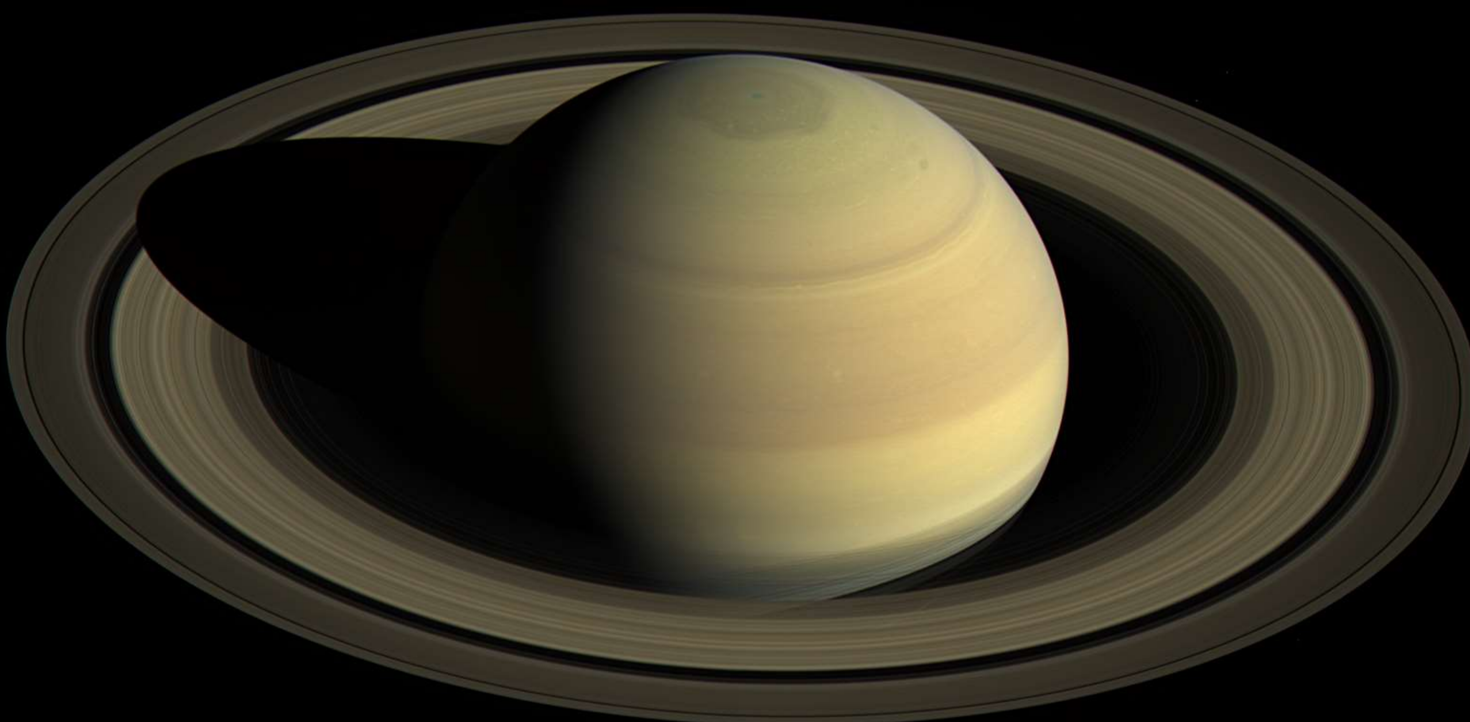
AST 2002
Introduction to Astronomy



A Few Quick Things…

E-mailing me: Must have AST2002 in the subject

Mary Hinkle, Graduate Teaching Assistant:

Office Hours: Mon 1:30-3:00pm. PSB 316

My office hours: Mon 3:00-4:00pm. PSB 308

Tue 3-4 pm. PSB 308

Last day to Drop Classes is Wednesday 21st March…

I am currently trying to get all grades onto Webcourses… Exam results should be up later today

Next Knights Under the Stars Event – Thu 22nd Mar 8:30-10:00pm

Opportunity to make up the 1% extra credit that was offered (if you haven't been yet, worth 2%)

What have we covered, and what is next?

Chapter 10: Other Planetary Systems: The New Science of Distant Worlds

10.1. Detecting Planets Around Other Stars

- How do we detect planets around other stars?

10.2. The Nature of Planets Around Other Stars

- What properties of extrasolar planets can we measure?
- How do extrasolar planets compare with planets in our Solar System?

10.3. The Formation of Other Planetary Systems

- Do we need to modify our theory of Solar System formation?
- Are planetary systems like ours common?

Why are extrasolar planets difficult to detect?

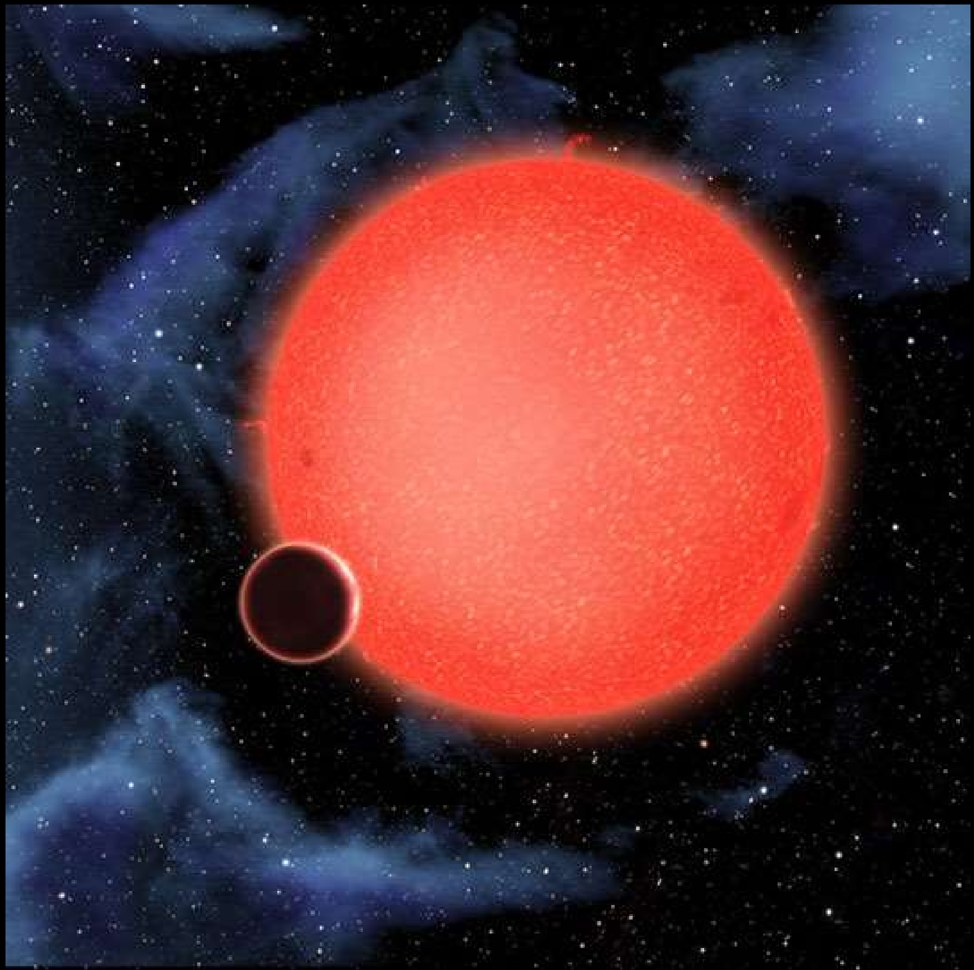
A Sun-like star is about a billion times brighter than the light reflected from its planets.

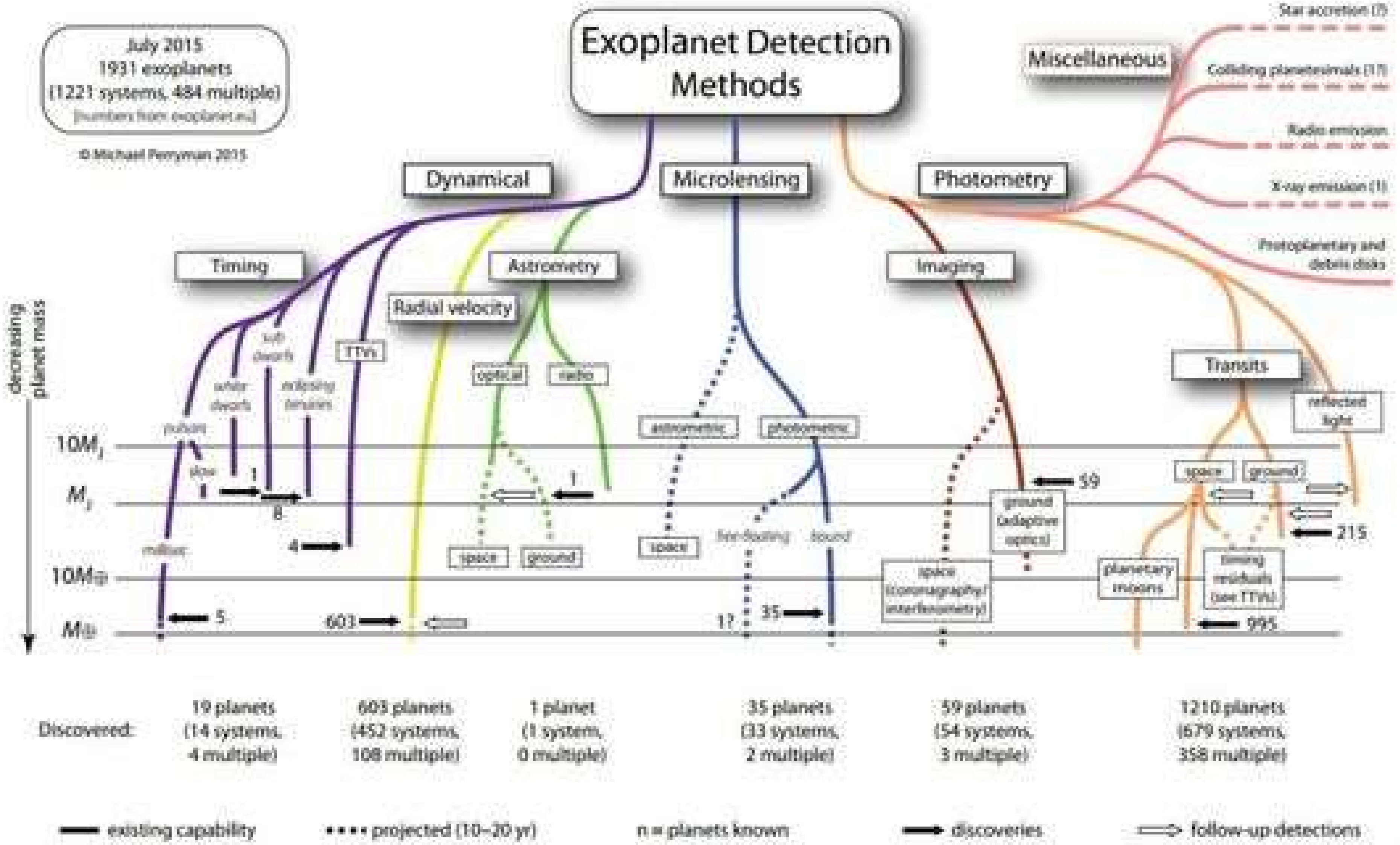
- Stars also have some variability in their light output

Planets are close to their stars, relative to the distance from us to the star.

- Equivalent to trying to see a pinhead on a grapefruit that is sitting in San Francisco … from Washington D.C.

