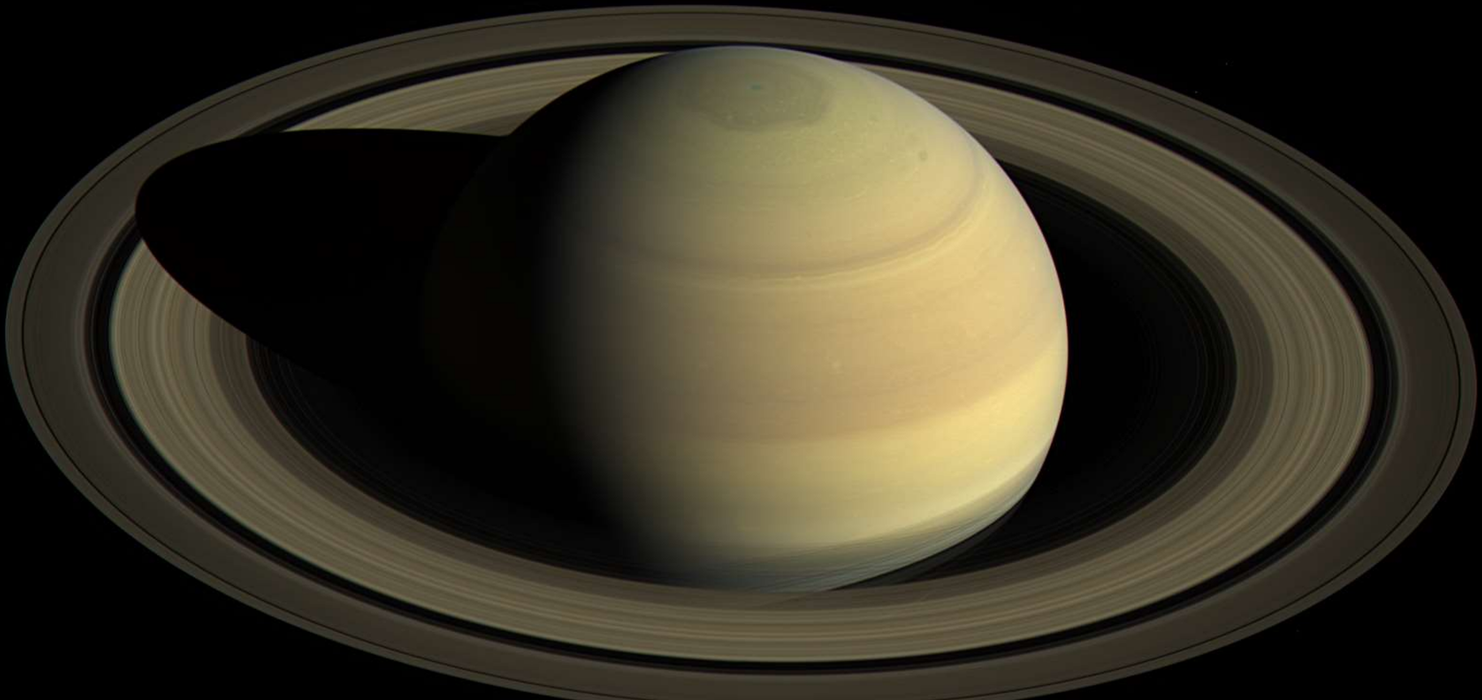
AST 2002
Introduction to Astronomy



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

Enjoy Spring Break

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

Do you want an extra 1% extra credit for showing up to class today?

A. No.
B. Yes.

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?

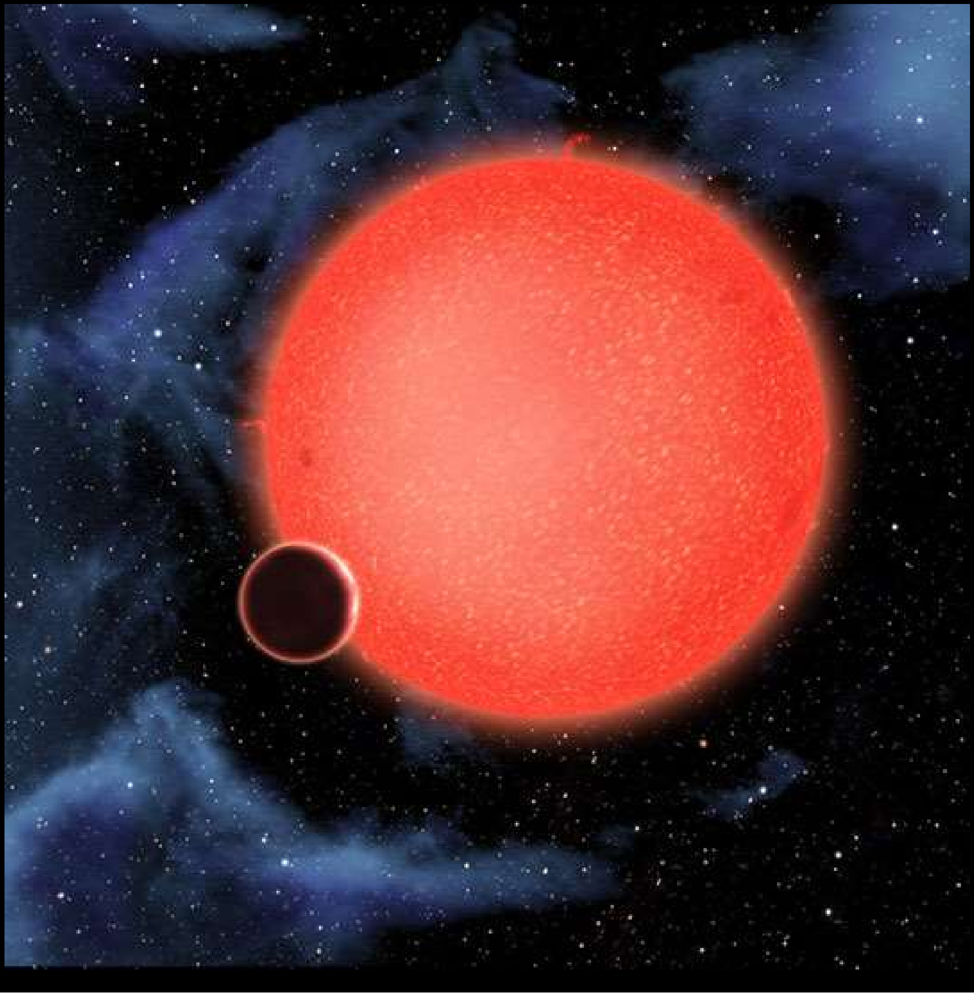
A Sun-like star is about a billion times brighter than the light reflected from its planets.

- 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…)



Categories of Planet Detection Methods…

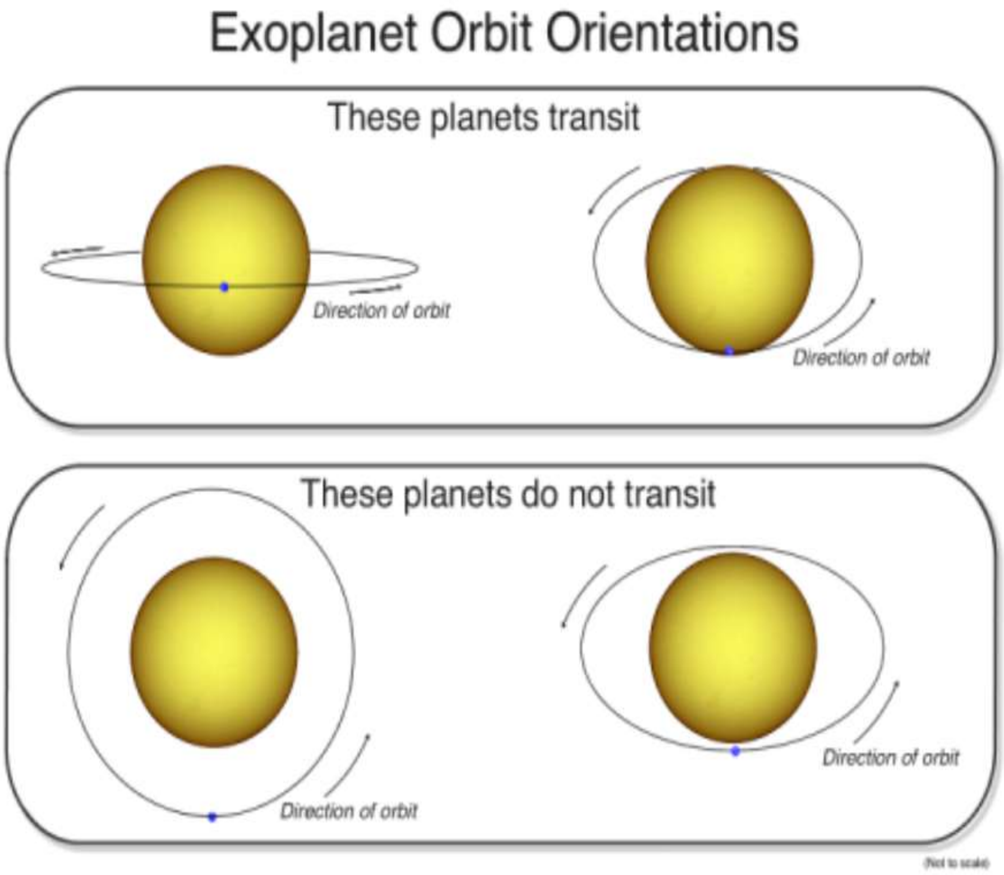
Direct:

