ASTR20A:
Introduction to Astrophysics I

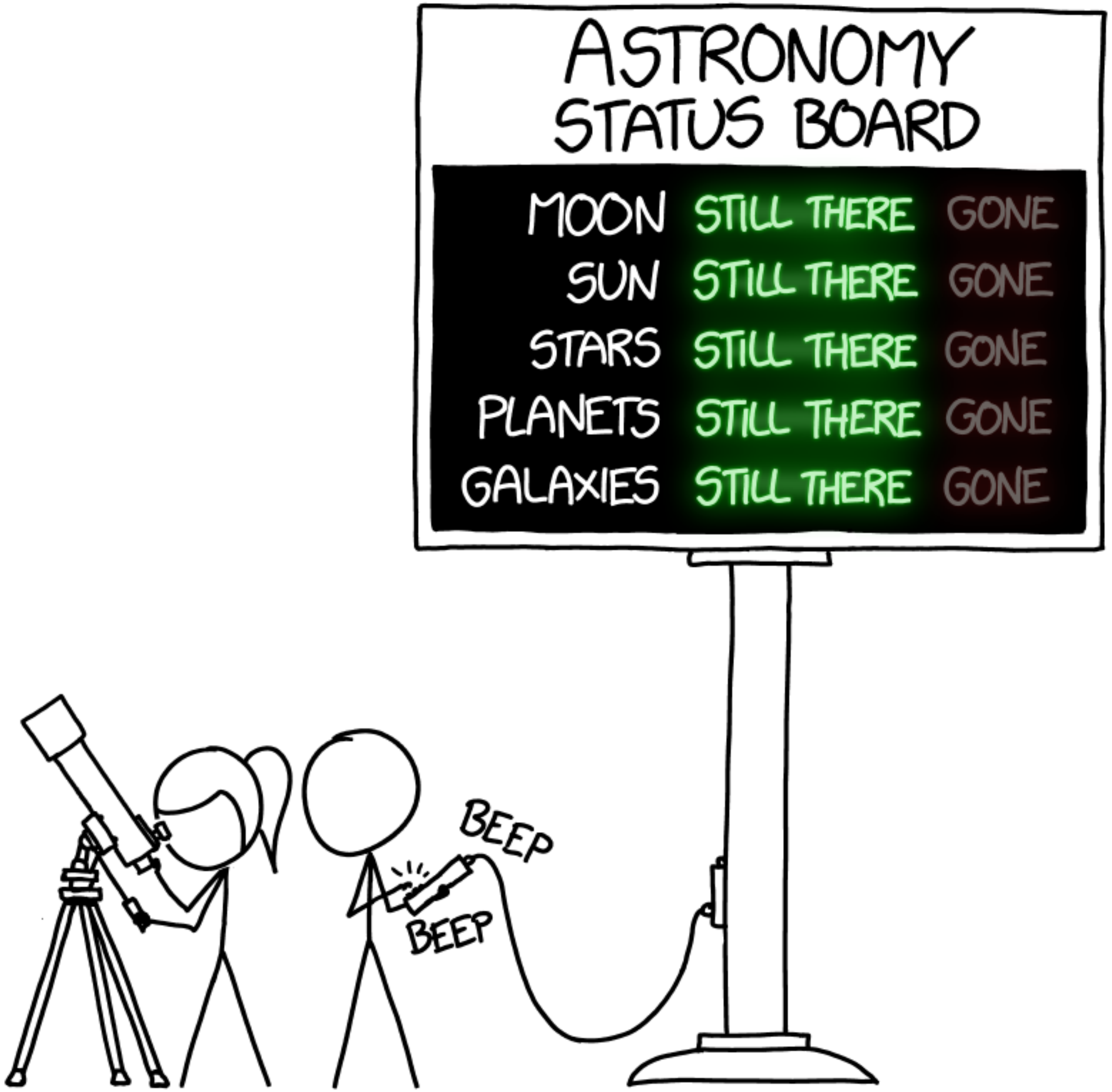
Dr. Devontae Baxter

Lecture 14 | Exoplanets

Thursday, November 20, 2025

Announcements

- HW #7 is due Tuesday, 11/25, by 11:59 pm.
- Coding project is due Sunday, 11/30 by 11:59 pm.



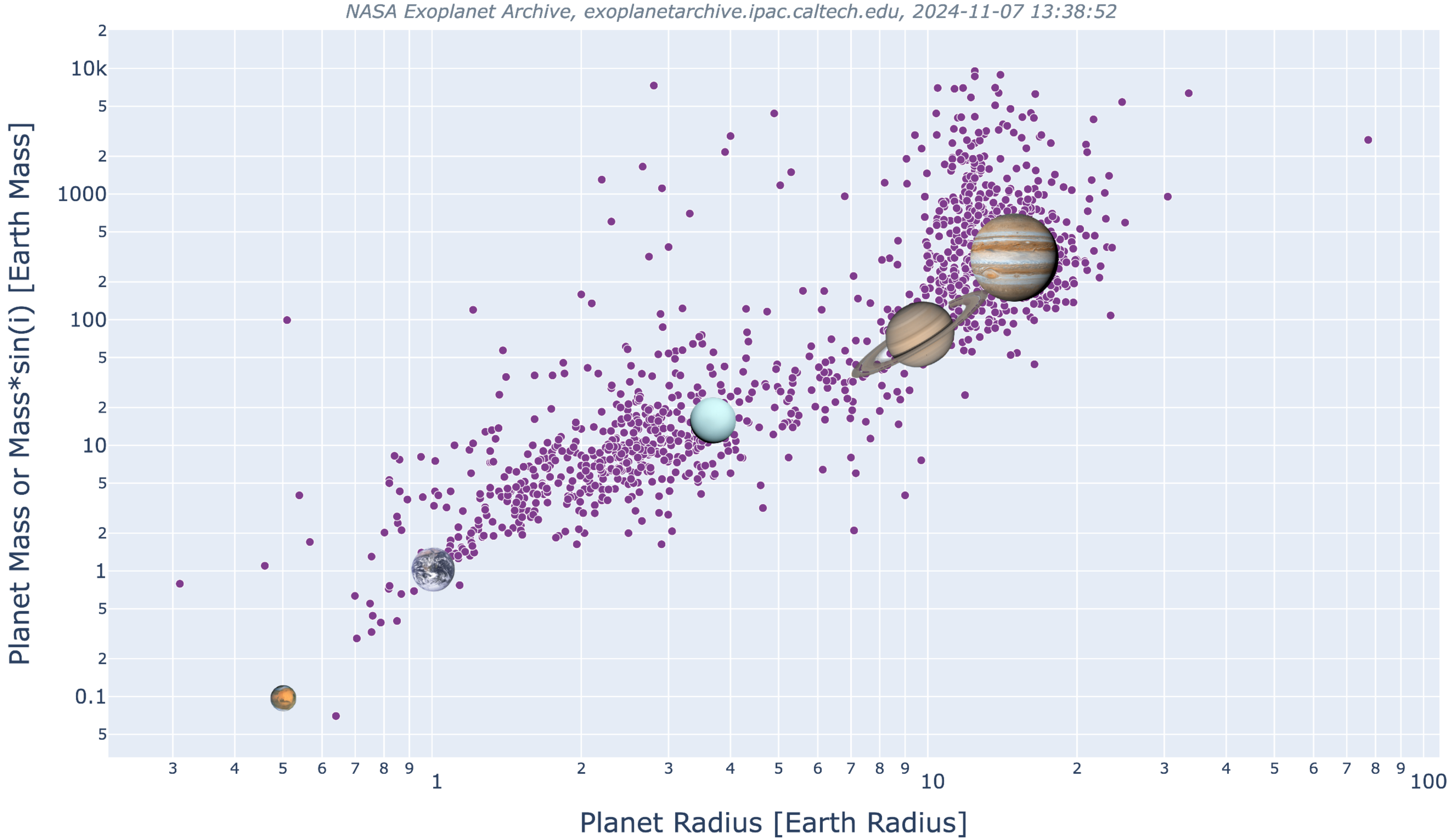
Learning Objectives

By the end of today's lecture you will be able to:

- Describe the different types of exoplanet detection methods.
- Explain the limitations and strengths of each detection method.
- Understand the exoplanet properties that each method allows us to infer.

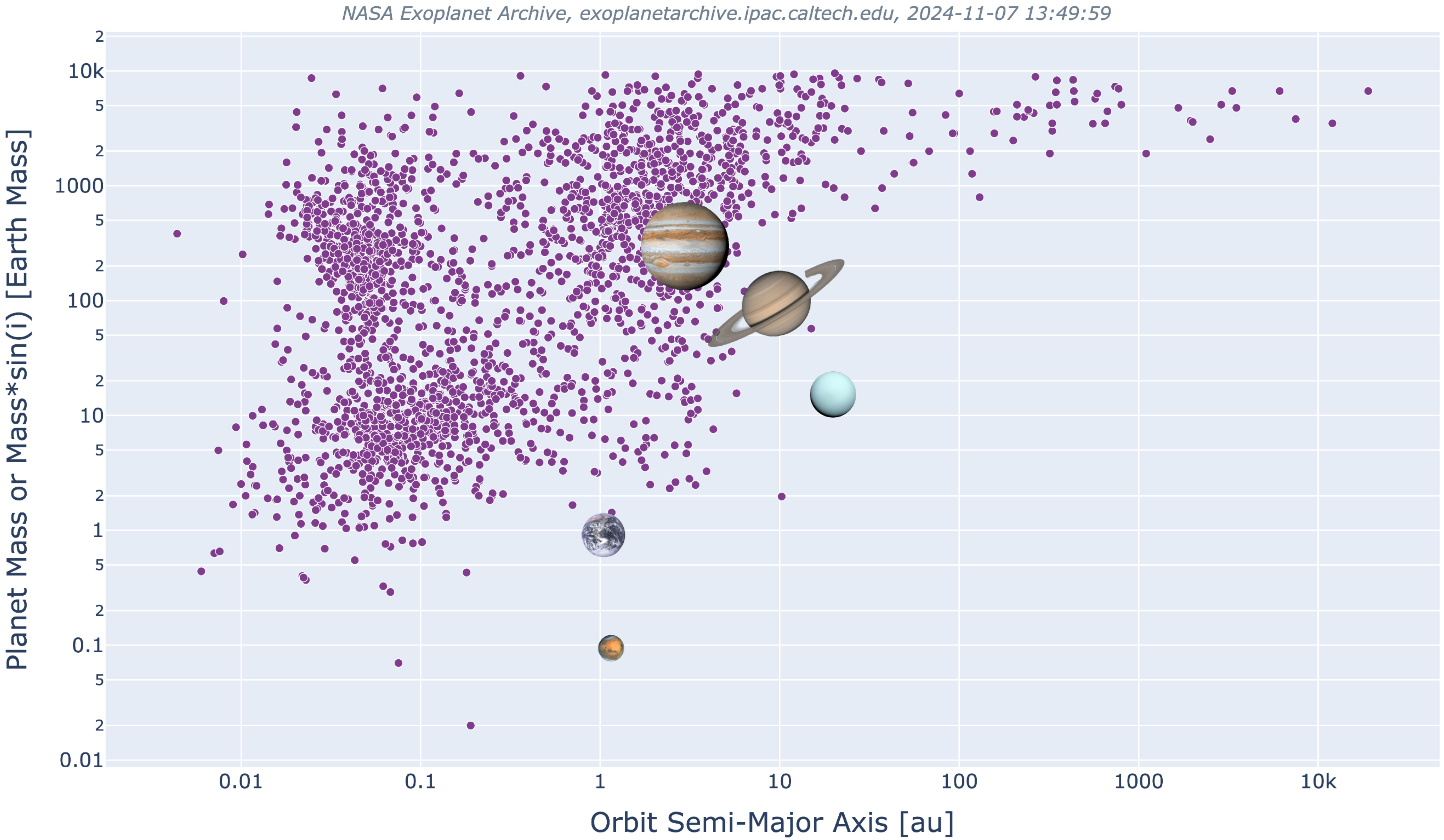
Exoplanets

We currently know of 6042 exoplanets (Oct 2025), discovered across all the different methods. Lots of planets with similar masses and radii to planets in the solar system



Exoplanets

However, these are all found around different types of stars at different orbital distances



Comparative Planetology

Our understanding of other worlds comes from comparisons to planets within the solar system.

We use terms such as “super-Earths,” “sub-Neptunes,” and “hot Jupiters” to describe exoplanets.

Initially we thought planets found around other stars would mimic the solar system since there is no reason to believe we are special/different.

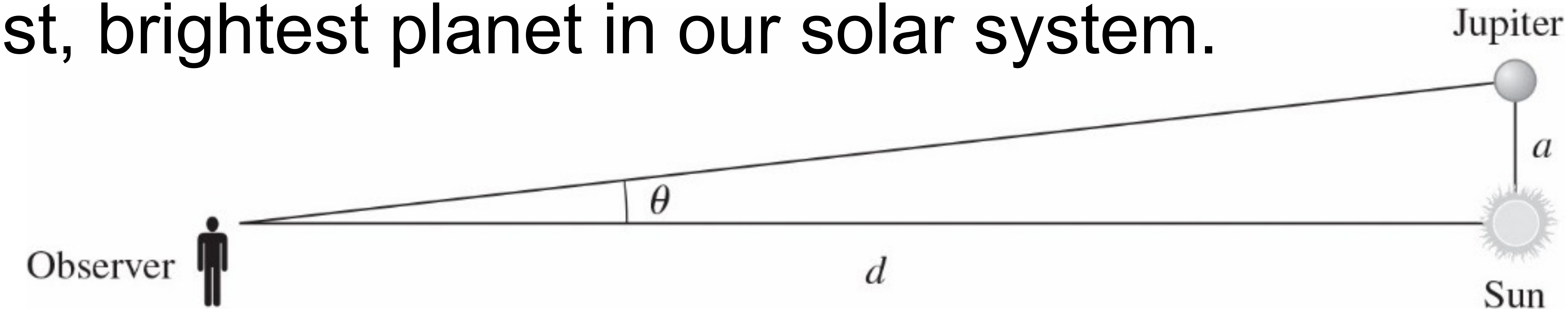
Solar System Formation in a Nutshell

We think all planetary systems undergo the same formation pathway as our solar system, therefore we would expect to see some similarities

1) Planetary orbits are all in nearly the same plane.
2) The star's equator lies close to this plane.
3) Planetary orbits are nearly circular.
4) Planets all orbit in the same direction.
5) Most planets (and the star) rotate in the same direction as the planets' orbital motion.

Exoplanet Detection (Direct Imaging)

Detecting exoplanets directly **is not trivial.** Consider Jupiter, the largest, brightest planet in our solar system.



The closest star to the Sun is Proxima Centauri at a distance of ~1.3 parsecs (270k AU).

The angular separation of Jupiter from the Sun seen from Proxima Centauri is

$$\theta = \frac{a}{d} = \frac{5.2\ \mathrm{AU}}{270000\ \mathrm{AU}} = 1.9 \times 10^{-5}\ \mathrm{radians}$$

Exoplanet Detection (Direct Imaging)

Astronomers like to speak in *arcseconds* though, so here's an easy conversion

$$\theta = 4.0 \text{ arcsec} \left(\frac{a}{5.2 \text{ AU}}\right)\left(\frac{d}{270{,}000 \text{ AU}}\right)^{-1}$$

Which, for this problem, is ~ 4 arcsec

Remember your equation for diffraction limited resolution, which states that

$$\theta = 1.22\frac{\lambda}{D} \rightarrow D = 1.22\frac{\lambda}{\theta}$$

Let's consider an optical telescope in the diffraction-limited case

$$D = 1.22\frac{6500 \text{ Å}}{1.9 \times 10^{-5} \text{ rad}} \approx 4.0 \text{ cm}$$

Meaning, at the distance of Proxima Centauri, an optical telescope with a diameter greater than 4cm could distinguish Jupiter from the Sun.

