Astrophysical Objects

Planet Formation

An introduction to modern Astrophysics chapter 23

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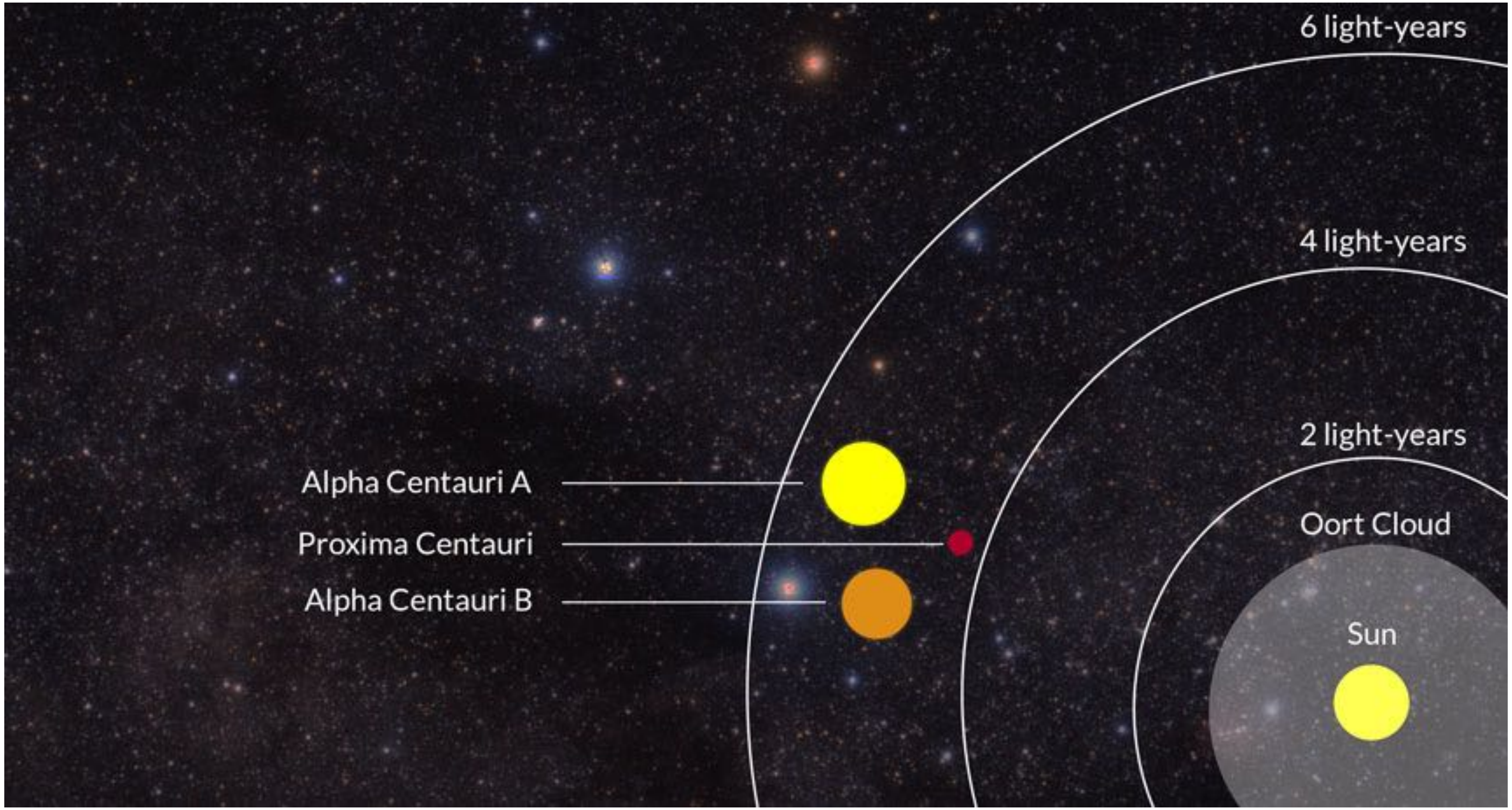
Exoplanets

Which one is the nearest planet that is outside the Solar System?

Exoplanets

The nearest planetary system to the Solar system is the one around Proxima Centauri: Proxima Centauri b



https://www.sciencenews.org/blog/context/visits-proxima-centauri-planet-probably-millennia-away

Exoplanets

- **What are the methods to detect exoplanets?**

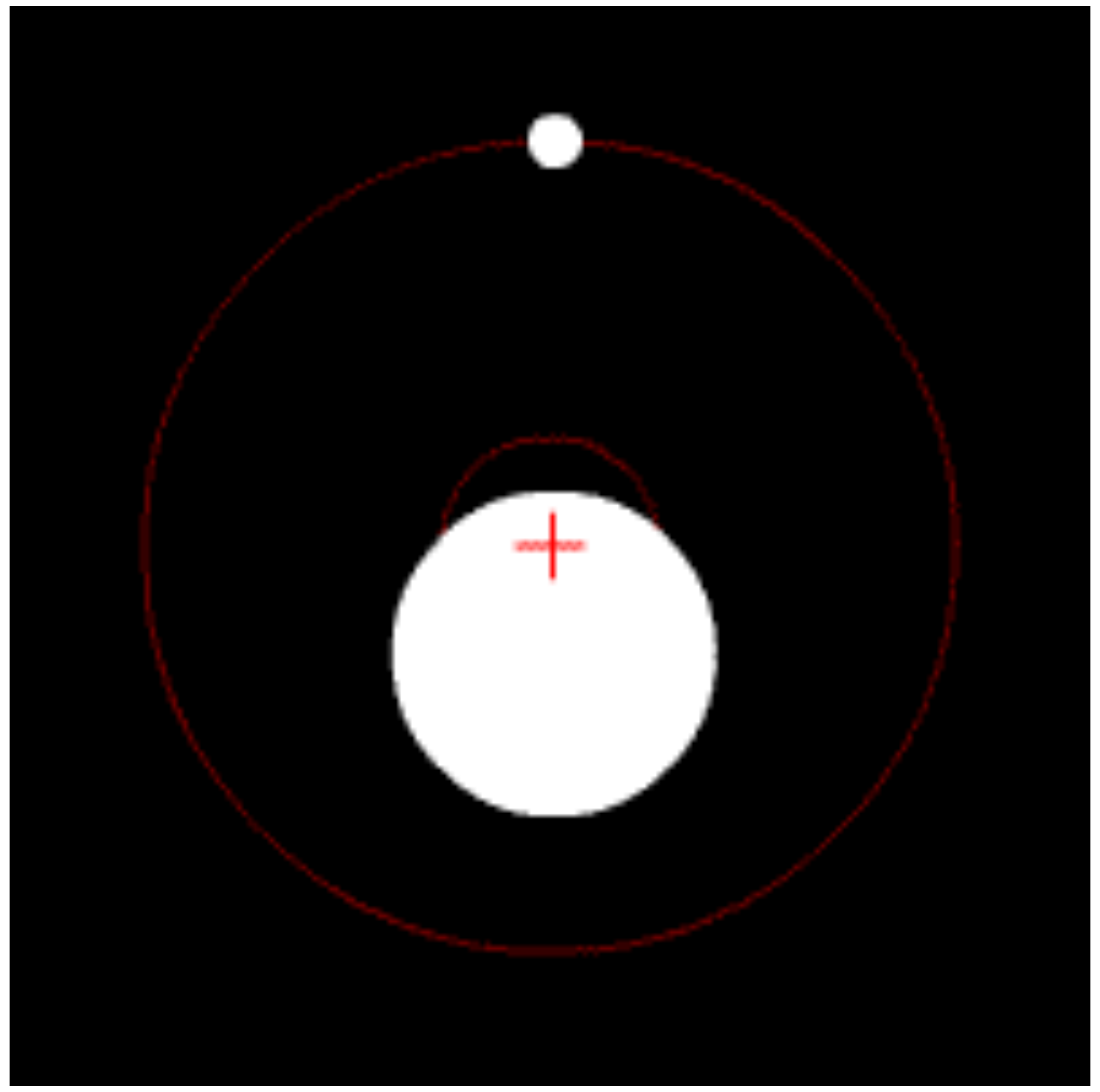
Exoplanets

- **Planets outside the Solar System are called exoplanets**
- To date more than 5500 exoplanets are known (2023)

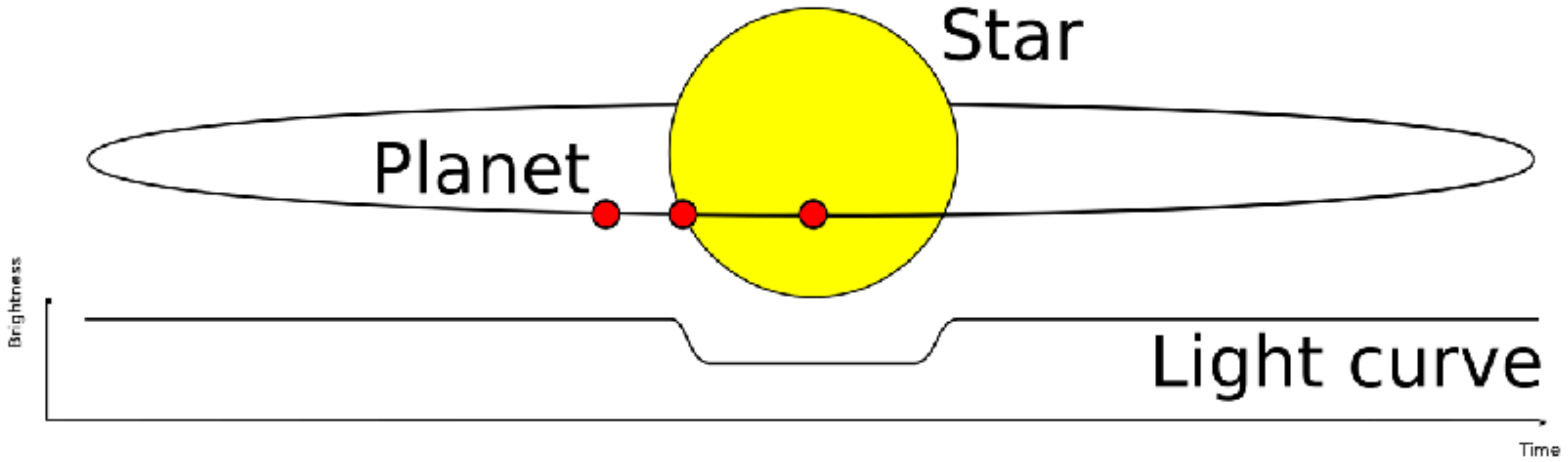
- Most common methods to detect exoplanets:
  - **RADIAL VELOCITY** - Watching for Wobble
  - **TRANSIT** - Searching for Shadows
  - **DIRECT IMAGING** - Taking Pictures
  - **GRAVITATIONAL MICROLENSING** - Light in a Gravity Lens
  - **ASTROMETRY** - Minuscule Movements

