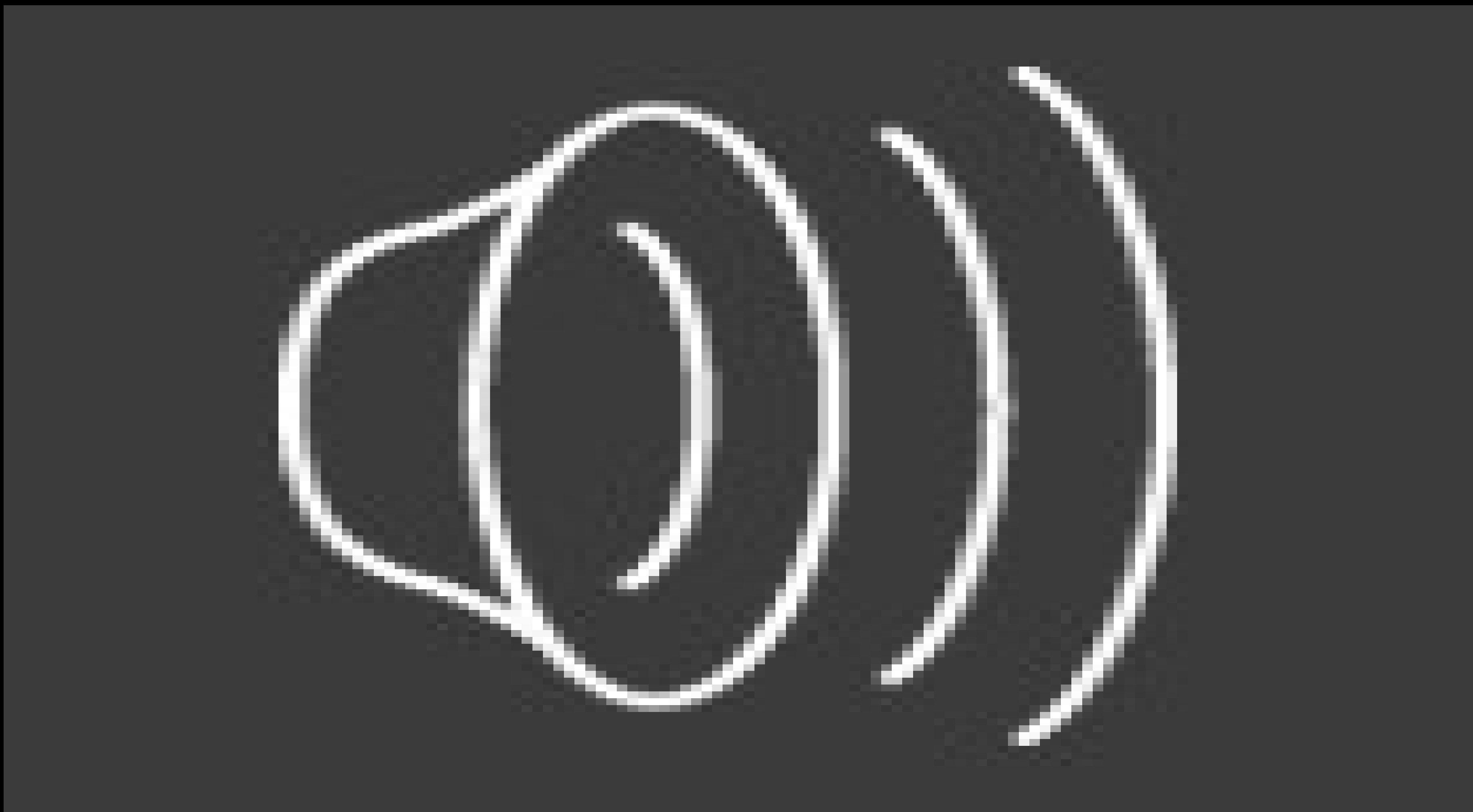
Announcements

- Midterm 2 results
  - Median score 34 (76% / 68% without bonus)
  - Mean 32.55 (72 / 65%)
  - Maximum 46, minimum 11
- All extra credits entered to D2L → check
- Today: Extrasolar planets
- Today: Quiz due at midnight
- Wednesday: Start with galaxies
  → start reading Chapter 14
- November 12, 8-9pm: Stargazing

Last Friday: Solar System Highlights: Real footage of Saturn & Jupiter



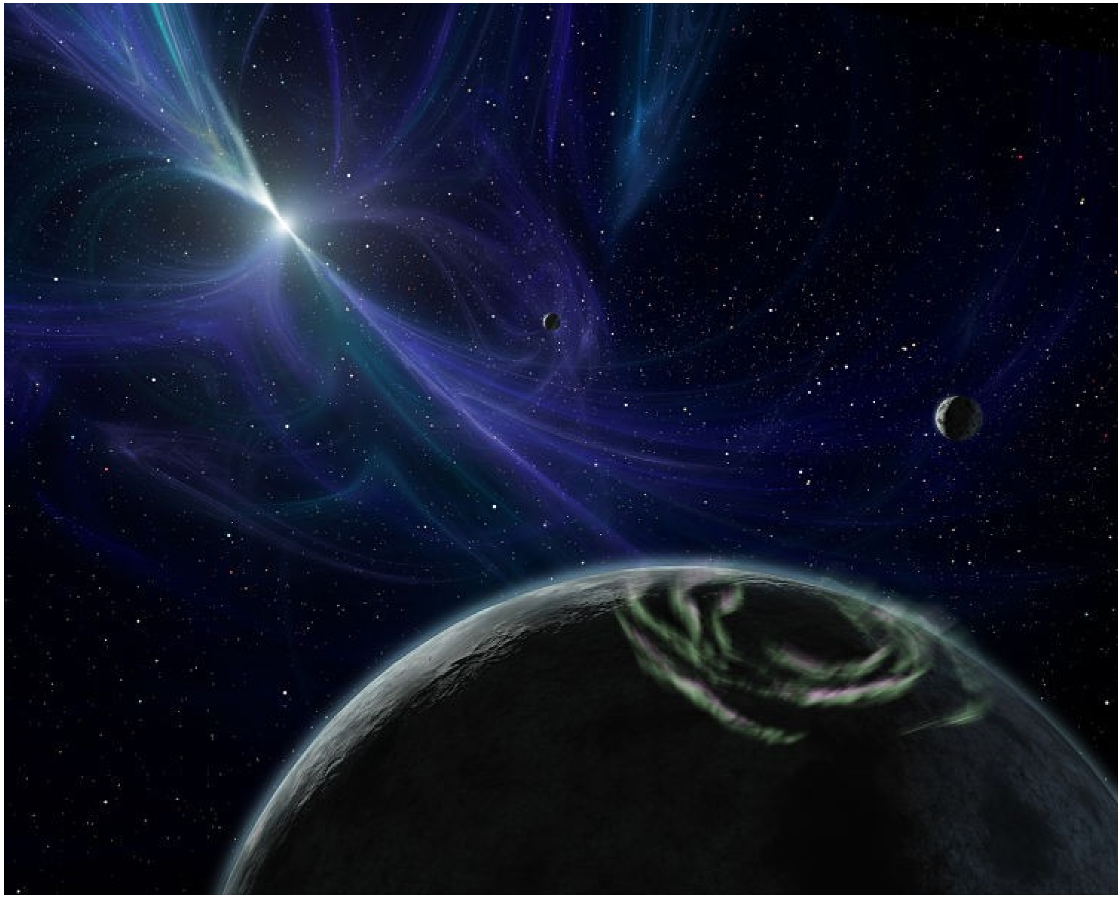
Source: https://www.youtube.com/watch?v=e8_lSgn_gTk


