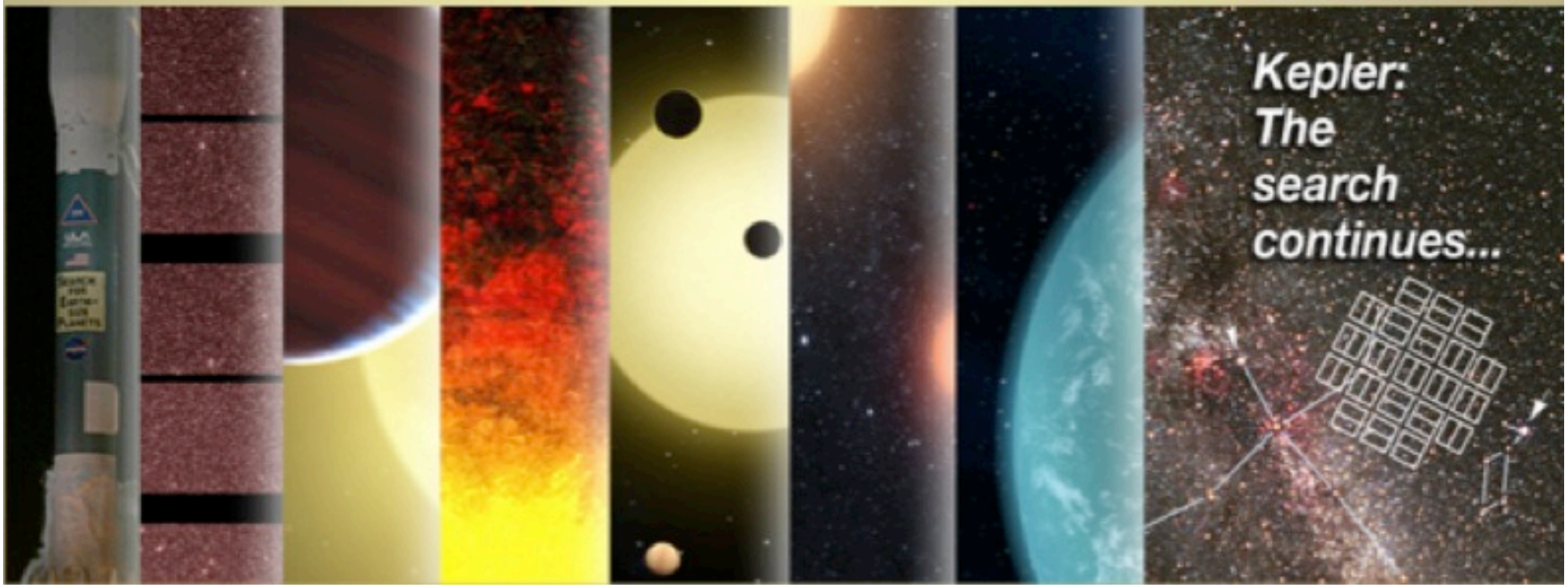
Overview

Kepler
A Search for Earth-size Planets

- The Kepler Mission
- Science Results
- Kepler's Impact on Exoplanets
- TESS – Searching for Earth's Closest Cousins



Critical Questions

Kepler
A Search for Earth-size Planets

- Are terrestrial planets common or rare?
- What are their sizes & orbital distances?
- How often are they in the habitable zone?
- What is their dependence on stellar properties?

Bottom Line: Are We Alone?

Key Technical Challenges

Kepler
A Search for Earth-size Planets

1. Terrestrial planets are really small ~100 ppm deep signatures

⇒ 20 ppm photometric precision

2. Transits occur on timescales of one hour to ~ ½ day

⇒ Sample at ½ hour cadence

3. Transiting planets are rare (geometric probability of alignment is ~0.5% for Earth analogs)

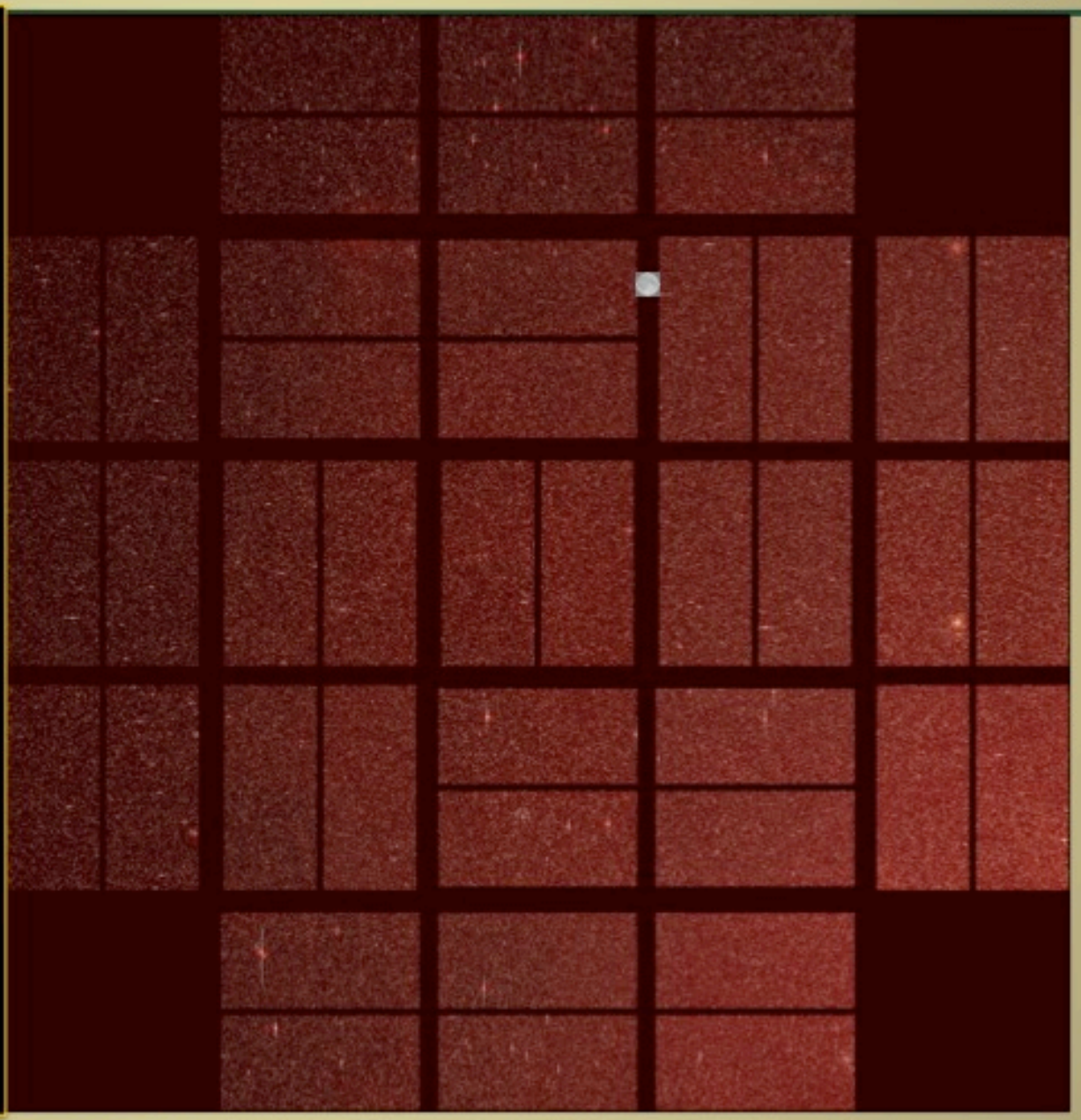
⇒ Observe ~100,000 stars

4. We don't know when a transit will occur

⇒ Stare at one FOV for 3.5-10 years and don't blink

First Light Image

Kepler
A Search for Earth-size Planets



Launched March 7 2009

Key Science Results

First Multiple Transit Planet System: Kepler-9b

Kepler
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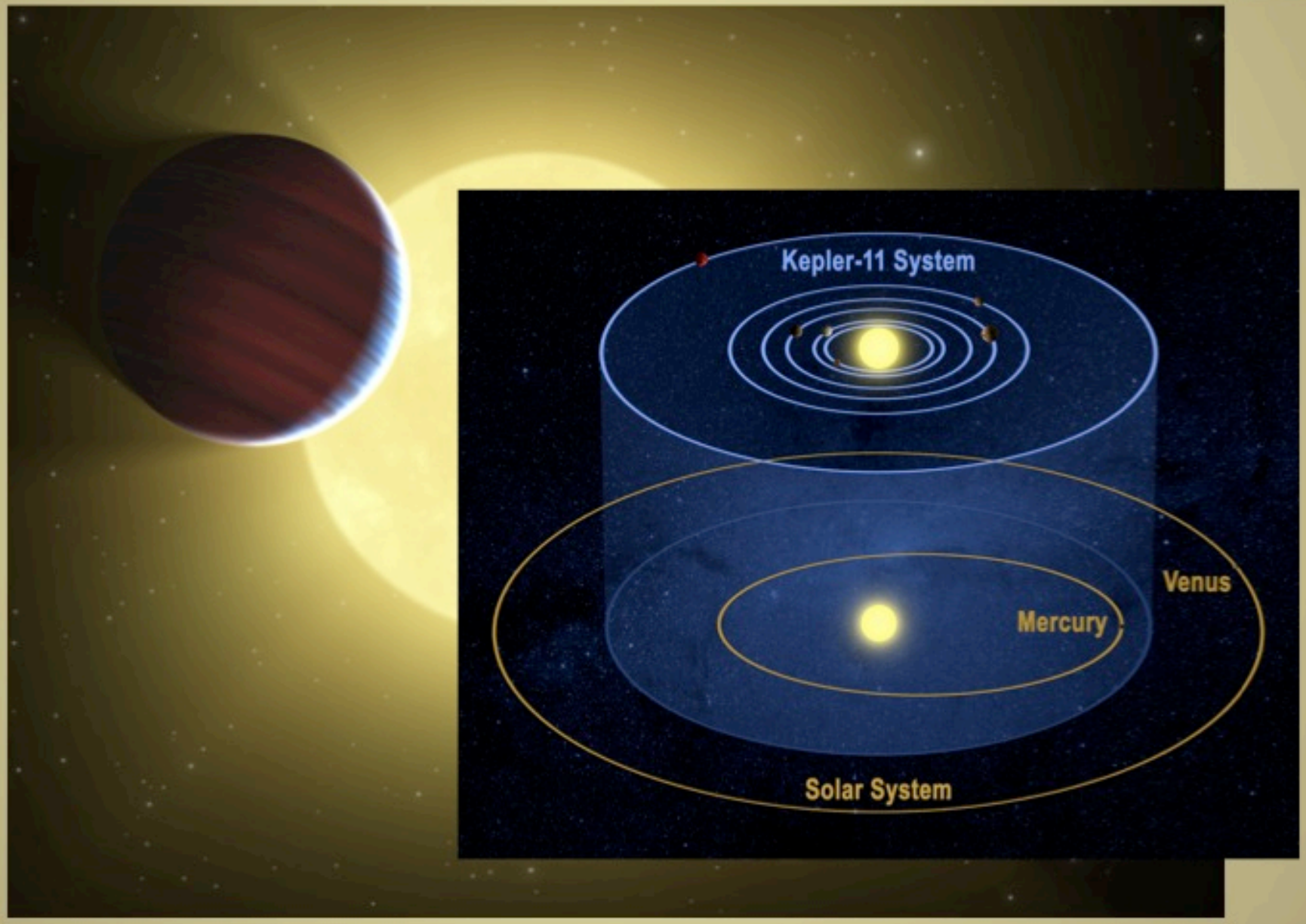

P1 = 19.24 days, P2 = 38.91 days

Transit-Timing Variations:

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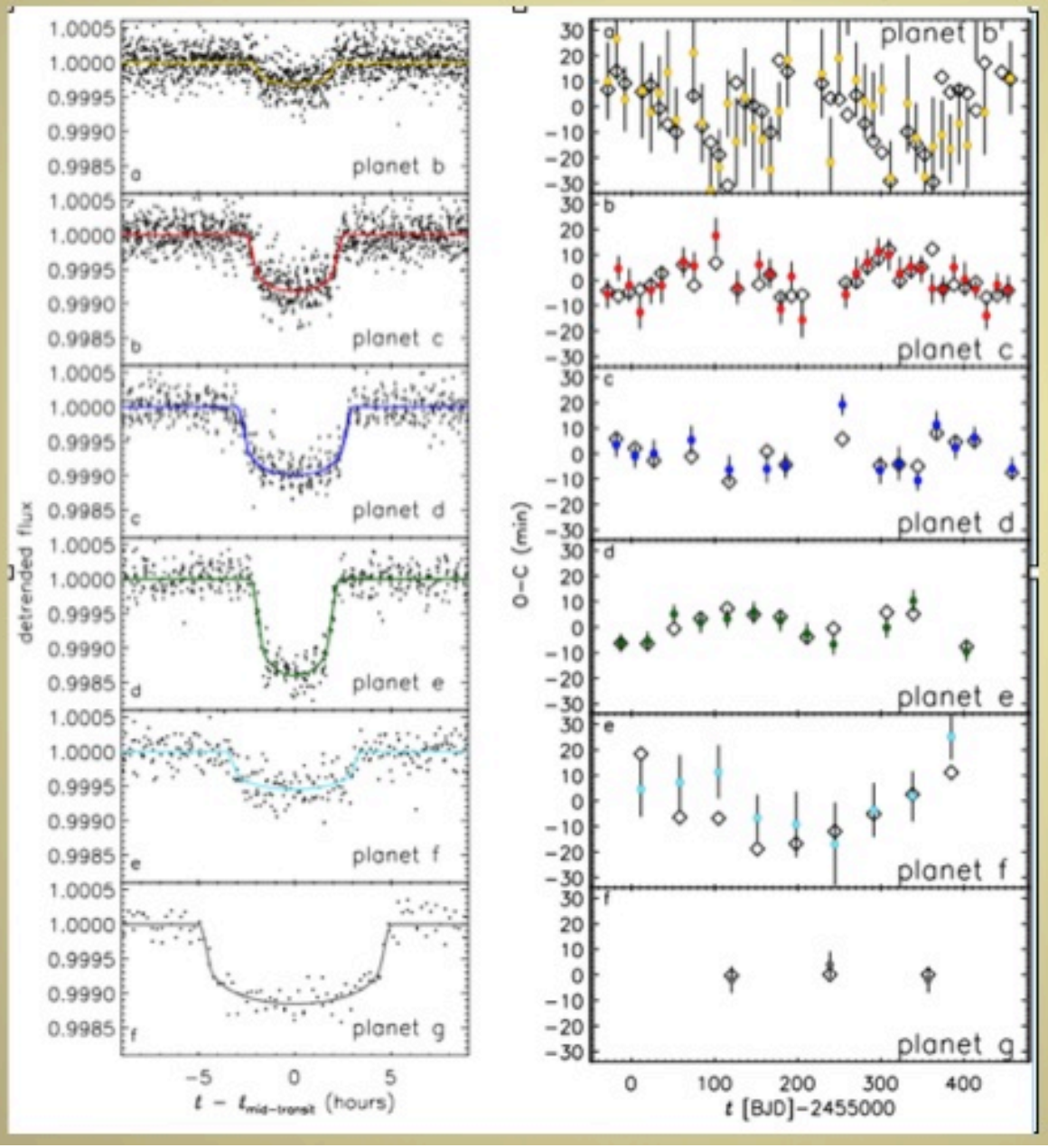
A Search for Earth-size Planets

Transits Time: Lead or Lag

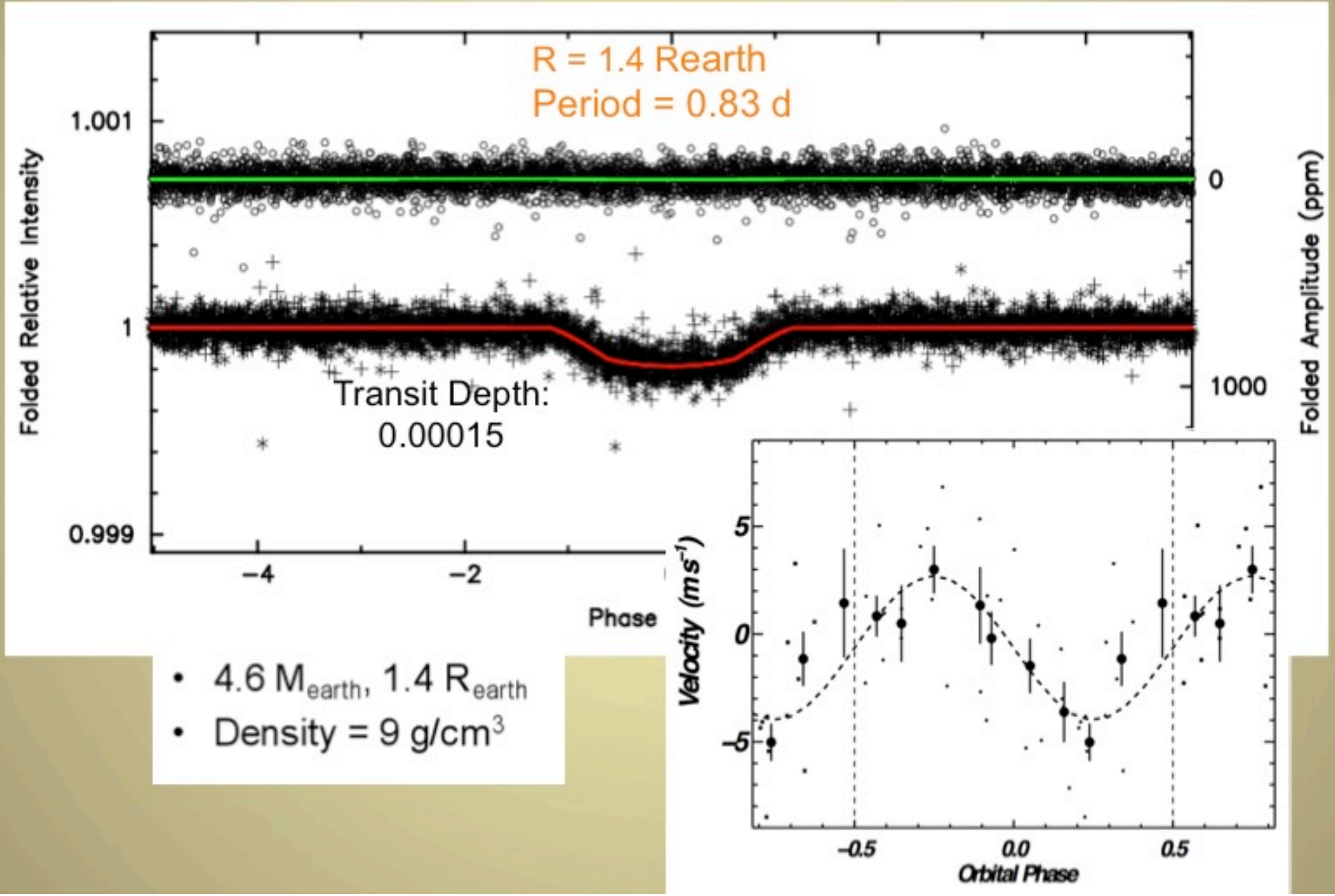


Transit-Time Variations due to planet-planet Interactions:

