Biases of the Transit Method

All exoplanet detection methods have biases.

These are very important to understand so we don’t develop an inaccurate sense of the number of habitable planets that might exist.

Concept Check

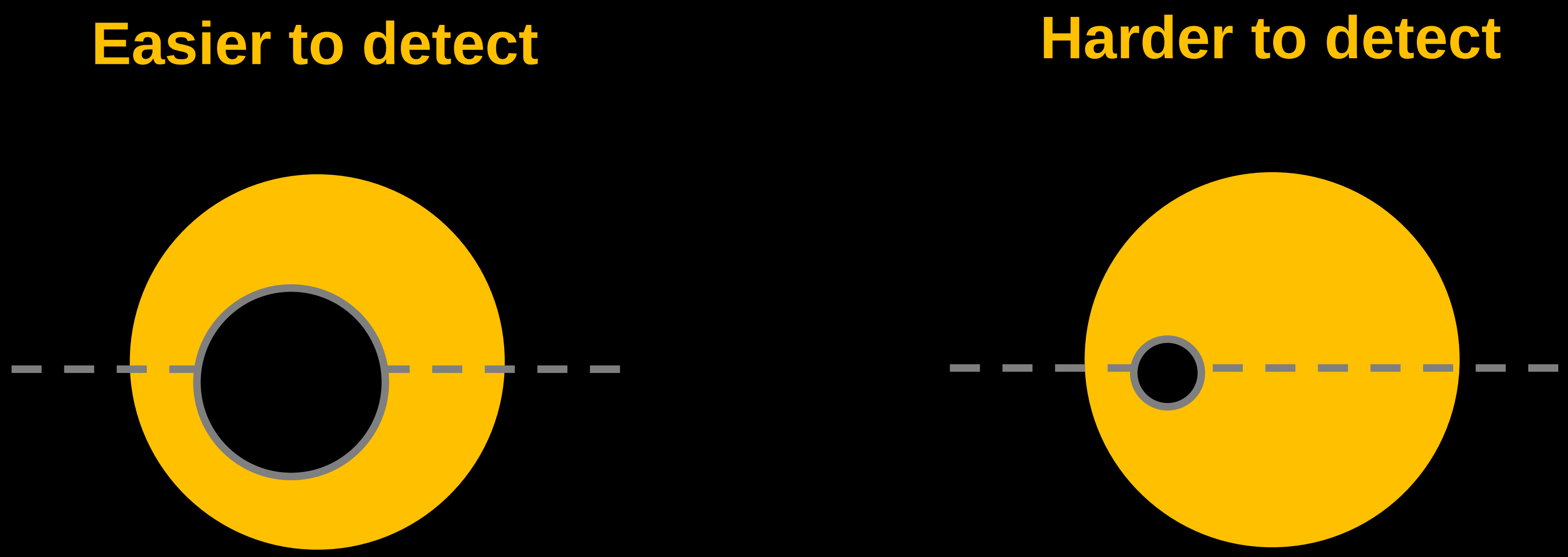
Which of the following properties would make a planet easier to detect with the transit method?

A. Larger orbital semimajor axis
B. Redder colour
C. Lack of an atmosphere
D. Larger radius

Concept Check

Which of the following properties would make a planet easier to detect with the transit method?

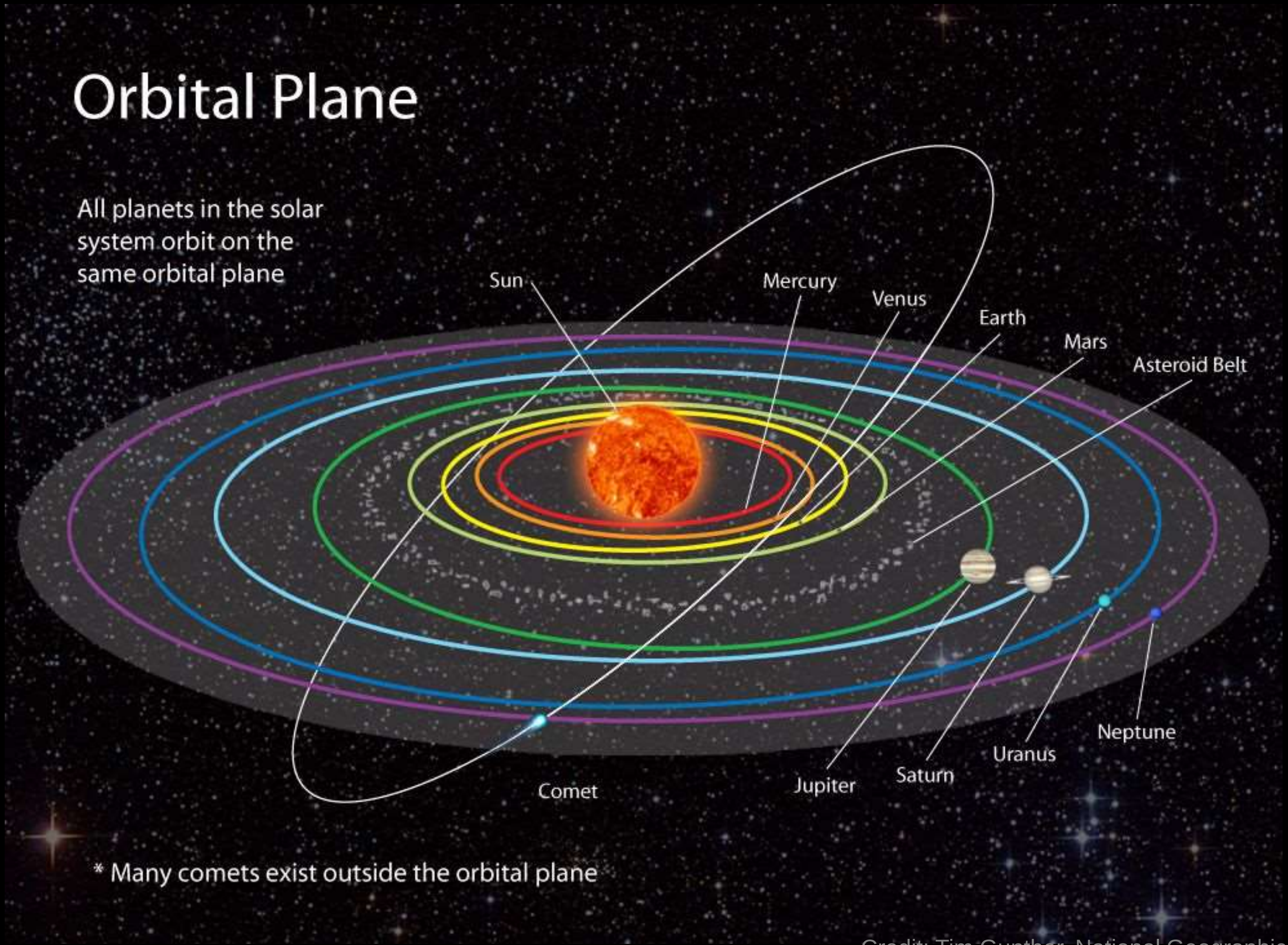
A. **Larger orbital semimajor axis**
B. **Redder colour**
C. **Lack of an atmosphere**
D. **Larger radius**



Planets with larger radii are easier to detect using the transit method.

So, the transit method is biased against finding smaller, terrestrial planets of the type we usually think of as good homes for life.

The transit method can also only find planets whose orbits are aligned with our line of sight so as to allow for visible transits.

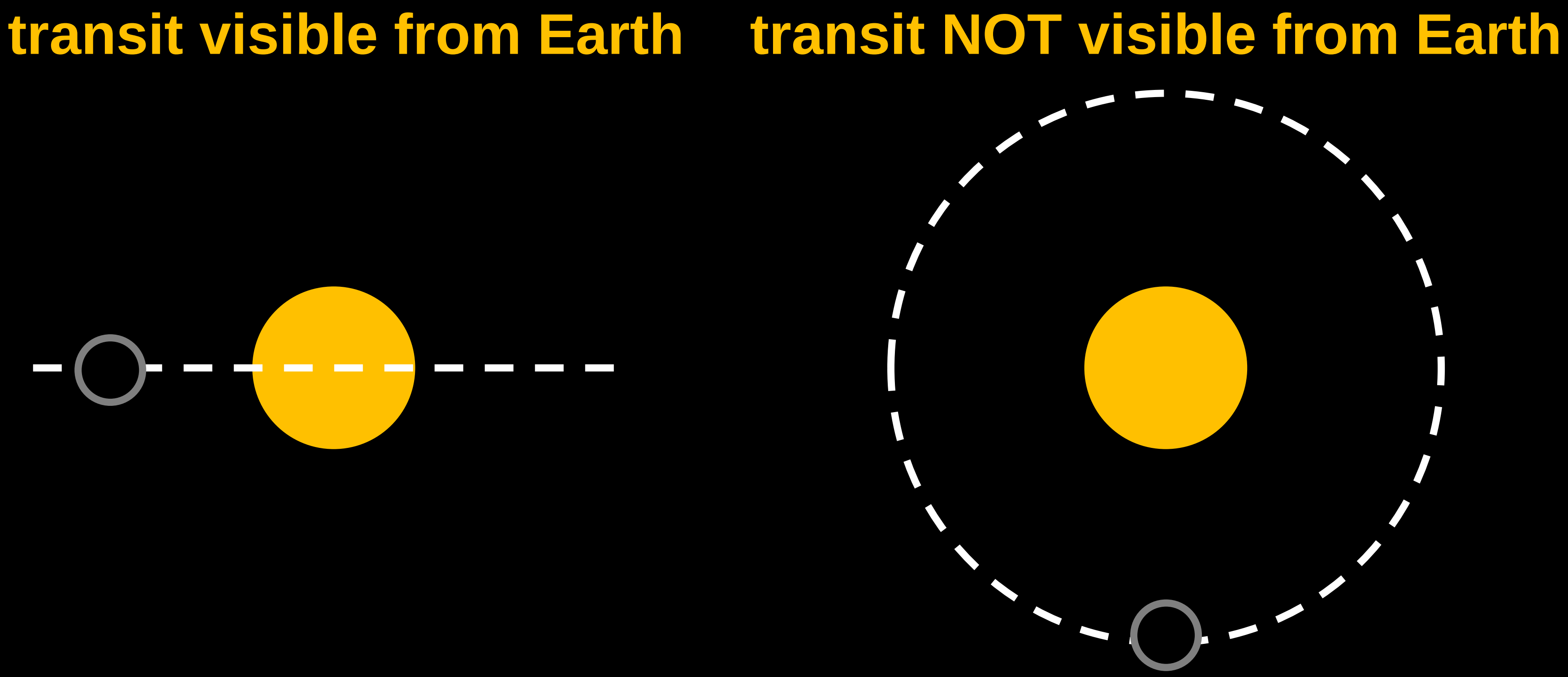


Credit: Tim Gunther, National Geographic

The orbital planes of other solar systems are randomly oriented relative to our own.

www.eso.org

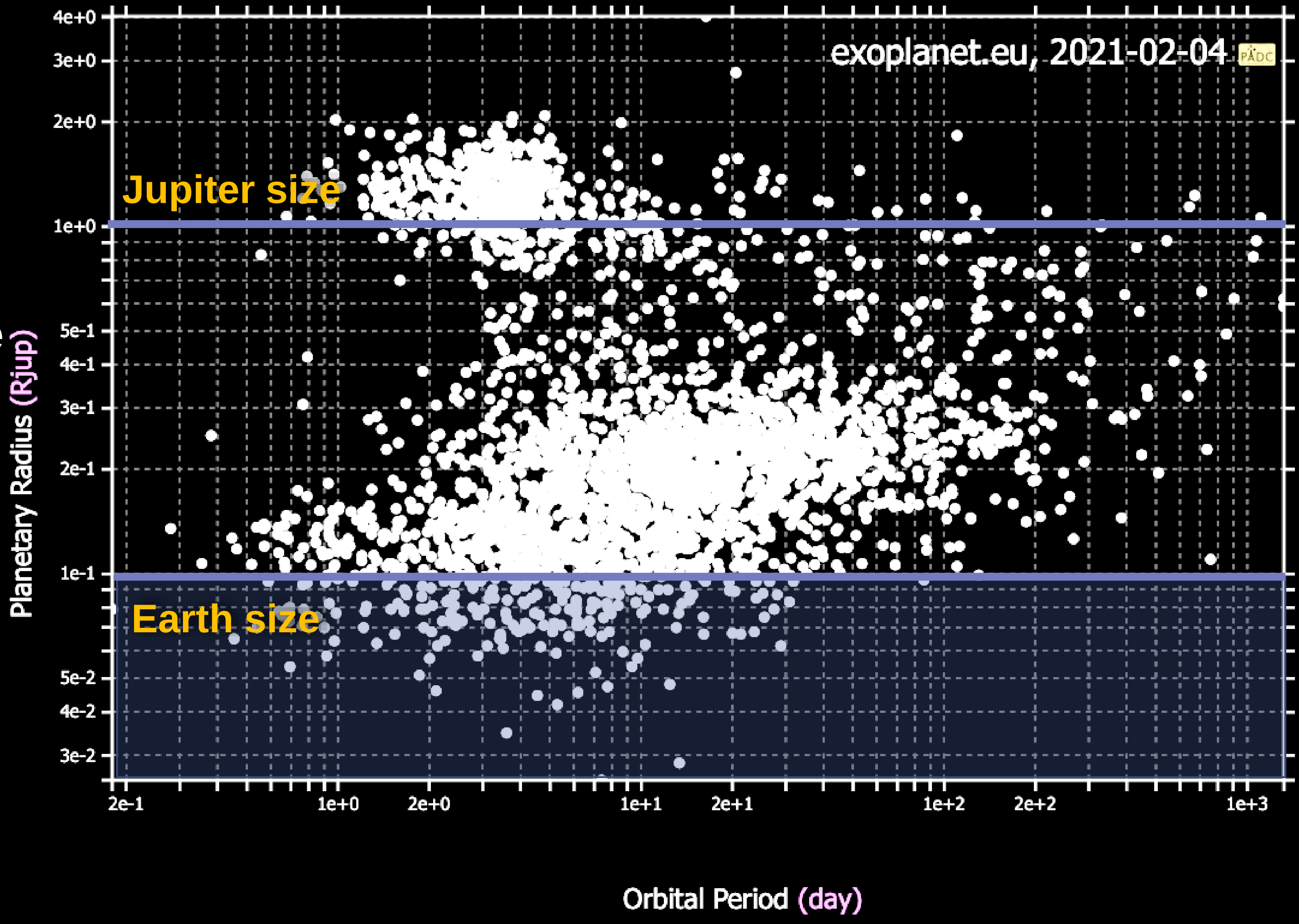
Credit: ESO/M. Kornmesser



The transit method can only detect planets whose orbits are edge-on to our line of sight.

Only a few percent of planetary systems are aligned close enough to edge-on for us to detect their planets using the transit method.

The transit method has difficulty finding Earth-sized and smaller planets with current telescopes because smaller planets produce shallower transits.



Concept Check

Given the nature of the transit method, it should be easier for it to find planets with:

A. long orbital periods

B. short orbital periods

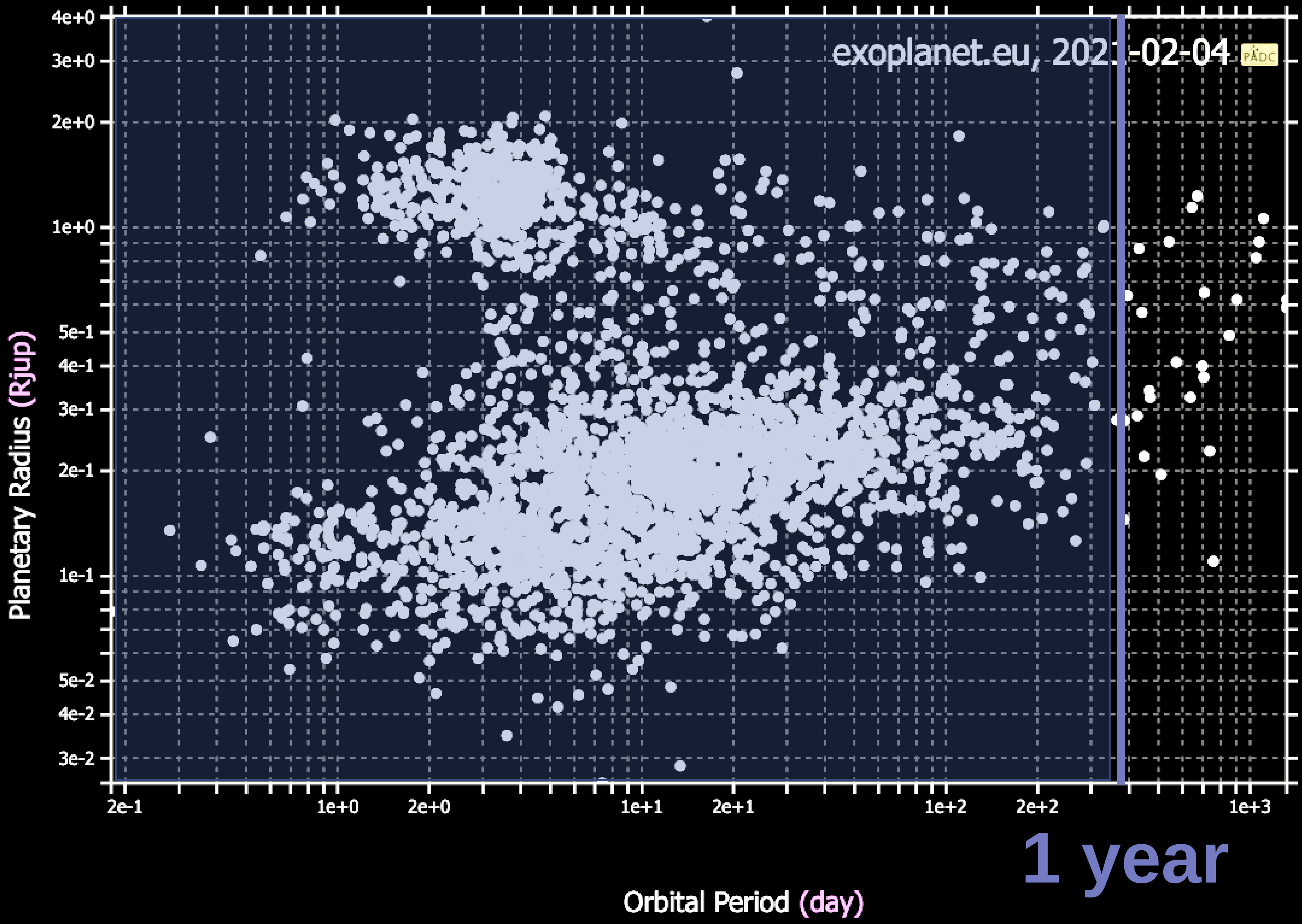
Concept Check

Given the nature of the transit method, it should be easier for it to find planets with:

A. long orbital periods

B. short orbital periods

Finding planets with longer orbital periods takes longer—typically three times their orbital period to be confident.



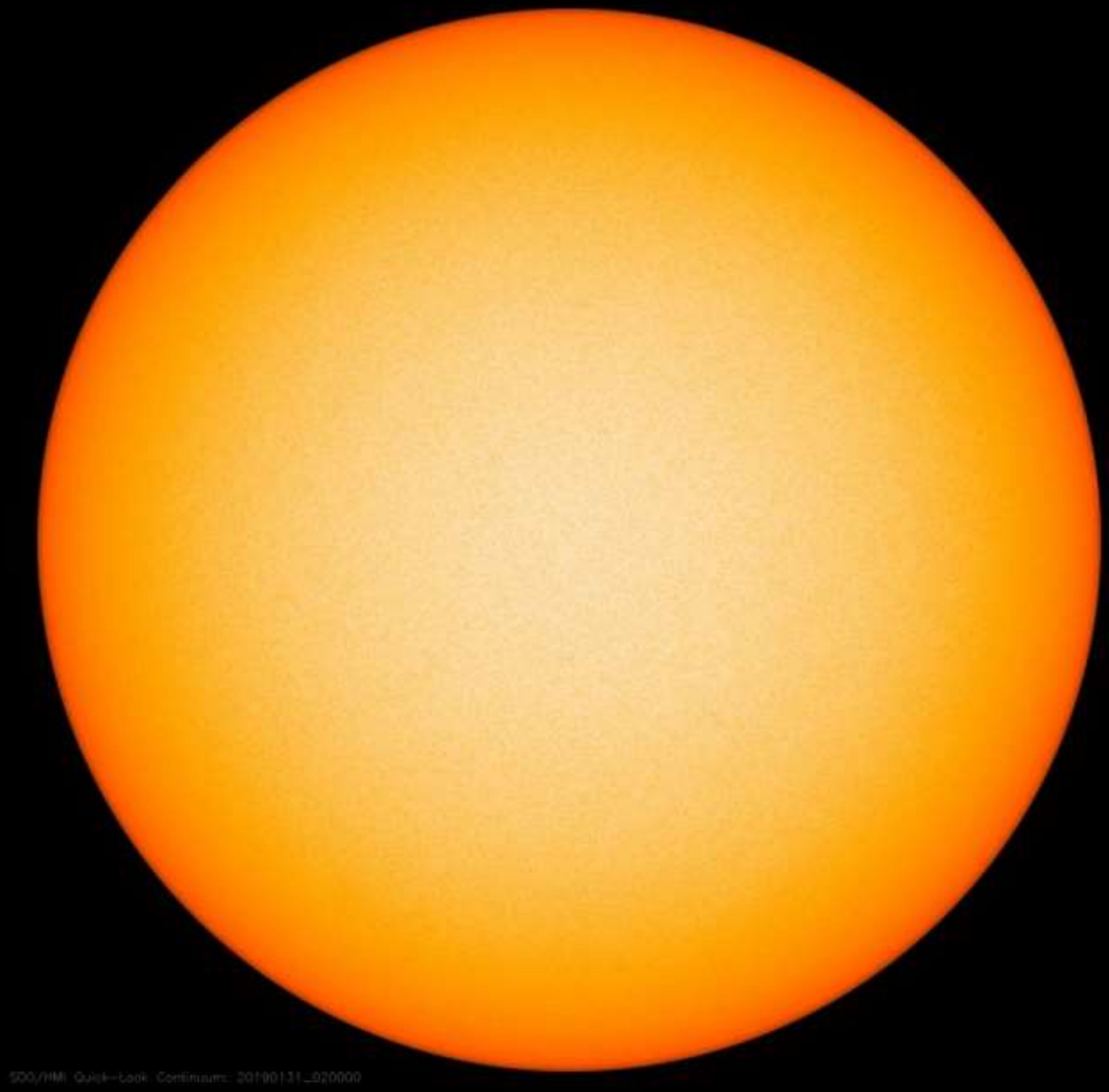
The transit method is biased toward finding larger planets with shorter orbital periods, and can only find planets in systems oriented edge-on to our line of sight.

Transit Method: Nuances

Now you know the basic technique for finding exoplanets using the transit method.

Let’s consider some nuances to the method.

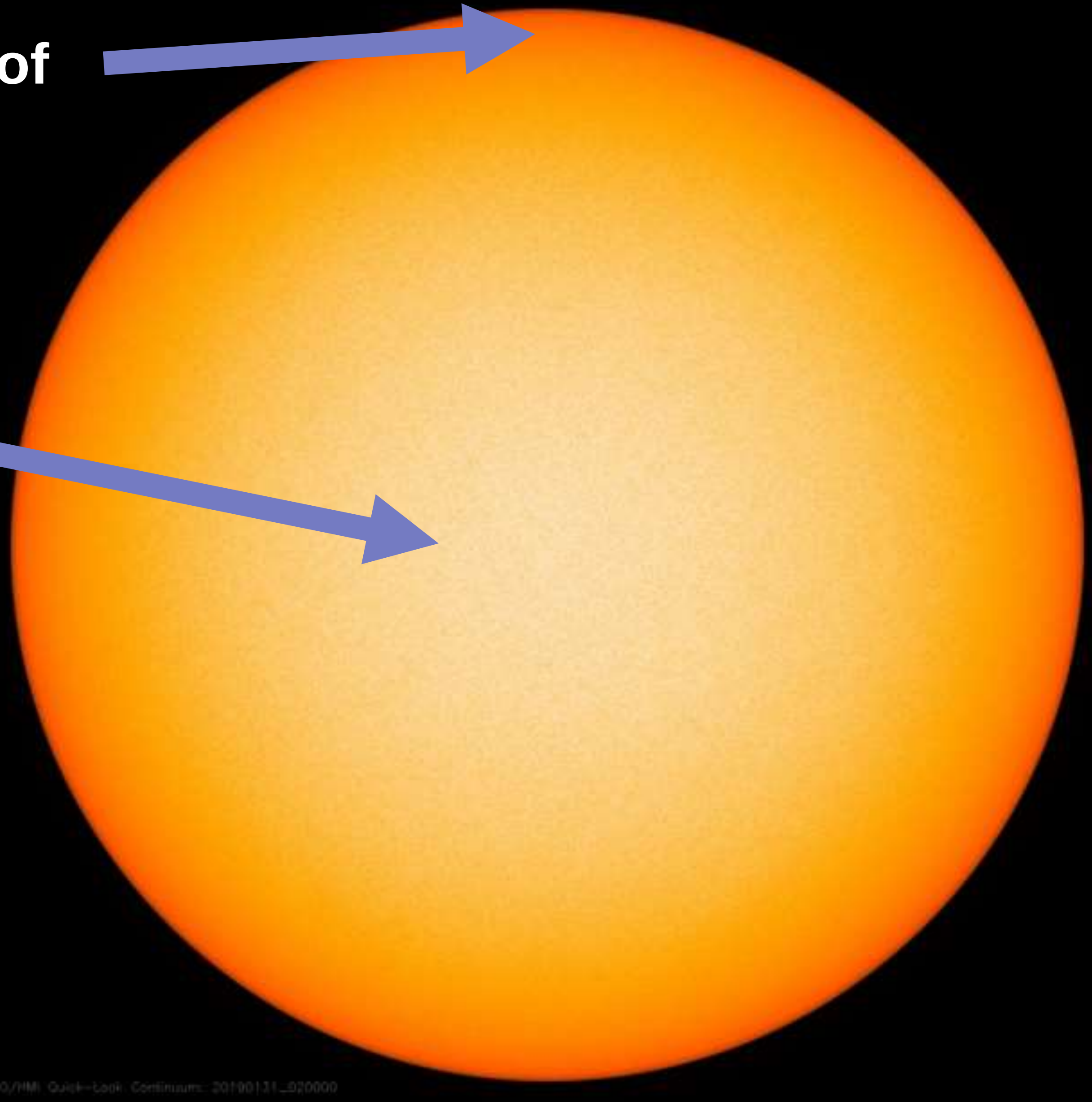
Real stars are not uniformly bright across their surfaces, as shown in this photograph of the Sun.



