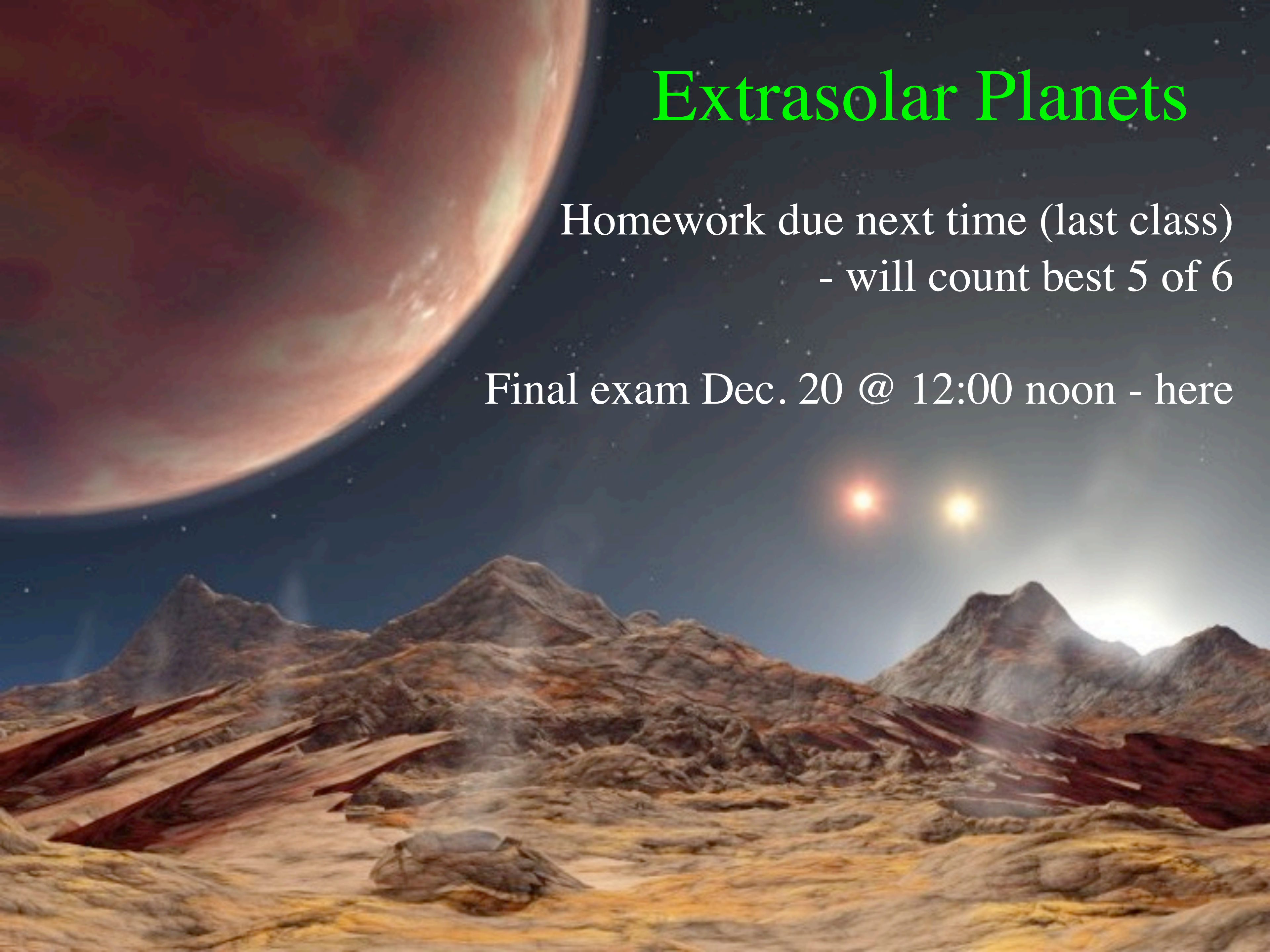
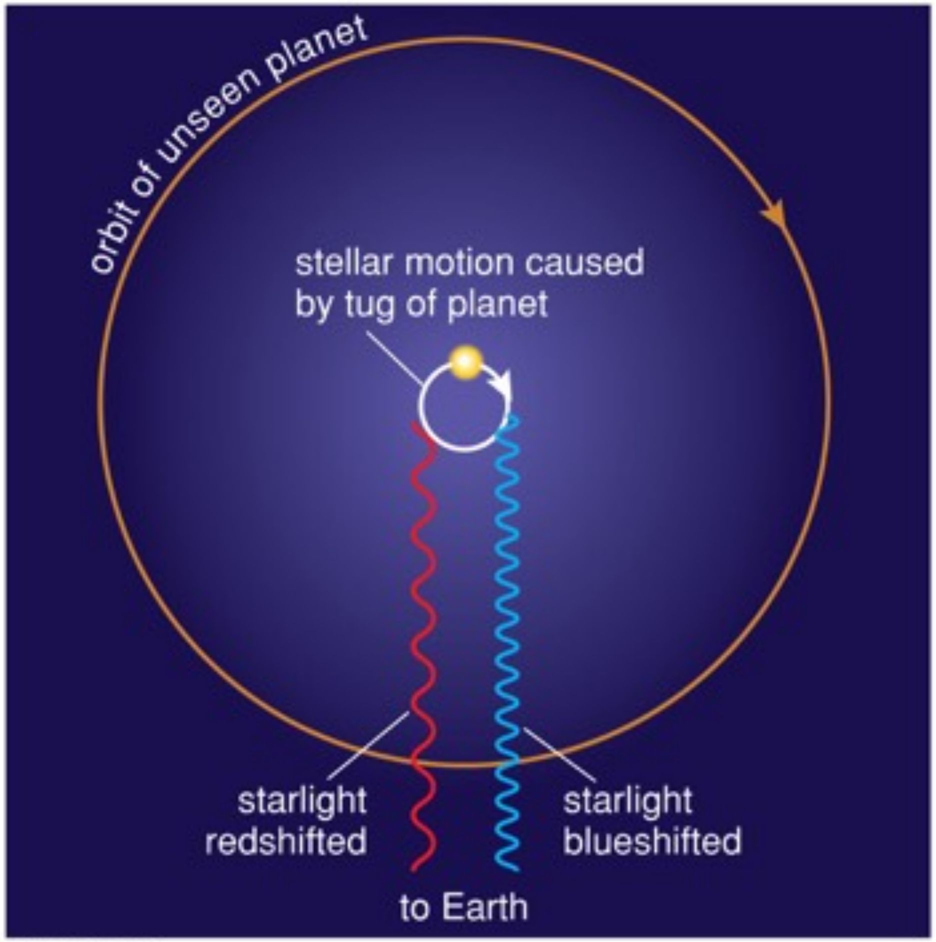
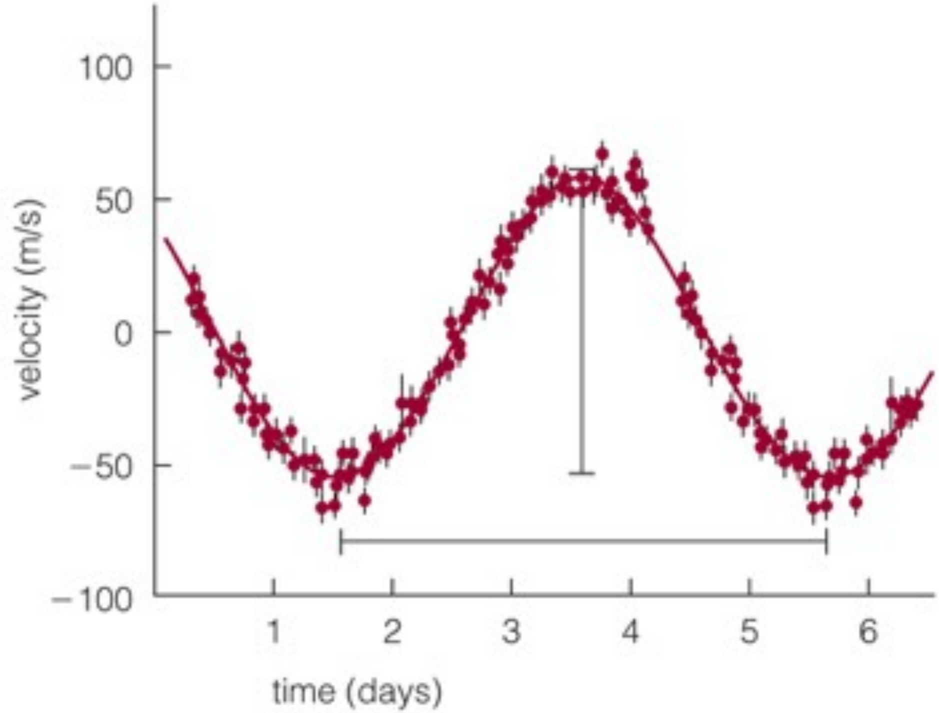

Extrasolar Planets
Homework due next time (last class)
- will count best 5 of 6
Final exam Dec. 20 @ 12:00 noon - here

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

Doppler Technique

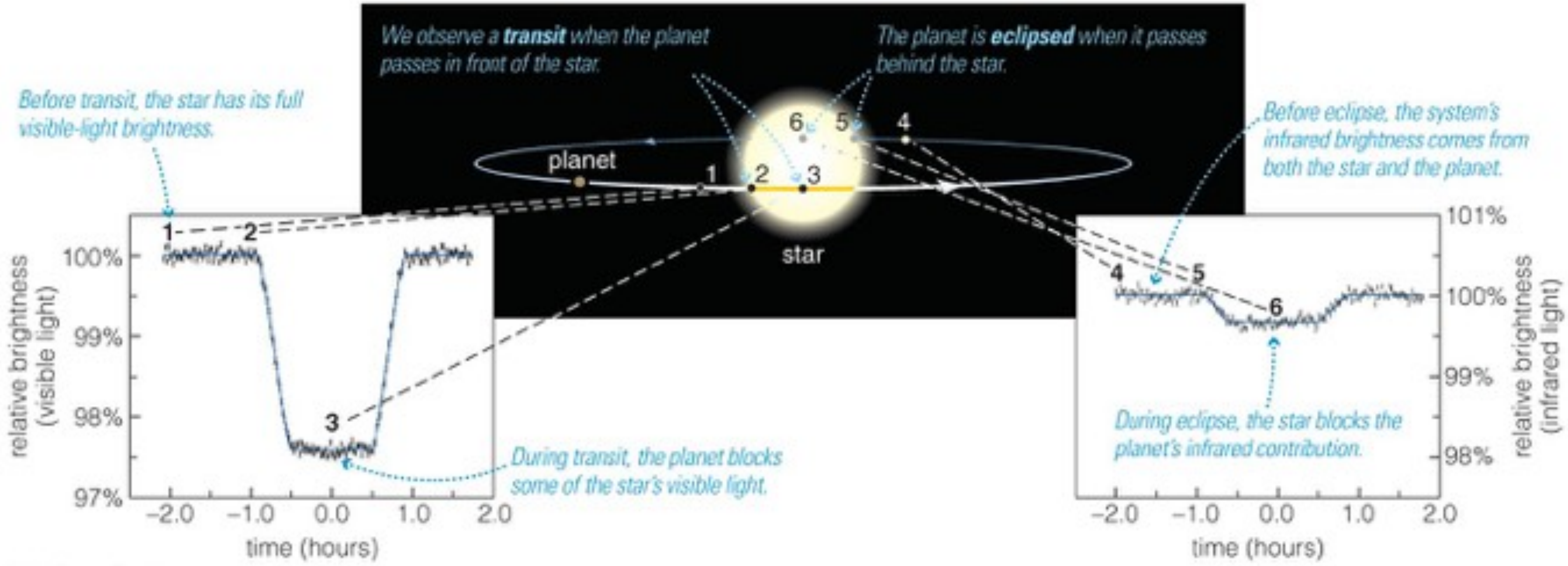




a A periodic Doppler shift in the spectrum of the star 51 Pegasi shows the presence of a large planet with an orbital period of about 4 days. Dots are actual data points; bars through dots represent measurement uncertainty.

