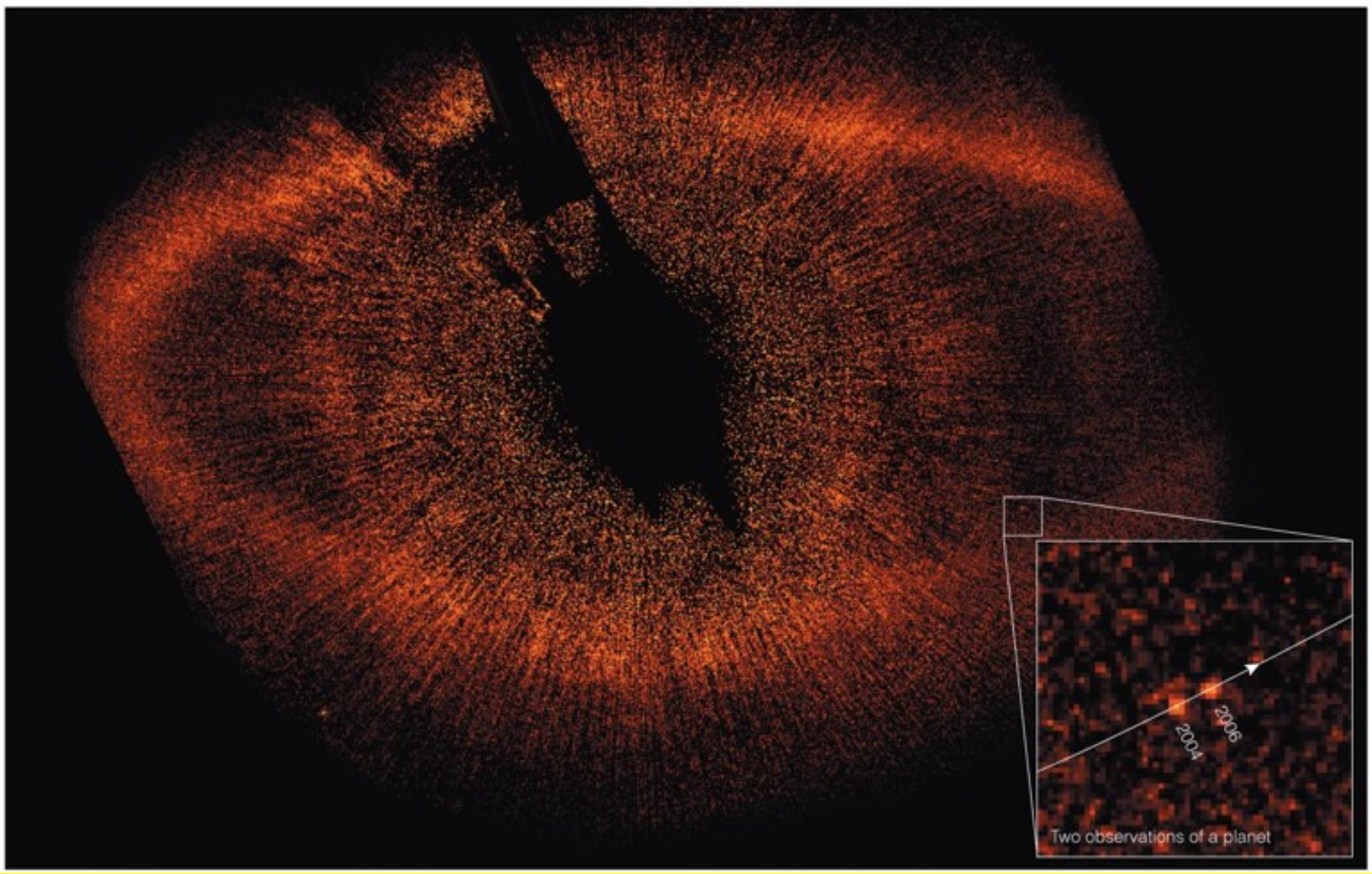
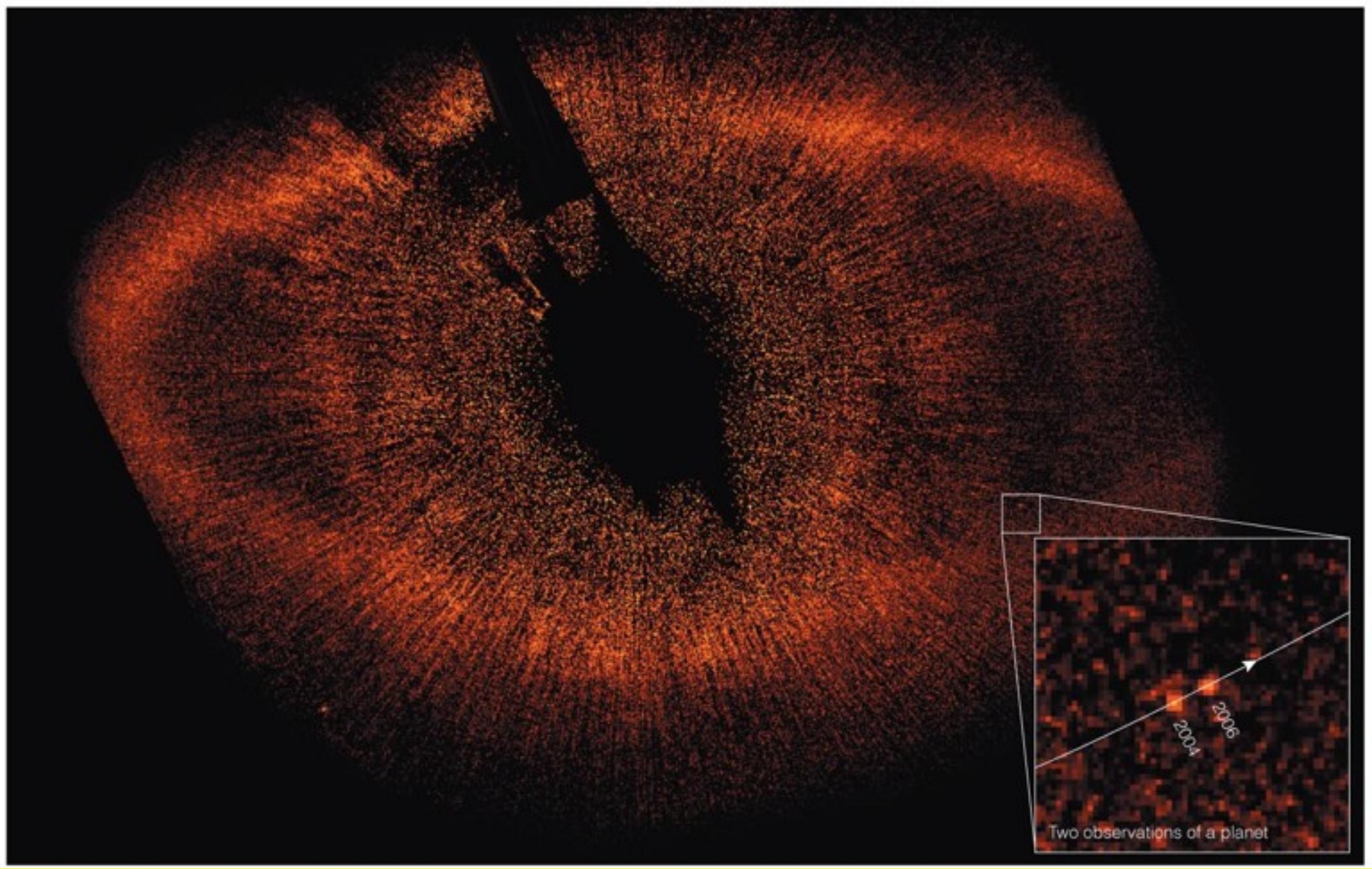
Other Planetary Systems: The New Science of Distant Worlds



Detecting Extrasolar Planets

- Why is it so difficult to detect planets around other stars?
- How do we detect planets around other stars?

Why is it so difficult to detect planets around other stars?



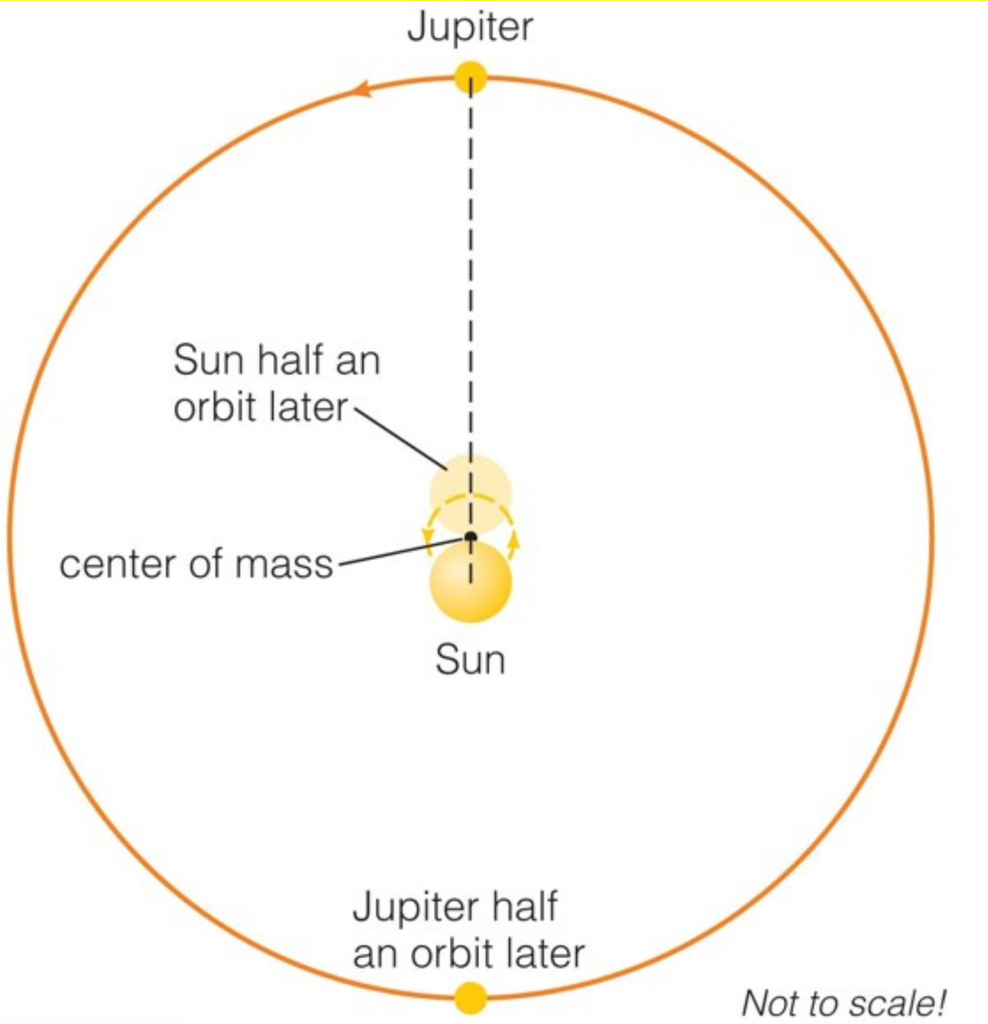
Brightness Difference

- A Sun-like star is about a billion times brighter than the light reflected from its planets.
- This is like being in San Francisco and trying to see a pinhead 15 meters from a grapefruit in Washington, D.C.

Special Topic: How Did We Learn That Other Stars Are Suns?

- Ancient observers didn't think stars were like the Sun because Sun is so much brighter.
- Christian Huygens (1629–1695) used holes drilled in a brass plate to estimate the angular sizes of stars.
- His results showed that, if stars were like Sun, they must be at great distances, consistent with the lack of observed parallax.

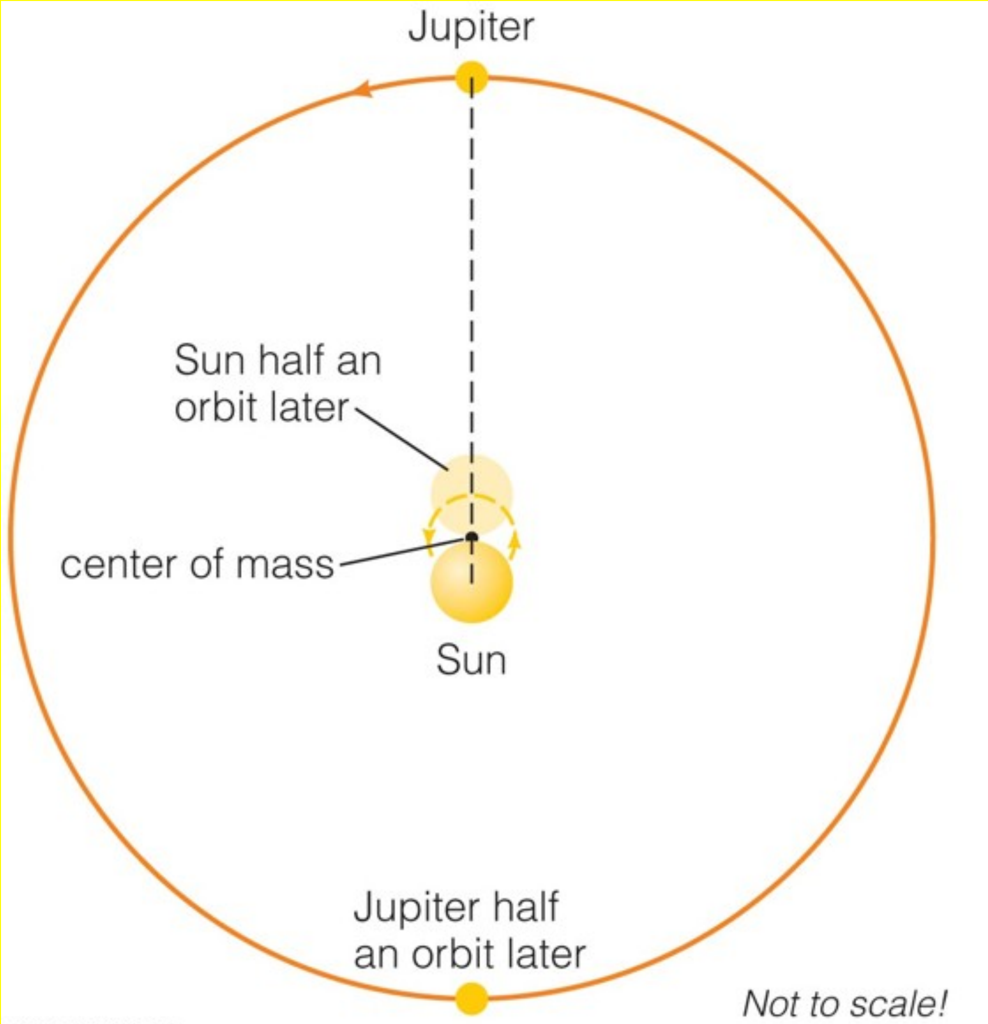
How do we detect planets around other stars?



Planet Detection

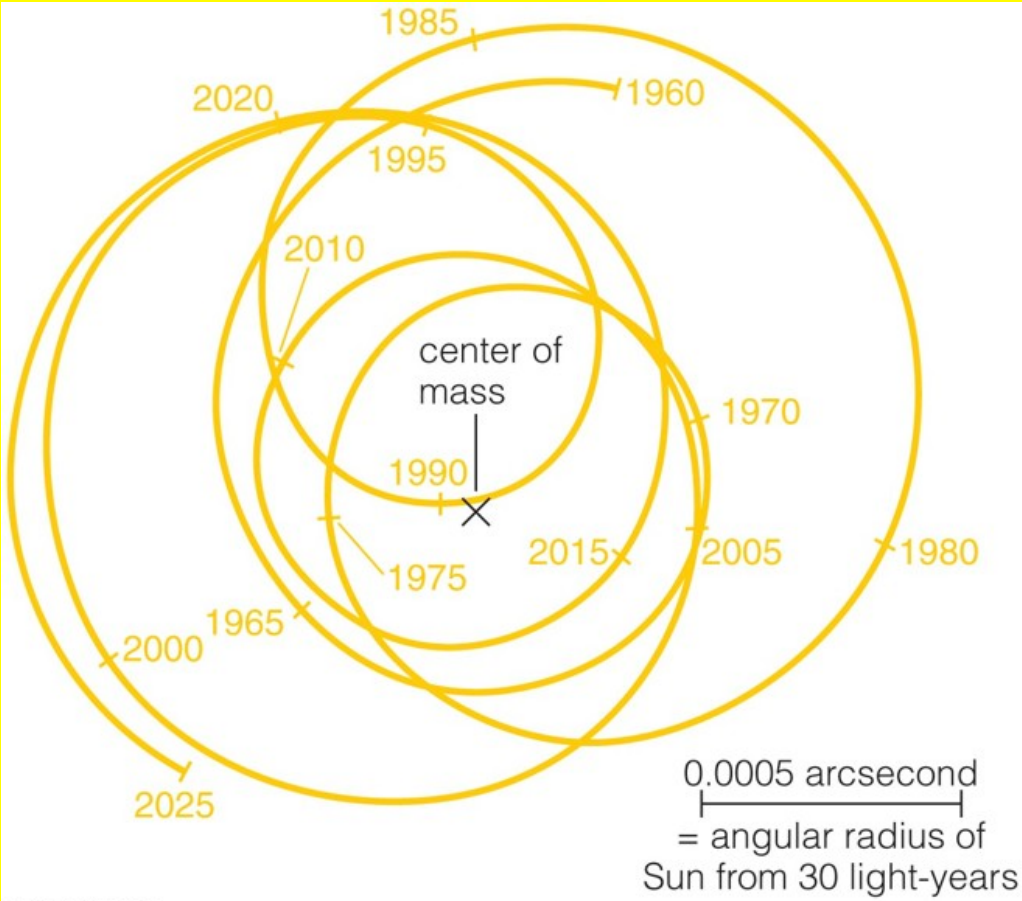
- **Direct:** pictures or spectra of the planets themselves
- **Indirect:** measurements of stellar properties revealing the effects of orbiting planets

Gravitational Tugs



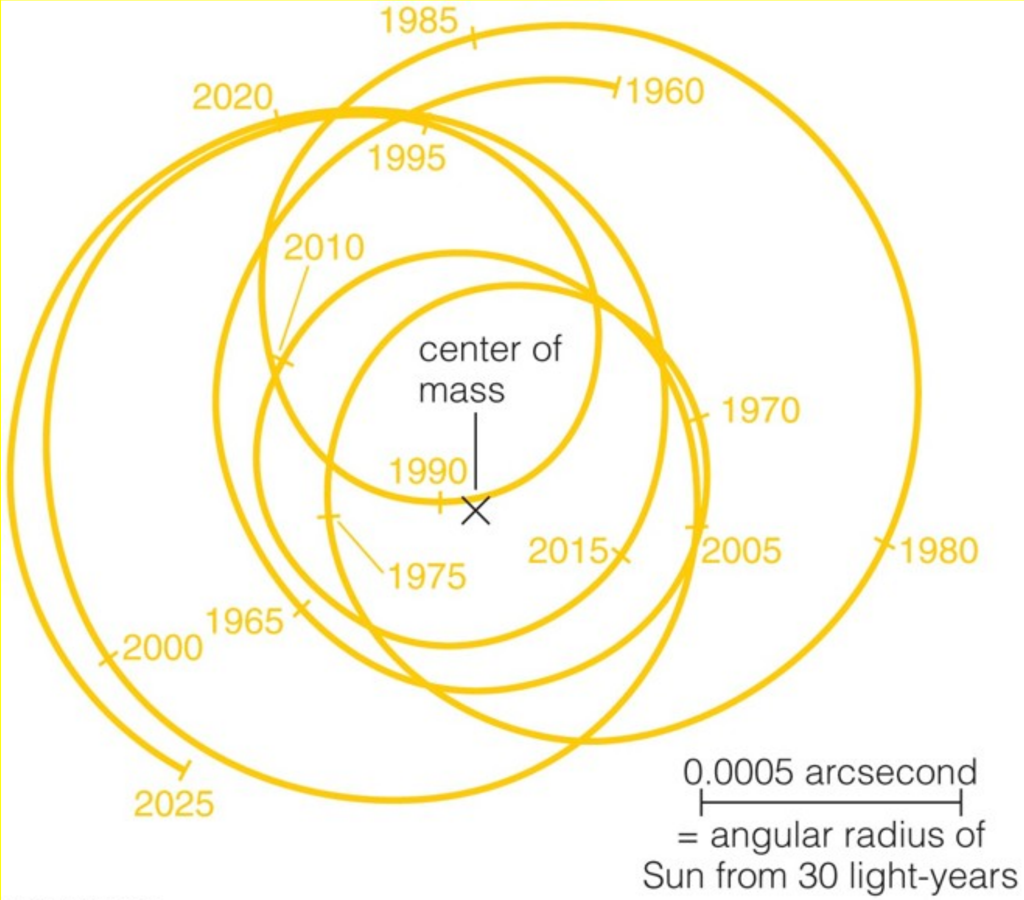
- The Sun and Jupiter orbit around their common center of mass.
- The Sun therefore wobbles around that center of mass with same period as Jupiter.

Gravitational Tugs



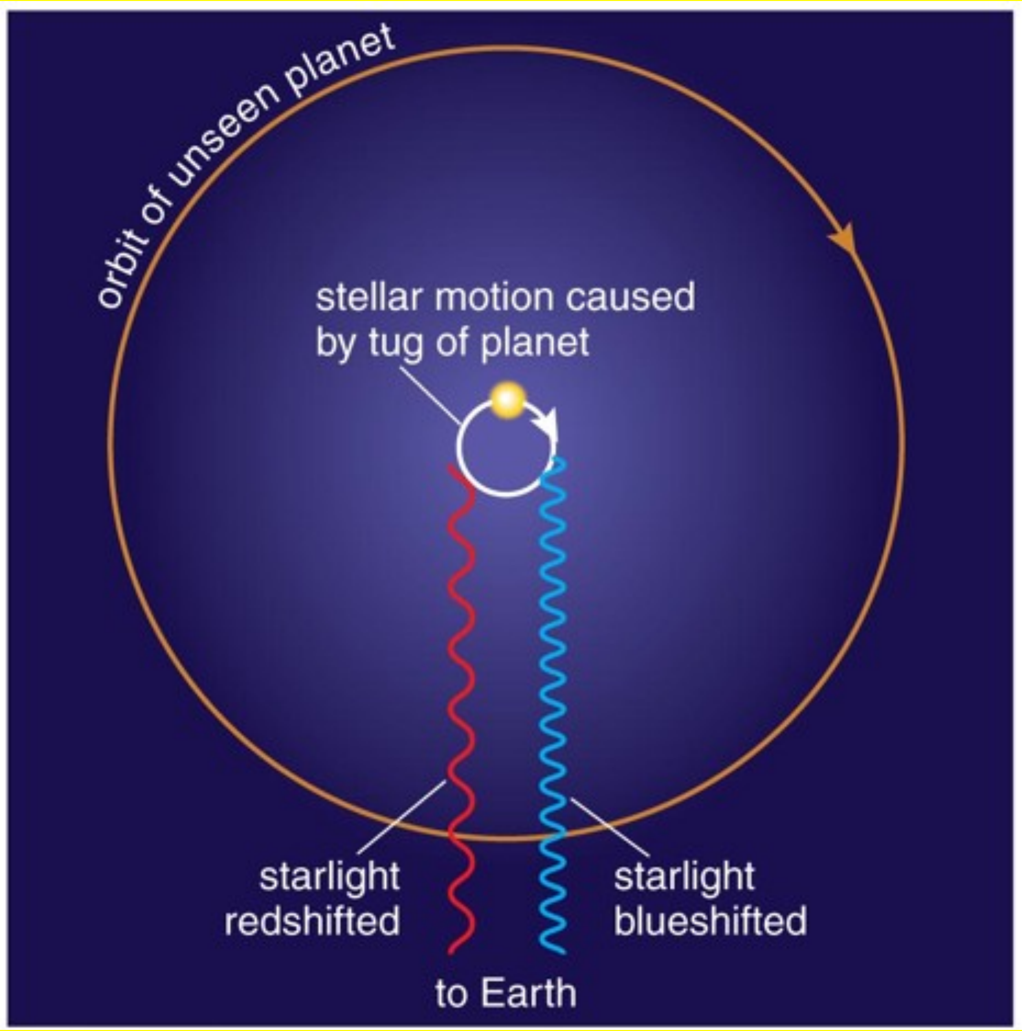
- The Sun's motion around the solar system's center of mass depends on tugs from all the planets.
- Astronomers around other stars that measured this motion could determine the masses and orbits of all the planets.

