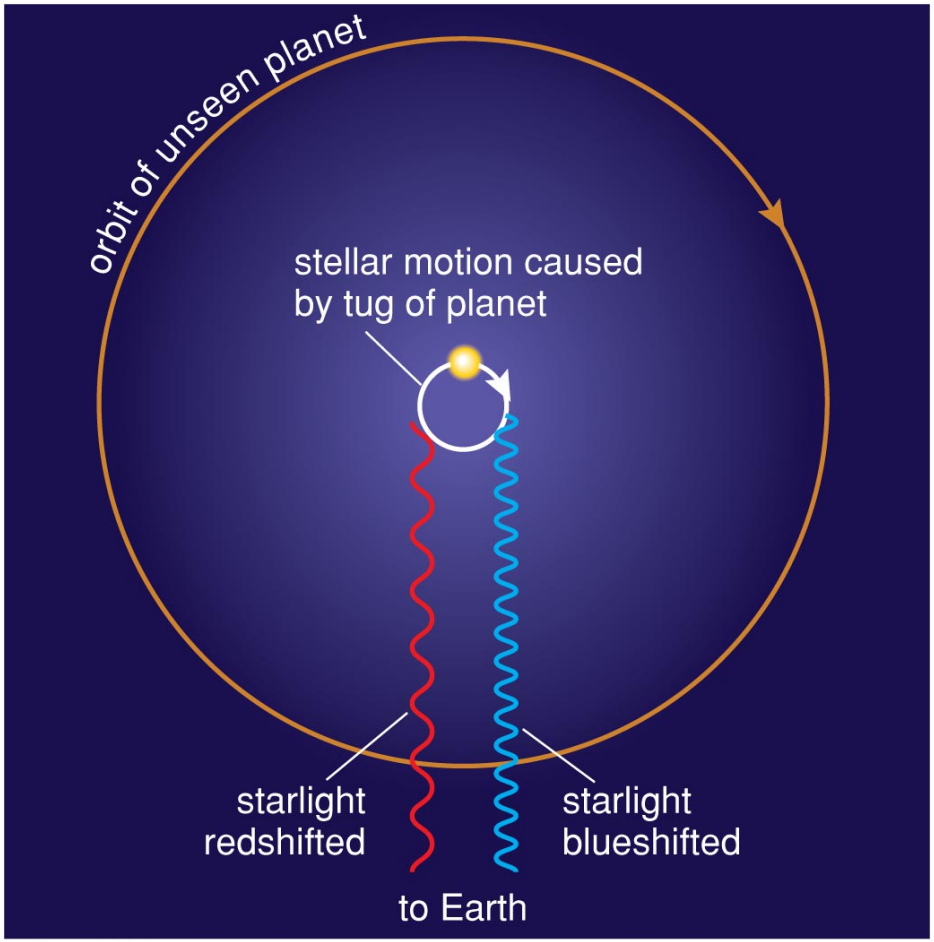
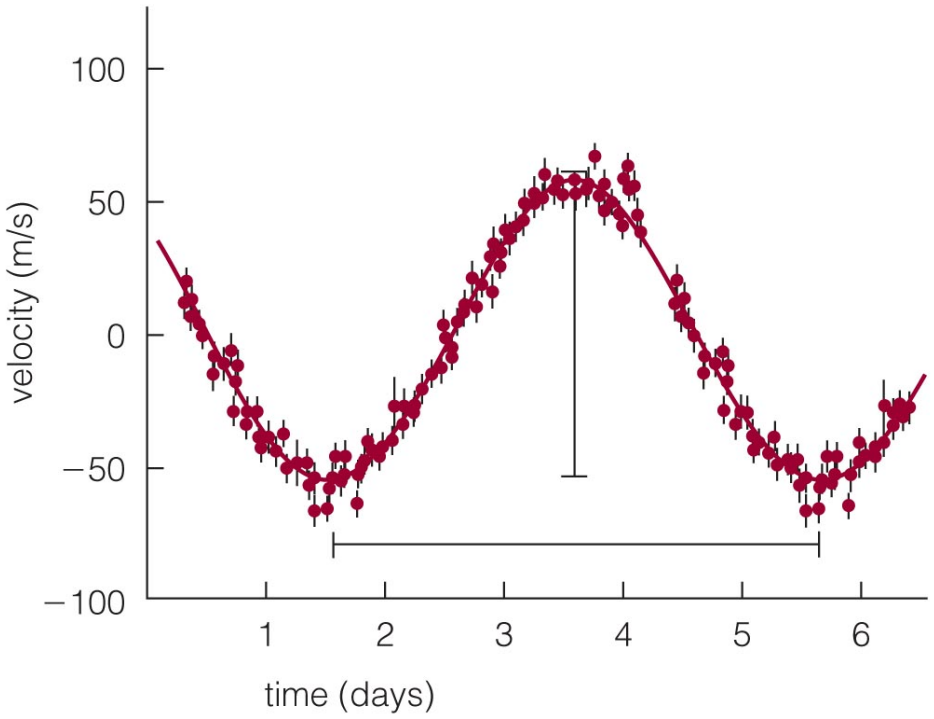
Doppler Technique



- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).
- Sun motion due to:
  - Jupiter: 11 m/s
  - Earth: 10 cm/s

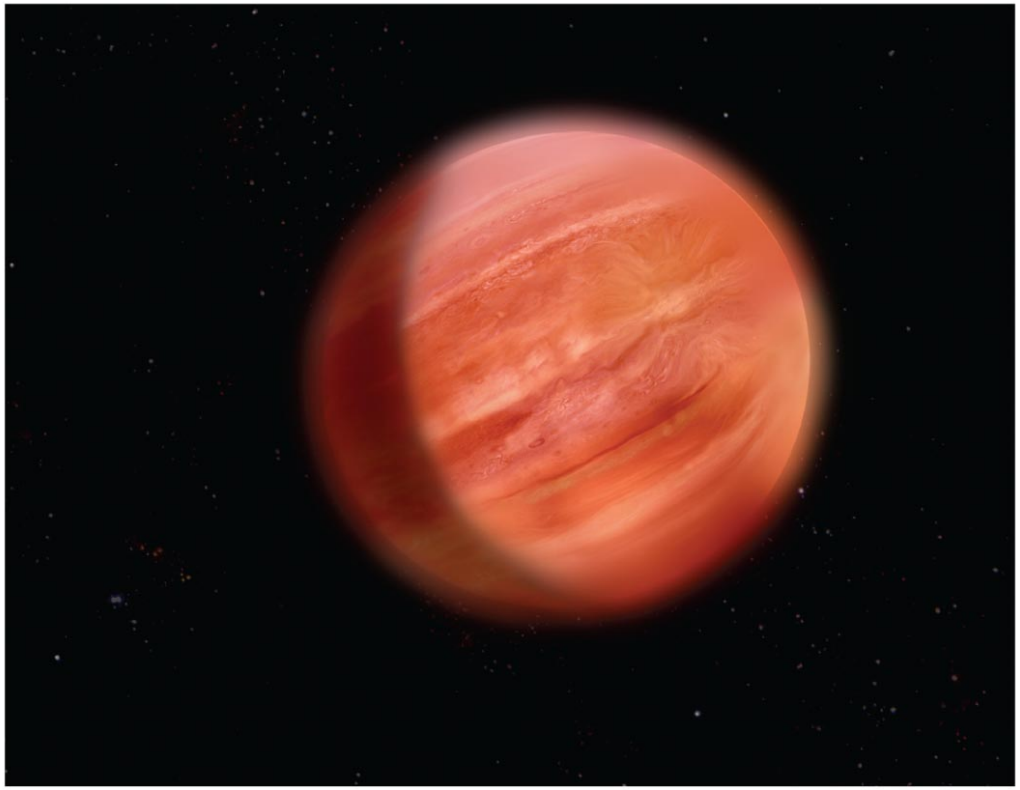
First Extrasolar Planet



a A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

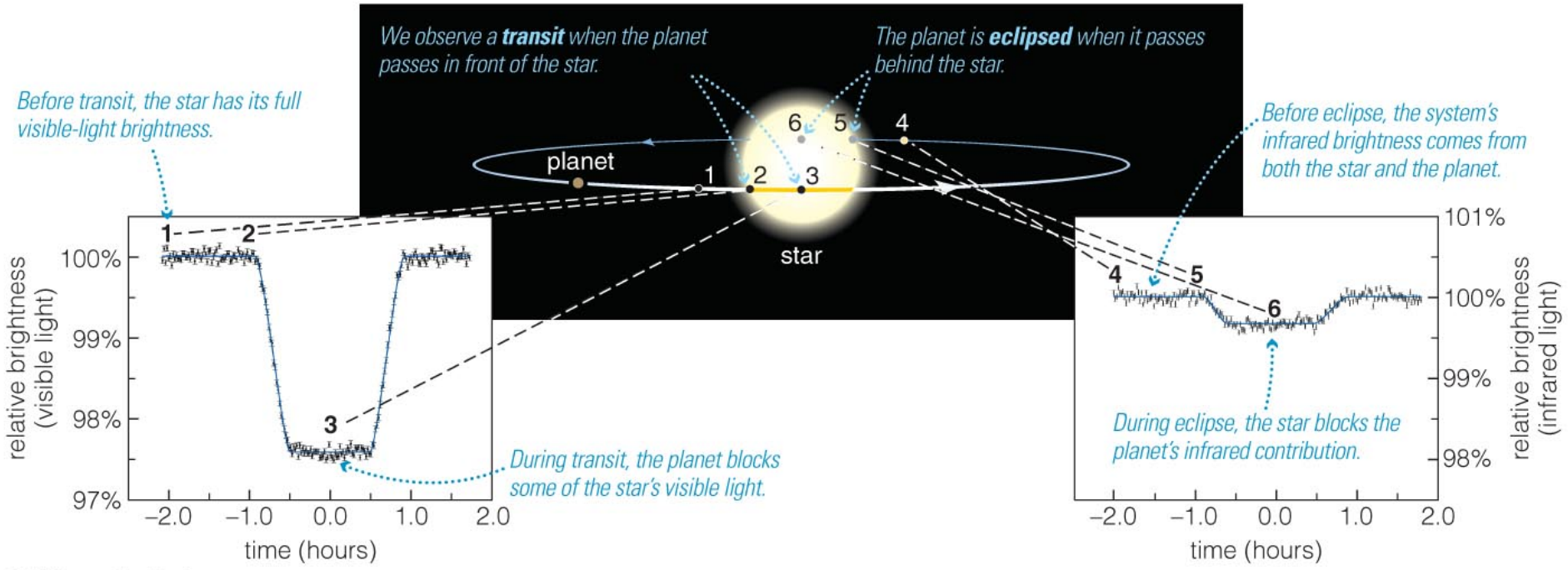
- In 1995: Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- Can only get a lower limit on the mass, since the planet may not be orbiting along our line of sight – we not be measuring all the velocity.

First Extrasolar Planet – A "Hot Jupiter"



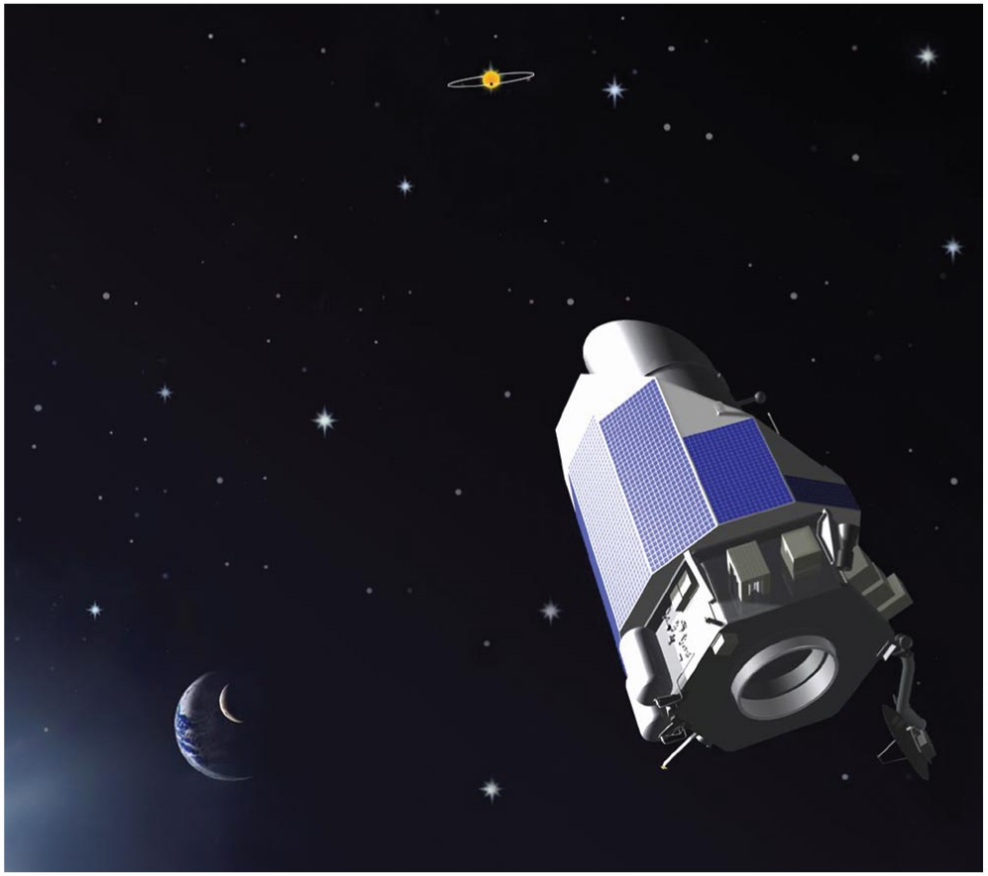
- The planet around 51 Pegasi has a mass at least as big as Jupiter's, despite its small orbital distance.
- *Why are the so-called "hot Jupiters" so weird?*