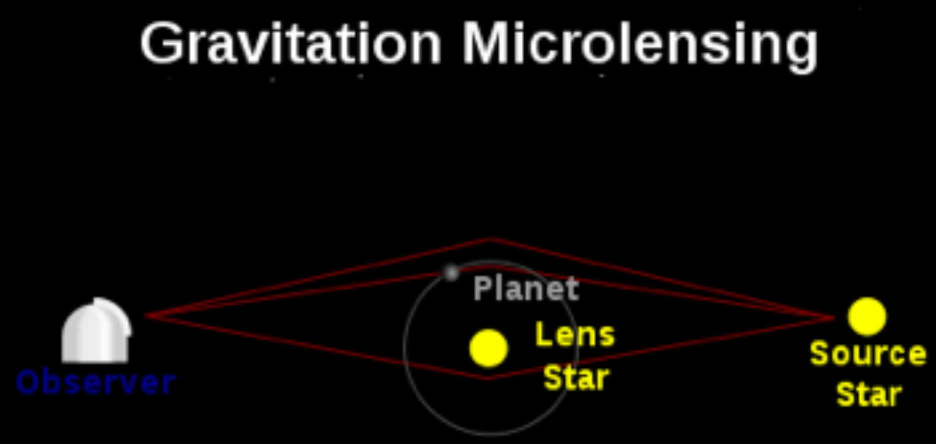
- Best seen edge-on

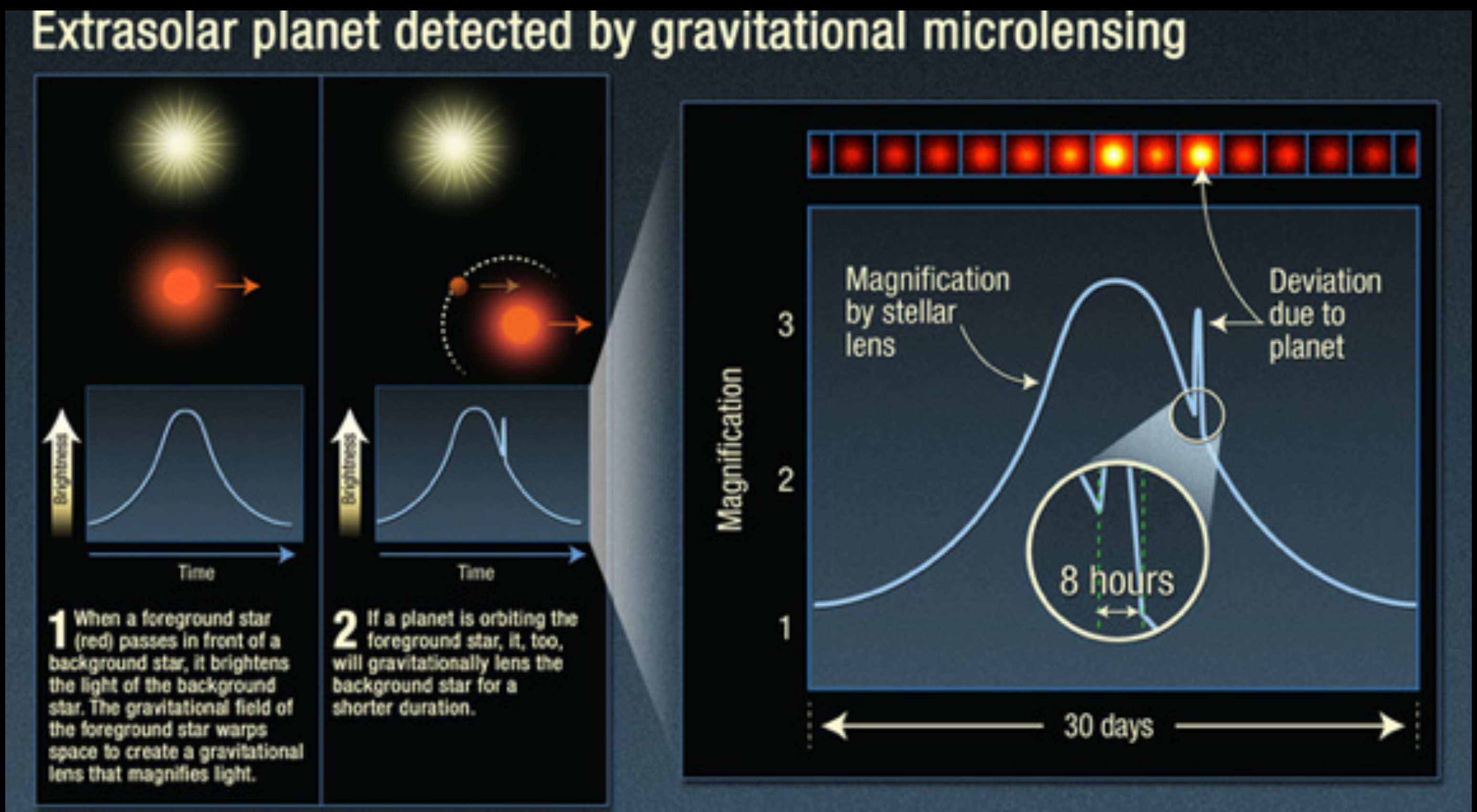
Transit Technique

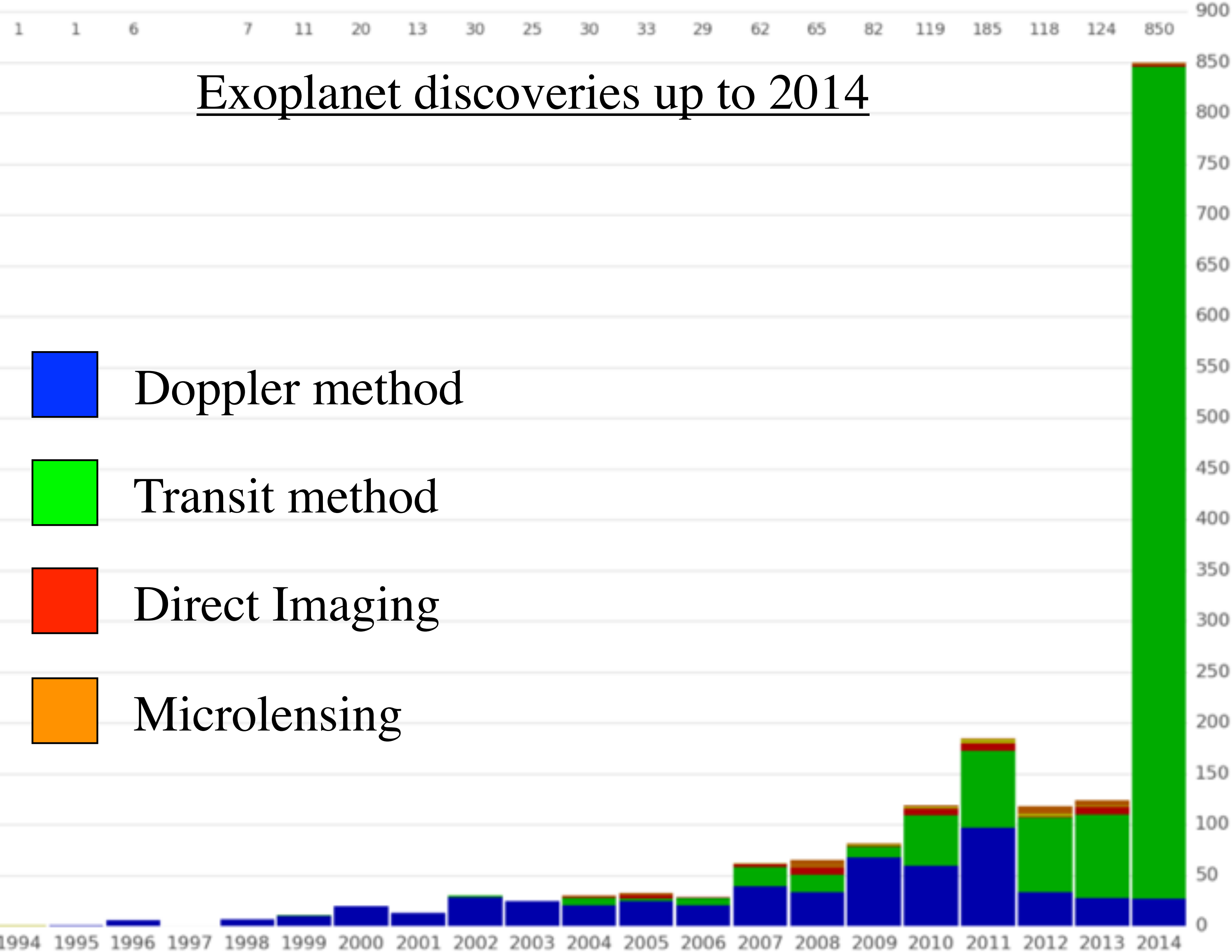


- A transit is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius.
  - best seen edge-on

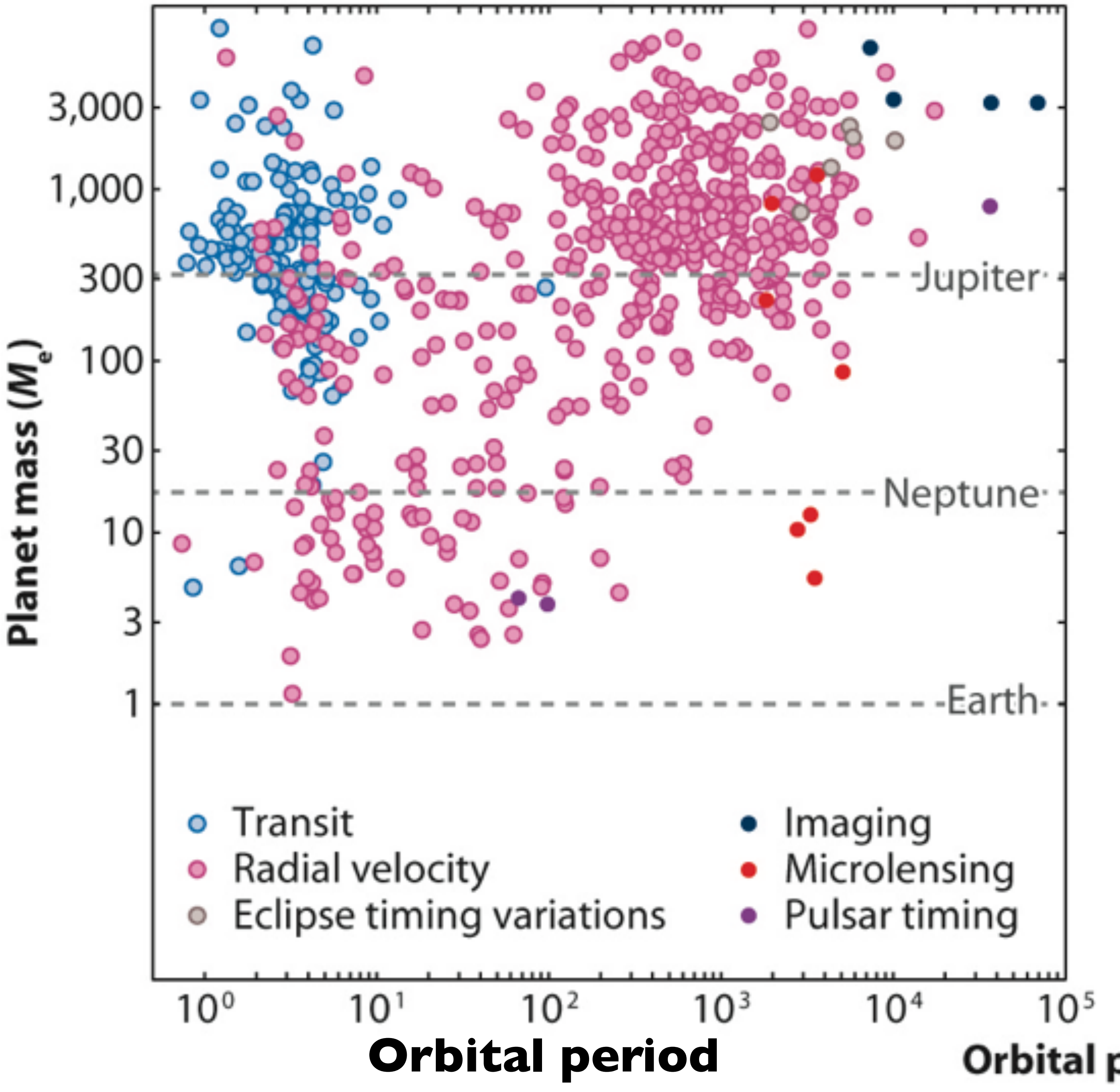
Gravitational lensing Technique



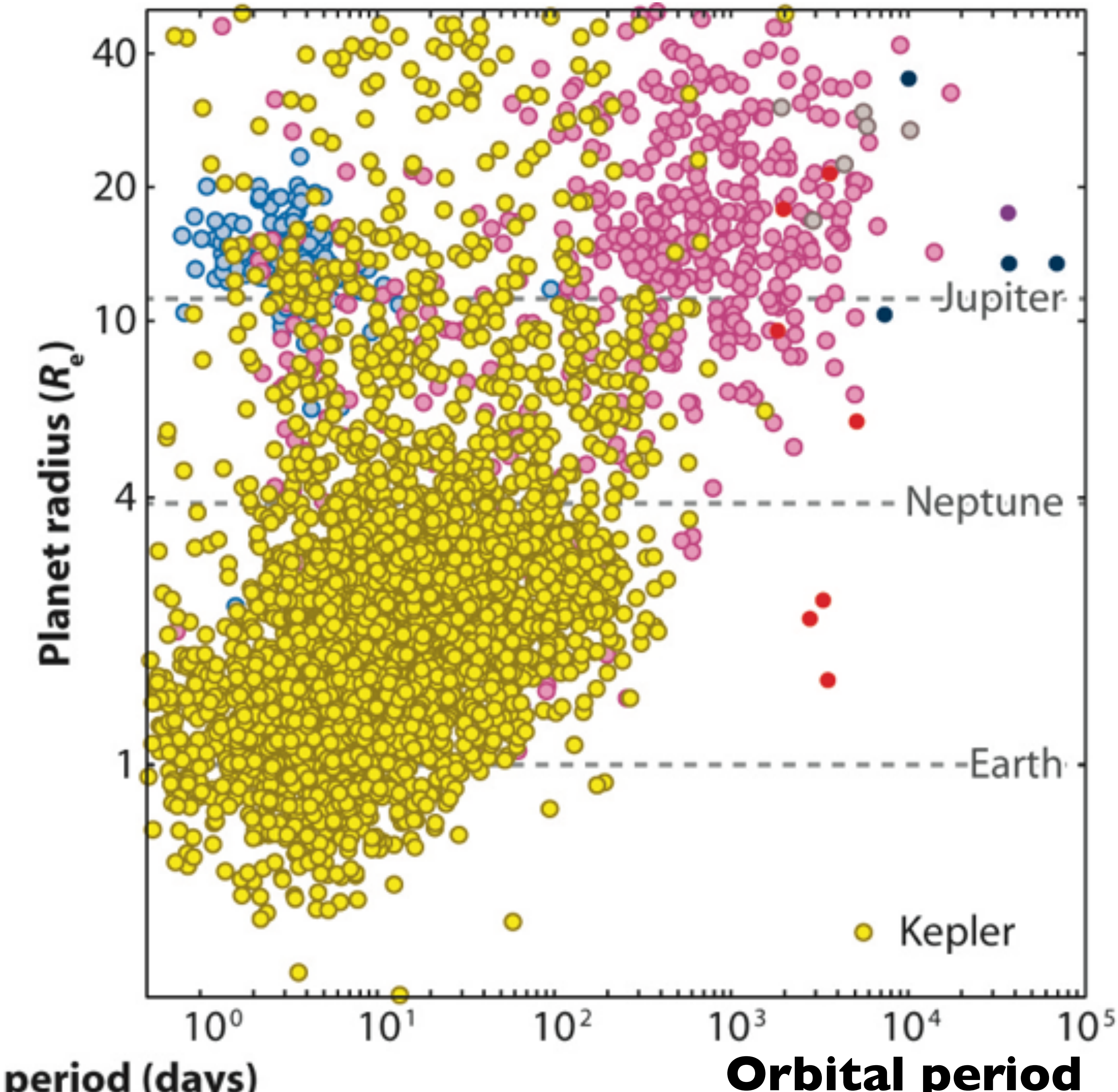



Exoplanet discoveries up to 2014
Doppler method
Transit method
Direct Imaging
Microlensing
1 1 6 7 11 20 13 30 25 30 33 29 62 65 82 119 185 118 124 850
1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014
0 50 100 150 200 250 300 350 400 450 500 550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

All methods have strong selection effects



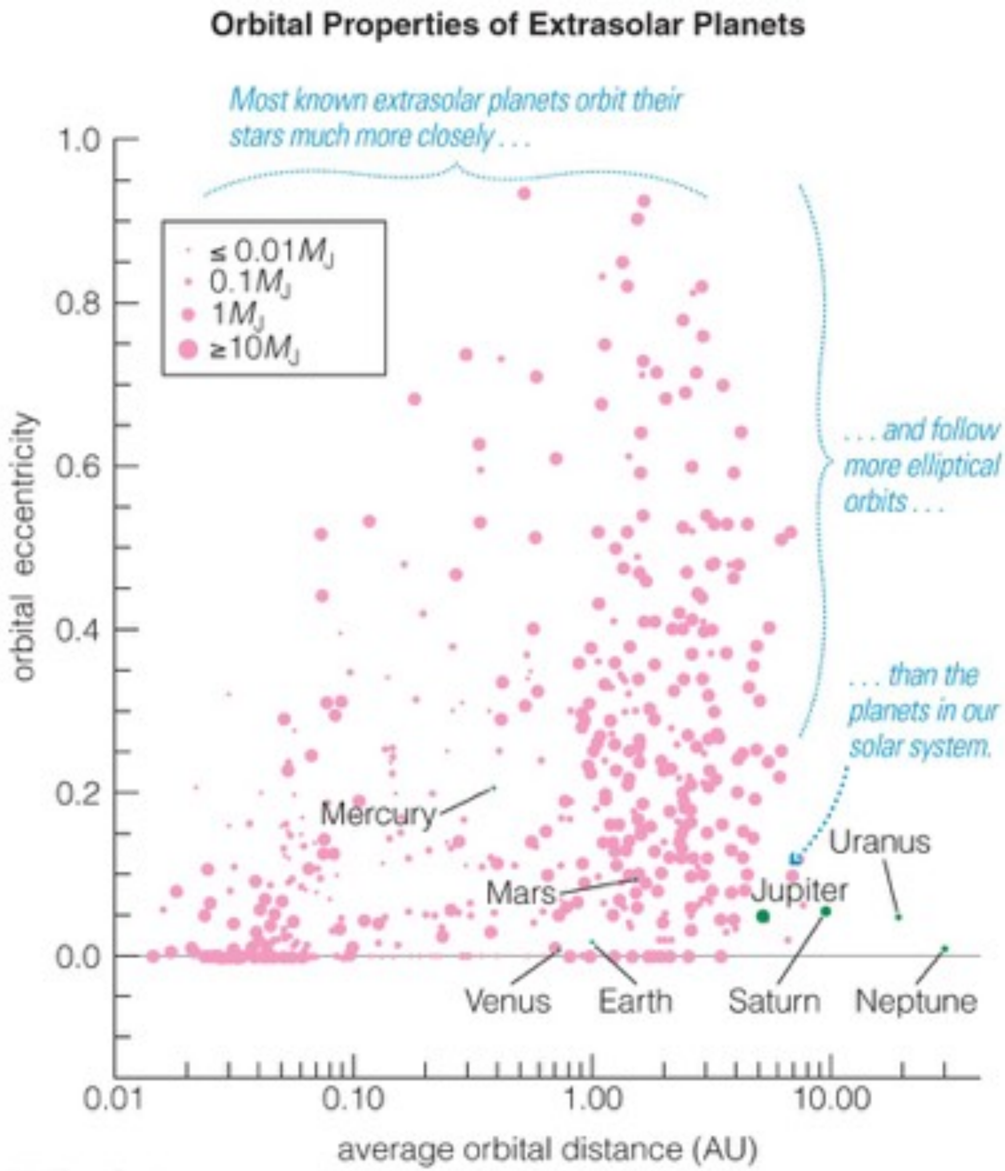
Orbital period



...and are good at measuring different things

Kepler is excellent at measuring radius; not necessarily mass.