Planet Masses

Kepler's First Rocky Planet: Kepler-10b

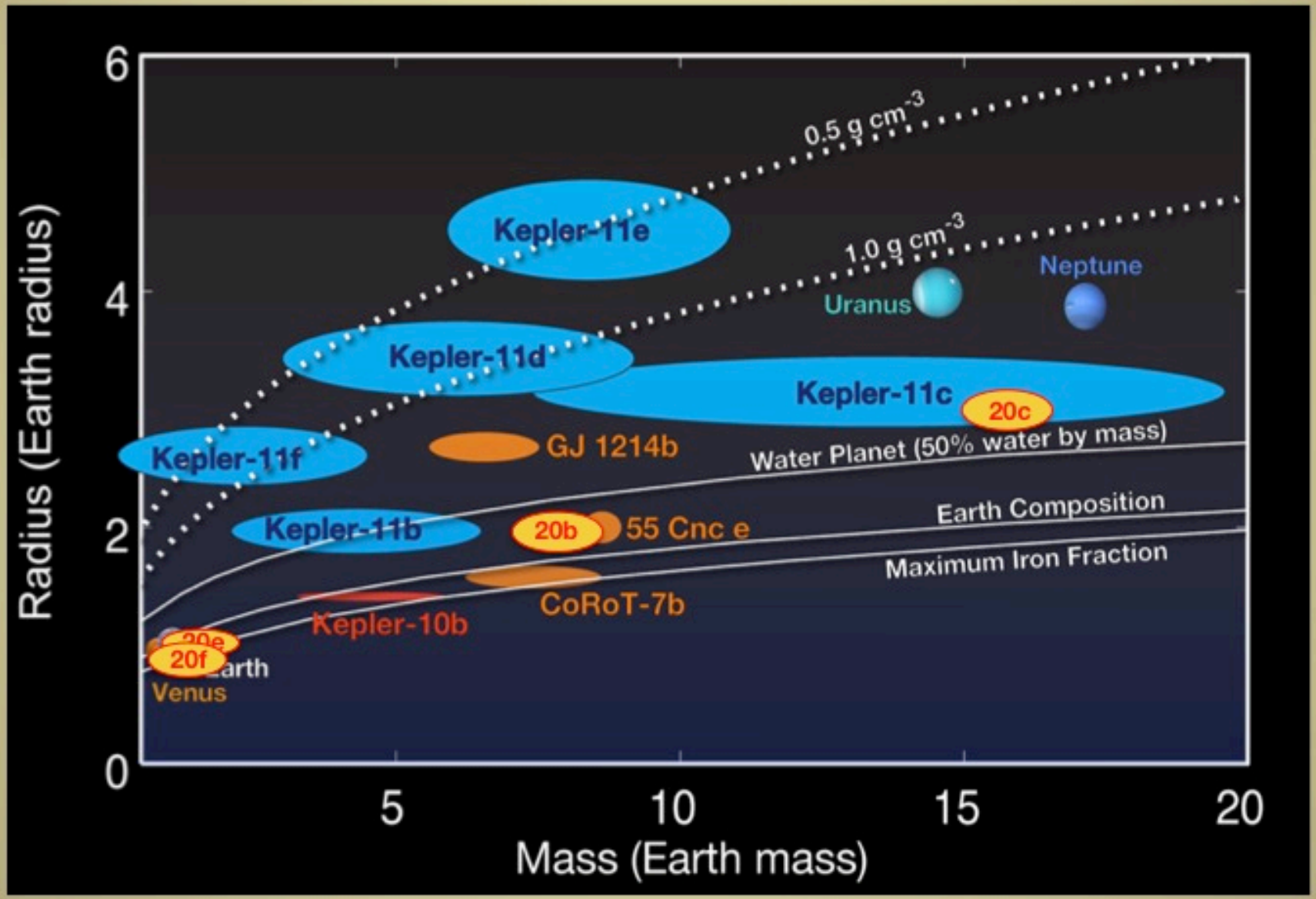
Kepler
A Search for Earth-size Planets



- 4.6 M_{earth}, 1.4 R_{earth}
- Density = 9 g/cm^3

Composition of Transiting Planets

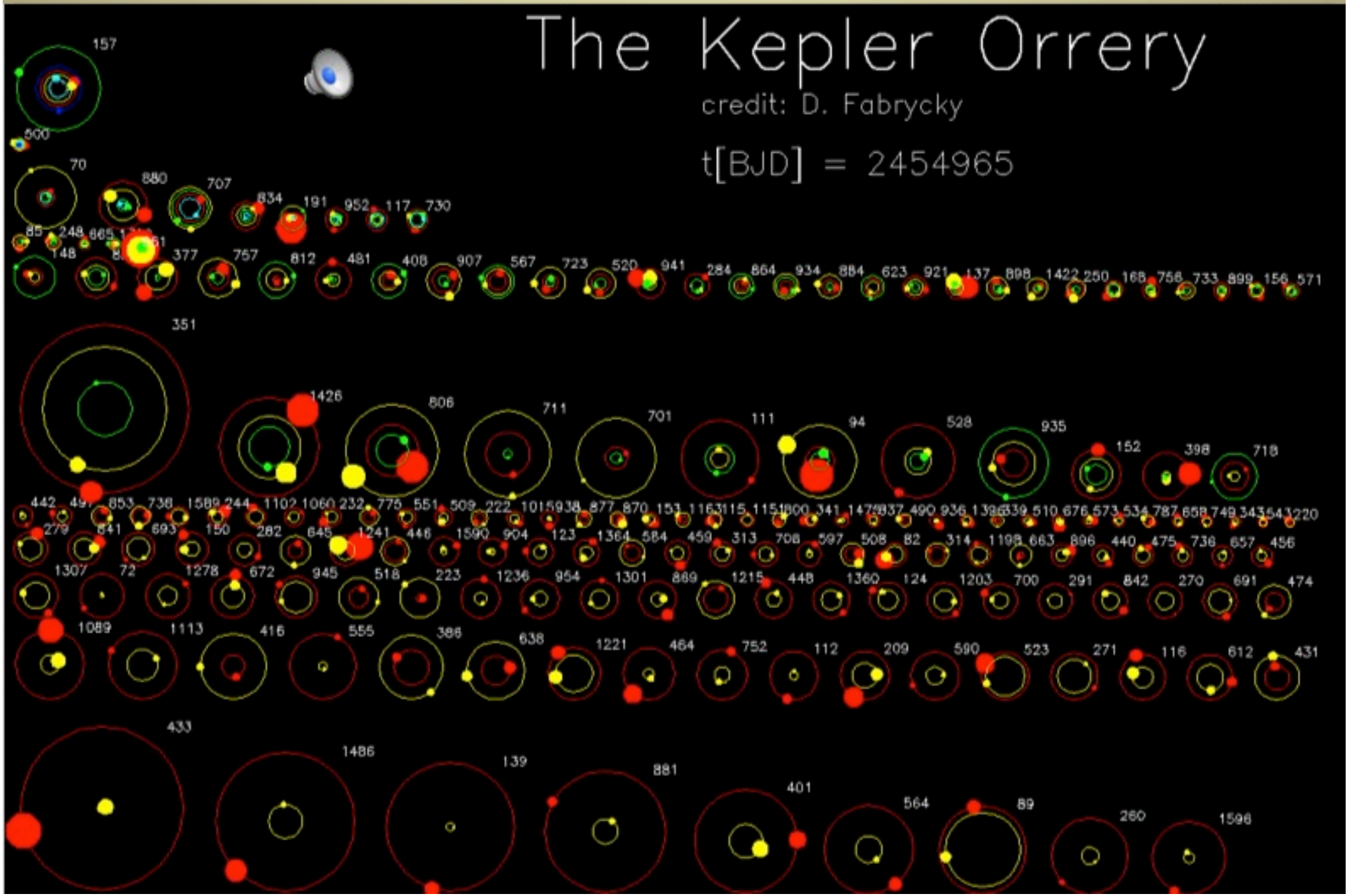
Kepler
A Search for Earth-size Planets



Hordes of Multiple Planet Systems

~500 such systems: 1 in 4 stars

Kepler
A Search for Earth-size Planets



A Possibly Disintegrating Planet?

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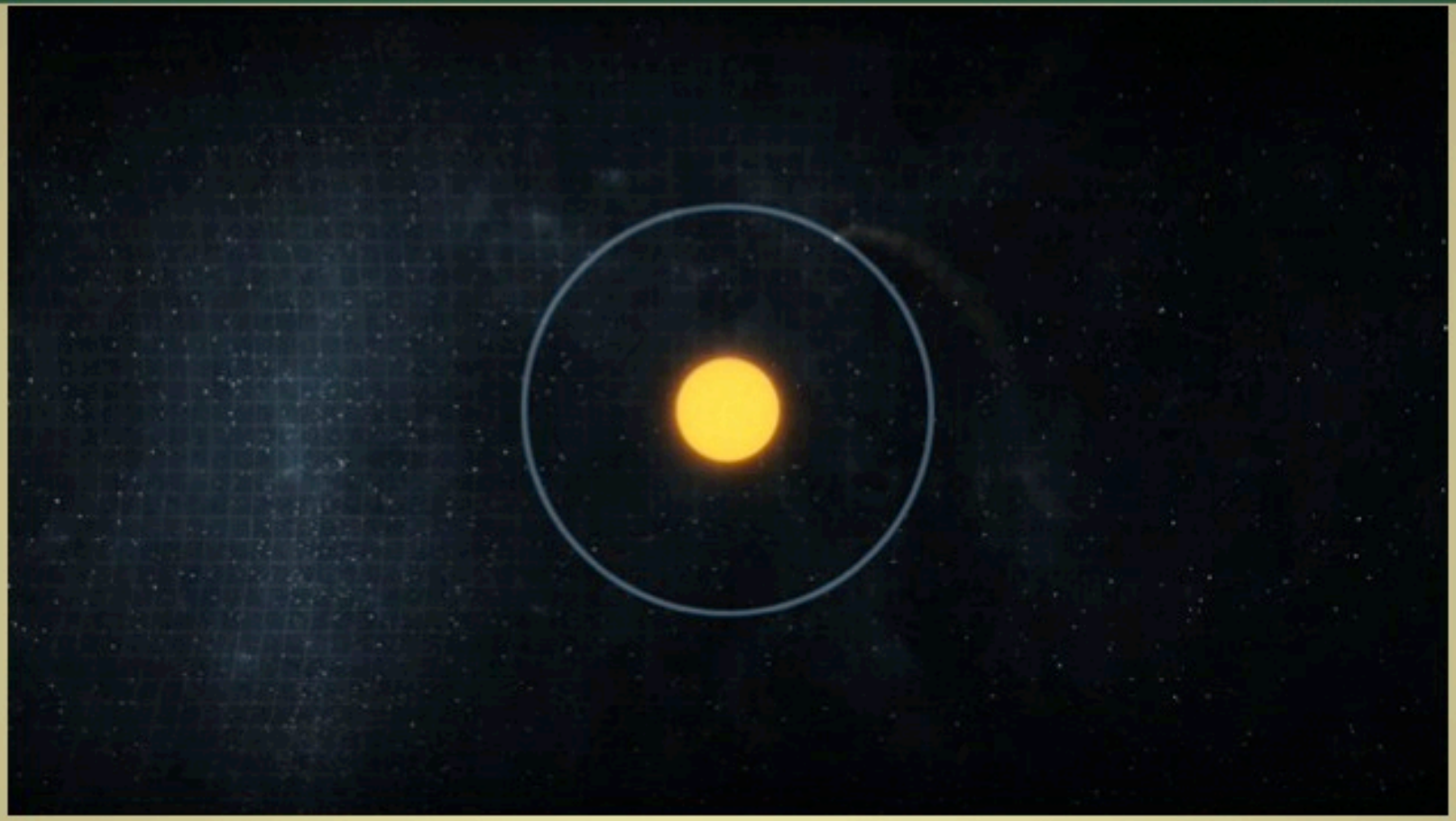
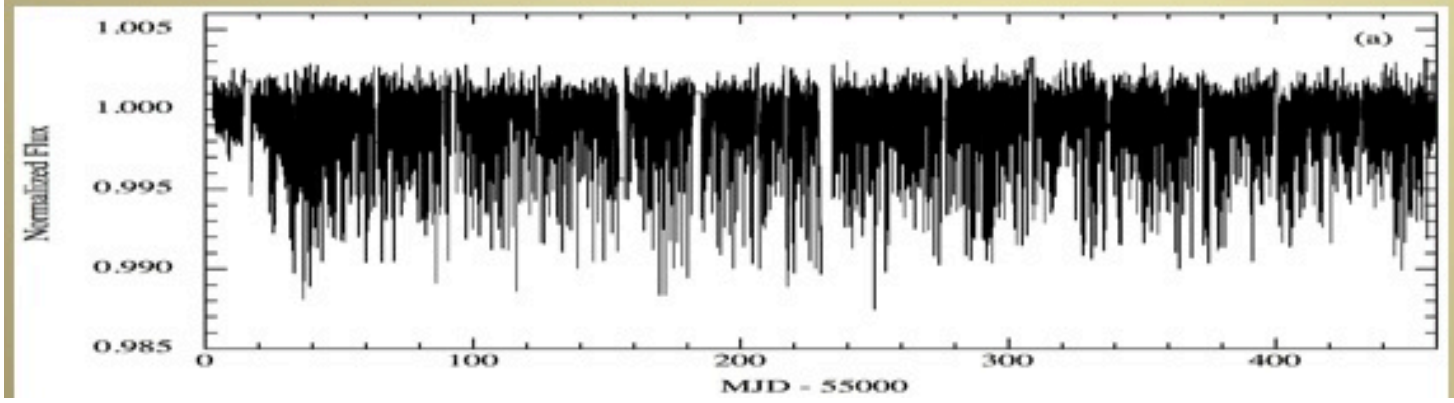
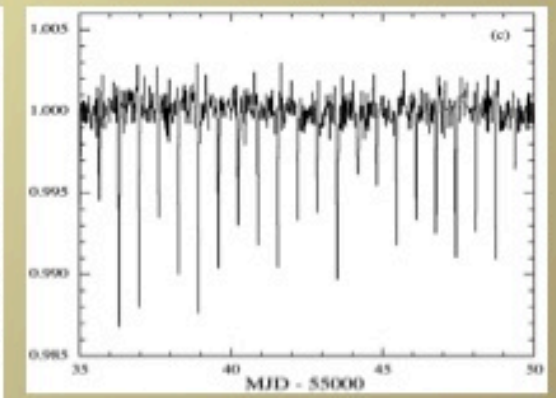
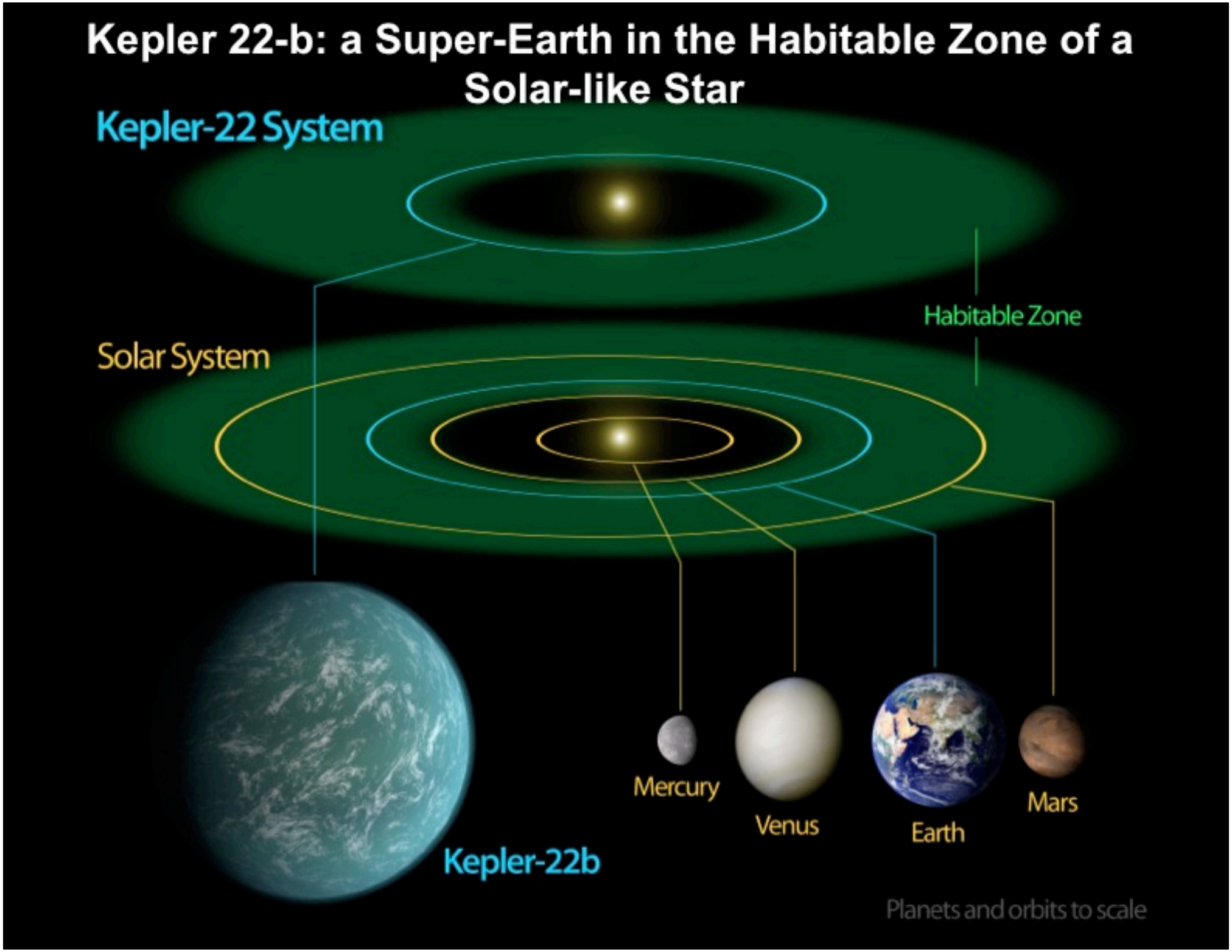
Rappaport et al. 2012

