Announcements

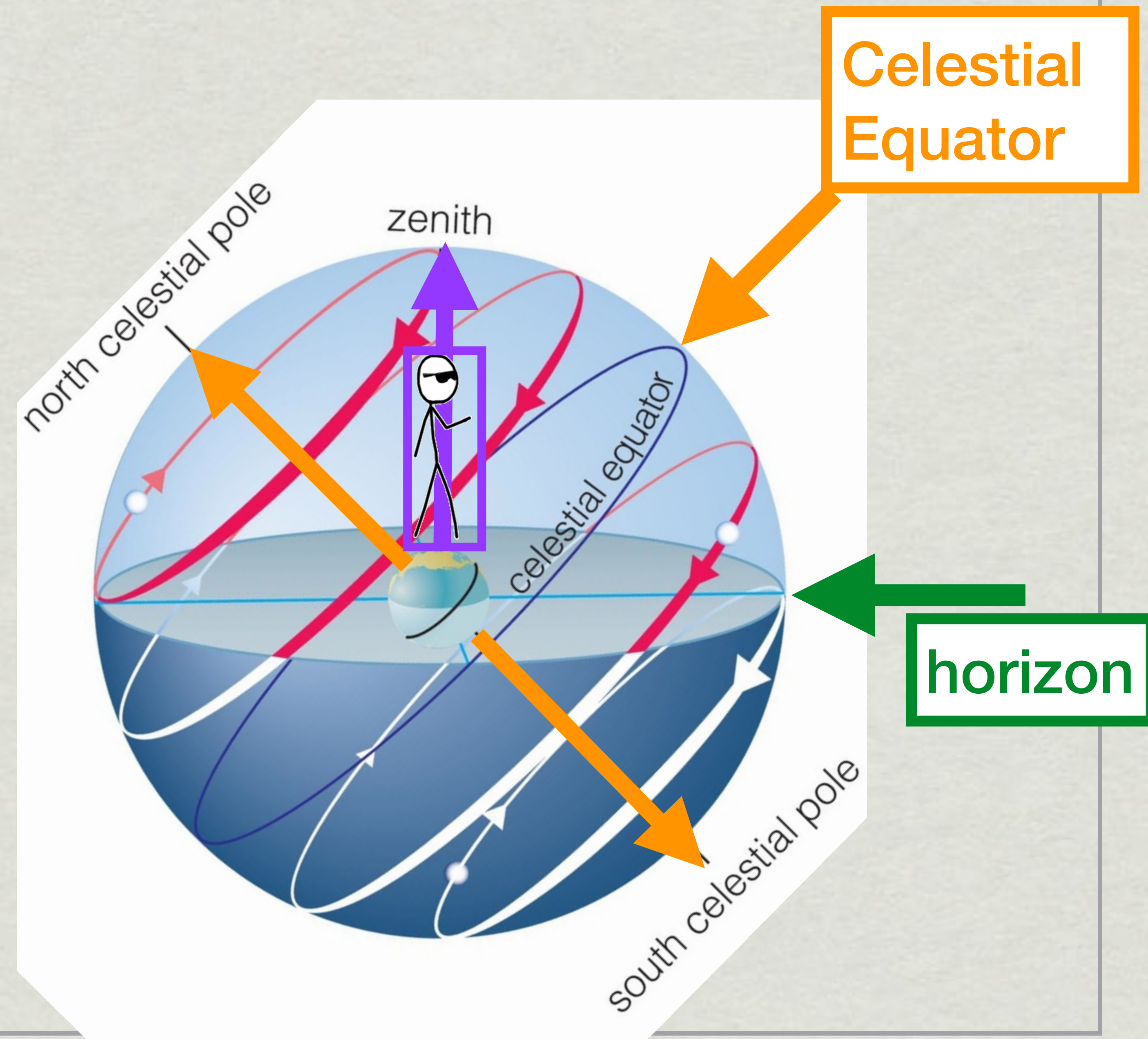
- Remember! the reading from 1/24 is due Sunday 2/11 at 5pm
- Midterm in-class Tuesday, 2/14
  - Content: everything through lecture 2/7, homework due 2/9 (Chapters 1,2,3,4). Review the homework and reading assignments
  - You will get a formula sheet and all numbers you need
    - will be posted this weekend
  - Bring a pencil and a non-web-enabled calculator. I'll provide the scantron form
- Midterm review sessions:
  - Friday, Feb. 10 4-5 pm NatSci2 Annex 101 (Plato)
  - Monday, Feb. 13 4-5pm NatSci2 Annex 101 (Marie)
  - Neither is required, you can go to either or both

Midterm Review

Also: Homeworks 1-4, Reading assignments Chapters 1-4

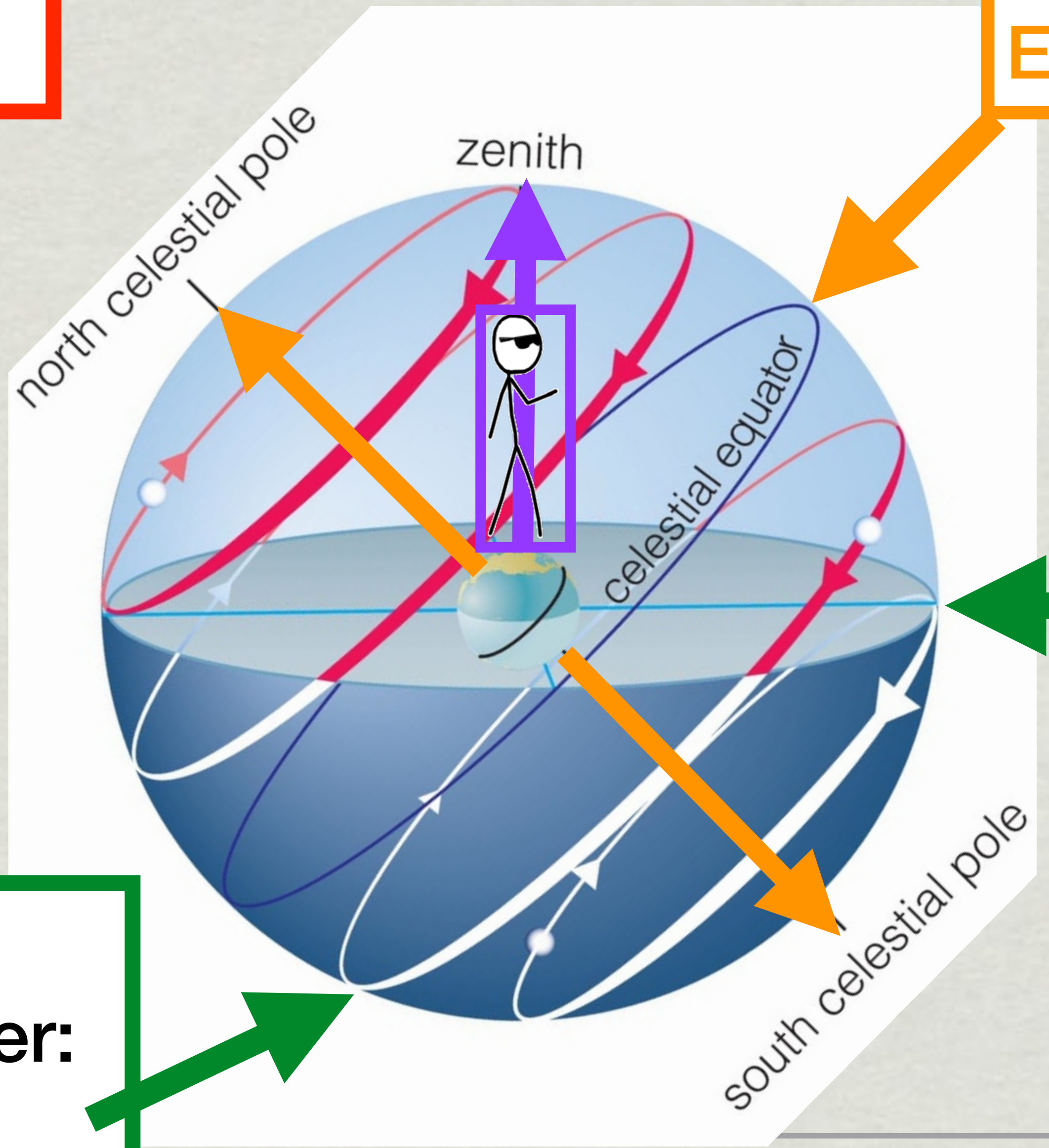
The Earth Spins on its Axis Once Per Day

- Celestial sphere: projection of latitude and longitude onto the sky
- Local coordinates: zenith and horizon



- Observers see the stars rise in the east and set in the west as the Earth turns on its axis
- The North Celestial Pole is overhead at the North Pole, but NOT in Santa Cruz (or anywhere else)

Stars that rise and set along the red tracks are visible for this observer

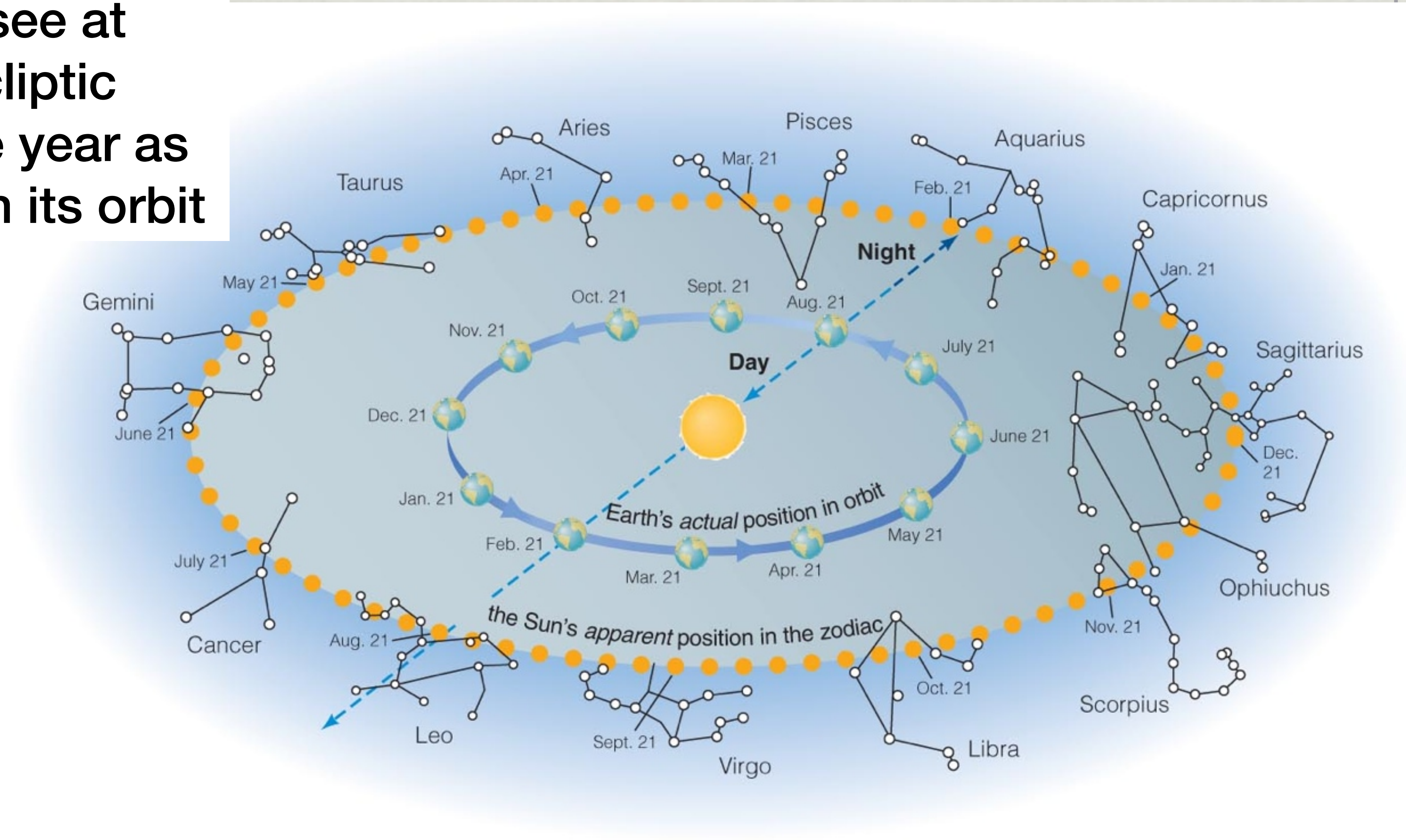


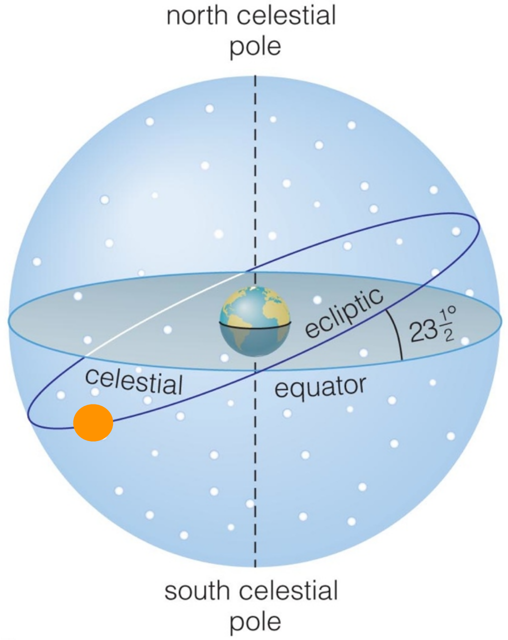
Stars that rise and set along the white tracks are never visible for this observer: they are always below the horizon

The Earth Orbits the Sun Once Each Year

Zodiac: Constellations on the Ecliptic

Constellation we see at night along the Ecliptic change during the year as the earth moves in its orbit

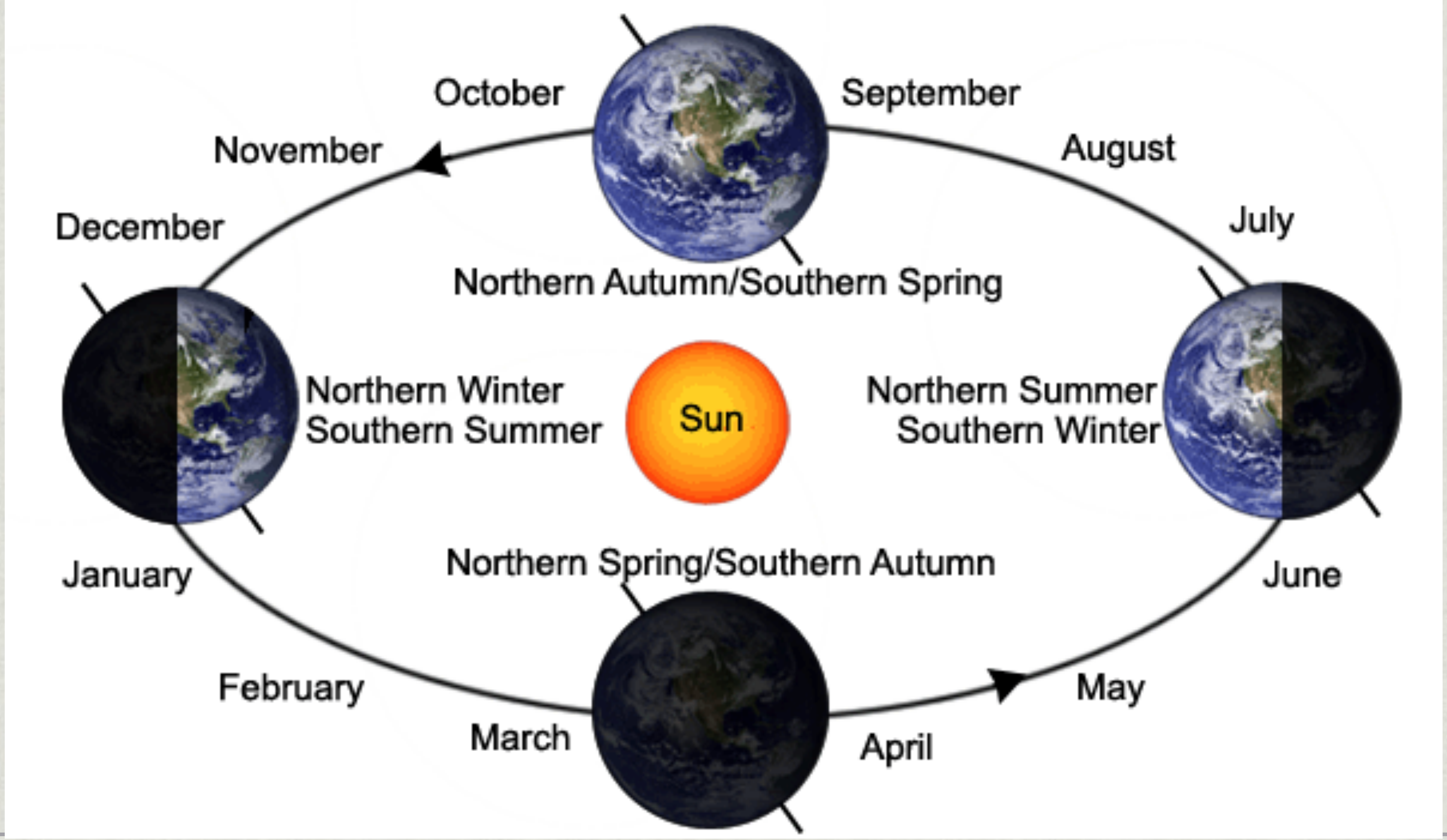




The Seasons

Tilt of Earth's axis: 23.5º

Angle remains constant as Earth orbits the sun each year

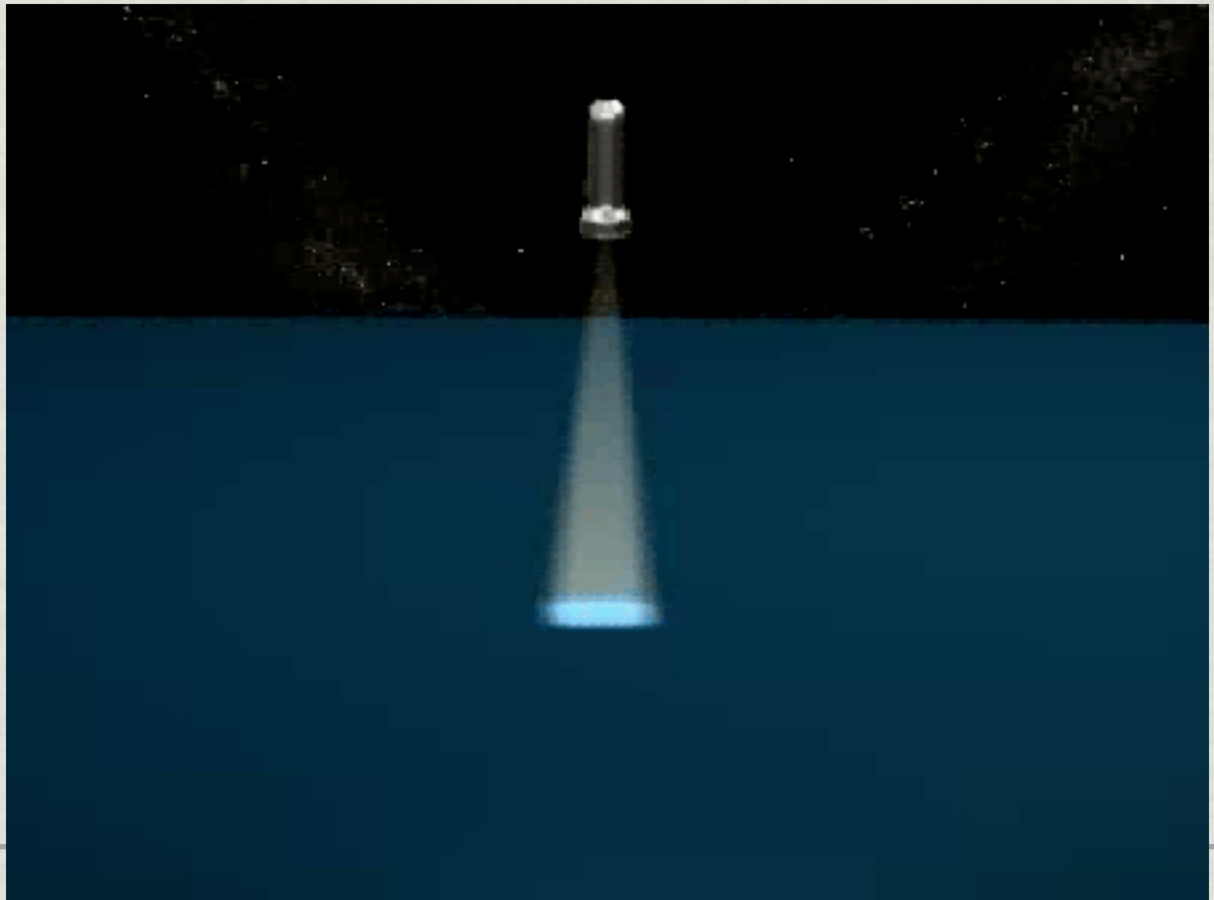


The Seasons, Recap

Light from the sun: delivers energy
Rate of energy flow: Watts (think about your electric bill)

At any place on earth, if the sun is overhead, max energy flow into that patch of ground

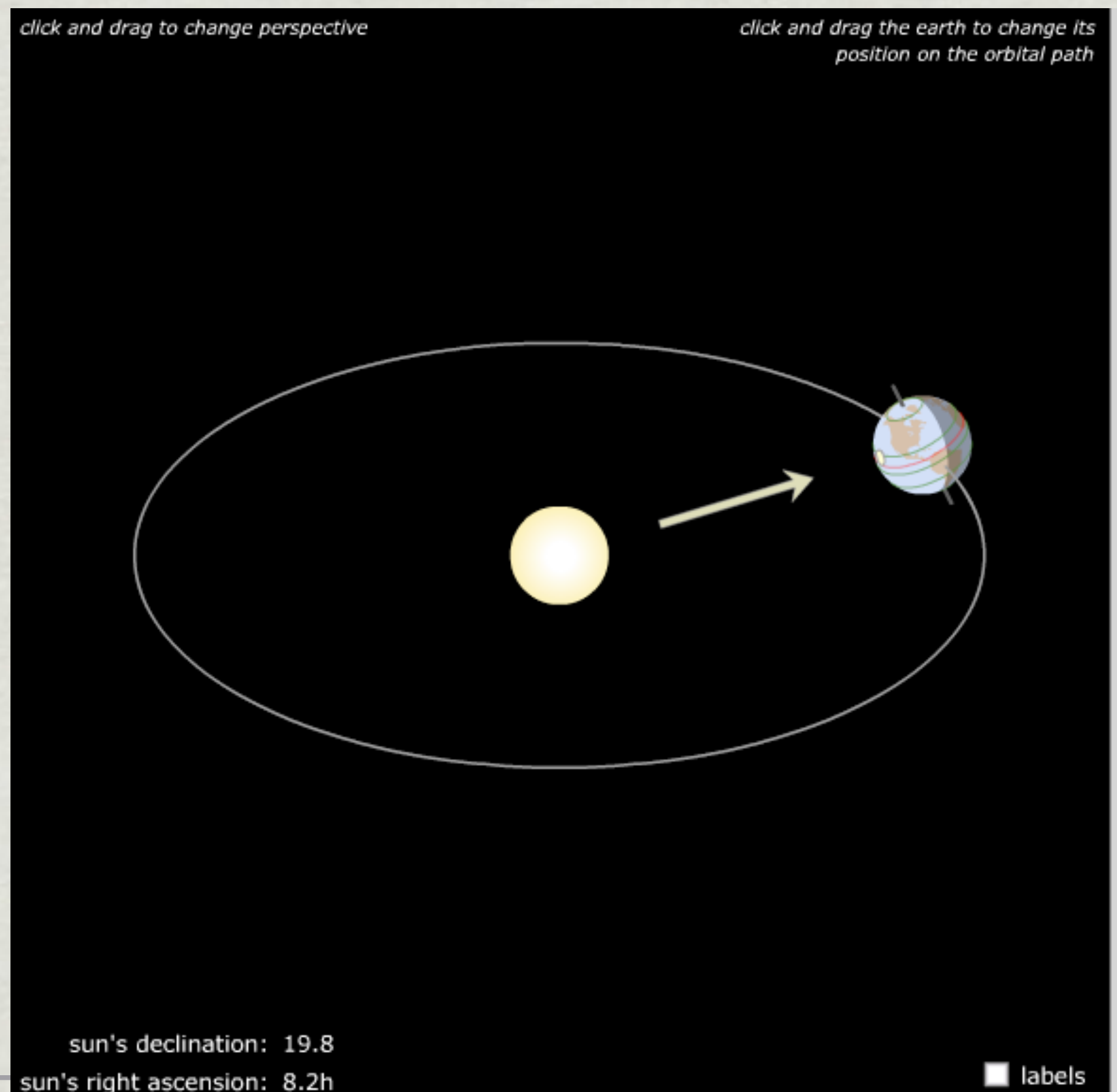
If sun is not overhead, same amount of energy flows into a larger patch of ground

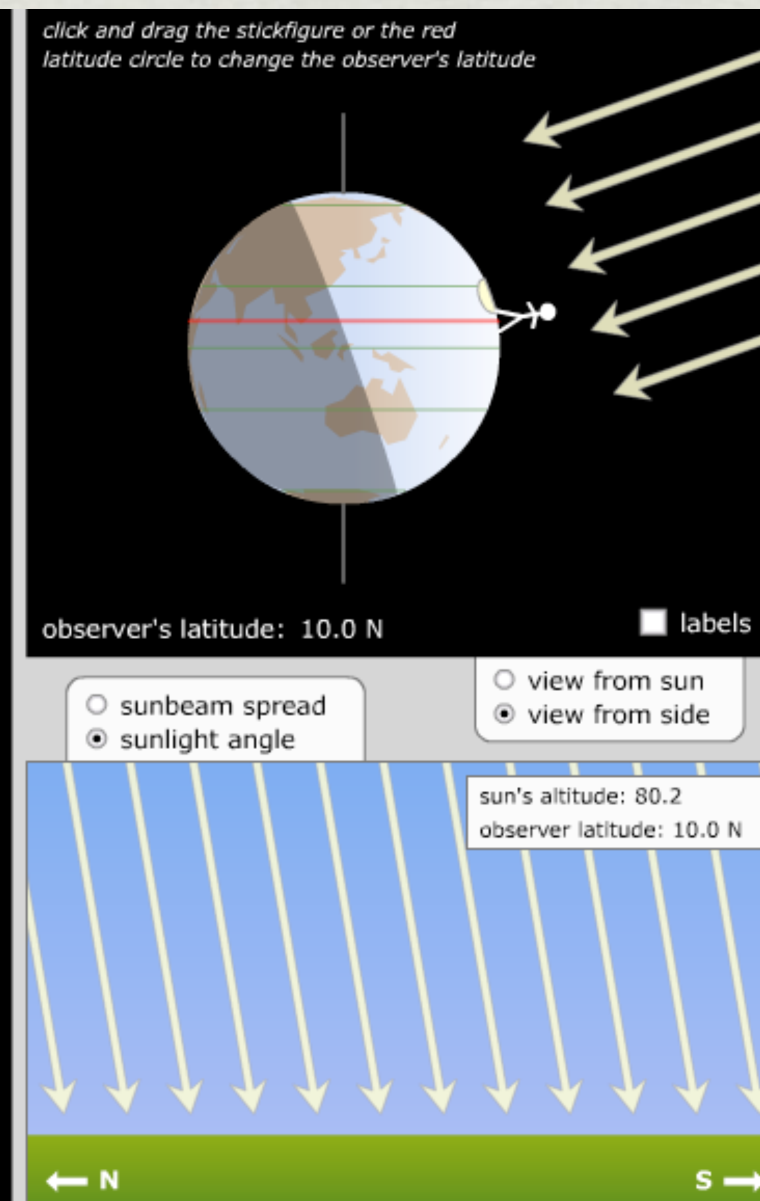


The Seasons, Recap

The direction of the Earth's axis is fixed as it orbits the sun.
The latitude where the sun is overhead changes over the year.
Rate of energy flow from sun into a patch of ground at any latitude changes over the year.
→Seasons!

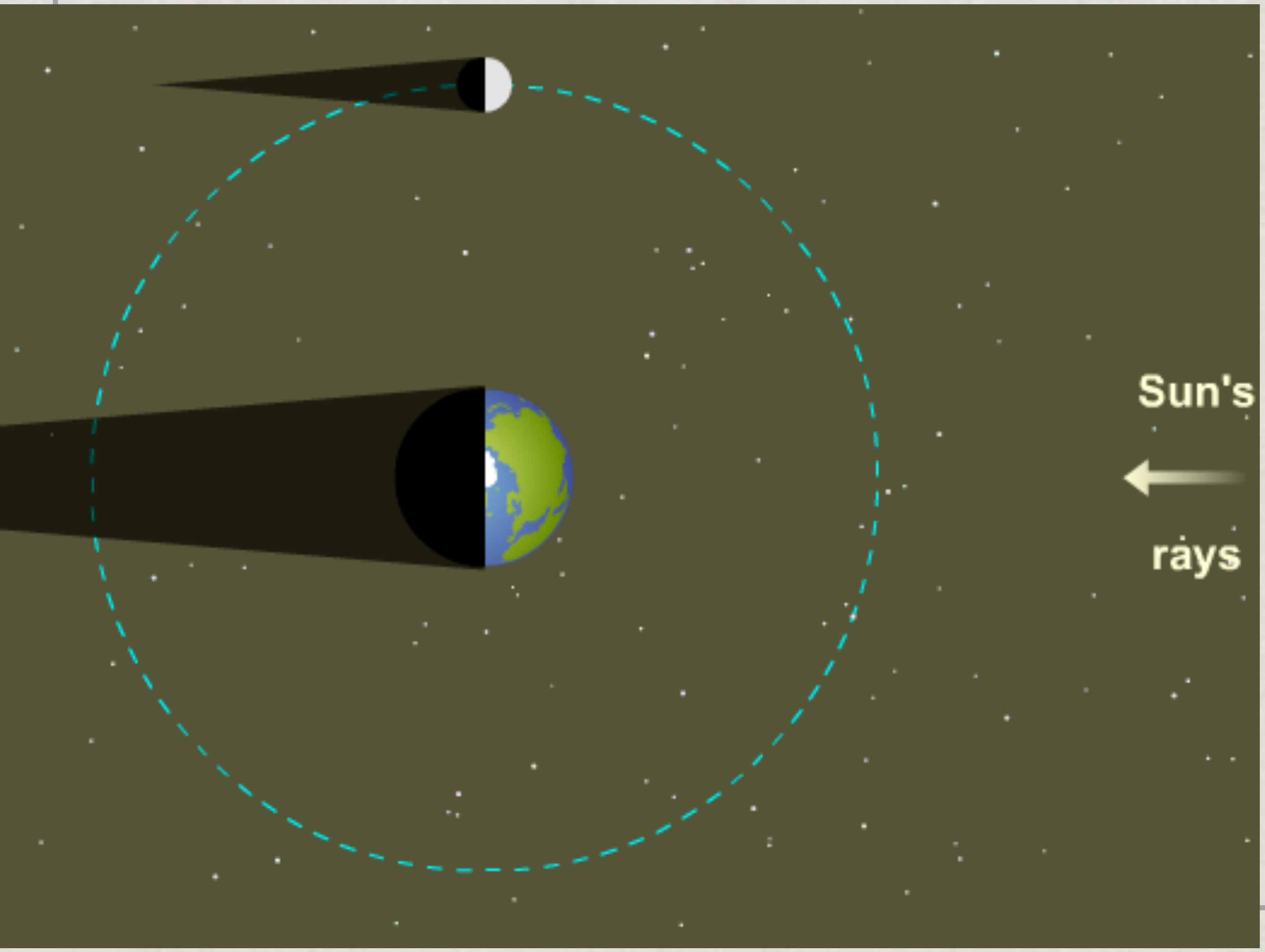
Not caused by changing distance to sun.





Phases of the Moon

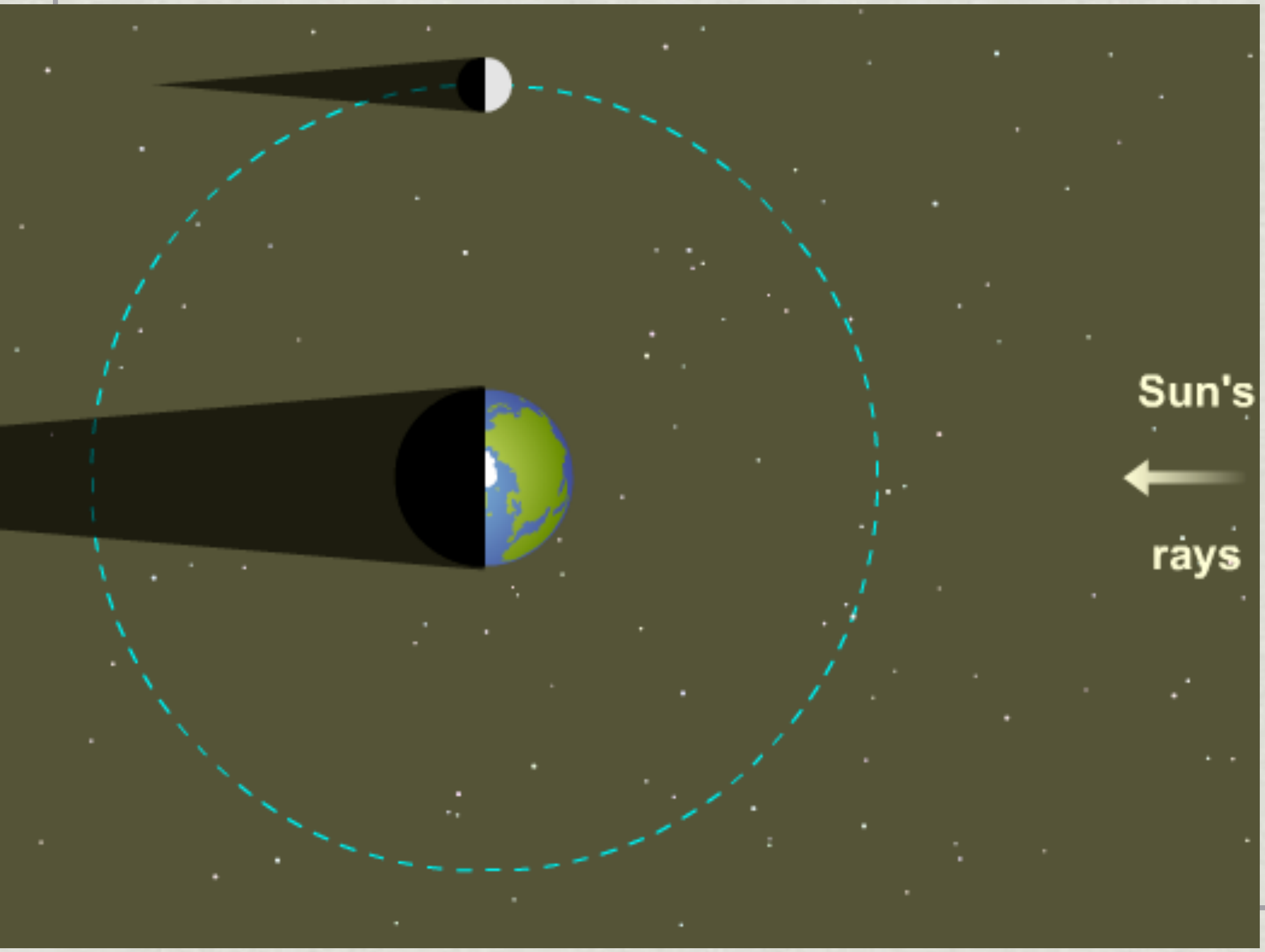
- The earth and moon cast shadows
- Phases of the moon are caused by how we see the sun illuminate the moon, *NOT* the earth's shadow on the moon

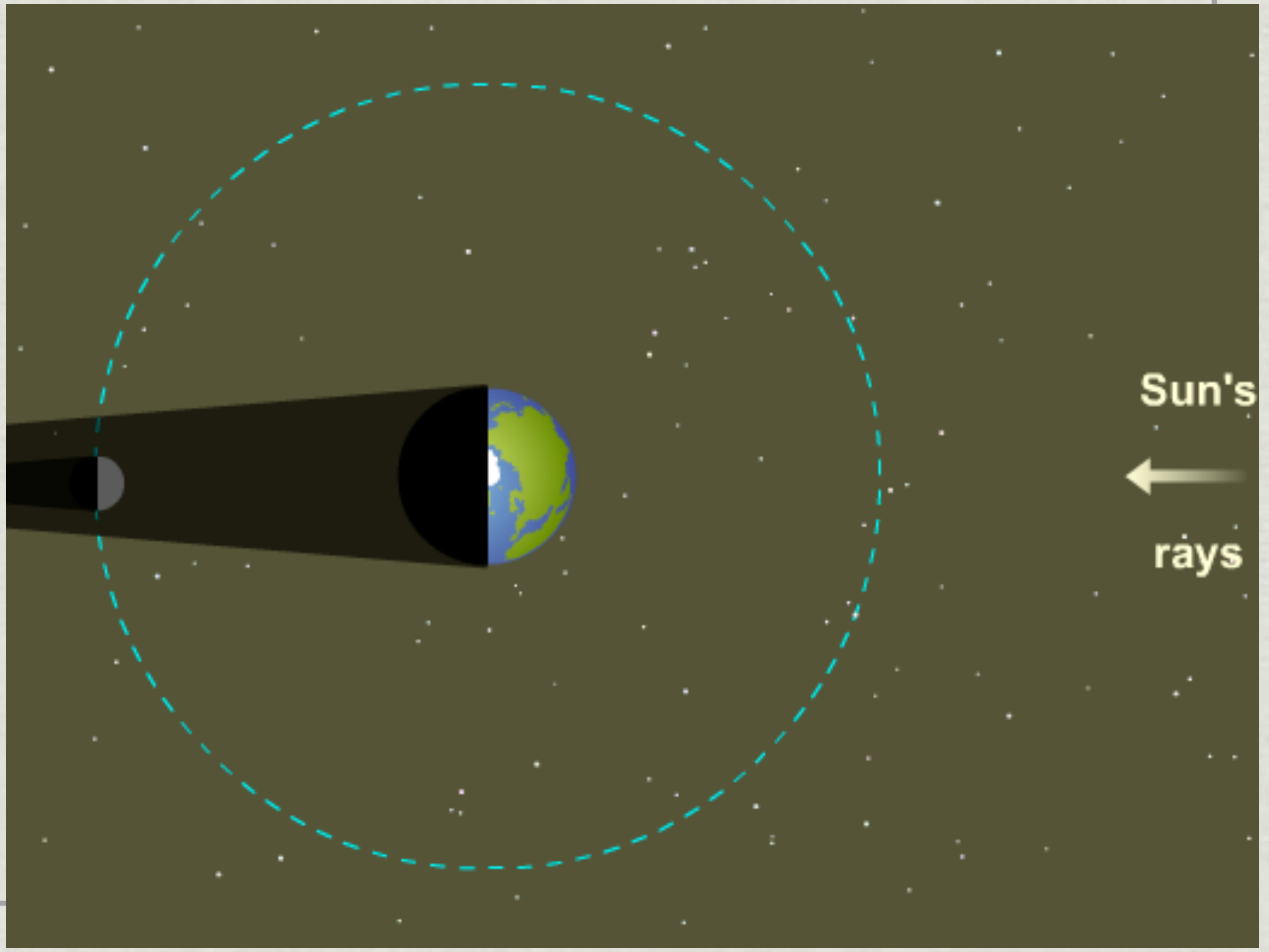


- The moon orbits the earth every 27 days
- Does the moon's illumination change much in a single day?
- What phase does someone in California see? How about someone in Moscow? In Rio?

Eclipses: Lunar Eclipse

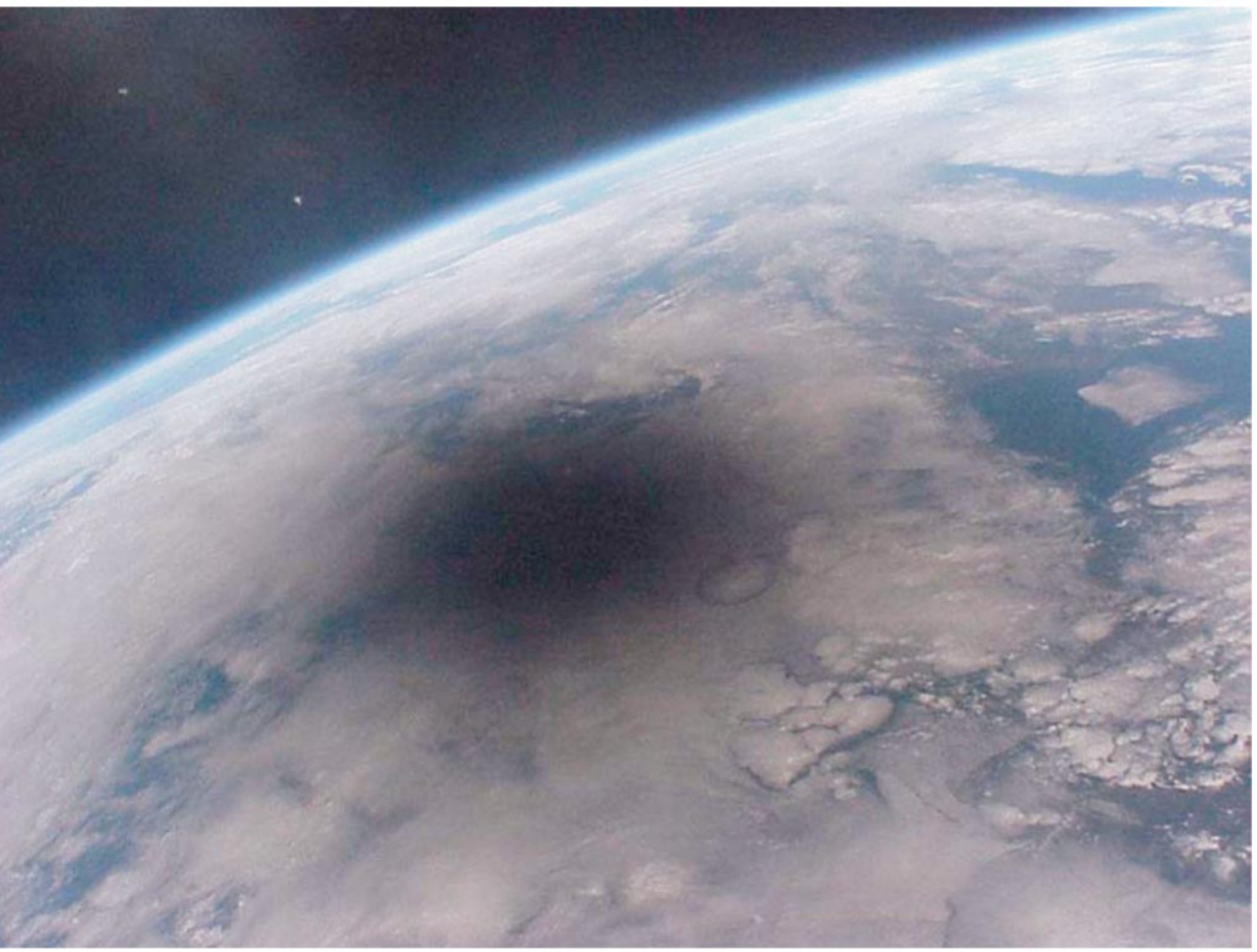
- The earth and moon cast shadows
- When the earth's shadow falls on the moon: Lunar eclipse
- What is the moon phase during a lunar eclipse?



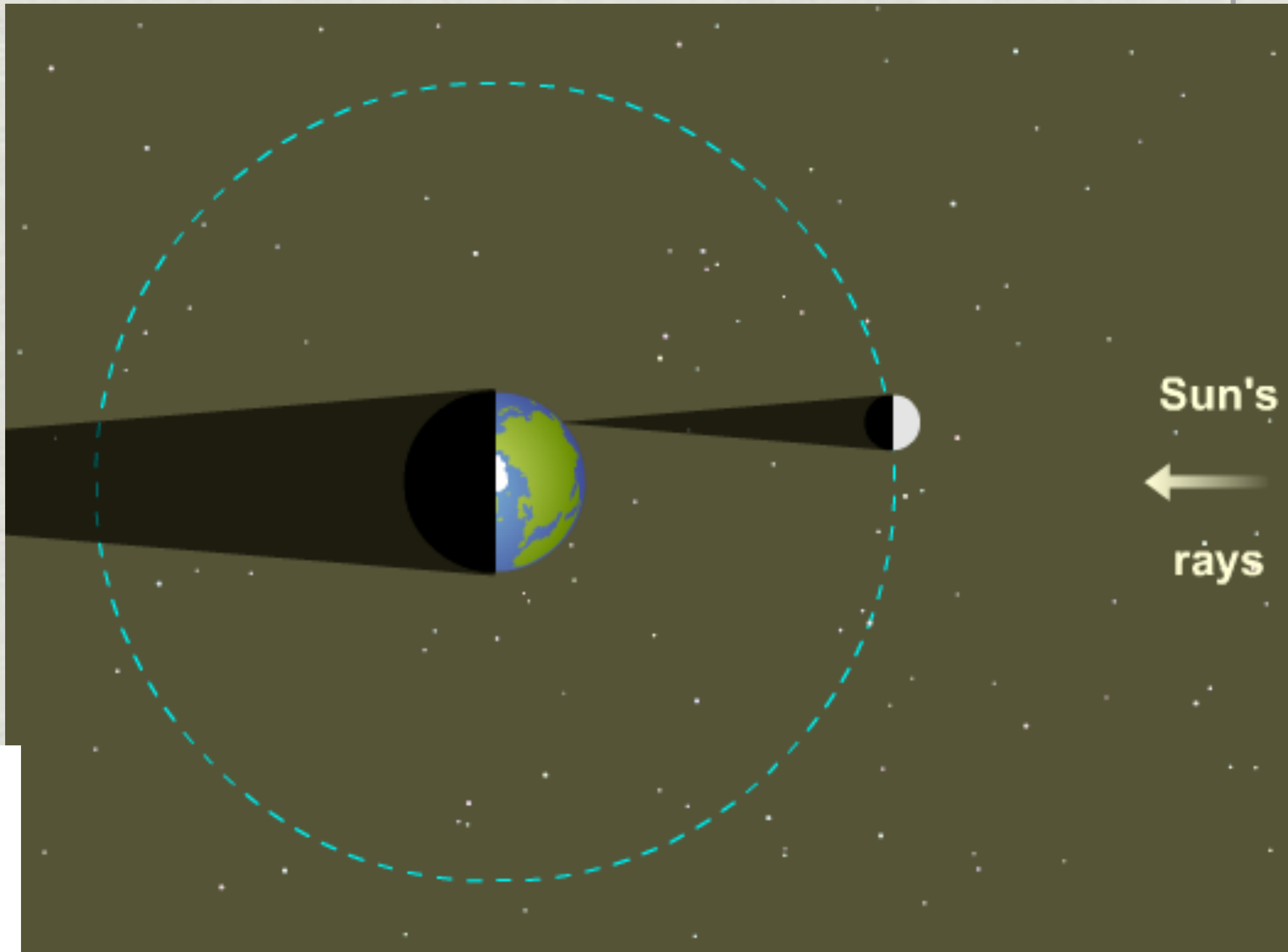


Eclipses: Solar Eclipse

- The earth and moon cast shadows
- When the moon's shadow falls on the earth: Solar eclipse
- What is the moon phase during a solar eclipse?



