ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 21: Exoplanets

Logistics

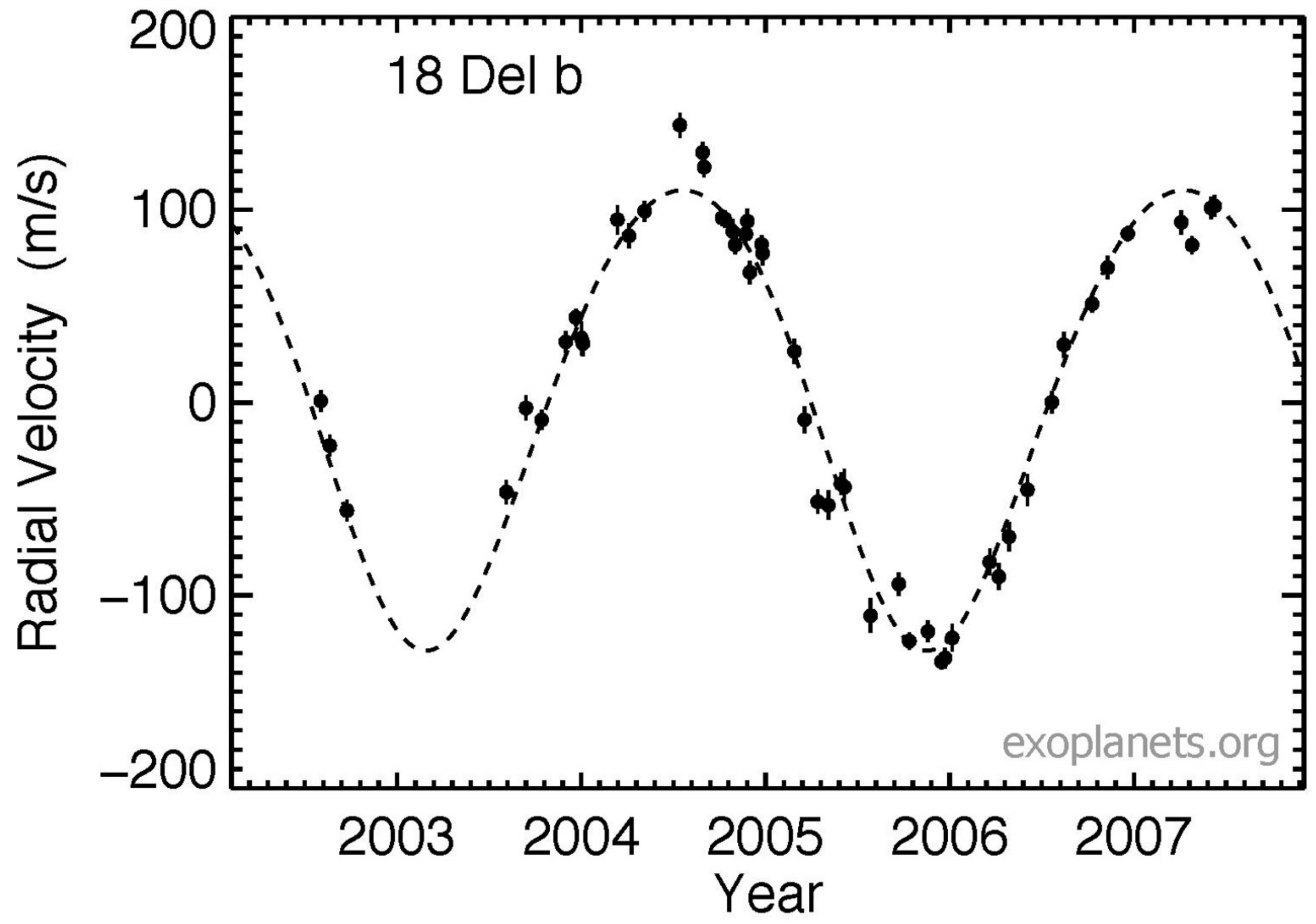
- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 5 due on Monday, November 7 at 11:59pm
- Order of Magnitude project written assignment due Monday, November 14 at the start of class
- Jury Duty

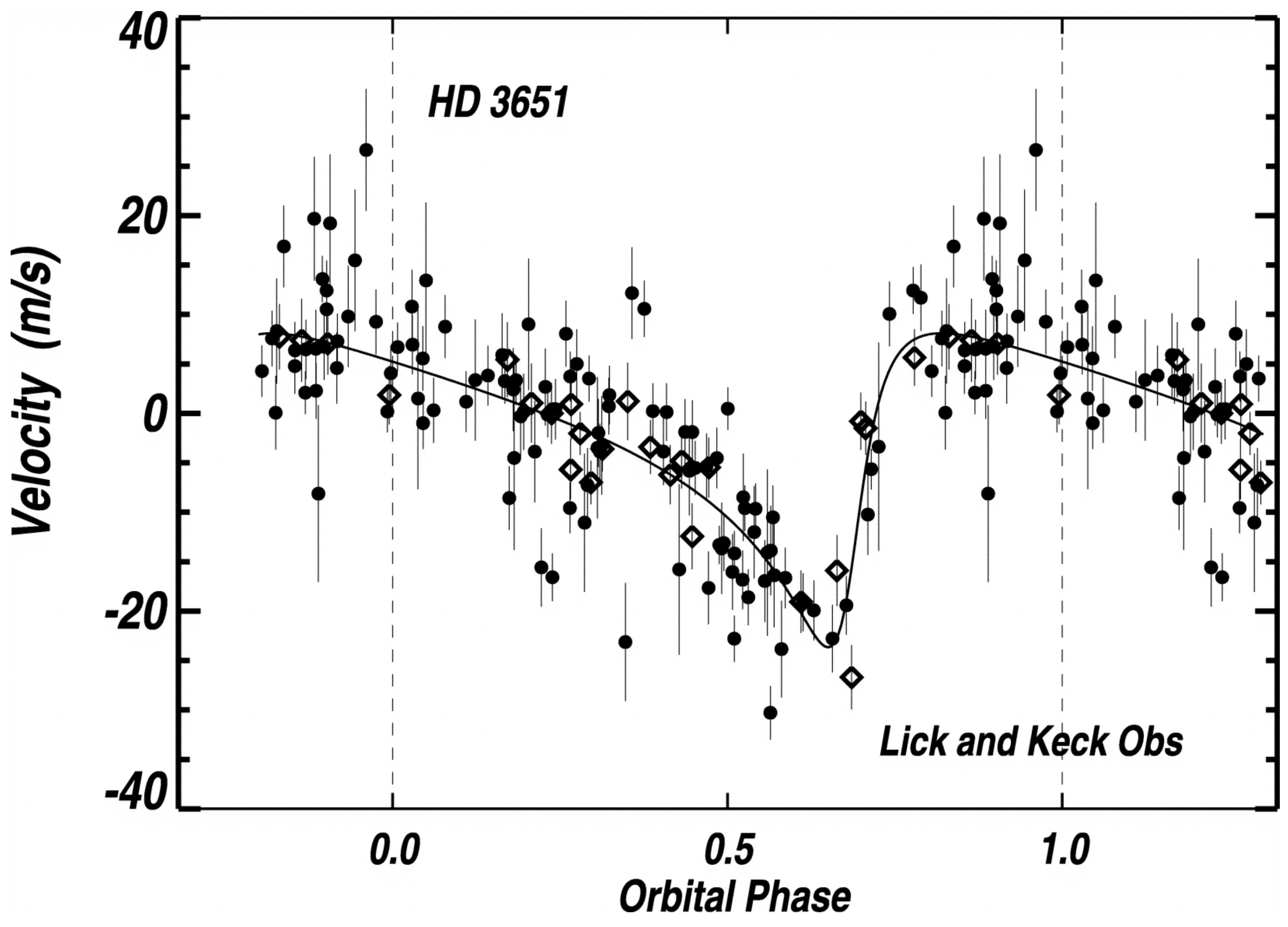
Review of the last class

- Modern relative RV precision (from a single observation of a well-behaved star with a stable RV spectrograph) is about:
  - (A) — 1 km/s
  - (B) — 100 m/s
  - (C) — 10 m/s
  - (D) — 1 m/s
  - (E) — 1 cm/s

