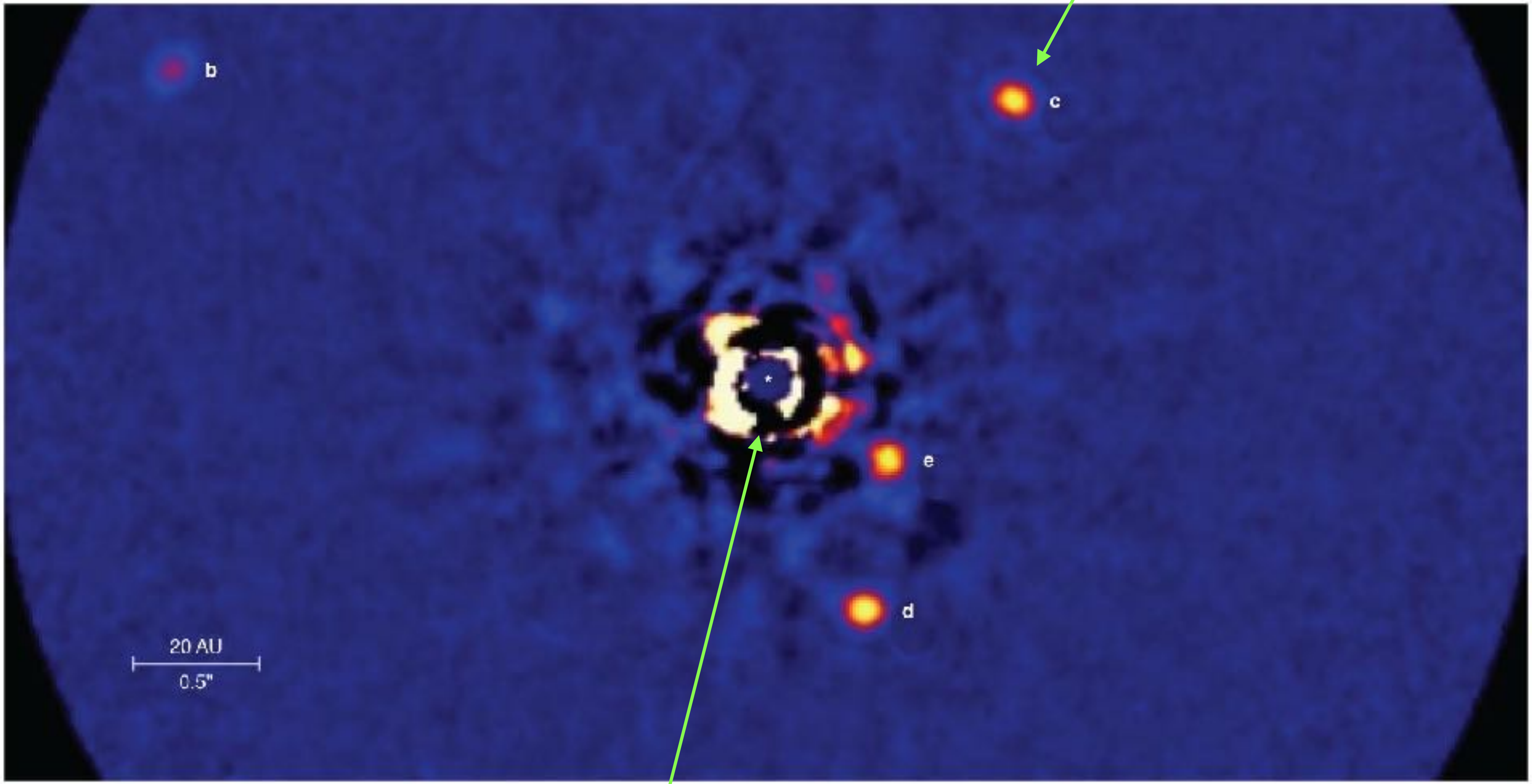
- Today
  - Extrasolar Planets
- Next week
  - Group Project Tuesday
    - Drake Equation - EXTRA credit
    - Homework 6 Due
  - Review Thursday

Planet Detection methods

- Direct: pictures 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

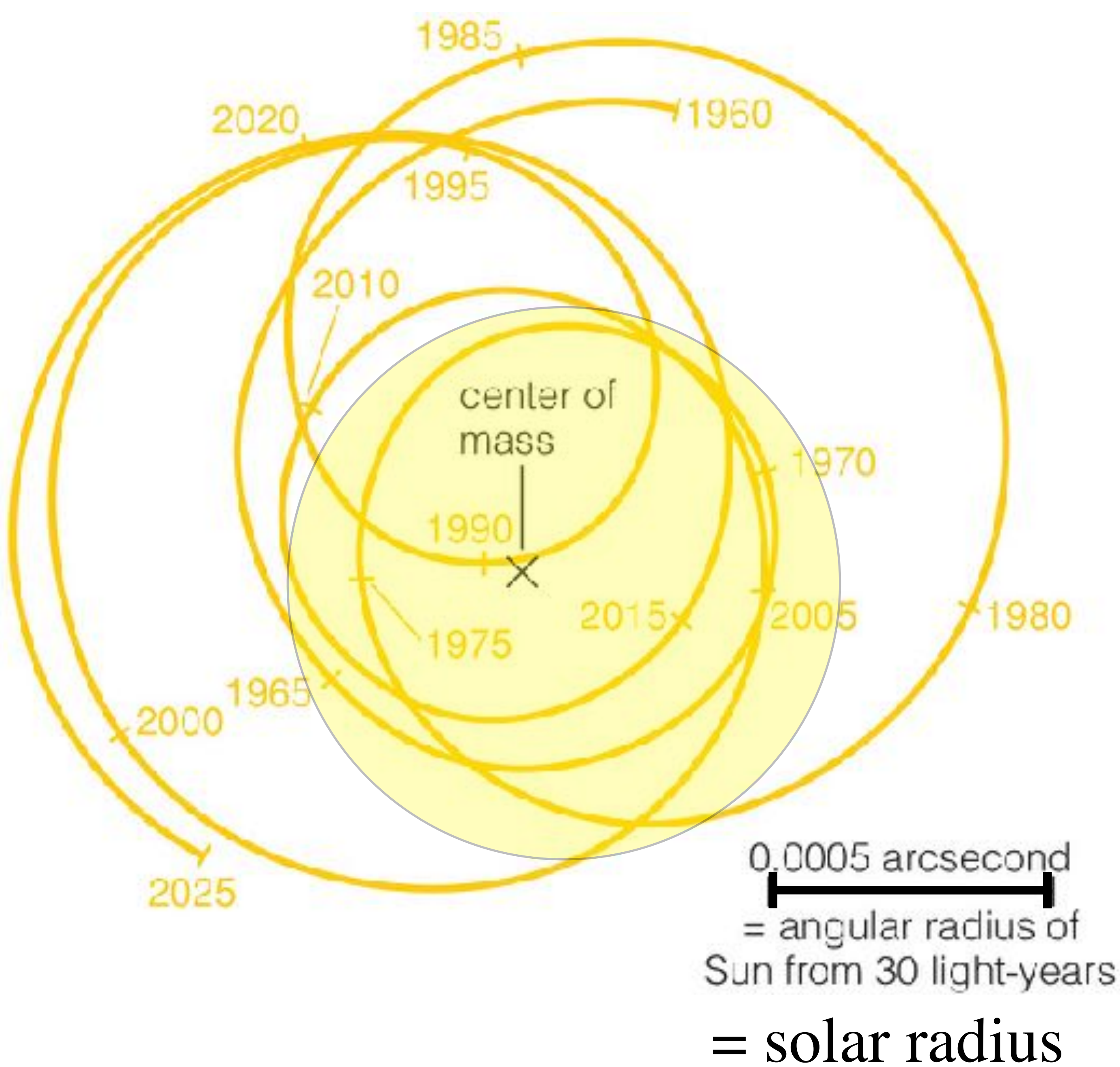
Direct Imaging

planets



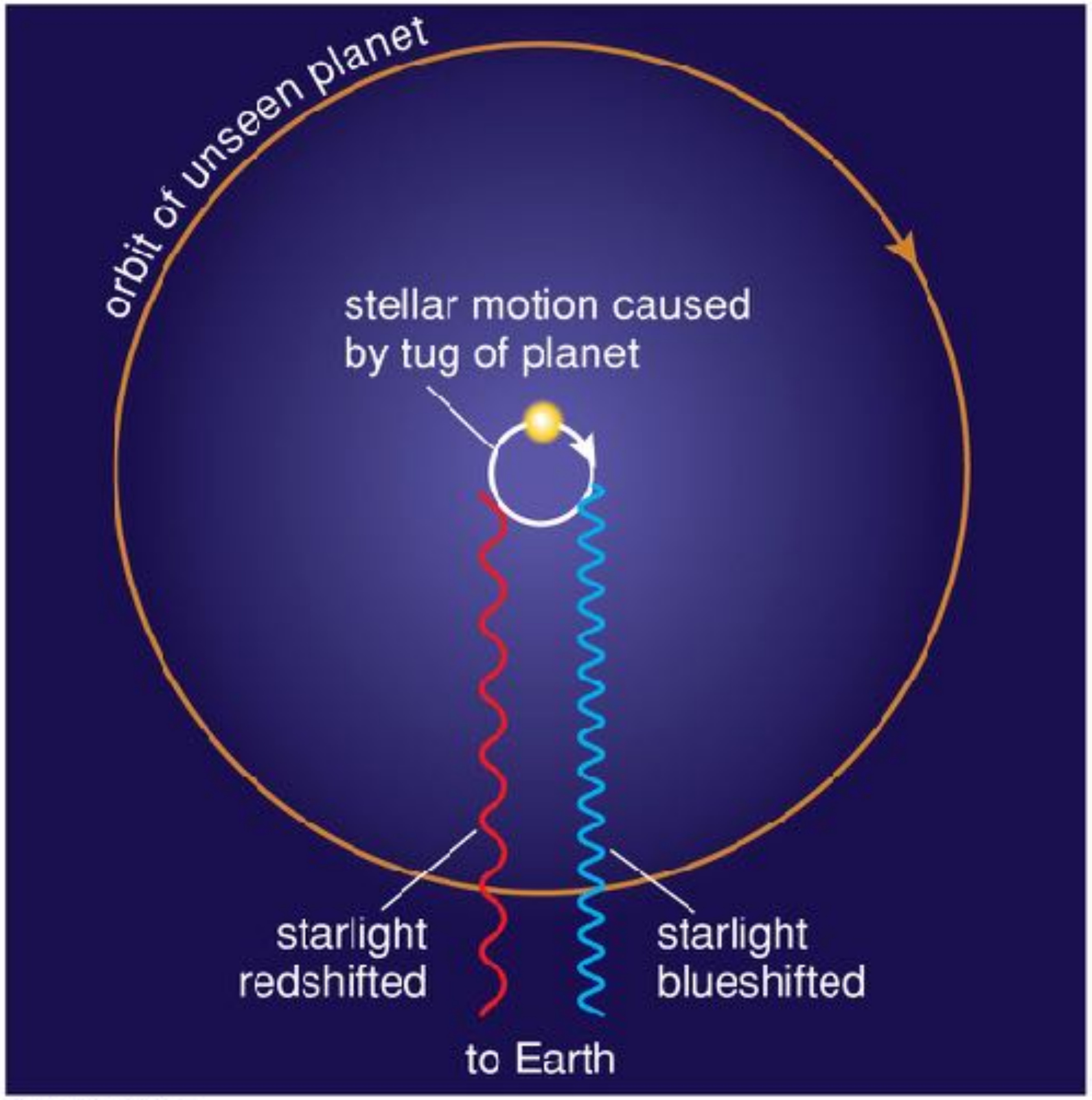
Coronograph blocks light from star, which is otherwise overwhelming.
Even blocked, a tiny fraction of scattered light make the mess you see here.

