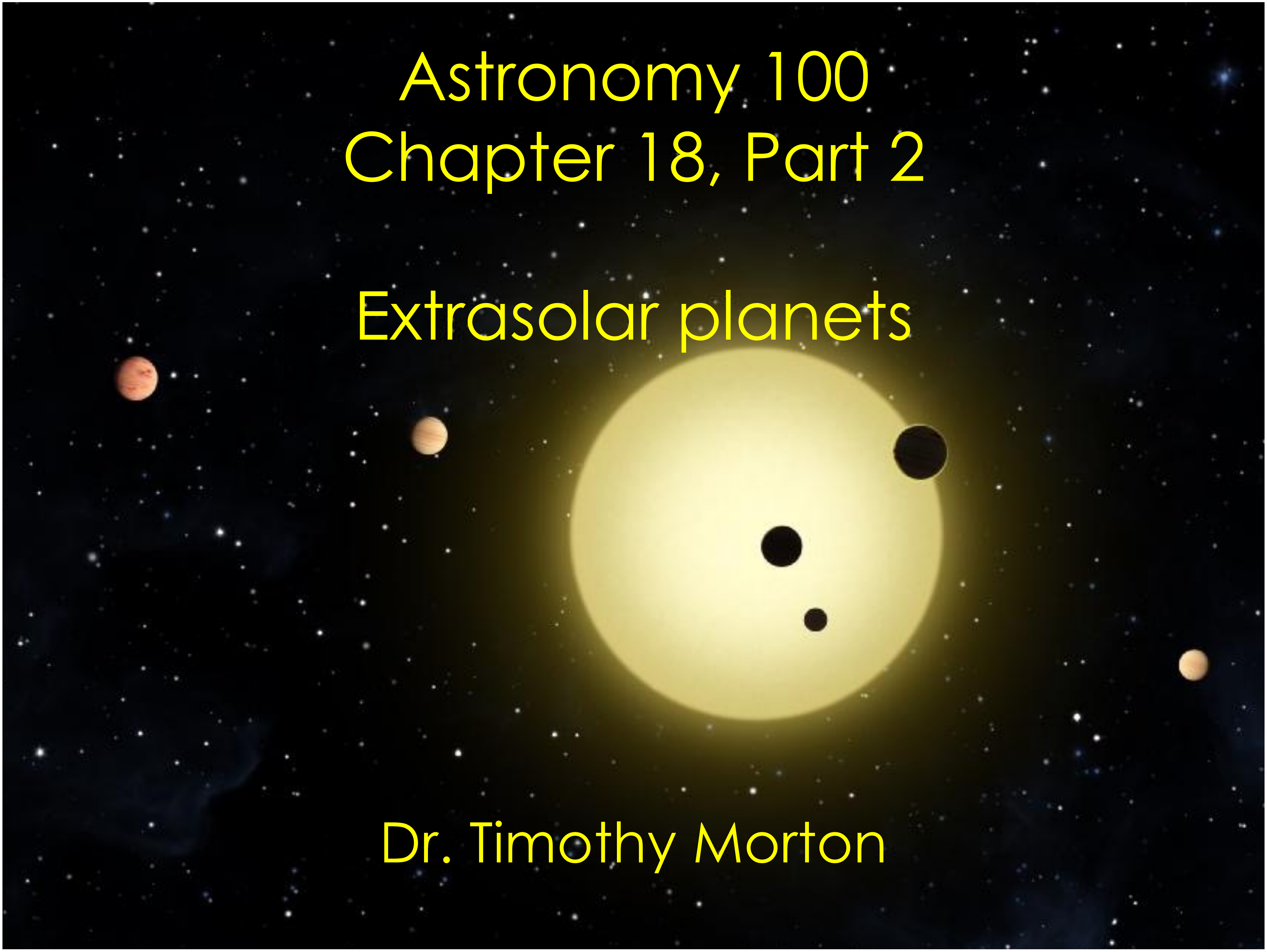
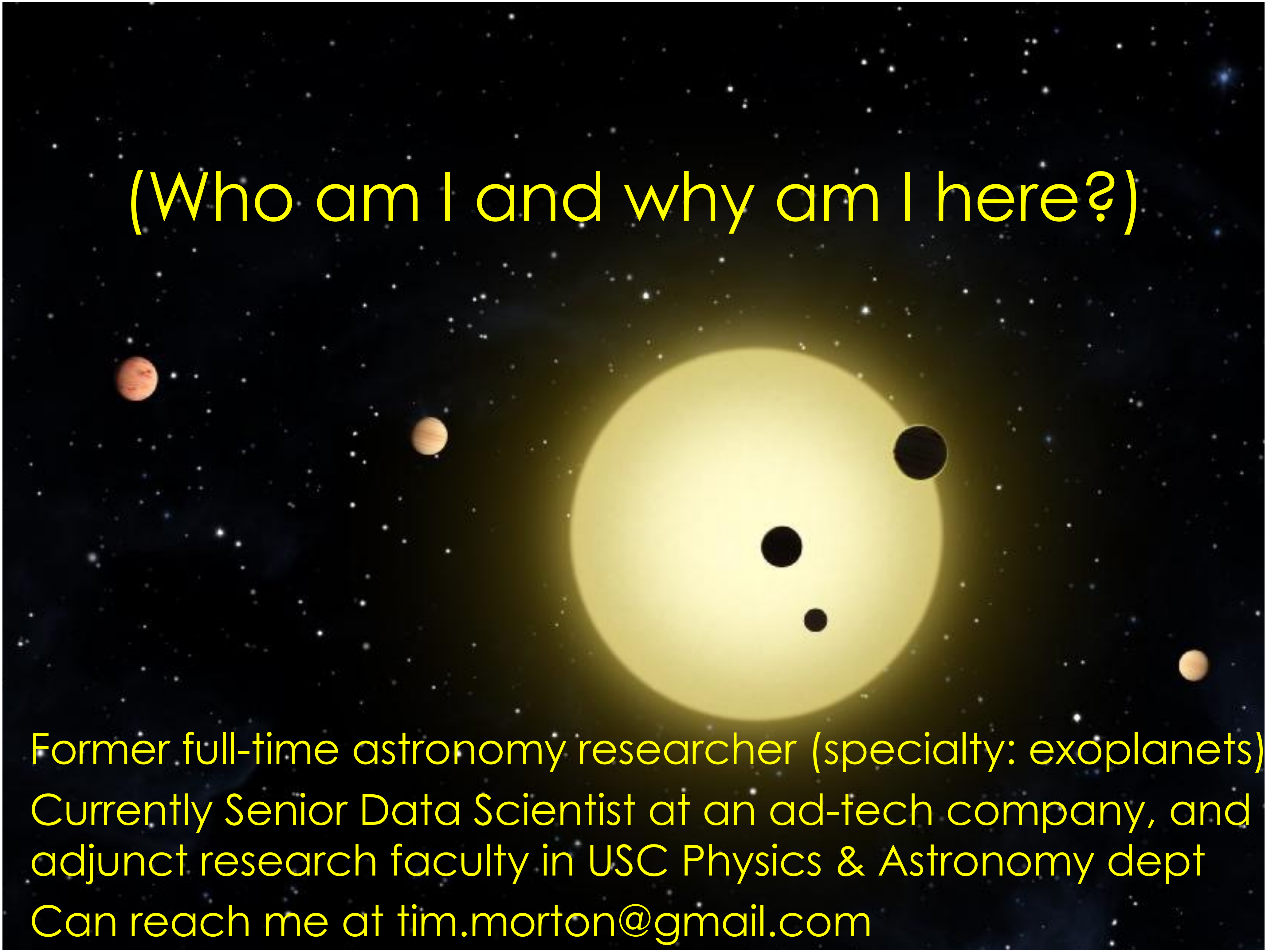
Astronomy 100
Chapter 18, Part 2

Extrasolar planets



Dr. Timothy Morton


(Who am I and why am I here?)
Former full-time astronomy researcher (specialty: exoplanets)
Currently Senior Data Scientist at an ad-tech company, and adjunct research faculty in USC Physics & Astronomy dept
Can reach me at tim.morton@gmail.com

question for you

How many planets do we know of?

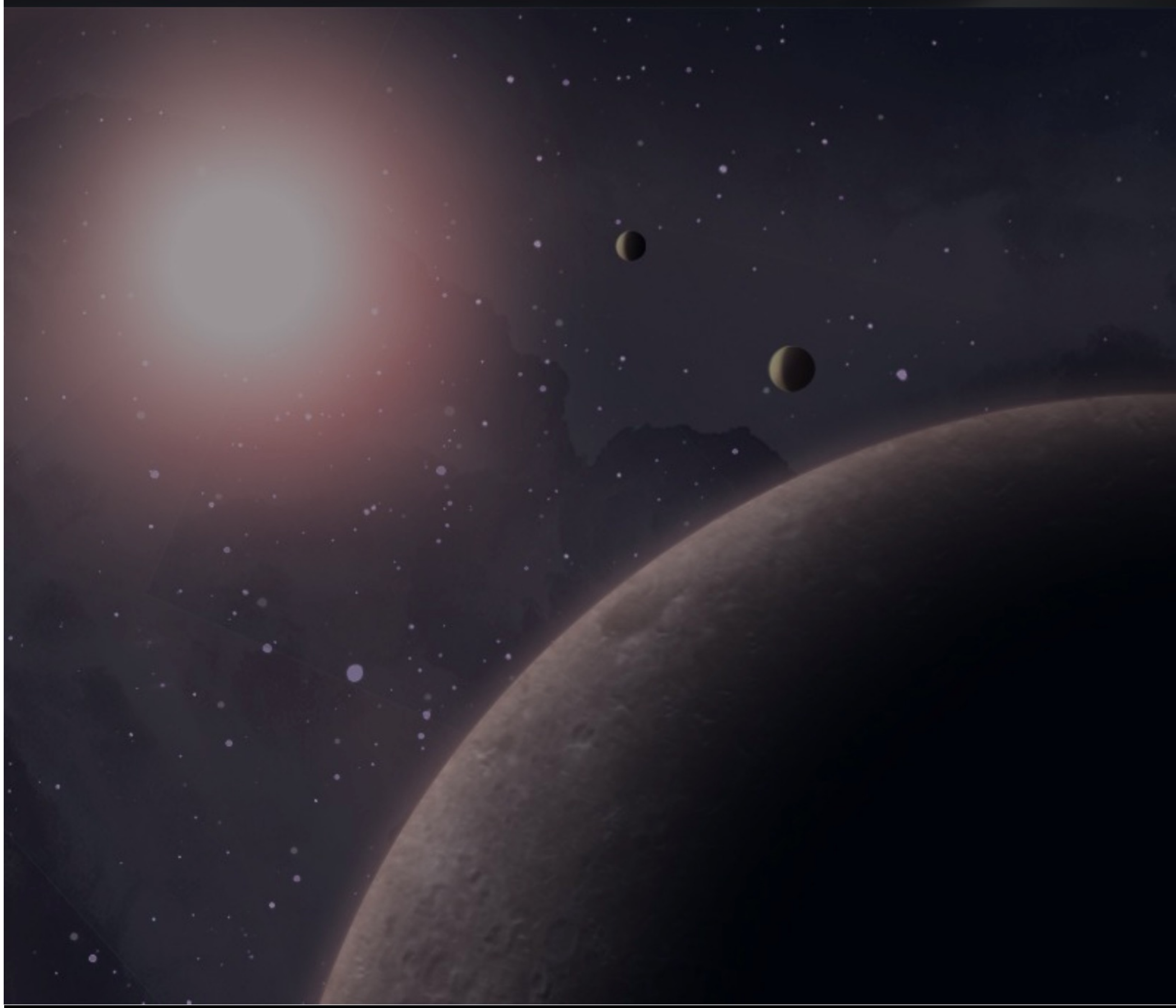
A. 1 (Earth is the only planet we can be sure *really* exists)
B. 8 (Mer Ven Ear Mar Jup Sat Ura Nep)
C. Thousands
D. Billions and billions.

https://exoplanetarchive.ipac.caltech.edu/

PROJECTS ABOUT GET INVOLVED TALK BUILD SIGN IN REGISTER

Planet Hunters TESS

ABOUT CLASSIFY TALK COLLECT



PLANET HUNTERS TESS

Join the Search for Undiscovered Worlds

LEARN MORE

GET STARTED!

You can do real research by clicking to get started here!