Astrometric Technique



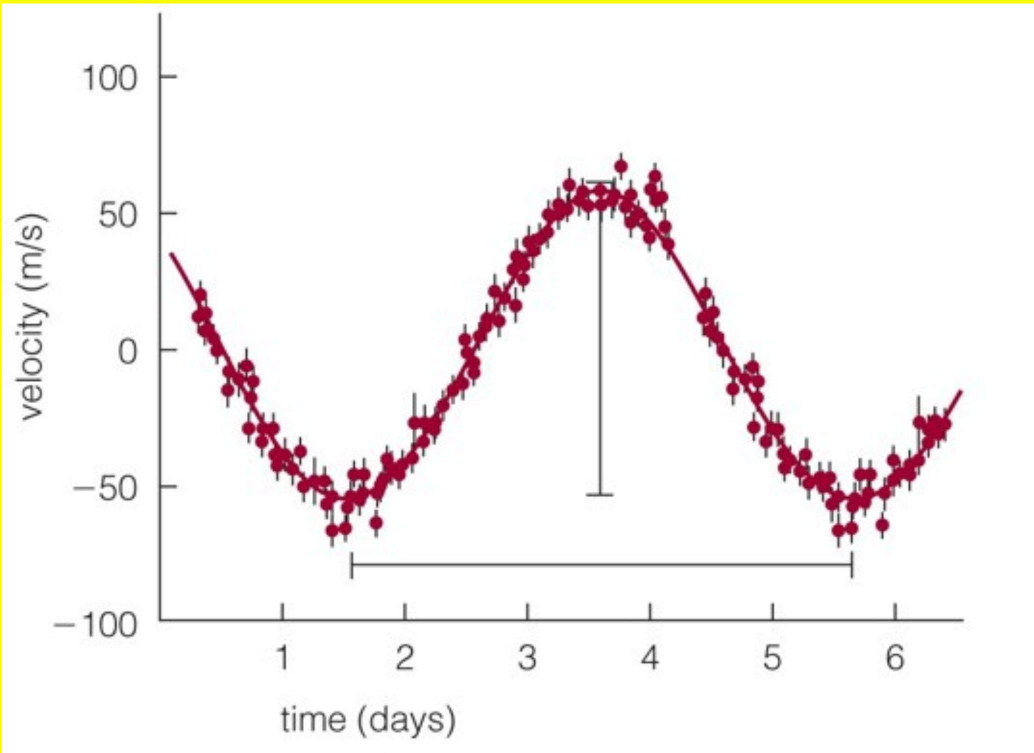
- We can detect planets by measuring the change in a star's position on sky.
- However, these tiny motions are very difficult to measure (~ 0.001 arcsecond).

Doppler Technique



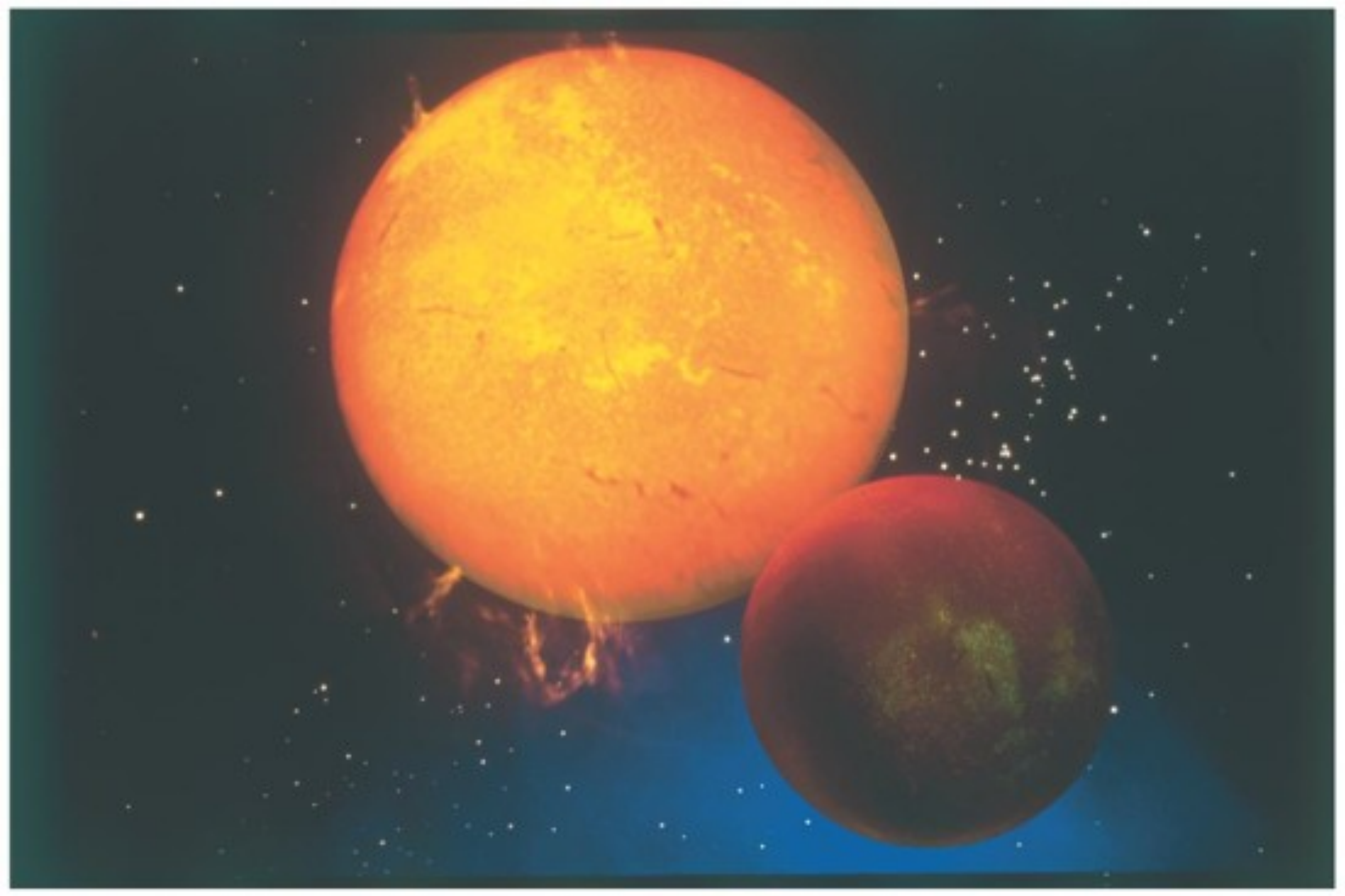
- Measuring a star's Doppler shift can tell us its motion toward and away from us.
- Current techniques can measure motions as small as 1 m/s (walking speed!).

First Extrasolar Planet



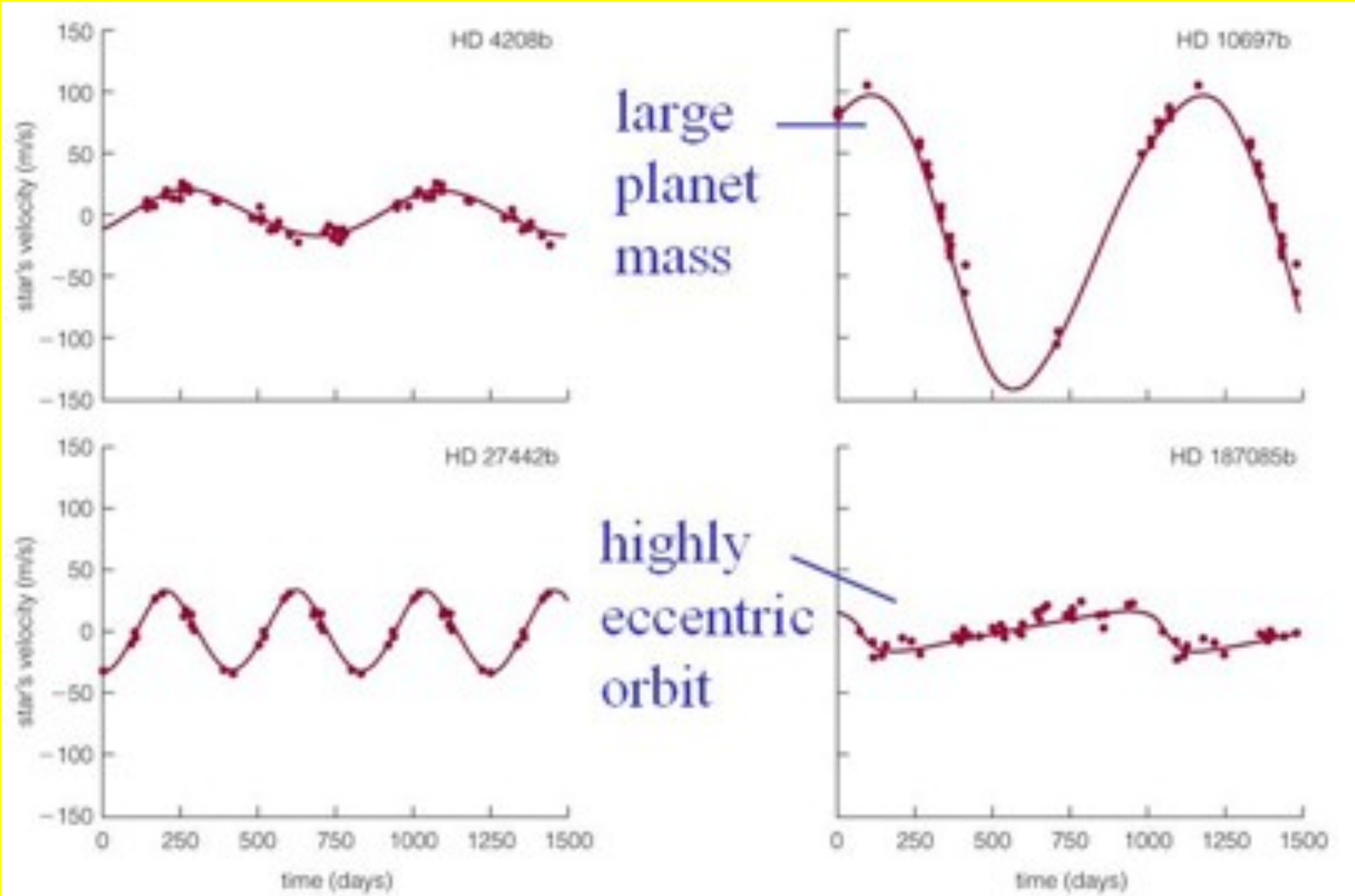
- Doppler shifts of the star 51 Pegasi indirectly revealed a planet with 4-day orbital period.
- This short period means that the planet has a small orbital distance.
- This was the first extrasolar planet to be discovered (1995).

First Extrasolar Planet



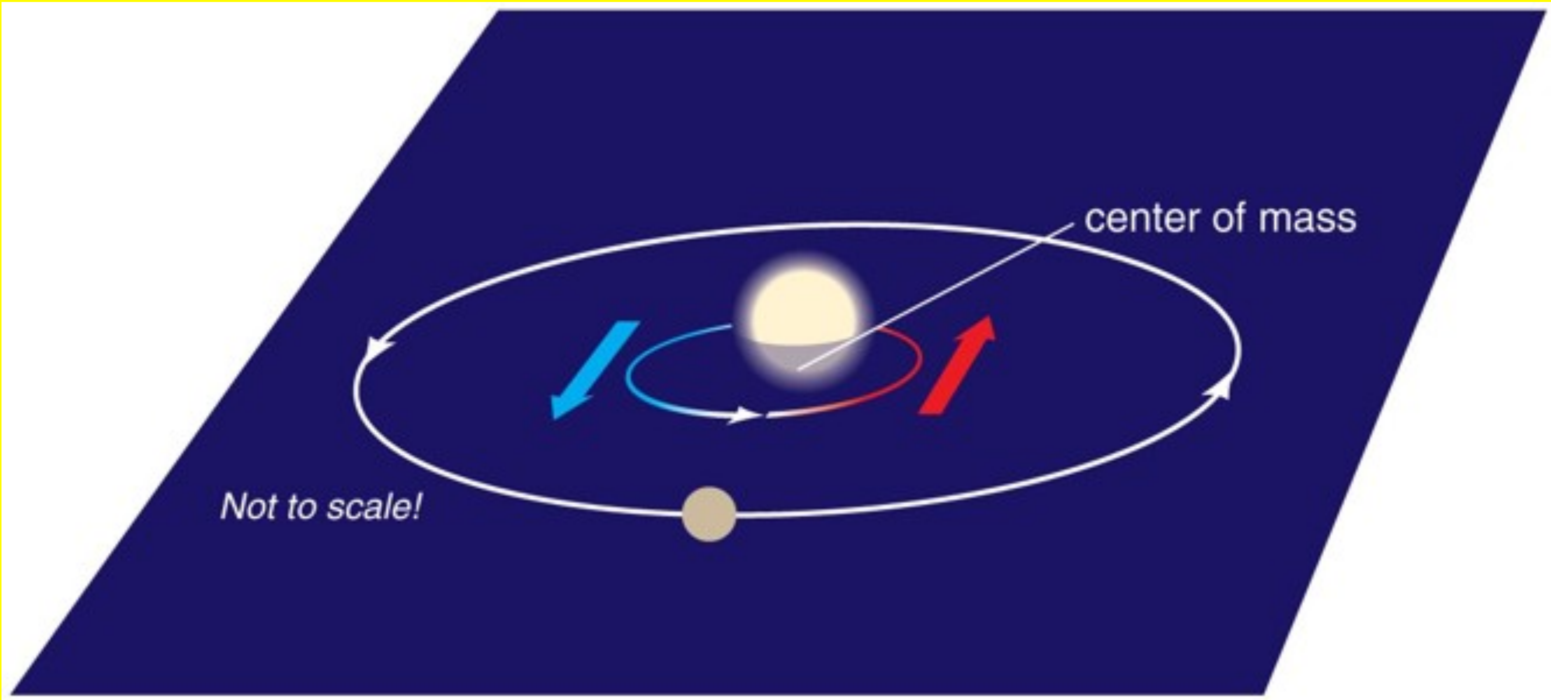
- The planet around 51 Pegasi has a mass similar to Jupiter's, despite its small orbital distance.

Other Extrasolar Planets



- Doppler shift data tell us about a planet's mass and the shape of its orbit.

Planet Mass and Orbit Tilt



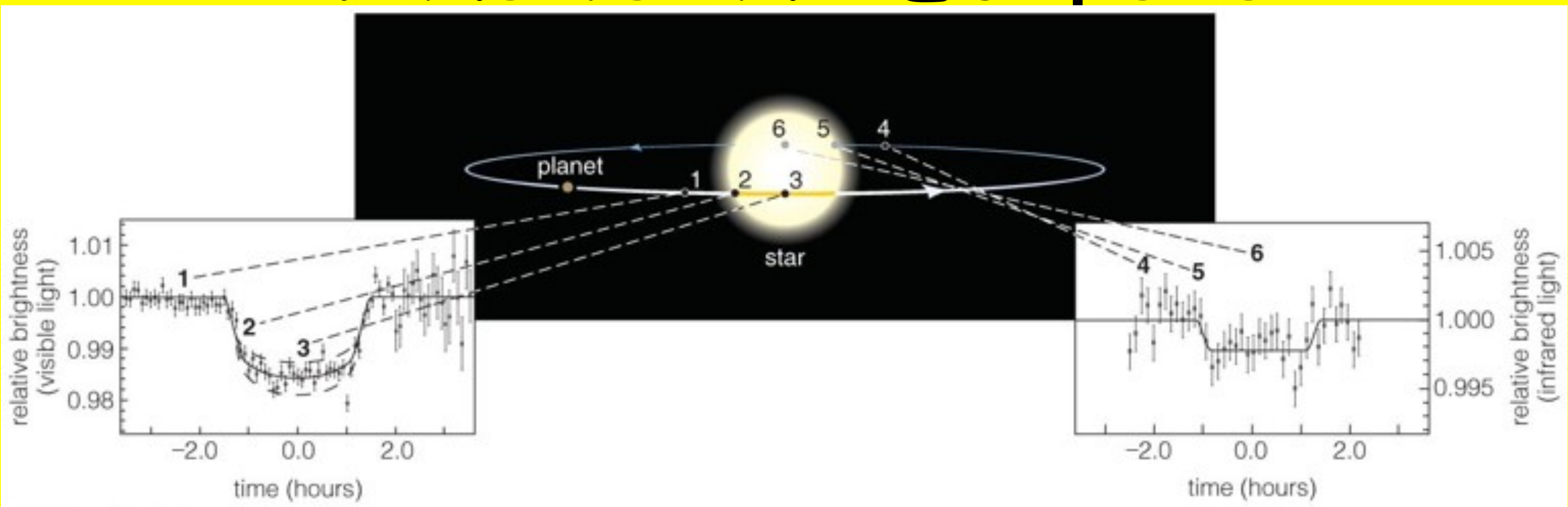
- We cannot measure an exact mass for a planet without knowing the tilt of its orbit, because Doppler shift tells us only the velocity toward or away from us.
- Doppler data give us lower limits on masses.

Thought Question

Suppose you found a star with the same mass as the Sun moving back and forth with a period of 16 months. What could you conclude?

A. It has a planet orbiting at less than 1 AU.
B. It has a planet orbiting at greater than 1 AU.
C. It has a planet orbiting at exactly 1 AU.
D. It has a planet, but we do not have enough information to know its orbital distance.

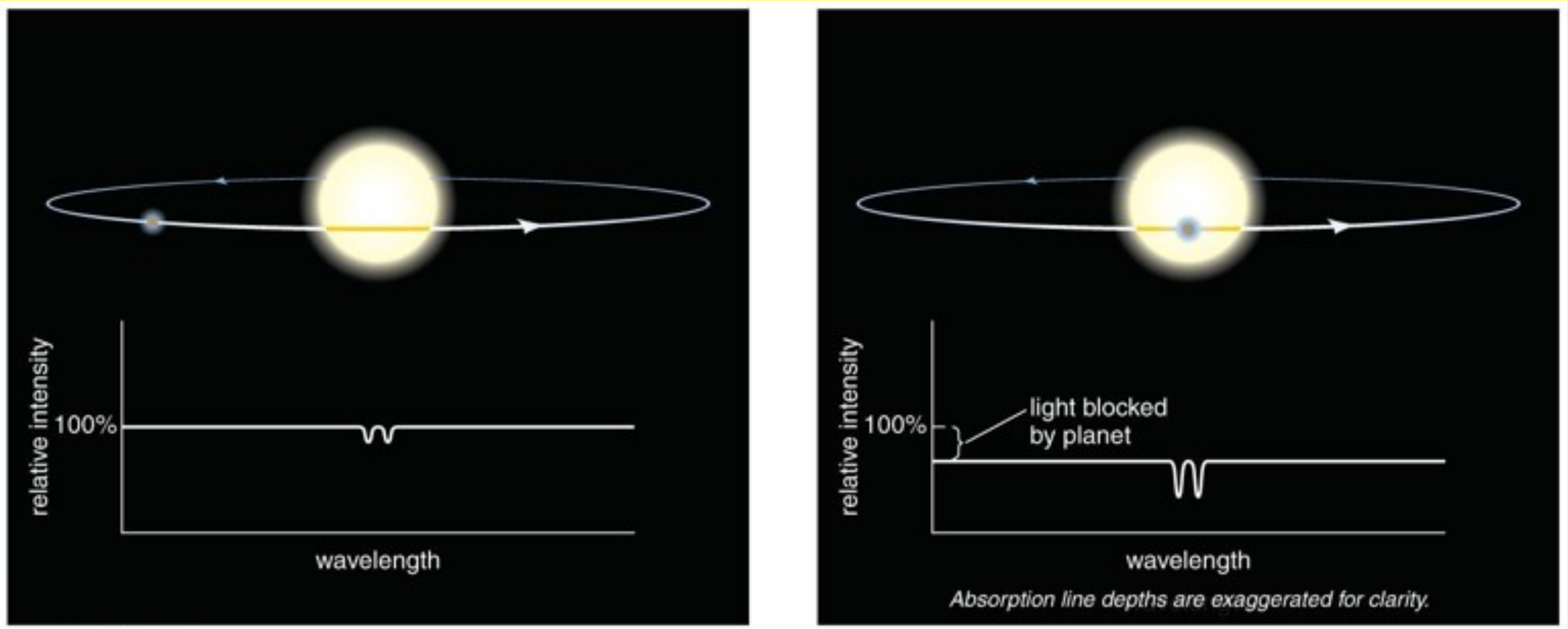
Transits and Eclipses



- 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.
- No orbital tilt: accurate measurement of planet mass

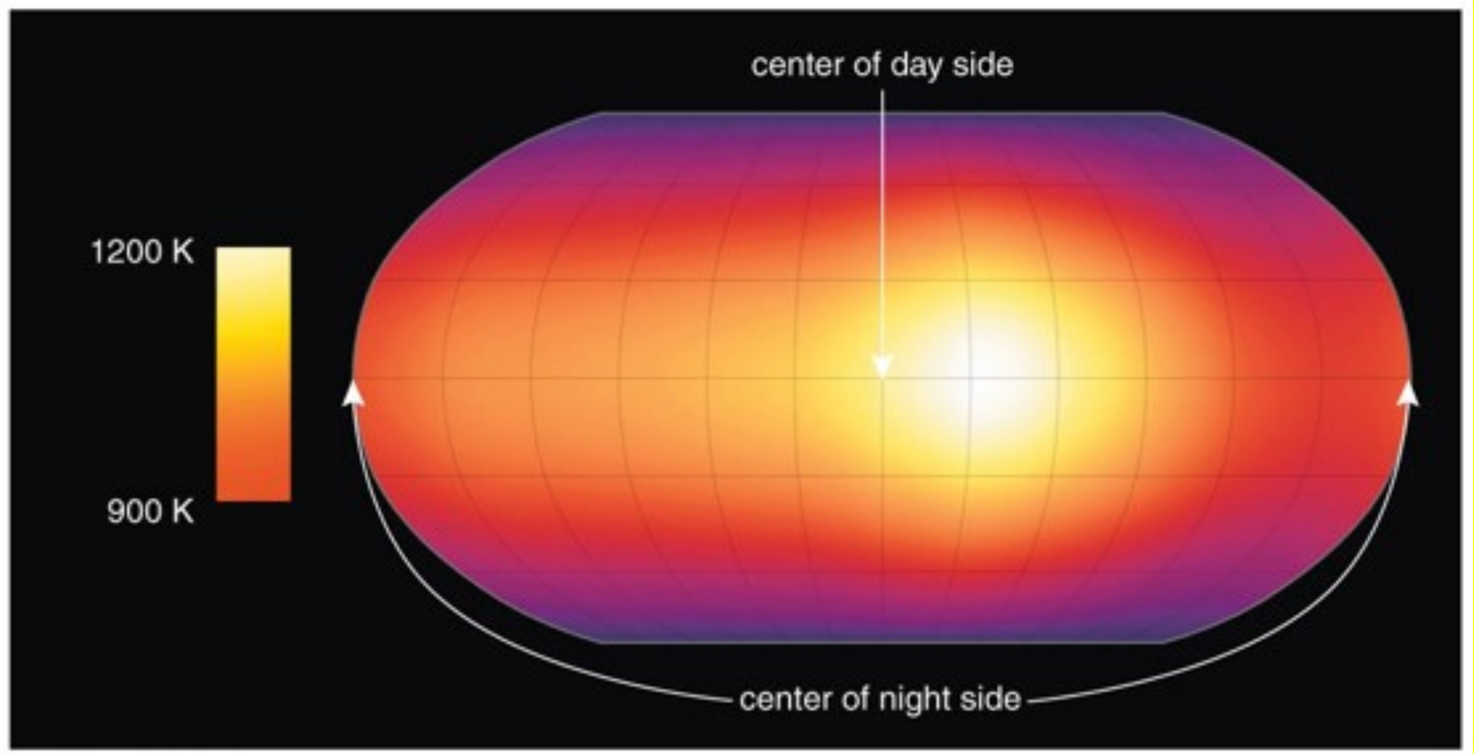
Interactive Figure

Spectrum During Transit



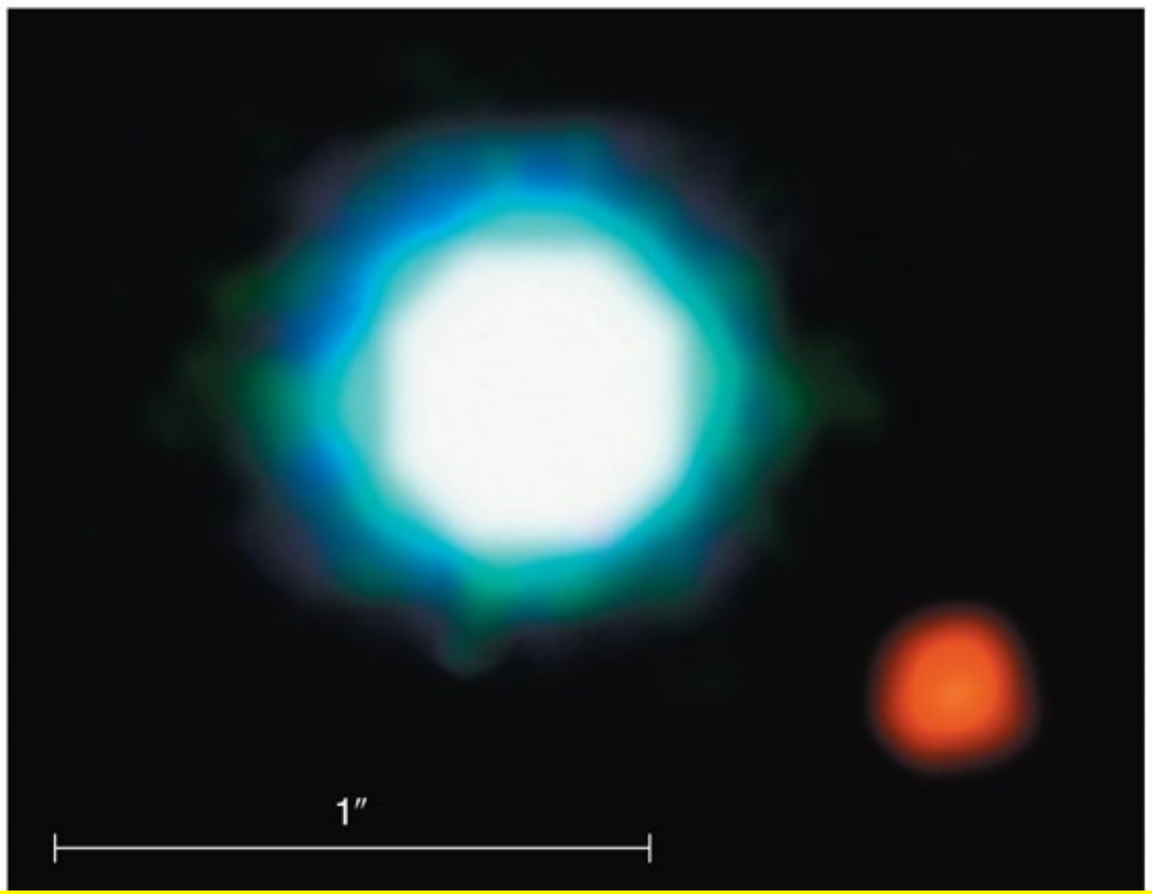
- Change in spectrum during a transit tells us about the composition of planet's atmosphere.

