Announcements

- **Quiz 9** on solar system due tonight, see also Problem Set 9
- Today: planets around other stars (Chapter 4.4)
- Next: **Galaxies**
  - Please read Chapter 14
- **Stargazing for extra credit on Wednesday**, weather permitting
  - 9 – 10 pm, roof of Physics building
  - More info on location and extra credit assignment on D2L (Content -> Handouts -> Stargazing)
  - Also April 21, 22, 23, 24: last chance

Astronomy 103

Extra-Solar Planets

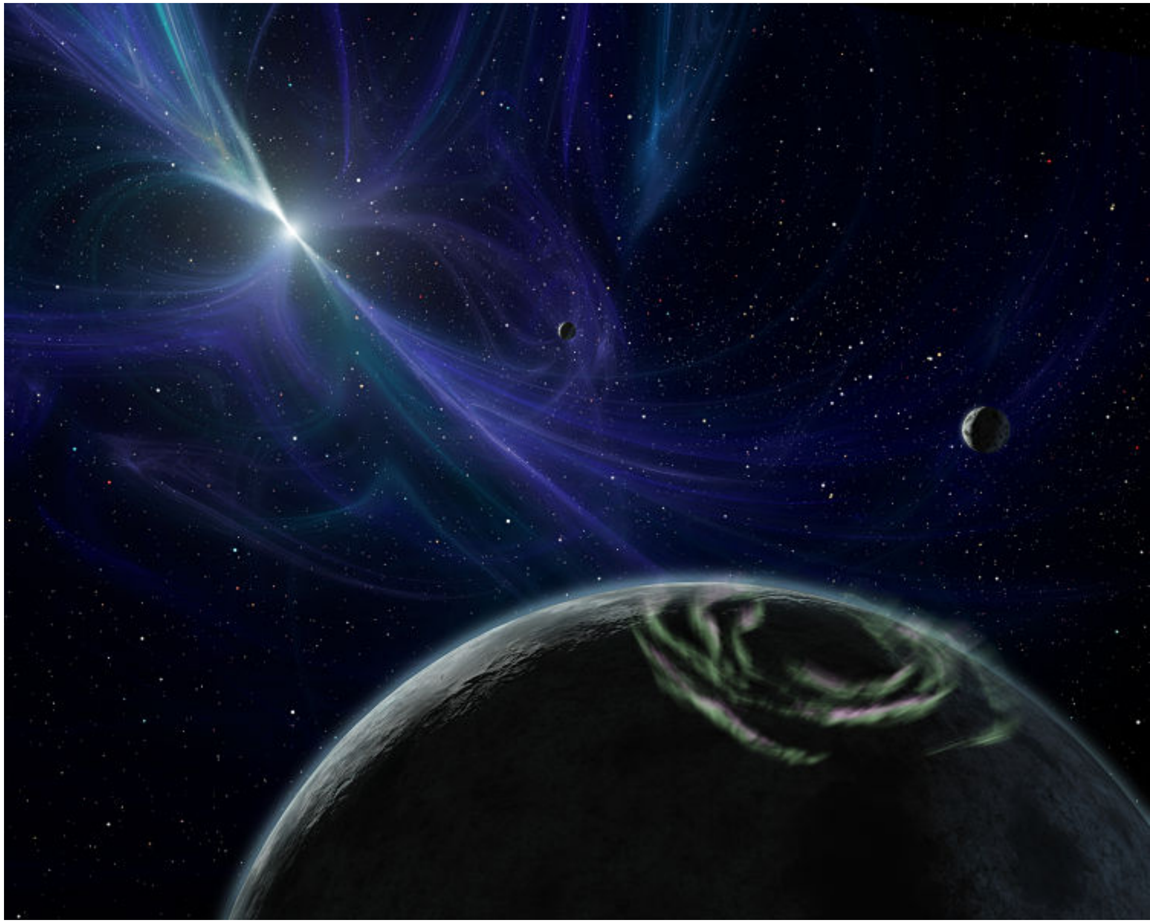
Please read chapter 4.4


Many years of speculation that planets exist outside our solar system…
But such planets are very hard to see (we're looking for a very very faint thing right next to a very very bright thing), so for many years finding them was not possible
This started to change in the 1990s

The Pulsar Planets

The first planets were found around the pulsar PSR B1257+12 in 1992.

They found 3 planets (4 suspected) from looking at the timing irregularities of the pulsar.



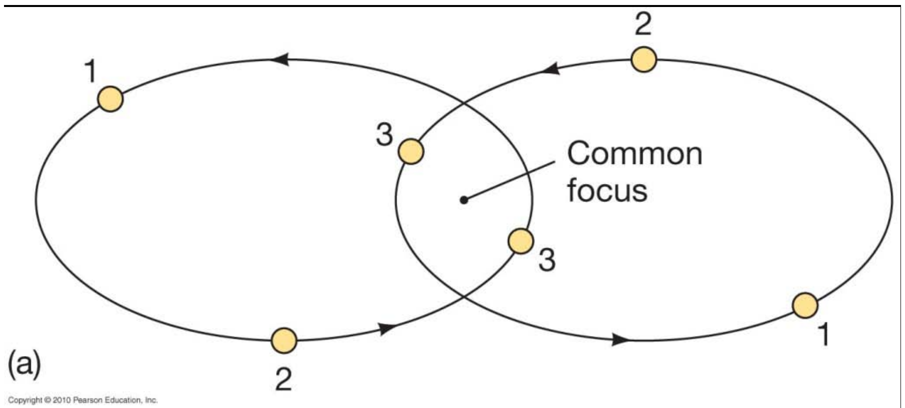
As planets orbit the pulsar, they exert tiny tugs on the pulsar which move it slightly out of place.

The Pulsar Planets

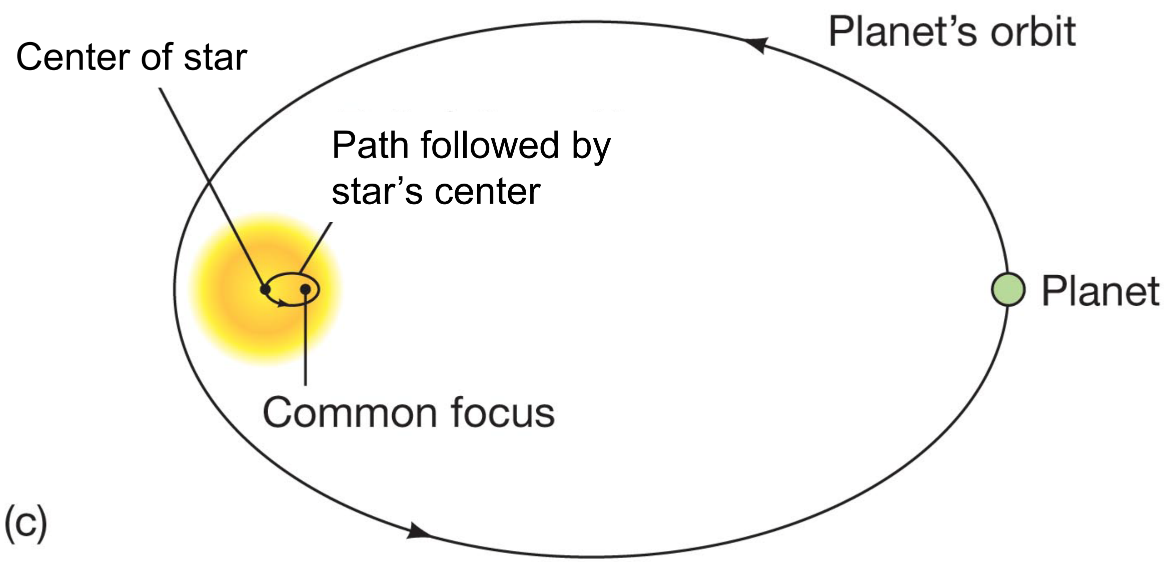
- It is amazing that planets can form in the aftermath of a supernova explosion
- BUT what we really want are planets that might harbor life
- So we need to develop techniques to be able to find planets around normal, main sequence stars

Technique 1: Radial Velocity

To understand the first technique for finding planets, we need to remember how orbits work

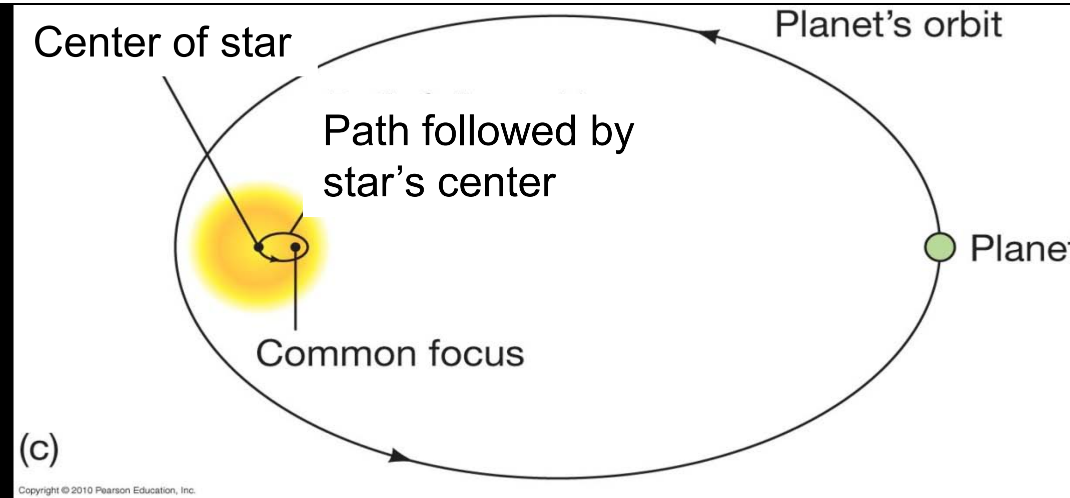


Two stars of the same mass orbit their common **center of mass**



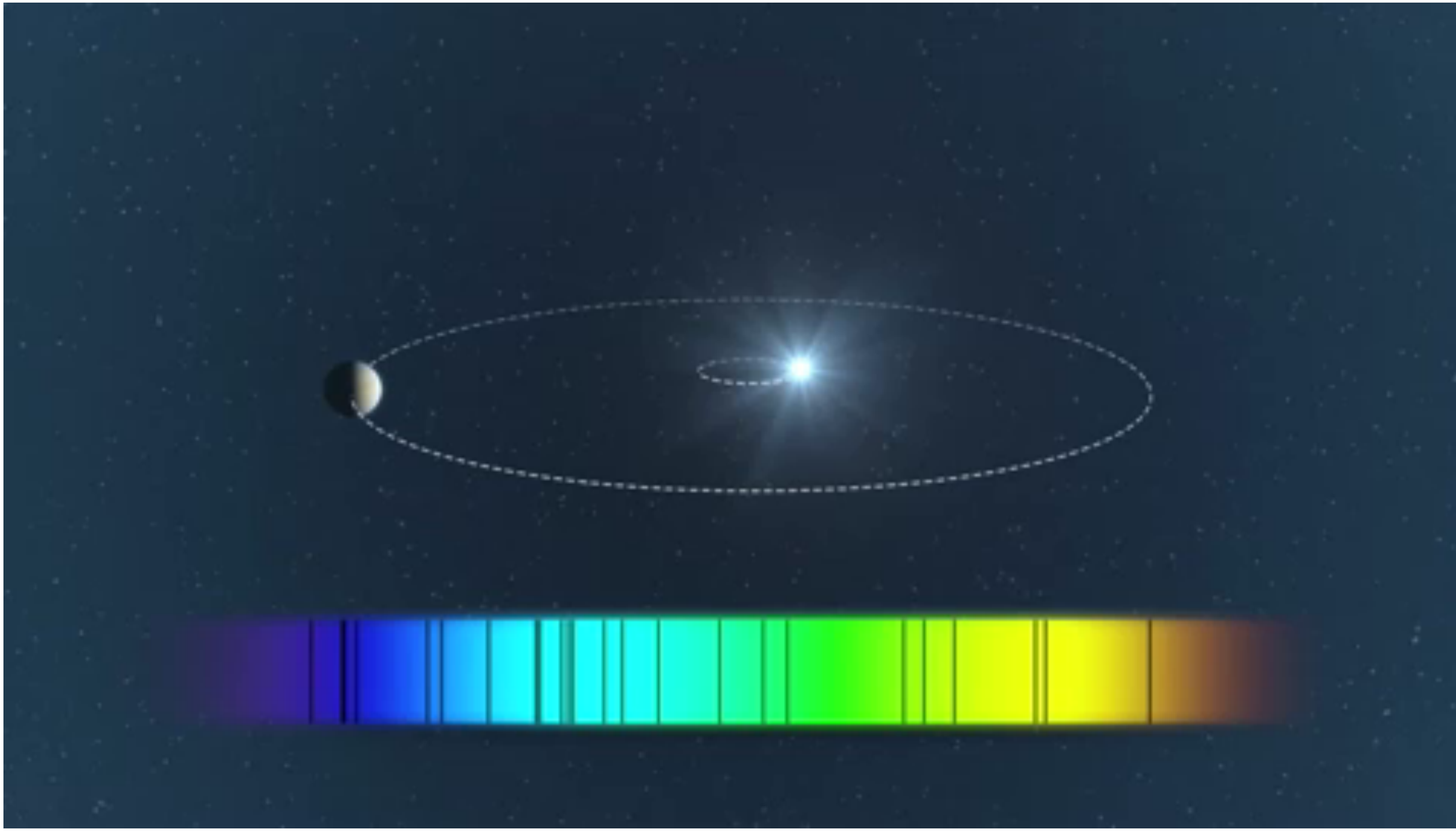
A planet and a star also orbit their common center of mass. Because the planet is much less massive, this may be inside the star, but it is not at the star's center. This causes the star to **wobble**.

