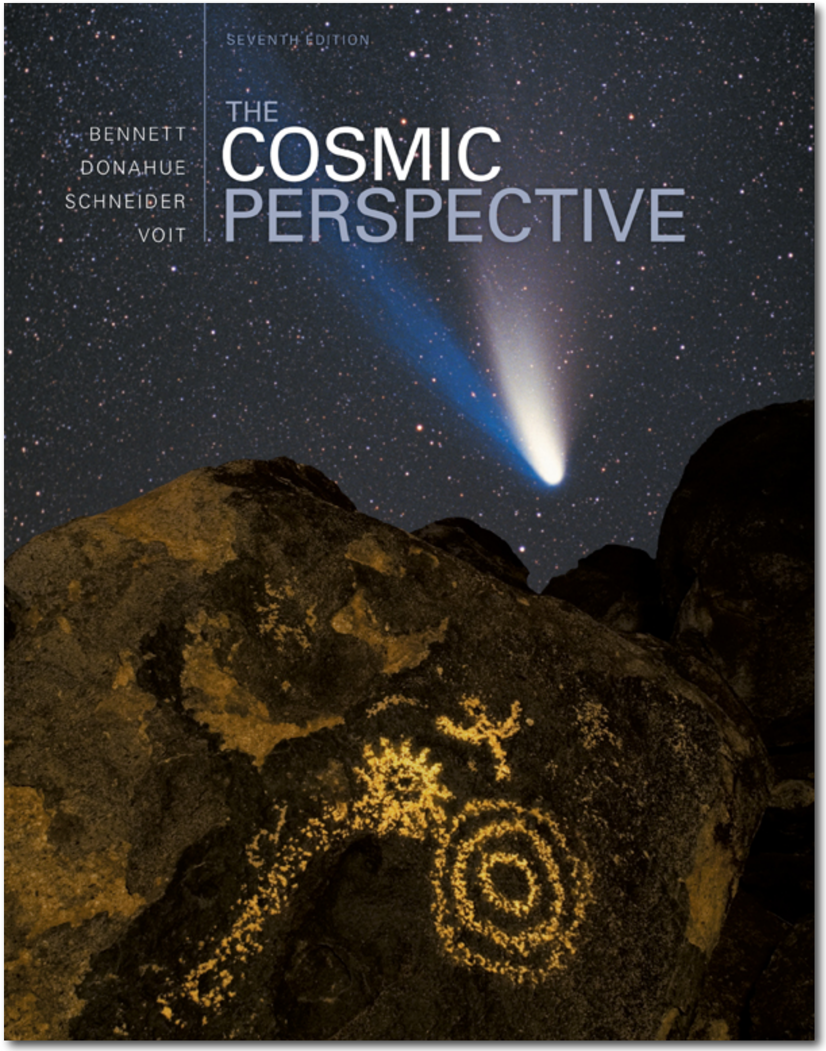
The Cosmic Perspective

Seventh Edition



Other Planetary Systems: The New Science of Distant Worlds

13.1 Detecting Planets Around Other Stars

- Our goals for learning:
  - **Why is it so challenging to learn about extrasolar planets?**
  - **How can a star's motion reveal the presence of planets?**
  - **How can changes in a star's brightness reveal the presence of planets?**

Brightness and Distance

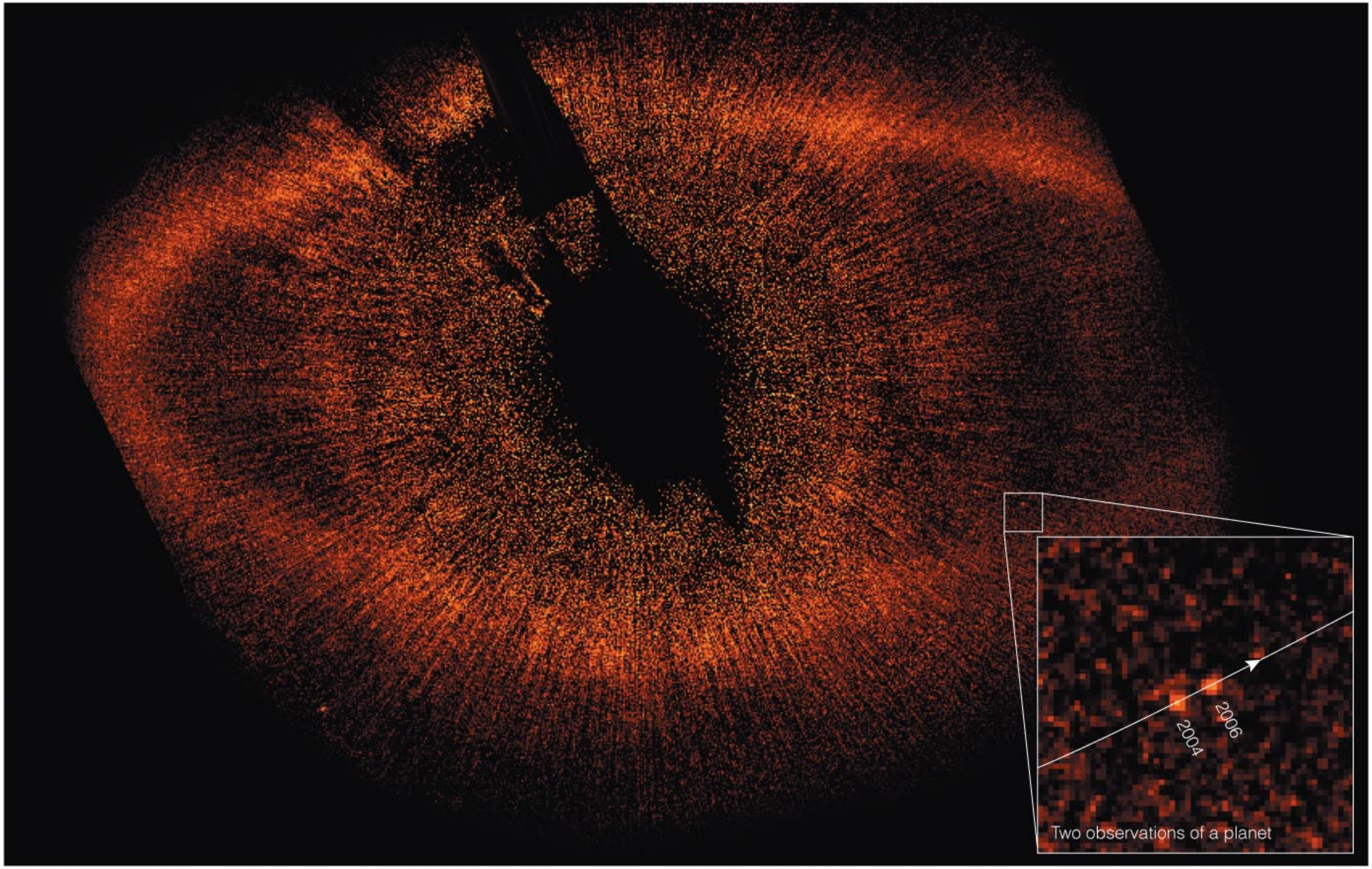
- A Sun-like star is about a billion times brighter than the light reflected from its planets.

- Planets are close to their stars, relative to the distance from us to the star.
  - This is like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D.C.

Planet Detection

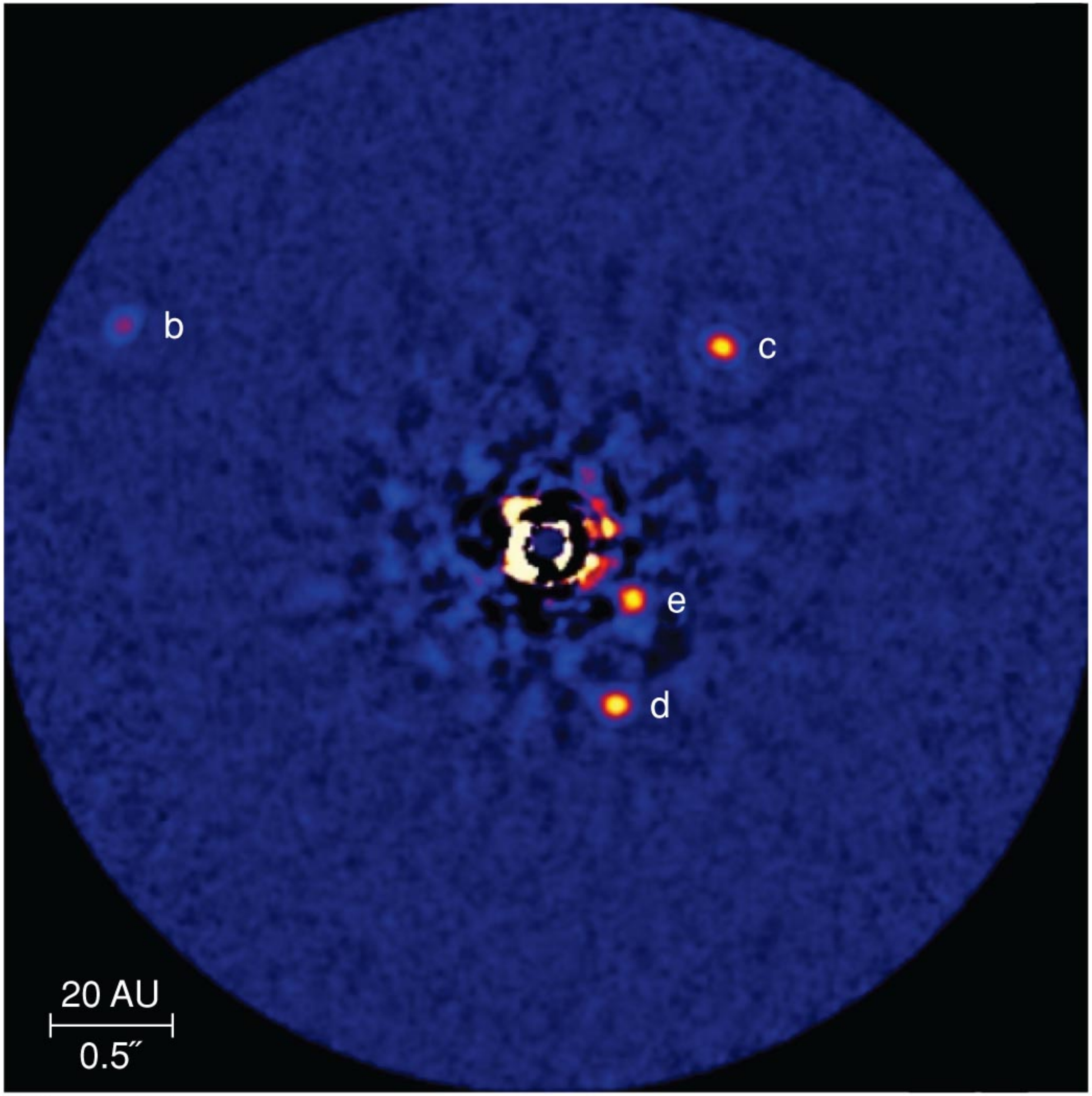
- **Direct:** pictures or spectra of the planets themselves

Direct Detection – Fomalhaut b



Direct Detection – HR 8799

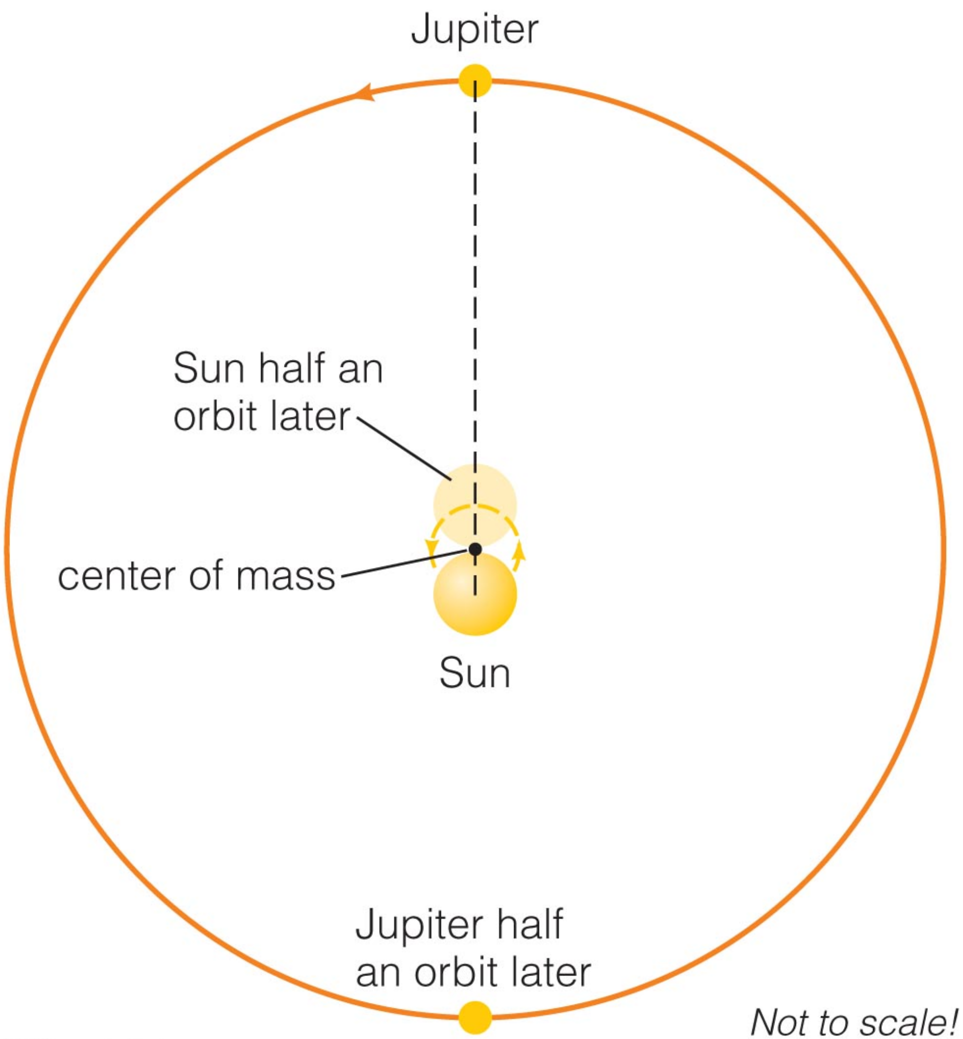
Video



Planet Detection

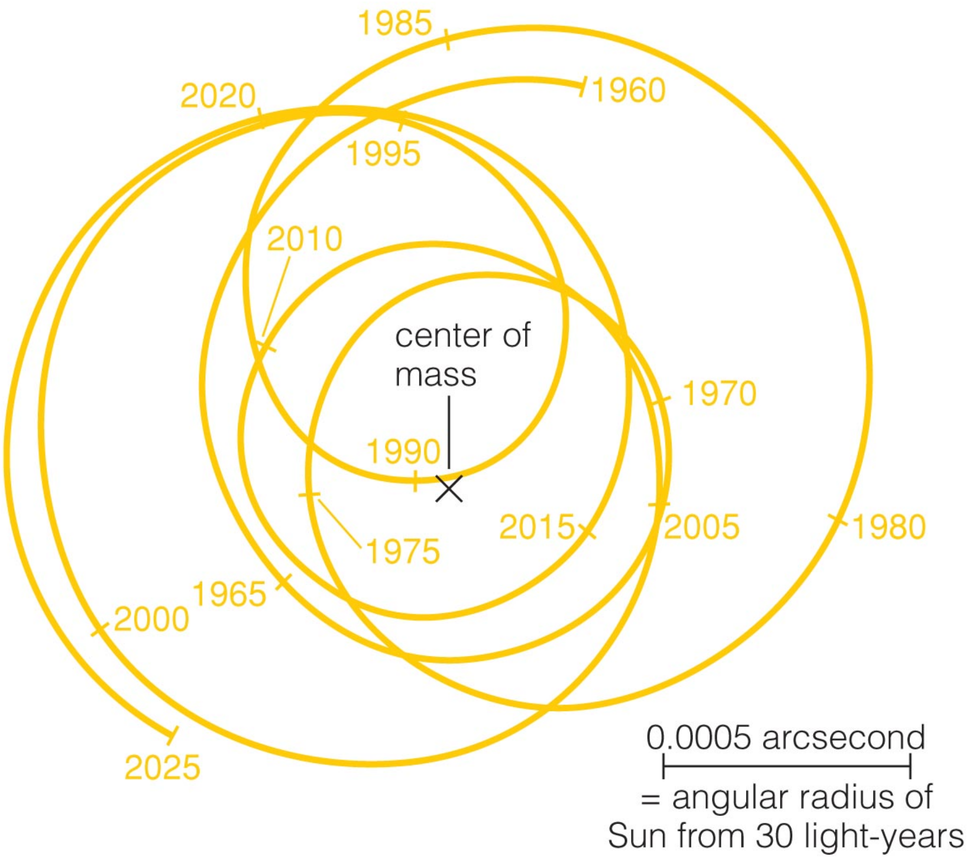
- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of the host star that reveal the effects of orbiting planets