0% COMPLETE
Do you see a Transit?

https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess

Discovery of Extrasolar Planets

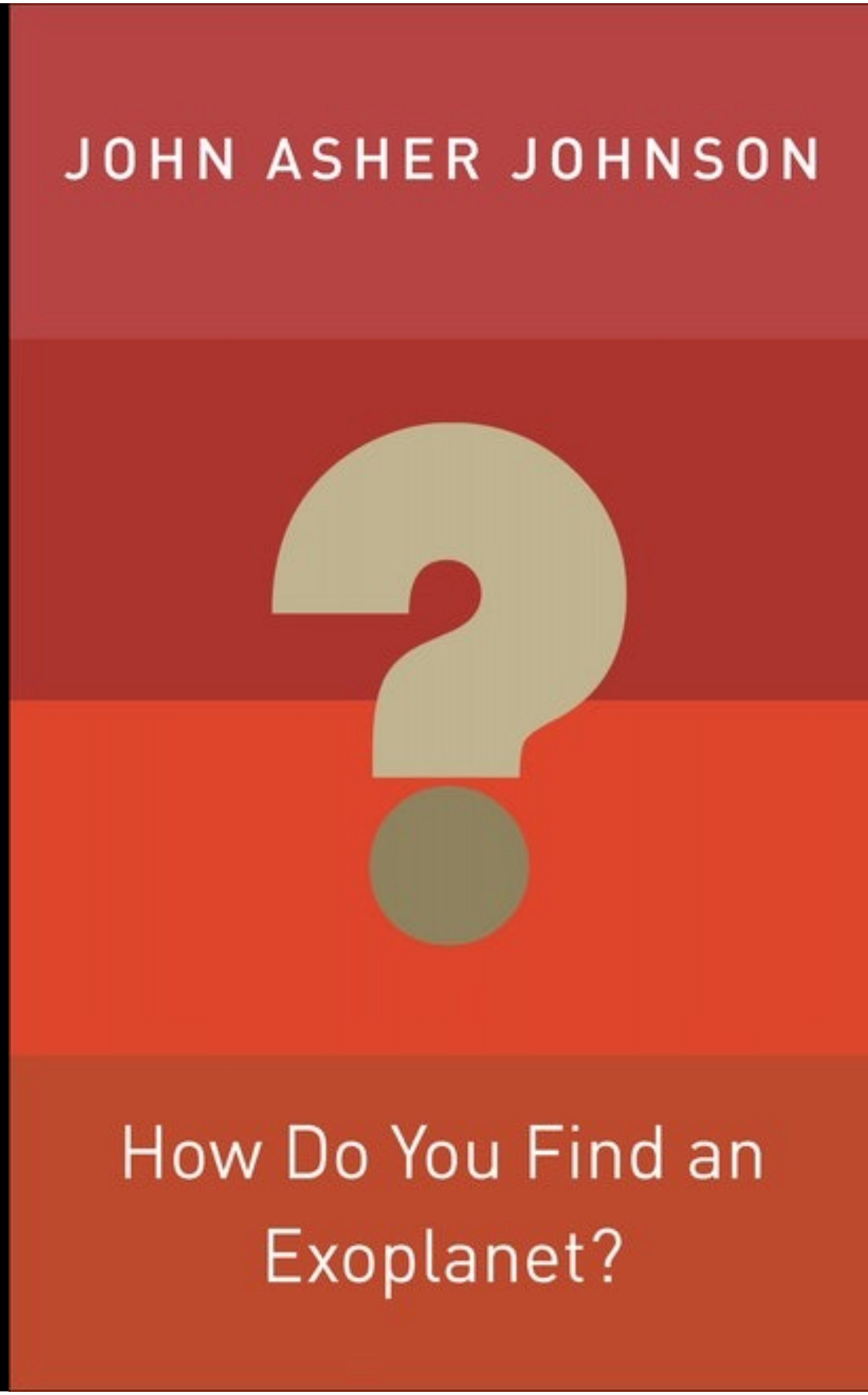
Exoplanets:

Cumulative Detections by Discovery Year

1989-2018

Plots generated Sept. 27, 2018

How to find an exoplanet?



*my PhD adviser

Ways to find exoplanets

star moves due to planet's gravity

1) Astrometry
2) Radial velocity (Doppler spectroscopy)
3) Pulsar timing
4) Transits — light from star blocked by planet
5) Microlensing
6) Direct imaging

planet shines brightly enough for us to see it

question for you

What of the following statements is true about gravitational orbits?

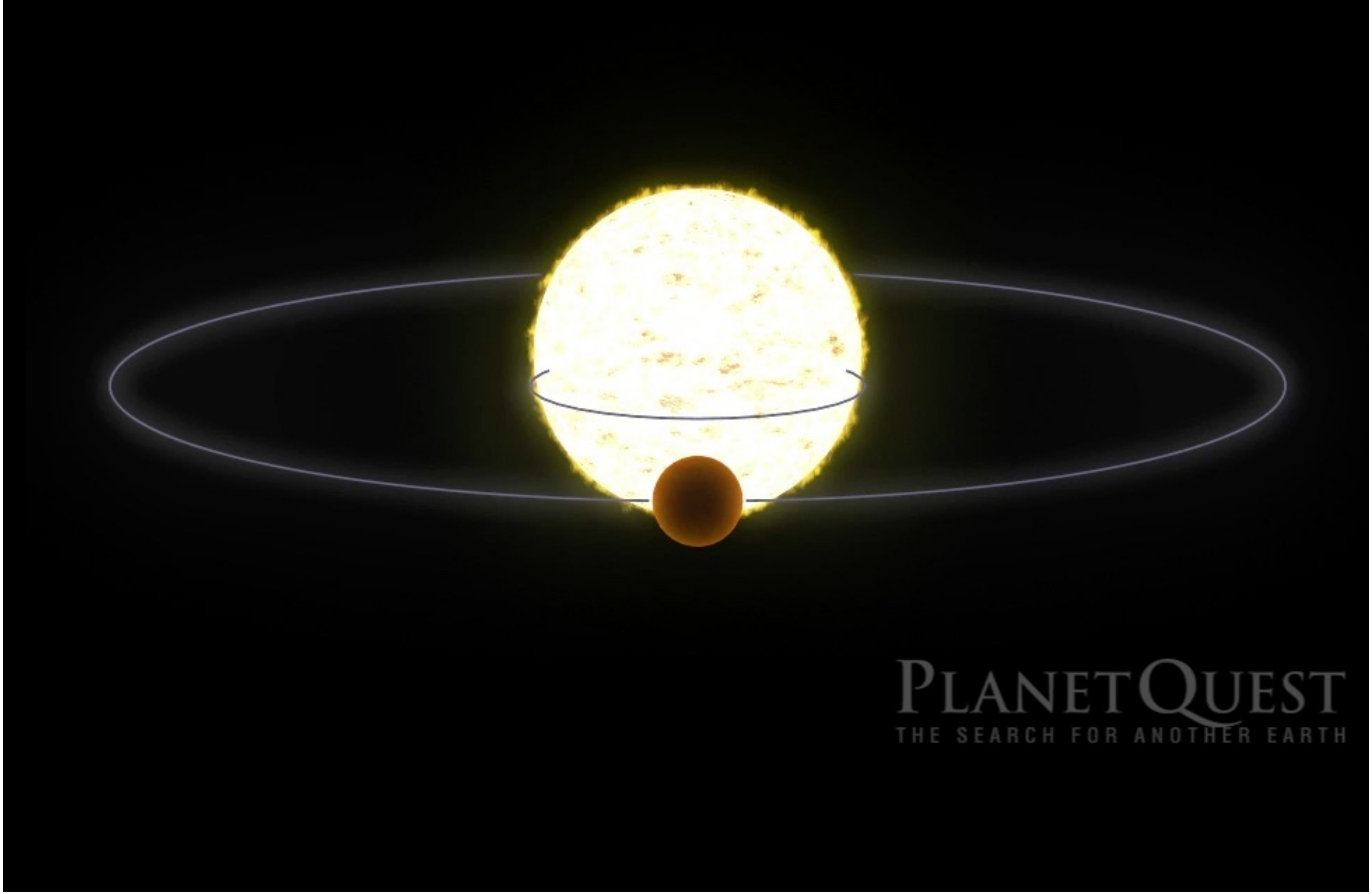
A. When one object orbits another, both objects actually move, but the larger one moves less.
B. When one object orbits another, the central object remains fixed, while the orbiting object moves in a circle or ellipse.
C. Orbits can only happen if one object is *much* smaller than another, like a satellite orbiting the Earth.
D. If two large objects are orbiting each other, the one that stays still is the one made of a denser material.

Astrometry

The “wobble” of a star

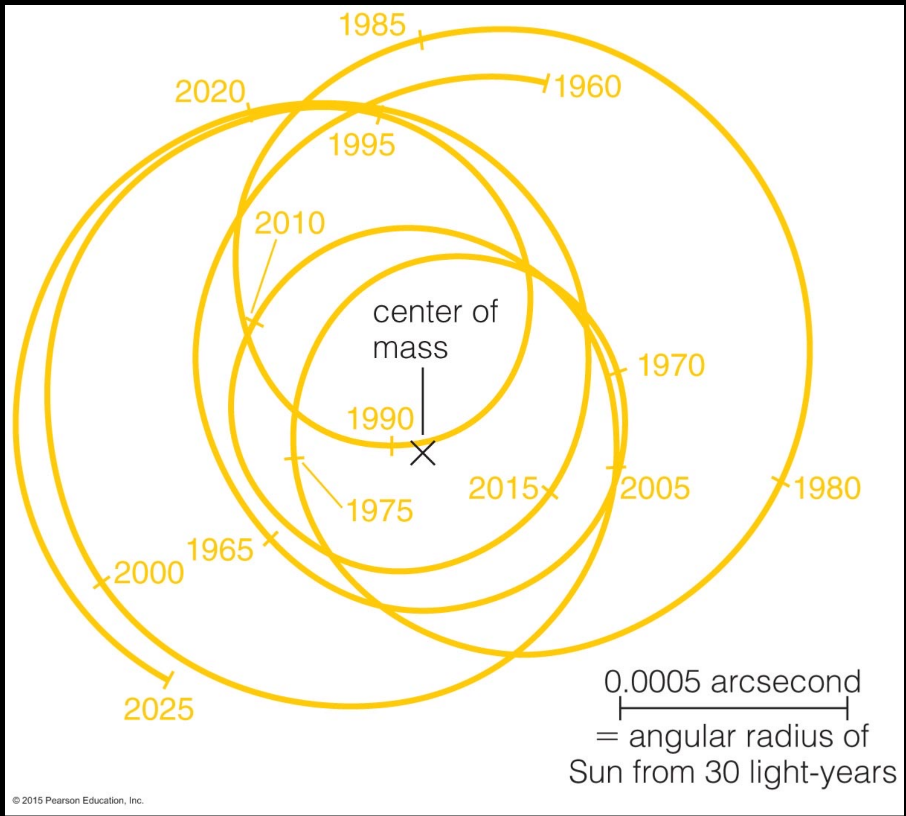
- If a star has a companion, whether it’s a planet or another star, then the two objects will orbit the common **center of mass**.
- Since planets are much smaller than stars, the star will move only a tiny bit (wobble), and this wobble can be detected from a distance.

The "wobble" of a star



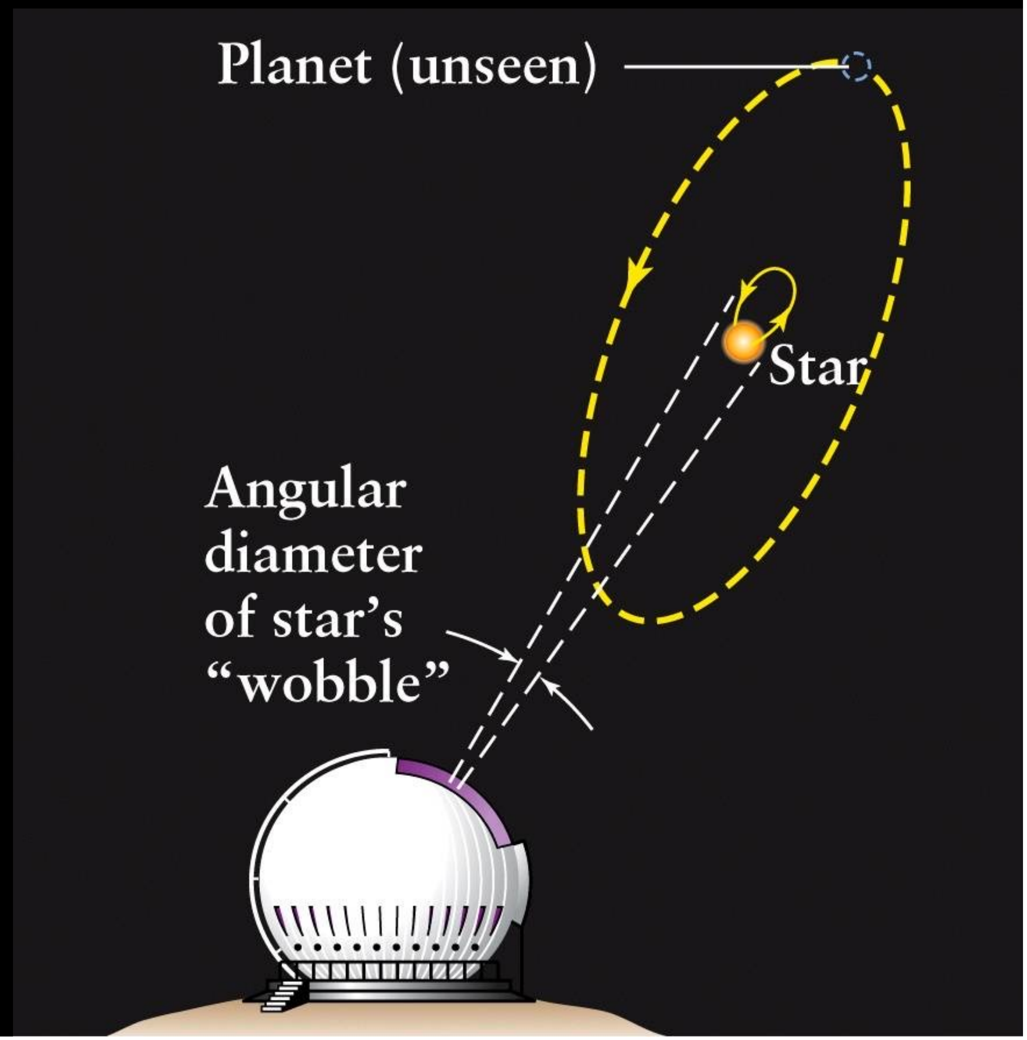
The "wobble" of a star

- If we watched our Sun from a distance of 30 light years, its wobble would be too weak for Hubble Space Telescope to measure!