Review of the last class

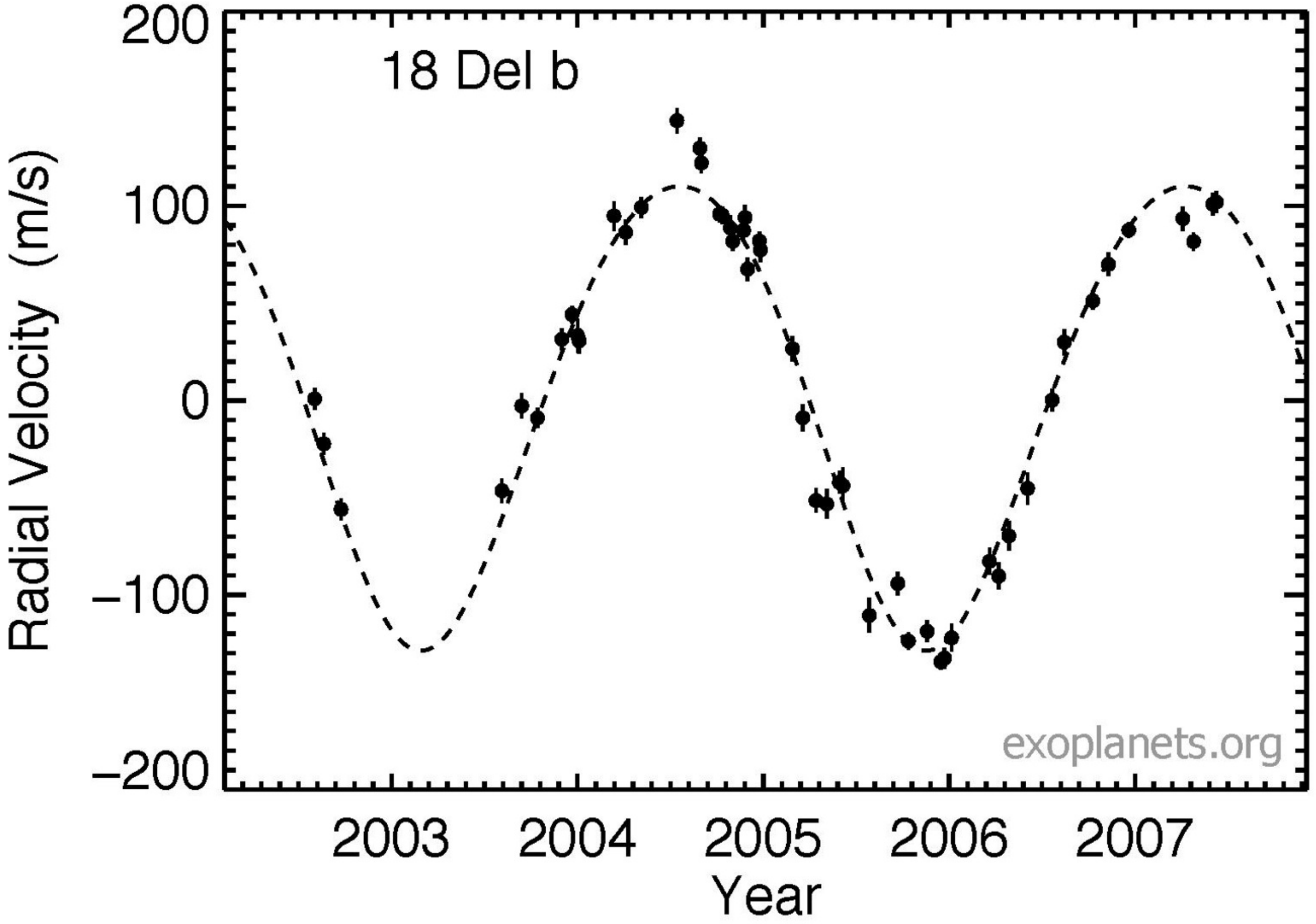
- Which exoplanet has a more eccentric orbit?
  - (A) — 18 Del b
  - (B) — HD 3651 b
  - (C) — They both have the same eccentricity
  - (D) — There's no way to tell





Review of the last class

- What is the (approximate) orbital period and K for 18 Del b?
  - (A) — 3 years and 200 m/s
  - (B) — 3 years and 100 m/s
  - (C) — 6 years and 200 m/s
  - (D) — 6 years and 100 m/s
  - (E) — 6 years and 400 m/s



Review of the last class

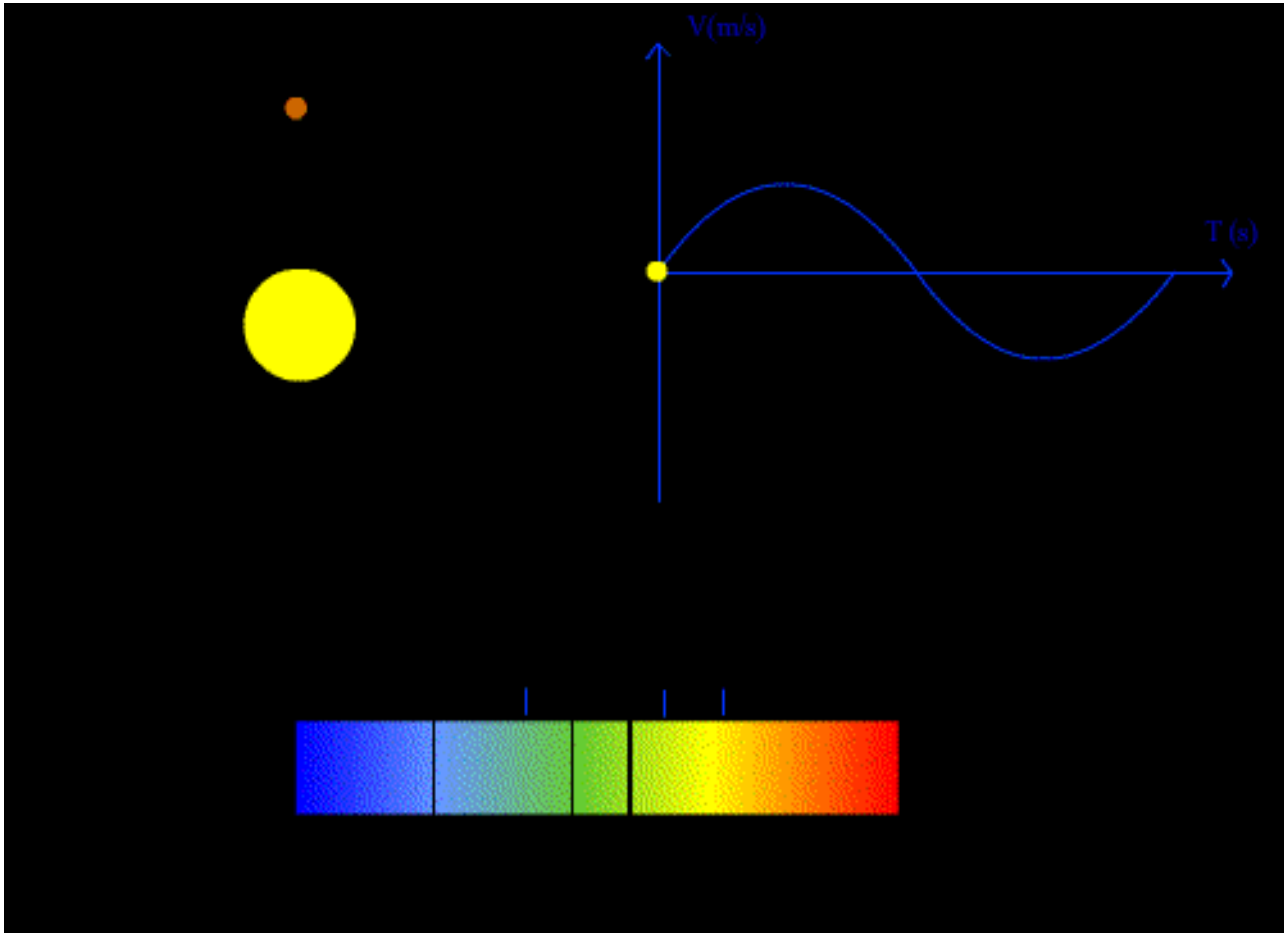
- If I wanted to make Earth easier to detect for alien astronomers by increasing the radial velocity amplitude, I should:
  - (A) — Increase Earth's mass, increase the Sun's mass, increase the eccentricity, increase Earth's semi-major axis
  - (B) — Increase Earth's mass, decrease the Sun's mass, increase the eccentricity, increase Earth's semi-major axis
  - (C) — Increase Earth's mass, increase the Sun's mass, increase the eccentricity, decrease Earth's semi-major axis
  - (D) — Increase Earth's mass, decrease the Sun's mass, increase the eccentricity, decrease Earth's semi-major axis
  - (E) — Decrease Earth's mass, decrease the Sun's mass, decrease the eccentricity, decrease Earth's semi-major axis

Review of the last class

- Exoplanet 1 has a 90 degree inclination angle with its star, while Exoplanet 2 has a 0 degree inclination angle with its star. Therefore:
  - (A) — Exoplanet 1 is likely to transit, and there will be no detectable RV signal from Exoplanet 1 on its star
  - (B) — Exoplanet 2 is likely to transit, and there will be no detectable RV signal from Exoplanet 2 on its star
  - (C) — Exoplanet 1 is likely to transit, and there will be no detectable RV signal from Exoplanet 2 on its star
  - (D) — Exoplanet 2 is likely to transit, and there will be no detectable RV signal from Exoplanet 1 on its star
  - (E) — Neither Exoplanet 1 or Exoplanet 2 will transit, and both will have detectable RV signals

The Radial Velocity Method

- A star with a planet will orbit the common center of mass of the star/planet system
- Some component (most of the time) of the star's motion will be along the line-of-sight
- That radial velocity (RV) can be detected by a shift in the star's absorption lines over an orbit



