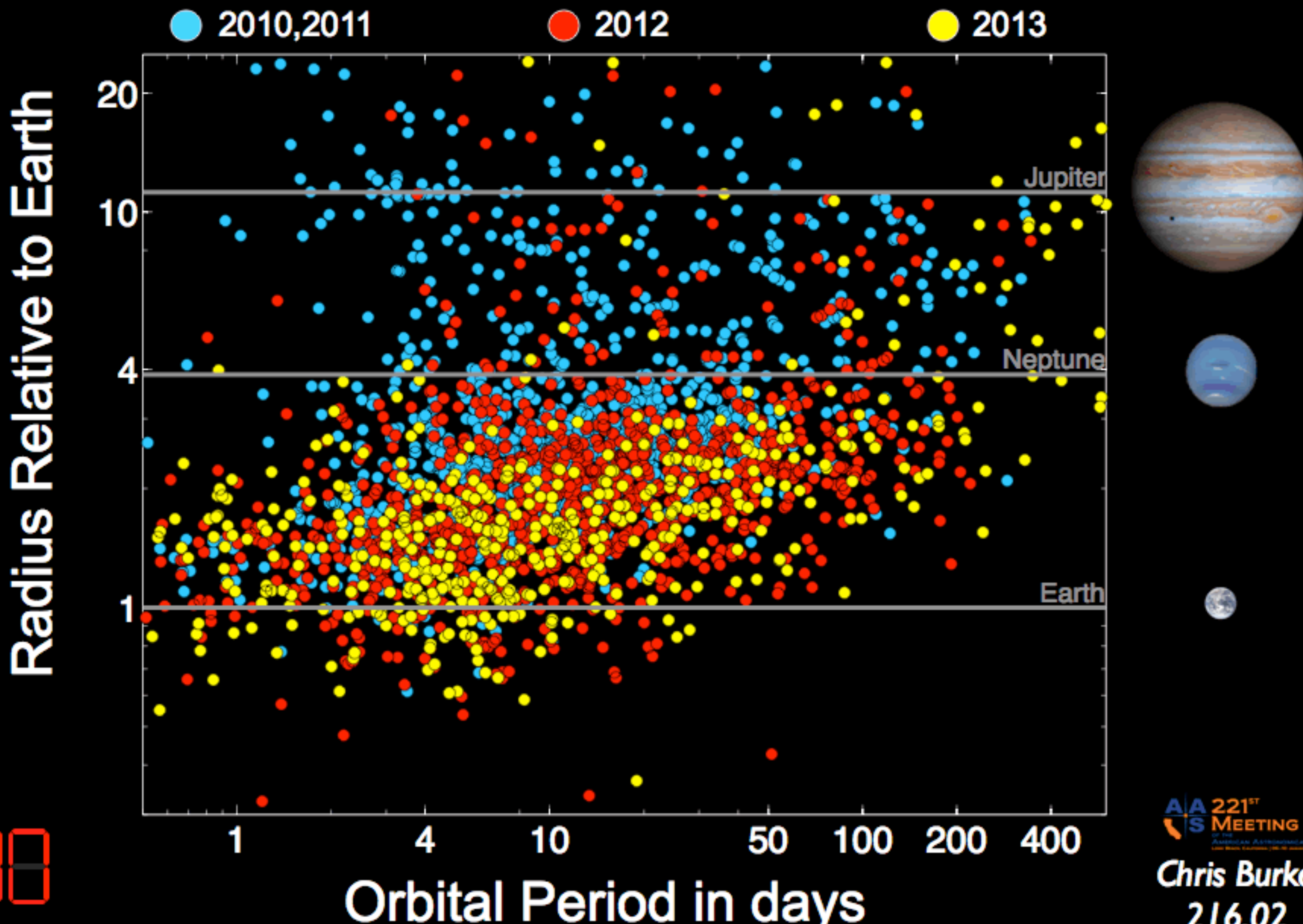


# Kepler Candidates as of February 1, 2011



# Kepler's Planet Candidates

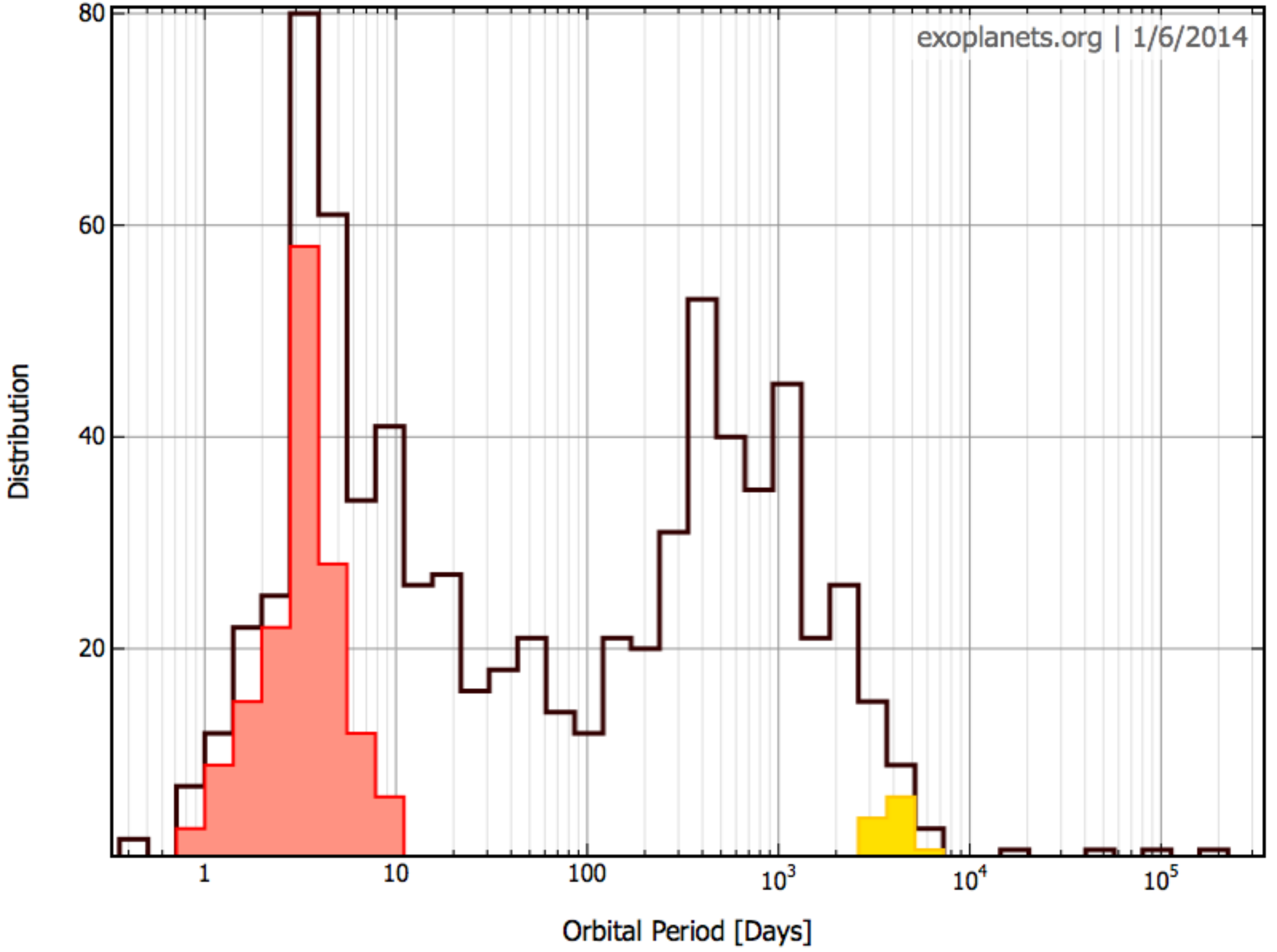
## 22 Months: May 2009 - Mar 2011



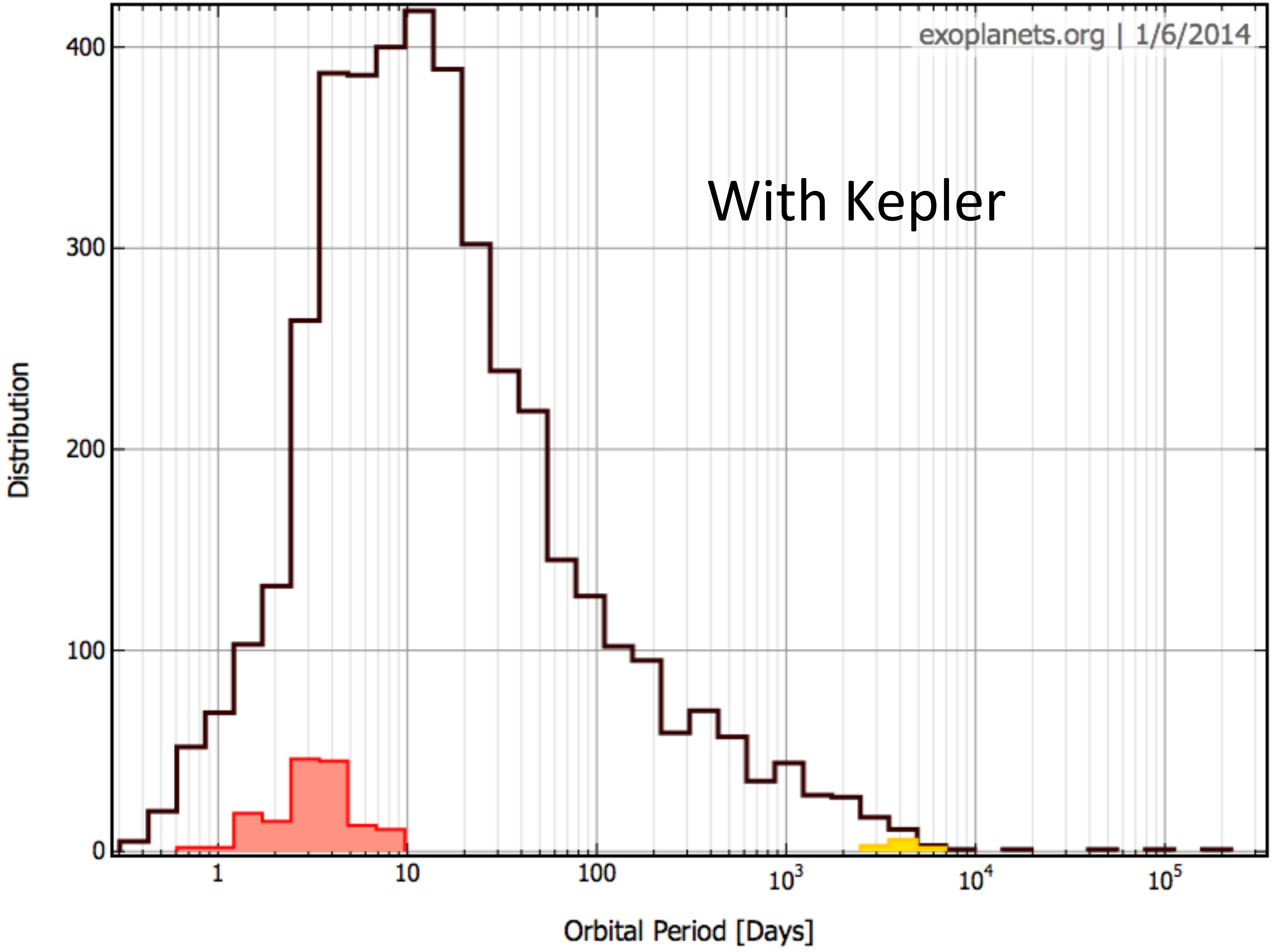

2740

221st Meeting