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

Ideas for finding planets

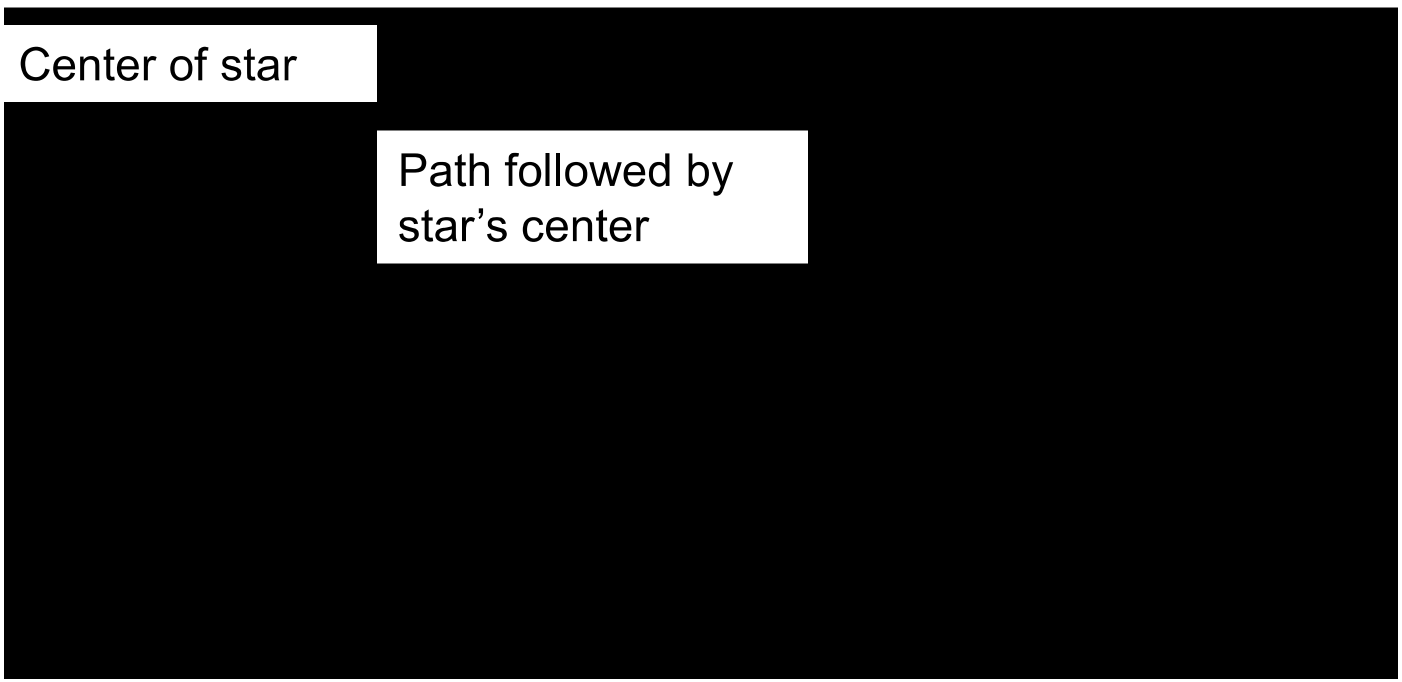
Basics: Orbits

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

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

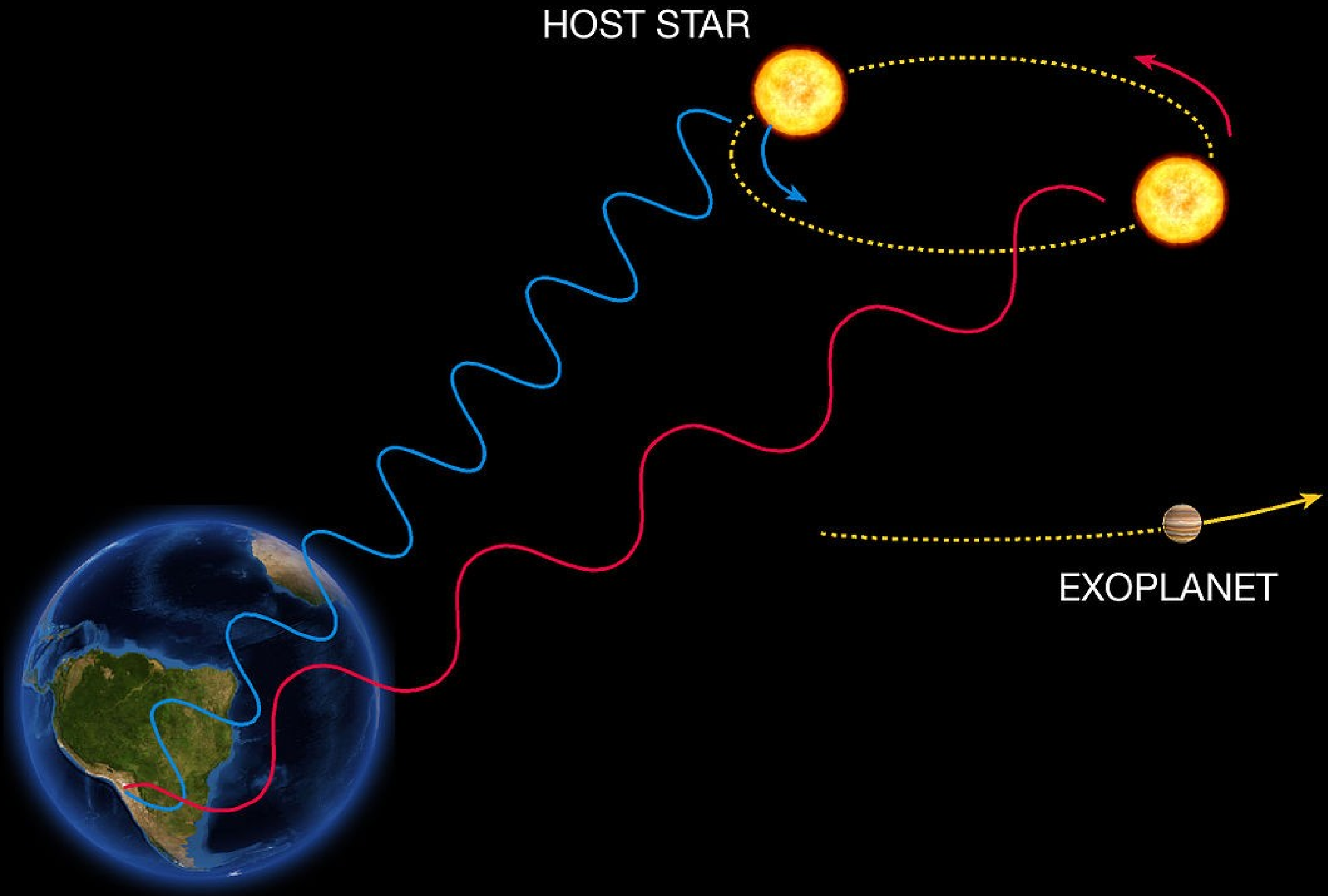
Basics: Orbits

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



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



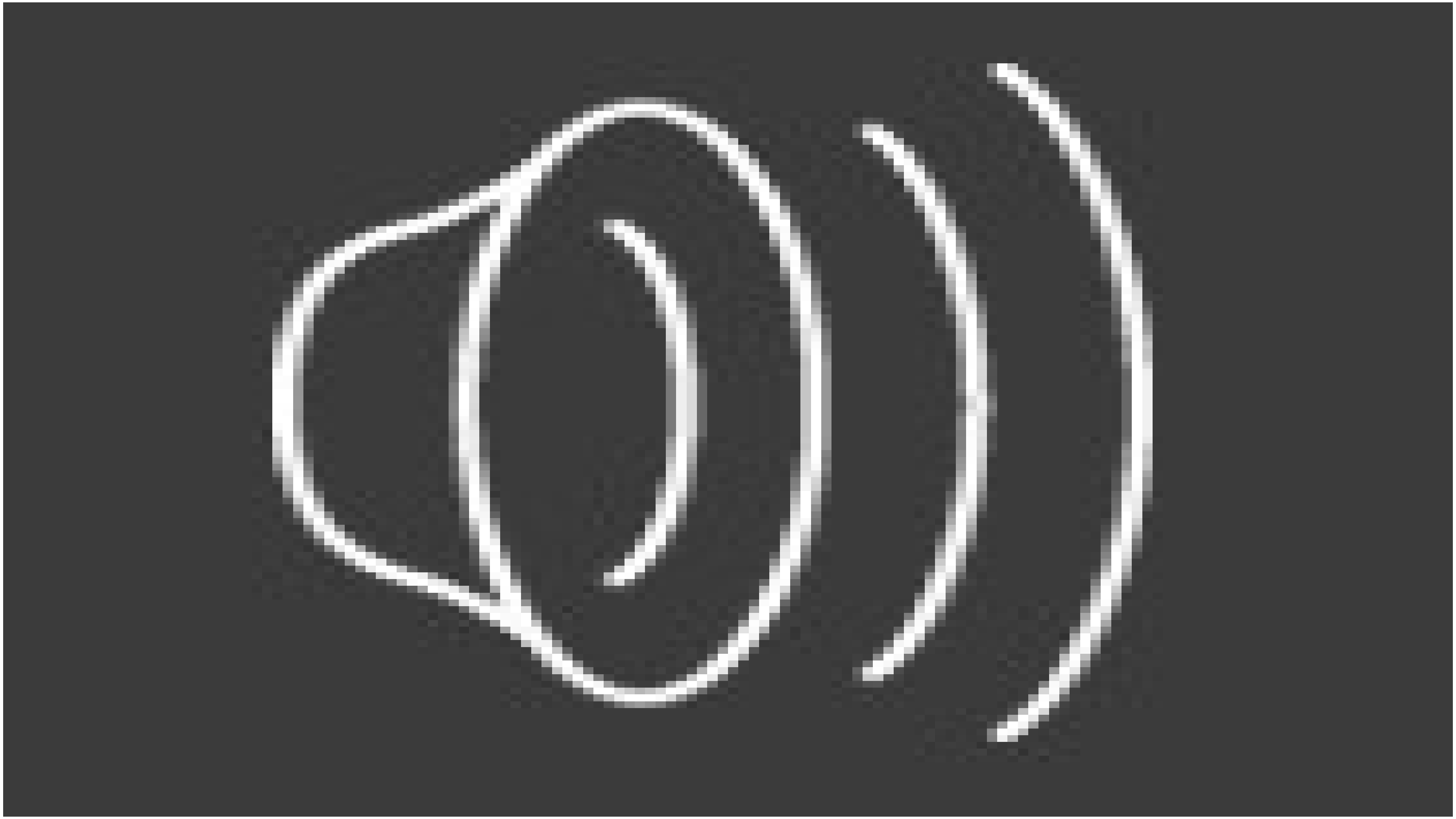
Technique 1: Radial Velocity

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

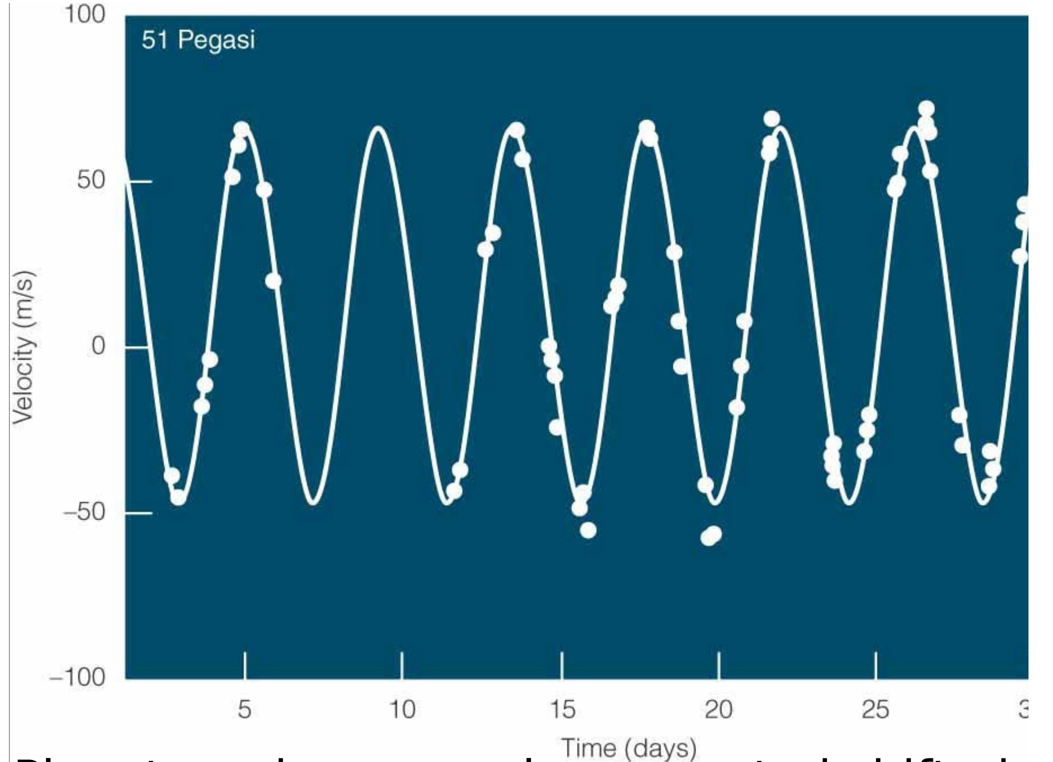


Technique 1: Radial Velocity

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!