What properties of extrasolar planets can we measure?

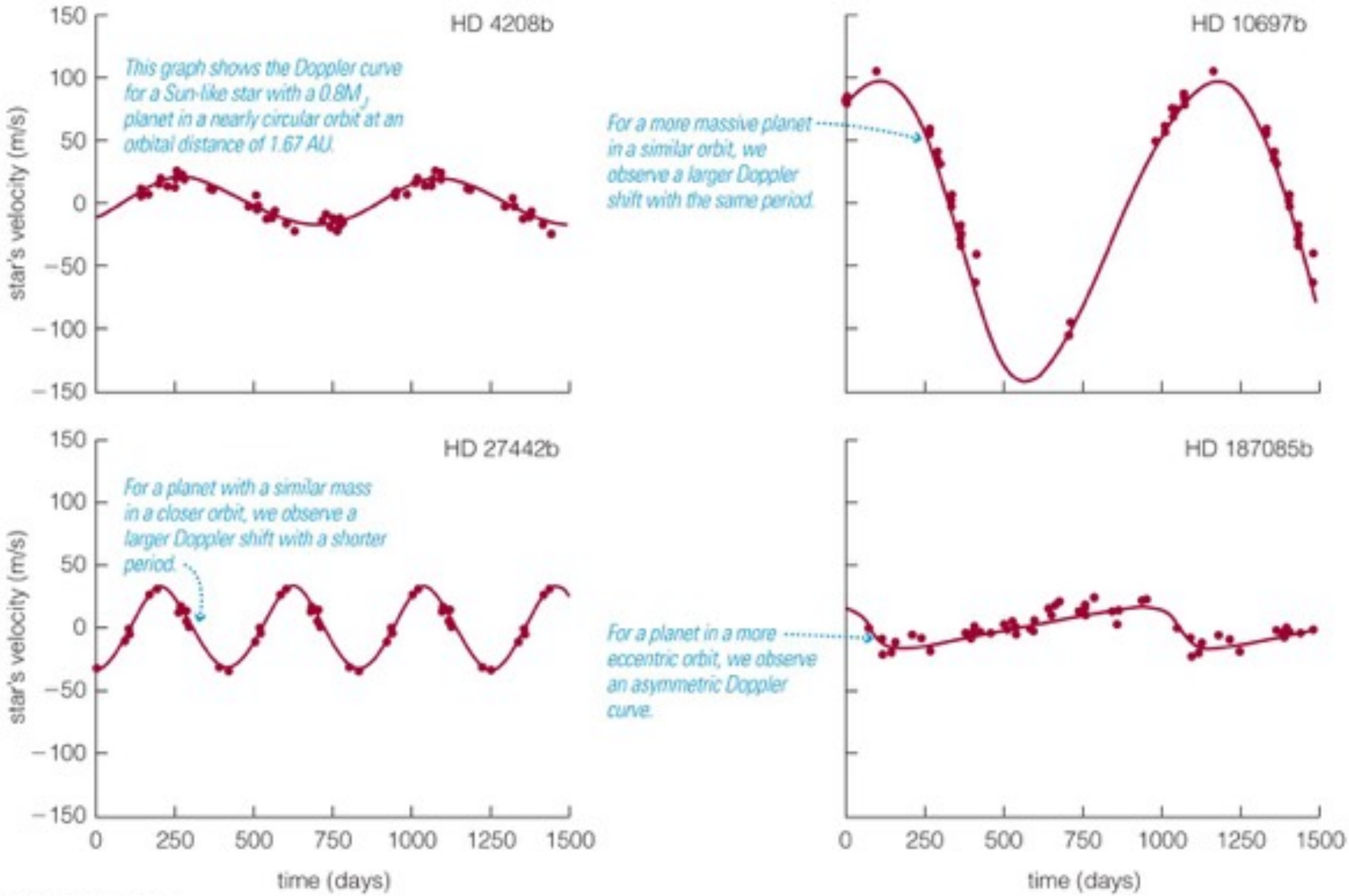


Measurable Properties

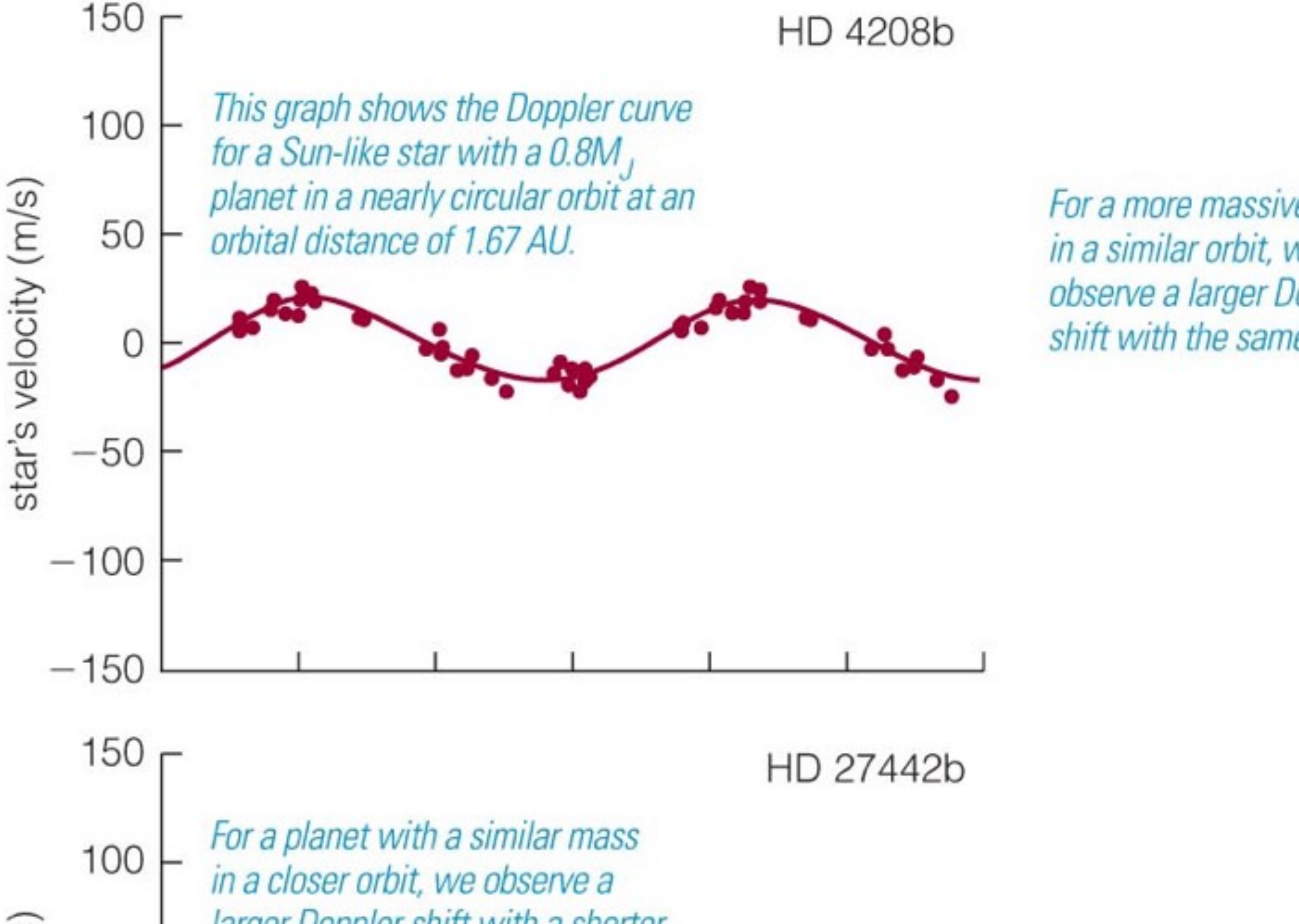
- Orbital period, distance, and shape (eccentricity)
- Planet mass, size, and density
- Atmospheric properties (sometimes)

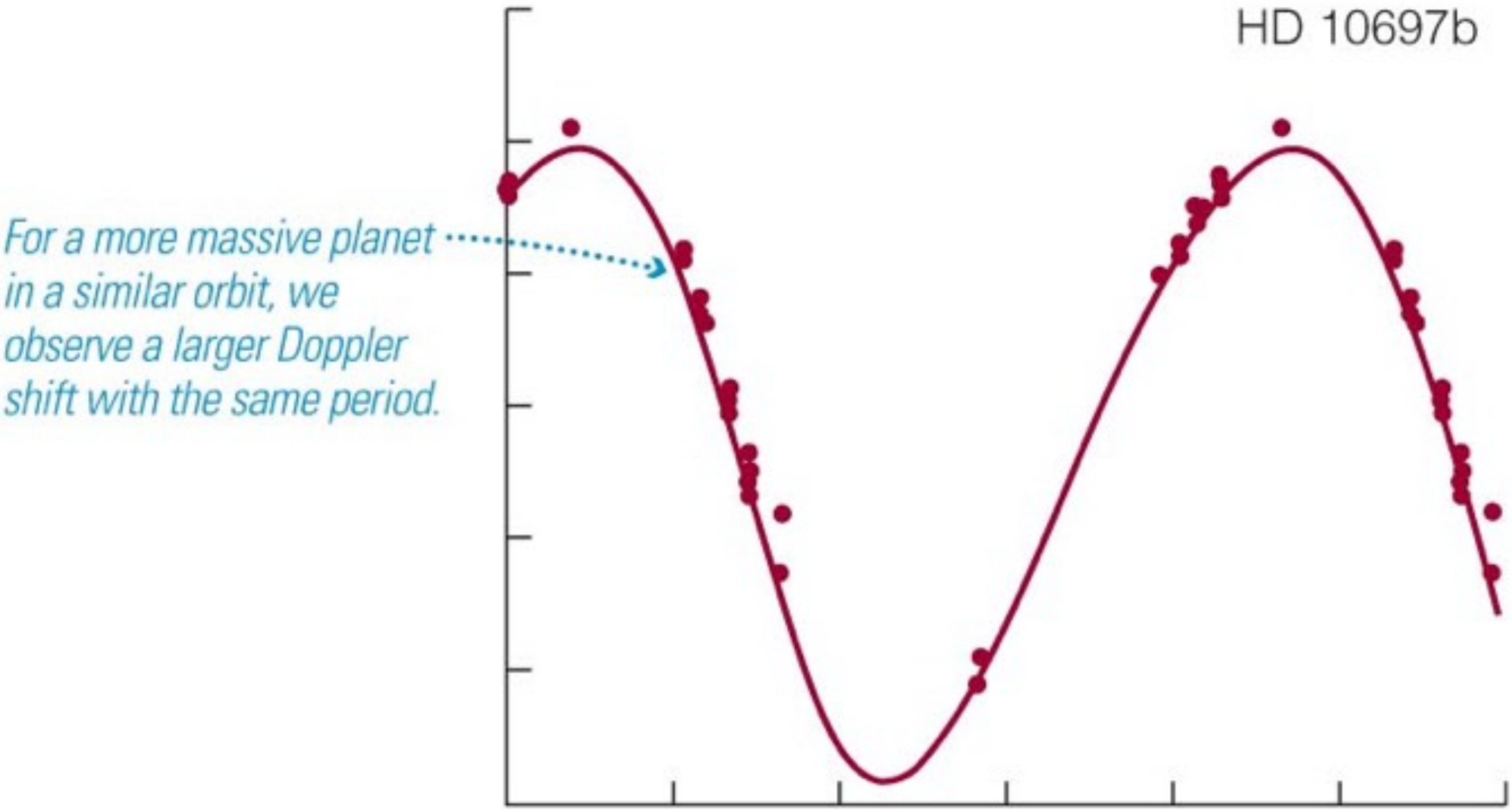
Exoplanet app
gives you scientific data
for thousands of exoplanets

What can Doppler shifts tell us?

