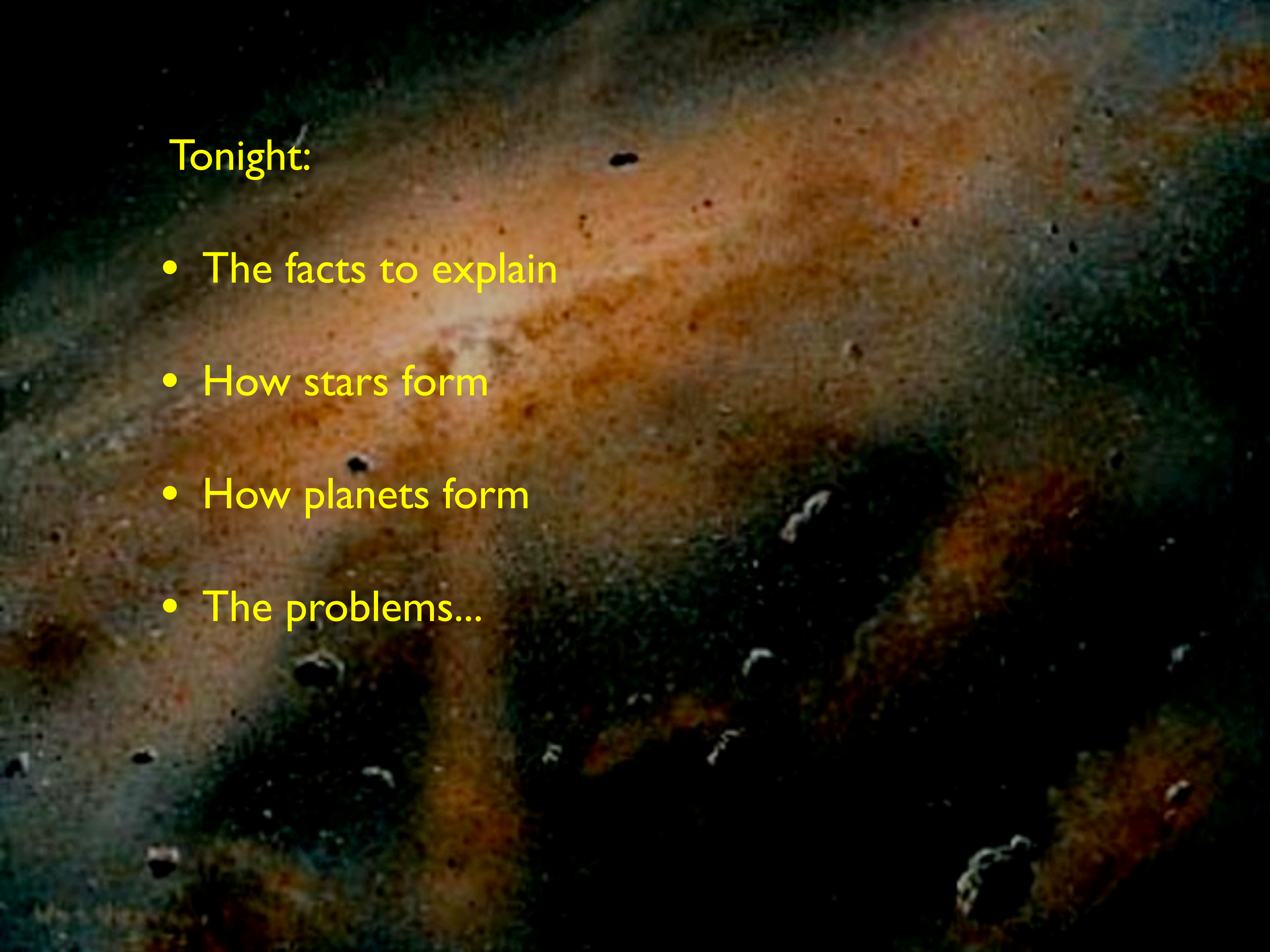
Modern Astronomy:
Voyage to the Planets

Lecture 9

The formation of the Solar System

University of Sydney
Centre for Continuing Education
Spring 2014



Tonight:

- The facts to explain
- How stars form
- How planets form
- The problems...

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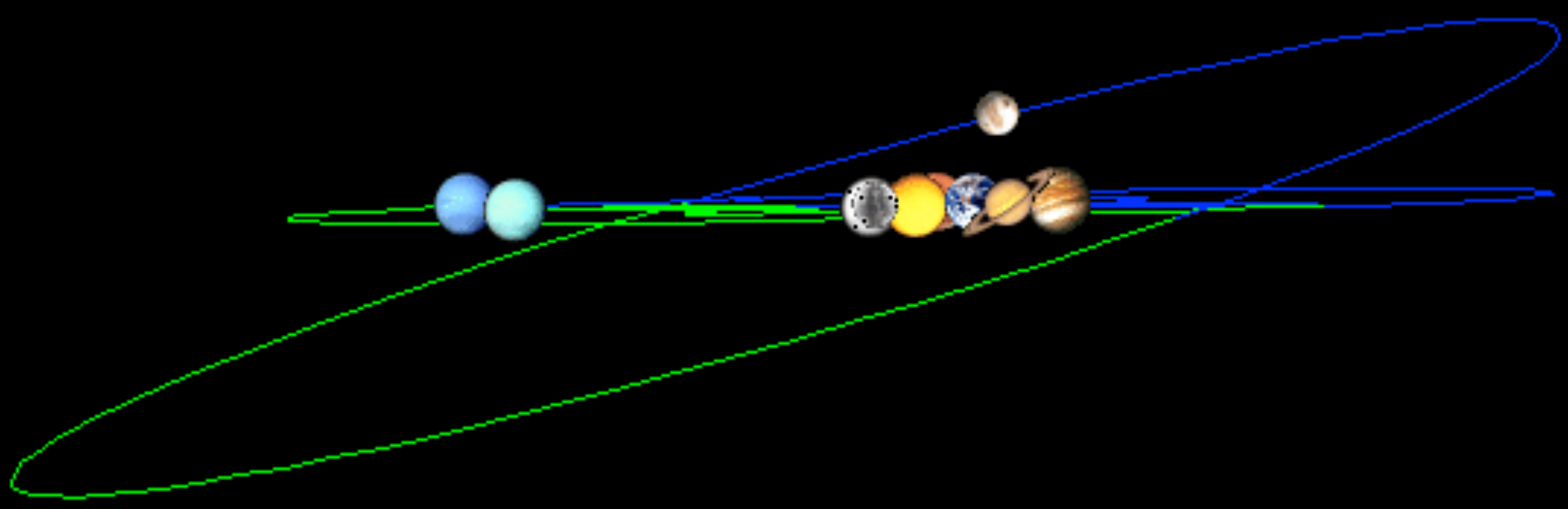
Unfortunately, we only have one planetary system to study in detail, so we have no real idea of the diversity of systems which could arise in other circumstances. Theoretical models have, naturally, concentrated on trying to reproduce the variety of worlds we see in this system. Only recently have we come to have new data from other stars... but we'll leave discussion of that till next week.

The Solar System, a summary

Let's take a quick look at the general features of the Solar System again. We've spent a long time looking at the details of the many marvellous worlds; here's a quick summary of the overall features, before we try to explain them.

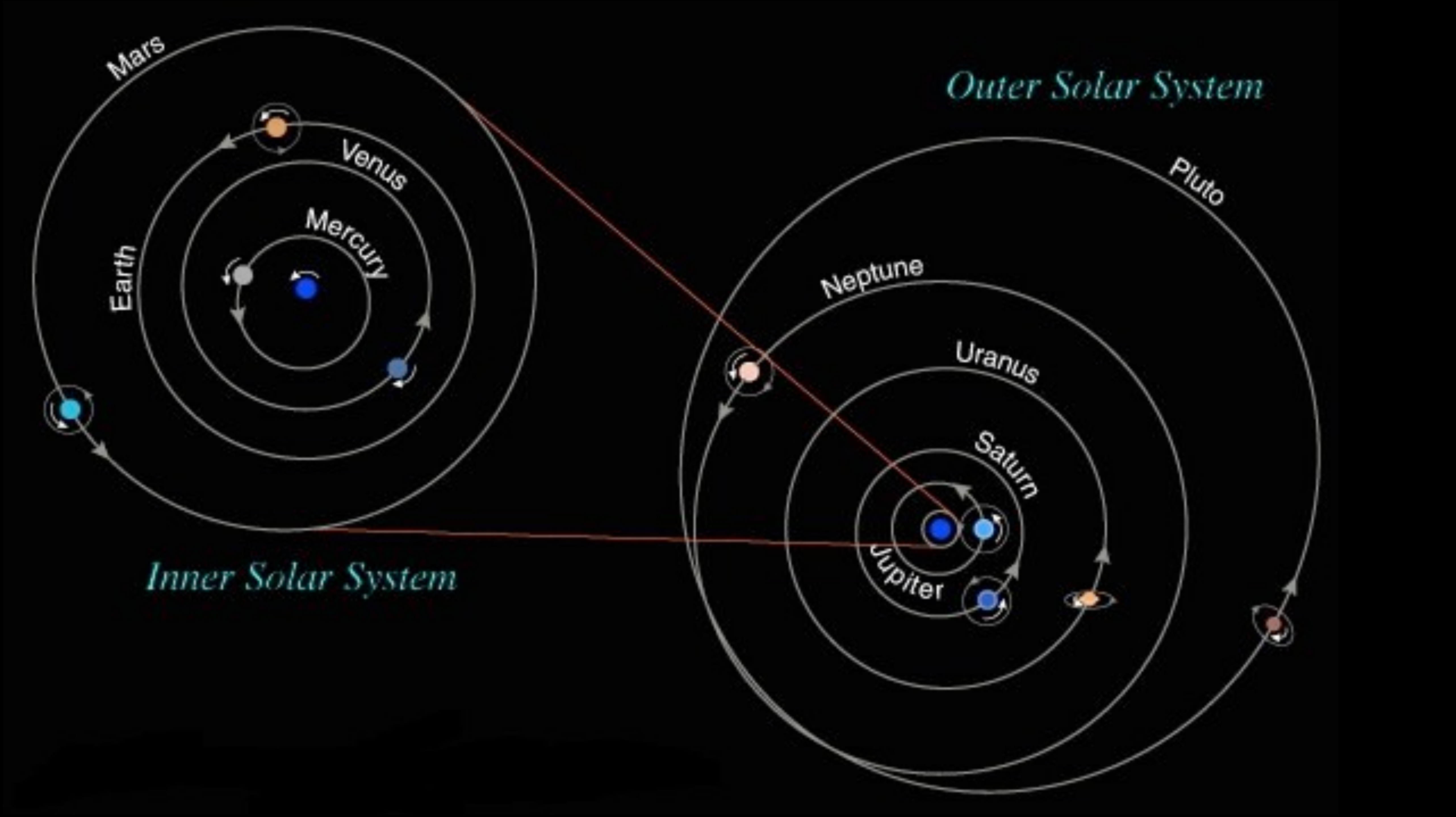
Any theory for the formation of the Solar System must be able to account for the following features.

The orbits of most planets and asteroids lie nearly in the same plane, and this is the plane of the Sun's equator.

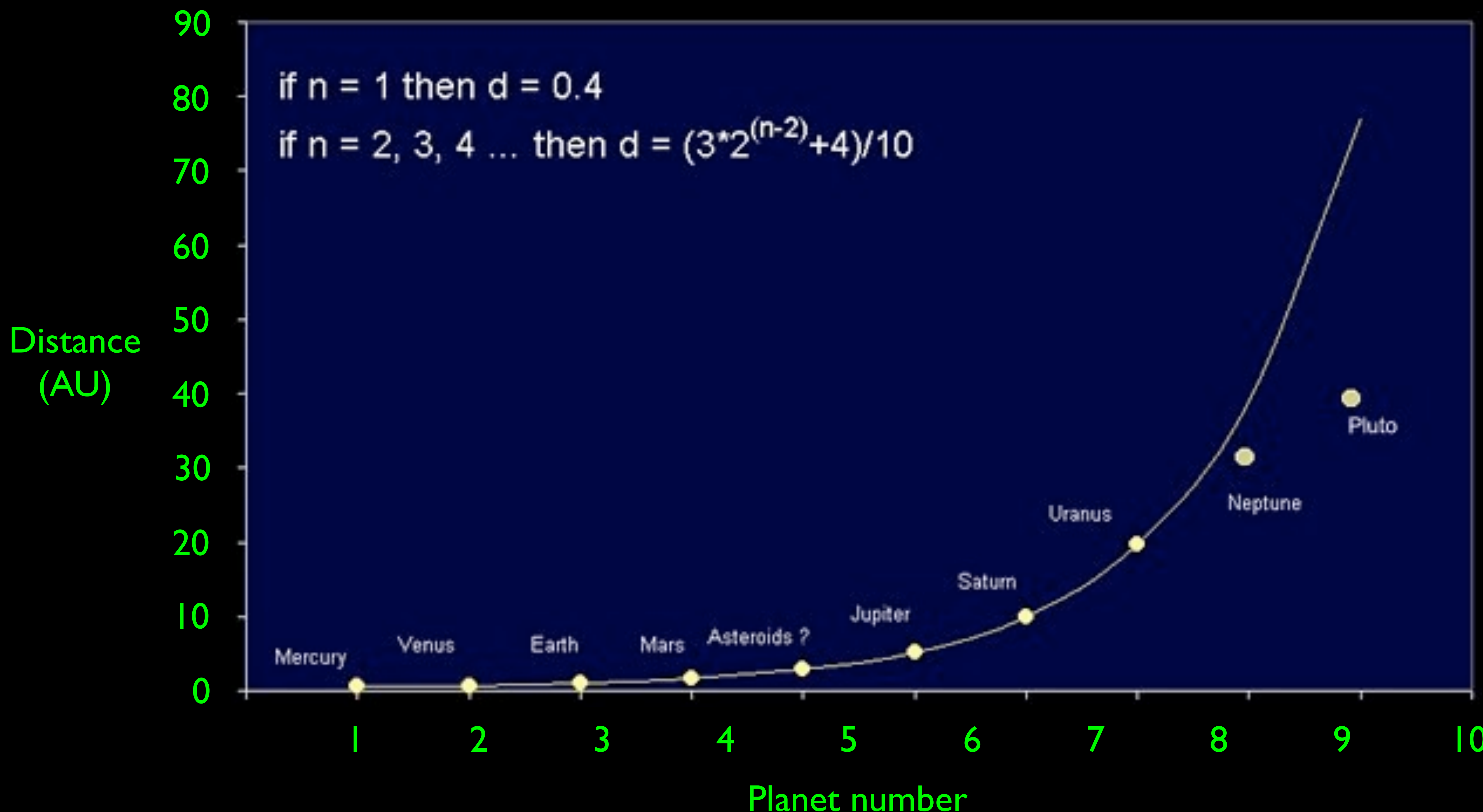


Position of the planets on 1 March 2005

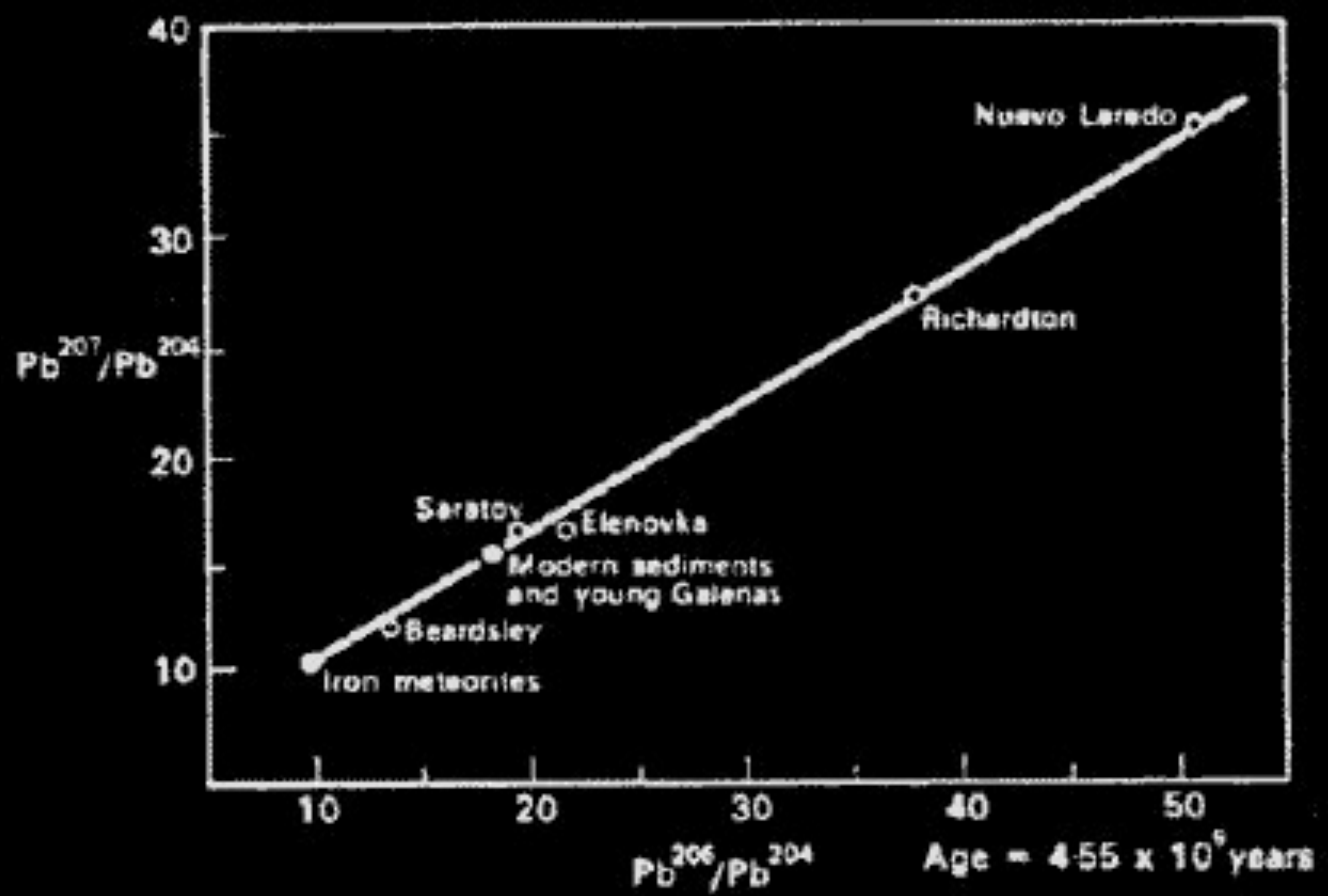
All planets (except Pluto) have orbits which are very close to circular. Most planets rotate in the same direction as the planets revolve.



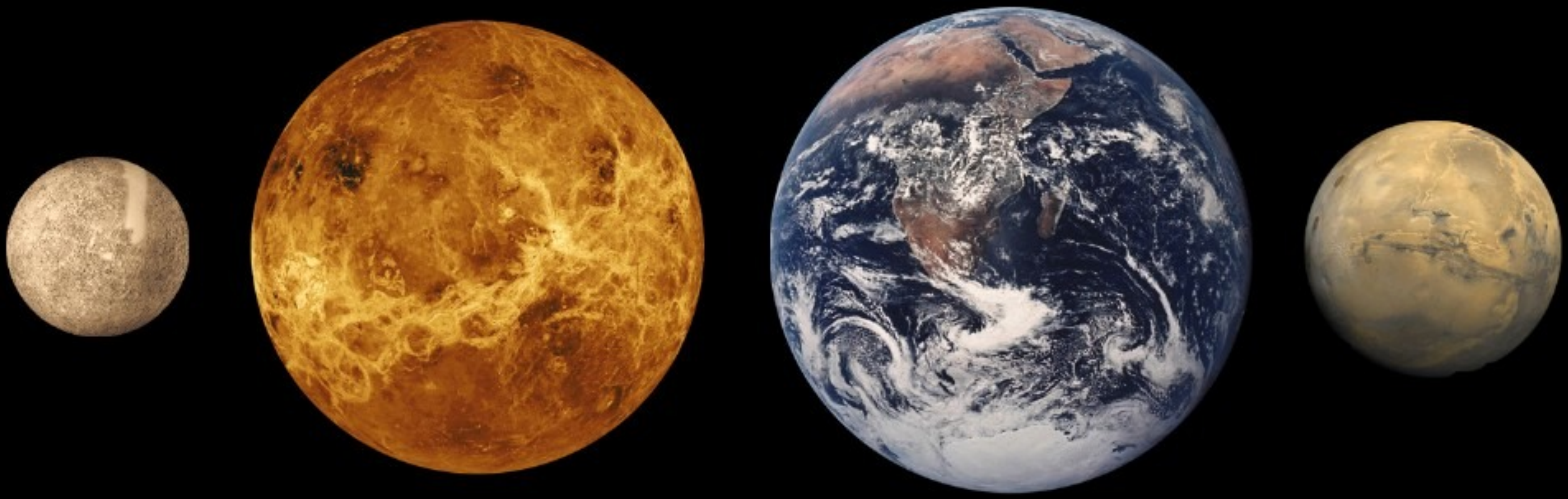
The planets are well separated, with the distance between planets increasing with distance from the Sun. *(Bode's Law?)*. The space between planets, apart from the Asteroid Belt, is almost completely empty.



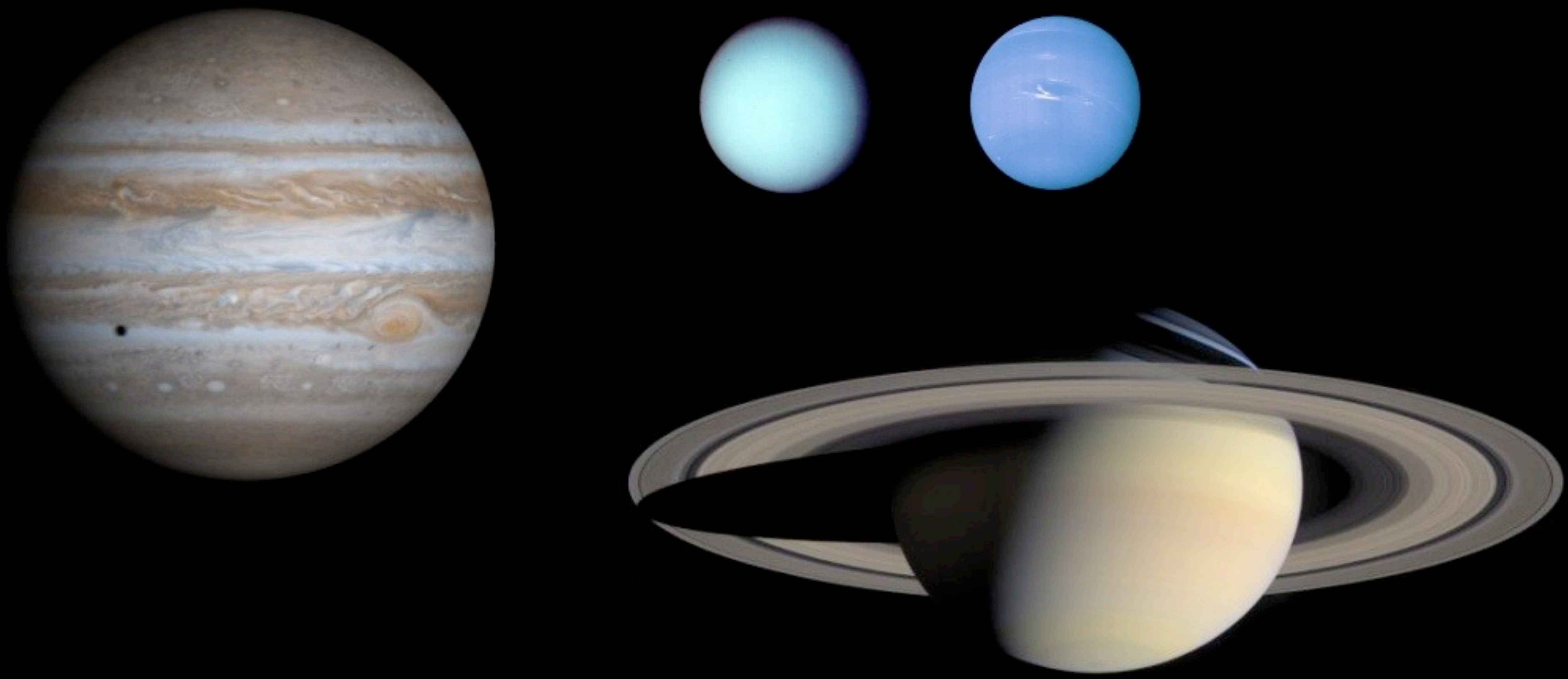
Meteorites have ages of 4.56 billion years. Rocks from the Moon and the Earth are younger, with lunar rocks typically being 3–4.4 billion years old, and terrestrial rocks are less than 3.9 billion years.



