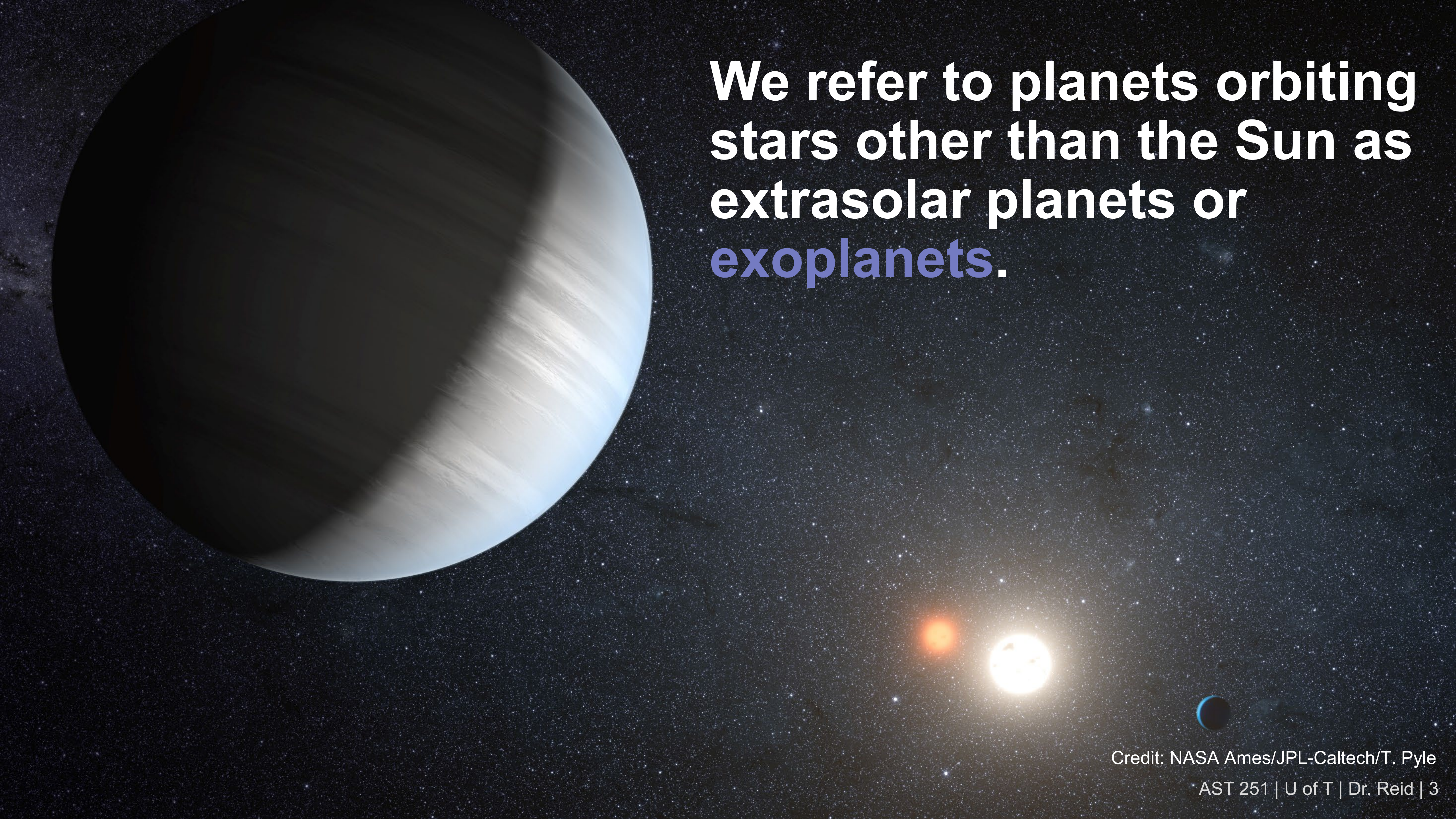
Searching for Habitable Planets

We are going to begin in other solar systems and develop a sense of the range of possible planet types, then return to our own solar system to examine individual planets up close.

We refer to planets orbiting stars other than the Sun as extrasolar planets or **exoplanets**.

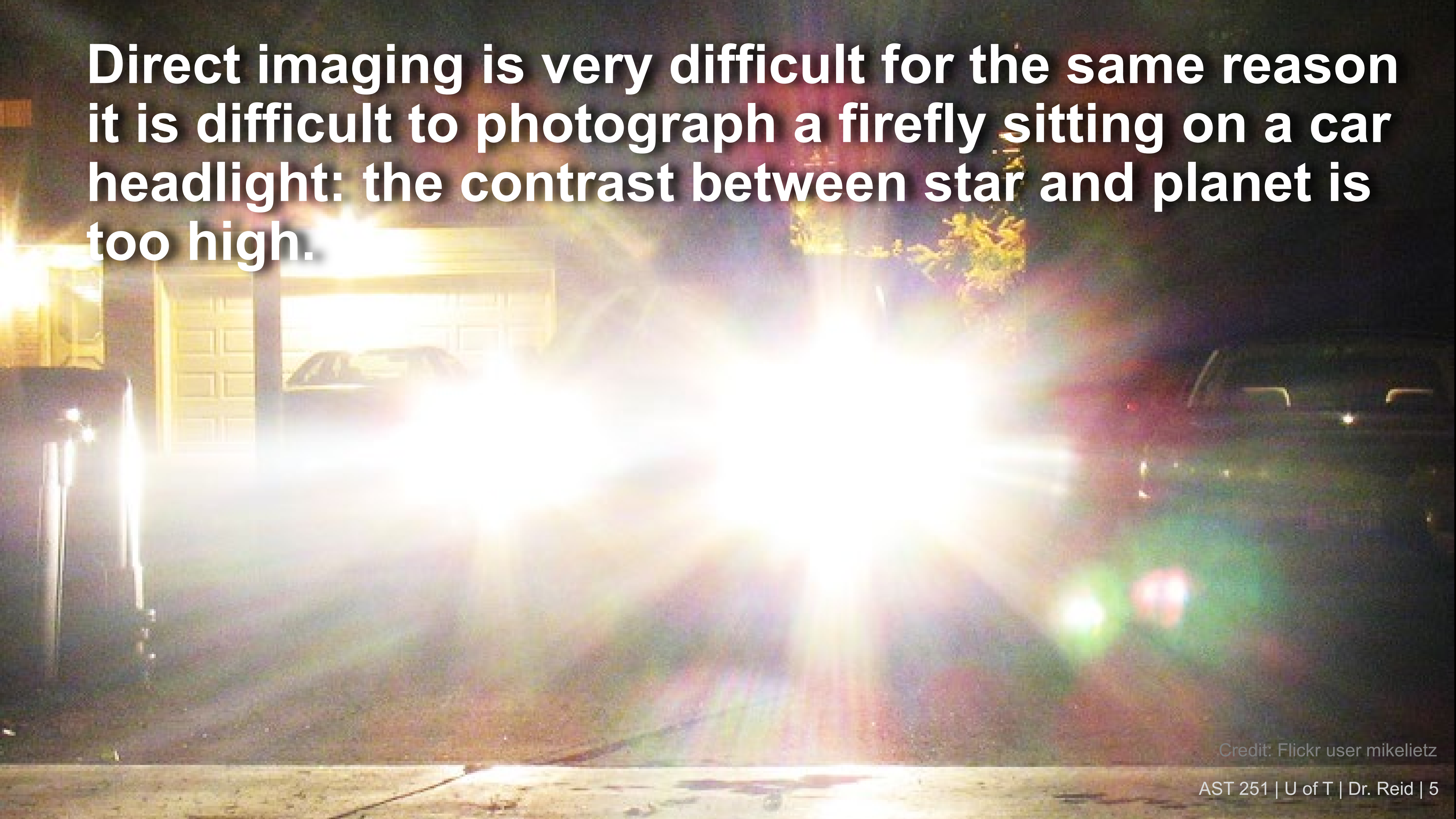


Credit: NASA Ames/JPL-Caltech/T. Pyle

The most obvious way to find an exoplanet is simply to photograph another star and examine the image for orbiting planets.

This technique is known as direct imaging.

Direct imaging is very difficult for the same reason it is difficult to photograph a firefly sitting on a car headlight: the contrast between star and planet is too high.

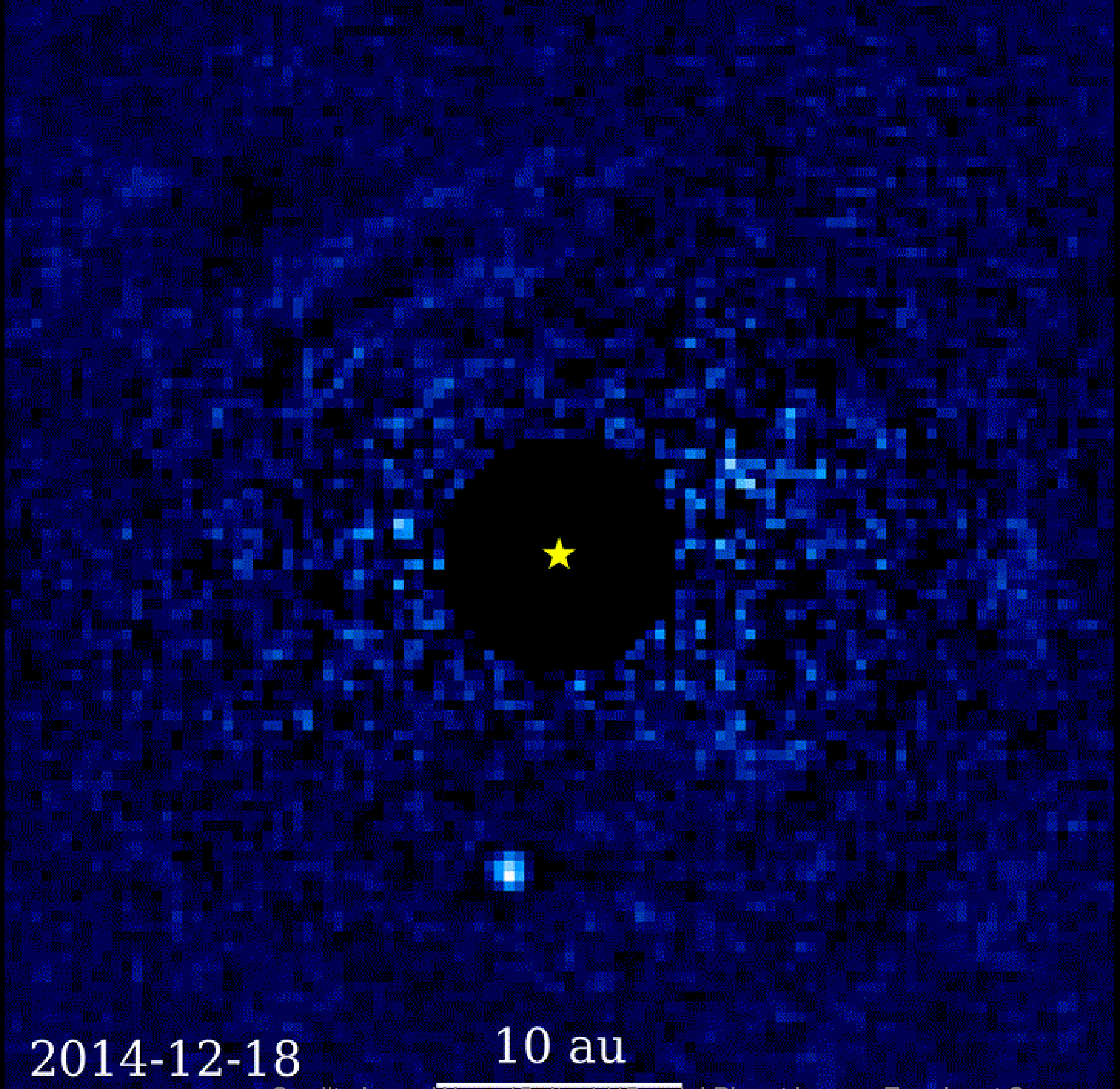


Credit: Flickr user mikelietz

Young, giant planets orbiting the star HR 8799.

This is typical of the level of detail we can see with direct imaging

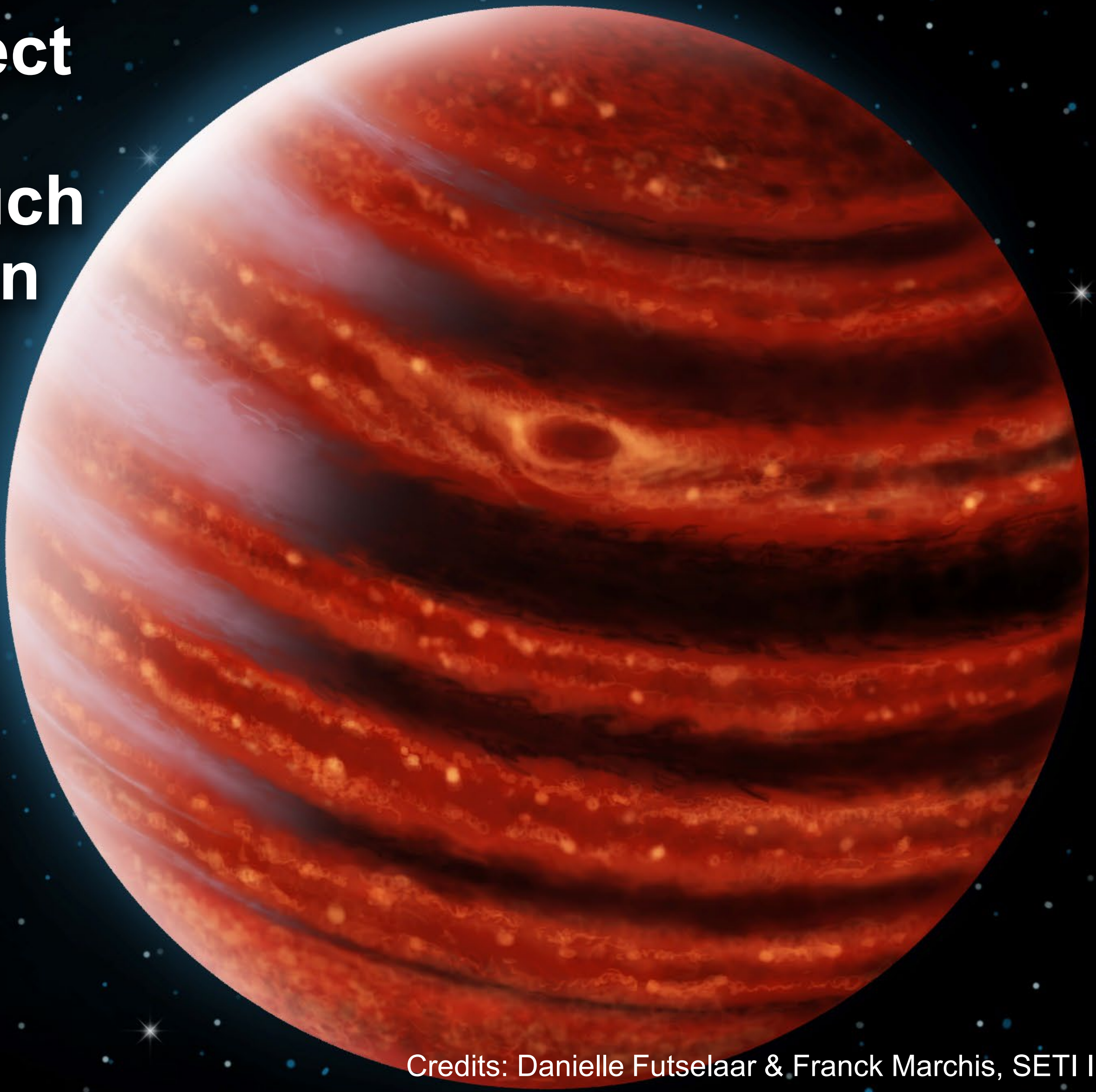
So far, direct imaging has detected only around 150 exoplanets.



Credit: Jason Wang (Caltech)/Gemini Planet Imager Exoplanet Survey

The planets we can currently detect using direct imaging are mostly young Jovian planets orbiting much farther from their parent stars than Jupiter orbits the Sun.

They are not likely homes for life.



Credits: Danielle Futselaar & Franck Marchis, SETI Institute

Direct imaging is the only method in which exoplanets are actually *seen*.

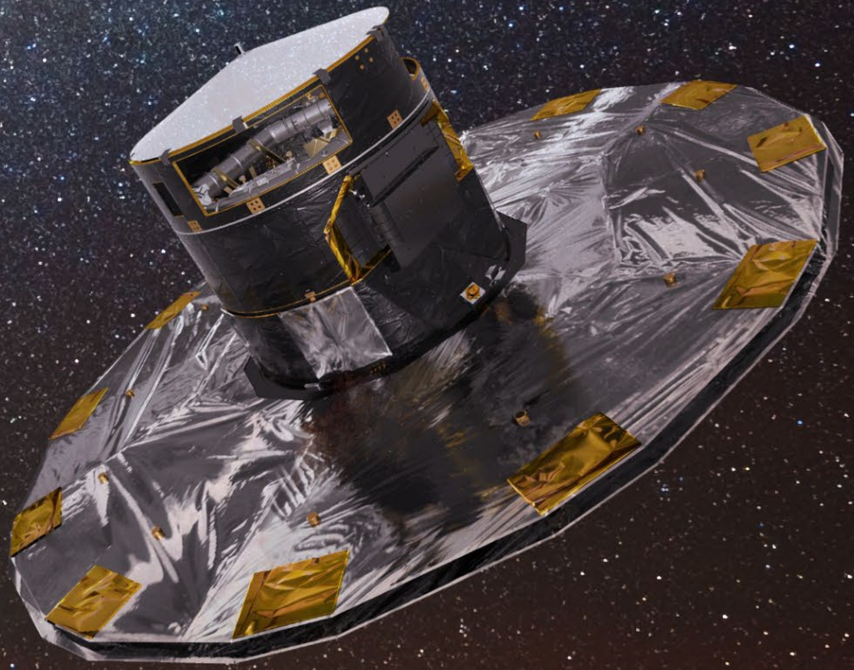
All of the other methods are in direct, meaning that the existence and properties of the planets are deduced from observations of the host star.

The **astrometric method** finds exoplanets by observing the motions of their ho ets

Credit: NASA

The astrometric method has only found a few exoplanets because the precision of the required measurements is beyond the capability of most telescopes.

However, the GAIA spacecraft is expected to discover around 10,000 exoplanets using the astrometric method within the next few years.