Planet produces regular, repeated shifted in spectral lines of star

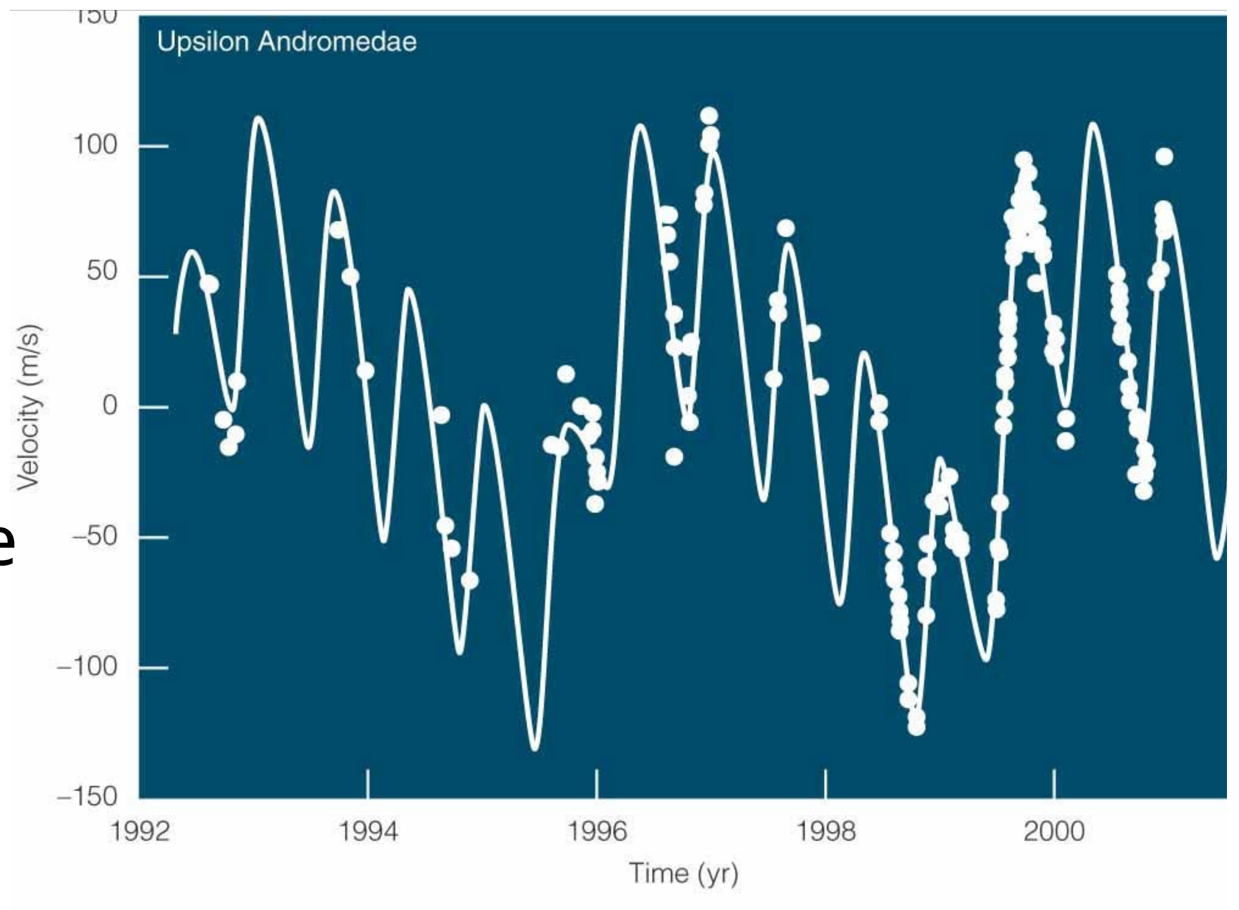
Totally unexpected, since Jupiter-like planets can't form next to stars

Technique 1: Radial Velocity

If there is more than one planet, the radial velocity curves can be complicated!

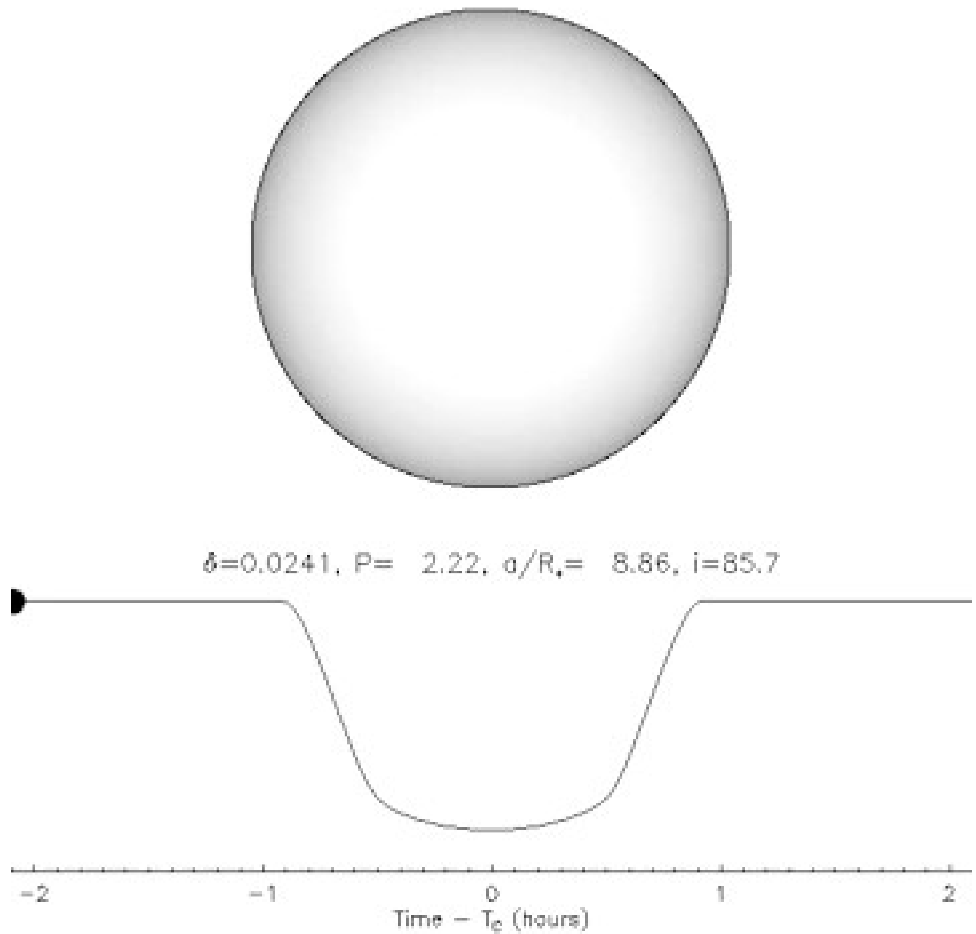
But we can break them down into contributions from each planet, to find multi-planet systems like Upsilon Andromedae