That is a pretty small telescope so we could detect this no problem, right?

*Exoplanet Detection (Direct Imaging)

Not so fast! First, we need to consider how bright Jupiter is relative to the Sun by comparing the luminosities of both bodies.

At visible wavelengths, Jupiter's luminosity is primarily the reflected light from the Sun, so its luminosity is given as

$$L_{\mathrm{Jup}} = \left(\frac{L_{\odot}}{4\pi a^2}\right)\left(\pi R_{\mathrm{Jup}}^2\right)A = \frac{L_{\odot}}{4}\left(\frac{R_{\mathrm{Jup}}}{a}\right)^2 A,$$

where A is the albedo of Jupiter (~0.51).

*Relevant for HW set.

*Exoplanet Detection (Direct Imaging)

We can compare this to the Sun's luminosity

$$\frac{L_{\mathrm{Jup}}}{L_{\odot}} = \frac{A}{4}\left(\frac{R_{\mathrm{Jup}}}{a}\right)^2 \approx \frac{0.51}{4}\left(\frac{7.2\times 10^4\ \mathrm{km}}{7.4\times 10^8\ \mathrm{km}}\right)^2 \approx 4\times 10^{-9}$$

That is a large **contrast ratio** (the comparison of brightness between two celestial objects). This is actually a really difficult measurement to make.

We call this exoplanet detection method **direct imaging**.

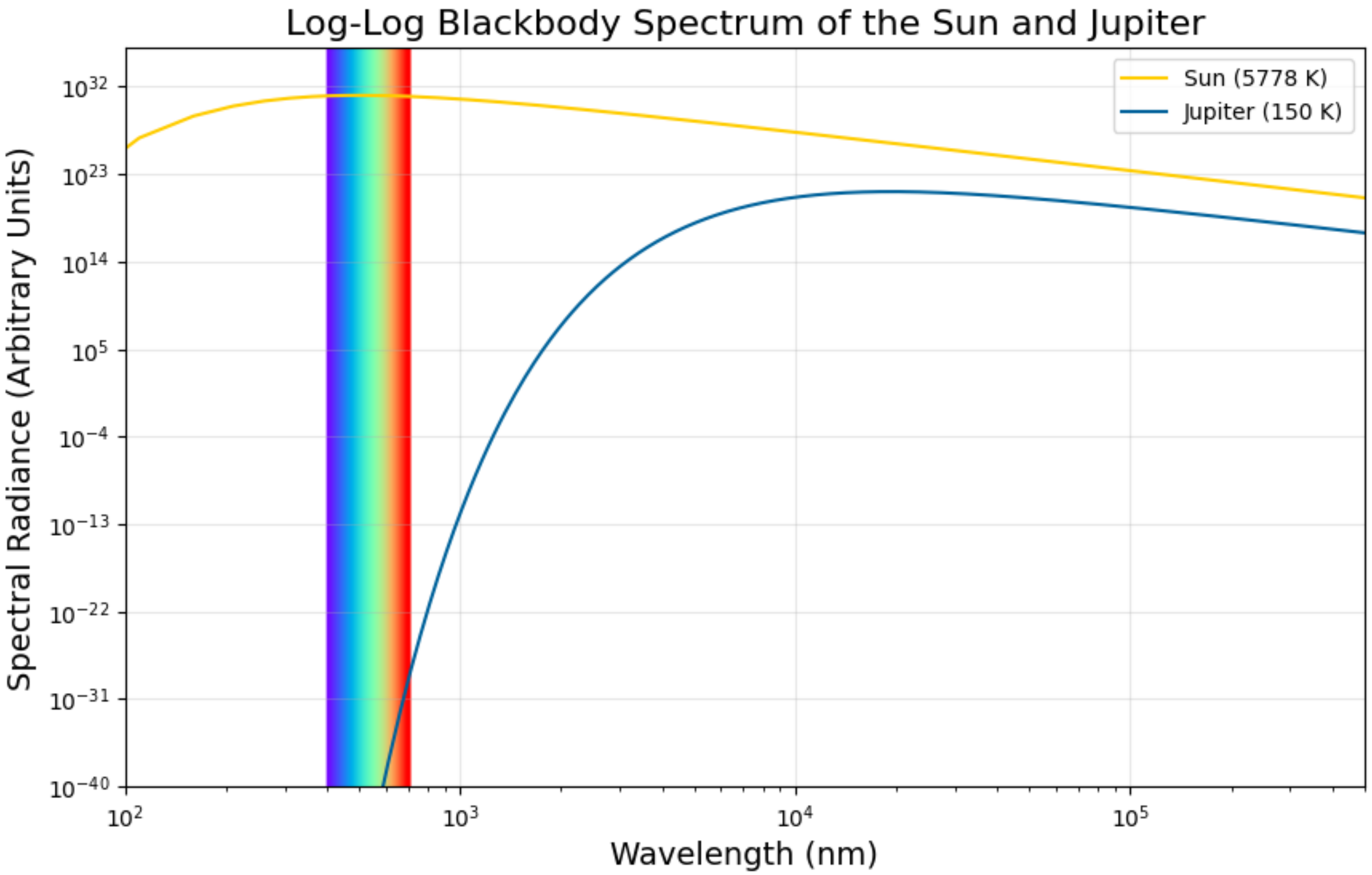
*Relevant for HW set.

Brain Break – Think-pair-share

The figure below shows the *blackbody brightness* of Jupiter and the Sun as a function of wavelength. We've seen that at visible wavelengths directly imaging a Jupiter from the distance of Proxima Centauri is extremely challenging.

1.) Is there an alternative wavelength range that would make this detection *easier*?

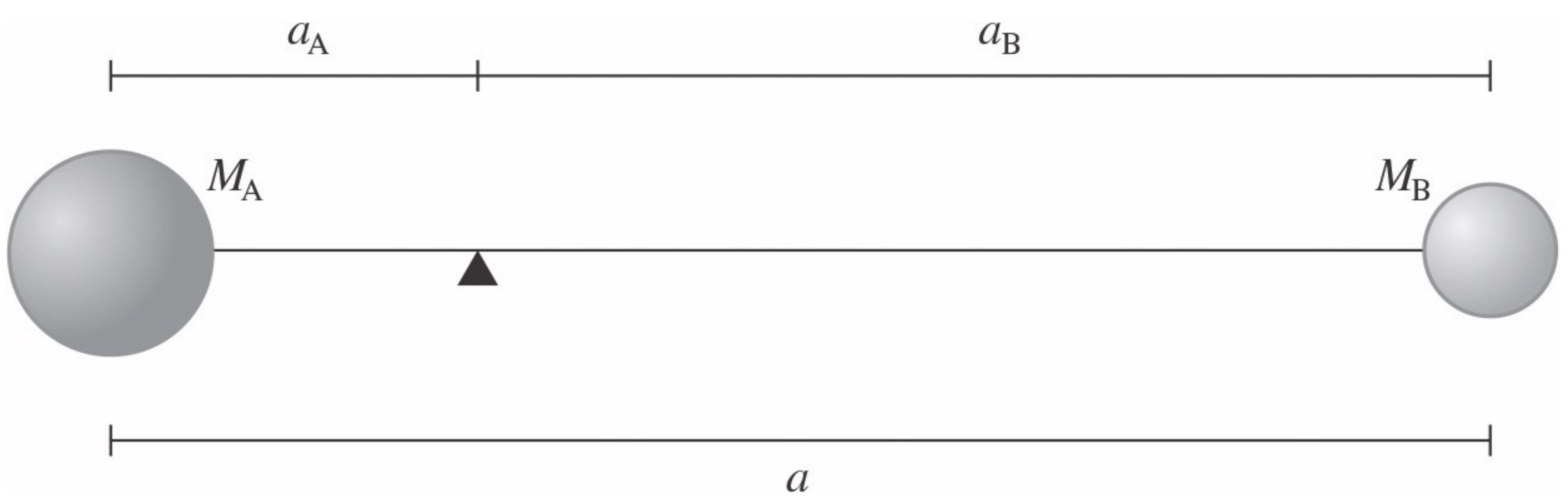
2.) Using this wavelength range, find the minimum telescope diameter required to resolve Jupiter from the Sun, assuming that you are observing from Proxima Centauri.



Exoplanet Detection (Astrometry)

What if instead we looked for the **planets influence on its host star,** without the need to directly detect the planet at all?

The planet will tug on the star since they orbit around their center of mass (CoM).



The animation below shows that, for a fixed orbital separation, **a higher planet-to-star mass ratio results in a larger "stellar wobble",** as seen from the increased size of the star's orbit around the center of mass.