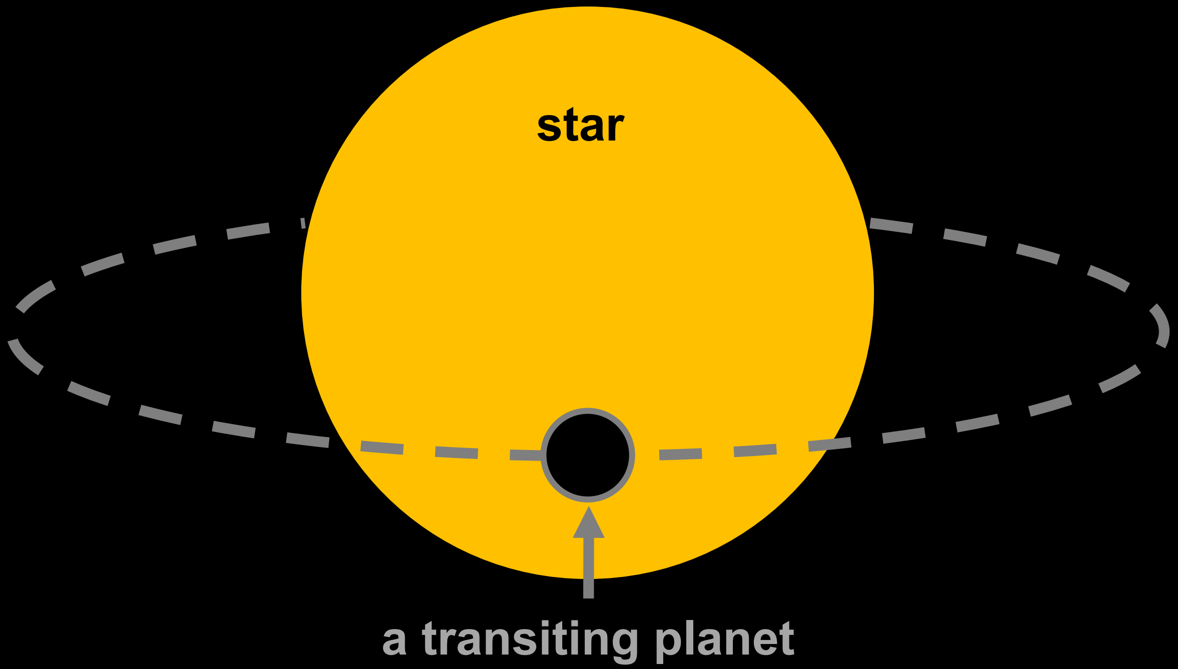


Credit: ESA/ATG medialab; background image: ESO/S. Brunier

There are several other detection methods, but overwhelmingly the two most successful ones have been the transit method and the radial velocity method.

We will start with the transit method and later combine it with the radial velocity method.

A transit occurs when one astronomical object passes in front of another from our point of view.



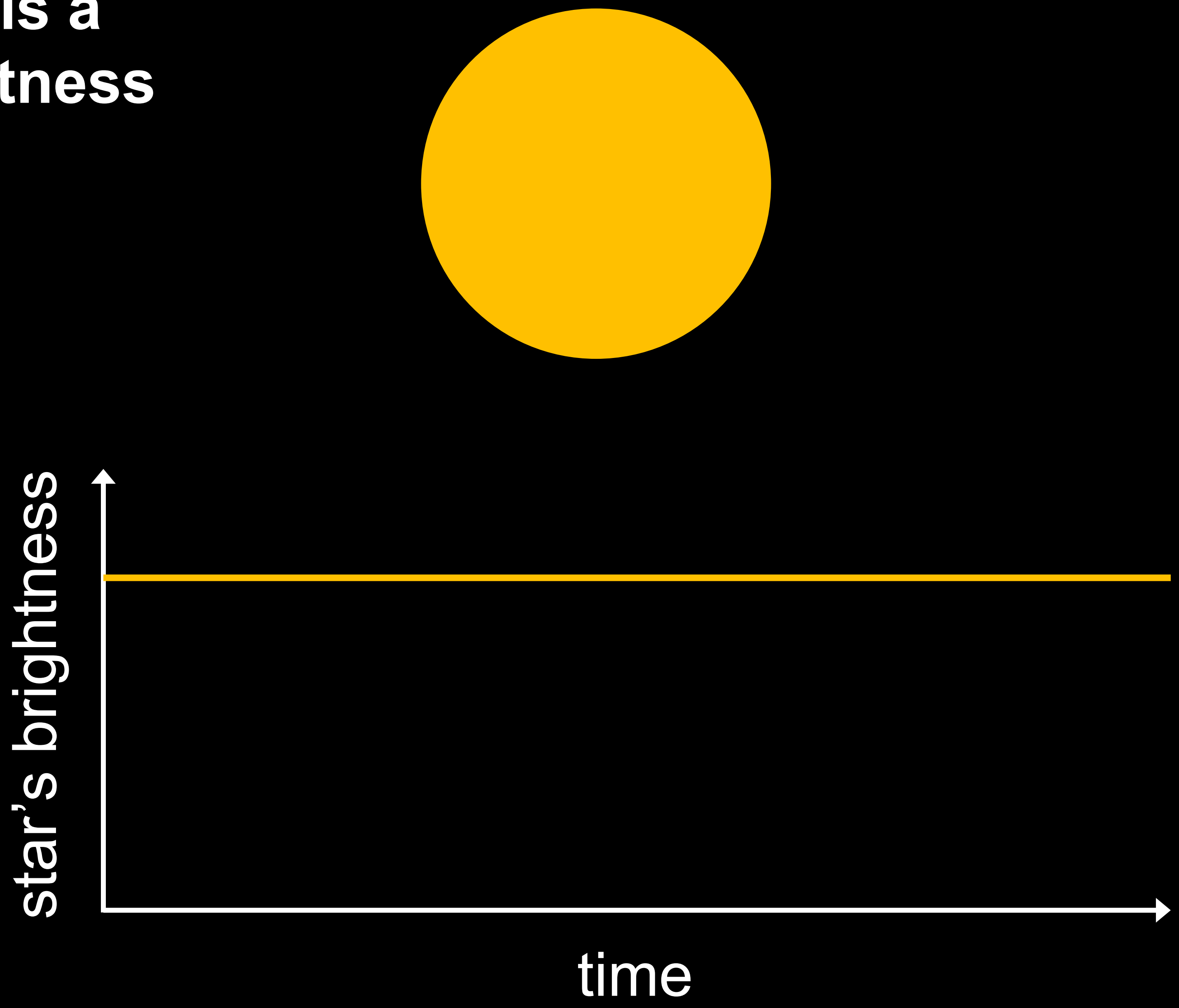
A transit of the Moon across the Sun, as seen by the STEREO spacecraft

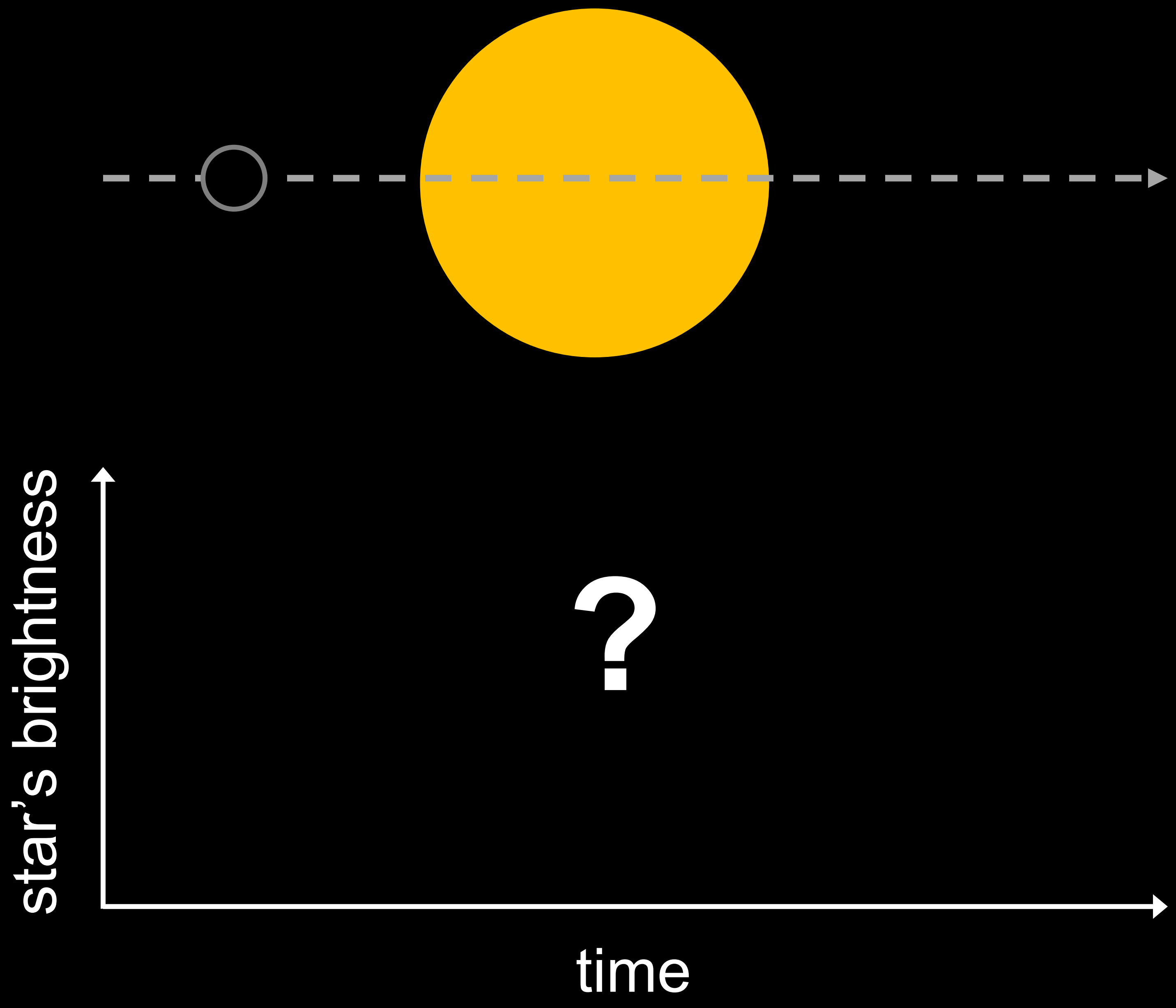
Credit: NASA/STEREO

Our current telescopes aren't powerful enough to actually *photograph* exoplanets transiting.

However, we can spot transits in a star's light curve.

The light curve of a star is a graph of the star's brightness versus time

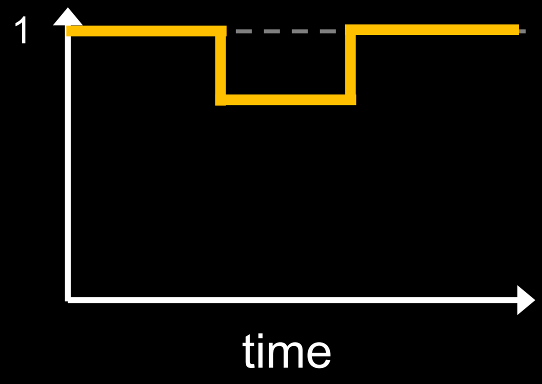



star's brightness
?
time

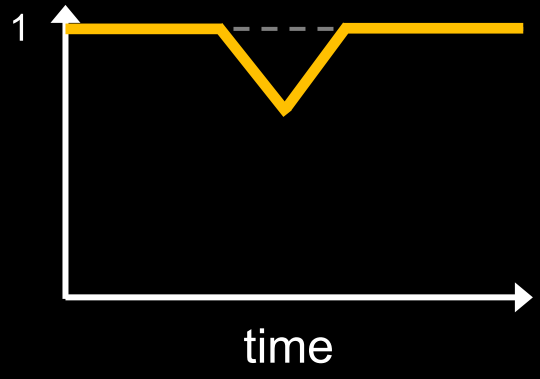
Concept Check

Which of the following would best illustrate the light curve for a planet transiting across the midplane of star?

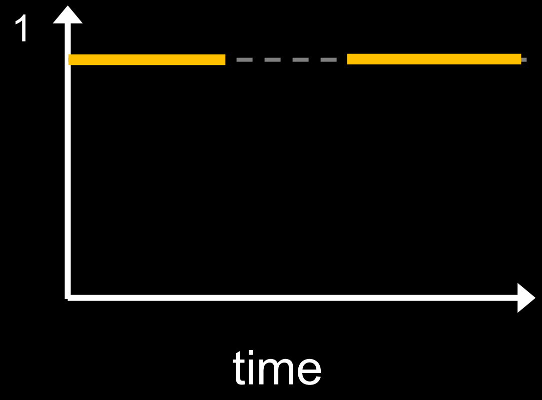
A



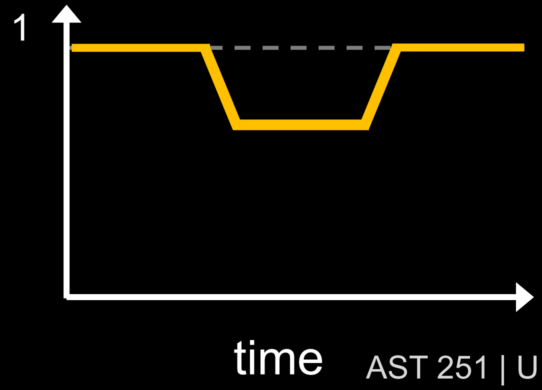
B



C



D



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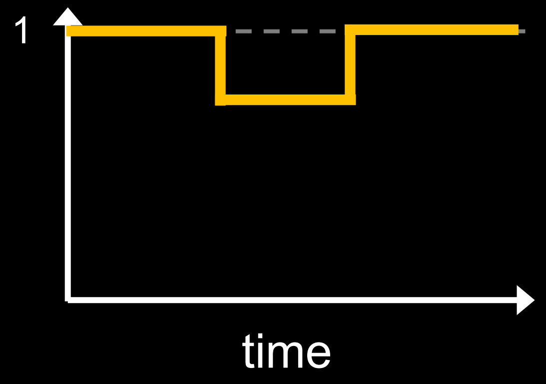

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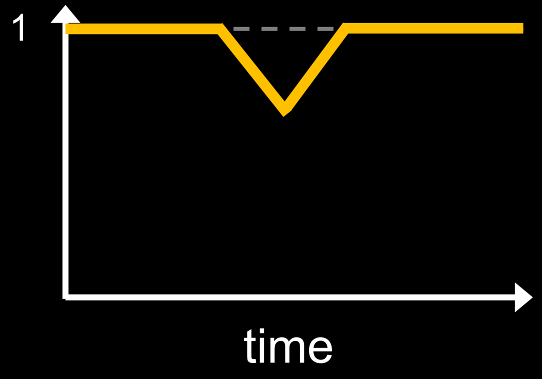

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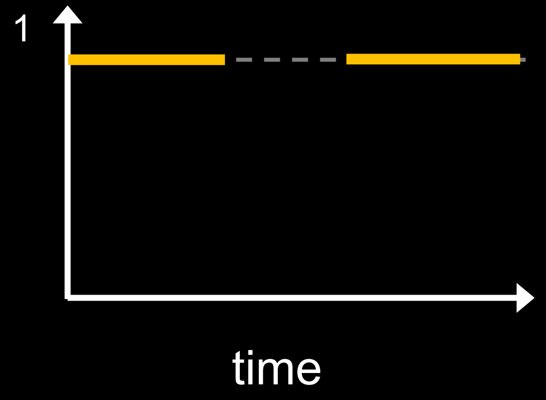
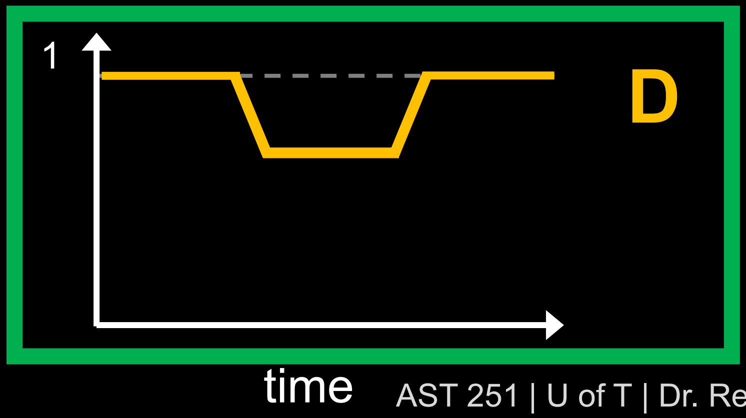
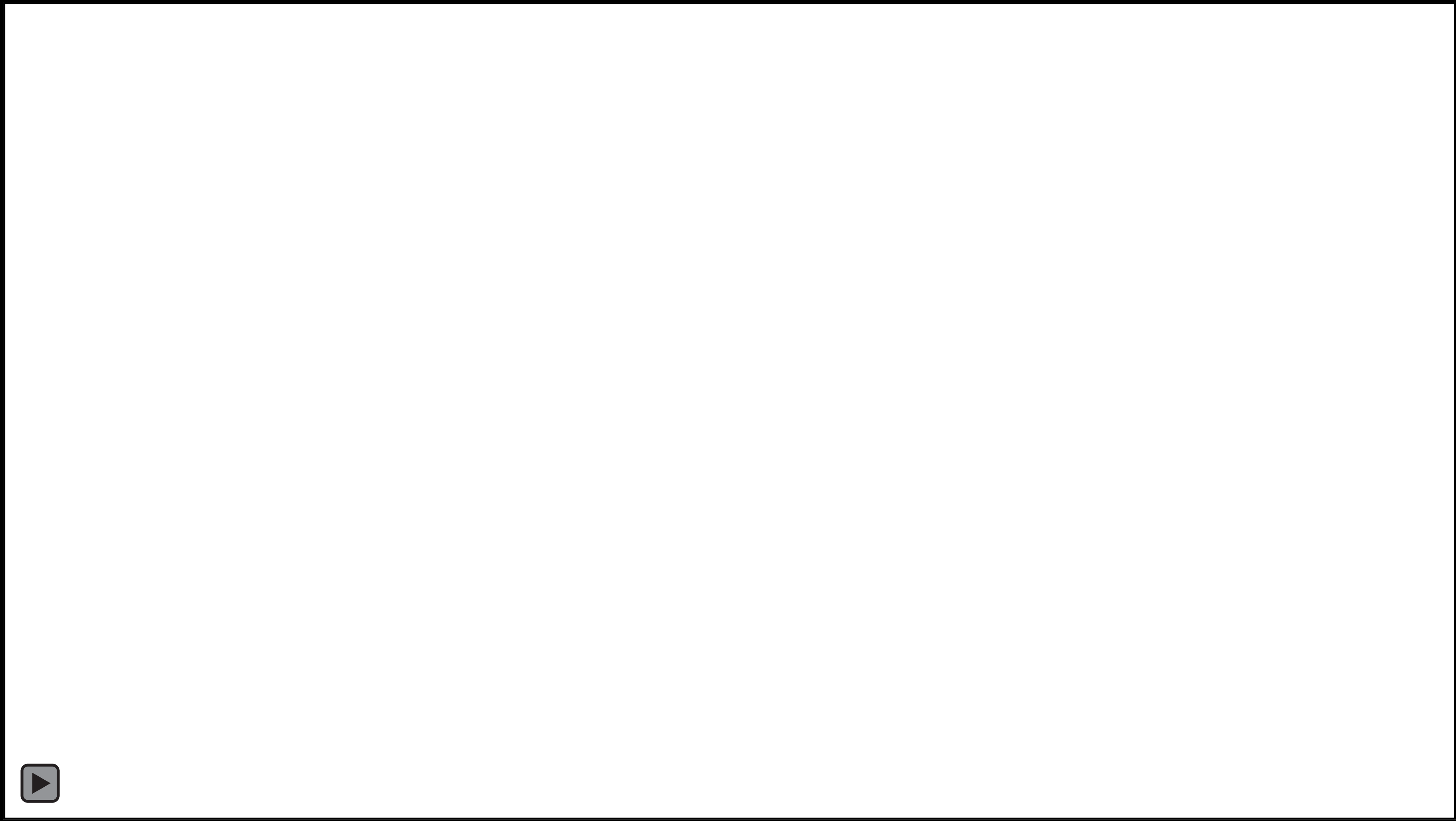
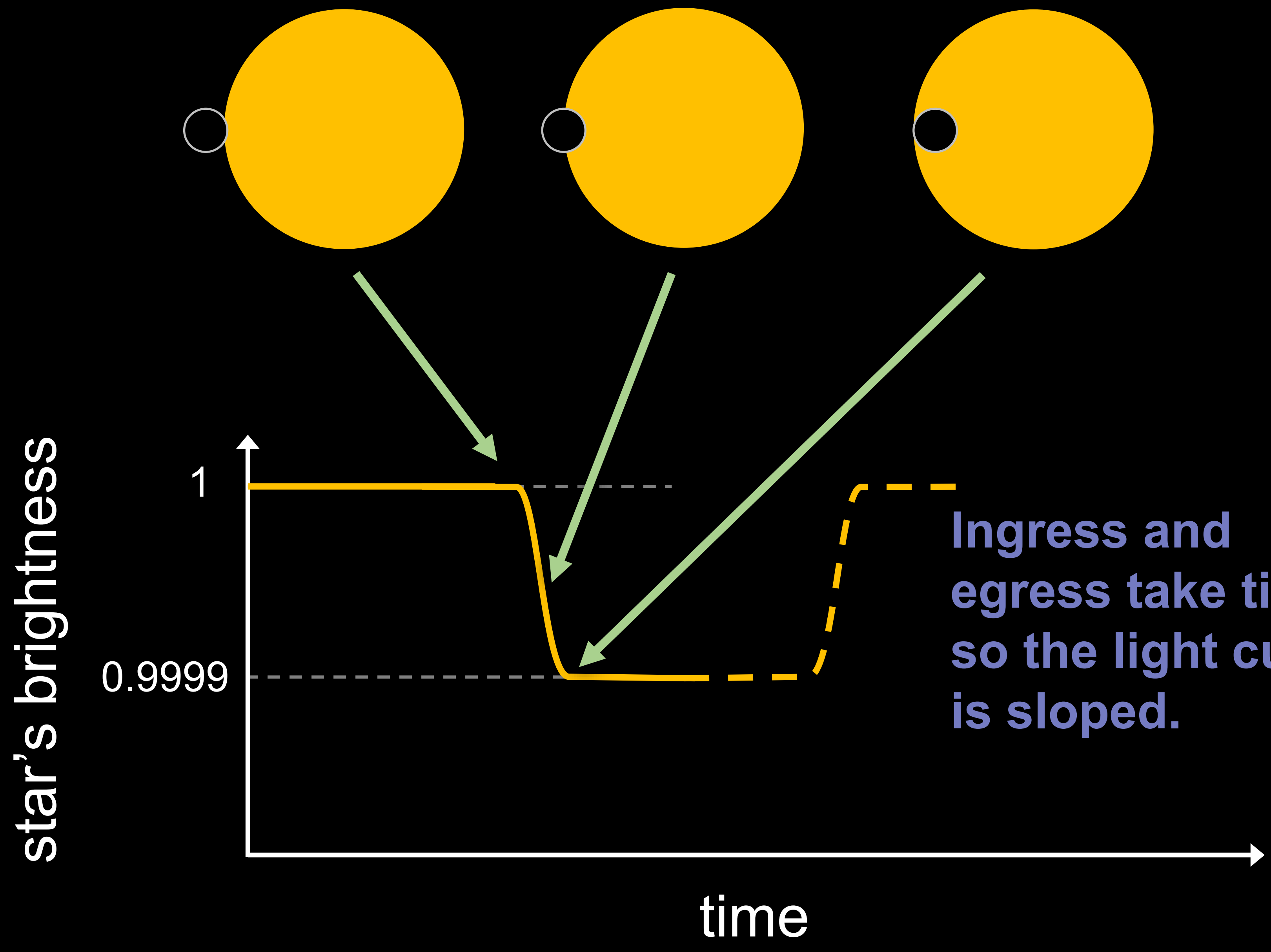