- Pictures (or spectra) of the planets themselves

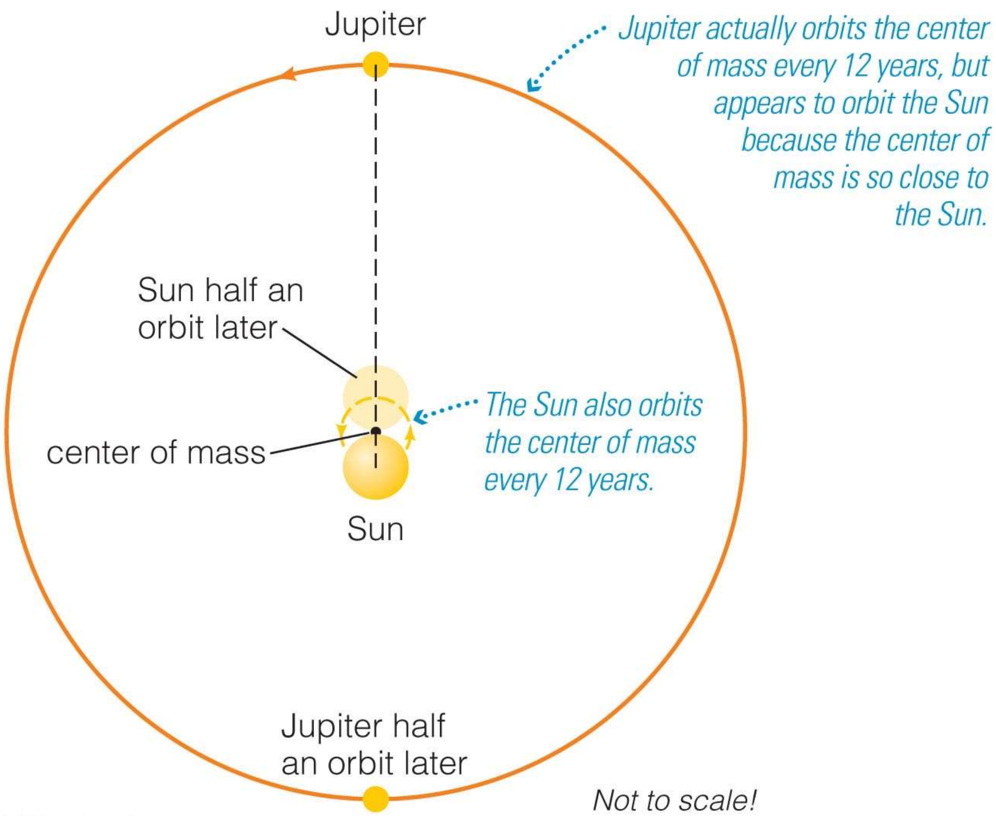
Indirect:

- Measurements of stellar properties revealing the effects of orbiting planets

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



Gravitational "Tugging"



Jupiter actually orbits the center of mass every 12 years, but appears to orbit the Sun because the center of mass is so close to the Sun.

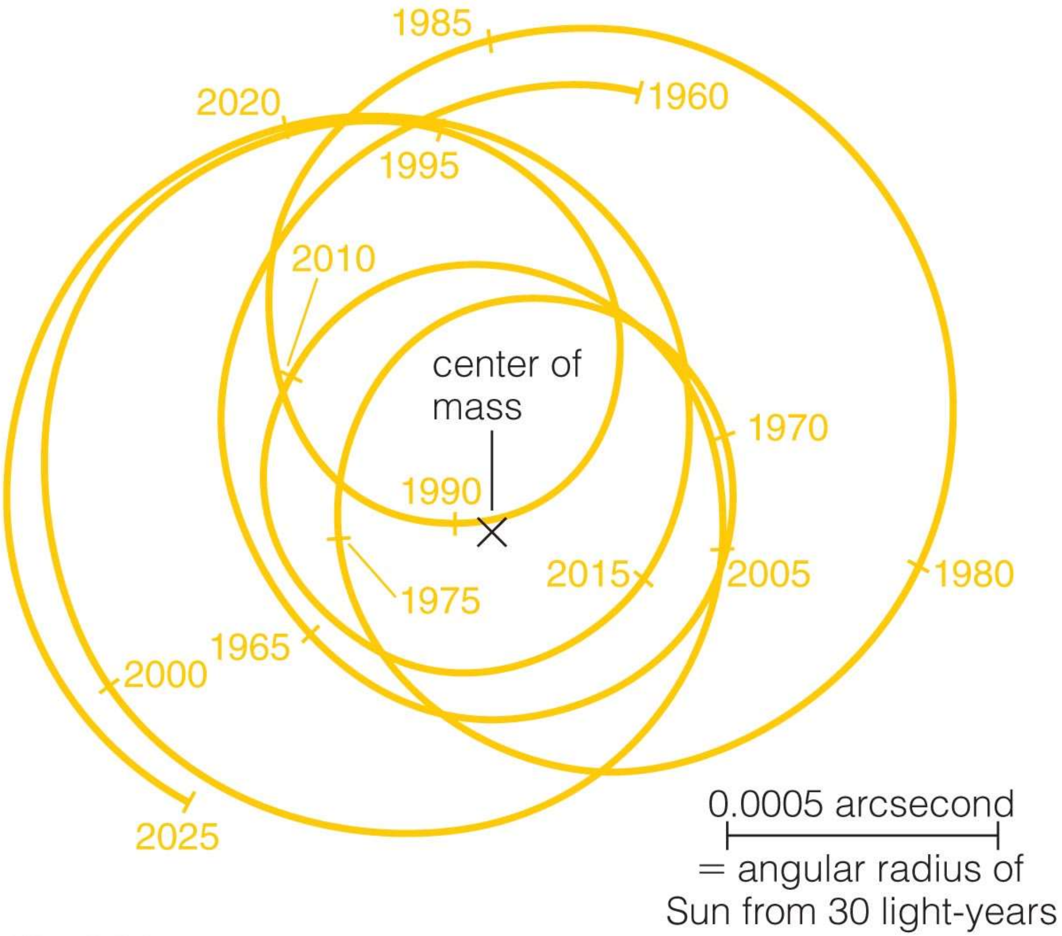
The Sun also orbits the center of mass every 12 years.

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 ***<u>all the planets</u>***.

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?

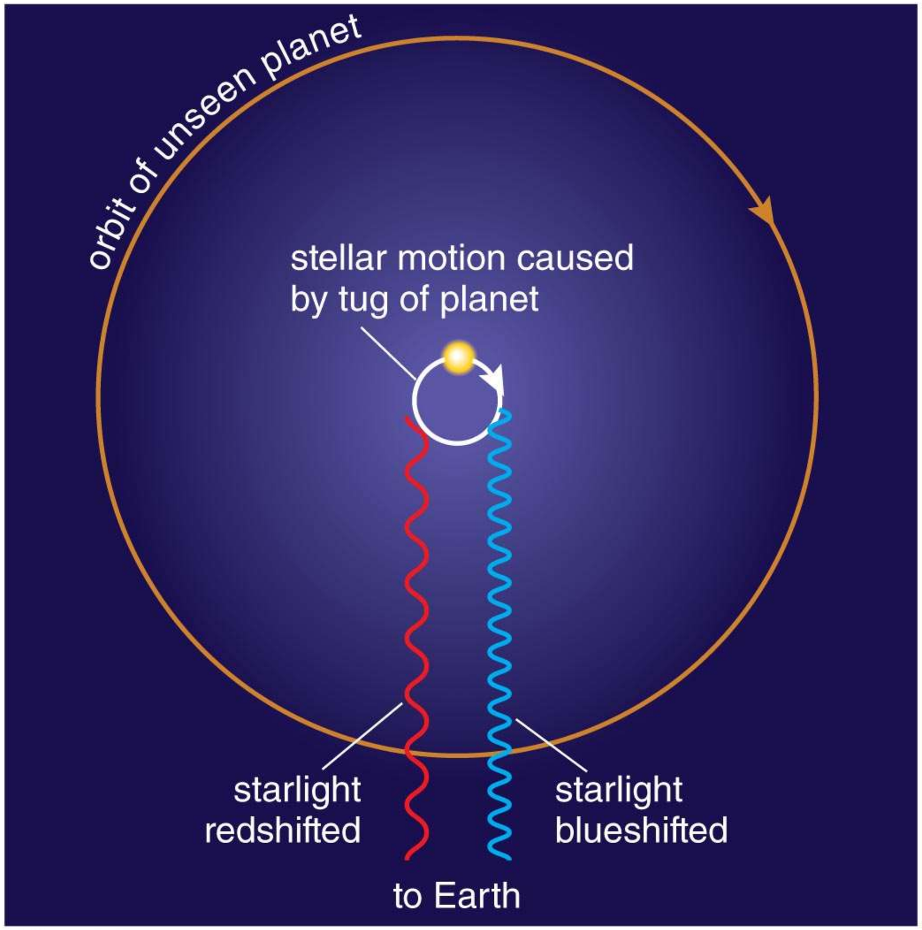
- Orbital period, distance and eccentricity
- Planetary mass

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)



