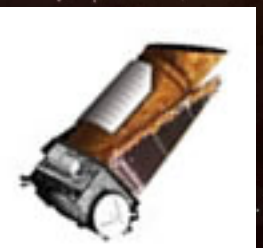
Kepler's Multiple Planet Systems



TITech & Kobe Univ.
February 2018

Jack J. Lissauer
NASA Ames

Outline

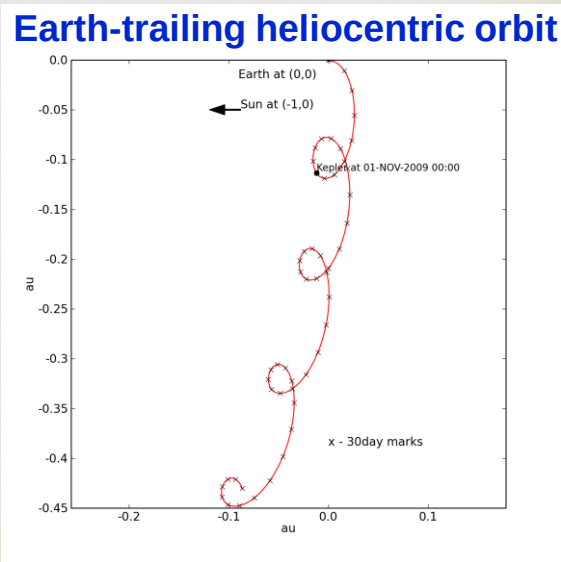
Solar System & Exoplanets

Kepler Mission

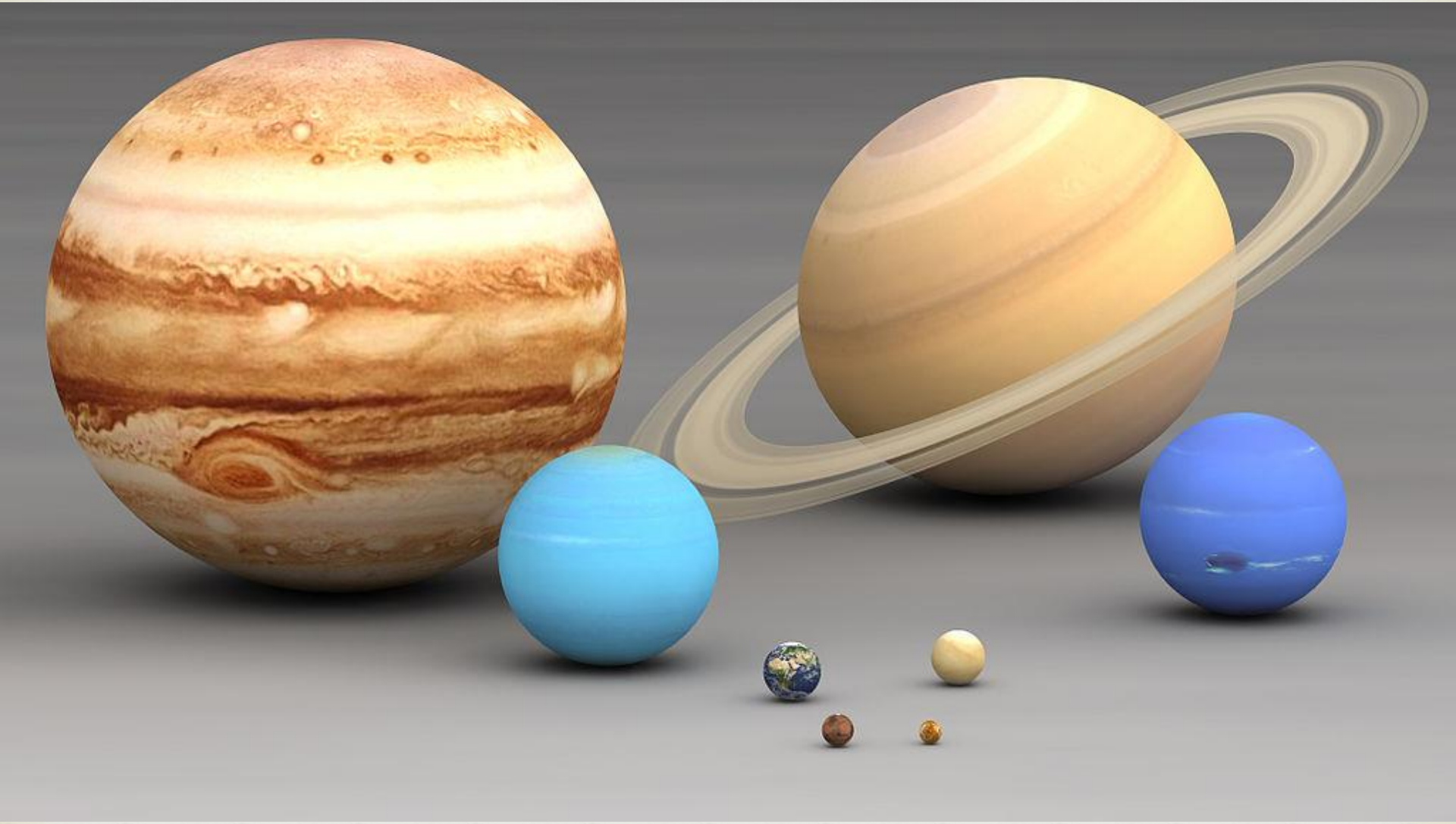
Kepler planets and planetery systems

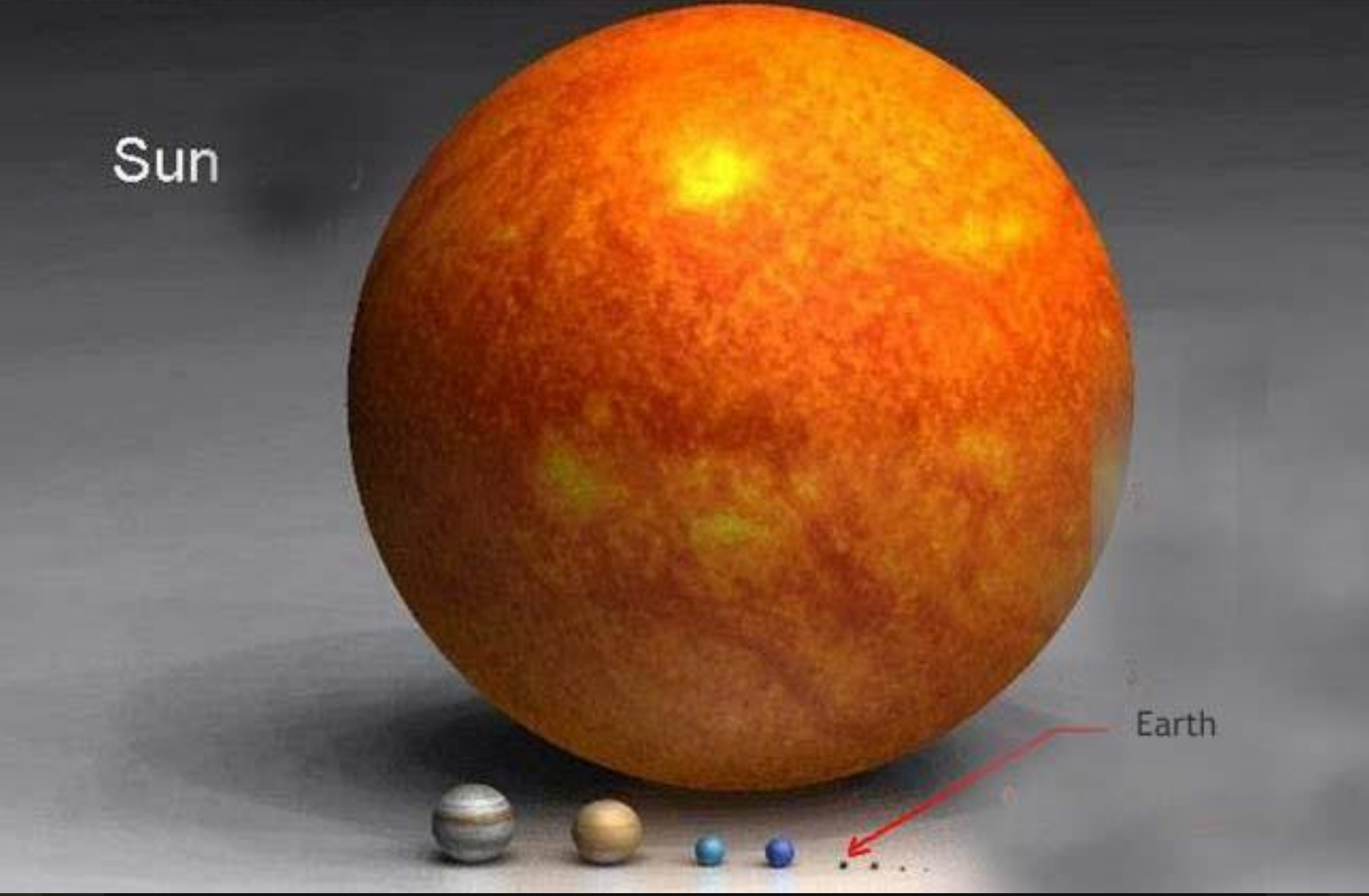
Principal *Kepler* findings

K2 & *TESS*

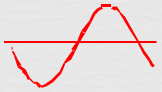
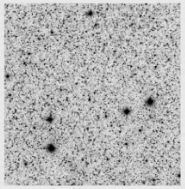
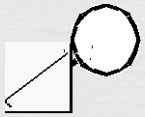
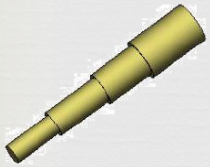


Planets in the Solar System

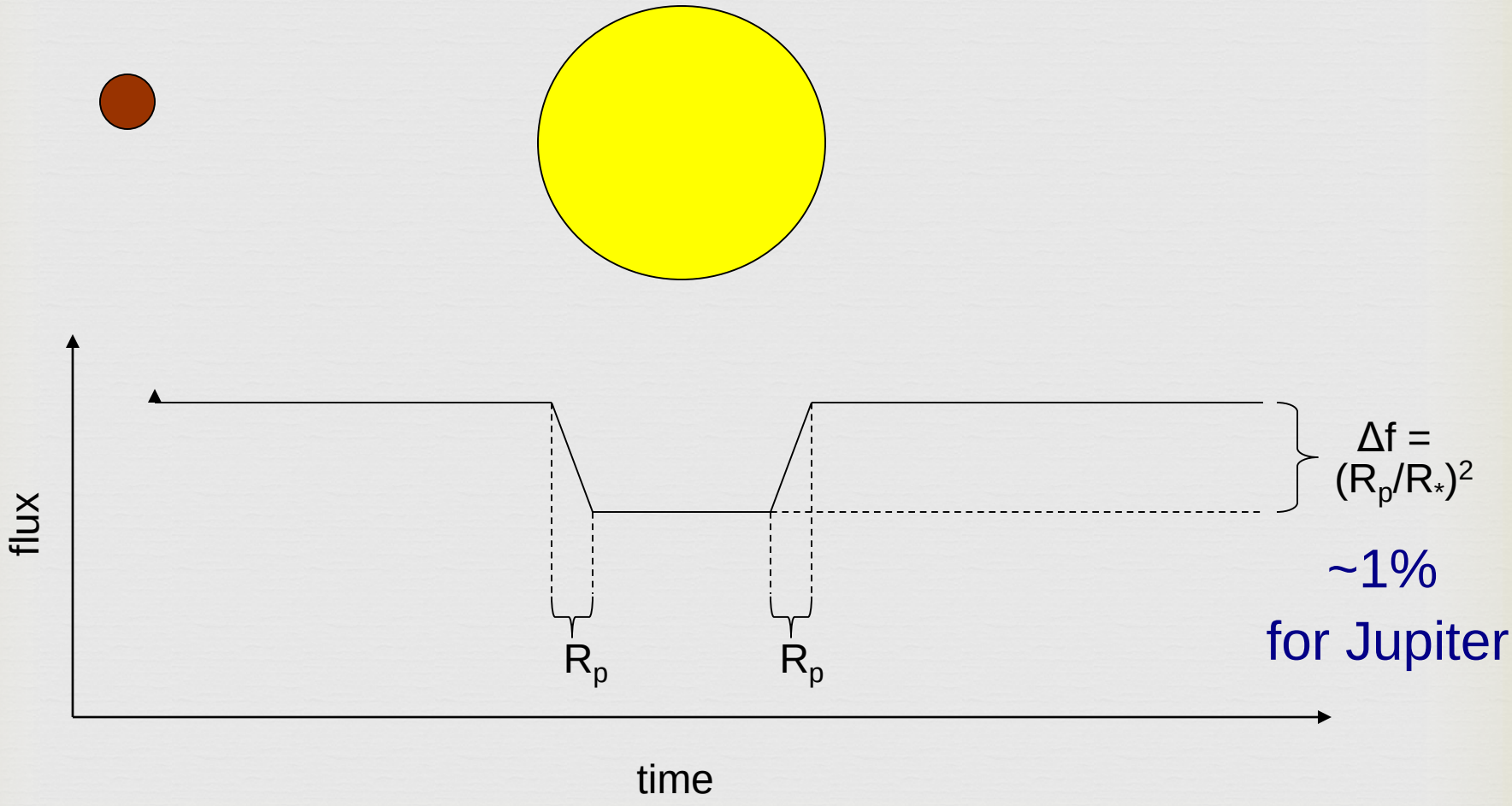



Sun
Earth

Techniques for Finding Extrasolar Planets

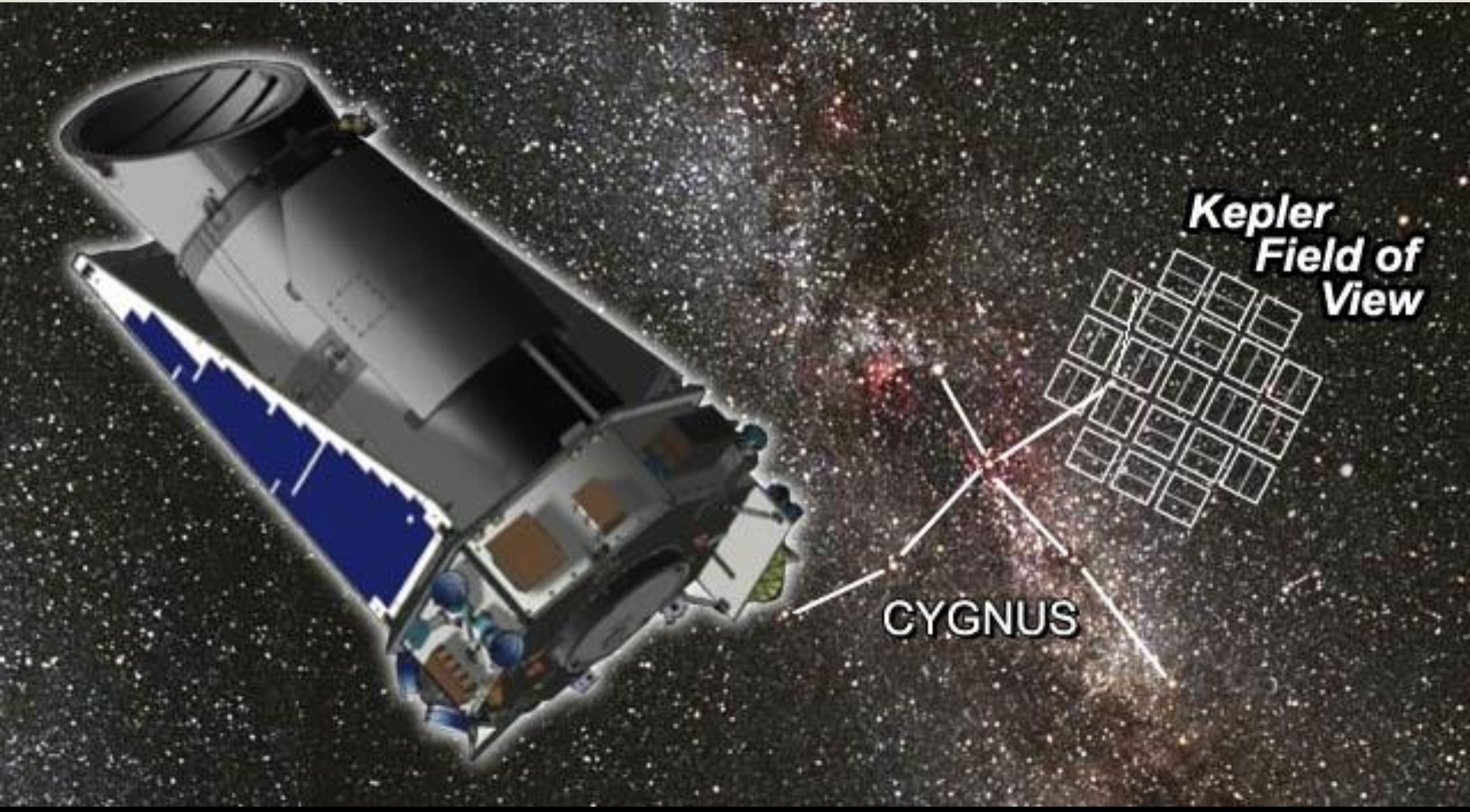
Method	Yield	Size Limit	Status
Pulsar Timing	m/M ; τ	Lunar	Successful (3+~3)
 Radial Velocity	$m \sin i$; τ	super-Earth	Successful (~700)
 Astrometry	m ; τ ; D_s ;	a	
Ground:		Jupiter	Ongoing
Space:		sub-Jupiter	Ongoing - *GAIA*
Transit Photometry	A ; τ ; $\sin i=1$		
 Ground		Neptune	Successful (300)
Space, 27 cm		sub-Neptune	*CoRoT* (~30)
Space, 1 m		**Mercury**	***Kepler* (>2000 + >2000)**
 Microlensing:	f(m,M,r,D_s,D_L)		
Ground		super-Earth	Successful (>50)
 Direct Imaging	*albedo*A* ; τ ; D_s ; a ; M		
Ground		Jupiter	Successful (>30)
Space		Earth	Being studied

Transit Lightcurve



Kepler Mission

- NASA, photometry of > 150,000 stars
- Searched for Earth-like planets in transit
- 30 minute cadence; 4 years observing same FOV
- ~30 ppm in 6 hours for bright targets ($m_v < 12$)

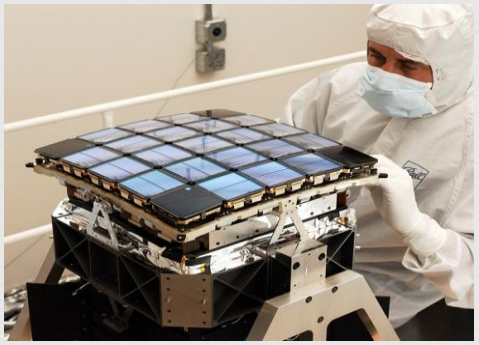


Kepler Mission Goals

Explore the structure and diversity of extrasolar planetary systems

1. Determine the **frequency of terrestrial planets in or near the habitable zone** of a wide variety of spectral types of stars;
2. Determine the distributions of **size** and **semi-major axis** of these planets;
3. Estimate the frequency and orbital distribution of planets in **multiple-star systems**;
4. Determine the distributions of semi-major axis, albedo, size, mass and density of short-period **giant planets**;
5. **Identify additional members** of each photometrically-discovered planetary system using complementary techniques;
6. Determine the **properties of those stars** that harbor planetary systems.