(that's our closest star…)





July 2015
1931 exoplanets
(1221 systems, 484 multiple)
© Michael Perryman 2015
Exoplanet Detection Methods
Miscellaneous
Star accretion (?)
Colliding planetesimals (1?)
Radio emission
X-ray emission (1)
Protoplanetary and debris disks
Dynamical
Microlensing
Photometry
Timing
Astrometry
Imaging
Radial velocity
decreasing planet mass
pulsars
white dwarfs
eclipsing binaries
TTVs
optical
radio
astrometric
photometric
Transits
reflected light
10M_J
M_J
10M⊕
M⊕
slow
millisec
1
8
4
5
603
1
space
ground
space
free-floating
bound
1?
35
59
ground (adaptive optics)
space (coronagraphy/ interferometry)
space
ground
planetary moons
timing residuals (see TTVs)
215
995
Discovered:
19 planets (14 systems, 4 multiple)
603 planets (452 systems, 108 multiple)
1 planet (1 system, 0 multiple)
35 planets (33 systems, 2 multiple)
59 planets (54 systems, 3 multiple)
1210 planets (679 systems, 358 multiple)
existing capability
projected (10–20 yr)
n = planets known
discoveries
follow-up detections

Categories of Planet Detection Methods…

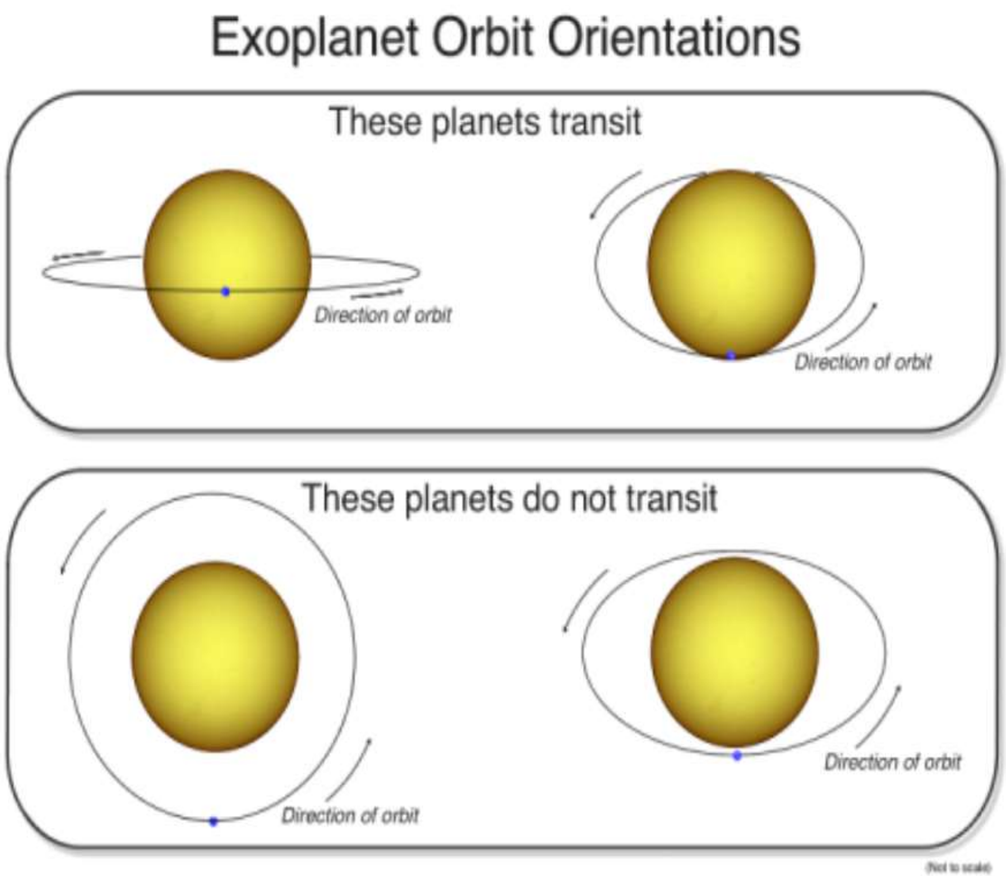
Direct:

- Pictures (or spectra) of the planets themselves

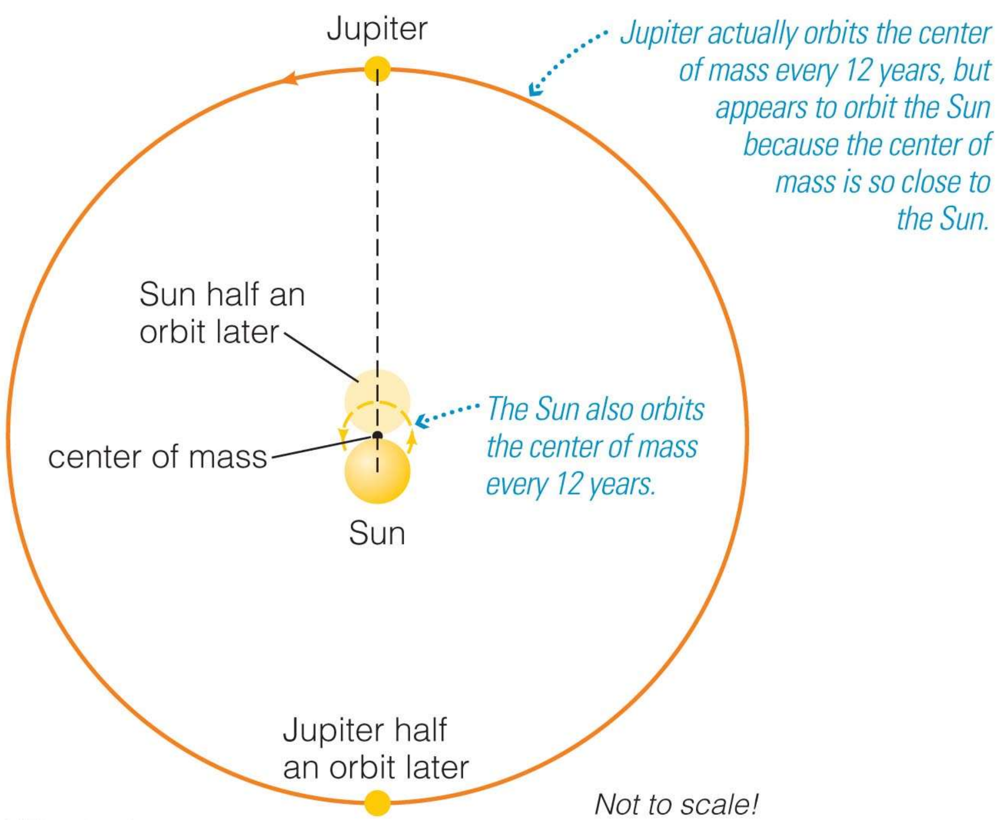
Indirect:

- Measurements of stellar properties revealing the effects of orbiting planets

Orientation of the planetary system relative to the star matters for both



Gravitational "Tugging"

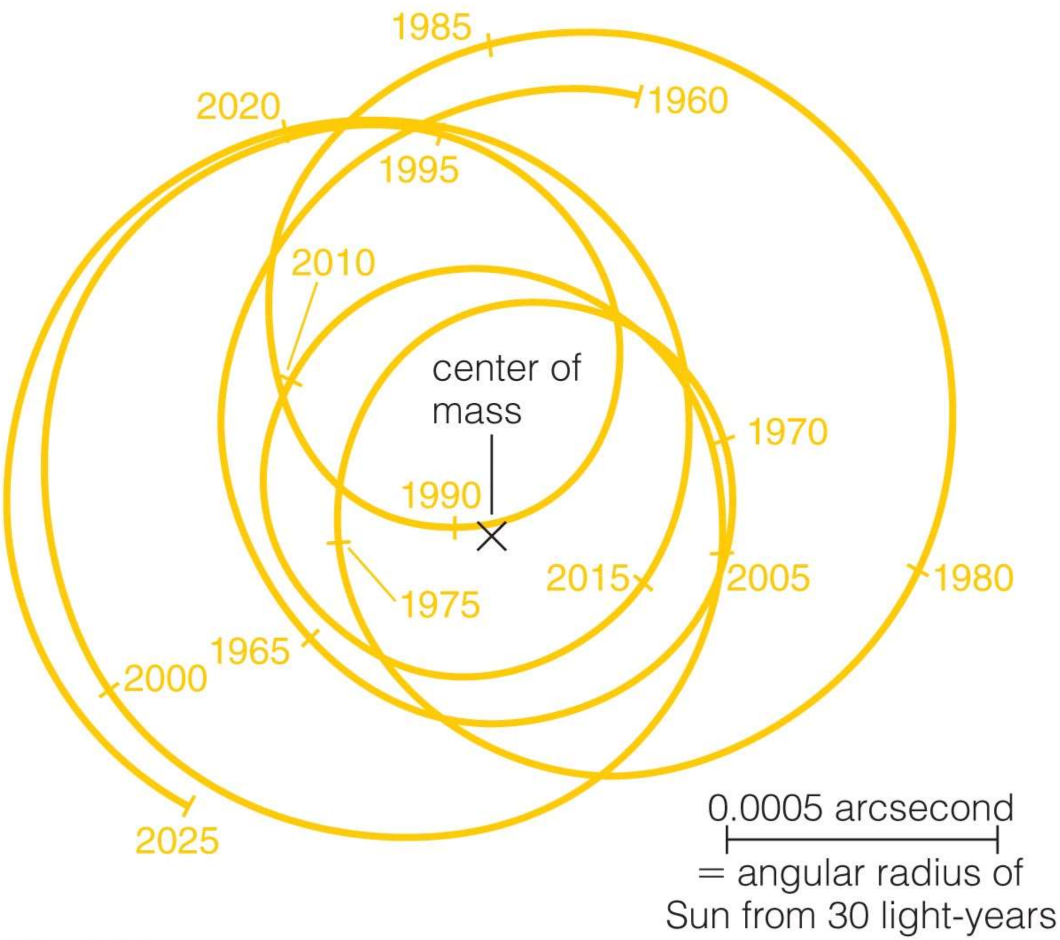


Remember:

Both the Sun and a Planet actually orbit around a common Barycenter (center of mass)

- 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***.

How Gravitational Tugs Affect our Solar System



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.

The Astrometric Technique
(An Indirect method)

The Detection of planets by measuring the stars *'Wobble'* in the sky caused by the gravitational effects of the planetary system.

These effects are small (~ 0.001 arcsecond, or 1 milliarcseconds and since orbital periods are long requires extended observations

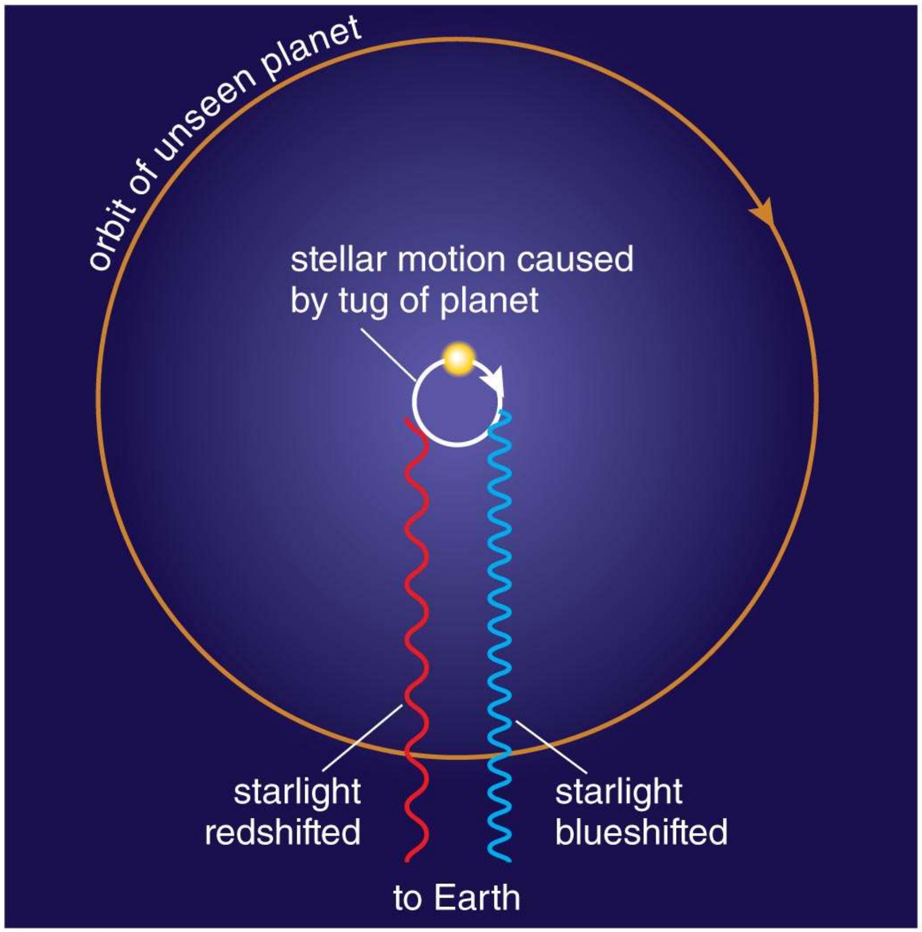
What can it (help) inform you of?

- Orbital period, distance and eccentricity
- Planetary mass

The GAIA Spacecraft (ESA) has been obtaining astrometric observations of a billion stars since 2013 (may last to 2022).