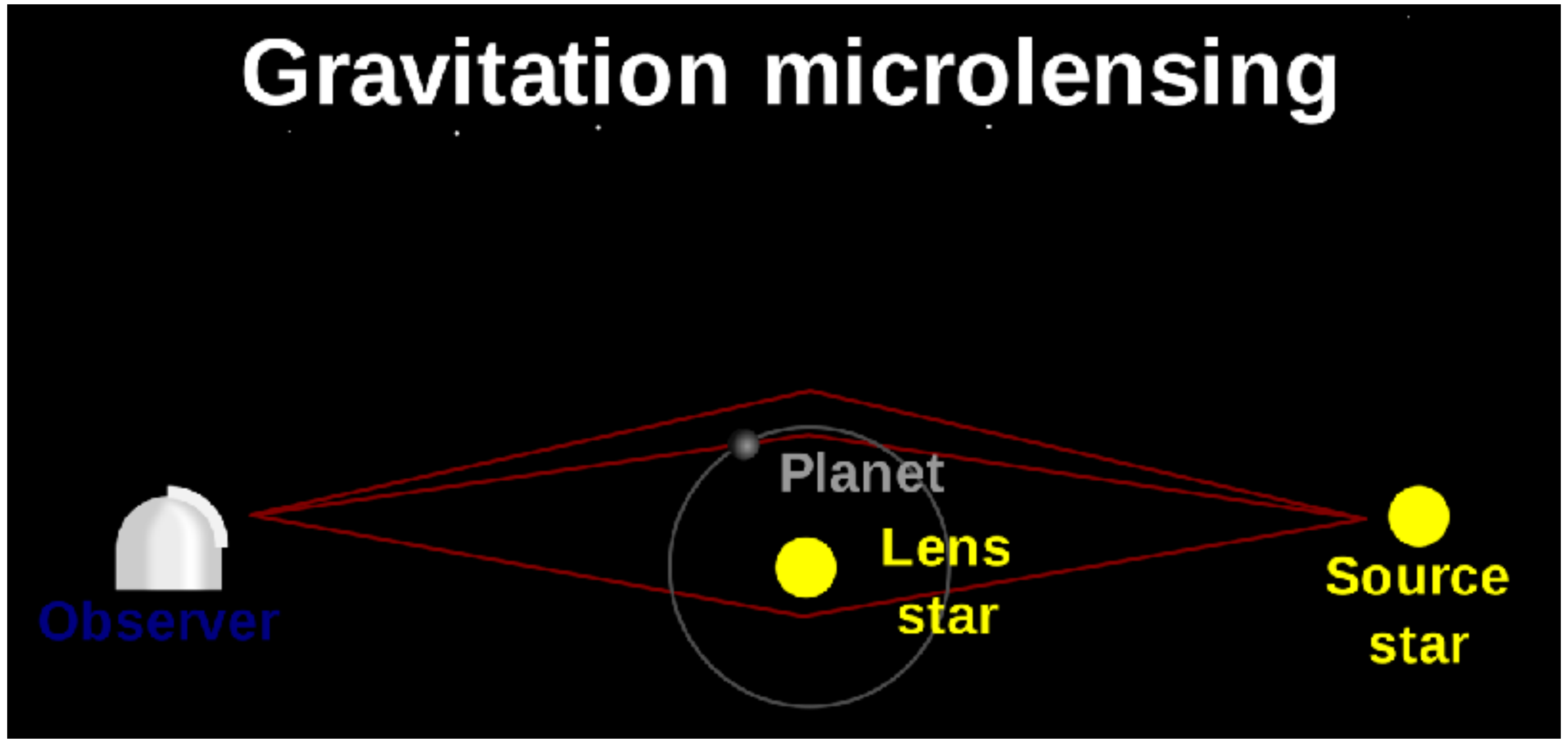
Exoplanets

- Astrometry

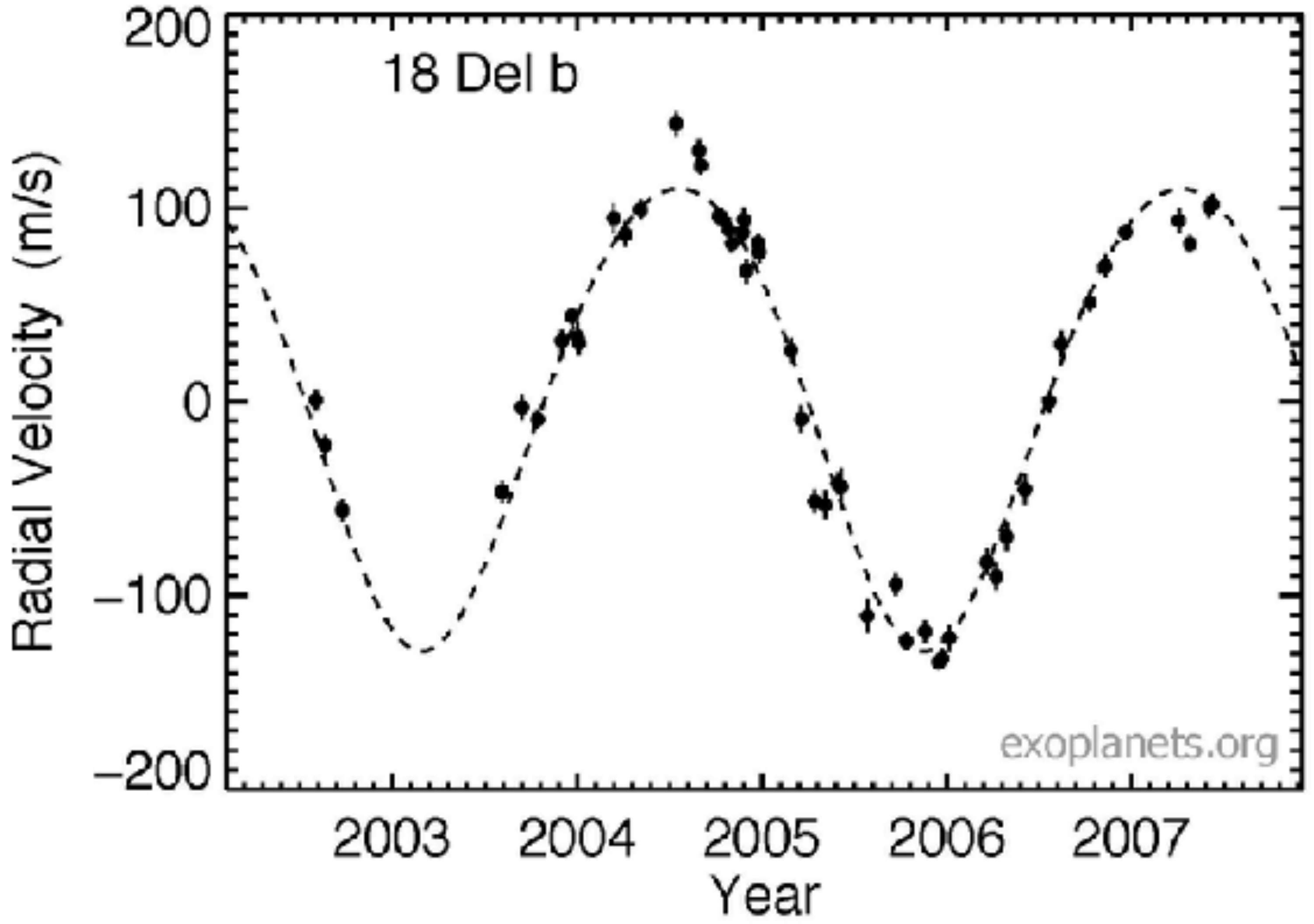


- Transit



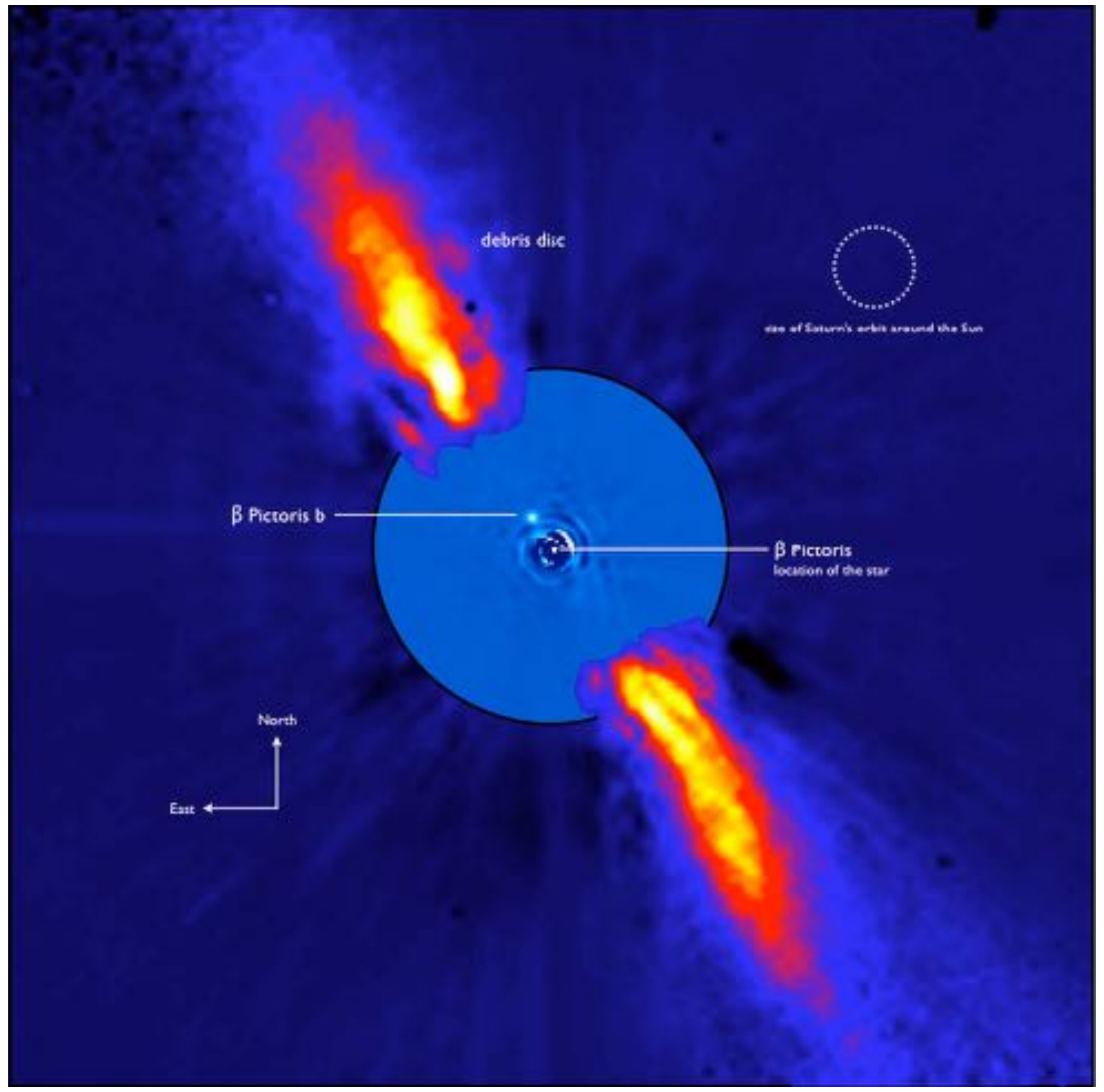


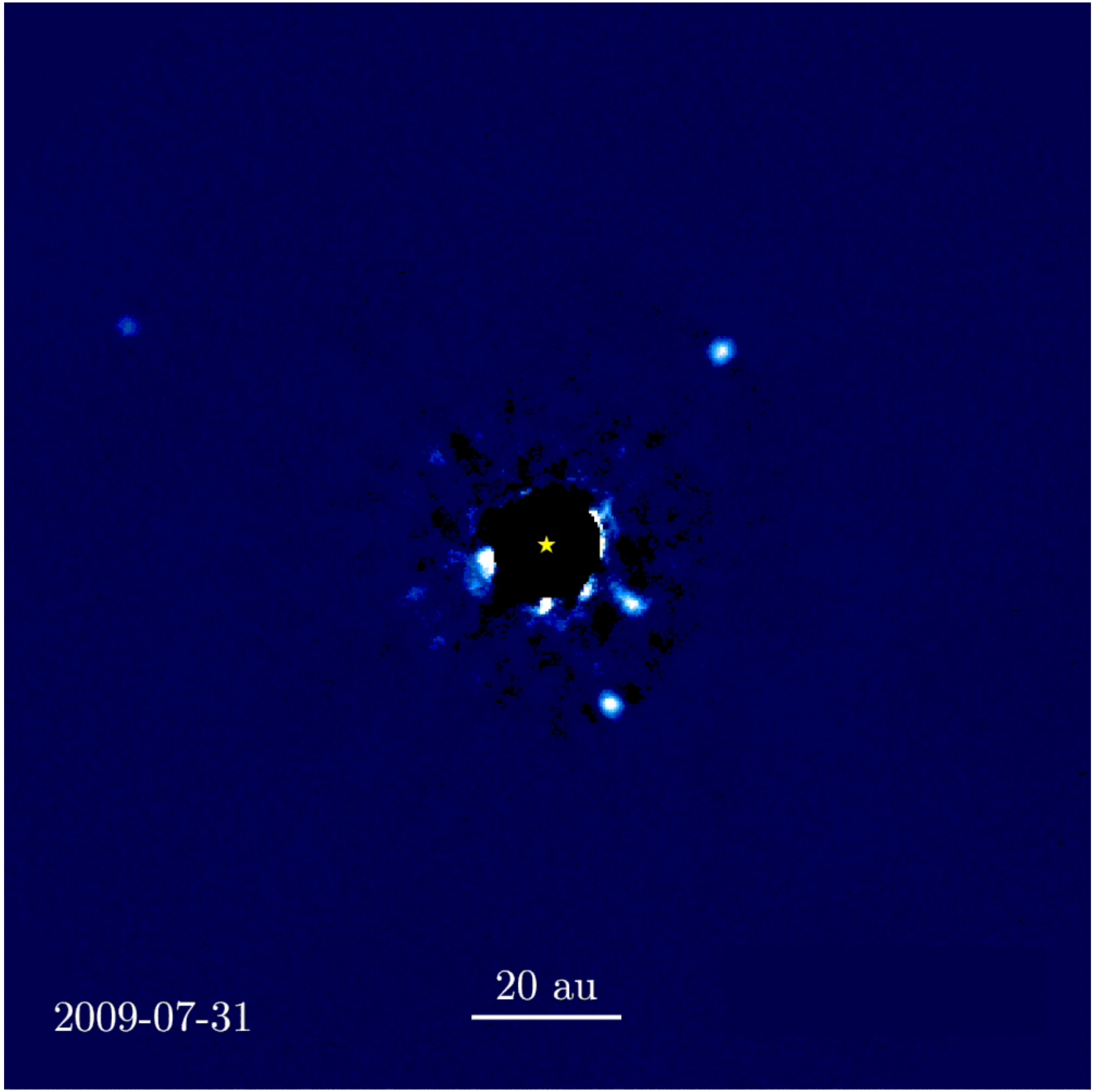
- Radial velocity



Exoplanets

- Direct imaging a planet around β **Pictoris**





Four exoplanets orbiting counterclockwise with their host star (**HR 8799**).
This video was created by using 7-10 still images over a decade, and using a computer to interpolate movement.