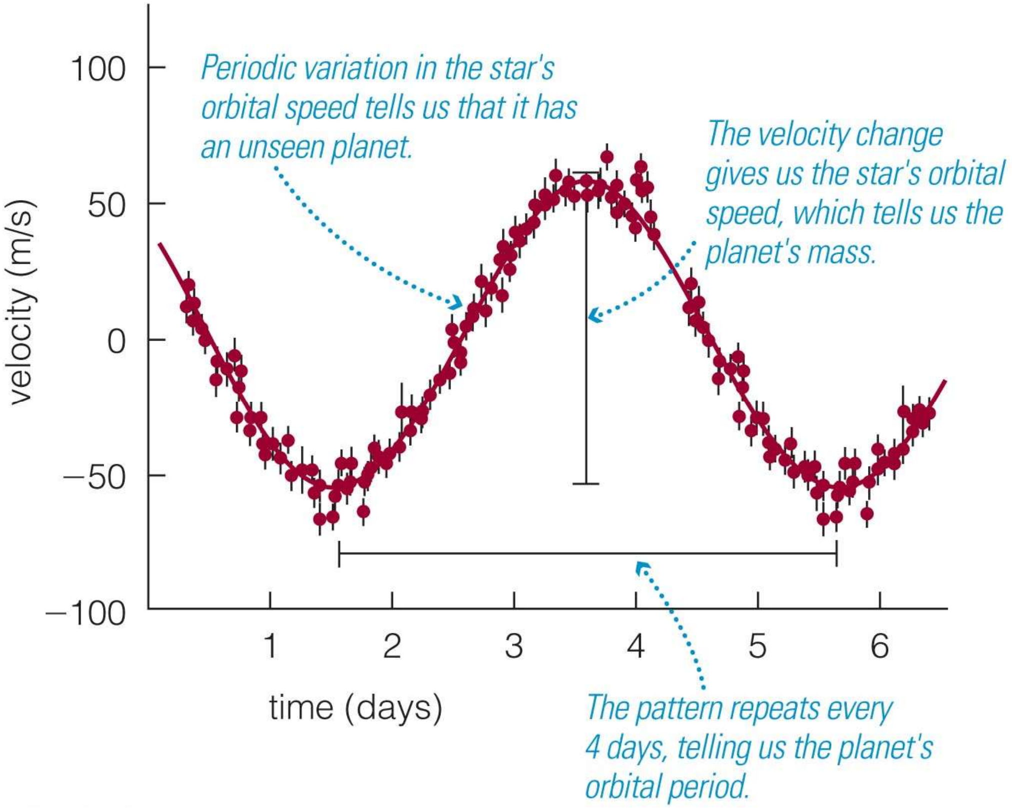
Requires the planetary system to be sufficiently 'edge-on'

- 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



Periodic variation in the star's orbital speed tells us that it has an unseen planet.

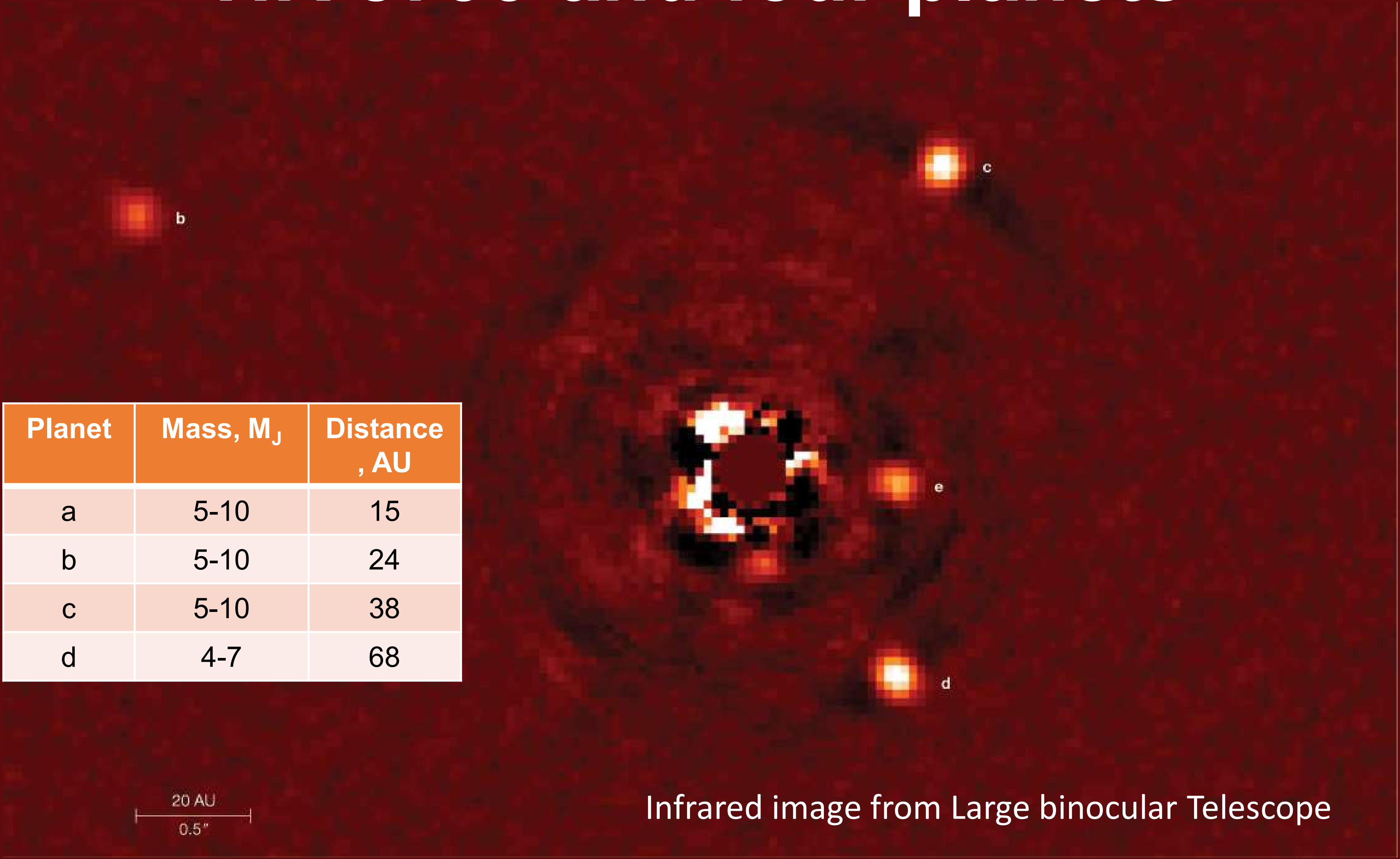
The velocity change gives us the star's orbital speed, which tells us the planet's mass.

The pattern repeats every 4 days, telling us the planet's orbital period.

- 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

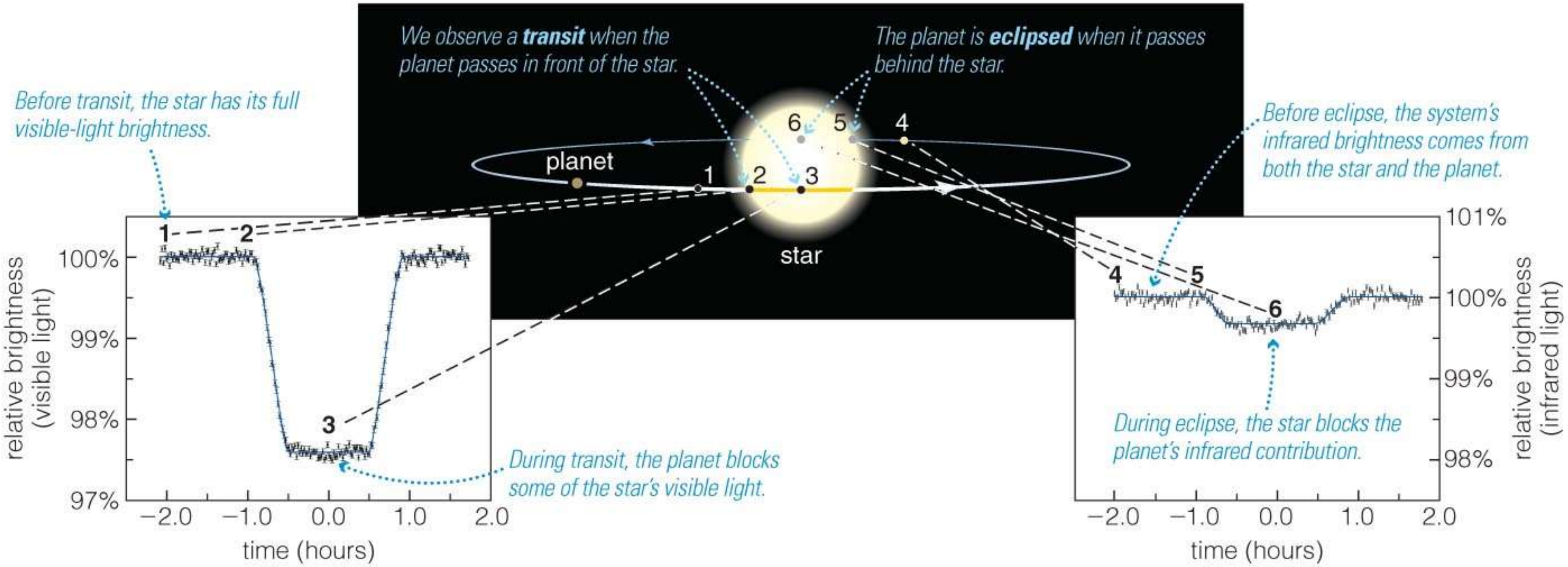


Planet	Mass, M_J	Distance , AU
a	5-10	15
b	5-10	24
c	5-10	38
d	4-7	68

Infrared image from Large binocular Telescope

The Transit Method

(Direct technique)



Before transit, the star has its full visible-light brightness.

We observe a ***transit*** when the planet passes in front of the star.

The planet is ***eclipsed*** when it passes behind the star.

Before eclipse, the system's infrared brightness comes from both the star and the planet.