Technique 1: Radial Velocity



- So as you look at a star which has an orbiting planet, the light of the star is redshifted as it moves away from you and blueshifted as it moves toward you
- This reveals the presence of a hidden body that pulls on the star, i.e., the planet
- Instead of looking for the planet directly, we look for the wobble it causes in the star

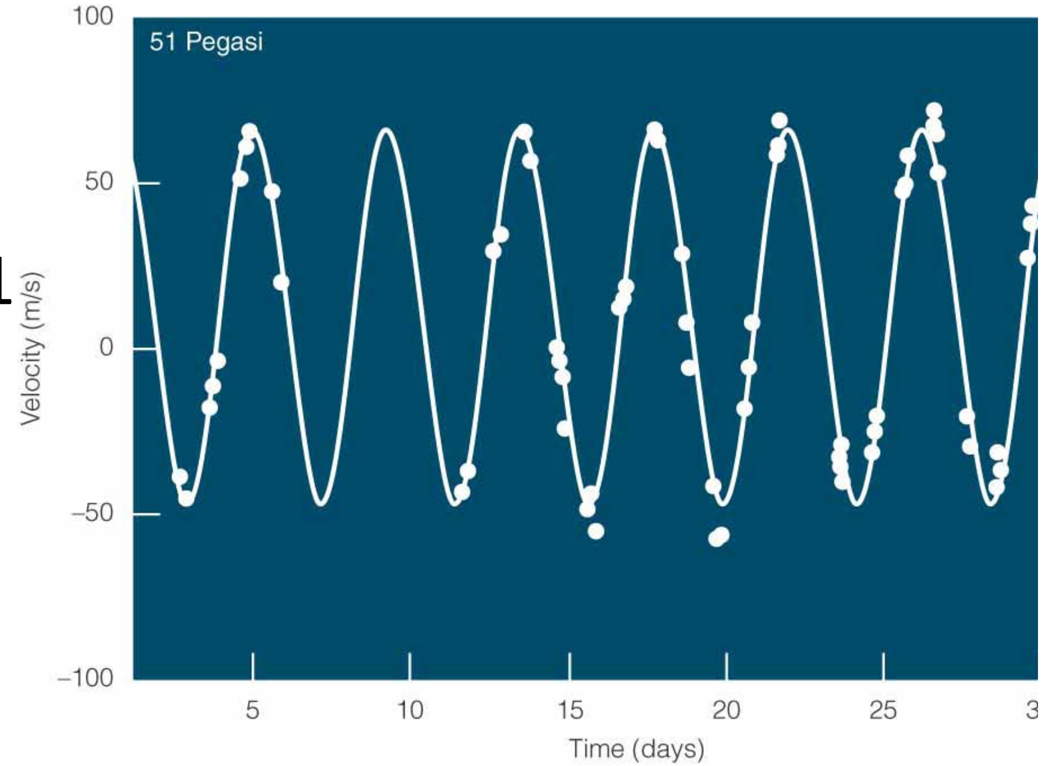
Technique 1: Radial Velocity



We look at the Doppler shifts in the spectral lines of these stars

Technique 1: Radial Velocity

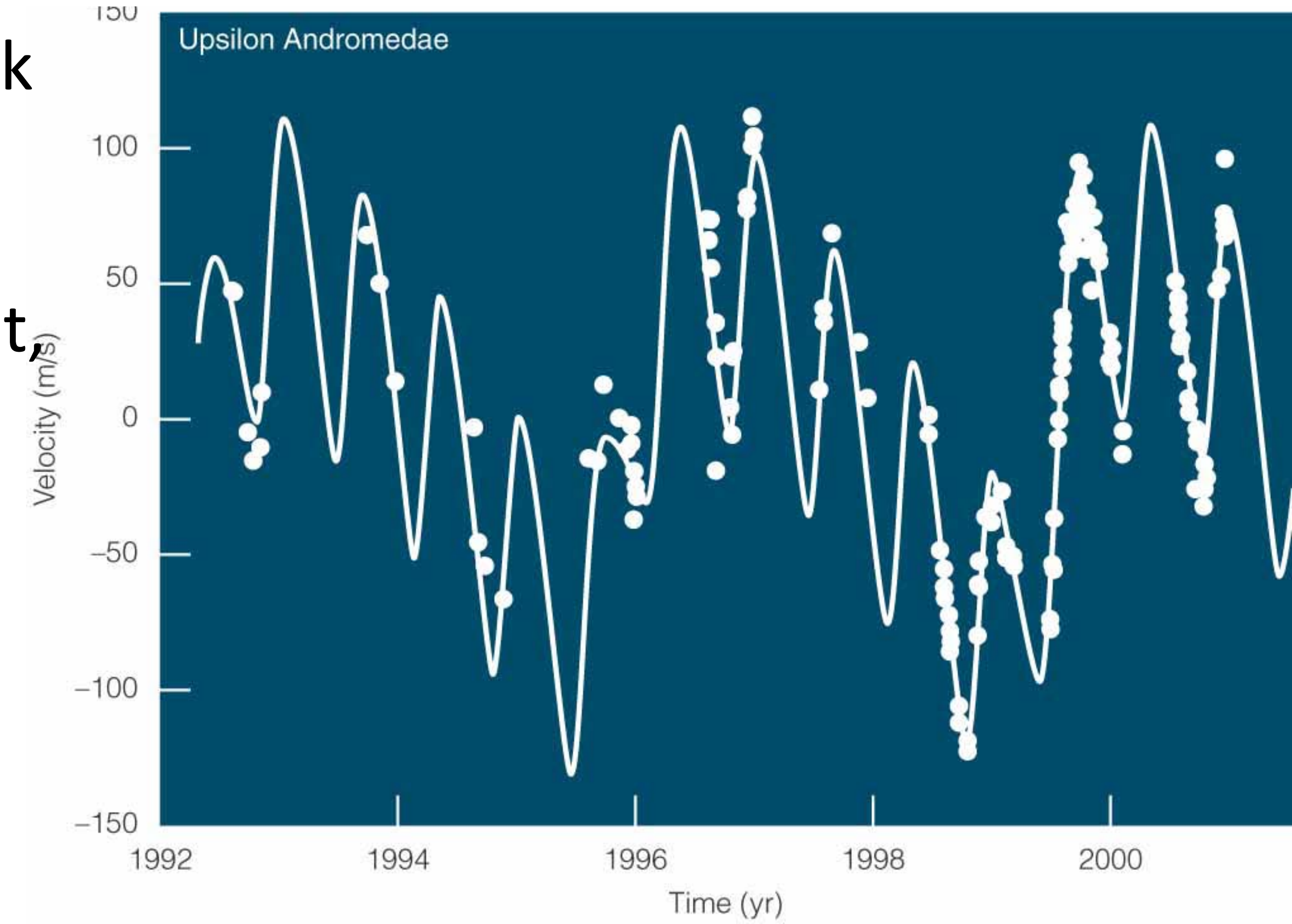
- Radial velocity was the first technique to find a planet around a normal star
- European team led by Michel Mayor found a planet in orbit around 51 Pegasi in 1995 using this technique
- About a 0.5 Jupiter mass planet in a short (4 day) orbit!
- Totally unexpected, since Jupiter-like planets can't form next to stars



Planet produces regular, repeated shifted in spectral lines of star

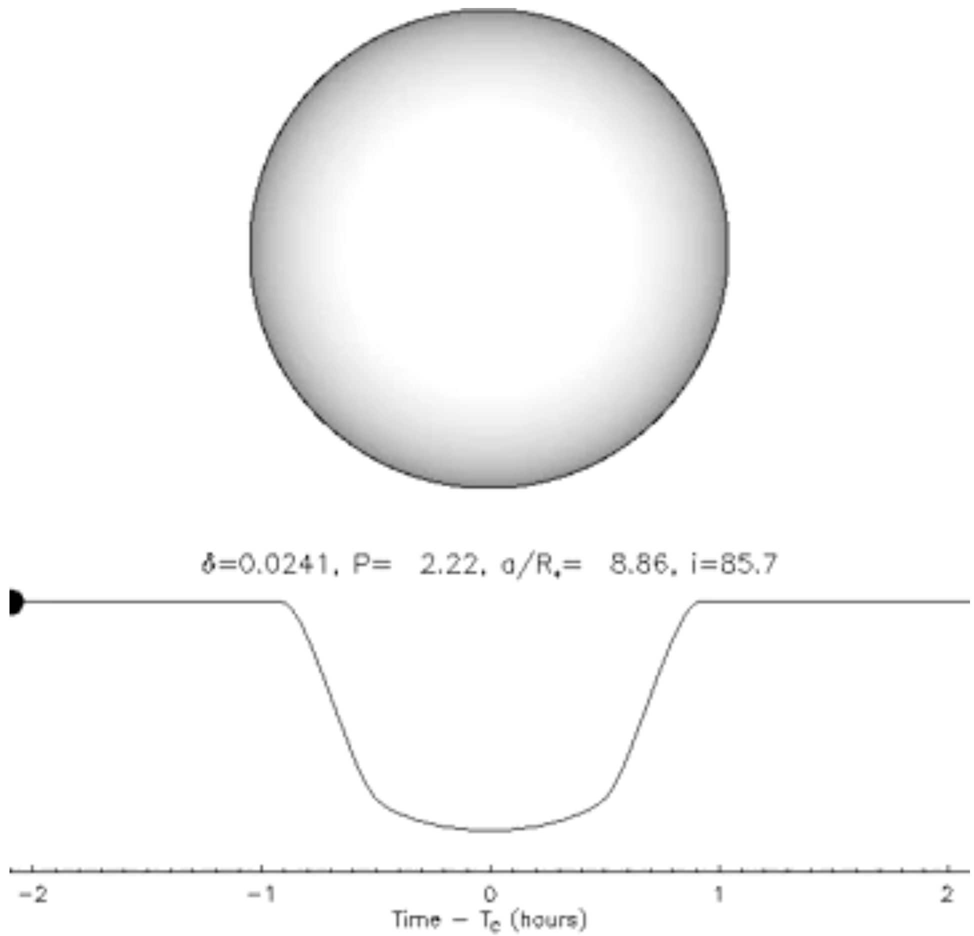
Technique 1: Radial Velocity

- If there is more than one planet, the radial velocity curves can be complicated!
- But we can break them down into contributions from each planet, to find multi-planet systems like Upsilon Andromedae
- 4 planets of around Jupiter mass



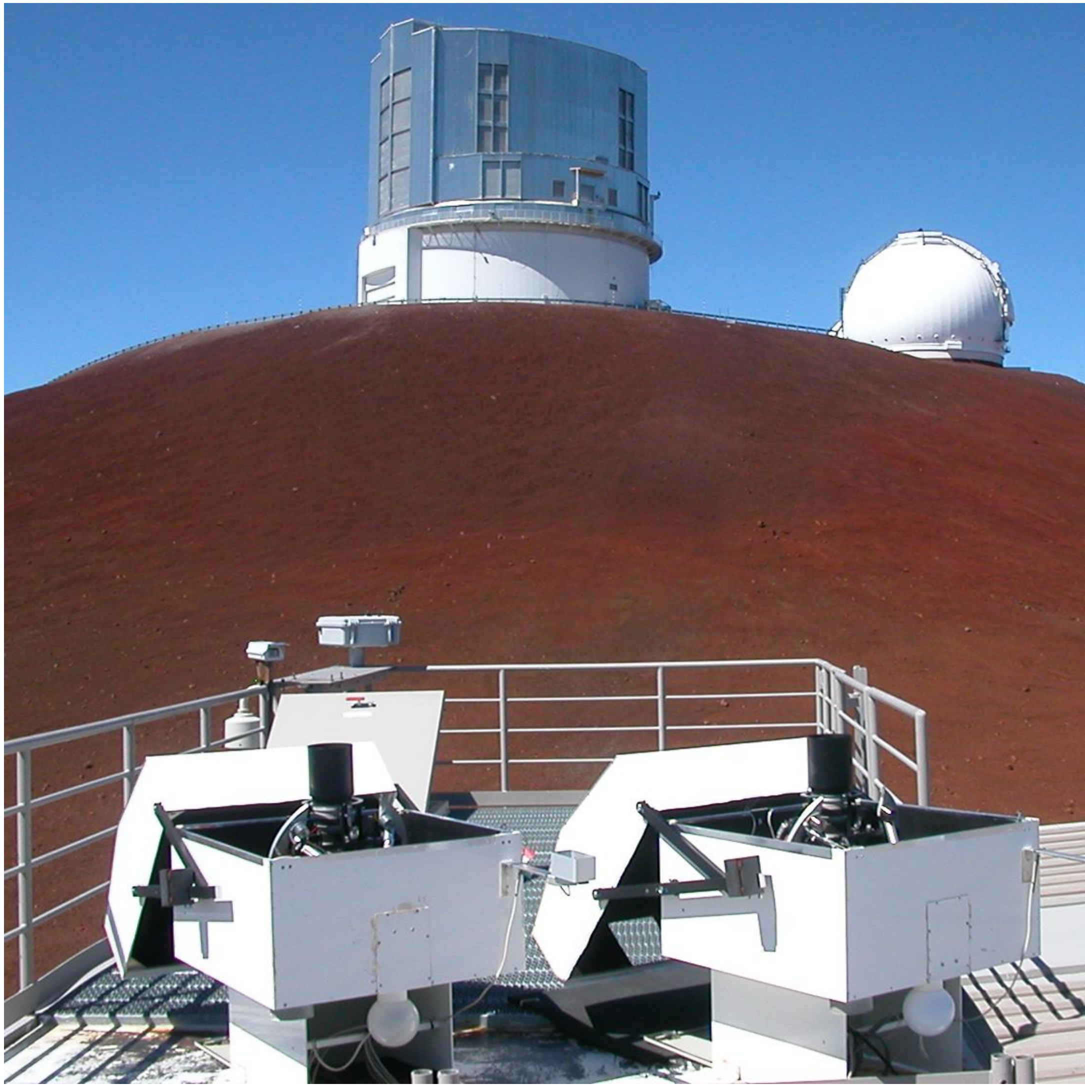
Technique 2: Transits

- Another way to find planets is to watch for eclipses, when planets pass in front of their parent star
- Look for a very small drop in the amount of light received
- This can tell us the radius of the planet, since we know how much of the light of the star is blocked