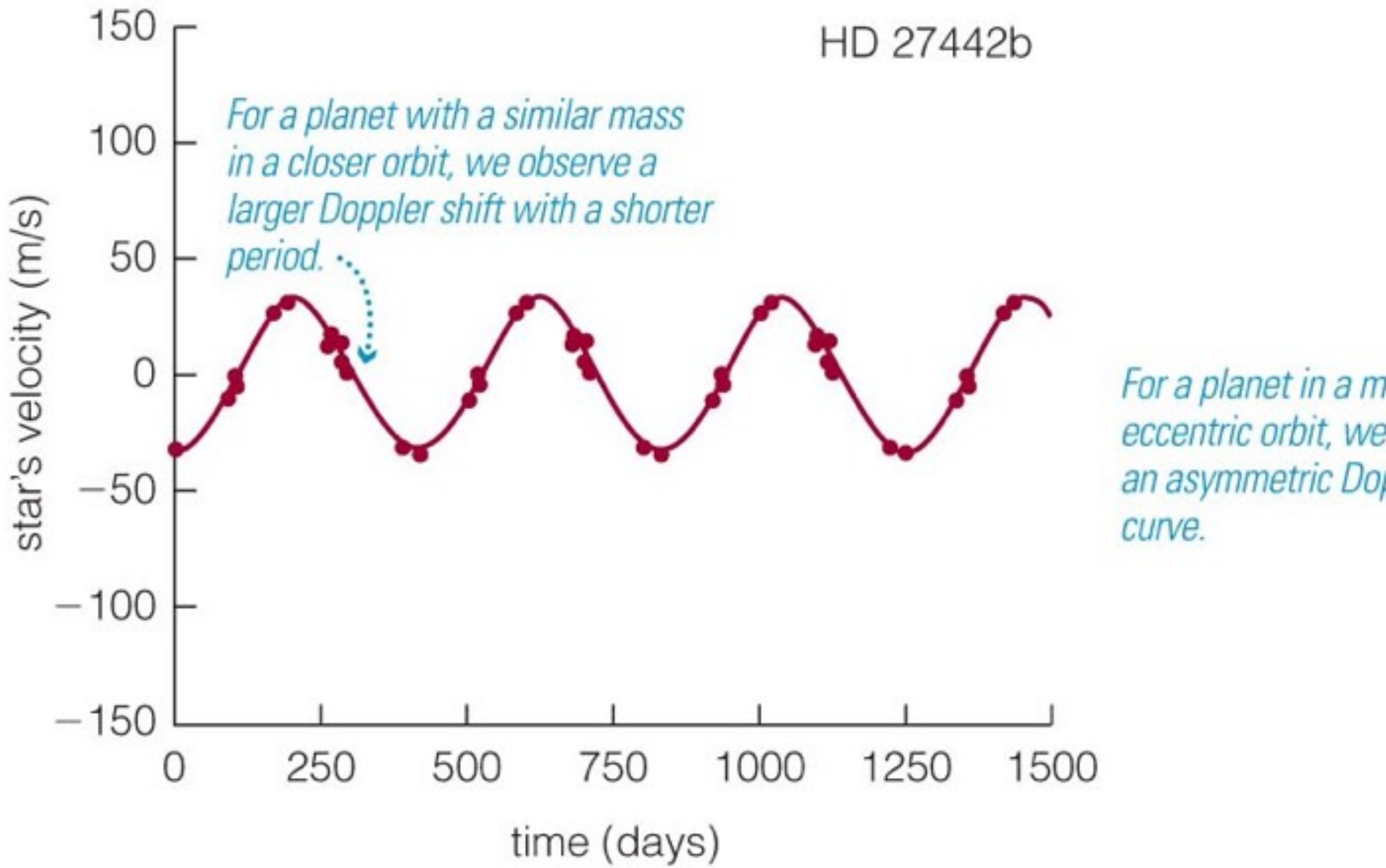


- Doppler shift data tell us about a planet's mass and the shape of its orbit.

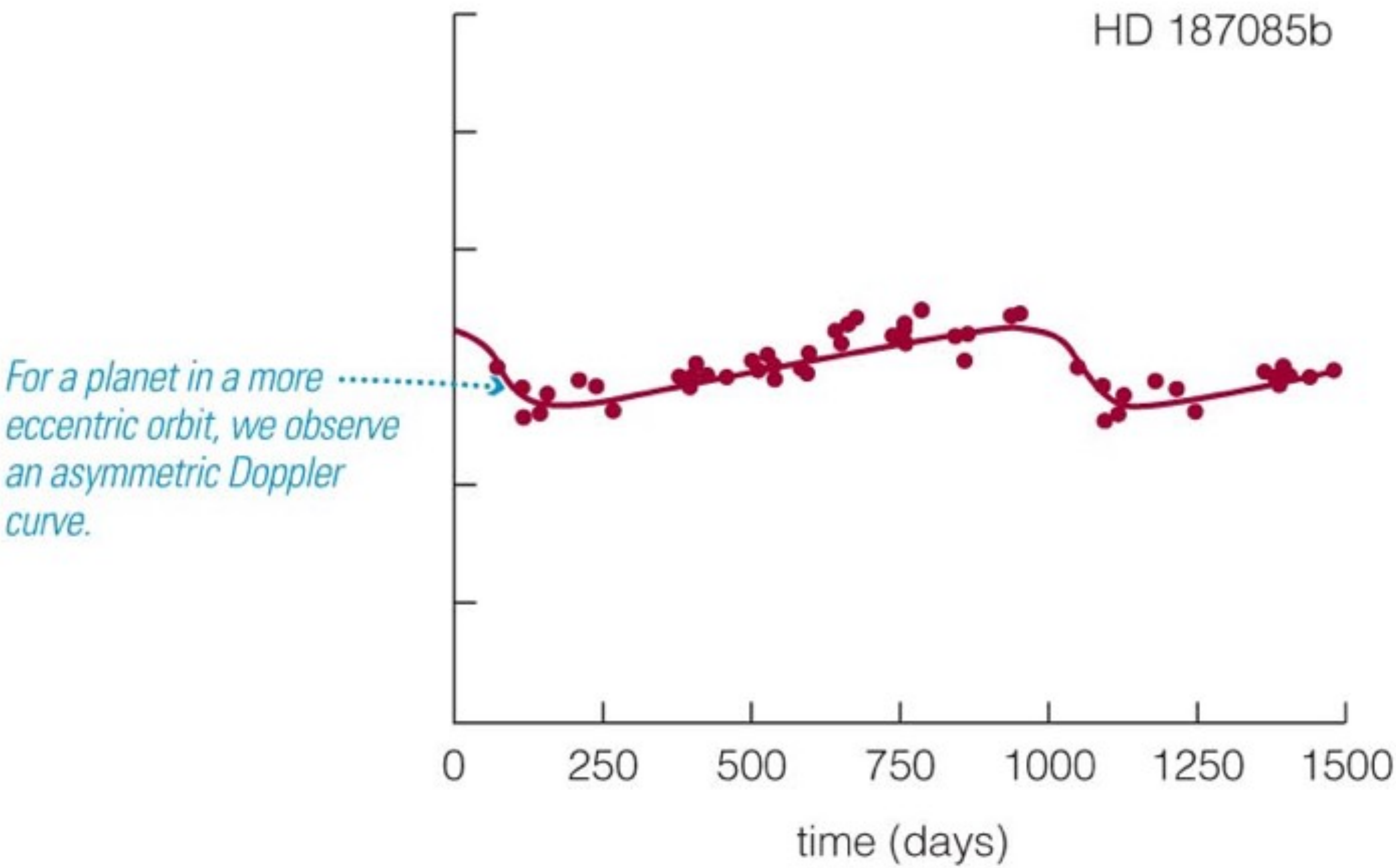

HD 4208b
150
100
50
0
−50
−100
−150
star's velocity (m/s)
This graph shows the Doppler curve for a Sun-like star with a 0.8M_J planet in a nearly circular orbit at an orbital distance of 1.67 AU.
For a more massiv
in a similar orbit, w
observe a larger D
shift with the sam
HD 27442b
150
100
For a planet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

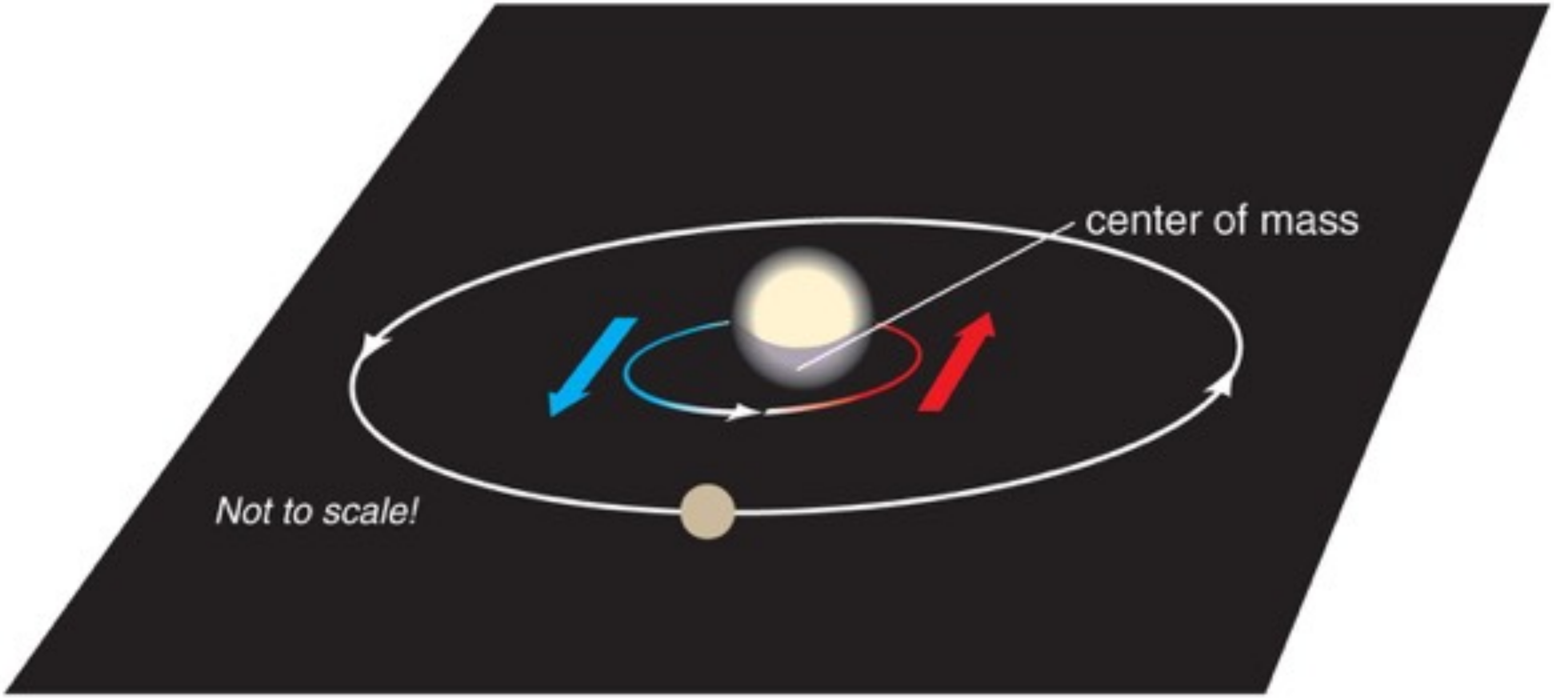

HD 187085b



HD 27442b
For a planet with a similar mass in a closer orbit, we observe a larger Doppler shift with a shorter period.
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 m
eccentric orbit, we
an asymmetric Dop
curve.


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

Planet Mass and Orbit Tilt

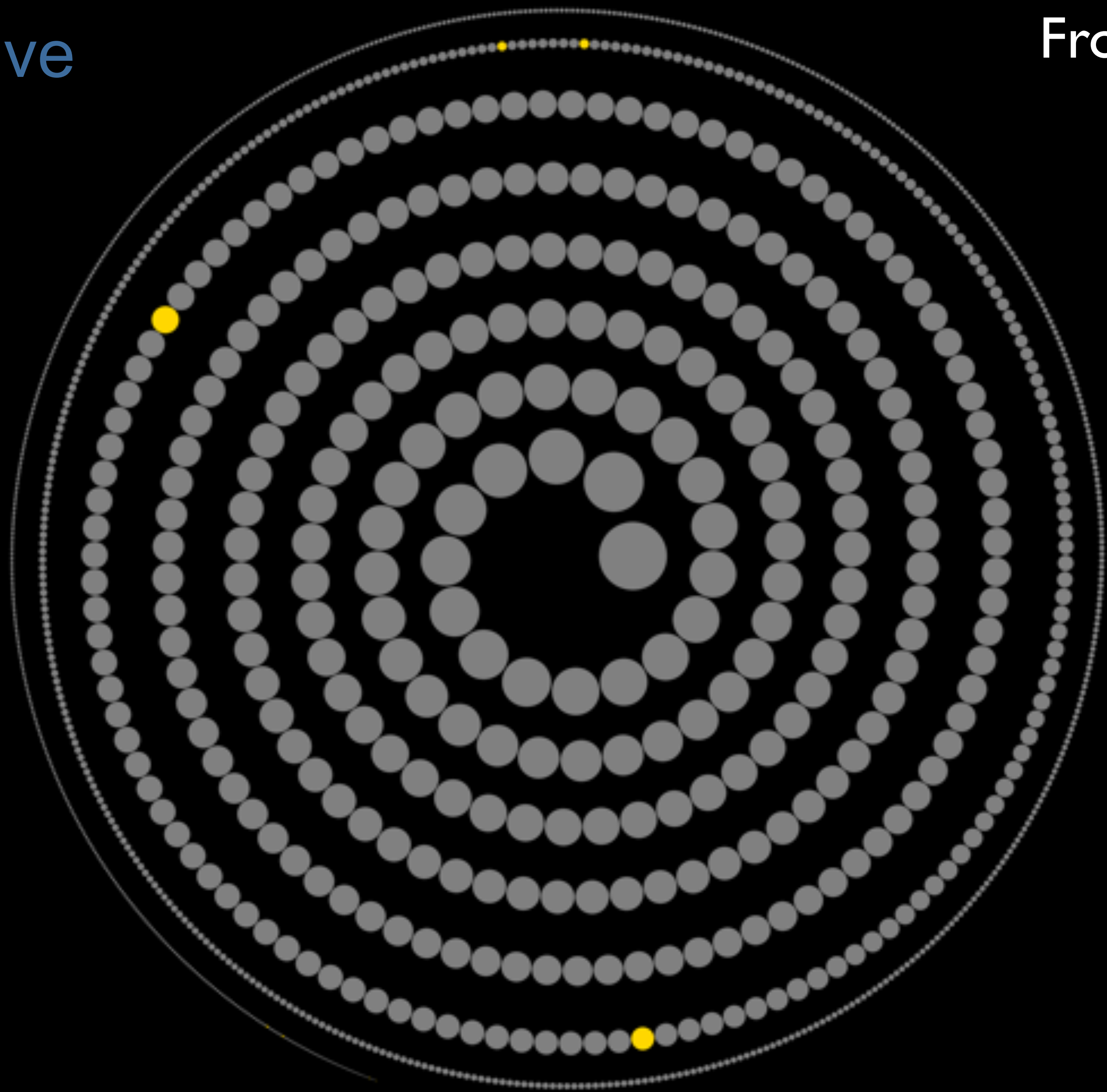


b We can detect a Doppler shift only if some part of the orbital velocity is directed toward or away from us. The more an orbit is tilted toward edge-on, the greater the shift we observe.