SPACECRAFT & INSTRUMENT

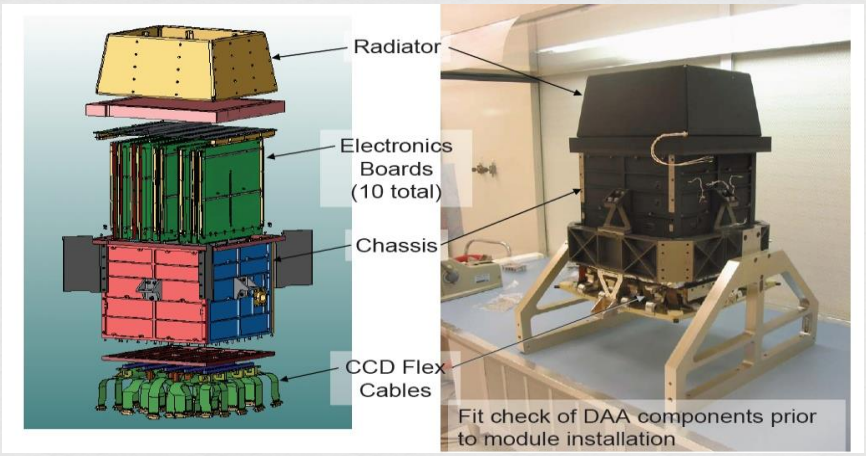


Large focal plane:
94.6 million science pixels

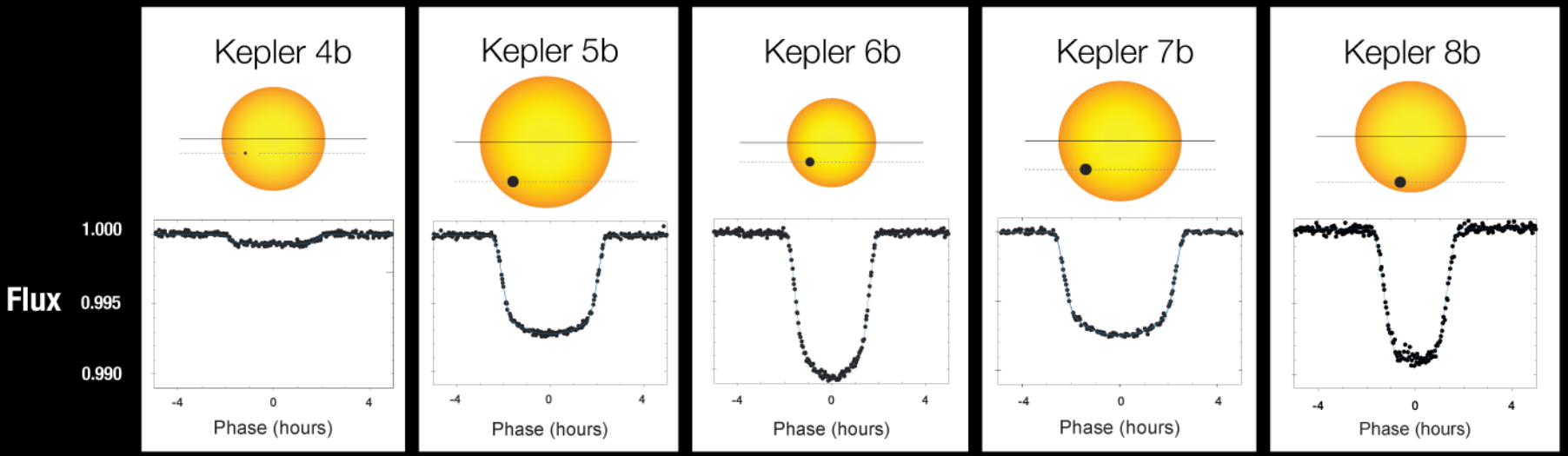
42 science CCDs,
2 channels each

4 fine guidance sensor (FGS) CCDs

CCDs controlled at -85C, Readout electronics at room temperature



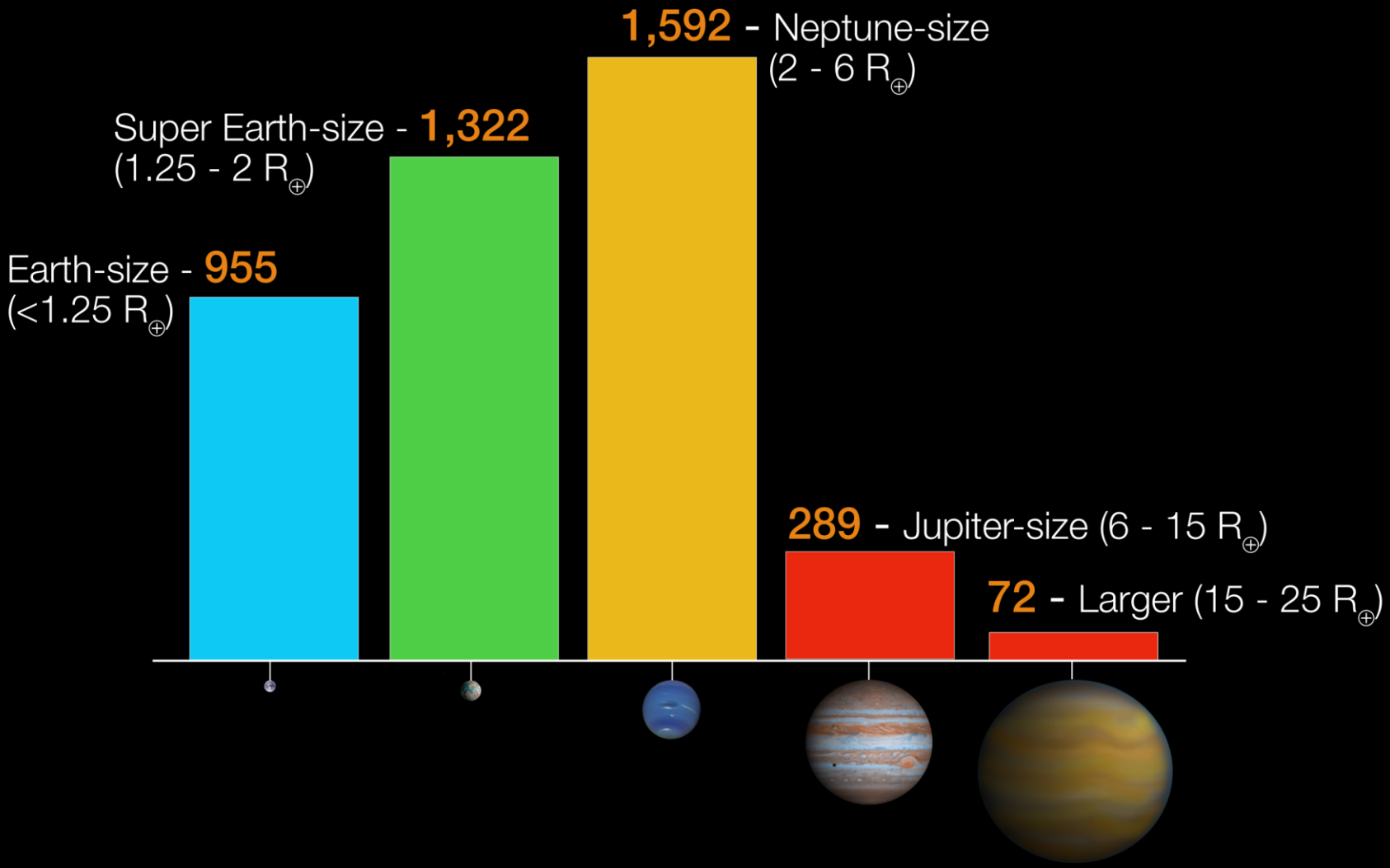
Transit Light Curves



Orbital Period (days)	3.2 days	3.5 days	3.2 days	4.9 days	3.5 days

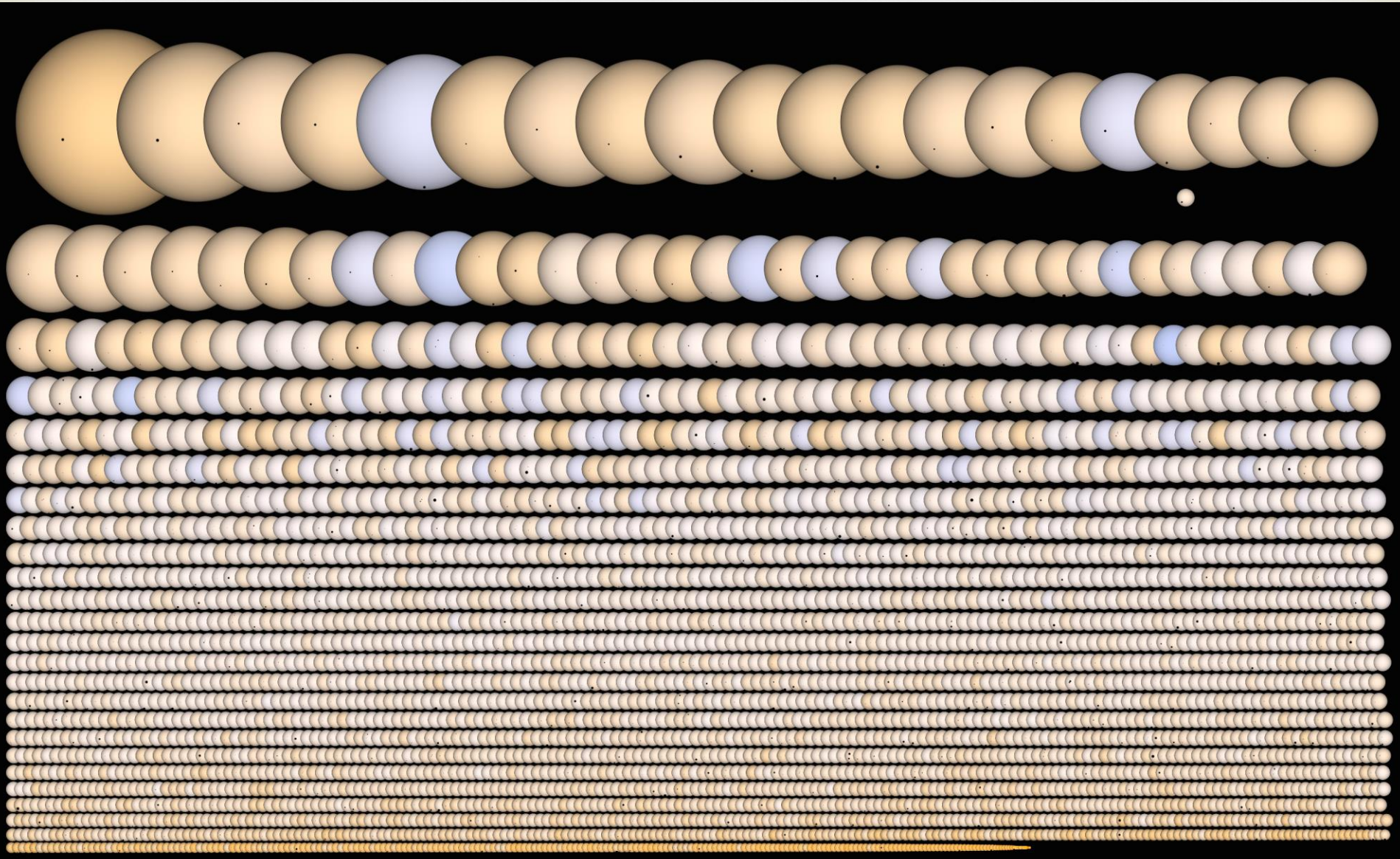
Sizes of Kepler Planet Candidates

As of July 23, 2015



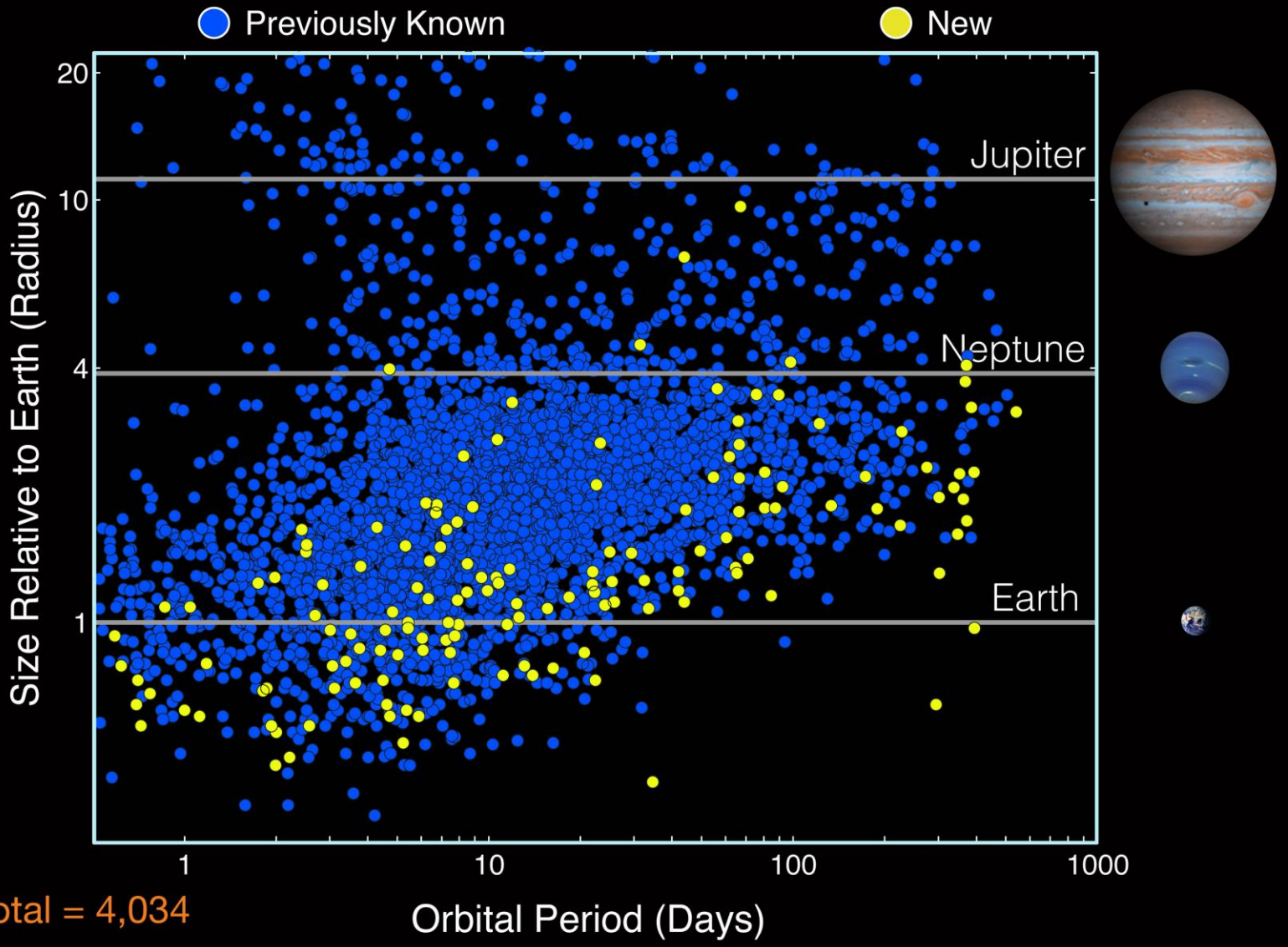
Kepler Planet Candidates & Their Stars

Jason Rowe, 2015



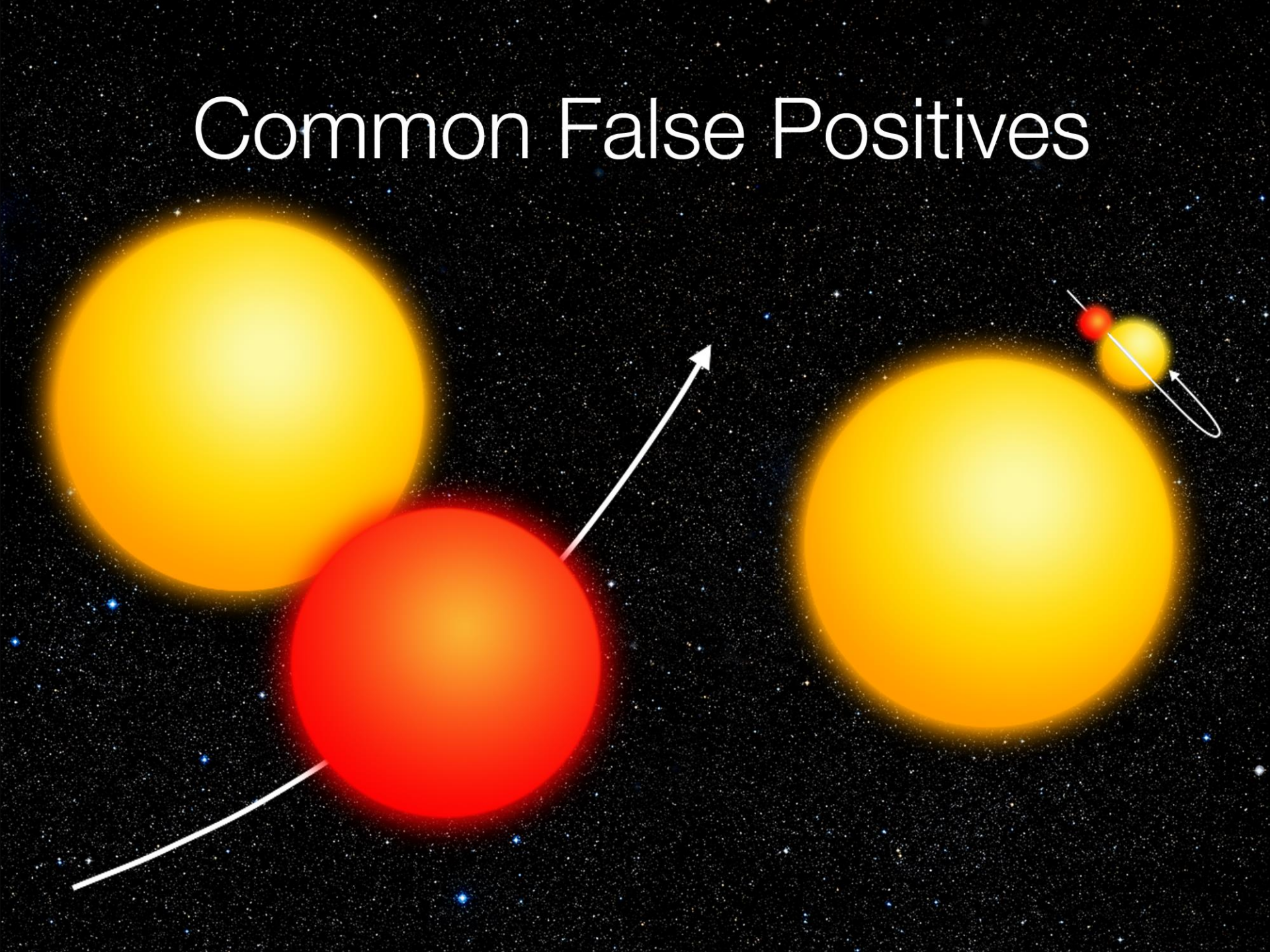
New Kepler Planet Candidates

As of June 2017



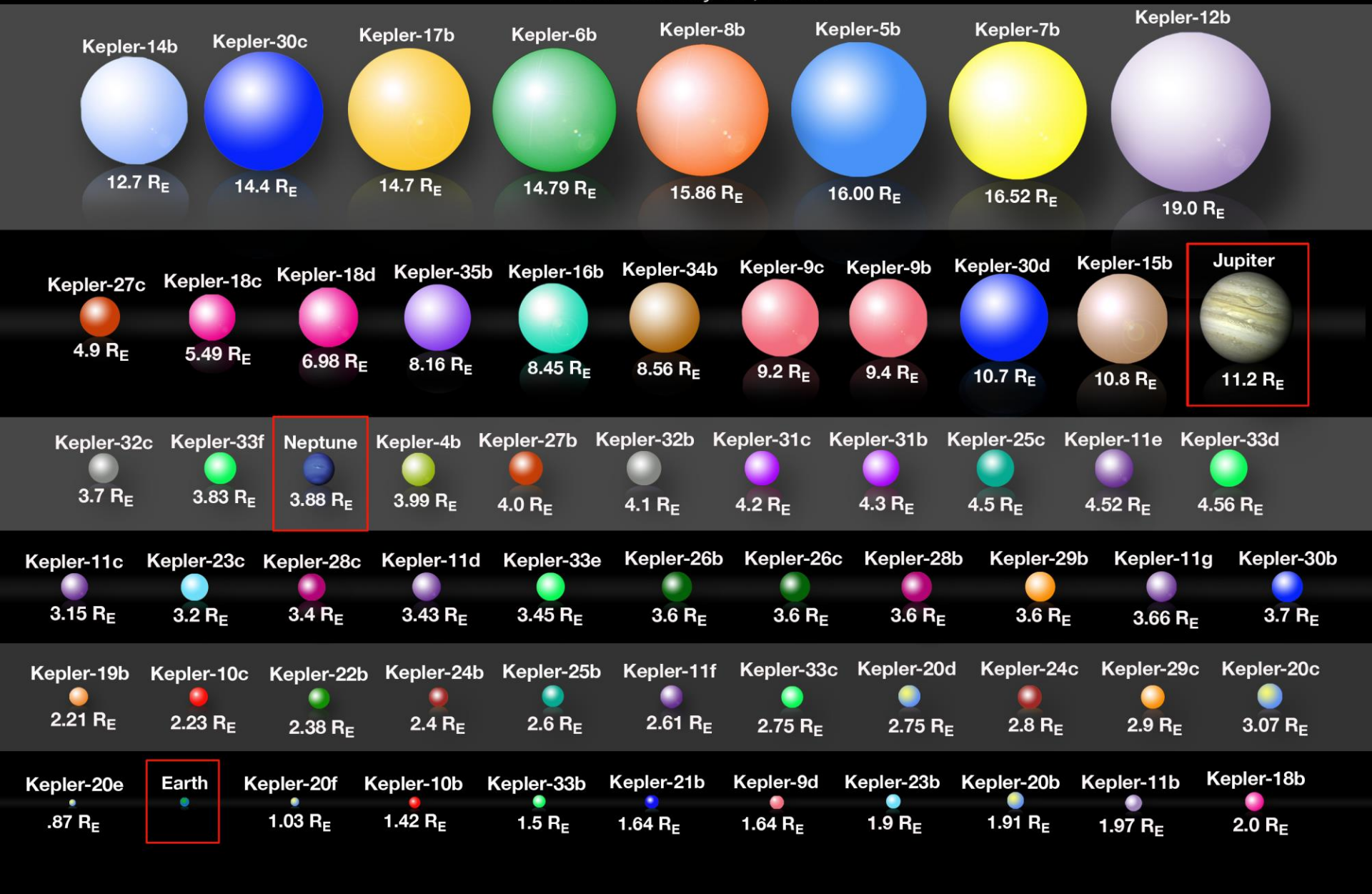
Total = 4,034

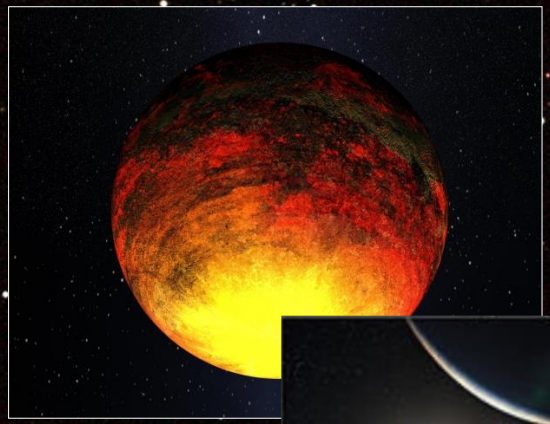
Common False Positives



Kepler Planets

As of February 27, 2012



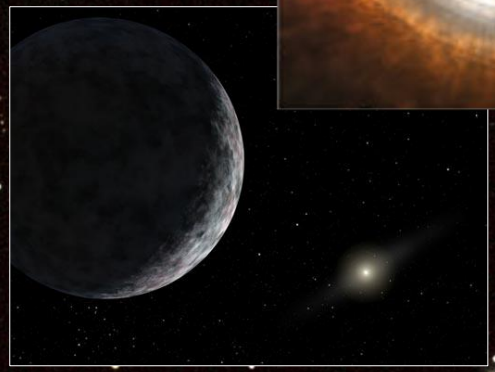


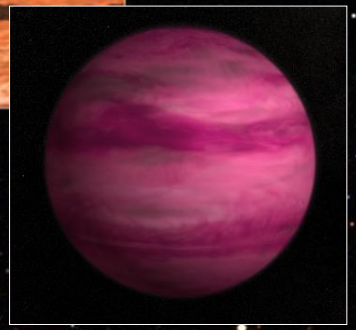






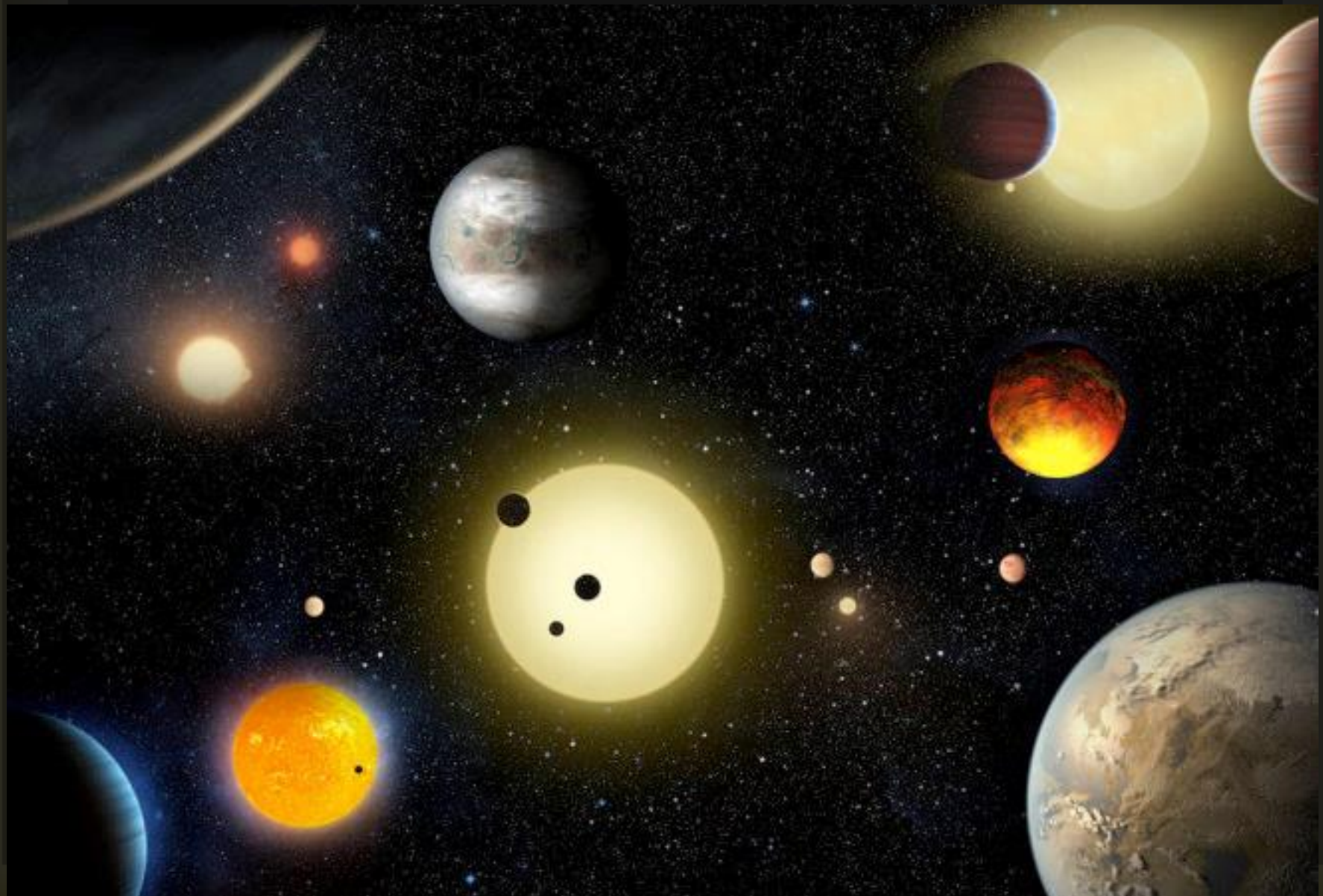


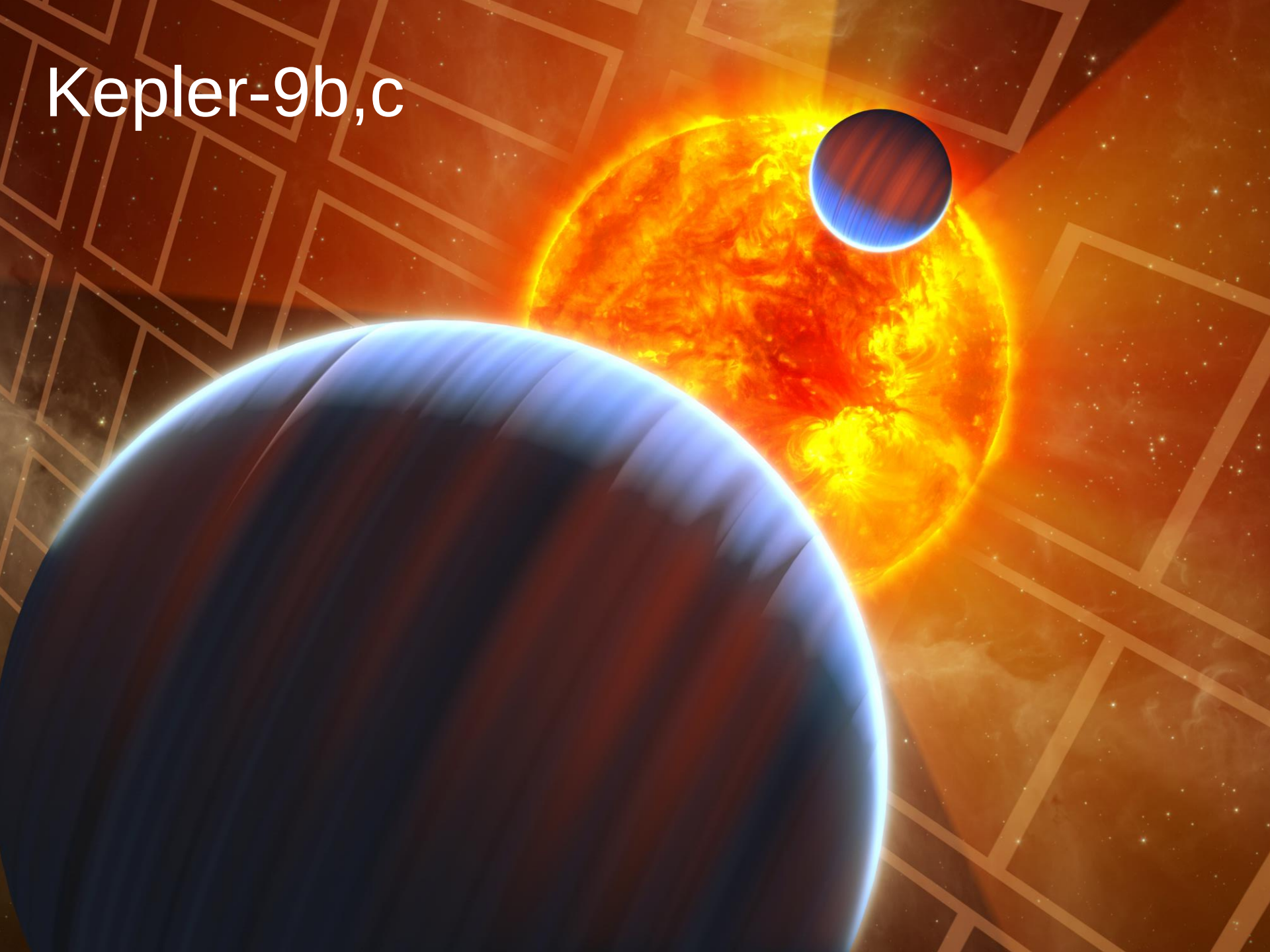





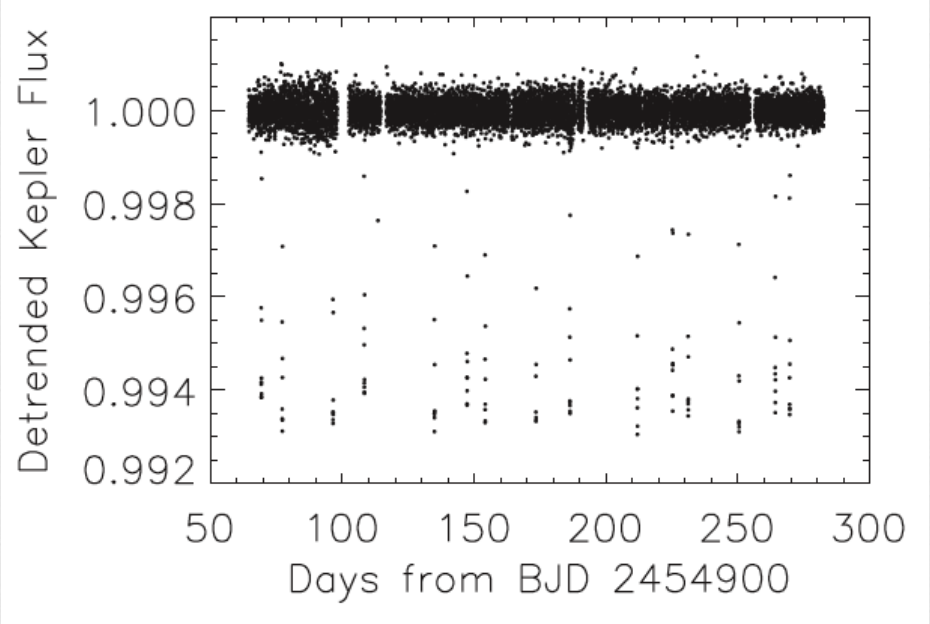

Artist Conceptions
(Science fiction)

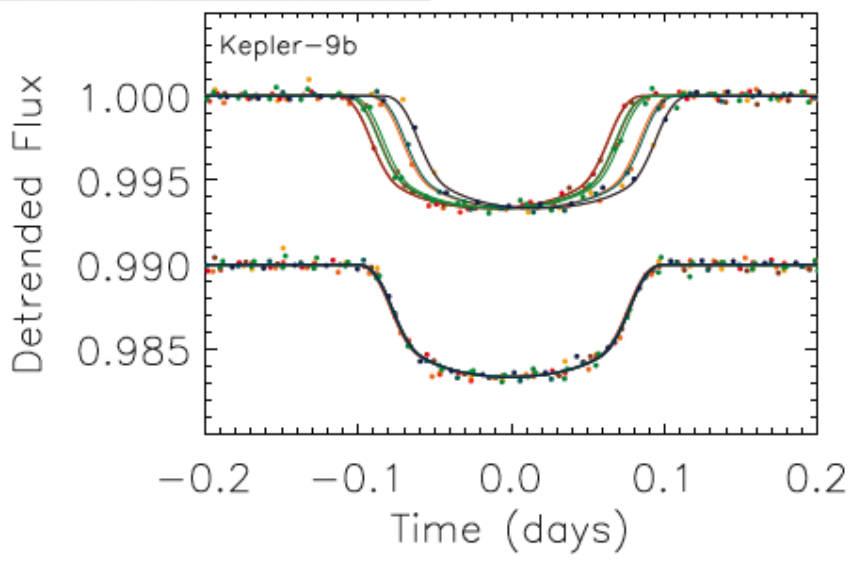
Kepler found a wide diversity of planets and planetary systems