Has an accuracy down to 10 microarcseconds (0.000010)

The Doppler Method
(An Indirect Technique)



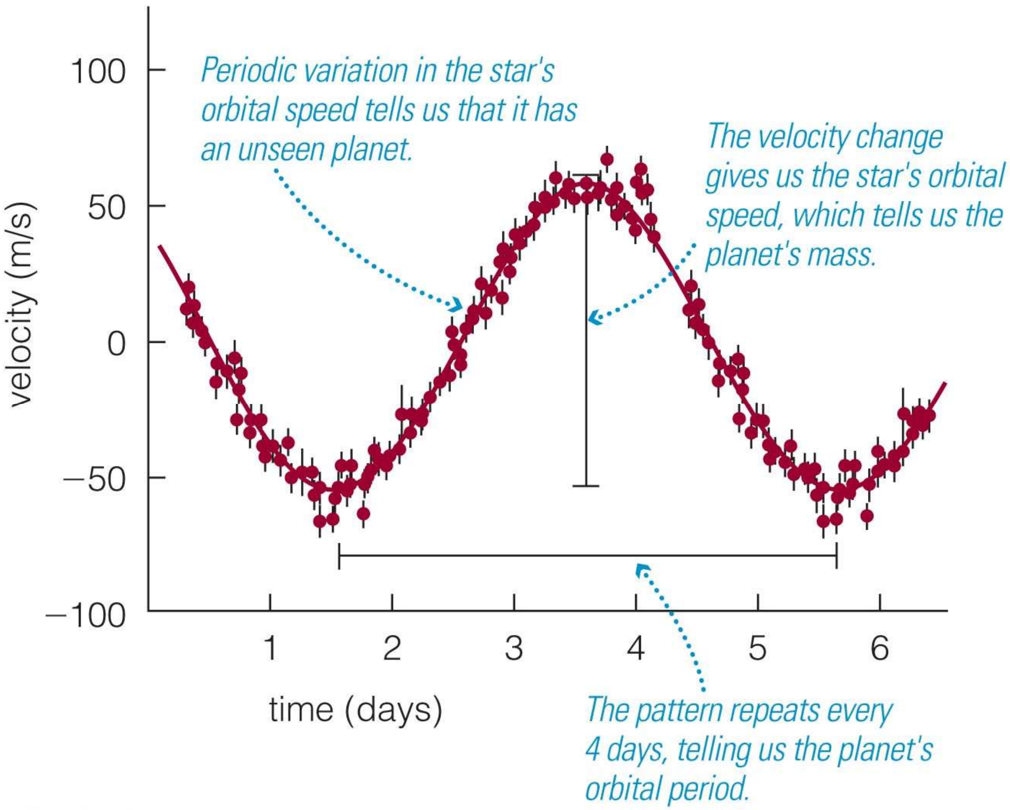
Requires the planetary system to be sufficiently 'edge-on'

- 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!).

What can it (help) inform you of?

- Orbital period, distance and eccentricity
- Planetary mass (minimum, max is factor of ~two larger)

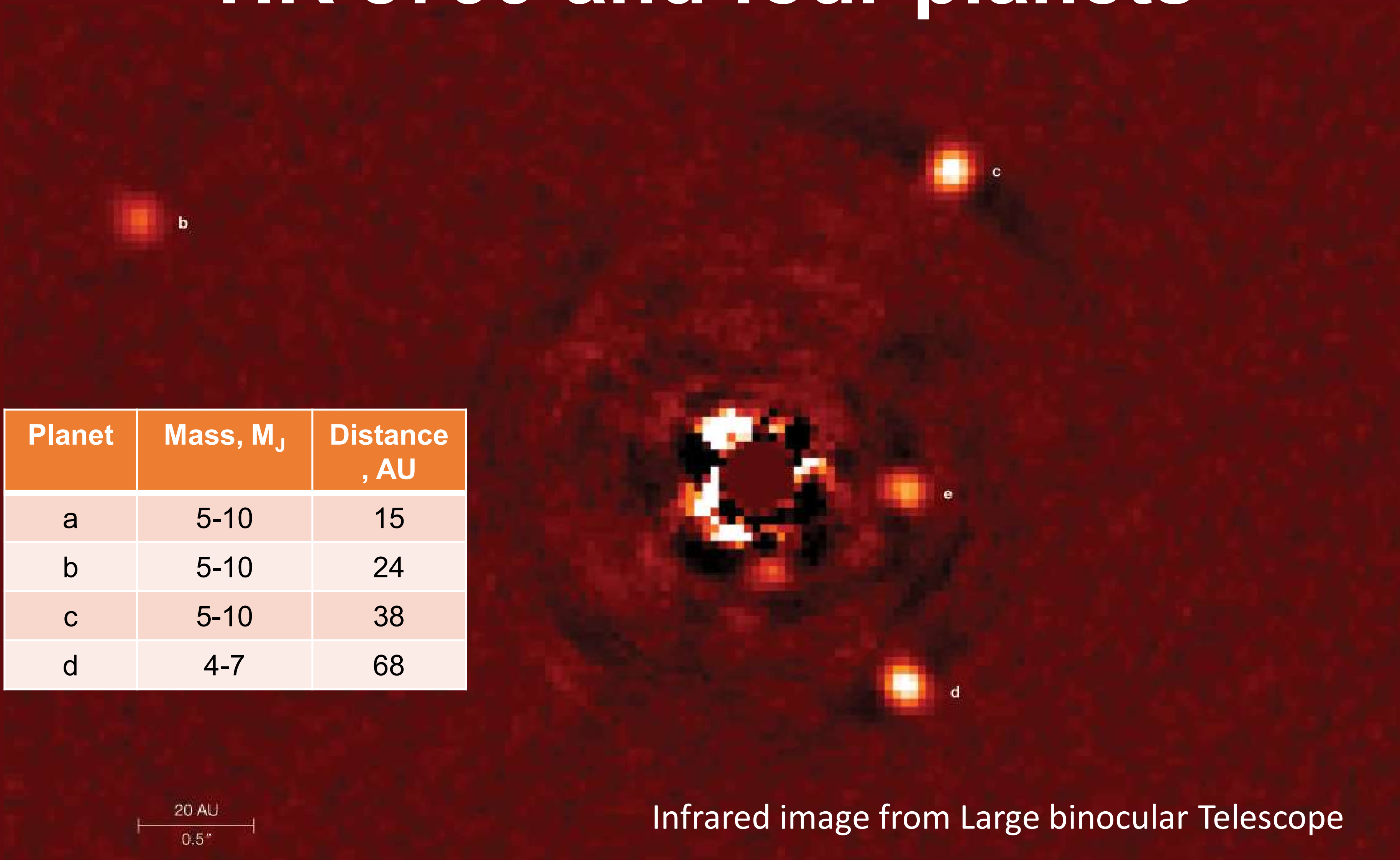
The First Extrasolar Planet Detection



- 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).
- Doppler shift measurements are often done as follow-ups to help constrain parameters such as planetary masses

Requires large portion of orbital period to be monitored. Bias towards 'Hot Jupiter' planets – large planets that orbit very close to their parent star with orbital periods of days…

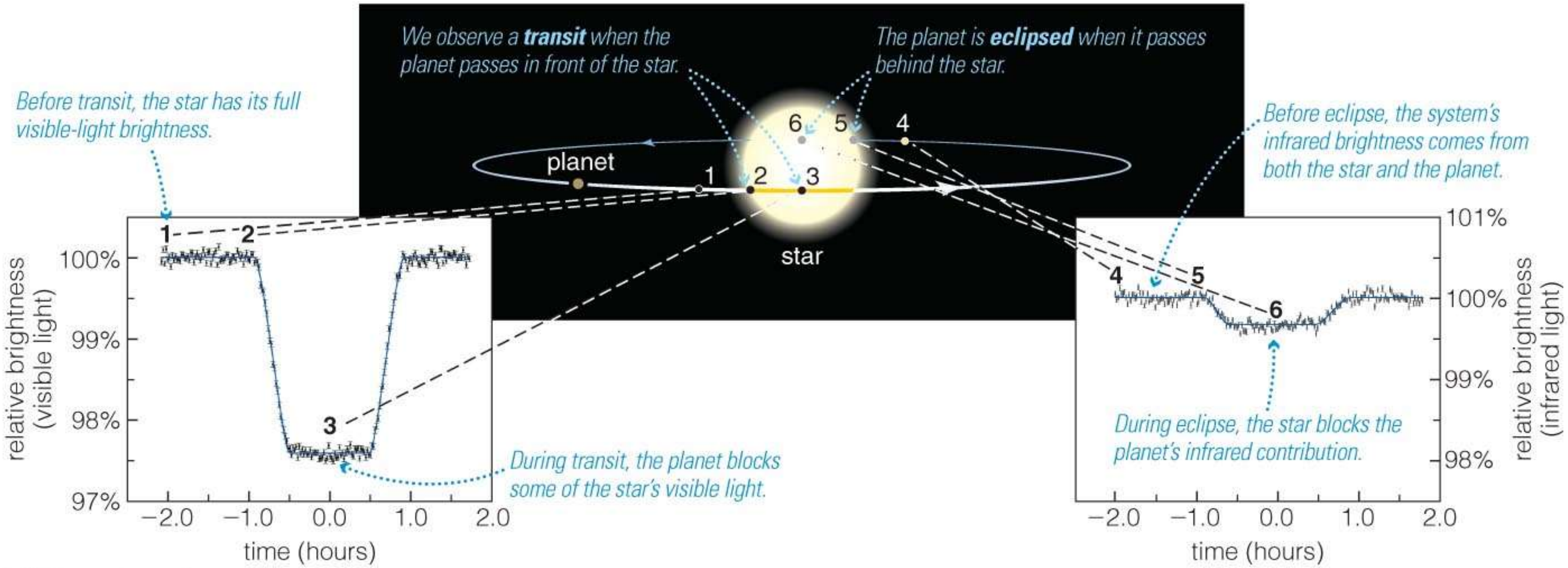
Example of Direct Imaging: star HR 8799 and four planets



Planet	Mass, M_J	Distance, AU
a	5-10	15
b	5-10	24
c	5-10	38
d	4-7	68

Infrared image from Large binocular Telescope

The Transit Method
(indirect technique)

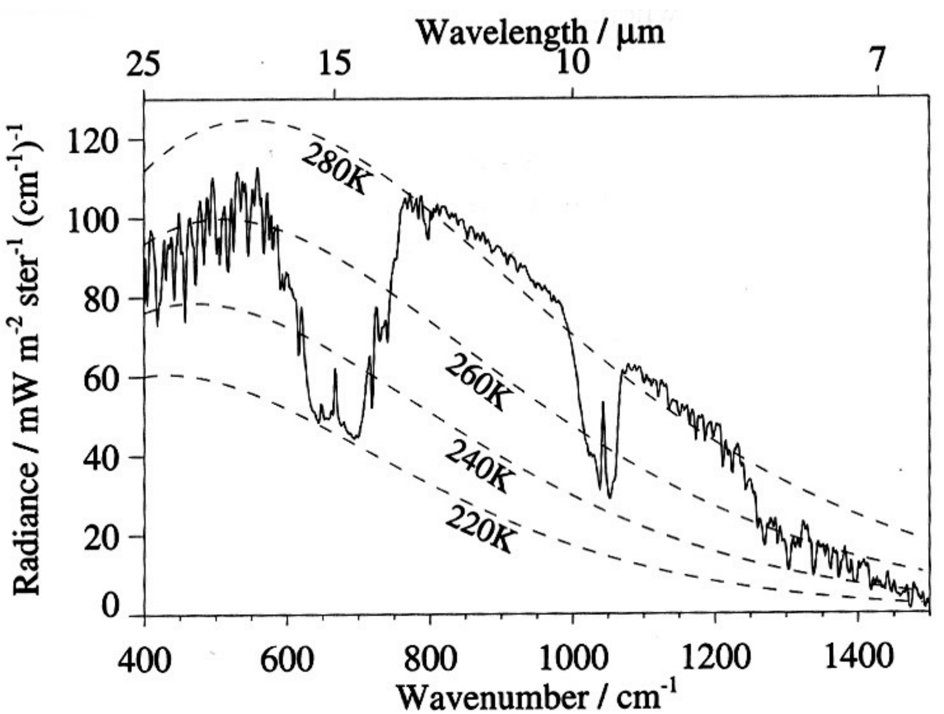


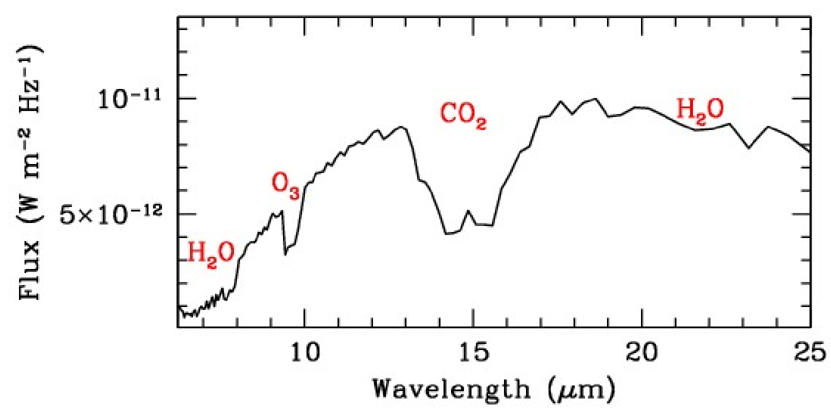
- A **transit** is when a planet crosses in front of a star.
- This reduces the star's apparent brightness and tells us planet's radius.
- Sometimes an **eclipse** – the planet passing behind the star, can also be detected. *(Contributions of exoplanet atmosphere are **now** hidden)*

The Transit Method
(Direct technique)

What can if help inform you of?