Radial velocity

The pulsar PSR B1257+12 has a planetary system with **three known pulsar planets,** named "Draugr" (PSR B1257+12 b or PSR B1257+12 A), "Poltergeist" (PSR B1257+12 c, or PSR B1257+12 B) and "Phobetor" (PSR B1257+12 d, or PSR B1257+12 C), respectively.

They were both the **first extrasolar planets** and the first pulsar planets to be discovered; B and C in 1992 and A in 1994.

A is the lowest-mass planet yet discovered by any observational technique, with somewhat less than twice the mass of Earth's moon.

The PSR B1257+12 planetary system[4]

Companion (in order from star)	Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
A (b / Draugr)	$0.020 \pm 0.002\ M_\oplus$	0.19	25.262 ± 0.003	0.0	~50°	—
B (c / Poltergeist)	$4.3 \pm 0.2\ M_\oplus$	0.36	66.5419 ± 0.0001	0.0186 ± 0.0002	53°	—
C (d / Phobetor)	$3.9 \pm 0.2\ M_\oplus$	0.46	98.2114 ± 0.0002	0.0252 ± 0.0002	47°	—

https://en.wikipedia.org/wiki/PSR_B1257%2B12

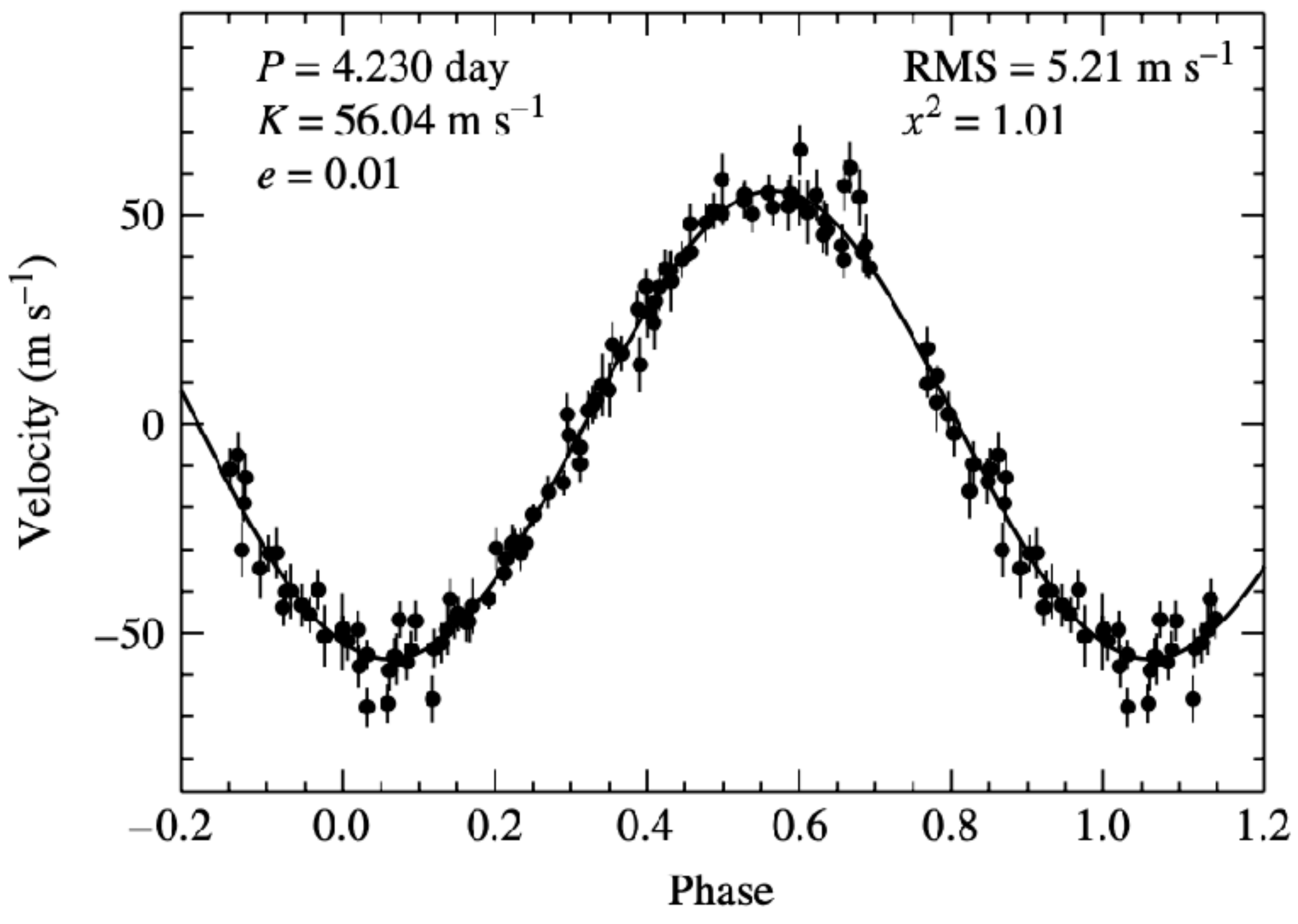
Radial velocity

51 Pegasi was the first regular star found to have a planet in orbit around it.

It was discovered **in 1995**, with a period of P = 4.23077 d in a nearly circular orbit (e < 0.01) around 51 Peg (a more recent radial velocity curve of 51 Peg.

Since the **system is not eclipsing**, and the planet is too faint to be visually identified, the inclination of the orbit of the planet (i) is unknown. As a result, only the quantity *m* sin*i* can be determined for the planet **from radial velocity measurements.**

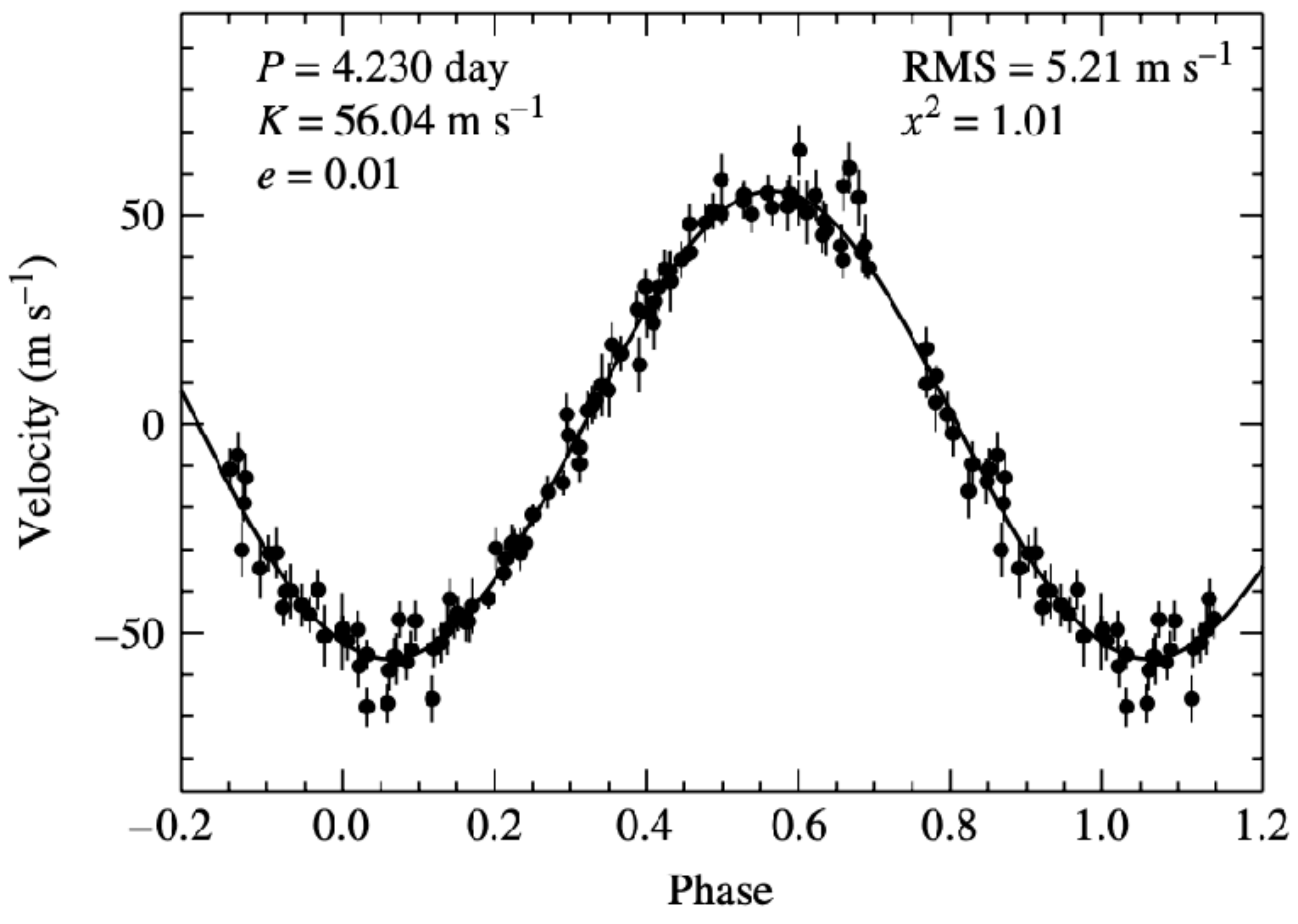
Given that the parent star is a near twin of our Sun, with a stellar mass of approximately 1 M⊙, the **lower mass limit of the orbiting planet** is obtained from the maximum radial velocity wobble of the star.



The radial velocity measurements of 51 Pegasi, revealing the presence of a planet orbiting only 0.051 AU from the star. The sinusoidal shape of the velocity curve is evidence of a very low orbital eccentricity

Radial velocity

$$\frac{a^3}{T^2} = \frac{G(M+m)}{4\pi^2}$$



Example: To determine the **minimum mass of the planet orbiting 51 Peg**, we must first determine its **orbital velocity**. From Kepler's third law, and assuming that the mass of the star is $m_{51} = 1\ M_\odot$ and that the planet's mass, m, is insignificant ($m \ll m_{51}$), we find

$$a = \left[\frac{GP^2(m_{51}+m)}{4\pi^2}\right]^{1/3} = 7.65 \times 10^9 \text{ m} = 0.051 \text{ AU}.$$

Since the **orbit of the planet** is nearly circular, the **orbital speed** of the planet is $v = 2\pi a/P = 131 \text{ km s}^{-1}$.

Noting from the Fig. that the amplitude of the star's observed radial velocity is $v_{r,max} = v_{51} \sin i = 56.04 \text{ m s}^{-1}$, we find that

$$m \sin i = m_{51} \frac{v_{51} \sin i}{v} = 8.48 \times 10^{26} \text{ kg} = 0.45\ M_J,$$

where M_J is the mass of Jupiter. Since $\sin i \leq 1$, the mass of the planet, 51 Peg b, must be greater than $0.45\ M_J$.

51 Peg b is one example of a **"hot Jupiter,"** one of a number of extrasolar planets that have been discovered having Jupiter-class masses but orbiting very close to their parent star.