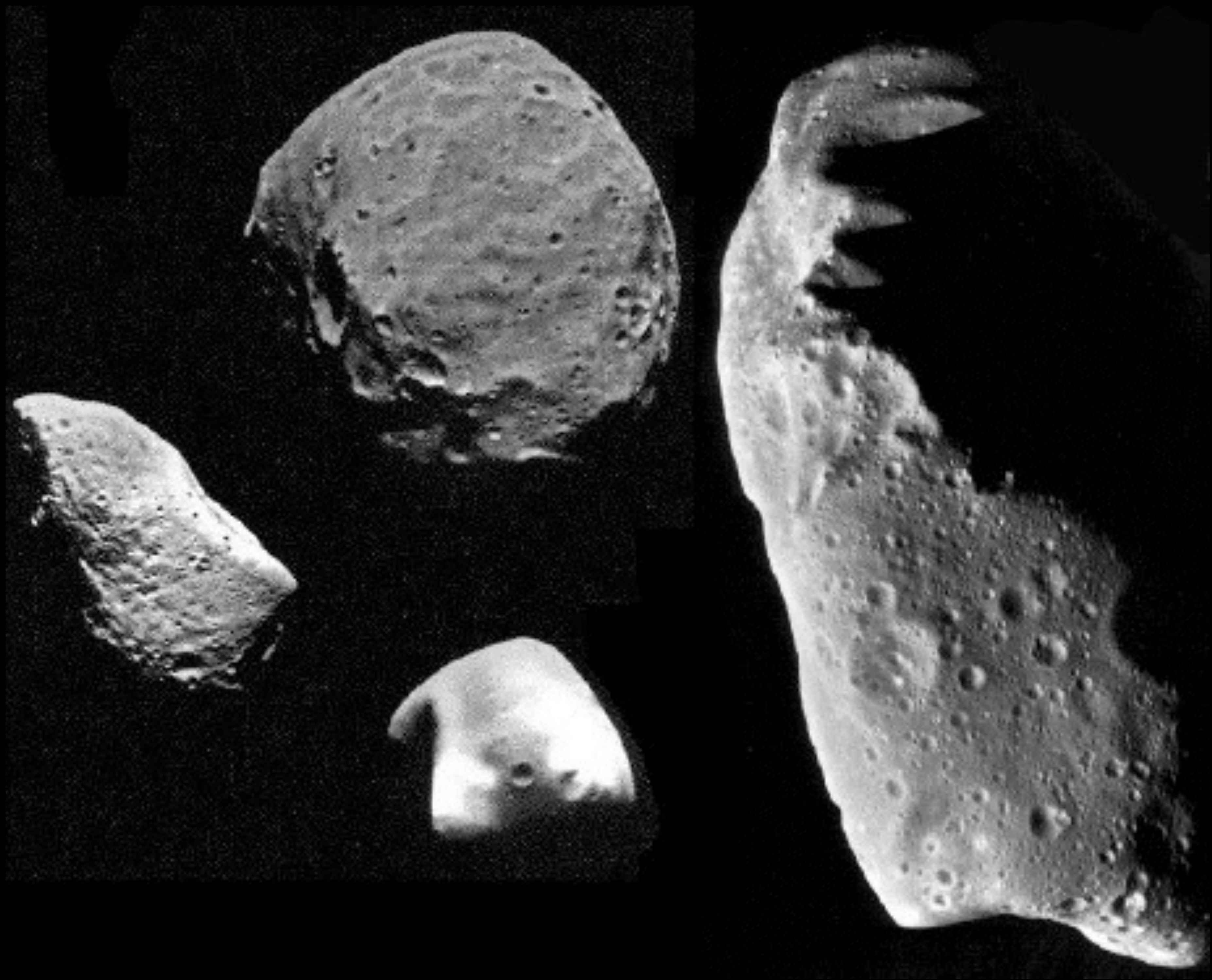
The small rocky terrestrial planets and asteroids lie closer to the Sun (all within 2AU). The closer planets are significantly denser than the further ones.



At larger distances (between 5 and 30 AU), we find the giants Jupiter and Saturn and then the somewhat smaller Uranus and Neptune. Jupiter and Saturn are mainly composed of hydrogen and helium, while Uranus and Neptune contain large amounts of ice and rock.



Between Mars and Jupiter is a large number of minor planets, with a total mass about 1/20 the mass of the Moon, and a range of sizes.

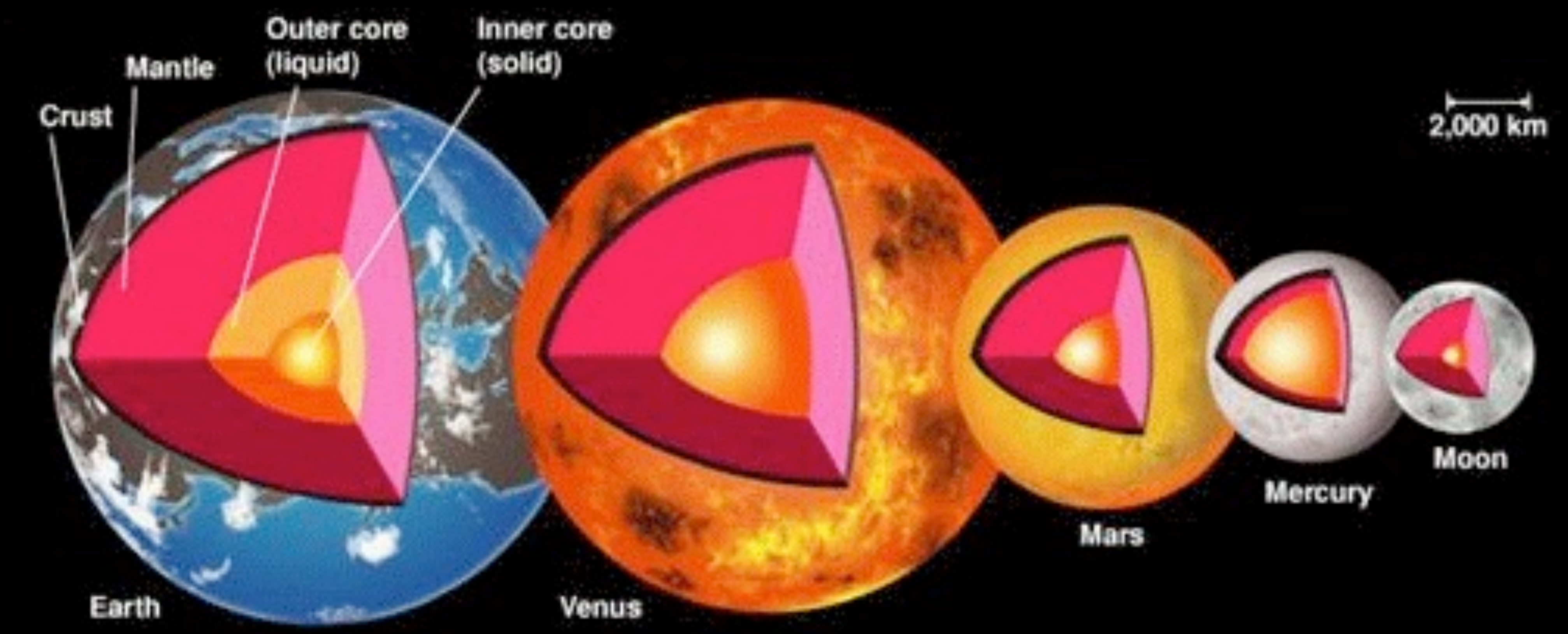


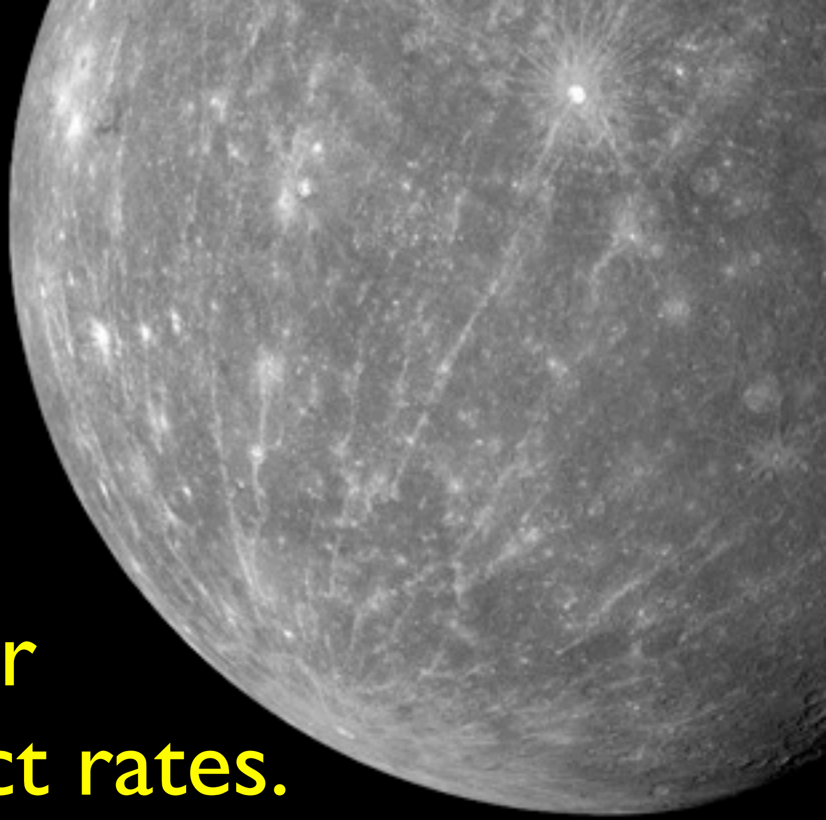
There is a large, roughly spherical collection of icy bodies circling the Sun beyond about 10,000 AU, called the Oort Cloud. Closer in, between 35 and 100 AU, is a flattened disk of similar bodies, known as the Kuiper Belt.

Most planets, and all giant planets, have satellites. Most close-in satellites orbit in the same direction as the planet's orbit, in the same plane as the planet's rotation. Satellites are all made of rock and ice, and Jupiter's satellites have the same density gradient as the inner planets.

Some of the smaller, more distant satellites (and Triton) orbit in a retrograde sense or in highly elliptical or inclined orbits.

All the major planets and most large moons and asteroids are differentiated, with the heavier metals sunk to the core and the lighter material on the outside. This implies that all these bodies were warm at some stage in the past.





Most planets and satellites show large numbers of impact craters, far more than could be produced over the age of the Solar System at current impact rates.

The Moon, Mercury, Phobos and Mimas

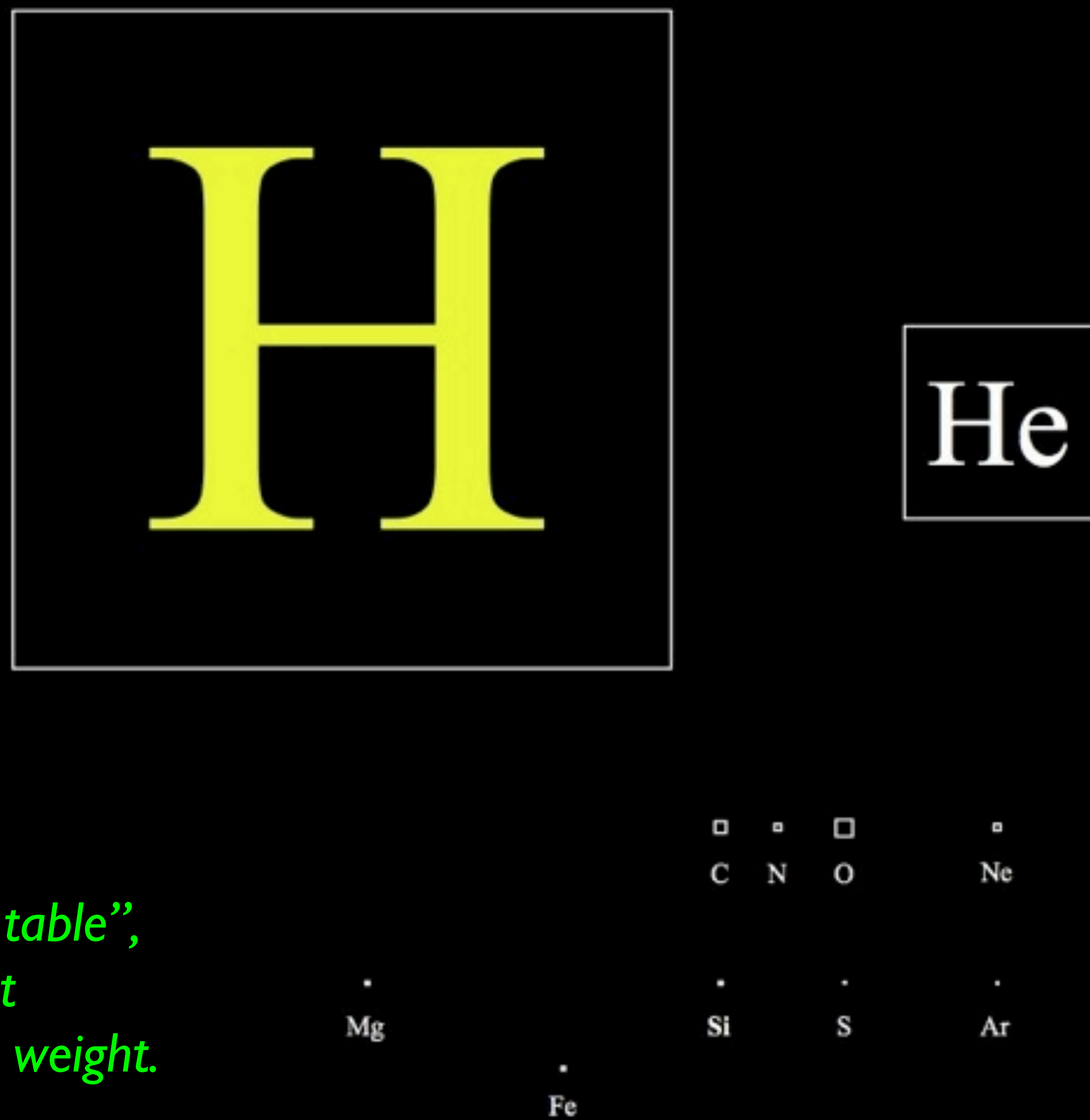
Our story begins with the vast clouds of gas between the stars.

The Great Nebula in Orion, M42

This gas is made up mostly of hydrogen and helium, formed in the Big Bang. However, a small but vital fraction consists of heavier elements like oxygen, carbon and silicon. These elements were manufactured deep in the cores of stars, and returned to the interstellar medium when those stars expired. Without these heavier elements, no rocky planets could form.

The Crab Nebula, left behind by the supernova explosion of 1054 AD

The interstellar material from which the solar system formed consists mostly of hydrogen and helium, with other elements less than one-thousandth as abundant as hydrogen.



The "Astronomer's Periodic table", with the size of the element indicating its abundance by weight. (Figure by Ben McCall)

The gas swirls around in space and collects in dense clouds. These clouds mix with the remaining primordial gas, and are known as *giant molecular clouds.*

Here is a molecular cloud you can see: the *Coalsack Nebula*

Orion and the Horsehead Nebula

Gravity, which attracts everything to everything else, tries to make the whole cloud collapse. But this inward force is resisted by *gas pressure*, which pushes outward against gravity.

As the cloud gets colder and denser, it eventually reaches a threshold where the pressure is not sufficient to support it, and it starts to collapse.

The collapsing cloud breaks into hundreds of fragments, each of which continues to collapse: the Sun was born in a cluster of young stars,
all born from the same
gas cloud.

A simulation of the collapse of a 50 solar mass gas cloud, 1 light-year across, eventually forming a cluster of about 50 stars (Bate et al. 2002)

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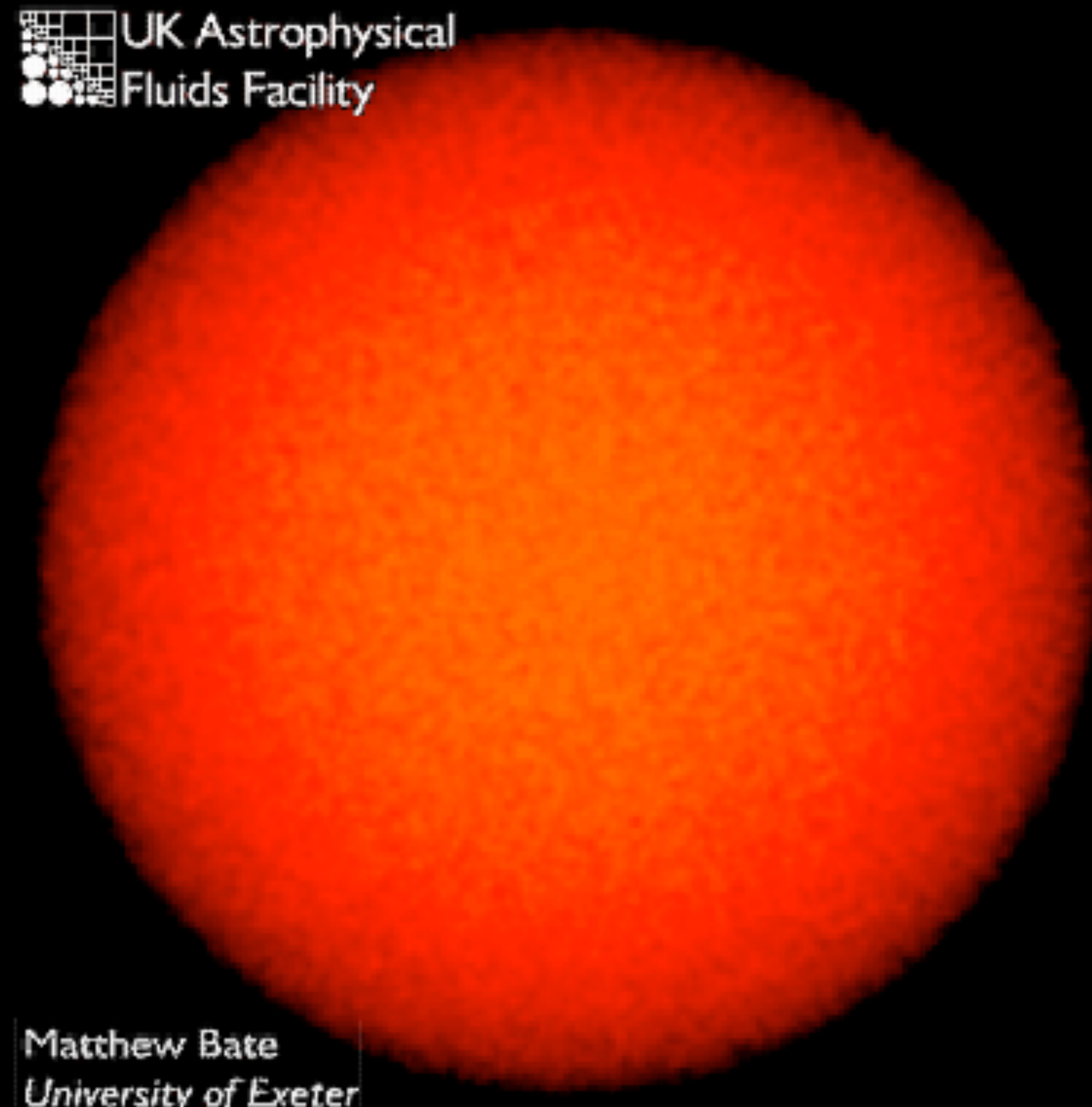
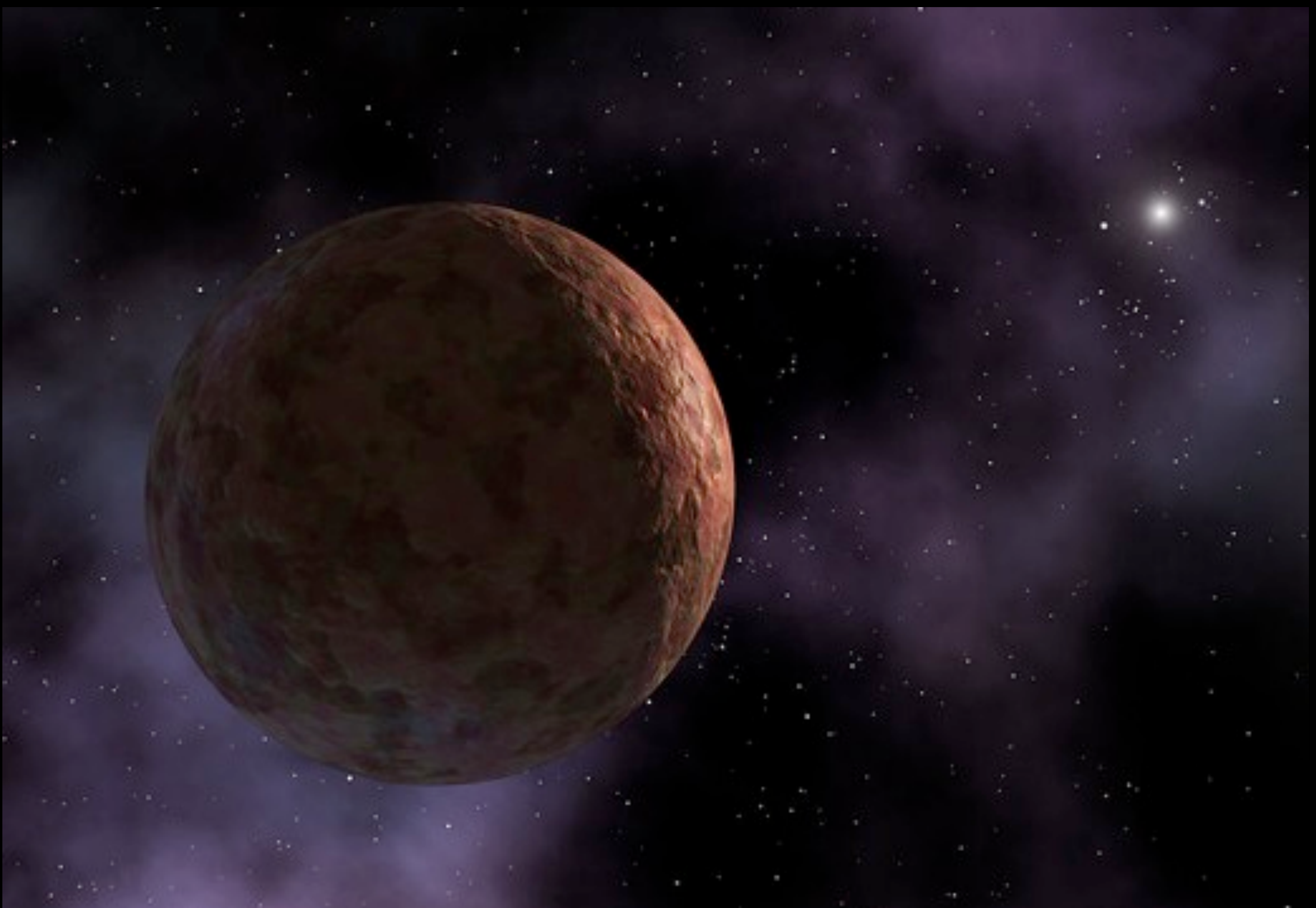
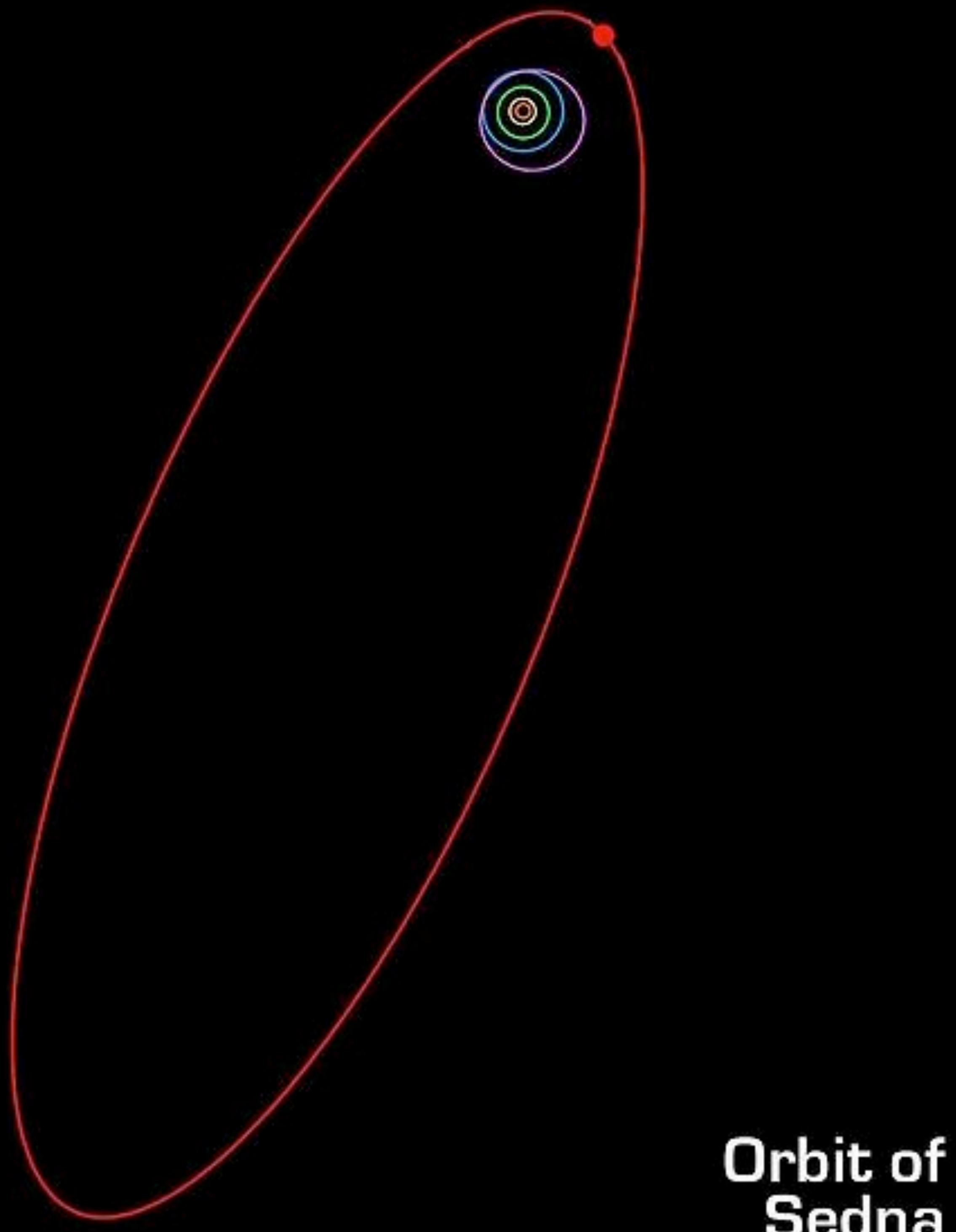


A simulation of the collapse of a 50 solar mass gas cloud, 1 light-year across, eventually forming a cluster of about 50 stars (Bate et al. 2002)

Recall that the highly eccentric orbit of Sedna must have been produced by a close encounter with another star. To perturb Sedna's orbit as much as this requires another star to approach within 200–300 AU.