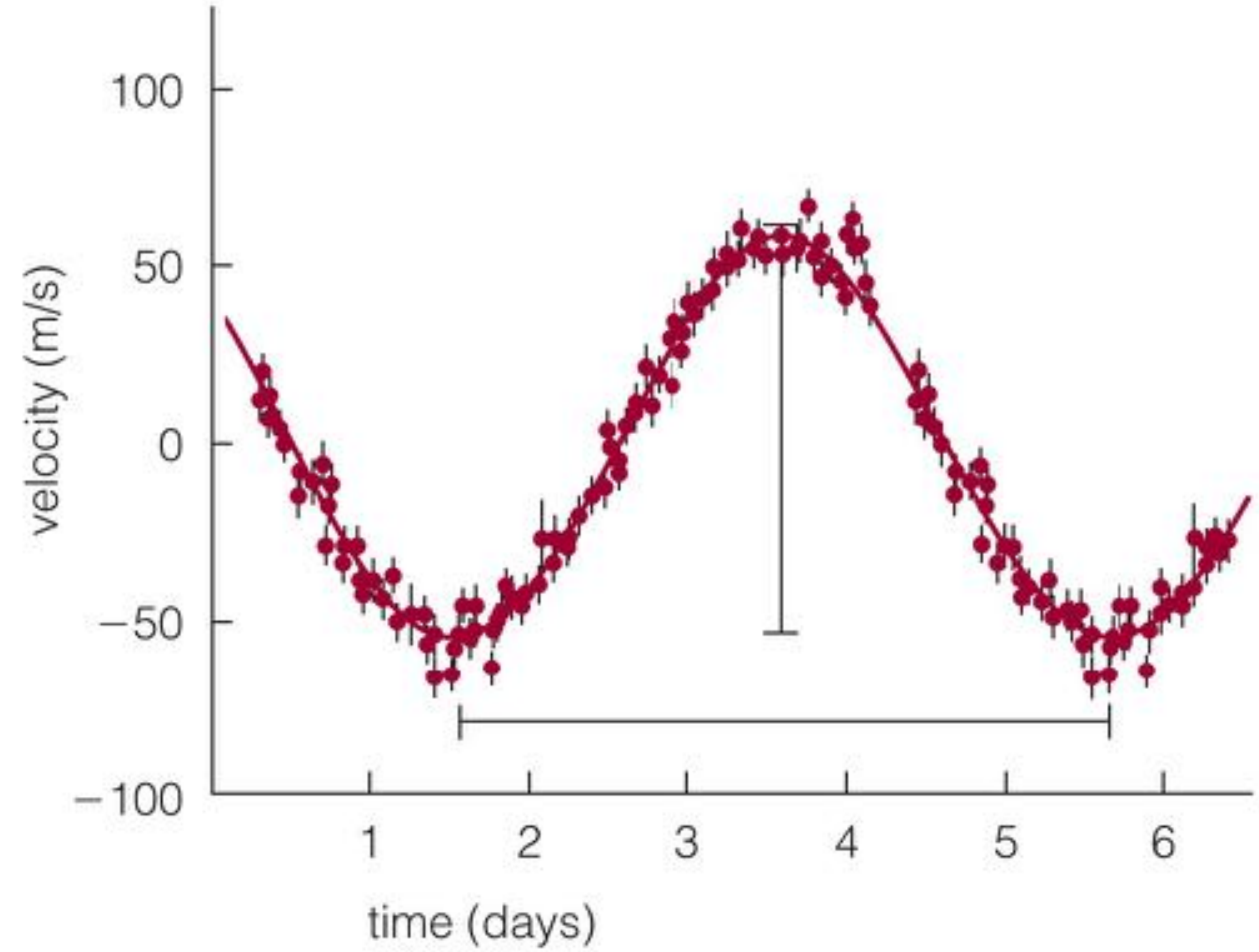
Astrometric Technique



- We can detect planets by measuring the change in a star's position on sky as its center of mass wobbles in response to orbiting planets.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).
- Best seen face-on