- 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

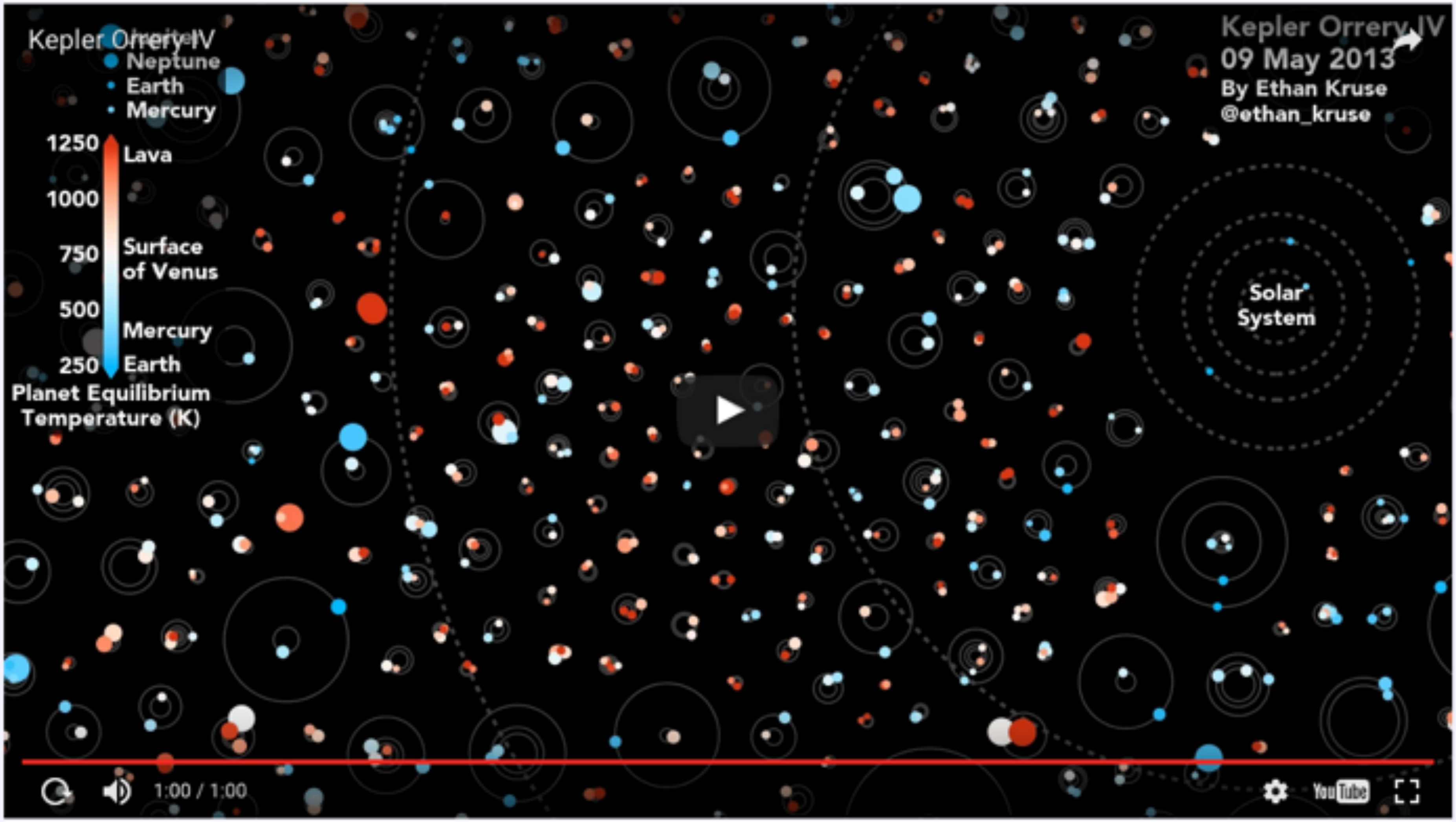


Astronomy Picture of the Day

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.

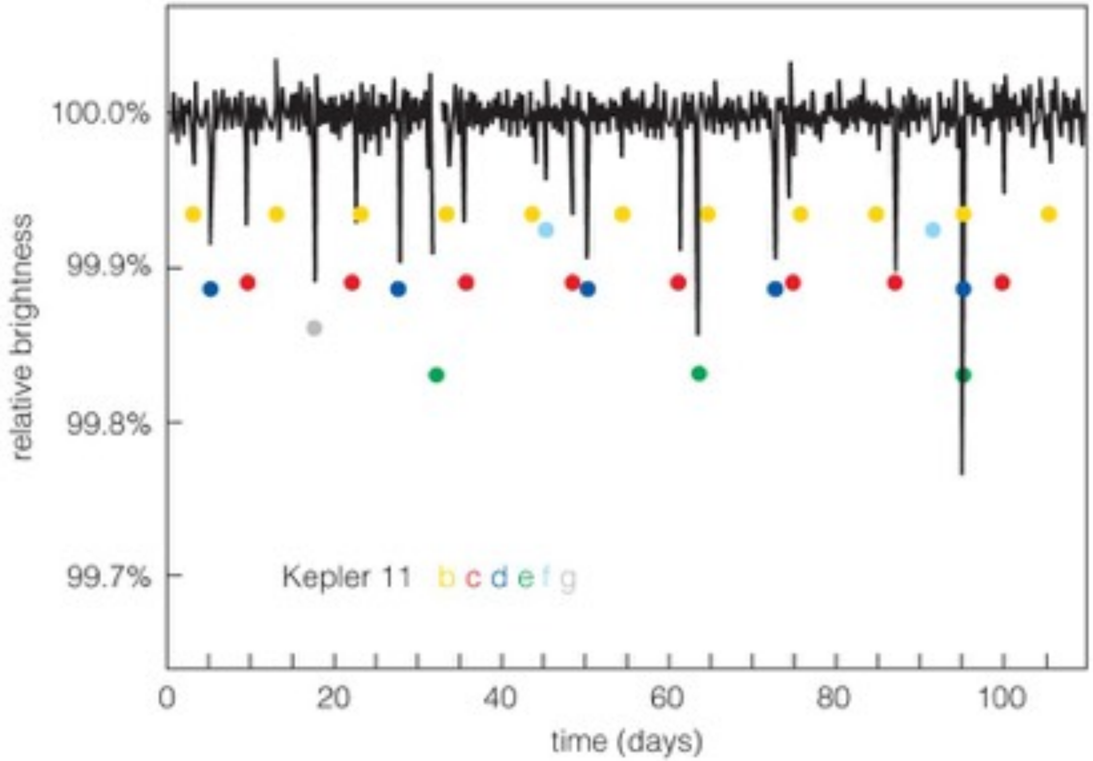
https://apod.nasa.gov/apod/ap151205.html

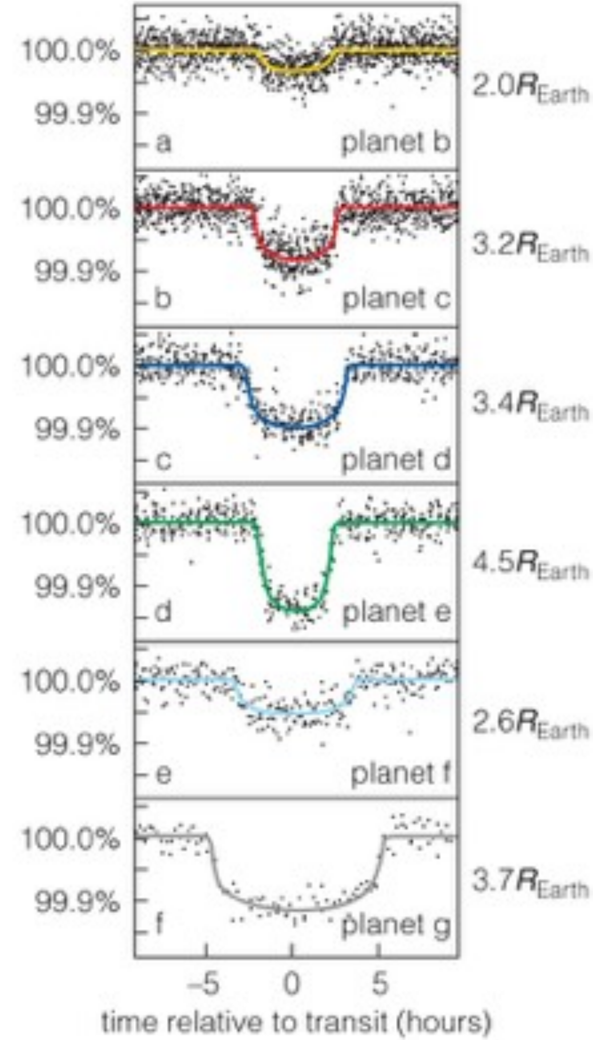
2015 December 5



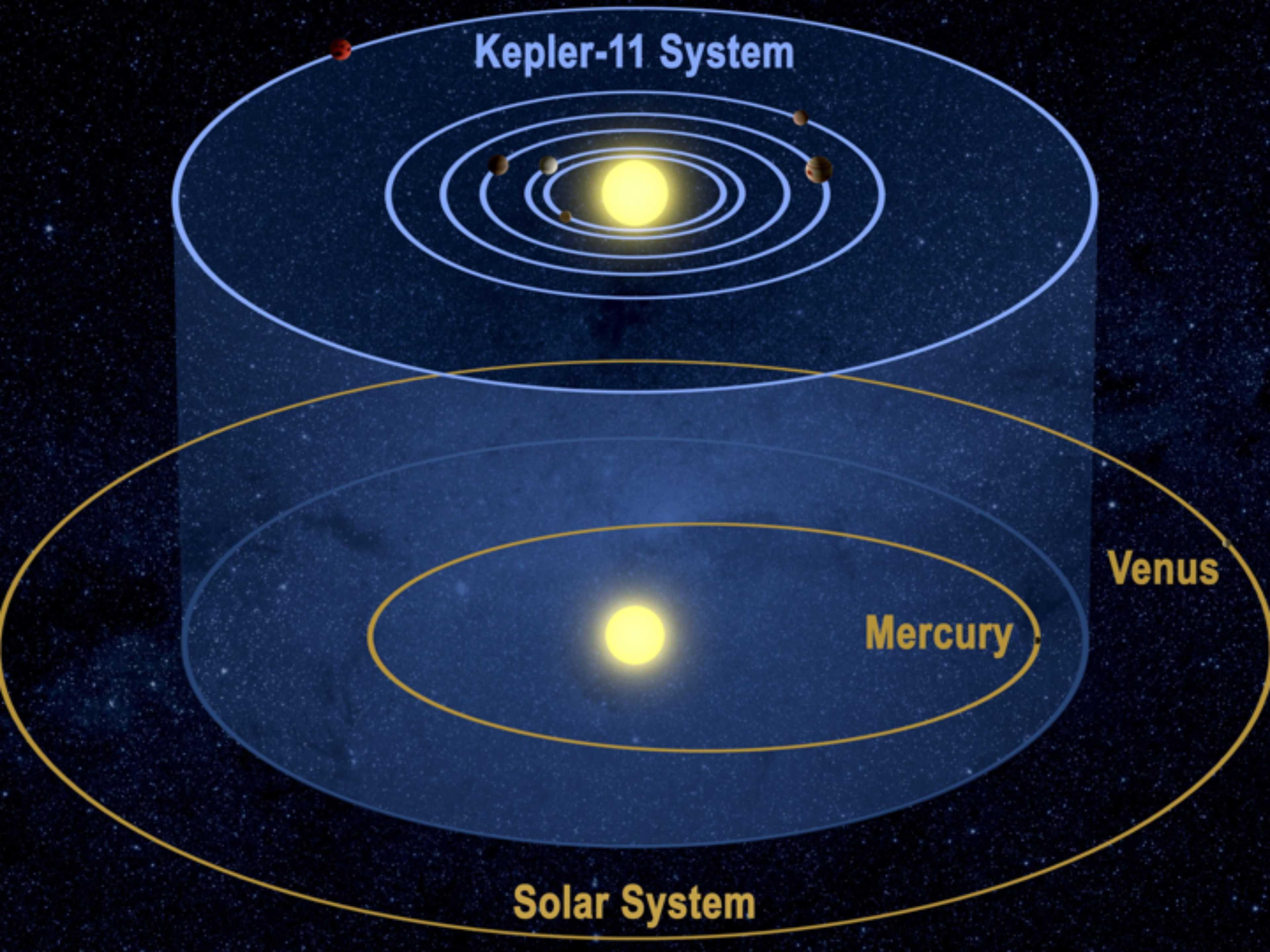
Kepler Orrery IV

The Kepler 11 system

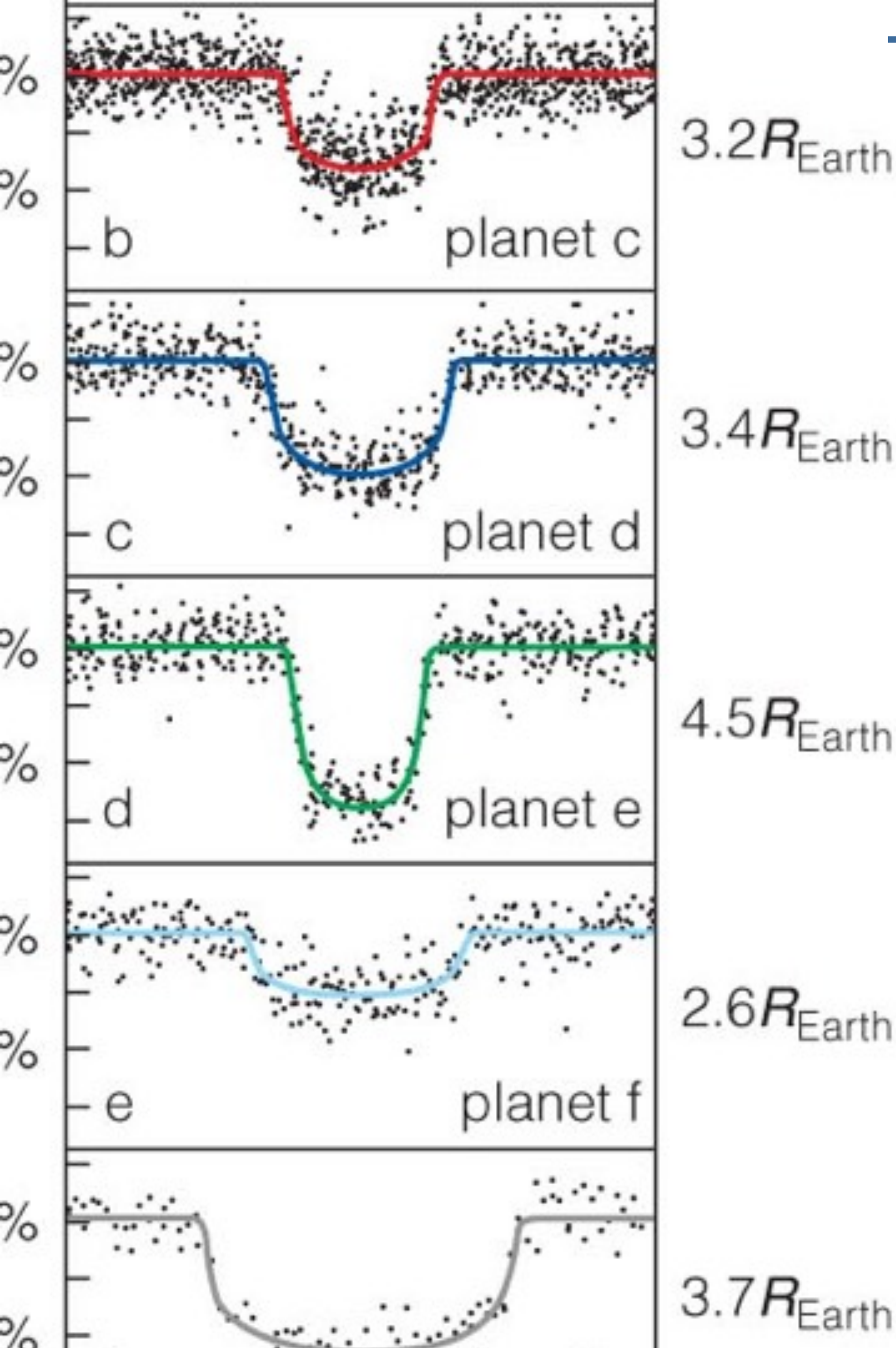




- The periods and sizes of Kepler 11's 6 known planets can be determined using transit data.
- These periods are short
  - longest Kepler g at 118 days