Technique 2: Transits

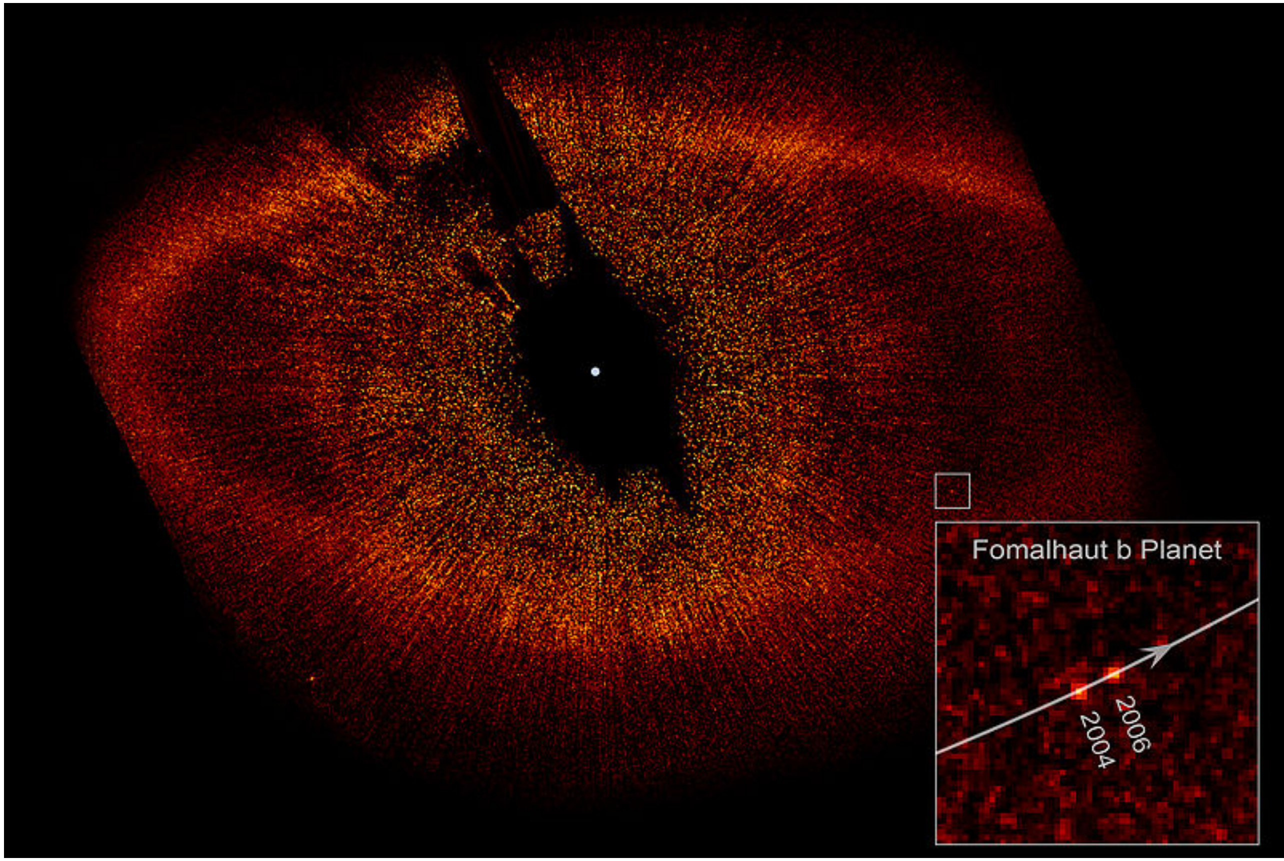
- This turns out to be easy!
- Can be done with small telescopes for bright stars
- Here is an example of a transit finder – called HATNet (Hungarian Automated Telescope Network)
- Telescopes are actually telephoto lenses
- Also done from space – more on that later



Technique 3: Direct Imaging

The most obvious way is to image the planet directly, but this is hard because the star is one billion times brighter than the planet.

Few planets seen this way, and mostly by luck – planet was discovered around the star Fomalhaut in 2008.

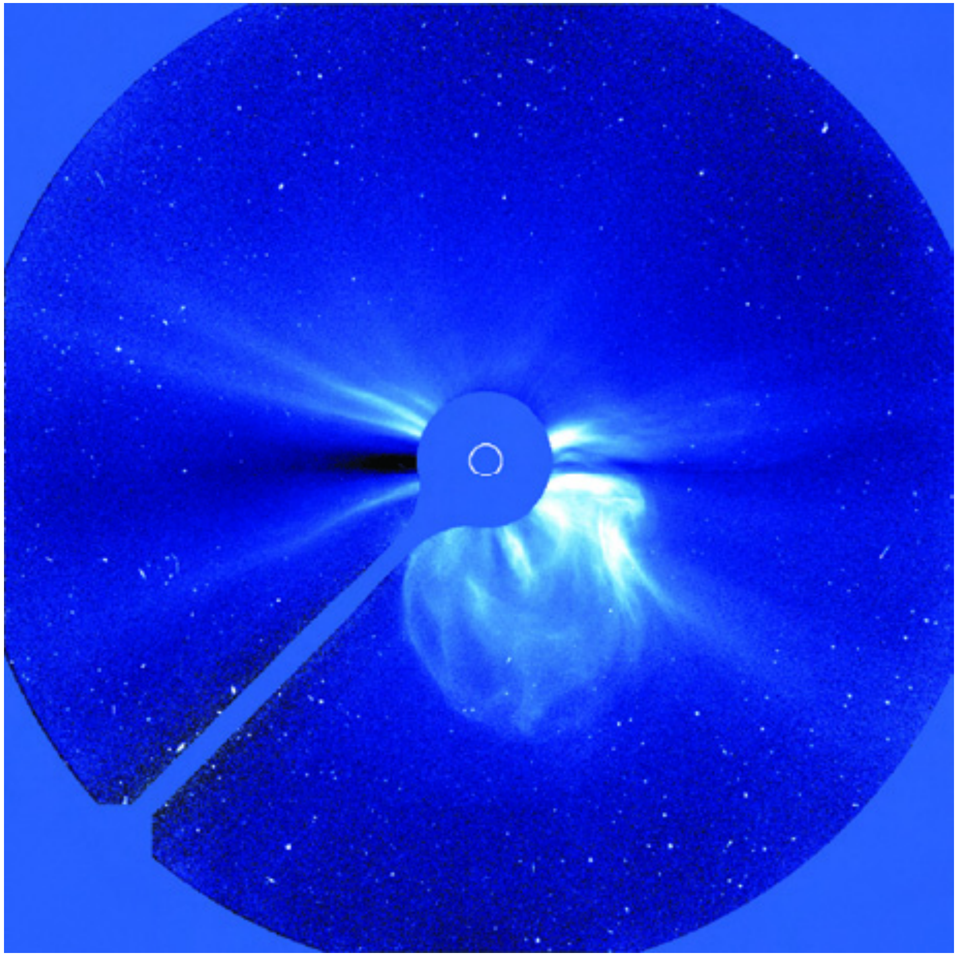


Technique 3: Direct Imaging

- One way to see planets is to block out the light of a star using a coronagraph

- This has been done for the Sun for years in order to study the corona – hence the name coronagraph

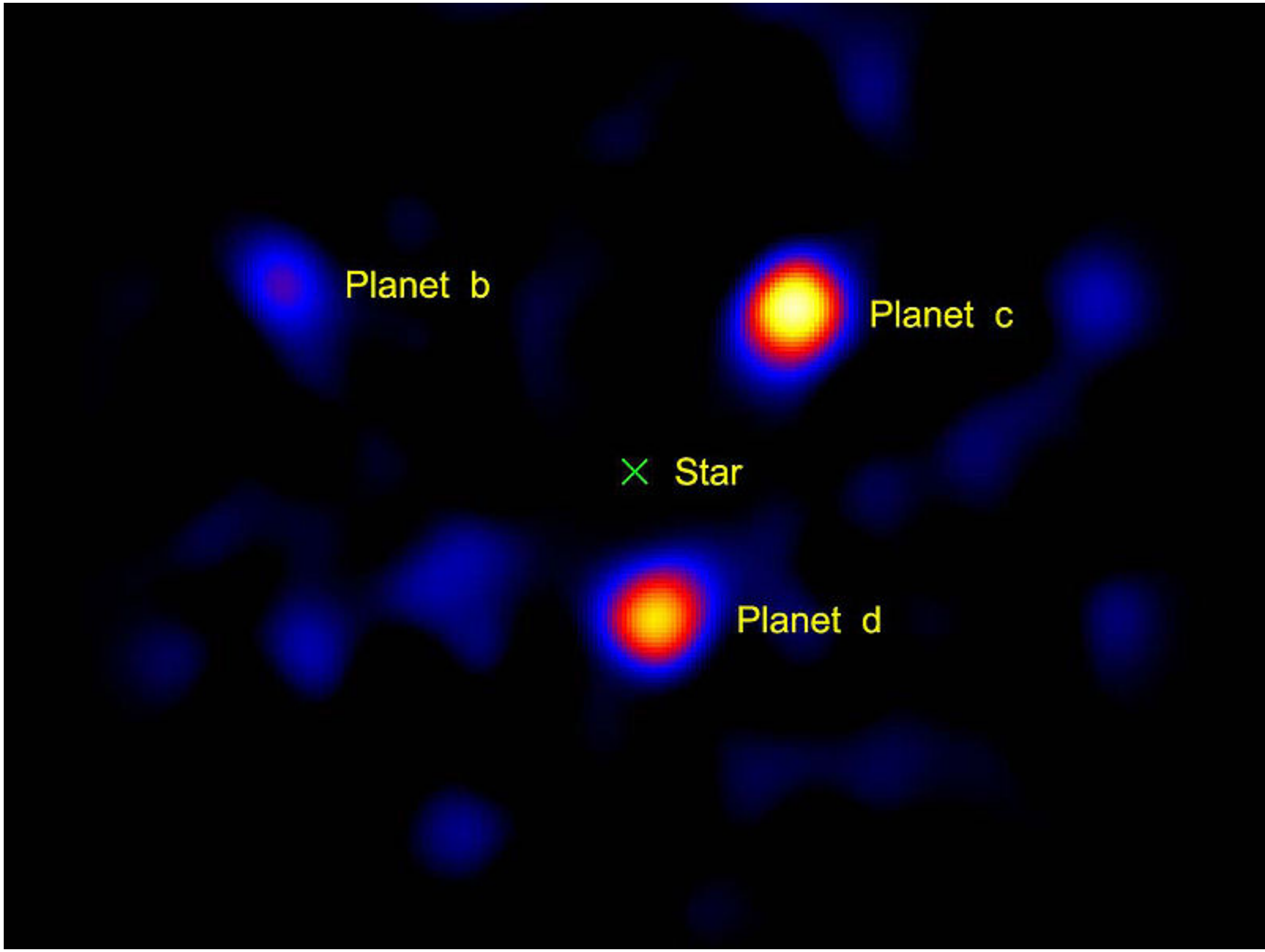
- But stars are so small that it is very hard to block out their light



Technique 3: Direct Imaging

In 2010 a new type of coronagraph was developed that allows the star to be precisely blocked out, leaving the planets around it.

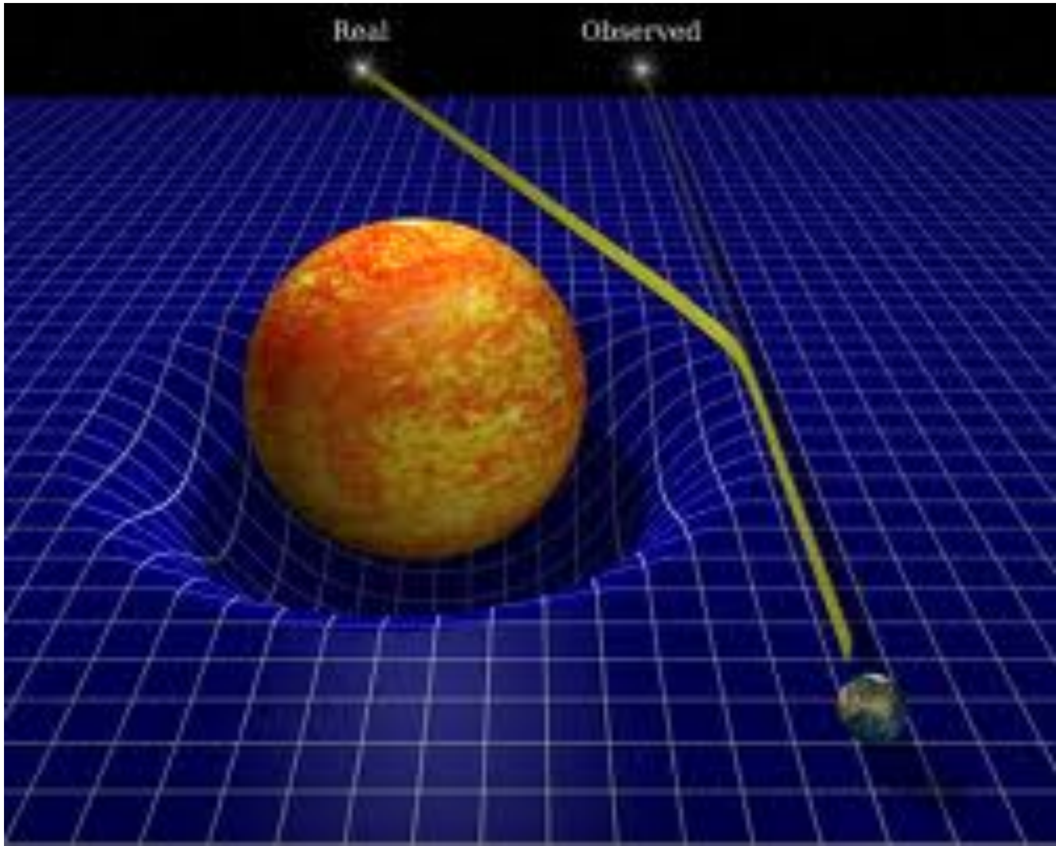
This is very exciting and might mean we can more easily image planets from the ground.



