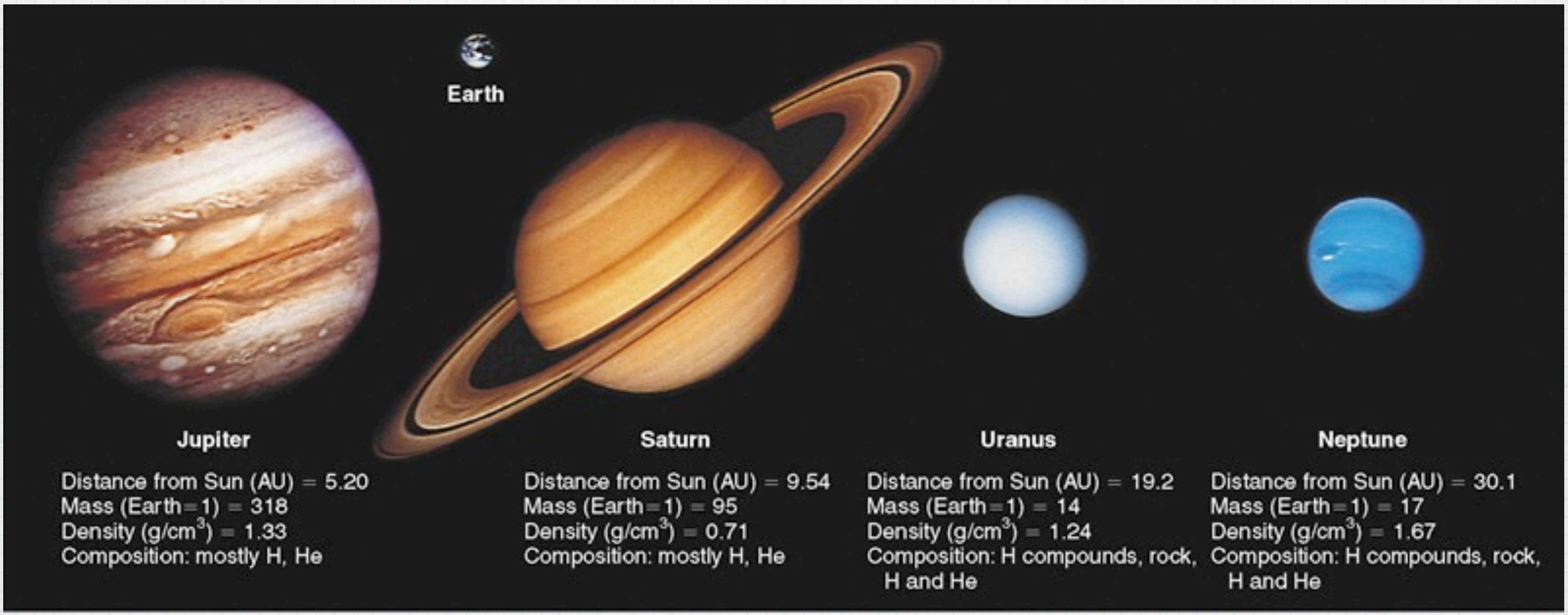
Jovian Planet Systems

Chapter 8

Very Different!

* Jovian planets
  * are larger
  * have different compositions (than the terrestrial ones)
  * have rings
  * have lots of moons