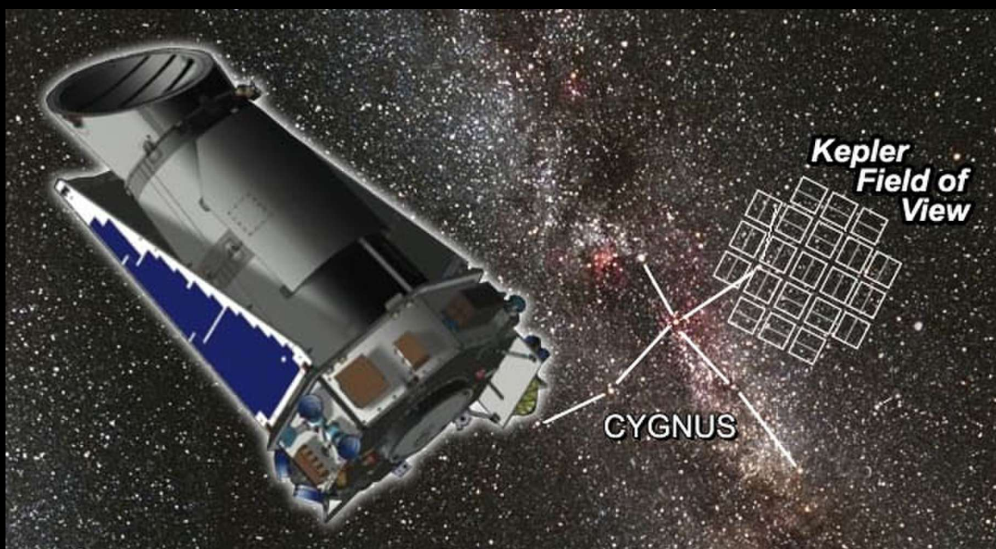
- *Orbital periods and distances*
- *Size of a planet (radius), which can be used to help determine density*
- *Atmospheric composition, and temperature (from black body)*





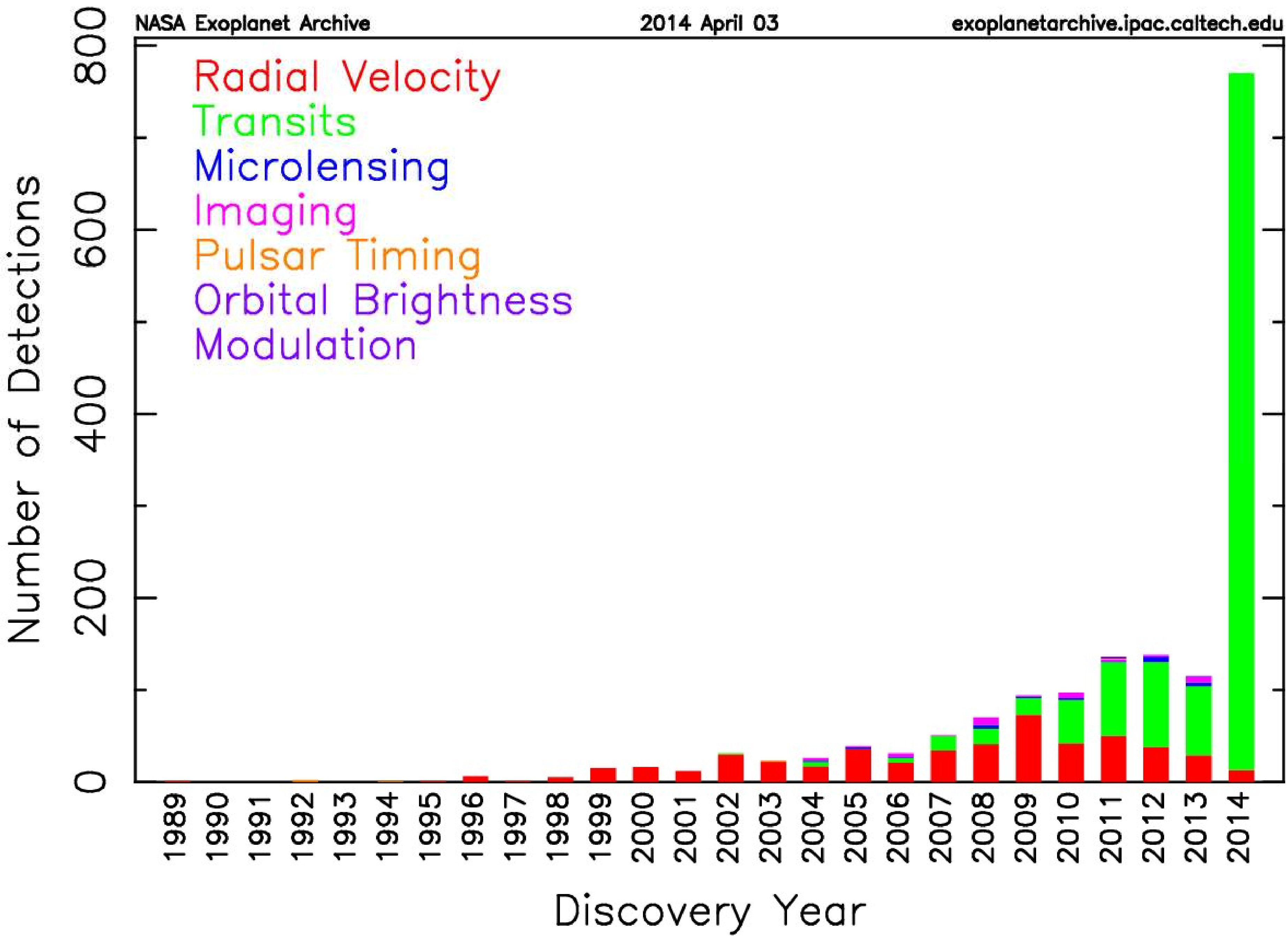
The James Webb Space Telescope will be able to determine atmospheric compositions as follow-up observations

The Kepler Spacecraft

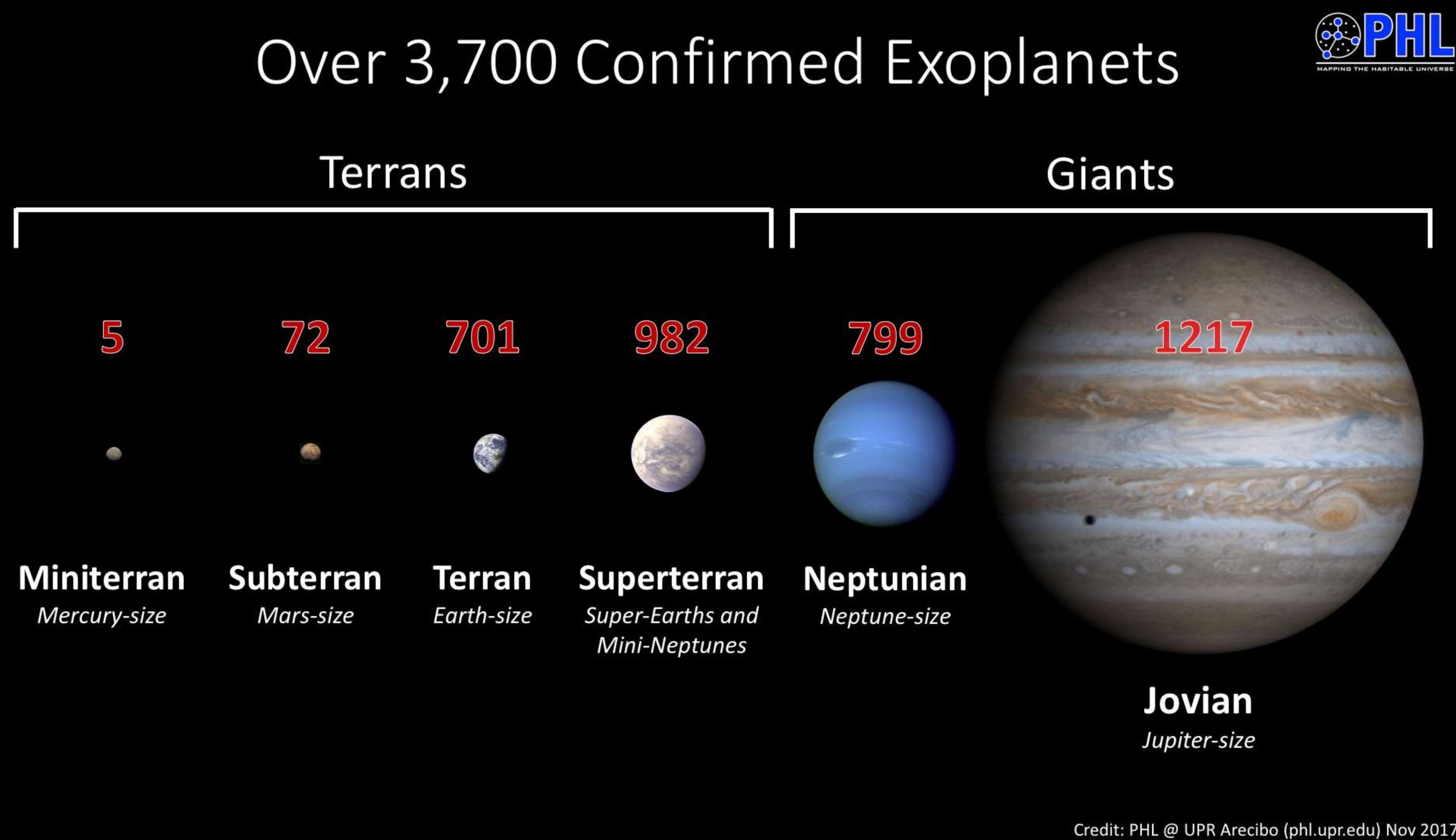


Detected over 1000 exoplanets in over 400 star systems

- NASA's *Kepler* mission searched for transits from 2009-2013.
- It was designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.
- Monitoring ~ 150,000 stars towards the constellation Cygnus