During transit, the planet blocks some of the star's visible light.

During eclipse, the star blocks the planet's infrared contribution.

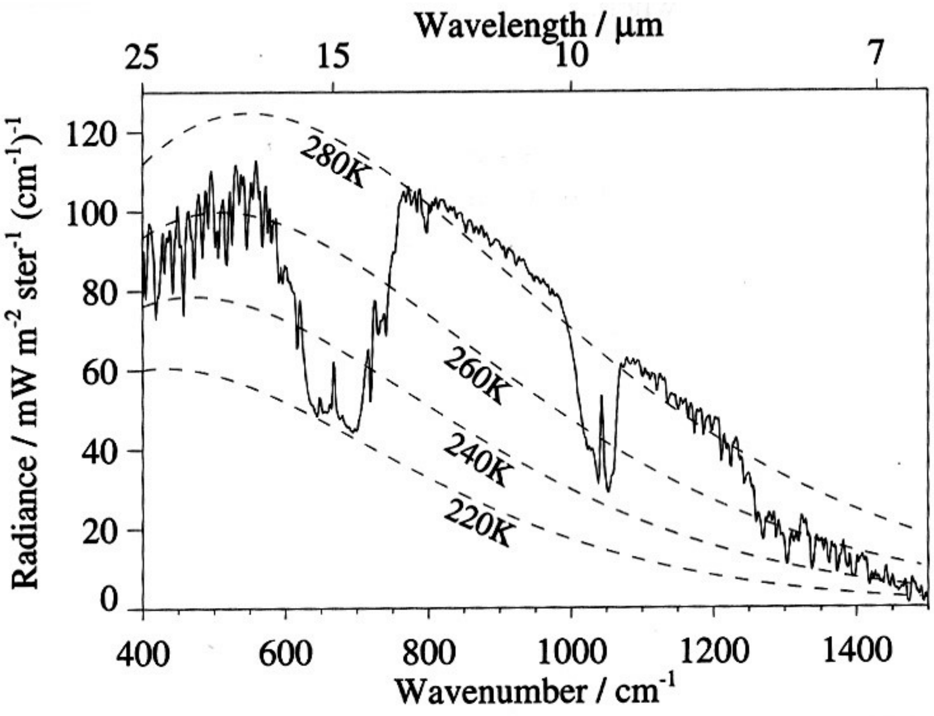
- A **transit** is when a planet crosses in front of a star.
- This reduces the star's apparent brightness and tells us planet's radius.
- Sometimes an **eclipse** – the planet passing behind the star, can also be detected. *(Contributions of exoplanet atmosphere are **now** hidden)*

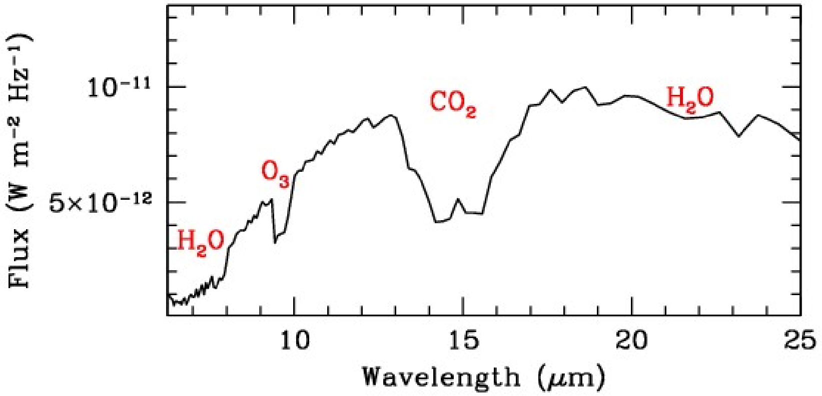
The Transit Method

(Direct technique)

What can if help inform you of?

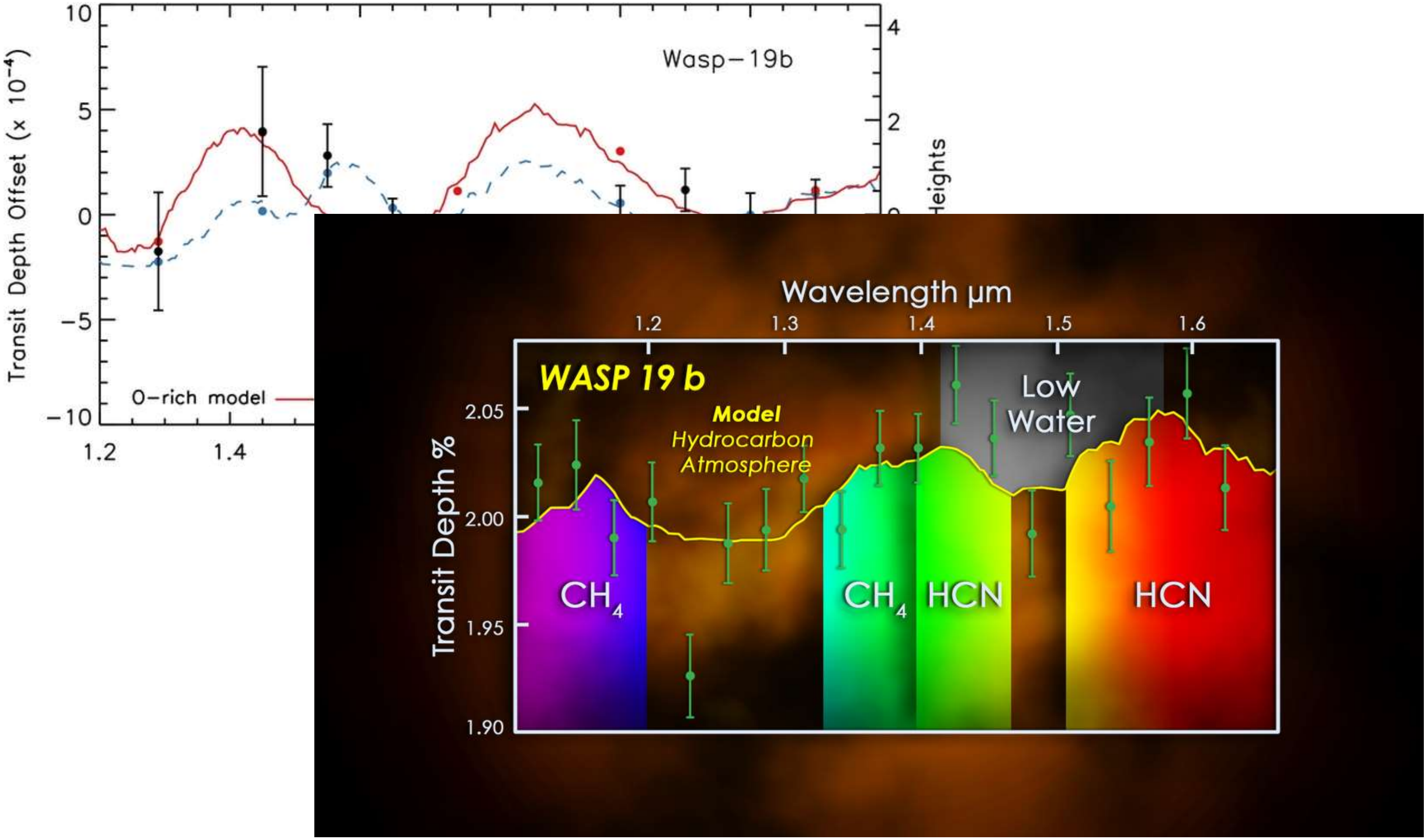
- *Orbital periods and distances*
- *Size of a planet (radius), which can be used to help determine density*
- *Atmospheric composition, and temperature (from black body)*



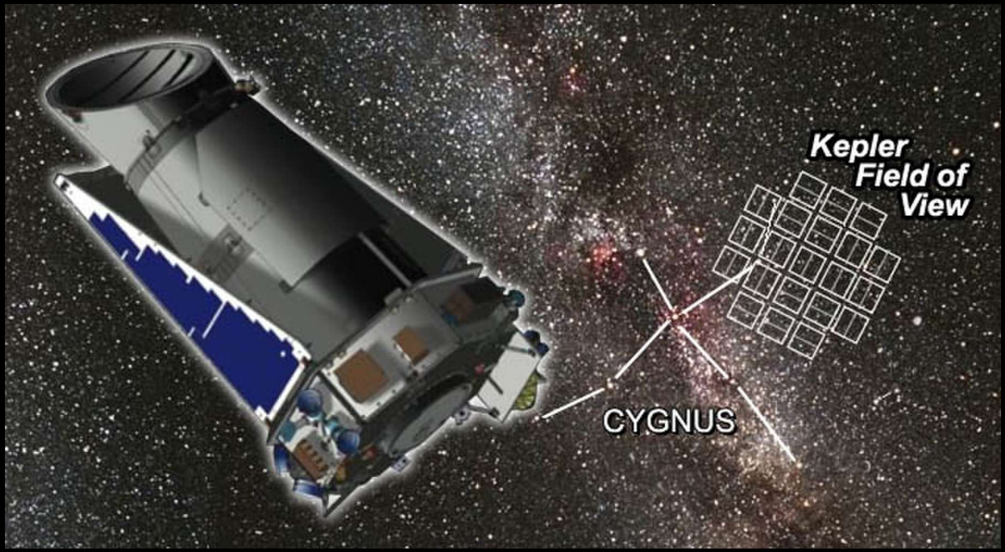


The James Webb Space Telescope will be able to determine atmospheric compositions as follow-up observations