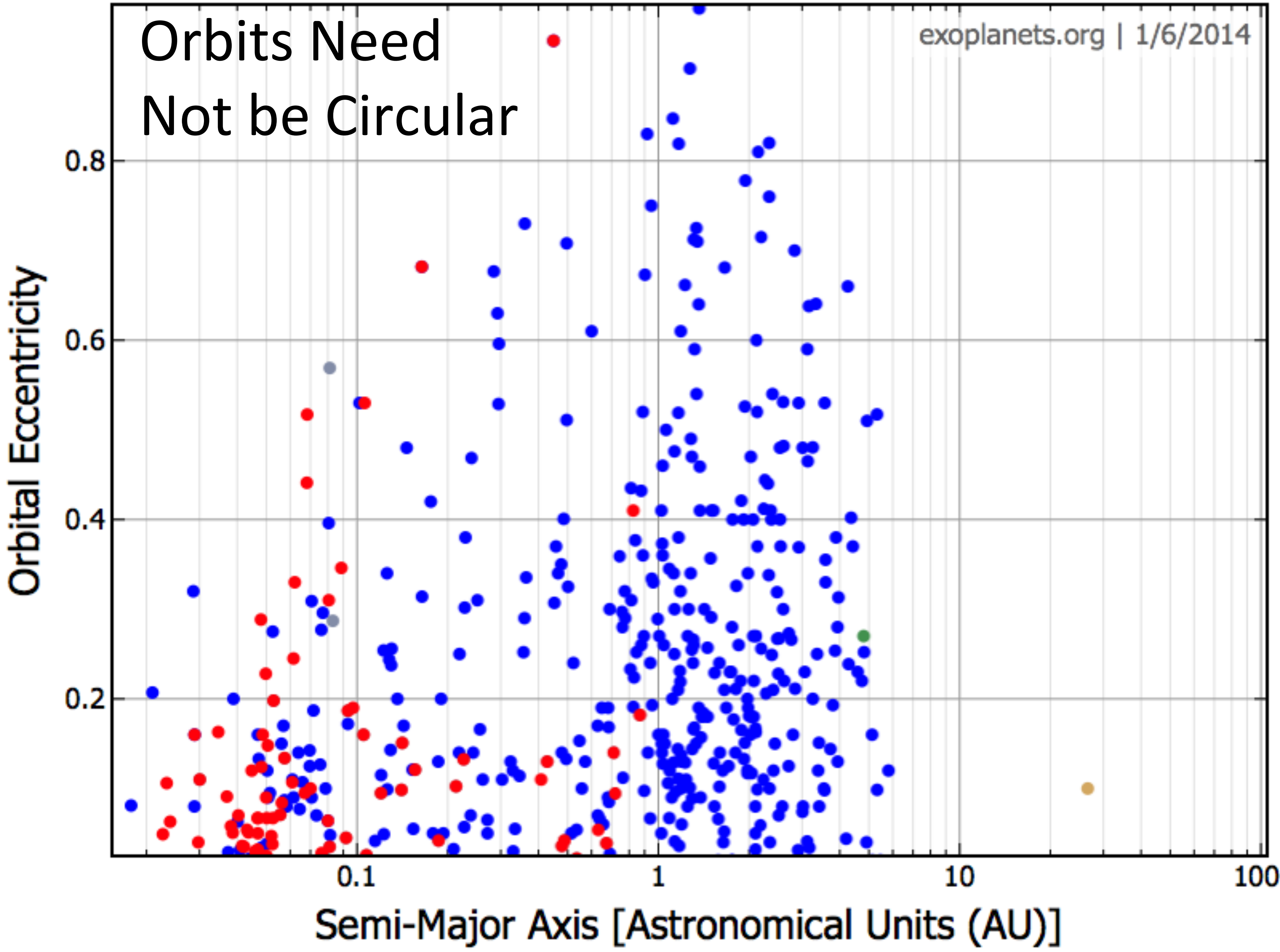
*Chris Burke: 216.02*

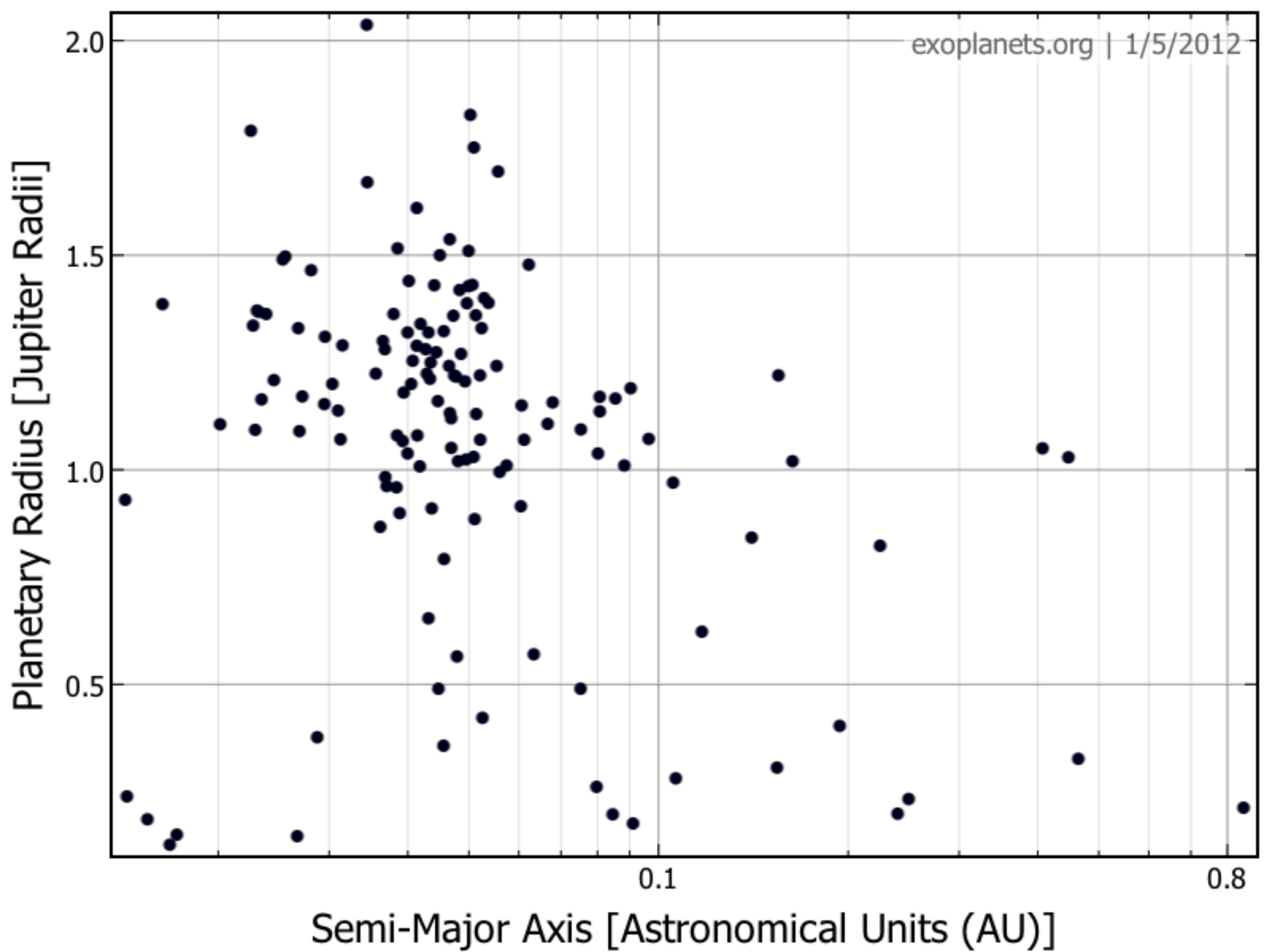


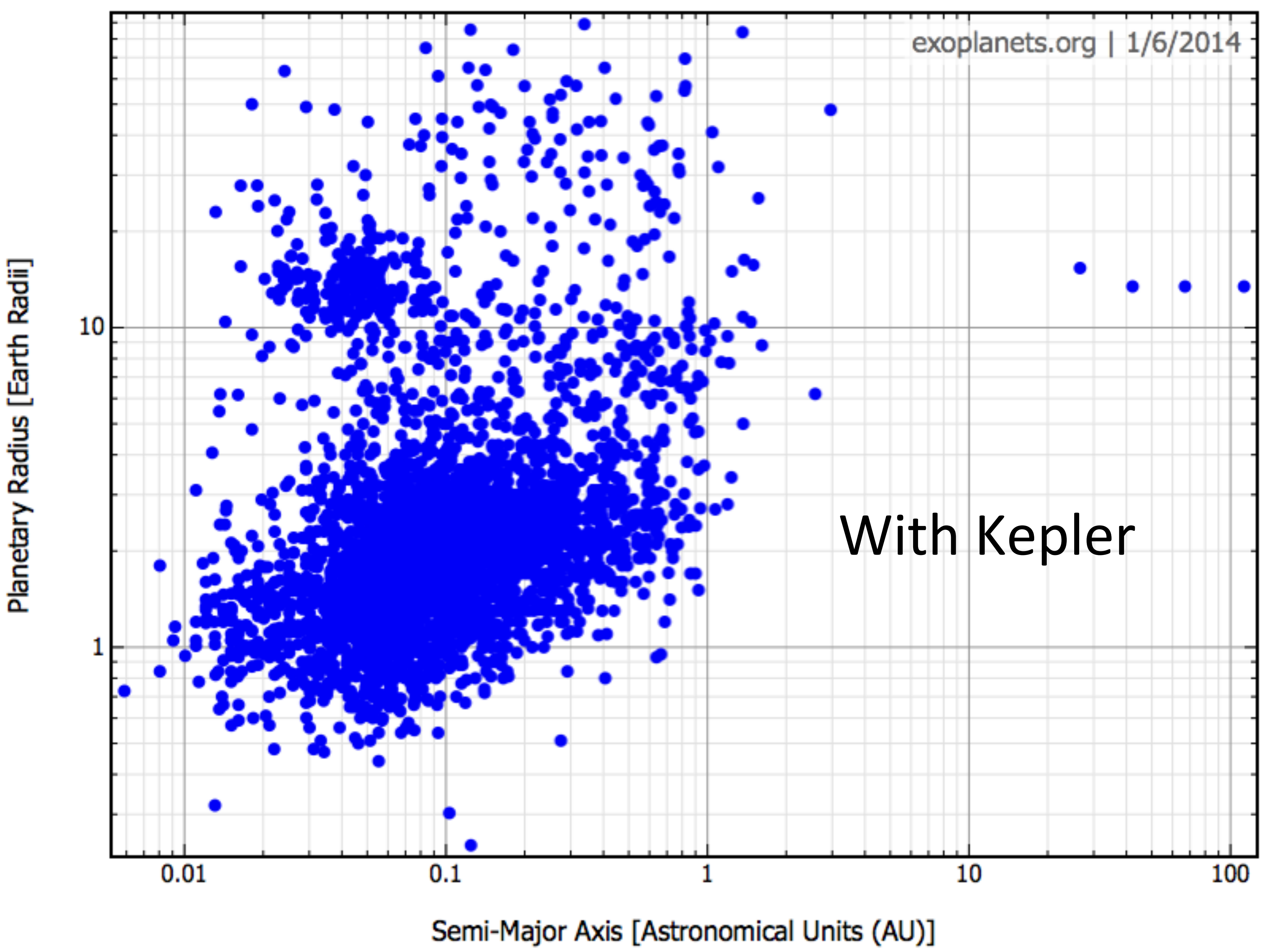
exoplanets.org | 1/6/2014
Distribution
Orbital Period [Days]
0
20
40
60
80
1
10
100
$10^3$
$10^4$
$10^5$