Gravitational Tugs



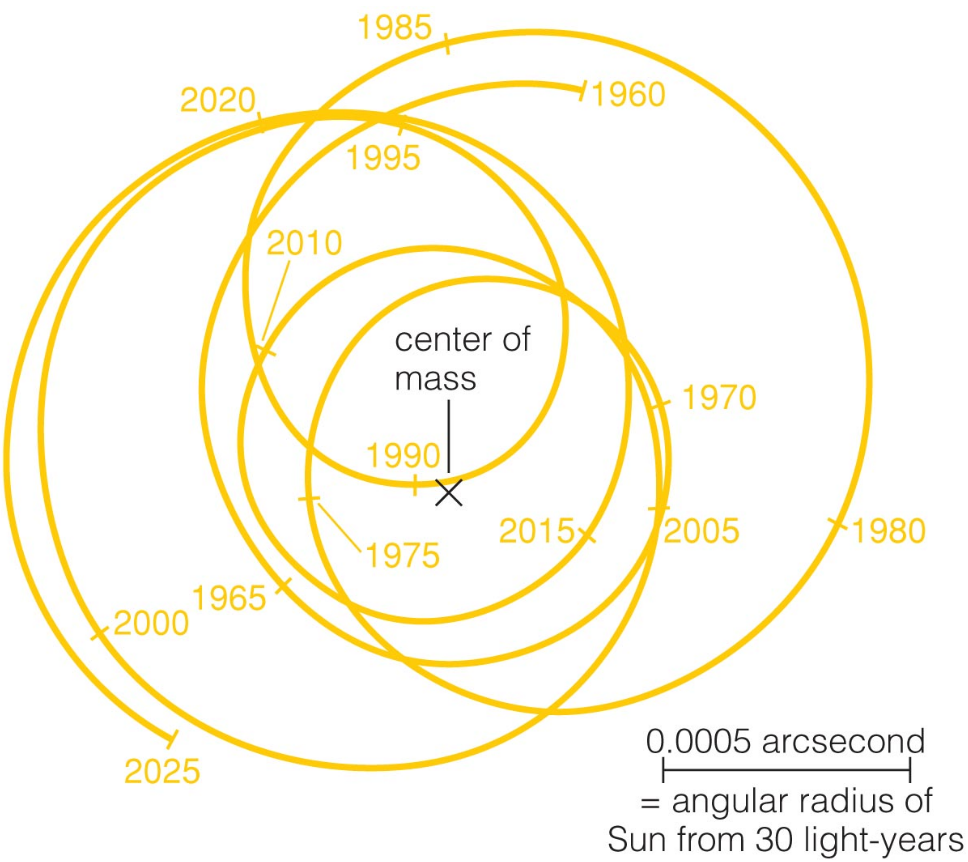
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



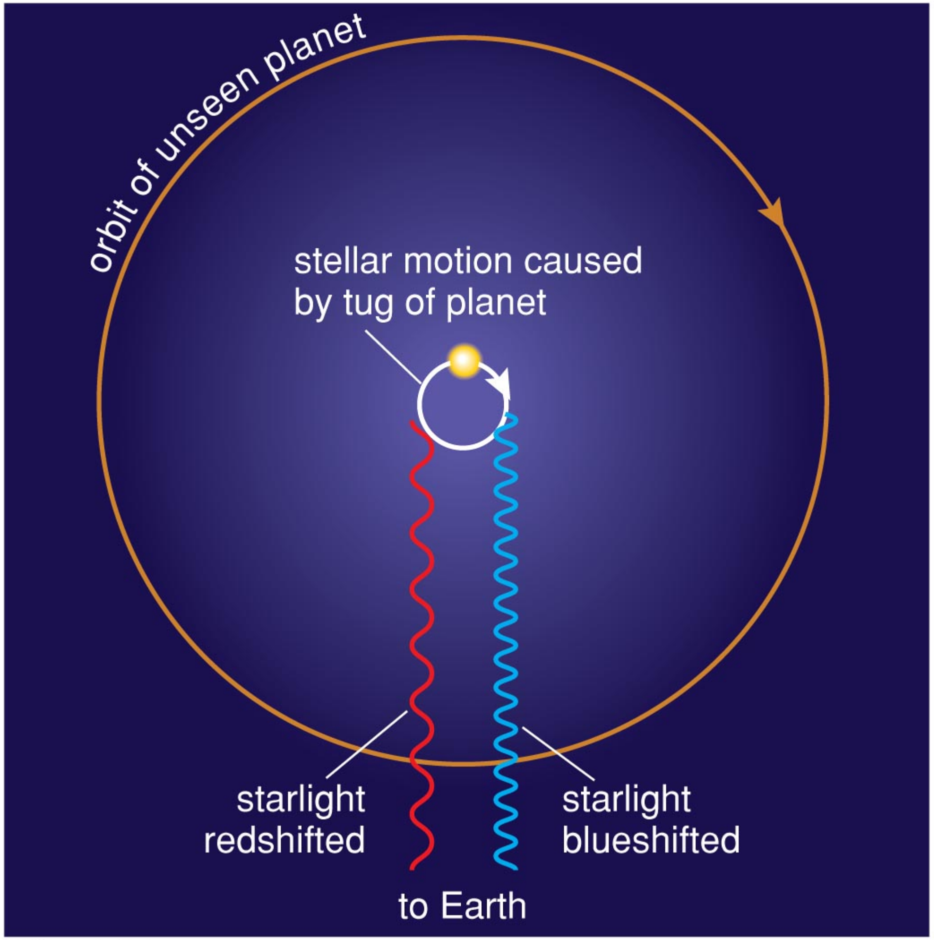
- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



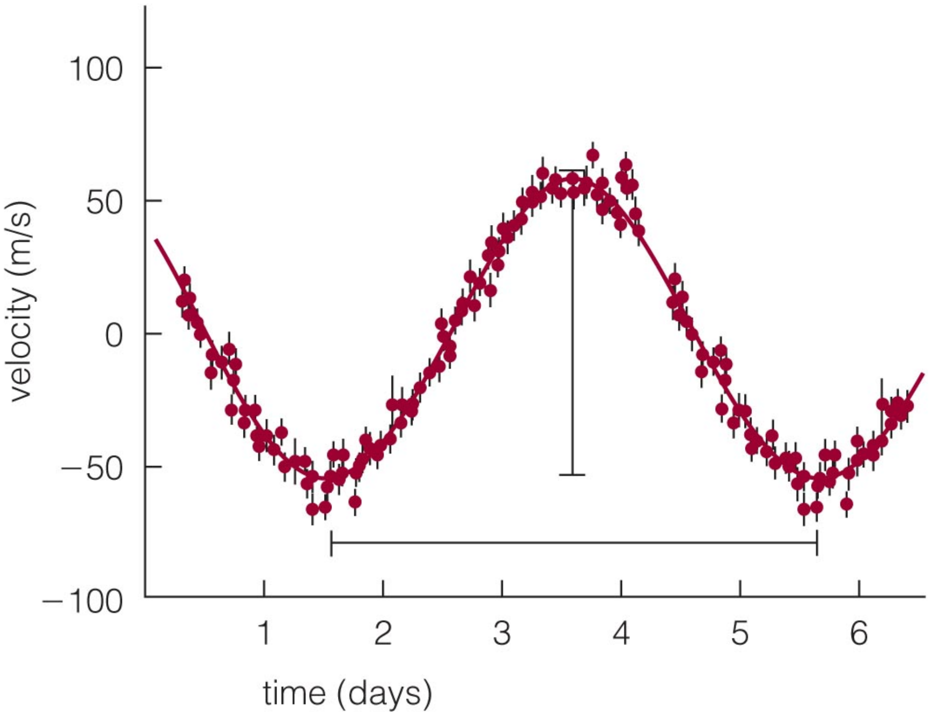
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).

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

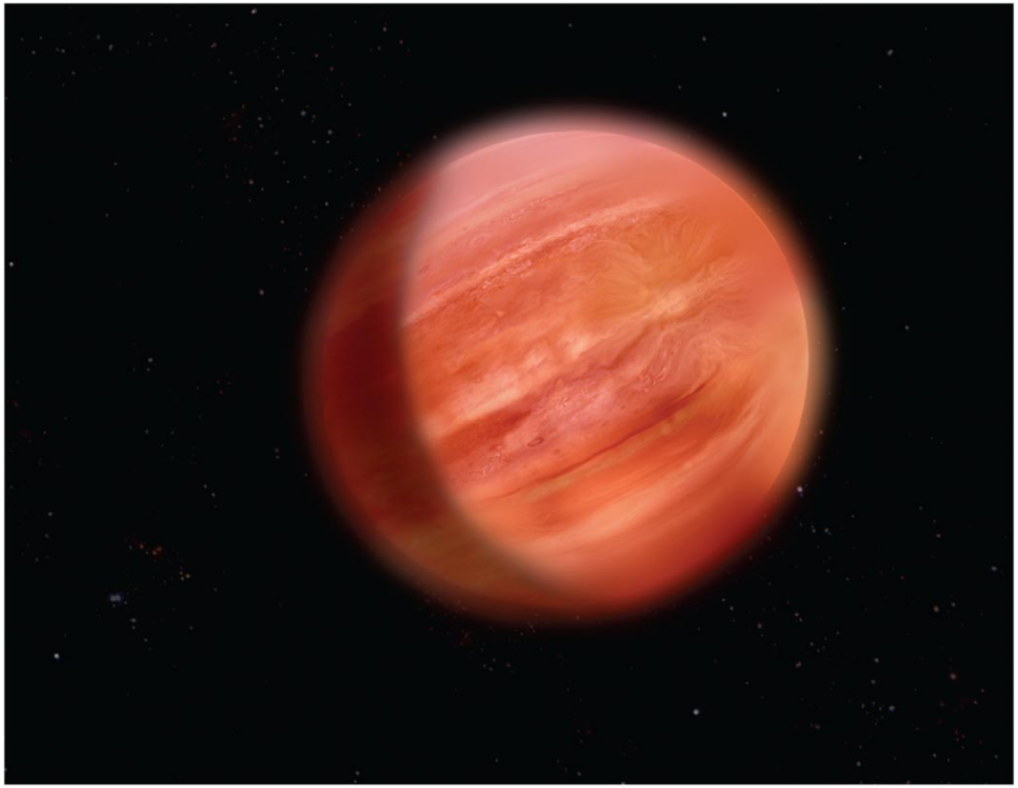
First Extrasolar Planet



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.

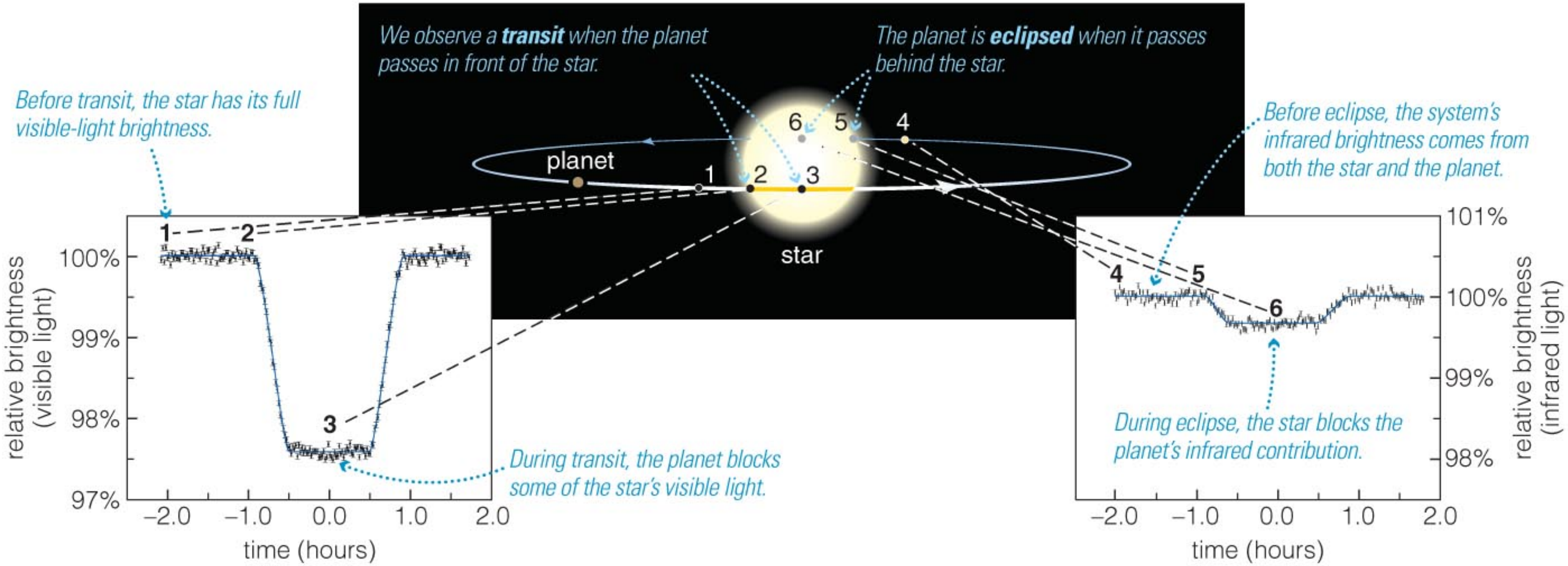
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered around a Sun-like star (1995).

First Extrasolar Planet – A "Hot Jupiter"



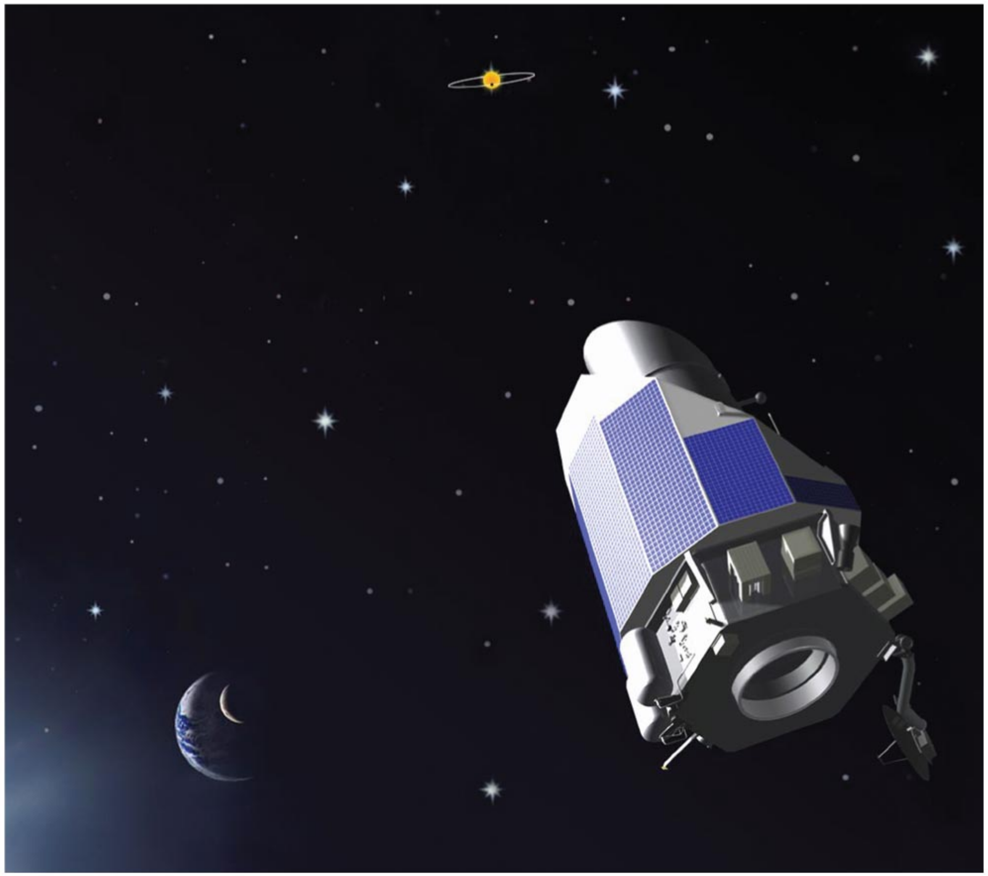
- The planet around 51 Pegasi has a mass similar to Jupiter's, despite its small orbital distance.
- *Why are the so-called "hot Jupiters" so weird?*