Transits and Eclipses

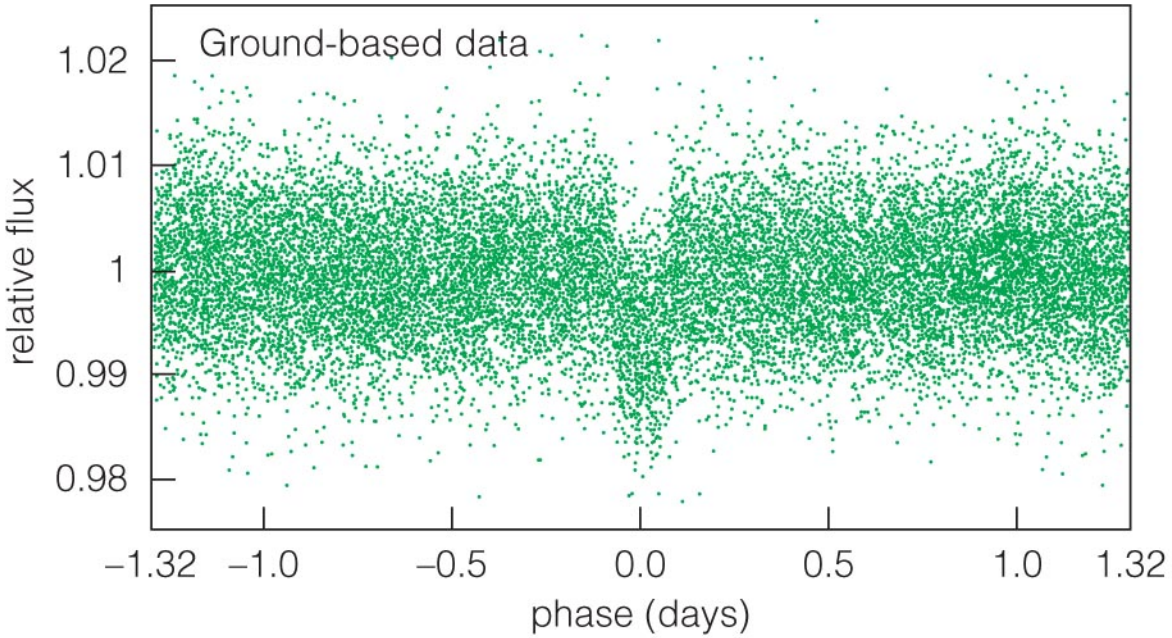


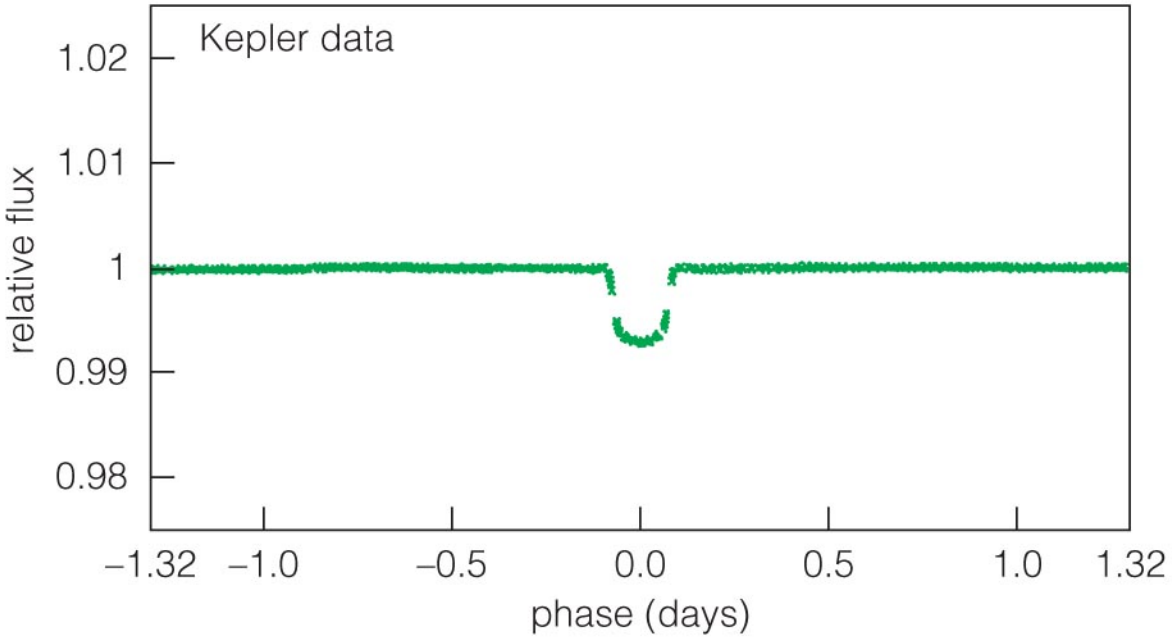
- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
- No orbital tilt: if we have a velocity curve for the star as well, we have an accurate measurement of planet mass

Kepler



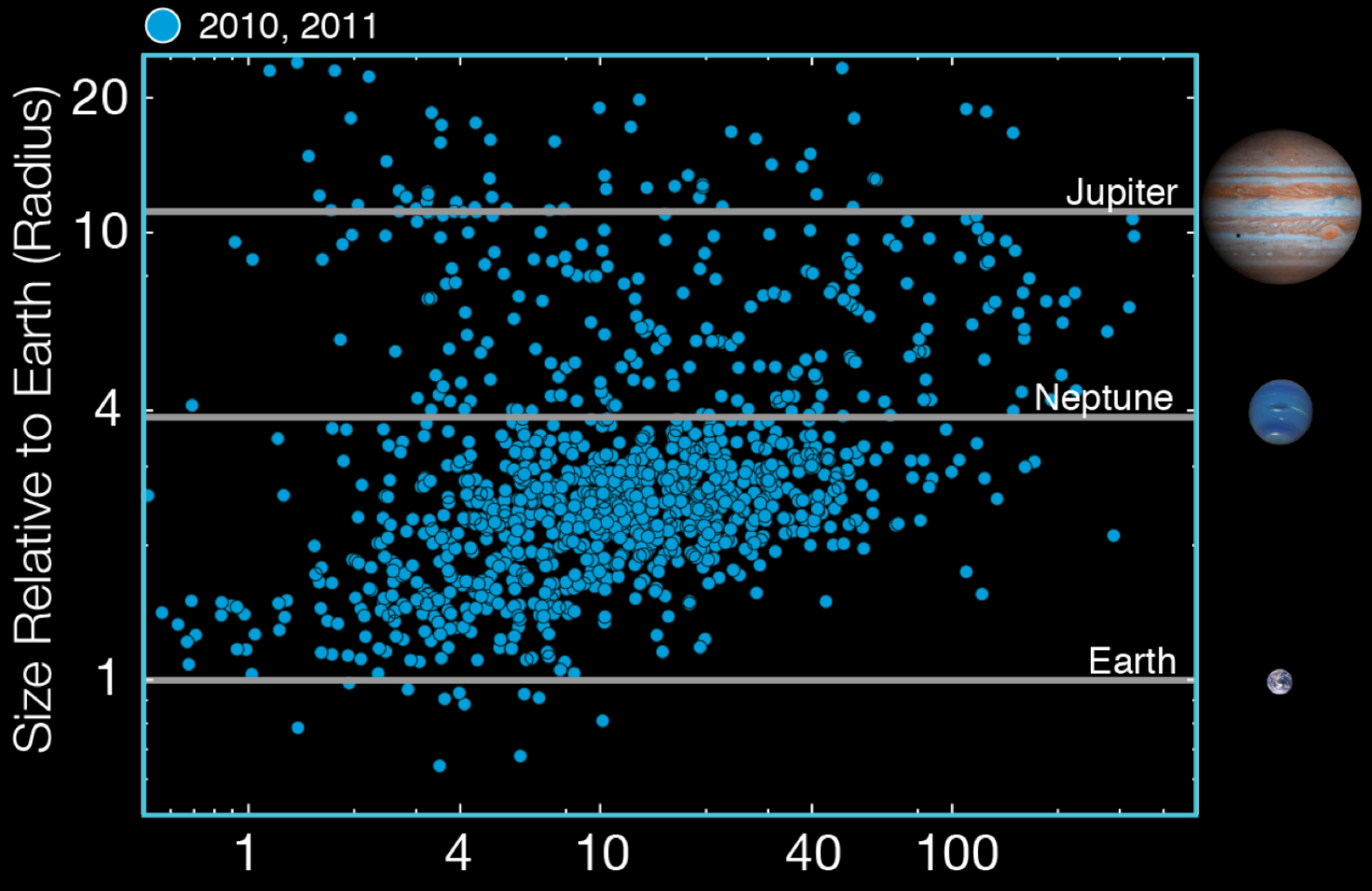
- NASA's *Kepler* mission was launched in 2008 to begin looking for transiting planets.
- It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.