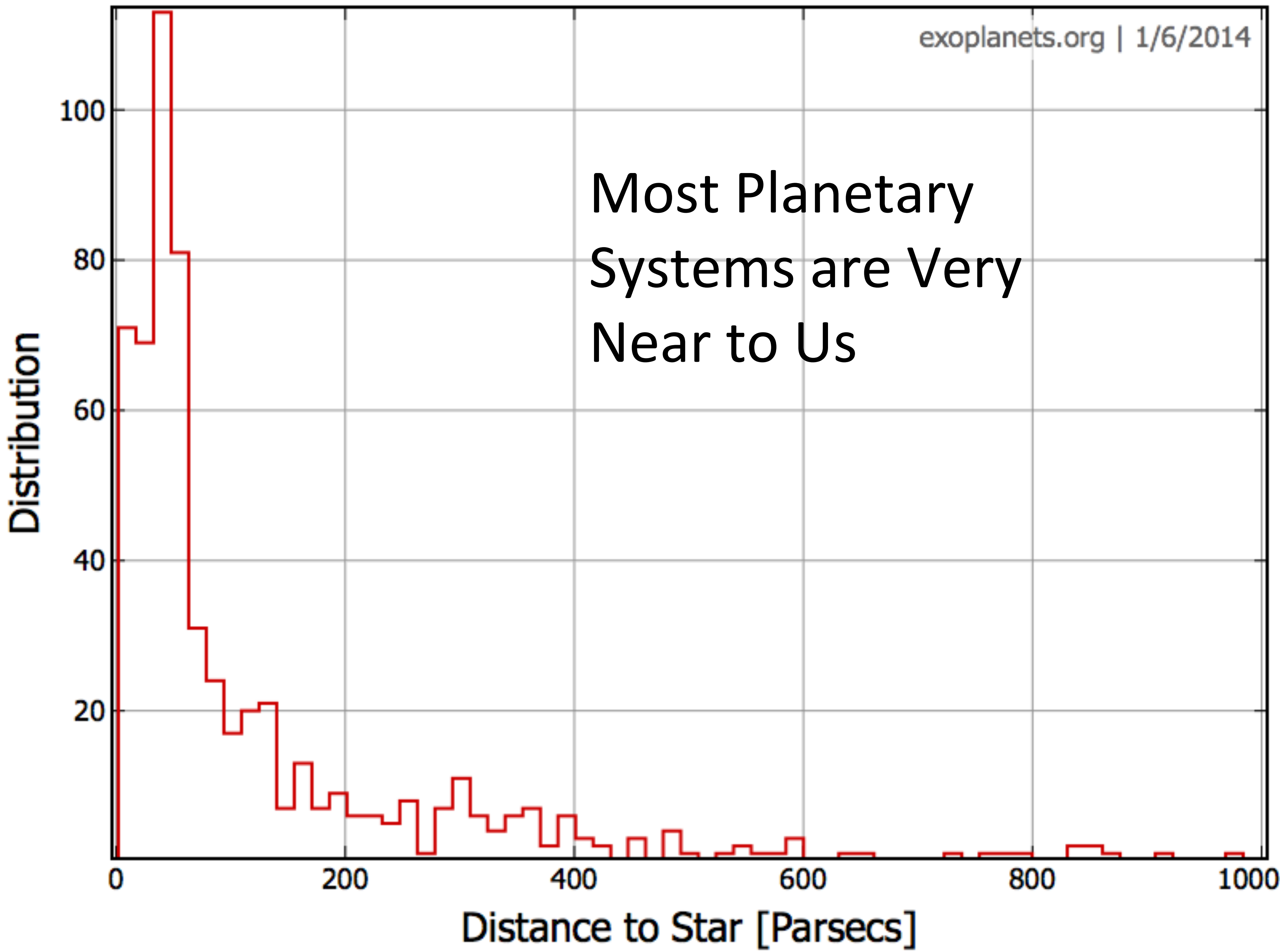

exoplanets.org | 1/6/2014
With Kepler
Distribution
400
300
200
100
0
1
10
100
$10^3$
$10^4$
$10^5$
Orbital Period [Days]