4 planets of around Jupiter mass

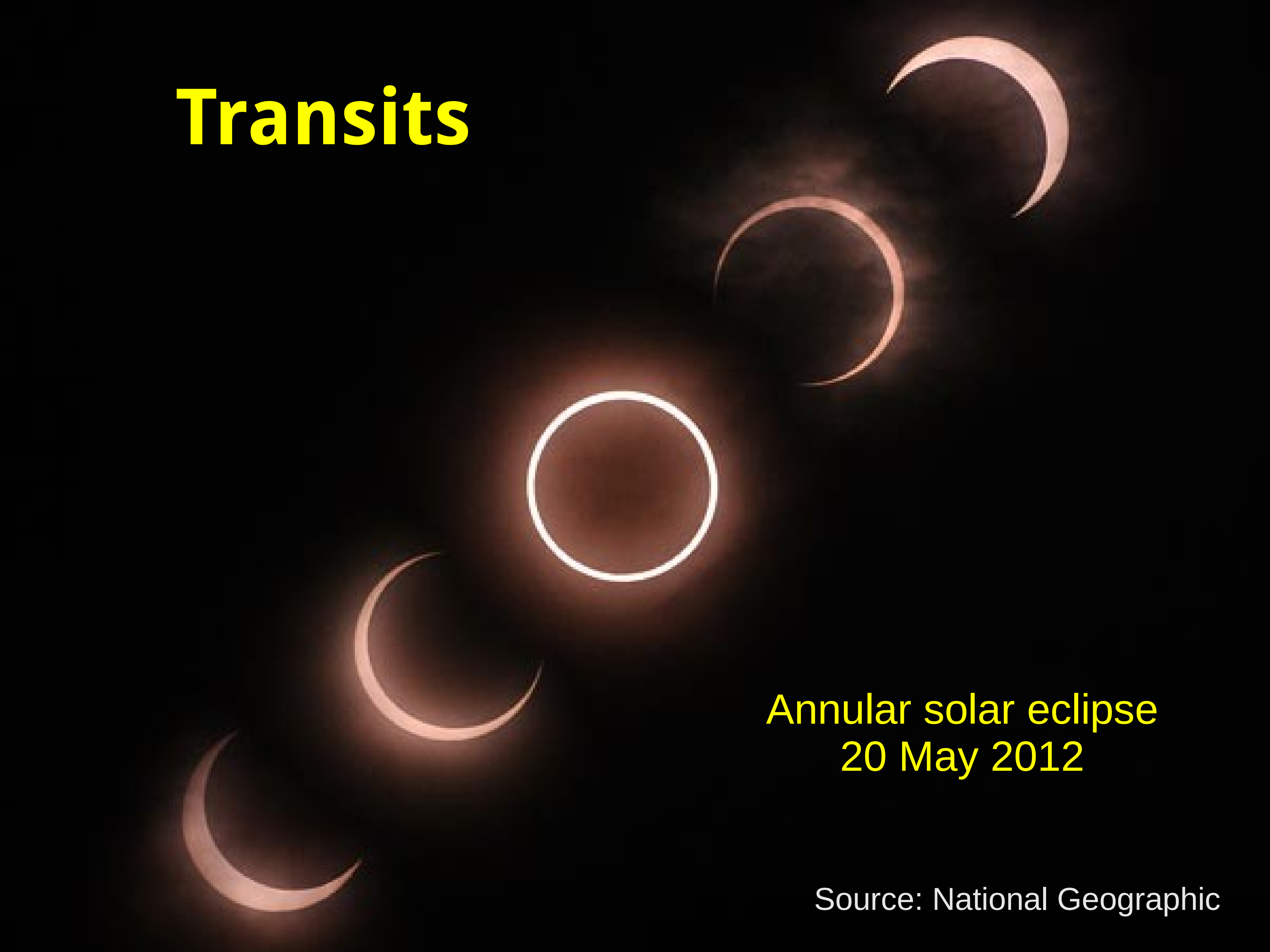


Technique 2: Transits

- 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



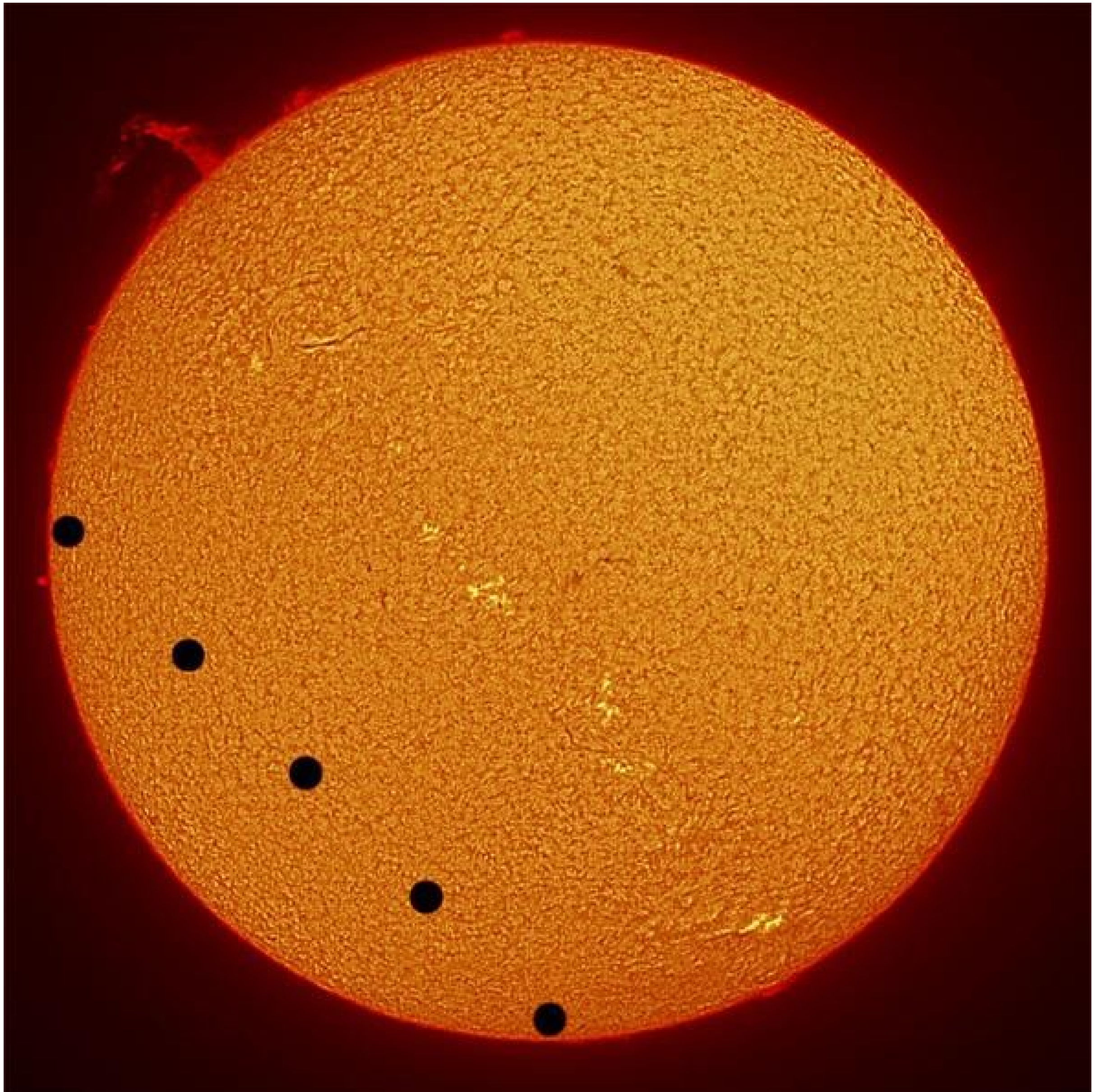
Transits



Annular solar eclipse
20 May 2012

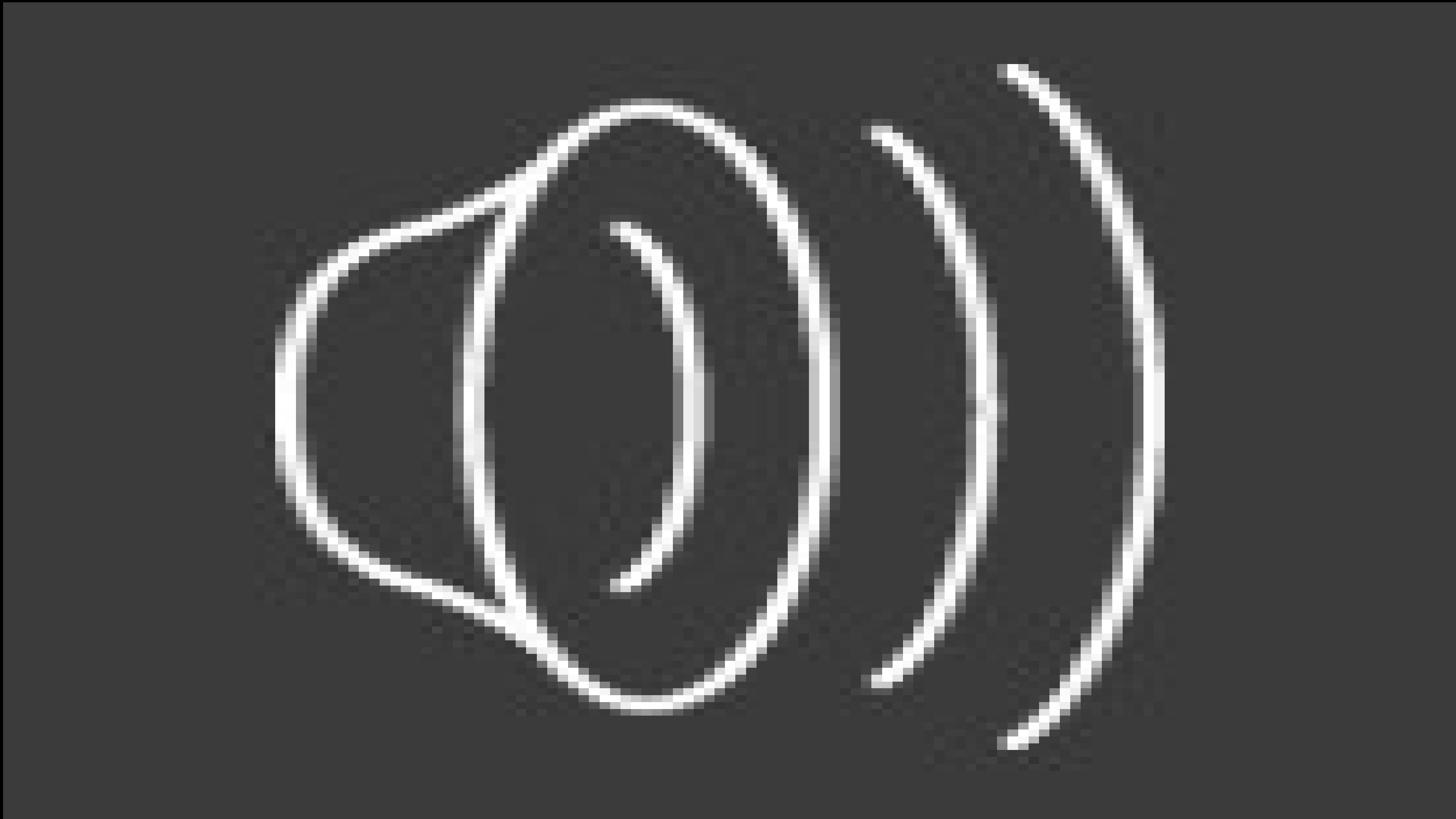
Source: National Geographic

Transit of Venus – June 5th 2012



Did you see it?It was your last chance!

Next transit: Dec. 10-11, 2117



Technique 2: Transits

This turns out to be easy!

Can be done with small telescopes for bright stars

Here is an example: SuperWASP in South Africa

Telescopes are actually telephoto lenses

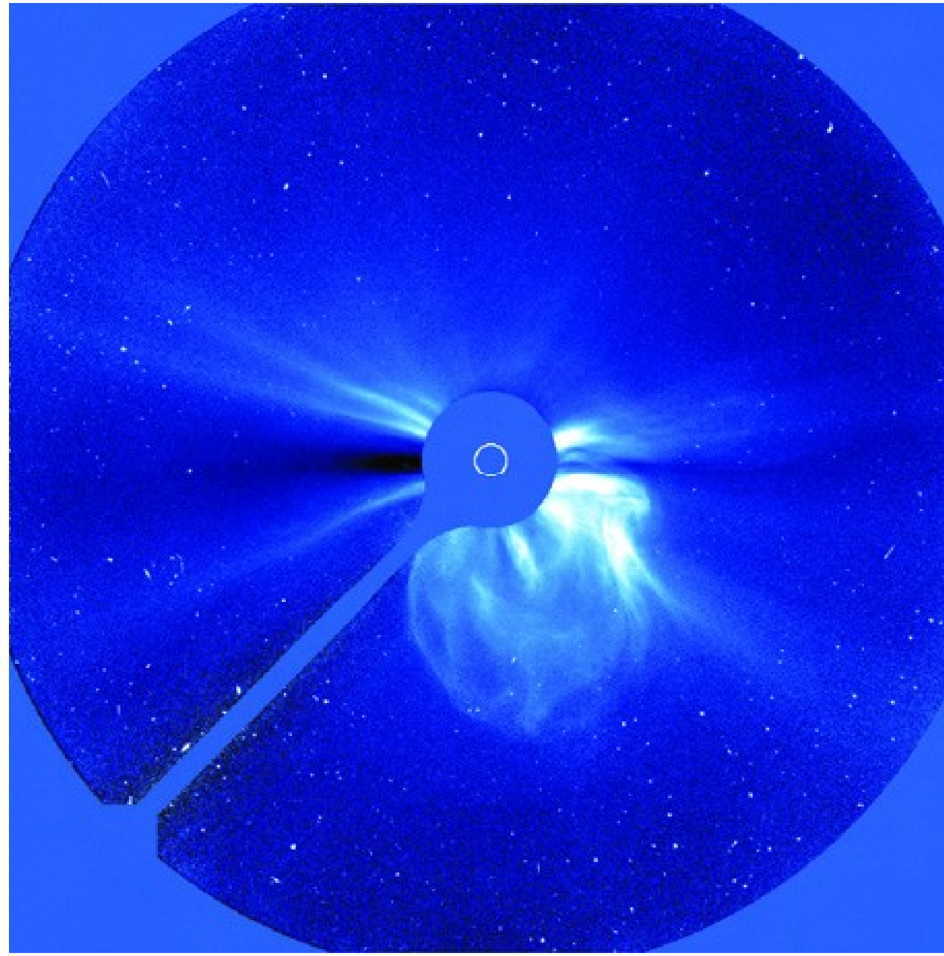
Also done from space – more on that later