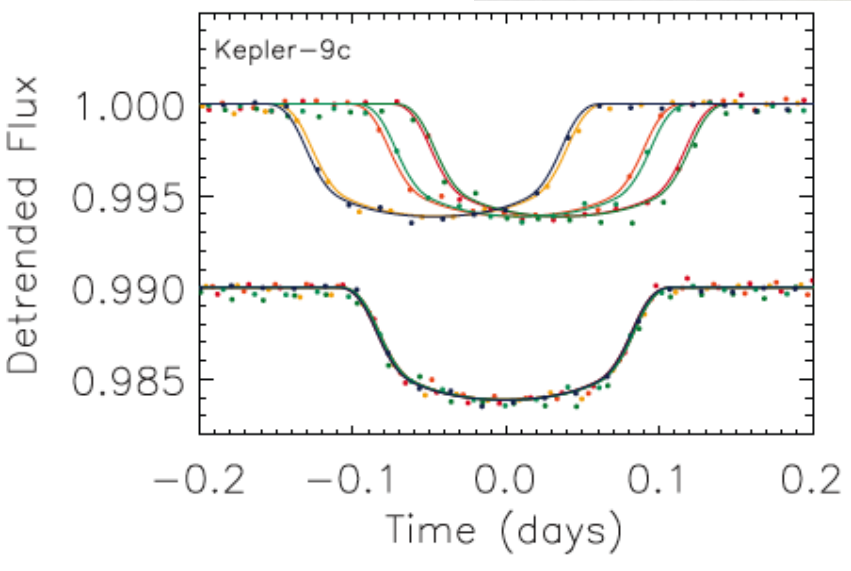



Kepler-9b,c

Kepler-9 b,c: Transit Timing Variations

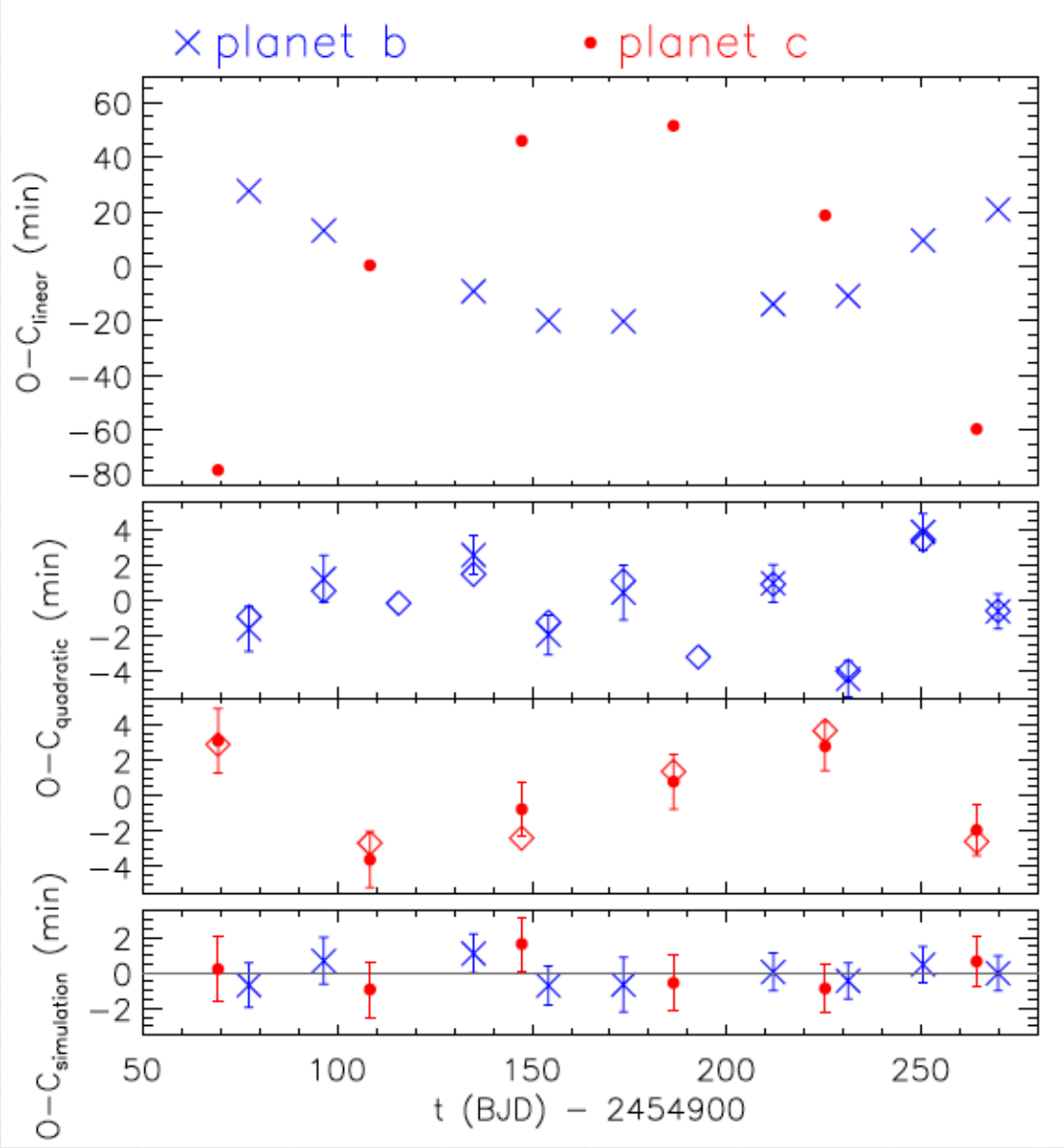






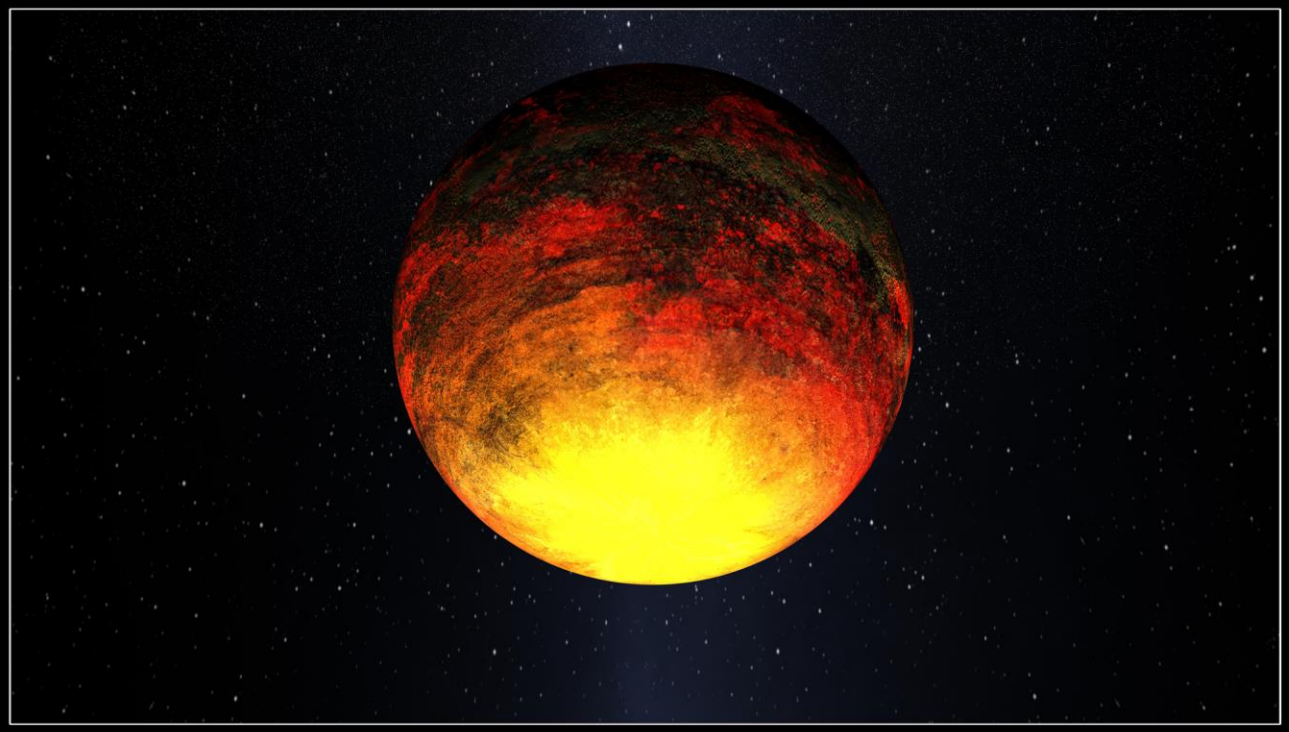
Transit timing - Planet perturbations

- Kepler-9 models without interactions give poor fits
- Models with planets affecting each other give good fits
- TTVs can be used to confirm planets & measure masses



Kepler's First Rocky Planet: Kepler-10b

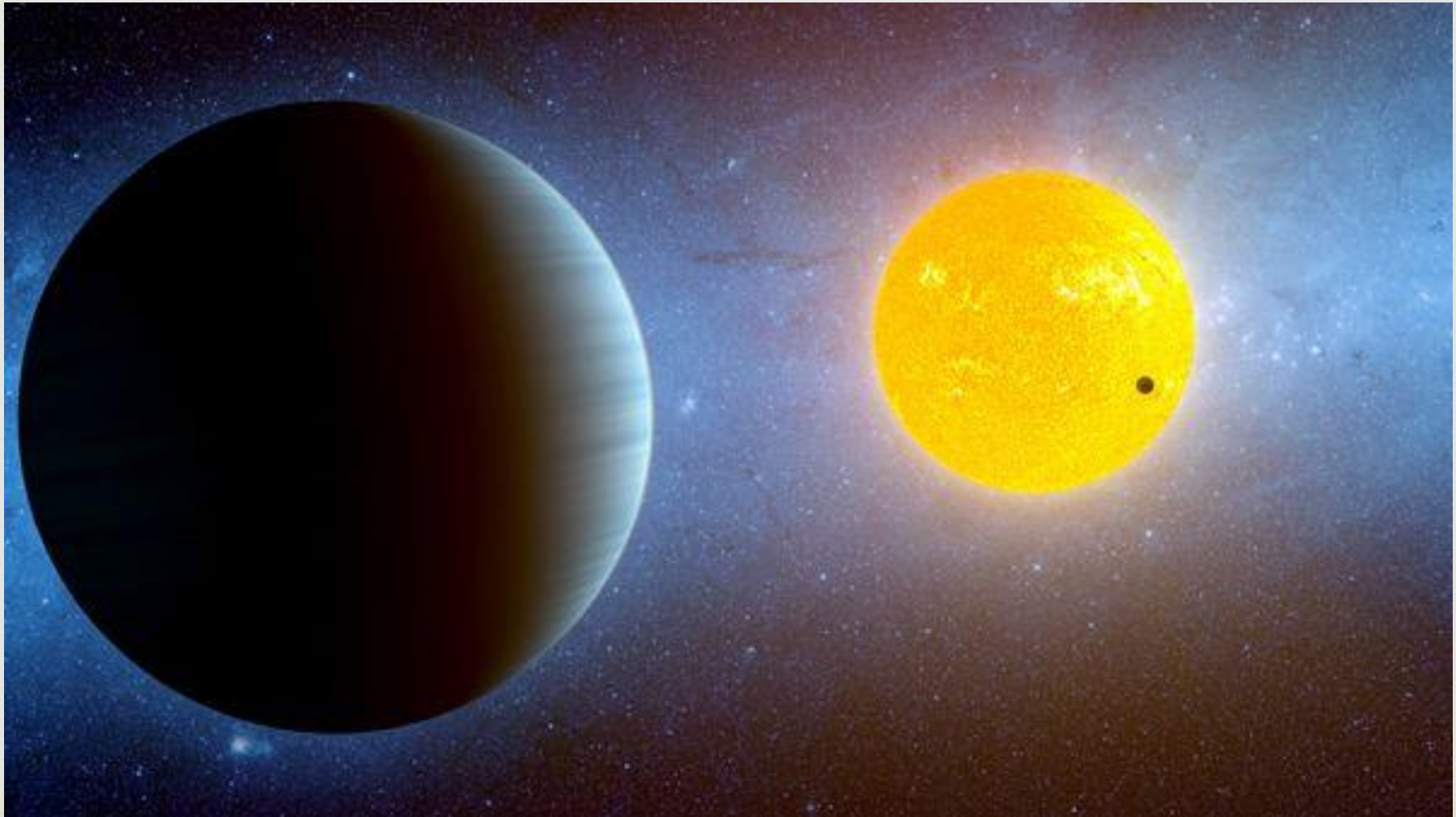
Kepler is giving us new knowledge about the frequency of near Earth-size planets.

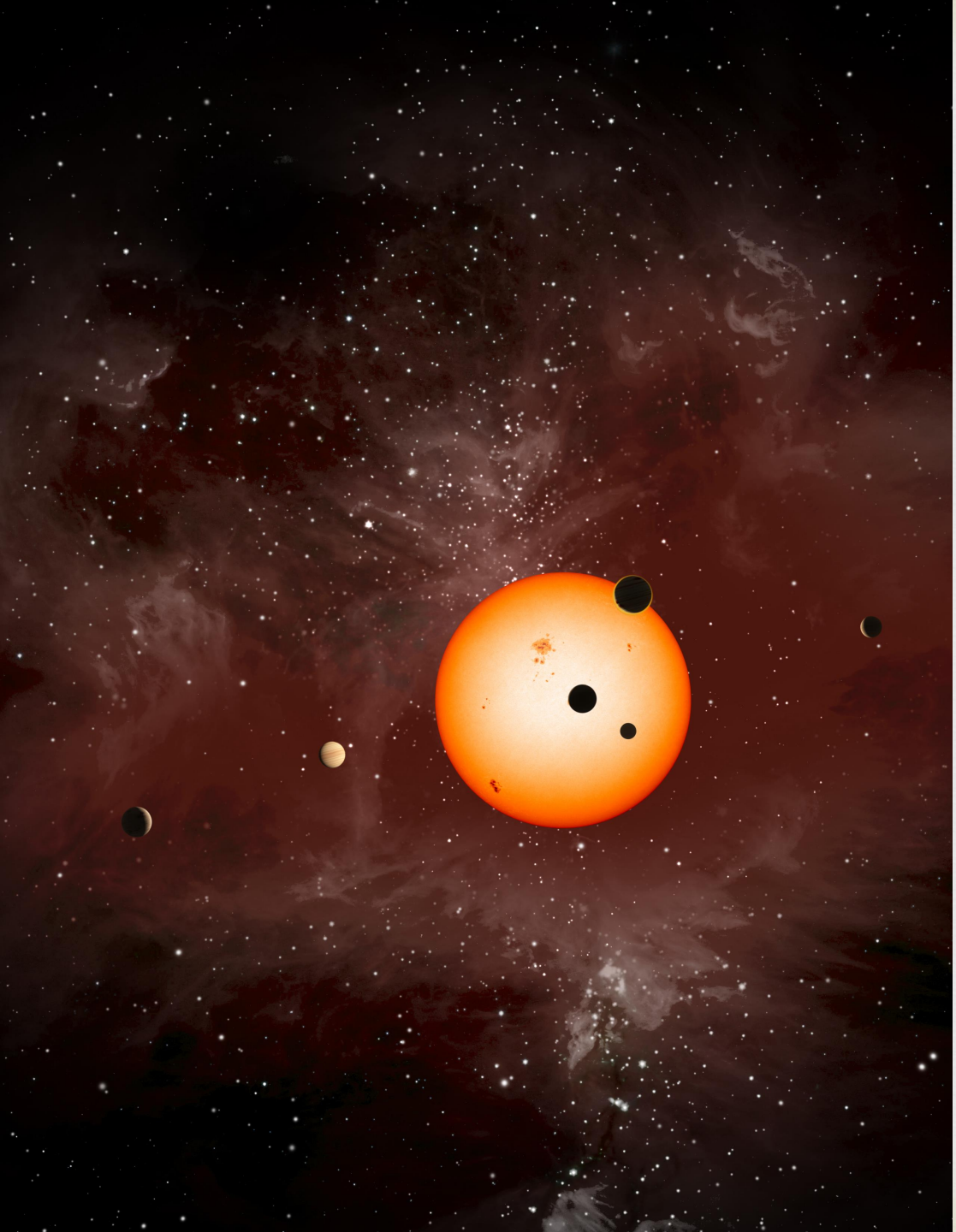


Kepler-10

10 b: R = 1.4 R_{Earth}, M = 4.6 M_{Earth}, P = 0.8 days

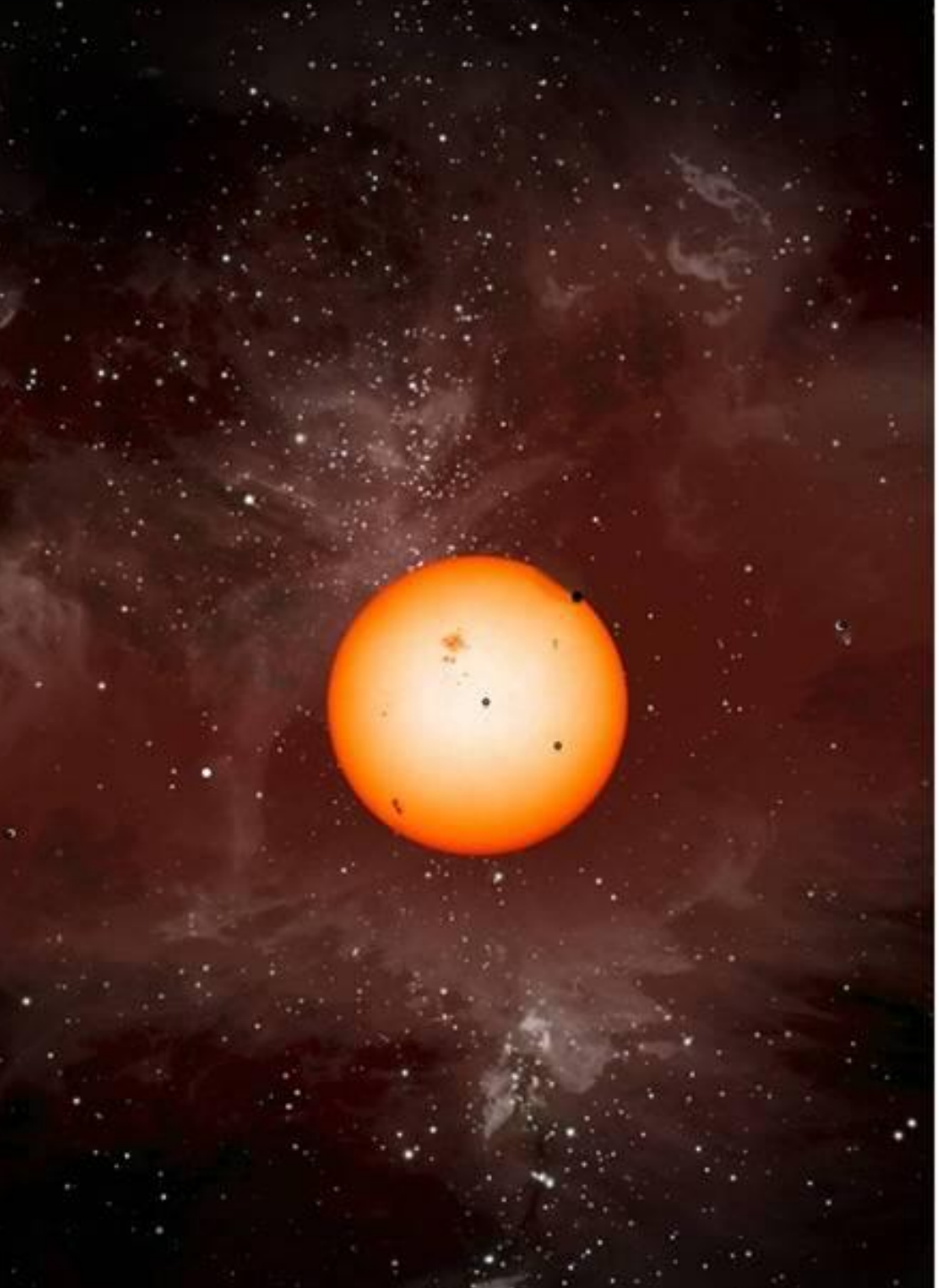
10 c: R = 2.2 R_{Earth}, M < 20 M_{Earth}, P = 45 days





Kepler-11

A really cool system with
6 transiting planets

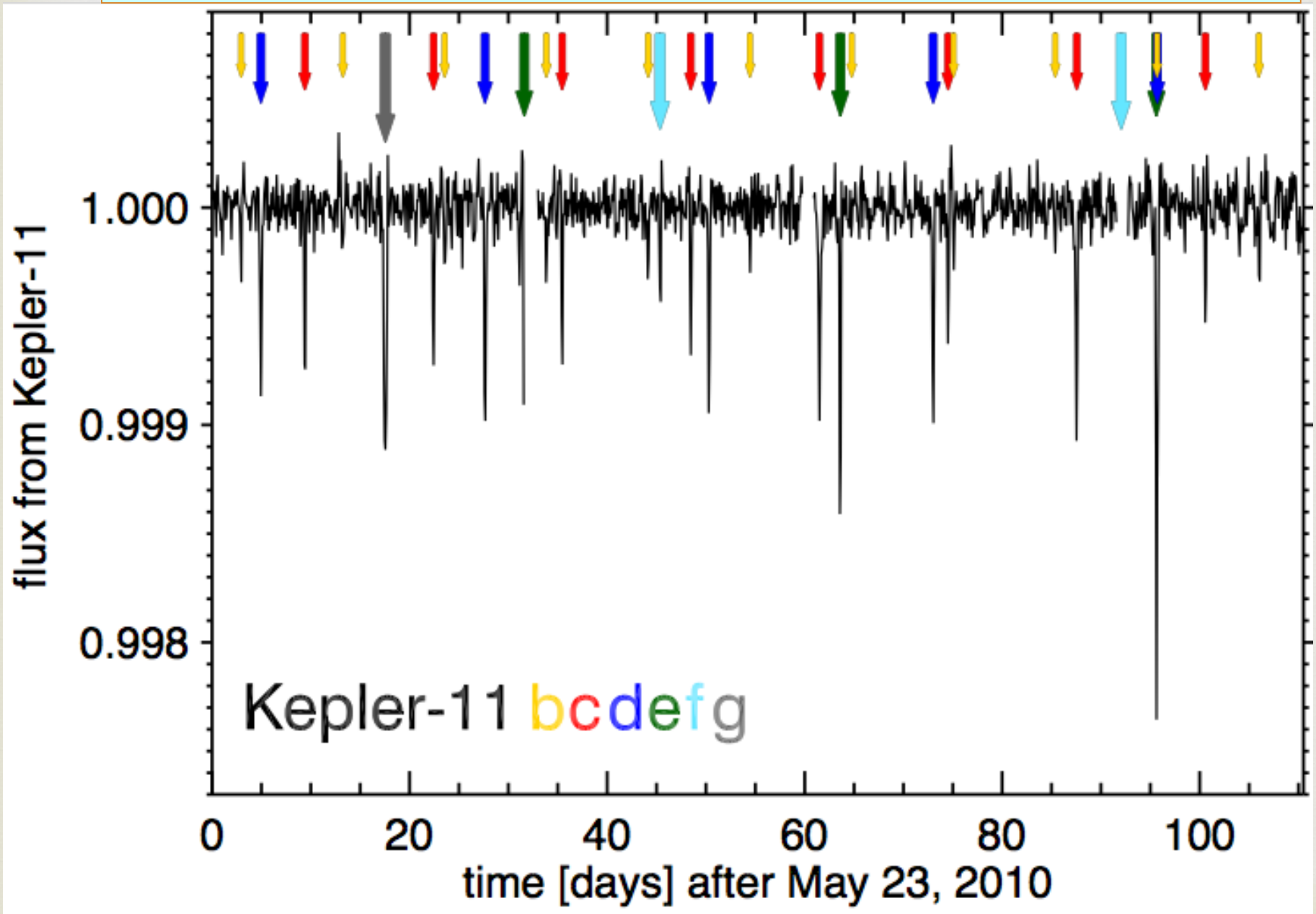


Kepler-11 Planets

Correct sizes relative to star

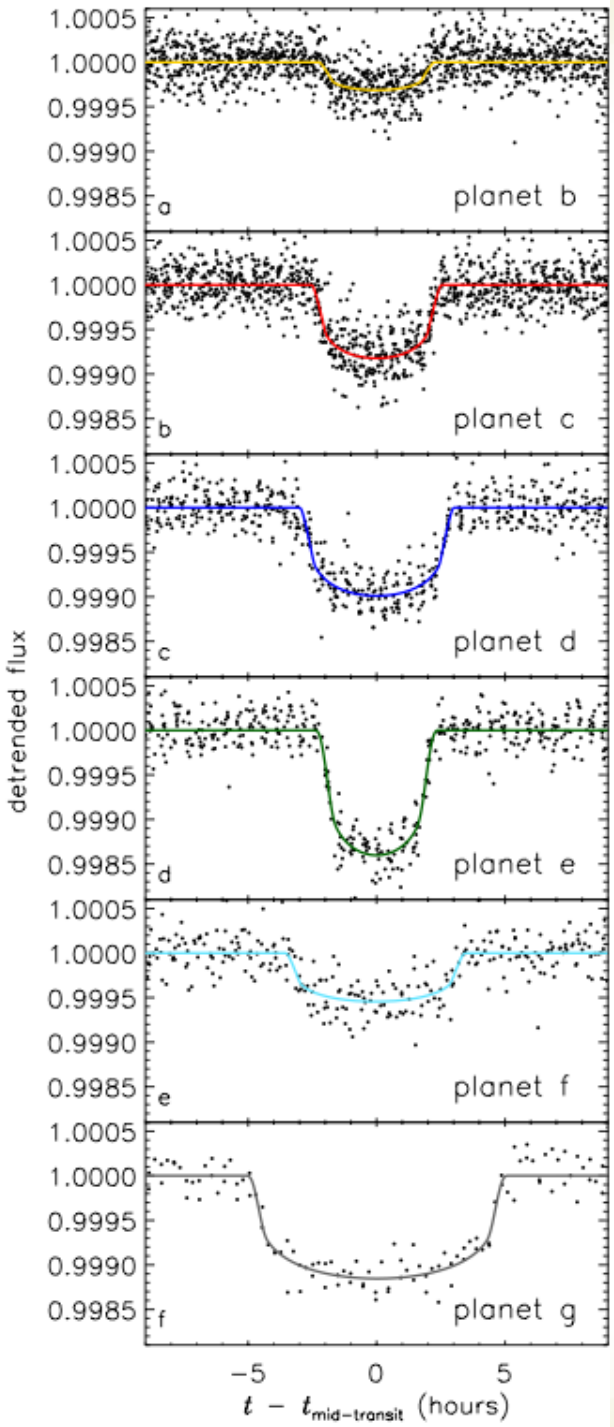
(Dan Fabrycky)