Credit: NASA/SDO

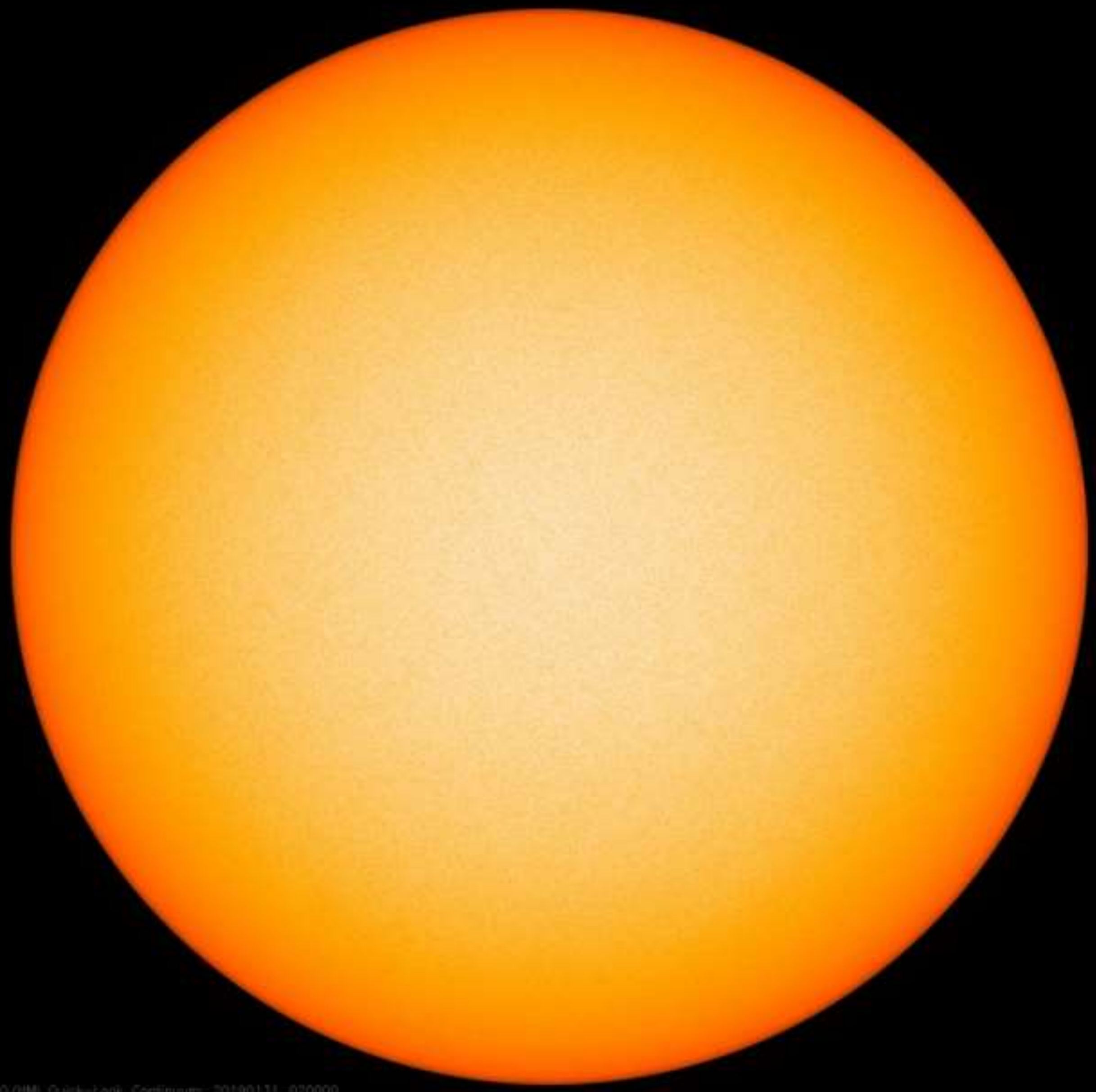
Light from these regions is coming from cooler layers of the star, so they appear redder and darker

Light from these regions is coming from hotter layers of the star, so they appear yellower and brighter



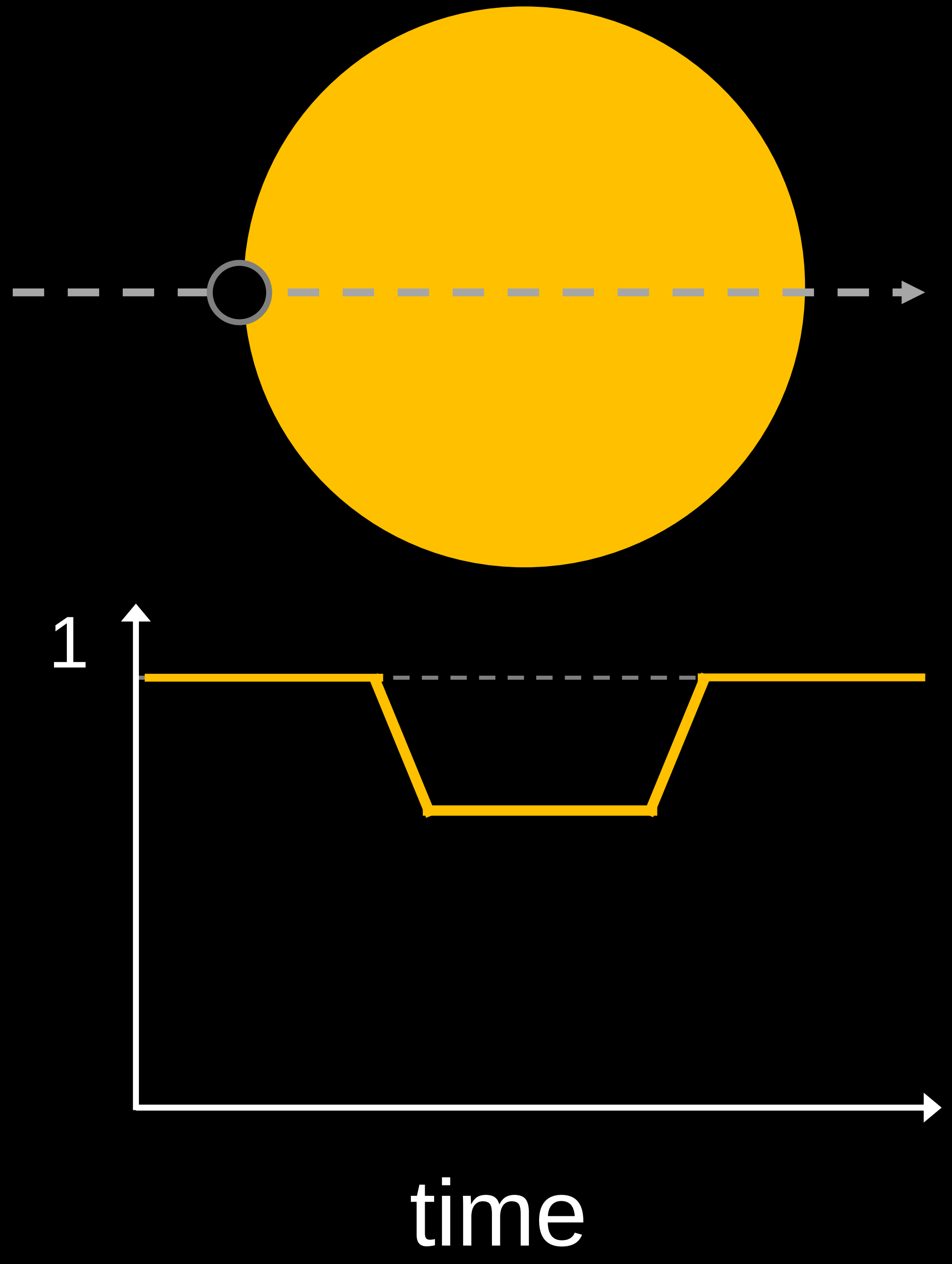
Credit: NASA/SDO

The edges of a star are called the “limbs”, so we call this effect **limb darkening**.

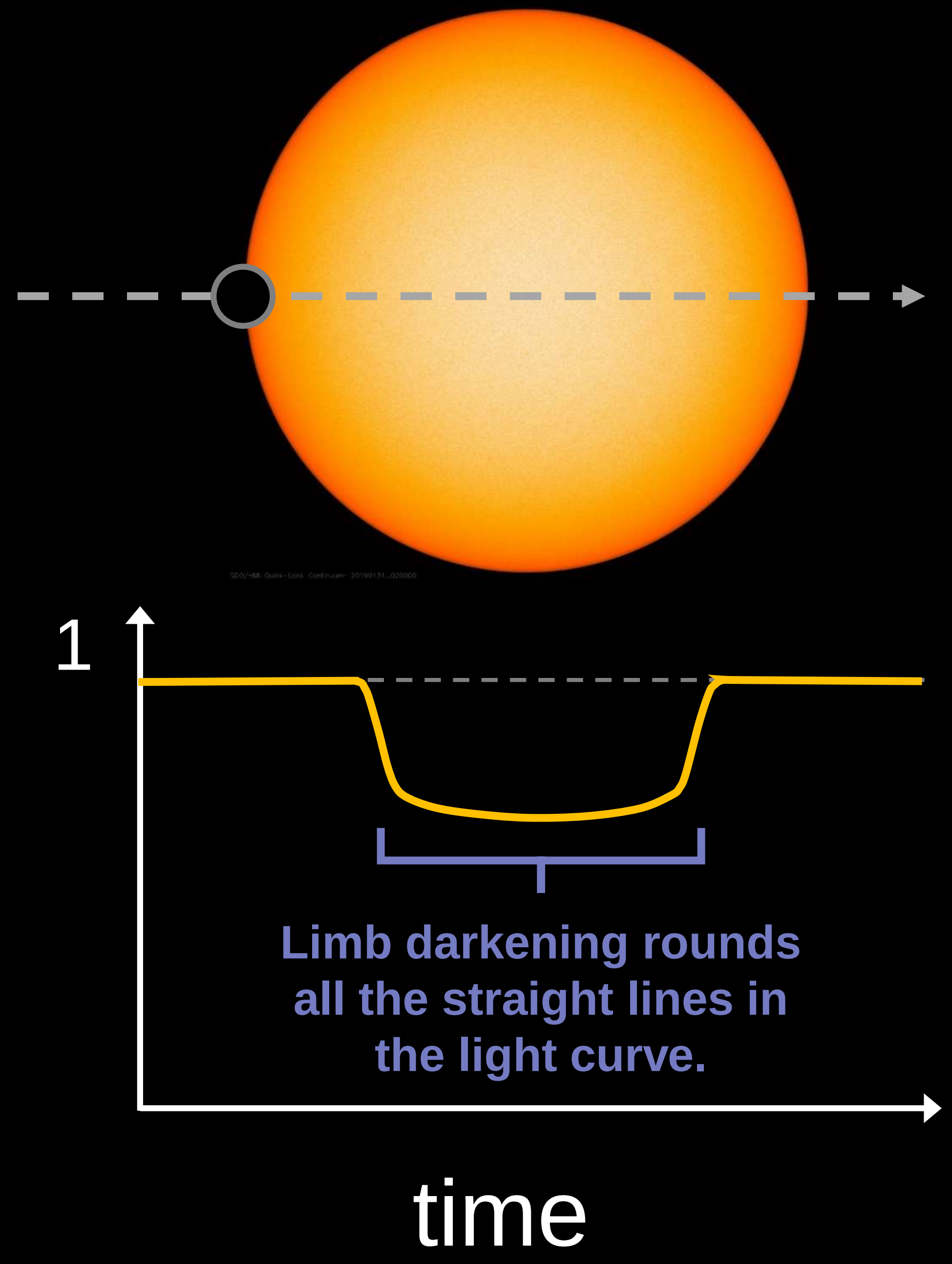


Credit: NASA/SDO

Transit light curve <u>without</u> limb darkening



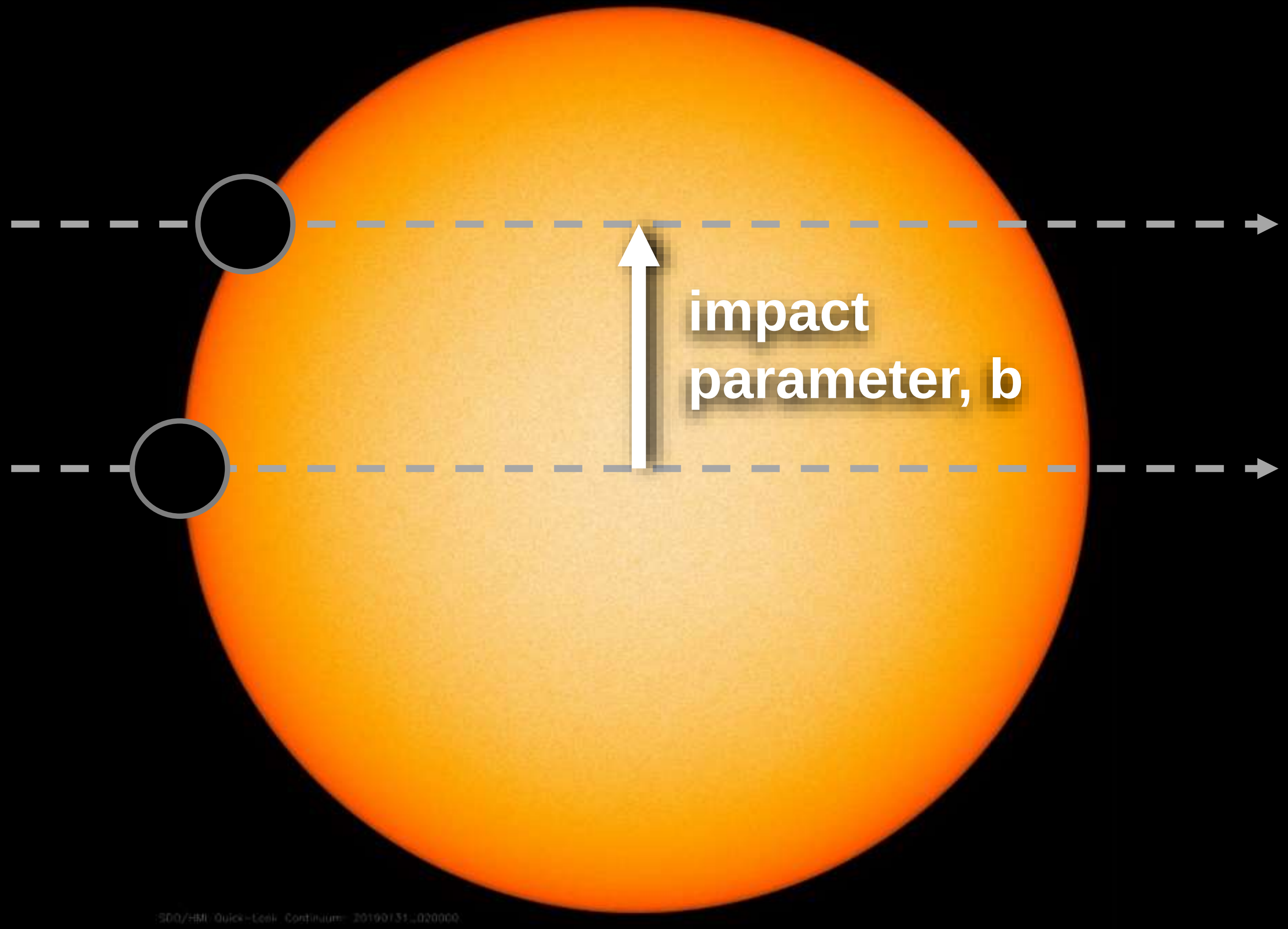
Transit light curve
with limb darkening



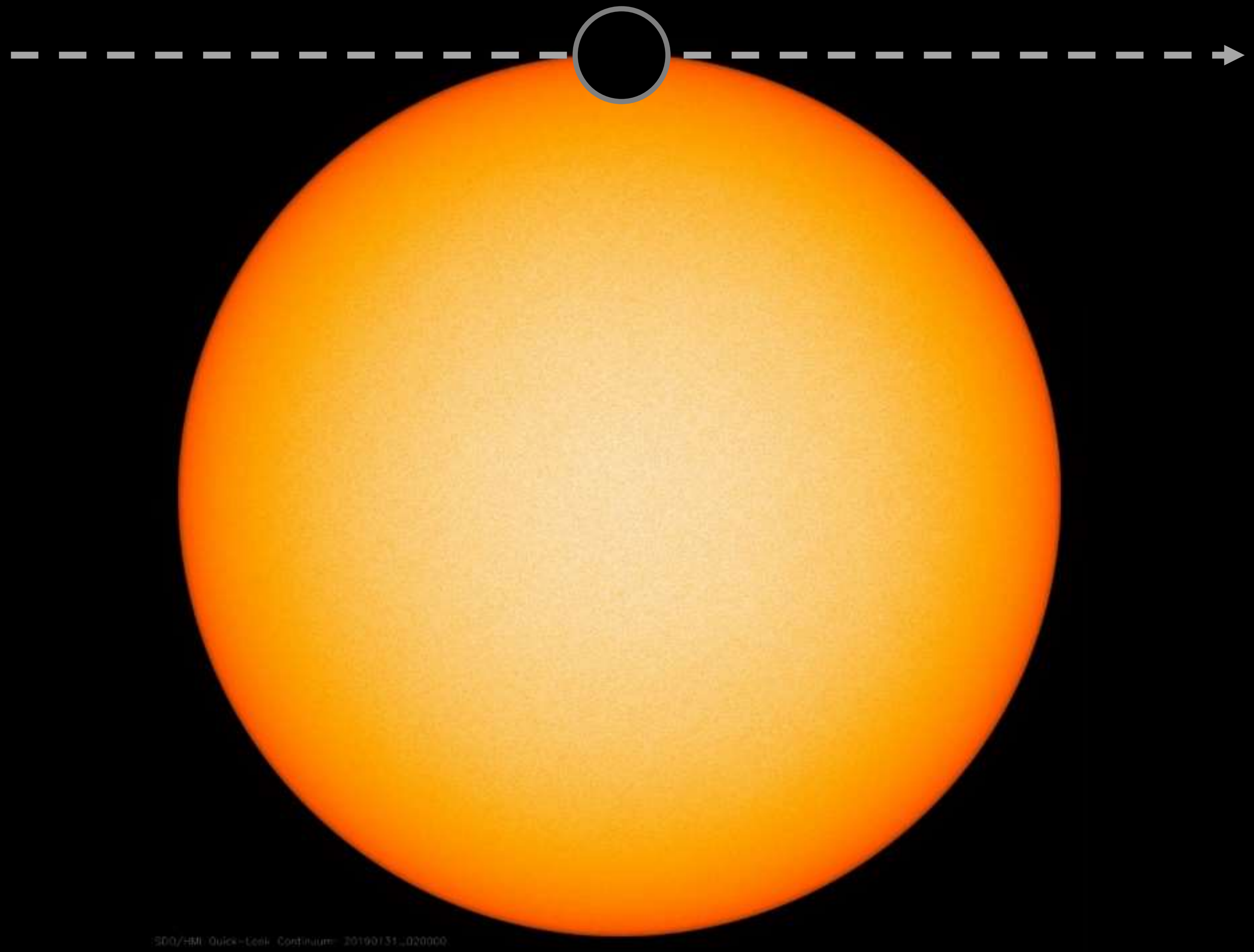
So far, we have assumed that the planet happens to cross the centre of the stellar disk.

What if it doesn't?

If the planet's orbit is tilted to our line of sight, it may pass across any part of the star's face.

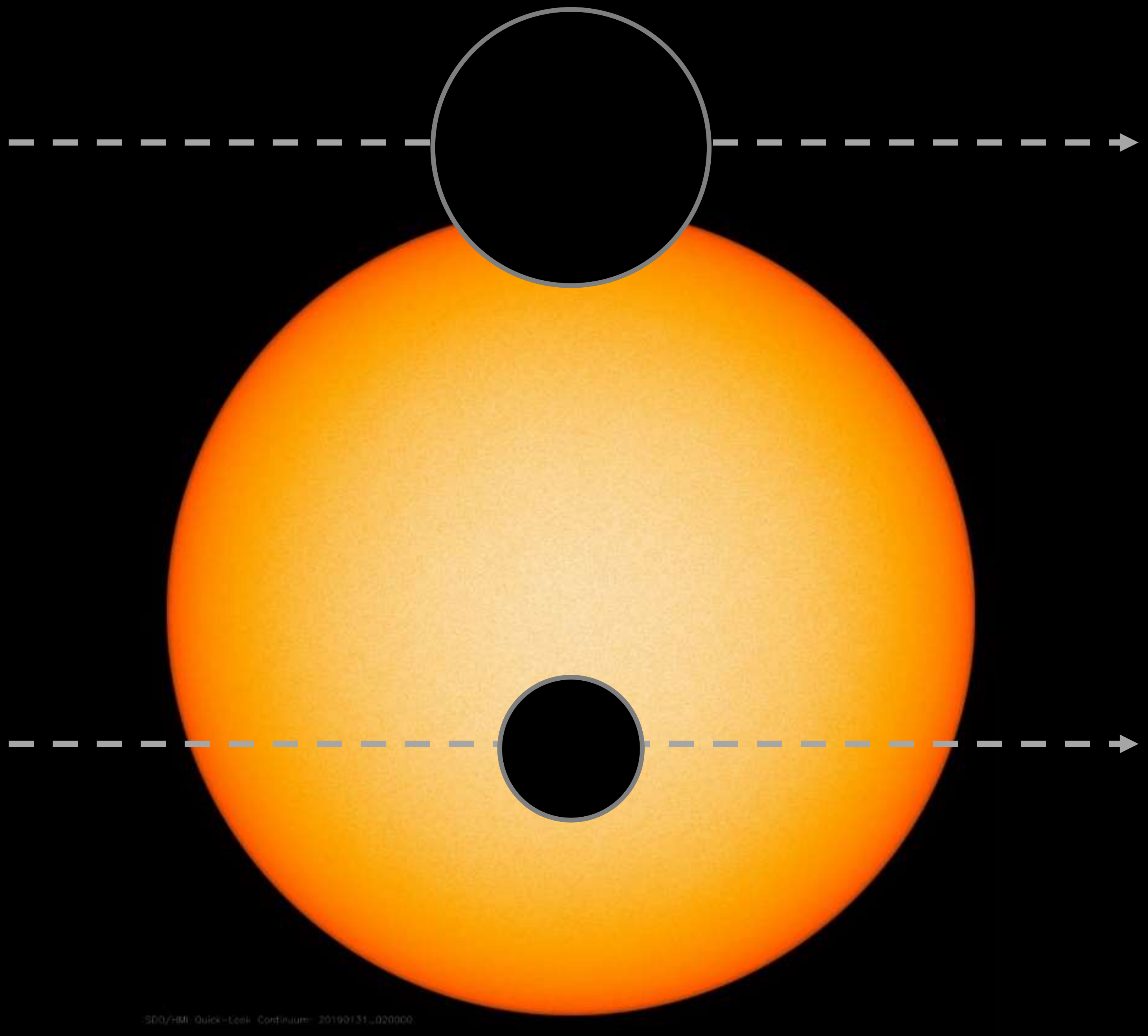


In some cases, only part of the planet may pass in front of the star. We call this grazing incidence.

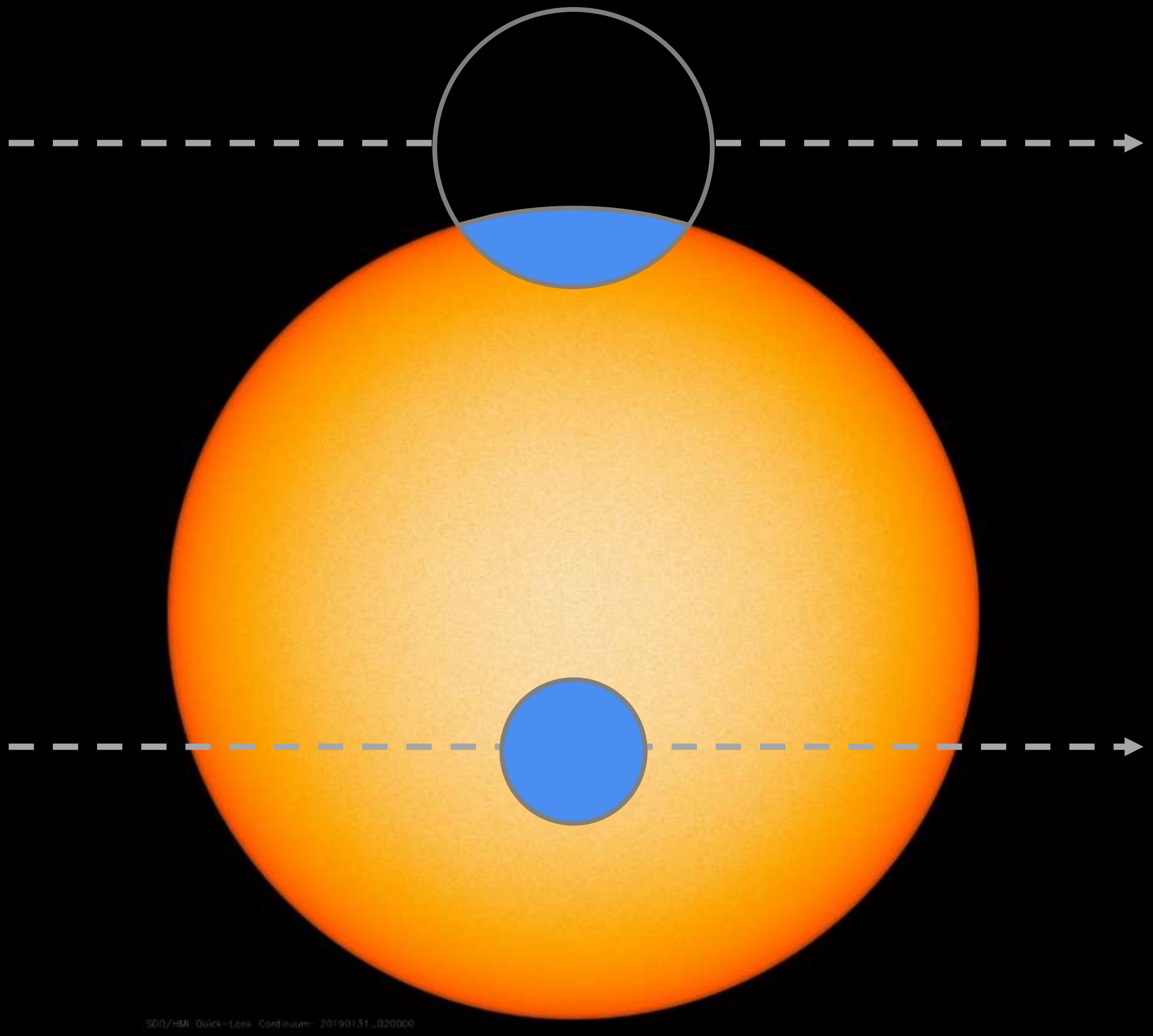


Limb darkening and grazing incidence can affect your interpretation of the transit depth, and hence your measurement of the planet’s radius.