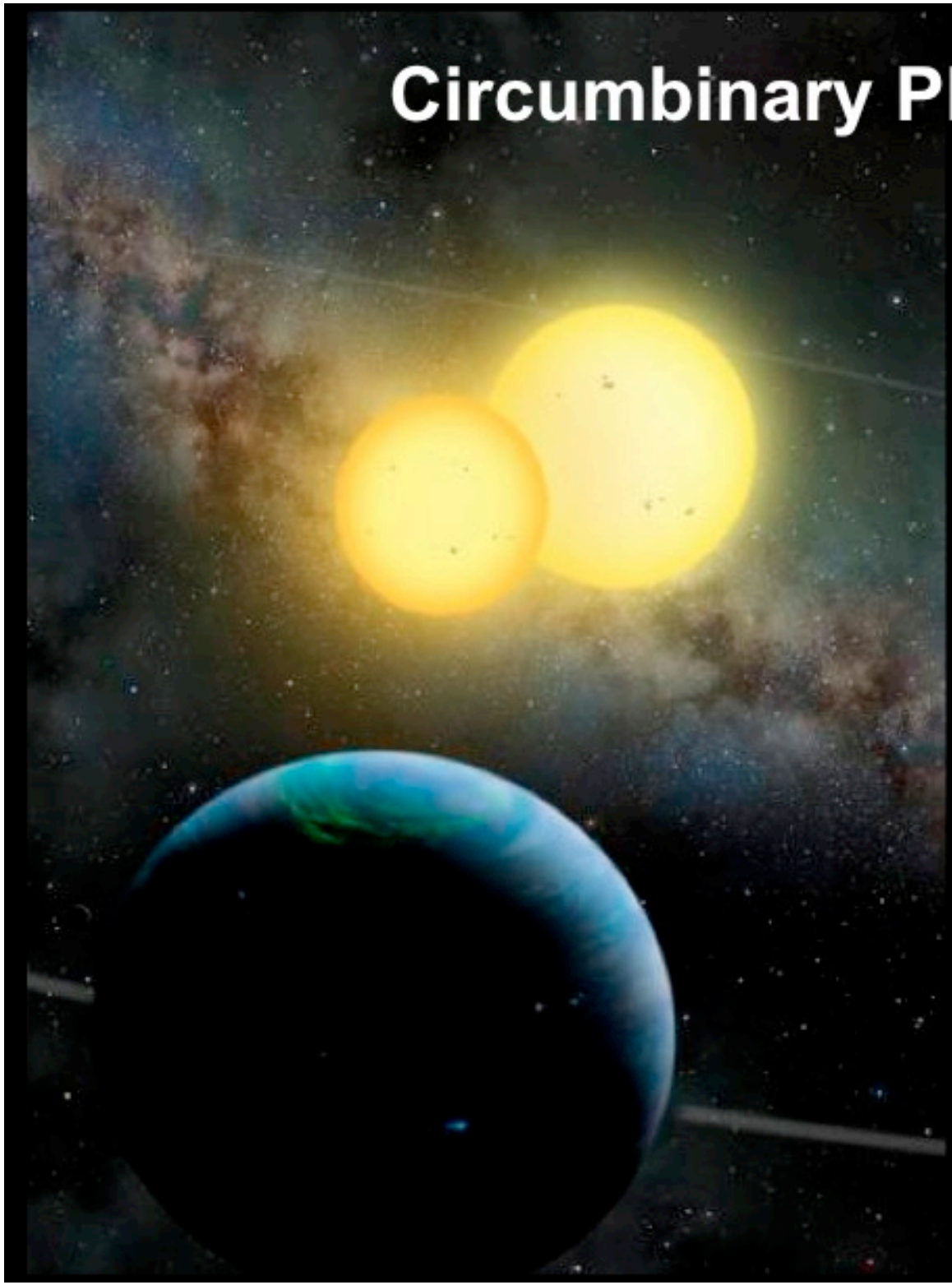







Kepler 22-b: a Super-Earth in the Habitable Zone of a Solar-like Star
Kepler-22 System
Habitable Zone
Solar System
Mercury
Venus
Earth
Mars
Kepler-22b
Planets and orbits to scale

Circumbinary Planets

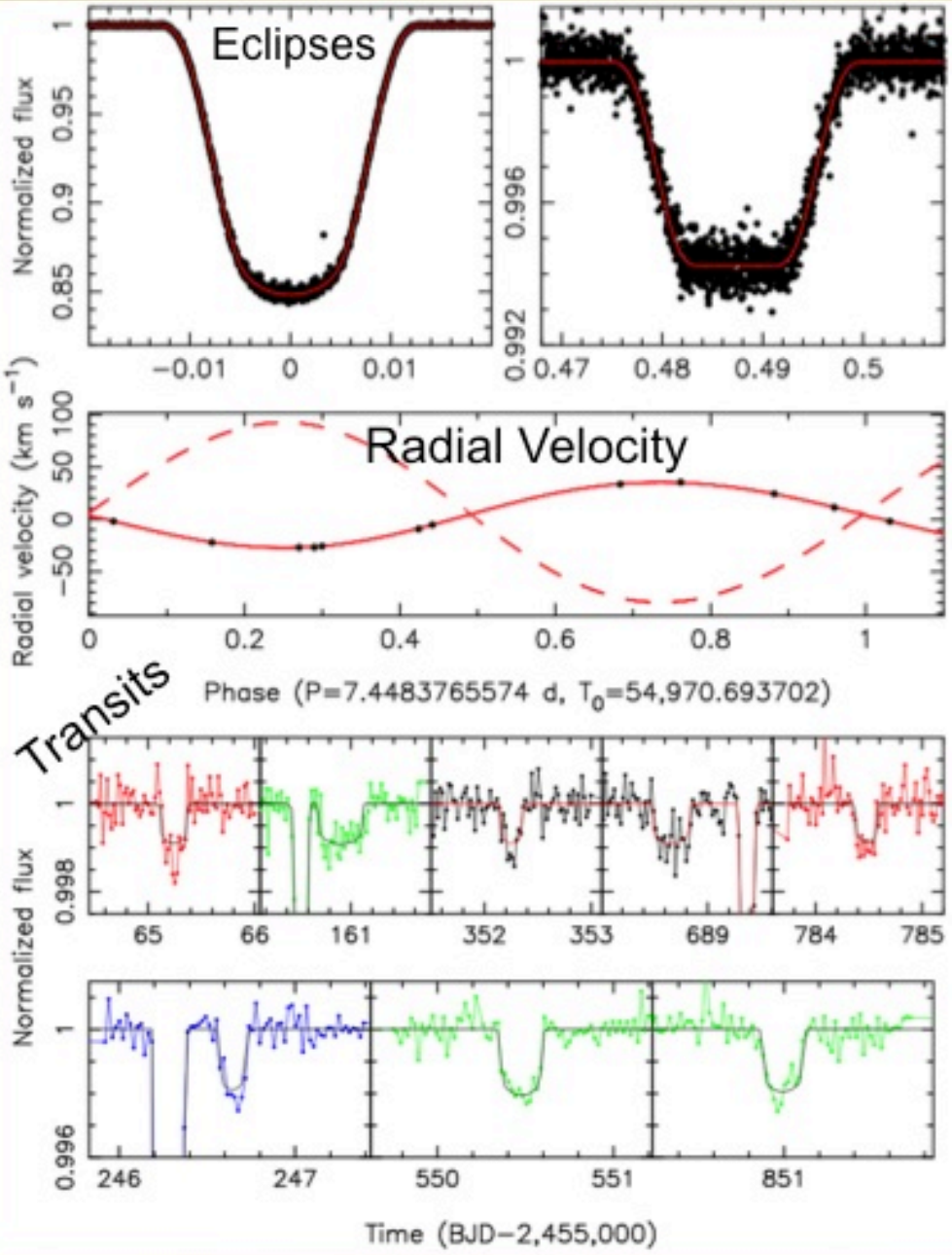


Artist view of Kepler 35.
With the discovery of the Kepler 16, 34, 35, 38 and 47 The Kepler mission has opened the new field of circumbinary planetary astronomy.

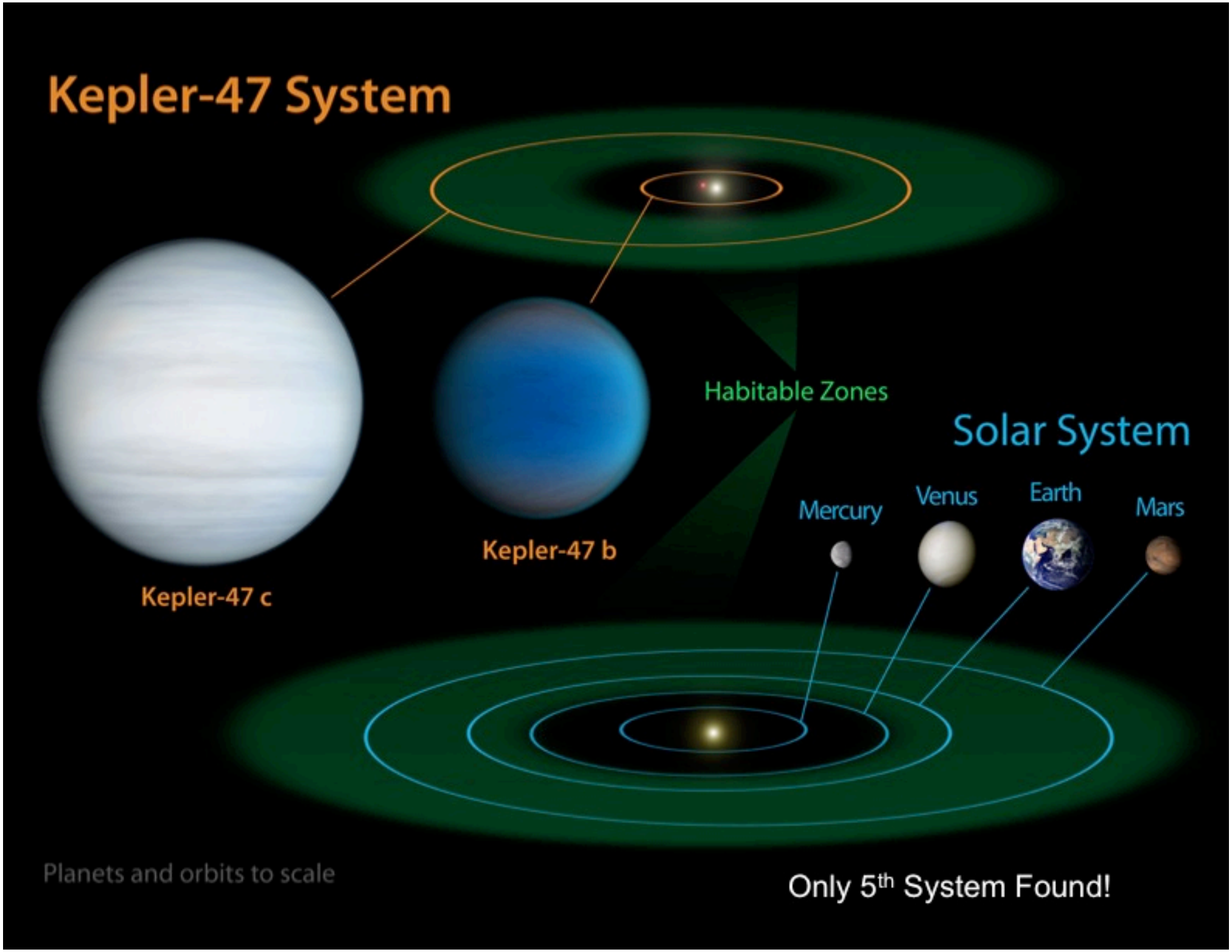
The planets orbiting in these Binary systems will experience Large incident flux changes, making their weather present seasonal changes many times during each planets year.

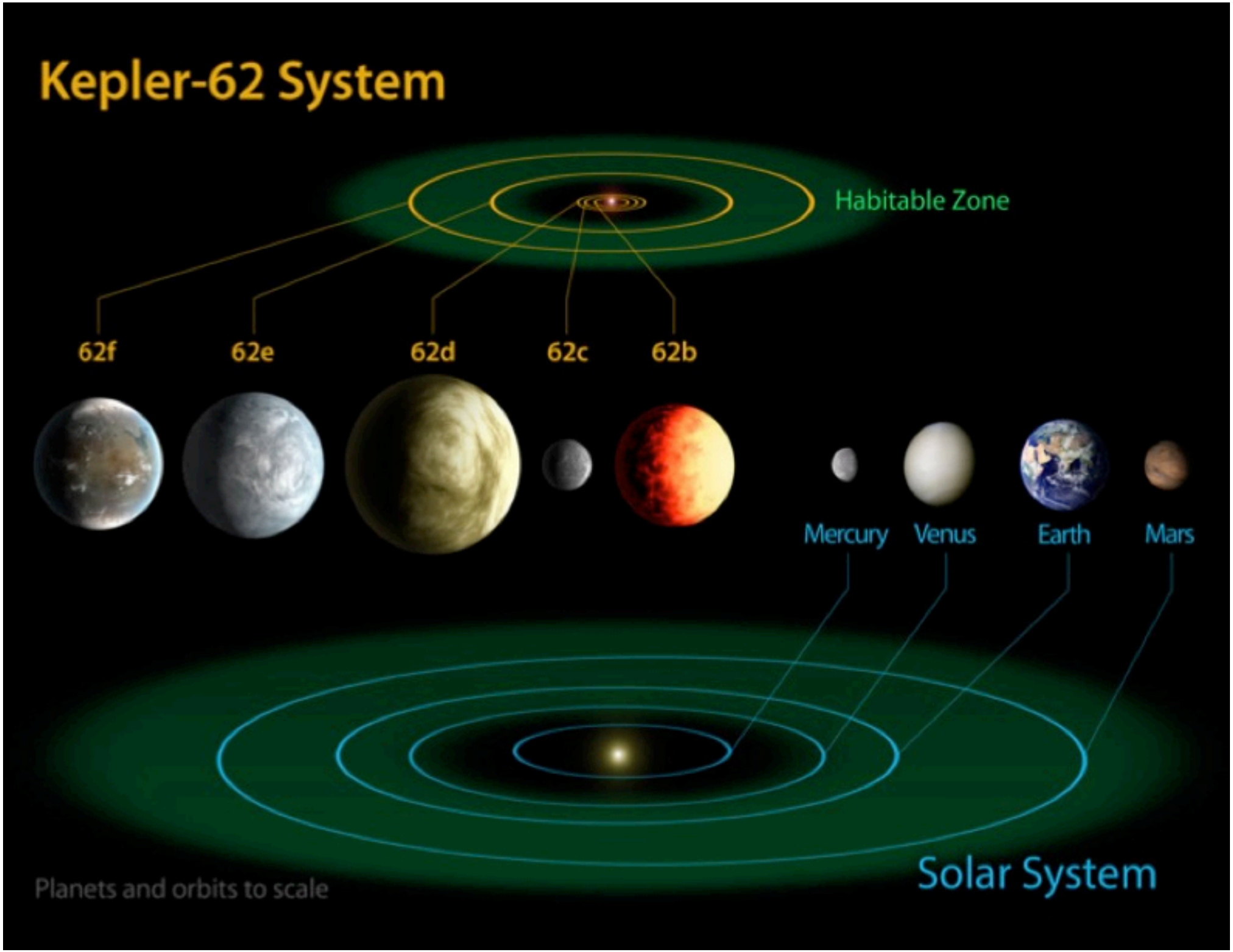
Kepler-47

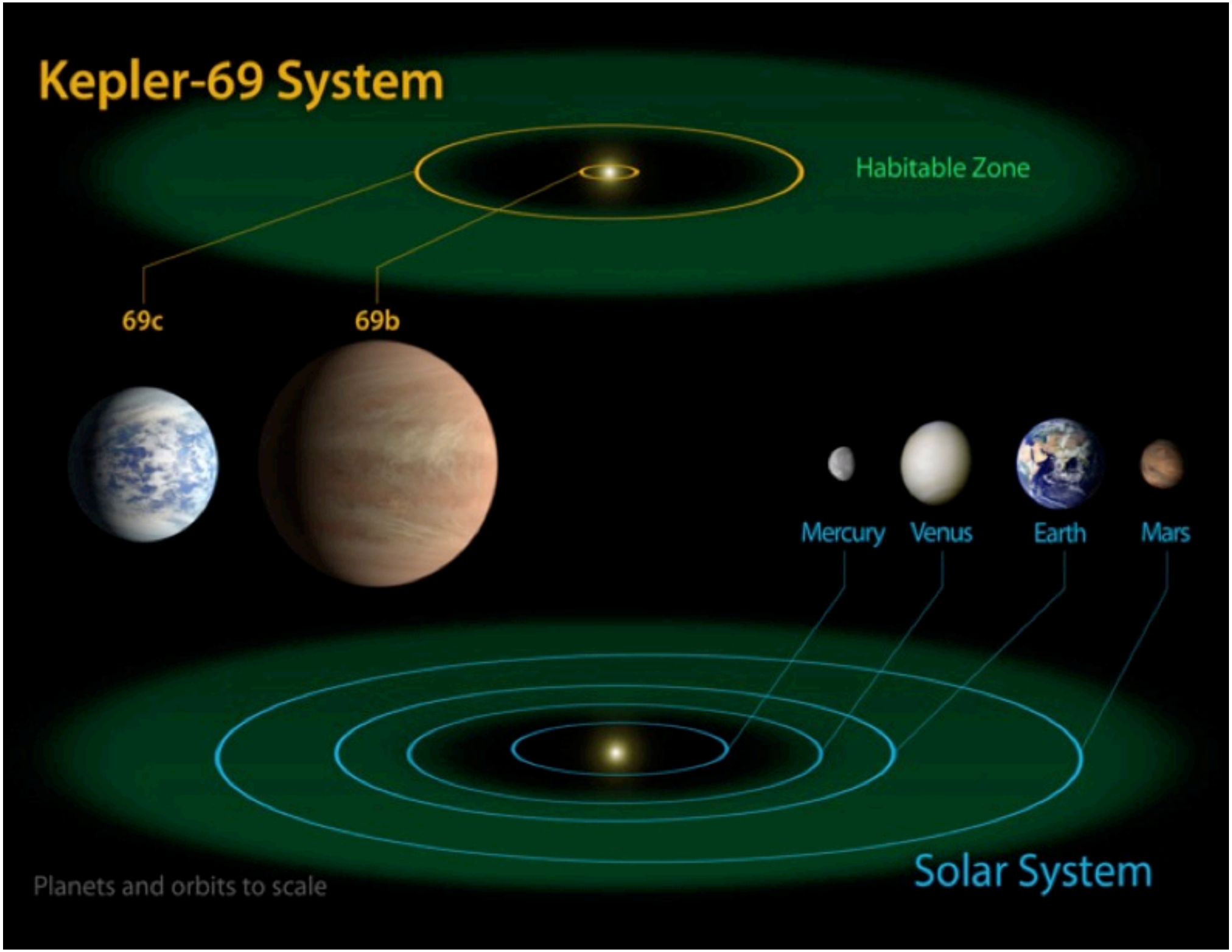
Kepler
A Search for Earth-size Planets



parameter	best fit	1σ uncertainty
Bulk Properties		
Mass of Star A, M_A ($M_\odot$)	1.043	0.055
Mass of Star B, M_B ($M_\odot$)	0.362	0.013
Radius of Star A, R_A ($R_\odot$)	0.964	0.017
Radius of Star B, R_B ($R_\odot$)	0.3506	0.0063
Temperature of Star A, $T_{\rm eff,A}$ (K)	5636	100
Temperature of Star B, $T_{\rm eff,B}$ (K)	3357	100
Luminosity of Star A, L_A ($L_\odot$)	0.840	0.067
Luminosity of Star B, L_B ($L_\odot$)	0.014	0.002
Radius of Planet b, R_b ($R_\oplus$)	2.98	0.12
Radius of Planet c, R_c ($R_\oplus$)	4.61	0.20
Stellar Orbit		
Semimajor Axis, a_{AB} (AU)	0.0836	0.0014
Orbital Period, P_{AB} (day)	7.44837695	0.00000021
Eccentricity, e_{AB}	0.0234	0.0010
Argument of Periapse, ω_{AB} (Degrees)	212.3	4.4
Orbital Inclination, i_1 (deg)	89.34	0.12
Planet b Orbit		
Semimajor Axis, a_b (AU)	0.2956	0.0047
Orbital Period, P_b (day)	49.514	0.040
Eccentricity (95% conf.), e_b	< 0.035	
Orbital Inclination, i_b (deg)	89.59	0.50
Mutual Orbital Inclination, I_b (deg)	0.27	0.24
Planet c Orbit		
Semimajor Axis, a_c (AU)	0.989	0.016
Orbital Period, P_c (day)	303.158	0.072
Eccentricity (95% conf.), e_c	< 0.411	
Orbital Inclination, i_c (deg)	89.826	0.010
Mutual Orbital Inclination, I_c (deg)	1.16	0.46


Kepler-47 System
Habitable Zones
Solar System
Mercury
Venus
Earth
Mars
Kepler-47 b
Kepler-47 c
Planets and orbits to scale
Only 5th System Found!