Transits and Eclipses

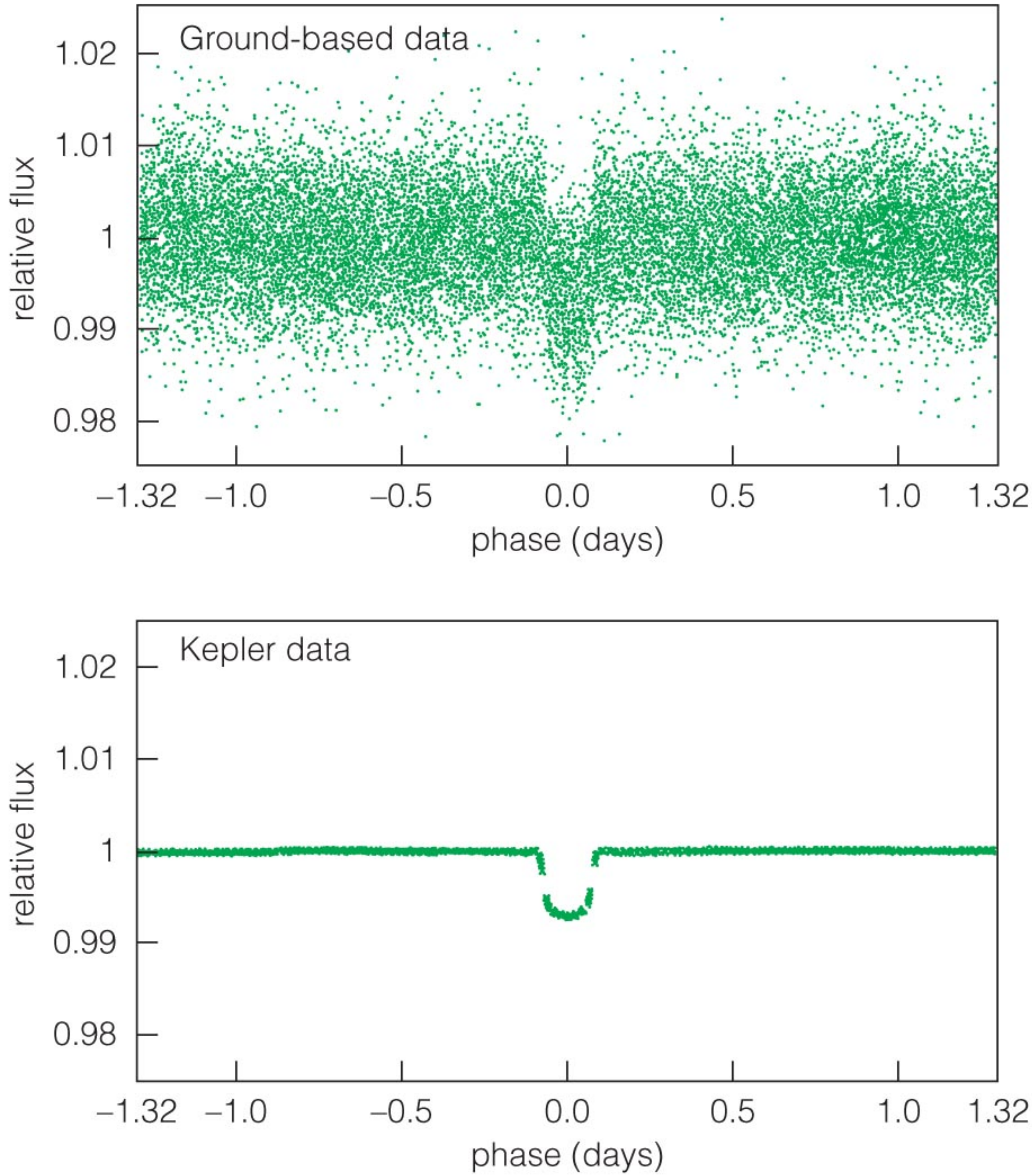


- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
- No orbital tilt: accurate measurement of planet mass

Kepler

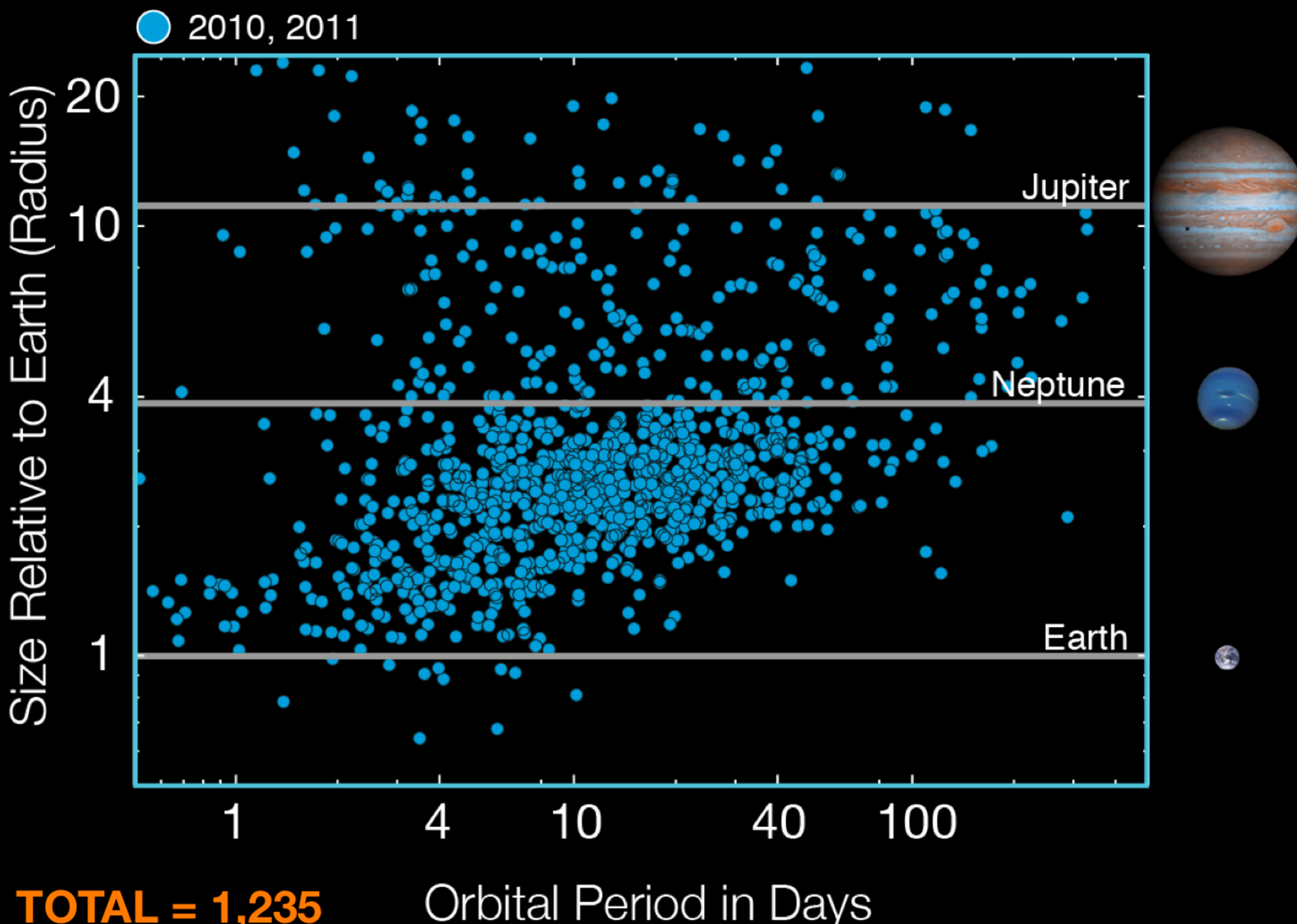


- NASA's *Kepler* mission was launched in 2008 to begin looking for transiting planets.
- It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.


Ground-based data
relative flux
1.02
1.01
1
0.99
0.98
−1.32
−1.0
−0.5
0.0
0.5
1.0
1.32
phase (days)
Kepler data
relative flux
1.02
1.01
1
0.99
0.98
−1.32
−1.0
−0.5
0.0
0.5
1.0
1.32
phase (days)