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

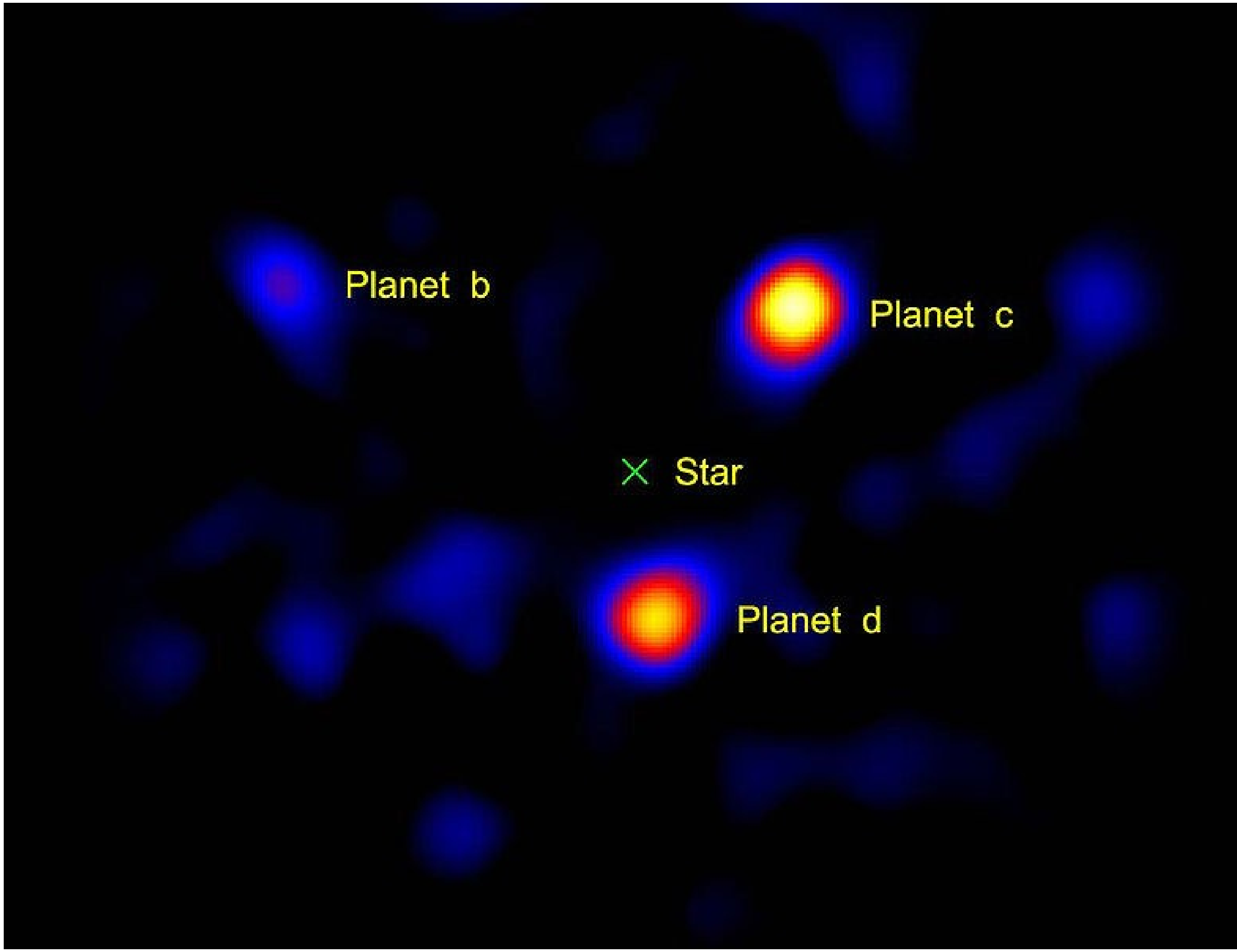
This has been done for the Sun for years in order to study the corona – hence the name coronagraph

