The Solar System and its Origin

Chapter 6 - part 2


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Mars
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million
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satellites

Solar System Formation: The Nebula Theory

* The best theory is that our Solar System was born from a dusty gas nebula
* This is backed up with a lot of evidence and computational models
* These models account for all the features found in our Solar System, including, of course, the exceptions

Reviewing the Exceptions

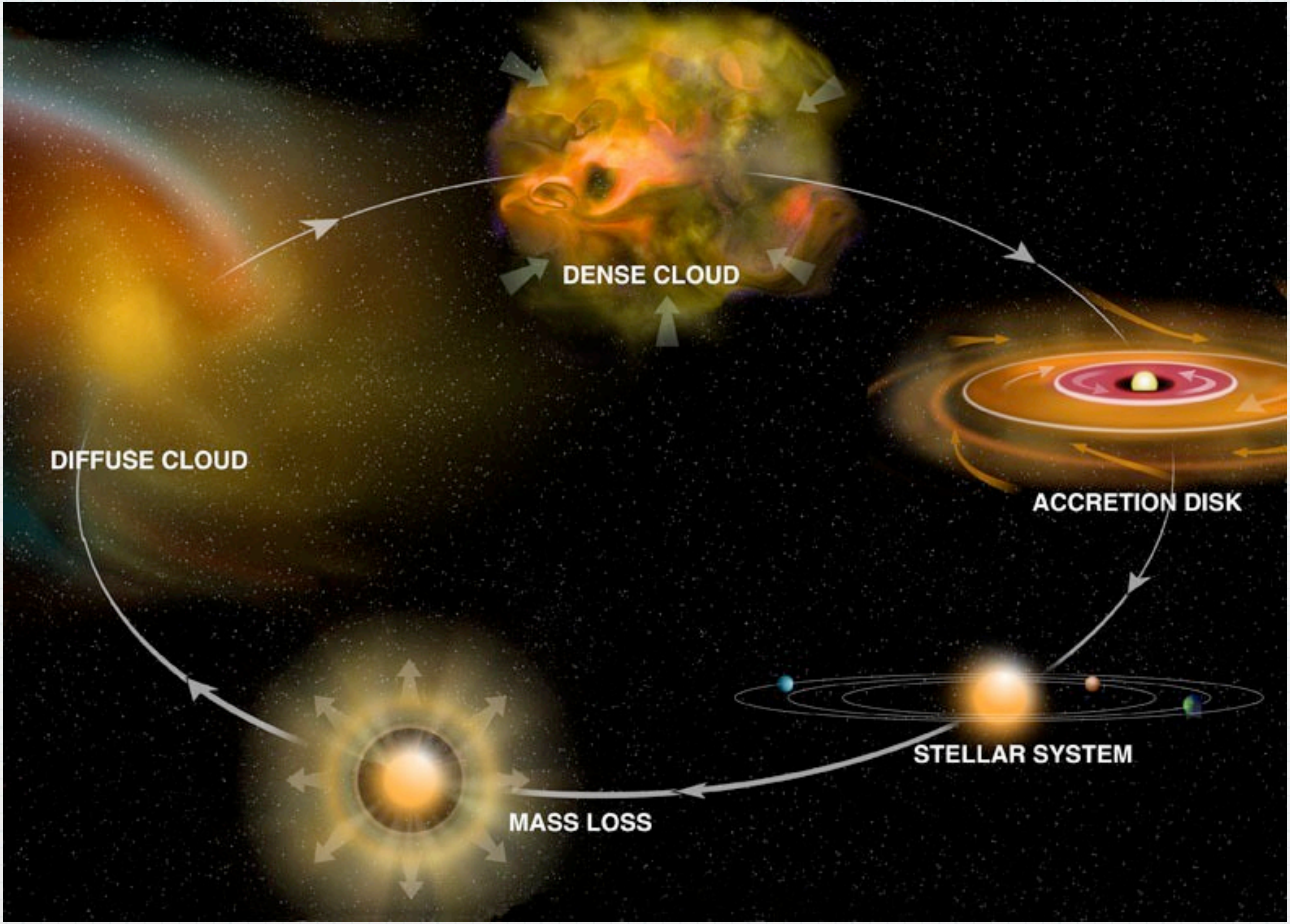
1. Venus rotates backwards
2. Uranus is rotating on its side
3. Earth, comparatively to its size, has the largest moon by far
4. Some small (jovians) moons orbit in the opposite direction that their planet does

(such as Triton and other inner satellites)

Birth of our Solar System

* A dense and cold cloud of gas collapsed under its own gravity: the solar nebula
* Where did this gas come from?
* It came from massive stars which previously died - some violently - in our galaxy: we call this galactic recycling

Galactic Recycling



Credit: Bill Saxton, NRAO/AUI/NSF

Birth of our Solar System...

* The Universe was born in the Big Bang event
* Hydrogen & helium were the only two chemical elements present when the Universe was young
* All other chemical elements have been produced since then by multiple generations of stars within their fusion reactors (their cores)

Birth of our Solar System...

* The Universe is 13.77 billion years old and stellar material recycling has been going on for about 13 billion years
* 4.6 billion years ago, only 2% of the original mass of hydrogen and helium of our galaxy had been converted to heavier elements by stellar nuclear fusion
* Our Solar System was born from that mix

Galactic Recycling

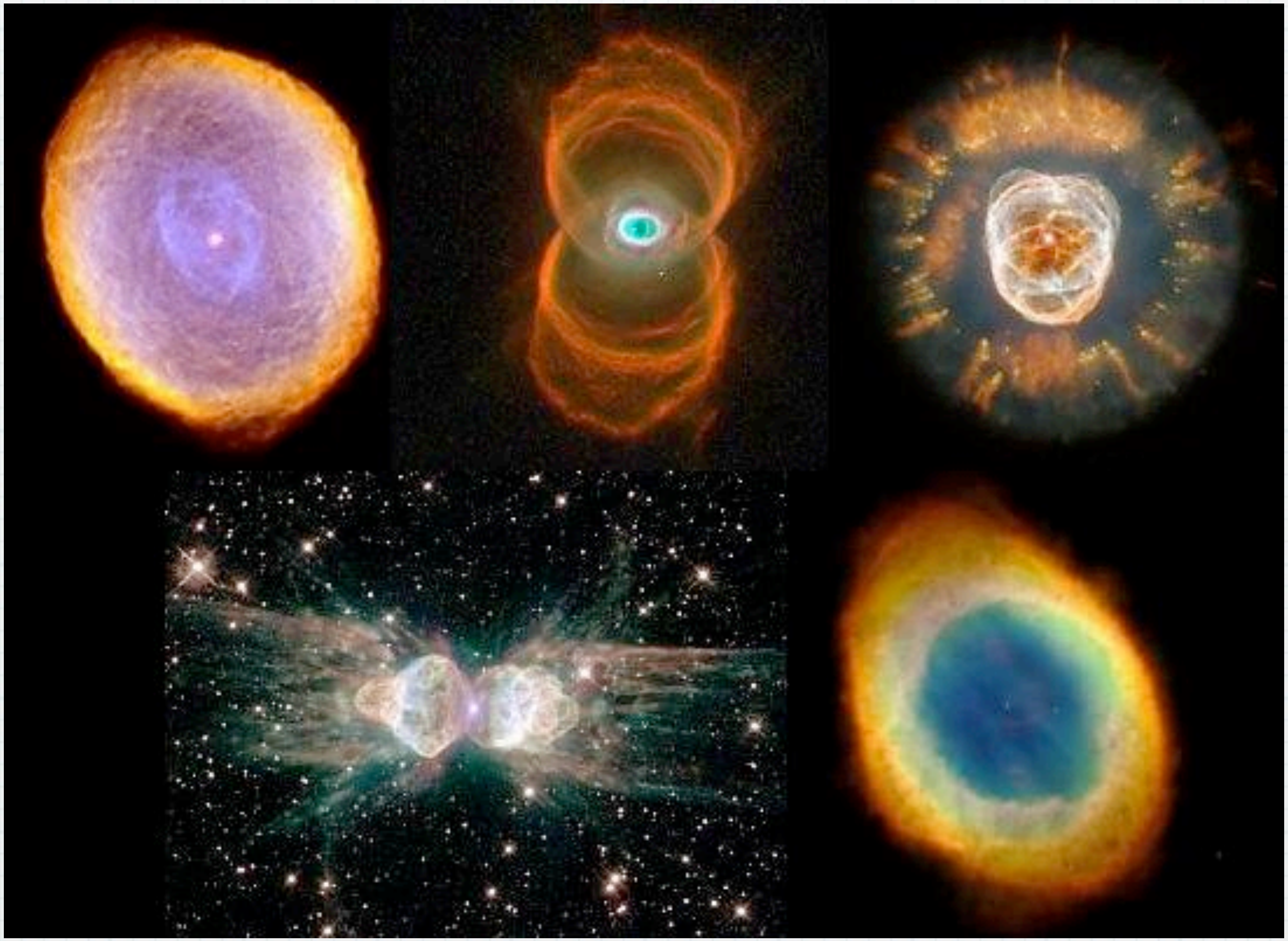
* Before our Solar System could be born, other stellar systems had to die
* When a star like our Sun exhausts its nuclear material it expels its outer envelope and forms a planetary nebula

* When a huge star exhausts its nuclear fuel it explodes violently (supernova) and forms a supernova remnant

Planetary Nebulae
(star deaths)

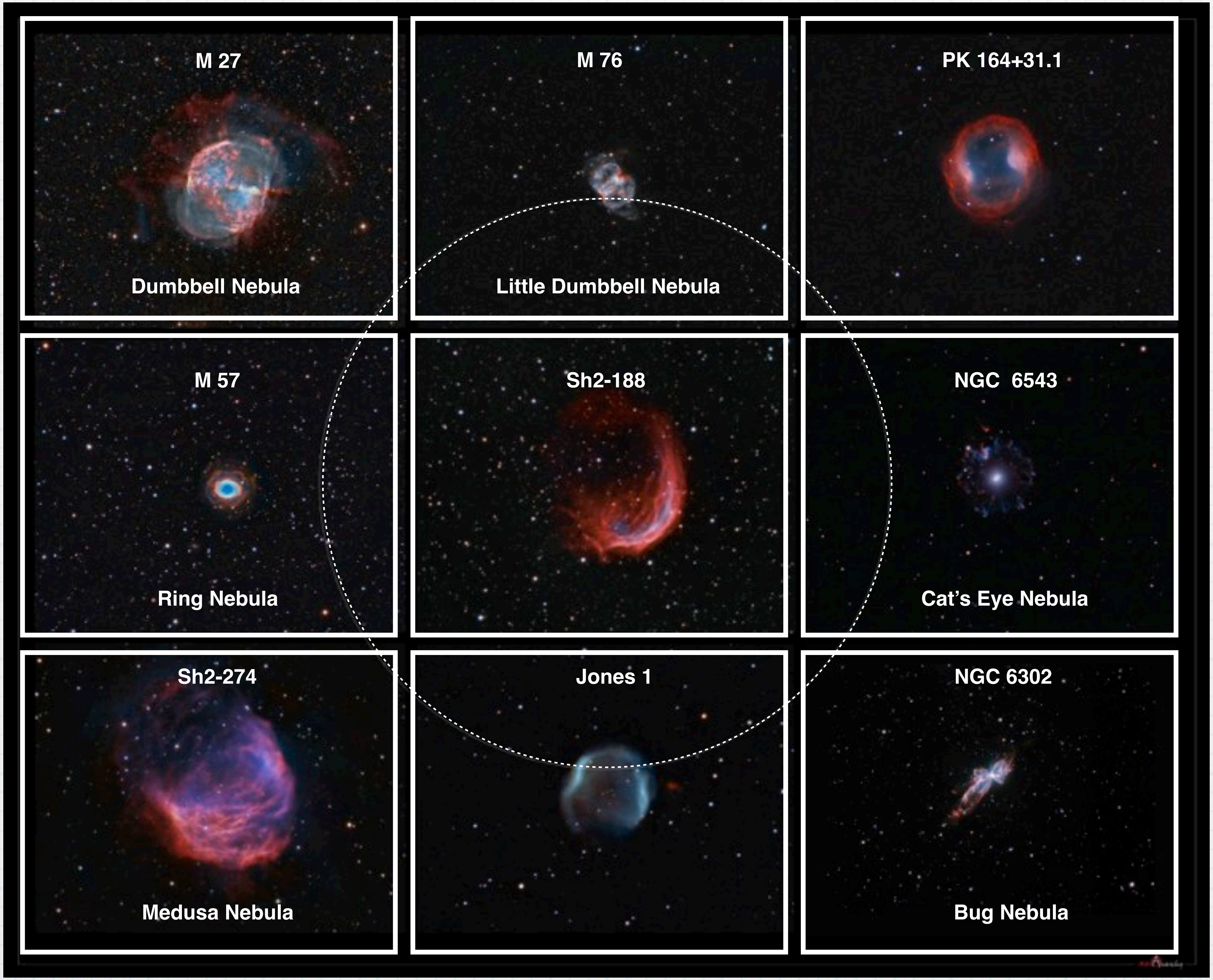
Planetary Nebula Gallery

Spirograph Hourglass Eskimo

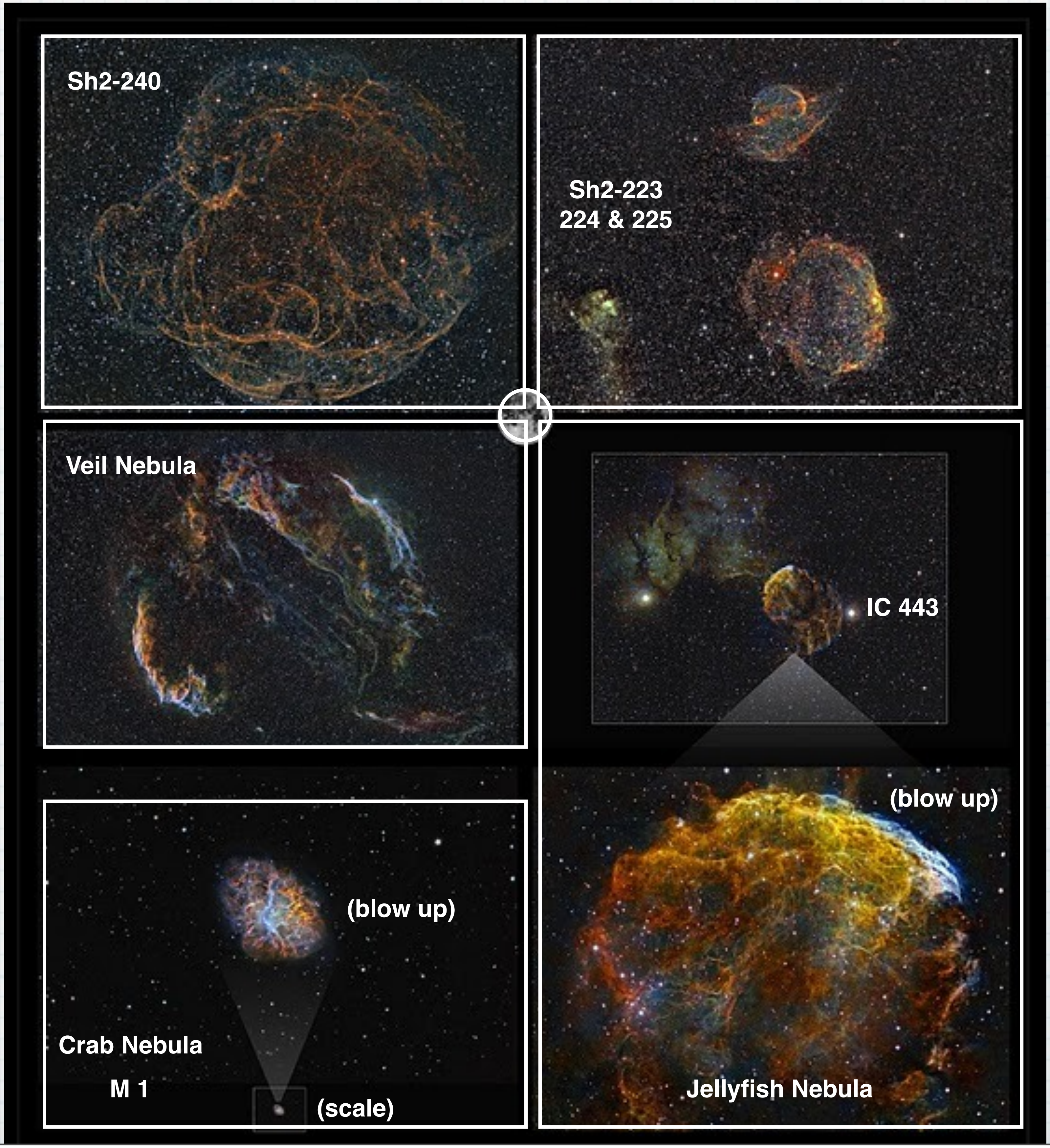


Ant Ring

Planetary Nebulae sizes to scale (with the Moon)
Planetary Nebula = death of a Sun-like star



Supernovae Remnants sizes to scale (with the Moon)
Supernova = death of a massive star



From Star Deaths to Stellar Nebulae

* As a planetary nebula or supernova shell expands into interstellar space
* it eventually encounters other such shells (as stars are formed in clusters)

From Star Deaths to Stellar Nebulae...

* Eventually their material mix and form a **stellar nebula** also called a **stellar nursery**
* Entering a spiral arm of our galaxy or colliding shock waves from another supernova are some of the mechanisms which **triggers a gas region of the nursery to collapse due to gravitational forces**

Stellar Nurseries...