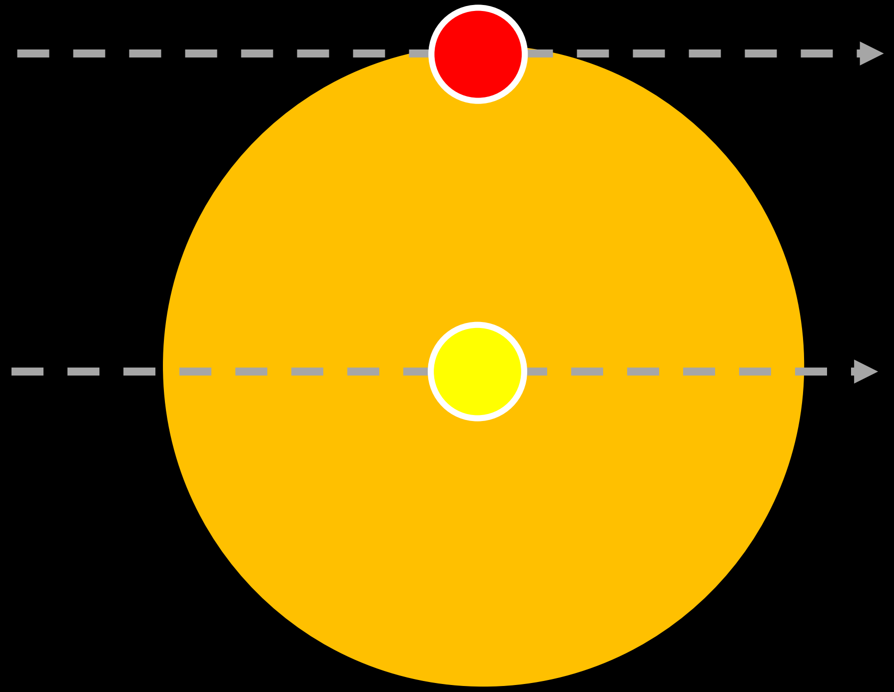
For example, a grazing transit of a large planet could be mistaken for a full transit of a smaller planet.



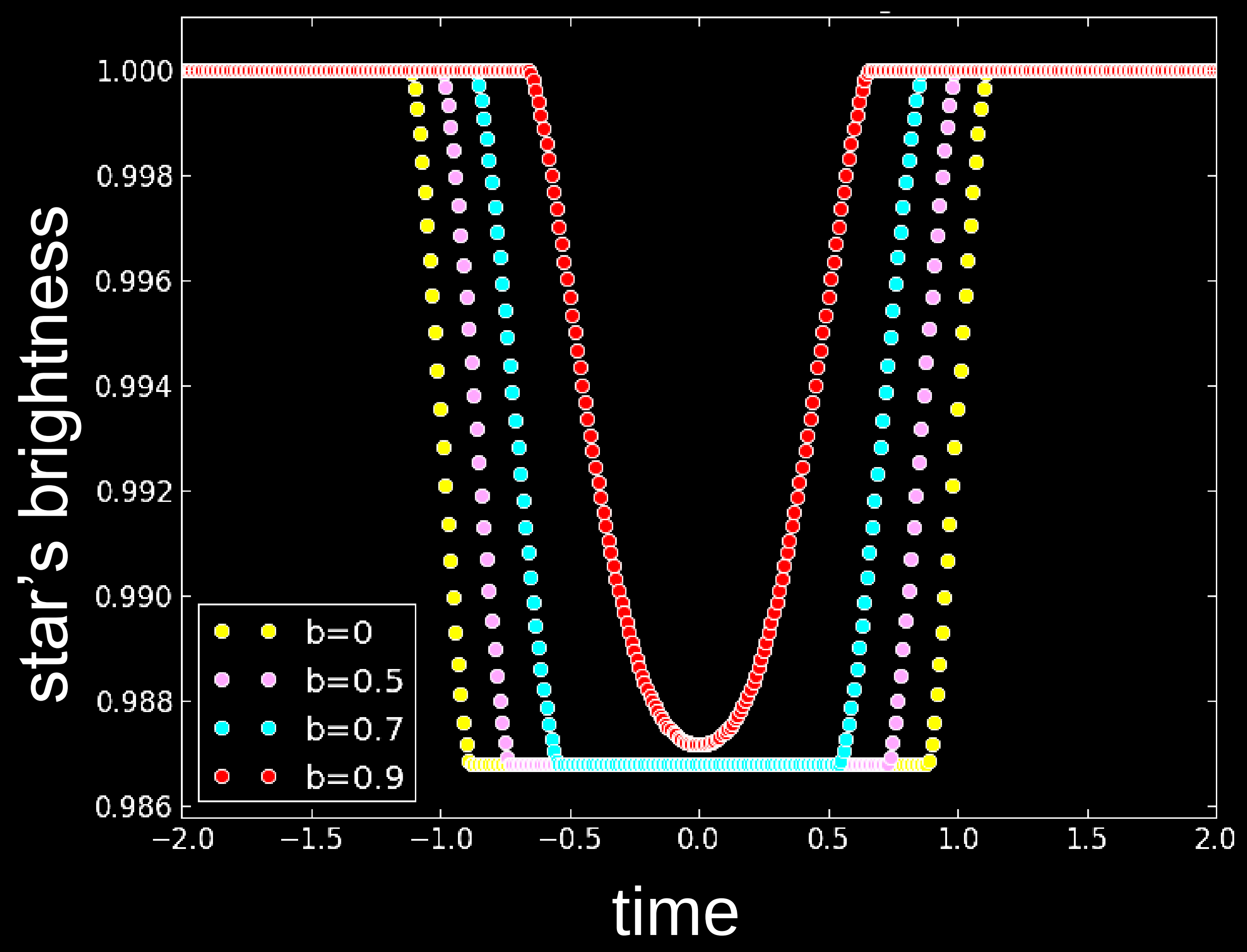
For example, a grazing transit of a large planet could be mistaken for a full transit of a smaller planet.



Careful examination of the shape of the transit in the light curve can distinguish these cases.

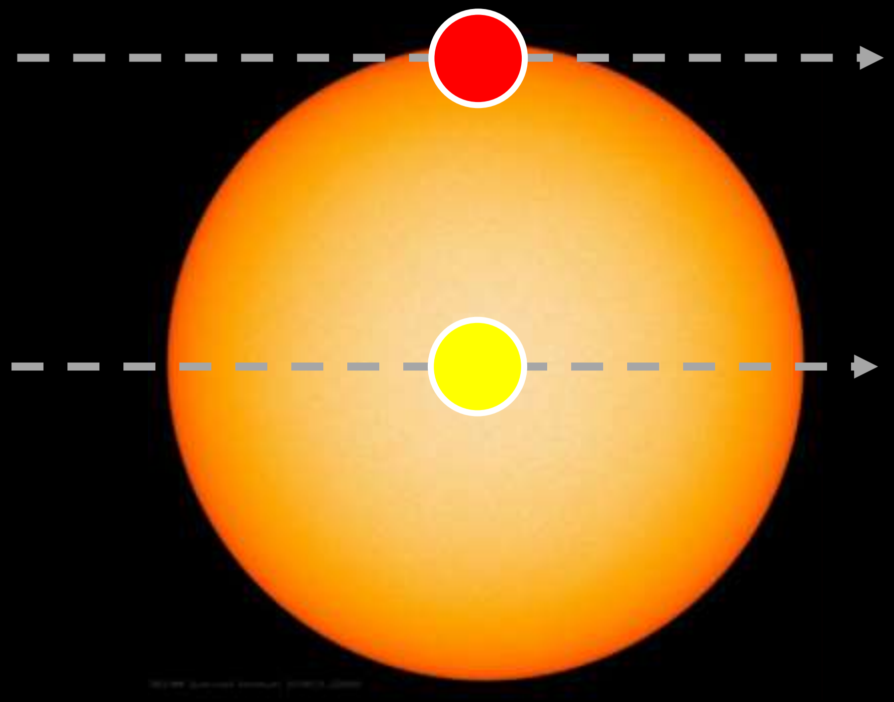


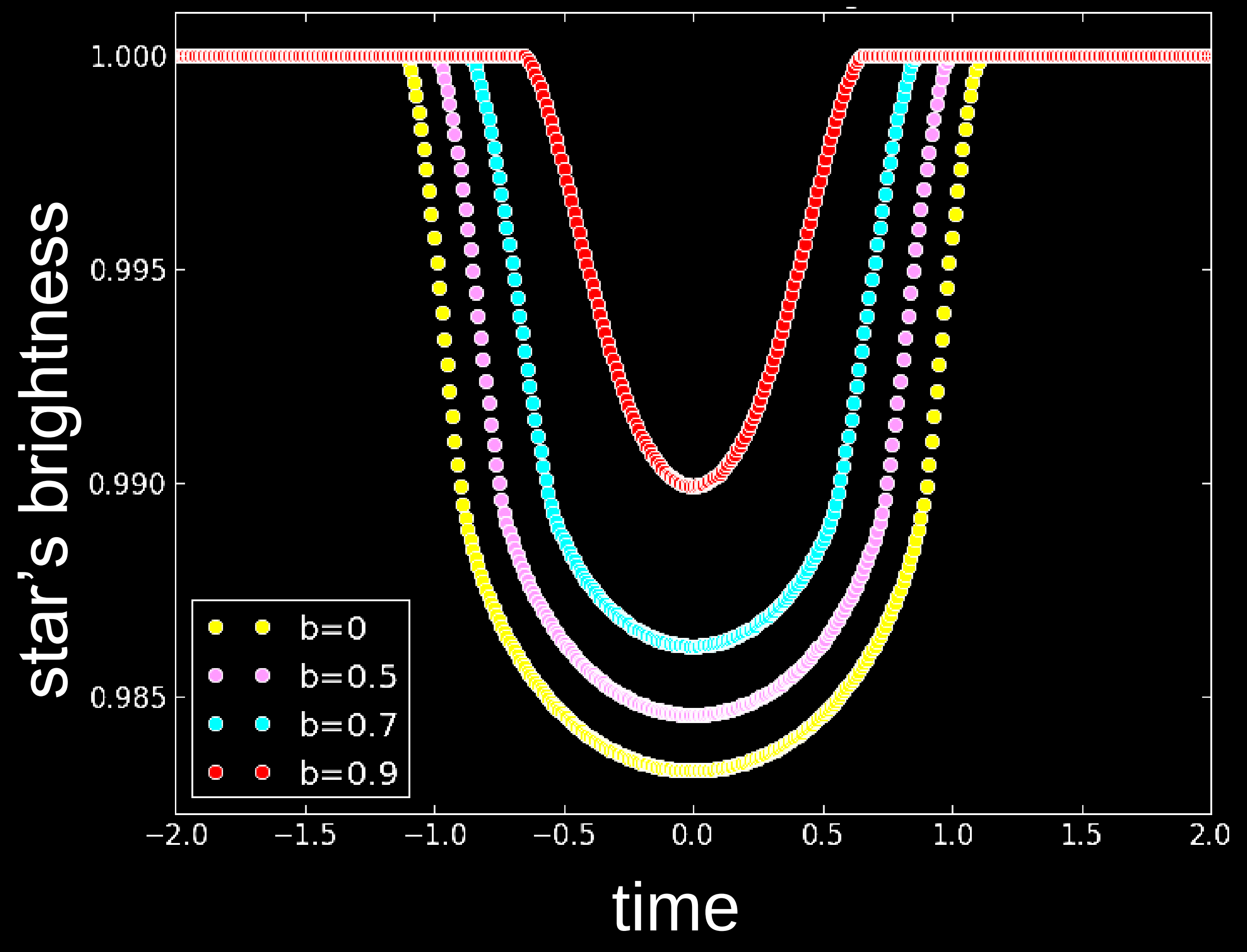
Without limb darkening



Credit: planethunters.org

With limb darkening



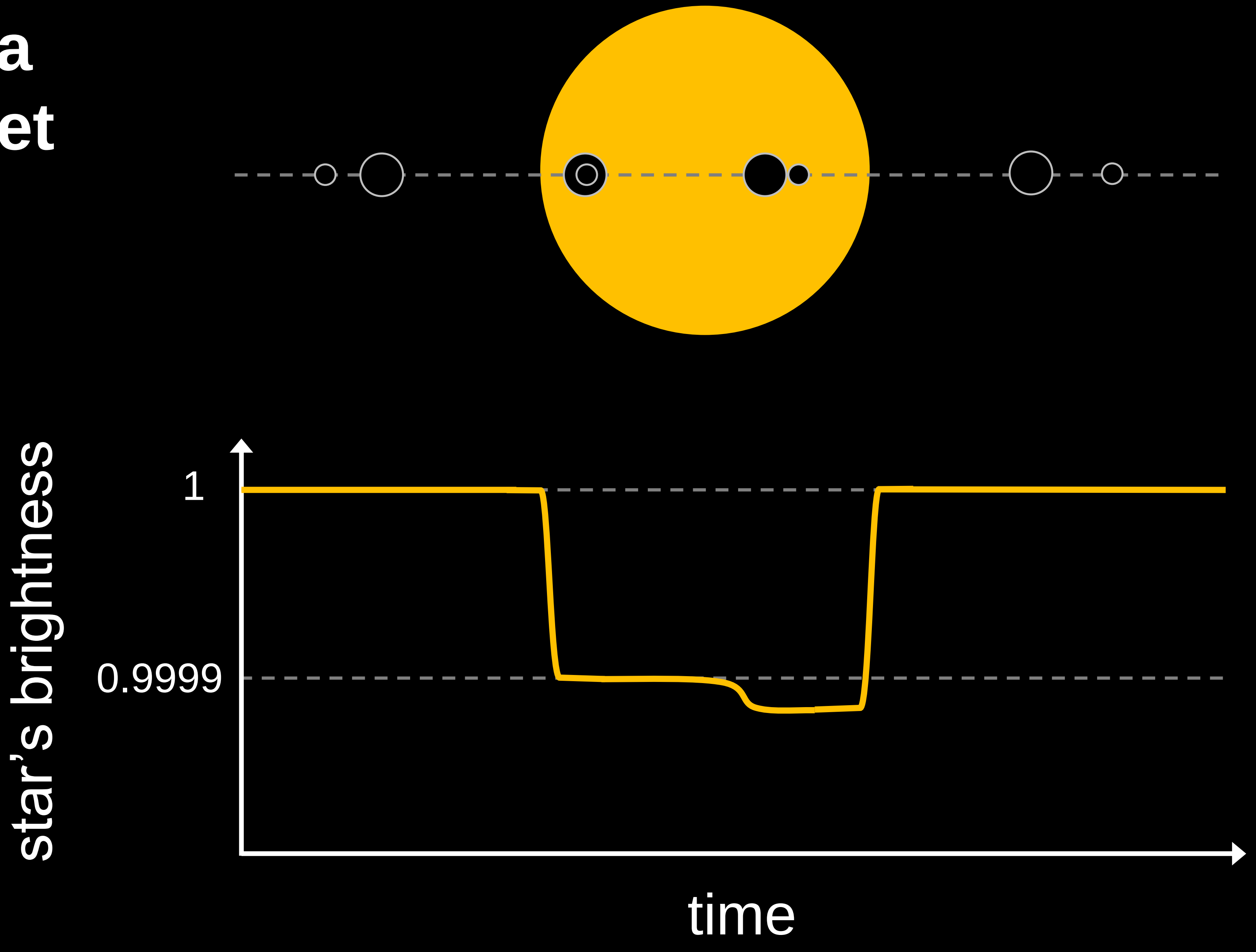


Credit: planethunters.org

What happens if an exoplanet has a moon?

Or a ring, like Saturn?

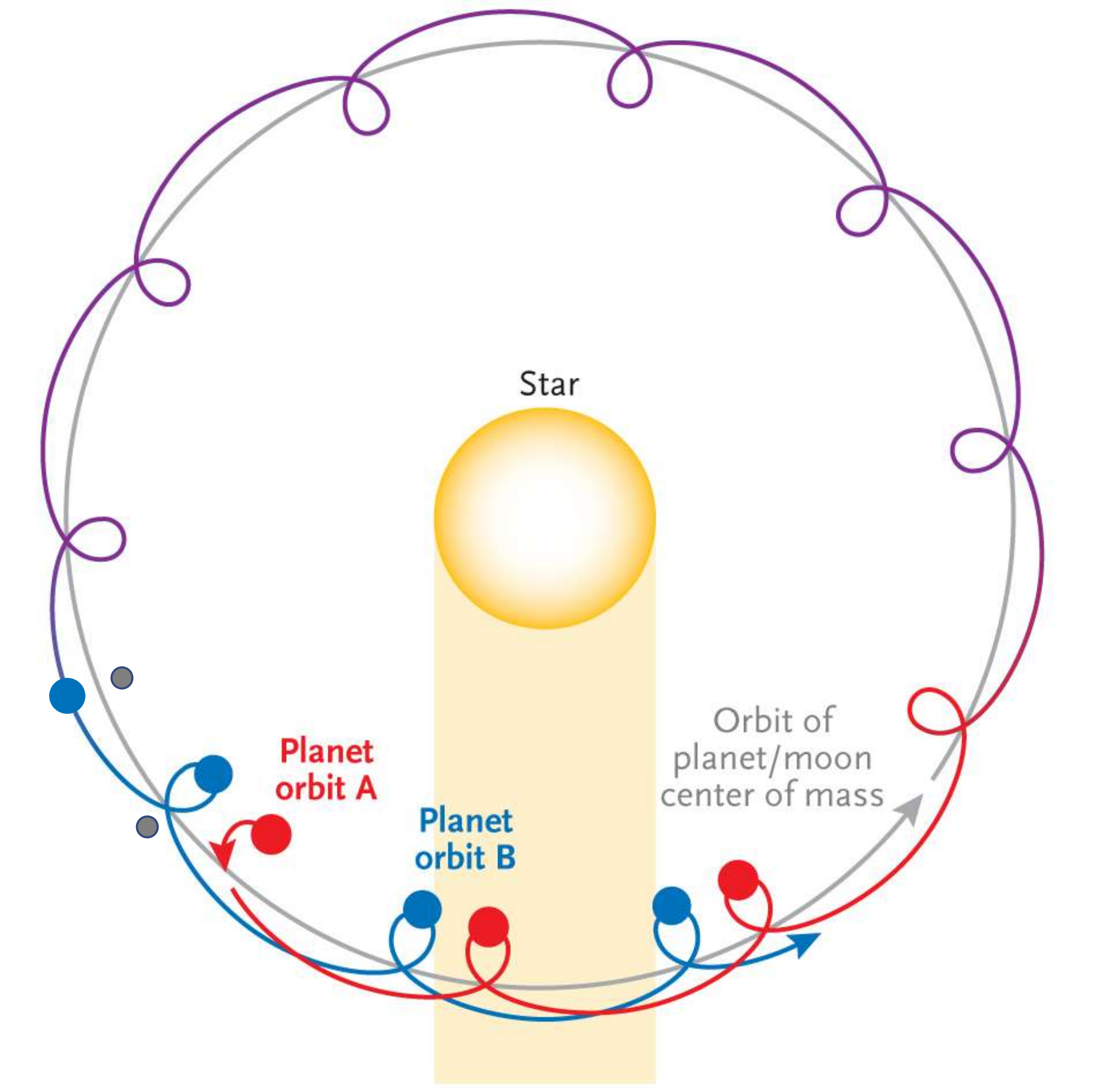
The light curve of a transiting exoplanet with an exomoon.



Credt: NASA's Goddard Space Flight Center and J. Koynock

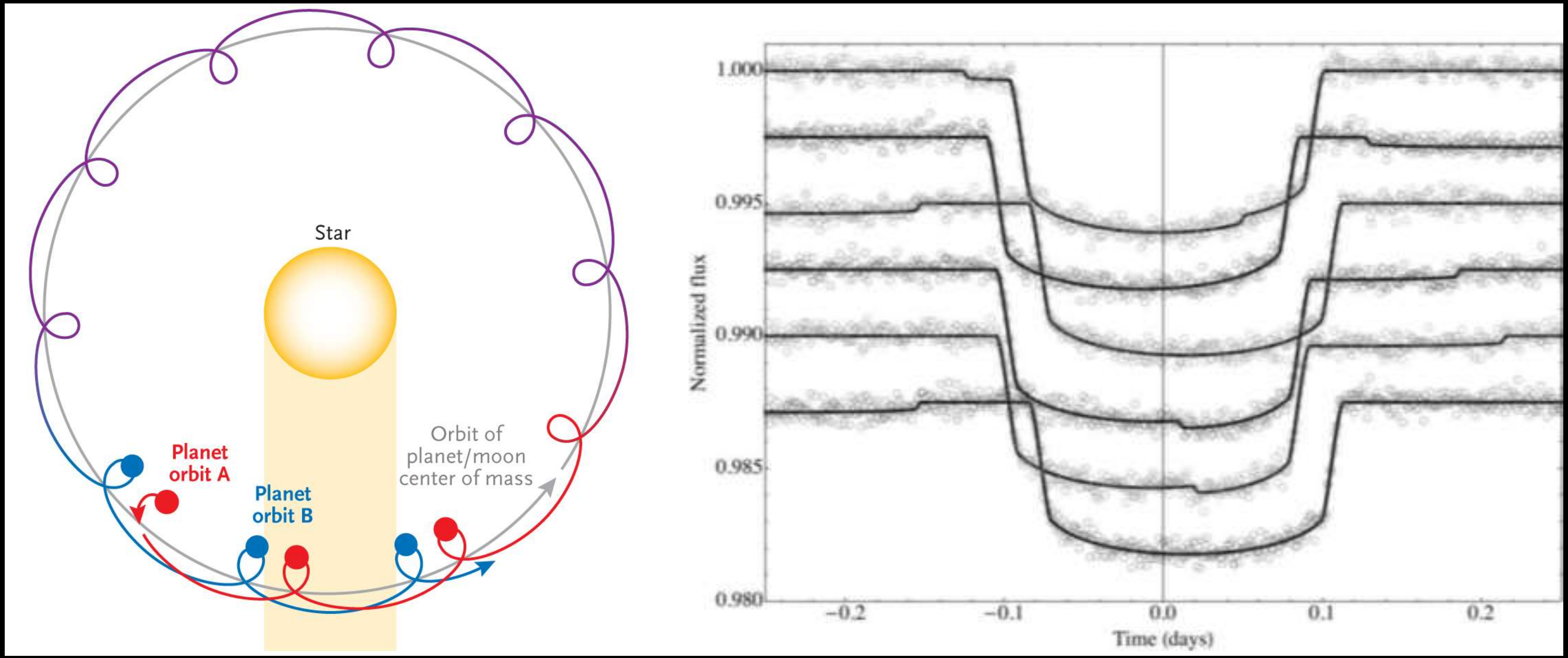
The existence of an exomoon can also be revealed by variations in the timing of the middle of the transit.

This technique is called *transit timing variation*.


Star
Planet
orbit A
Planet
orbit B
Orbit of
planet/moon
center of mass

As the planet and its Moon orbit their common centre of mass, the exact timing of the middle of the transit varies from one orbit of the planet around the star to the next.

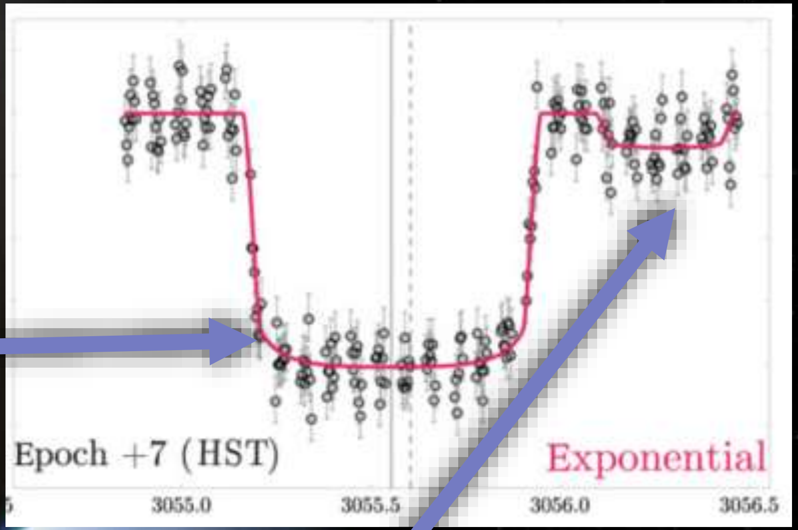
(Kipping, 2014, arXiv:1405.1455)



In October 2018, the first evidence of an exomoon emerged.

(Teachey & Kipping, Science, 2018)

planet



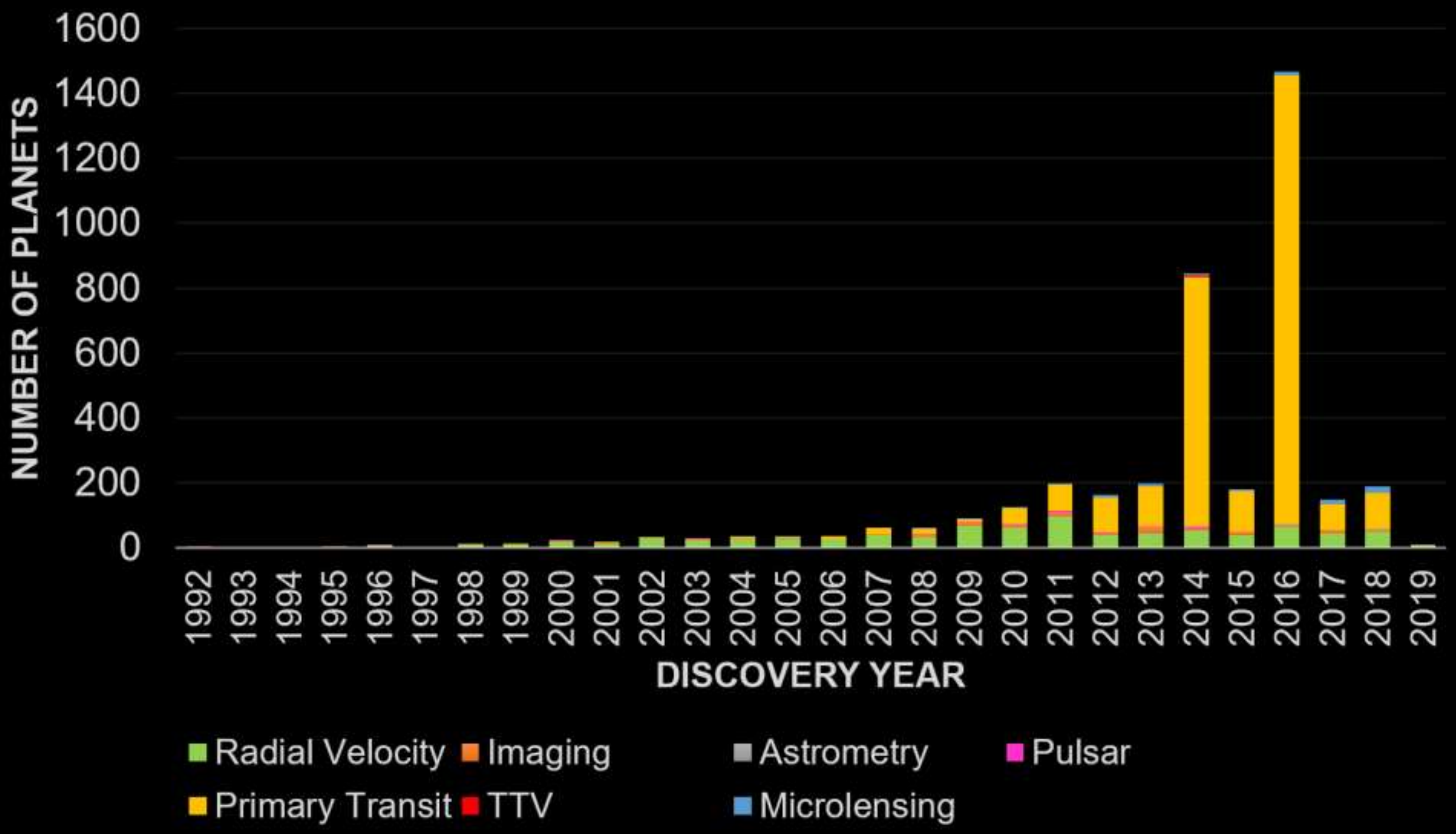
moon

Credit: Dan Durda

Results of the Transit Method

To date, the transit method has been by far the most successful planet-finding method, detecting more than 3000 confirmed exoplanets.