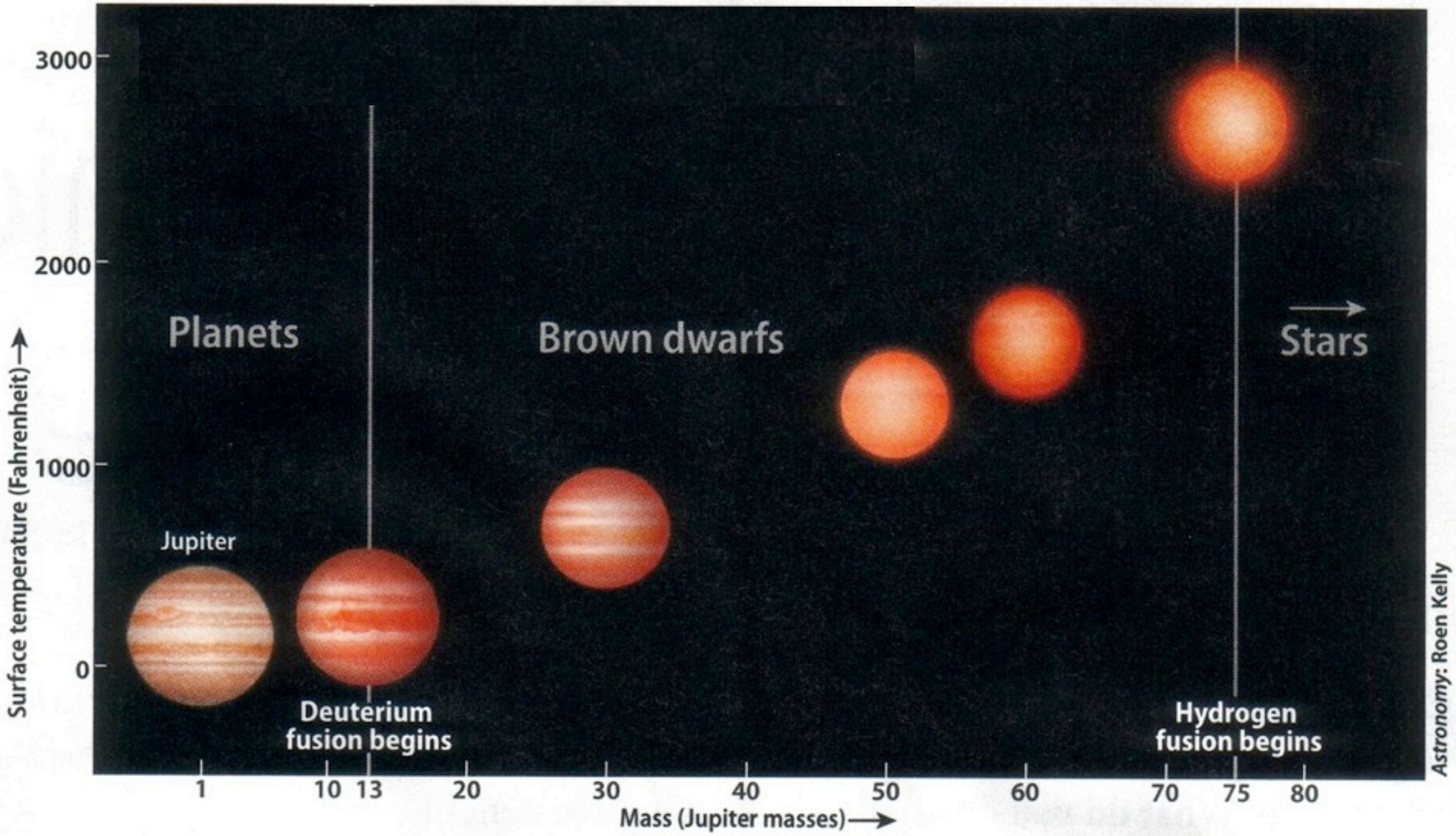
Jovian Comparisons



Jupiter

* Large for a planet, too small for a star
* With 80 times more mass, it would have been a red dwarf star (a cool star)
* With 13 to 75 M_J times more mass, it would have been a brown dwarf (a failed star)
* Jupiter has insufficient pressures in the core to reach the necessary temperatures to jumpstart fusion

From a planet to a star



The distinction between gas giant planets and brown dwarfs ("failed stars") is a vague one. To separate these objects into different groups, astronomers focus on their temperatures and masses.

Jovian Formation

* The Jovian planets formed beyond the frost line (where hydrogen compounds could freeze into ices)
* Lots more hydrogen compounds than rocks and metals existed throughout the Solar System but they remained gaseous within the frost line

Jovian Formation...

* The initial planetesimals formed from rocks & metals (like the terrestrial planets) and hydrogen compounds
* These 4 planetesimals are thought to have grown to roughly the same size, (about 10 times the mass of the Earth)

Jovian Formation...

* They then acquired large amounts of hydrogen and helium gas - which they captured with their bigger gravitational attraction
* Jupiter and Saturn captured a lot more hydrogen and helium than Uranus and Neptune

Differences between the Jovian Planets

* Jupiter and Saturn captured a lot of hydrogen and helium: these gasses now make up the vast majority of their masses
* Their ice-rich composition (H-compounds) are
  * 3% of Jupiter's mass, and
  * 10% of Saturn's

Differences...