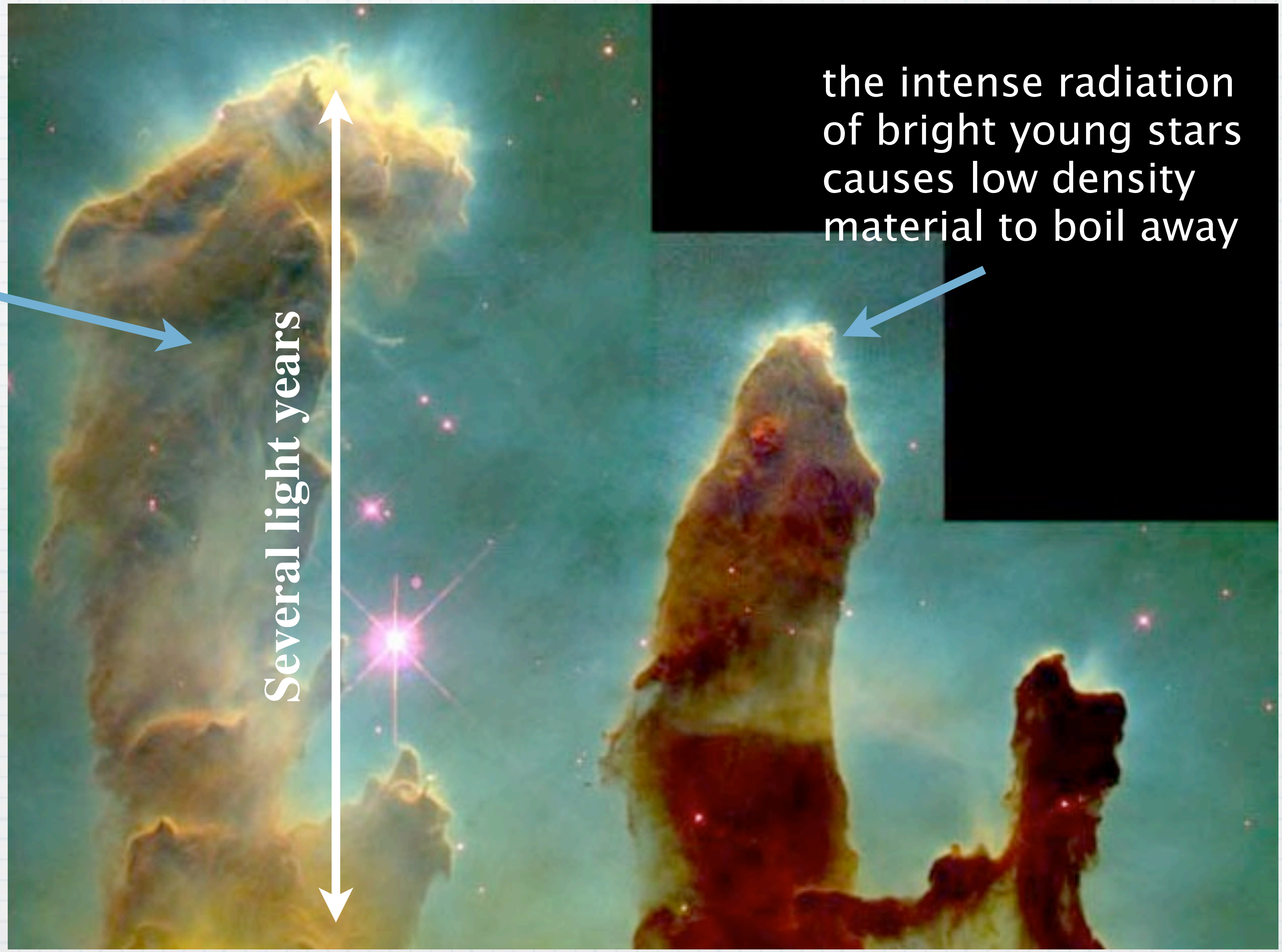
Many of the filamentary structures visible in this image are actually shock waves - fronts where fast moving material encounters slow moving gas

Stellar Nurseries

M16

Eagle Nebula

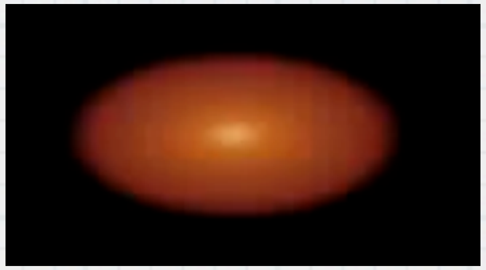
Evaporating gaseous globules (EGG)



Birth of the Solar System

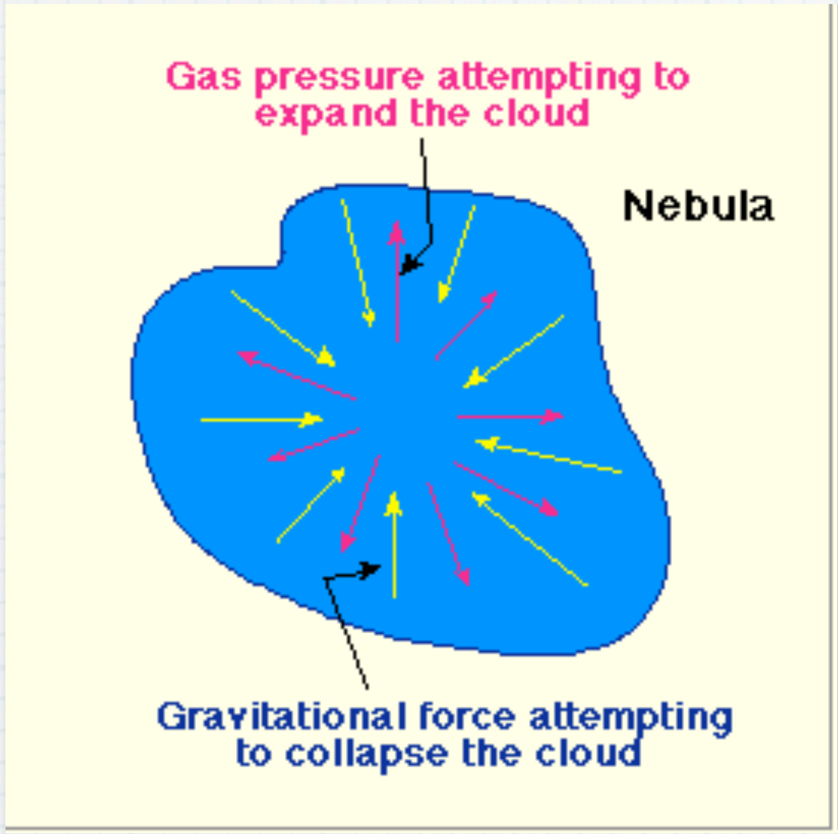
- Once started - since gravity works as an attractive force with a distance inverse square law ($\propto 1/d^2$) - the gravitational collapse of a large cloud of very cold and very low density gas cannot be stopped and accelerates

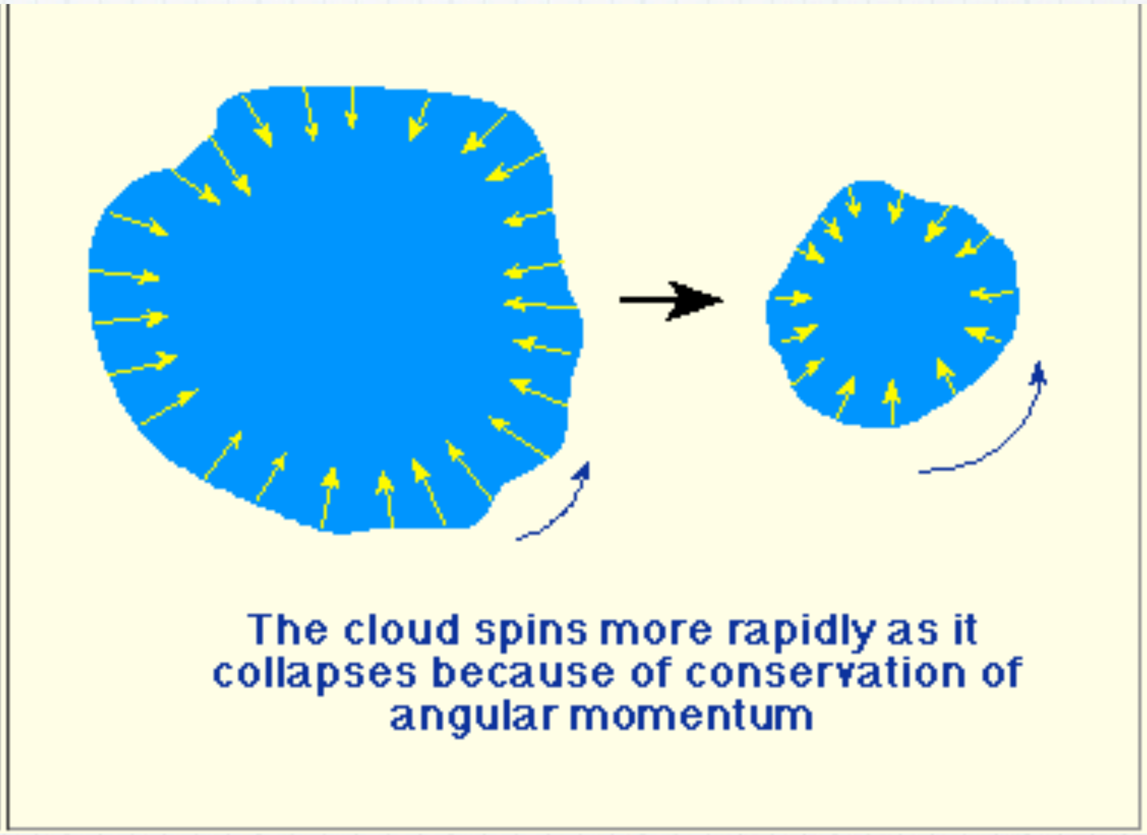
Collapsing, Heating, Spinning, and Flattening



Collapsing, Heating, Spinning, and Flattening

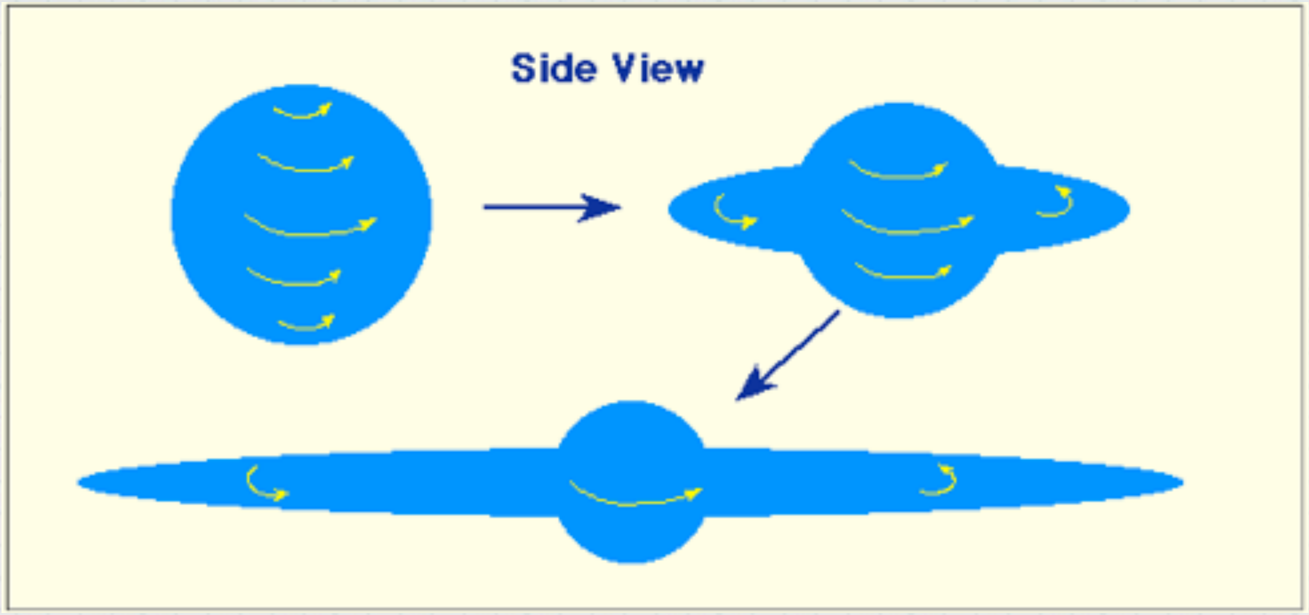
Original cloud is large, diffuse and cold





Due to the conservation of energy law, the cloud heats up as it collapses and spins up

Particle collisions flatten the cloud into a disk



Final result is a spinning flattened disk where most of the mass is at the center and where the temperature is hottest at the center

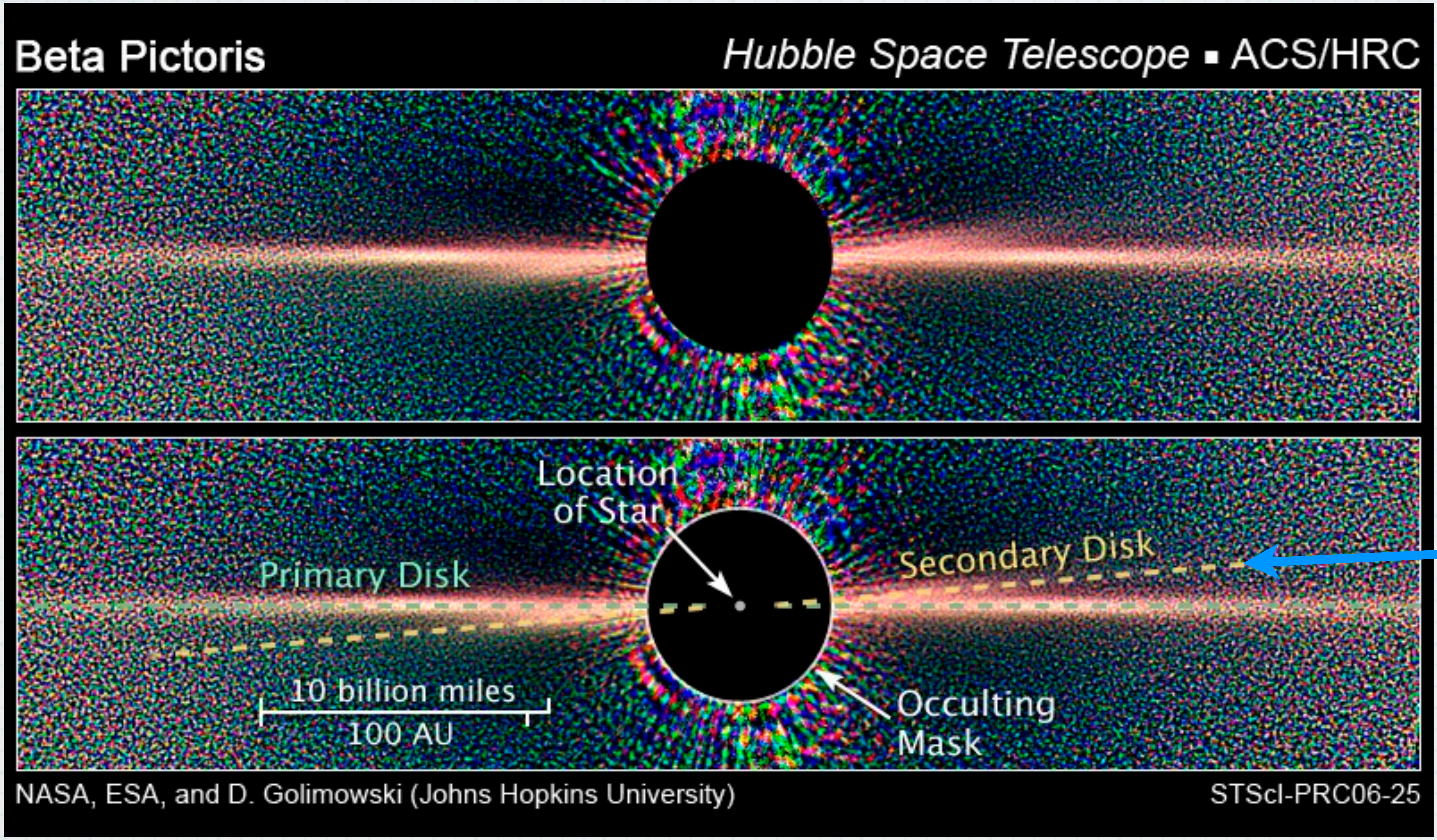
Orderly Motions in the Solar System

* Gravity forces the cloud to become smaller (hence hotter) and its spin increases (Conservation of Angular Momentum)

* Collisions flattens the cloud into a disk: Collisions (frictional forces) between gas particles in cloud gradually reduce random and "up & down" motions

Evidence of such disks...

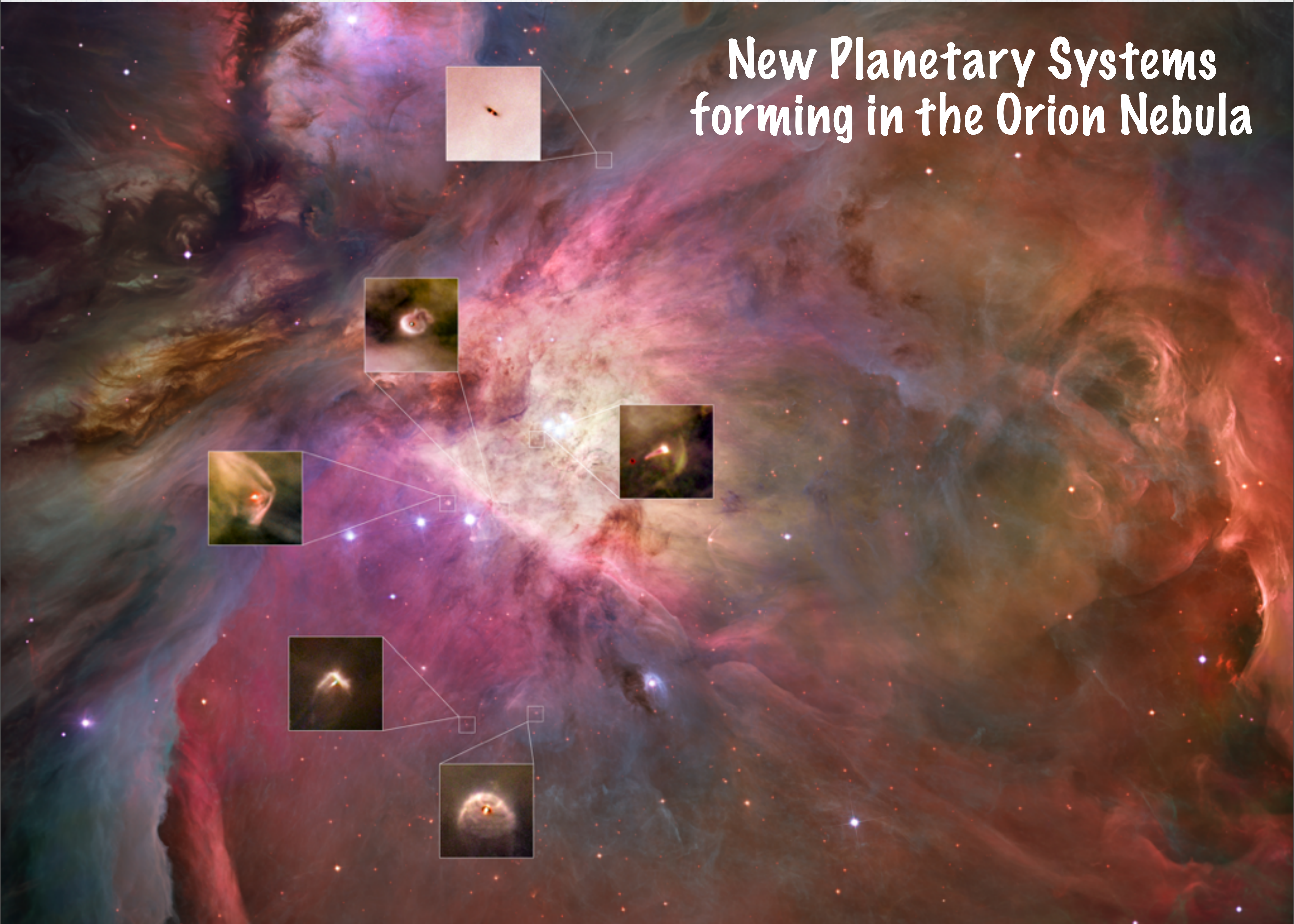
Coronagraphic image of circumstellar protoplanetary disk
Hubble sees two disks around Beta Pictoris