By definition of CoM,

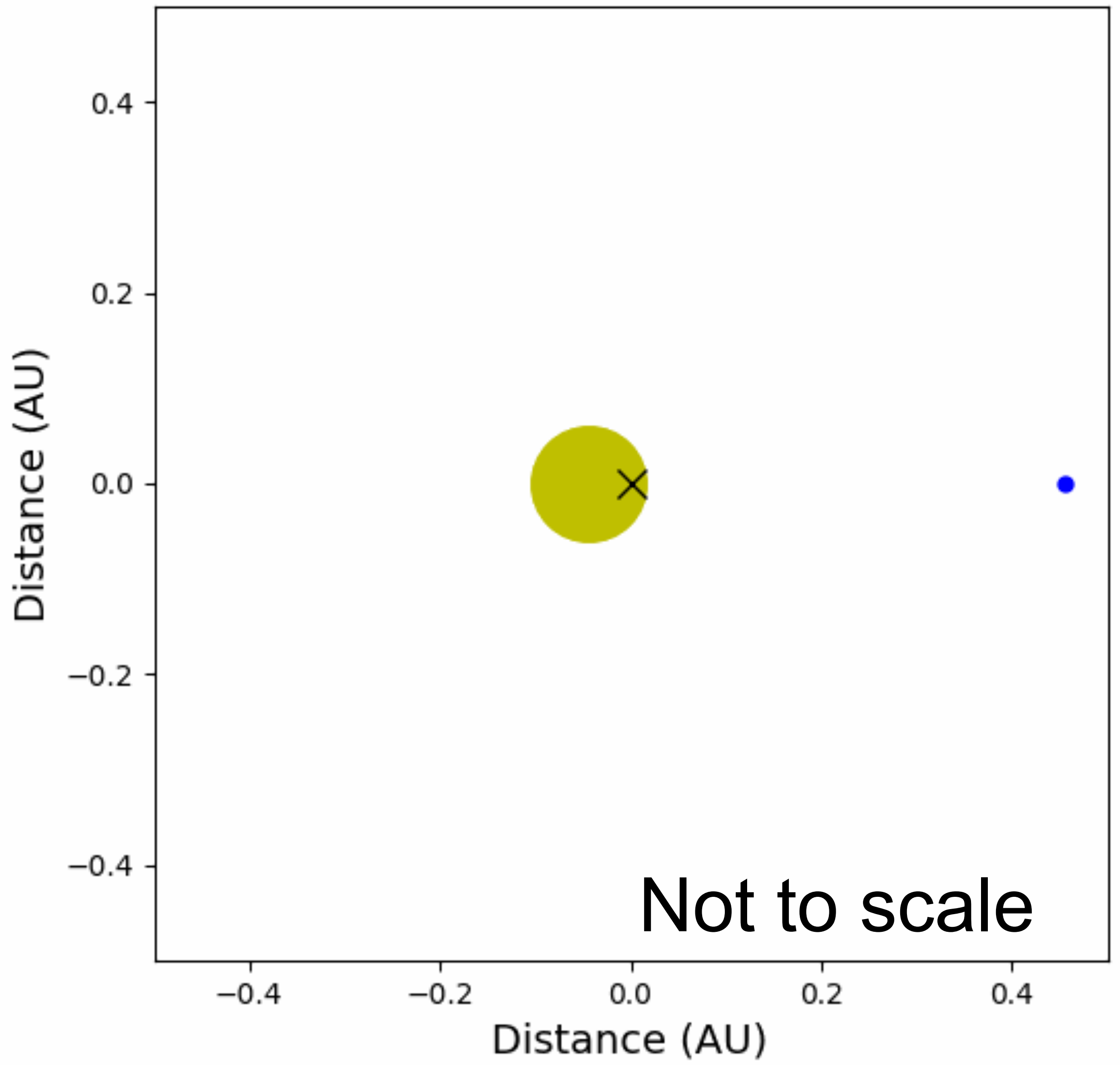
$$a_A M_A = a_B M_B$$

Which we can rewrite as,

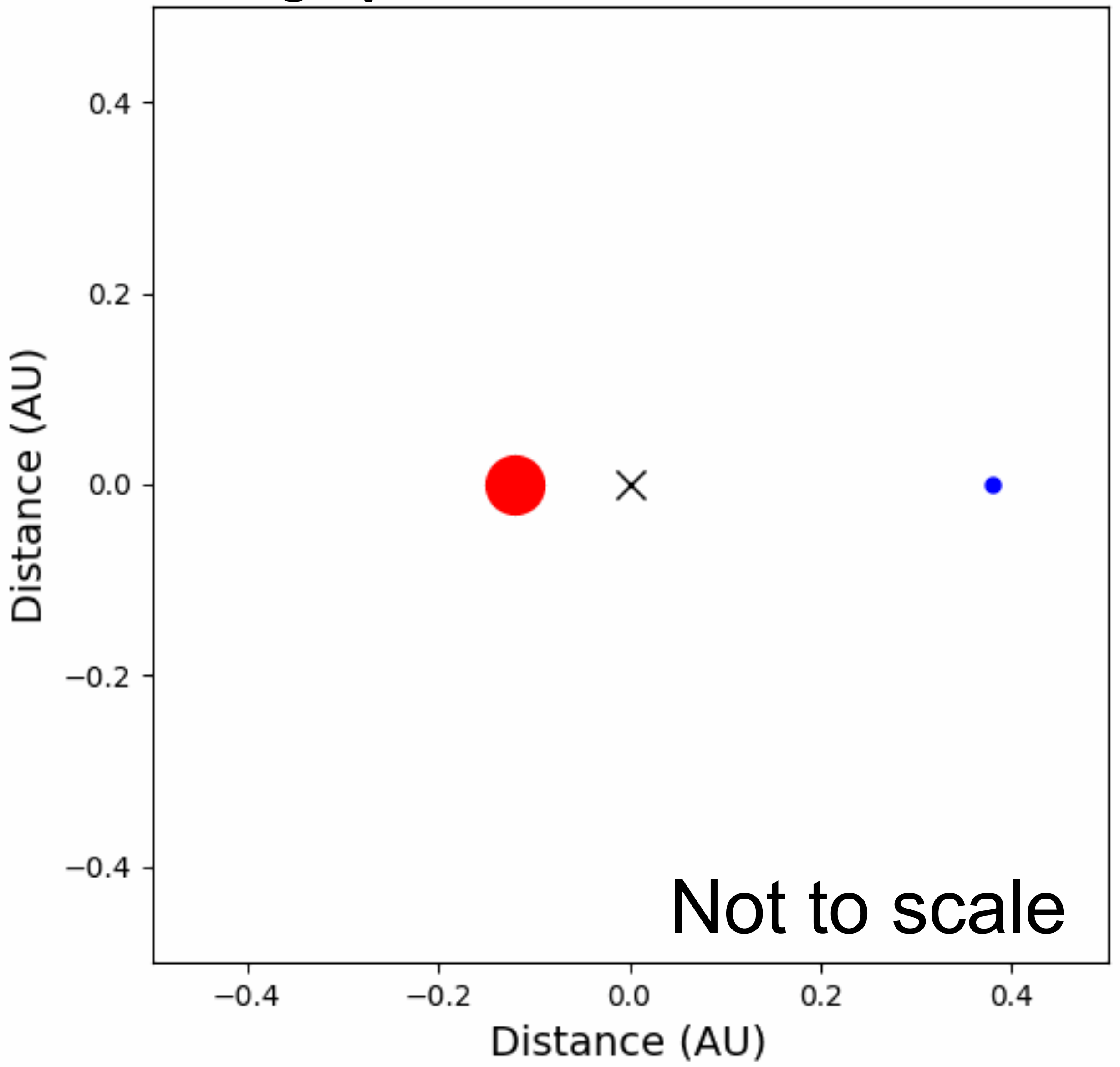
$$\frac{a_B}{a_A} = \frac{M_A}{M_B}$$

The center of mass is **always closer to the more massive object.**

Low planet-to-star mass ratio



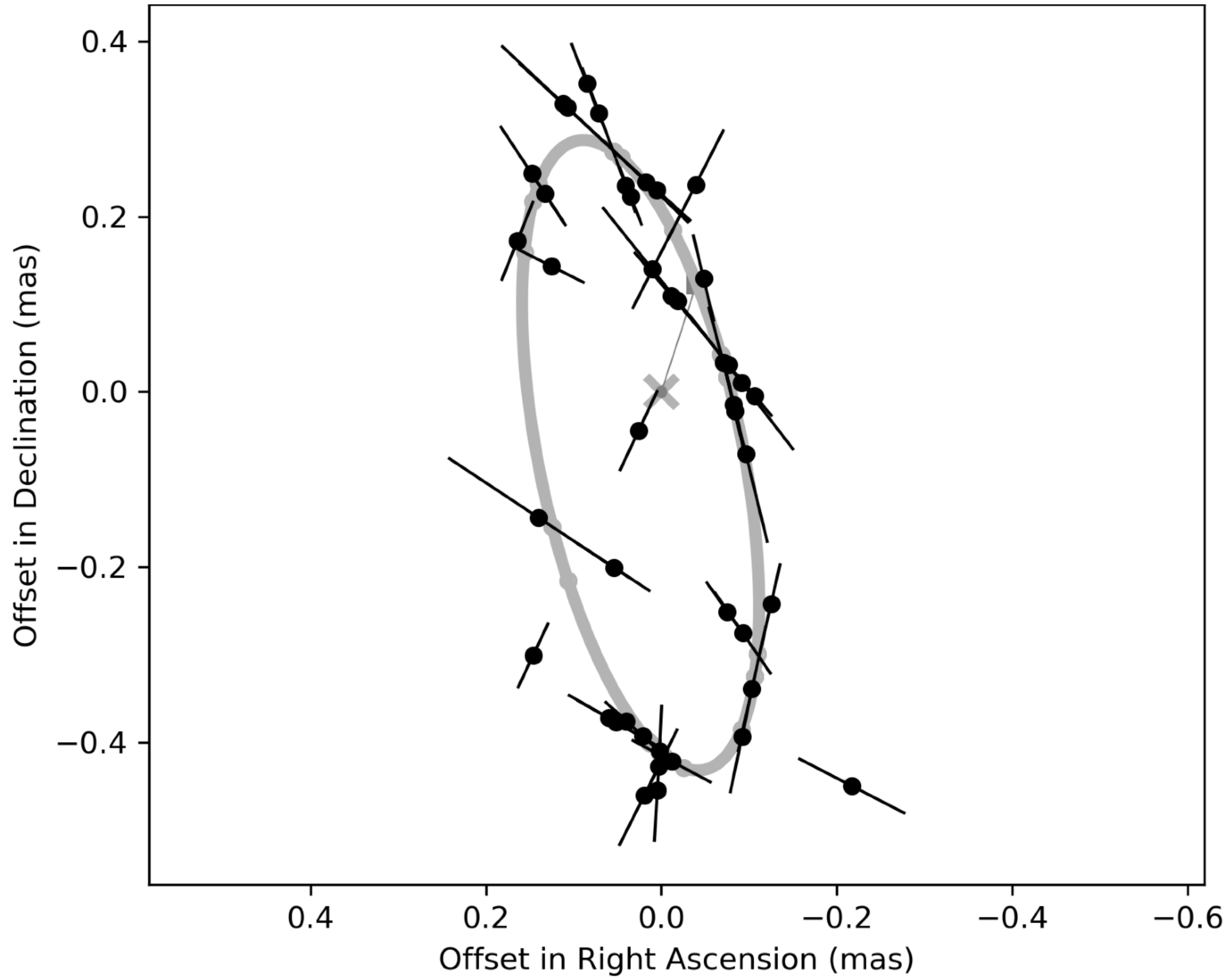
High planet-to-star mass ratio



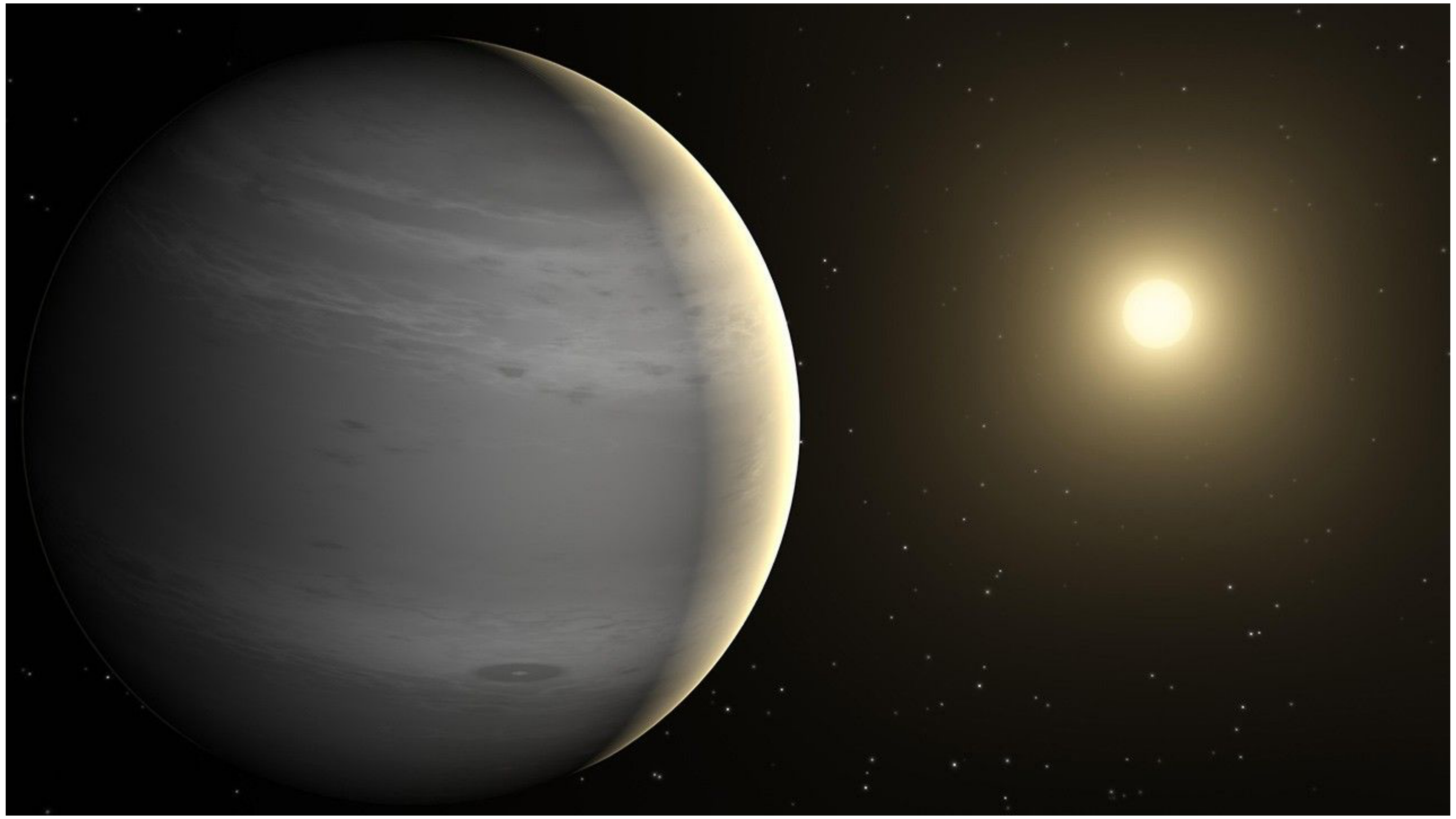
Exoplanet Detection (Astrometry)

If you detect the planet through the “wobble” of its host star, we call this an **astrometric** detection.

Astrometric orbit of HD81040



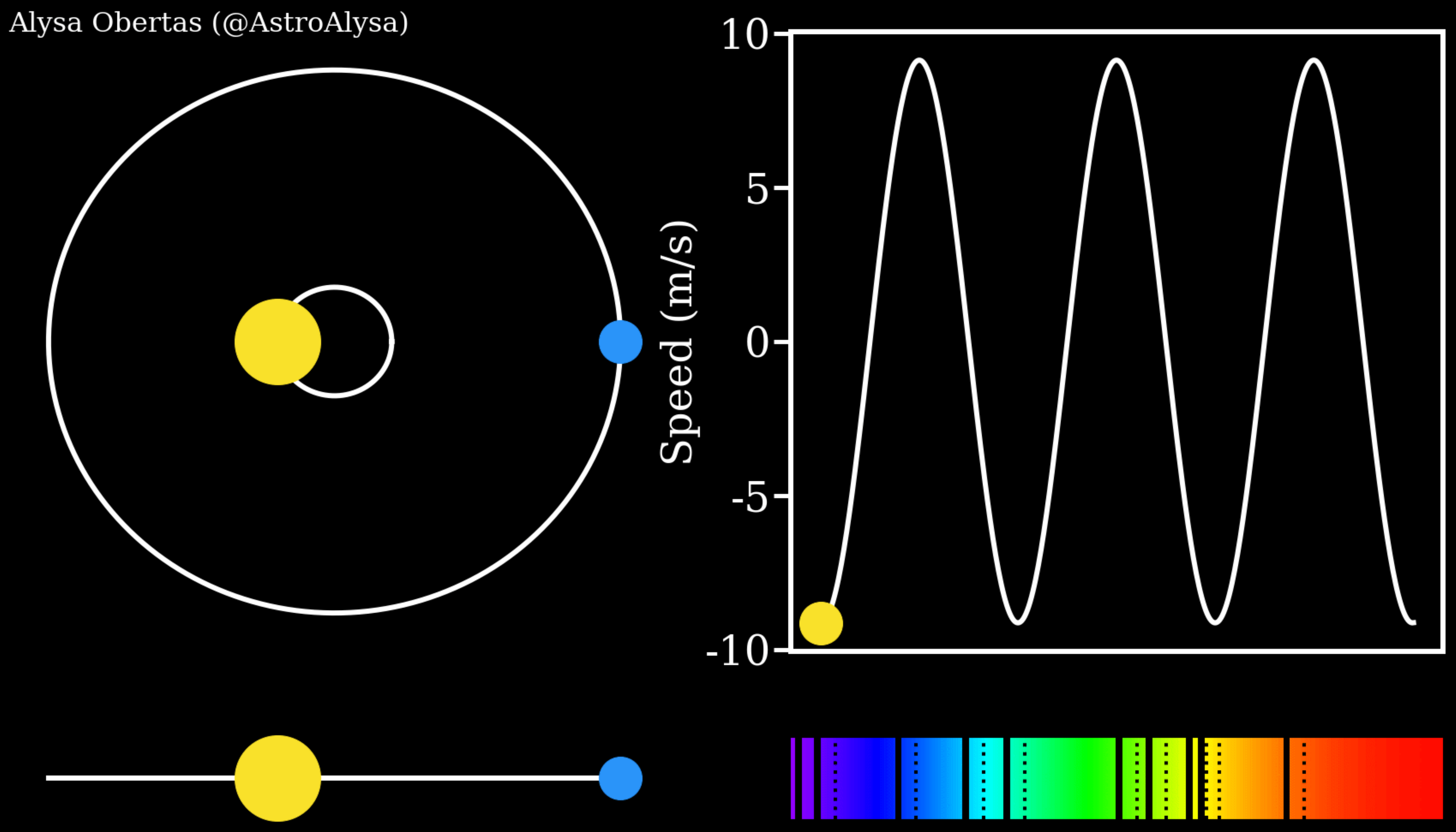
Artist rendition of the gas giant HD81040B orbiting its host star



Above is the astrometric detection of a gas giant planet by *Gaia* using this technique.

Exoplanet Detection (Radial Velocity)

If the orientation of the orbital plane is (mostly) along the line of sight, we can detect the motion through spectroscopy.



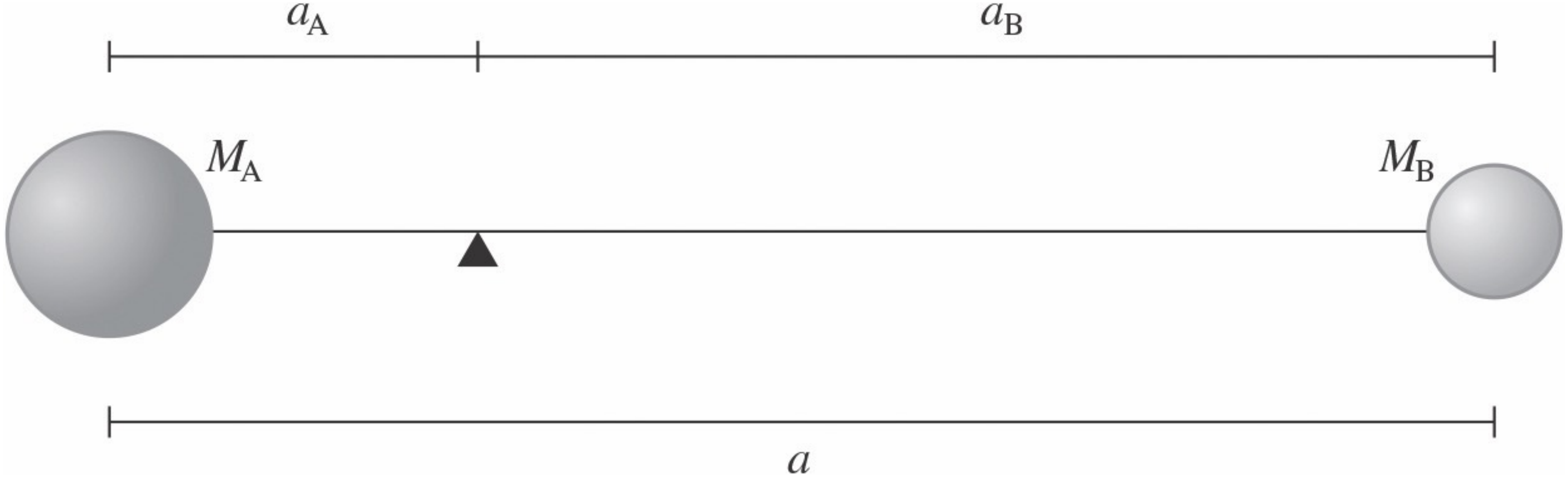
As the star moves *towards* us the spectrum is shifted to bluer/shorter wavelengths (blueshift), and as it moves *away* it's shifted to redder/longer wavelengths (redshift)

Exoplanet Detection (Radial Velocity)

If we see a shift in doppler shift in wavelength ($\Delta\lambda$) that is directly related to the speed of the object (v_r) through

$$\frac{\Delta\lambda}{\lambda} = \frac{v_r}{c}$$

Let's consider the simple case where we have a star of mass M_{A} and a planet of mass M_{B} on a circular orbit about their CoM.

