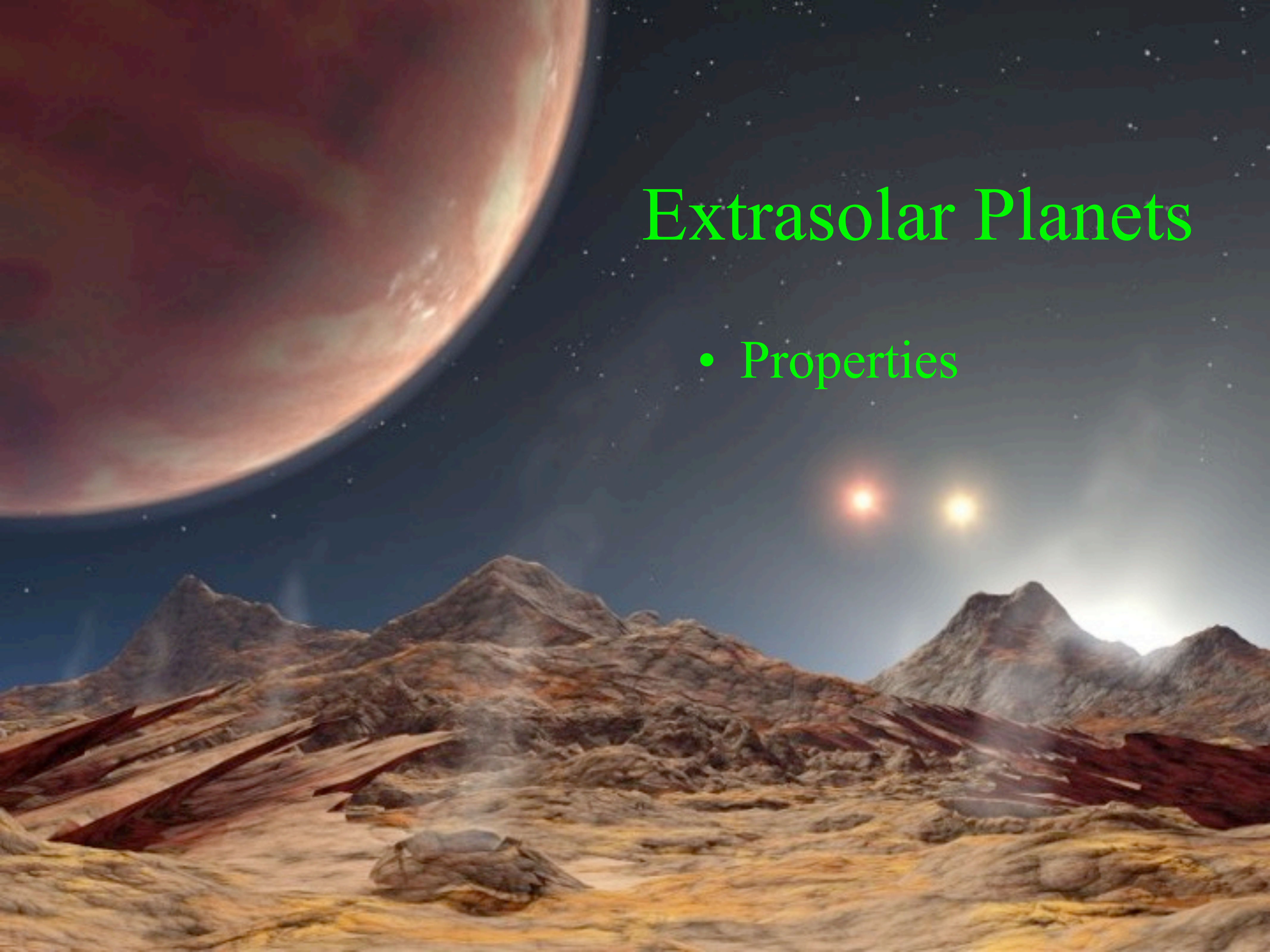
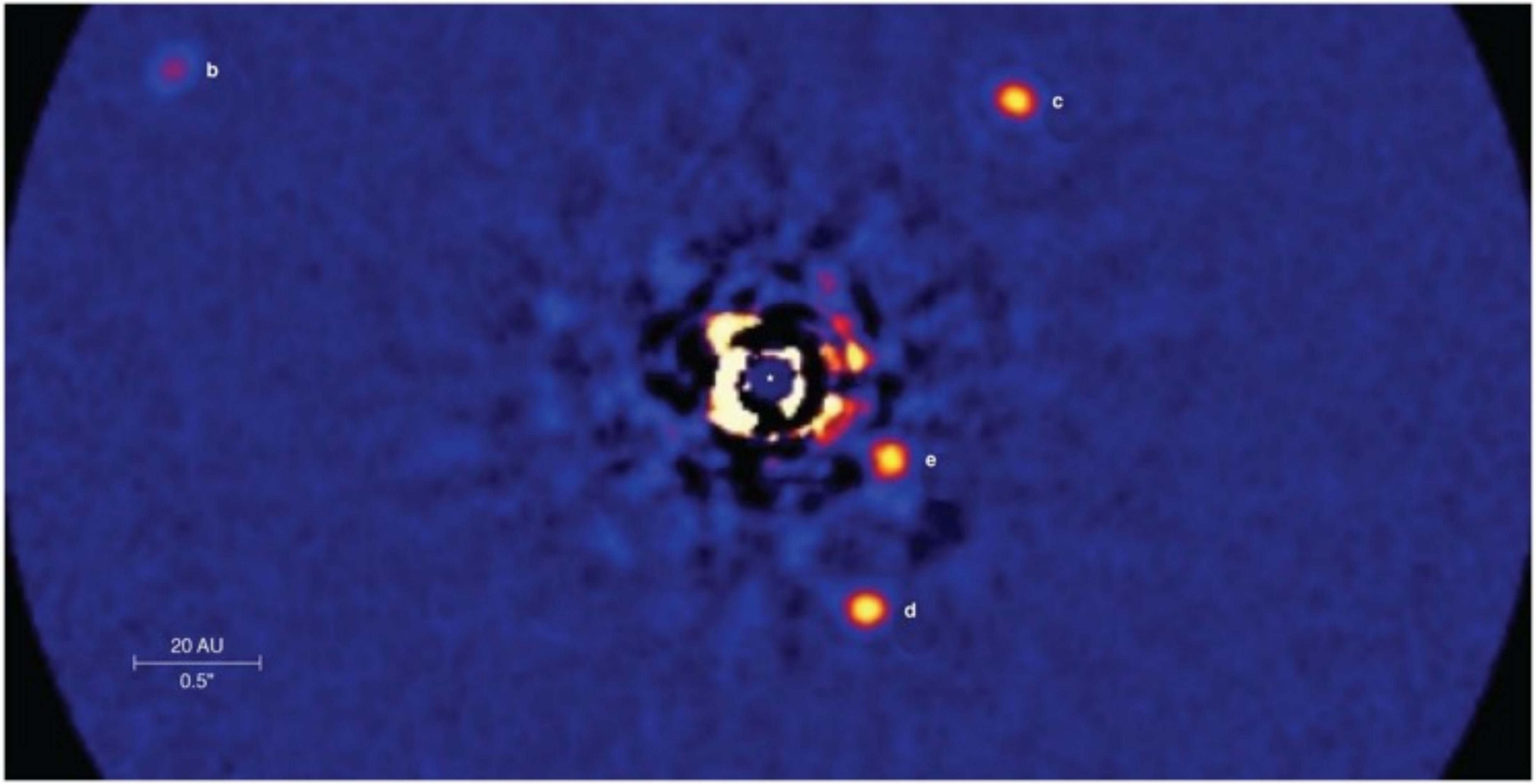
Extrasolar Planets

- Properties



Finding extrasolar planets is hard

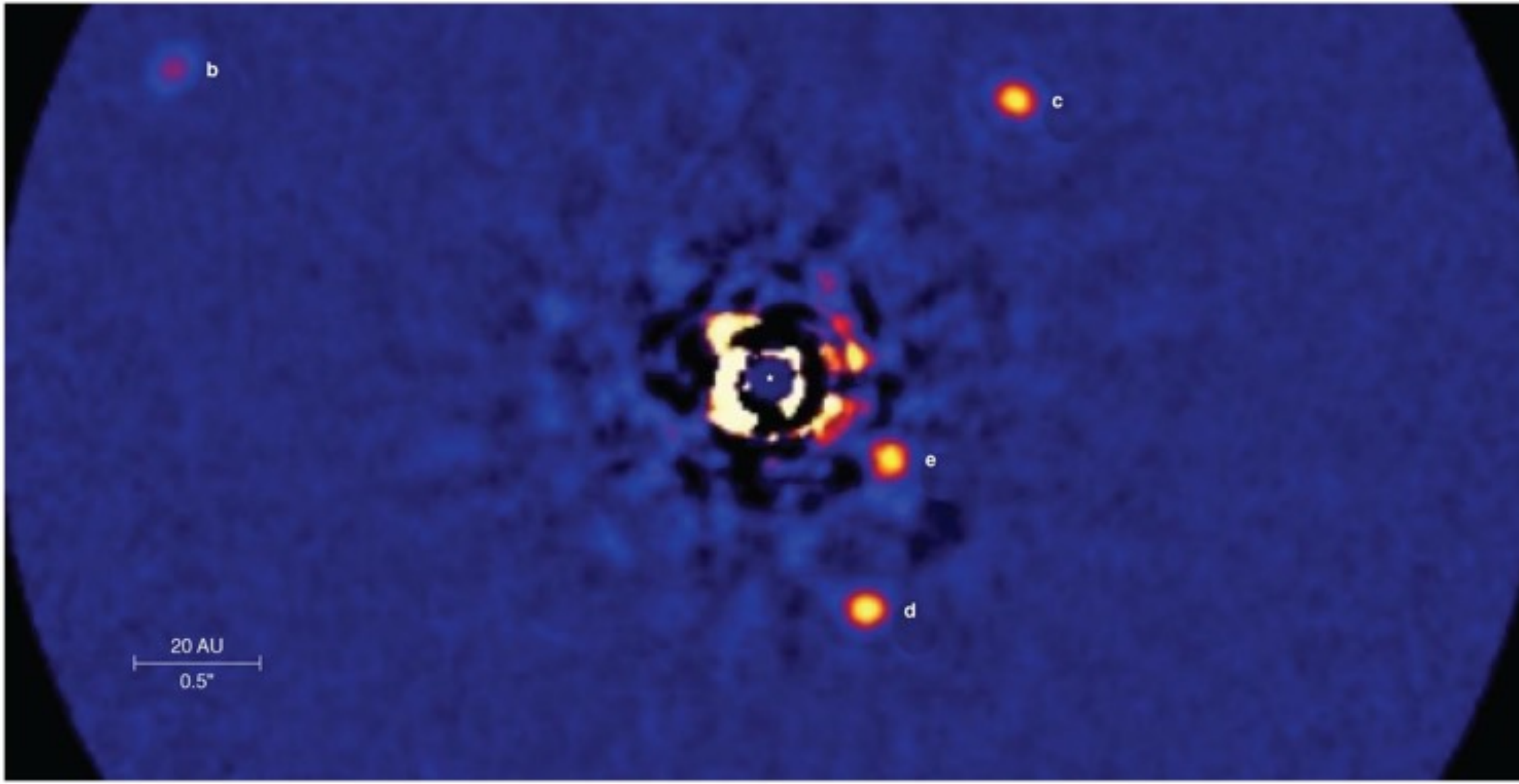
quick recap



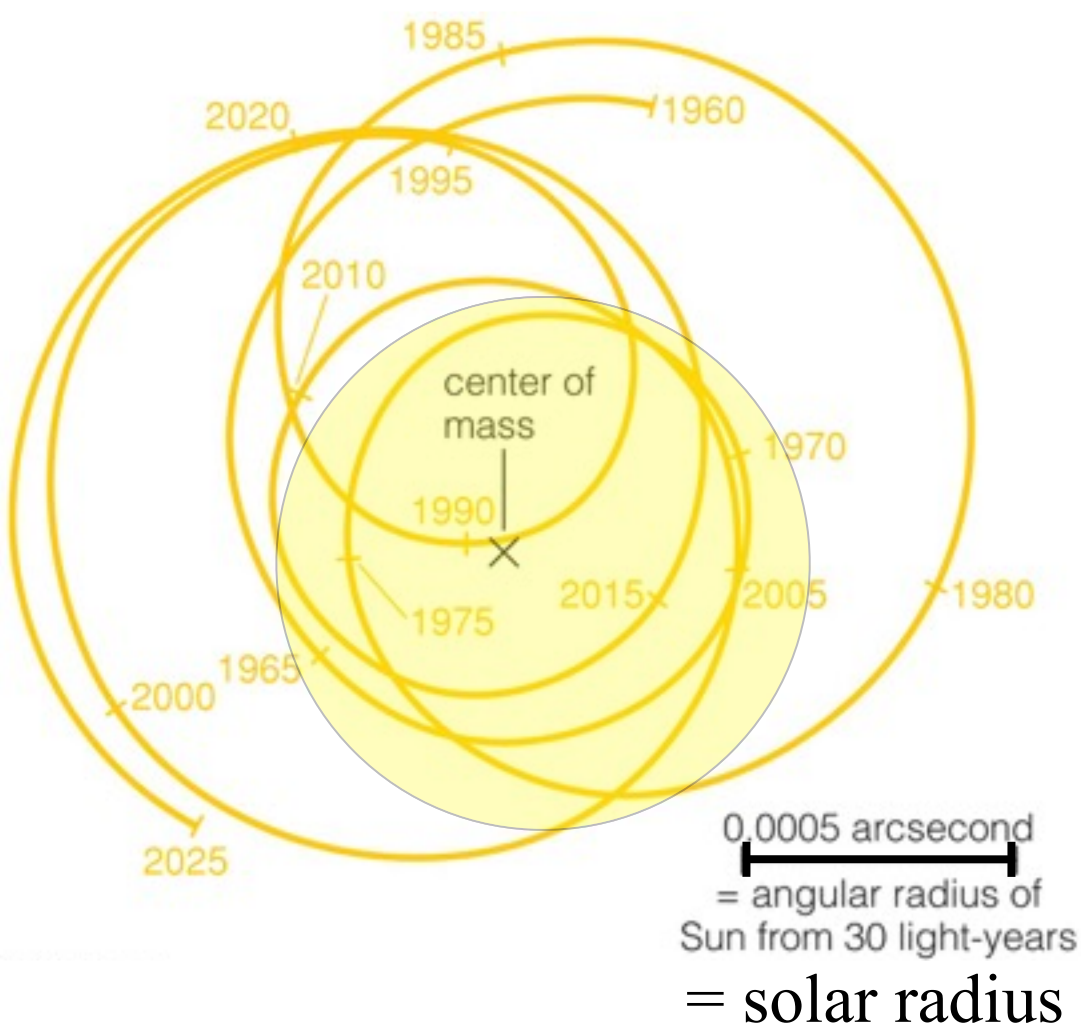
Planet Detection

- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets
  - Astrometric method (face-on)
  - Doppler method (edge-on)
  - Transit method (edge-on)
  - Gravitational lensing