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


Kepler-69 System
Habitable Zone
69c
69b
Mercury
Venus
Earth
Mars
Solar System
Planets and orbits to scale

Why Do Stars Sing?

To Help Asteroseismologists Learn About Stars

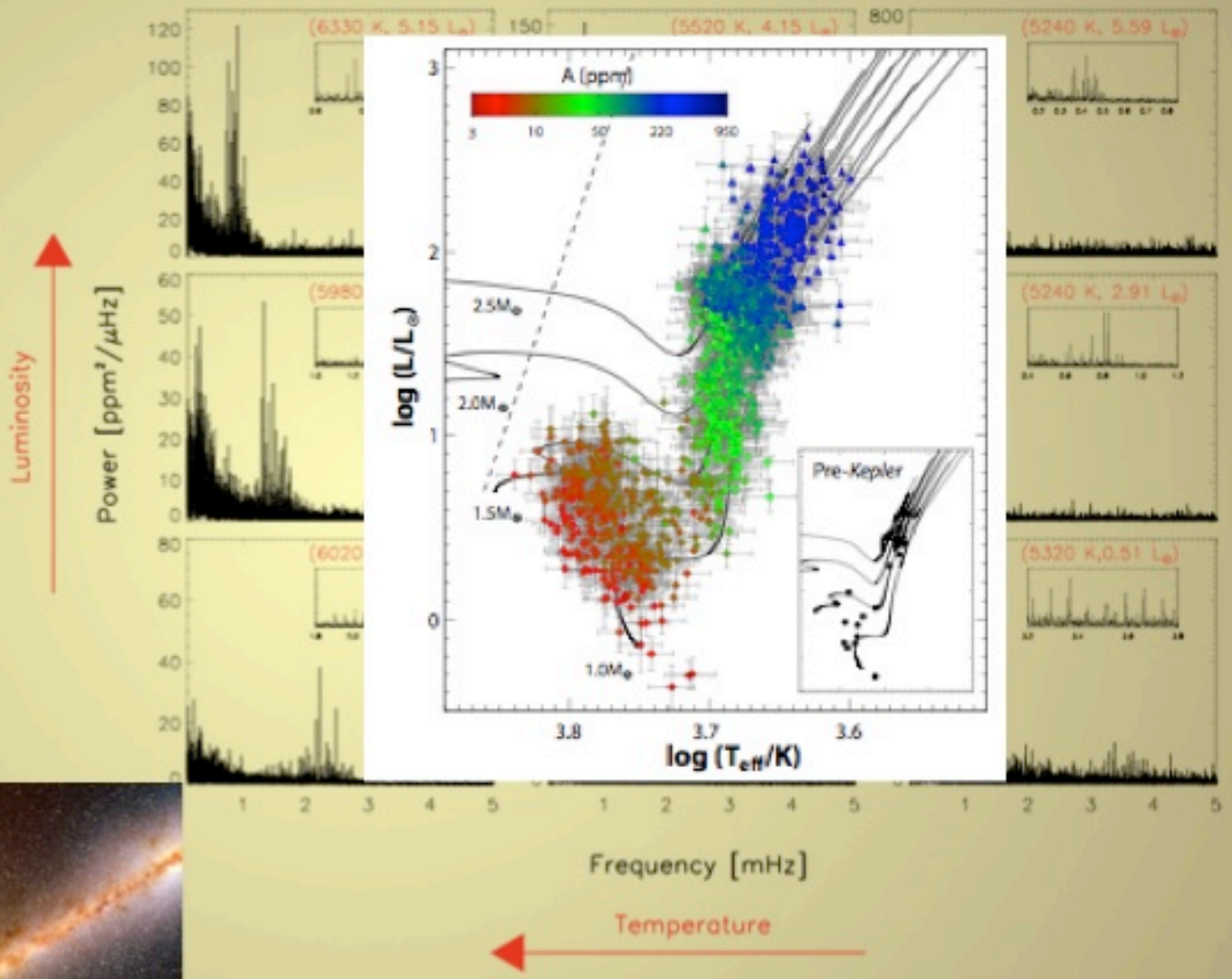
Why Do Stars Sing?

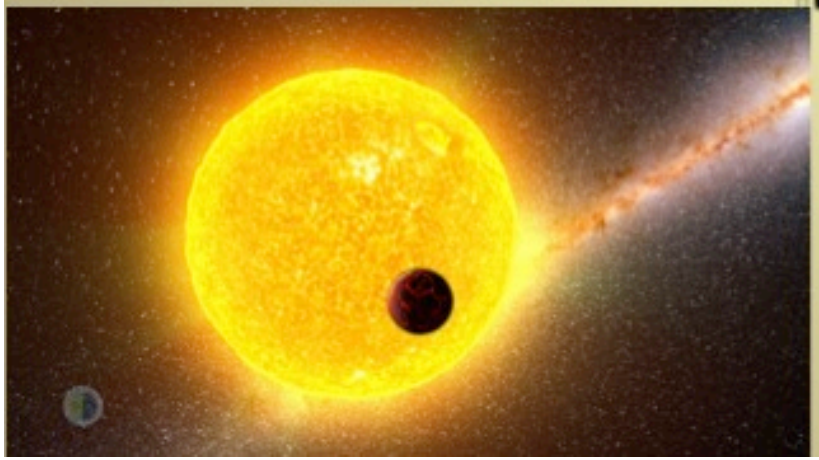
Kepler
A Search for Earth-size Planets

Stars are large resonant cavities that ring like bells

We've measured acoustic modes for >500 solar-like stars

Asteroseismology gives unprecedented precision in size, mass of stars

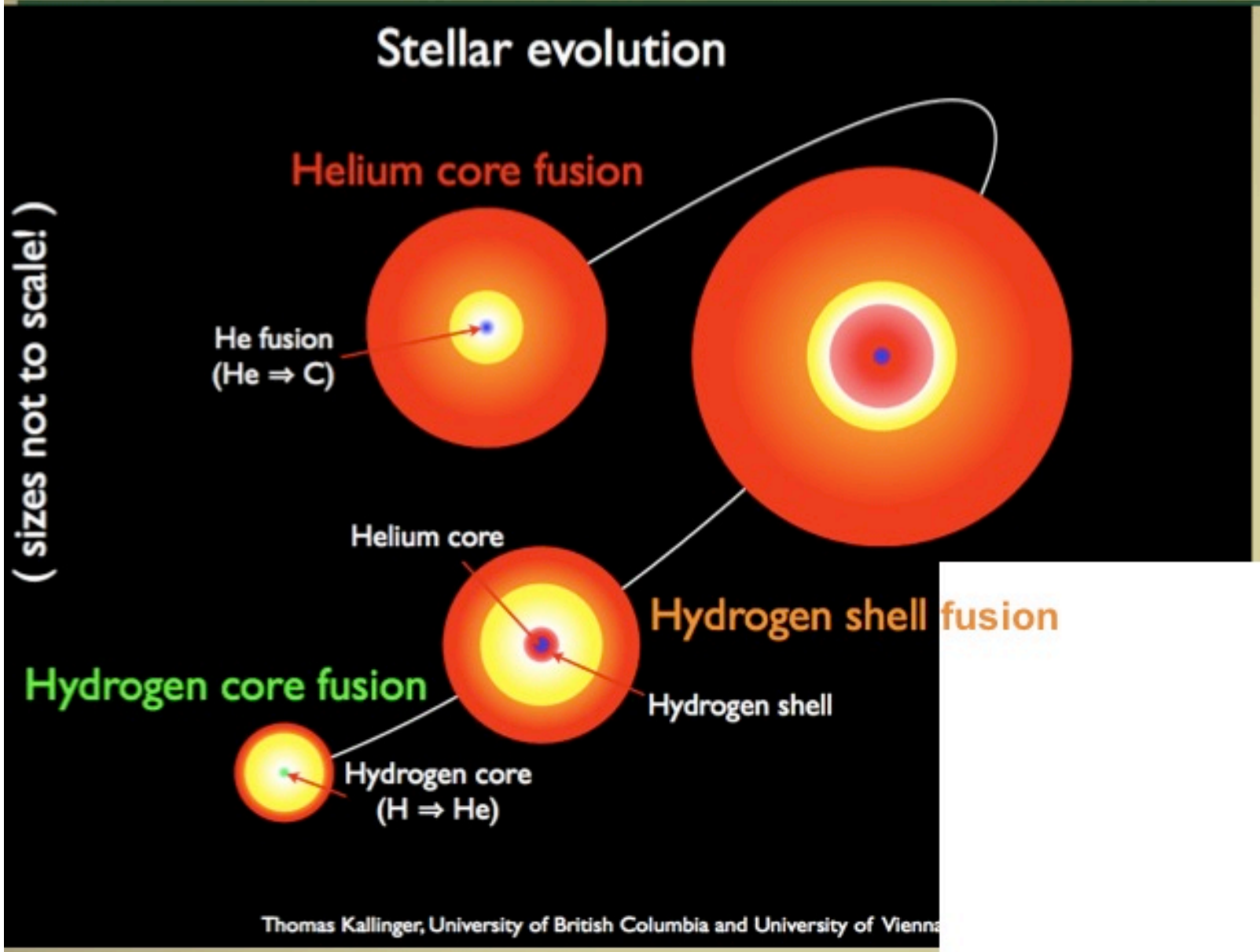




Chaplin et al 2011, Science

Star Songs Tell the Deep Inside Story of the Stars

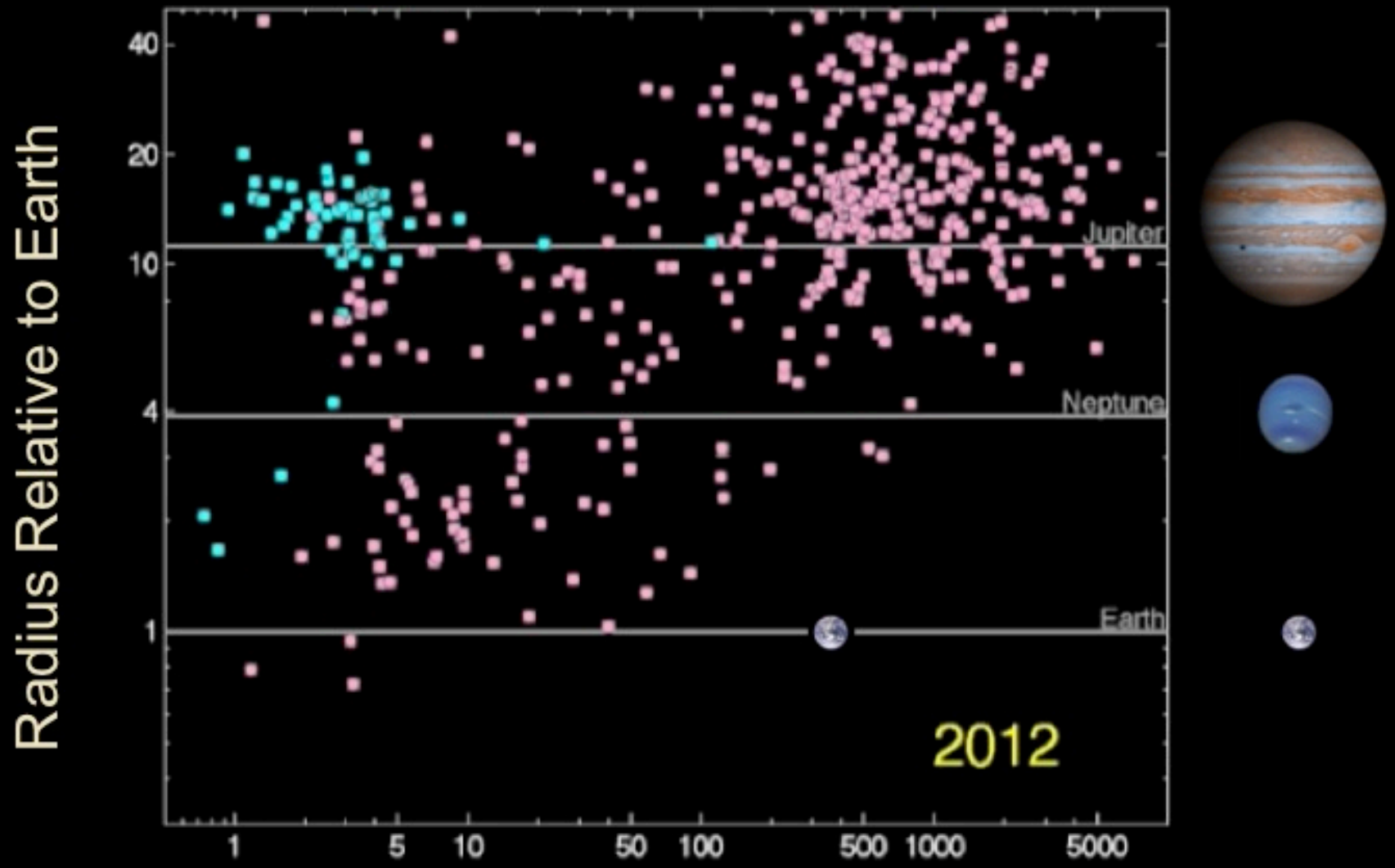
Kepler
A Search for Earth-size Planets



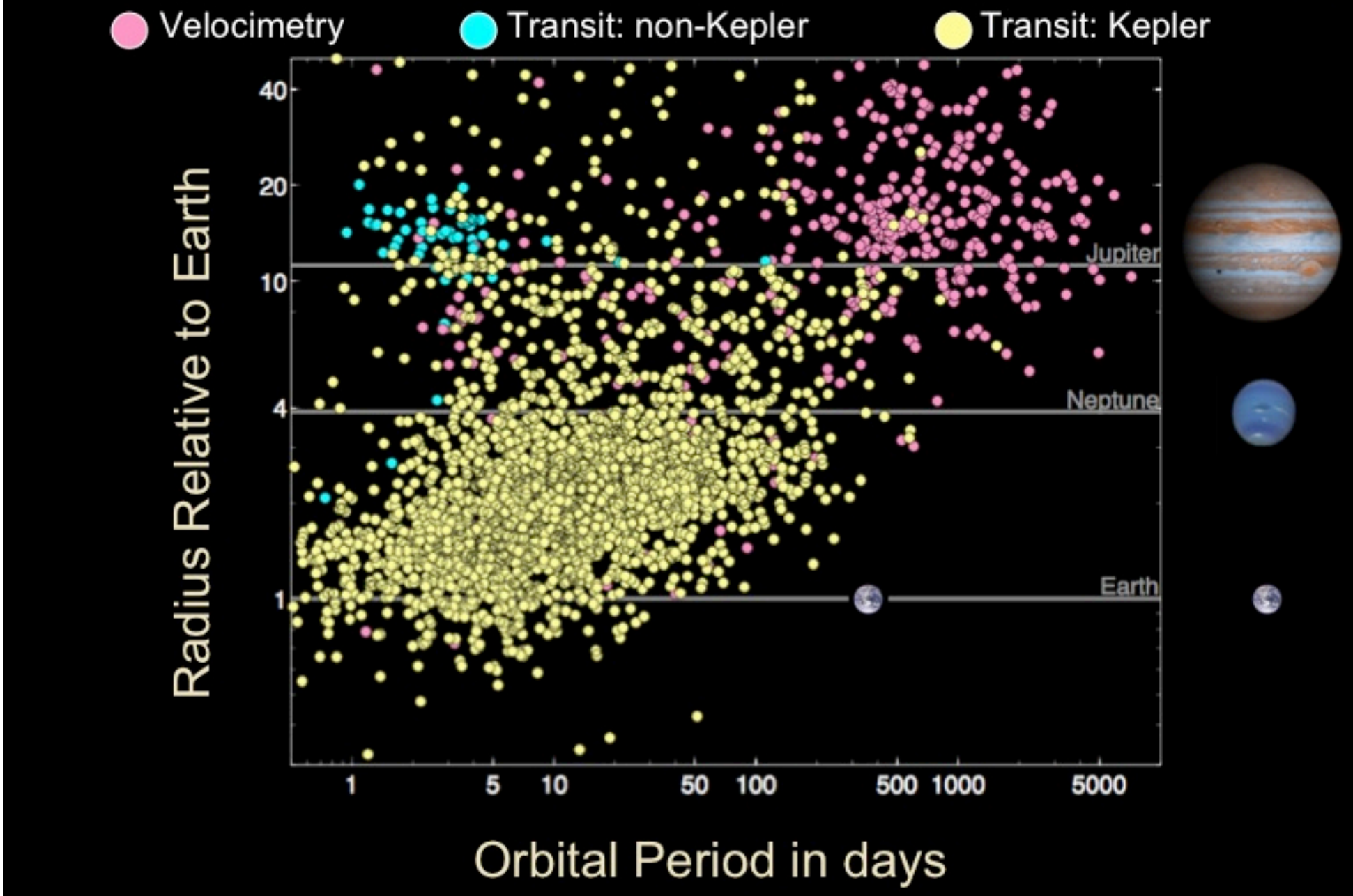
Kepler's Impact on Science of Exoplanets