Picture of the Moon's shadow on earth during a solar eclipse



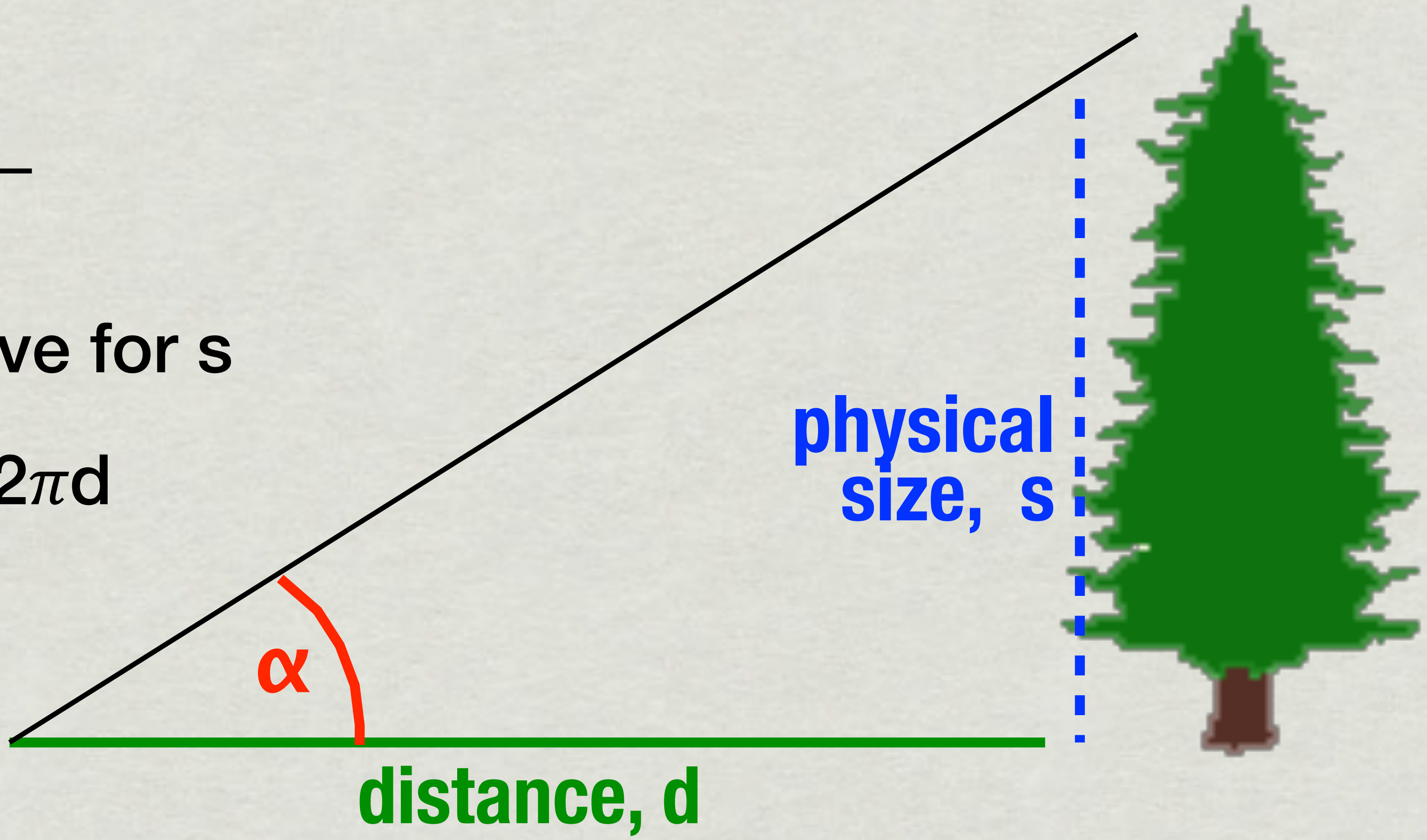
Distance and Angular Size

- you can always measure the angular size α
- sometimes you know the distance, **d**
- use angular size and distance to measure the physical size, **s**

$$\frac{\alpha}{360^\circ} = \frac{s}{2\pi d}$$

rearrange, solve for s

$$s = \frac{\alpha}{360^\circ} \times 2\pi d$$



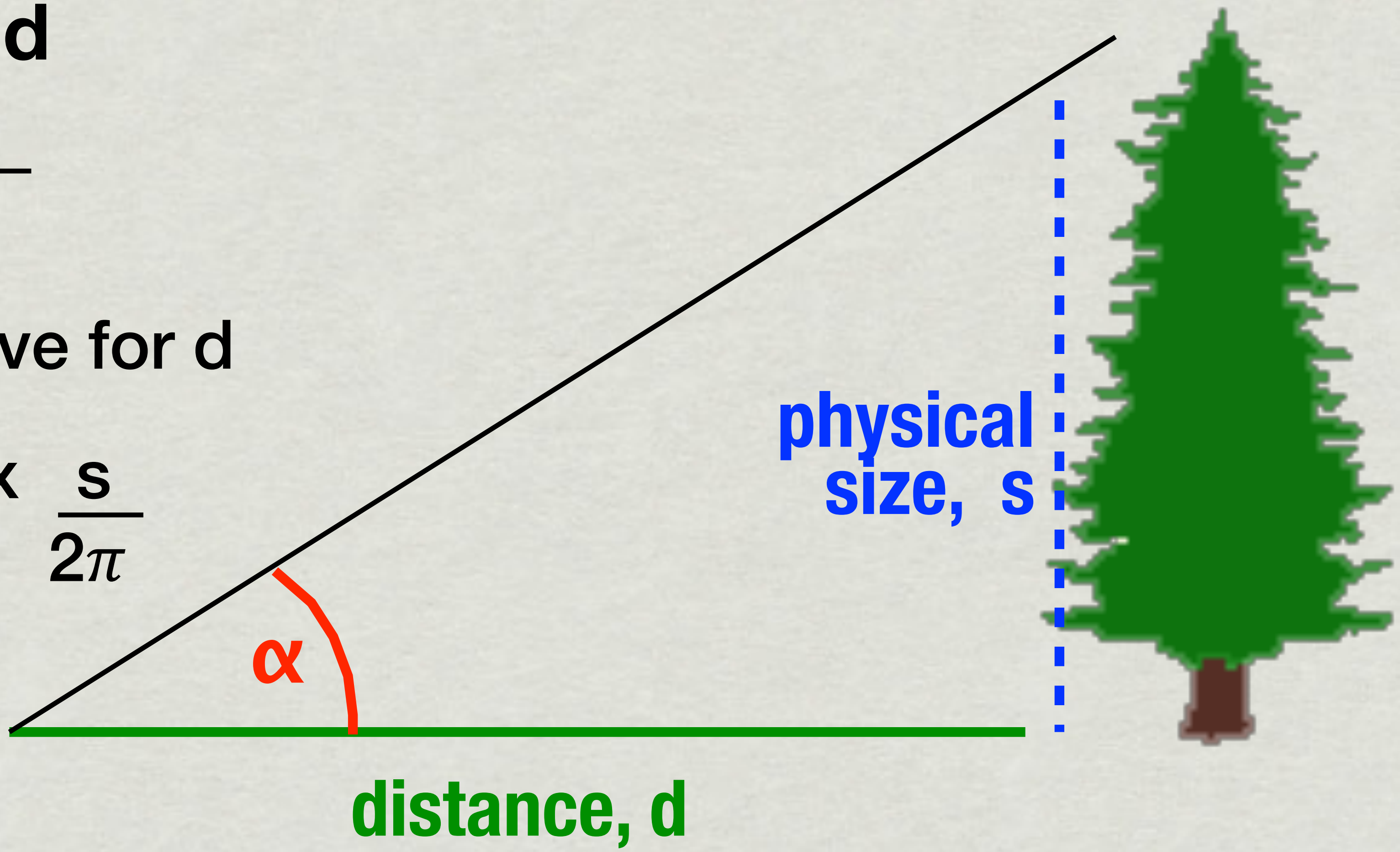
Distance and Angular Size

- you can always measure the angular size α
- sometimes you know the physical size, **s**
- use relation between angular size physical sizes to measure the distance, **d**

$$\frac{\alpha}{360^\circ} = \frac{s}{2\pi d}$$

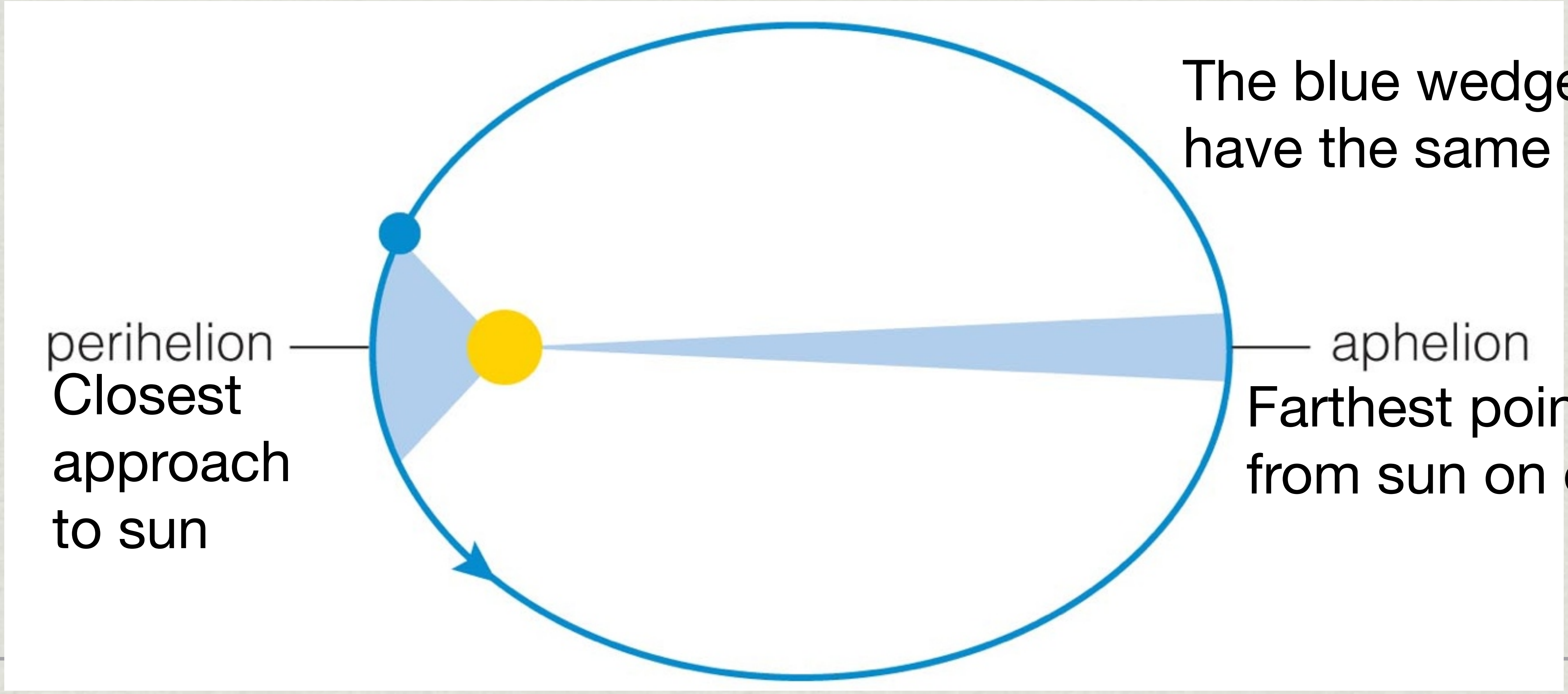
rearrange, solve for d

$$d = \frac{360^\circ}{\alpha} \times \frac{s}{2\pi}$$



Kepler's Laws, Recap

- Kepler's First Law: The orbits of the planets are ellipses, the sun at one focus
- Kepler's Second Law: A planet moving along its orbit sweeps out equal area in equal time



Kepler's Laws, Recap

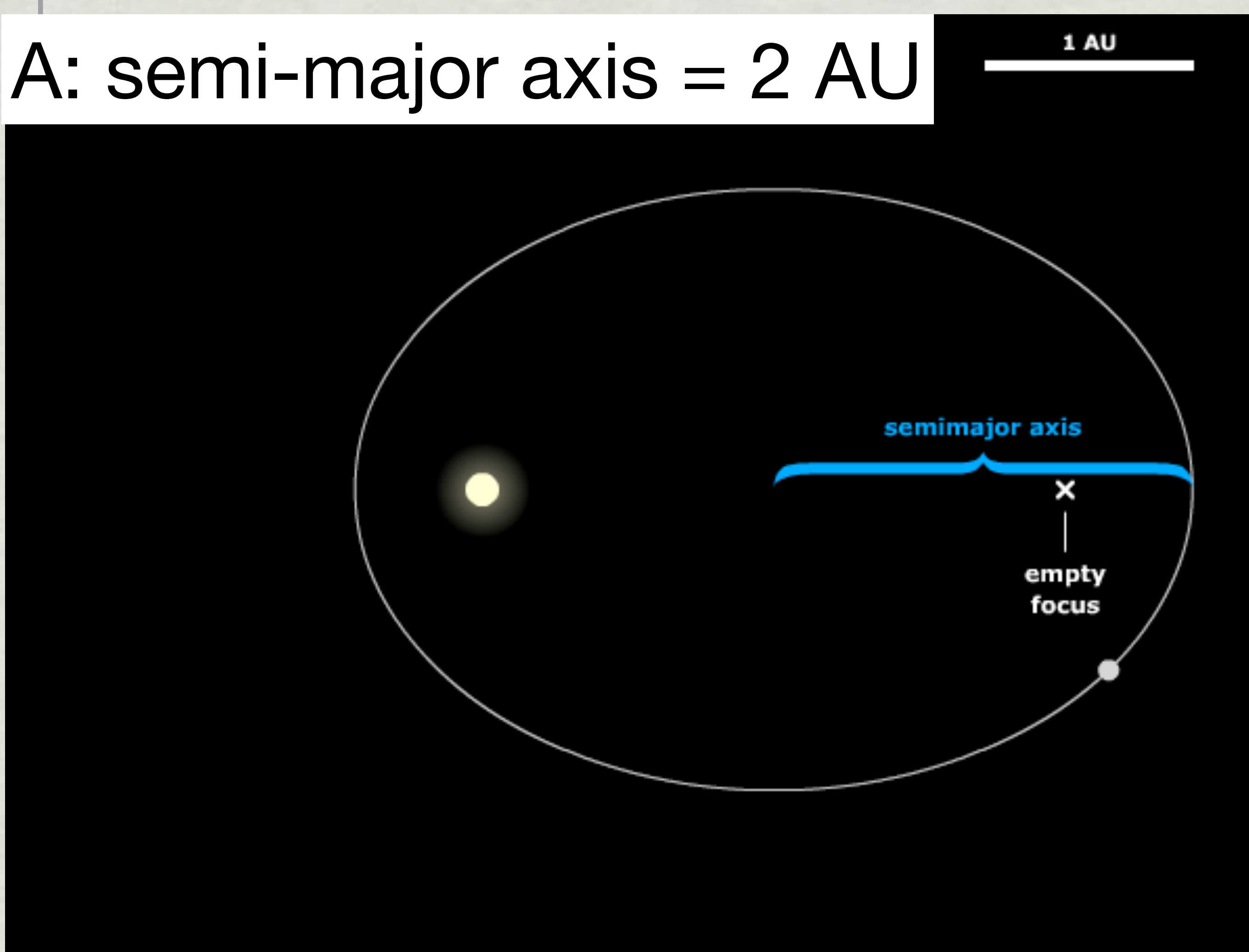
Two planets (A and B) in orbit around the same star.

Which planet has the largest speed when it is closest to the star?

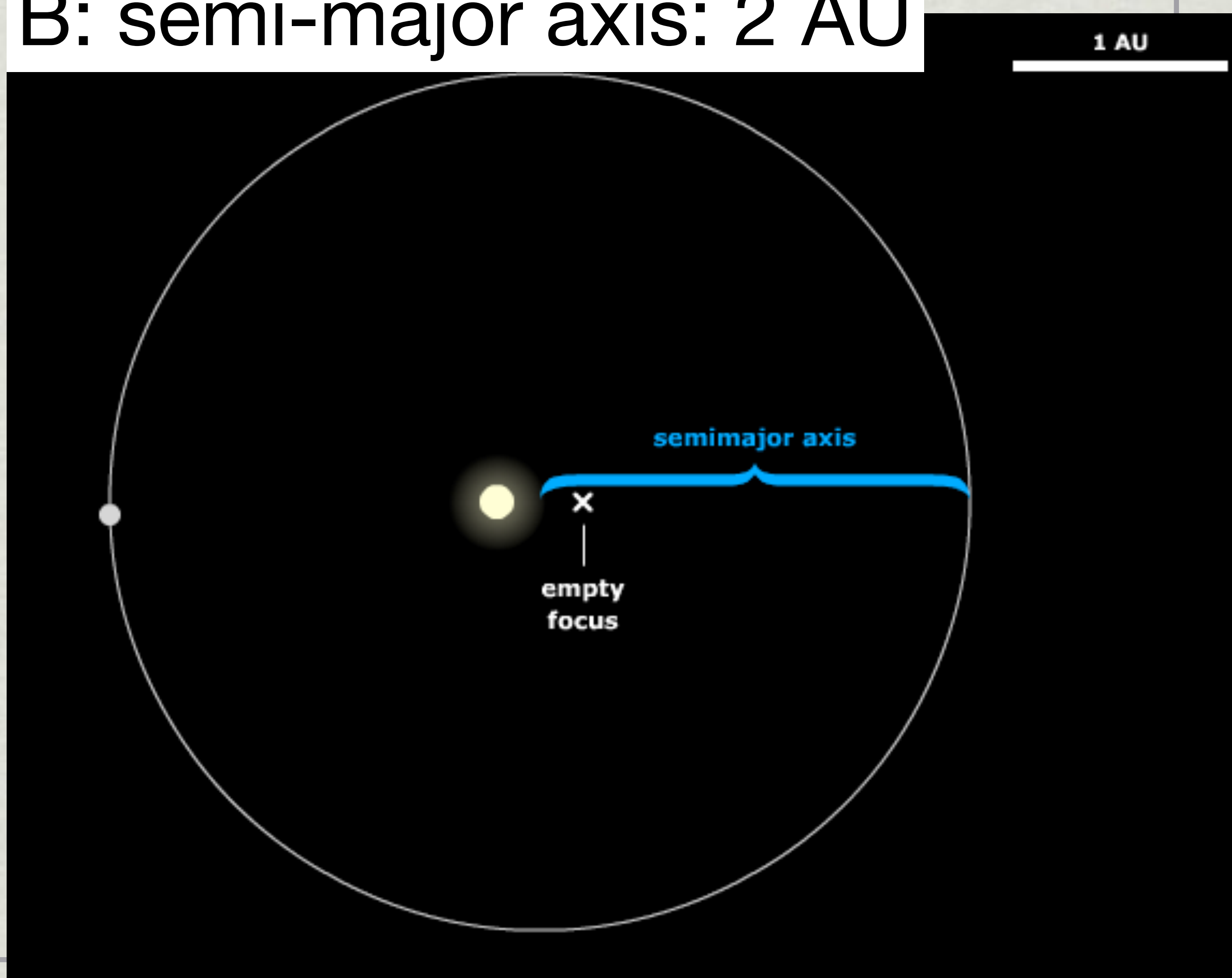
A

B

A: semi-major axis = 2 AU



B: semi-major axis: 2 AU



Kepler's Laws, Recap

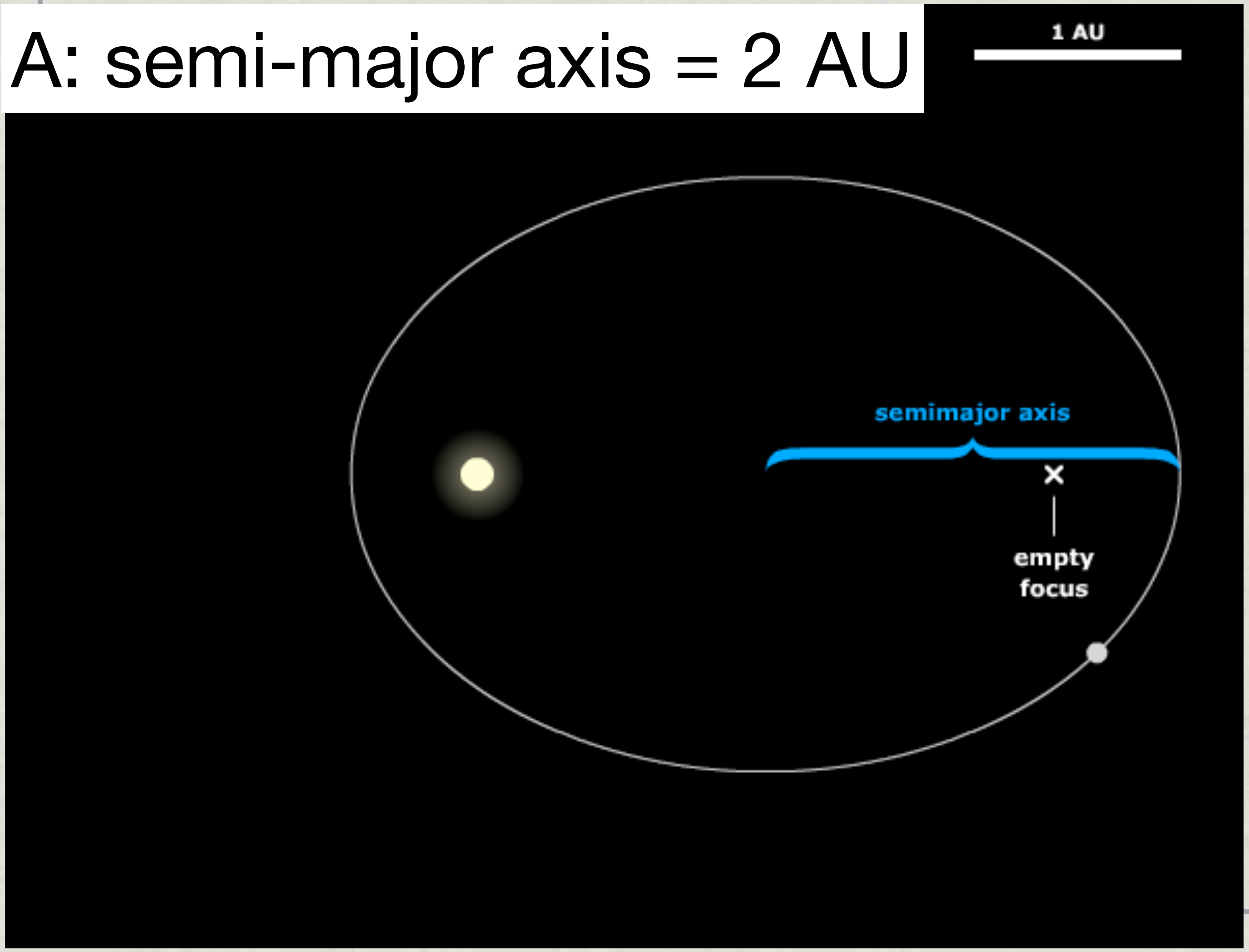
Two planets (A and B) in orbit around the same star.

Which planet has the largest speed when it is closest to the star?

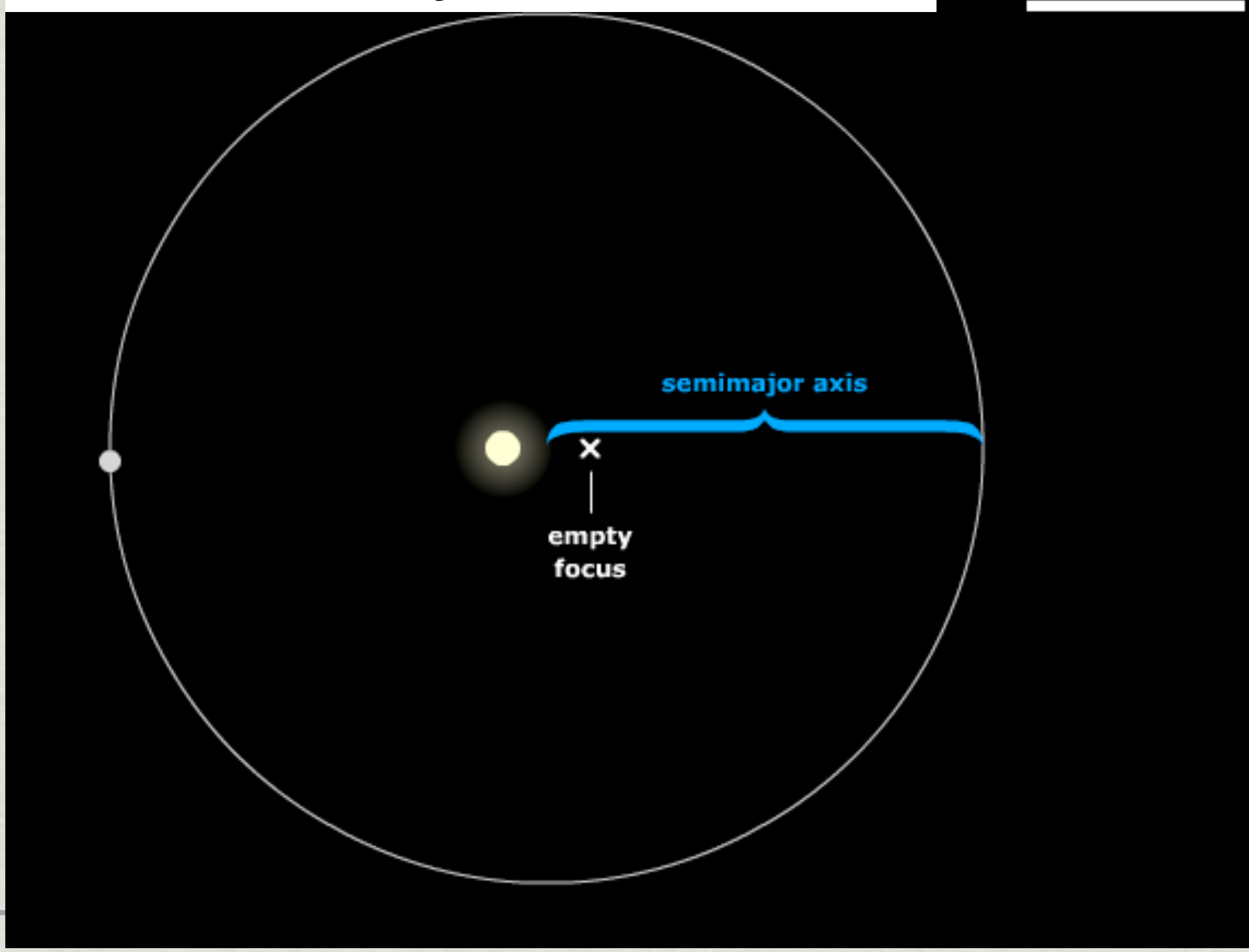
A

B

A: semi-major axis = 2 AU



B: semi-major axis: 2 AU



Kepler's Laws, Recap

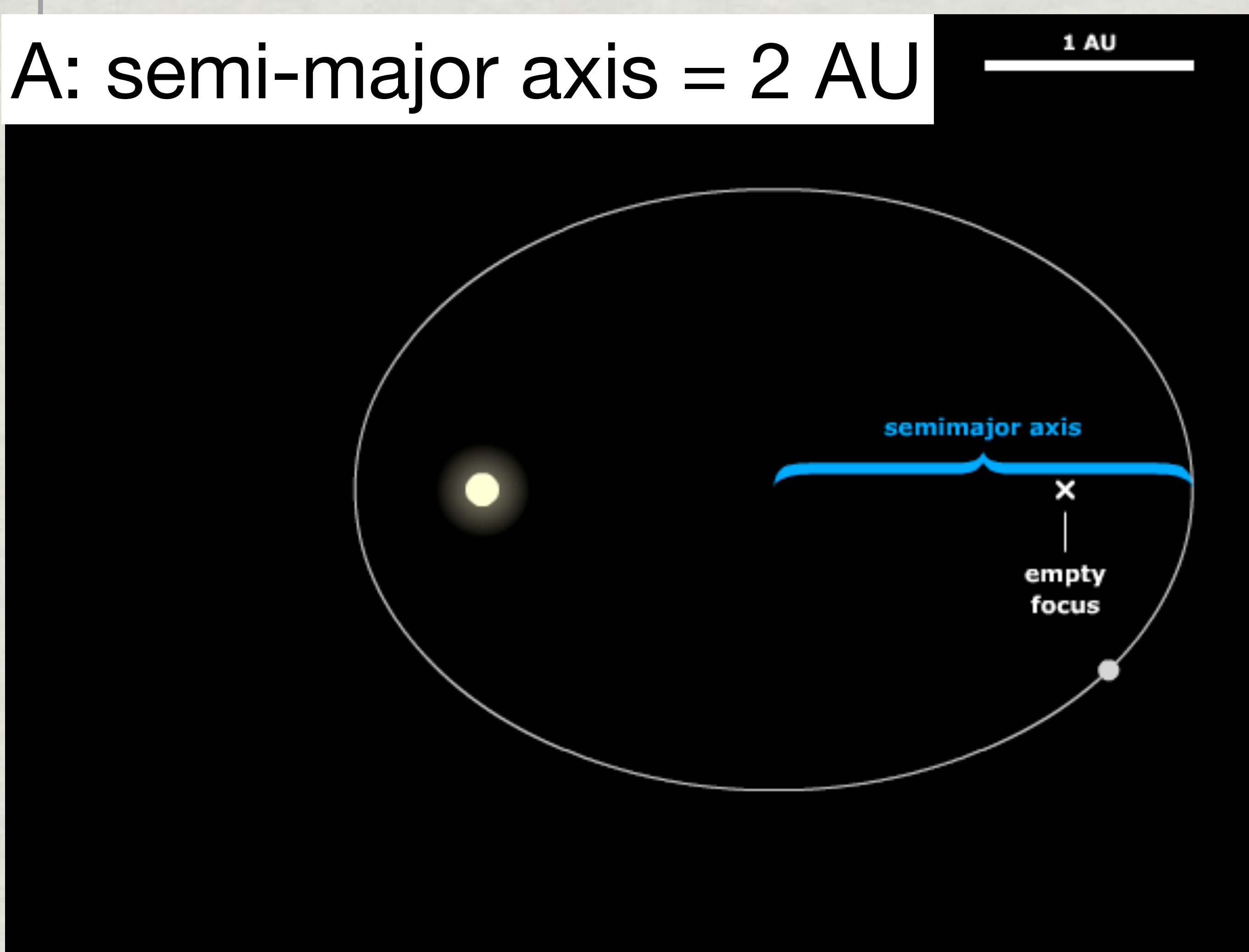
Two planets (A and B) in orbit around the same star.

Which planet has the largest speed when it is farthest from the star?

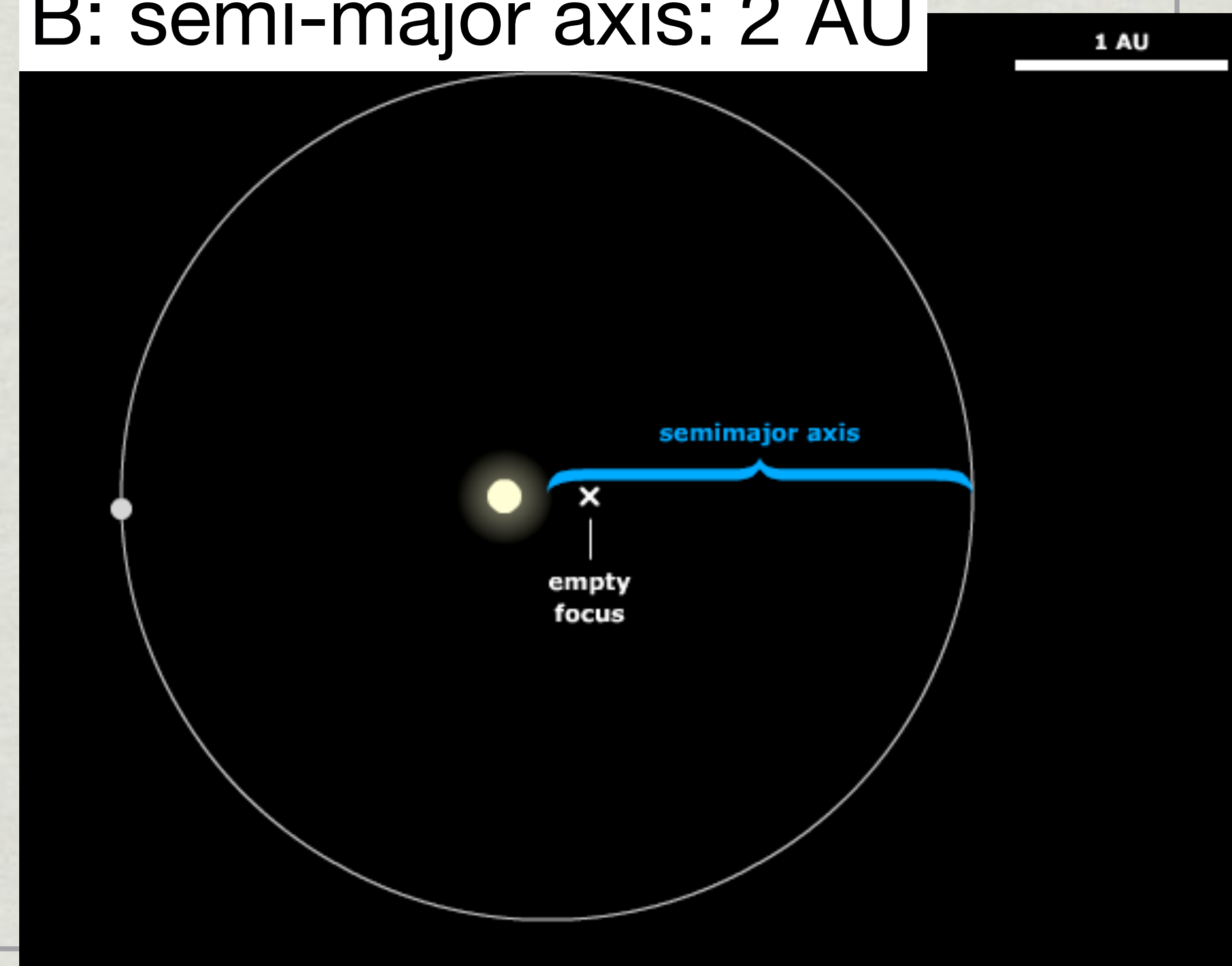
A

B

A: semi-major axis = 2 AU



B: semi-major axis: 2 AU



Kepler's Laws, Recap

Two planets (A and B) in orbit around the same star.

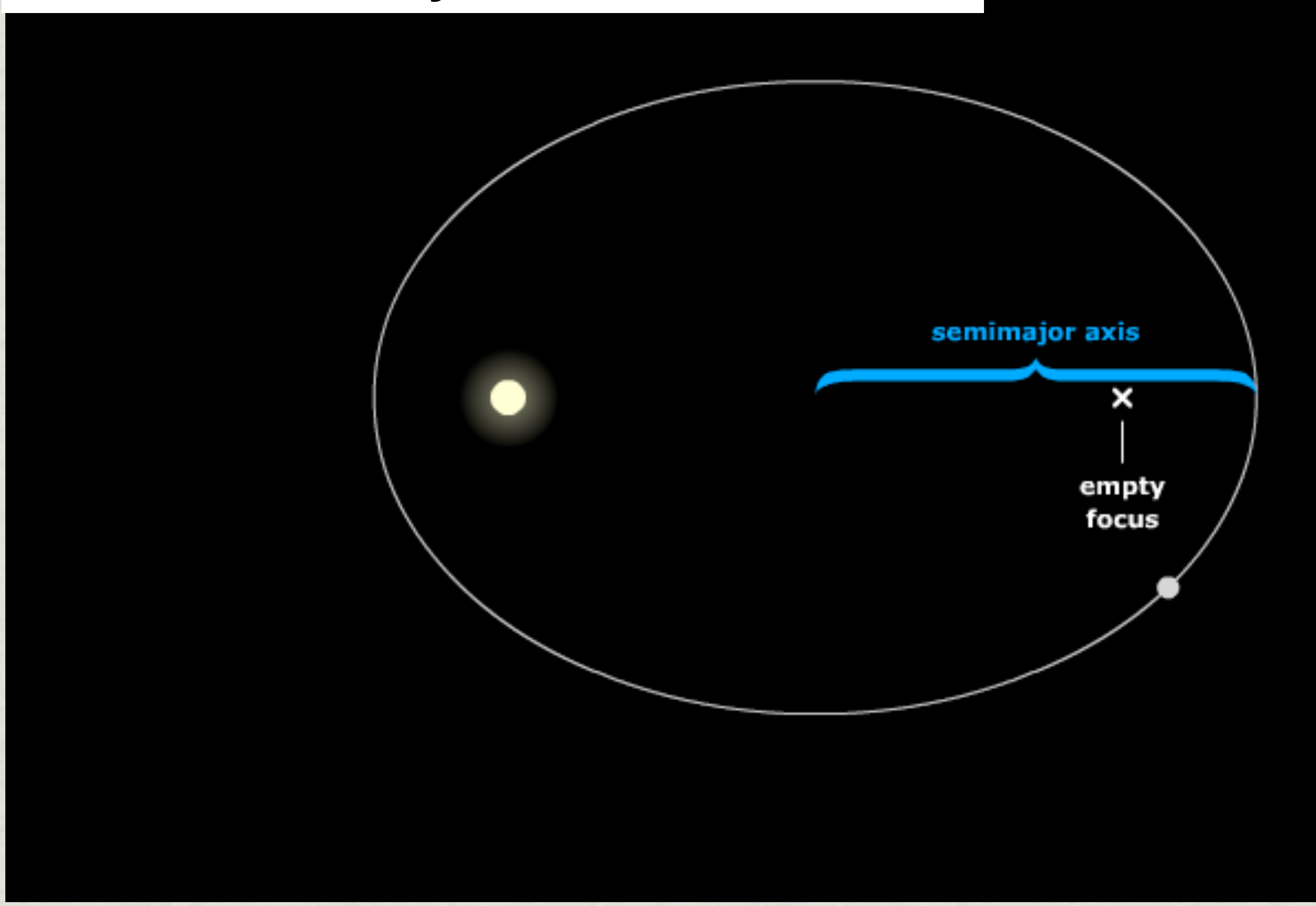
Which planet has the largest speed when it is farthest from the star?

A

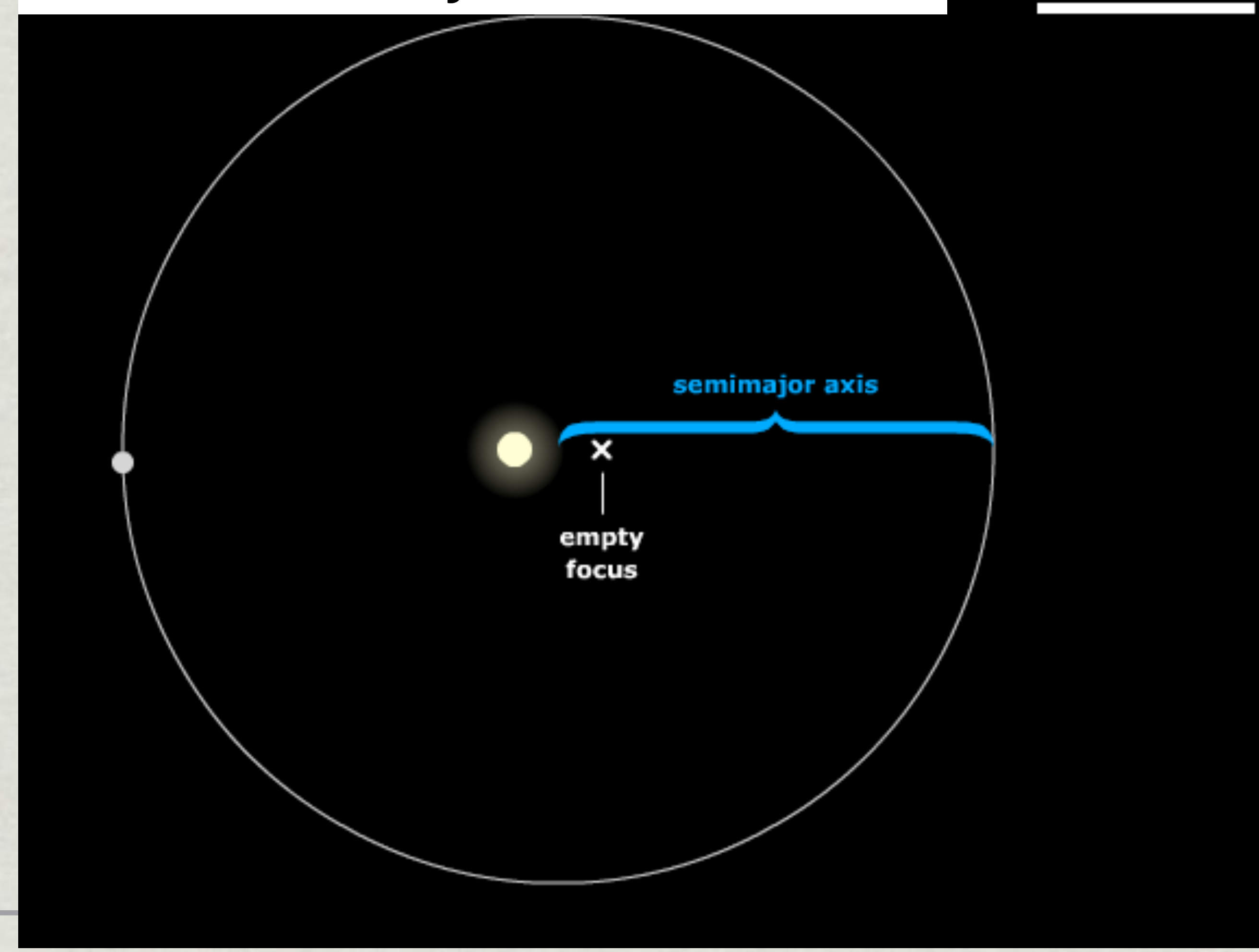
B

Kepler's 2nd law: planets sweep out equal area in equal time

A: semi-major axis = 2 AU



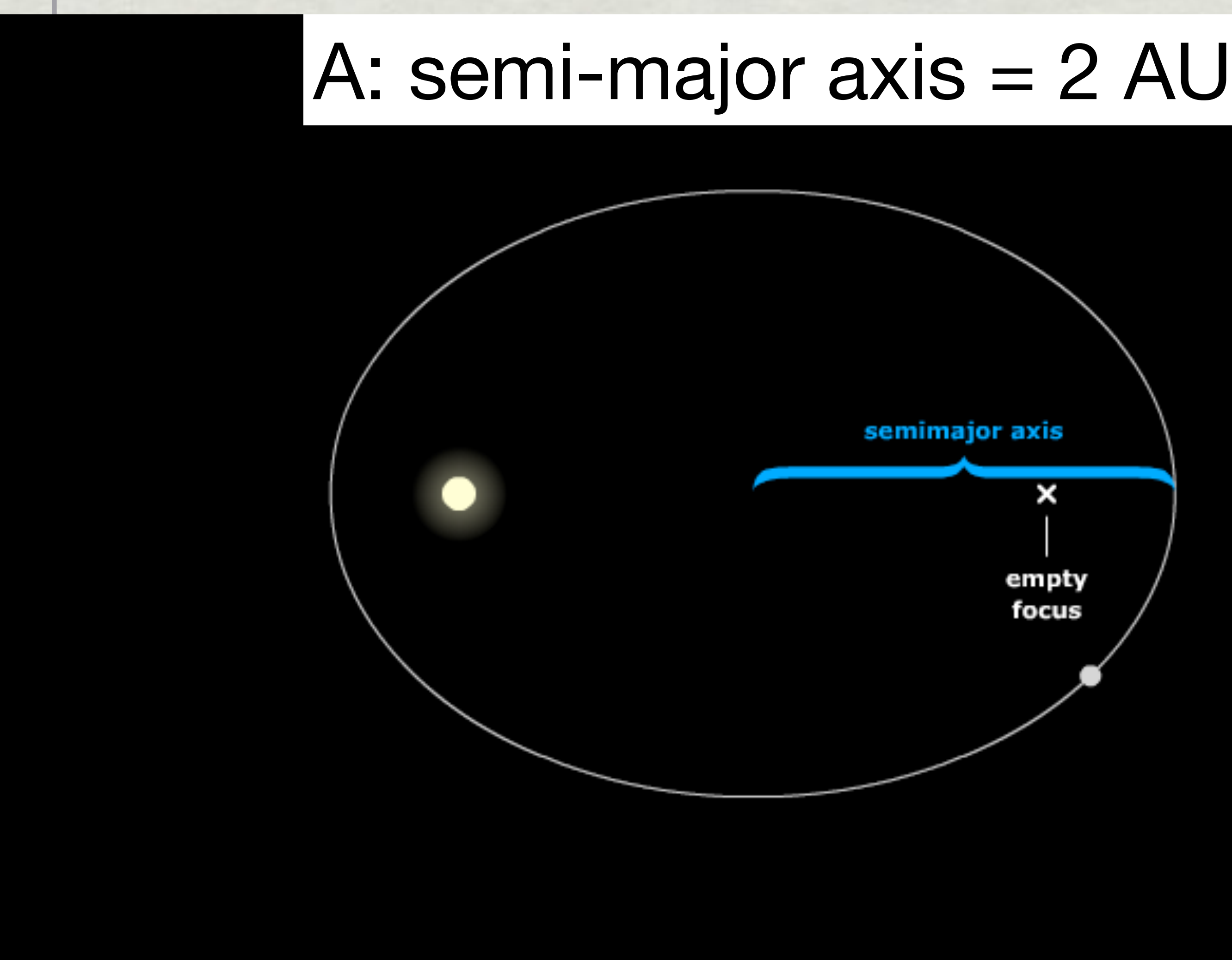
B: semi-major axis: 2 AU

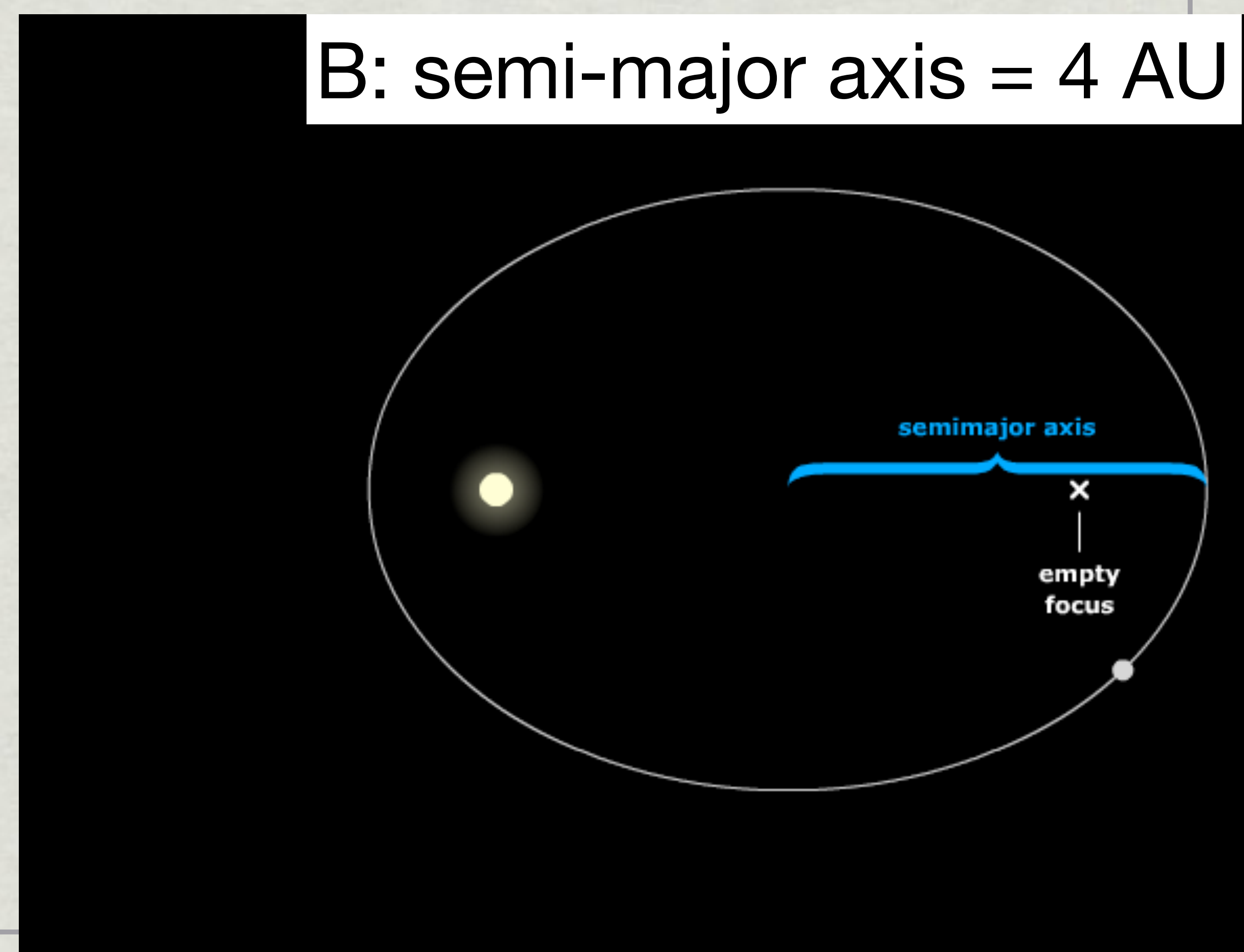


Kepler’s Laws, Recap

Two planets (A and B) in orbit around the same star.