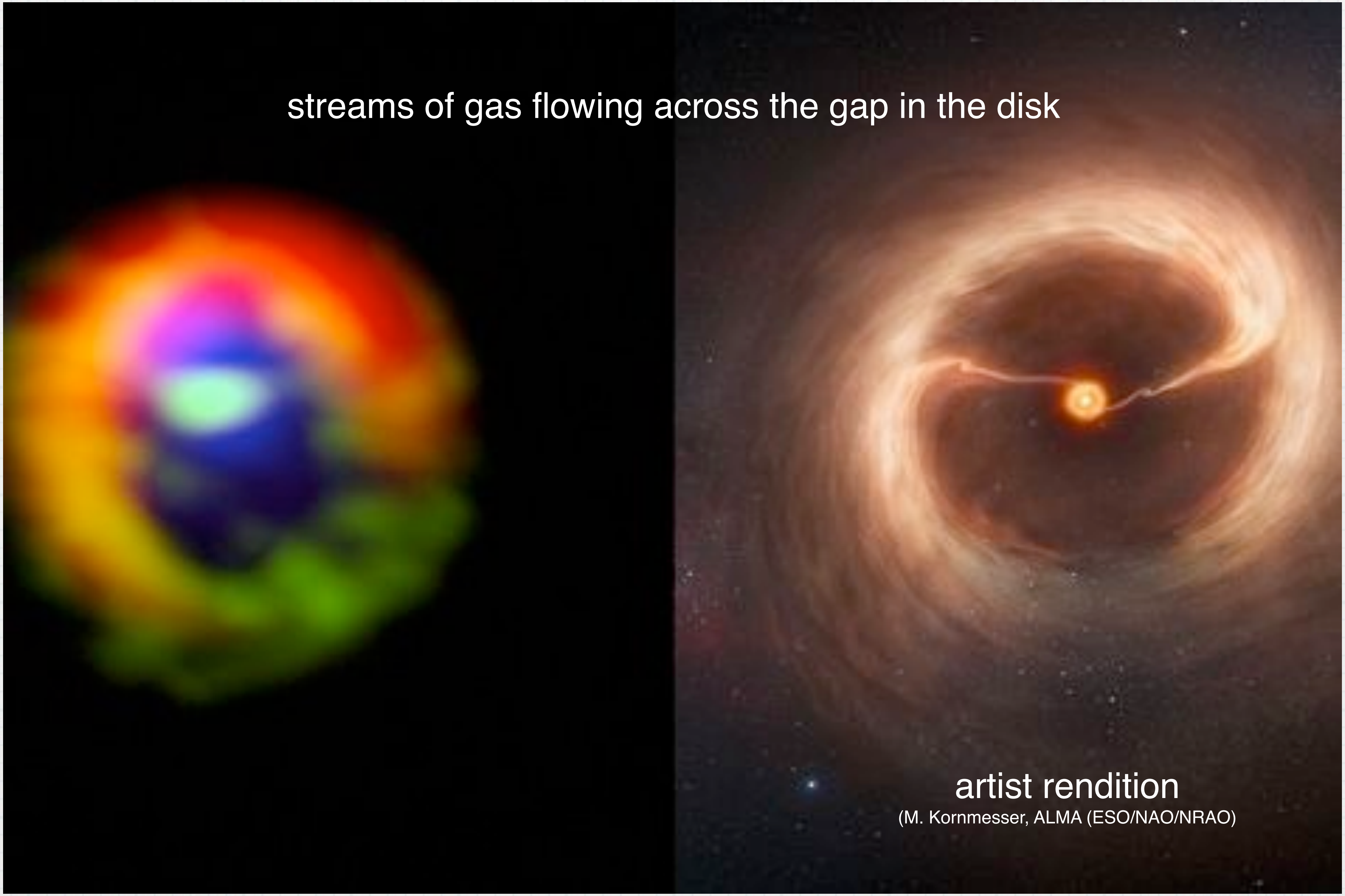
circumstantial evidence for the existence of a planet

Observational Data

1. So we have observational evidence of cloud collapse,
2. Infrared radiation has been detected from many nebulae where star systems appear to be forming,
3. And we are seeing structures of flattened and spinning disks around other stars


New Planetary Systems
forming in the Orion Nebula

Giant Gas Planet Being Formed (star HD 142527)



Modeling Data

* Computer simulations of data representative of our observations which follow the laws of physics successfully reproduce most of the general characteristics of motions in our Solar System

➡ We are on the right track

Snapshot

* Where did the Solar System come from?
* The cloud of gas that gave birth to our Solar System was the product of recycling of gas through many generations of stars within our galaxy. This gas consisted of 98% hydrogen and helium and 2% everything else combined

Snapshot

* What caused the orderly patterns of motion in our Solar System?
* A collapsing gas cloud naturally tends to heat up, spin faster, and flatten out as it shrinks in size. Thus, our Solar System began as a spinning disk of gas. The orderly motions we observe today all came from the orderly motion of this spinning disk of gas

Planet Formation

* Once the solar nebula had collapsed into a flattened disk (∅: 200 AU),

➡ planet formation started

* Chemical composition of the nebula:
  * 98% hydrogen & helium
    * H: 73%, He: 25%
  * 2% heavier elements (called "metals")

Two Types of Planets

Location is everything

1. The terrestrial planets formed in the warm inner regions of the condensing and spinning disk
2. The jovian (gas) planets formed in its colder outer regions

Planetary Formation Steps

* There are two major planetary formation steps:

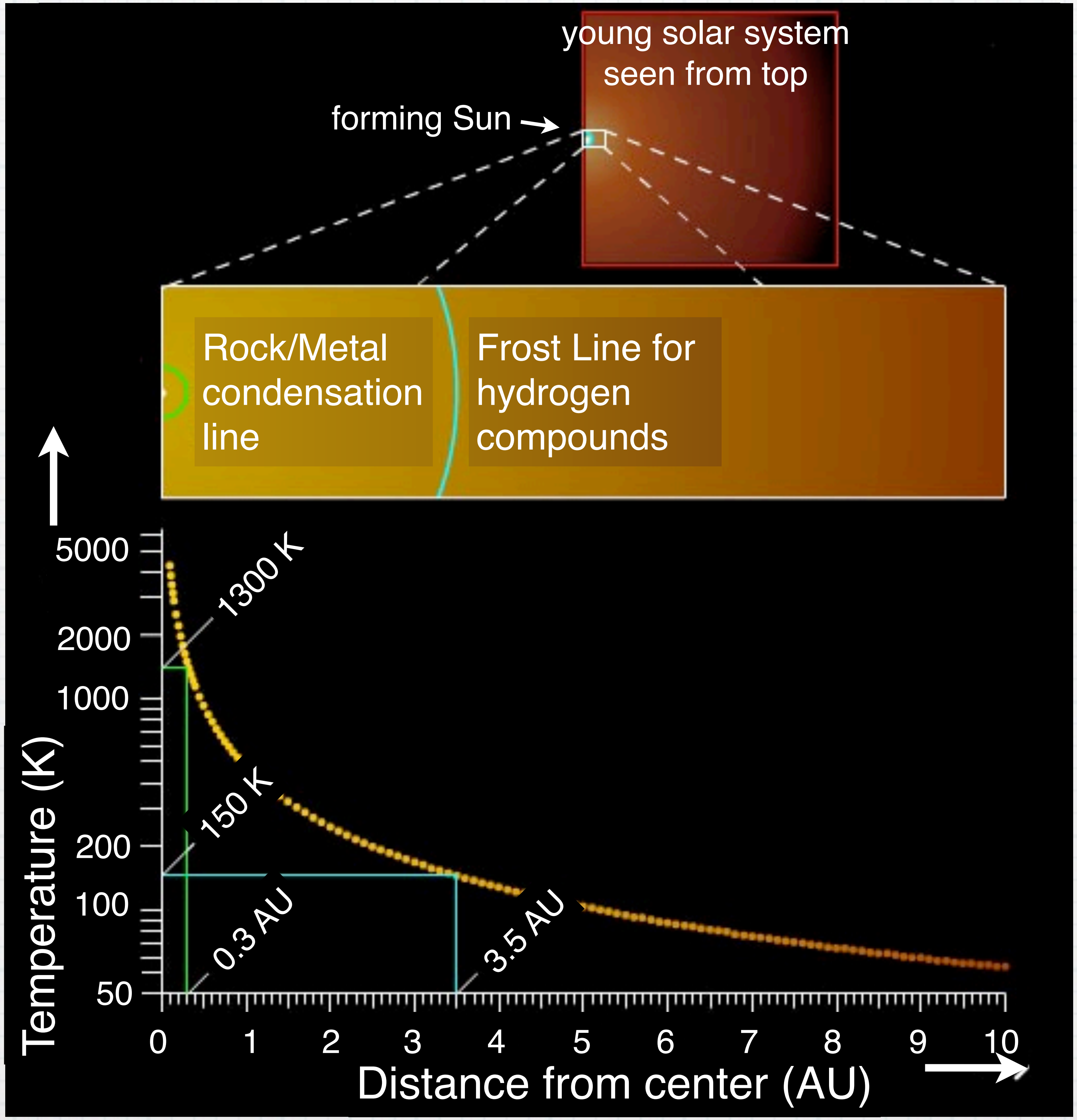
1. Equilibrium Condensation, &
2. Collisional Accretion

1. Equilibrium Condensation

* What materials are likely to condense in solid form in a particular region of the solar nebula?

✓ Condensation: going from gas to liquid and solid states

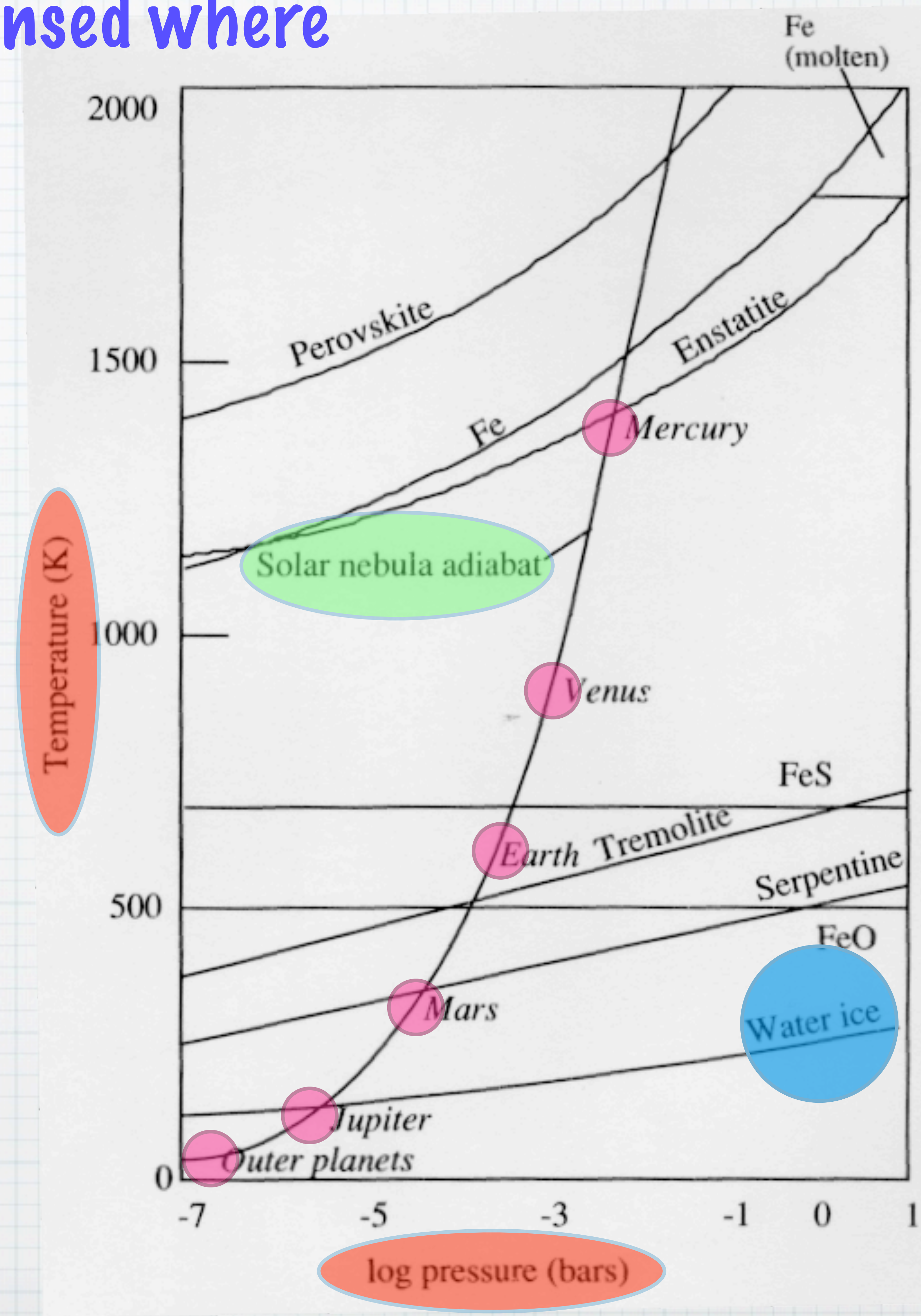
The Frost Line



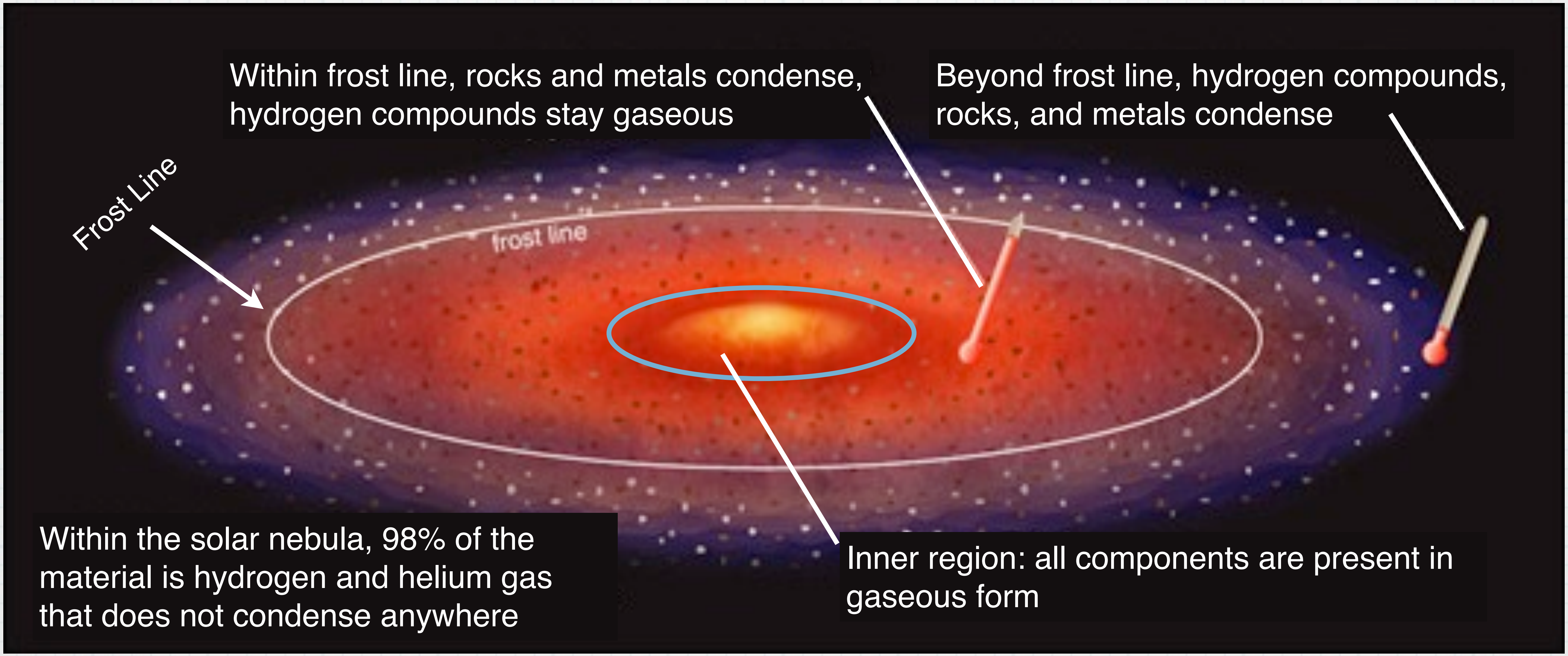
What condensed where

The point of this slide is not to remember the values

It is there to show that **we can calculate pretty much what materials can condense at the locations of the planets (or anywhere else in the collapsing solar nebula)**



Condensation Summary...



Condensation Summary...

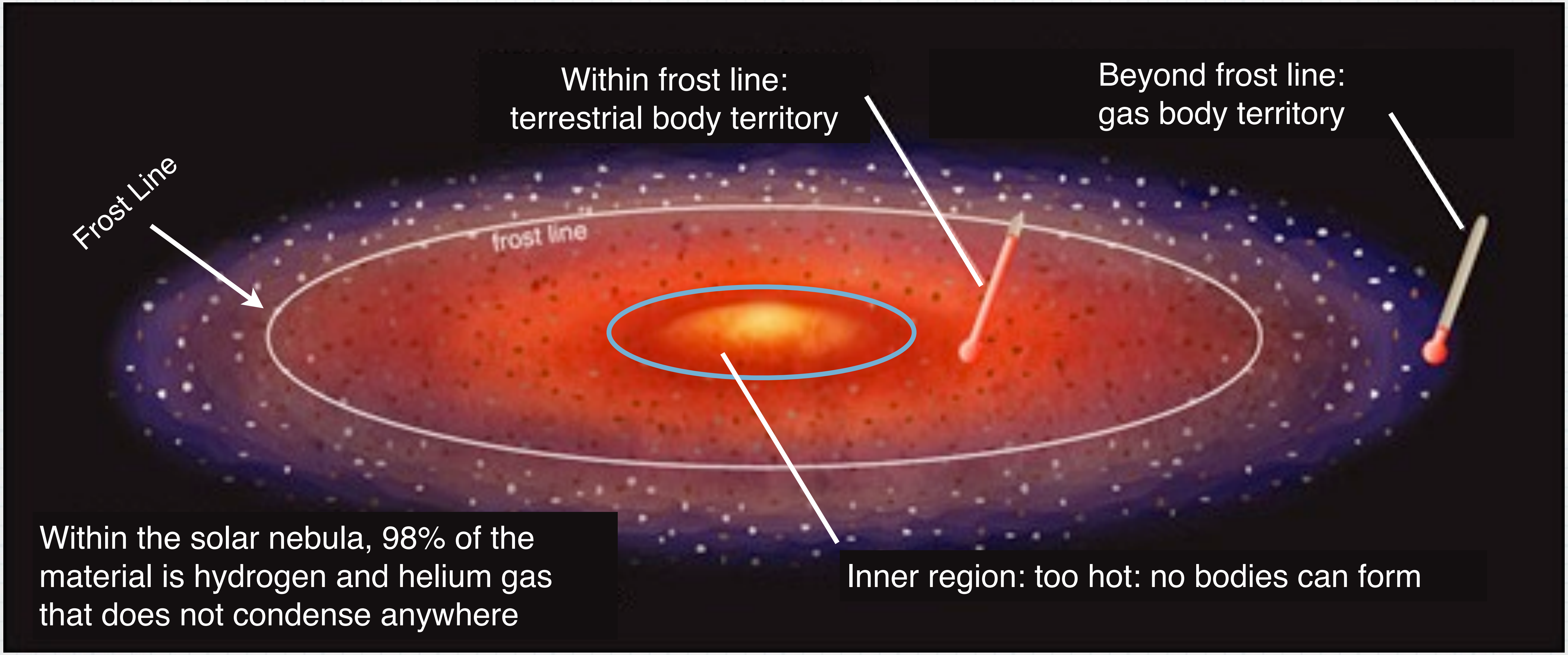
Four major categories of ingredients exist in the solar nebula

1. Hydrogen and helium gas (98%) which stays gaseous all over
2. Metals (0.2%) such as iron, nickel and aluminum (1,000 K < T_c < 1,600 K)
3. Rocks (0.4%) (500 K < T_c < 1,300 K)
4. Hydrogen compounds (1.4%) such as water, methane, ammonia (T_c < 150 K)

Condensation Summary...

* The vast majority of the solar nebula's mass does not condense (hydrogen & helium)
* In the inner most regions of the nebula, near where the Sun is forming, nothing condense: it is too hot (T > 1,600 K)
* Farther, metals and some rocks condense into tiny particles (terrestrial body territory)
* Farther along, past a line called the frost line, hydrogen compounds condense into ices (ice body territory)

Condensation Summary...



Condensation Summary...

* Equilibrium condensation gives us the starting points for the chemical composition of the planets
* But how do they actually form?
* The current situation is that we are left with a disk of small grains with a chemical composition which varies with distance from the center (Sun)

2. Collisional Accretion

* Several factors can built up **planetesimals**

1. Collisions of dust grains
2. Electrostatic bindings
3. Gravitational (local) attraction

* Calculations show that these processes build planetesimals up to **tens of kilometers in diameter in less than one million years**

Runaway Accretion

* The bigger an object, the bigger its gravity and therefore its ability to accrete further:

  a. the biggest planetesimals grow the fastest

  b. the smaller ones get destroyed by fast collisions (turned into smaller objects)

➡ So one object will dominate a region because of a runaway accretion

The Making of Terrestrial Planets

* Solids seeds of metal and rock in the inner solar system grew into full-fledged planets via a planetesimal stage
* Accretion via collisions, electrostatic binding and gravitational attraction turns large boulders into planetesimals

The Making of Terrestrial Planets...