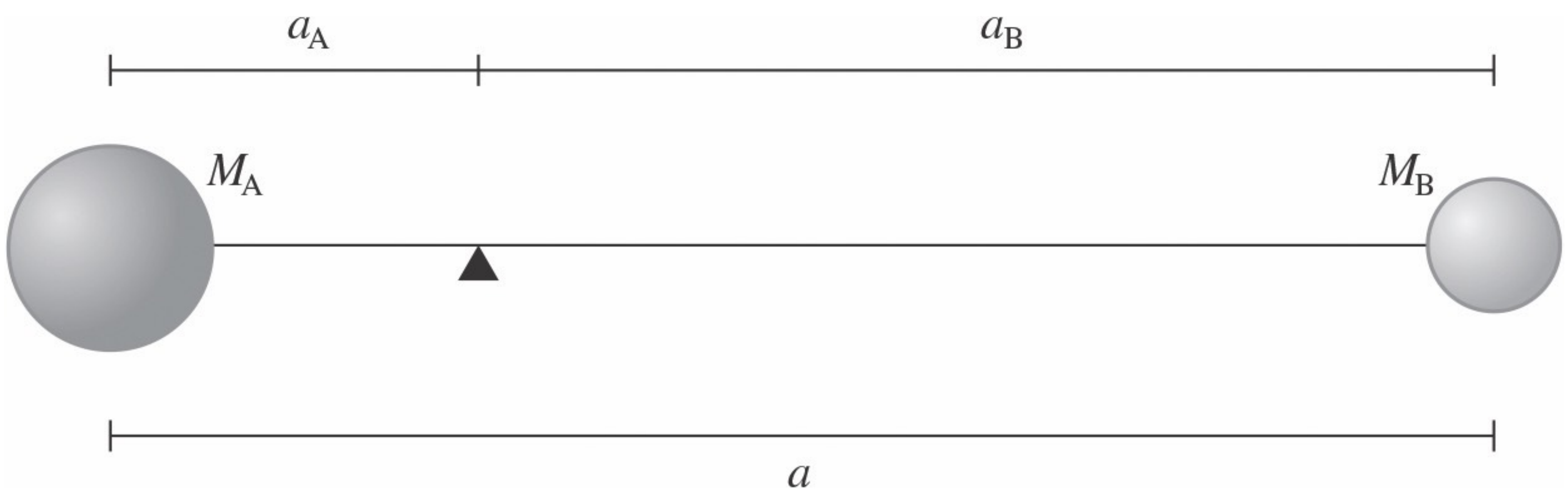


Exoplanet Detection (Radial Velocity)

The orbital periods of the star and planet are the same, i.e., they take equal amounts of time to orbit around their CoM.

Therefore, if they are moving with speeds v_A and v_B

$$P = \frac{2\pi a_A}{v_A} = \frac{2\pi a_B}{v_B}$$



From the CoM we can deduce

$$\frac{v_A}{v_B} = \frac{a_A}{a_B} = \frac{M_B}{M_A}$$

Exoplanet Detection (Radial Velocity)

Let's use the Jupiter–Sun system as an example. Approximating Jupiter's orbit as circular, its orbital speed is

$$v_B = \frac{2\pi a_B}{P} = \frac{2\pi\,(5.2\ \mathrm{AU})}{11.9\ \mathrm{yr}} = \frac{2\pi\,(5.2\times 1.50\times 10^{8}\ \mathrm{km})}{11.9\times 3.16\times 10^{7}\ \mathrm{s}} \approx 13\ \mathrm{km\ s^{-1}}\,.$$

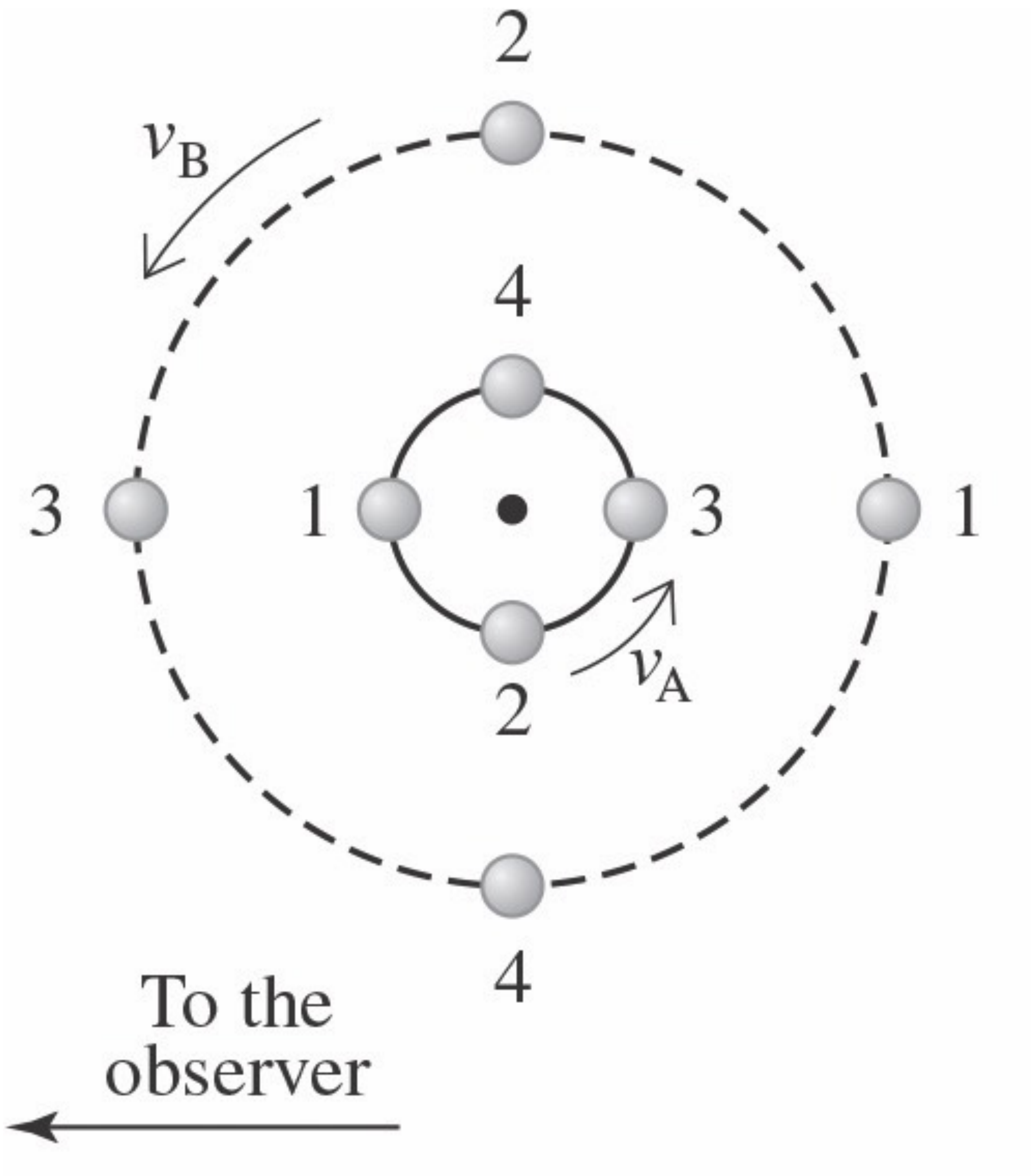
The orbital speed of the Sun around the center of mass is then

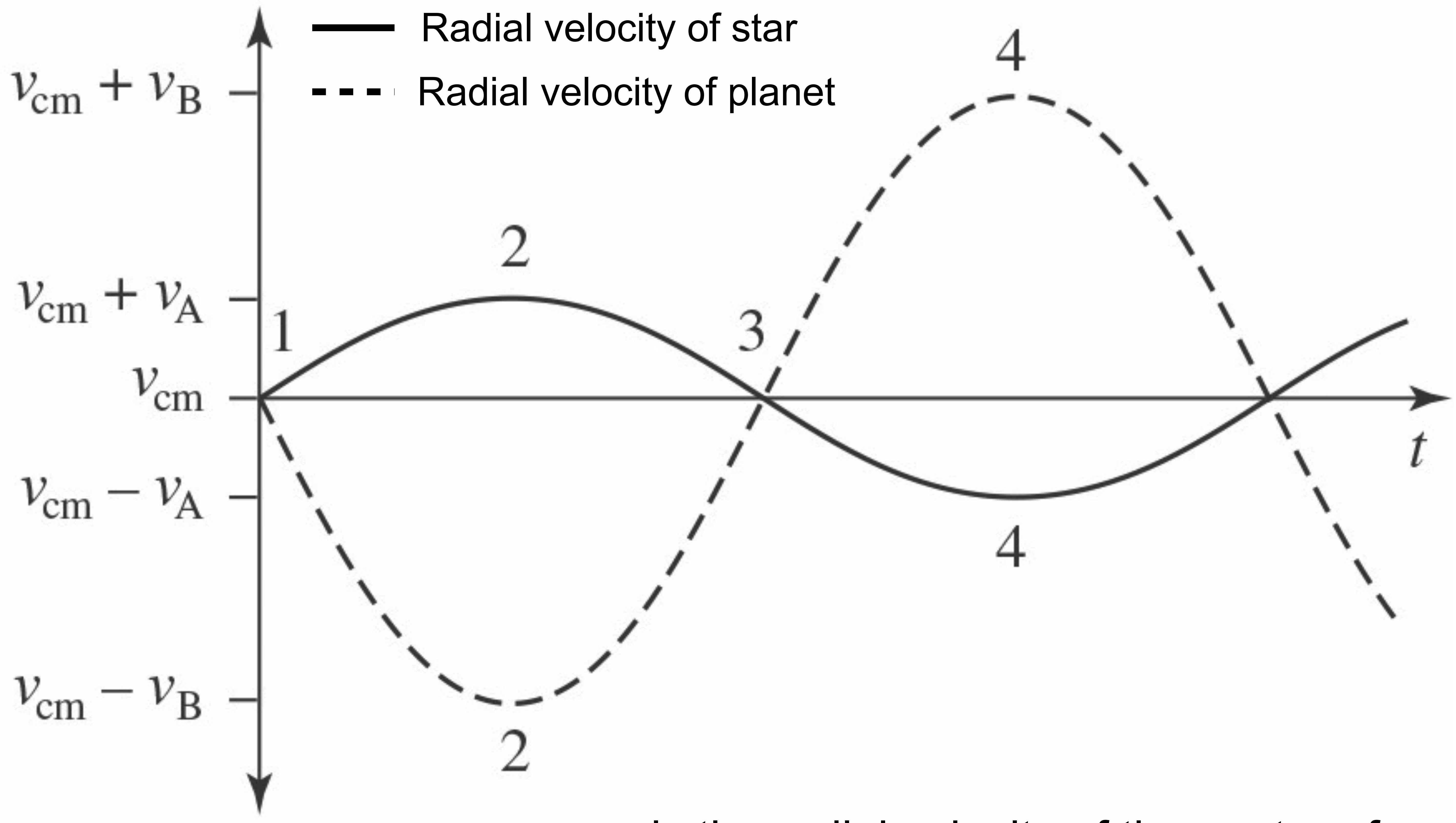
$$v_A = \frac{M_B}{M_A} v_B = 0.001\times 13\ \mathrm{km\ s^{-1}} \approx 13\ \mathrm{m\ s^{-1}}\,.$$

With current techniques, the radial velocity of relatively bright stars can be measured to within $\sim 1\ \mathrm{m\ s^{-1}}$; thus, it is technologically feasible to detect Jupiter-like exoplanets from their effect on the radial velocity of Sun-like stars.

Exoplanet Detection (Radial Velocity)

By measuring shifts in the star's spectral lines, we can construct its *radial velocity curve*, from which the **masses of both the star and planet can be inferred.**





v_{cm} is the radial velocity of the center of mass

Note: This represents the ideal scenario of an edge-on system consisting of a single star and a single planet.

Exoplanet Detection (Radial Velocity)

From Kepler's third law we know:

$$\left(a_{\mathrm{A}} + a_{\mathrm{B}}\right)^3 = \frac{G\left(M_{\mathrm{A}} + M_{\mathrm{B}}\right)}{4\pi^2} P^2$$

In the case where $M_A \gg M_B$, and hence $a_B \gg a_A$, we can simplify the modified version of Kepler's third law:

$$(a_A + a_B)^3 = \frac{G(M_A + M_B)}{4\pi^2} P^2 \ \rightarrow a_B^3 \approx \frac{GM_A}{4\pi^2} P^2$$

As we'll see in Lecture 15, we can determine a star's mass from its spectrum.

With this information, we can calculate the orbit of its exoplanet using the following formula:

$$a_B \approx 1\ \mathrm{AU} \left(\frac{M_A}{1\ M_\odot}\right)^{1/3} \left(\frac{P}{1\ \mathrm{yr}}\right)^{2/3}$$

Exoplanet Detection (Radial Velocity)

Using the relation $a_B = \frac{M_A}{M_B} a_A$, we can rewrite the size of the orbit planet's orbit as,

$$a_B^3 \approx \frac{M_A^3}{M_B^3} a_A^3 \approx \frac{G M_A P^2}{4\pi^2}$$

Solving for the planet's mass (M_B), we find

$$M_B \approx \left(\frac{4\pi^2 M_A^2}{G P^2} a_A^3 \right)^{1/3}$$

Although a_A, the size of the star's orbit, is generally too small to be measured astrometrically, we can substitute $2\pi a_A = P v_A$ into the equation to yield

$$M_B \approx \left(\frac{M_A^2 P}{2\pi G} v_A^3 \right)^{1/3}$$

Thus, by measuring the amplitude of the star's radial velocity curve (v_A), we can infer the planet's mass!