* Uranus and Neptune pulled in much less hydrogen and helium
* Uranus' hydrogen and helium content is about a third of the planet's mass
* Same for Neptune but its higher density suggests a slightly more massive initial planetesimal

Distance from the Sun

* The density of solid particles diminishes away from the Sun (bigger volume)

* Thus more distant planetesimals took longer to assemble and hence acquire enough mass to gravitationally attract hydrogen and helium

Distance from the Sun...

* Jupiter was the first Jovian planetesimal to acquire hydrogen and helium,
* followed by Saturn,
* and later by Uranus,
* and then Neptune

Solar Wind Blowing

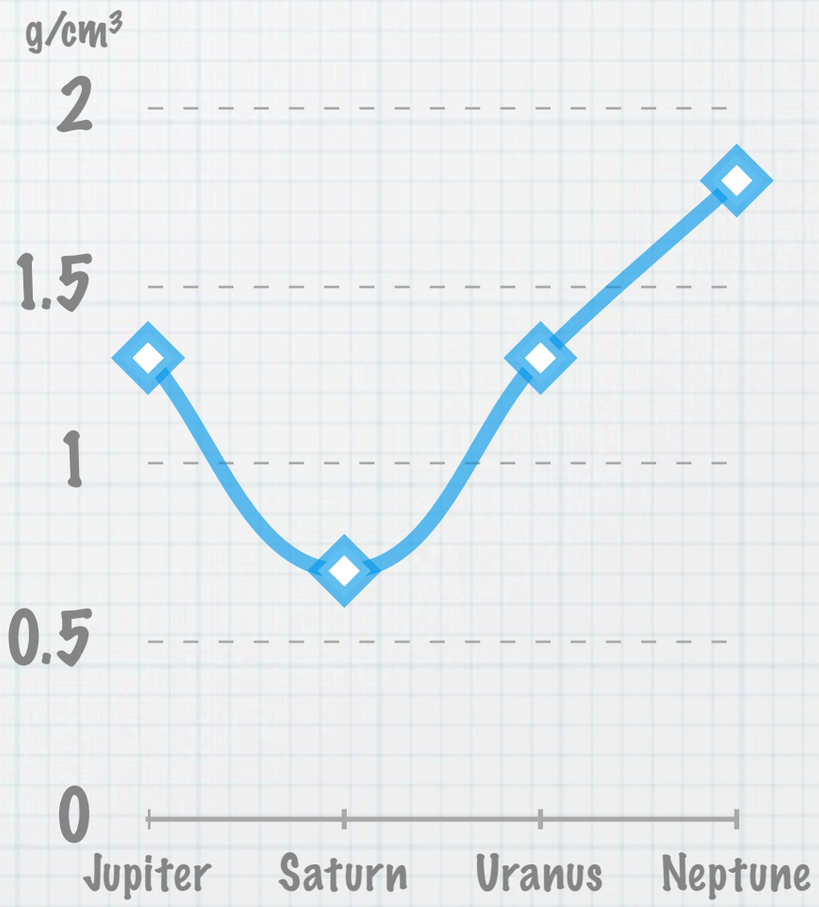
* However when the solar wind blew the hydrogen and helium away from the Solar System, all the Jovian planets stopped acquiring hydrogen and helium at about the same time

* Uranus and Neptune had less time to capture these gasses

➡ That is why they are smaller

Jupiter's Density Abnormality

* Saturn is less dense than Uranus which is less dense than Neptune



* We expect that: Uranus and Neptune captured less hydrogen and helium

* But Jupiter is more dense than Saturn... Why?