Doppler Technique

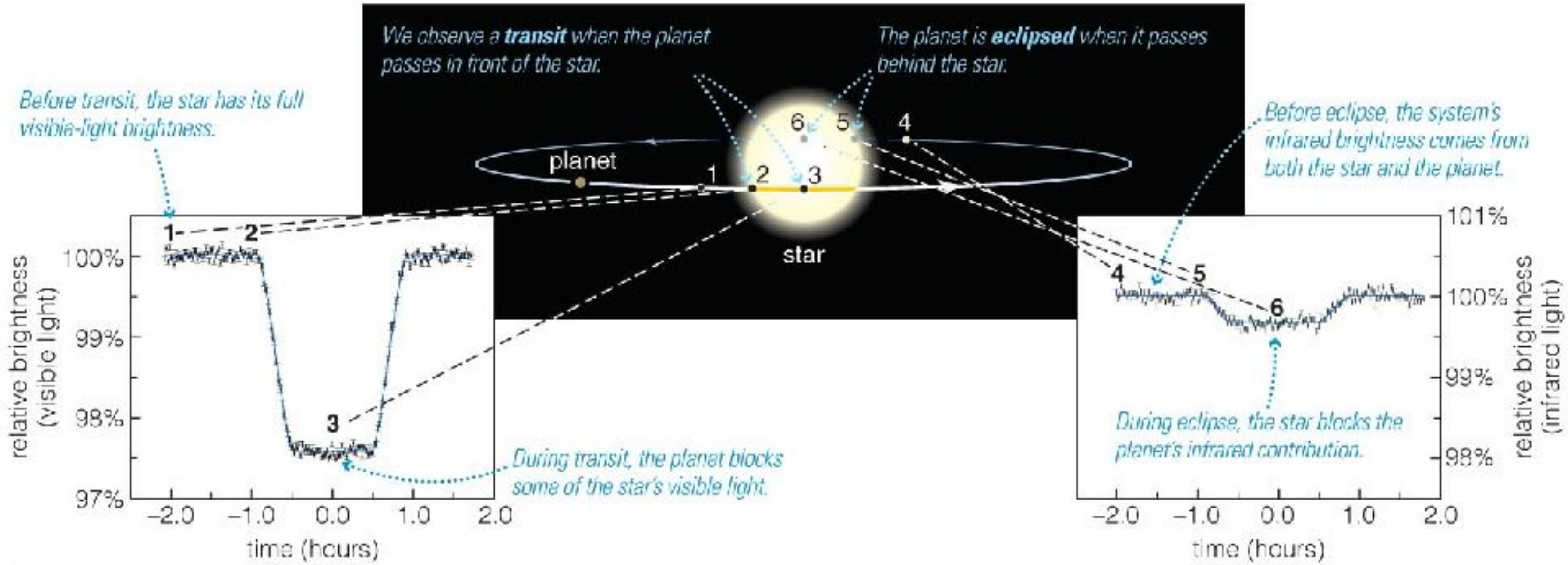




a A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

- Best seen edge-on

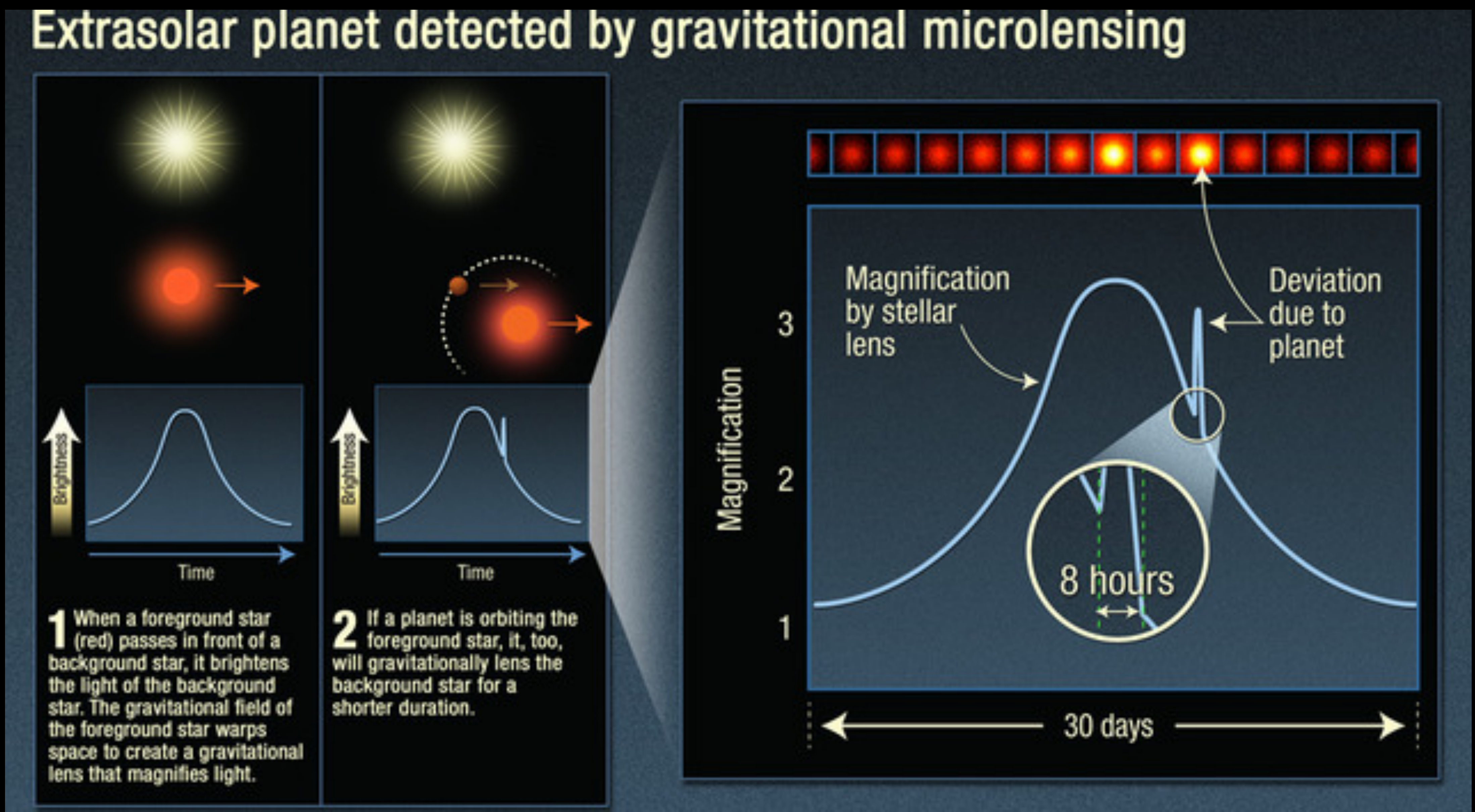
Transit Technique

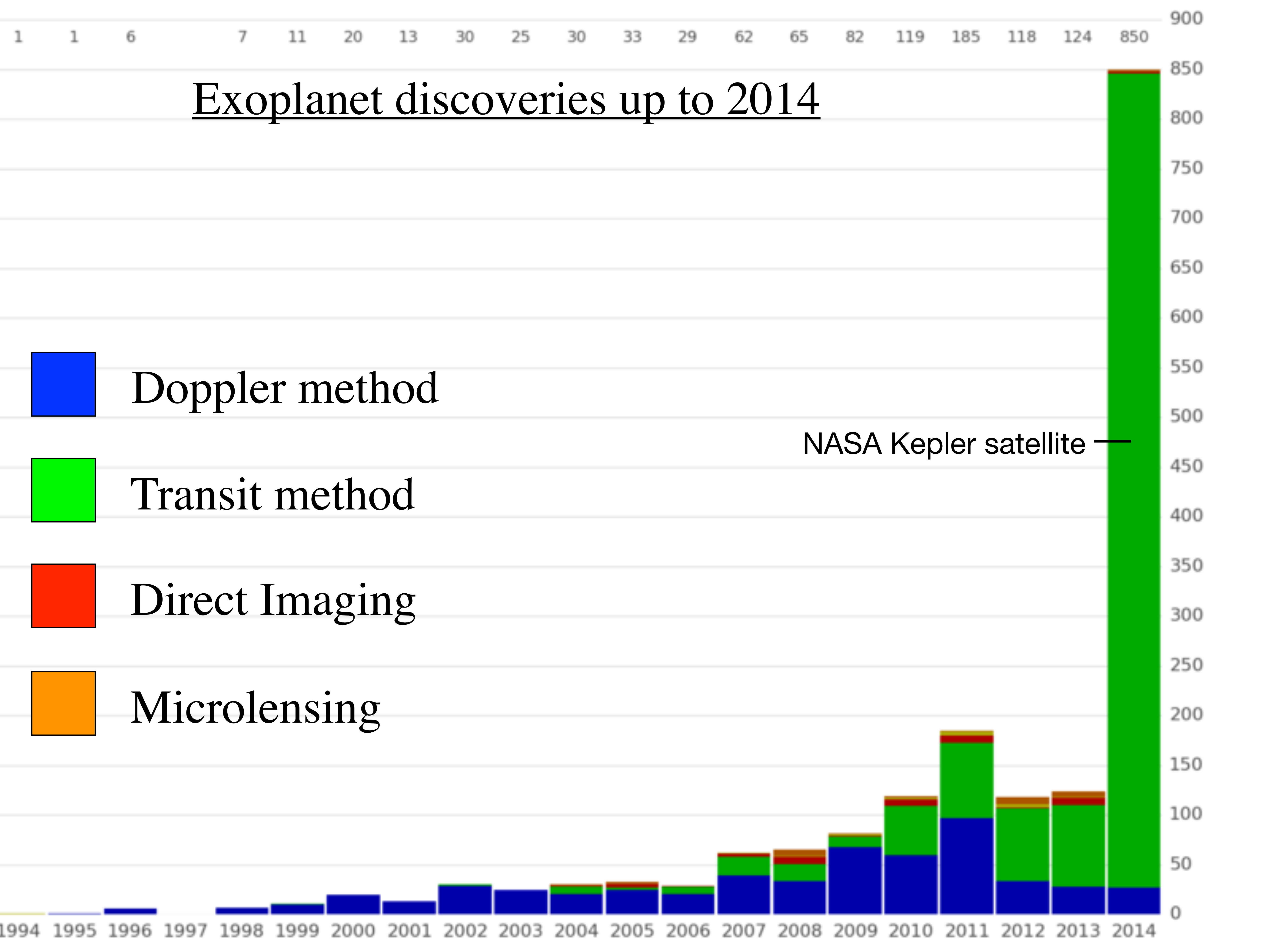


- A transit is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
  - best seen edge-on

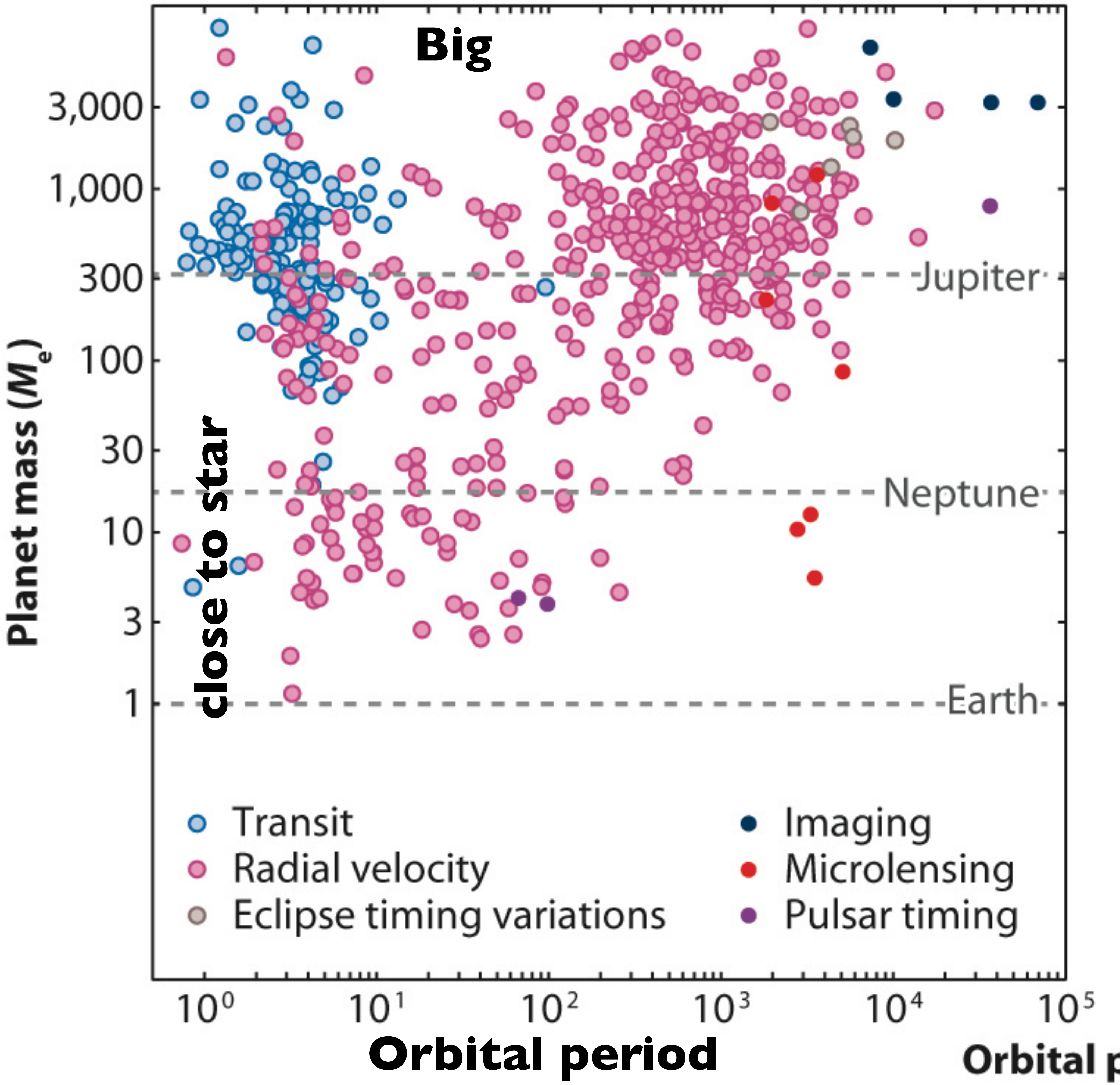
Gravitational lensing Technique

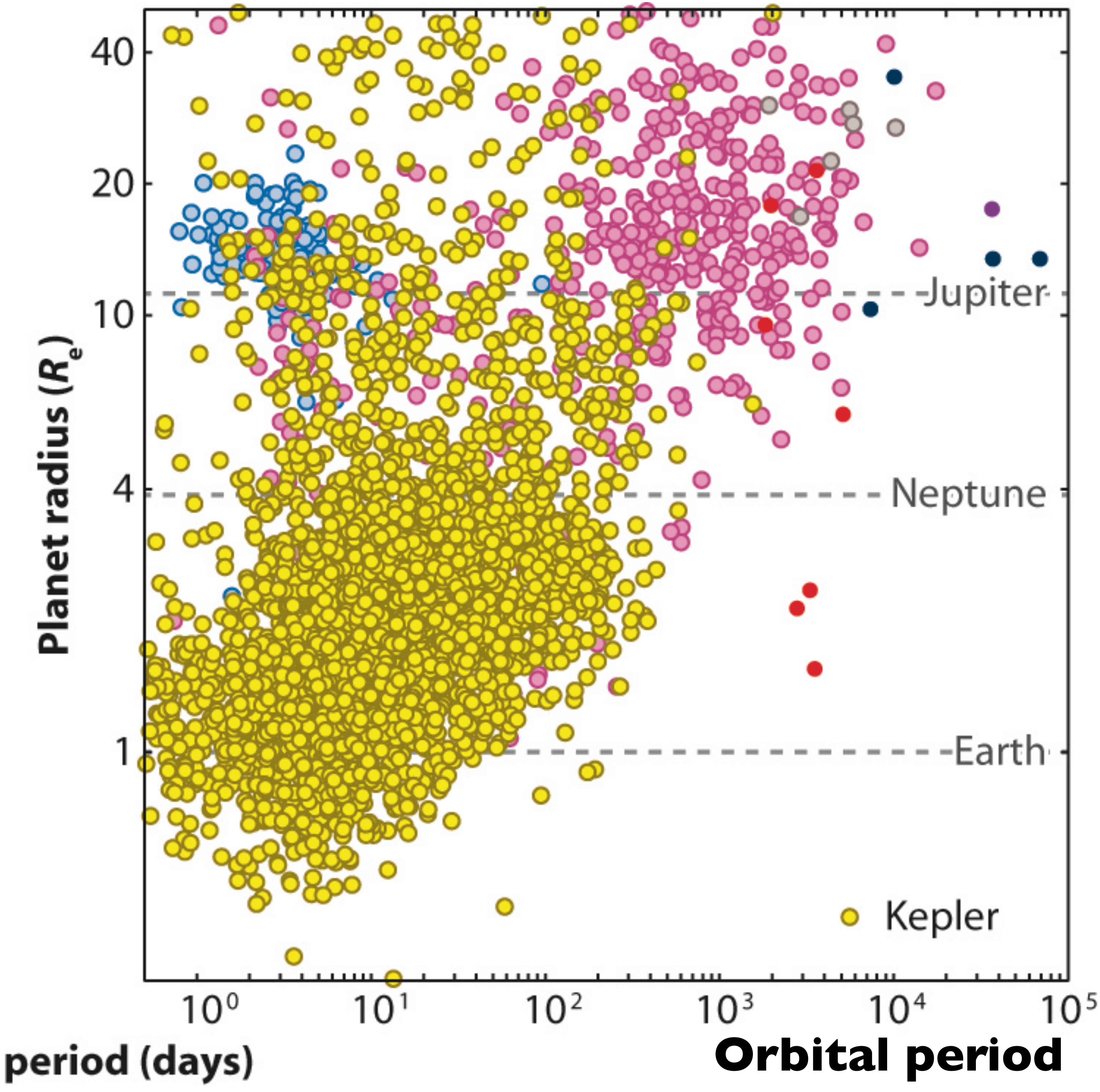
Gravitation Microlensing




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

All methods have strong selection effects

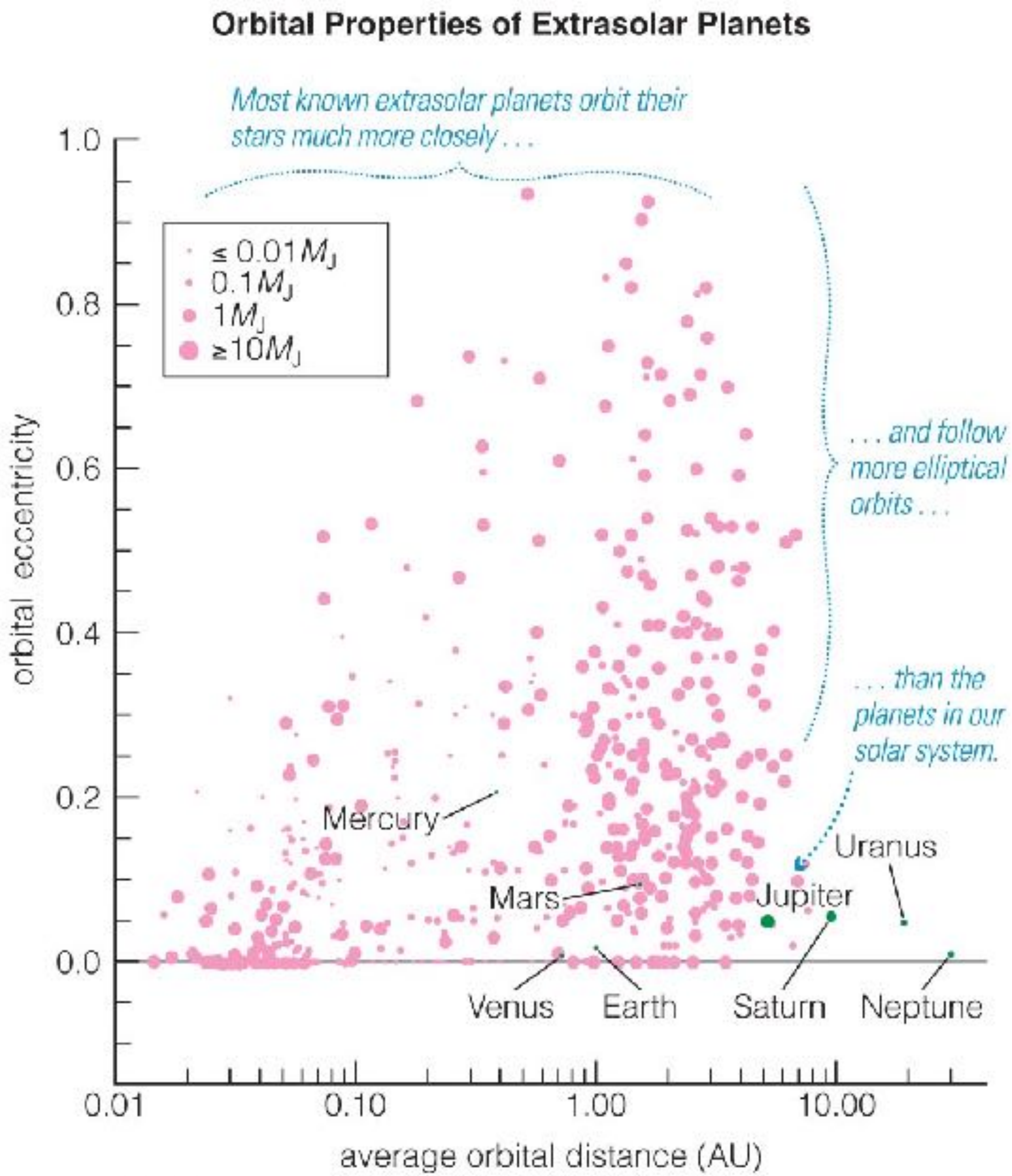




...and are good at measuring different things

Kepler is excellent at measuring radius; not necessarily mass.

