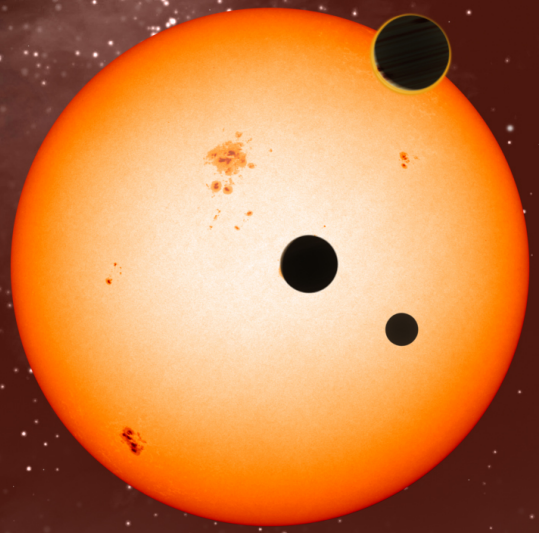
NASA's *Kepler* Mission

William Borucki, Science Principal Investigator



Ames Research Center

Ball

JPL

LASP

LHS

SAO

SETI Institute

PART OF THE SCIENCE TEAM AND A FEW OF THE MANY WHO HAVE MADE *KEPLER* POSSIBLE

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Christopher Allen[32], Howard Anderson[2], Jason Barnes[34], Alan Boss[19], Don Brownlee[22], Frederick Bruhweiler[33], Stephen T. Bryson[1], Lars Buchhave[10], Hema Chandrasekaran[5], David Charbonneau[10], David Ciardi[29], Bruce D. Clarke[5], Jessie Dotson[1], Debra Fischer[16], Michael Haas[1], Elliott Horch[24], Howard Isaacson[2], John Asher Johnson[29], Jie Li[5], Toby Owen[21], Andrej Prsa[35],Elisa V. Quintana[5], Jason Rowe[1], Phillip MacQueen[7], William Sherry[15], Peter Tenenbaum[5], Guillermo Torres[10] , Joseph D. Twicken[5], Jeffrey Van Cleve[5], Ekaterina Verner[33], Lucianne Walkowicz[2], Haley Wu[5] , Jeffrey Kolodziejczak[31],

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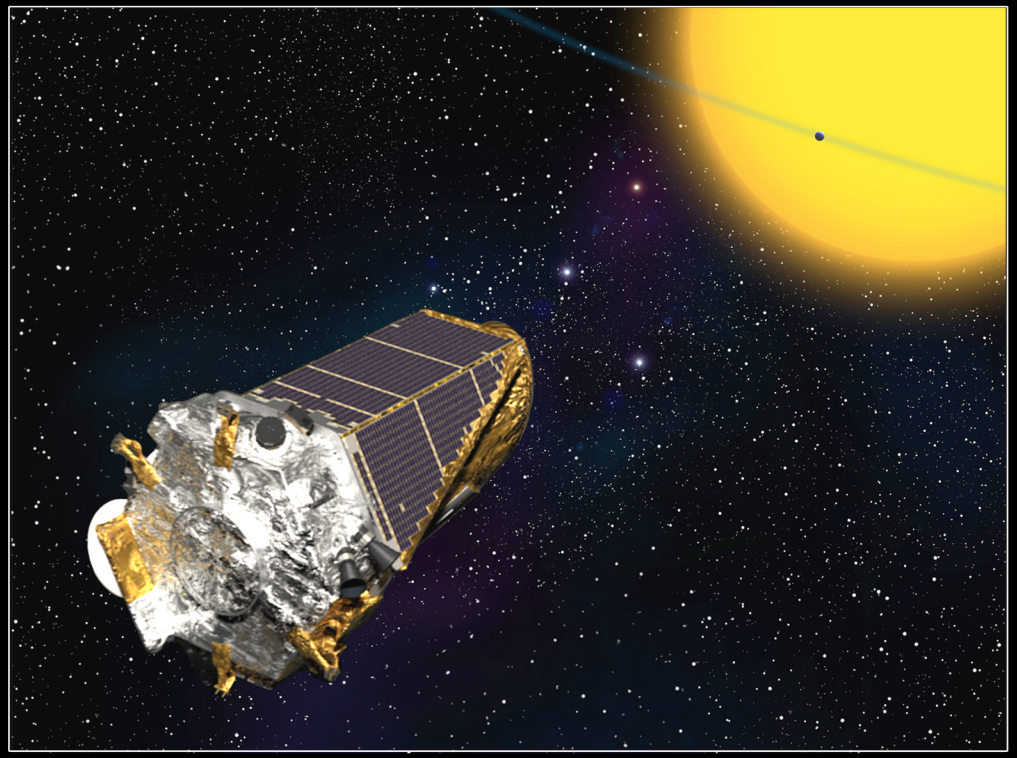
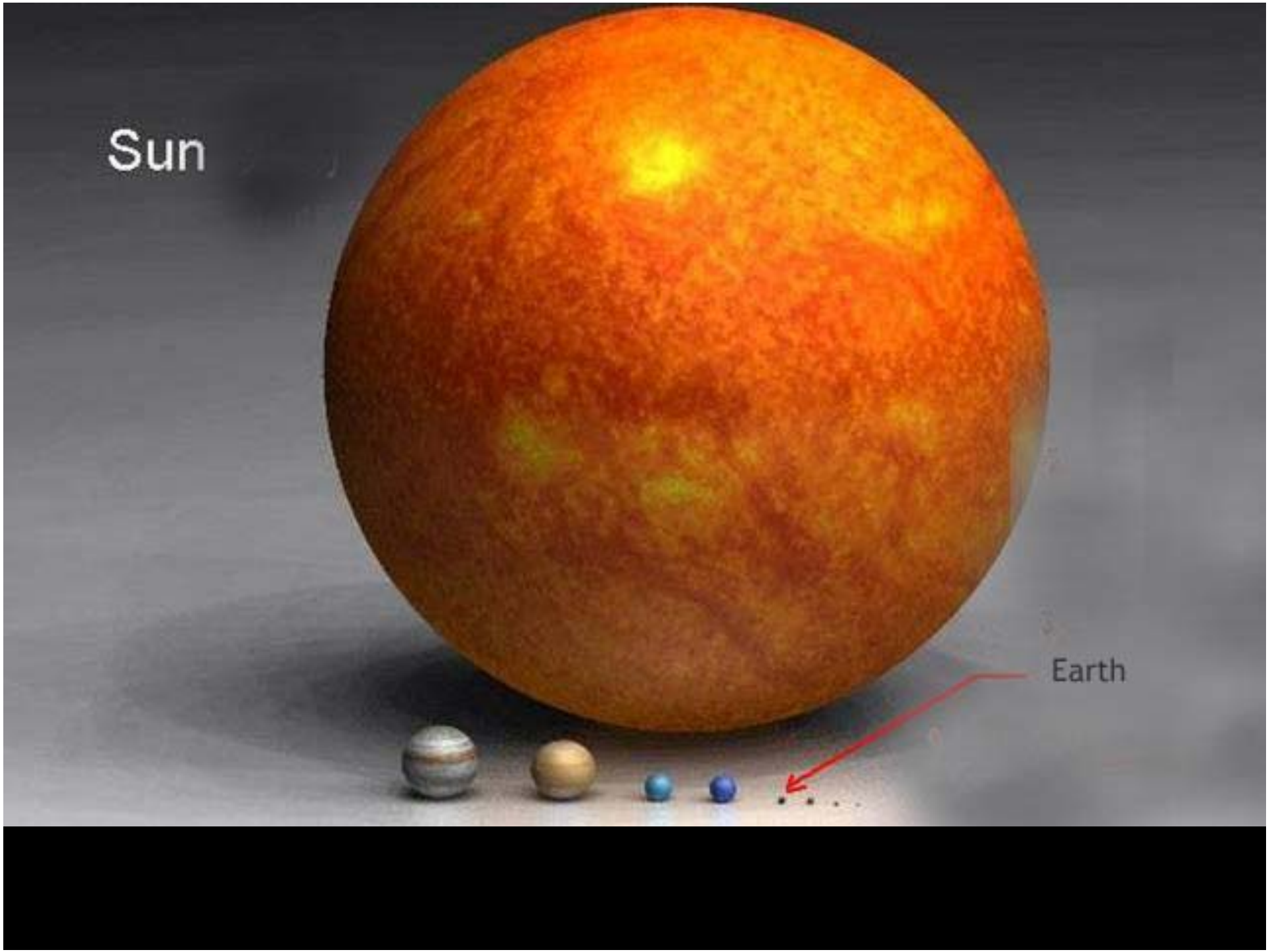
NASA's Kepler Mission

- Determine the frequency of Earth-size and larger planets in the habitable zone of sun-like stars
- Determine the size and orbital period distributions of planets




Sun
Earth

Transits Can Reveal Earth-size Planets

From **TRANSIT DATA** obtain:

Duration, depth, orbital period and inclination.

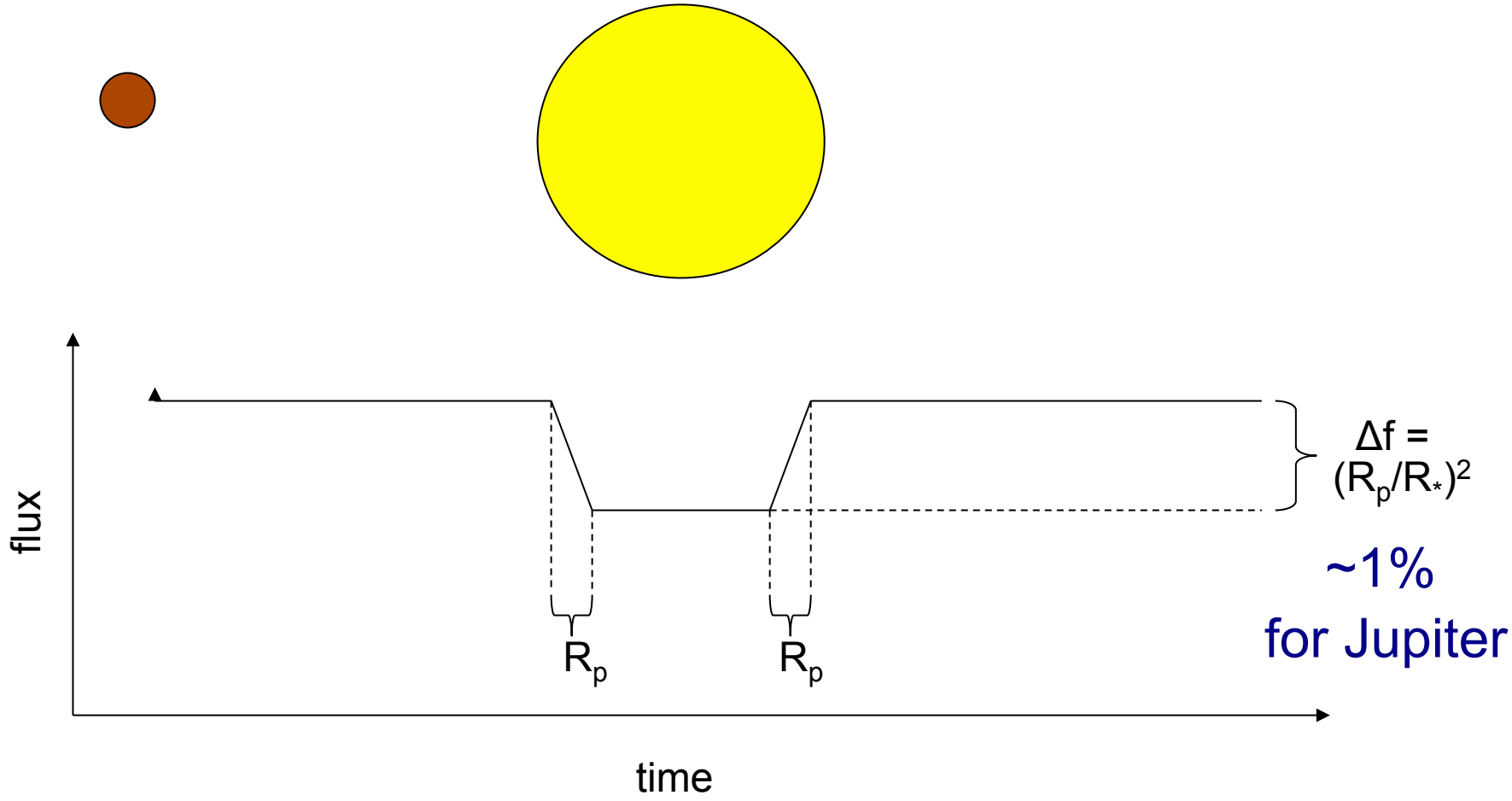
Derive planet sizes and orbital radii (when combined with stellar information)

From **ENSEMBLE of PLANETARY SYSTEMS** obtain:

Estimates frequency of planet formation for inner planets.

Requires thousands of stars because most orbits won't be aligned properly

Transit Lightcurve

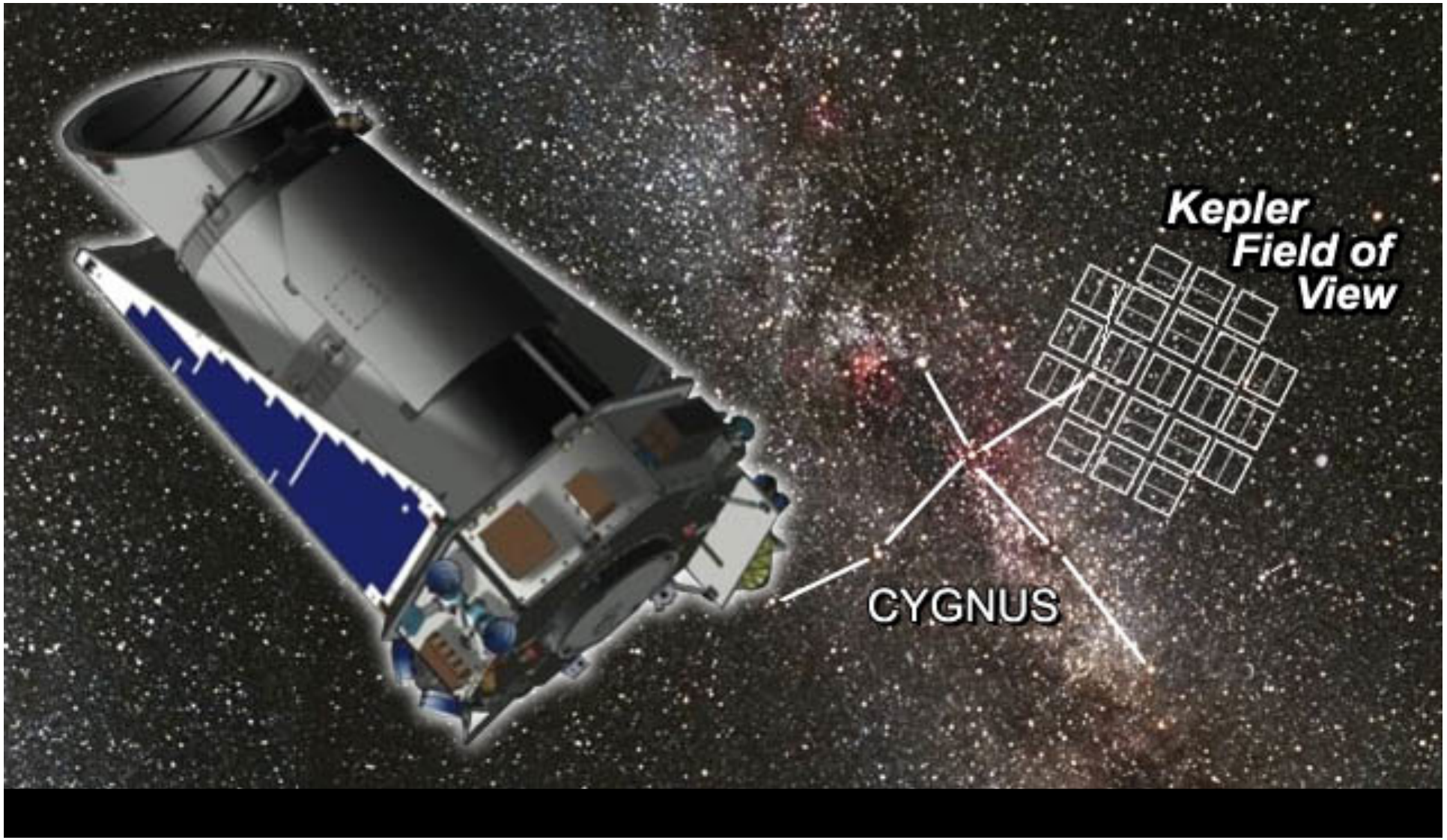


Josh Pepper

2004 Venus Transit at Sunrise

Kepler Mission

- NASA, photometry of > 150,000 stars
- Looking for Earth-like planets in transit
- < 40 ppm in 6 hours; 30 minute cadence

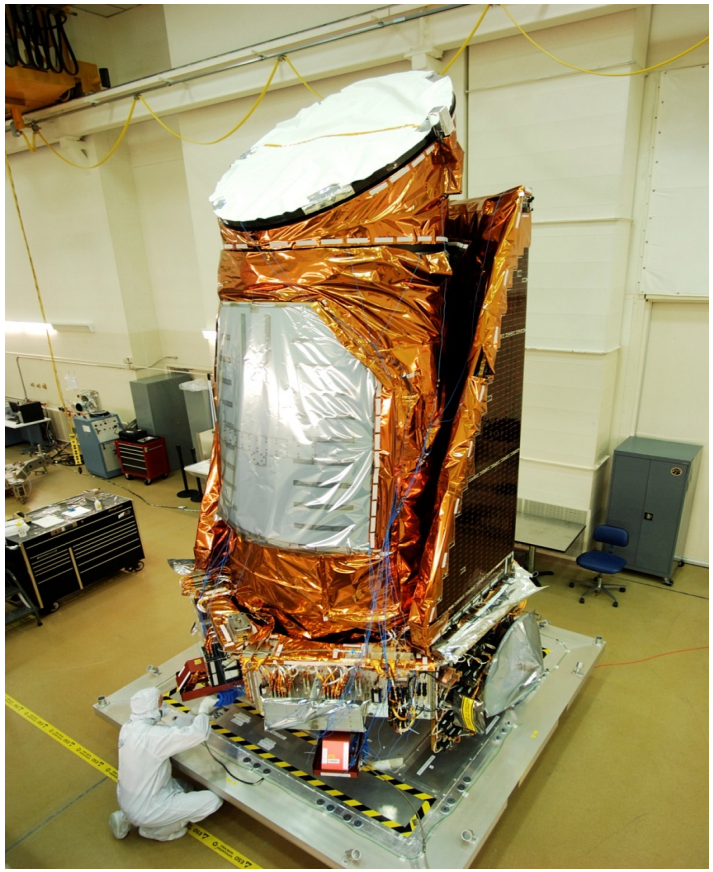


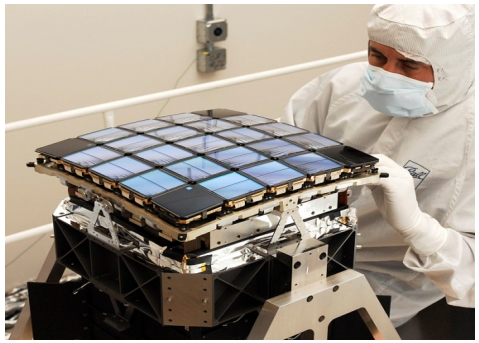
Kepler Mission Goals

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



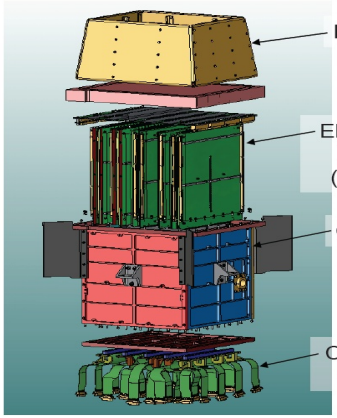


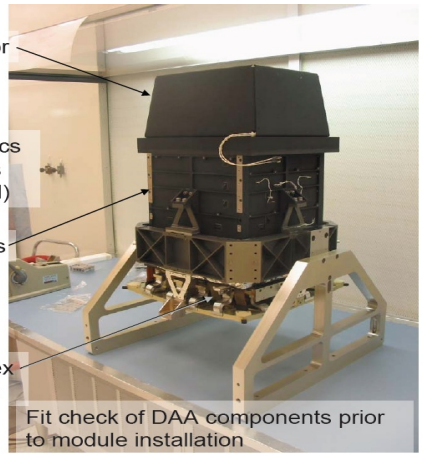
Largest focal plane for a NASA flight mission: 94.6 million science pixels

42 science CCDs, 2 channels each

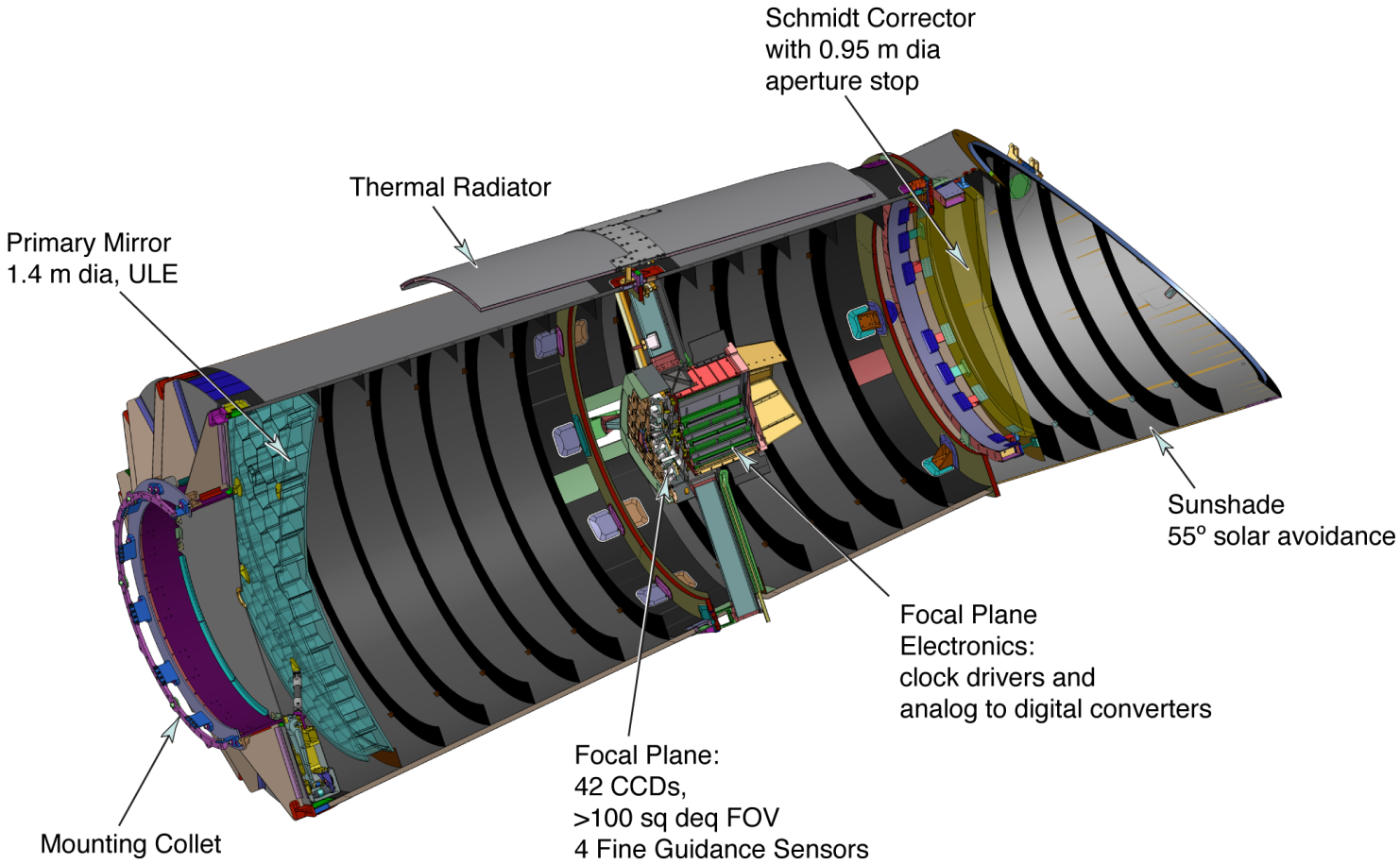
4 fine guidance sensor (FGS) CCDs

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



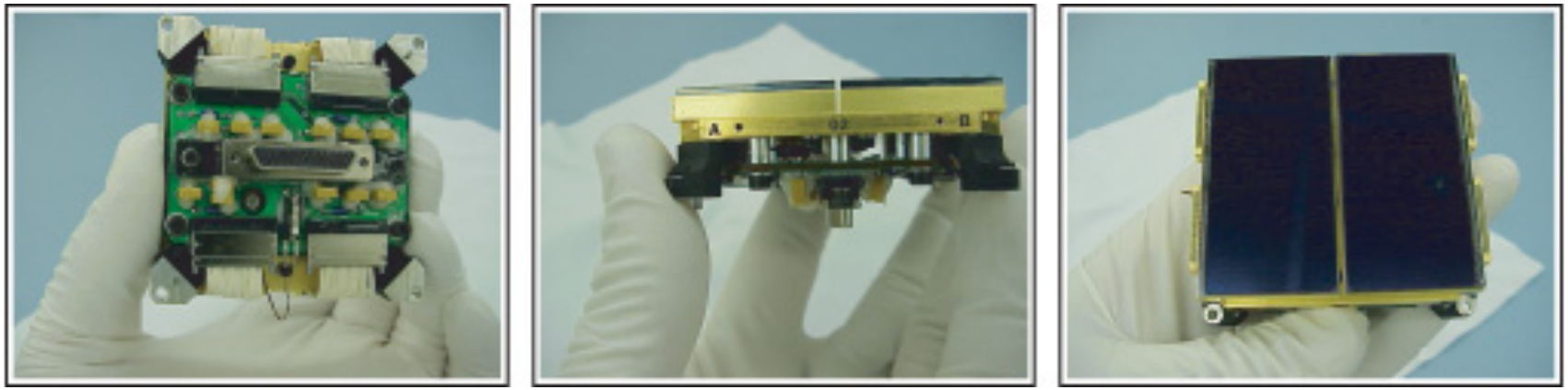


The Photometer



The overall height with the spacecraft and sunshade is 4.3 m.

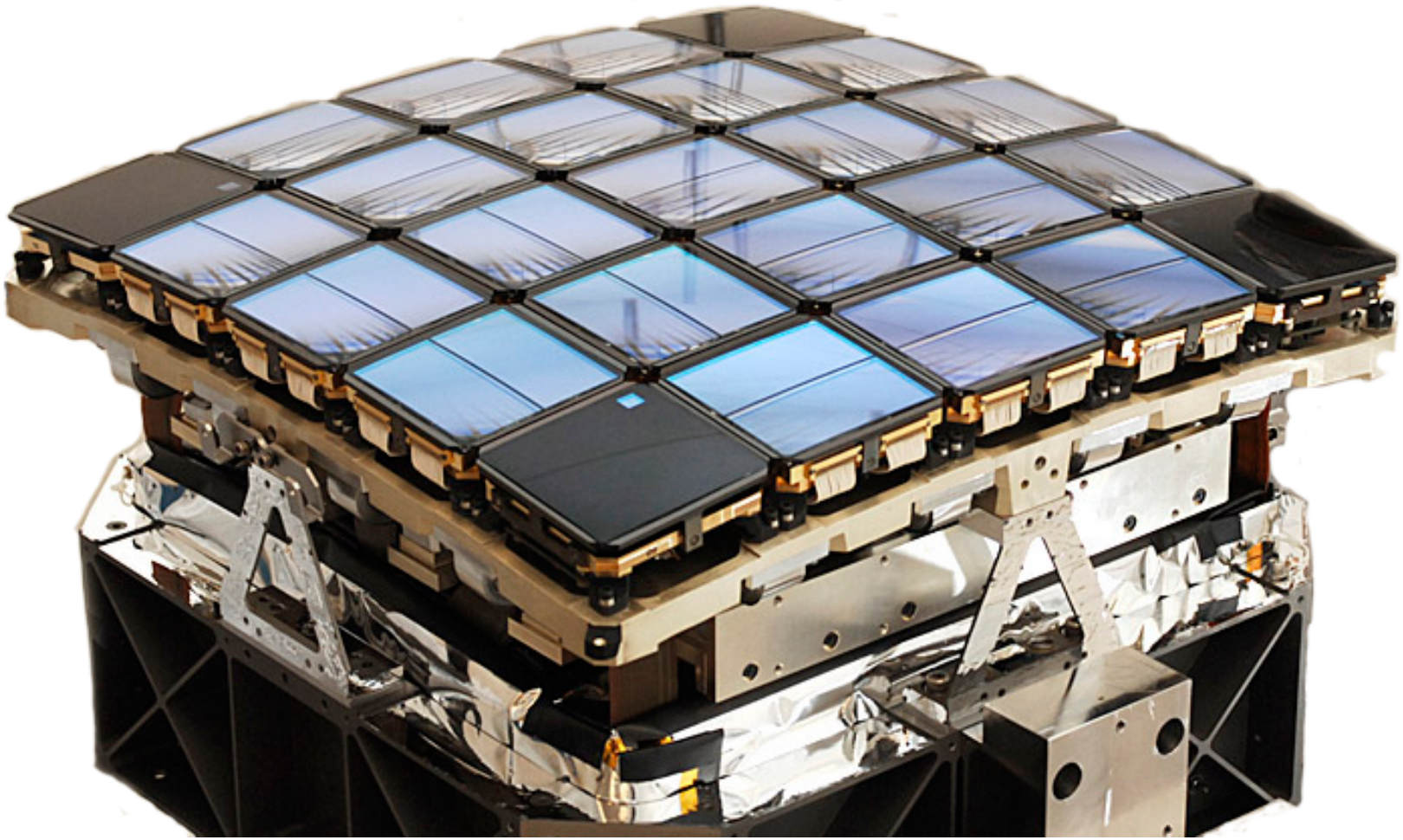
Kepler CCDs



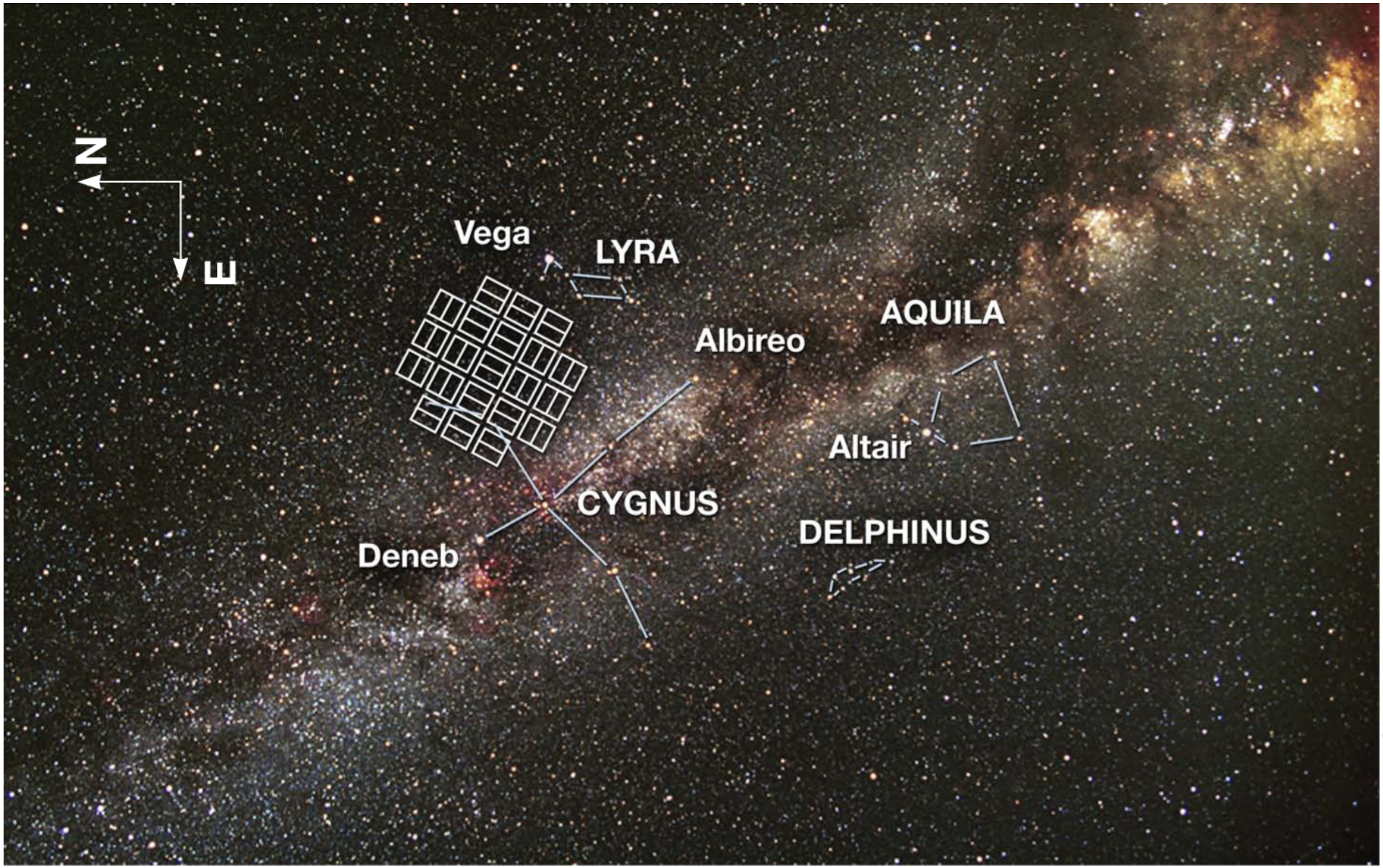
Views of a prototype module composed of
two CCDs mounted to a common carrier

Each CCD is 2200 columns by 1024 rows, thinned, back-illuminated, anti-reflection coated, 4-phase devices manufactured by **e2v**.
Each CCD has two outputs with the serial channel on the long edge.
The pixels are 27 μm square, corresponding to 3.98 arcsec on the sky.