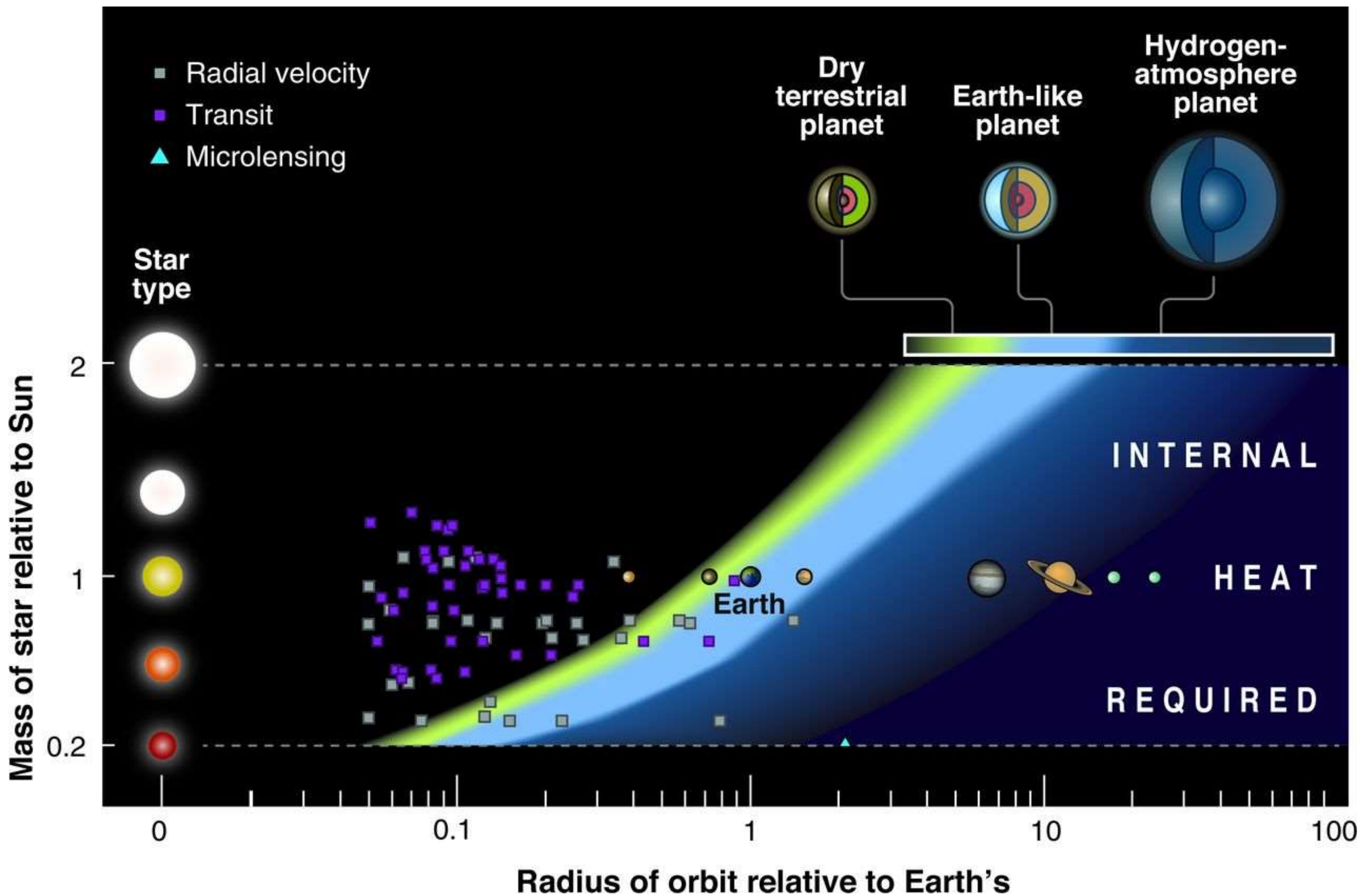

NASA Exoplanet Archive
2014 April 03
exoplanetarchive.ipac.caltech.edu
Radial Velocity
Transits
Microlensing
Imaging
Pulsar Timing
Orbital Brightness
Modulation
Number of Detections
0
200
400
600
800
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Discovery Year

Summary of Detections to Date

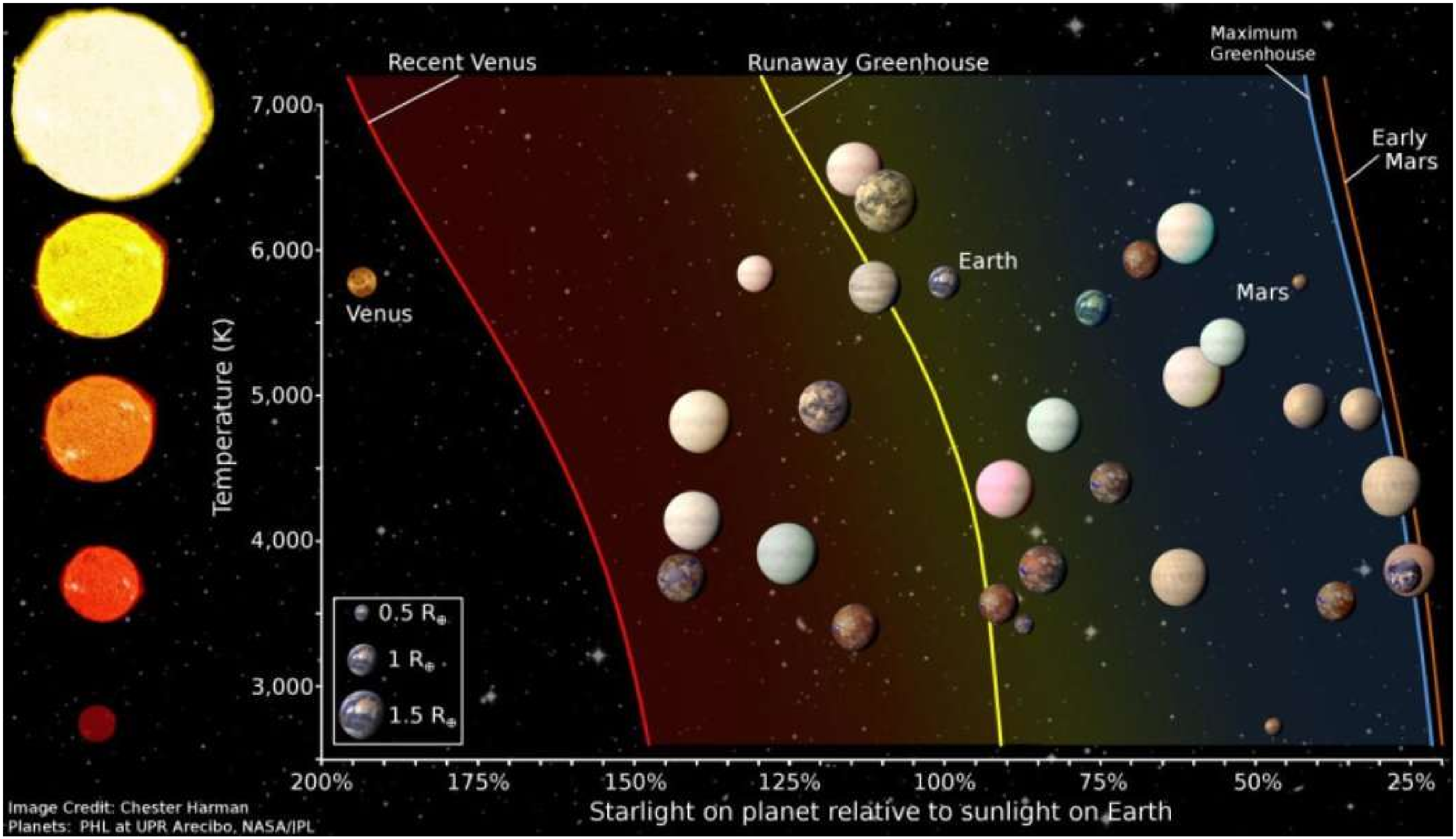


The Habitable Zone

The Habitable Zone Around Other Stars



The Habitable Zone Around Other Stars



iClicker Question

In order to maximize your chance of seeing a faint, cooler planet next to a brighter, hotter star, you should observe:

A. Using visible light.
B. Using ultraviolet light.
C. Using infrared light.
D. Using X-ray light.

iClicker Question

In order to maximize your chance of seeing a faint, cooler planet next to a brighter, hotter star, you should observe:

A. Using visible light.
B. Using ultraviolet light.
C. **Using infrared light.**
D. Using X-ray light.

iClicker Question 2

The shorter the period of the Doppler curve,

A. The closer the unseen planet is to the star
B. The farther the unseen planet is from the star
C. The greater the mass of the planet
D. The smaller the mass of the planet
E. A and C.

iClicker Question 2

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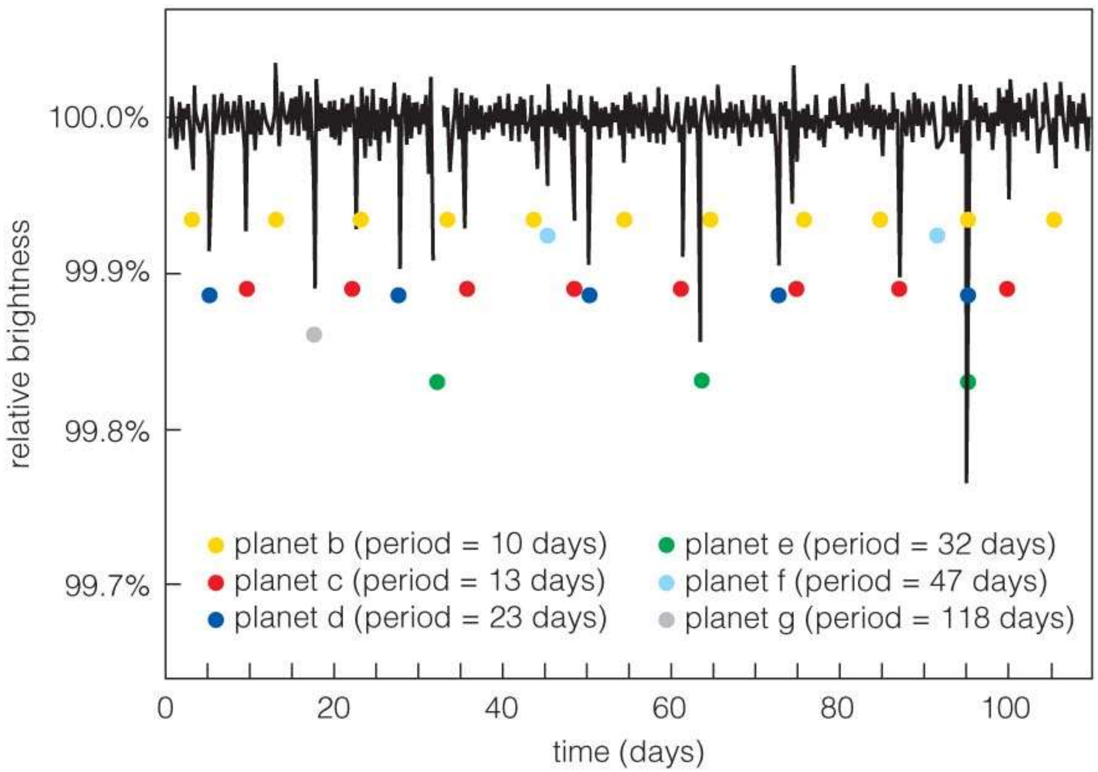
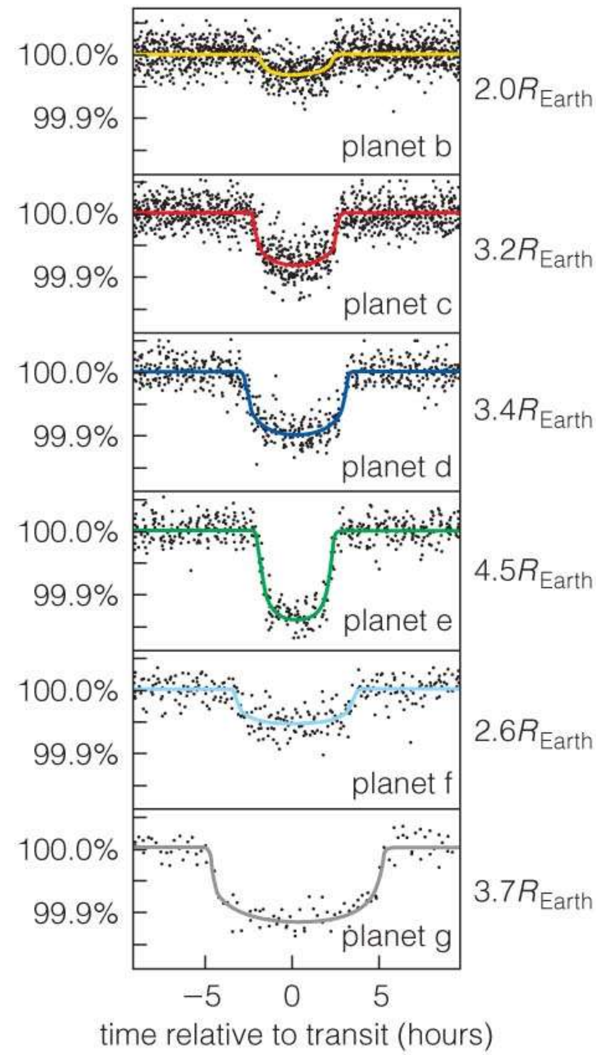
D. The smaller the mass of the planet
E. A and C.

Transit Example: The Kepler 11 system





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

Relationship Between Size and Fraction of Light Blocked

- A Larger planet will block a larger area of the Stars surface during a transit
- Although too distant, we know the fraction of light is proportional to the area of the planet and the area of the star, as follows:

Fraction of light blocked$= \frac{area\ planet}{area\ Star} = \frac{\pi r^2(planet)}{\pi r^2(Star)} = \frac{r^2(planet)}{r^2(Star)}$

Example: If a star has a radius of 800,000 km (1.15 R_{sun}), and the planet blocks 1.7% of the star's light during a transit, what is the radius of the planet?