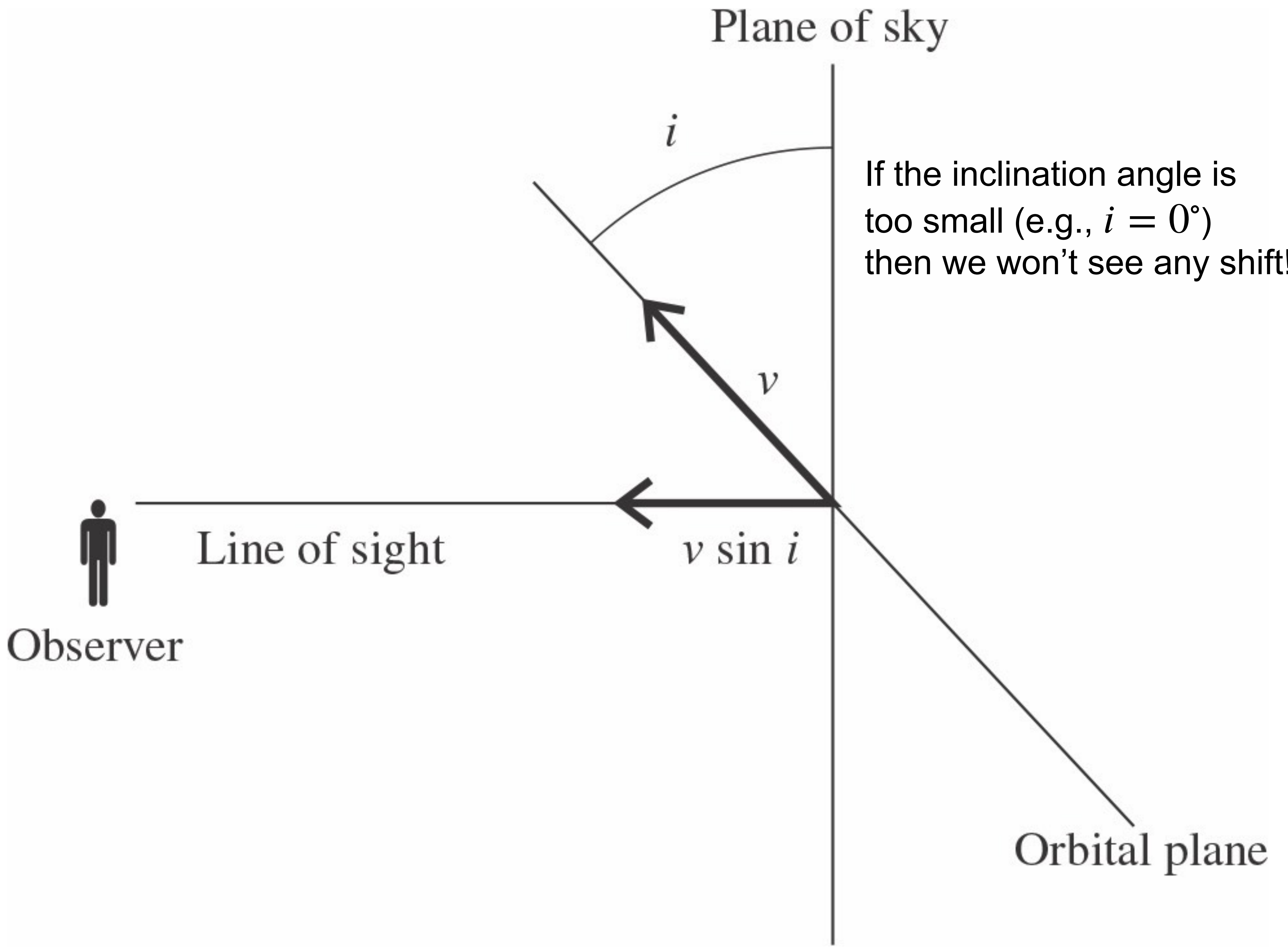
Exoplanet Detection (Radial Velocity)

However, this specific case **assumes that the orbital plane is directly along our line of sight.** In general, we *do not know* the "inclination angle" of the orbit!

- In reality, using the radial velocity method alone, we can only measure $v_A \sin i$ (and hence $M_B \sin i$).

- Since v_A is not directly observable, we cannot determine M_B precisely.

- Instead, the radial velocity method only allows us to compute the planet's **minimum mass.**



If the inclination angle is too small (e.g., $i = 0°$) then we won't see any shift!


Pause

Exoplanet Detection (Transit Method)

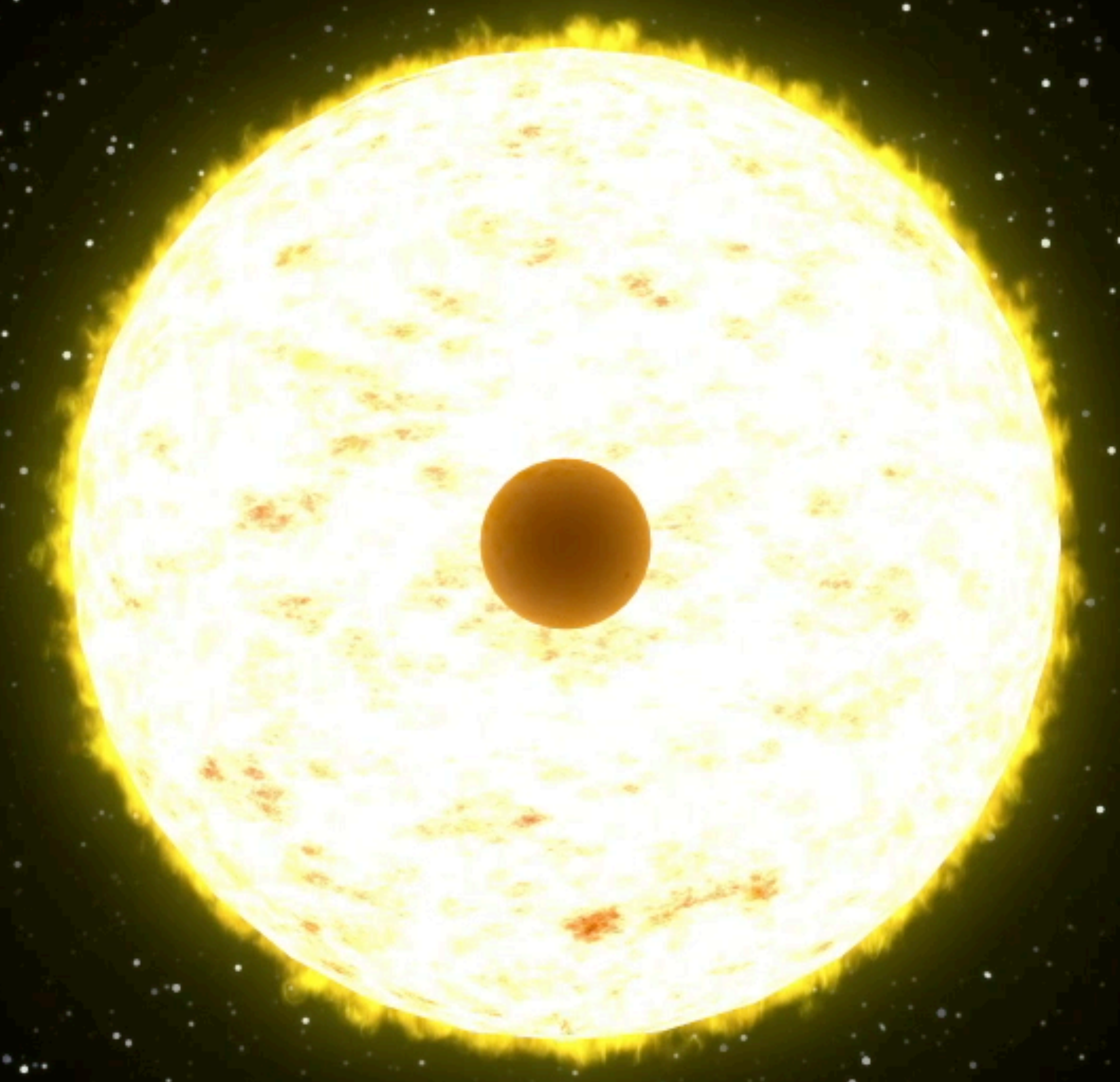
Let's consider the case when the orbital plane is *exactly* aligned with your line of sight (i.e., $i = 90°$)

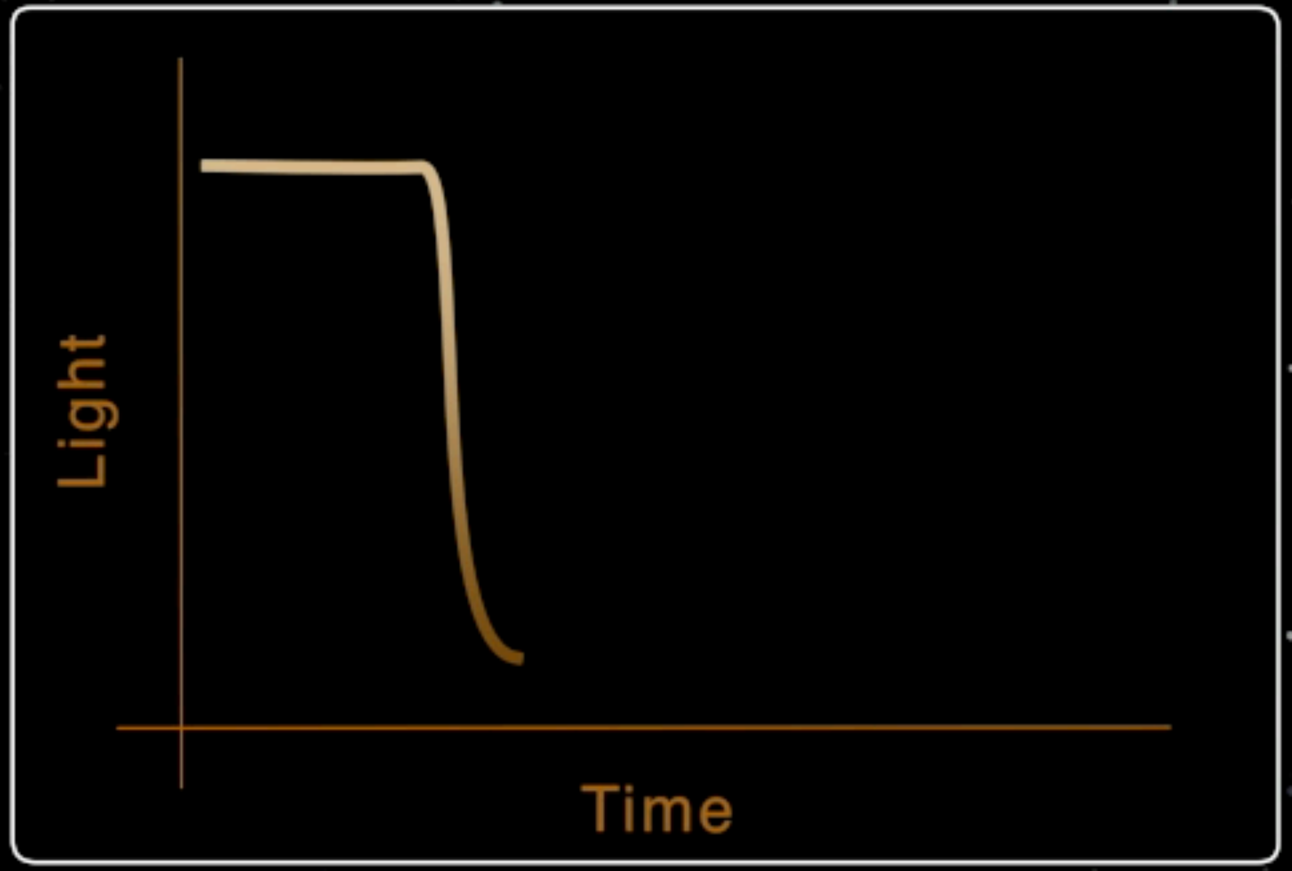
In this case **the planet passes directly in front of the star as we observe it through its orbit.**

However, just using the radial velocity technique **we would never know if it's exactly aligned with our line of sight**, we need some other information to break the "$\sin(i)$ degeneracy".

Exoplanet Detection (Transit Method)

As a planet moves in front of its star, it blocks out some light, and we can detect this change using extremely sensitive *photometers*.





Exoplanet Detection (Transit Method)

The dip in brightness observed <u>at mid-transit</u> **is directly proportional the the ratio of the size of the star and planet.**

$$\frac{\delta F}{F} = \frac{\pi R_B^2}{\pi R_A^2} = \left(\frac{R_B}{R_A}\right)^2$$

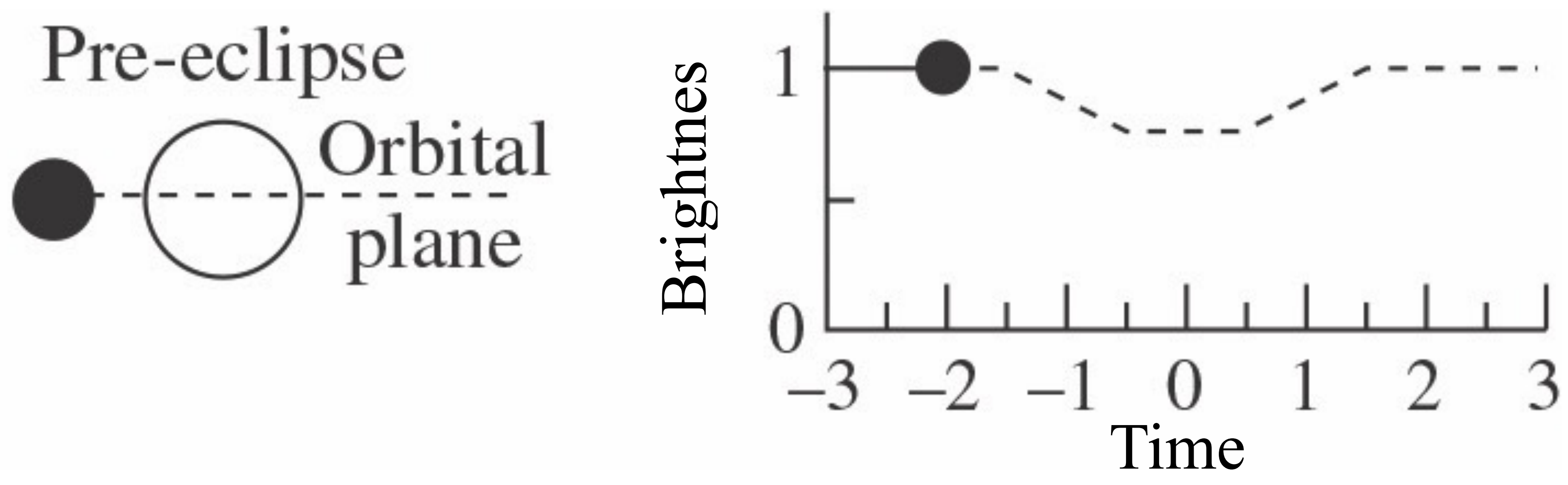
We know that Jupiter is about 1/10 the size of the Sun, so the observed dip in brightness for the Jupiter-Sun system would be

$$\left(\frac{R_\mathrm{B}}{R_\mathrm{A}}\right)^2 = \left(\frac{1}{10}\right)^2 = 0.01 = 1\% \text{ change in brightness}$$

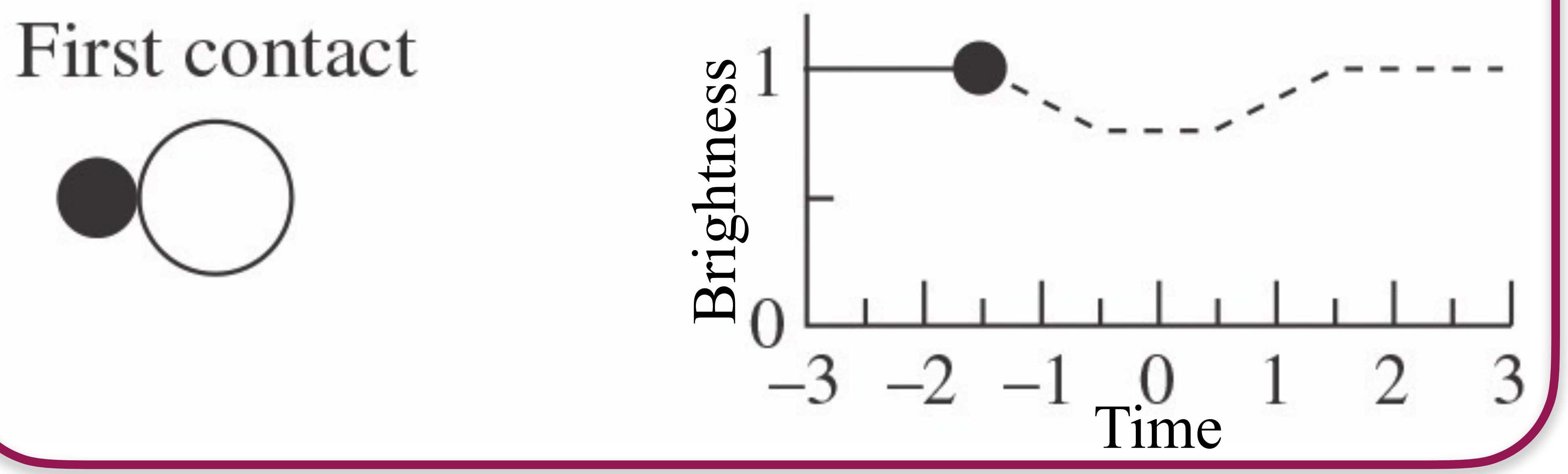
Exoplanet Detection (Transit Method)

The shape of the “light curve” (observed flux vs. time) informs us about the phase of the transit.