For now, let the star be our Sun. So A and B are planets in our solar system

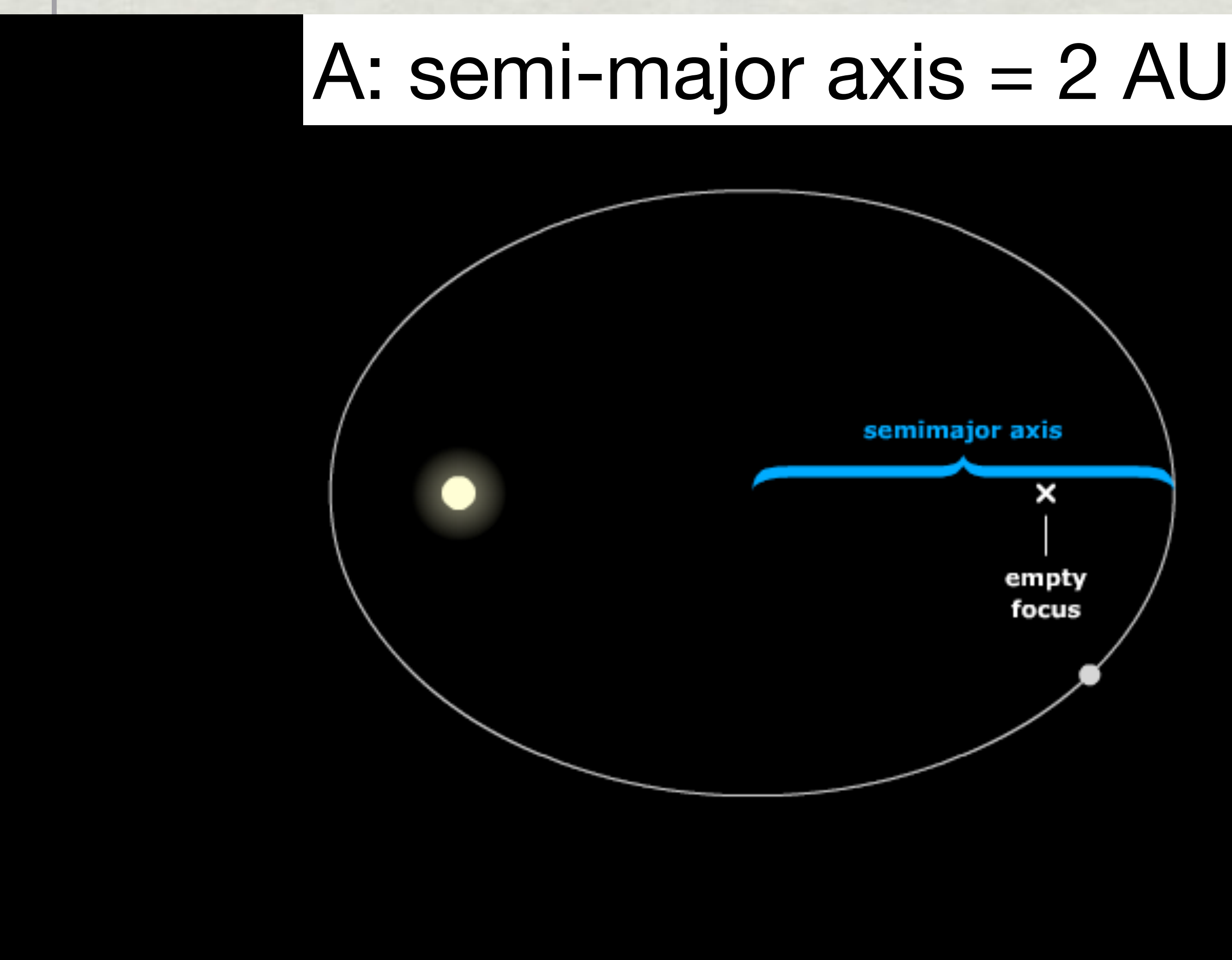


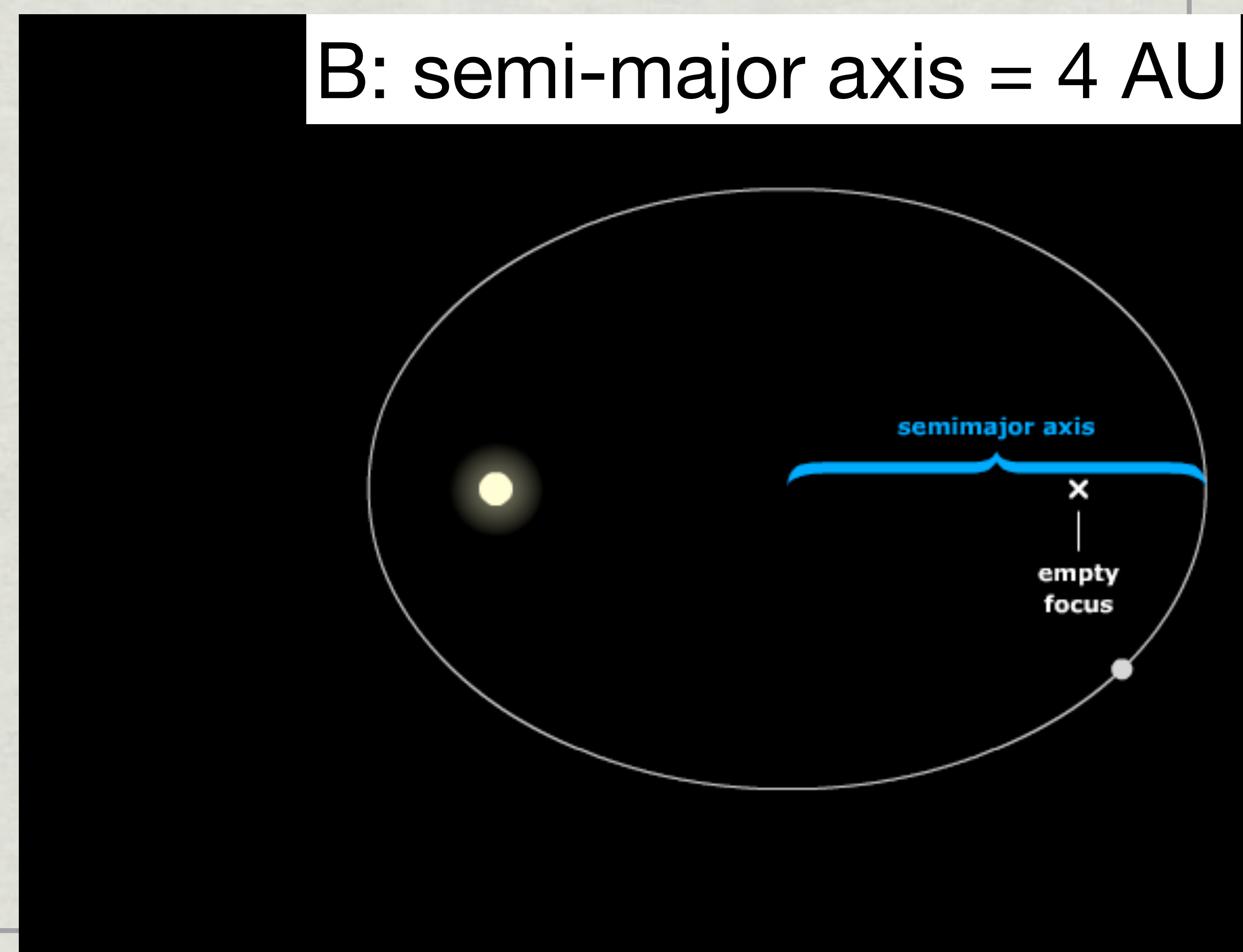


Kepler's Laws, Recap

Two planets (A and B) in orbit around our sun.
The semi-major axis of A is 2 AU, the semi-major axis of B is 4 AU.

- the semi-major axis of an ellipse is also the average distance of a point on the ellipse to one focus
  → The average radius of a planet's orbit is the semi-major axis



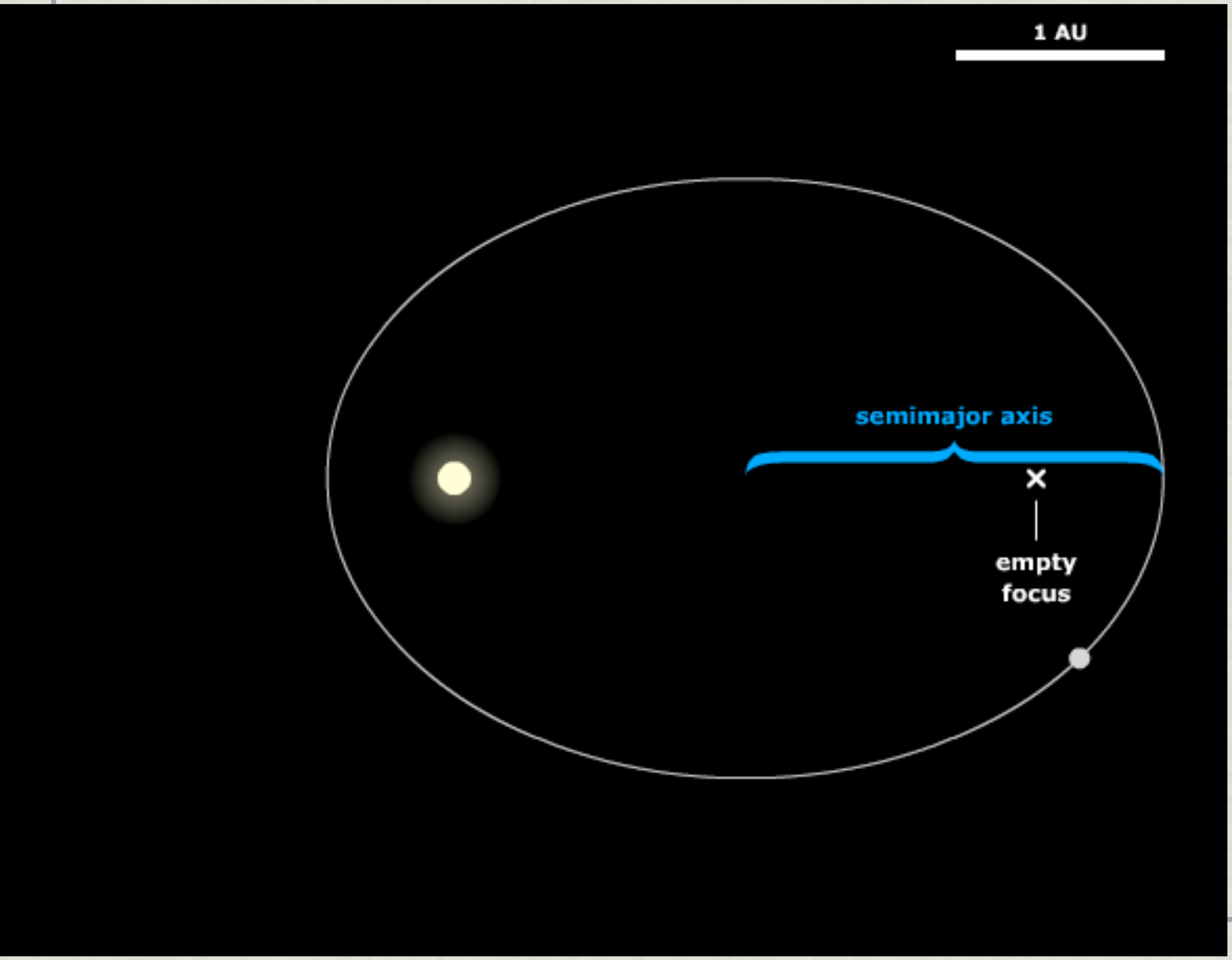


Kepler's Laws, Recap

A planet in orbit around our sun.

Period **P**: time it takes to complete one orbit

A = average radius of the orbit; average distance between the sun and the planet



Kepler's 3rd law: $P^2 = A^3$

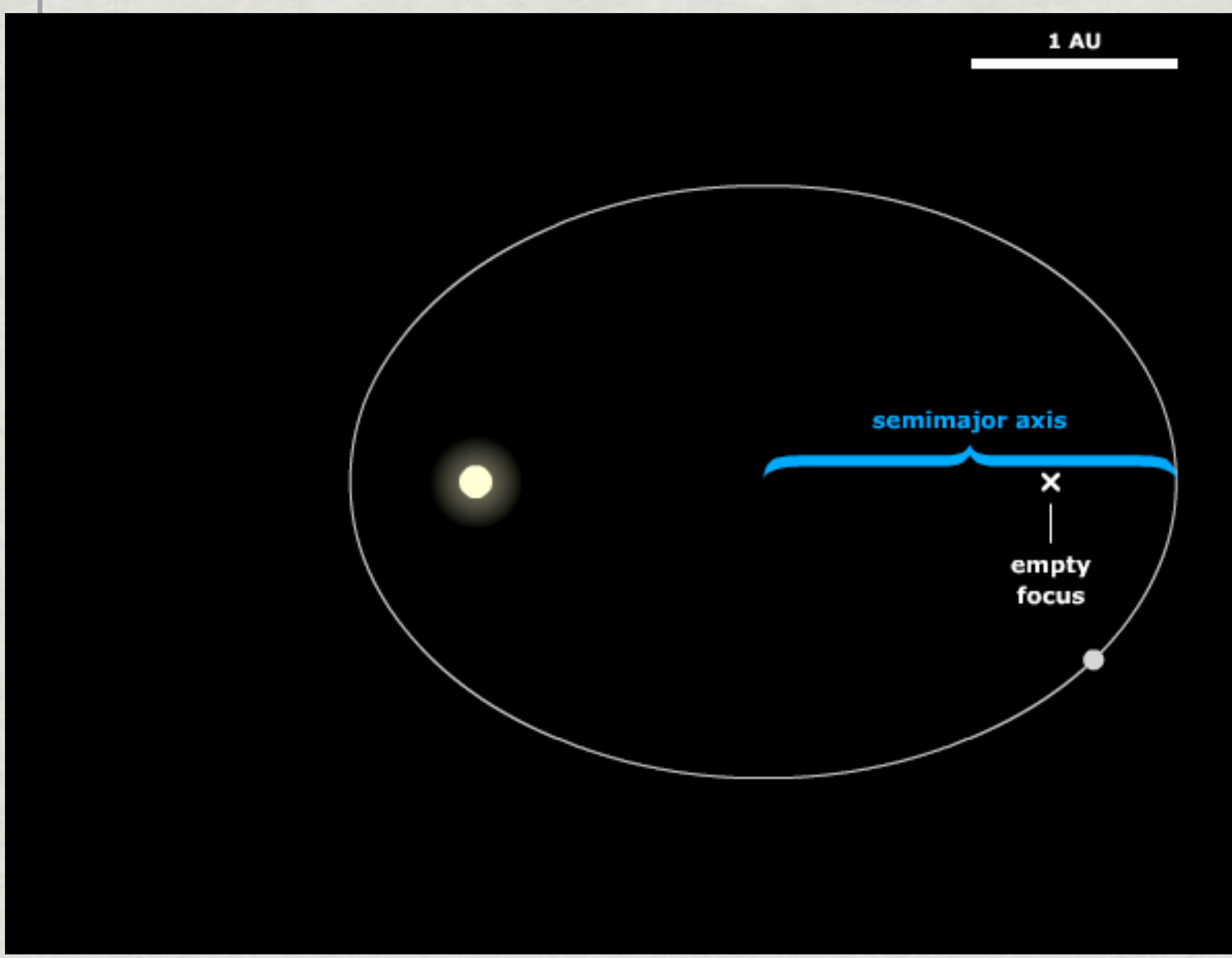
Kepler's Laws, Recap

P = orbital period
A = average radius

Kepler's 3rd law: $P^2 = A^3$

$$\frac{P^2}{A^3} = \frac{(1\ \text{AU})^3}{(1\ \text{year})^2} = \text{Constant} = 1$$

for our solar system, for distance in AU and period in years.



So for our solar system, $P^2 = A^3$

Kepler's Laws, Recap

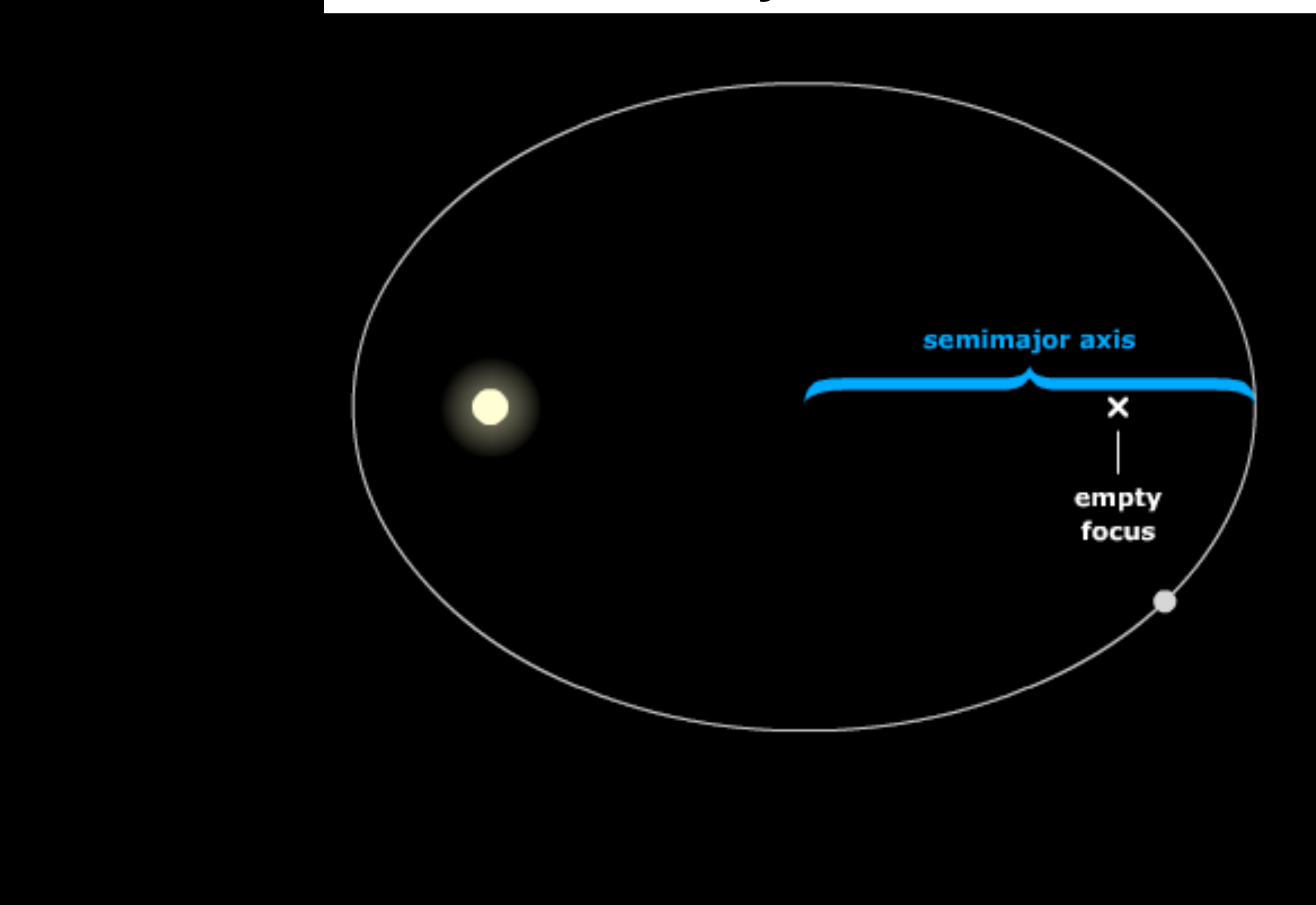
Two planets (X and Y) in orbit around our sun.

Which one take longest to complete an orbit?

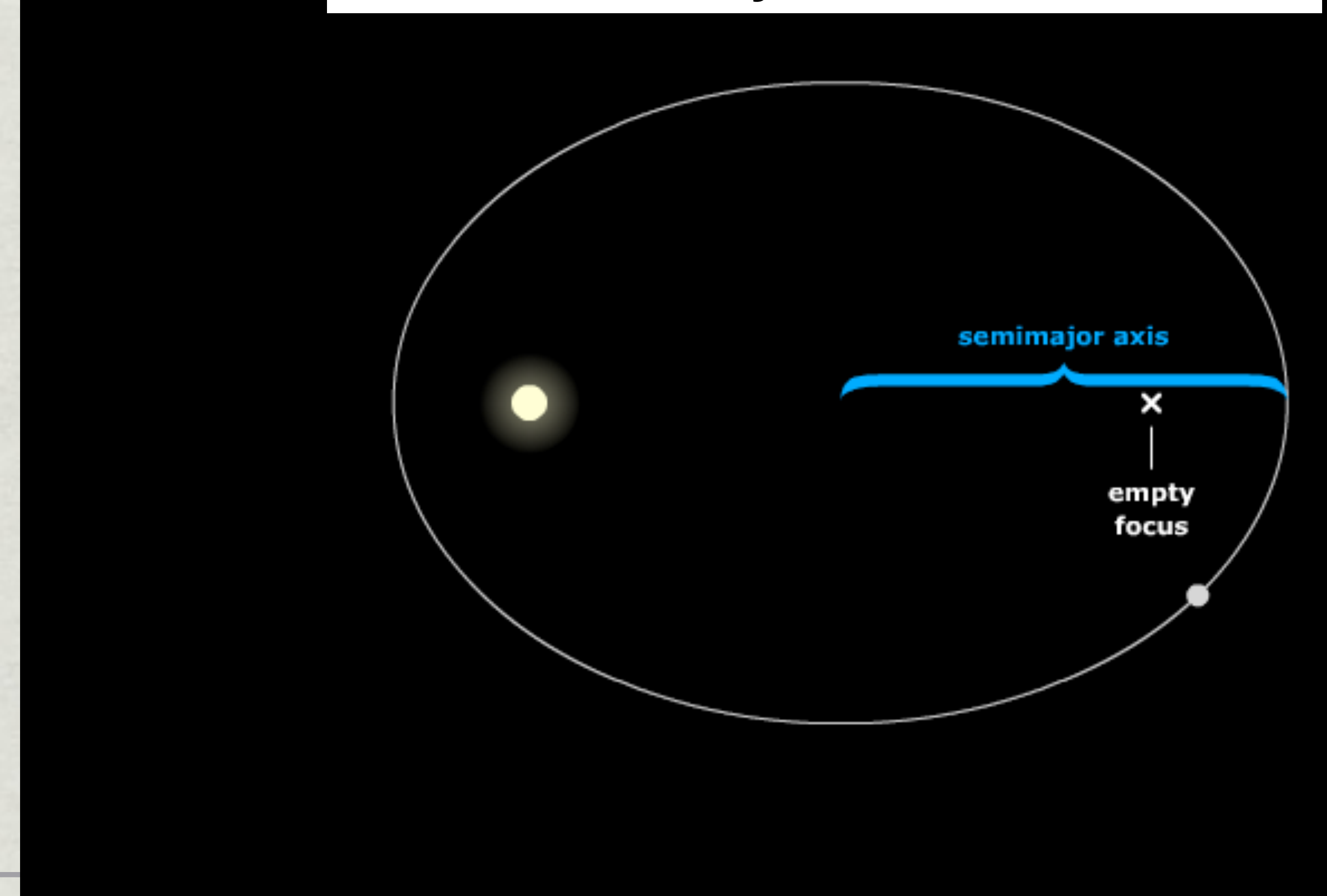
A X
B Y
C they take the same time

Kepler's 3rd law: $P^2 = A^3$

X: semi-major axis = 2 AU



Y: semi-major axis = 4 AU



Kepler's Laws, Recap

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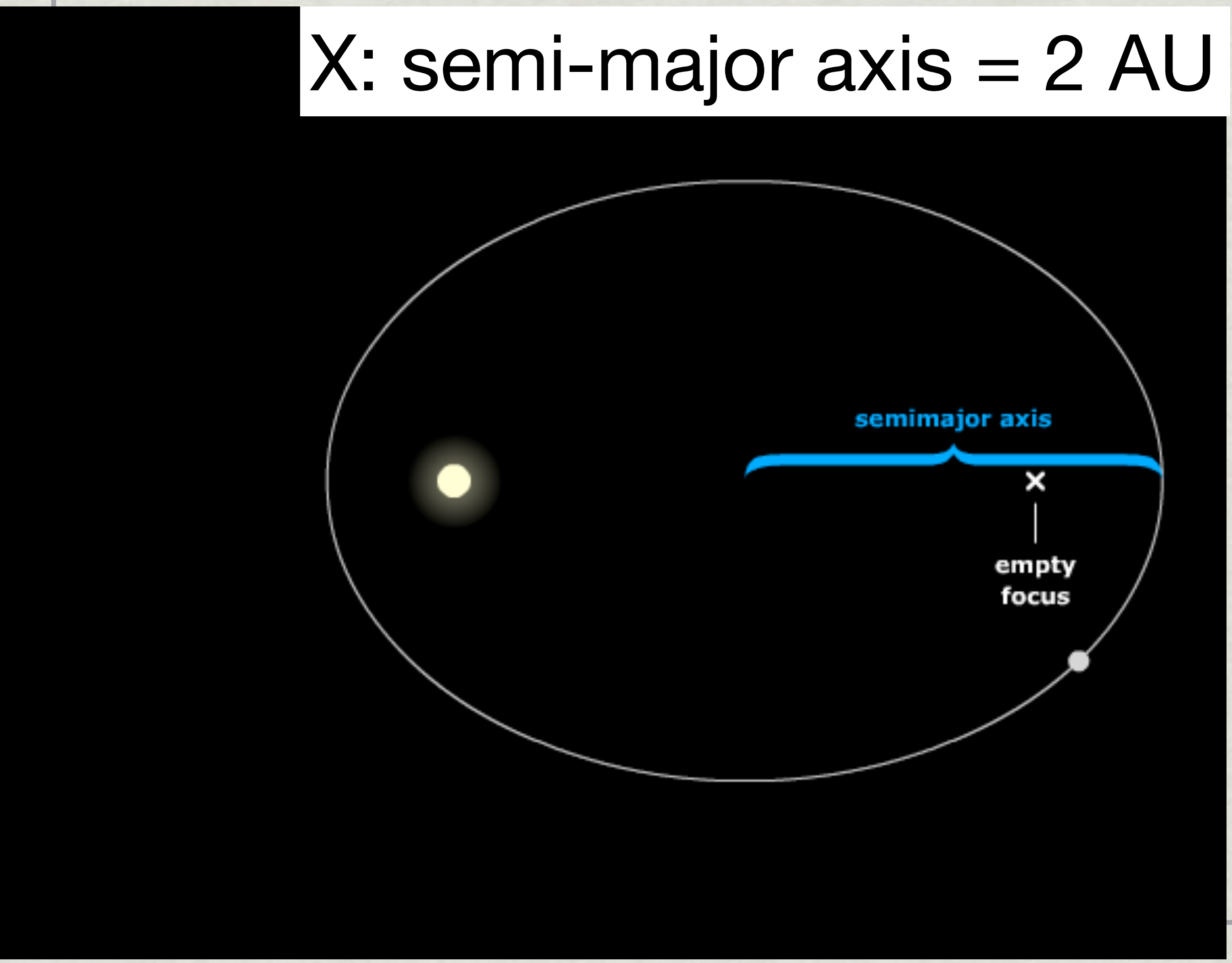
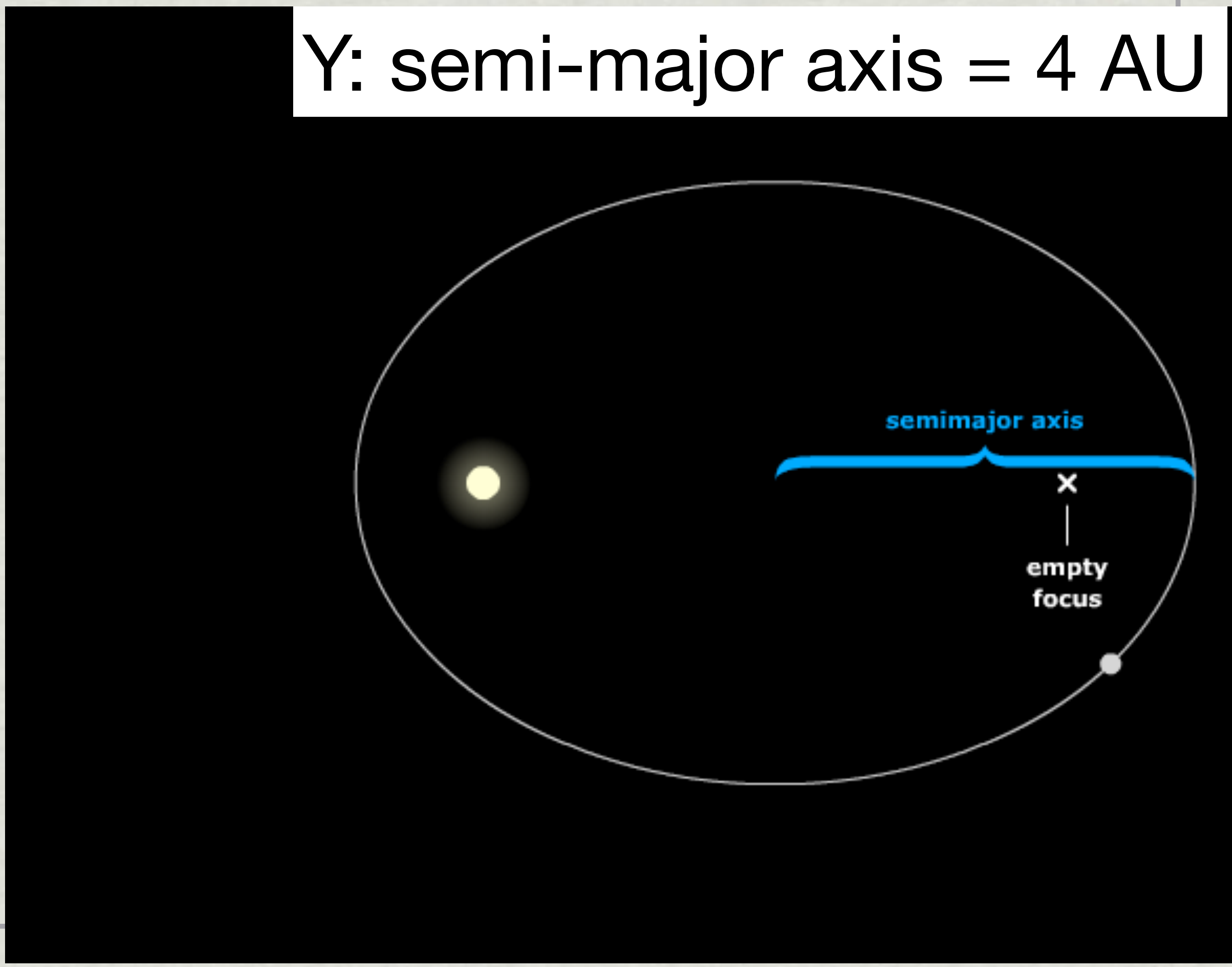


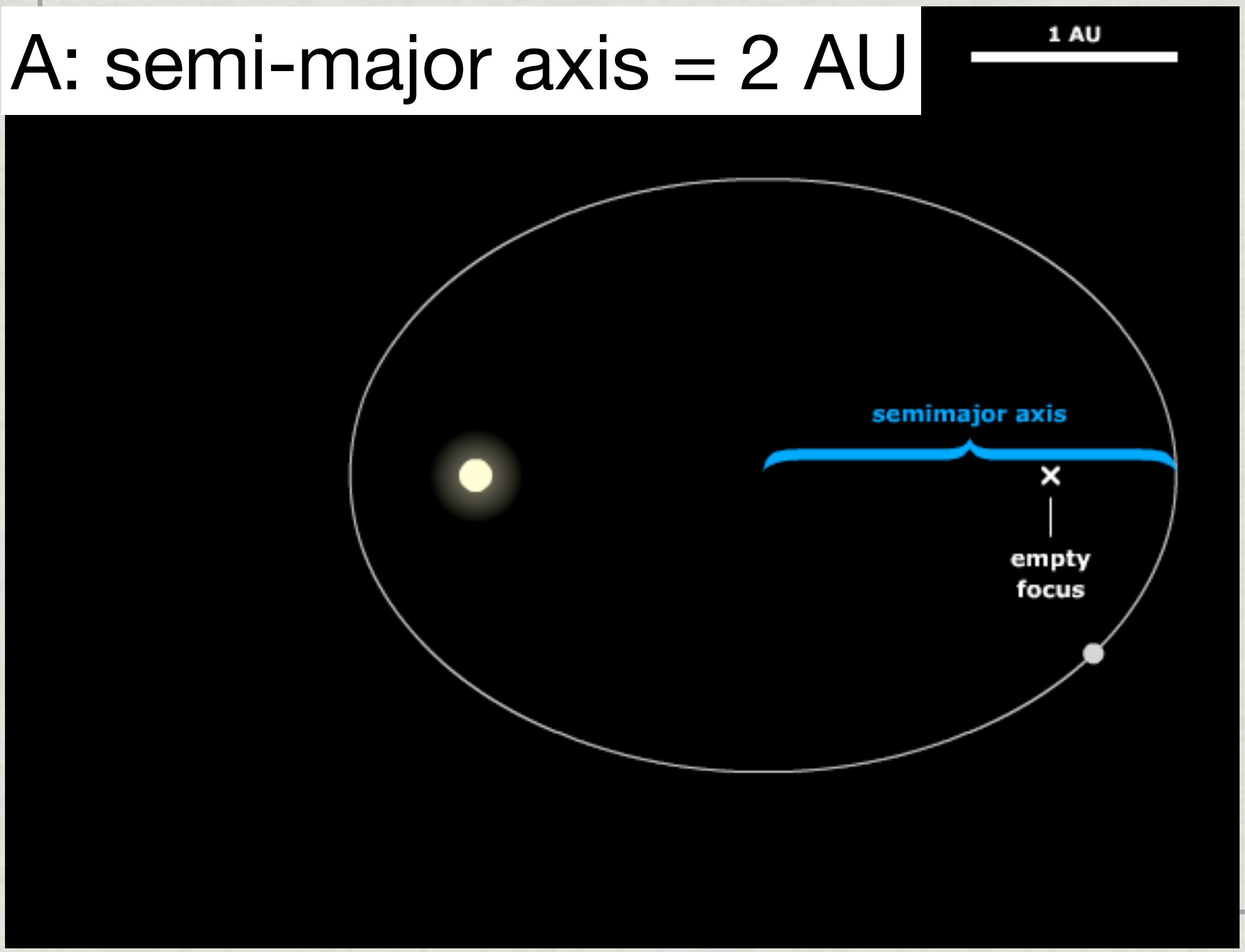


Kepler's Laws, Recap

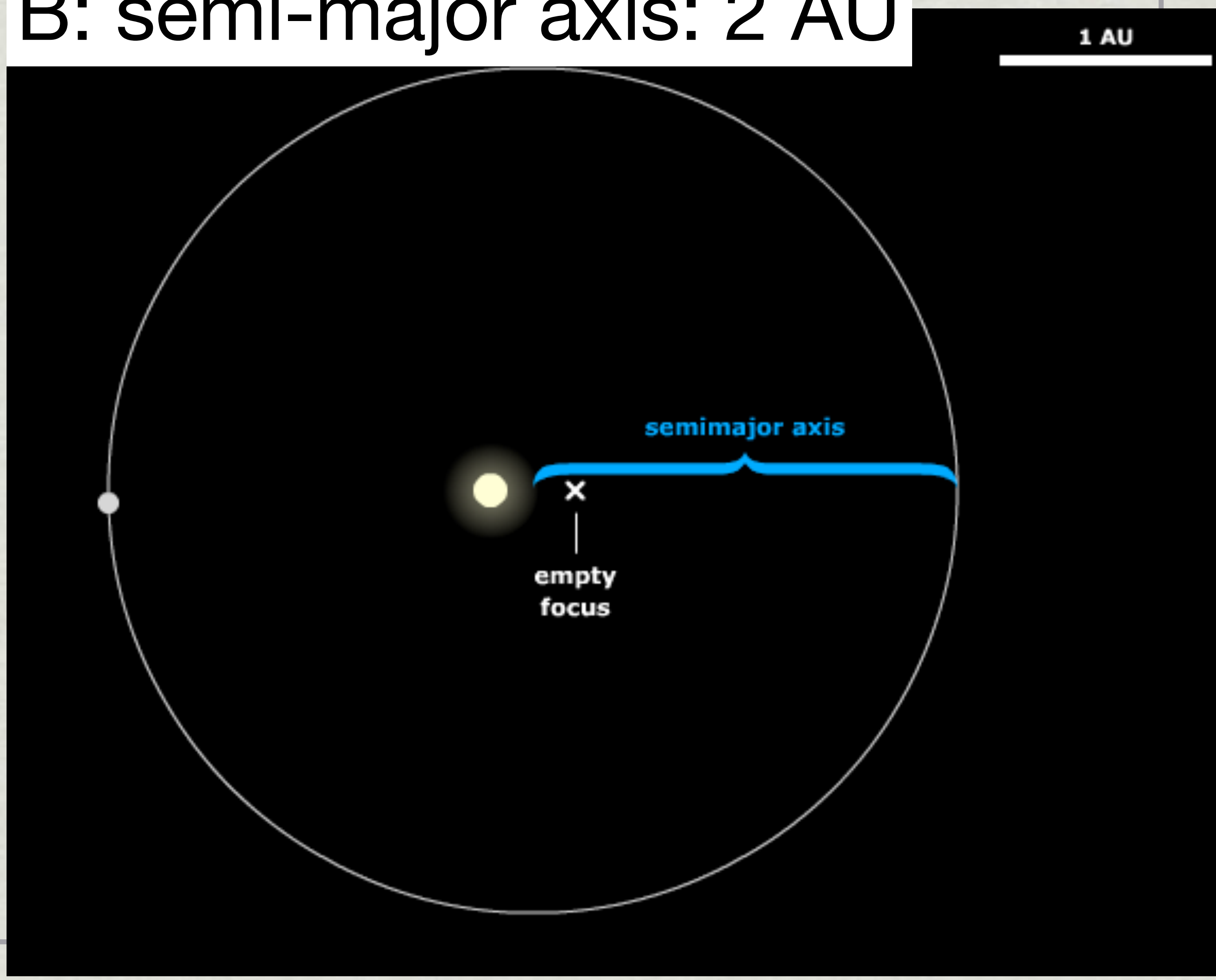
Two planets (A and B) in orbit around the same star. For now, let the star be our Sun. So A and B are planets in our solar system.

How long does it take planet A to orbit the star?

A: semi-major axis = 2 AU



B: semi-major axis: 2 AU



Kepler's Laws, Recap

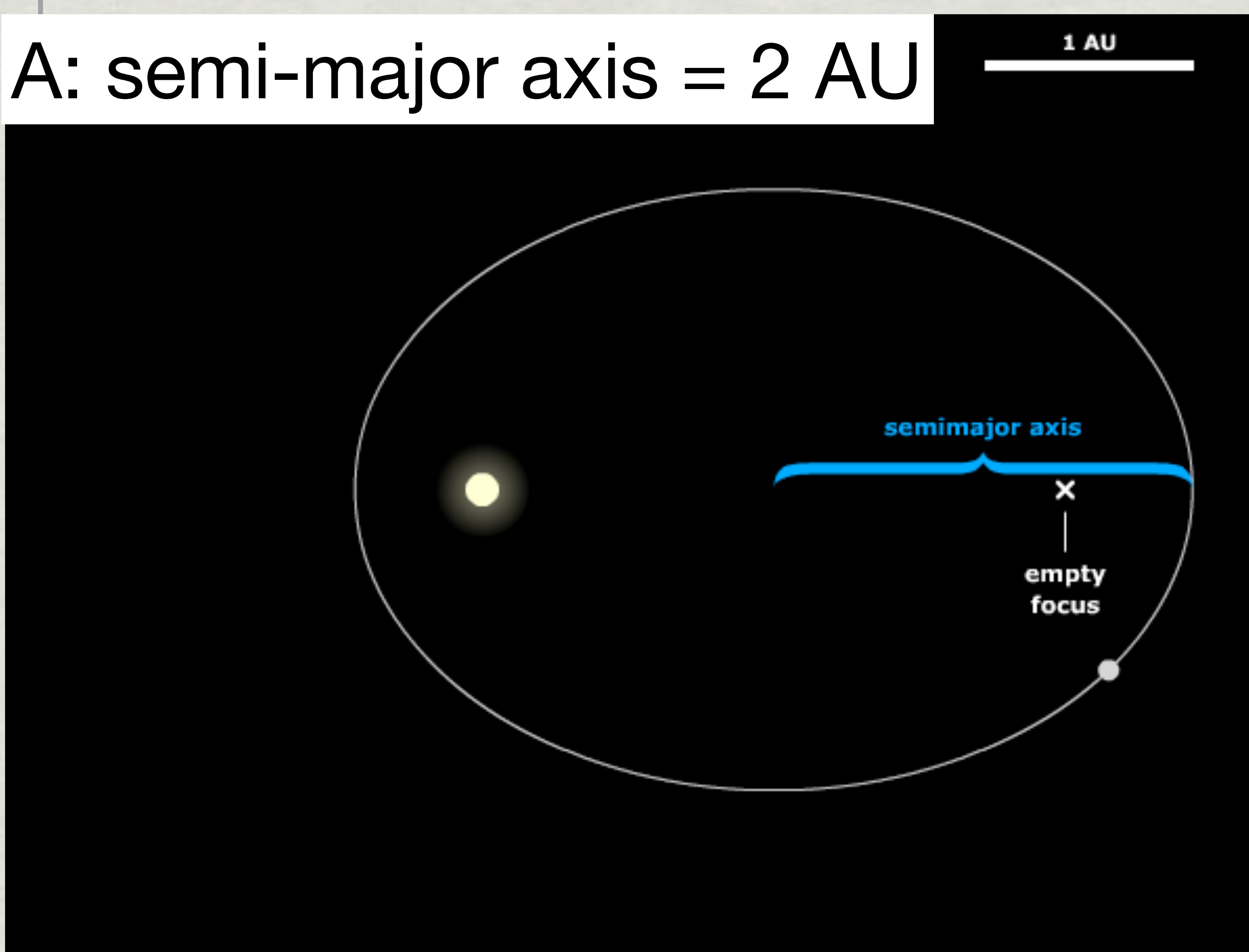
How long does it take planet A to orbit the sun?

Period P: time it takes to complete one orbit

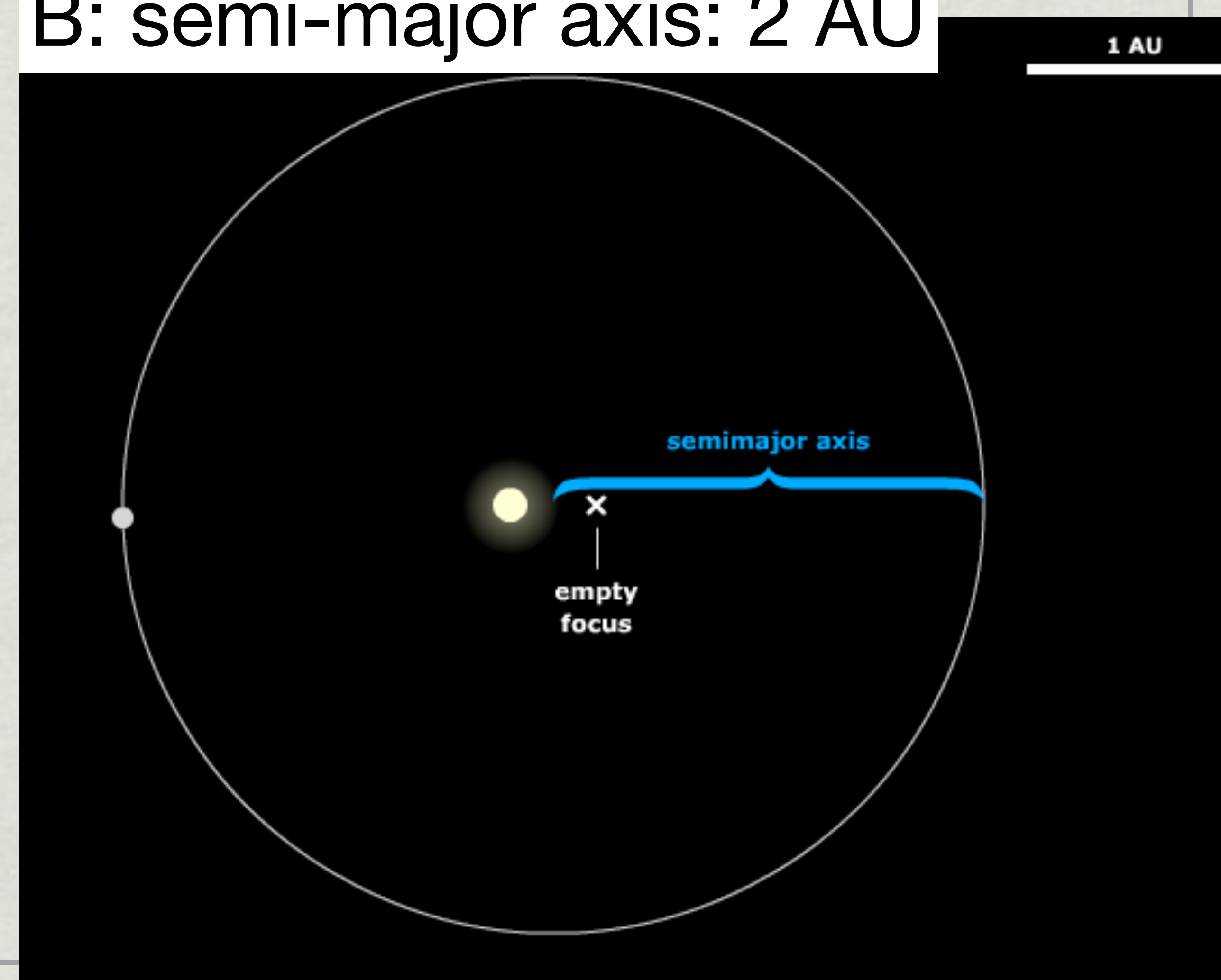
A = average radius of the orbit; average distance between the sun and the planet

Kepler's 3rd law: $P^2 = A^3$

A: semi-major axis = 2 AU



B: semi-major axis: 2 AU



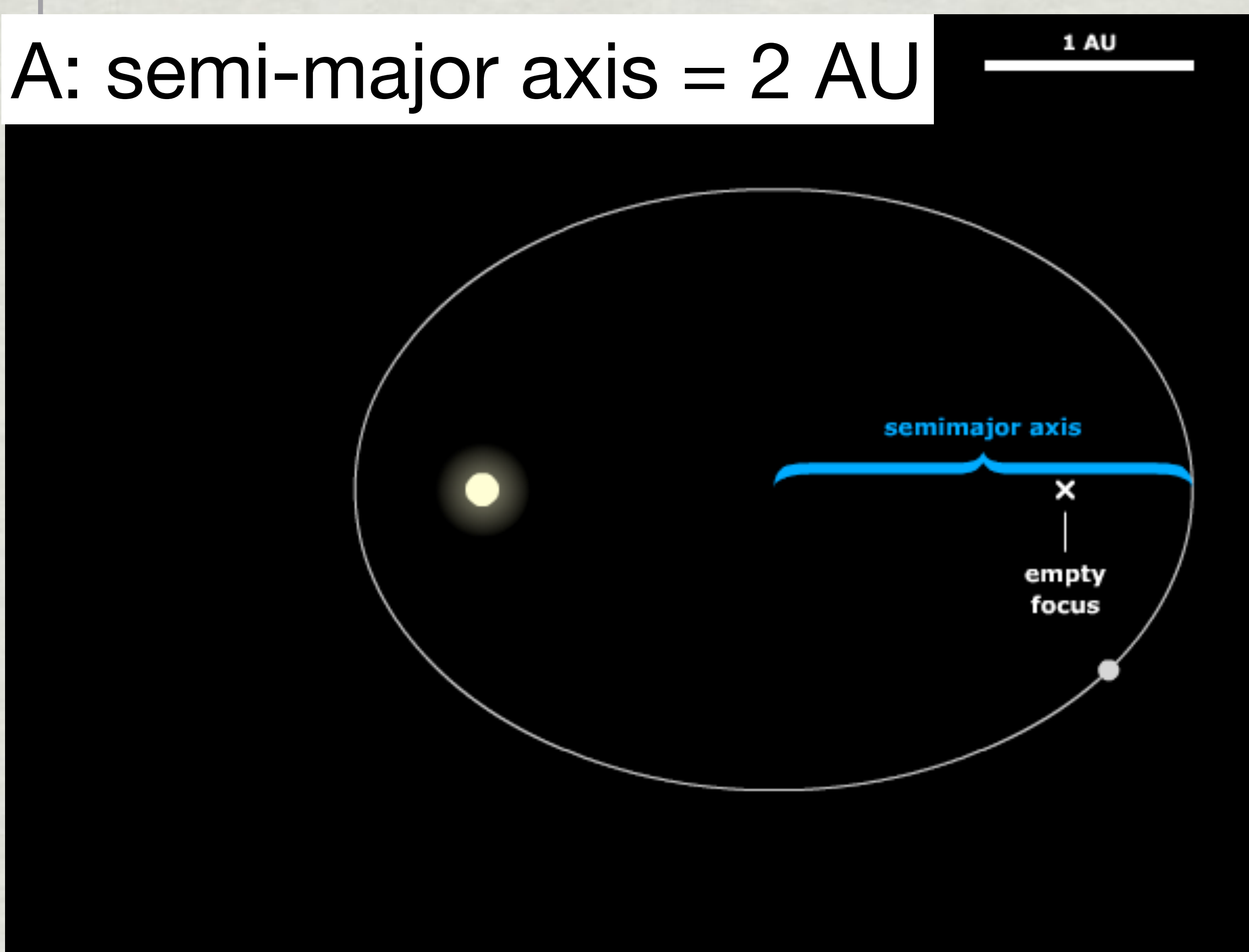
Kepler's Laws, Recap

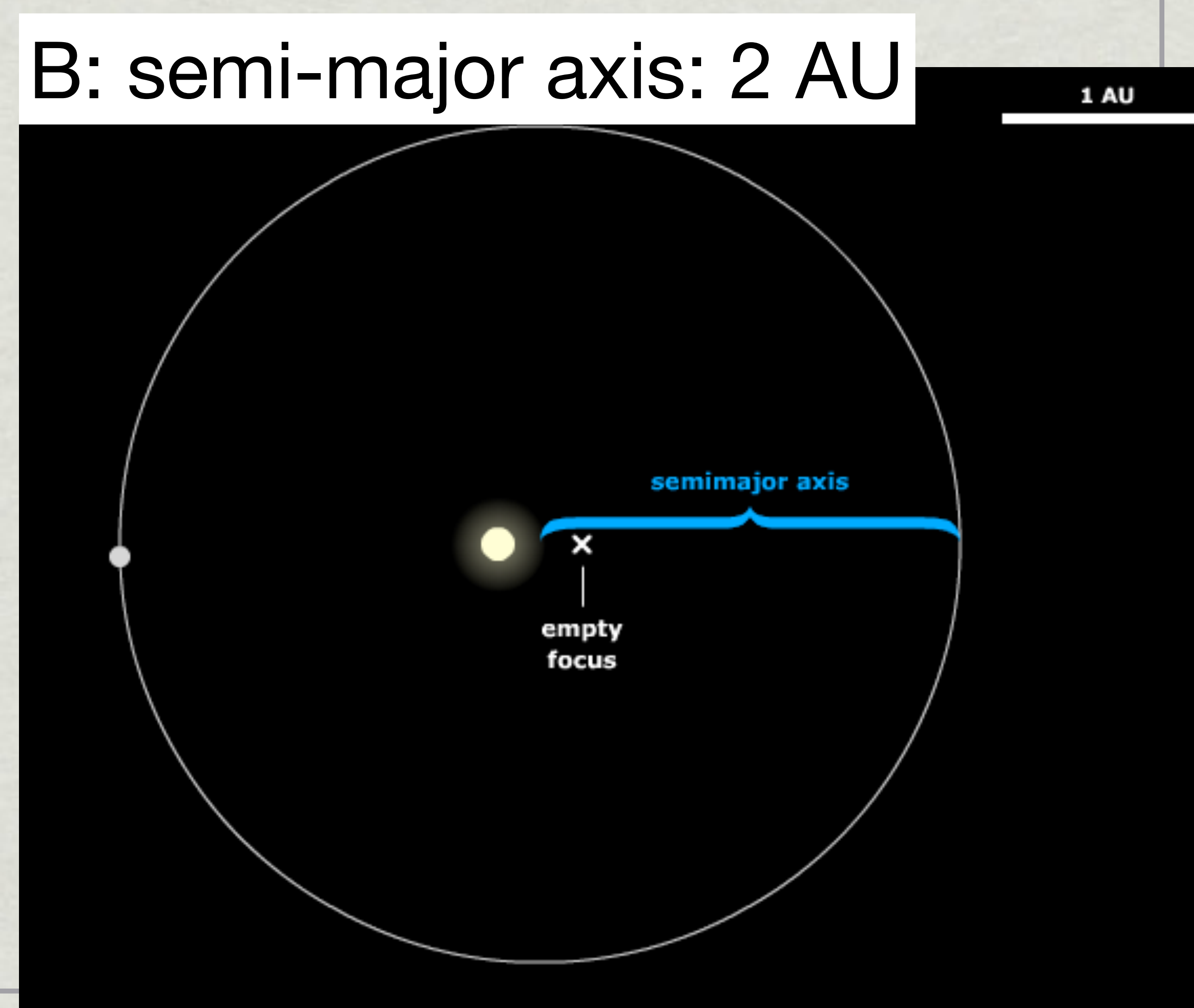
How long does it take planet A to orbit the sun?