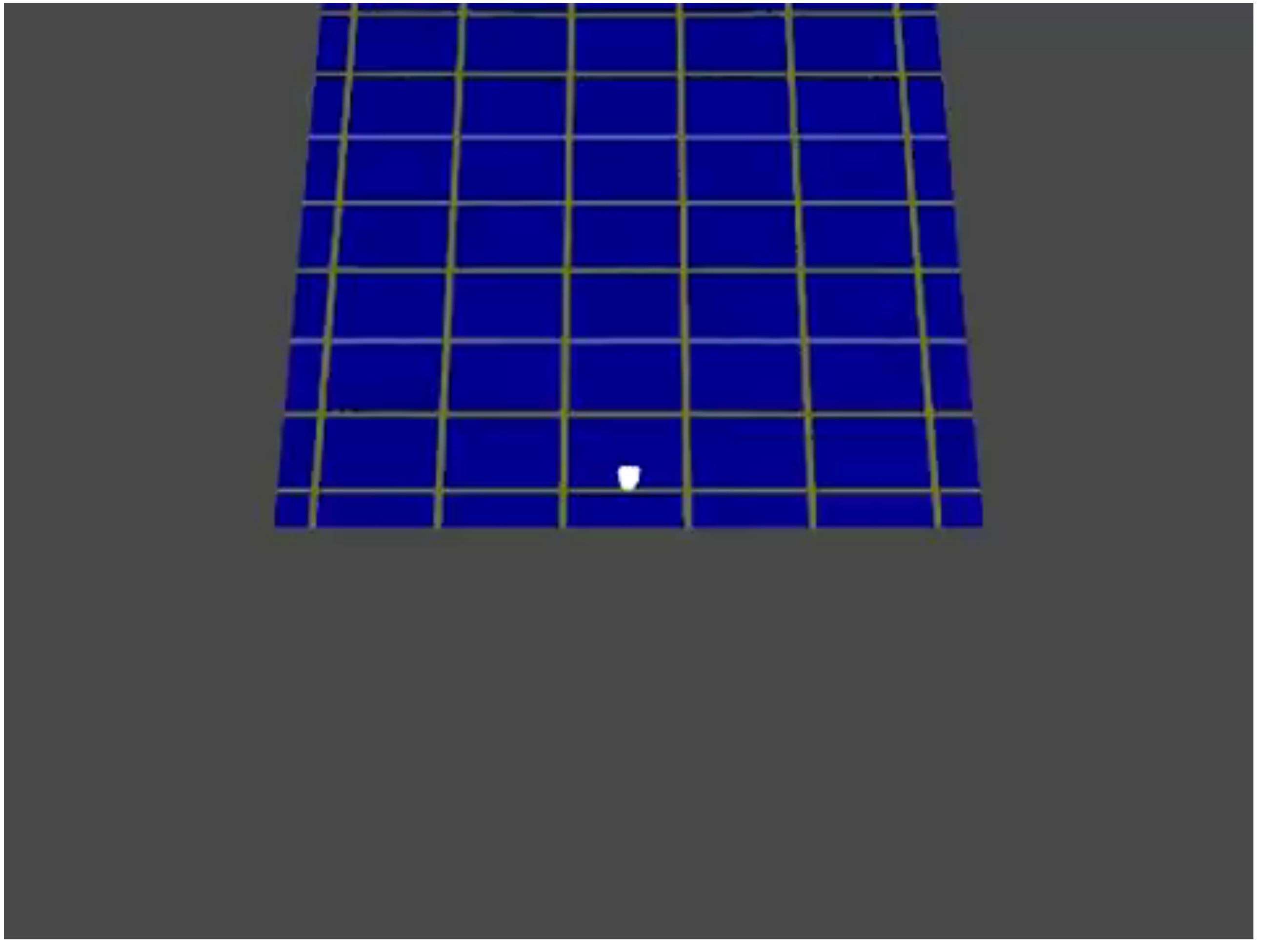
Planets around HR 8799

Technique 4: Microlensing

- Remember Einstein's great insight was that everything moves in straight lines – it's just that what it means to be straight can changes
- The curvature of space-time bends both matter and light
- So light will bend as it moves around a massive body like a star or galaxy



Gravitational lensing



An animation of the bending of light around a massive object

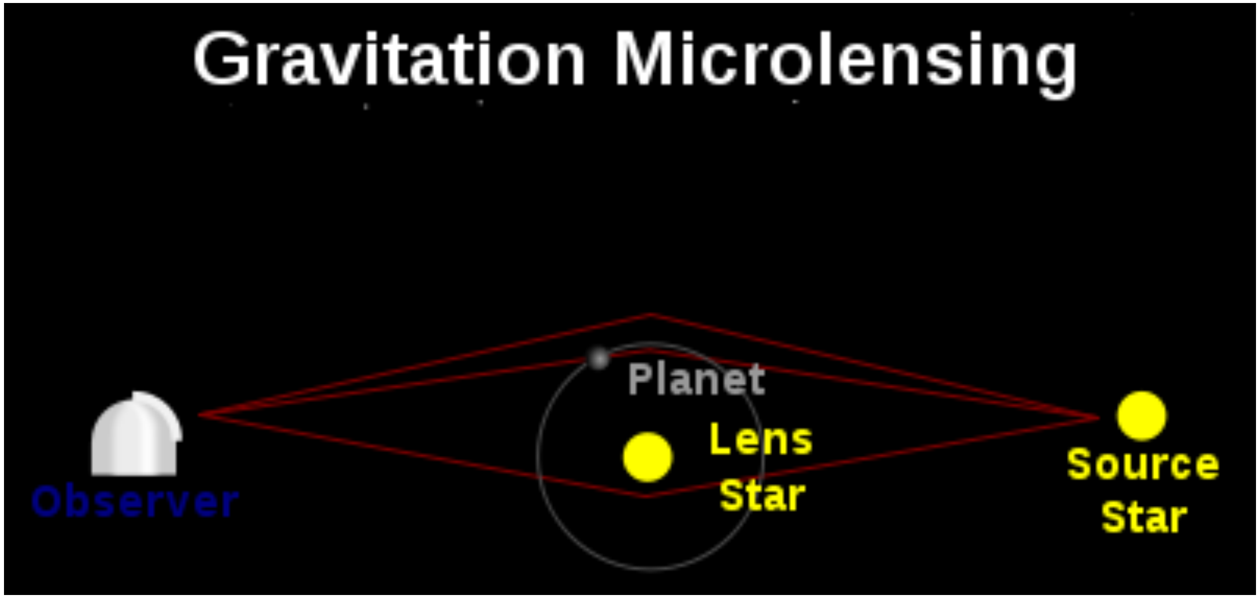
Gravitational Lensing

Gravitational lensing is seen around clusters of galaxies, the biggest objects in the universe.

Background galaxies are seen as stretched objects.

Lensed galaxies

Microlensing

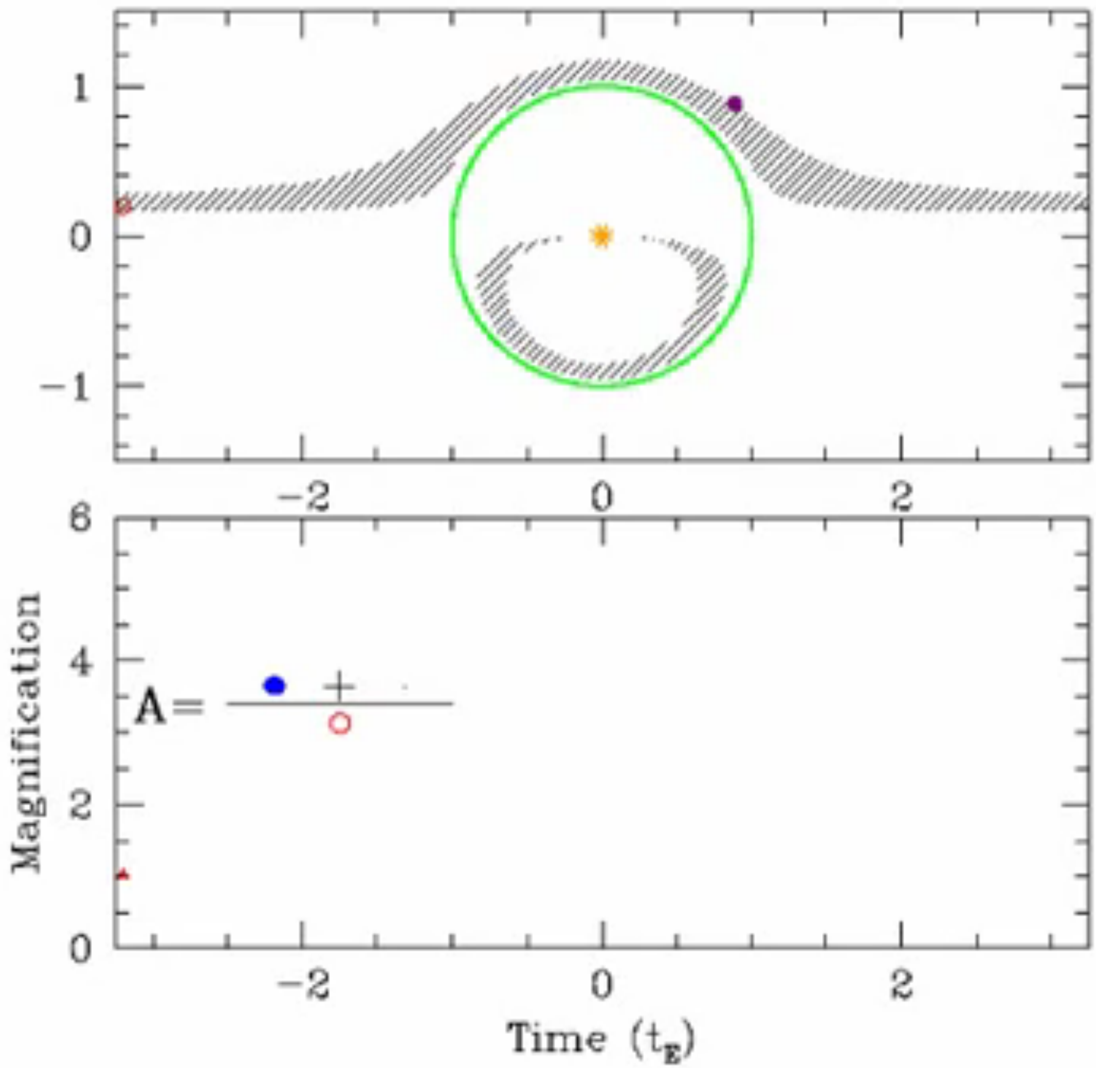


- Gravitational lensing can happen on a much smaller scale – by stars rather than galaxies
- In this case light is only weakly bent, but it can make a distant star appear much brighter as the lens moves in front of it

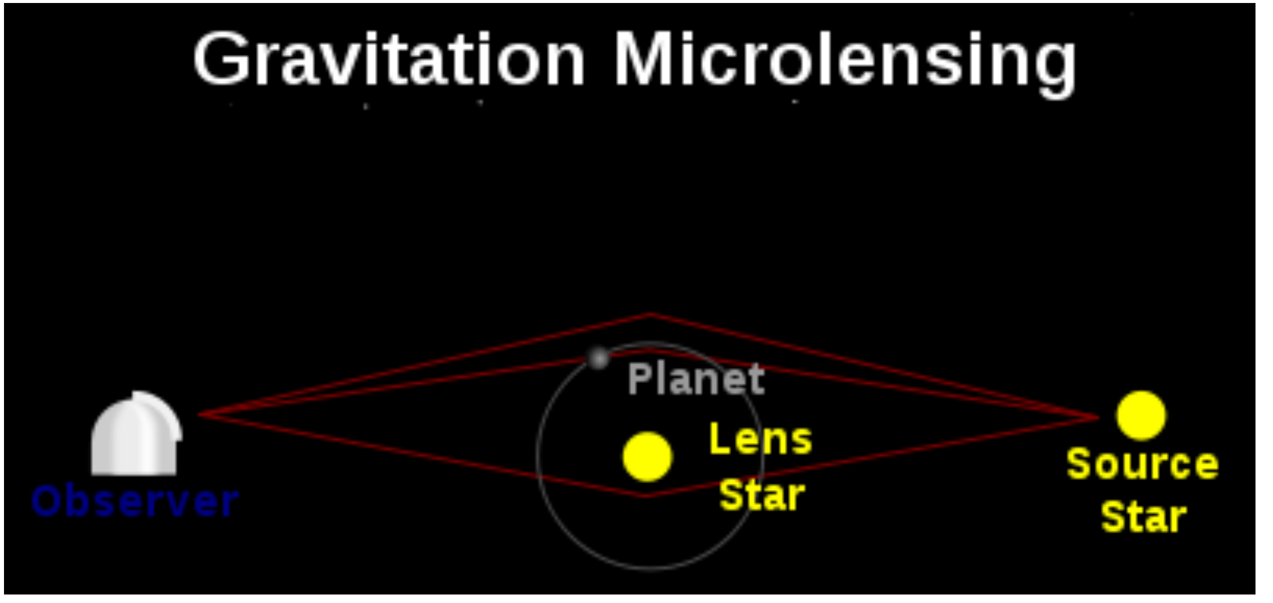
Technique 4: Microlensing

If there is a planet in just the right place around the lensing star, we see a sudden spike in the magnification.