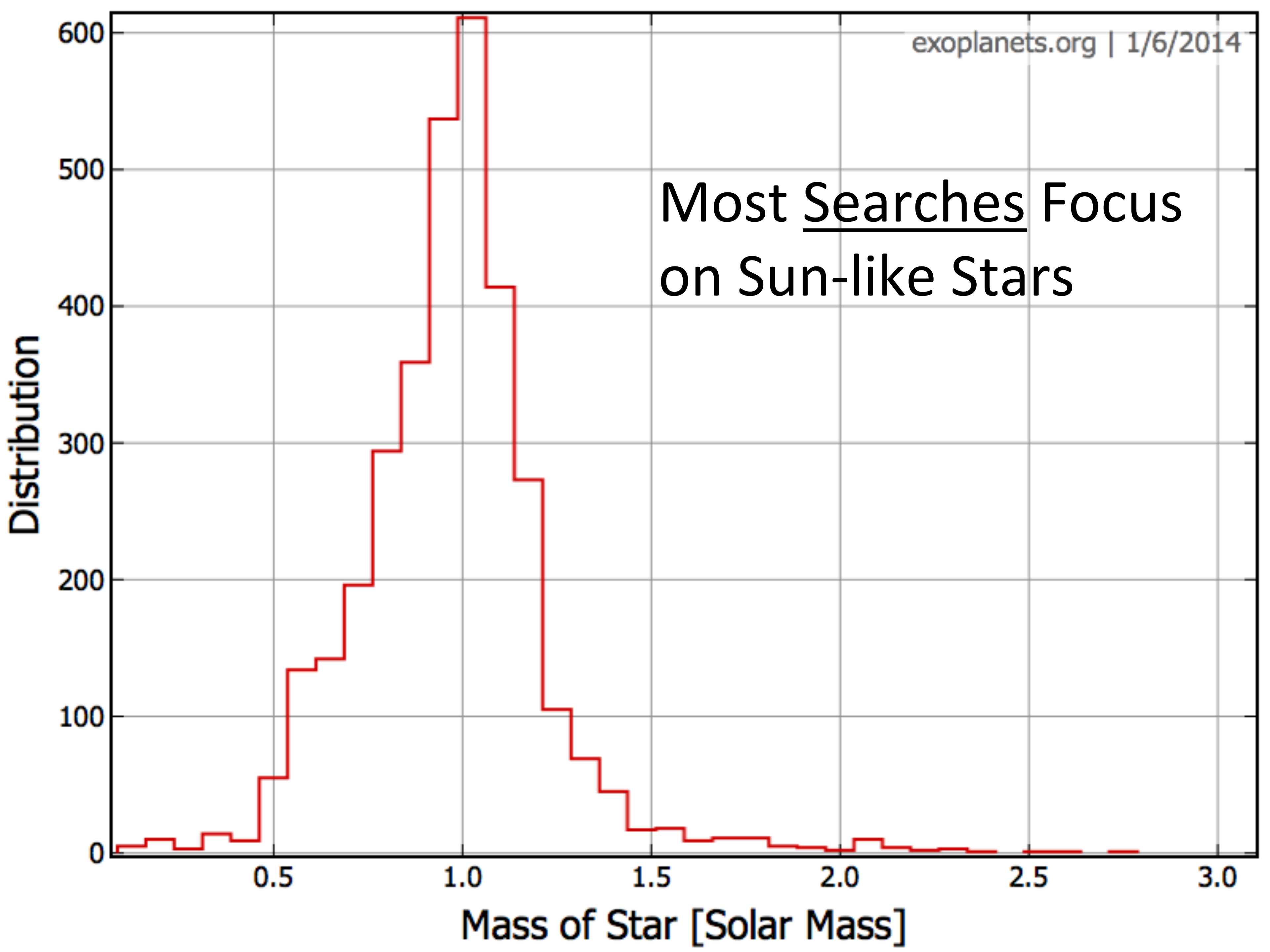
# Orbits Need Not be Circular

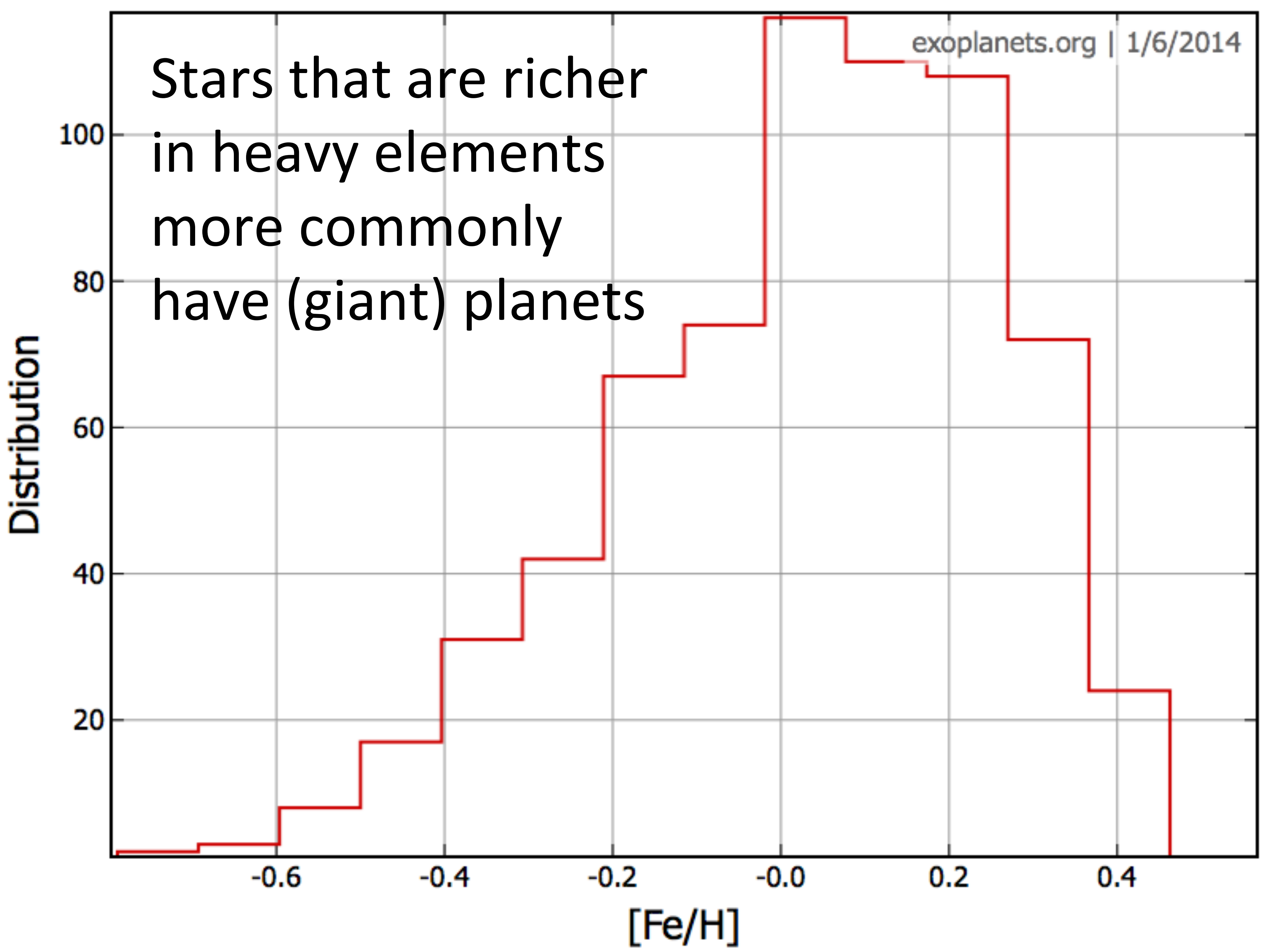



exoplanets.org | 1/5/2012
Planetary Radius [Jupiter Radii]
2.0
1.5
1.0
0.5
0.1
0.8
Semi-Major Axis [Astronomical Units (AU)]


exoplanets.org | 1/6/2014
With Kepler
Planetary Radius [Earth Radii]
10
1
0.01
0.1
1
10
100
Semi-Major Axis [Astronomical Units (AU)]

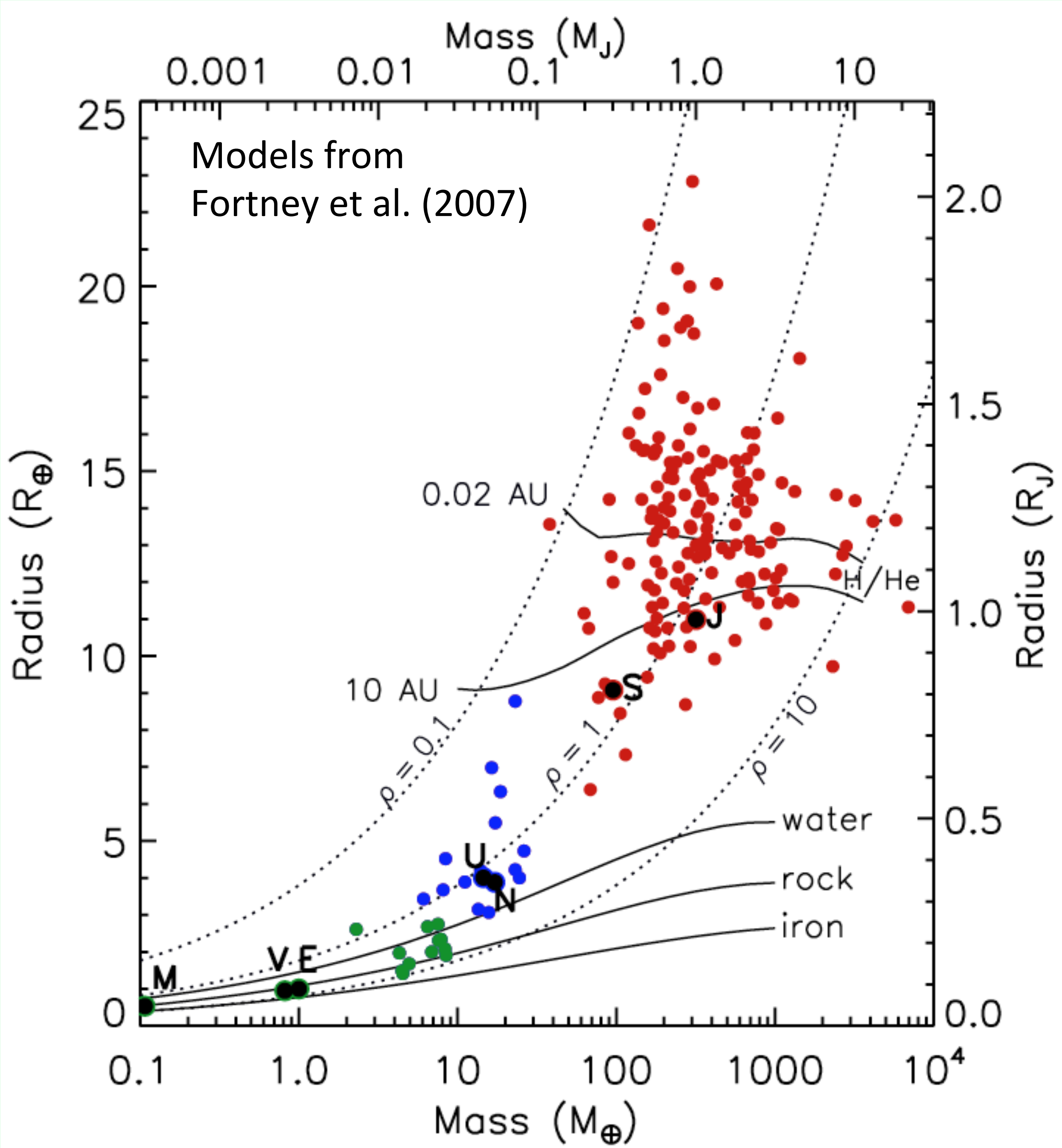

exoplanets.org | 1/6/2014
Most Planetary Systems are Very Near to Us
Distribution
Distance to Star [Parsecs]
0
20
40
60
80
100
200
400
600
800
1000

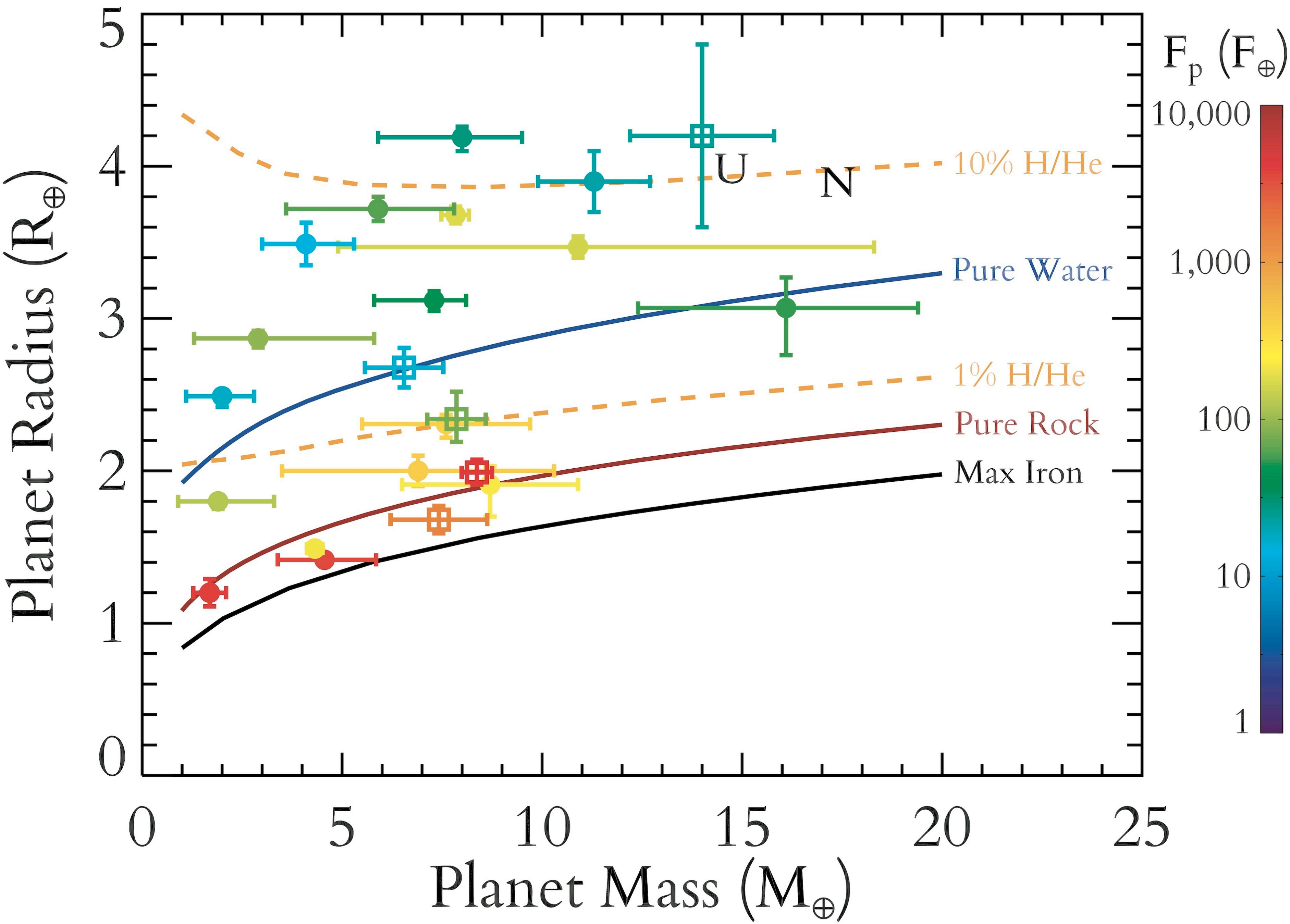

exoplanets.org | 1/6/2014
Most Searches Focus on Sun-like Stars
Distribution
600
500
400
300
200
100
0
0.5
1.0
1.5
2.0
2.5
3.0
Mass of Star [Solar Mass]



Stars that are richer in heavy elements more commonly have (giant) planets
exoplanets.org | 1/6/2014
Distribution
100
80
60
40
20
-0.6
-0.4
-0.2
-0.0
0.2
0.4
[Fe/H]