1. Initially we only see the star.

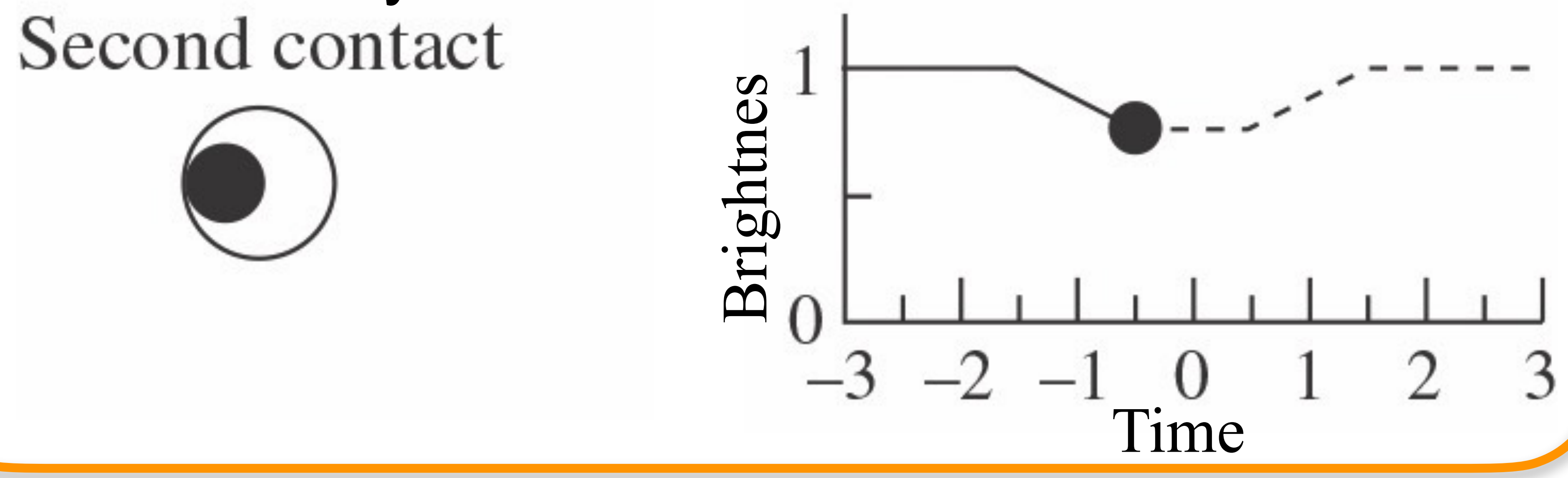


2. The point right before the transit begins.

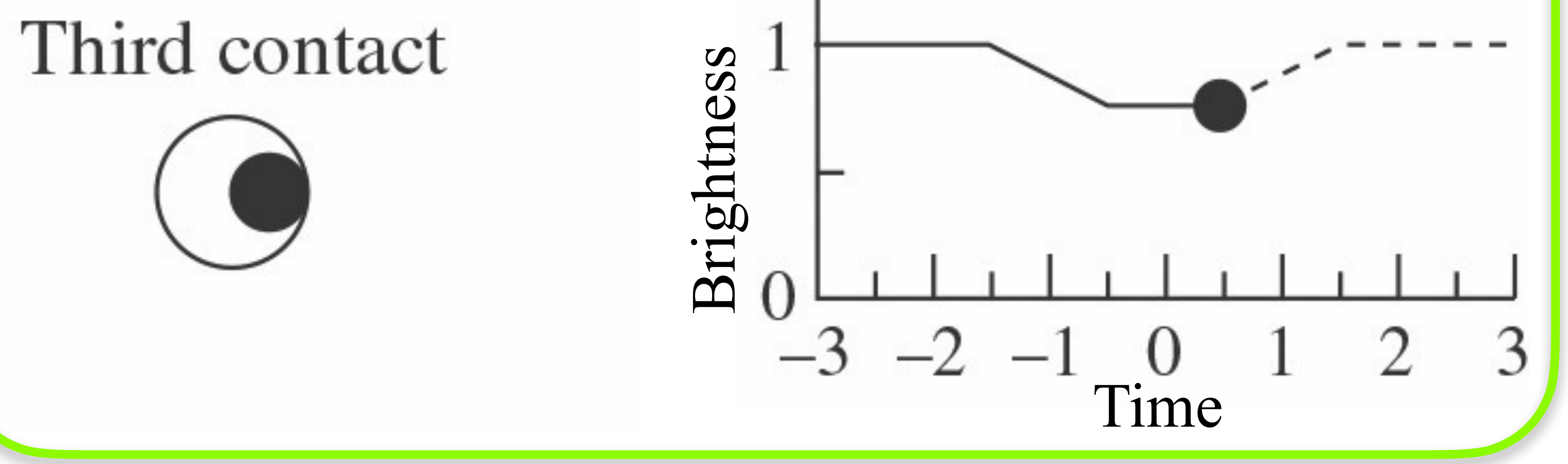


The time between **first and second** contact gives us the **size of the planet!**

3. Gradual decrease in brightness as the planet moves to fully block the star

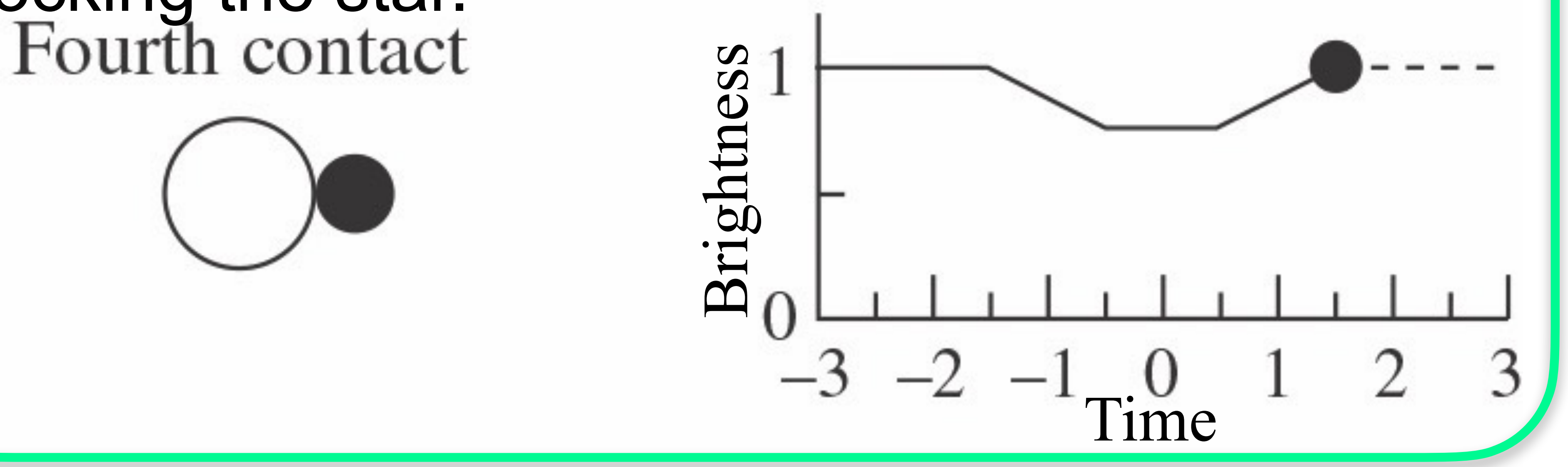


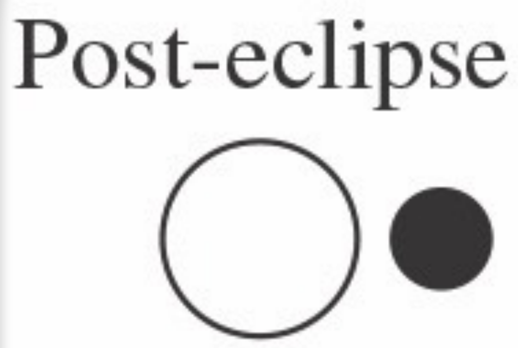
4. We see a relatively flat trough as the planet passes across the disk of the star



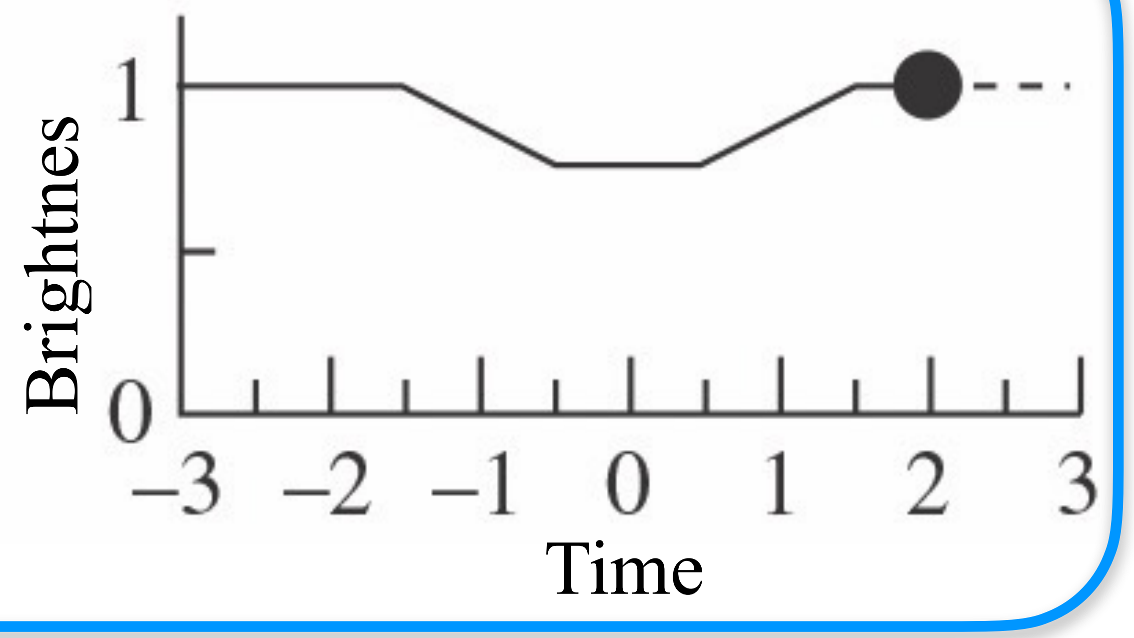
The time between **first and third** contact gives us the **size of the star!**

5. Gradual increase as the planet moves to stop blocking the star.



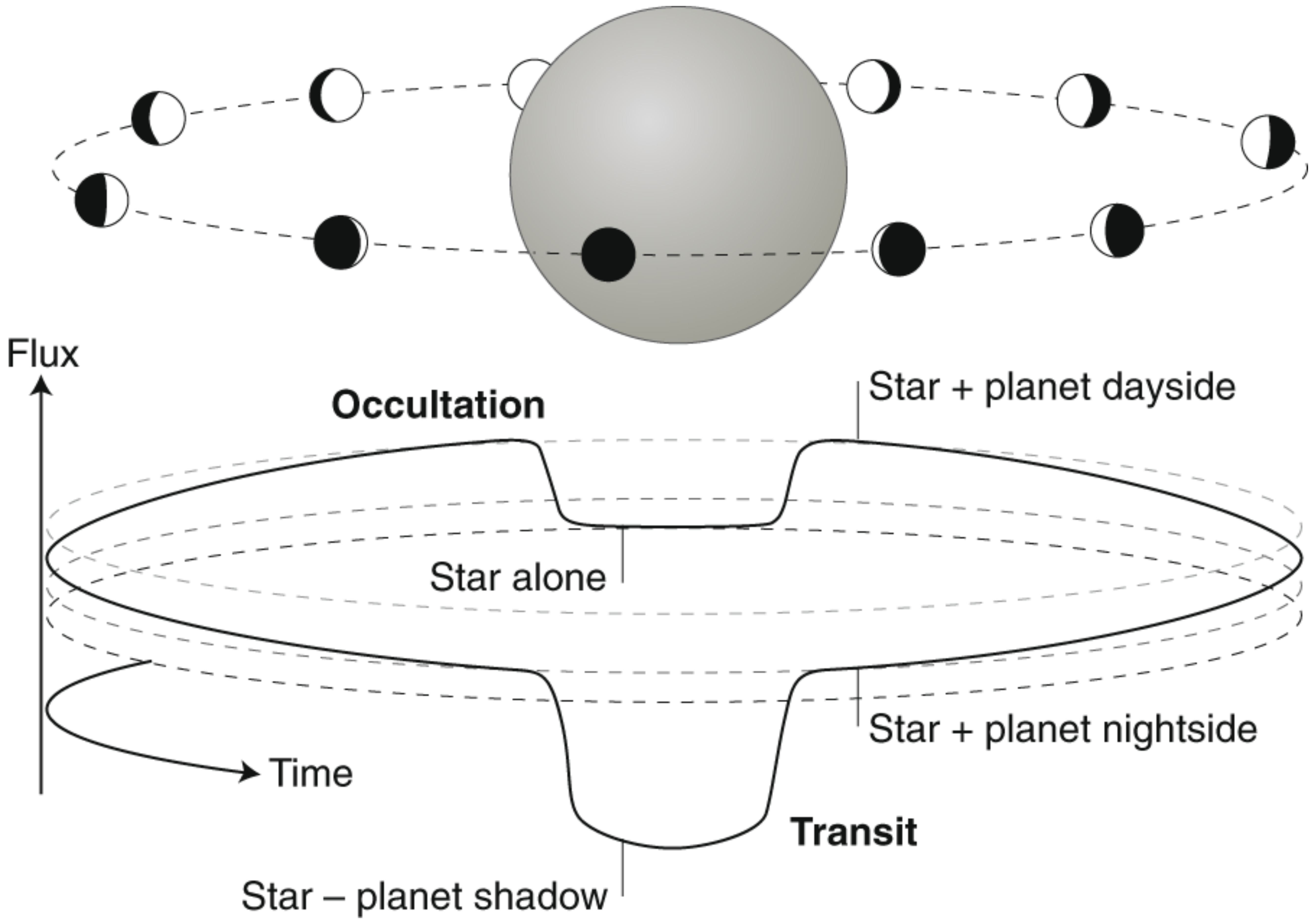


6. We see just the star again.



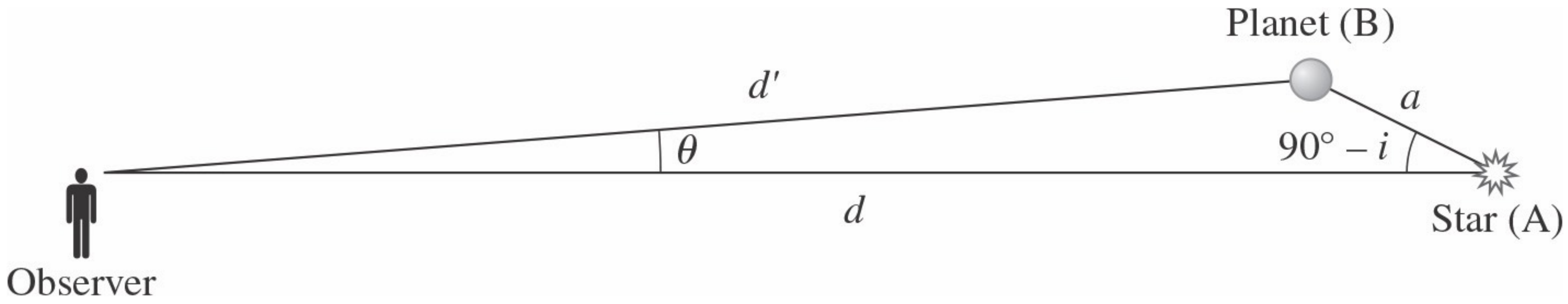
Exoplanet Detection (Transit Method)

The reality however is that the transit can look more complicated



Condition for a planet to transit

Considering the specific geometry required, we can do some math to estimate how many planetary systems will be transiting systems.