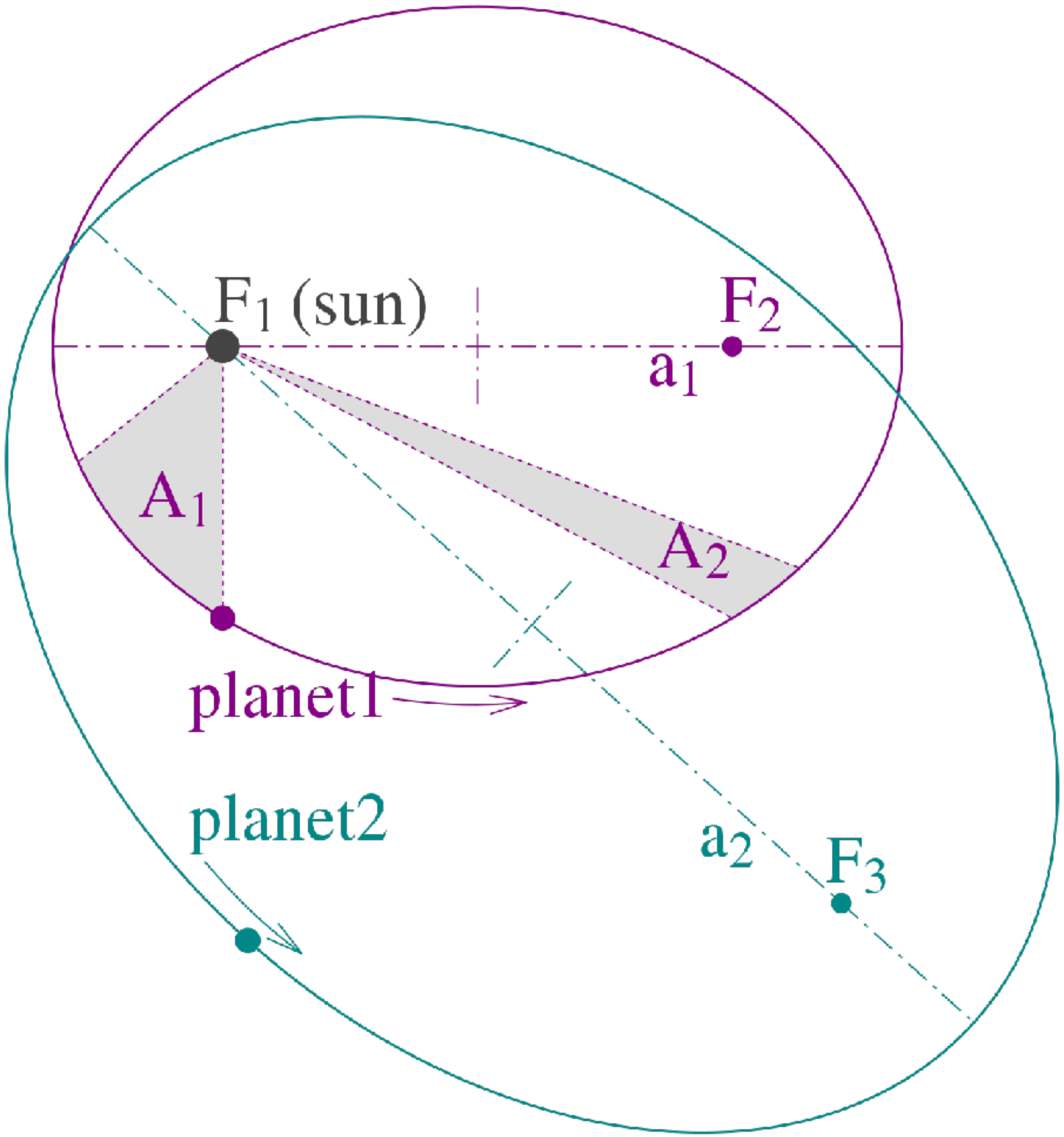
Kepler's laws

Illustration of Kepler's three laws with two planetary orbits.

1. The orbits are ellipses, with focal points F_1 and F_2 for the first planet and F_1 and F_3 for the second planet. The Sun is placed at focal point F_1.
2. The two shaded sectors A_1 and A_2 have the same surface area and the time for planet 1 to cover segment A_1 is equal to the time to cover segment A_2.
3. The total orbit times for planet 1 and planet 2 have a ratio . $\left(\frac{a_1}{a_2}\right)^{3/2}$

$$\boxed{\frac{a^3}{T^2} = \frac{G(M+m)}{4\pi^2}}$$

More details: https://en.wikipedia.org/wiki/Kepler%27s_laws_of_planetary_motion



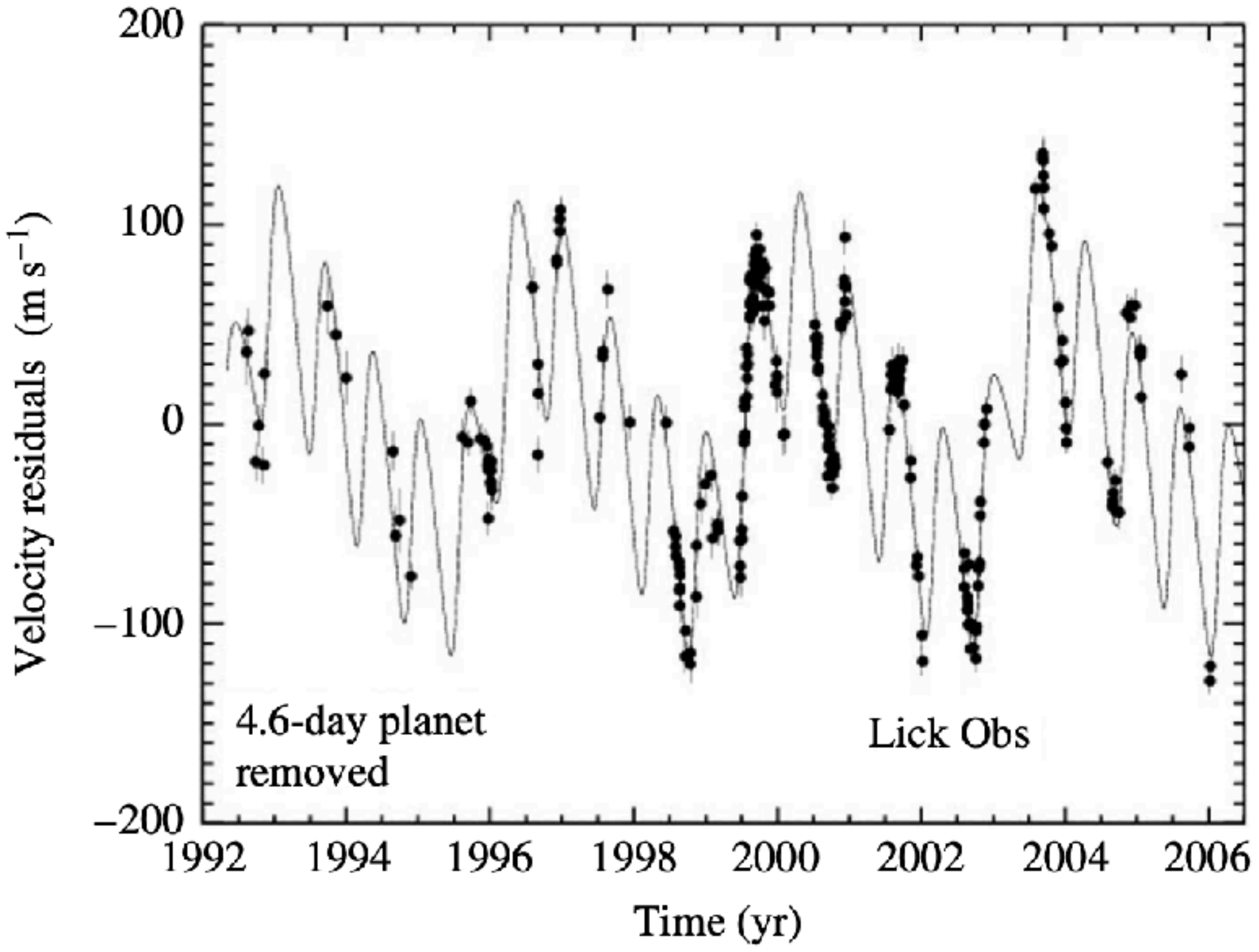
Multi planet systems

A number of extrasolar planetary systems have been found through the radial velocity technique to have **multiple planets in orbit about the central stars.**

An example of one such system is **υ Andromedae**; see Fig. After the orbital perturbations due to the 4.6-d orbit of one planet were removed from the radial velocity curve of the star, evidence remained of additional perturbations.

- The υ And system contains **at least three planets** with orbital periods of 4.6 d, 241 d, and 1284 d,
- with m sini: of 0.69 M_J, 1.89 M_J, and 3.75 M_J, respectively.
- The mass of the F8V parent star is estimated to be 1.3 $M_\odot$.

878 systems with more than one planet (2023)



The residuals in the **radial velocity measurements** of υ Andromedae after the gravitational perturbations of the 4.6-day planet have been removed.

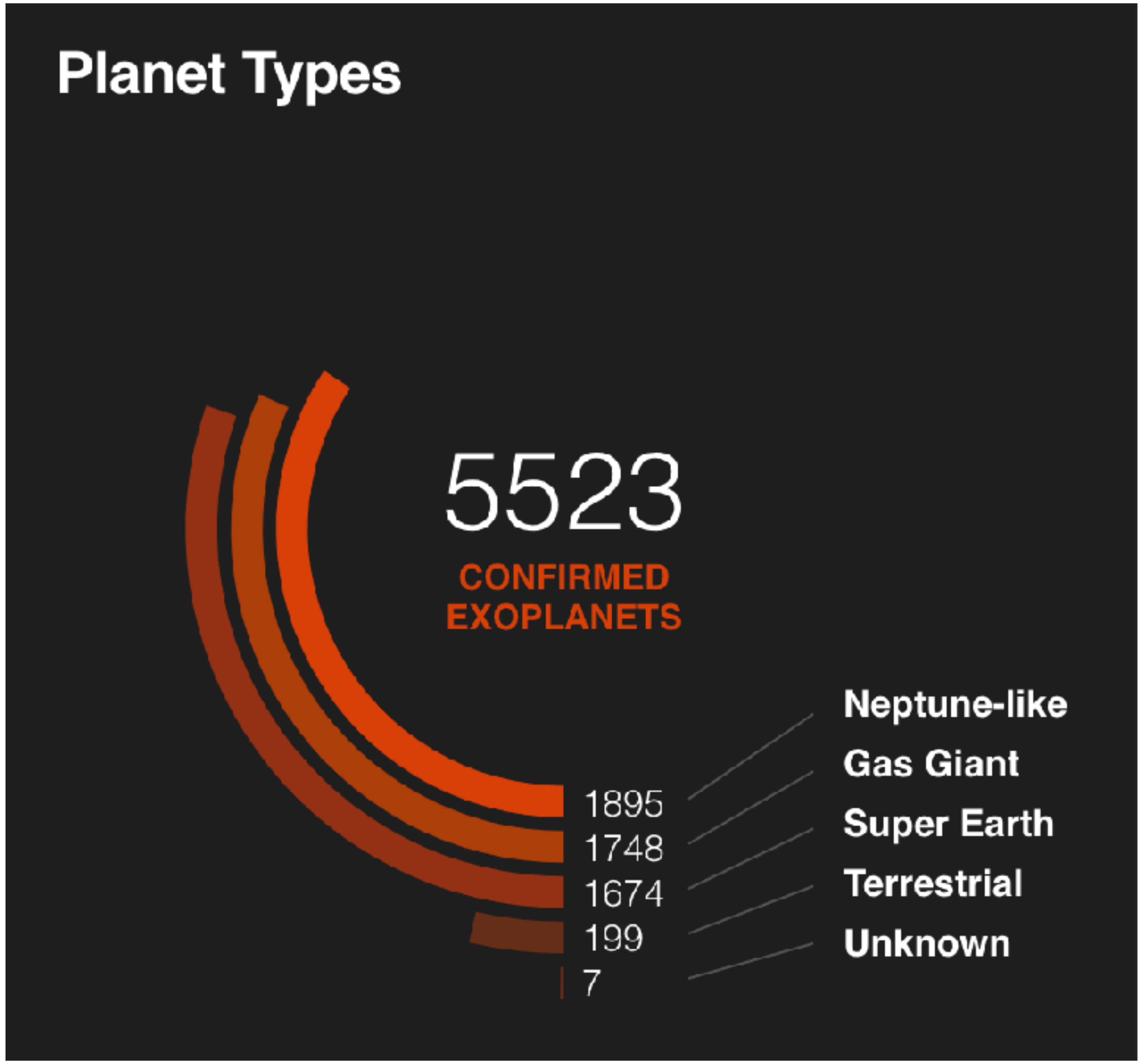
The data reveal the **presence of at least three planets orbiting υ And.**

Mass distribution

Initially, the radial velocity technique was able to discover only very massive (Jupiter-class) planets in close-in orbits around their parent stars.