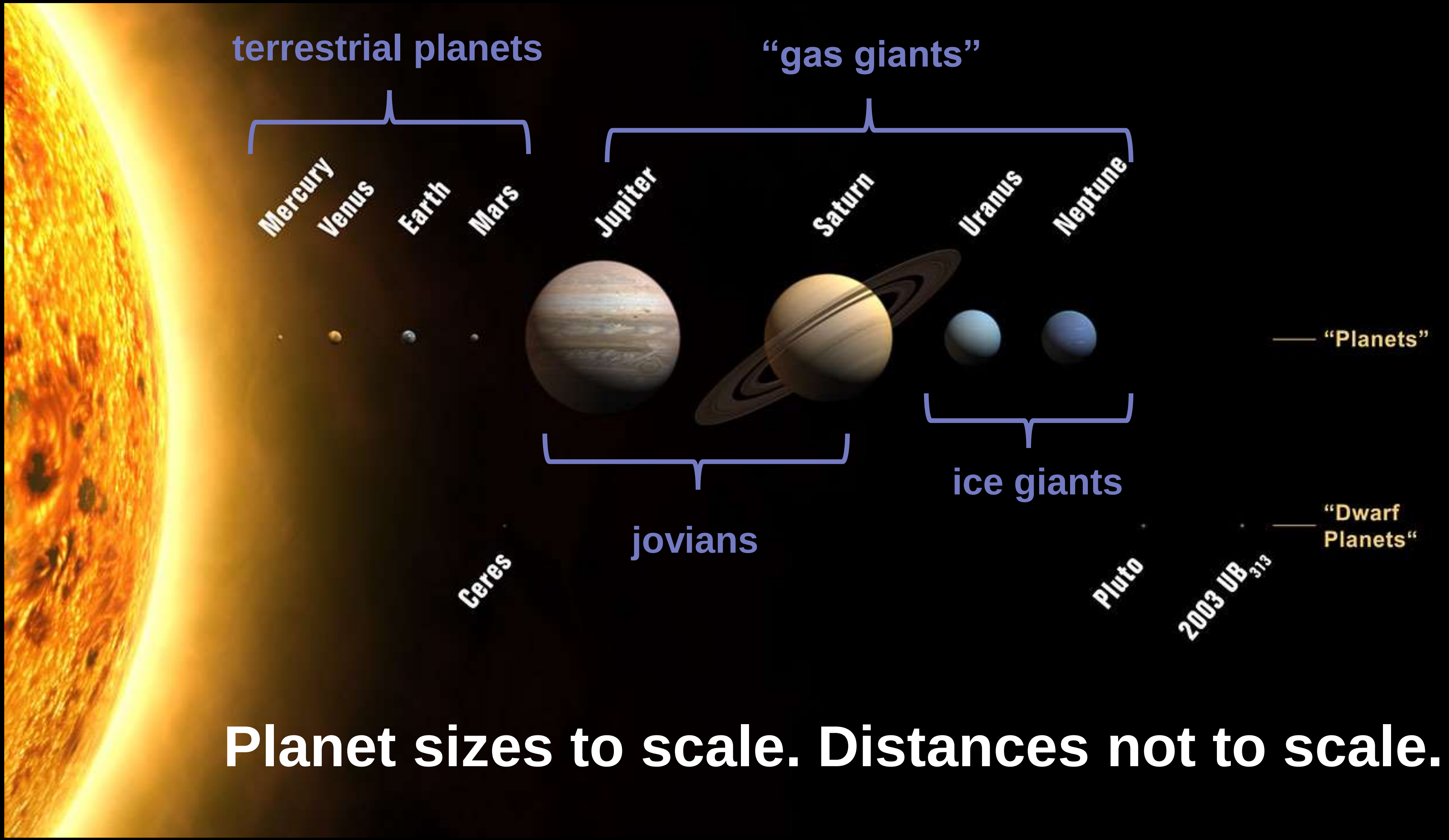
Exoplanets by discovery year and method



Much of the success of this method was due to the **Kepler space telescope**, which was operational from 2009-2018.

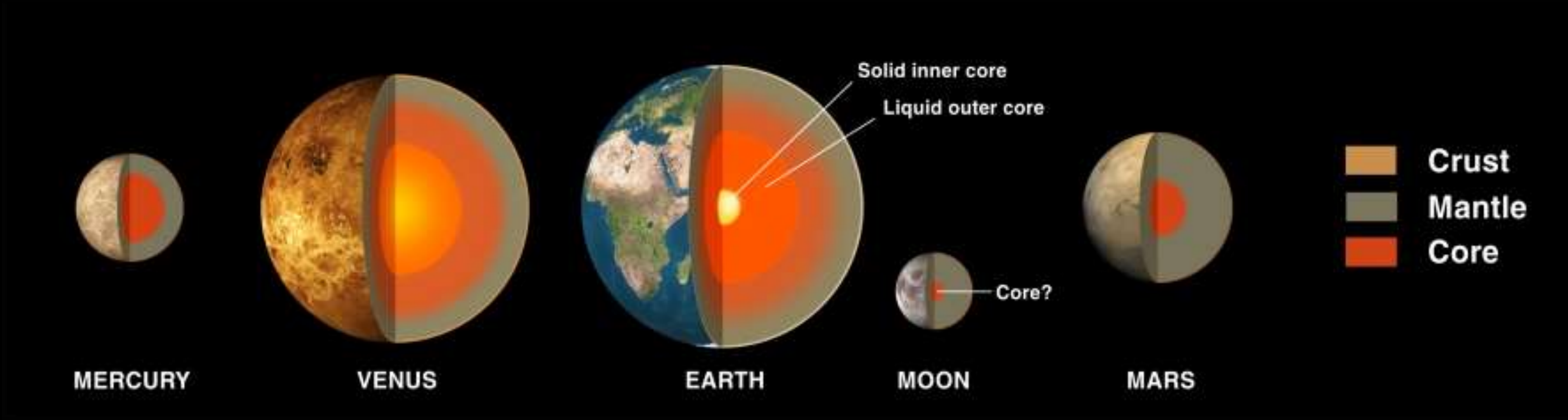
Credit: NASA/Ames Research Center/W. Stenzel/D. Rutter

Kepler has expanded the range of known types of planets beyond those found in our own solar system.


terrestrial planets
"gas giants"
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
"Planets"
ice giants
jovians
Ceres
Pluto
2003 UB313
"Dwarf Planets"
Planet sizes to scale. Distances not to scale.

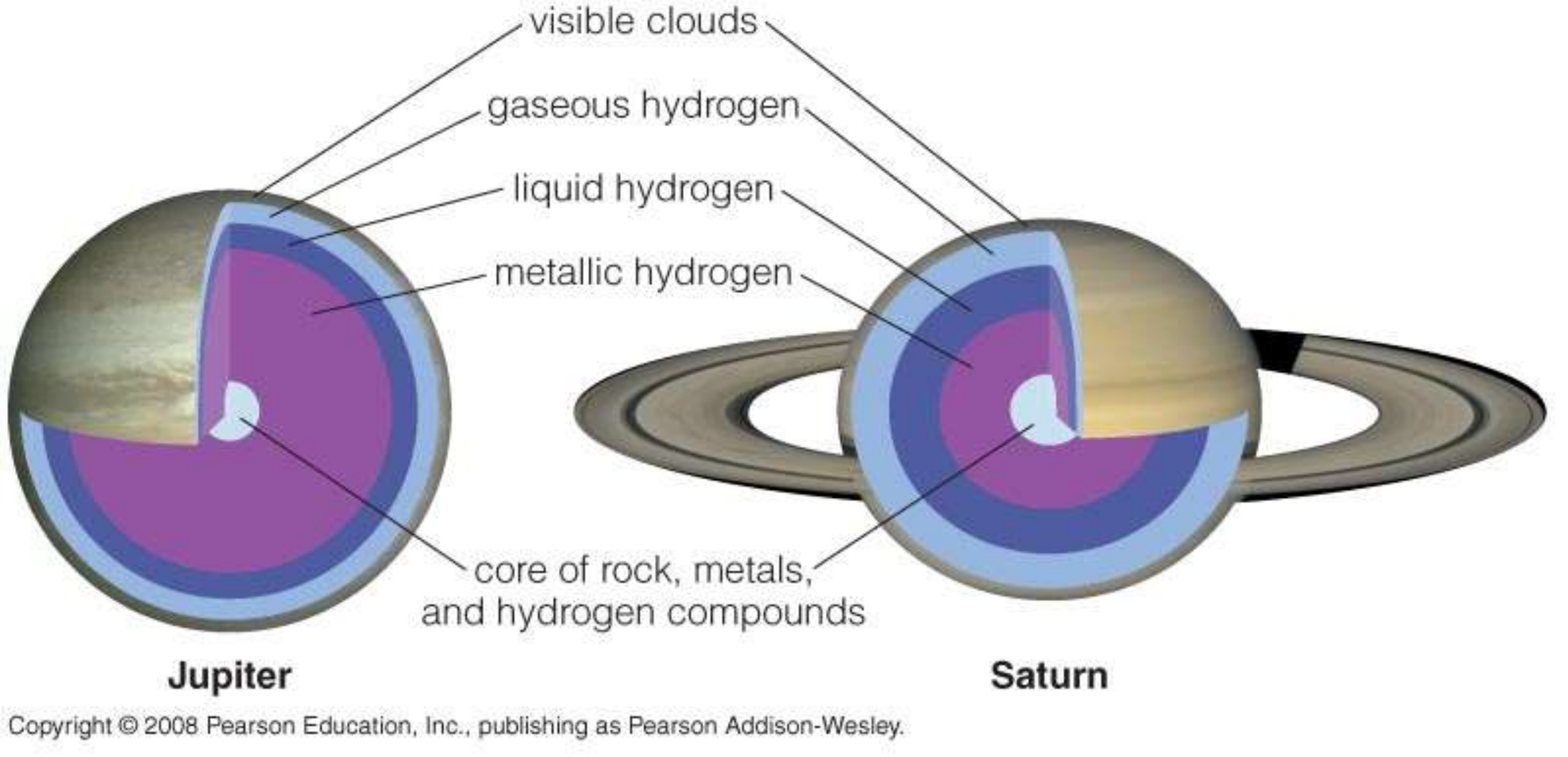
Credit: NASA

Terrestrial planets: mainly rock with thin atmospheres

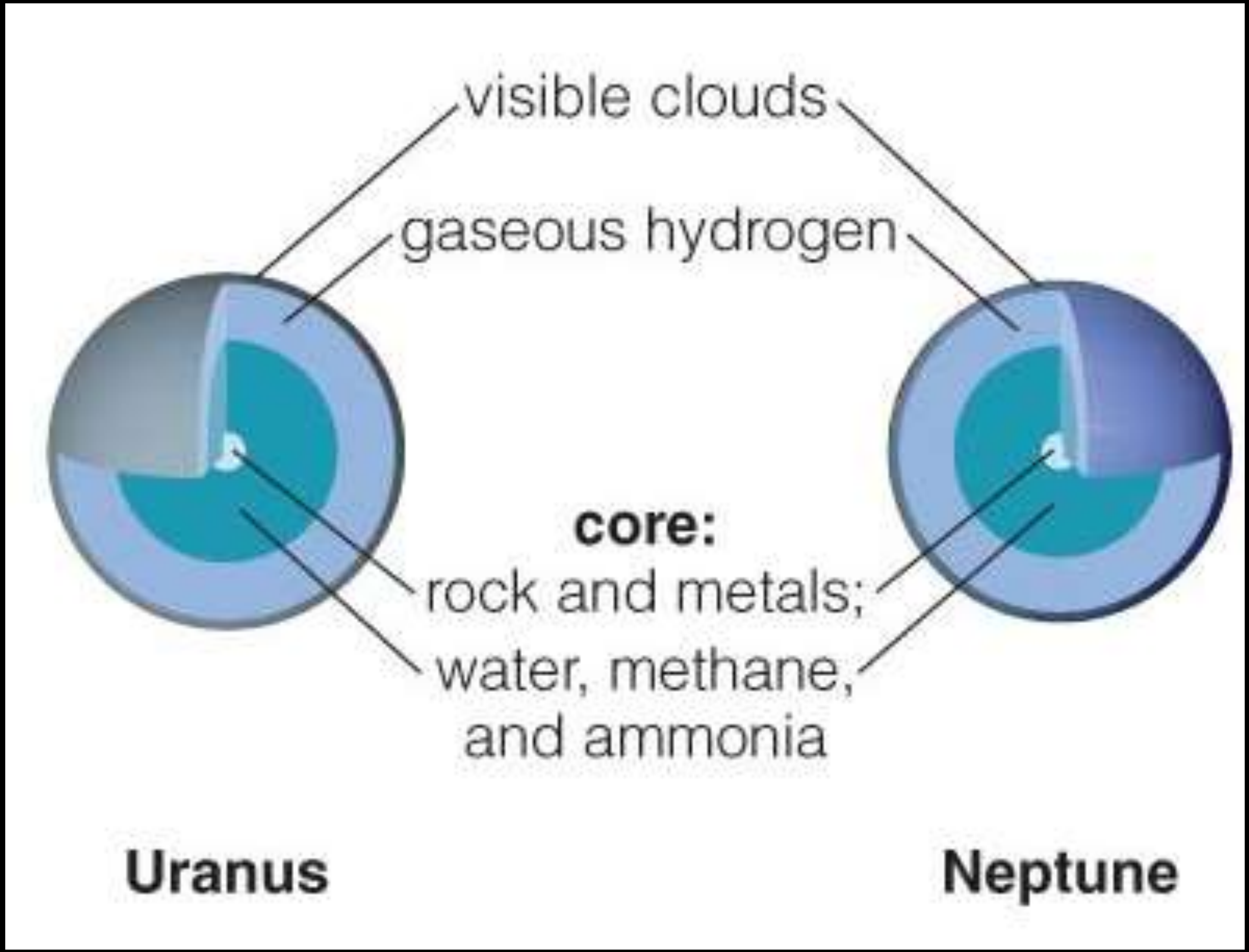


Credit: NASA/JPL

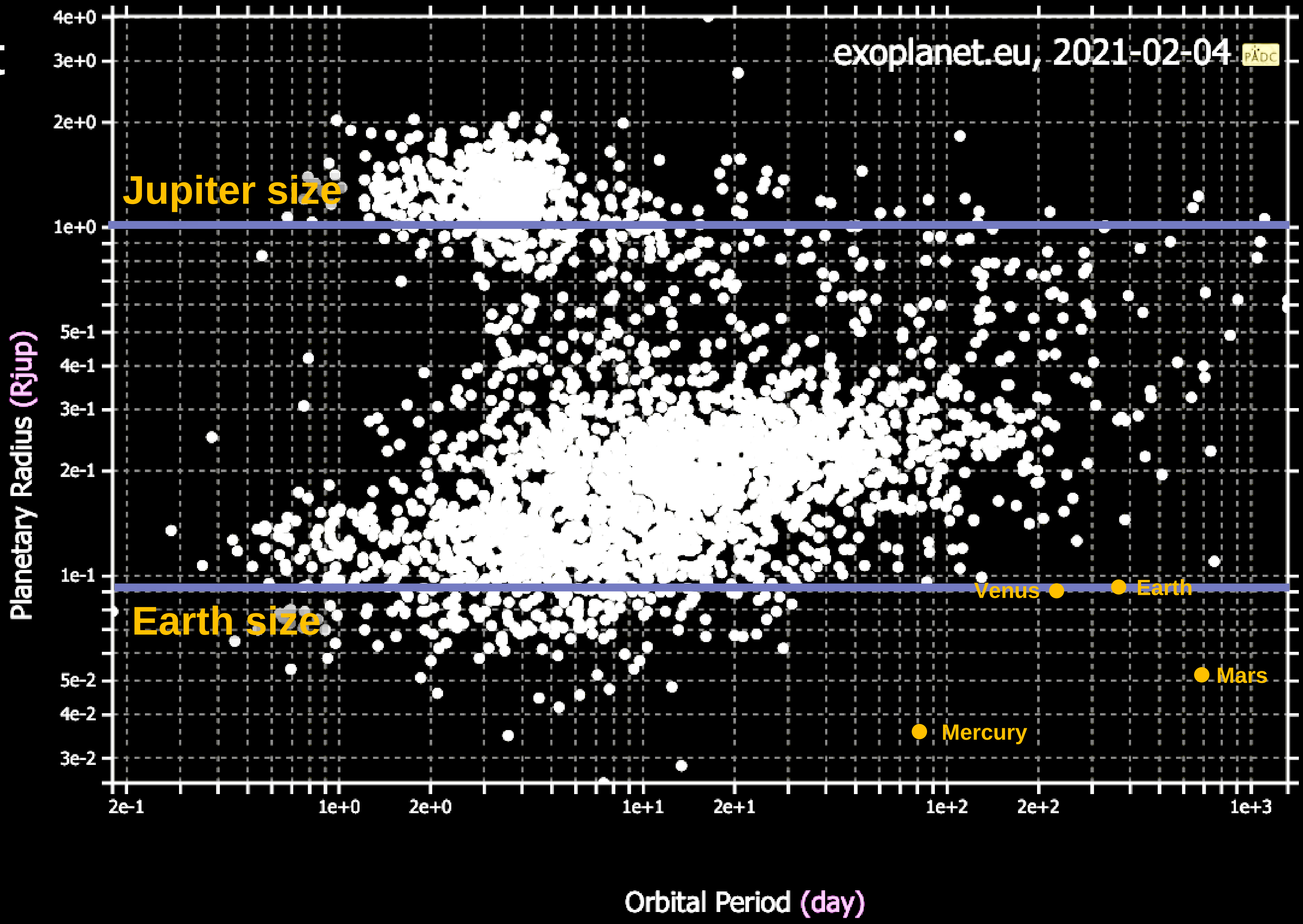
Jovian planets: mostly liquid hydrogen with thick gaseous atmospheres and rocky cores the size of terrestrial planets.



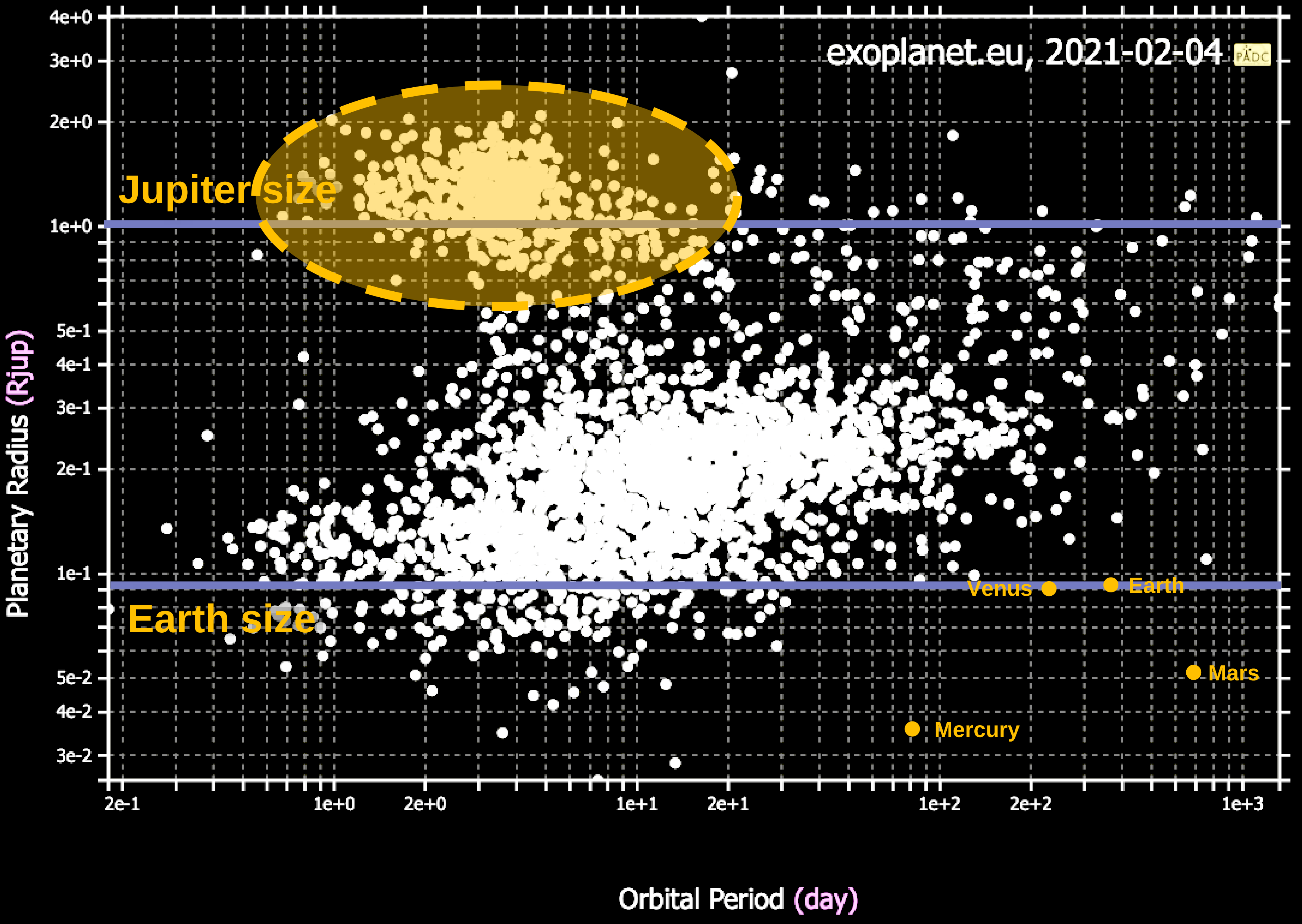
Ice giants/Neptunian: slushy liquid interiors with thick gaseous atmospheres and small rocky cores



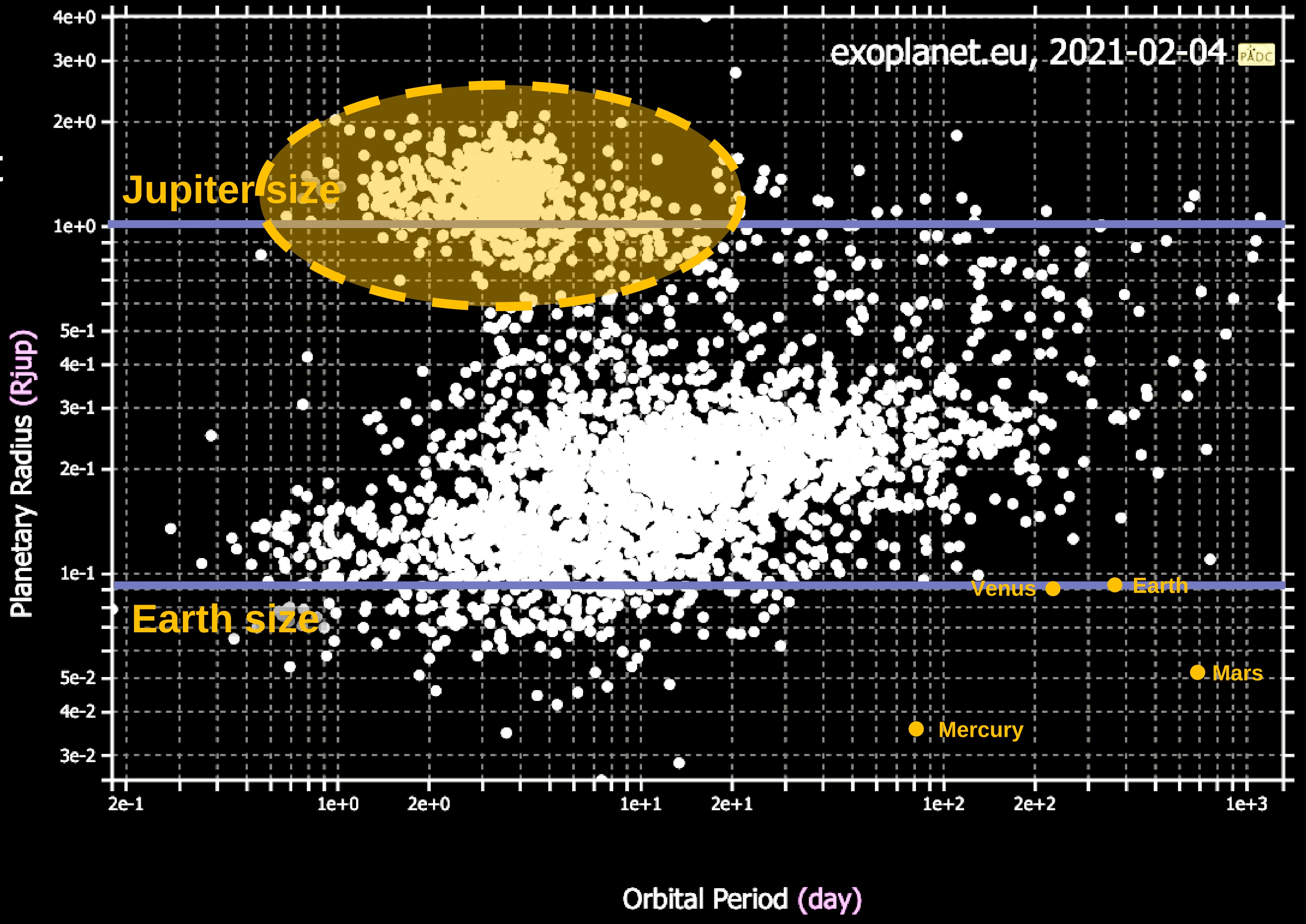
Confirmed exoplanet detections using the transit method—most of them very unlike the planets of our own solar system.