OASA

Response Card Question

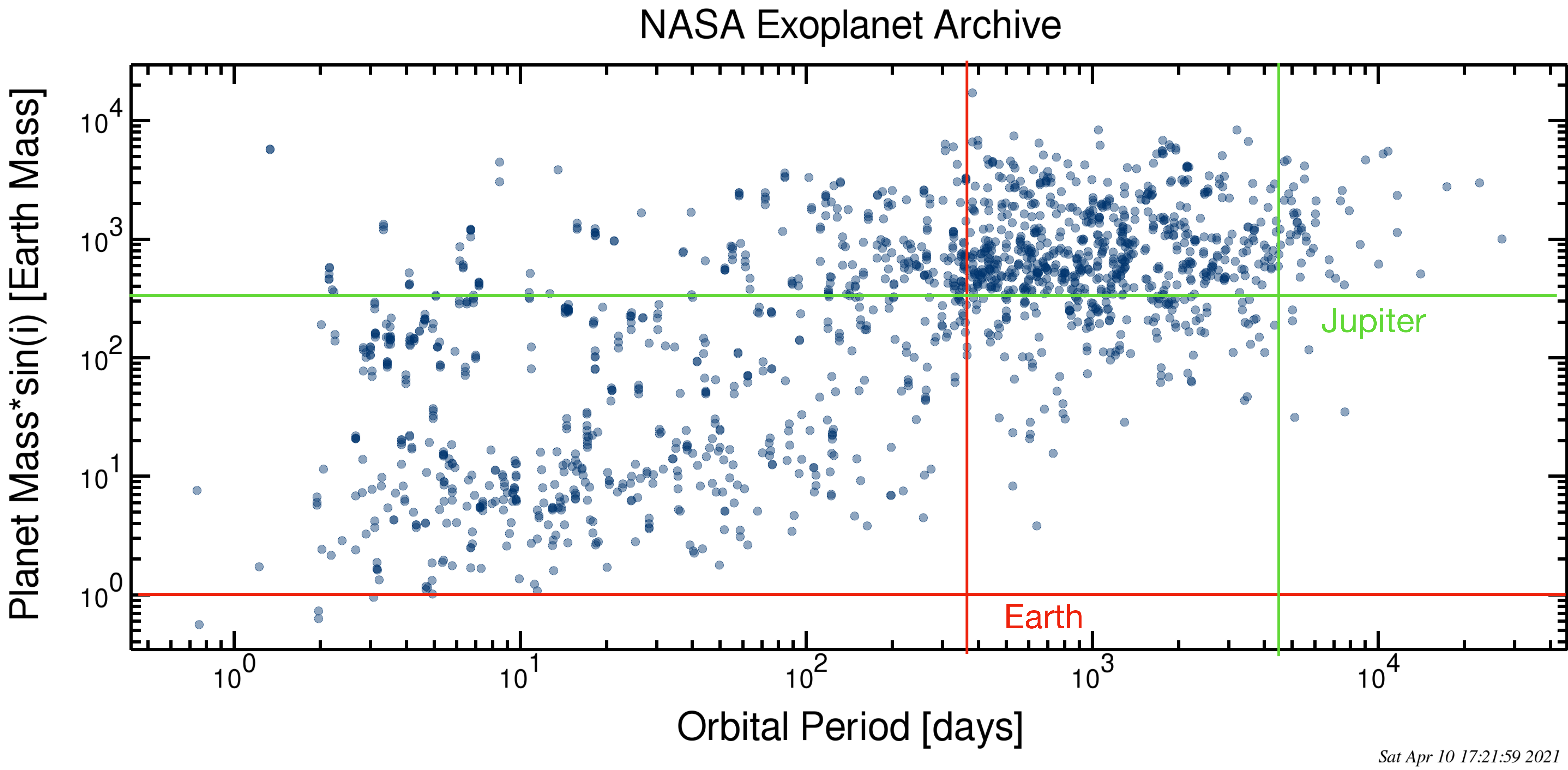
- Precision RV spectrographs have been operating since about 1990. Therefore, we expect the RV technique to be able to detect planets around Sun-like stars as far away from their stars as ________ is to our Sun

  - (A) — Earth (1 AU)
  - (B) — Jupiter (5 AU)
  - (C) — Saturn (10 AU)
  - (D) — Uranus (20 AU)
  - (E) — Neptune (30 AU)

Radial Velocity

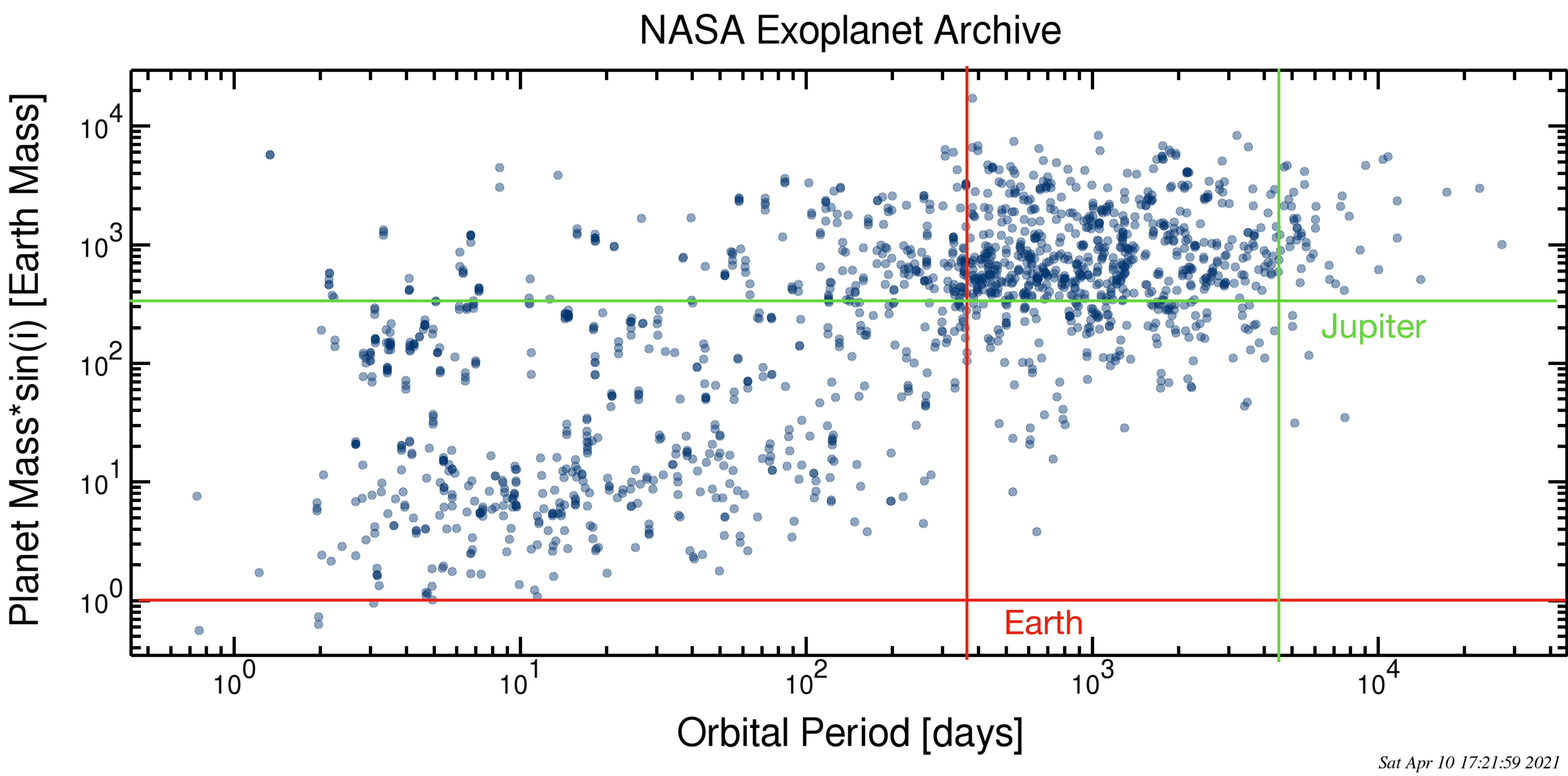
- Modern instruments can measure velocity to better than 1 meter/second (human walking speed)

- Can measure:
  - Orbital period
  - Orbital eccentricity
  - Minimum Planet Mass (unknown inclination angle)



Radial Velocity

- Biases:
  - More sensitive to edge-on systems than face-on ones
  - Works best for stars with lots of narrow absorption lines: F, G, K stars
    - older, inactive stars are easier
  - Radial velocity is largest (easier to detect) for more massive planets, and planets that are close to the star
  - Need to see most of the Radial Velocity curve to detect and characterize the planet, so need to have measurements for most of an orbital period



Exoplanet Demographics

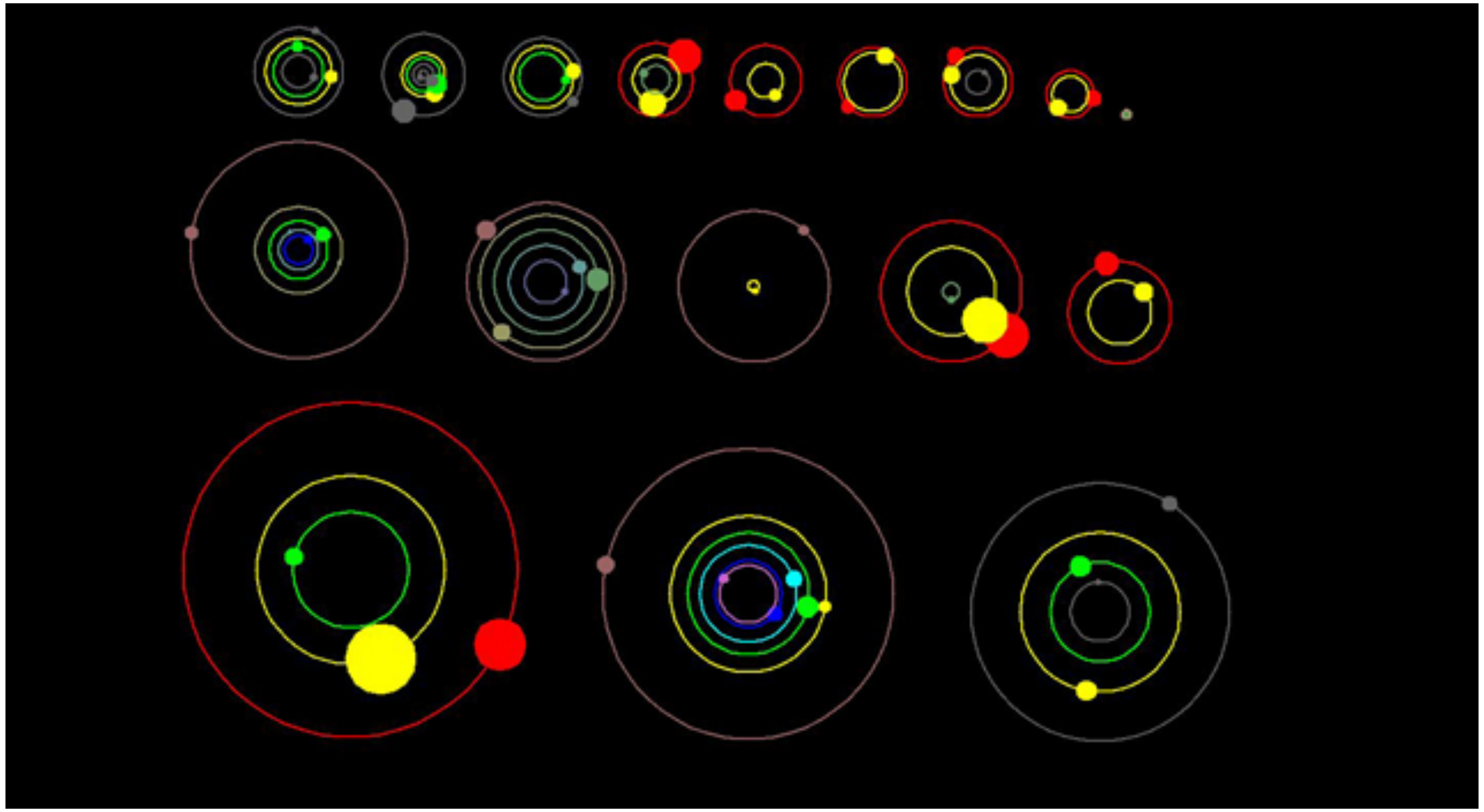
- Planet Fraction: fraction of stars with planets