Planet Candidates

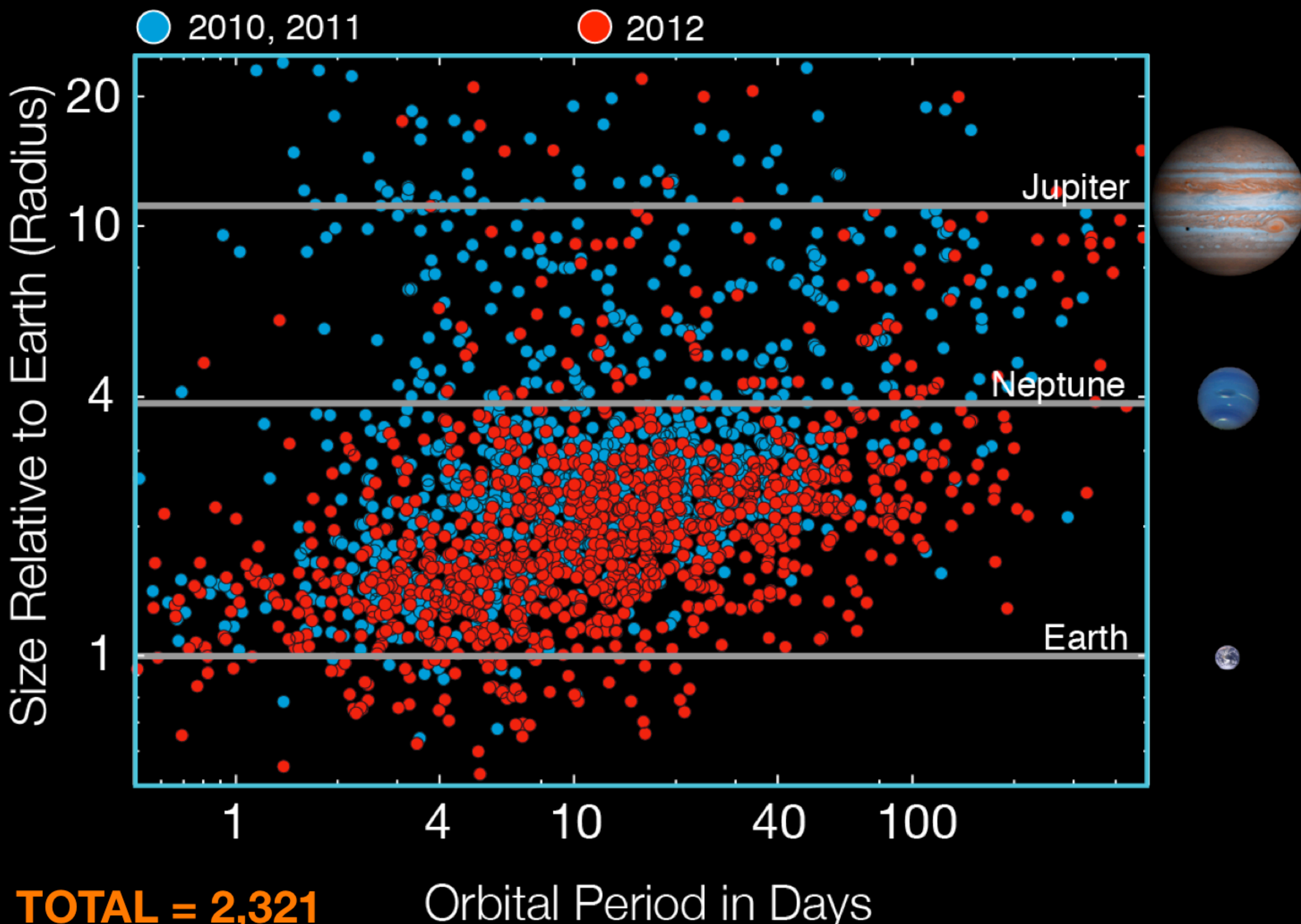
As of February 1, 2011



Courtesy Christopher Burke

Planet Candidates

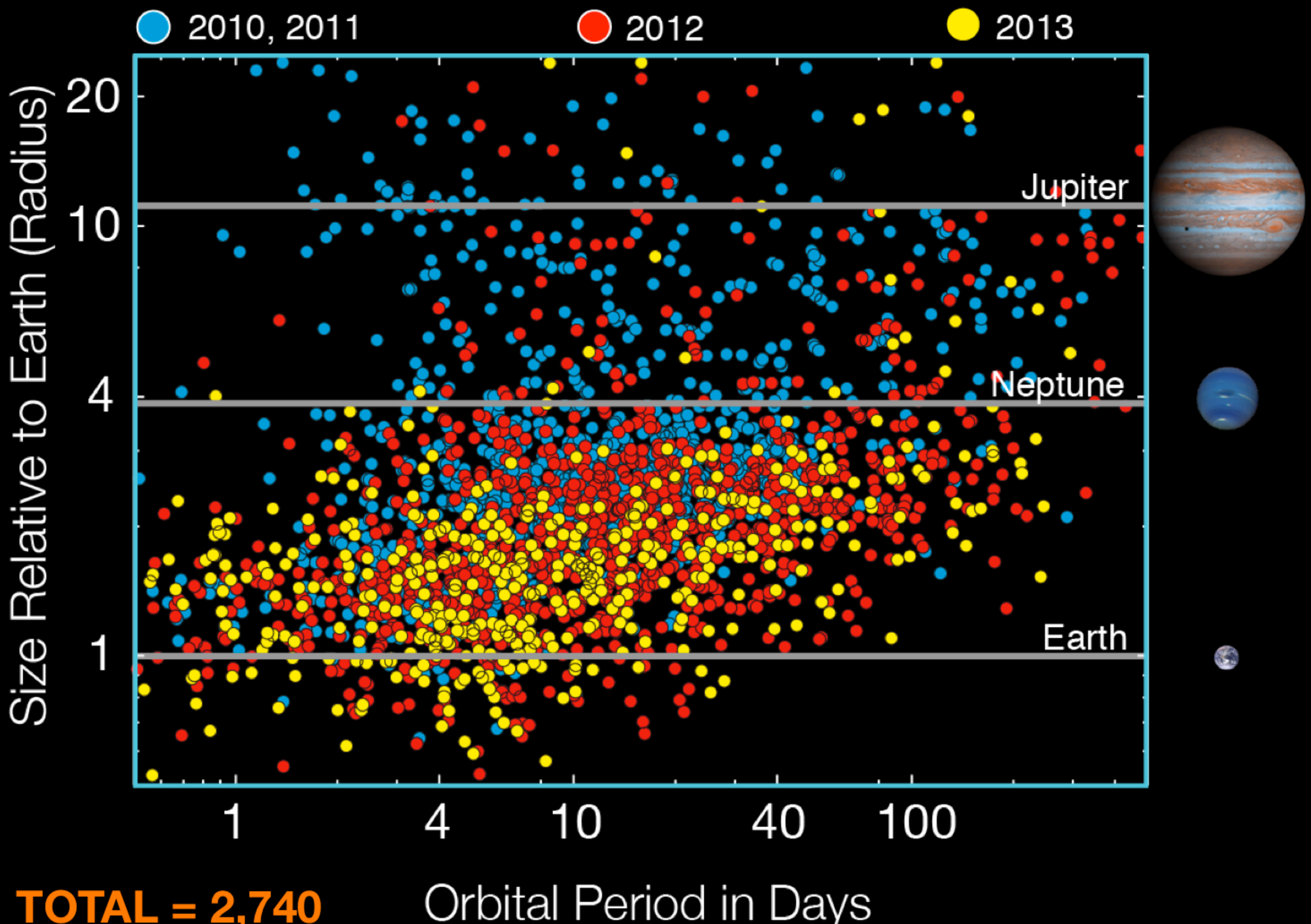
As of February 27, 2012



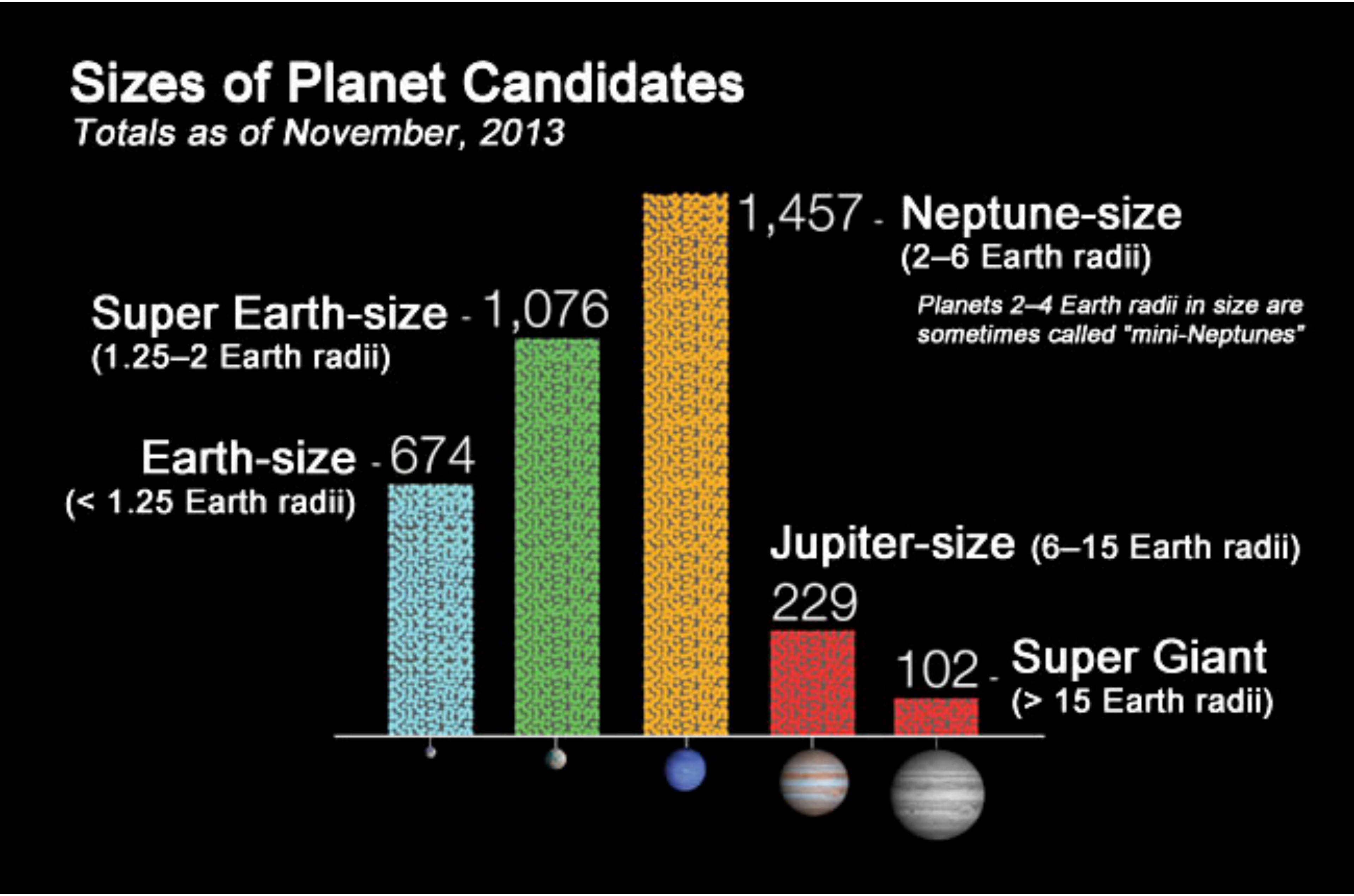
Courtesy Christopher Burke

Planet Candidates

As of January 7, 2013



Courtesy Christopher Burke


Sizes of Planet Candidates
Totals as of November, 2013
1,457 - Neptune-size
(2–6 Earth radii)
Planets 2–4 Earth radii in size are sometimes called "mini-Neptunes"
Super Earth-size - 1,076
(1.25–2 Earth radii)
Earth-size - 674
(< 1.25 Earth radii)
Jupiter-size (6–15 Earth radii)
229
102 - Super Giant
(> 15 Earth radii)

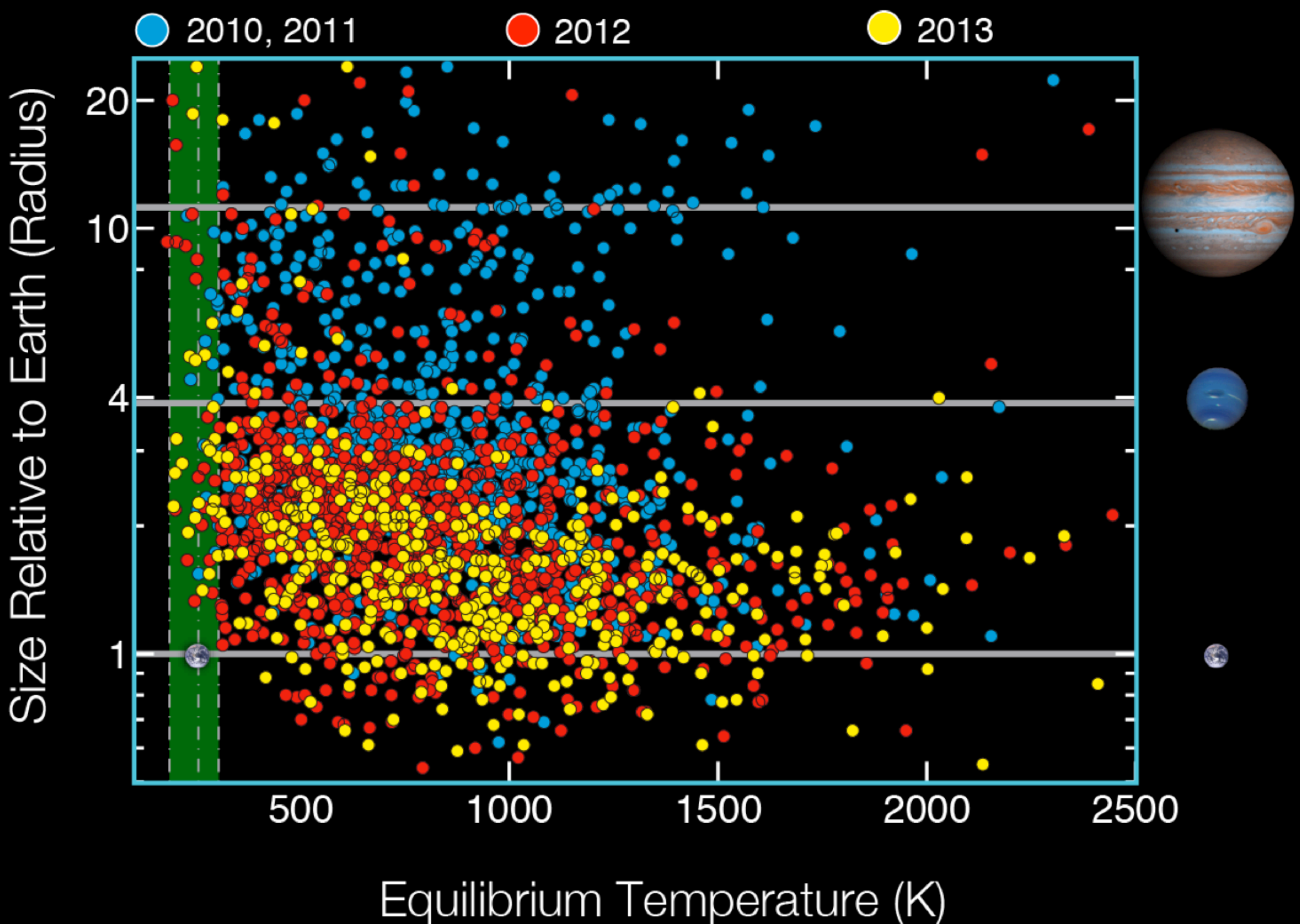
Kepler Transiting Multi-Candidate Systems

CANDIDATE SYSTEMS Number of Planet Candidates	CATALOGS 2012	2013
●	1,428	1,569
● ●	246	299
● ● ●	84	112
● ● ● ●	30	44
● ● ● ● ●	8	11
● ● ● ● ● ●	1	1