D





Credit: NASA

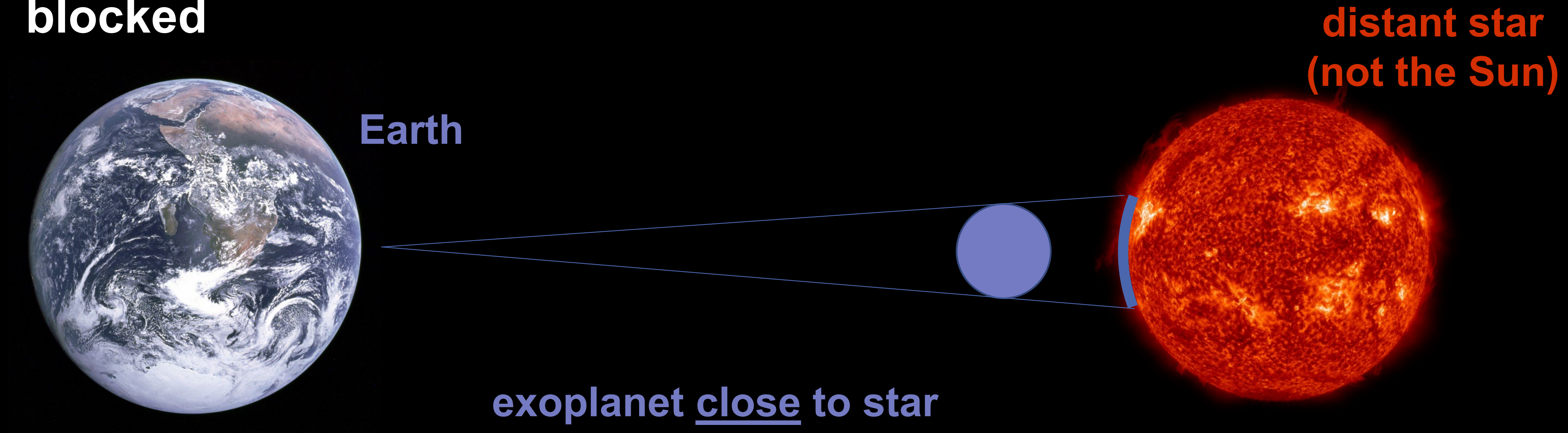


Ingress and egress take time, so the light curve is sloped.

The amount of light blocked by a planet varies with the size of the planet.

So, we can use the transit method to directly measure the size of the planet, *even without seeing the planet!*

At first, it may seem that it's the distance between the star and the exoplanet that determines how much of the star's light is blocked



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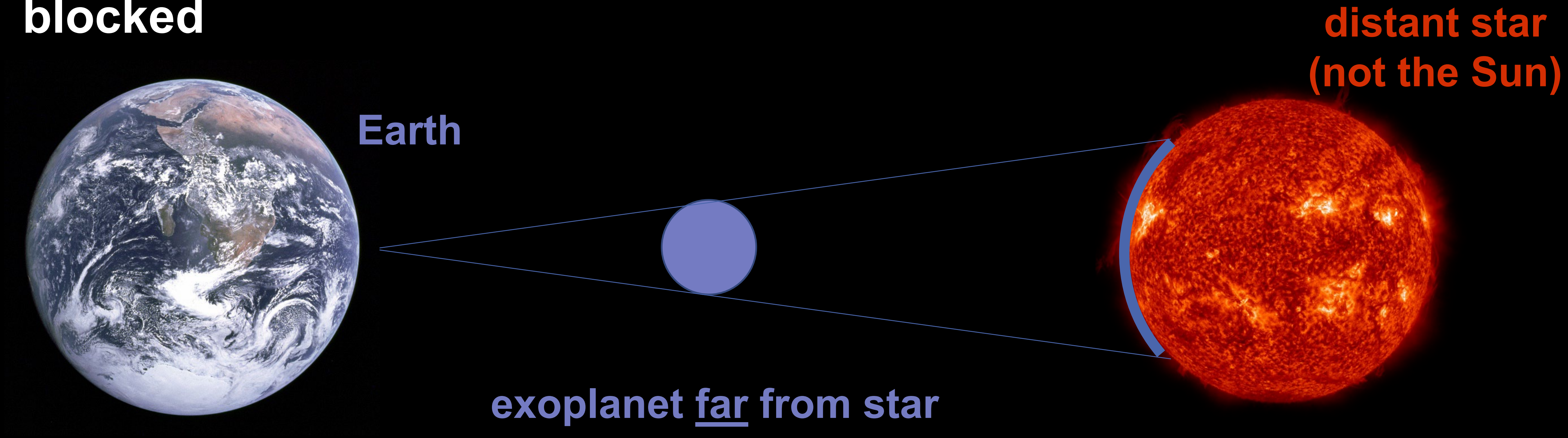
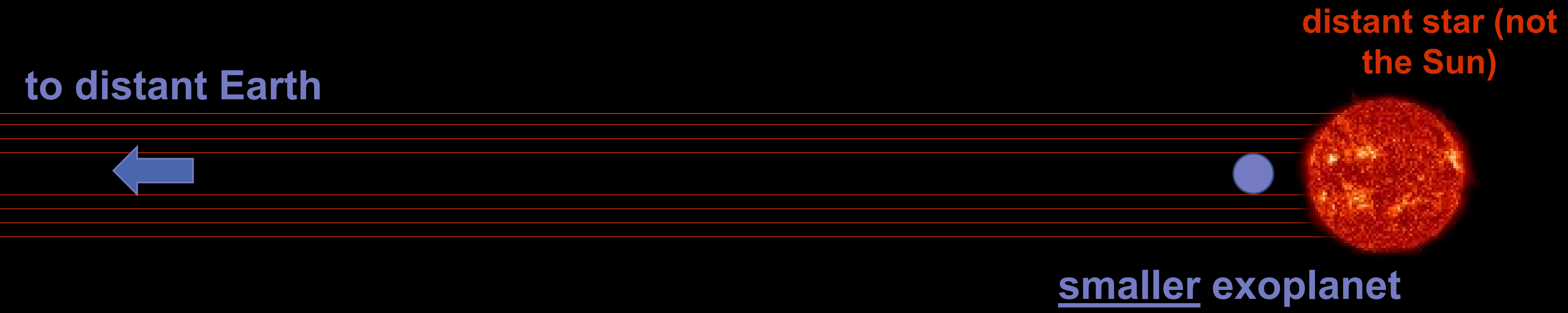


In reality, the Earth is so far away that the light rays received from the other star are almost parallel. Larger planets simply block more of them.



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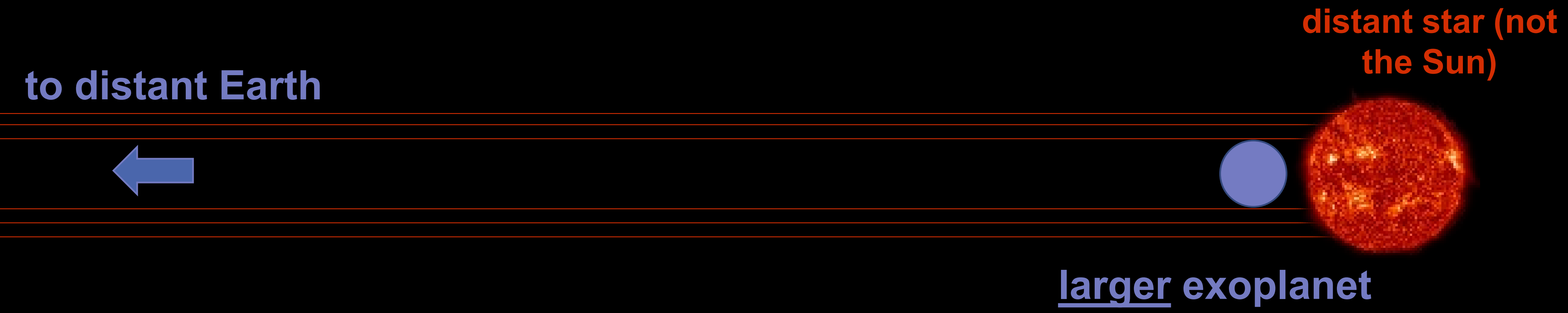
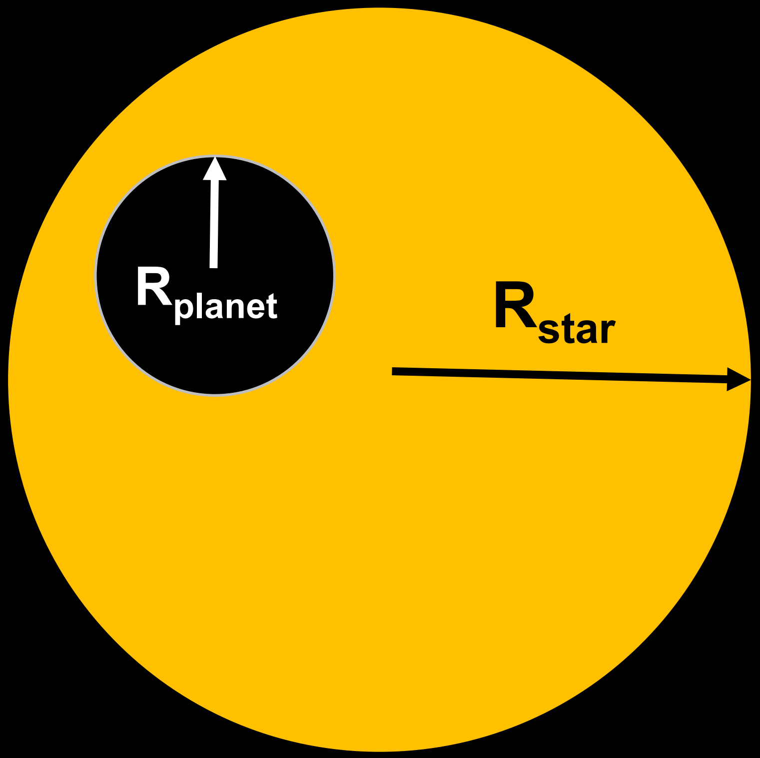
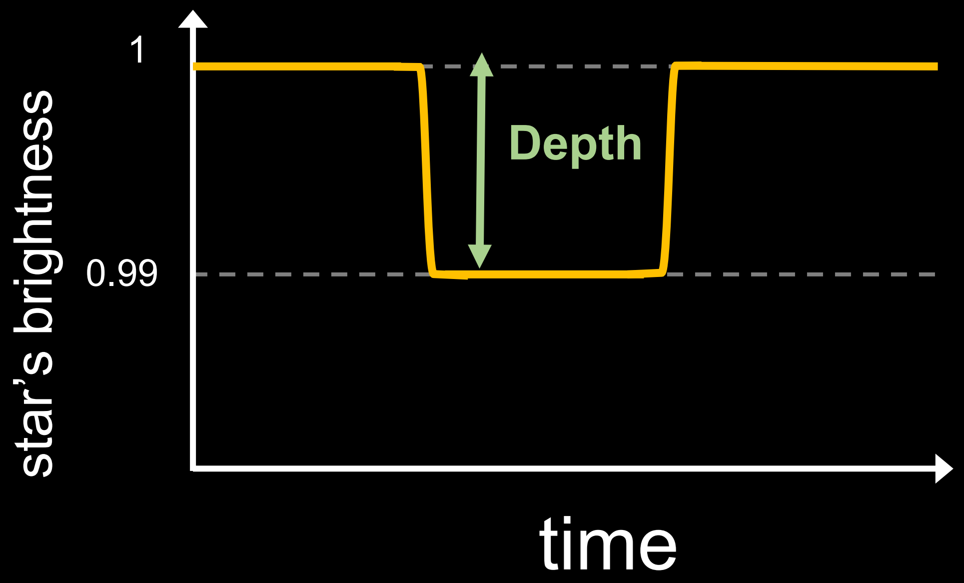
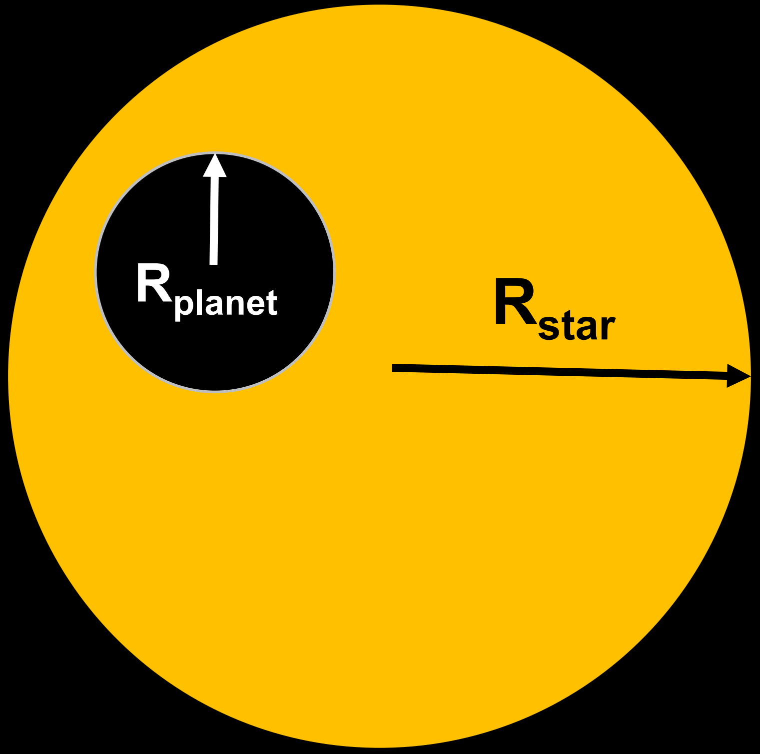
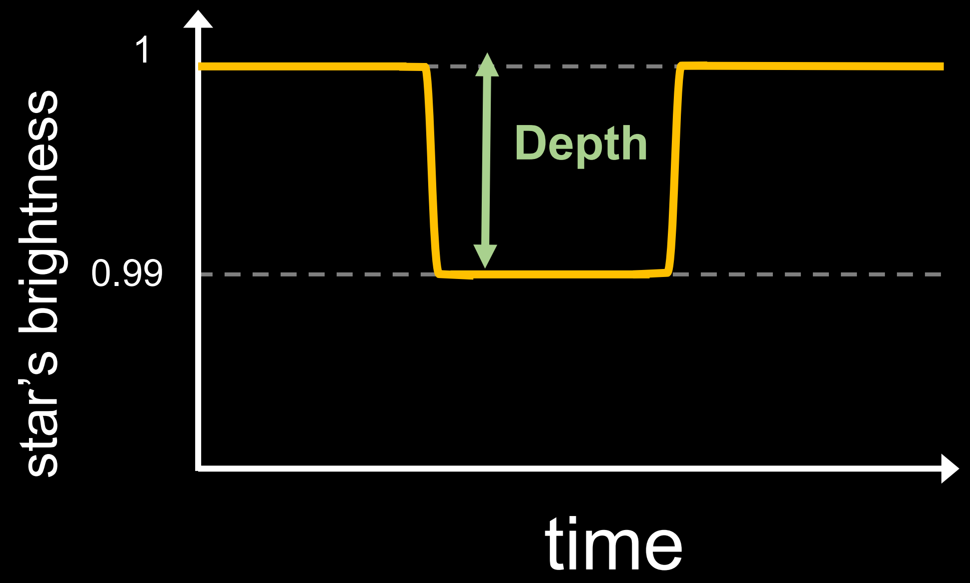






$$\textbf{Depth} = \frac{\text{cross−sectional area of planet}}{\text{cross−sectional area of star}}$$