Planet Candidates

As of February 1, 2011

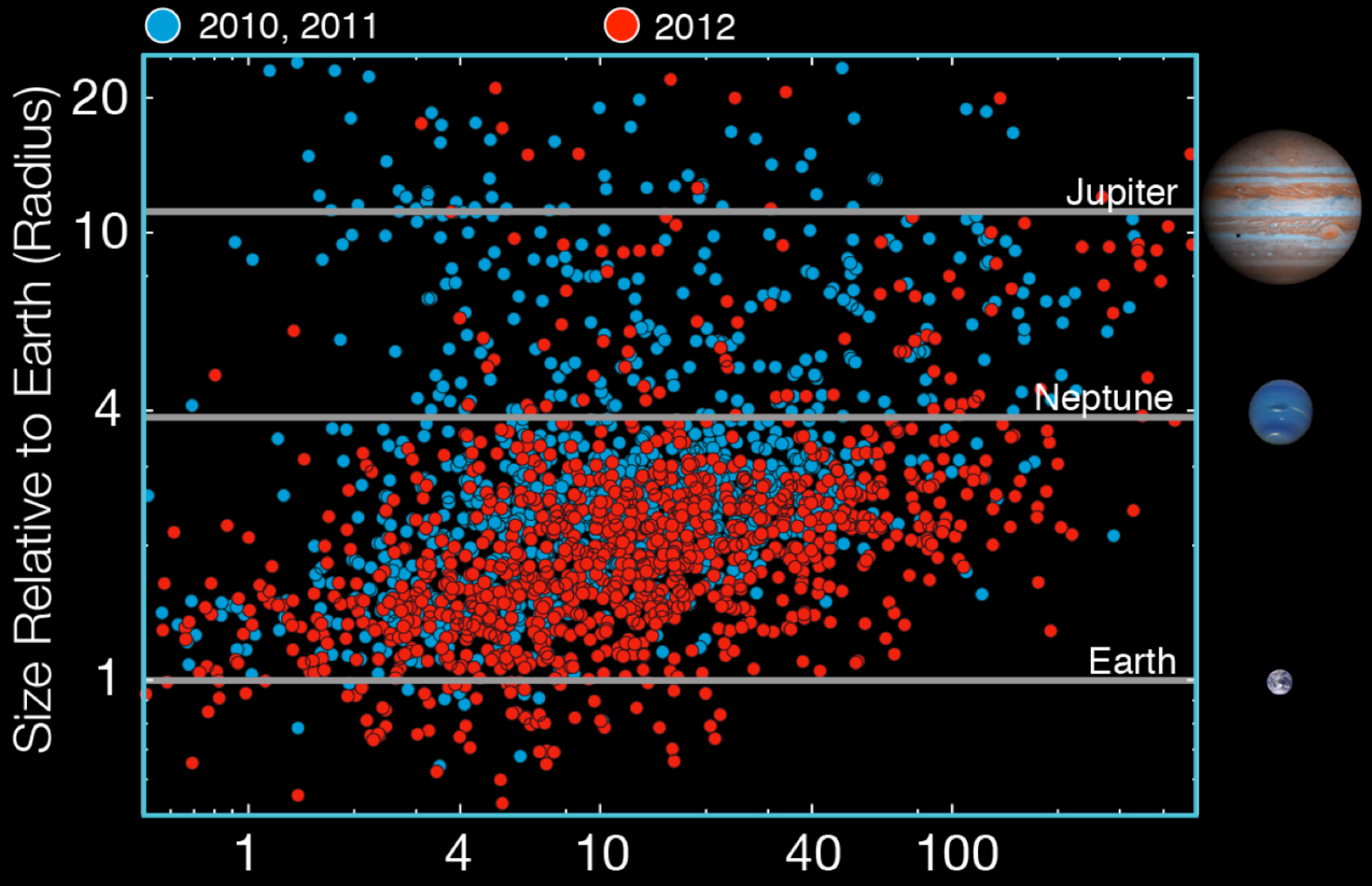


TOTAL = 1,235

Courtesy Christopher Burke

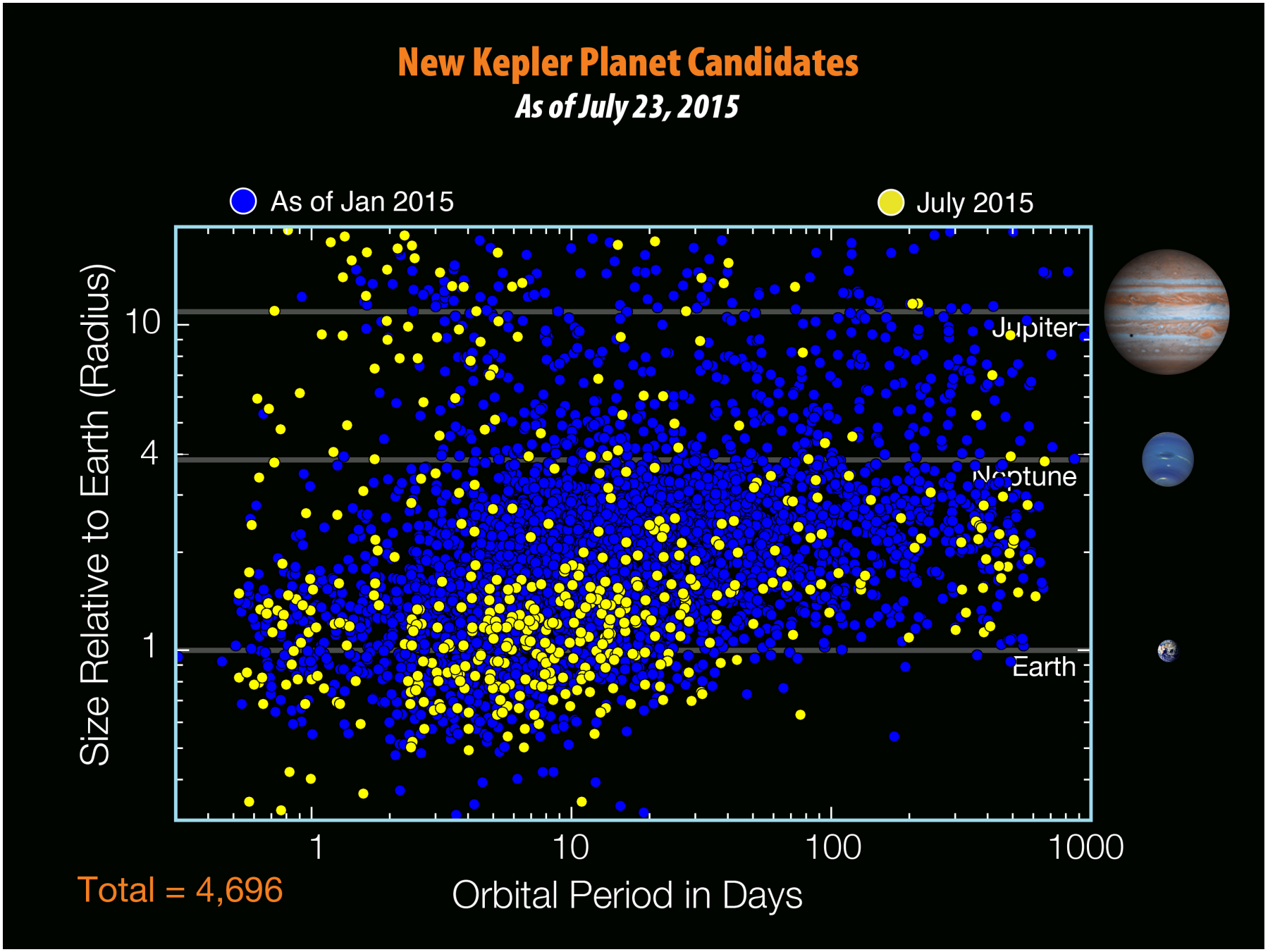
Planet Candidates

As of February 27, 2012



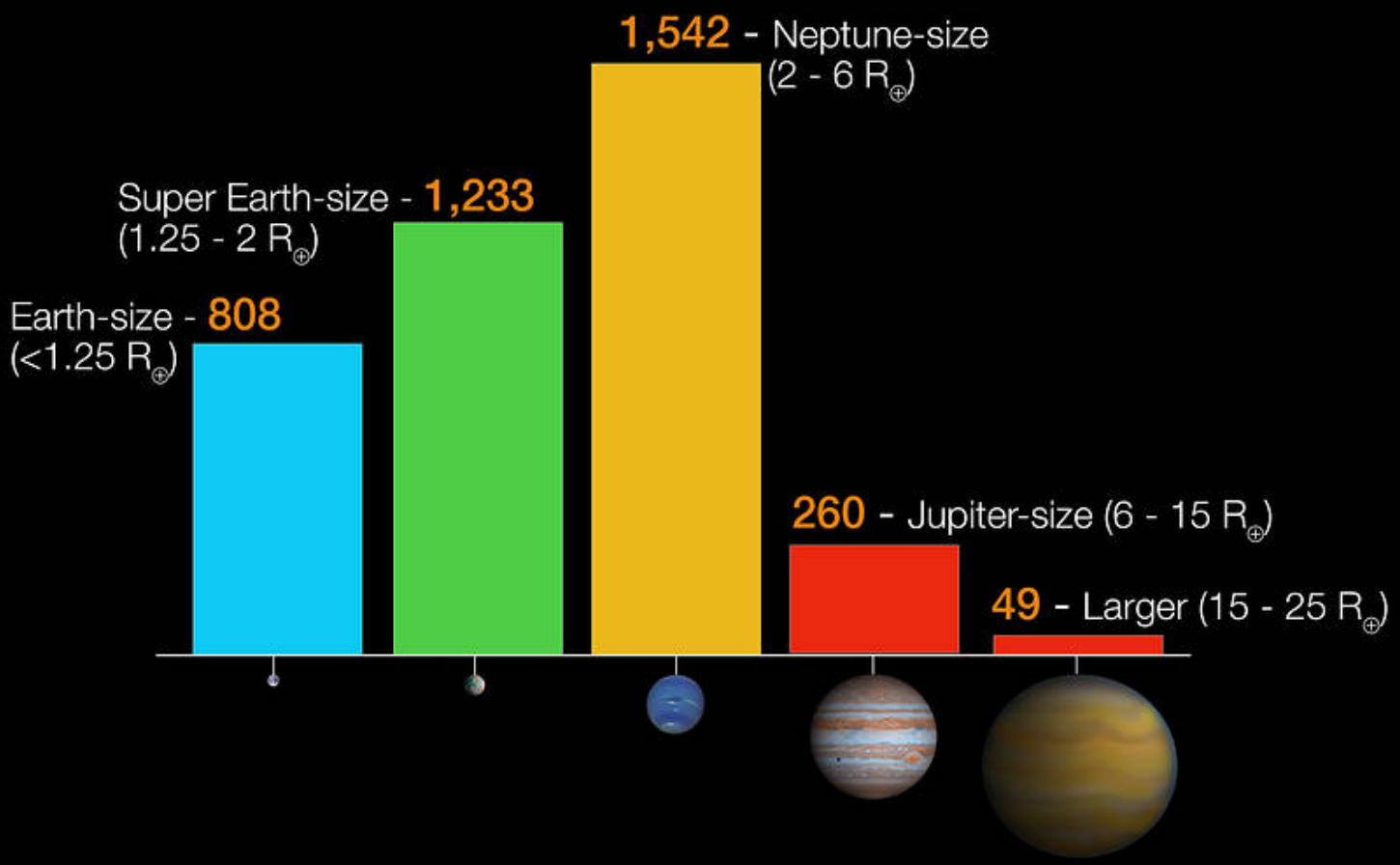
TOTAL = 2,321

Courtesy Christopher Burke


New 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

Sizes of Kepler Planet Candidates

Totals as of January 6, 2015



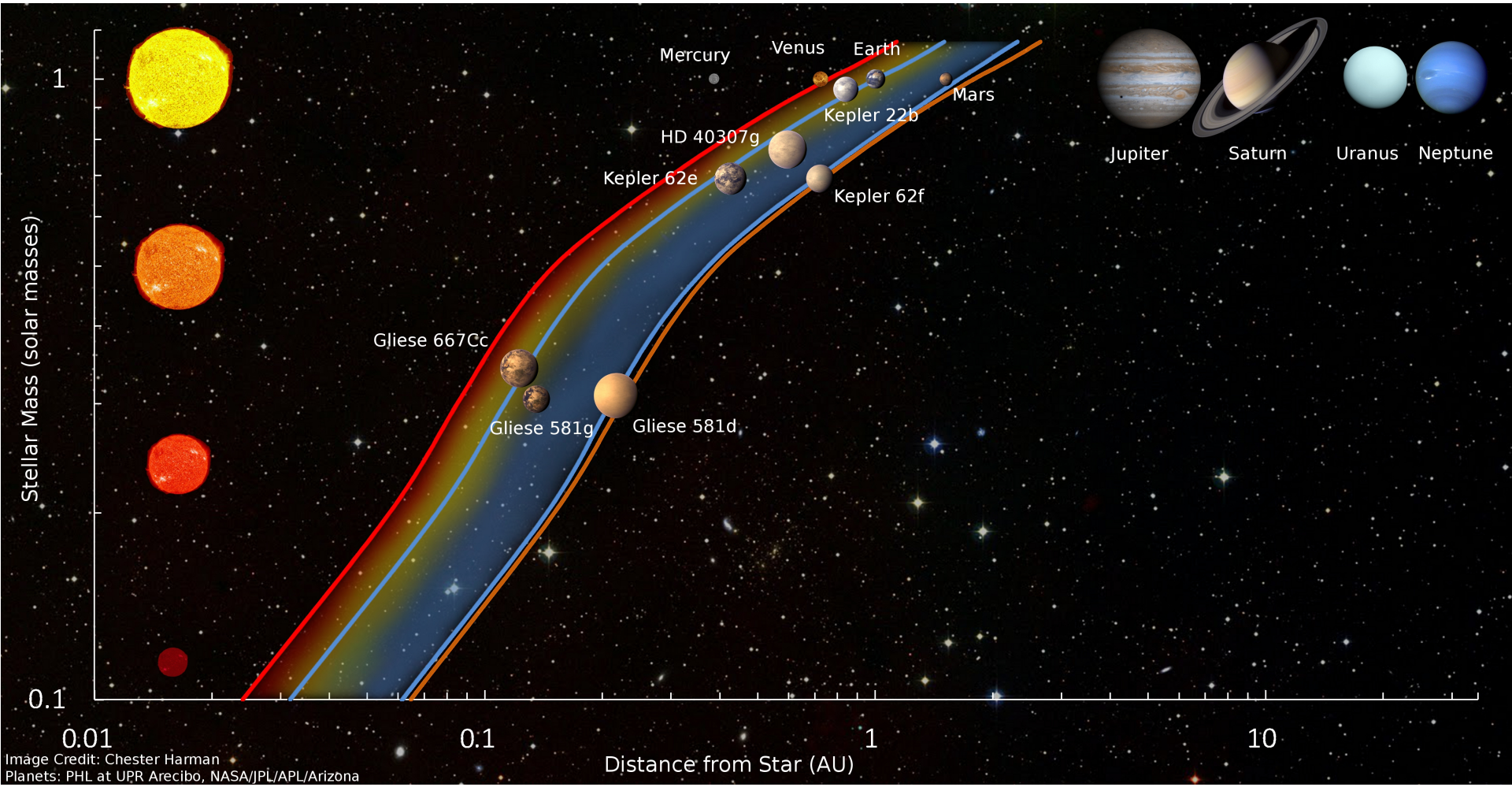
The "Habitable Zone"

The region around a star where planetary surface temperatures would allow for liquid water.

For our solar system, the habitable zone ranges from somewhat inside Earth's orbit to about the distance of Mars (~ 0.9 – 1.4 AU).

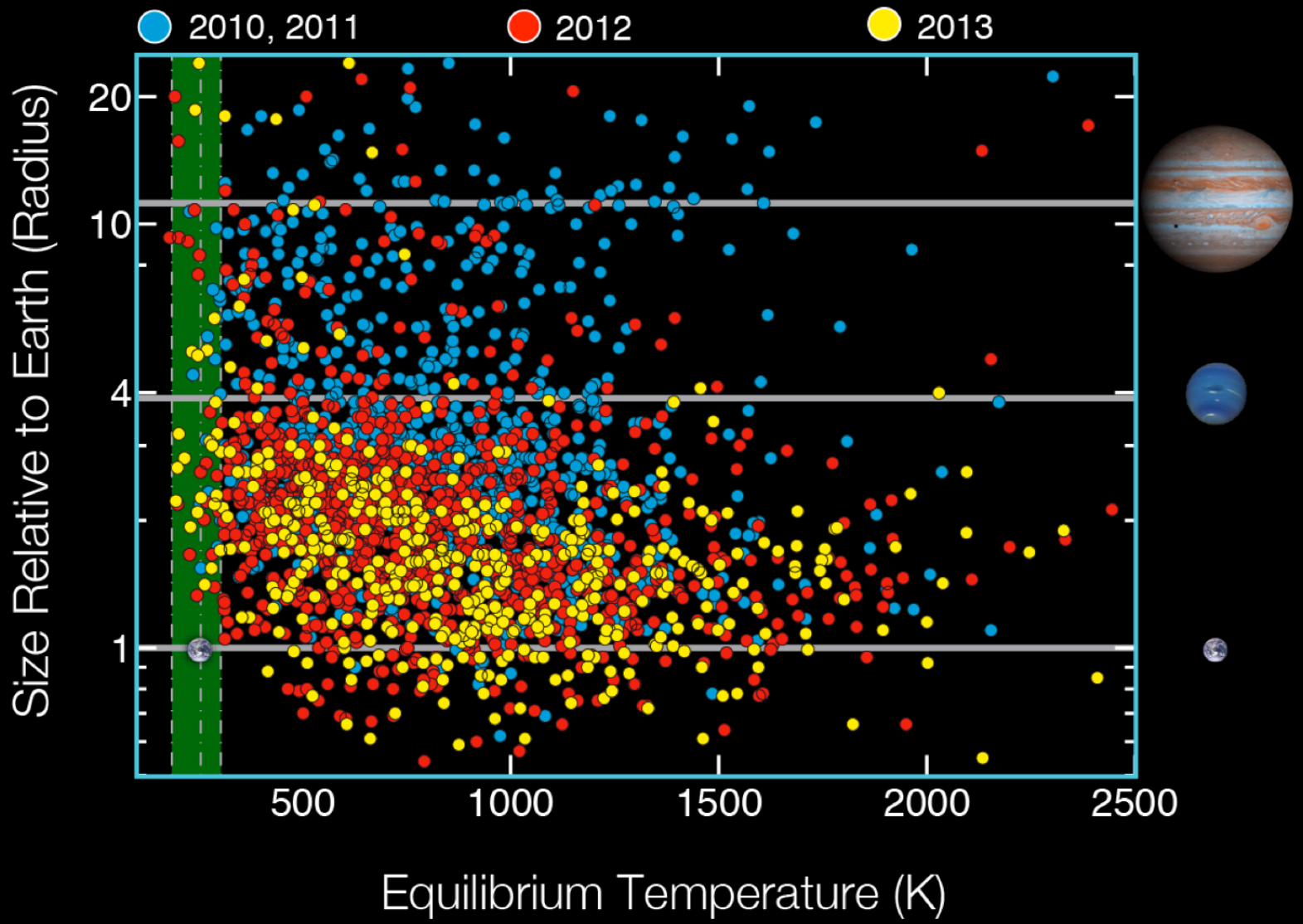
For cooler, fainter stars, the habitable zone is closer to the star.