Surface Temperature Map



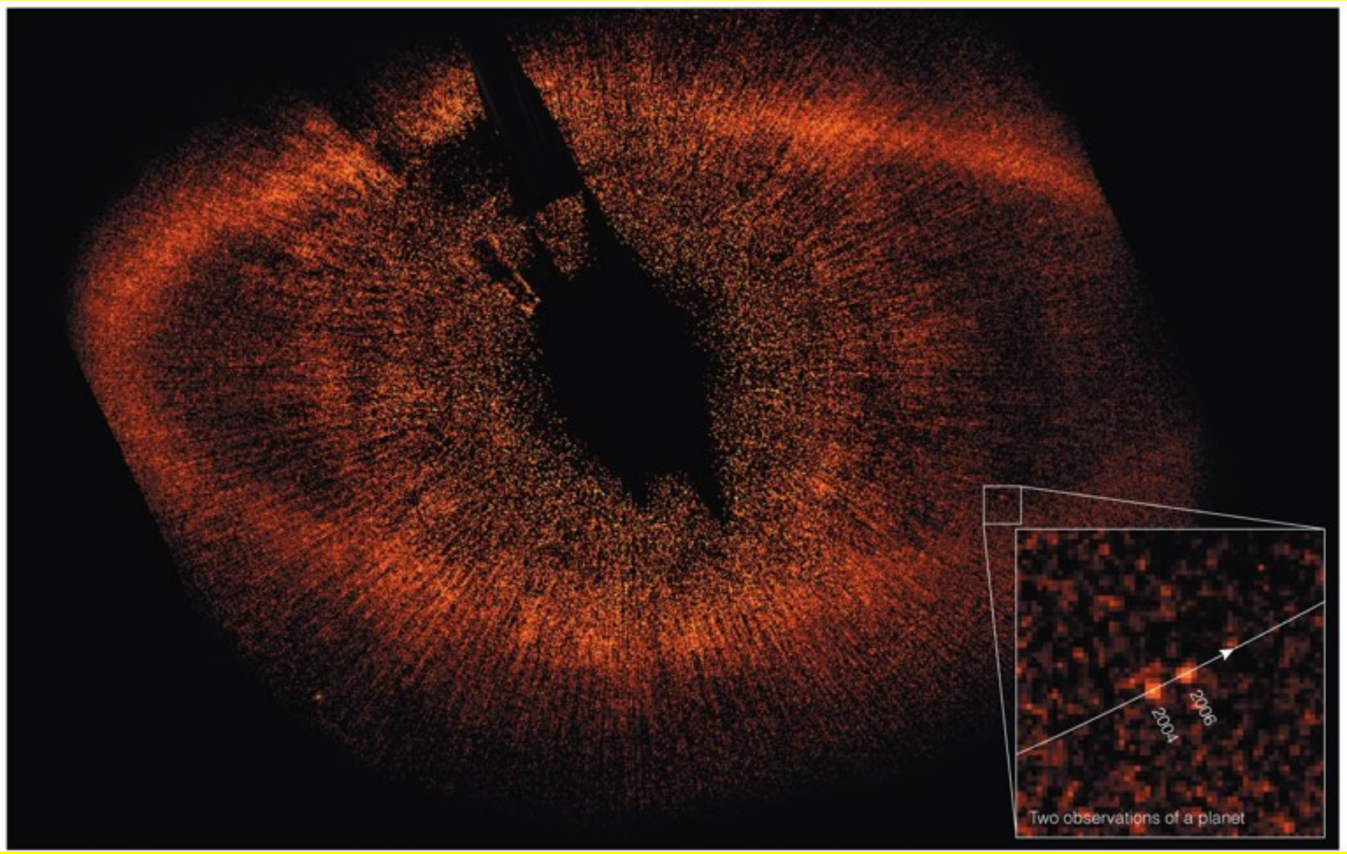
- Measuring the change in infrared brightness during an eclipse enables us to map a planet's surface temperature.

Direct Detection



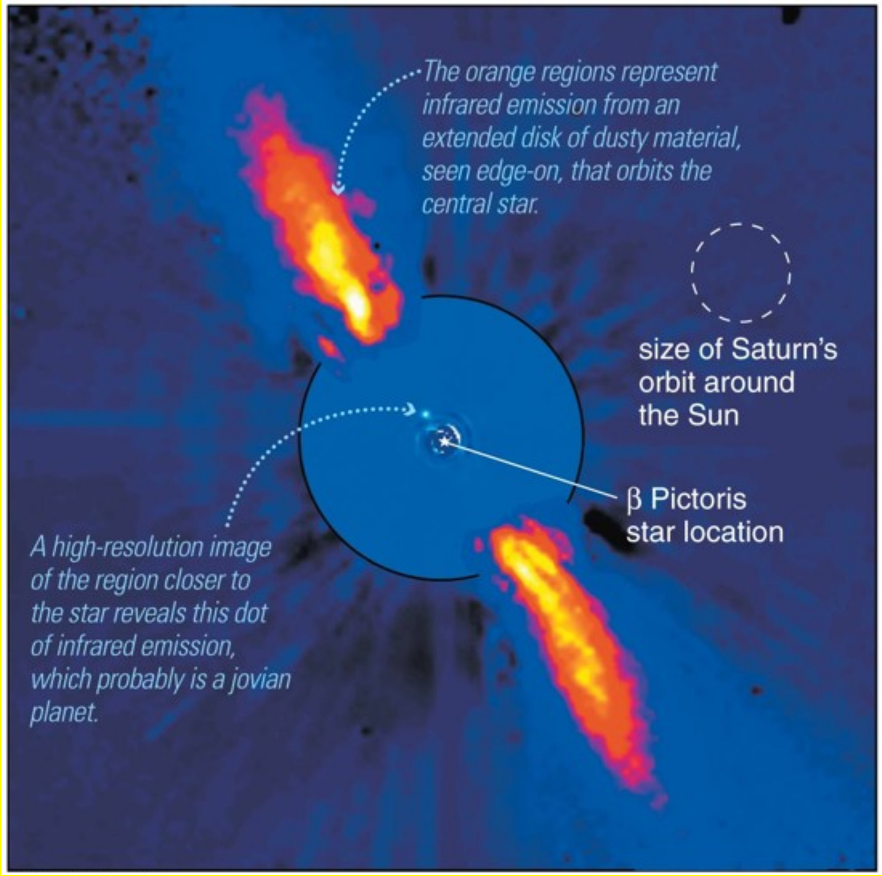
- Special techniques like adaptive optics are helping to enable direct planet detection.

Direct Detection



- Techniques that help block the bright light from stars are also helping us to find planets around them.

Direct Detection



- Techniques that help block the bright light from stars are also helping us to find planets around them.

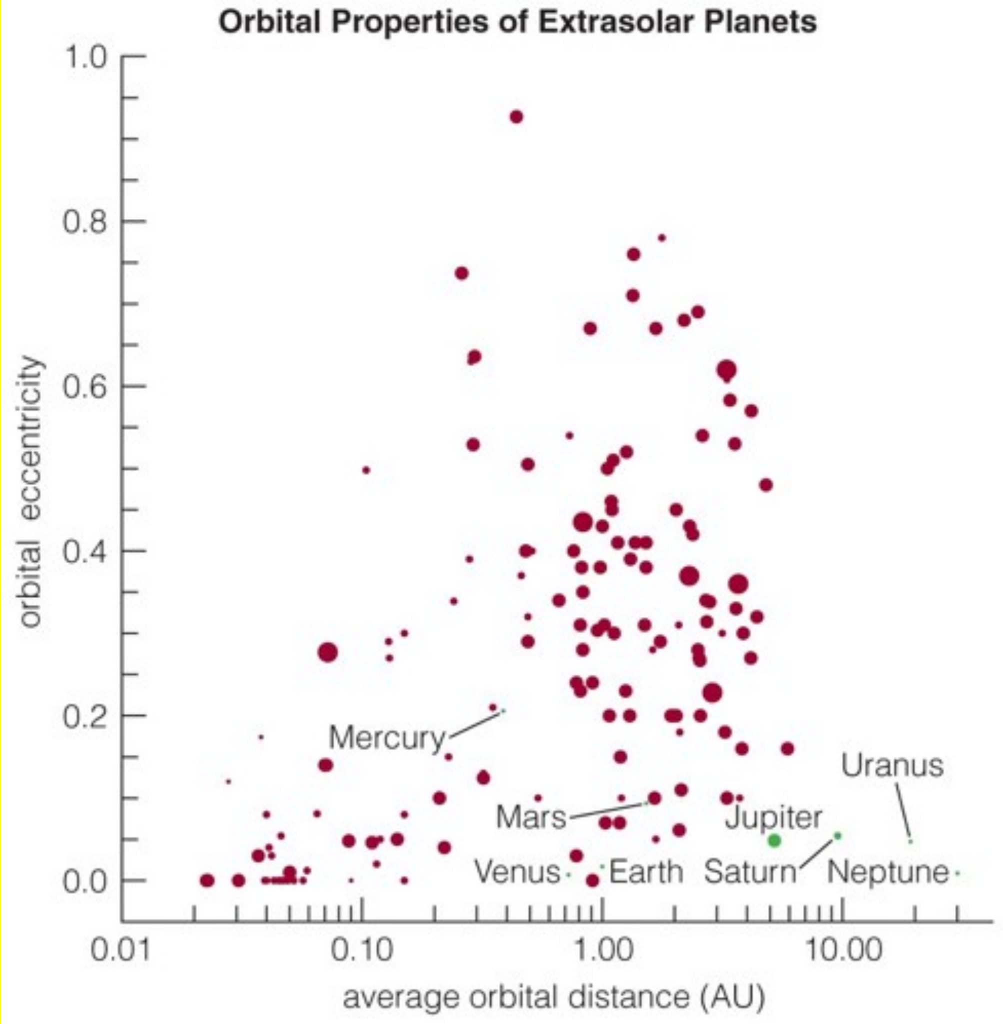
Other Planet-Hunting Strategies

- **Gravitational Lensing:** Mass bends light in a special way when a star with planets passes in front of another star.
- **Features in Dust Disks:** Gaps, waves, or ripples in disks of dusty gas around stars can indicate presence of planets.

The Nature of Extrasolar Planets

- What have we learned about extrasolar planets?
- How do extrasolar planets compare with planets in our solar system?

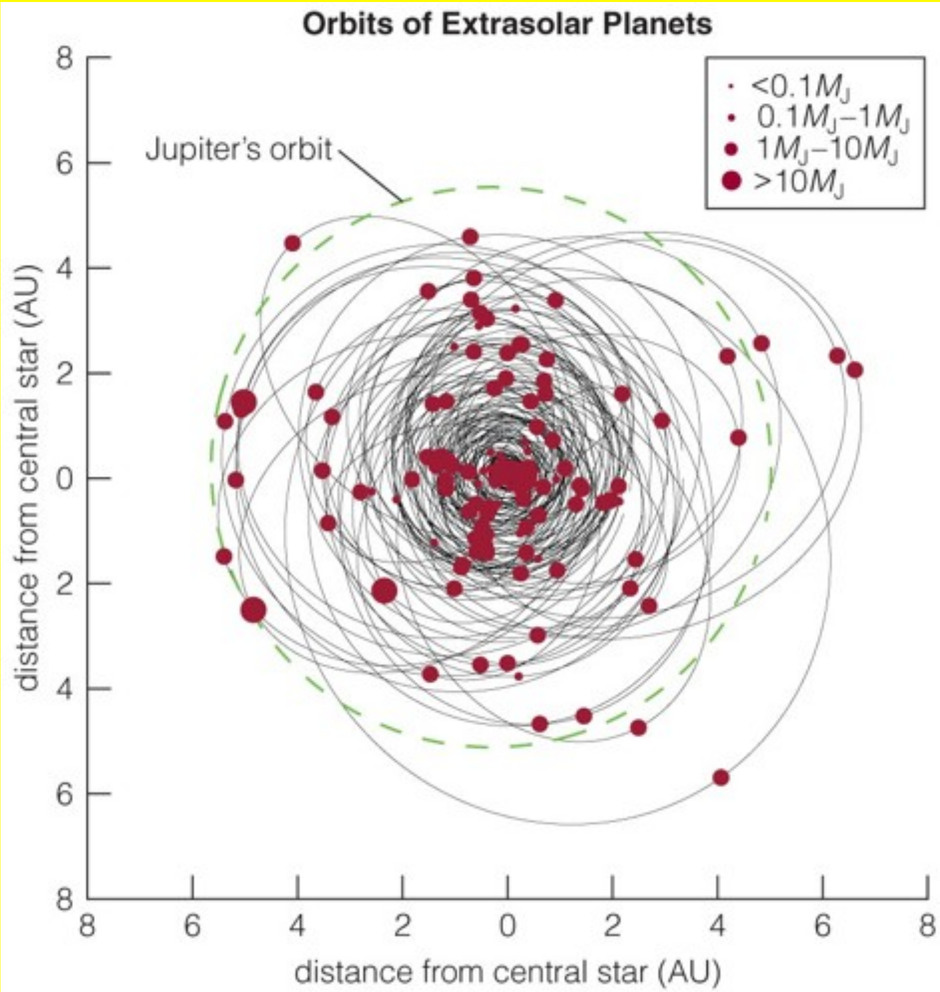
What have we learned about extrasolar planets?



Measurable Properties

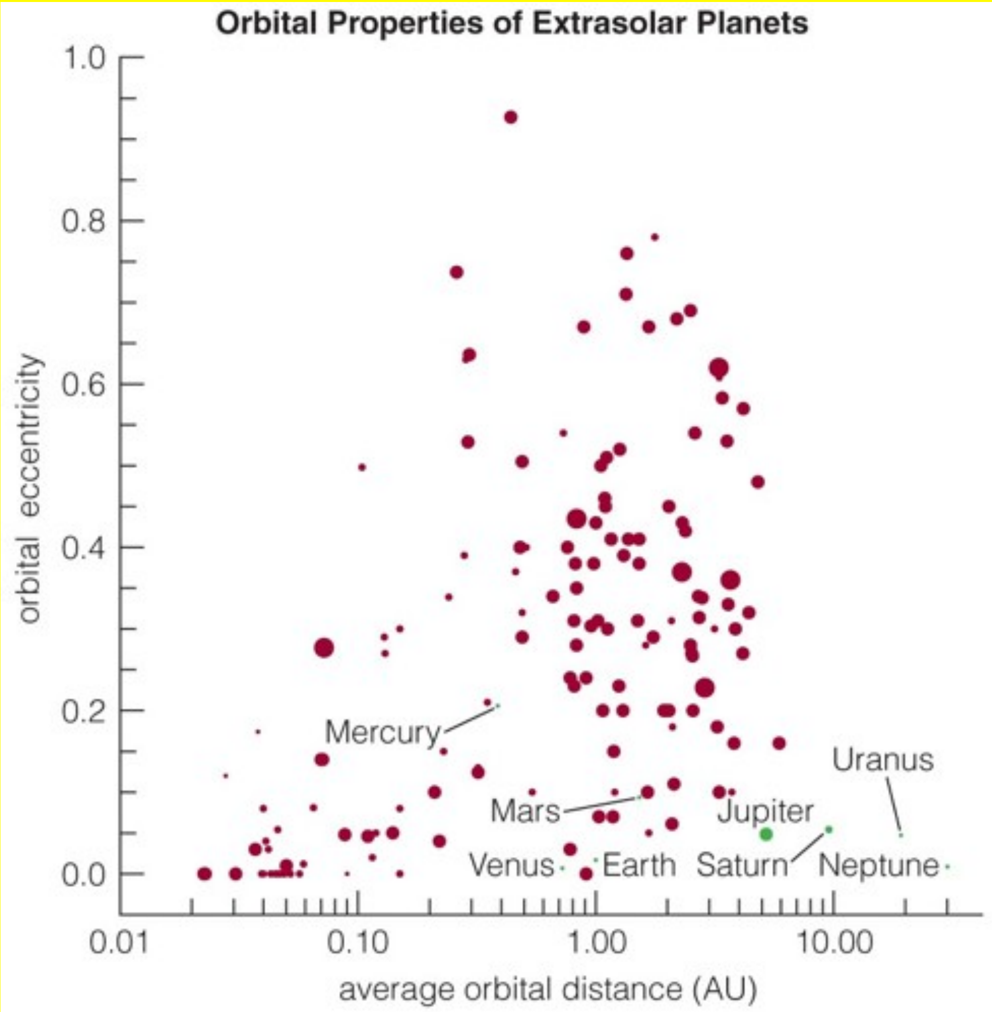
- Orbital period, distance, and Shape
- Planet mass, size, and density
- Composition

Orbits of Extrasolar Planets



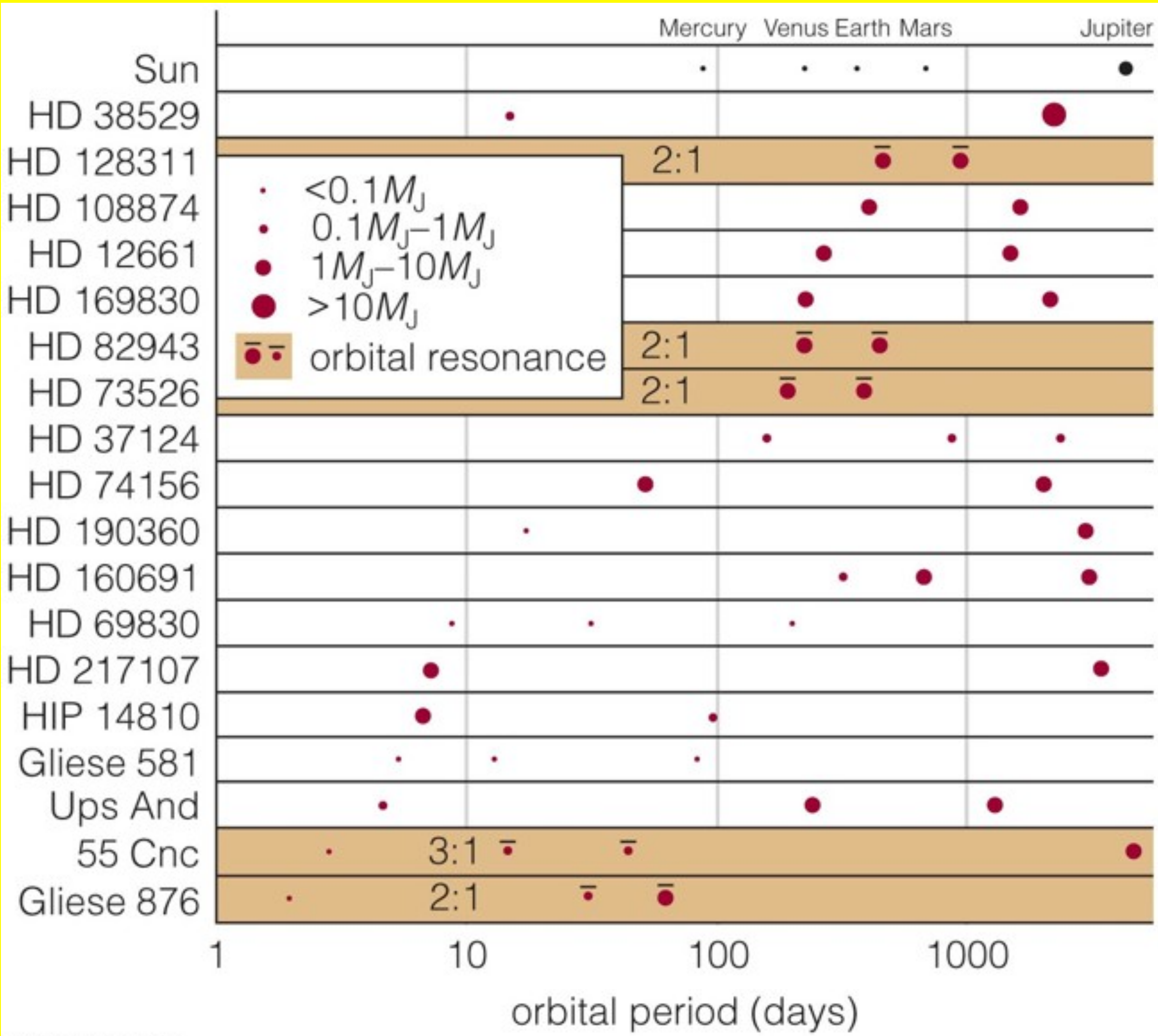
- Most of the detected planets have orbits smaller than Jupiter's.
- Planets at greater distances are harder to detect with the Doppler technique.

Orbits of Extrasolar Planets



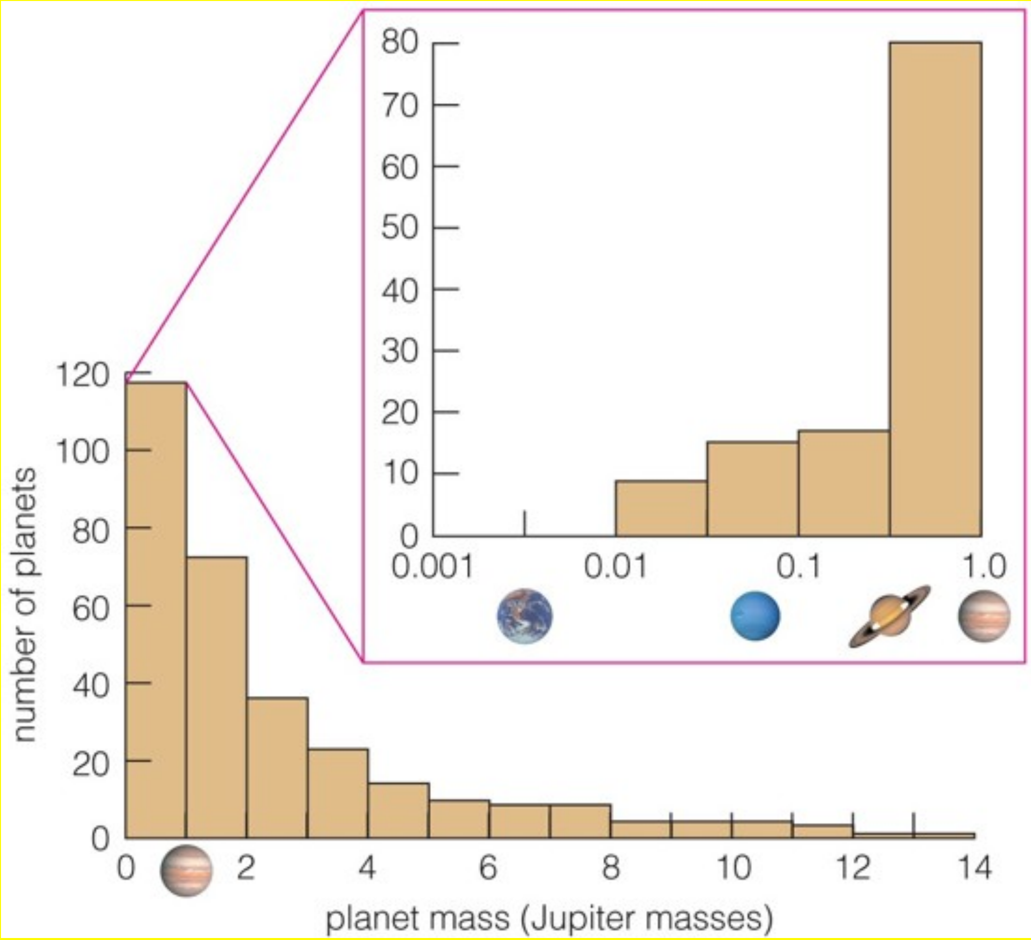
- Orbits of some extrasolar planets are much more elongated (have a greater eccentricity) than those in our solar system.

Multiple-Planet Systems



- Some stars have more than one detected planet.

Orbits of Extrasolar Planets



- Most of the detected planets have greater mass than Jupiter.
- Planets with smaller masses are harder to detect with Doppler technique.

How do extrasolar planets compare with planets in our solar system?

Surprising Characteristics

- Some extrasolar planets have highly elliptical orbits.

- Some massive planets, called *hot Jupiters*, orbit very close to their stars.