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

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

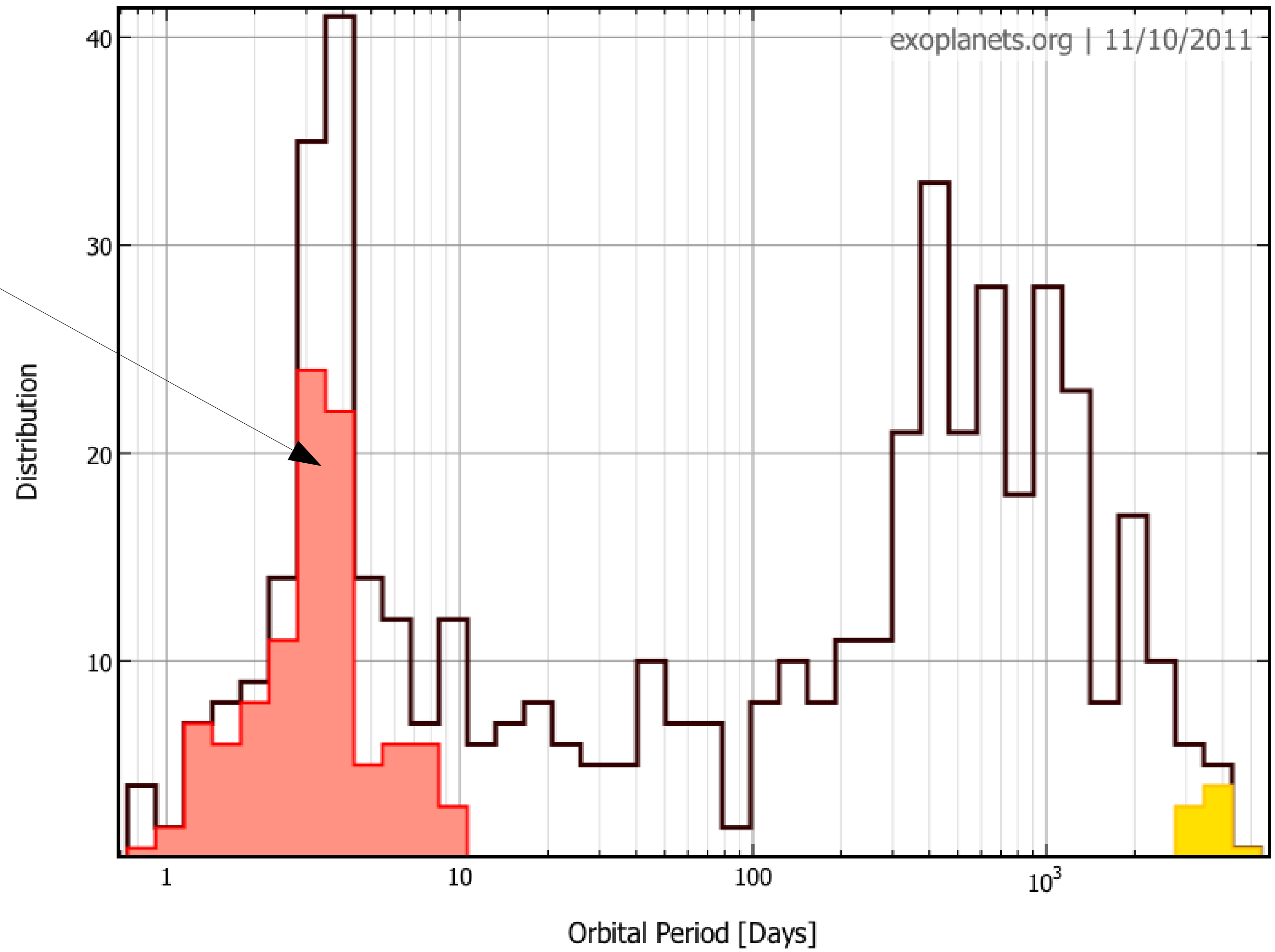
Extrasolar Planets

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

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

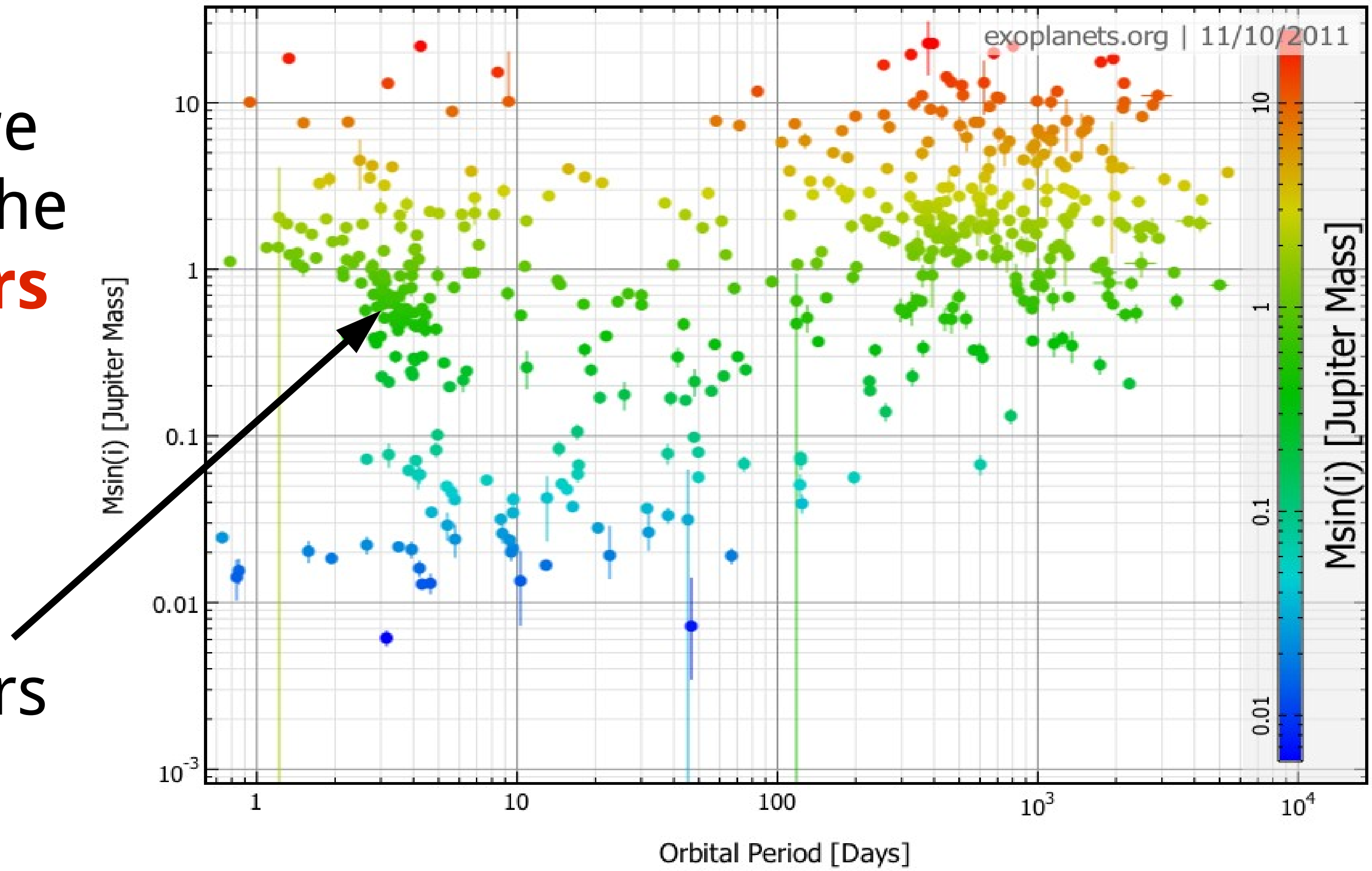
3 day pileup



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**

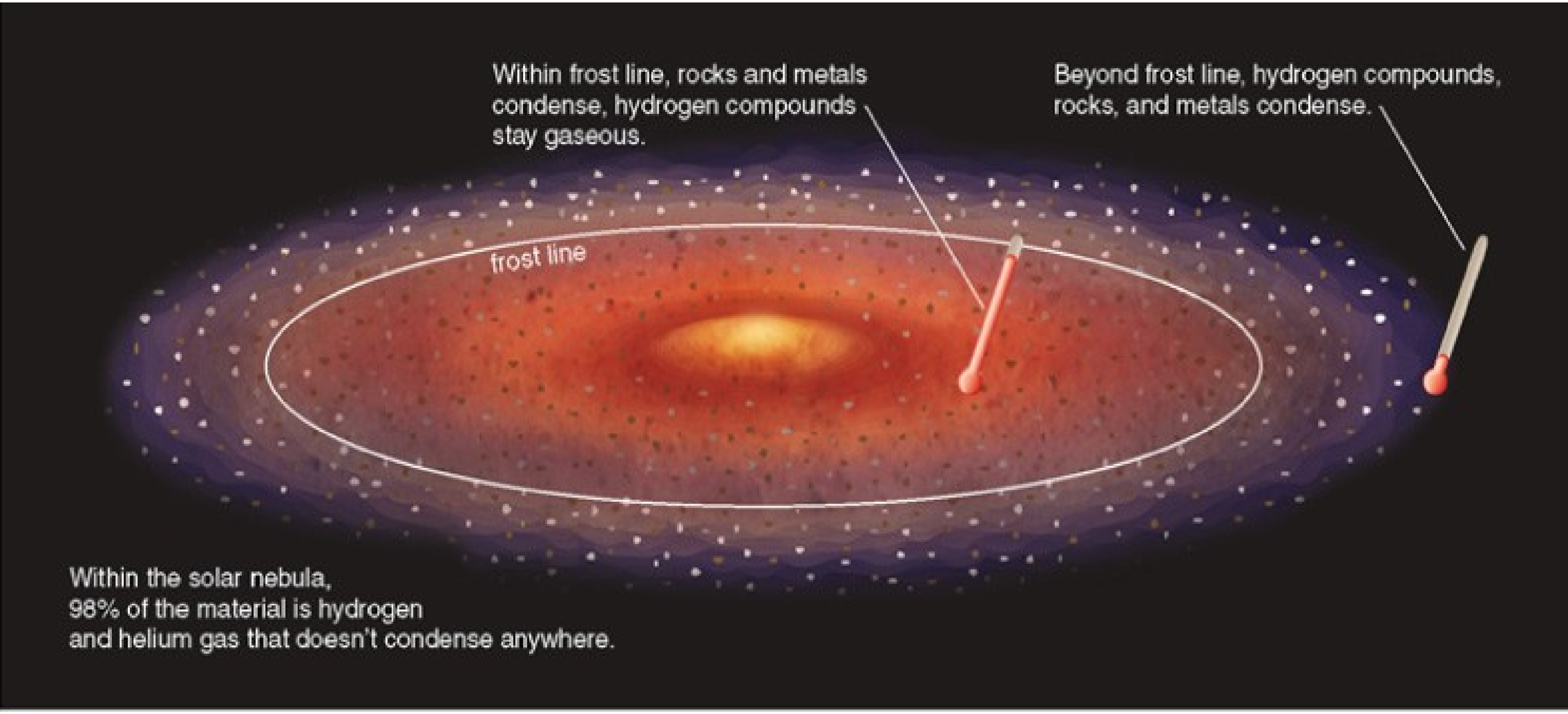


Hot Jupiters

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

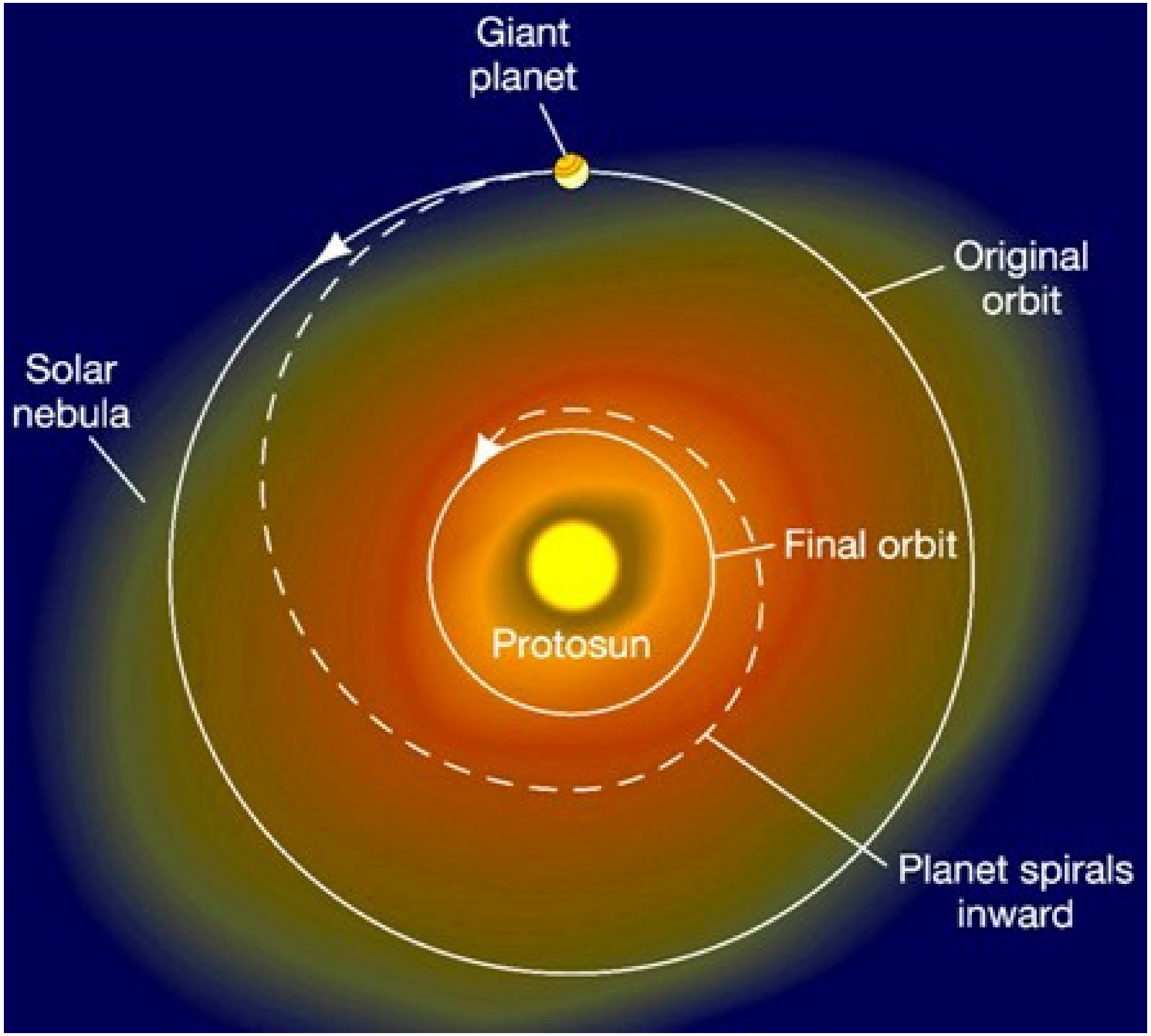


Recall that you need big cores to form Jupiter. Bigger cores are possible if you can gather more material. In regions where the gas is so cold that ices form – the **snow line or frost line** – you have the extra stuff.

Planetary Migration

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

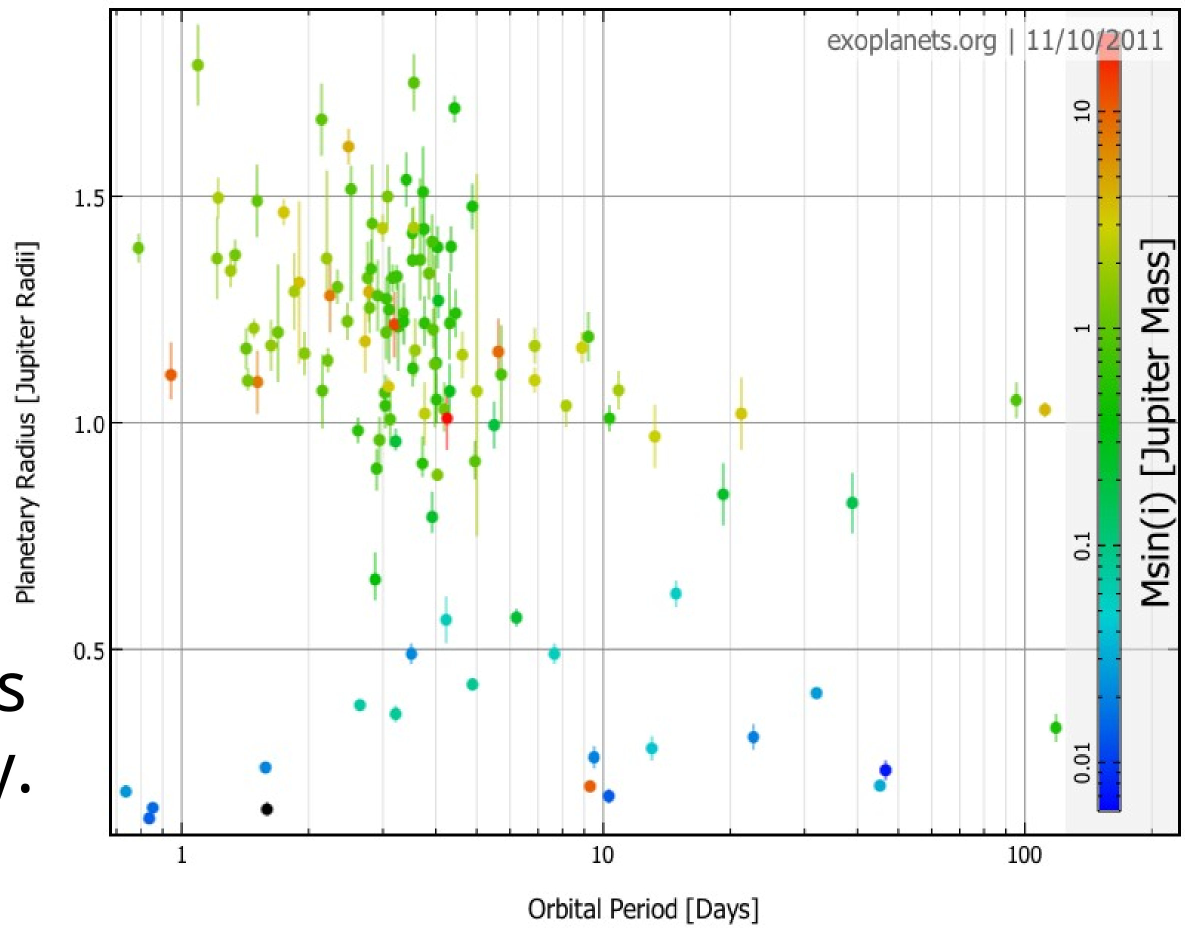
This is called **planetary migration** and might explain the hot Jupiters.