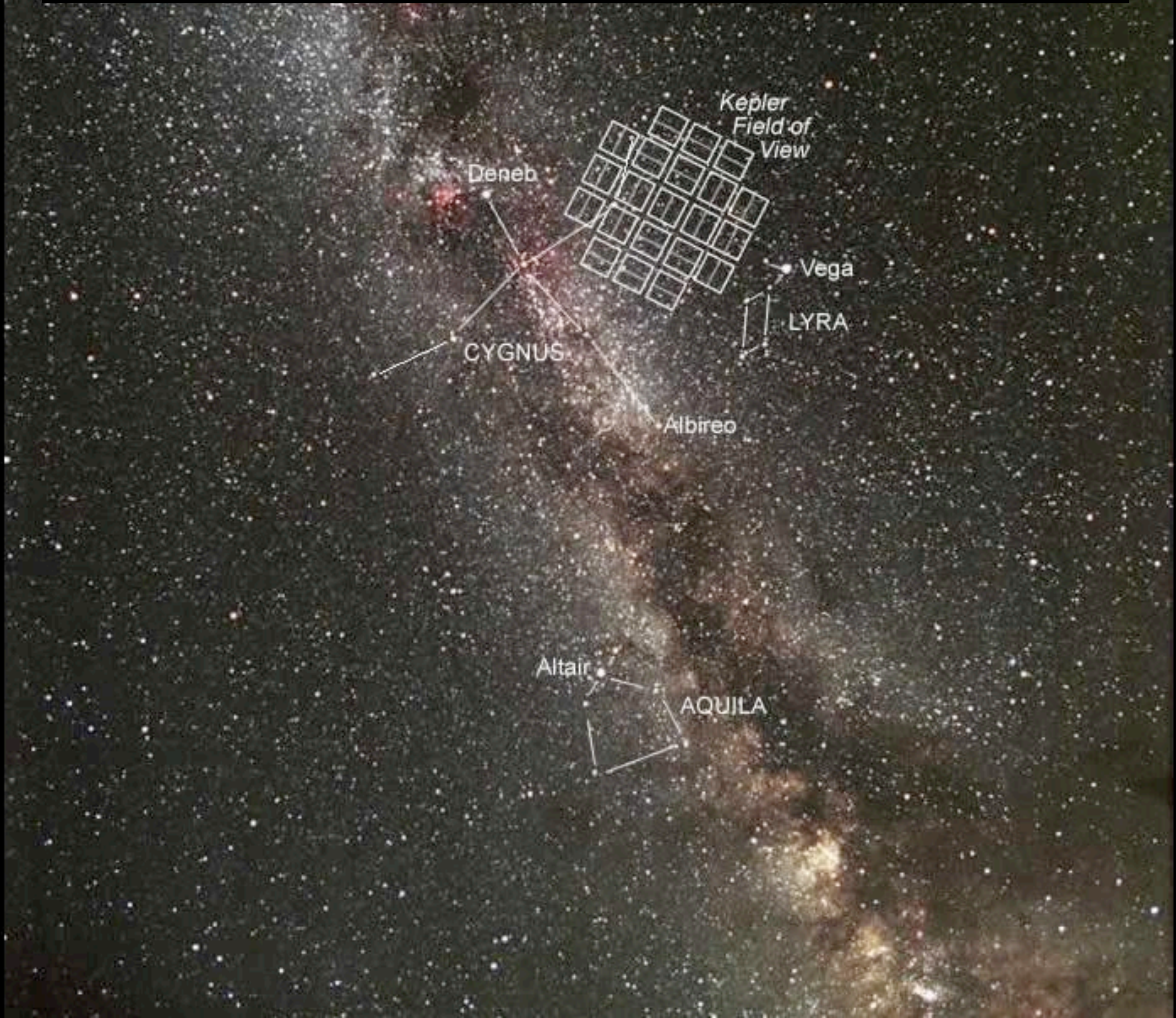
# Planetary Masses and Radii Tell Us a Great Deal about Composition

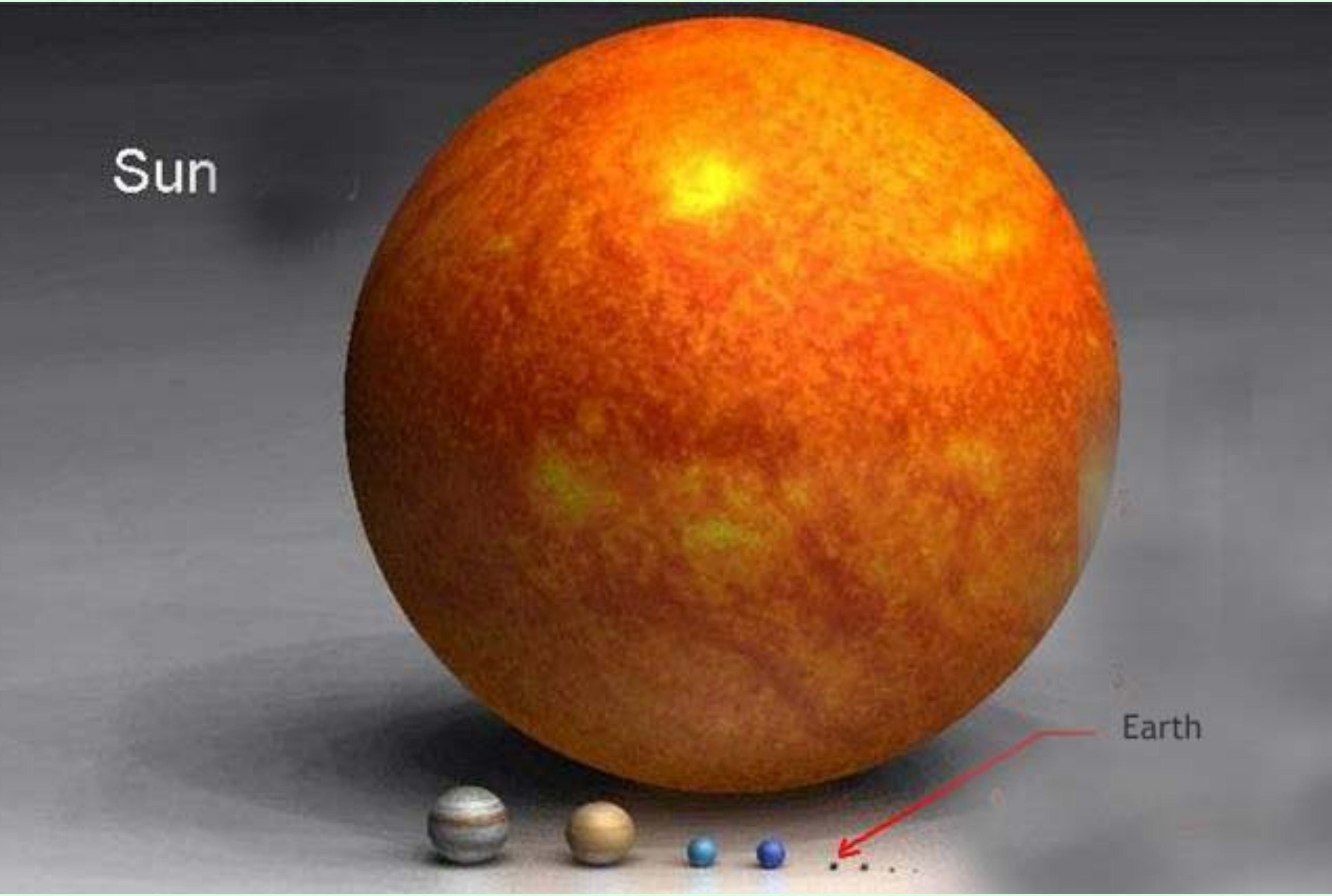




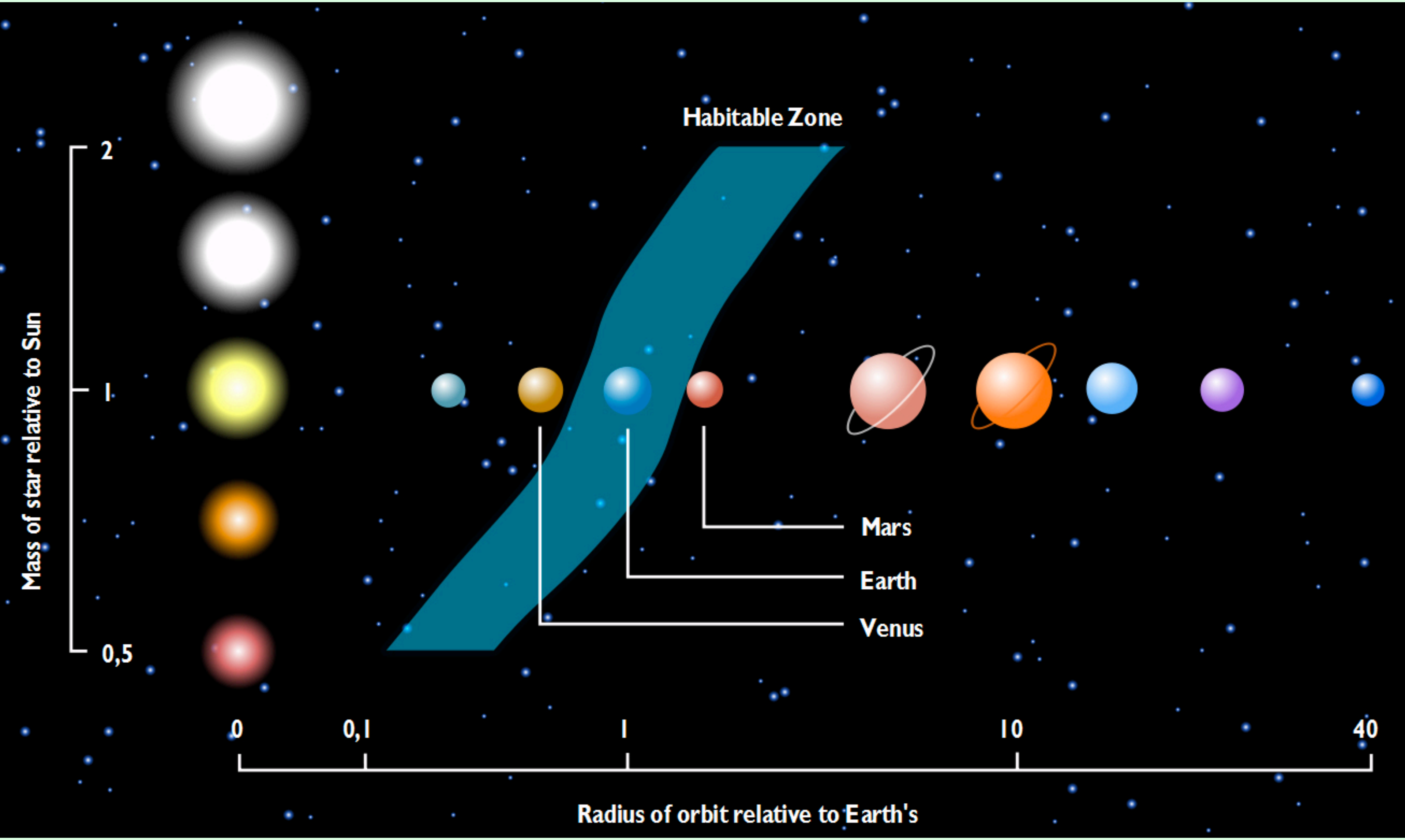
Planet Radius ($R_\oplus$)
Planet Mass ($M_\oplus$)
$F_p$ ($F_\oplus$)
10,000
1,000
100
10
1
10% H/He
Pure Water
1% H/He
Pure Rock
Max Iron
U
N
0
1
2
3
4
5
0
5
10
15
20
25