A star born in a typical cluster will usually have such a close encounter once in 10 million years.



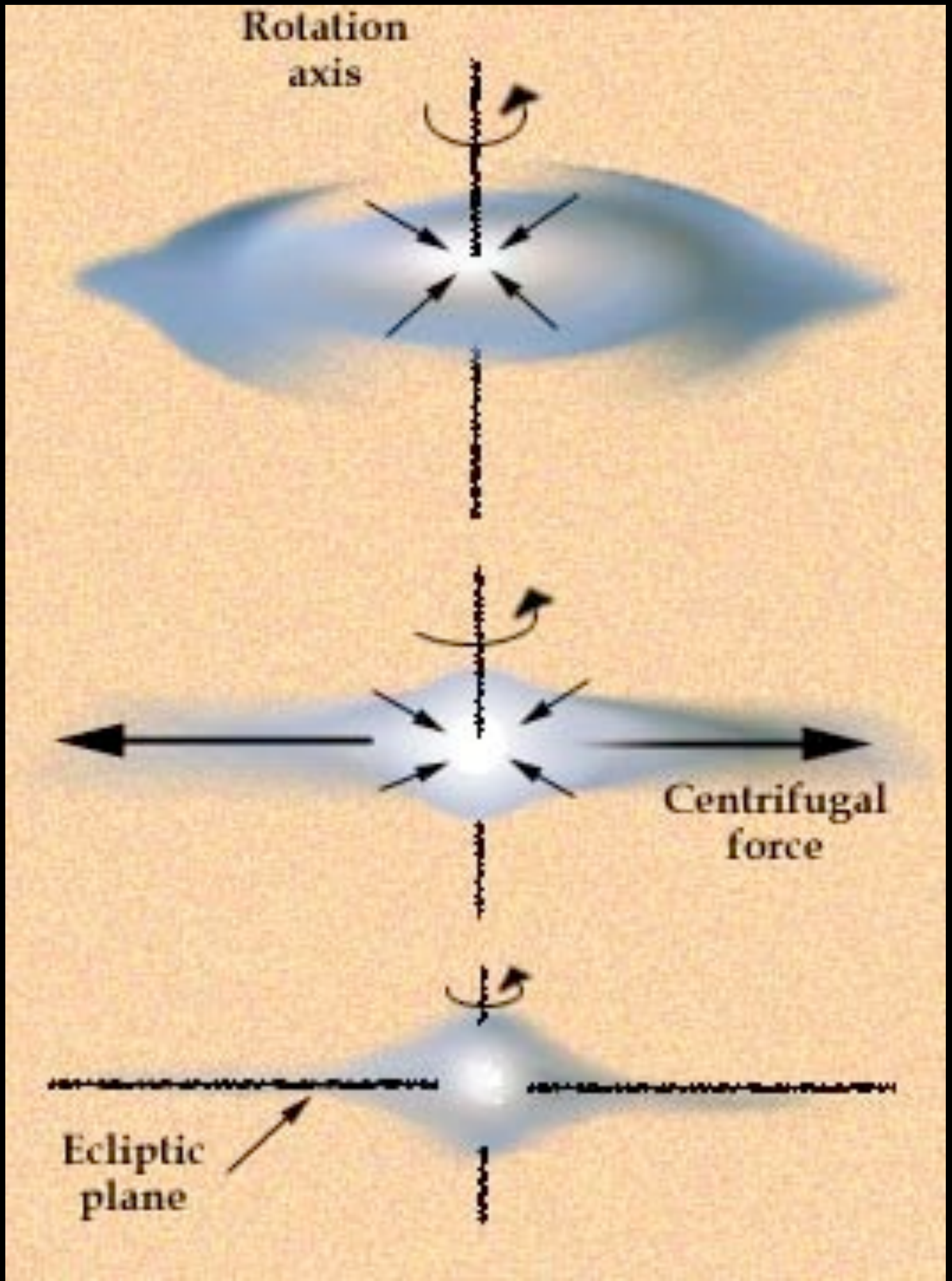


As each cloud fragment collapses, it tends to flatten into a disk. The central region collapses fastest, and begins to heat up: the cloud is collapsing from the inside. As the density increases, the cloud becomes opaque, trapping the heat within the cloud. This then causes both the temperature and pressure to rise rapidly. The collapsing cloud is now a *protostar*, surrounded by a disk of gas.

Artist's impression of a young star surrounded by a dusty protoplanetary disk.

The collapsing cloud will be rotating slightly, even if only due to Galactic rotation. The cloud shrinks by a factor of 10,000 or more, so any slight rotation is greatly amplified and the cloud will end up rotating rapidly.

What's more, it will end up as a *disk*, because while angular momentum makes it hard to collapse to the centre, there is nothing to stop the gravitational collapse to the plane.



Conservation of angular momentum is what ice skaters use when they speed up a spin.

Nancy Kerrigan - 1994 Lillehammer Olympics free skating

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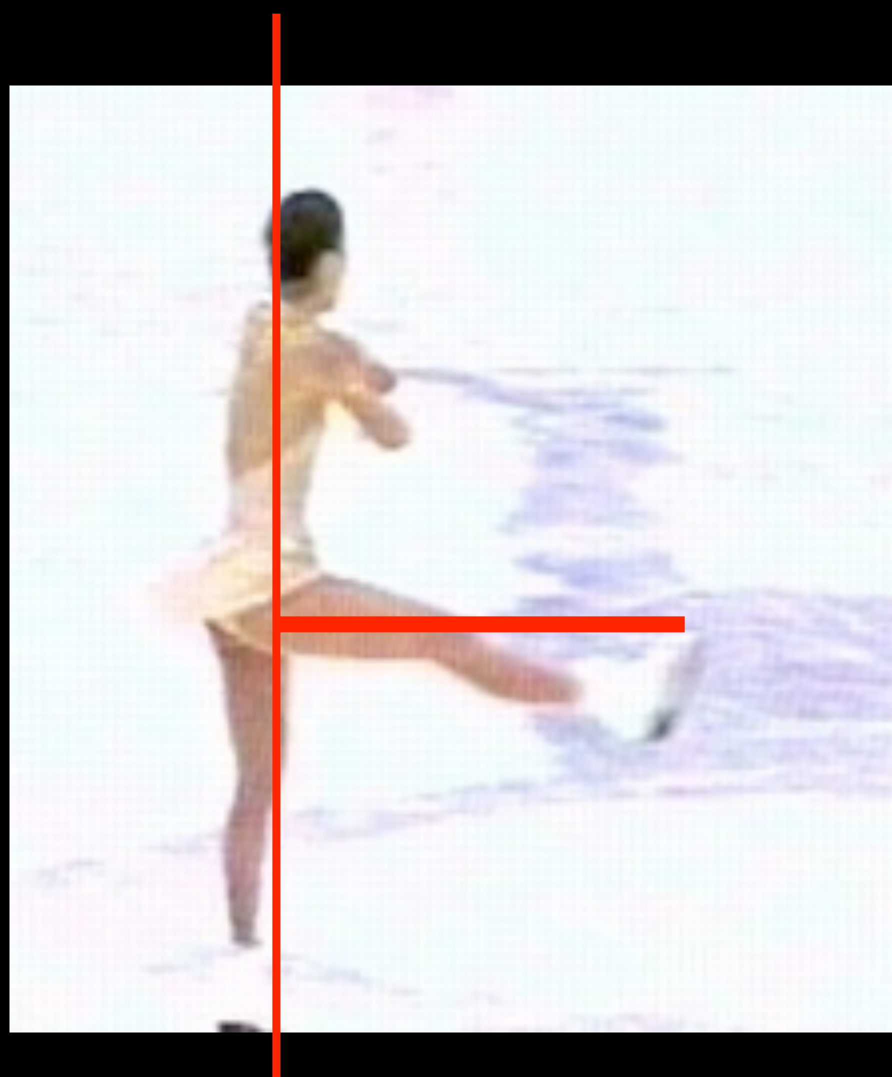
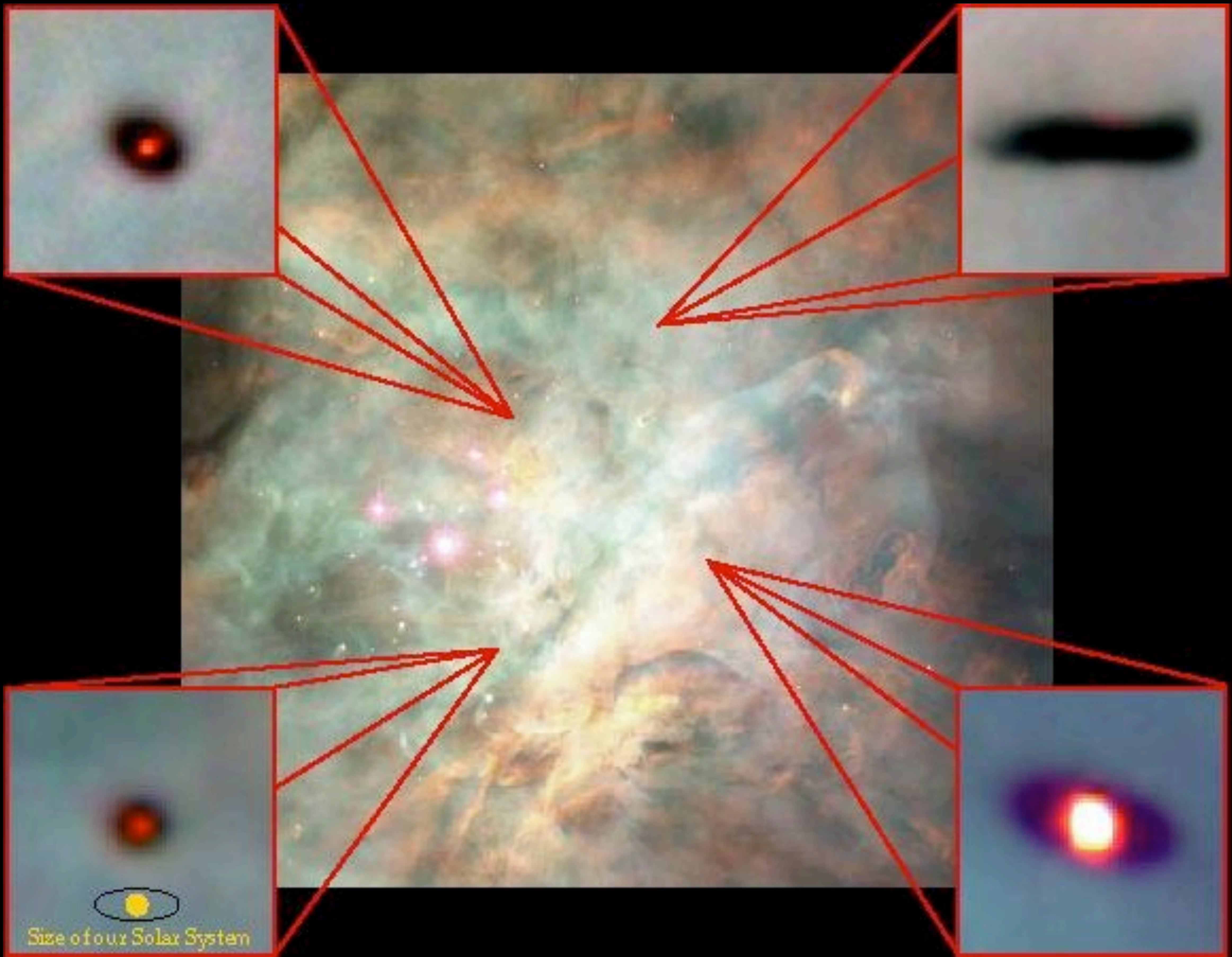
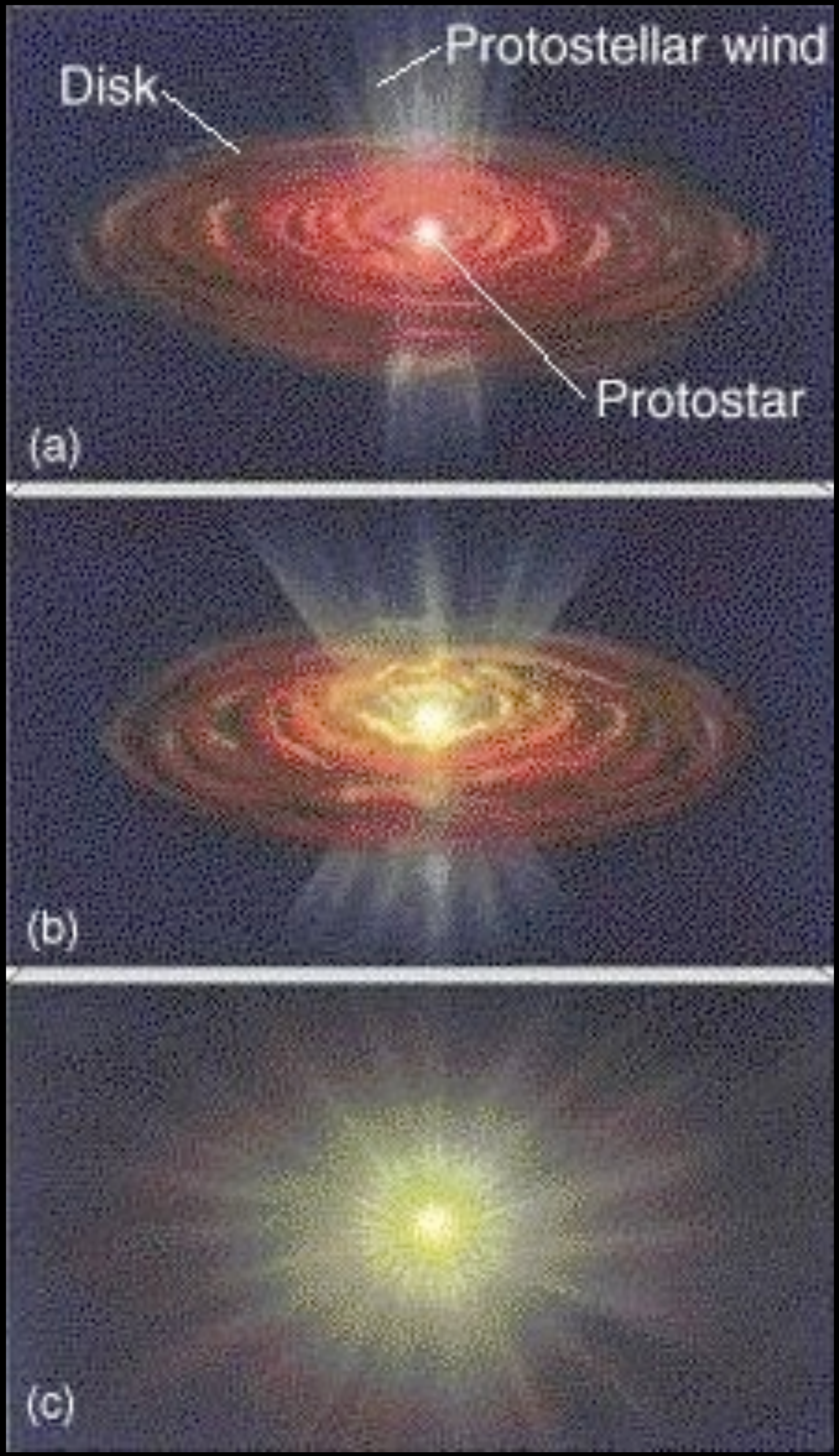
By bringing her arms and legs into line, the skater reduces the average distance of her mass from the axis of rotation, so the rate of spin must increase.



We can actually see these disks around newborn stars.



The cloud collapses from the inside out, with the interior caving in more quickly than the outer regions. This collapse raises the temperature of the gas, as the gravitational kinetic energy is converted into heat. For a while, this thermal energy can be radiated away, and the collapse can continue, but as the density increases, the heat gets trapped, and the temperature of the central core rises until it reaches 1 million degrees, when hydrogen can begin fusing into helium. This produces enough energy to stop the collapse: a star has been born.



Here are some pictures from HST. The Eagle Nebula shows a region of star formation. The pillars in the centre are dense regions of gas.


Newborn stars evaporate the end of the pillar, revealing globules which are currently collapsing to form stars.


The Wizard Nebula, NGC 7380

Planet formation

So we have formed a star. But what about the planets?

Clearly the planets form in the disk of gas and dust surrounding our newborn star. But how?

We have some clues about *when* the planets must have formed. You recall from our discussion of meteorites that there are several types, some showing they came from differentiated bodies, and some more primitive.

The ages of both these types can be measured, with surprising results. The parent bodies of meteorites began to form very soon after the formation of primitive grains: within 1 million years. Differentiated meteorites have ages which are only 10 million years younger than the oldest grains.

The giant planets must have formed within 10 million years, before the new Sun swept away the gas.

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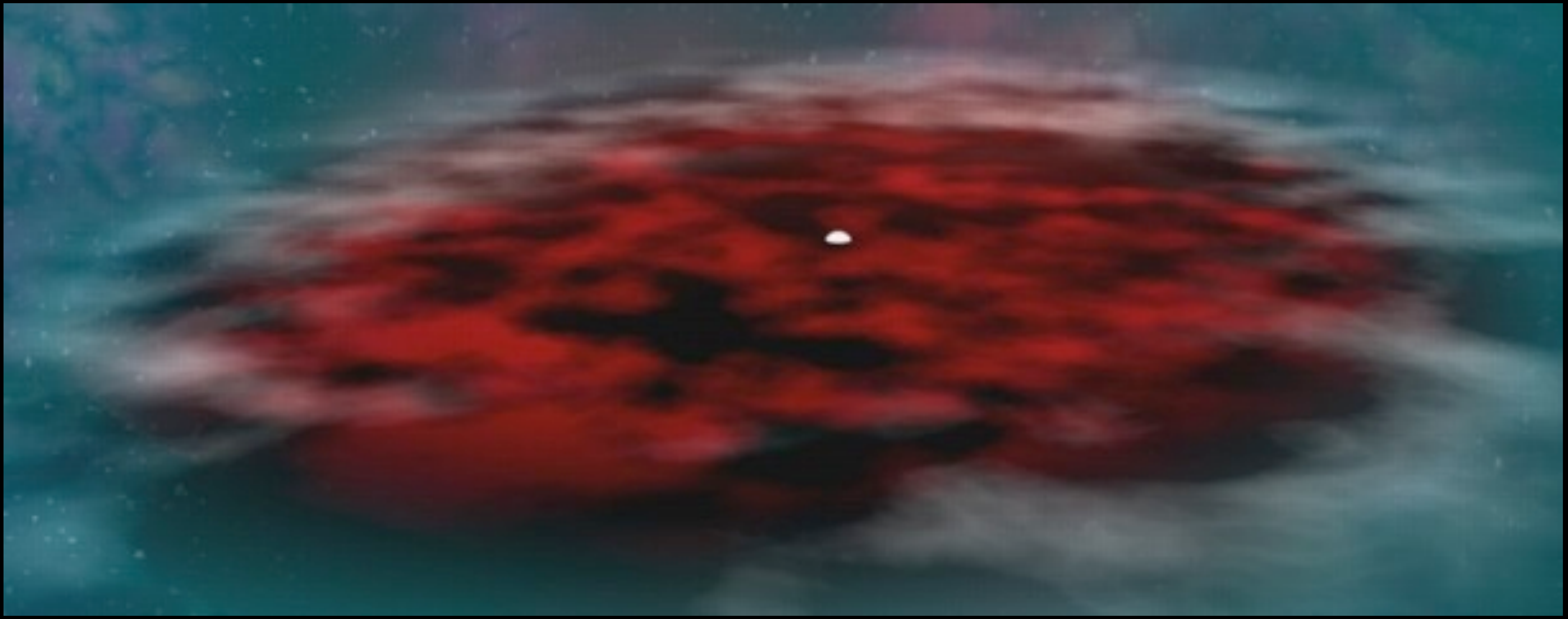
- *coagulation phase*: First dust forms from the interstellar gas cloud — **1 cm**
- *accretion phase*: This dust then starts sticking together — **1 km**
- *runaway growth*: Gravity becomes important as the protoplanets grow — **1000 km**
- *the era of carnage*: The last few collisions have planet-shattering effects — **10,000 km**

Phase 1: Coagulation

The disk starts out with the same elements which were in the molecular cloud. It consists almost entirely of gas, with a tiny amount of dust. Which molecules form depends on local conditions in the disk. Different molecules have different temperatures at which they can "freeze out" of the disk.

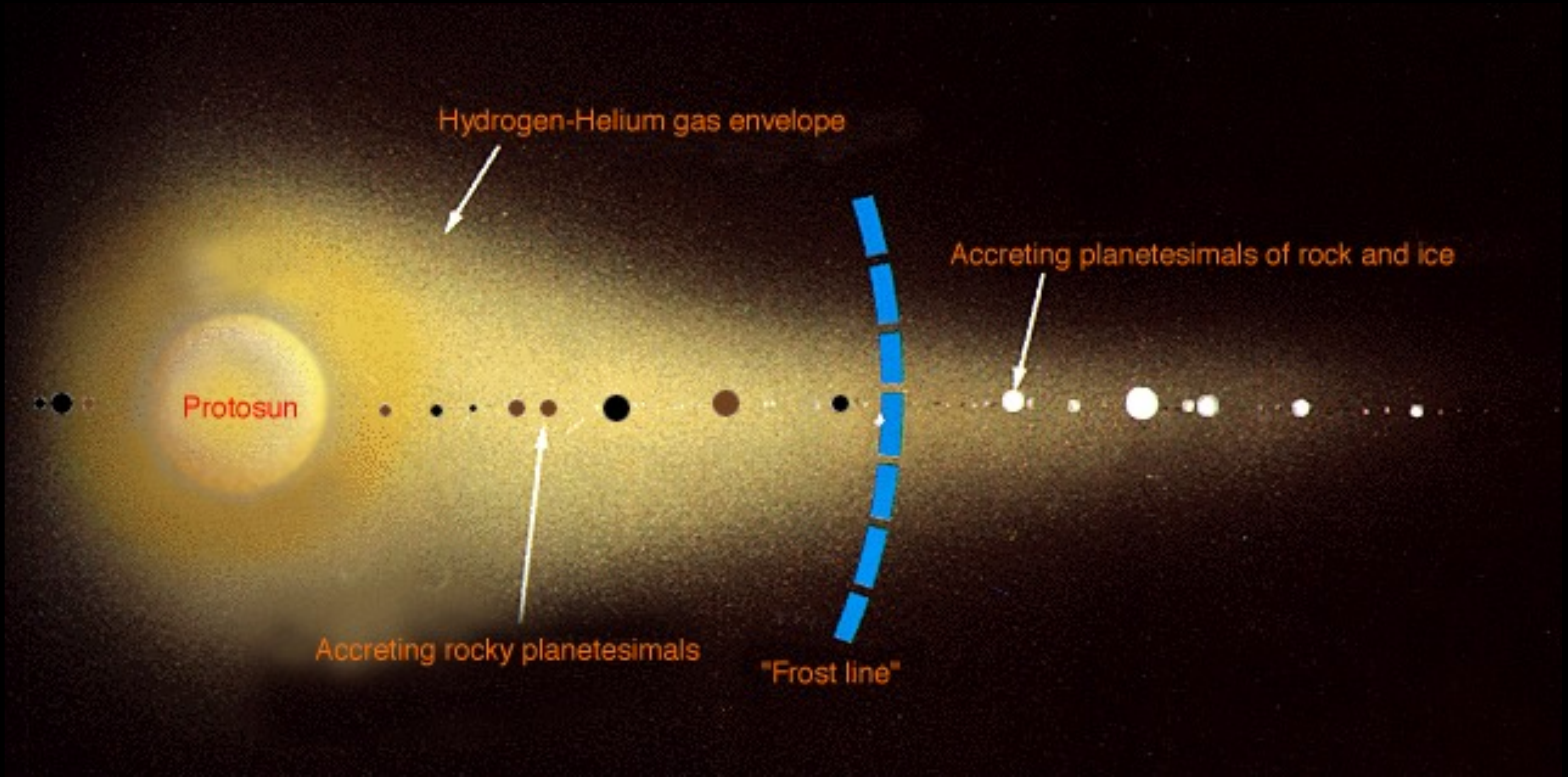


The disk is hotter near the centre, close to the protostar, so different materials condense out at different radii.