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.

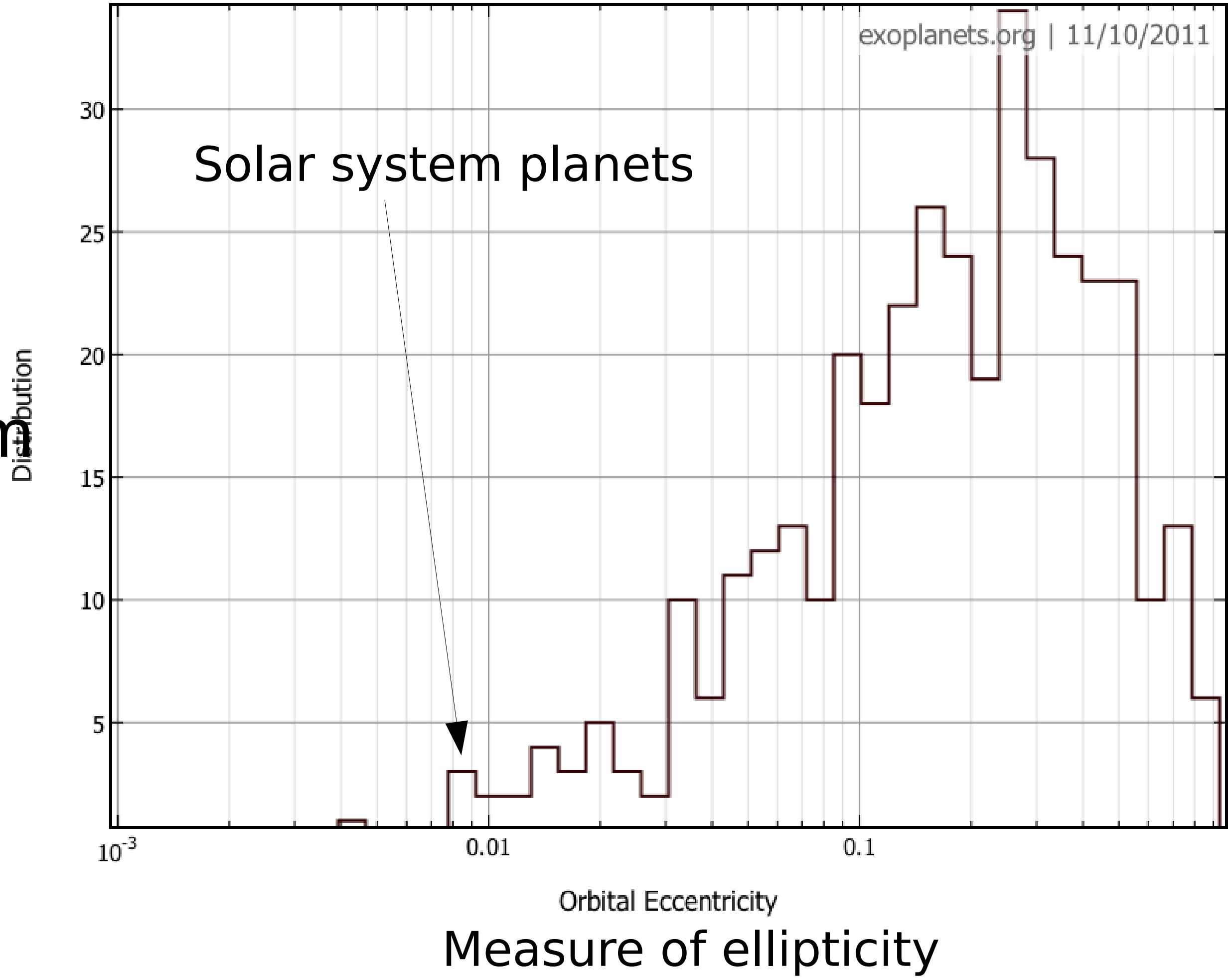


A Great Diversity of Solar Systems

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.



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

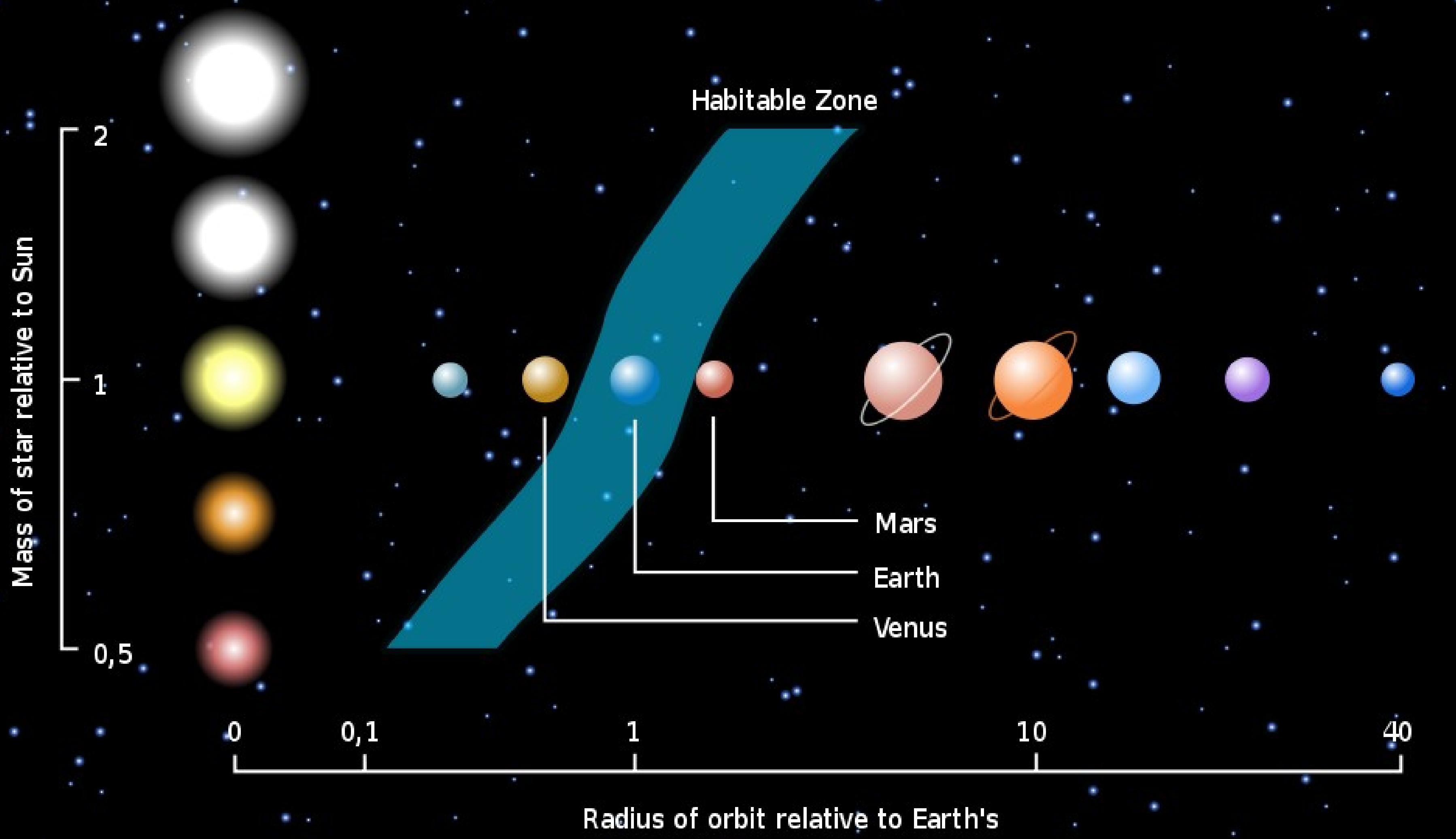
One of the main goals of planet searchers is to find a planet about the size of Earth in a region around a star where it is not too hot nor too cold