What properties of extrasolar planets can we measure?



Measurable Properties

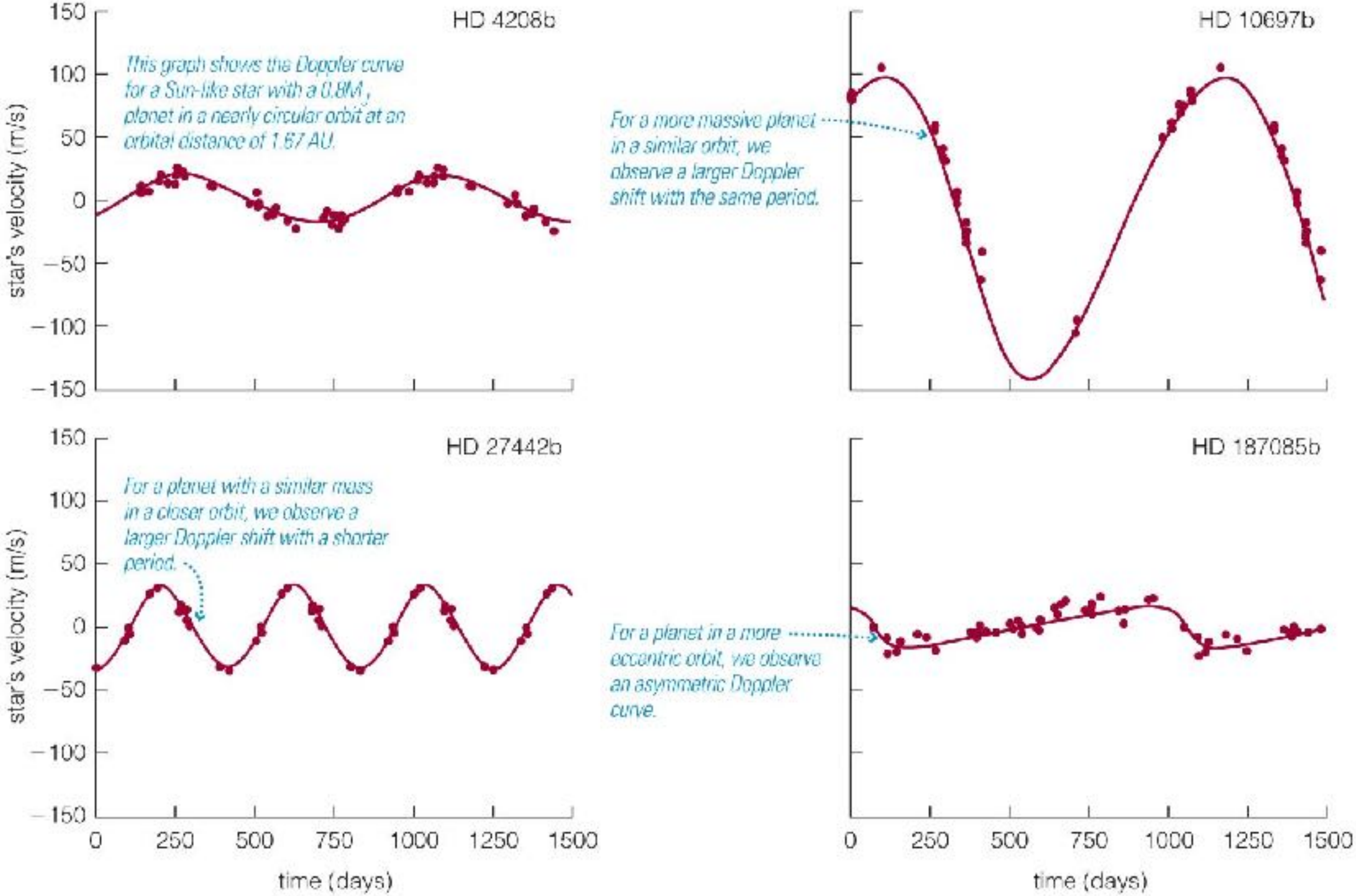
- Orbital period, distance, and shape (eccentricity)
- Planet mass, size, and density
- Atmospheric properties (sometimes)

Exoplanet app

gives you scientific data

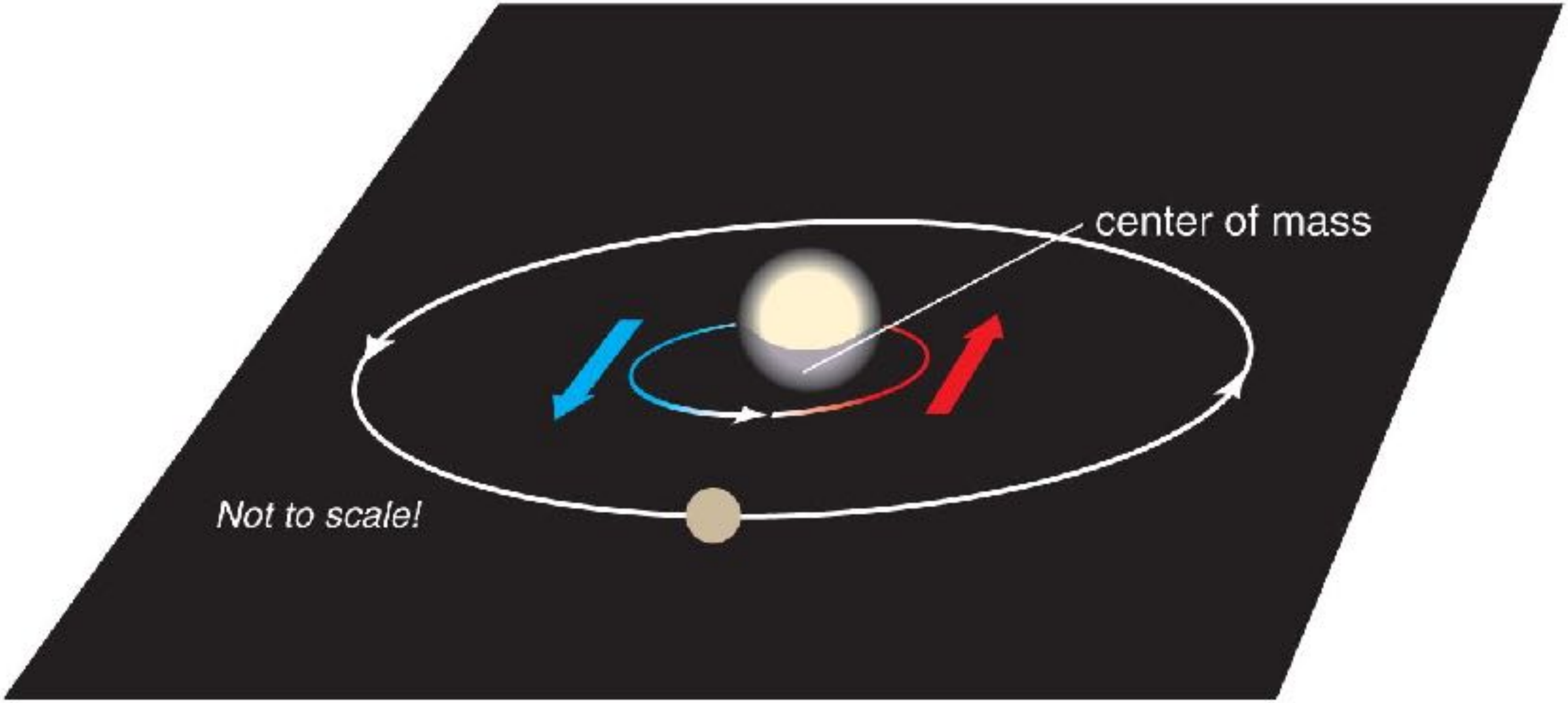
for thousands of exoplanets

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

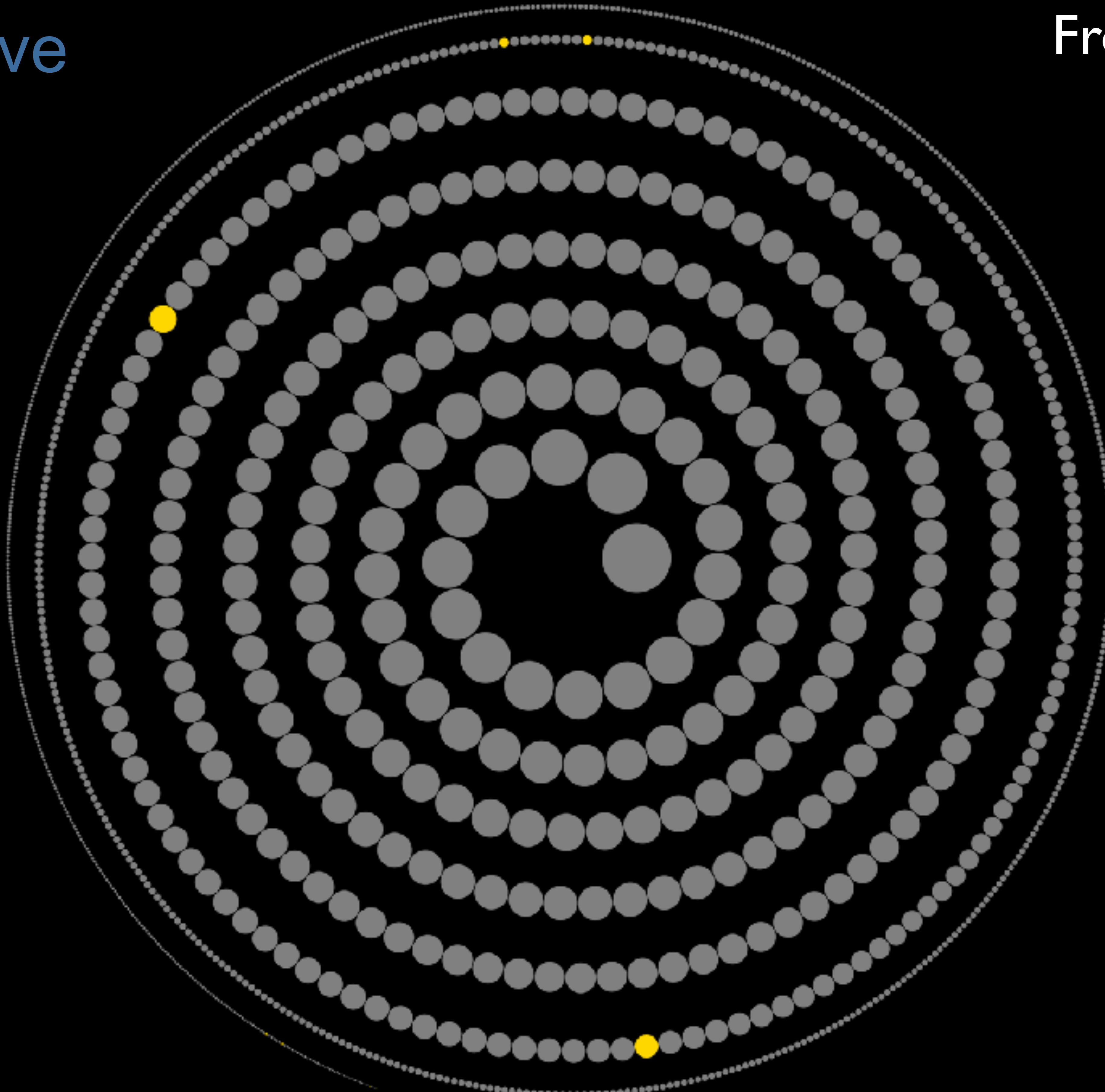


b We can detect a Doppler shift only if some part of the orbital velocity is directed toward or away from us. The more an orbit is tilted toward edge-on, the greater the shift we observe.