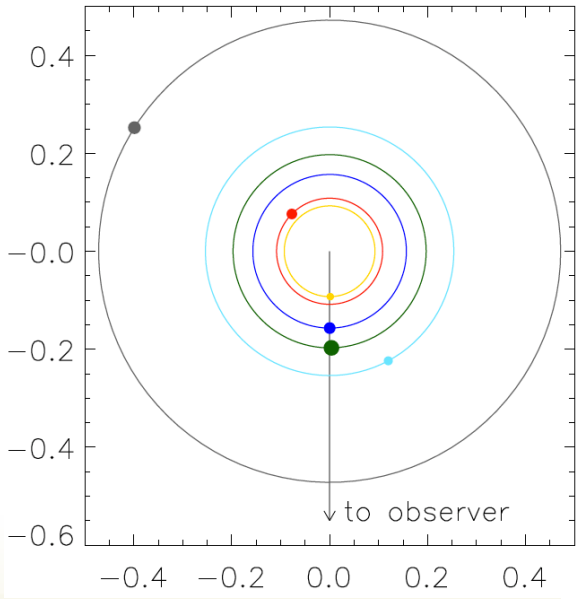
Kepler-11: Six Transiting Planets

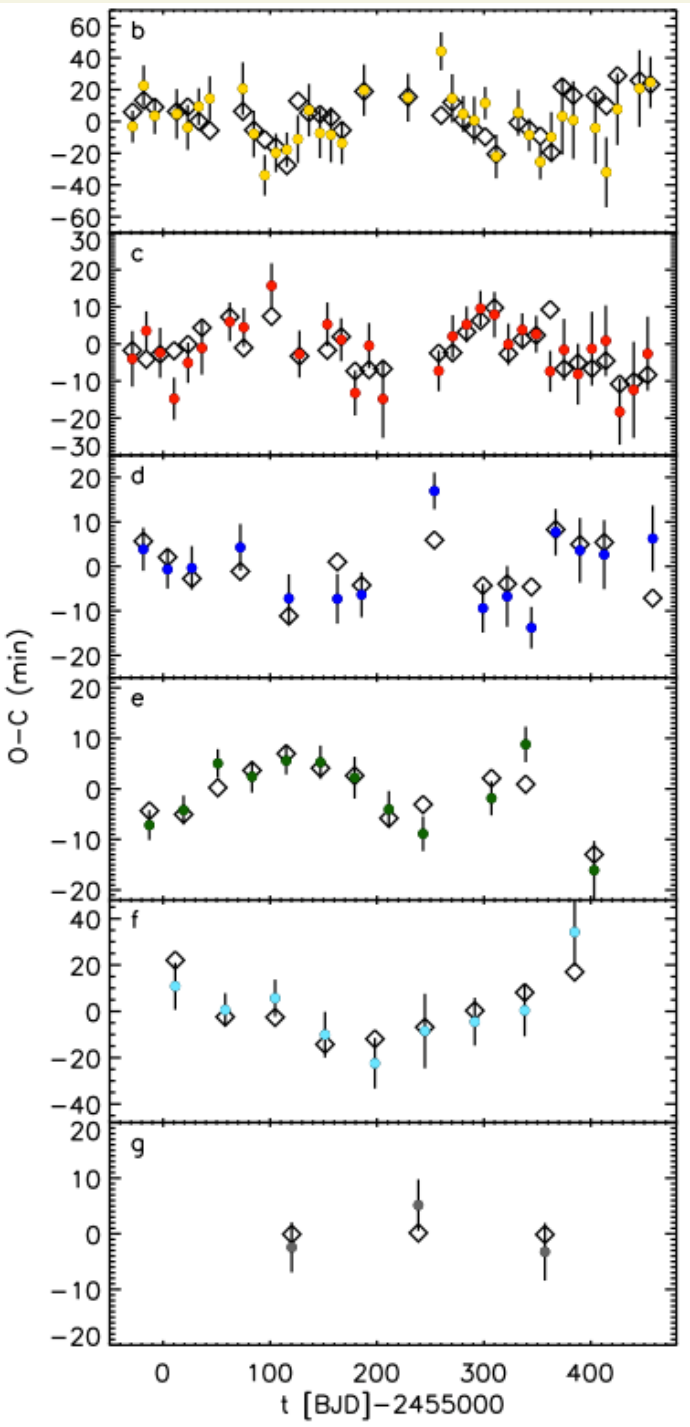


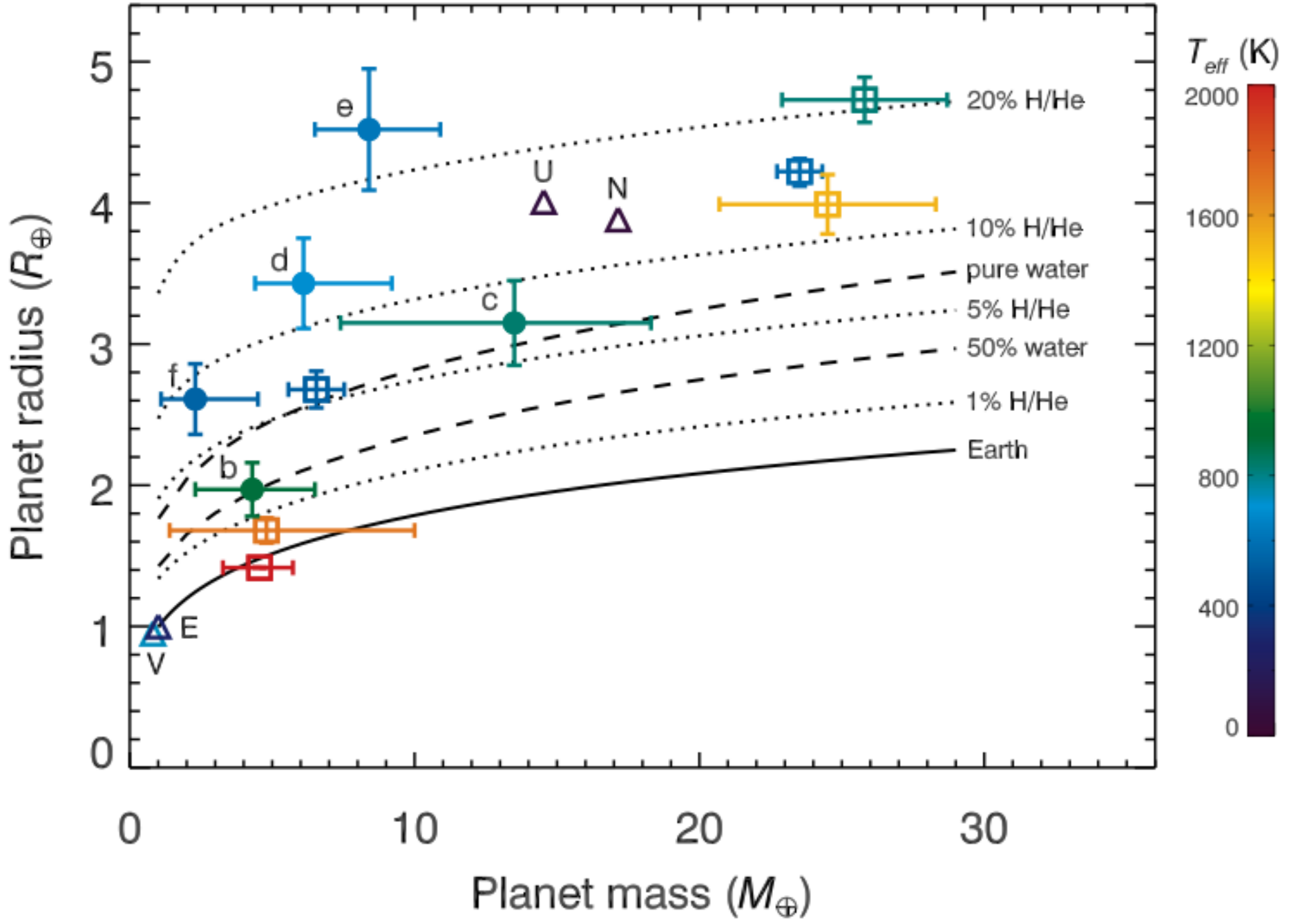
← Transits

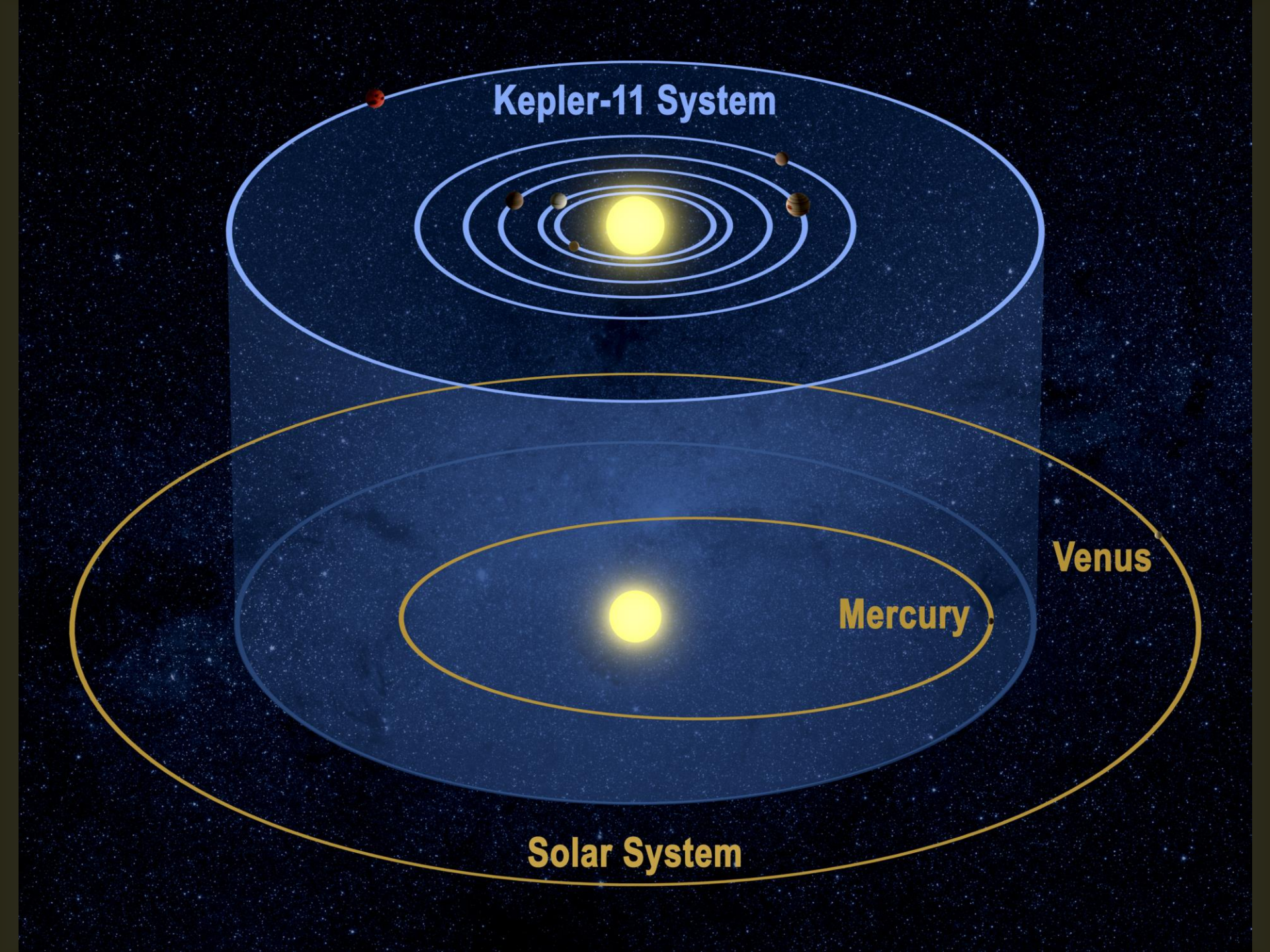
TTVs →








Planet radius ($R_\oplus$)
Planet mass ($M_\oplus$)
0
1
2
3
4
5
0
10
20
30
e
d
c
f
b
U
N
E
V
20% H/He
10% H/He
pure water
5% H/He
50% water
1% H/He
Earth
T_{eff} (K)
2000
1600
1200
800
400
0


Kepler-11 System
Venus
Mercury
Solar System

Effect of Planet in Gap Between Kepler-11 f & g on Fit to TTVs of Observed Planets

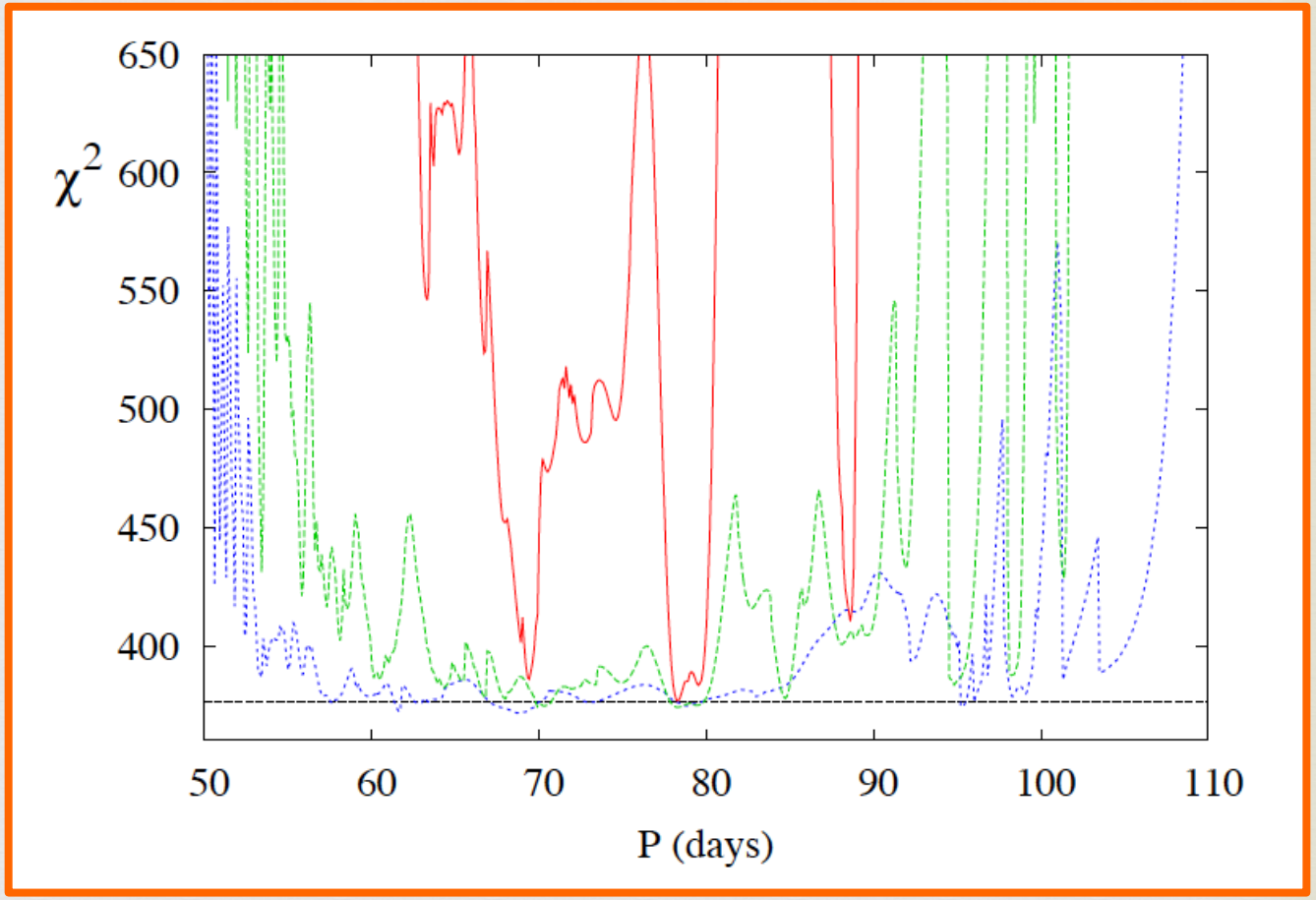
Mass of unseen planet

1 M_{Earth}

3 M_{Earth}

10 M_{Earth}

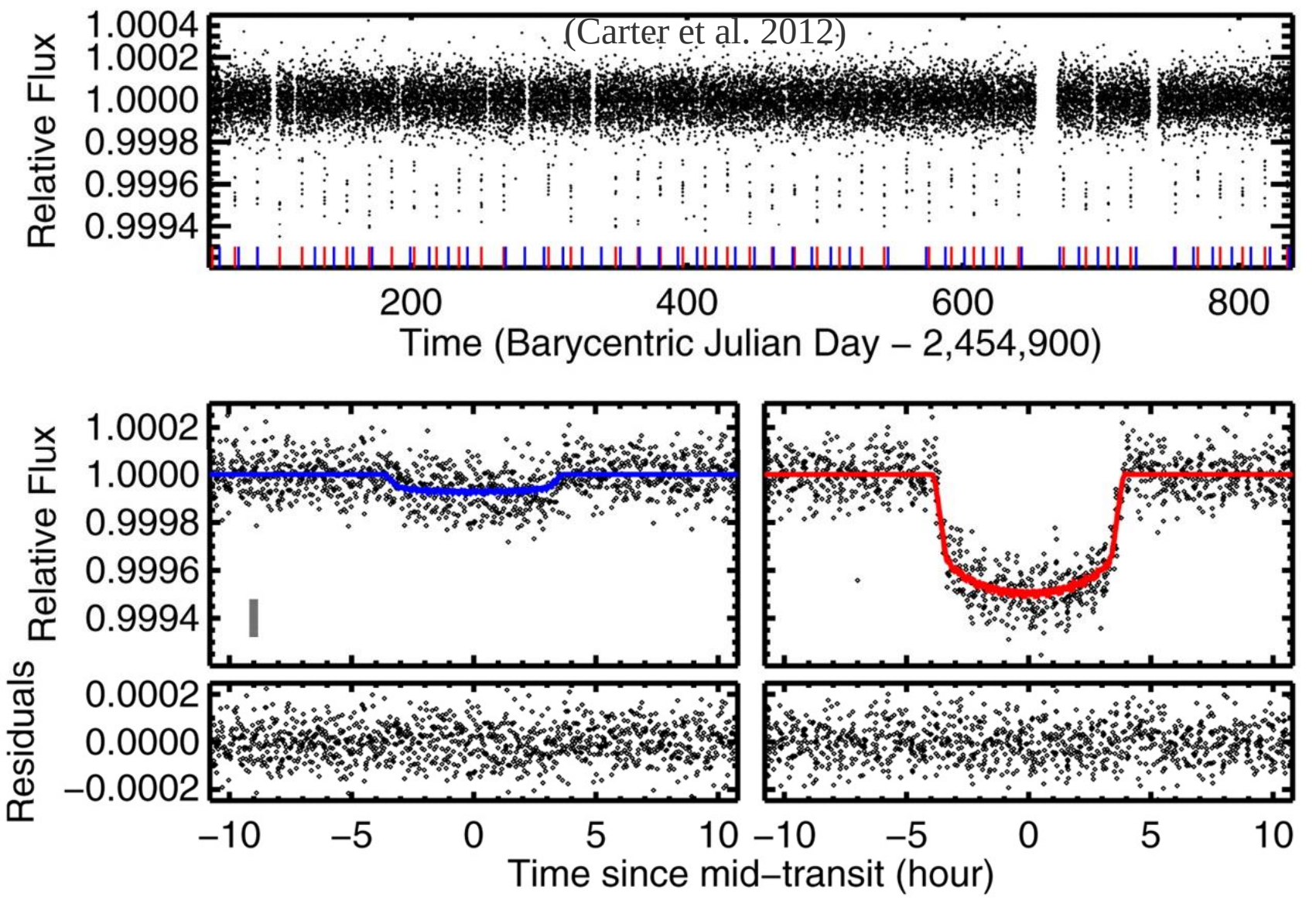
---- no unseen planet

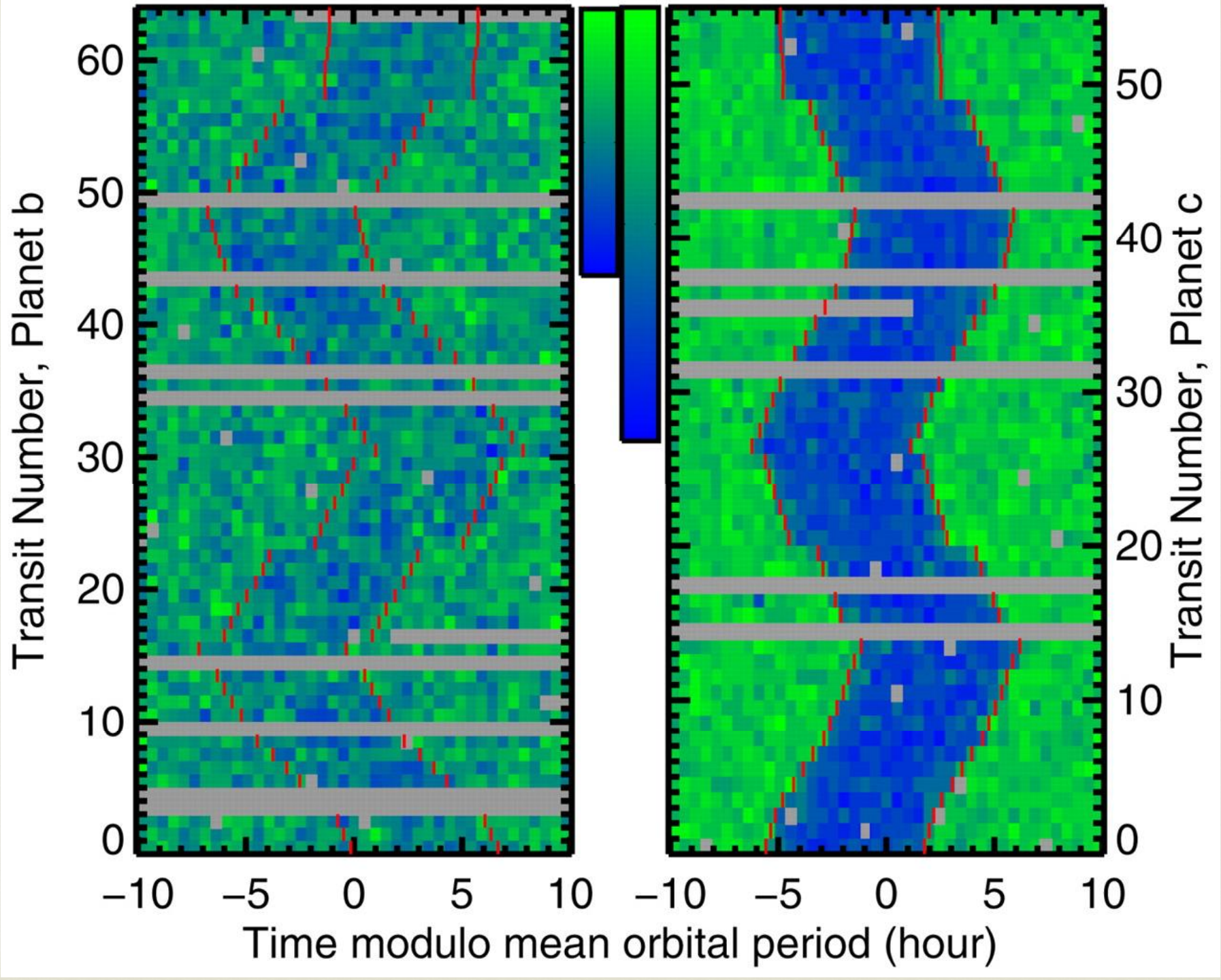


No evidence for a missing planet between f & g

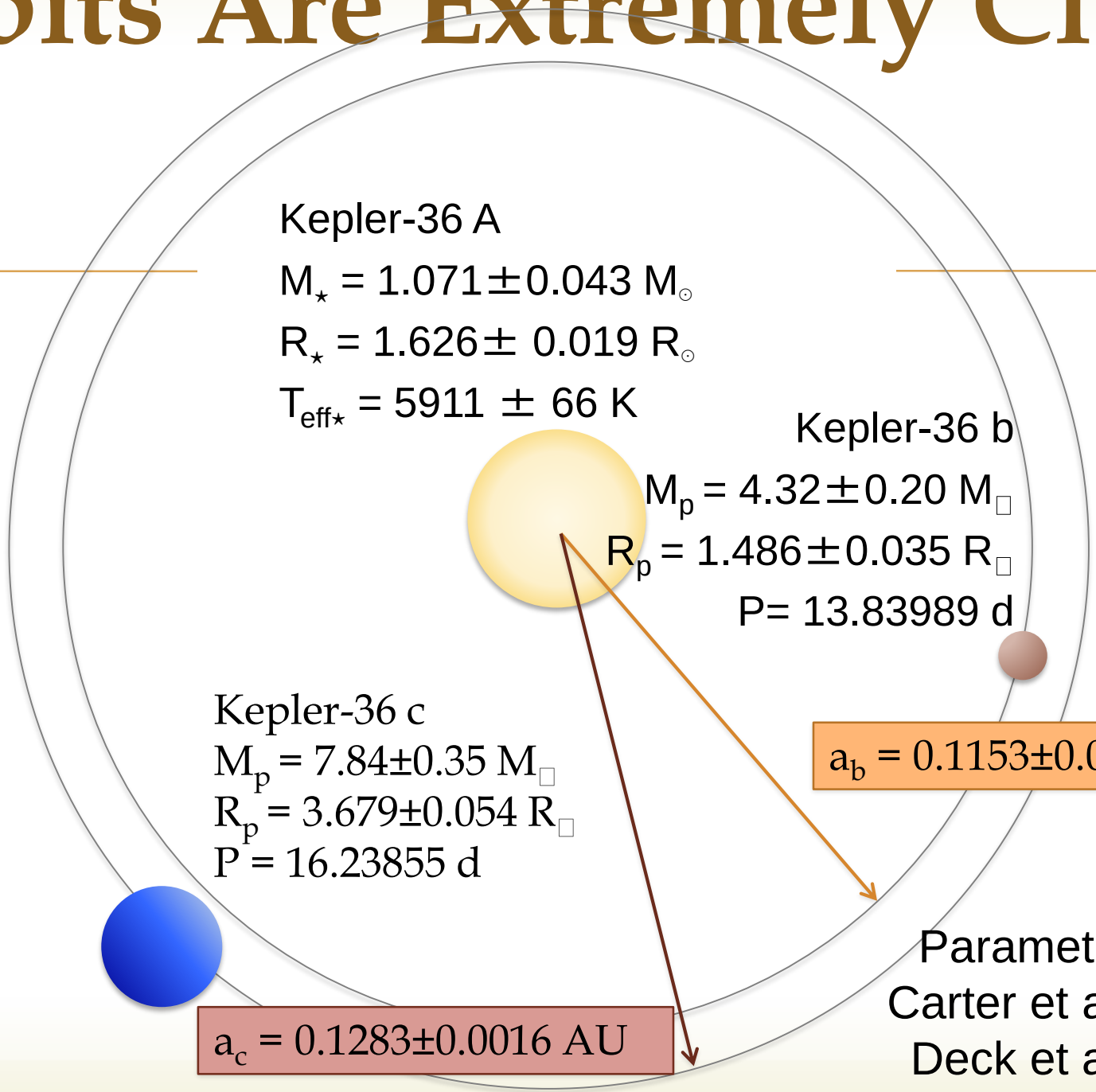
(Jontof-Hutter et al. 2017)

Kepler-36: A Pair of Planets with Neighboring Orbits and Dissimilar Densities



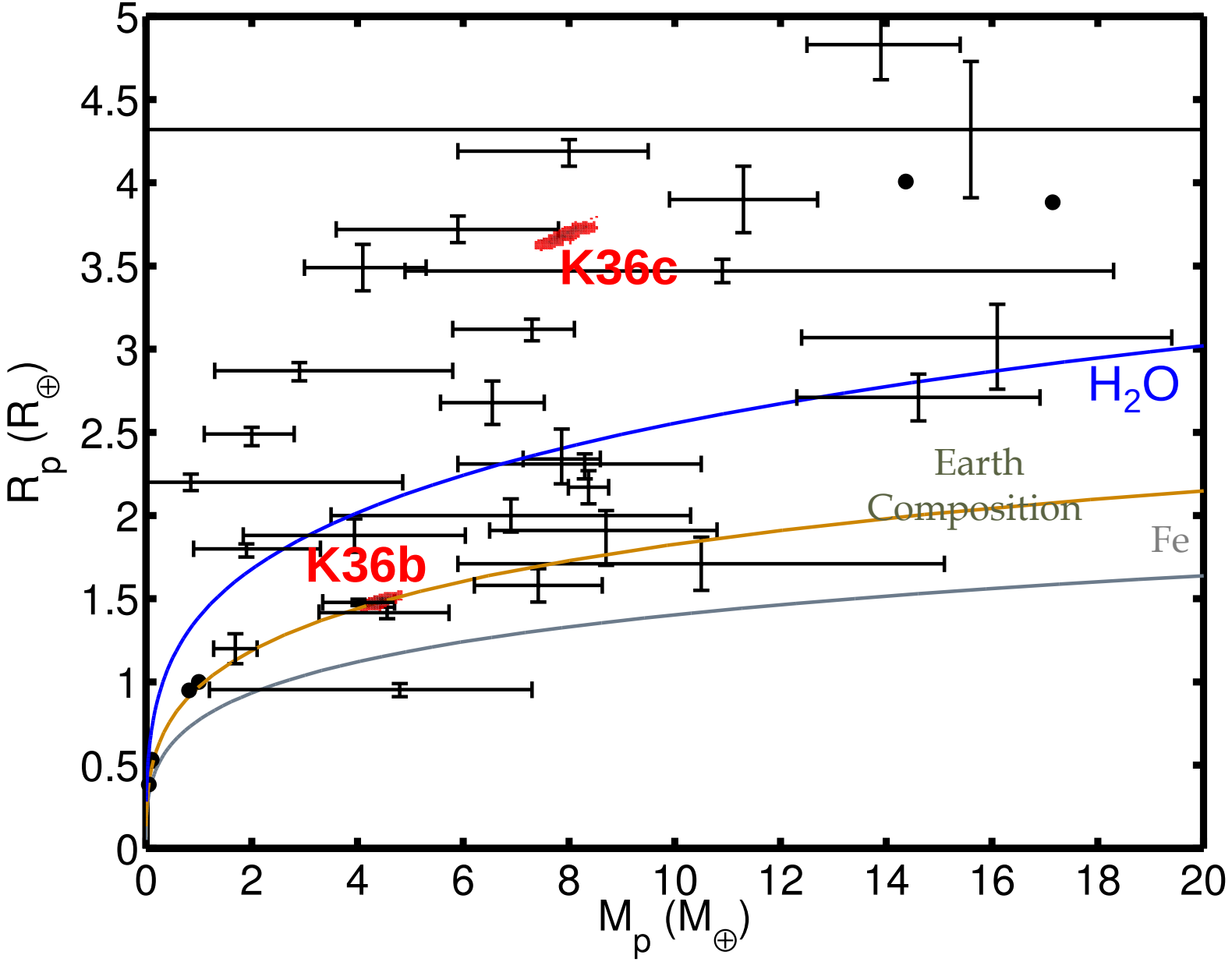

Transit Number, Planet b
Transit Number, Planet c
Time modulo mean orbital period (hour)
0
10
20
30
40
50
60
−10
−5
0
5
10

Orbits Are Extremely Close



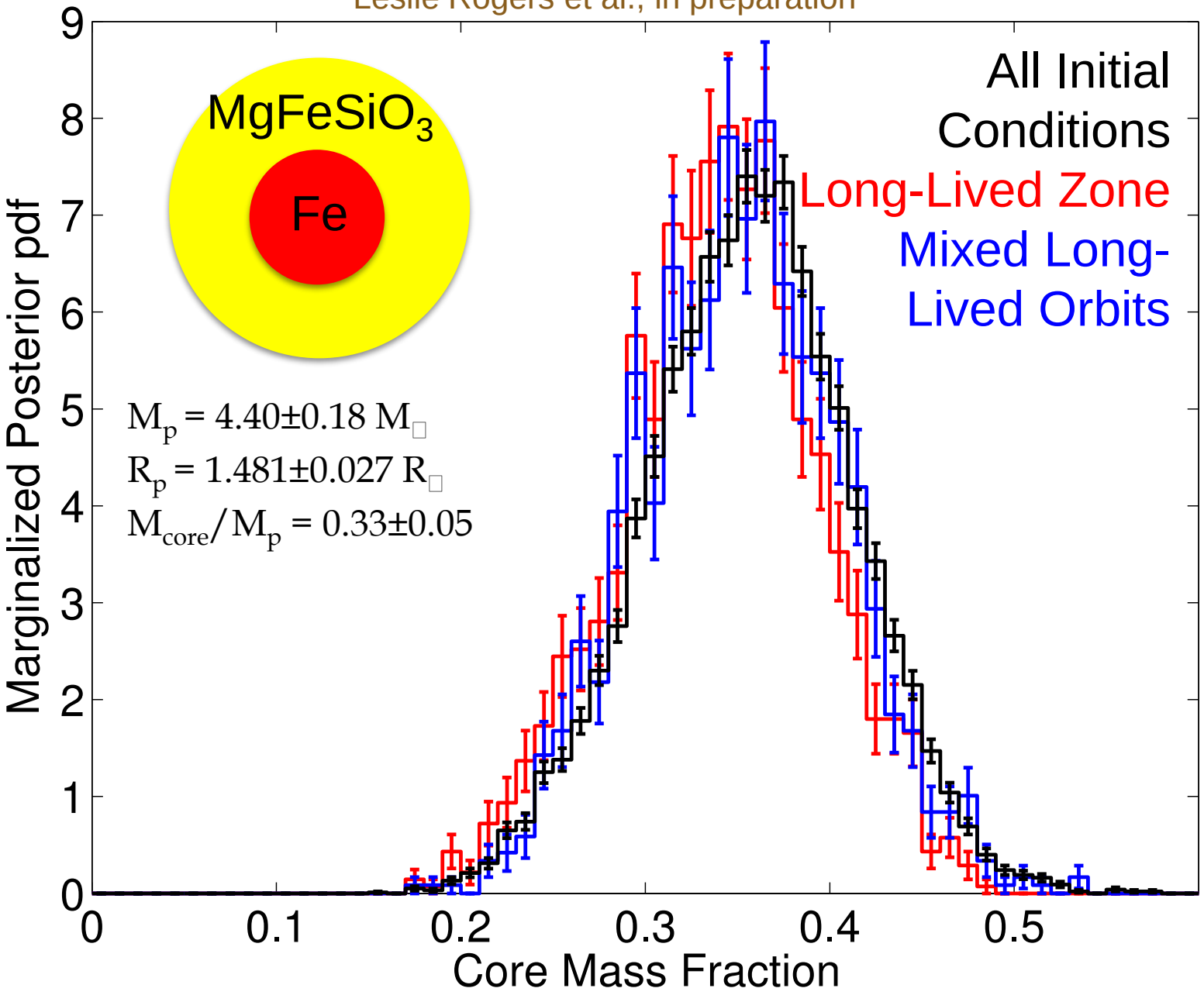
Parameters from:
Carter et al. (2012)
Deck et al. (2012)

Kepler-36 b Mass Measured within 4.2%, Radius Measured within 1.8%



Kepler-36 b is Consistent with an Earth-like Composition

Leslie Rogers et al., in preparation



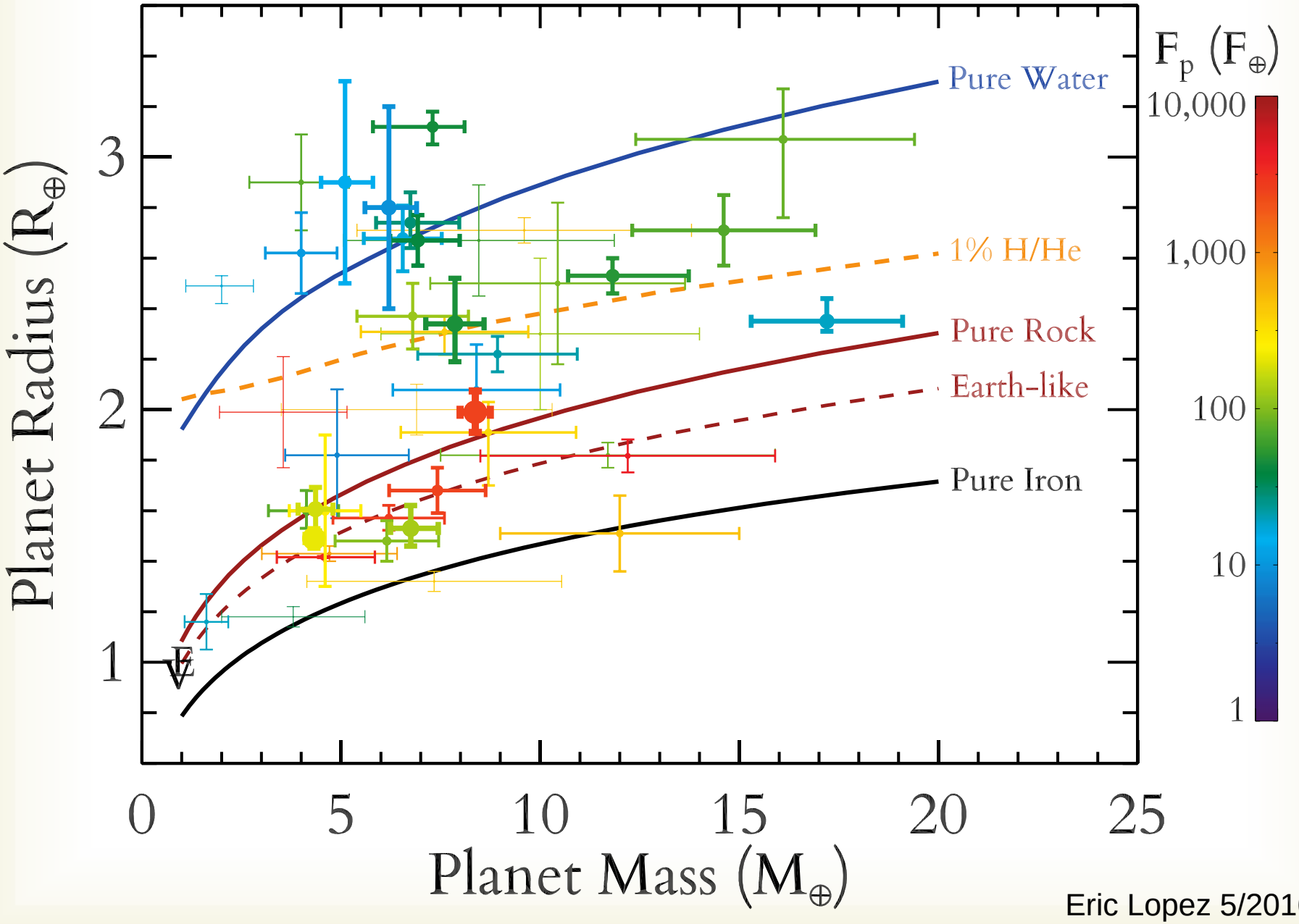
- Kepler-36 b is the rocky exoplanet with best constrained mass, density, and composition: mass known within 4.2%, radius to 1.8%, density to 4.6%.