The Focal Plane

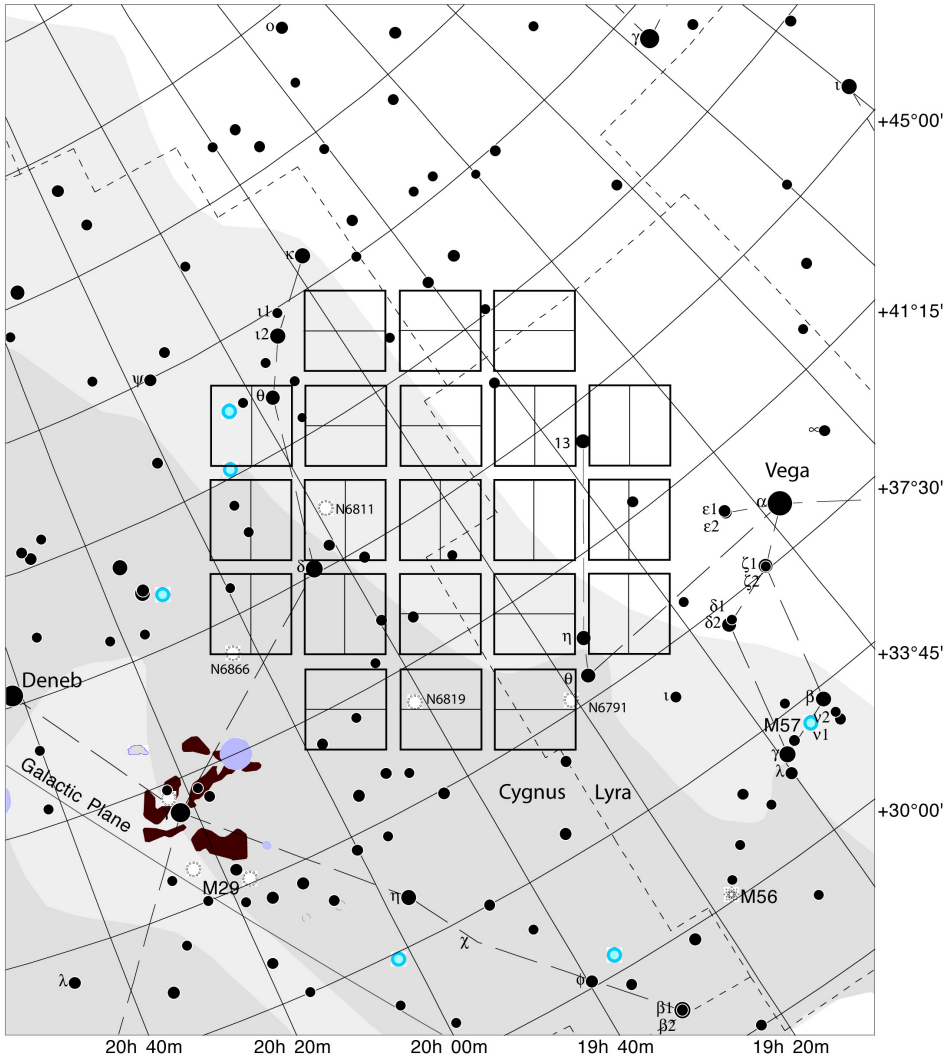


Star Field: Cygnus-Lyra

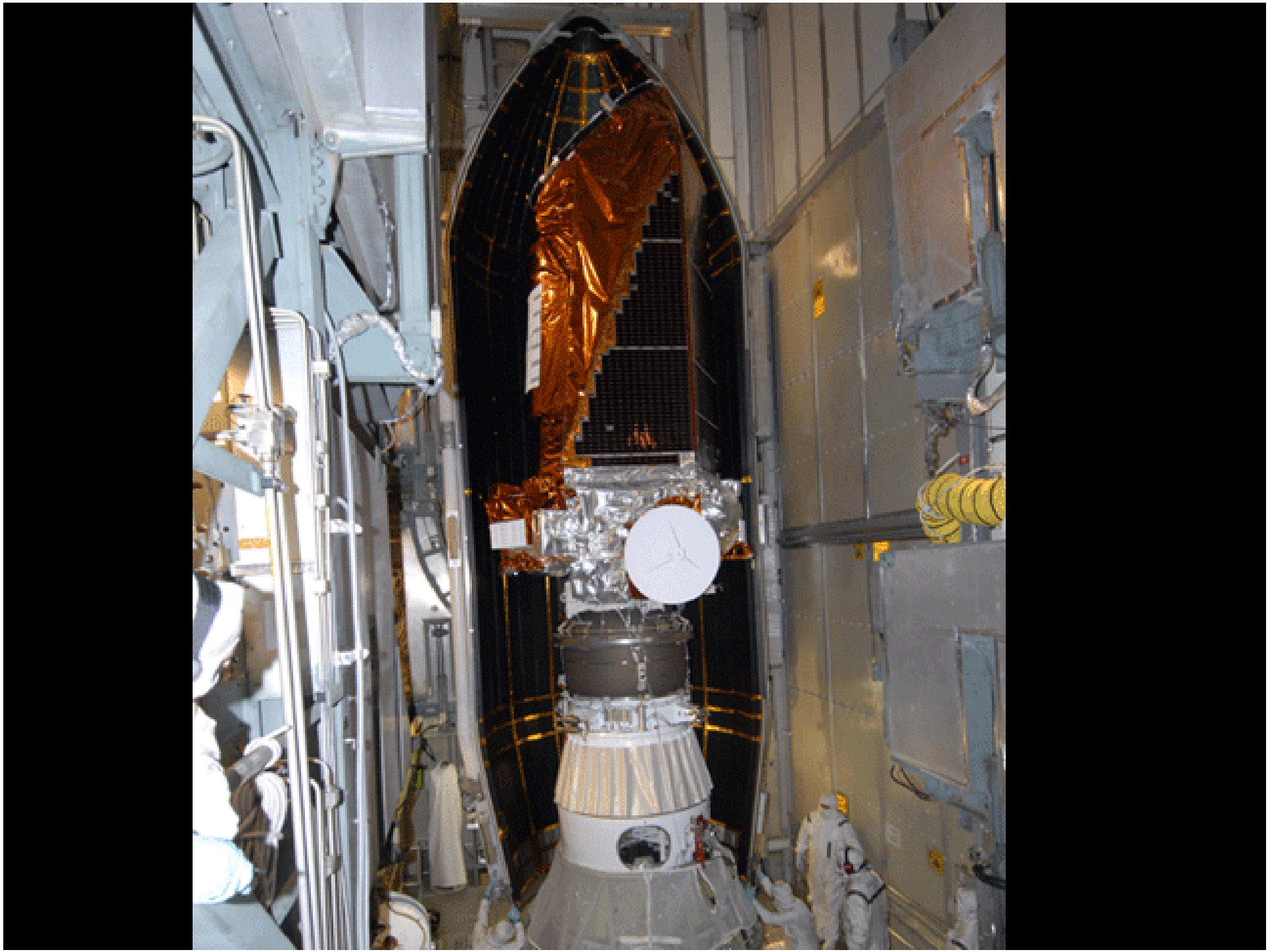


Milky Way photo by Carter Roberts

FIELD OF VIEW IN CYGNUS



A region of the extended solar neighborhood in the Cygnus-Lyra regions along the Orion arm of our galaxy has been chosen.

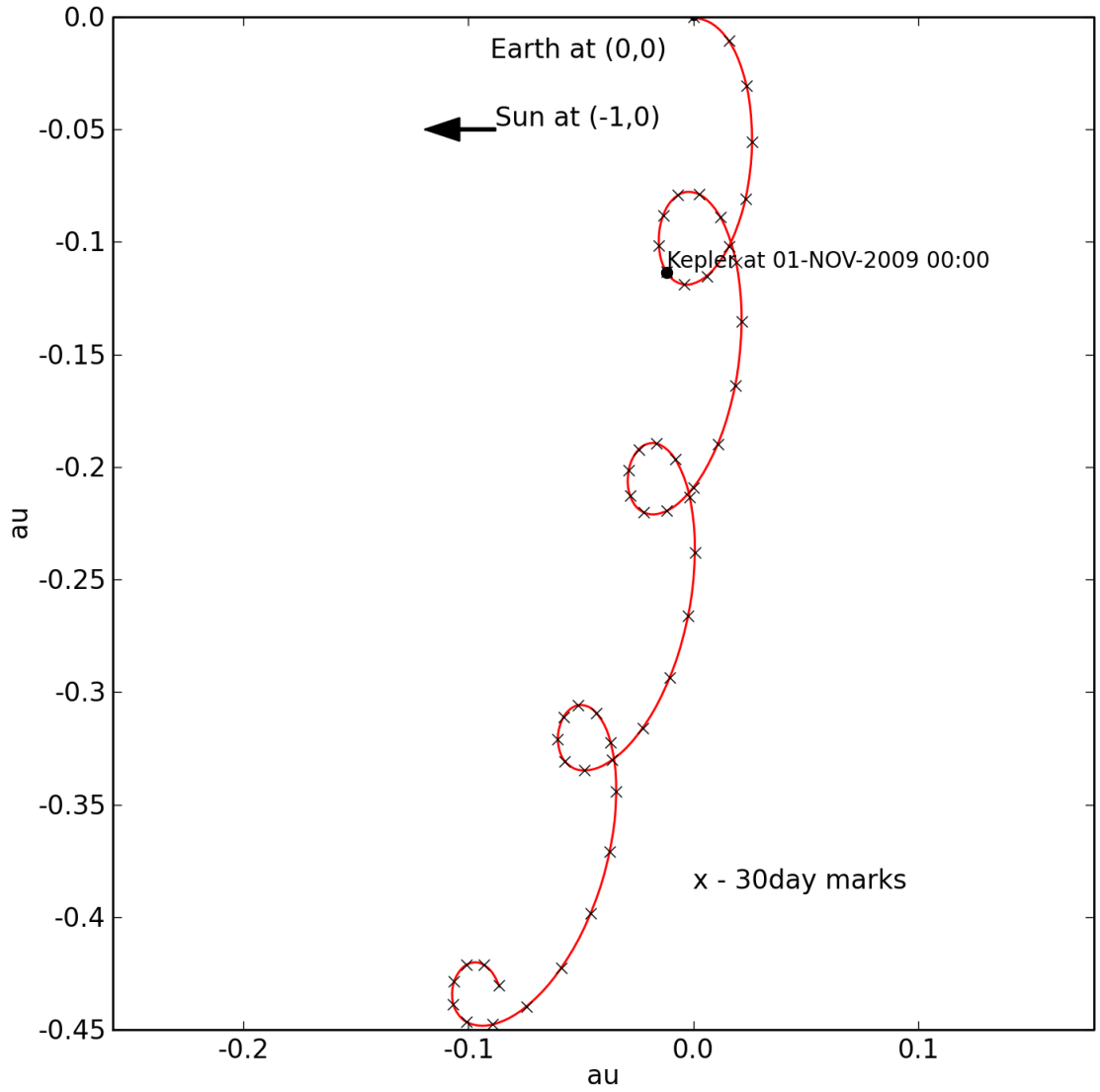


In March of 2009 Kepler rose
Seeking shadows of planets …
Are any like Earth?

Launch of *Kepler*

March 6, 2009, Cape Canaveral Air Force Station, FL

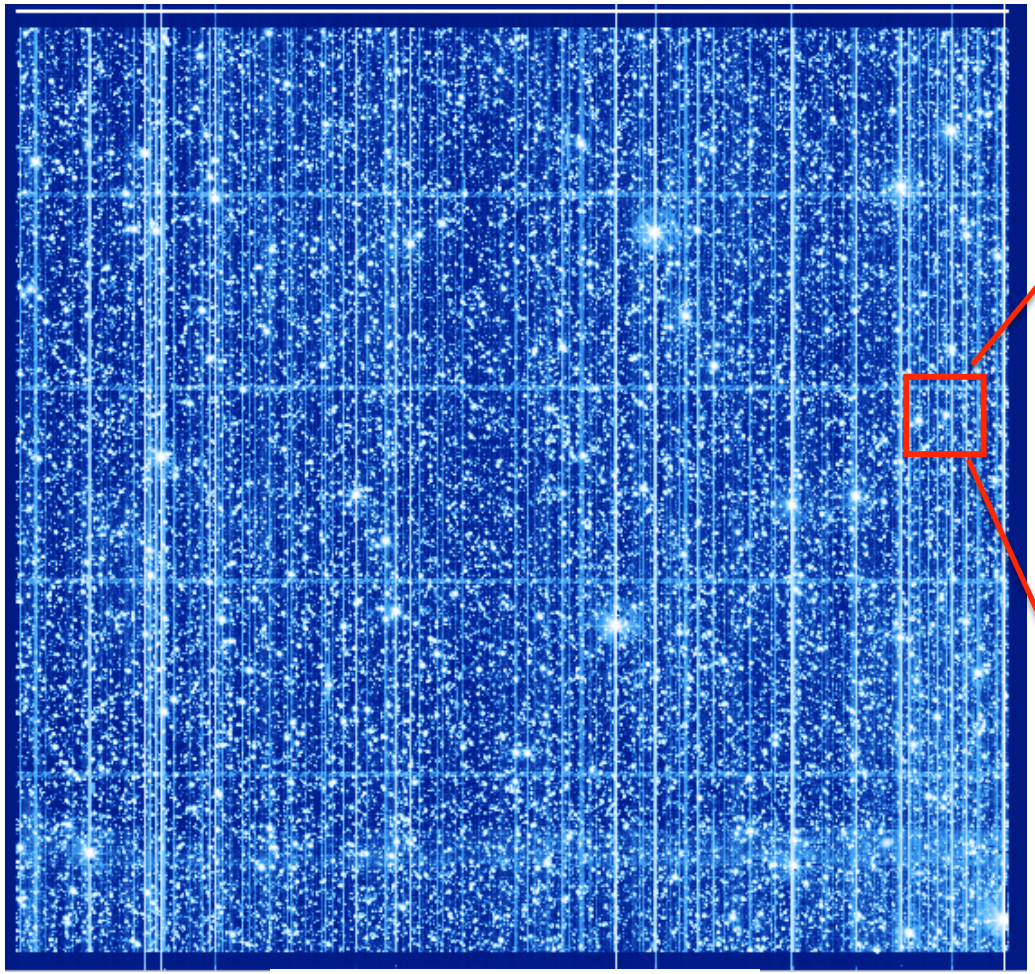
Earth-trailing heliocentric orbit



Kepler Full Frame Image

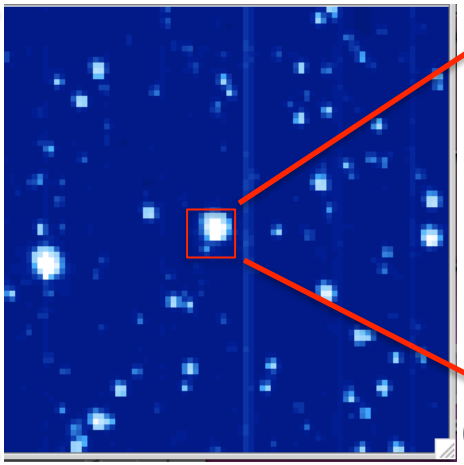
Pixel Level Data From Kepler

Module 17 Output 2



1.13 (h) x1.22 (w) degrees

Zoomed Image
near HAT-P-7b



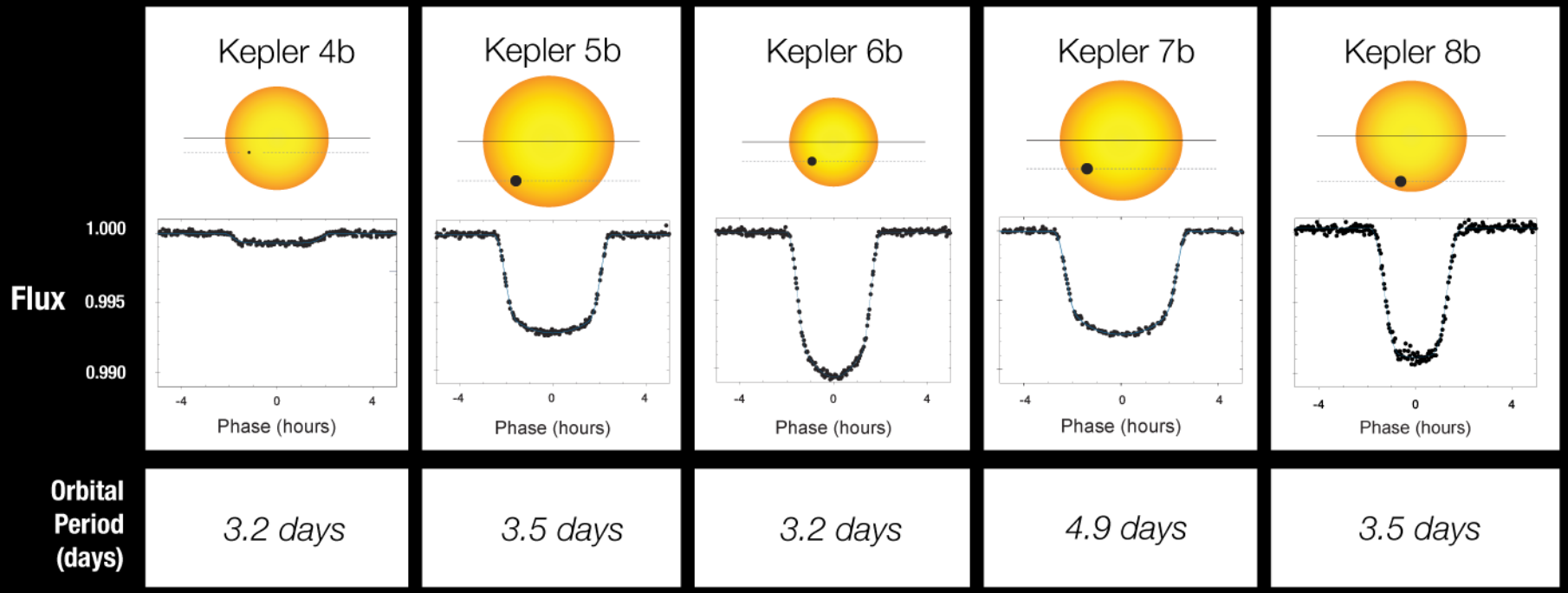
0.09x0.09 degrees
80x80 pixels
6400 pixels total

HAT-P-7b
LC pixels

6.6x6.6 millidegrees
28 pixels collected
Black = no data

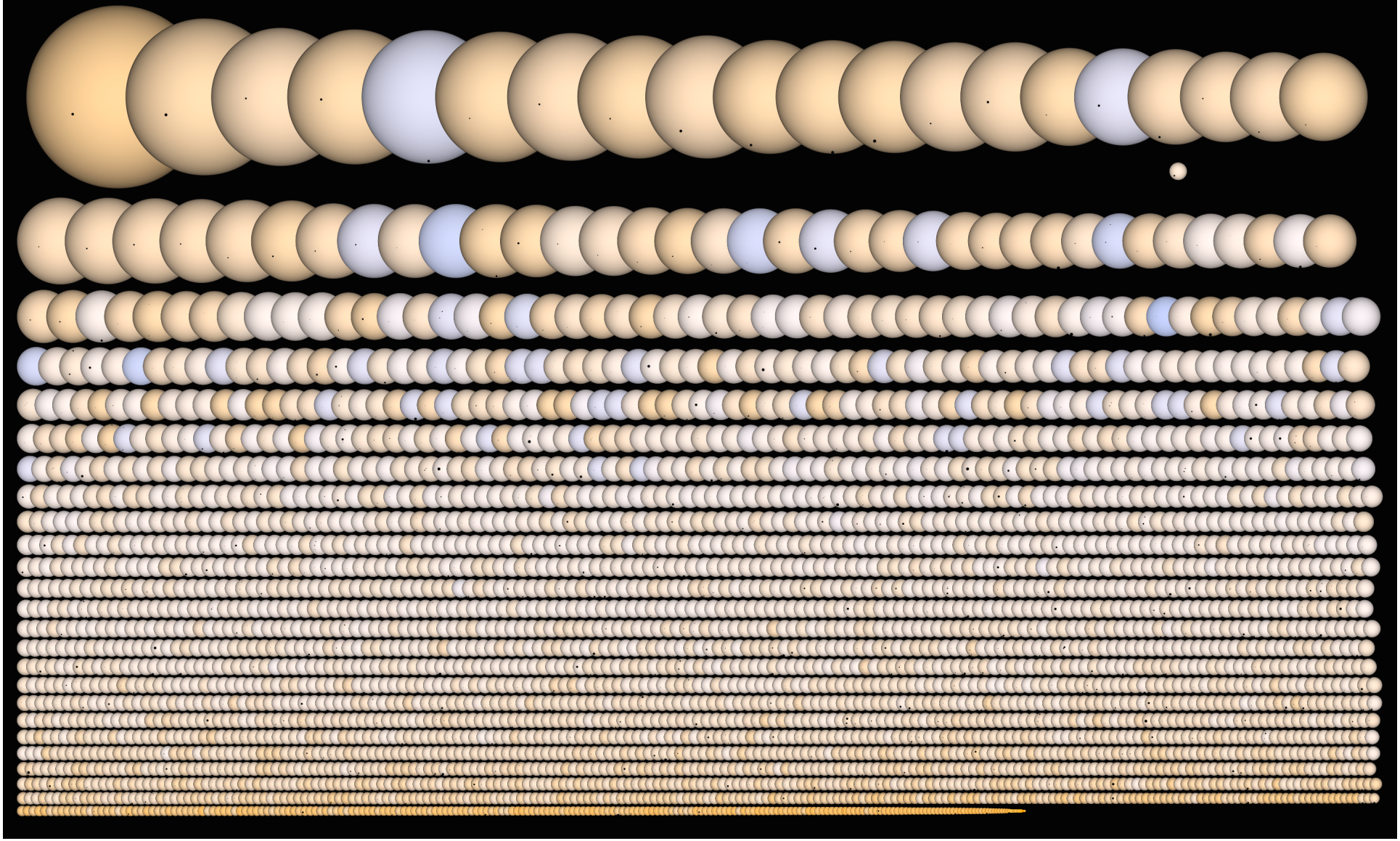
Scaled to show faint detail

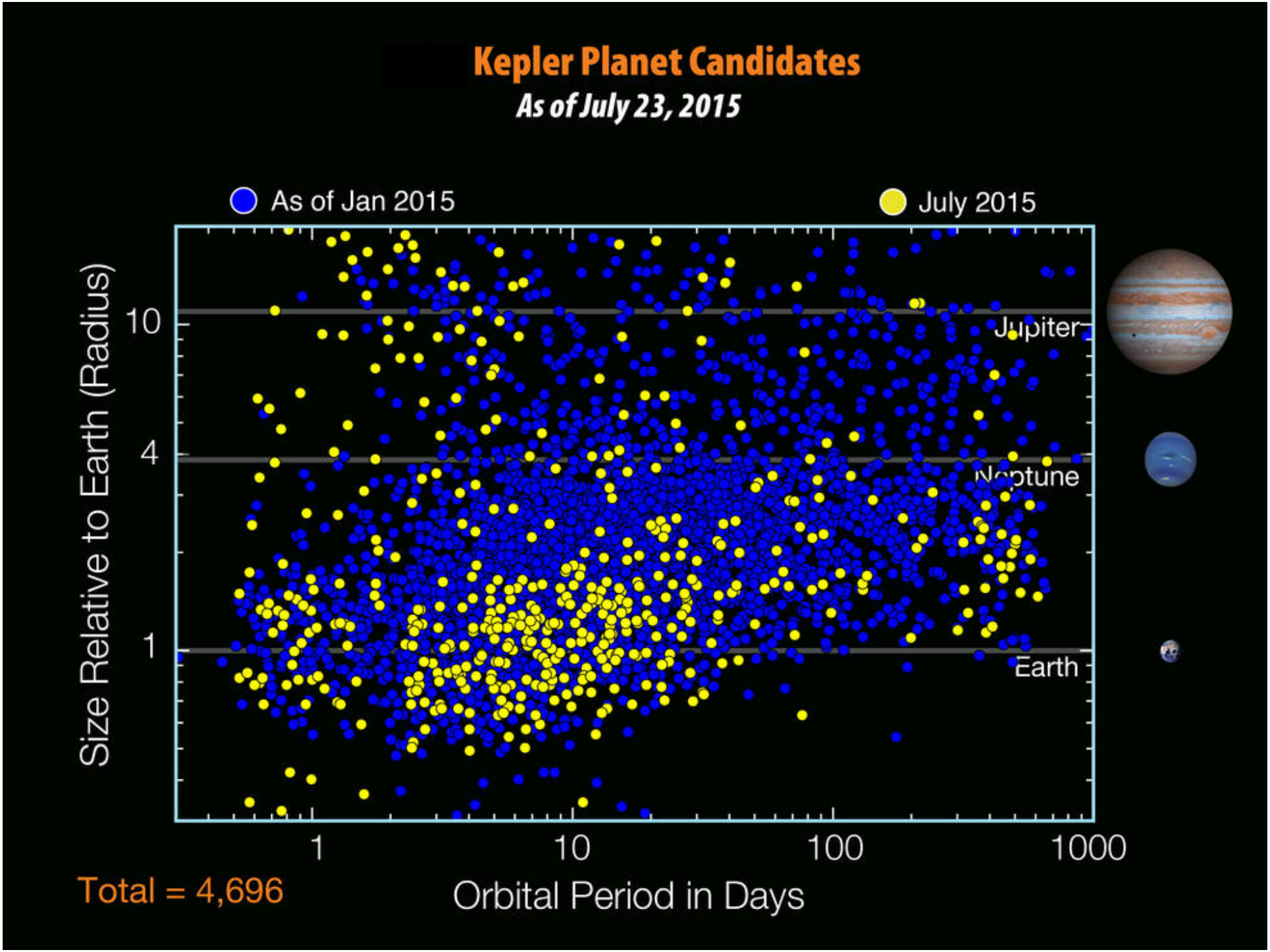
Transit Light Curves



Kepler Planet Candidates & Their Stars

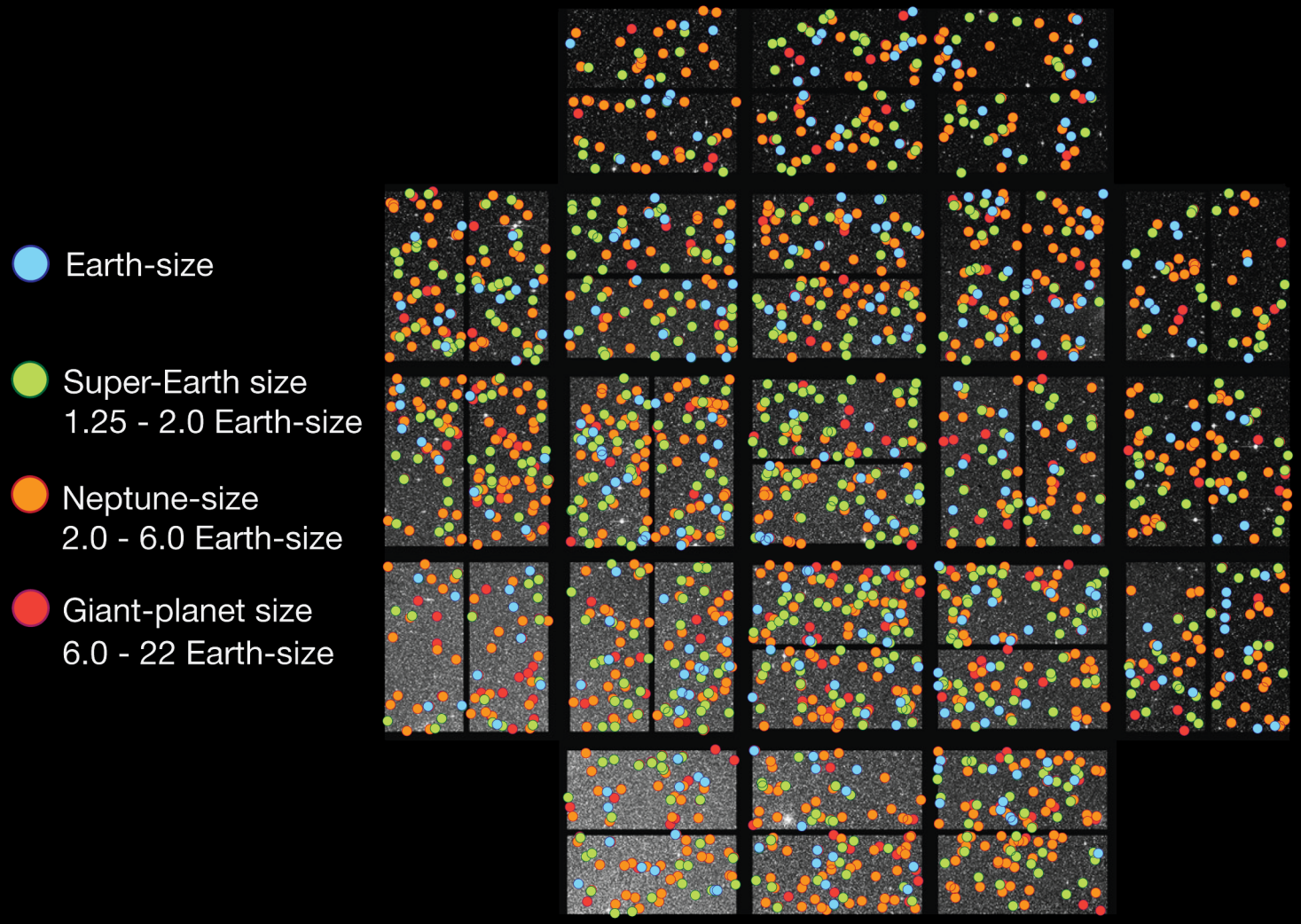
(Jason Rowe, 2015)

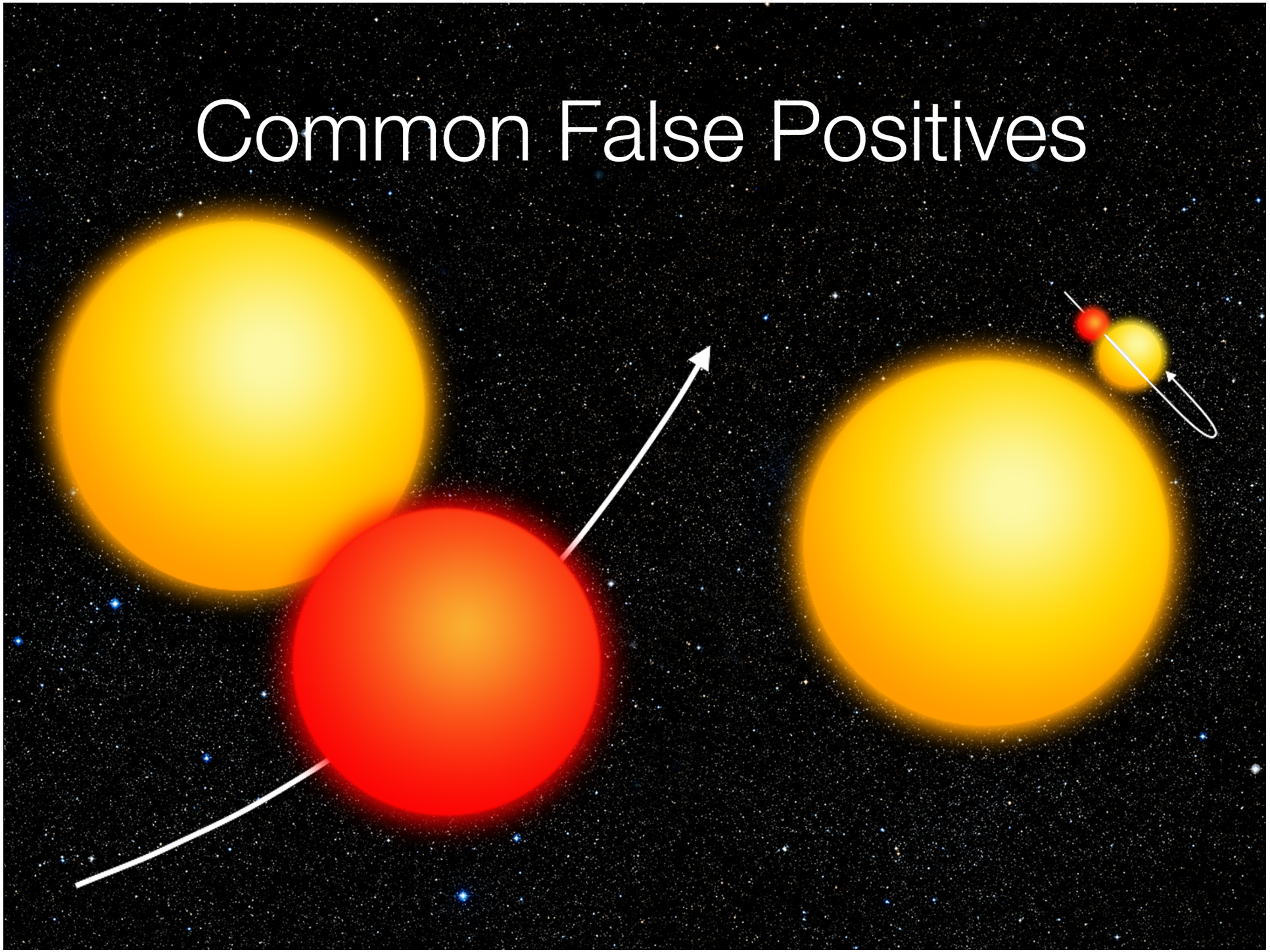



Kepler Planet Candidates
As of July 23, 2015
As of Jan 2015
July 2015
Size Relative to Earth (Radius)
10
4
1
Jupiter
Neptune
Earth
1
10
100
1000
Orbital Period in Days
Total = 4,696