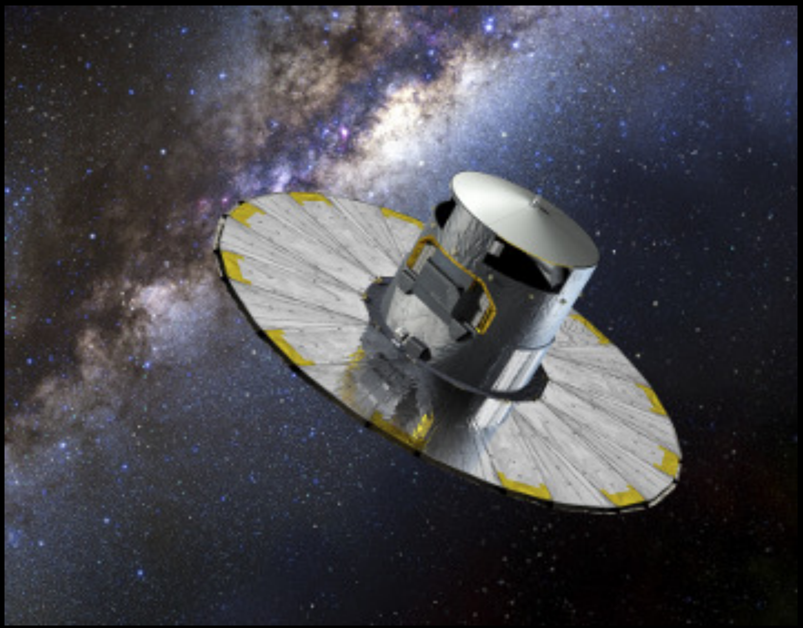
Limits of Astrometry

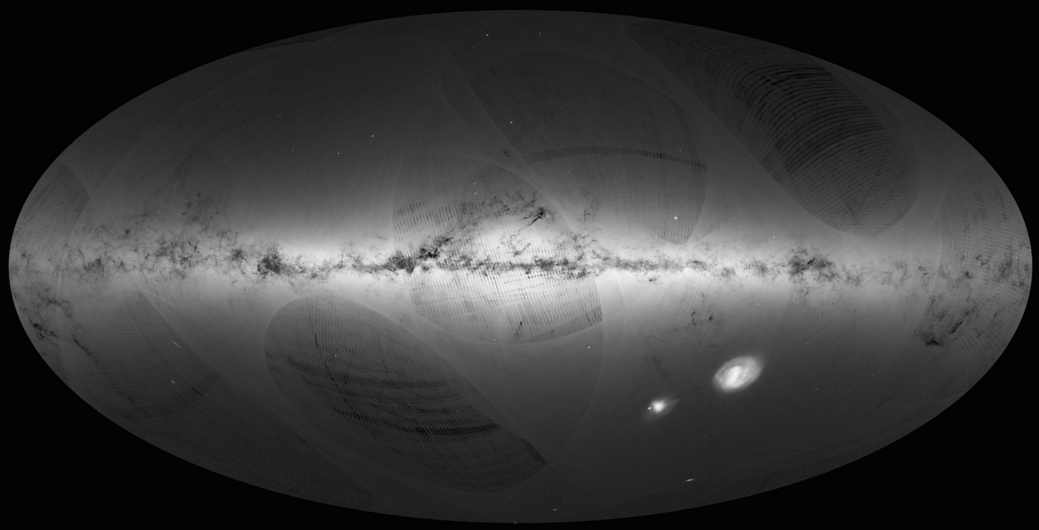
- Current technology allows us to detect a Jupiter-sized planet from a distance of 10 ly, or a stellar "wobble" of 0.0005 arcsecond (0.00000014 degrees!).
- **Works best for massive planets orbiting far from their central star.**
- Using interferometry, two telescopes working together can obtain a much better result.



The ESA Gaia mission

- Launched 2013; first data set released 2016.
- Using astrometry to catalog 1 billion stars in the Milky Way.
- Will use astrometry and transit method to look for extrasolar planets.
- Predictions: Gaia should find around 10,000 exoplanets in the next few years using astrometry!

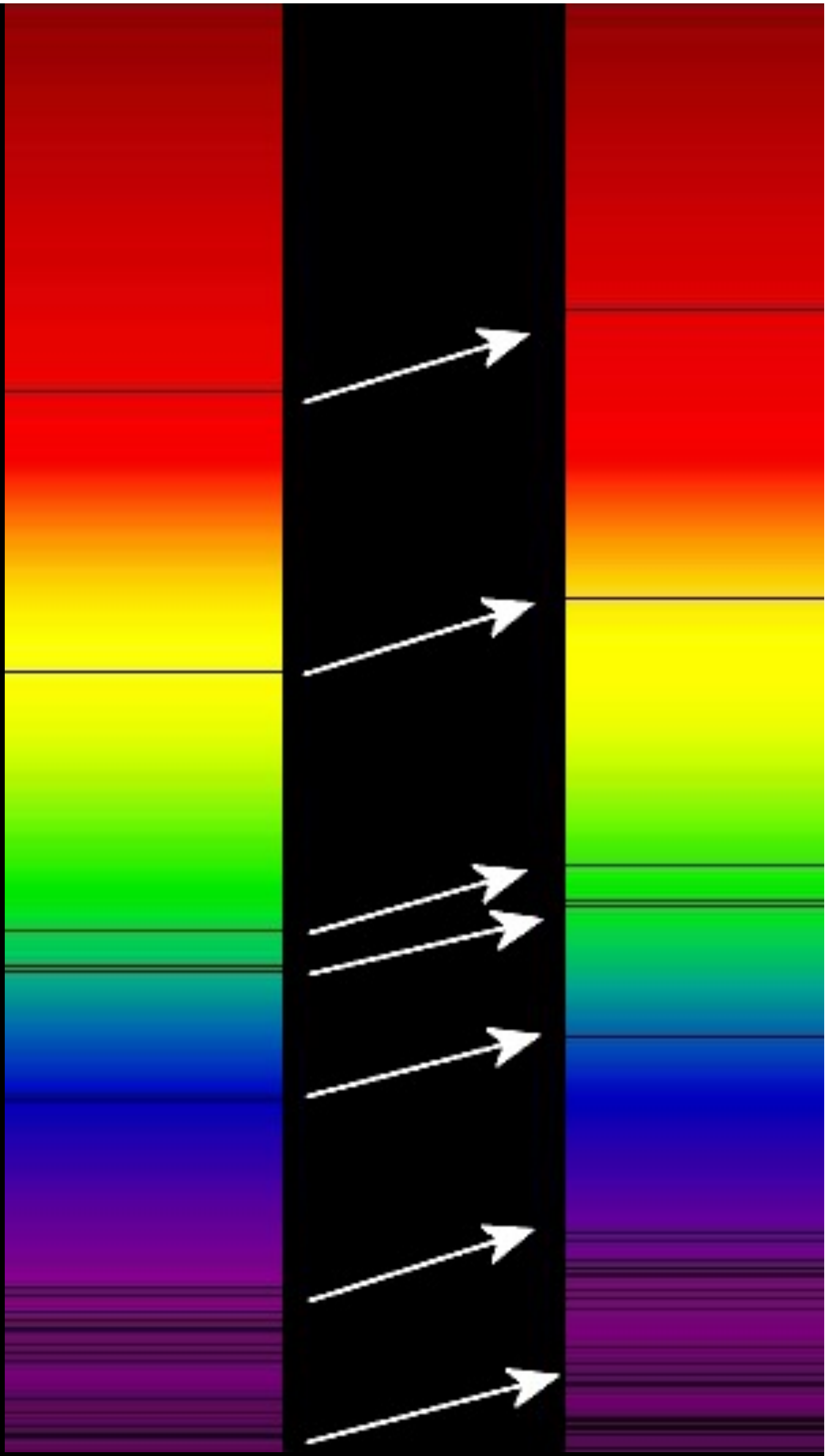




Radial velocity
(Doppler spectroscopy)

The Doppler Effect

- Light from a moving object is shifted in wavelength:
  - Towards red for objects moving away from observer.
  - Towards blue for objects moving toward observer.



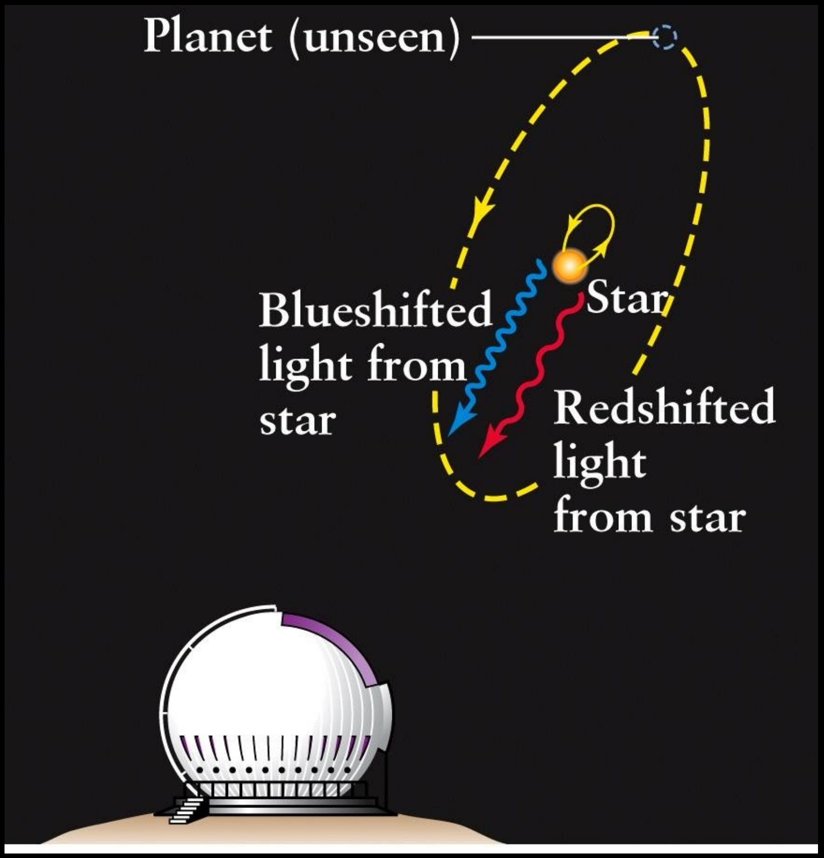
"First" Radial Velocity Discovery

- First confirmed planet orbiting a "normal" star came in 1995: 51 Pegasi b, a "hot Jupiter."
- Mass of 51 Pegasi b is about half of Jupiter, but with an orbital period of 4 days, at a distance of 0.05 AU (compare to Mercury, 0.31 AU).
- (A different hot Jupiter was actually discovered in 1988, but thought to not be a planet)

Methods of Detection:
Radial Velocity or Doppler Spectroscopy

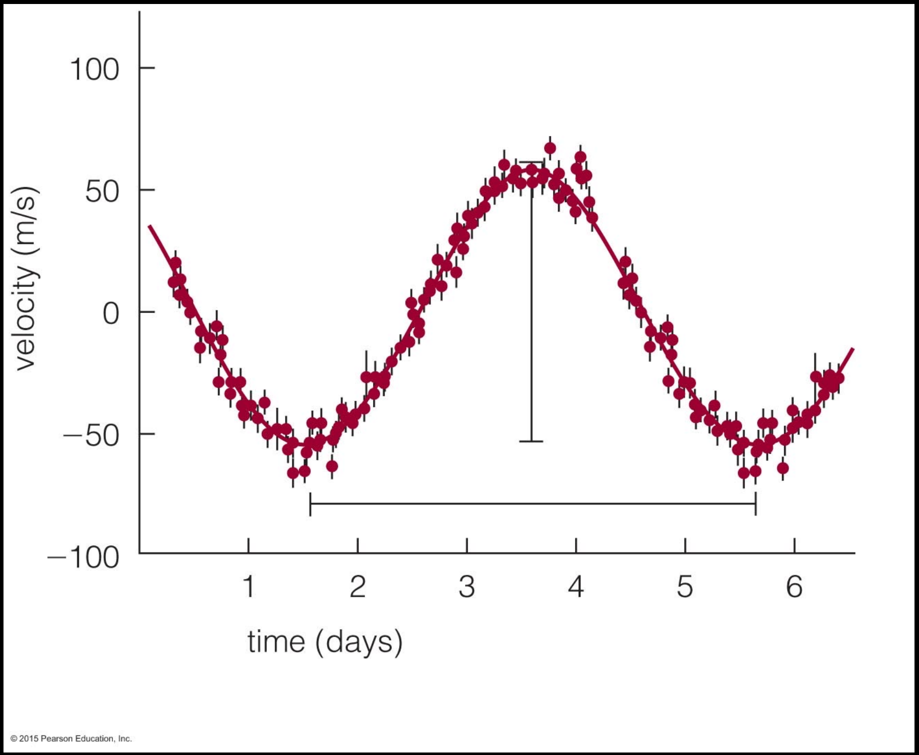
Radial Velocity

- The planets can “tug” parent stars.
- This motion affects the stars’ spectral lines we see.
- Works best for **<u>big planets, close to their stars</u>**.