* Planetesimals grow larger as they have more surface which makes them grow even larger
* Collisions between them have the effect that the larger ones survive while the others are fragmented and absorbed by the larger ones

➡ At the end, only a few survive

The Making of Jovian Planets

* Accretion works the same way

1. but there is more solid material due to the condensation of ices (mixture of H, O, C, N atoms)

2. due to their larger initial masses [rocks-metals-ices], the jovian planetesimals also gravitationally attract hydrogen and helium

Clearing the Solar Nebula

* The vast majority of hydrogen and helium does not become part of the planets and is blown into interstellar space by the solar wind
* The solar wind is made up of free protons and electrons (charged particles)
* When the Sun was young, its solar wind was much stronger than it is now

Clearing the Solar Nebula...

* If the gas had not been blown, the terrestrial planets would eventually have been covered with iced hydrogen compounds
* If the gas had been blown too soon, the terrestrial planets might not have formed as their raw materials would have been swept away

Clearing the Solar Nebula...

- The characteristics of the star which is forming along is an extremely important factor for the whole system - from birth to death
- As we shall see in future chapters, some stars evolve a lot faster than others

Asteroids & Comets

* They are the leftovers from the planet formation era

1. **Asteroids** are **rocky/metal leftovers**
2. **Comets** are **icy leftovers**

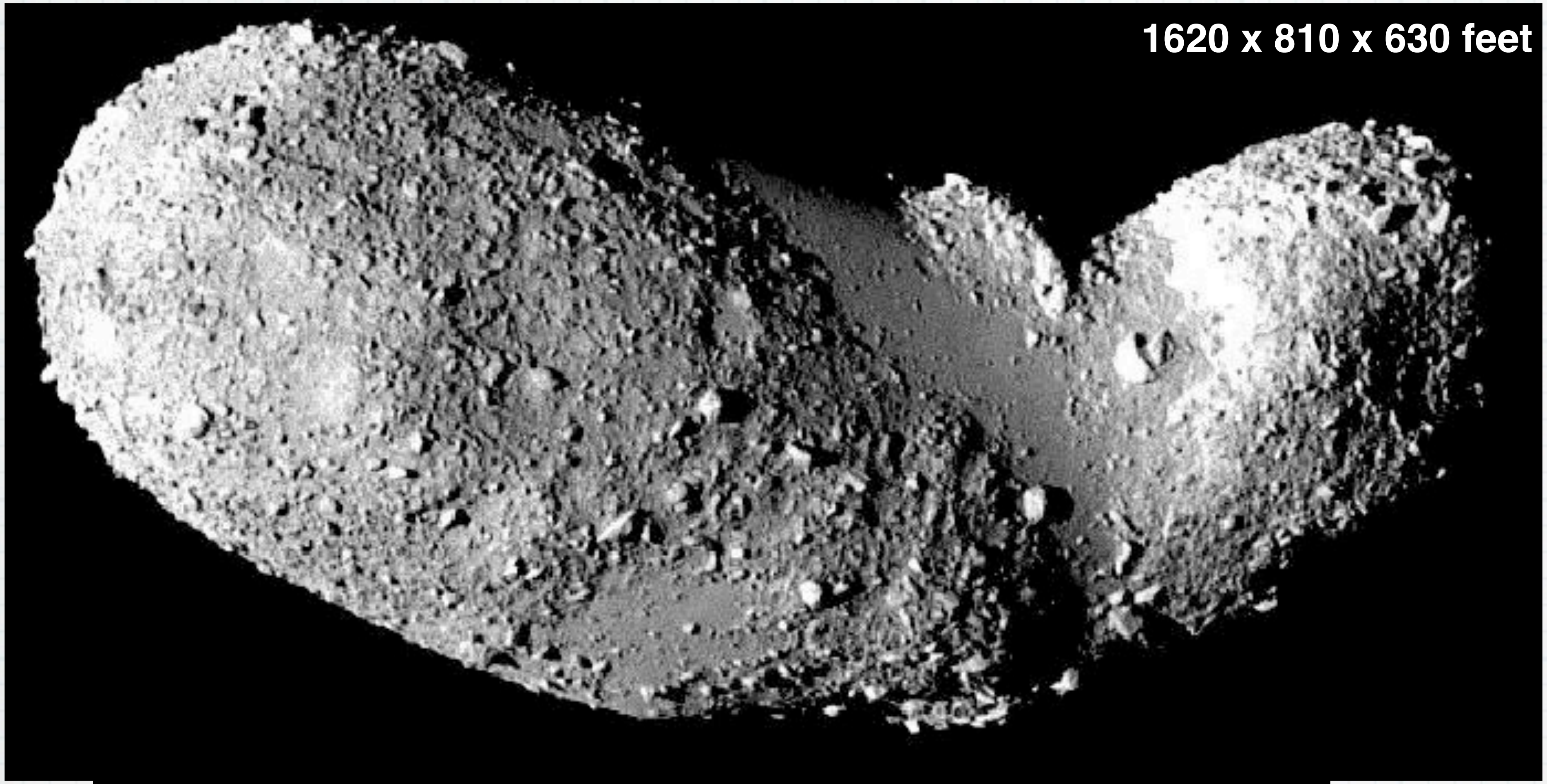
* Evidence for this comes from analysis of meteorites and spacecraft visits to comets and asteroids and computer simulations

Asteroids & Comets...

* Actually, this theory allowed astronomers to predict that a belt of comets existed in the neighborhood of the orbits of Neptune and Pluto (in the early 1900s)

➡ This was observed decades later

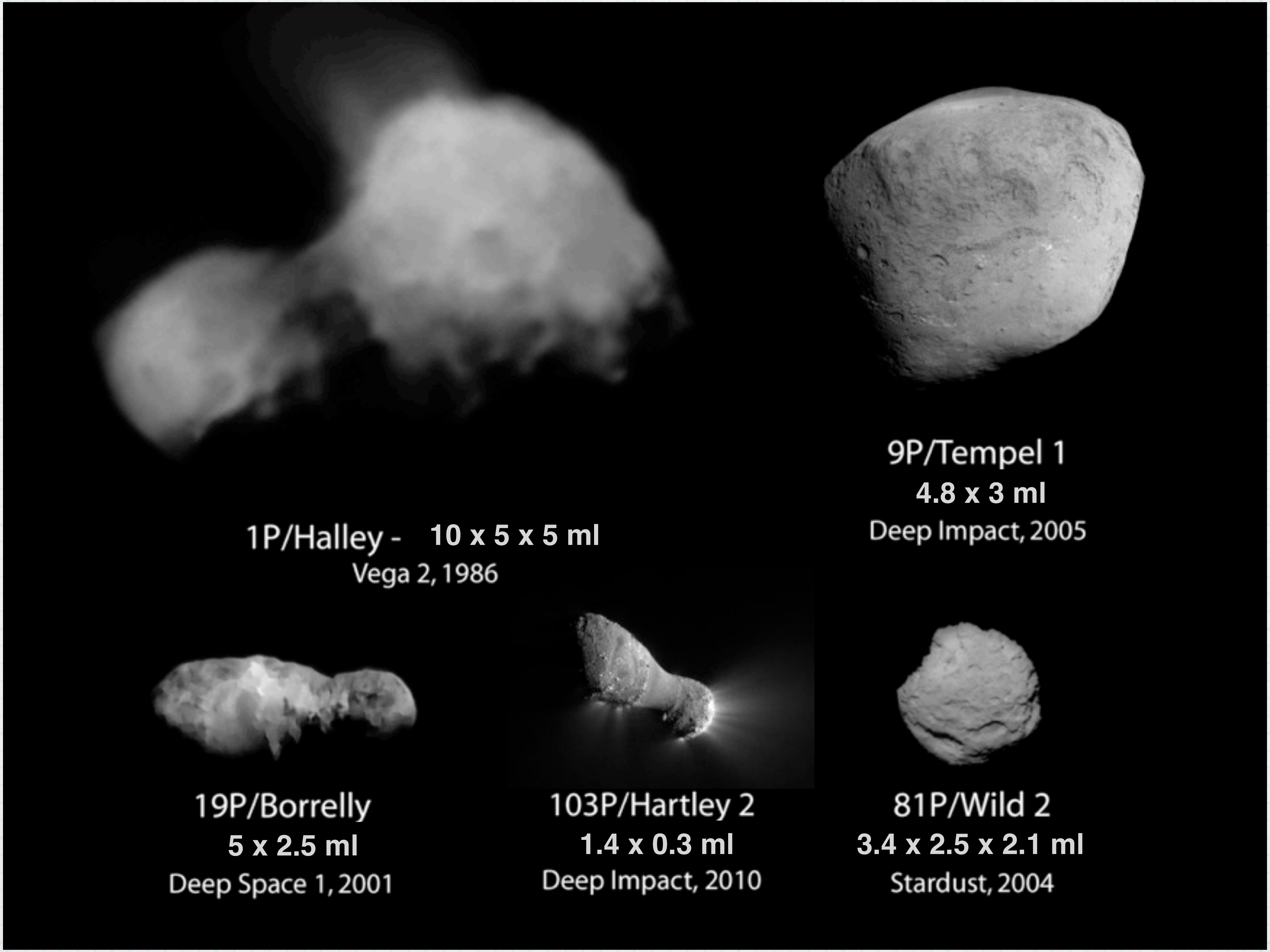
Some asteroids visited by spacecrafts



Itokawa
imaged Nov, 2005

Ida and moon Dactyl
imaged Aug. 28, 1993

Some comets visited by spacecrafts



The Exceptions

* So far we have explained all the major features of our solar system
* **What about the exceptions** such as our Moon's large size, the odd rotations of Venus and Uranus and the orbital rotation of satellites which go opposite to their planets' spins???

The Exceptions...

* Most of these exceptions are due to collisions or close encounters
* As previously stated, the planets formed by accretion and collision
* The vast majority of these collisions occurred in the first few hundred million years of our Solar System's history
* A period called the Heavy Bombardment

The Heavy Bombardment Period

* Every world in the Solar System was continuously impacted during that period
* We see numerous impact craters on Mercury, the Moon, Mars and Jovian satellites
* We do not see that many on Venus and Earth because of erosion due to weathering and volcanic activity

Illustration of an Impact Event on Earth

Meteor Crater, near Flagstaff, Arizona
∅: 1,200 meters, 170 meters deep

due to a chunk of iron and nickel about 55 meter across and about 10 million to 100 million years ago

The Heavy Bombardment Period...

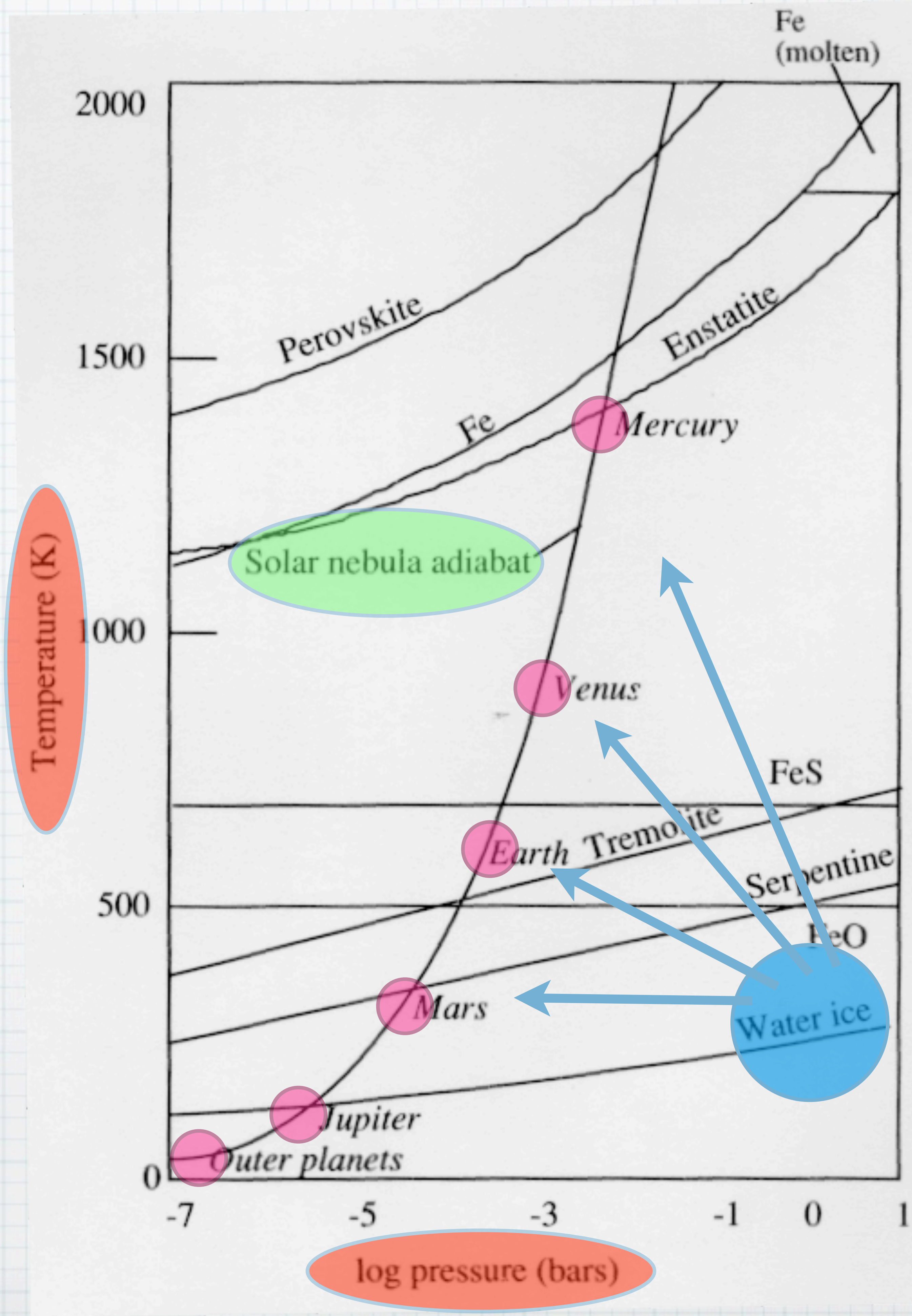
* More importantly, these impacts also captured material that condensed from other regions of the Solar System

➡ This is why Earth has water

* That water (and other hydrogen compounds) was part of planetesimals which formed beyond the orbit of Mars

The Heavy Bombardment Period brought water and other ices to the inner Solar System (and minerals)

Collisions results on some bodies losing orbital energy, hence they get closer to the Sun (they "fall" in)



Captured Moons

* Some satellites have unusual orbits:
  a. they are in the opposite direction of their planet's spin
  b. they are highly inclined with that planet rotation axis
* because they did not form "in place" but were captured instead

Captured Moons...

* To be captured, an object must lose orbital energy
* For moons orbiting Jovian planets, this can be explained by atmospheric friction (although there is a size limit of a few kilometers in diameter)
* Mars' moons were captured the same way

Captured Moons...

* What about our Moon?

  a. The Moon did not form simultaneously with the Earth: they would share density and composition and they do not

  b. The Moon's density is much lower than the Earth and its composition is similar than the Earth's upper mantle

Giant Impacts

- ➡ We strongly suspect the Moon was formed when a Mars-sized object collided with the Earth
- * The Earth was not destroyed, nor was its axis overly tilted
- * That giant impact blasted away rocks from the Earth's outer layers and sent it in orbit around our planet

Giant Impacts...

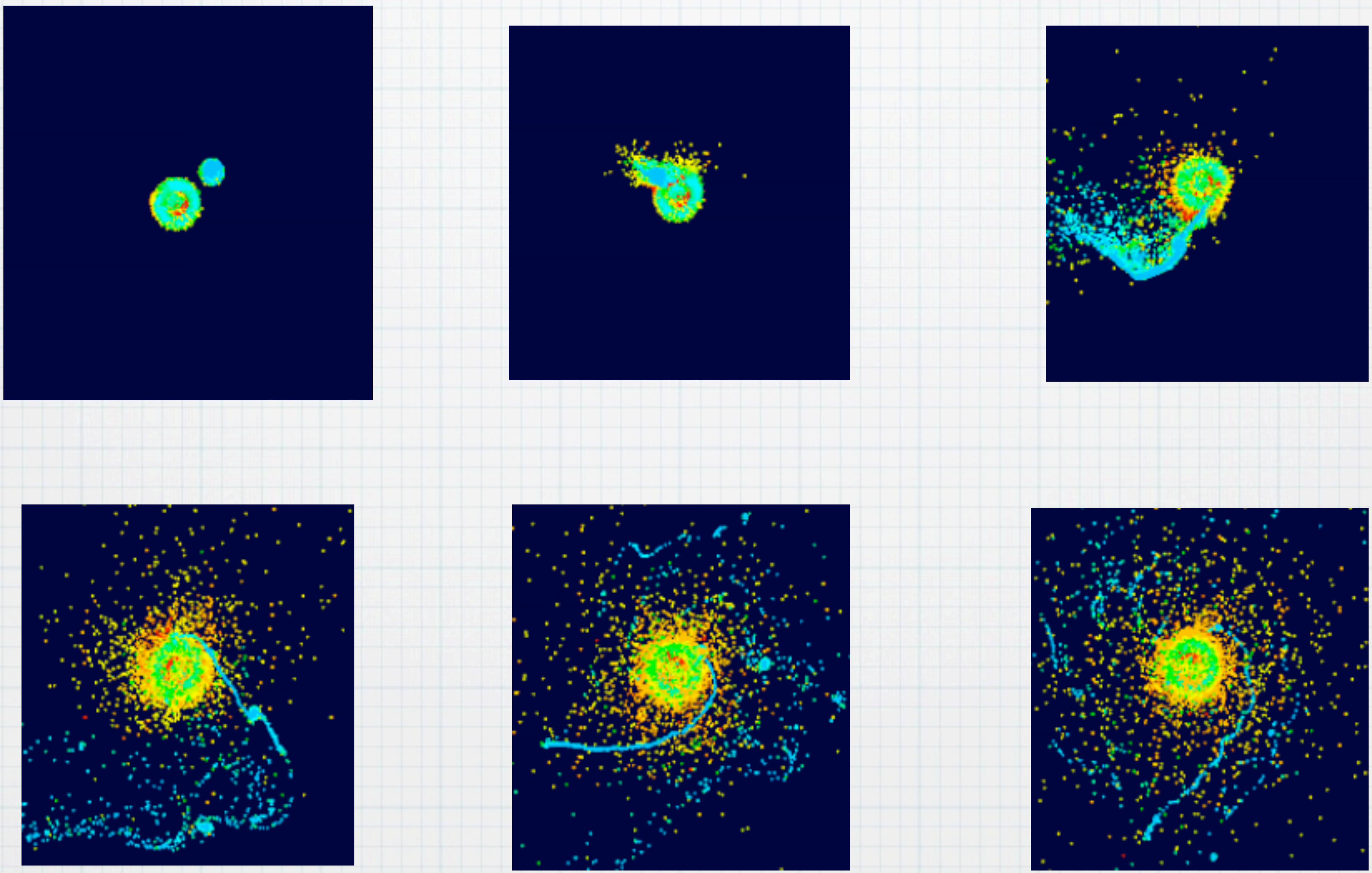
* Computer simulation show that this material could have re-accreted and formed our Moon

* Supporting features for this scenario:

1. The Moon's composition is similar to the Earth's outer layers

2. The Moon has a much smaller proportion of easily vaporized ingredients (like water) than the Earth

Creation of our Moon?