Solution: we rearrange the equation as follows…

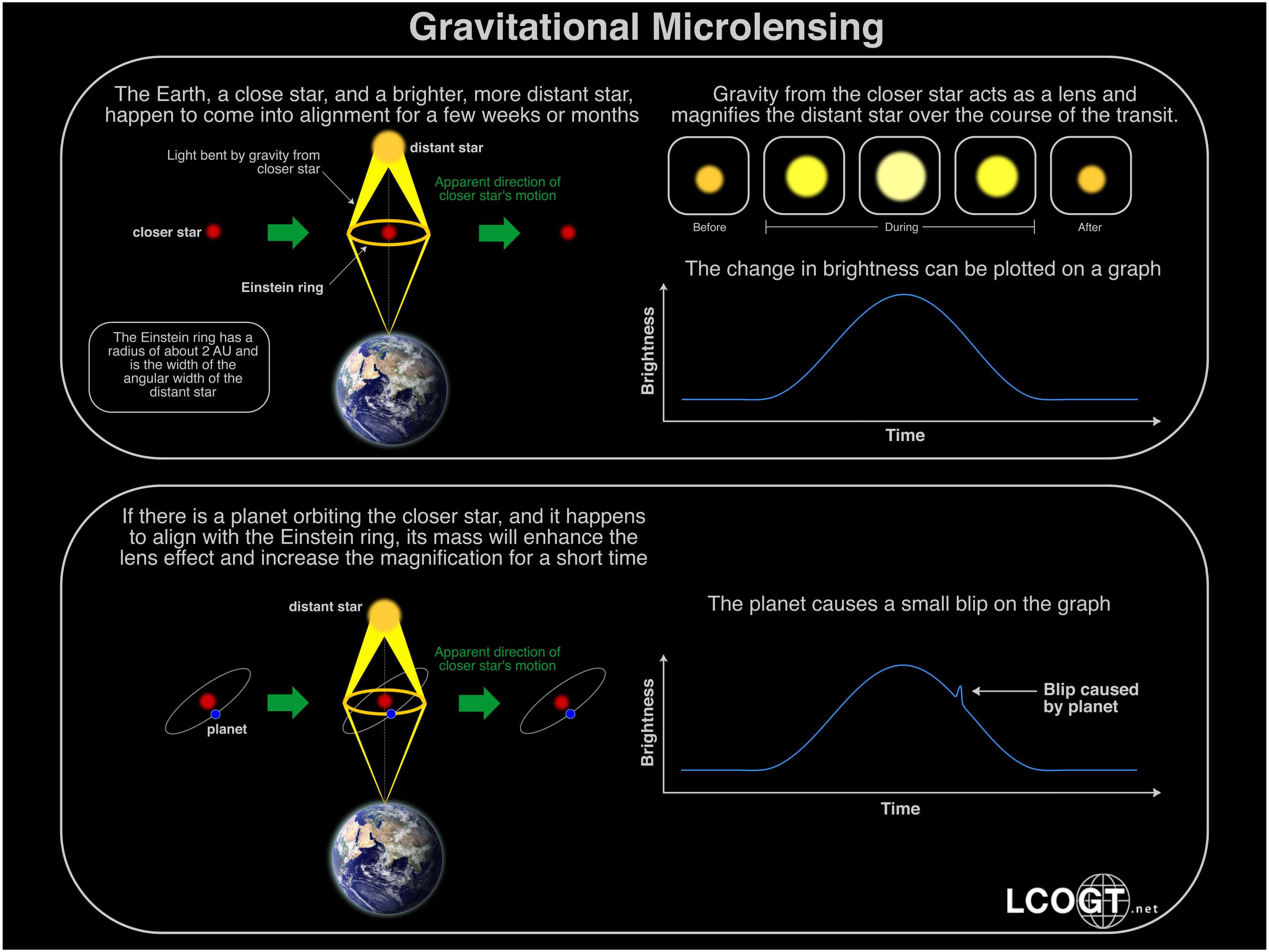
$$r_{planet} = r_{Star} \times \sqrt{\text{fraction of light blocked}}$$

$$= 800{,}000\ km\ \times \sqrt{0.017}$$

$\sim 100{,}000\ km$ (cf. Jupiter has radius ~71,500 km)

Video of Microlensing

https://www.youtube.com/watch?time_continue=1&v=FHh0Qx7LPJY

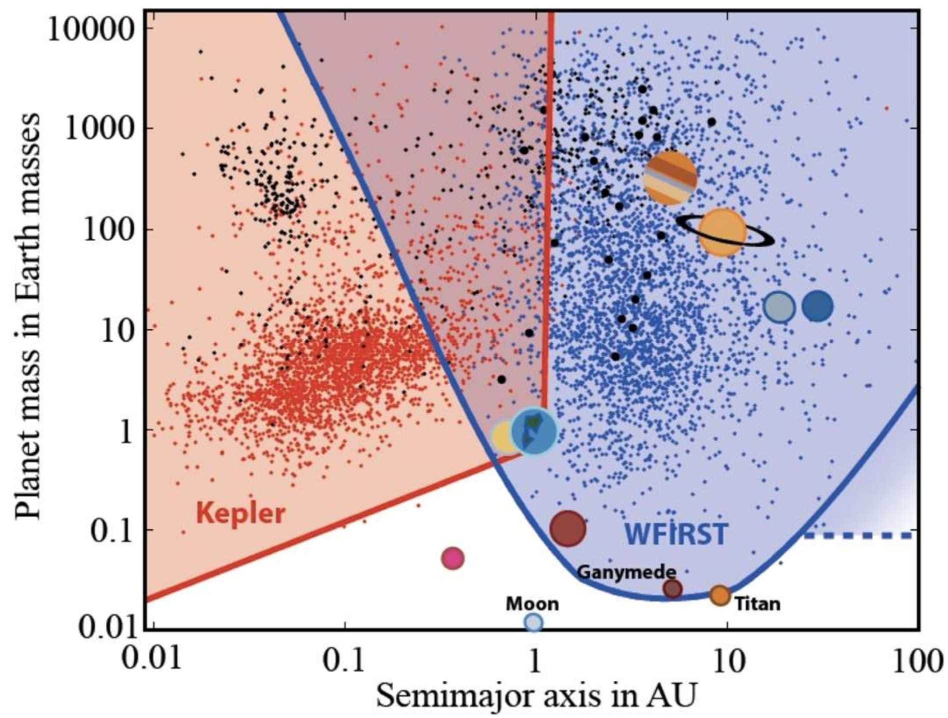

Gravitational Microlensing
The Earth, a close star, and a brighter, more distant star, happen to come into alignment for a few weeks or months
Light bent by gravity from closer star
distant star
Apparent direction of closer star's motion
closer star
Einstein ring
The Einstein ring has a radius of about 2 AU and is the width of the angular width of the distant star
Gravity from the closer star acts as a lens and magnifies the distant star over the course of the transit.
Before
During
After
The change in brightness can be plotted on a graph
Brightness
Time
If there is a planet orbiting the closer star, and it happens to align with the Einstein ring, its mass will enhance the lens effect and increase the magnification for a short time
distant star
Apparent direction of closer star's motion
planet
The planet causes a small blip on the graph
Blip caused by planet
Brightness
Time
LCOGT.net

Gravitational microlensing:

Surprisingly good at detecting 'Earth-like planets'

Wide **F**ield **I**nfra**r**ed **S**urvey **T**elescope (WFIRST) (NASA)

- Mid 2020s launch
- Would provide both direct imaging as well as be able to use microlensing to detect planets
- Can detect objects down to almost as small as our moon



But only get a snapshot of the system…
…. Mass & orbital distance estimates.

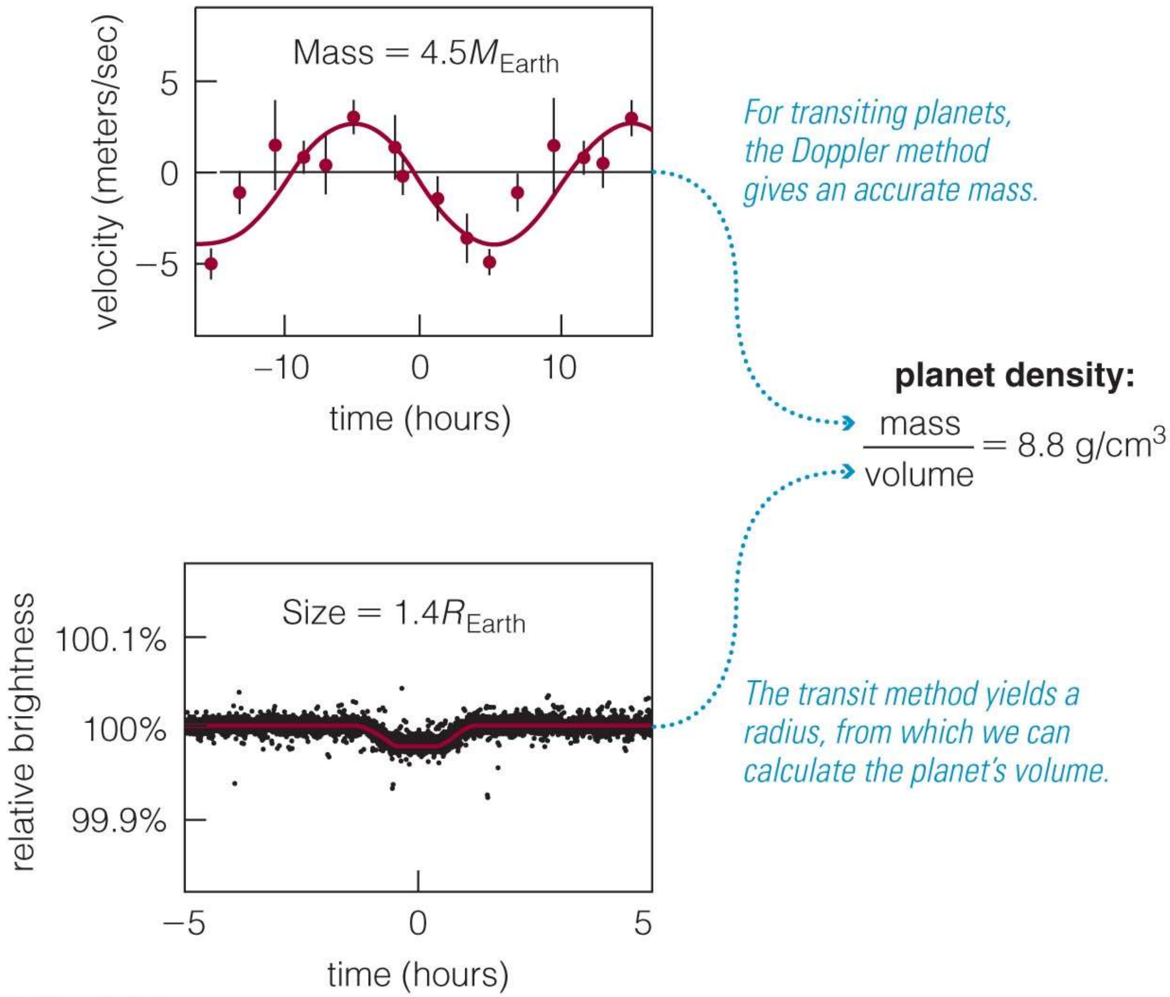
Measurable Properties

Planetary Property	Method(s) Used	Explanation
period	Doppler, astrometric, or transit	We directly measure orbital period.
distance	Doppler, astrometric, or transit	We calculate orbital distance from orbital period using Newton's version of Kepler's third law.
eccentricity	Doppler or astrometric	Velocity curves and astrometric star positions reveal eccentricity.
mass	Doppler or astrometric	We calculate mass based on the amount of stellar motion caused by a planet's gravitational tug.
size (radius)	transit	We calculate size based on the amount of dip in a star's brightness during a transit.
density	transit plus Doppler	We calculate density by dividing the mass by the volume (using the size from the transit method).
atmospheric composition, temperature	transit or direct detection	Transits and eclipses provide data on atmospheric composition and temperature.

Planet mass and orbital tilt:

- We cannot measure an exact mass for a planet without knowing the tilt of its orbit using the doppler technique since it only forms us of the velocity towards/away from us
- Doppler will only provide lower limit on masses, but can provide excellent complimentary information for planets detected by the transit method, which must be edge-on.

The importance of Follow up Studies:
What does density tell us about our Solar System?



iClicker Question 3

Suppose you found a star similar to the Sun (similar size, mass, age, etc.) and it was moving back and forth with a period of 2 years. What could you conclude?