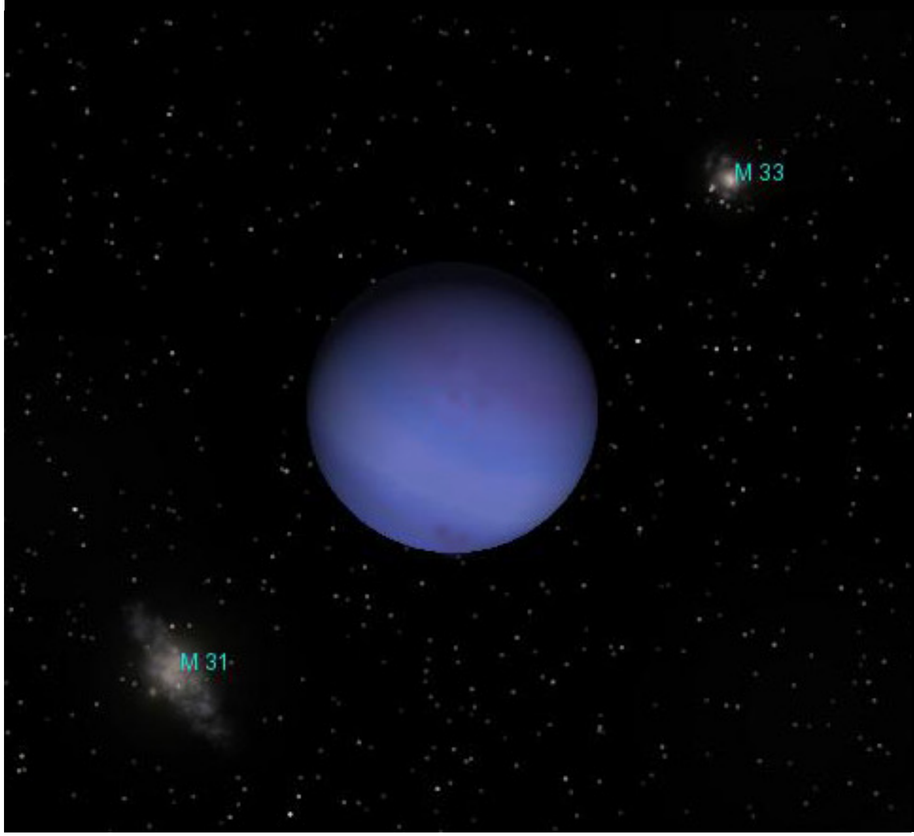
How Does Doppler Spectroscopy Work?

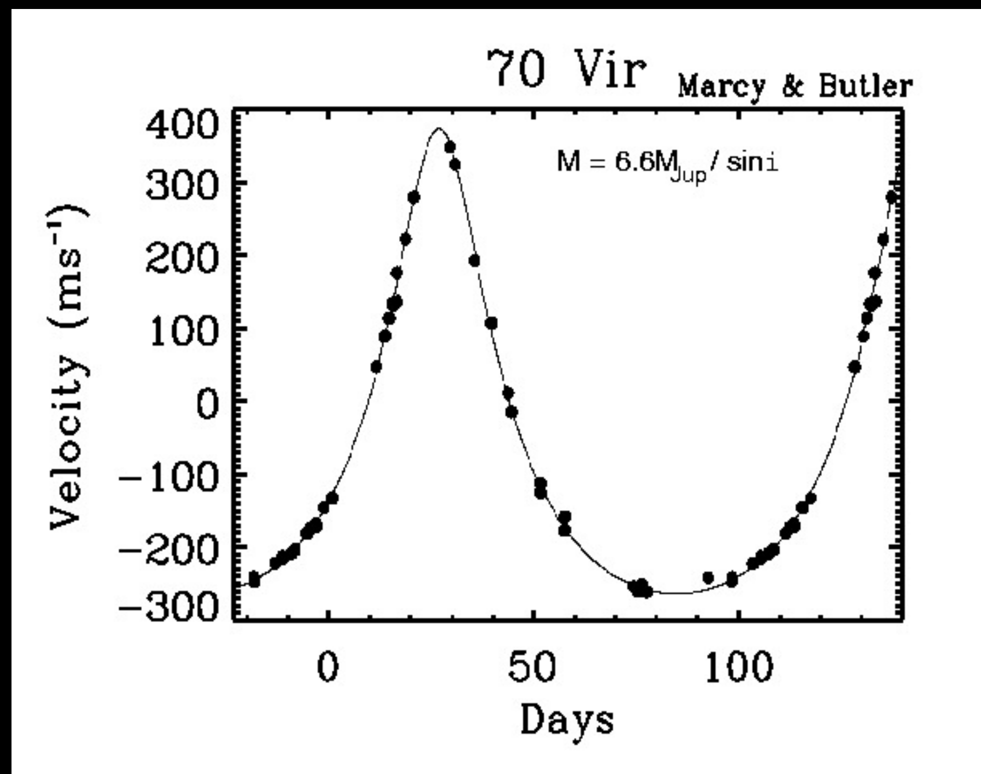
- A periodic variation in the star's position tells us that it has an unseen companion, possibly a planet.
- The velocity change (vertical axis) gives the planet's <u>mass</u>, while the period of the variation gives the planet's <u>orbital period</u>.



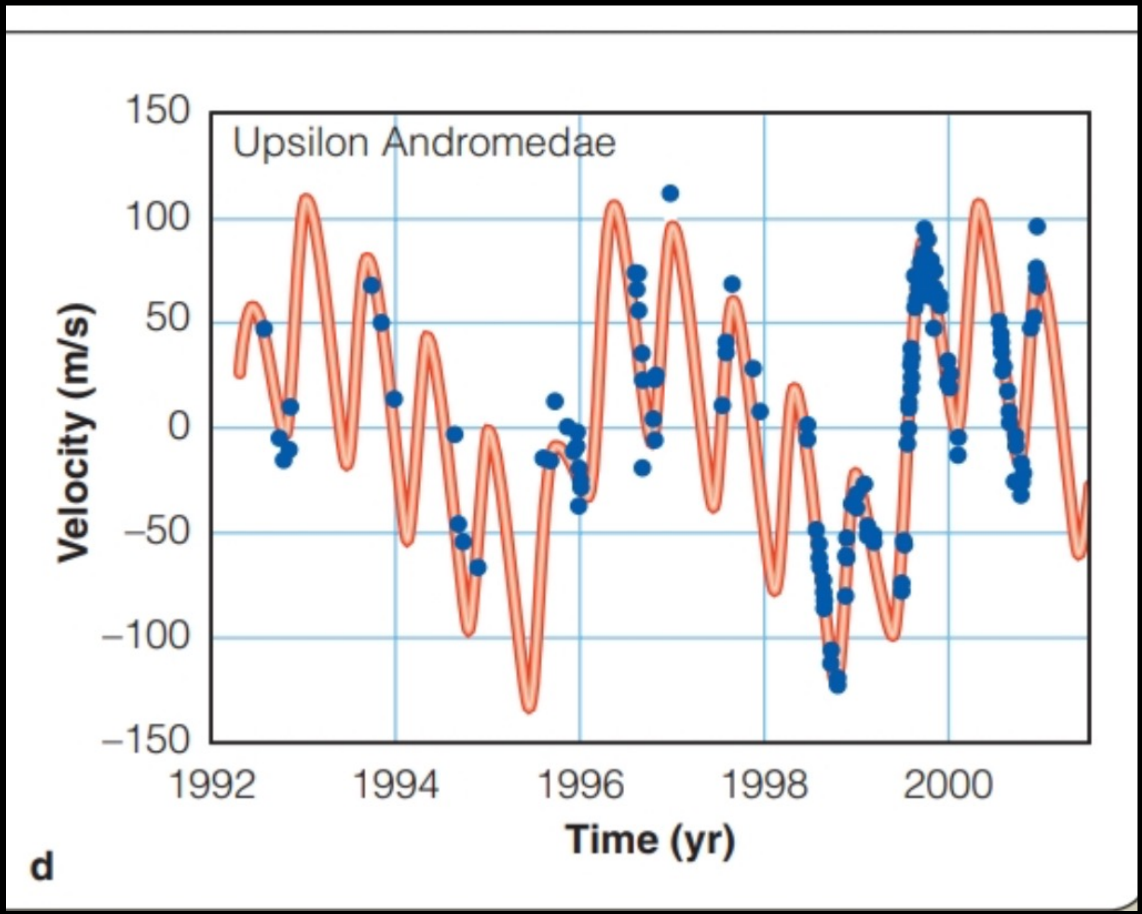
Doppler Spectroscopy in the Real World

- 70 Virginis b is an “eccentric Jupiter” (approx. 7.5 times Jupiter’s mass) orbiting its parent star every 116 days.





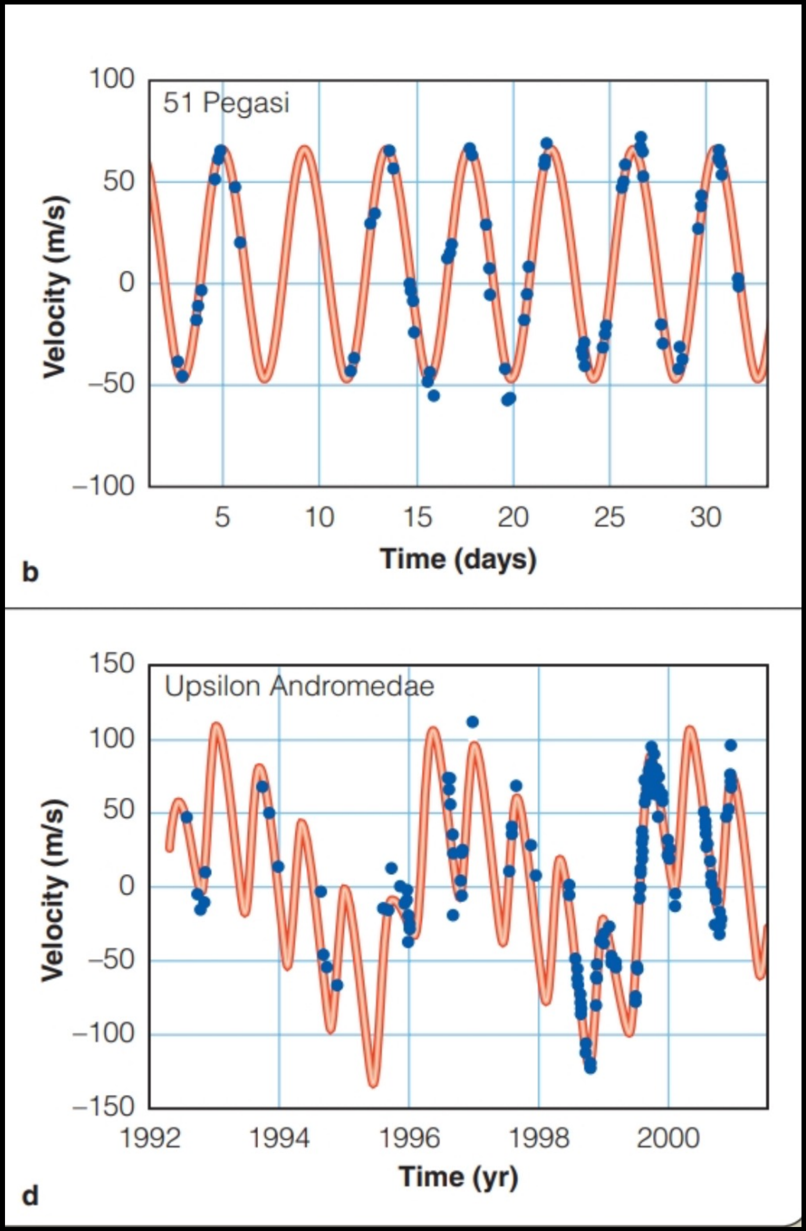
What is going on here?



Doppler spectroscopy in multi-planet systems

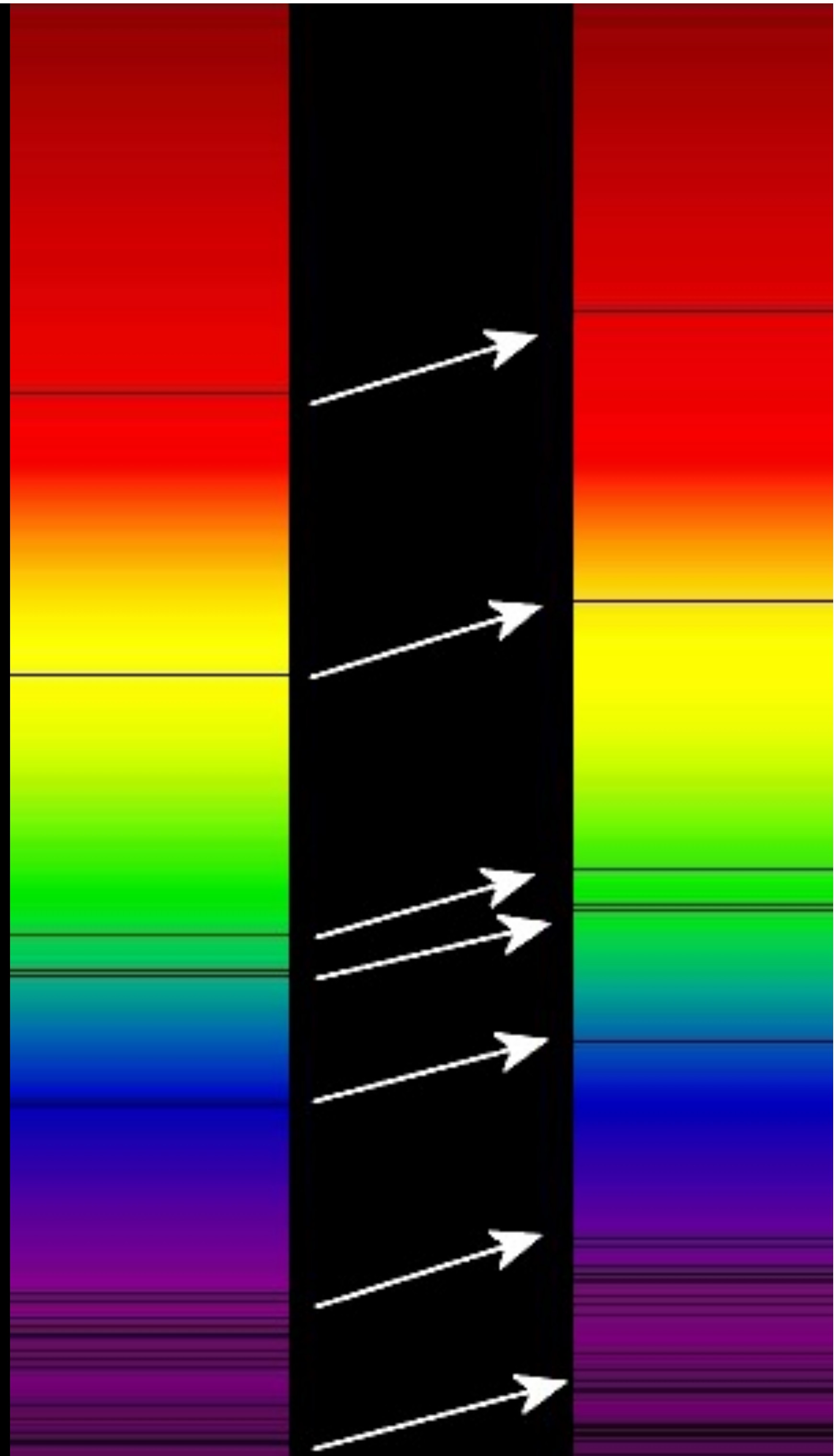
Top: 51 Pegasi, single planet.