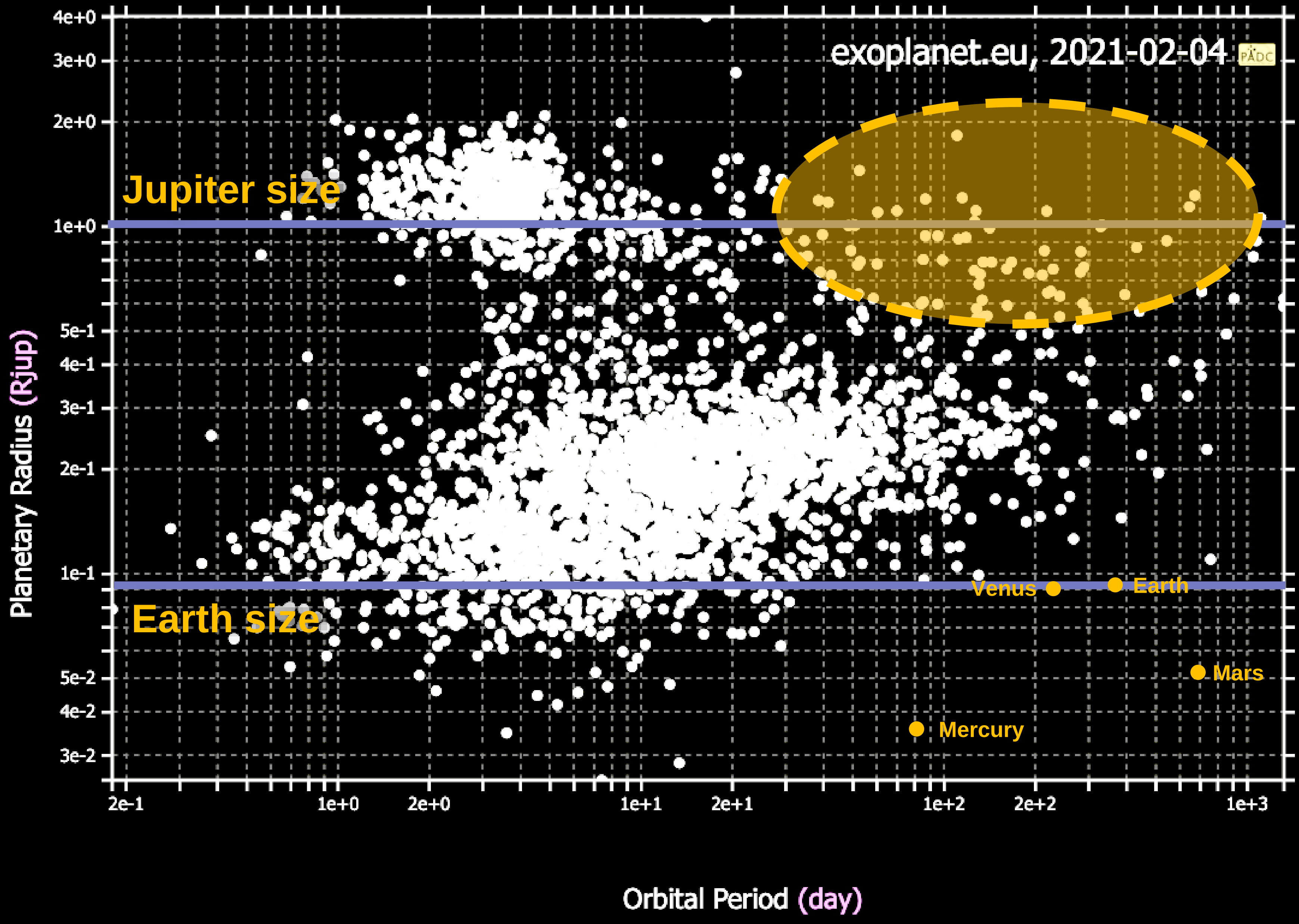
Planets in this general area are Jovian, but they orbit very close to their parent stars, so we call them hot Jupiters.



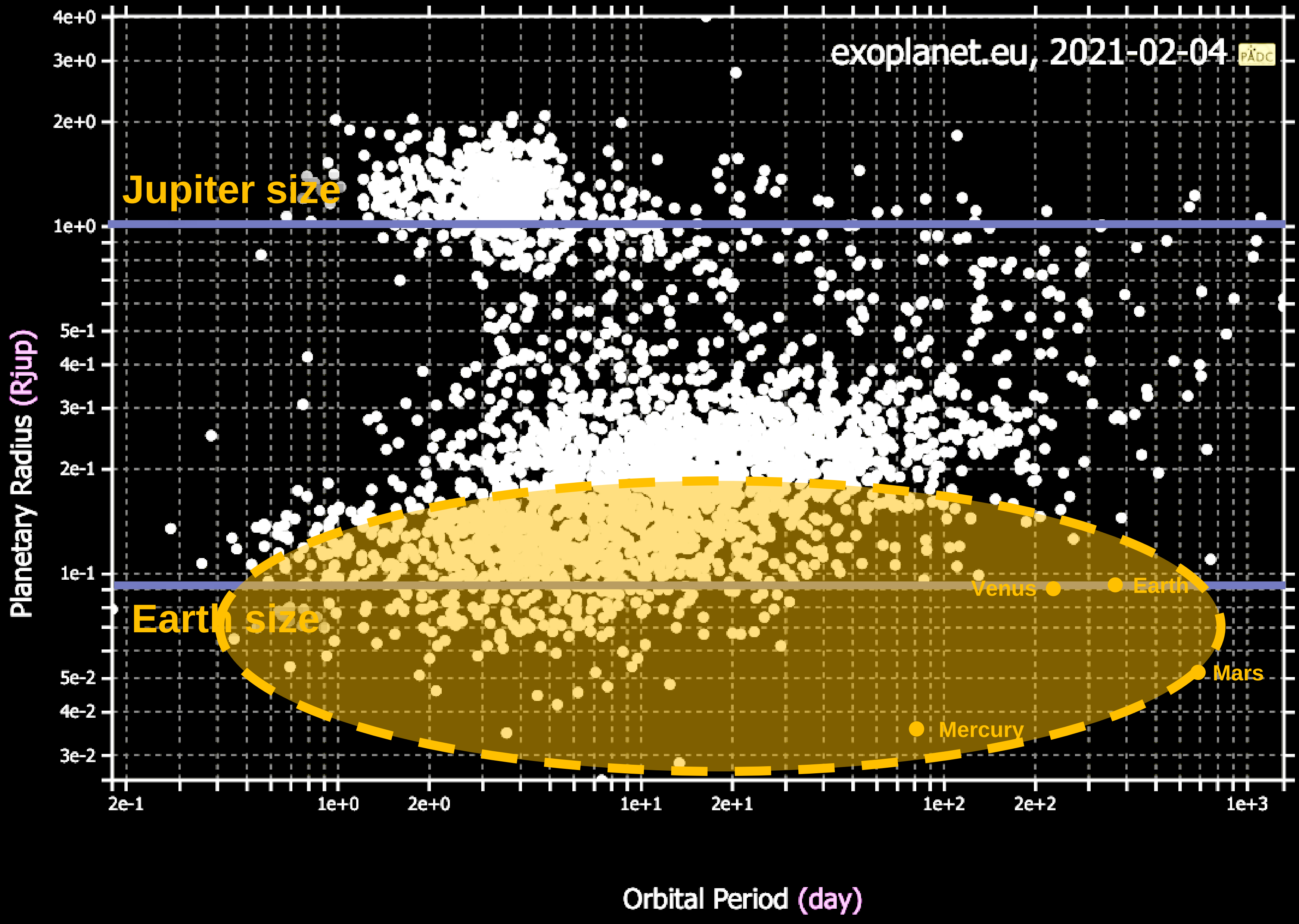
Note that this diagram does not indicate the spectral type of the host star. If the host star is small and cool, these planets might not be "hot".



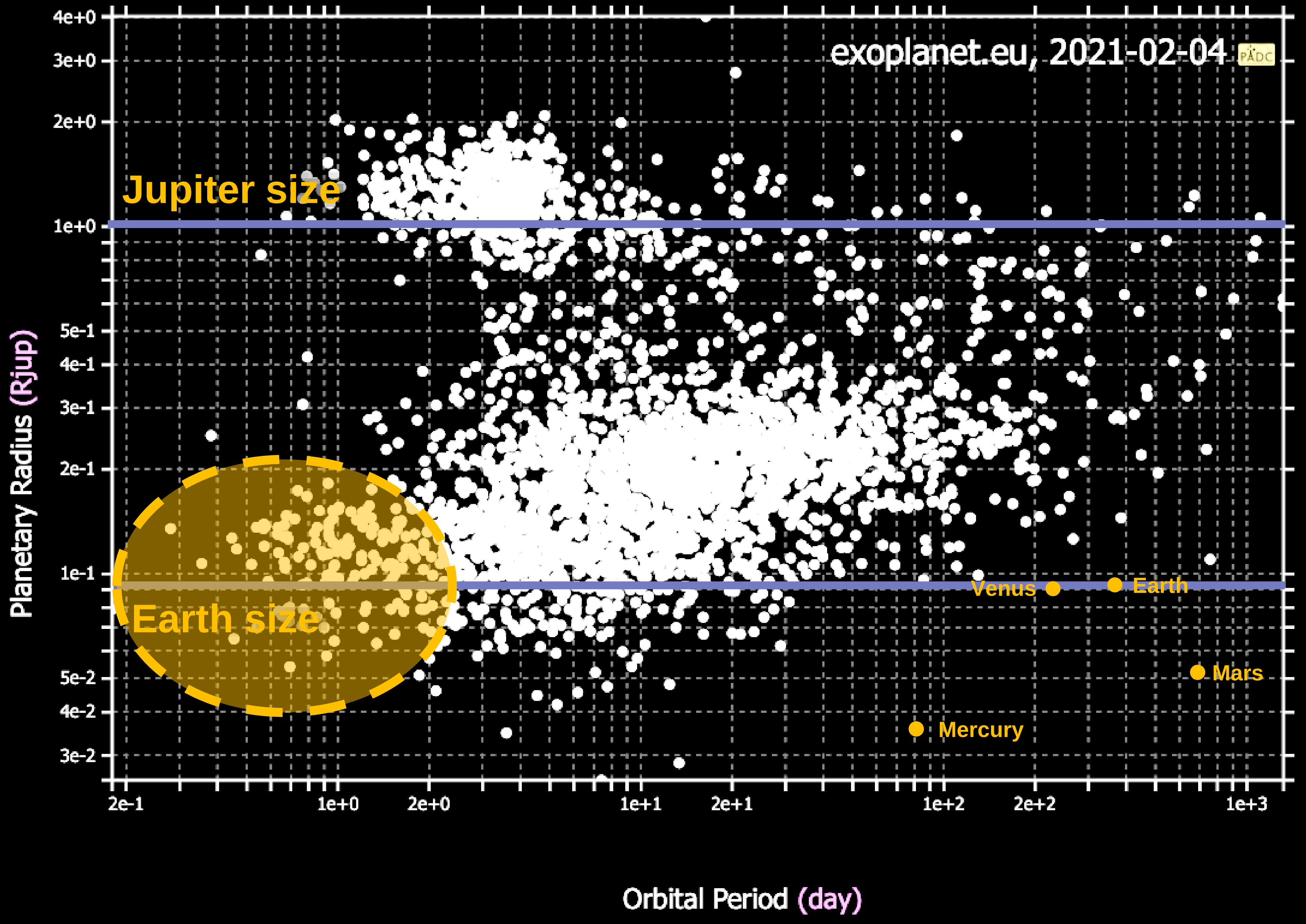
Planets in this corner of the diagram are also Jovian, but they would be somewhat cooler.



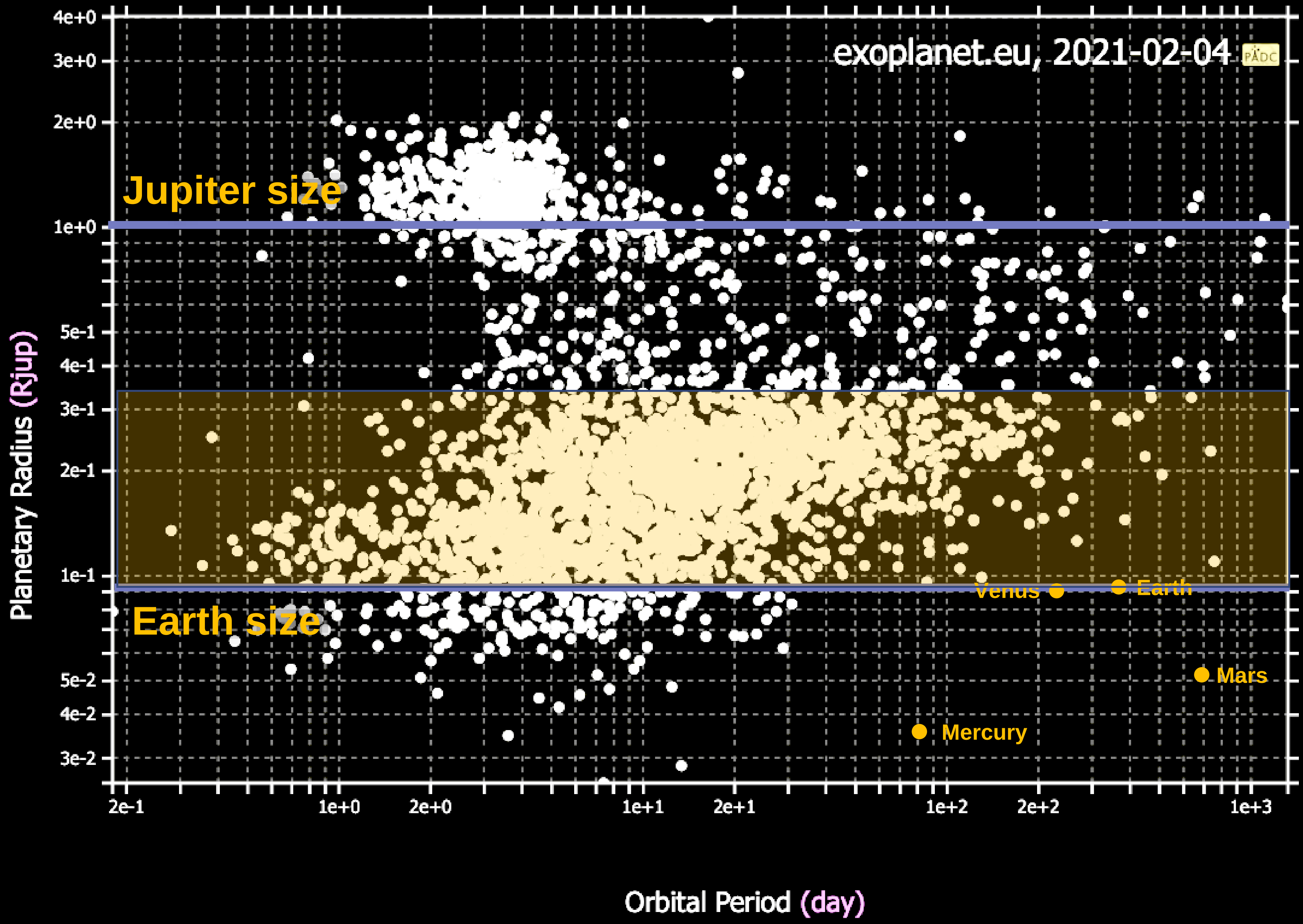
Planets toward the bottom of the diagram would be rocky and could be either hot or cold depending on how close they orbited to their host star.

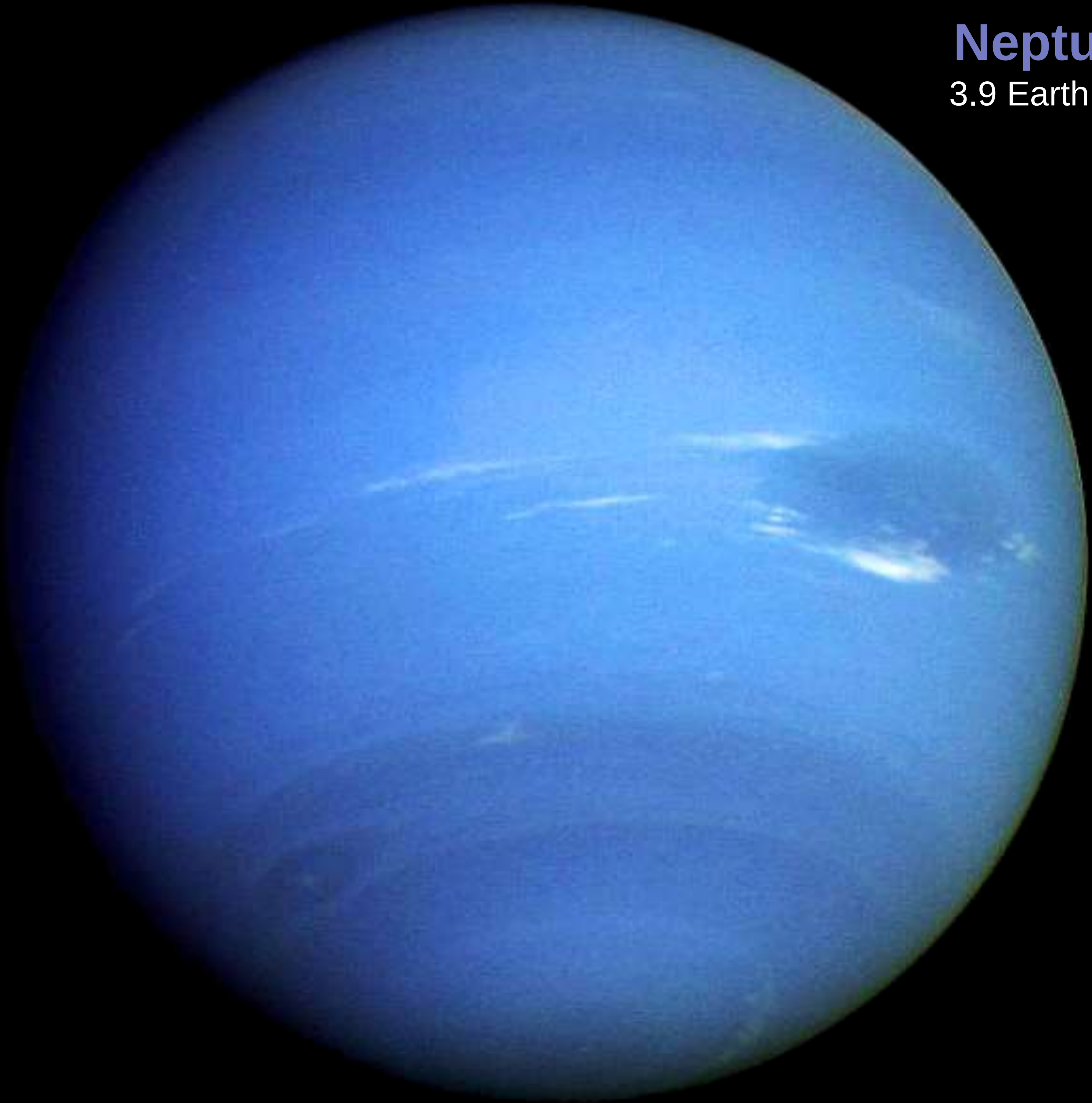


Terrestrial planets very close to their stars are sometimes called lava worlds.



Planets in the middle range from about 1-4 Earth radii, are ambiguous. We have no planets in this size range in our solar system.