The “Habitable Zone”



Candidates in the Habitable Zone

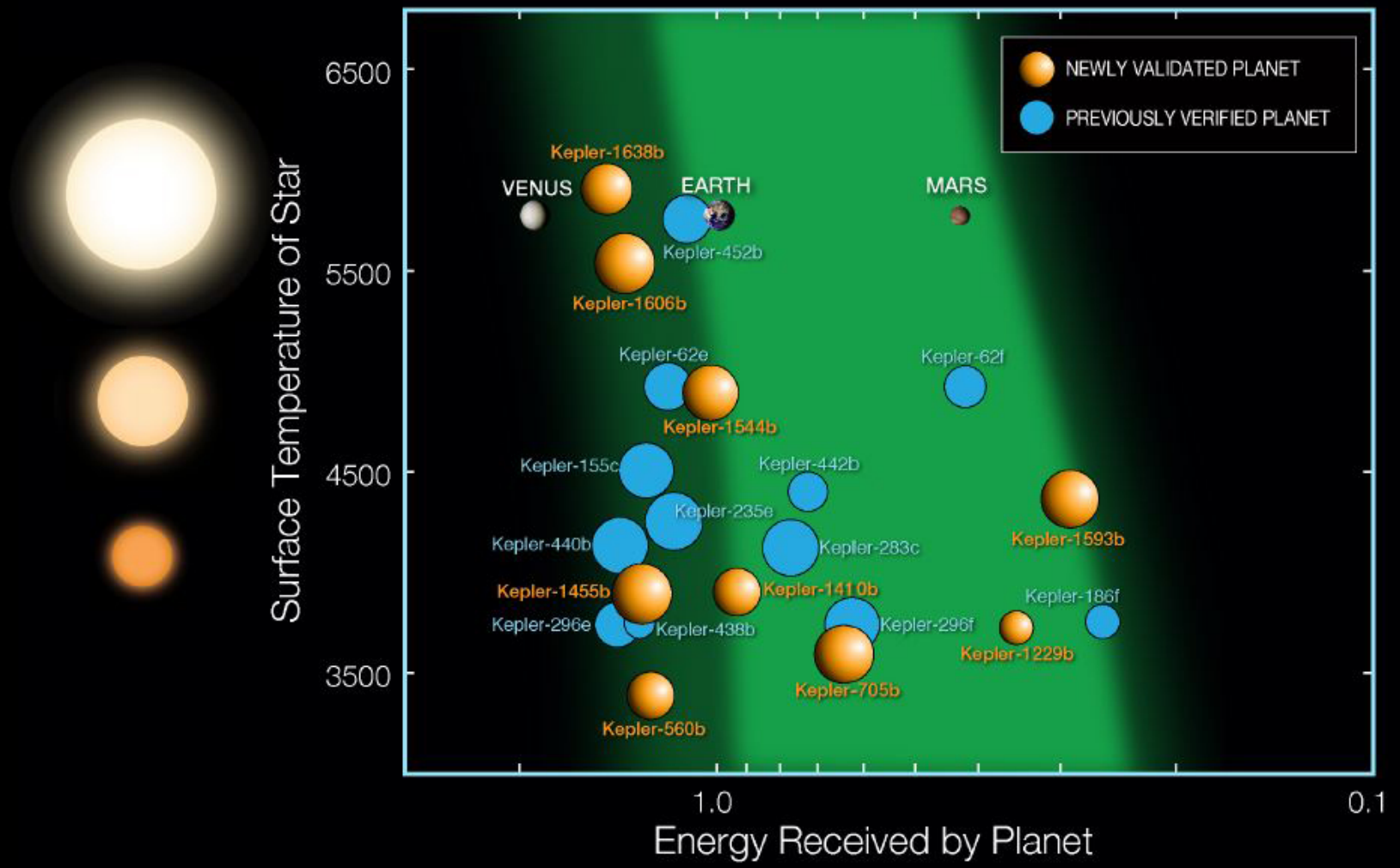
As of January 7, 2013



Courtesy Christopher Burke

Kepler's Small Habitable Zone Planets

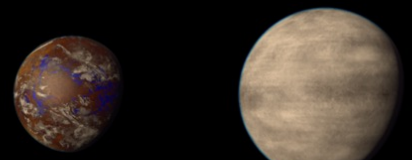
As of May 10, 2016



Potentially Habitable Exoplanets

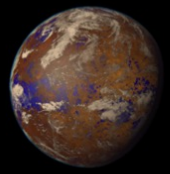
PHL

Ranked by Distance from Earth (light years)



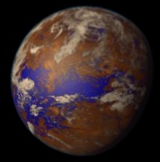
[4.2 ly]
Proxima Cen b

[13 ly]
Kapteyn b*

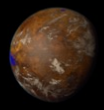


[22 ly]
GJ 667 C c

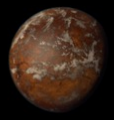
[22 ly]
GJ 667 C e*



[22 ly]
GJ 667 C f*



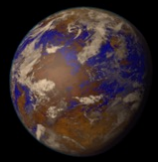
[39 ly]
TRAPPIST-1 e



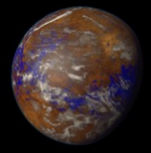
[39 ly]
TRAPPIST-1 f

[39 ly]
TRAPPIST-1 g

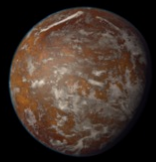
[561 ly]
Kepler-186 f



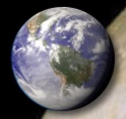
[770 ly]
Kepler-1229 b



[1115 ly]
Kepler-442 b



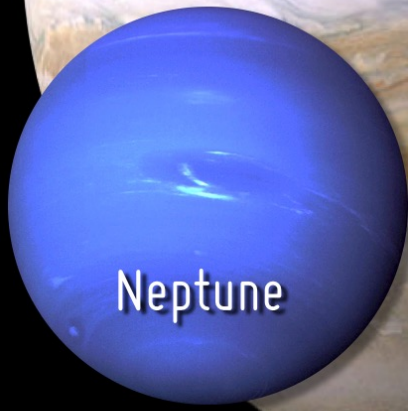
[1200 ly]
Kepler-62 f



Earth

Mars

Jupiter



Neptune

Artistic representations. Earth, Mars, Jupiter, and Neptune for scale.
Distance is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) February 23, 2017

What have we learned?

- **Why is it so challenging to learn about extrasolar planets?**
  - Direct starlight is billions of times brighter than the starlight reflected from planets.
- **How can a star's motion reveal the presence of planets?**
  - A star's periodic motion (detected through Doppler shifts or by measuring its motion across the sky) tells us about its planets.
  - Transiting planets periodically reduce a star's brightness.

What have we learned?

- **How can changes in a star's brightness reveal the presence of planets?**
  - Transiting planets periodically reduce a star's brightness.
  - The *Kepler* mission has found thousands of candidates using this method.

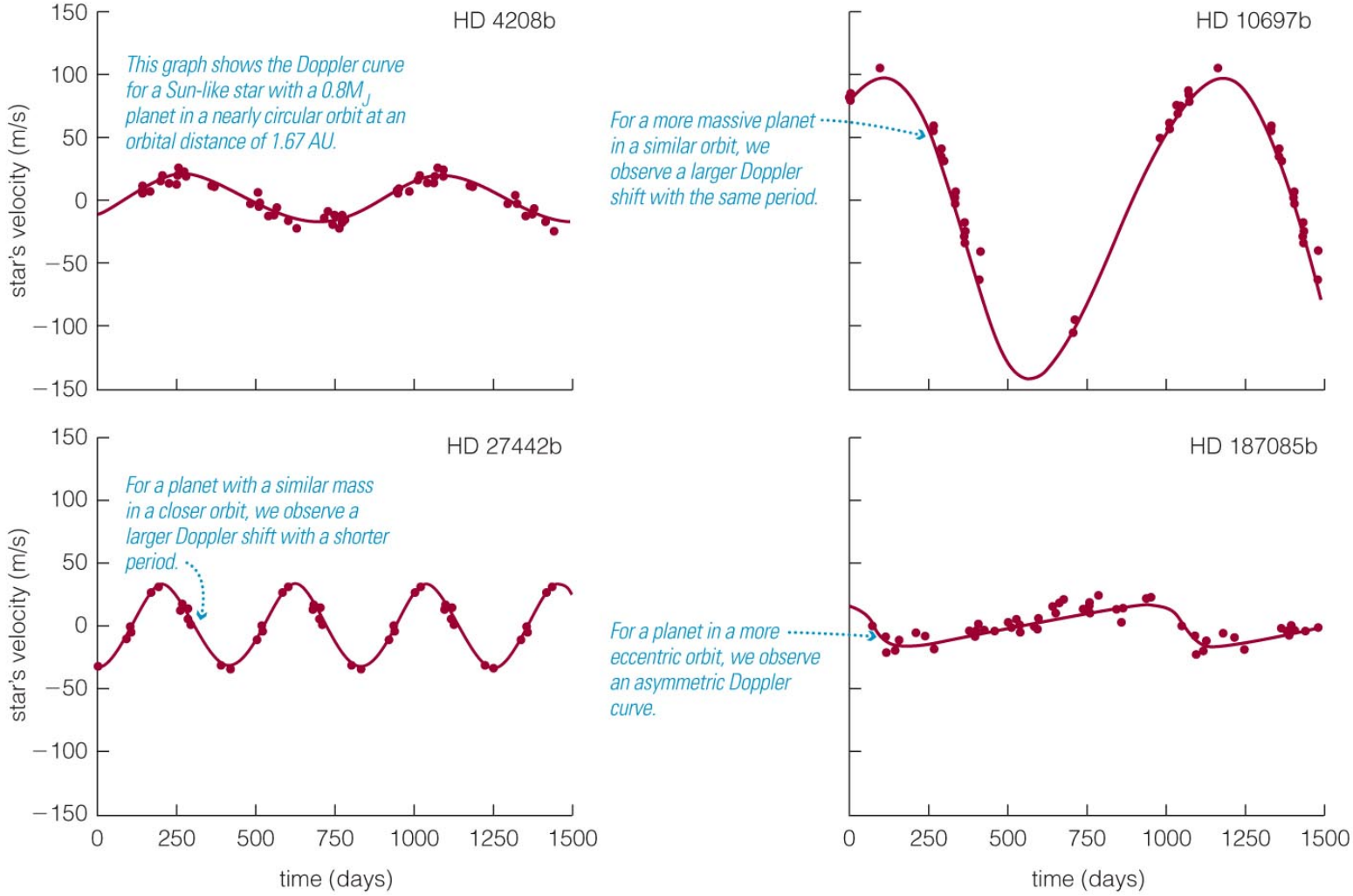
13.2 The Nature of Planets Around Other Stars

- Our goals for learning:
  - **What properties of extrasolar planets can we measure?**
  - **How do extrasolar planets compare with planets in our solar system?**