In the above image, if the angle θ is *too large* **this system will not transit.**

The observer will see a transit when the angle θ between the planet's center and the star's center satisfies the relation:

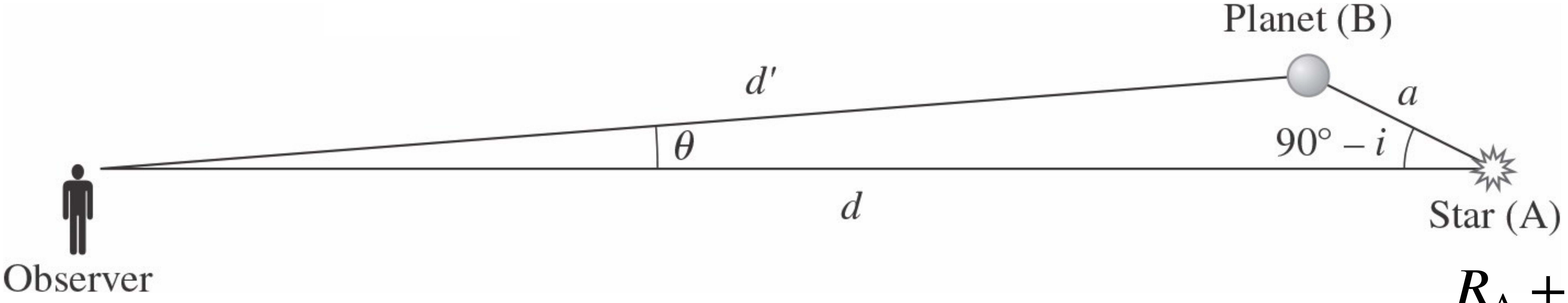
$$\theta \leq \theta_A + \theta_B = \frac{R_A}{d} + \frac{R_B}{d'} \approx \frac{R_A + R_B}{d}$$

Where, θ_A and θ_B are the angular radii of the star and planet, respectively.

Condition for a planet to transit

Using the law of sines we find,

$$\frac{\sin(\theta)}{a} = \frac{\sin(90^\circ - i)}{d'}$$

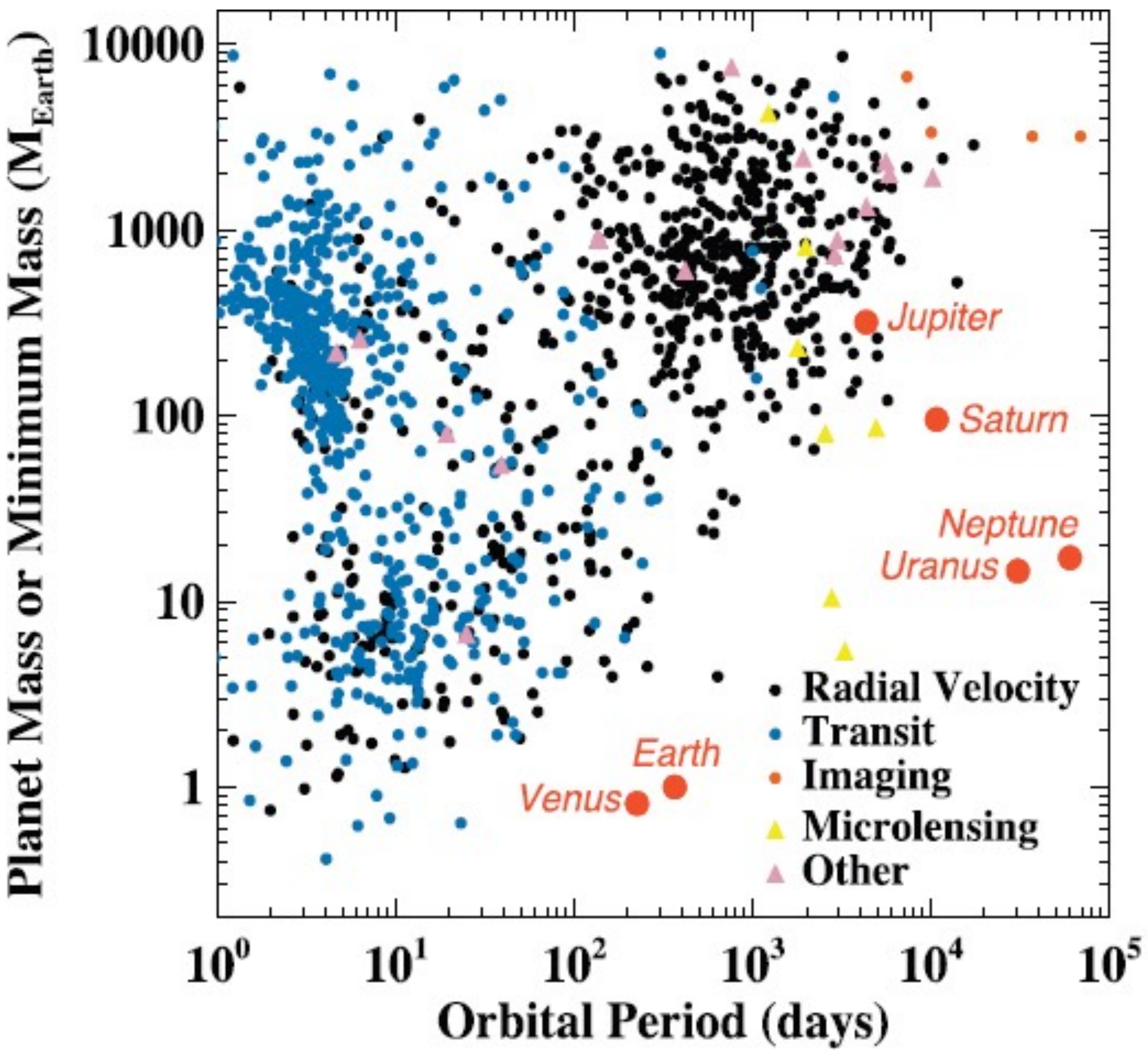


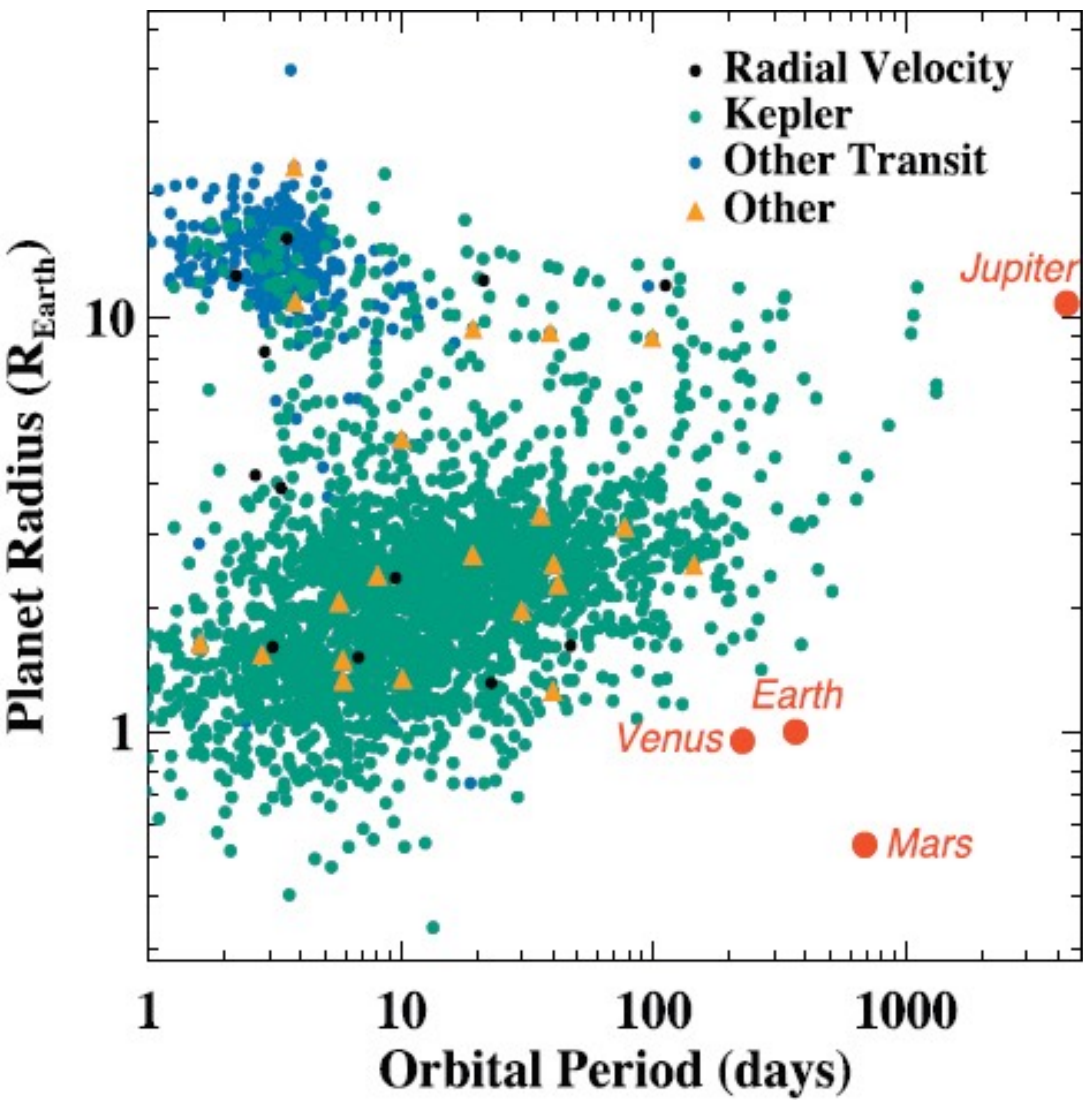
Combining this with the condition for a transiting system $\theta \leq \theta_A + \theta_B \approx \dfrac{R_A + R_B}{d}$

We obtain,

$$\frac{a}{d}\cos(i) \leq \frac{R_A + R_B}{d}$$

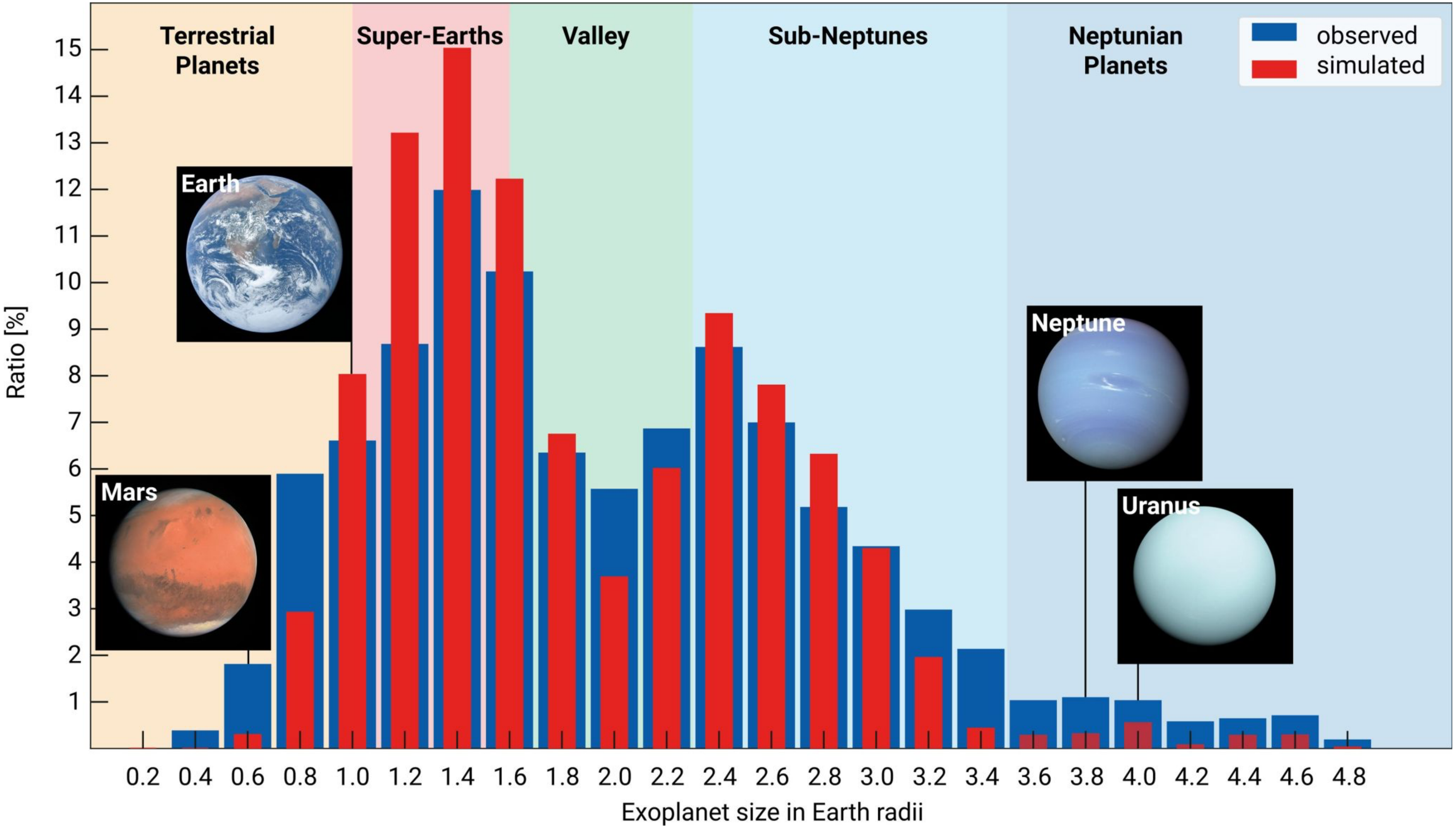
Different methods have different sensitivities