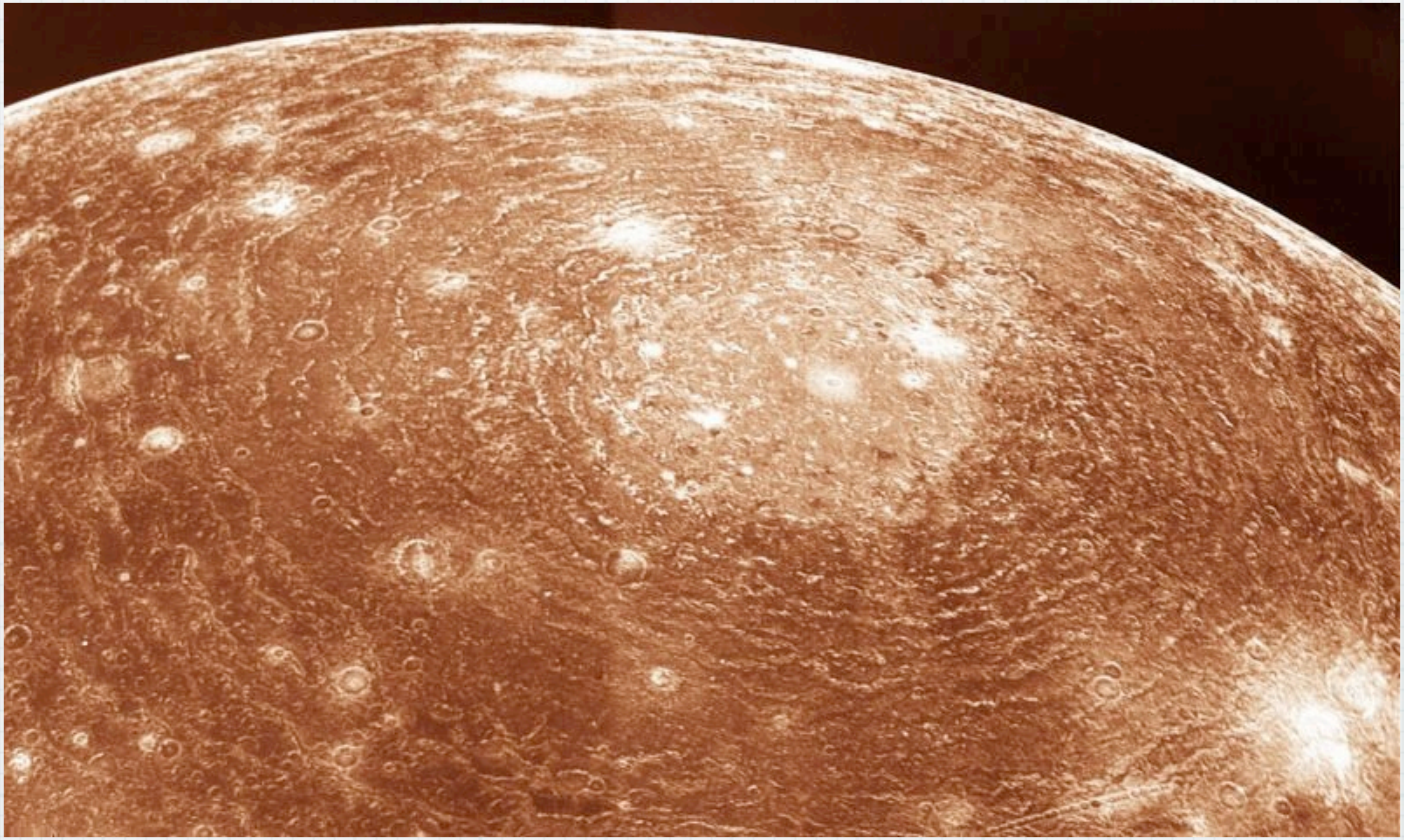


Giant Impacts...

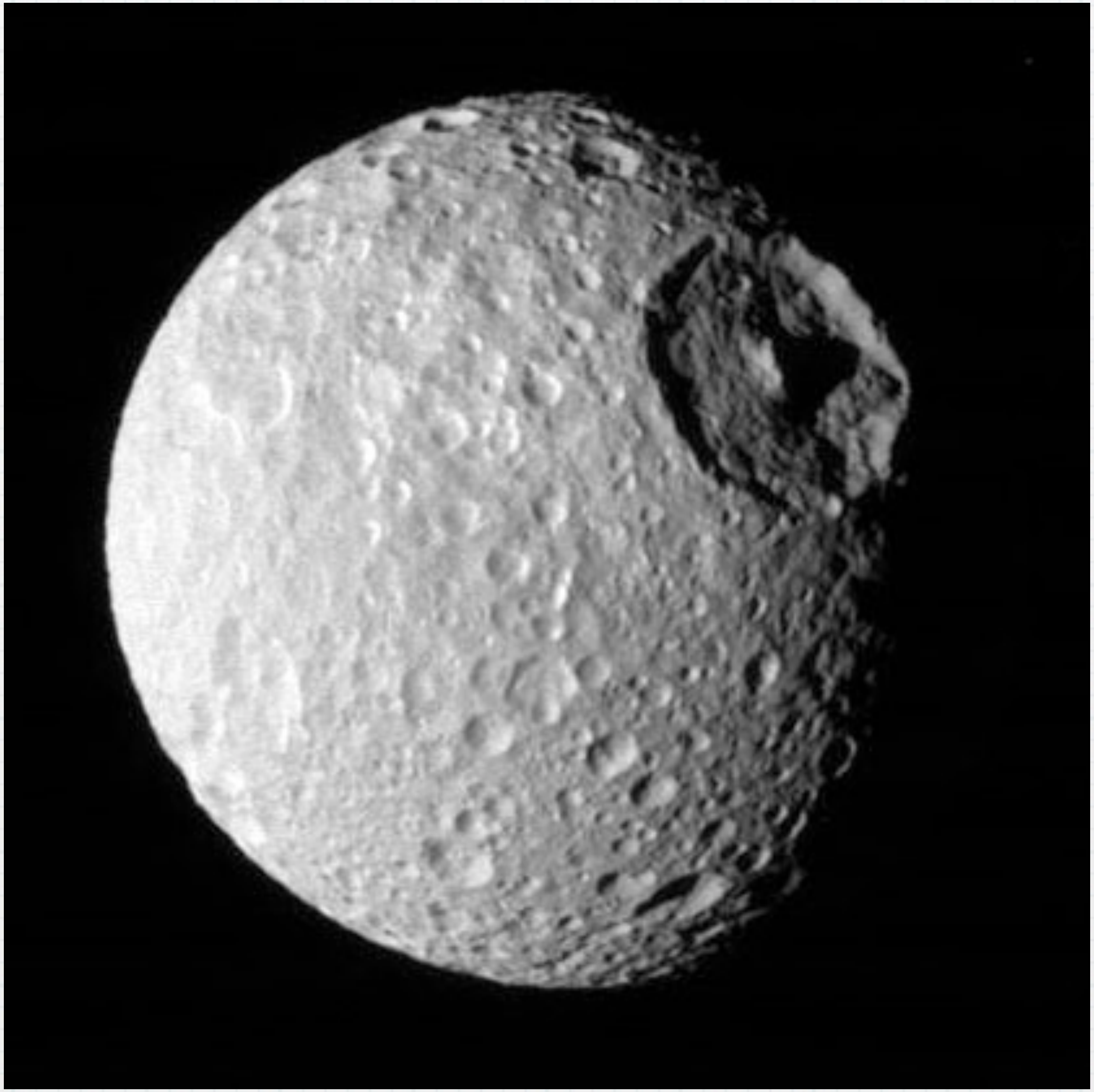
* Giant impacts can also explain why Venus and Uranus have odd tilts
    * Venus: the planet was flipped almost 180° by the impact (or the spin was reversed)
    * Uranus: flipped/tipped on its side (98°)
    * Earth, Mars, Saturn, & Neptune: "minor" tilts (less than 30°)

Examples of Giant Impacts

1. Valhalla crater on Callisto (a moon of Jupiter)



2. Herschel Crater on Mimas
(a moon of Saturn)



When did the Planets Form?

* Computer models show that **planetary formation took no more than a few tens of millions of years**
* Can we date when it started?
* Via **radiometric dating**, we have measured that planets began to form via accretion about **4.6 billion years ago!**

When did the Planets Form?...

* The radiometric dating method relies on accurately measuring proportions of various atoms and their isotopes in rocks
* A radioactive isotope has a nucleus that will undergo a spontaneous change
* Recall than an isotope is a chemical element which has a different number of neutrons than the "common" version

Physics Corner

* Radioactivity is the act of emitting radiation spontaneously

* For some reason, an atomic nucleus becomes unstable and needs to lose energy to regain stability. It does that by emitting subatomic particles (proton, neutron, electron) via the weak nuclear force
* This is also called nuclear decay

Physics Corner...

* This decay can changes an element into a different one (as the number of protons dictates the element)
* Potassium (stable) has 19 protons and 20 neutrons (Potassium-39)
* Potassium-40 will decay into argon-40
* Potassium-41 is stable (22 neutrons)

Physics Corner...

* The rate at which a particular amount of radioactive material halves that amount is called the half-life
* That rate never changes
* The half-life of potassium-40 is 1.25 billion years

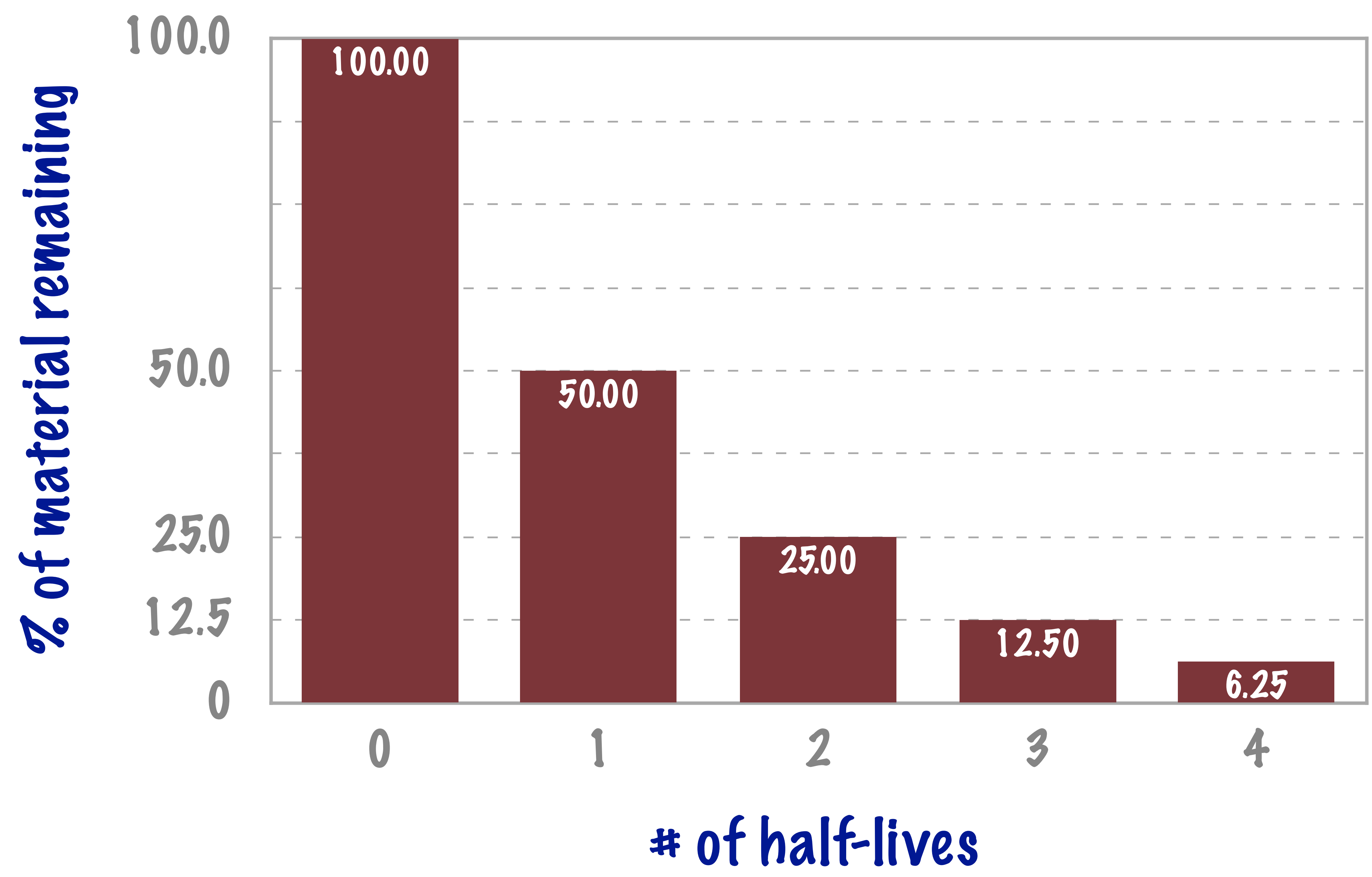
Rock Dating

* Consider a rock that contained 1 microgram of potassium-40 and no argon-40 when it formed (argon-40 does not occur "naturally")

1. 1.25 billion years later, the rock contains 0.5 microgram of potassium-40 and 0.5 microgram of argon-40

2. 1.25 billion years later, the rock has 0.25 microgram of potassium-40 and 0.75 microgram of argon-40

Radioactive Amount and Half-Life



Rock Dating...

* What about argon-40?
* Argon-40 is a gas that never combines with other elements
* It did not condense in the solar nebula
* Trapped argon-40 gas in a mineral can only come from potassium-40 radioactive decay

Rock Dating...

* Hence by measuring the amount of trapped argon-40 gas and the amount of potassium-40 in the same rock

➡ That rock can then be dated

* Geologists use other radioactive isotopes as well to help confirm the age of formation of a rock

Earth Rocks, Moon Rocks and Meteorites

* The oldest Earth rock we dated is 4 billion years old
* However, the Earth's surface has been reshaped through time so it is older
* Moon rocks have been dated to as far back as 4.4 billion years

➡ So the Moon formed at least 4.4 billion years ago

Earth Rocks, Moon Rocks and Meteorites...

* Hence the Earth is older still
* Fallen meteorites, which have not melted since the solar nebula condensed are the oldest rocks in the Solar System
* Careful analysis shows that they are 4.568 billion years old

➡ Our Solar System formed about 4.6 billion years ago

Snapshot

* Why are there two types of planets?
* Planets formed around solid “seeds” that condensed from gas and then grew through accretion. In the inner Solar System, temperatures were so high that only metal and rock could condense. In the outer Solar System, cold temperatures allowed more abundant ices to condense along with metal and rock

Snapshot

* Where did asteroids and comets come from?
* Asteroids are the rocky leftover planetesimals of the inner Solar System
* Comets are the icy leftover planetesimals of the outer Solar System

Snapshot

* How do we explain the existence of our Moon and other “exceptions to the rules”?
* Most of the exceptions probably arose from collisions or close encounters with leftover planetesimals, especially during the Heavy Bombardment period that occurred early in the Solar System’s history

Snapshot

* When did the planets form?
* The planets began to accrete in the solar nebula about 4.6 billion years ago, a fact we determine from radiometric dating of the oldest meteorites

Other Planetary Systems

* A decade ago we could not dream of detecting planets orbiting other stars
* Now we have conclusive proof of more than 865 such planets (updated Feb. 14, 2013) with another 2,926 awaiting confirmation (updated Feb. 2013)
* They are called exoplanets, or extra solar planets

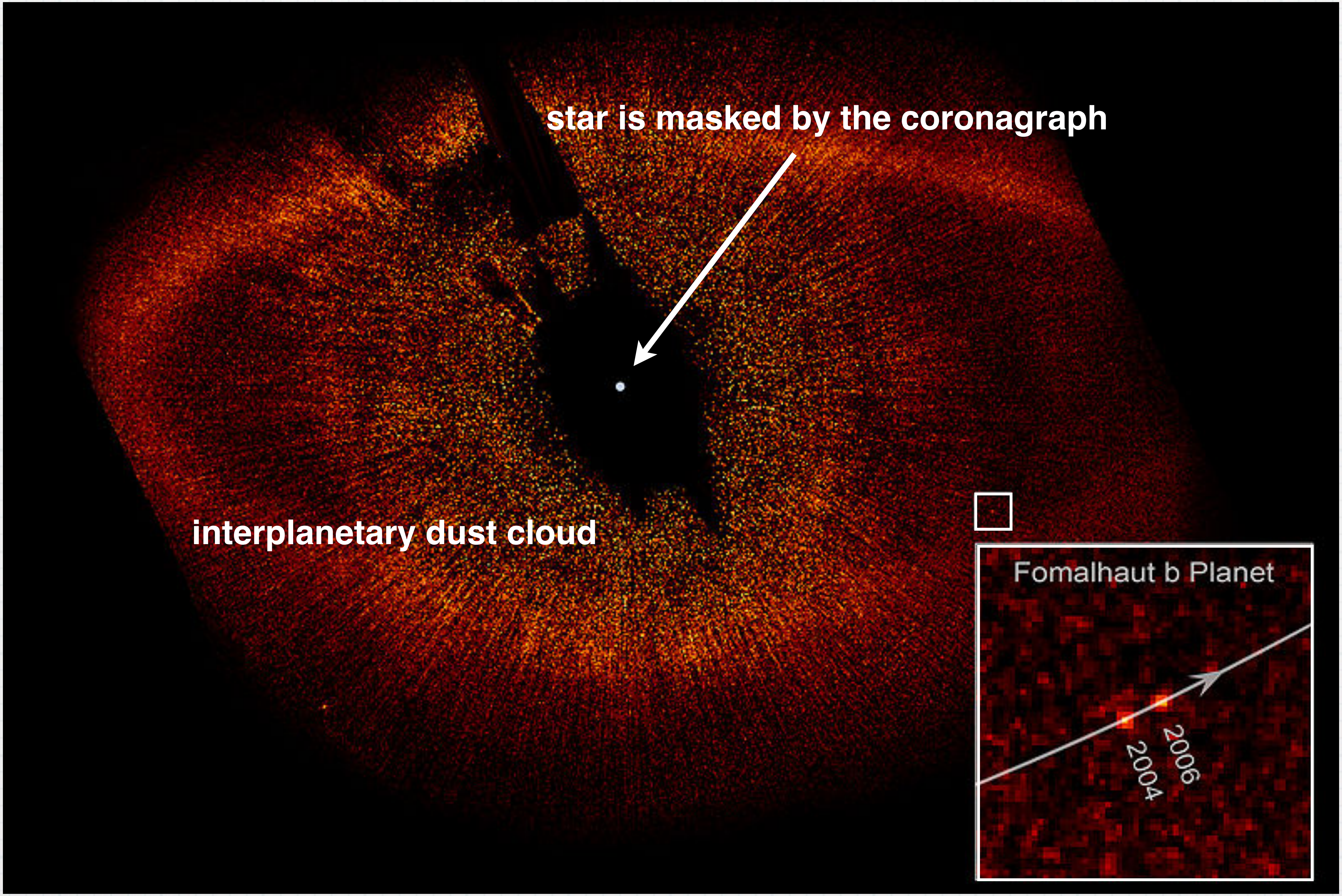
Other Planetary Systems...

* Using very recent data, scientists estimates that there are about **300 billion planets in our galaxy** (from about 200 billion stars)
* Out of these, 1/200, or **1.5 billion planets exist in the Habitable Zone** (where H_2O can exist in solid, liquid and gas states)

Other Planetary Systems...