- Kepler-36 b's mass and radius are consistent with an Earth-like composition. An iron-enhanced Mercury-like composition is ruled out.

- In contrast, Kepler-36 c requires several percent of its mass in a hydrogen-rich envelope. (L. A. Rogers et al. in prep)

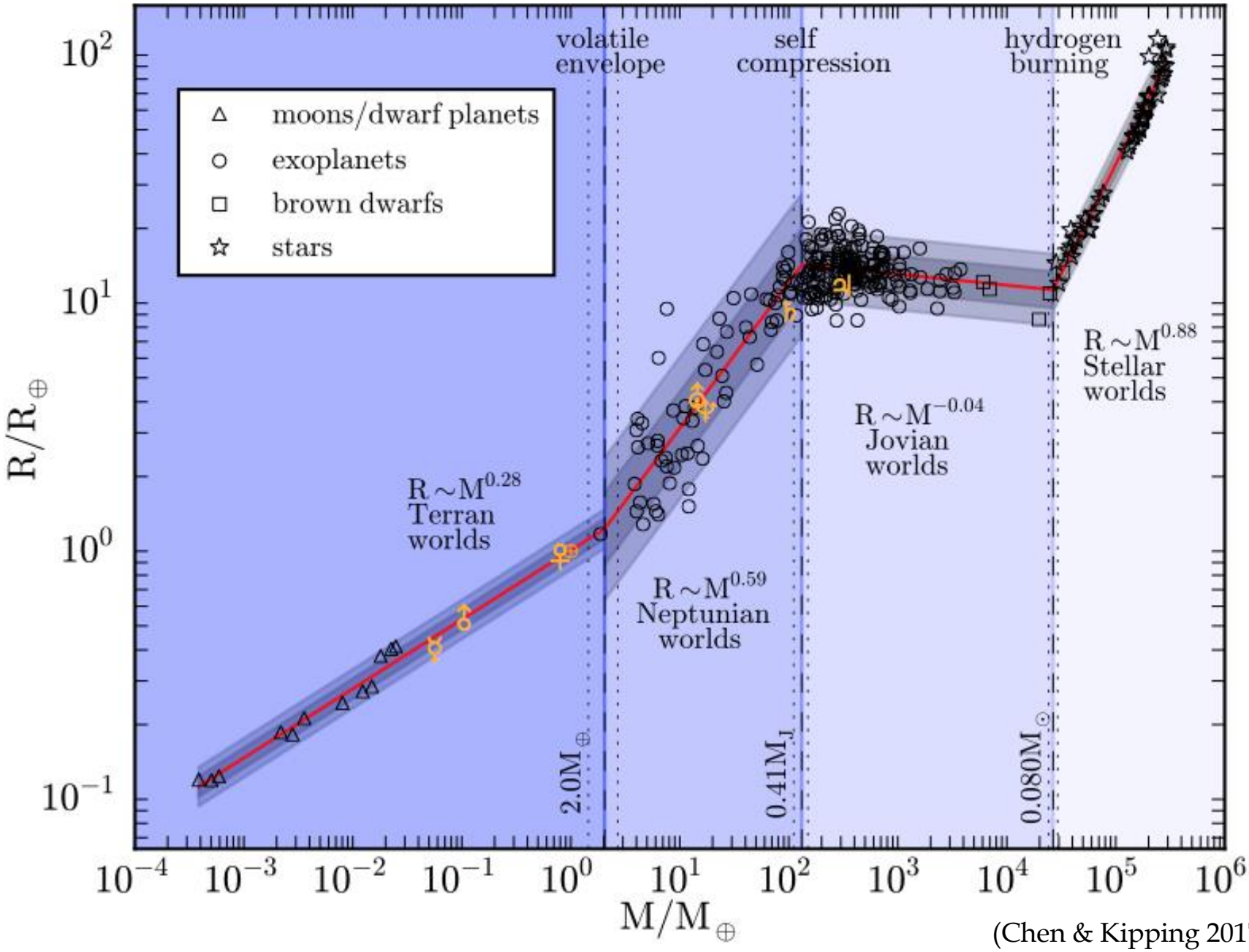
Figure Credit: NASA; Frank Melchior, frankacaba.com; Eric Agol

Mass vs. Radius for sub-Neptune Exoplanets



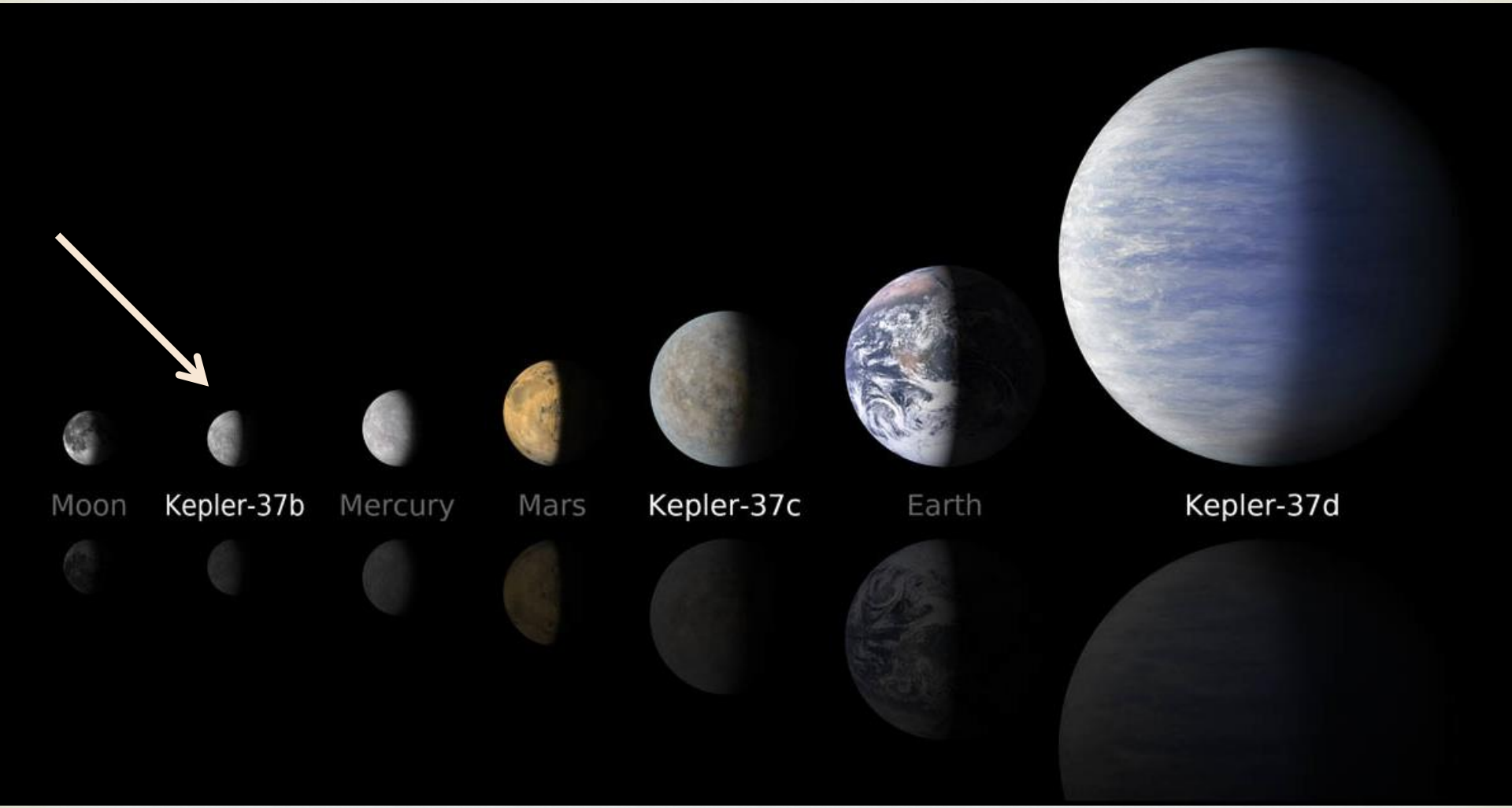
Eric Lopez 5/2016

Mass-Radius Relationship for Planets and Small Stars



(Chen & Kipping 2017)

The Smallest Known Planet



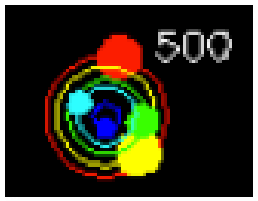
A Very Small Planetary System

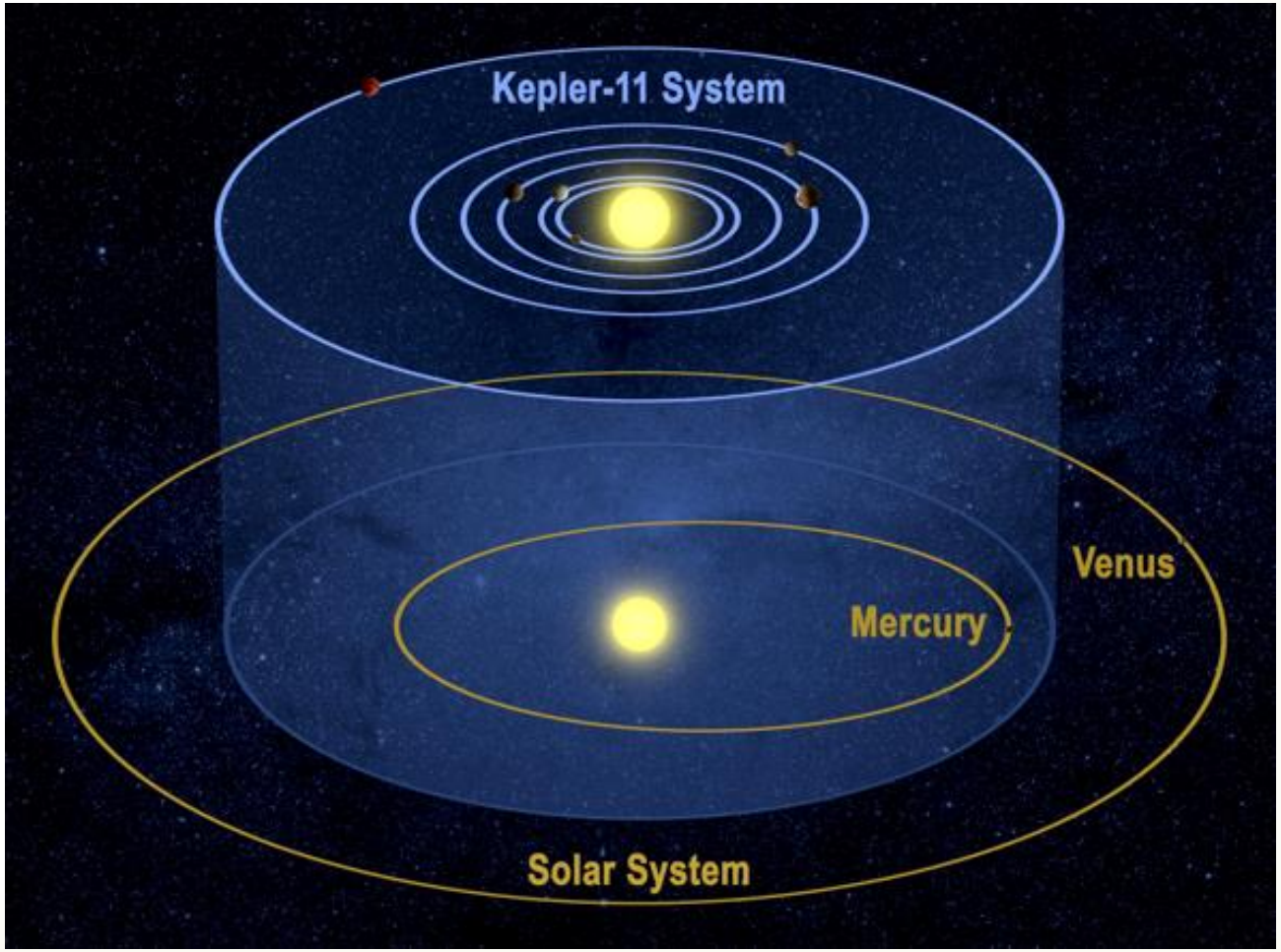
KOI-500

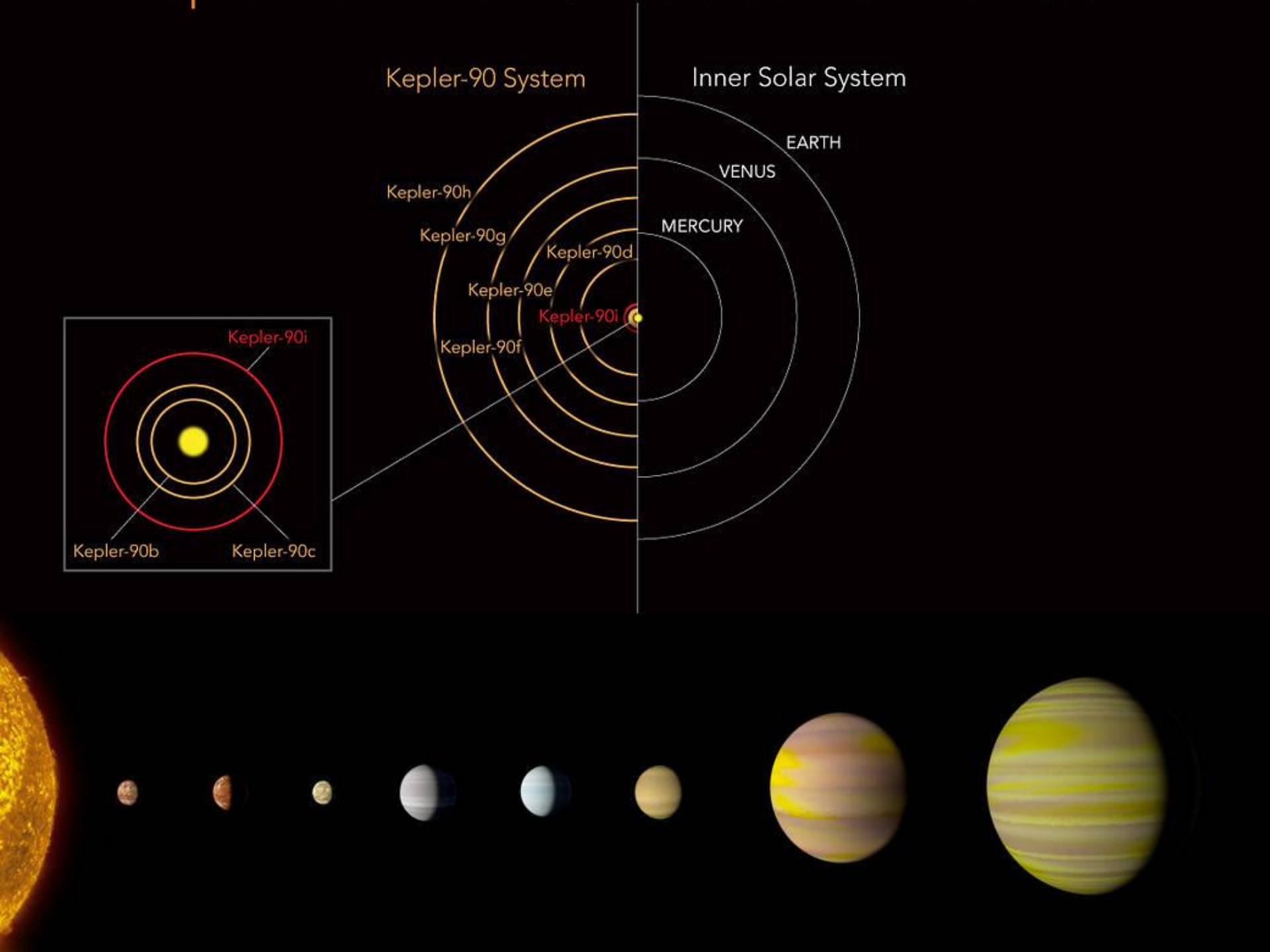
also known as

Kepler-80

planet	P (days)	Mp(Mearth)
500.05	0.9867790	1.5
500.03	3.0721660	2.2
500.04	4.6453530	4.4
500.01	7.0534780	8.0
500.02	9.5216960	8.5



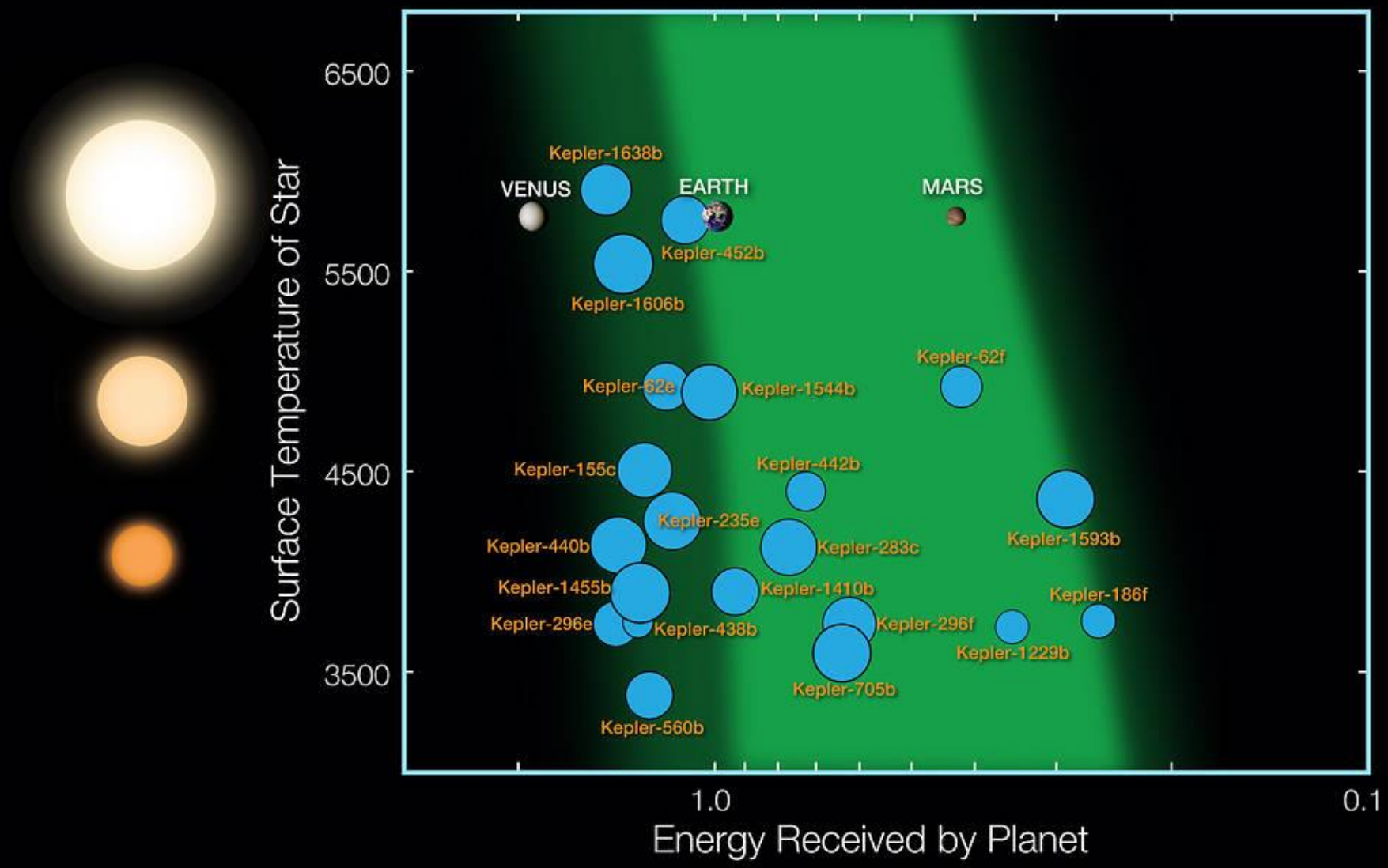



Kepler-90 System
Inner Solar System
EARTH
VENUS
MERCURY
Kepler-90h
Kepler-90g
Kepler-90d
Kepler-90e
Kepler-90i
Kepler-90f
Kepler-90i
Kepler-90b
Kepler-90c