Direct Imaging

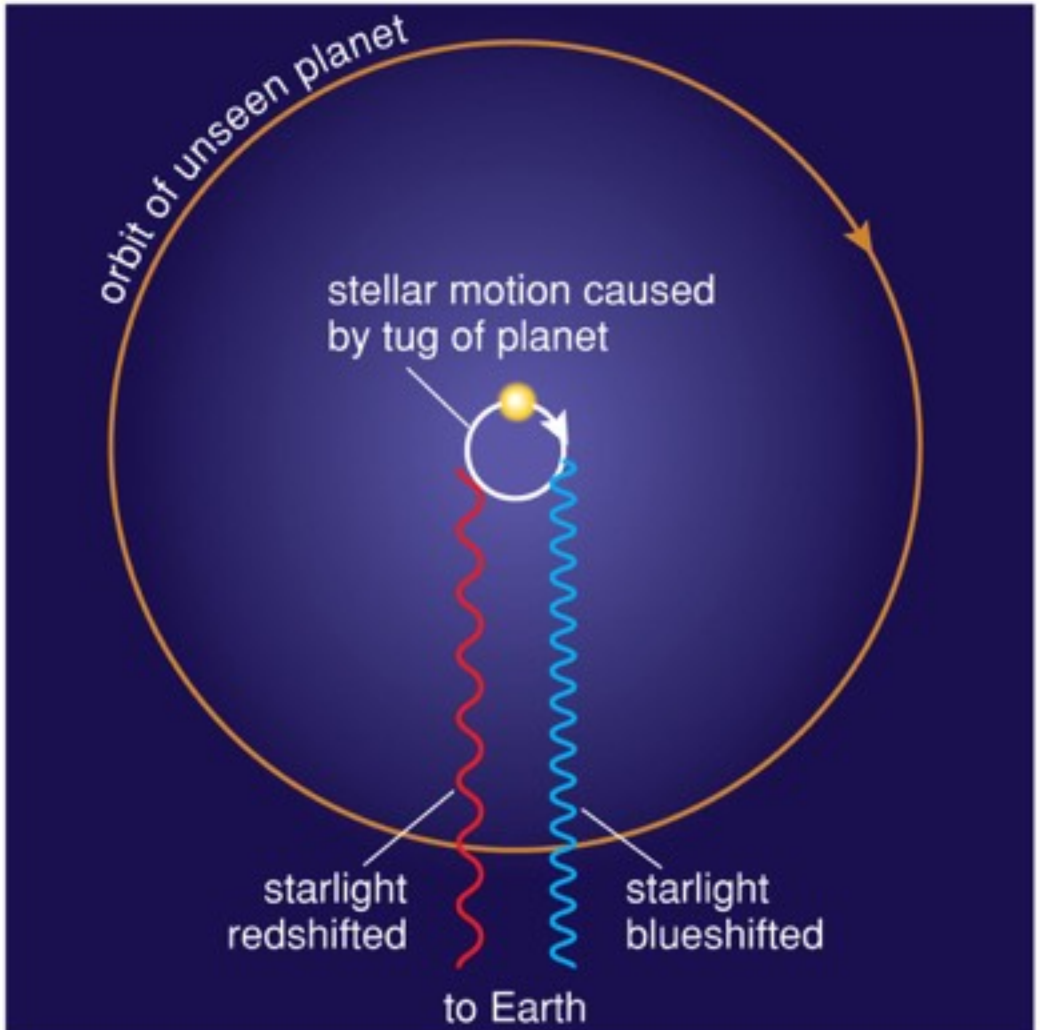


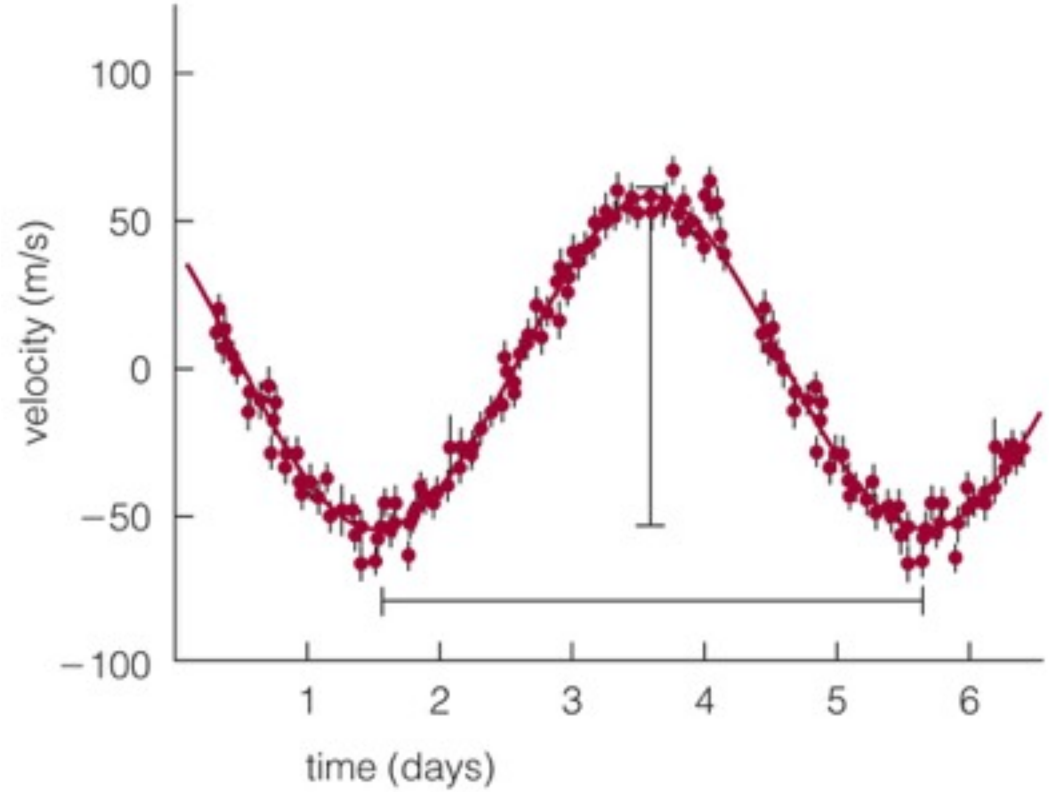
Astrometric Technique



- 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).
- Best seen face-on

Doppler Technique

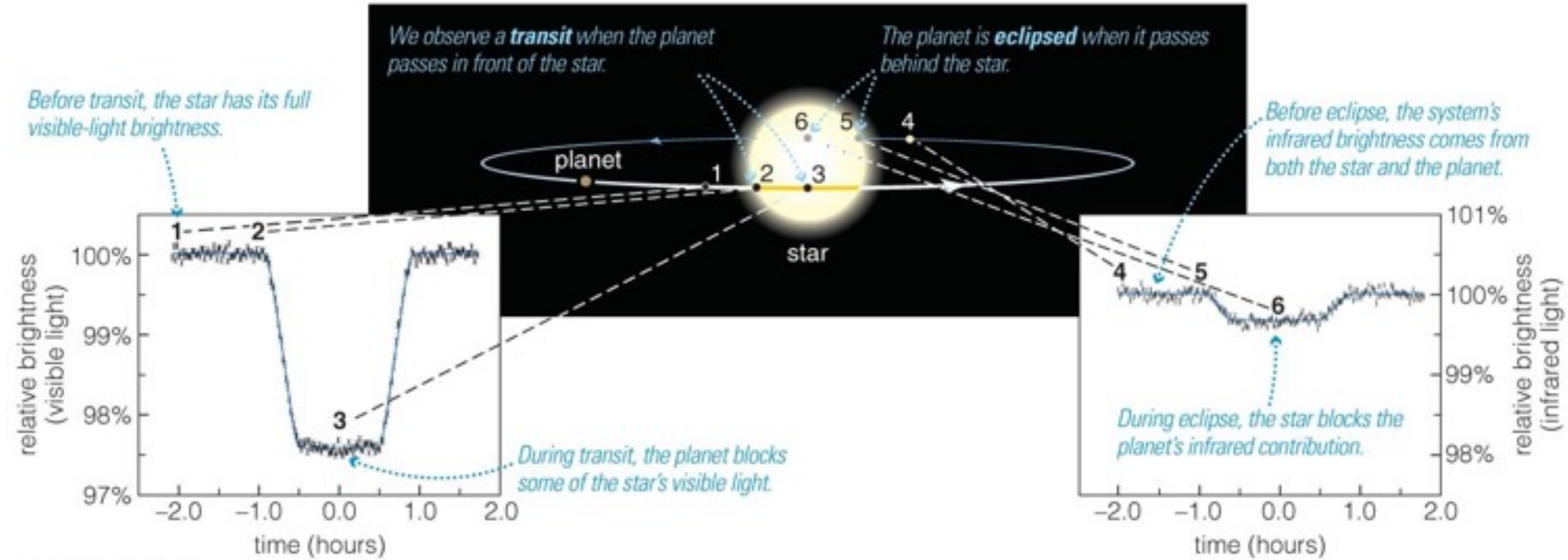




a A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

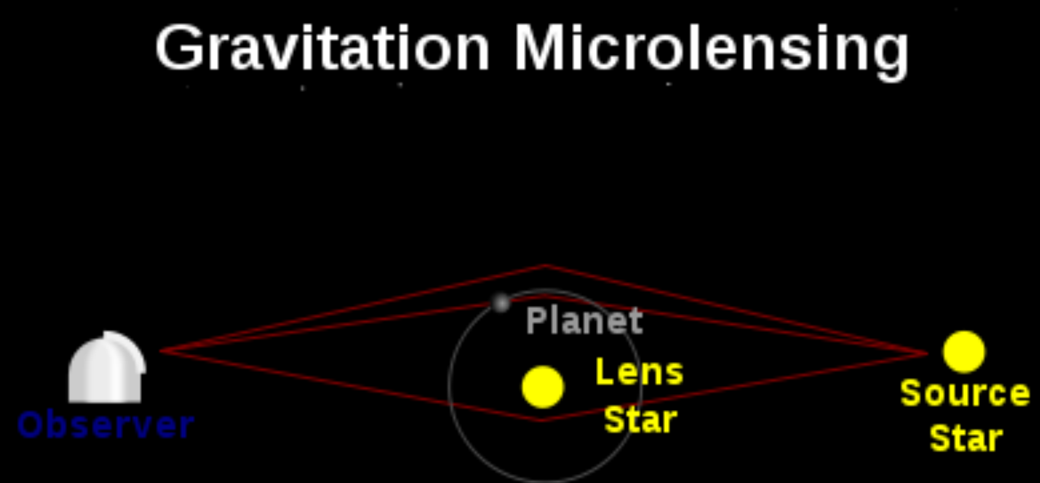
- Best seen edge-on

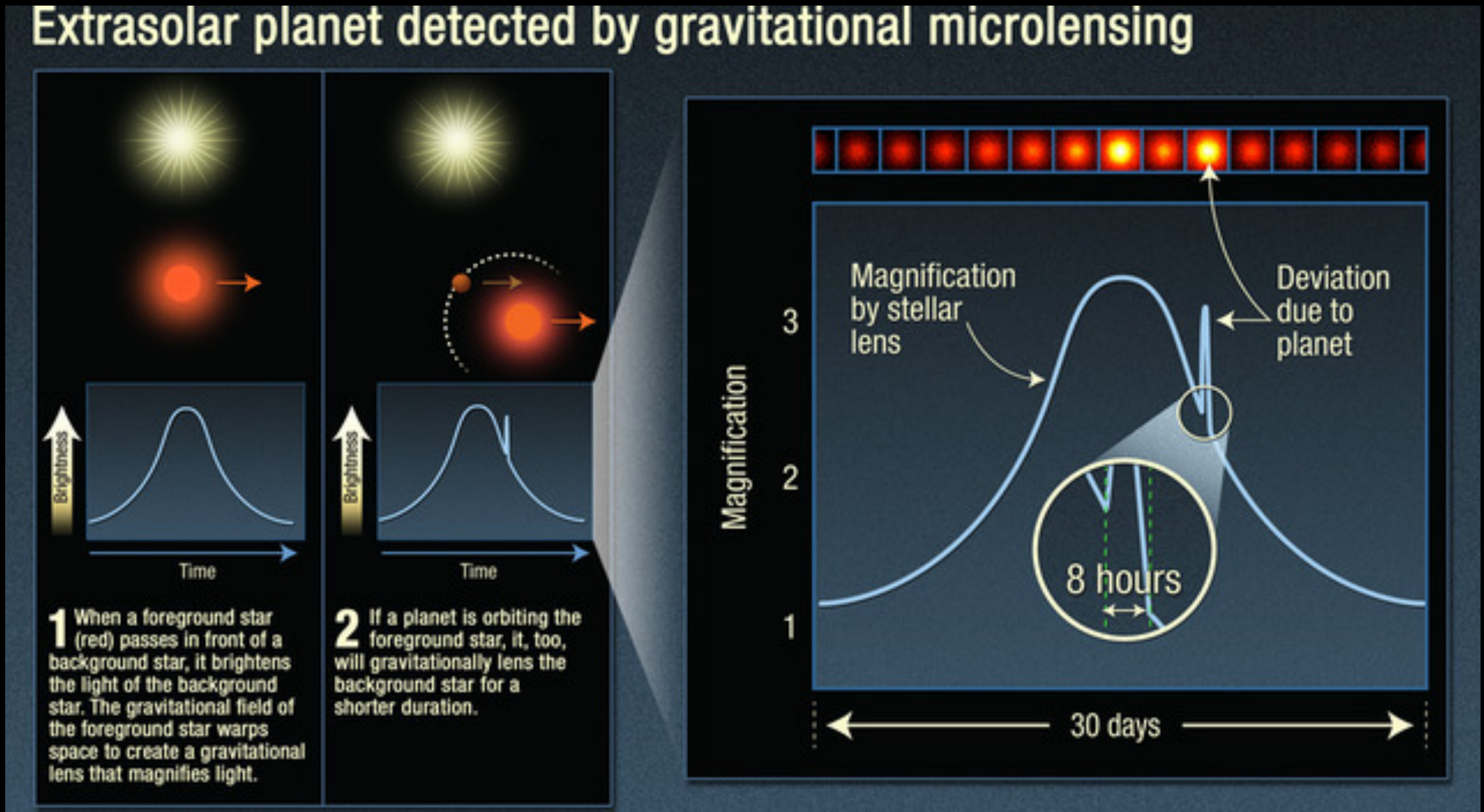
Transit Technique

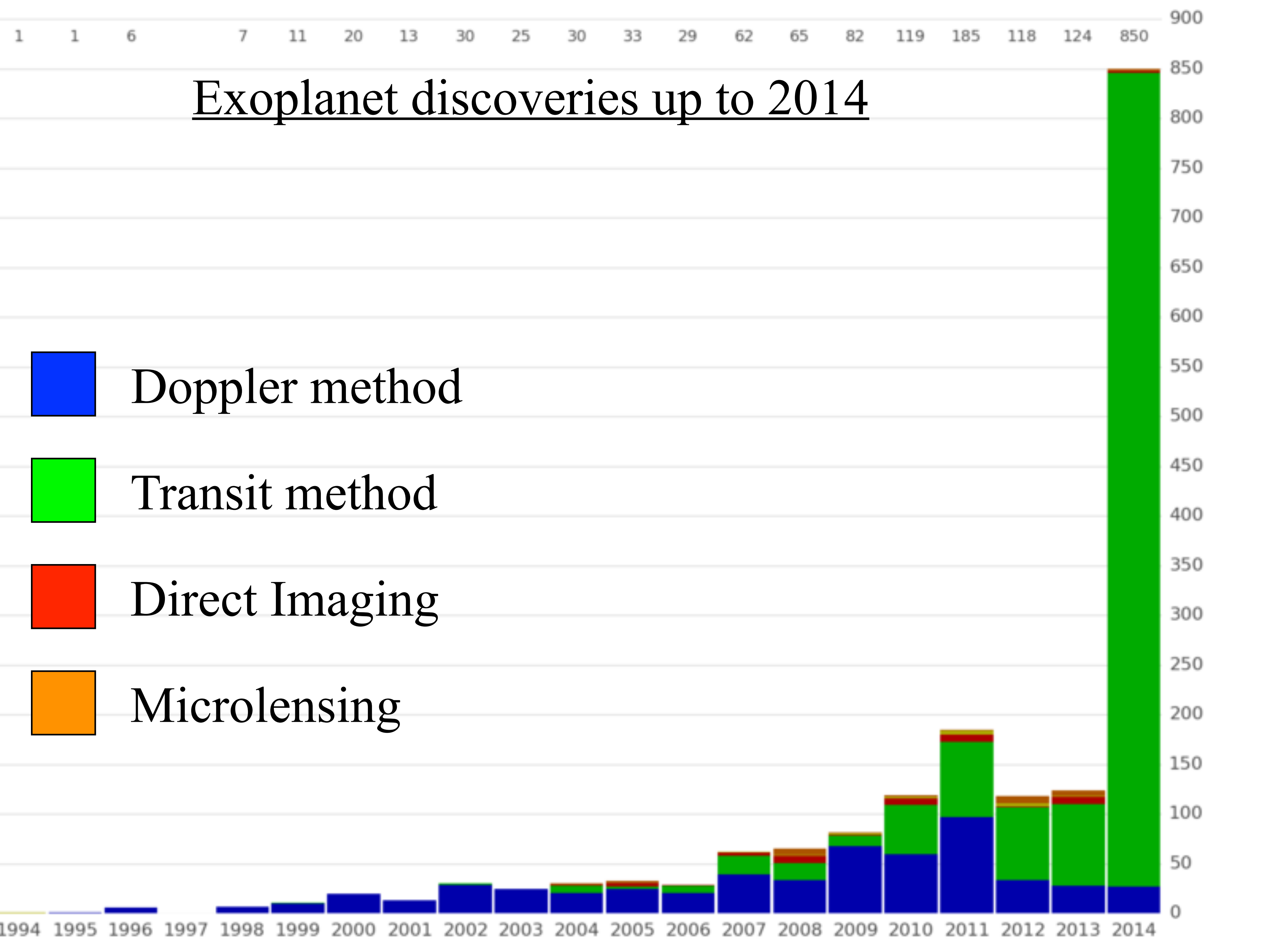


- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
  - best seen edge-on

Gravitational lensing Technique

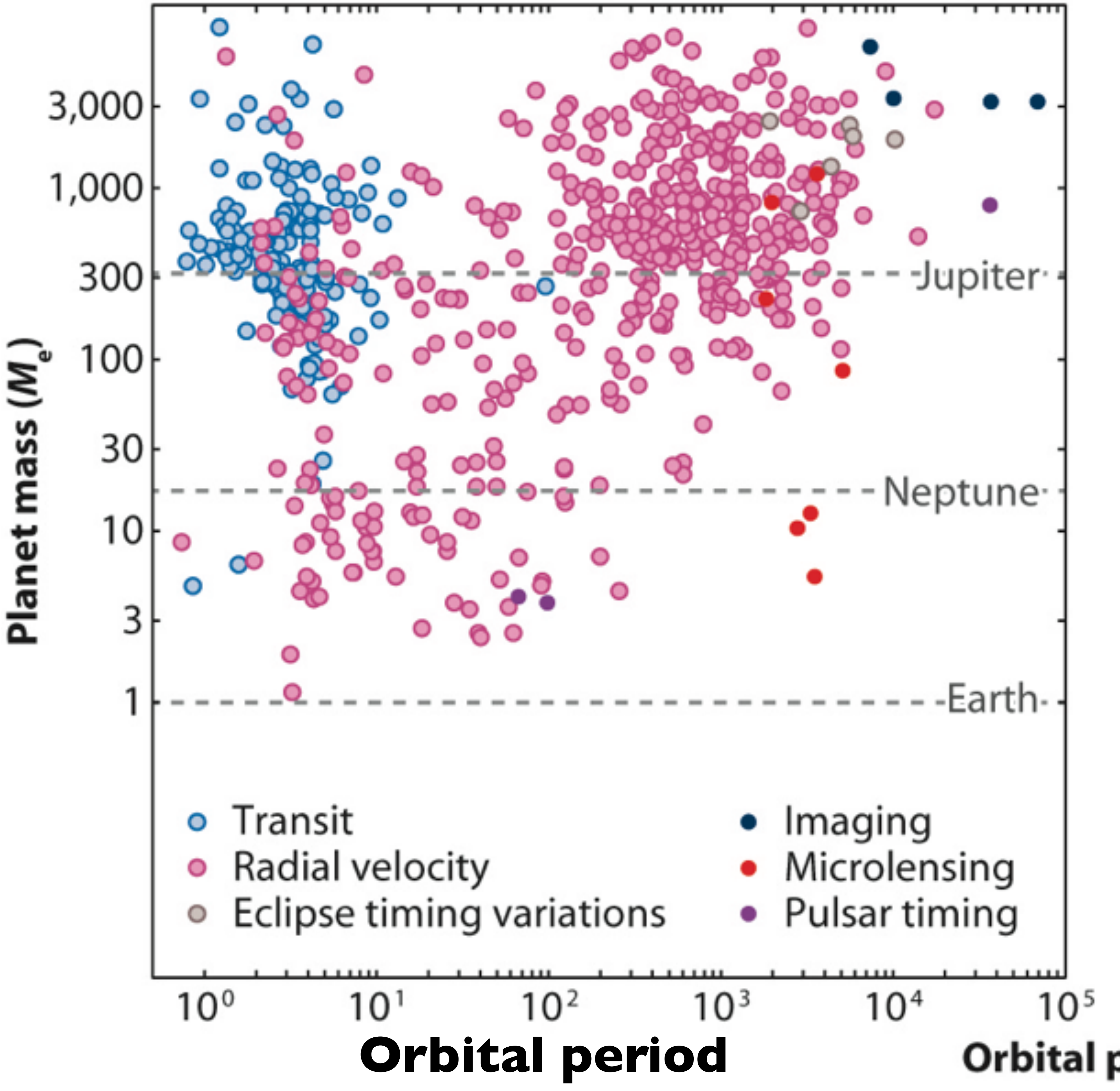


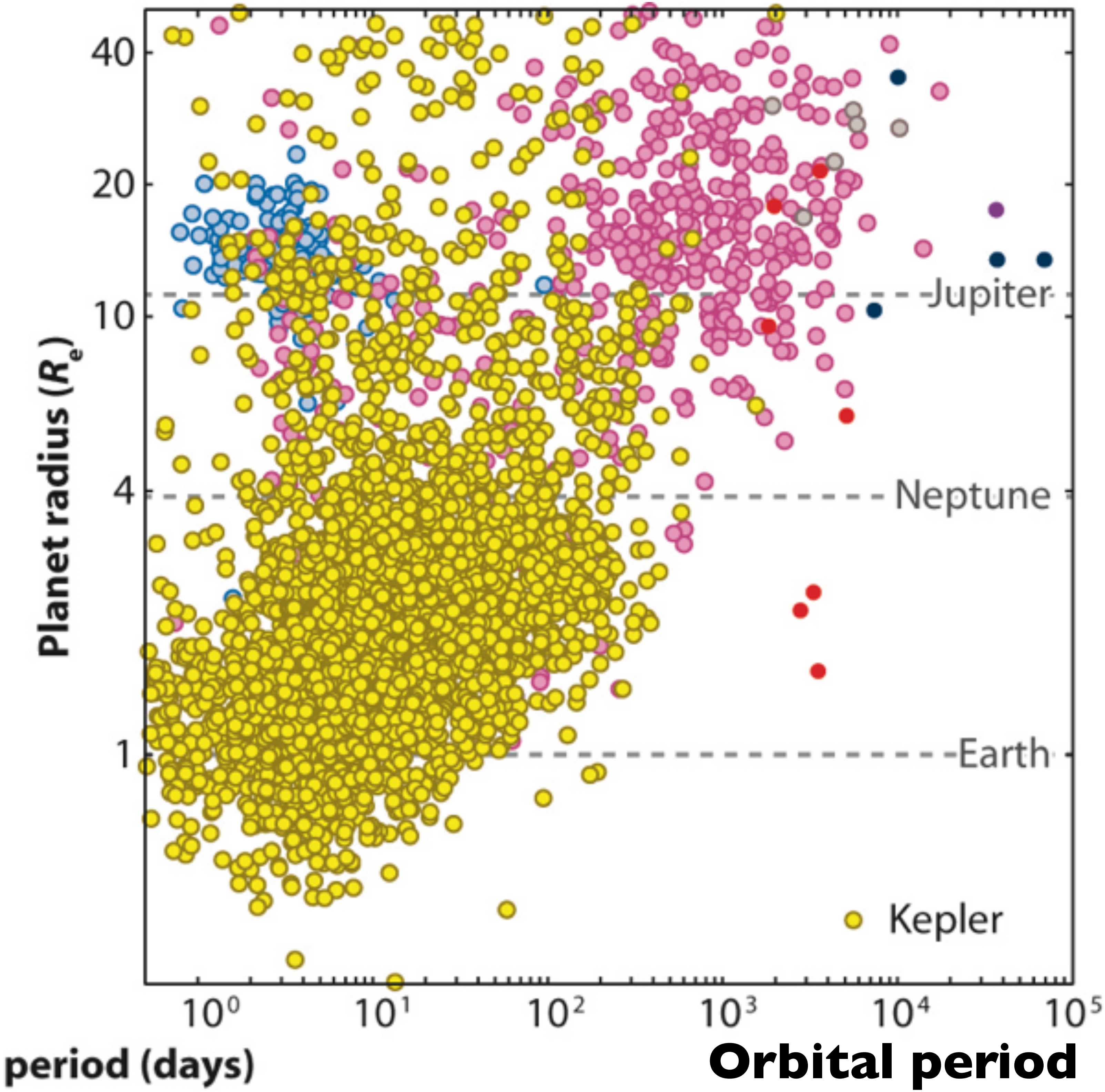




Exoplanet discoveries up to 2014
Doppler method
Transit method
Direct Imaging
Microlensing
1 1 6 7 11 20 13 30 25 30 33 29 62 65 82 119 185 118 124 850
900 850 800 750 700 650 600 550 500 450 400 350 300 250 200 150 100 50 0
1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014