Example of Subtraction of Spectra to Get Atmospheric Compositions



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

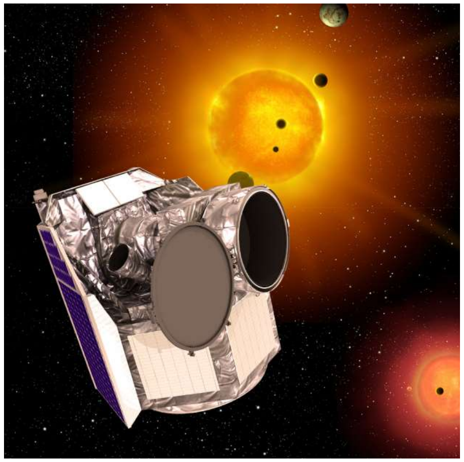
Next Generation Transit Method Spacecraft

NASA's TESS (Transiting Exoplanet Survey Satellite)

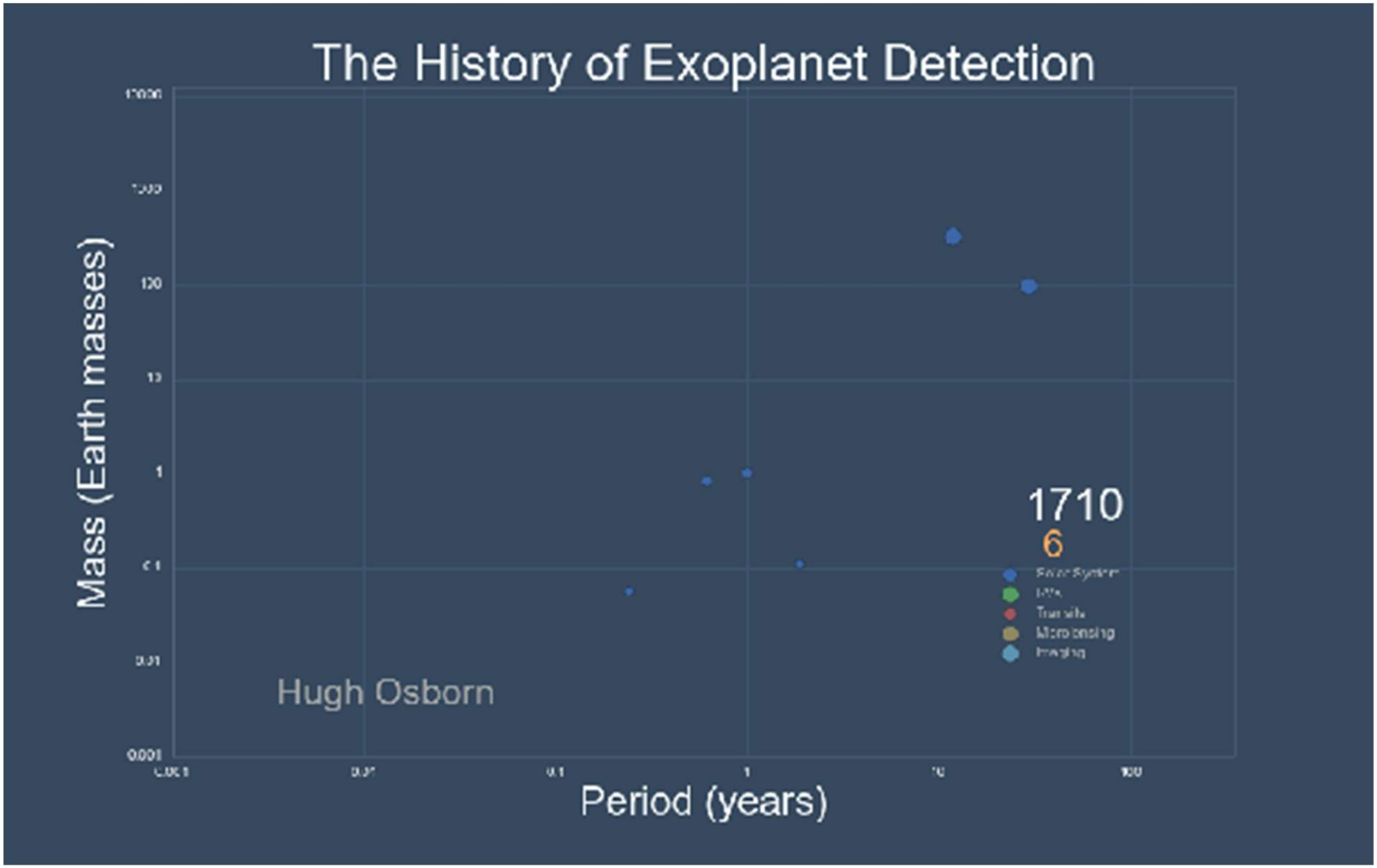
- Launch April 2018(?)
- Monitor ~ 500,000 stars in area 400 times that of Kepler
- Includes 1,000 closest Red Dwarf stars
- Expected to discover >3000 exoplanets

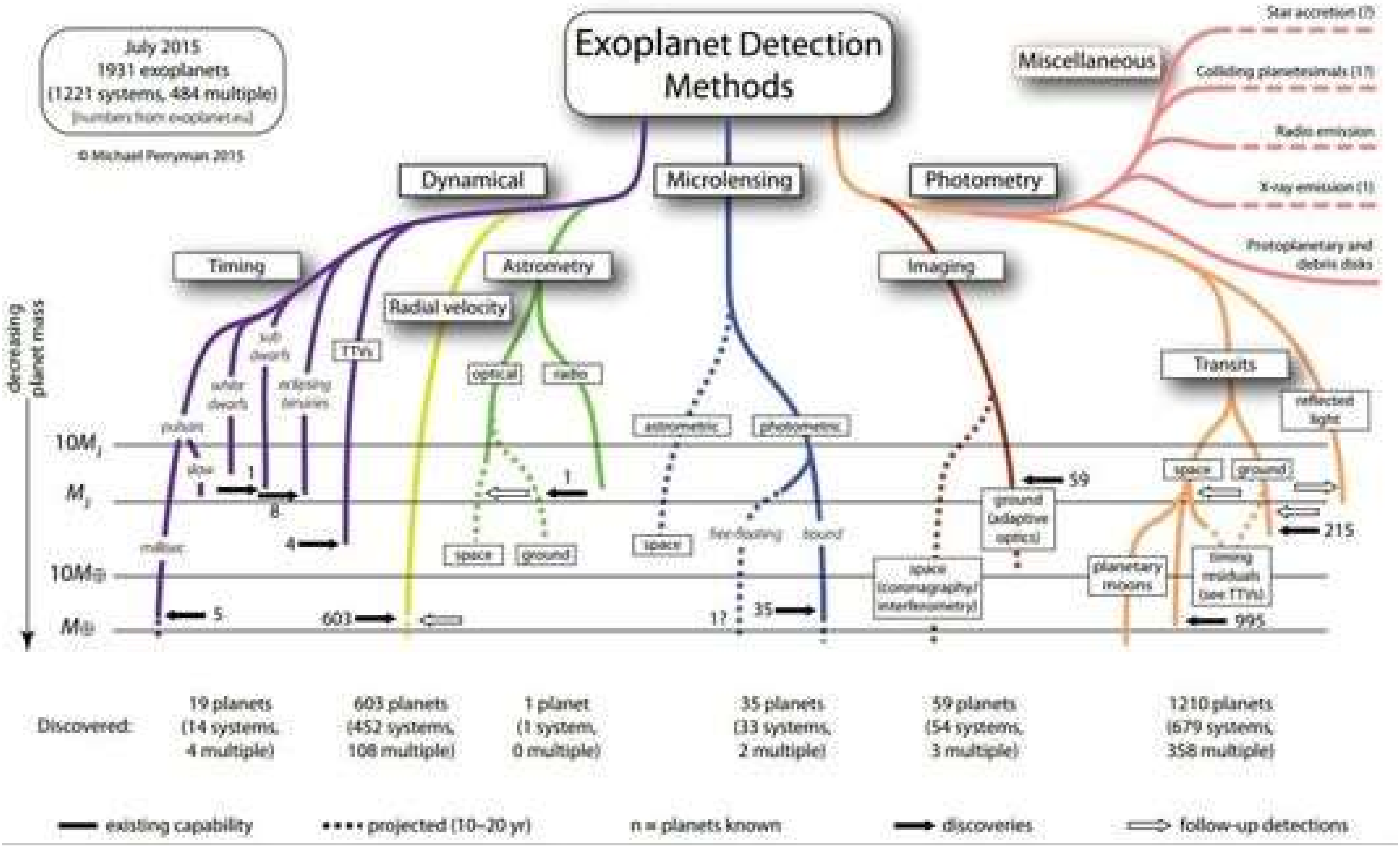
ESA's CHEOPS (**Ch**aracterizing **E**x**op**lanets **S**atellite)