* A planet is a billion times fainter than its parent star, so to observe a planet directly is very tricky but it can be done
* To visually see a planet the size of Jupiter orbiting the nearest star to us is equivalent to being able to see a marble from a distance of 4,000 km

Fomalhaut with Disk Ring and extrasolar planet b

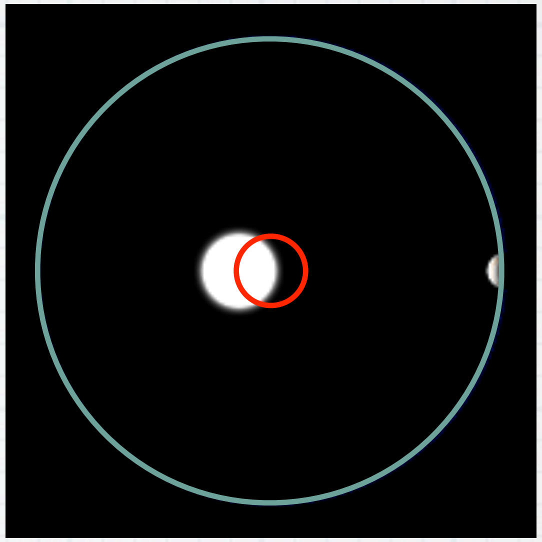


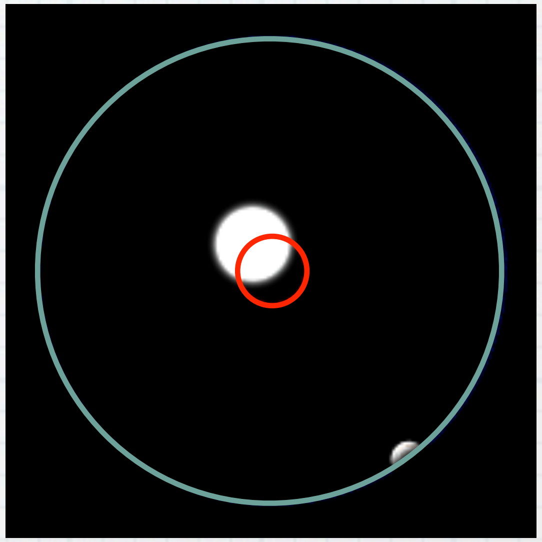
imaged with the Hubble Space Telescope's coronagraph

Other Planetary Systems...

* Detection is usually done by indirectly observing that planet's effects on its star
* Effects measured by spectrographs (Doppler shifts), photometers (Transit Photometry and Microlensing) and accurate position measurements (Astrometry)

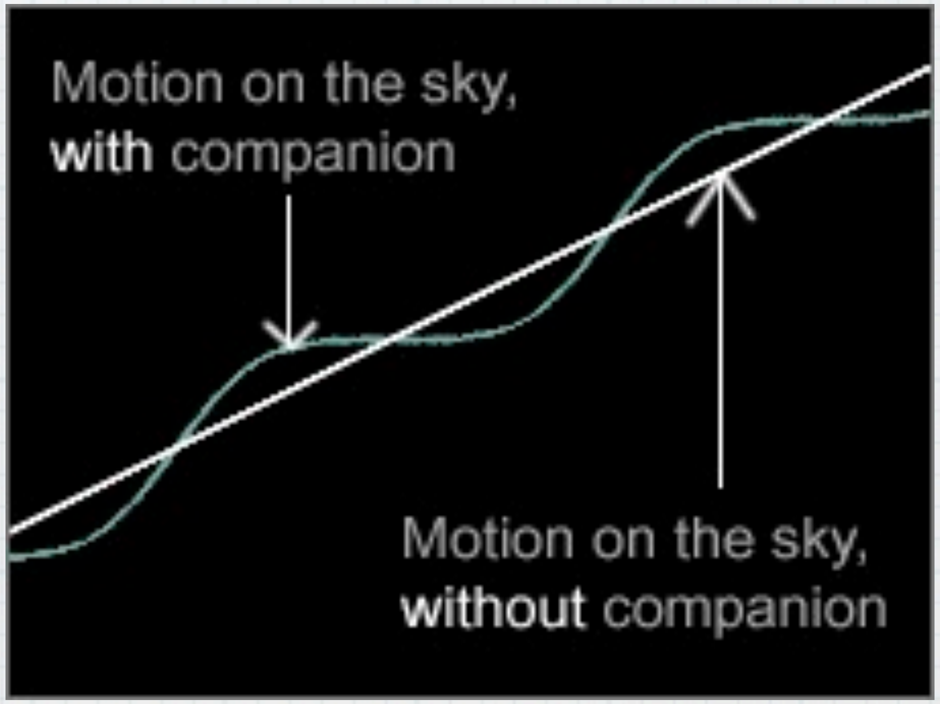
Astrometry





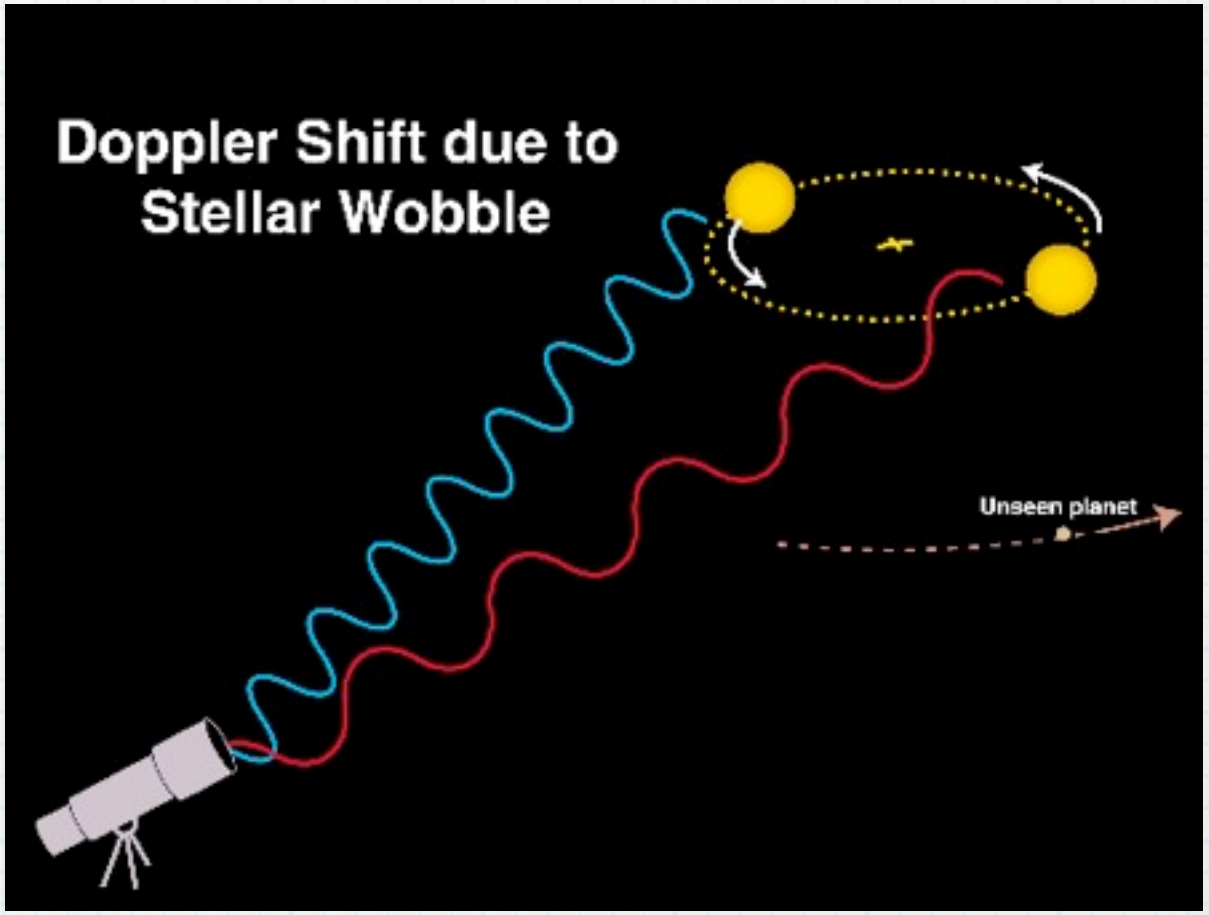
* **Astrometry** is used to look for the periodic wobble that a planet induces in the position of its parent star

➡ Need: very accurate instruments to measure the position of a star against the background sky



Doppler Shifts

* Variations in the speed with which the star moves towards or away from Earth can be deduced from the displacement in the parent star's spectral lines due to the Doppler effect

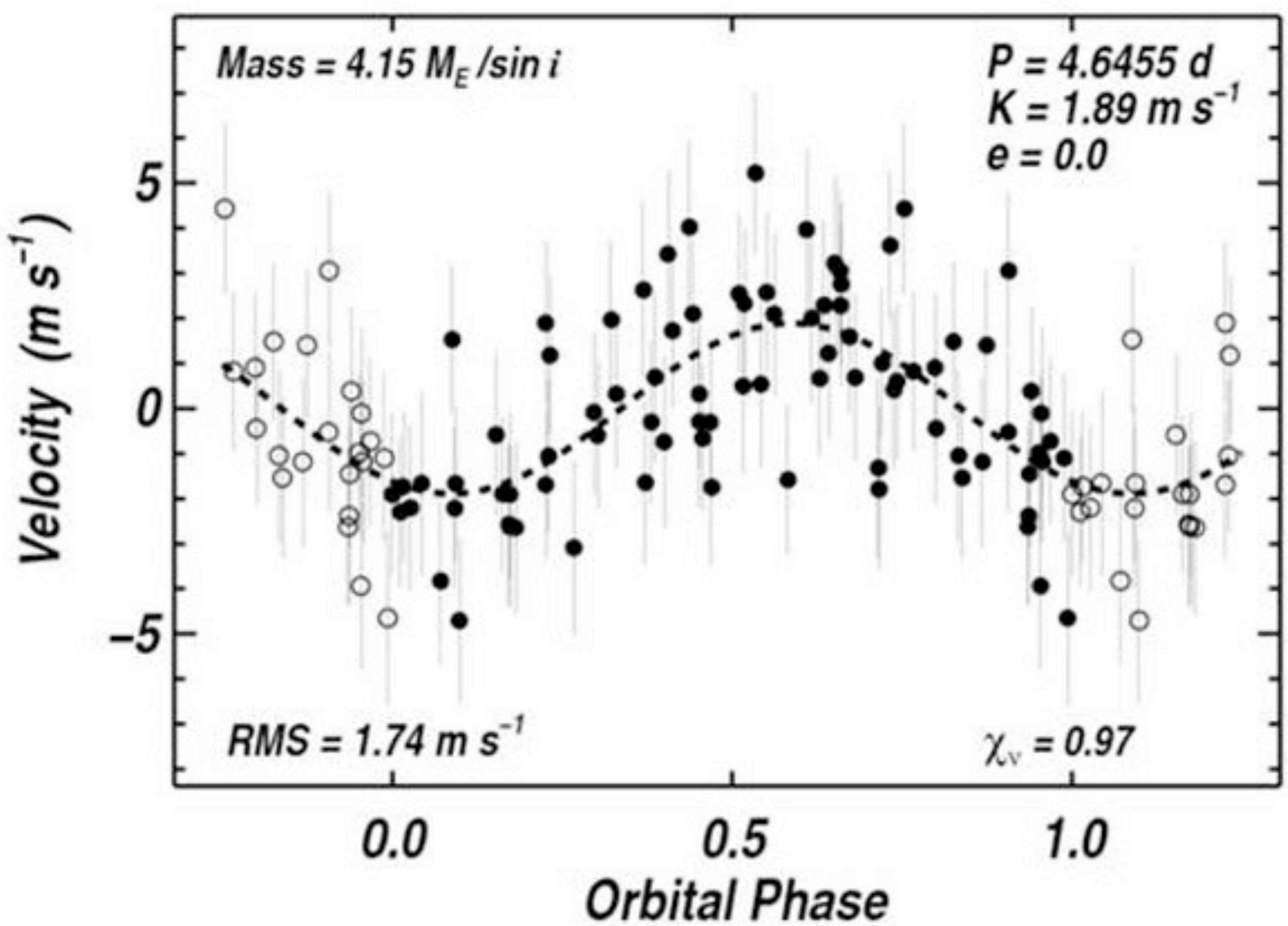


This has been by far the most productive technique used

Data from Keck Telescope Spectrograph

NASA-UC Eta-Earth Survey *

Super-Earth orbiting HD 156668 (K3V, 24pc)



Msini = 4.15 M_{Earth}
P = 4.6 d
a = 0.05 AU
K = 1.89 m/s (!)

Lowest velocity amplitude.
2nd lowest msini .

* 230 GKM stars Observed using Keck Telescope

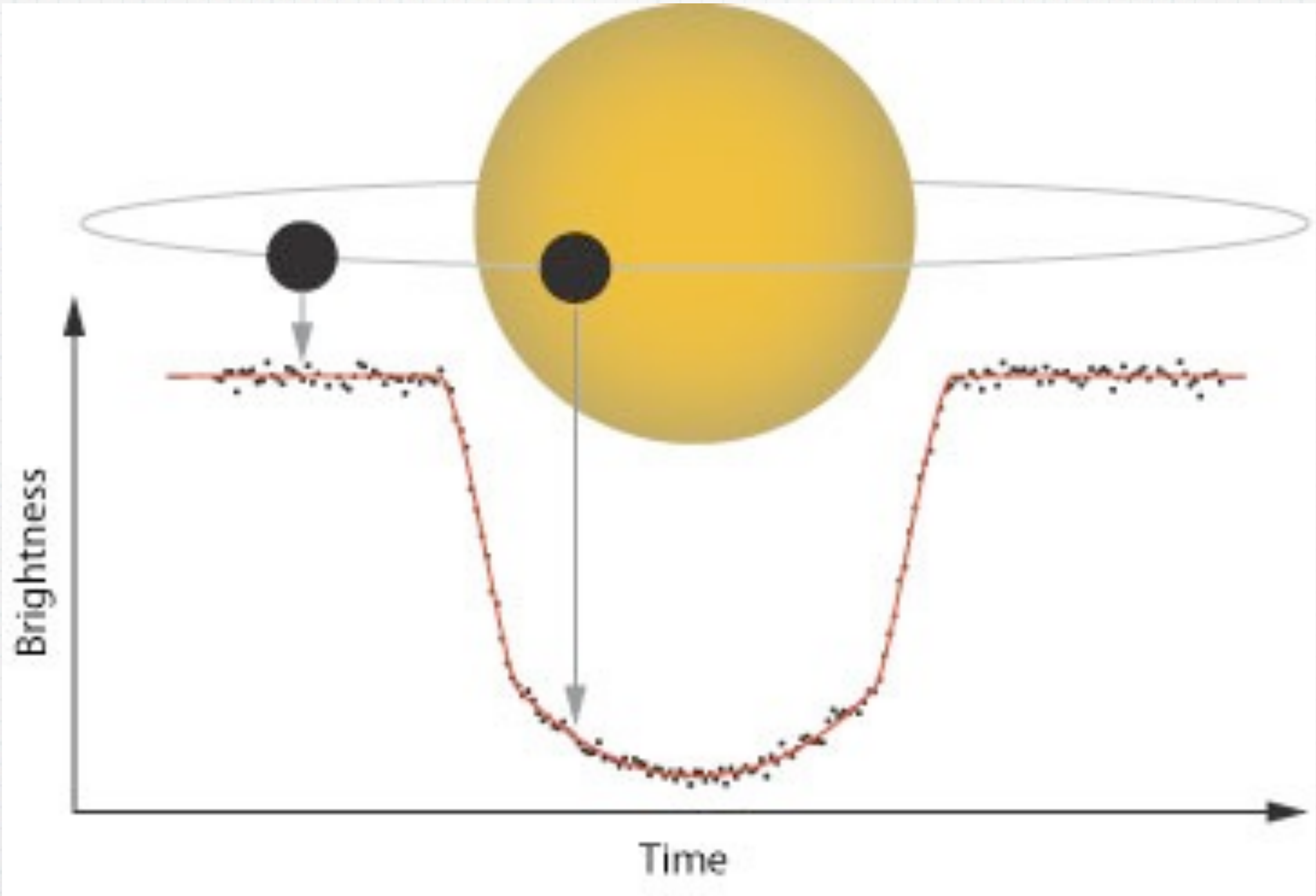
2nd Super-Earth from Eta-Earth Survey

more to come ...

Howard, Marcy, and CPS group (ApJ, submitted)
Announced today (Jan 6) in AAS session 348.06

Transit Photometry

This technique measures the periodic dimming of the star along the line of sight of the observer



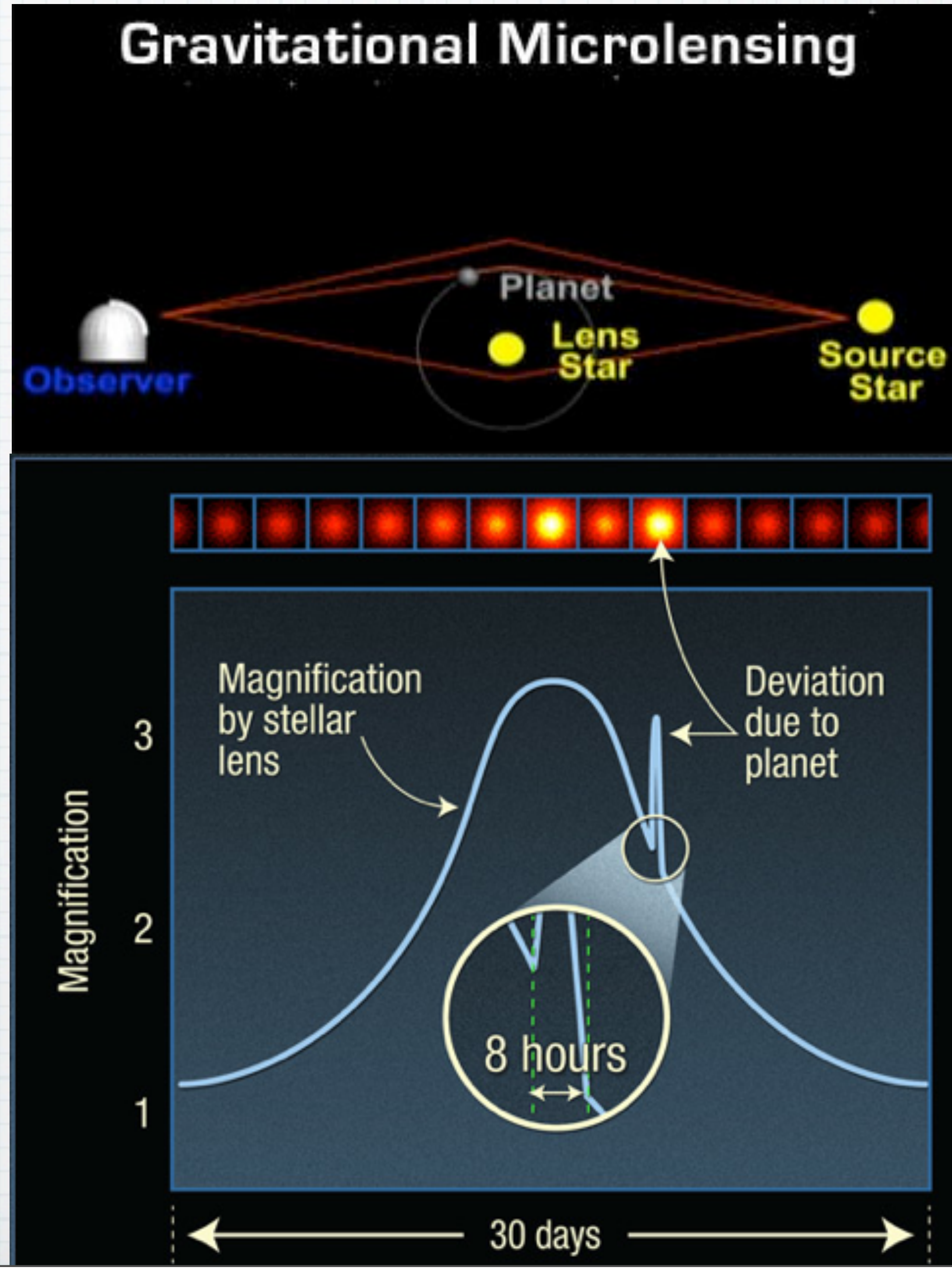
Microlensing

* **Microlensing** is a method which needs the star being studied to pass in front of a more distant one (line-of-sight)
* The closer object's gravity acts like a lens and causes the distant star to brighten: a planet orbiting the nearer object will add a slight blip to the otherwise smooth light curve