Kepler's 3rd law: $P^2 = A^3$

A about 9 years
B about 3 years
C about 4 years

P = orbital period
A = average radius





Kepler's Laws, Recap

How long does it take planet A to orbit the sun?

Kepler's 3rd law: $P^2 = A^3$

A about 9 years

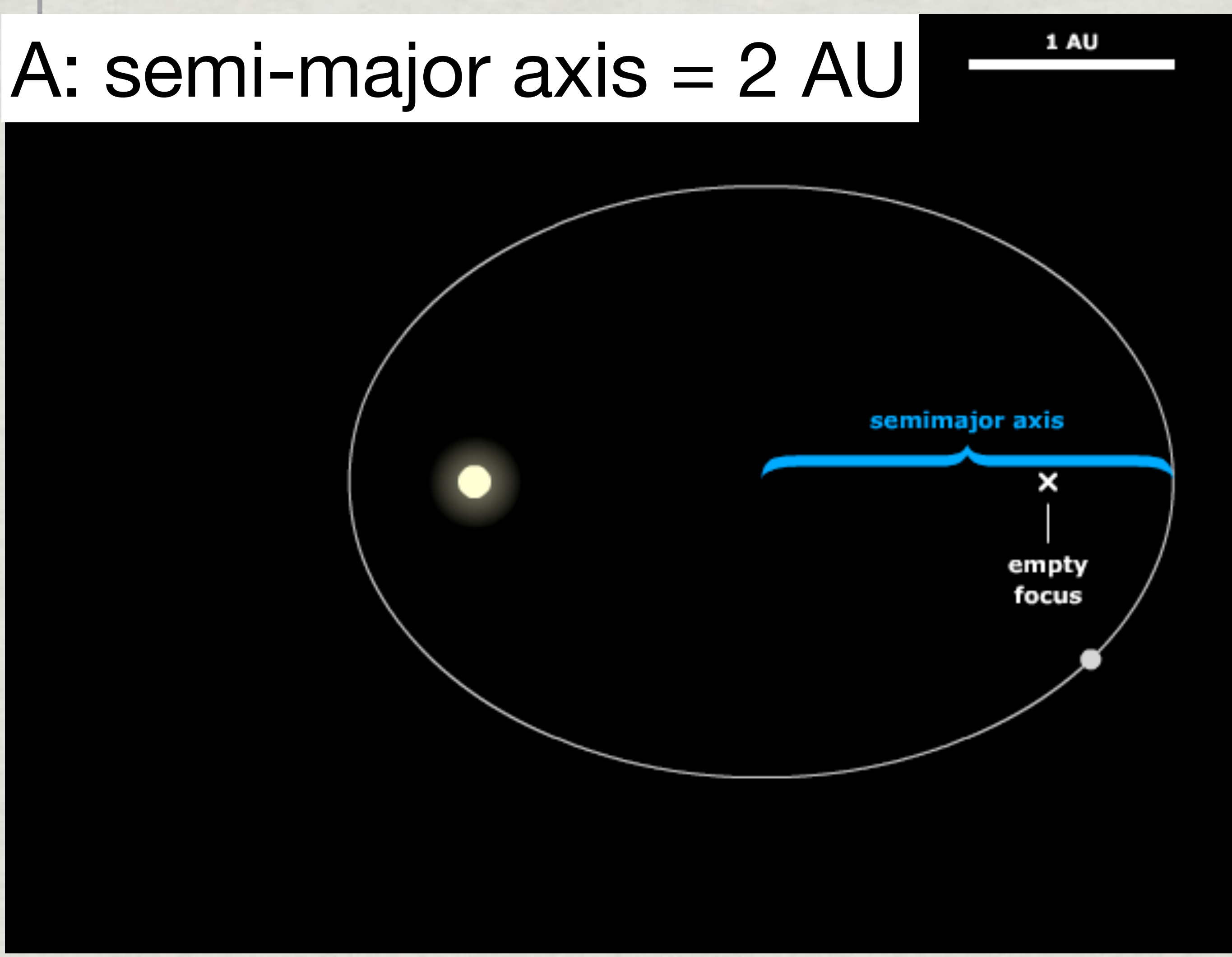
B about 3 years

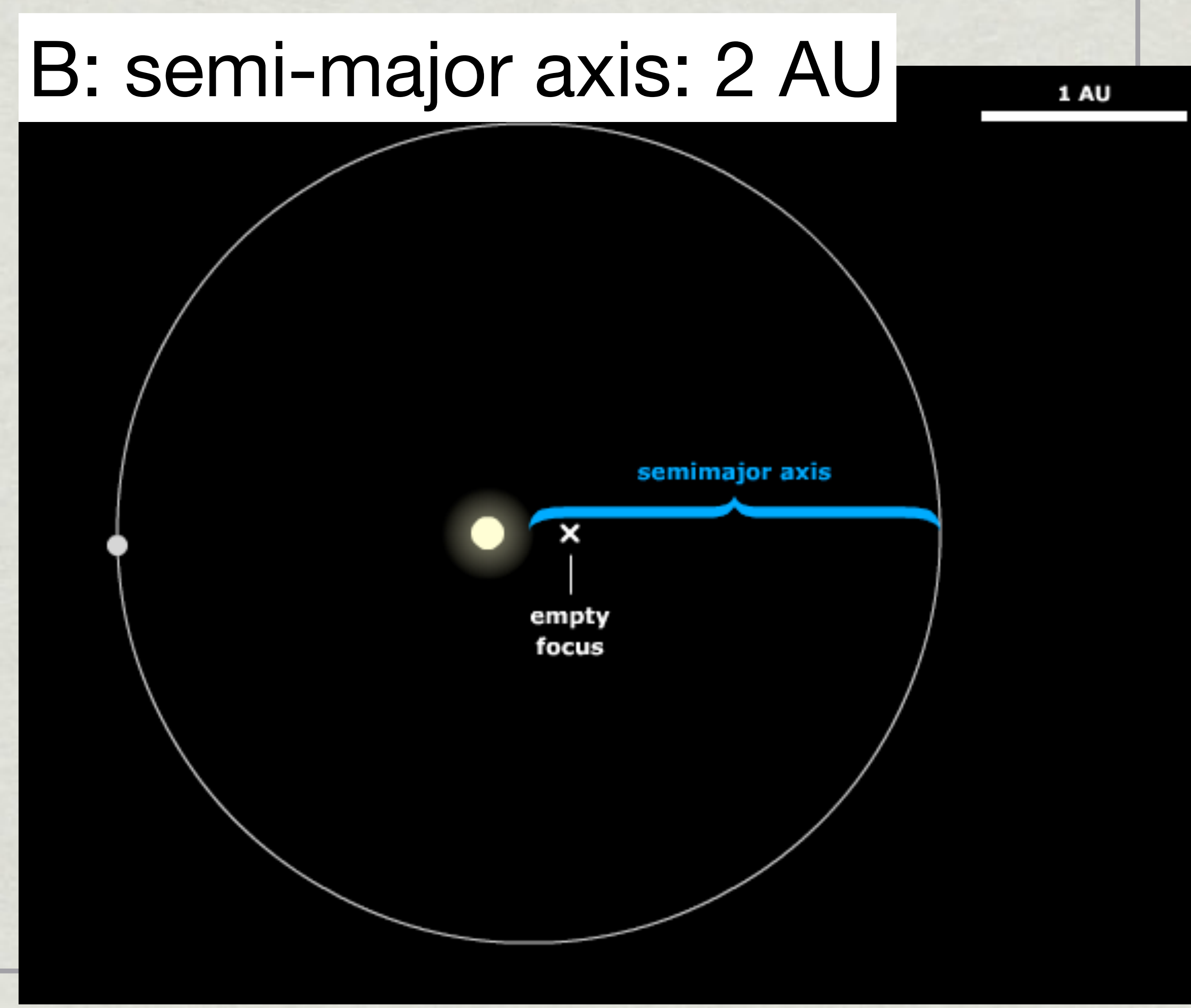
C about 4 years

$P^2 = A^3 = (2\ AU)^3 = 8\ AU^3$

$P^2 = 8\ years^2$

$P = \sqrt{8} = 2.83 \sim 3$ years





Kepler's Laws, Recap

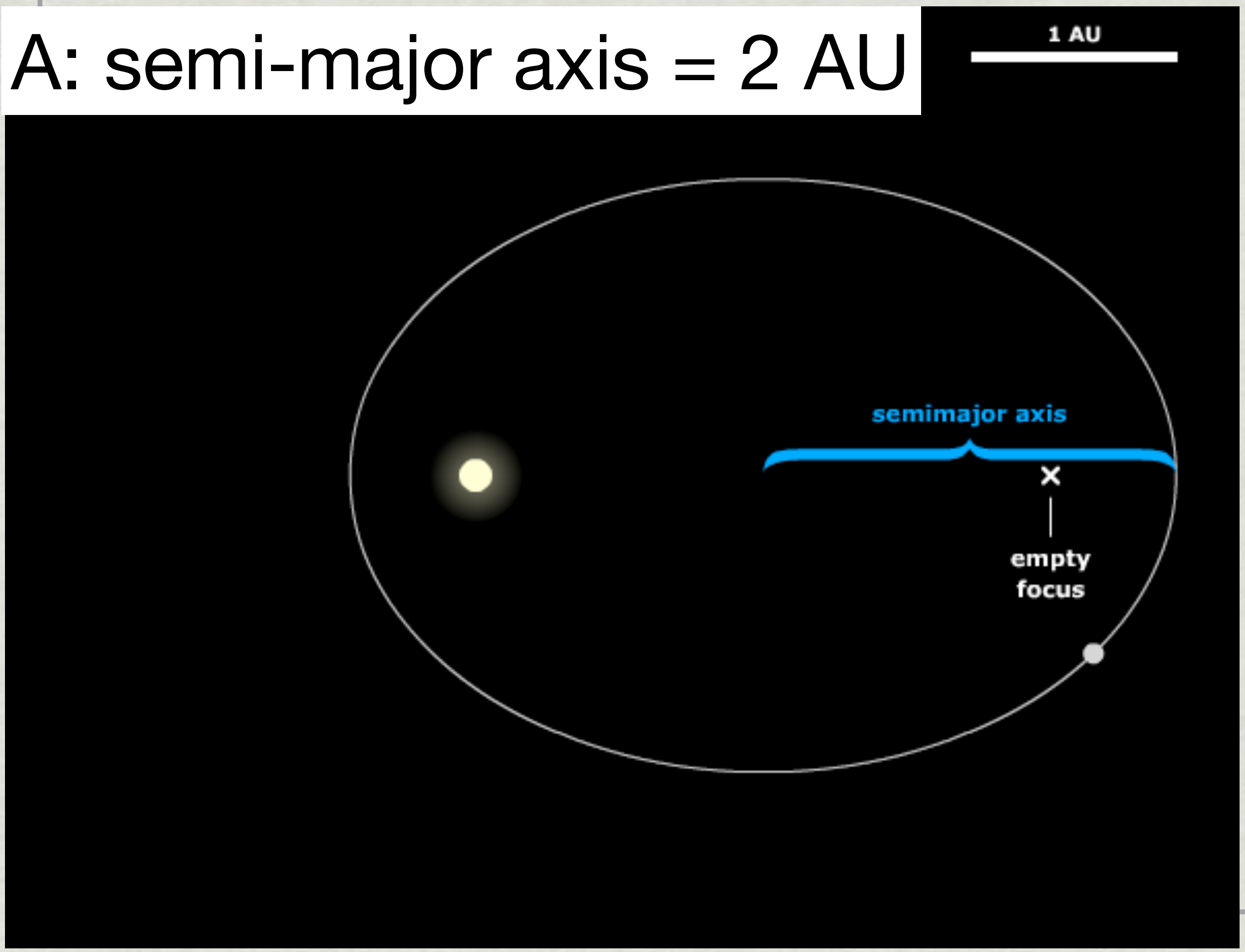
Two planets (A and B) in orbit around the sun.

How long does it take planet B to orbit the sun?

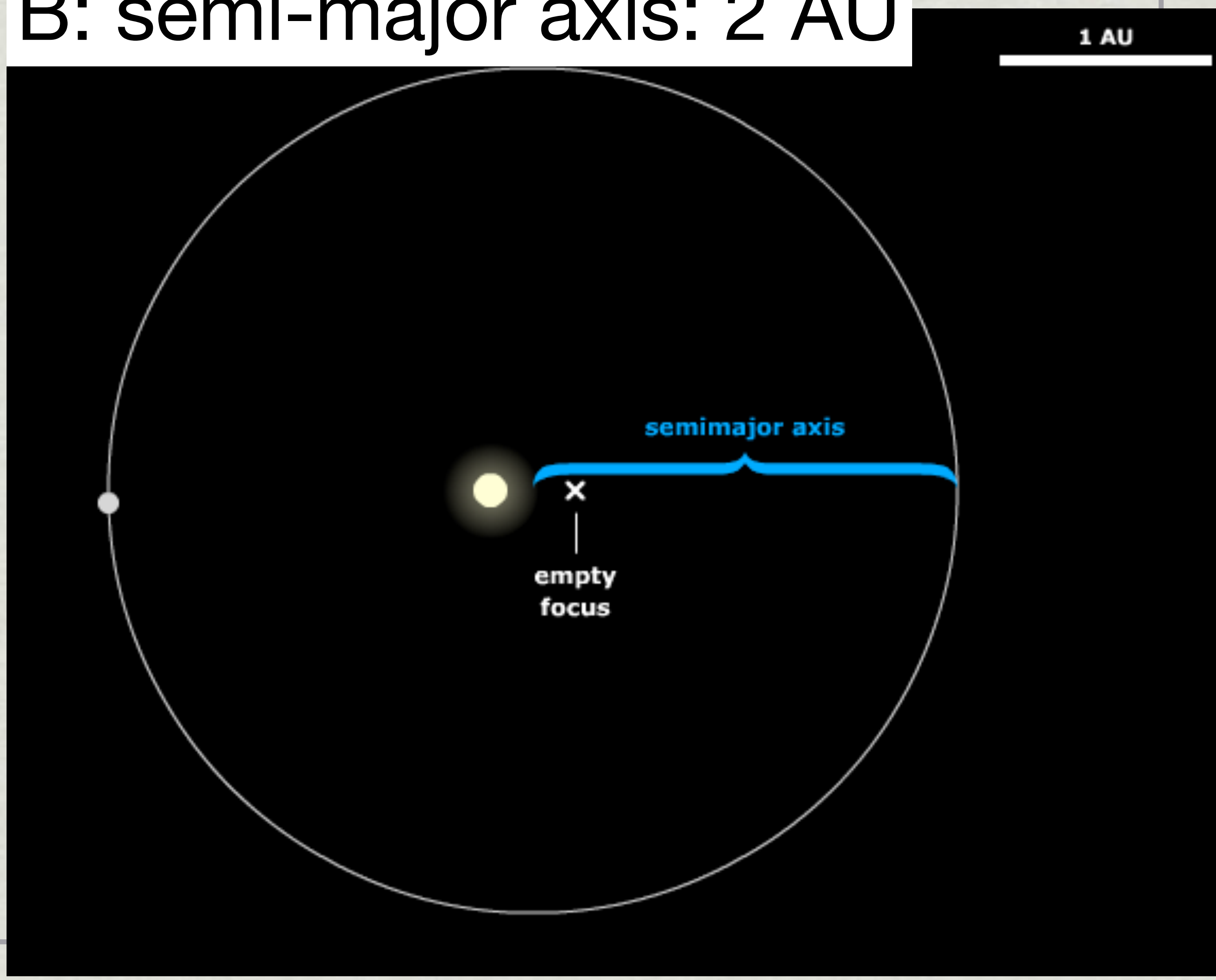
A about 9 years
B about 3 years
C about 4 years

Kepler's 3rd law:
$P^2 = A^3$

A: semi-major axis = 2 AU



B: semi-major axis: 2 AU



Kepler's Laws, Recap

Two planets (A and B) in orbit around the sun.

How long does it take planet B to orbit the sun?

A about 9 years

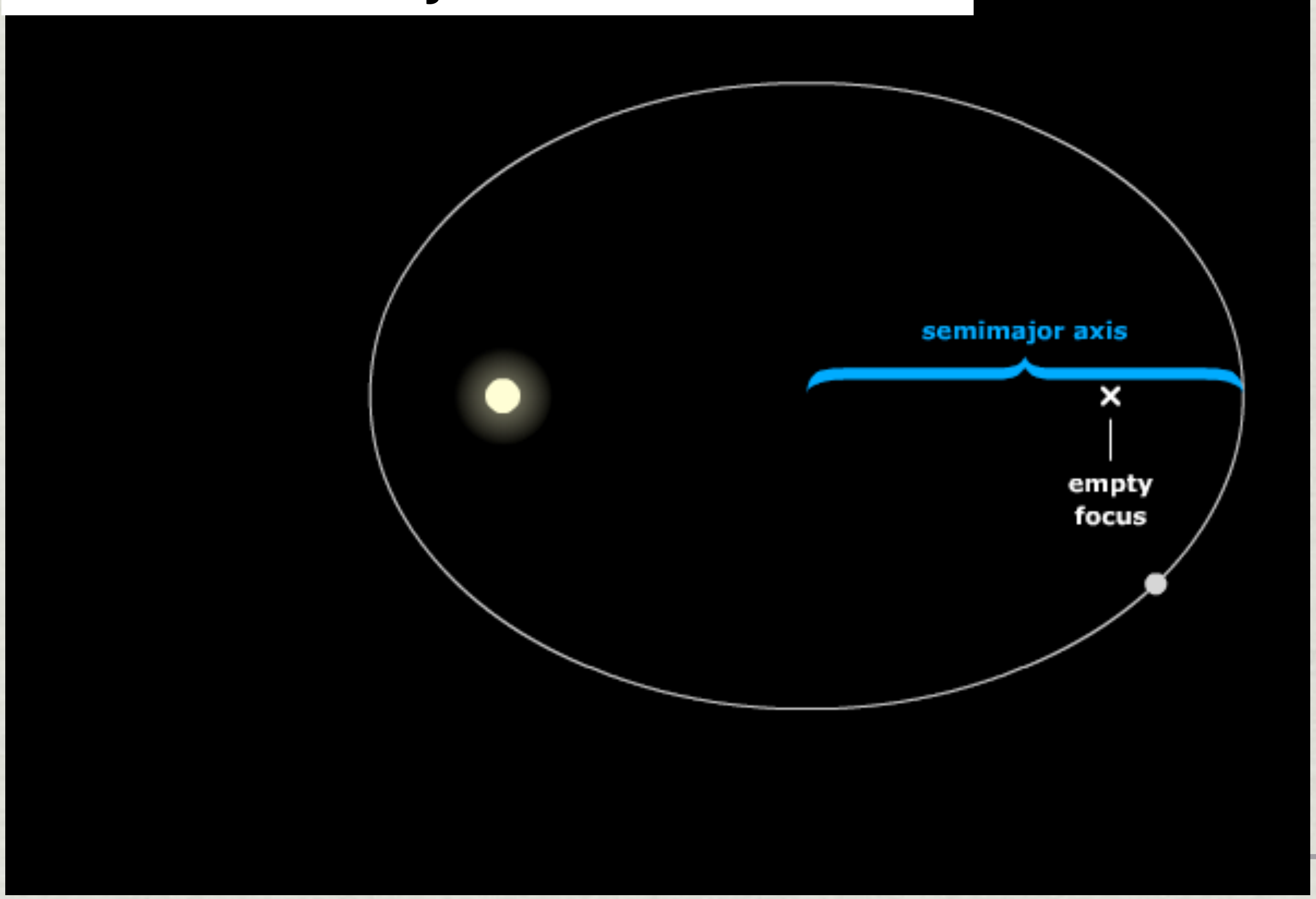
B about 3 years

C about 4 years

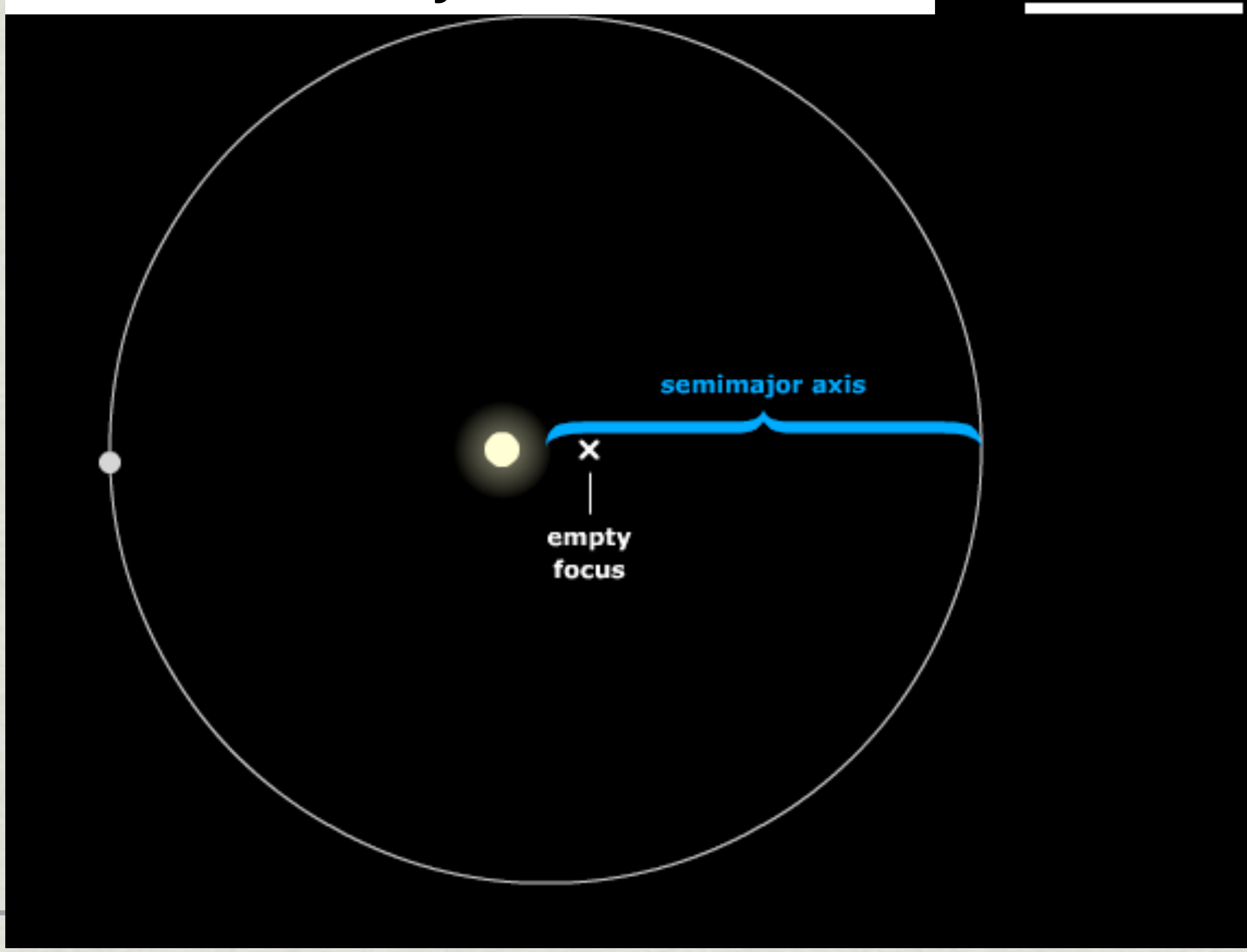
$P^2 = A^3$

Semi-major axis is the same for both planets

A: semi-major axis = 2 AU

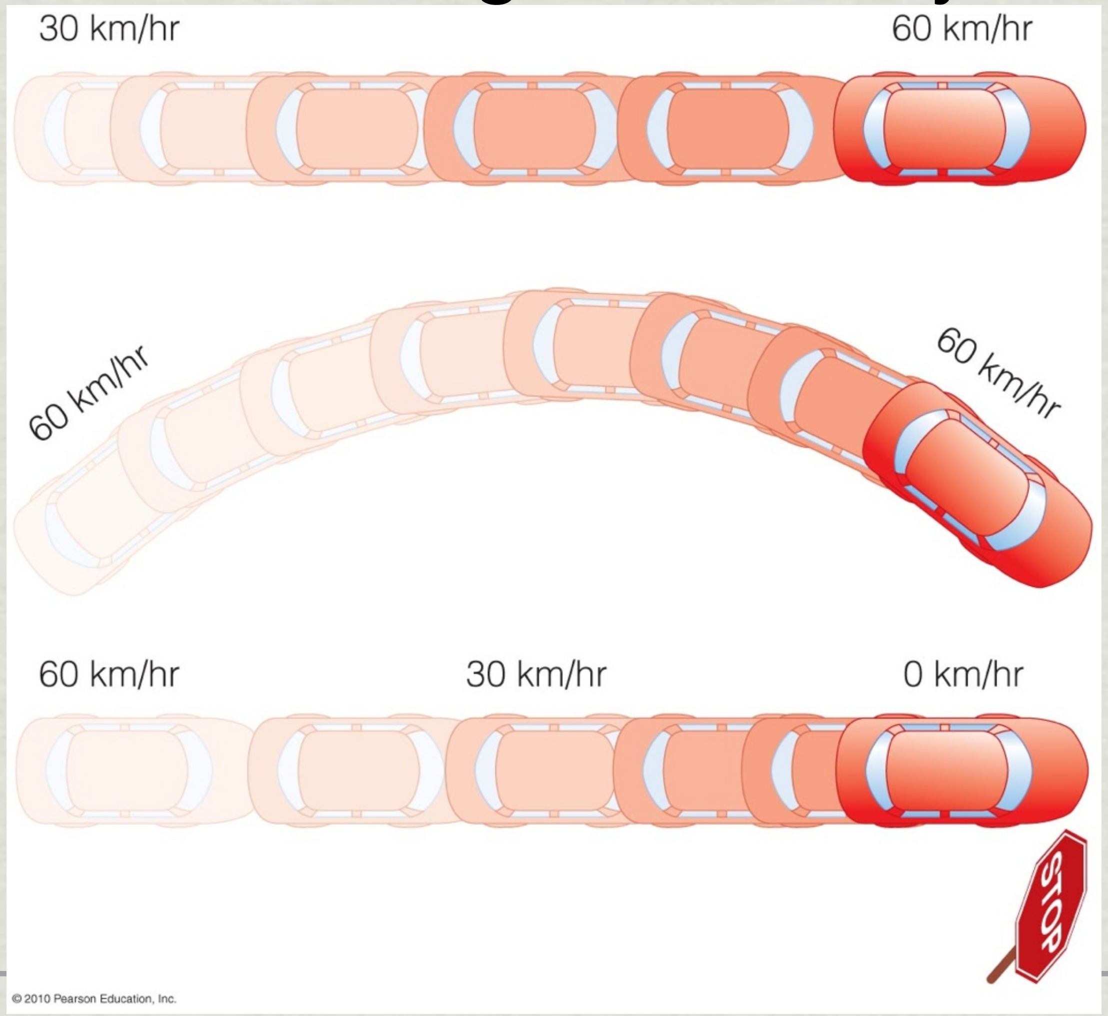


B: semi-major axis: 2 AU



Describing Motion: Acceleration

- **Acceleration**: $\frac{\text{Change in Velocity}}{\text{Change in Time}}$
  - units: $\frac{\text{meters/second}}{\text{second}}$ = meters/second^2 (m/s^2)
  - change in velocity: change in speed or direction



All three motions shown here are accelerations

Newton’s First Law

Objects in motion stay in motion,

objects at rest stay at rest,

unless acted on by a force.

- To change a velocity (an acceleration) requires a Force
- Force = mass x acceleration

  familiar form: $F = m a$
- For as long as you apply a force, you get an acceleration

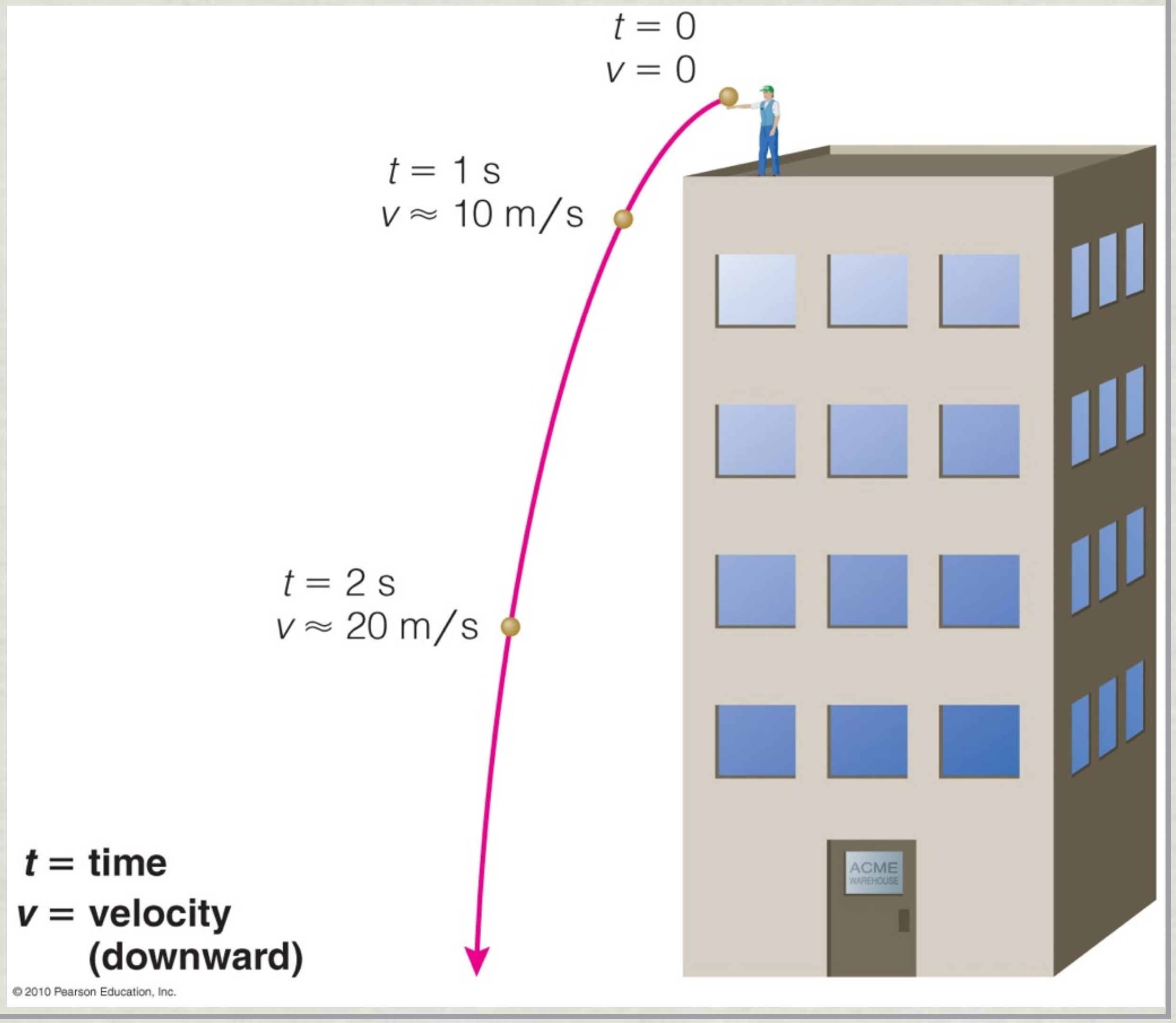
Describing Motion: Acceleration

- Force = mass x acceleration

  familiar form: F = m a

- For as long as you apply a force, you get an acceleration

Acceleration from force of Earth's Gravity: 9.8 m/s^2



That's 22 miles/hour/second

That gravitational force acts all the time the ball is falling.

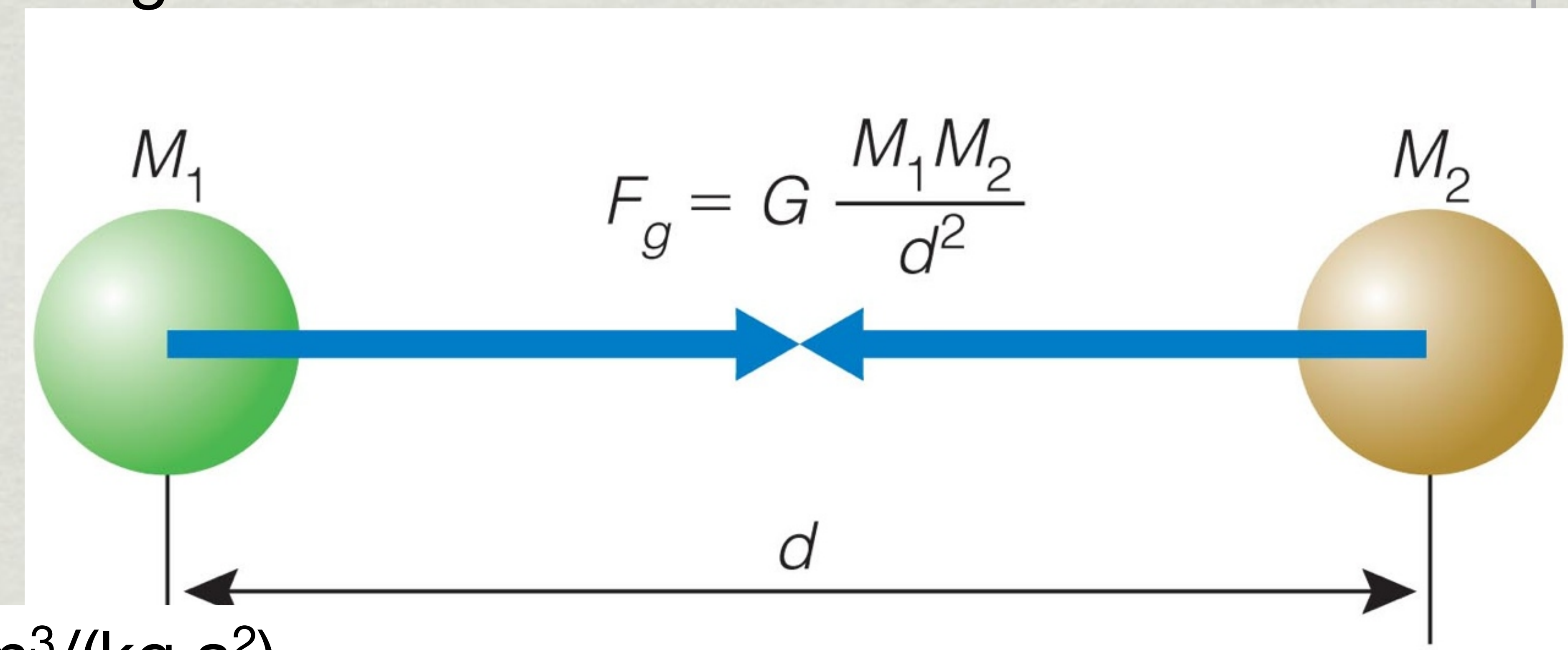
What does that mean?
After 1 second: speed is 22 mph
After 2 seconds: speed is 44 mph
After 3 seconds: speed is 66 mph

Gravity

- The force that holds you onto the Earth, the moon moving in orbit around the earth, the planets moving in their orbits around the sun, is Gravity

Force from gravity:

- Force of **M1** on **M2** = Force of **M2** on **M1** (Newton's 3rd law)
- Force weaker for larger d
- Force stronger for larger **M1** and/or **M2**



$G = 6.67 \times 10^{-11}\ m^3/(kg\ s^2)$

Force, Acceleration, Momentum

Newton's Law: $F = m\,a$

Gravitational force $F = \dfrac{G\,M_{earth}\,m_{rock}}{d^2}$

Which rock has greater acceleration?

$$F = m_{rock}\,a = \frac{G\,M_{earth}\,m_{rock}}{d^2}$$

A the big one
B the small one
C they have the same acceleration
D you don't have enough information

Force, Acceleration, Momentum

Newton's Law: F = m a

Which rock has greater acceleration?

$$F = m_{rock}\, a = \frac{G\, M_{earth}\, m_{rock}}{d^2}$$

A the big one
B the small one
C they have the same acceleration
D you don't have enough information

Force, Acceleration, Momentum

Newton's Law: F = m a

$$F = ma = \frac{G\,M\,m}{d^2}$$

Which rock has greater acceleration?

$$F = \cancel{m}_{rock}\, a = \frac{G\,M_{earth}\,\cancel{m}_{rock}}{d^2}$$

$$a = \frac{G\,M_{earth}}{d^2}$$

A the big one
B the small one
C they have the same acceleration
D you don't have enough information

Force, Acceleration, Momentum

Newton's Law: $F = m a$

$$F = m_{rock}\, a = \frac{G\, M_{earth}\, m_{rock}}{d^2}$$

Which rock hits the ground first?

Which rock feels a stronger force from gravity?

Force, Acceleration, Momentum

Newton's Law: $F = m\,a$

$$F = m_{rock}\,a = \frac{G\,M_{earth}\,m_{rock}}{d^2}$$

Which rock feels a stronger force from gravity?

$$a = \frac{G\,M_{earth}}{d^2}$$

Which rock has a larger mass?
What does that mean for the force it feels?

Force, Acceleration, Momentum

Newton's Law: F = m a

Which rock has greater acceleration?

Both have the same acceleration

Which rock hits the ground first?

They land at the same time: same acceleration, so same speed when they hit the ground

Which rock feels a stronger force from gravity?

The bigger rock: F = m a

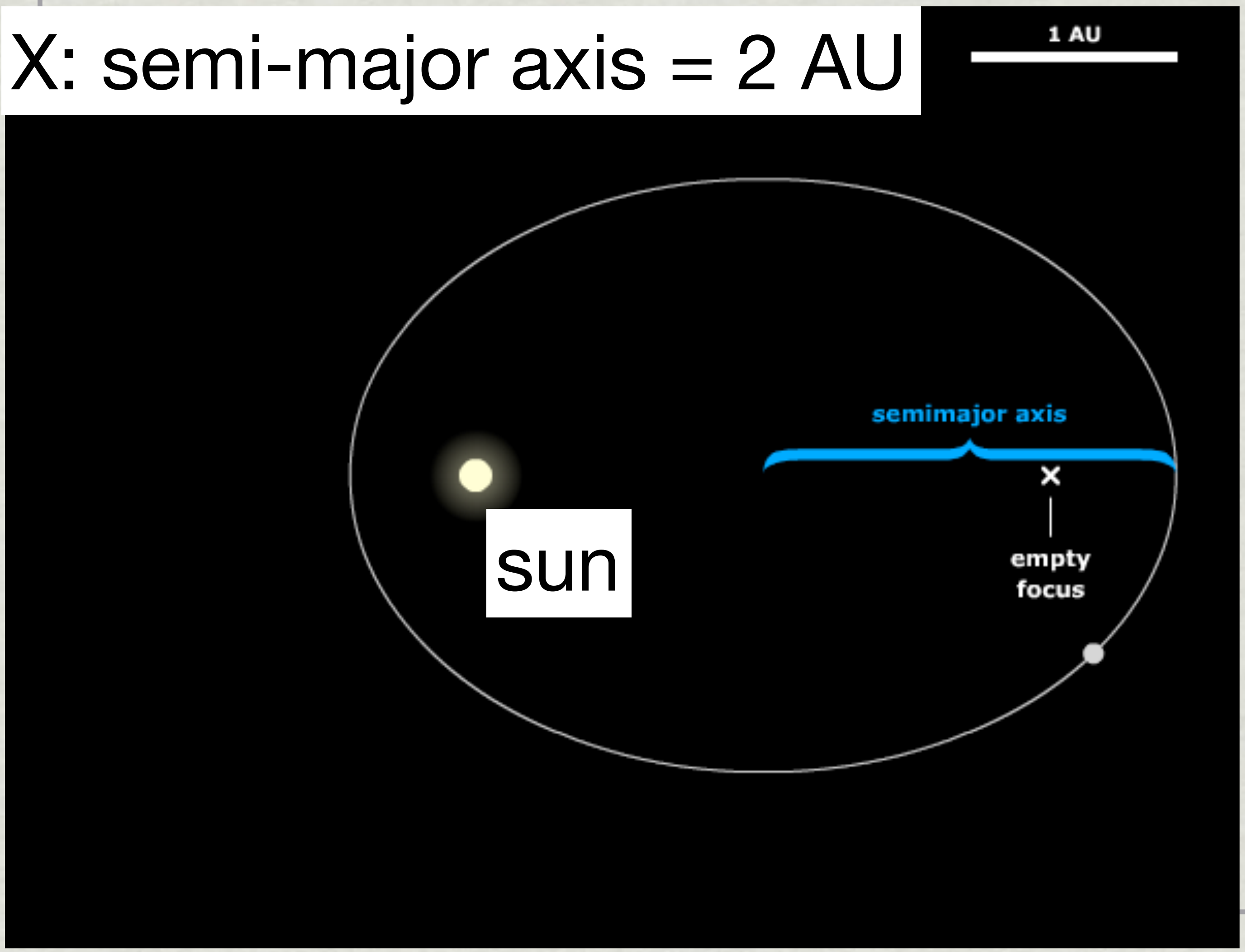
They both feel the same acceleration, so the rock with larger mass feels the stronger force. It weighs more!

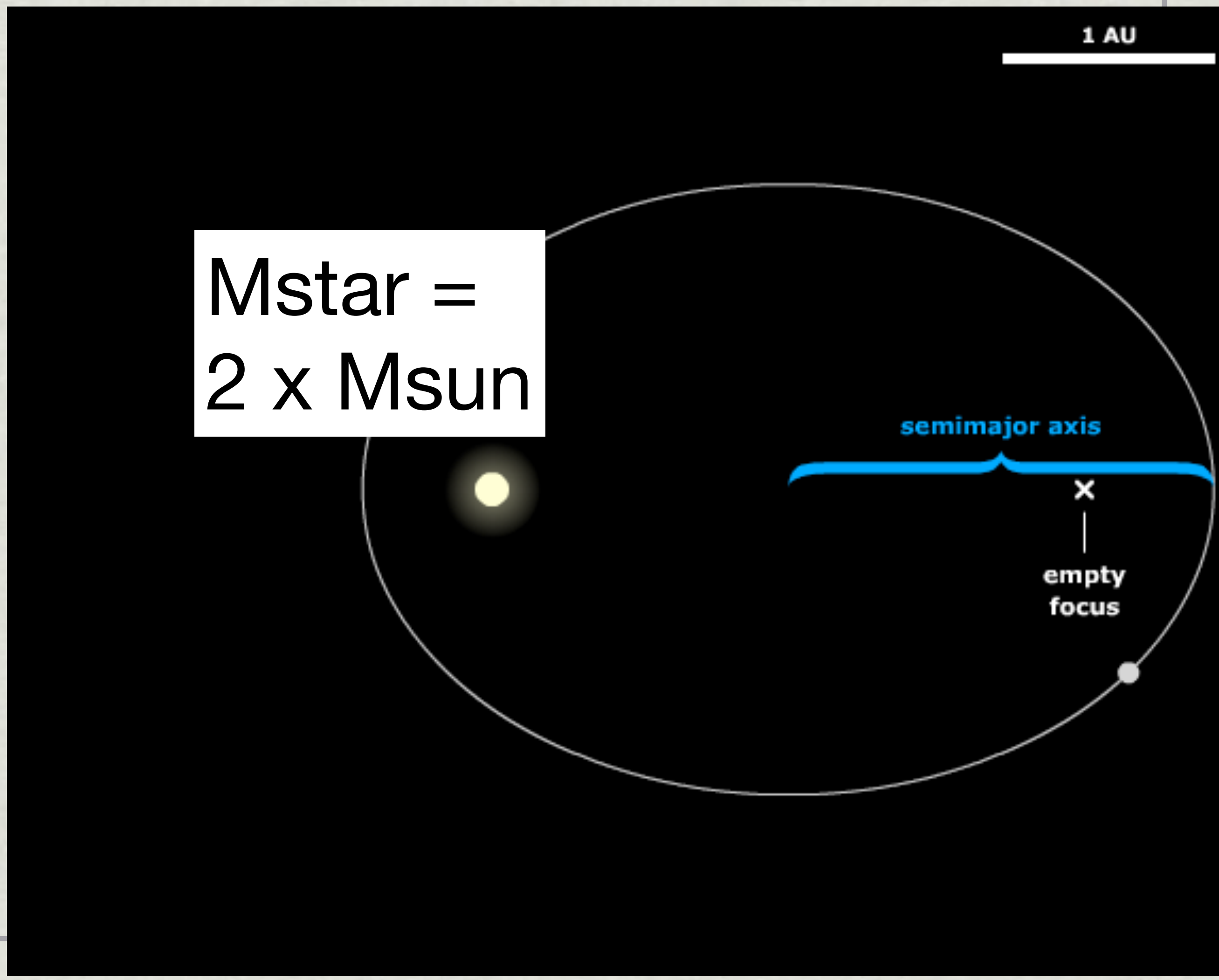
Kepler's Laws and Gravity

What about planets orbiting stars that are not the sun?

How long does it take planet X to orbit this star?

If the star is twice as massive as the sun, does it take more or less time to complete an orbit?