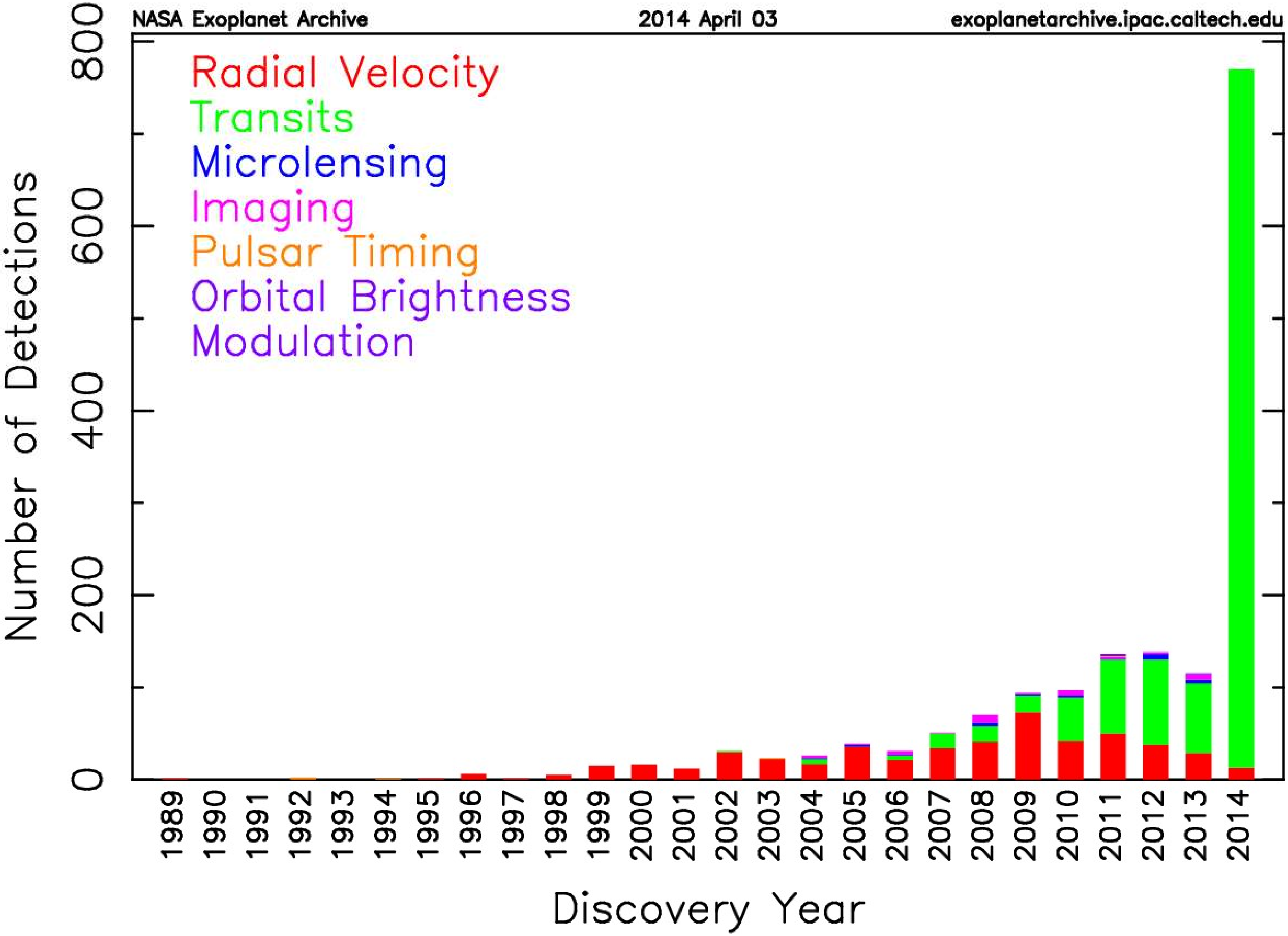
- Launch end of 2018(?)
- Focus to measure radii of previously detected exoplanets to help determine densities
- Shallow transit focus (Earth-like)



Exoplanet Detection (2017 version)




July 2015
1931 exoplanets
(1221 systems, 484 multiple)
[numbers from exoplanet.eu]
© Michael Perryman 2015
Exoplanet Detection Methods
Dynamical
Microlensing
Photometry
Miscellaneous
Star accretion (?)
Colliding planetesimals (1?)
Radio emission
X-ray emission (1)
Protoplanetary and debris disks
Timing
Radial velocity
Astrometry
Imaging
Transits
reflected light
decreasing planet mass
pulsars
white dwarfs
sub dwarfs
eclipsing binaries
TTVs
slow
millisec
optical
radio
space
ground
astrometric
photometric
space
free-floating
bound
space (coronagraphy/interferometry)
ground (adaptive optics)
space
ground
planetary moons
timing residuals (see TTVs)
$10M_J$
M_J
$10M_⊕$
$M_⊕$
1
8
4
5
603
1
1?
35
59
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


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
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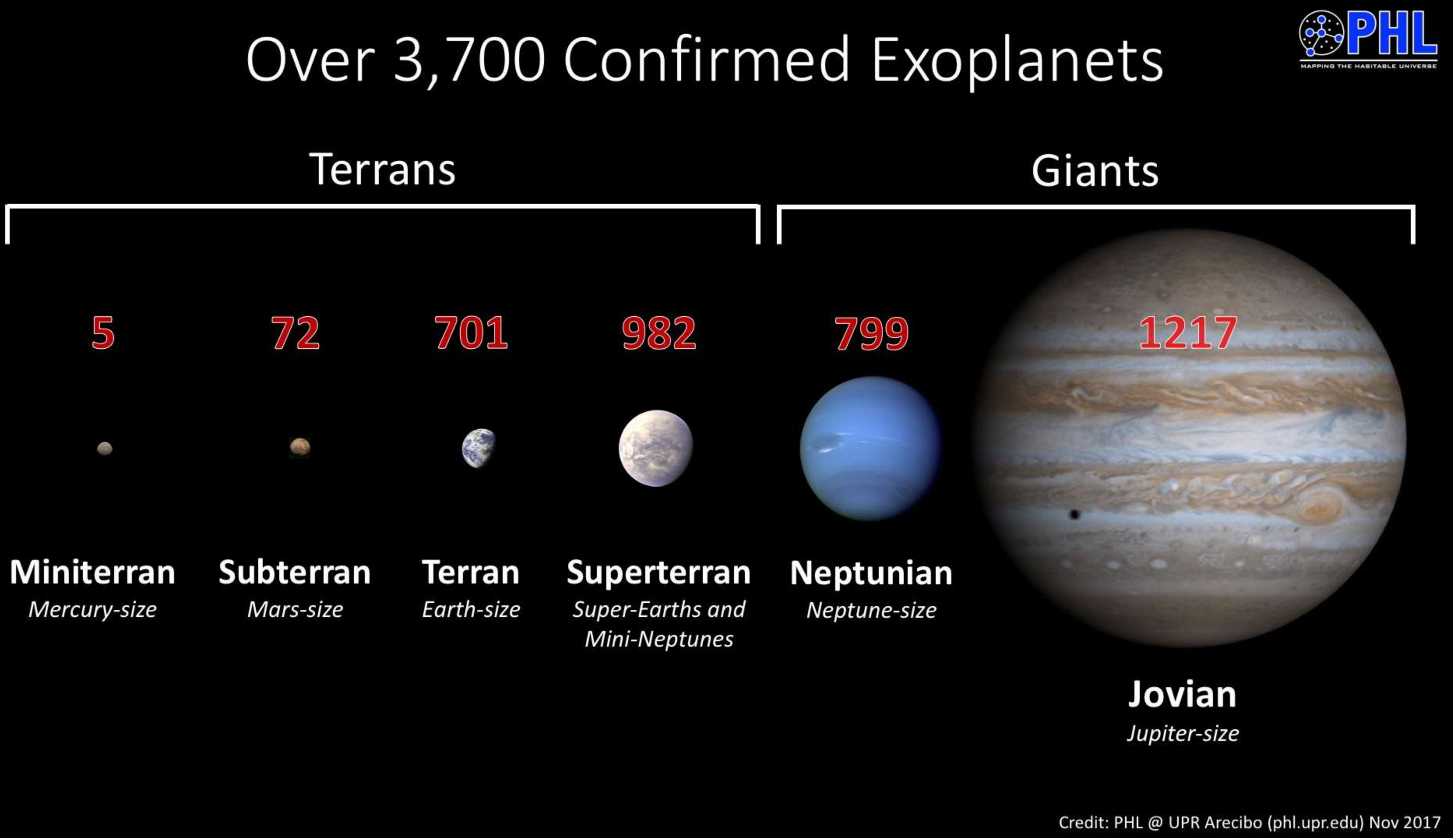
2006
2007
2008
2009
2010
2011
2012
2013
2014
Discovery Year