Kepler-11 System
Venus
Mercury
Solar System

The Kepler 11 system

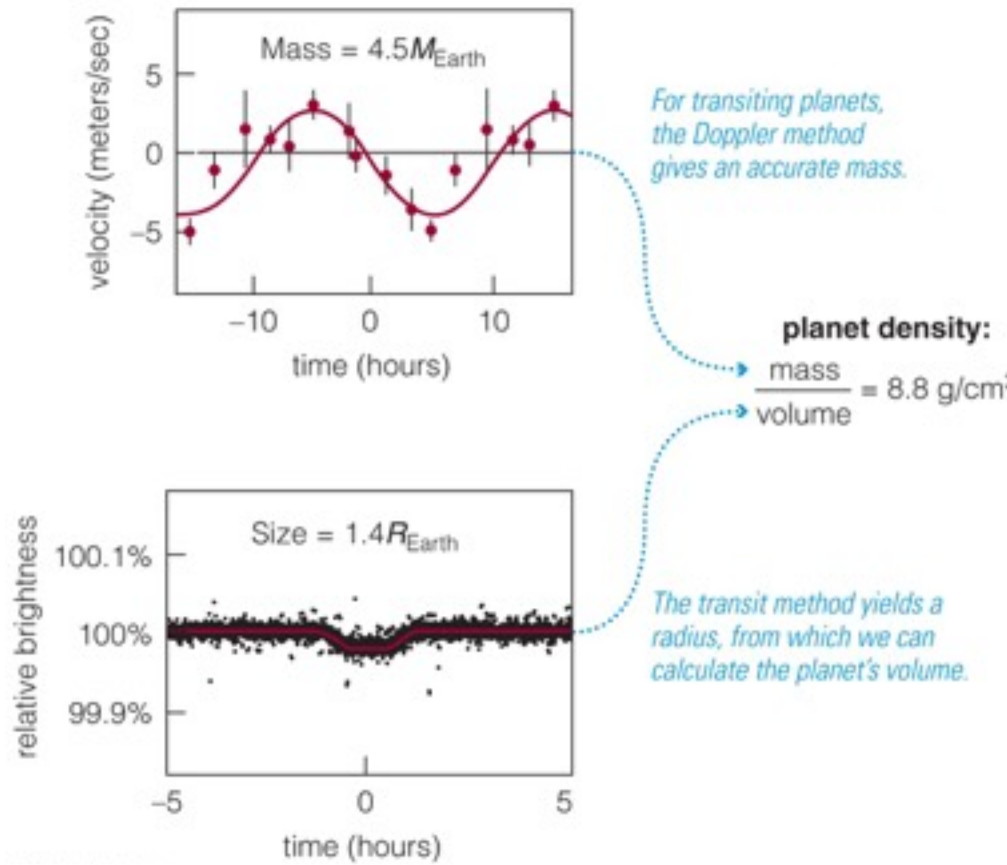


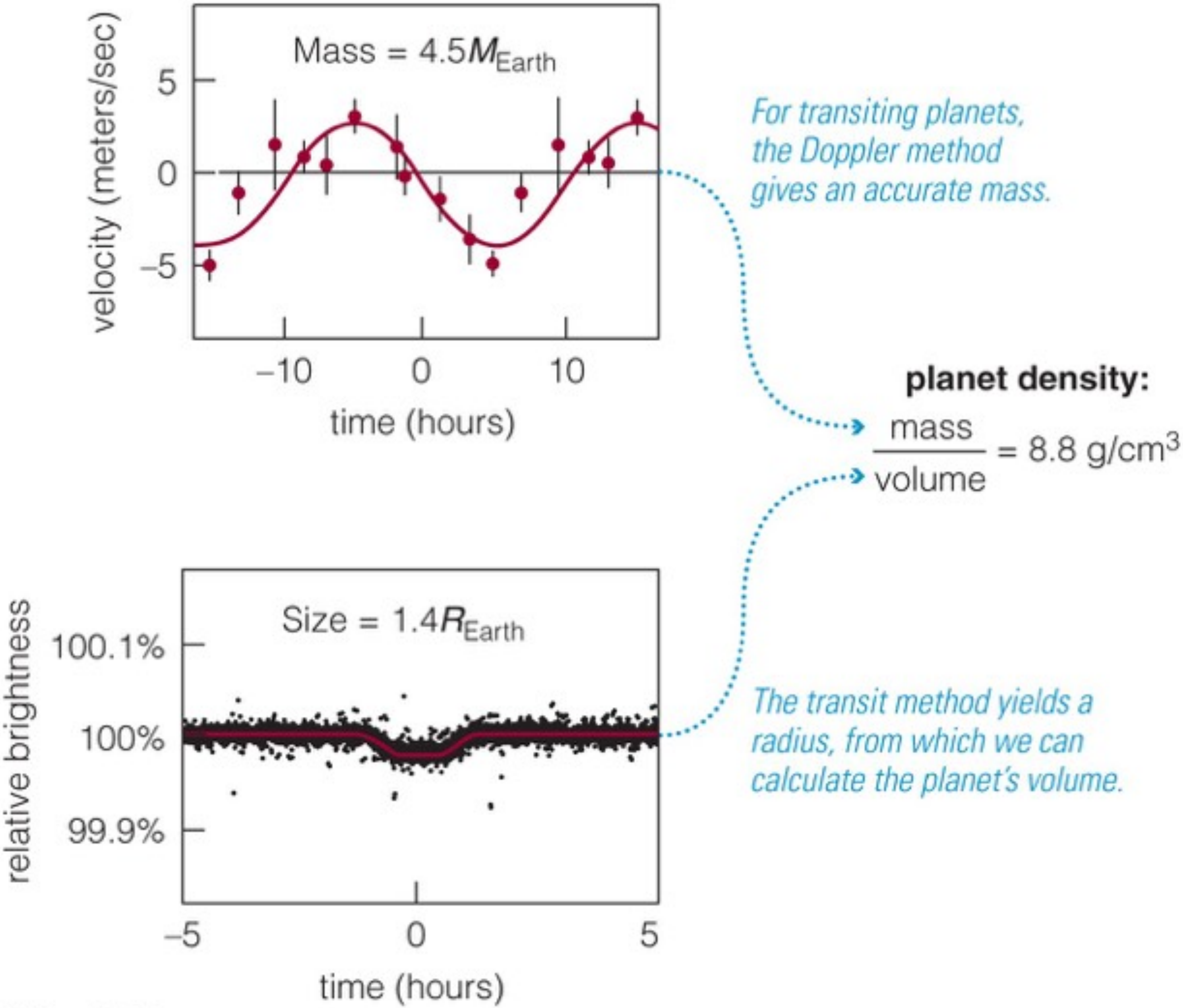
- Note sizes - all planets in this system a few times the size of the Earth!

- 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.

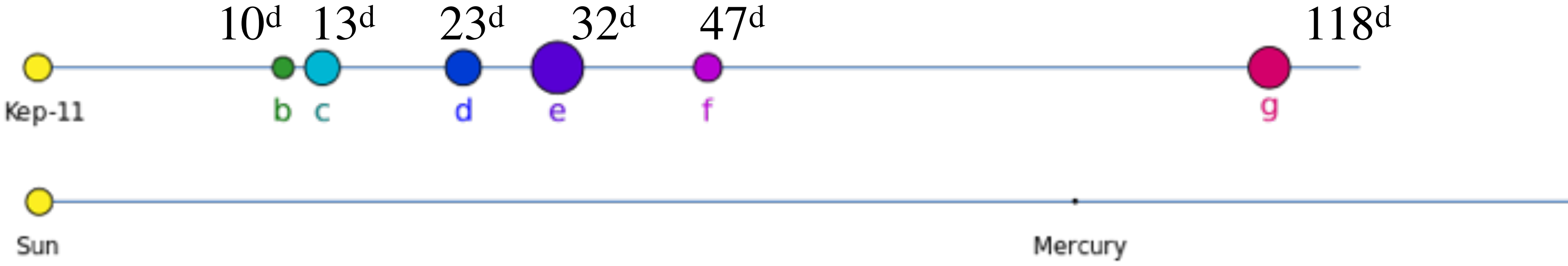




Mass = 4.5M_{Earth}
velocity (meters/sec)
5
0
−5
−10
0
10
time (hours)
For transiting planets, the Doppler method gives an accurate mass.
planet density:
$\frac{\text{mass}}{\text{volume}} = 8.8\ \text{g/cm}^3$
Size = 1.4R_{Earth}
relative brightness
100.1%
100%
99.9%
−5
0
5
time (hours)
The transit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

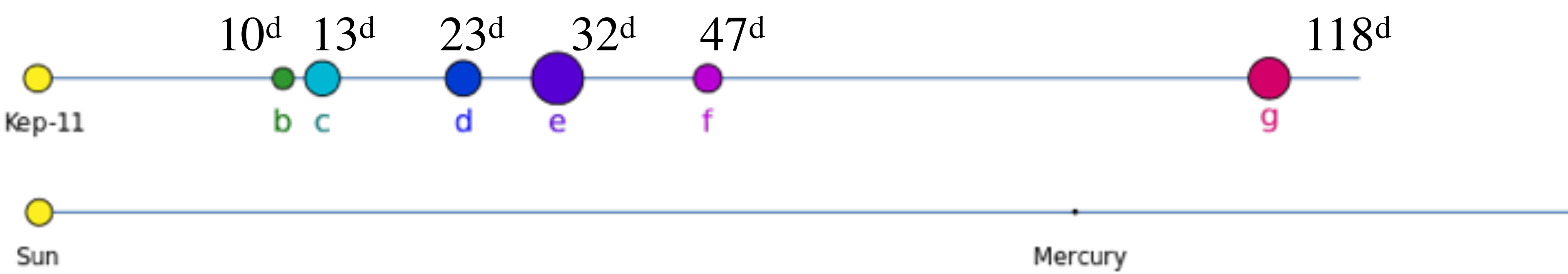
The Kepler 11 system

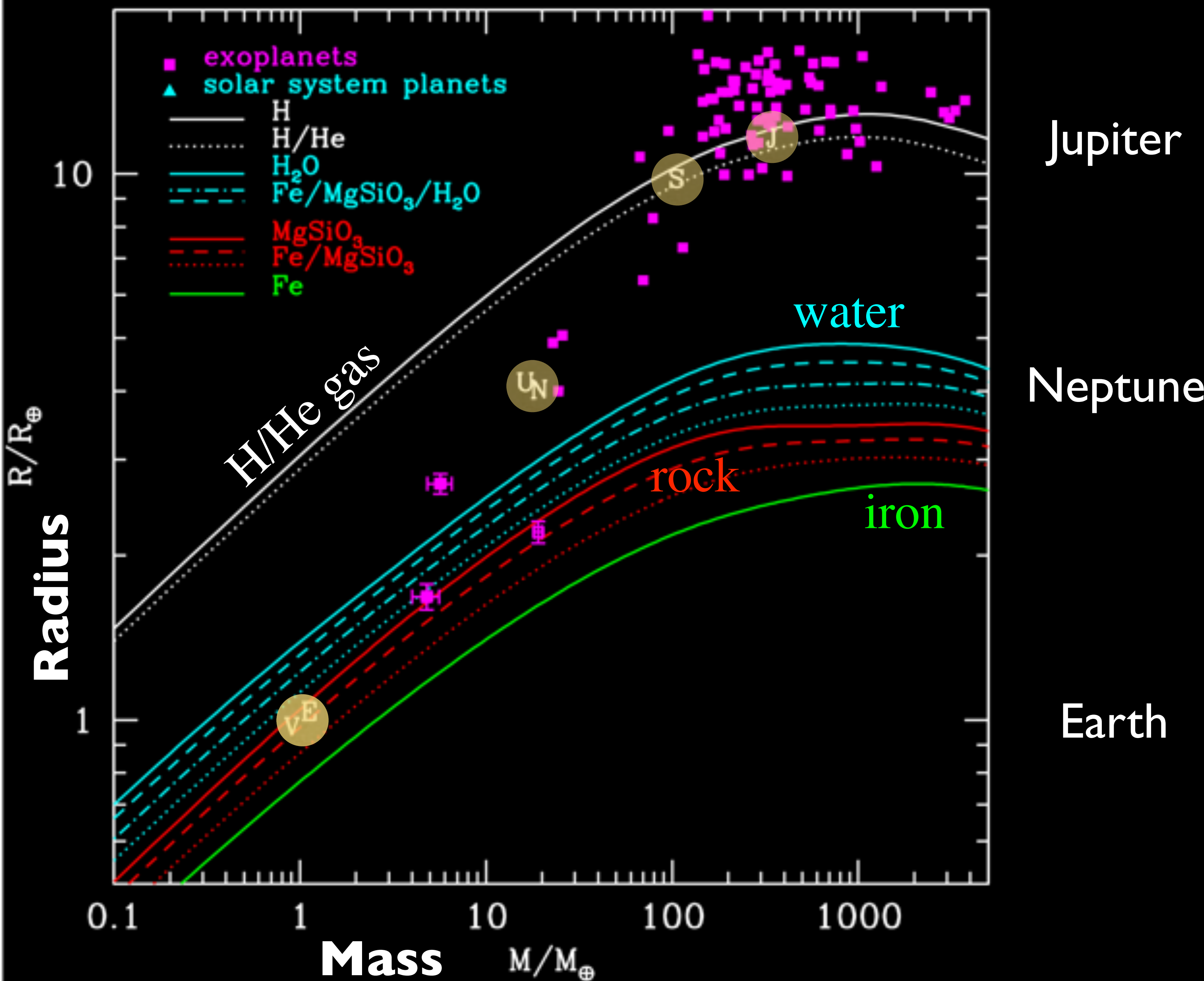
- The densities of all these planets are low
  - 0.6 - 1.7 g/cc (Typical of Jovian planets)
- What does this imply about the solar nebula hypothesis?