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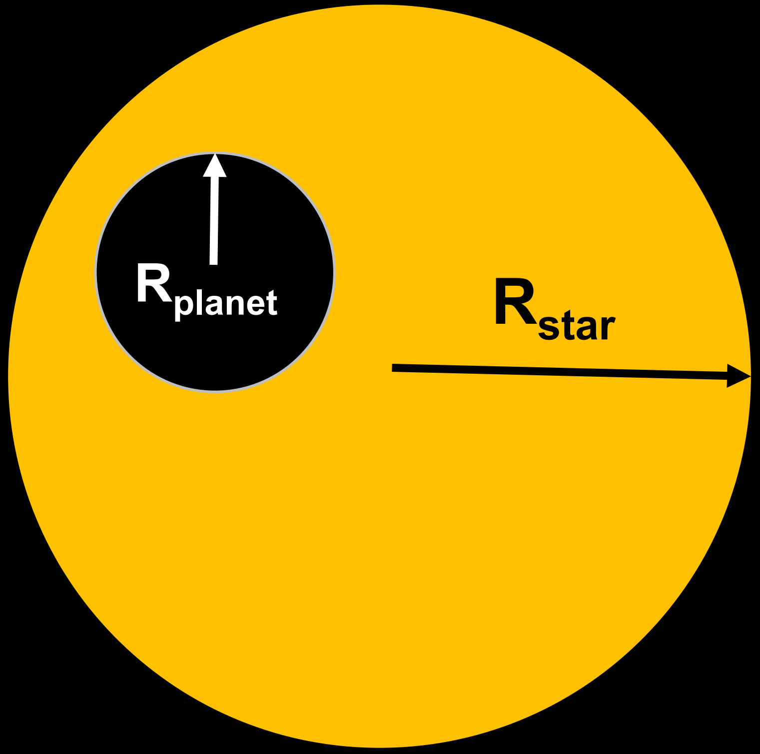

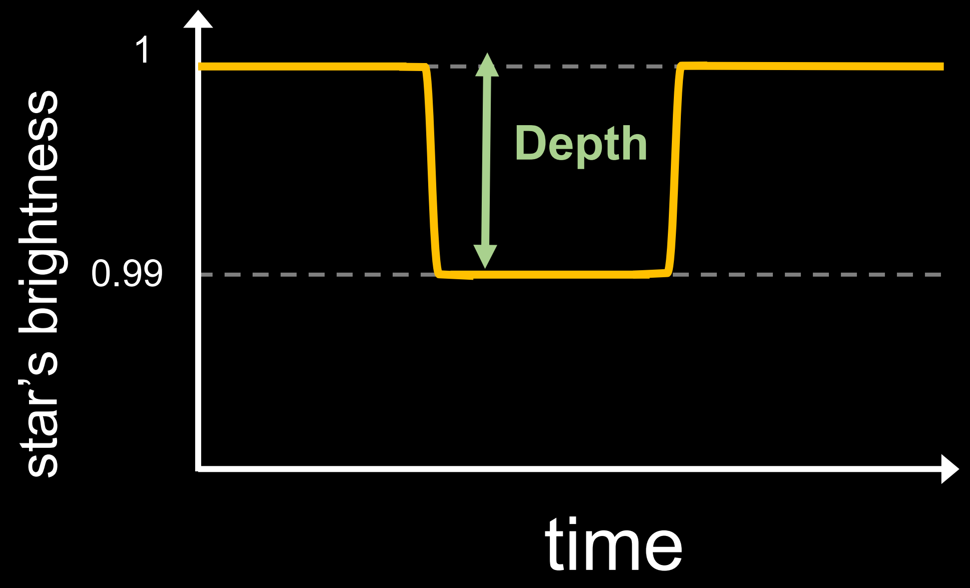

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Concept Check

Observations of a star 2.1 times the radius of the Sun reveal a transit with a depth of 0.0033. What is the radius of the transiting planet?

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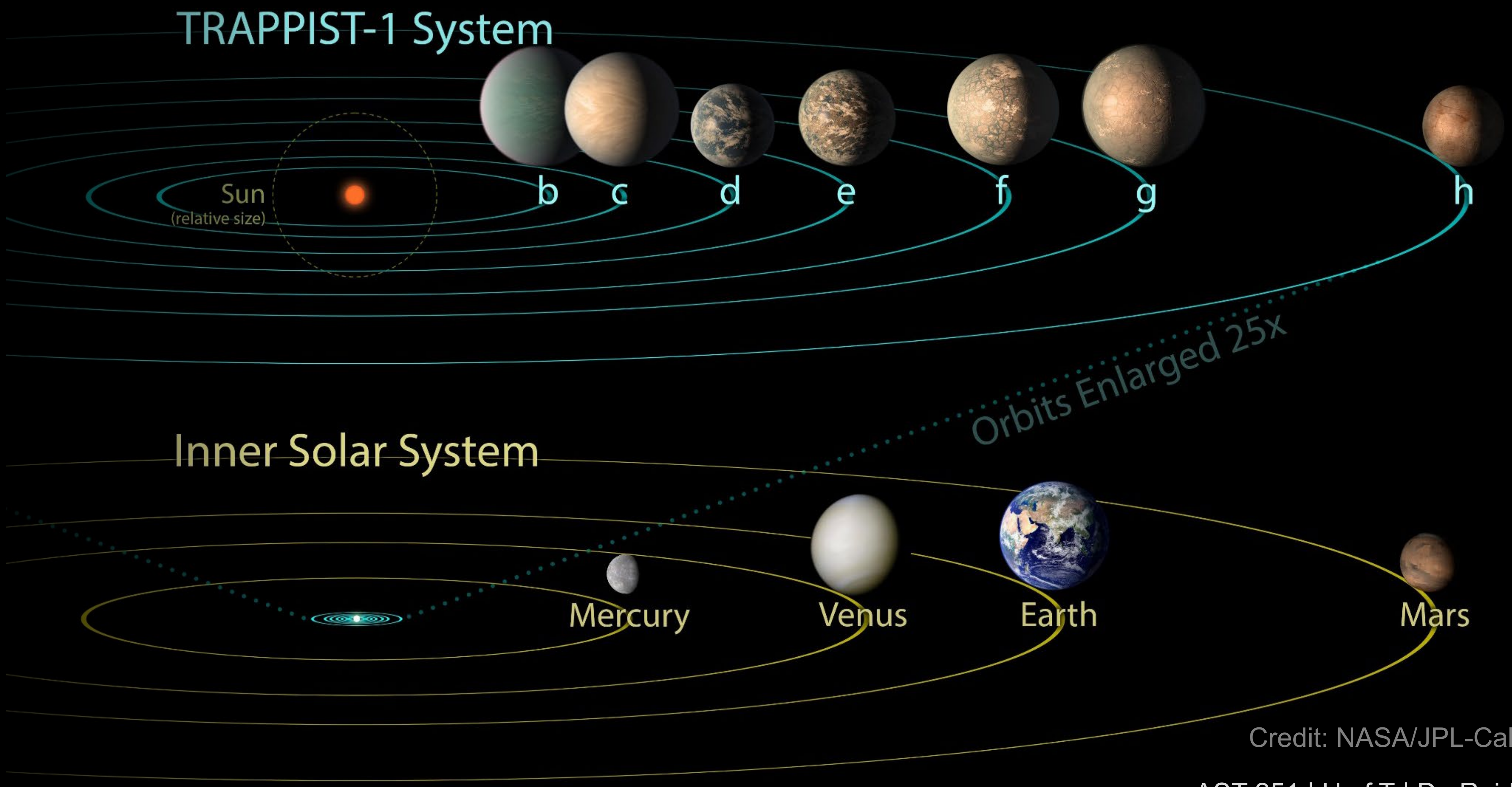
$$\mathrm{R_{planet}} = 0.12\mathrm{R}_{Sun}$$

Sanity check—is this a reasonable size for a planet?

Measuring transit depths allows us to measure the sizes of each planet in an exoplanetary system, even though we can't see the planets themselves.



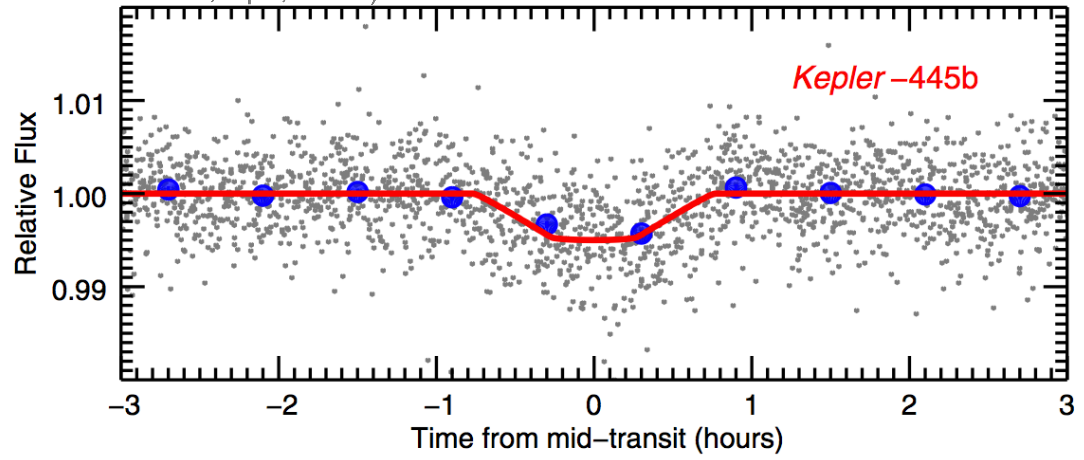
Credit: NASA/JPL-Caltech

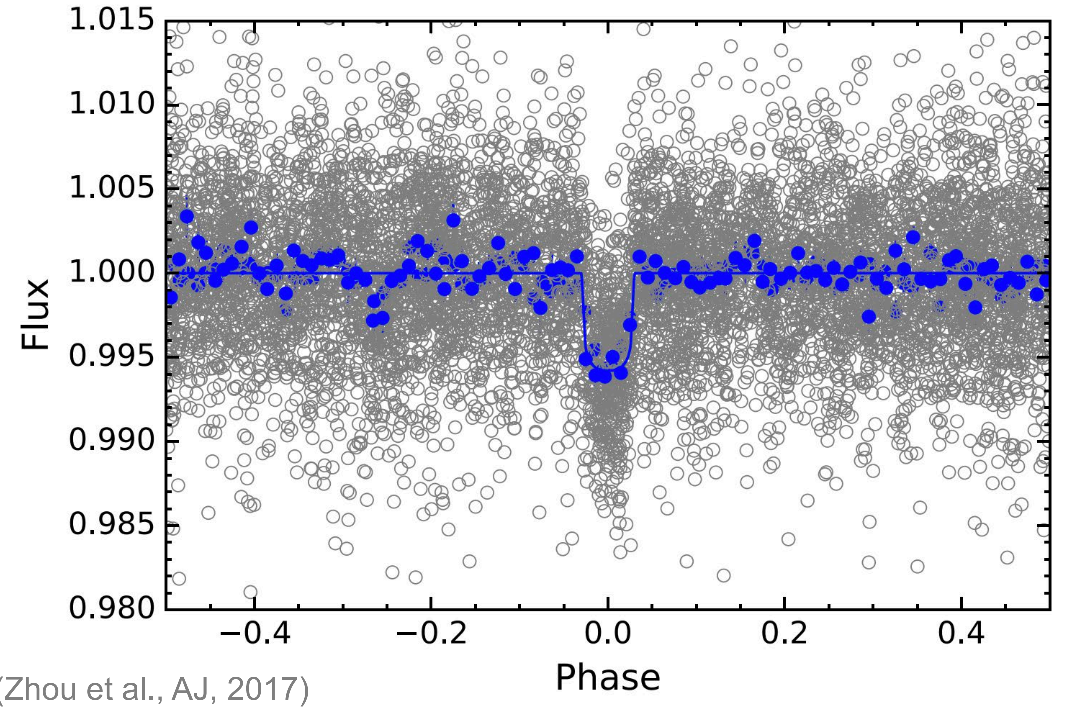
Numerous factors can make it challenging to interpret light curves and identify planets.

Can you think of anything other than a transiting planet that might cause a dip in a star’s light curve?

The light curves of real stars contain some amount of “noise”, which can make it more difficult to distinguish the transits and measure their depths accurately.

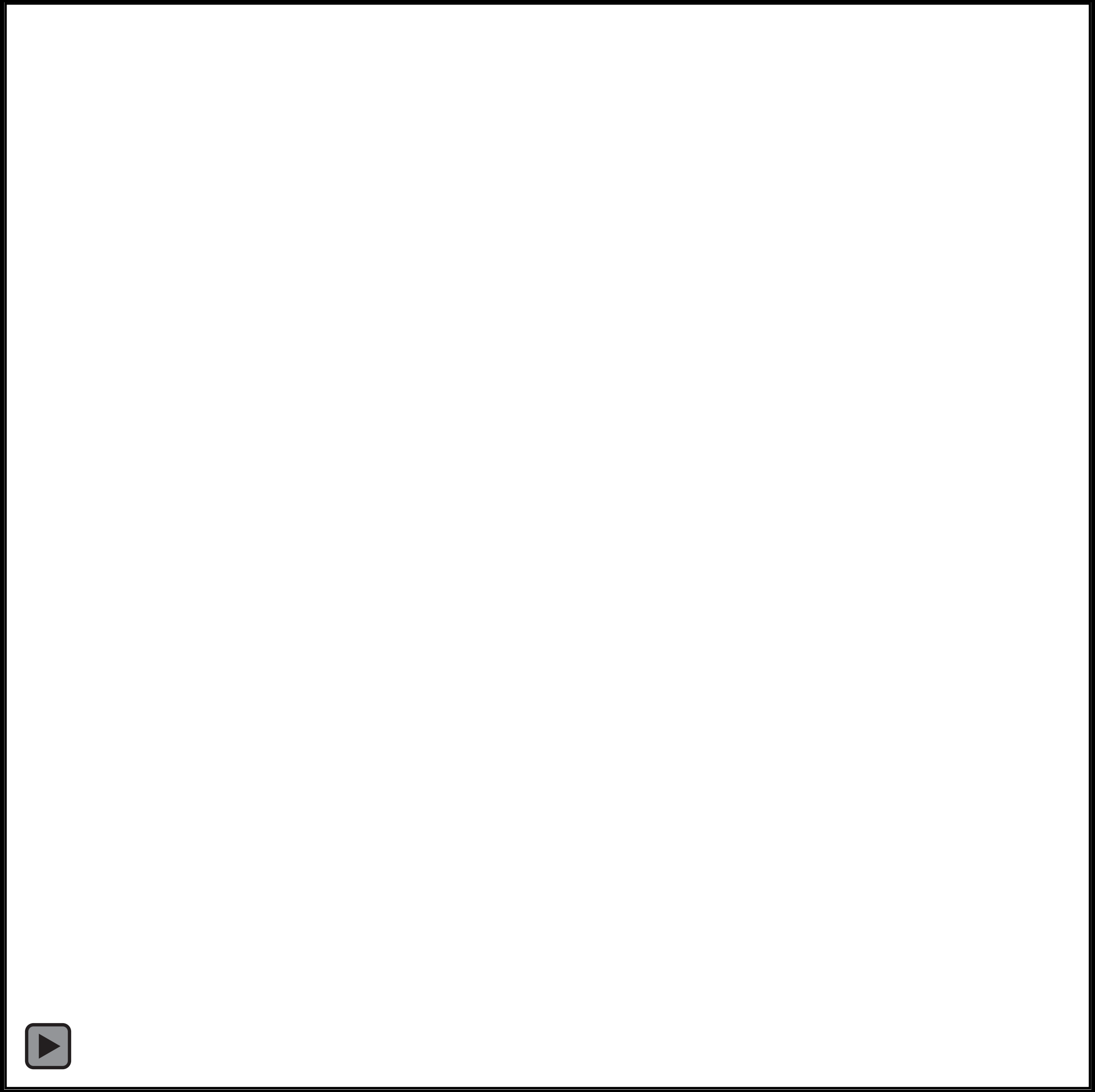
(Muirhead et al., ApJ, 2015)





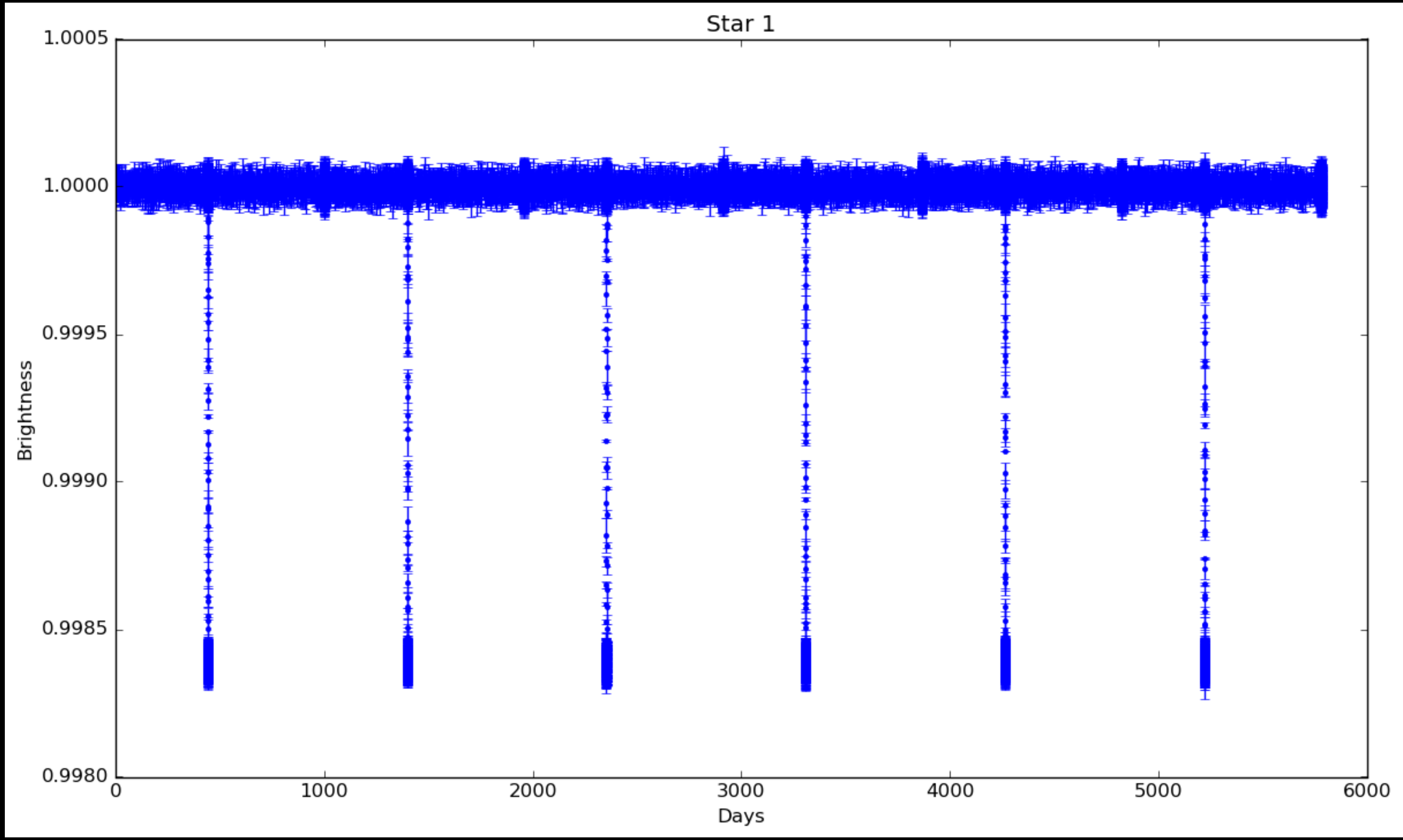
(Zhou et al., AJ, 2017)

A sunspot on the host star can produce an effect similar to a transiting planet.



Credit: NASA/SDO

To confirm that a transit is caused by a planet, we look for multiple transits of the same depth repeating at regular intervals, corresponding to successive orbits of the planet.



Concept Check

If aliens were monitoring our Sun for transits of Earth, how often would they see them?