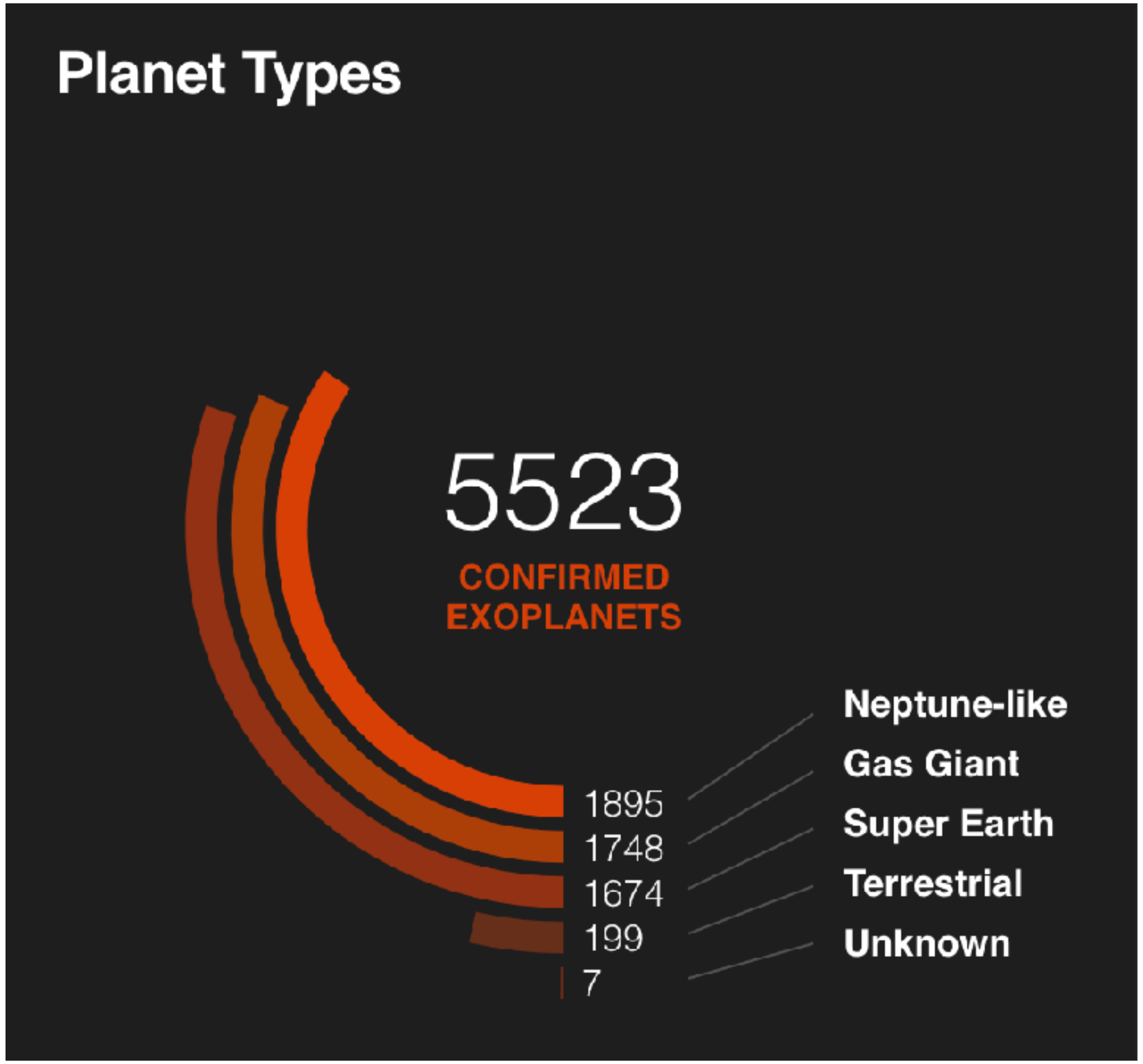
One of the reasons for this selection effect is that these objects exert the greatest **gravitational influence** on their parent star and generate the largest reflex radial velocities.

The other reason is that a star must be observed over a **time interval greater than the orbital period** of the planet before the existence of the planet can be confirmed. As the amount of time increases for the systems being surveyed, the **longer time-line data have allowed researchers to find lower-mass planets** and planets orbiting farther from the star.

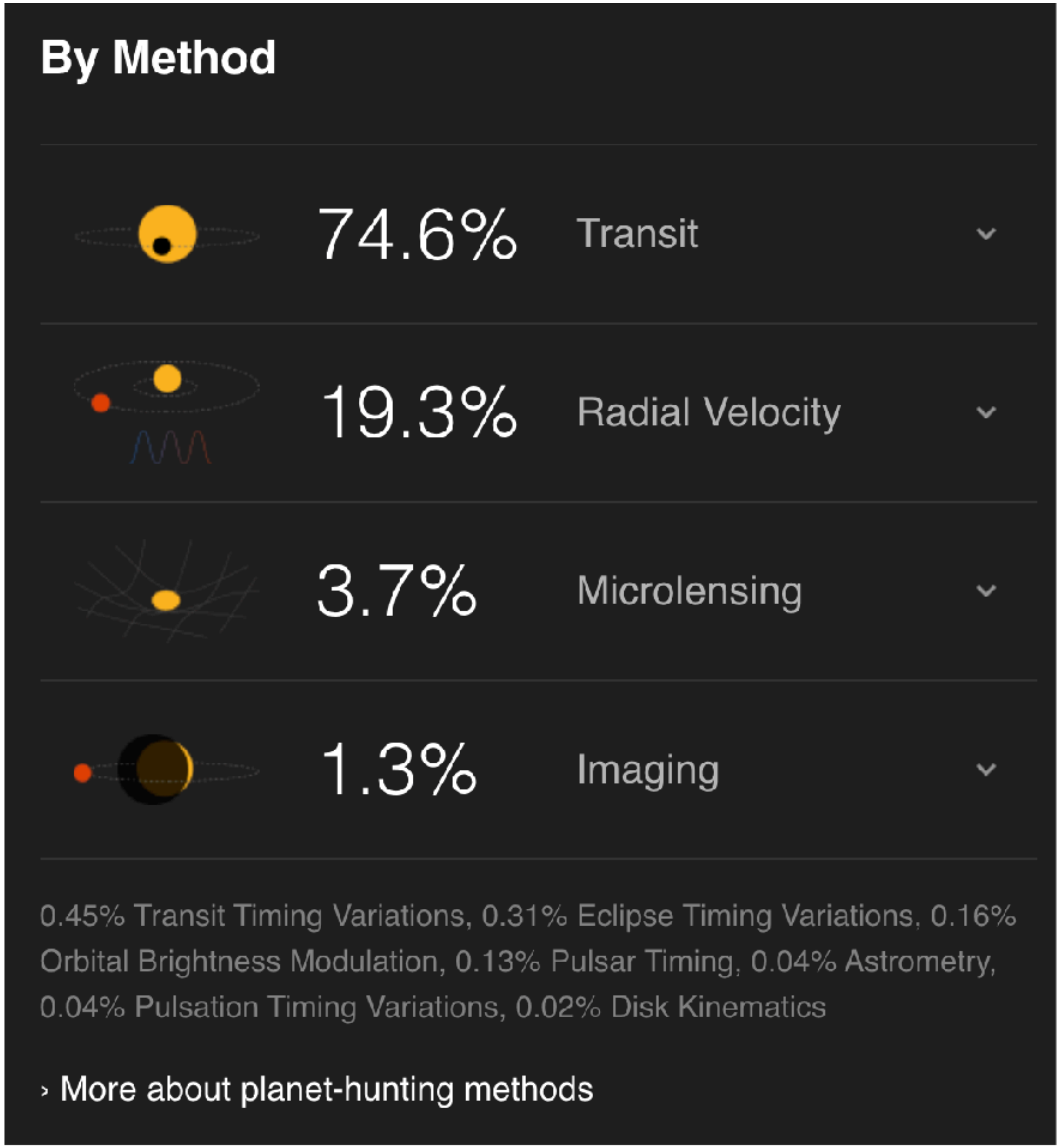


https://exoplanets.nasa.gov/

Exoplanet census



5 October 2023



https://exoplanets.nasa.gov/

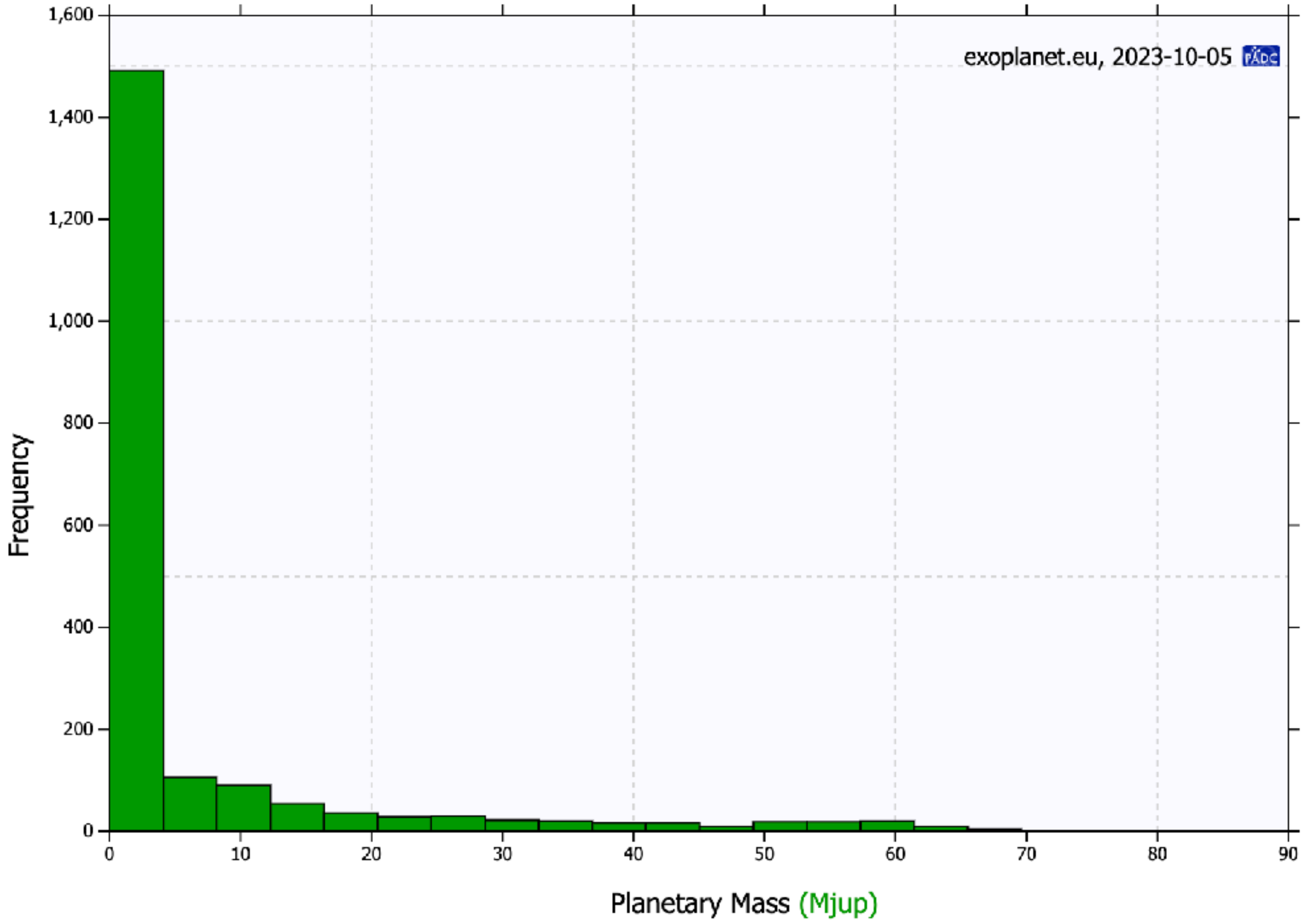
Exoplanet census

https://exoplanets.nasa.gov/

Mass distribution

Over time, selection effects are systematically diminishing.