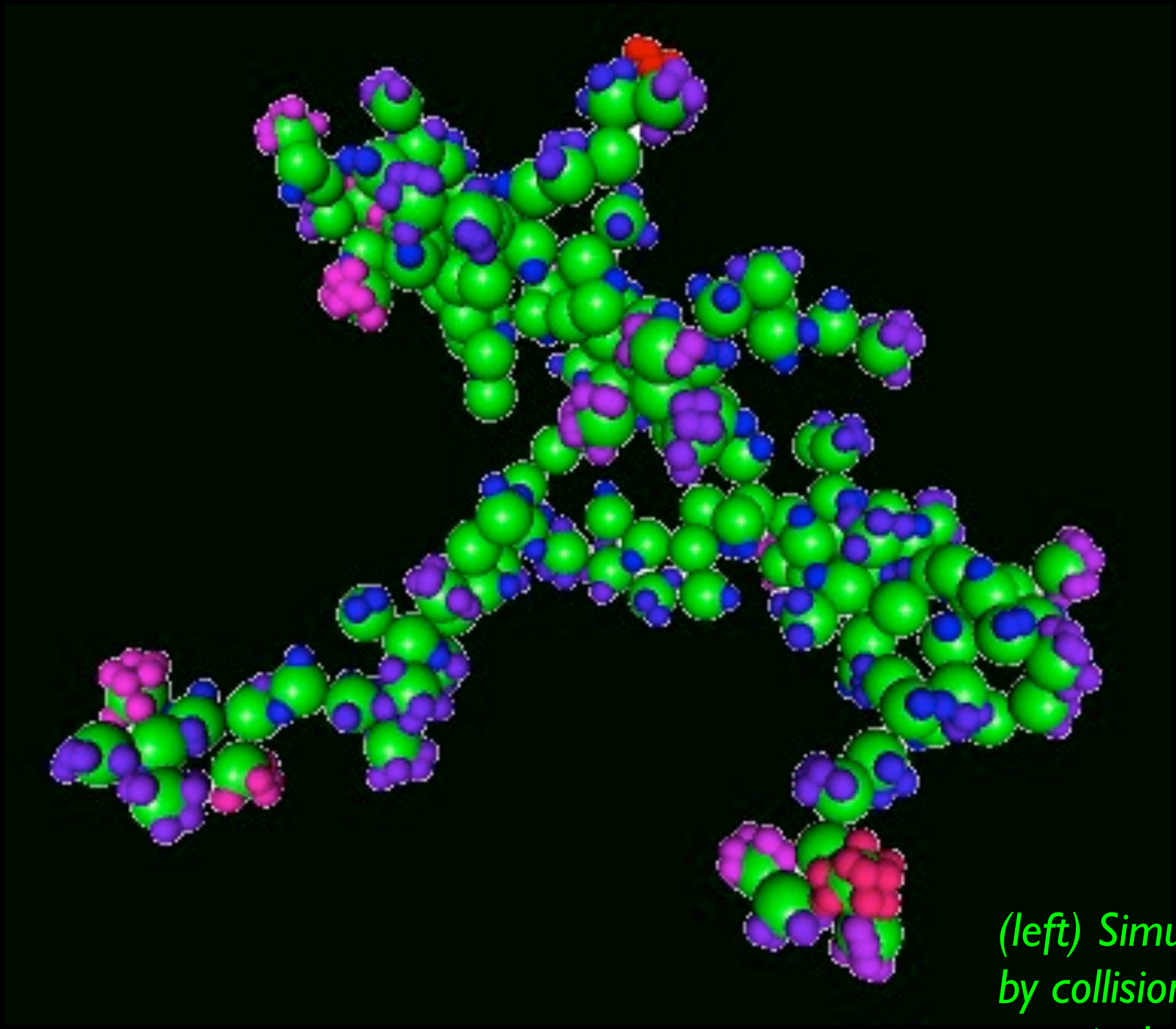
At high temperatures (< 2000K) rocky minerals and metals like iron condense.

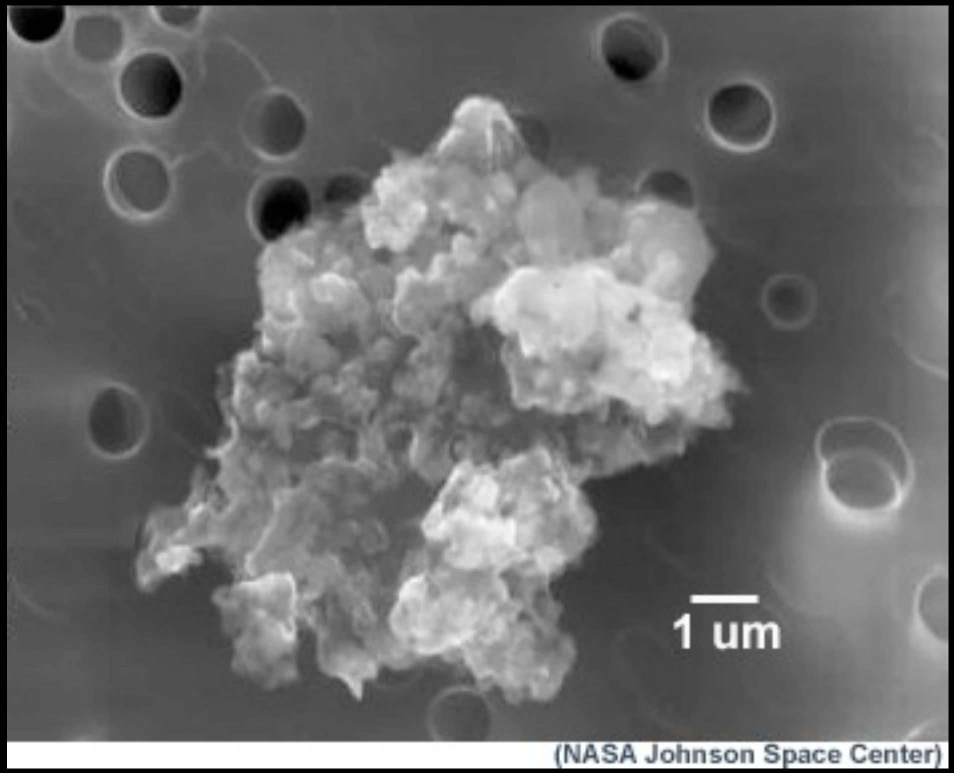
Below about 270 K water ice condenses, as well as ammonia and methane.

The distance at which water can freeze out is called the *ice line*. Beyond that distance there is much more mass available.

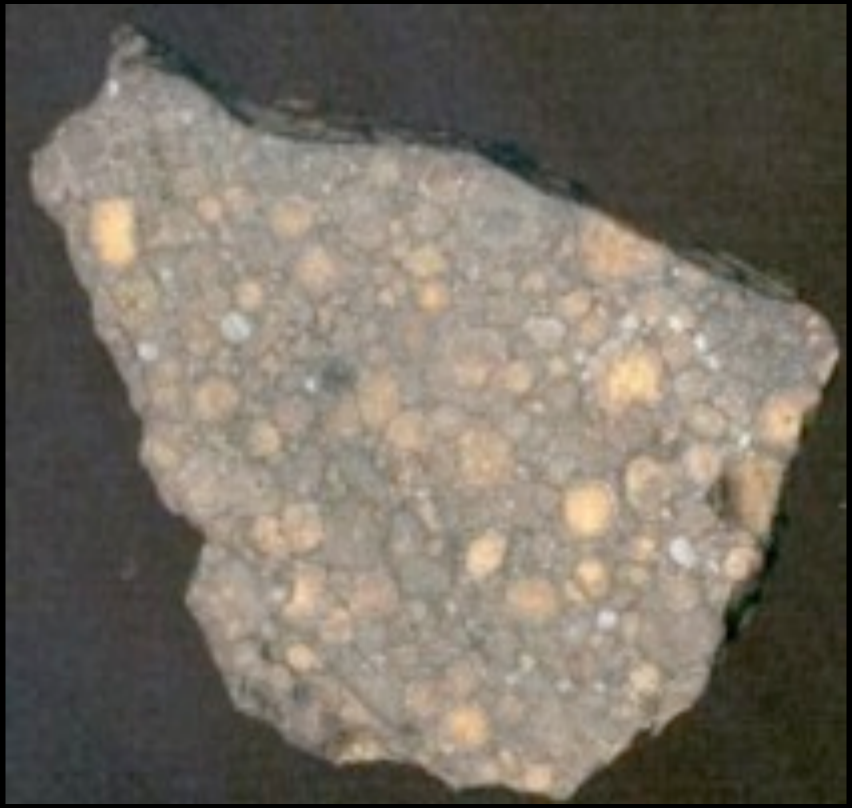


The condensing materials stick together by colliding and sticking together using normal chemical forces. They form loose fractal aggregates, described as "fluffy dustballs".





(left) Simulation of a molecular aggregate formed by collisions; (above) Electron microscope image of a typical cosmic dust particle



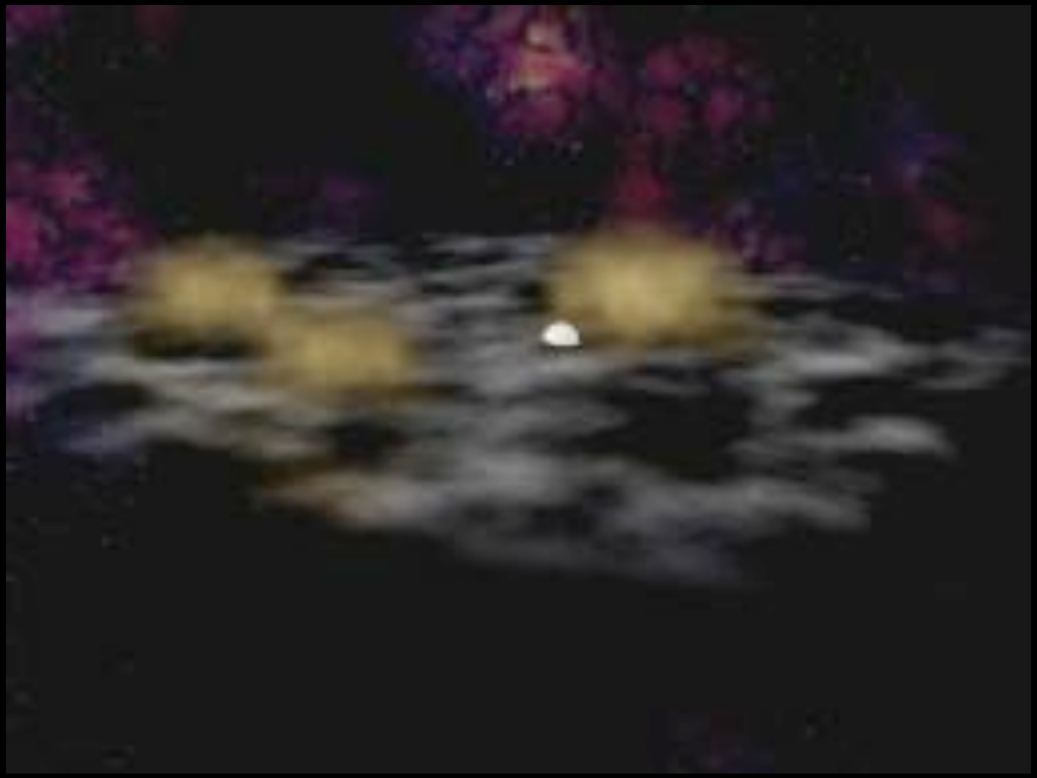
Many meteorites contain *chondrules*, which are the oldest objects in the Solar System. They have been melted and rapidly cooled, so the fluffy dustballs turned into smooth spheres.

But how were they melted? No-one knows for sure: perhaps passage through shocks in the disk, or lightning in the disk (seen in volcano plumes)

Phase 2: Accretion

The next phase is the formation of *planetesimals* (bodies up to about 1 km in size) through accretion.

The dust-ball aggregates settle to the plane of the disk, growing through collisions all the time. Within 10,000 years, the particles have grown to a centimetre or more in size.



As particles grow, they experience substantial drag in the disk. This makes the particles orbit slower than their Keplerian velocity, and a rock of about 1m in size would spiral in to the Sun in only 100 years or so.

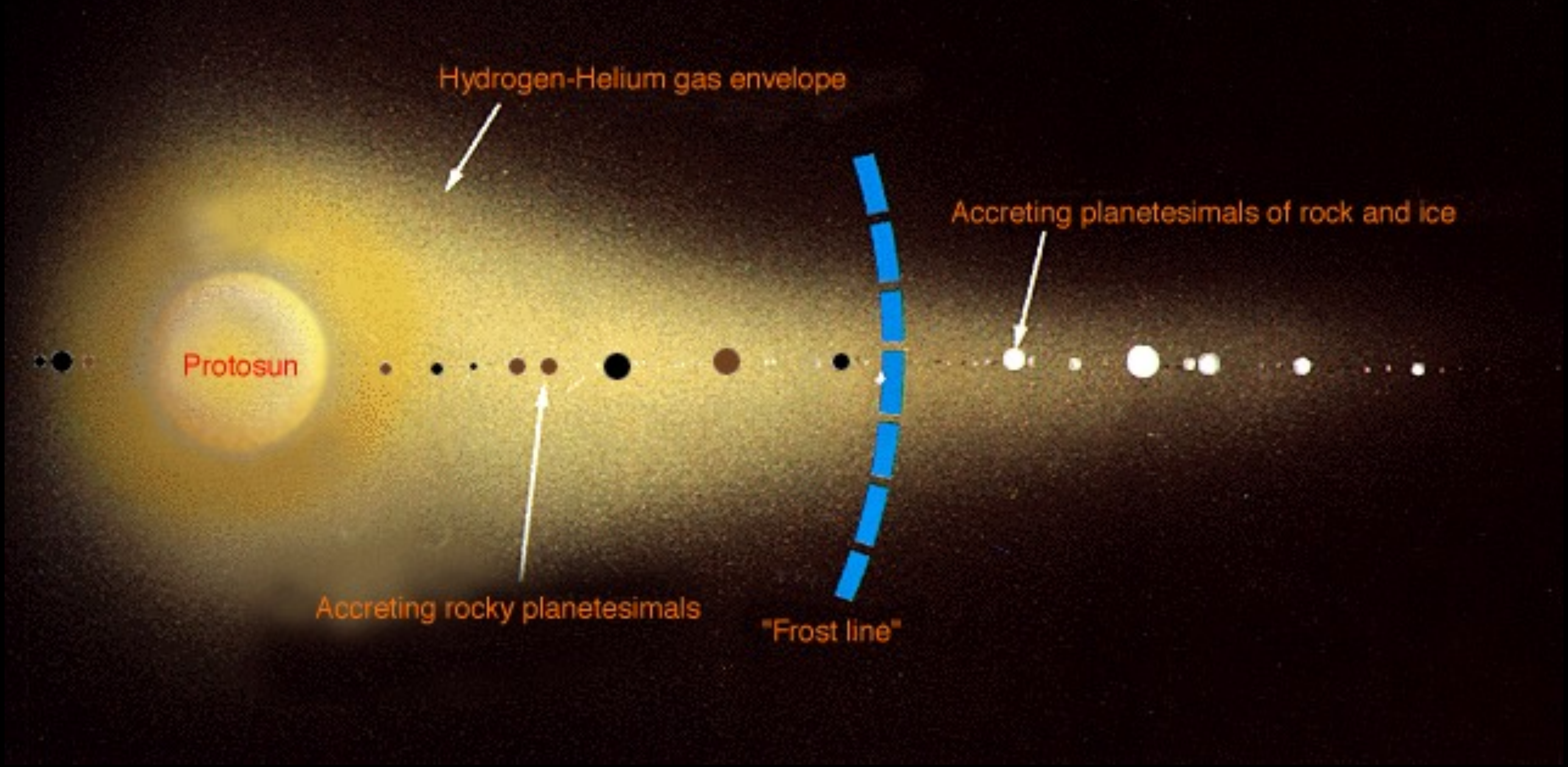
The planetesimals must grow very quickly to kilometre size, by which size the drag is less (because the surface area to mass ratio drops).

Phase 3: Runaway growth

Once the particles reach about 1 km in size, gravity starts becoming important. The larger planetesimals can sweep up more material, so the biggest bodies grow much faster than smaller ones – a process known as *runaway growth*.

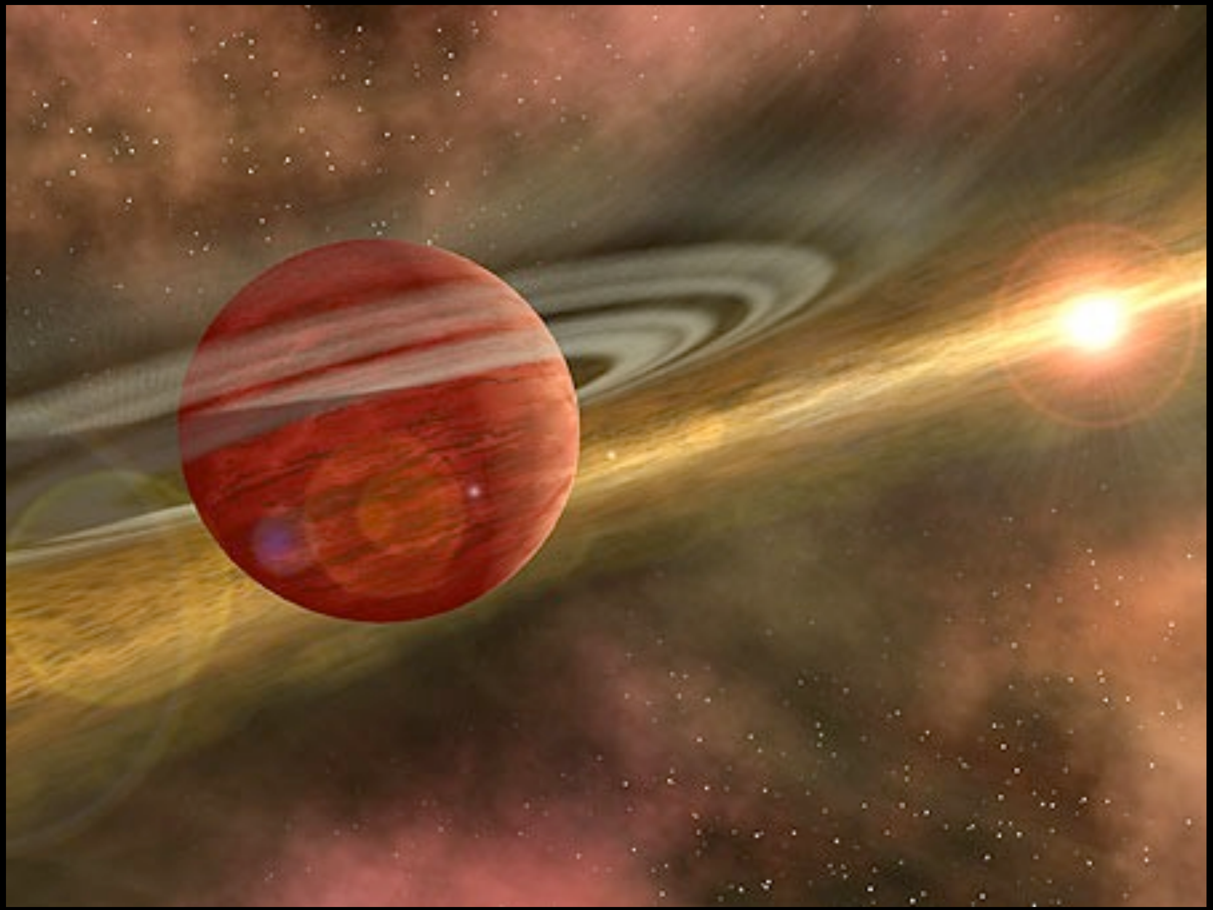
Runaway growth ends when the planetesimal (now called a *planetary embryo*) has consumed nearly everything within its reach.

The runaway growth phase ends with massive protoplanets fairly well spaced, since each has accreted everything within its gravitational sphere of influence.



The giant planets appear to have formed by first accreting a core of several Earth masses. This core was more massive than the proto-planets in the inner Solar System because the proto-Jovian planets were beyond the ice line. Once this solid mass had accumulated, the planet starts accreting gas more and more efficiently, in a runaway gas accretion phase. Jupiter and Saturn grew much larger because they formed further in, where the disk was thicker.

The giant planets were hot when they were accreted. This expanded their atmospheres to vastly larger dimensions than they have today. Gradually they radiated away this heat and shrank, leaving a disk of gas, ice and dust in orbit: a small-scale analogue of the solar nebula. From these disks emerged the regular satellites and ring systems.



Satellites must have formed from this disk around their primary, just like miniature planetary systems. This disk was heated by the forming planet, leading to gradients of composition just like those we see in the planets.

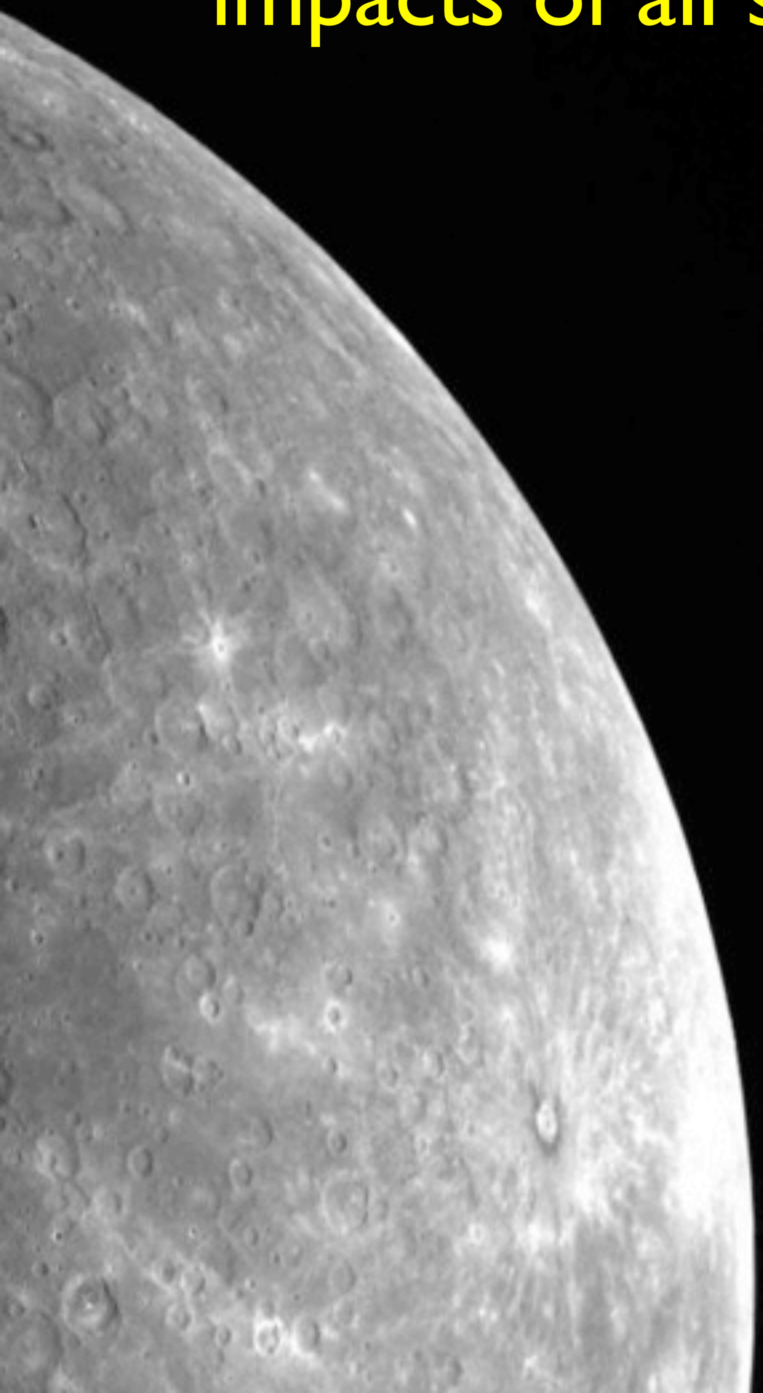
The irregular satellites are captured planetesimals, captured by the gravitational field and/or the extended atmospheres of the proto-planets.

The Earth's moon and Charon have a different origin.

Phase 4: The era of carnage

Once the protoplanets have reached the size of the Moon or larger, the final stages of planet formation begins, where the hundred or so protoplanets are reduced to the current handful. The planetary embryos perturb each other into crossing orbits, leading to giant impacts. This last handful of impacts has left permanent scars on nearly every member of the Solar System.

The evidence for this late stage bombardment is all over the Solar System: *every* old surface bears witness to having been battered by impacts of all sizes.