$$\frac{\text{Number of Stars with Planets}}{\text{Total Number of Stars}}$$

- Planet Occurrence: number of planets per star

$$\frac{\text{Total Number of Planets}}{\text{Total Number of Stars}}$$

- Very important in exoplanet demographics to correct for the biases of your technique: completeness



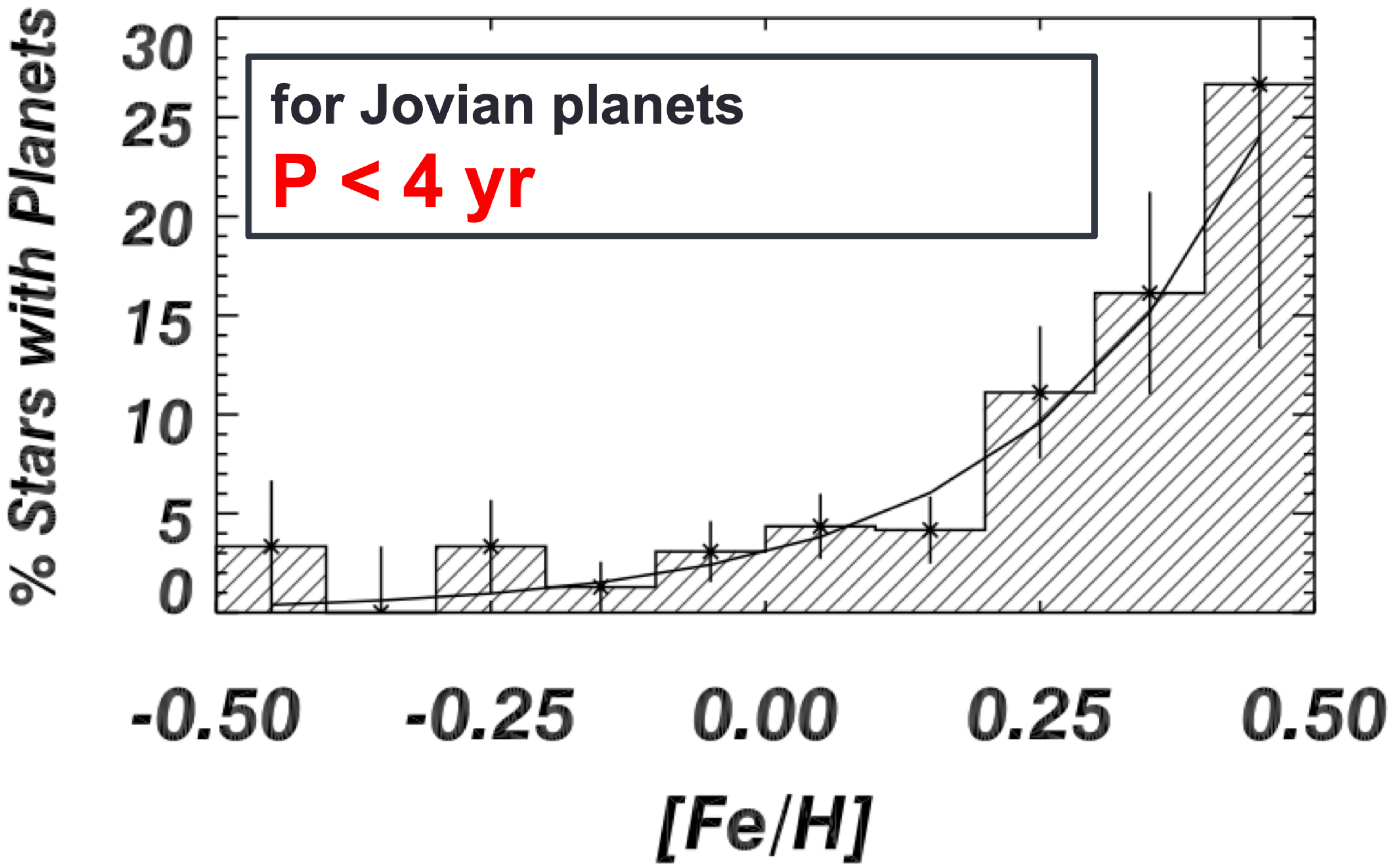
Eric Ford/NASA Ames/UCSC

Response Card Question

- Suppose every star in the Universe had a solar system identical to our own (8 planets). What is the planet fraction and planet occurrence in that case?
  - (A) — PF: 100%, PO: 100%
  - (B) — PF: 800%, PO: 100%
  - (C) — PF: 100%, PO: 800%
  - (D) — PF: 800%, PO: 800%

Planet/Metallicity Correlation

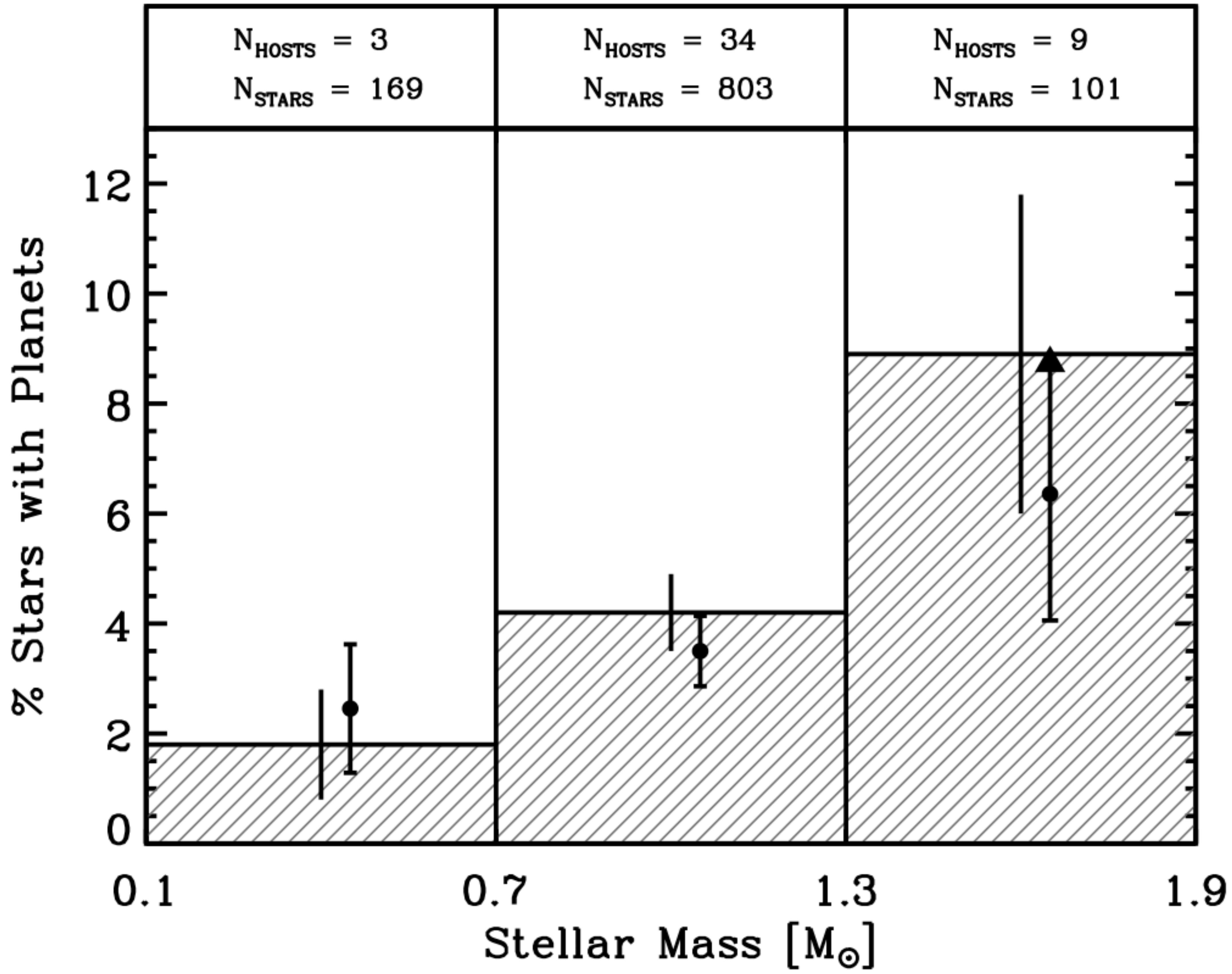
- For:
  - planets about the mass of Jupiter or larger
  - orbiting FGK stars
  - periods less than 4 years
- Higher metallicity stars are more likely to host these types of planets