A. Once a day
B. Once a week
C. Once a month
D. Every six months
E. Once a year

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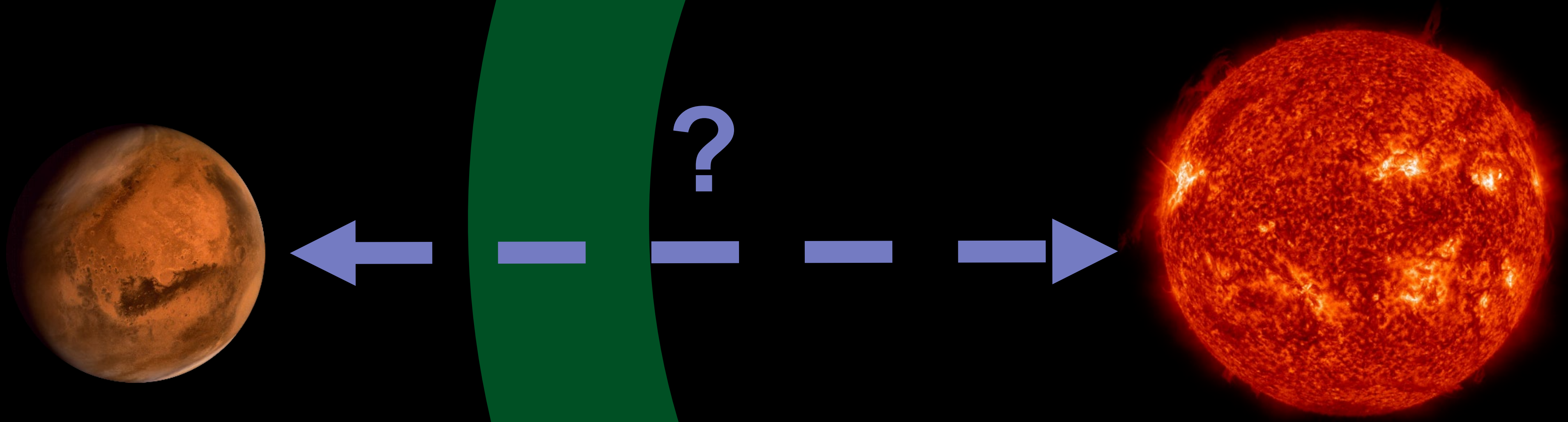
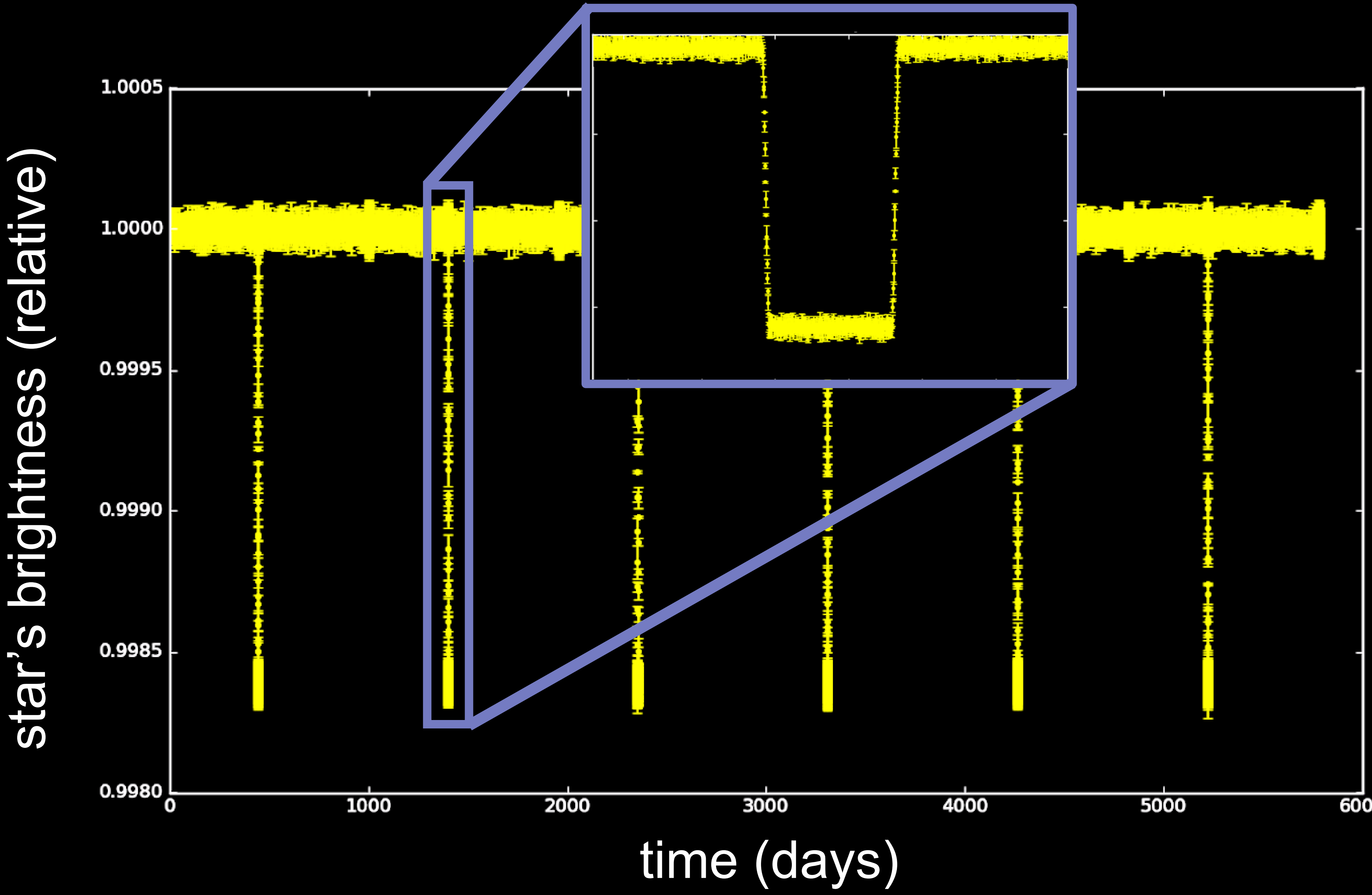
How to Decide Whether a Transiting Planet is in the Habitable Zone

What can we learn from a transit light curve, beyond that a planet exists and its radius?

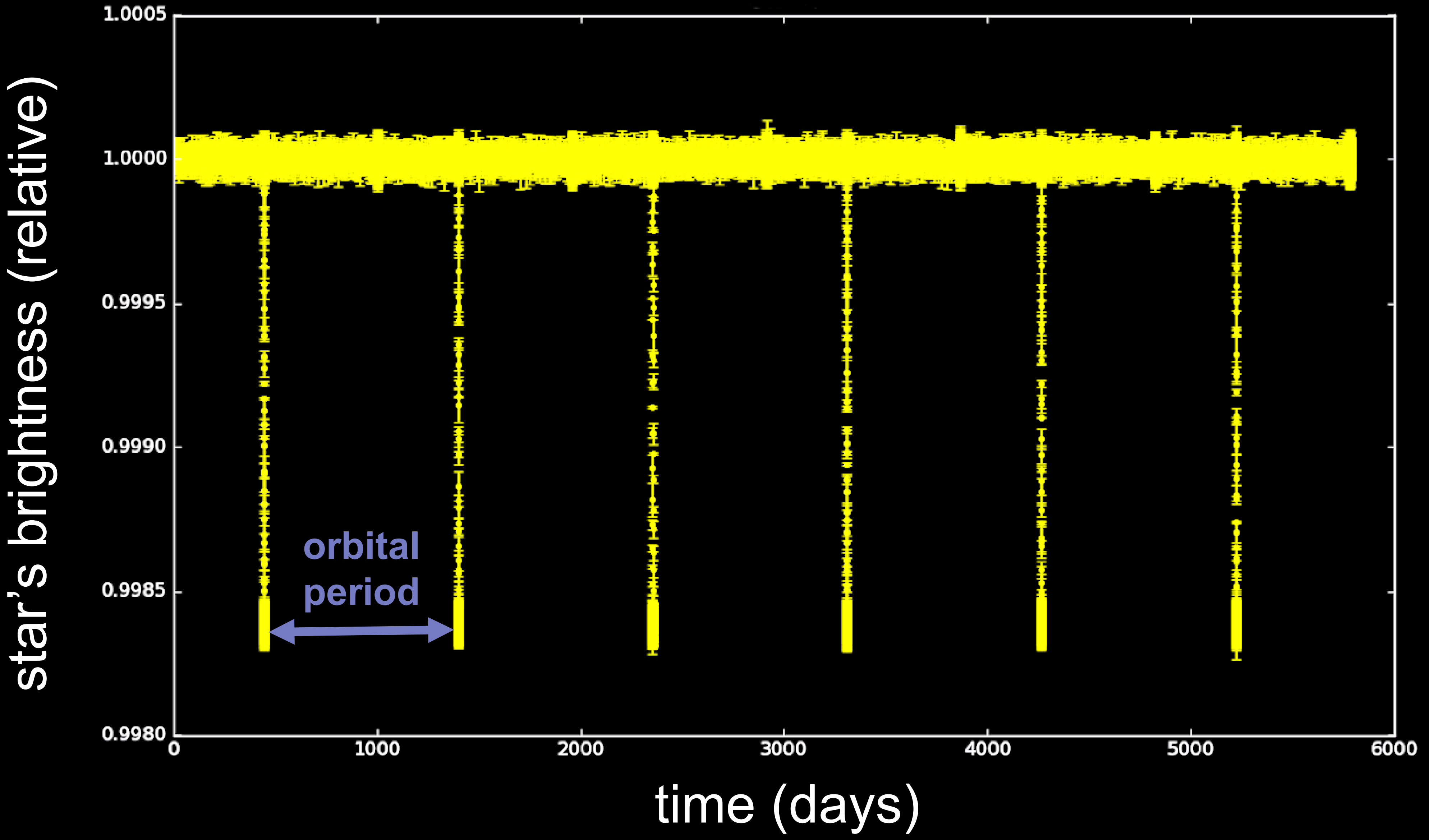
One critical piece of information is how far the planet orbits from the star. Is it in the habitable zone?



The distance at which a planet orbits is directly related to the time it takes to orbit, called its orbital period.



star's brightness (relative)
1.0005
1.0000
0.9995
0.9990
0.9985
0.9980
0
1000
2000
3000
4000
5000
6000
time (days)



star's brightness (relative)
1.0005
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0.9980
orbital
period
0
1000
2000
3000
4000
5000
6000
time (days)

The relationship between a planet's orbital period and its distance from its parent star can be worked out from Kepler's third law.

German astronomer Johannes Kepler (1571-1630) worked out the three laws of planetary.

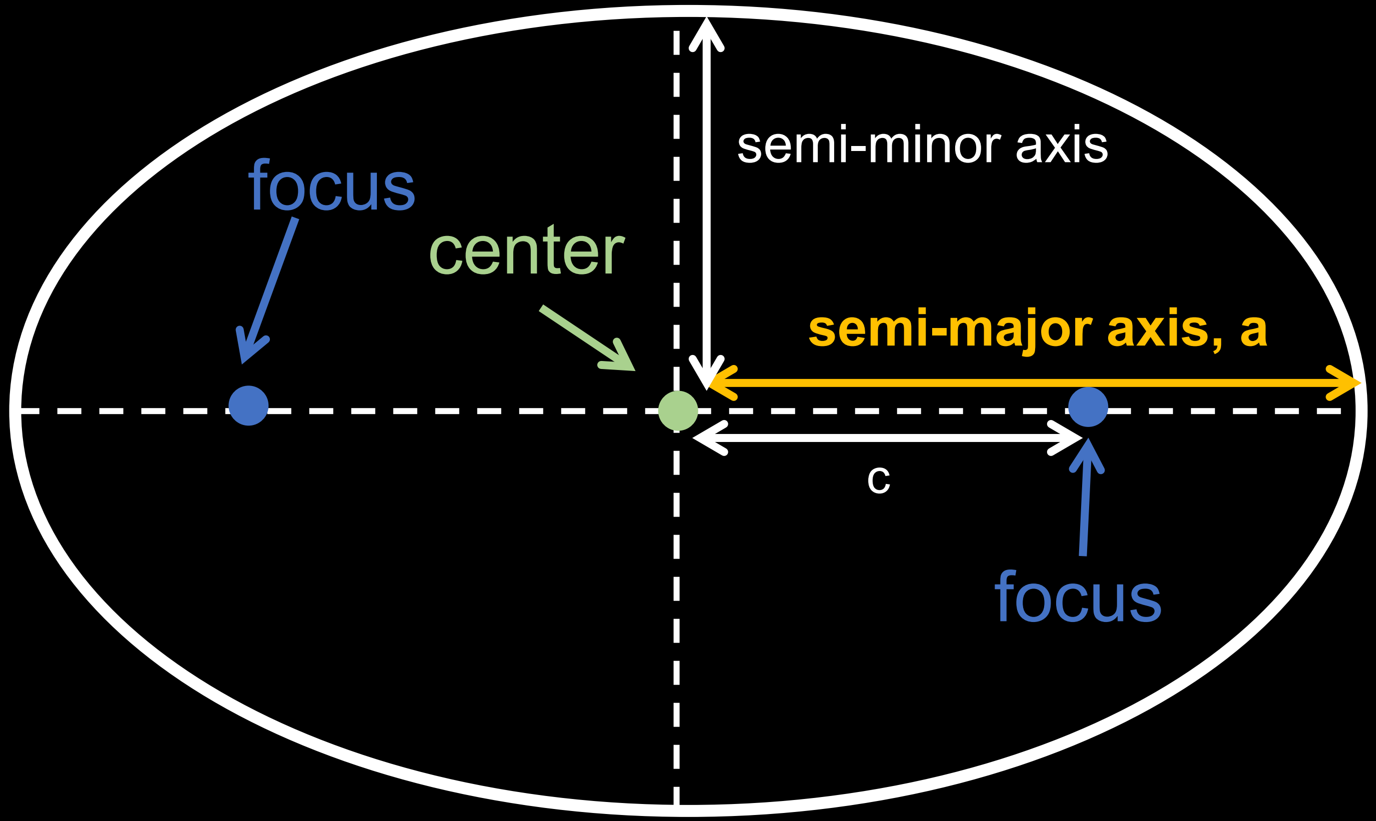
Kepler’s laws are actually just consequences of Newton’s Law of Gravity, which hadn’t been discovered in Kepler’s time.

Credit: Public domain

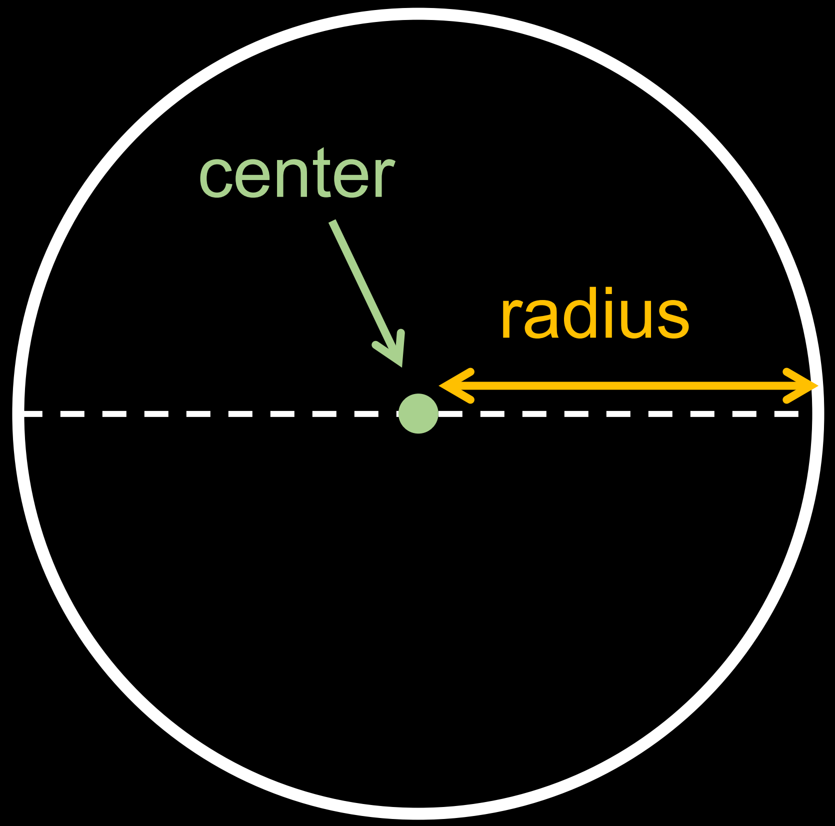
Kepler's First Law

All planets orbit their parent stars in elliptical orbits with the star* at one focus.

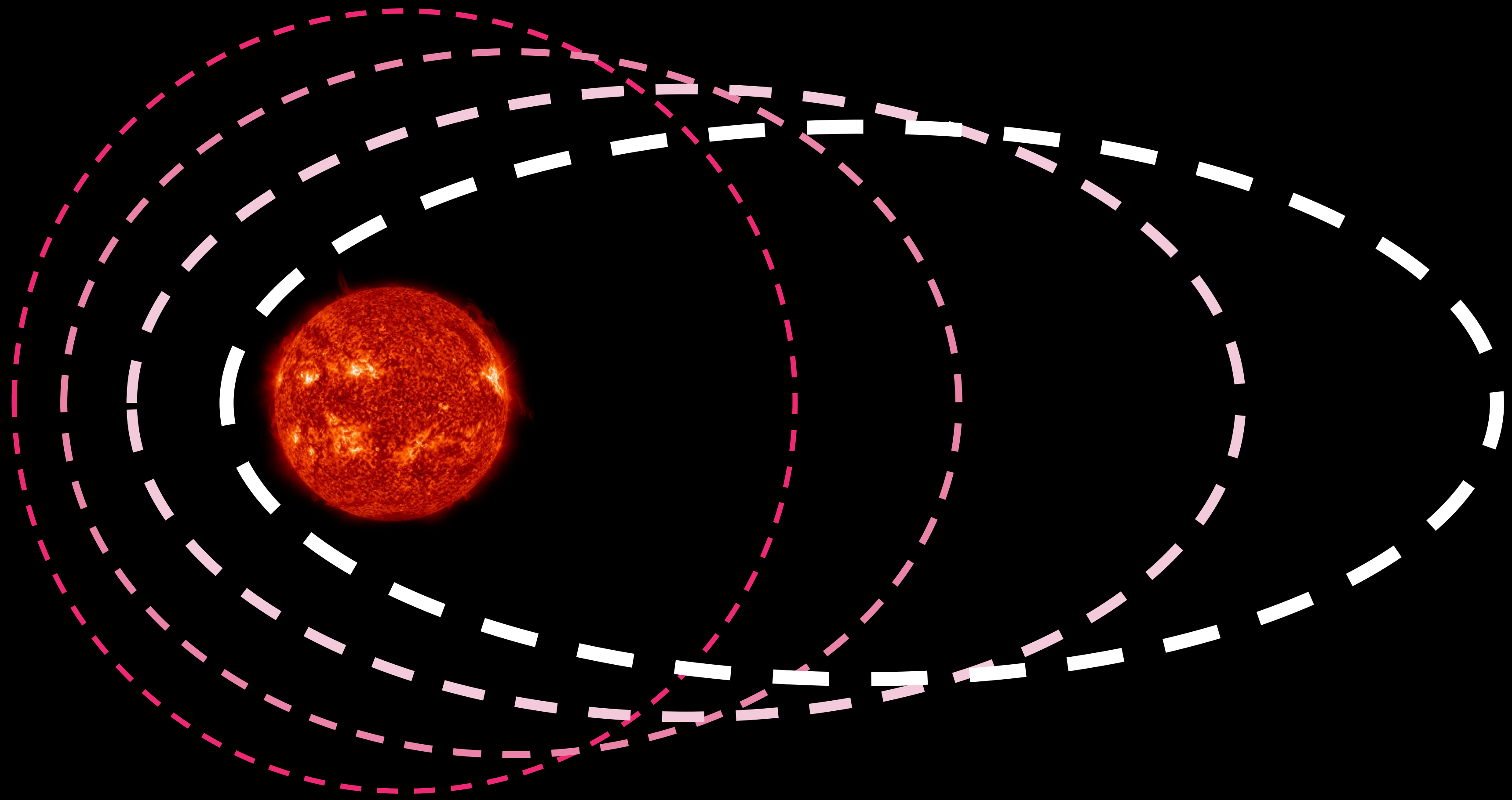
*This is technically not correct—the center of mass of the system is at one focus. However, in the general case that the star is much more massive than any of its planets, the difference is small. We will return to this point.