Exoplanet Detections, 1995-2012

Velocimetry Transit: non-Kepler Transit: Kepler

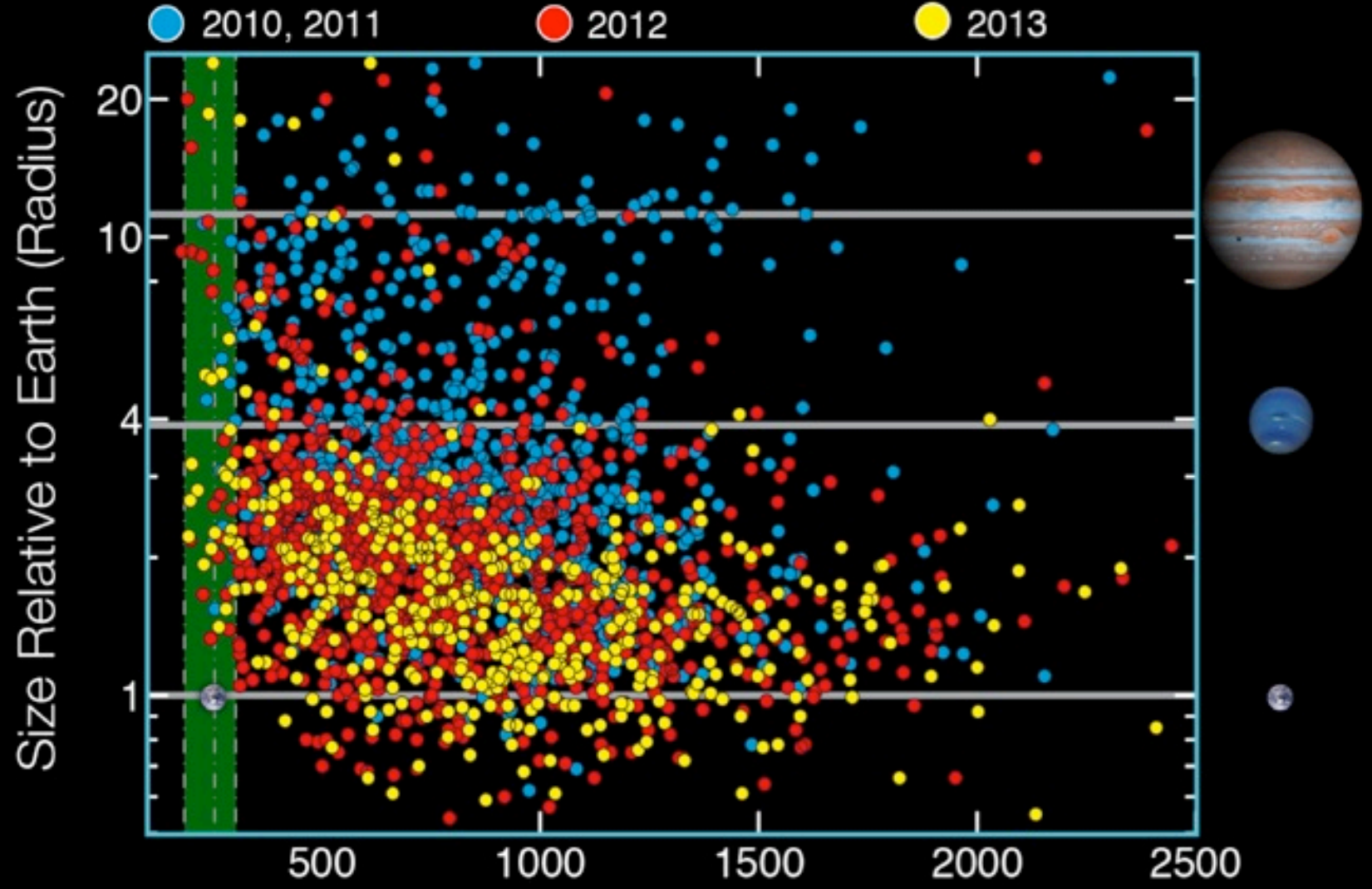


Exoplanet Detections, 1995-2013



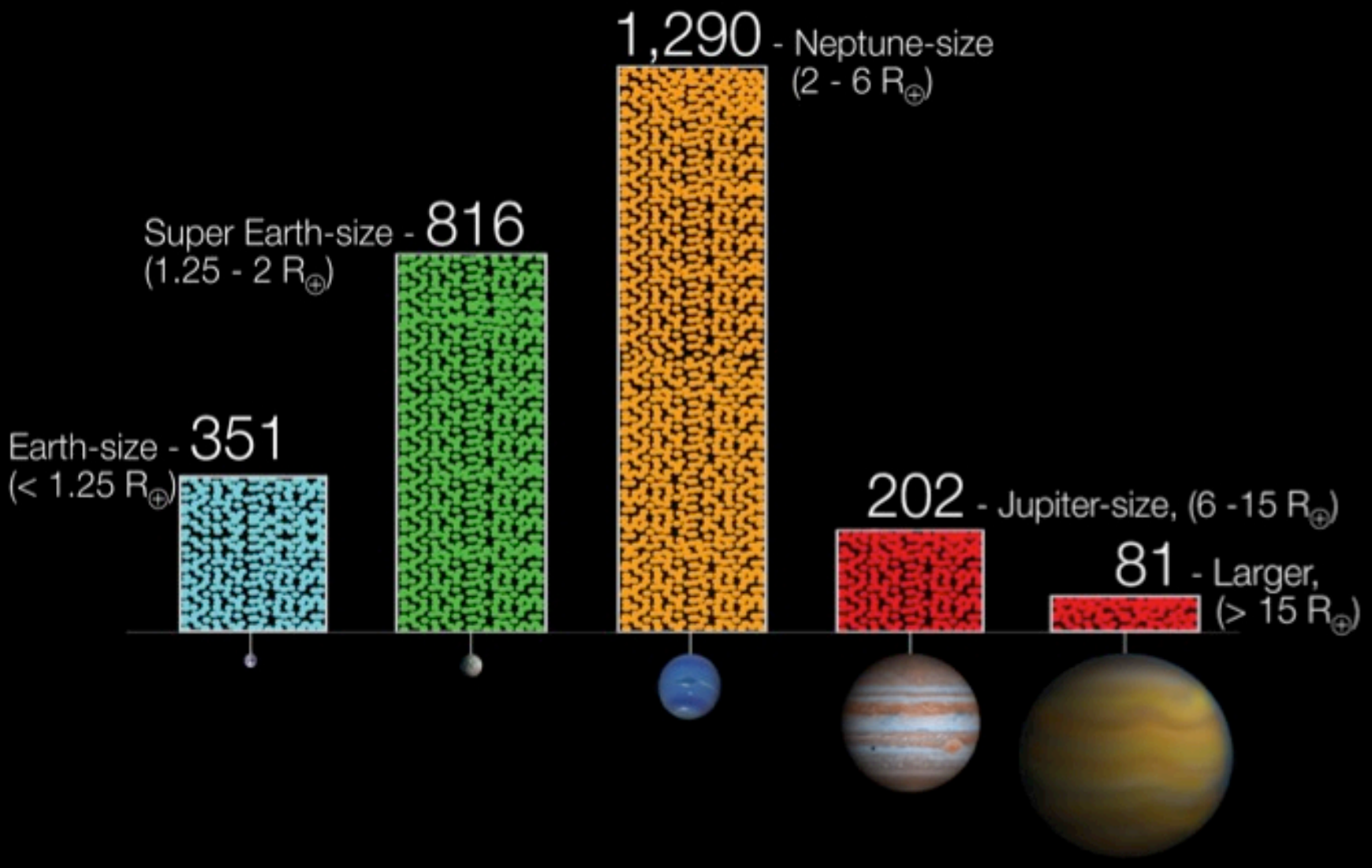
Candidates in the Habitable Zone

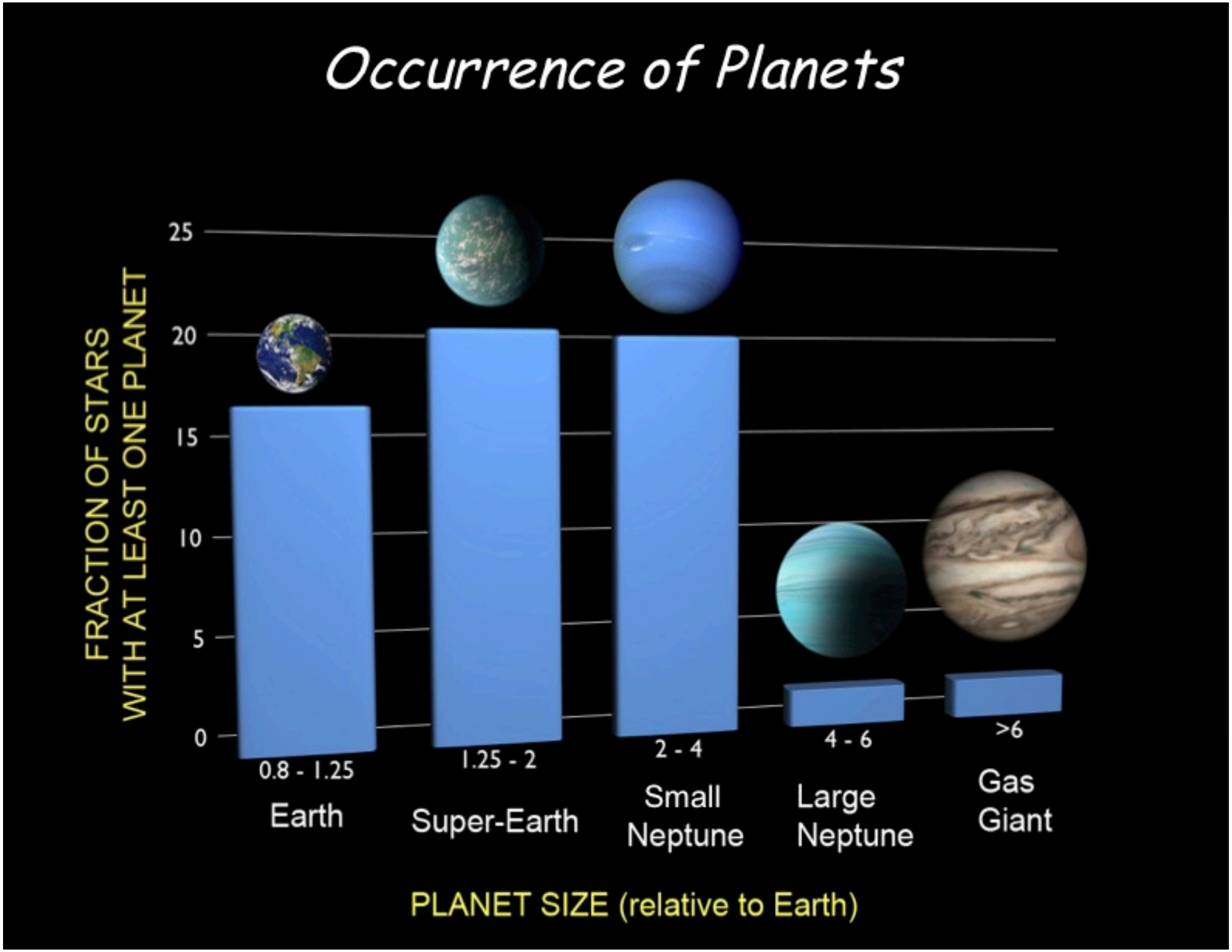
As of January 7, 2013

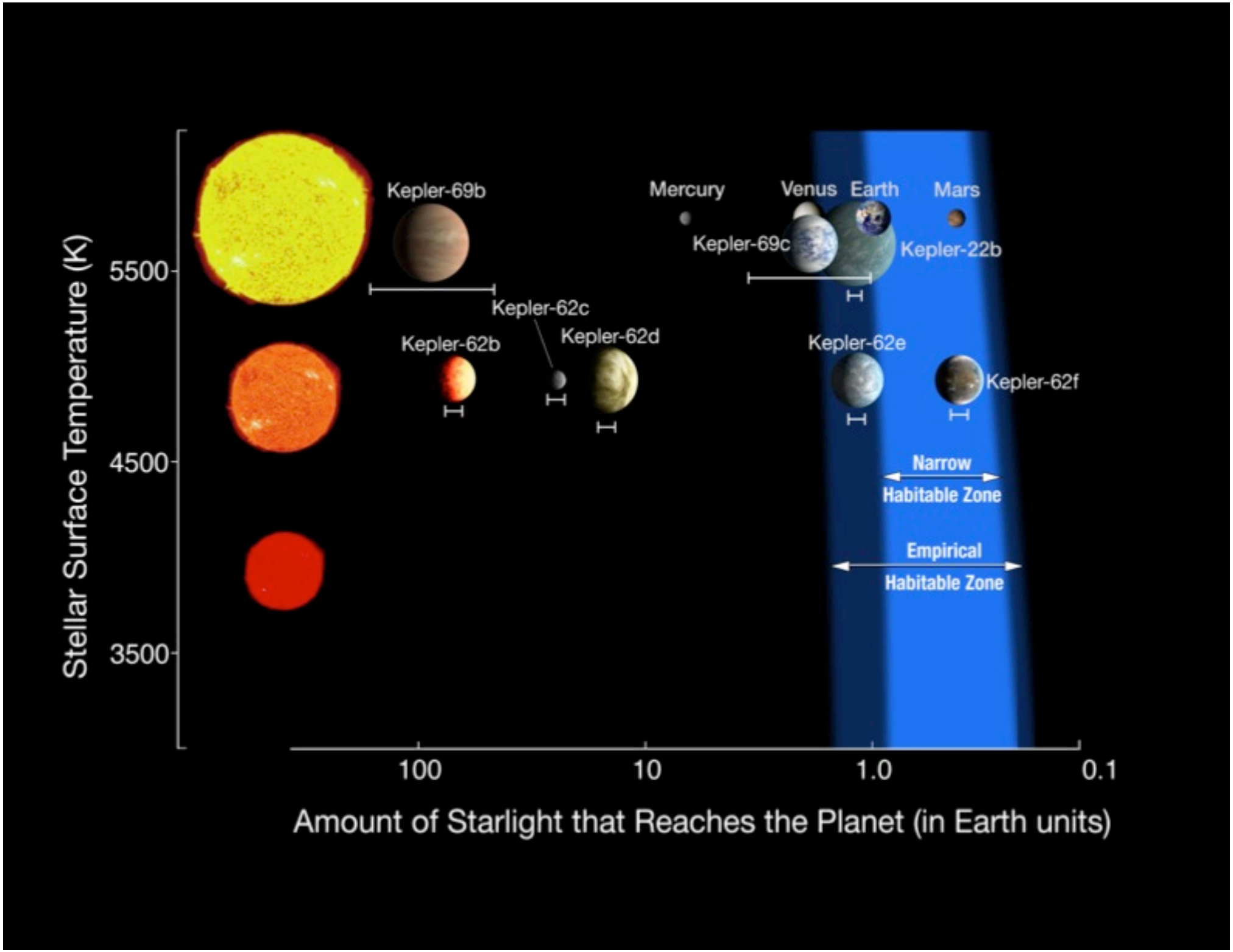


2,740 Planet Candidates

As of January 2013



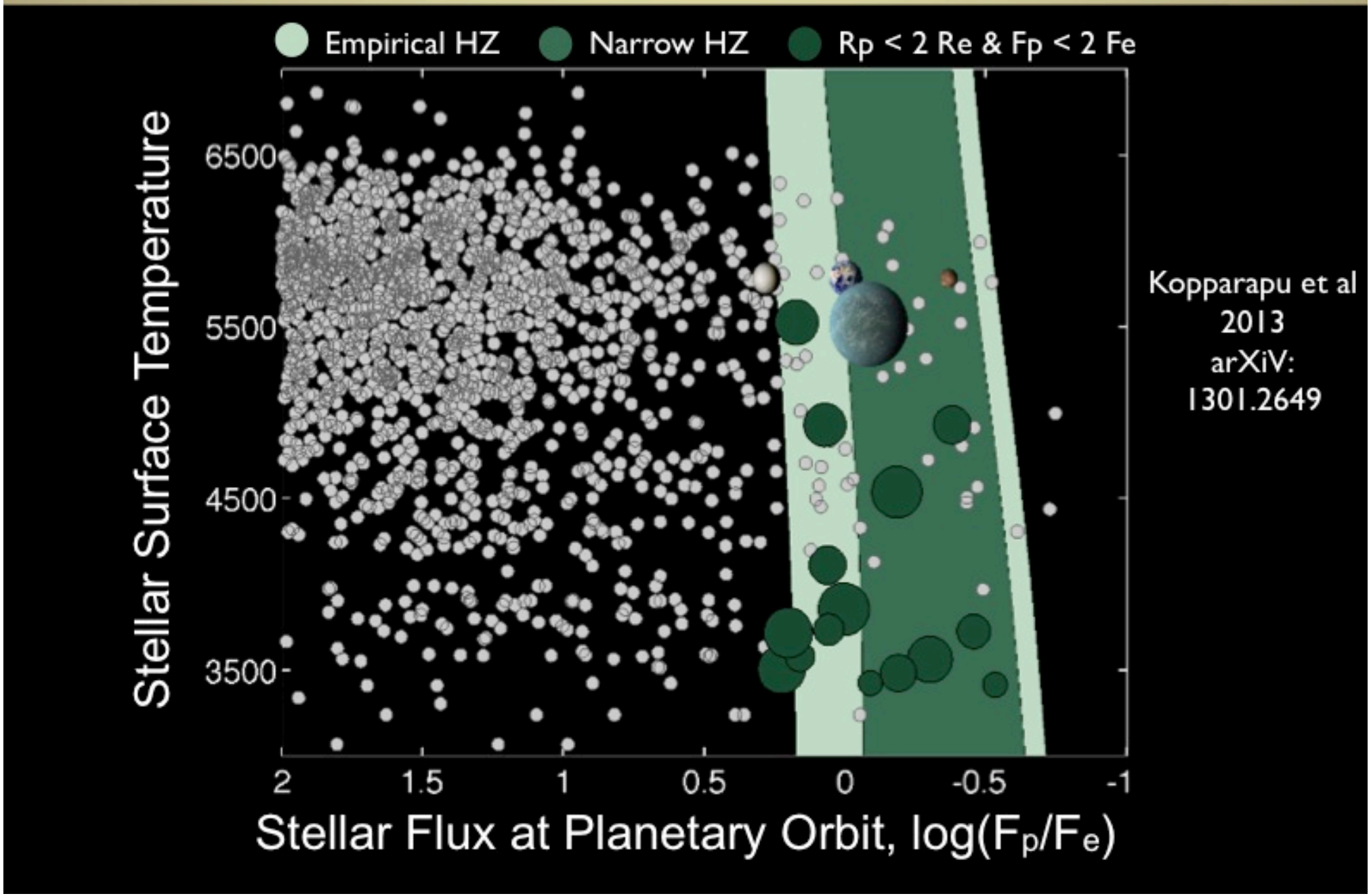

Occurrence of Planets
FRACTION OF STARS WITH AT LEAST ONE PLANET
25
20
15
10
5
0
0.8 - 1.25
1.25 - 2
2 - 4
4 - 6
>6
Earth
Super-Earth
Small Neptune
Large Neptune
Gas Giant
PLANET SIZE (relative to Earth)