Locations of Kepler Planet Candidates

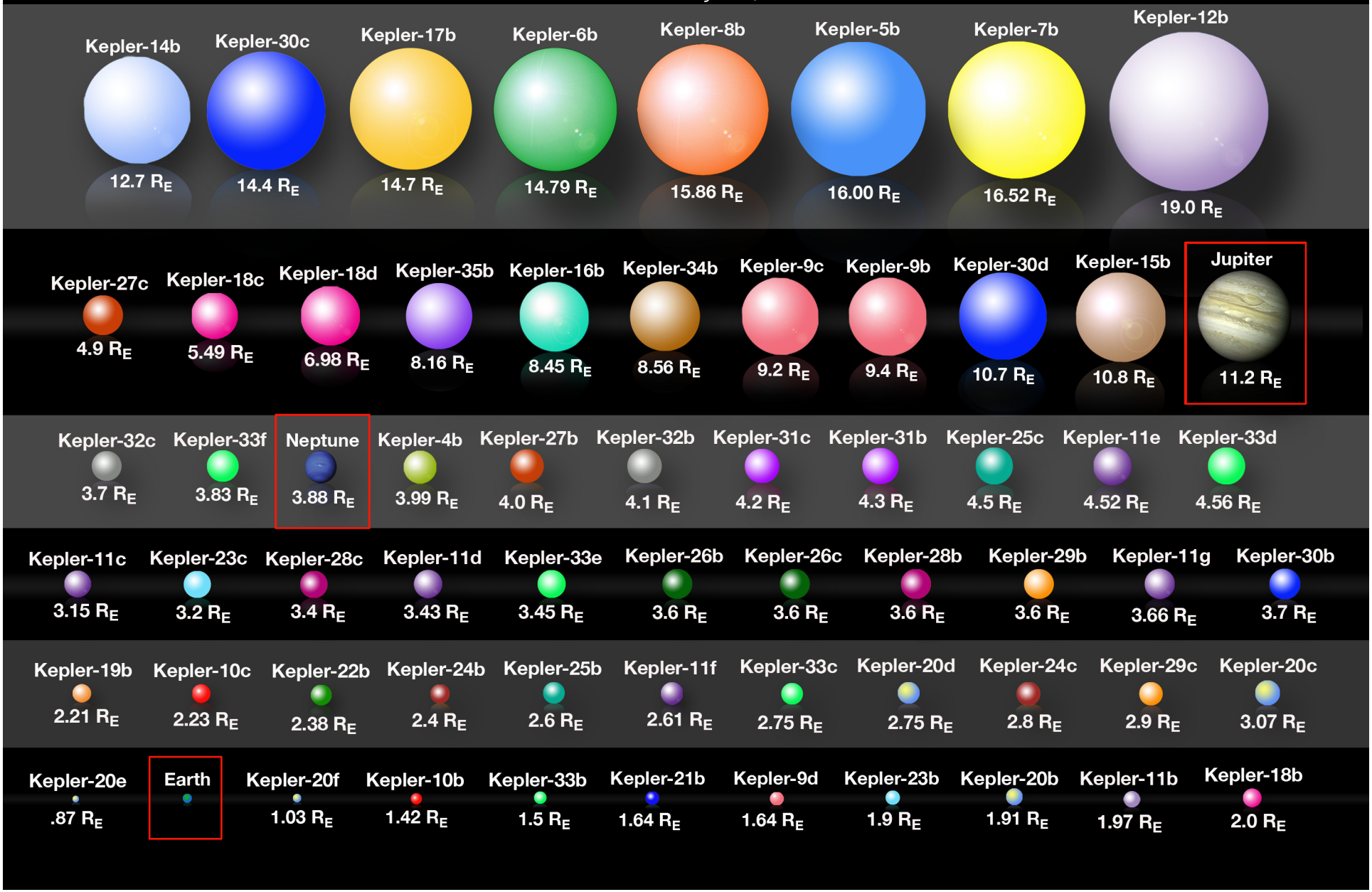
As of January 7, 2013



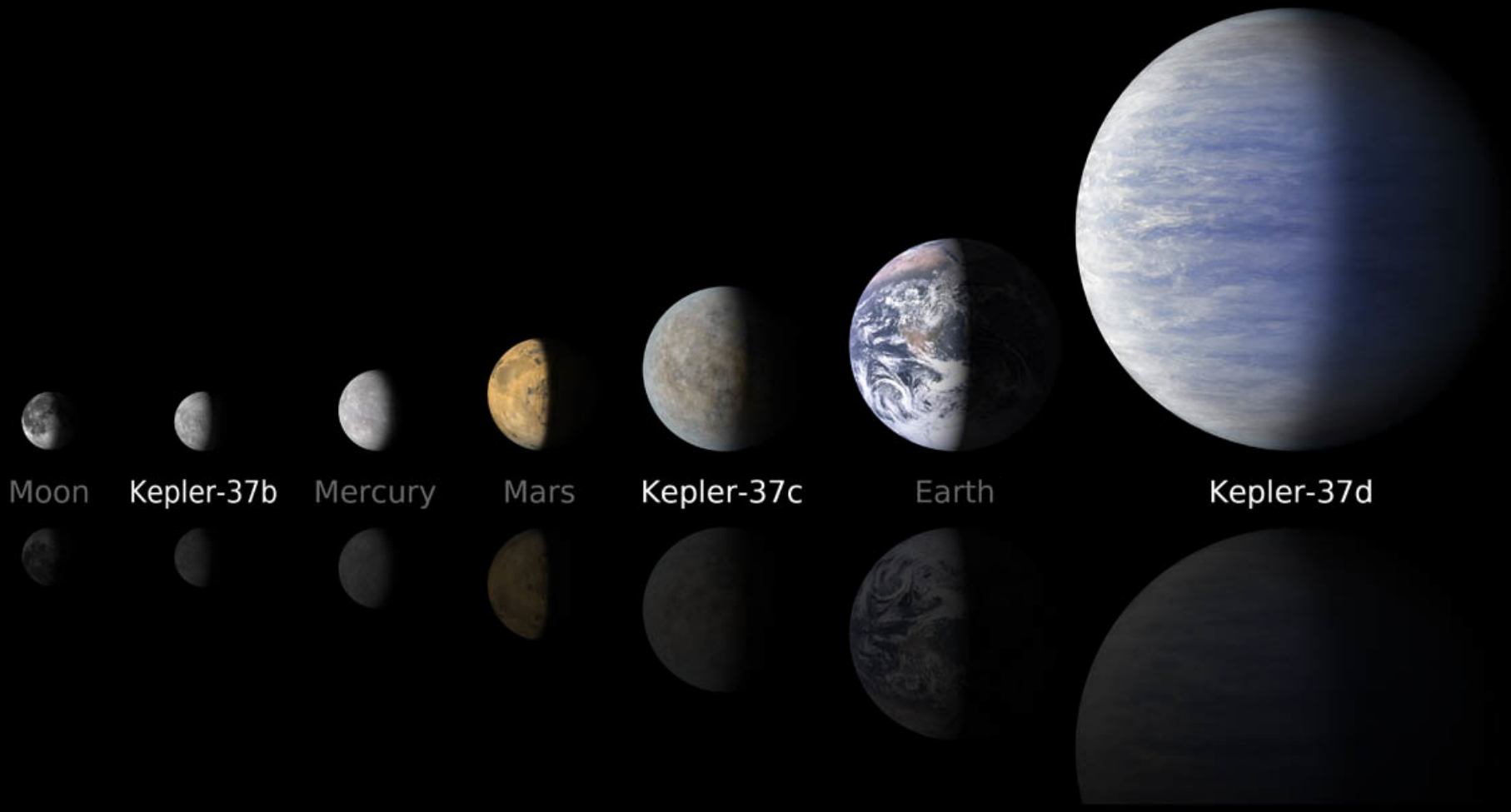

Common False Positives

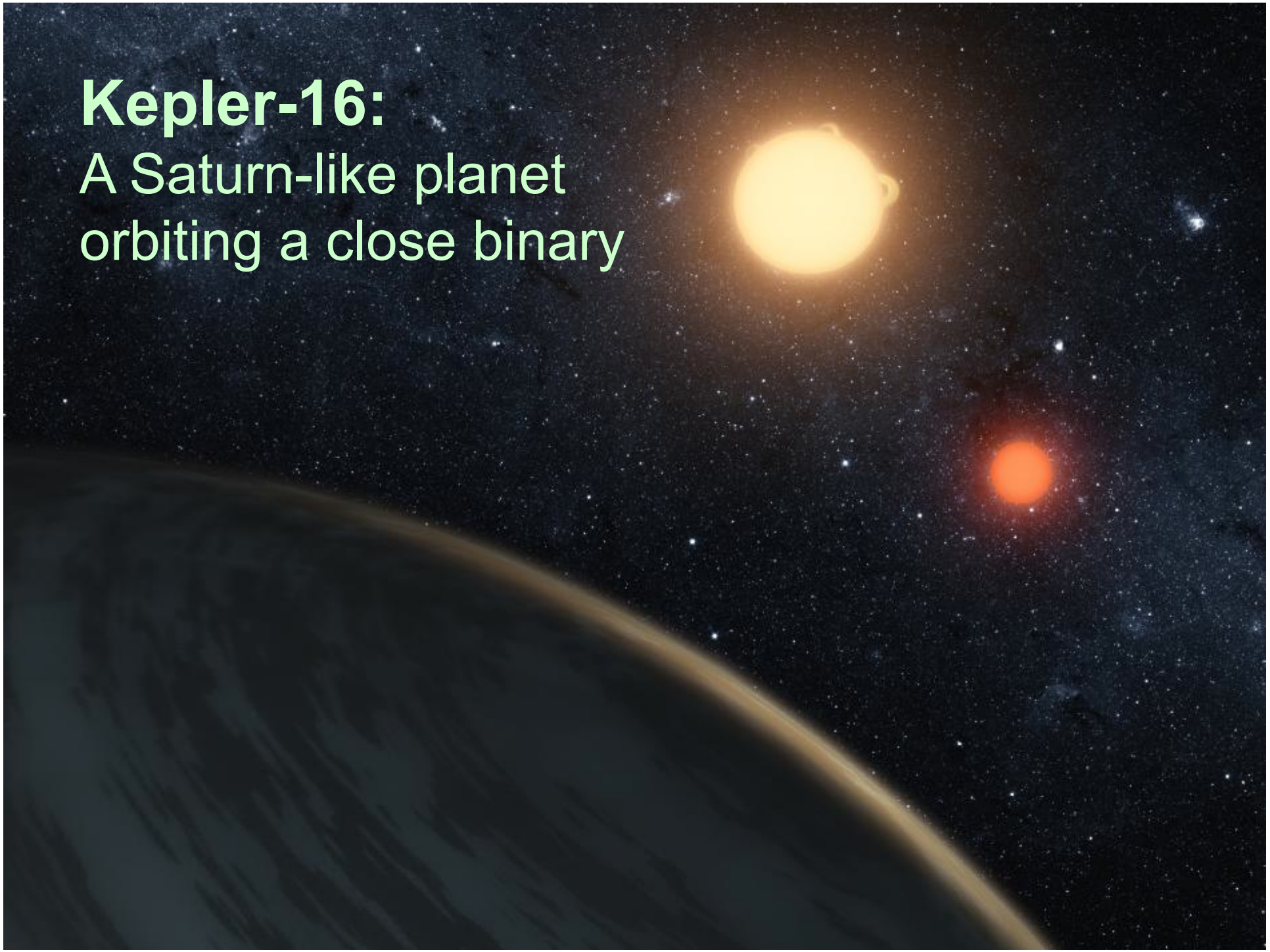
Kepler Planets

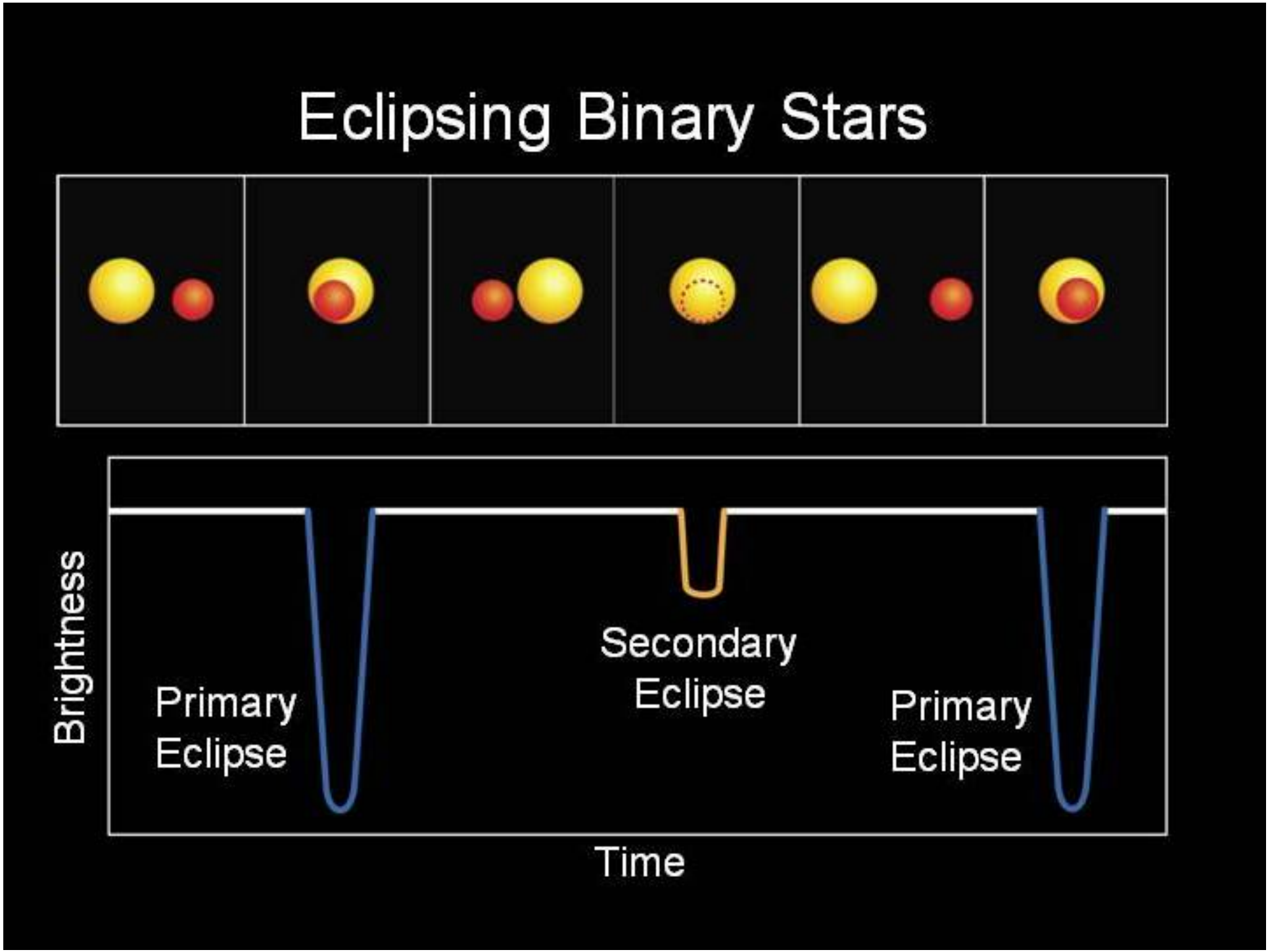
As of February 27, 2012

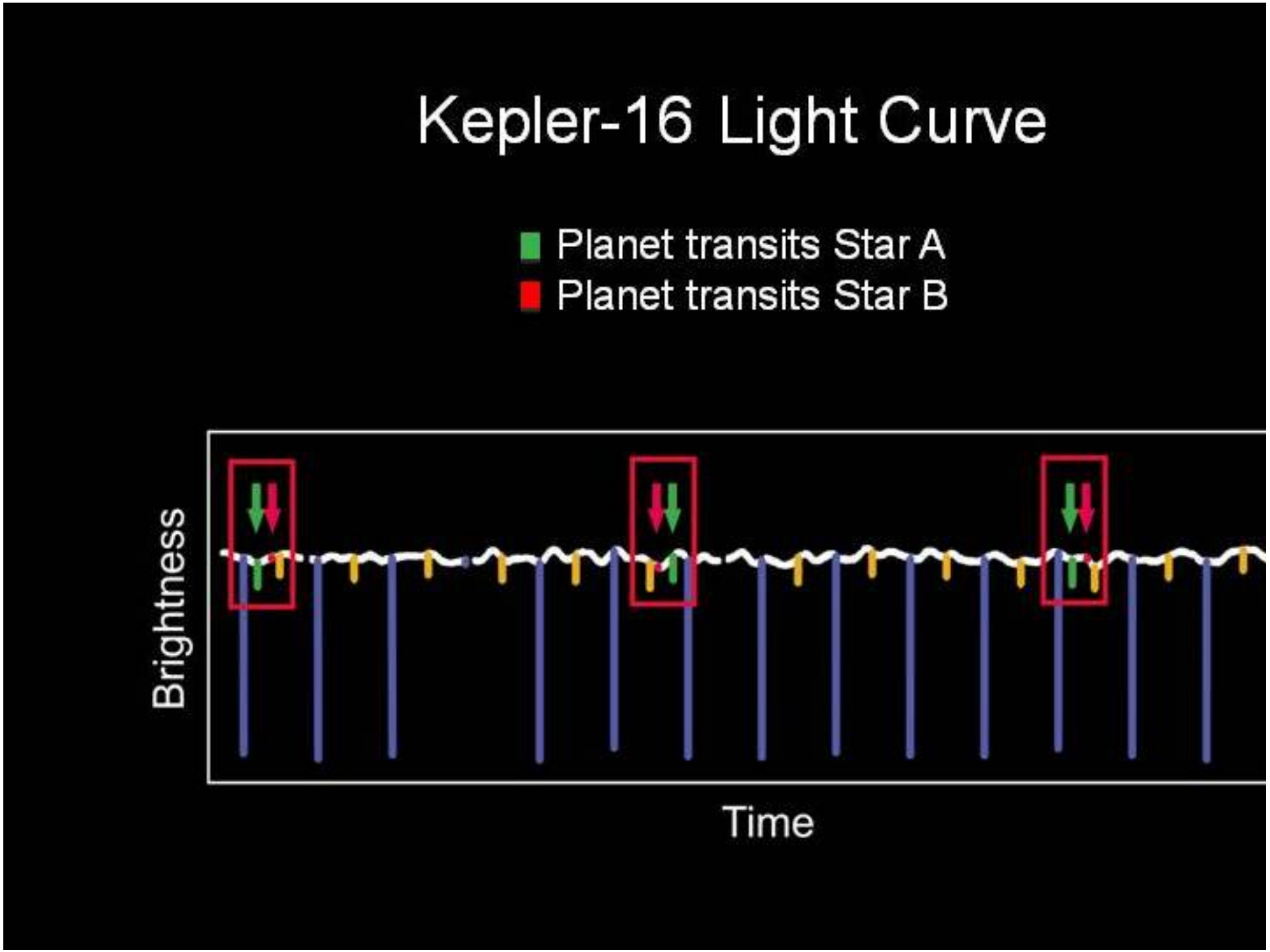


The Smallest Known Planet



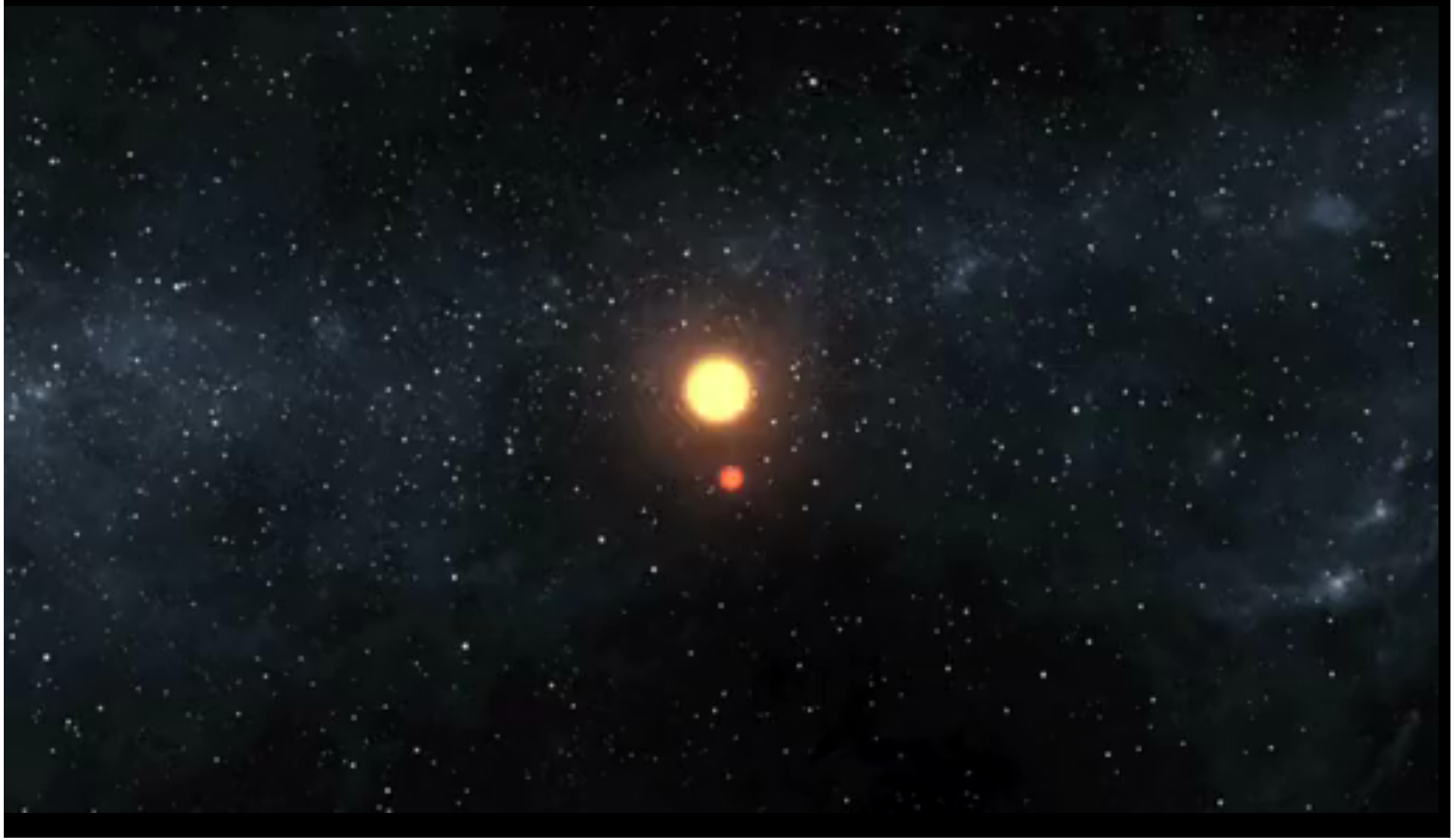

Kepler-16:
A Saturn-like planet
orbiting a close binary

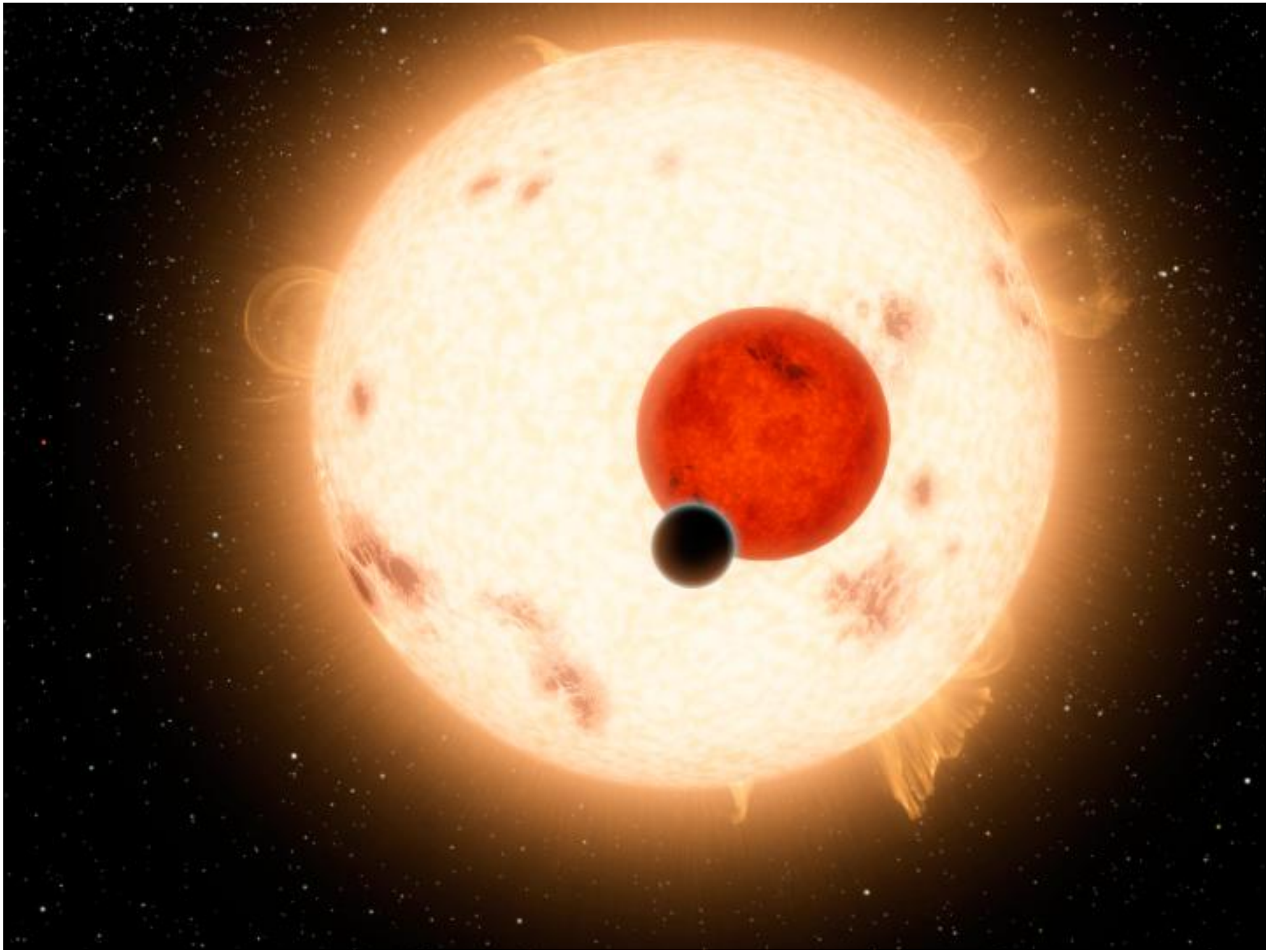

Eclipsing Binary Stars
Brightness
Primary Eclipse
Secondary Eclipse
Primary Eclipse
Time


Kepler-16 Light Curve
Planet transits Star A
Planet transits Star B
Brightness
Time

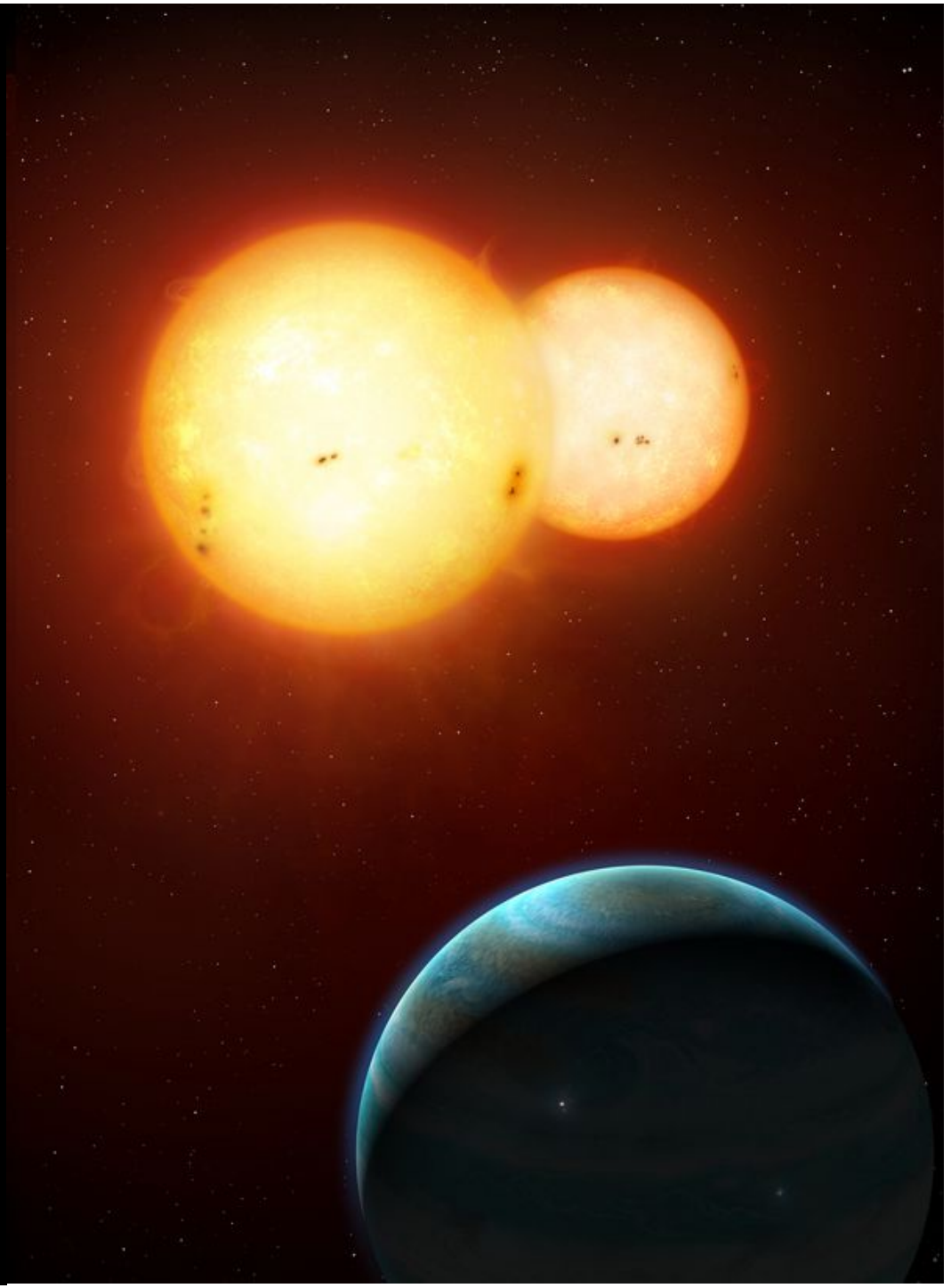
Kepler-16 System

Kepler-16 from above

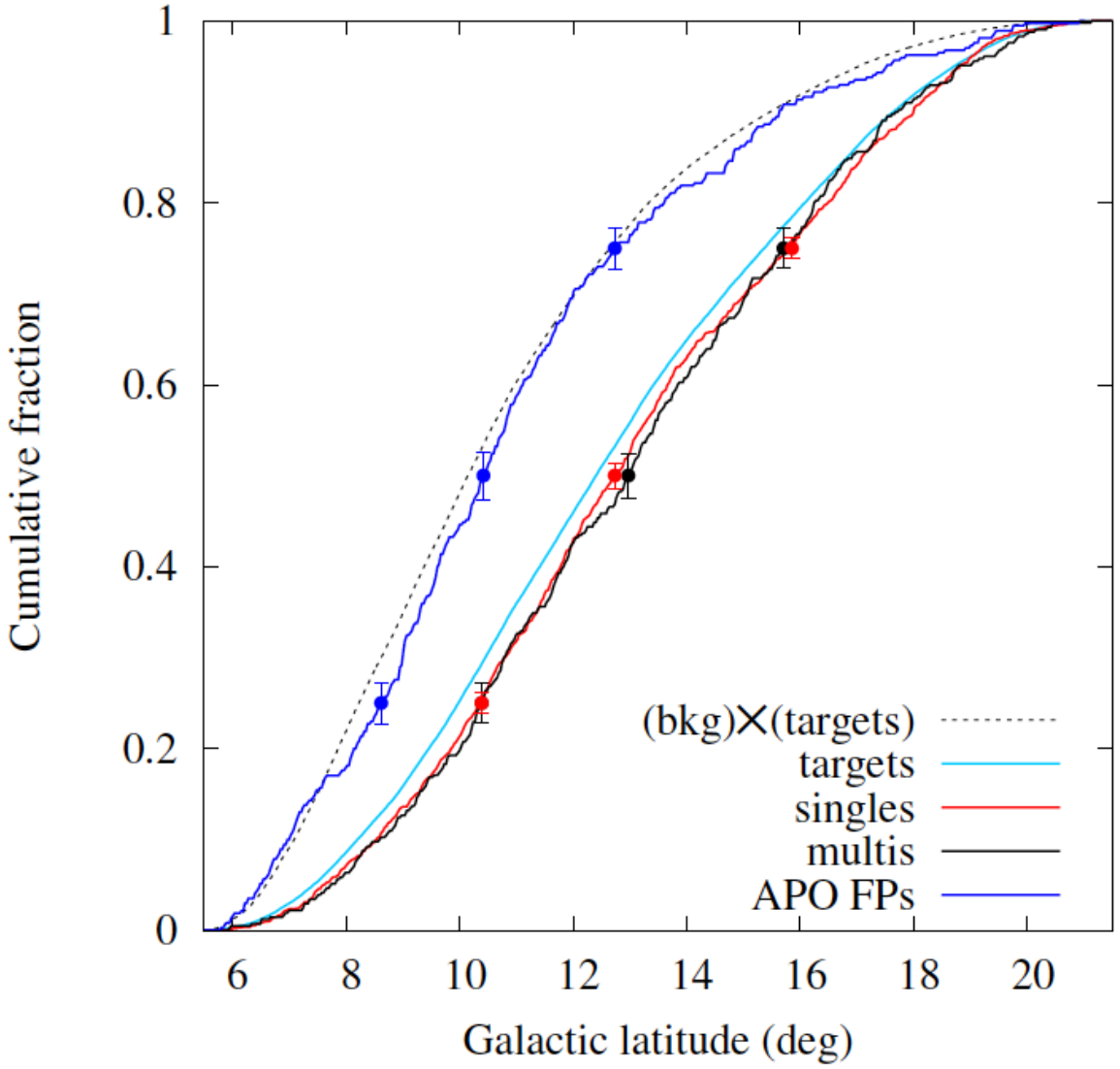




Kepler-35(AB)b



Distributions vs. Galactic Latitude



Planet candidates, including multis, track targets, not BGEB FPs

Few planet candidates are BGEB FPs!

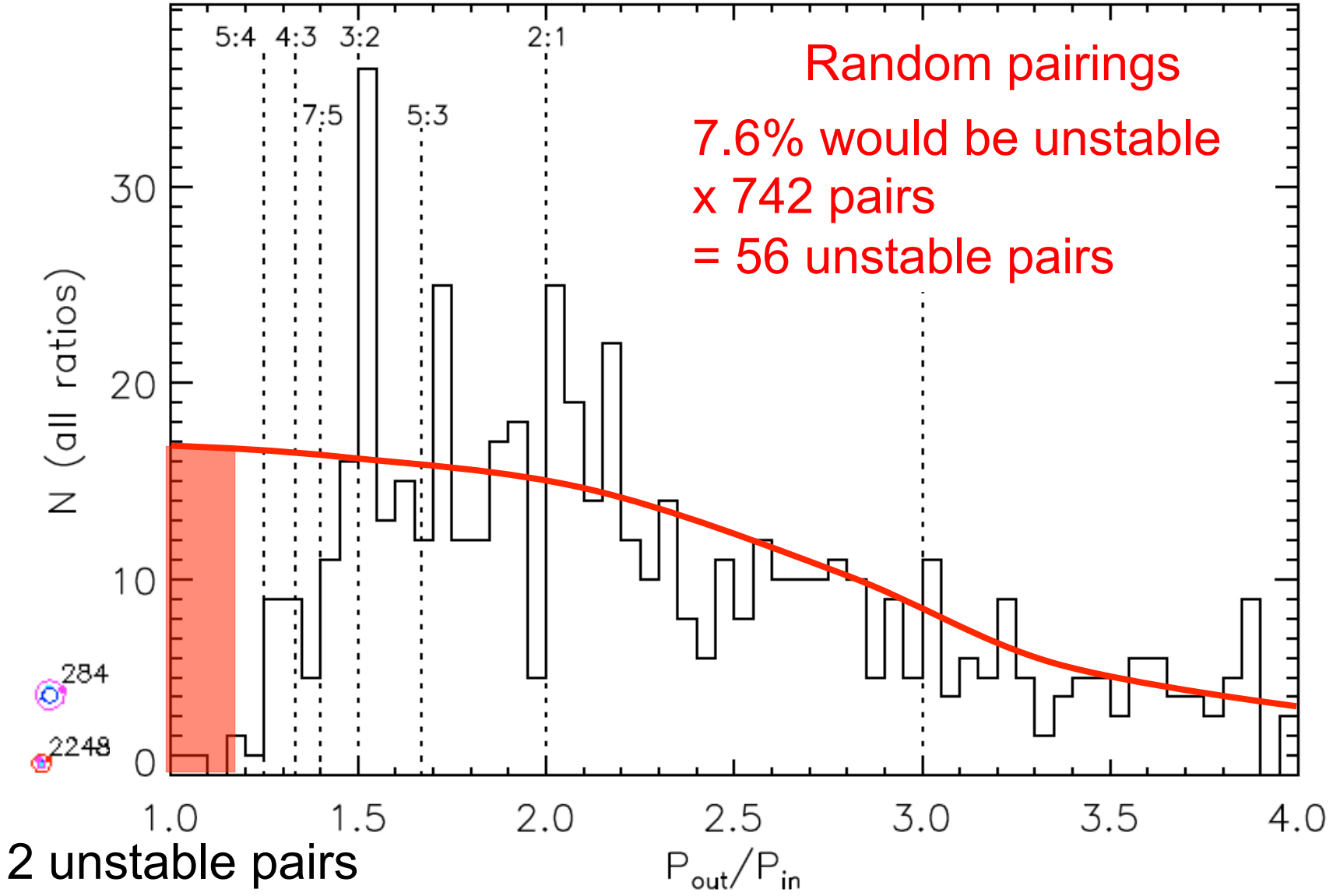
Most Multi-planet Candidates are Planets

- 140,000 high-quality *Kepler* targets
- 1723 targets with very good KOIs as of 2013 (1.23% of the targets)
- 172 false positives (assume 10% are FPs)
- EBs are distributed randomly among targets
- Fraction of targets near EB = 172/140000 = 0.123%
- Number of very good KOIs (planet or EB) accompanied by EB = 1723 x 0.123% = 3

Then we expect only 1.23% x 172= 2 multis with a FP

But we observe 410 multis (with 1054 planet candidates)!

Period ratios and stability



2 unstable pairs

“False Multi” Scenarios

- One of the transit signals is from a background binary star or background star with planets, blended.
- The transits are from planets around different, physically-bound, stars.

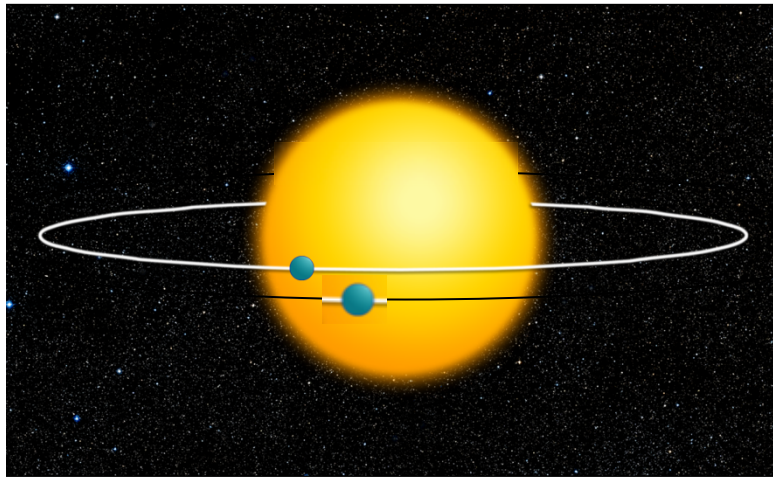
- If all pairs were “false multis”, ~ 56 would seem unstable.
- 2 pairs seem unstable => ~ 3 - 4% are “false multis”
- ~ 96% are real => high fidelity for statistical investigations.

Double Planets:

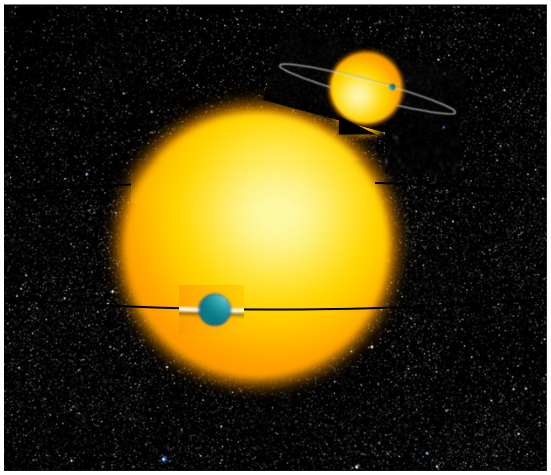
Orbiting 1 or 2 stars?