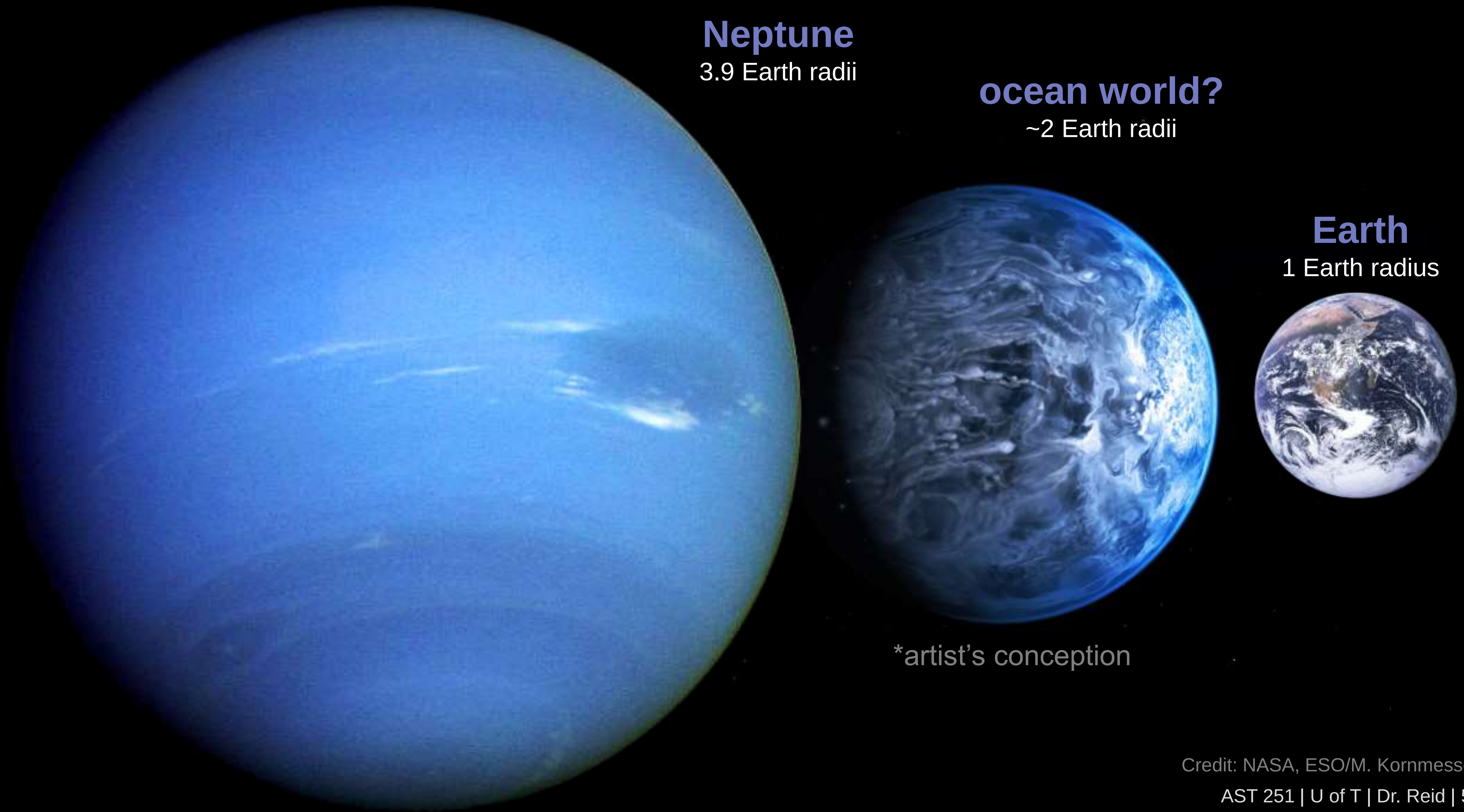
Neptune
3.9 Earth radii

super Earth?
~1.5 Earth radii

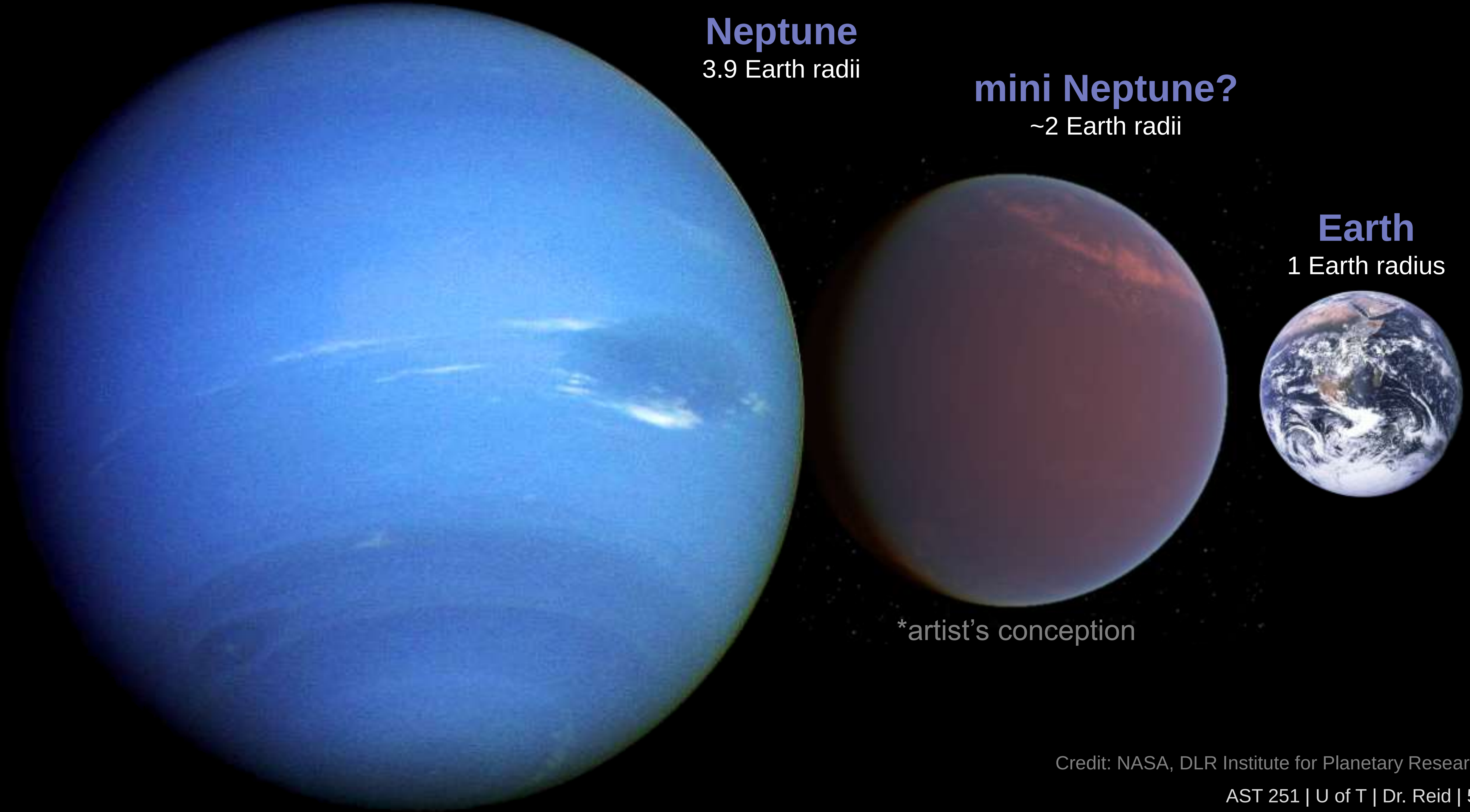
*artist's conception

Earth
1 Earth radius

Credit: NASA, ESO/M. Kornmesser

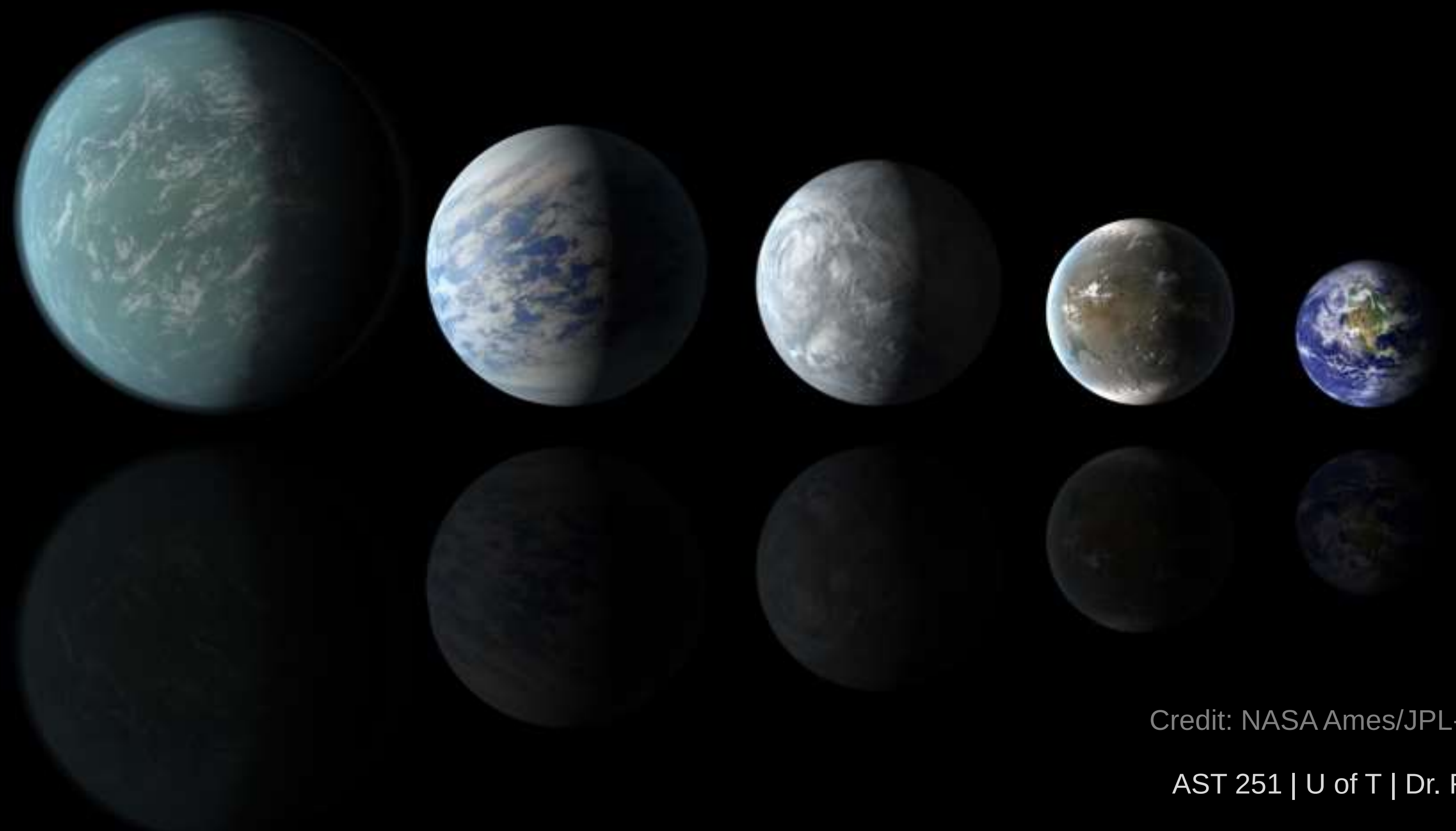


Credit: NASA, ESO/M. Kornmesser



Credit: NASA, DLR Institute for Planetary Research

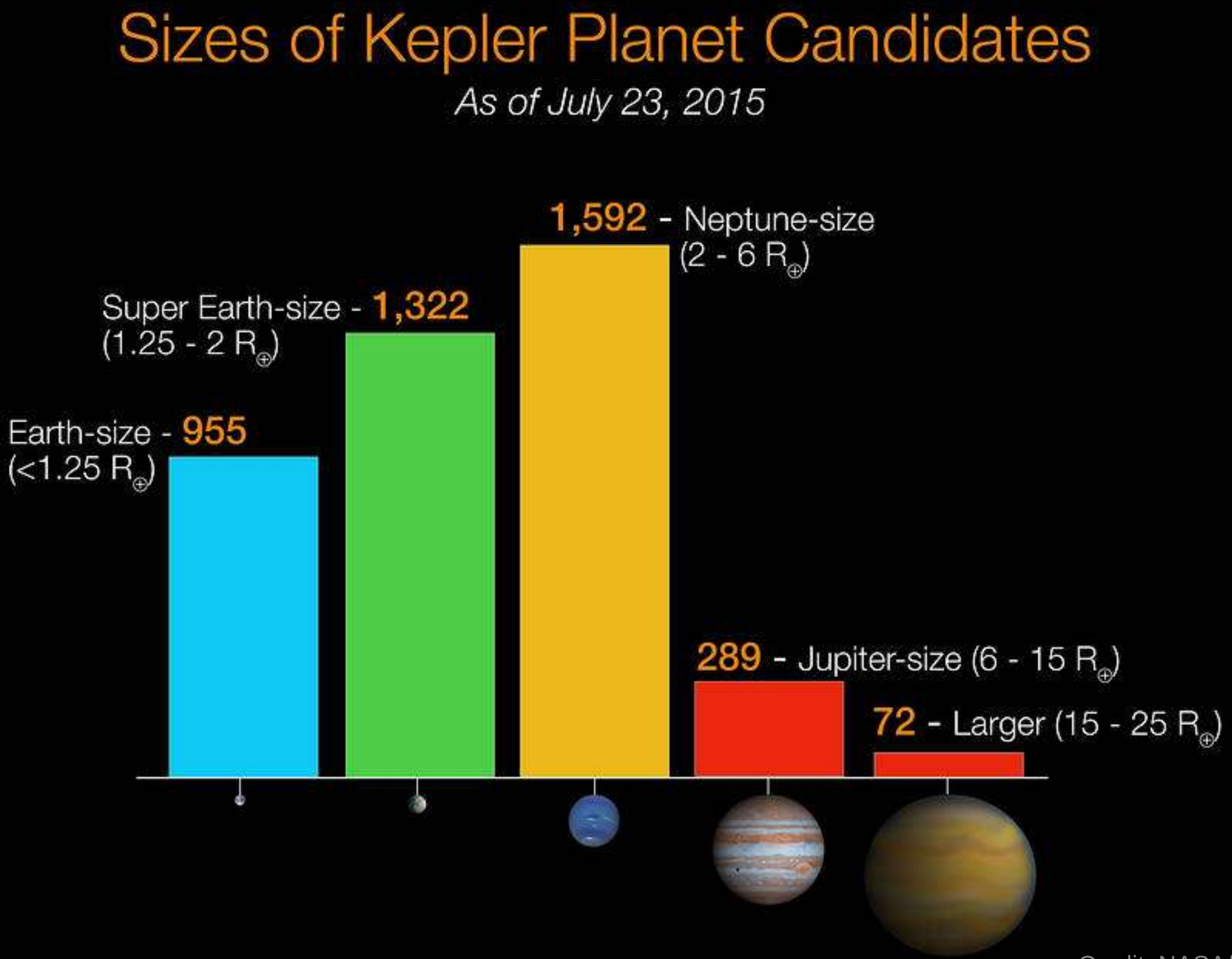
There is probably a spectrum of different types of planets in the size range between Earth and Neptune. Some may be habitable.



Credit: NASA Ames/JPL-Caltech

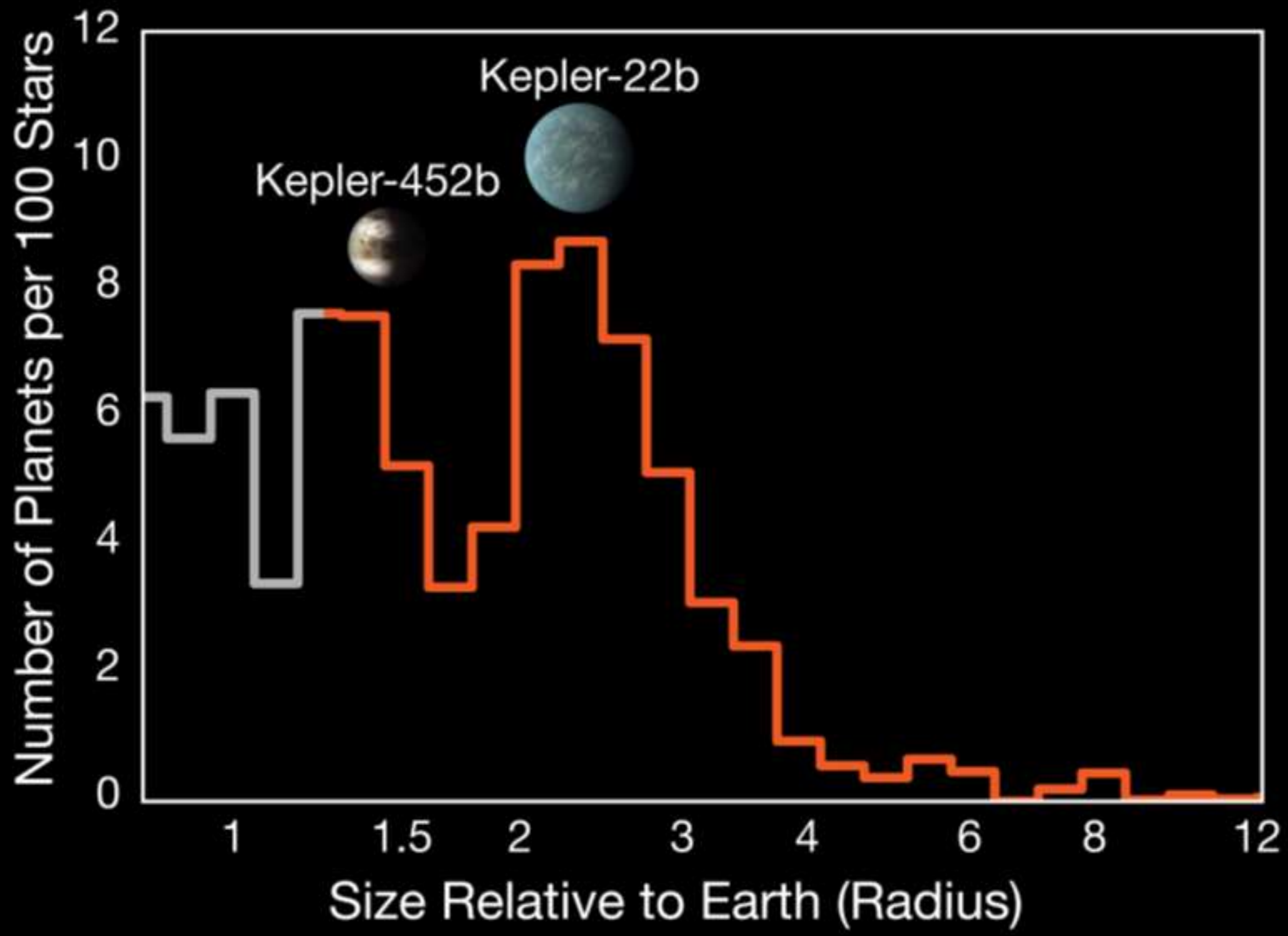
The distribution of planet sizes found so far has been surprising in several ways.

Neptune-sized planets seem to be the most common.



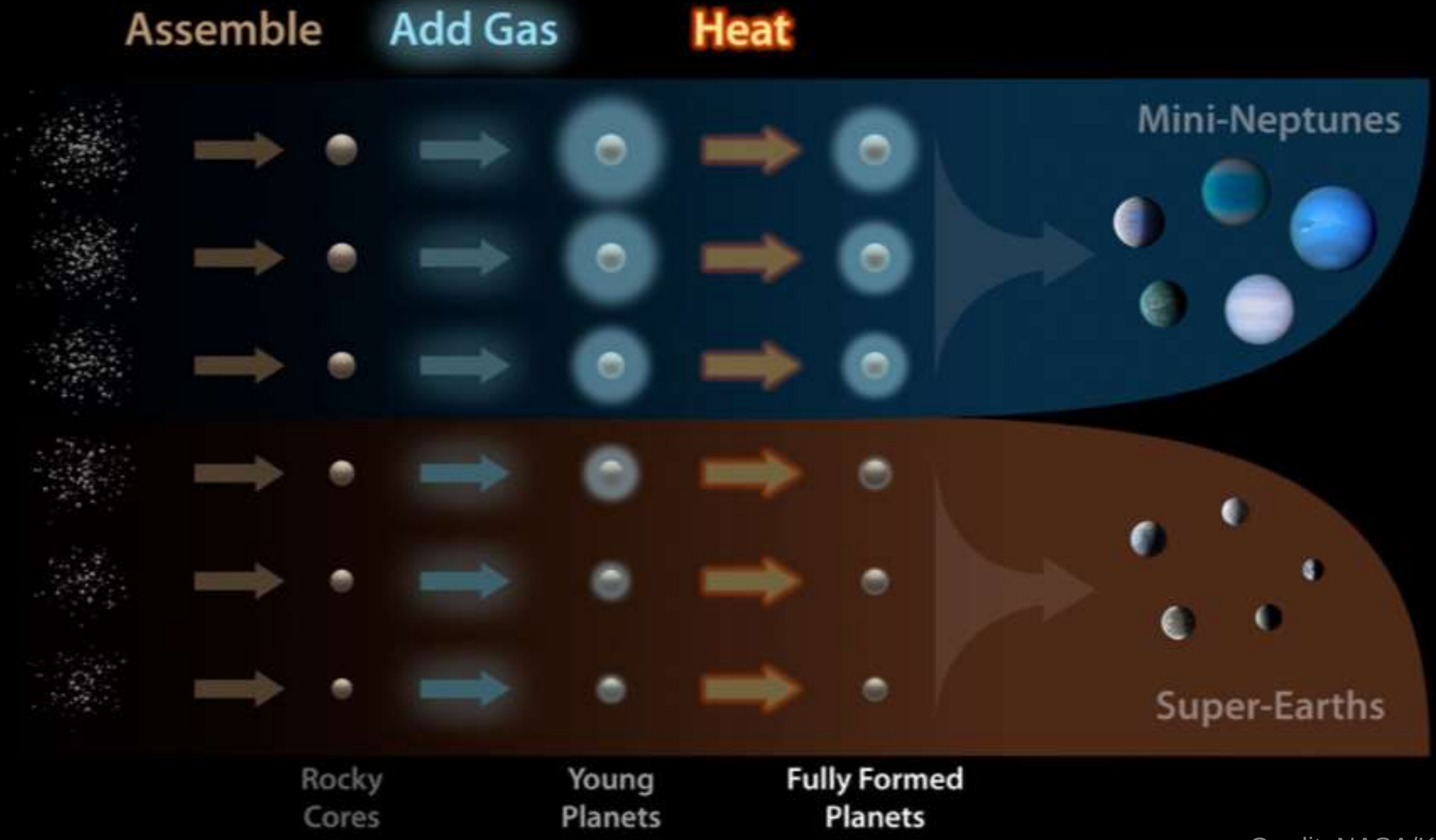
Credit: NASA/Kepler

Planets around 1.75 Earth radii seem to be uncommon.



Credit: NASA/Kepler

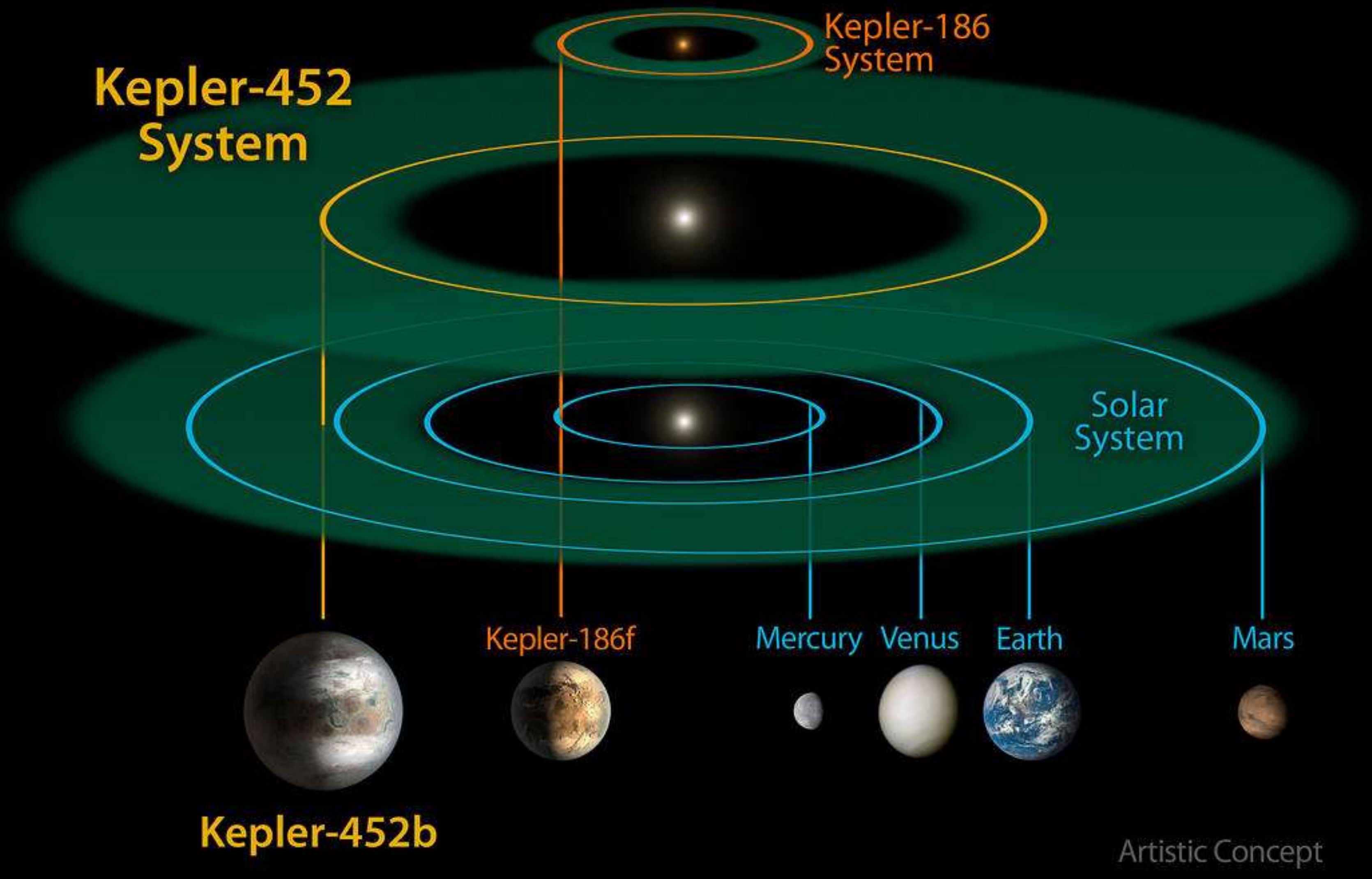
Perhaps planets around 1.75 Earth radii are rare because, when forming, they either lose their atmospheres and become smaller, or gain very thick atmospheres and become larger.



Credit: NASA/Kepler

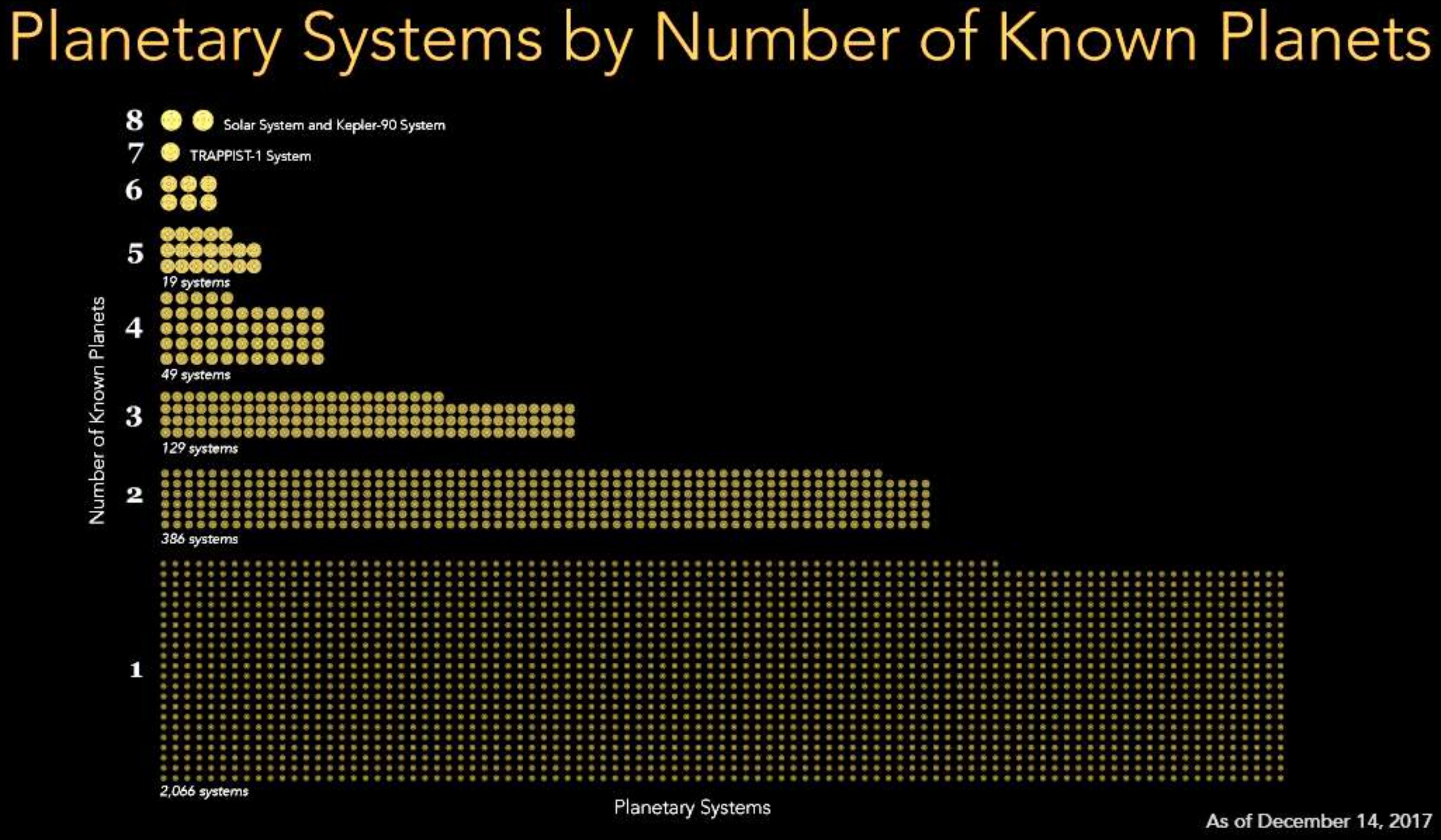
Let’s examine a few individual systems up close.

Earth-sized planets have been found orbiting many types of stars.



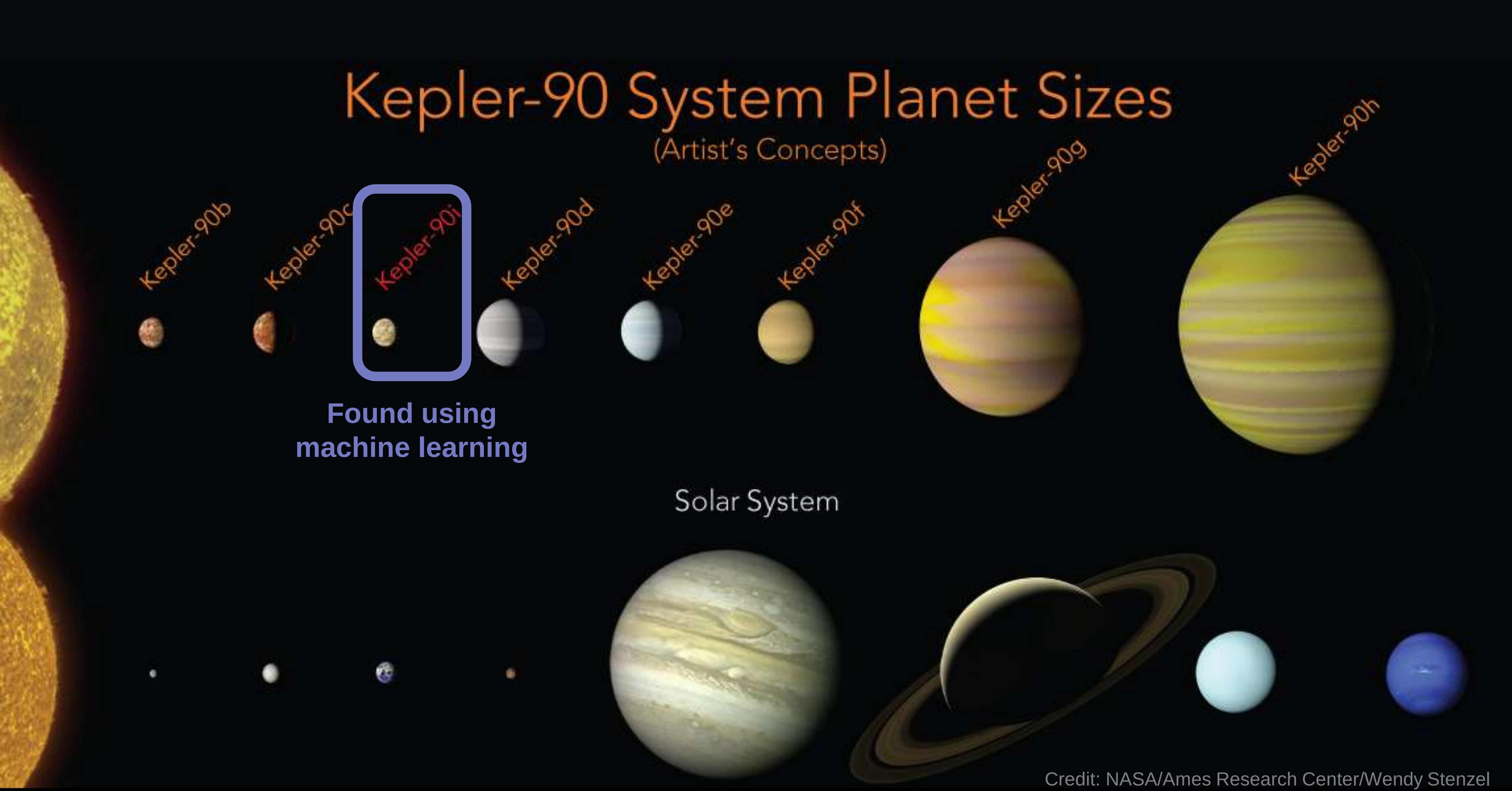
Credit: NASA/Kepler

As our planet-finding techniques improve and our observations continue, we find more and more planets in multi-planet systems.