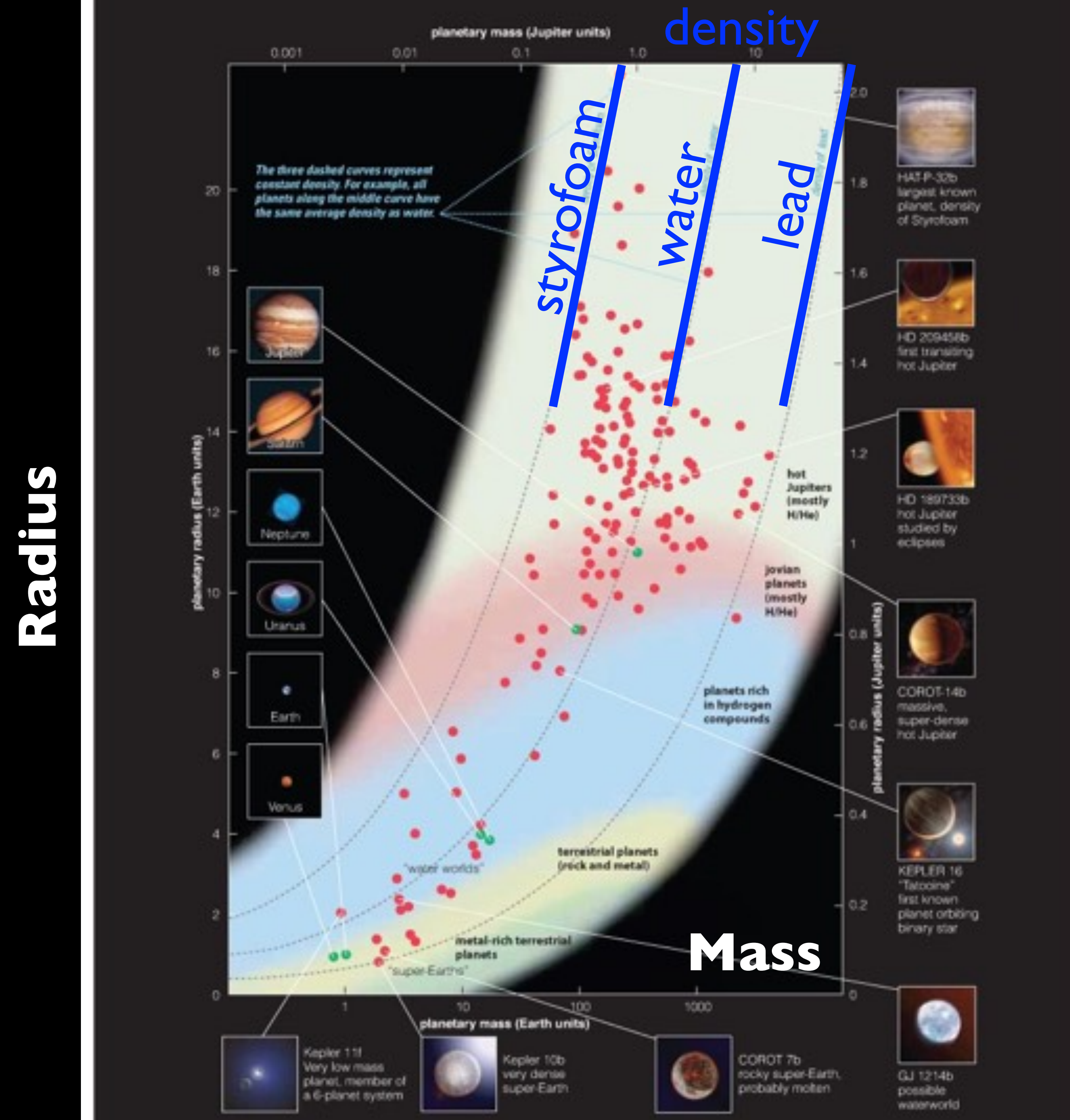
The Kepler 11 system

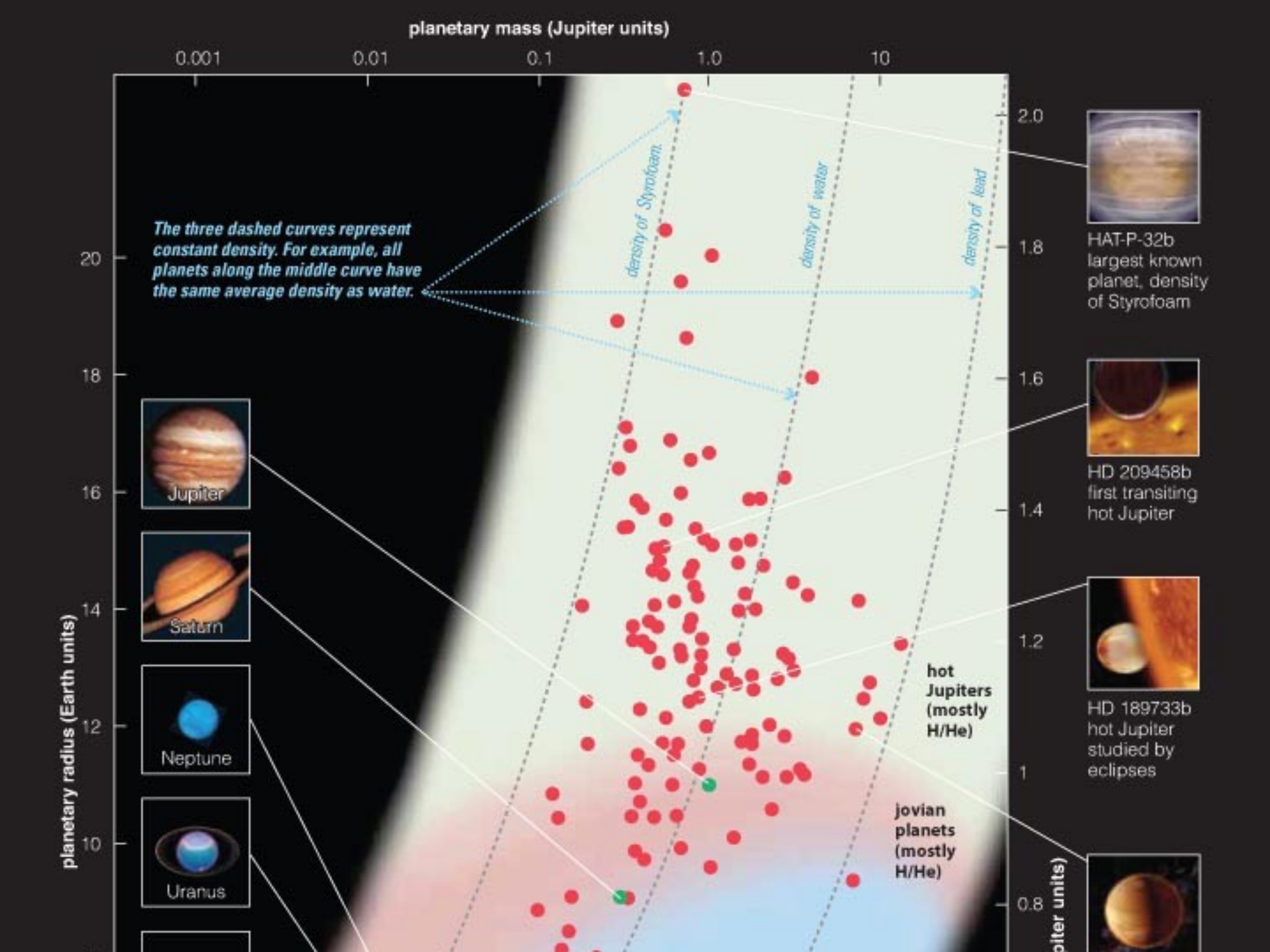
- The densities of all these planets are low
  - 0.6 - 1.7 g/cc
- Star is
  - 0.96 mass of sun
  - 1.07 radius of sun
  - 8.5 Gyr old (sun is 4.5 Gyr)
- Tightly packed system that is nevertheless stable
  - despite lack of orbital resonances



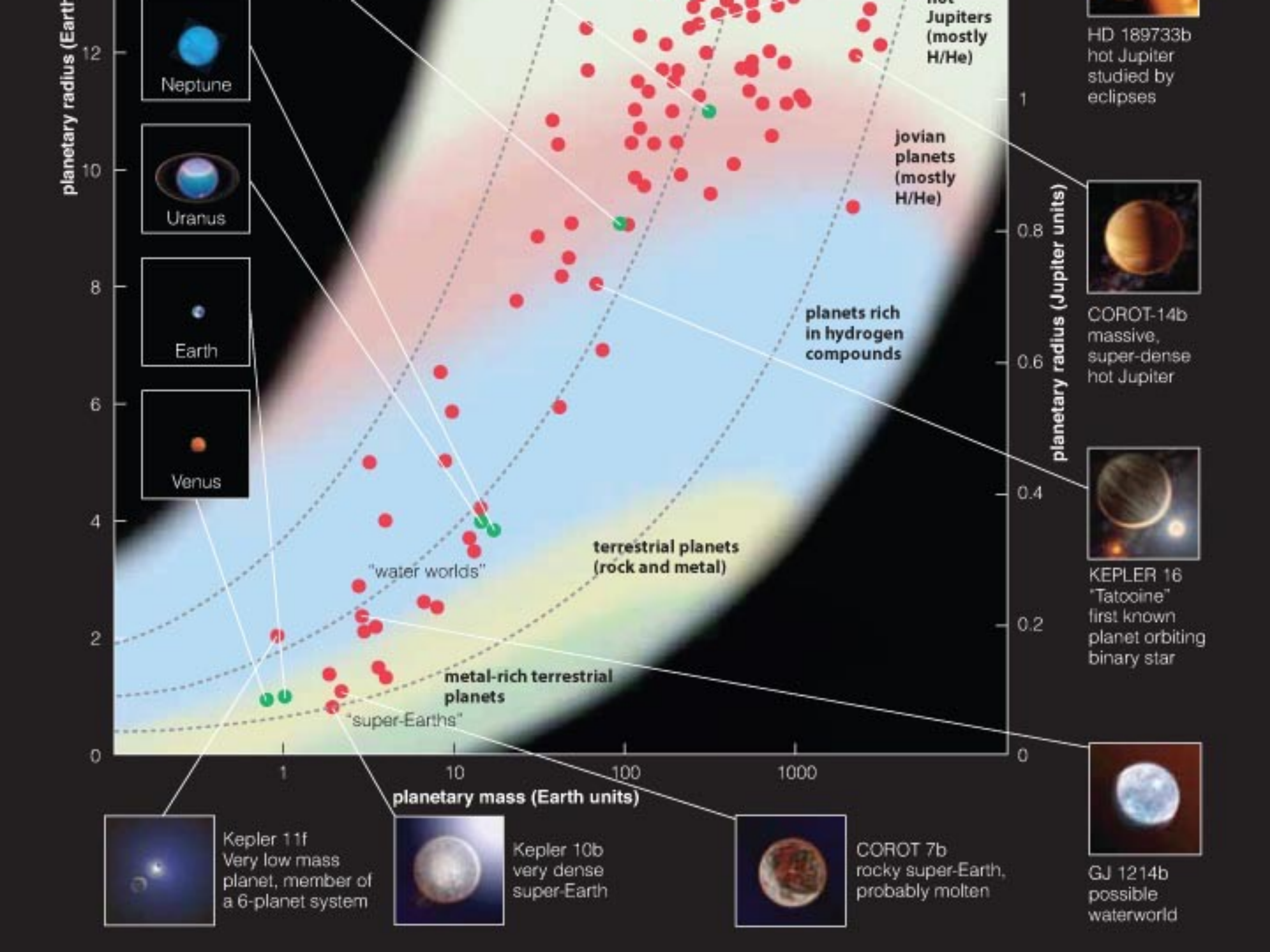

exoplanets
solar system planets
H
H/He
H_2O
$Fe/MgSiO_3/H_2O$
$MgSiO_3$
$Fe/MgSiO_3$
Fe
H/He gas
water
rock
iron
J
S
U N
V E
Jupiter
Neptune
Earth
10
1
0.1
1
10
100
1000
$R/R_\oplus$
Radius
Mass
$M/M_\oplus$

Exoplanet properties in general:
size vs. mass





planetary mass (Jupiter units)
0.001
0.01
0.1
1.0
10
planetary radius (Earth units)
20
18
16
14
12
10
2.0
1.8
1.6
1.4
1.2
1
0.8
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
hot Jupiters (mostly H/He)
jovian planets (mostly H/He)
HAT-P-32b largest known planet, density of Styrofoam
HD 209458b first transiting hot Jupiter
HD 189733b hot Jupiter studied by eclipses



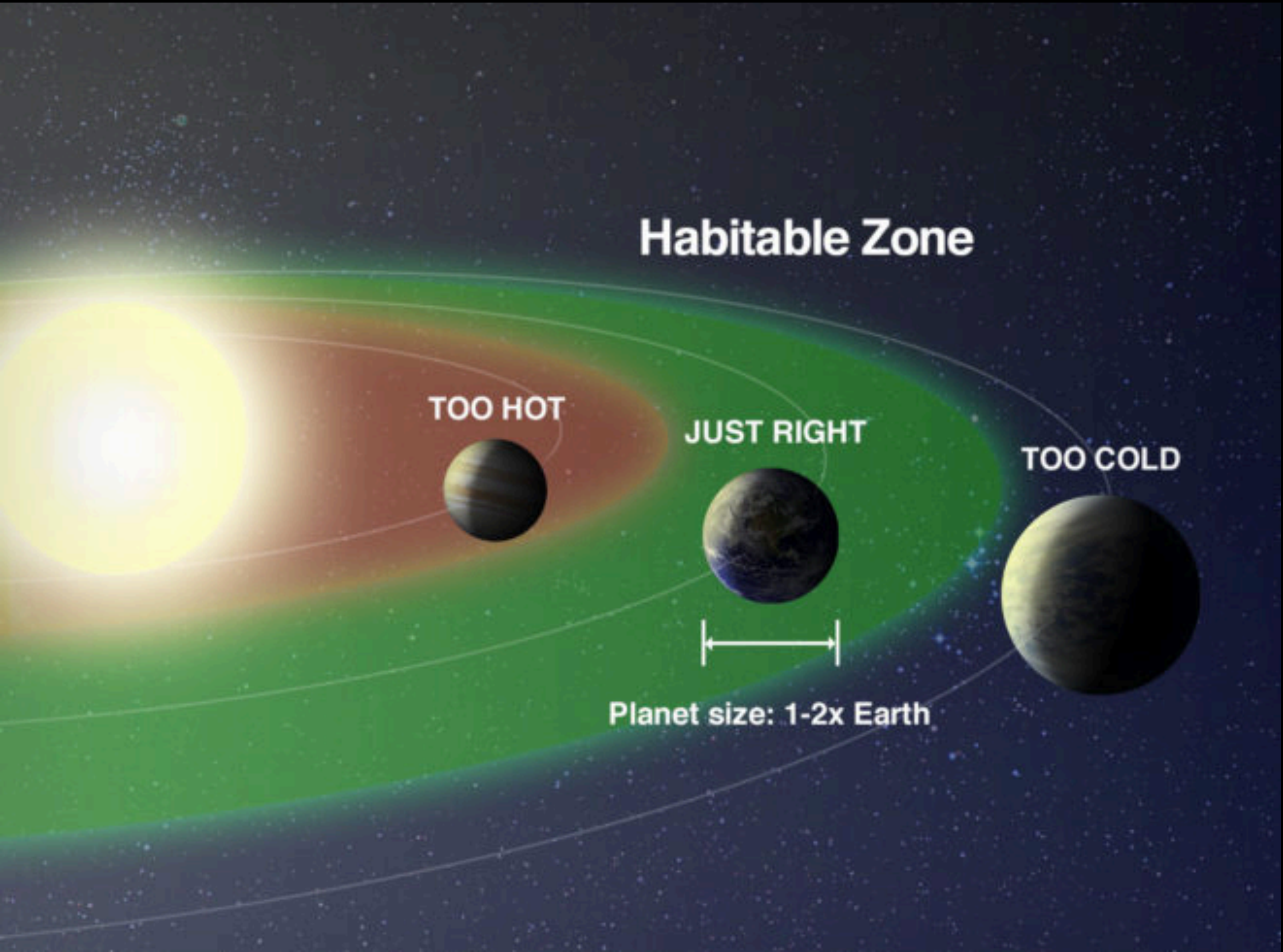
Jupiters
(mostly
H/He)
HD 189733b
hot Jupiter
studied by
eclipses
Neptune
Uranus
Earth
Venus
jovian
planets
(mostly
H/He)
COROT-14b
massive,
super-dense
hot Jupiter
planets rich
in hydrogen
compounds
KEPLER 16
"Tatooine"
first known
planet orbiting
binary star
terrestrial planets
(rock and metal)
"water worlds"
metal-rich terrestrial
planets
"super-Earths"
planetary radius (Jupiter units)
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
10
12
1
10
100
1000
planetary mass (Earth units)
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

Like Luke Skywalker's planet "Tatooine" in *Star Wars*, Kepler-16b orbits a pair of stars. Depicted here as a terrestrial planet, Kepler-16b might also be a gas giant like Saturn. Prospects for life on this unusual world aren't good, as it has a temperature similar to that of dry ice. But the discovery indicates that the movie's iconic double-sunset is anything but science fiction.

NASA's Exoplanet Exploration Program. Jet Propulsion Laboratory, Pasadena CA.