Measurable Properties

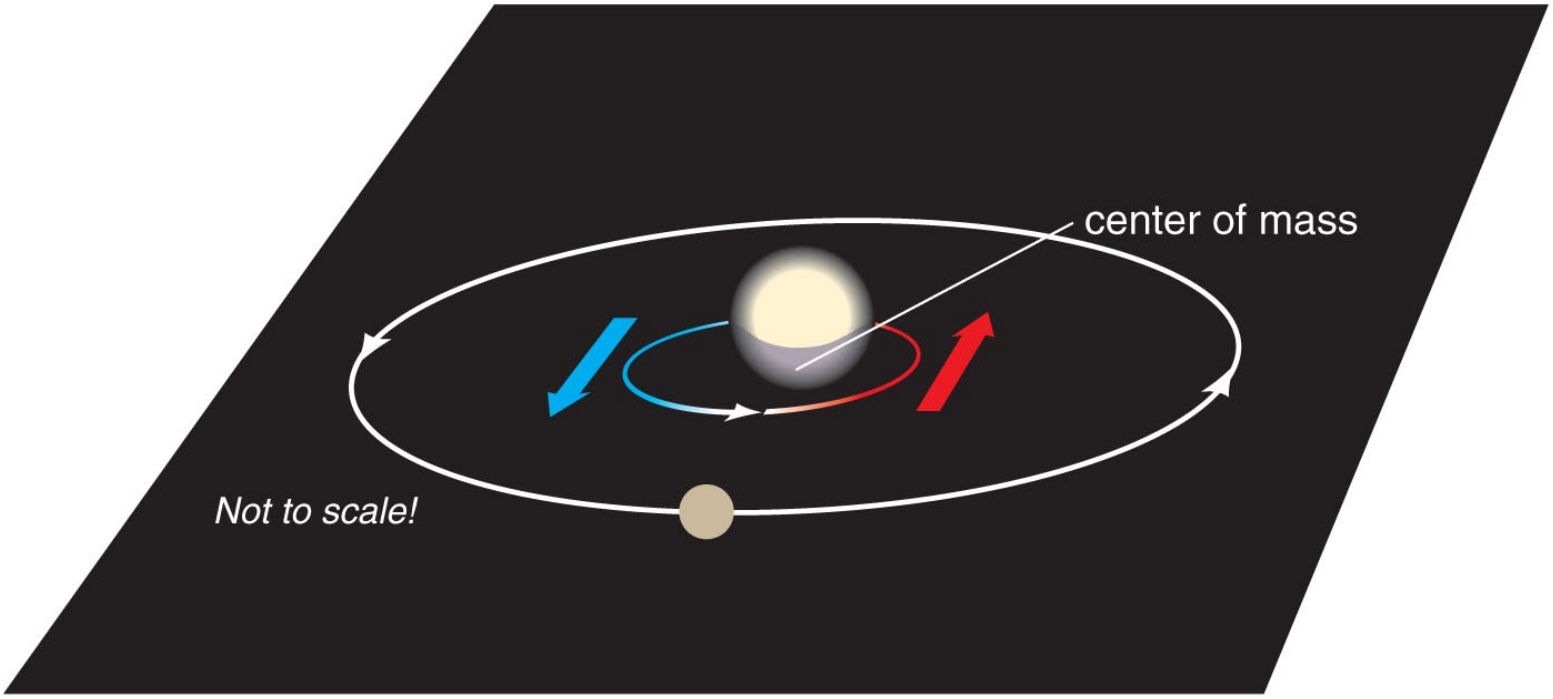
- Orbital period, distance, and shape
- Planet mass, size, and density
- Atmospheric properties

What can Doppler shifts tell us?



- Doppler shift data tell us about a planet's mass and the shape of its orbit.

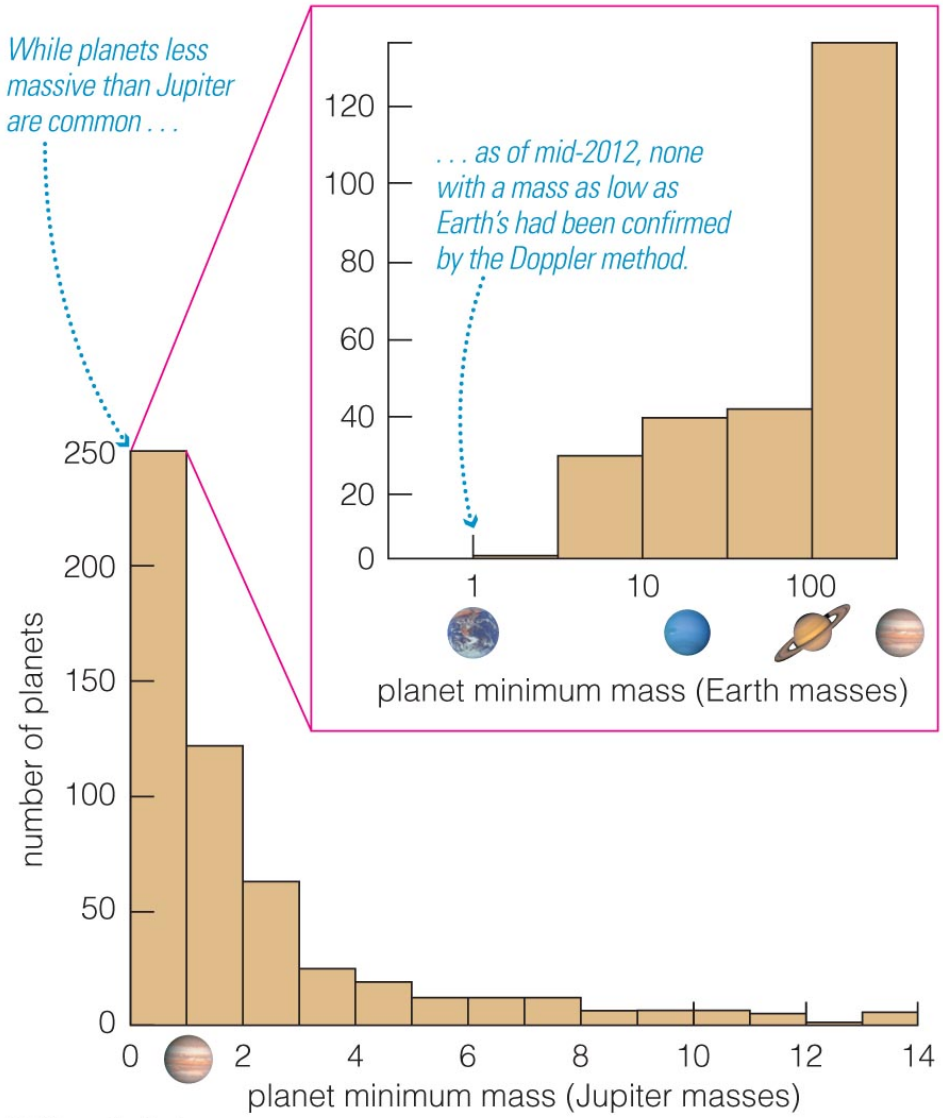
Planet Mass and Orbit Tilt



b We can detect a Doppler shift only if some part of the orbital velocity is directed toward or away from us. The more an orbit is tilted toward edge-on, the greater the shift we observe.

- We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.
- Doppler data give us lower limits on masses.

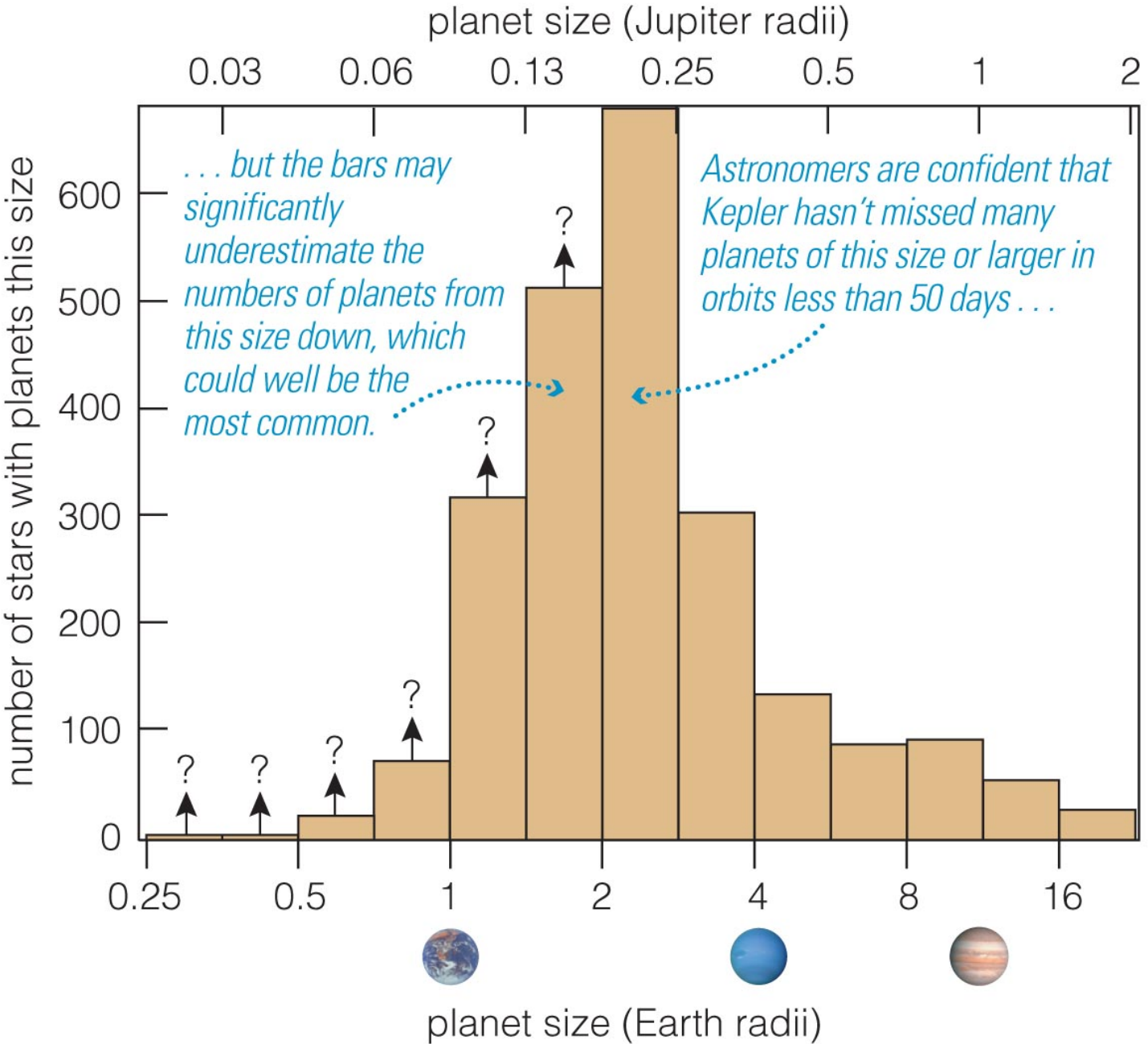
Masses of Extrasolar Planets



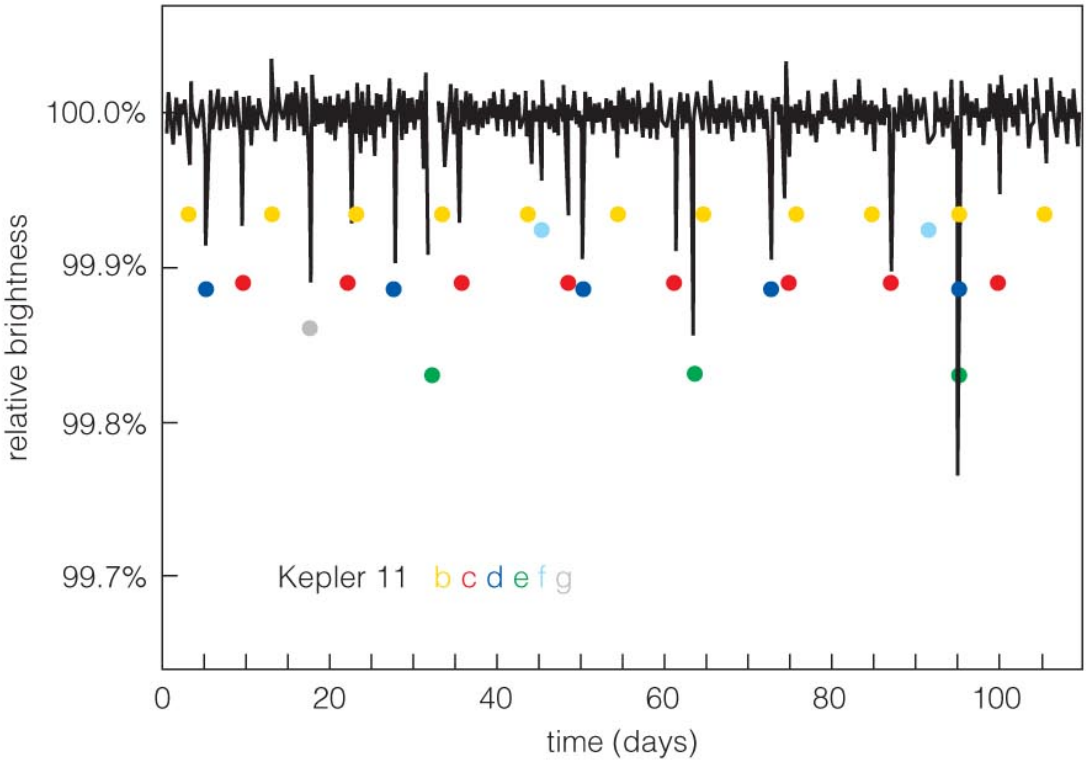
Doppler results

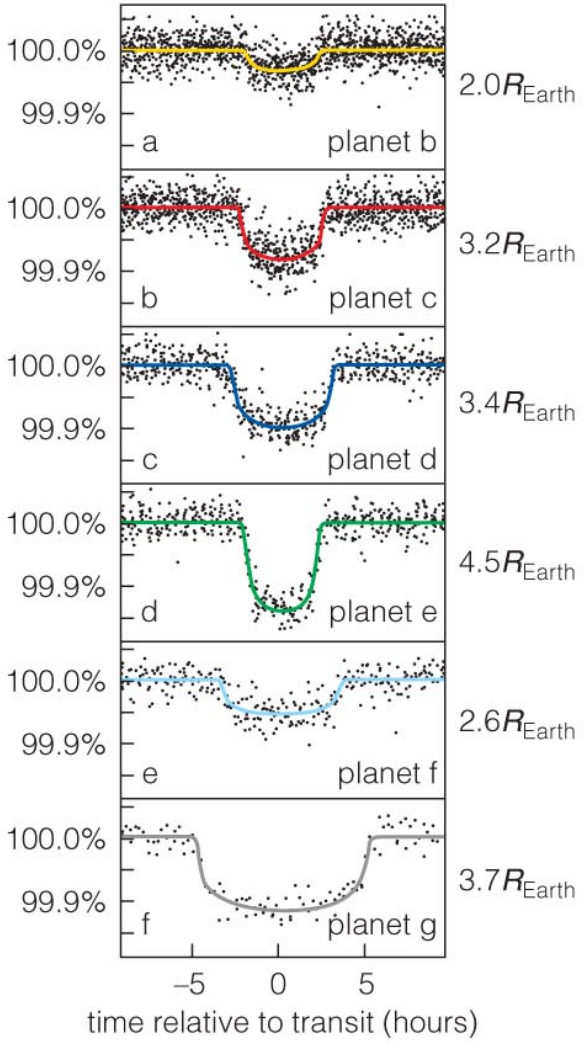
- Most of the detected planets have greater mass than Jupiter.
- Planets with smaller masses are harder to detect with Doppler technique.