Double Transit signal could be due to:

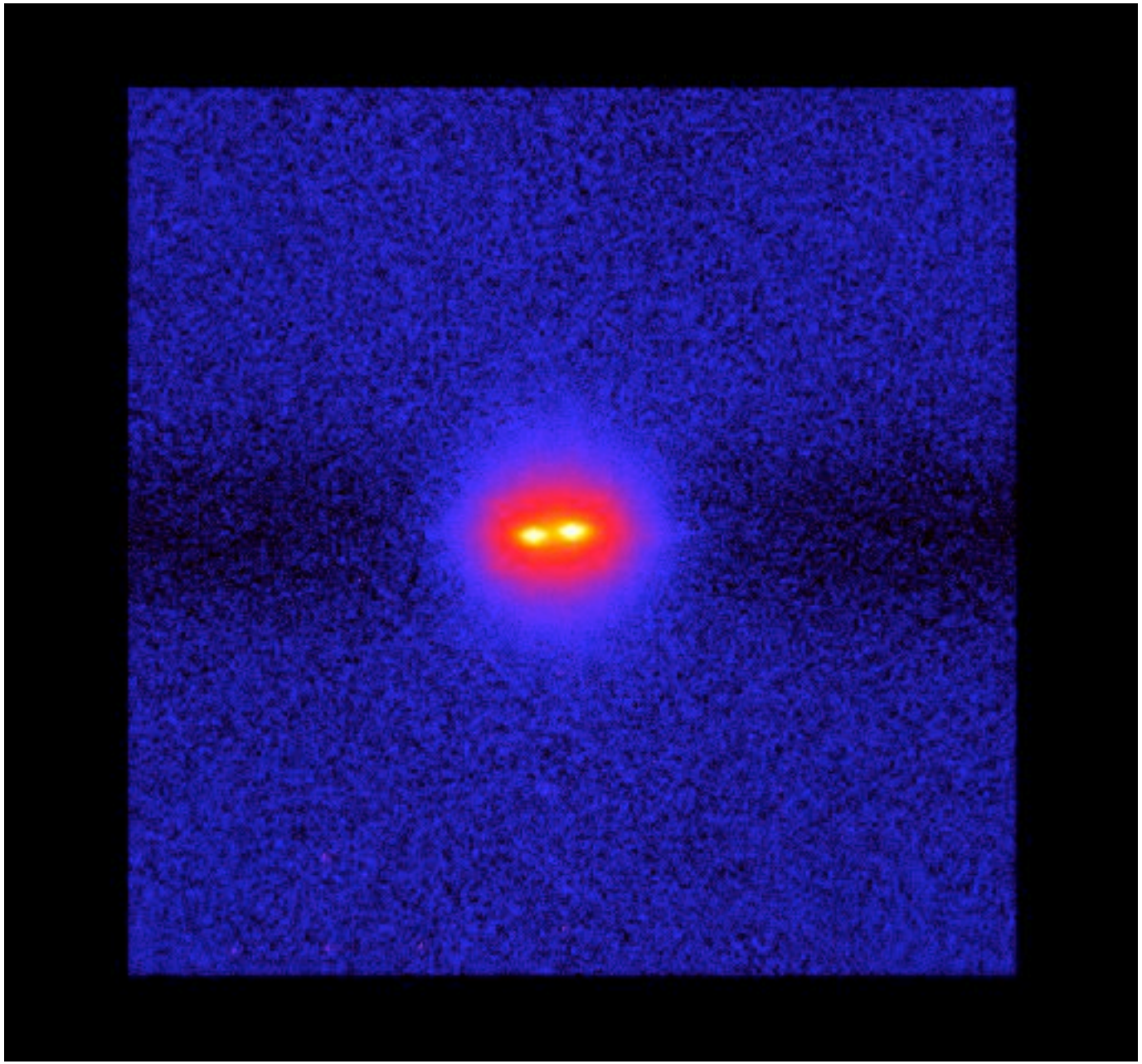
Two Planet System



2 Stars with 1 Planet each



KOI-284, The 1st Unstable Multi



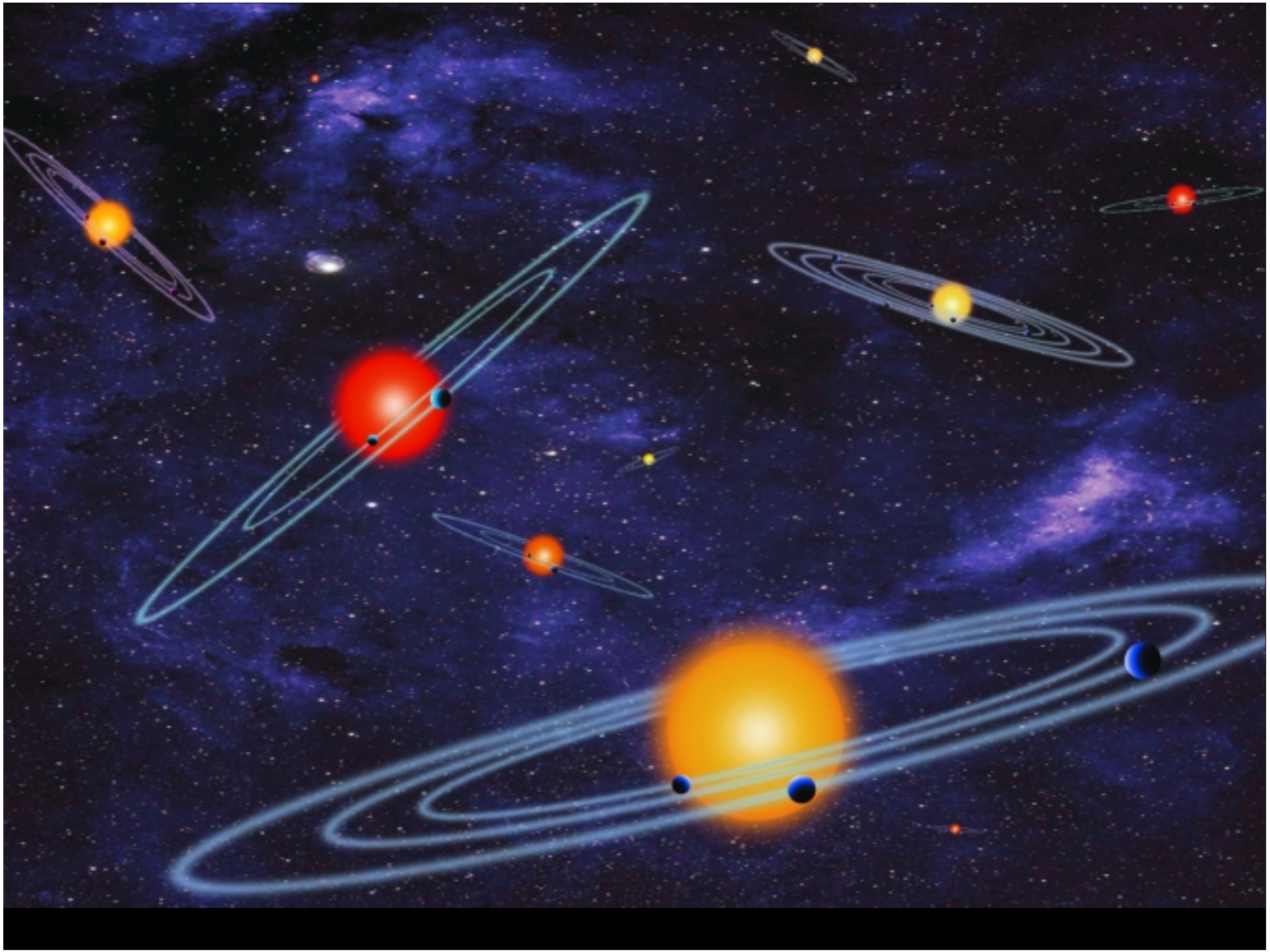
3 candidates

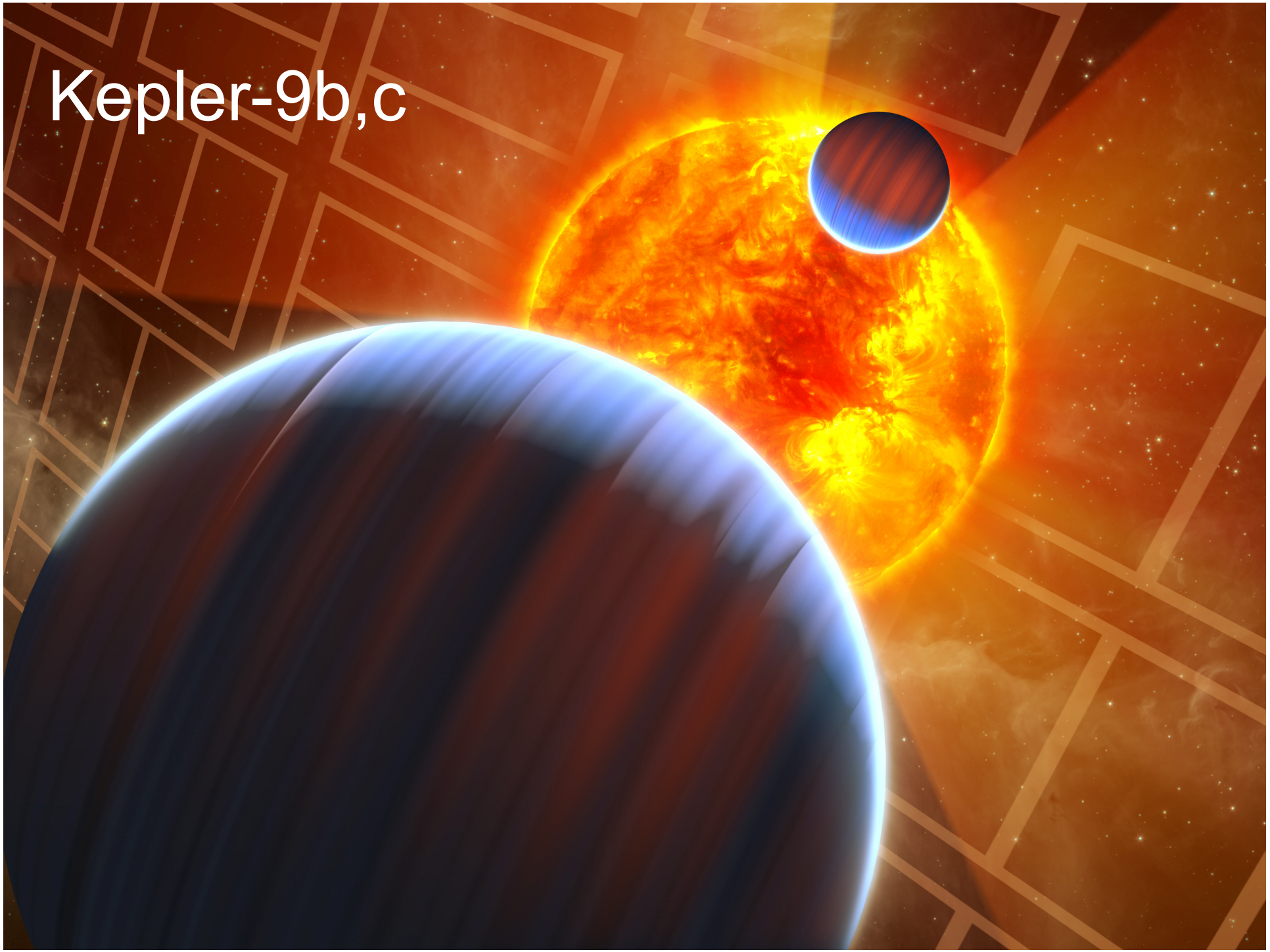
Periods:

6.18, 6.42, 18.0 days

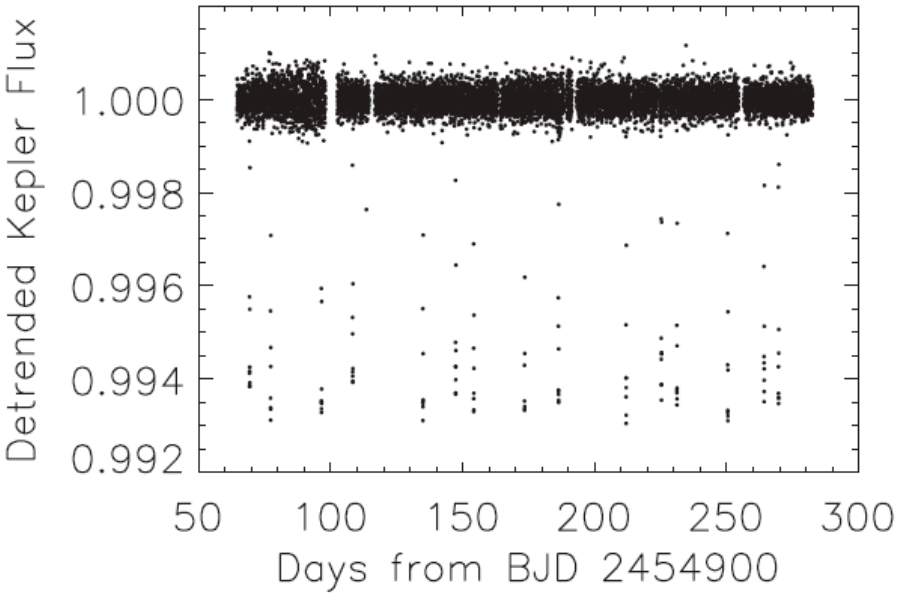
The one multi (of the group of 170 studied) that is clearly unstable

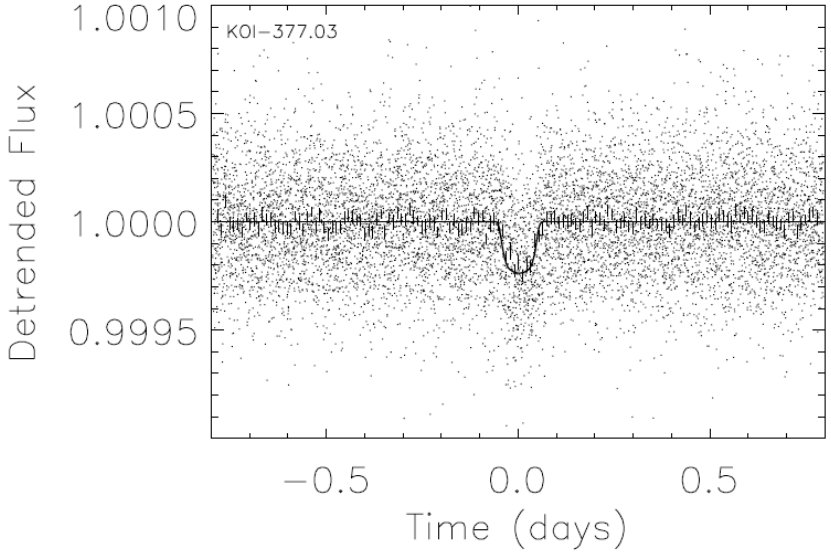
Most likely answer: one star has 2 planets, the other has 1

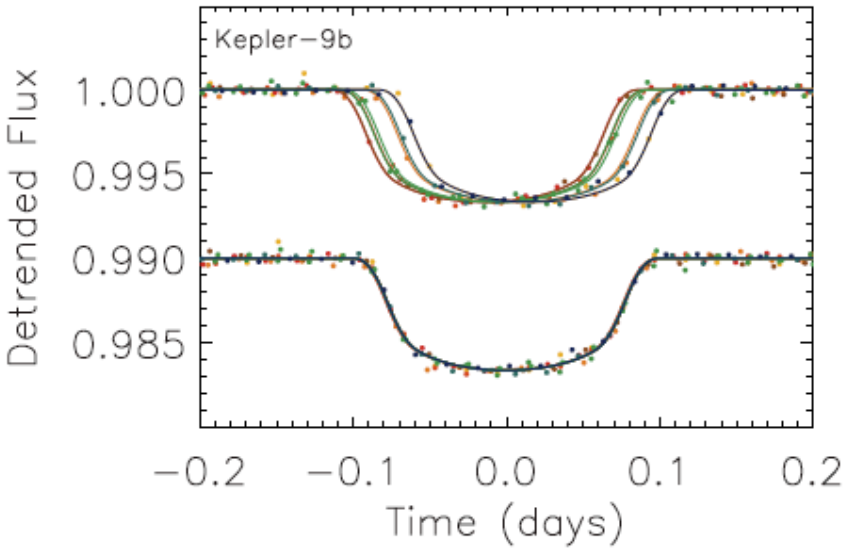


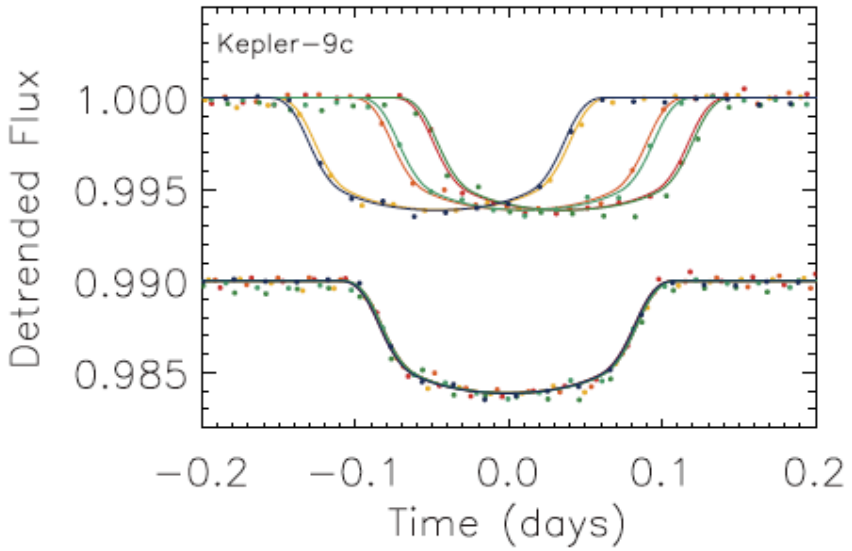

Kepler-9b,c

Kepler-9 b,c,d


Detrended Kepler Flux
1.000
0.998
0.996
0.994
0.992
50
100
150
200
250
300
Days from BJD 2454900

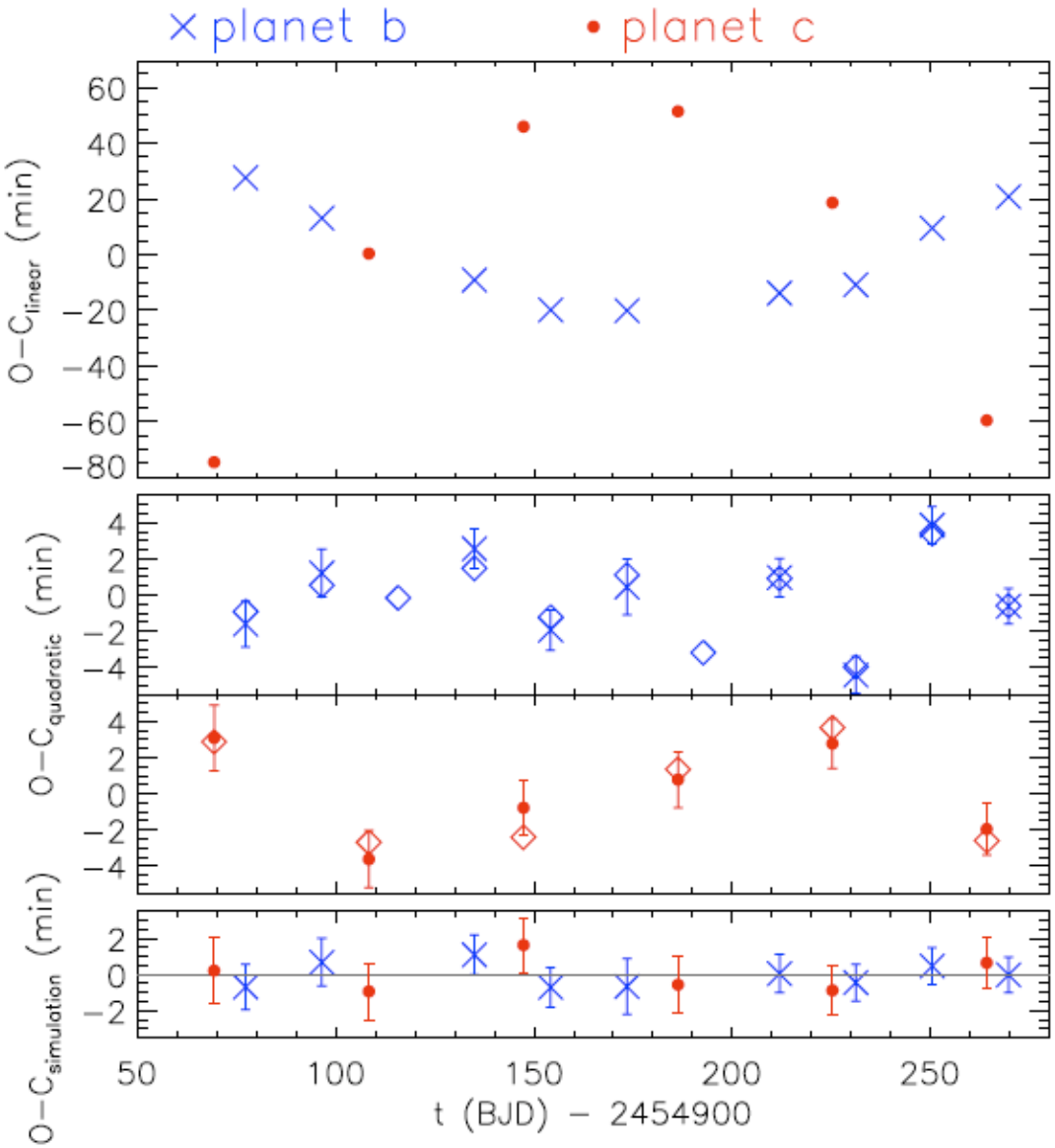

KOI−377.03
Detrended Flux
1.0010
1.0005
1.0000
0.9995
−0.5
0.0
0.5
Time (days)


Kepler−9b
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)


Kepler−9c
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)

Transit timing - Planet perturbations

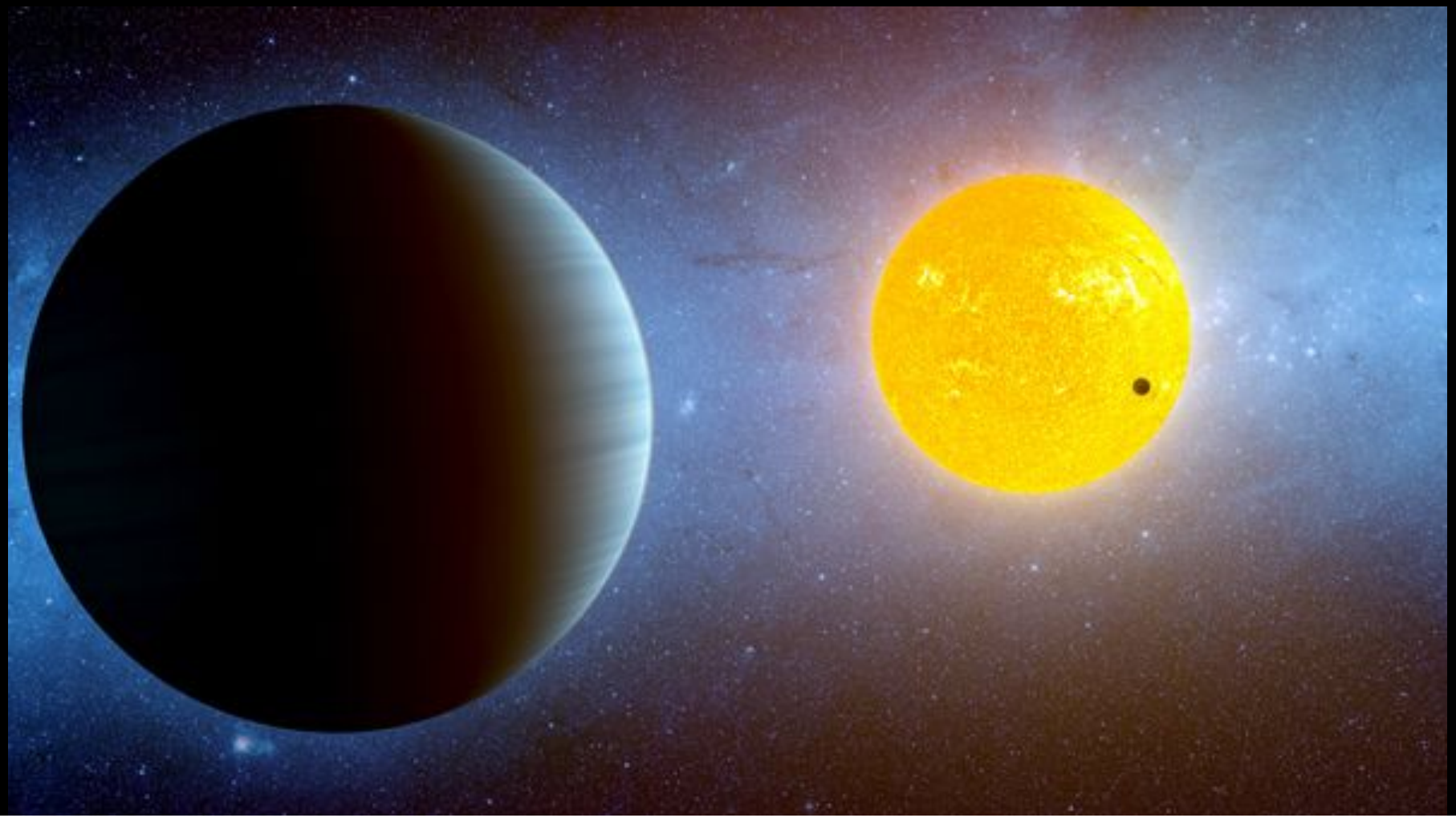
- Models without interactions give poor fits
- Models with planets affecting each other give good fits
- TTVs can be used to confirm planets & measure masses



Kepler-10

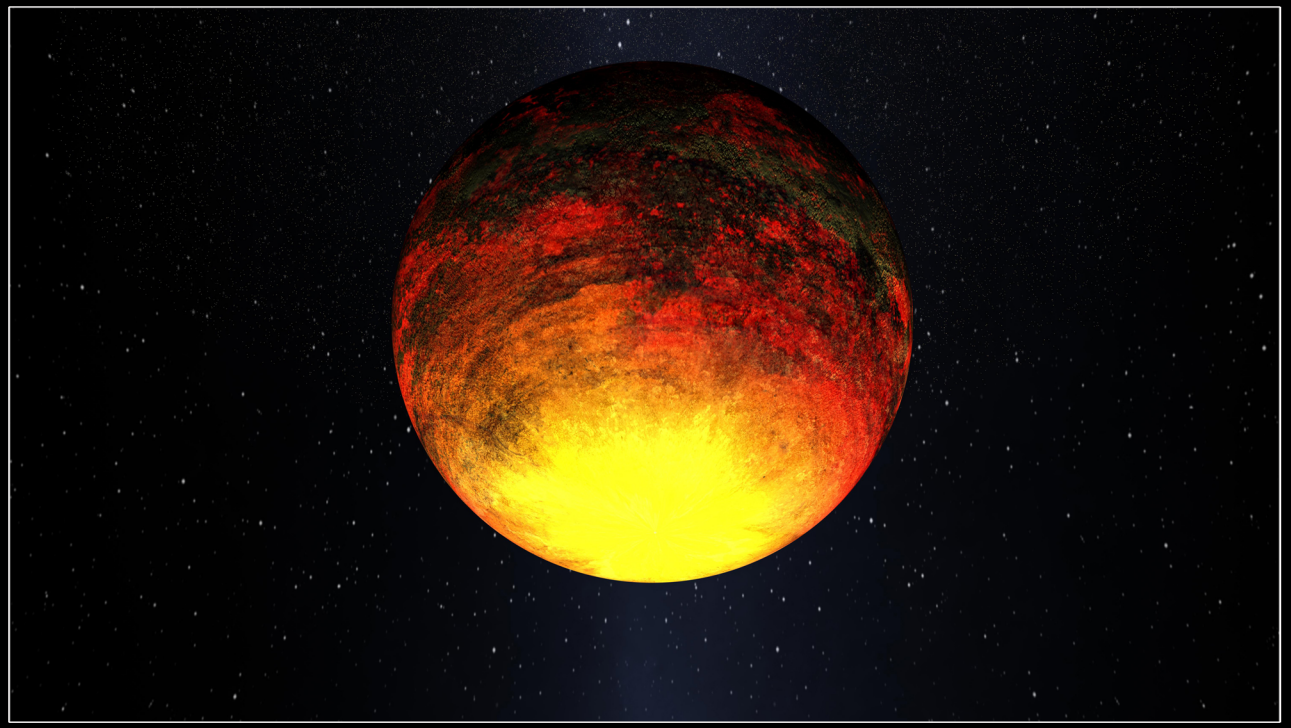
10b: R = 1.4 R_{Earth}, M = 4.6 M_{Earth}, P = 0.8 days

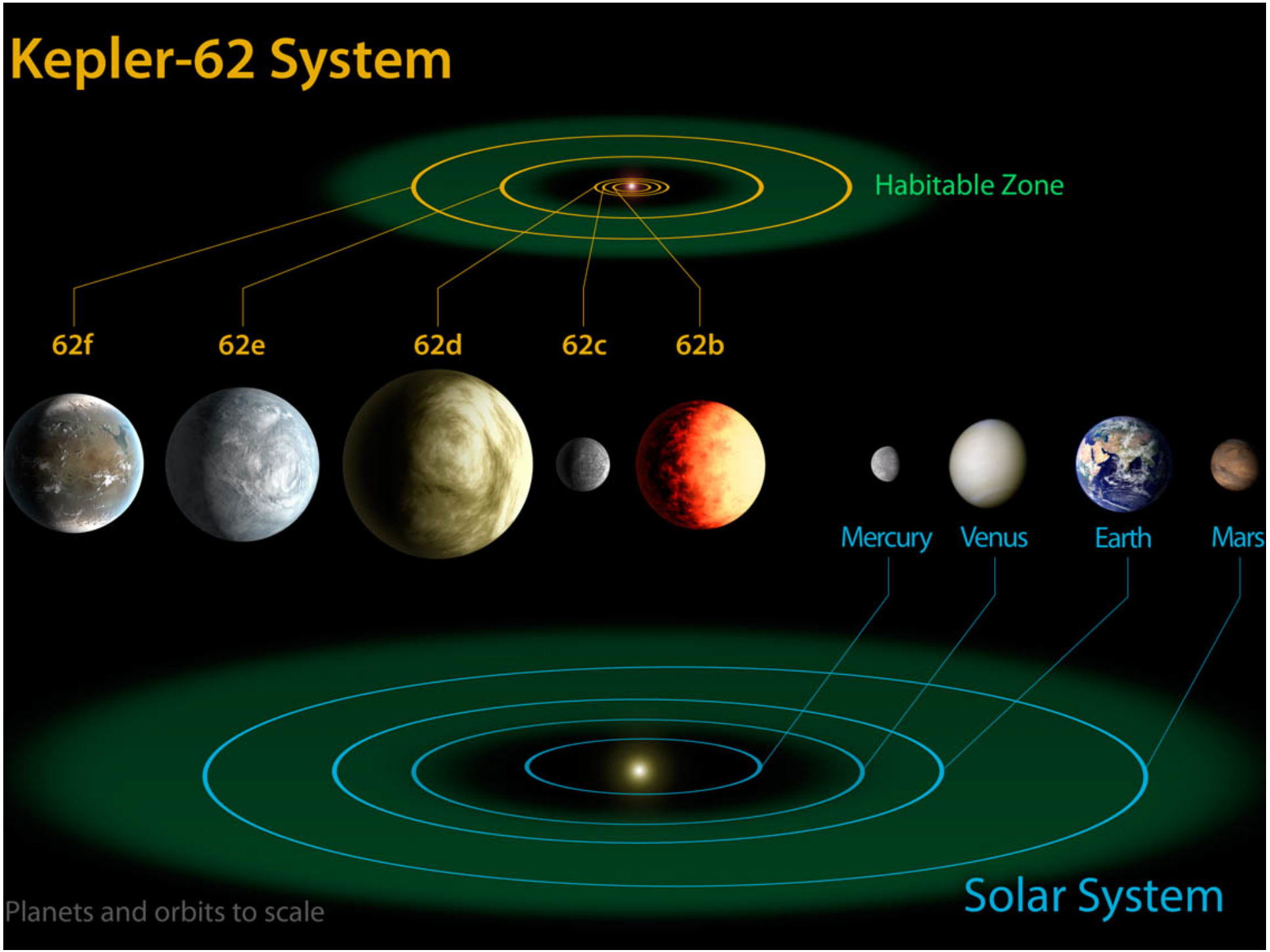
10c: R = 2.2 R_{Earth}, M < 20 M_{Earth}, P = 45 days

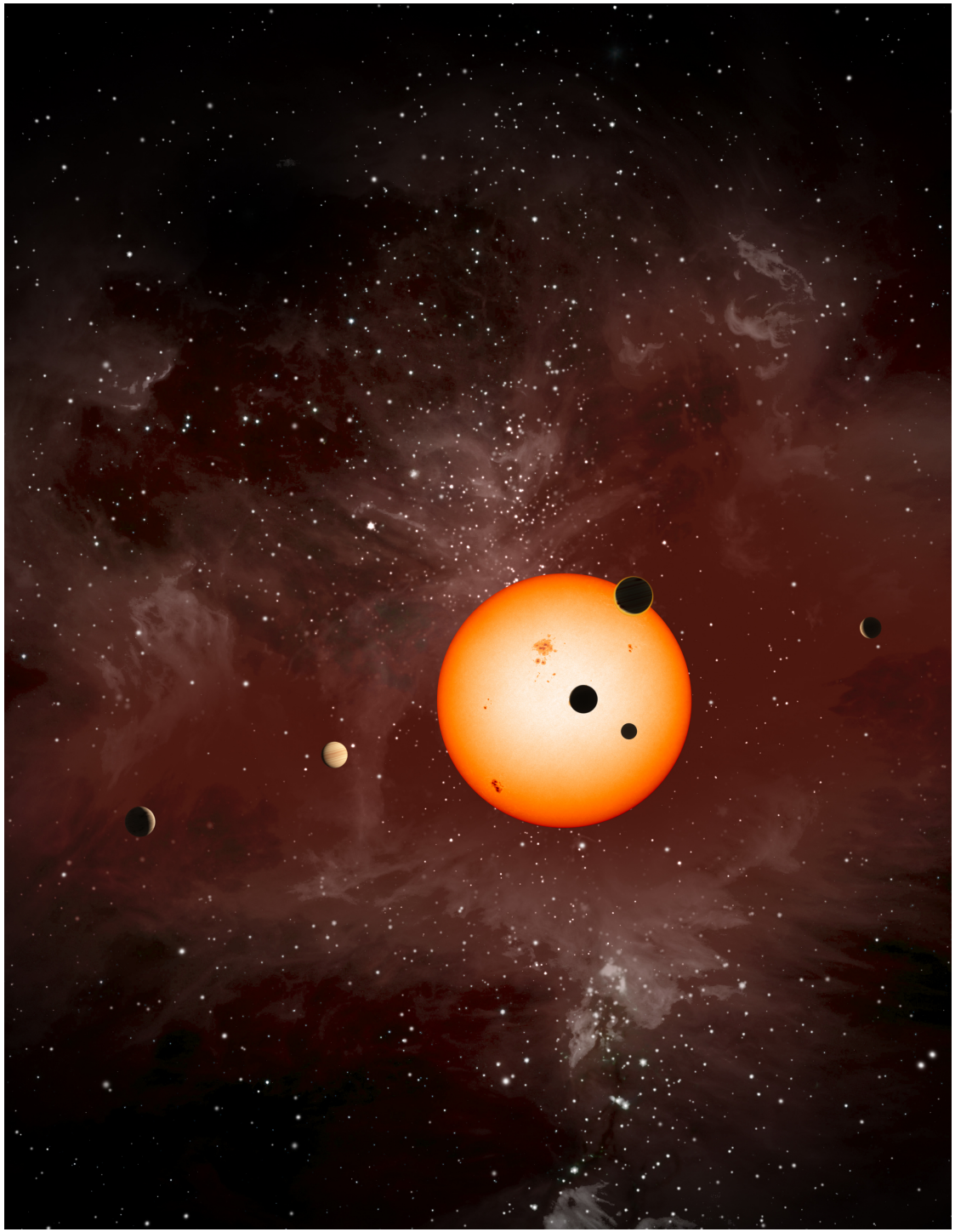


Kepler's First Rocky Planet: Kepler-10b

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

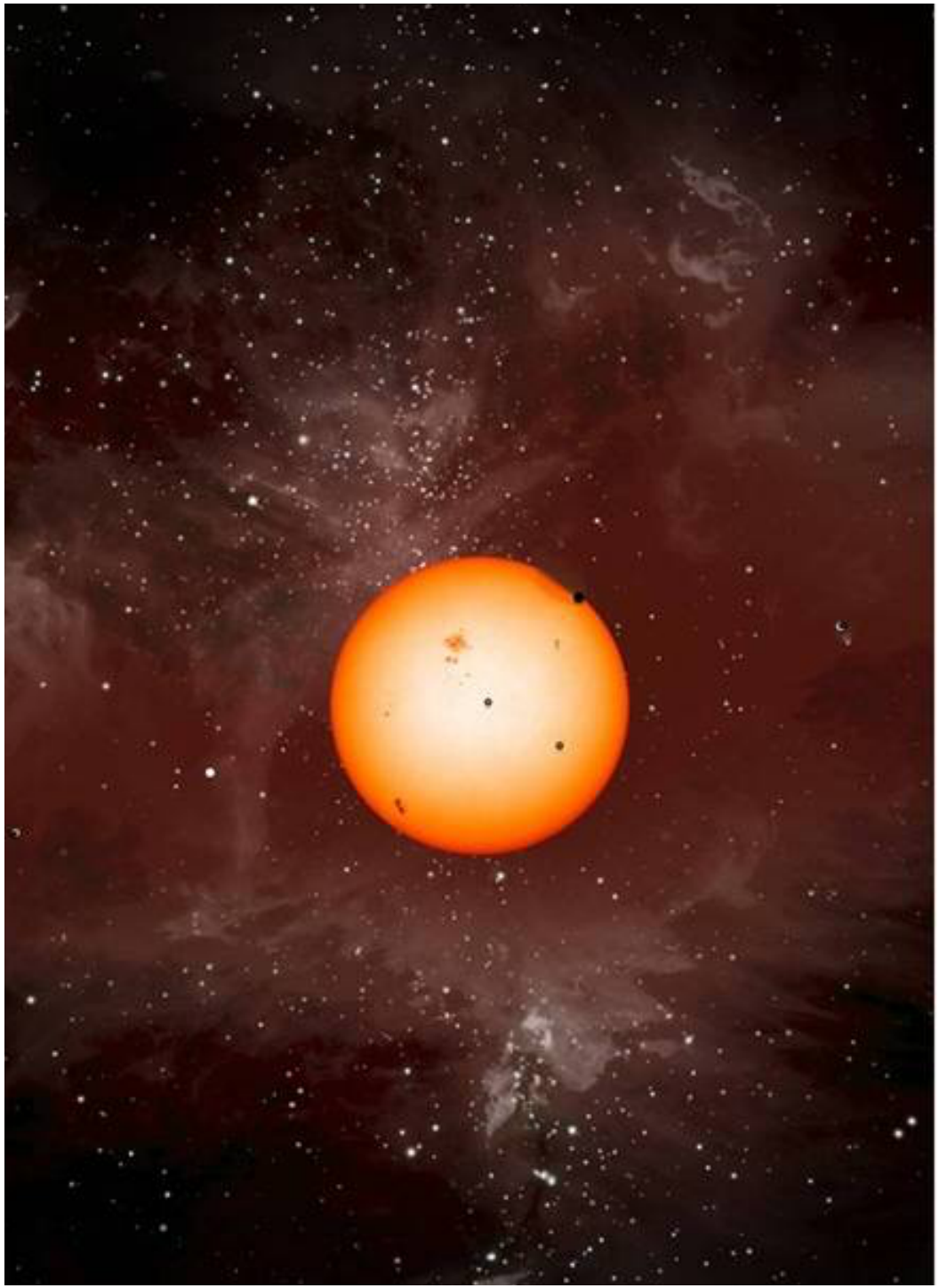



Kepler-62 System
Habitable Zone
62f
62e
62d
62c
62b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale



Kepler-11

A really cool system with 6 transiting planets

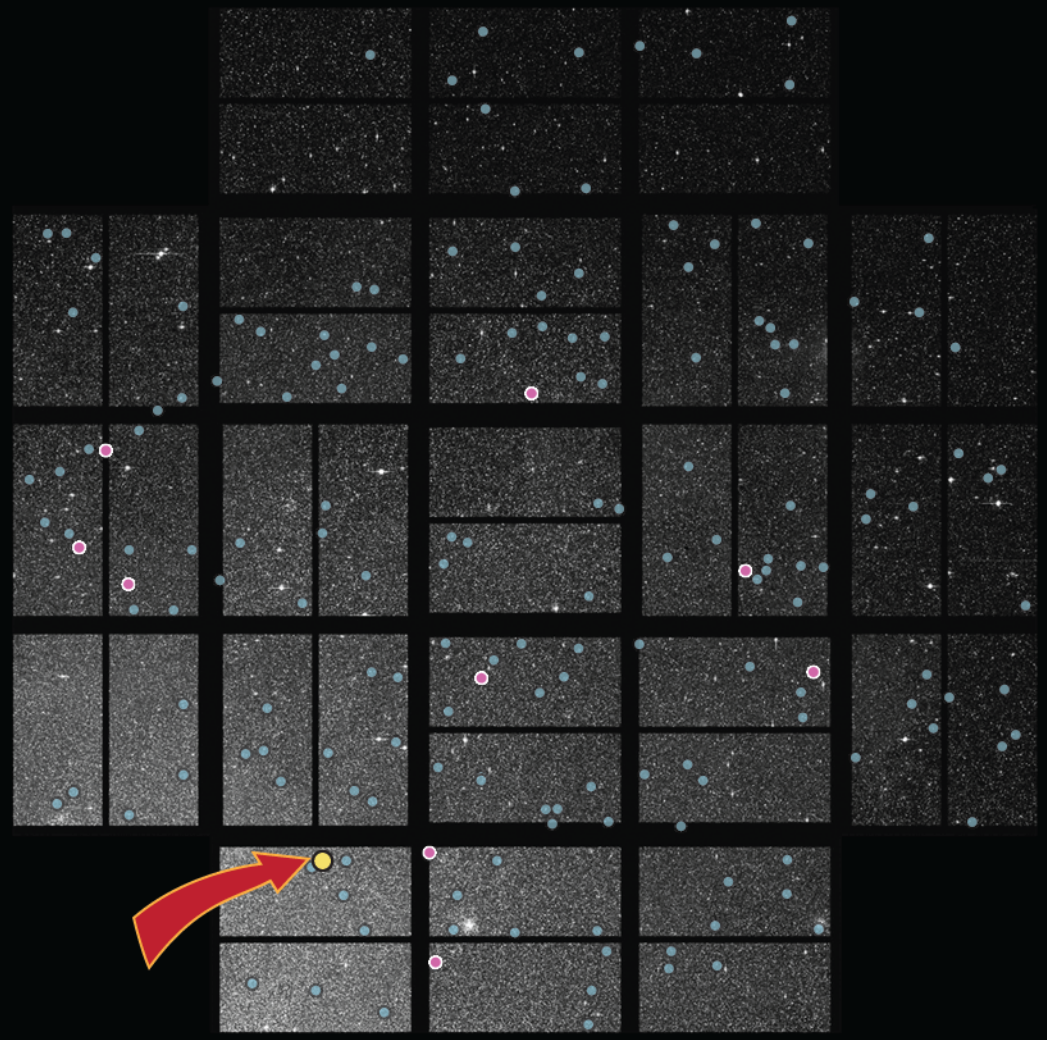


Kepler-11 Planets

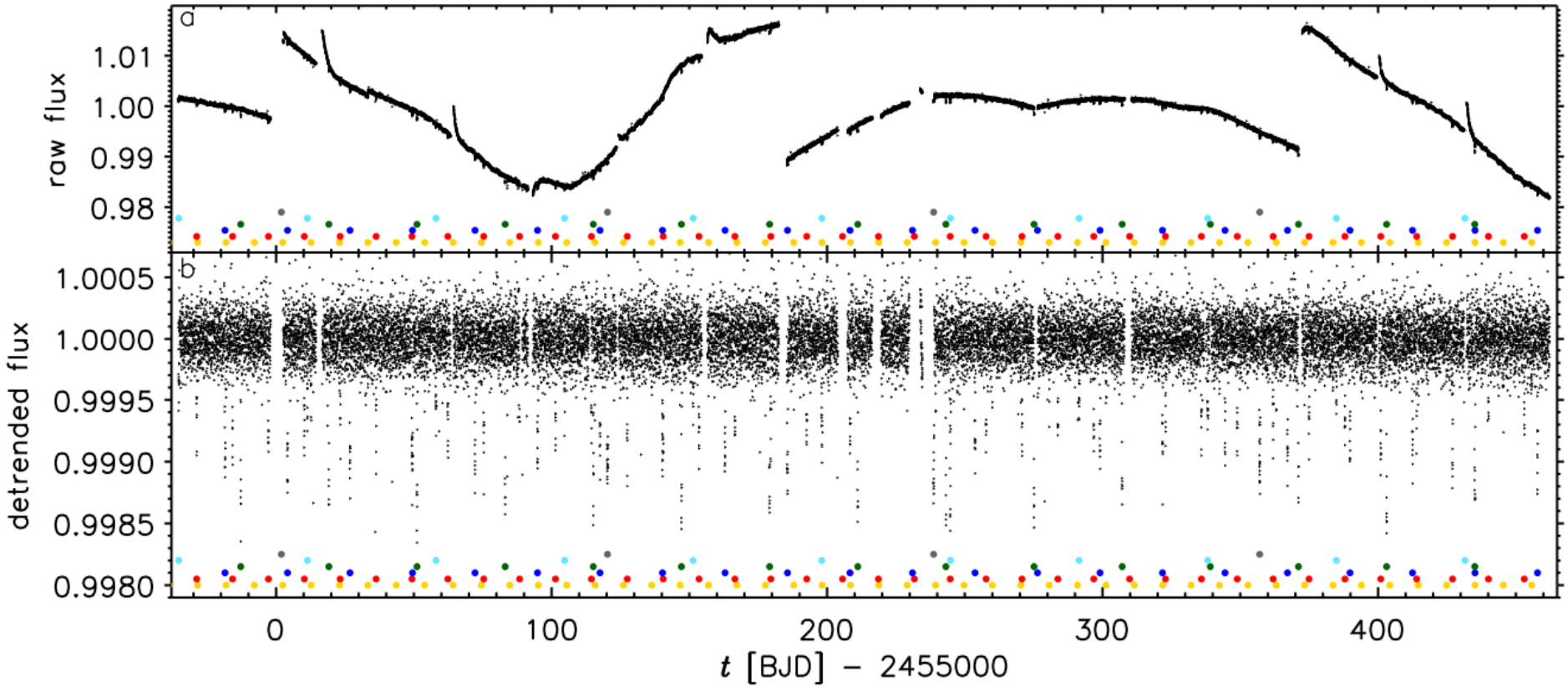
Correct sizes relative to star

(Dan Fabrycky)

Kepler-11: Six Planets

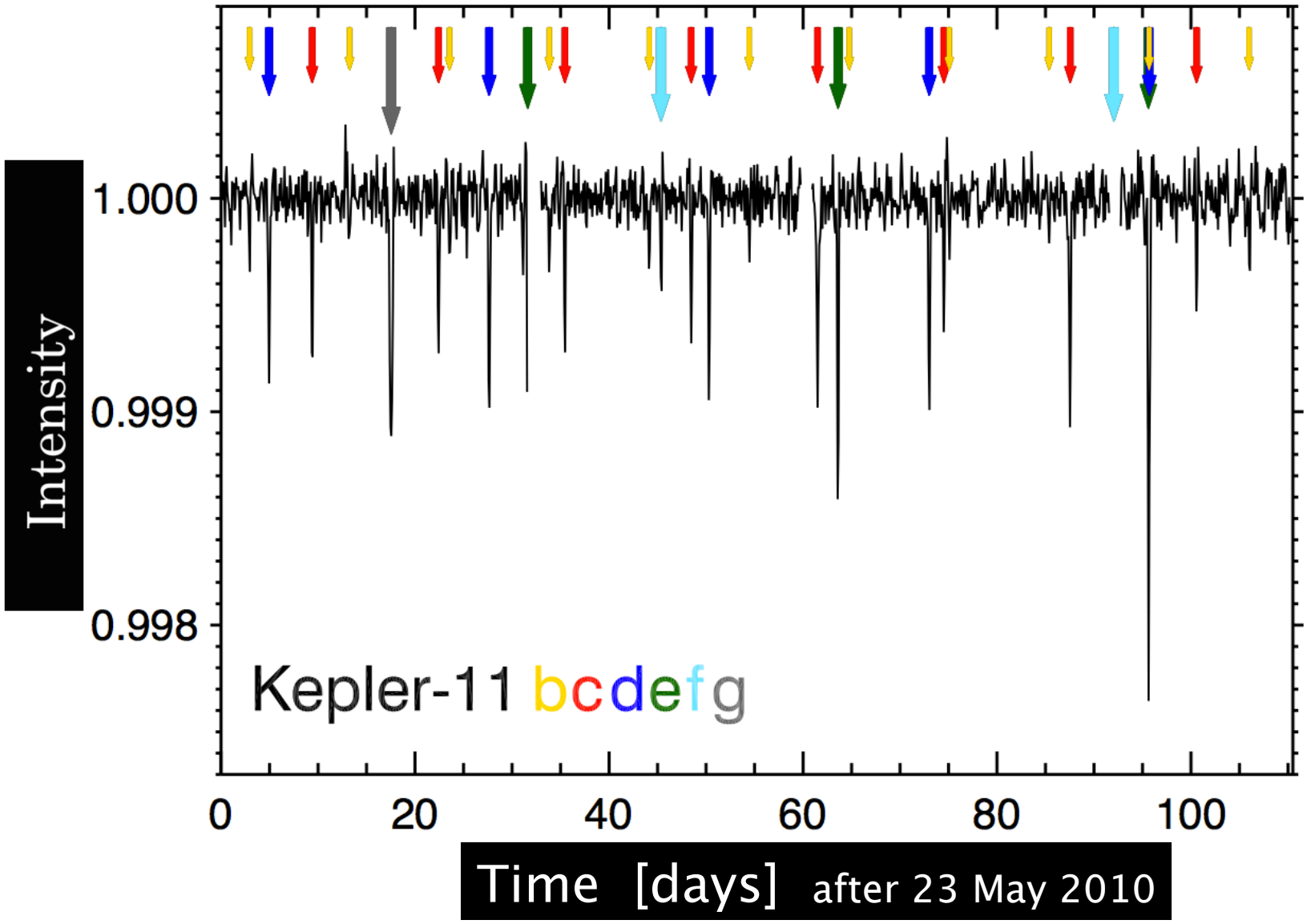


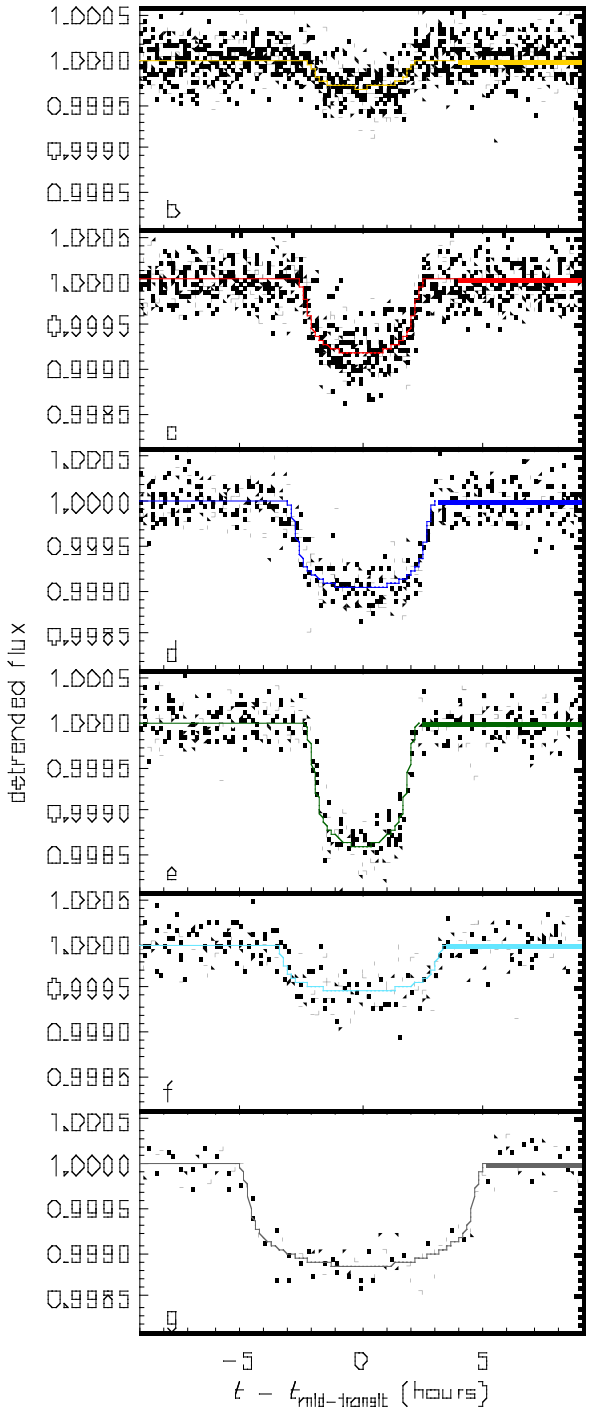
Lightcurve Q1-Q6

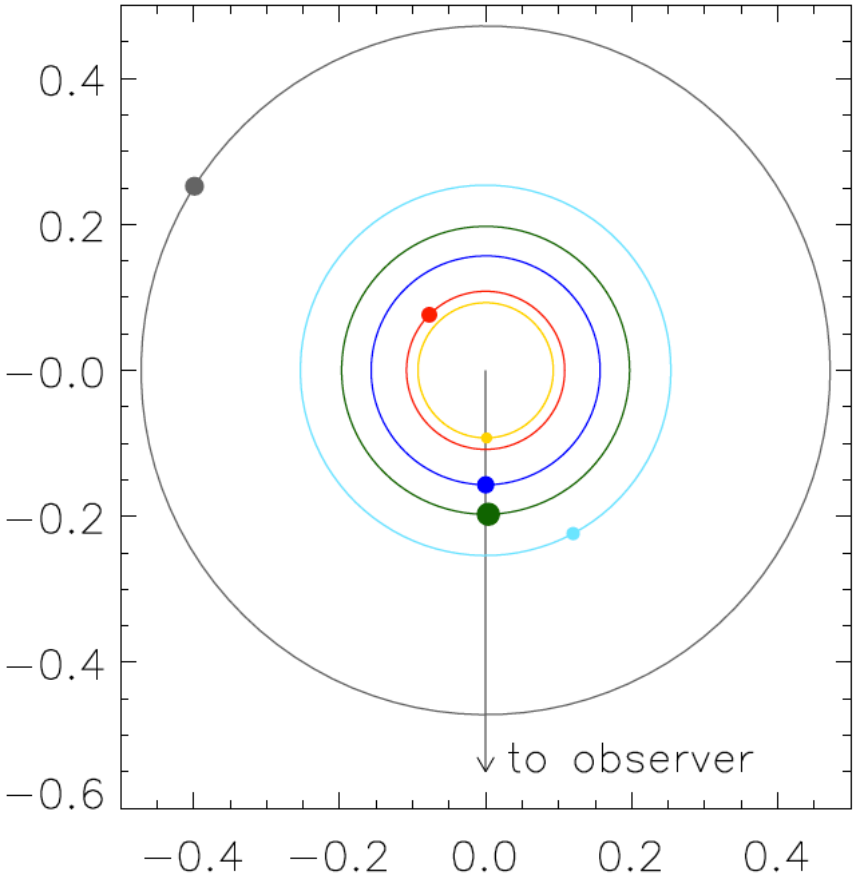


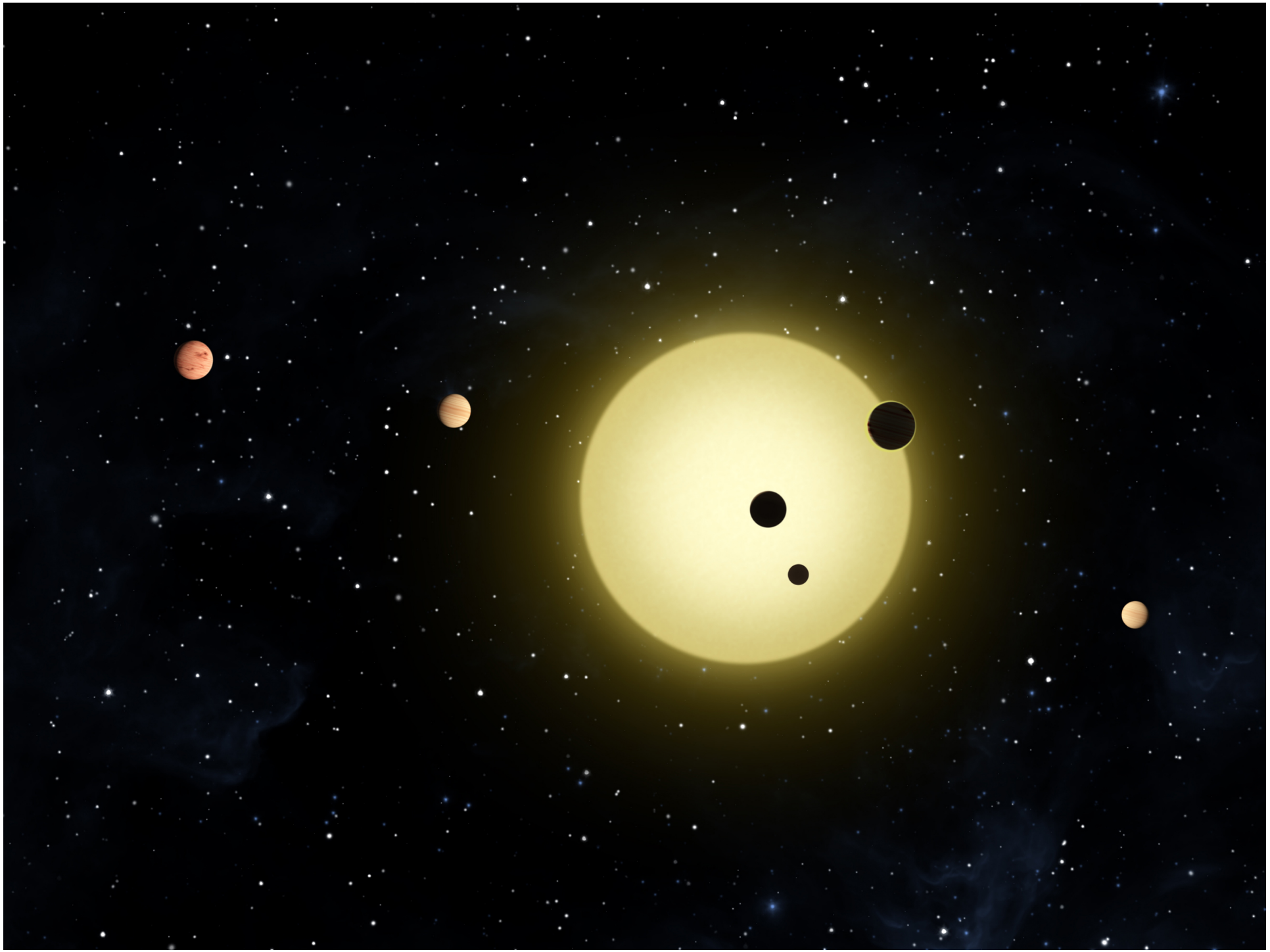
- Colored dots represent transits of six planets

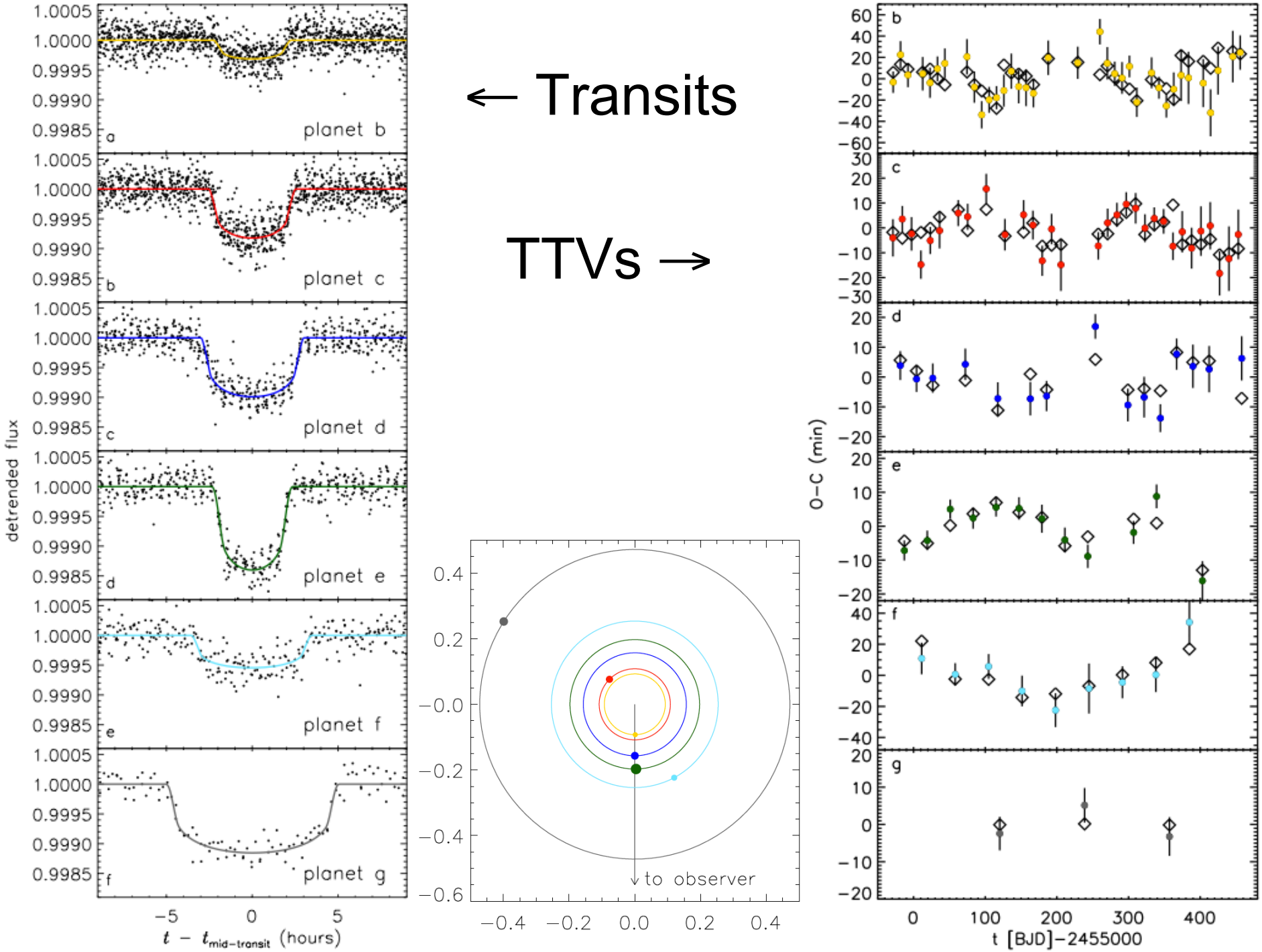
Kepler-11: Six Transiting Planets

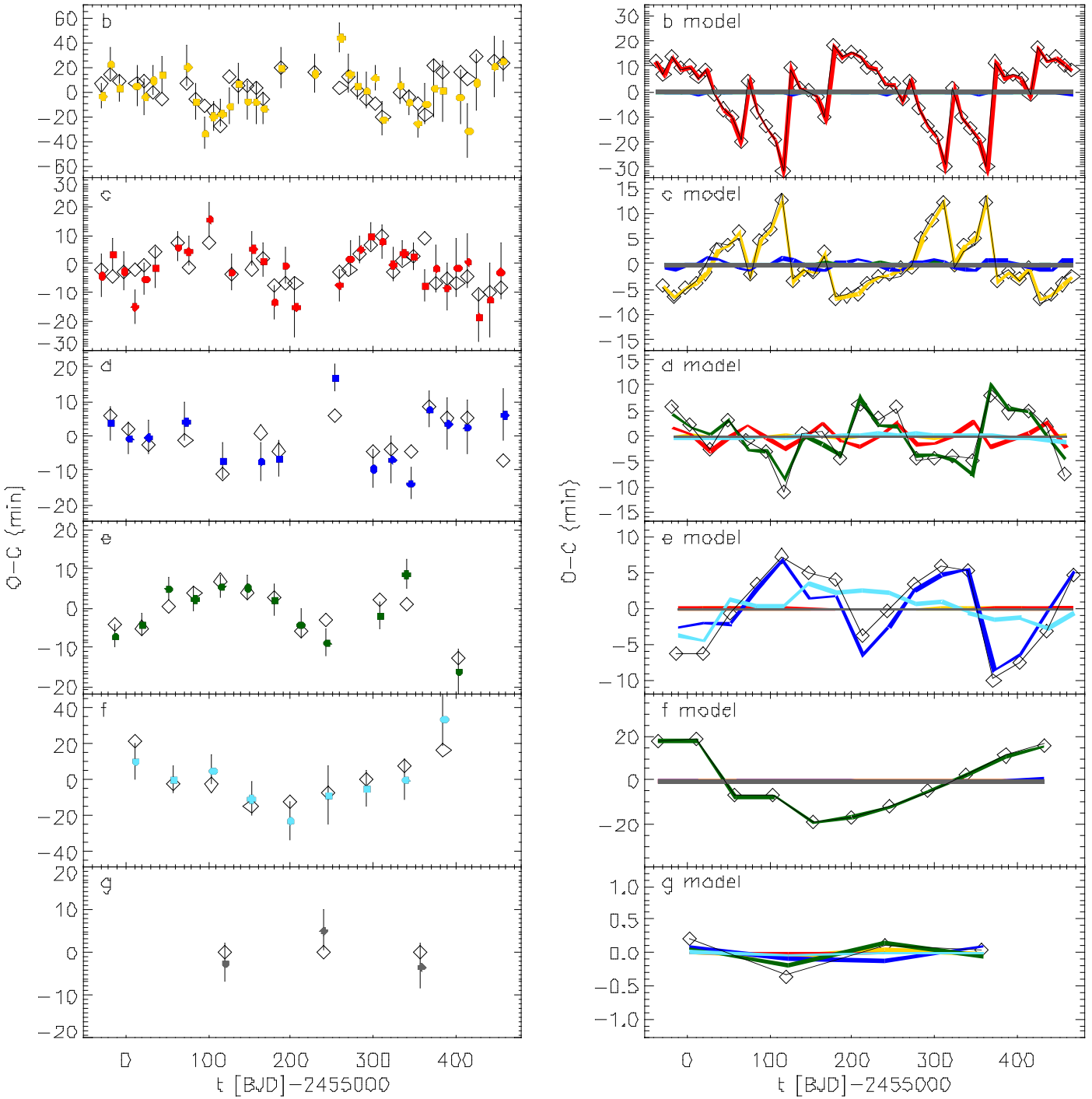



detrended flux
b
c
d
e
f
g
t − t_mid-transit (hours)


0.4
0.2
−0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
to observer




← Transits
TTVs →
detrended flux
planet b
planet c
planet d
planet e
planet f
planet g
t − t mid−transit (hours)
to observer
O−C (min)
t [BJD]−2455000


b
c
d
e
f
g
b model
c model
d model
e model
f model
g model
O−C (min)
t [BJD]−2455000

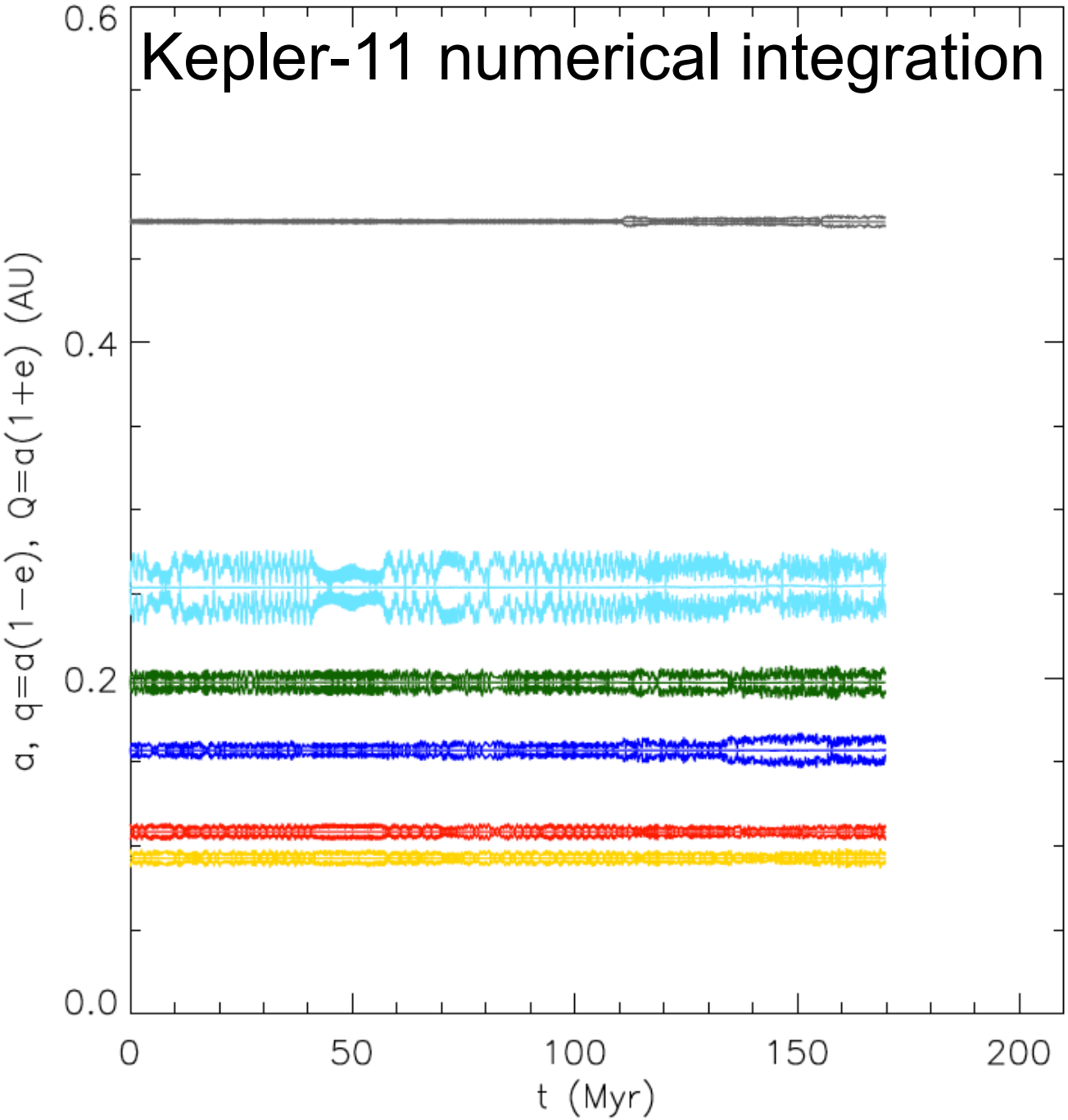
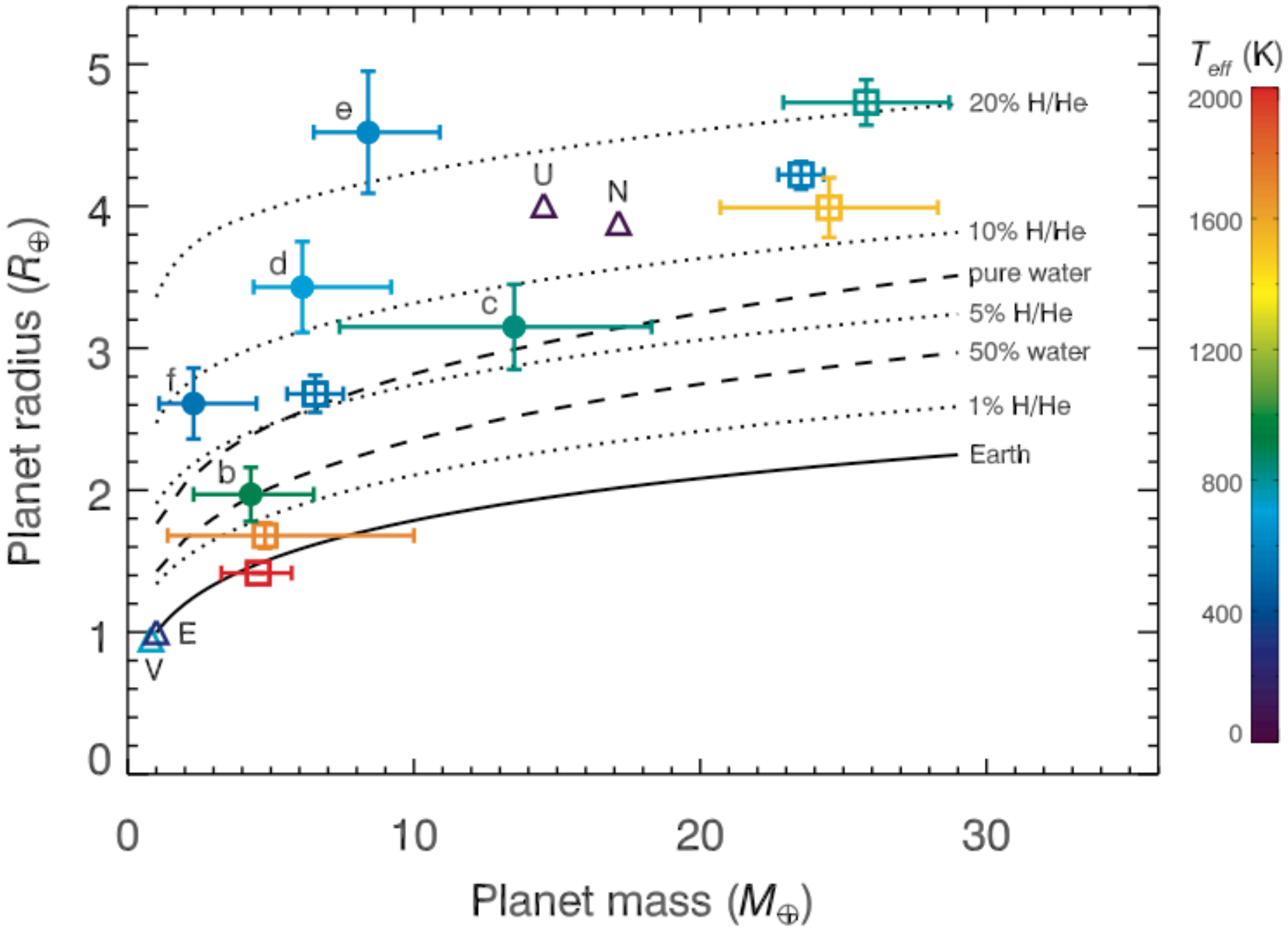