Fischer & Valenti 2005

Stellar Mass Correlation

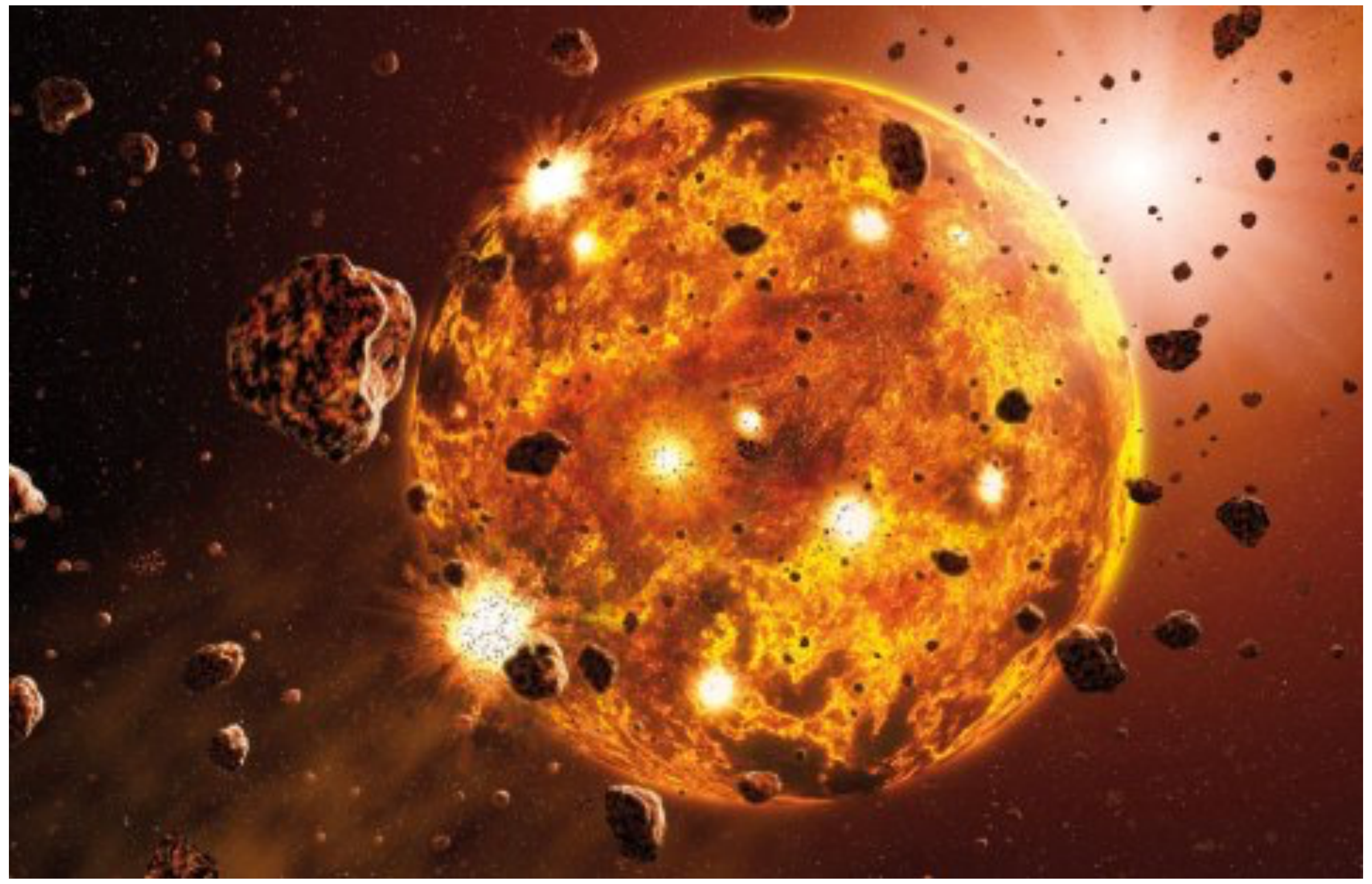
- For:
  - planets about the mass of Jupiter or larger
  - periods less than 4 years
- Higher mass stars are more likely to host these types of planets



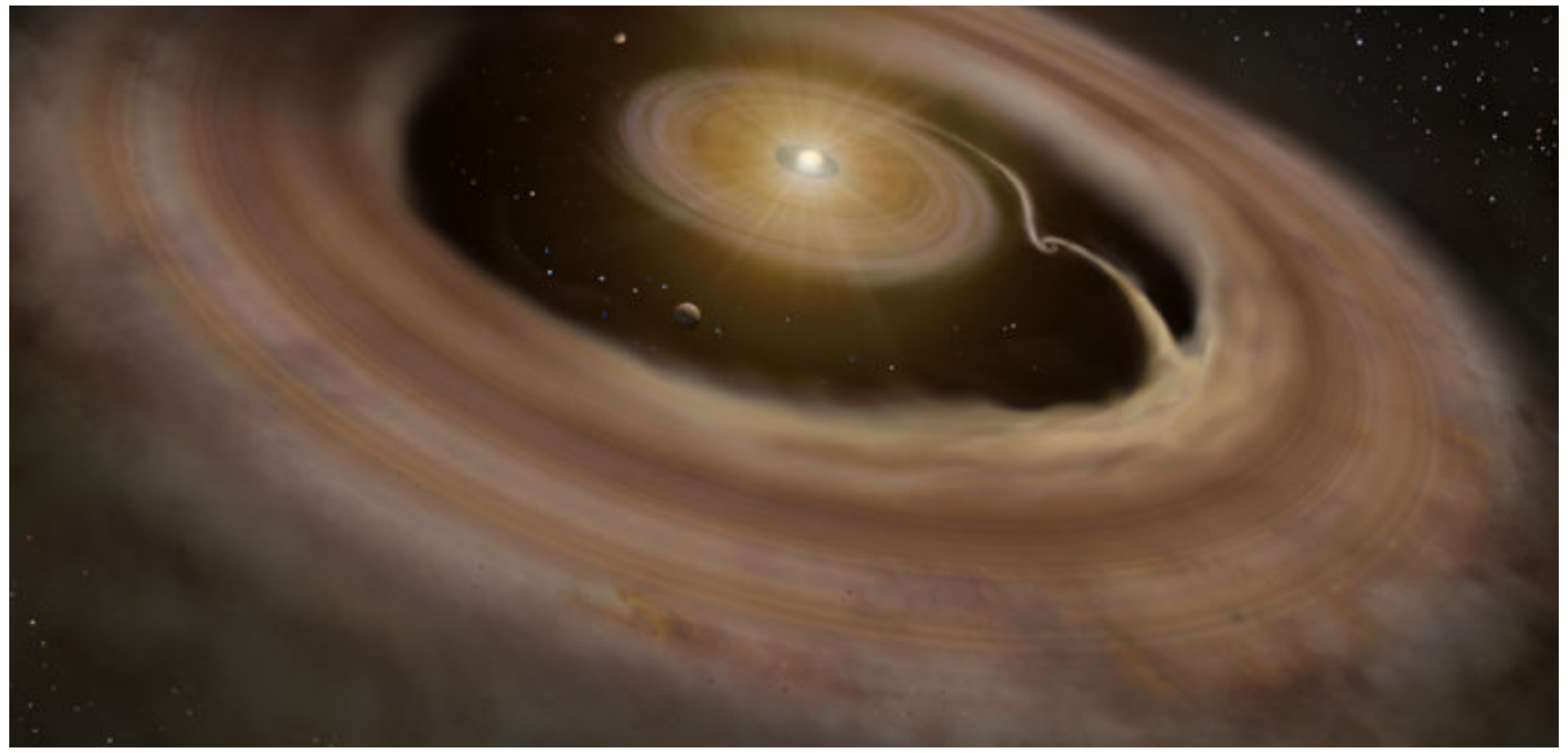
Johnson et al. 2007

Core Accretion

- One of the two main theories for how to make giant planets
- Bottom-up formation
- Step 1: form a ~10 Earth mass core of solids
  - mainly ices (water, methane, ammonia)
- Step 2: at 10 Earth masses, gravity is strong enough to accrete gas from the protoplanetary disk
- A race against time: the gas in the disk only lasts a few million years
  - Stellar wind photoevaporates gas in the disk after the star forms