Planet Sizes (from Kepler)



The Kepler 11 system

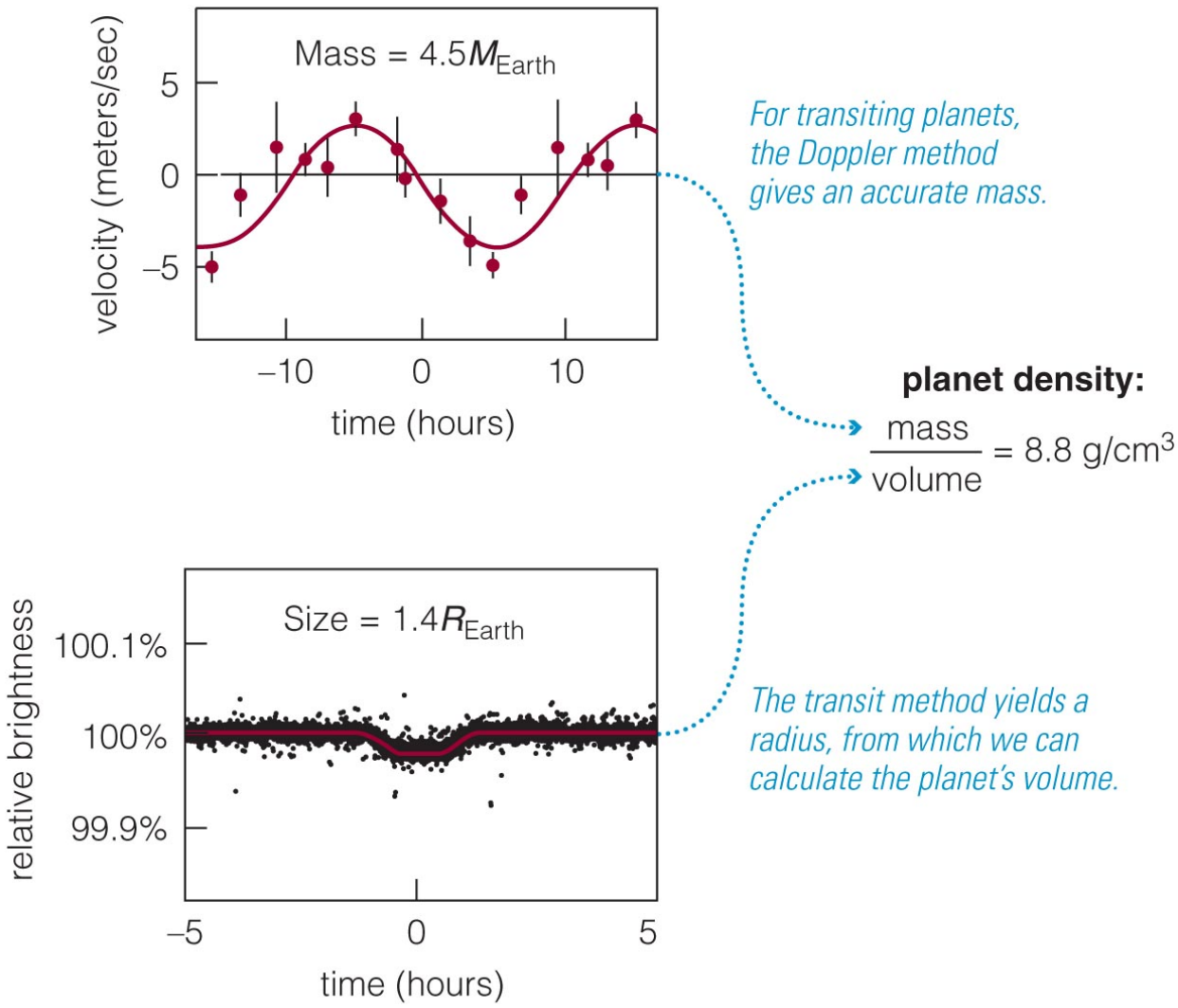




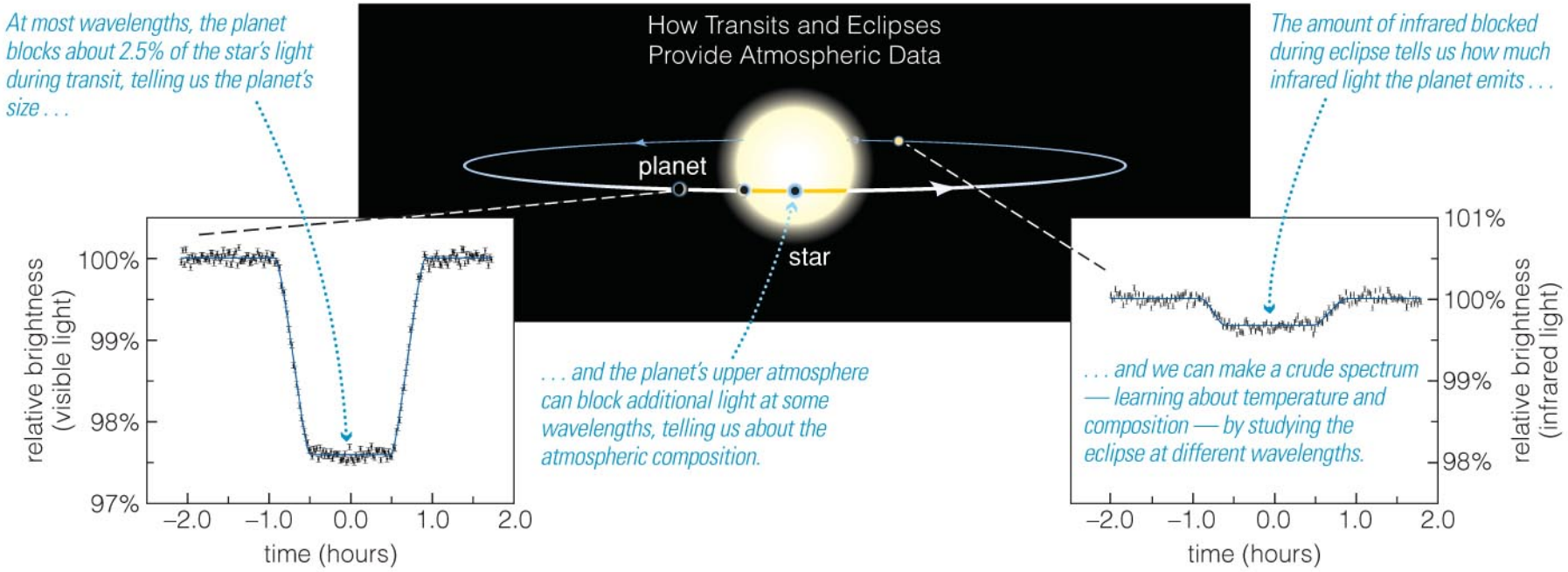
- The periods and sizes of Kepler 11's 6 known planets can be determined using transit data.

Calculating density

Using mass, determined using the Doppler technique, and size, determined using the transit technique, density can be calculated.

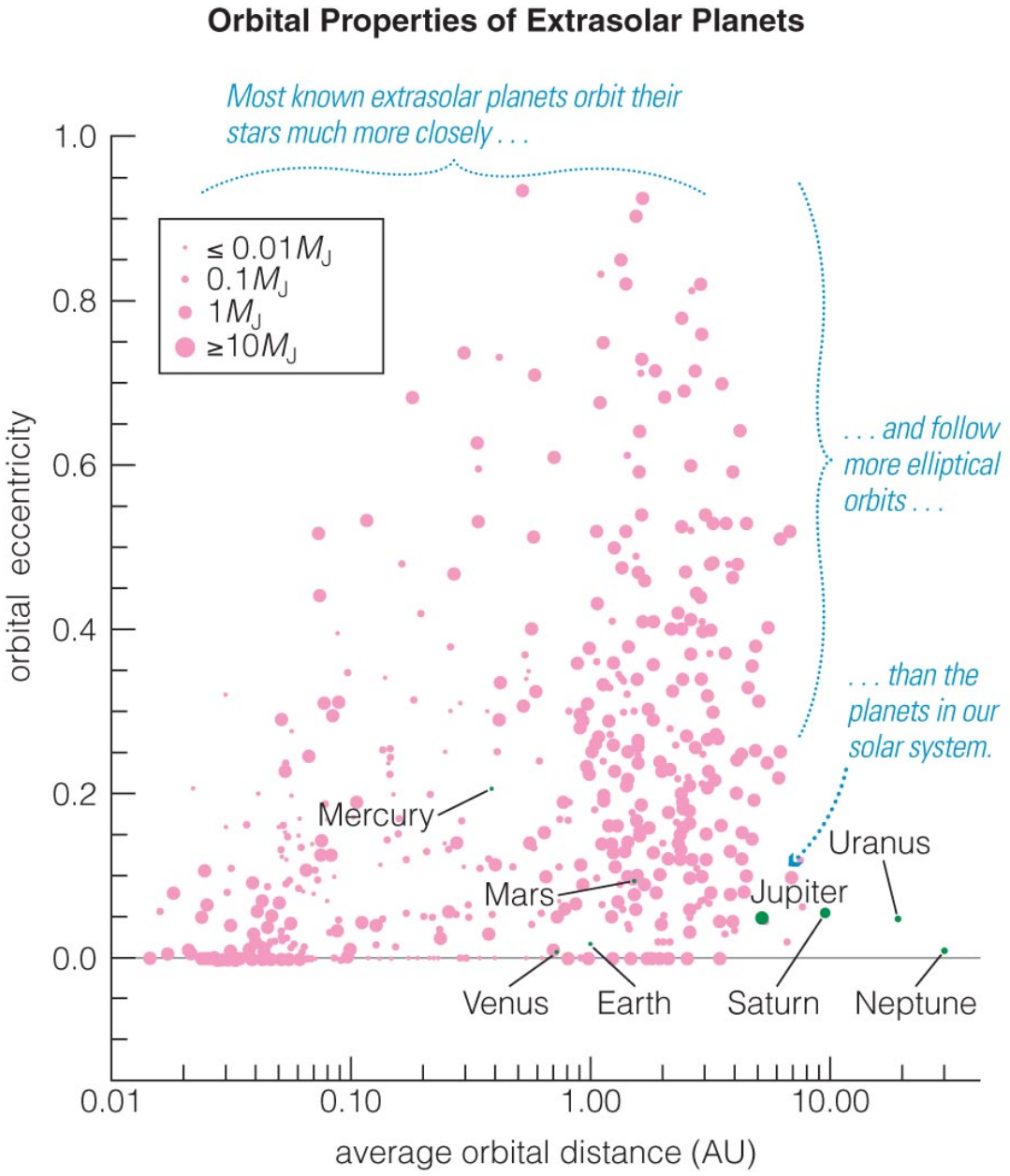


Spectrum During Transit



- Change in spectrum during a transit tells us about the composition of planet's atmosphere.