All methods have strong selection effects





Orbital period

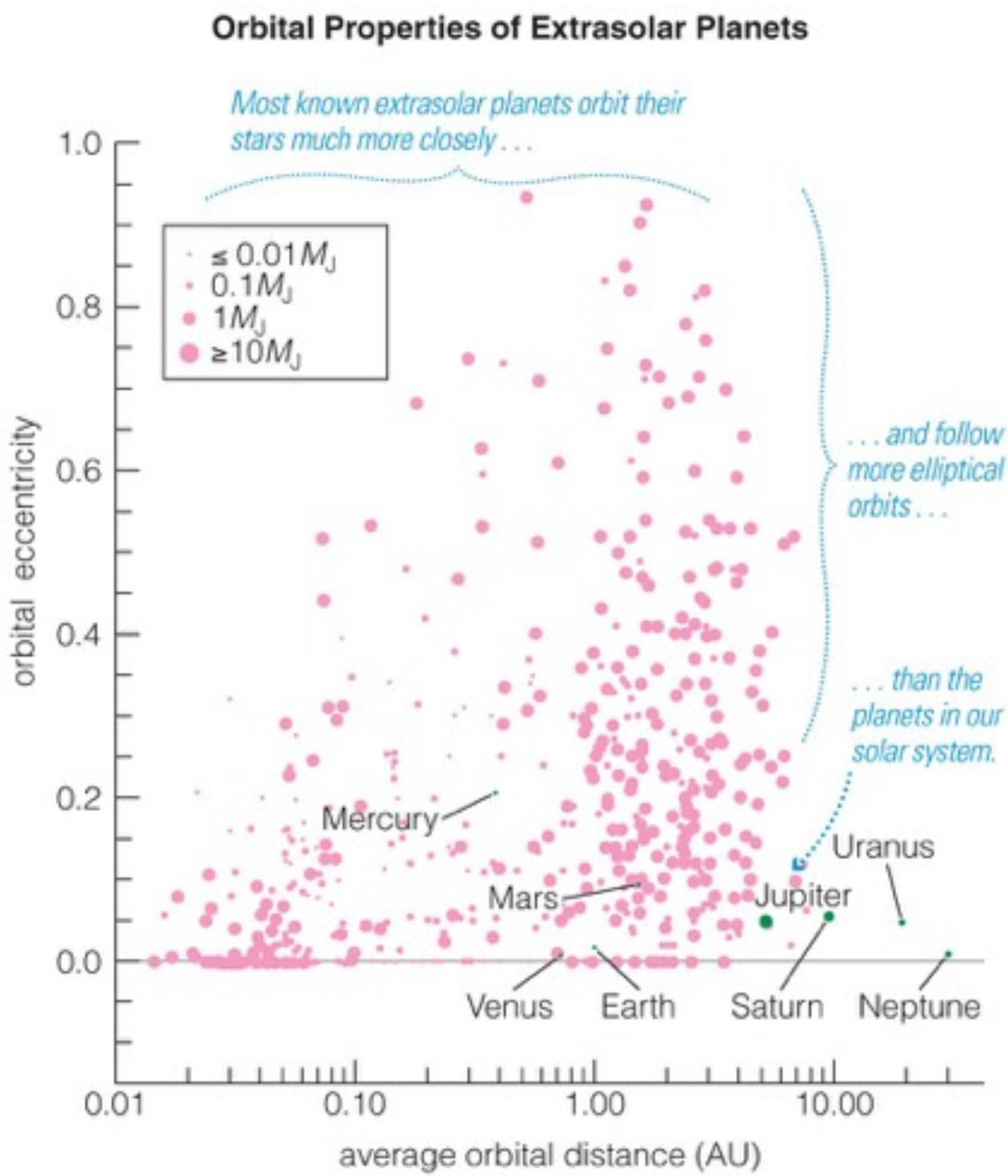
...and are good at measuring different things

Kepler is excellent at measuring radius; not necessarily mass.

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?

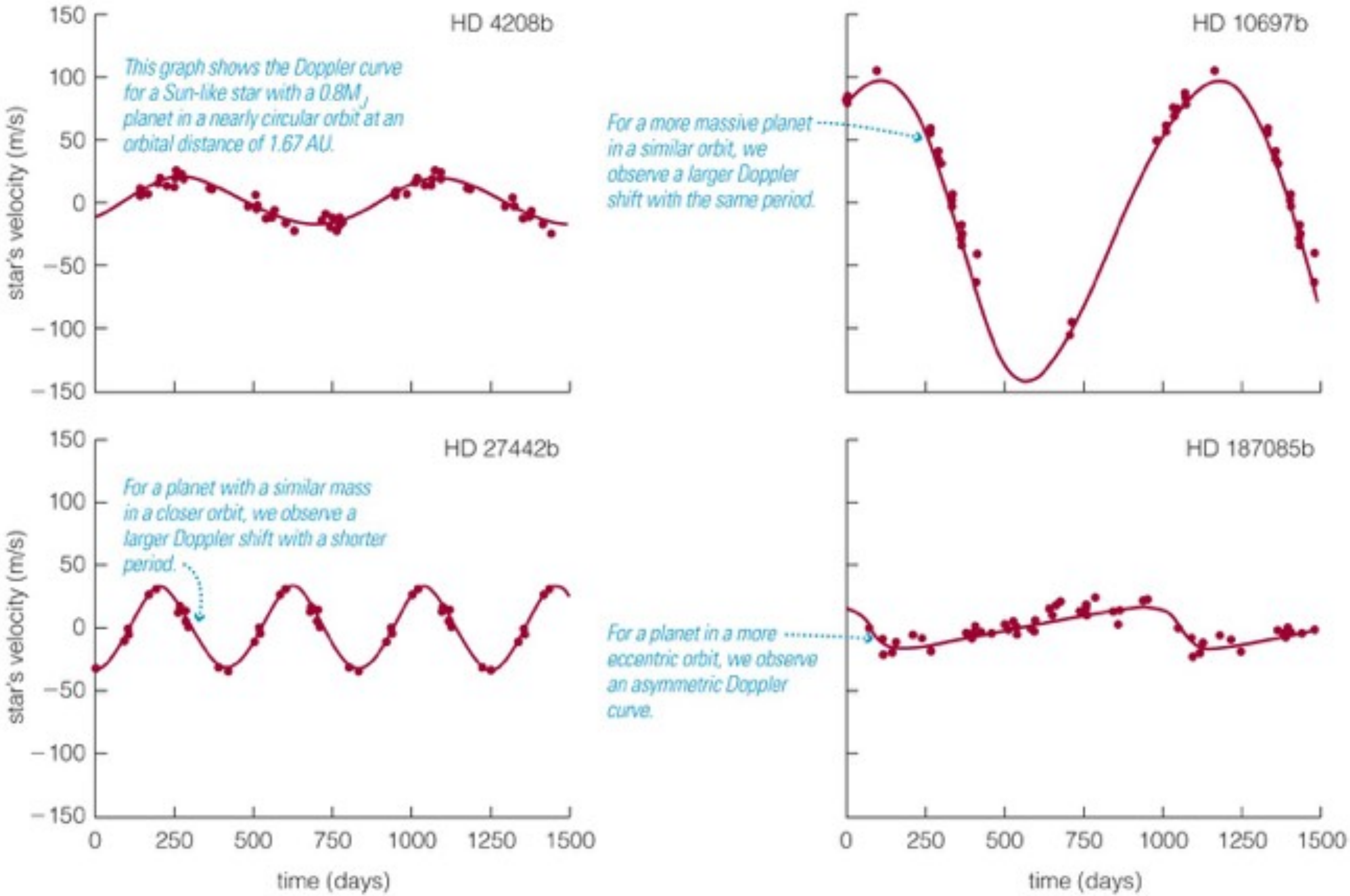


Measurable Properties

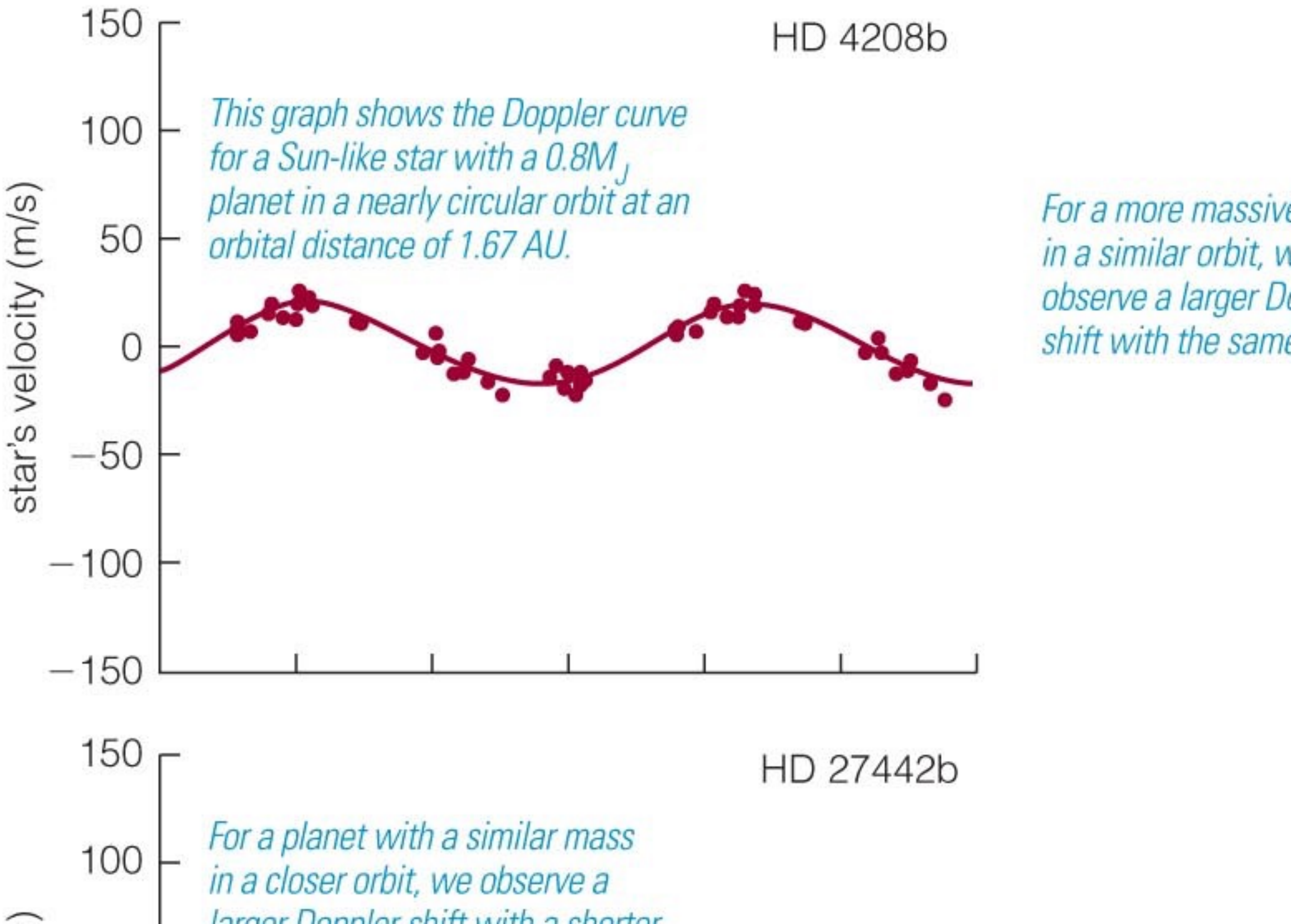
- Orbital period, distance, and shape (eccentricity)
- Planet mass, size, and density
- Atmospheric properties (sometimes)

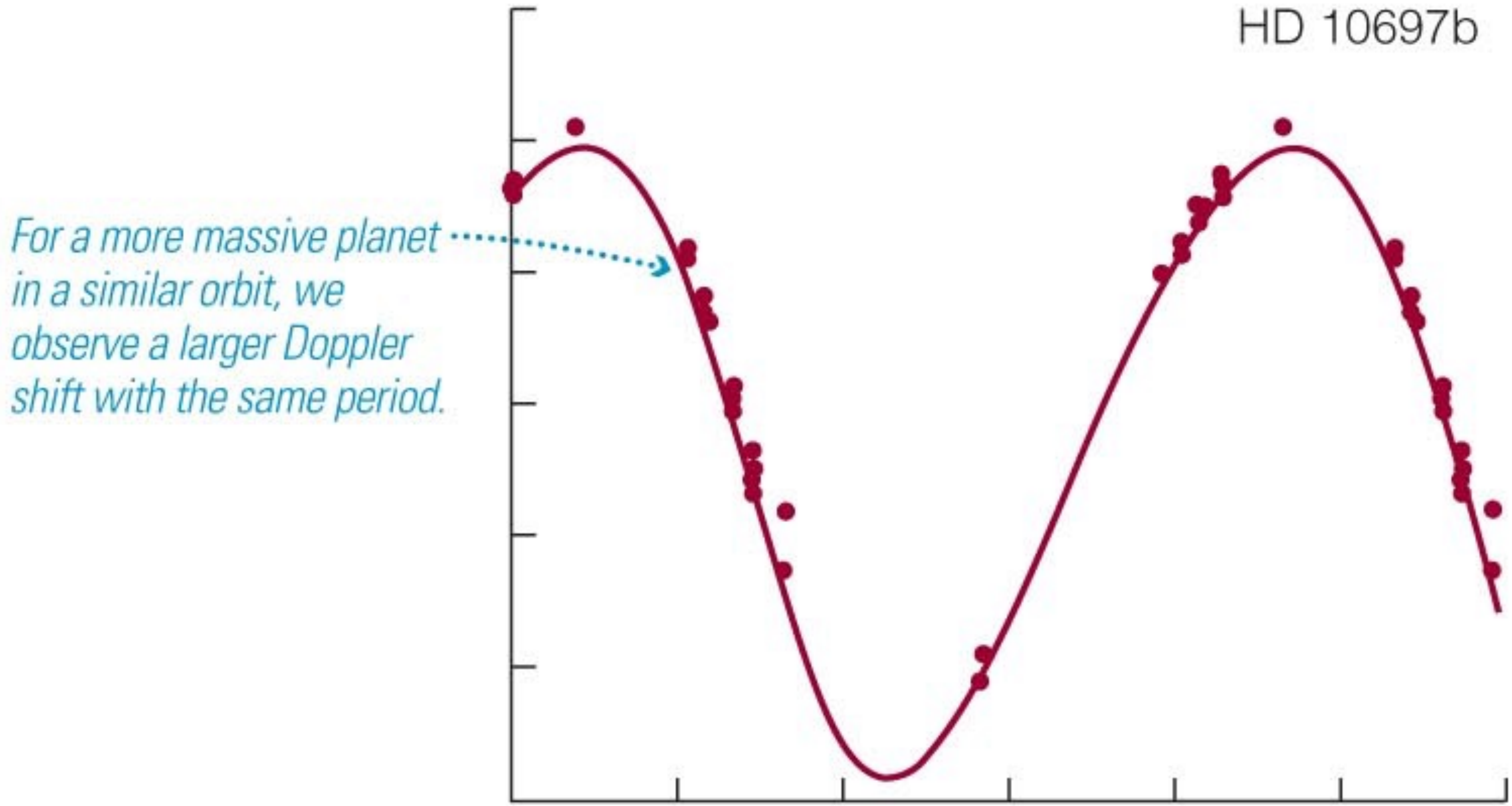
Exoplanet app

What can Doppler shifts tell us?