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

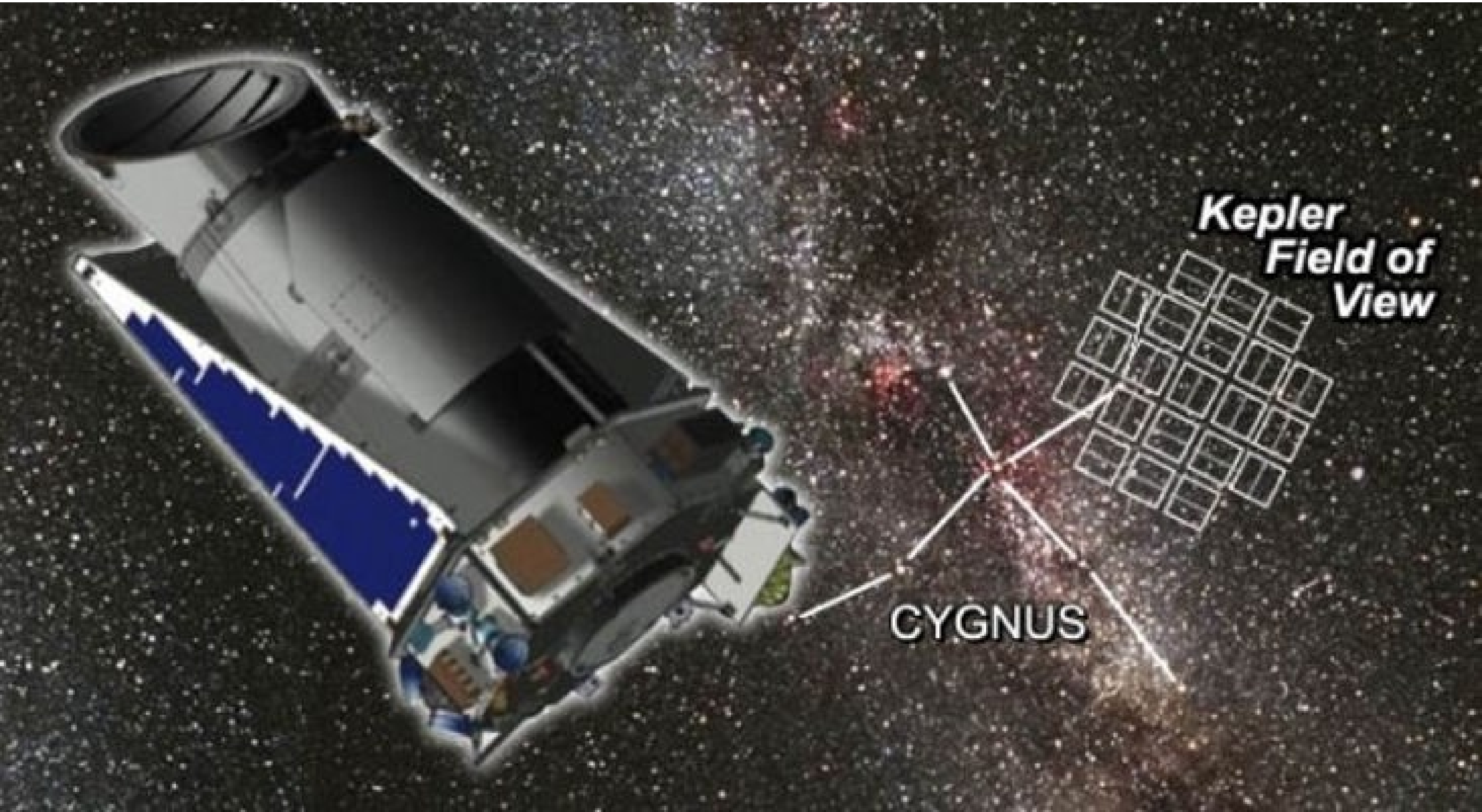
Planets in the habitable zone are sometimes known as "Goldilocks planets"

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



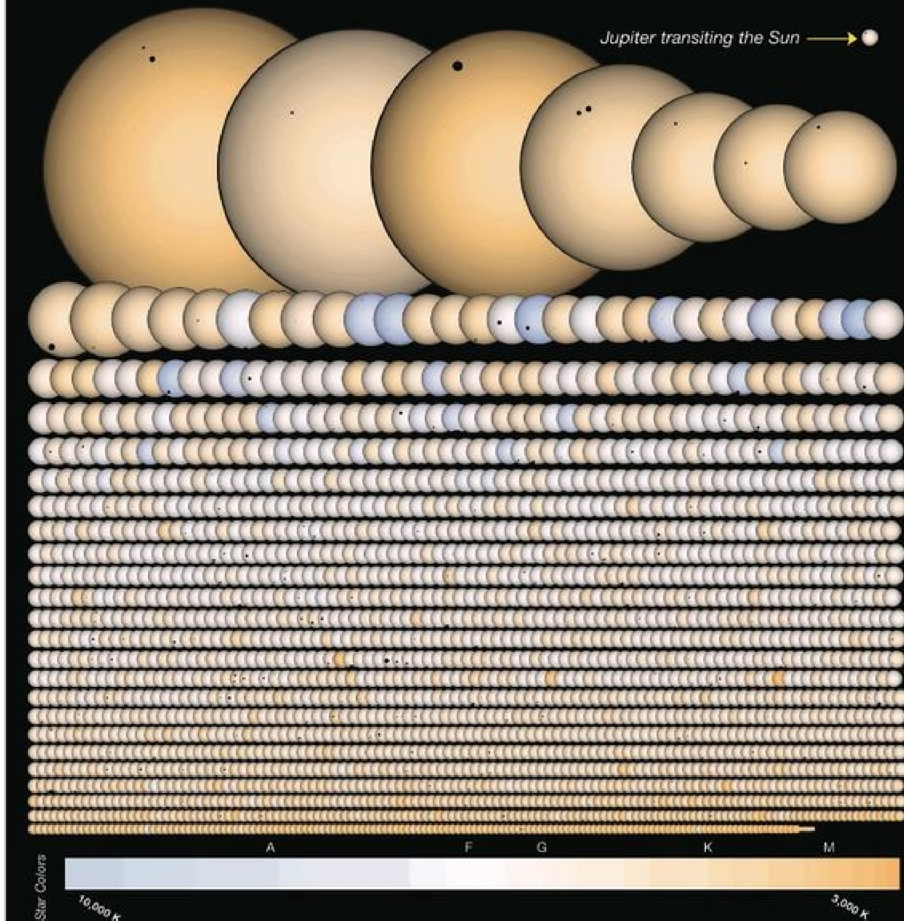
Kepler

- 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

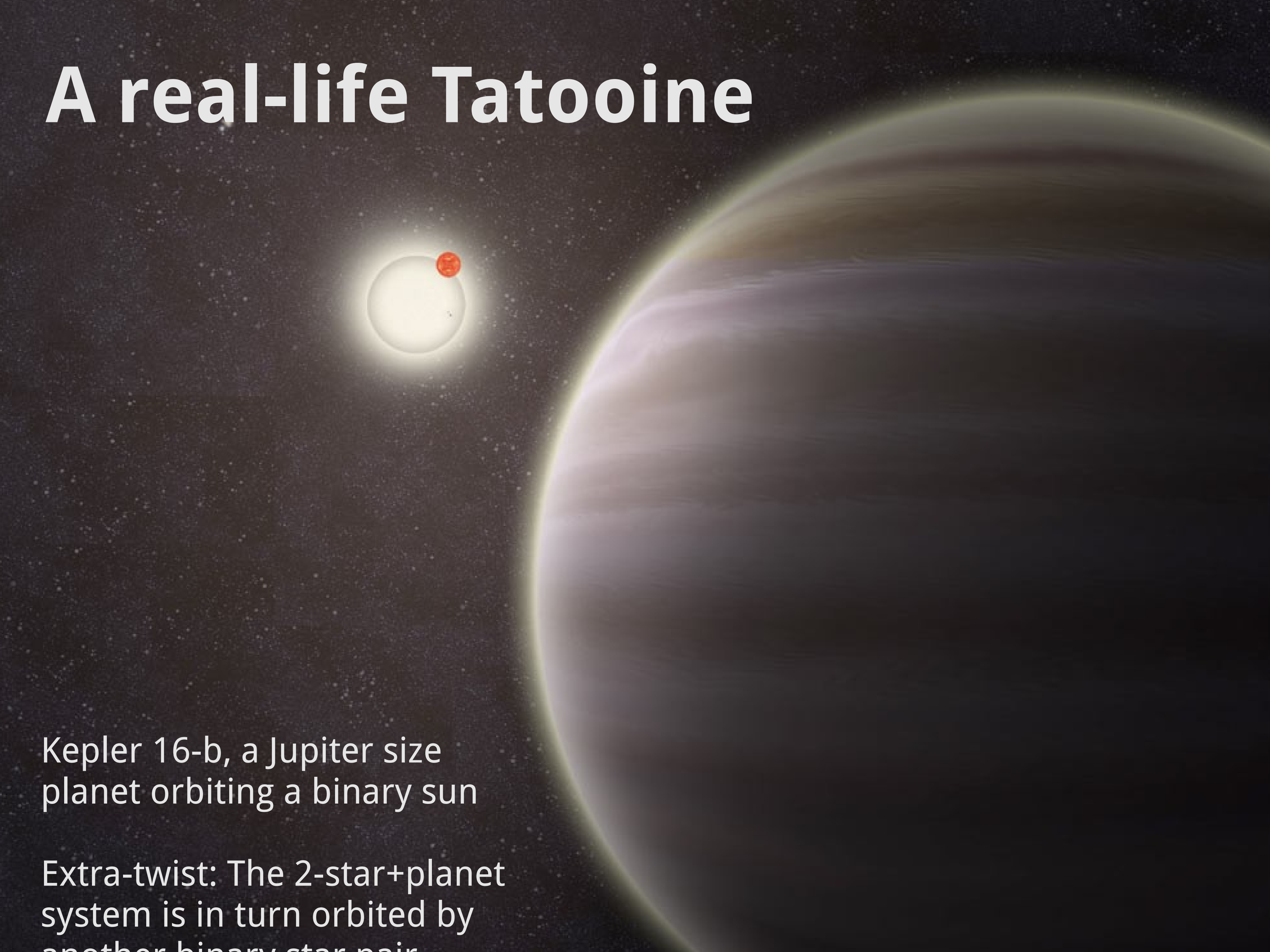


Using NASA's planet-hunting Kepler spacecraft, astronomers have discovered 2,740 planet candidates orbiting 2,036 other suns in a search for Earth-size worlds. The search began in 2009. Kepler monitors a rich star field for planetary transits, which cause a slight dimming of starlight when a planet crosses 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

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!



A real-life Tatooine

Kepler 16-b, a Jupiter size planet orbiting a binary sun

Extra-twist: The 2-star+planet system is in turn orbited by another binary star pair

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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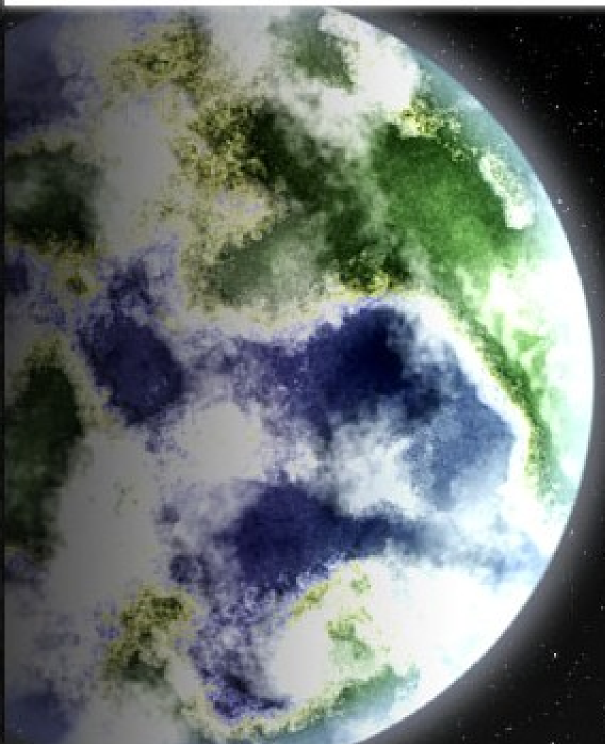
exoplanets.org

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



Table

Plots

1492 EOD Planets
Planets with good orbits listed in the Exoplanet Orbit Database

24 Other Planets
Including microlensing and imaged planets

1516 Total Confirmed Planets

3359 Unconfirmed Kepler Candidates

4875 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.