Bottom: Upsilon Andromedae, at least four planets.



Doppler precision

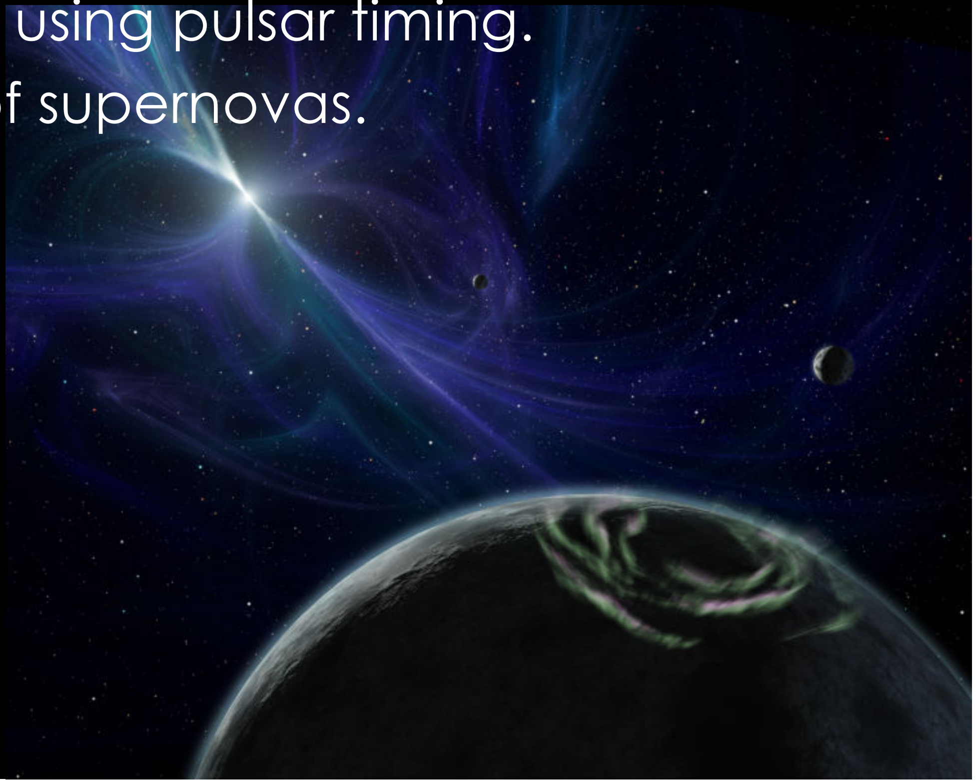
- “Normal” Doppler precision in astronomy is typically measured in km/s (e.g., to see a by-eye-visible shift in the locations of lines in stellar spectra)
- The planet around 51 Peg (first RV detection) moves its star at a speed of about 50 m/s.
- State-of-the-art instruments & analysis techniques can measure the motions of stars down to less than 1 m/s!
- Earth’s gravity induces a 10 cm/s motion of the Sun!



Pulsar timing

Methods of Detection: Pulsar Timing

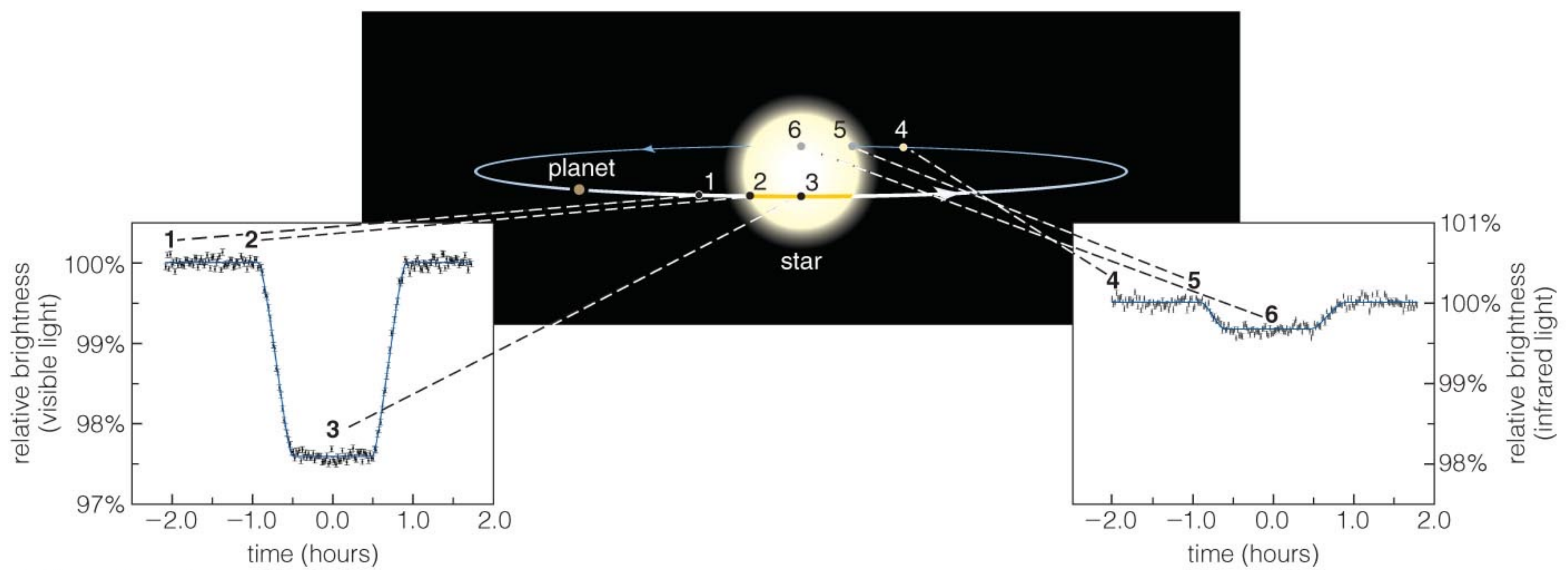
- Pulsars are rapidly rotating neutron stars that emit radio waves at very regular intervals.
- A pulsar that is being tugged by orbiting planets will have anomalies in the timing of radio waves.
- Pulsar timing is very precise, and planets as small as 0.1 times Earth's mass can be found.
- First extrasolar planet was found using pulsar timing.
- Pulsars are rare, and remnants of supernovas.



Transits

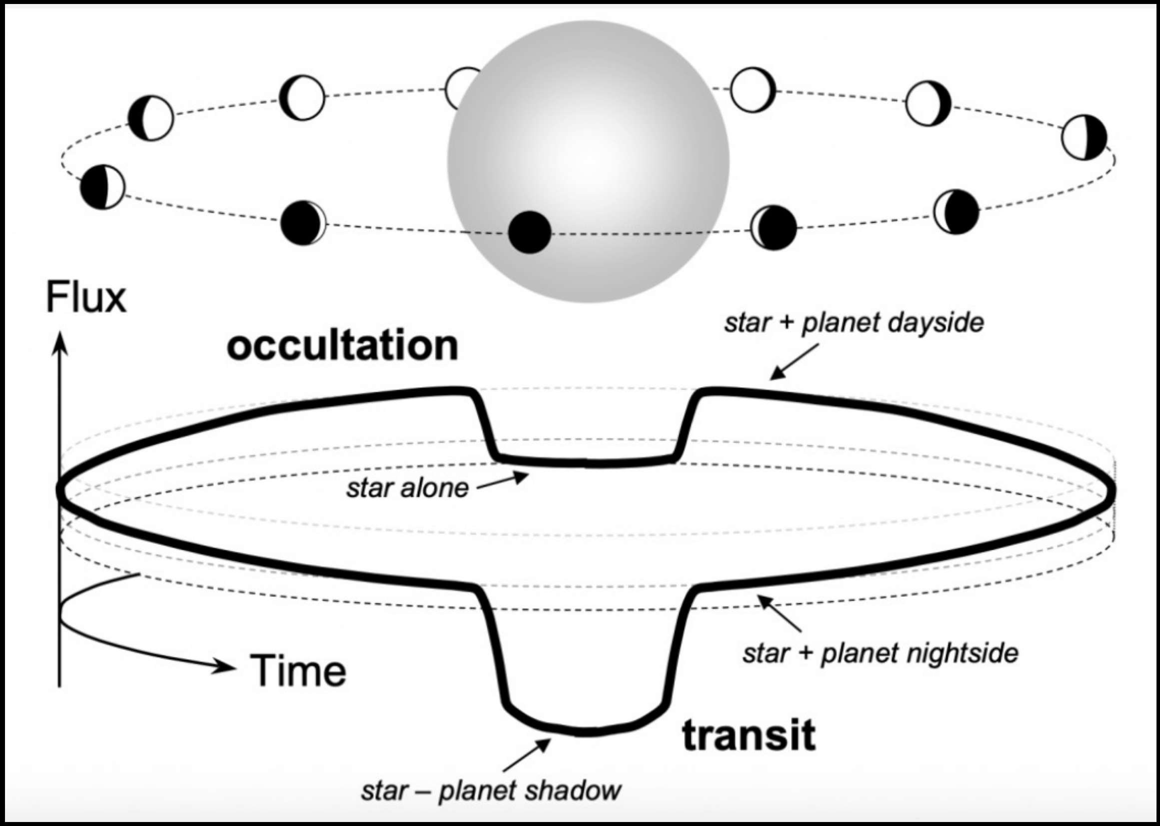
Methods of Detection: Transit

- As a planet crosses in front of the parent star, the star dims by a tiny bit
  - Jupiter-sized planet causes star's brightness to decrease by 1%
  - Earth-sized planet by 0.01% !
- Challenge: in order to see this, the planet's orbit has to be in the same plane as our line-of-sight with the star.

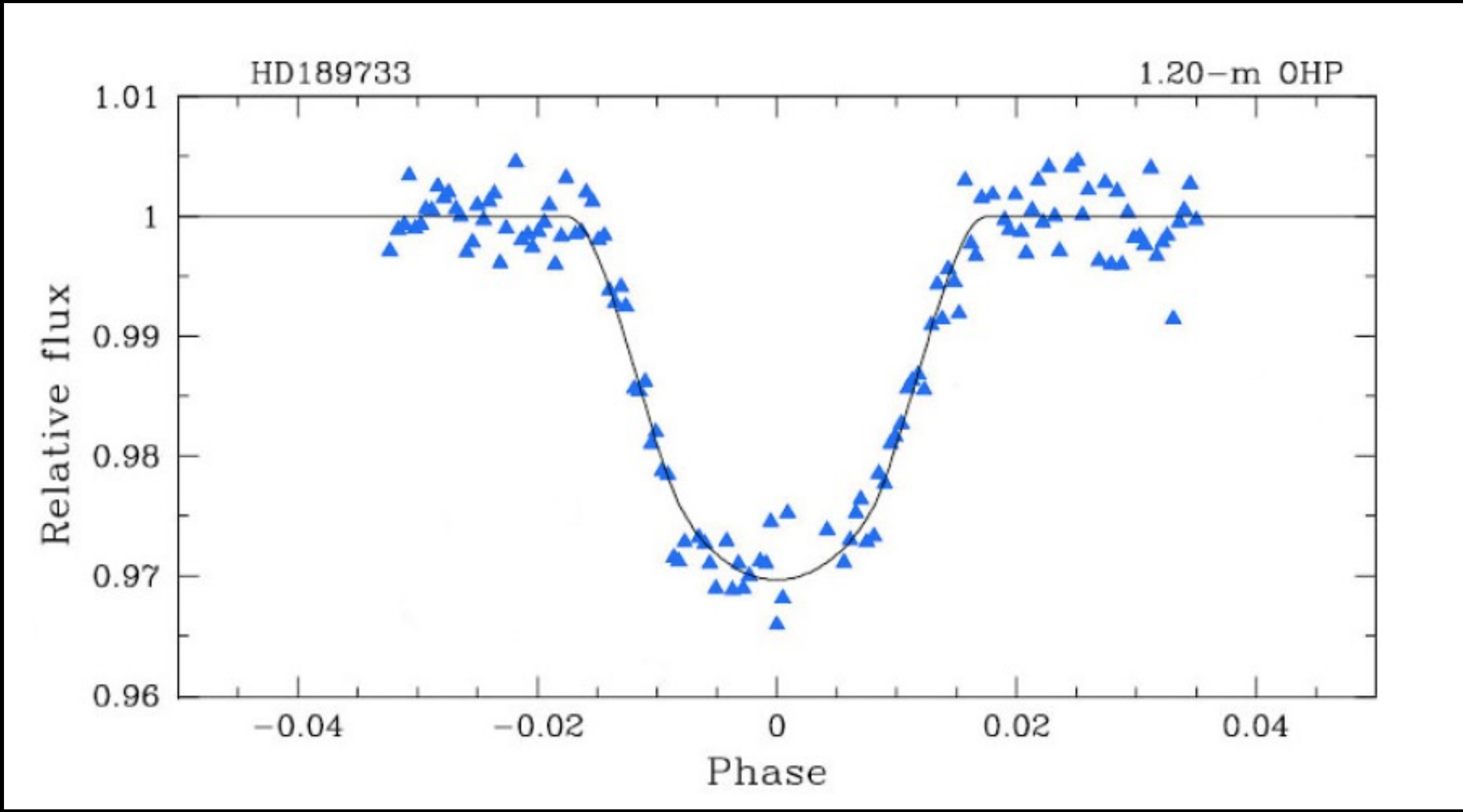


What the Transit Method can tell us

- Primarily, the transit signal measures the radius of the planet.
- During the transit, spectroscopy can be used to determine the composition of the planet's atmosphere.
- Occultation behind the parent star can be used to determine the planet's temperature.