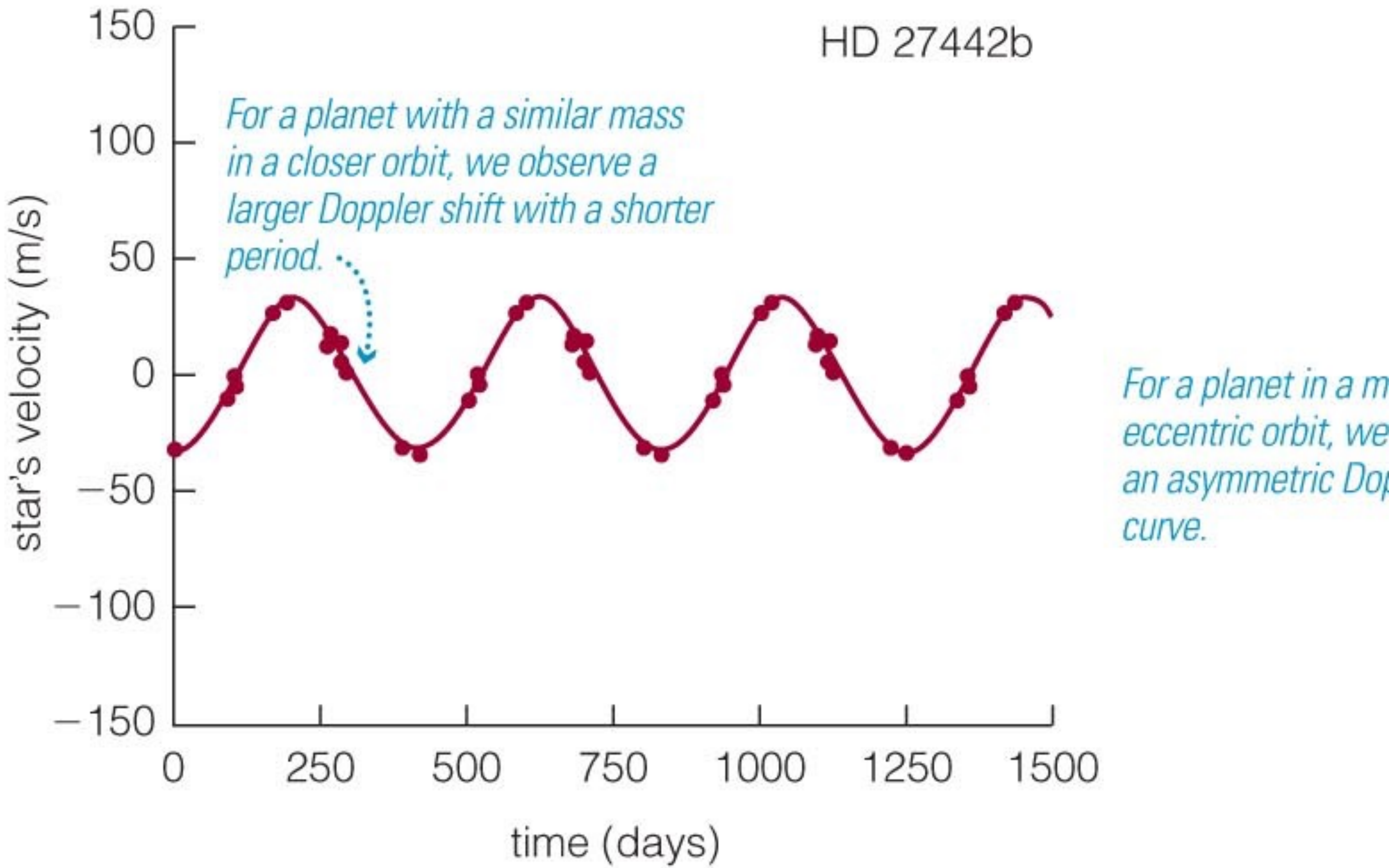


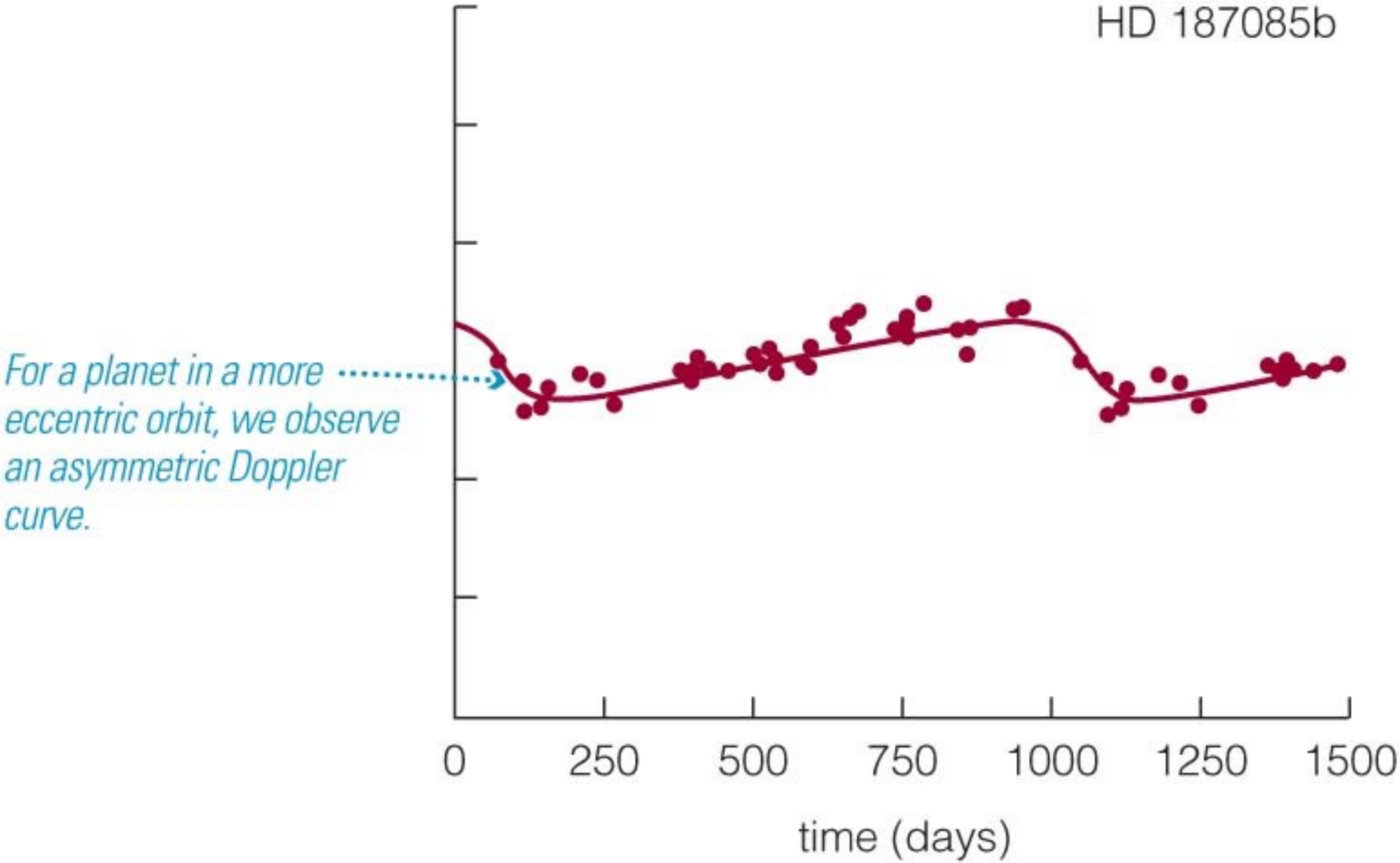
- Doppler shift data tell us about a planet's mass and the shape of its orbit.


150
100
50
0
−50
−100
−150
star's velocity (m/s)
HD 4208b
This graph shows the Doppler curve for a Sun-like star with a $0.8M_J$ planet in a nearly circular orbit at an orbital distance of 1.67 AU.
For a more massive
in a similar orbit, w
observe a larger D
shift with the same
150
100
HD 27442b
For a planet with a similar mass
in a closer orbit, we observe a

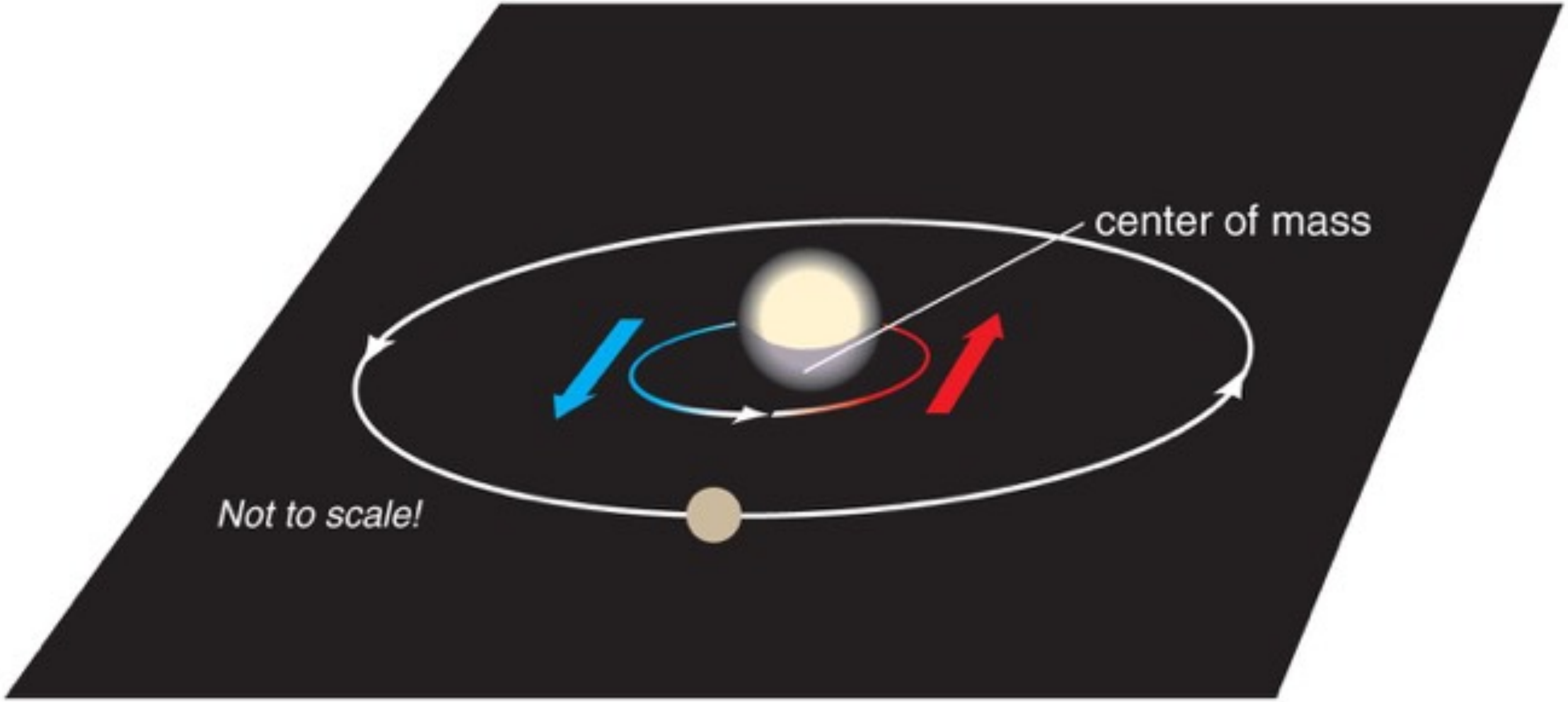

HD 10697b
For a more massive planet in a similar orbit, we observe a larger Doppler shift with the same period.


HD 187085b


HD 27442b
For a planet with a similar mass in a closer orbit, we observe a larger Doppler shift with a shorter period.
For a planet in a
eccentric orbit, we
an asymmetric
curve.
star's velocity (m/s)
150
100
50
0
−50
−100
−150
0
250
500
750
1000
1250
1500
time (days)


For a planet in a more eccentric orbit, we observe an asymmetric Doppler curve.
HD 187085b
0
250
500
750
1000
1250
1500
time (days)

Planet Mass and Orbit Tilt

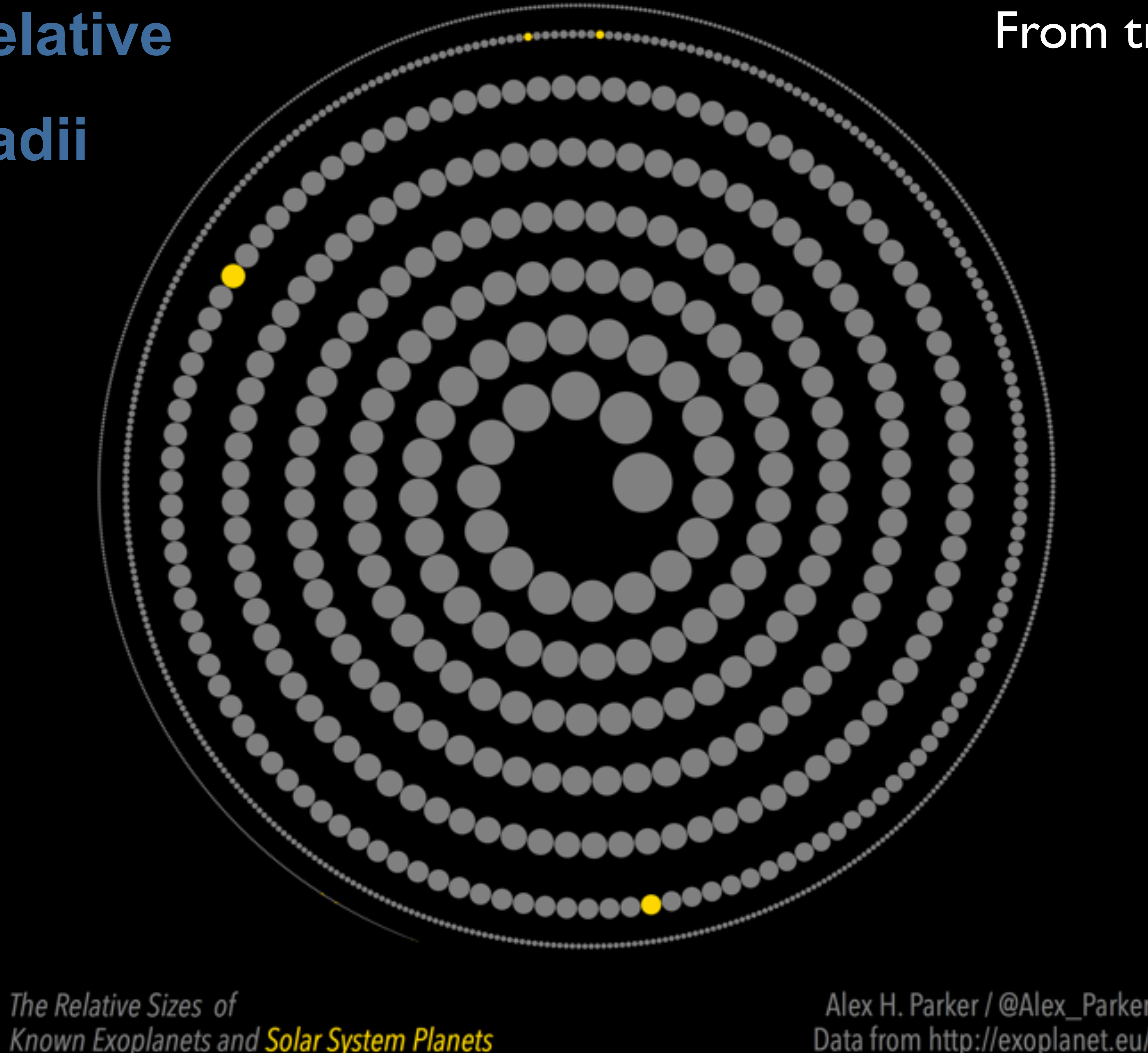


b We can detect a Doppler shift only if some part of the orbital velocity is directed toward or away from us. The more an orbit is tilted toward edge-on, the greater the shift we observe.

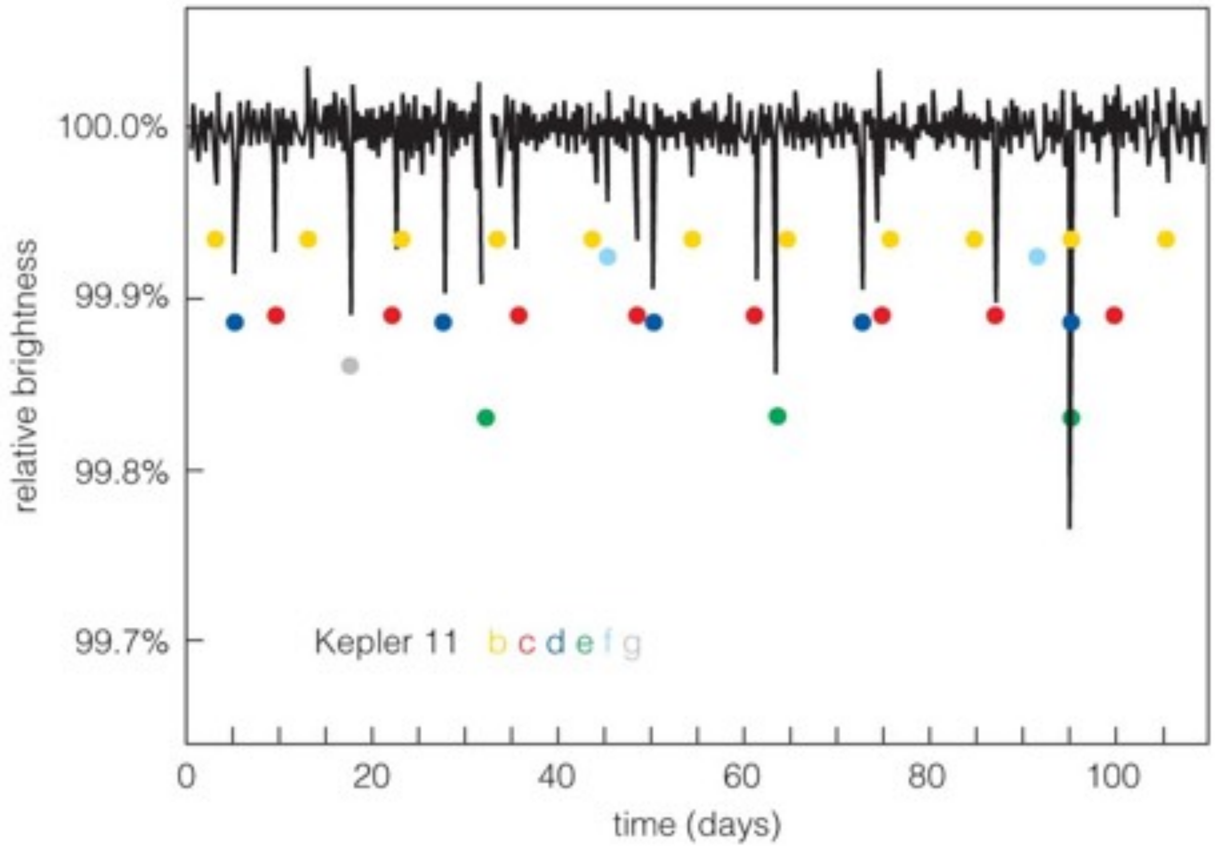
- We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.
- Doppler data give us lower limits on masses, M*sin(i)