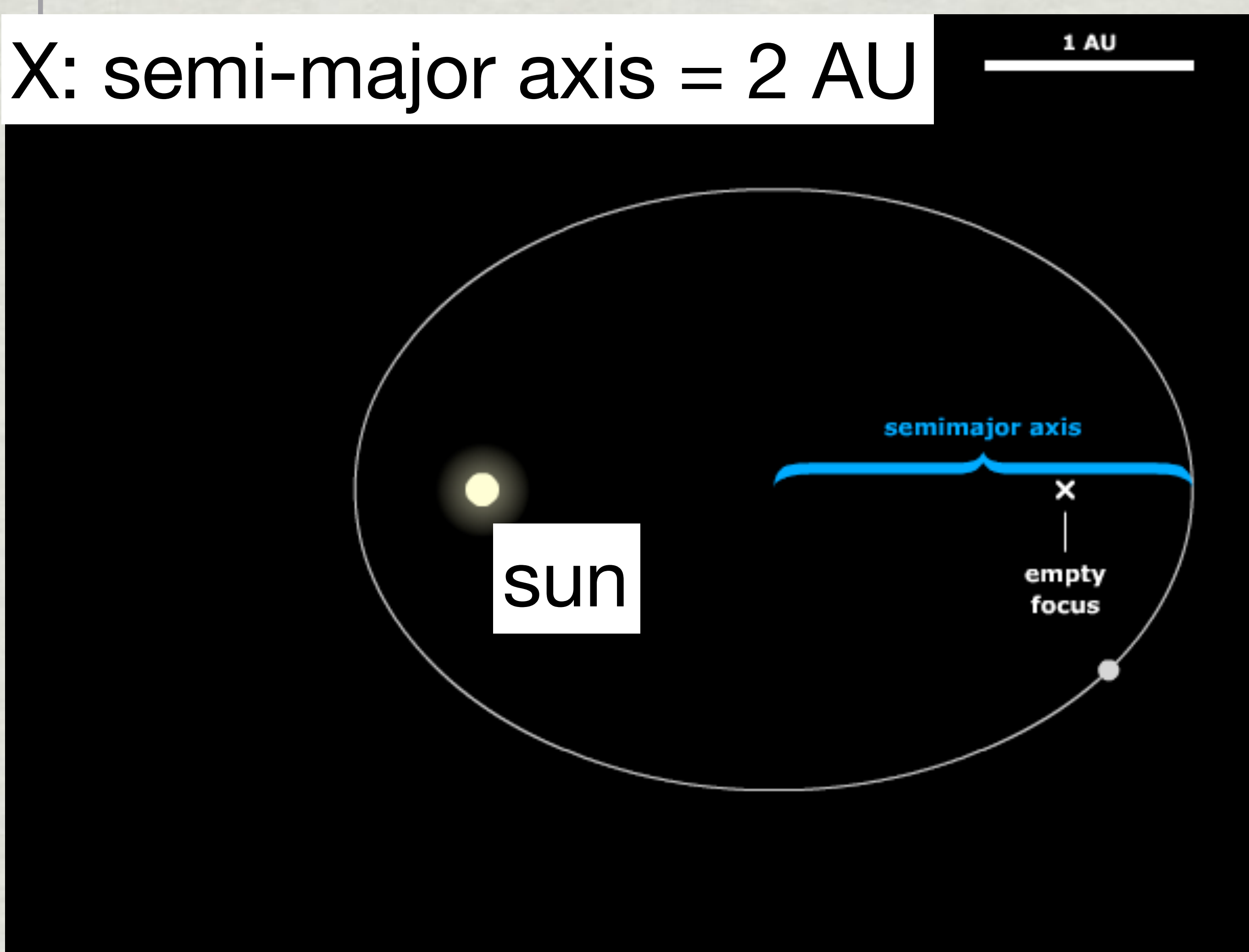


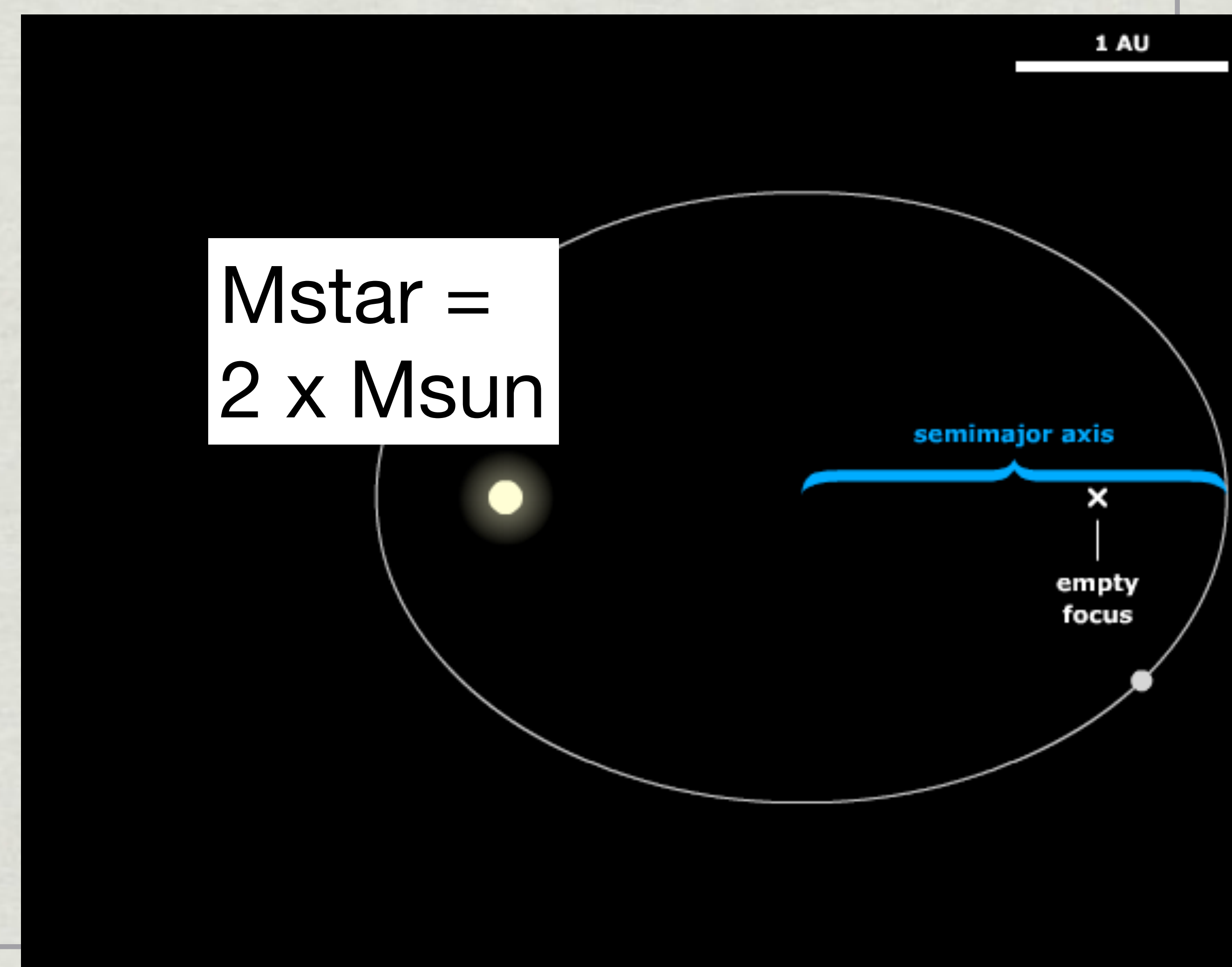


Kepler's Laws and Gravity

Newton's version of Kepler's 3rd law: $$\frac{P^2}{A^3} = \frac{(2\pi)^2}{G\,(M_1+M_2)} \sim \frac{(2\pi)^2}{G\,M_*}$$

Just use star mass M of the star if it is much larger than all the planets





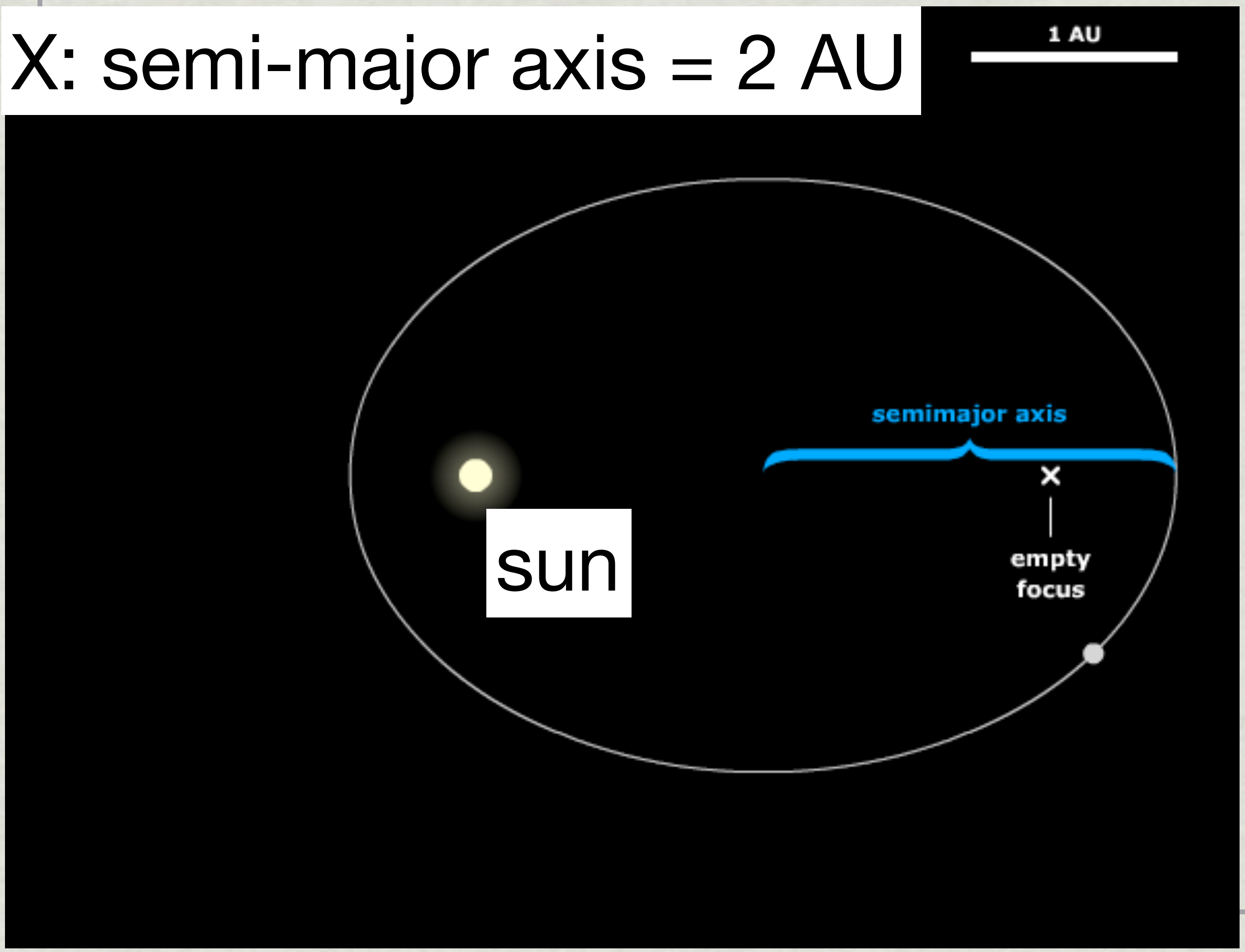
Kepler's Laws and Gravity

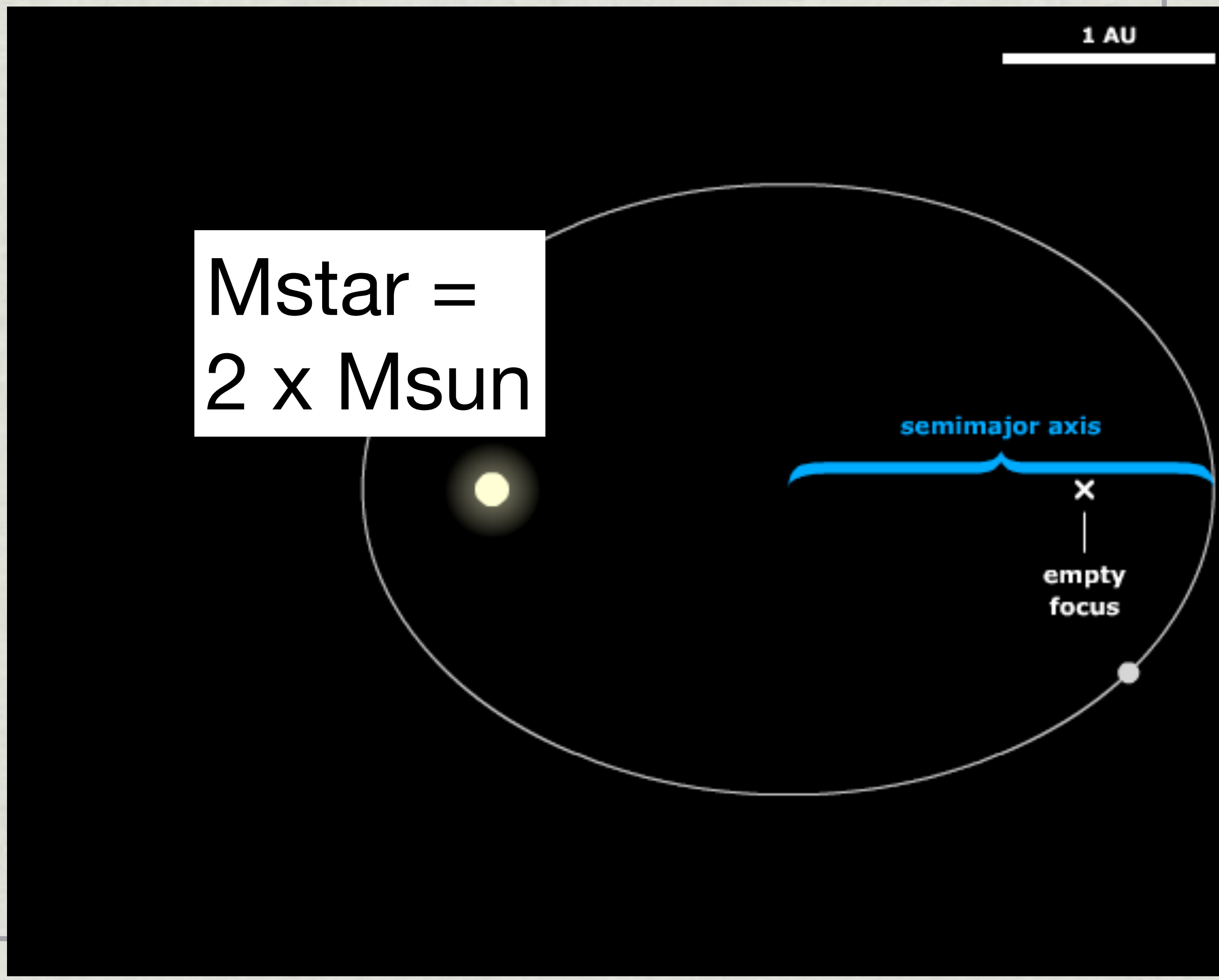
Newton's version of Kepler's 3rd law: $\frac{P^2}{A^3} = \frac{(2\pi)^2}{G M_*}$

M* is twice as large as Msun

Planet X orbits both the sun and the other star at average distance A

Does P get larger or smaller for X in orbit around the other star?





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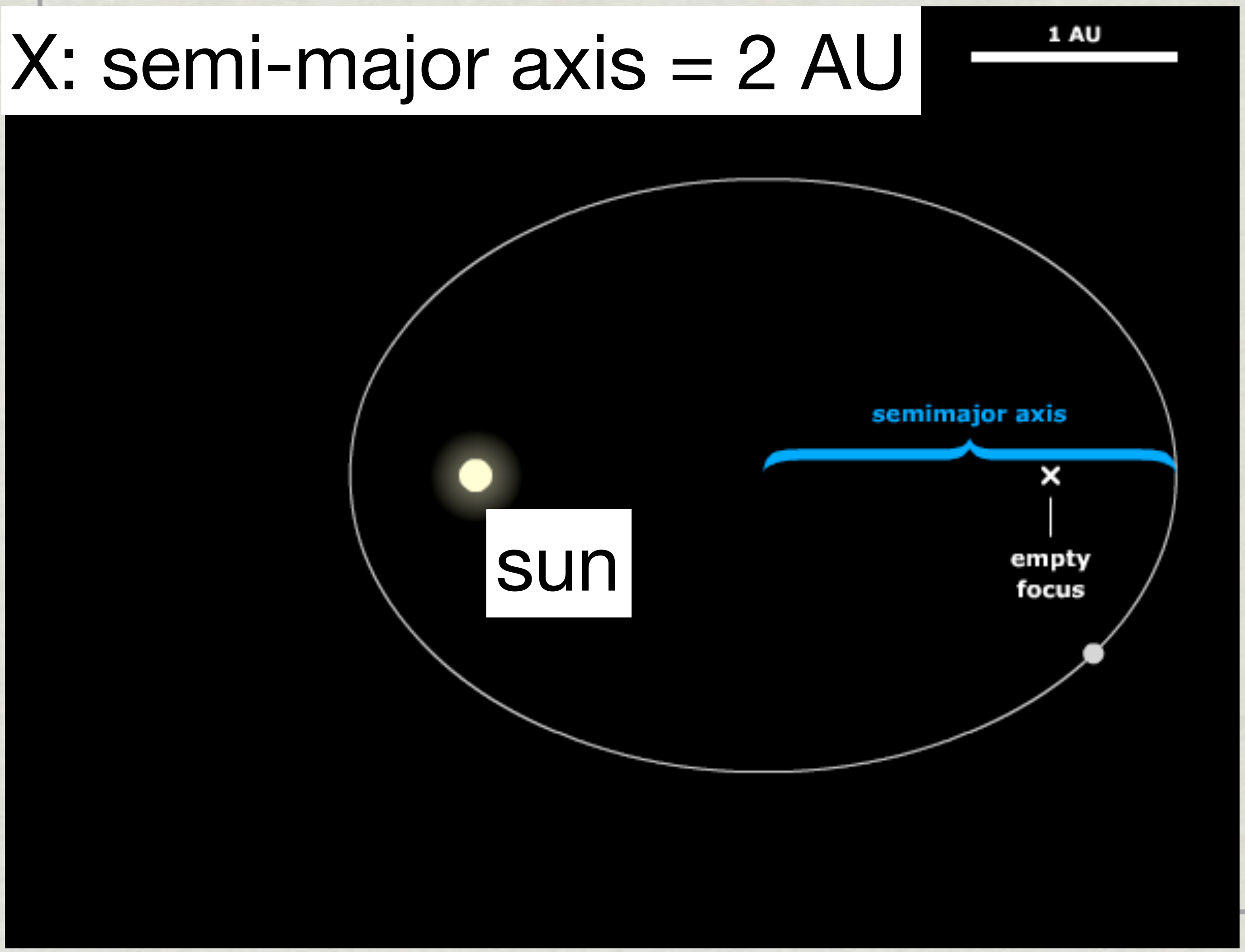
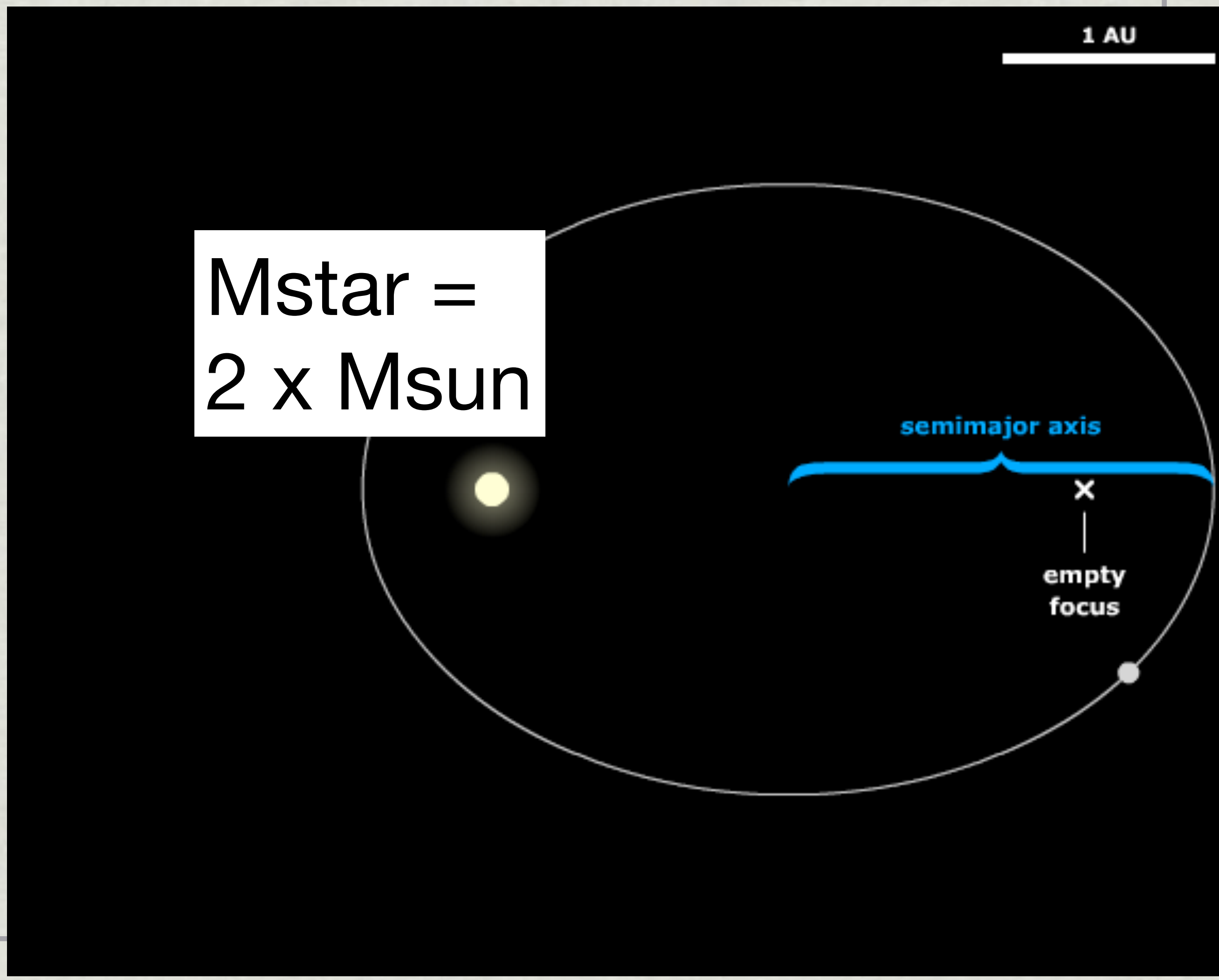
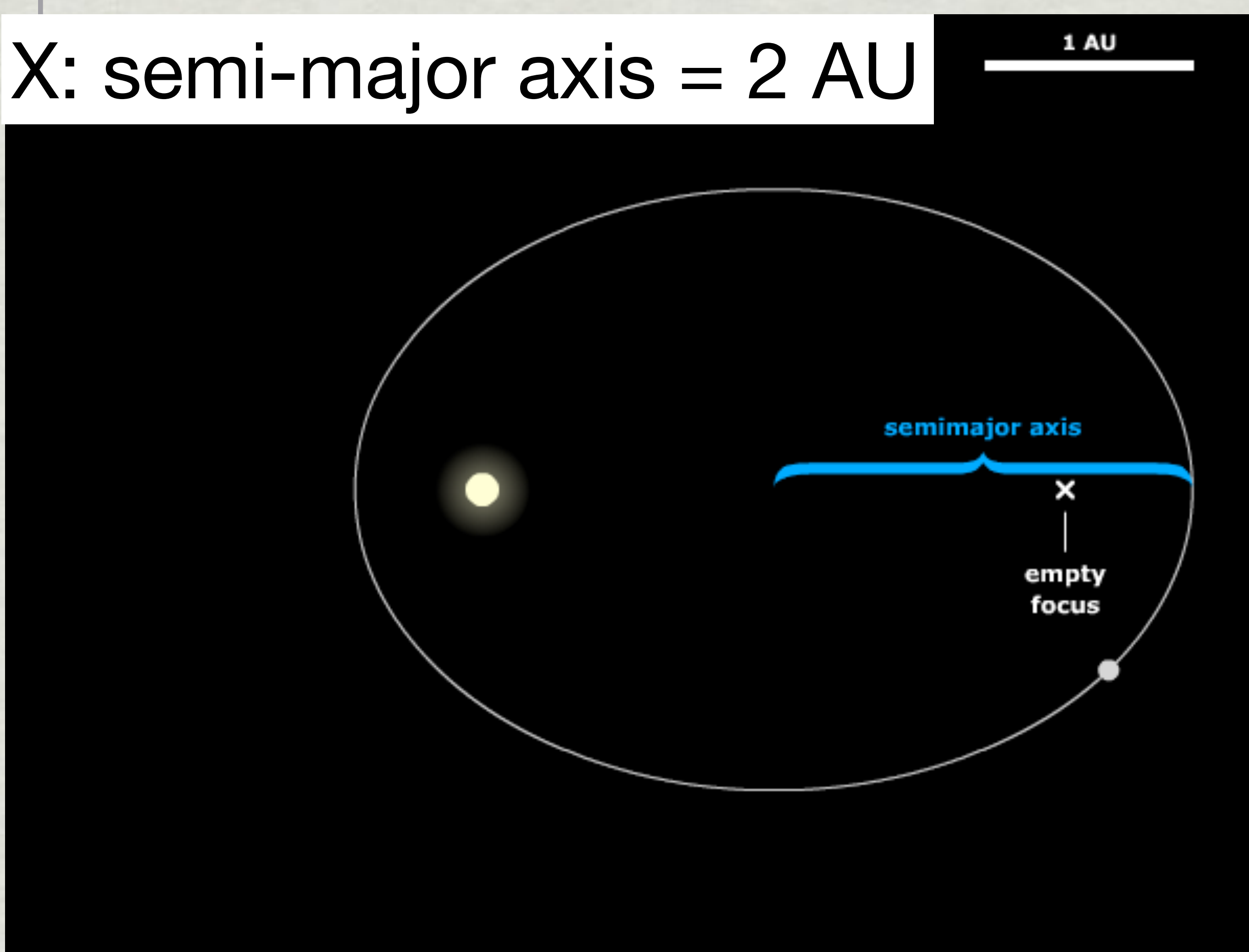




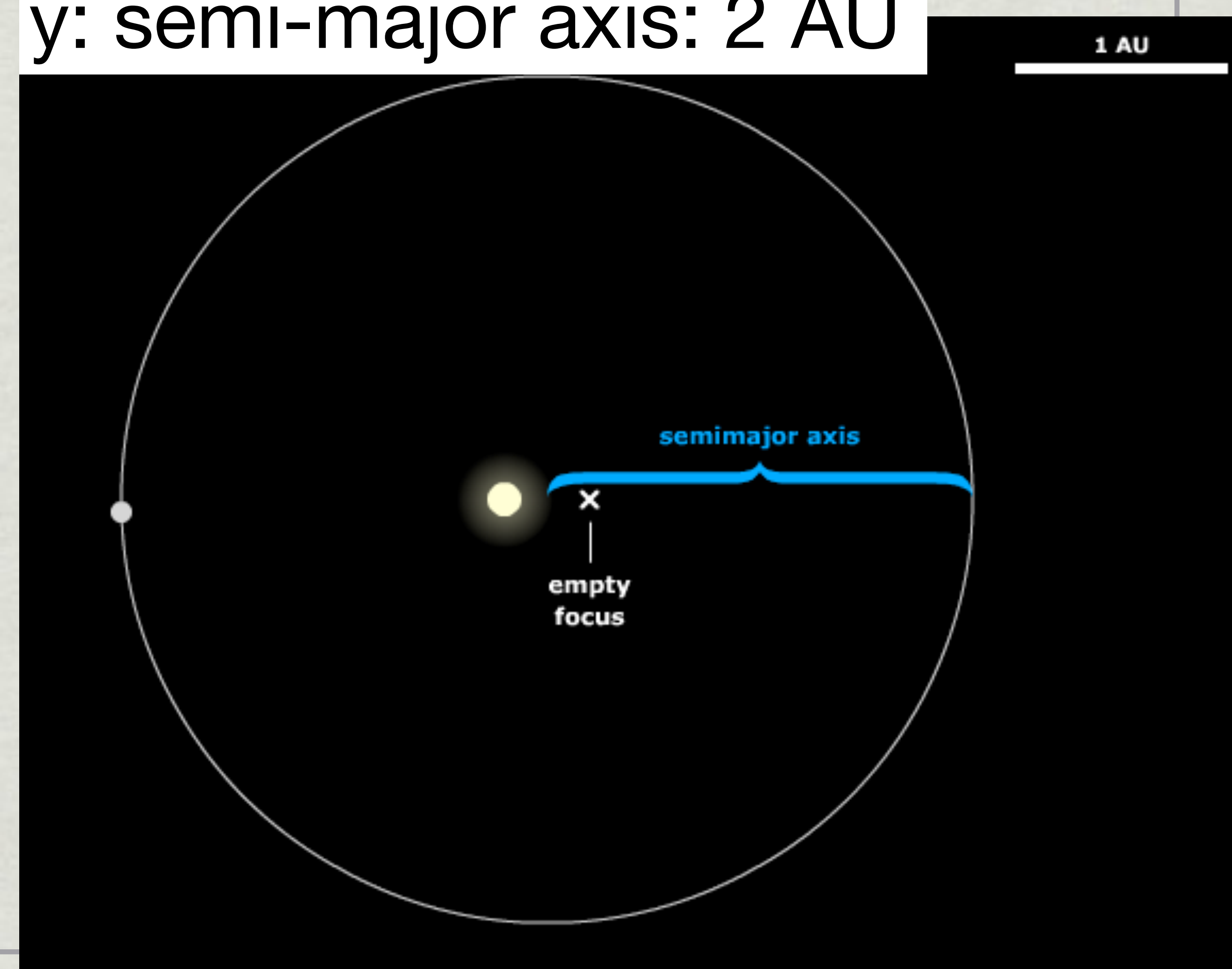
Kepler's Laws and Gravity

Where does planet X feel the strongest force from gravity?

X: semi-major axis = 2 AU



y: semi-major axis: 2 AU



Kepler's Laws and Gravity

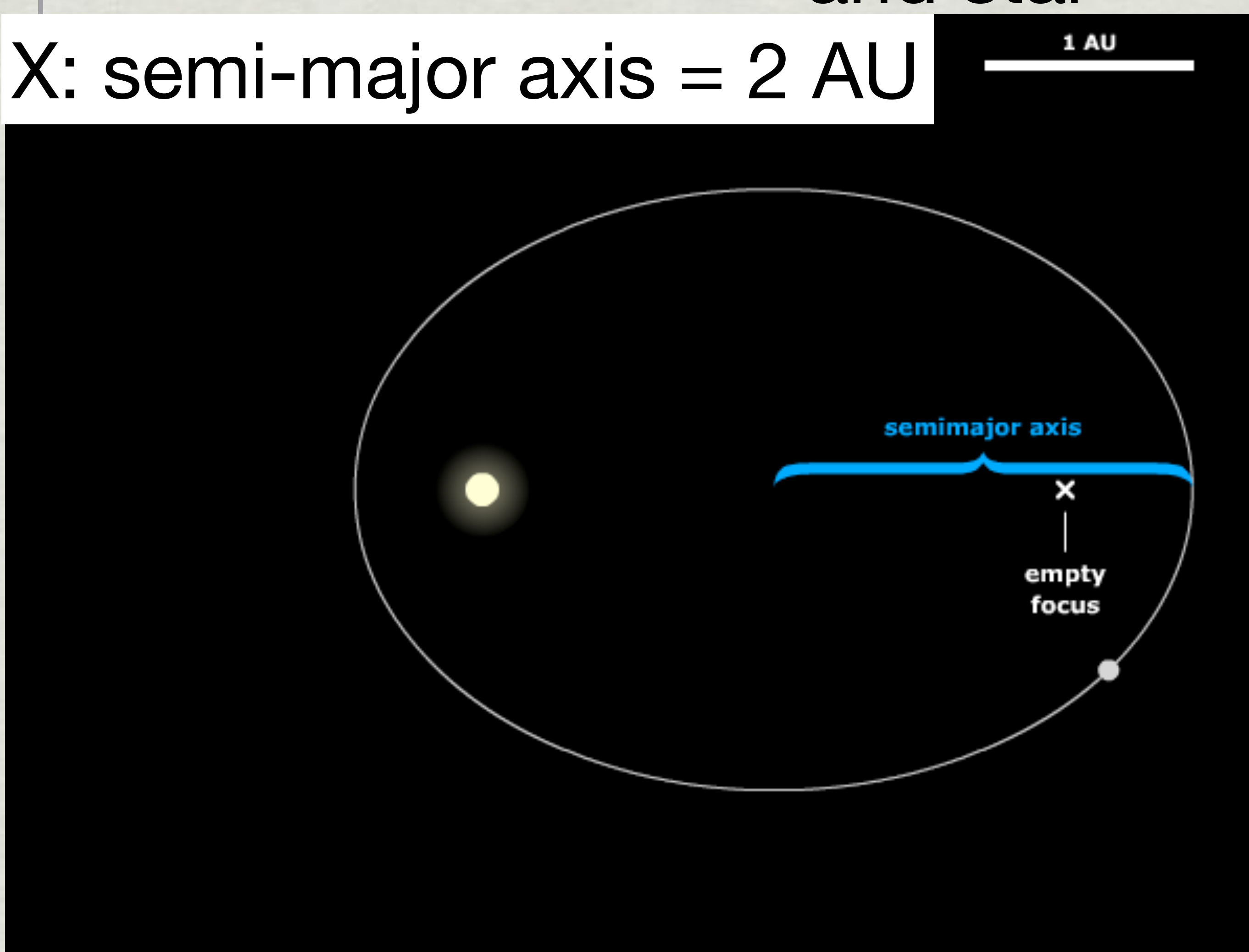
Where does planet X feel the strongest force from gravity?

$$F = \frac{G\,M\,m}{d^2}$$

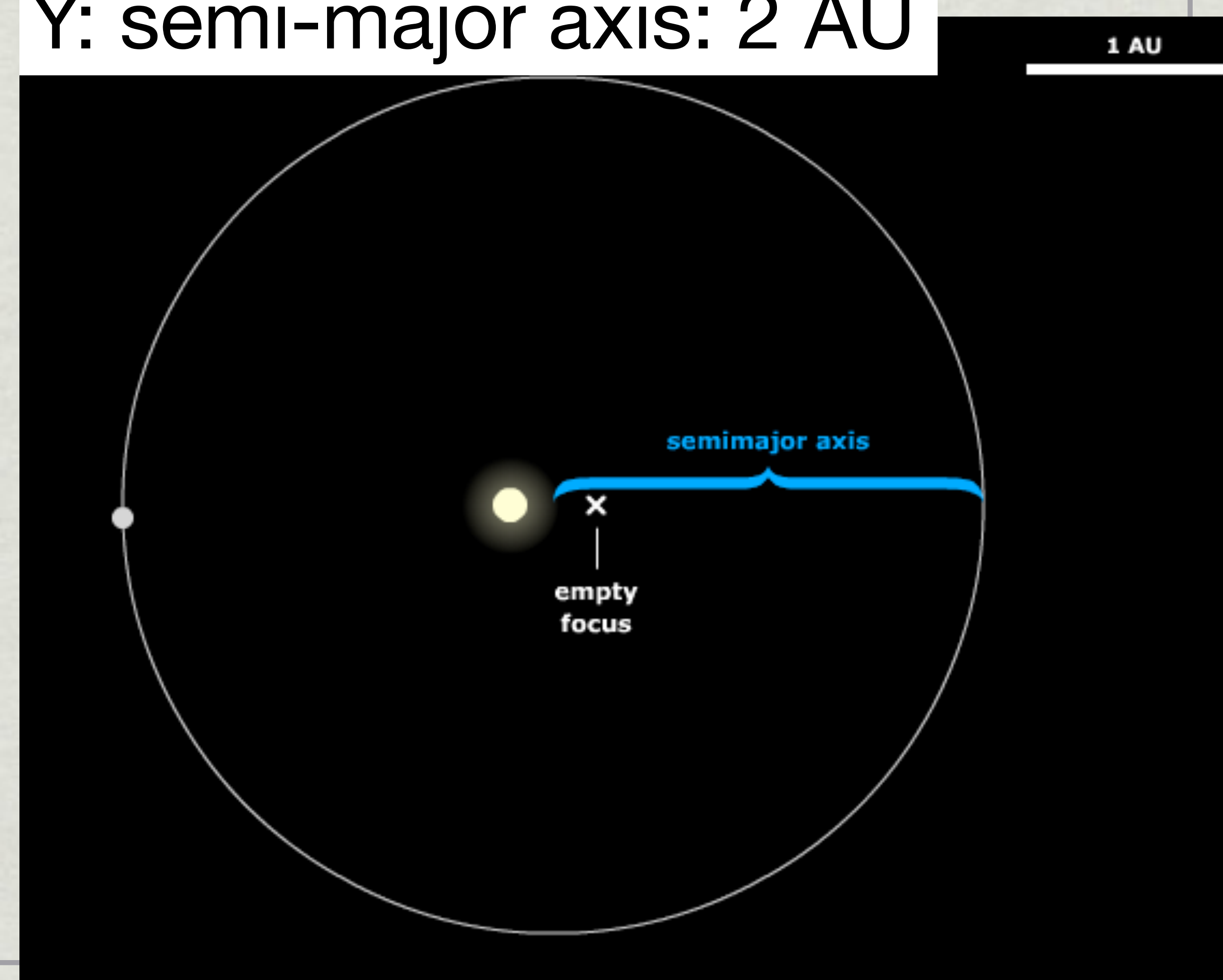
F = force due to gravity
M = mass of star
m = mass of planet
d = distance between planet and star

G = a number that describes the strength of the gravitational force everywhere in our universe

X: semi-major axis = 2 AU

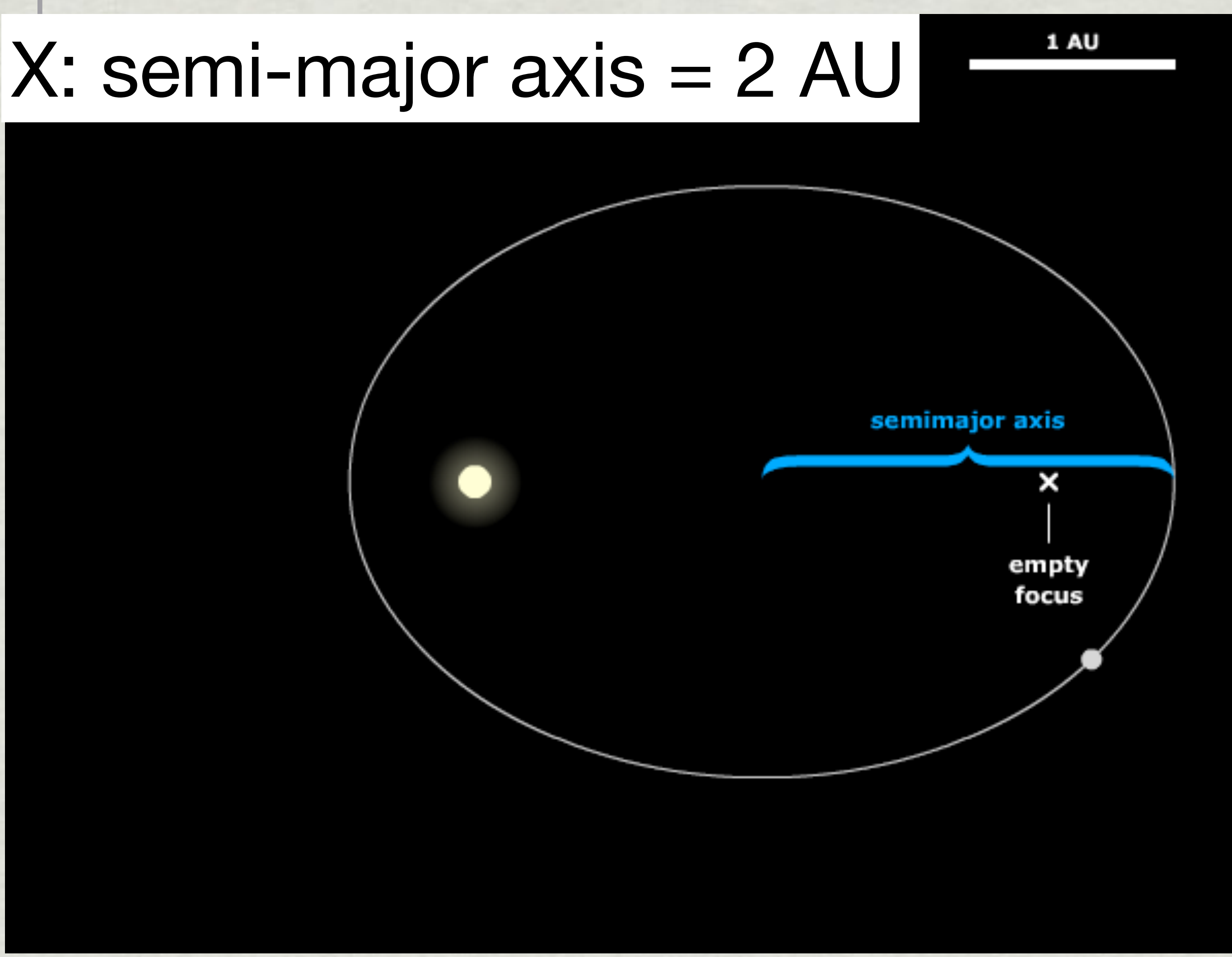


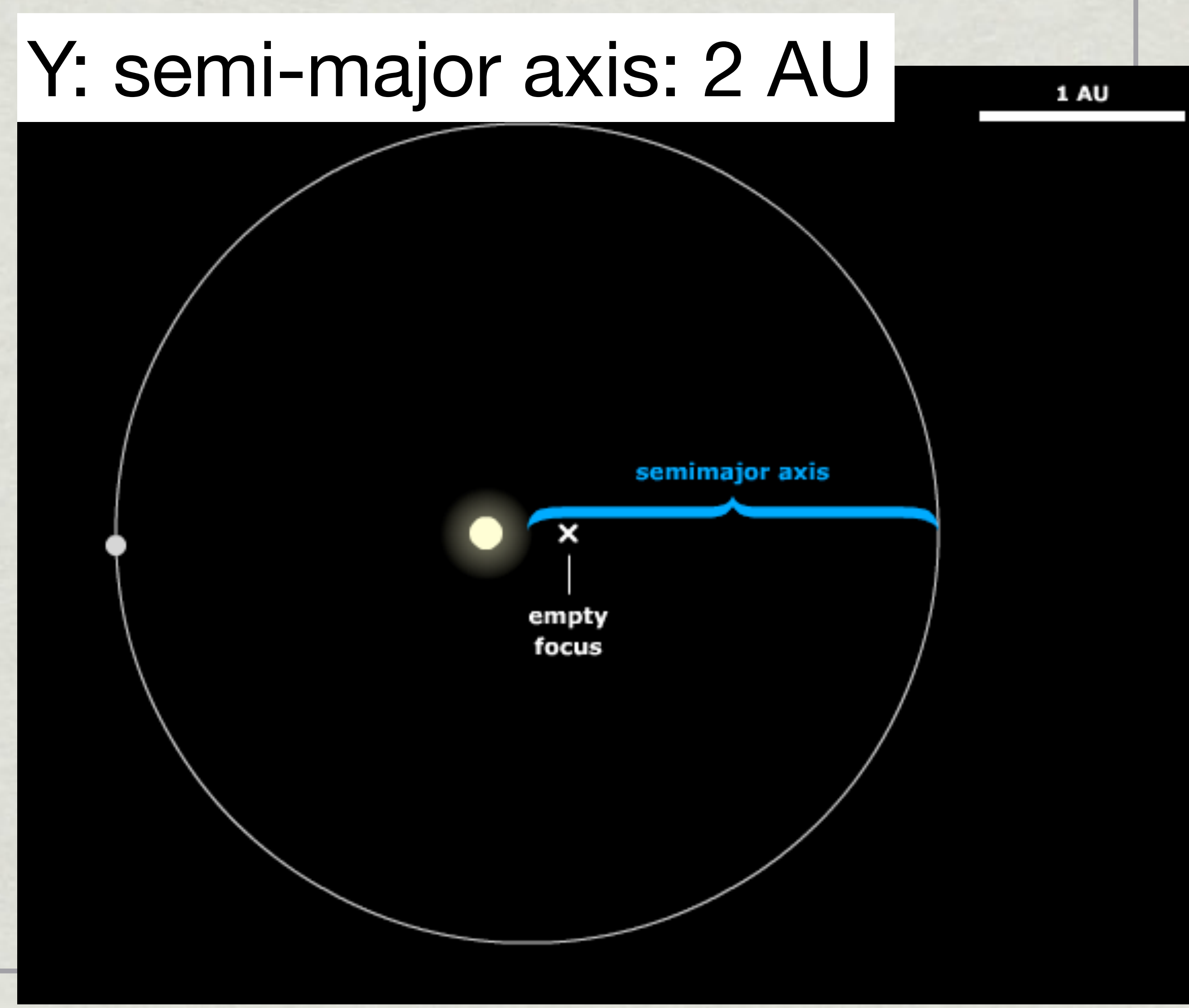
Y: semi-major axis: 2 AU



Kepler's Laws and Gravity

At what point in its orbit is planet X accelerating?





Kepler's Laws and Gravity

Where does planet X feel the strongest force from gravity?

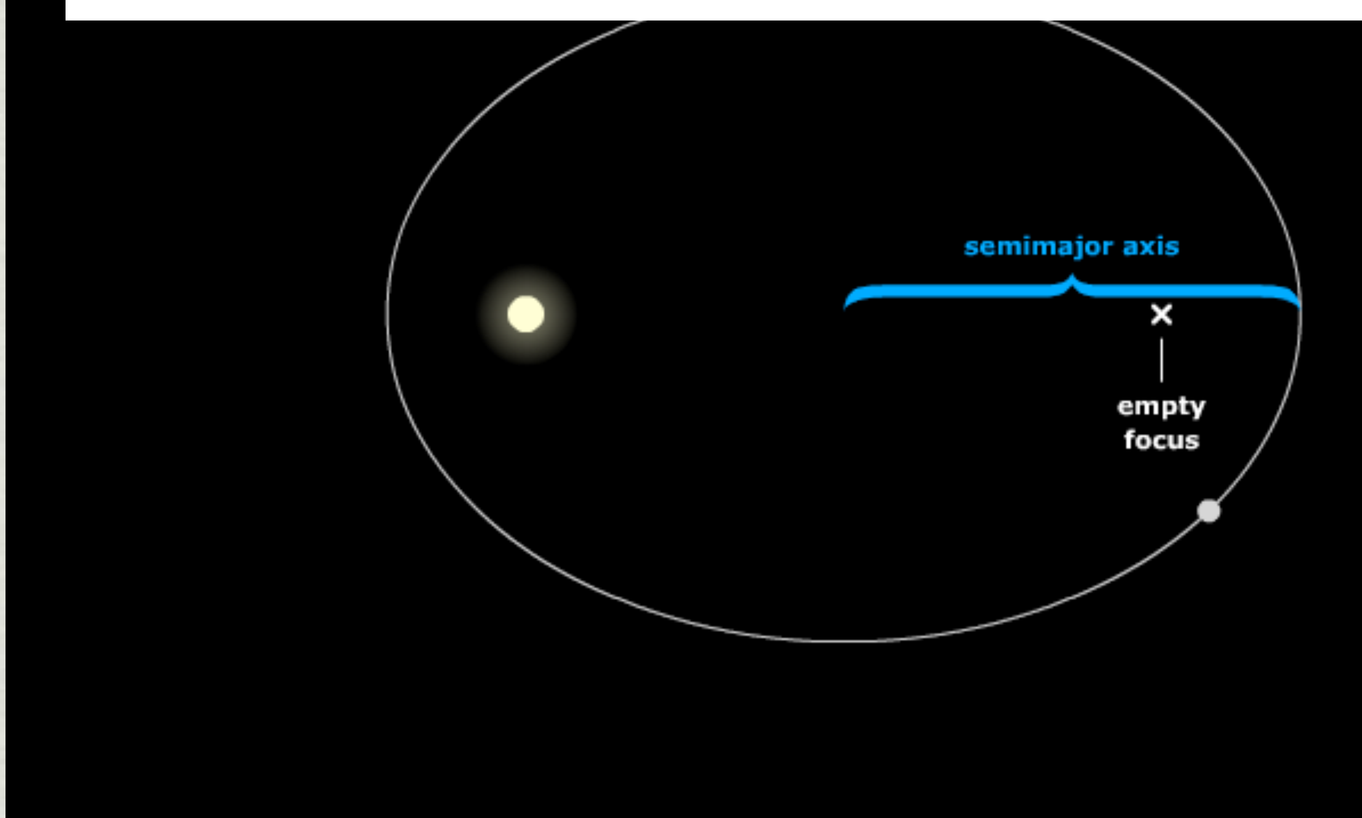
Closest approach. $F = GM_pM_s/d^2$, force largest where d smallest

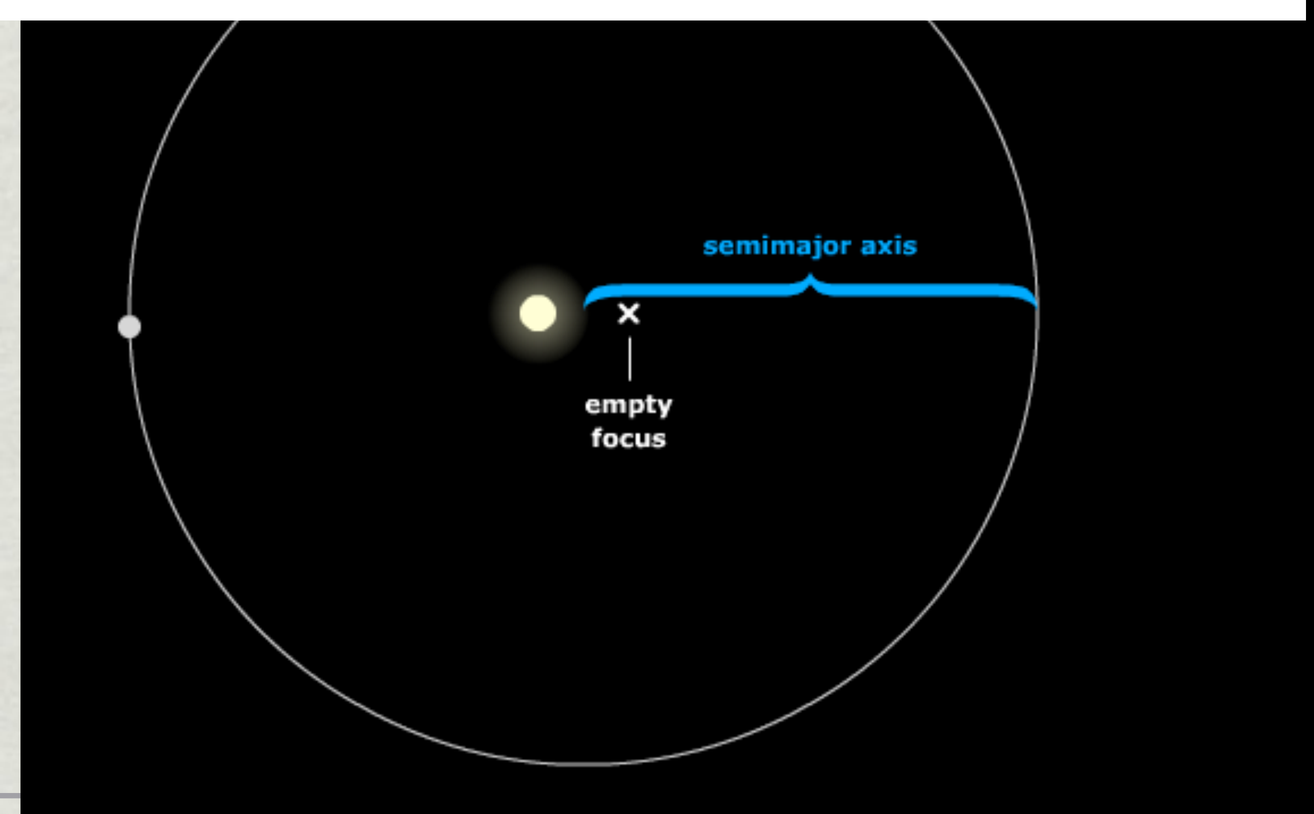
At what point in its orbit is planet X accelerating?

Always: it is moving along a curved path, so its velocity is always changing

Where is the velocity of planet X largest?

Closest approach to the star. We know this from Kepler's law, conservation of angular momentum and conservation of energy





Force, Acceleration, Momentum

Newton's Law: $F = m\,a = \dfrac{\text{Change in Momentum}}{\text{Change in Time}}$

$$F = m_{rock}\,a = \frac{G\,M_{earth}\,m_{rock}}{d^2}$$

Now drop the rocks on the moon.

Is the acceleration of the rocks larger or smaller than it was on earth?

A smaller
B larger
C the same
D don't know enough to answer

Force, Acceleration, Momentum

Newton's Law: $F = m\,a = \dfrac{\text{Change in Momentum}}{\text{Change in Time}}$

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Force, Acceleration, Momentum

Newton's Law: $F = m\,a = \dfrac{\text{Change in Momentum}}{\text{Change in Time}}$

$$F = m_{rock}\, a = \frac{G\, M_{moon}\, m_{rock}}{d^2}$$

Now drop the rocks on the moon.

Is the acceleration of the rocks larger or smaller than it was on earth?

$$F = m_{rock}\, a = \frac{G\, M_{moon}\, m_{rock}}{d^2}$$

A smaller

B larger

C the same

D don't know enough to answer

Force, Acceleration, Momentum

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$$F = m_{rock}\, a = \frac{G\, M_{moon}\, m_{rock}}{d^2}$$

Now drop the rocks on the moon.

Is the acceleration of the rocks larger or smaller than it was on earth?

$$F = \cancel{m}_{rock}\, a = \frac{G\, M_{moon}\, \cancel{m}_{rock}}{d^2}$$

A smaller
B larger
C the same
D don't know enough to answer

$$a = \frac{G\, M_{moon}}{d^2}$$

Force, Acceleration, Momentum

Newton's Law: $F = m\,a = \dfrac{\text{Change in Momentum}}{\text{Change in Time}}$

$$F = m_{rock}\,a = \frac{G\,M_{moon}\,m_{rock}}{d^2}$$

Now drop the rocks on the moon.