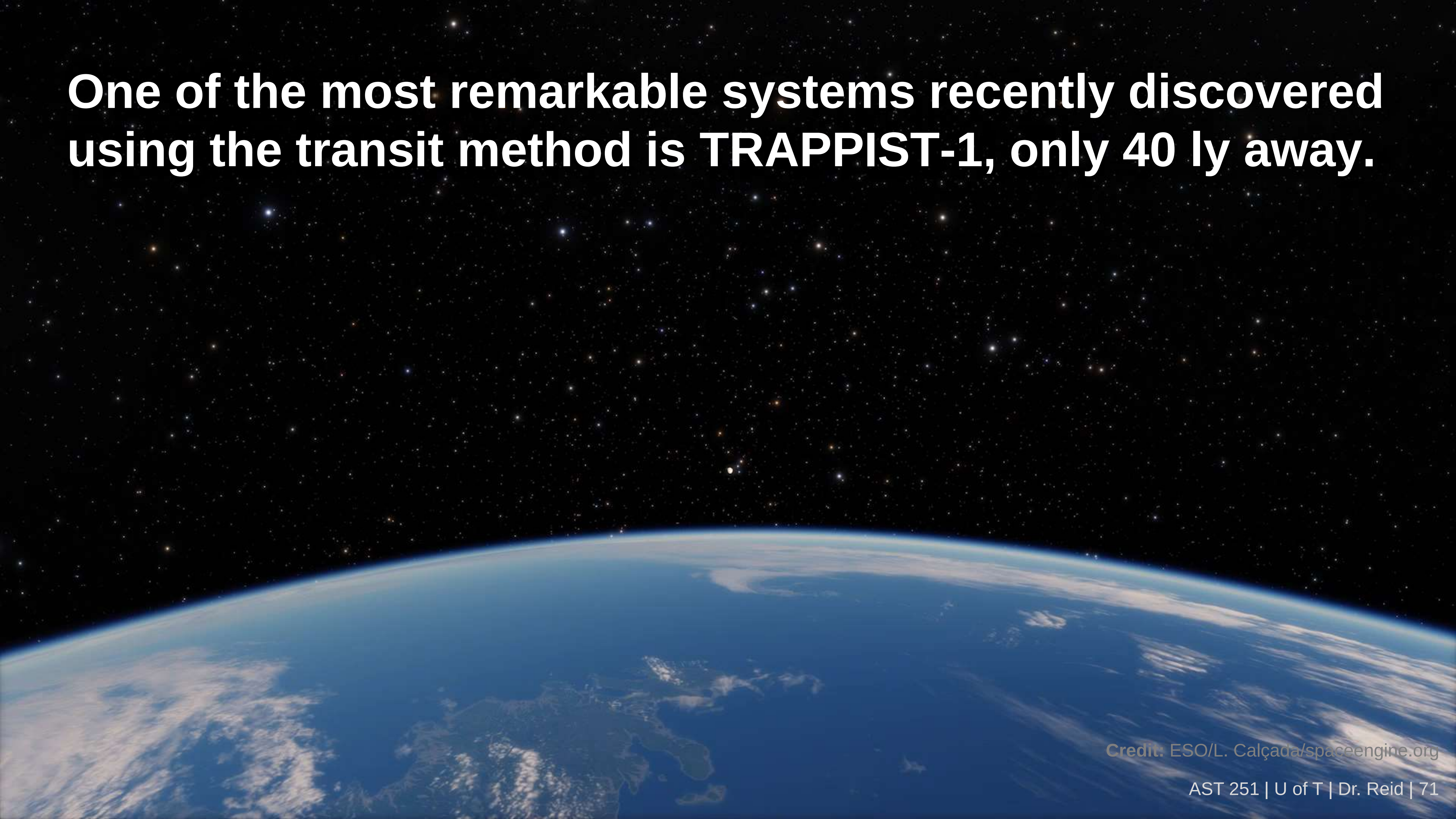
Credit: NASA/Ames Research Center/Wendy Stenzel and The University of Texas at Austin/Andrew Vanderburg

Modern exoplanet searches increasingly rely on machine learning algorithms to find hard-to-spot planets in the data.


Kepler-90 System Planet Sizes
(Artist's Concepts)
Kepler-90b
Kepler-90c
Kepler-90i
Kepler-90d
Kepler-90e
Kepler-90f
Kepler-90g
Kepler-90h
Found using
machine learning
Solar System
Credit: NASA/Ames Research Center/Wendy Stenzel

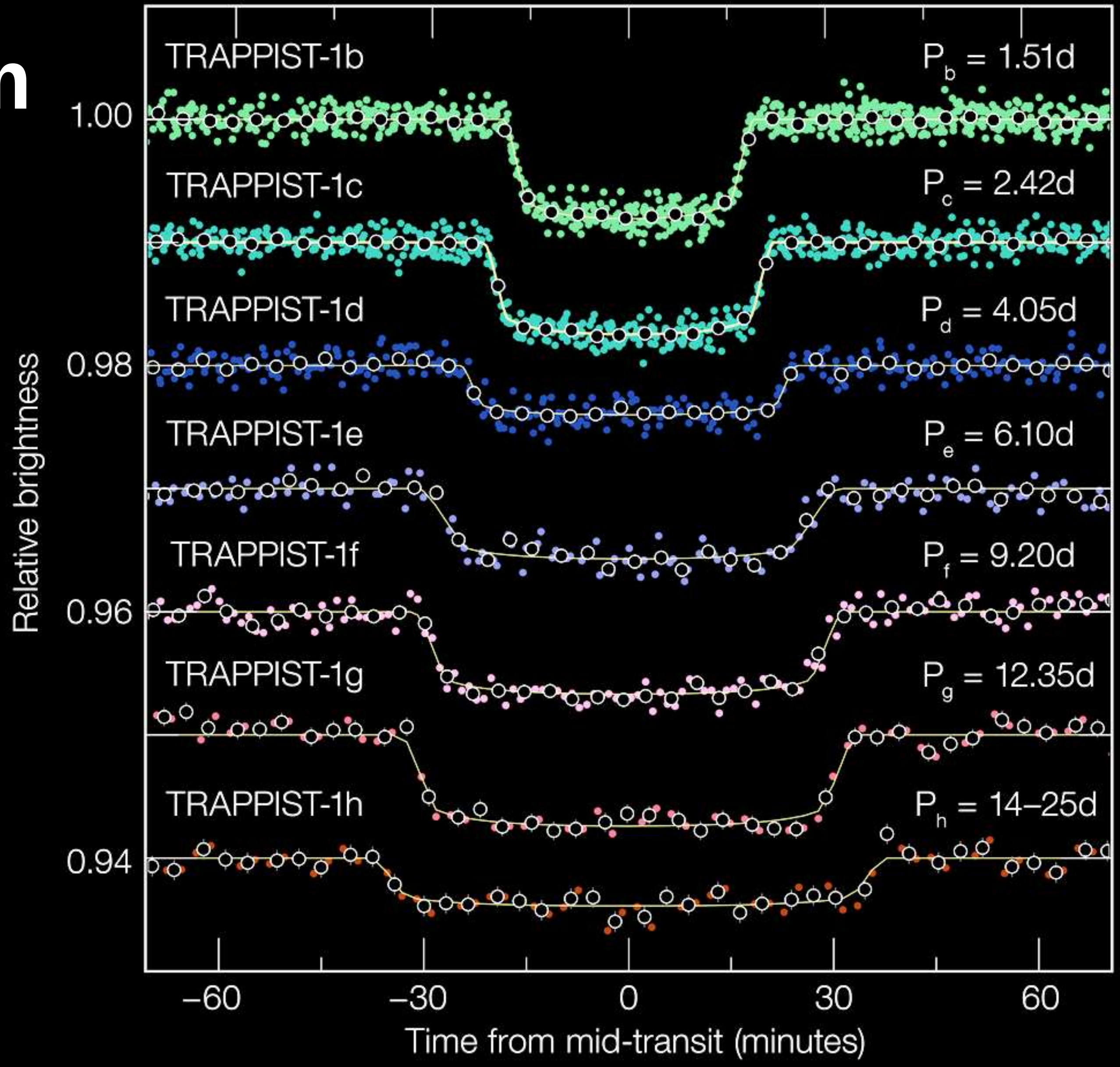
Now, time to sit back and use your imagination.

One of the most remarkable systems recently discovered using the transit method is TRAPPIST-1, only 40 ly away.



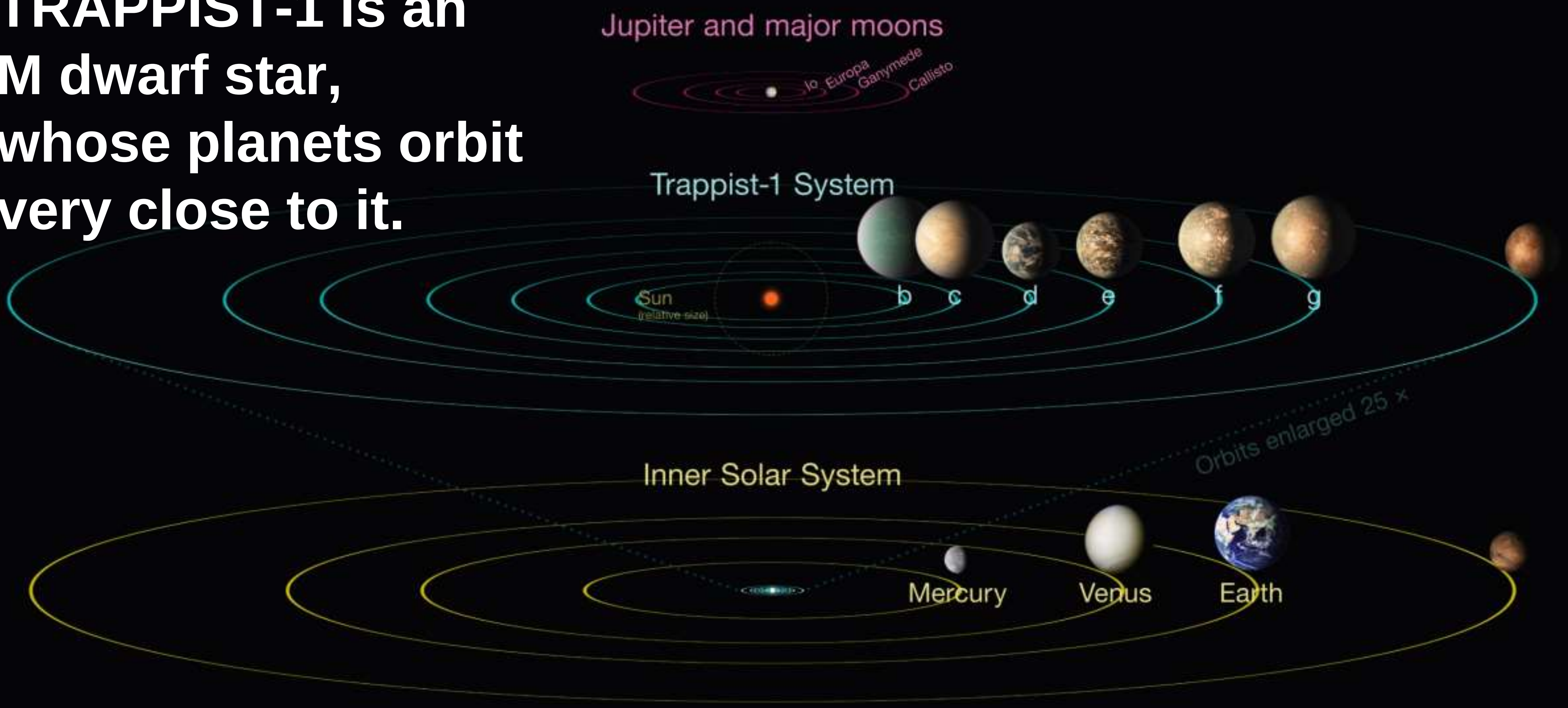
Credit: ESO/L. Calçada/spaceengine.org

The TRAPPIST-1 system has 7 known planets.



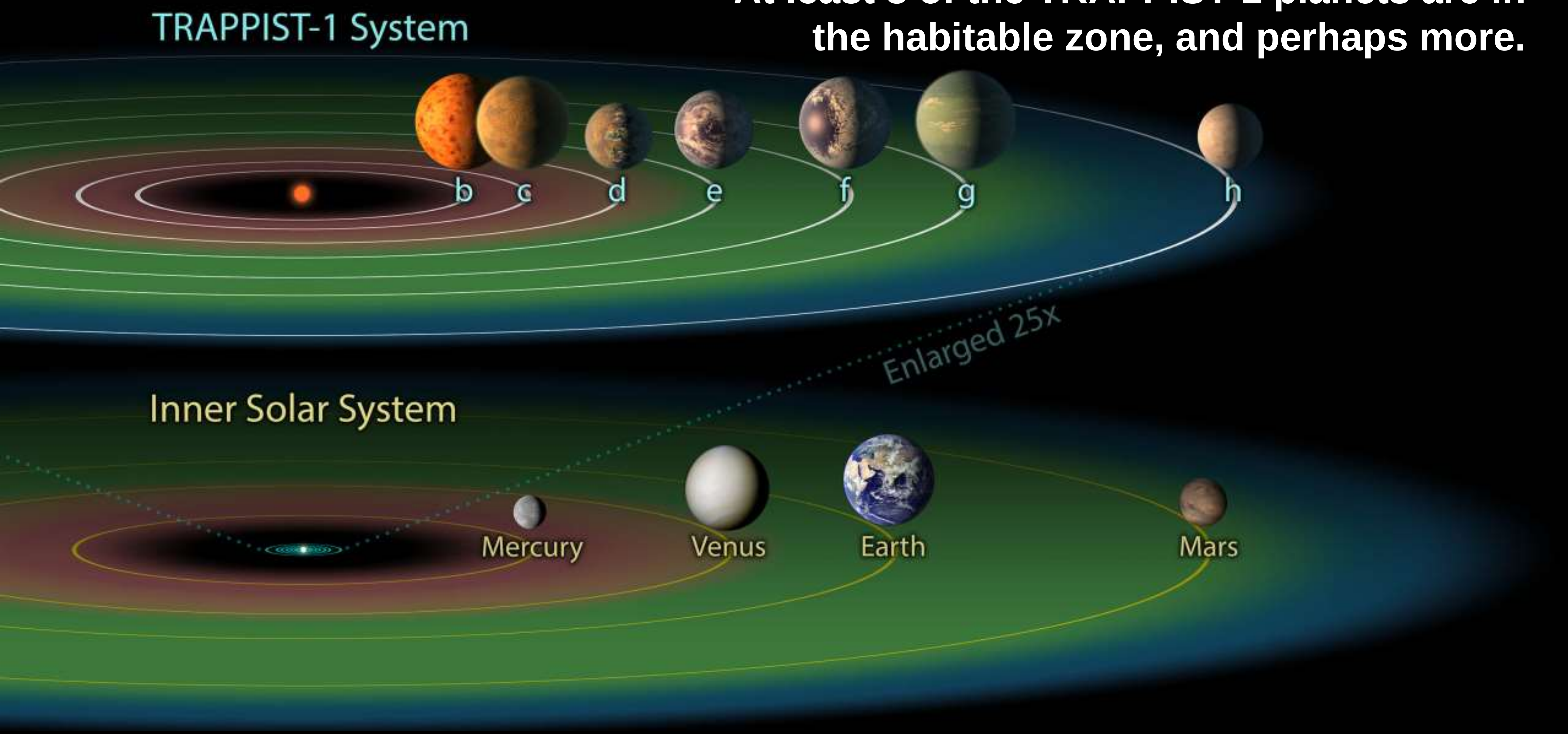
Credit: ESO/M. Gillon et al.

TRAPPIST-1 is an M dwarf star, whose planets orbit very close to it.



Credit: NASA/JPL-Caltech

At least 3 of the TRAPPIST-1 planets are in the habitable zone, and perhaps more.



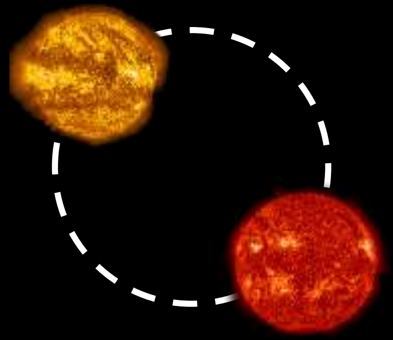
Credit: NASA/JPL

Credit: ESO/M. Kornmesser


PLANET HOP FROM
TRAPPIST-1e
VOTED BEST "HAB ZONE" VACATION

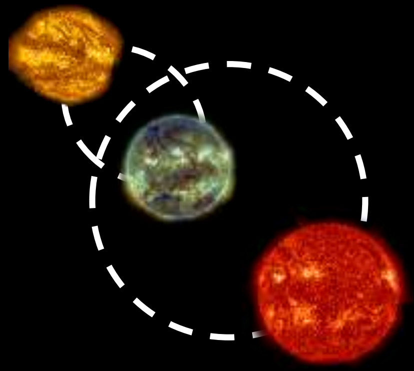
56%

of stars systems are single stars



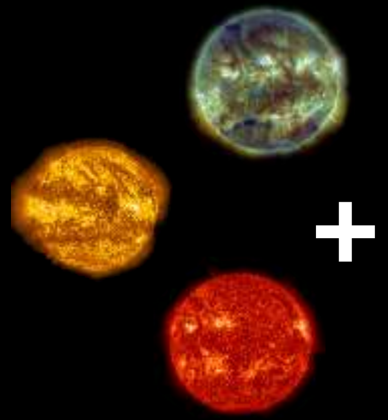
33%

of stars systems are binary stars



8%

of stars systems are trinary stars

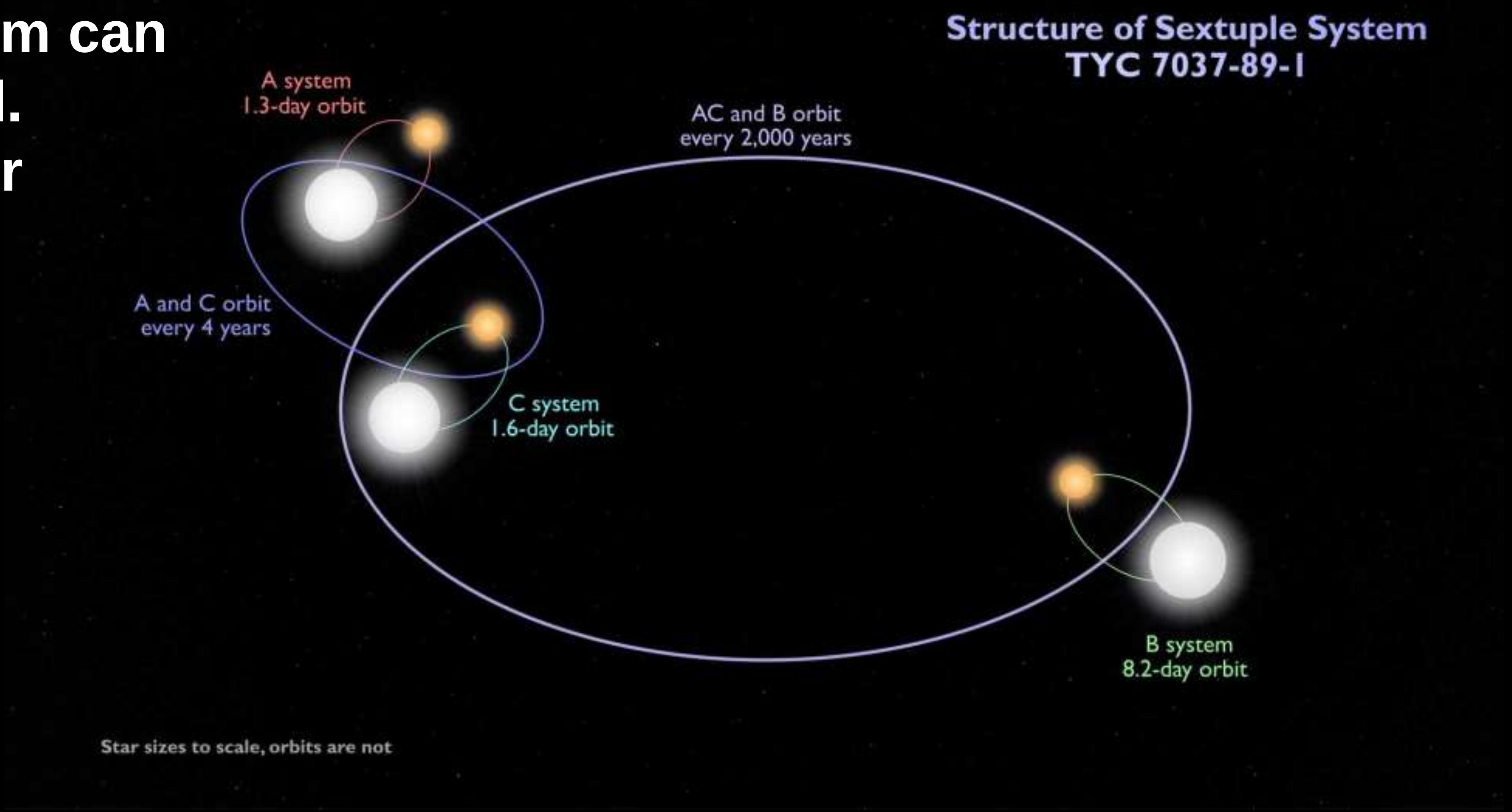


3%

of stars systems are higher-order multiples

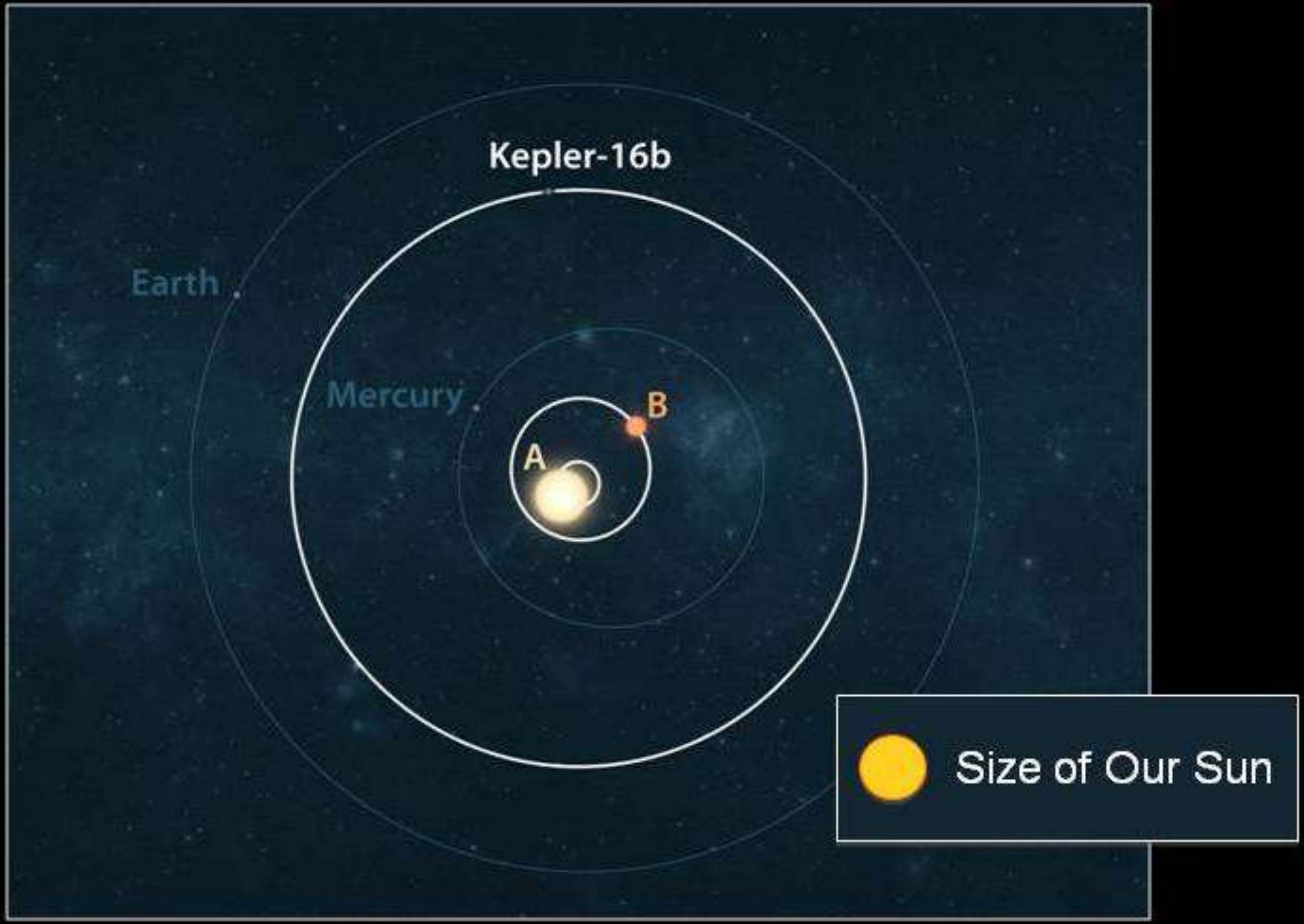
Source: Raghavan et al., ApJS, 2010

The orbits of stars in a multiple system can get complicated. What about their planets?

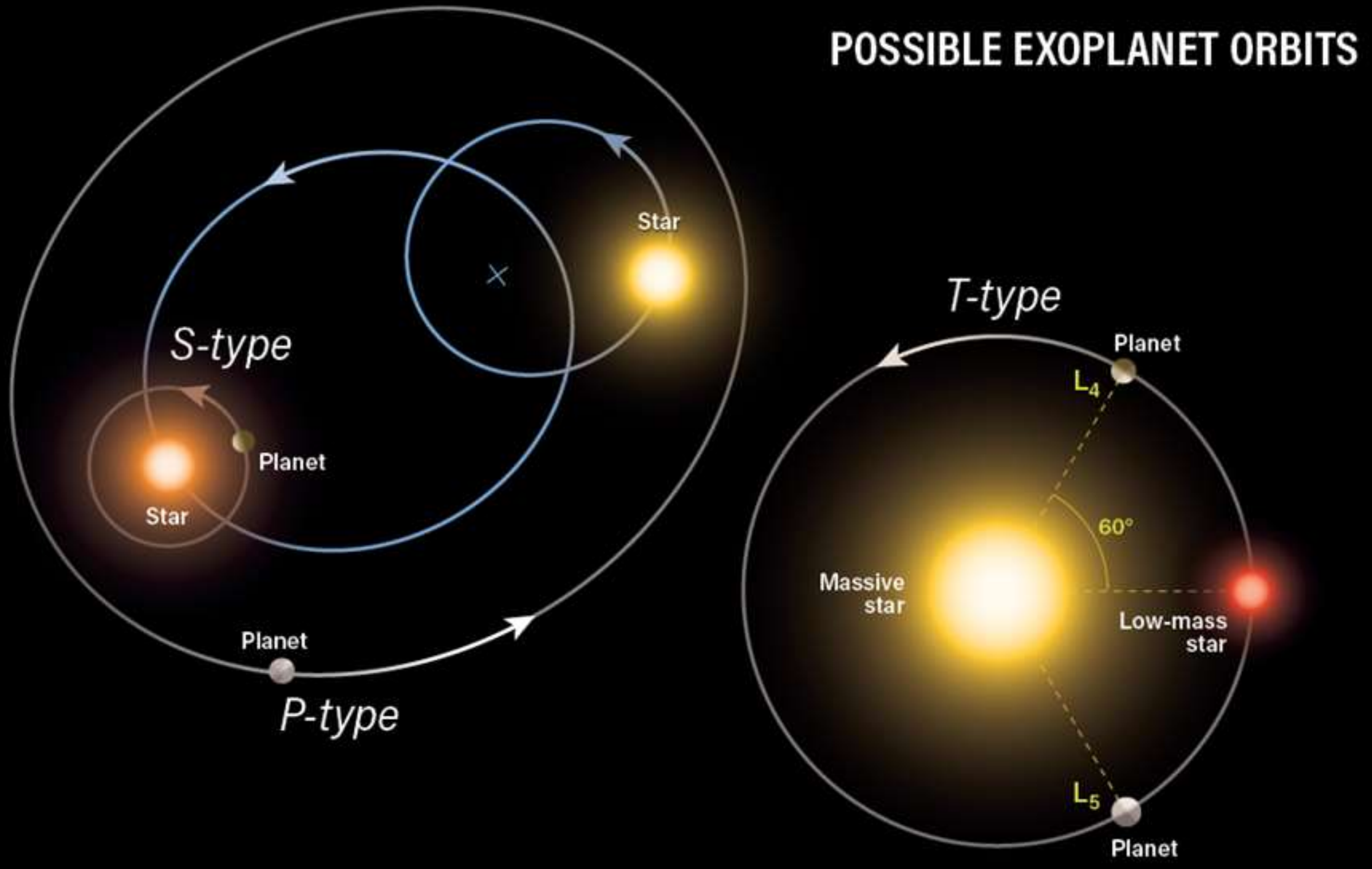


Credit: NASA's Goddard Space Flight Center

Kepler-16b is a circumbinary planet, meaning that it orbits a pair of stars.