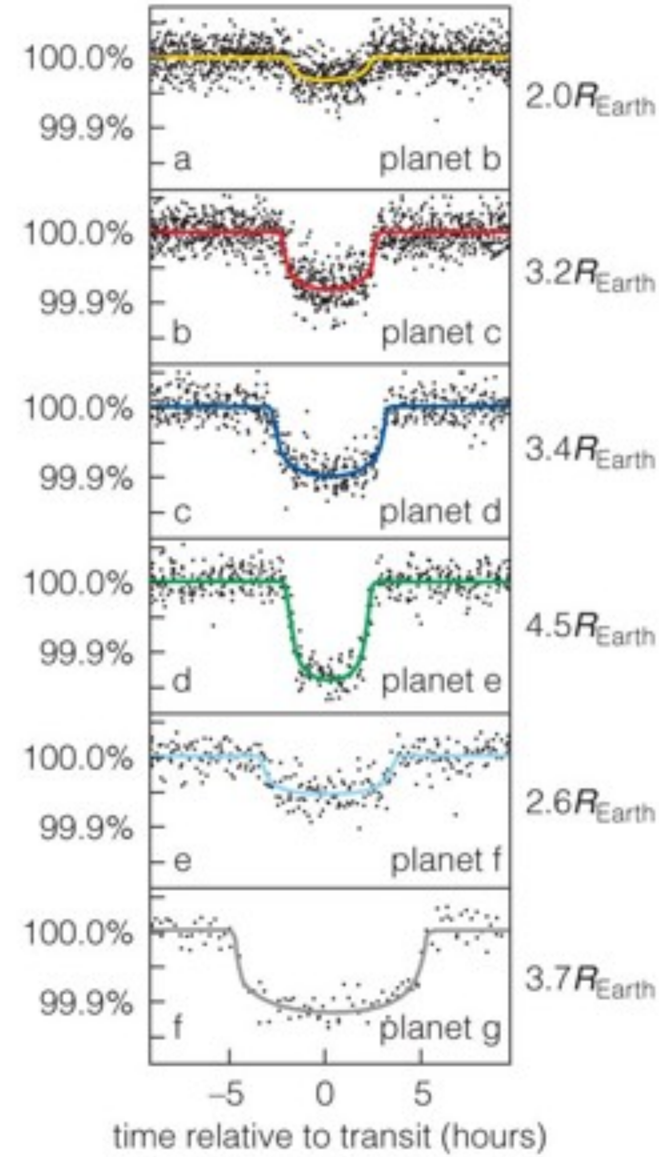
Relative Radii

From transits

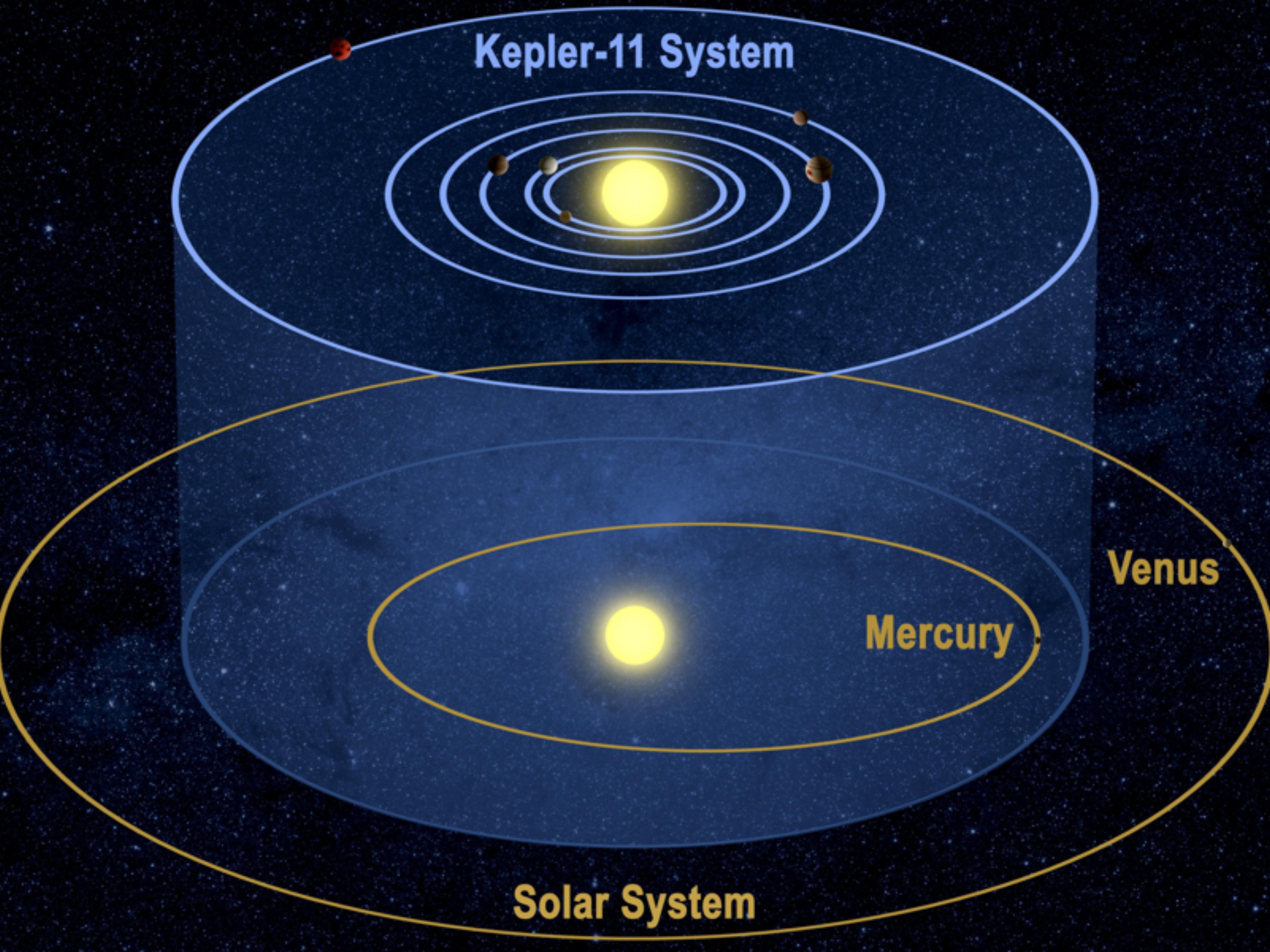


The Kepler 11 system



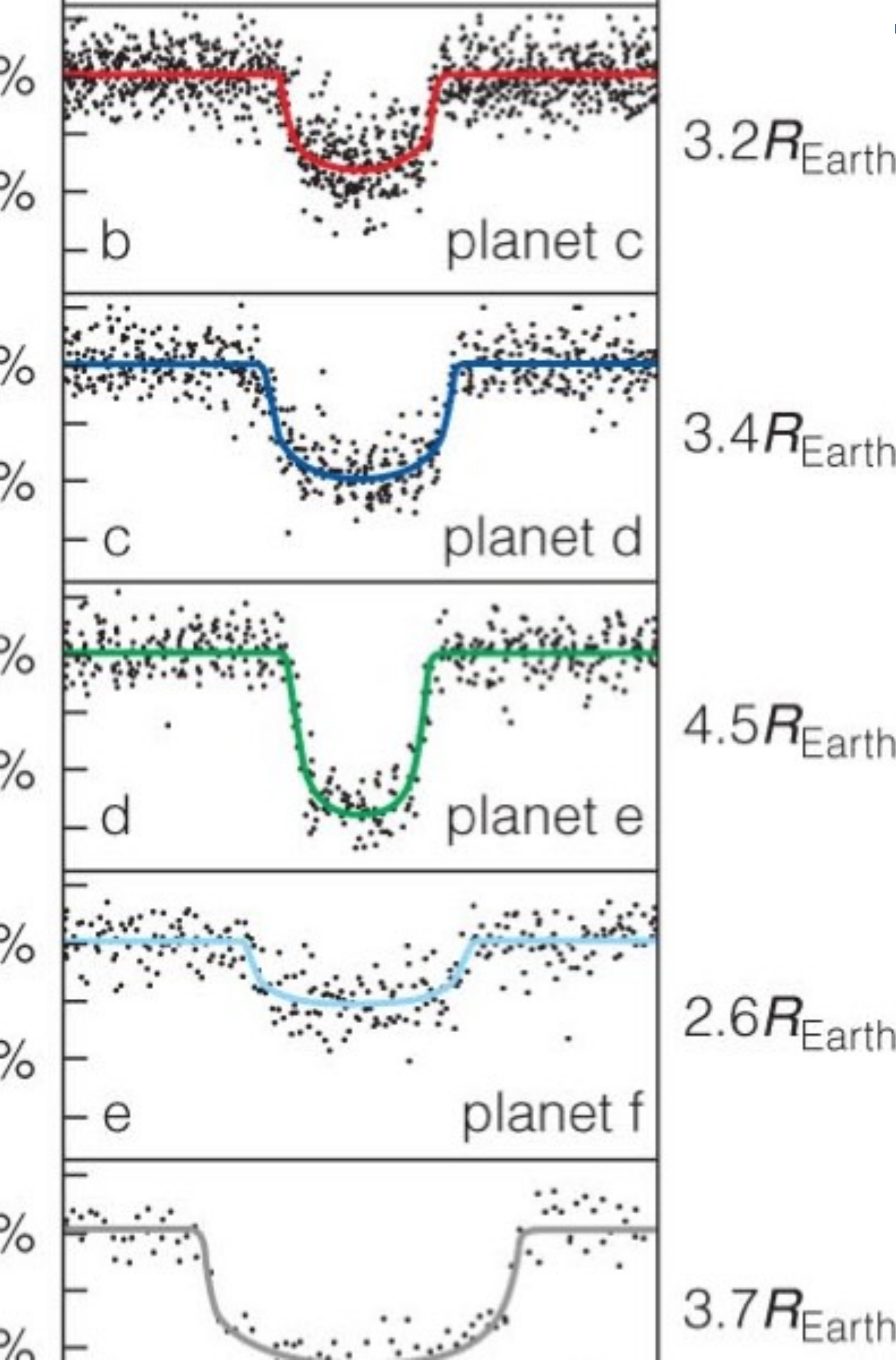


- The periods and sizes of Kepler 11's 6 known planets can be determined using transit data.
- These periods are short
  - longest Kepler g at 118 days
- Tightly packed system!



Kepler-11 System
Venus
Mercury
Solar System

The Kepler 11 system

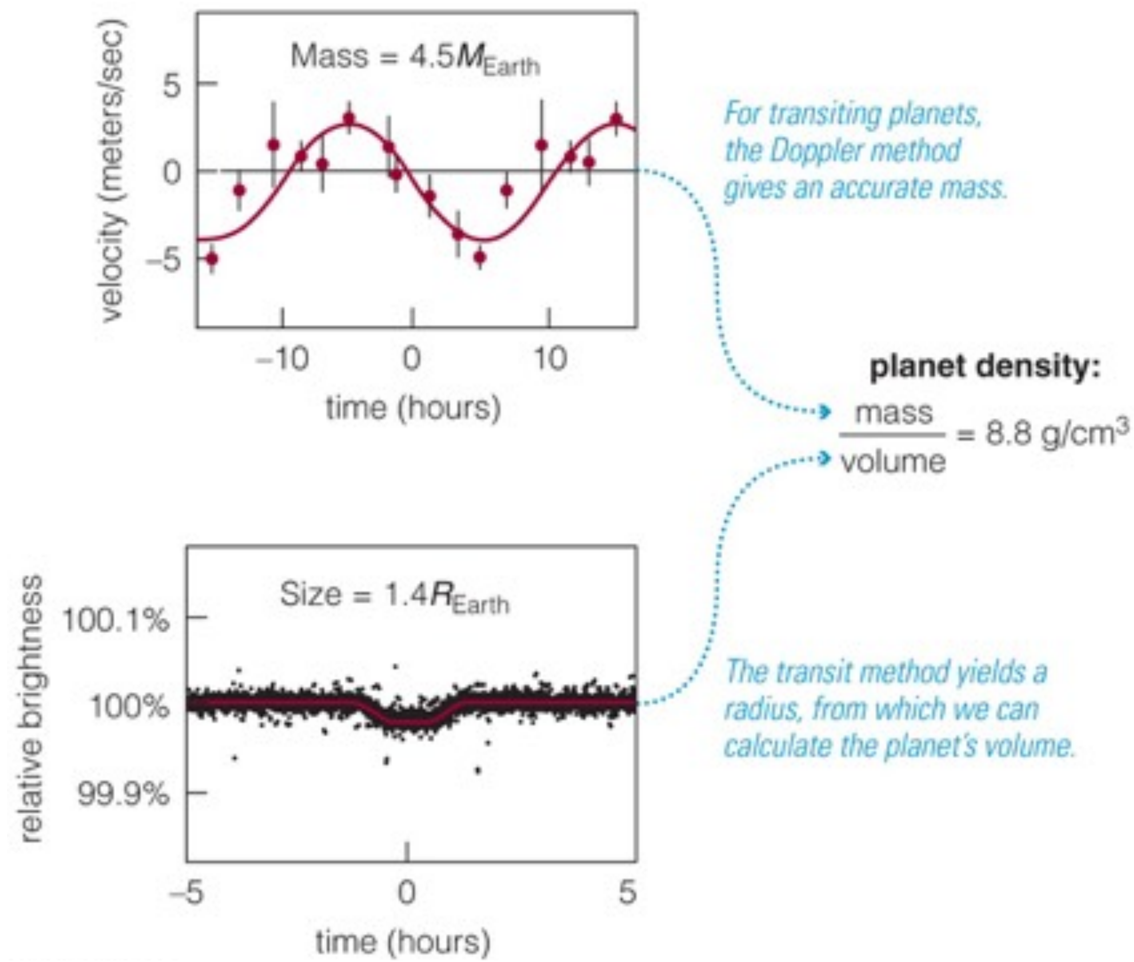


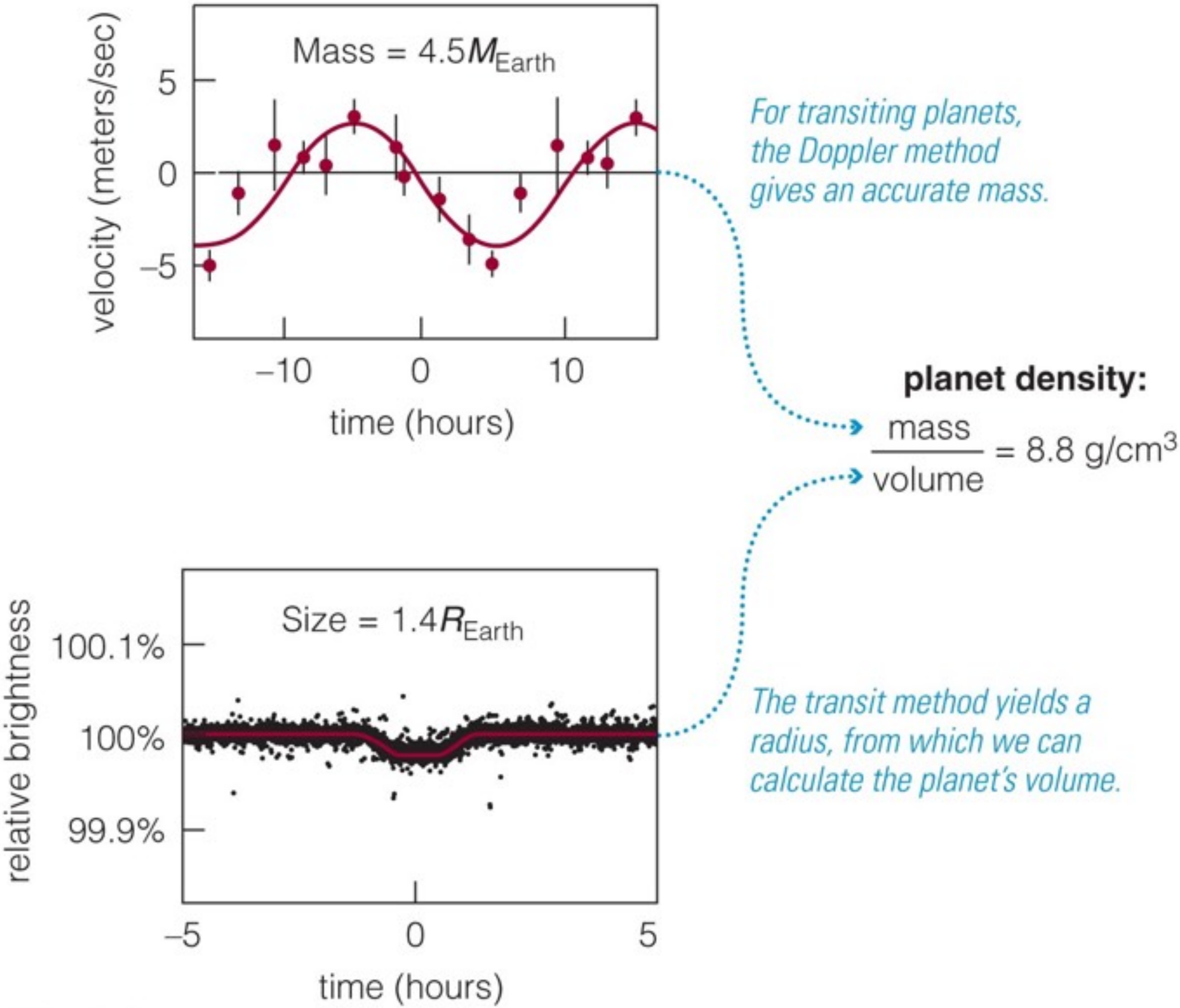
- Note sizes - all planets in this system a few times the size of the Earth!

- Uranus is 4 R_E;
- Neptune 3.8 R_E

Calculating density

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



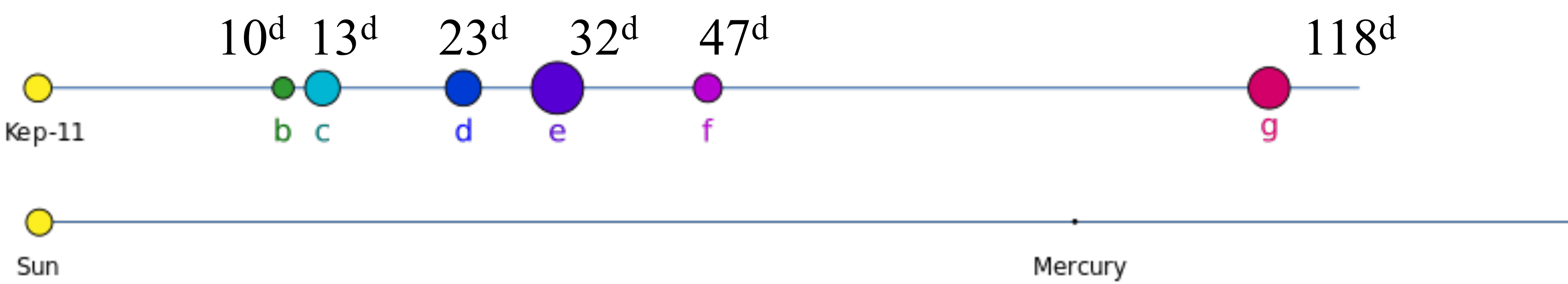


Mass = 4.5M_{Earth}
velocity (meters/sec)
5
0
–5
–10
0
10
time (hours)
For transiting planets, the Doppler method gives an accurate mass.
planet density:
$\frac{\text{mass}}{\text{volume}}$ = 8.8 g/cm^3
Size = 1.4R_{Earth}
relative brightness
100.1%
100%
99.9%
–5
0
5
time (hours)
The transit method yields a radius, from which we can calculate the planet's volume.

The Kepler 11 system

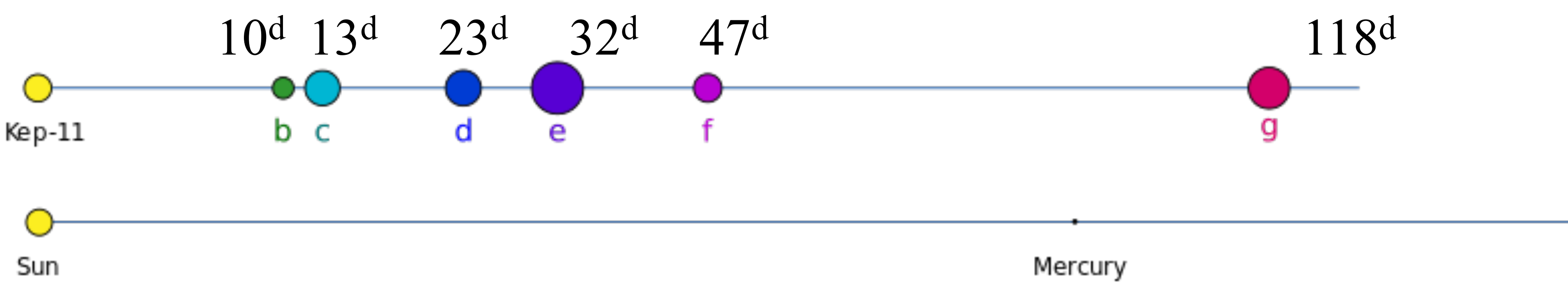
- The densities of all these planets are low
  - 0.6 - 1.7 g/cc

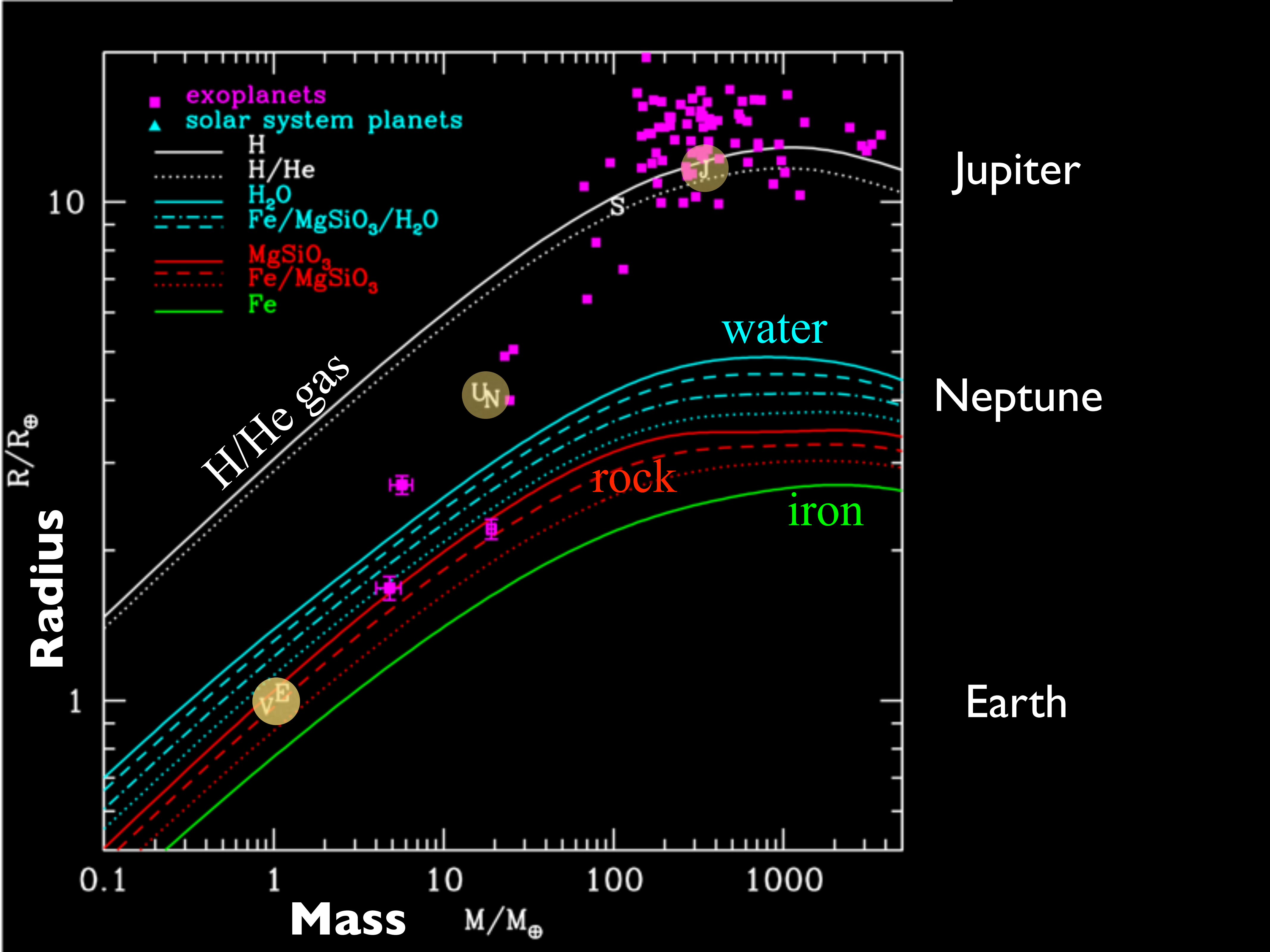
- What does this imply about the solar nebula hypothesis?