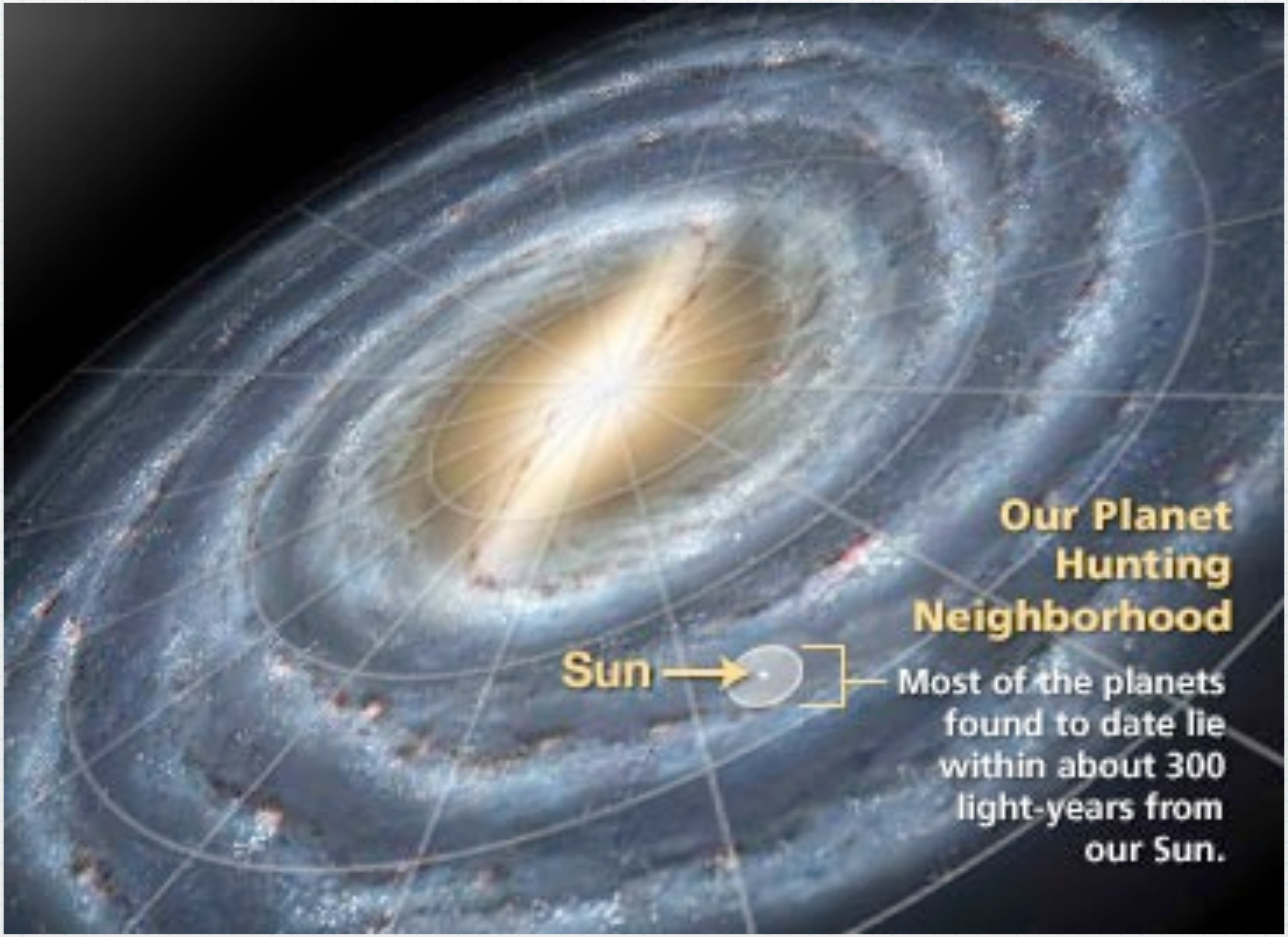
Microlensing...

The necessary alignment

High-resolution light curve



Planet Hunting Ground in our Milky Way

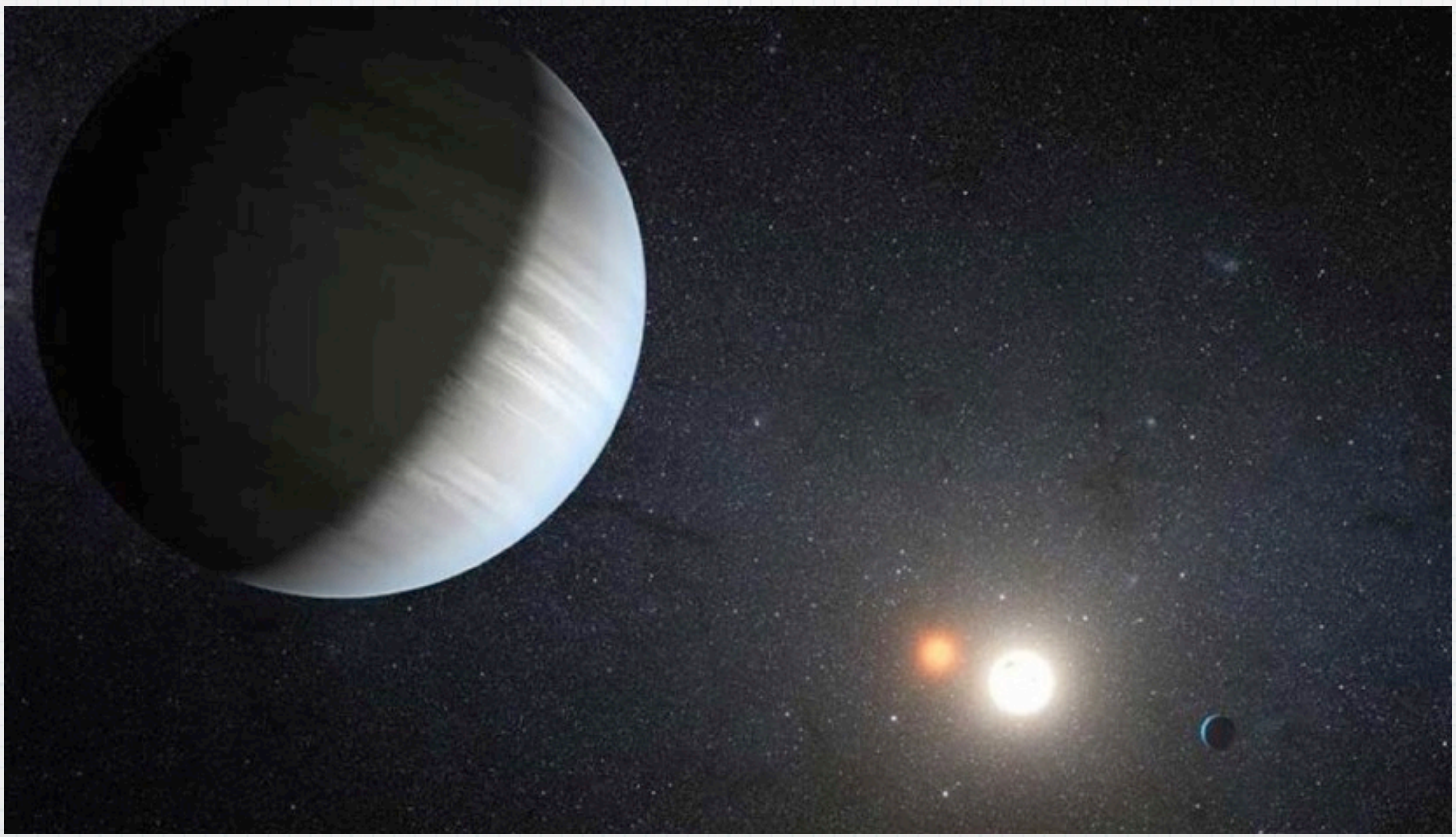


Current Thoughts

* The discovery of extrasolar planets gives us an opportunity to test our theory of the formation of our own Solar System
* At first, extrasolar planets that were discovered were massive yet orbited quite close to their central star
* Now, we are discovering Earth-like planets orbiting their star at Earth-like distances

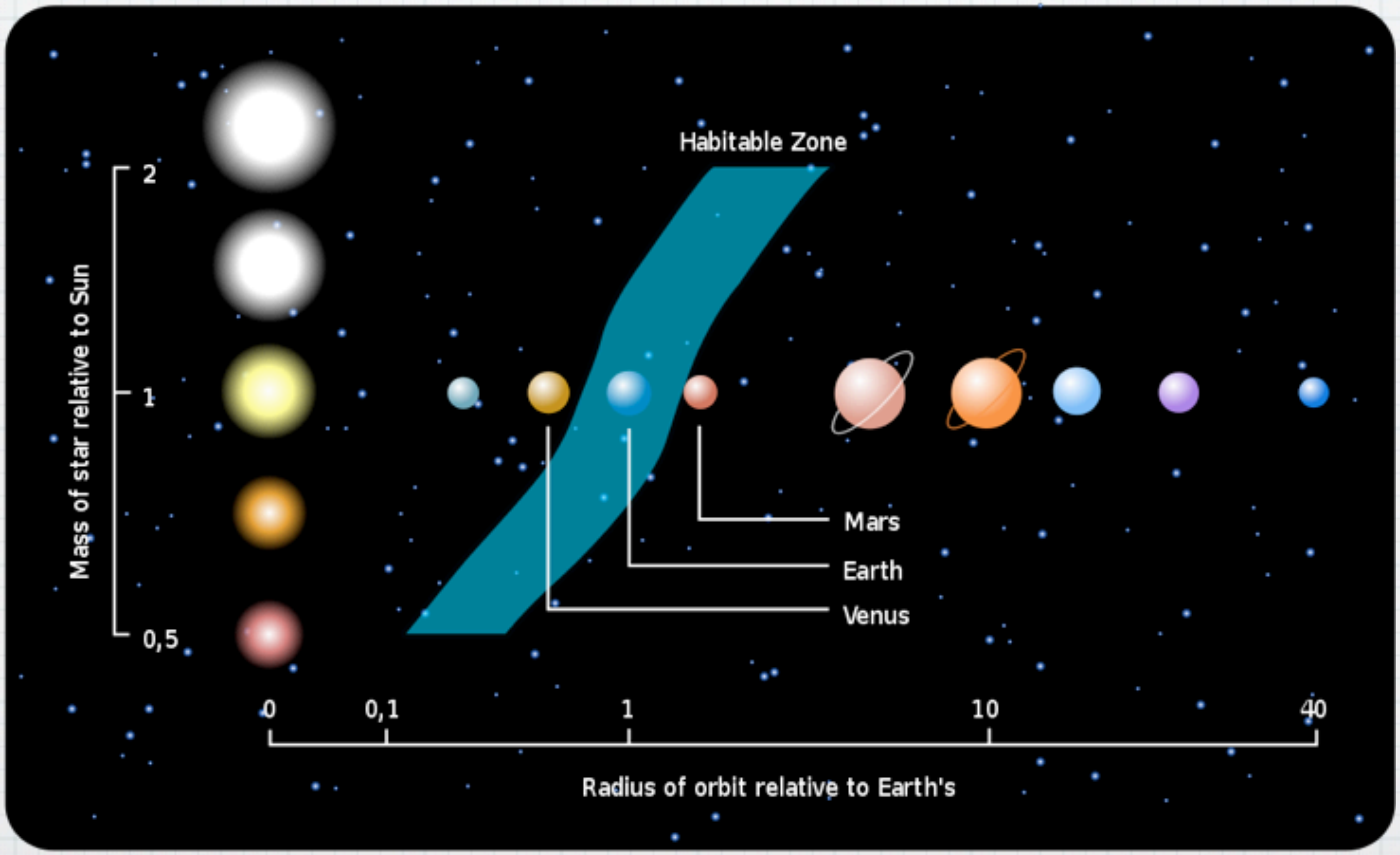
Current Thoughts...

* Tatooine found? Our instruments are also detecting planets orbiting twin star systems

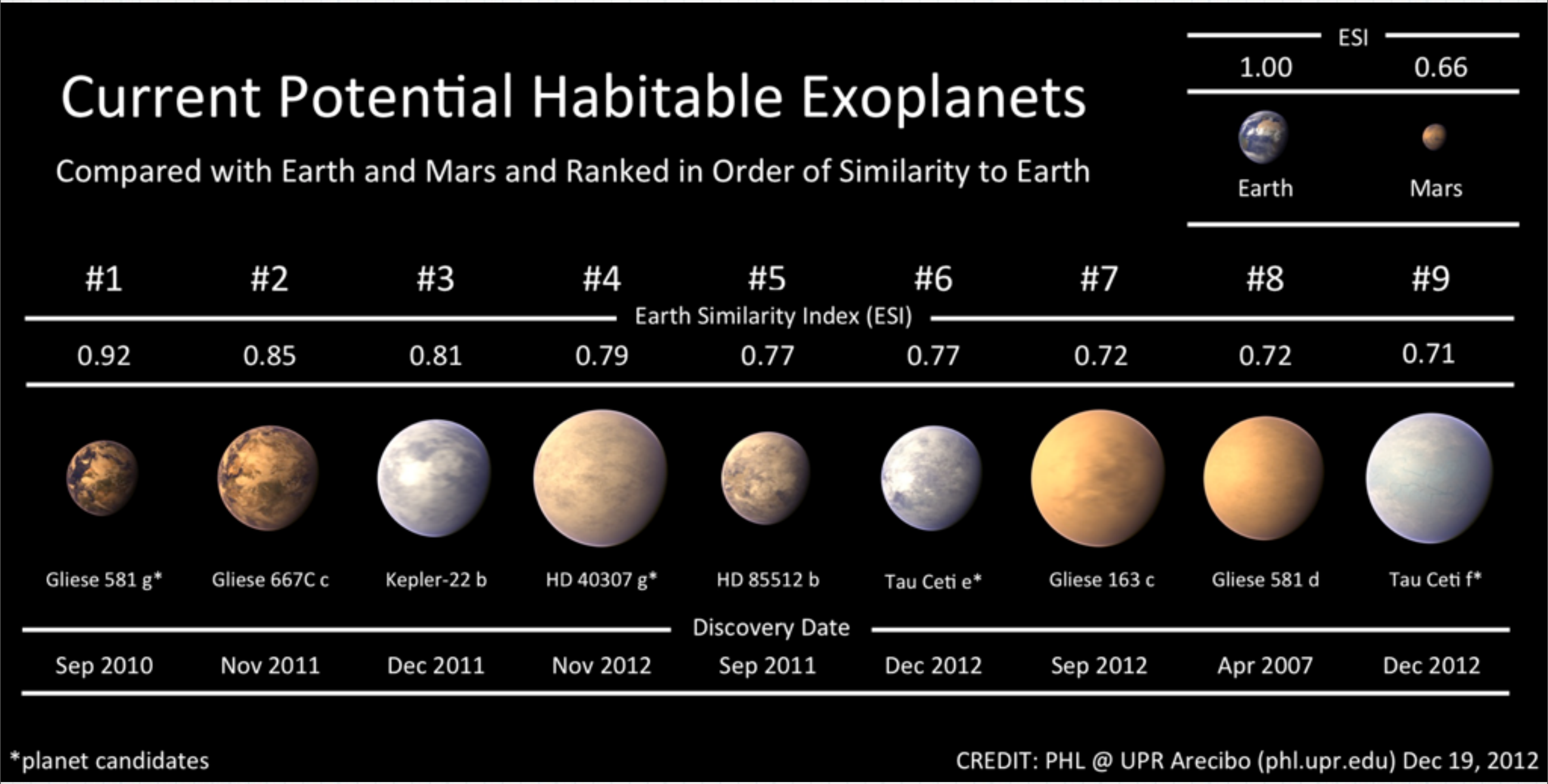


Habitable Zone

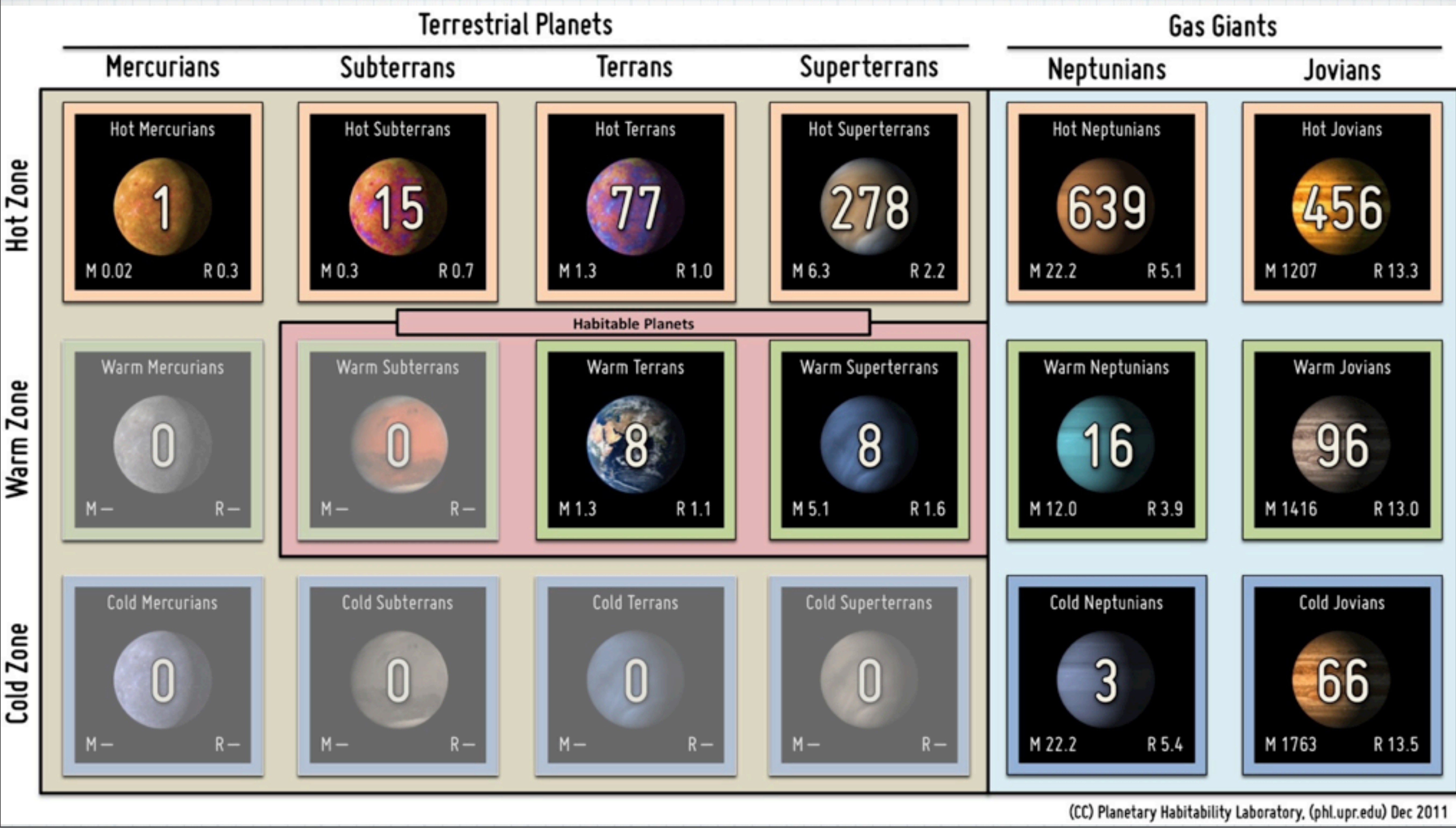
* A **habitable zone** (HZ) is a region of space where conditions are favorable for life as it may be found on Earth