Courtesy Christopher Burke

Candidates in the Habitable Zone

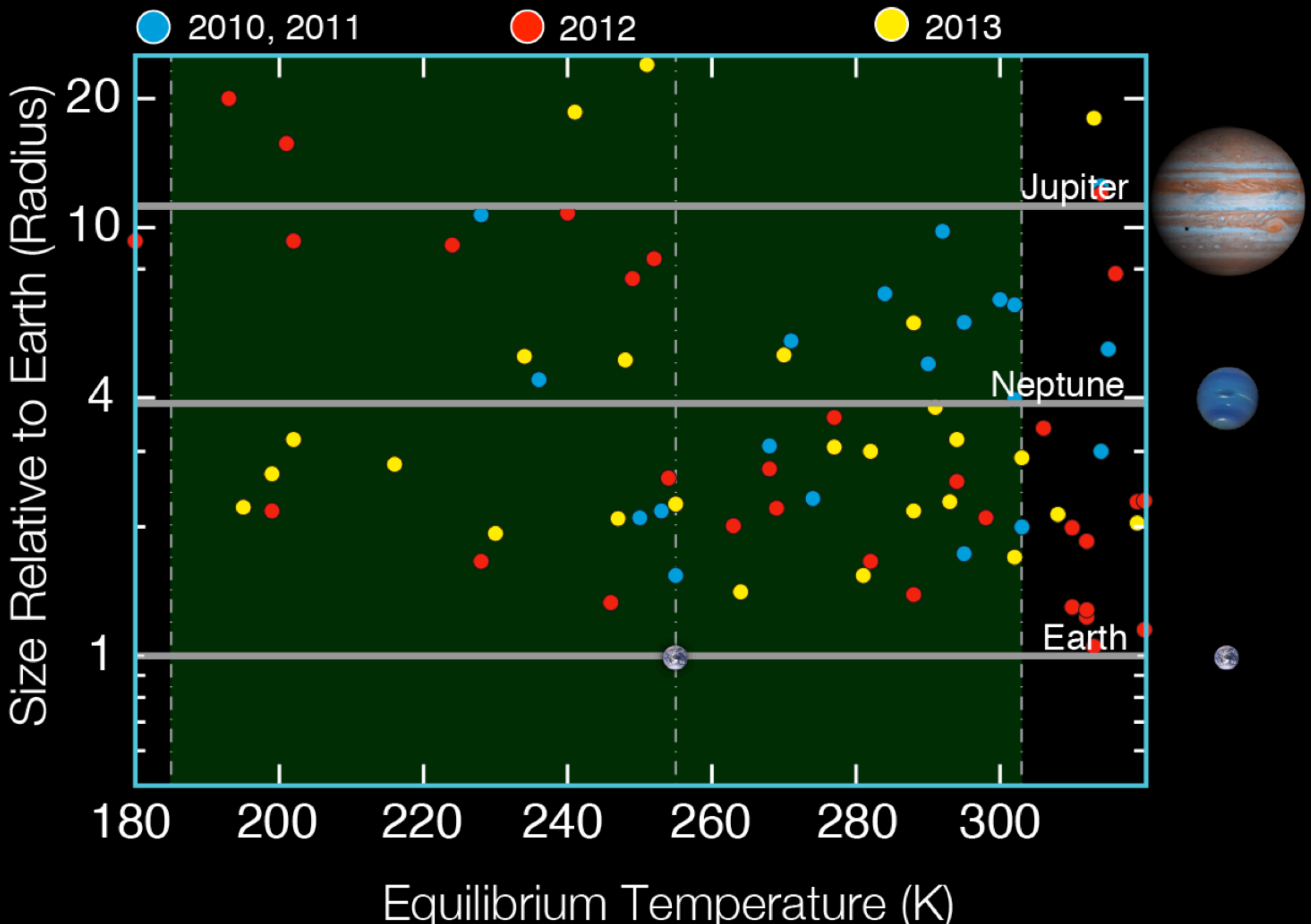
As of January 7, 2013



Courtesy Christopher Burke

Candidates in the Habitable Zone

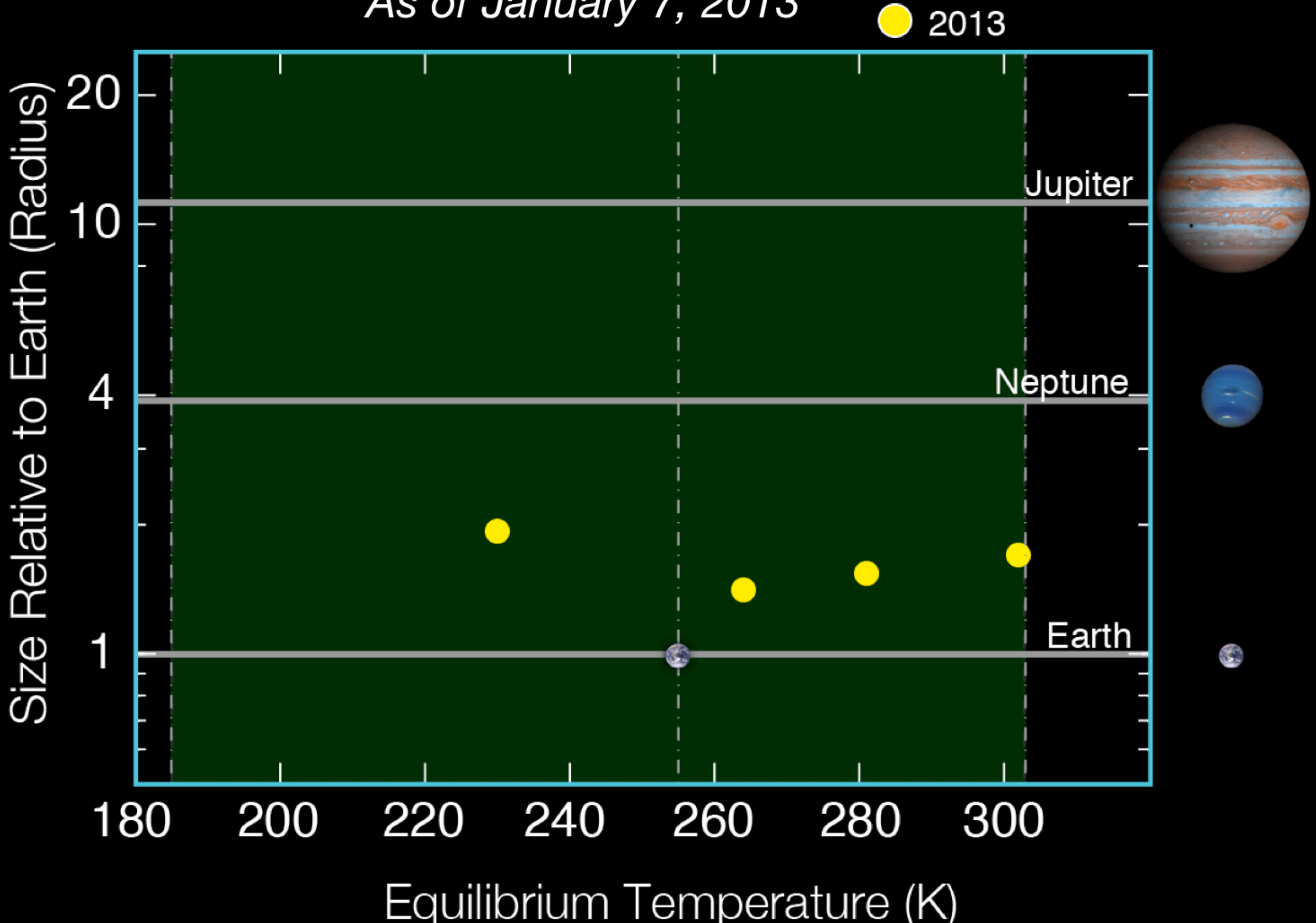
As of January 7, 2013



Courtesy Christopher Burke

New Super Earth-size Candidates in the Habitable Zone

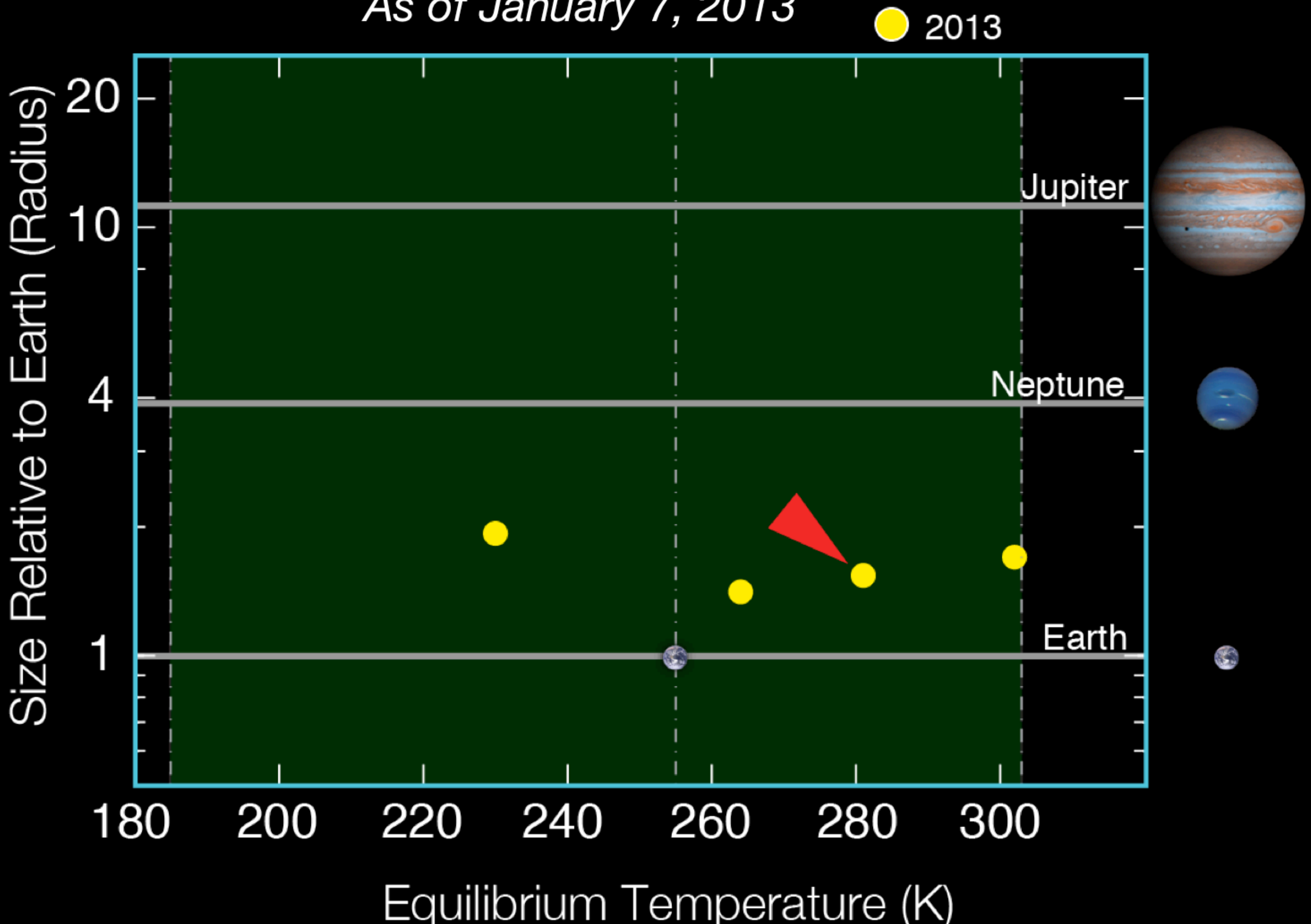
As of January 7, 2013



Courtesy Christopher Burke

One Candidate Orbits a Star Like our Sun

As of January 7, 2013



Courtesy Christopher Burke

The Exoplanet Database

- How fast are we discovering planets around other stars?
- What are their masses, sizes, orbits, etc?

Check out http://exoplanet.eu

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.

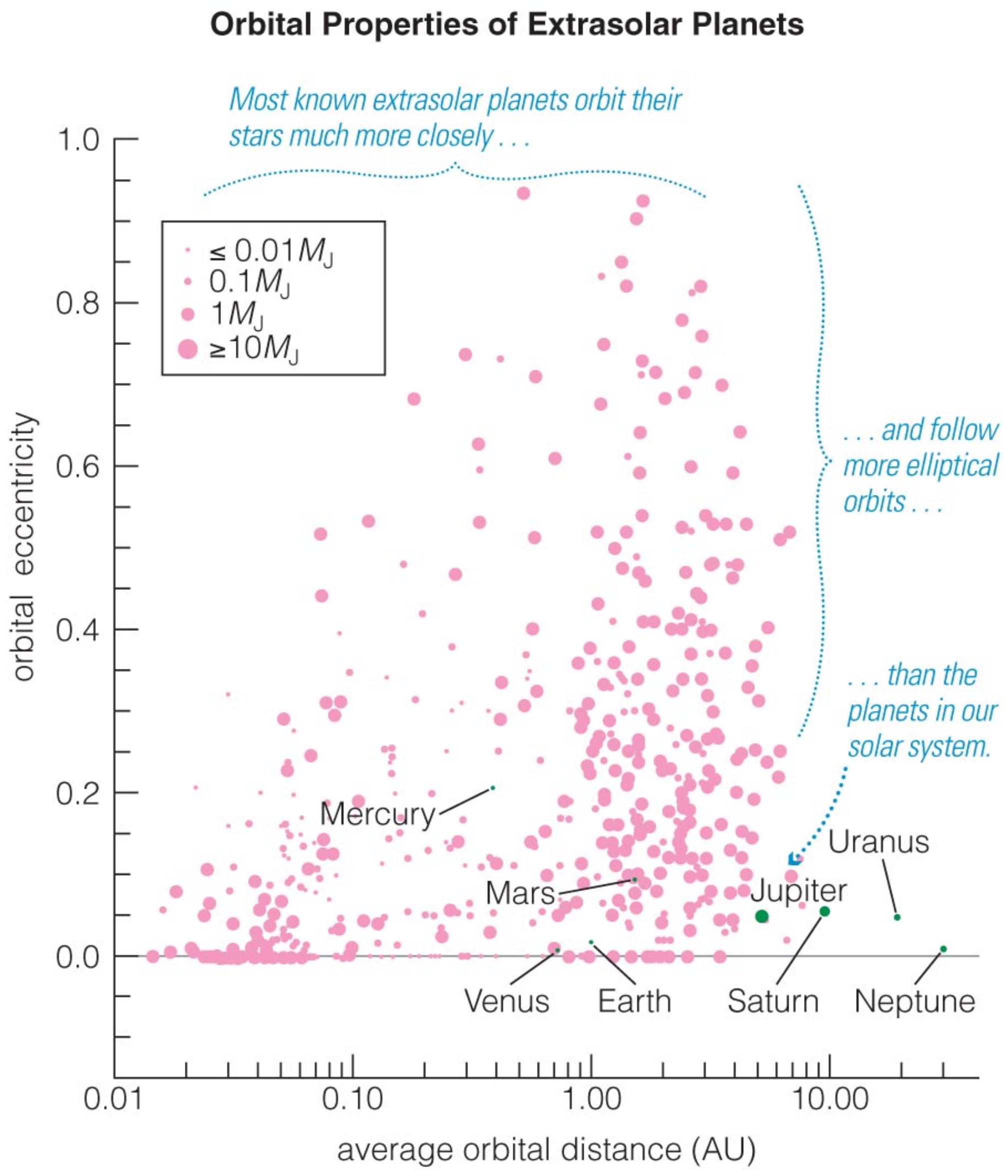
What have we learned?

- **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?**

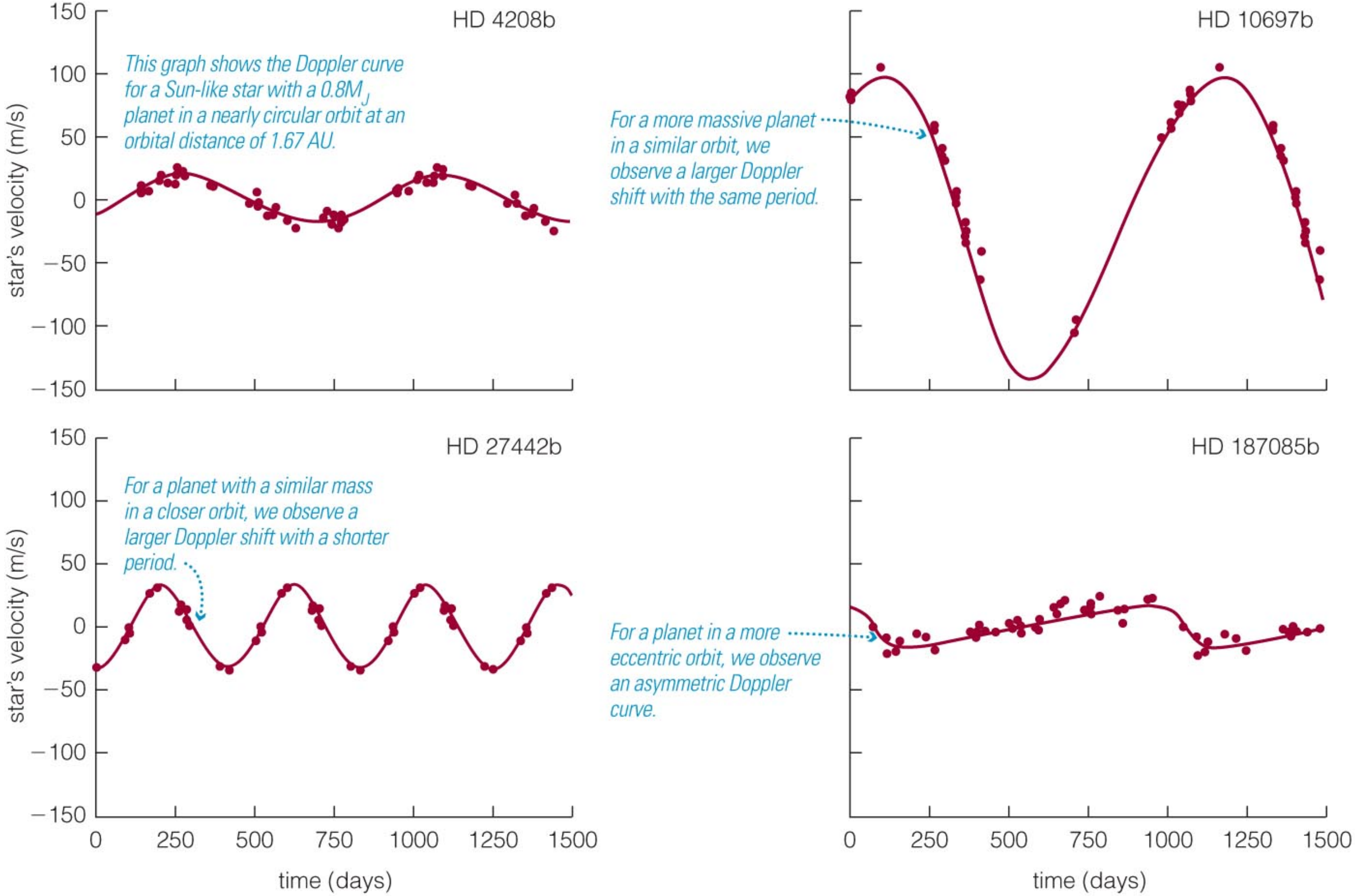
What properties of extrasolar planets can we measure?



Measurable Properties

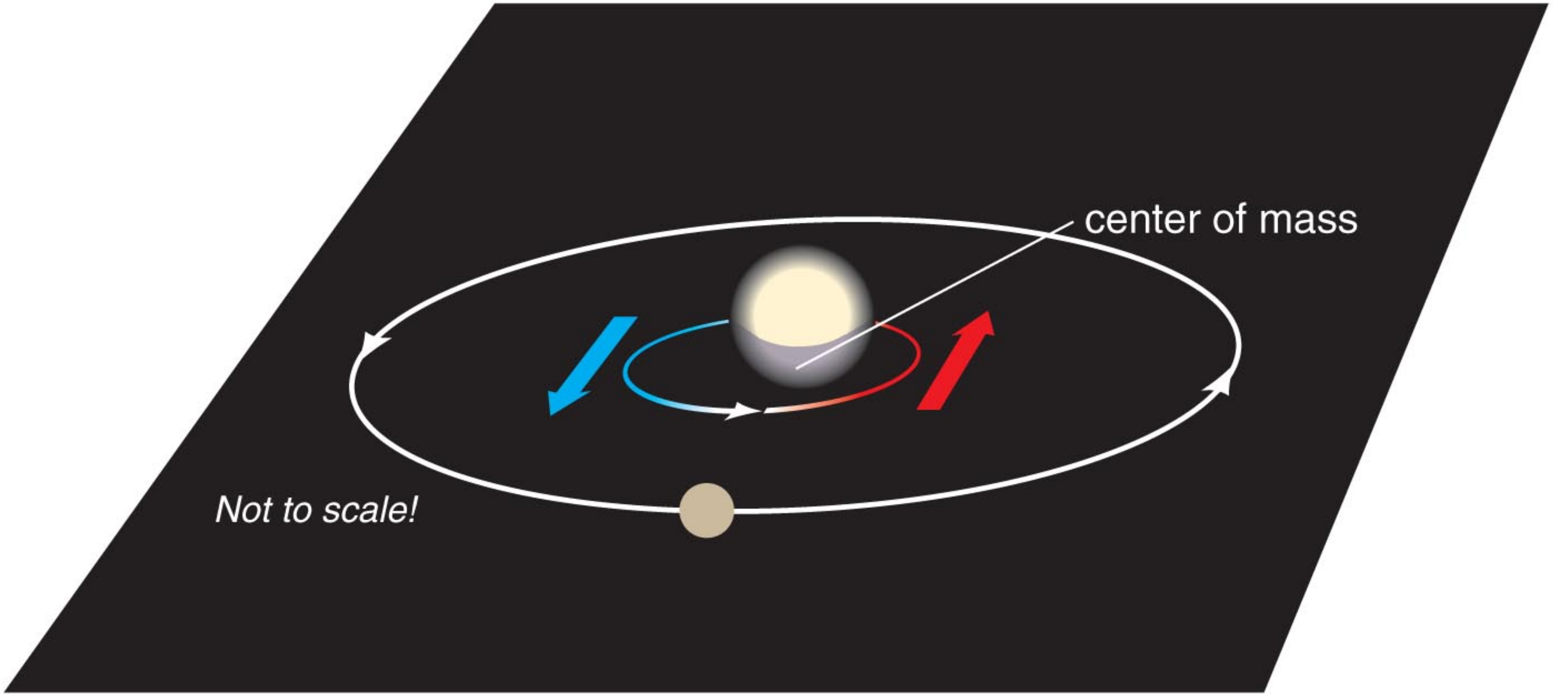
- Orbital period, distance, and shape
- Planet mass, size, and density
- Atmospheric properties

What can Doppler shifts tell us?



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

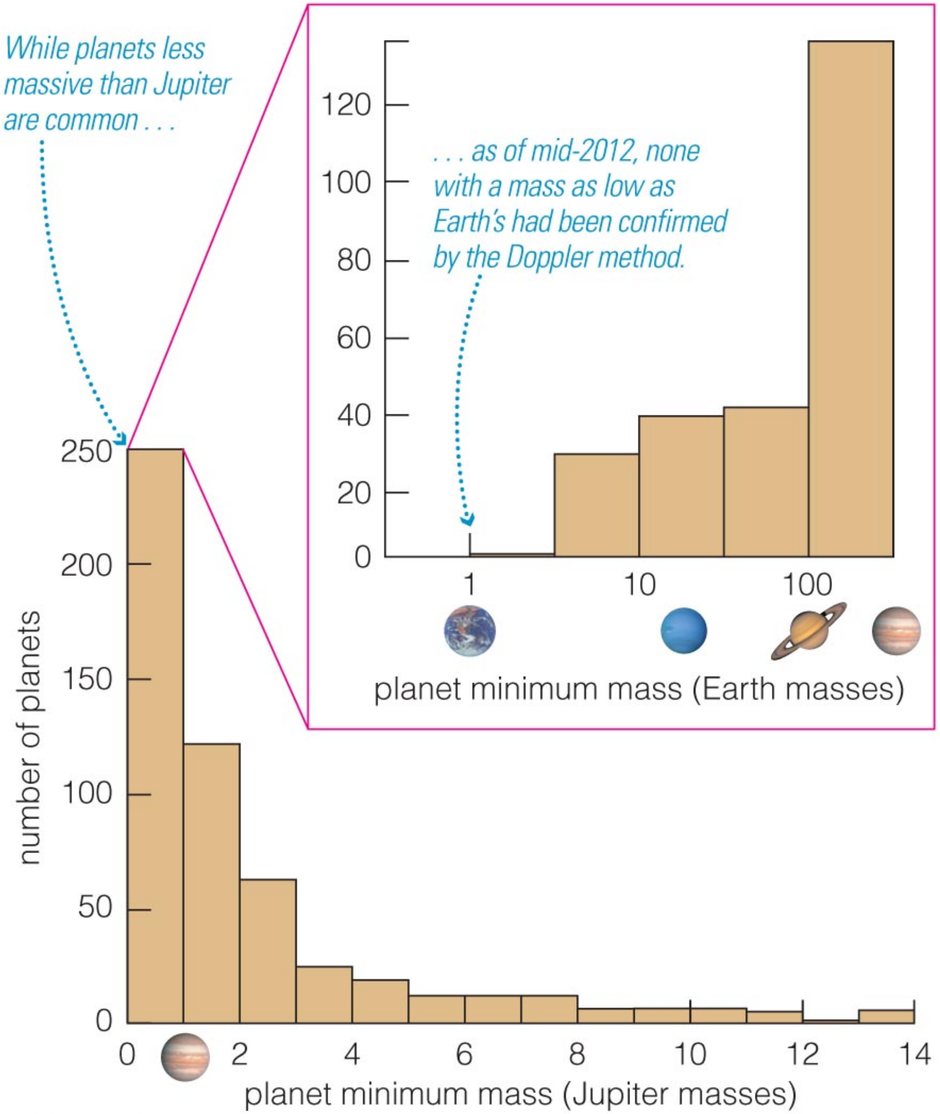
Planet Mass and Orbit Tilt



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.