# What Kepler is Showing Us About the Frequency And Structure Of Planets Around Other Stars




Sun
Earth

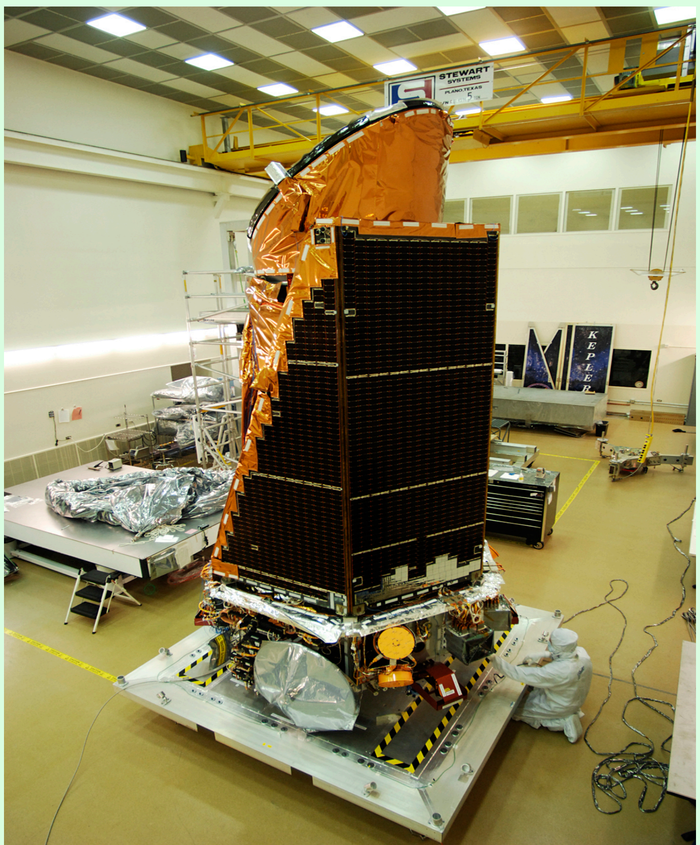
Kepler is designed to find Earth-sized planets in Earth-like orbits around Sun-like stars

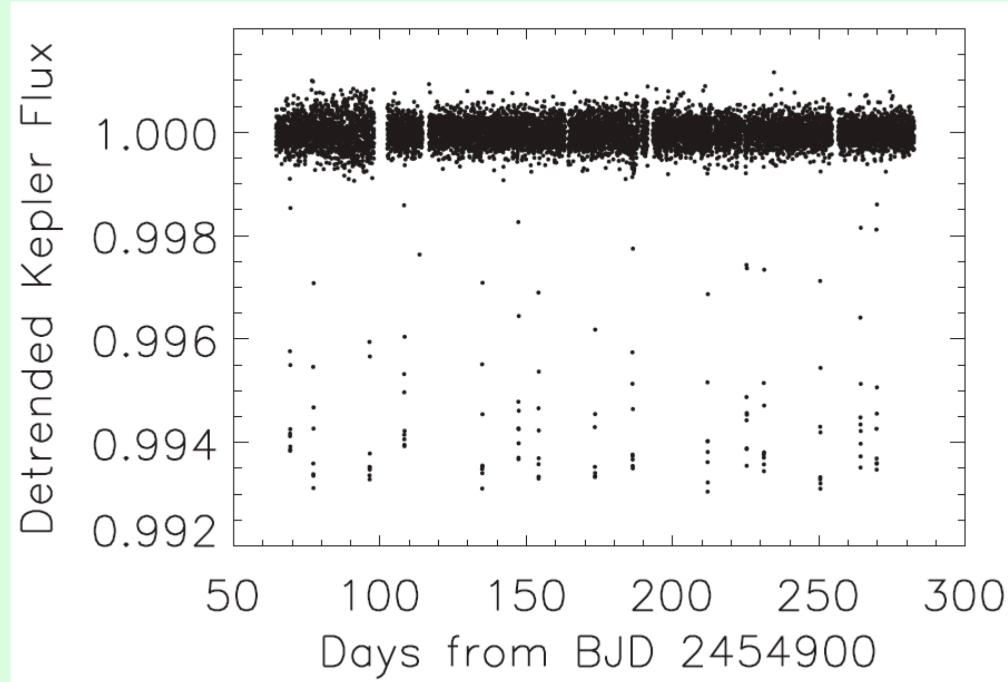


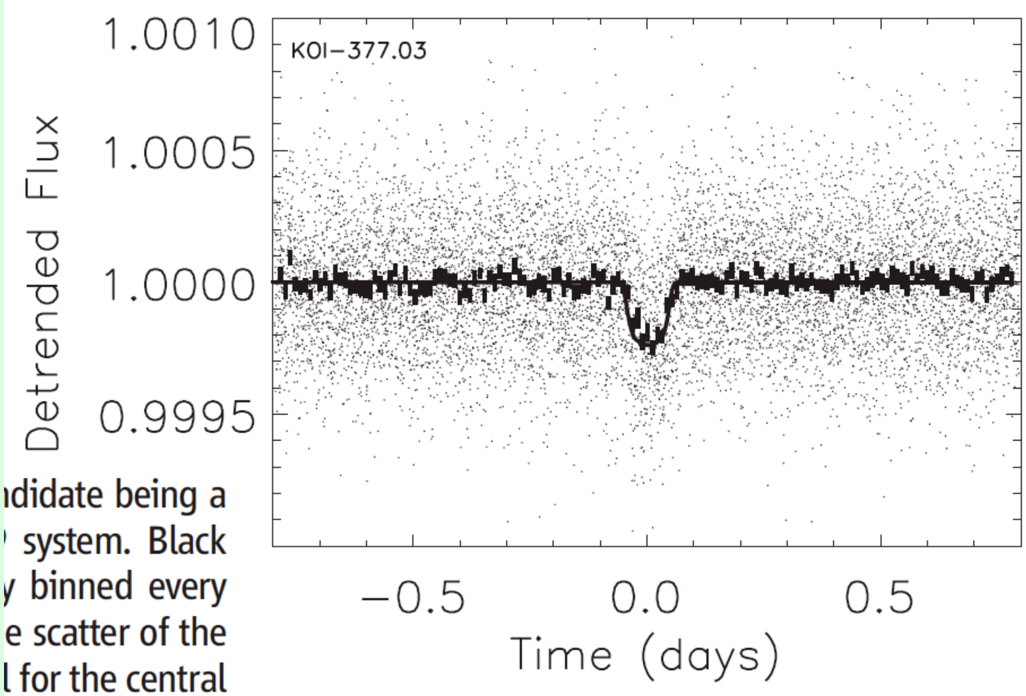
# Showcasing the Kepler Planets

- Kepler monitored about 150,000 stars every 30 minutes
- The team announced 200 “confirmed planets” so far
- Kepler has announced 3500+ candidates, around 90% of which are thought to be real planets
  - Previous number of known exoplanets was 600
- How do we visualize these 3500+ planets when we know so little about them?
- No pictures!!!

- *Kepler Mission* is optimized for finding habitable planets (0.5 to 5 $M_{\oplus}$) in HZ (near 1 AU) of Sun-like stars
- Continuously monitor 150,000 stars for 4 years using 1 meter telescope