Summary of Detections to Date

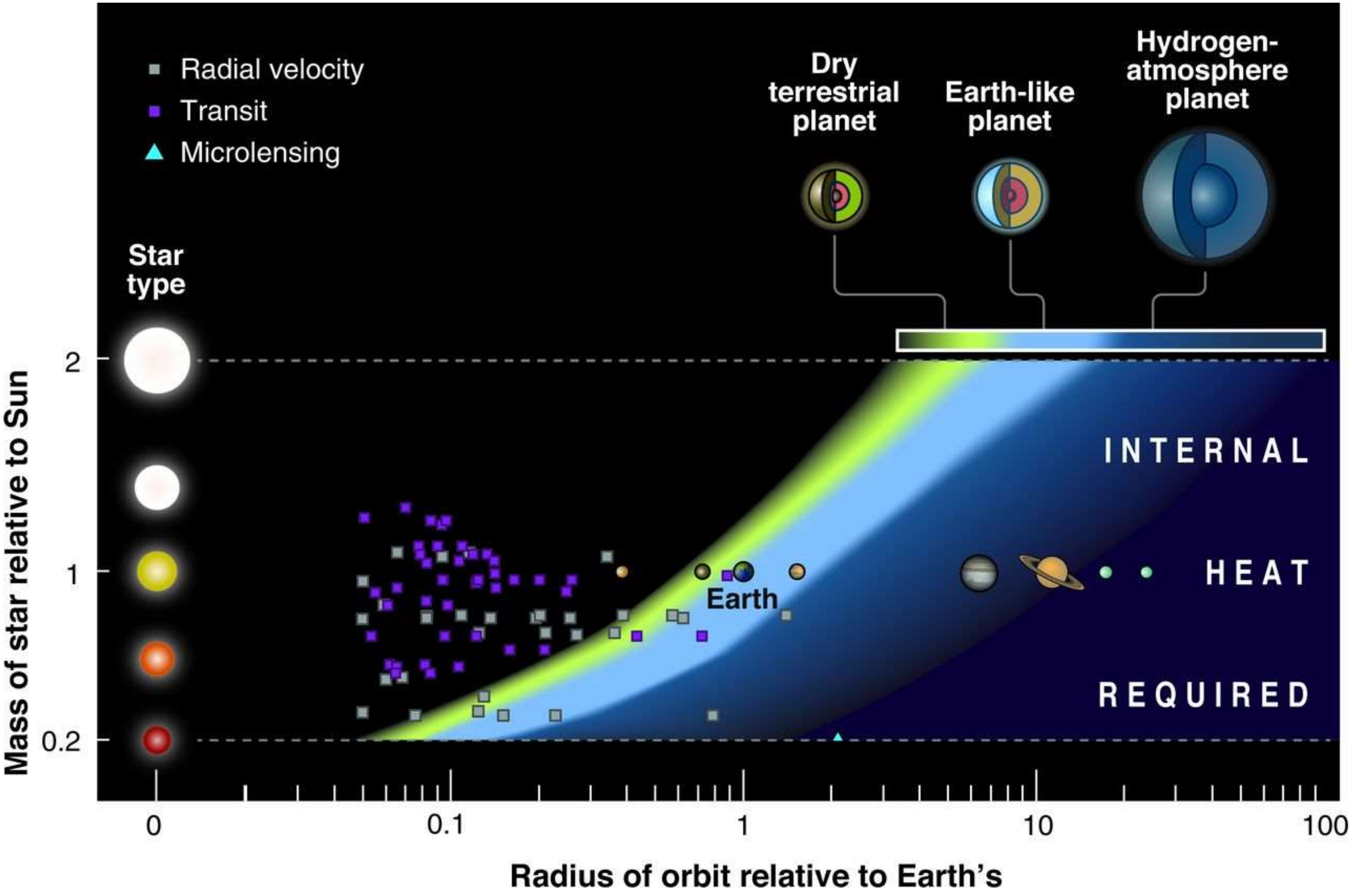


Over 3,700 Confirmed Exoplanets

Credit: PHL @ UPR Arecibo (phl.upr.edu) Nov 2017

The Habitable Zone

The Habitable Zone Around Other Stars



The Habitable Zone Around Other Stars

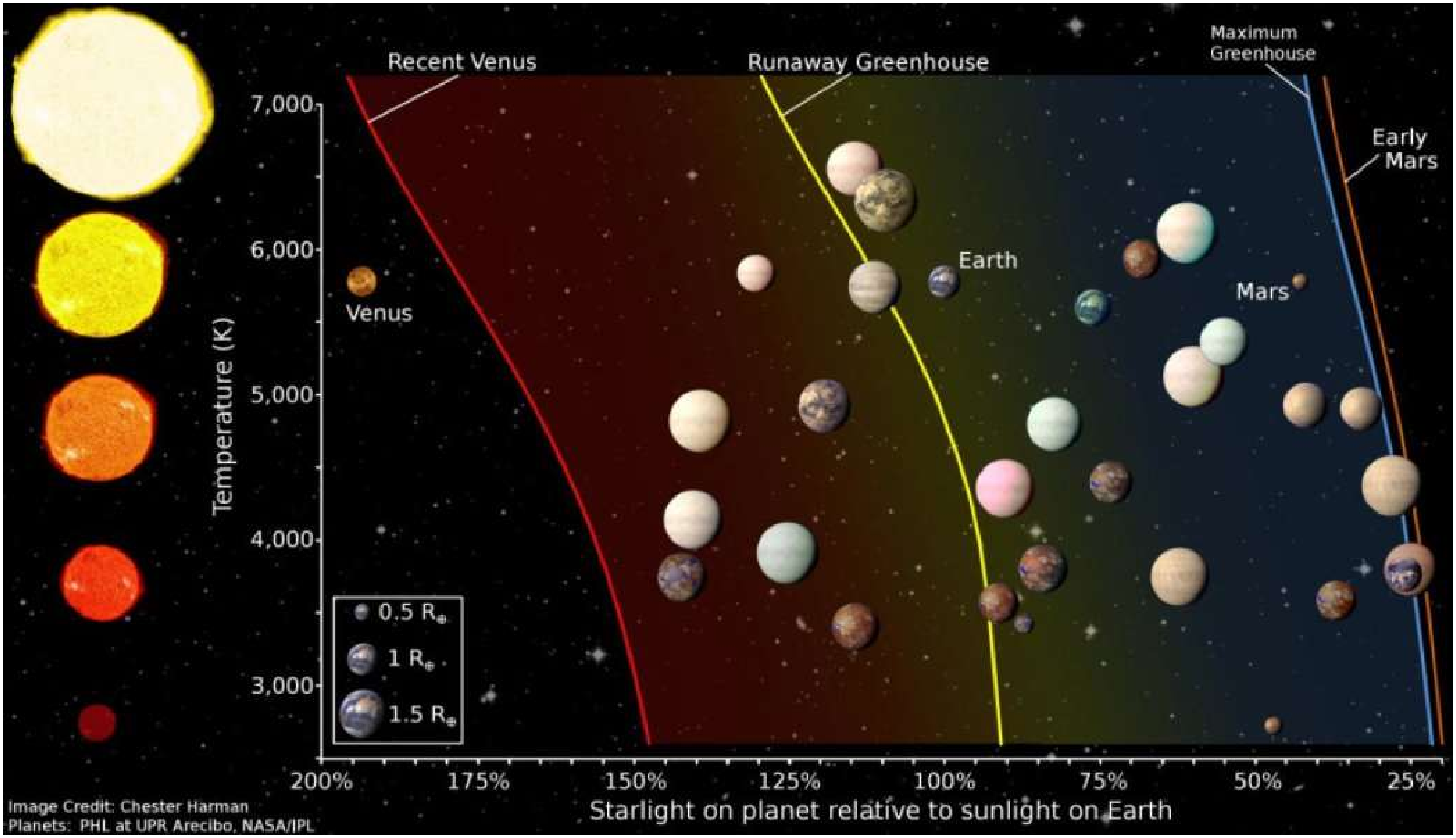
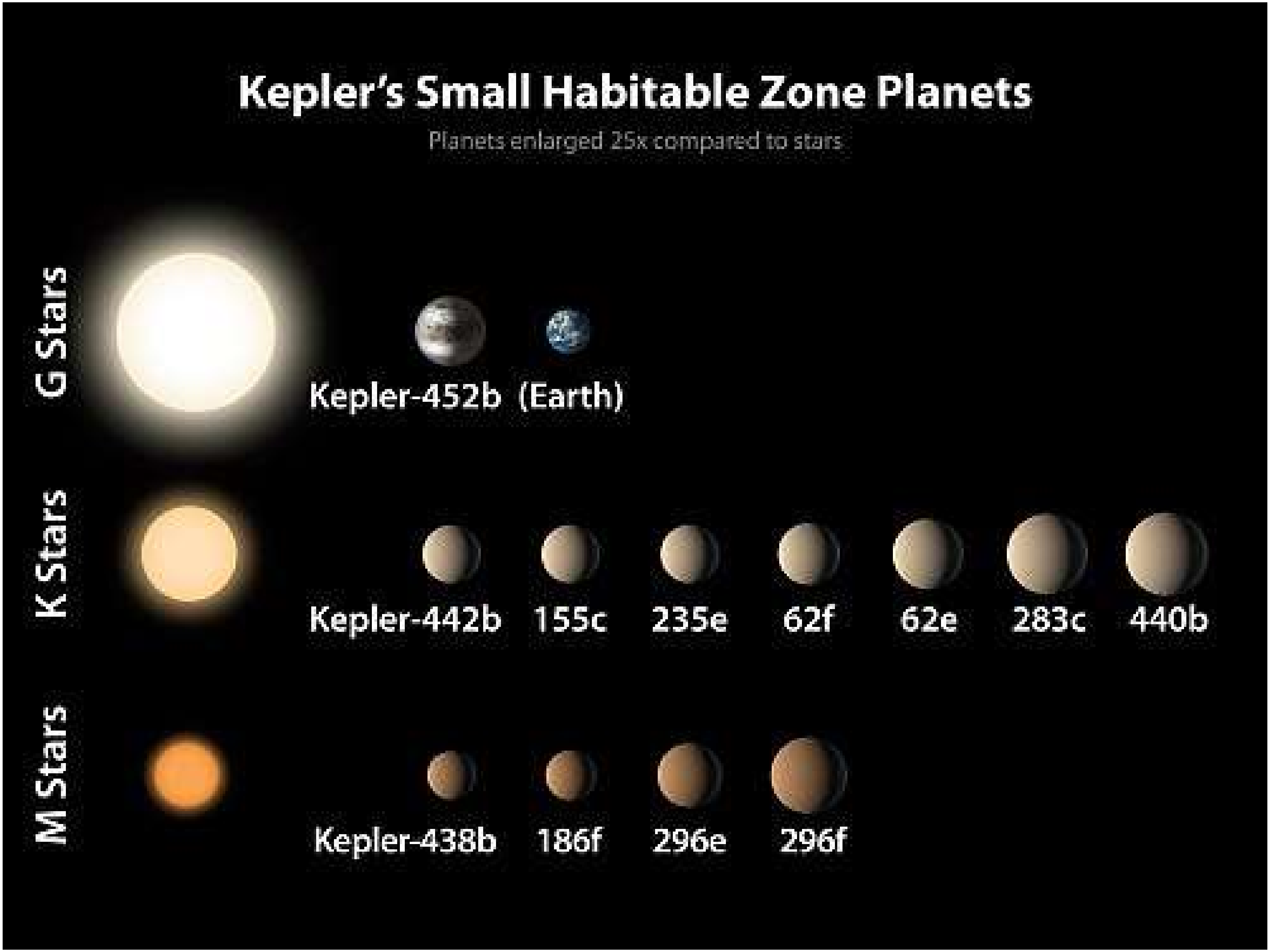
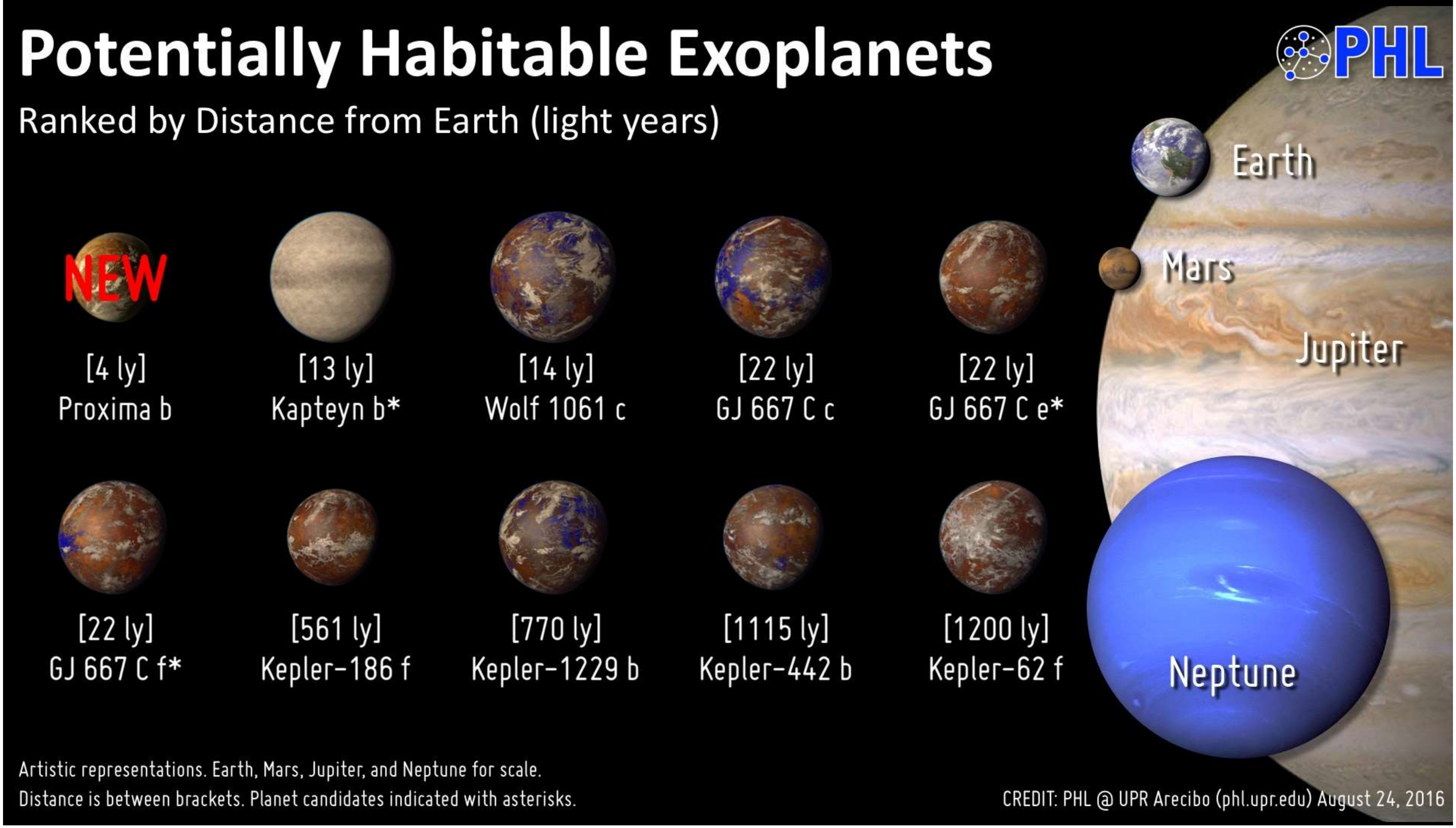


Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/JPL


Kepler's Small Habitable Zone Planets
Planets enlarged 25x compared to stars
G Stars
Kepler-452b
(Earth)
K Stars
Kepler-442b
155c
235e
62f
62e
283c
440b
M Stars
Kepler-438b
186f
296e
296f

Potentially Habitable Exoplanets



Potentially Habitable Exoplanets

Ranked by Distance from Earth (light years)

[4 ly]
Proxima b

[13 ly]
Kapteyn b*

[14 ly]
Wolf 1061 c

[22 ly]
GJ 667 C c

[22 ly]
GJ 667 C e*

[22 ly]
GJ 667 C f*

[561 ly]
Kepler-186 f

[770 ly]
Kepler-1229 b

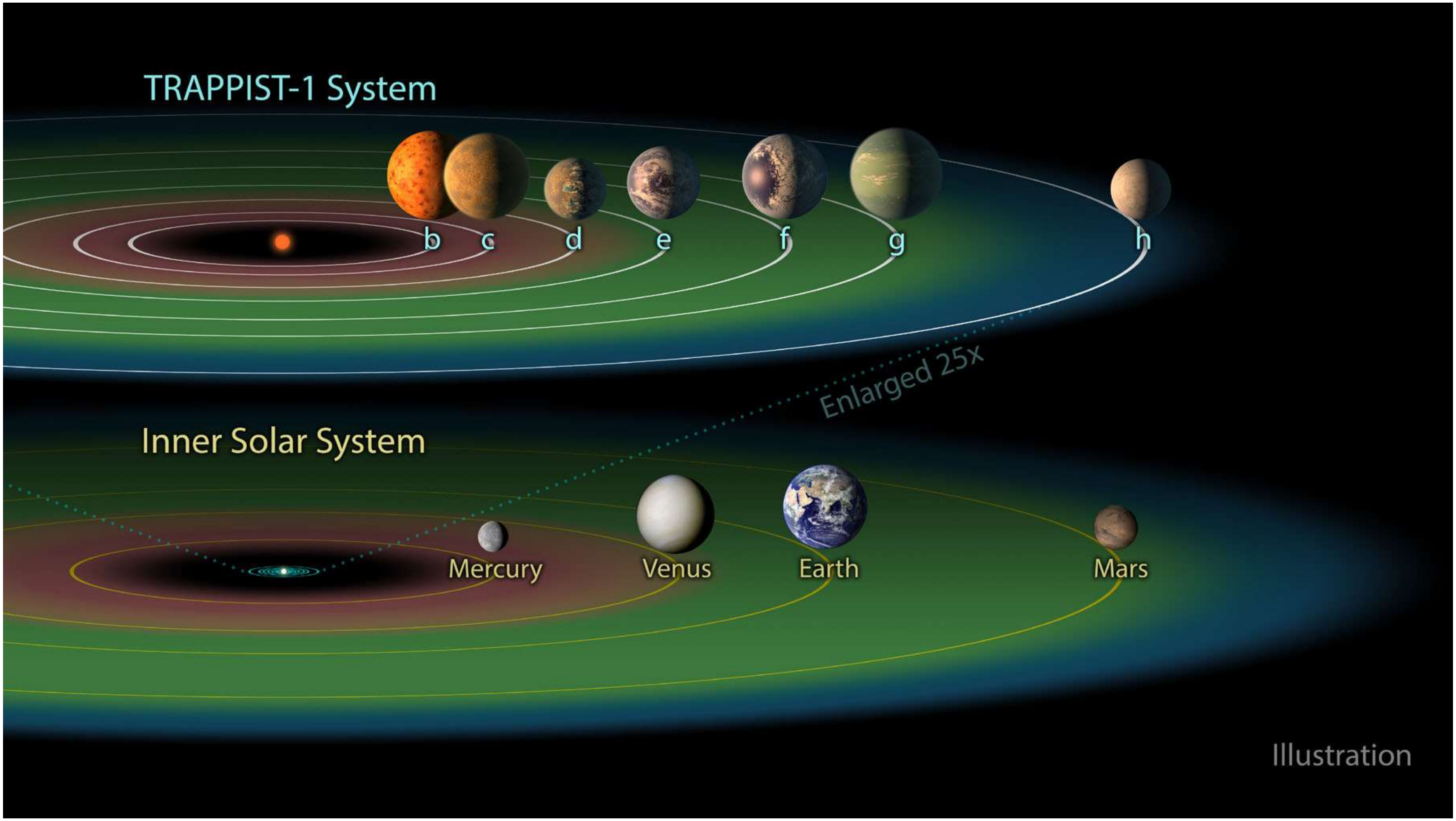
[1115 ly]
Kepler-442 b

[1200 ly]
Kepler-62 f

Artistic representations. Earth, Mars, Jupiter, and Neptune for scale.
Distance is between brackets. Planet candidates indicated with asterisks.

CREDIT: PHL @ UPR Arecibo (phl.upr.edu) August 24, 2016

Trappist 1 System (40 light-years away)



End of Todays Lecture