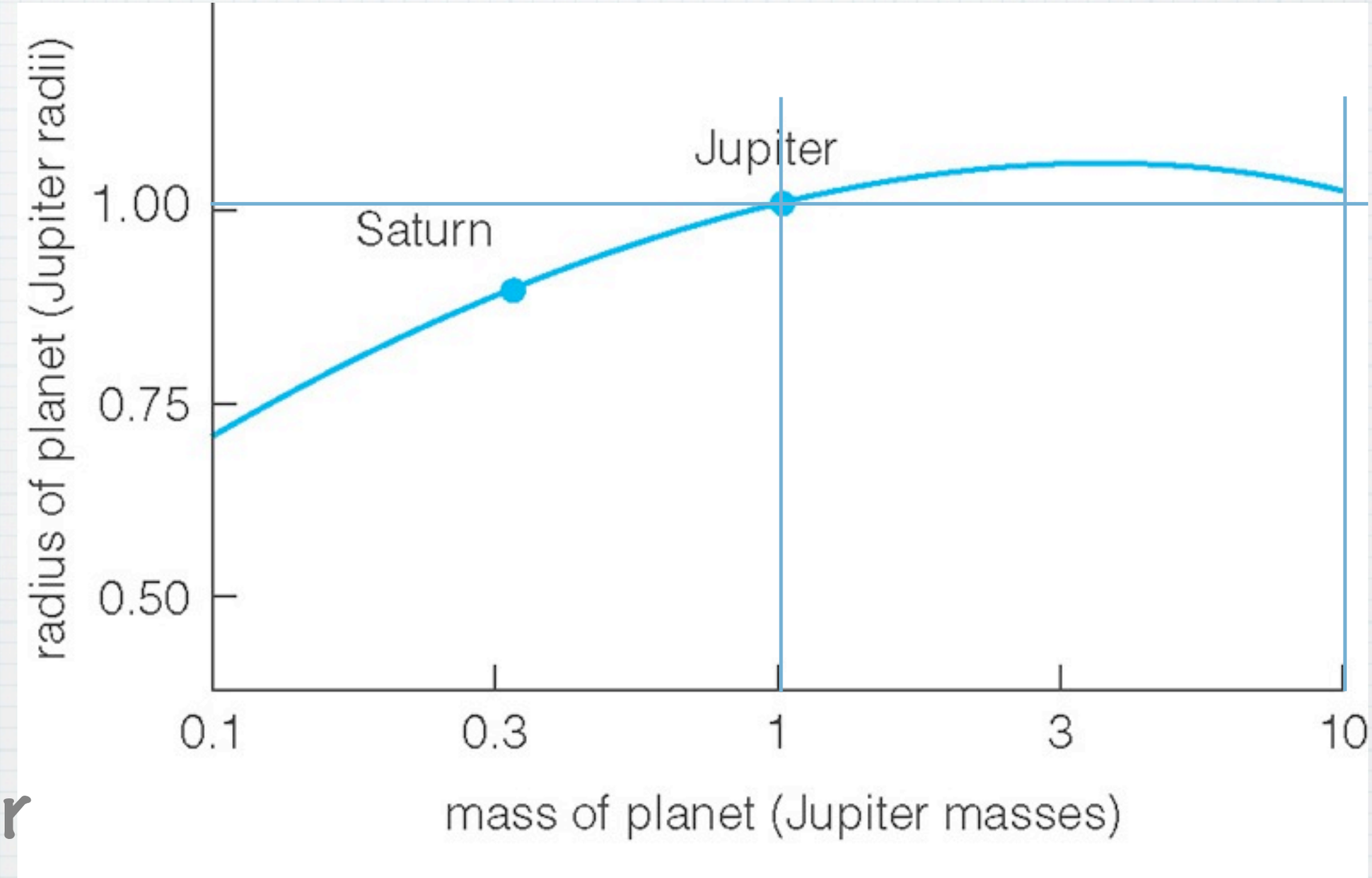
Jupiter's Density Abnormality...

* Density is mass divided by volume
* How does a gas compress?
* It is not a linear relationship

Jupiter has 3 times Saturn's mass but is only 16% larger

Note that if Jupiter was over 10 times its mass, it would pack into a smaller volume

Gaseous planet's mass versus radius



Hydrogen Compressibility

* The reason for this is that

1. a gas does not compress linearly
2. hydrogen will change state with increasing densities

* Hydrogen will go **from gas to liquid to metallic** (note: a metal shares electrons)

Inside Jupiter

* Jupiter does not have a solid surface
* As one goes deeper, it gets hotter and denser (higher pressure)
* Computer models tell us that Jupiter and Saturn have distinct internal layers, mostly made of hydrogen and helium (but for their core)

Inside Jupiter...