- 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, M*sin(i)

Relative Radii

From transits



The Relative Sizes of Known Exoplanets and Solar System Planets

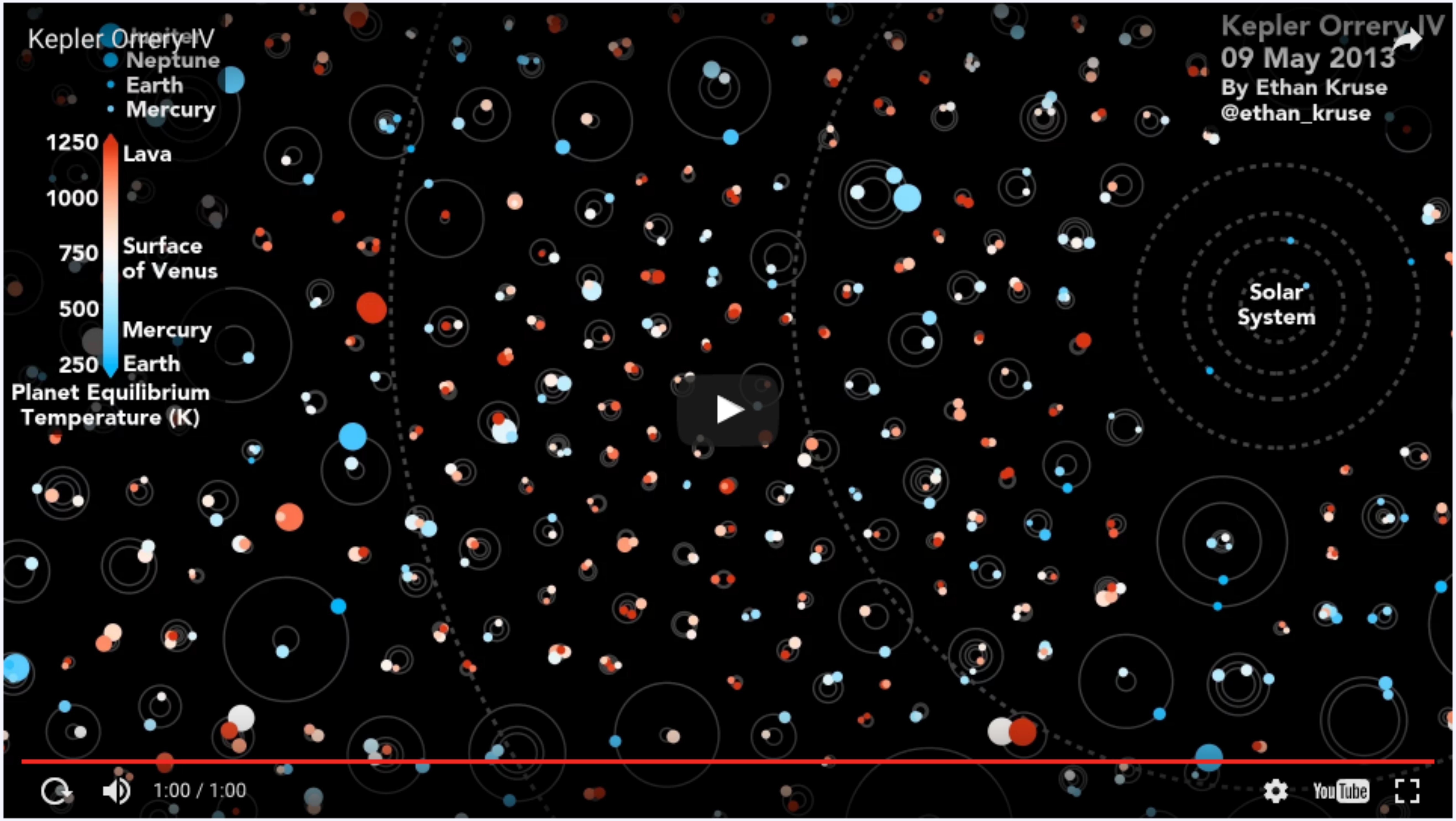
Alex H. Parker / @Alex_Parker
Data from http://exoplanet.eu/

Astronomy Picture of the Day

over the cosmos! Each day a different image or photograph of our fascinating universe is featured, along with a brief explanation written by professional astronomer.

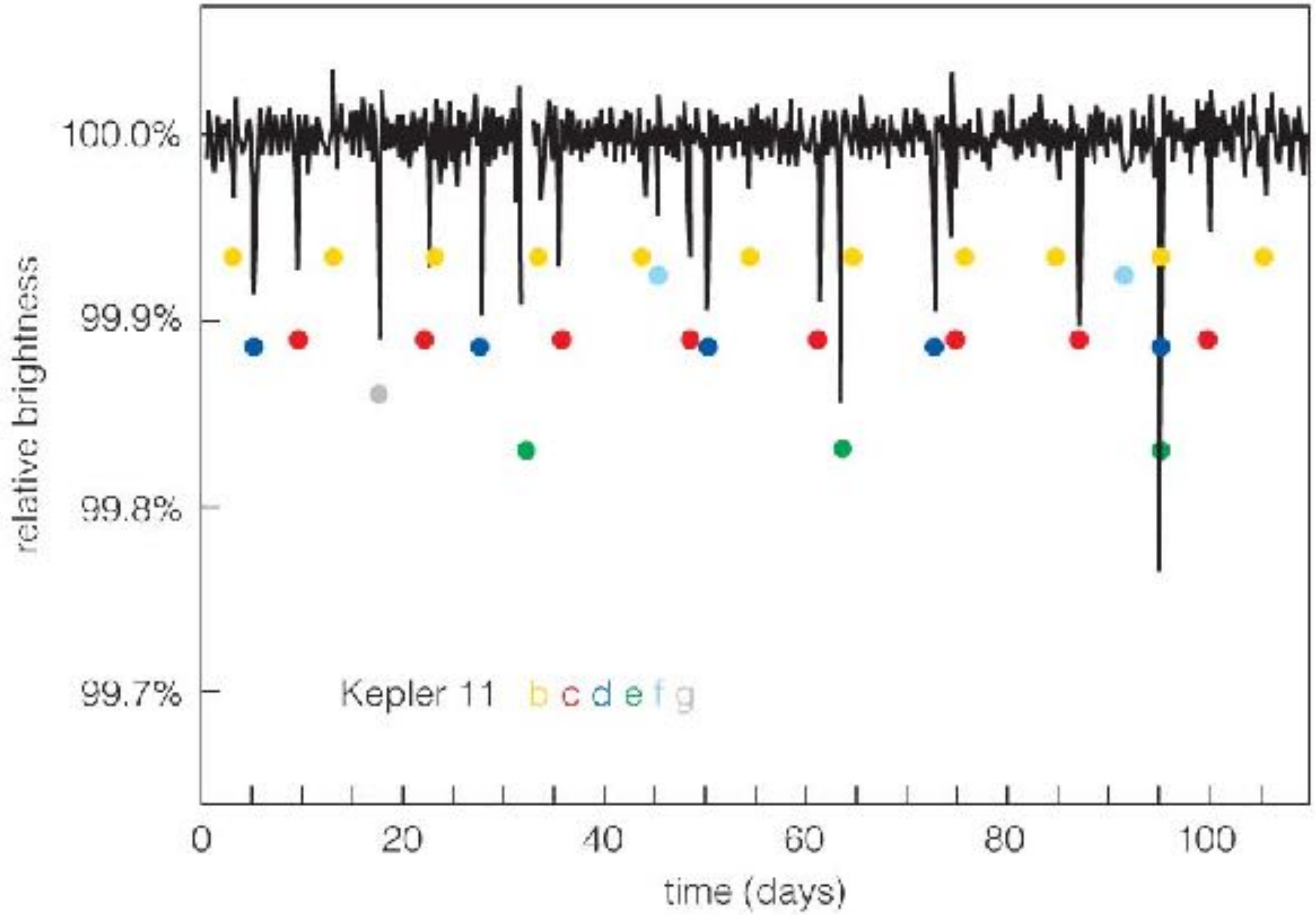
https://apod.nasa.gov/apod/ap151205.html