This ellipse has **eccentricity** = c/a = 0.6



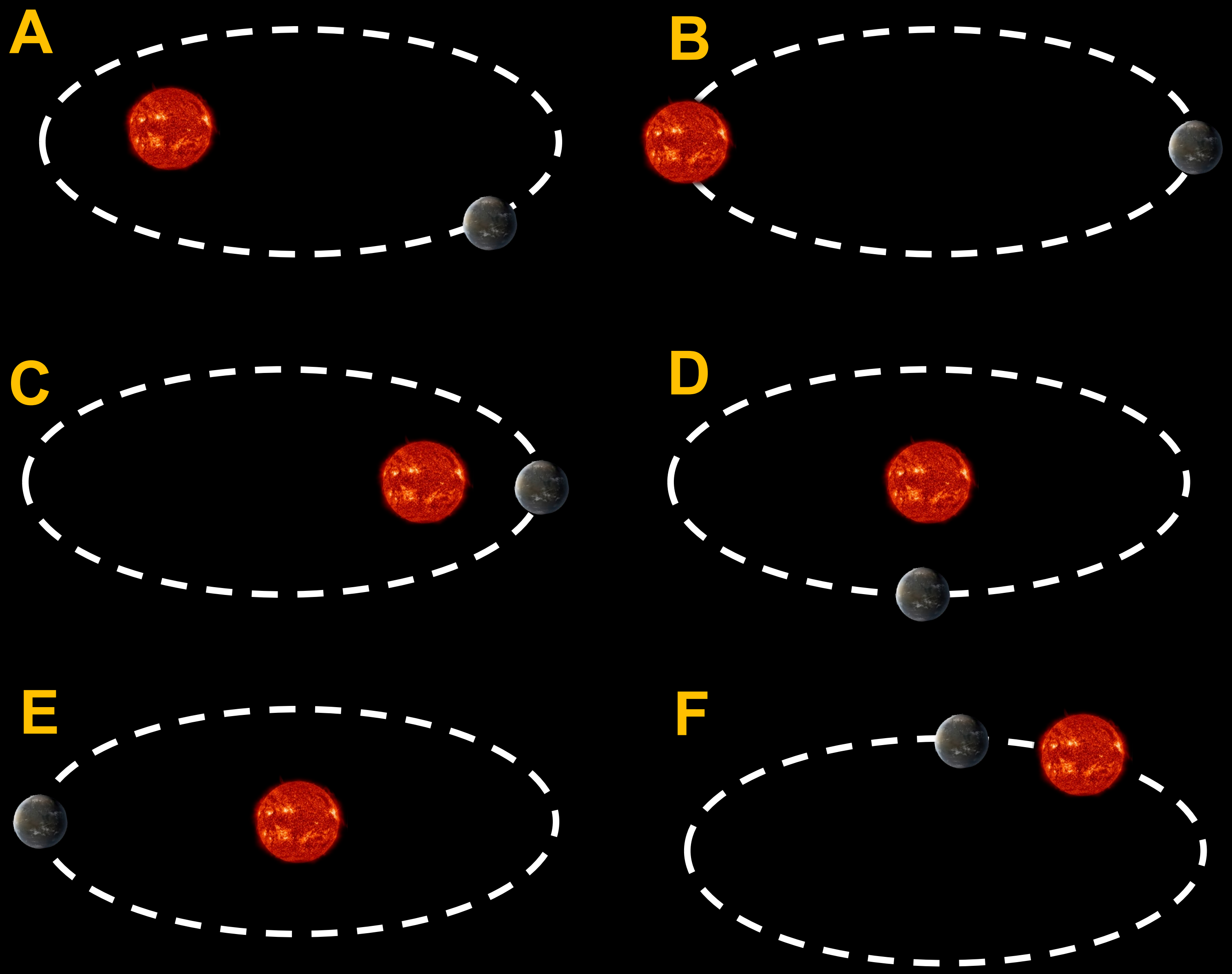
This ellipse has **eccentricity** = 0 (i.e. it's a circle)



Orbits with different eccentricities (thicker line → higher e)

Concept Check

Which of these diagrams shows a planet orbiting a star in a way that follows Kepler's first law? All diagrams are viewed from <u>directly overhead</u>.



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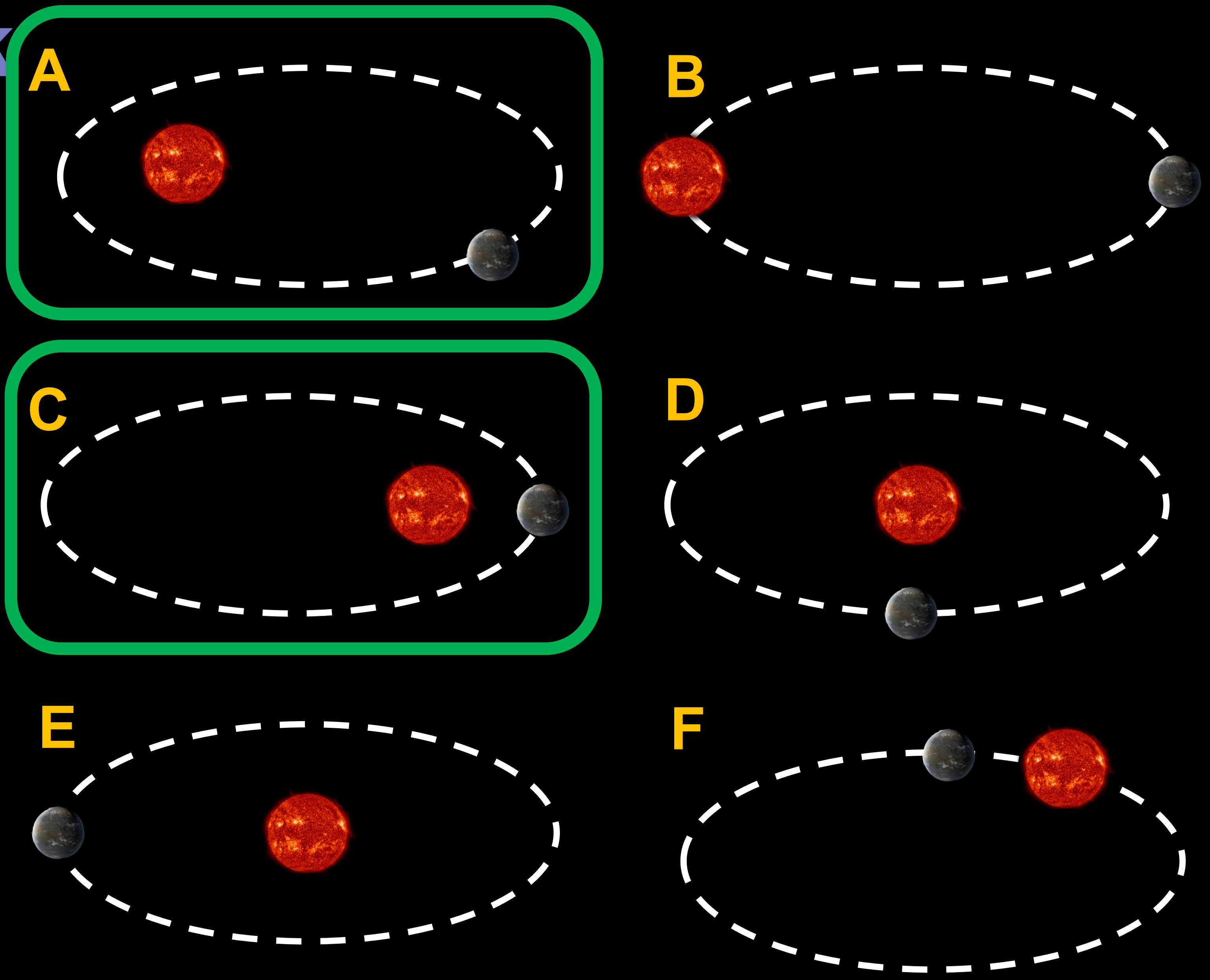
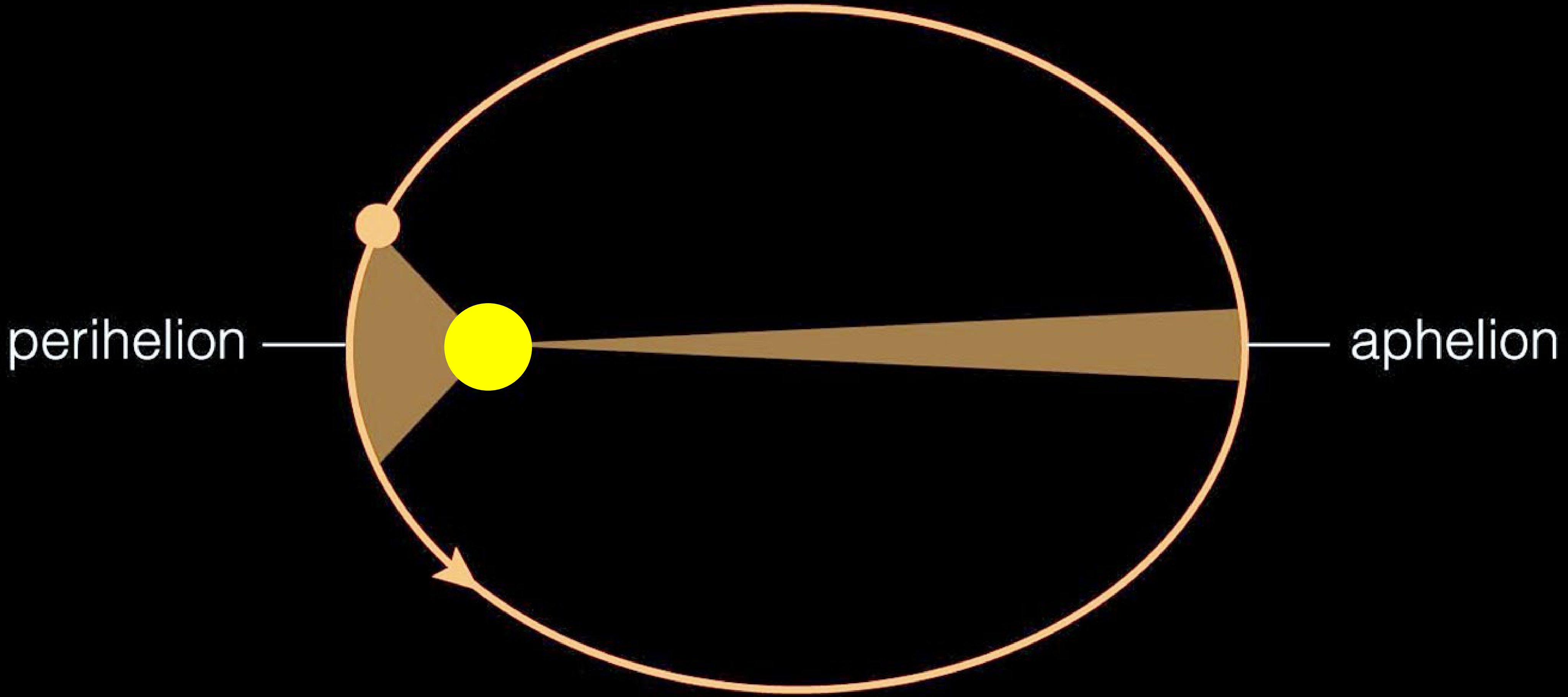


Credit: YouTube user Ms. Edge

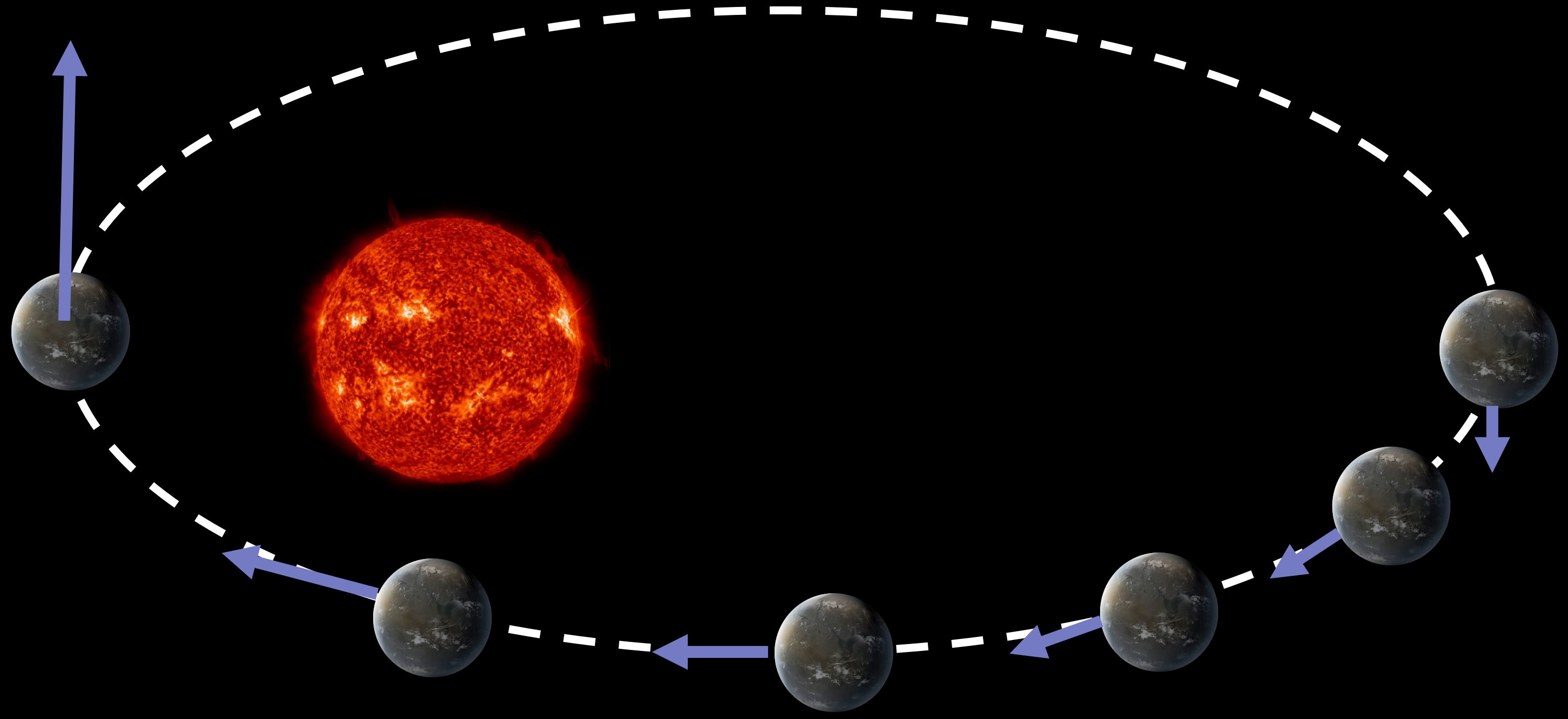
Kepler's Second Law*

As they orbit, planets sweep out equal areas in equal times.

*This is the one that confuses everyone. It's really a statement of the conservation of angular momentum.



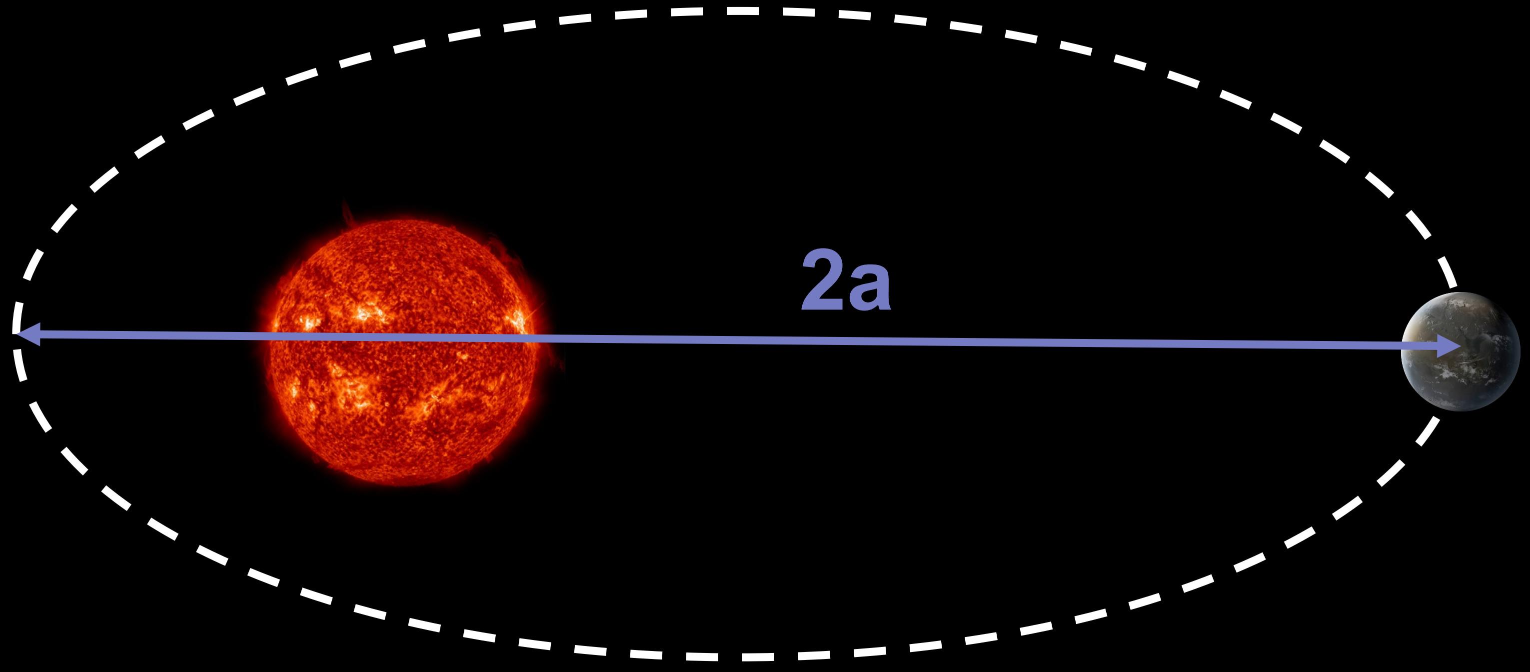
Credit: Pearson Education



Snapshots of an orbiting planet spaced at equal times—the planet moves faster closer to the star.