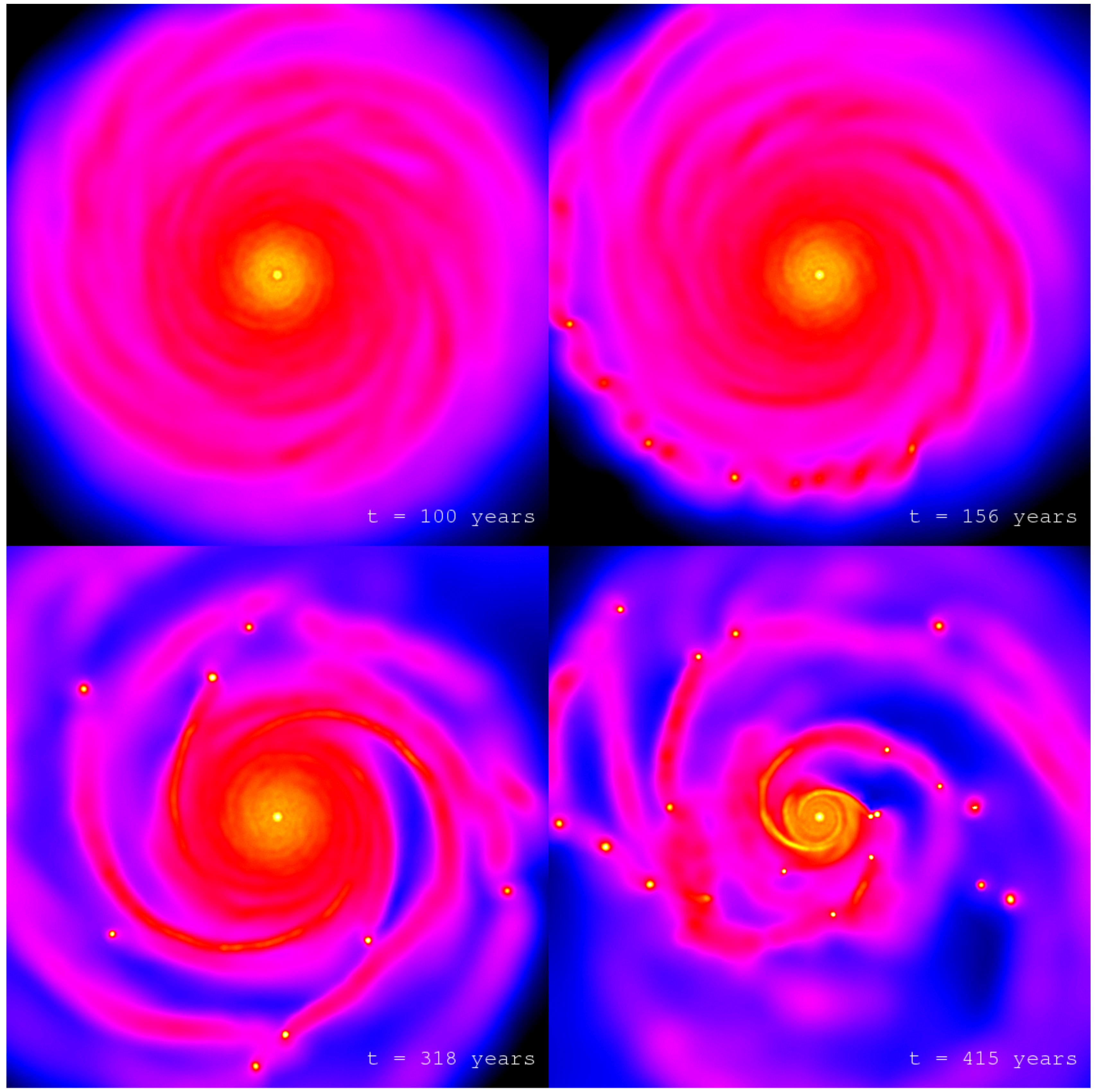
Alan Brandon/Nature



The Graduate Institute for Advanced Studies/NOAJ

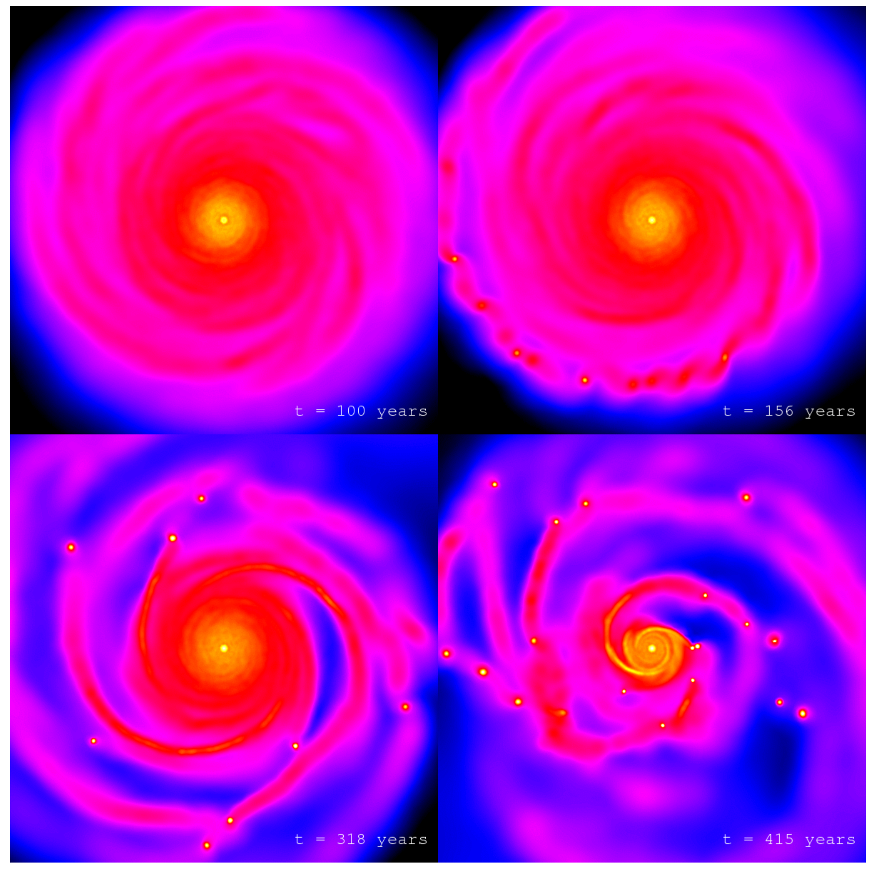
Gravitational Instability

- The second main theory for how to make giant planets
- Top-down formation
- Protoplanetary disk, if conditions are right, fragments
    - over densities quickly grow (by gravity)
- Much much faster and efficient than core accretion



G. Lufkin et al.

Demographics and Giant Planet Formation

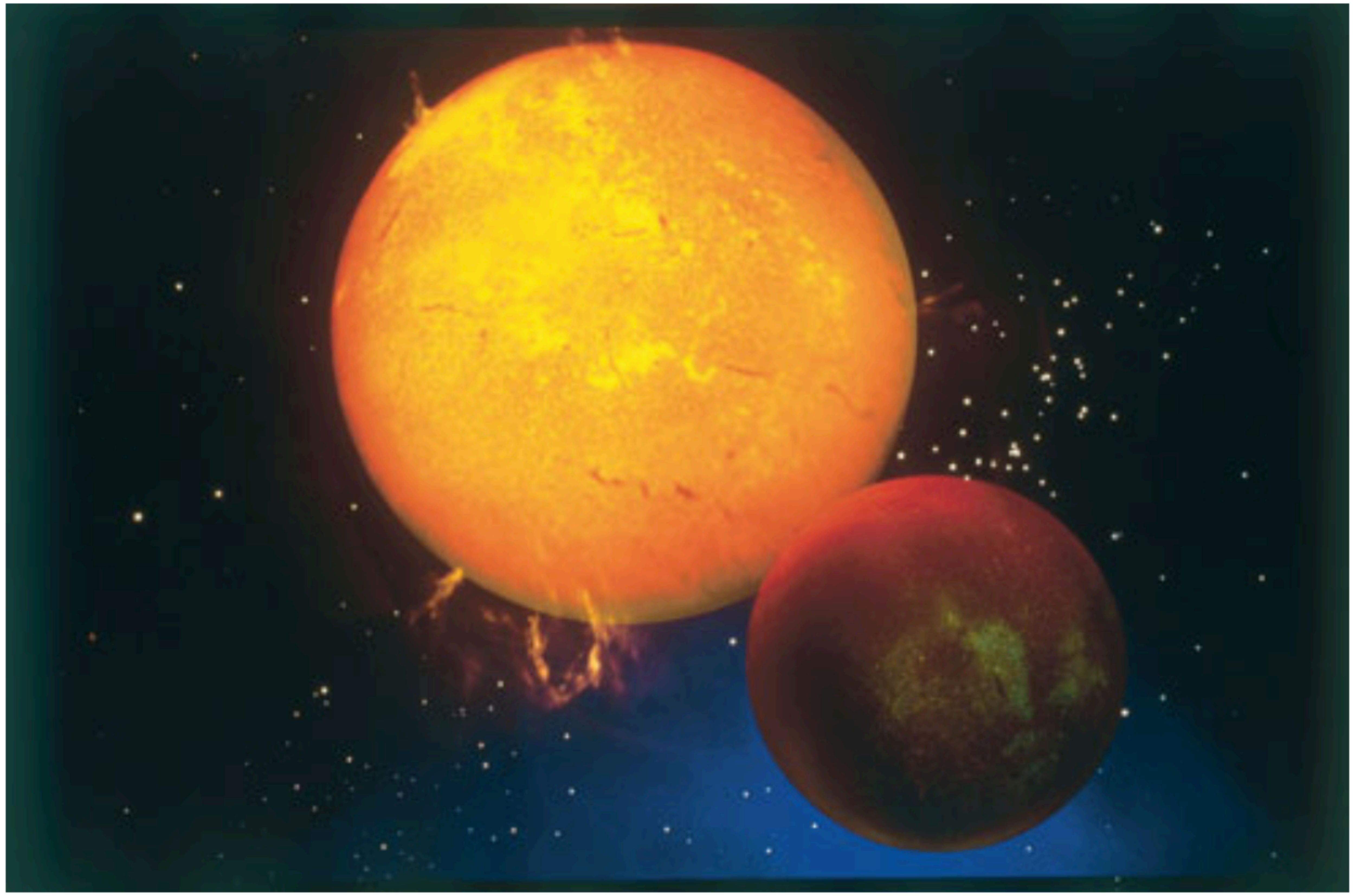


- Core Accretion
- Predicts more giant planet cores forming at higher metallicity
- Predicts more giant planets orbiting higher mass stars