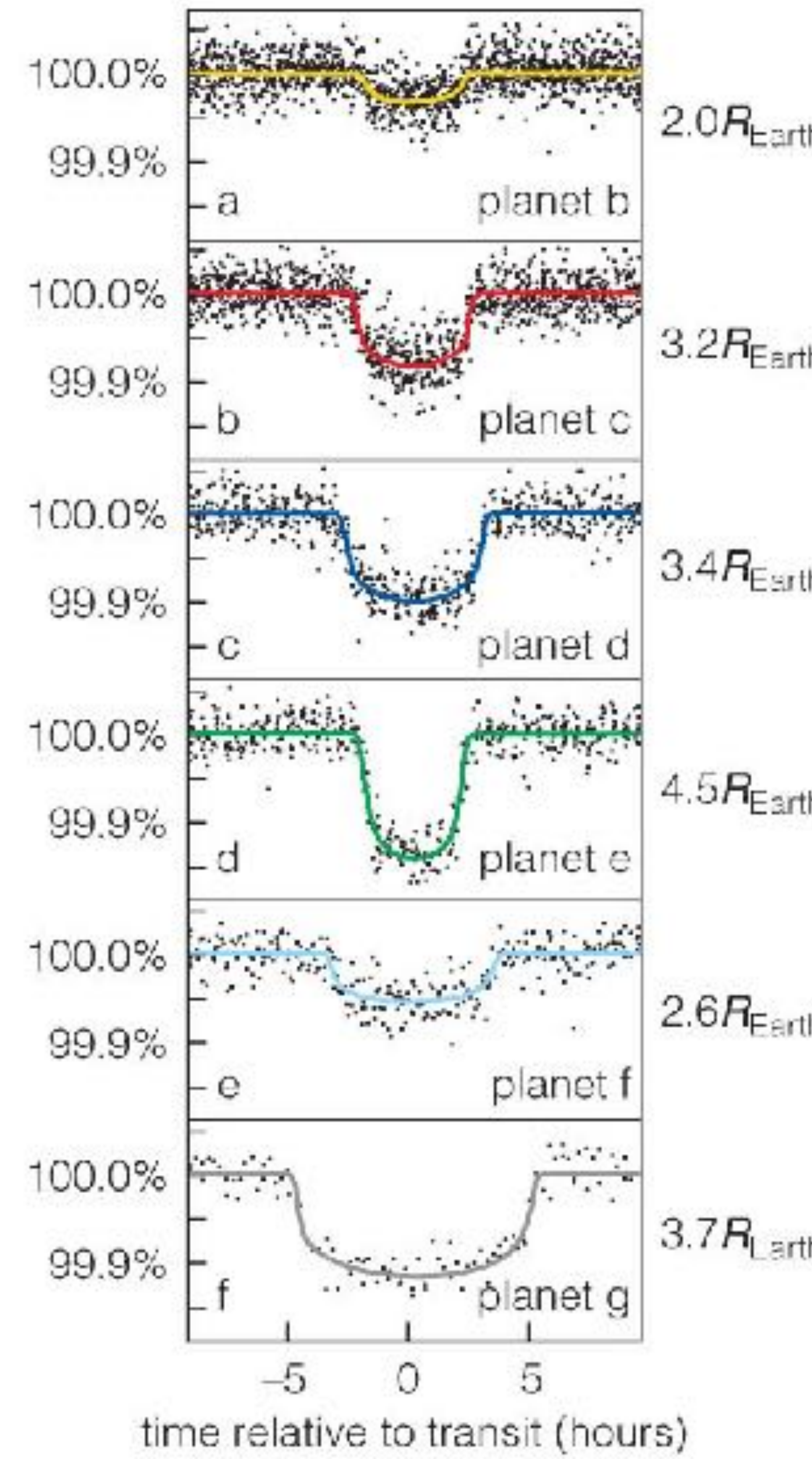
2015 December 5



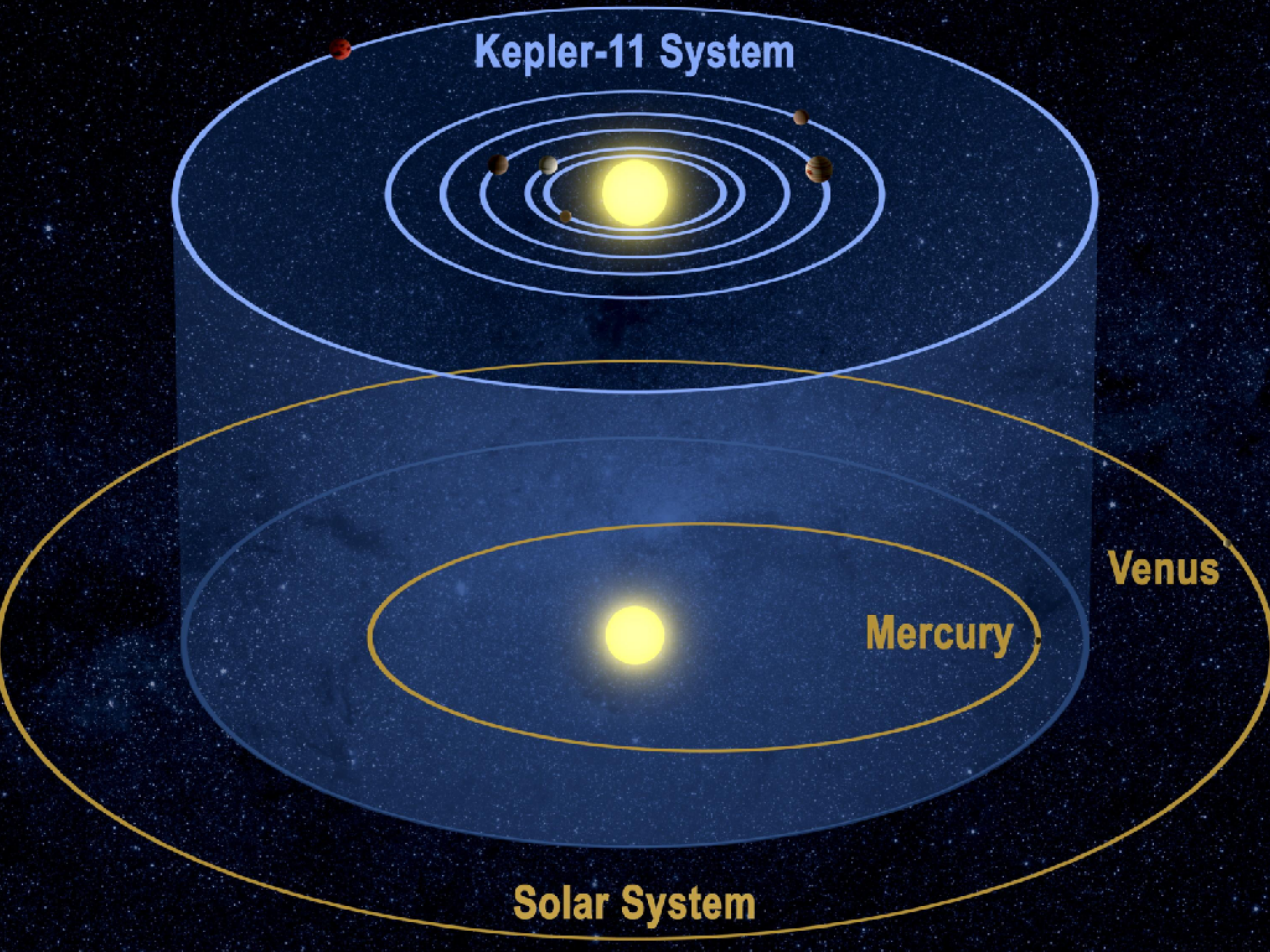
Kepler Orrery IV

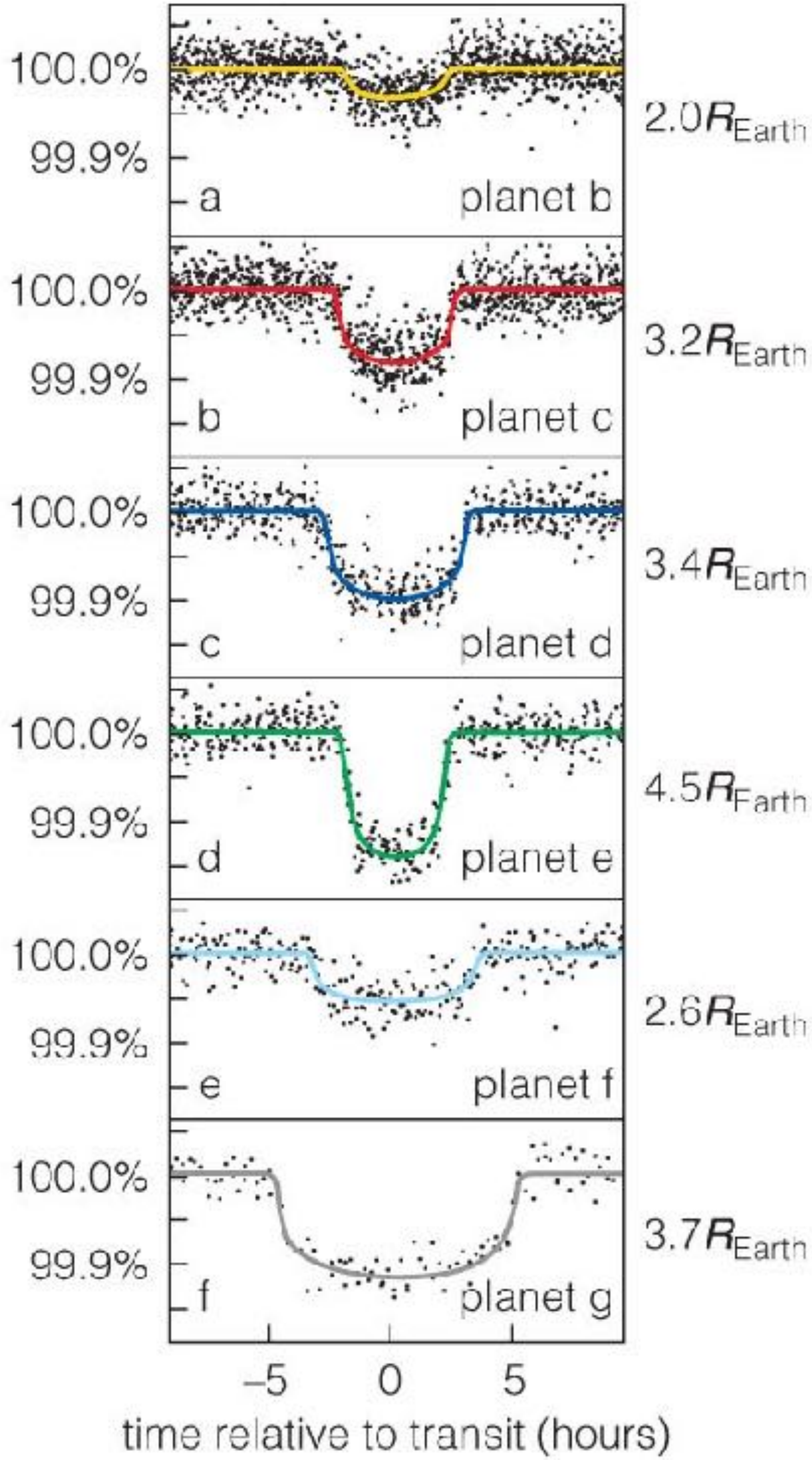
The Kepler 11 system





- 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



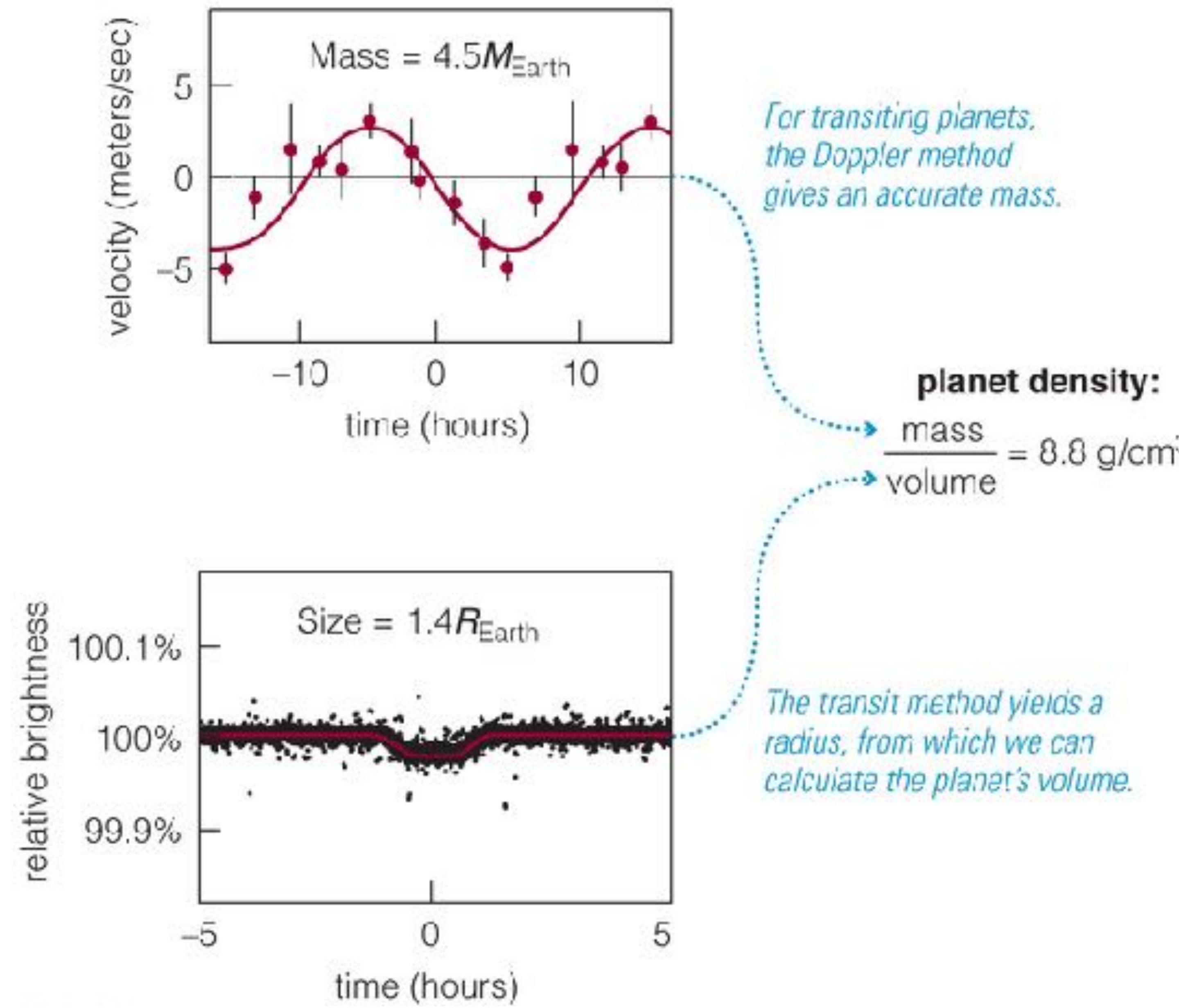
The Kepler 11 system

- 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

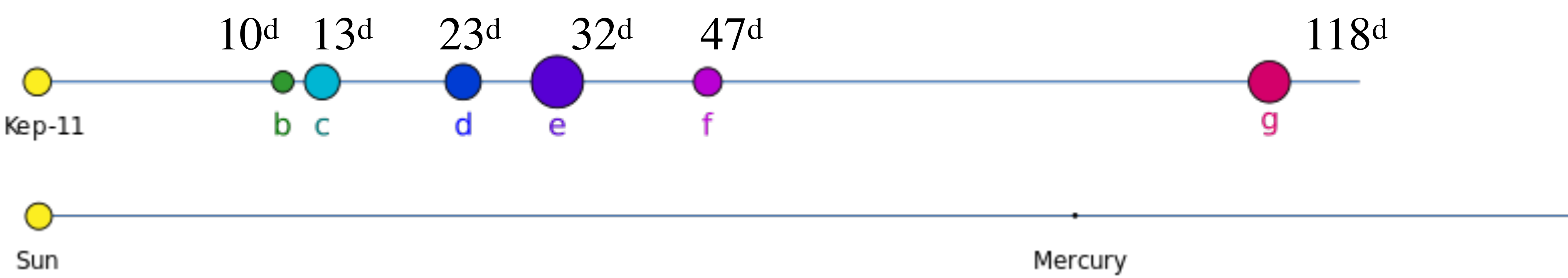
Calculating density

- Mass and size specify the density
- Mass is determined using the Doppler technique
- Size is determined using the transit technique.