That spike tells us that a small body is sitting in just the right place, and we can tell how massive the small body is



Microlensing



- Disadvantage: relies on chance alignment of the two stars, so measurement cannot be repeated
- Planets detected this way usually far away
- But monitoring enough stars can tell us how common Earth-like planets are in galaxy

Extrasolar planets

- All these different techniques are useful for finding planets

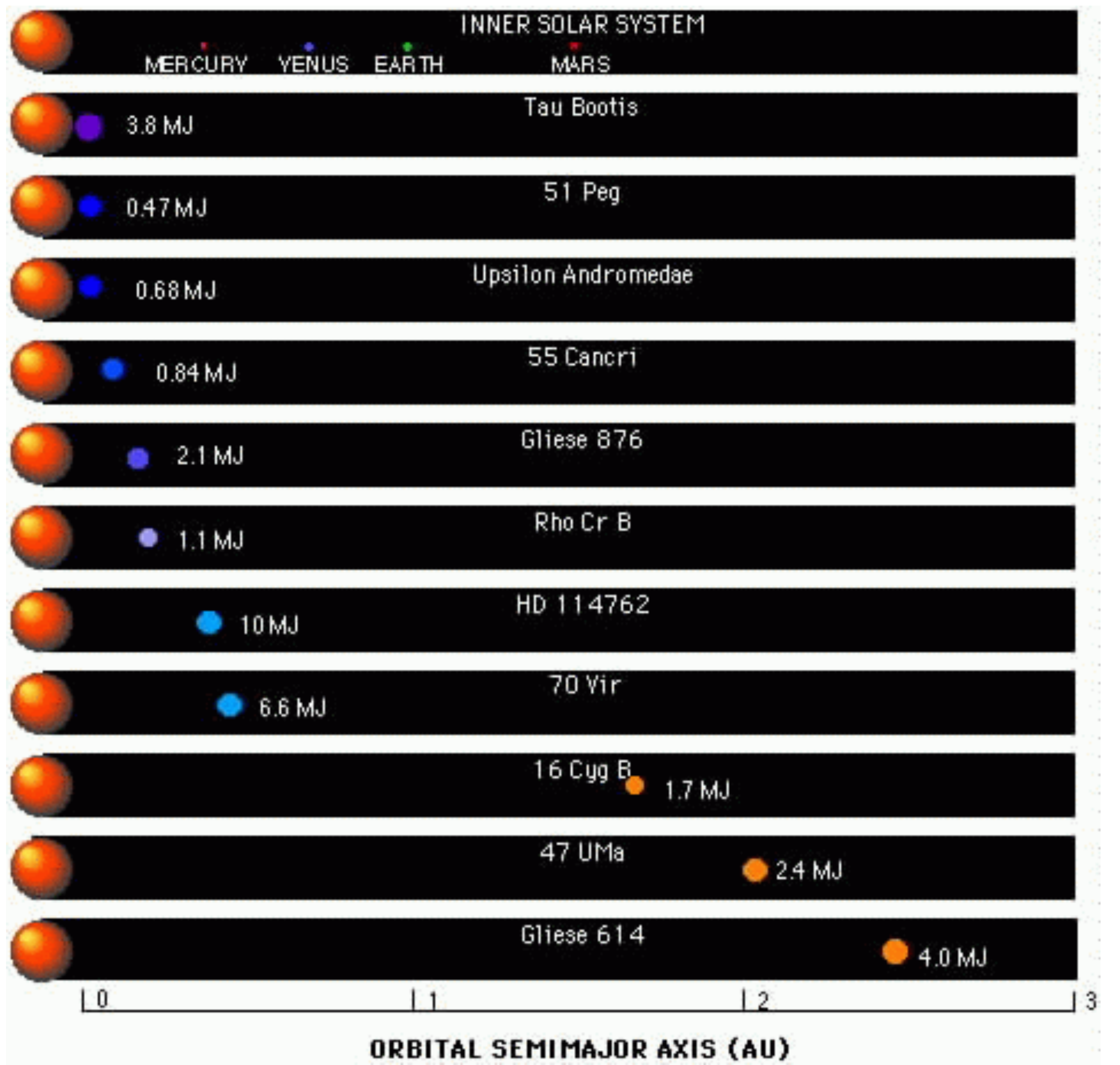
- Radial velocity – gives mass
- Transits – gives size
- Direct imaging – it might give size, but it's always good to actually see the planet
- Microlensing – gives mass, and for a long time was the only way to detect Earth-mass planets

- **The combination of radial velocity and transits is the most powerful technique now**

Radial velocity surveys have been the workhorse of planet finding, but this is starting to change to transits.

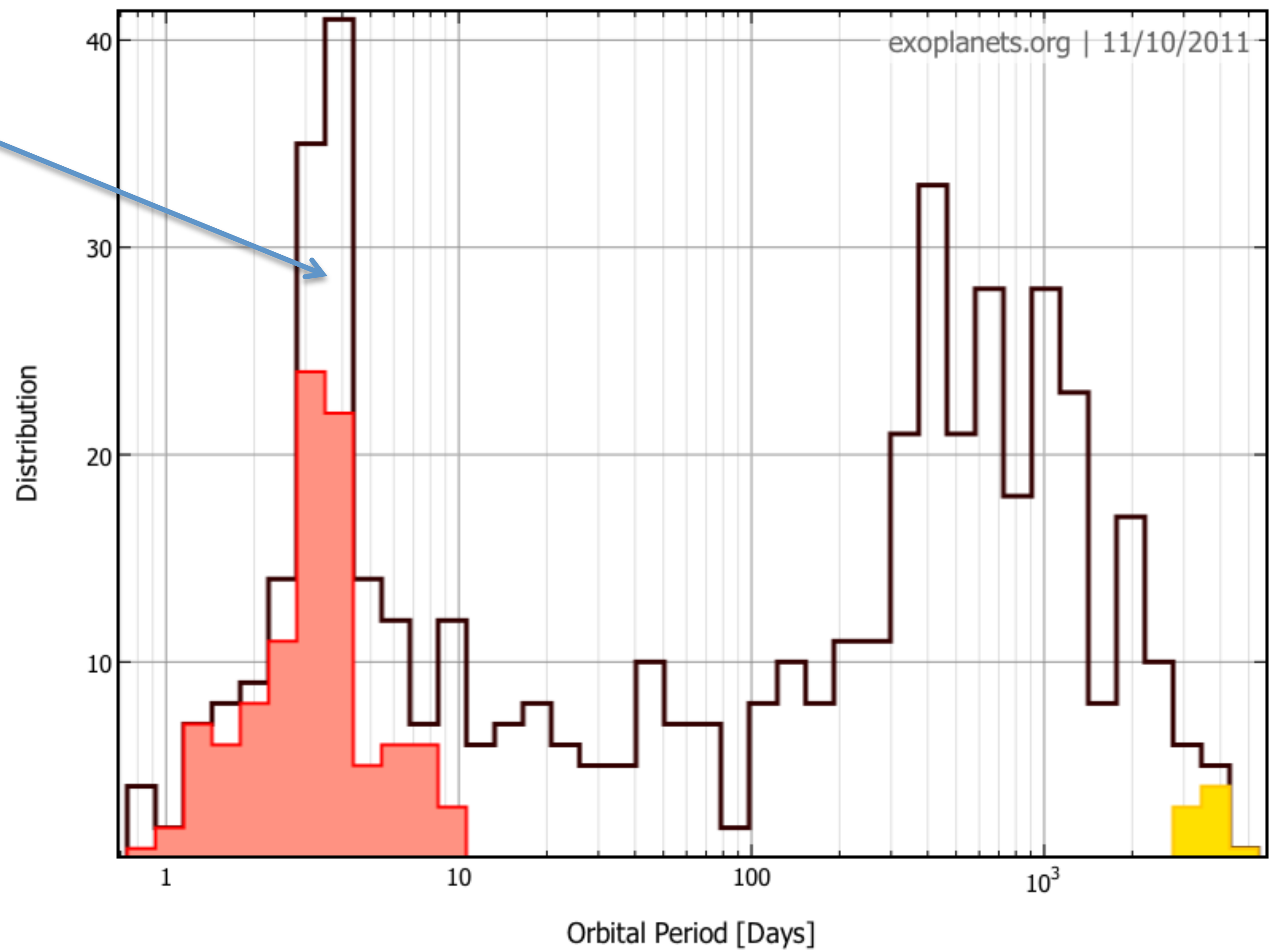
These methods are sensitive to massive planets, so most planets found are around Jupiter's mass

Extrasolar Planets



When astronomers began look for extrasolar planets, they found many planets with about 3-day orbits. This is called the 3-day pileup.

3 day pileup

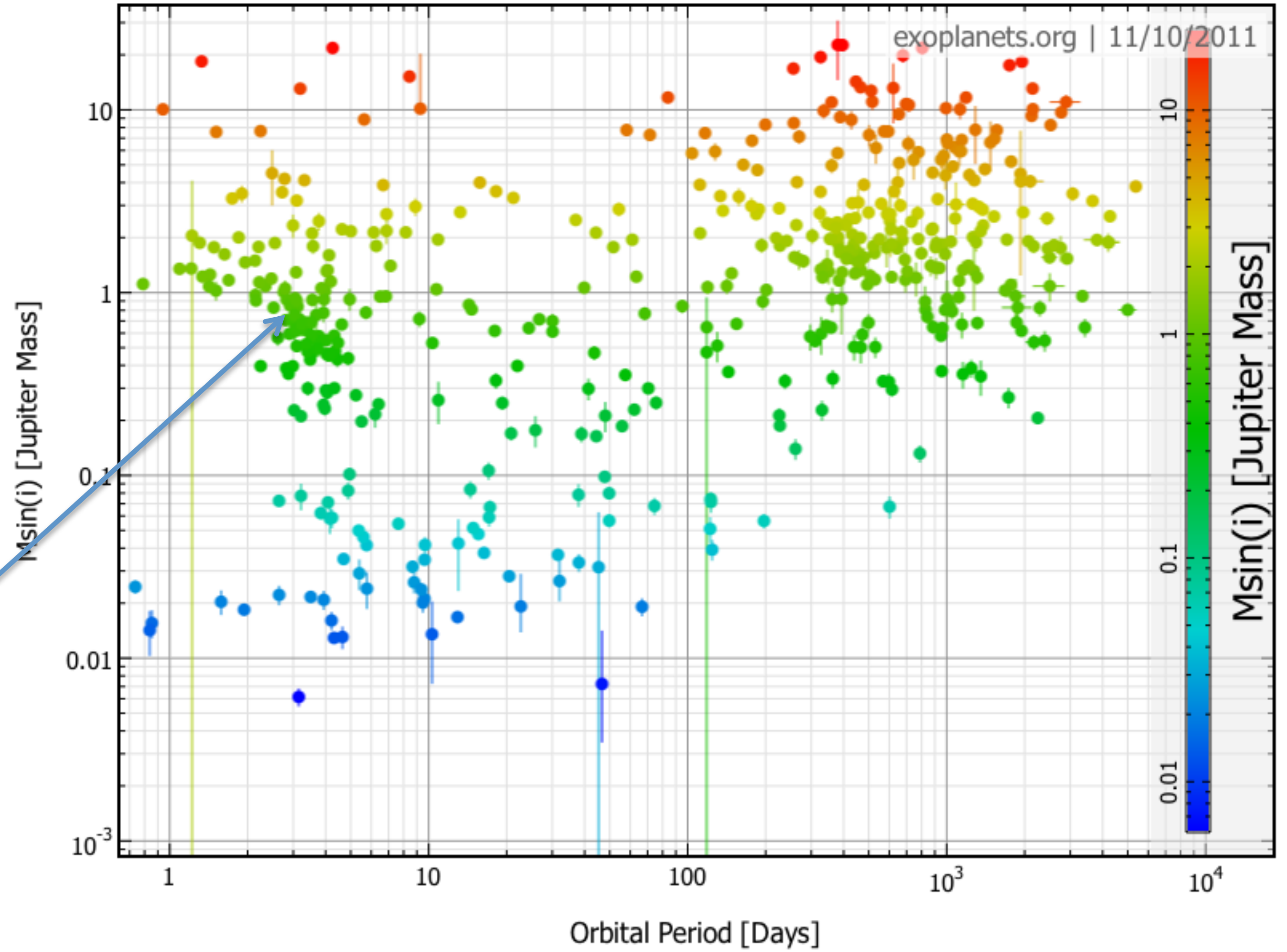


Hot Jupiters

What kind of planets are at 3-days? For the most part, these planets are all Jupiter-mass or bigger.

So these are known as the hot Jupiters

Hot Jupiters



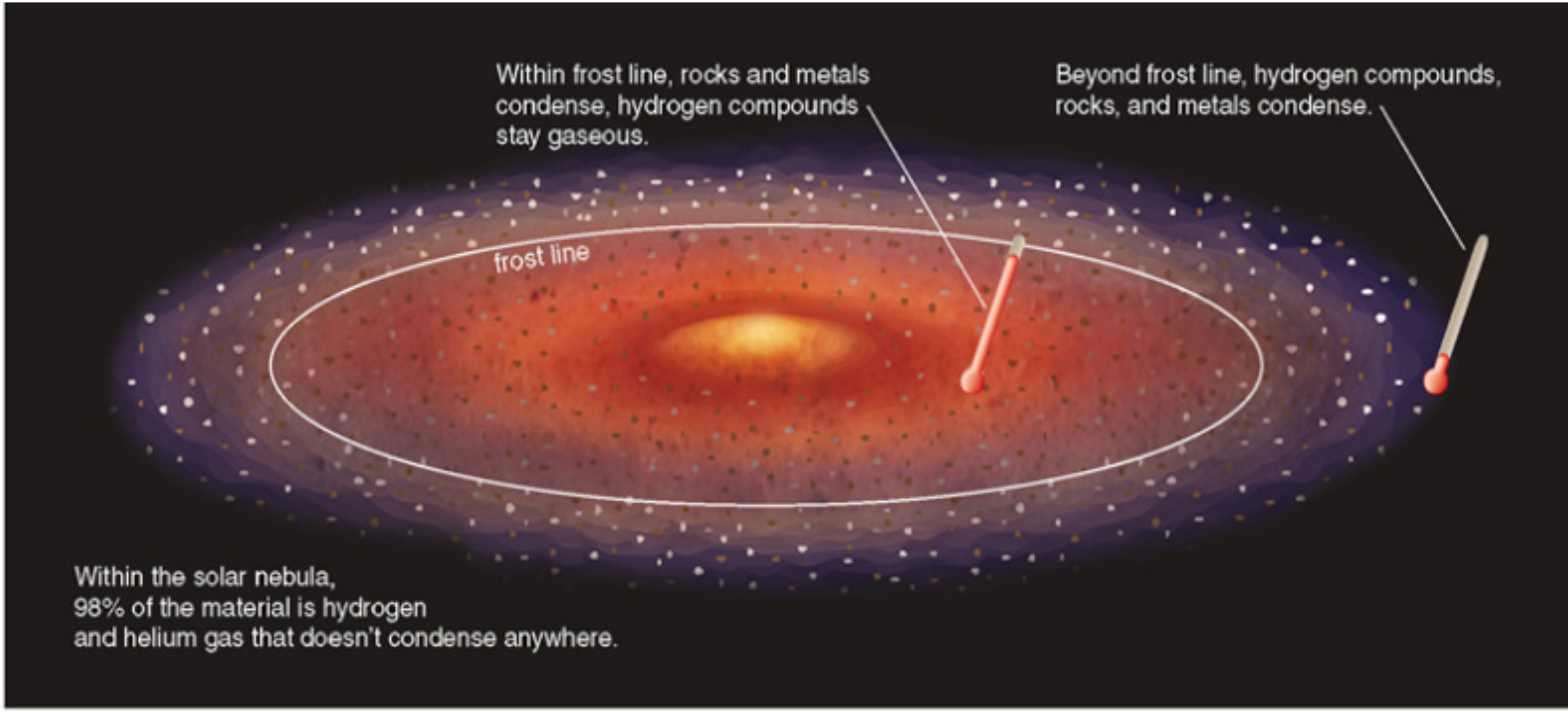
Hot Jupiters

- How might you make hot Jupiters?