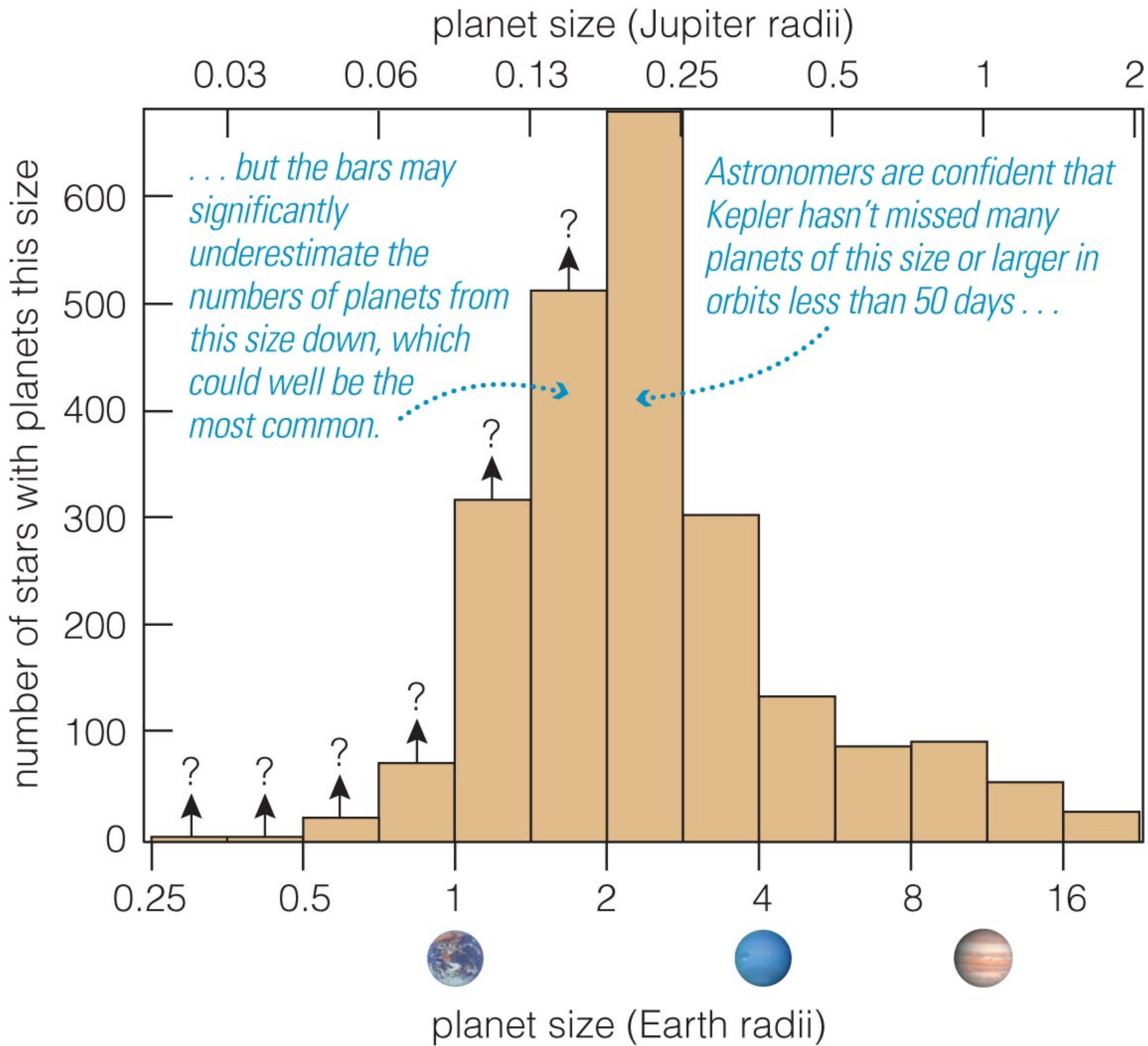
Masses of Extrasolar Planets



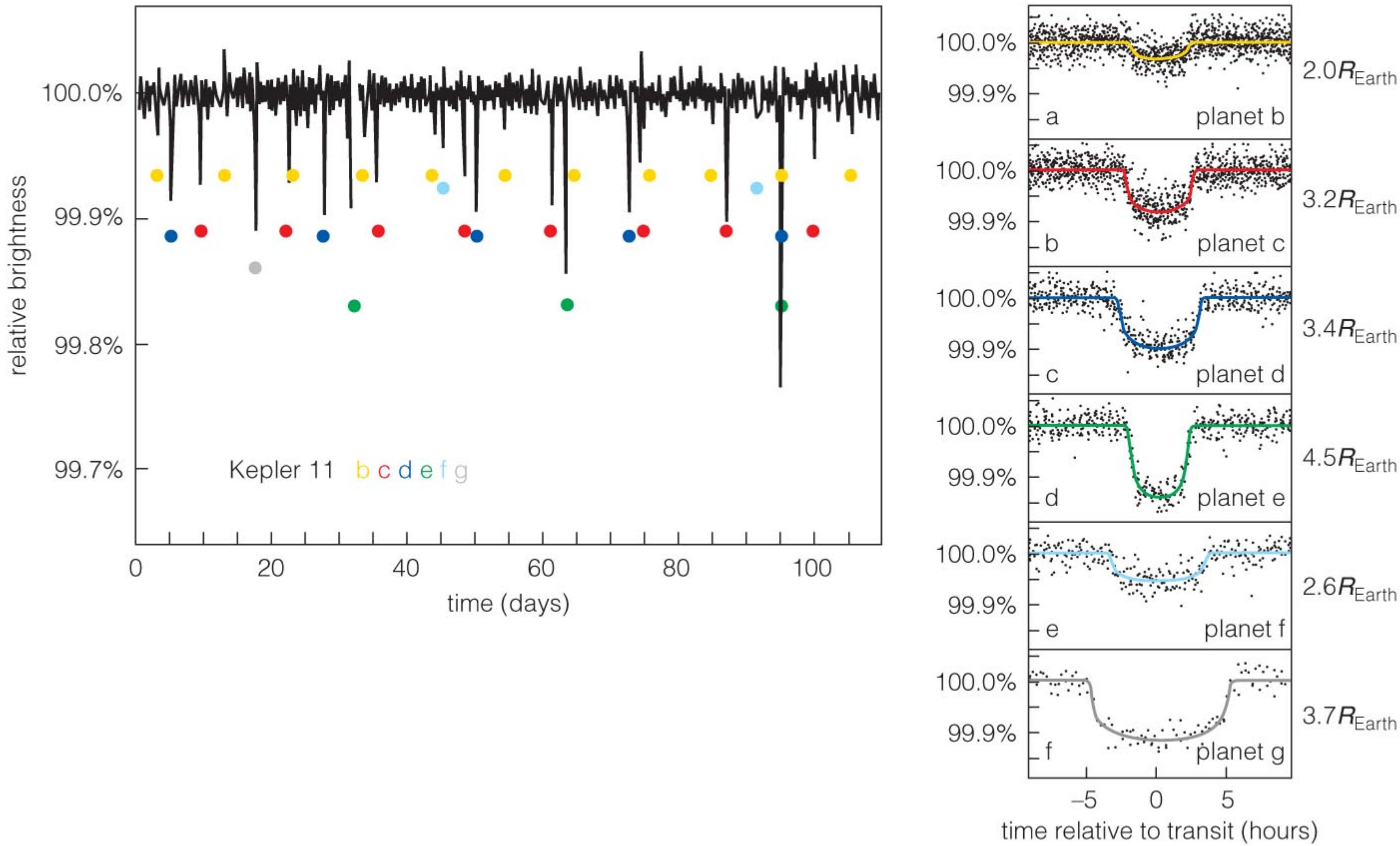
Doppler results

- 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)



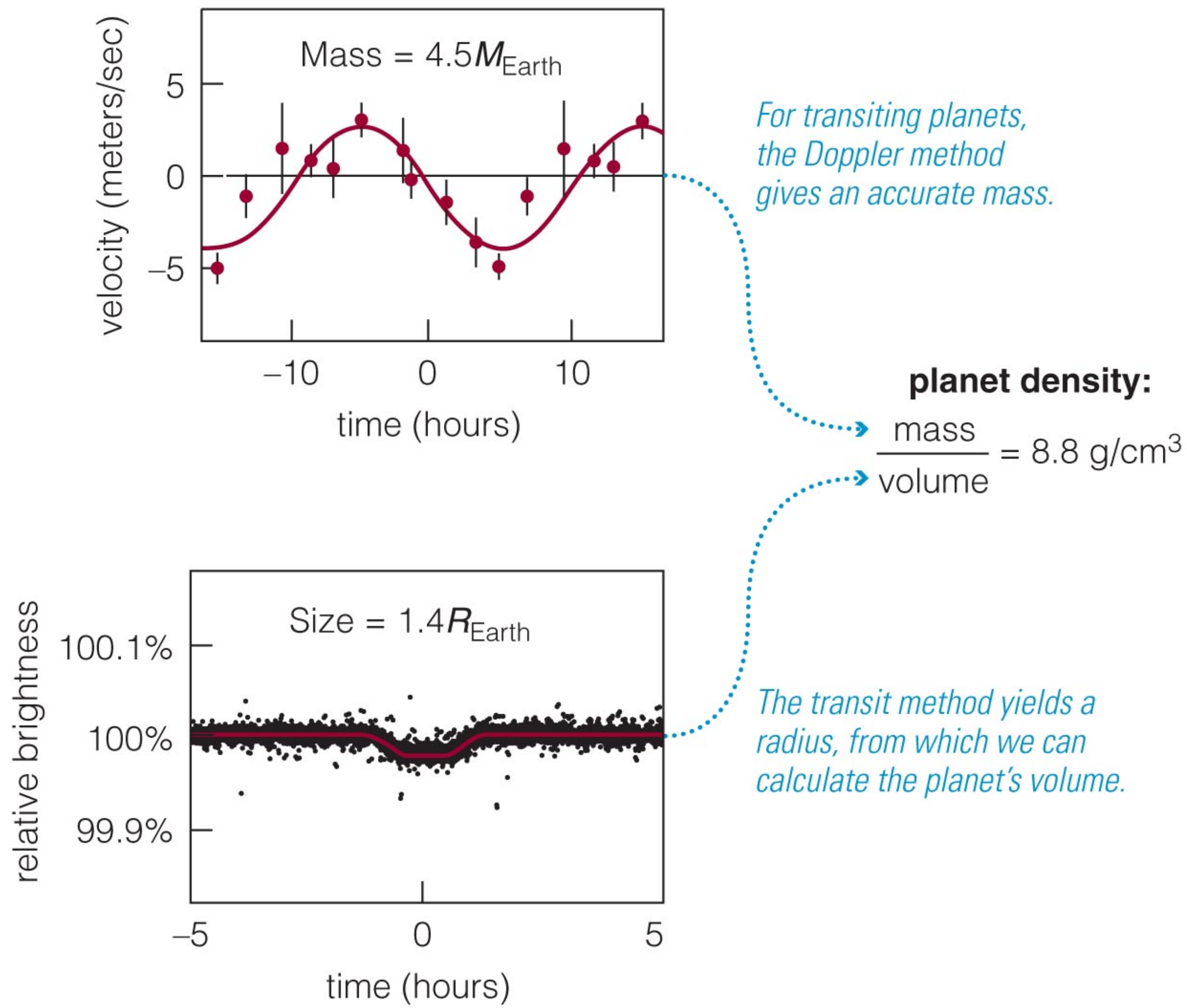
The Kepler 11 system



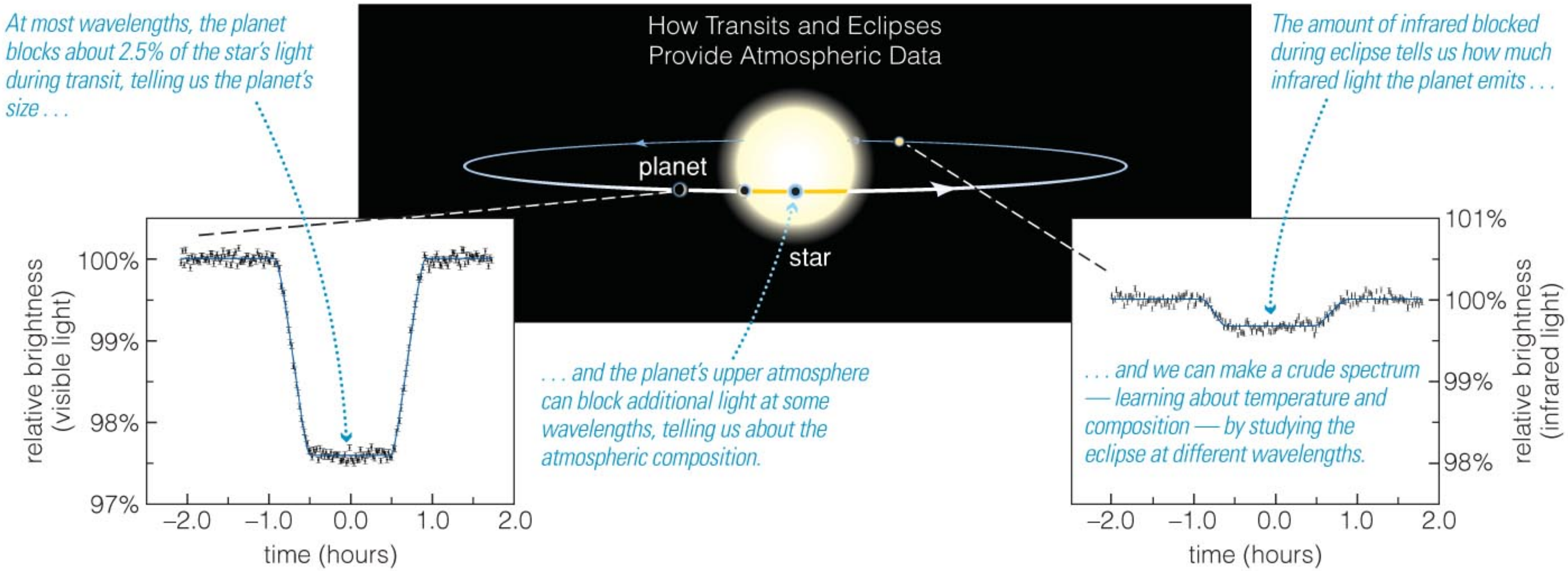
- The periods and sizes of Kepler 11's 6 known planets can be determined using transit data.