Do the rocks fall faster or slower than they did on earth?

$$F = \cancel{m}_{rock}\,a = \frac{G\,M_{moon}\,\cancel{m}_{rock}}{d^2}$$

$$a = \frac{G\,M_{moon}}{d^2}$$

Force, Acceleration, Momentum

Newton's Law: $F = m\,a = \dfrac{\text{Change in Momentum}}{\text{Change in Time}}$

$$F = m_{rock}\,a = \frac{G\,M_{moon}\,m_{rock}}{d^2}$$

Now drop the rocks on the moon.

Do the rocks weigh more or less than they did on earth?

$$F = m_{rock}\,a_{rock}$$

$$a_{rock} = \frac{GM_{moon}}{d^2}$$

Force, Acceleration, Momentum

Newton's Law: $F = m\ a = \dfrac{\text{Change in Momentum}}{\text{Change in Time}}$

$$F = m_{rock}\ a = \frac{G\ M_{moon}\ m_{rock}}{d^2}$$

Now drop the rocks on the moon.

Is the acceleration of the rocks larger or smaller than it was on earth? smaller

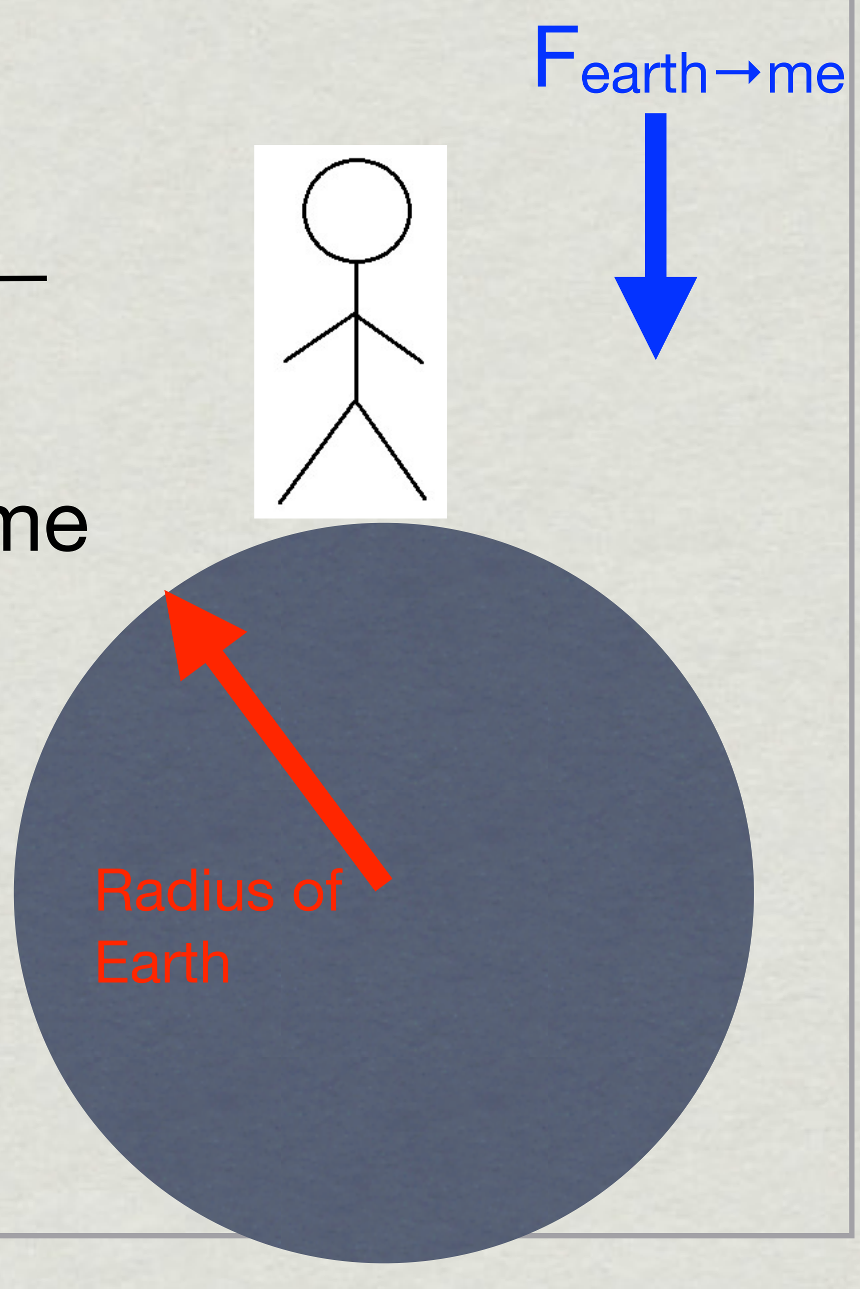
Do the rocks fall faster or slower than they did on earth? slower

Do the rocks weigh more or less than they did on earth? less

Surface Gravity and Weight

- The earth's surface gravity ***g***: acceleration you feel at the surface of the earth, pulls you toward the ground
- **g** is an acceleration, but it is an important one so it gets its own letter

Surface Gravity: $F_{earth \rightarrow me} = \dfrac{G\, M_{me}\, M_{earth}}{R^2_{earth}}$



The force of the earth's gravitational pull on me

$F_{earth \rightarrow me} = Ma = M_{me}\, \mathbf{g}$

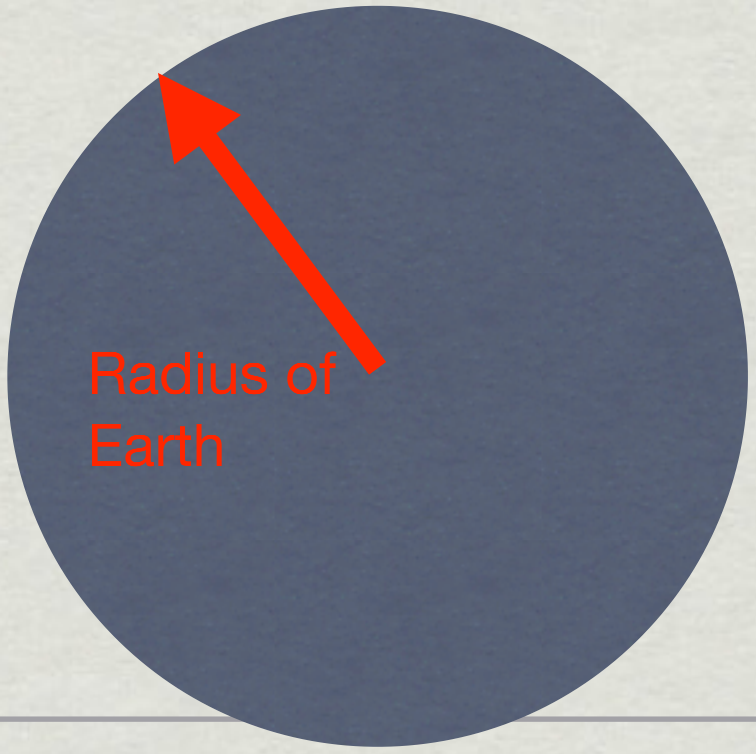
= my mass x acceleration from Earth's gravitational pull

Surface Gravity and Weight

- The earth's surface gravity ***g***: acceleration you feel at the surface of the earth, pulls you toward the ground
- **g** is an acceleration, but it is an important one so it gets its own letter

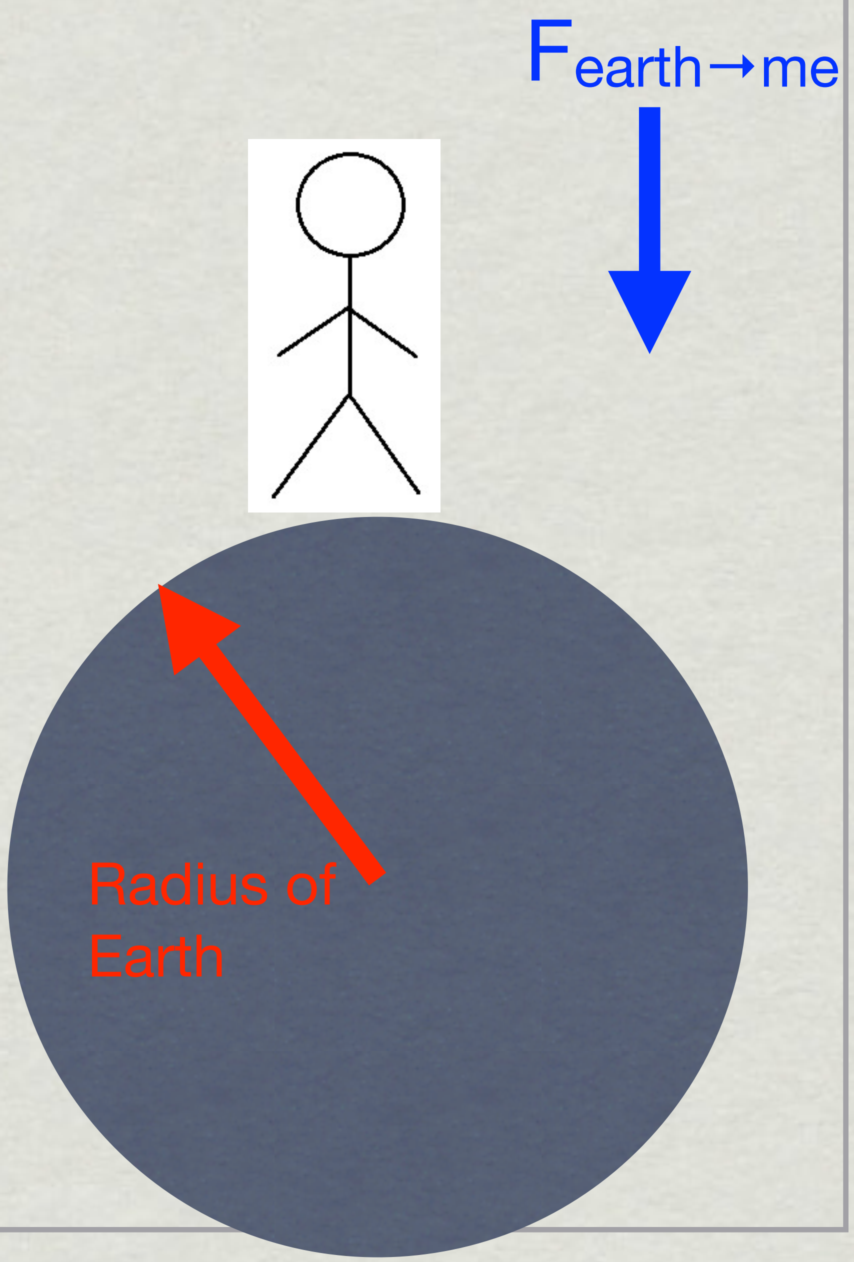
Surface Gravity: $$F_{earth\rightarrow me} = \frac{G\, M_{me}\, M_{earth}}{R^2_{earth}}$$

How does my acceleration change if I am far above the Earth's surface in a balloon?



Force, Mass and Weight

- Your mass: amount of stuff in you
  - same anywhere in the universe
- Your weight: Force on your mass due to Earth's surface gravity
- My mass: 68 kg
- Acceleration of earth's gravity: 9.8 m/s^2
- Force: 668 kg m/s^2, my weight



Force, Mass and Weight

Jupiter has a different mass and radius than earth

$$a_{\text{Gravity, Jupiter}} = \frac{G\,M_{\text{Jupiter}}}{R^2_{\text{Jupiter}}}$$

$M_{\text{Jupiter}} = 2 \times 10^{27}$ kg

$R^2_{\text{Jupiter}} = 7 \times 10^{7}$ m

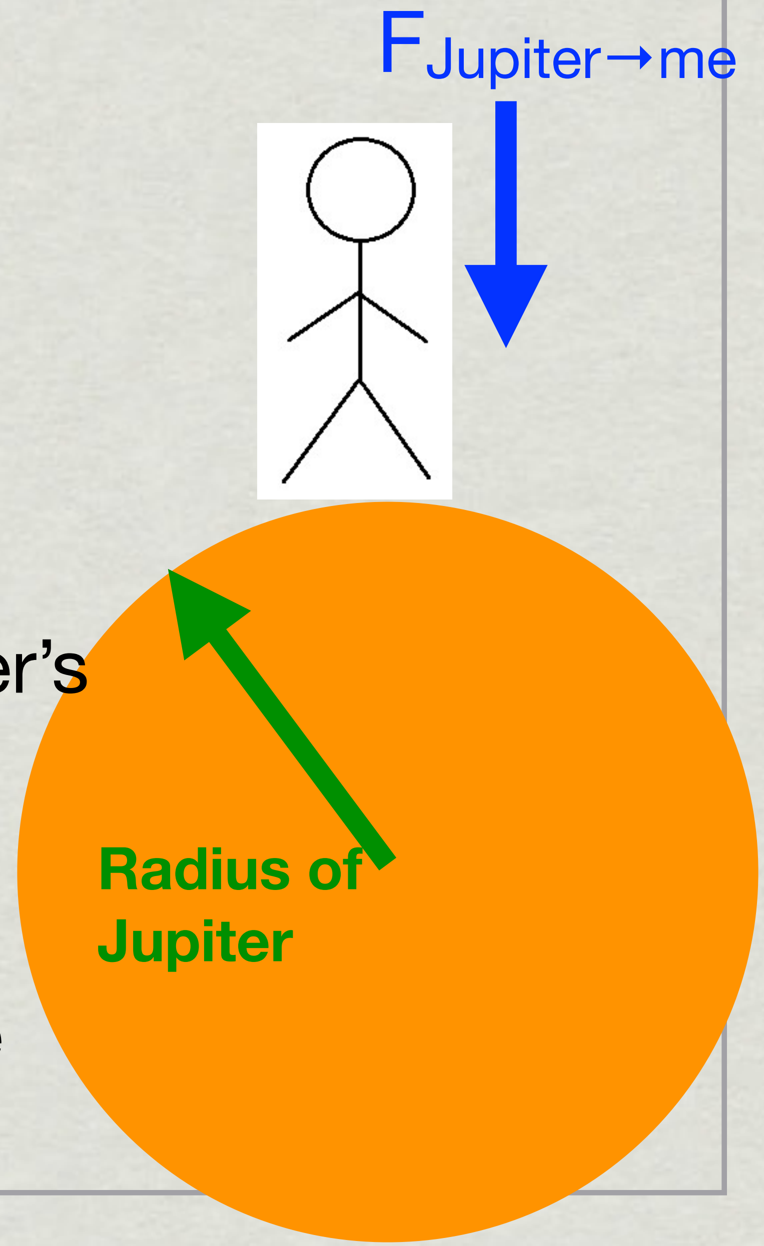
$a_{\text{Gravity, Jupiter}} = 27\ \text{m/s}^2$

Compare g, acceleration due to Earths gravity: 9.8 m/s^2

You would experience a greater acceleration from Jupiter's gravity

You would weigh more on Jupiter

Moon has weaker surface gravity: you weigh less on the moon



Orbits and Circular Motion

- Combine:

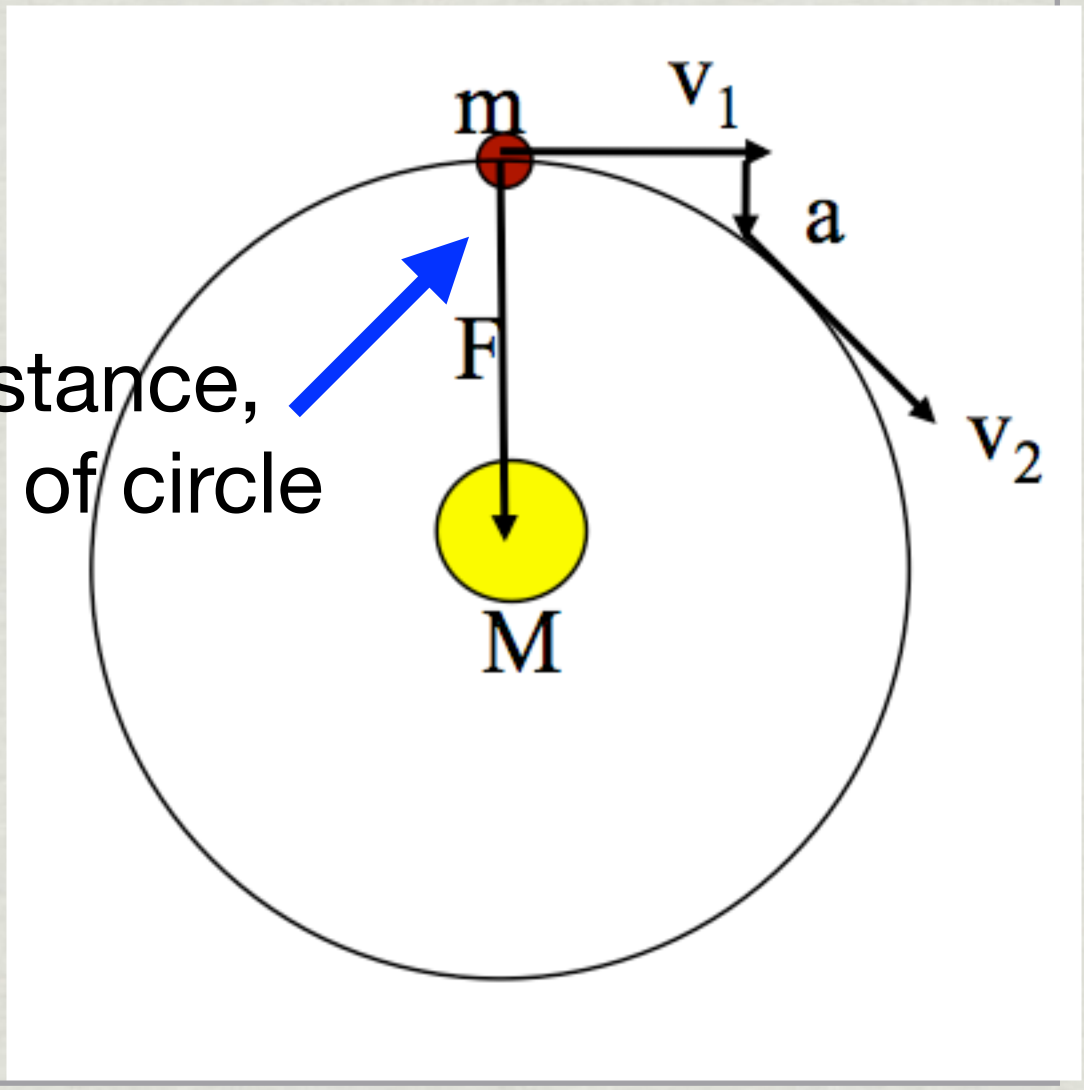
  Acceleration required to keep an object in circular motion: $\dfrac{v^2}{d}$

  with acceleration from Gravity $= \dfrac{G\,M}{d^2}$

$$\frac{v^2}{d} = \frac{G\,M}{d^2}$$

$$v = \sqrt{\frac{G\,M}{d}}$$

d = distance,
radius of circle



v = speed for an object in stable circular motion around mass M at distance d

- Depends on M and d, not m
- slower for d large, M small

Energy and Orbits

$$v = \sqrt{\frac{G\,M}{d}}$$

speed for an object in stable circular motion around mass M at distance d

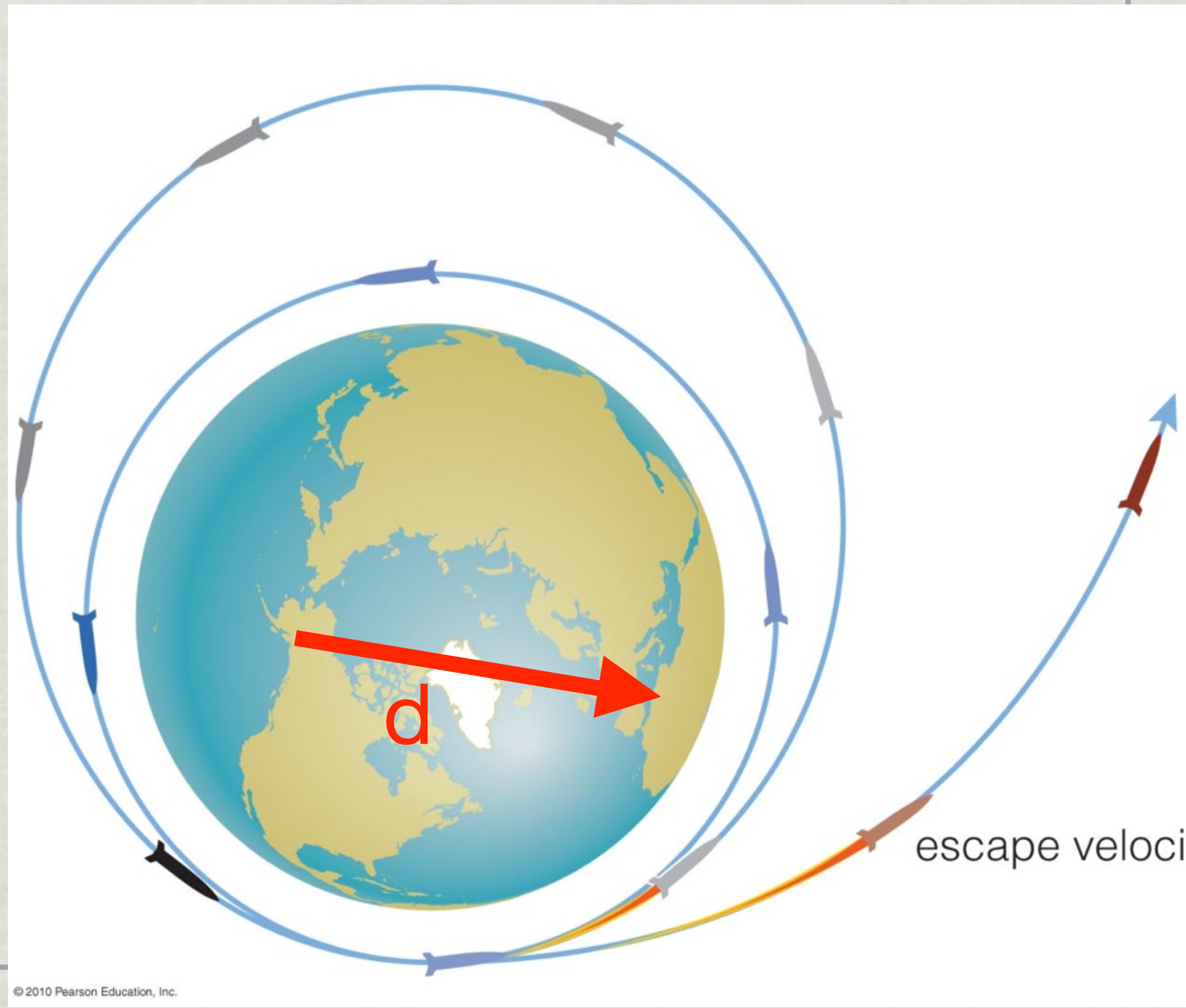
$$v_{escape} = \sqrt{\frac{2\,G\,M}{d}}$$

escape speed for an object at distance d from mass M

For an orbit around mass M,
being at larger d = smaller v_{escape}

v_{escape} larger for larger M

Does it depend on the mass of the rocket?



Light

Energy carried by a single photon is related to its wavelength and frequency:

$$\text{Energy} = E = h\,v = \frac{h\,c}{\lambda}$$

λ = wavelength   Units: meters
v = frequency   Units: sec^{-1}
c = speed of light
  3×10^8 m/s = 300,000,000 m/s
h = Planck's constant
  6.626×10^{-24} Joule sec

- Energy increases if v increases: wave vibrates faster
- Energy decreases if λ increases: wave size gets larger

Planck's constant h:

Same everywhere in the universe (like G, a "universal constant")

Sets how wave size relates to the amount of energy in a photon packet

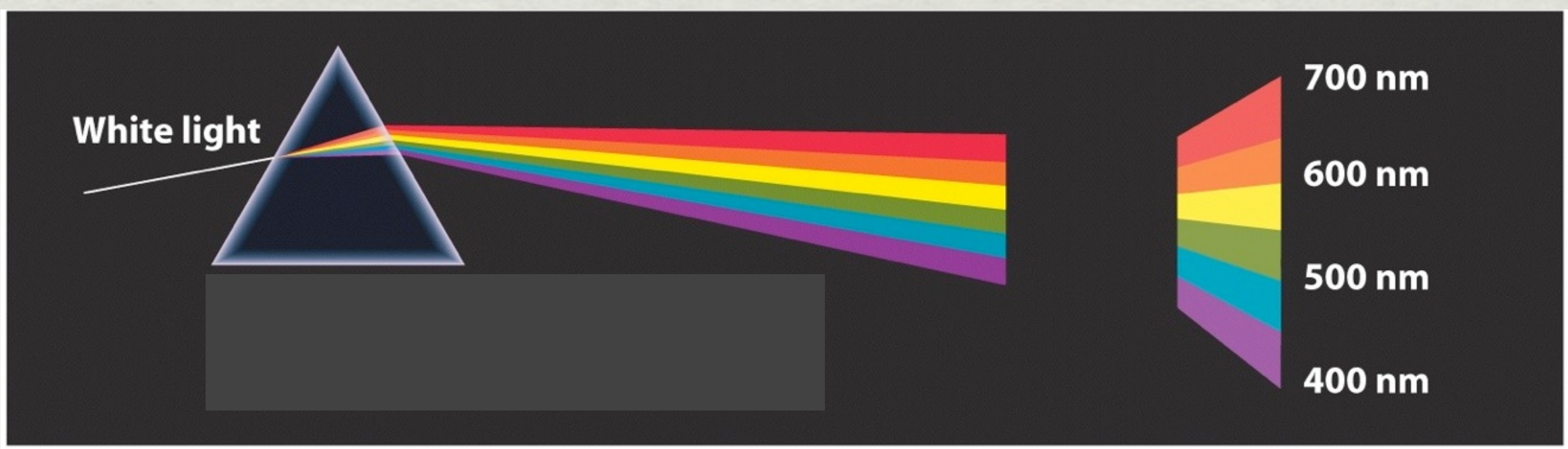
Light

Prisms bend the path of photons according to their energy
White light contains a *continuum* of energies (wavelengths)

We see the energy of photons as color of light
Different colors = different wavelengths of light

Violet light: shortest wavelength we can see, highest energy
Red light: longest wavelength we can see, lowest energy

$1\ \text{nm} = 1\text{x}10^{-9}\ \text{m} = 1\text{x}10^{-6}\ \text{mm}$



Thermal Emission

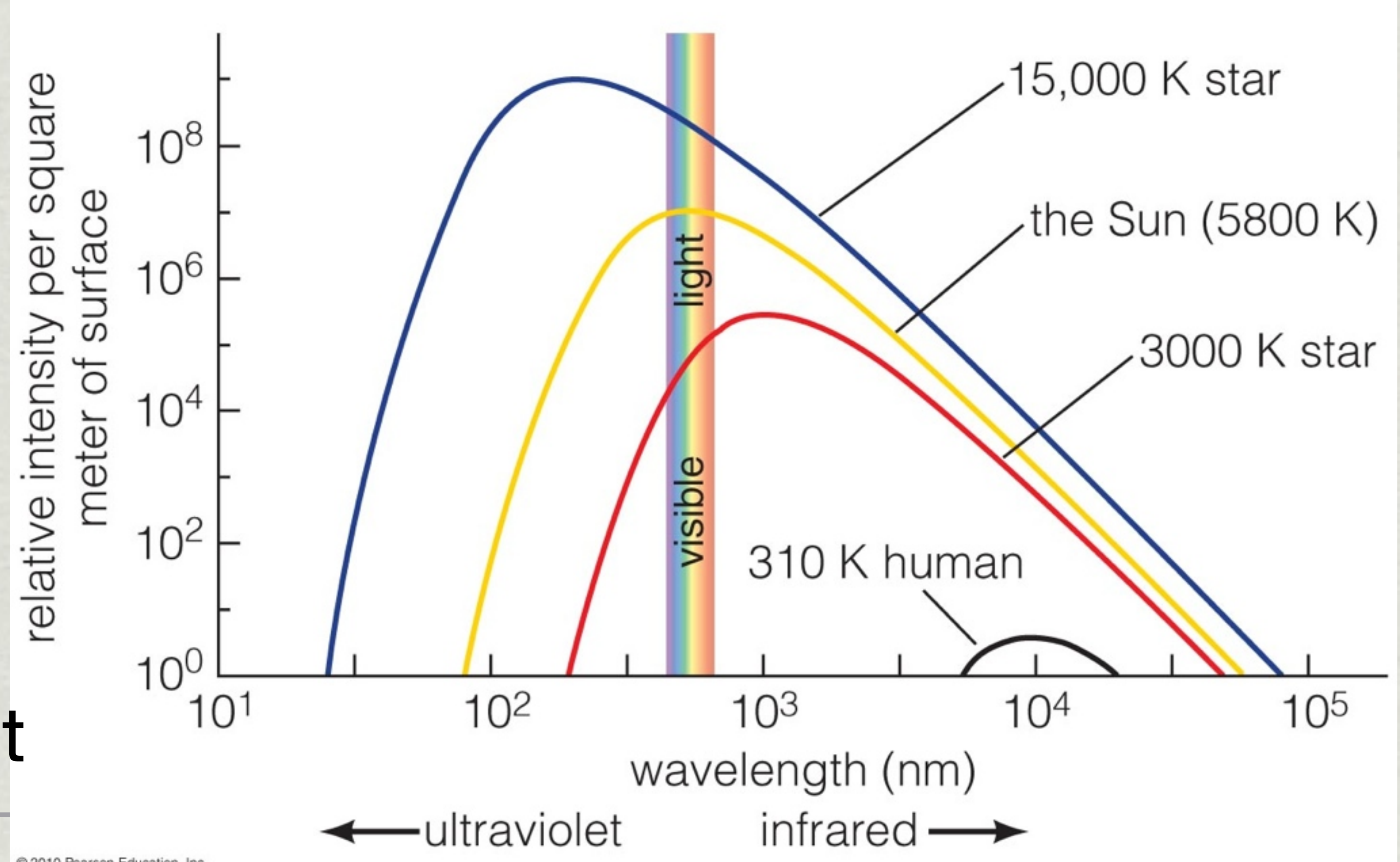
What is this graph? Number of photons (amount of energy) emitted at each wavelength

Total number of photons: add up intensity at each wavelength

Peak: wavelength where maximum number of photons emitted

Graph of thermal radiation always has this shape.

Number of photons at each wavelength is easy to predict



Properties of Thermal Radiation

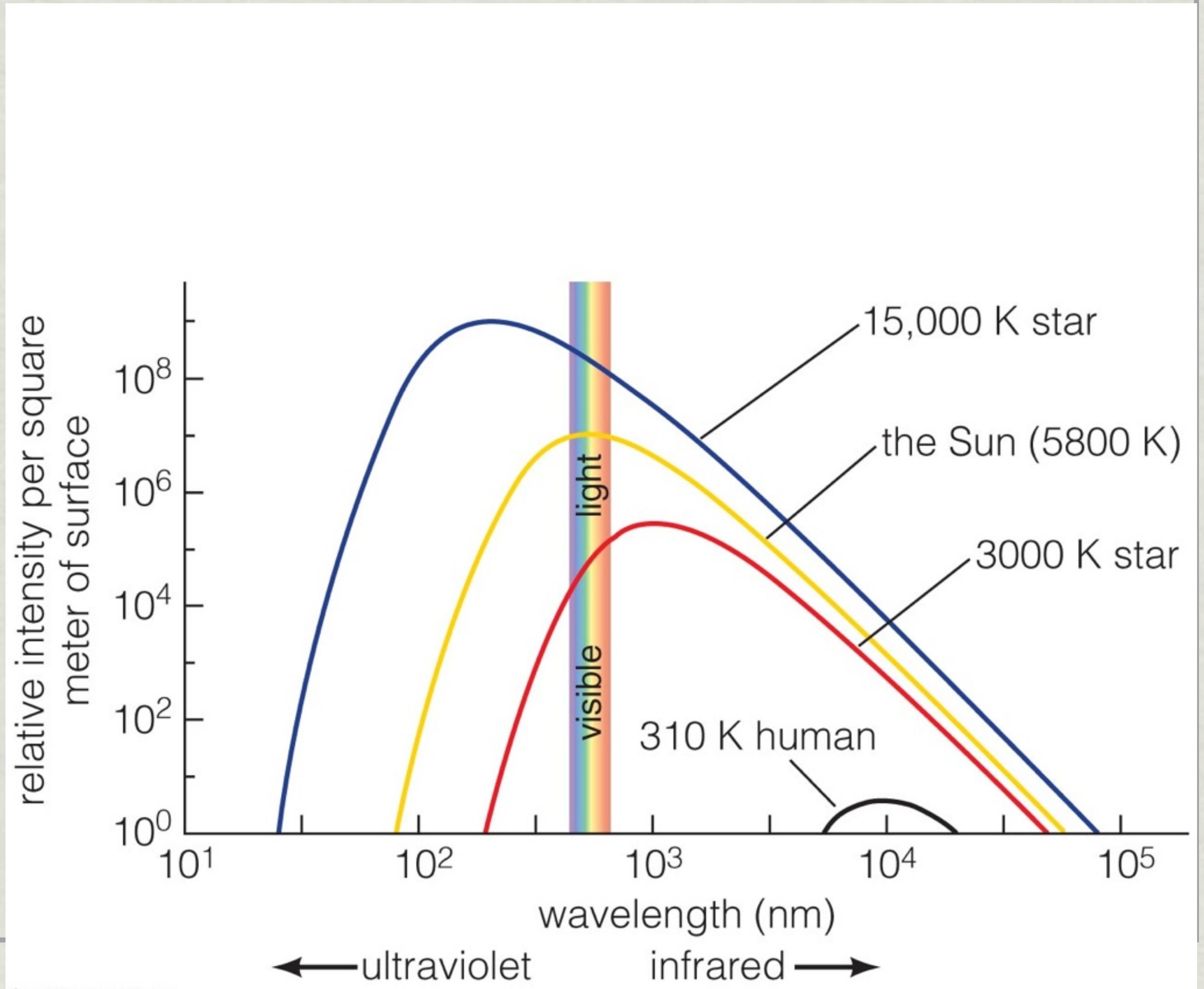
Wien's Law: hotter object: wavelength were most of the photons are emitted is bluer

$$\lambda_{peak} = \frac{2.9 \text{ mm K}}{T}$$

←divide 2.9 by temperature in K to get peak wavelength in mm

We can use the thermal radiation spectrum as a thermometer:

measure the peak wavelength and learn the temperature



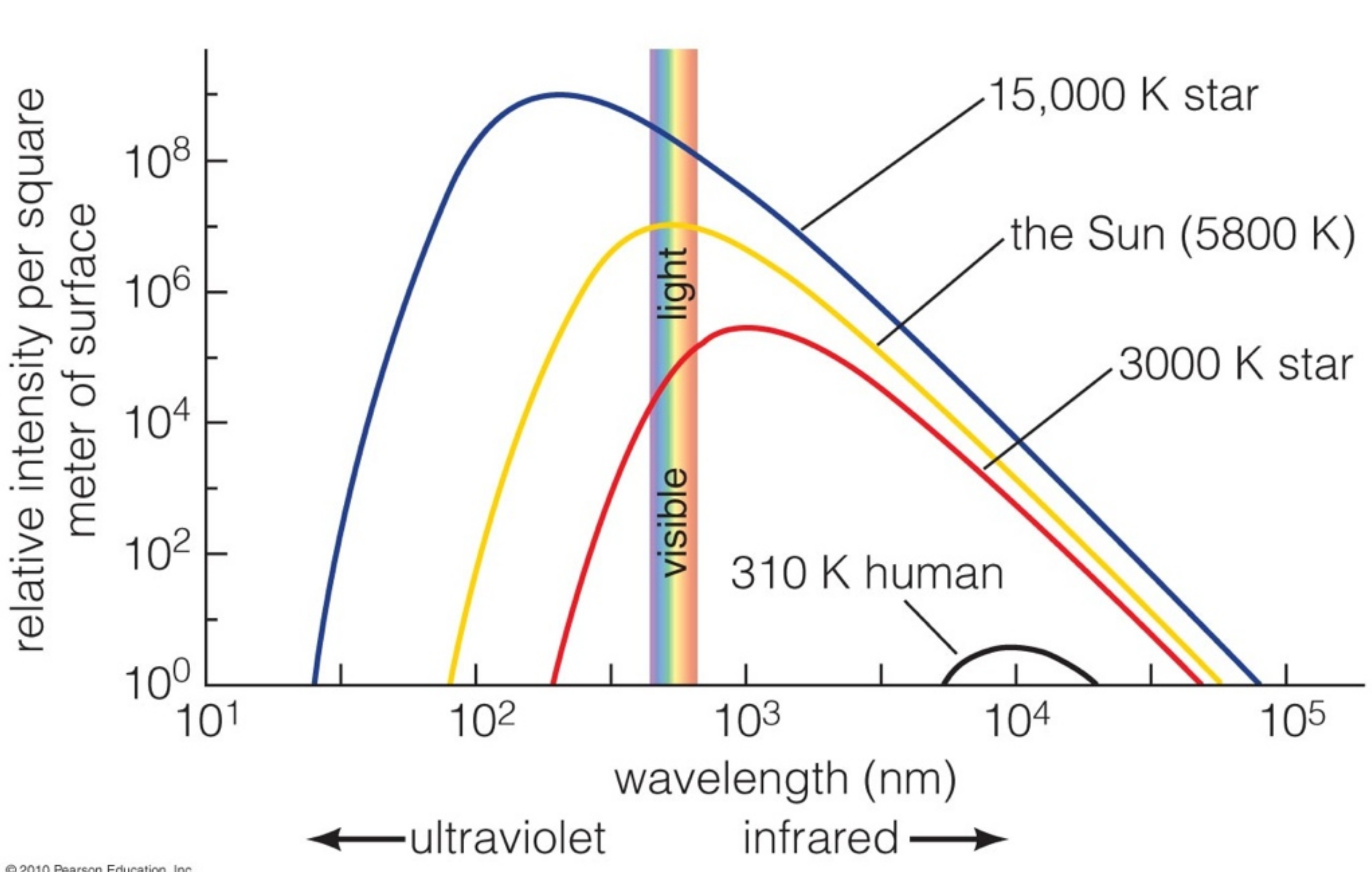
Thermal Emission

Cooler object:

- peak number of photons is emitted at red wavelengths: red color
- fewer total photons emitted: dim

Hotter object:

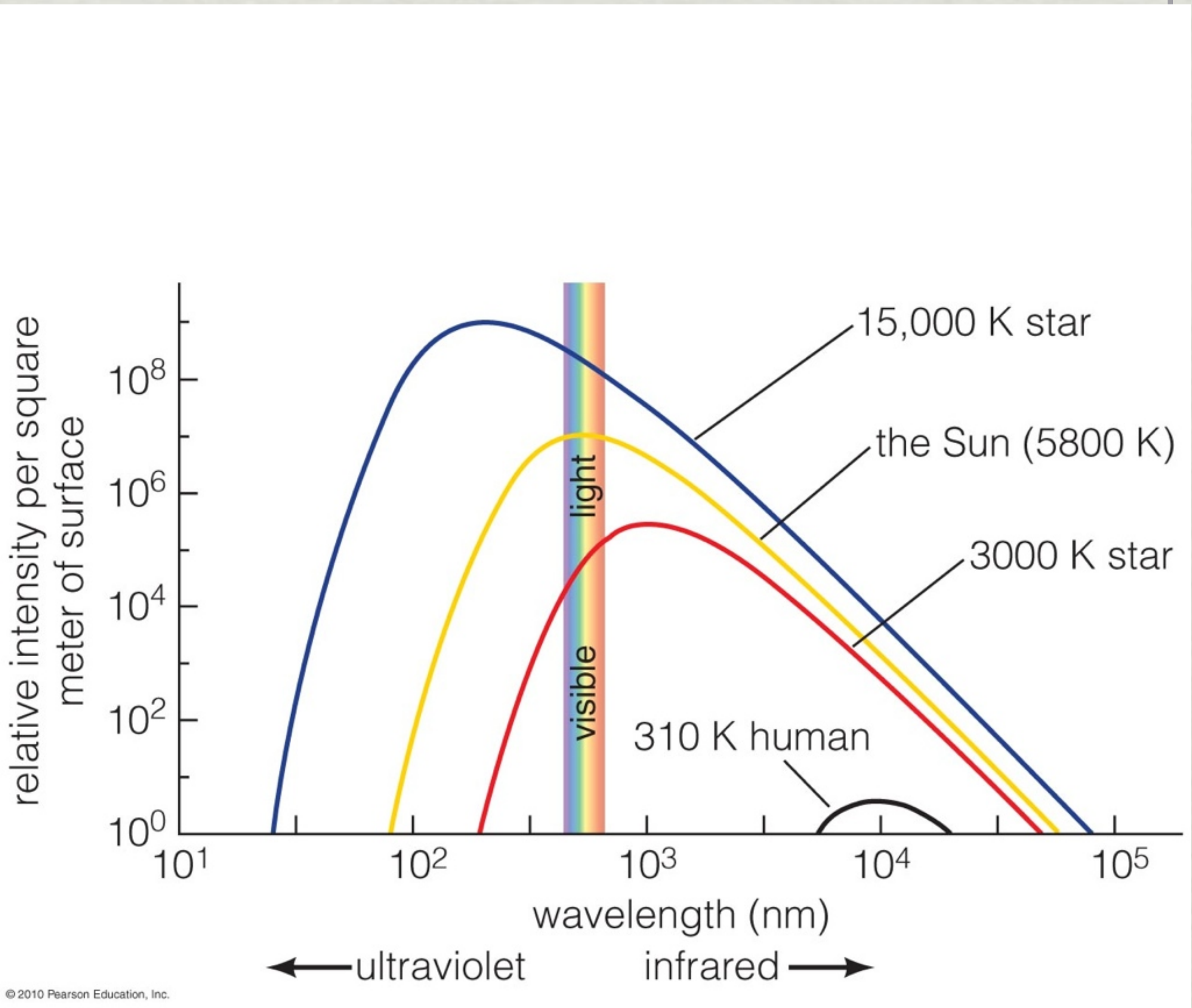
- peak number of photons is emitted at blue wavelengths: blue color
  - we see white because our eyes aren't good at seeing very blue light
- more total photons emitted: bright



Thermal Emission

Cooler object: peak number of photons is emitted at red wavelengths, fewer total photons emitted

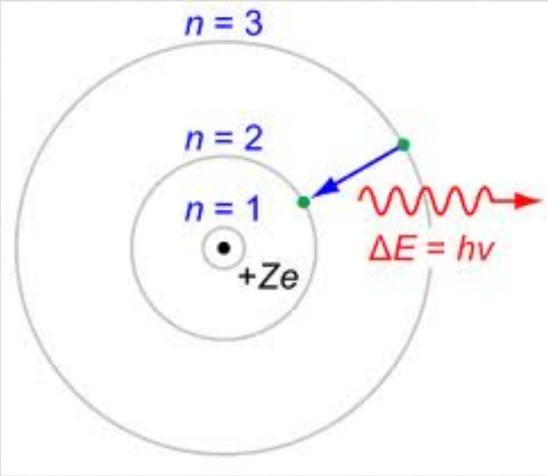
Hotter object: peak number of photons is emitted at blue wavelengths, more total photons emitted



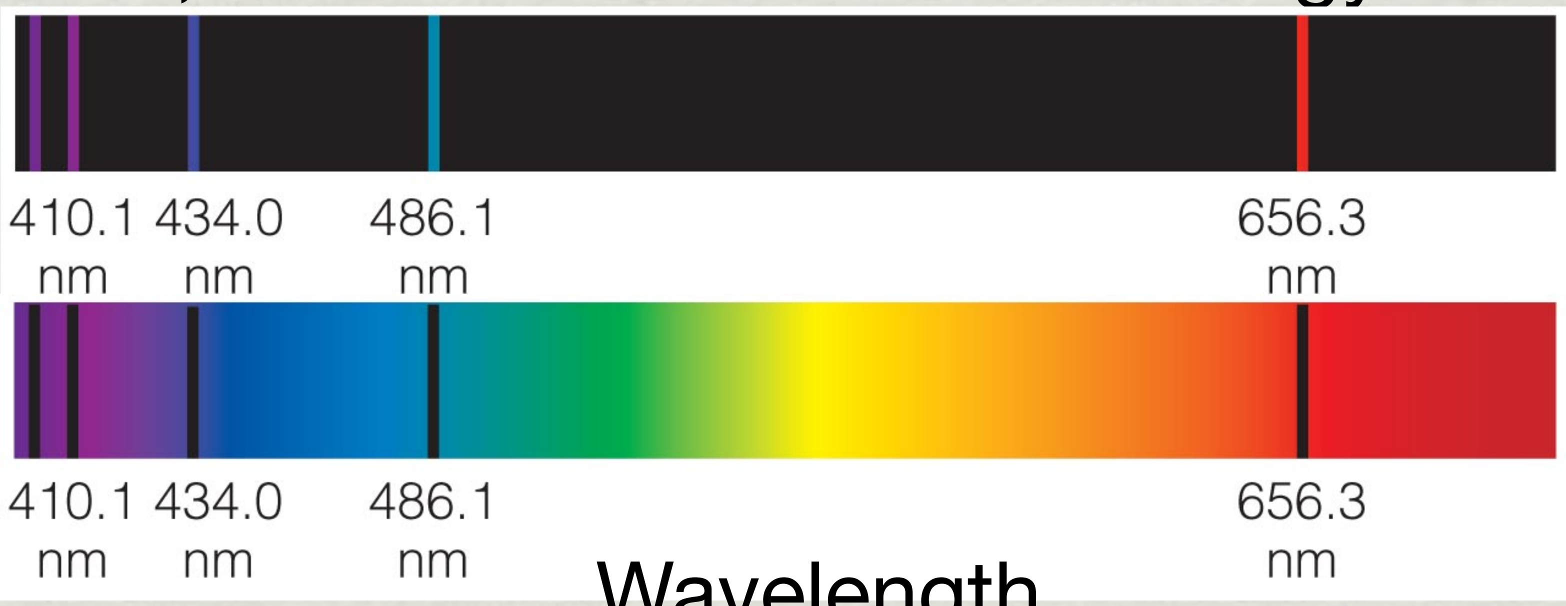
Light and Atoms

- Atoms: release and absorb photons only with certain energies
  - Different chemical elements: determined by number of protons and electrons
  - Each element has a unique set of energy levels that its electrons can occupy
  - Electrons can only move between available energy levels

Get energy = absorb a photon, electron moves to a higher energy level
Release energy = emit a photon, electron falls to a lower energy level



Hydrogen: Emission and Absorption of light

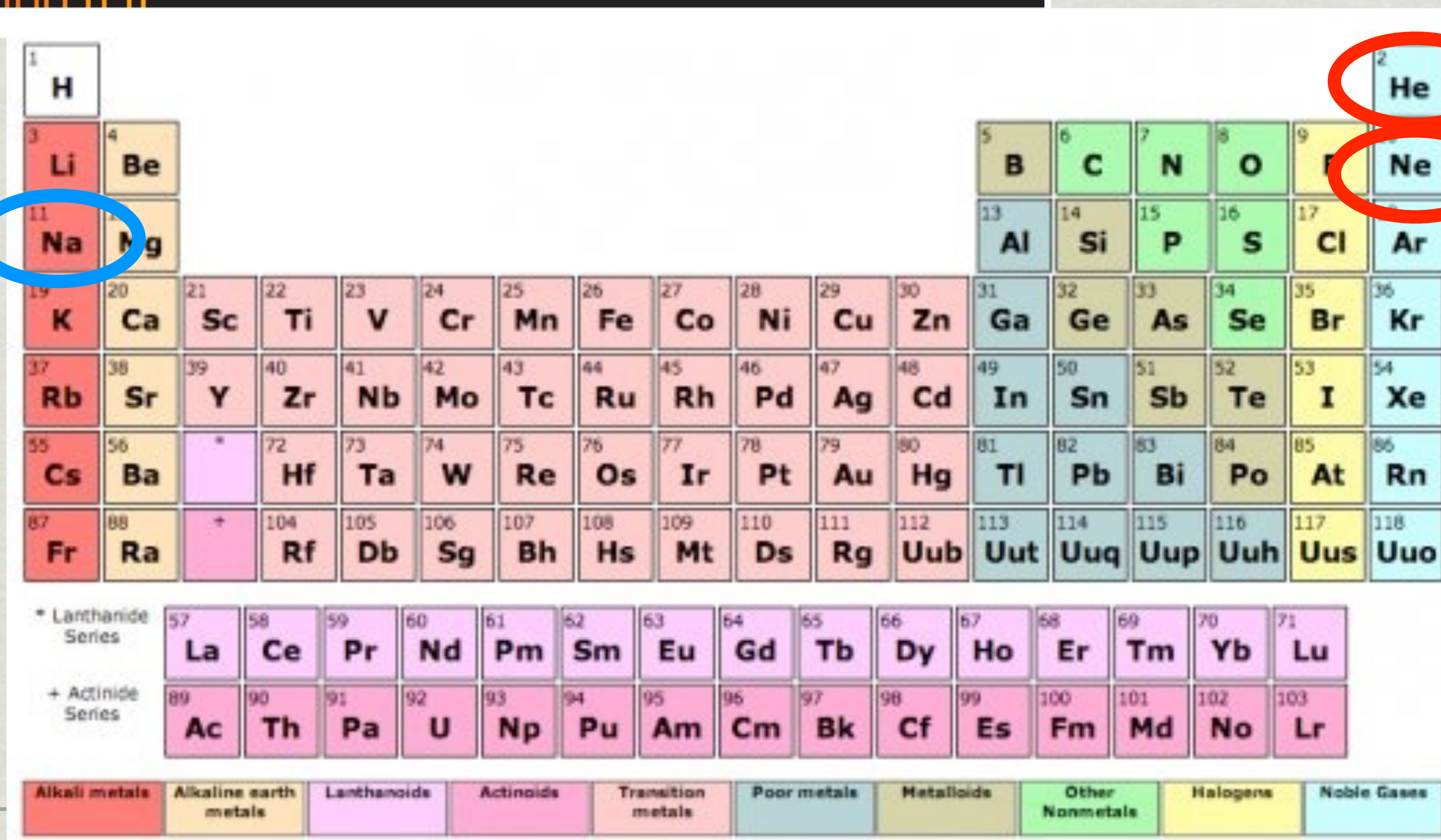


Light and Atoms

- Atoms: release and absorb photons only with certain energies
  - Different chemical elements: determined by number of protons and electrons
  - Each element has a unique set of energy levels that its electrons can occupy
  - Each element has its own fingerprint of energy levels

Wavelength

Light Emission "Fingerprints"



Doppler Effect

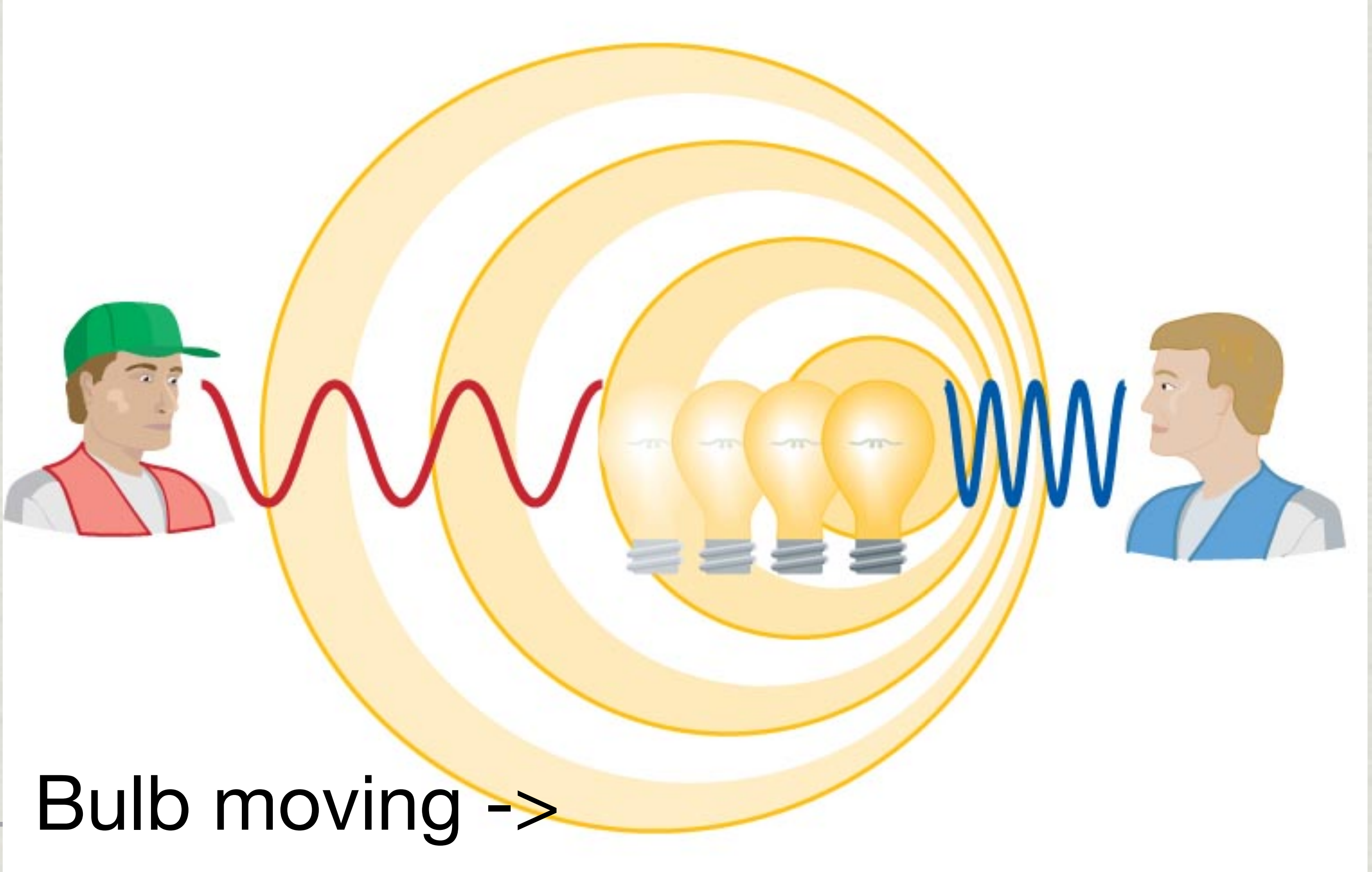
Light from an object moving toward you: peaks bunch up.
Wavelength gets shorter, frequency gets faster.