- You can’t form them there because it is inside the snow line

- So you have to make them outside the snow line and move them inward

Forming Jovians

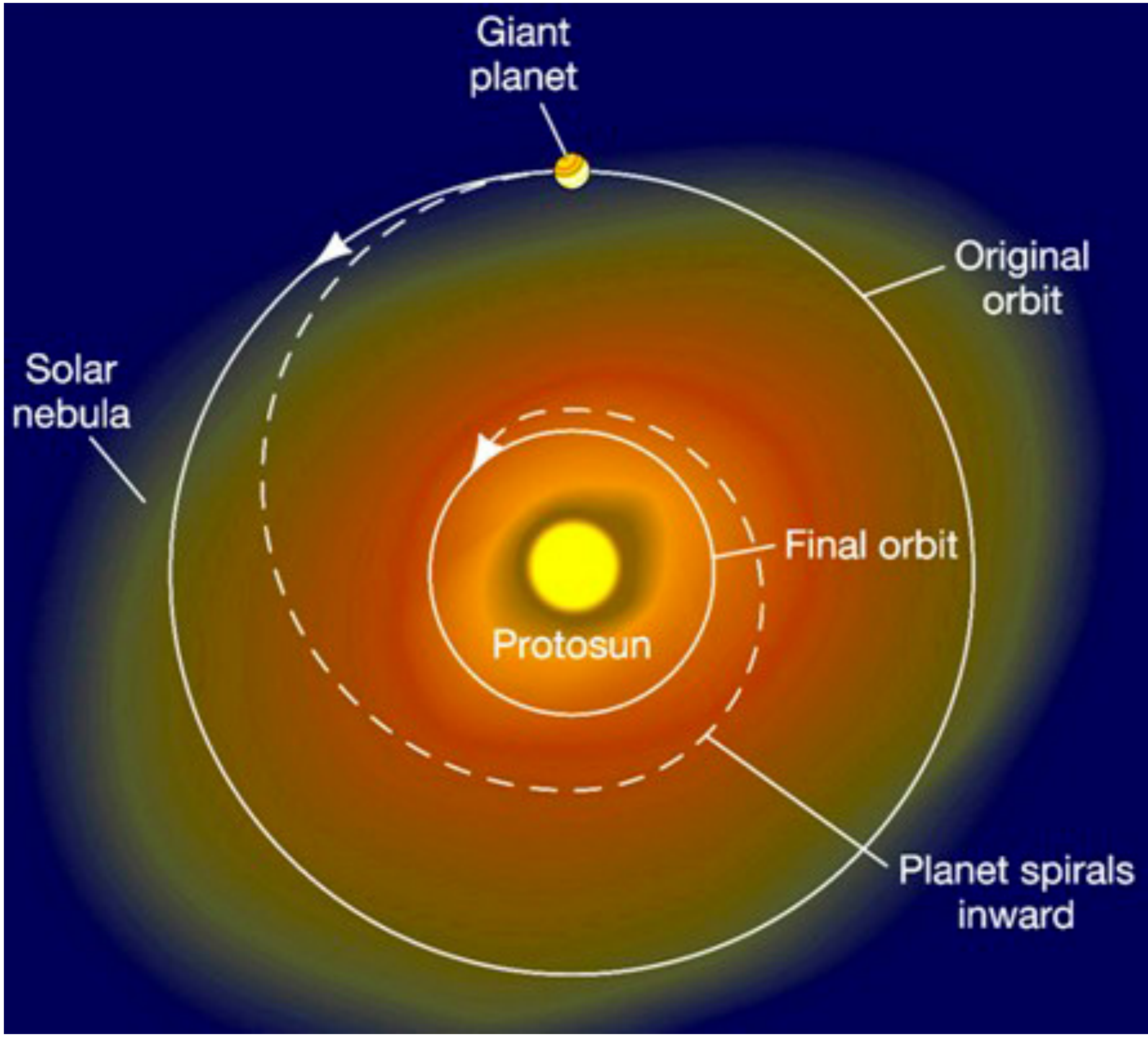


Recall that you need big cores to form Jupiter. Bigger cores are possible if you can gather more material. In regions where the gas is so cold that ices form – the snow line or frost line – you have the extra stuff.

Planetary Migration

If a giant planet forms while the gas disk is still around, the planet may sink inward toward the star.

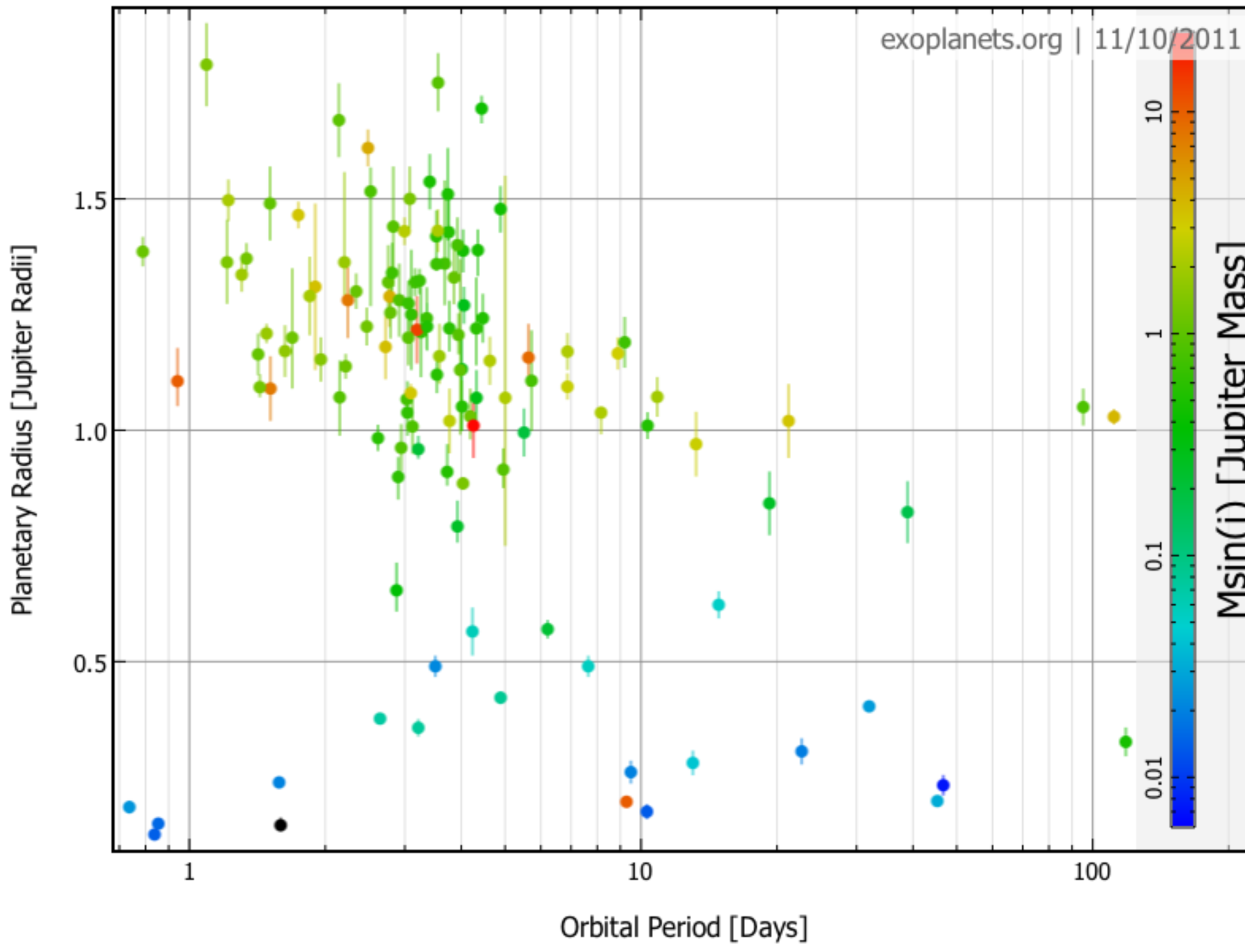
This is called **planetary migration** and might explain the hot Jupiters.



Hot Jupiters

For some of these hot Jupiters, we also have transit data – get their size as well. And mass + size gives density…

The 2nd big surprise is that they are bigger than expected – probably because intense heat from the star puffs up the atmosphere of the planet. These planets have very low density.



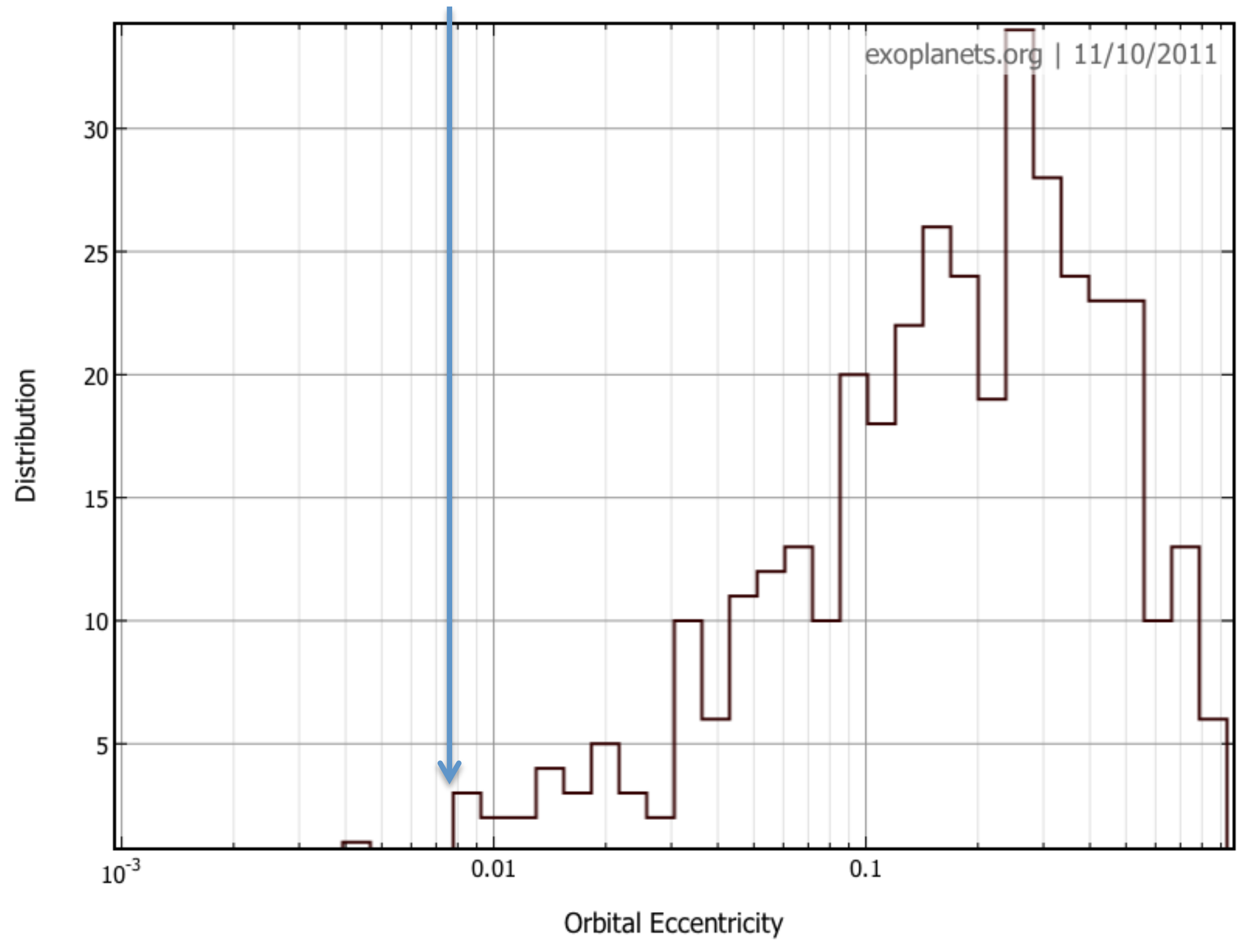
A Great Diversity of Solar Systems

The planets of our solar system are in nearly circular orbits.

But this is not true of the extrasolar planets. They are much more elliptical than the solar system planets.

We also saw that a lot of these planets are much closer to their star that our planets.