Hot Jupiters

Jupiter

Composed primarily of hydrogen and helium
5 AU from the Sun
Orbit takes 12 Earth years
Cloudtop temperatures ≈130 K
Clouds of various hydrogen compounds
Radius = 1 Jupiter radius
Mass = 1 Jupiter mass
Average density = 1.33 g/cm^3
Moons, rings, magnetosphere

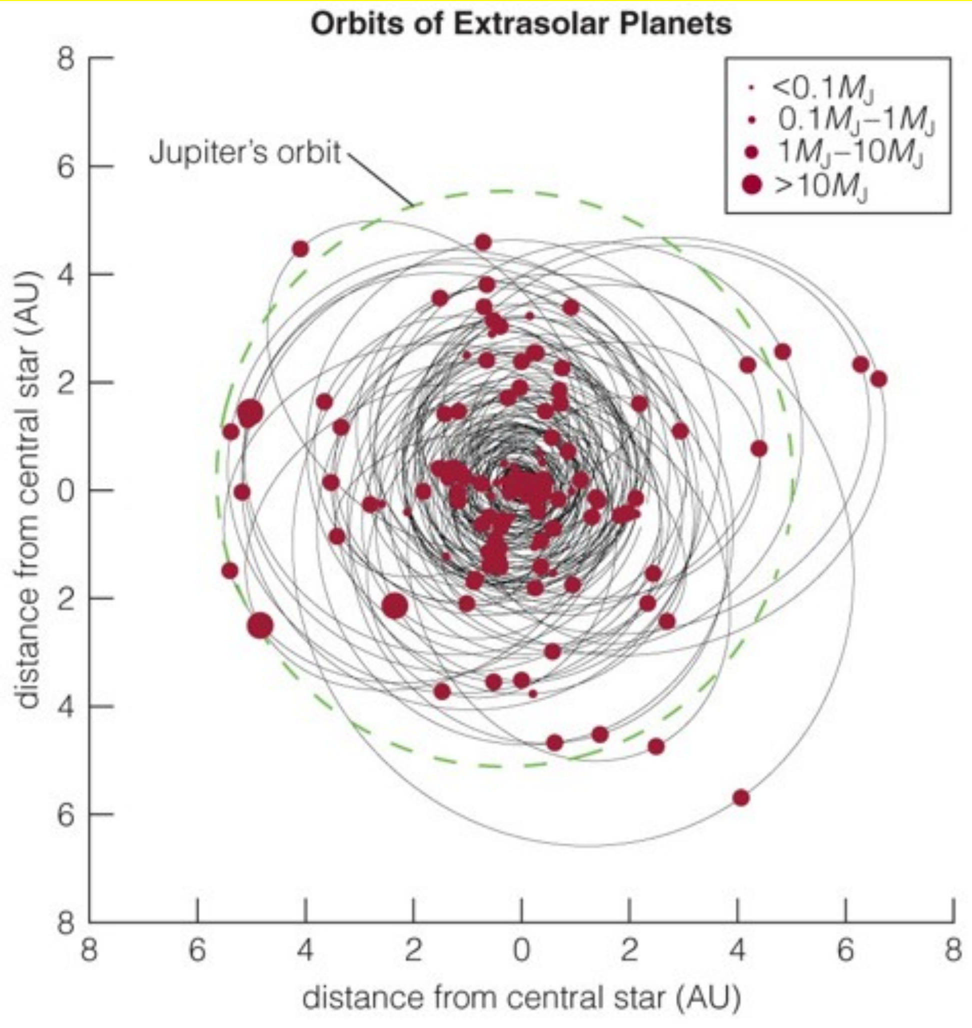
Hot Jupiters orbiting other stars

Composed primarily of hydrogen and helium
As close as 0.03 AU to their stars
Orbit as short as 1.2 Earth days
Cloudtop temperatures up to 1300 K
Clouds of "rock dust"
Radius up to 1.3 Jupiter radii
Mass from 0.2 to 2 Jupiter masses
Average density as low as 0.2 g/cm^3
Moons, rings, magnetospheres: unknown

The Formation of Other Solar Systems

- Can we explain the surprising orbits of many extrasolar planets?
- Do we need to modify our theory of solar system formation?

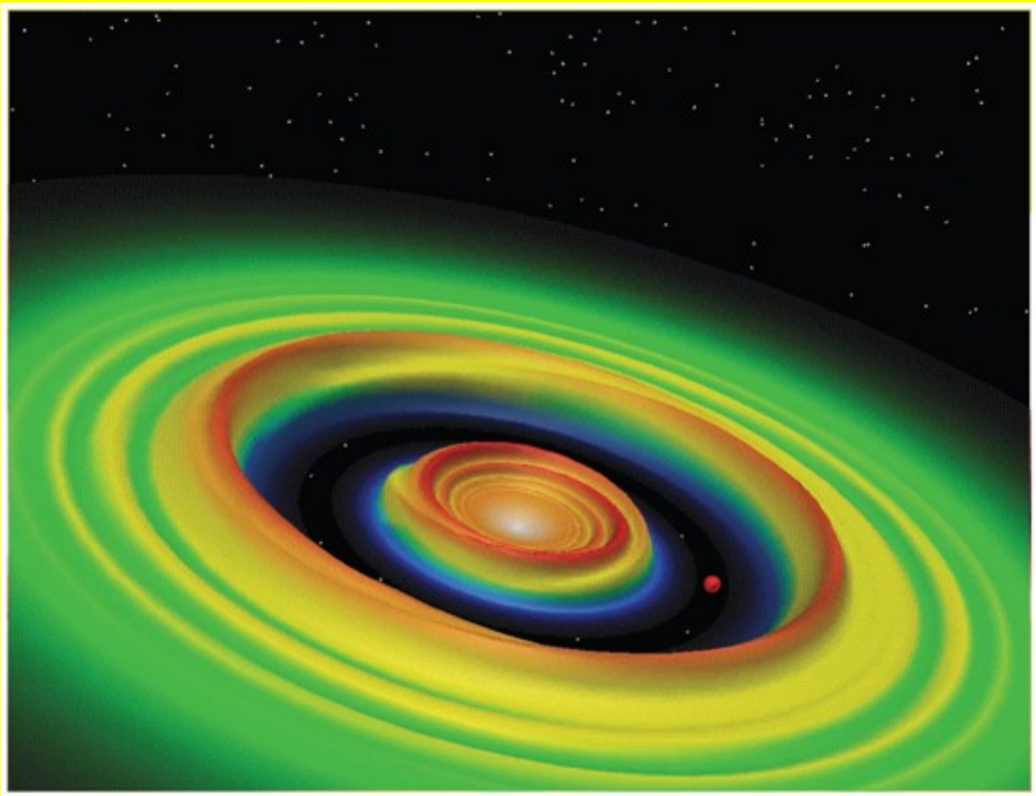
Can we explain the surprising orbits of many extrasolar planets?



Revisiting the Nebular Theory

- The nebular theory predicts that massive Jupiter-like planets should not form inside the frost line (at << 5 AU).
- The discovery of hot Jupiters has forced reexamination of nebular theory.
- *Planetary migration* or gravitational encounters may explain hot Jupiters.

Planetary Migration

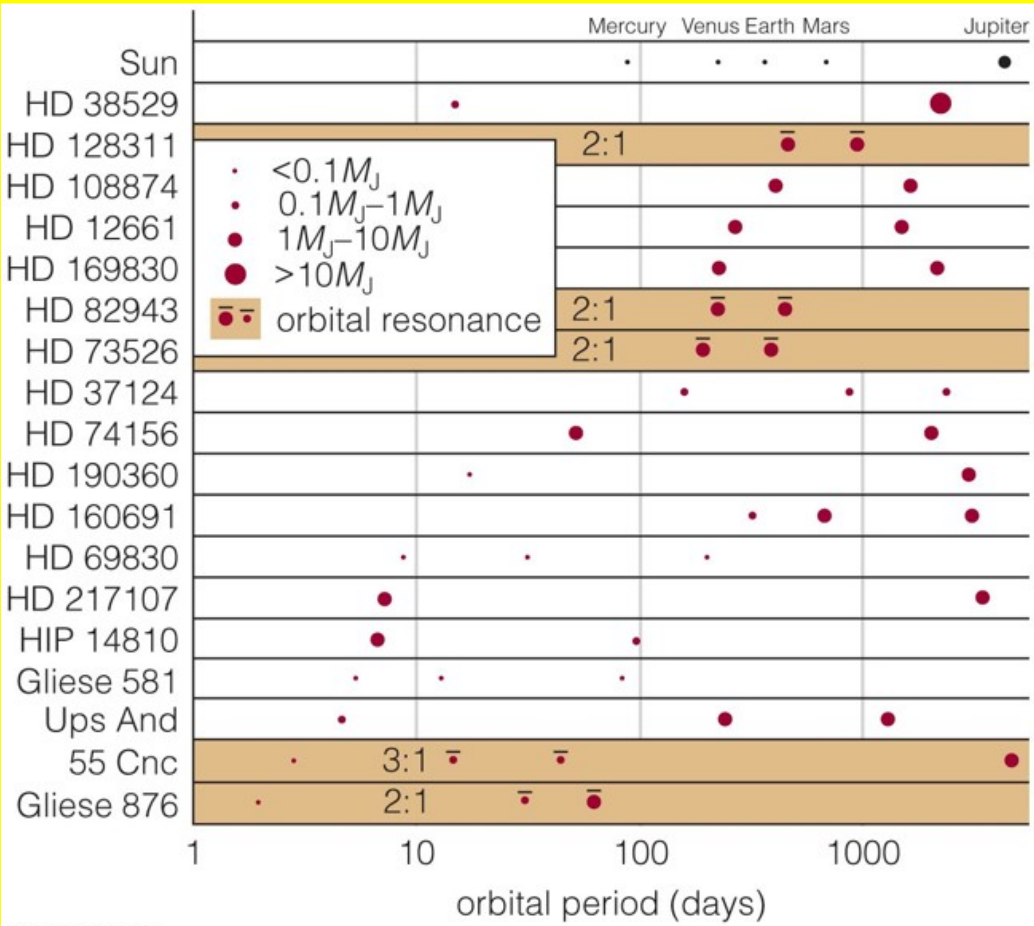


- A young planet's motion can create waves in a planet-forming disk.
- Models show that matter in these waves can tug on a planet, causing its orbit to migrate inward.

Gravitational Encounters

- Close gravitational encounters between two massive planets can eject one planet while flinging the other into a highly elliptical orbit.
- Multiple close encounters with smaller planetesimals can also cause inward migration.

Orbital Resonances



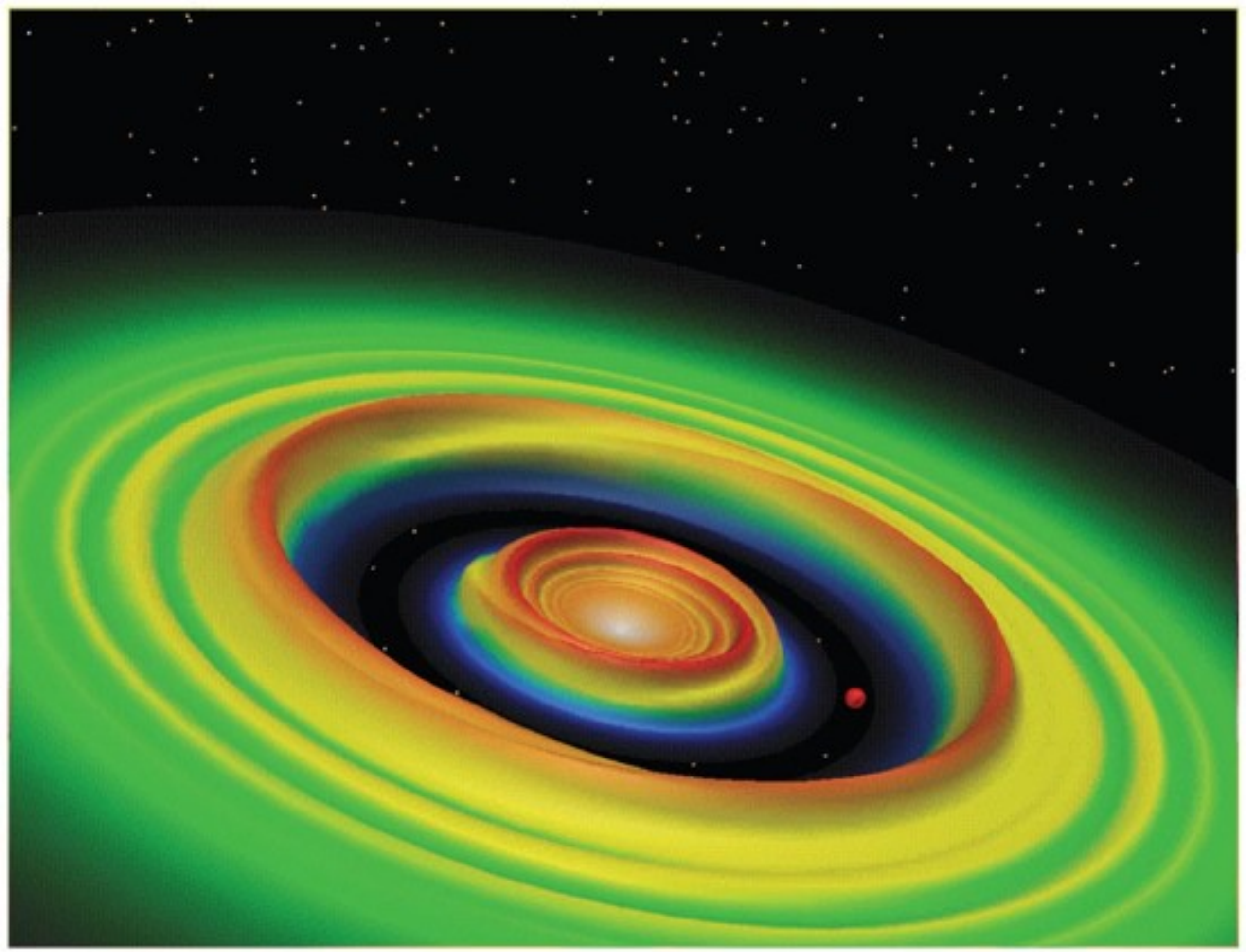
- Resonances between planets can also cause their orbits to become more elliptical.

Thought Question

What happens in a gravitational encounter that allows a planet's orbit to move inward?

A. It transfers energy and angular momentum to another object.
B. The gravity of the other object forces the planet to move inward.
C. It gains mass from the other object, causing its gravitational pull to become stronger.

Do we need to modify our theory of solar system formation?



Modifying the Nebular Theory

- Observations of extrasolar planets have shown that the nebular theory was incomplete.

- Effects like planetary migration and gravitational encounters might be more important than previously thought.

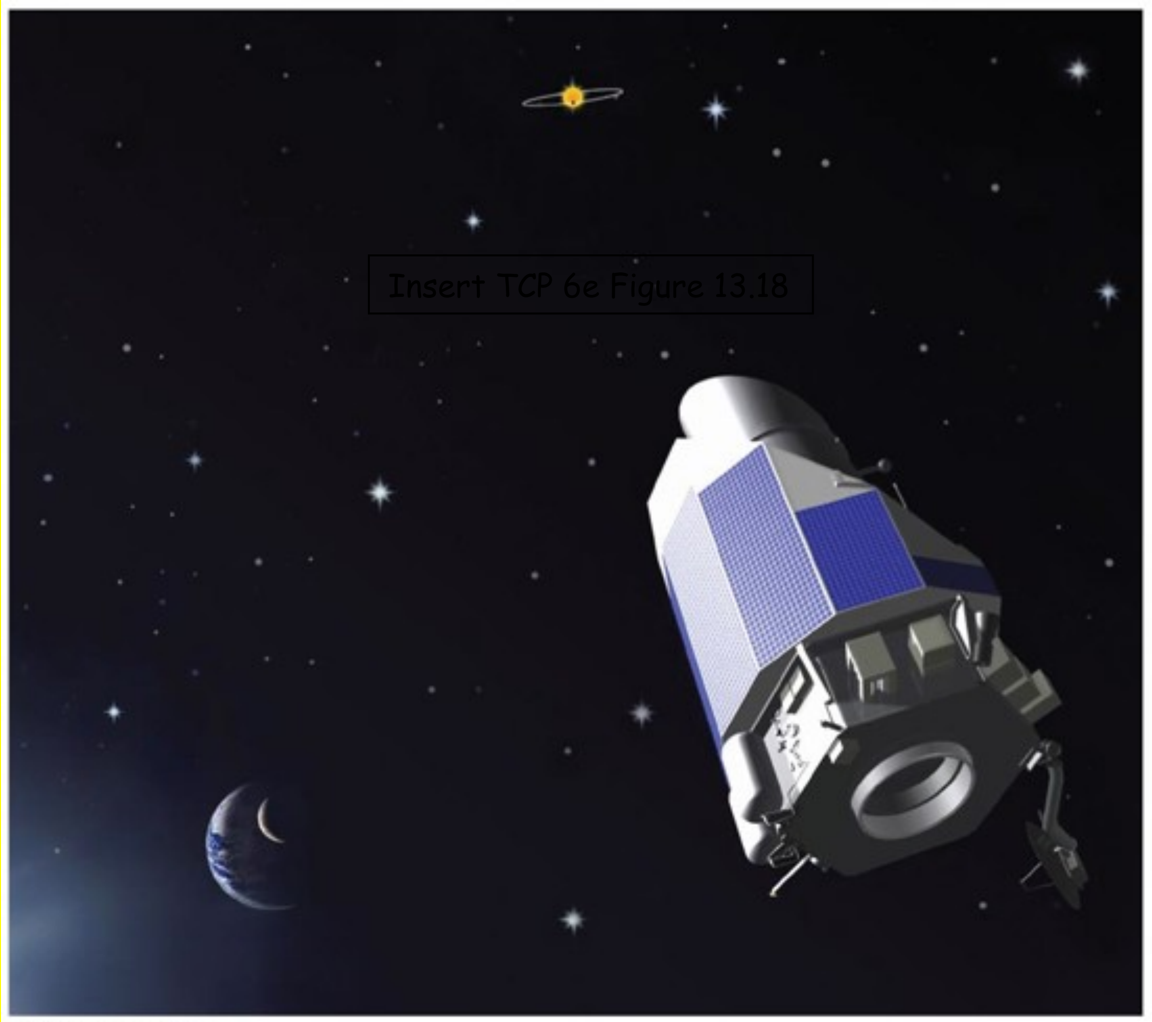
Planets: Common or Rare?

- One in ten stars examined so far have turned out to have planets.
- The others may still have smaller (Earth-sized) planets that current techniques cannot detect.

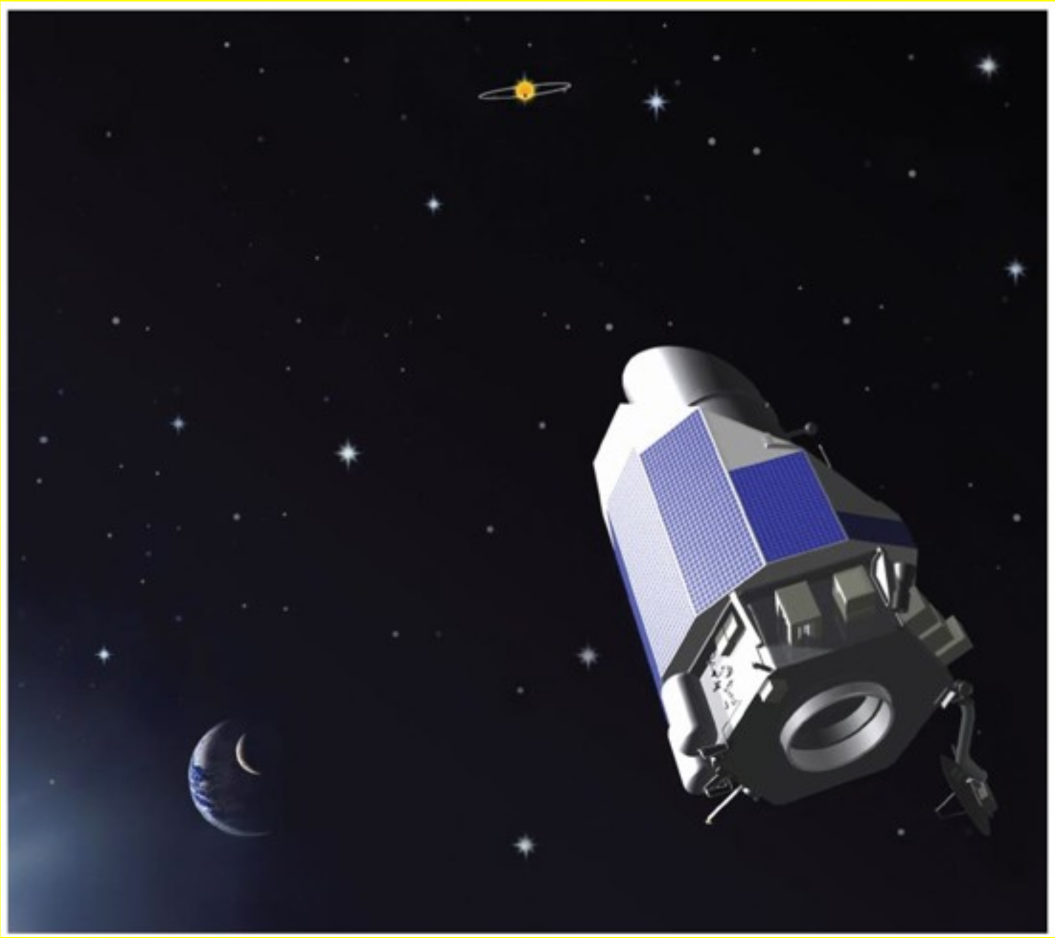
Finding More New Worlds

- How will we search for Earth-like planets?

How will we search for Earth-like planets?



Transit Missions



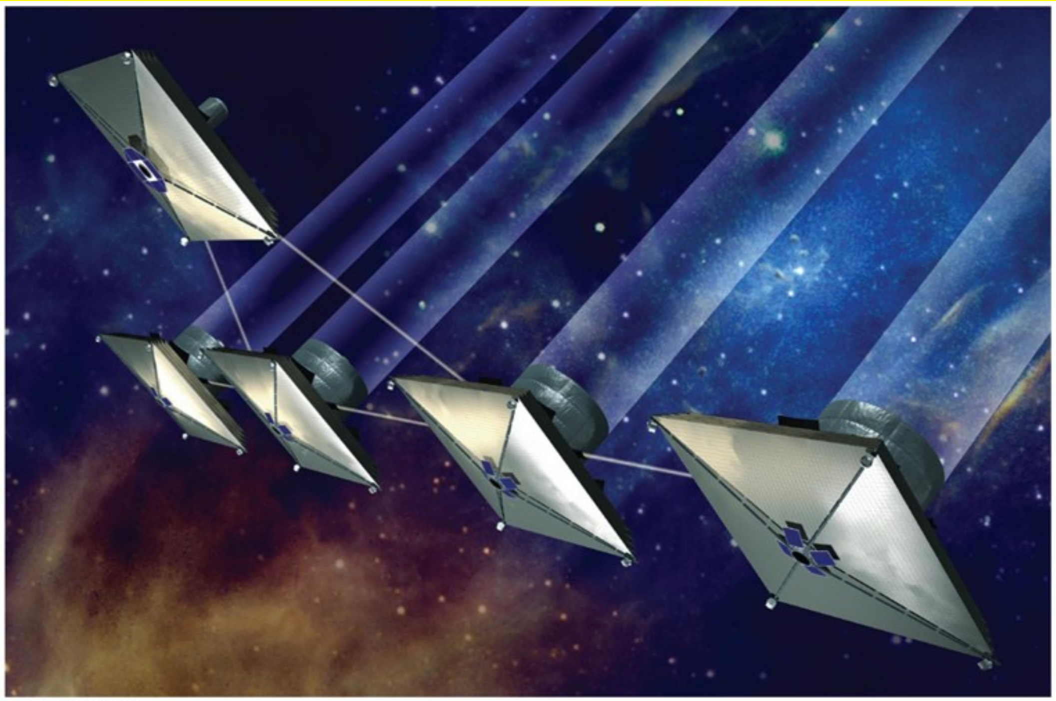
- NASA's *Kepler* mission was launched in 2008 to begin looking for transiting planets.
- It is designed to measure the 0.008% decline in brightness when an Earth-mass planet eclipses a Sun-like star.

Astrometric Missions

- *GAIA:* a European mission planned for 2011 that will use interferometry to measure precise motions of a billion stars

- *SIM: A* NASA mission that will use interferometry to measure star motions even more precisely (to 10^{-6} arcseconds)

Direct Detection



Mission concept for NASA's Terrestrial Planet Finder (TPF)

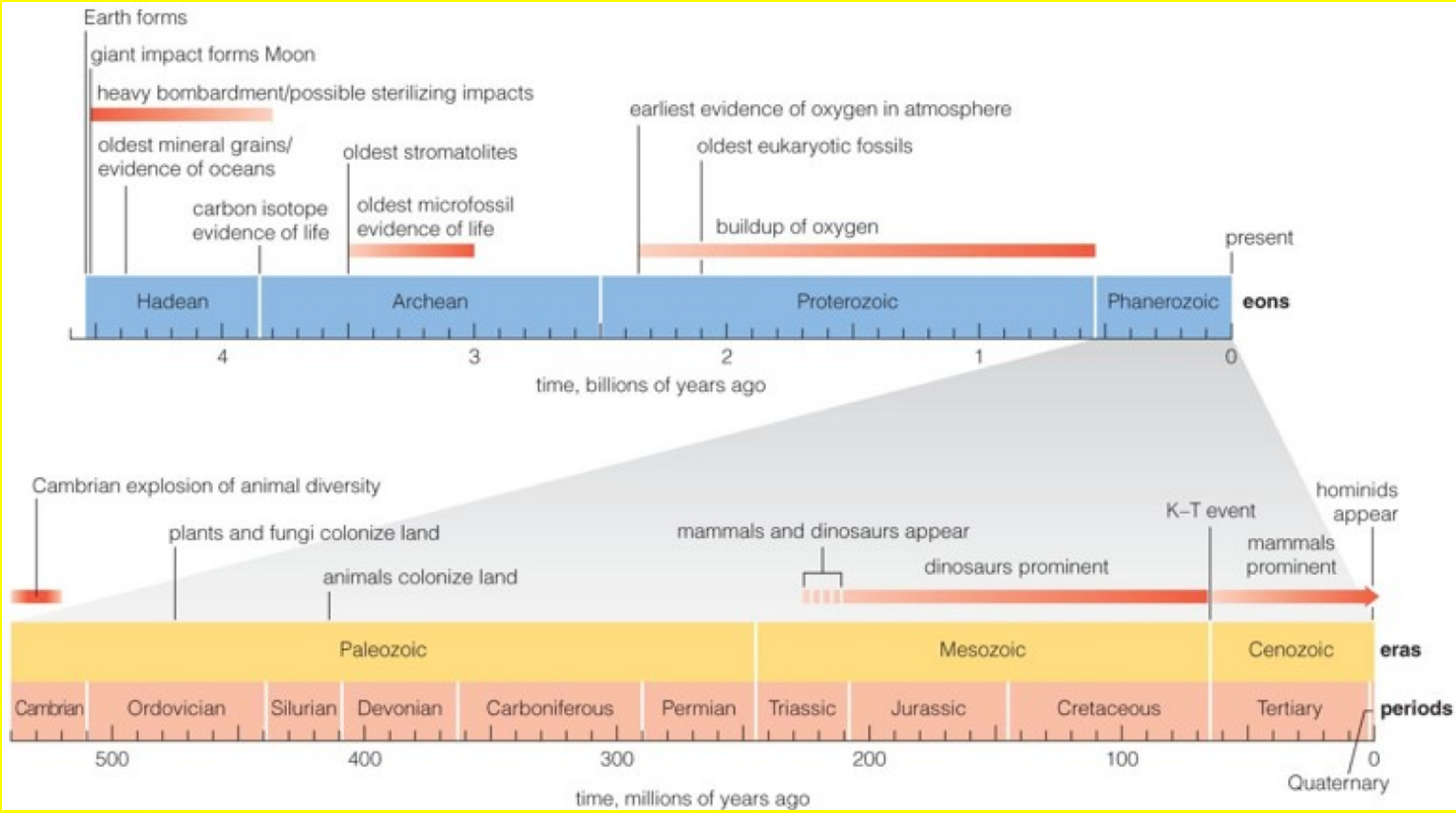
- Determining whether Earth-mass planets are really Earth-like requires direct detection.
- Missions capable of blocking enough starlight to measure the spectrum of an Earth-like planet are being planned.