A. It has a planet orbiting at less than 1 AU

B. It has a planet orbiting at greater than 1 AU

C. It has ha planet orbiting at exactly 1 AU

D. It has a planet, but we don’t know its mass so we can’t know its orbital distance for sure

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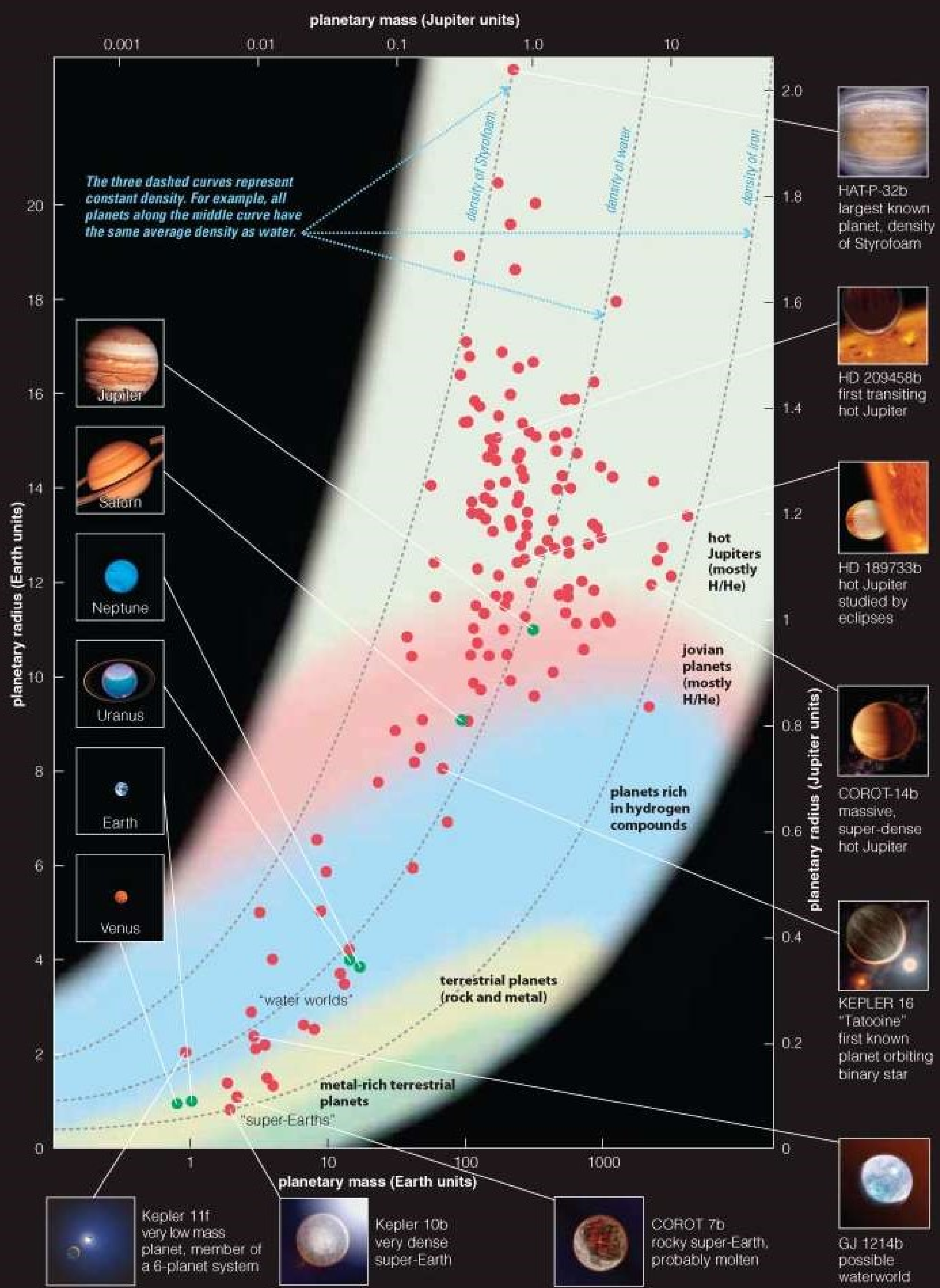


Exoplanets Properties Compared

- Much wider array of physical properties compared to the planets in our Solar System
- Some have the density of Styrofoam
- Some have the density of Iron
- Some planets have highly elliptic orbits
- Massive planets (hot Jupiters) are found close to their host stars…

10.3. The Formation of Other Planetary Systems

- Do we need to modify our theory of Solar System Formation?
- Are Planetary Systems like ours common?

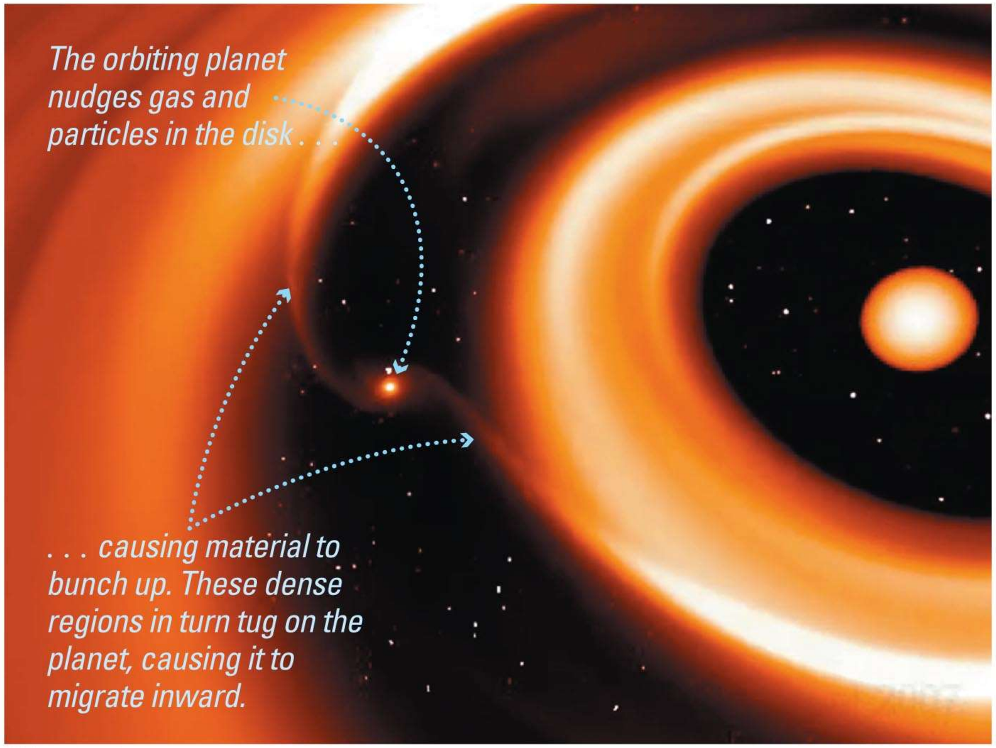
Revisiting the Nebula Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 5 AU).
- The discovery of hot Jupiters must force a reexamination of nebular theory.

Solution: *Planetary Migration…*

- 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.

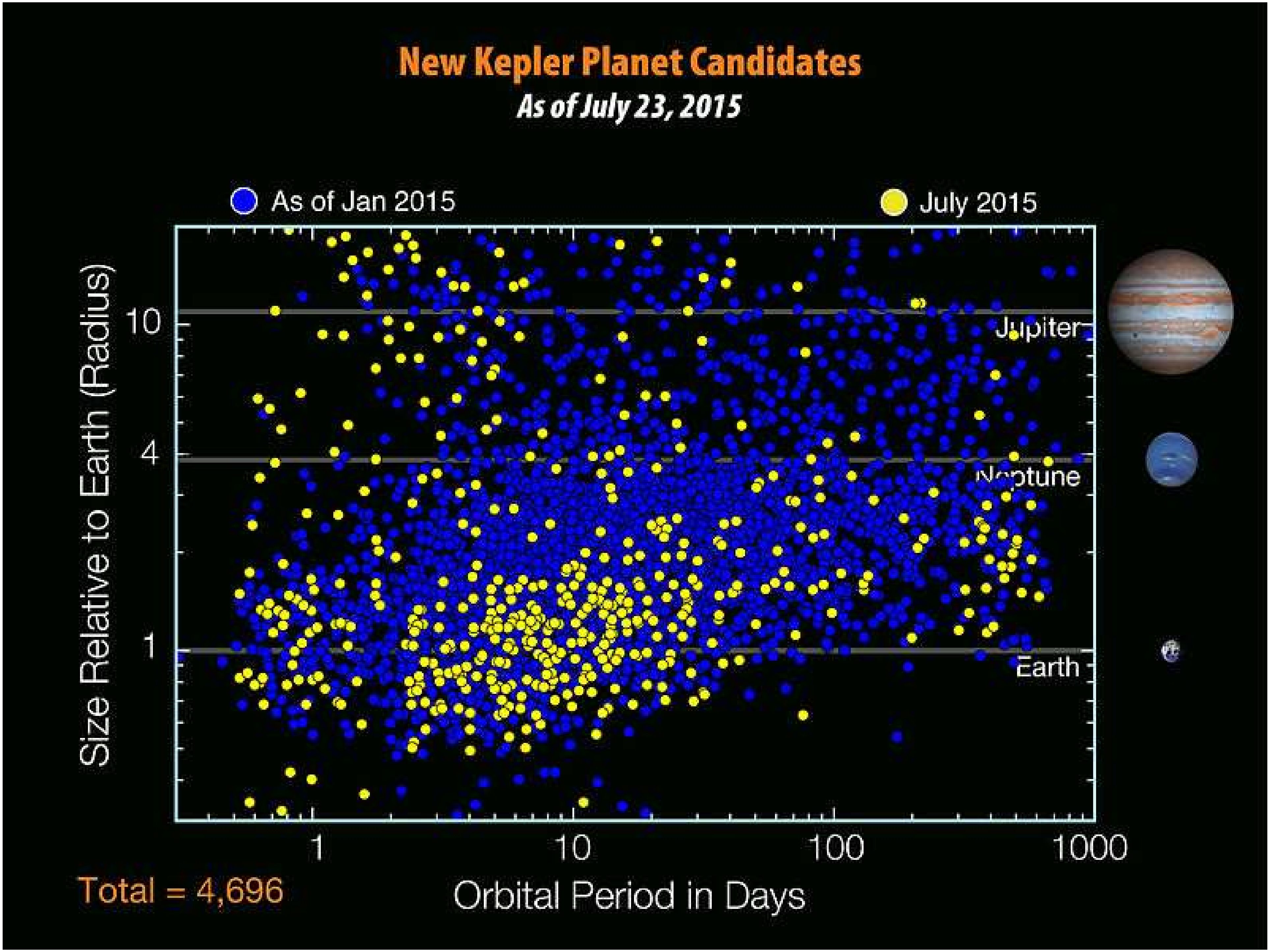
Planetary Migration II:



- 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.
- Have identified some planets close to their stars which will crash into their host star within 1 million years
- Also have found evidence of planetary like material in outer layers of some stars.