The Kepler 11 system

- The densities of all these planets are low
  - 0.6 - 1.7 g/cc
- Star is
  - 0.96 mass of sun
  - 1.07 radius of sun
  - 8.5 Gyr old (sun is 4.5 Gyr)
- Tightly packed system that is nevertheless stable
  - despite lack of orbital resonances

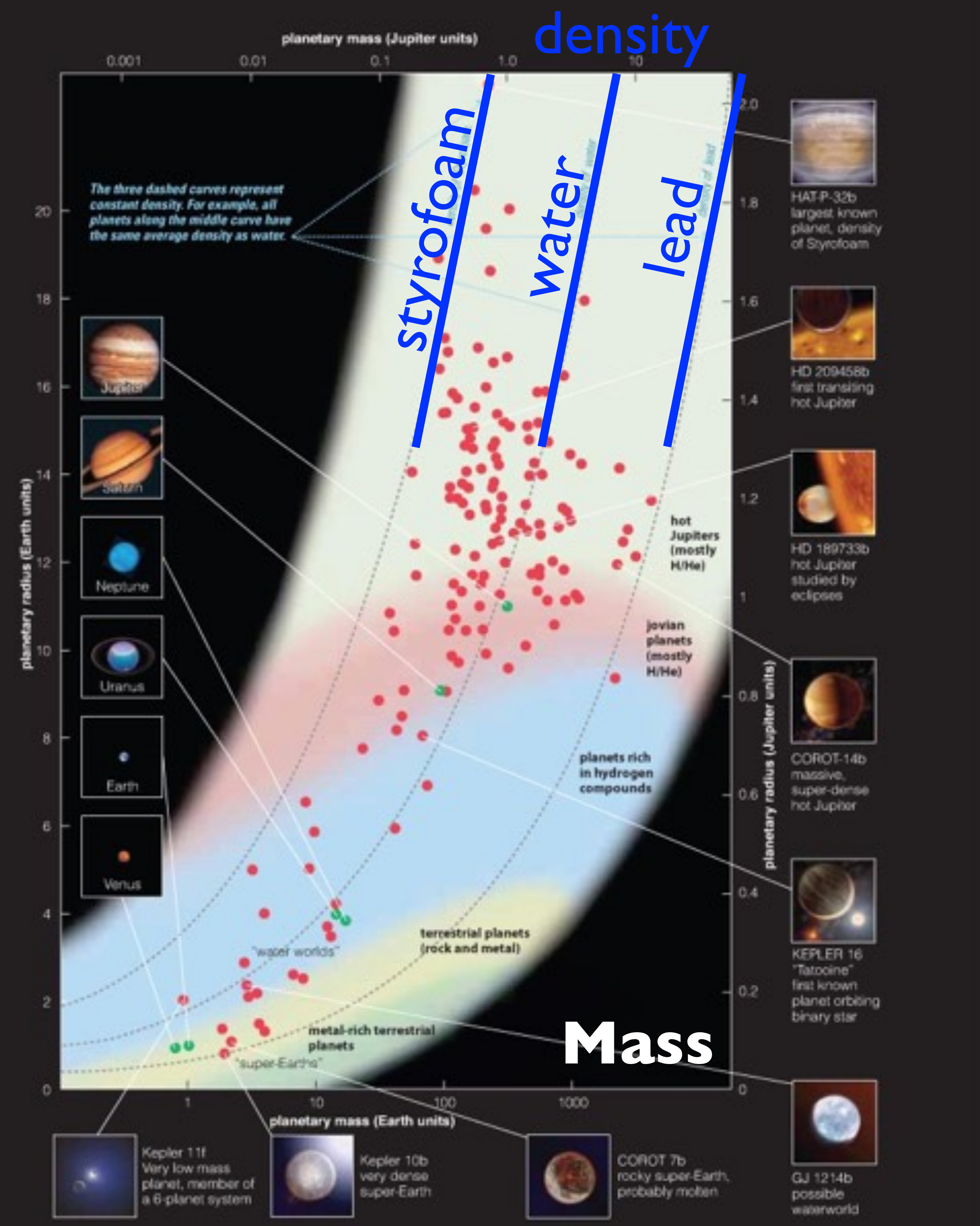


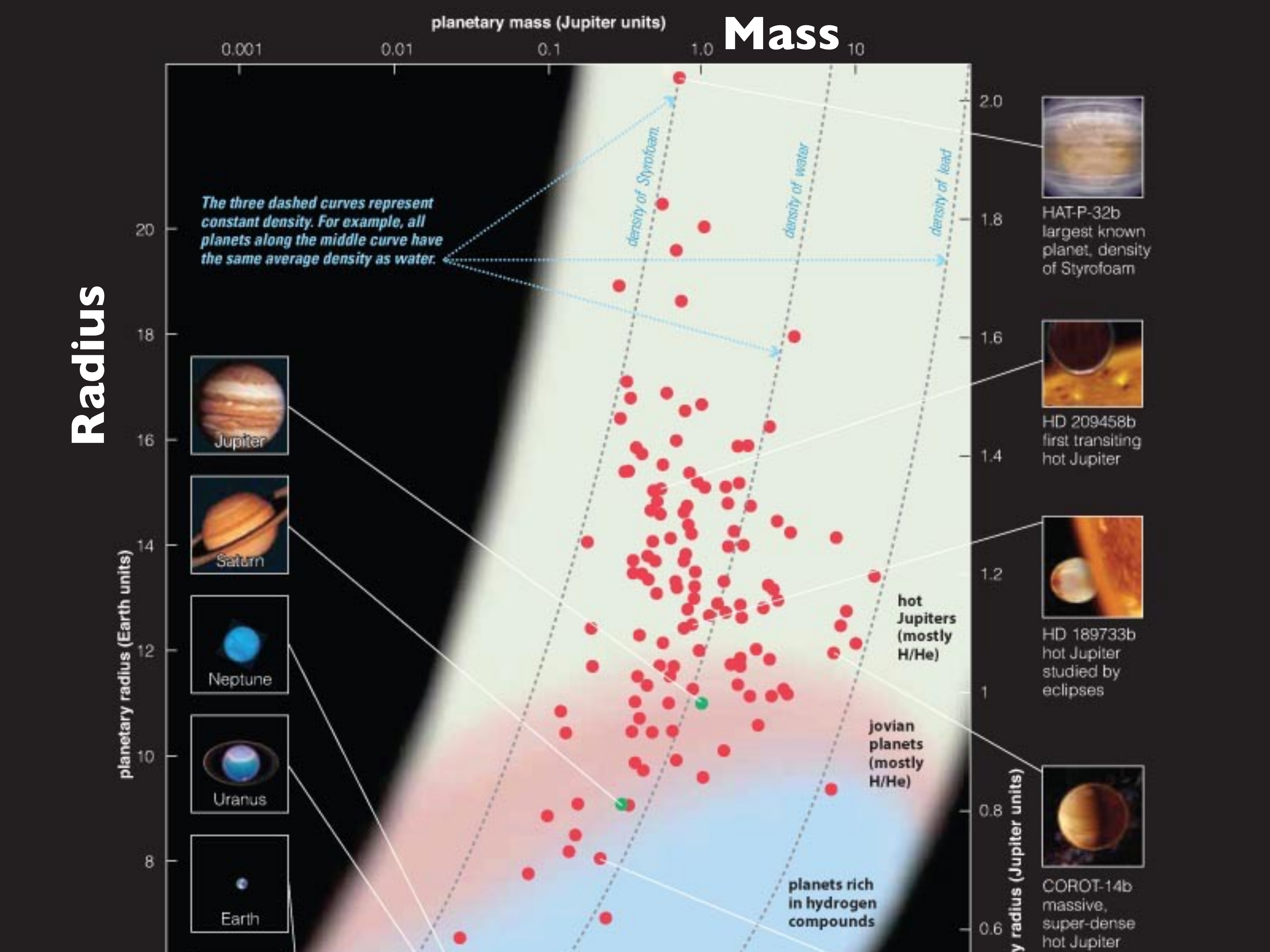


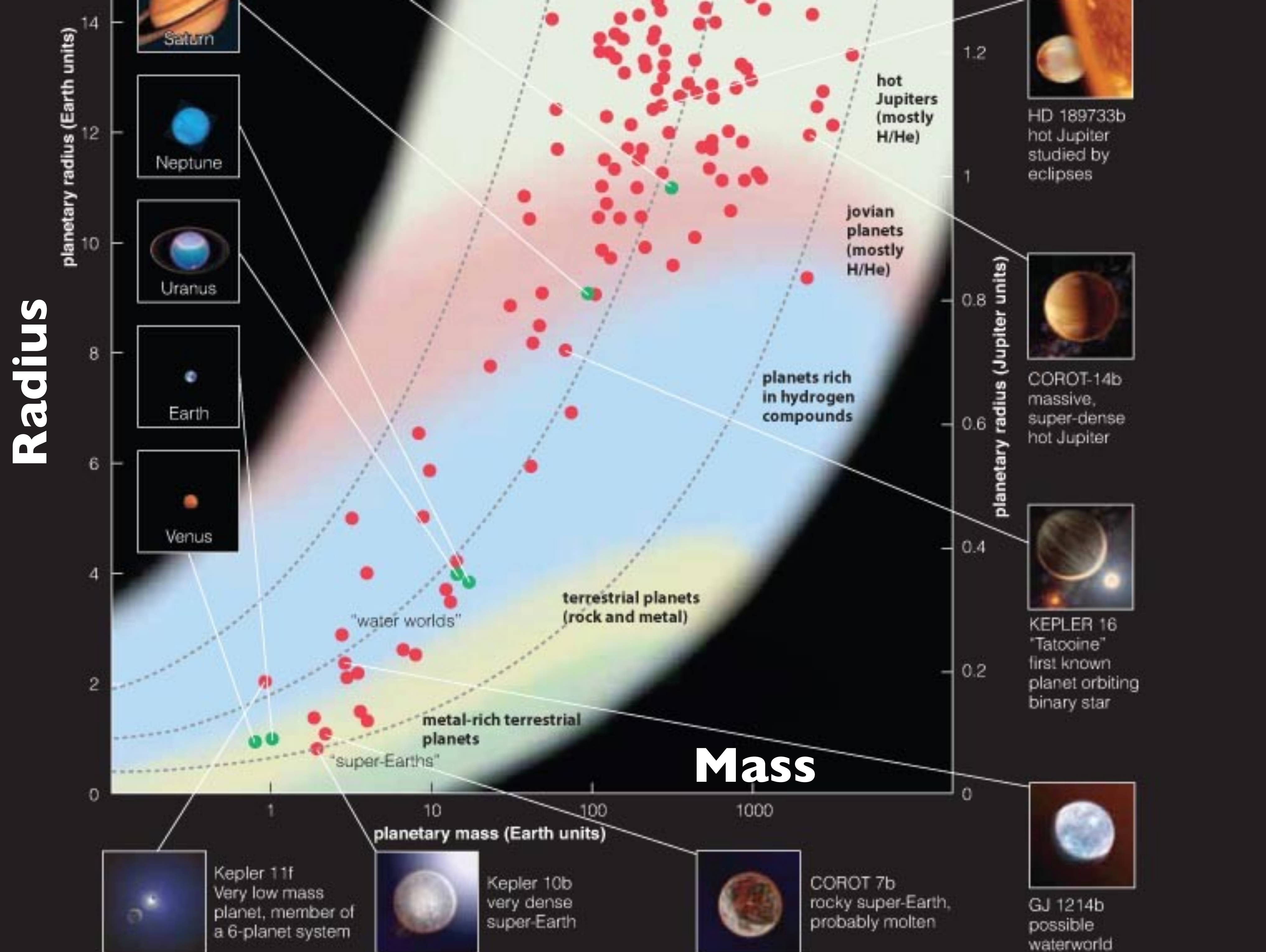
exoplanets
solar system planets
H
H/He
H_2O
$Fe/MgSiO_3/H_2O$
$MgSiO_3$
$Fe/MgSiO_3$
Fe
H/He gas
water
rock
iron
Jupiter
Neptune
Earth
Radius
$R/R_\oplus$
Mass
$M/M_\oplus$
10
1
0.1
1
10
100
1000
S
J
U
N
V
E

Exoplanet properties in general: size vs. mass

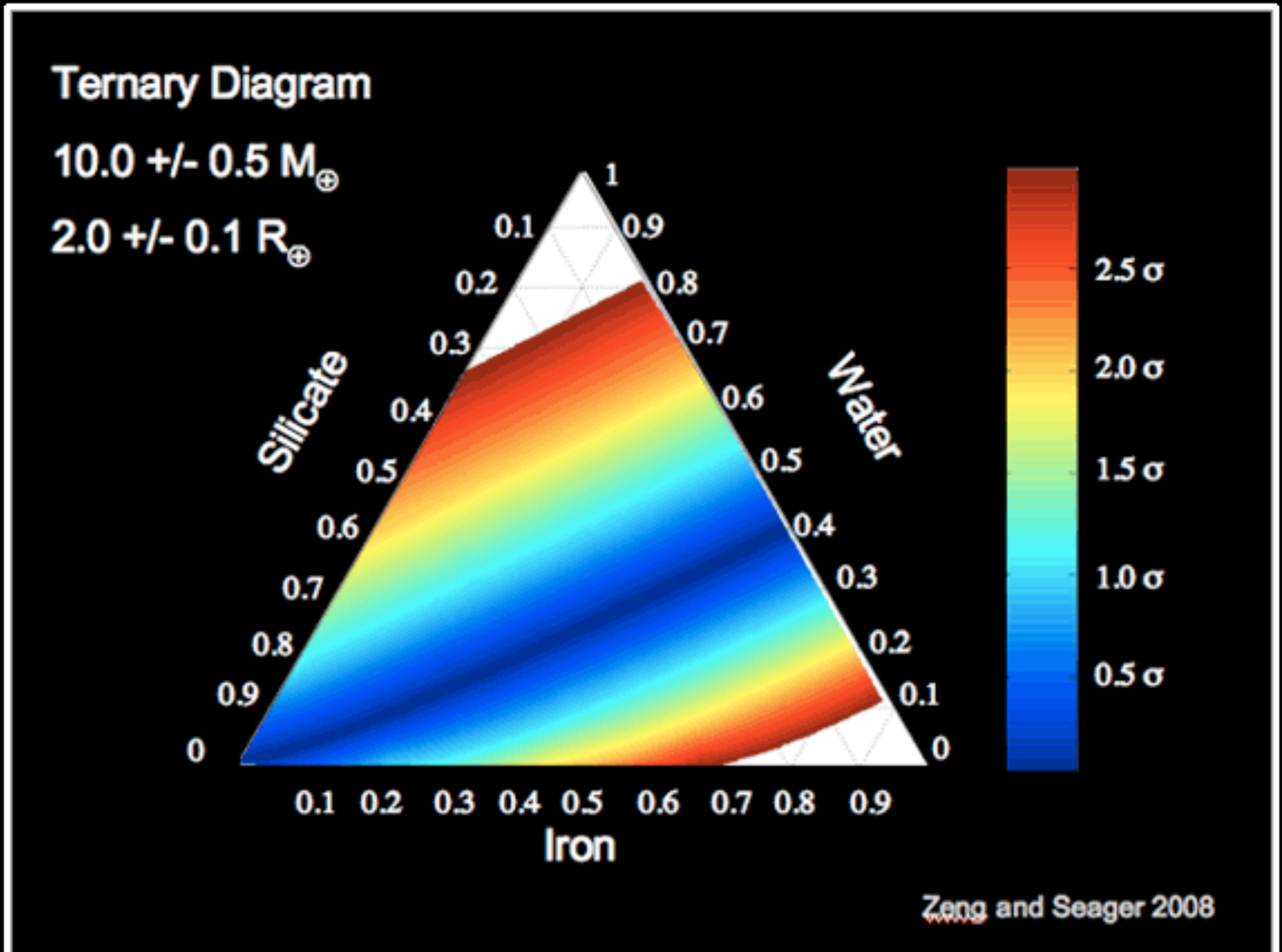
Radius



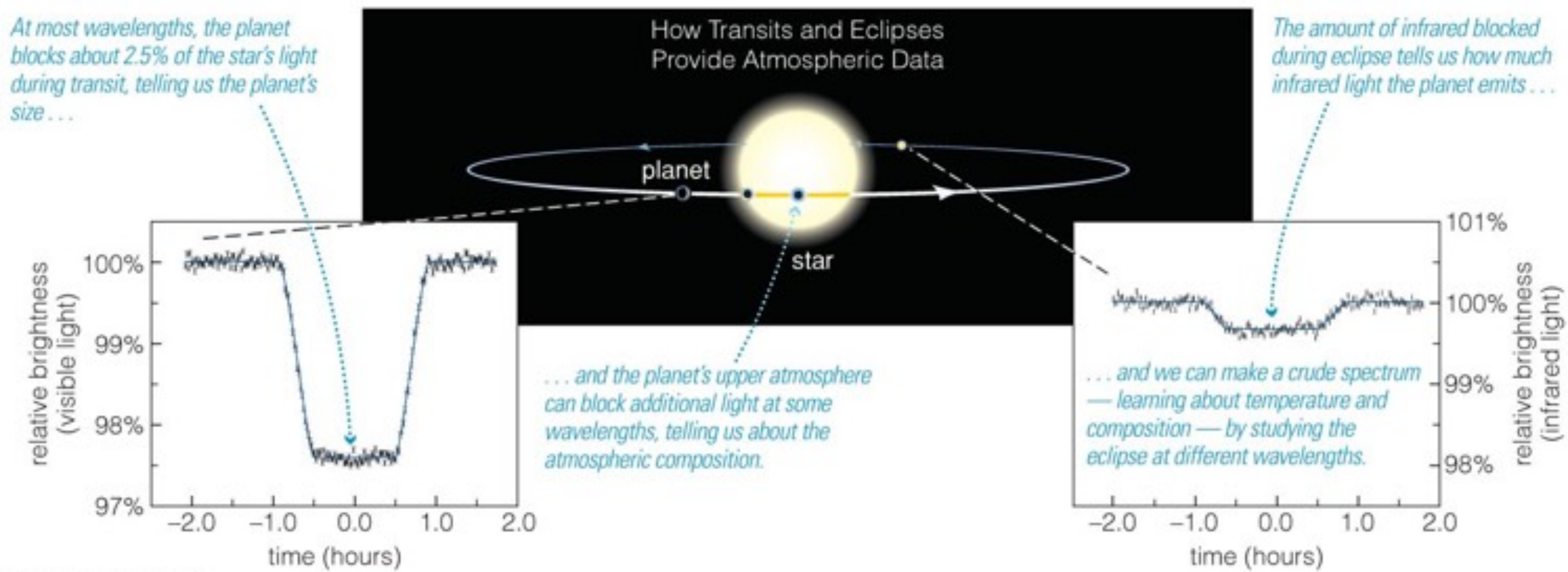

Mass
Radius
planetary mass (Jupiter units)
0.001
0.01
0.1
1.0
10
planetary radius (Earth units)
20
18
16
14
12
10
8
y radius (Jupiter units)
2.0
1.8
1.6
1.4
1.2
1
0.8
0.6
The three dashed curves represent constant density. For example, all planets along the middle curve have the same average density as water.
density of Styrofoam
density of water
density of lead
Jupiter
Saturn
Neptune
Uranus
Earth
HAT-P-32b largest known planet, density of Styrofoam
HD 209458b first transiting hot Jupiter
HD 189733b hot Jupiter studied by eclipses
COROT-14b massive, super-dense hot Jupiter
hot Jupiters (mostly H/He)
jovian planets (mostly H/He)
planets rich in hydrogen compounds