Kepler-11 numerical integration
0.6
0.4
0.2
0.0
0
50
100
150
200
t (Myr)
a, q=a(1−e), Q=a(1+e) (AU)

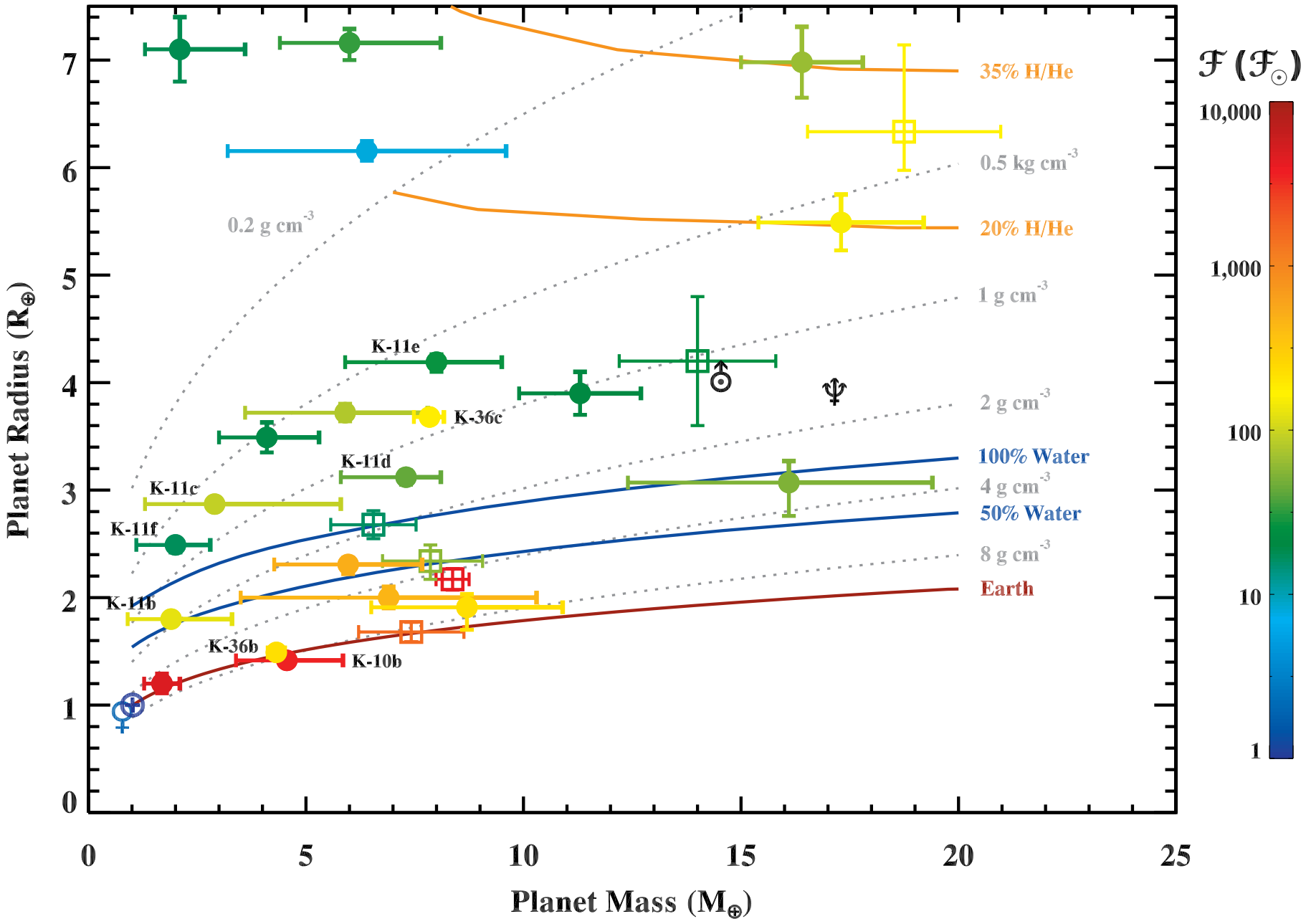
Image: NASA/Pyle

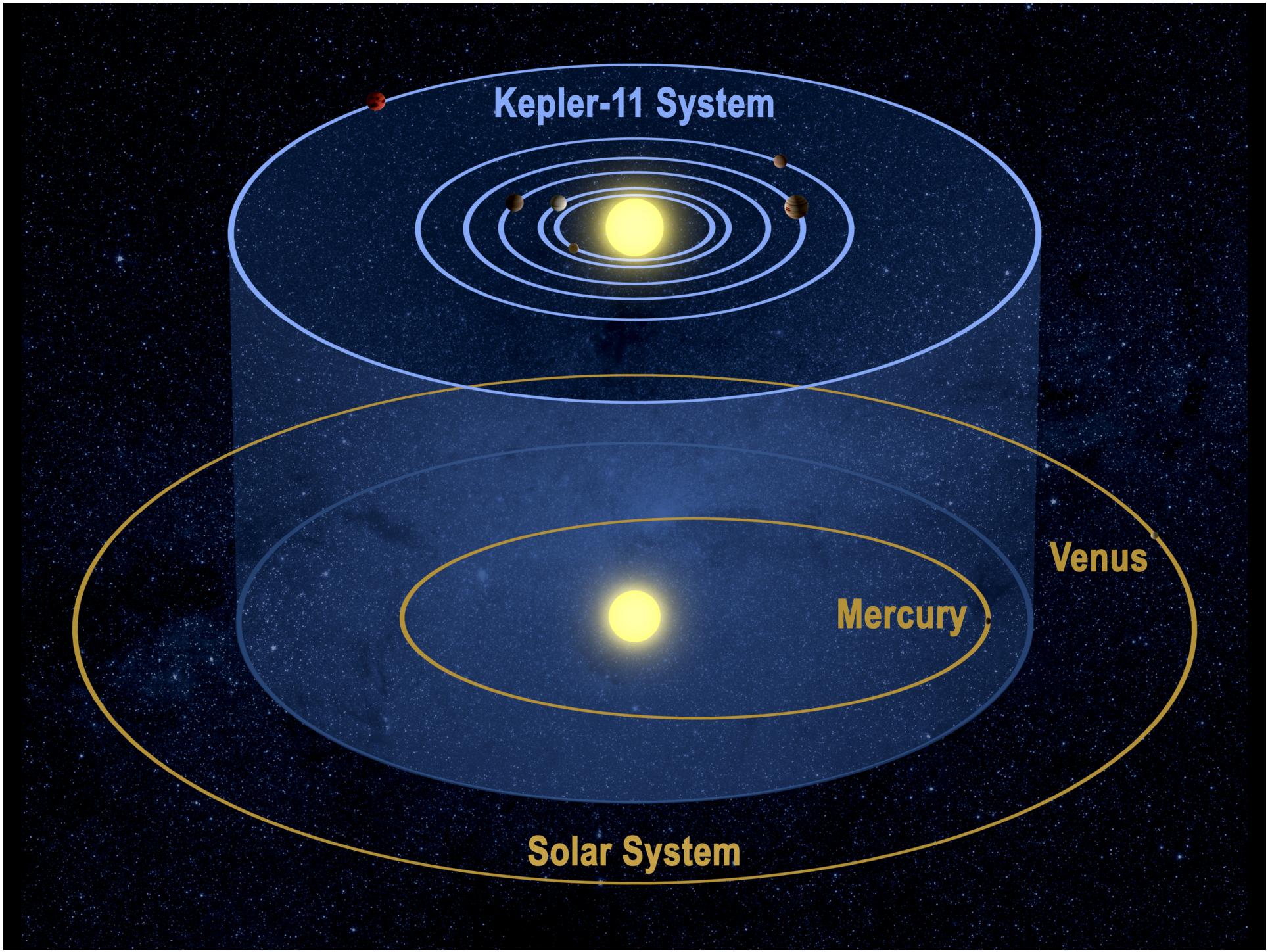
Kepler-11 Planets

Planet	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Density (g cm^{-3})	a (AU)	e	Flux ($F_{\odot,1AU}$)
b	$\mathbf{1.9}^{+1.4}_{-1.0}$	$\mathbf{1.80}^{+0.03}_{-0.05}$	$\mathbf{1.72}^{+1.25}_{-0.91}$	$\mathbf{0.091}^{+0.001}_{-0.001}$	$\mathbf{0.045}^{+0.068}_{-0.042}$	**125.1**
c	$\mathbf{2.9}^{+2.9}_{-1.6}$	$\mathbf{2.87}^{+0.05}_{-0.06}$	$\mathbf{0.66}^{+0.66}_{-0.35}$	$\mathbf{0.107}^{+0.001}_{-0.001}$	$\mathbf{0.026}^{+0.063}_{-0.013}$	**91.6**
d	$\mathbf{7.3}^{+0.8}_{-1.5}$	$\mathbf{3.12}^{+0.06}_{-0.07}$	$\mathbf{1.28}^{+0.14}_{-0.27}$	$\mathbf{0.155}^{+0.001}_{-0.001}$	$\mathbf{0.004}^{+0.007}_{-0.002}$	**43.7**
e	$\mathbf{8.0}^{+1.5}_{-2.1}$	$\mathbf{4.19}^{+0.07}_{-0.09}$	$\mathbf{0.58}^{+0.11}_{-0.16}$	$\mathbf{0.195}^{+0.002}_{-0.002}$	$\mathbf{0.012}^{+0.006}_{-0.006}$	**27.6**
f	$\mathbf{2.0}^{+0.8}_{-0.9}$	$\mathbf{2.49}^{+0.04}_{-0.07}$	$\mathbf{0.69}^{+0.29}_{-0.32}$	$\mathbf{0.250}^{+0.002}_{-0.002}$	$\mathbf{0.013}^{+0.011}_{-0.009}$	**16.7**
g	< 25	$\mathbf{3.33}^{+0.06}_{-0.08}$	<4	$\mathbf{0.466}^{+0.004}_{-0.004}$	< 0.15	**4.8**

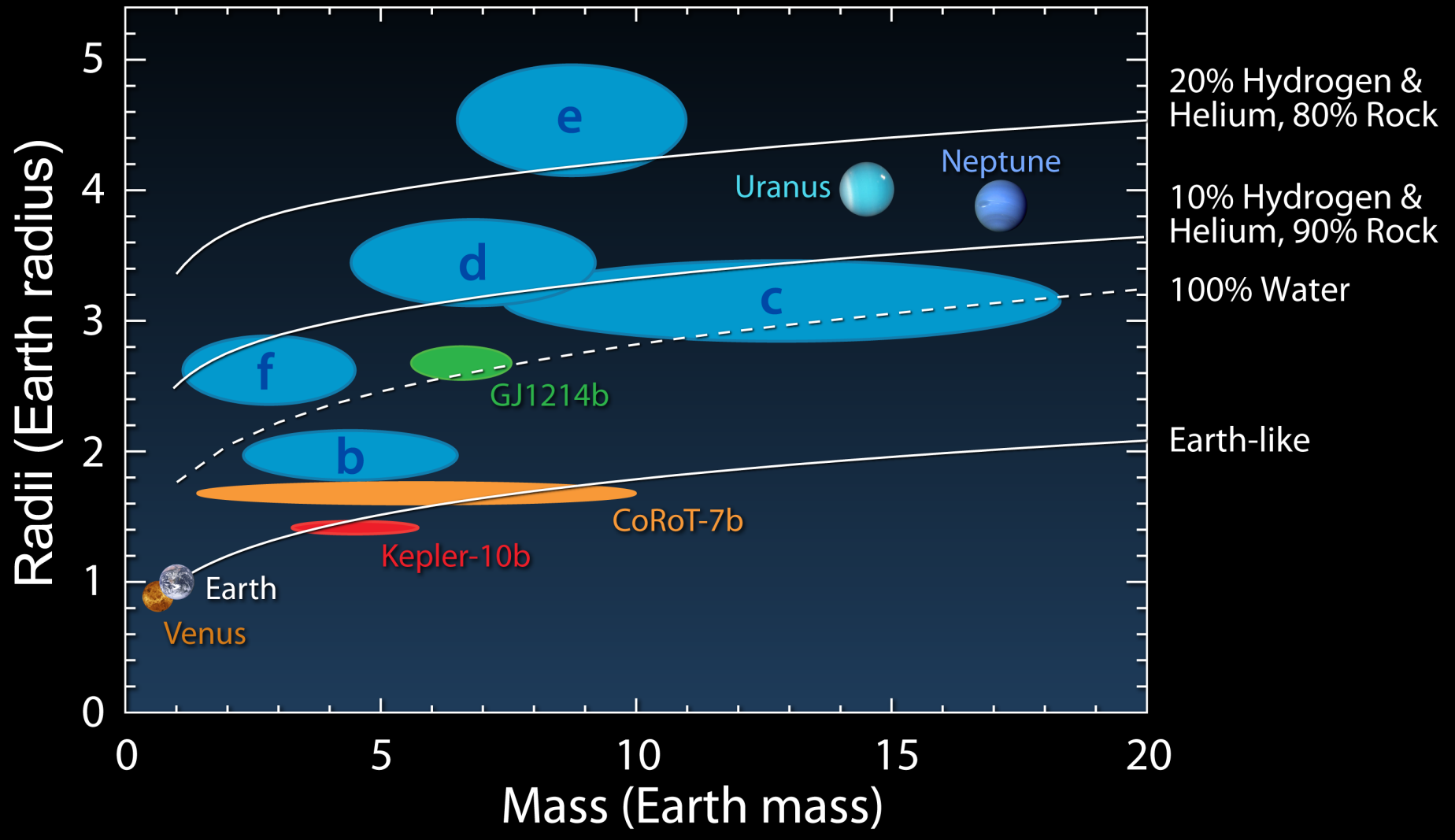

Planet radius ($R_\oplus$)
Planet mass ($M_\oplus$)
0
1
2
3
4
5
0
10
20
30
e
d
c
f
b
U
N
E
V
20% H/He
10% H/He
pure water
5% H/He
50% water
1% H/He
Earth
T_{eff} (K)
2000
1600
1200
800
400
0

Mass vs. Radius for sub-Neptune Exoplanets




Kepler-11 System
Venus
Mercury
Solar System

Composition of Kepler-11 Planets



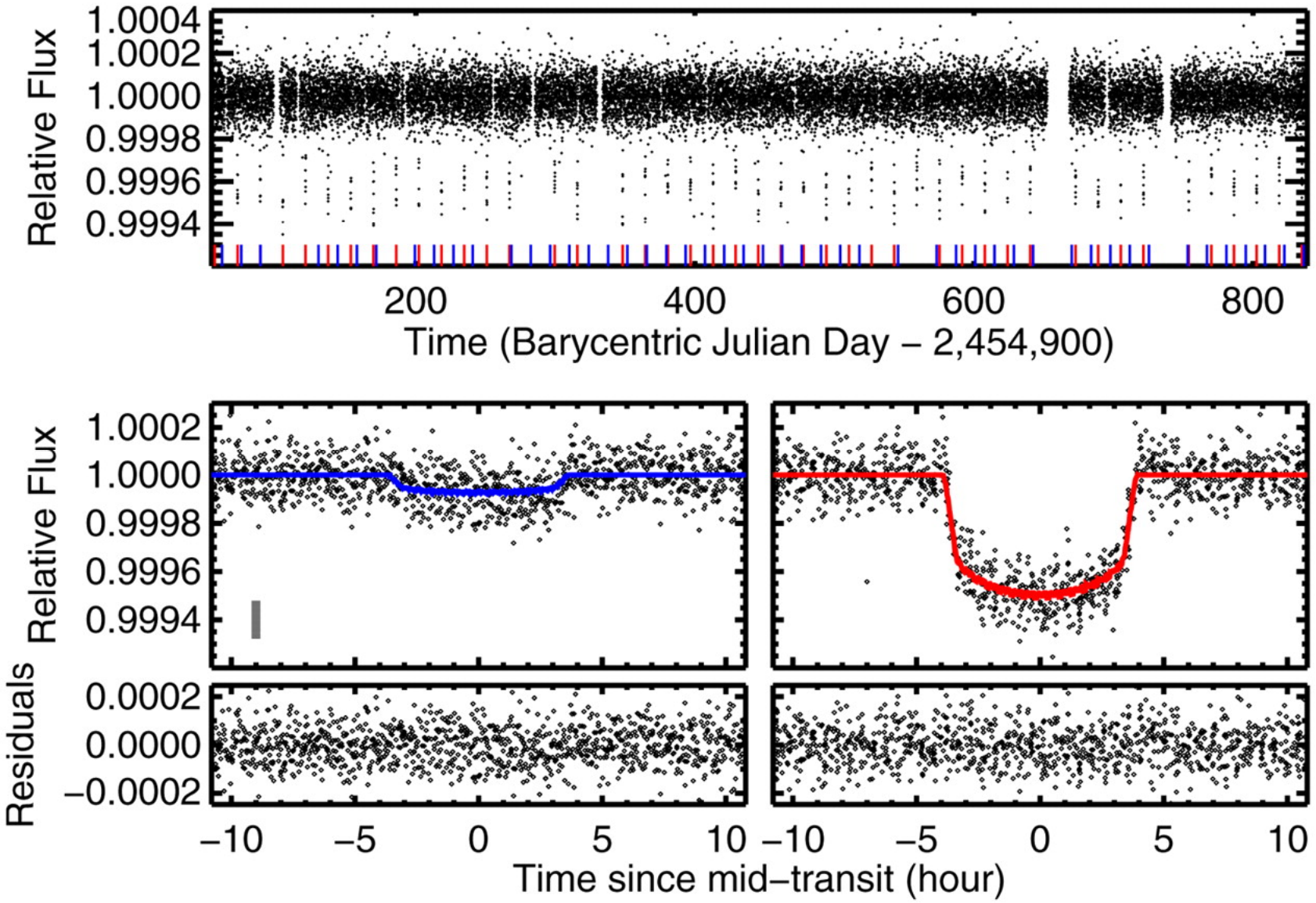
Summary

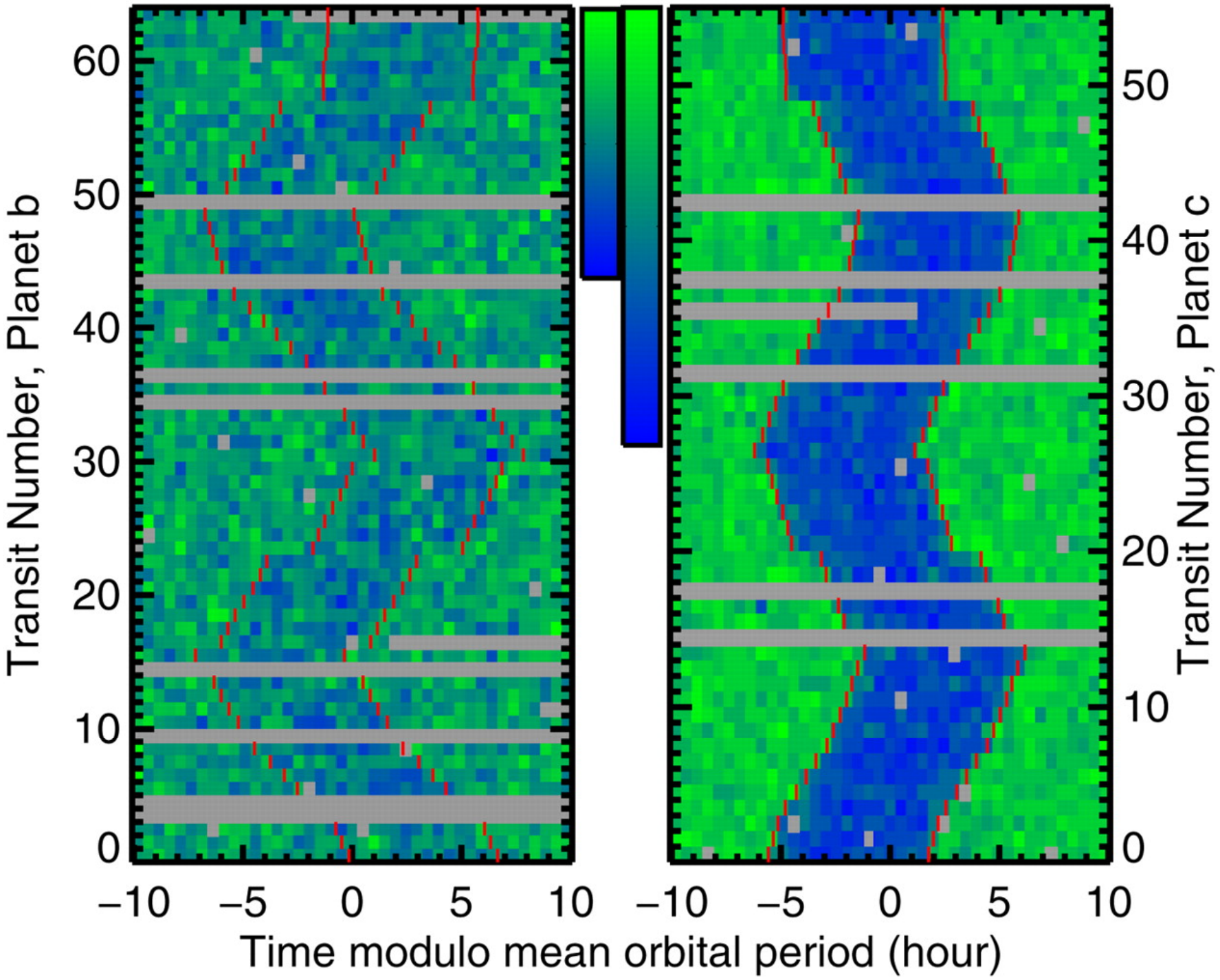
- Kepler-11 is a surprisingly flat system of six planets.
- The five inner planets comprise the most closely-spaced planetary system known.
- The planets are mid-sized: 2-5 times as large as Earth.
- Most have low densities, implying mixtures of solids and light gases.


FINDING NEW
PLANETS
2011
Kepler
NASA
Lathrop
DELLOSSO FAMILY FARM

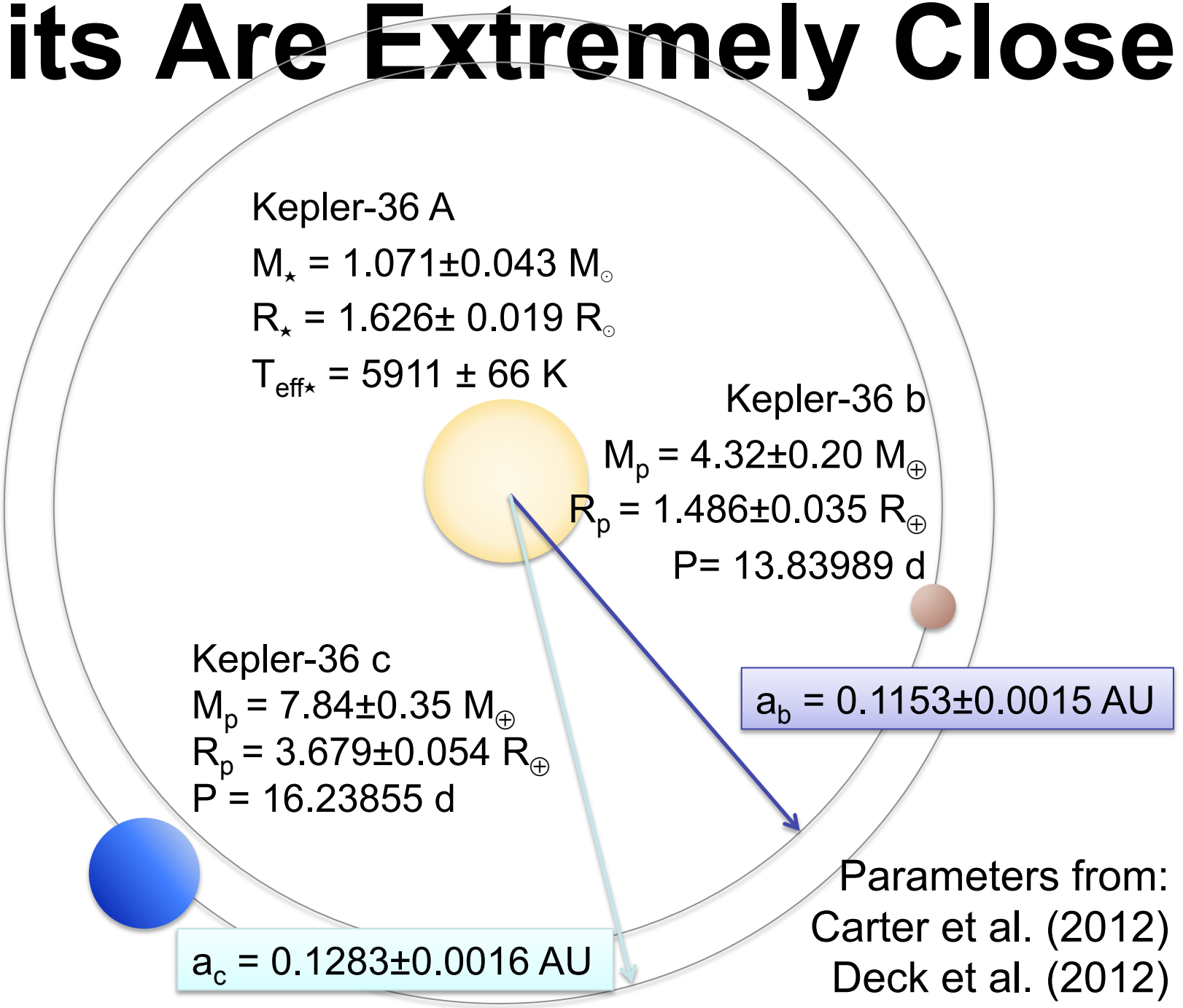
Kepler-36: A Pair of Planets with Neighboring Orbits and Dissimilar Densities

(Carter et al. 2012)

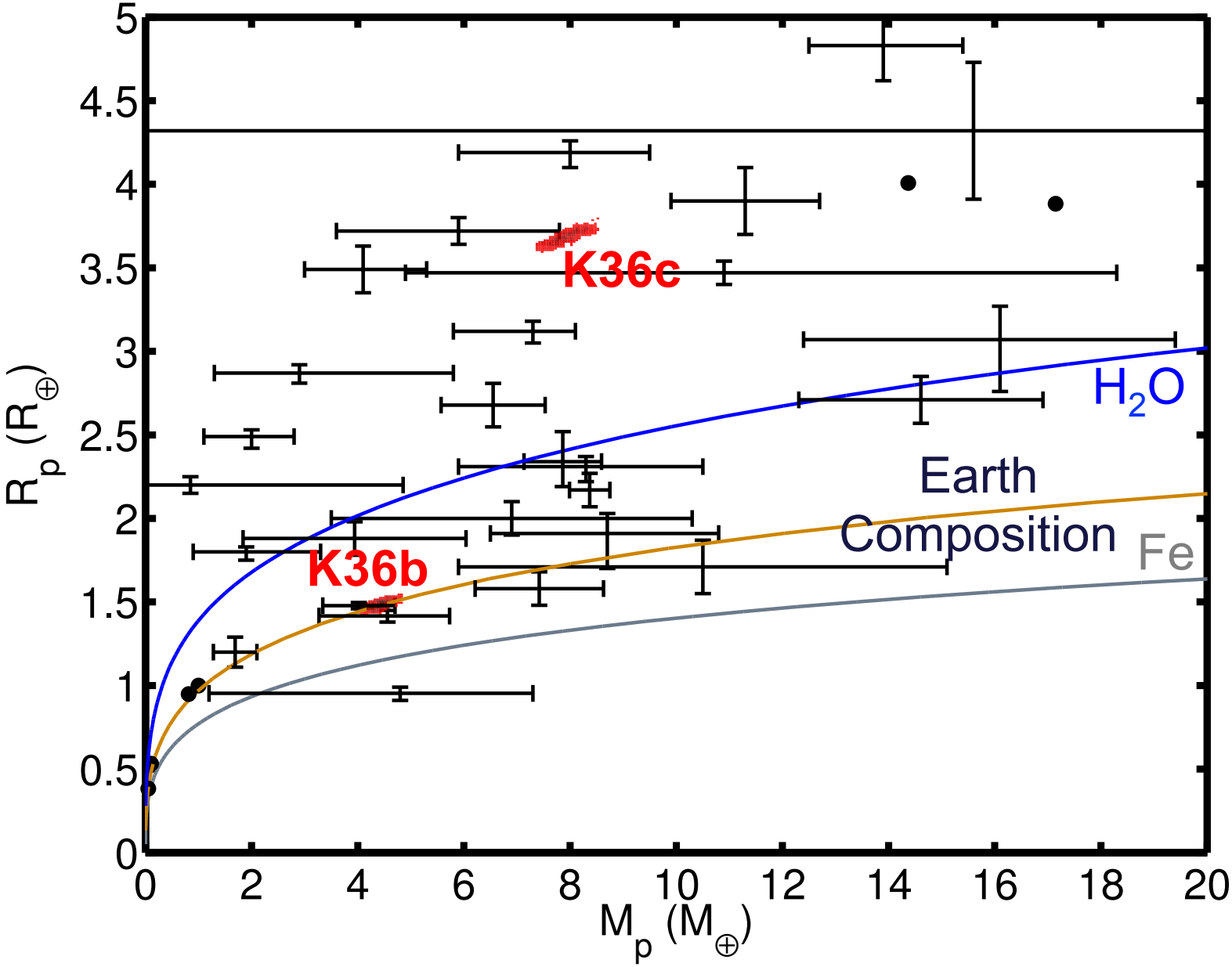



Transit Number, Planet b
60
50
40
30
20
10
0
Transit Number, Planet c
50
40
30
20
10
0
−10
−5
0
5
10
−10
−5
0
5
10
Time modulo mean orbital period (hour)

Orbits Are Extremely Close

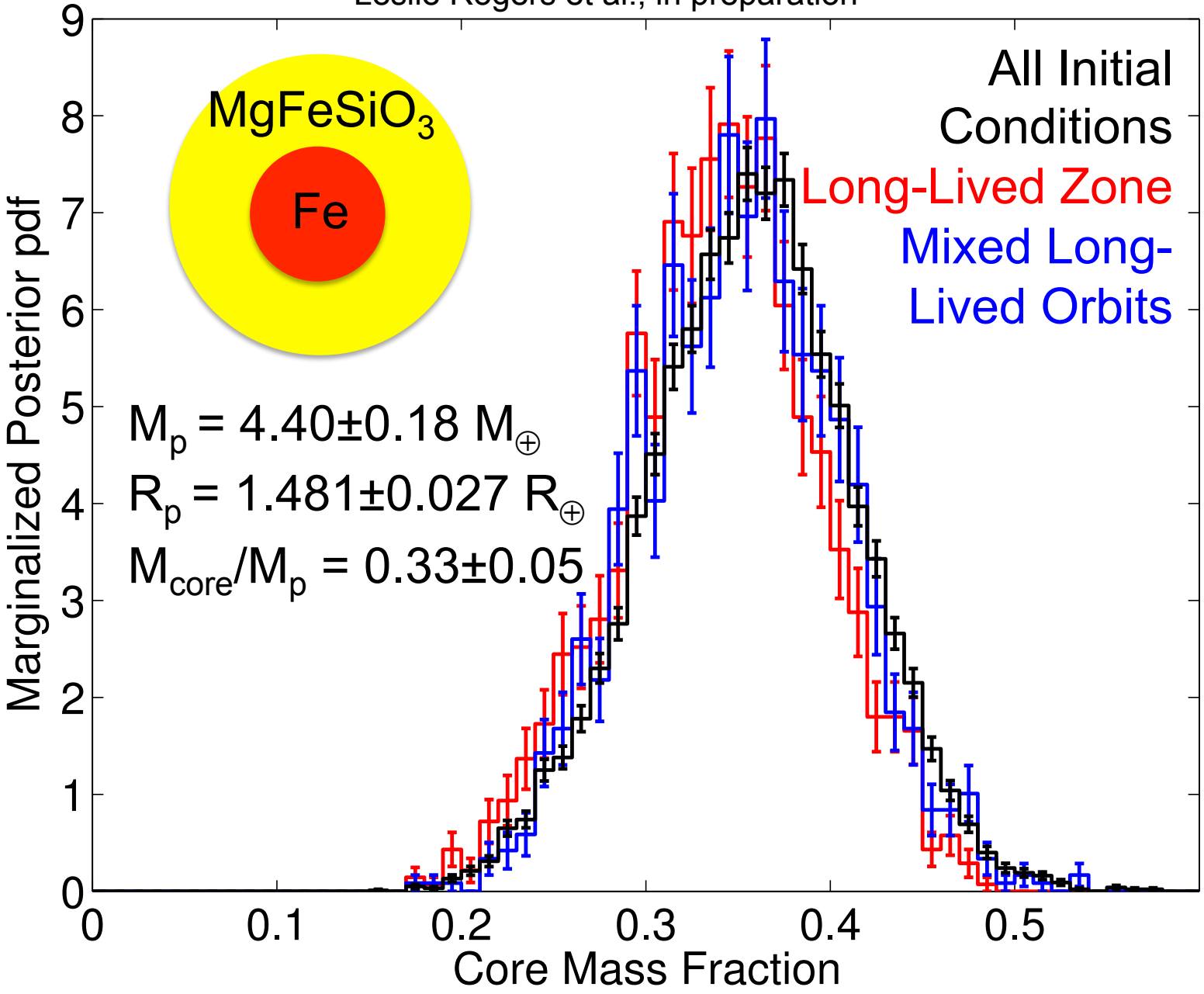


Kepler-36 b Mass Measured within 4.2%, Radius Measured within 1.8%



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

Leslie Rogers et al., in preparation



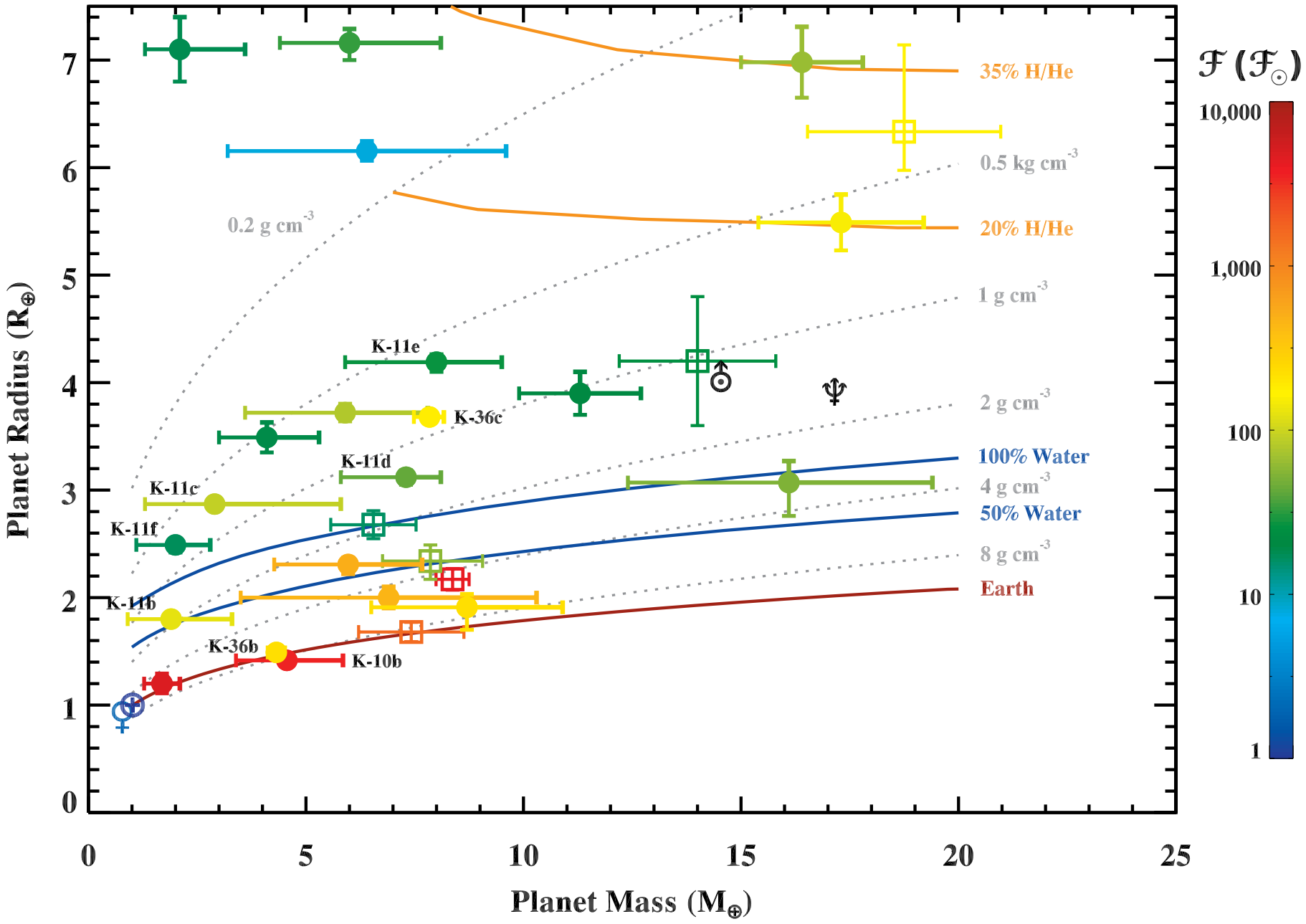
- Kepler-36 b is the rocky exoplanet with best constrained mass, density, and composition: mass known within 4.2%, radius to 1.8%, density to 4.6%.