Kepler-16:
A Saturn-like planet
orbiting a close binary

Kepler's Small Habitable Zone Planets

As of May 10, 2016



Kepler's Small Habitable Zone Planets

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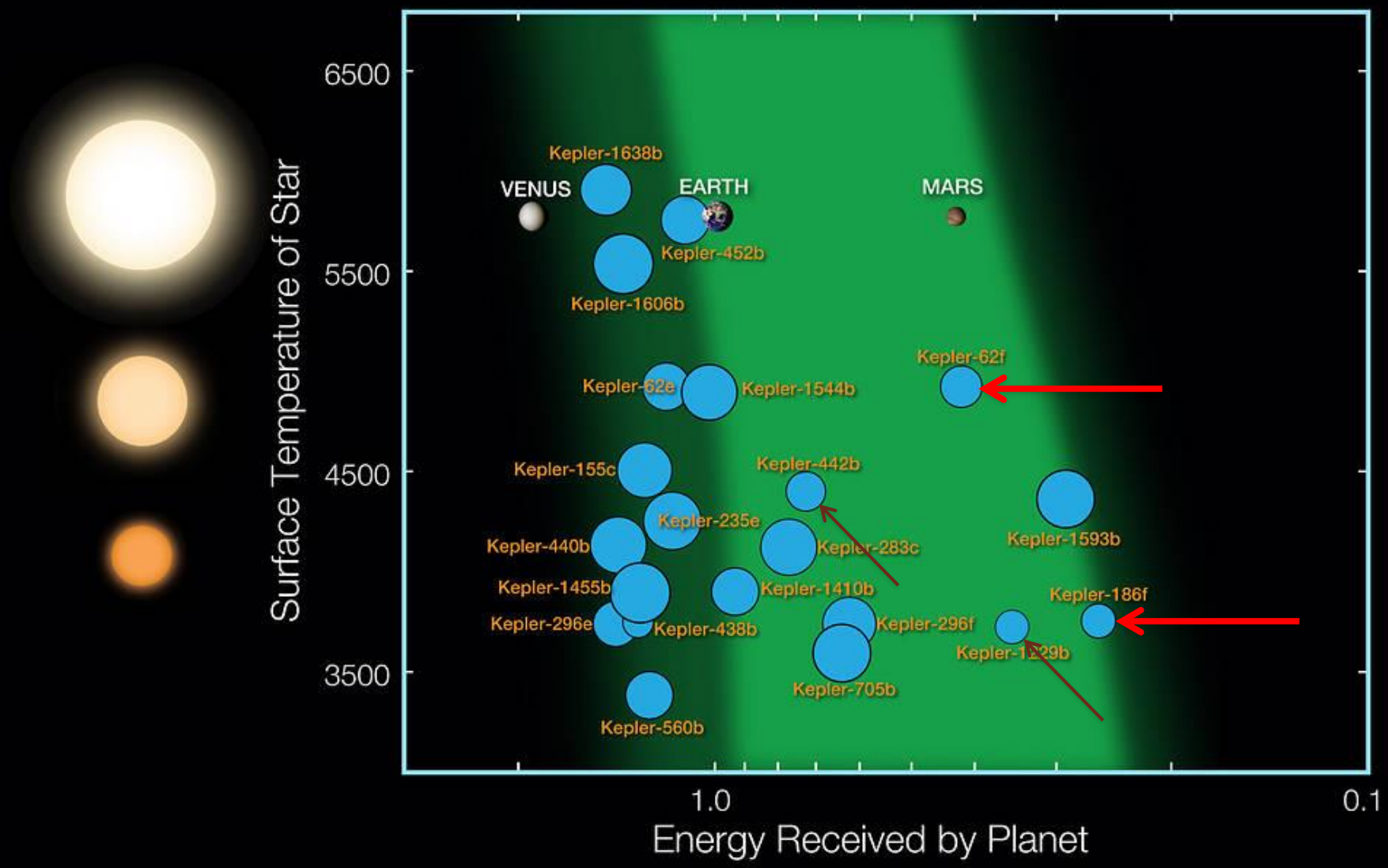
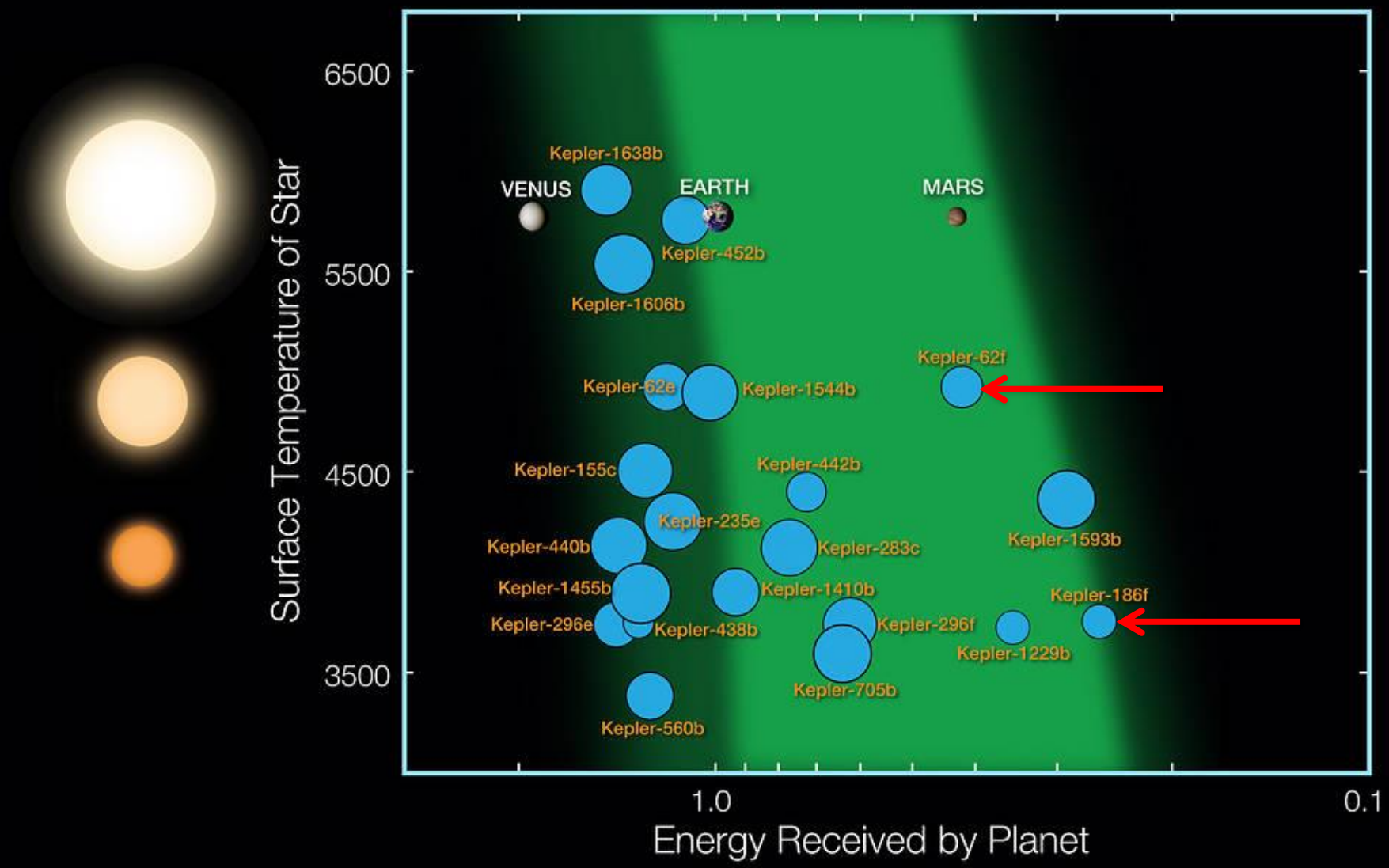
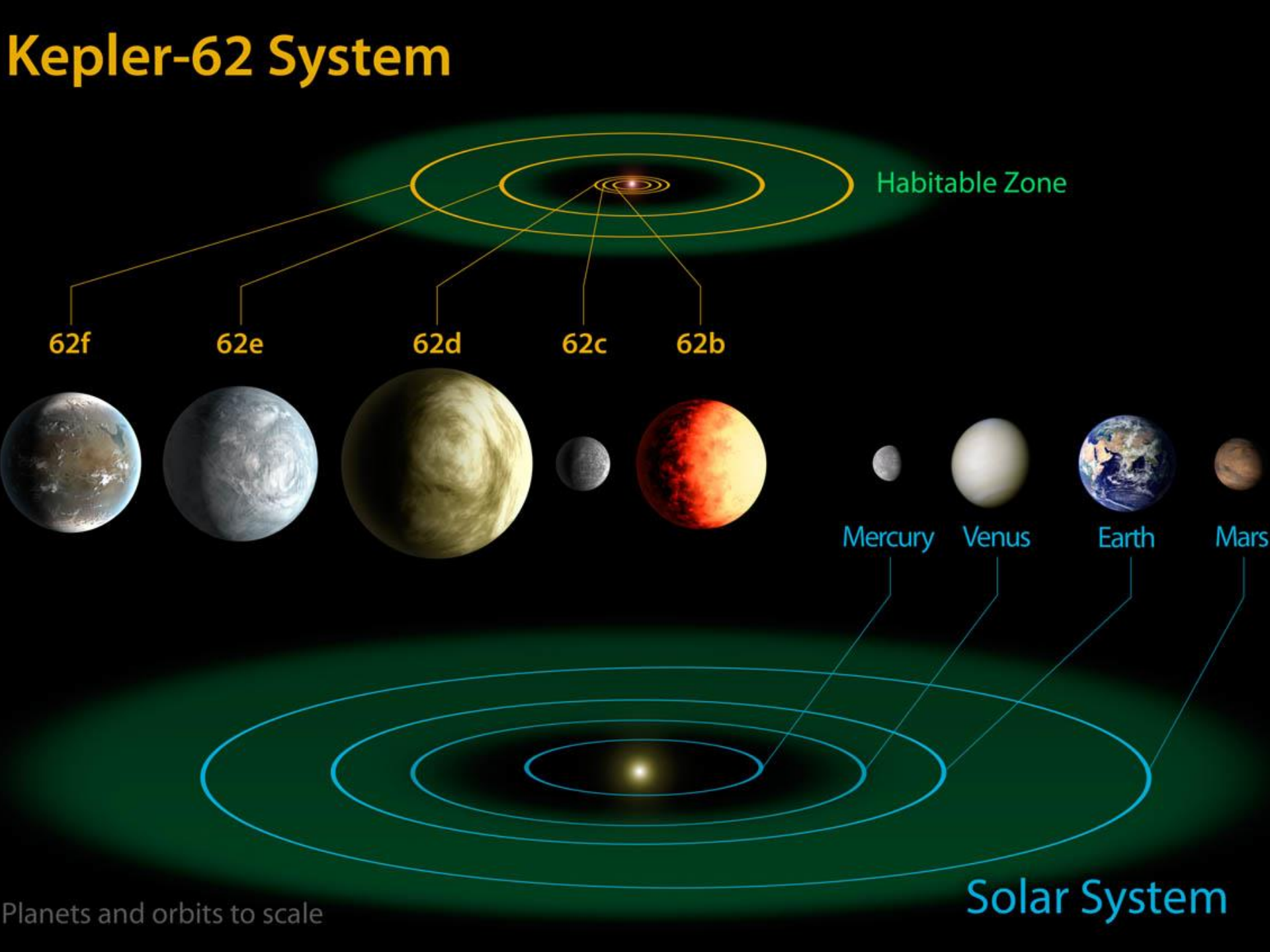
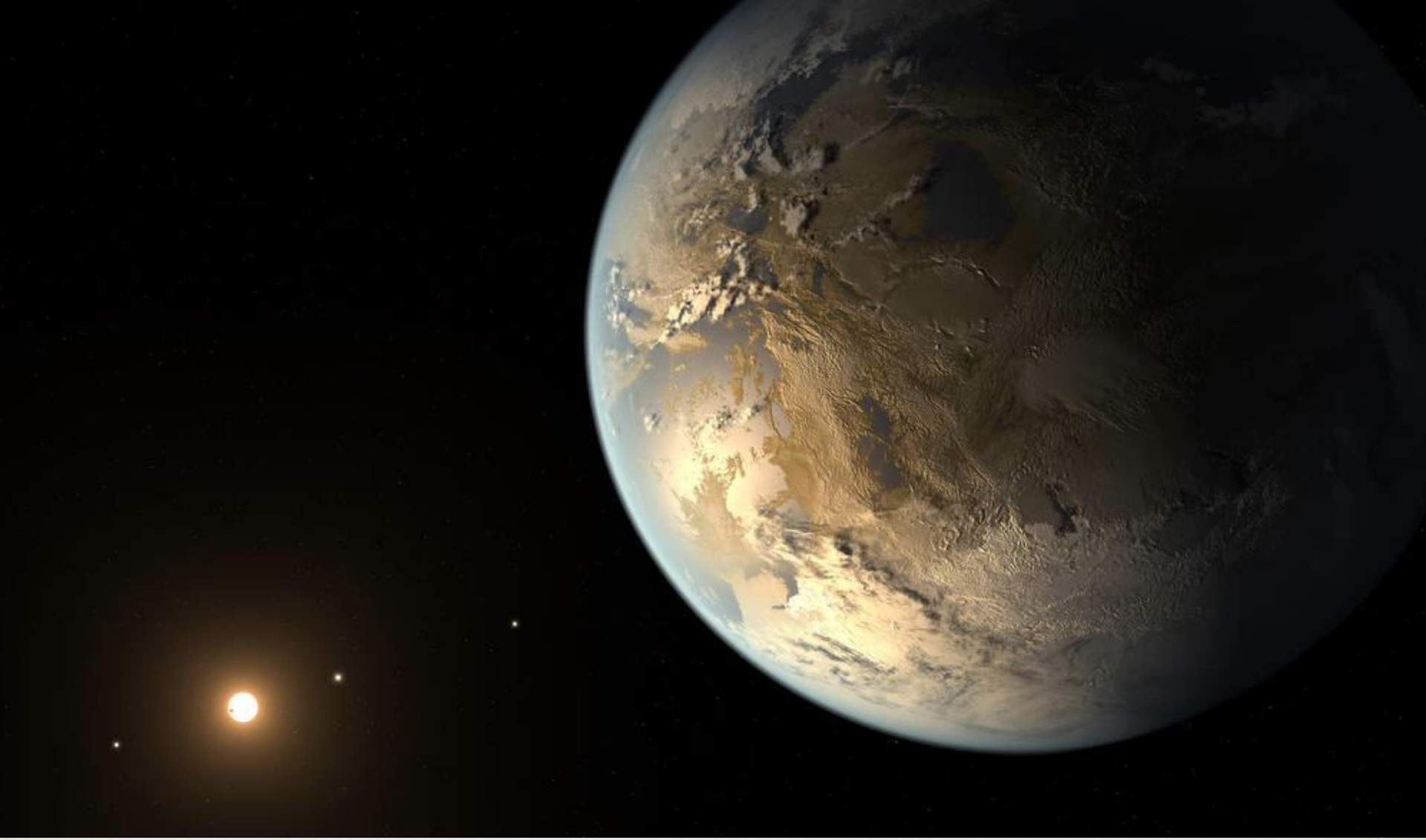


Kepler's Small Habitable Zone Planets

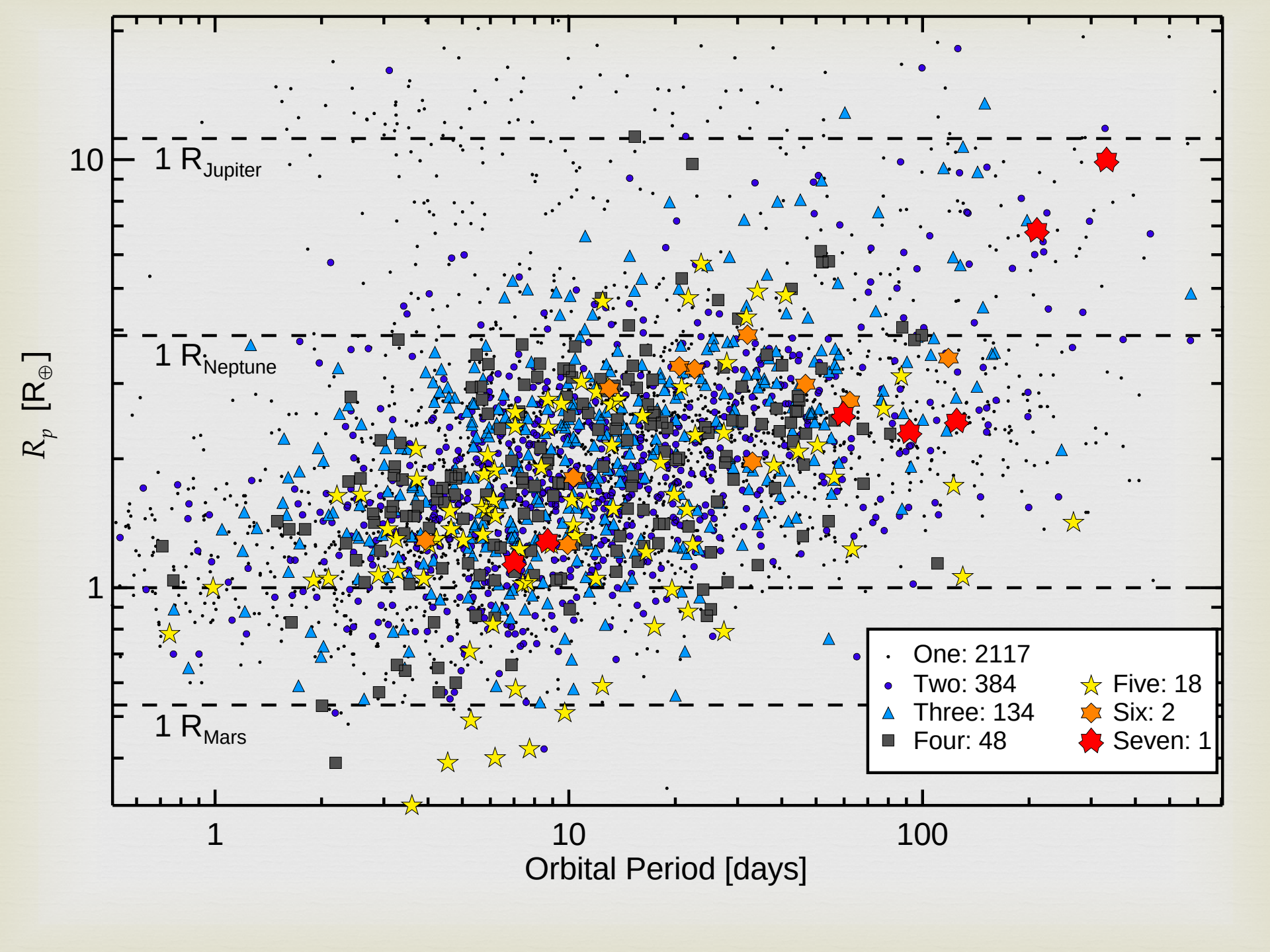
As of May 10, 2016

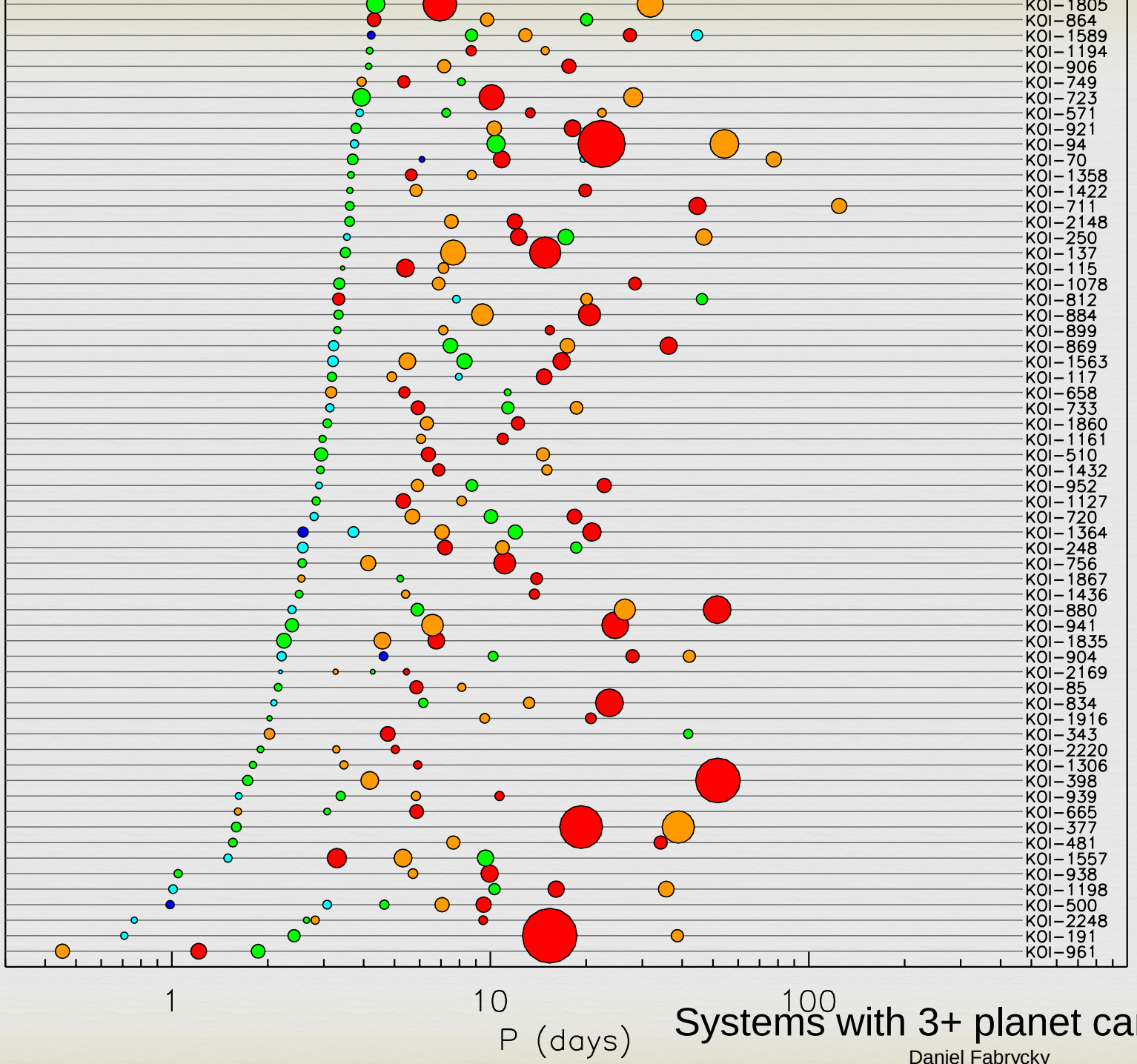



Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale



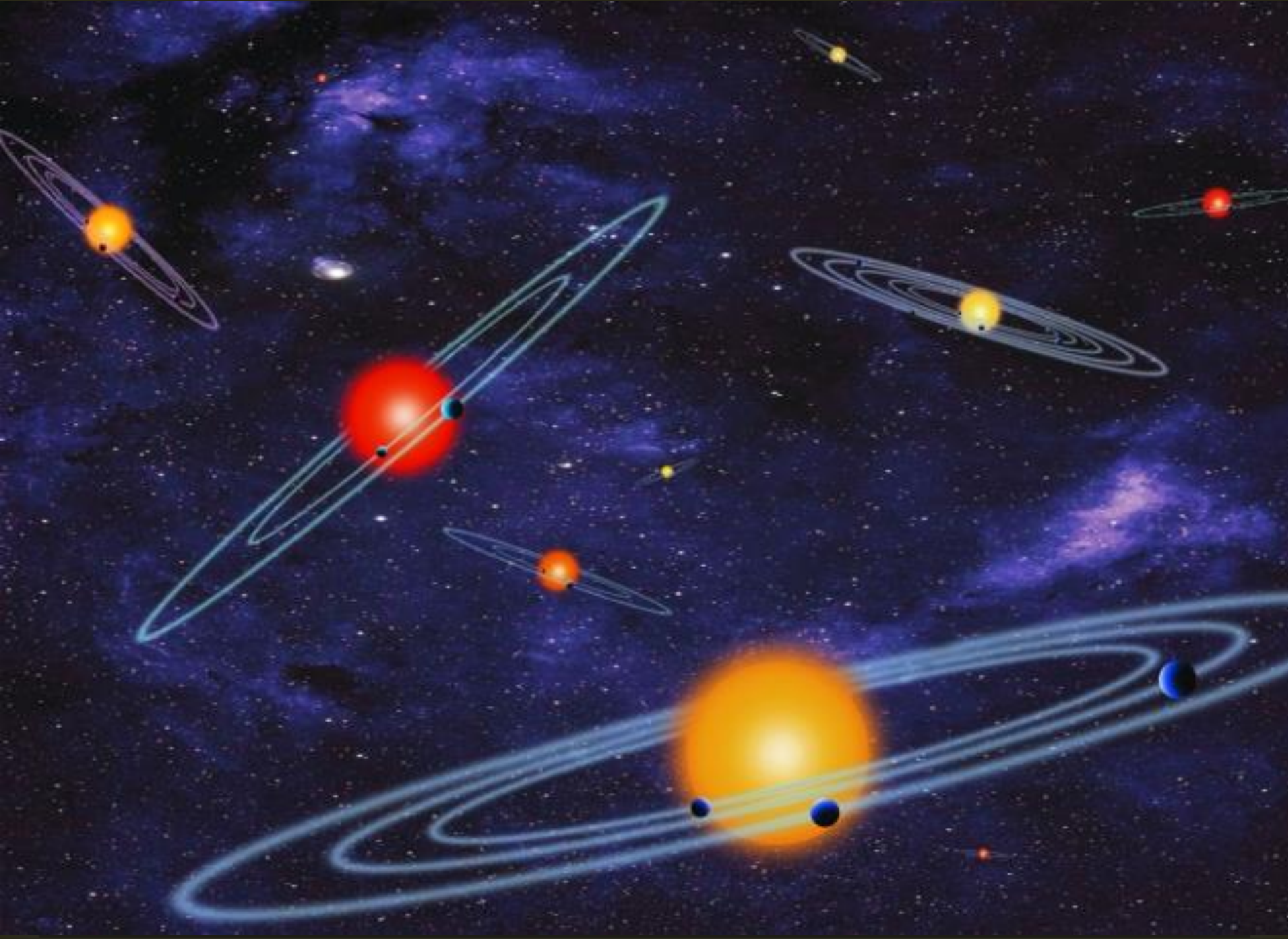
Kepler-186 f: a planet slightly larger than Earth in the habitable zone of an M dwarf


10
1
1 R_Jupiter
1 R_Neptune
1 R_Mars
R_p [R_⊕]
1
10
100
Orbital Period [days]
One: 2117
Two: 384
Three: 134
Four: 48
Five: 18
Six: 2
Seven: 1