Life in the Universe

Life on Earth

- When did life arise on Earth?
- How did life arise on Earth?
- What are the necessities of life?

When did life arise on Earth?

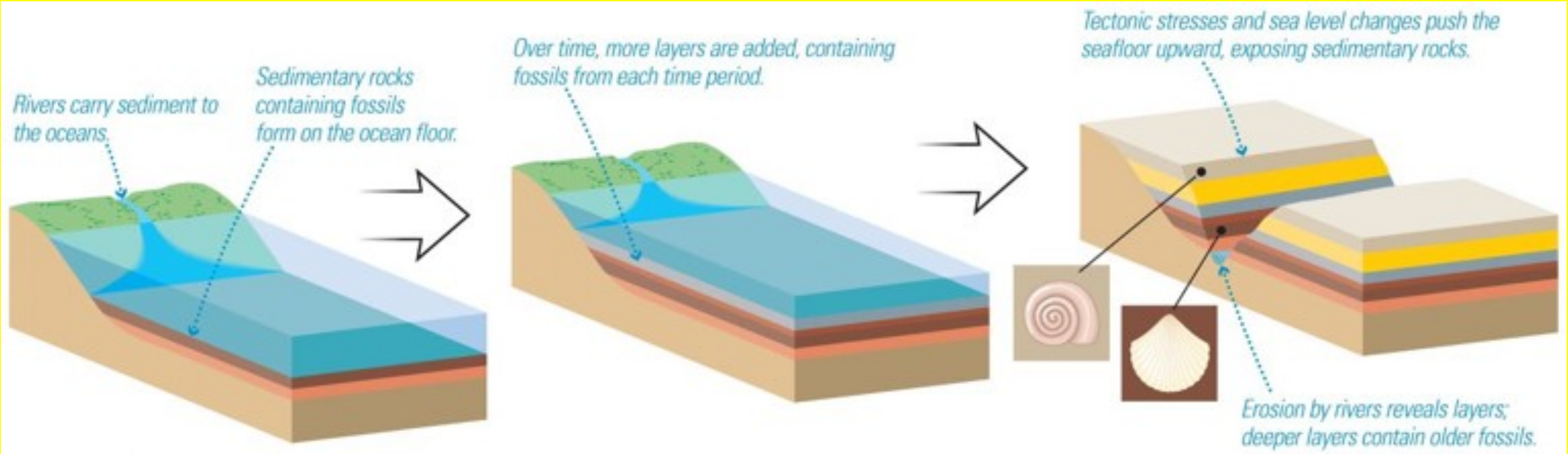


Earliest Life Forms

- Life probably arose on Earth more than 3.85 billion years ago, shortly after the end of heavy bombardment.

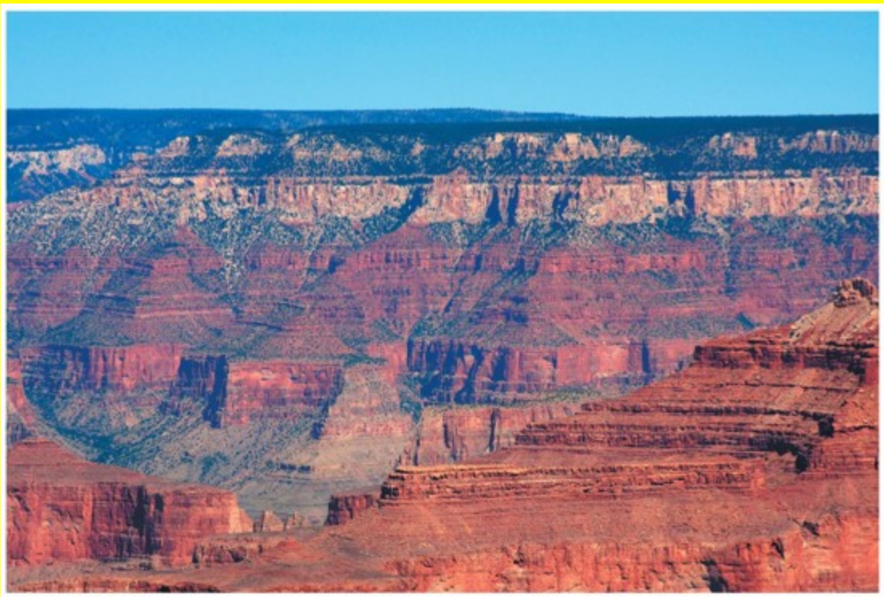
- Evidence comes from fossils, carbon isotopes.

Fossils in Sedimentary Rock



- Relative ages: deeper layers formed earlier
- Absolute ages: radiometric dating

Fossils in Sedimentary Rock

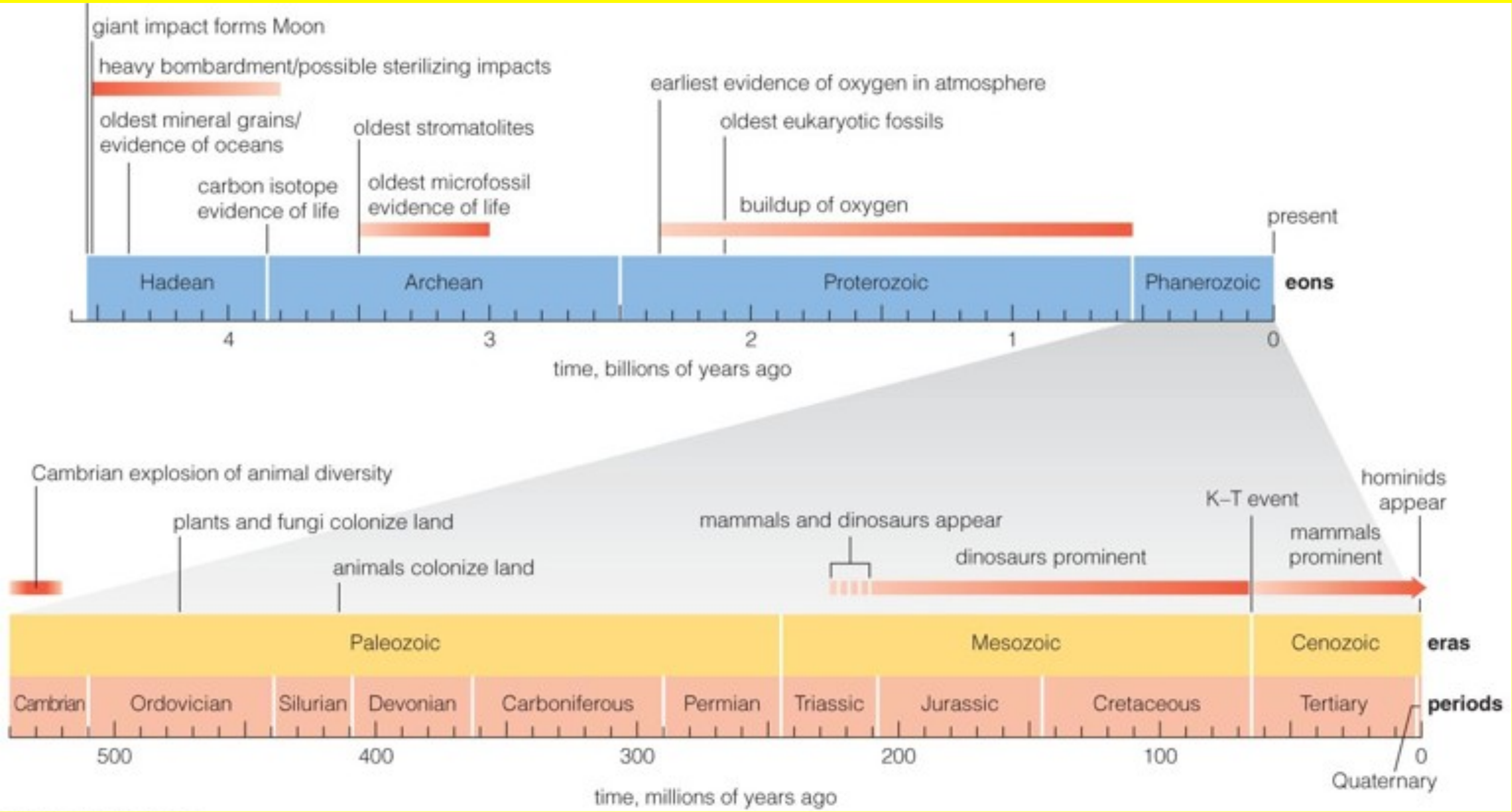


- Rock layers of the Grand Canyon record 2 billion years of Earth's history.

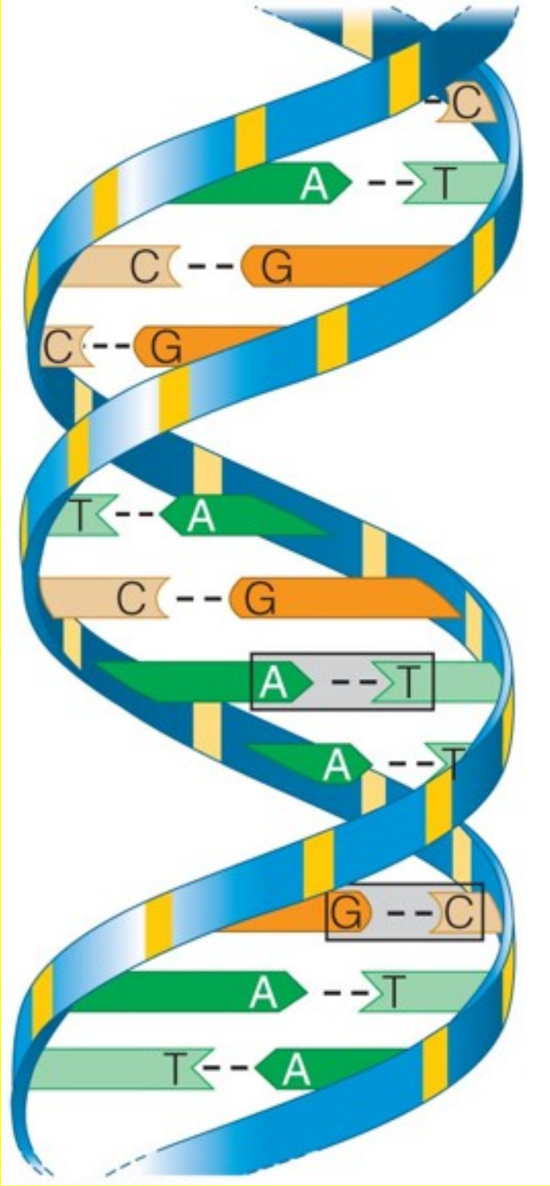
Earliest Fossils

- The oldest fossils show that bacteria-like organisms were present over 3.5 billion years ago.
- Carbon isotope evidence dates the origin of life to more than 3.85 billion years ago.

The Geological Time Scale



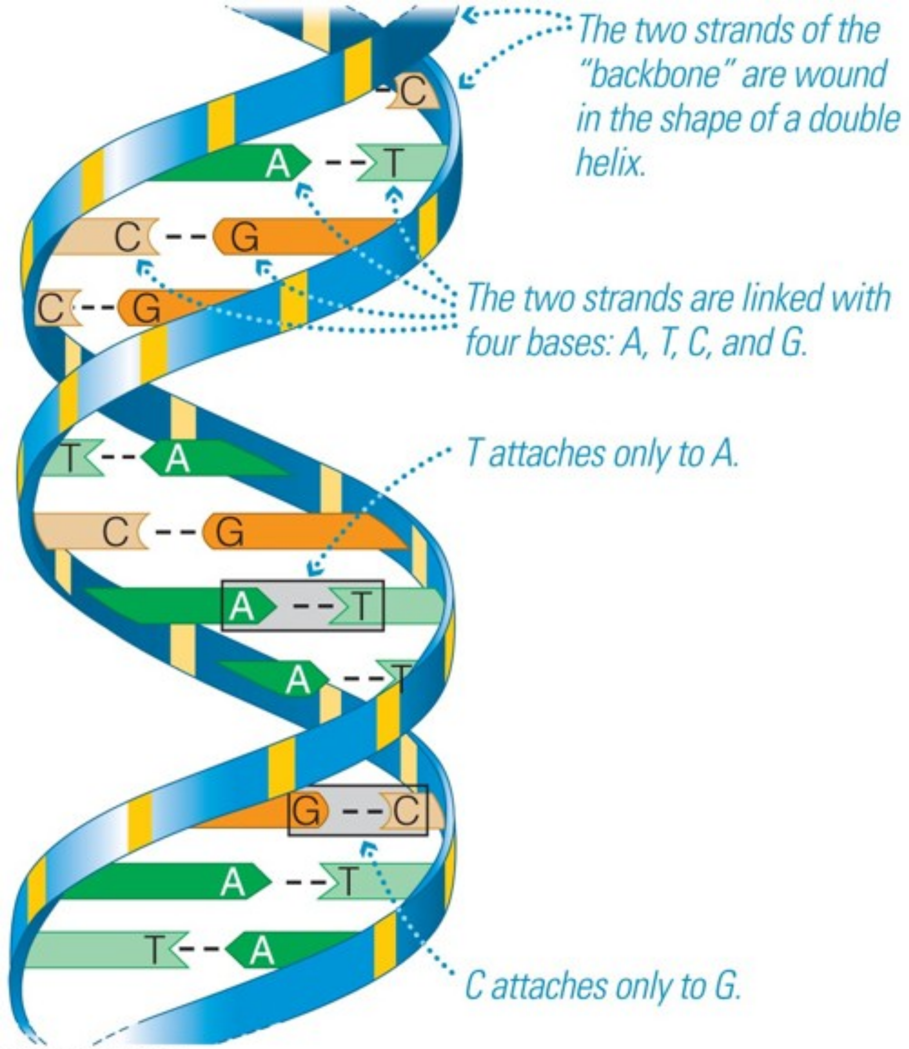
How did life arise on Earth?



Origin of Life on Earth

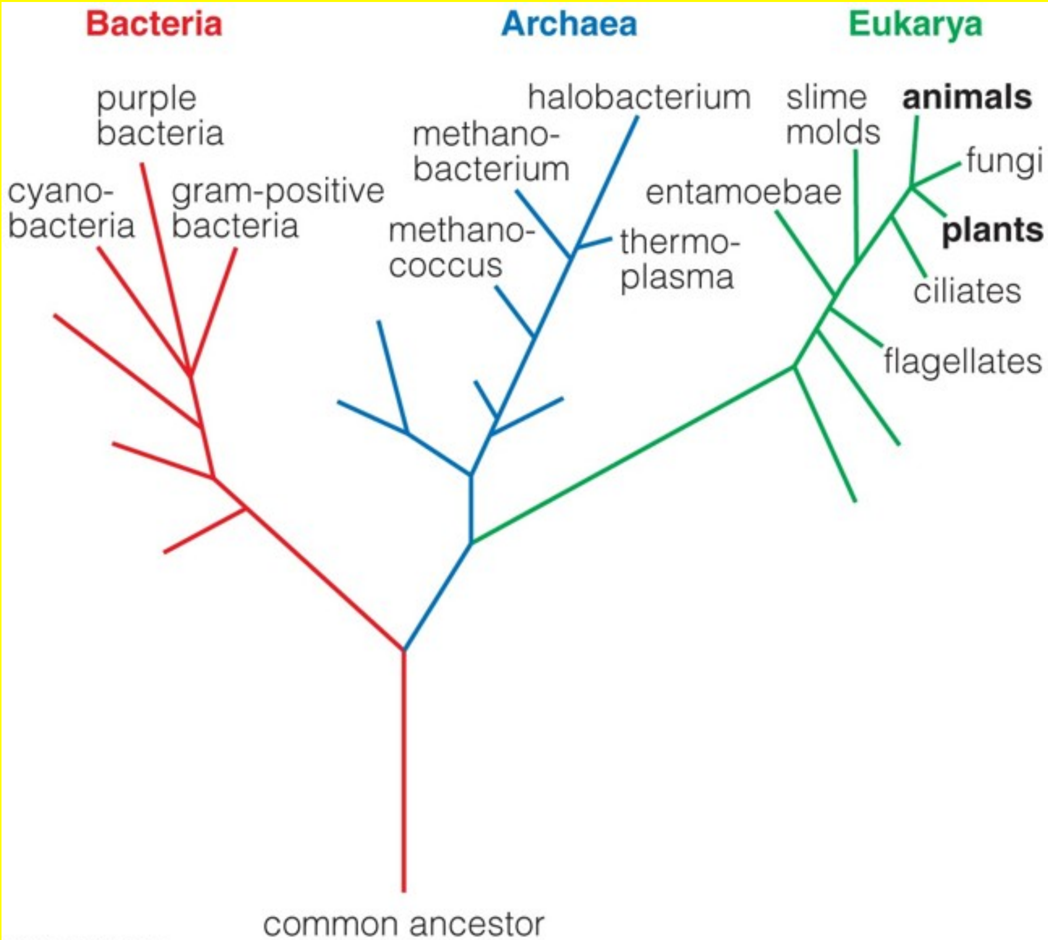
- Life evolves through time.
- All life on Earth shares a common ancestry.
- We may never know exactly how the first organism arose, but laboratory experiments suggest plausible scenarios.

The Theory of Evolution



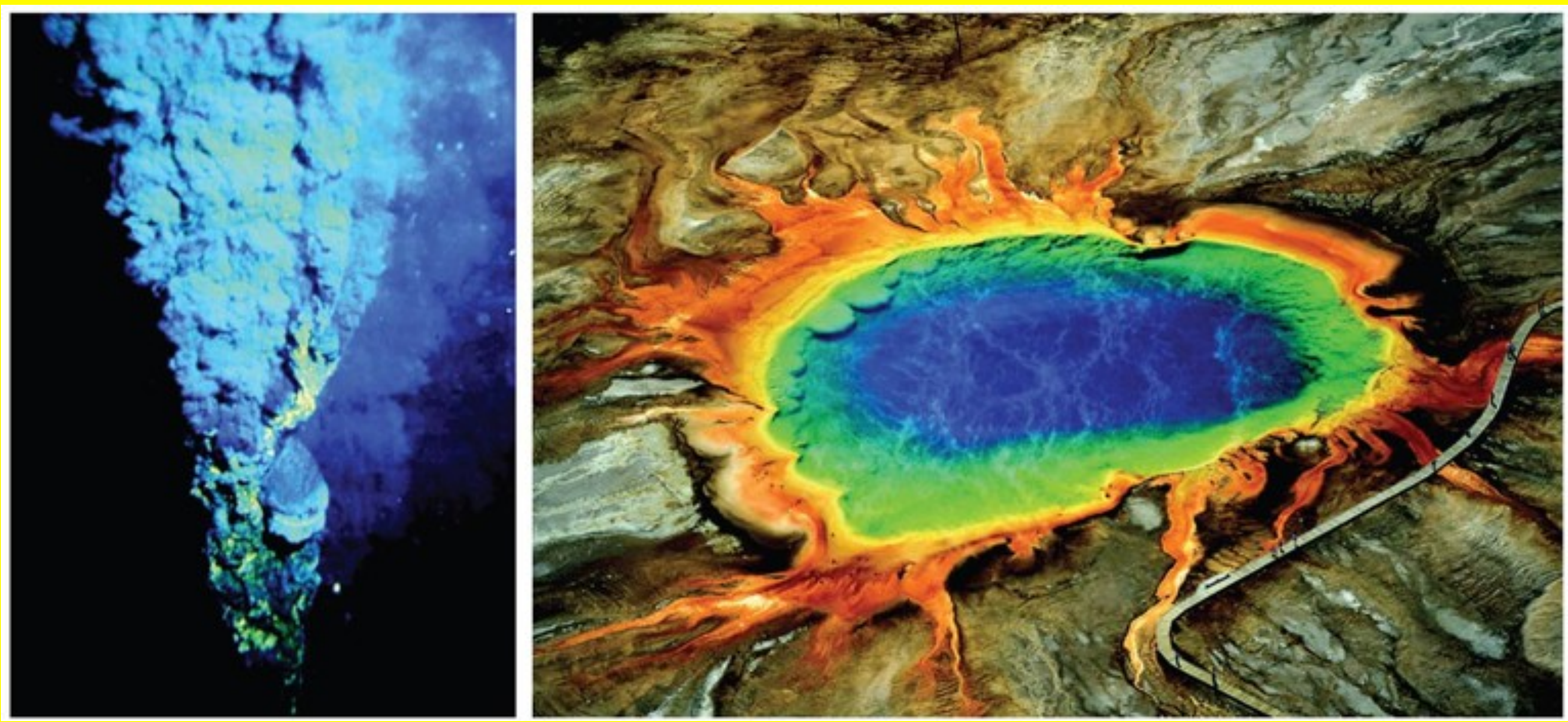
- The fossil record shows that evolution has occurred through time.
- Darwin's theory tells us HOW evolution occurs: through **natural selection**.
- Theory supported by discovery of DNA: evolution proceeds through **mutations**.