As is evident from statistical studies of the systems investigated so far, nature seems able to produce planets with a range of masses, with the **lowest-mass planets being the most common**.



http://exoplanet.eu/

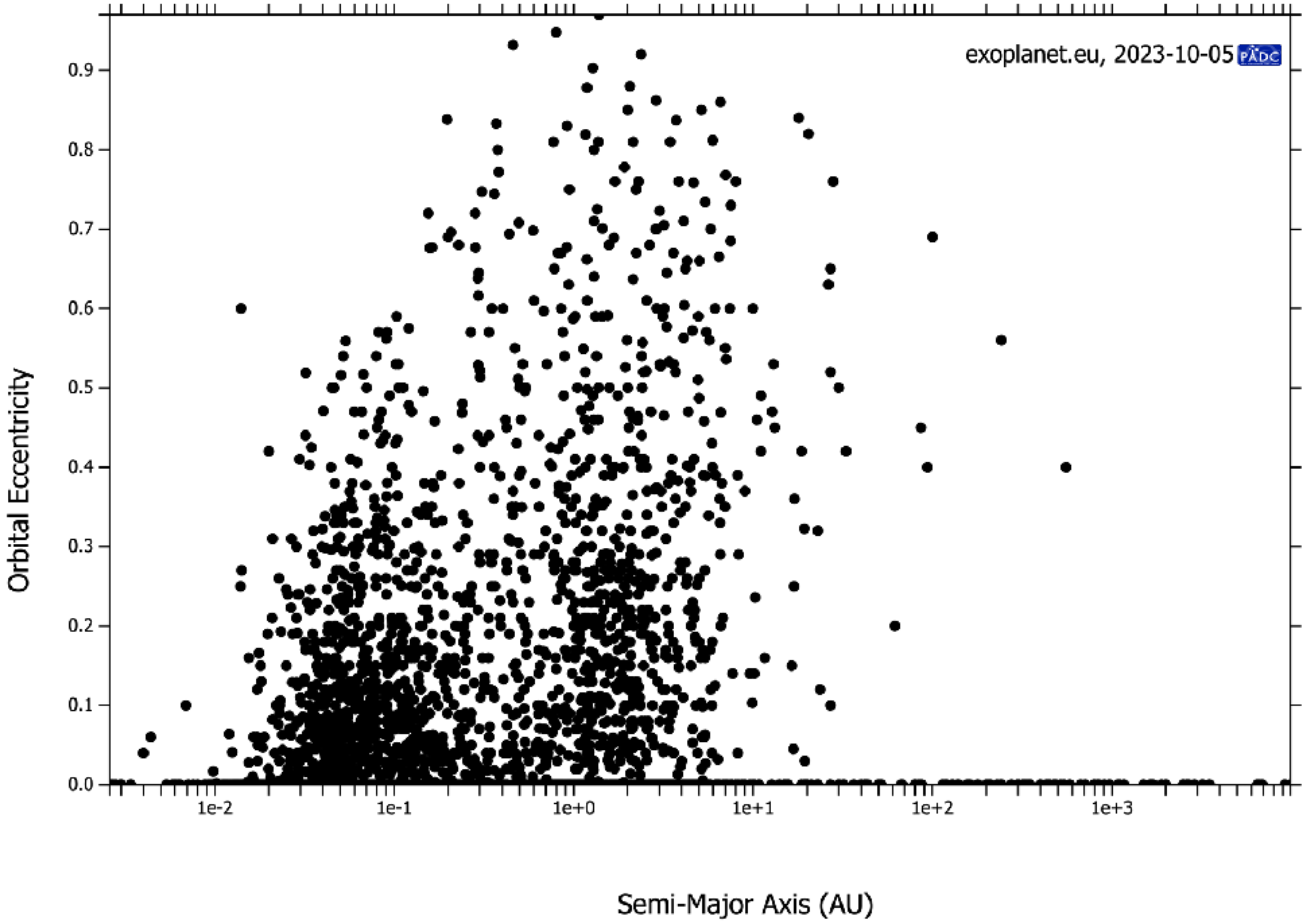
Distribution of Orbital eccentricities

It is also interesting to note the relationship between orbital eccentricity (e) and semimajor axis for extrasolar planets (Fig.).

Those **planets that are orbiting close to their parent star tend to have circularized orbits** (or at least orbits with smaller eccentricities).

Planets orbiting **farther from their parent star may have high orbital eccentricities.**

However, from the data obtained thus far, only a few planets are known to have eccentricities of greater than 0.5, and less even fewer have eccentricities in excess of 0.75.



http://exoplanet.eu/

Planet hosting stars

There is at least one planet on average per star.

About **1 in 5 Sun-like stars have an "Earth-sized" planet in the habitable zone**.

Most known exoplanets orbit stars roughly similar to the Sun, i.e. main-sequence stars of spectral categories F, G, or K.

Lower-mass stars (red dwarfs, of spectral category M) are **less likely to have planets** massive enough to be **detected by the radial-velocity method**.

Despite this, several **tens of planets around red dwarfs** have been discovered by the Kepler telescope, which uses the **transit method** to detect smaller planets.

Using data from Kepler, a **correlation has been found between the metallicity of a star and the probability that the star hosts a giant planet**, similar to the size of Jupiter. Stars with higher metallicity are more likely to have planets, especially giant planets, than stars with lower metallicity.

Some **planets** orbit one member of a **binary star system**, and several circumbinary planets have been discovered which orbit both members of a binary star. A few planets in **triple star systems** are known and one in the **quadruple system** Kepler-64.

High Metallicity

An early trend was (2005) that planetary systems were **preferentially form around metal-rich (Population I) stars.**

One way to quantify the **metallicity** is by comparing the **ratios of iron to hydrogen** in stars relative to our Sun, defining the metallicity to be

$$\boxed{[\mathrm{Fe/H}] \equiv \log_{10}\left[\frac{(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\mathrm{star}}}{(N_{\mathrm{Fe}}/N_{\mathrm{H}})_{\odot}}\right],}$$

where N_{Fe} and N_{H} represent the *number* of iron and hydrogen atoms, respectively.

Stars with [Fe/H] < 0 are **metal-poor relative to the Sun**, and stars with [Fe/H] > 0 are relatively **metal-rich.**

For comparison, extremely metal-poor (Population II) stars in the Milky Way Galaxy have been measured with values of [Fe/H] as low as –5.4, while the highest values for metal-rich stars are about 0.6.

High Metallicity

Gas giants are more common around metal rich stars

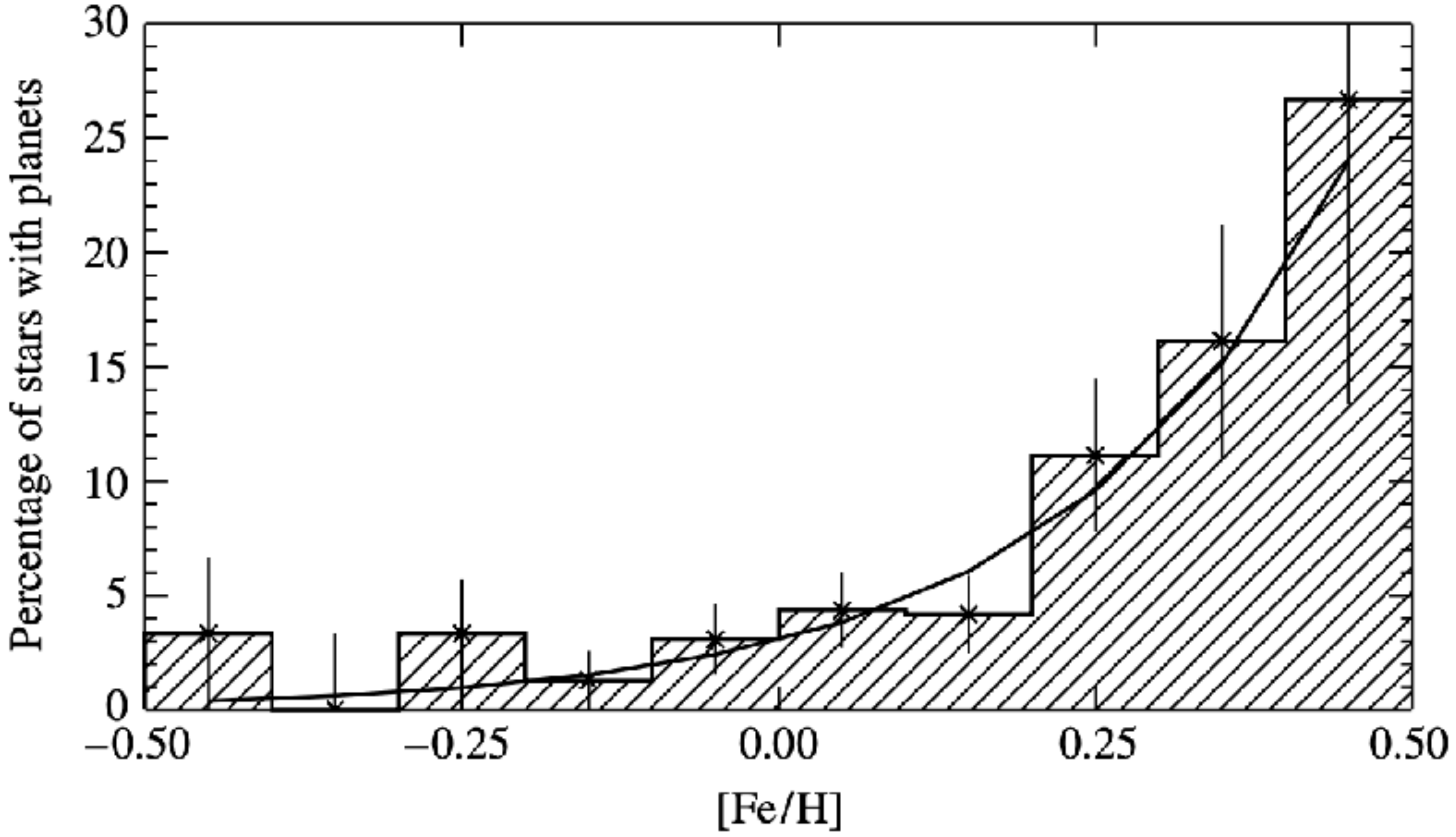


FIGURE 5 The percentage of stars found to have planetary systems, relative to the number of stars investigated in each metallicity bin. The solid curve is given by Eq. (3). (Figure adapted from Fischer and Valenti, *Ap. J.*, *622*, 1102, 2005.)

Measuring Radii and density

How can we measure the radius and the density?

Measuring Radii and density

The **transit of a planet across the disk of the parent star** provides further information about the planet. From the **timing of the eclipse,** and using **atmospheric models of the star** that include limb darkening, it is possible to **determine the planet's radius.**

Of course, once the radius is determined, the planet's **average density** may also be computed.

From the small number of systems where this has been possible, it appears that the **Jupiter-class planets have densities that are similar to those of the gas giants in our Solar System**.

However, some of the so-called **"hot Jupiters"** that orbit close to the parent star appear to be somewhat **inflated** (e.g., HD 209458b and OGLE-TR-10b).

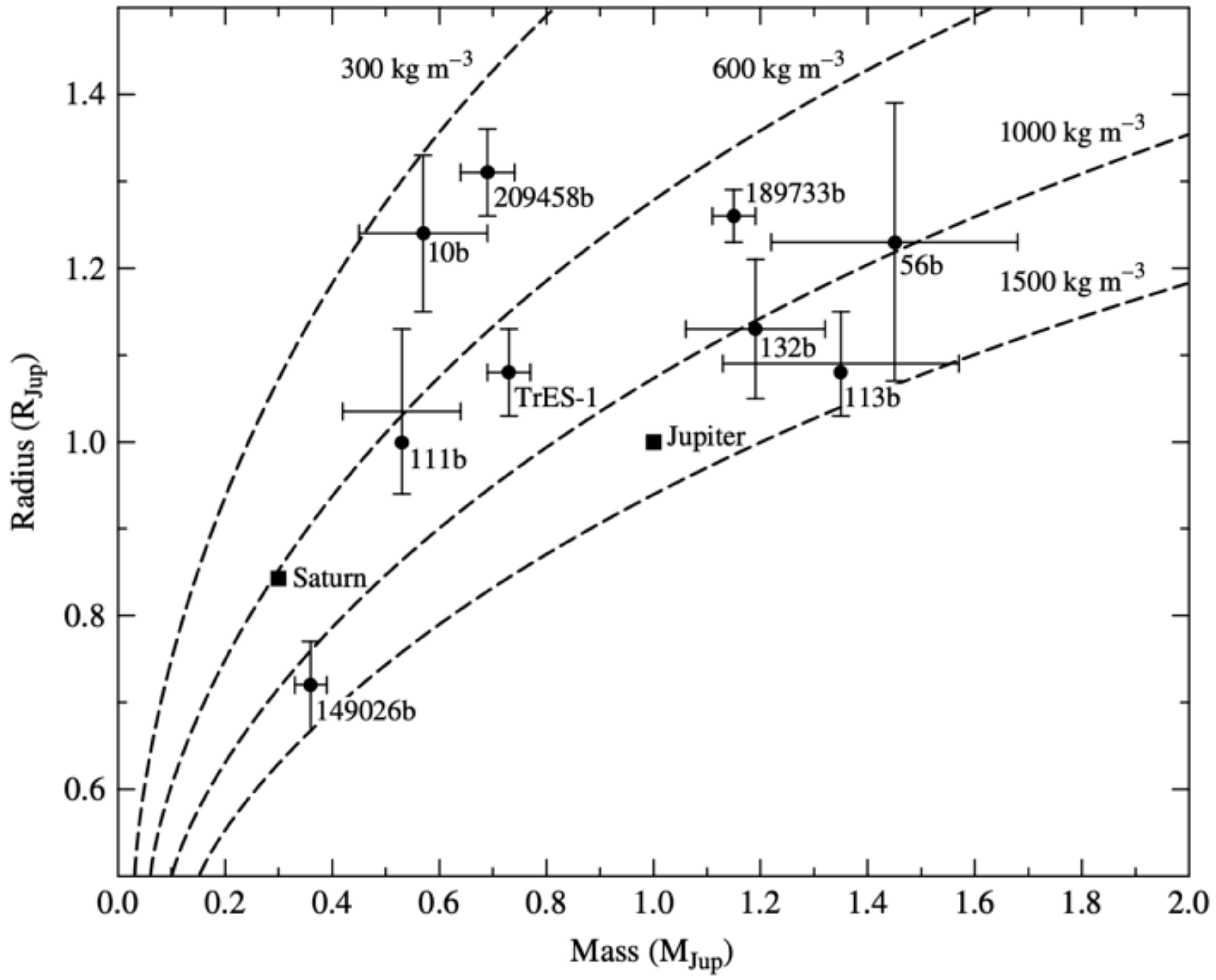


FIGURE 6 The relationship between radius and mass for transiting extrasolar planets. The dashed lines correspond to specific average mass densities. (Adapted from a figure provided by Debra A. Fischer, private communication.)