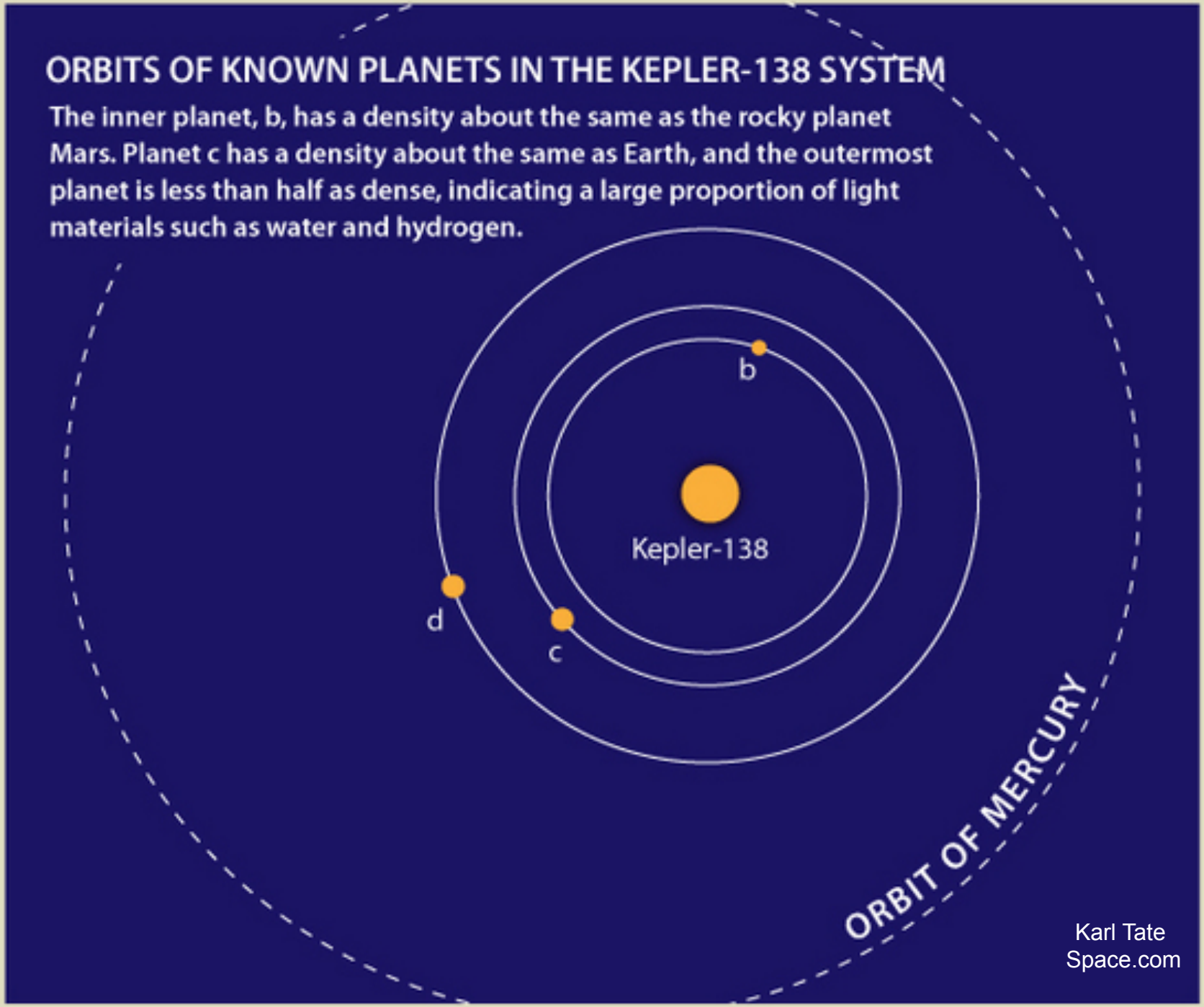
- Kepler-36 b's mass and radius are consistent with an Earth-like composition. An iron-enhanced Mercury-like composition is ruled out.

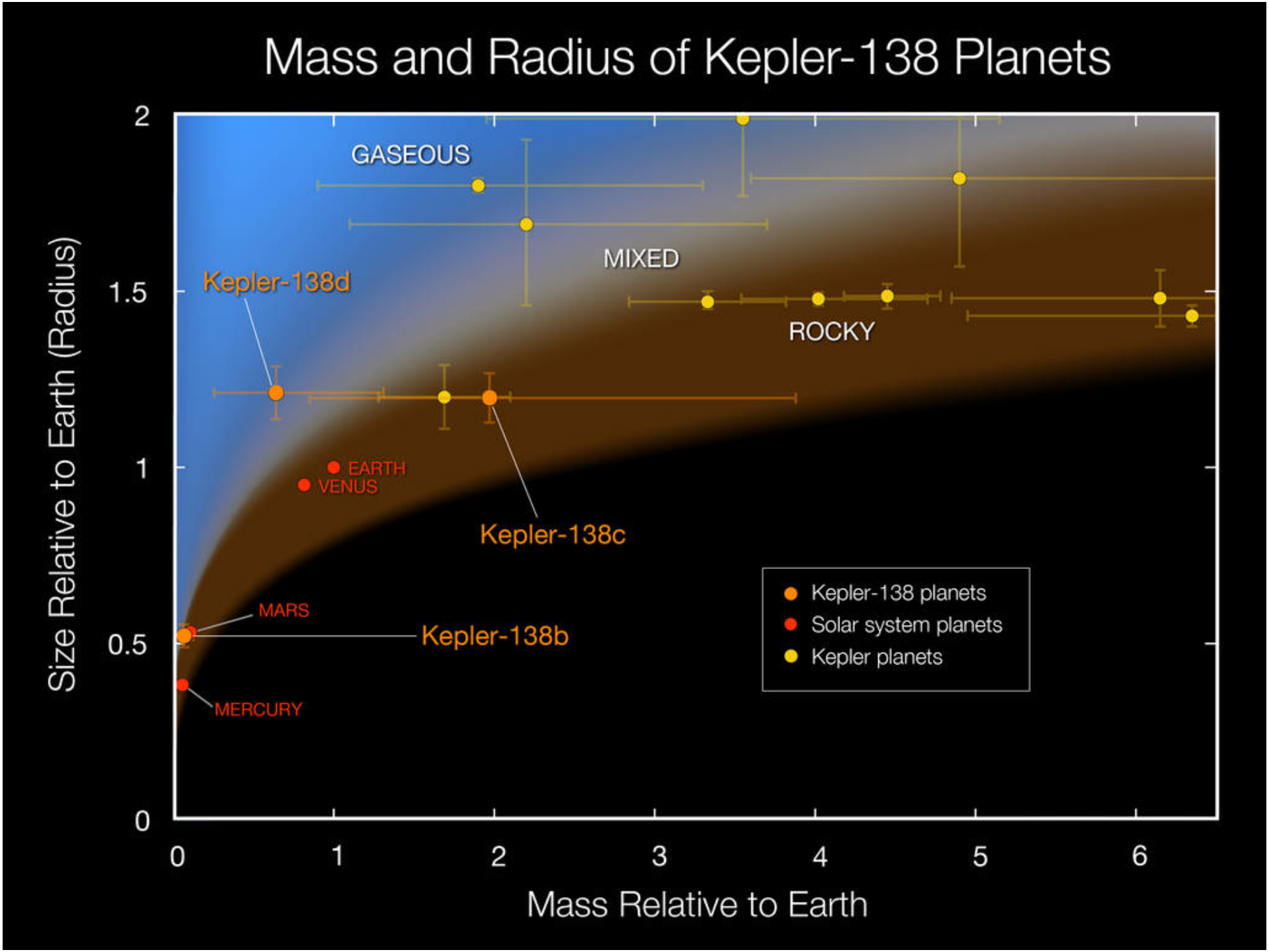
- In contrast, Kepler-36 c requires several percent of its mass in a hydrogen-rich envelope. (L. A. Rogers et al. in prep)


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

Mass vs. Radius for sub-Neptune Exoplanets




ORBITS OF KNOWN PLANETS IN THE KEPLER-138 SYSTEM
The inner planet, b, has a density about the same as the rocky planet Mars. Planet c has a density about the same as Earth, and the outermost planet is less than half as dense, indicating a large proportion of light materials such as water and hydrogen.
b
Kepler-138
d
c
ORBIT OF MERCURY
Karl Tate
Space.com


Mass and Radius of Kepler-138 Planets
GASEOUS
MIXED
ROCKY
Kepler-138d
EARTH
VENUS
Kepler-138c
MARS
Kepler-138b
MERCURY
Kepler-138 planets
Solar system planets
Kepler planets
Size Relative to Earth (Radius)
Mass Relative to Earth
0
0.5
1
1.5
2
0
1
2
3
4
5
6

Kepler-138

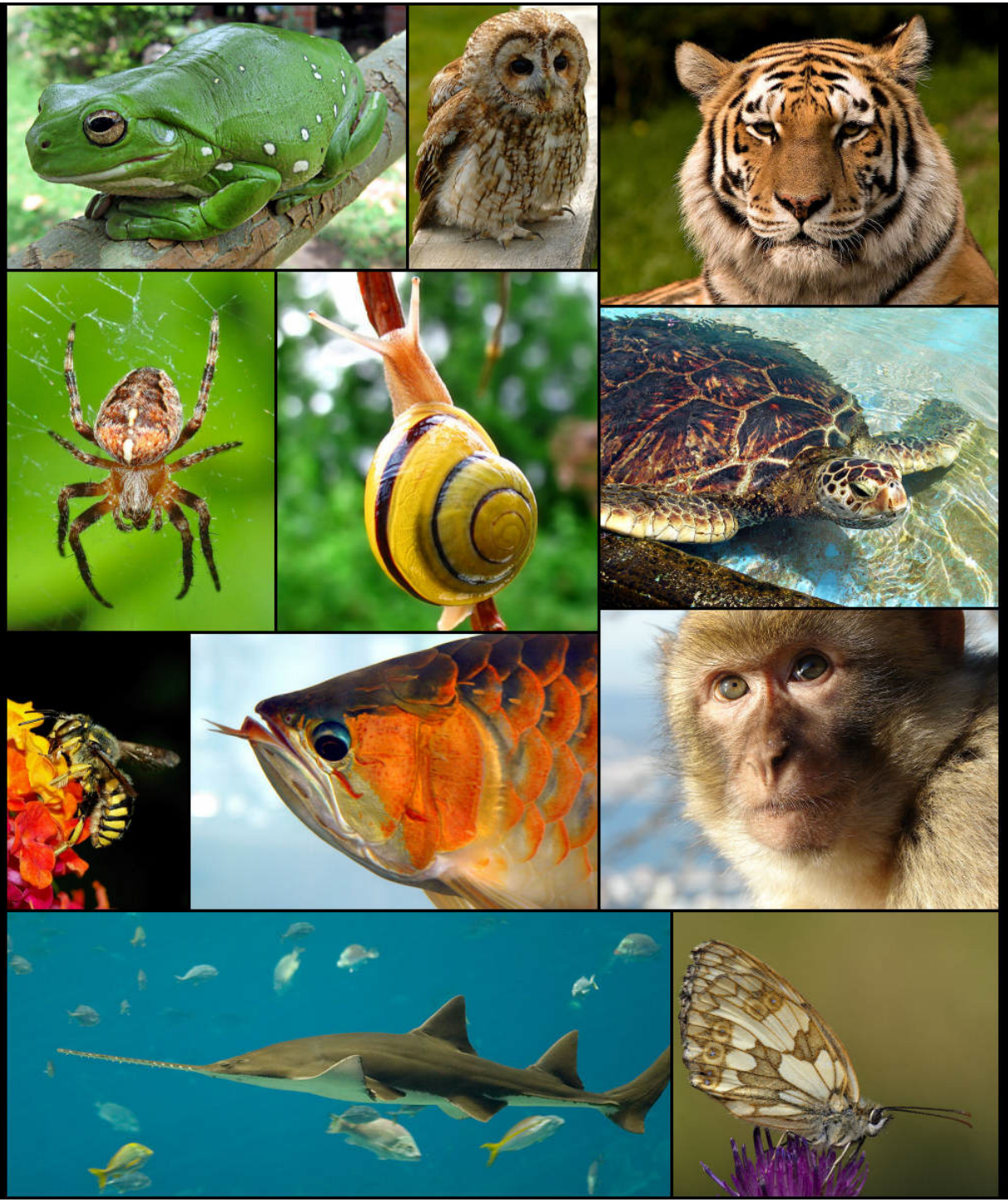
‘b’ is Mars-size

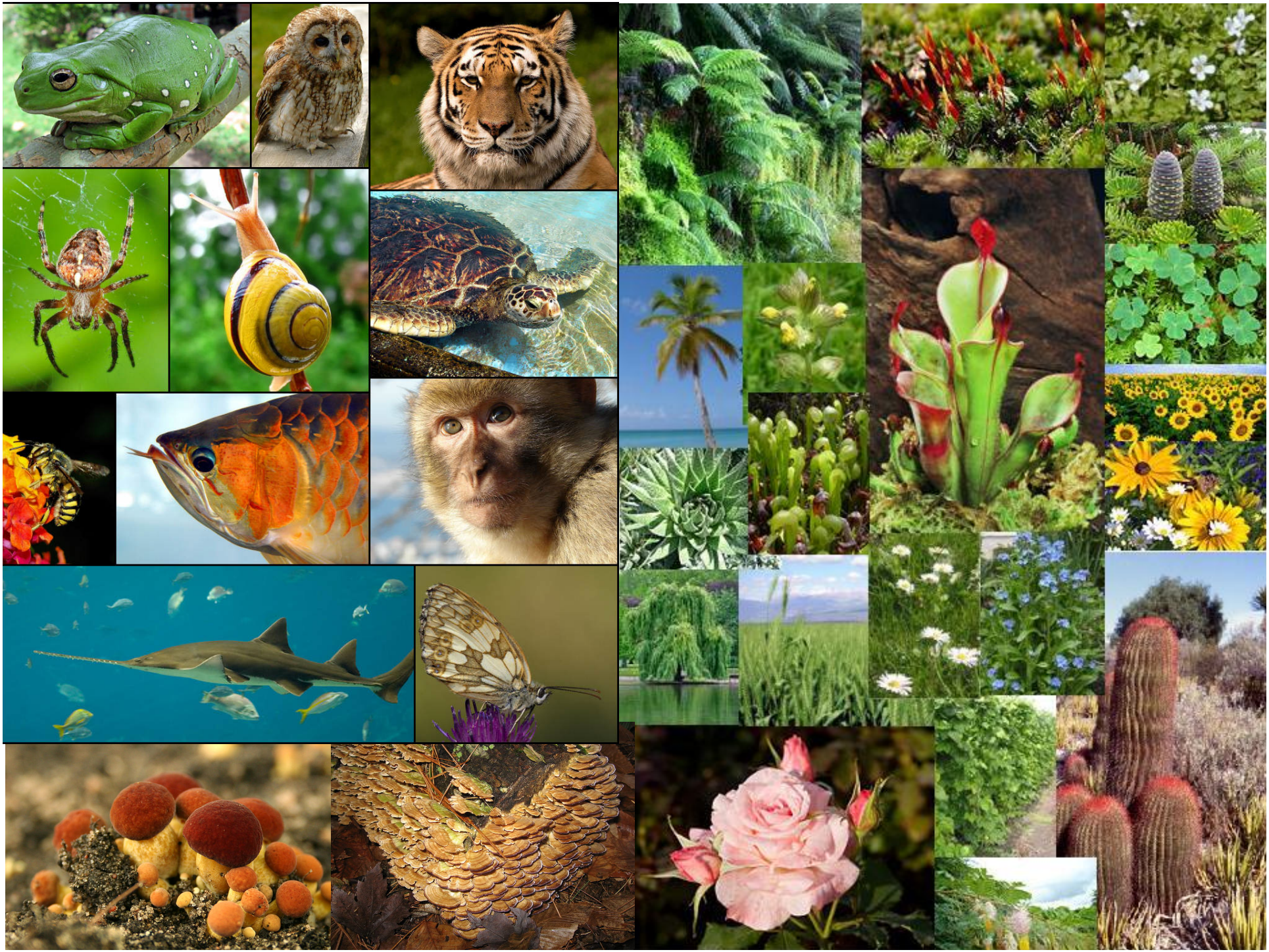
‘c’ and ‘d’ have $R_p = 1.2\ R_{Earth}$

‘c’ is rocky

‘d’ is less dense than rock (1/3 as massive as ‘c’)

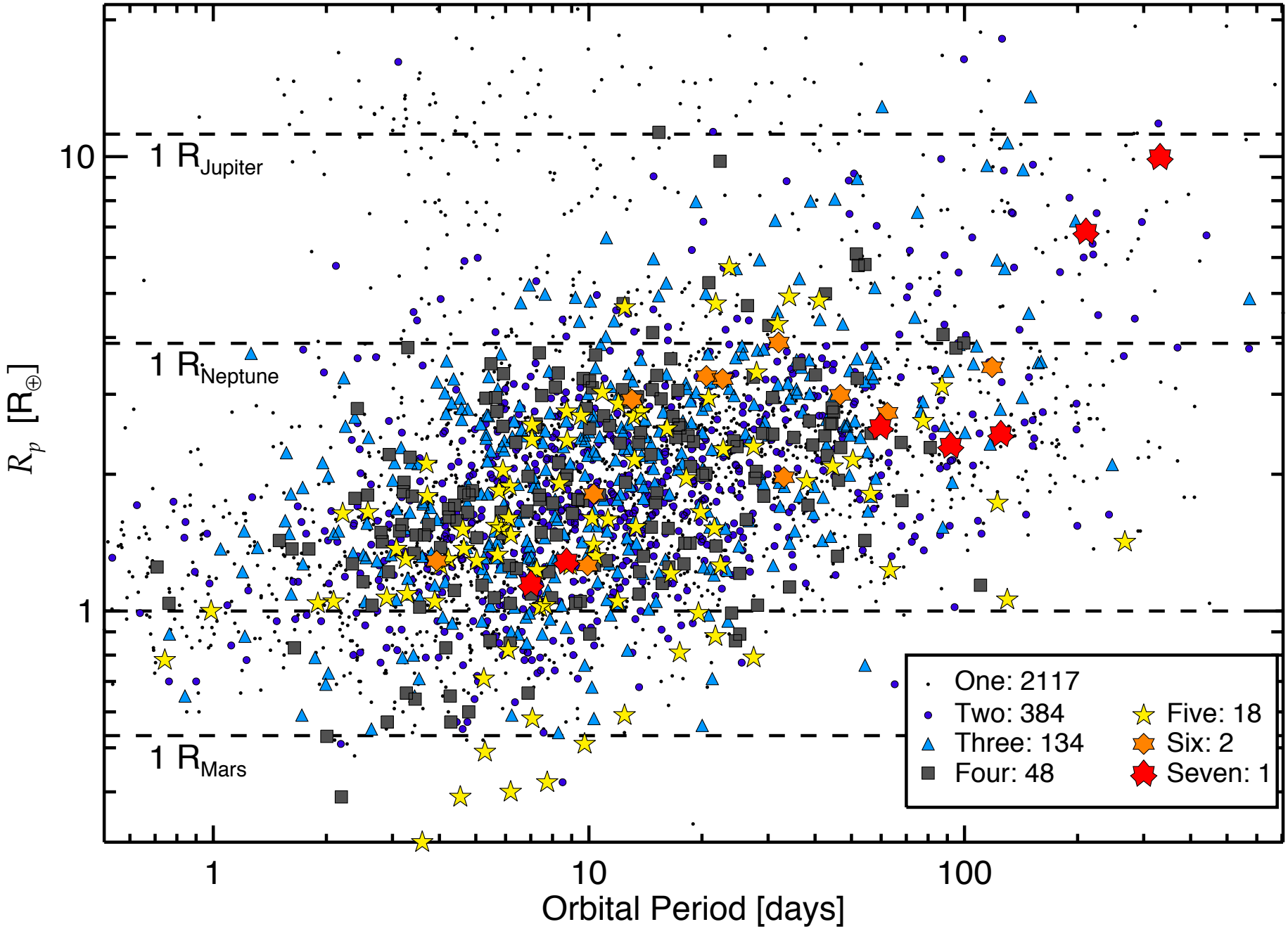
Jontof-Hutter et al. 2015

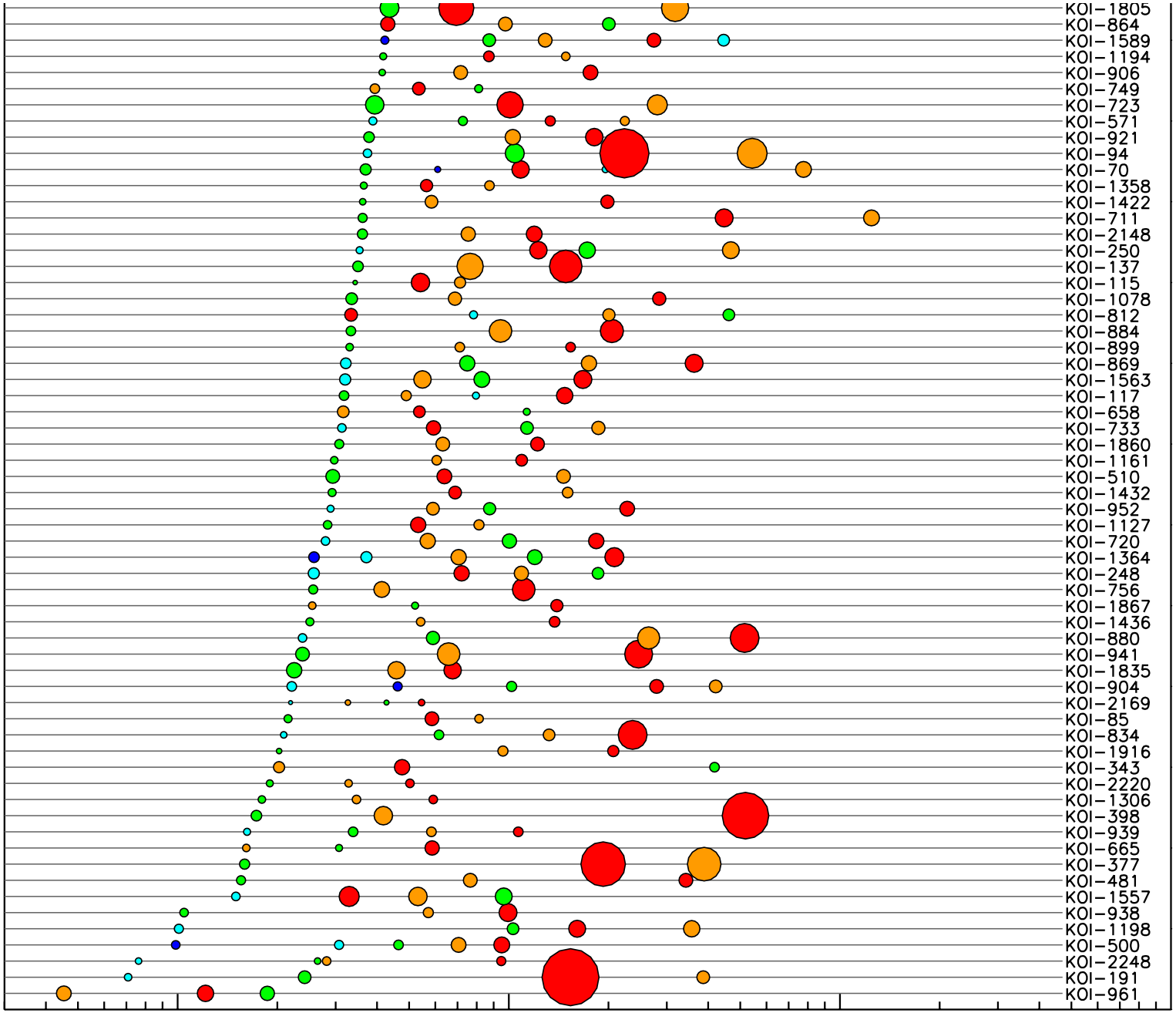




Q1-Q12 Planet Candidates

- 3538 planet candidates
- Multi-planet systems:
  - 2 planets: 464
  - 3 planets: 149
  - 4 planets: 50
  - 5 planets: 20
  - 6 planets: 4
  - 7 planets: 1 (KOI-351)


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

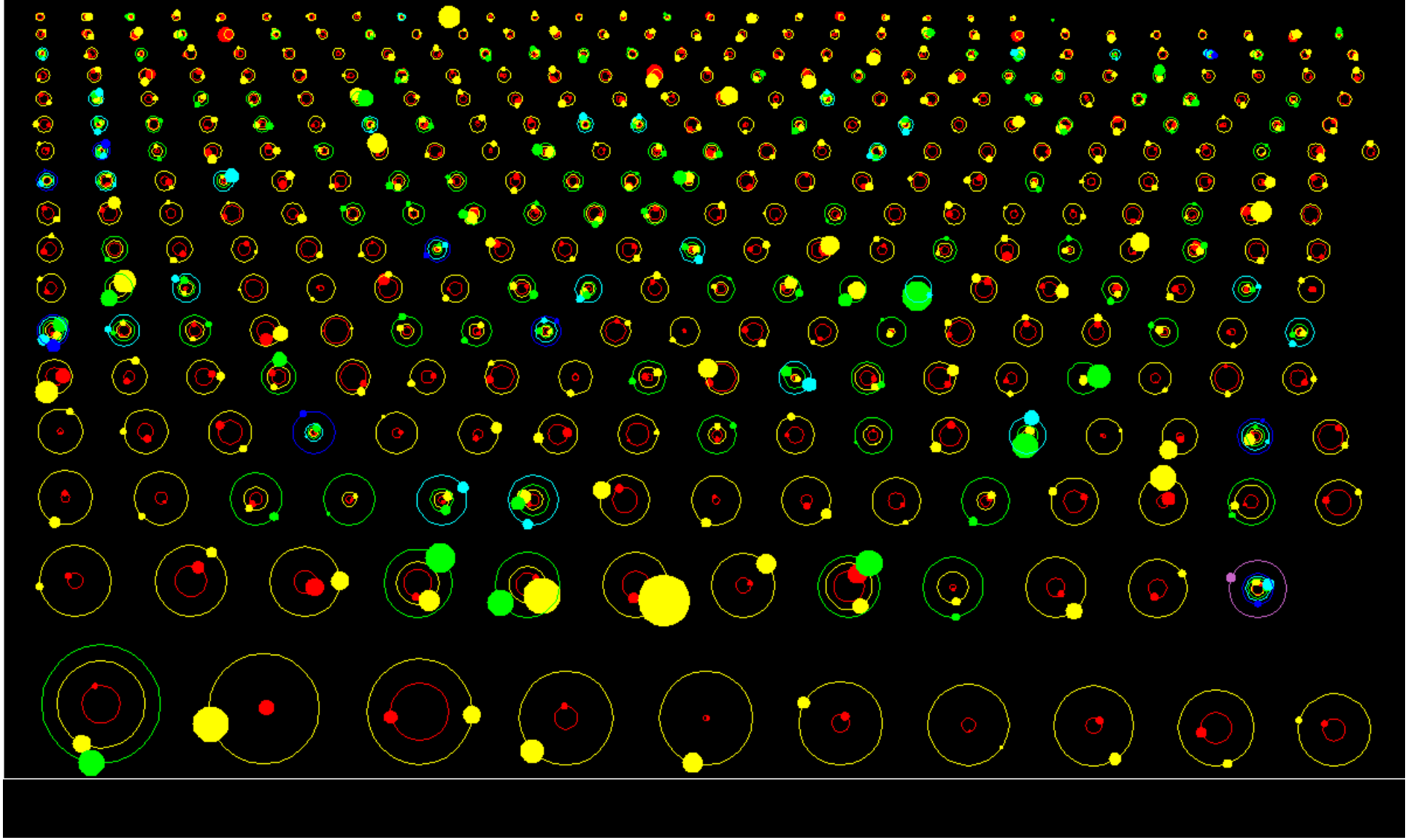


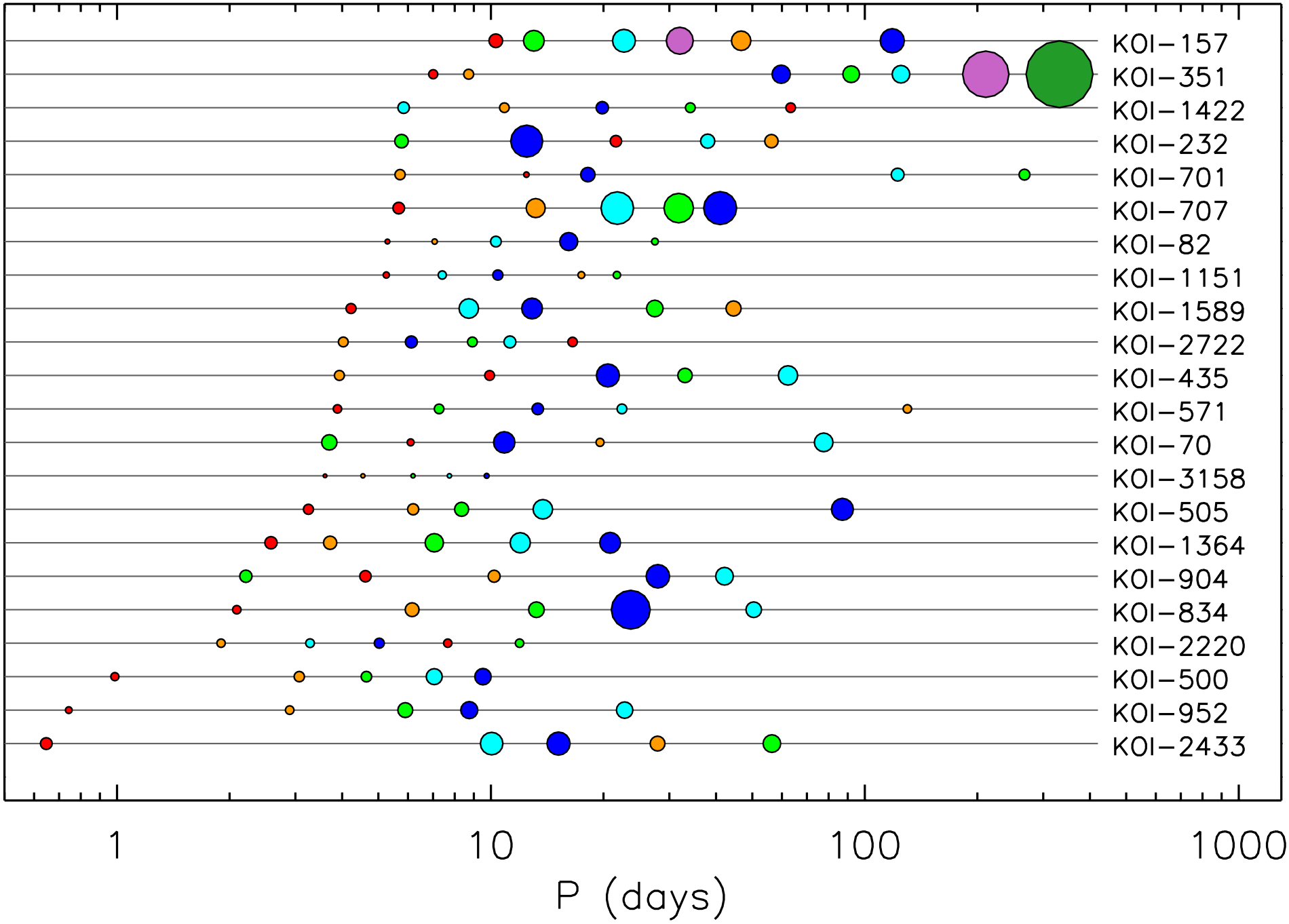
Systems with 3+ planet candidates

The Kepler Orrery II

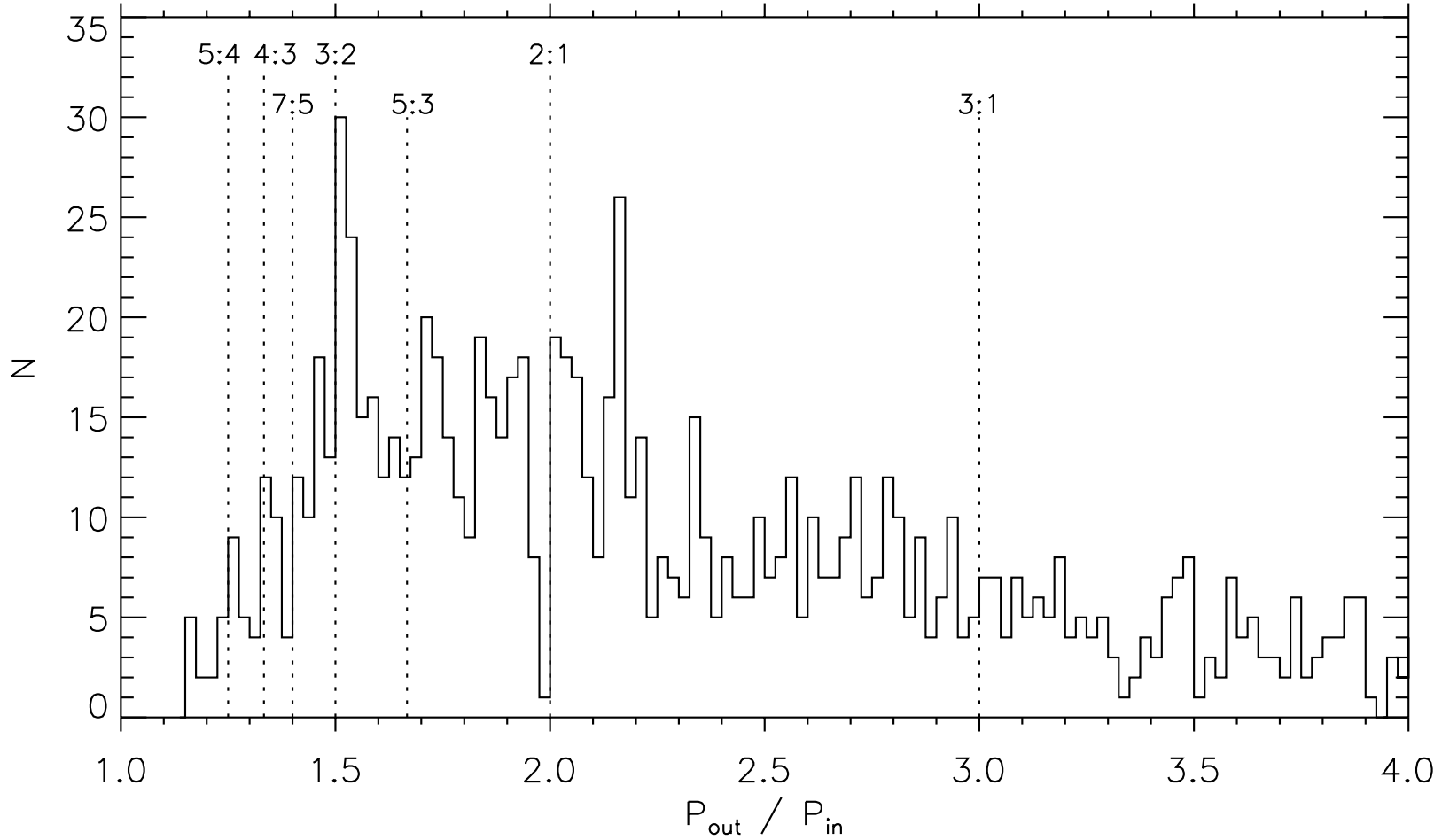
t[BJD] = 2454965

D. Fabrycky 2012




KOI−157
KOI−351
KOI−1422
KOI−232
KOI−701
KOI−707
KOI−82
KOI−1151
KOI−1589
KOI−2722
KOI−435
KOI−571
KOI−70
KOI−3158
KOI−505
KOI−1364
KOI−904
KOI−834
KOI−2220
KOI−500
KOI−952
KOI−2433
1
10
100
1000
P (days)