Tree of Life

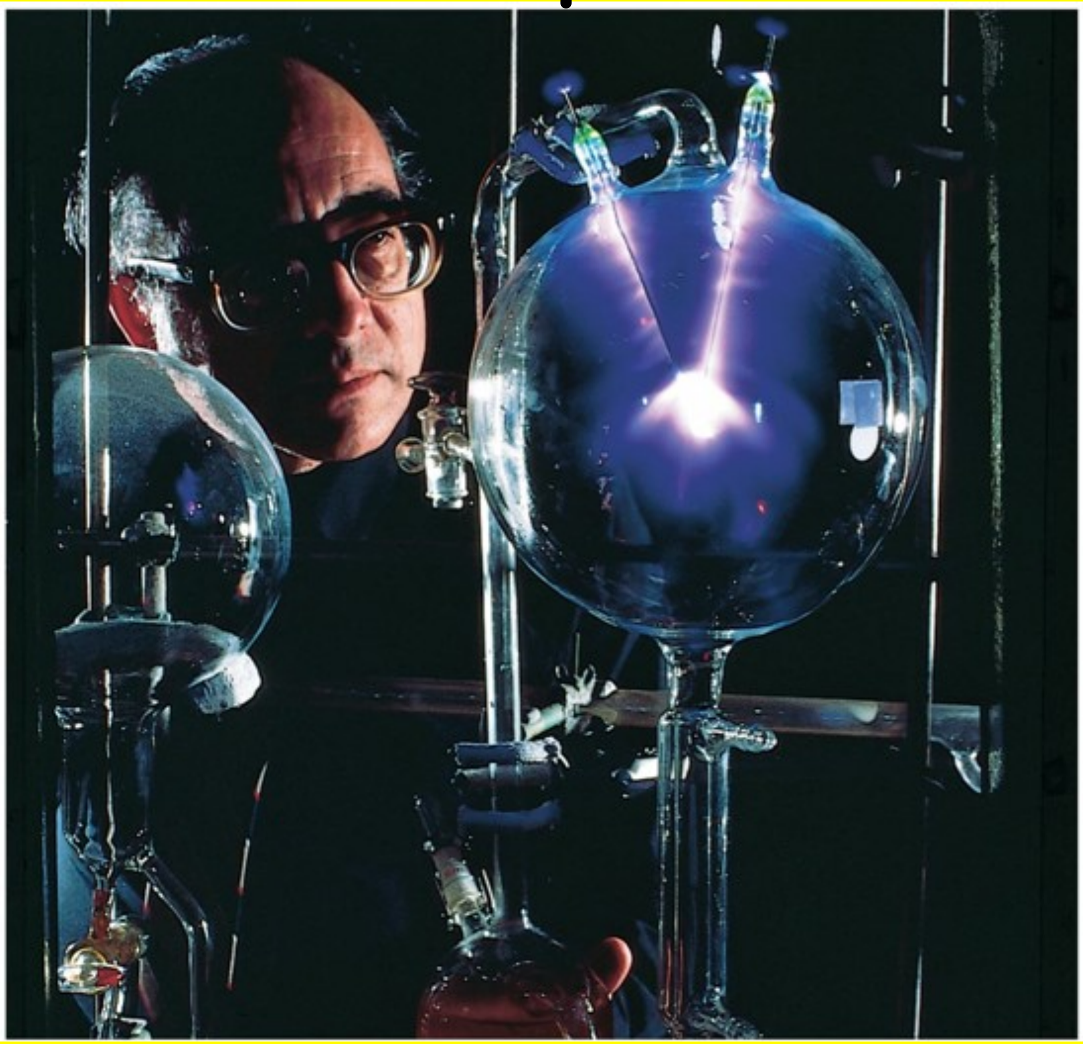


- Mapping genetic relationships has led biologists to discover this new "tree of life."
- Plants and animals are a small part of the tree.
- Suggests likely characteristics of common ancestor

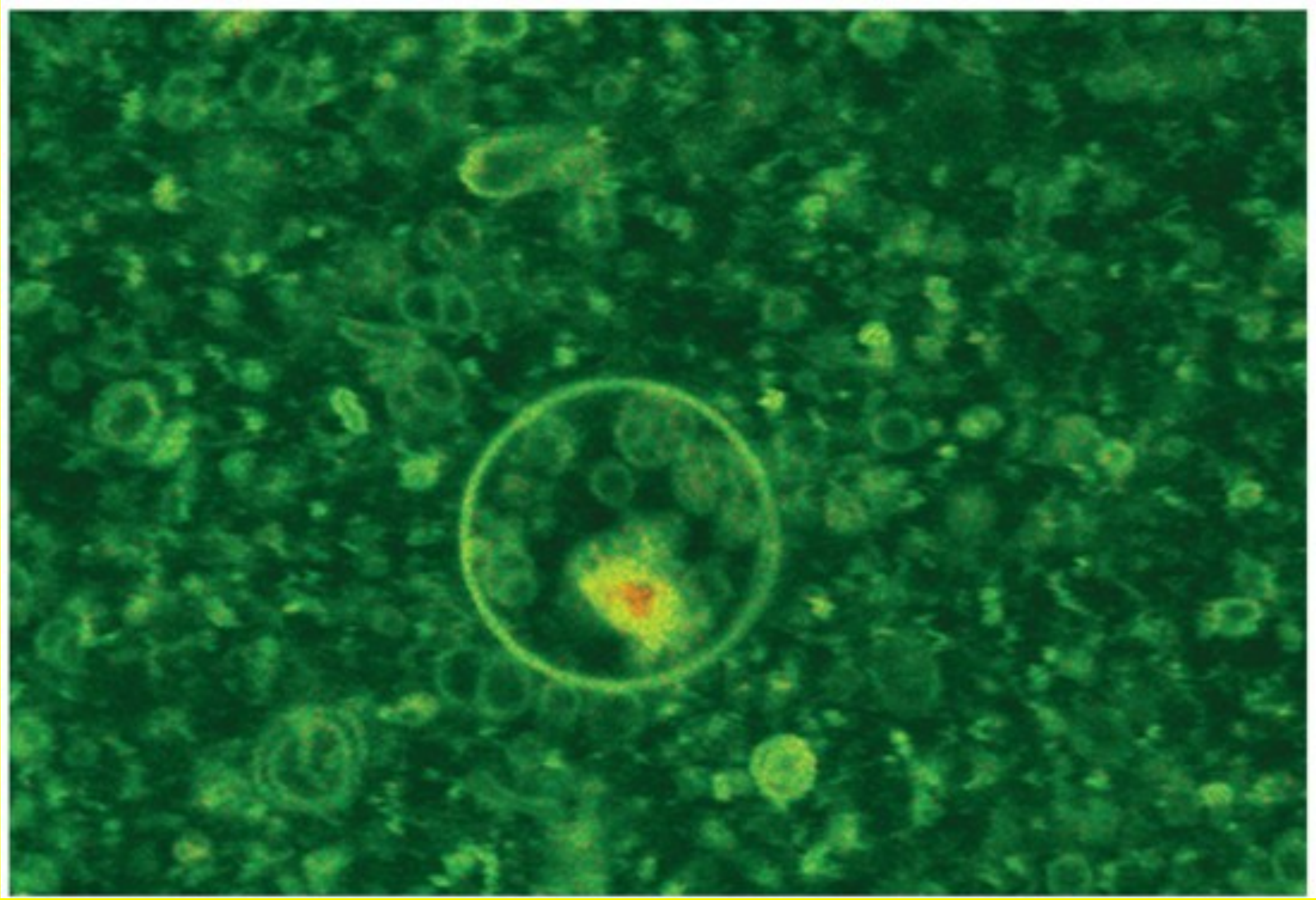
- These genetic studies suggest that the earliest life on Earth may have resembled the bacteria today found near deep ocean volcanic vents (*black smokers*) and geothermal hot springs.



Laboratory Experiments

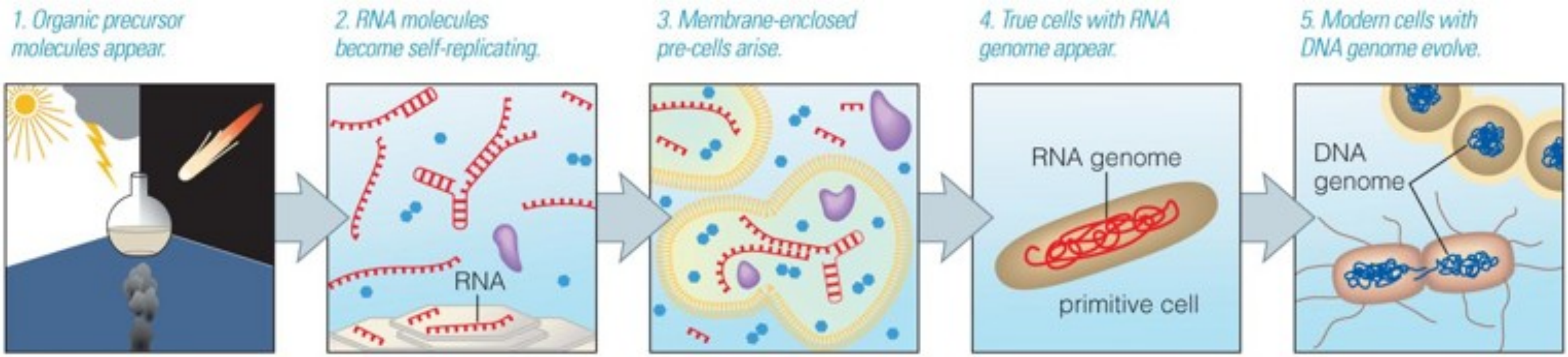


- The Miller-Urey experiment (and more recent experiments) show that the building blocks of life form easily and spontaneously under the conditions of early Earth.



Microscopic, enclosed membranes or "pre-cells" have been created in the lab.

Chemicals to Life?



Could life have migrated to Earth?

- Venus, Earth, Mars have exchanged tons of rock (blasted into orbit by impacts).
- Some microbes can survive years in space.

Brief History of Life

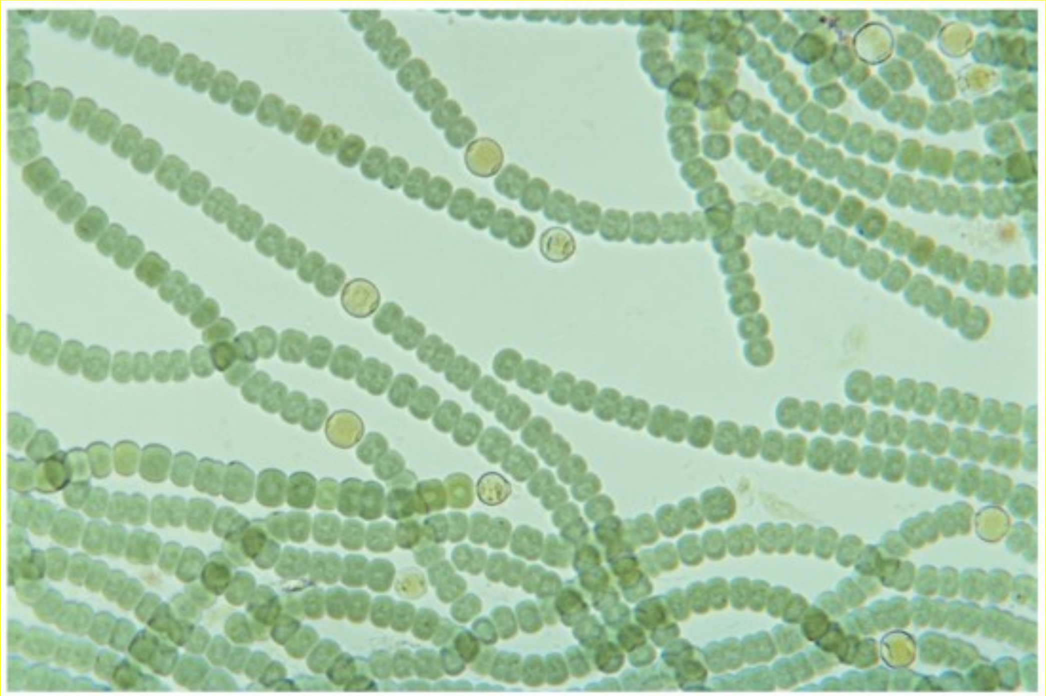
- 4.4 billion years - early oceans form
- 3.5 billion years - cyanobacteria start releasing oxygen
- 2.0 billion years - oxygen begins building up in atmosphere
- 540–500 million years - Cambrian Explosion
- 225–65 million years - dinosaurs and small mammals (dinosaurs ruled)
- Few million years - earliest hominids

Thought Question

You have a time machine with a dial that you can spin to send you randomly to any time in Earth's history. If you spin the dial, travel through time, and walk out, what is most likely to happen to you?

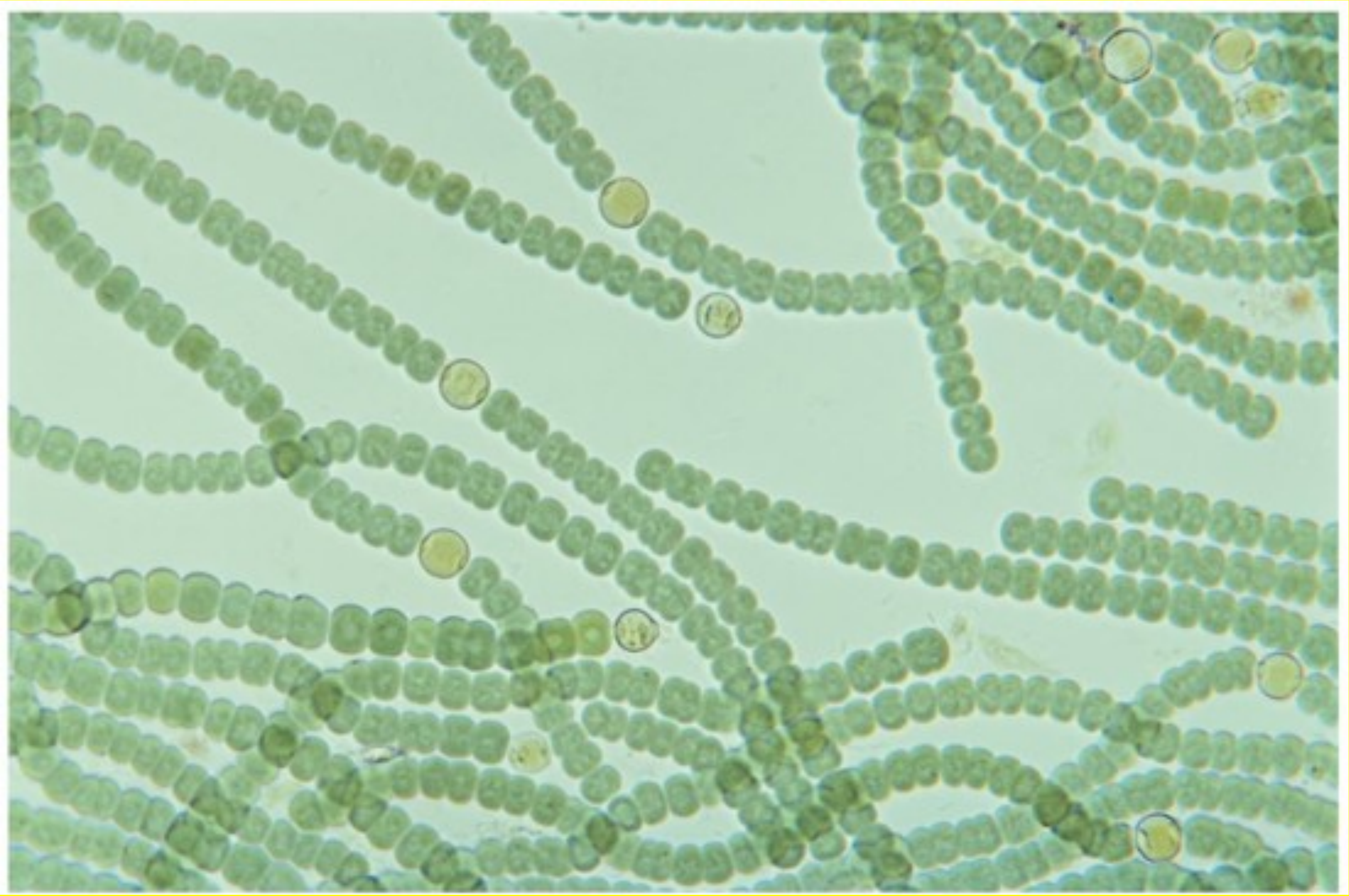
A. You'll be eaten by dinosaurs.
B. You'll suffocate because you'll be unable to breathe the air.
C. You'll be consumed by toxic bacteria.
D. Nothing. You'll probably be just fine.

Origin of Oxygen



- Cyanobacteria paved the way for more complicated life forms by releasing oxygen into atmosphere via photosynthesis.

What are the necessities of life?

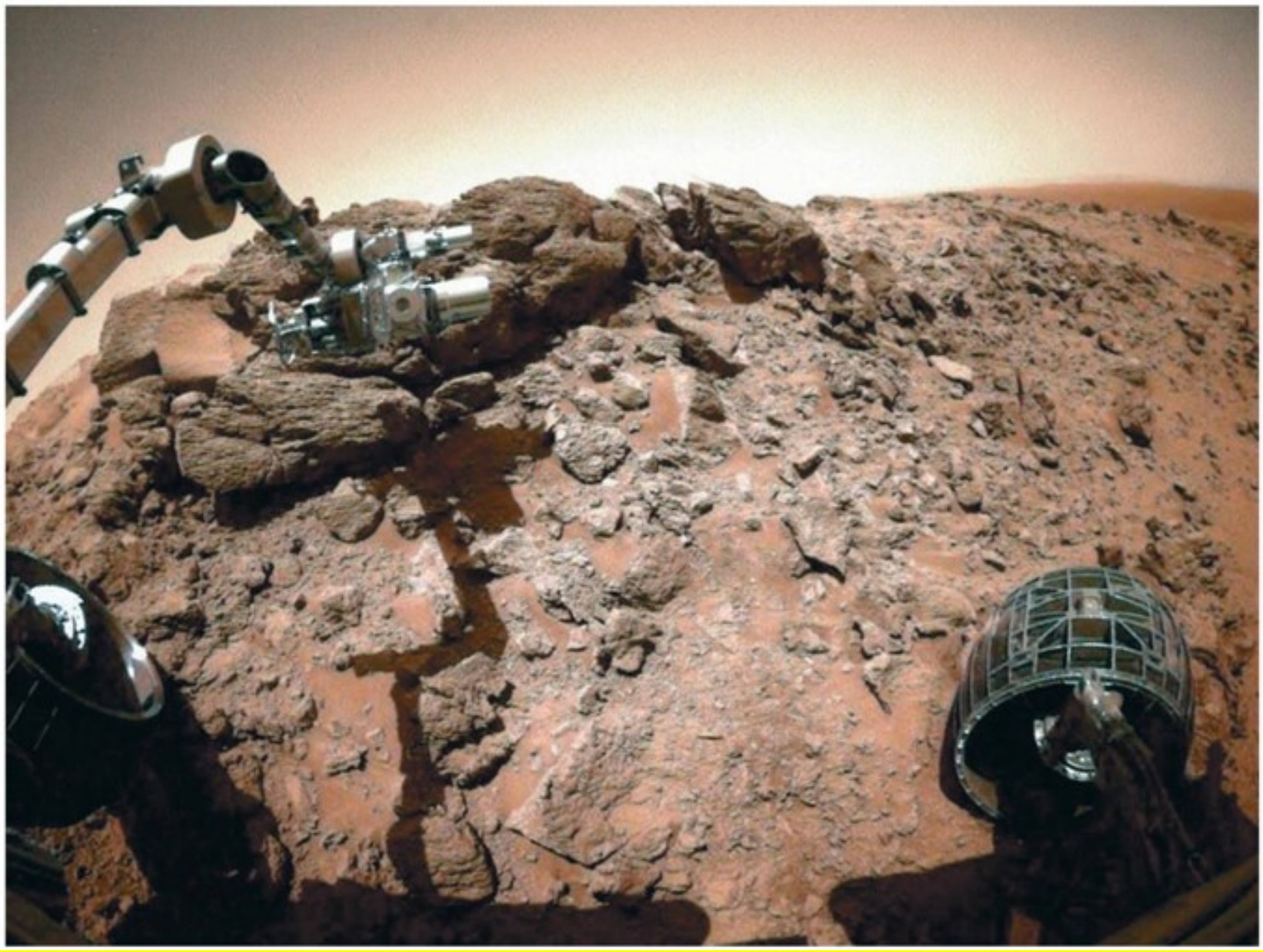


Necessities for Life

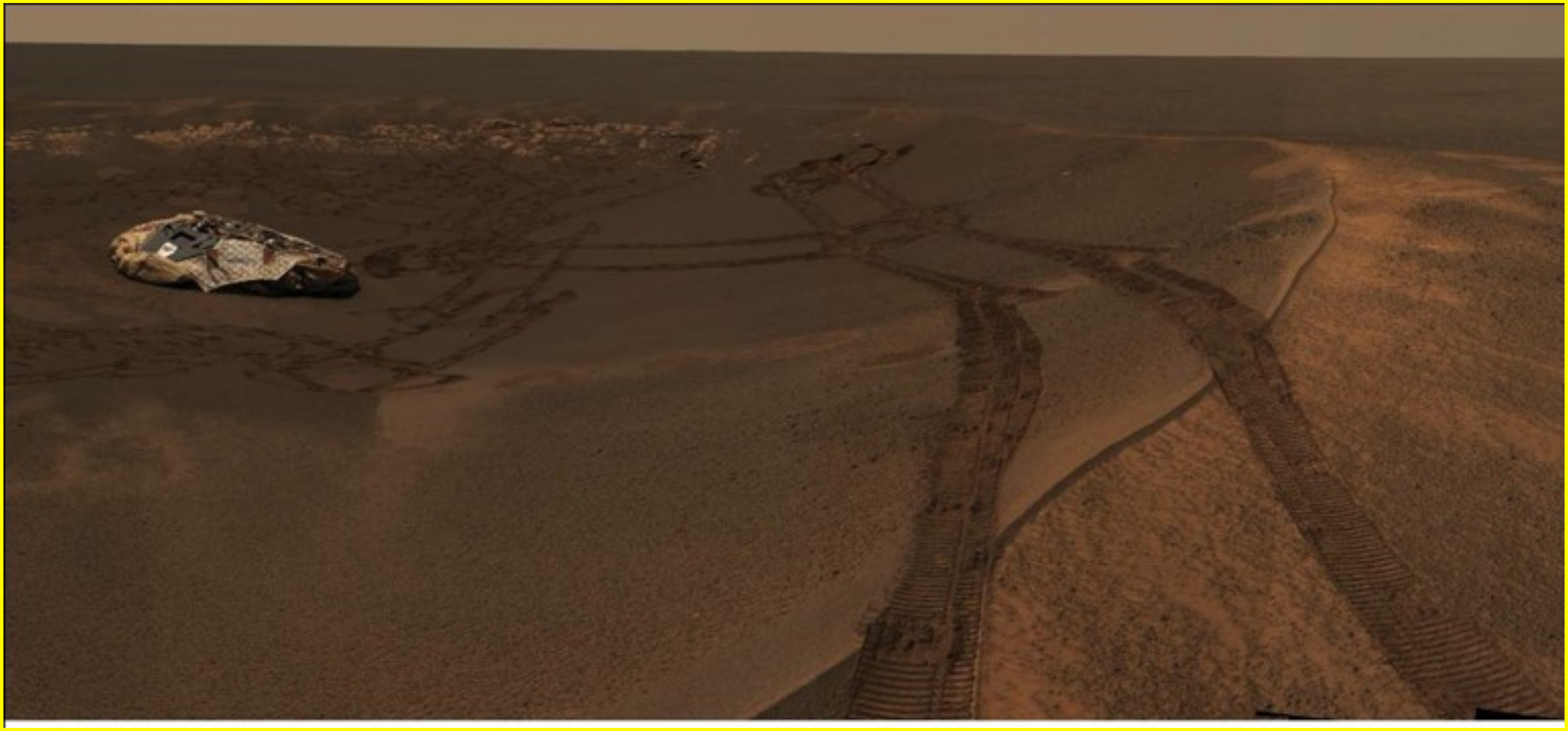
- A nutrient source
- Energy (sunlight, chemical reactions, internal heat)
- Liquid water (or possibly some other liquid)

Hardest to find on other planets

Could there be life on Mars?



Searches for Life on Mars



- Mars had liquid water in the distant past.
- Still has subsurface ice; possibly subsurface water near sources of volcanic heat

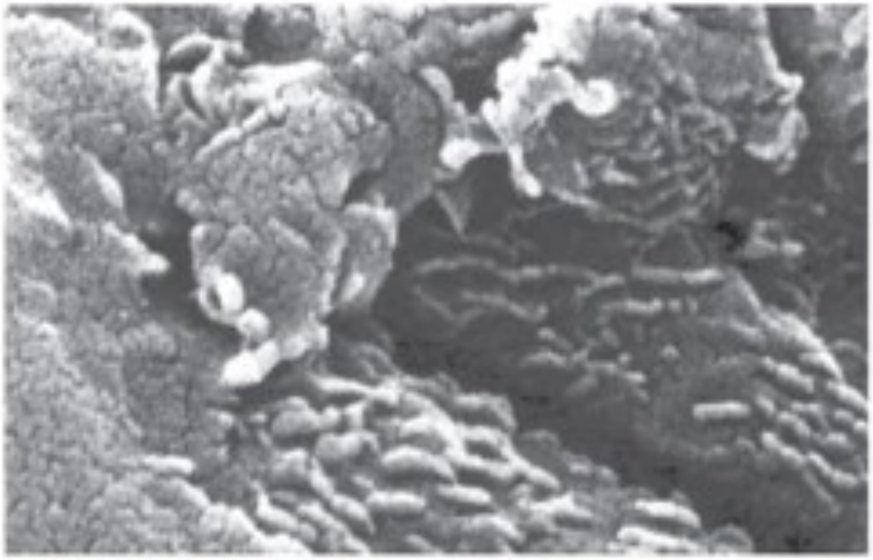
In 2004, NASA *Spirit* and *Opportunity* rovers sent home new mineral evidence of past liquid water on Mars.

The Martian Meteorite debate

Composition indicates origin on Mars.

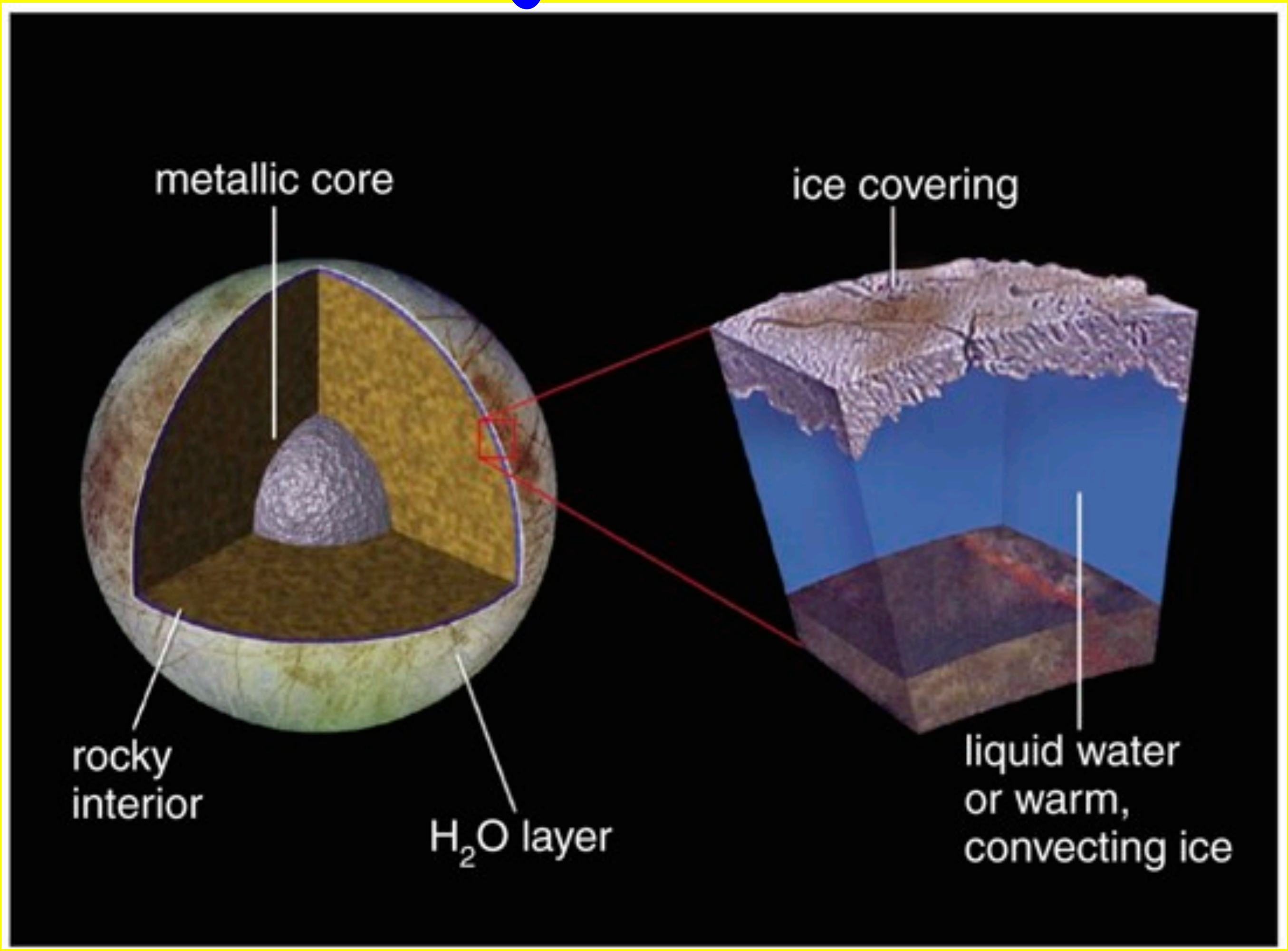
- 1984: meteorite ALH84001 found in Antarctica
- 13,000 years ago: fell to Earth in Antarctica
- 16 million years ago: blasted from surface of Mars
- 4.5 billion years ago: rock formed on Mars

- Does the meteorite contain fossil evidence of life on Mars?