Radius
Mass
planetary radius (Earth units)
planetary radius (Jupiter units)
planetary mass (Earth units)
0
2
4
6
8
10
12
14
1
10
100
1000
0.2
0.4
0.6
0.8
1
1.2
Saturn
Neptune
Uranus
Earth
Venus
hot Jupiters (mostly H/He)
jovian planets (mostly H/He)
planets rich in hydrogen compounds
"water worlds"
terrestrial planets (rock and metal)
metal-rich terrestrial planets
"super-Earths"
HD 189733b hot Jupiter studied by eclipses
COROT-14b massive, super-dense hot Jupiter
KEPLER 16 "Tatooine" first known planet orbiting binary star
GJ 1214b possible waterworld
Kepler 11f Very low mass planet, member of a 6-planet system
Kepler 10b very dense super-Earth
COROT 7b rocky super-Earth, probably molten

Possible mix of water, rock, and iron to make a planet with 10 times Earth's mass & 2 times its radius

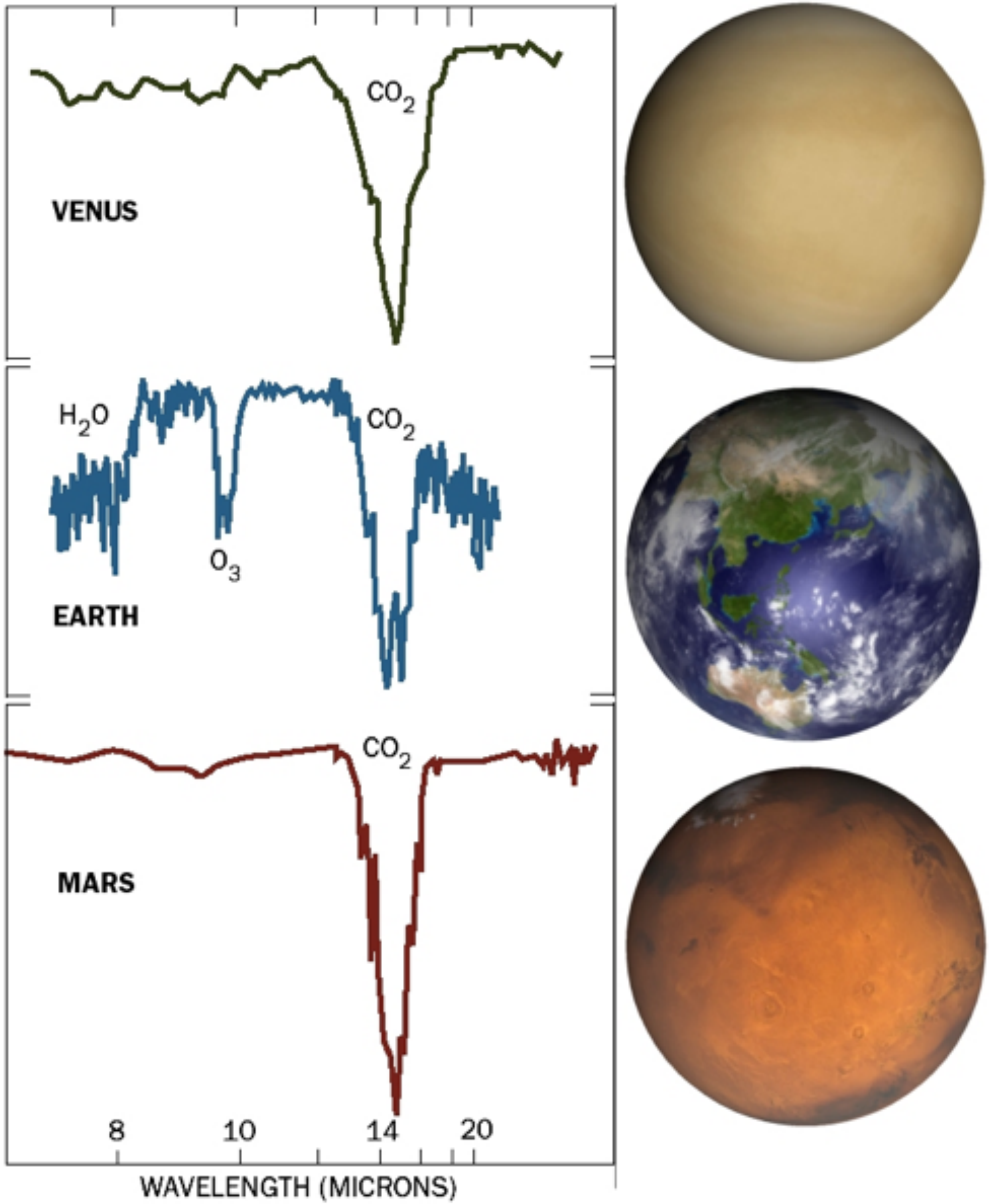


Spectrum During Transit



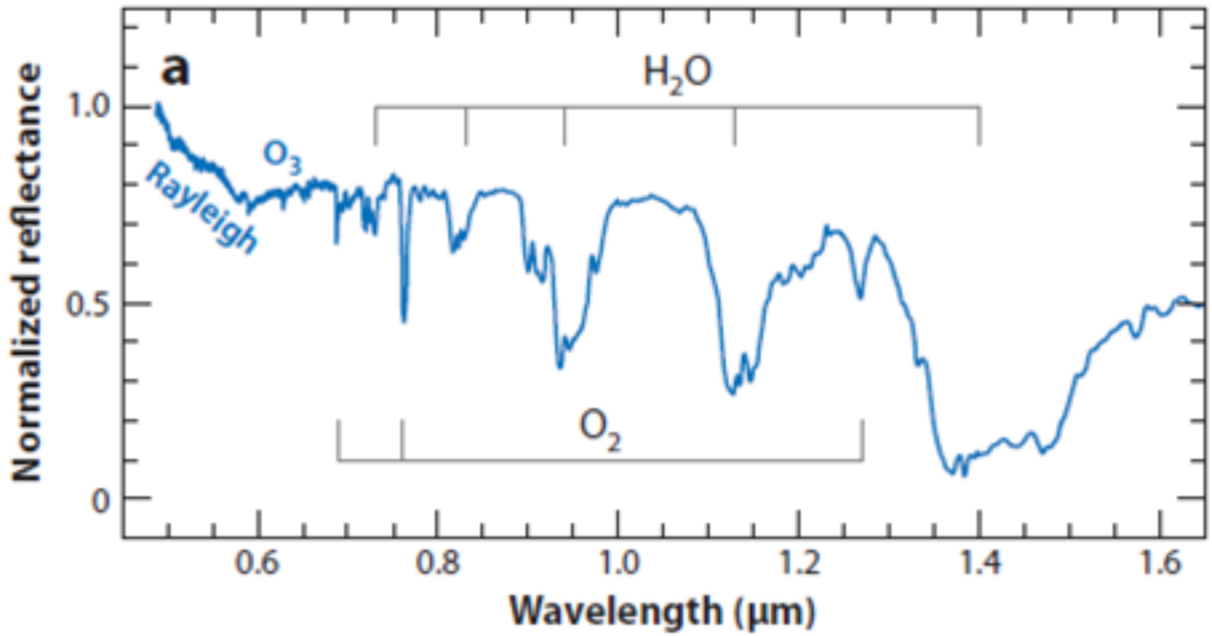
- Change in spectrum during a transit tells us about the composition of planet's atmosphere.

Oxygen in an exoplanet atmosphere would be a strong hint that photosynthetic life is present

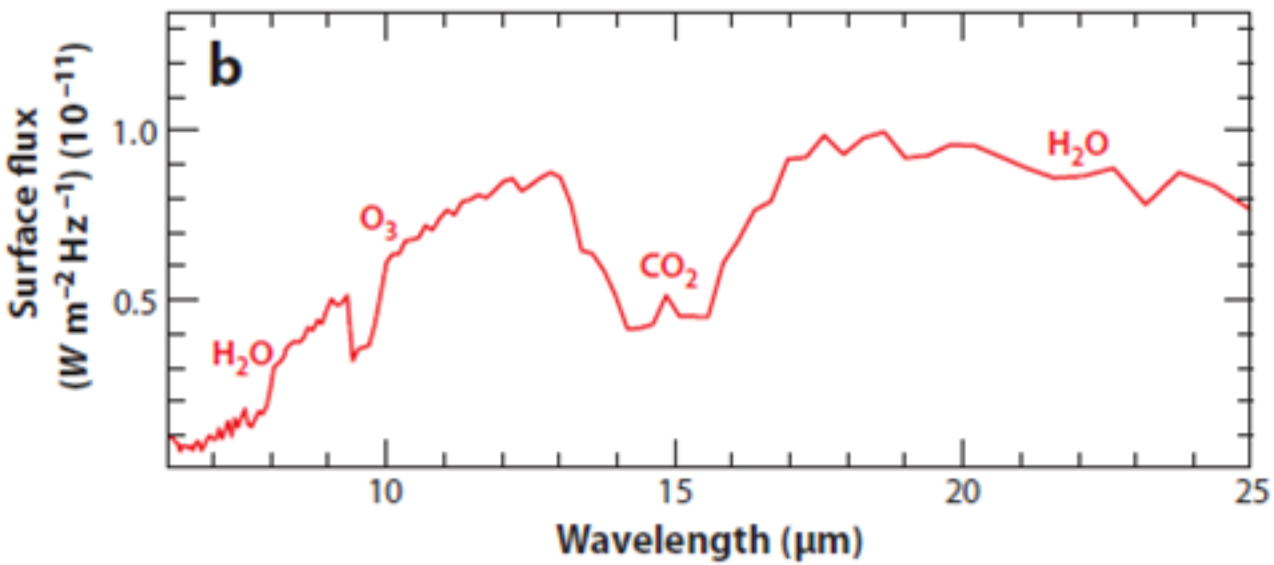


Earth spectrum in greater detail

Reflection (optical & near IR)



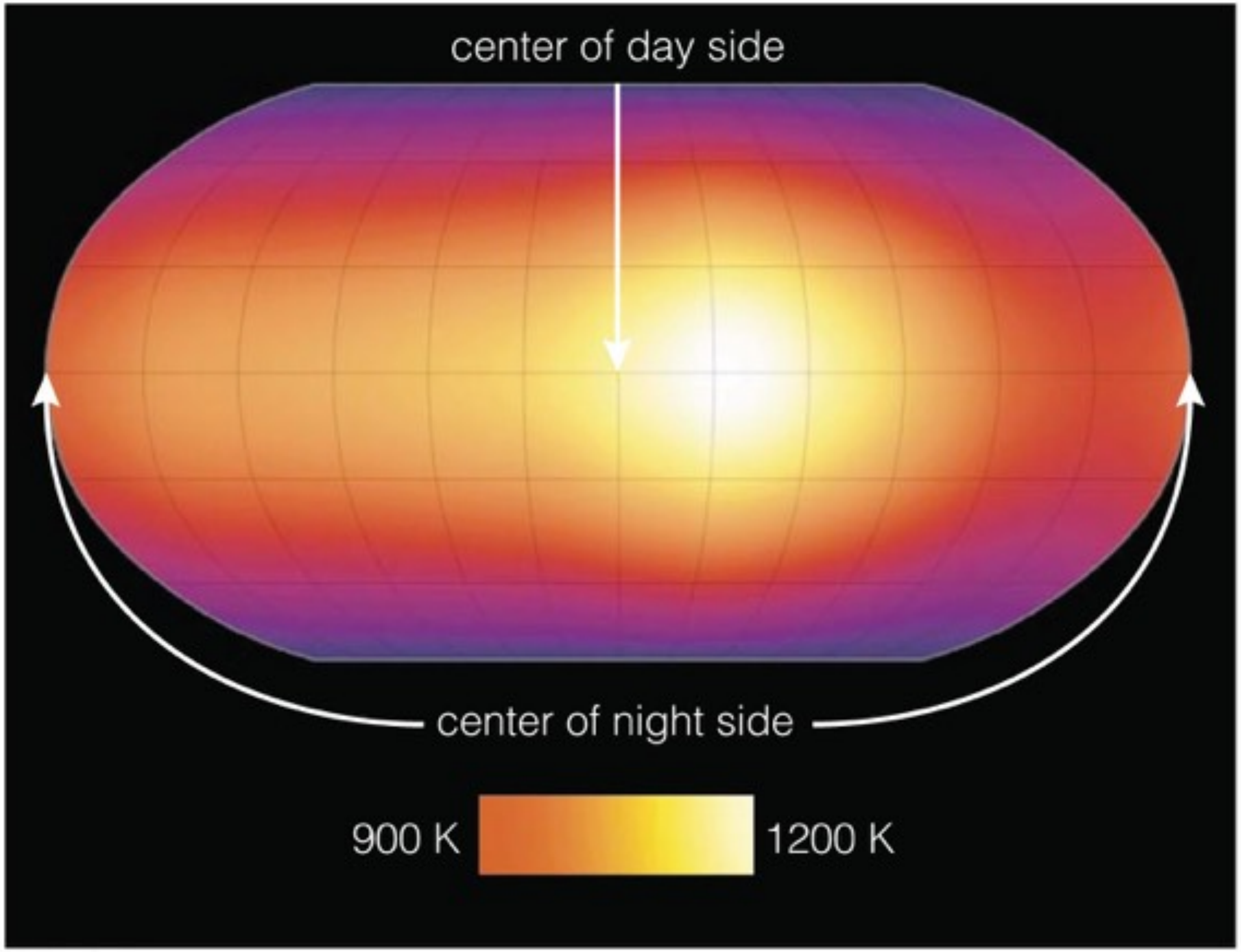
Emission (mid IR)



Oxygen in an exoplanet atmosphere would be a strong hint that photosynthetic life is present

Surface Temperature Map

HD 189733b

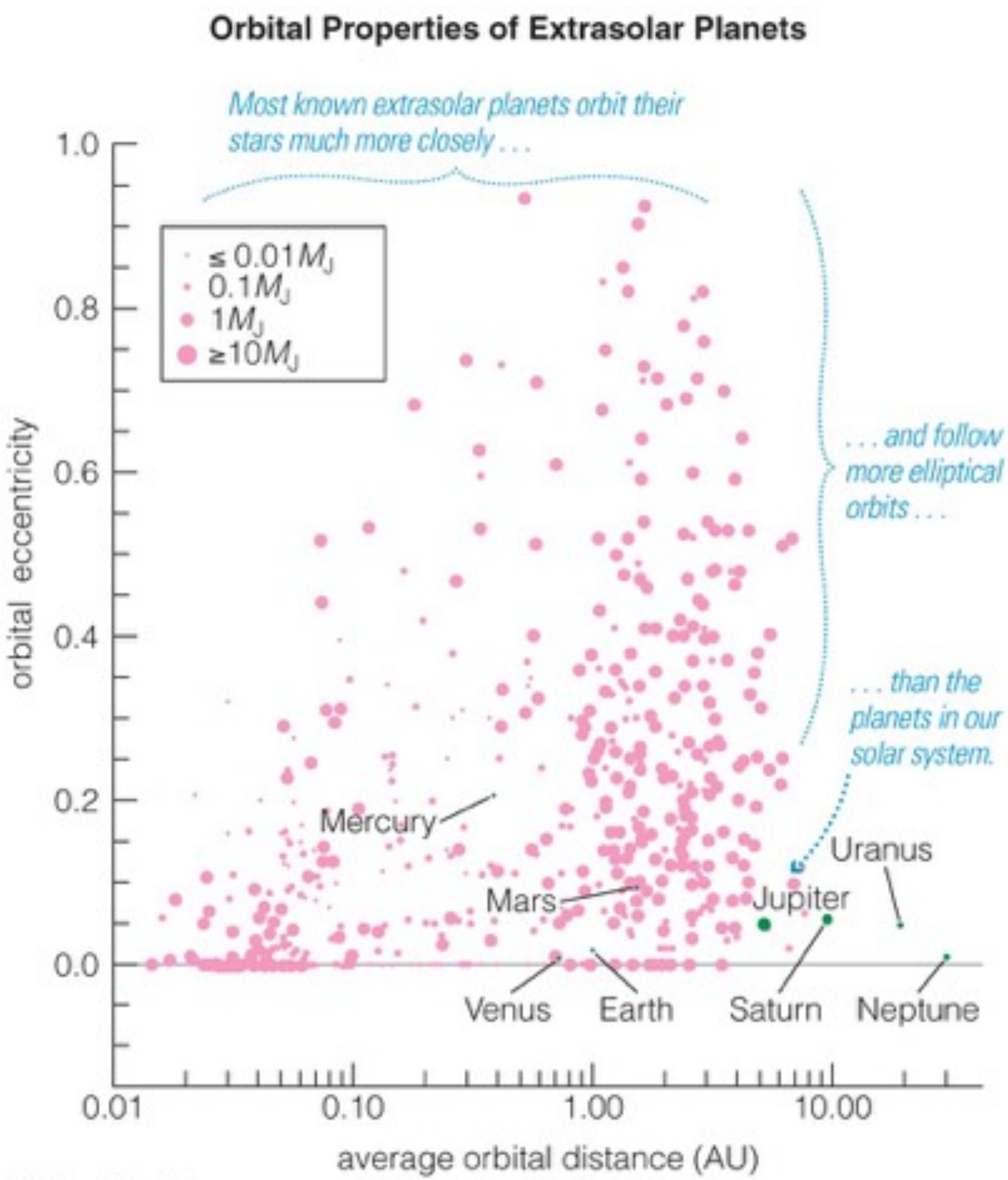


Highest temperature offset from noon: strong winds? Rotation? (should be tidally locked)

Note temperature scale for this "Hot Jupiter" (Earth ave. T = 287 K)