Current Potential Habitable Exoplanets



The Habitable Exoplanets Catalog: A Periodic Table



Snapshot

* How do we detect planets around other stars?
* So far, we are only able to detect exoplanets (extrasolar planets) indirectly by observing the planet's effects on the star it orbits. Most discoveries to date have been made with the Doppler technique, in which Doppler shifts reveal the gravitational tug of a planet (or more than one planet) on a star

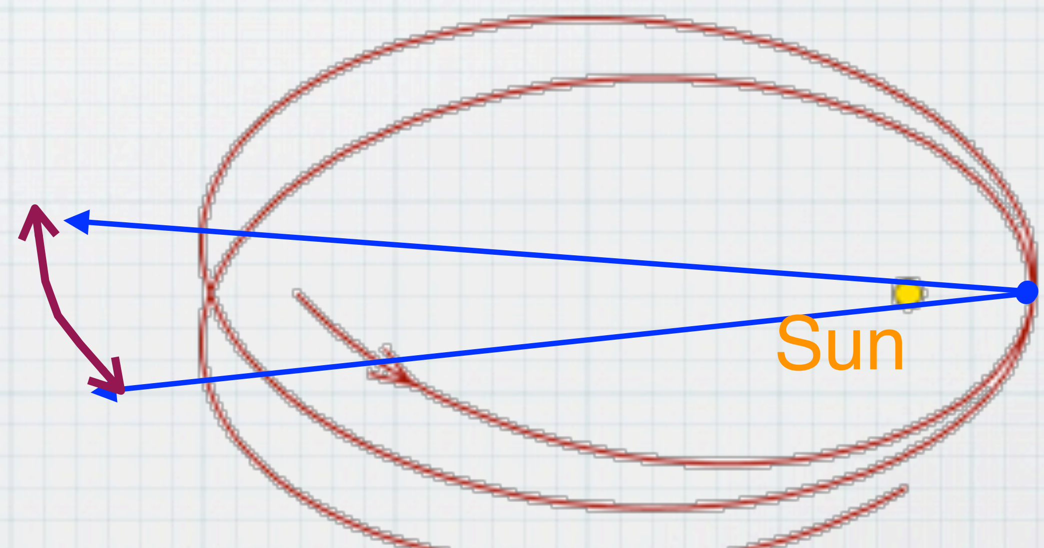
Snapshot

* How do we detect planets around other stars?
* However, other techniques are now being used successfully as well such as: **transit photometry**, **microlensing**, and **astrometry**

Mercury Orbital Anomaly

* Newtonian physics cannot explain all of Mercury's orbit. There is a discrepancy:
* The calculations show that Mercury's orbit is off by +1 orbit off every 3,013,900 years over actual observations

➡ an embarrassment!



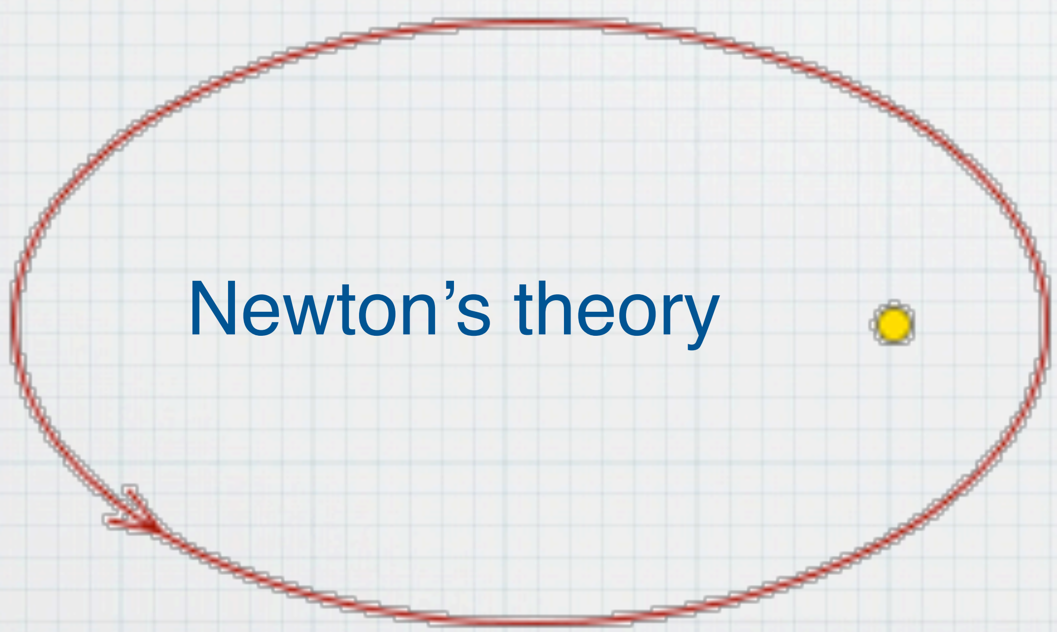
Mercury's exaggerated orbit anomaly

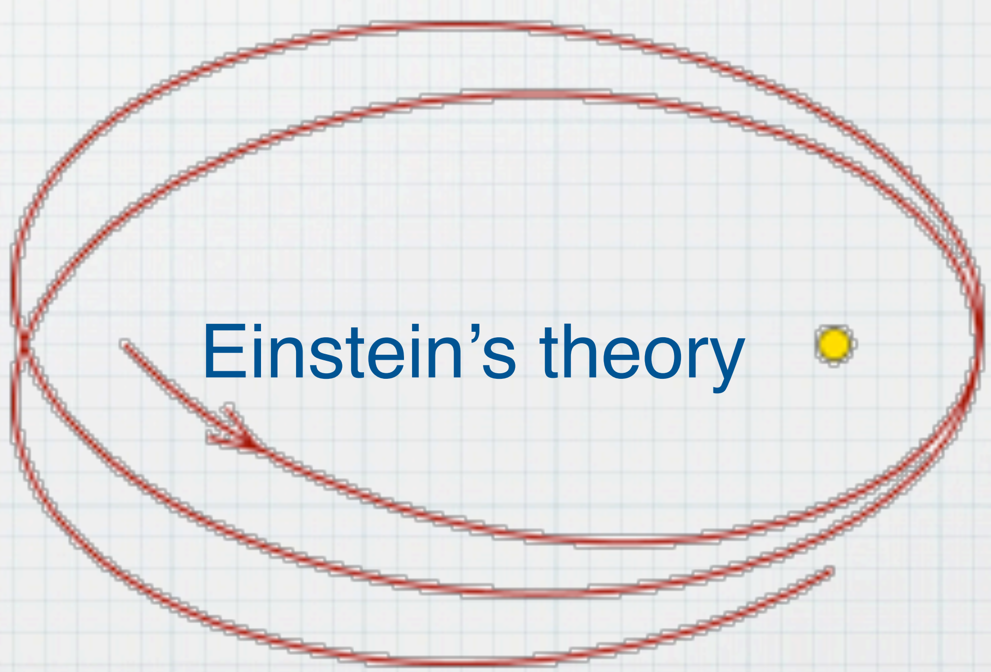
Mercury Orbital Anomaly...

* **Einstein** came to the rescue!
* **His General Theory of Relativity** is more precise (exact) to explain orbital mechanics than Newton's
* Newton's mistake: **time and space are distinct entities in his theory**
* But not in Einstein's...

Mercury Orbital Anomaly...

* In Newton's theory, two bodies will always orbit one another in a closed ellipse
* In Einstein's theory, two bodies will orbit one another in a rotating (open) ellipse

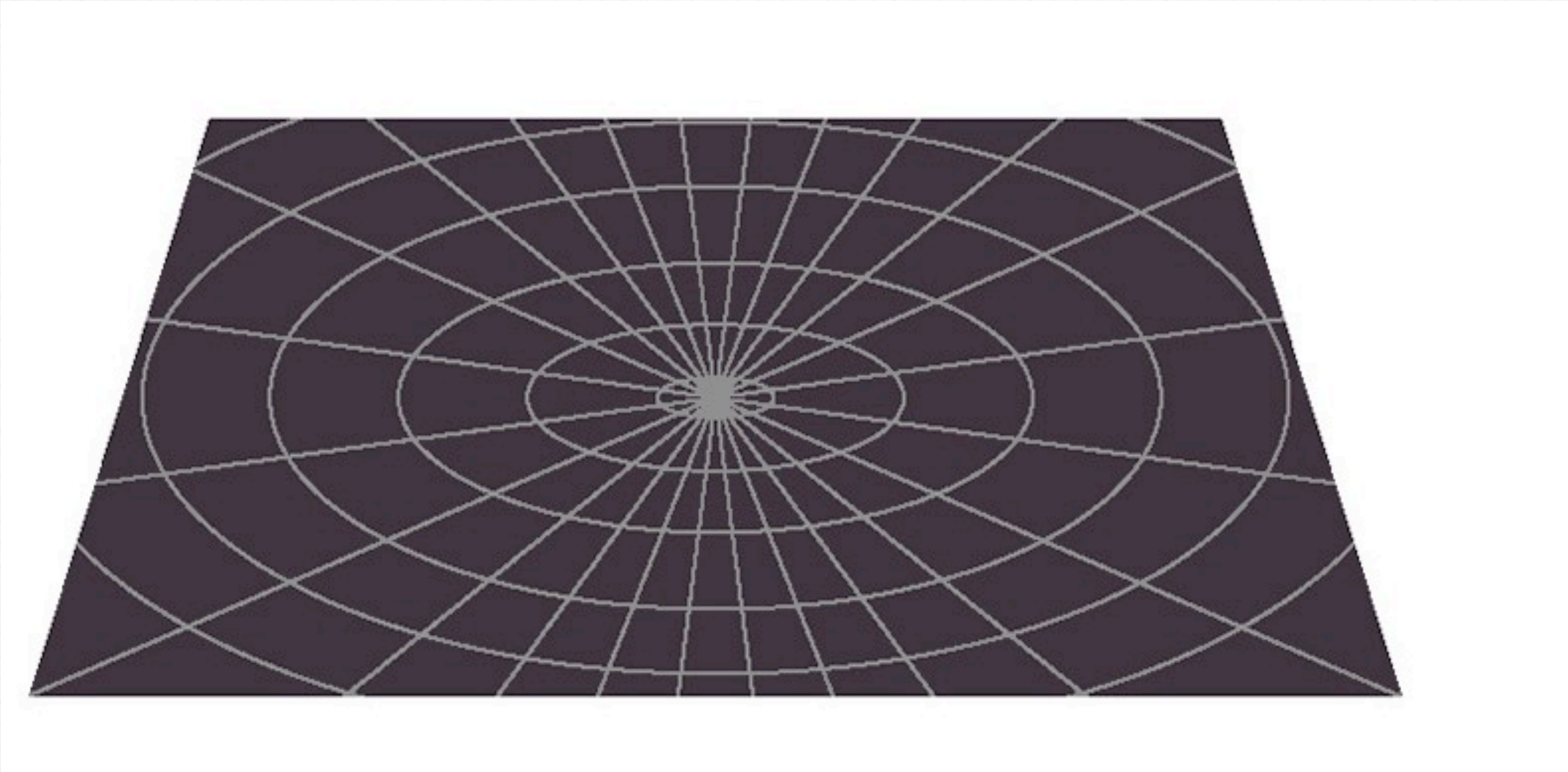




Mercury Orbital Anomaly...

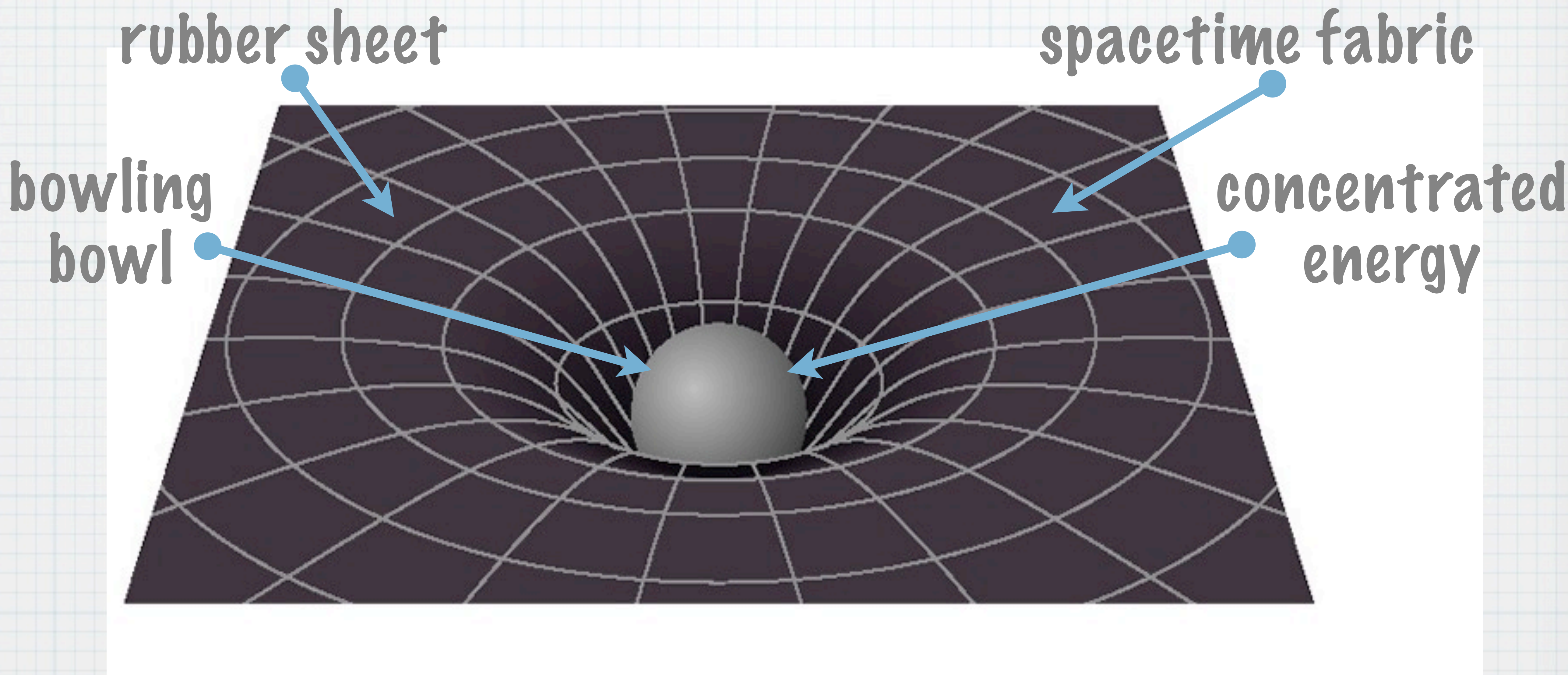
* In Newton's Theory of Gravitation, time does not play a role, nor does radiative energy (photons)
* In Einstein's General Theory of Gravitation, radiative energy adds to the force of gravity and affects the flow of time; it is a more complete theory

Mercury's orbital anomaly...



Imagine a two-dimensional rubber sheet
This is a representation of 3-D space and time (1-D)

Mercury's orbital anomaly...



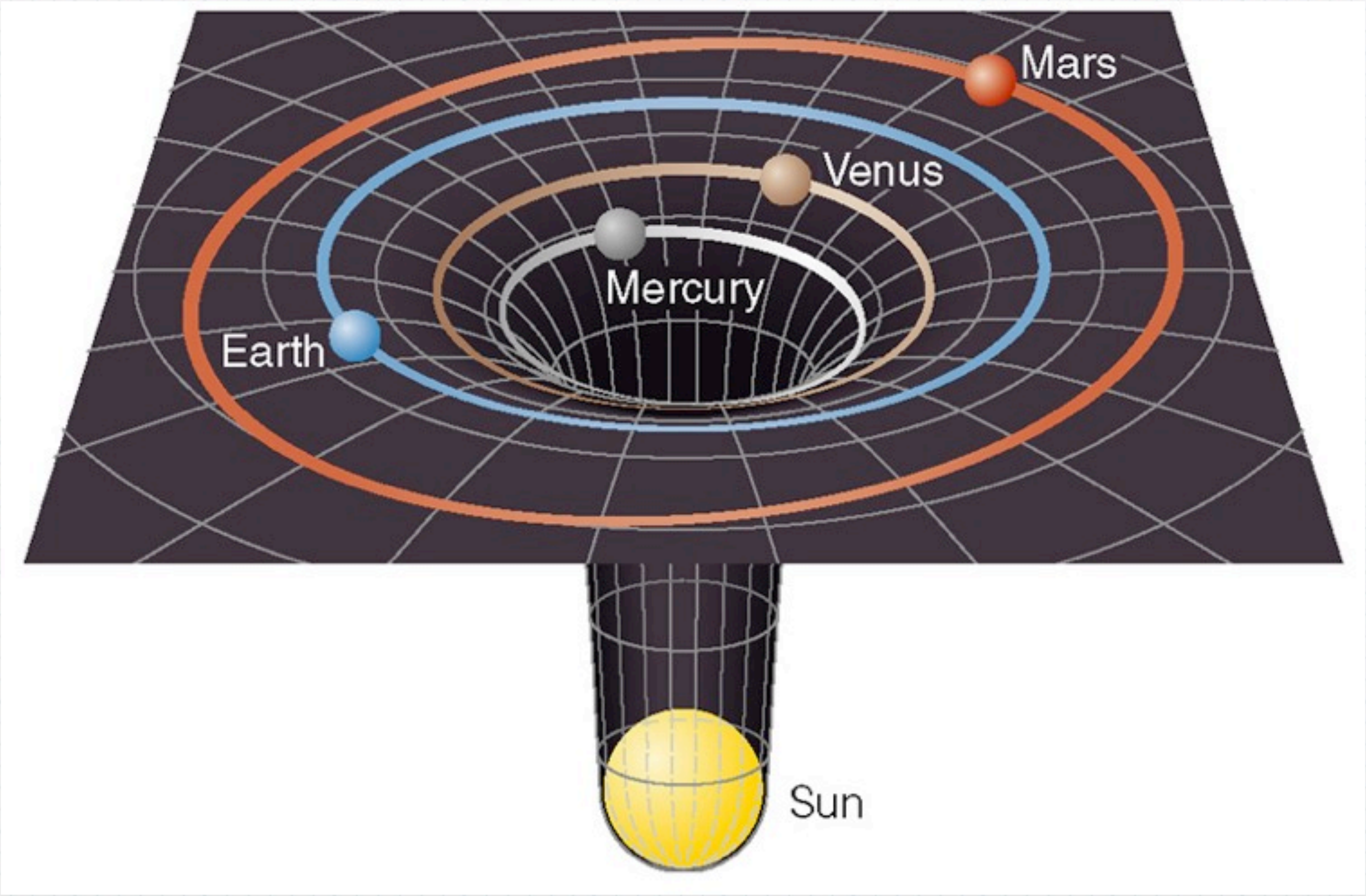
As energy (mass) is localized on the rubber sheet, it distorts it (spacetime fabric)

Einstein's Theory of General Relativity states that:

Gravity arises from the curvature of the spacetime, i.e.:

gravitational 'force' is replaced by local geometry of spacetime

Mercury's orbital anomaly...



Mercury's orbit is measurably affected by the Sun's spacetime distortions

References

- Evolution of the Moon
  - http://www.youtube.com/watch?v=UIKmSQqp8wY
- The Habitable Exoplanets Catalog
  - http://phl.upr.edu/projects/habitable-exoplanets-catalog
- Finding Life on other worlds
  - http://www.youtube.com/watch?v=ClmV49_-GIQ#!