Systems with 3+ planet candidates

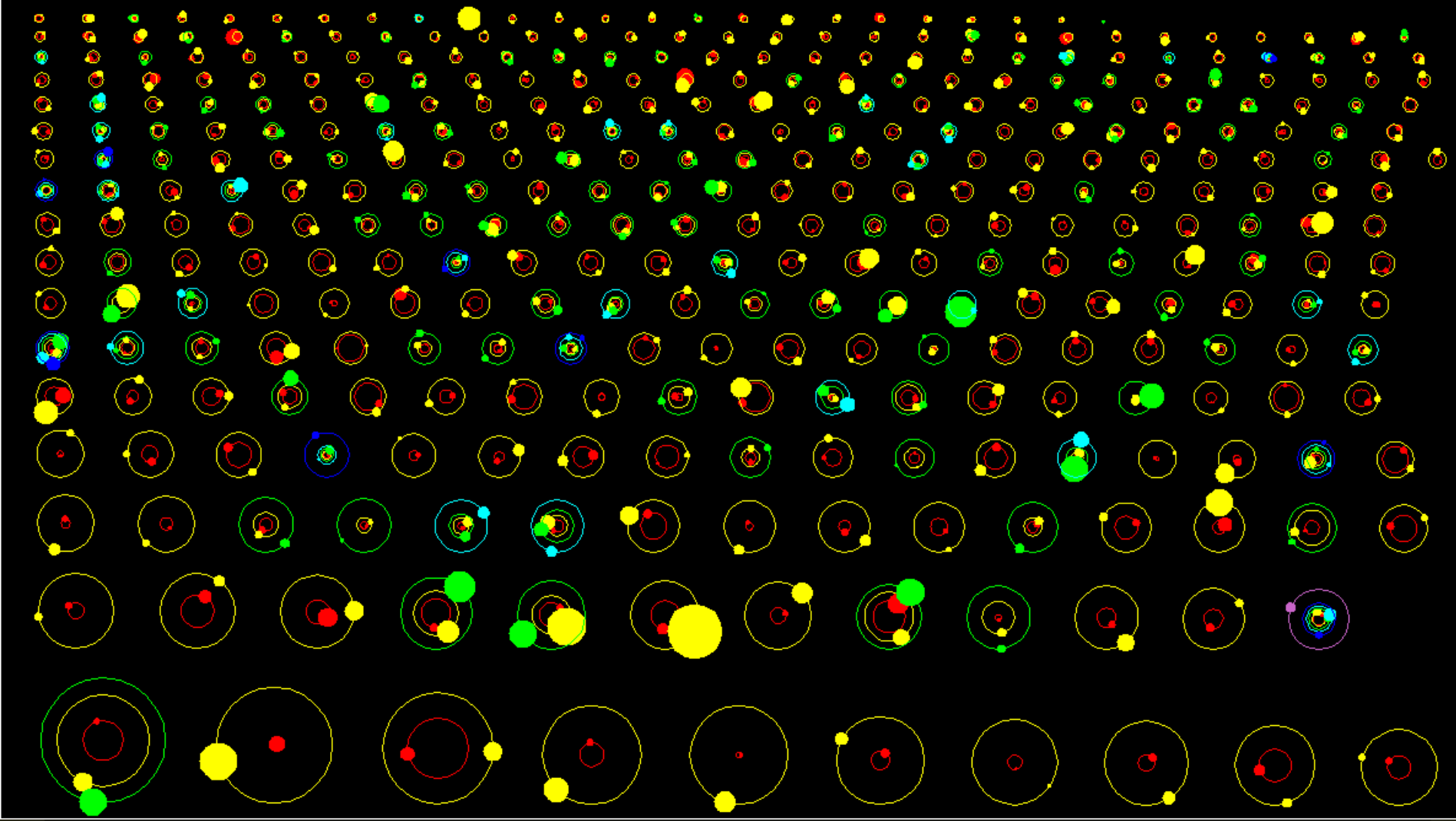
Daniel Fabrycky



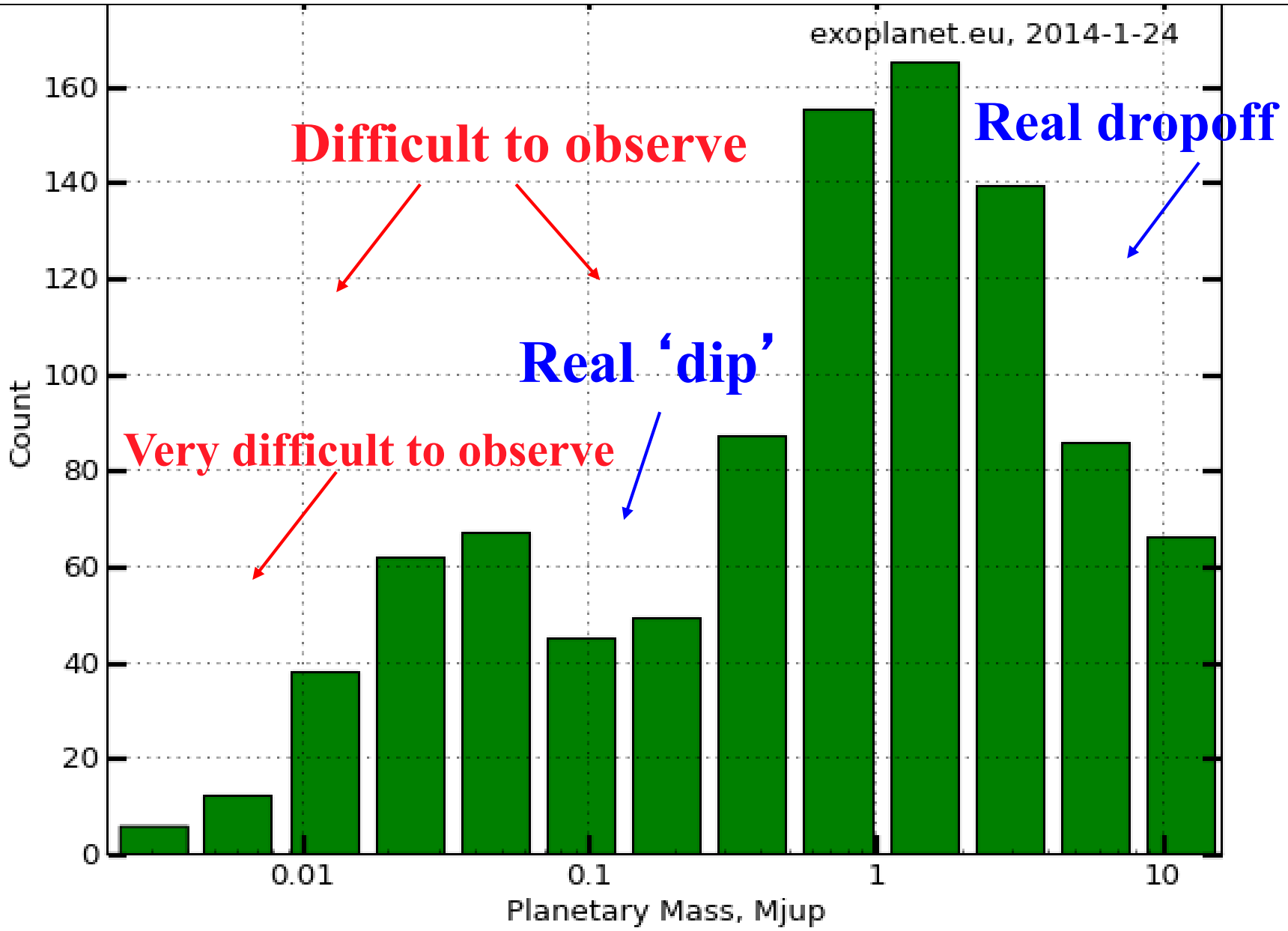
The Kepler Orrery II

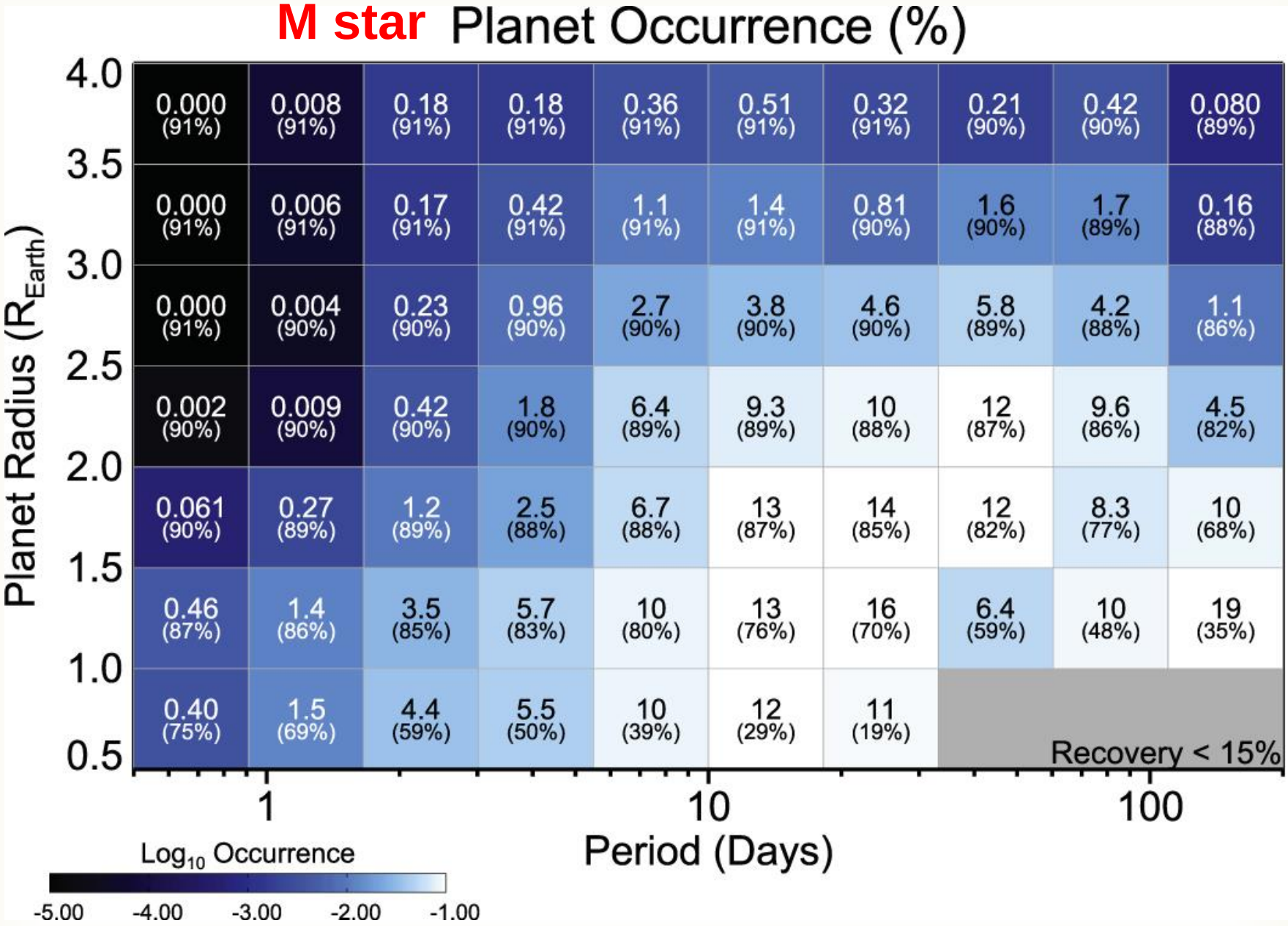
t[BJD] = 2454965

D. Fabrycky 2012



Mass Distribution of RV Planets

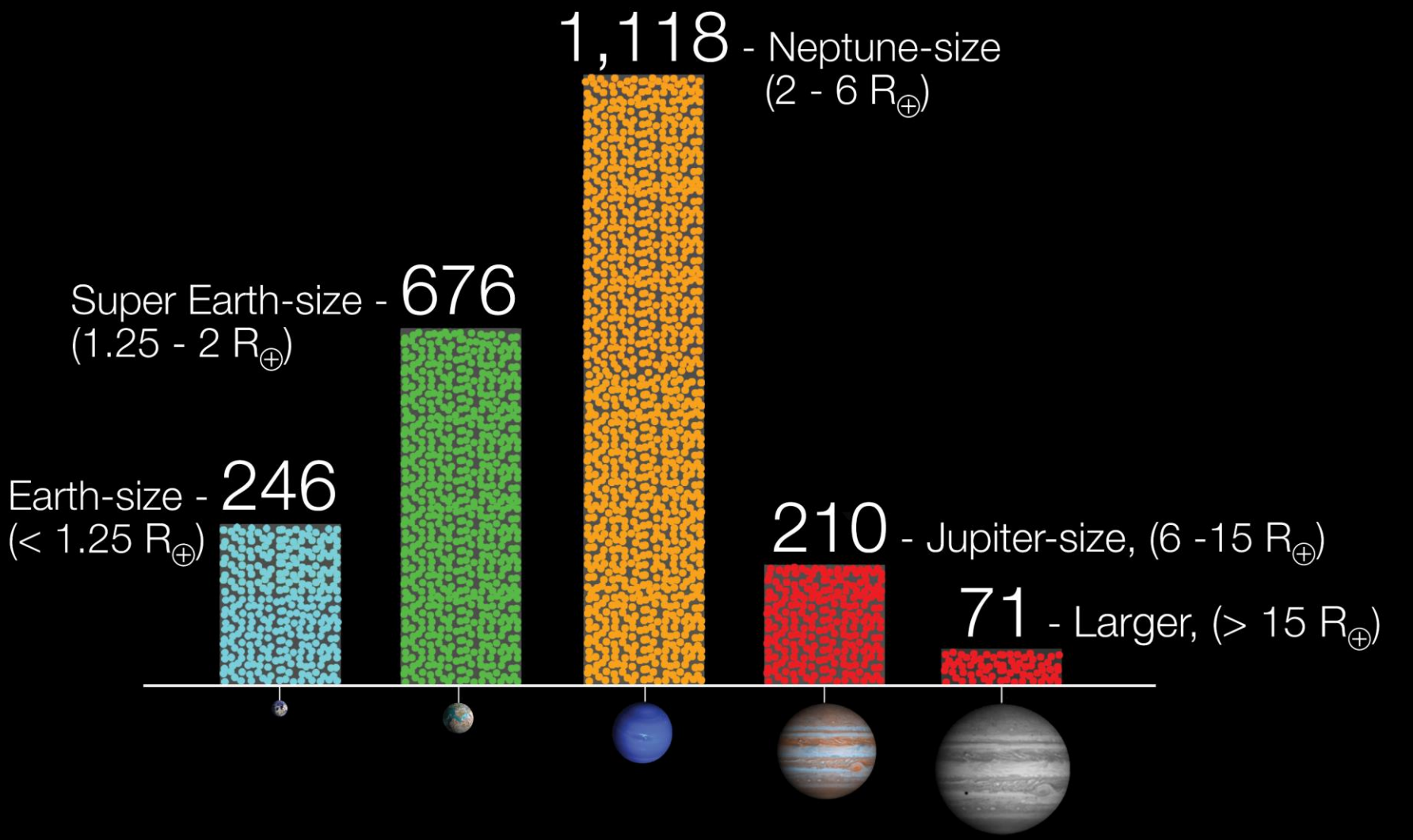




Dressing & Charbonneau (2015)

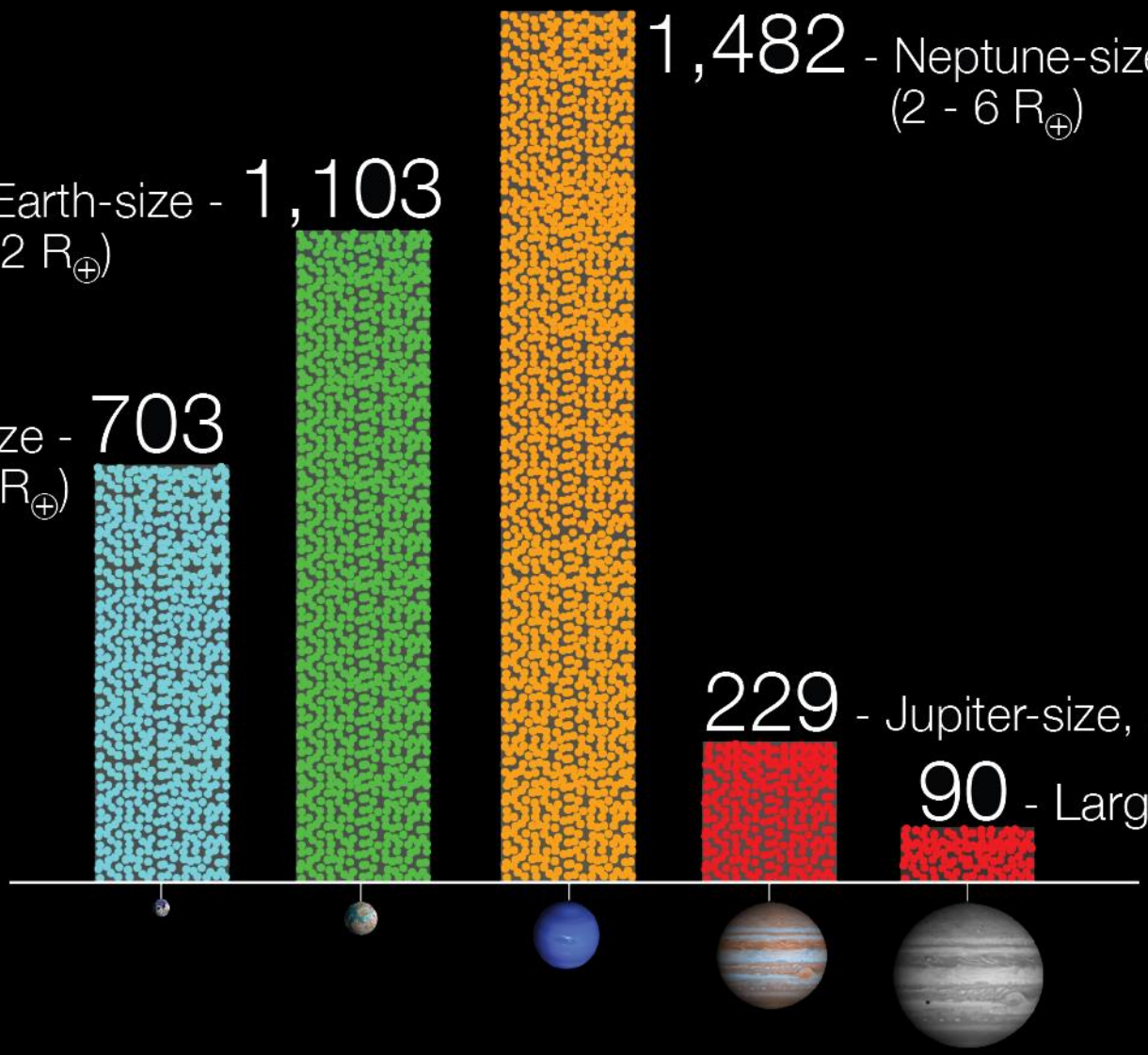
Sizes of Planet Candidates

As of February 27, 2012



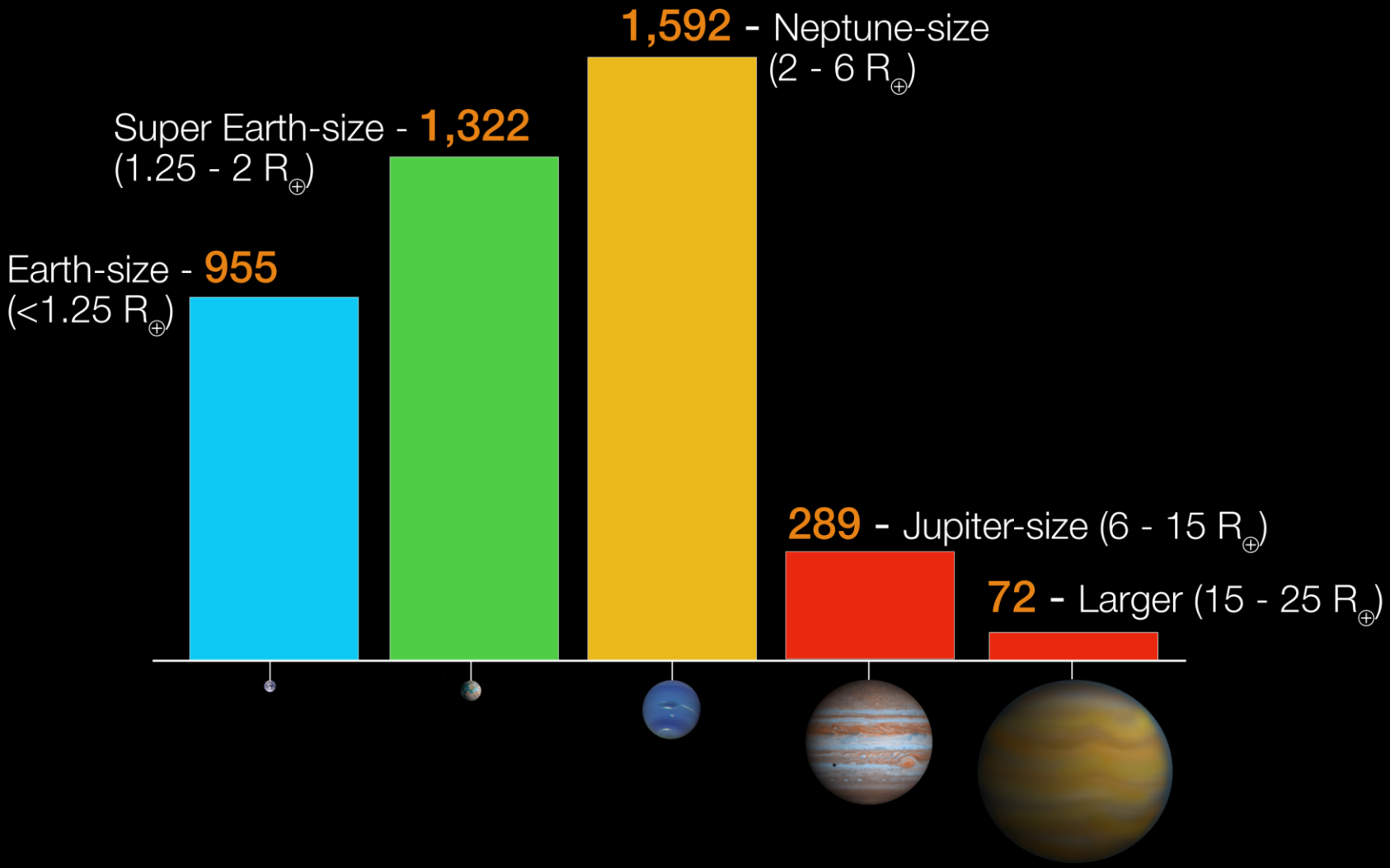
Sizes of Planet Candidates

Totals as of November, 2013

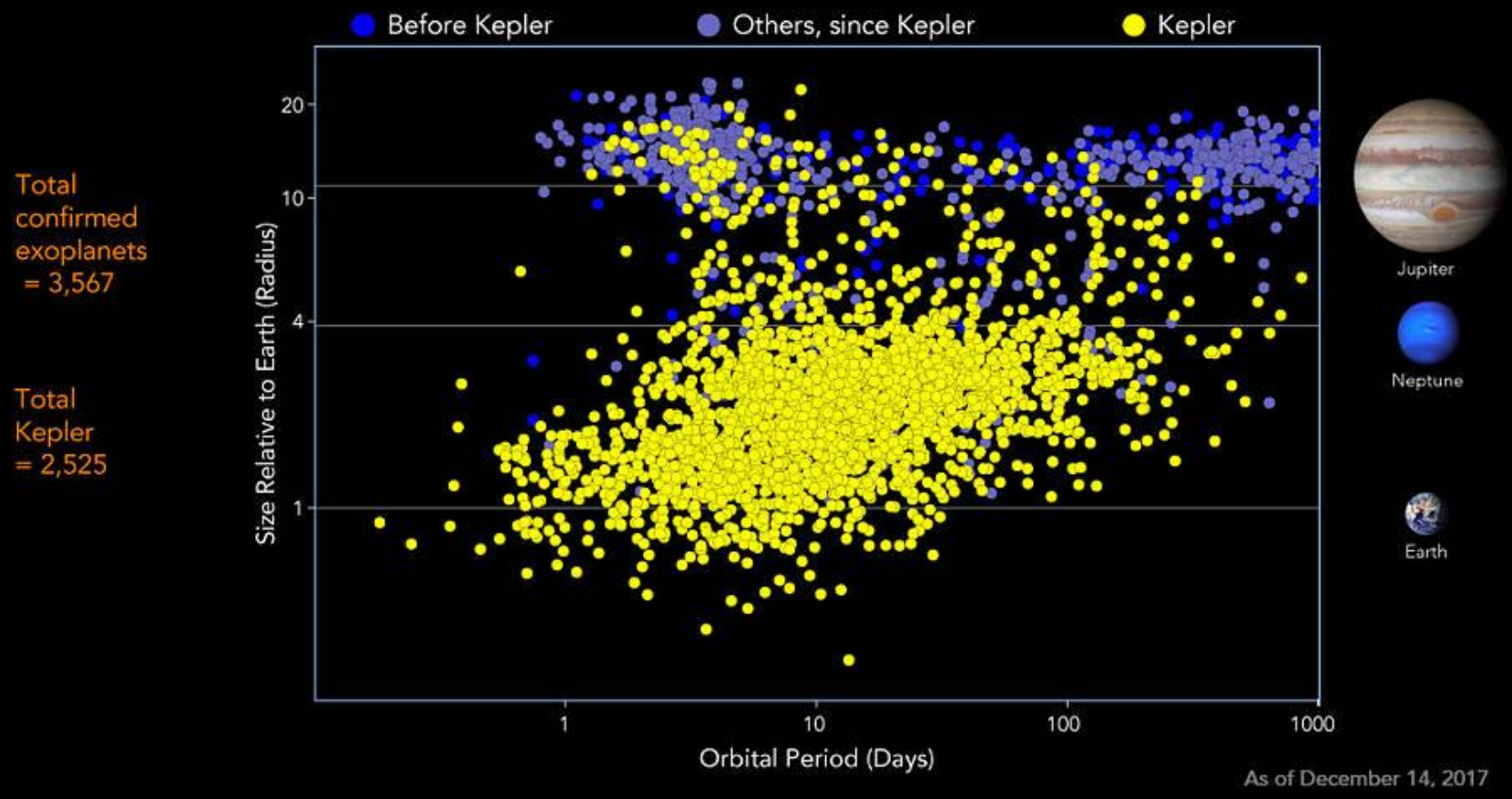


Sizes of Kepler Planet Candidates

As of July 23, 2015



Exoplanet Discoveries



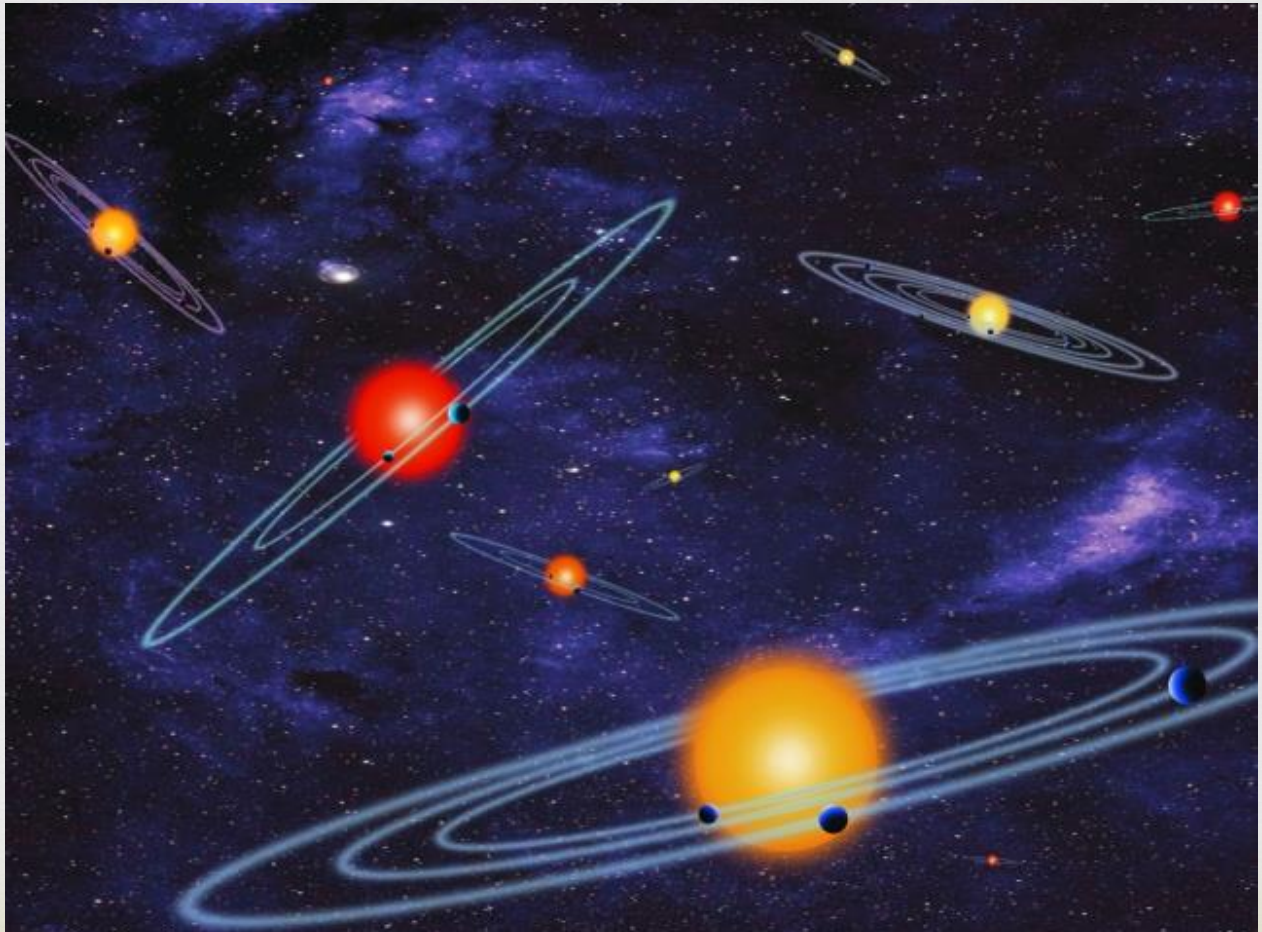
- ~70% of known planets were discovered by *Kepler/K2*

Key *Kepler* Findings

Planets, especially “small” ones, are common

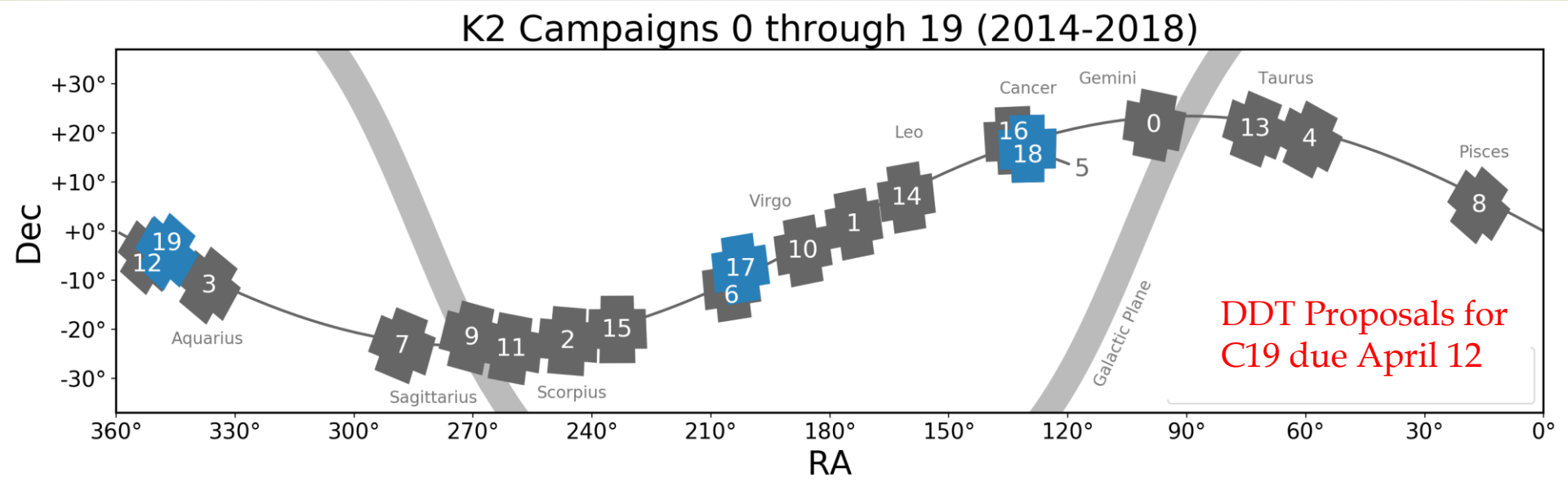
Planetary systems are flat, like the Solar System

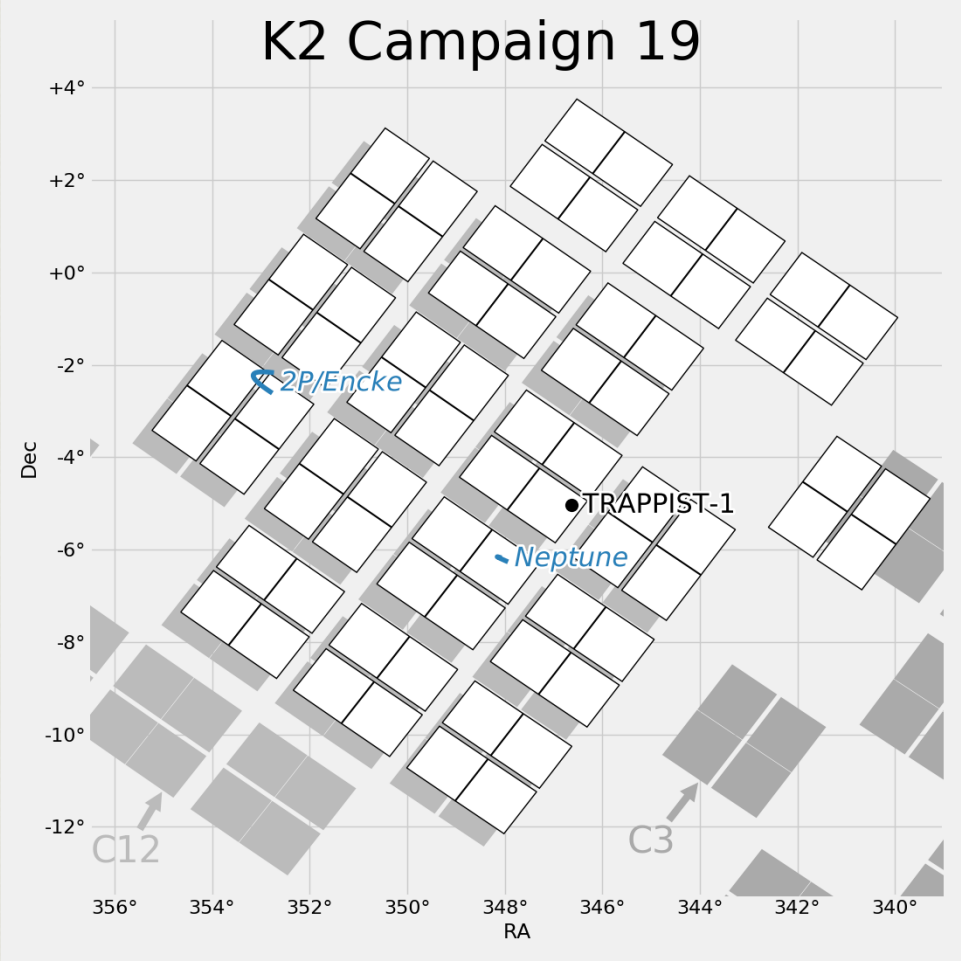
Planets & planetary systems are extremely diverse



K2: Good Science from a Broken Spacecraft

- In May of 2013, *Kepler* lost its 2nd gyroscope and could no longer point at its original field of view
- *Kepler* can still observe in its orbital plane





August 6, 2018 – October 10, 2018

- Forward facing to facilitate simultaneous ground observations
- Partial overlaps with C3 & C12
- Return to Trappist-1
- Return to Neptune
- Comet 2P/Encke