Direct imaging detects long period (large distance) planets
Radial velocity detects larger, closer-in planets
Transit method detects short period planets at all sizes

Sizes of known exoplanets

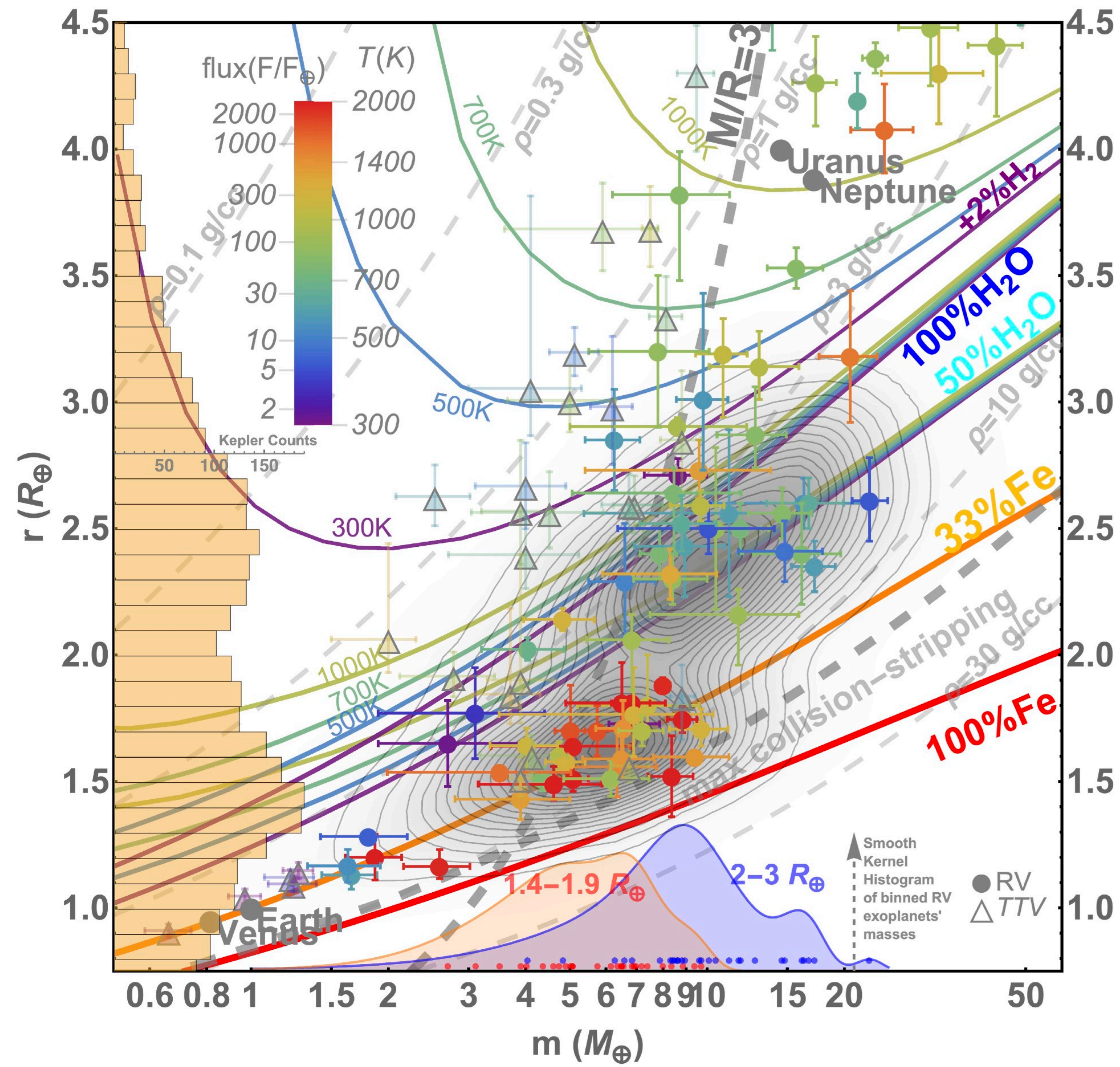


Lot’s of “super-Earths” and “sub-Neptunes”, but none in our solar system.

Densities of exoplanets

Combining radii and mass measurements we can estimate the average density!

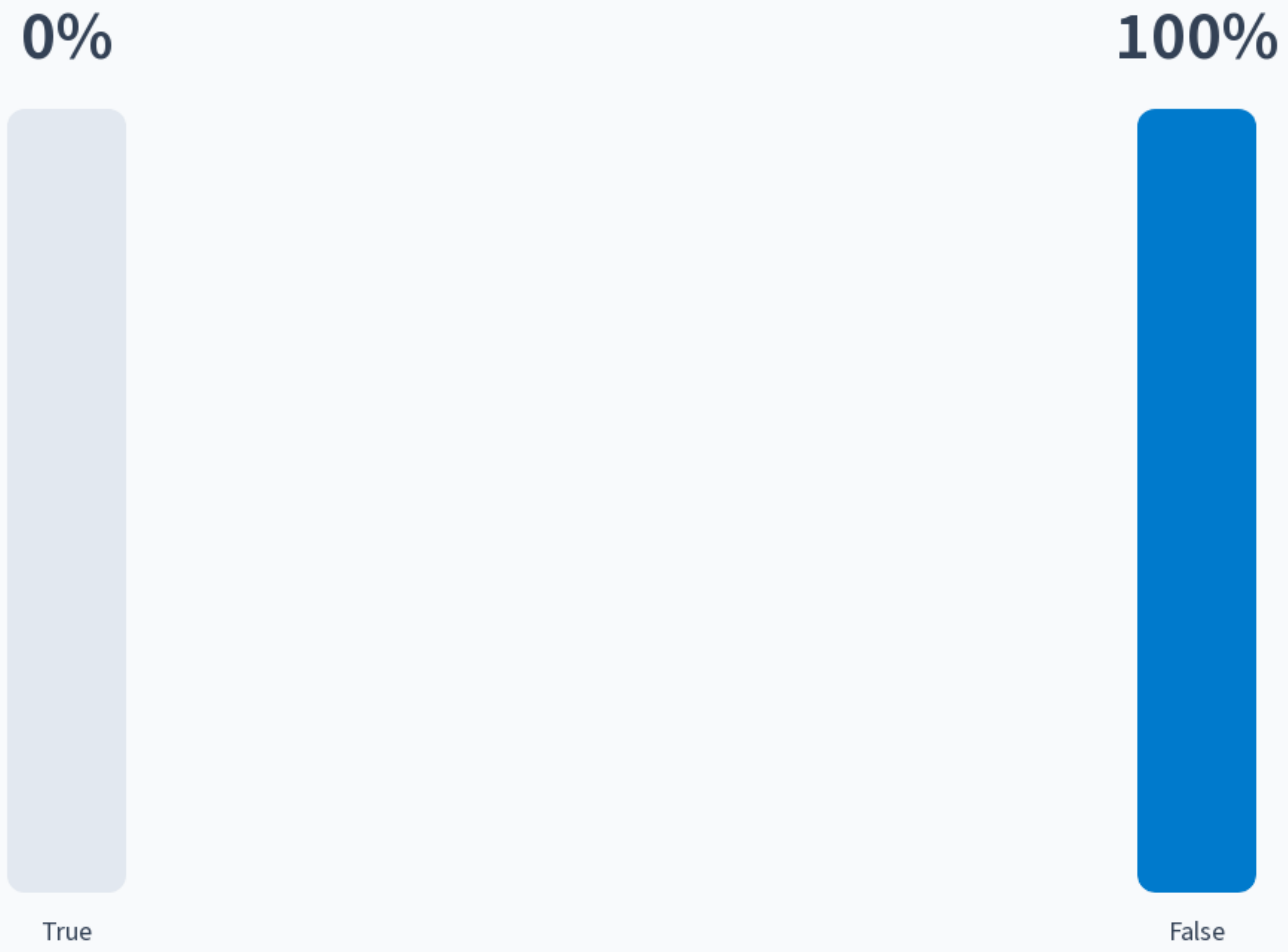
This allows us to compare these to densities with different bulk compositions!



Assessment of Learning Objectives

True or False: Using the radial velocity method alone, we can determine a planet's radius and minimum mass.

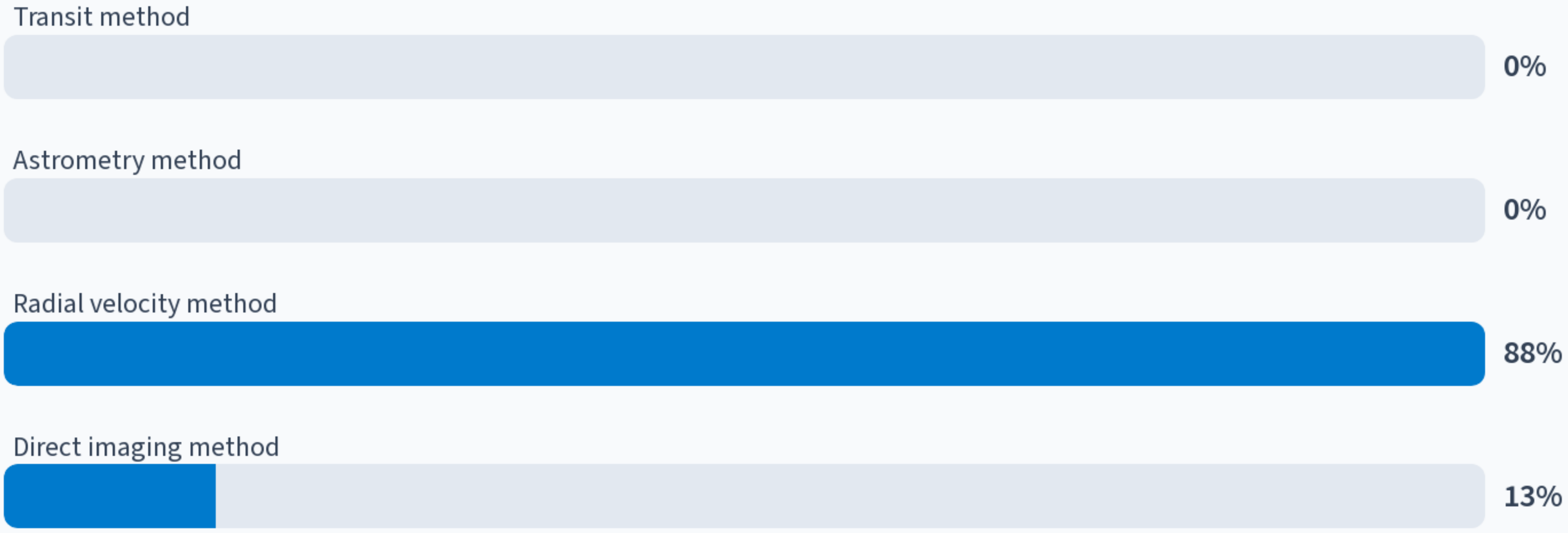
True or False: Using the radial velocity method alone, we can determine a planet's radius and minimum mass.



Which method detects exoplanets by measuring Doppler shifts in a star's spectrum?

Transit method	0%
Astrometry method	0%
Radial velocity method	0%
Direct imaging method	0%

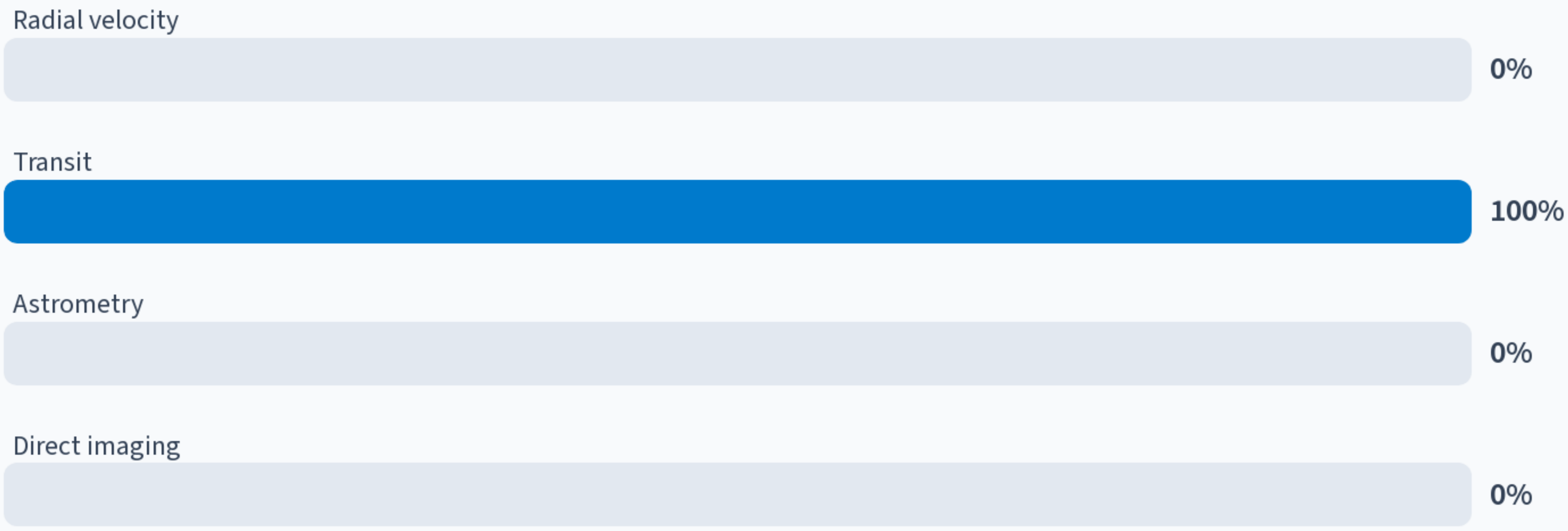
Which method detects exoplanets by measuring Doppler shifts in a star's spectrum?



Which detection method allows us to determine the radius of an exoplanet?

Radial velocity	0%
Transit	0%
Astrometry	0%
Direct imaging	0%

Which detection method allows us to determine the radius of an exoplanet?



What is the primary limitation of the direct imaging method for detecting exoplanets?

It requires the planet to transit its host star.

0%

It can only detect planets along our line of sight.

0%

It is extremely challenging due to the star’s overwhelming brightness compared to the planet.

0%

It can only measure the planet’s minimum mass.

0%

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0%

It can only detect planets along our line of sight.
0%

It is extremely challenging due to the star’s overwhelming brightness compared to the planet.
100%

It can only measure the planet’s minimum mass.
0%

Reminders

- **HW #7 is due Tuesday, 11/25, by 11:59 pm.**
- **Coding project is due Sunday, 11/30 by 11:59 pm.**
- Log into canvas and submit your answer to the discussion question by the end of the day to receive participation credit.