Twice as big in volume as the Earth, HD 40307g straddles the line between "Super-Earth" and "mini-Neptune" and scientists aren't sure if it has a rocky surface or one that's buried beneath thick layers of gas and ice. One thing is certain, though: at eight times the Earth's mass, its gravitational pull is much, much stronger.

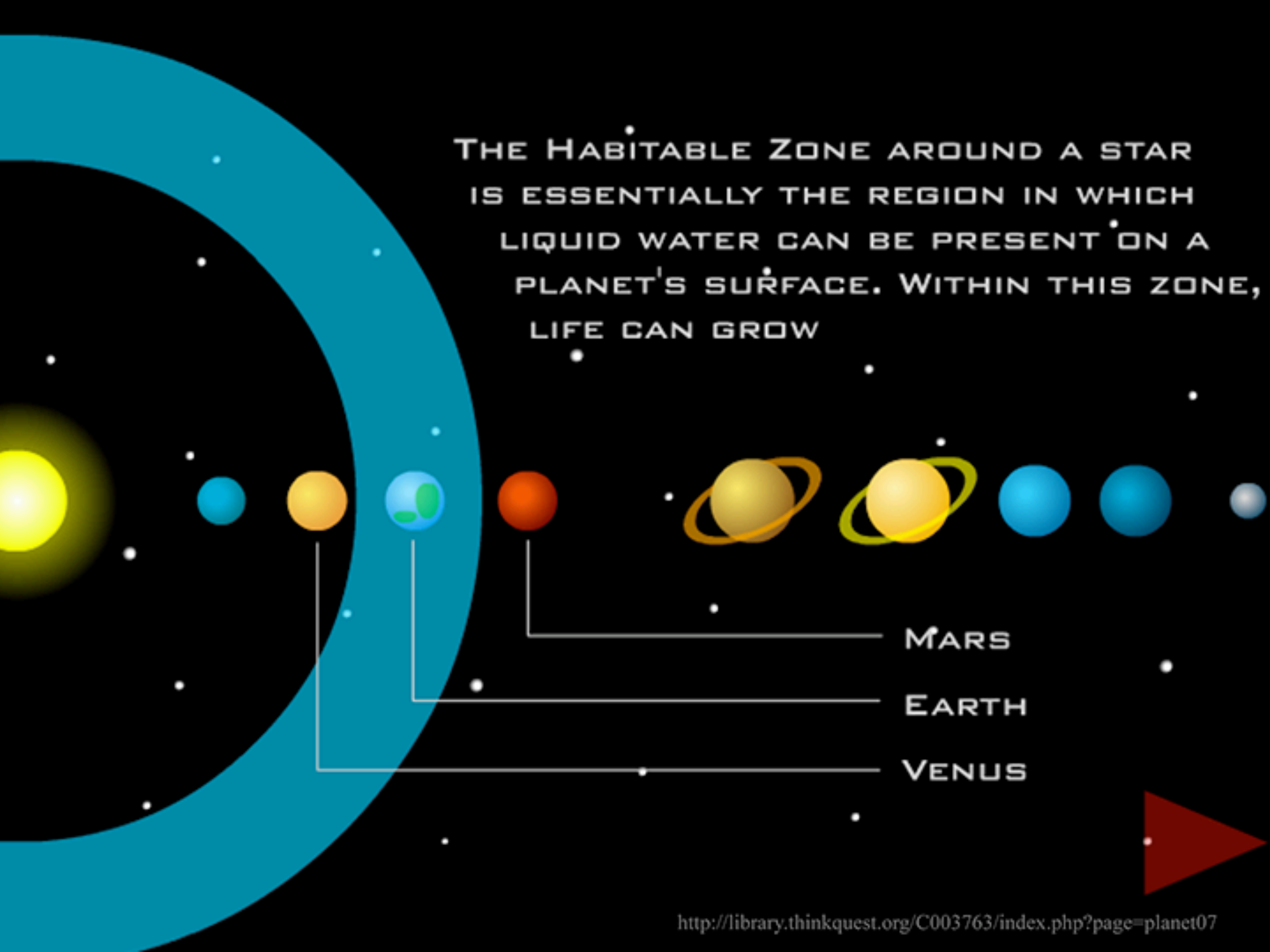
Might exoplanets be home to life?



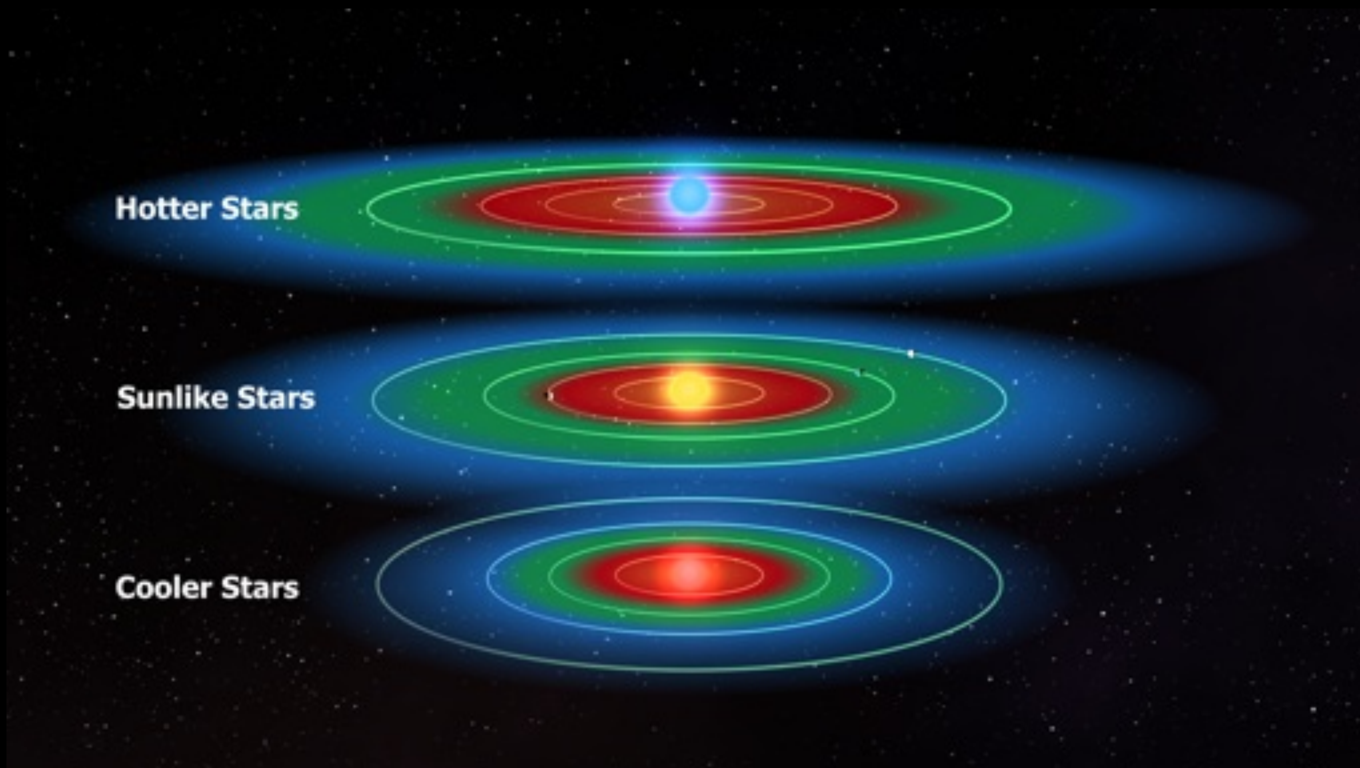
Habitable Zone

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


The Habitable Zone around a star
is essentially the region in which
liquid water can be present on a
planet's surface. Within this zone,
life can grow
Mars
Earth
Venus
http://library.thinkquest.org/C003763/index.php?page=planet07

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

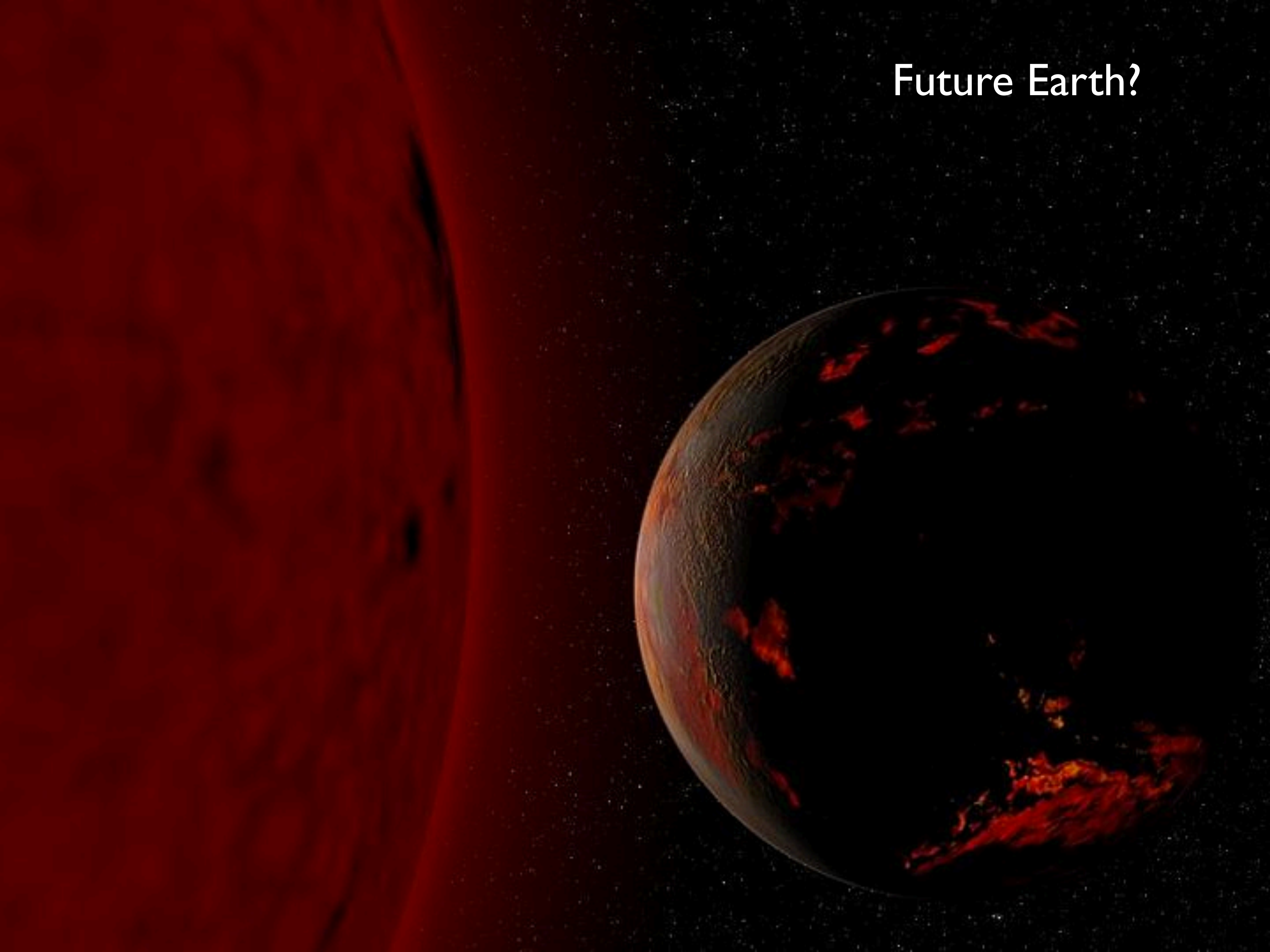


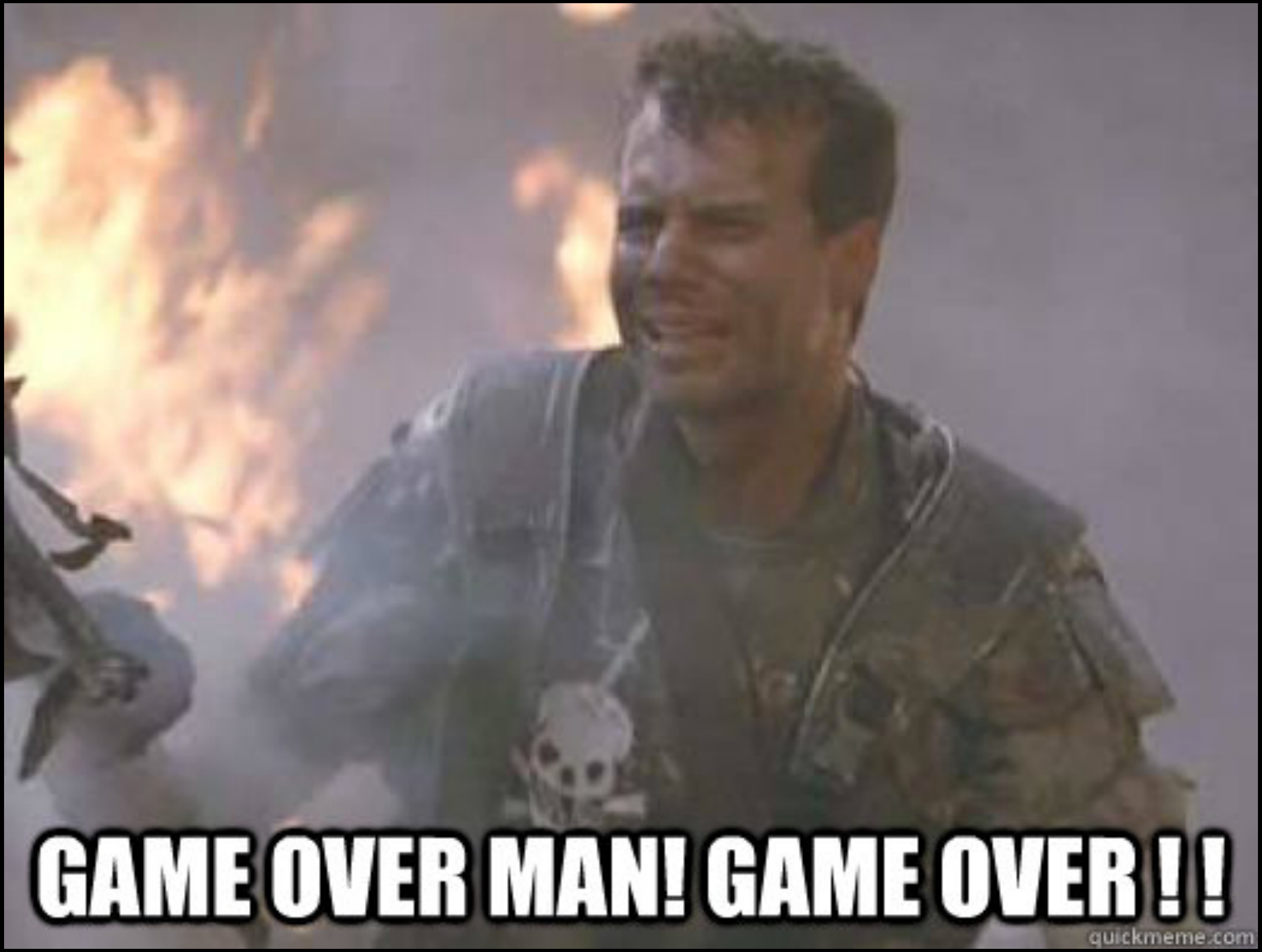
Stars evolve over billions of years, gradually becoming brighter - planets may slip out of the habitable zone as a result

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?




GAME OVER MAN! GAME OVER ! !
quickmeme.com