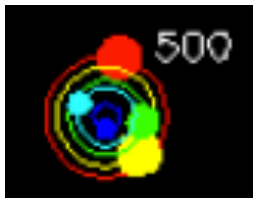
Kepler Planets in Multis: Period Ratios

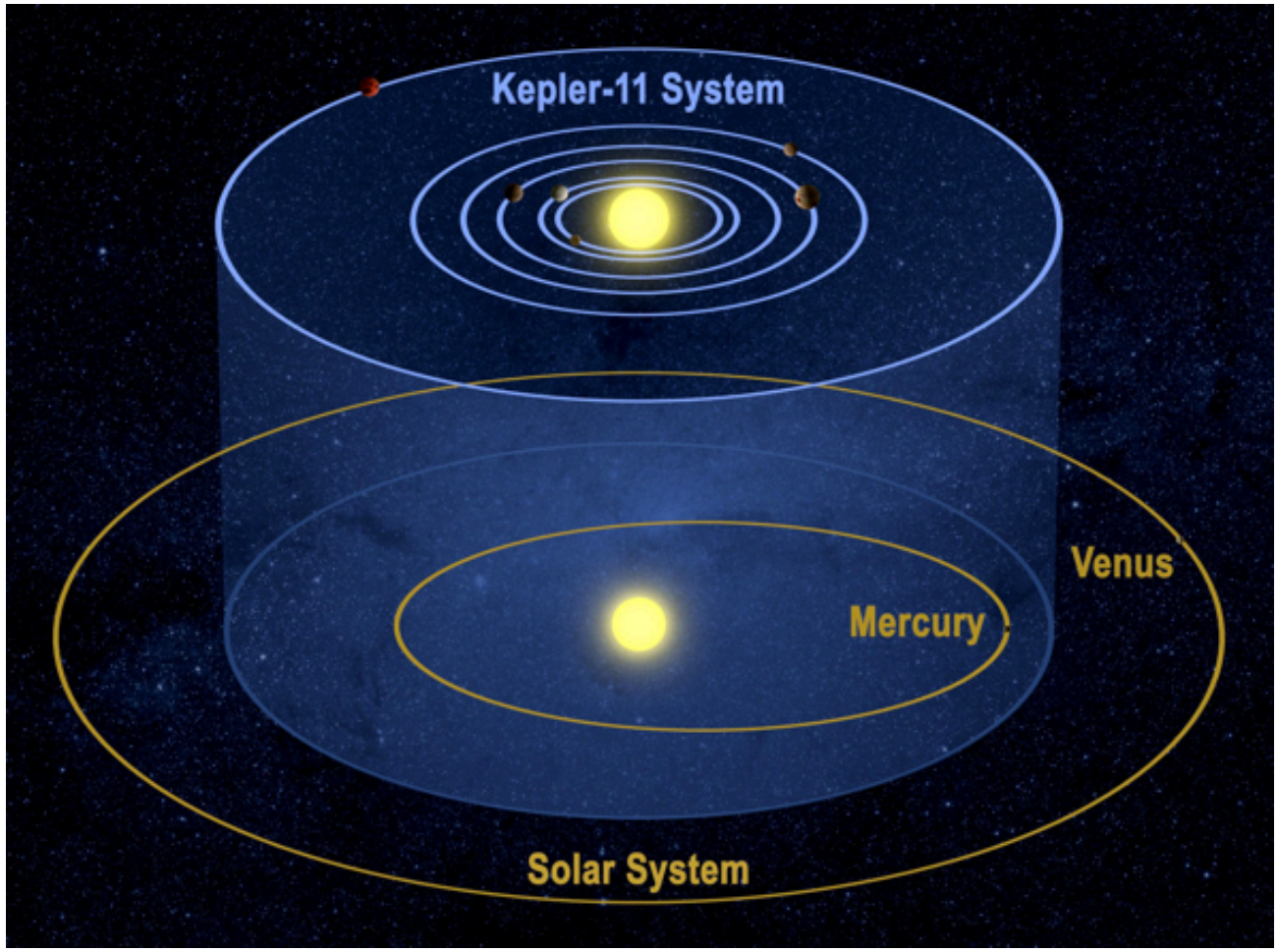


- Broad distribution – most pairs are non-resonant
- Factor-of-2 enhancements near 2:1 and 3:2 resonance
- Enhancement is on the *wide* side of the resonance

Kepler-80 = KOI-500

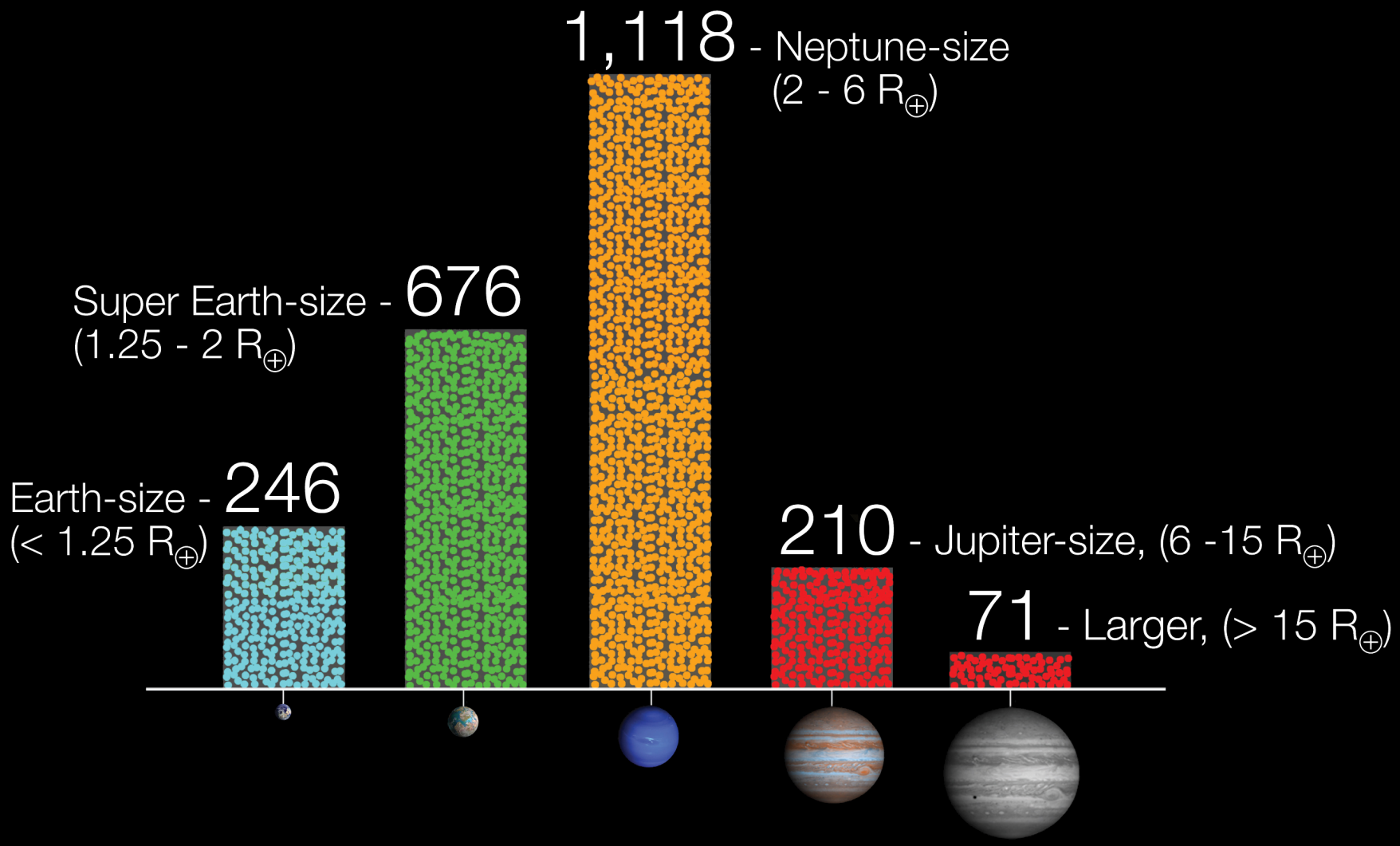
planet	P (days)	Mp(Mearth)
500.05	0.9867790	1.5
500.03	3.0721660	2.2
500.04	4.6453530	4.4
500.01	7.0534780	8.0
500.02	9.5216960	8.5

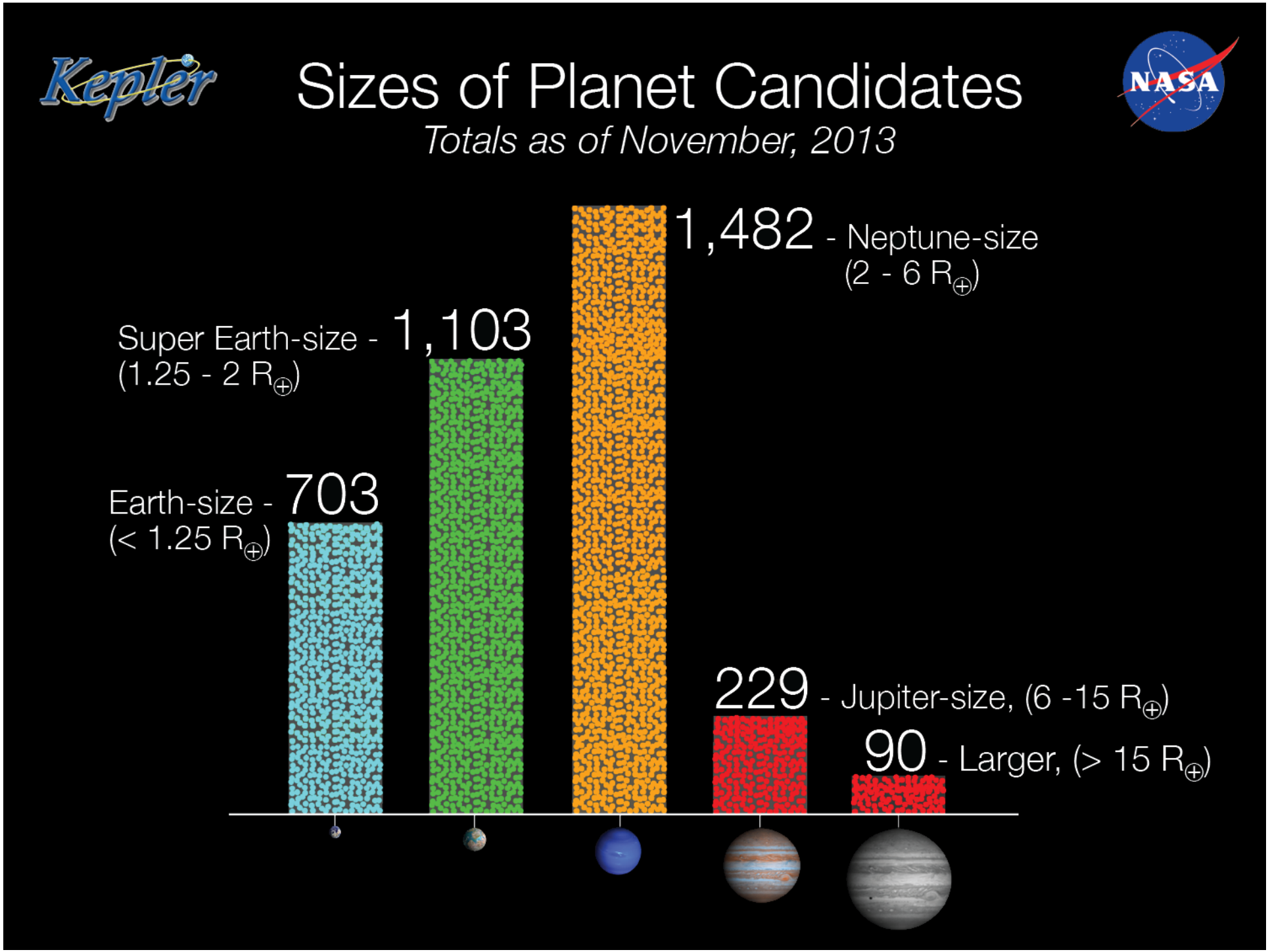


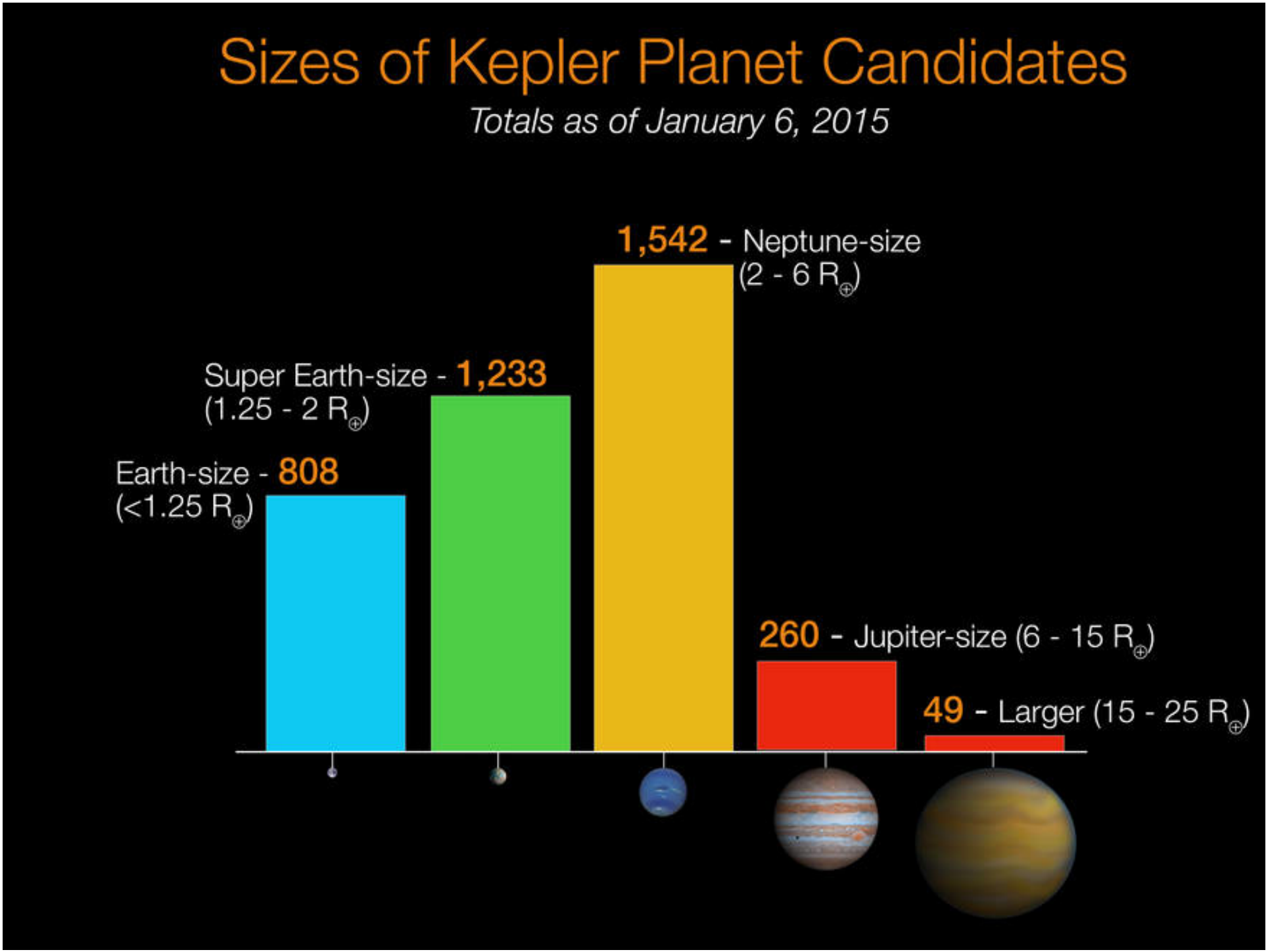


Sizes of Planet Candidates

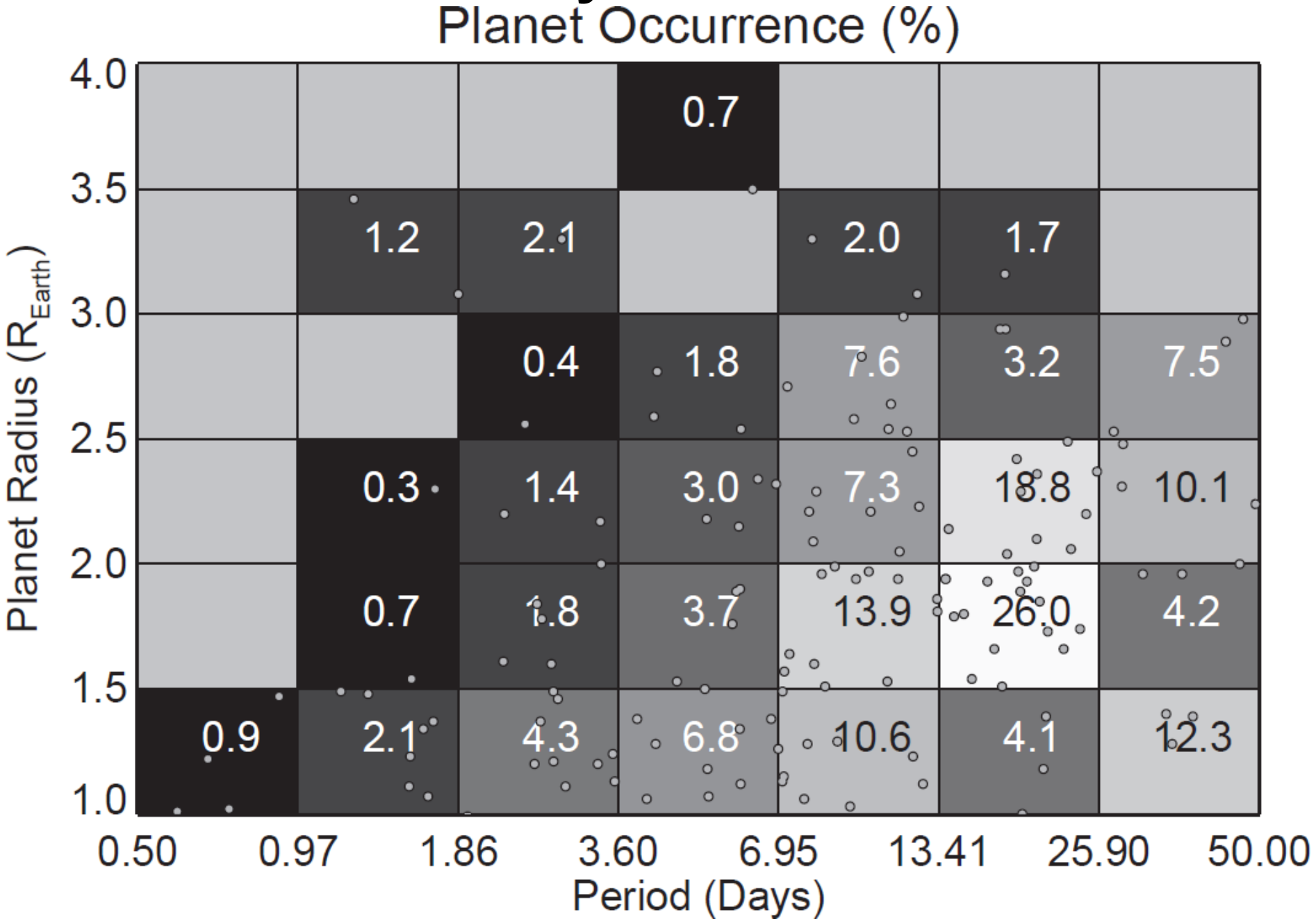
As of February 27, 2012




Kepler
Sizes of Planet Candidates
Totals as of November, 2013
NASA
1,482 - Neptune-size
(2 - 6 R⊕)
Super Earth-size - 1,103
(1.25 - 2 R⊕)
Earth-size - 703
(< 1.25 R⊕)
229 - Jupiter-size, (6 -15 R⊕)
90 - Larger, (> 15 R⊕)

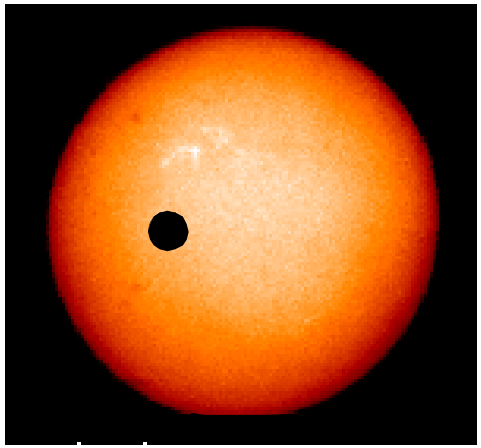

Sizes of Kepler Planet Candidates
Totals as of January 6, 2015
Earth-size - 808
(<1.25 R⊕)
Super Earth-size - 1,233
(1.25 - 2 R⊕)
1,542 - Neptune-size
(2 - 6 R⊕)
260 - Jupiter-size (6 - 15 R⊕)
49 - Larger (15 - 25 R⊕)

M Dwarfs Have Many Planets (Dressing & Charbonneau 2015)

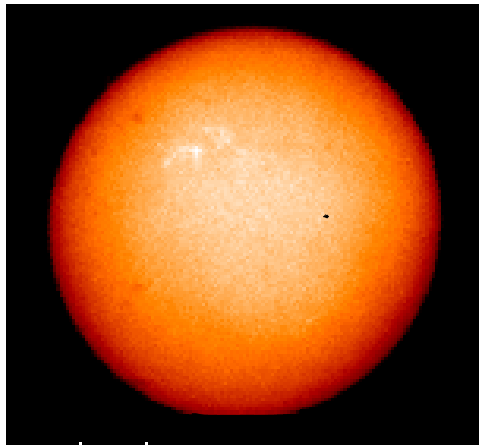


DETECTING EARTH-SIZE PLANETS

- The relative change in brightness ($\Delta L / L$) is equal to the relative areas (A_{planet} / A_{star})



Jupiter:
1% area of the Sun (1/100)

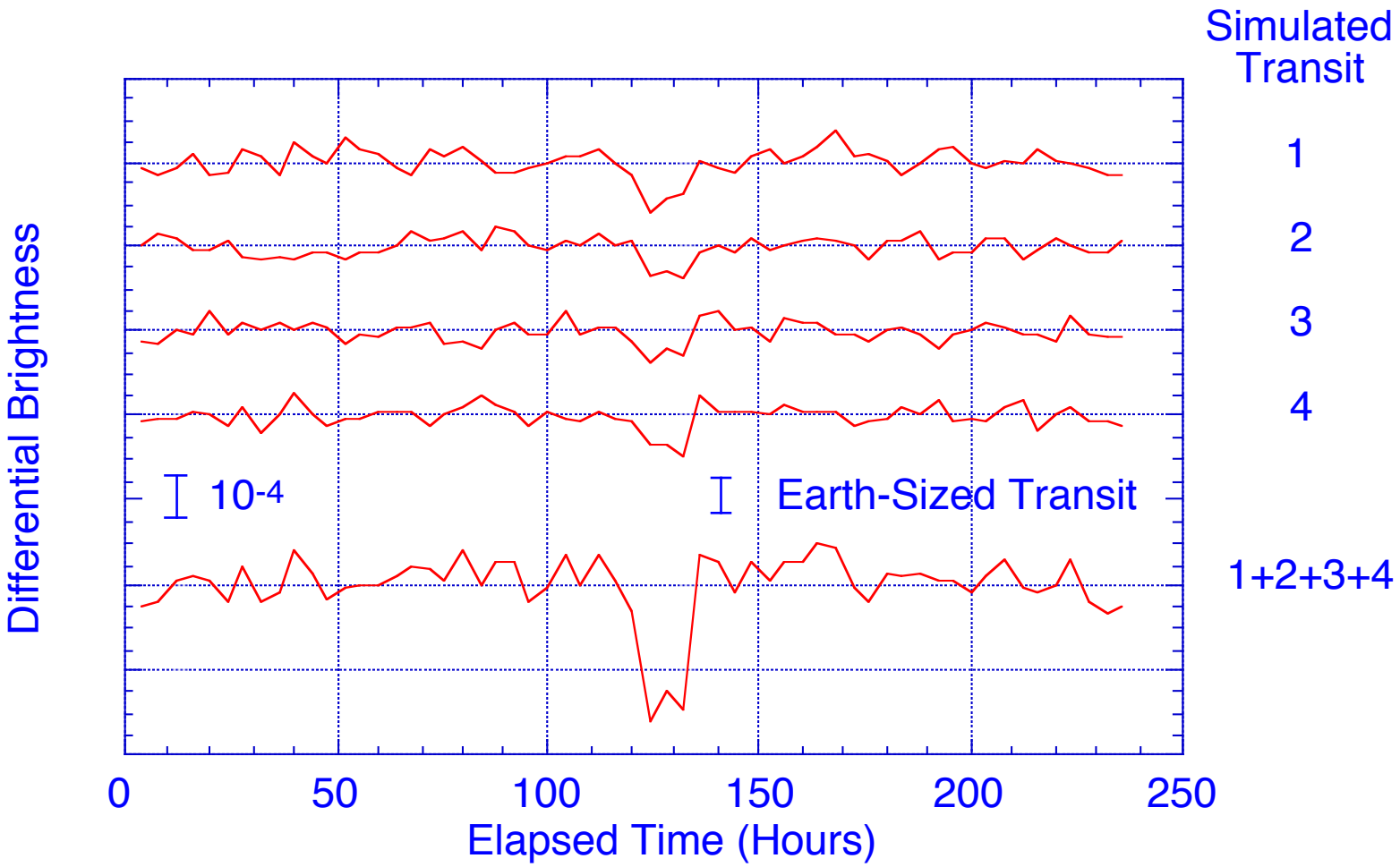


Earth or Venus
0.01% area of the Sun (1/10,000)

- To measure 0.01% must get above the Earth's atmosphere
- Method is robust but you must be patient:

  Require at least 3 transits preferably 4 with same brightness change, duration (how long the star is dimmer) and period (time between dimmings)

SIMULATION OF FOUR EARTH-SIZED TRANSITS

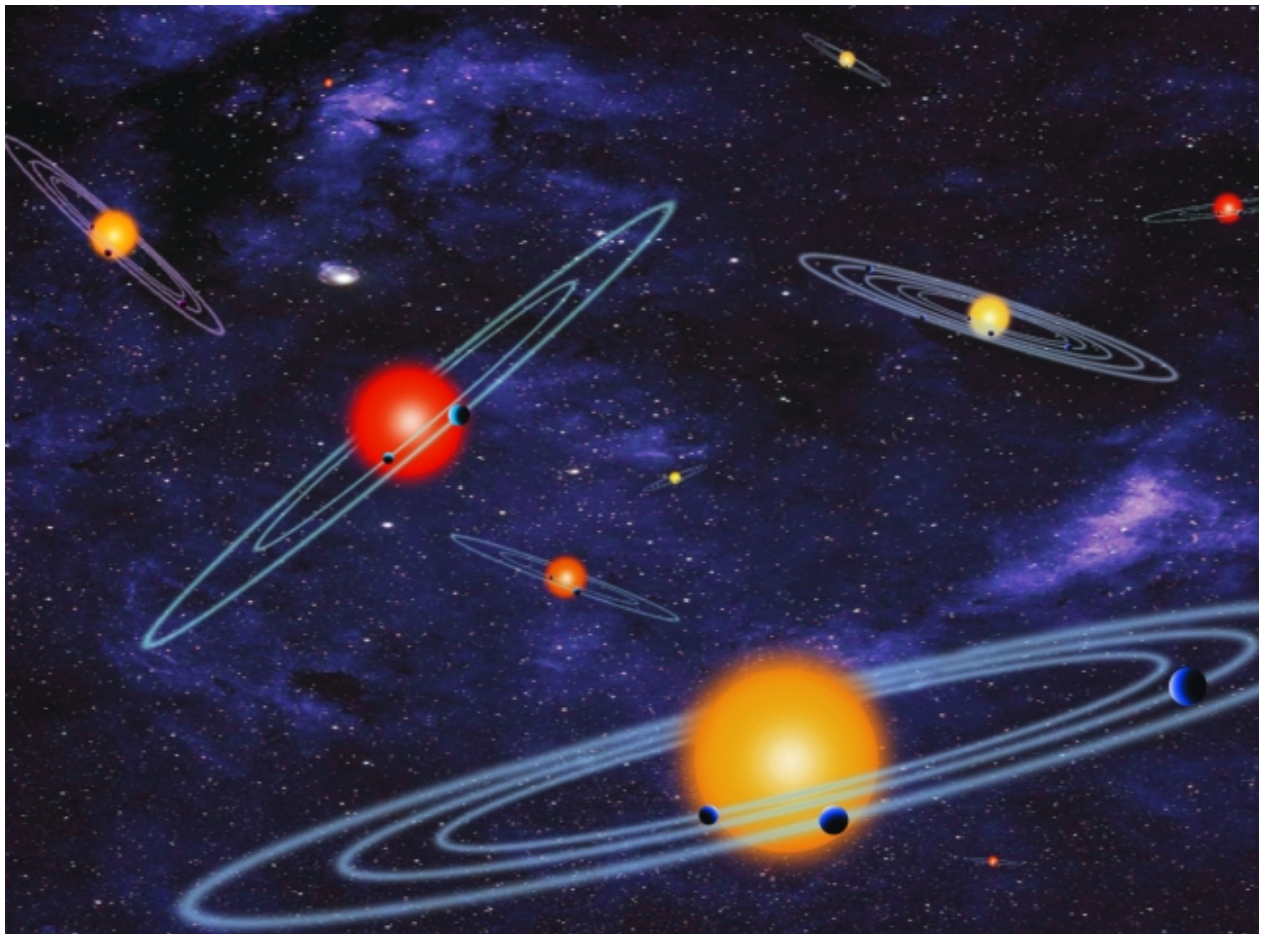


Kepler's Key Findings

Planets, especially "small" ones, are common

Planetary systems are flat, like the Solar System

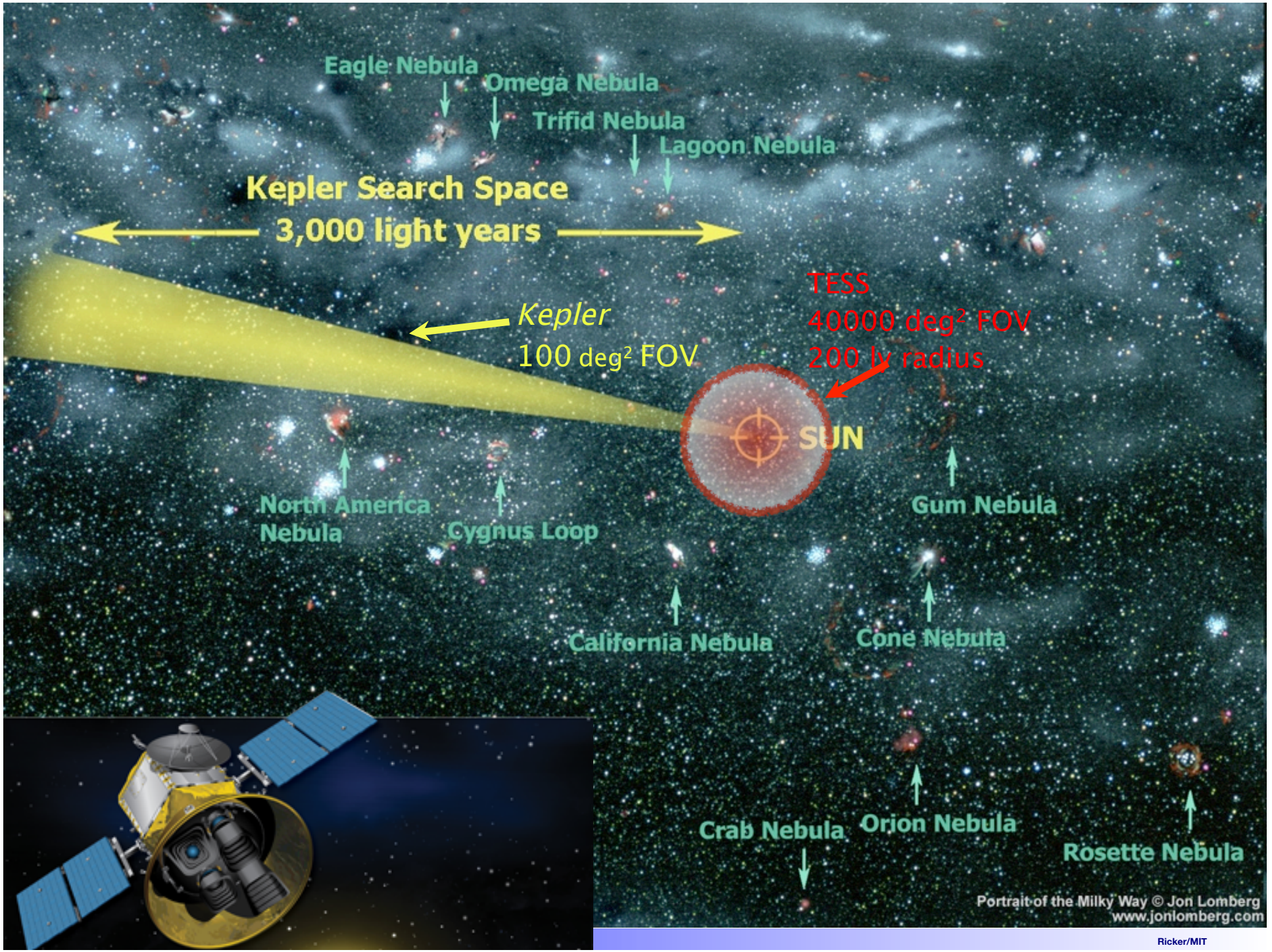
Planets & planetary systems are extremely diverse



Transiting Exoplanet Survey Satellite (TESS)

NASA's Next Exoplanet Mission

- George Ricker, MIT, Principal Investigator
- Launch on Falcon-9 scheduled for 2017


Eagle Nebula
Omega Nebula
Trifid Nebula
Lagoon Nebula
Kepler Search Space
3,000 light years
Kepler
100 deg² FOV
TESS
40000 deg² FOV
200 ly radius
SUN
North America Nebula
Cygnus Loop
Gum Nebula
California Nebula
Cone Nebula
Crab Nebula
Orion Nebula
Rosette Nebula
Portrait of the Milky Way © Jon Lomberg
www.jonlomberg.com

Conclusions

688 Kepler target stars have 2 or more planet candidates (1706 candidates)

Multi-planet systems tell us a great deal about the architecture of planetary systems

Kepler-11 is supercalifragilisticexpialidocious

Movies available at:

http://kepler.nasa.gov/multimedia/animations/