Stellar Surface Temperature (K)
5500
4500
3500
Kepler-69b
Kepler-62c
Kepler-62b
Kepler-62d
Mercury
Venus
Earth
Mars
Kepler-69c
Kepler-22b
Kepler-62e
Kepler-62f
Narrow
Habitable Zone
Empirical
Habitable Zone
100
10
1.0
0.1
Amount of Starlight that Reaches the Planet (in Earth units)

Habitable Zone Candidates

22 Months: May 2009 - Mar 2011

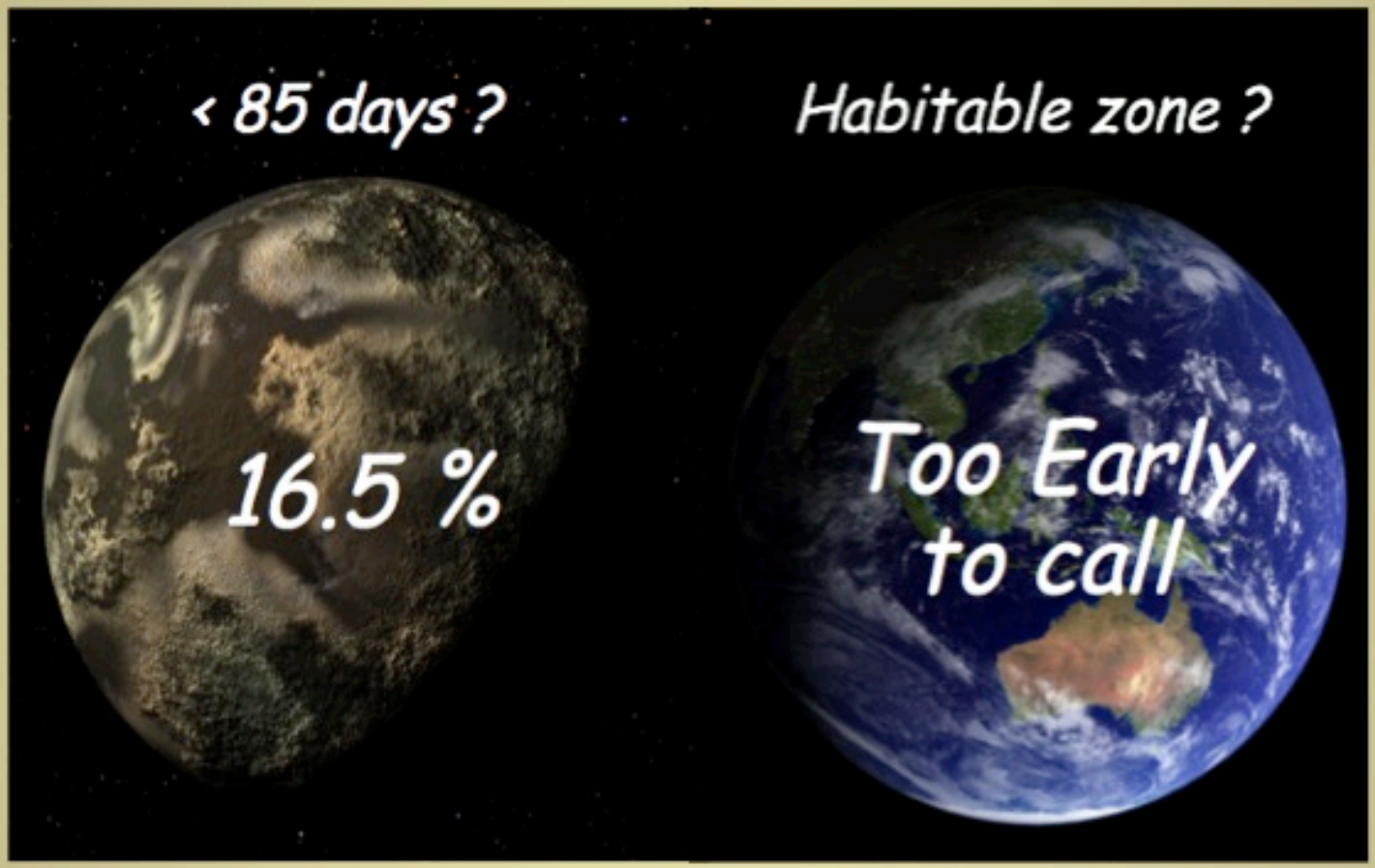
Kepler
A Search for Earth-size Planets



Kopparapu et al
2013
arXiV:
1301.2649

Occurrence Rate versus Size

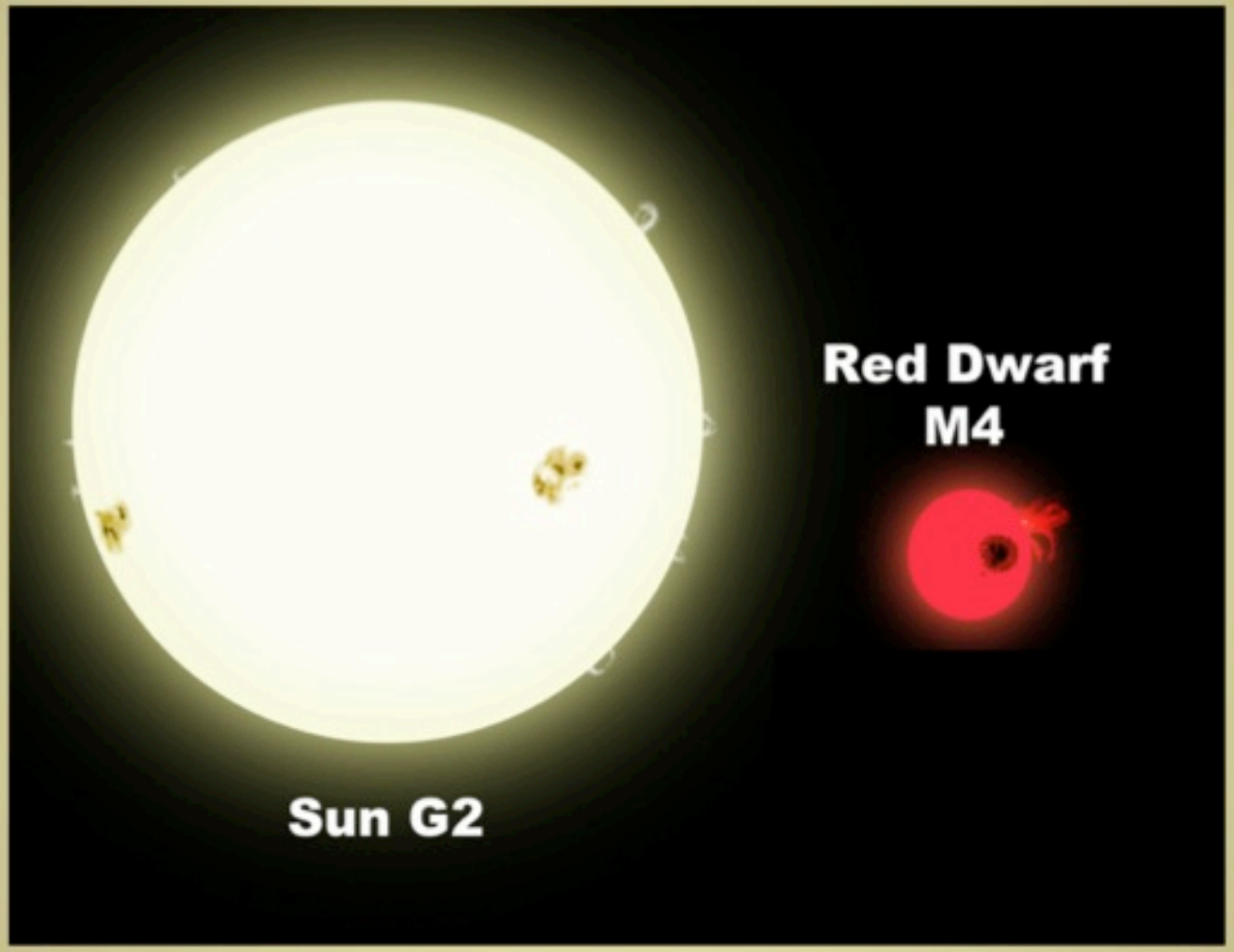
Kepler
A Search for Earth-size Planets



One is six stars has an earth-size planet within P = 85 days
At least 70% of stars have a planet
of any type within 400 days

Planets Orbiting the Coolest Stars

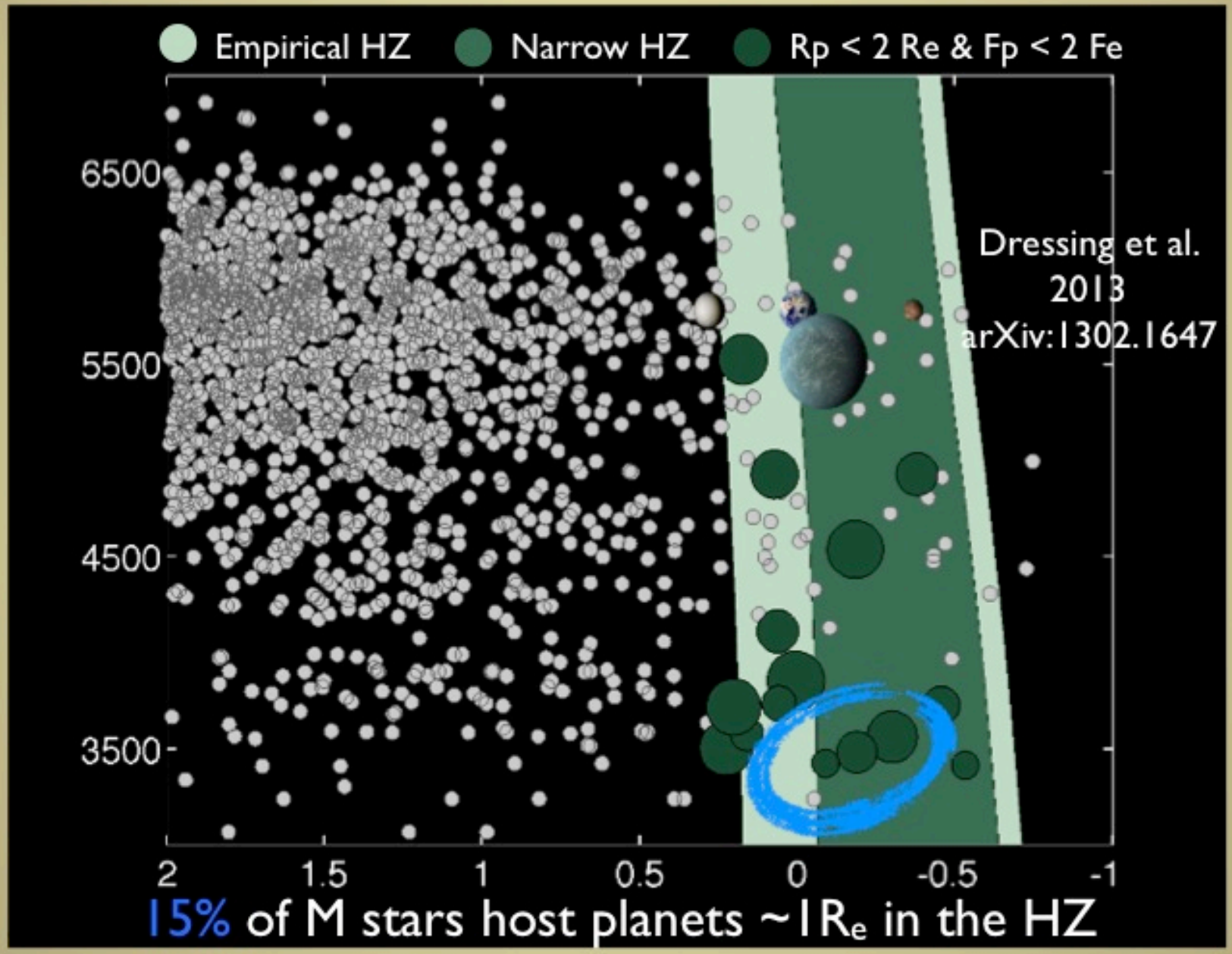
Kepler
A Search for Earth-size Planets



For Red Dwarfs: At least 60% host a planet smaller than Neptune

3 Small HZ Candidates Orbiting M-type Stars

Kepler
A Search for Earth-size Planets



Overview of Statistics

Kepler
A Search for Earth-size Planets

Main Sequence Stars in general:

- 17% of main sequence stars have an earth-size planet within P = 85 days (Fressin et al)
- At least 70% of main sequence stars have a planet within P = 400 days (Fressin, measured)
- 45% of FGK stars have a 1-3 R_{earth} planet with P=5-500 days. (Marcy, extrapolation)

M-type main sequence stars:

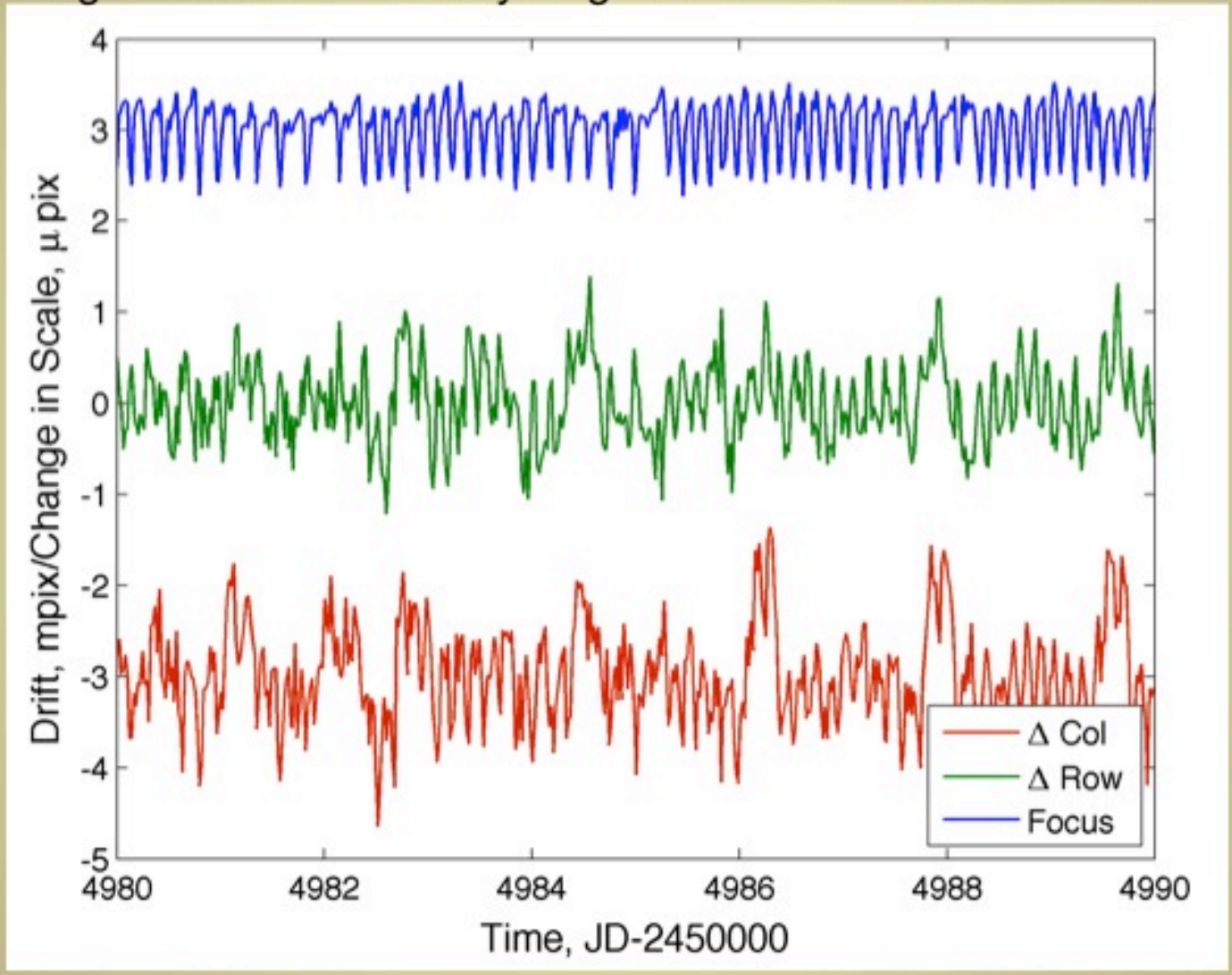
- 60% of M dwarfs harbor a planet smaller than Neptune
- **15% of M dwarfs harbor a planet smaller than 2 Re in the HZ**