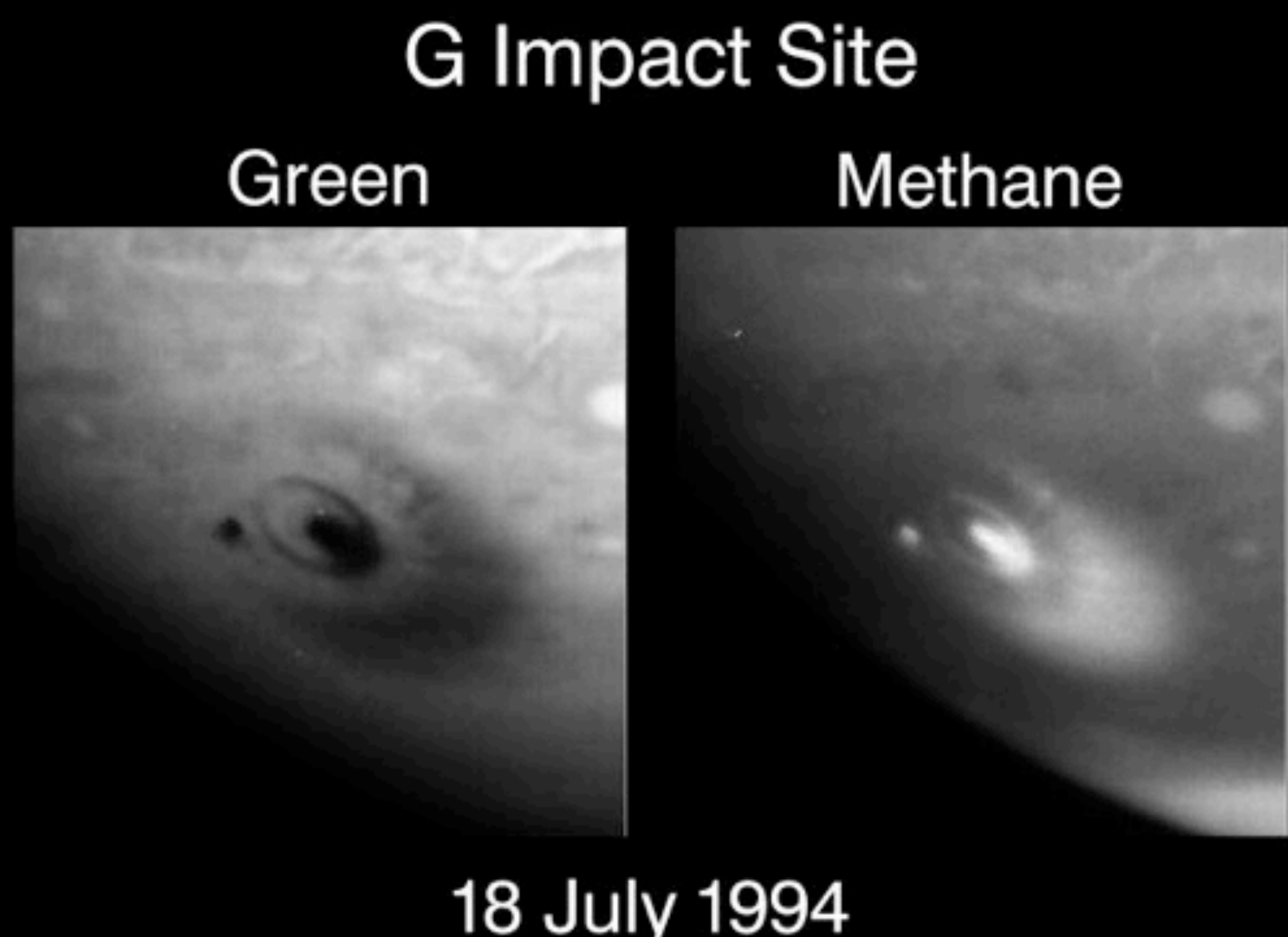


(from left) Mercury, Mathilde, Callisto and Mimas

At this stage, most of a planet's mass is being accumulated from planetesimals of radius 10 km or larger. About 70% of the kinetic energy of the impacts is converted into heat. By the time the proto-planet reaches about 20% of the mass of the Earth, the temperature at the surface is about 1500°. The surface of the planet melts, with heavier material sinking and lighter material floating: the interior *differentiates*.

The bombardment of the Solar System has not stopped, only reduced in intensity. In July 2004, we got a chance to see an impact in detail, when Comet Shoemaker-Levy 9 impacted on Jupiter: the very-very-late stages of planetary accretion.

(left) Composite photo, assembled from separate images of Jupiter and Comet P/Shoemaker-Levy 9, as imaged by the Hubble Space Telescope. (below) The G impact site 1h45m after impact, seen by HST.

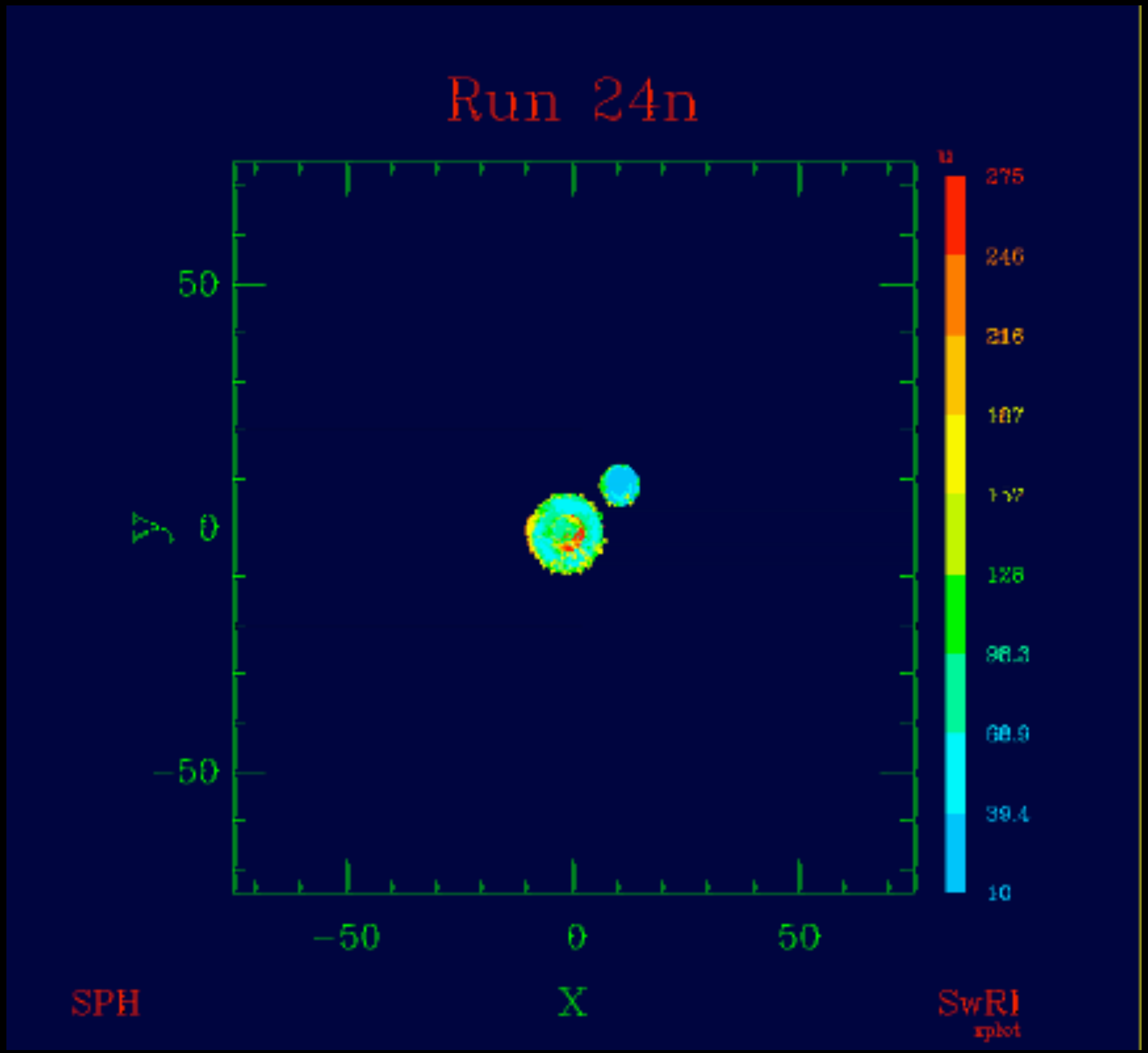


Since the last few impacts were so violent, the last stage of planetary accretion was far from orderly. The random nature of the impacts means we can't expect to find general, predictive laws which explain the current states of the planets.

The Earth's moon was formed as the result of a collision between the proto-Earth and another planet-sized body. Material from the impact was thrown into orbit and coalesced into the Moon.

This explains why the other terrestrial planets do *not* have a moon, because the Moon-impacting event was reasonably unusual.

Calculations showed that the impactor had to be the size of Mars in order to eject enough material into orbit to form the Moon.



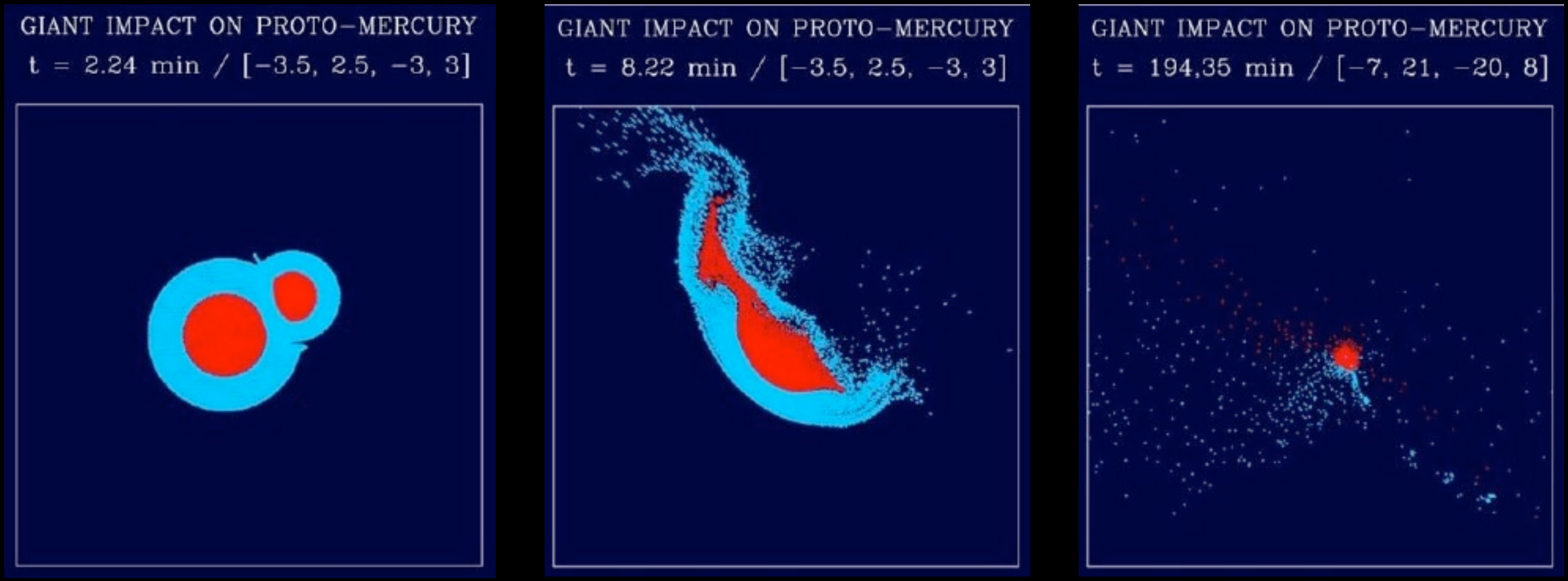
Animation showing the impact of a Mars-size proto-planet with the young Earth. The animation covers only 24 hours, ending with the Earth surrounded by a disk of debris, from which the Moon will coalesce.

The impact that made the Moon was just the biggest in a whole spectrum of impacts. While the planets were forming, there was a continuous distribution of sizes of objects: ten Moons for every Mars-sized object, ten Marses for every Earth, and so on. Smaller impacts will tend to cancel out, but the biggest impact can only come from one direction and one angle, and so can have very different results.

We now think that the following oddities are the result of giant impacts in the very last stages of planet formation.

Charon was probably also formed in a giant impact: it is hard to explain the enormous mass ratio of Pluto/Charon in any other way. This impact probably also tipped Pluto's spin axis all the way over.

Mercury: Mercury's giant iron core may also be the remnant of a giant impact. An off-axis collision with a proto-planet of comparable size may have vaporised the silicate-rich mantle of the proto-Mercury, leaving behind an iron-rich core.



Simulation of a glancing impact on a proto-Mercury. Much of the lighter mantle material (blue) is ejected from the inner solar system altogether, leaving a remnant rich in core material.

Mars: The Martian crustal dichotomy could have been formed by a giant impact, if it only struck a glancing blow.

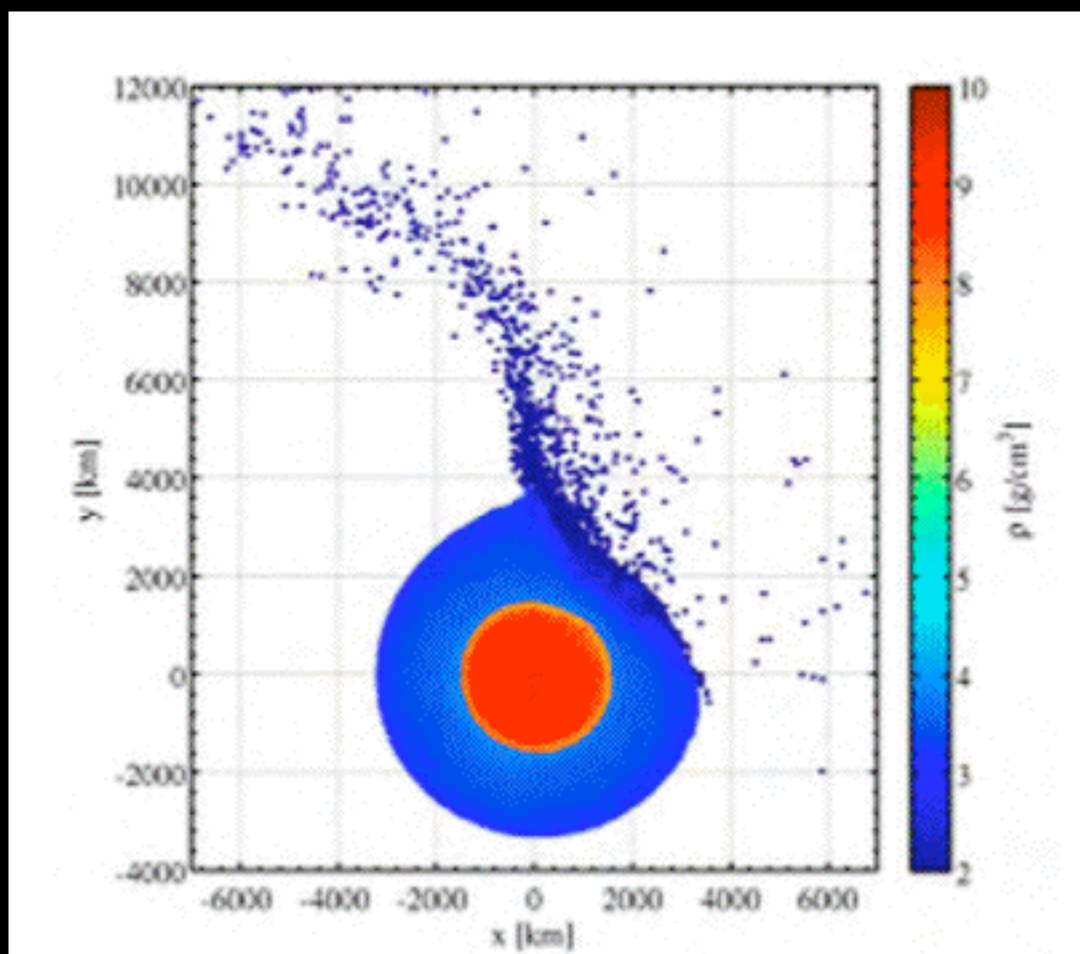
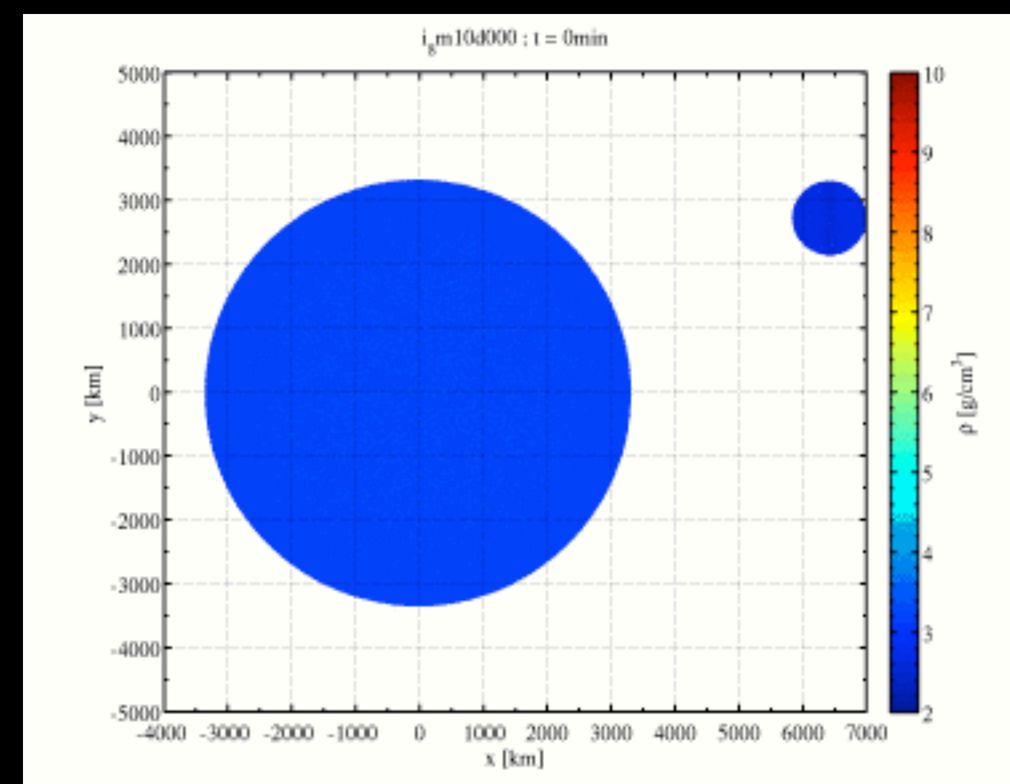
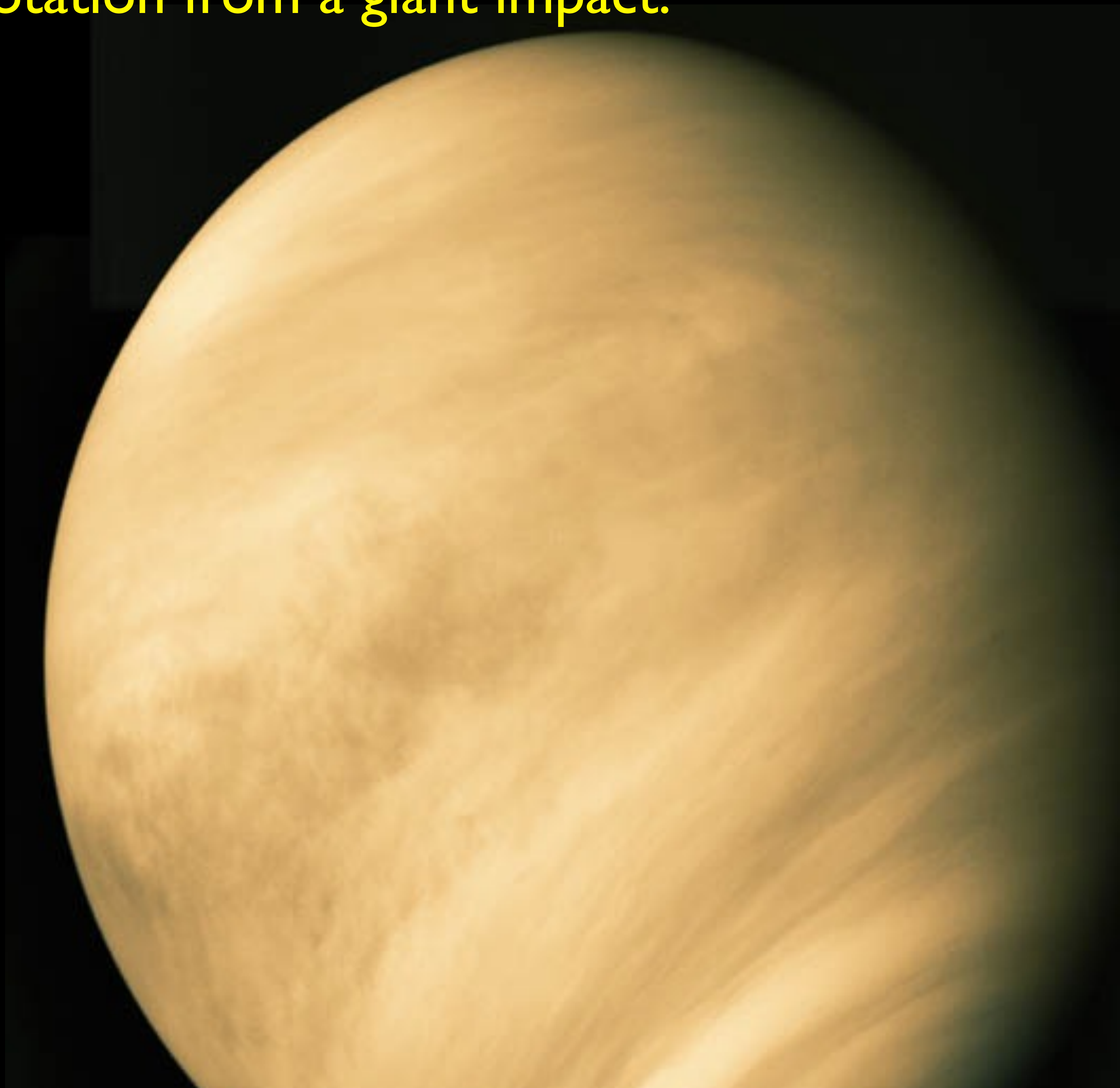


Figure 1. Snapshot of an impact simulation: t = 25 min after impact. Half-space shown. Impact parameters v = 6 km/s, $D_{impactor}$ = 860 km, 1.45×10^{29} J, D_{crater} ~ 8000 km, impact angle = 30 deg.



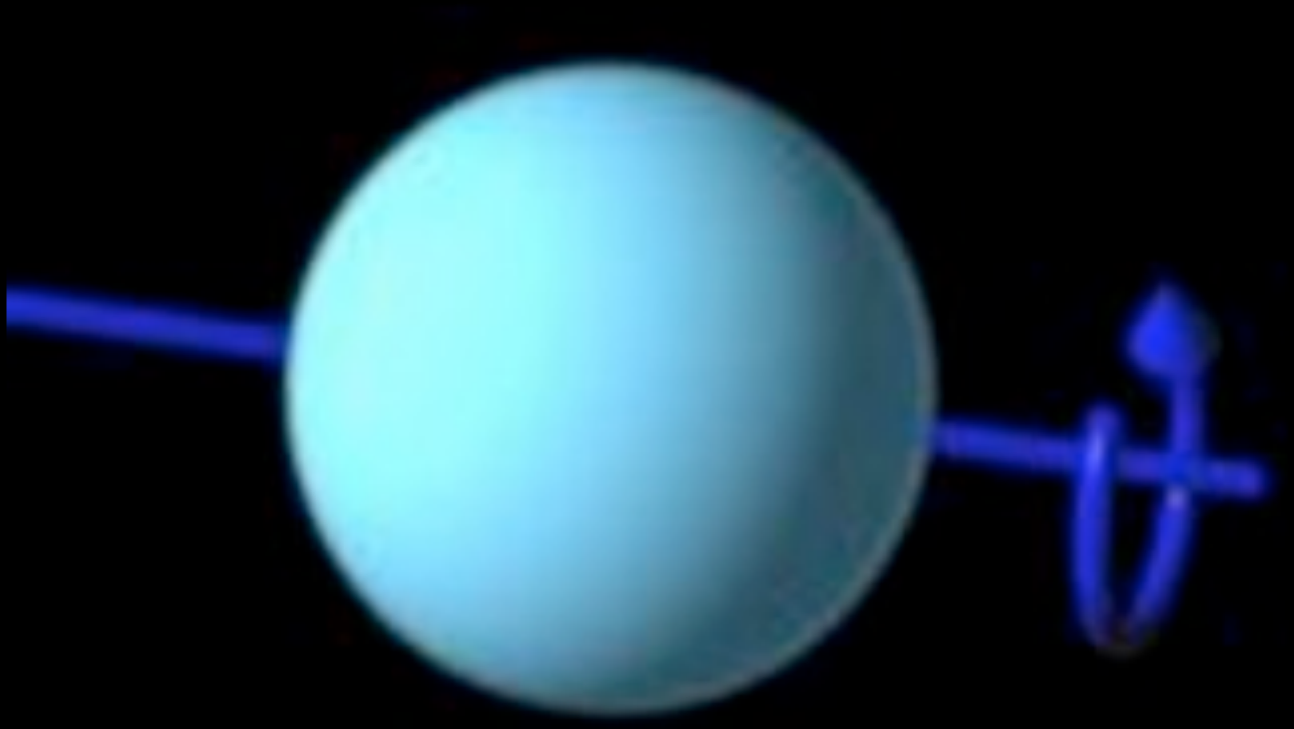
Venus: Venus may have acquired not only its tipped axis but also its slow rotation from a giant impact.