Measuring Radii and density

2005

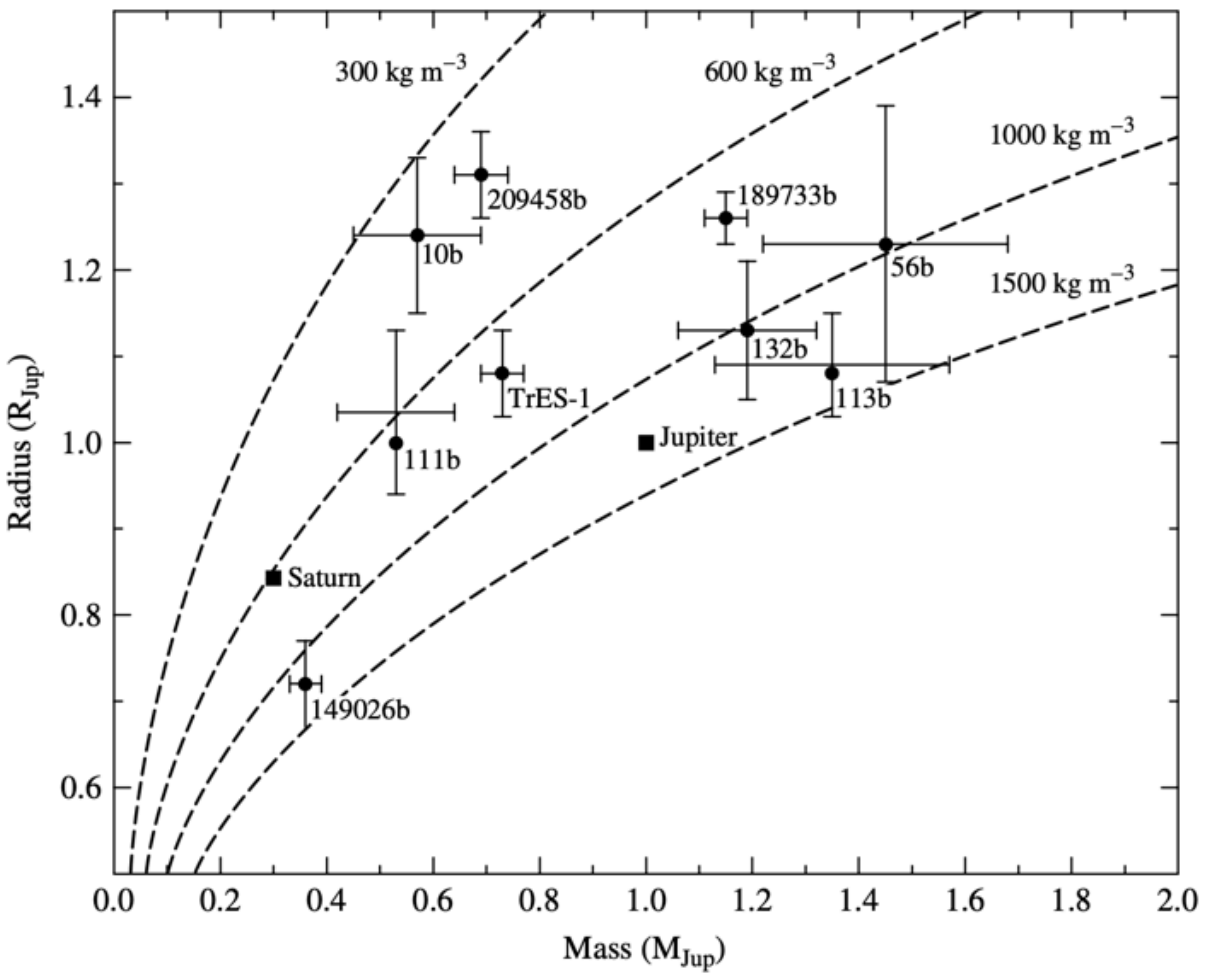


FIGURE 6 The relationship between radius and mass for transiting extrasolar planets. The dashed lines correspond to specific average mass densities. (Adapted from a figure provided by Debra A. Fischer, private communication.)

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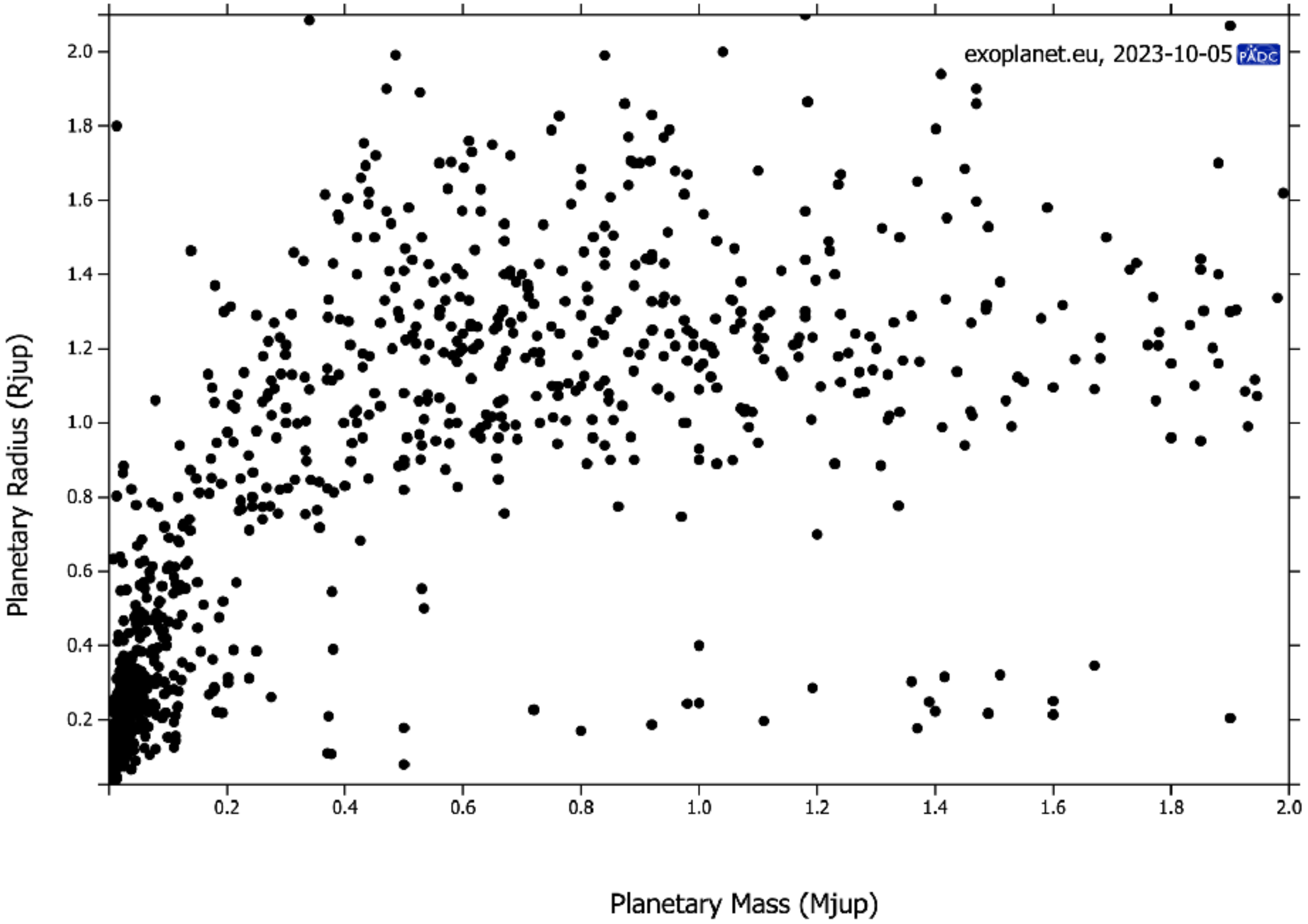
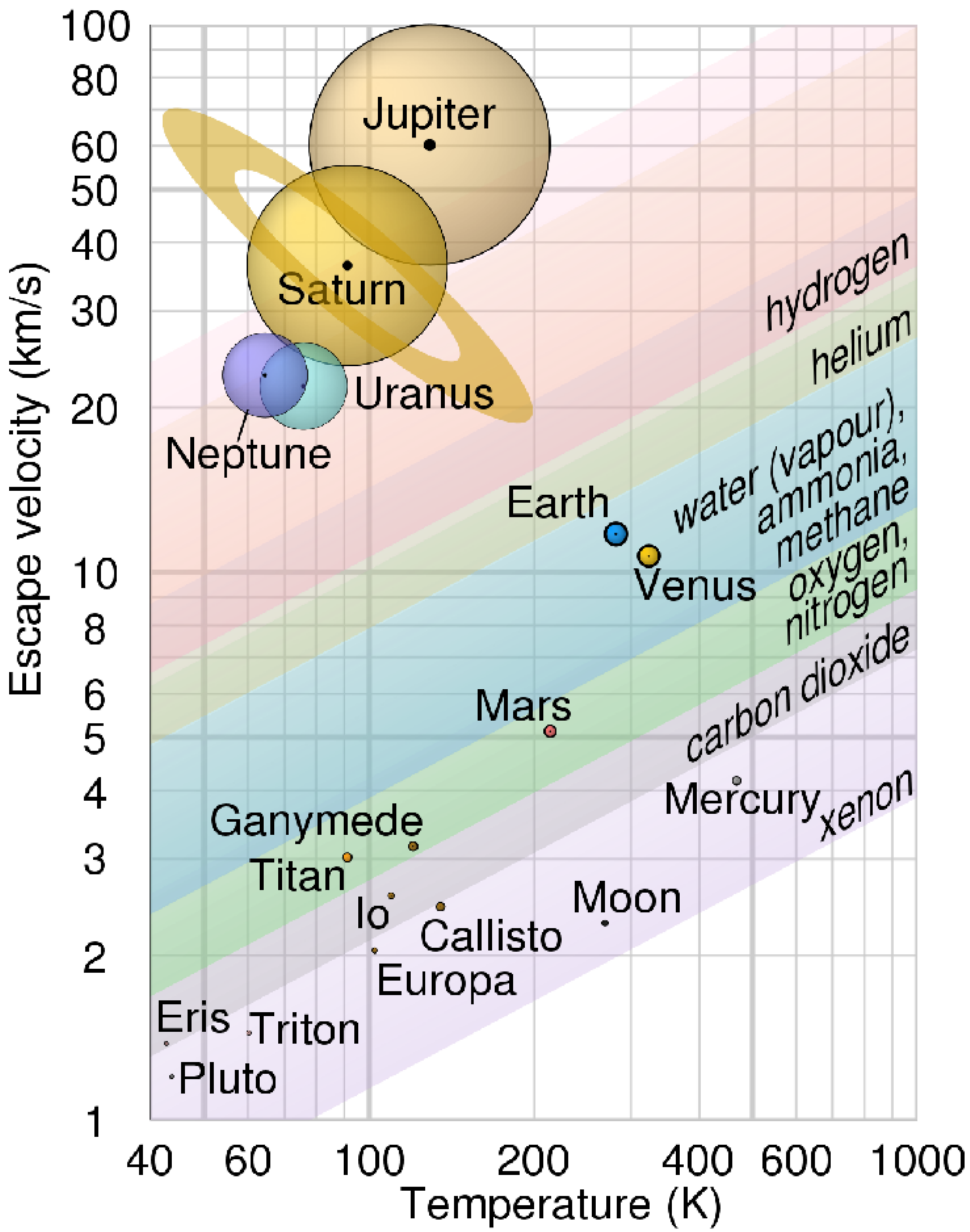