- Gravitational Instability

Hot Jupiters

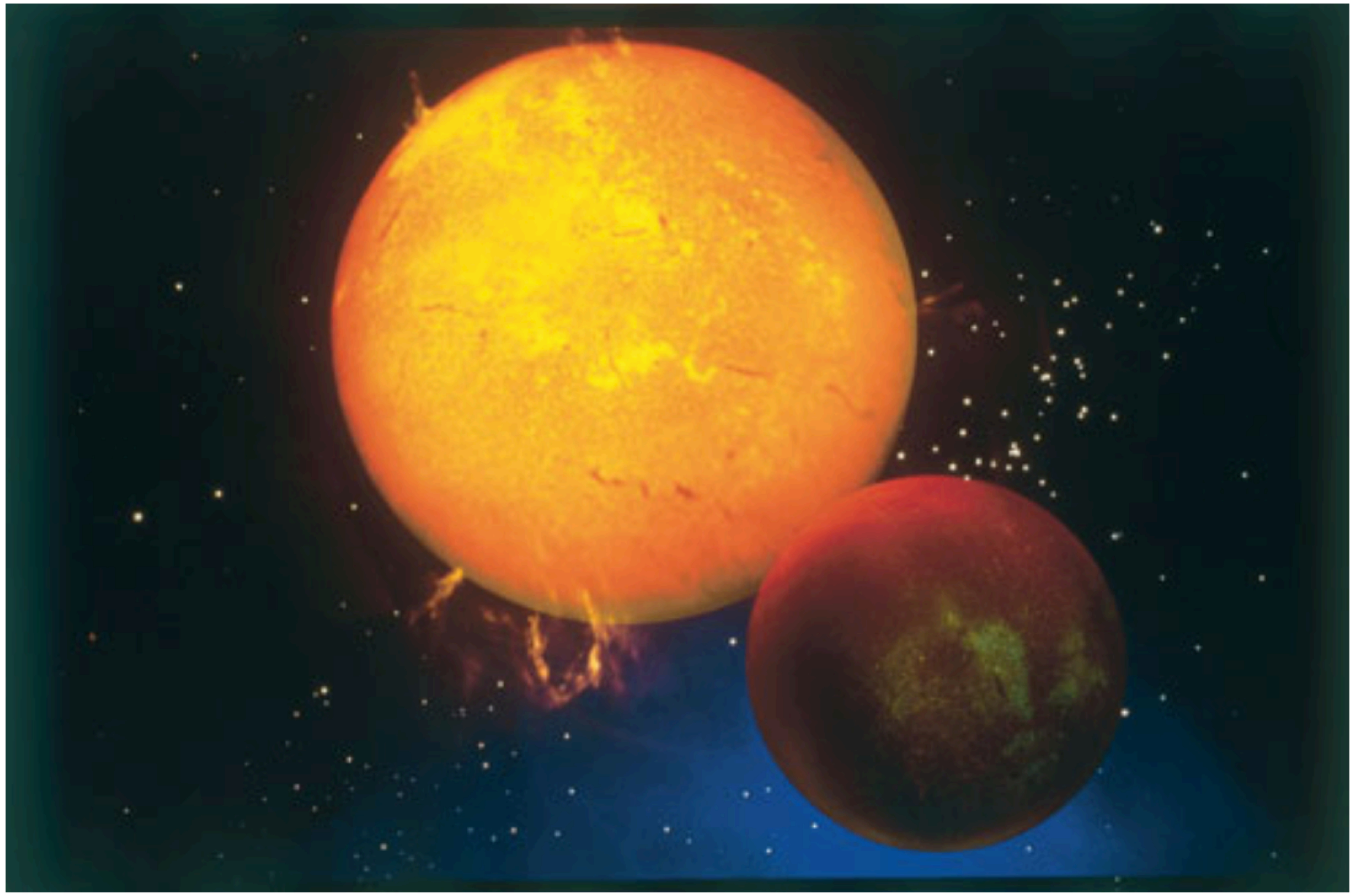
- About the mass of Jupiter, but very close to their stars
- 51 Peg b has a 5-day orbit (0.05 AU, 8 times closer to its star than Mercury is to the Sun), and a minimum mass of 0.5 Jupiter masses
- These are very easy to detect with radial velocities, and so these were the first exoplanets to be found
- About 5% of FGK stars have a Hot Jupiter orbiting them



“Life in the Universe”

Hot Jupiters

- Models of planet formation have a hard time forming Hot Jupiters where we see them
  - Not enough gas at that part of the disk
- Formed at ~5-10 AU like our Jupiter, then migrated inward?
  - Gravitational interactions with other planets
  - Interactions with the disk
- Given how close they are to their host star, most Hot Jupiters are in tidally circularized orbits



"Life in the Universe"

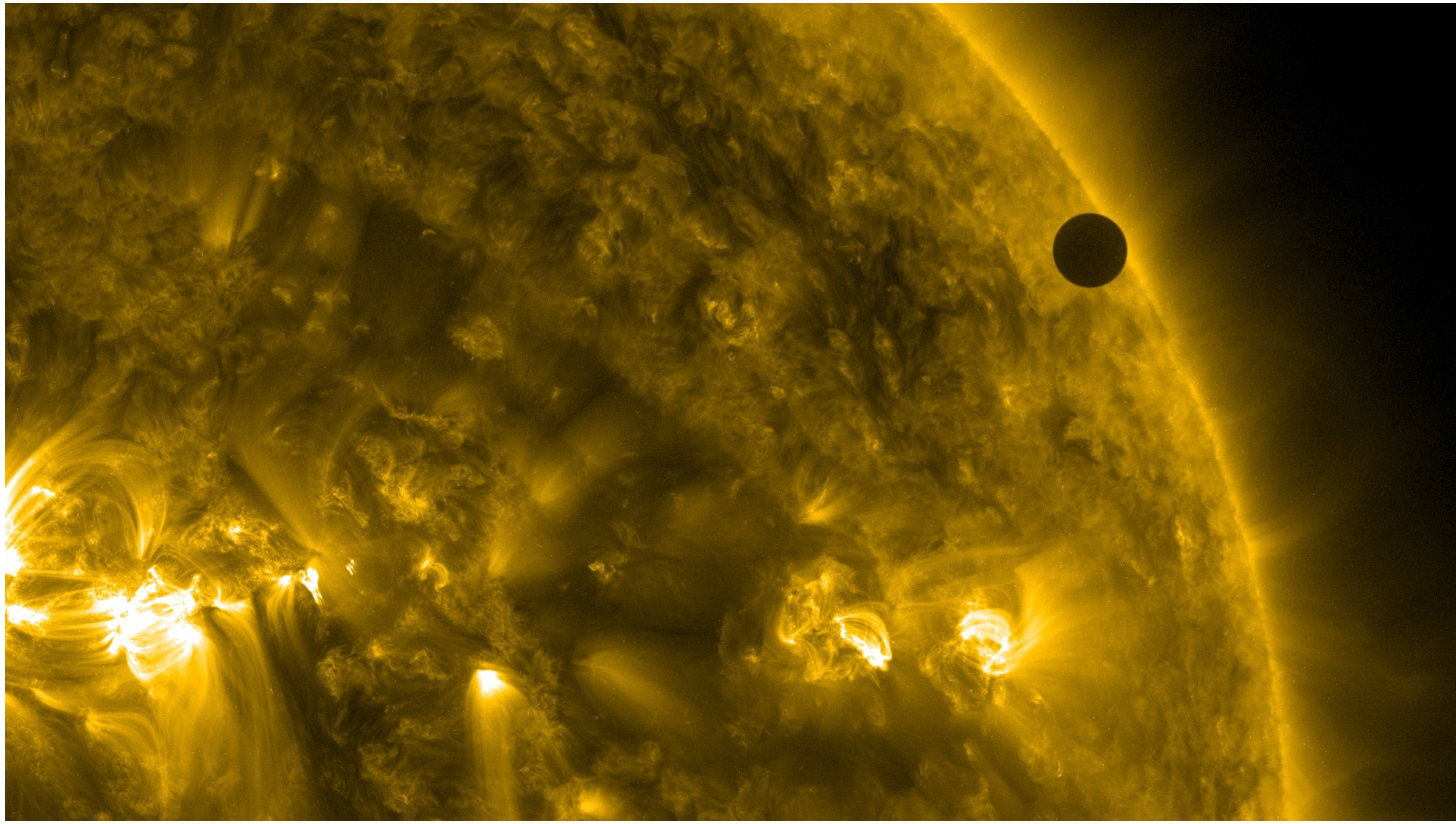
Break

The Transit Method

- For a small fraction of stars with planets in the galaxy, Earth happens to be aligned just right (inclination angle very close to 90 degrees) for the planet's orbit to take it in a line between the star and Earth

- We once again don't detect the planet directly, but rather indirectly detect it: light from the star dims when the planet is passing in front of the star