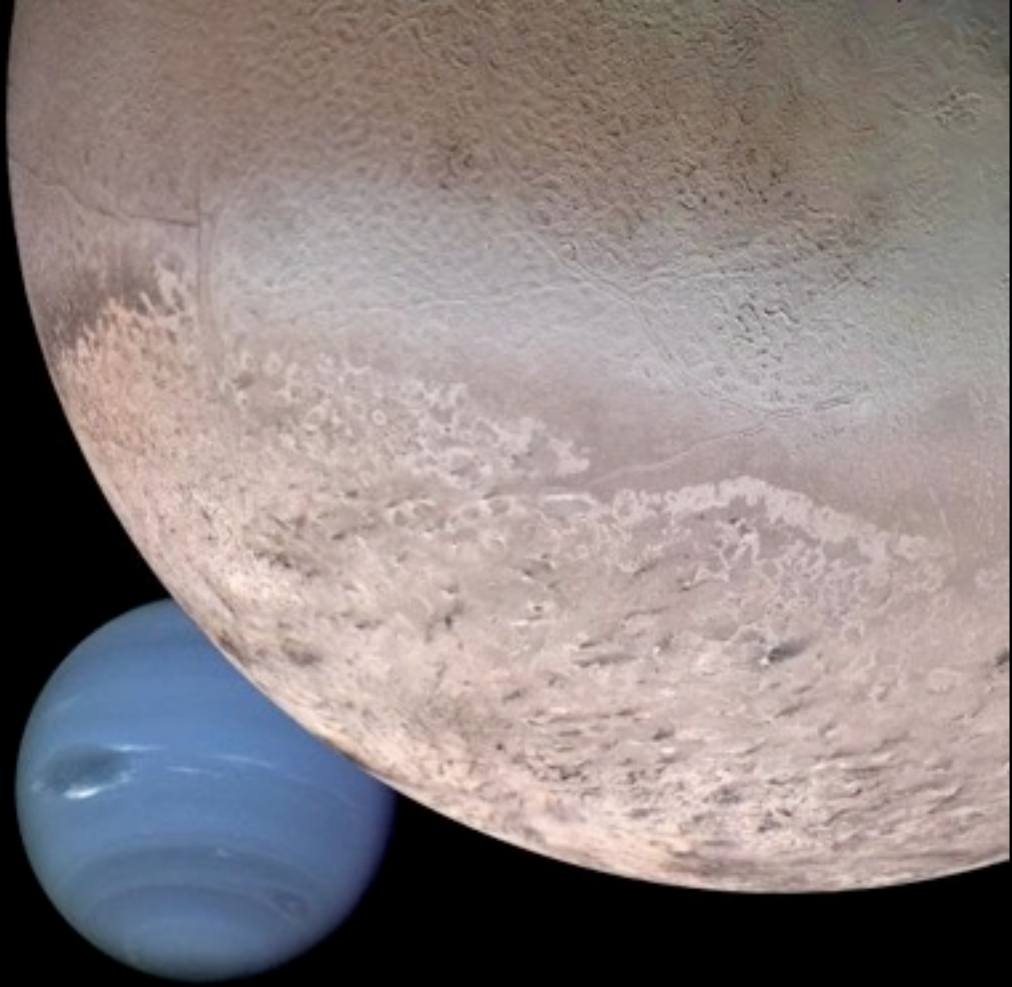
In fact, the spins of most planets are assumed to arise from the accumulation of angular momentum imparted by the various planetesimals which accreted, possibly modified by later tidal forces.

Mars' current spin period is probably close to its primordial period, since its moons are too small for tidal forces to be effective. Ordered accretion cannot produce a spin this rapid (25 h), so must arise from one or a few giant impacts.

Uranus: Uranus' extreme tilt (98°) is thought to have been caused by a giant impact. A body of at least 2 Earth masses hit the proto-Uranus at an oblique angle, tilting the spin axis. A large amount of material spun off the equator left a disk in orbit from which the current system of moons eventually assembled. In contrast, if the final impact on Neptune was nearly straight down, it would heat the planet but not leave a disk, explaining the absence of regular satellites around Neptune.



Triton: Triton, with its retrograde and highly inclined orbit about Neptune, is most likely a Kuiper belt object which wandered close to Neptune. There, it was captured into orbit, possibly colliding with (and destroying) one of Neptune's regular satellites. The initial orbit would have been highly eccentric, but tidal interactions with Neptune would have circularised it, taking about a billion years. This tidal energy would have acted as a major heat source.



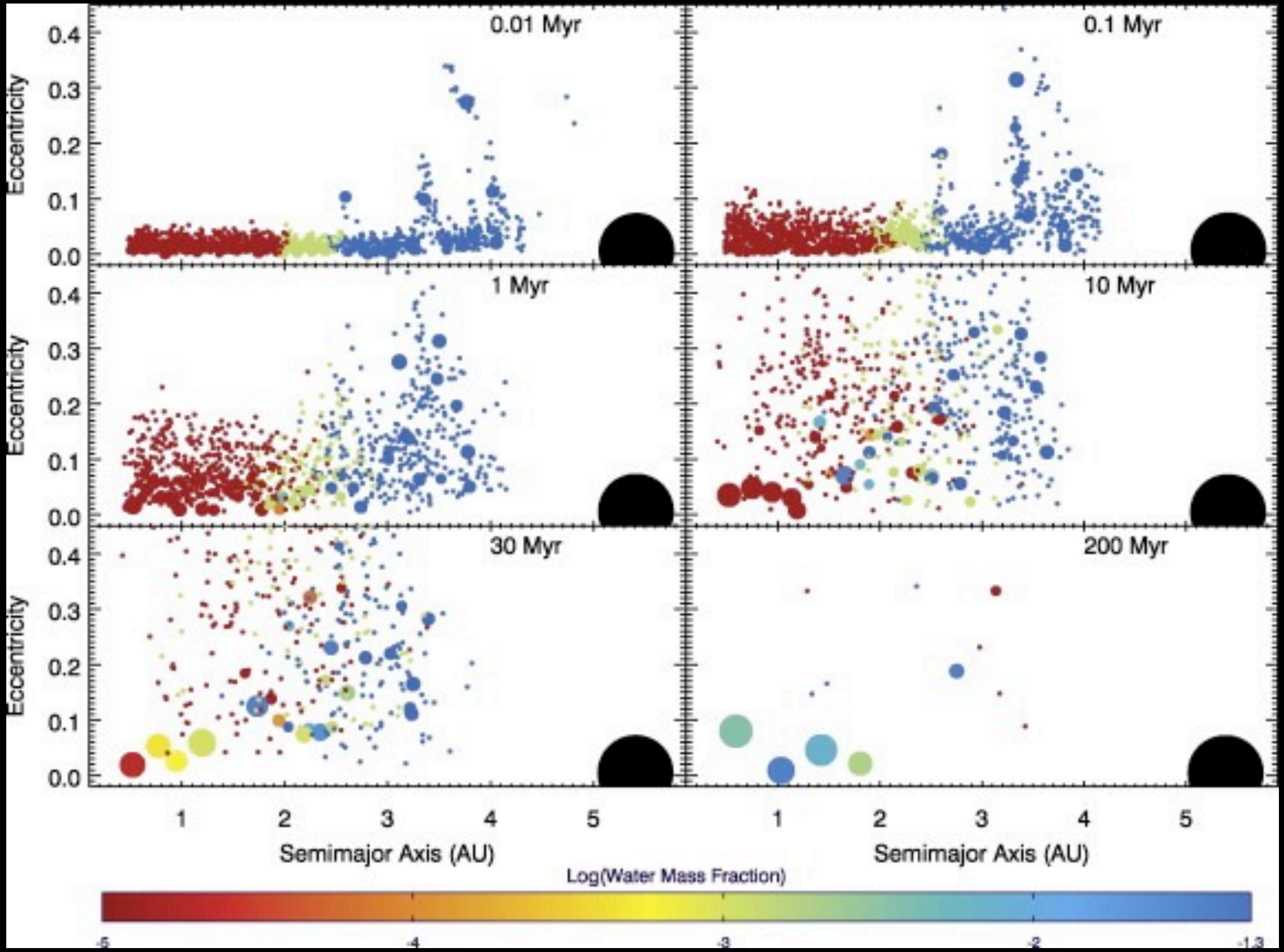
Neptune's original satellite system would have been destroyed by mutual collisions when Triton induced chaotic perturbations in their orbits. *Nereid* was almost ejected from the system, but not quite.

The giant planets acquired their atmospheres during their formation. The much smaller terrestrial planets, however, couldn't hold on to much gas during their formation, and what atmosphere they had was probably lost during the major bombardment.

As the impact rate dropped and the planets started to cool, atmospheres accumulated around Venus, Earth and Mars, from volcanic outgassing and comet impacts.

Santa Maria Volcano, Guatamela

Here is a numerical model of the accumulation of the terrestrial planets. As the protoplanets perturb each others orbits and collide, they also mix up, so that planetary embryos which were born far from the Sun can end up in the inner solar system. This is probably where the water in the inner planets came from.



Six snapshots in time for a computer simulation of terrestrial planet formation by Raymond et al (2009). The size of each body is proportional to its mass, while the colour corresponds to the water content by mass, going from red (dry) to blue (5% water). The large black circle represents Jupiter.

Meanwhile, the outer parts of the proto-stellar disk never coalesce into planets. Outside the orbits of the planets, the Sun is left with a disk of icy bodies beyond Neptune.

One problem is that it is very hard to account for Uranus and Neptune. Neither planet would have had enough time to grow as big as they did in the thin outer regions of the Solar System: they do not accrete planetesimals fast enough to grow.

We will be discussing planets in other solar systems next week; but their discovery quickly led to a radical idea: planets might not stay put where they were formed. In other words, planets might *migrate*.

Planetary migration can happen in a number of ways. In the early Solar System, it mostly took place due to gravitational interactions between planets and the disk of planetesimals. The combined interactions can slowly change the size and shape of the planet orbits, as the icy bodies are slingshotted from one planet to the next.

When researchers incorporated this suggestion into their models, several long-standing problems could be explained.

The *Nice Model* suggests that giant planets migrated from an initial compact configuration, much closer to the Sun than their present positions. Comets were slung from one planet to the next, which gradually caused Uranus, Neptune, Saturn and the belt to migrate outwards. In other words, Uranus and Neptune formed much closer in, where material was more abundant, and migrated outwards due to interactions with Jupiter and Saturn.

The following is a simulation of such a process. The cores of the four giants formed at similar distances from the Sun, about 15–20 AU. Beyond them was a large, dense disk of planetesimals.

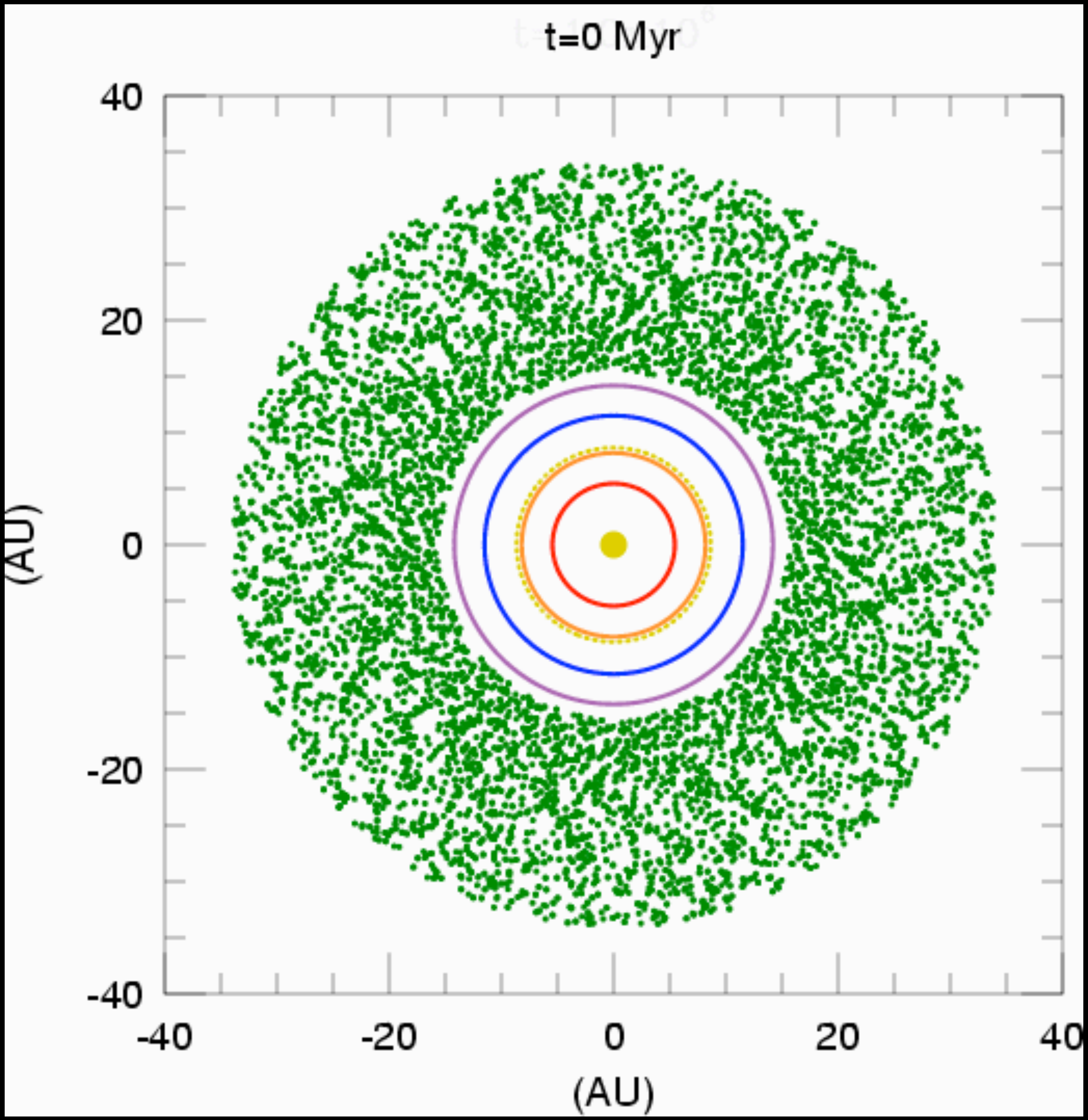
The orbits of the giant planets slowly expand, until after about 700 My, Saturn comes into 1:2 resonance with Jupiter. This makes the orbits of Uranus and Neptune unstable, and their orbits scatter into the disk. This sends a large amount of material into the inner Solar System, producing the late heavy bombardment of the Earth and Moon, and possibly contributes to the atmospheres of the terrestrial planets.

Jupiter

Saturn

Uranus

Neptune



A bit more slowly:

Jupiter

Saturn

Uranus

Neptune

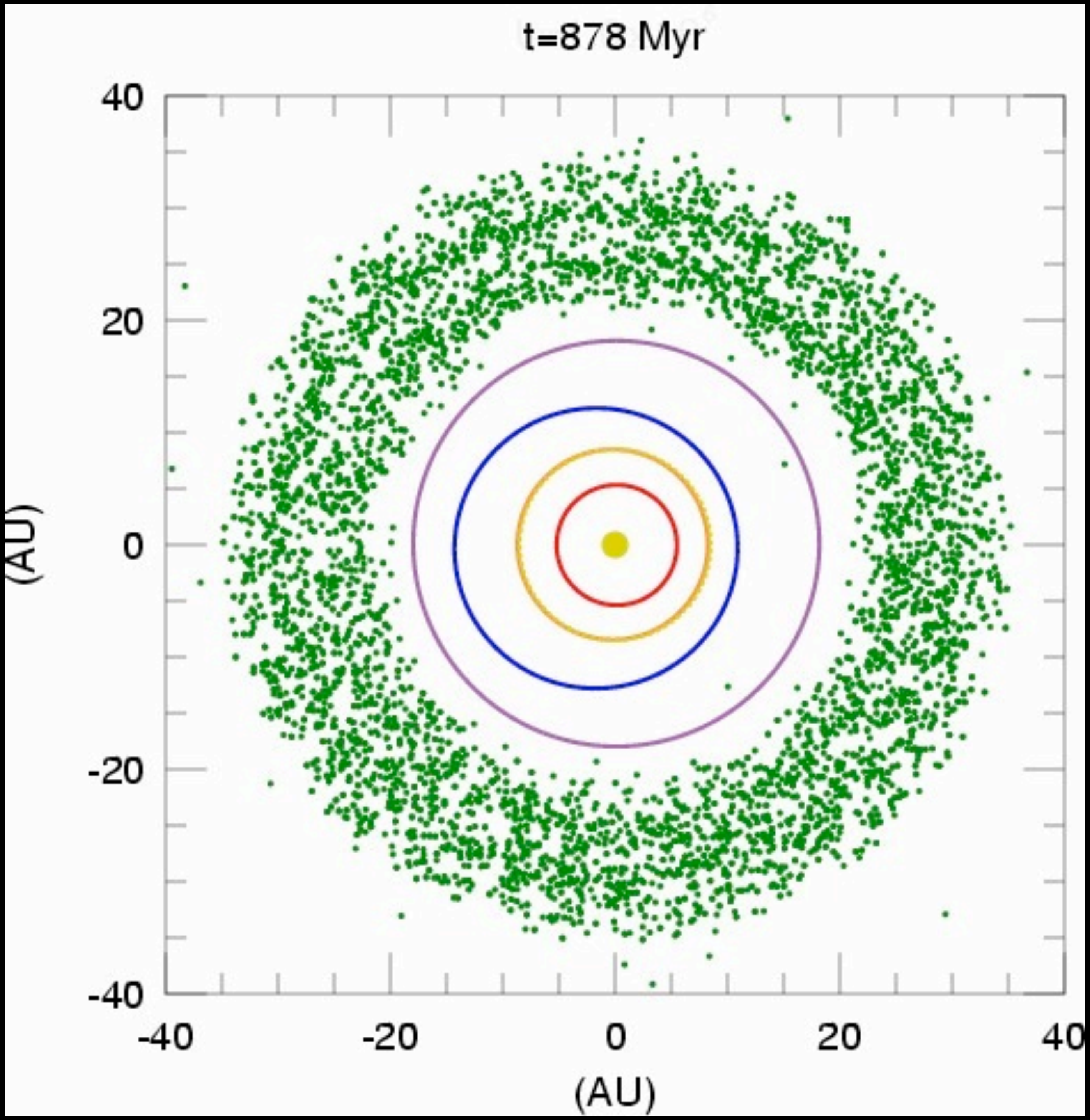
A bit more slowly:

Jupiter

Saturn

Uranus

Neptune



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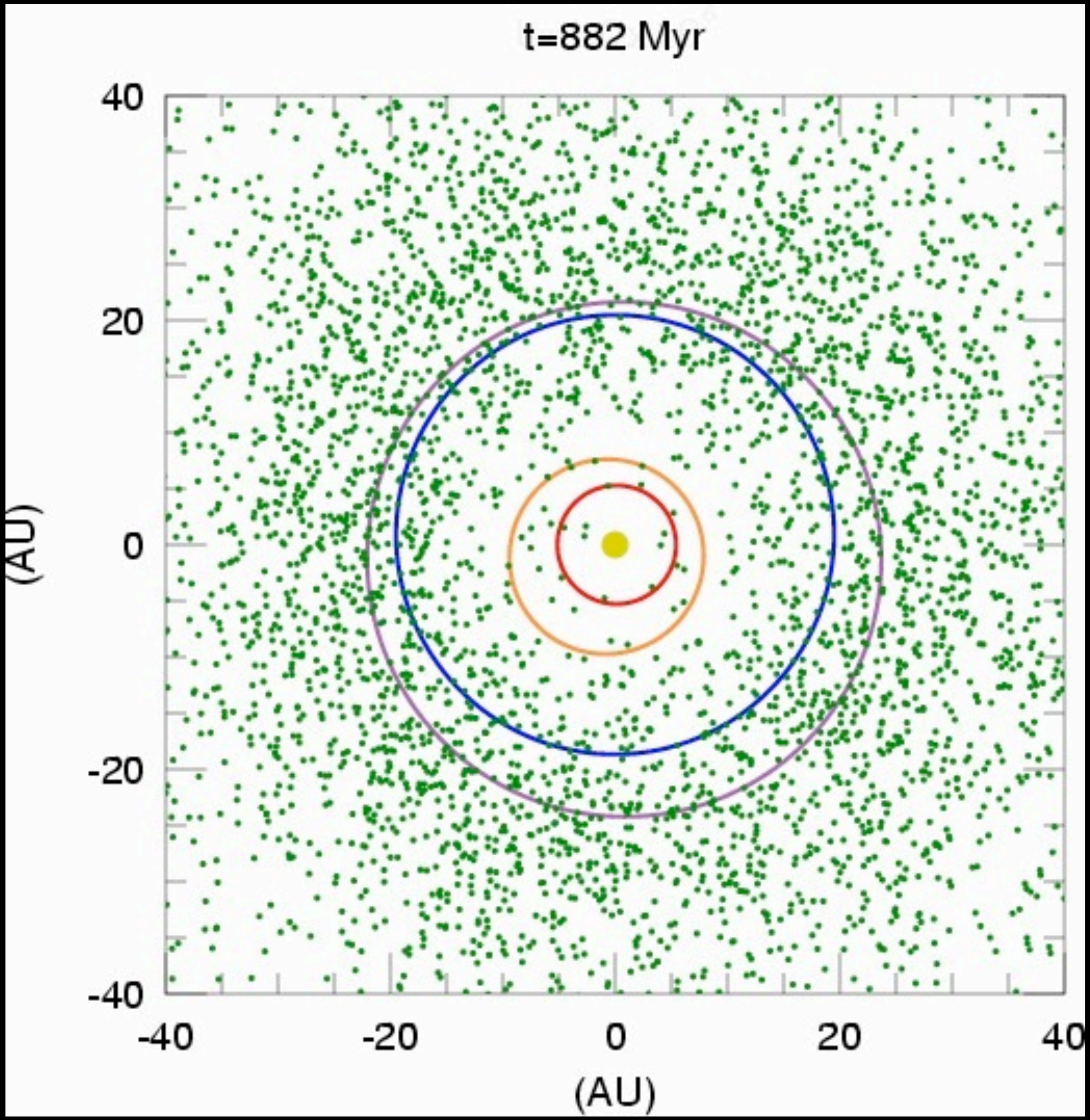

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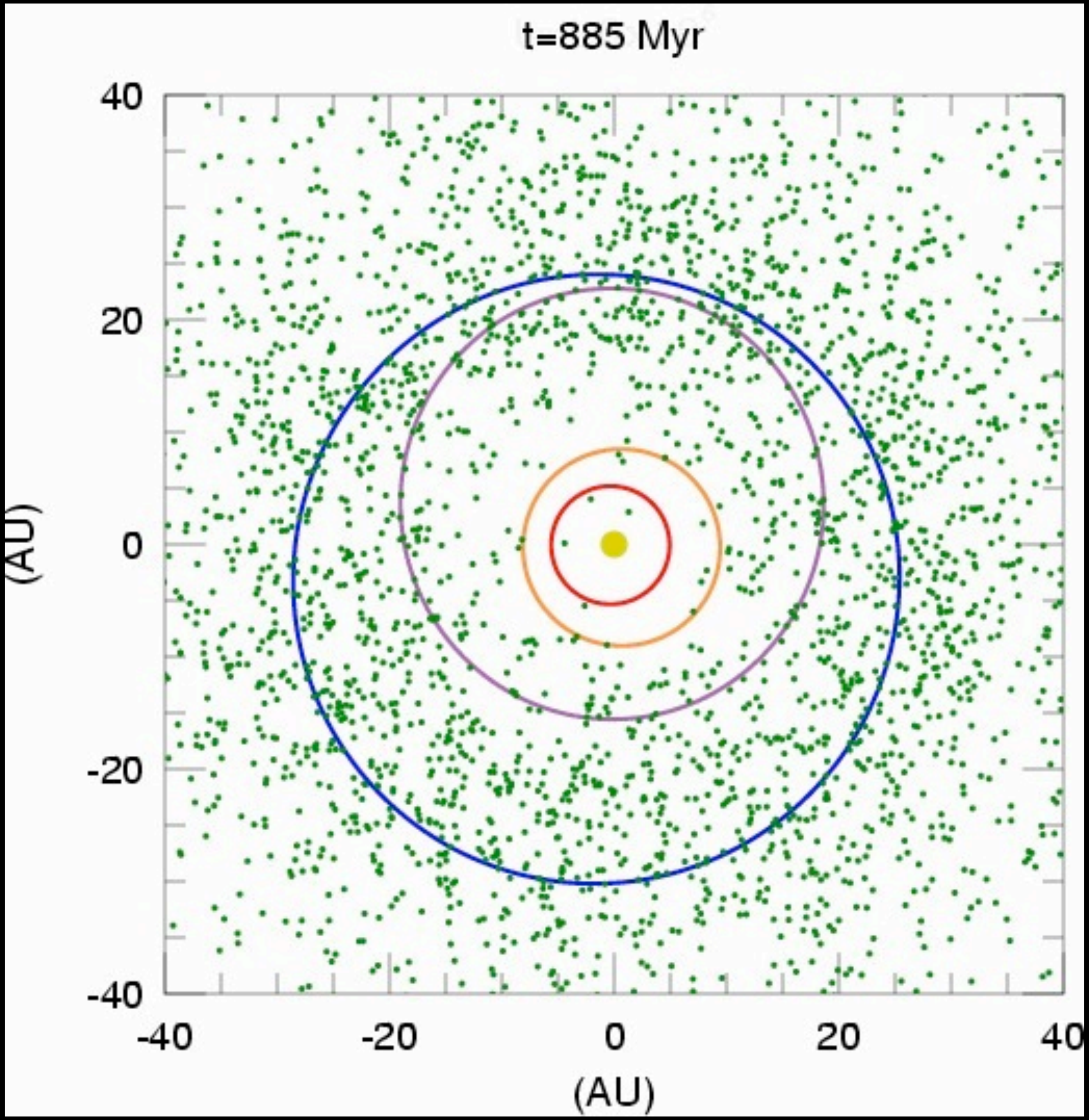