Kepler's Third Law

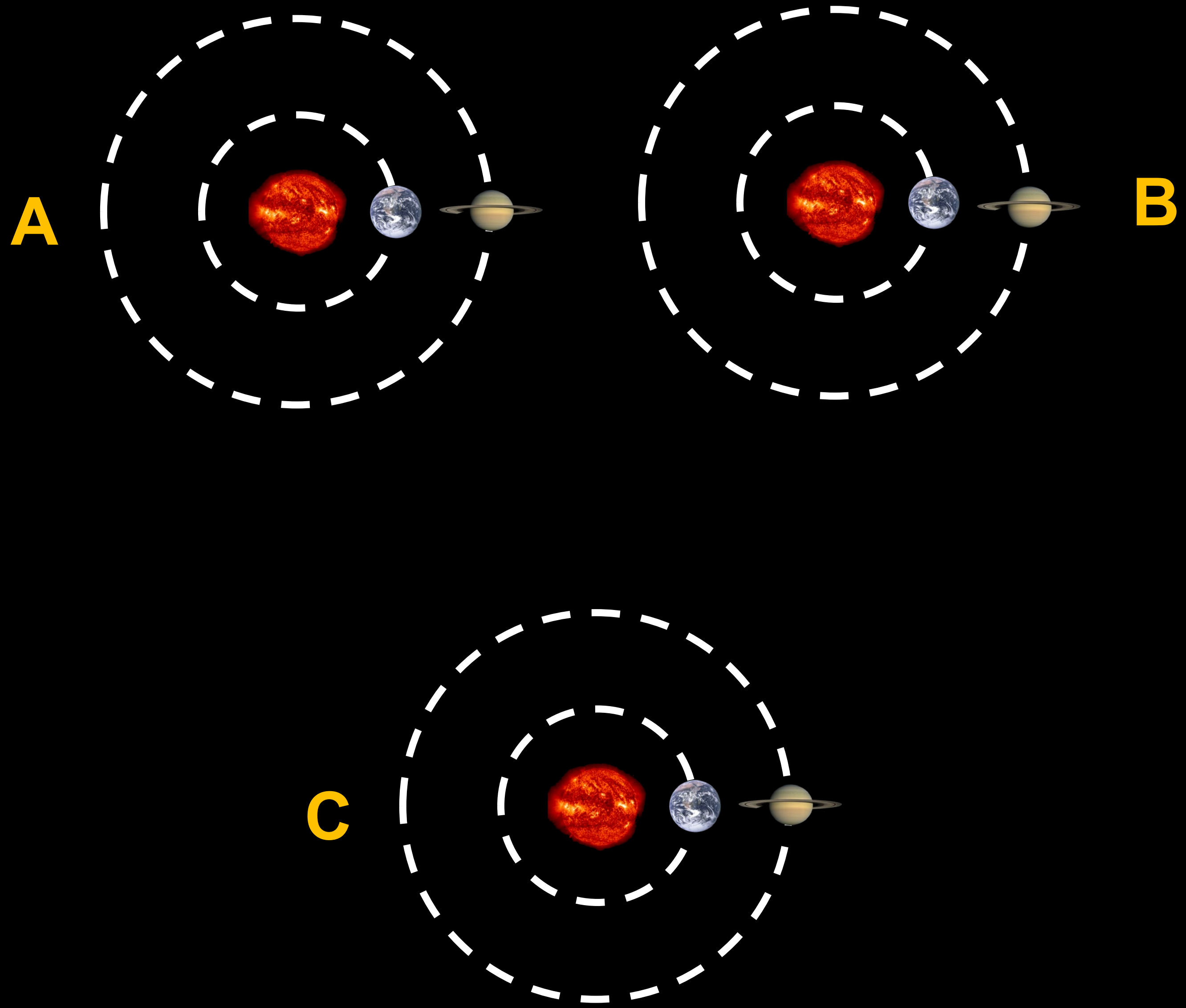
The square of a planet's orbital period is proportional to the cube of its orbital semi-major axis.



$$P^2 = \frac{4\pi^2}{G(M_{planet} + M_{star})} a^3$$

Concept Check

Which of these diagrams shows a set of planets orbiting in accordance with Kepler’s third Law?



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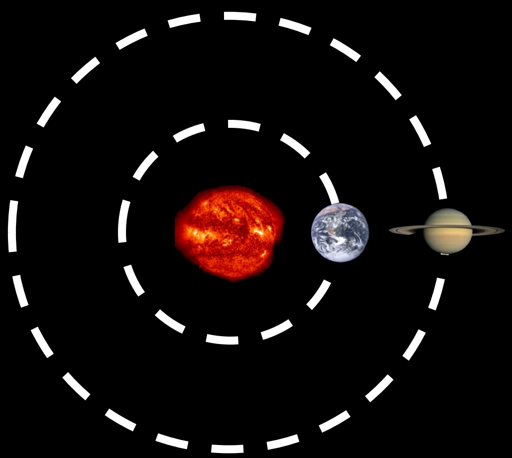
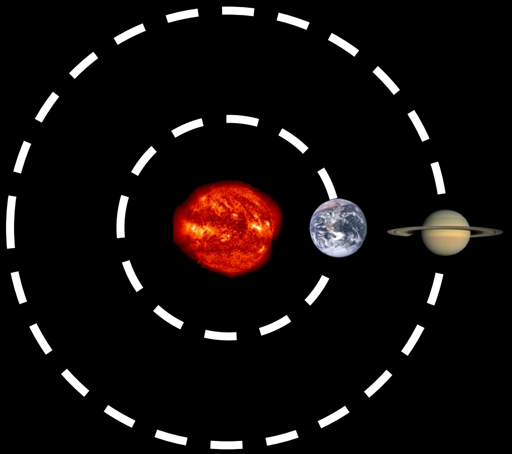
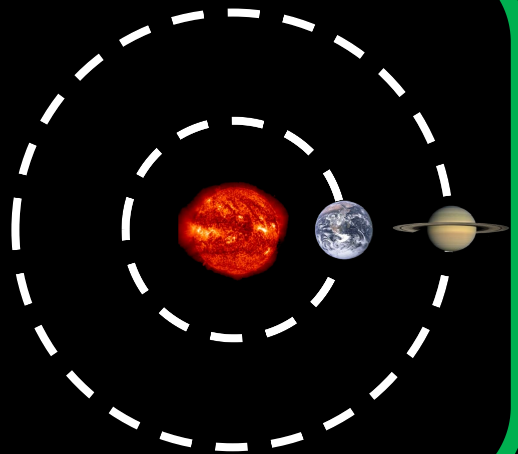




B

C



If we assume the mass of the planet is much less than the mass of the star, we can use Kepler's Third Law to work out the planet's orbital semimajor axis from its orbital period:

$$P^2 = \frac{4\pi^2}{G(M_{planet} + M_{star})} a^3$$

if $M_{star} \gg M_{planet}$

$$P^2 \cong \frac{4\pi^2}{GM_{star}} a^3$$

Let's say $P = 2.1$ years and $M_{star} = 2.0\ M_{\odot}$. To find a, first convert everything to standard units (m, s, kg, etc.)

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$M_{star} = 2M_{Sun}$ = (2)(1.989 x 10^{30} kg) = 3.978×10^{30} kg

$$\mathbf{a} \cong \left[\frac{(6.674 \times 10^{-11}\ \mathrm{m^3 kg^{-1} s^{-2}})(3.978 \times 10^{30}\mathrm{kg})}{4(3.14159)^2}(6.627 \times 10^{7}\mathrm{s})^2\right]^{1/3}$$

Let's say P = 2.1 years and M_{star} = 2.0 $M_{\odot}$. To find a, first convert everything to standard units (m, s, kg, etc.)

Convert P to seconds:
P = (2.1 y)(365.24 days/y)(86400 s/day) = 6.627×10^{7} s

Convert M_{star} to kg:
$M_{star} = 2M_{Sun}$ = (2)(1.989 x 10^{30} kg) = 3.978×10^{30} kg

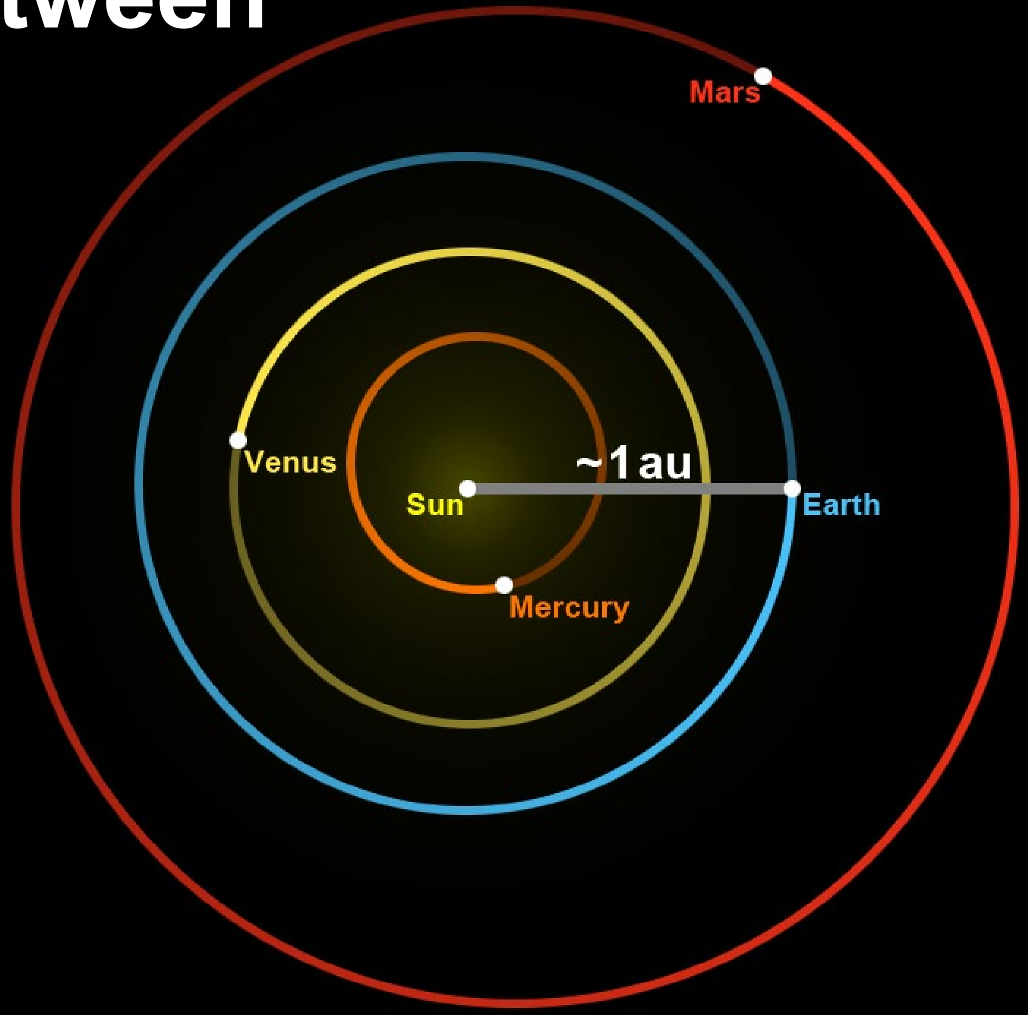
$$\mathbf{a} \cong \left[\frac{(6.674\times10^{-11}\ \mathrm{m^3kg^{-1}s^{-2}})(3.978\times10^{30}\mathrm{kg})}{4(3.14159)^2}(6.627\times10^{7}\mathrm{s})^2\right]^{1/3}$$

$$\mathbf{a} \cong 3.09\times10^{11}\mathrm{m} = 2.1\ \mathrm{AU}$$

1 AU = 1 Astronomical Unit

≈ average distance between Earth and the Sun

≈ 150 million km



Credit: Wikimedia Commons user Huritisho

WolframAlpha PRO FOR EDUCATORS

(G*2*(mass of the sun)*(2.1 years)^2/(4*pi^2))^(1/3)

Web Apps | Examples | Random

Assuming Newtonian gravitational constant for "G" | Use Gibbs or more instead

Input interpretation:

$$\sqrt[3]{(G\ \text{(Newtonian gravitational constant)}) \times 2\,(M_\odot\ \text{(solar mass)}) \times \frac{(2.1\ \text{years})^2}{4\pi^2}}$$

Open code

Result:

3.09×10^{11} meters

Unit conversions:

192 million miles

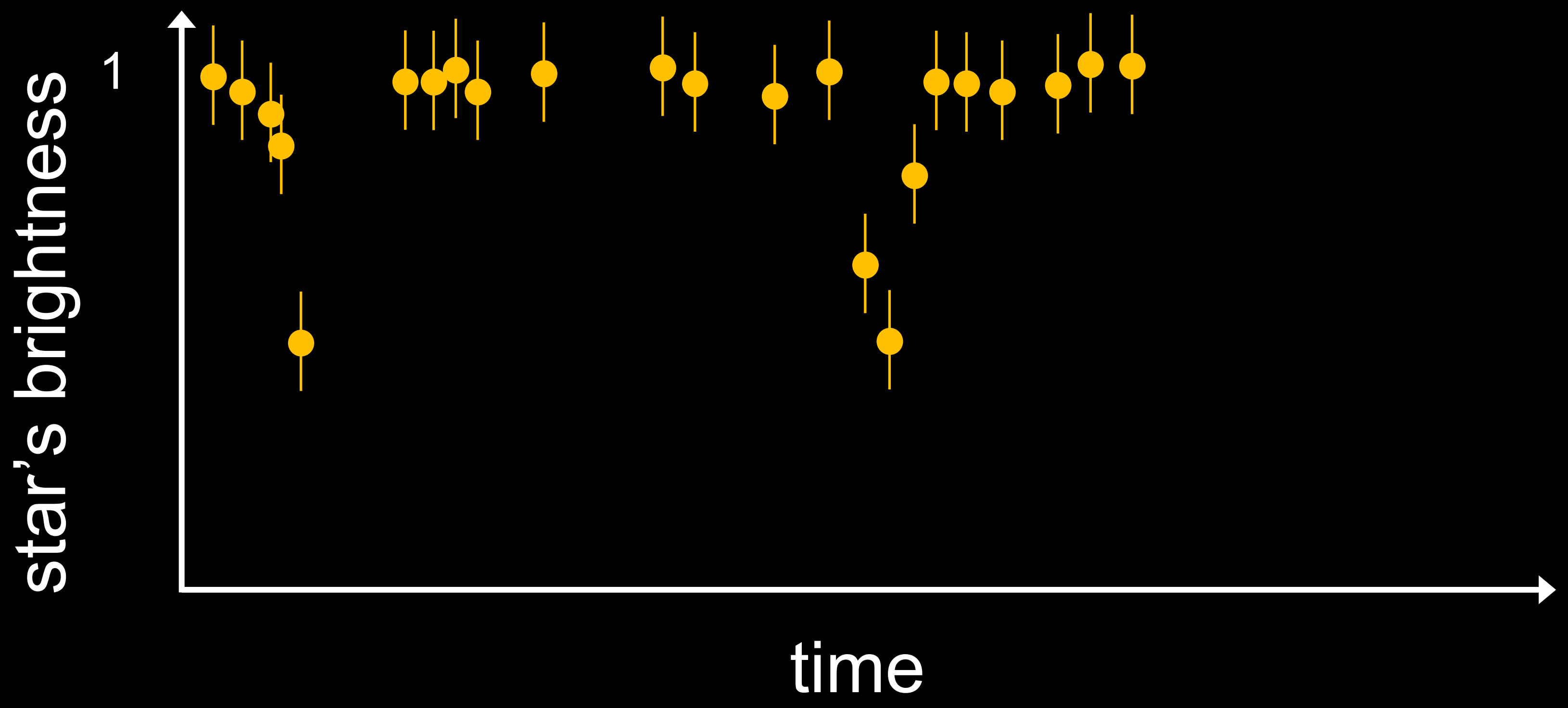
3.09×10^{8} km (kilometers)

2.07 au (astronomical units)

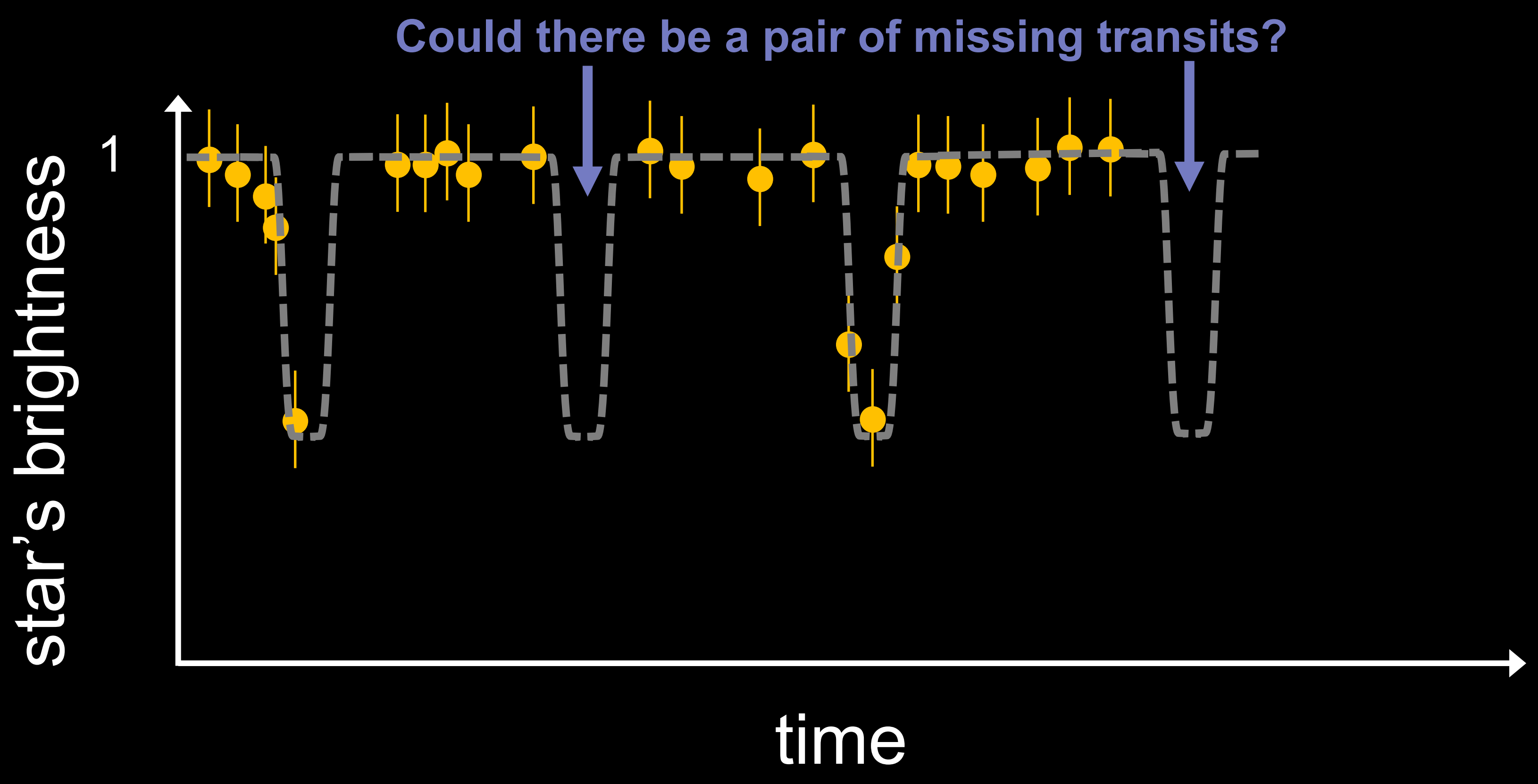
So, from the transit depth, we get the planetary radius.

From the orbital period, we get the orbital semimajor axis.