Solar system planets



Measure of ellipticity

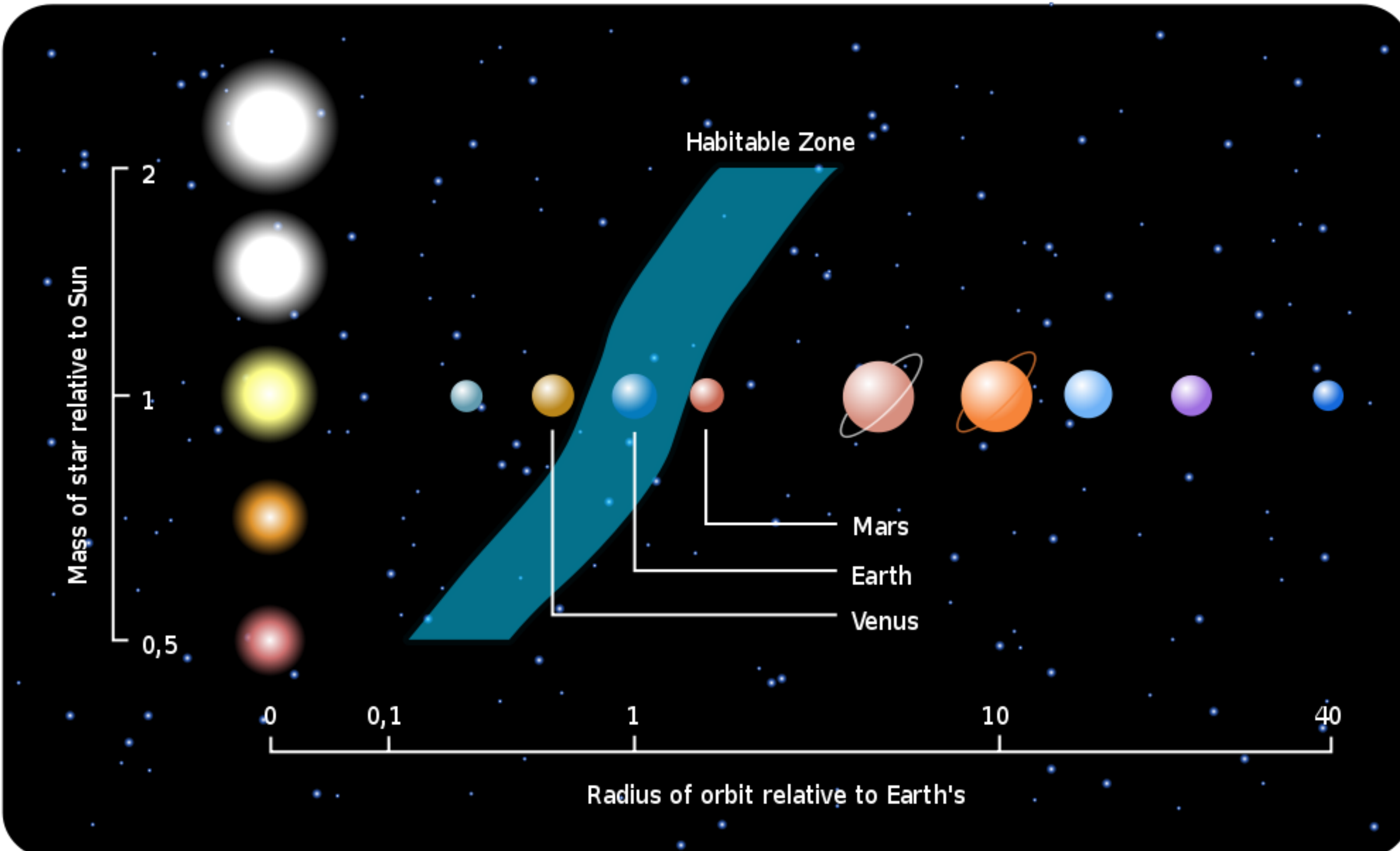
Is our solar system special?

- Most planets that are found are really close to their star – totally unlike our solar system
- This is because they are much easier to find in radial velocity and transit surveys
- This is called a **selection effect**. Accounting for this to figure out the real distribution is HARD
- But this is now changing with the Kepler satellite

Finding Earths

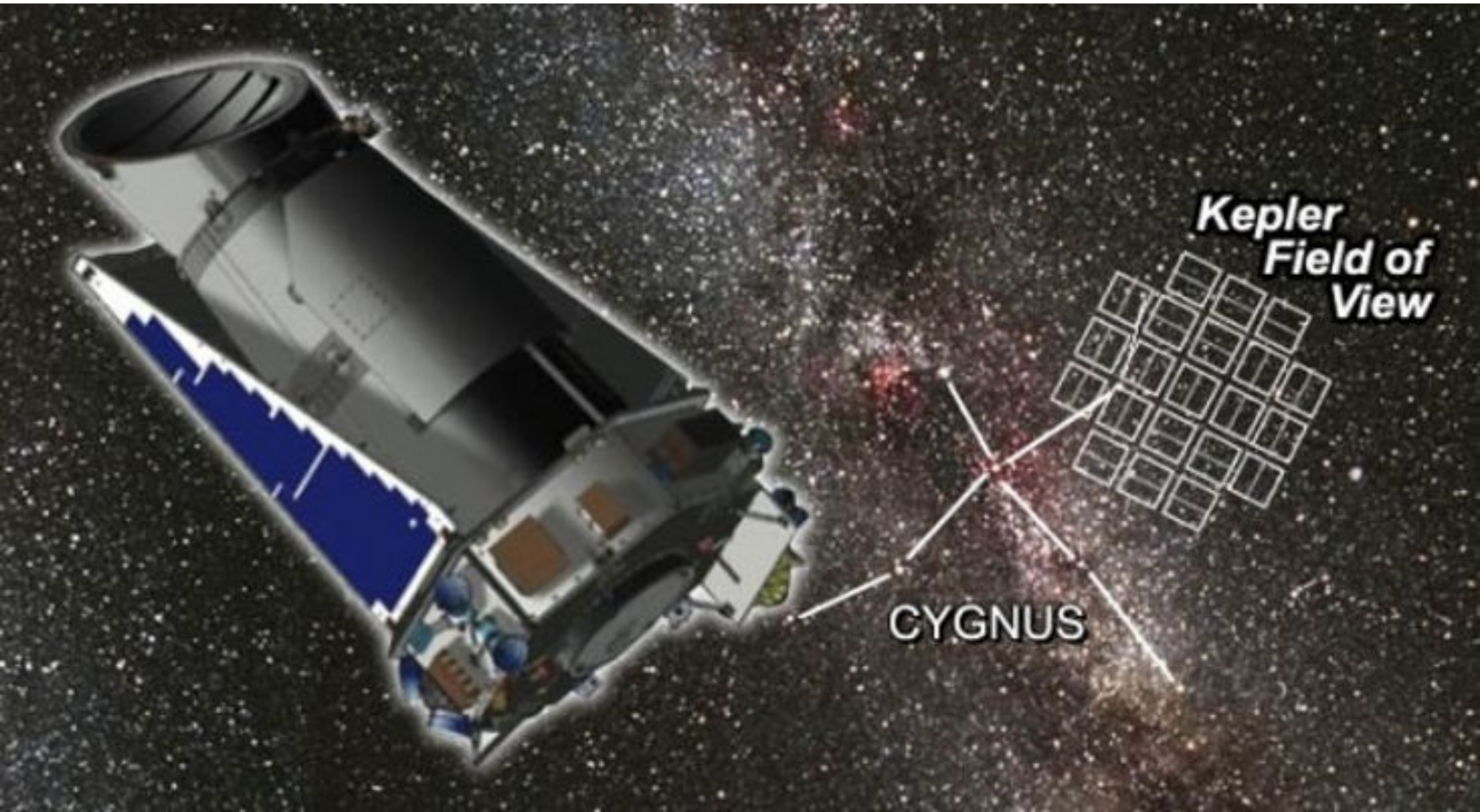
- One of the main goals of planet searchers is to find a planet about the size of Earth in a region around a star where it is not too hot nor too cold
- This is called the **habitable zone**, and it's defined as the range of distances from the star at which the temperature is right for liquid water to exist on the surface of a planet
- This will depend on the temperature of the star, and the temperature of a planet will also depend on its atmosphere
- Planets in the habitable zone are sometimes known as "Goldilocks planets"

The Habitable Zone



Kepler

Finding Earth-like planets is the key mission of the Kepler satellite, which is monitoring 150,000 stars to look for transiting planets



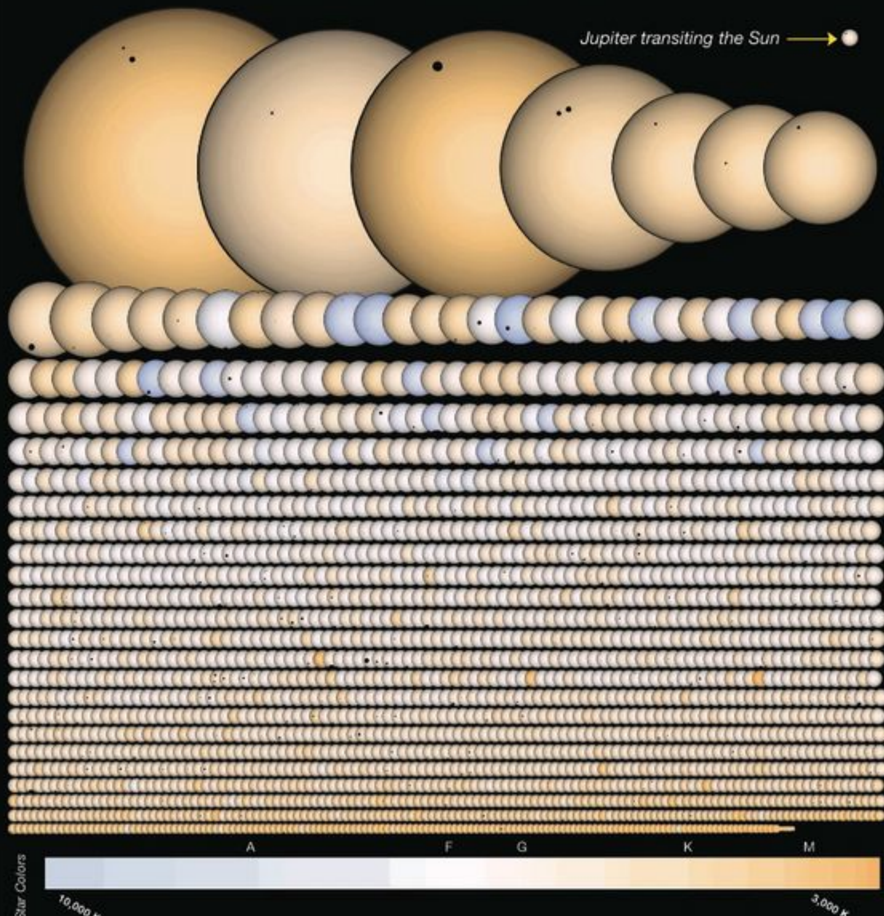
Kepler

- Space observatory, launched 2009, mission extended to 2016 but recently modified due to failure of reaction wheels on spacecraft
- Continuously monitors brightness of 150,000 stars in a fixed field of view, looking for planetary transits
- Earth-like transit produces a brightness change of 84 parts per million and lasts for 13 hours
- Results so far: 961 confirmed exoplanets in more than 76 stellar systems, and 2,903 unconfirmed planet candidates
- November 2013: as many as 40 billion habitable Earth-size planets in the galaxy – one out of every five Sun-like stars has a planet the size of Earth in the habitable zone