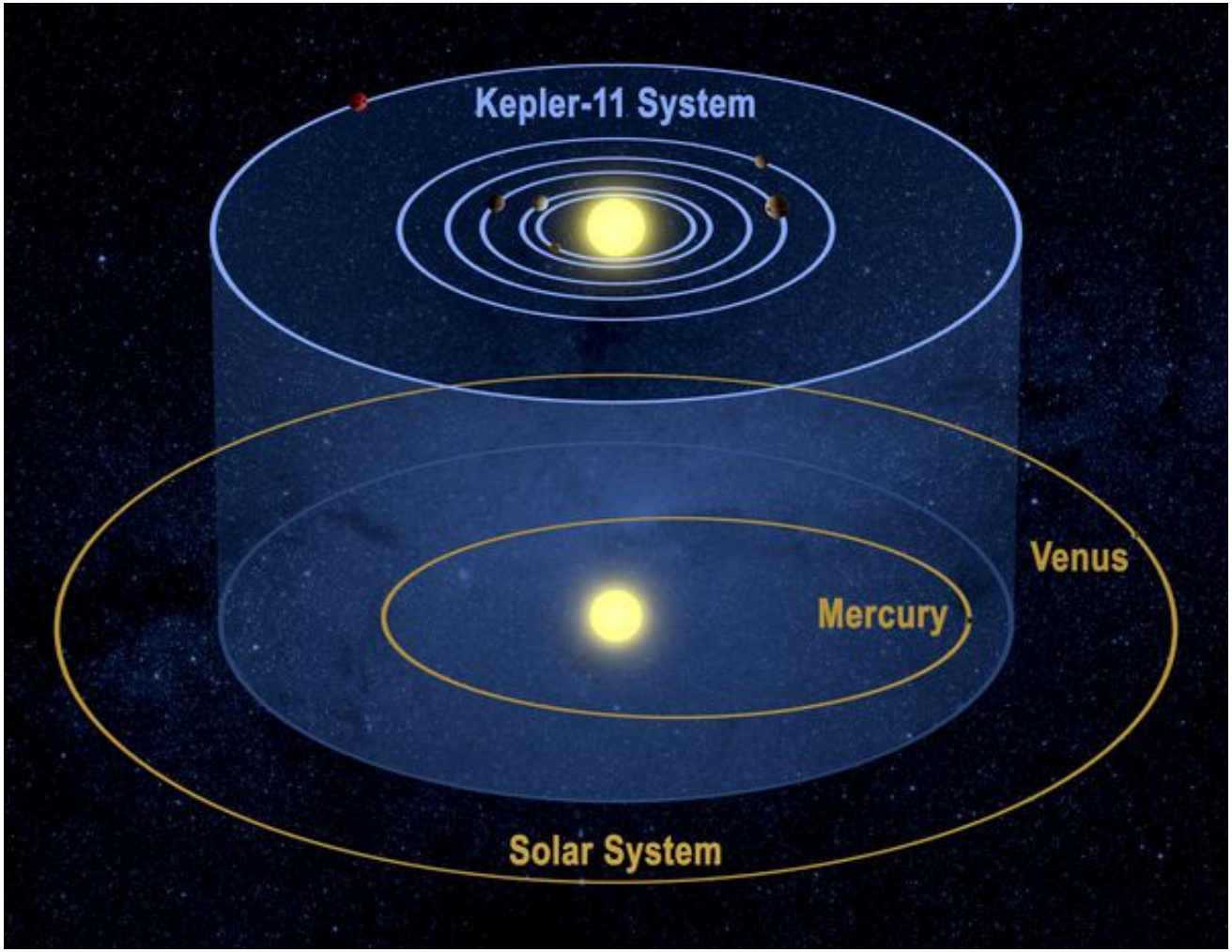
Orbits of Extrasolar Planets



Most of the detected planets have orbits smaller than Jupiter's.

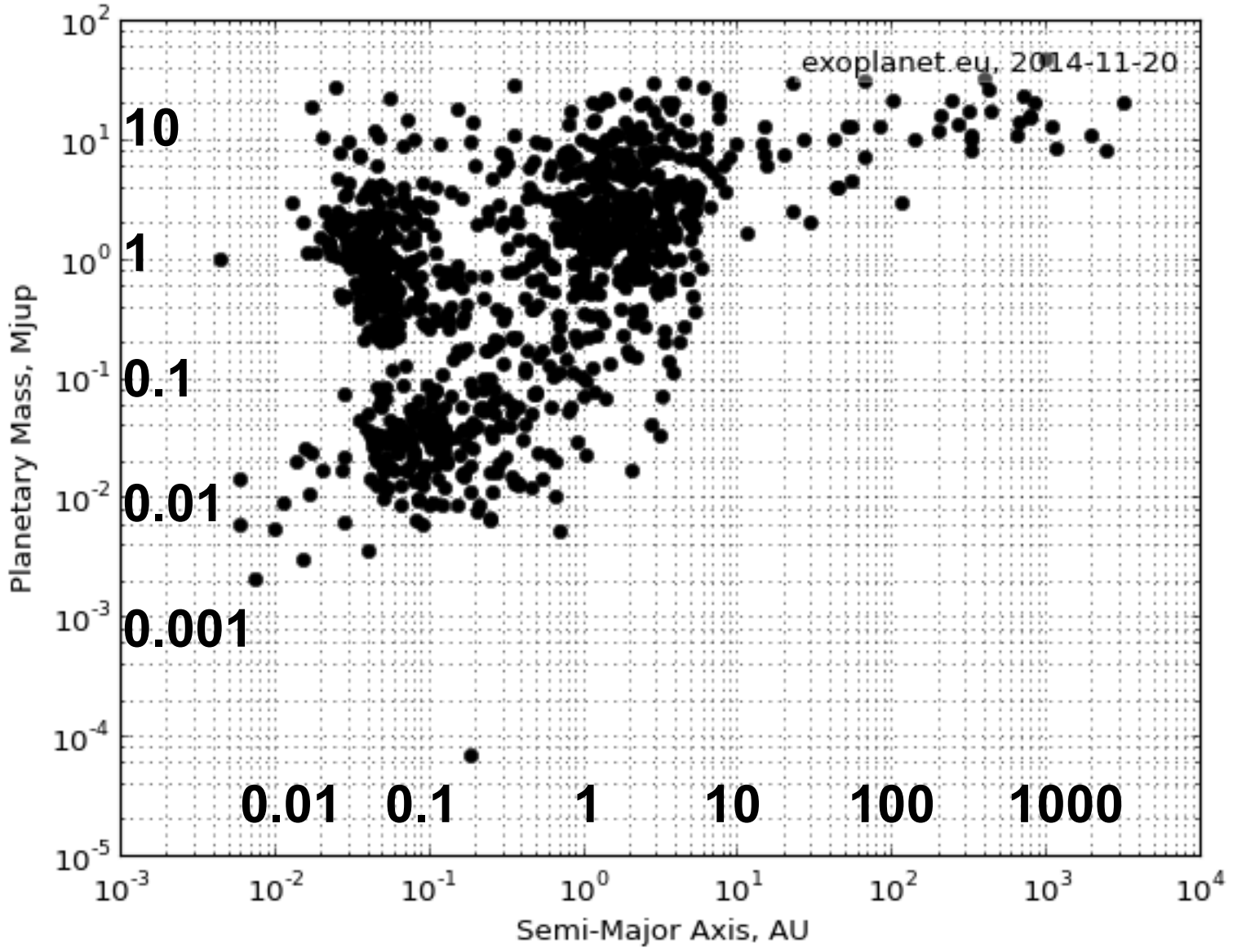
Planets at greater distances are harder to detect with either the Doppler or Transit techniques. (Why?)

Tightly Packed Systems: Kepler 11

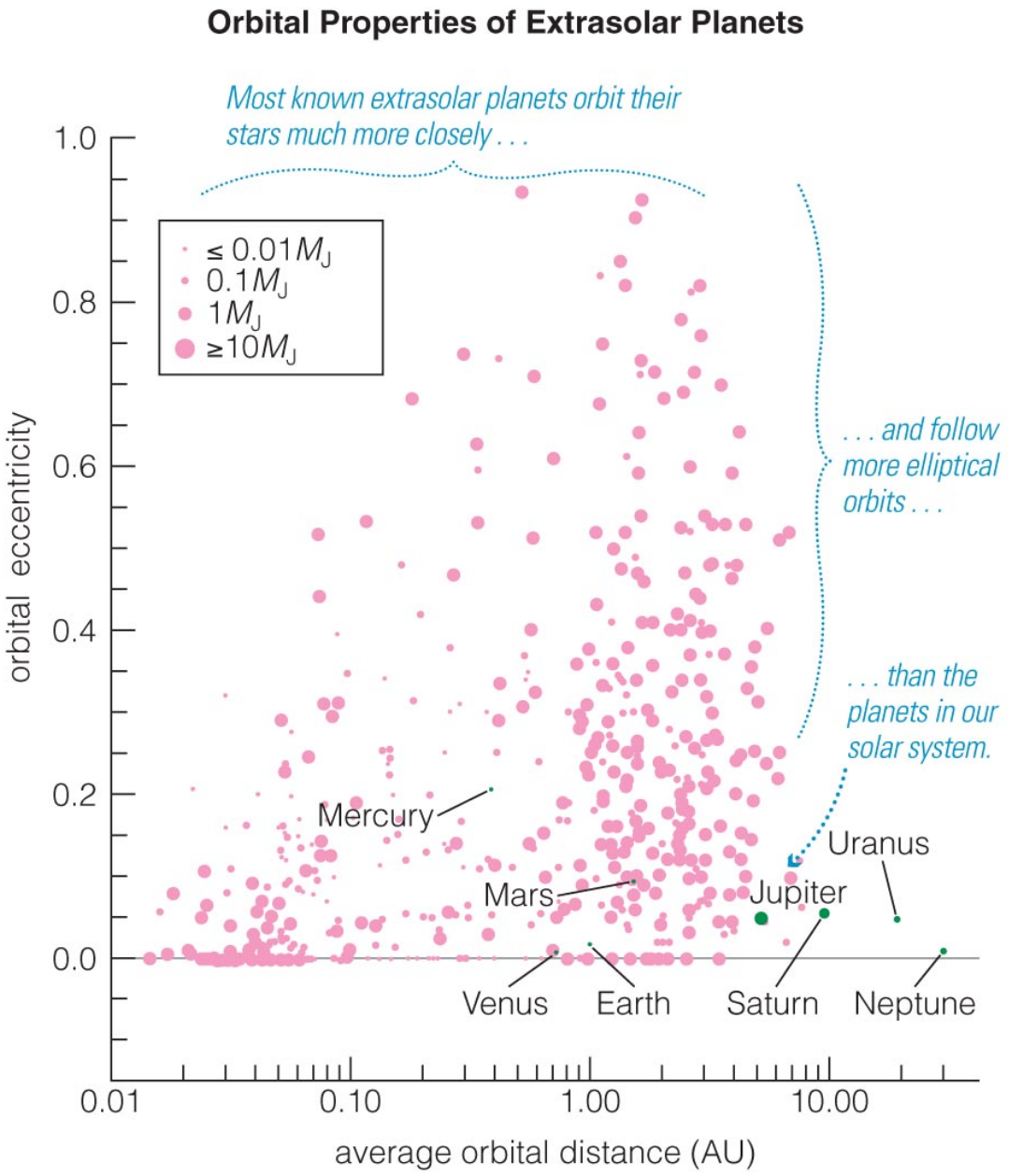


Take a look at a graphic of all the Kepler systems!