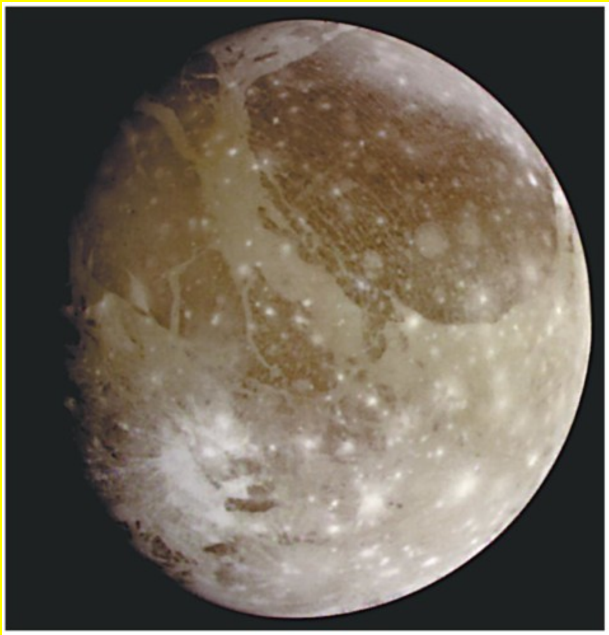


Most scientists are not yet convinced.

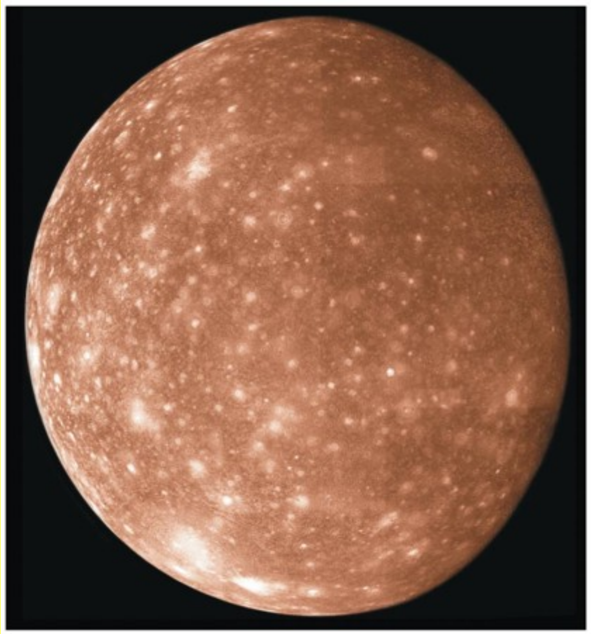
Could there be life on Europa or other jovian moons?



- Ganymede, Callisto also show some evidence for subsurface oceans.
- Relatively little energy available for life, but there still may be enough.
- Intriguing prospect of THREE potential homes for life around Jupiter alone.

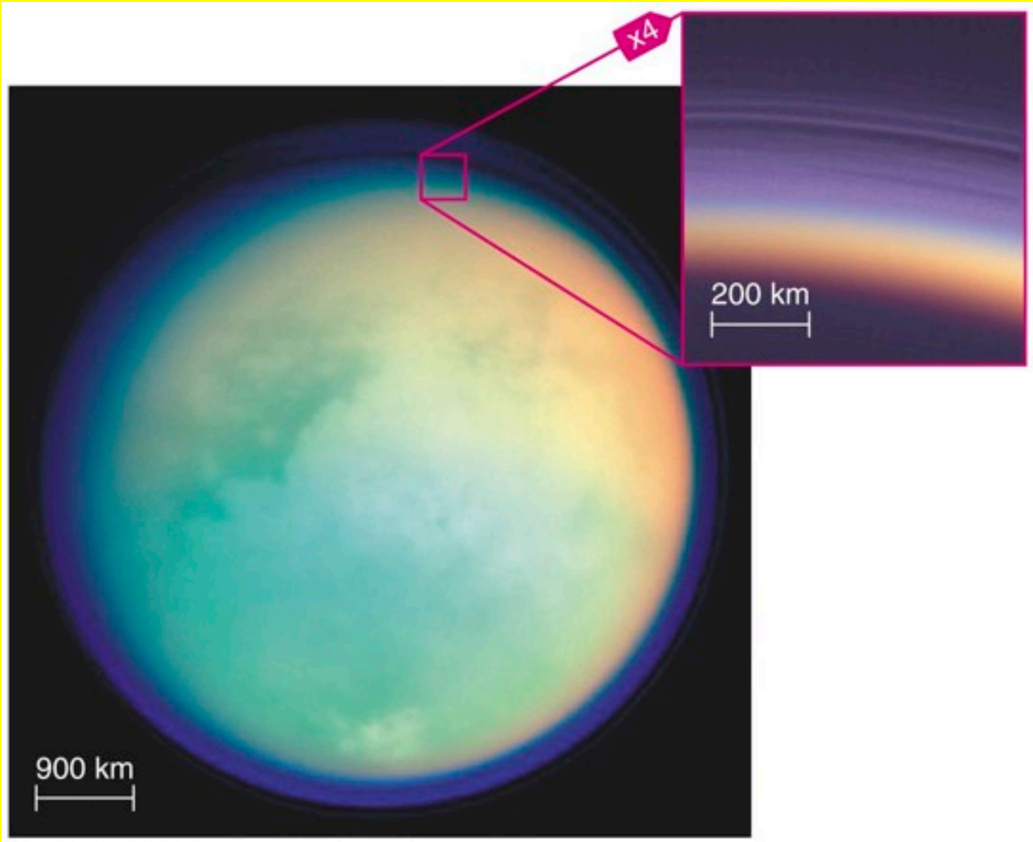


Ganymede



Callisto

Titan



- The surface is too cold for liquid water (but there may be some deep underground).
- Has lakes of liquid ethane/methane on its surface.

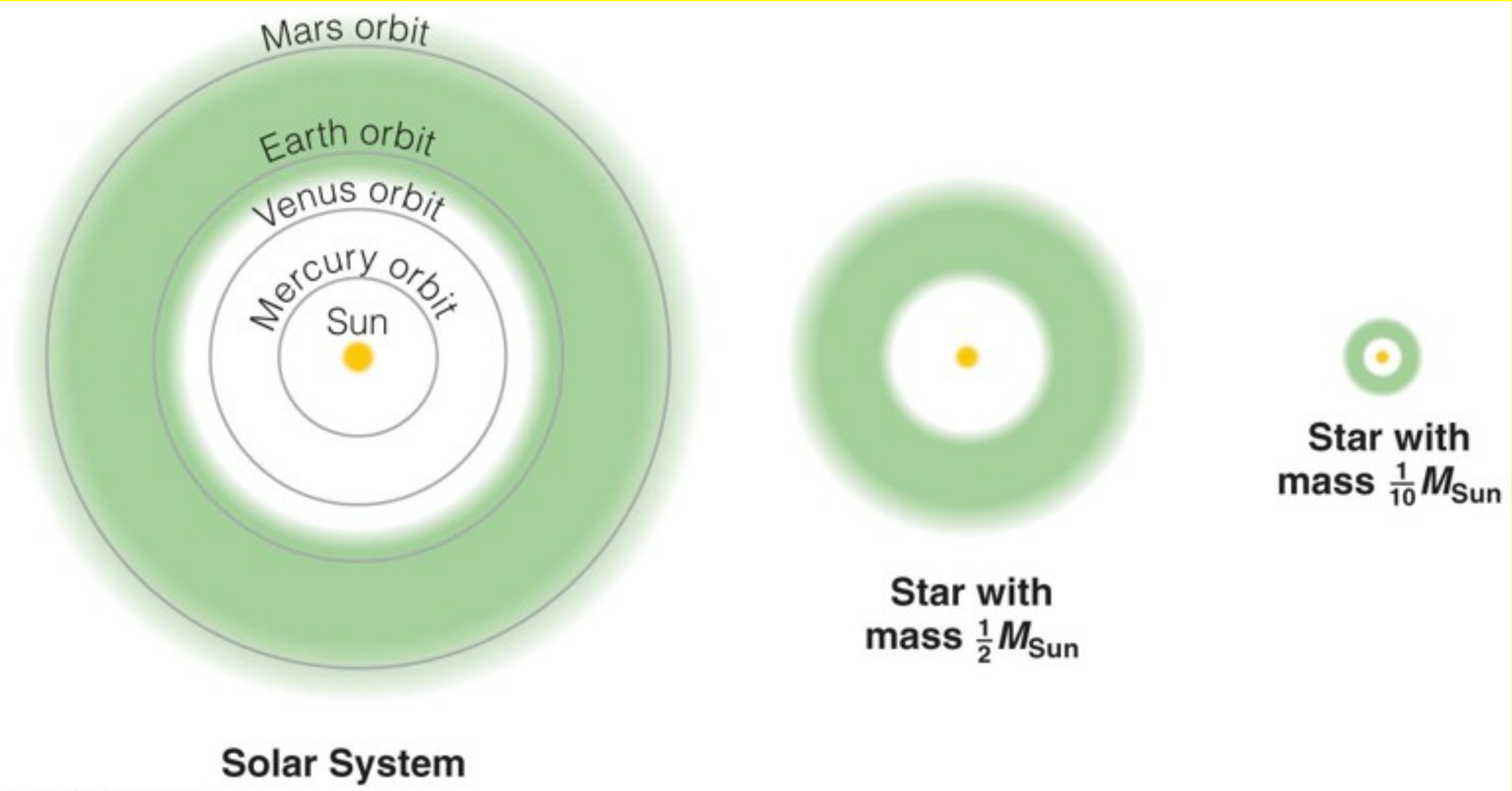
Enceladus

- Ice fountains suggest that Enceladus may have a subsurface ocean.

Life around Other Stars

- Are habitable planets likely?
- Are Earth-like planets rare or common?

Are habitable planets likely?



Habitable Planets

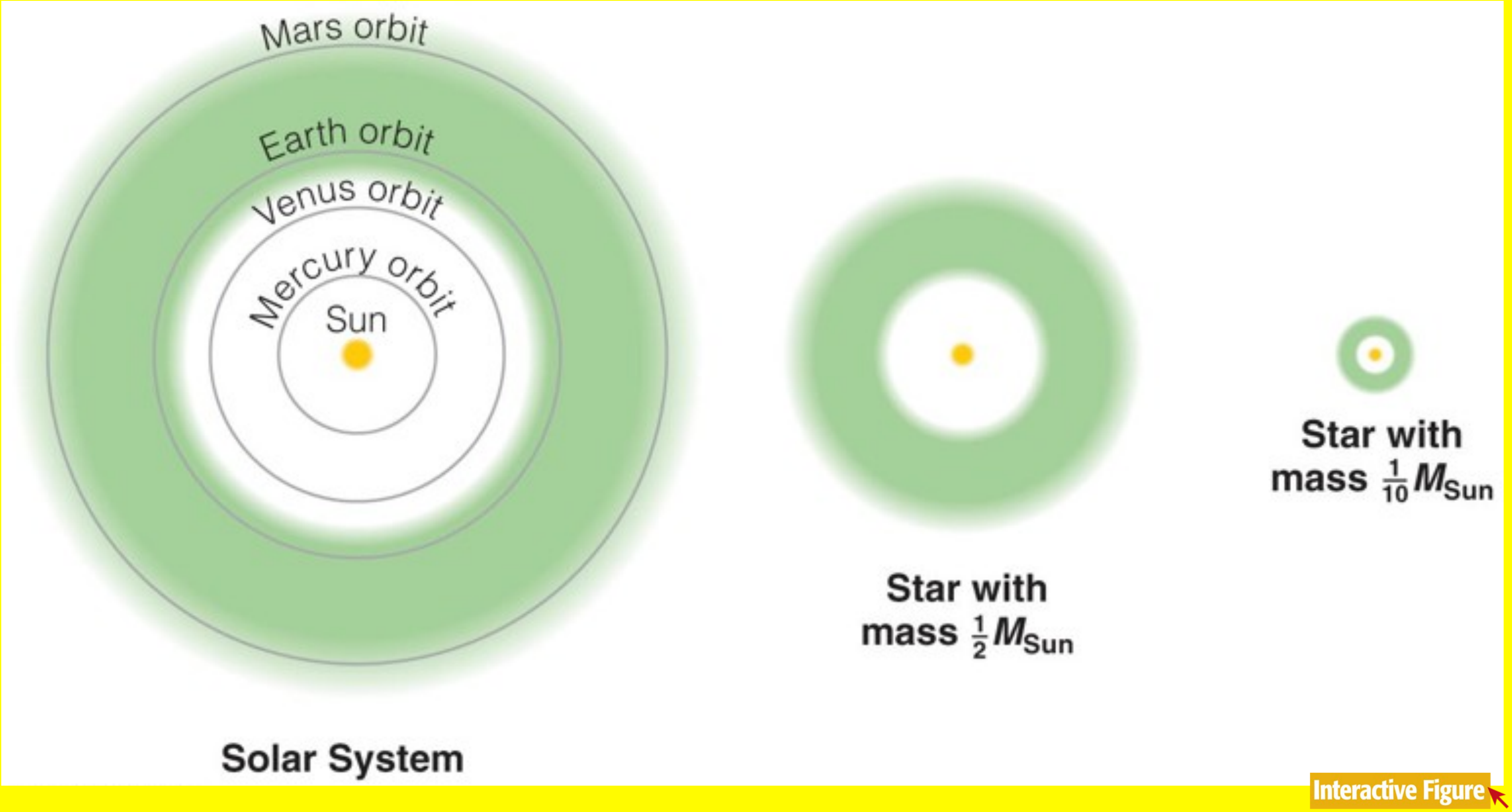
Definition:

- A **habitable** world contains the basic necessities for life as we know it, including liquid water.
- It does *not* necessarily have life.

Constraints on star systems:

1) Old enough to allow time for evolution (rules out high-mass stars - 1%)
2) Need to have stable orbits (*might* rule out binary/multiple star systems - 50%)
3) Size of "habitable zone": region in which a planet of the *right size* could have liquid water on its surface

Even with these constraints, billions of stars in the Milky Way could potentially have habitable worlds.



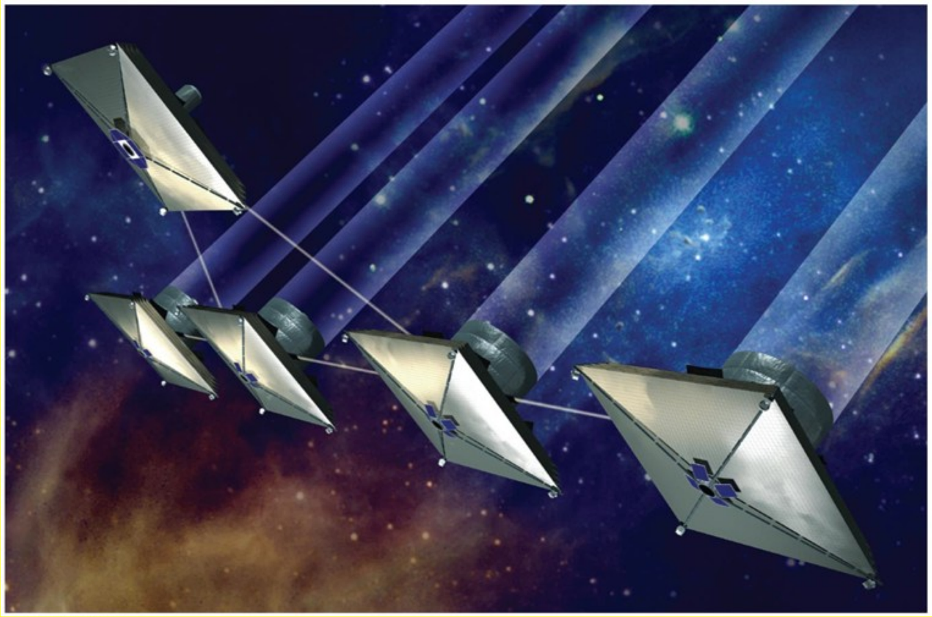
The more massive the star, the larger its habitable zone— and the higher probability of a planet existing in this zone.

Finding them will be hard

Recall our scale model solar system:

- Looking for an Earth-like planet around a nearby star is like standing on the East Coast of the United States and looking for a pinhead on the West Coast—with a VERY bright grapefruit nearby.
- But new technologies will allow us to search for such planets.

- *Kepler* (launched in 2009) will monitor 100,000 stars for transit events for 4 years.



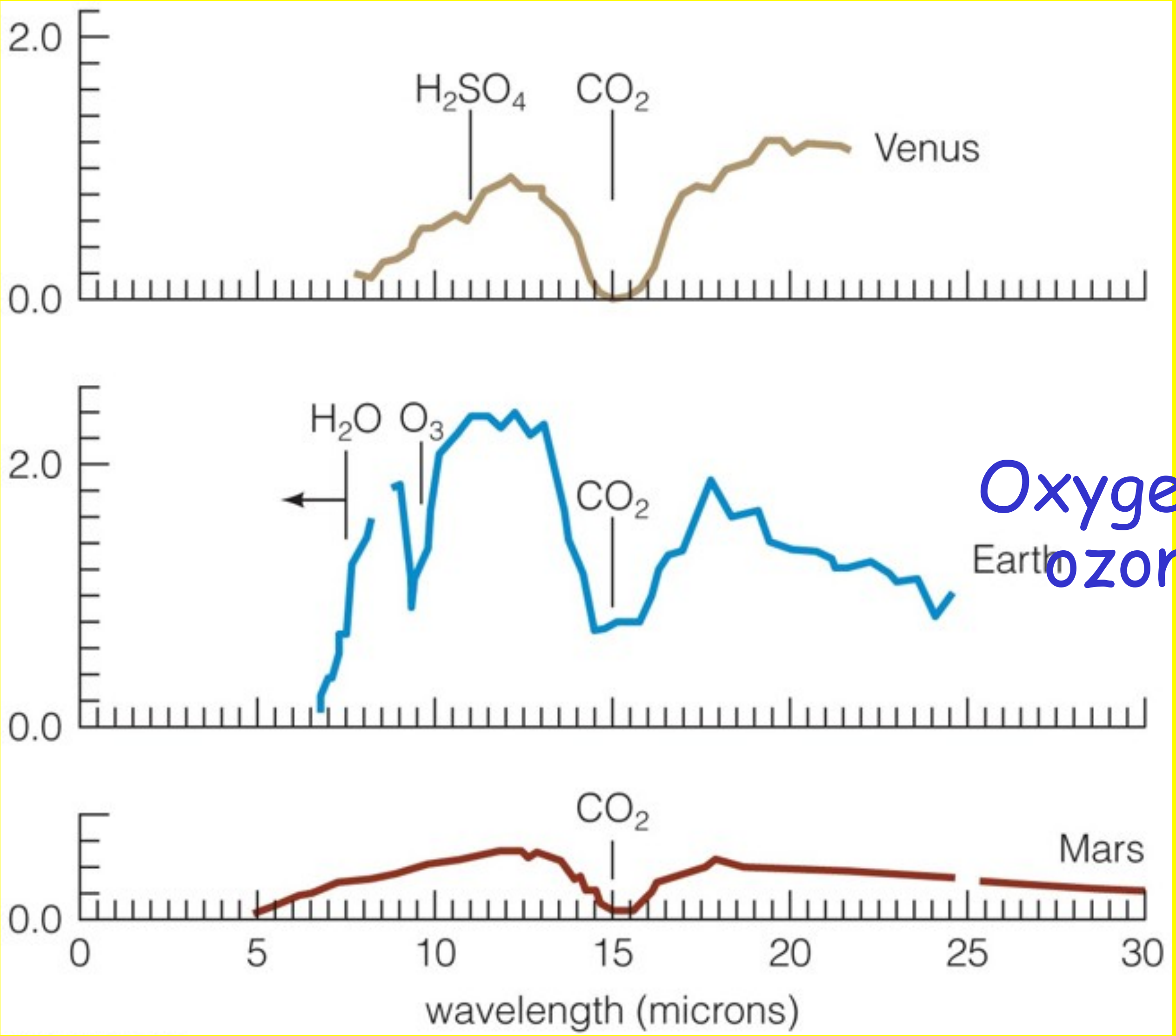
Later: *SIM* and *TPF* interferometers may obtain spectra and crude images of Earth-size planets.

Spectral Signatures of Life

Venus

Earth

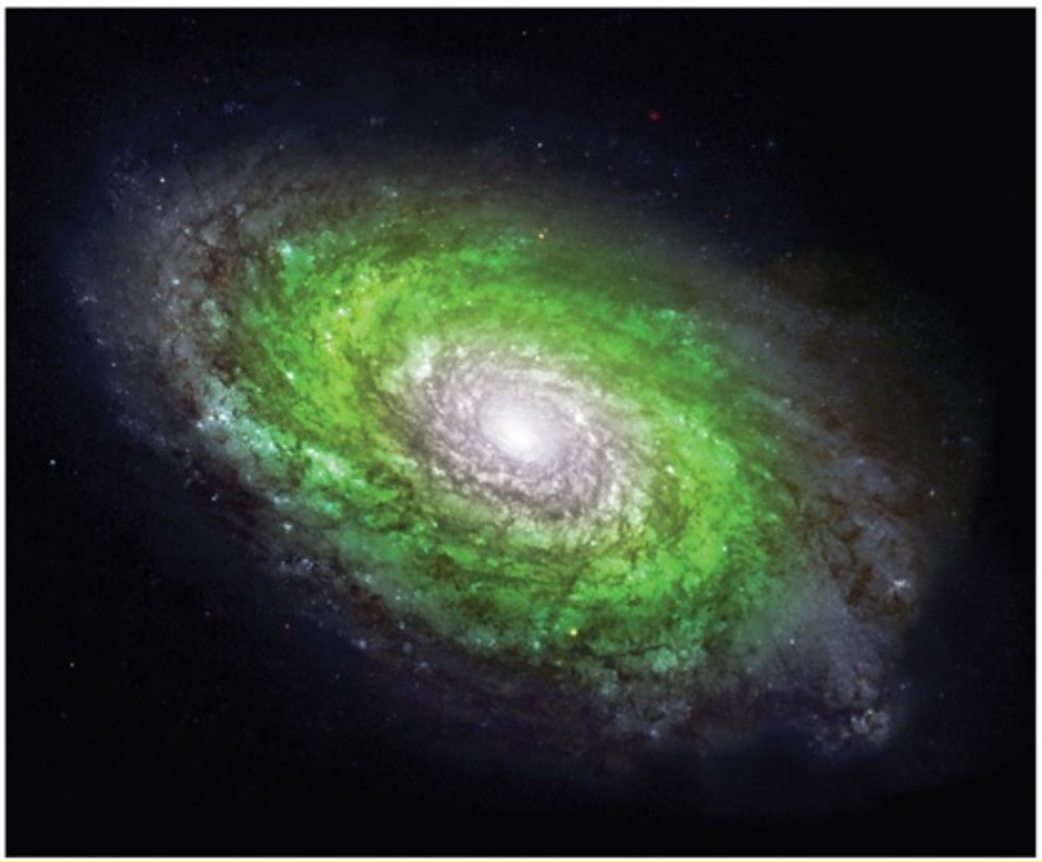
Mars



Oxygen/ ozone

Are Earth-like planets rare or common?