National Aeronautics and Space Administration

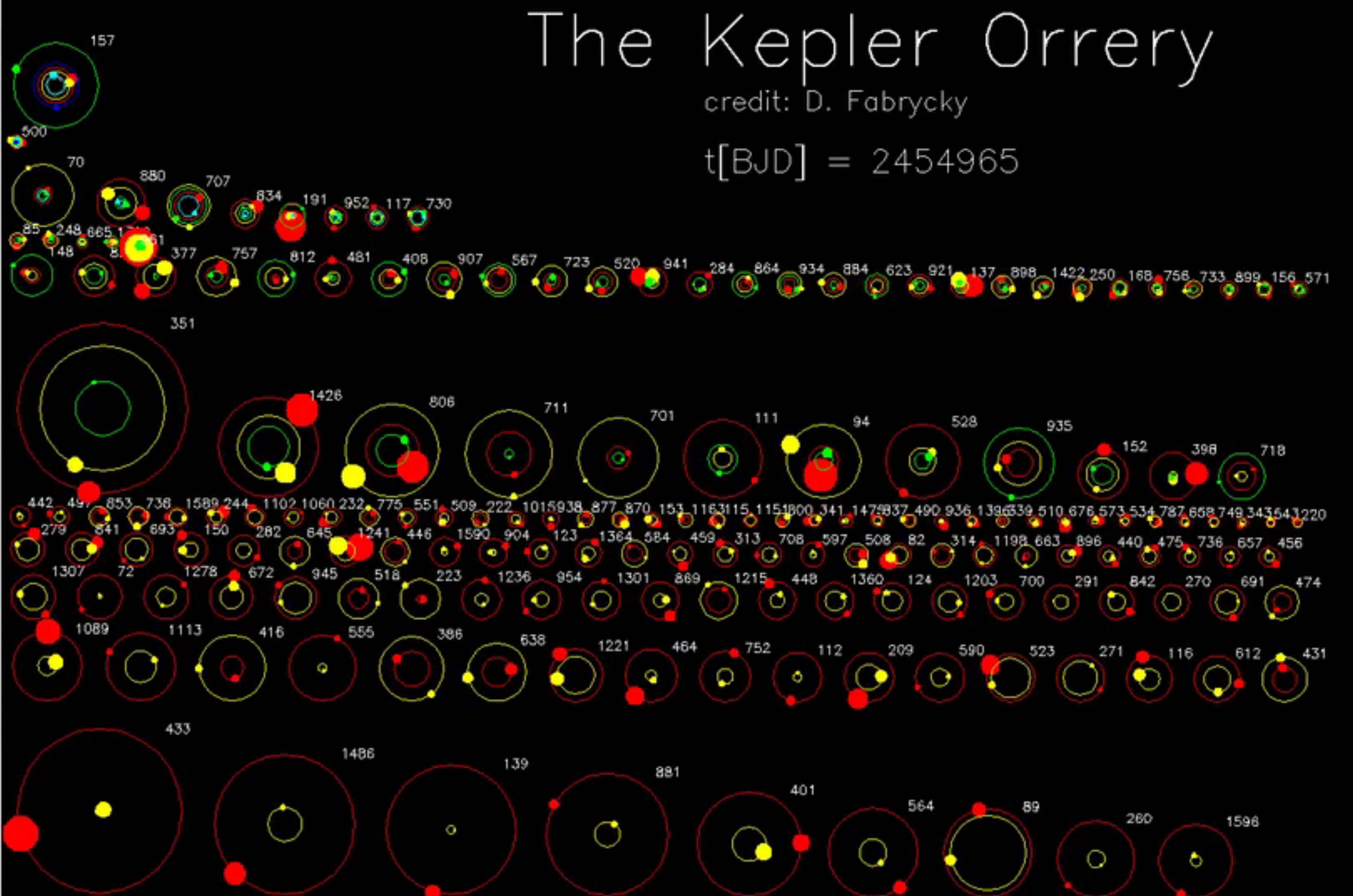
KEPLER'S PLANET CANDIDATES

2,740 AS OF JANUARY, 2013



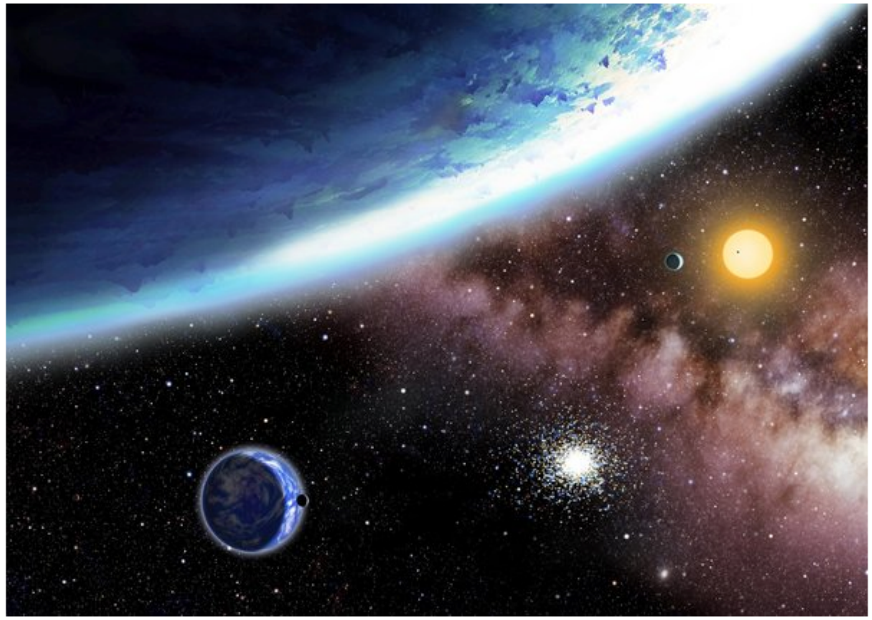
Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 2,740 planet candidates orbiting 2,036 other suns in a search for Earth-size worlds. The search began in 2009. Kepler monitors a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses the face of its star. In "Kepler's Planet Candidates," the systems are ordered by star diameter. The star's color represents its temperature as shown in the lower scale, and the letters (A, F, G, K, M) designate star types. The simulated stellar disks and the planet silhouettes are shown at the same scale, with saturated star colors. Look carefully: some systems have multiple planets. For reference, Jupiter is shown transiting the Sun. Higher resolutions of this graphic are available at http://Kepler.NASA.gov/images/graphics

www.nasa.gov



All multiple-planet systems discovered by Kepler as of 2/2/2011

Far-Off Planets Like the Earth Dot the Galaxy



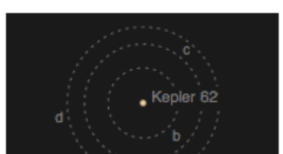
Harvard Smithsonian Center for Astrophysics, via Associated Press

A rendering of Kepler 62f and two outer planets, which may lie in a habitable zone where liquid water could exist on the surface.

By DENNIS OVERBYE
Published: November 4, 2013 | 526 Comments

The known odds of something — or someone — living far, far away from Earth improved beyond astronomers' boldest dreams on Monday.

Multimedia



Interactive Feature
Kepler's Tally of Planets

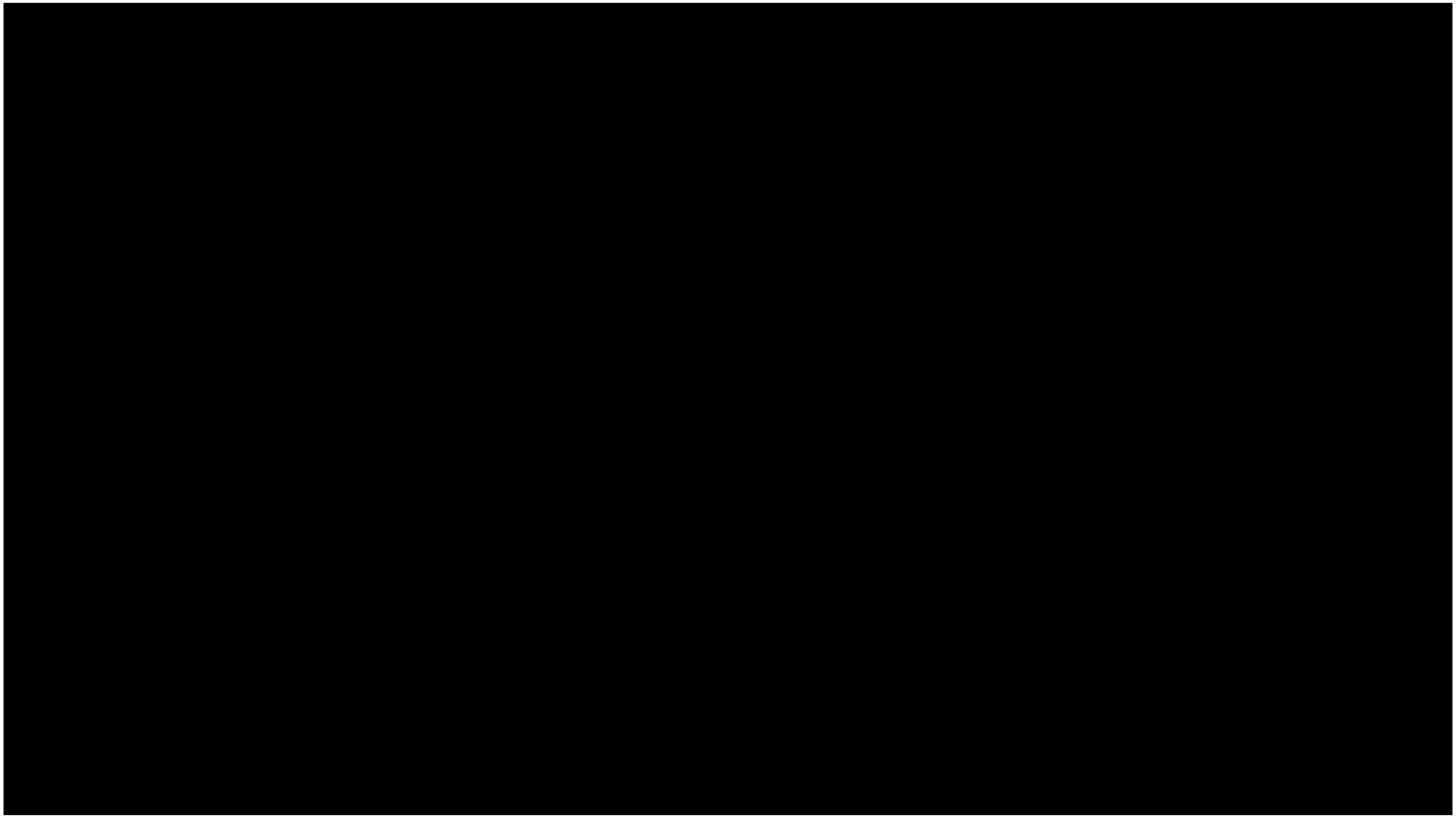
Astronomers reported that there could be as many as 40 billion habitable Earth-size planets in the galaxy, based on a new analysis of data from NASA's Kepler spacecraft.

One out of every five sunlike stars in the galaxy has a planet the size of Earth circling it in the Goldilocks zone — not too hot, not too cold — where surface temperatures should be compatible with liquid water, according to a herculean three-year calculation

Billions of planets

- Studied 42,000 stars from Kepler mission
- Found 603 planets, including 10 that are Earth size (1-2 Earth-radii) and receive comparable levels of stellar energy to that of Earth (within a factor of four)
- Account for Kepler's imperfect detectability of such planets by putting signatures of fake planets into data, calculating fraction recovered
- Fraction of stars with Earth-like planets is about 22%
- Nearest Earth-like planet may be only 12 light years away!

The "Star Wars'' planet



Another Kepler discovery: a planet with two suns

The first extra-solar planet around a normal star was detected by observing

A. the "wobble" of the parent star using spectroscopy

B. starlight reflected by its surface

C. an eclipse when the planet blocks the light of its parent stars

D. the planet's changing phases as it orbits its star

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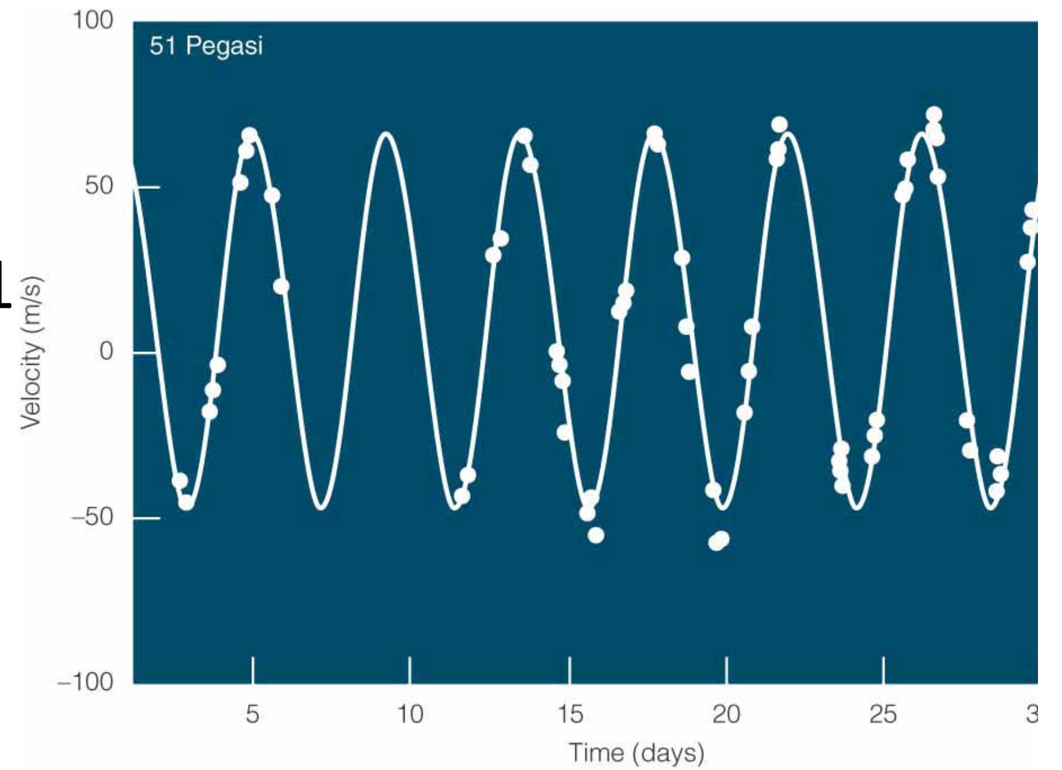
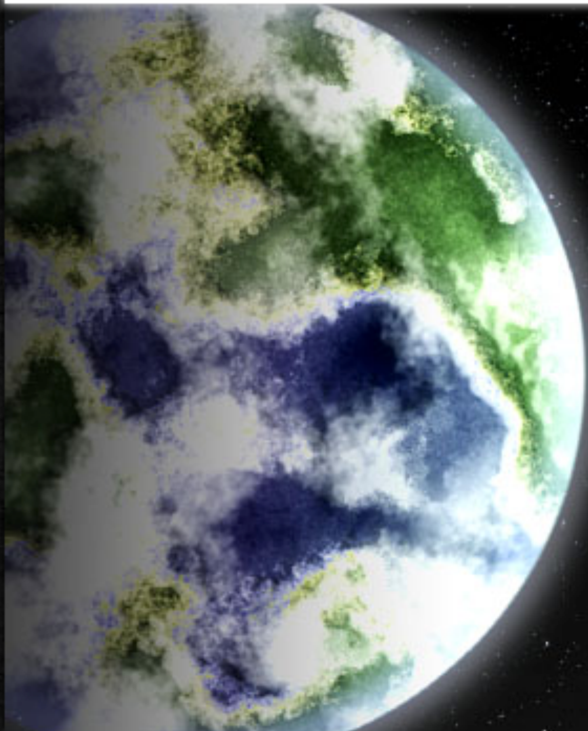


Planet produces regular, repeated shifted in spectral lines of star

exoplanets.org

Exoplanets Data Explorer | Methodology and FAQ | Exoplanets Links | California Planet Survey



Table

Plots

1463 EOD Planets
Planets with good orbits listed in the Exoplanet Orbit Database

27 Other Planets
Including microlensing and imaged planets

1490 Total Confirmed Planets

3705 Unconfirmed Kepler Candidates

5195 Total Planets
Confirmed planets + Kepler Candidates

The Exoplanet Data Explorer is an interactive table and plotter for exploring and displaying data from the Exoplanet Orbit Database. The Exoplanet Orbit Database is a carefully constructed compilation of quality, spectroscopic orbital parameters of exoplanets orbiting normal stars from the peer-reviewed literature, and updates the Catalog of nearby exoplanets.

A detailed description of the Exoplanet Orbit Database and Explorers is published here and is available on astro-ph.

In addition to the Exoplanet Data Explorer, we have also provided the entire Exoplanet Orbit Database in CSV format for a quick and convenient download here. A list of all archived CSVs is available here.

Help and documentation for the Exoplanet Data Explorer is available here. A FAQ and overview of our methodology is here, including answers to the questions "Why isn't my favorite planet/datum in the EOD?" and "Why does site X list more planets than this one?".