Calculating density

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

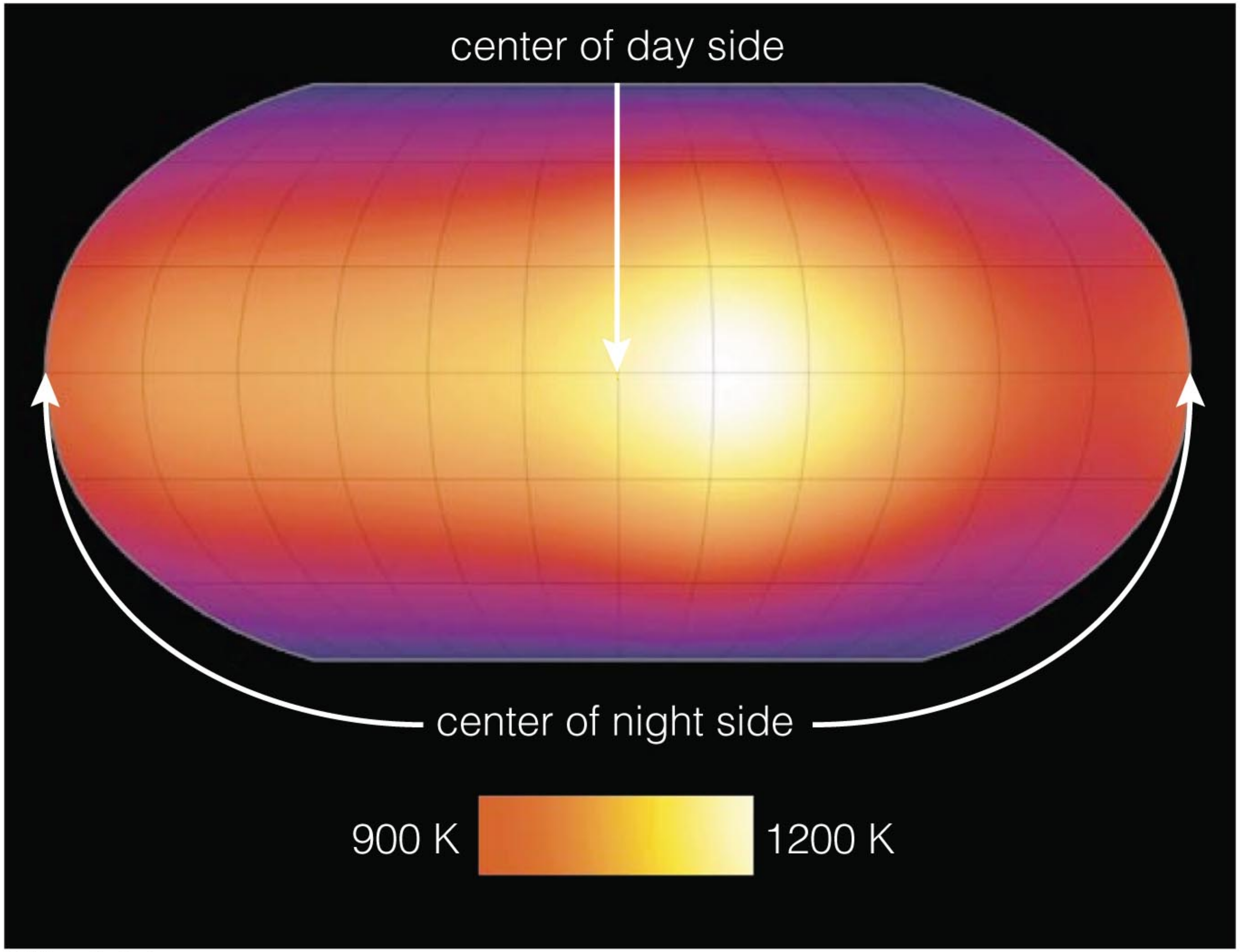


Spectrum During Transit



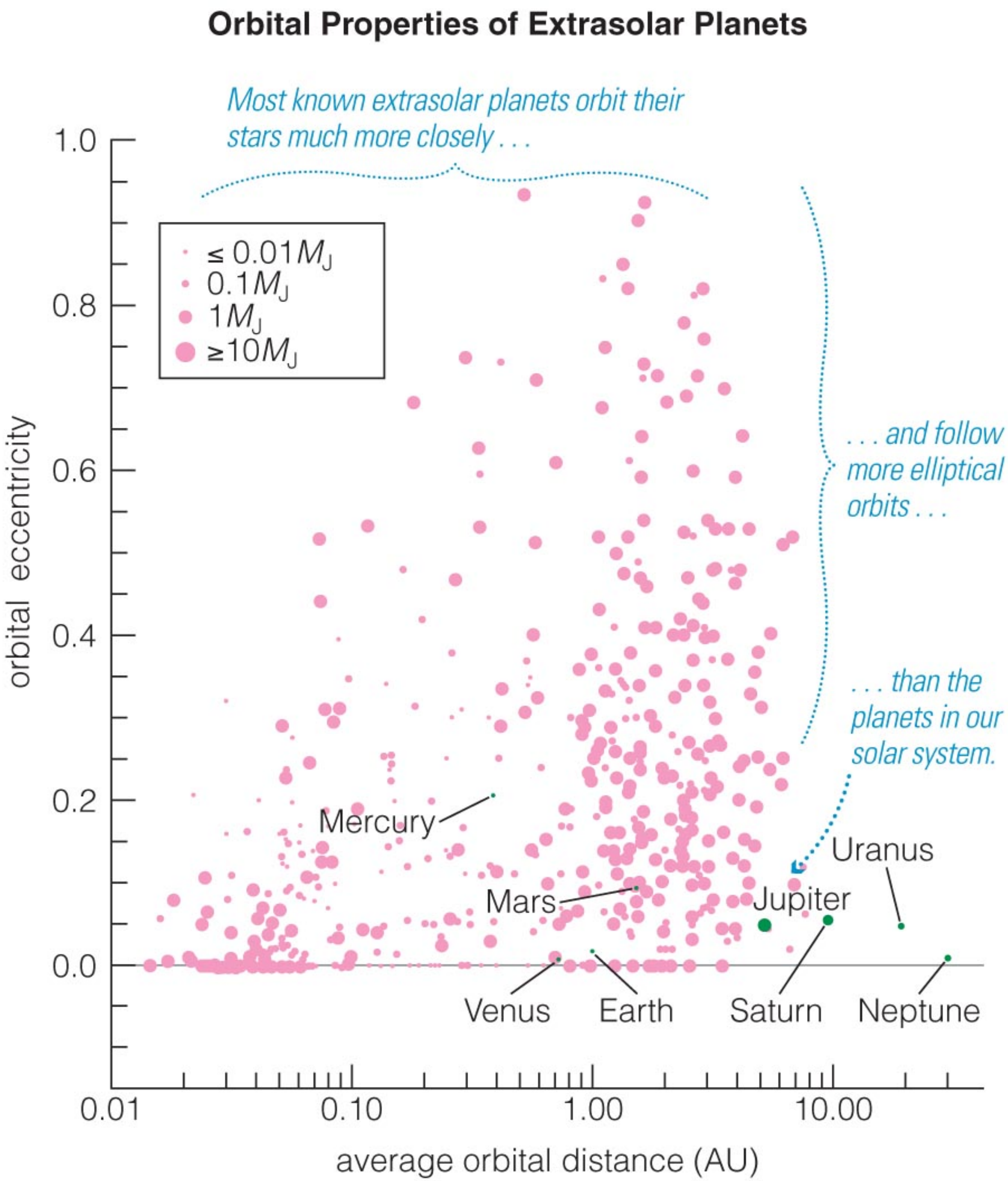
- Change in spectrum during a transit tells us about the composition of planet's atmosphere.

Surface Temperature Map



- Measuring the change in infrared brightness during an eclipse enables us to map a planet's surface temperature.

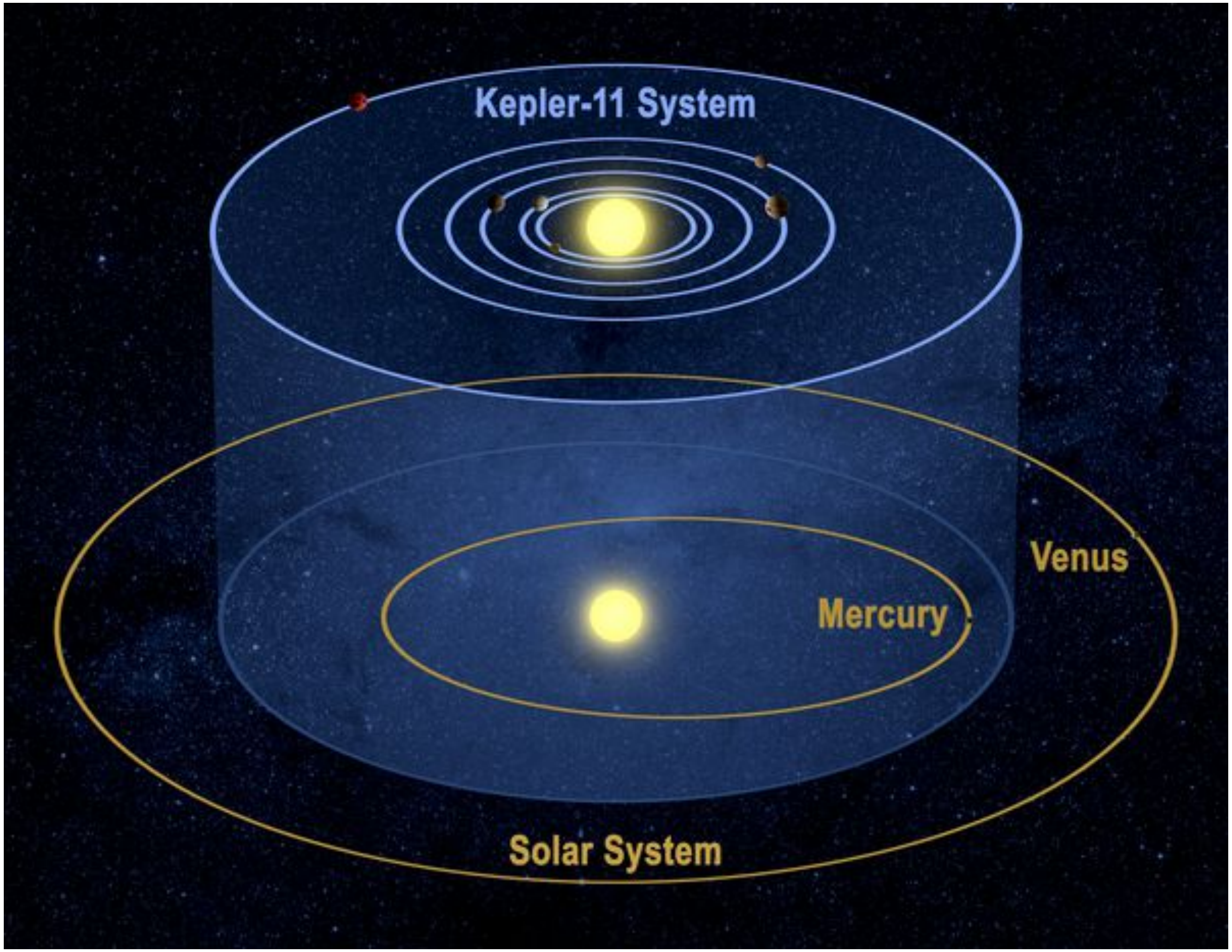
Orbits of Extrasolar Planets



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

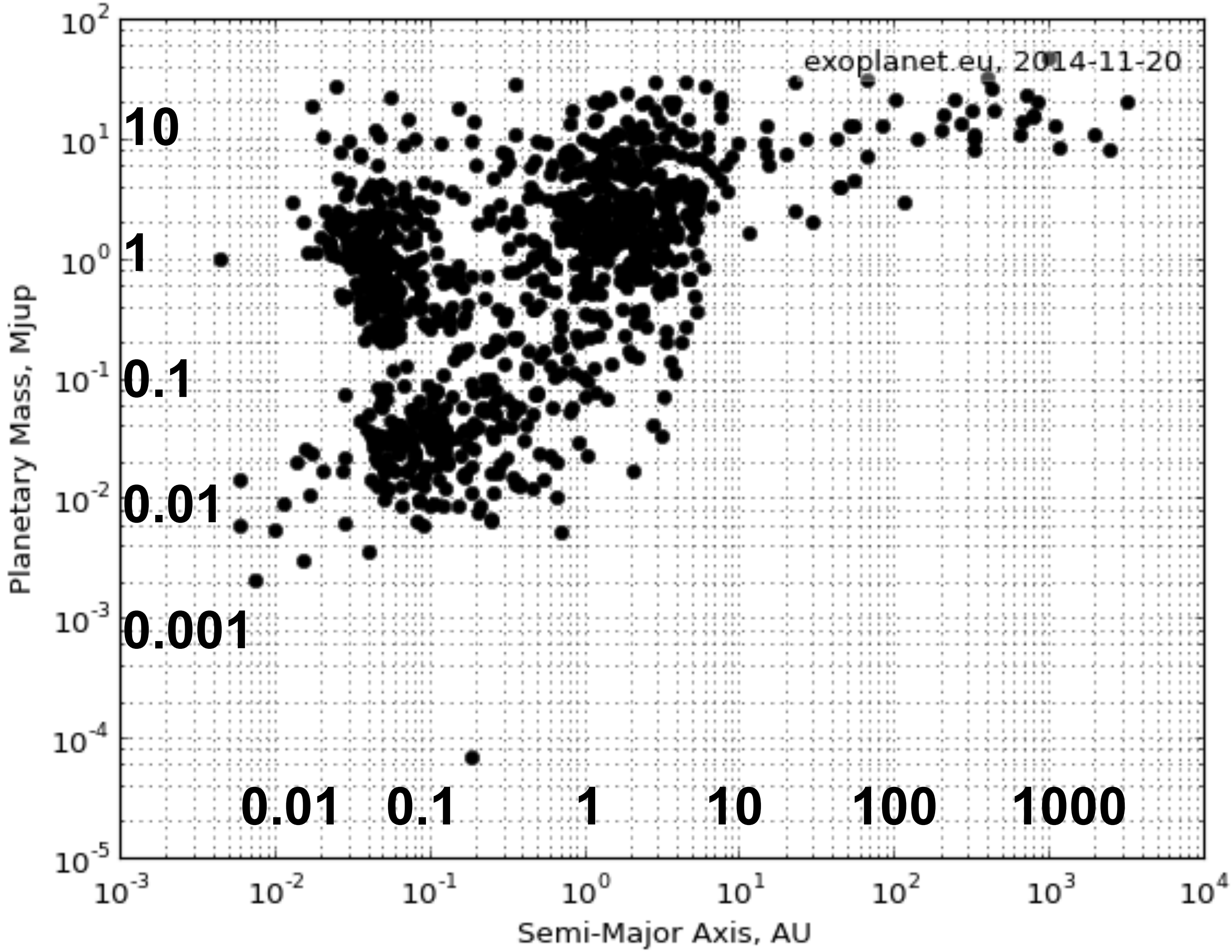
Planets at greater distances are harder to detect with either the Doppler or Transit techniques. (Why?)

Tightly Packed Systems: Kepler 11

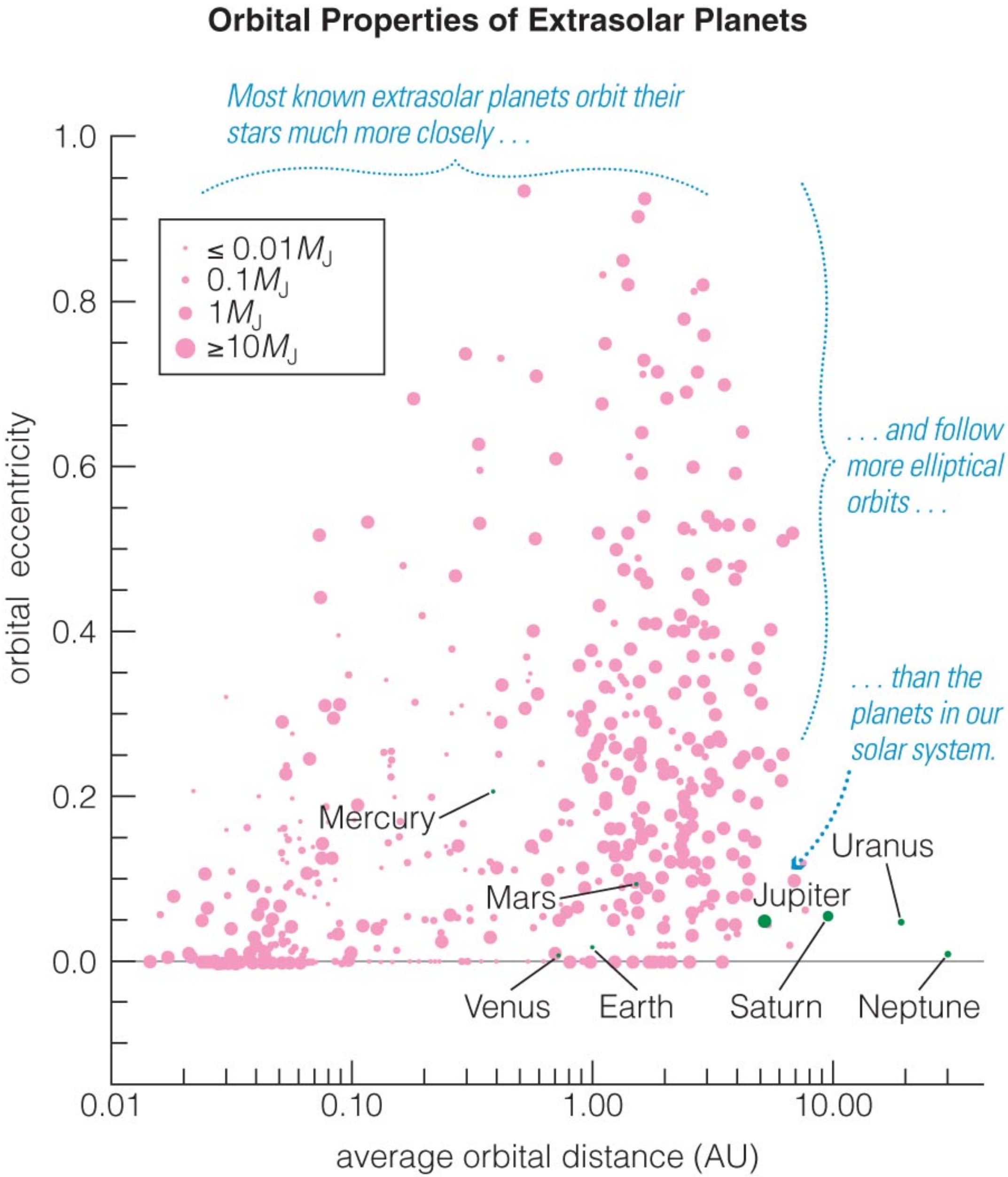


[Take a look at a graphic of all the Kepler systems!]