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

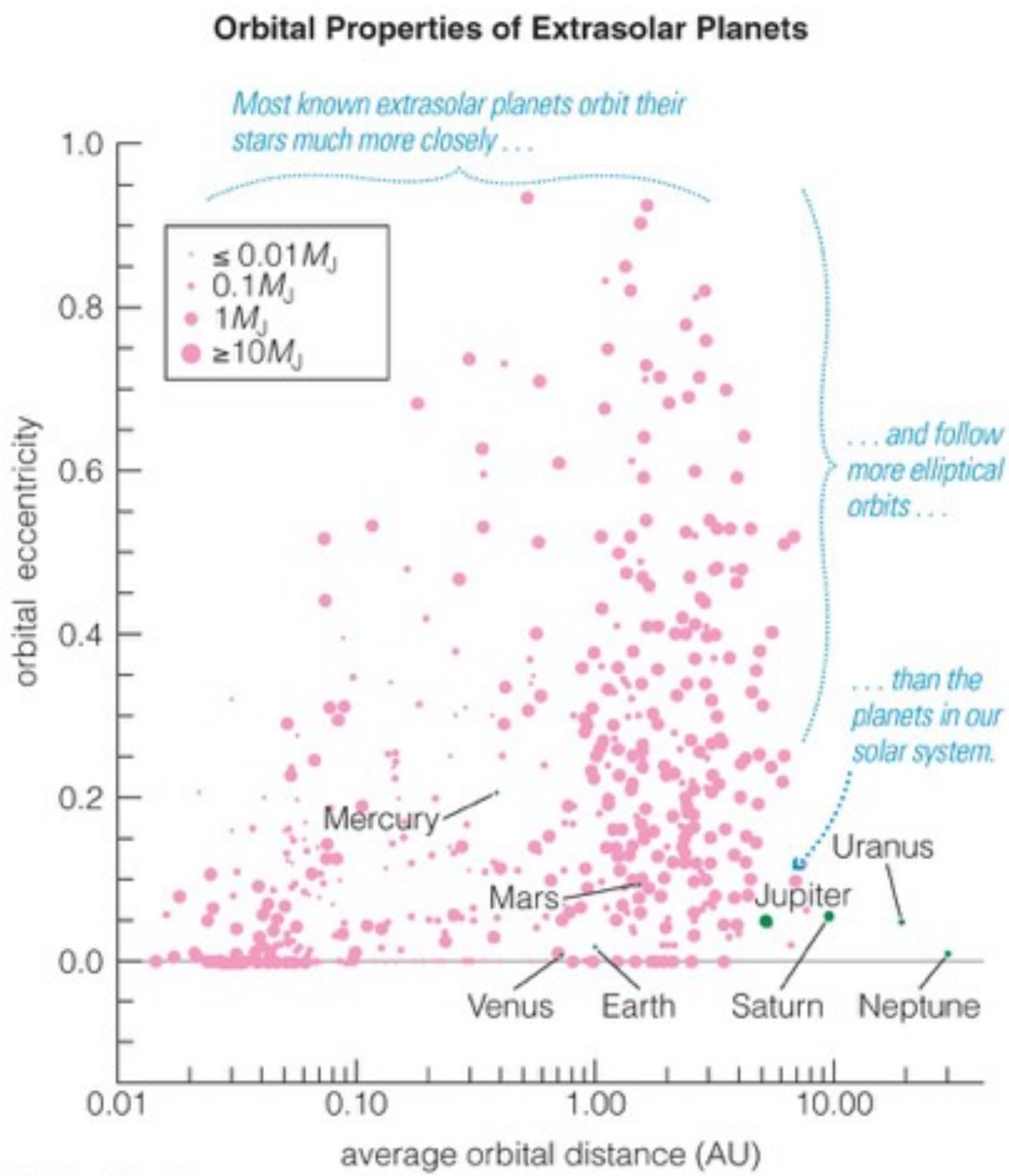
Orbits of Extrasolar Planets



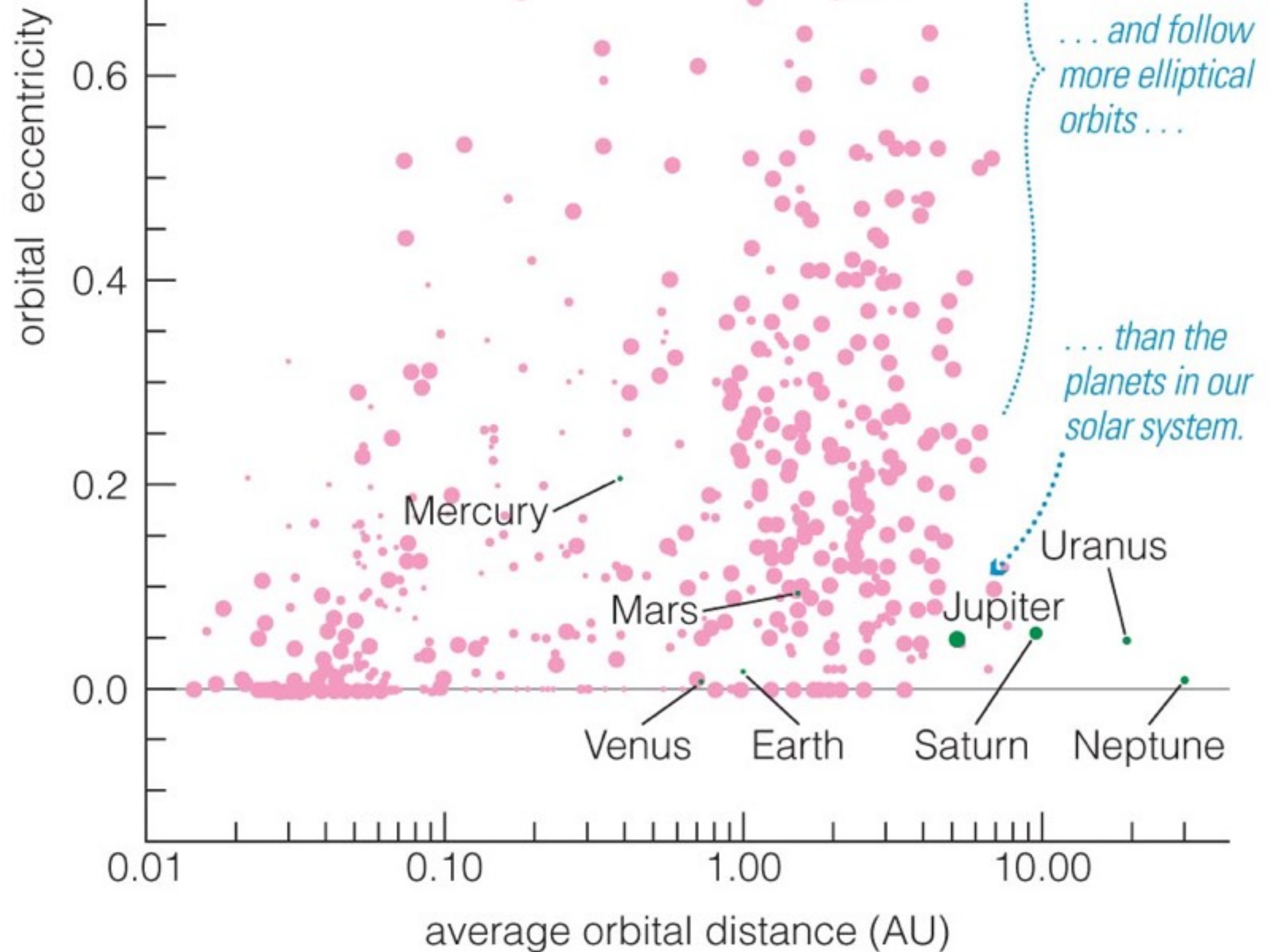
- Most of the detected planets have orbits smaller than Jupiter's.
- Planets at greater distances are harder to detect with the Doppler technique.

Selection effect: Doppler signal largest for high mass planets close to their host star.

Orbits of Extrasolar Planets

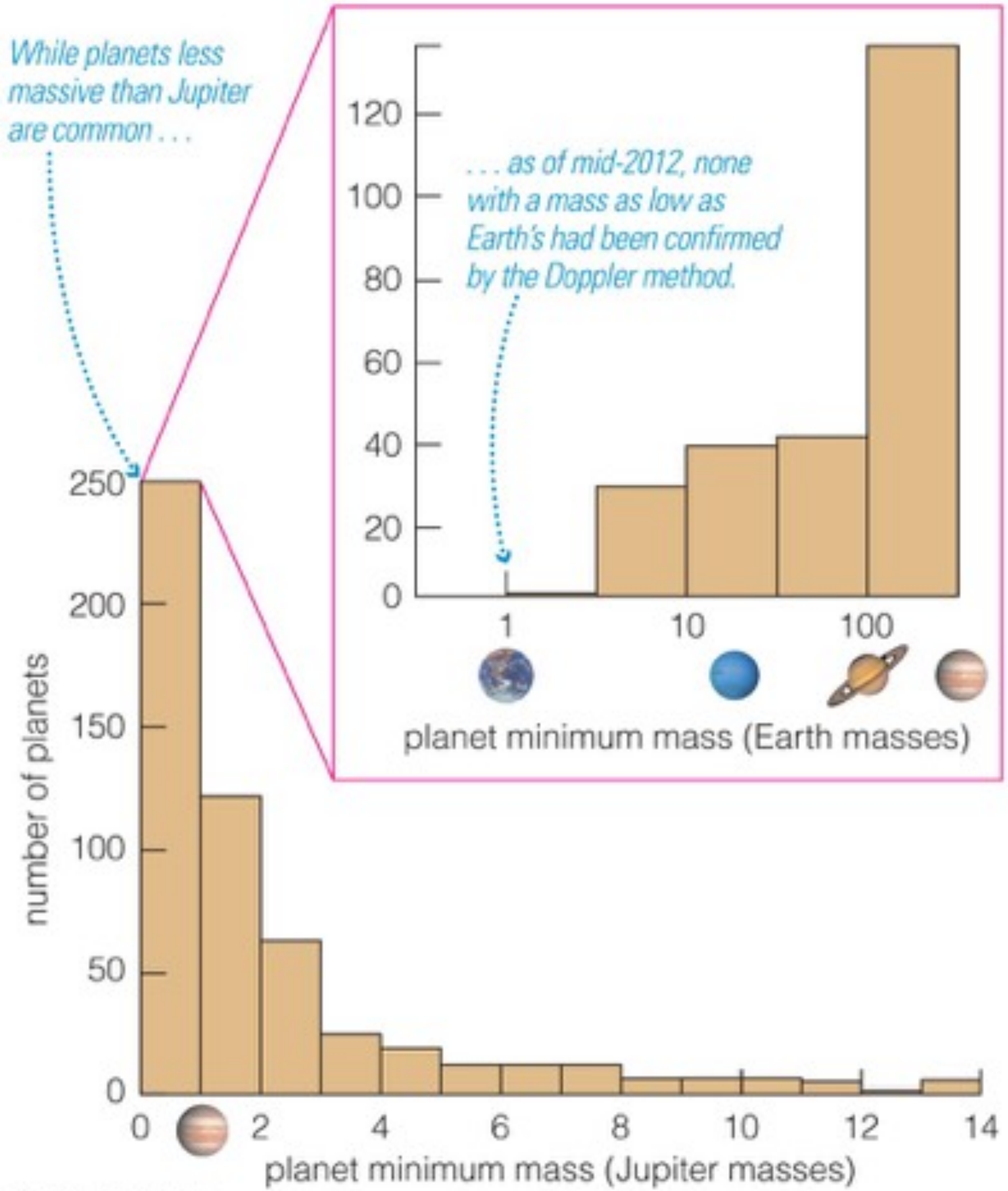


- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.



orbital eccentricity
0.6
0.4
0.2
0.0
. . . and follow more elliptical orbits . . .
. . . than the planets in our solar system.
Mercury
Mars
Jupiter
Uranus
Venus
Earth
Saturn
Neptune
0.01
0.10
1.00
10.00
average orbital distance (AU)

Orbits of Extrasolar Planets



- Most of the detected planets have greater mass than Jupiter.
- *Kepler* data not included here.
- Planets with smaller masses are harder to detect with Doppler technique.

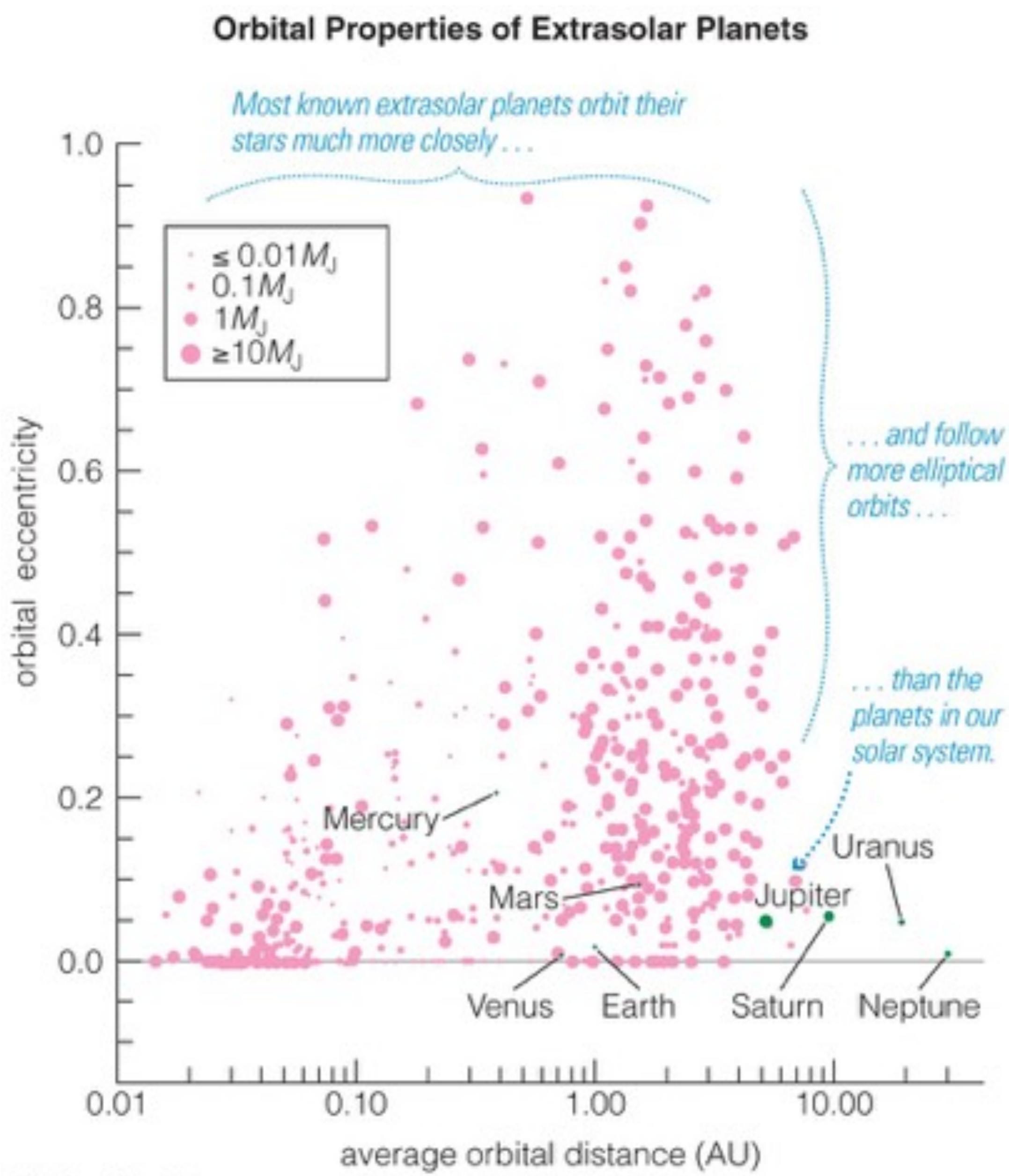
Surprising Characteristics

- 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.

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?**

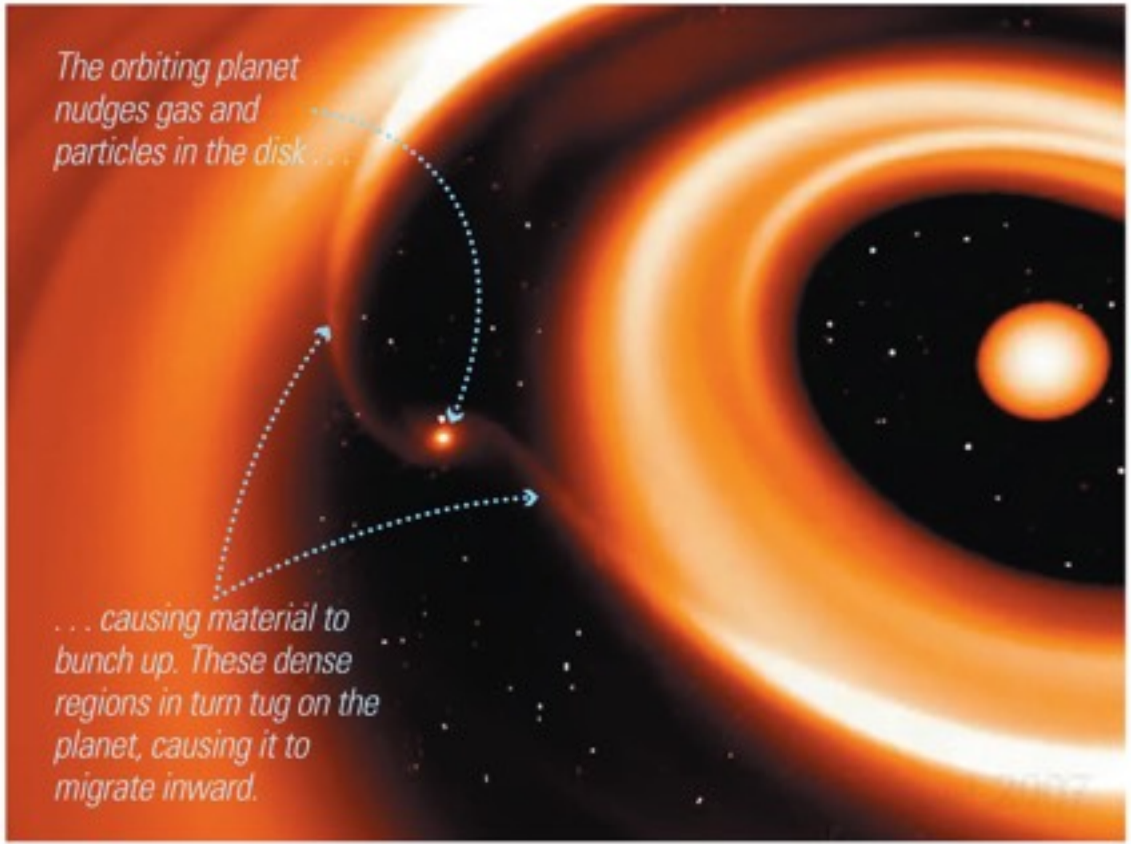
Can we explain the surprising orbits of many extrasolar planets?



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

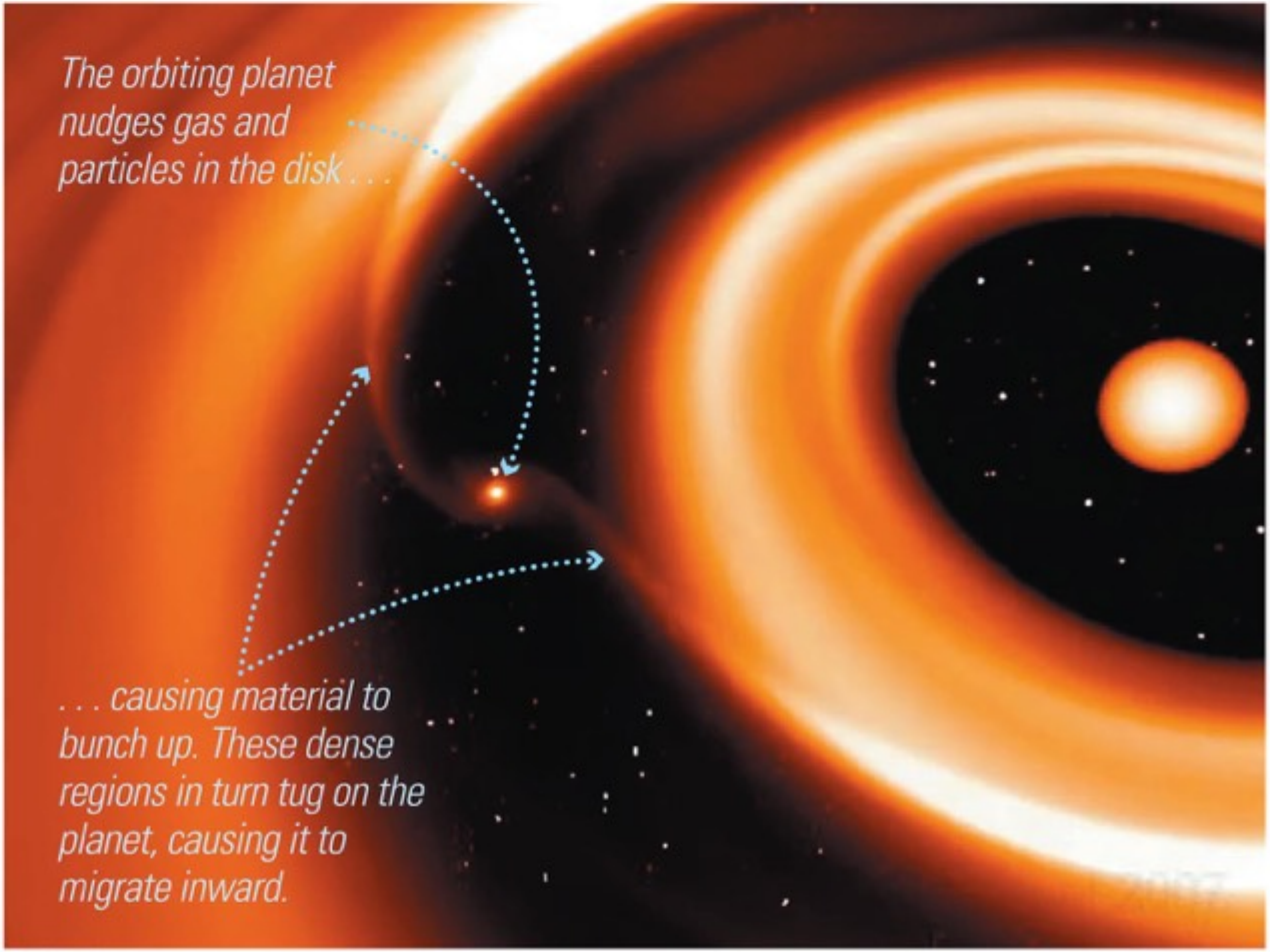


- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

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?



Modifying the Nebular Theory

- 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.