A Cautionary Note from *Kepler*

Short Timescale Instrumental Errors

Kepler
A Search for Earth-size Planets

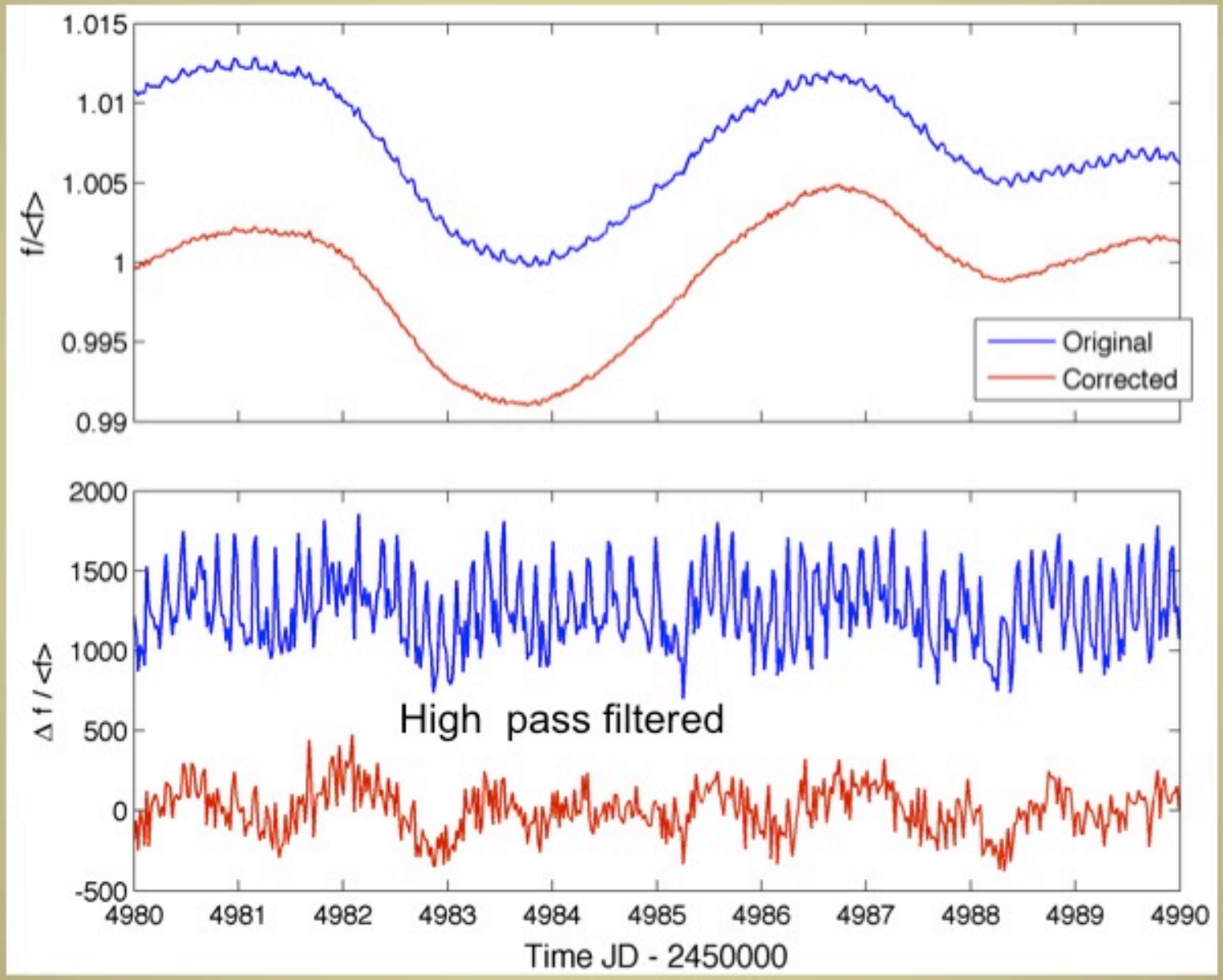
Signature of a heater cycling on the reaction wheels 3/4



***Kepler* is sensitive to its thermal environment**

Correcting Instrumental Effects

Kepler
A Search for Earth-size Planets



Excess Stellar Variability

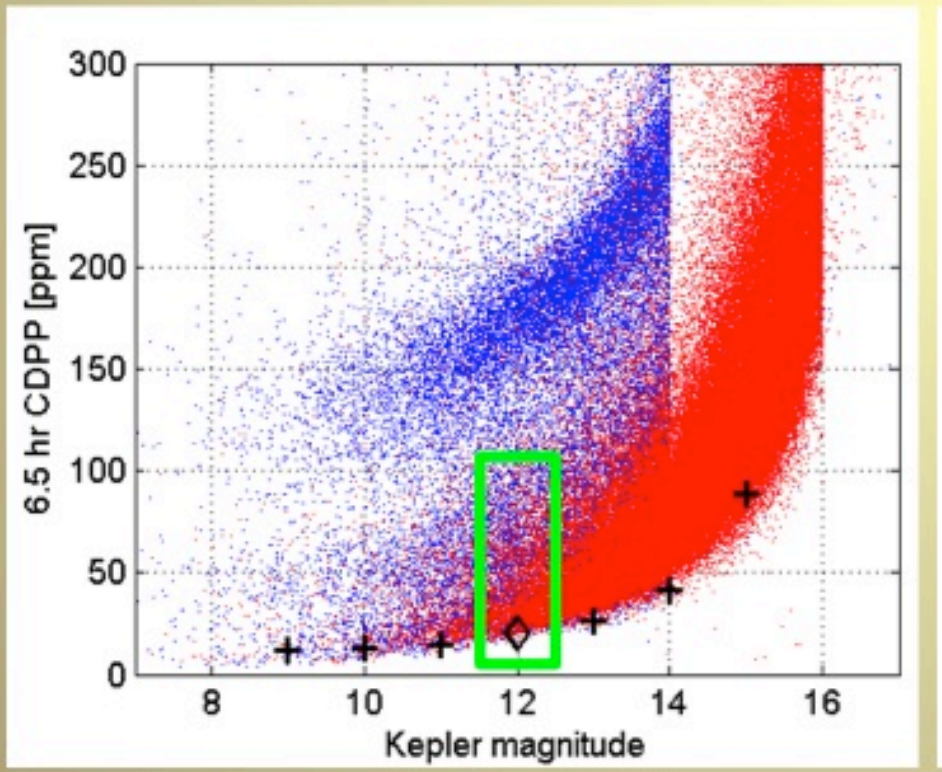
Kepler
A Search for Earth-size Planets

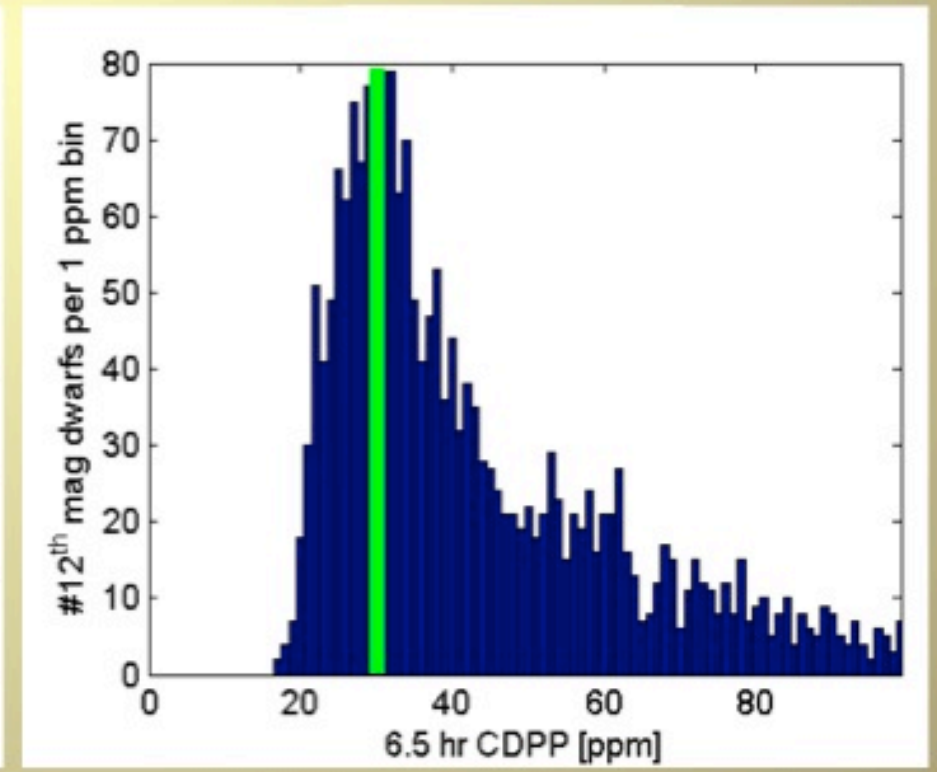
Original Noise Budget (Kp=12):
- 14 ppm Shot Noise
- 10 ppm Instrument Noise
- 10 ppm Stellar Variability

=> 20 ppm Total Noise

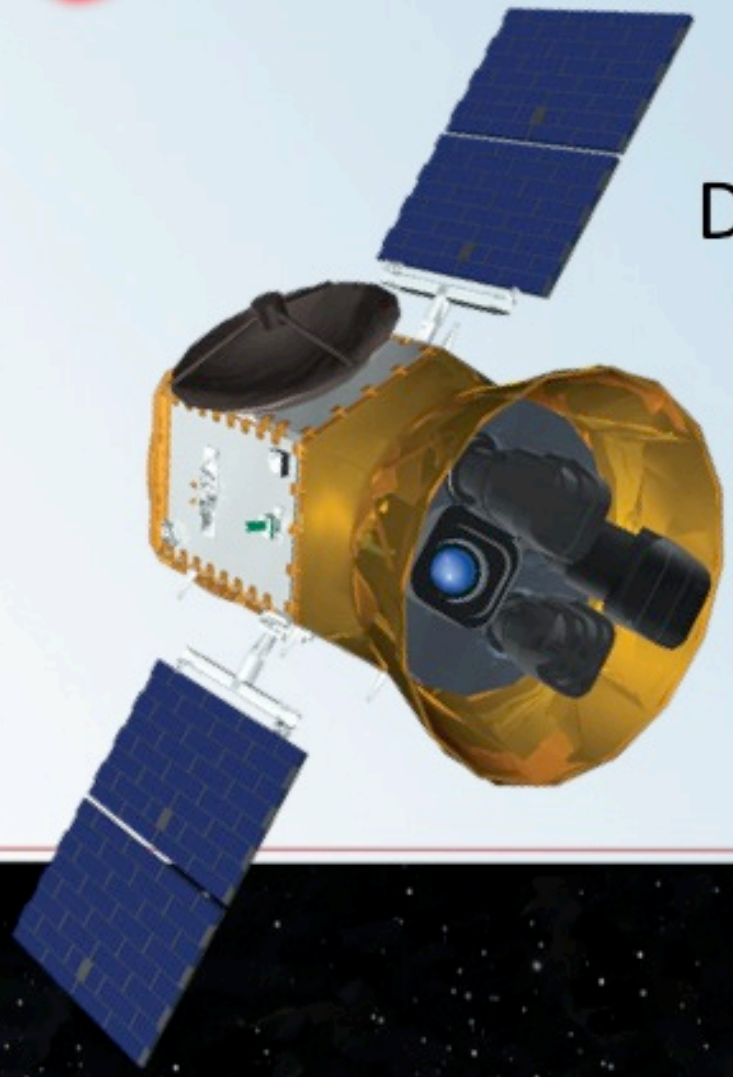
Reality (11.5 ≤ Kp ≤ 12.5)
- 17 ppm Shot Noise
- 13 ppm Instrument Noise
- 20 ppm Stellar Variability

=> ~29 ppm Total Noise





Transiting Exoplanet Survey Satellite



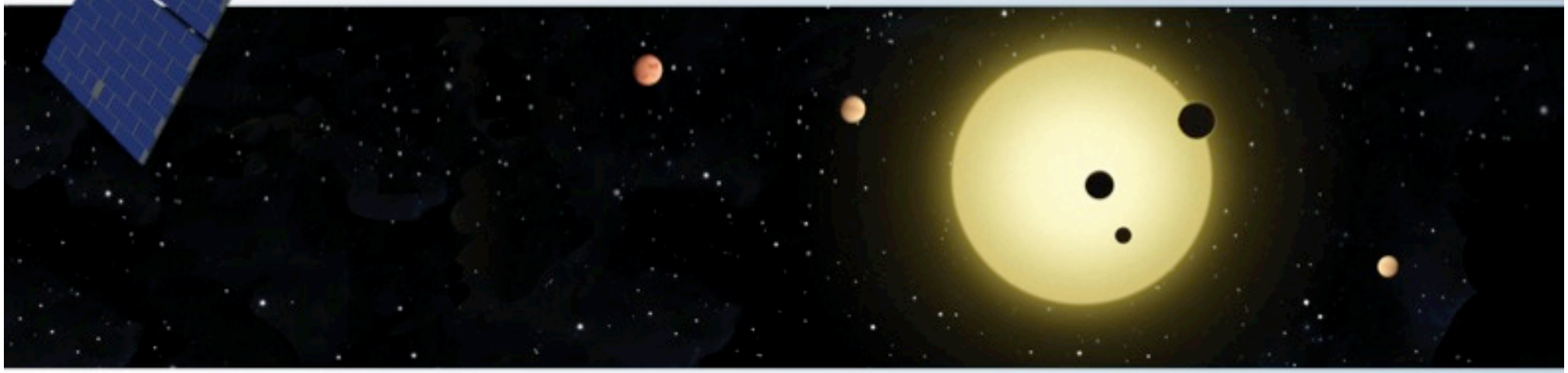
The TESS Mission:

Discovering New Earths and Super-Earths in the Solar Neighborhood

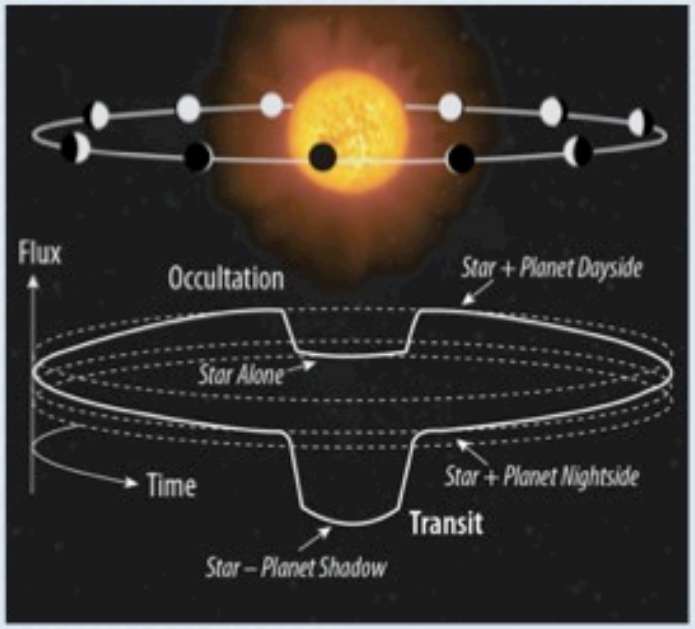
Jon Jenkins (SETI Institute)

on behalf of George Ricker (MIT)

PLATO 2.0 Workshop 29 July 2013

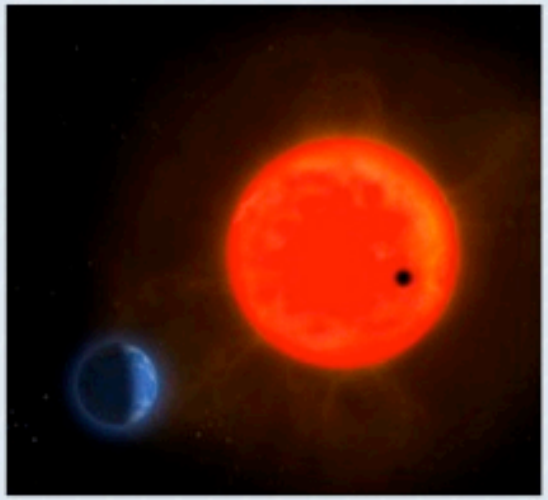


TESS Science Goals and Drivers



- Discover Transiting Earths and Super-Earths Orbiting Bright, Nearby Stars
  - Rocky Planets & Water Worlds
  - Habitable planets
- Discover the "Best" ~1000 Small Exoplanets
  - "Best" means "Readily characterizable"
    - Bright Host Stars
    - Measurable Mass & Atmospheric Properties
  - Only 2 small transiting exoplanets orbiting bright hosts are known

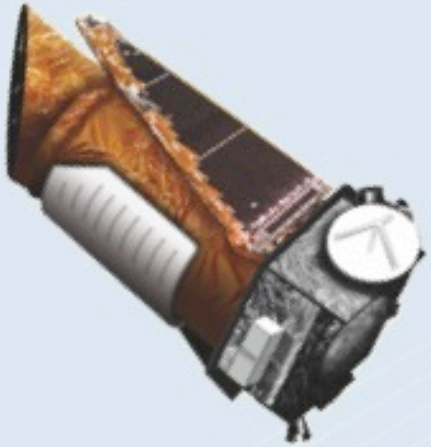
- All Sky Survey of Bright Stars
  - F, G, K dwarfs: +4 to +12 magnitude
  - M dwarfs known within ~200 light-years
  - 500,000 target stars in two years



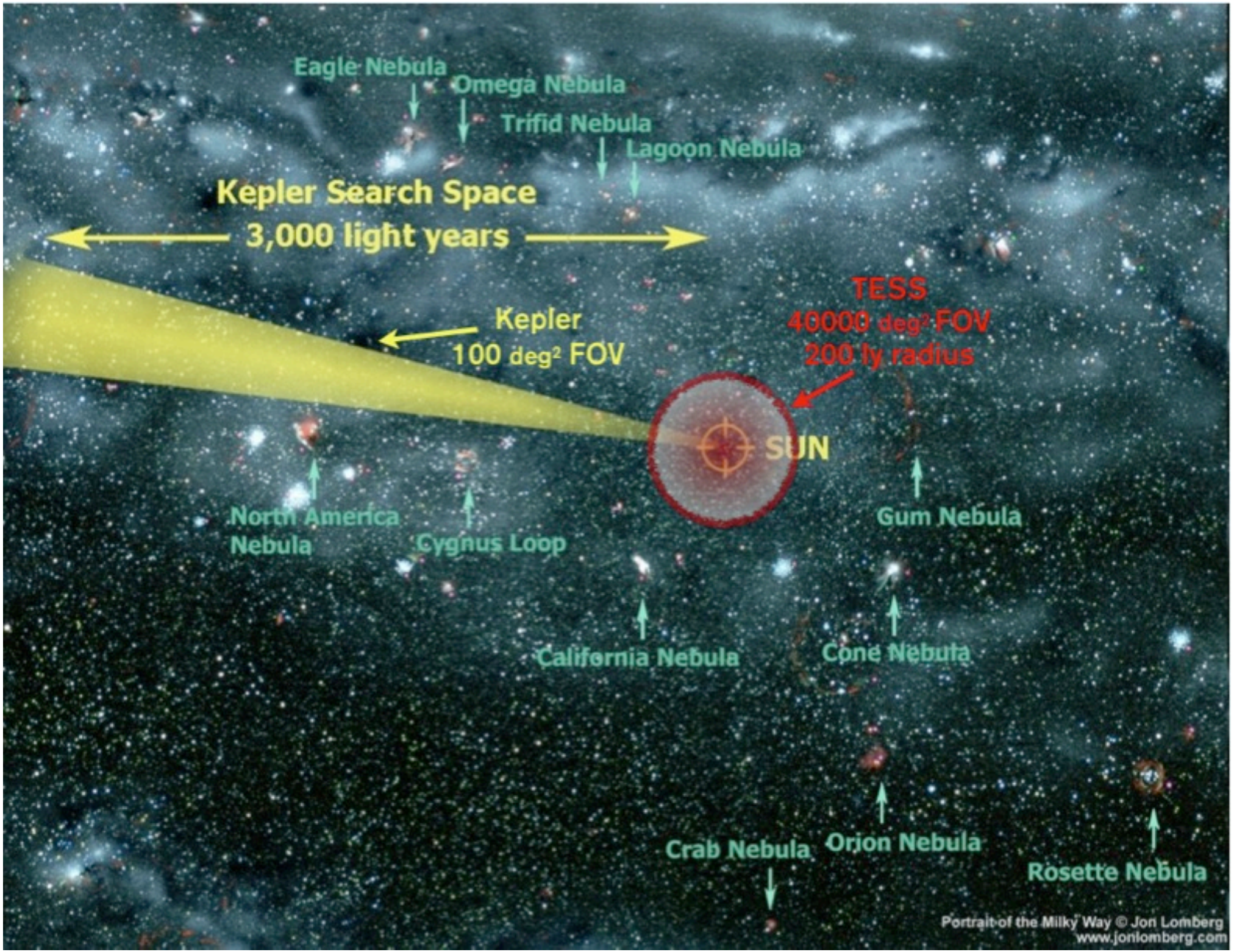
TESS and Kepler Answer Different Questions