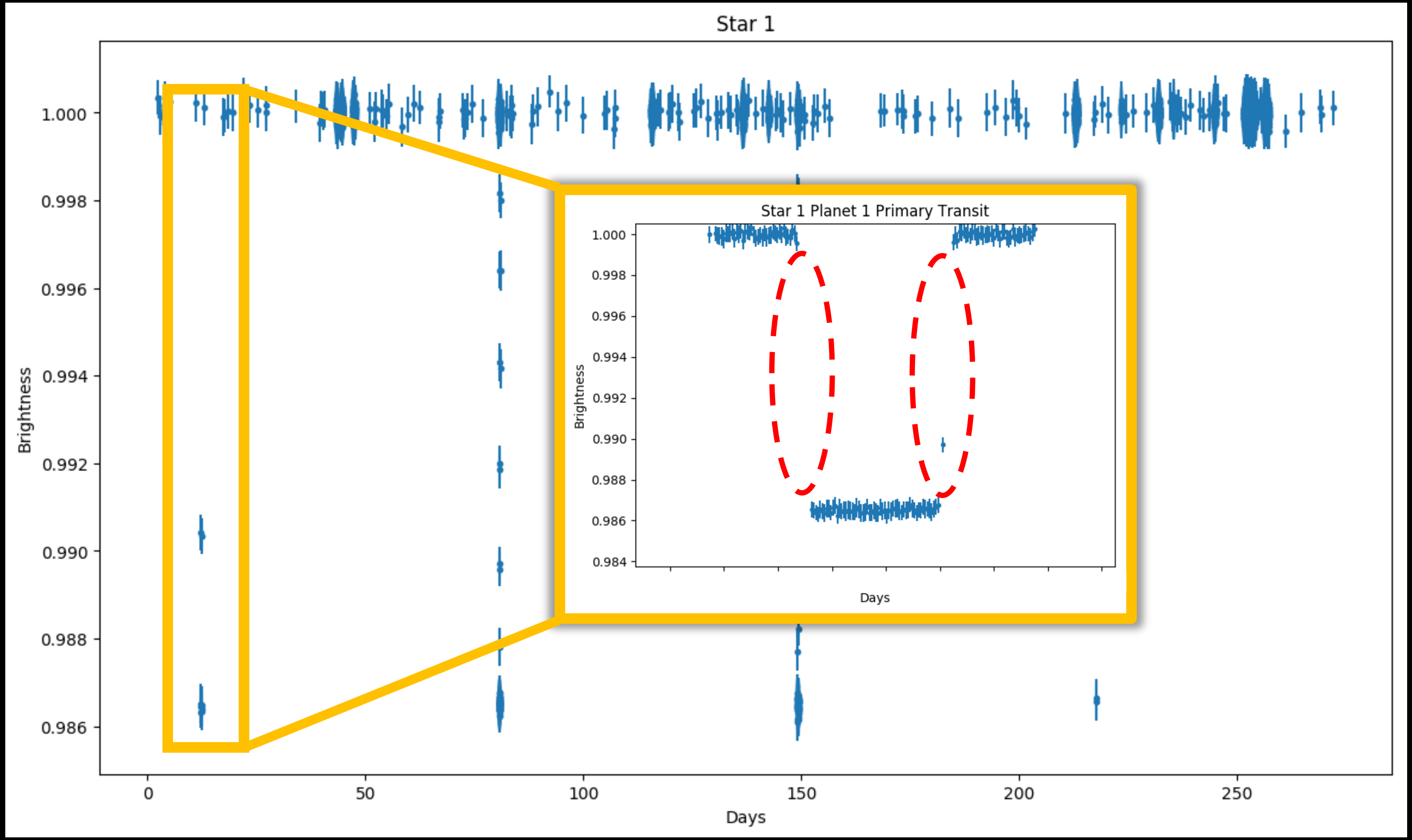
Thus, we can figure out roughly what type of planet we have, and whether it's in the habitable zone!



Low cadence observations can make it difficult to measure the orbital period correctly.



Low cadence observations can make it difficult to measure the orbital period correctly.

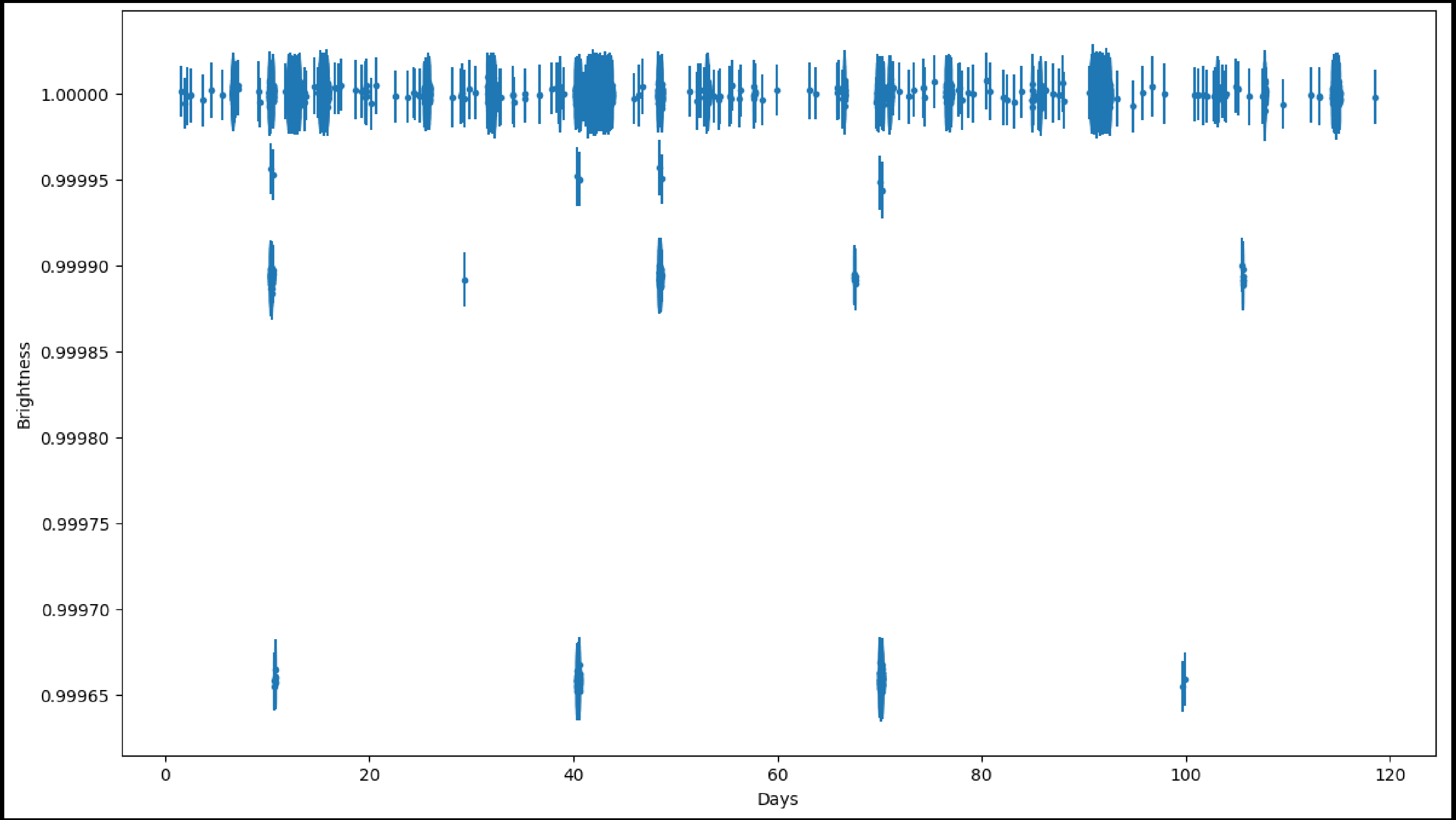


Lower cadence can also cause you to miss ingress and/or egress, which are typically very fast.

The interpretation of light curves is further complicated when there are multiple planets present, which is extremely common.

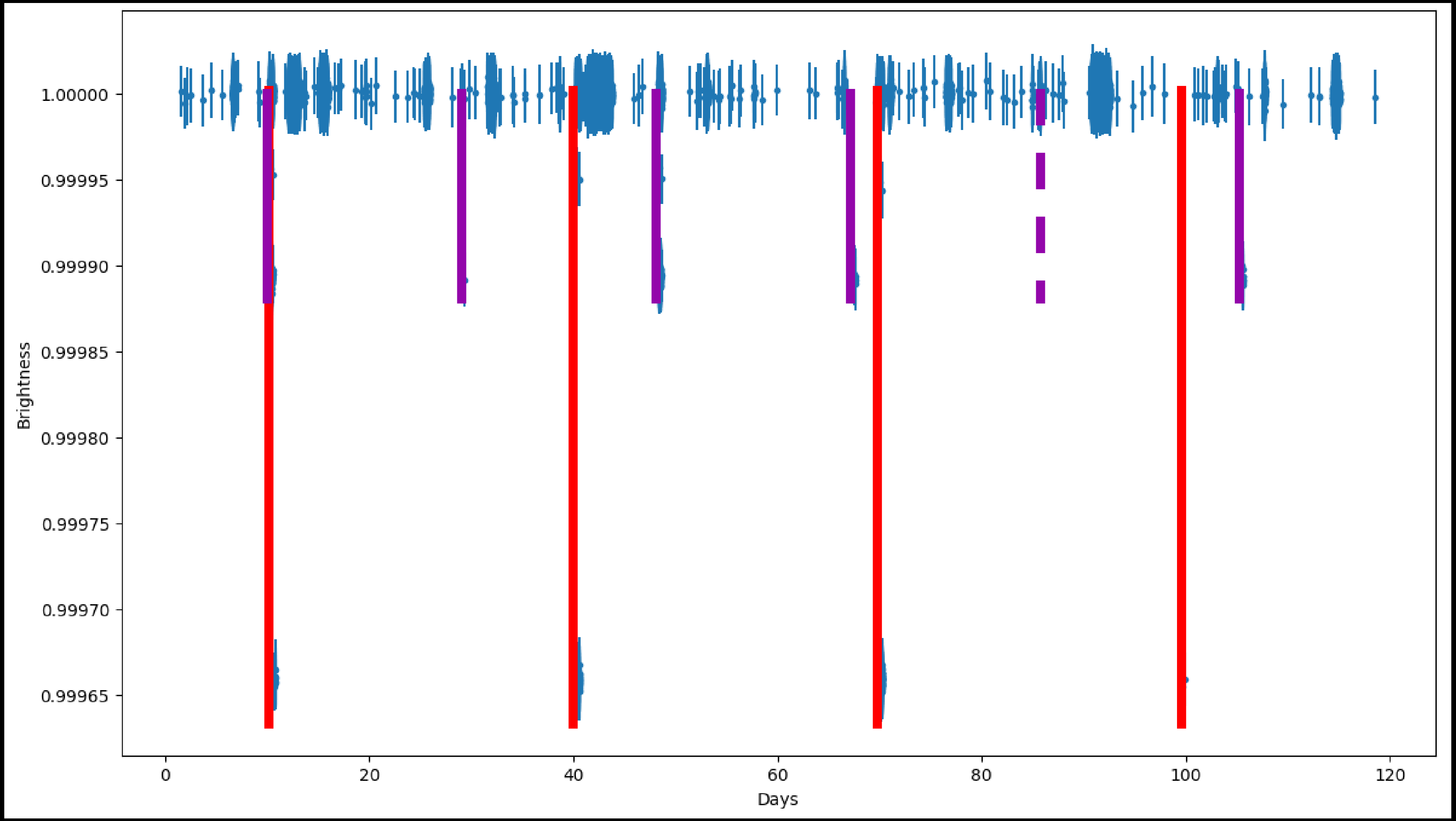
Concept Check

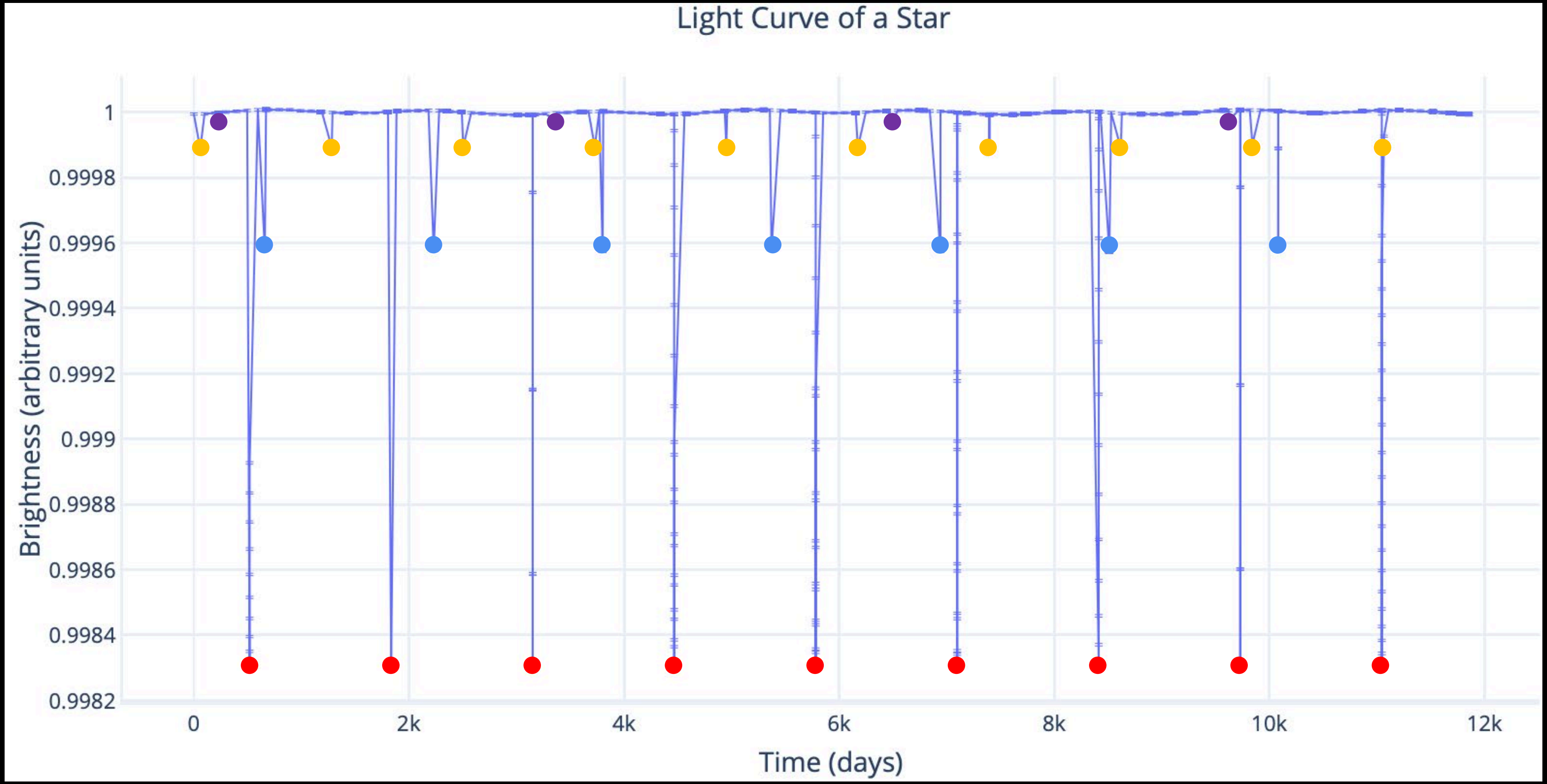
How many planets do you see in this light curve?



Concept Check

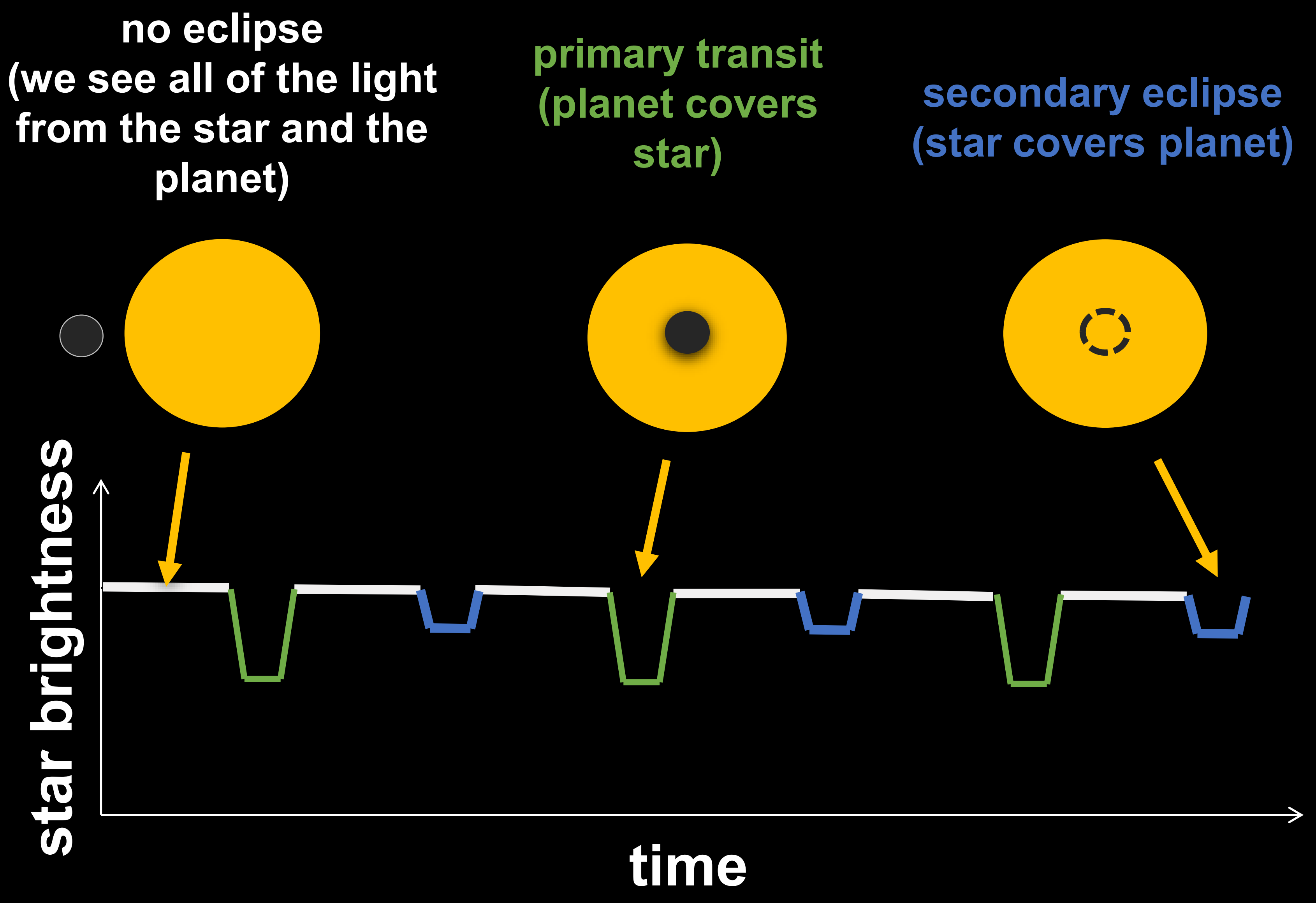
How many planets do you see in this light curve?





Light Curve of a Star
Brightness (arbitrary units)
1
0.9998
0.9996
0.9994
0.9992
0.999
0.9988
0.9986
0.9984
0.9982
0
2k
4k
6k
8k
10k
12k
Time (days)

Planets themselves emit & reflect light, which means that there’s a secondary eclipse when the planet passes behind the star.


no eclipse
(we see all of the light from the star and the planet)
primary transit
(planet covers star)
secondary eclipse
(star covers planet)
star brightness
time

You’re now ready to:

1. Identify candidate planets using the transit method, including multi-planet systems
2. Distinguish planets from non-planets
3. Measure their sizes
4. Measure their distances from the host star and decide whether they’re in the habitable zone