Remember: $E = h\nu = \frac{hc}{\lambda}$ So light become blue: Blue Shift

For an object moving away from you, peaks stretch out.

Wavelength gets longer, frequency gets slower.

Light becomes redder: Red Shift



Doppler Effect

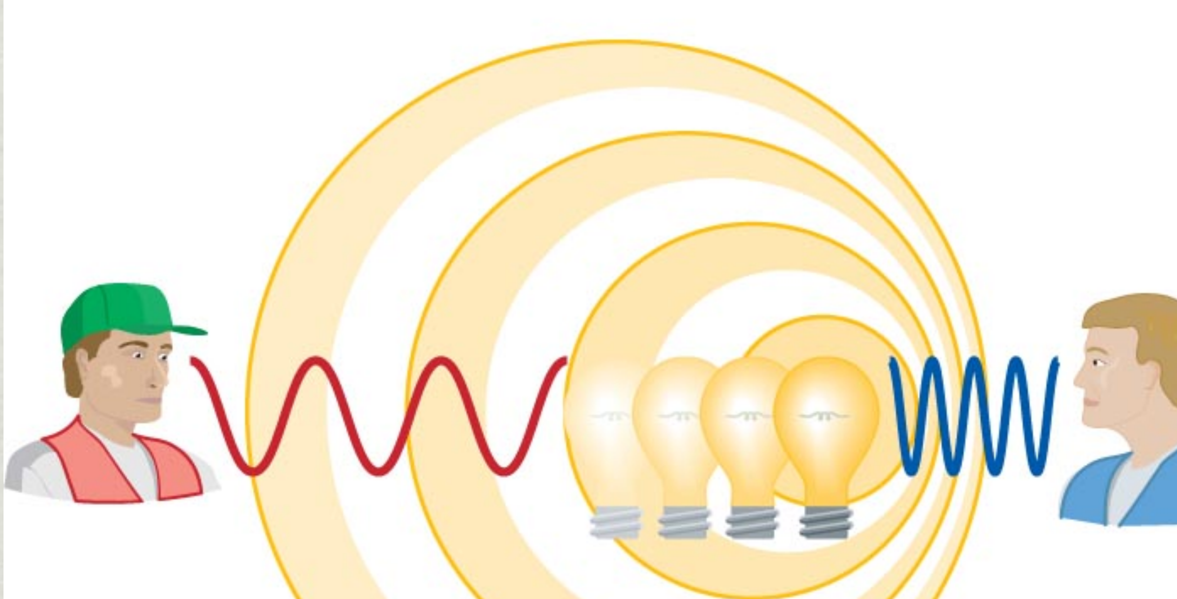
The amount of wavelength change you measure, red or blue, is proportional to the velocity of the light source toward you or away from you.

This is the velocity of the source along your "line of sight"

Doppler formula for light: $$\frac{V_{LoS}}{c} = \frac{\Delta\lambda}{\lambda_{rest}} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}$$

$\frac{V_{LoS}}{c}$ is also called the "redshift"

If $\lambda_{shift} > \lambda_{rest}$, $V_{LoS} > 0$ and the source is moving away from the observer

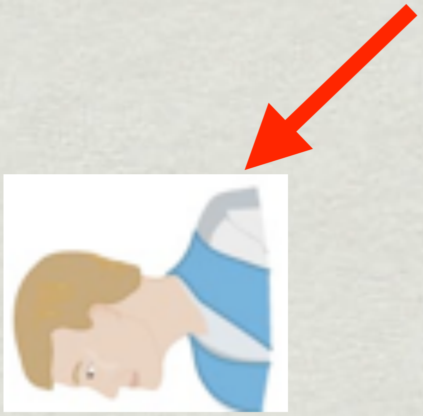


Bulb moving ->

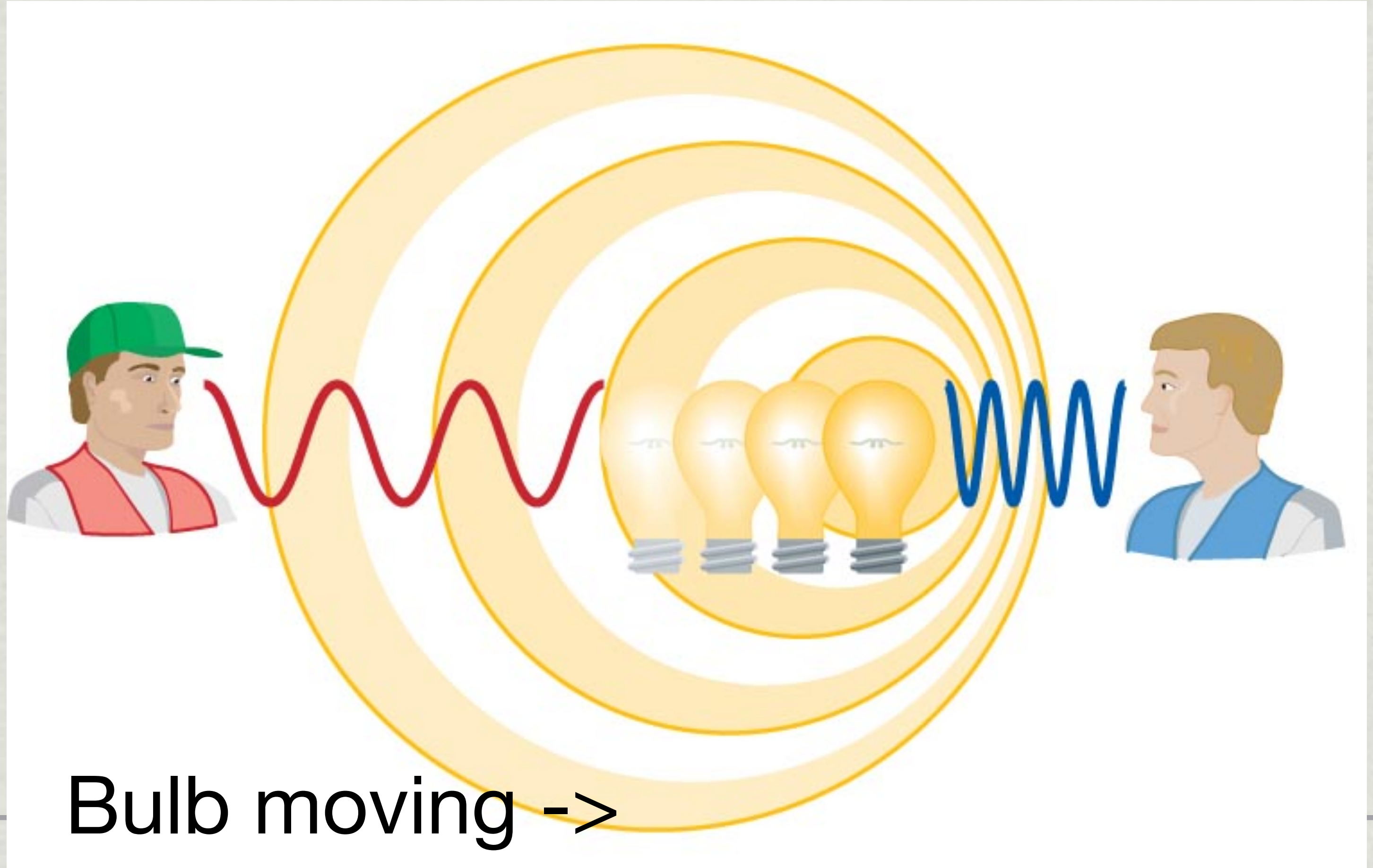
Doppler Effect

Doppler shift tells you only about the velocity along your line of sight.

Dotted: line of sight
Red and gray arrows: velocity

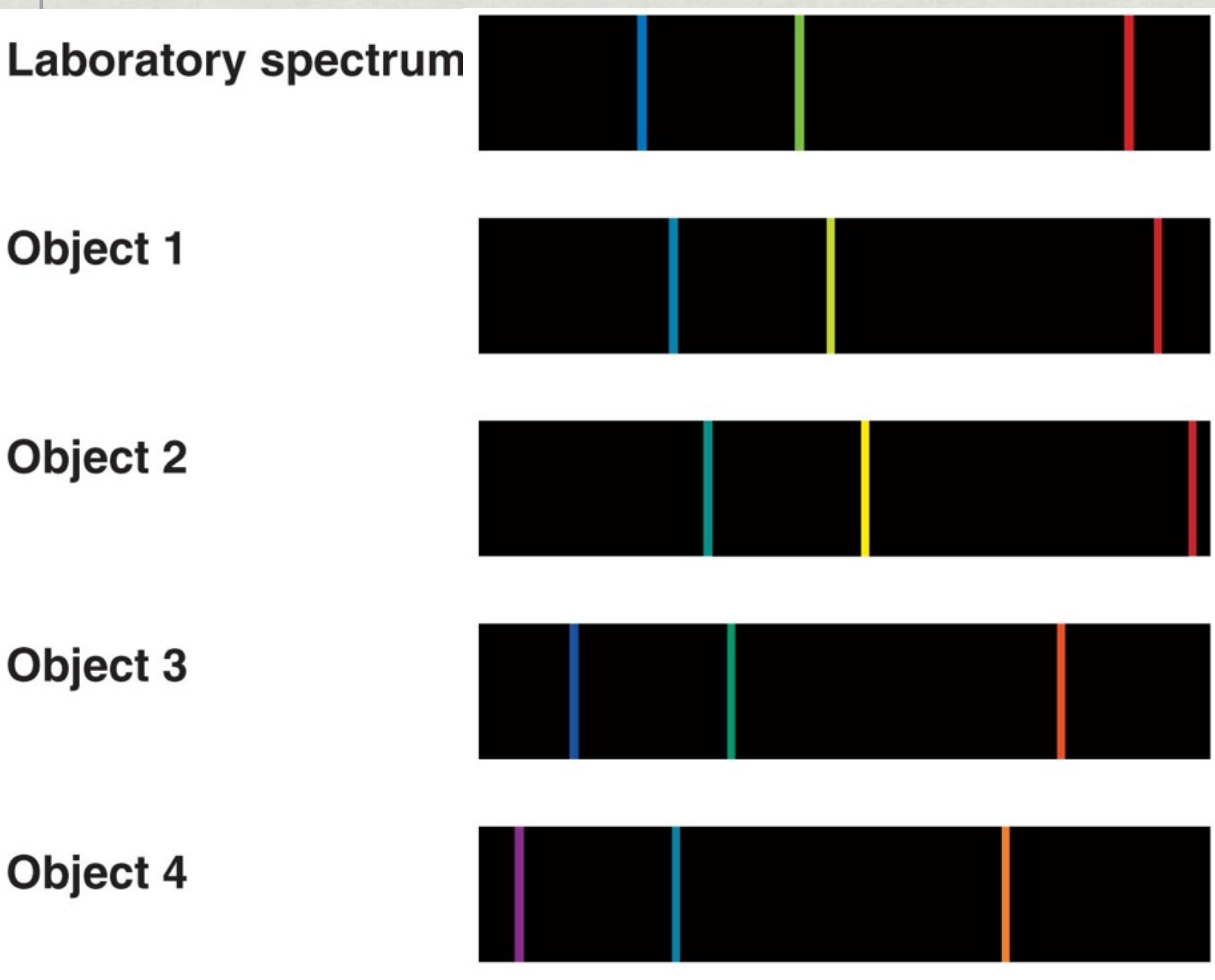


This observer doesn't see any Doppler shift: object is not moving toward or away from him.



Doppler Shift

We can measure the velocity (direction and speed) of a light source from its Doppler Shift.



Rest

Red shift, moving away

Larger red shift, moving away faster

Blue shift, moving toward you

Larger blue shift, moving toward you faster

Fun with Gravity: Finding Planets

- Gravity can be used to weigh stuff we can't put on a scale, like stars and planets

$$\frac{d^3}{P^2} = \boxed{\frac{G\,M}{(2\pi)^2}}$$

- We can even use it to weigh stuff we can't see, and prove that it is there

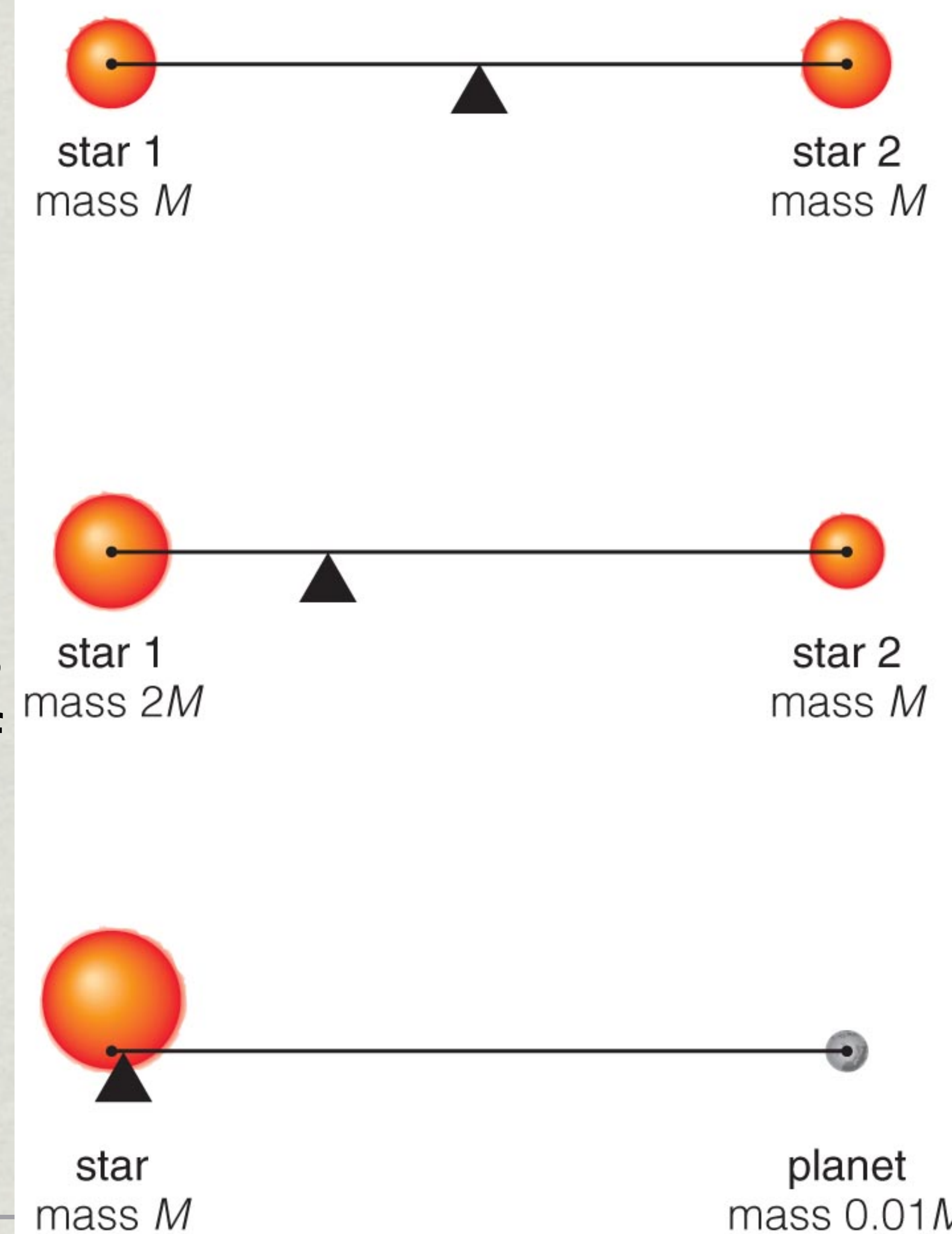
Center of Mass and Orbits

Newton's 3rd Law: if something (like a moon) is in orbit around something more massive (like a planet), the massive object feels a force, too.

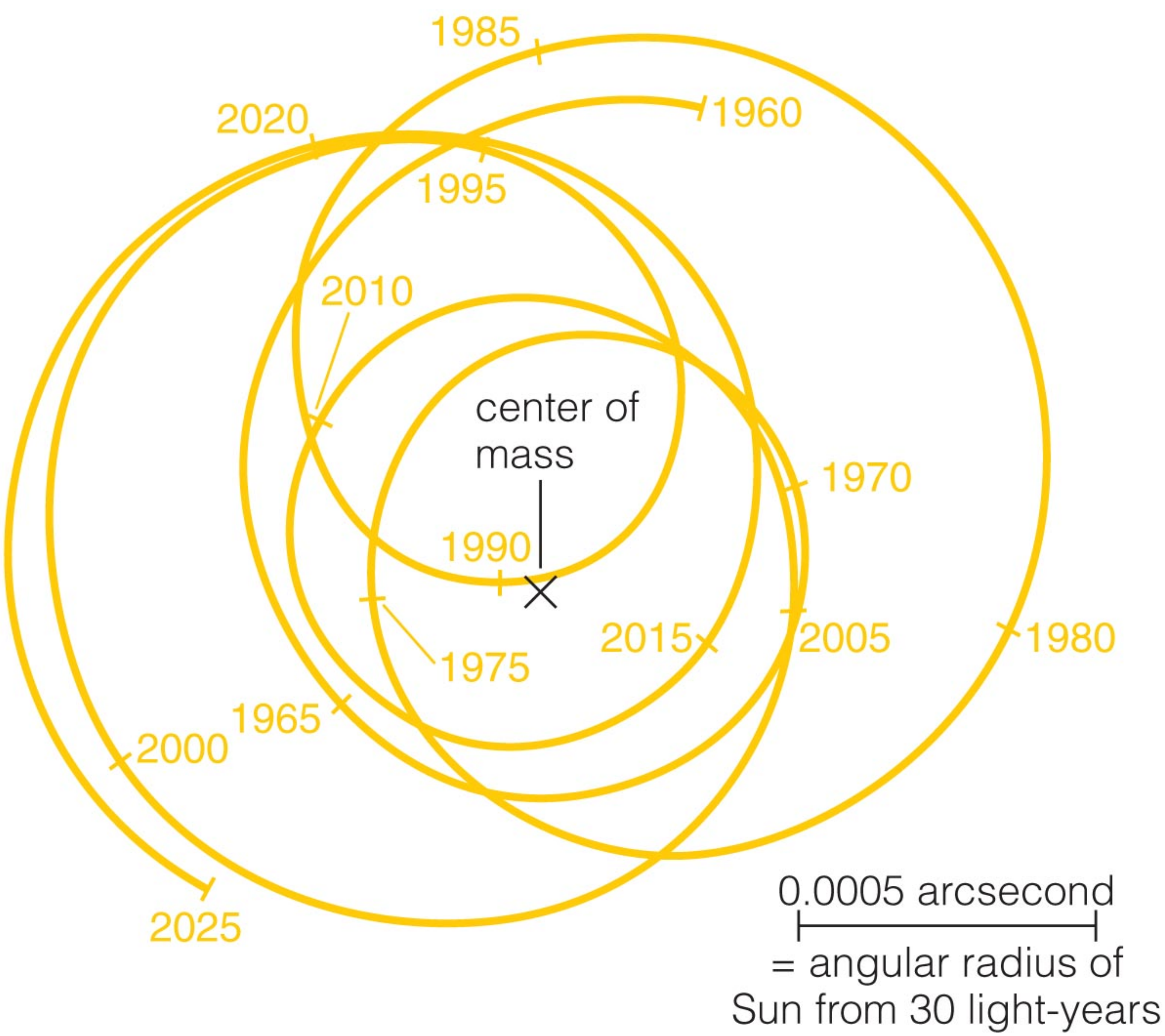
Two objects orbit their Center of Mass (CM). Both have the same orbital period.

Kepler's 1st Law: planets orbit in ellipses with the sun at one focus. The Center of Mass is what is really at the focus.

For one object much more massive than the other, CM very close to the center of the massive object, sometimes *inside*

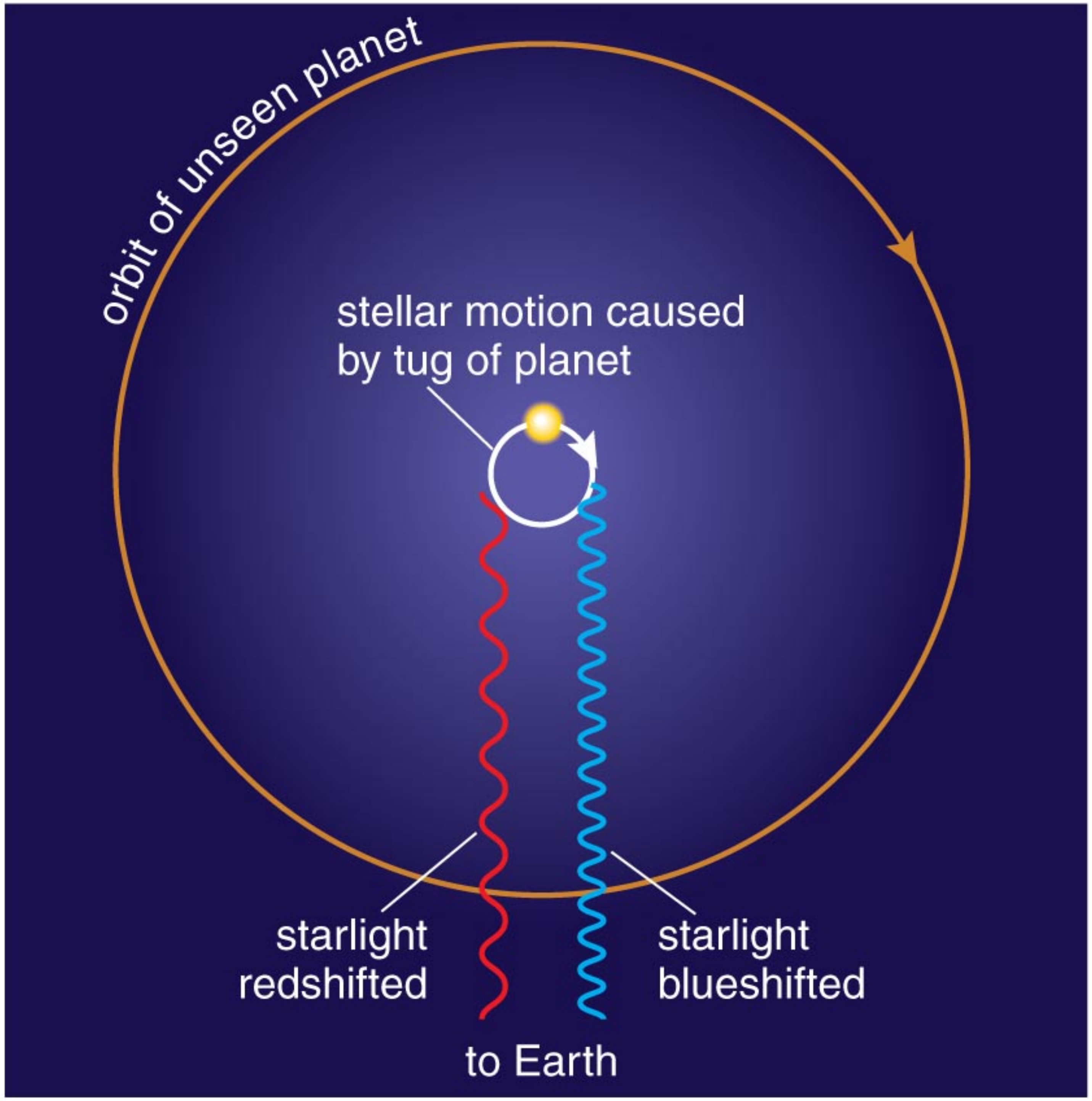


Gravitational Tugs



The motions are tiny: 0.001 arcseconds, just too tiny to measure from the ground. Gaia satellite is making this measurement now!

- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.



- Measuring a star's Doppler shift can tell us its motion toward and away from us.

- Current techniques can measure motions as small as 1 m/s (walking speed!).

Newton's Version of Kepler's 3rd Law

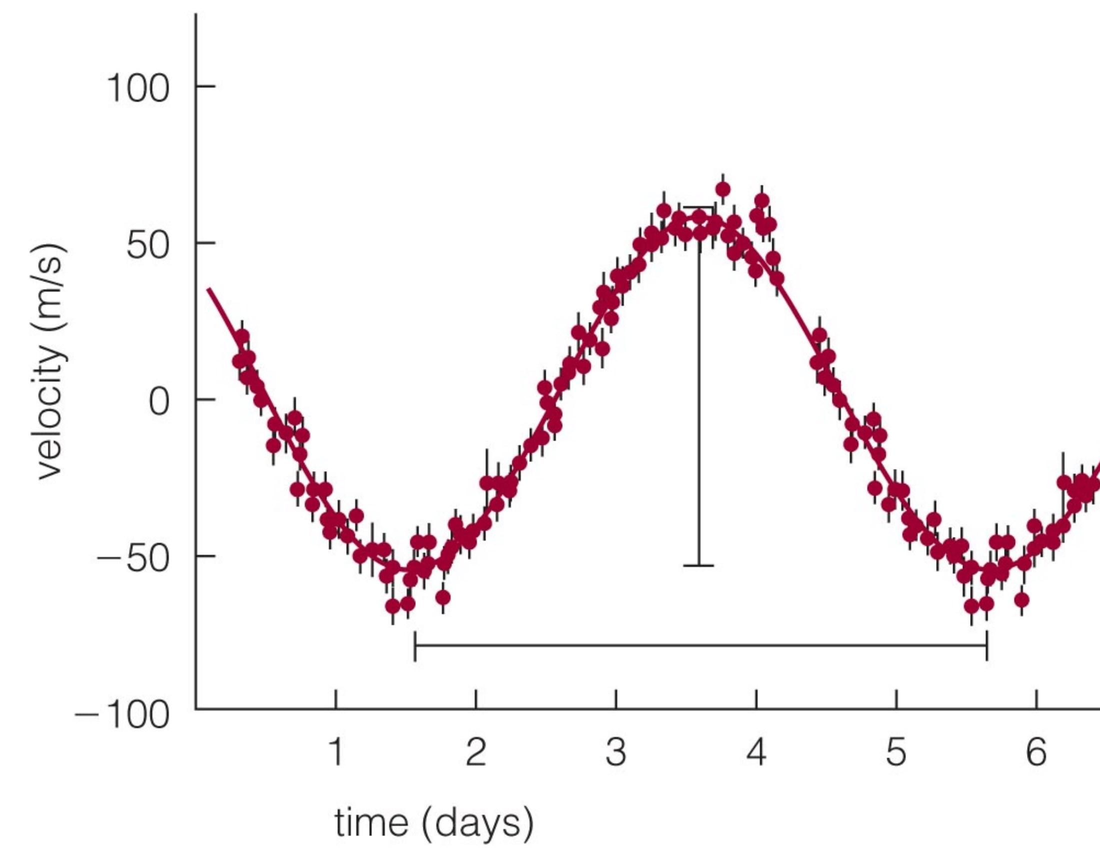
$$\frac{d^3}{P^2} = \frac{G\,(M_1+M_2)}{(2\pi)^2}$$

This is the more exact version.

1) Measure the Doppler velocity shift of the star around the CM of the orbit. Look for the pattern to repeat and measure the orbit period. This is also the period of the orbit of the planet around the CM

Velocity of ***star*** 51 Pegasi

Planet discovered in 1995



2) We know a bunch about stars (later in the quarter), use that to estimate the mass of the star (M_1)

3) Then use Newton's version of Kepler's 3rd law, assume M_2 small, solve for d = radius of orbit of the planet

Newton's Version of Kepler's 3rd Law

$$\frac{d^3}{P^2} = \frac{G\,(M_1+M_2)}{(2\pi)^2}$$

This is the more exact version.

1) Measure the Doppler velocity shift of the star around the CM of the orbit, measure the orbit period, also the period of the orbit of the planet around the CM

2) Estimate the mass of the star (M_1) from knowing about stars

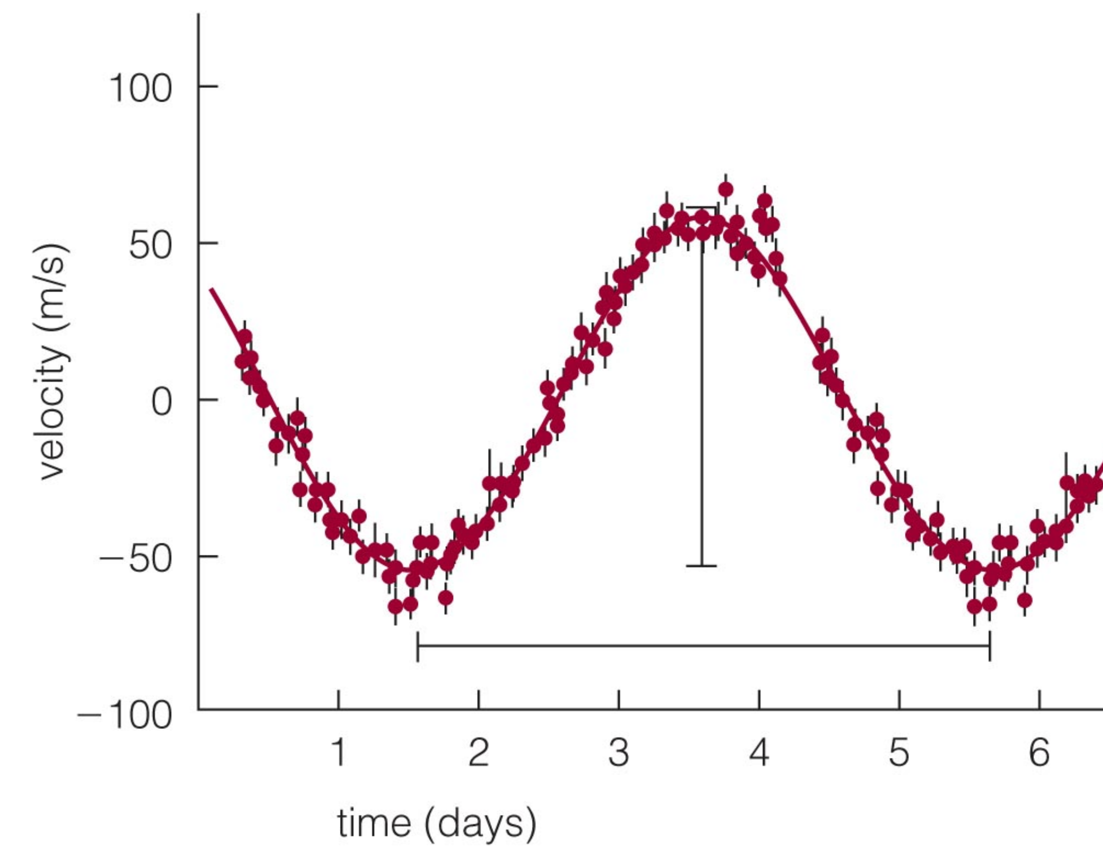
3) Use Newton's version of Kepler's 3rd law solve for d = radius orbit of planet

4) Compute velocity of planet: $v = \frac{2\pi d}{P}$

5) use conservation of momentum to solve for planet mass: have M,v for star from steps 1 and 2, v for planet from step 4. $mv_{star} = mv_{planet}$

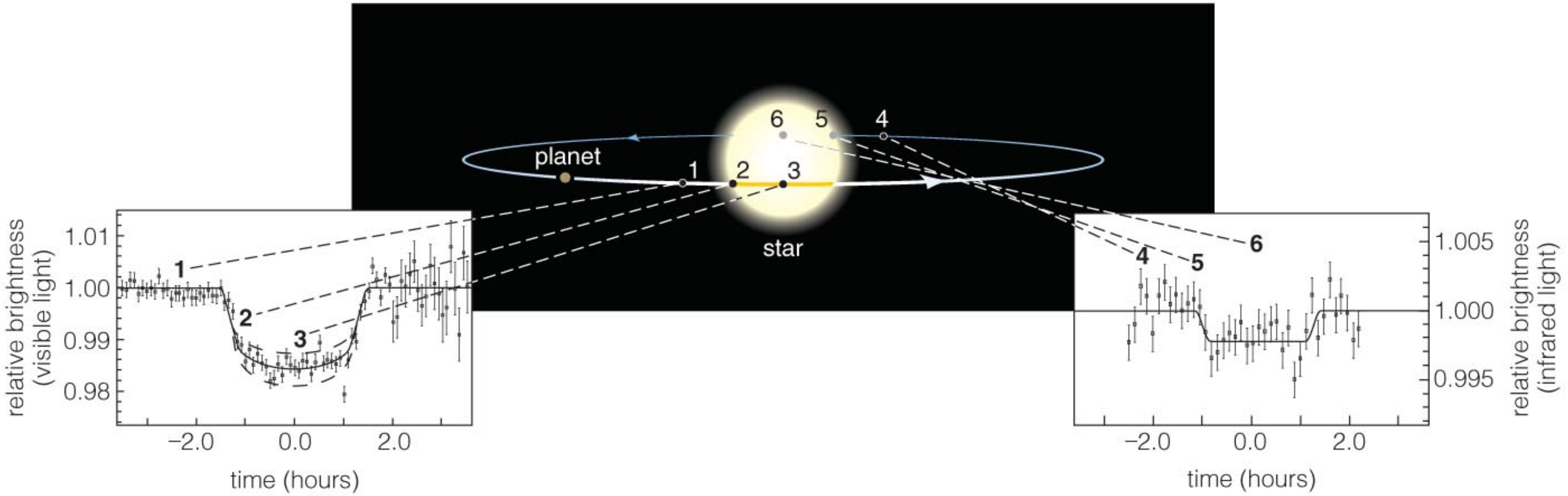
Velocity of ***star*** 51 Pegasi

Planet discovered in 1995

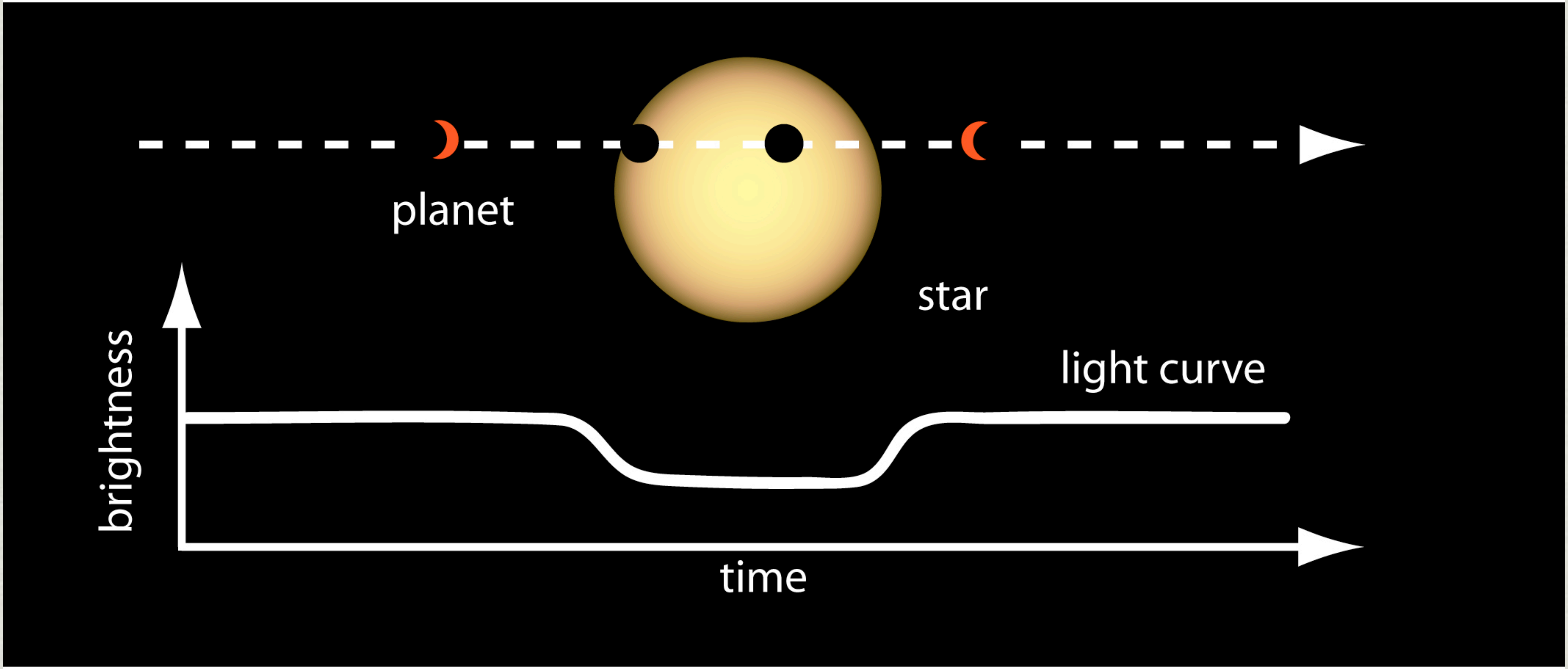


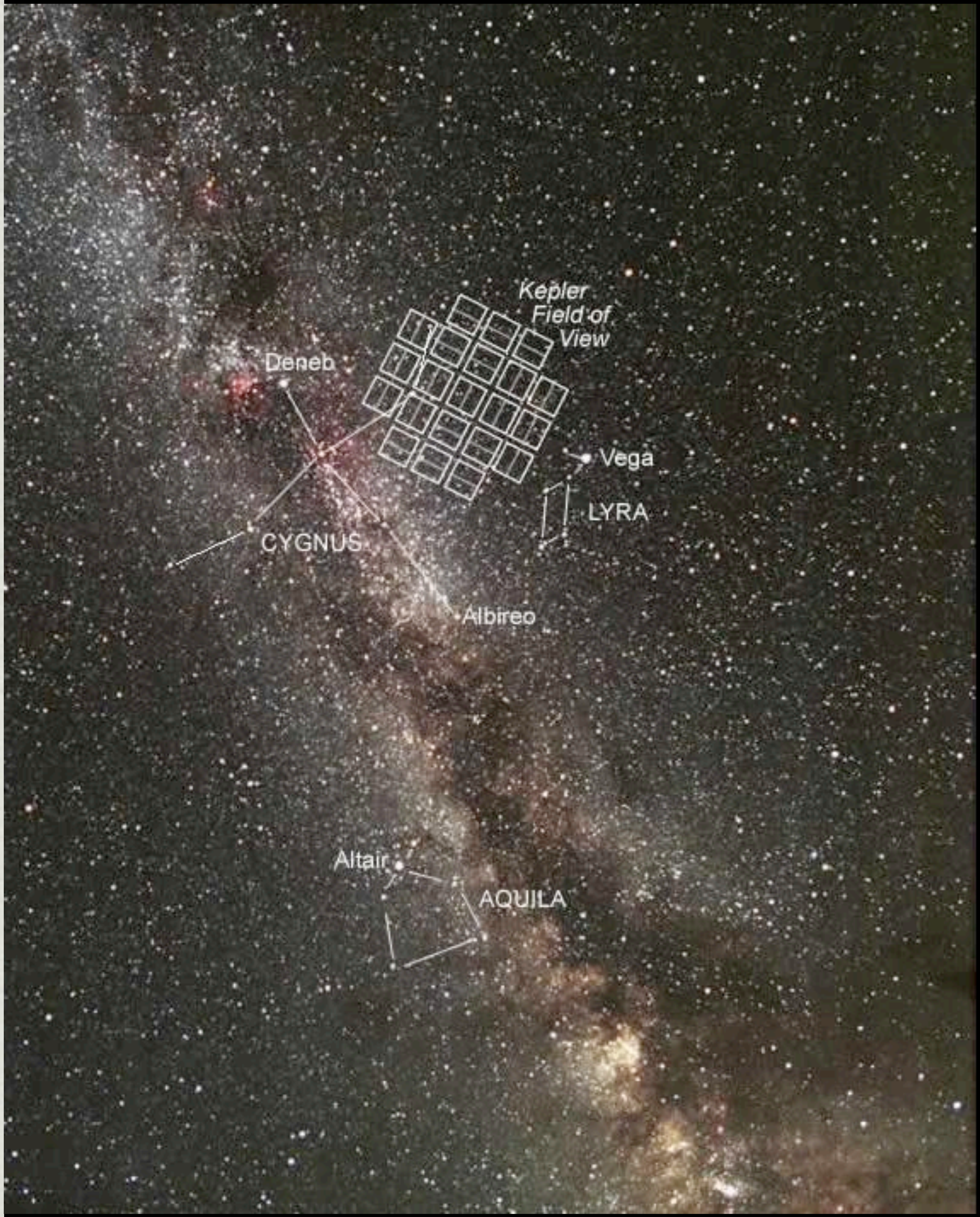
The Automated Planet Finder at Lick Observatory on Mt. Hamilton
A machine for Doppler detection of extra solar planets

Transits and Eclipses



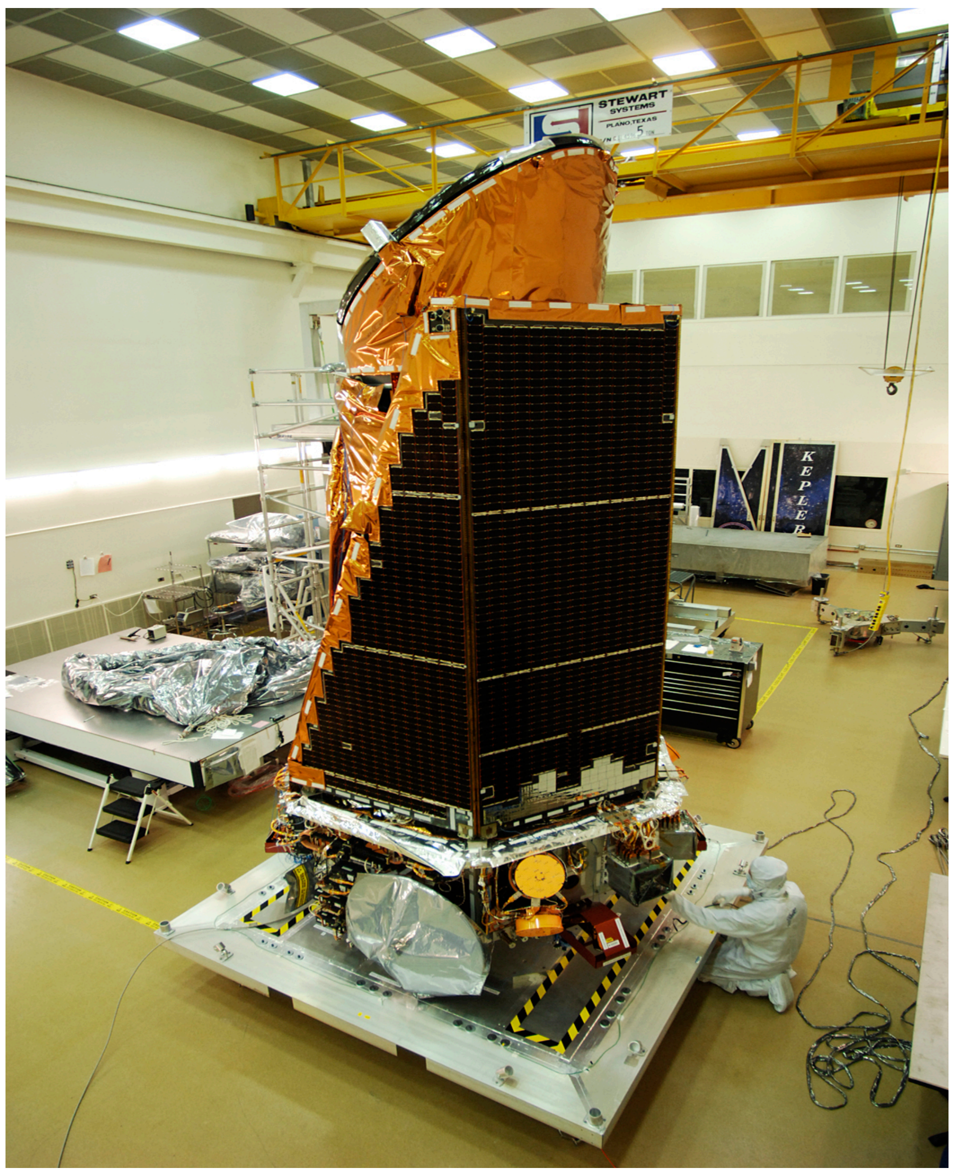
- A **transit** is when a planet crosses in front of a star.
- The resulting eclipse reduces the star's apparent brightness and tells us planet's radius (if we know the star's radius!)
- No orbital tilt: accurate measurement of planet mass if you also get radial velocity
- You "miss" most of the planetary systems, though