The Kepler 11 system

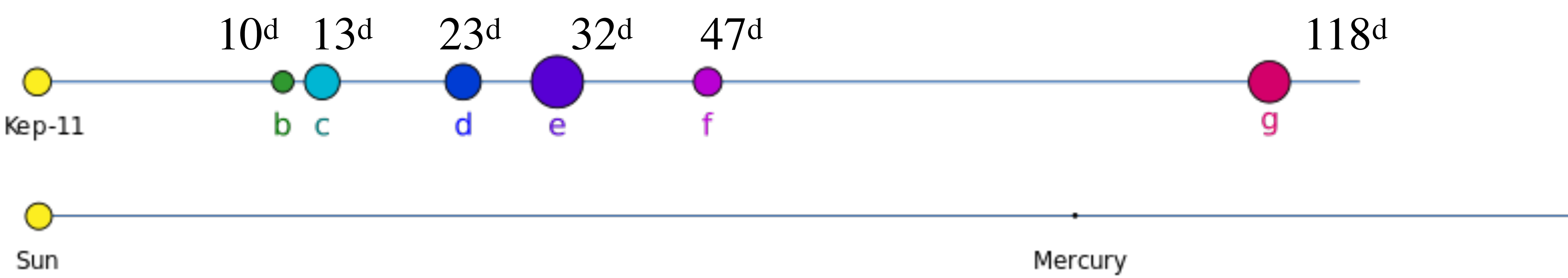
- The densities of all these planets are low
  - 0.6 - 1.7 g/cc (Typical of Jovian planets)
- Star is
  - 0.96 mass of sun
  - 1.07 radius of sun
  - 8.5 Gyr old (sun is 4.5 Gyr)
- Tightly packed system that is nevertheless stable
  - despite lack of orbital resonances

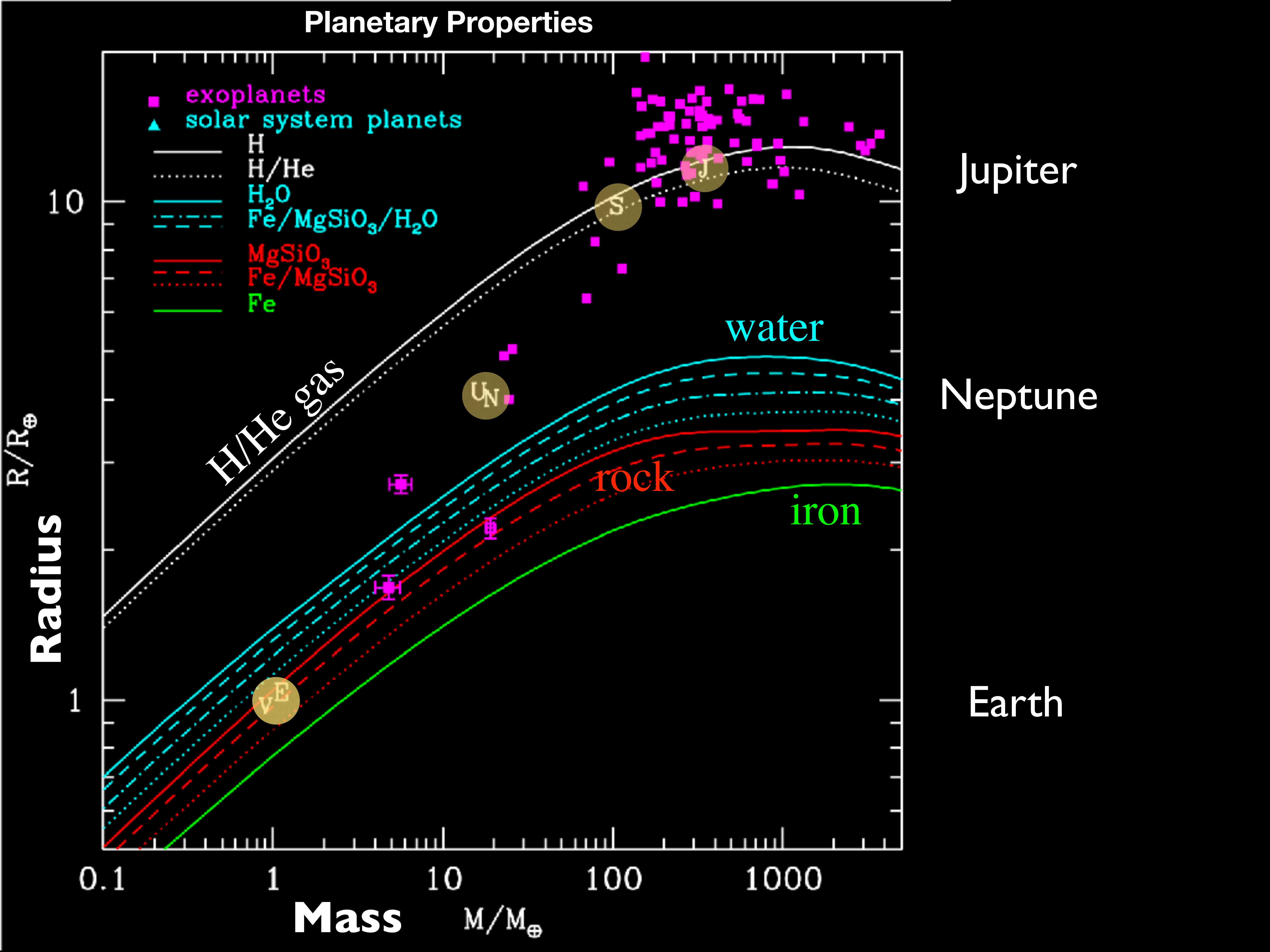


The Kepler 11 system

- The densities of all these planets are low
  – 0.6 - 1.7 g/cc   (Typical of Jovian planets)

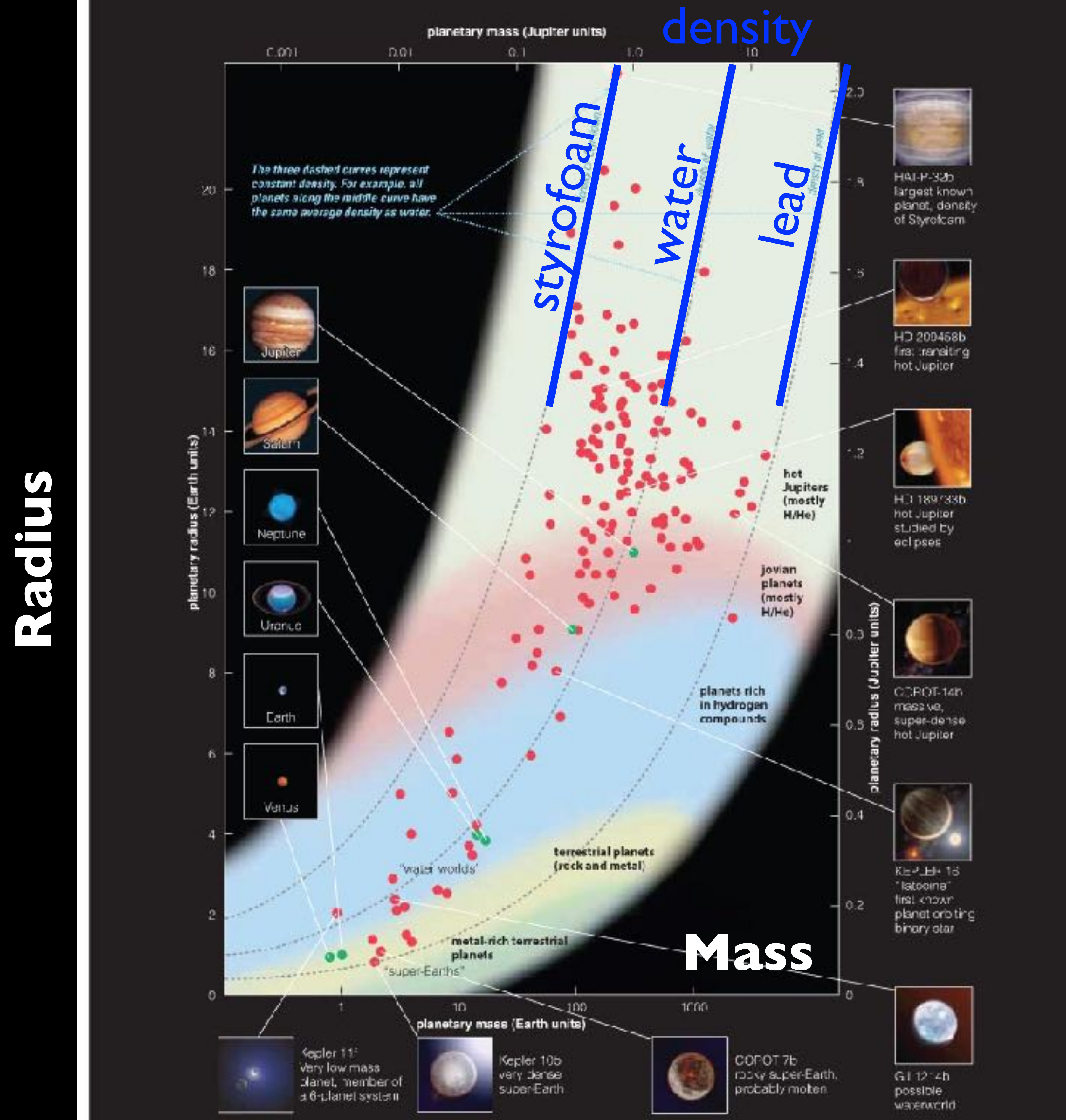
- What does this imply about the solar nebula hypothesis?