Elements and Habitability

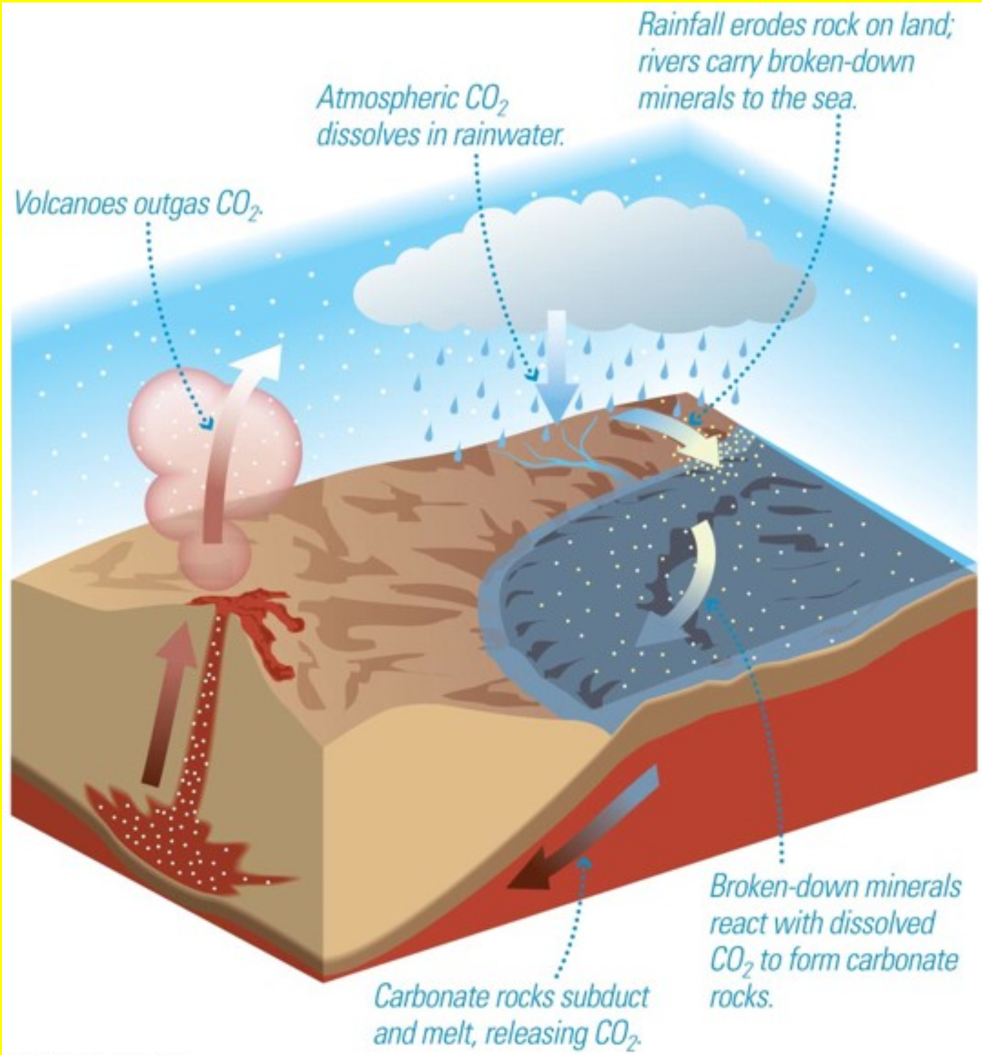


- Some scientists argue that the proportions of heavy elements need to be just right for the formation of habitable planets.
- If so, then Earth-like planets are restricted to a galactic habitable zone.

Impacts and Habitability

- Some scientists argue that Jupiter-like planets are necessary to reduce rate of impacts.
- If so, then Earth-like planets are restricted to star systems with Jupiter-like planets.

Climate and Habitability



- Some scientists argue that plate tectonics and/or a large moon are necessary to keep the climate of an Earth-like planet stable enough for life.

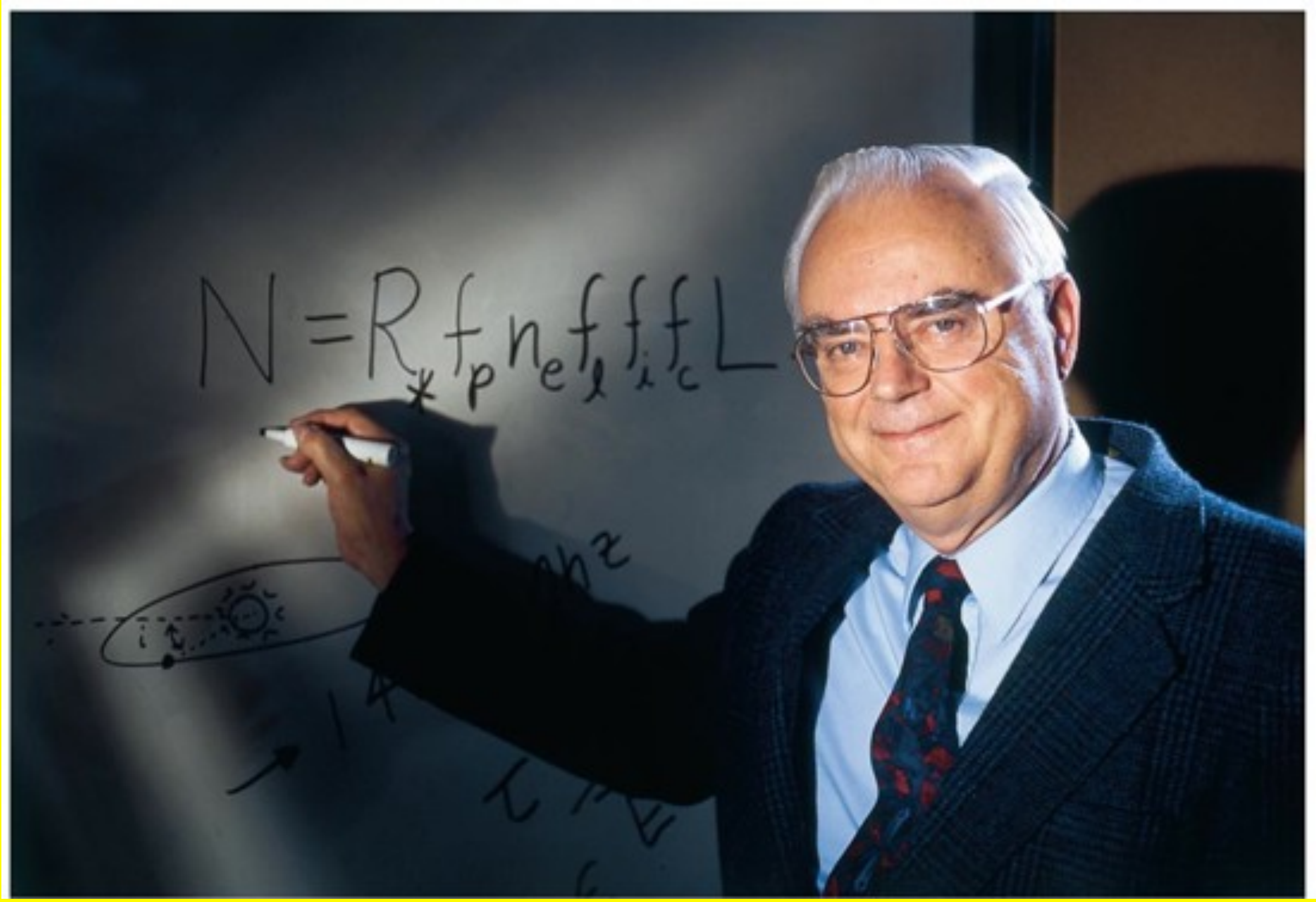
The Bottom Line

We don't yet know how important or negligible these concerns are.

The Search for Extraterrestrial Intelligence

- How many civilizations are out there?
- How does SETI work?

How many civilizations are out there?



The Drake Equation

Number of civilizations with whom we could potentially communicate

$$= N_{HP} \times f_{life} \times f_{civ} \times f_{now}$$

N_{HP} = total number of habitable planets in galaxy

f_{life} = fraction of habitable planets with life

f_{civ} = fraction of life-bearing planets with civilization at some time

f_{now} = fraction of civilizations around *now*

We do not know the values for the Drake equation.

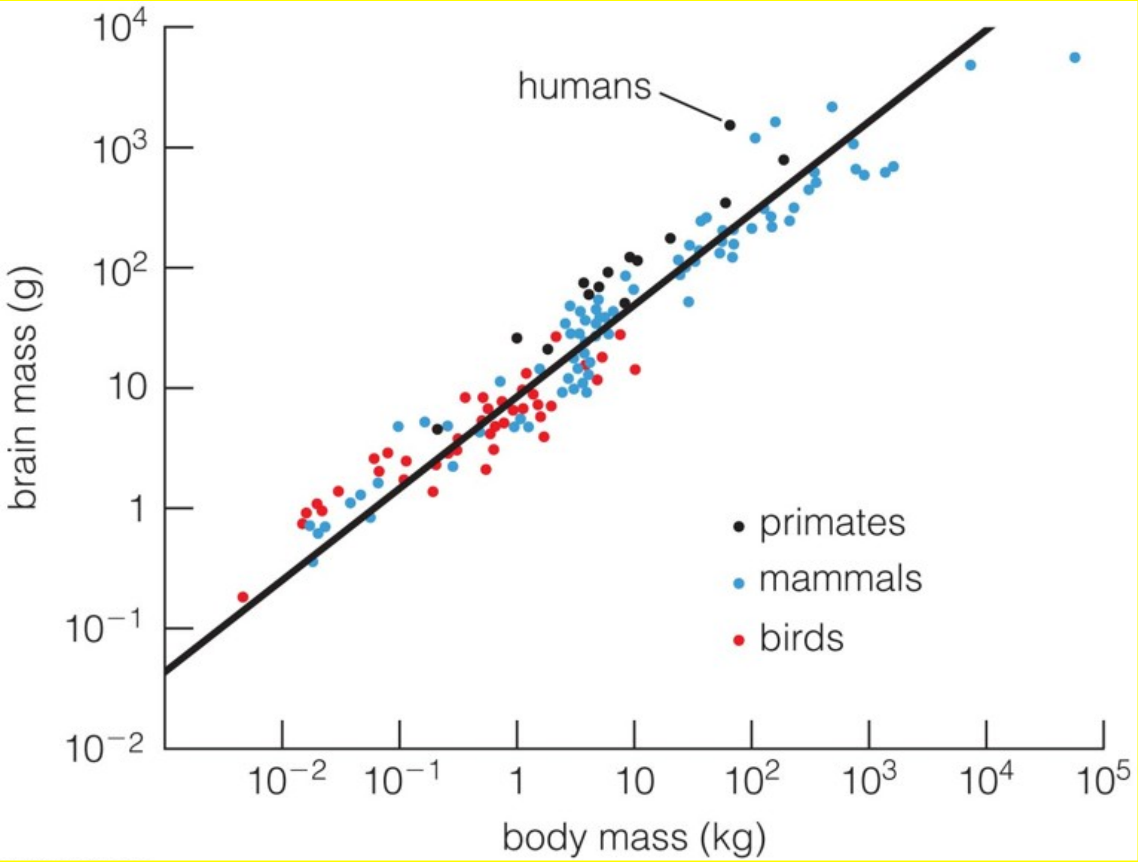
N_{HP} : probably billions

f_{life} : ??? hard to say (near 0 or near 1)

f_{civ} : ??? took 4 billion years on Earth

f_{now} : ??? depends on whether civilizations can survive long-term

Are we "off the chart" smart?



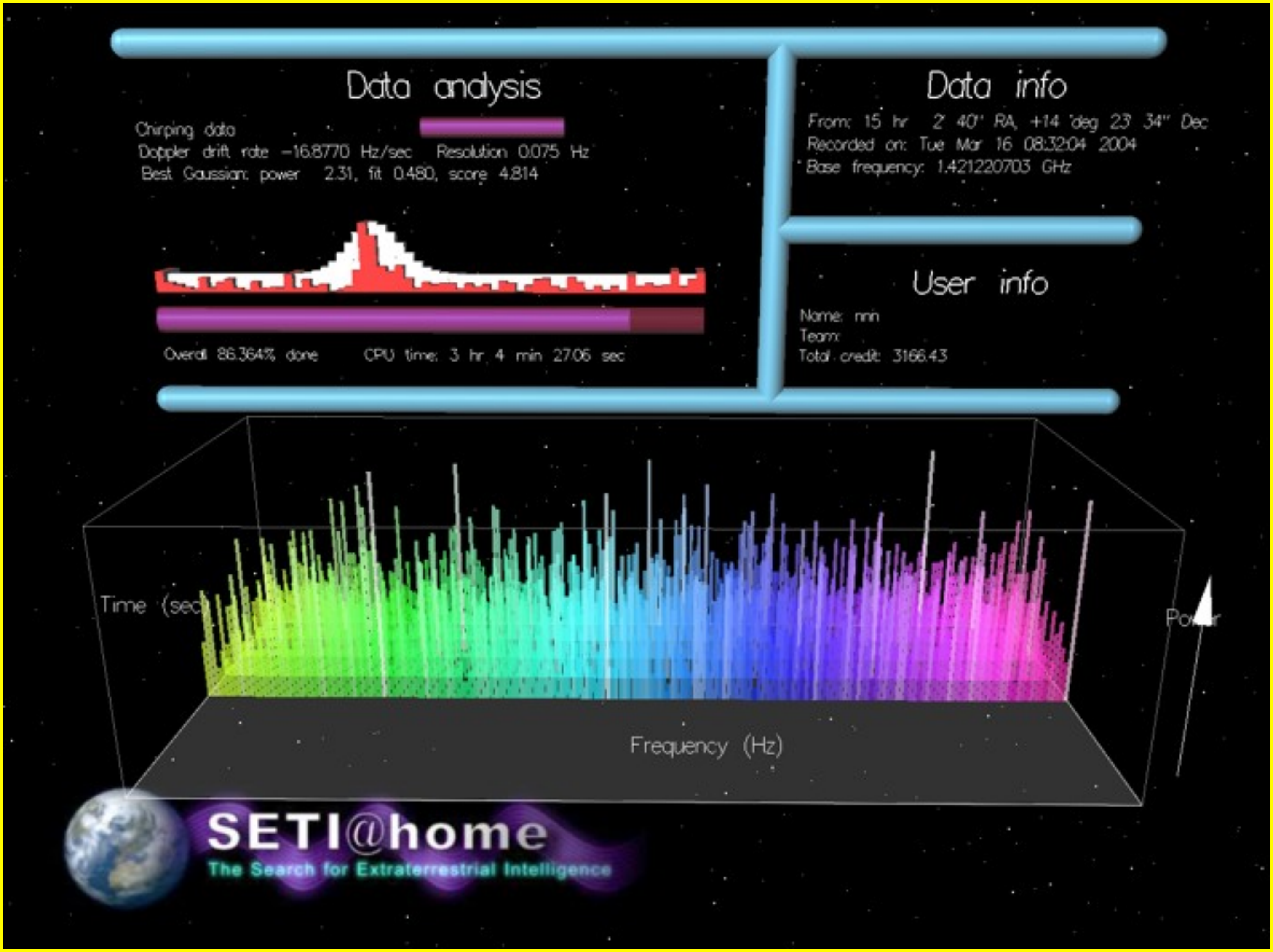
- Humans have comparatively large brains.
- Does that mean our level of intelligence is improbably high?

How does SETI work?

SETI experiments look for **deliberate** signals from extraterrestrials

We've even sent a few signals ourselves…

Earth to globular cluster M13: Hoping we'll hear back in about 42,000 years!



Your computer can help! SETI @ Home: a screensaver with a purpose

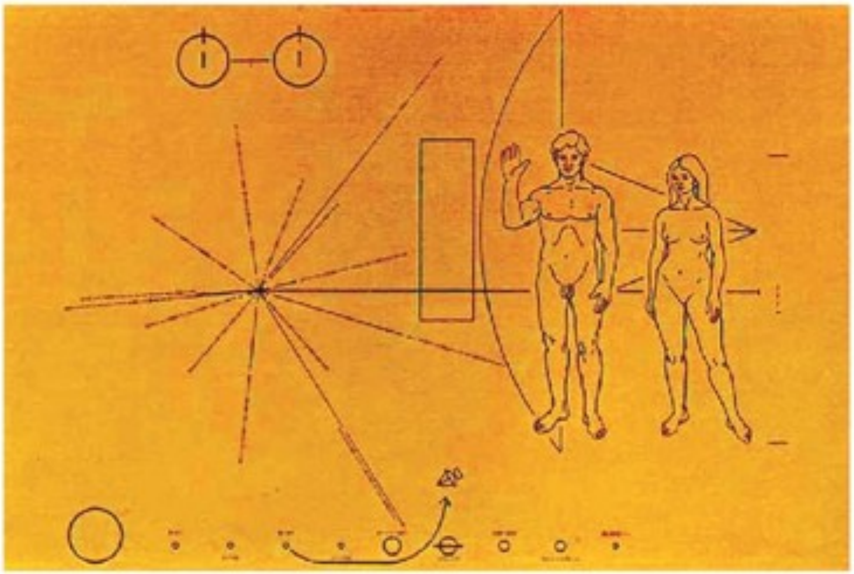
Interstellar Travel and Its Implications to Civilization

- How difficult is interstellar travel?
- Where are the aliens?

How difficult is interstellar travel?

Current Spacecraft

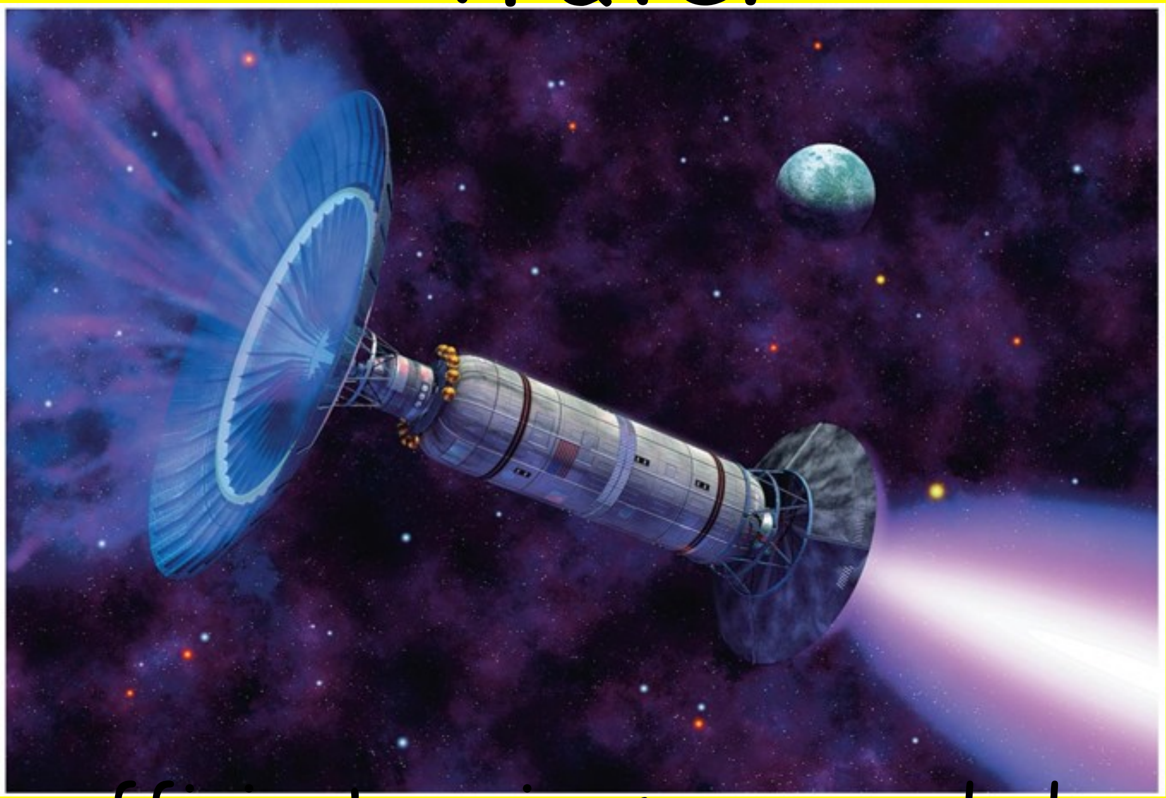
- Current spacecraft travel at <1/10,000*c*; 100,000 years to the nearest stars



Pioneer plaque

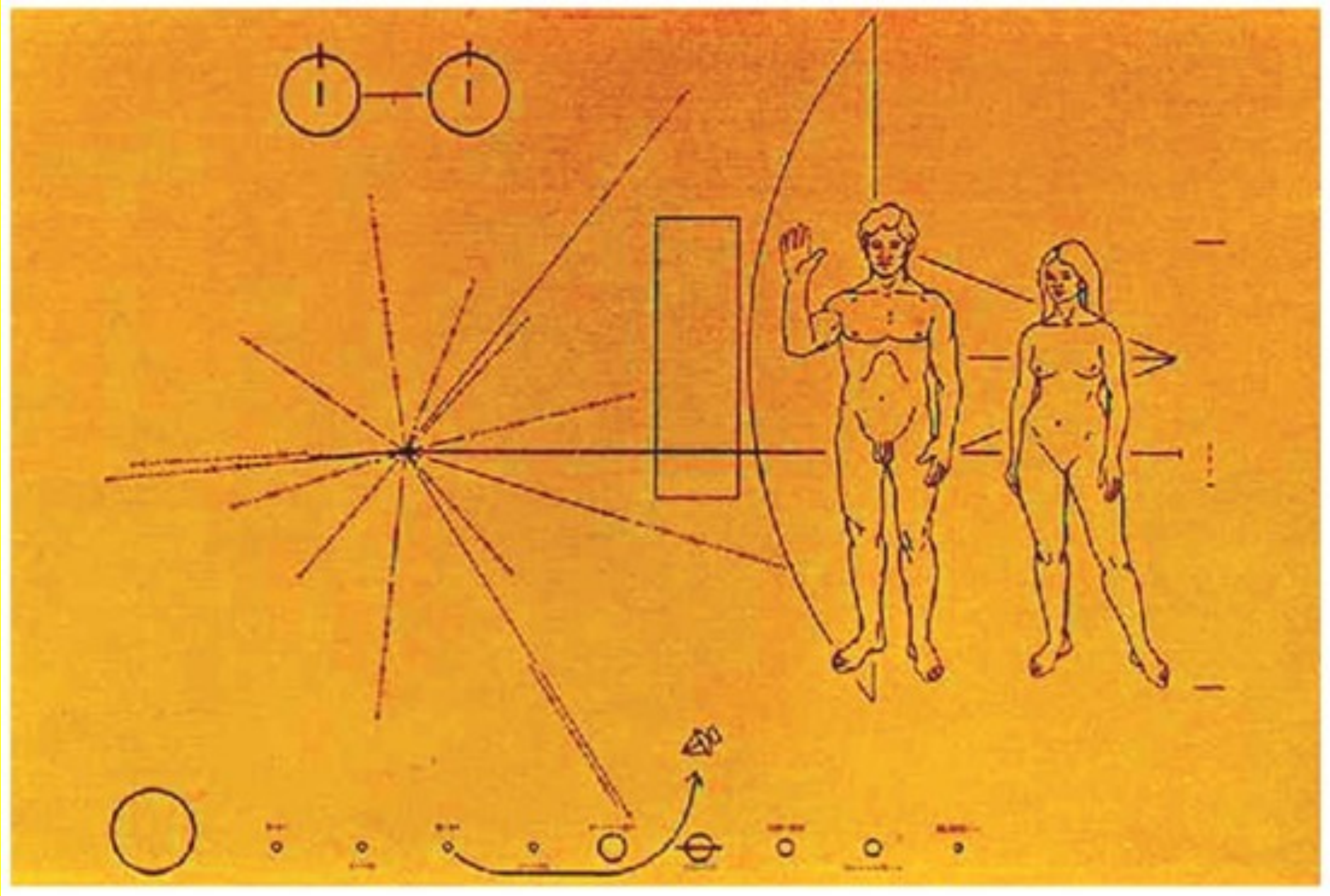
Voyager record

Difficulties of Interstellar Travel



- Far more efficient engines are needed.
- Energy requirements are enormous.
- Ordinary interstellar particles become like cosmic rays.
- Social complications of time dilation.

Where are the aliens?

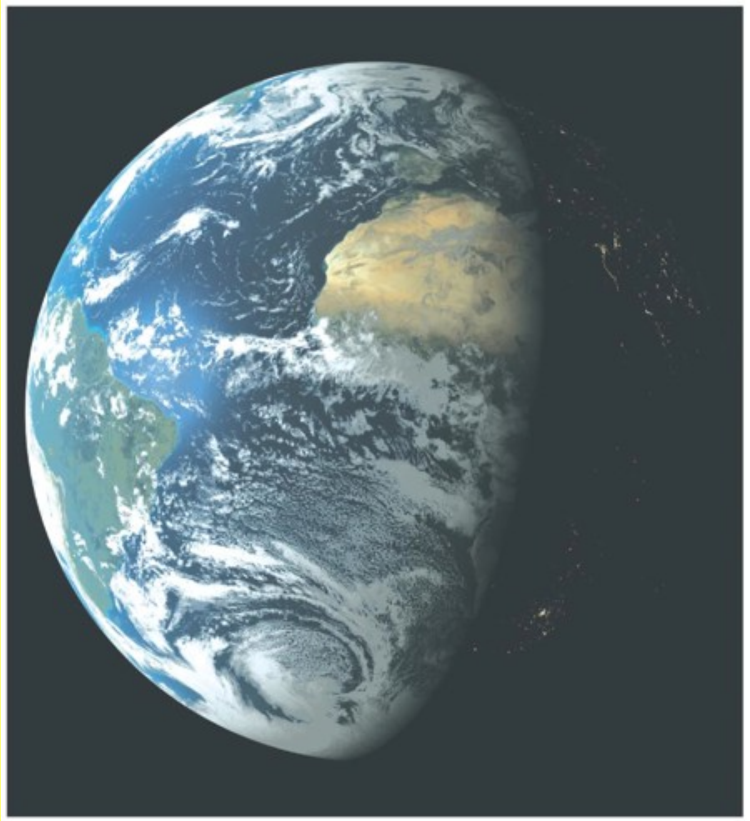


Fermi's Paradox

- Plausible arguments suggest that civilizations should be common. For example, even if only 1 in 1 million stars gets a civilization at some time $\Rightarrow$ 100,000 civilizations
- So why we haven't we detected them?

Possible solutions to the paradox

1) We are alone: life/civilization is much rarer than we might have guessed.
   - Our own planet/civilization looks all the more precious…



Possible solutions to the paradox

2) Civilizations are common, but interstellar travel is not because:
   - interstellar travel is more difficult than we think.
   - the desire to explore is rare.
   - civilizations destroy themselves before achieving interstellar travel.

These are all possibilities, but not very appealing…

Possible solutions to the paradox

3) There IS a galactic civilization…

… and some day we'll meet them.