What a real transit looks like



First transiting planet (*not this one) was found with a 4” telescope!

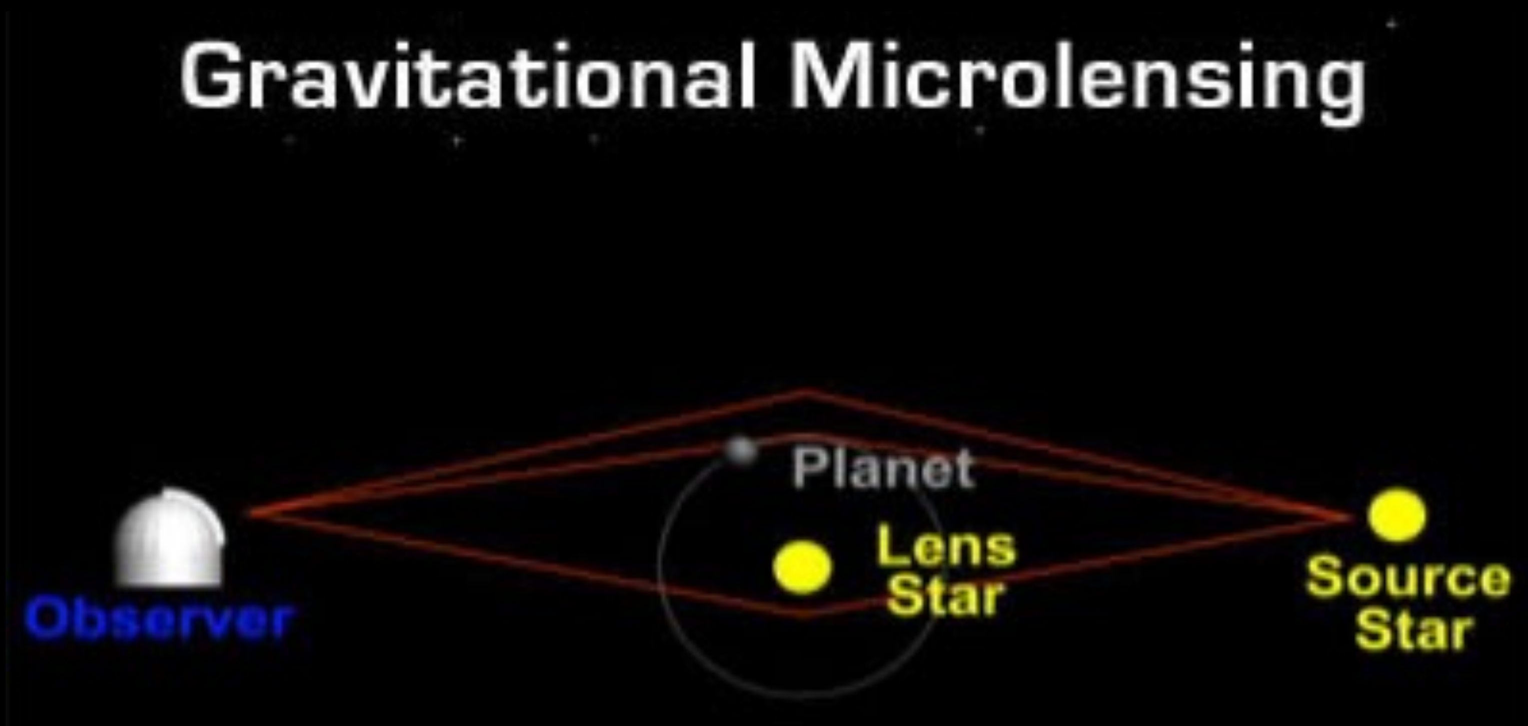
Transits can be complicated in multiple-planet systems!

PLANETQUEST
THE SEARCH FOR ANOTHER EARTH

Microlensing

Gravitational Microlensing

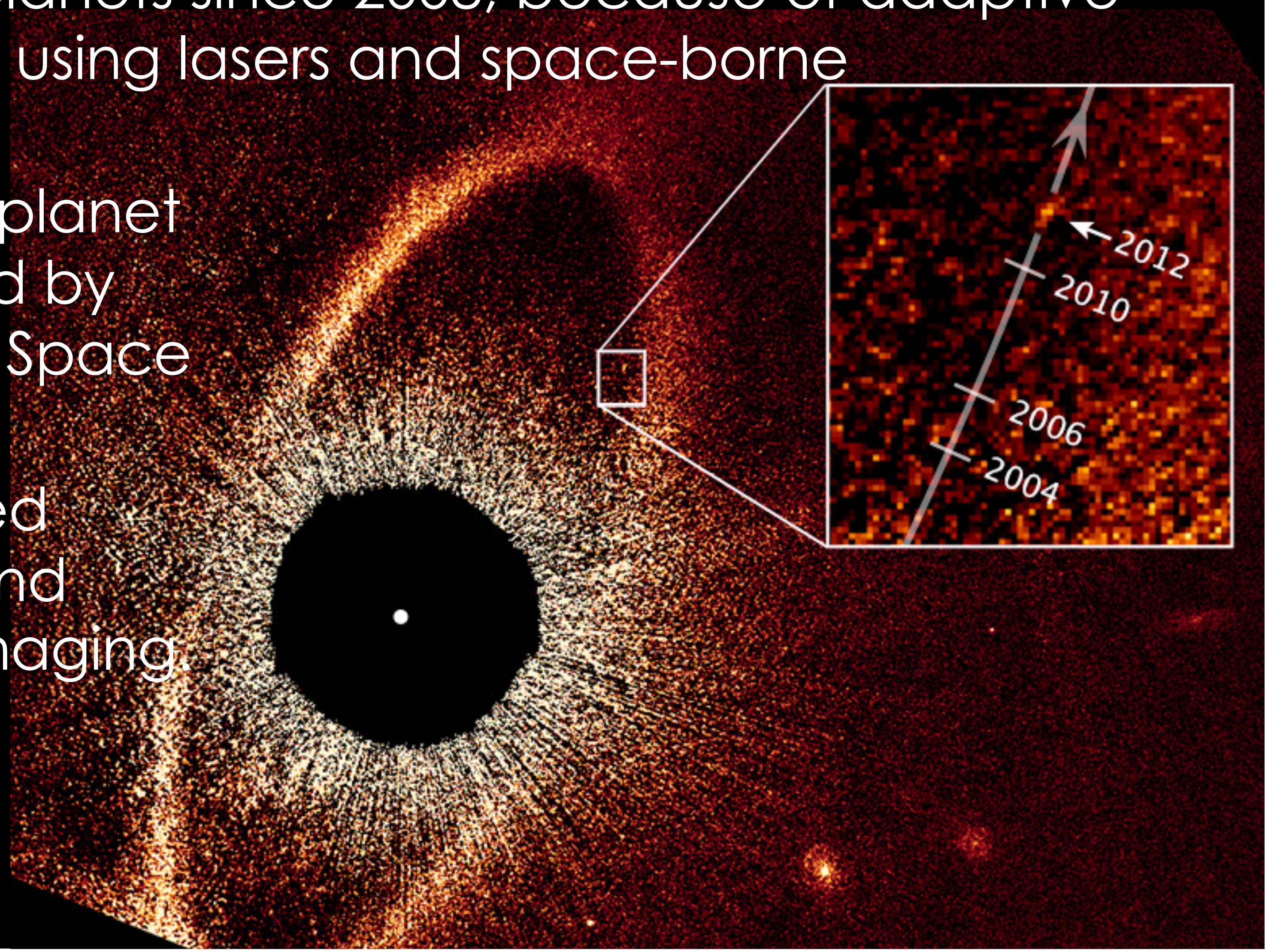
- Planet adds its own effect to gravitational microlensing of background stars.
- Requires the use of robotic telescopes and observations of a large number of stars.



Direct imaging

Direct Imaging

- We have only been able to directly image extrasolar planets since 2008, because of adaptive optics (AO) using lasers and space-borne telescopes.
- Fomalhaut planet was imaged by the Hubble Space Telescope.
- 50 confirmed planets found by direct imaging.

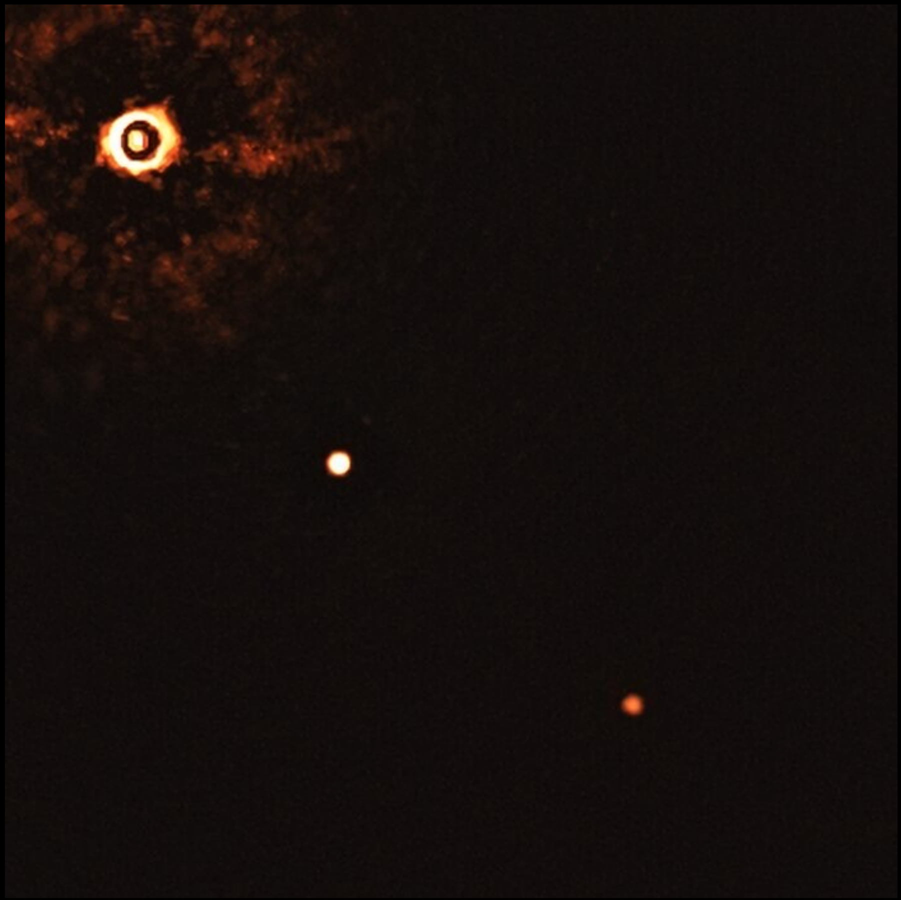


Direct Imaging: first success

- In the same month as Fomalhault b, first successful direct imaging of an extrasolar planet from an Earth-based telescope was the companion of the brown dwarf 2M1207 by the European Southern Observatory's Very Large Telescope in Chile.

Recent imaging success

- First image of a multi-planet system around a Sun-like star announced in 2020.
- Both planets are gas giants.



Discoveries by method

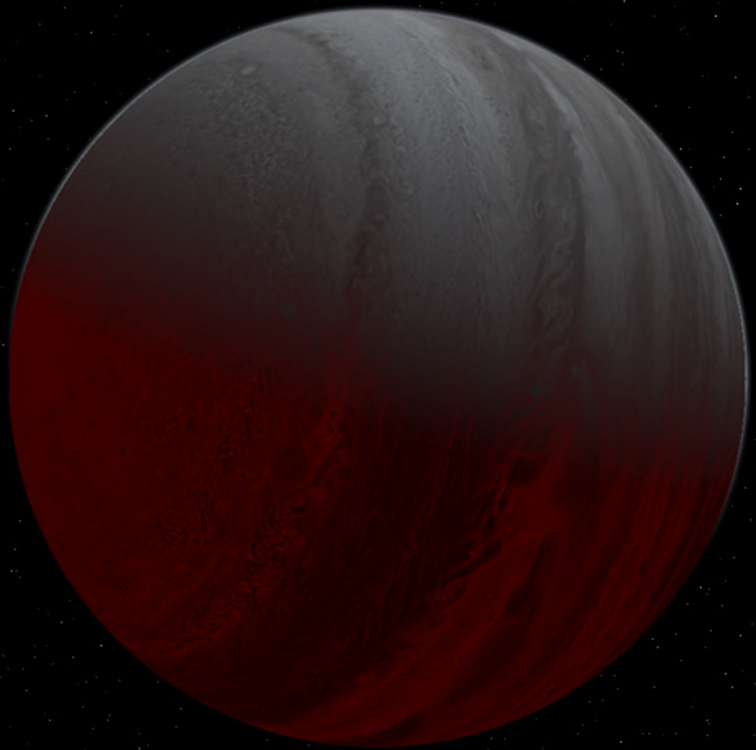
75.9%	Transit	
19.3%	Radial Velocity	
2.3%	Microlensing	
1.2%	Imaging	

0.5% Transit Timing Variations, 0.38% Eclipse Timing Variations, 0.17% Pulsar Timing, 0.14% Orbital Brightness Modulation, 0.05% Pulsation Timing Variations, 0.02% Disk Kinematics, 0.02% Astrometry