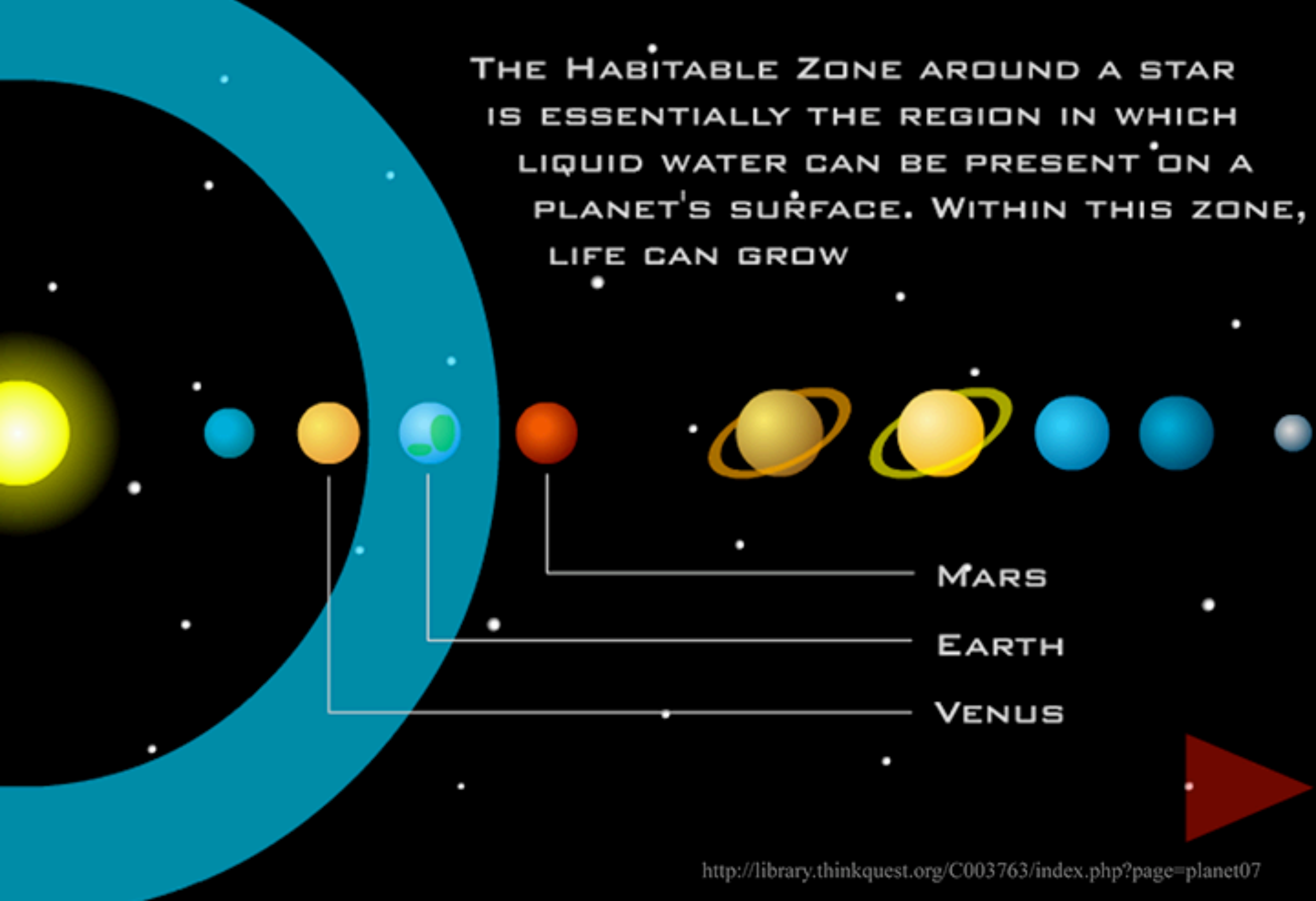


Planetary Properties
exoplanets
solar system planets
H
H/He
H_2O
$Fe/MgSiO_3/H_2O$
$MgSiO_3$
$Fe/MgSiO_3$
Fe
H/He gas
water
rock
iron
S
J
U N
V E
Jupiter
Neptune
Earth
10
1
0.1
1
10
100
1000
Radius
$R/R_\oplus$
Mass
$M/M_\oplus$

Exoplanet properties in general: size vs. mass



Might exoplanets be home to life?

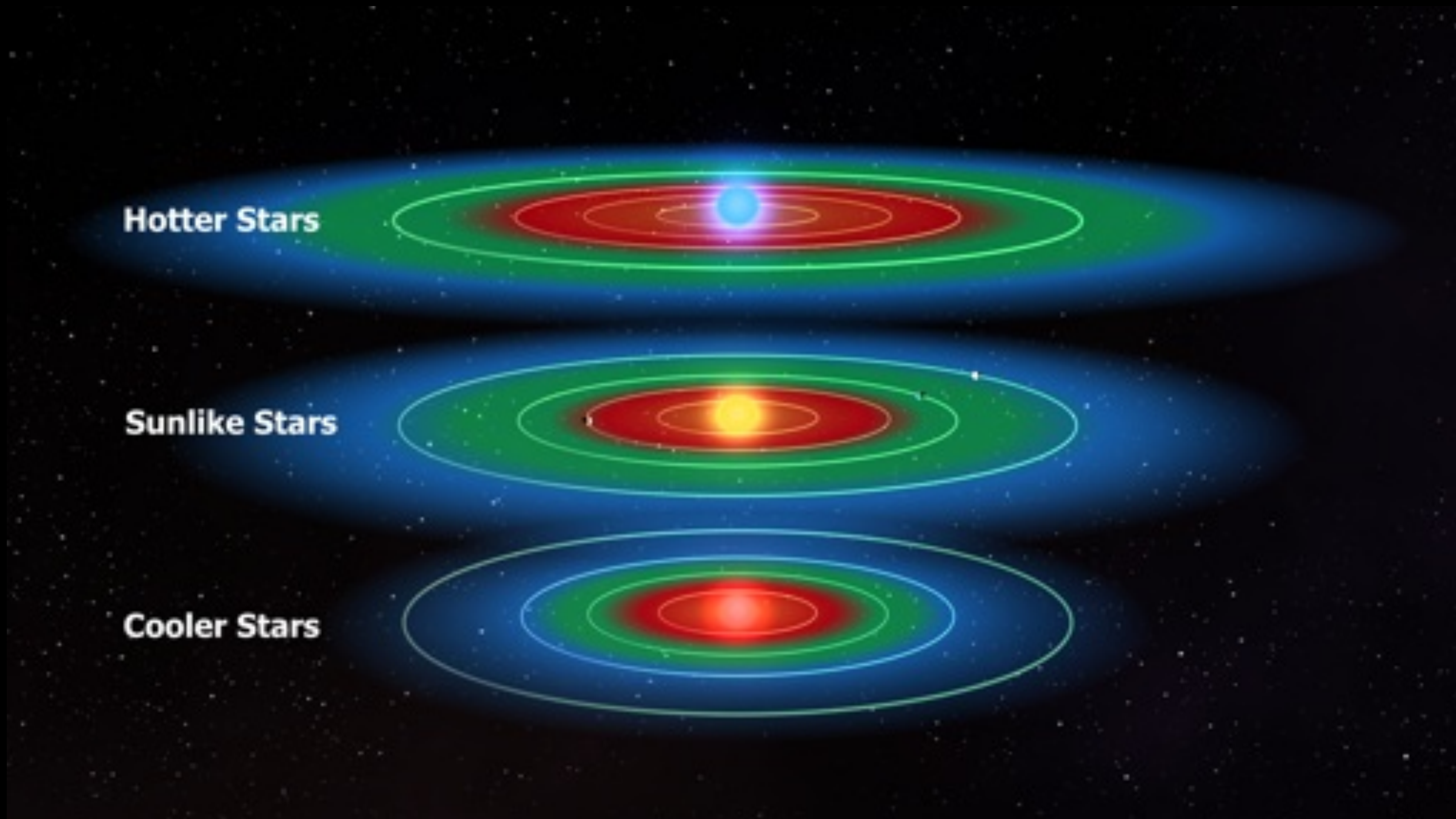


Habitable Zone

for terrestrial life

- Depends on
  - Brightness of star
    - also the spectrum of star - too much UV? too little?
  - Distance of planet from star
  - Nature of planet
    - surface gravity
    - atmosphere
      - greenhouse gases
      - water
  - other... some argue the moon is a necessary shield against too many major impacts

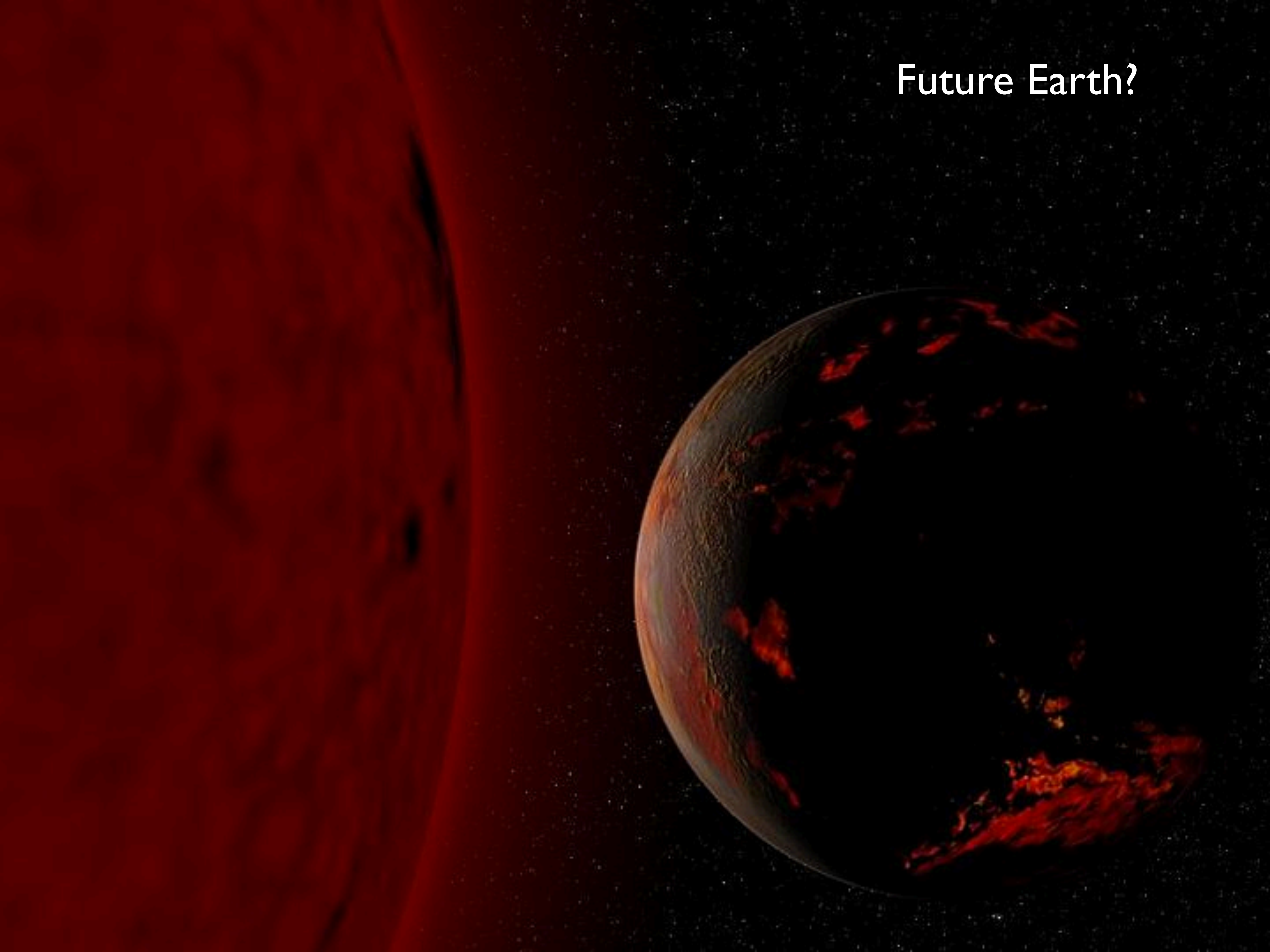
Presumably, the habitable zone is farther out form hot, bright stars and closer in to faint, cool ones.



Stars evolve over billions of years, gradually becoming brighter - planets may slip out of the habitable zone as a result

For the Earth, expect

- The sun increases slowly in brightness
- in 600 million years, the Carbon cycle may have progressed to the point that the atmosphere may lack sufficient CO_2 to sustain plant life
- In ~ 1 billion years, solar luminosity will have increased ~10%, evaporating the oceans (“wet greenhouse”)
- In ~6 billion years, the sun will expand into a red giant, potentially swelling far enough to encompass the orbit of the Earth


Future Earth?