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.
- Planets that are close to their star may have ‘puffed-up’ atmospheres, which can explain the very low densities observed

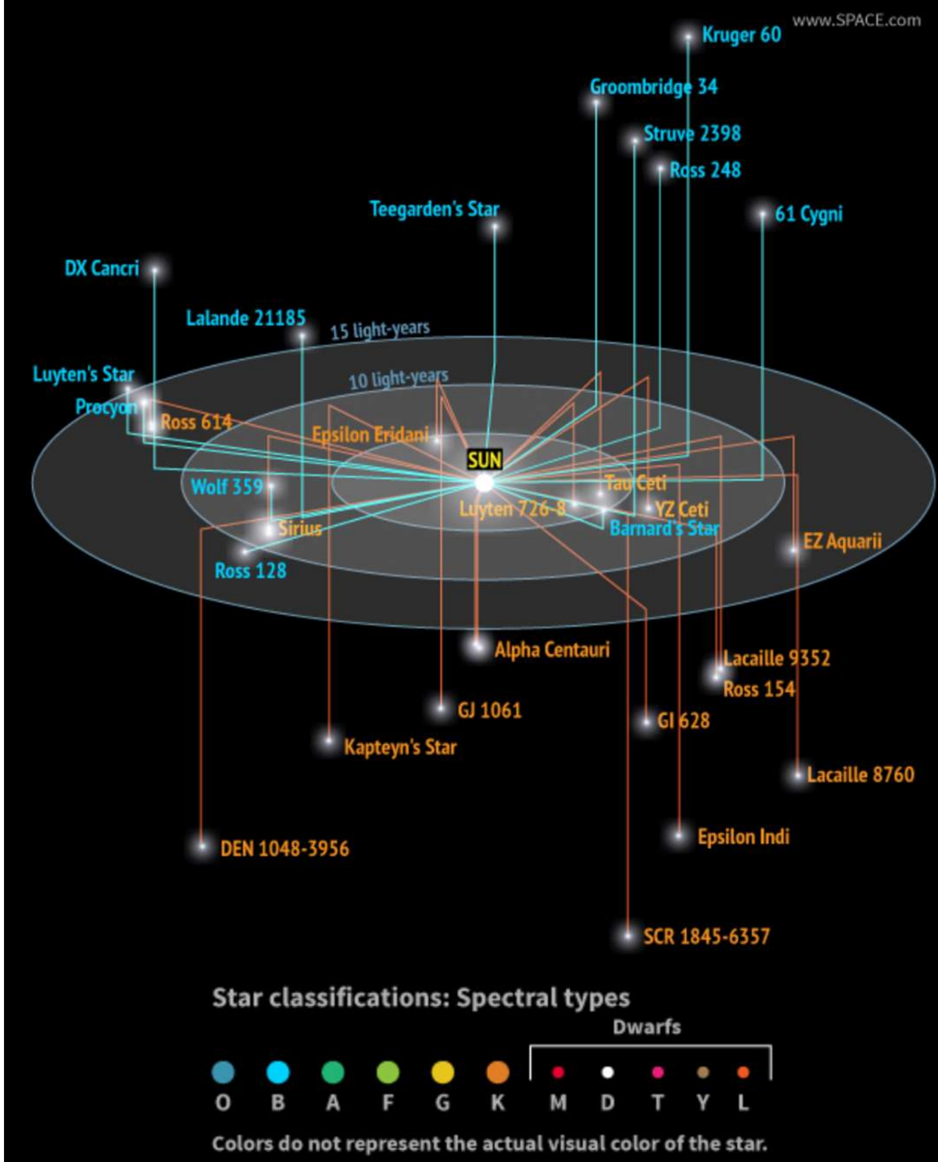

New Kepler Planet Candidates
As of July 23, 2015
As of Jan 2015
July 2015
Size Relative to Earth (Radius)
10
4
1
Jupiter
Neptune
Earth
1
10
100
1000
Orbital Period in Days
Total = 4,696

Extrasolar Planets Summary

Based on extrapolations from data collected so far:

- There is >1 planet per star, on average per star
- At least 1 in 5 Sun-like stars have an Earth-sized planet within the habitable zone
- Estimated 11-40 billion Earth-sized exoplanets estimated within the Milky Way Galaxy Alone

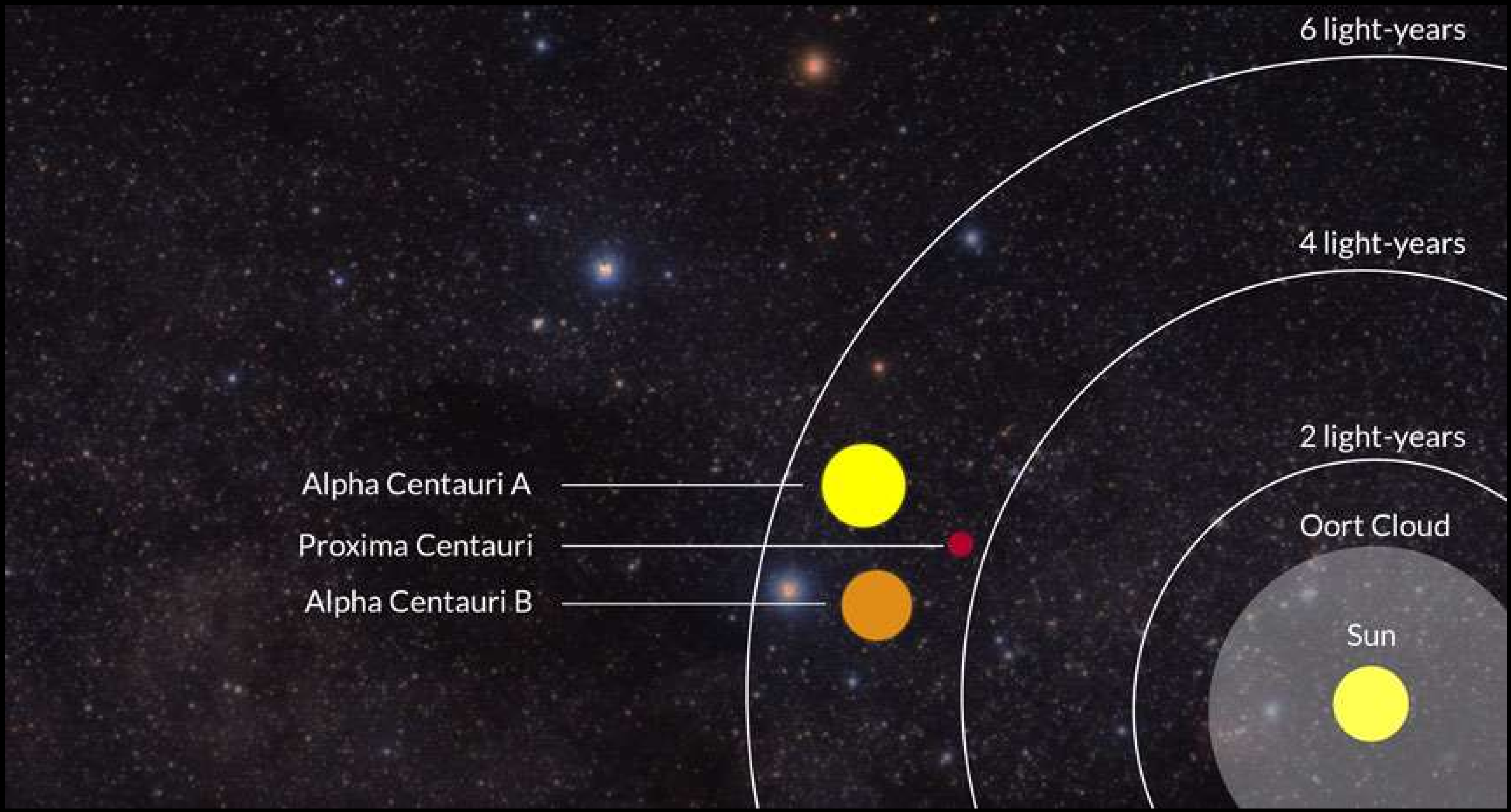
Other Nearby Stars (from ch2_pt2)



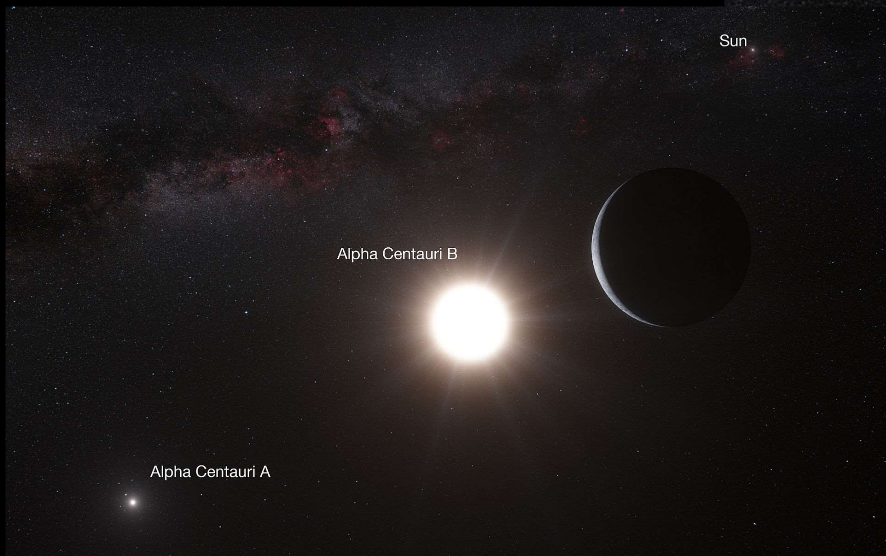
	Star system	Distance in light-years	Stellar type (s)	Observed planets
1	Alpha Centauri	4.24-4.37	M, G, K	1 +1
2	Barnard's Star	5.96	M	
3	Wolf 359	7.78	M	
4	Lalande 21185	8.29	M	
5	Sirius	8.58	A, D	
6	Luyten 726-8	8.73	M, M	
7	Ross 154	9.68	M	
8	Ross 248	10.32	M	
9	Epsilon Eridani	10.52	K	2
10	Lacaille 9352	10.74	M	
11	Ross 128	10.92	M	
12	EZ Aquarii	11.27	M, M, M	
13	Procyon	11.40	F, D	
14	61 Cygni	11.40	K, K	
15	Struve 2398	11.53	M, M	
16	Groombridge 34	11.62	M, M	
17	Epsilon Indi	11.82	K, T, T	
18	DX Cancri	11.83	M	
19	Tau Ceti	11.89	G	5
20	GJ 1061	11.99	M	
21	YZ Ceti	12.13	M	
22	Luyten's Star	12.37	M	
23	Teegarden's Star	12.51	M	
24	SCR 1845-6357	12.57	M, T	
25	Kapteyn's Star	12.78	M	
26	Lacaille 8760	12.87	M	
27	Kruger 60	13.15	M, M	
28	DEN 1048-3956	13.17	M	
29	UGPS 0722-05	13.26	T	
30	Ross 614	13.35	M, M	

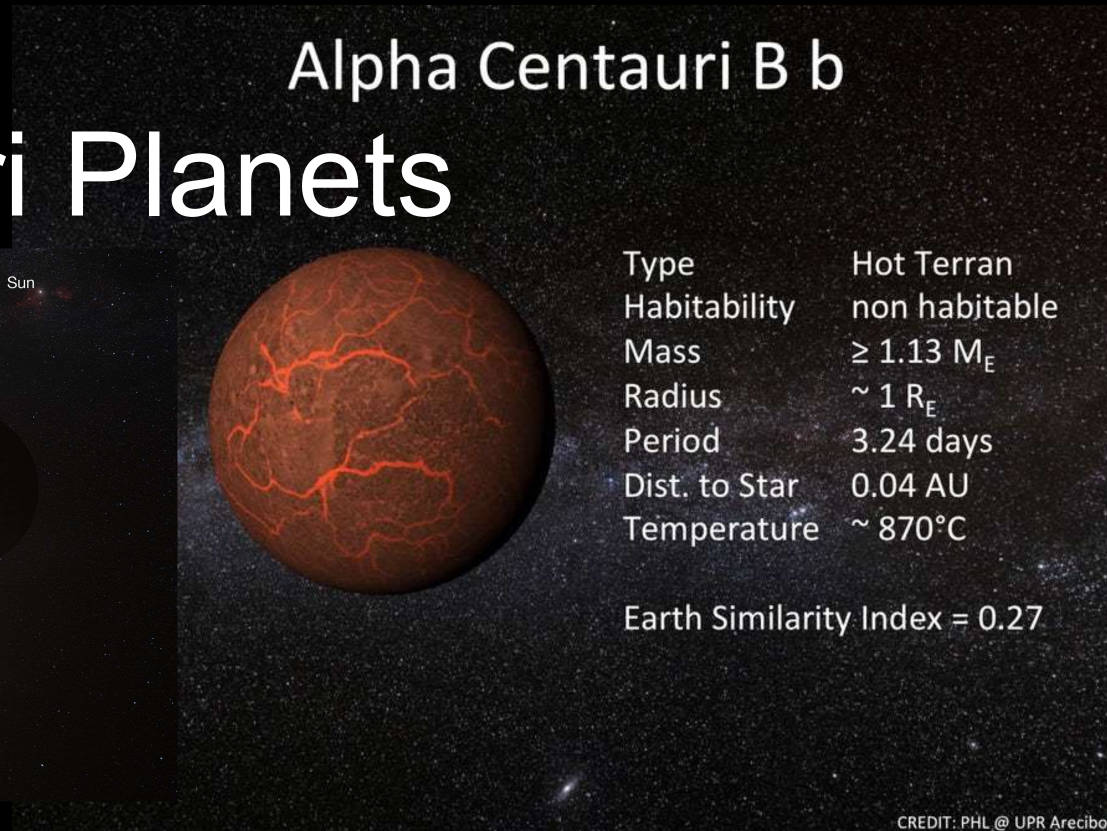
https://www.space.com/18964-the-nearest-stars-to-earth-infographic.html

The Alpha Centauri System



Alpha Centauri Planets





Proxima Centauri b discovered in 2016

Mass >1.27 M_E

Period 11.2 days

Dist. To star 0.05 AU

End of Todays Lecture