Hot Jupiters

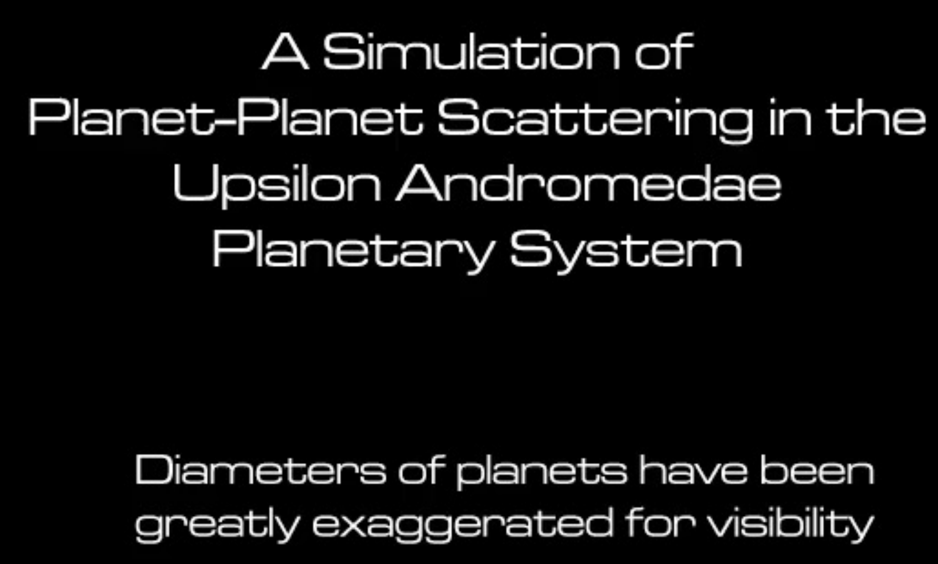
Hot Jupiters

- Mass up to several times that of Jupiter.
- Orbit that is within 0.5 AU.
- Low densities as they’re exposed to high levels of radiation from their parent star.
- Hundreds of hot Jupiters found to date.
- Location may be explained by inward orbital migration.



Nothing Wrong with Nebular Theory!

- Just as Uranus and Neptune were flung outward in our Solar System, it's equally probable that gas giants could be flung inward.



question for you

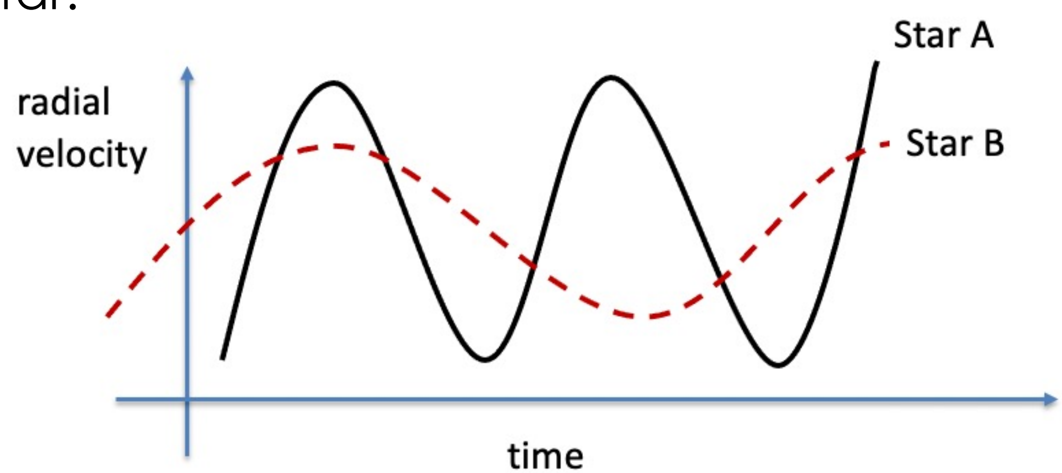
Why were Hot Jupiters the first exoplanets to be found?

A. By random chance.
B. Because they are the most common type of planets in our Galaxy and were the most likely planets to be detected.
C. Because they radiate their own heat and thus are easier to detect against the light of their stars.
D. Because they are massive and close enough to substantially tug on their stars.
E. I have no idea.

question for you

RV curves are shown for Star A and Star B, both of which have the same mass as the Sun. From this information, which of the following can we conclude?

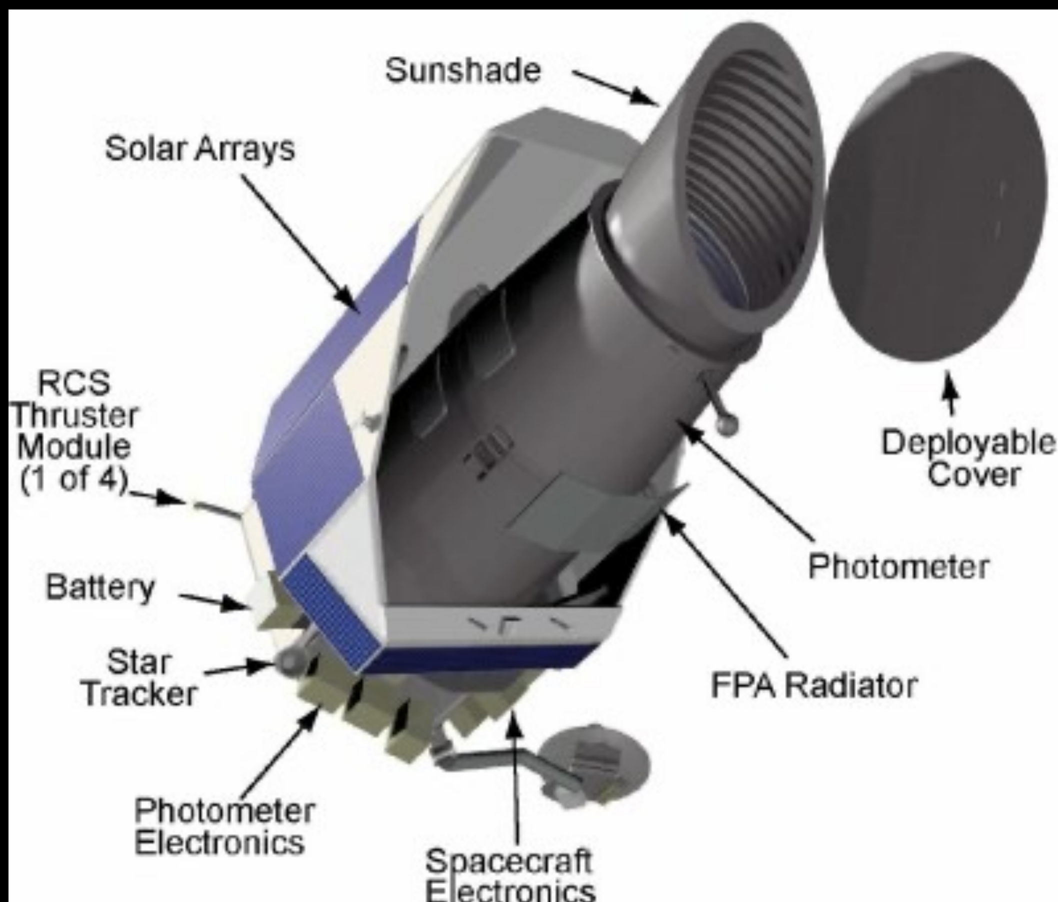
A. The planet orbiting star A is brighter than planet orbiting star B.
B. The planet orbiting star B is brighter than planet orbiting star A.
C. The planet orbiting star A is farther from its star than planet B is from its star.
D. The planet orbiting star B is farther from its star than planet A is from its star.



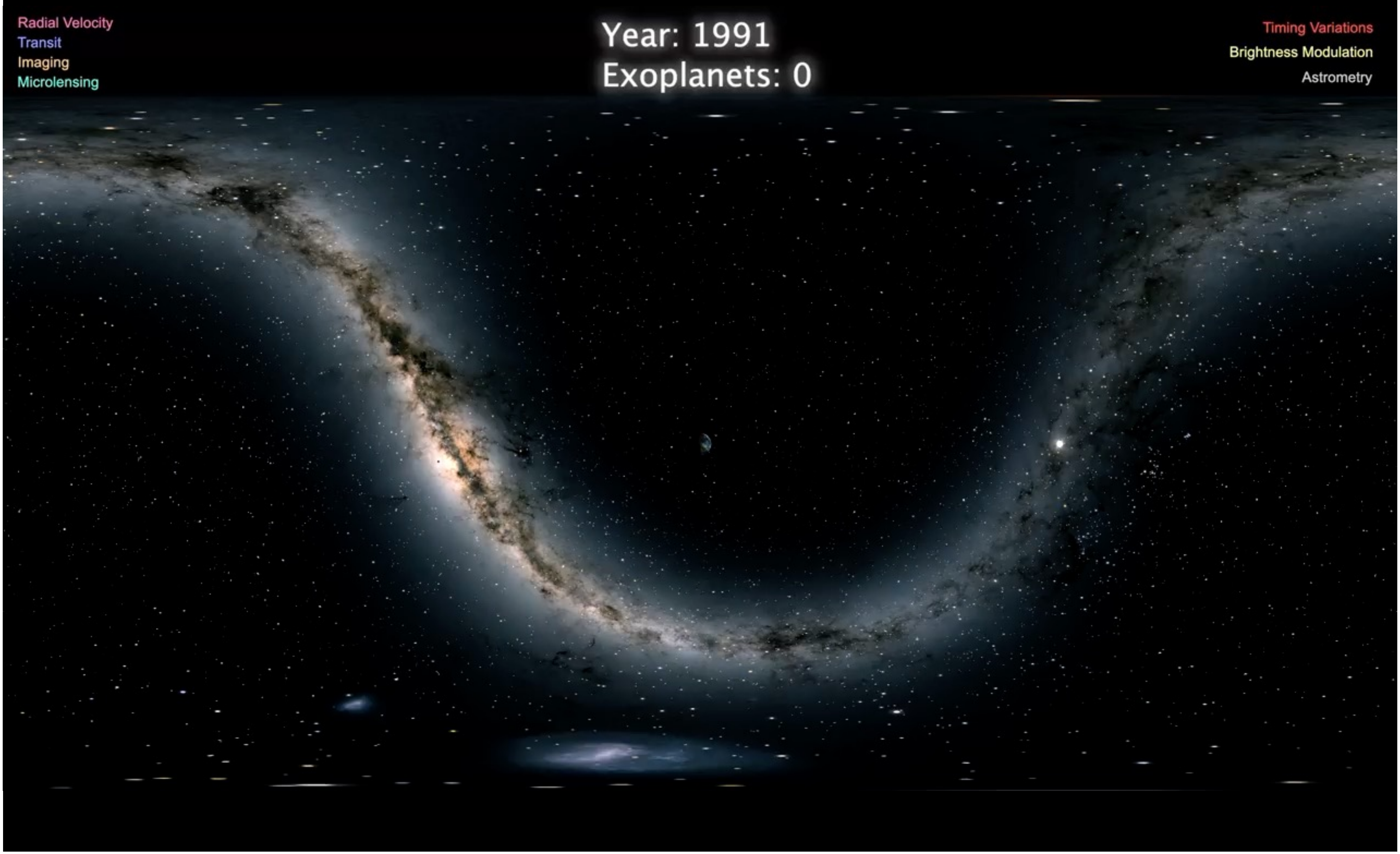
Observations

The Kepler Mission

- Kepler Mission was launched in March 2009 and used transit method to scan 150,000 stars in the Constellation Cygnus.
- Kepler able to detect planets much smaller than Earth.
- Mission ended in 2018.