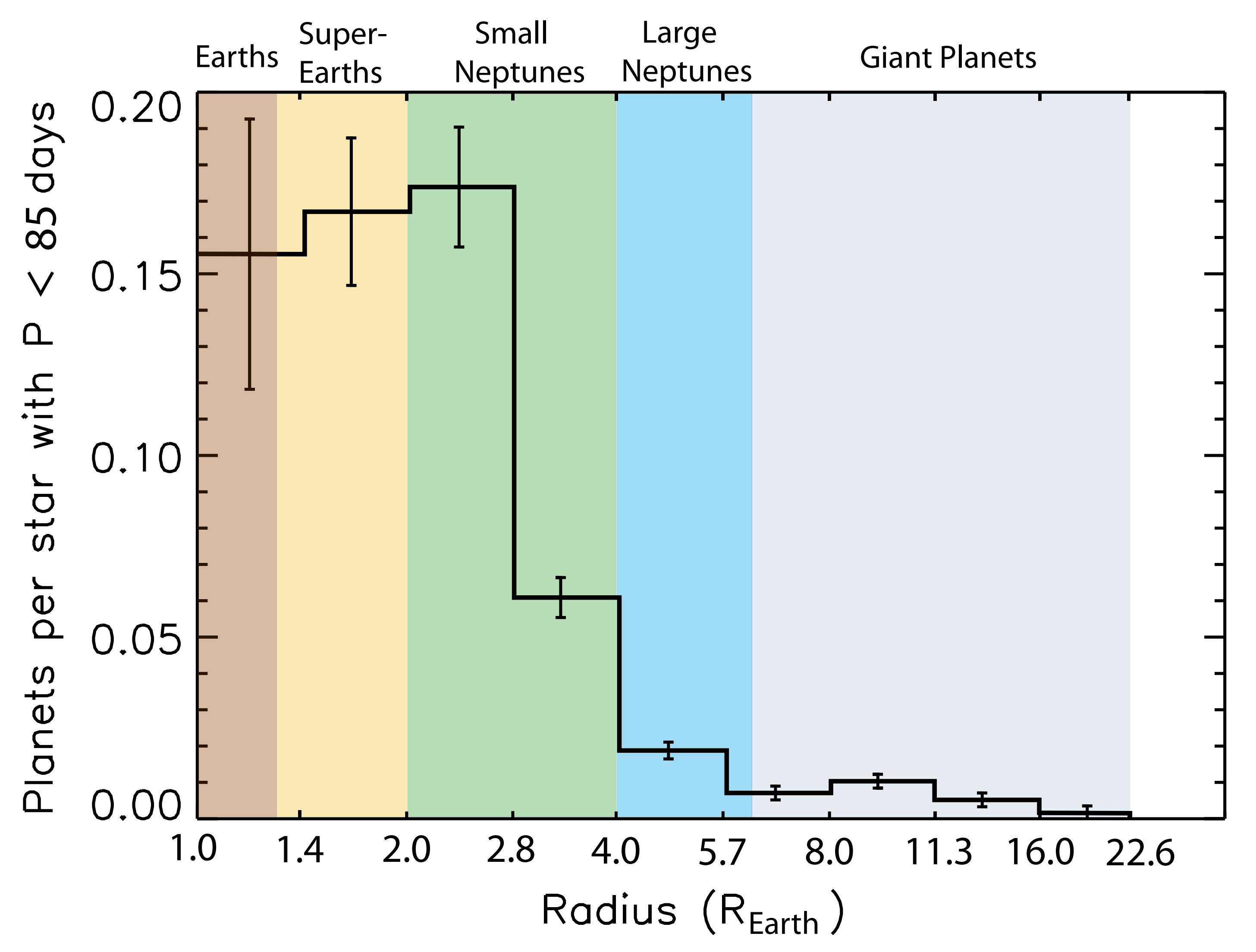



ndidate being a
system. Black
y binned every
e scatter of the
l for the central

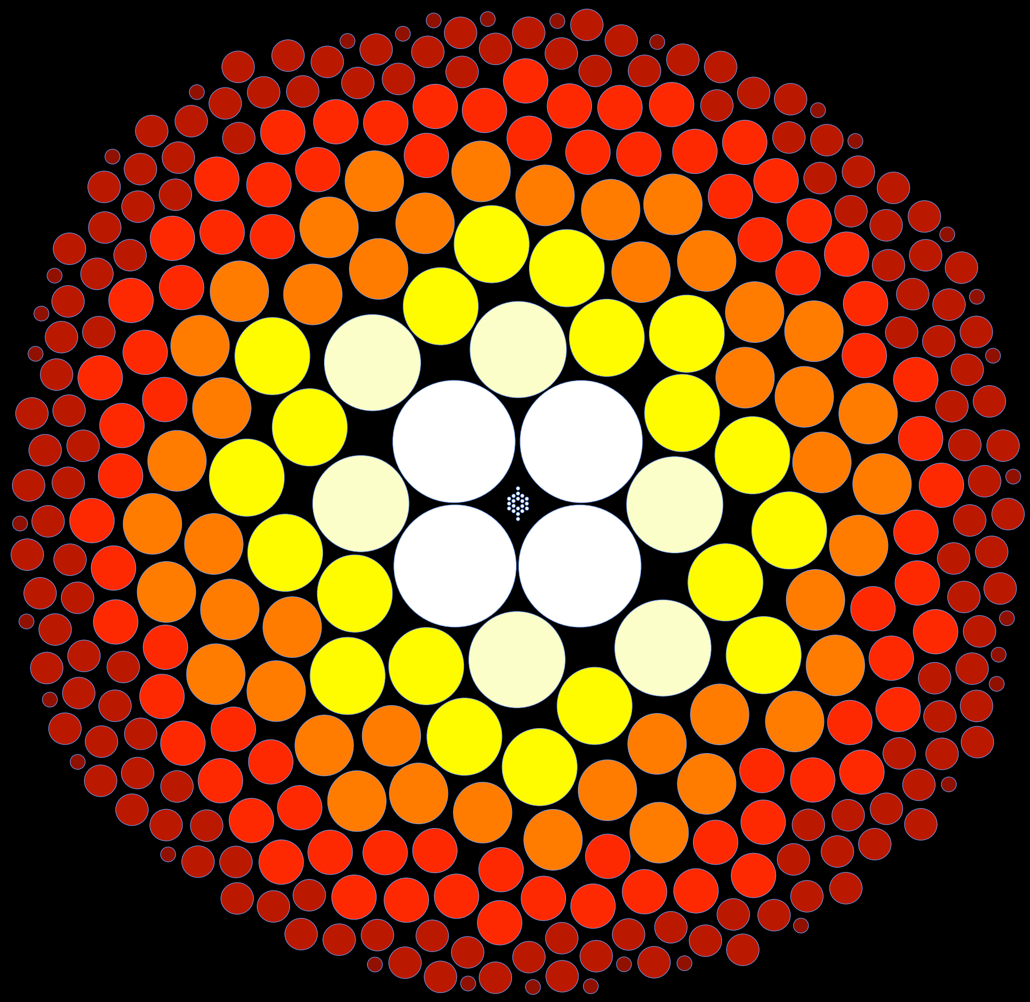
# The frequency of planets within 85 days of Sun-like stars




Based on ~2300 planet candidates

Fressin et al. (2013)

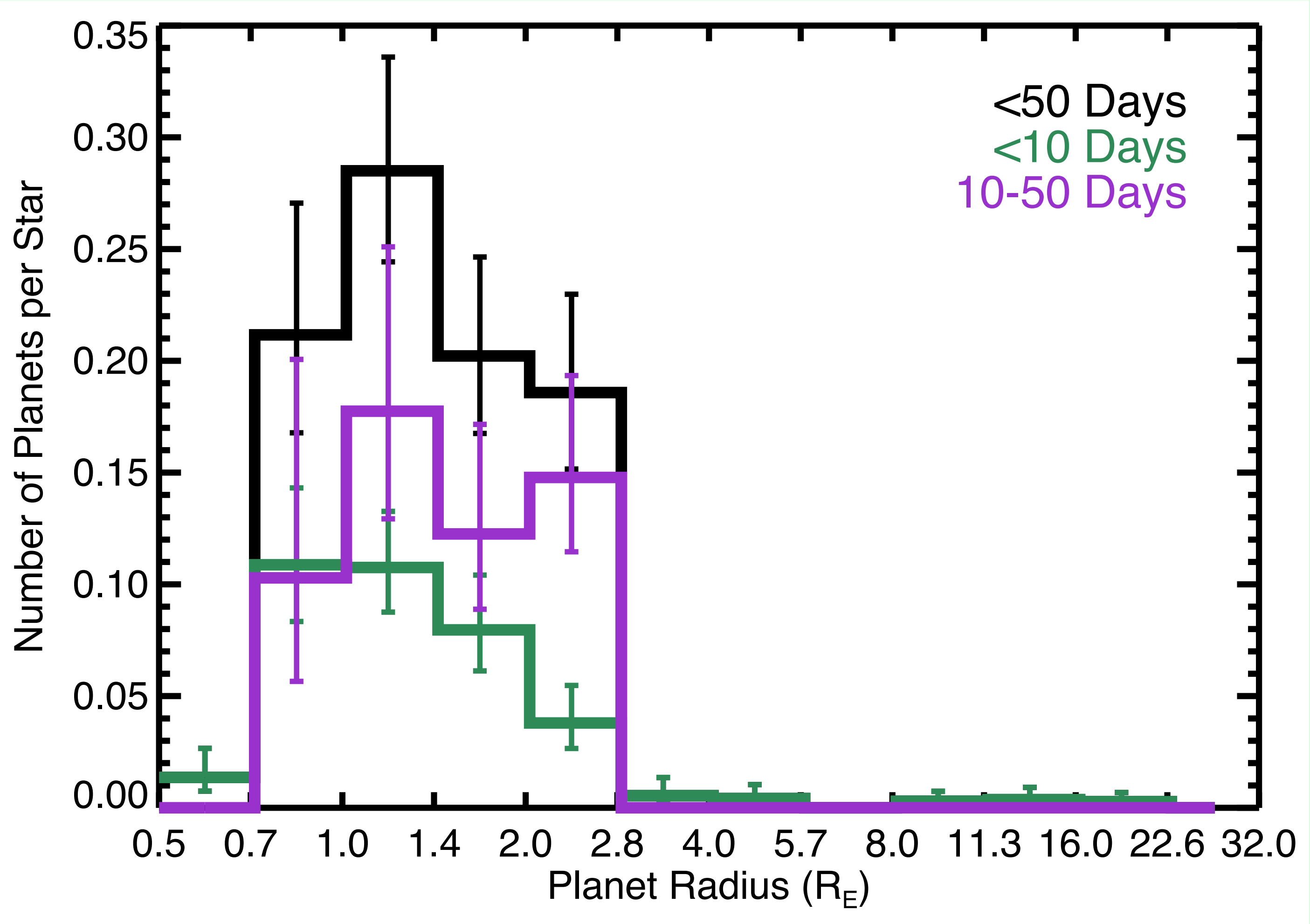
# Stars within 30 lightyears of the Sun



| | |
|---|---|
| O | 0 |
| B | 0 |
| A | 4 |
| F | 6 |
| G | 20 |
| K | 44 |
| M | 246 |

Todd Henry, Georgia State University

# The frequency of planets within 50 days of M stars

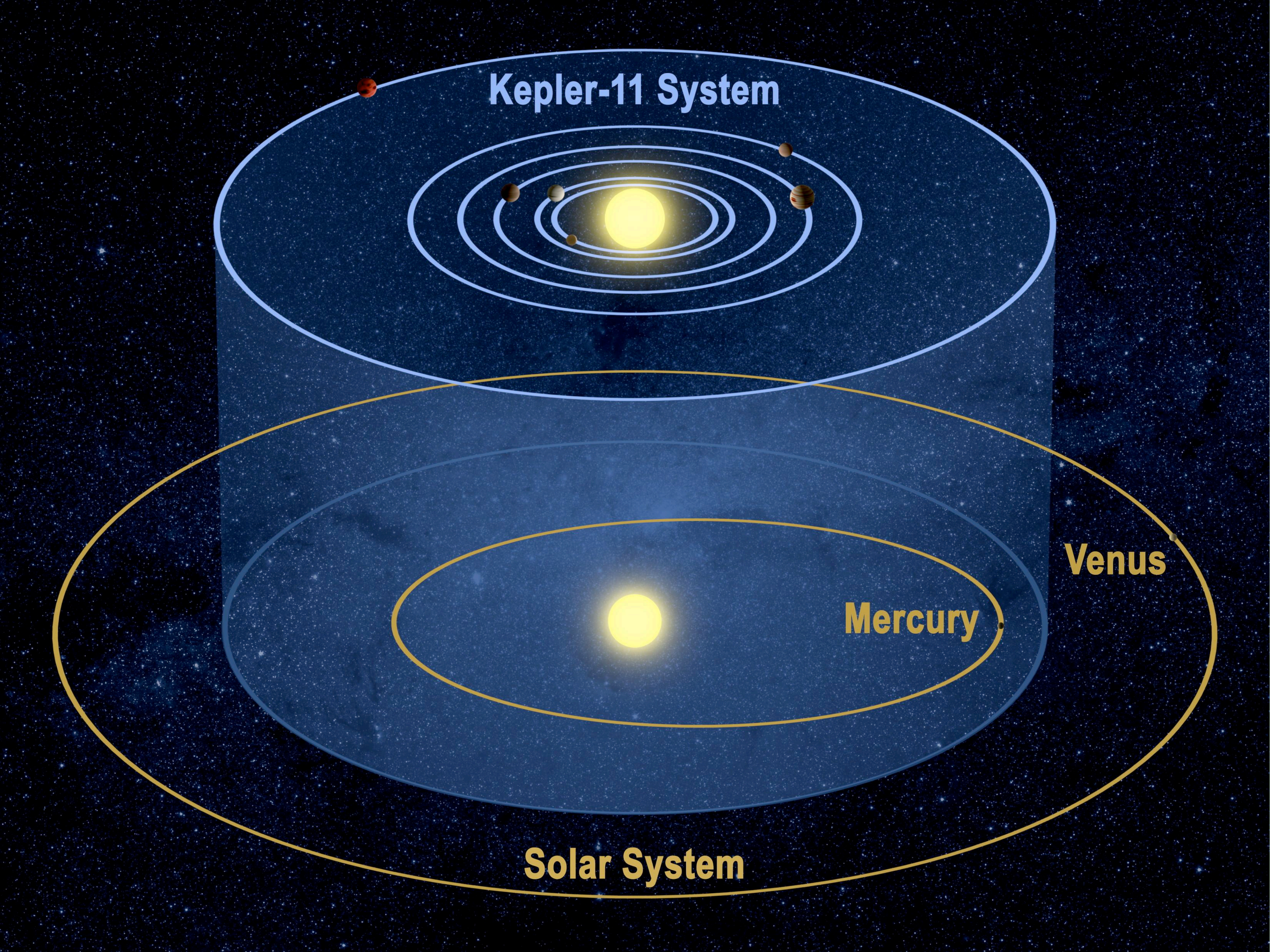



Swift, Johnson, et al. (2013): 1.5 planets per M star within ~85 days

Dressing & Charbonneau (2013)