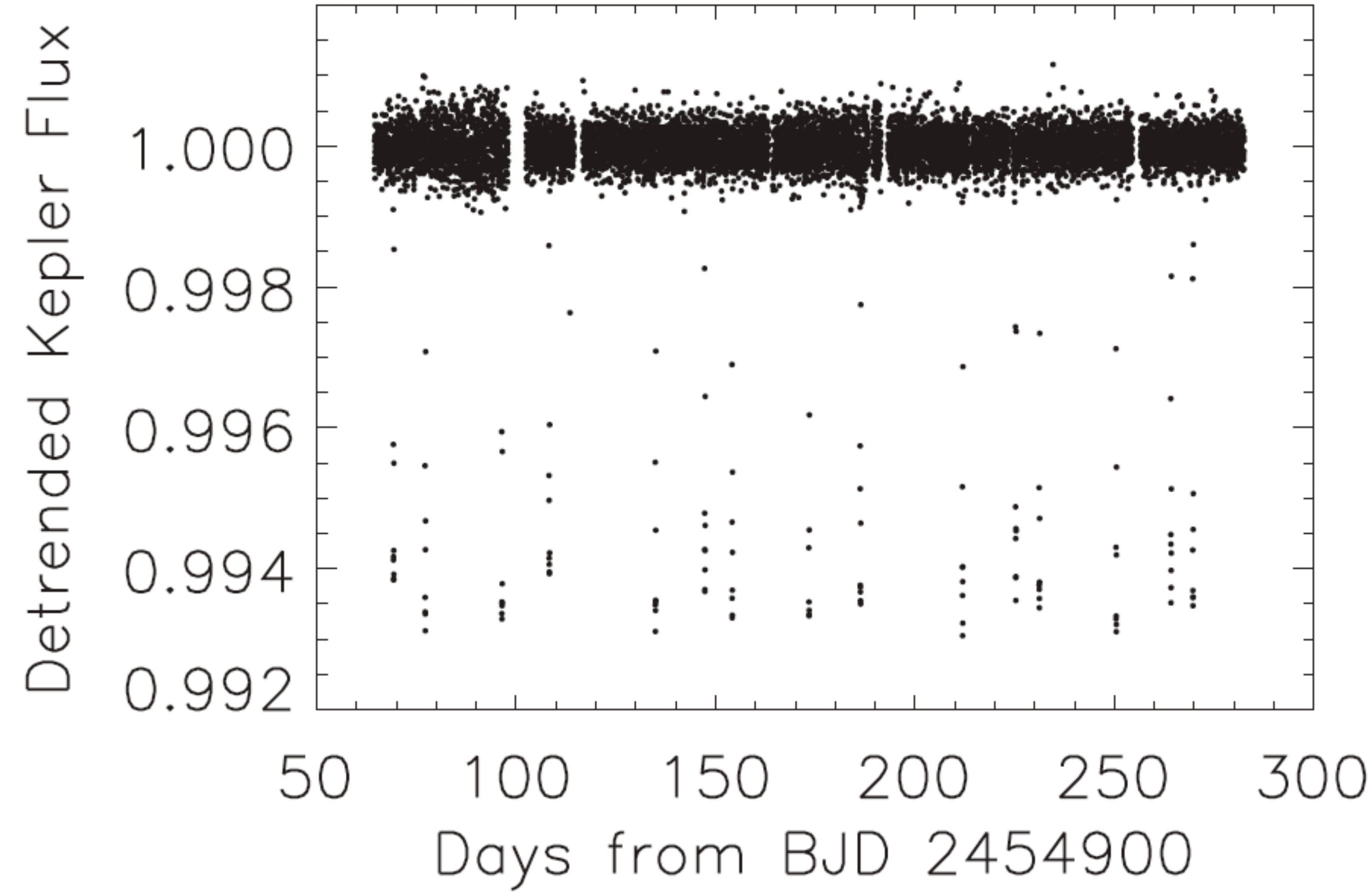

planet
star
light curve
brightness
time

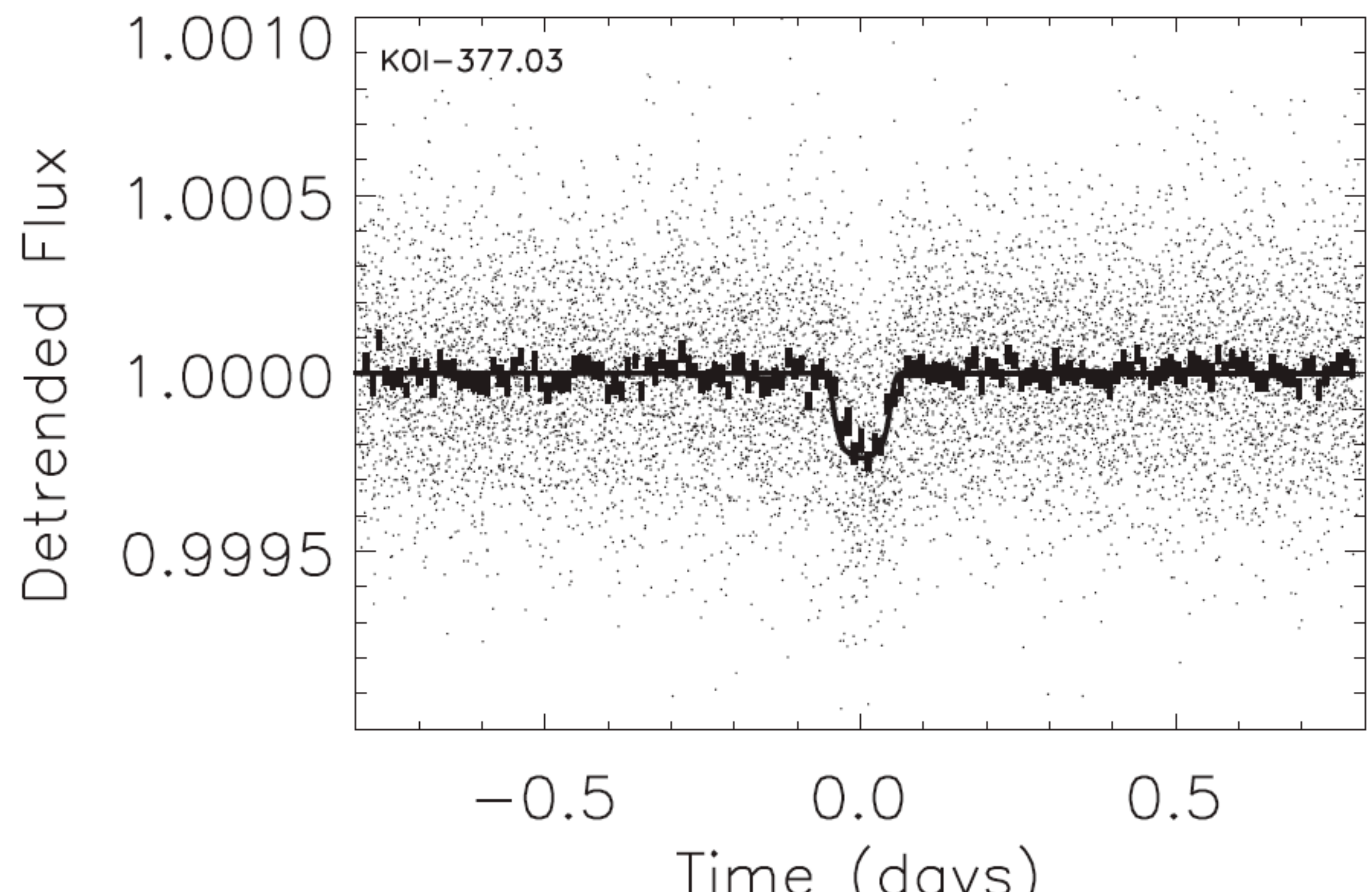


- The idea of the *Kepler* Mission was from Bill Borucki, NASA Ames, in the Mid 1980s
- If you sample a large enough number of stars (a "statistically significant sample"), you can determine the fraction of Sun-like stars that have Earth-size planets in Earth-size orbits
- Having a large sample size is essential to the entire project
- 95 megapixel space camera built to do one thing exceptionally well

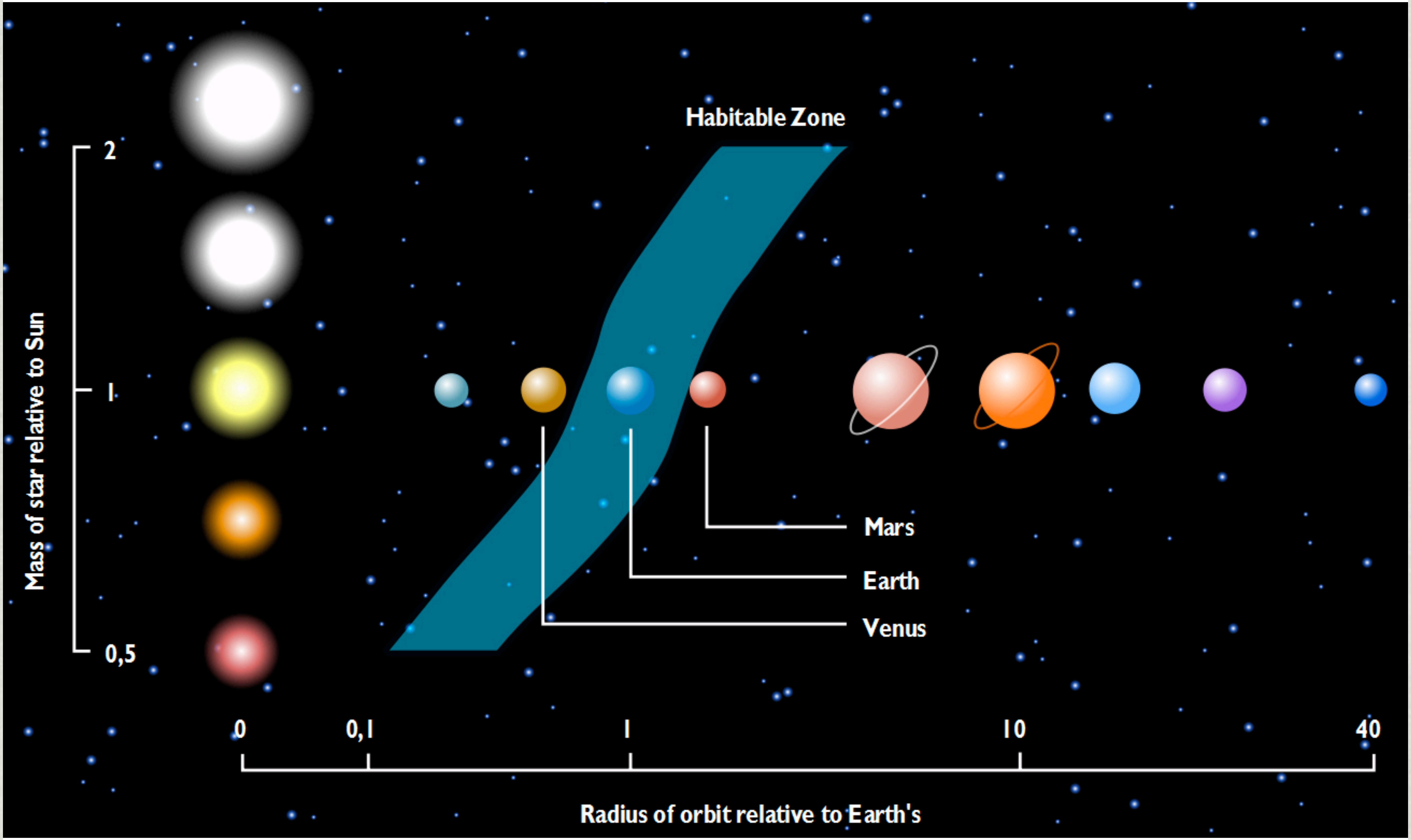
- *Kepler Mission* is optimized for finding potentially habitable planets (0.5 to 1.5 Earth radii) in the *Habitable Zone* (near 1 AU) of Sun-like stars
- Continuously monitoring 150,000 stars for 3.5 years (now 7.5 years!) using a 1 meter telescope







The habitable zone is defined a planetary temperature range when liquid water can exist at the planet's surface



Kepler-11: Picking out the Planets

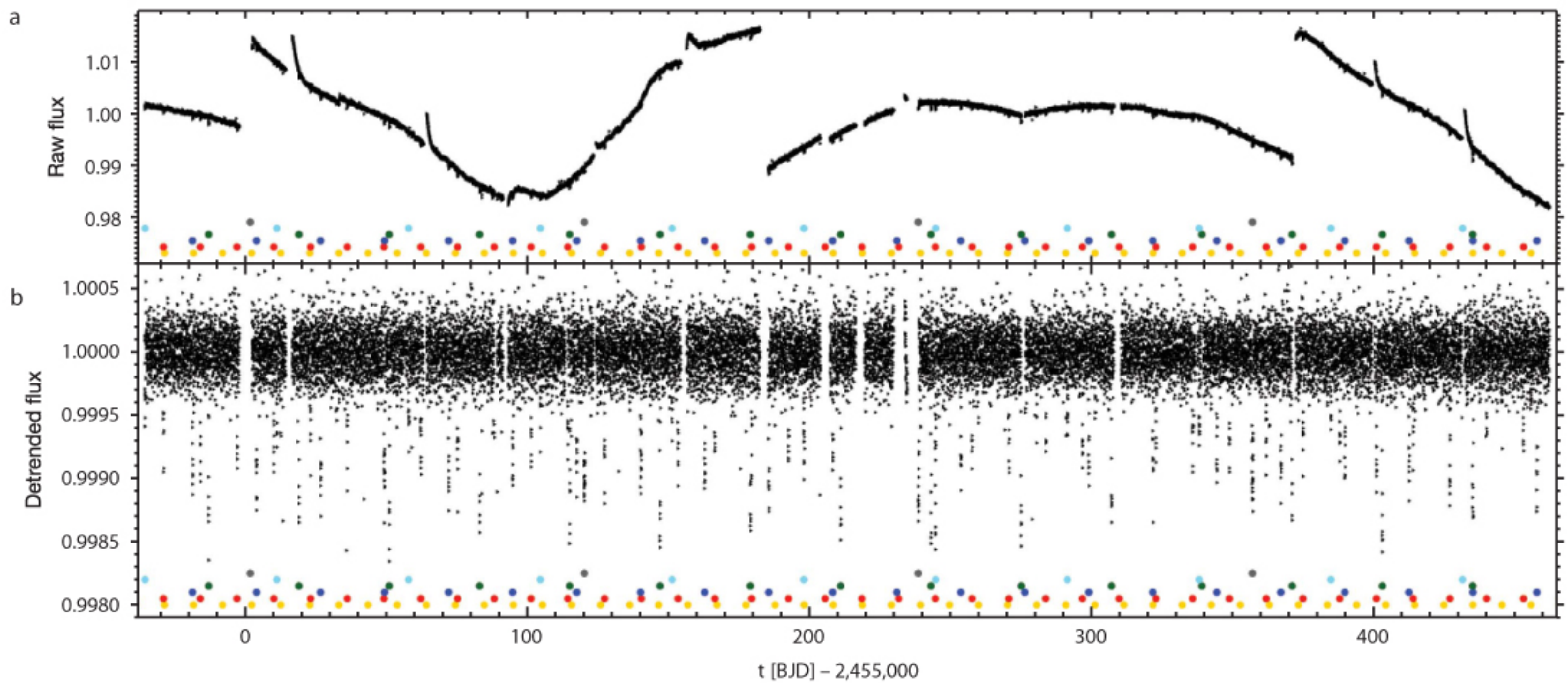
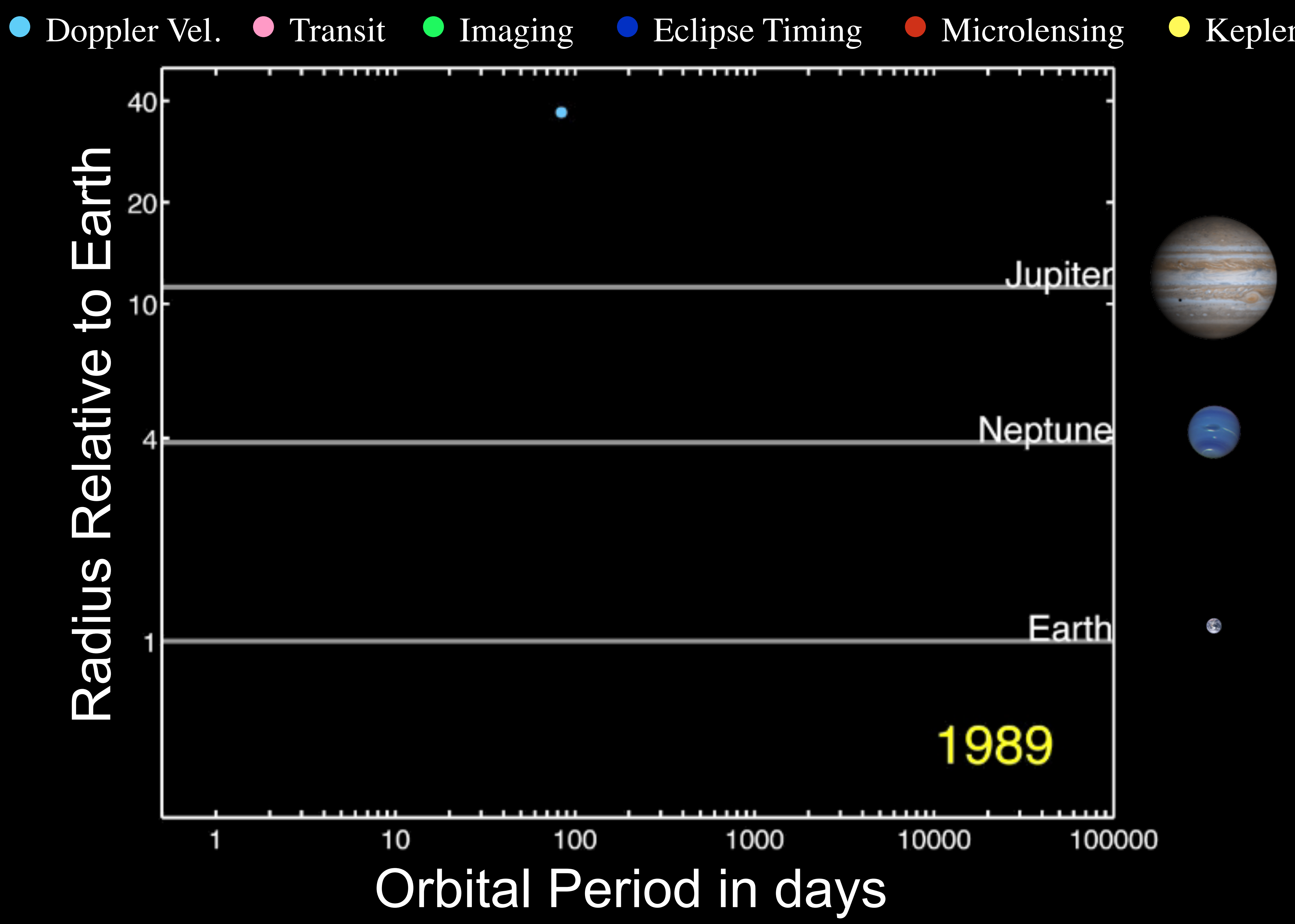


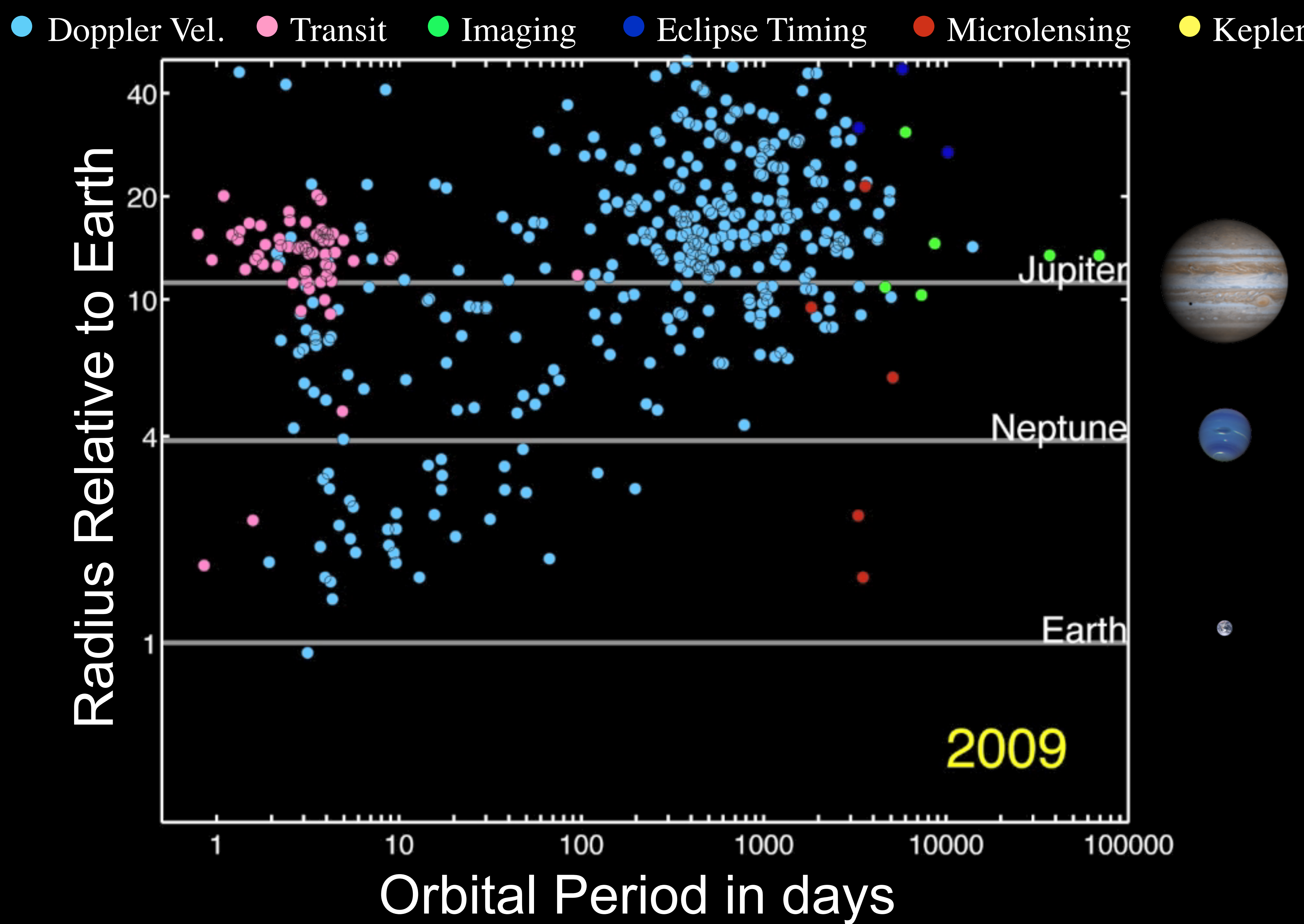
Table 1 | Planet properties

Planet	Period (days)	Epoch (BJD)	Semi-major axis (AU)	Inclination (°)	Transit duration (h)	Transit depth (millimagnitude)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g cm^{-3})
b	10.30375 ± 0.00016	2,454,971.5052 ± 0.0077	0.091 ± 0.003	$88.5^{+1.0}_{-0.6}$	4.02 ± 0.08	0.31 ± 0.01	1.97 ± 0.19	$4.3^{+2.2}_{-2.0}$	$3.1^{+2.1}_{-1.5}$
c	13.02502 ± 0.00008	2,454,971.1748 ± 0.0031	0.106 ± 0.004	$89.0^{+1.0}_{-0.6}$	4.62 ± 0.04	0.82 ± 0.01	3.15 ± 0.30	$13.5^{+4.8}_{-6.1}$	$2.3^{+1.3}_{-1.1}$
d	22.68719 ± 0.00021	2,454,981.4550 ± 0.0044	0.159 ± 0.005	$89.3^{+0.6}_{-0.4}$	5.58 ± 0.06	0.80 ± 0.02	3.43 ± 0.32	$6.1^{+3.1}_{-1.7}$	$0.9^{+0.5}_{-0.3}$
e	31.99590 ± 0.00028	2,454,987.1590 ± 0.0037	0.194 ± 0.007	$88.8^{+0.2}_{-0.2}$	4.33 ± 0.07	1.40 ± 0.02	4.52 ± 0.43	$8.4^{+2.5}_{-1.9}$	$0.5^{+0.2}_{-0.2}$
f	46.68876 ± 0.00074	2,454,964.6487 ± 0.0059	0.250 ± 0.009	$89.4^{+0.3}_{-0.2}$	6.54 ± 0.14	0.55 ± 0.02	2.61 ± 0.25	$2.3^{+2.2}_{-1.2}$	$0.7^{+0.7}_{-0.4}$
g	118.37774 ± 0.00112	2,455,120.2901 ± 0.0022	0.462 ± 0.016	$89.8^{+0.2}_{-0.2}$	9.60 ± 0.13	1.15 ± 0.03	3.66 ± 0.35	<300	–

Exoplanet Detections, 1989-2009

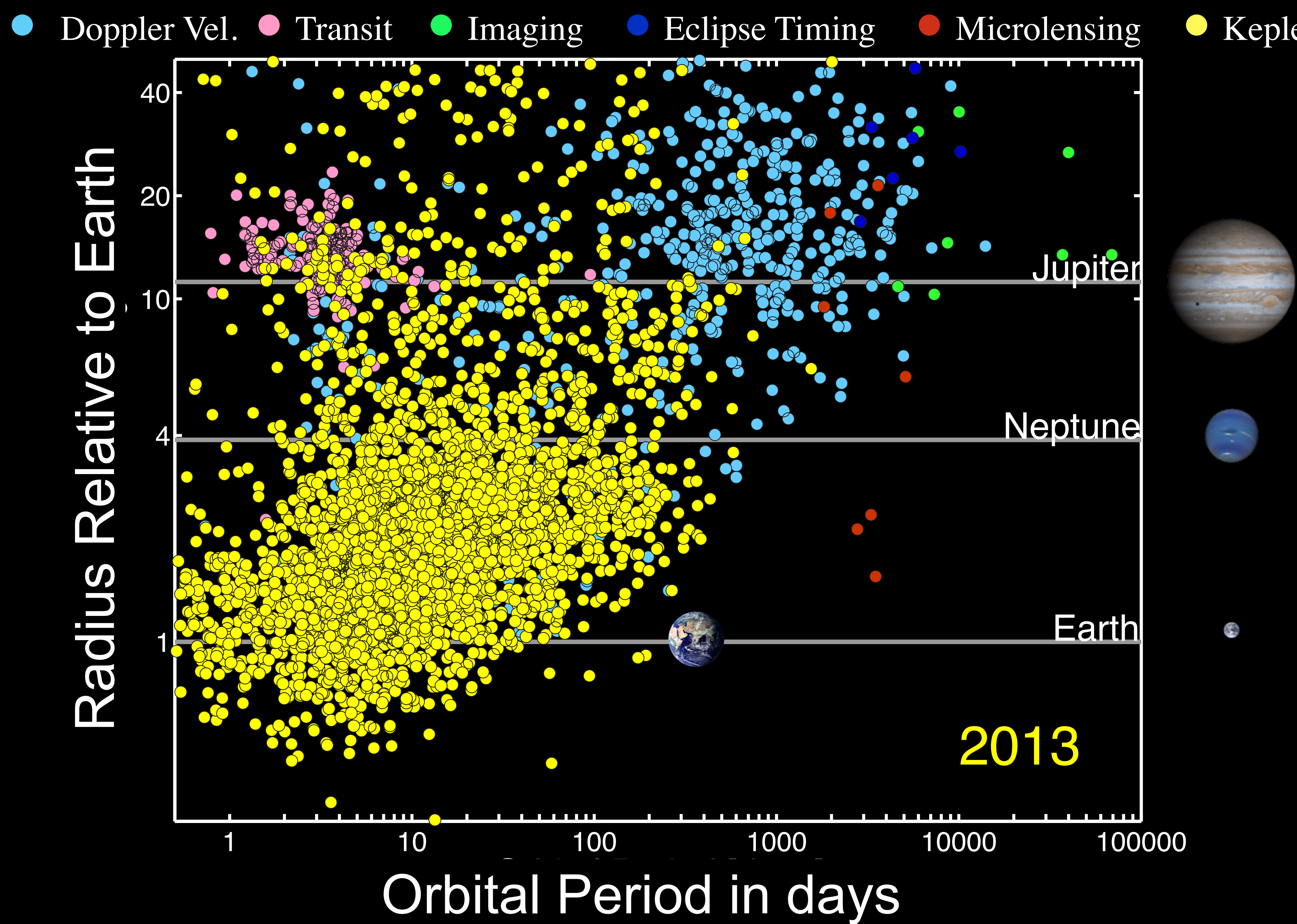


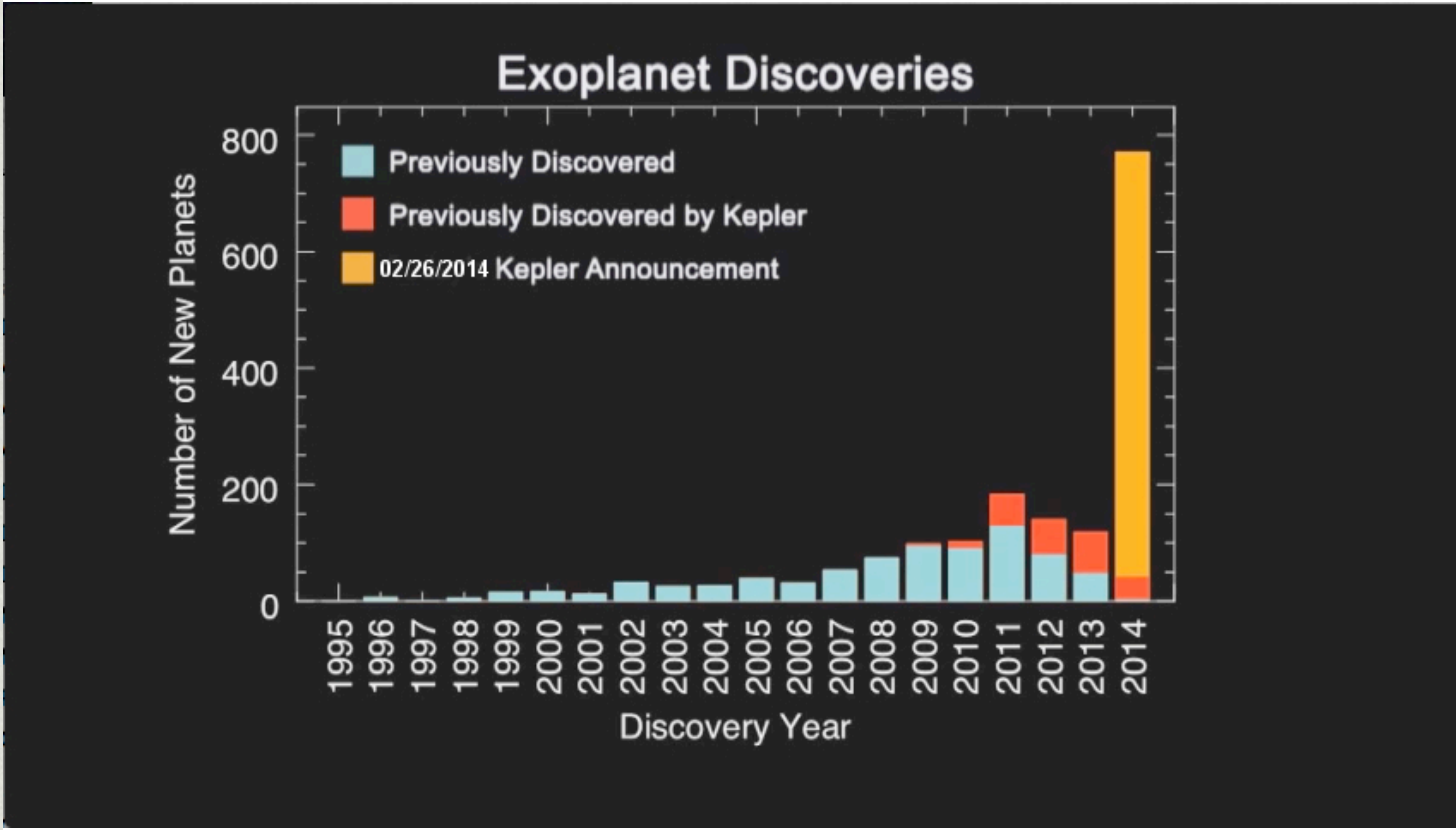
Exoplanet Detections, 1989-2013

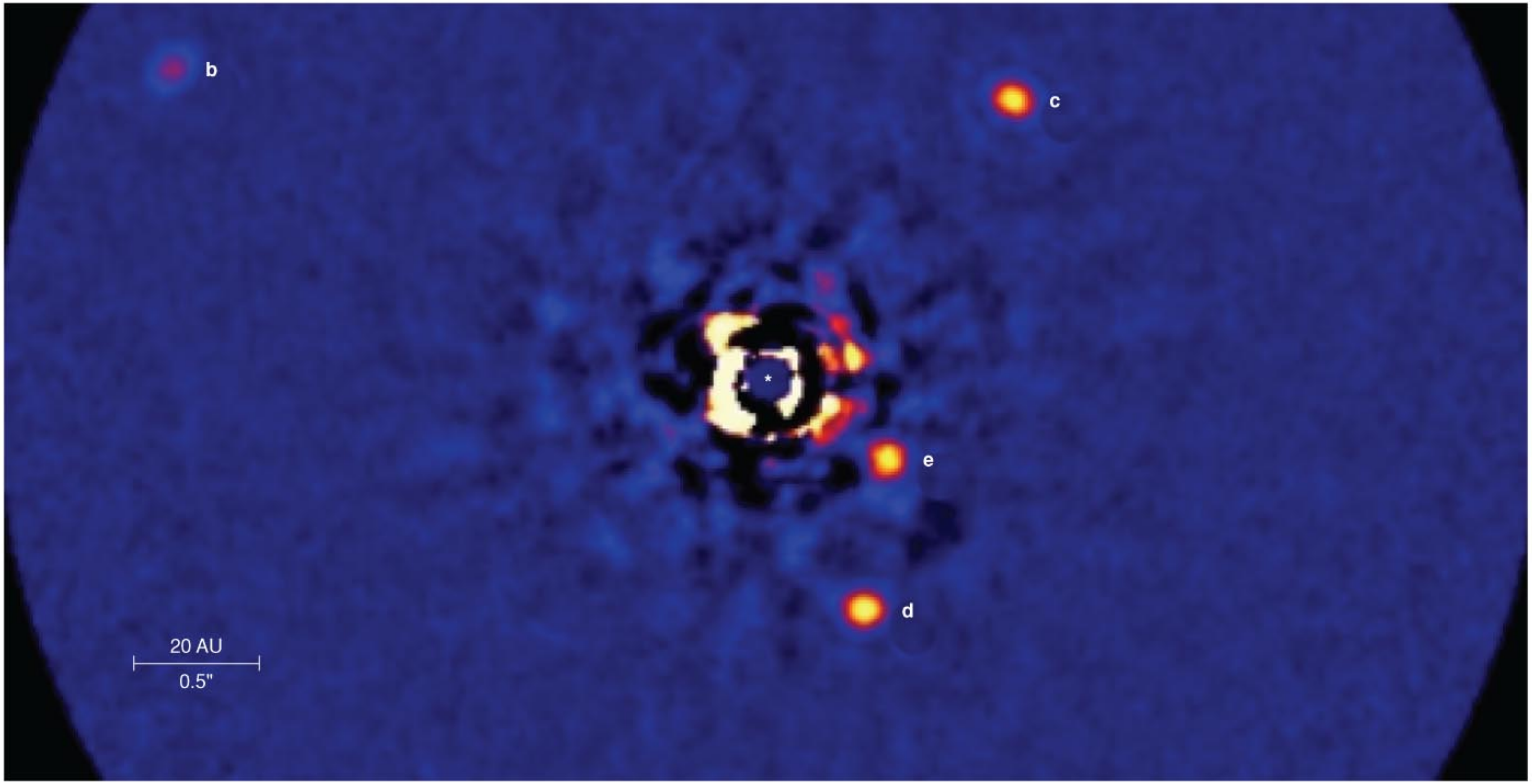


Kepler Detections:

(Based on 34 Months of Data)

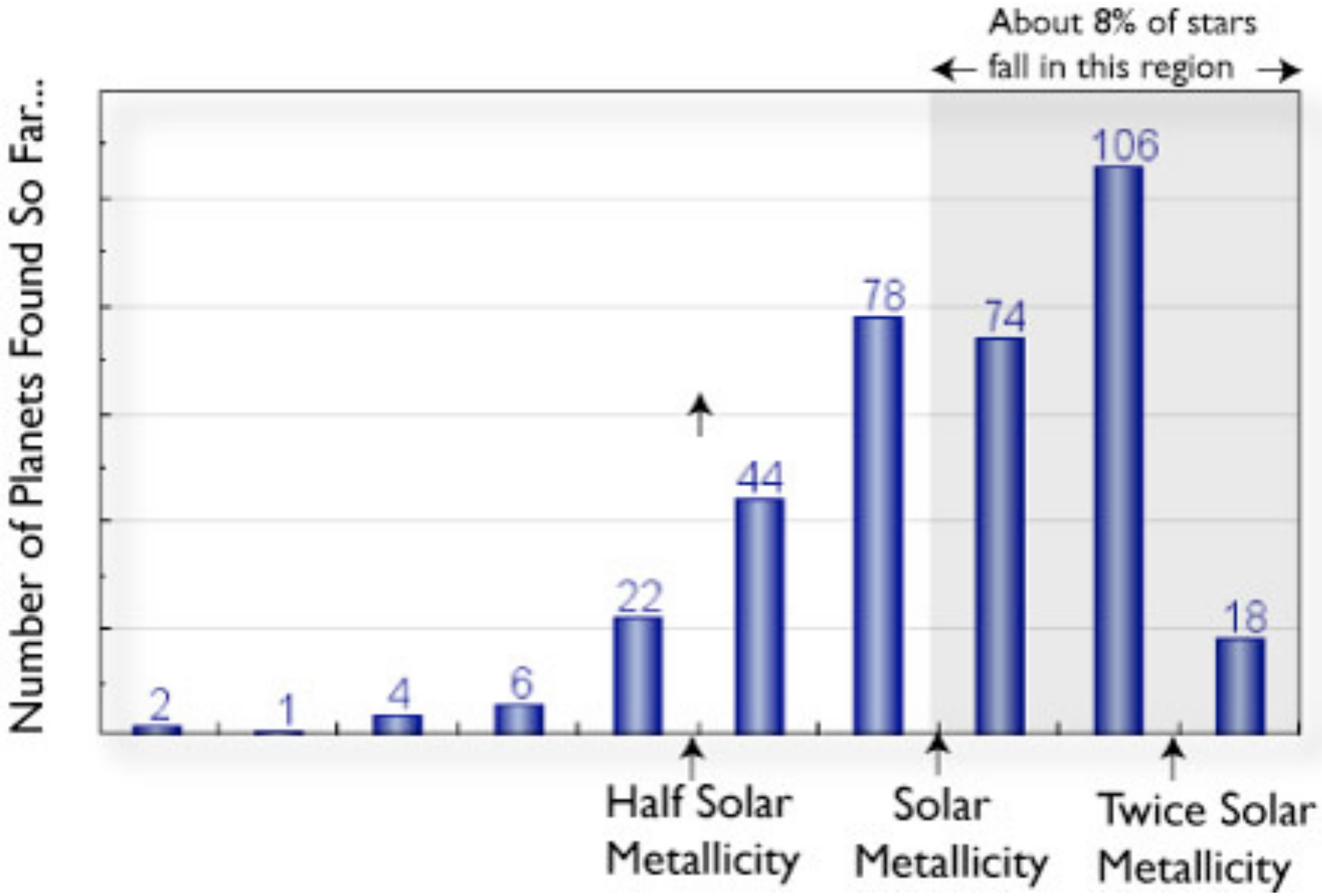



Exoplanet Discoveries
Previously Discovered
Previously Discovered by Kepler
02/26/2014 Kepler Announcement
Number of New Planets
0
200
400
600
800
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
Discovery Year



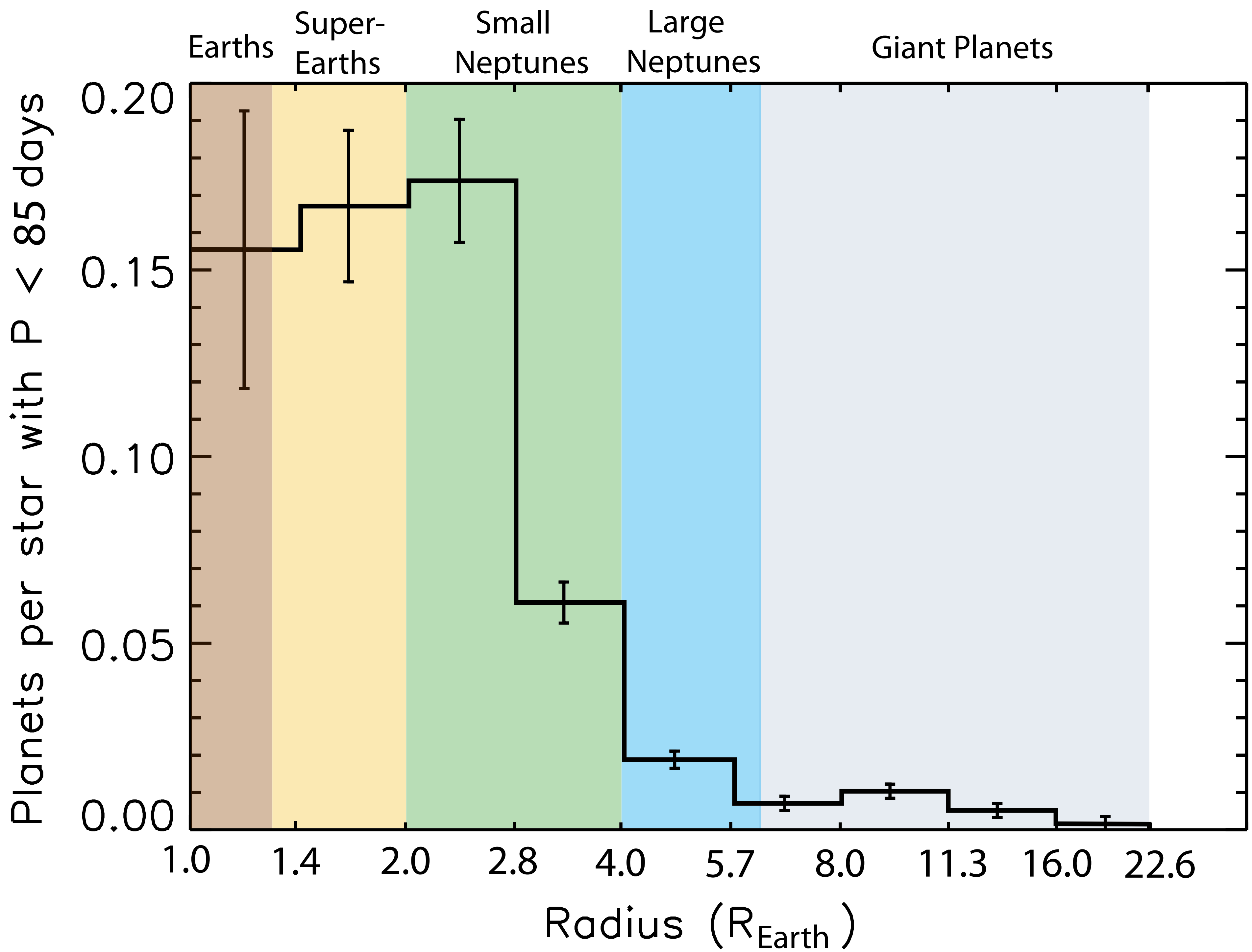
HR 8799: 4-planet system

One more important thing to add:



- Giant planets (which are easiest to detect) are preferentially found around stars that are abundant in iron – “metallicity”
  - Iron is the easiest heavy element to measure in a star
  - Heavy-element rich planetary systems make planets more easily

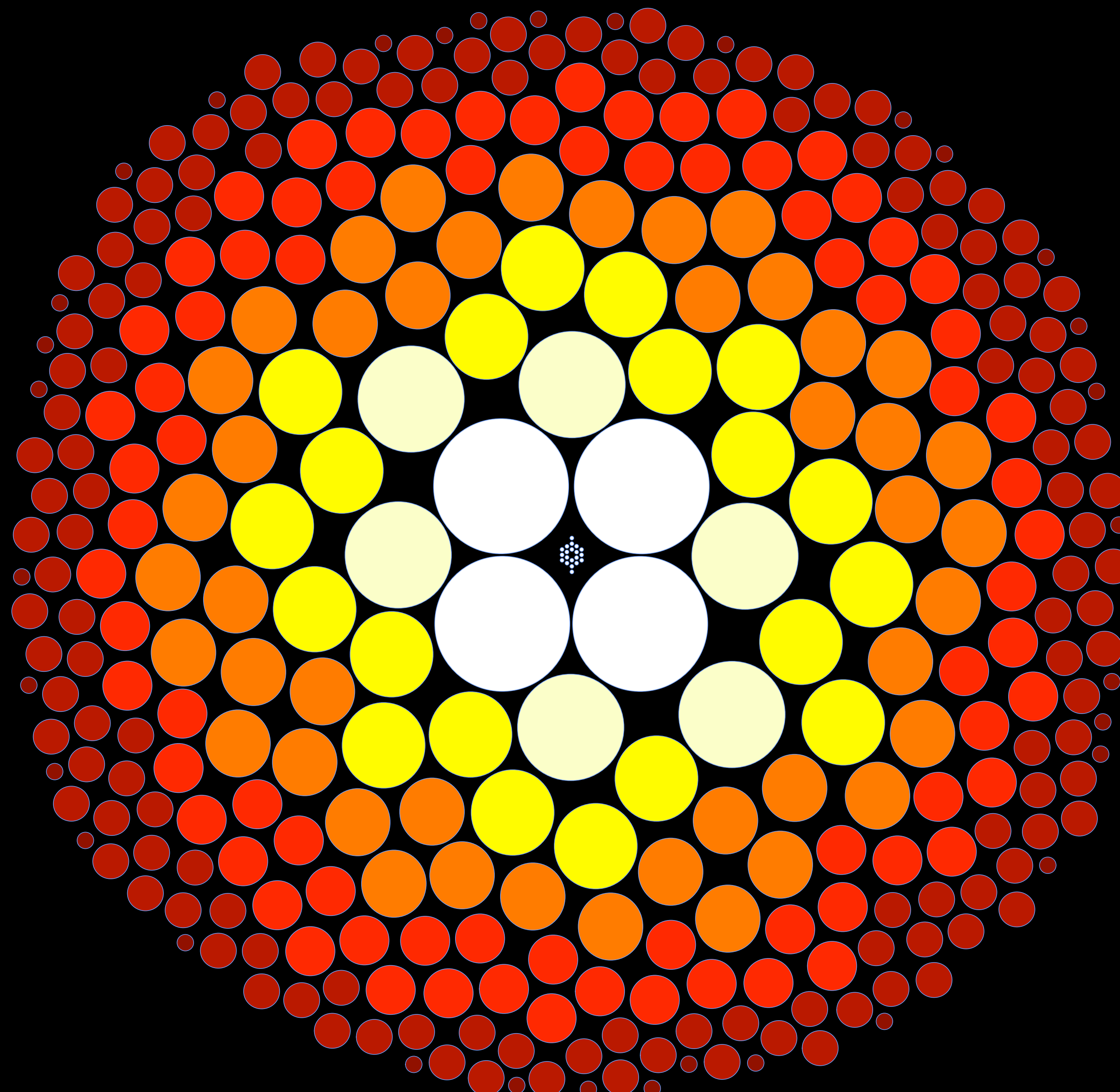
The frequency of planets within 85 days of Sun-like stars



Based on ~2300 planet candidates

Fressin et al. (2013)

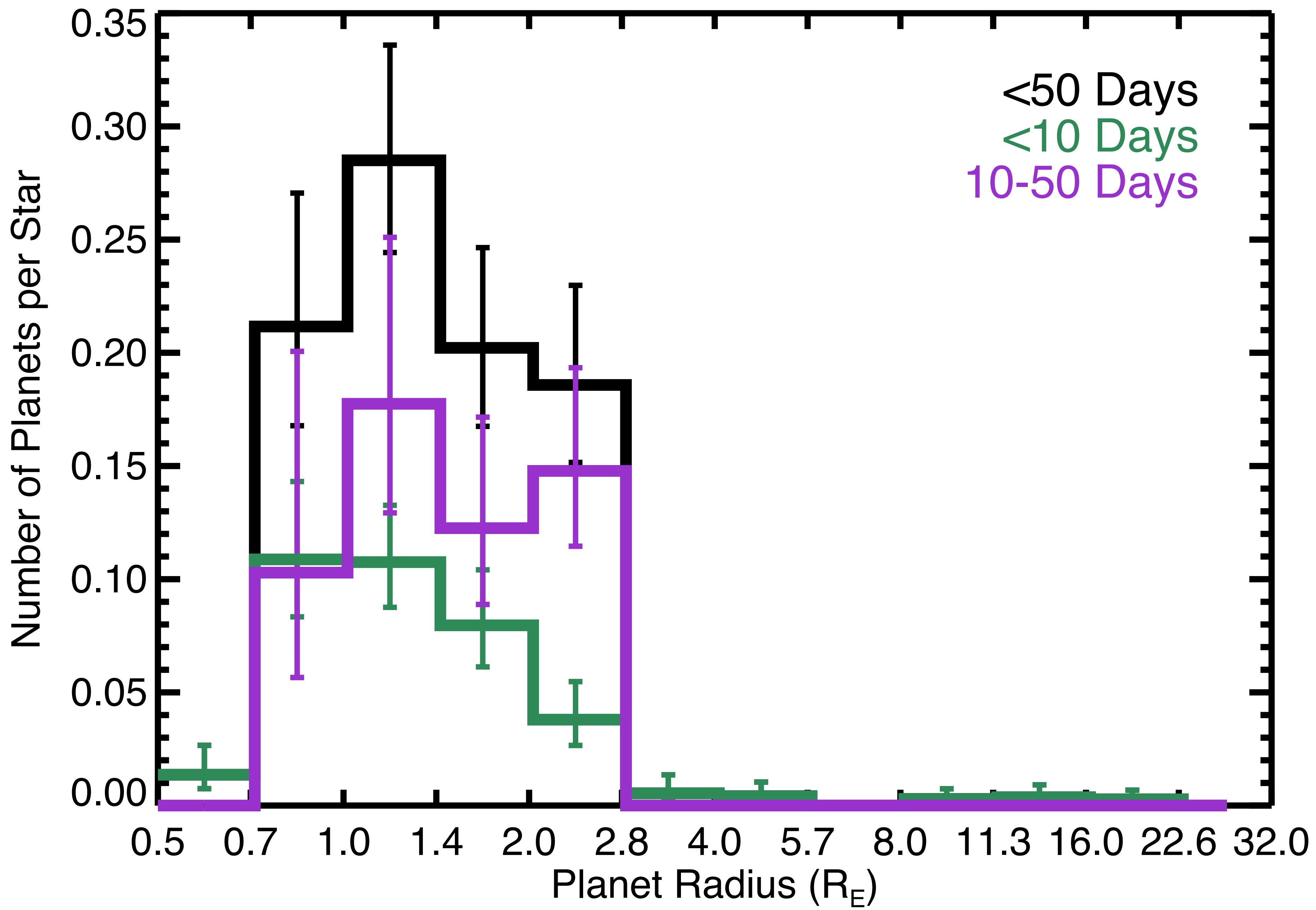
Stars within 30 lightyears of the Sun



O	0
B	0
A	4
F	6
G	20
K	44
M	246

Todd Henry, Georgia State University

The frequency of planets within 50 days of M stars



1.5 planets per M star within ~80 days