- By monitoring the brightness of stars, planets can be detected



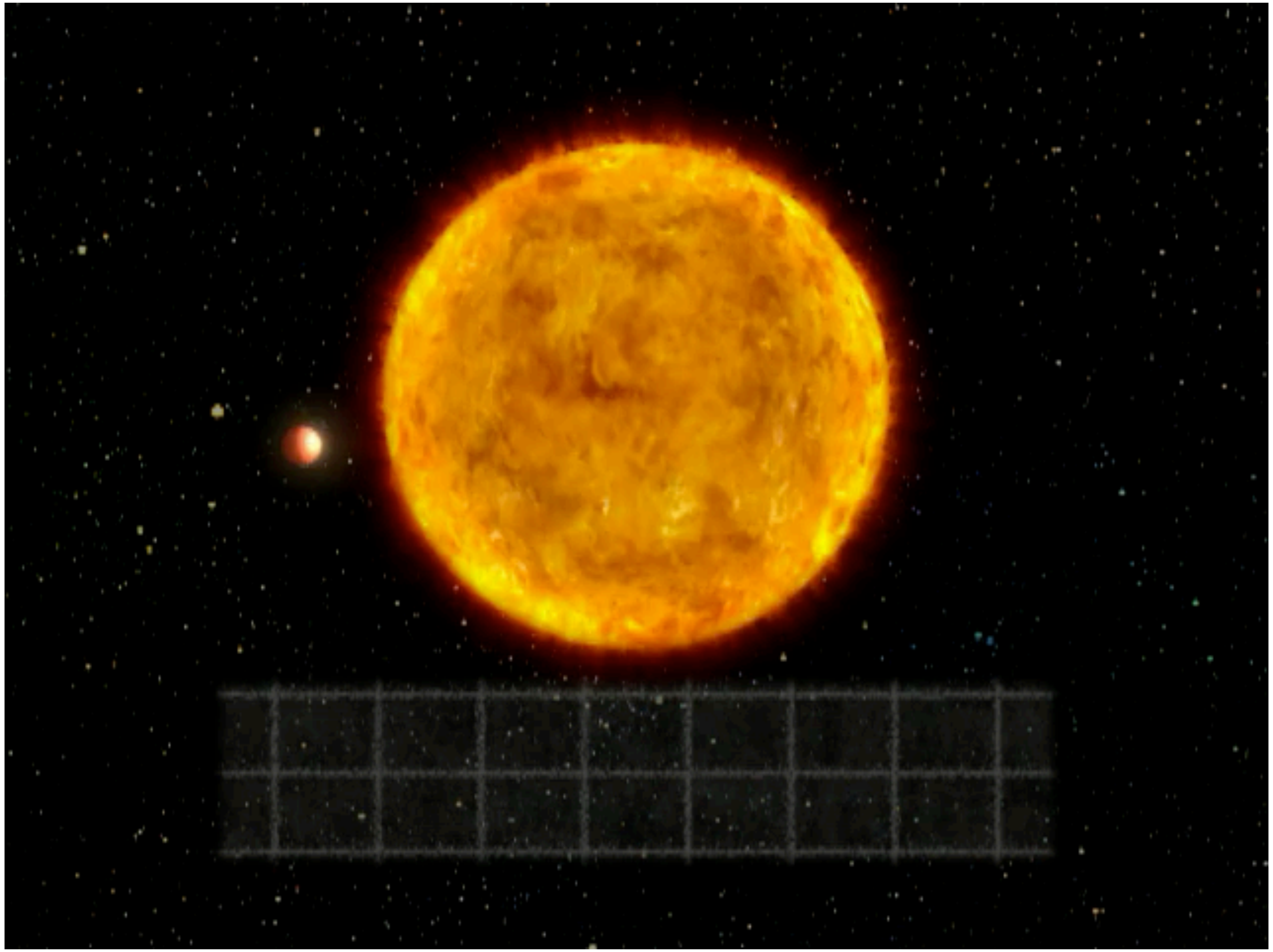
NASA/SDO

Partner Question: Transits

- HD 209458 b (very similar to Jupiter) transits its host star (very similar to the Sun) once every 4 days.

- (1) How much fainter does the star get during a transit? (hint: we, the observer, are very very far away from the HD 209458 system)

- (2) How long (in hours) does a transit of HD 209458 b last? (hint: the planet is much smaller than the star, and the semi-major axis of the planet's orbit is much larger than the star, and assume inclination angle is 90.0 degrees)



NASA/Hubble

Partner Question: Transits

- HD 209458 b (very similar to Jupiter) transits its host star (very similar to the Sun) once every 4 days.

- (1) How much fainter does the star get during a transit? (hint: we, the observer, are very very far away from the HD 209458 system)

- If we're far away, we can think of the star and the planet as circles, with one circle blocking out the other. Then we just need to compare areas, and remember that Jupiter is 10x smaller than the Sun.

$$\frac{F_{lost}}{F_{orig}} = \frac{A_P}{A_S} = \frac{\pi R_P^2}{\pi R_S^2} = \left(\frac{R_P}{R_S}\right)^2 = \left(\frac{1}{10}\right)^2 = \frac{1}{100} = 1\,\%$$

- (2) How long (in hours) does a transit of HD 209458 last? (hint: the planet is much smaller than the star, and the semi-major axis of the planet's orbit is much larger than the star, and assume inclination angle is 90.0 degrees)

- Ok, so given these hints, we can ignore the fact that the orbit is a circle during the transit, and we can ignore the time it takes for the planet to go from just touching the star to being fully in front at the edge. The distance the planet has to travel, then, is just the diameter of the star. If we can figure out the speed, we can get the duration of the transit

Partner Question: Transits

- Since the planet's orbit is a circle (thank you tides for making the math easier!), the total distance the planet moves during one orbit is the circumference of a circle with radius equal to the semi-major axis, and it takes one orbital period to do so:

$$v = \frac{2\pi a}{P}$$

- We don't know semi-major axis, but we do know period. Kepler's third law to the rescue:

$$P^2 = \frac{a^3}{M} \qquad a = P^{2/3}M^{1/3} \qquad v = \frac{2\pi P^{2/3}M^{1/3}}{P} = 2\pi P^{-1/3}M^{1/3}$$

- A note about units, we used the version of Kepler's third law that only works if period is in years, mass is in solar masses, and semi-major axis is in AU. So we now have velocity in AU/year. Let's plug in numbers and convert to km/s, since in the next step we'll get the radius of the Sun in km

- $$v = 2\pi P^{-1/3}M^{1/3} = 2x3x\frac{1^{1/3}}{(10^{-2})^{1/3}} = 2x3x100^{1/3} = 2x3x(5) = 30AU/year$$

Partner Question: Transits

- $$v = 30AU/year \frac{1.5x10^8 km}{1AU} \frac{1year}{3x10^7 s} = 30x5km/s = 150km/s$$

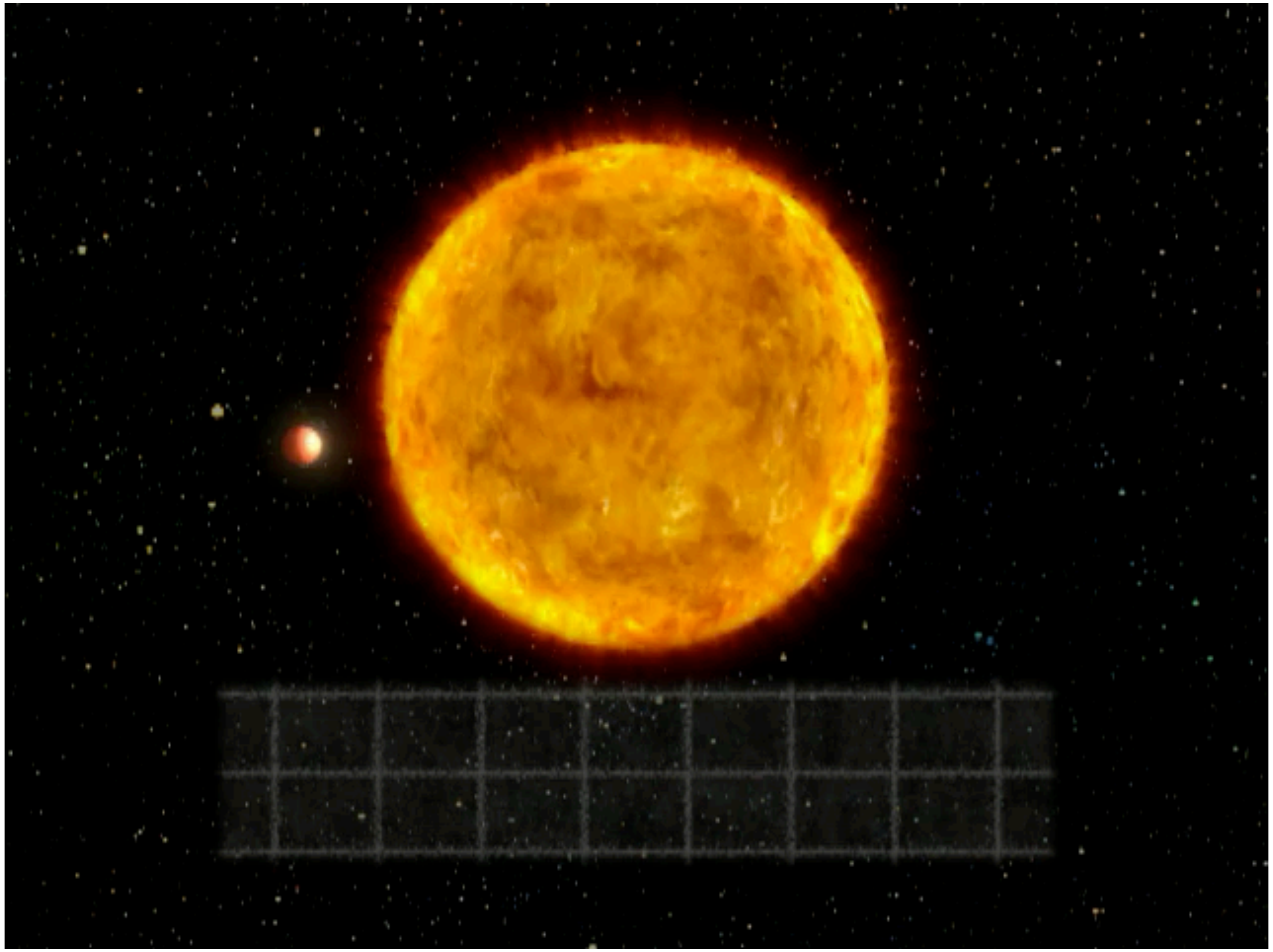
- Then, what's the star's diameter? Well, the Earth has a 6000 km radius, so a 12000 km diameter, and the Sun is 100x larger than Earth, so the Sun's diameter (and therefore HD 209458's diameter) is 1.2 million km

- Finally, since we know distance and velocity, we can get the duration of the transit:

$$T_D = \frac{D_*}{v} = \frac{1.2x10^6 km}{150km/s} = 10^4 s \frac{1hour}{3600s} = 3hours$$

Transits

- For a Jupiter-sized planet, about 1% of the star's light will be blocked by the planet
- For a Hot Jupiter, a transit will happen once every few days, and last a couple of hours
- These are very feasible numbers for ground-based telescopes
- After the first Radial Velocity planets were discovered in 1995, astronomers began monitoring the brightness of their host stars, hoping some planets would transit



NASA/Hubble

For next time

- Reading: Planetary Science, 12.2.3-12.2.5
- Homework 5 due Monday, November 7, at 11:59pm