Orbits of Extrasolar Planets: Mass/Distance

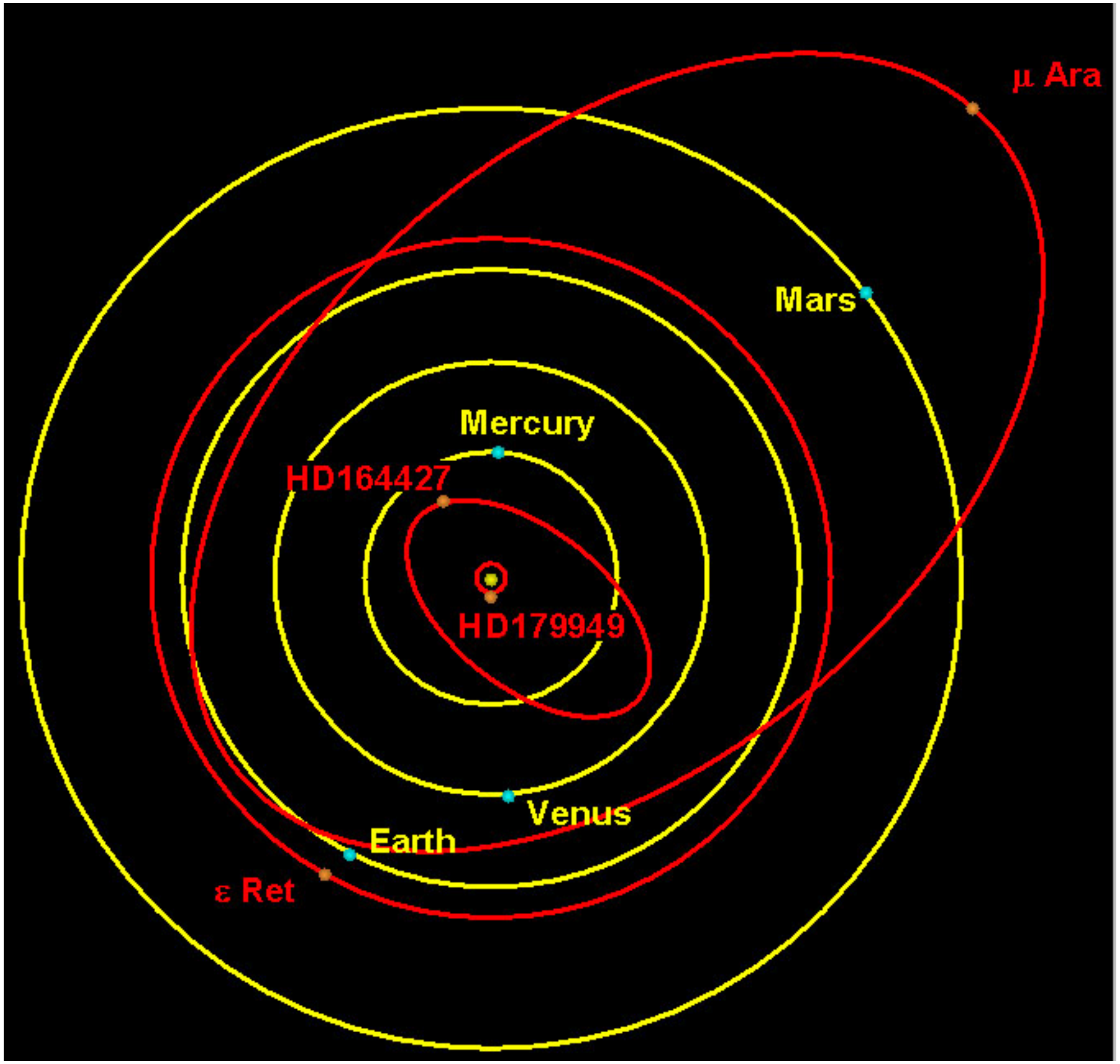


Orbits of Extrasolar Planets

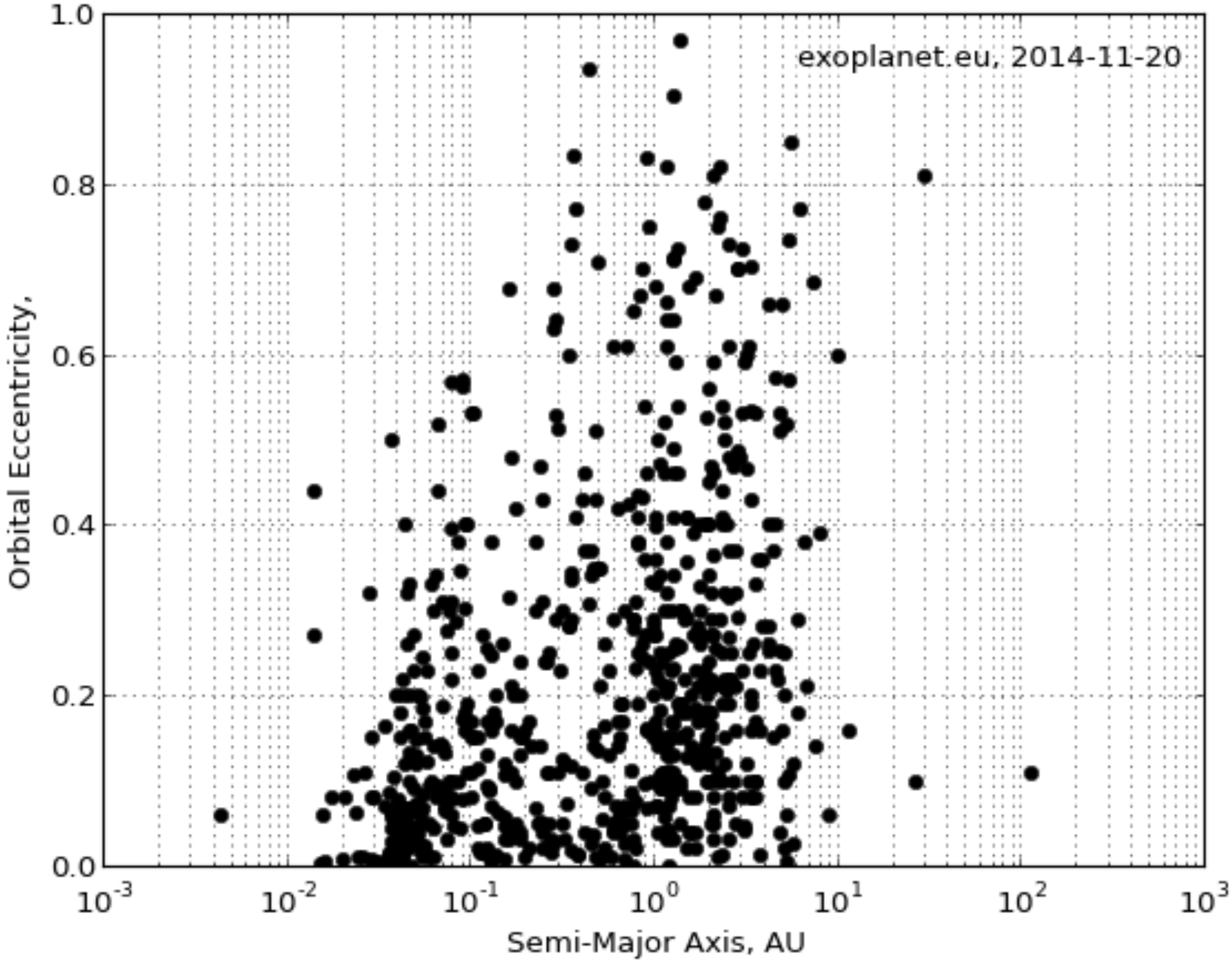


Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

Eccentric Orbits



Orbits of Extrasolar Planets: Eccentricity



0.01 0.1 1 10 100 1000

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.

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.

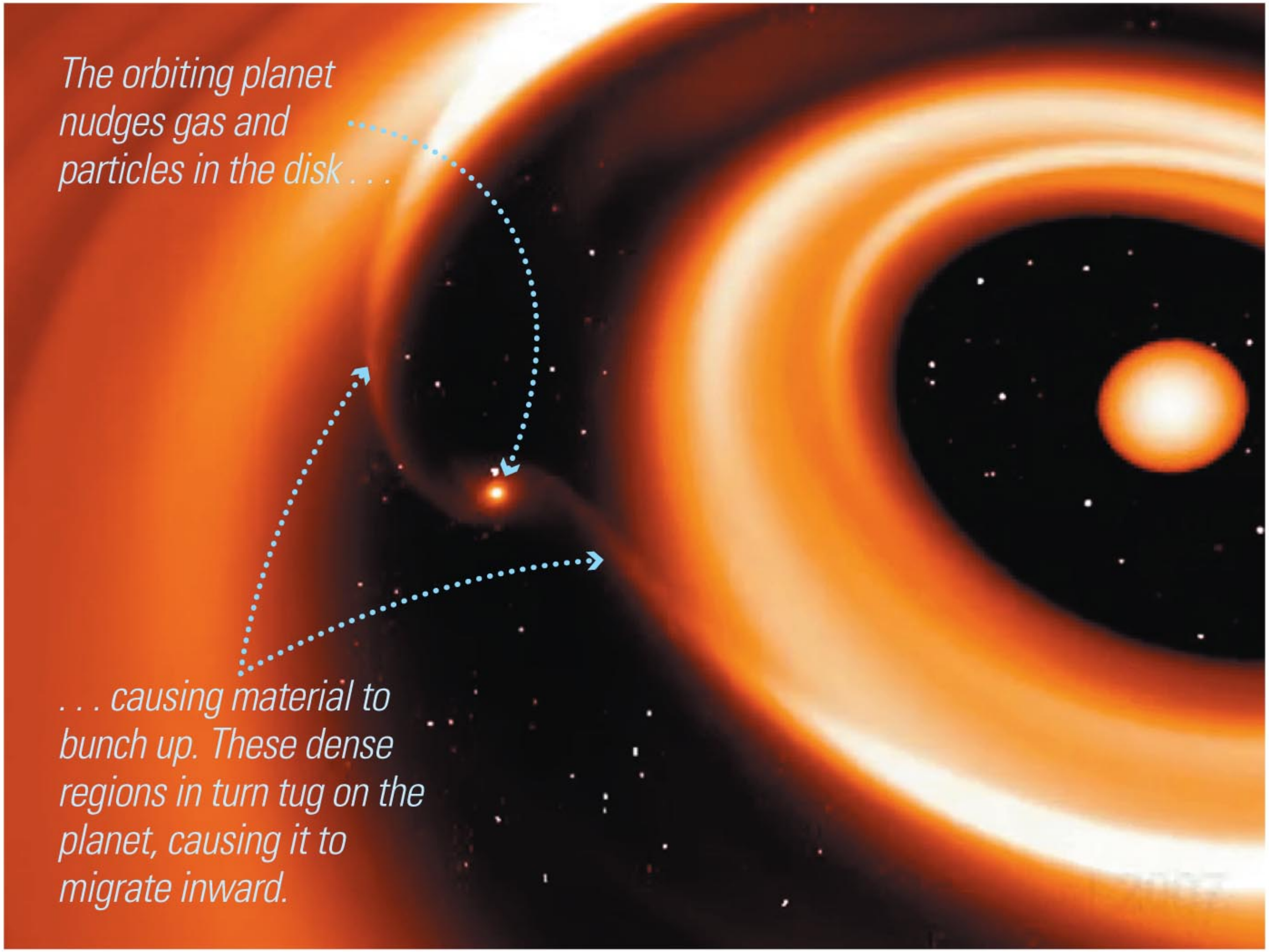
13.3 The Formation of Other Solar Systems

- 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

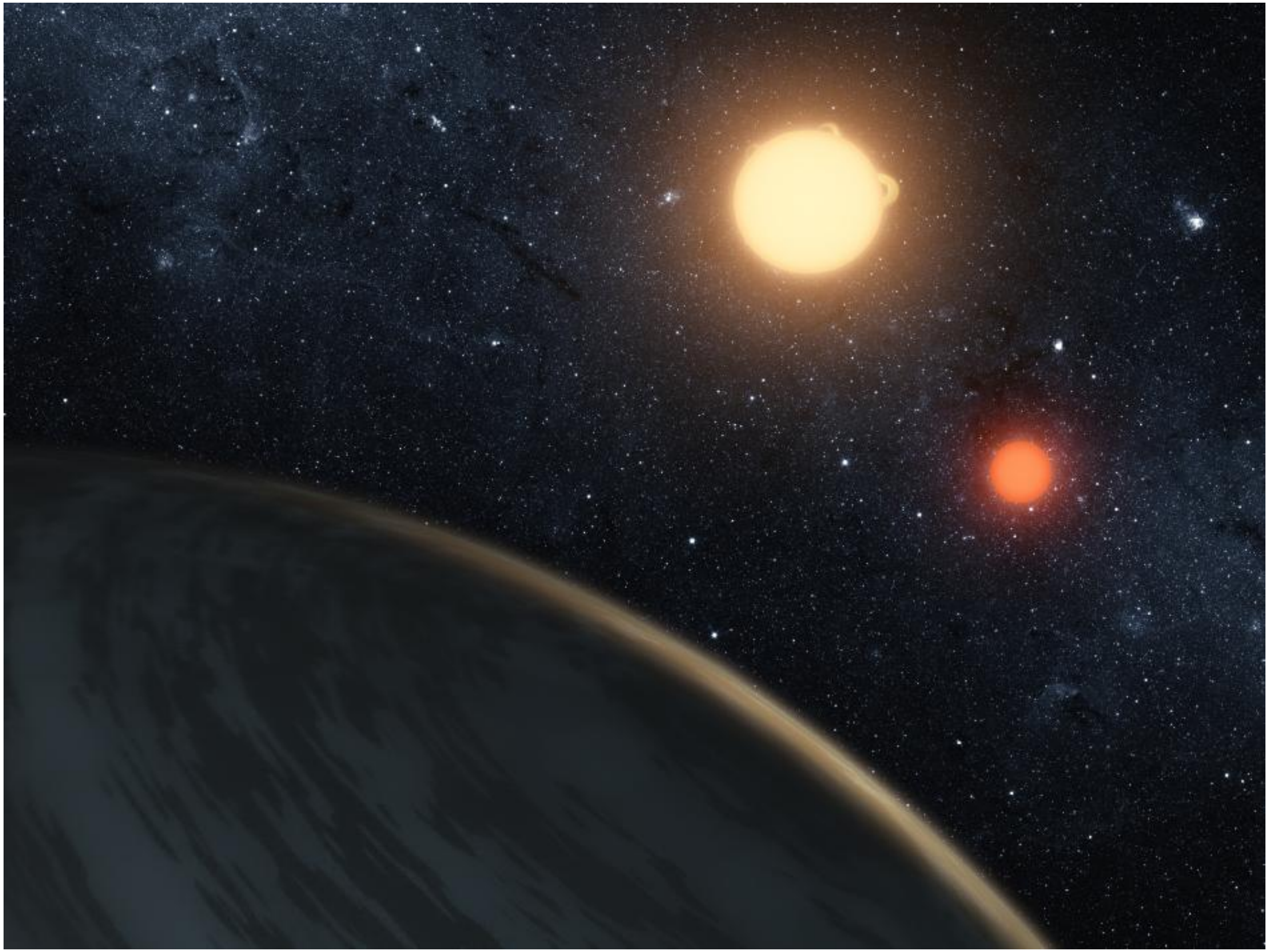
- Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit.
- Multiple close encounters with smaller planetesimals can also cause inward migration.
- Resonances may also contribute.

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.