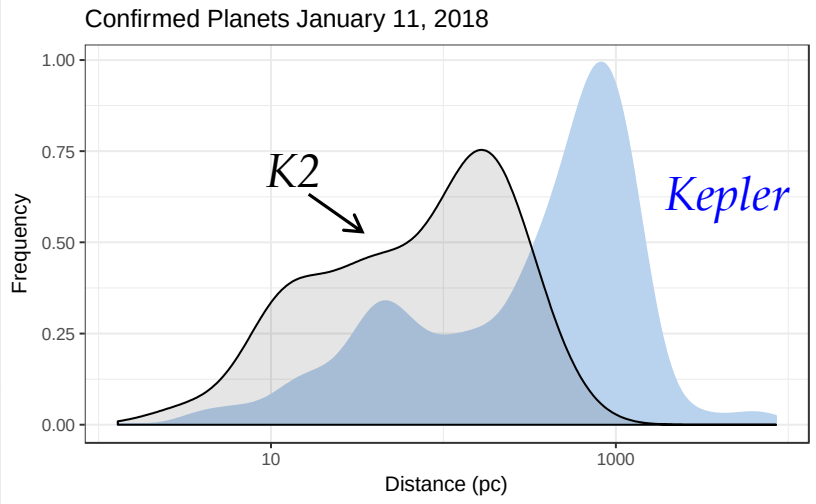
DDT deadline is April 12, 2018

keplerscience.arc.nasa.gov

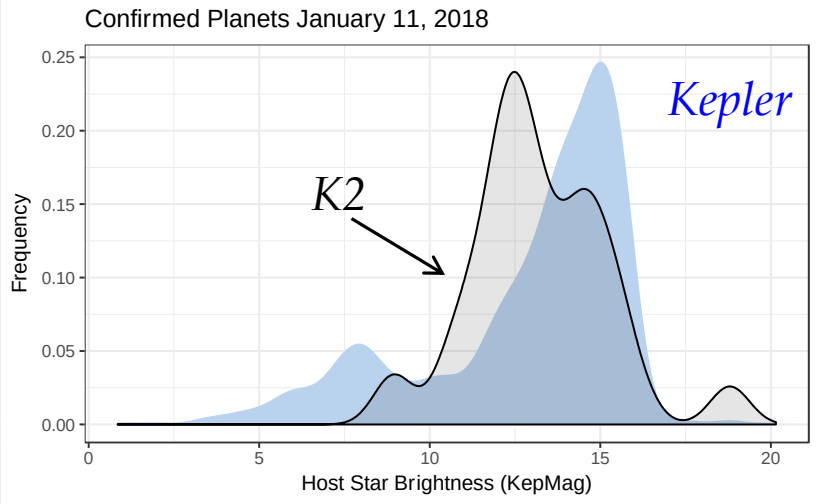
Exoplanets: *K2* vs. *Kepler*

- *Kepler* had better precision, stared at the same stars for much longer and observed more stars simultaneously
- *K2* has observed more total stars, with the best targets (brighter stars and M dwarfs) chosen from many fields of view
- *Kepler* provided more information about properties of planets and planetary systems, but *K2* has found many planets that are better for follow-up

Typical *K2* Planets are

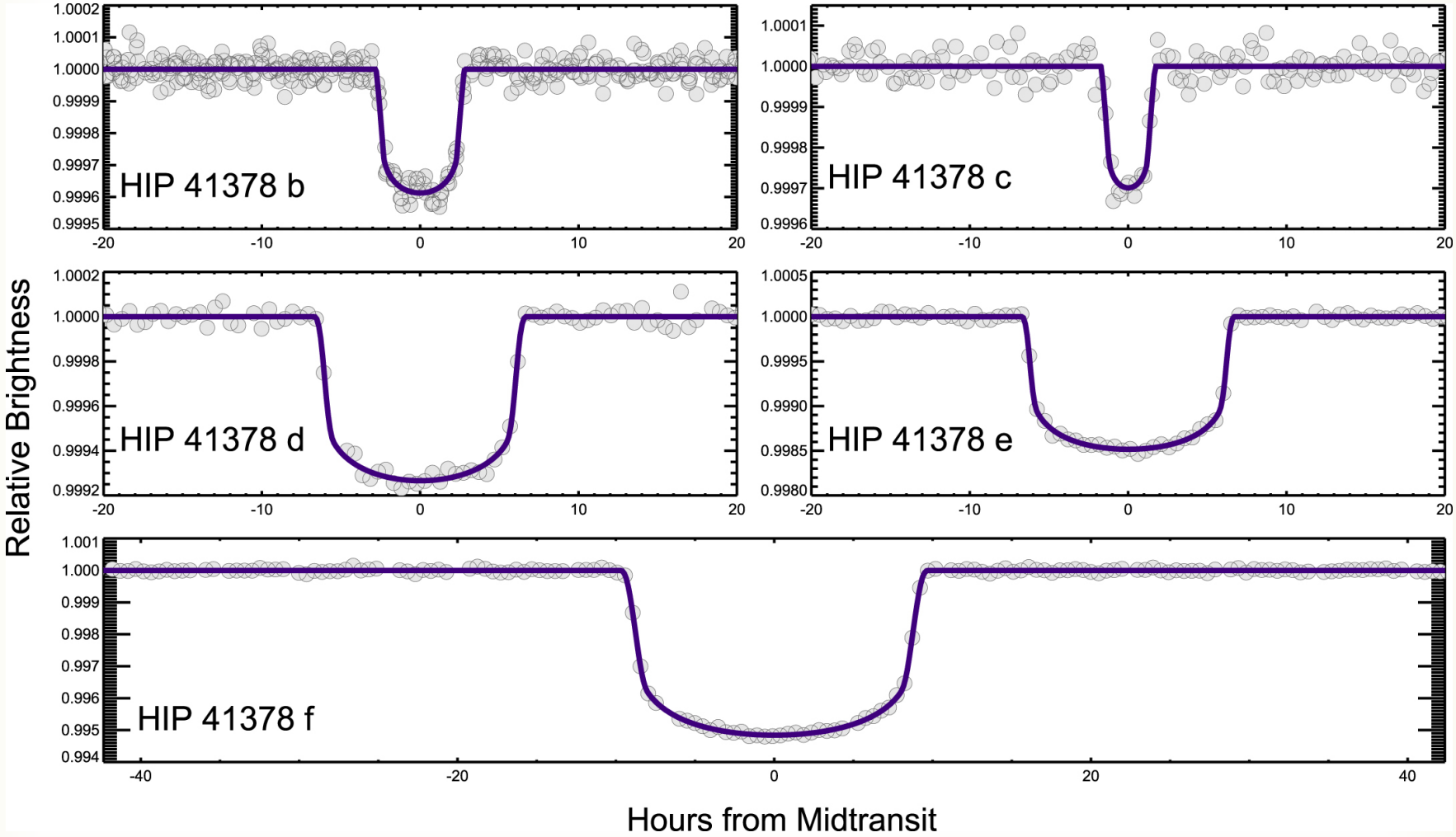


around closer stars



around brighter stars

5 planet system found by *K2*

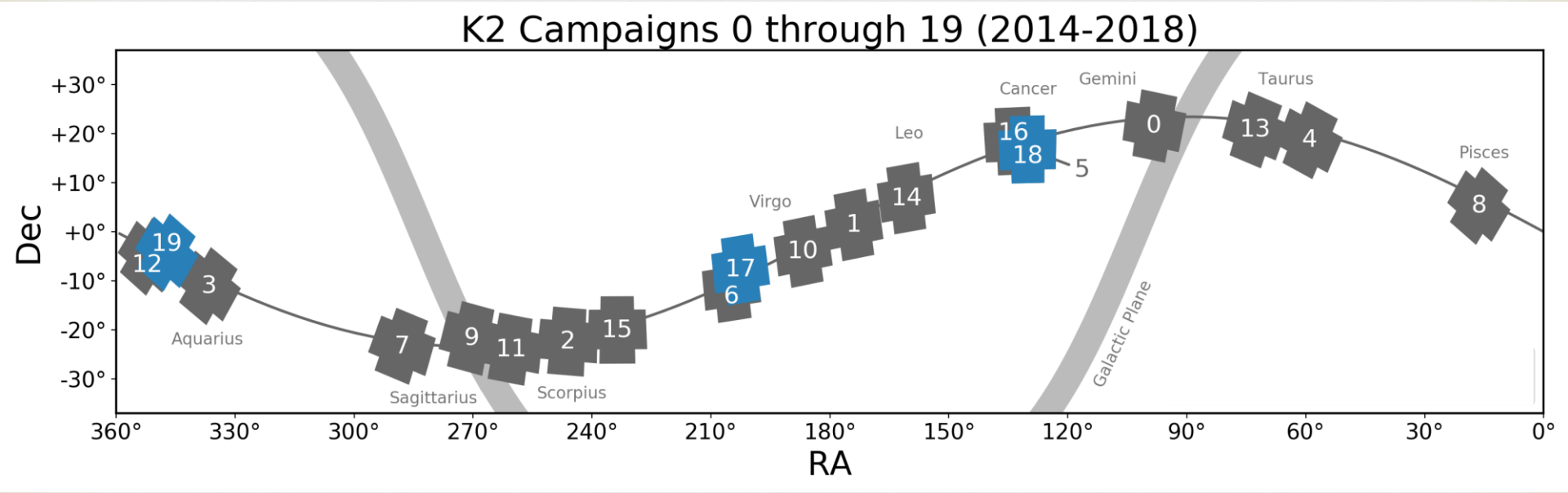


Vanderburg et al. 2016

Multis Observed by *K2*

Kepler gyros failed – Spacecraft repurposed as *K2*

Many FOVs, focus on bright stars and small stars

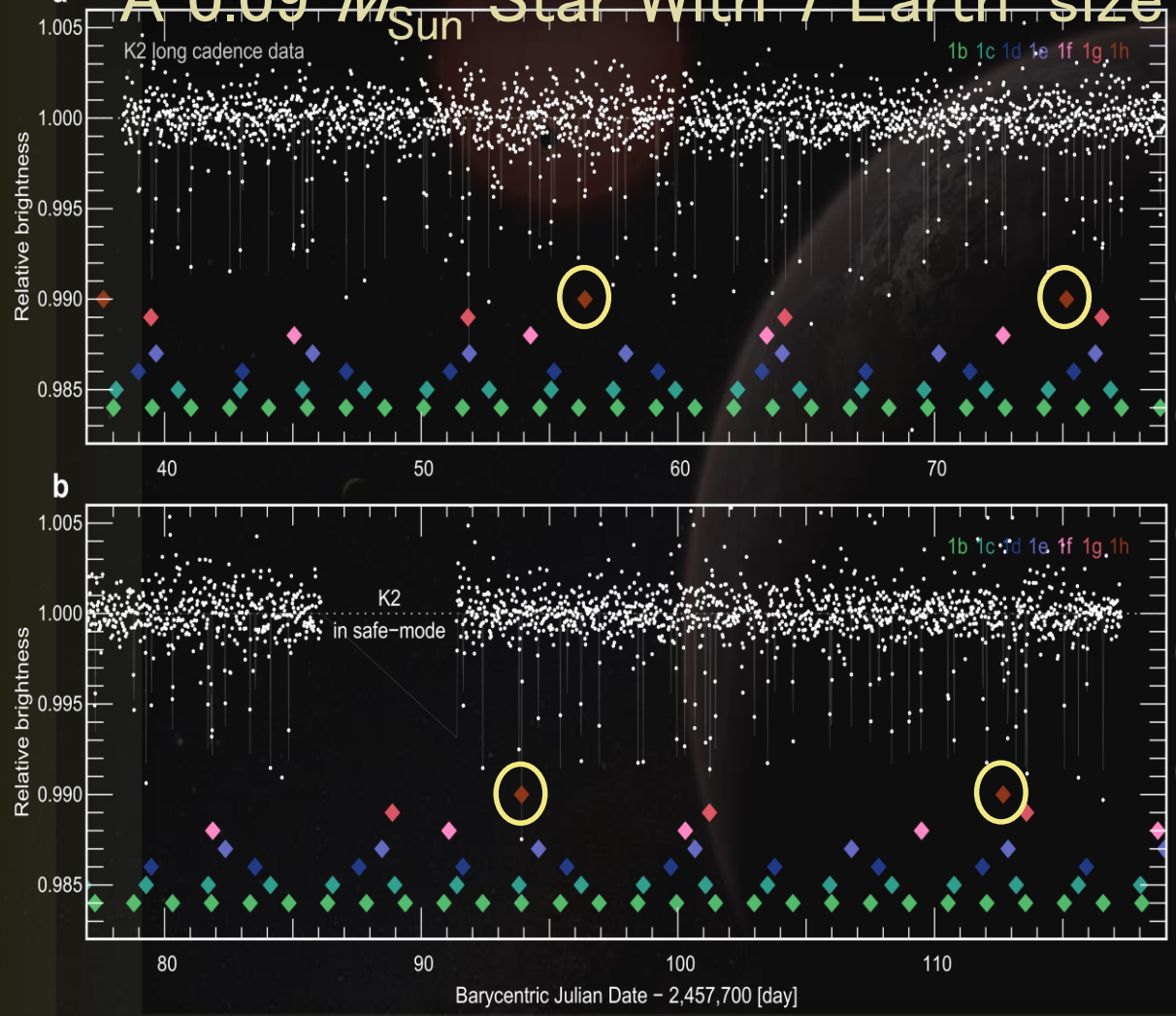


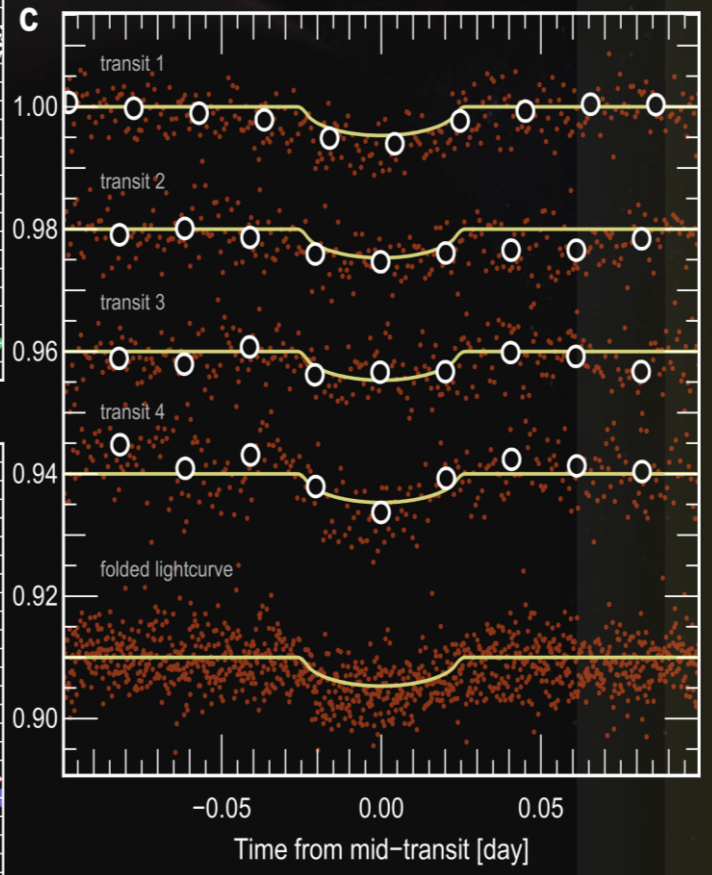
Dozens of multis discovered, with as many as 5 planets

Observed TRAPPIST-1

K2 Observations of TRAPPIST-1

A 0.09 M_{Sun} Star With 7 Earth-size Transiting Planets

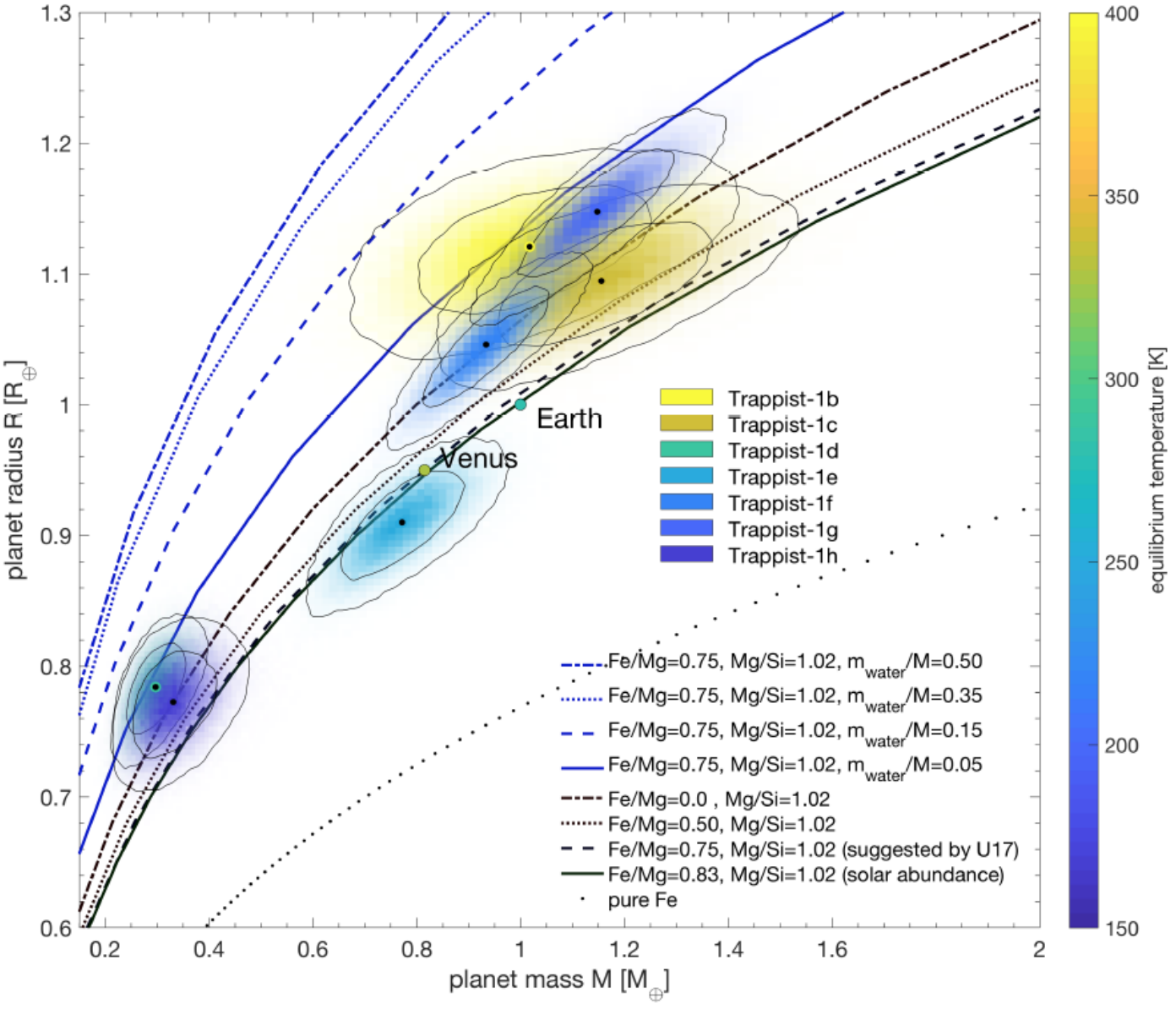




The period of TRAPPIST-1h: 18.764 d (3:2)

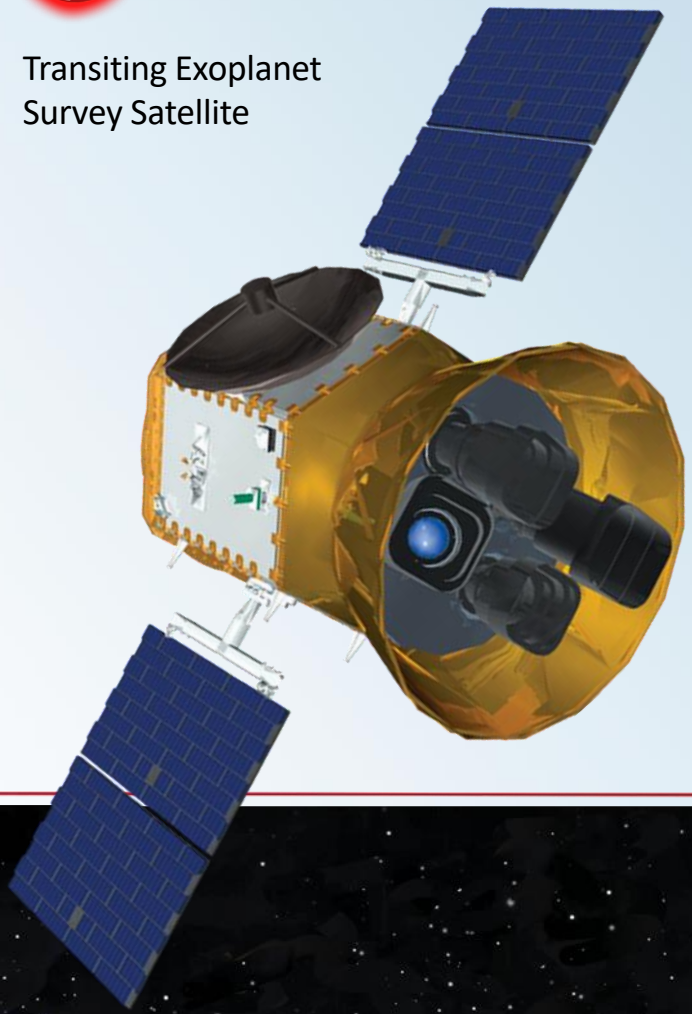
Luger et al. 2017

Mass-Radius Diagram for TRAPPIST-1 Planets



Grimm et al. (2018)

Transiting Exoplanet
Survey Satellite

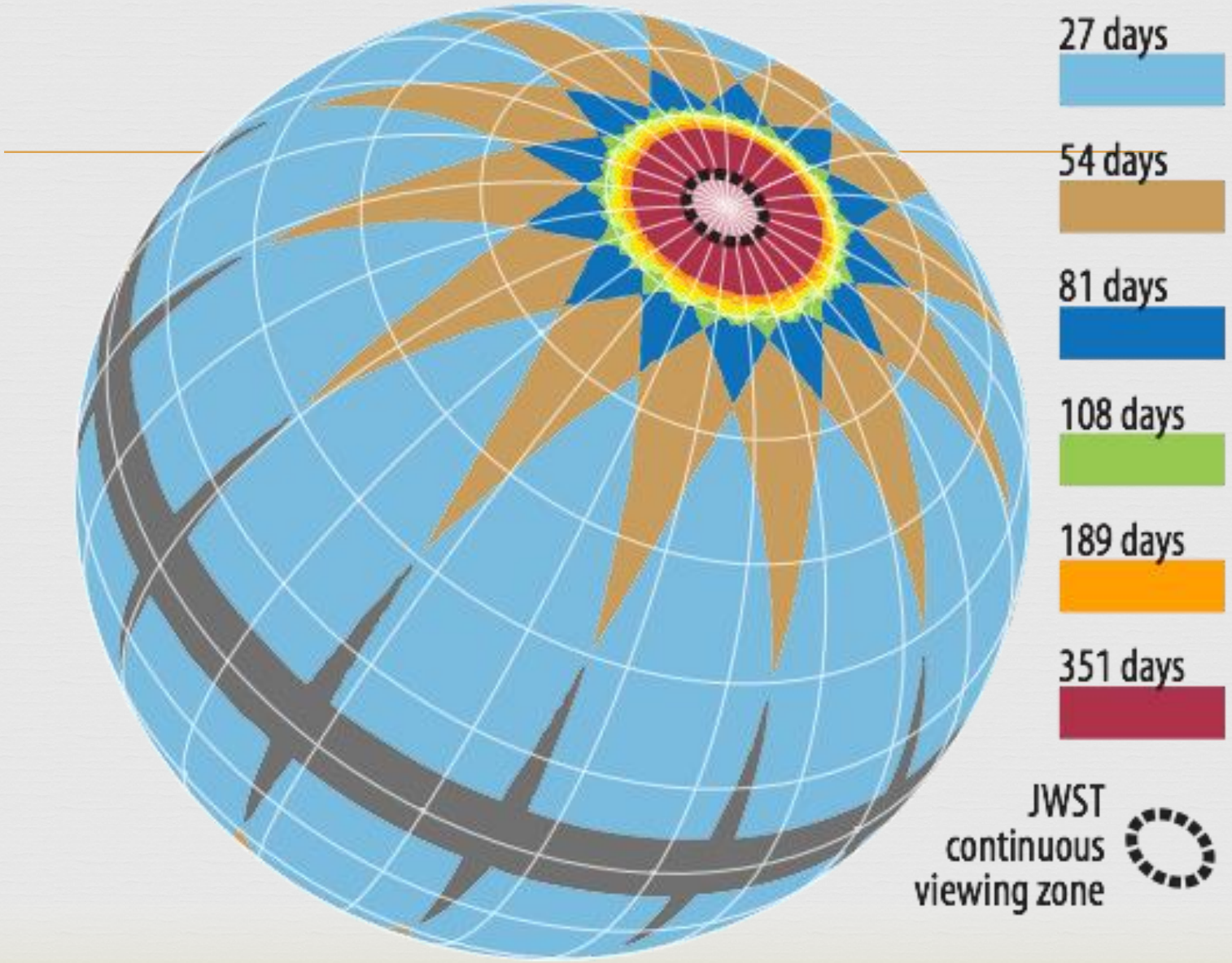


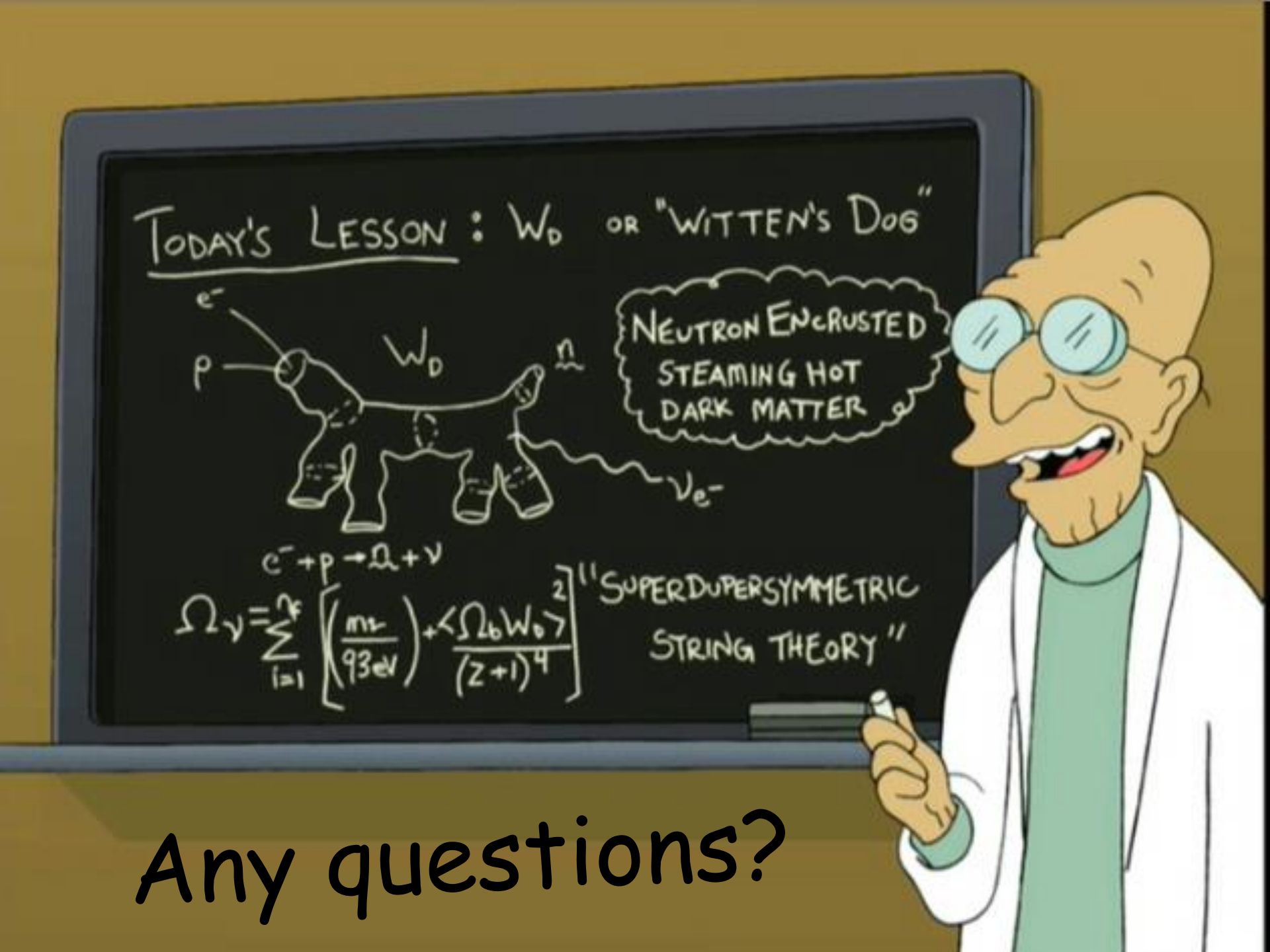
TESS: Discovering New Earths and Super-Earths in the Solar Neighborhood

George Ricker (MIT), PI

Launch: 2018 March 20

TESS Sky Coverage





Any questions?