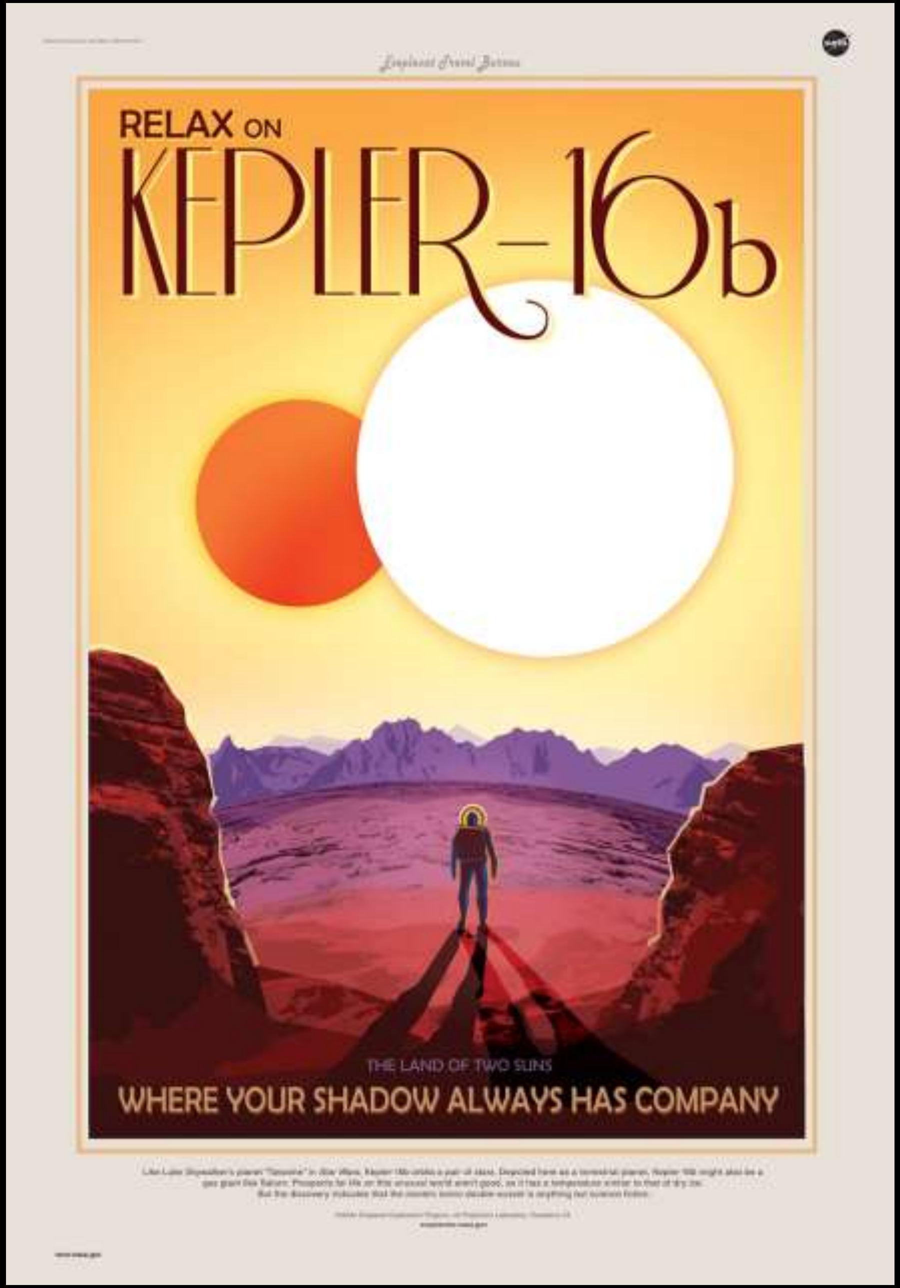


Credit: NASA/JPL-Caltech

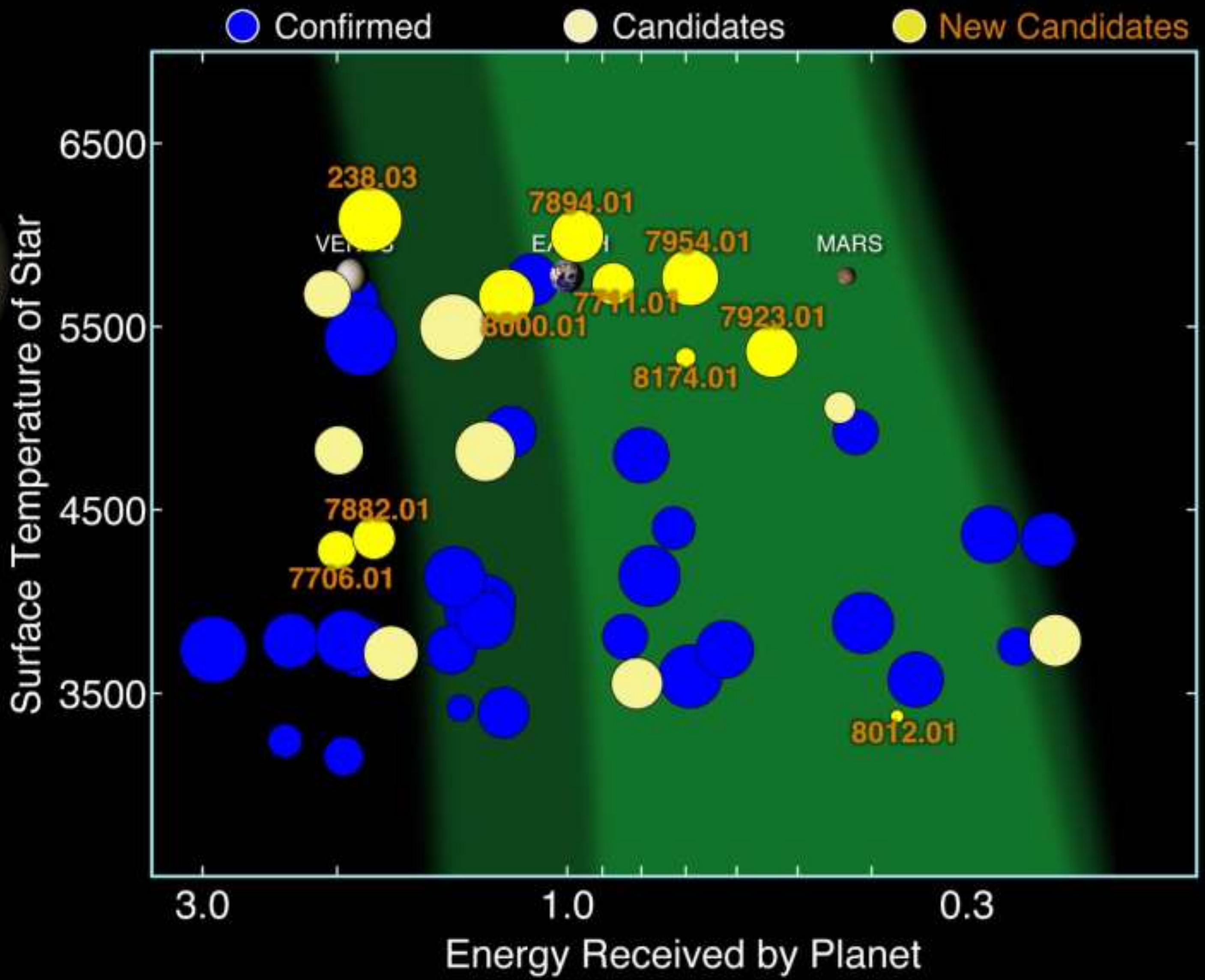


Credit: Astronomy magazine, Roen Kelly

Orbiting in a multiple-star system could pose challenges to planetary habitability. This would depend strongly on how close the planet orbits to the stars.



So far, dozens of Earth-size transiting exoplanets have been found in or near the habitable zone of their parent stars.



Credit: NASA/Kepler

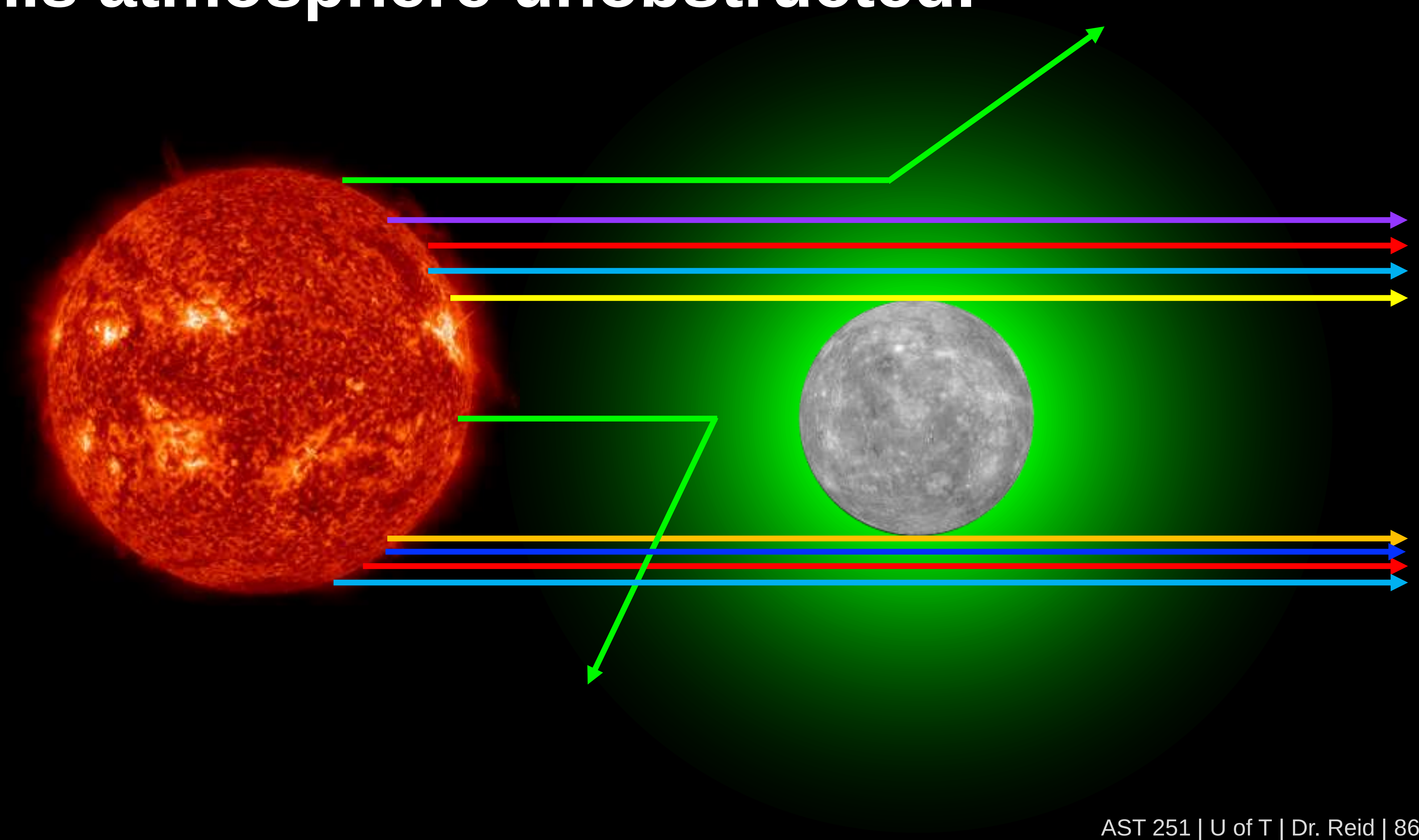
As we have discussed, the habitability of a planet depends crucially on its atmosphere.

What can we say about the atmospheres of exoplanets?

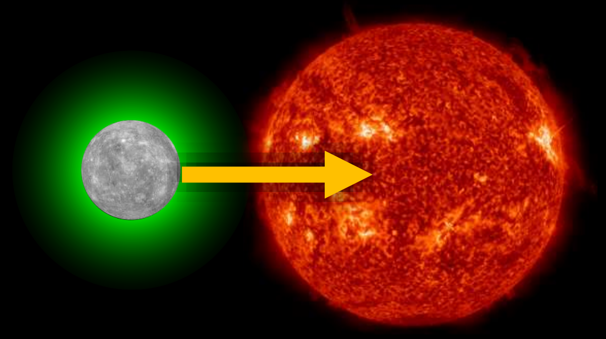
Using the method of transit spectroscopy, it is sometimes possible to measure the chemical composition of exoplanet’s atmosphere.

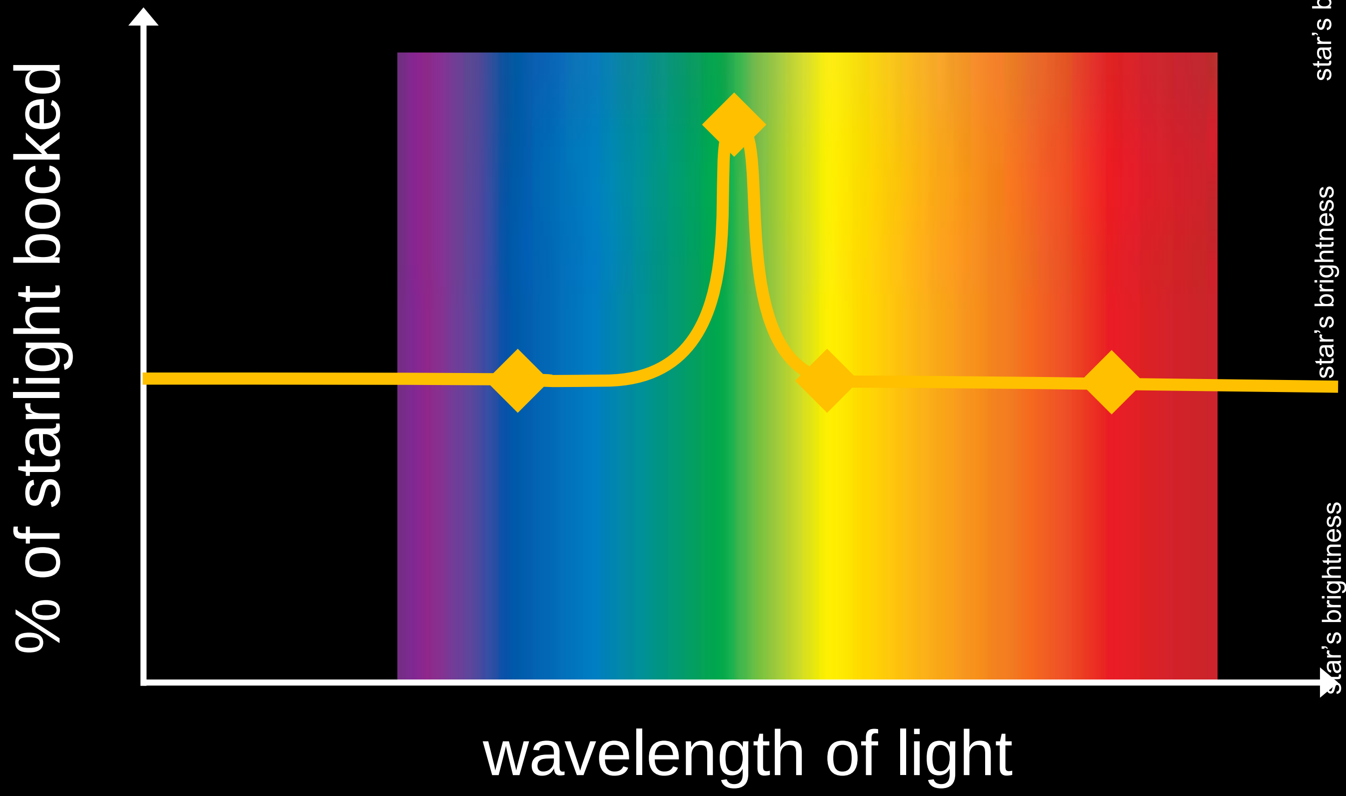
Imagine a planet with a very simple atmosphere, consisting of single type of atom that only absorbs or emits a single colour of green light.

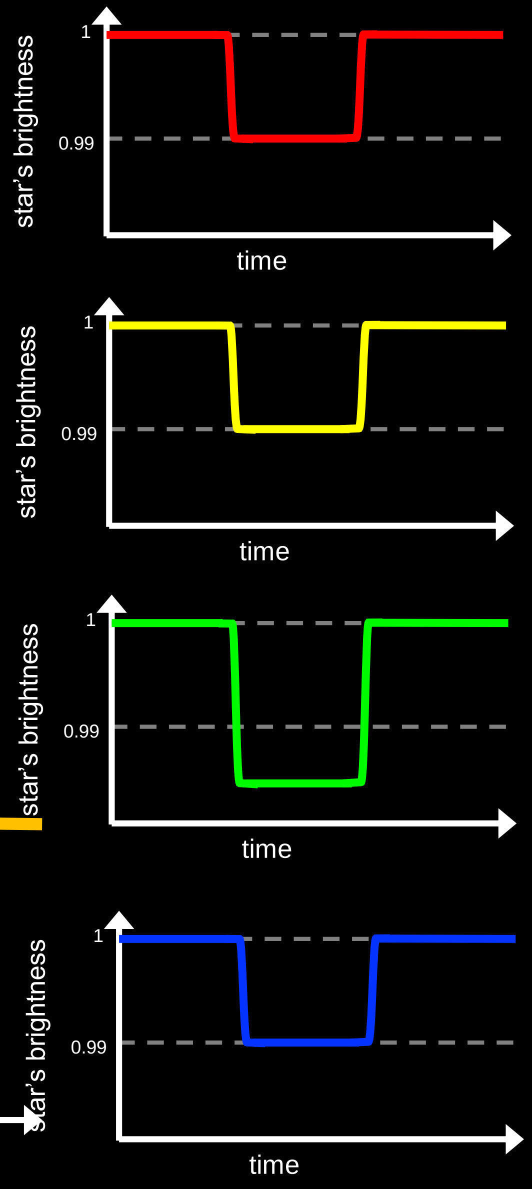
Light of colours other than green will pass through this atmosphere unobstructed.



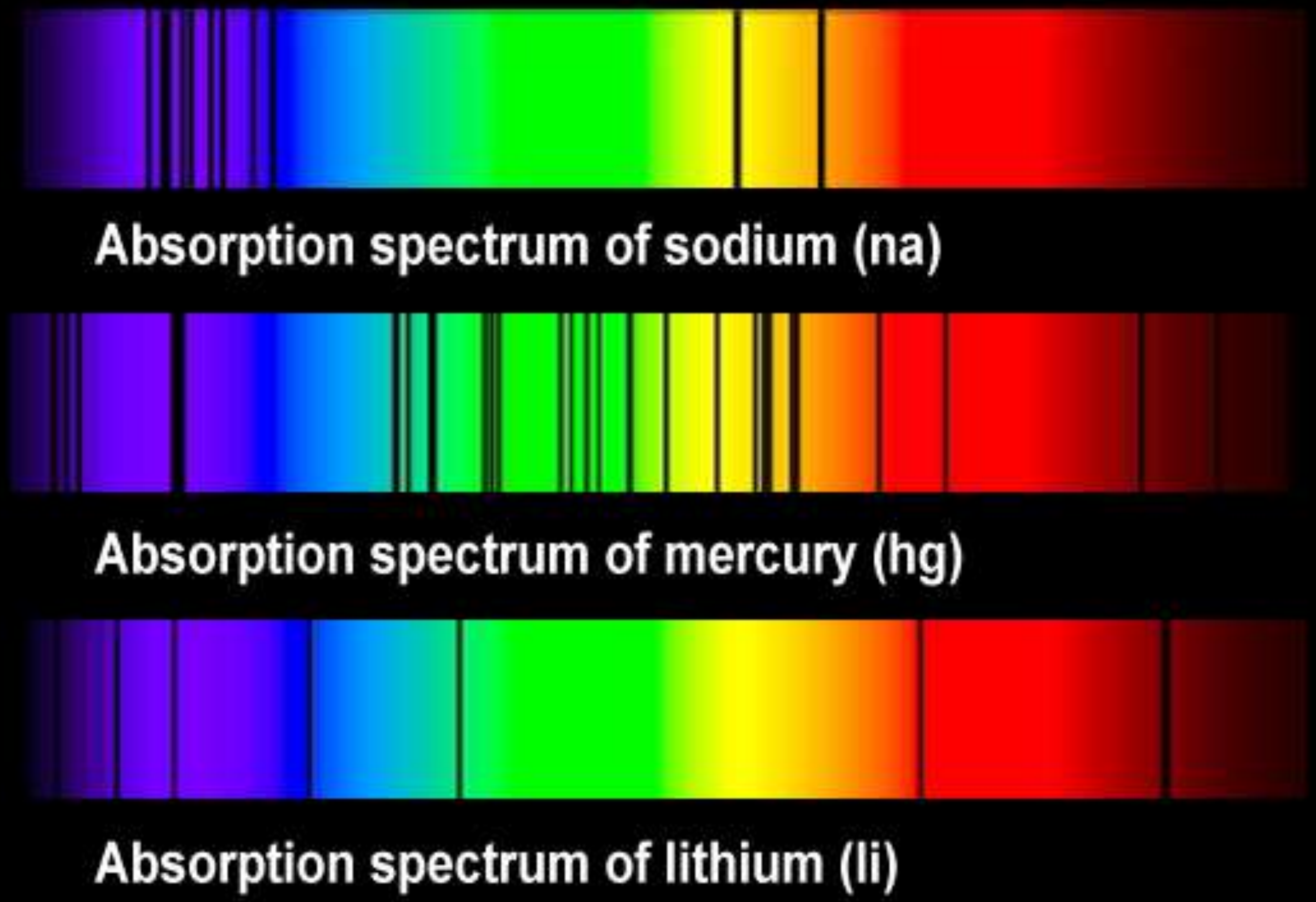
Because the atmosphere blocks green light, the transit will be slightly deeper in green light than in other colours.





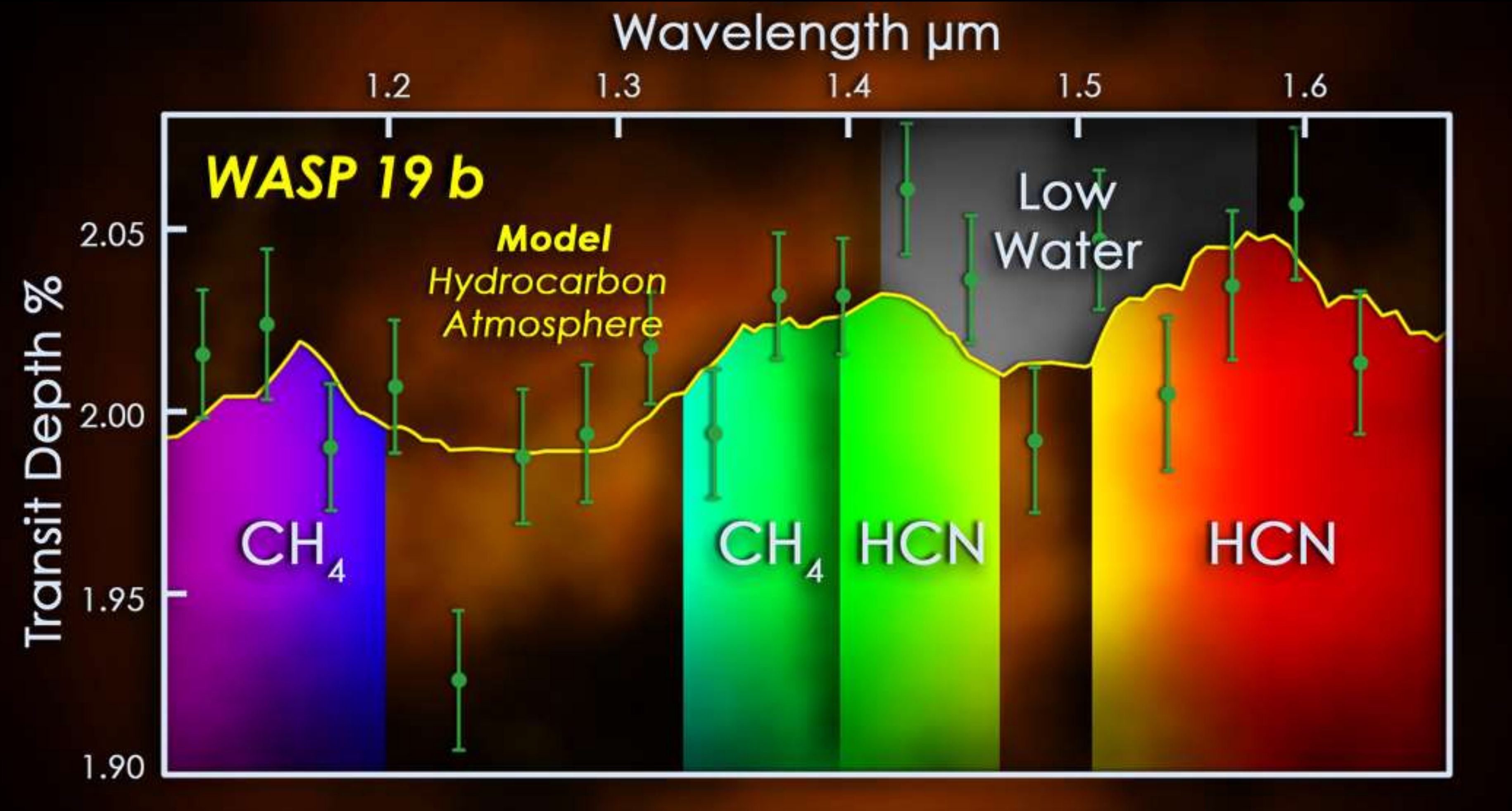


A real planetary atmosphere contains many chemicals, each of which selectively absorbs differing amounts of different colours of light.



Credit: astronoo.com

By measuring the depth of the transit at many different wavelengths, we can construct a coarse spectrum of the planet's atmosphere.



Credit: NASA's Goddard Space Flight Center, Additional animations courtesy ESA/Hubble

Summary

- The transit method has found thousands of exoplanets
- Many of these planets are of unfamiliar types
- Of these, dozens are potentially habitable
- We are beginning to be able to characterize the atmospheres of these planets

Just for Fun

To explore the surfaces of some of these exciting worlds, go to:

https://exoplanets.nasa.gov/alien-worlds/exoplanet-travel-bureau/

Try this out!

https://exoplanets.nasa.gov/eyes-on-exoplanets/