Detecting the Atmosphere

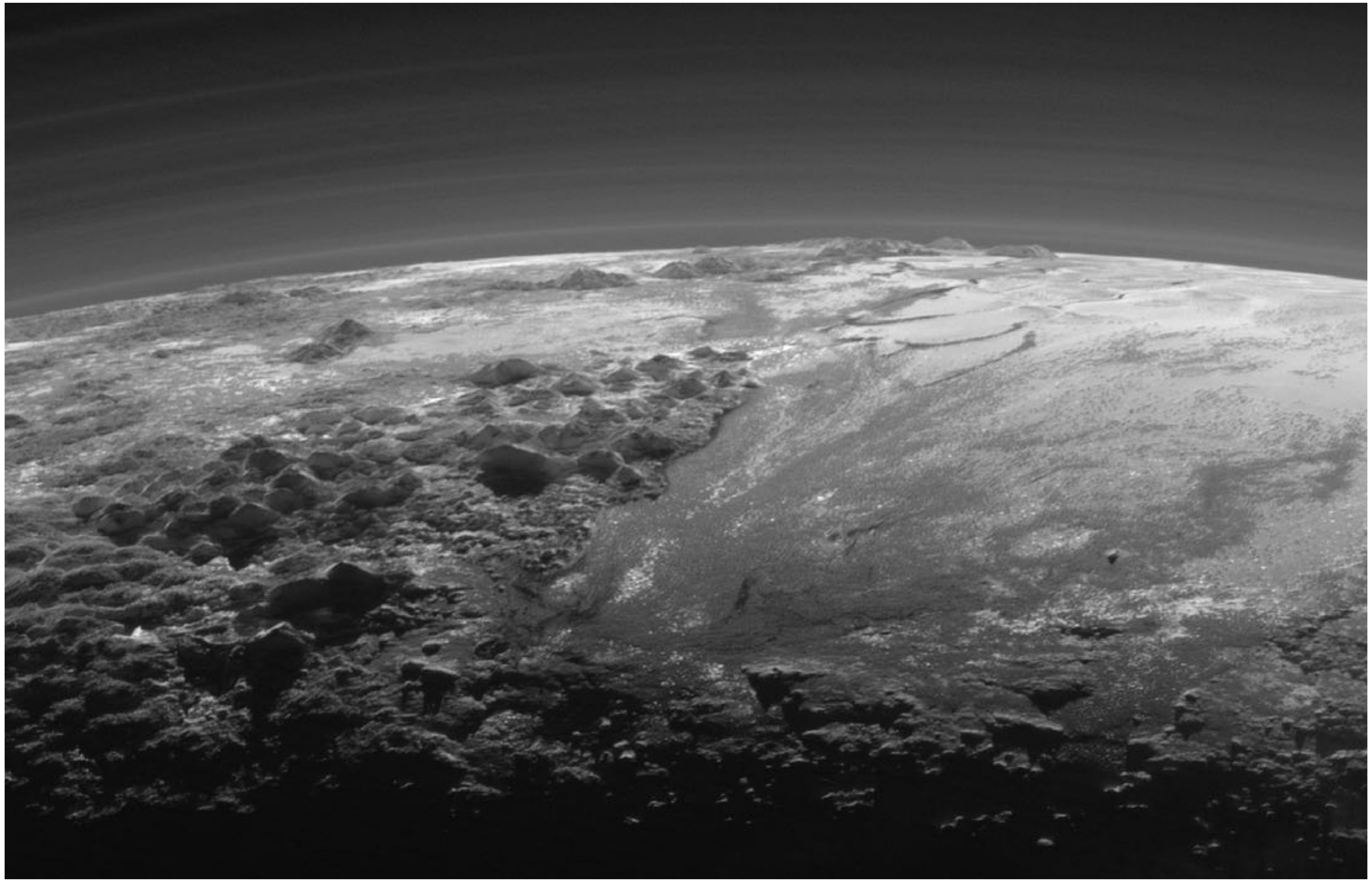
How many solar system objects have atmospheres?

Detecting the Atmosphere



Graphs of escape velocity against surface temperature of some Solar System objects showing which gases are retained. The objects are drawn to scale, and their data points are at the black dots in the middle.

Detecting the Atmosphere



15 minutes after its closest approach to Pluto on July 14, 2015, NASA's New Horizons spacecraft looked back toward the sun and captured a near-sunset view of the rugged, icy mountains and flat ice plains extending to Pluto's horizon.

The backlighting highlights more than a dozen layers of haze in Pluto’s atmosphere.

Detecting the Atmosphere

How can we measure the atmosphere?

Detecting the Atmosphere

Several planets outside the Solar System (exoplanets) have been observed to have atmospheres. At the present time, most atmosphere detections are of **hot Jupiters or hot Neptunes that orbit very close to their star and thus have heated and extended atmospheres.**

Observations of exoplanet atmospheres are of **two types**.

- First, **transmission photometry or spectra** detect the light that passes through a planet's atmosphere as it transits in front of its star.
- Second, the direct emission from a planet atmosphere may be detected by **differencing the star plus planet light** obtained during most of the planet's orbit with the light of just the star during secondary eclipse (when the exoplanet is behind its star).

The **first observed** extrasolar planetary atmosphere was made in **2001. Sodium** in the atmosphere of the planet HD 209458 b was detected during a set of four **transits** of the planet across its star. Later observations with the Hubble Space Telescope showed an enormous **ellipsoidal envelope of hydrogen, carbon and oxygen around the planet**.

Detecting the Atmosphere

This envelope reaches temperatures of 10,000 K. The planet is estimated to be losing $(1–5)\times10^8$ kg of hydrogen per second. This type of **atmosphere loss may be common to all planets orbiting Sun-like stars closer than around 0.1 AU**.

In addition to hydrogen, carbon, and oxygen, HD 209458 b is **thought to have water vapor in its atmosphere**.

Sodium and water vapour has also been observed in the atmosphere of HD 189733 b, another hot gas giant planet.

In October 2013, the detection of **clouds in the atmosphere of Kepler-7b** was announced, and, in December 2013, also in the atmospheres of Gliese 436 b and Gliese 1214 b.

In May 2017, glints of light from Earth, seen as twinkling from an orbiting satellite a million kilometres away, were found to be reflected light from ice crystals in the atmosphere. The technology used to determine this may be useful in studying the atmospheres of distant worlds, including those of exoplanets.

Detecting the Atmosphere

What should we look for if we are interested in signatures of life?

Detecting the Atmosphere

What should we look for if we are interested in signatures of life?

Methane

Detection of methane in astronomical bodies is of interest to science and technology, as it may be **evidence of extraterrestrial life (biosignature)**, it may help provide organic ingredients for life to form, and also, methane could be used as a fuel or rocket propellant for future robotic and crewed missions in the Solar System.

Is methane common in the Solar System?

Detecting the Atmosphere

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Methane
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Is methane common in the Solar System?

Titan – the atmosphere contains 1.6% methane and thousands of methane lakes have been detected on the surface. In the upper atmosphere, methane is converted into more complex molecules including acetylene, a process that also produces molecular hydrogen. There is evidence that acetylene and hydrogen are recycled into methane near the surface. This suggests the **presence of either an exotic catalyst or an unknown form of methanogenic life.** Methane showers, probably prompted by changing seasons, have also been observed. On October 24, 2014, methane was found in polar clouds on Titan.

Methane is an important trace gas in **Earth's atmosphere, it makes up 0.00017%.**

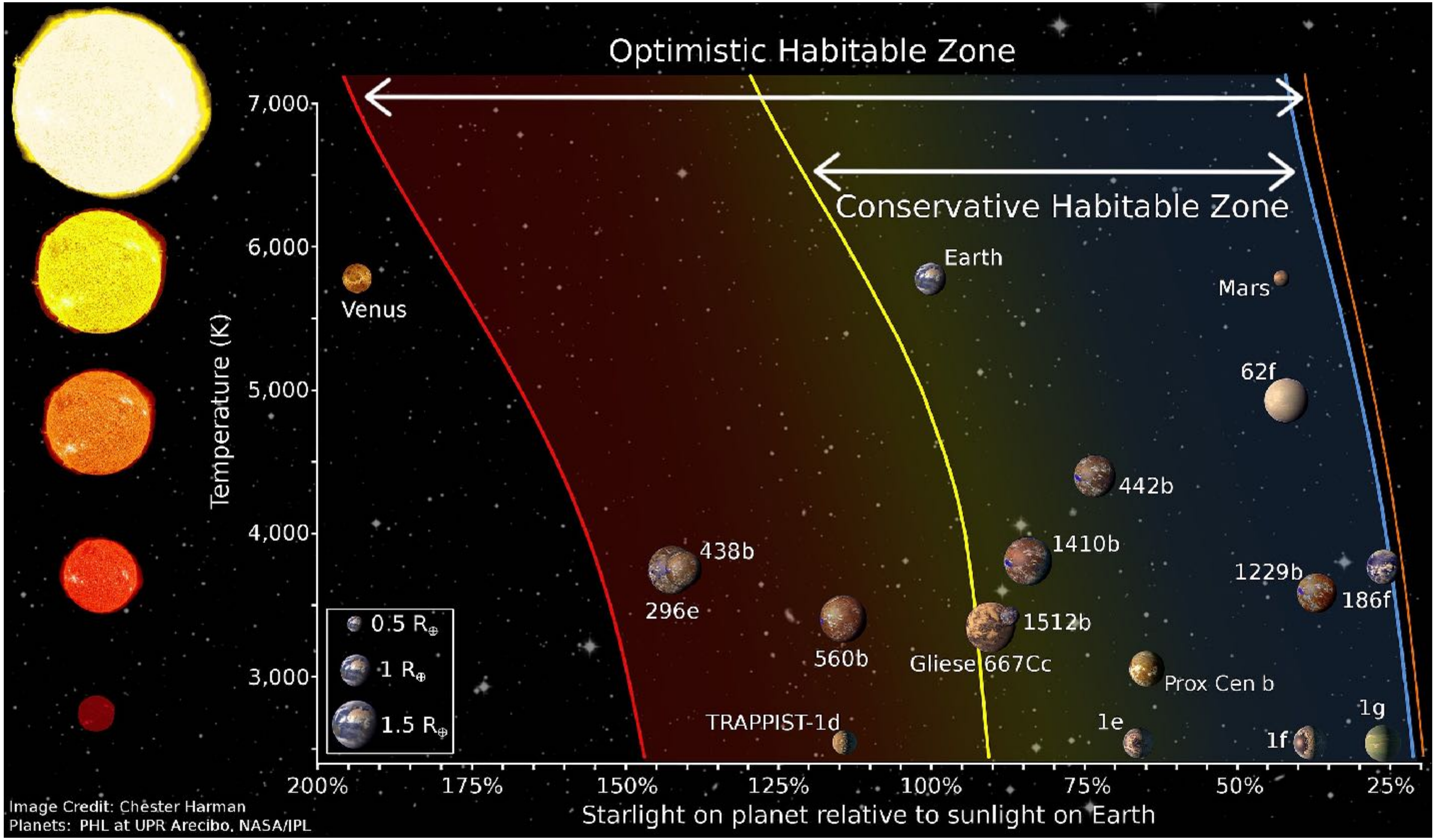
Searching for life

In astronomy and astrobiology, the **habitable zone** (HZ), is the range of orbits around a star within which a planetary surface can support **liquid water** given sufficient atmospheric pressure.
The bounds of the HZ are based on Earth's position in the Solar System and the amount of radiant energy it receives from the Sun. Due to the importance of liquid water to Earth's biosphere, the nature of the HZ and the objects within it may be instrumental in determining the scope and distribution of planets capable of supporting Earth-like extraterrestrial life.

About 1 in 5 Sun-like stars have an "Earth-sized" planet in the habitable zone. Assuming there are 200 billion stars in the Milky Way, it can be hypothesized that there are 11 billion potentially habitable Earth-sized planets in the Milky Way.

Proxima Centauri b, located about 4.2 light-years (1.3 parsecs) from Earth in the constellation of Centaurus, is the **nearest known exoplanet,** and is orbiting in the habitable zone of its star.

Searching for life



Planet or Brown dwarf?

With the detection of a few extrasolar planets having masses more than a factor of ten larger than the mass of Jupiter, the question is again raised concerning the definition of a planet. At the **low-mass end,** large Kuiper belt objects such as **Pluto** have been classified as planets. At the upper end, what distinguishes a planet from a brown dwarf?

Two different criteria have been proposed to answer this question.

One suggestion is tied to the **formation process of planets and stars**. Stars form from the **gravitational collapse of a gas cloud.** As we will explore further in the next section, planets are generally believed to form **from a bottom-up accretion process,** although there has been speculation that gravitational collapse in the star's accretion disk may also produce planets. One proposed definition of planet is that it is an object that forms through a process beginning with the bottom-up accretion of planetesimals, whereas a **brown dwarf forms directly from gravitational collapse**. The challenge with such a definition is determining after the fact how a particular object may have formed.

Planet or Brown dwarf?

A second criterion that has been proposed is based on **whether or not the object that forms is massive enough ever to have had nuclear fusion occur in its core**. Computer models of very low-mass objects indicate that if **the mass of the object is greater than 13 M_J, deuterium can burn** while the object is forming.
The rate of energy production would not be sufficient to stabilize the object during gravitational collapse, but deuterium burning can be sufficient to affect the luminosity of the object during collapse. At the other end, stars with mass of at least 0.072 $M_\odot$ (75 M_J) for solar composition undergo nuclear fusion at a sufficient rate to stabilize them at the low-mass end of the main sequence.

Thus, it is proposed that **brown dwarfs** should be considered as being those objects having masses between these two limits **($13\ M_J < M_{bd} < 75\ M_J$)**; in other words, brown dwarfs are "stars" that burn some deuterium but never reach a stable nuclear-burning phase during contraction. Given the difficulty with the formation-mechanism criterion, the nuclear-reaction/mass-based criterion is generally favored.