- Kepler:

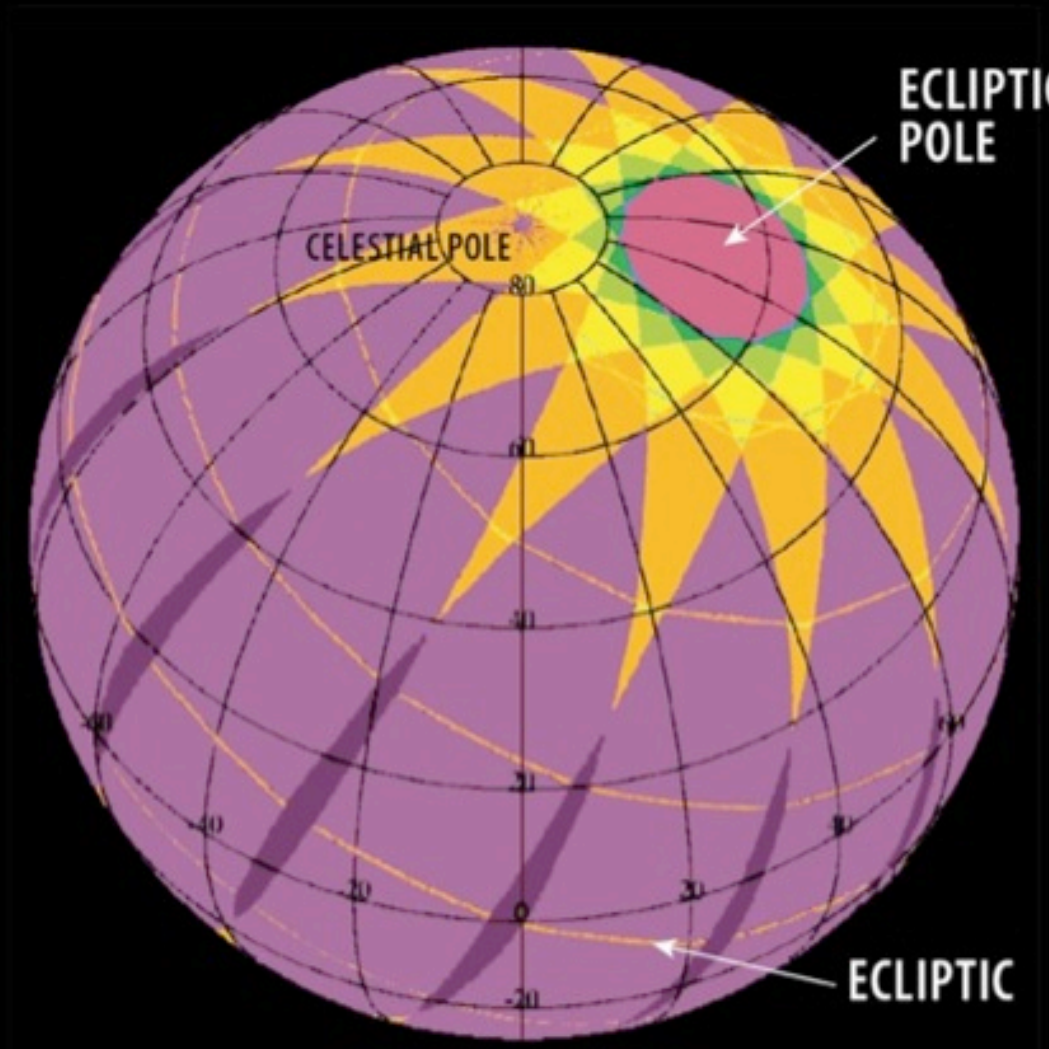
How common are true Earth analogs?



- TESS:
- Where are the nearest transiting rocky planets?


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

TESS Sky Coverage



JWST Continuous Viewing Zone (CVZ)

27 DAYS

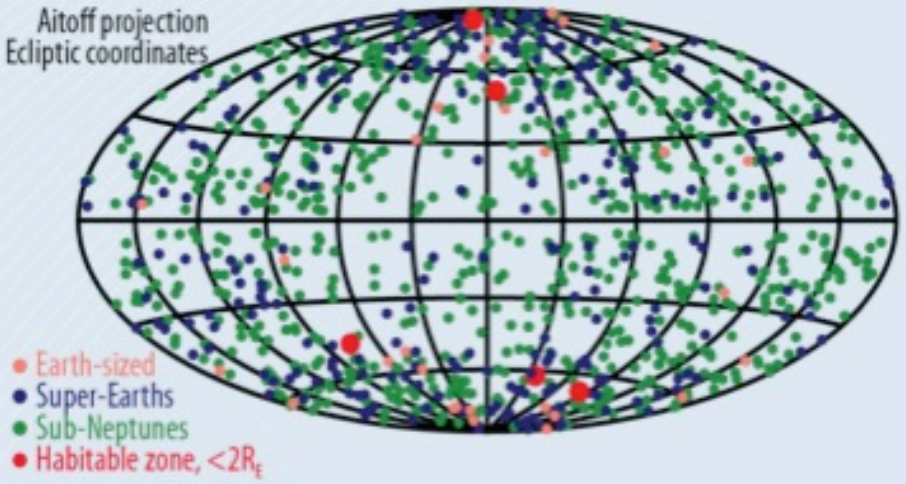
54 DAYS

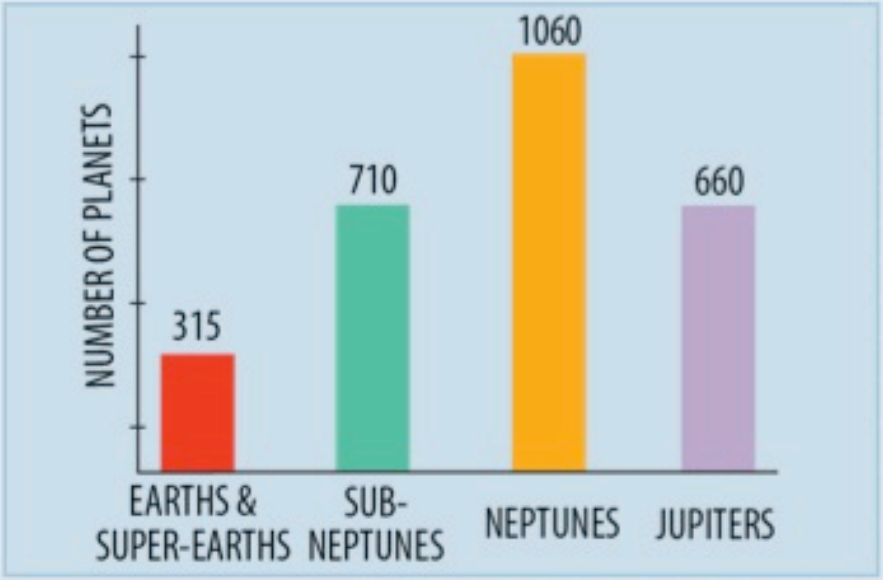
81 DAYS

108 DAYS

>162 DAYS

Predicted Science Yield from TESS Mission

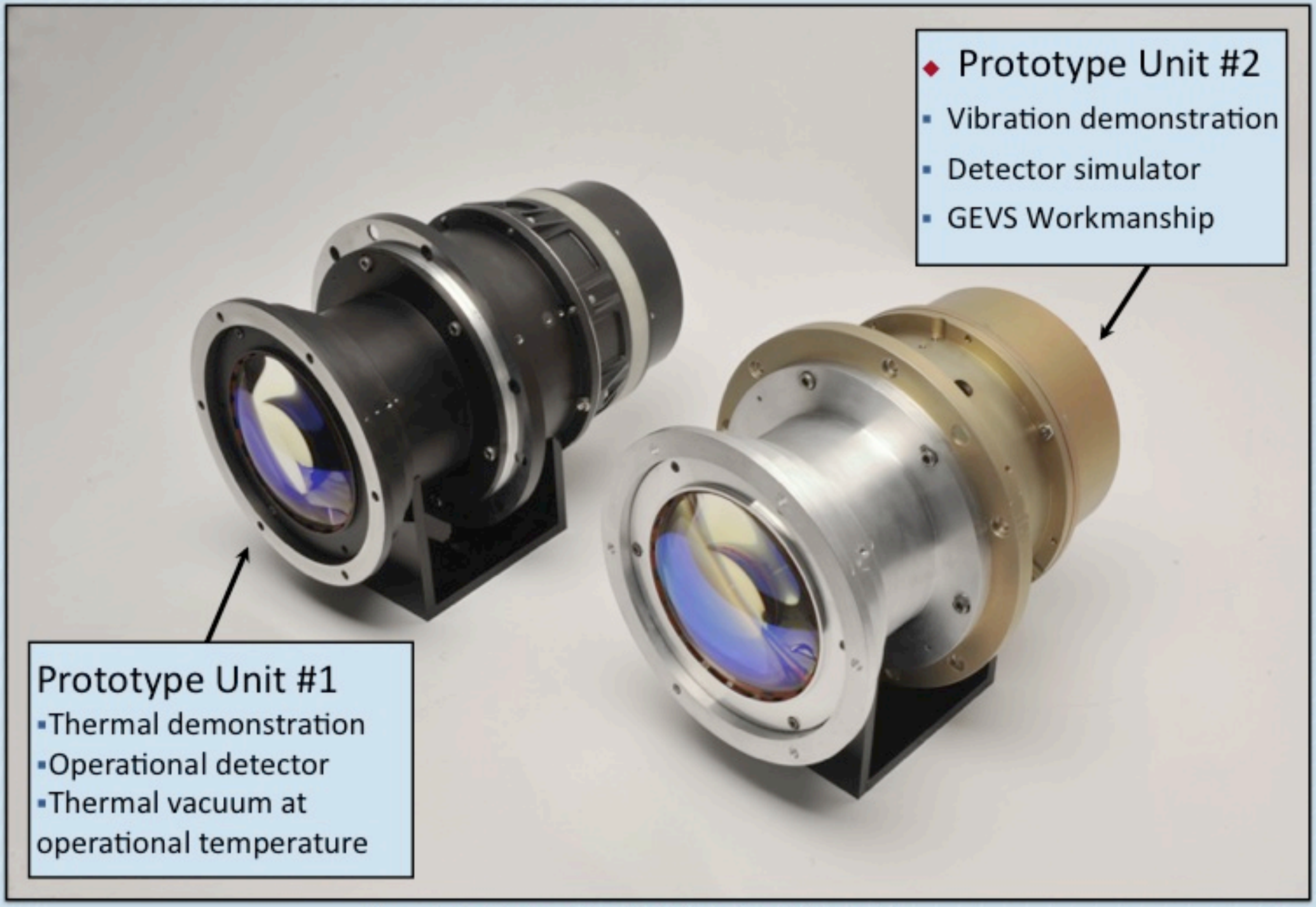




TESS Will Discover ~300 Earths & Super-Earths

TESS Wide FOV CCD Camera

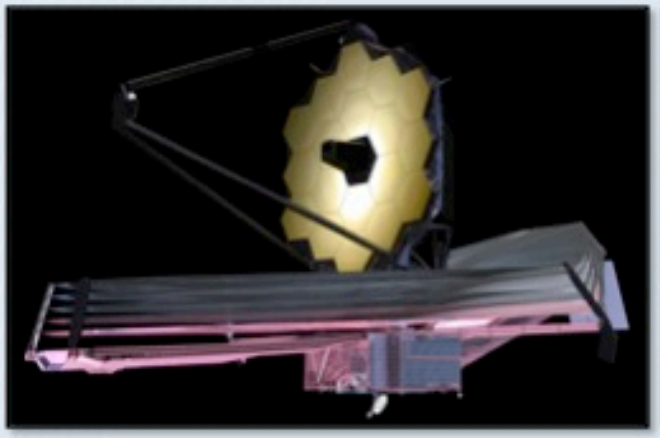
TESS Prototype Cameras



Full Size Replica of TESS

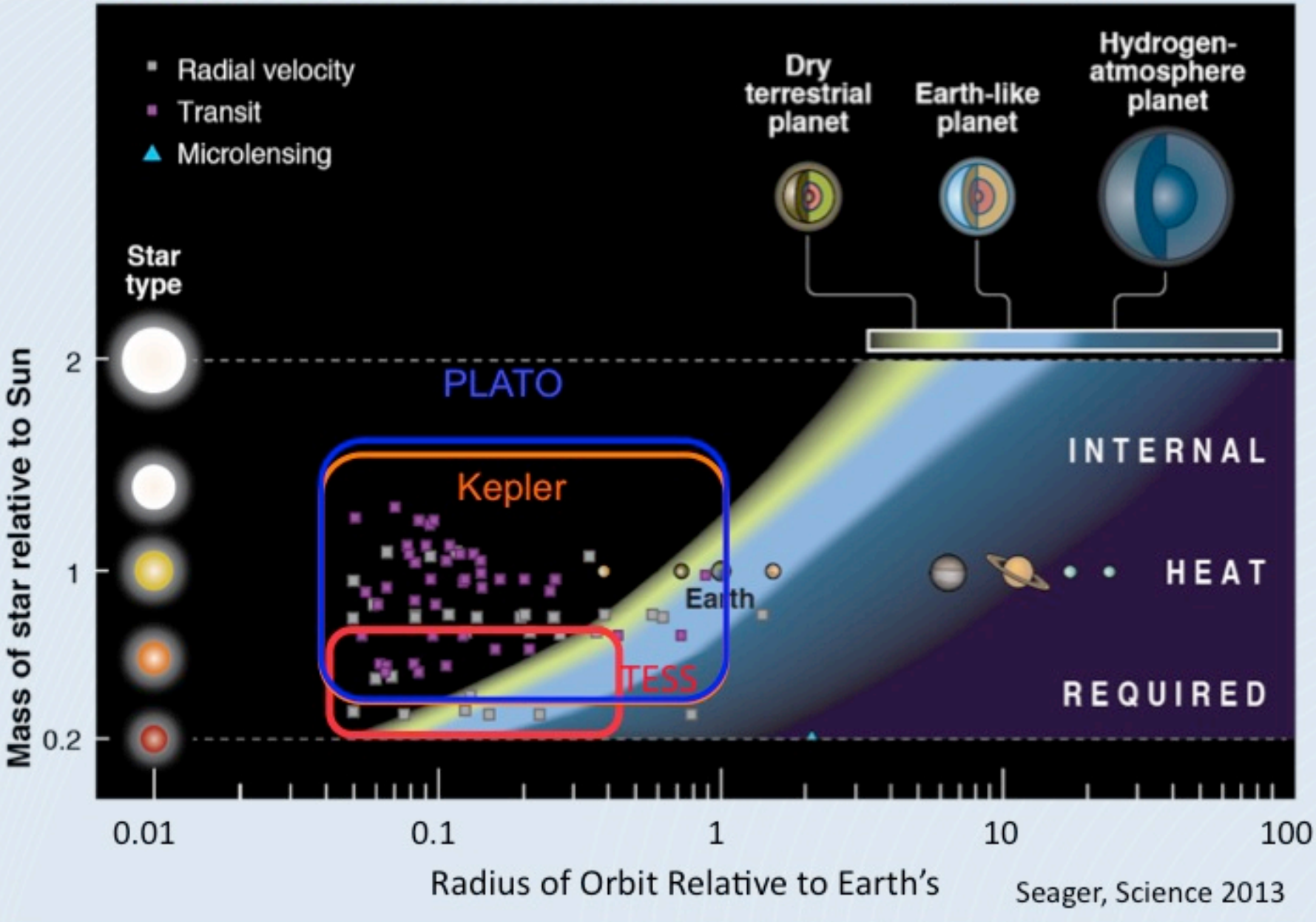
TESS Enables Atmospheric Characterization

- TESS will identify a set of the best and smallest nearby exoplanet targets for characterization of atmospheres using:
  - JWST
  - Extremely Large Telescopes (ELTs)
  - Future Exoplanet Explorers, Probes, and Large Missions



The Habitable Zone

TESS and PLATO WILL find planets around bright, nearby stars



Seager, Science 2013

Exoplanet Missions

PLATO

ECHO

JWST

AFTA

COROT

MOST

TESS

Kepler

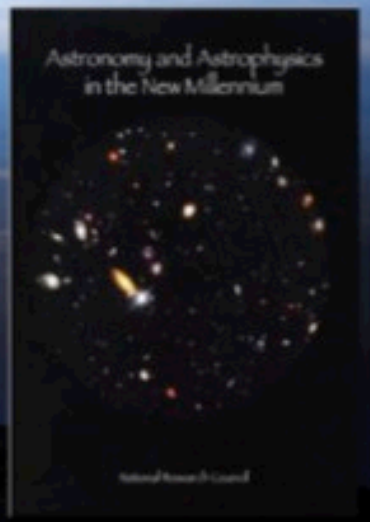
CHEOPS

New Worlds Telescope

Spitzer

Hubble

Ground-based Observatories



2001 Decadal Survey

2010 Decadal Survey

Summary

Kepler
A Search for Earth-size Planets

- *Kepler* has initiated an explosion of exoplanet research, effectively tripling the number of known exoplanets
- There are an astonishing number of multiple planet systems and these are remarkably coplanar – like the solar system
- *Kepler* asteroseismology has led to major breakthroughs: (1) for dwarfs many precision applications and ensemble comparisons enabled, (2) the finding of, and outline of how to interpret g-, or mixed-modes in red giants.
- *Kepler* has pushed technology on all fronts.
- There is still much to glean from the data we already have: over one year of data has yet to be searched
- *Kepler's* legacy will last for decades

- NASA's quest for exoplanets continues with TESS

Raise a Cheer for Kepler