## Kepler-11

- The most densely-packed planetary system yet found
- 5 planets within the orbit of Mercury
- Masses obtained only from Transit Timing Variations, with no Stellar RV
- Relatively low density for all planets implies thick H/He atmospheres for most


Kepler-11 System
Venus
Mercury
Solar System

# Kepler-11: Picking out the Planets

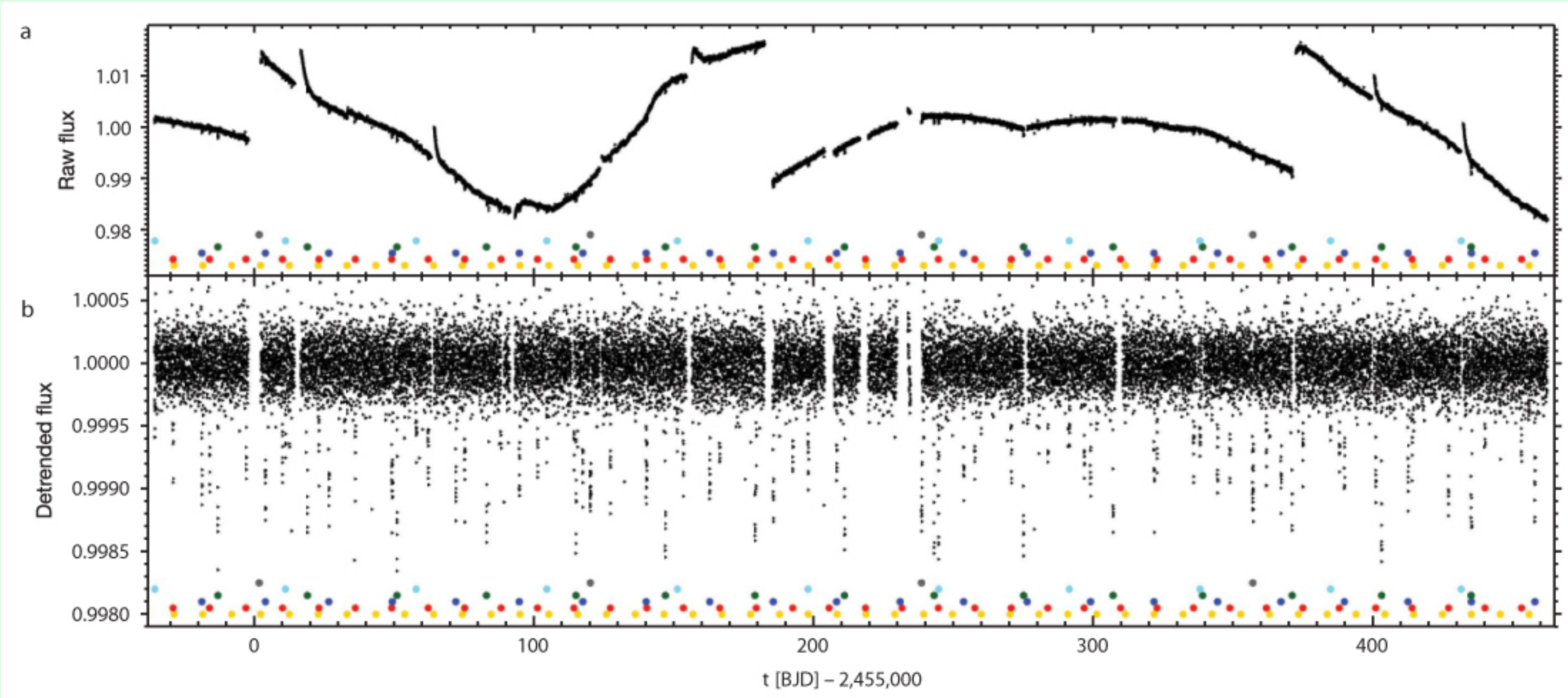
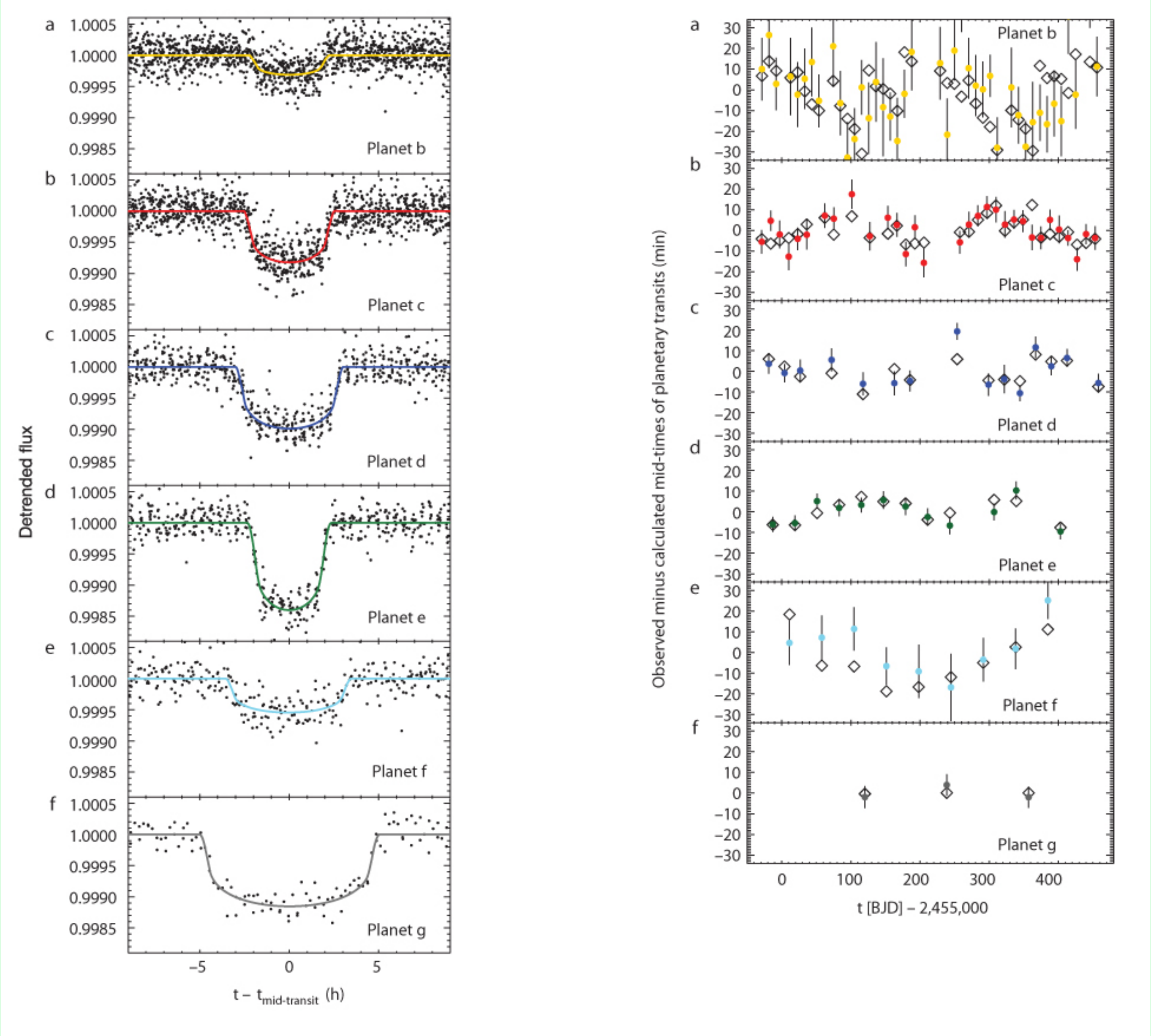



**Table 1 | Planet properties**

| Planet | Period (days) | Epoch (BJD) | Semi-major axis (AU) | Inclination (°) | Transit duration (h) | Transit depth (millimagnitude) | Radius ($R_\oplus$) | Mass ($M_\oplus$) | Density (g cm$^{-3}$) |
|---|---|---|---|---|---|---|---|---|---|
| b | $10.30375 \pm 0.00016$ | $2,454,971.5052 \pm 0.0077$ | $0.091 \pm 0.003$ | $88.5^{+1.0}_{-0.6}$ | $4.02 \pm 0.08$ | $0.31 \pm 0.01$ | $1.97 \pm 0.19$ | $4.3^{+2.2}_{-2.0}$ | $3.1^{+2.1}_{-1.5}$ |
| c | $13.02502 \pm 0.00008$ | $2,454,971.1748 \pm 0.0031$ | $0.106 \pm 0.004$ | $89.0^{+1.0}_{-0.6}$ | $4.62 \pm 0.04$ | $0.82 \pm 0.01$ | $3.15 \pm 0.30$ | $13.5^{+4.8}_{-6.1}$ | $2.3^{+1.3}_{-1.1}$ |
| d | $22.68719 \pm 0.00021$ | $2,454,981.4550 \pm 0.0044$ | $0.159 \pm 0.005$ | $89.3^{+0.6}_{-0.4}$ | $5.58 \pm 0.06$ | $0.80 \pm 0.02$ | $3.43 \pm 0.32$ | $6.1^{+3.1}_{-1.7}$ | $0.9^{+0.5}_{-0.3}$ |
| e | $31.99590 \pm 0.00028$ | $2,454,987.1590 \pm 0.0037$ | $0.194 \pm 0.007$ | $88.8^{+0.2}_{-0.2}$ | $4.33 \pm 0.07$ | $1.40 \pm 0.02$ | $4.52 \pm 0.43$ | $8.4^{+2.5}_{-1.9}$ | $0.5^{+0.2}_{-0.2}$ |
| f | $46.68876 \pm 0.00074$ | $2,454,964.6487 \pm 0.0059$ | $0.250 \pm 0.009$ | $89.4^{+0.3}_{-0.2}$ | $6.54 \pm 0.14$ | $0.55 \pm 0.02$ | $2.61 \pm 0.25$ | $2.3^{+2.2}_{-1.2}$ | $0.7^{+0.7}_{-0.4}$ |
| g | $118.37774 \pm 0.00112$ | $2,455,120.2901 \pm 0.0022$ | $0.462 \pm 0.016$ | $89.8^{+0.2}_{-0.2}$ | $9.60 \pm 0.13$ | $1.15 \pm 0.03$ | $3.66 \pm 0.35$ | $<300$ | – |

# Kepler-11: Lightcurves and Transit Times



For the Rest of the Week:
Read Chapter 1 in Our Book