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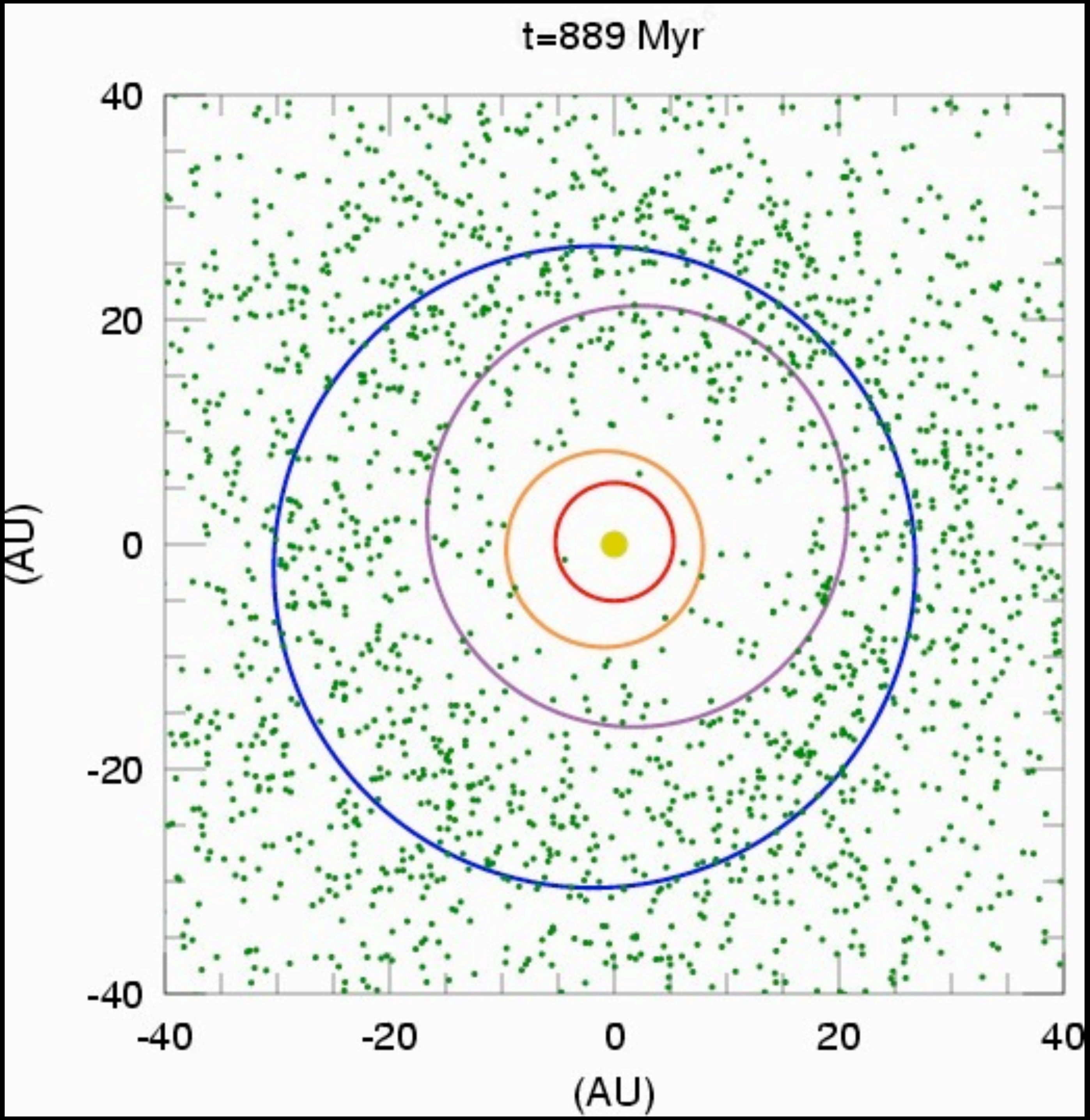

A bit more slowly:

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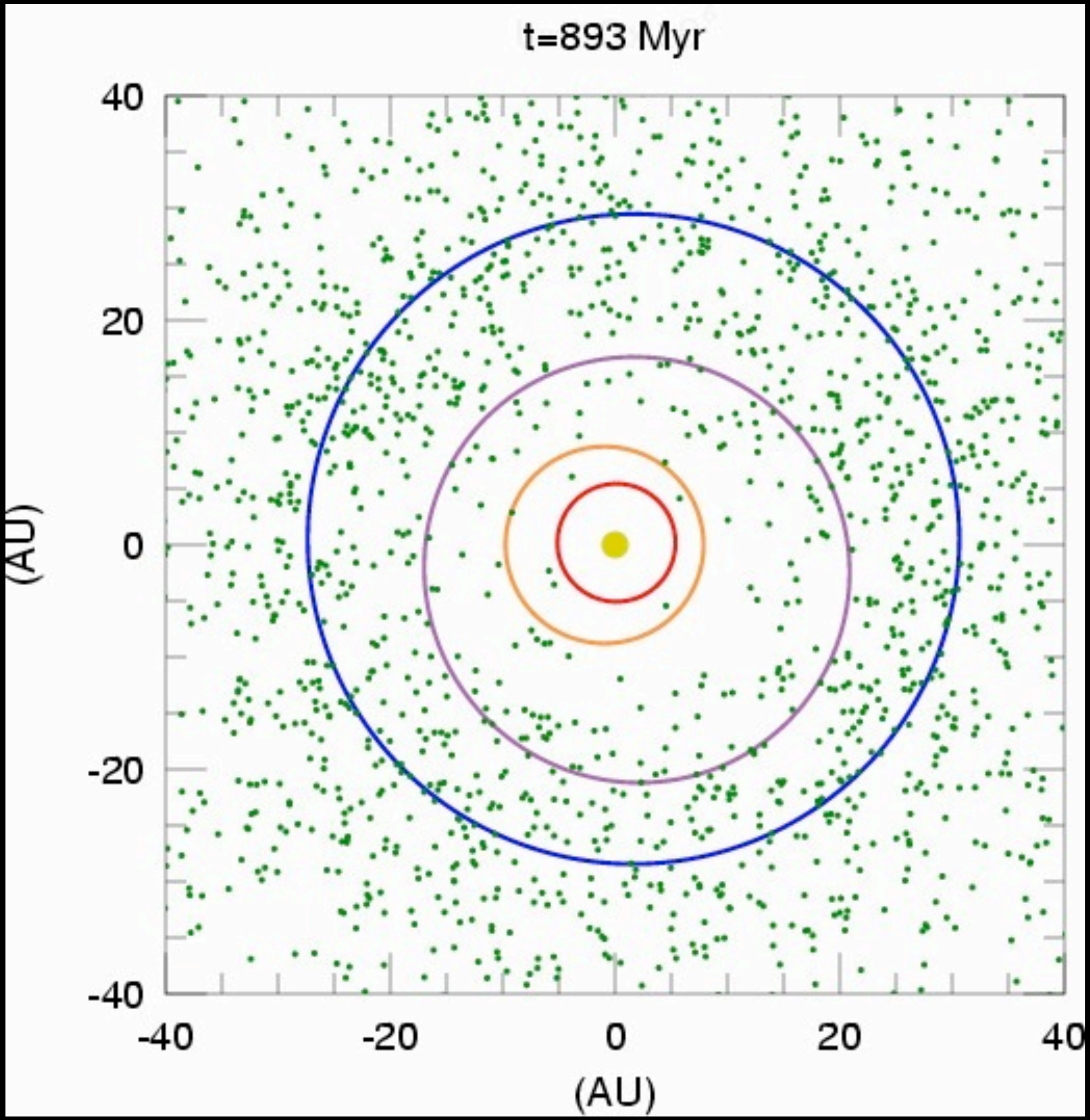

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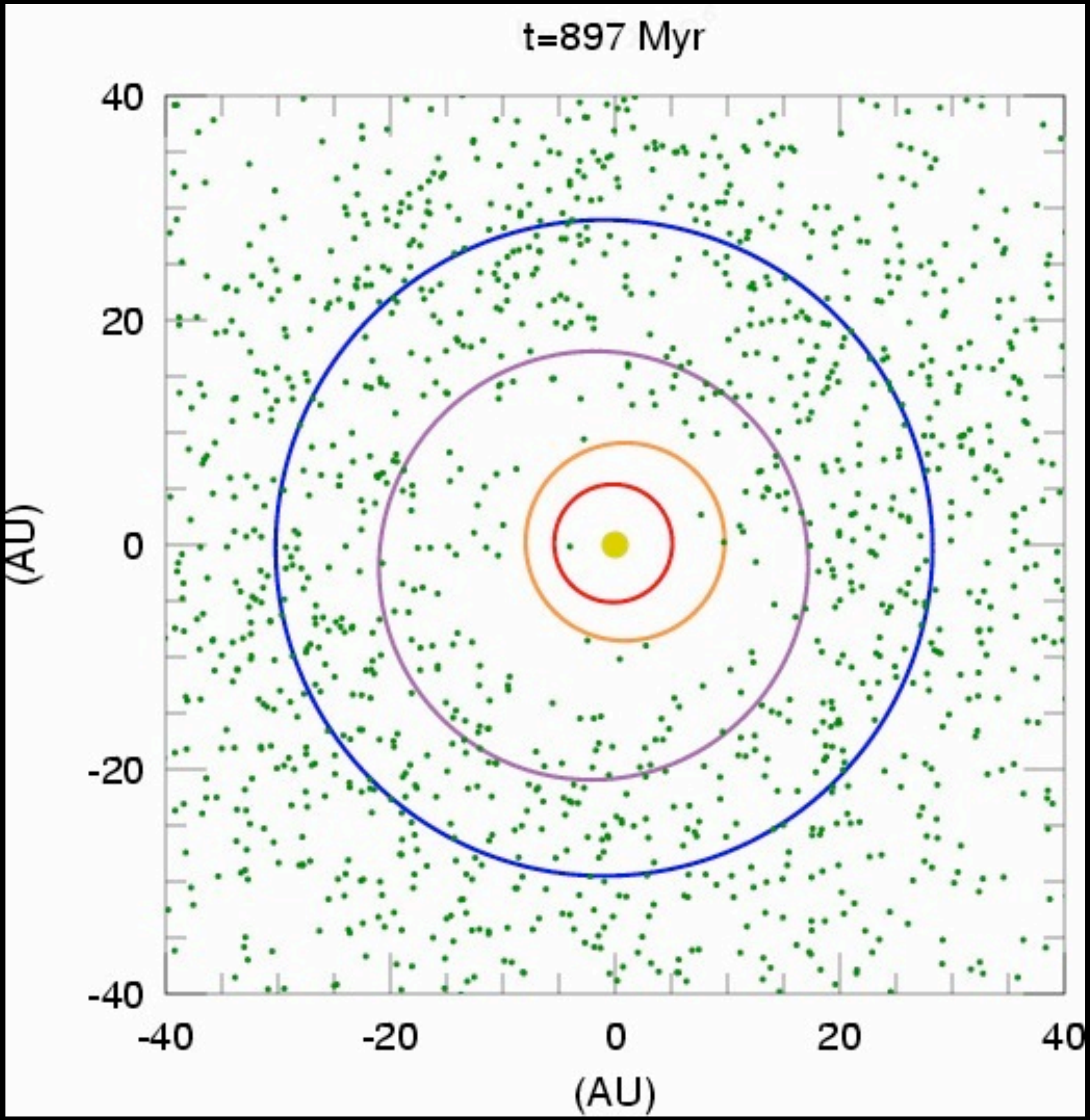

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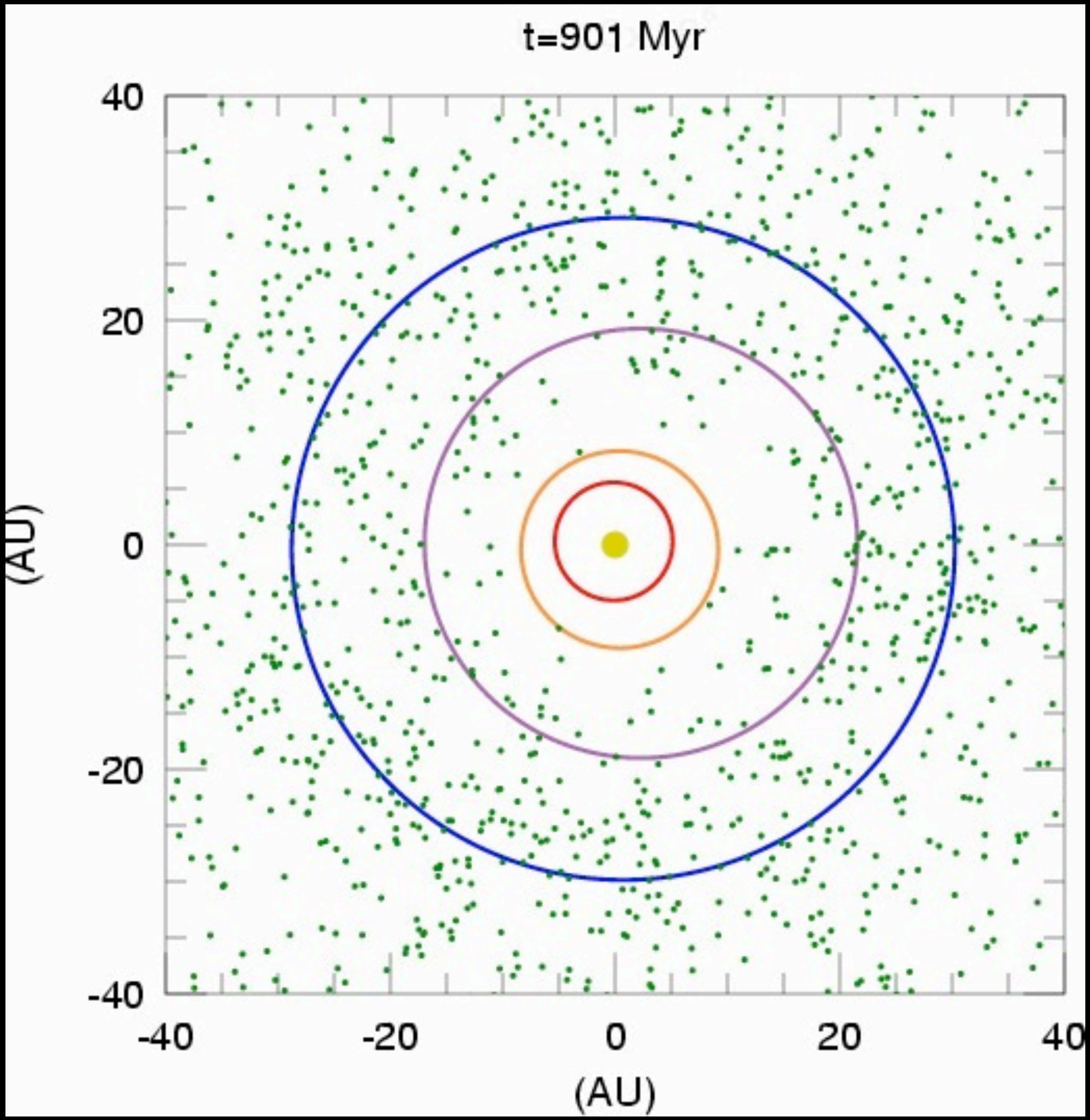

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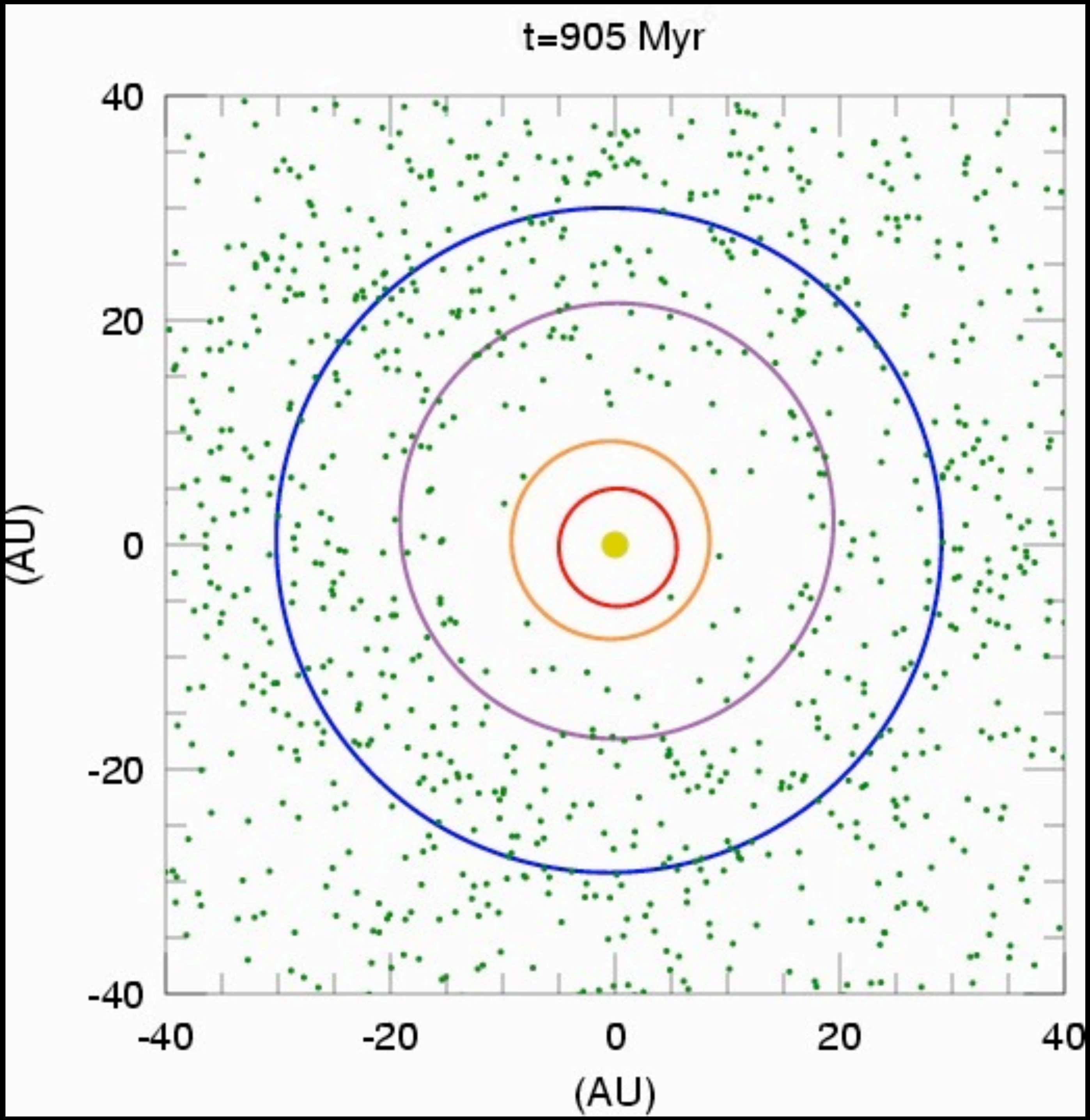