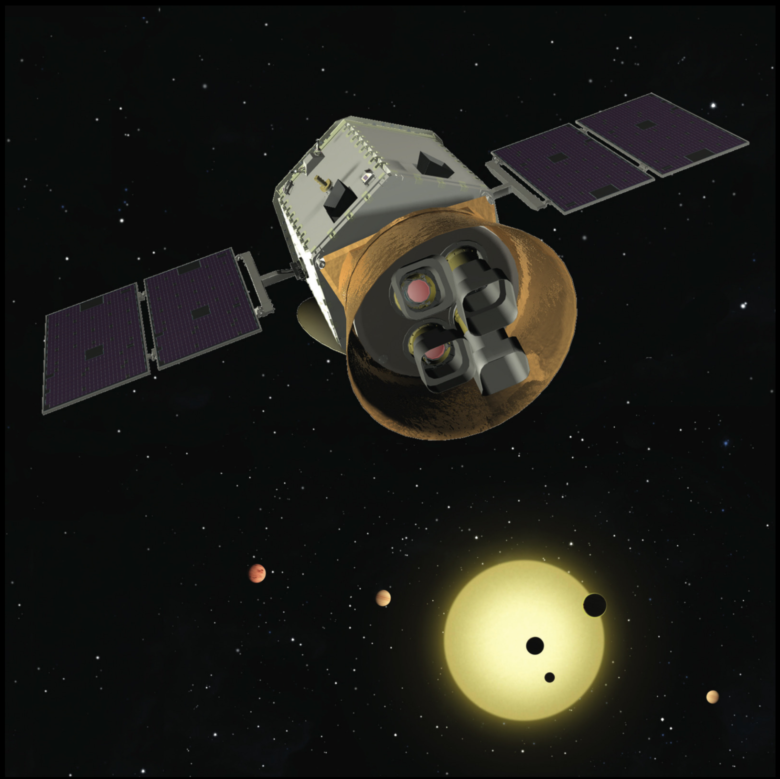


~4000 Planets…

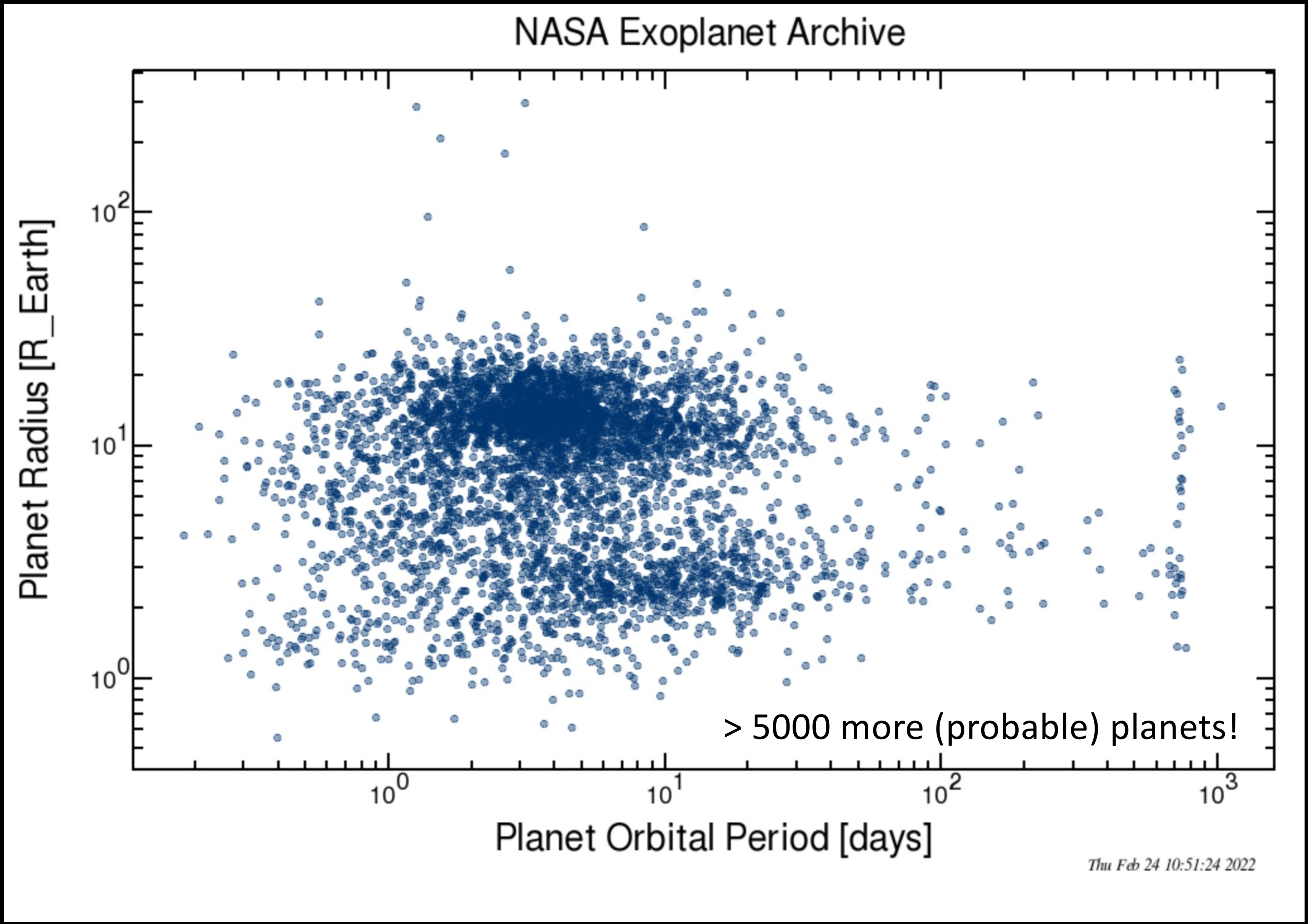


Transiting Exoplanet Survey Satellite (TESS)

- Launched April 18, 2018.
- Surveying 500,000 G and K class stars and 1000 of the nearest red dwarf stars.



Current TESS Candidates

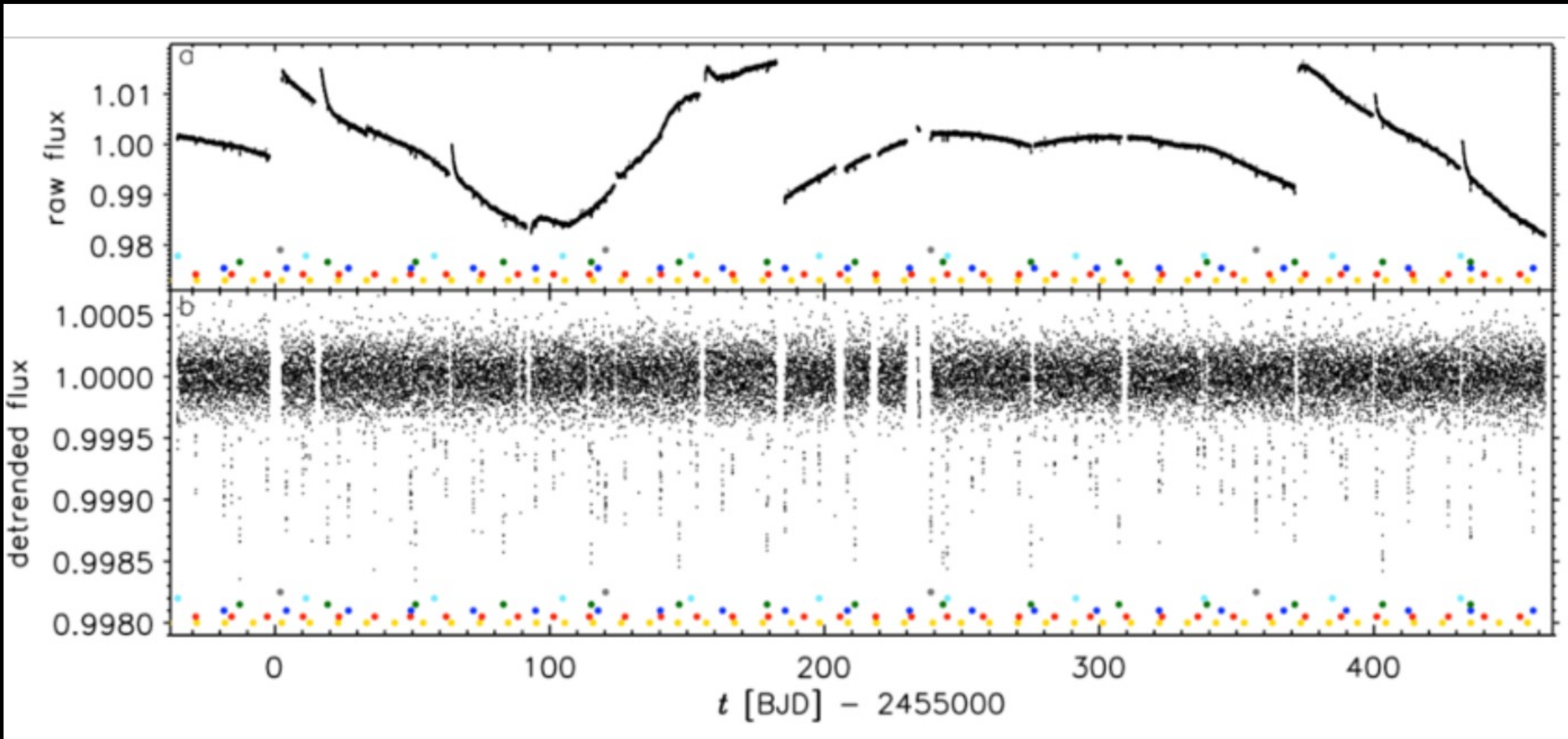


Just How Many Exoplanets?

- Based on the Kepler science data, it is expected that the Milky Way galaxy contains as many planets as it does stars (100 – 400 billion).
- Estimate of 17 billion Earth-sized rocky planets in our galaxy alone!

Compact multi-planet systems

Compact multi-planet systems

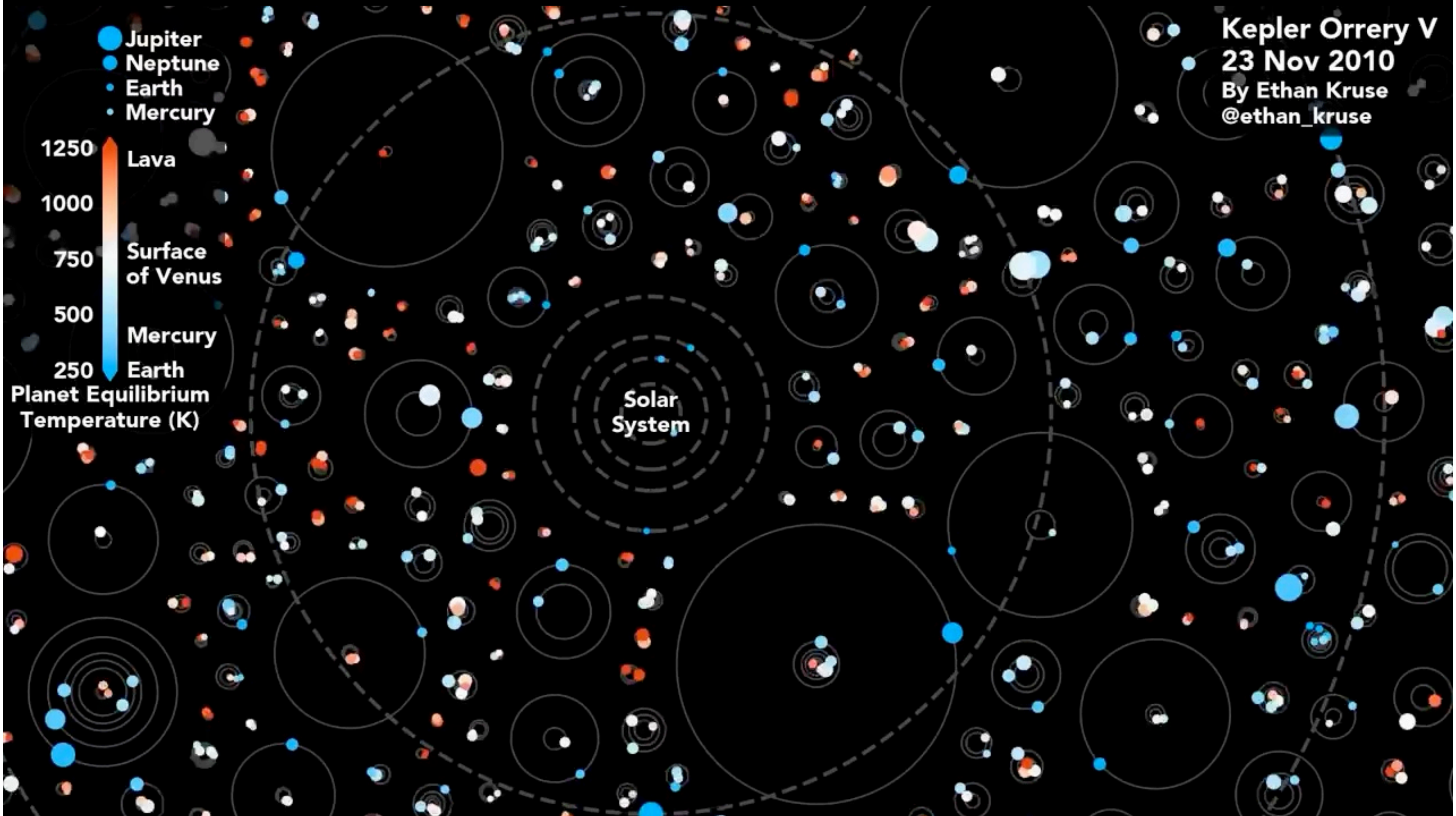


Kepler-11 discovery data

Planets of Multiple Star Systems

- Planets found orbiting stars in many multiple star systems, including triple-star systems.
- Difficult for planets to have stable orbits around binary or multiple stars; much easier if stellar separation is more than 200 AU.

Kepler Orrery



question for you

What kinds of planets are easiest to find using the transit method?

A. Any large hot Jupiters, with short orbital periods.
B. Any small cold rocky planets, with short orbital periods.
C. Planets in orbits aligned with our line of sight, with long orbital periods.
D. Planets in orbits aligned with our line of sight that orbit with short orbital periods.
E. I have no idea.

What did we learn in Chapter 18, Part 2?

- Stars that have exoplanets orbiting them wobble due to an offset of the center of gravity of the system. This wobble is very very difficult to measure directly.
- Astrometry attempts to directly measure wobble using precise measurements of a star's position.
- The radial velocity or Doppler spectroscopy technique looks for red/blue shifts in a star's light as it wobbles due to the presence of planets.
- Radial velocity is the most accurate technique for confirming the existence of extrasolar planets.

What did we learn in Chapter 18, Part 2?

- In the radial velocity technique, the change of velocity gives the planet's mass, the period of variation gives the orbital period of the planet, and asymmetries indicate how the planet's orbit is tilted.
- Pulsar timing technique measures the wobble in the high-intensity light produced by a pulsar.
- The transit method measures the dip in starlight when a planet passes in front of its star. This technique has yielded the largest number of discovered exoplanets.

What did we learn in Chapter 18, Part 2?

- The Kepler Space Telescope and the Transiting Exoplanet Survey Satellite (TESS) both use the transit method to locate planets.
- Direct imaging is actually photographing the planet orbiting a star.
- Hot jupiters are jovian (gaseous) planets in very tight orbits around their star. Their location is thought to be a result of inward migration during the formation of the star system.
- Planets can have stable orbits in multiple star systems.

What did we learn in Chapter 18, Part 2?

- Kepler discoveries have shown that planets come in all sizes, not just the ones in our solar system.
- Based on Kepler results, estimates indicate that there are at least as many planets in our galaxy as stars, and at least 17 billion Earth like planets just in our galaxy!