Orbits of Extrasolar Planets: Mass/Distance

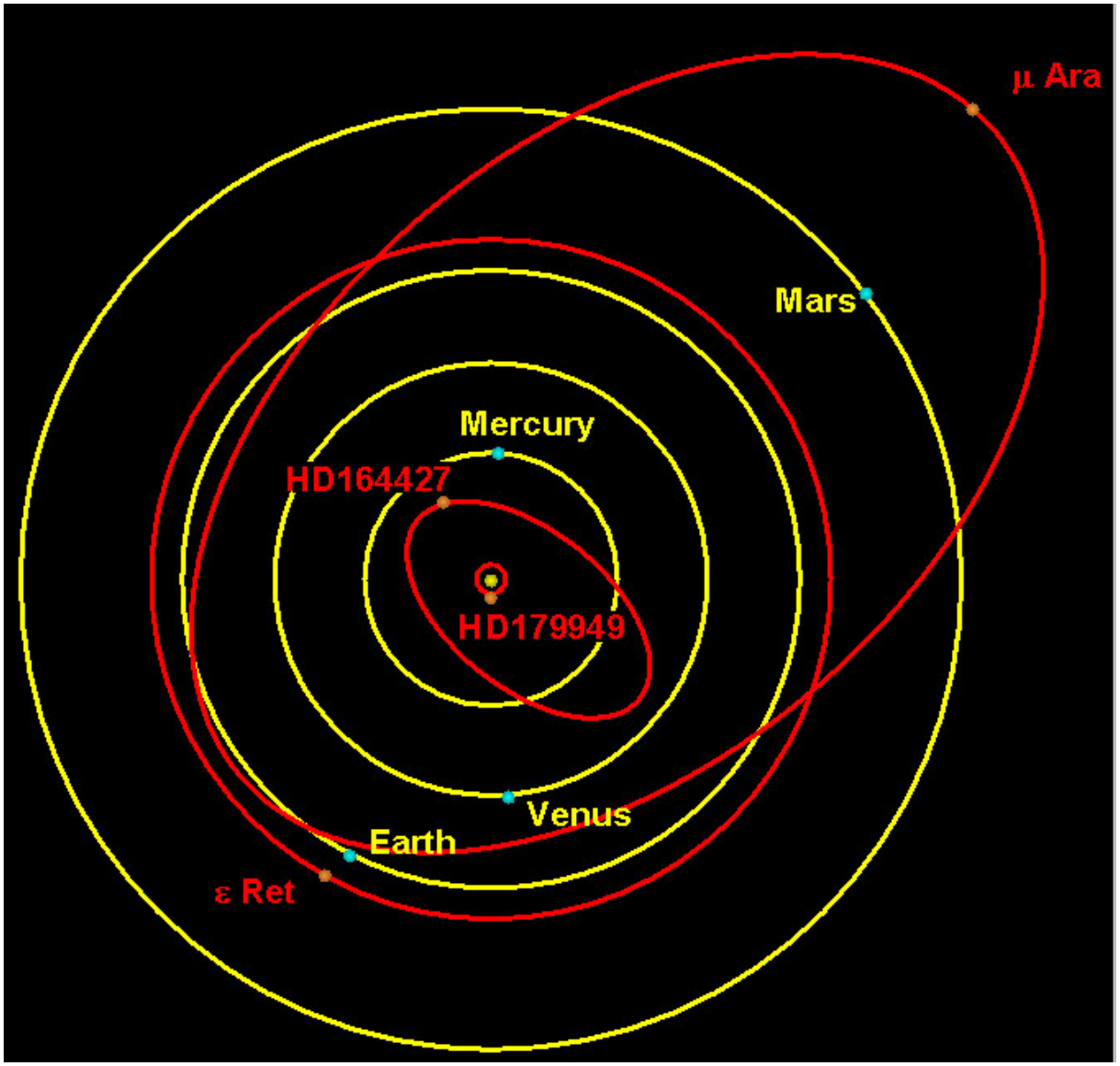


Orbits of Extrasolar Planets

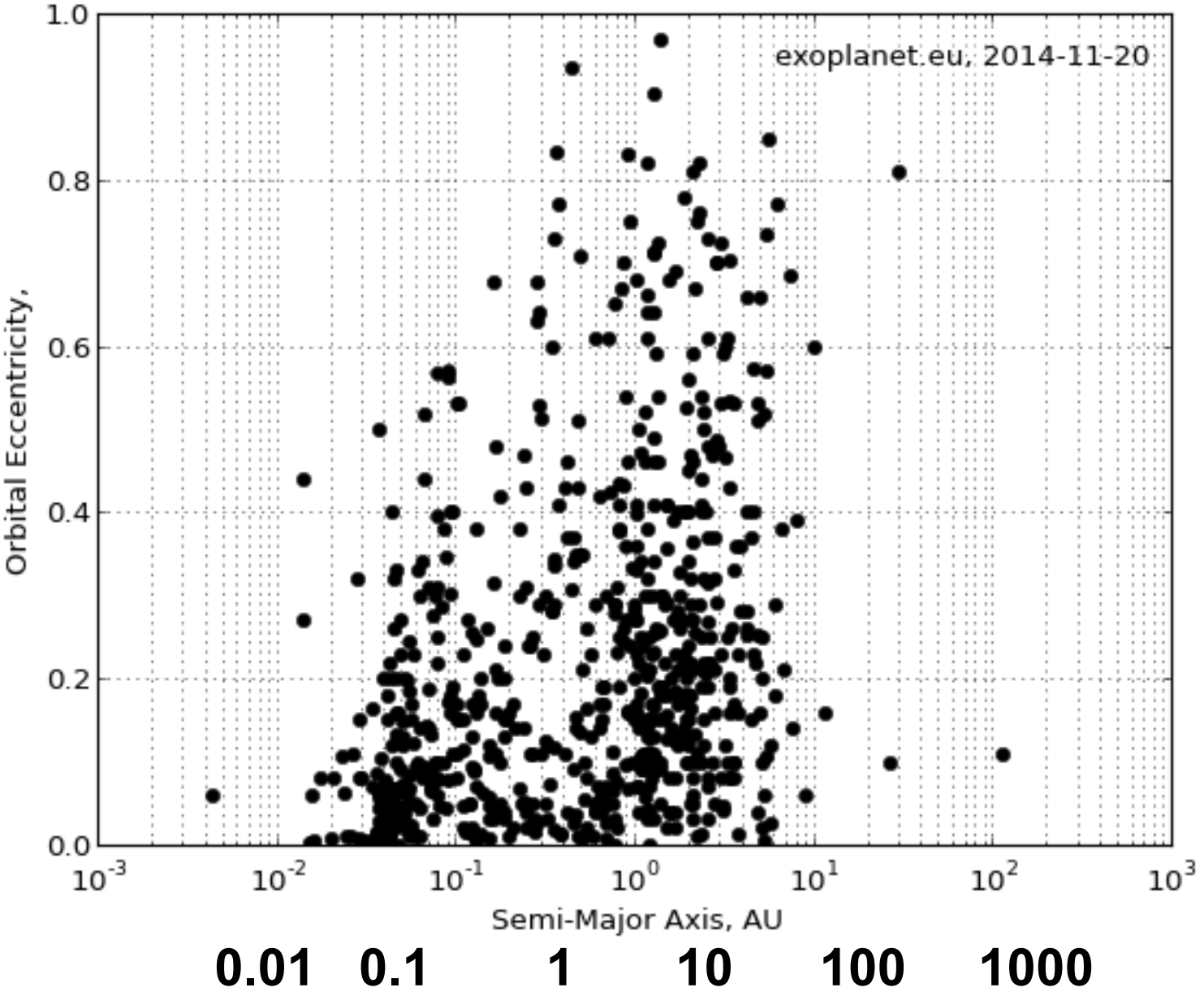


Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

Eccentric Orbits



Orbits of Extrasolar Planets: Eccentricity



Surprising Characteristics

- Some extrasolar planets have highly elliptical orbits.
- Planets show huge diversity in size and density.
- Some massive planets, called *hot Jupiters*, orbit very close to their stars.

- But we are also finding planets that ***could*** be Earth-like….

What have we learned?

- **What properties of extrasolar planets can we measure?**
  - Orbital properties, such as period, distance, and shape.
  - Planetary properties, such as mass and size.
  - Atmospheric properties, such as temperature and composition.

What have we learned?

- **How do extrasolar planets compare with planets in our solar system?**
  - Planets with a wide variety of masses and sizes.
  - Many orbiting close to their stars and with large masses.

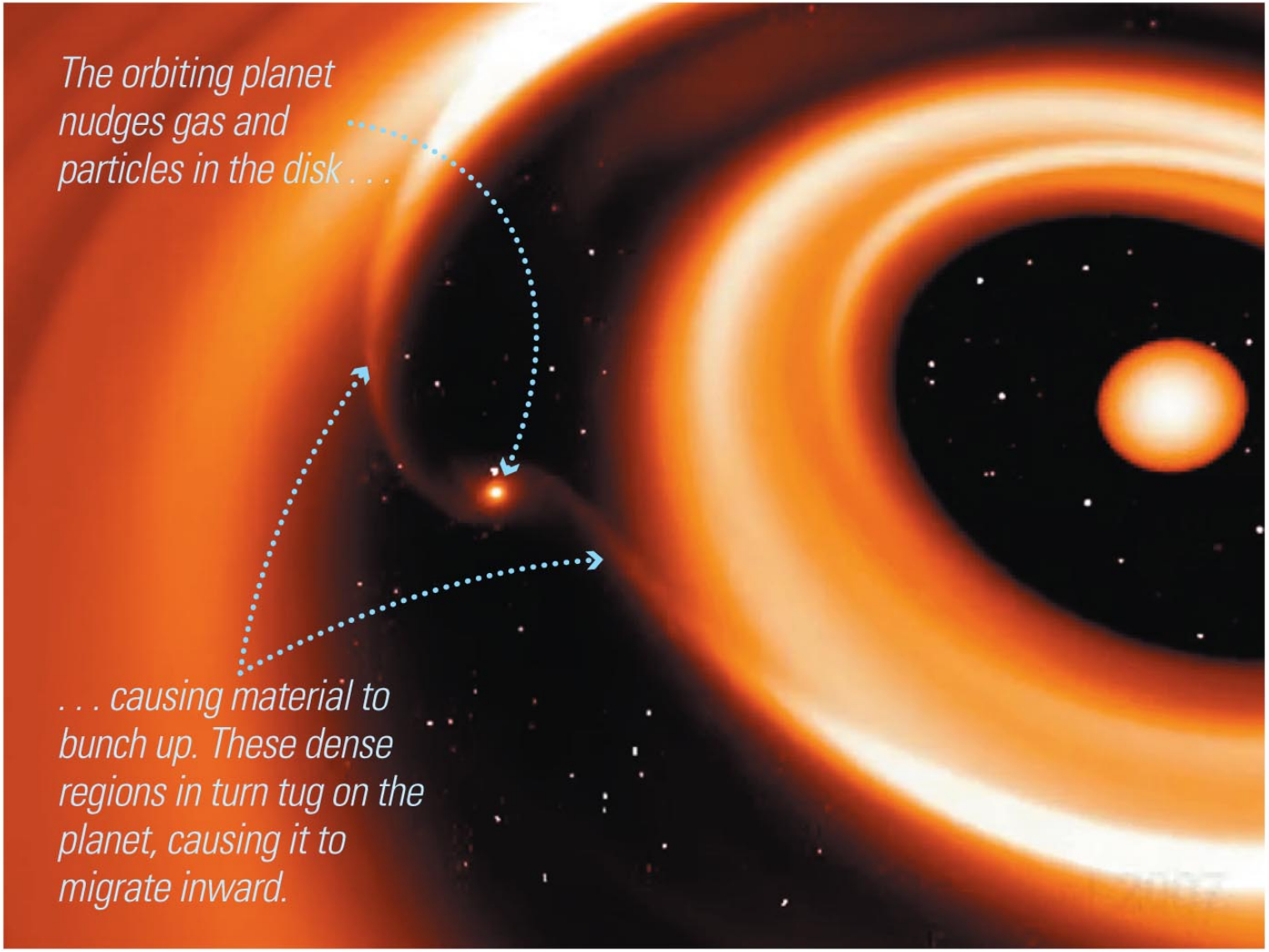
13.3 The Formation of Other Solar Systems

- Our goals for learning:
  - **Can we explain the surprising orbits of many extrasolar planets?**
  - **Do we need to modify our theory of solar system formation?**

Revisiting the Nebular Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 5 AU).
- The discovery of hot Jupiters has forced reexamination of nebular theory.
- *Planetary migration* or gravitational encounters may explain hot Jupiters.

Planetary Migration



Gravitational Encounters and Resonances

- Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit.
- Multiple close encounters with smaller planetesimals can also cause inward migration.
- Resonances may also contribute.

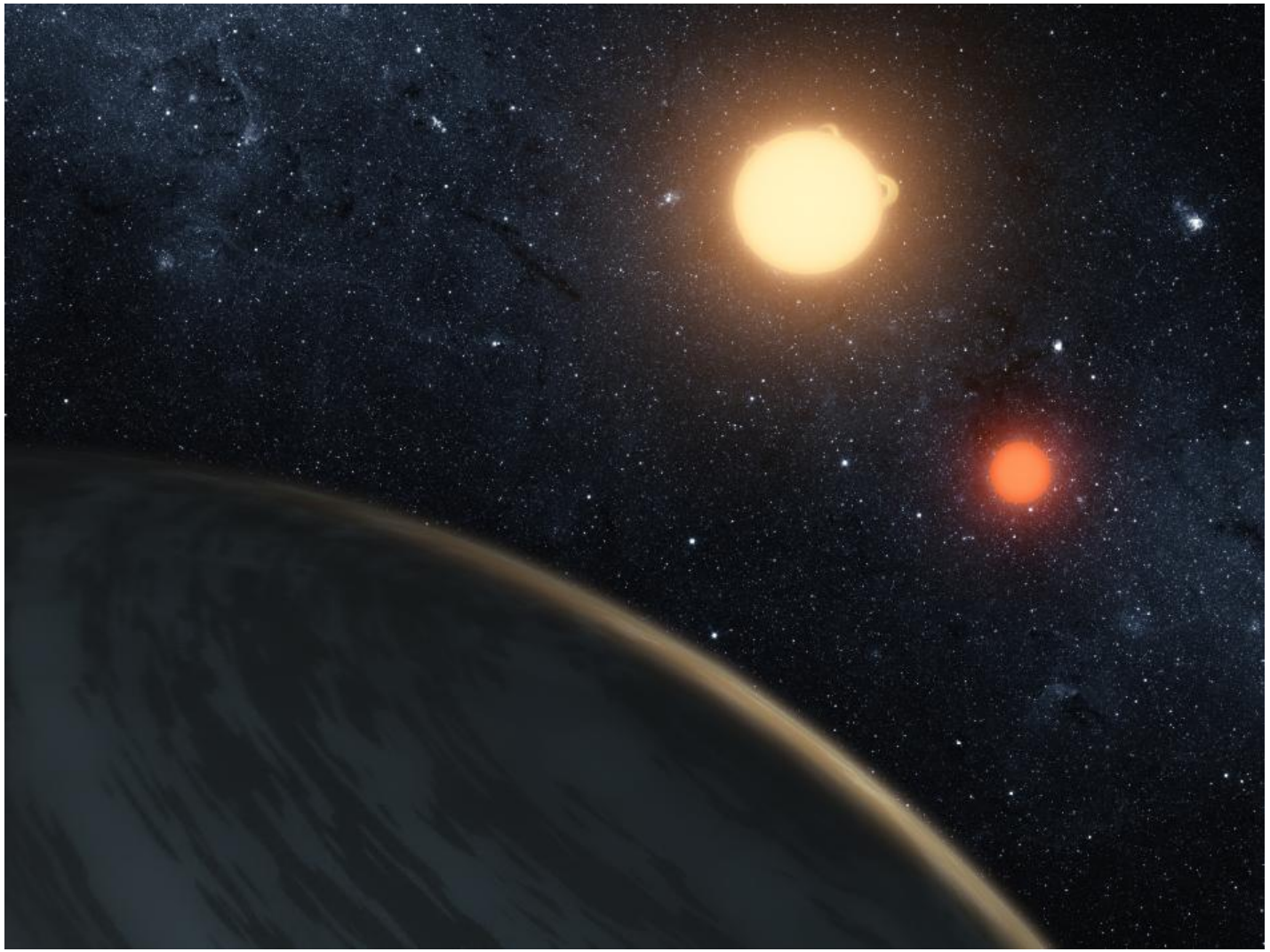
Do we need to modify our theory of solar system formation?

- Observations of extrasolar planets have shown that the nebular theory was incomplete.

- Effects like planetary migration and gravitational encounters might be more important than previously thought.

Tattooine

Tattooine



What have we learned?

- **Can we explain the surprising orbits of many extrasolar planets?**
  - Original nebular theory cannot account for the existence of hot Jupiters.
  - Planetary migration or gravitational encounters may explain how Jupiter-like planets moved inward.
- **Do we need to modify our theory of solar system formation?**
  - Migration and encounters may play a larger role than previously thought.