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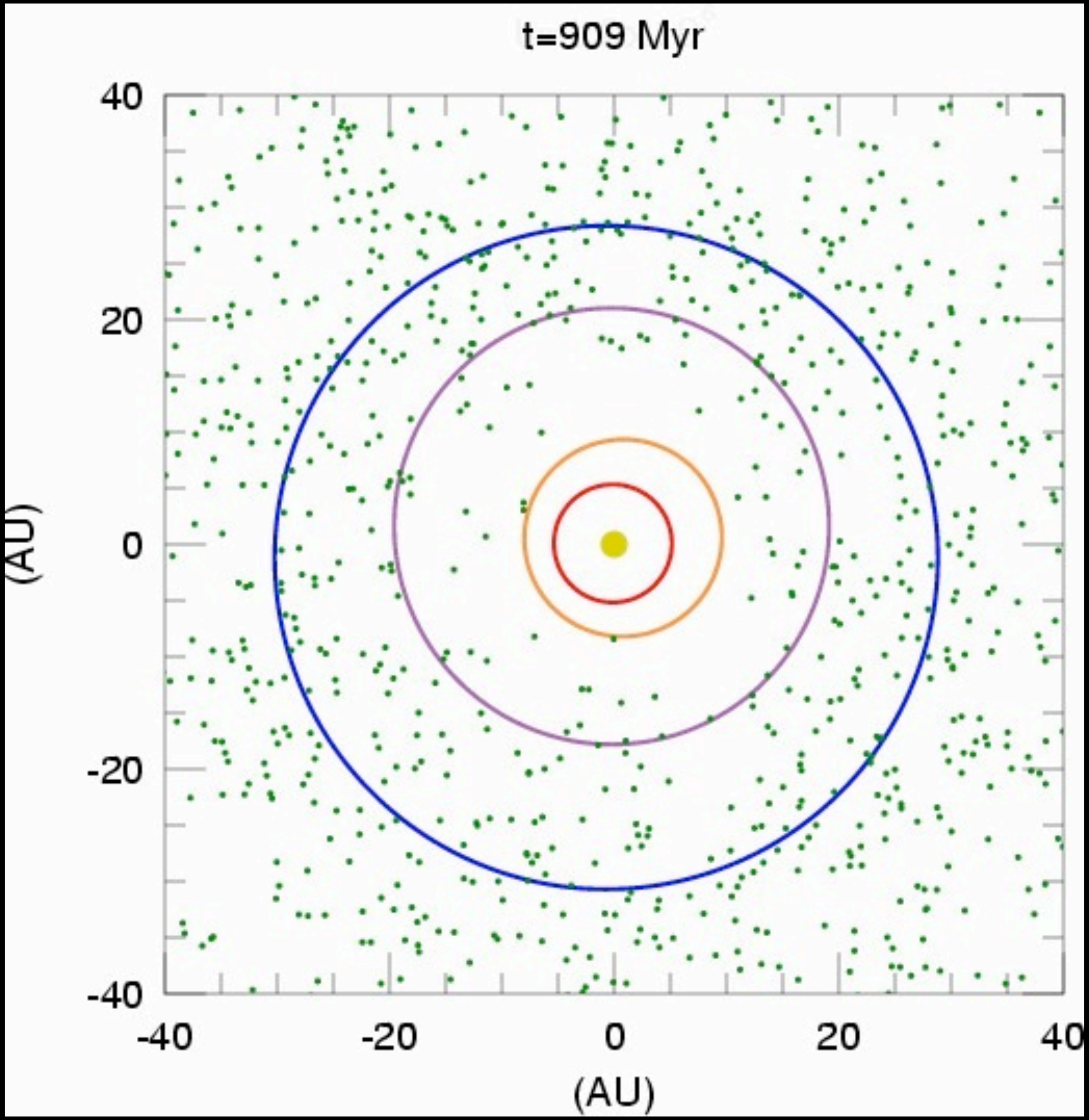
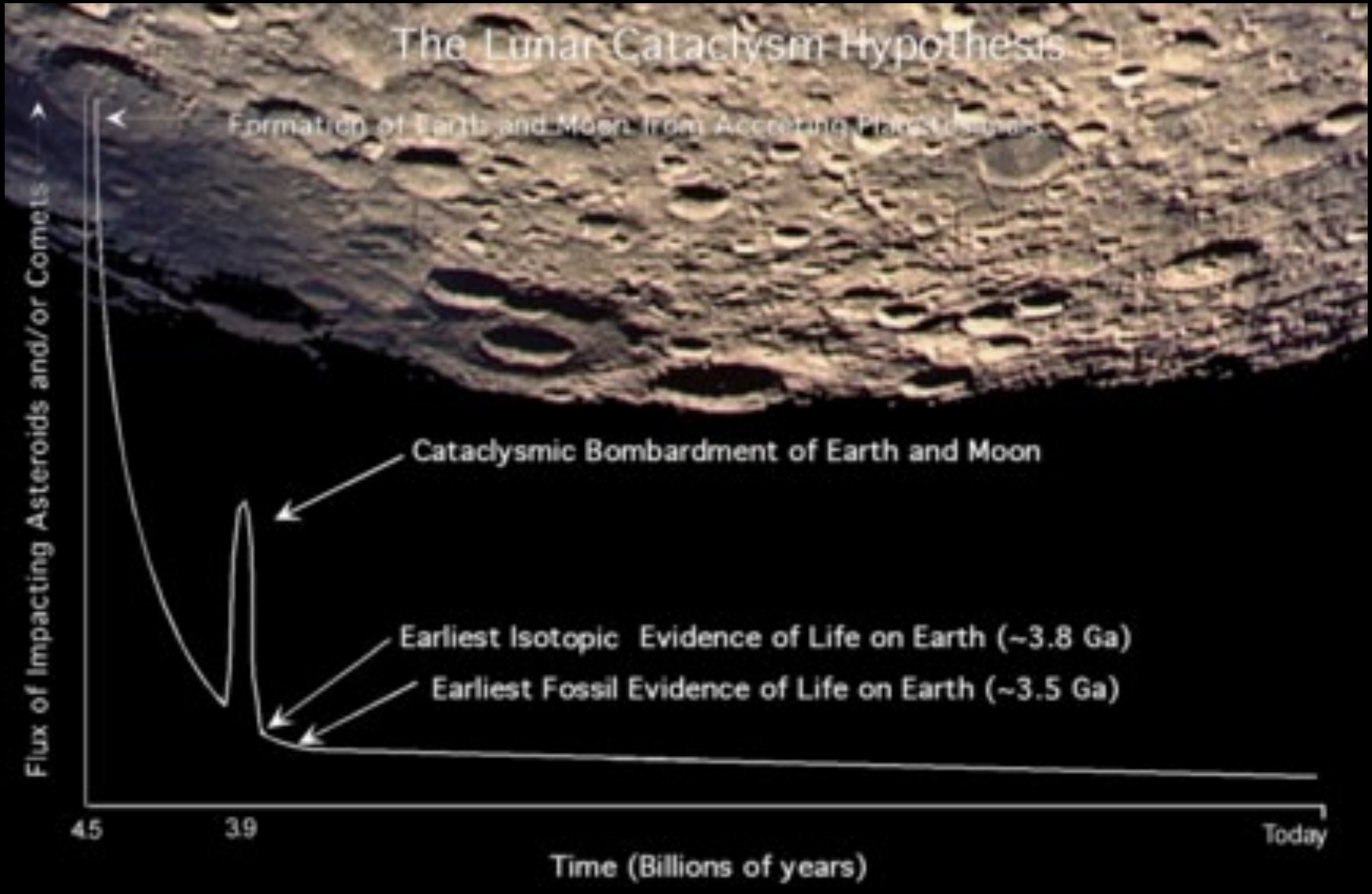
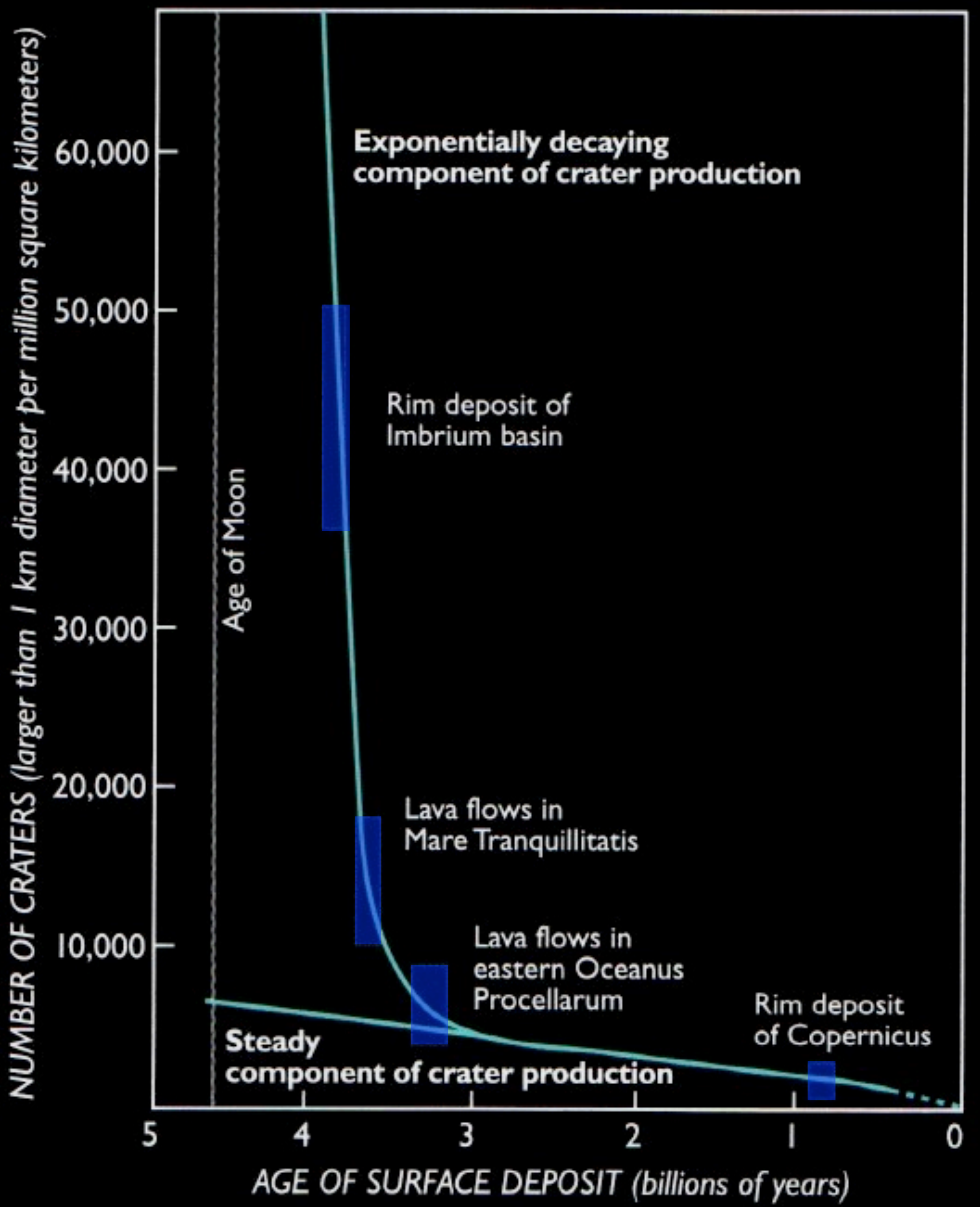
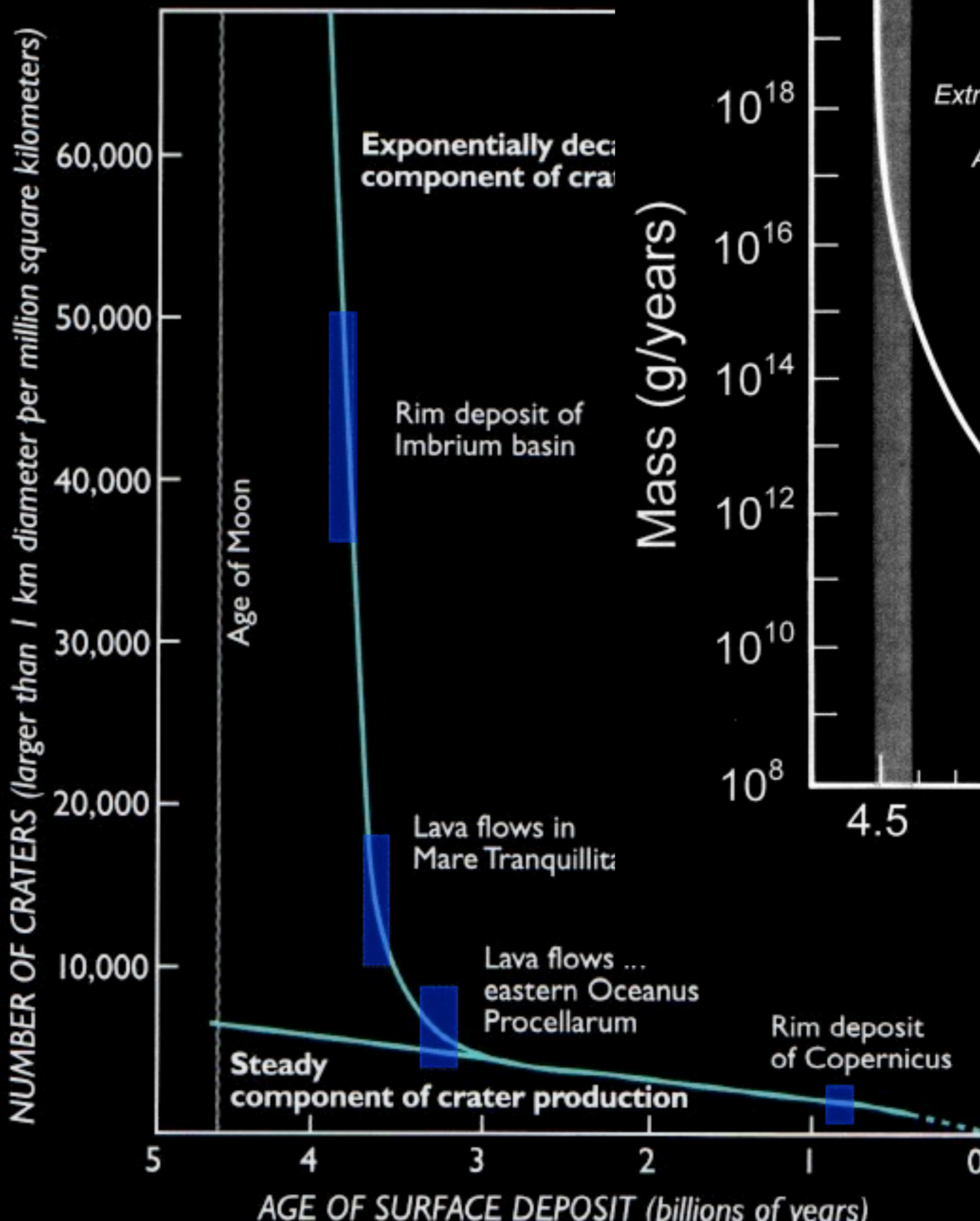


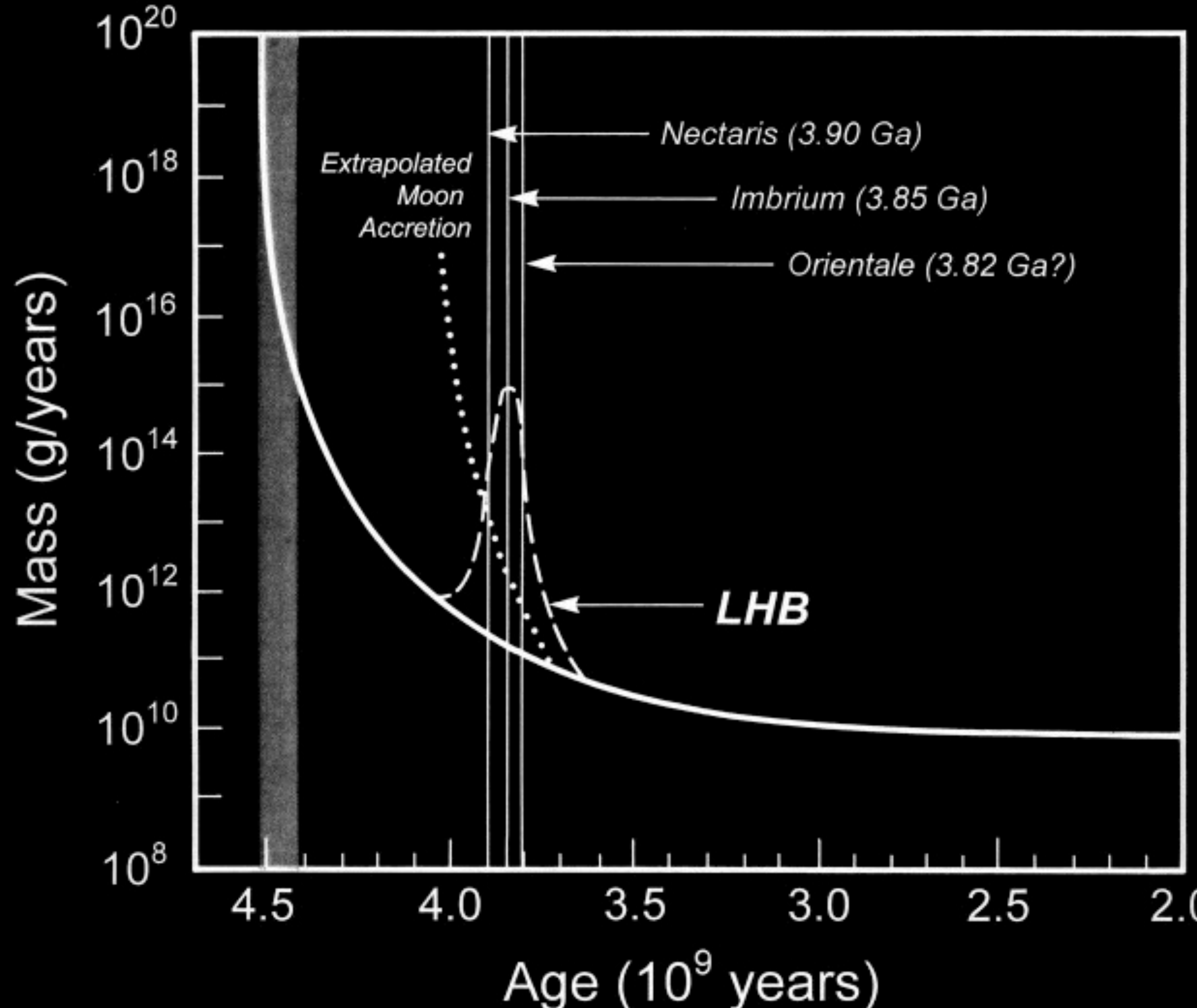
There is evidence that the Earth and the Moon underwent a brief but cataclysmic episode of bombardment about 3.9 billion years ago: the *late heavy bombardment*. These were the impacts which produced the great basins on the Moon, and may also be related to the emergence of life on Earth.





Dating of rocks from Apollo landing sites compared with crater densities show that the rapid cratering rate during the late heavy bombardment fell off dramatically between 3.9 and 3.3 billion years ago, giving way to a slower, steady rate of crater production. (From Shoemaker 1999).





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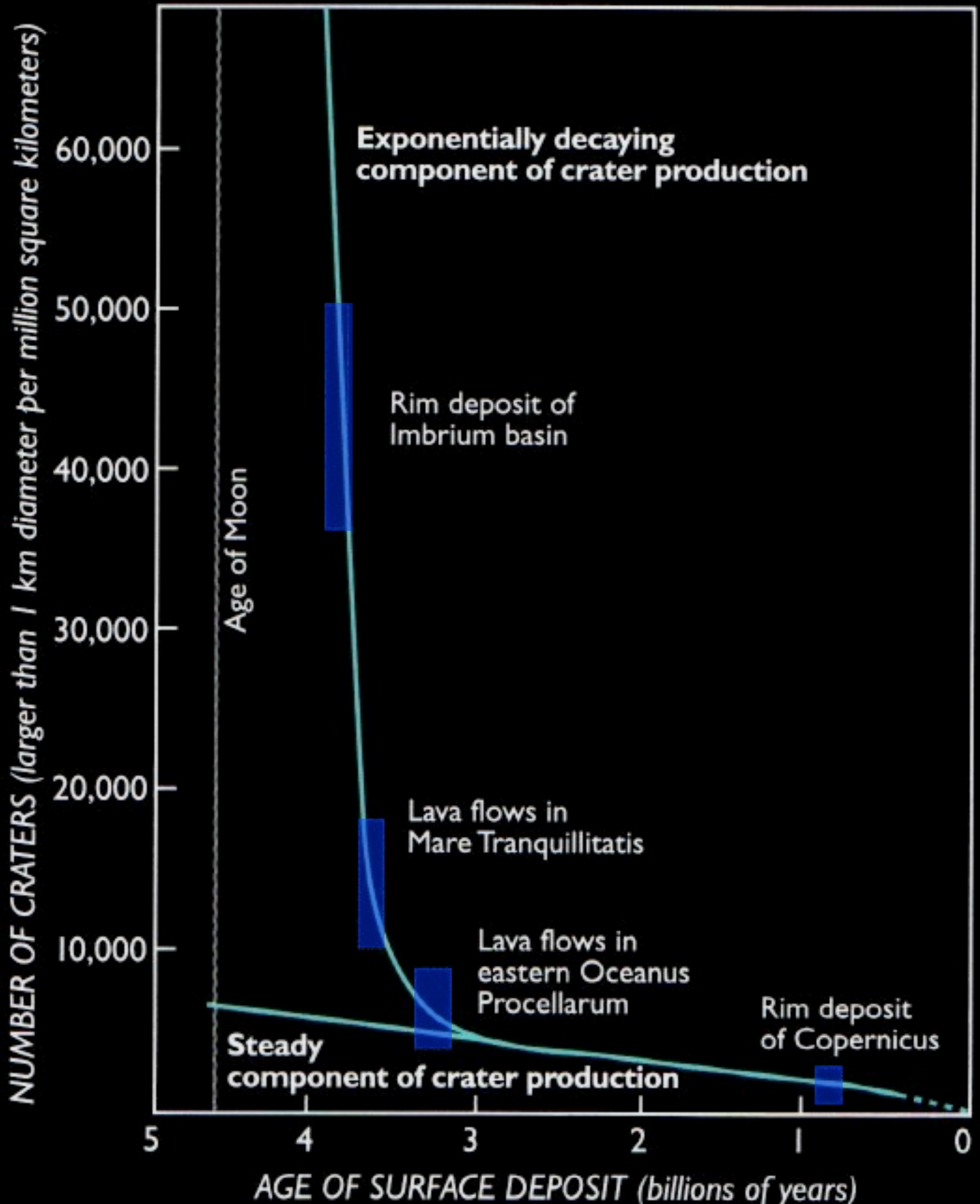
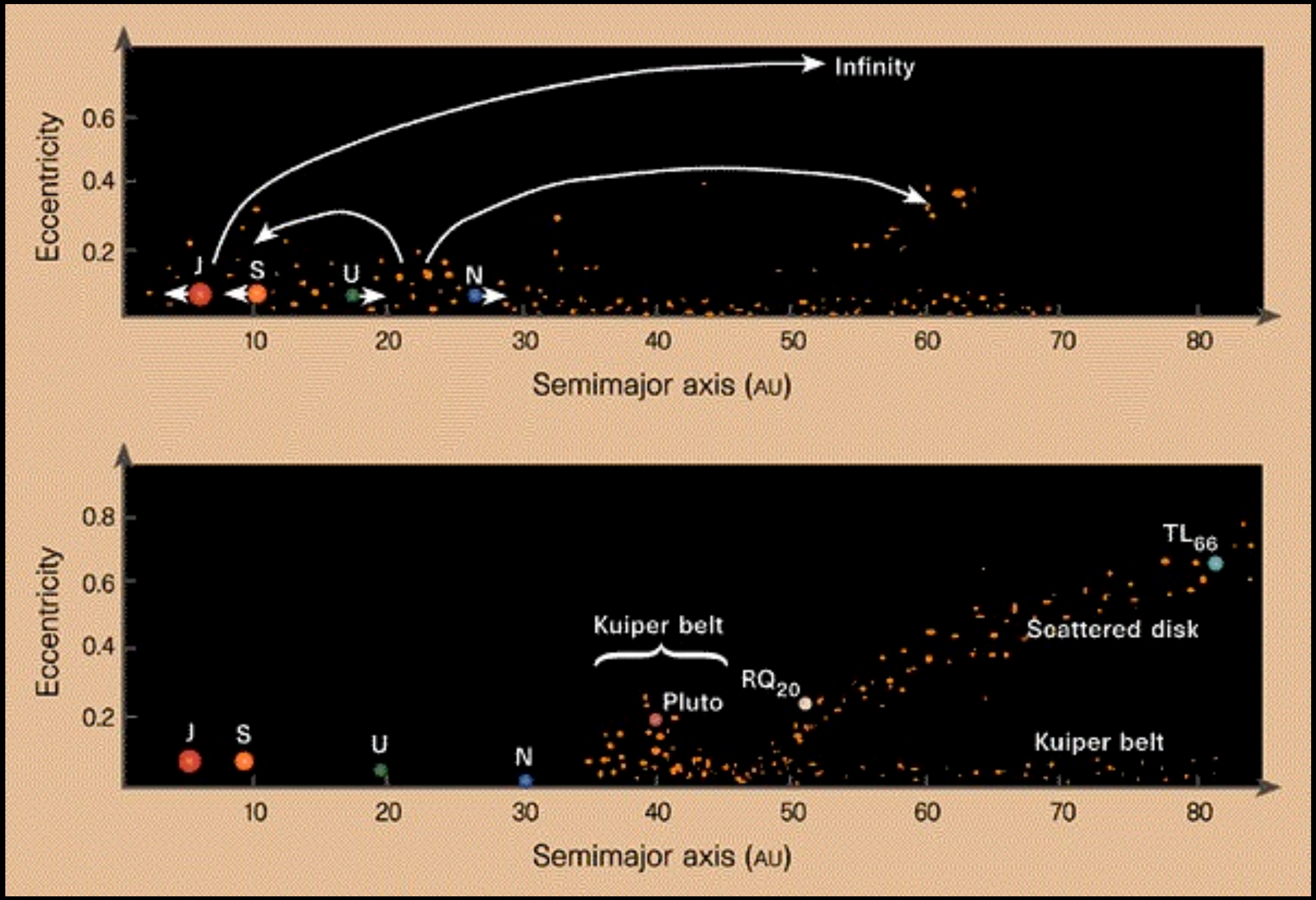


Dating of rocks from Apollo landing sites compared with crater densities show that the rapid cratering rate during the late heavy bombardment fell off dramatically between 3.9 and 3.3 billion years ago, giving way to a slower, steady rate of crater production. (From Shoemaker 1999).

During the late heavy bombardment, the whole inner Solar System was pummeled. The Earth would have been hit by an impact similar to the one that killed the dinosaurs every twenty years.

The *scattered disk* of the Kuiper Belt consists of object deflected out of Uranus' and Neptune's formation zones. Other bodies were scattered inwards towards Jupiter and Saturn, which, being more massive, can scatter them right out of the Solar System.



The *Grand Tack* theory suggests that Jupiter might have already migrated more than once by this time. The theory suggests that Jupiter formed first and migrated inwards through the protoplanetary disk, until a resonance with Saturn reversed it, causing it to move back across the asteroid belt to its current location.

This migration would have wreaked havoc with this region of the disk, depleting both Mars and the asteroid belt of material. This would explain both Mars' warm size and the great variety of icy and rocky objects in the asteroid belt.

So we believe we have a general understanding of the formation of the Solar System. The planetesimal hypothesis explains the composition of the planets, their relative sizes, the shapes and directions of their orbits, and their satellite systems.

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How does this theory stack up when confronted with the new evidence reaching us about extra-solar planets?

So we believe we have a general understanding of the formation of the Solar System. The planetesimal hypothesis explains the composition of the planets, their relative sizes, the shapes and directions of their orbits, and their satellite systems.

How does this theory stack up when confronted with the new evidence reaching us about extra-solar planets?

Not well....

Further reading

Most books about planets, including the ones I've recommended to you so far, discuss the formation of planets in greater or lesser detail.

- I found one lovely book I haven't told you about yet: **"The Story of the Solar System"** by Mark Garlick (Cambridge, 2002) is by that rarest of creatures, an artist who is also a scientist. The book itself is at a reasonably elementary level, describing the birth, life and death of the Solar System, but the paintings he has done to go with each page are wonderful.
- "**The Big Splat: or How our moon came to be**" by Dana Mackenzie (John Wiley & Sons, 2003) is a very readable book about theories of the origin of the moon, and how we arrived at the current consensus. An extremely enjoyable read.
- There's a terrific new book out called **"From Dust to Life: The origin and evolution of our Solar System"** by John Chambers and Jacqueline Mitton (Princeton UP, 2014). Really up-to-date description of what we know, though it starts all the way back with ancient cosmology, which I didn't really think was necessary.
- There's a beautiful illustrated timeline of the Solar System at The Lunar and Planetary Institute's **"Evolution of Our Solar System: A Journey through Time"** at http://www.lpi.usra.edu/education/timeline/

- The Planetary Science Institute has a nice page about the origin of the Moon at http://www.psi.edu/epo/moon/moon.html
- The "Grand Tack" theory is described at https://solarsystem.nasa.gov/scitech/display.cfm?ST_ID=2429
- There's a nice article about the possible connection between the formation of Uranus and Neptune and the bombardment of the Moon at PSRD Discoveries: **"Uranus, Neptune and the Mountains of the Moon"**, http://www.psrd.hawaii.edu/Aug01/bombardment.html, and another one called **"Gas Giants and Lunar Bombardment"** at http://www.psrd.hawaii.edu/Aug06/cataclysmDynamics.html
- There was a very interesting article in the September 1999 issue of Scientific American called "**Migrating Planets**" by Renu Malhotra, on the idea that the outer planets may not have formed where we see them now. This will be important when we talk about extrasolar planets next week.

Sources for images used:

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- Scattering of Uranus and Neptune: from "The Early Dynamical Evolution of the Outer Solar System: A Fairy Tale" by Hal Levinson, http://www.boulder.swri.edu/~hal/talks.html
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- Scattered disk: from Stewart 1997, "The Solar System: The frontier beyond Neptune", Nature 387 658.
- Extrasolar image: artist's impression of the Tau Gruis system, by David A. Hardy http://www.hardyart.demon.co.uk/html/p-extra1.html