* Instead the layers differ in the mix of these gasses
* **Gas state**: the outer layer, goes 10% of the radius down. This can be considered the "**atmosphere**" of the planet
* **Liquid state**: next 10% down. 2000 K temperature and 500,000 times Earth's surface pressure (yet density is less than water, between 0.5 to 1.0 g/cm)

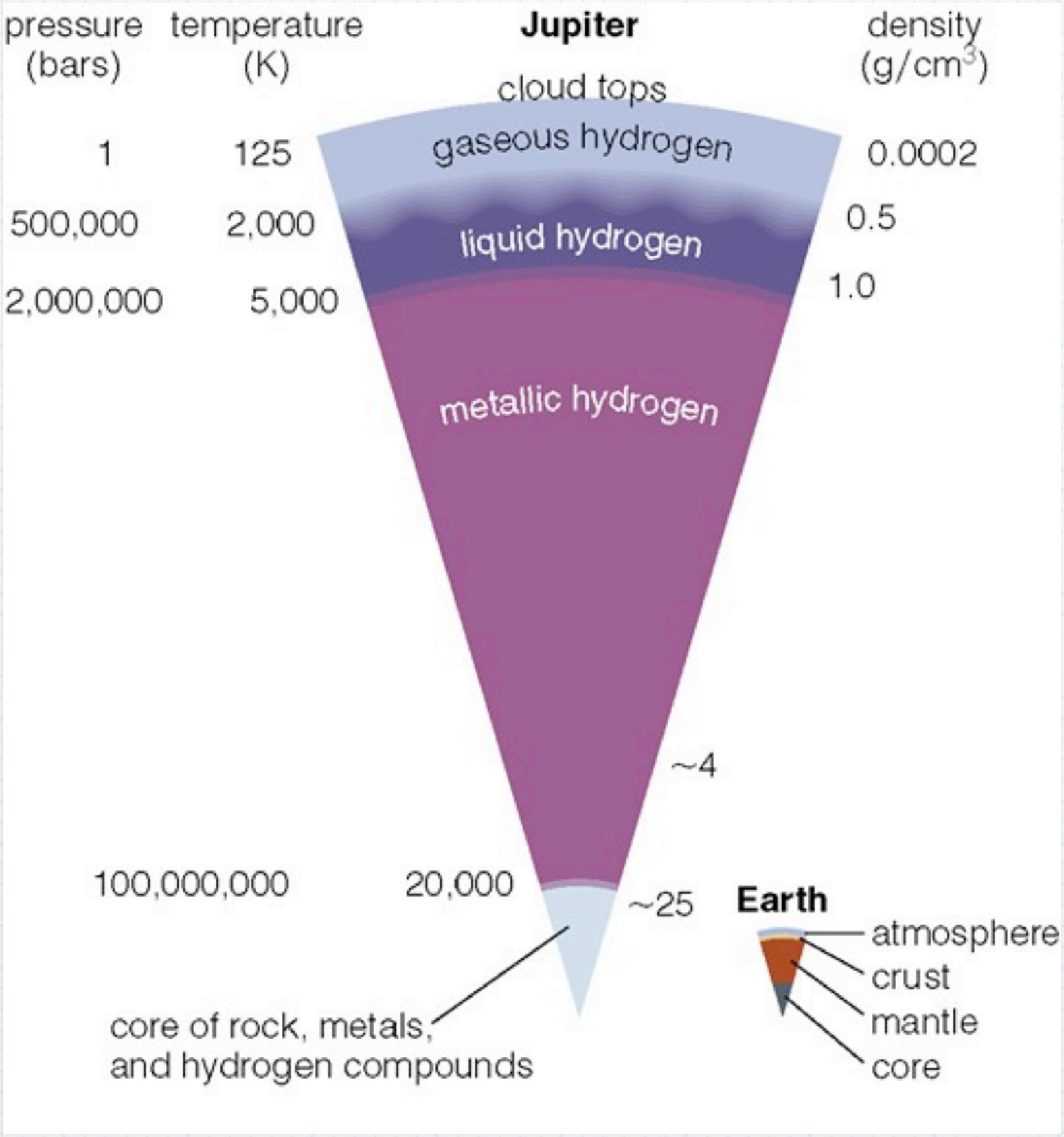
Inside Jupiter...

* Then **metallic hydrogen**
  * temperatures and pressures force hydrogen into a compact metallic form
  * electrons are free to move around

➡ **this layer powers the planet's intense magnetic field**

Inside Jupiter...

* Lastly: the core
* A mix of hydrogen compounds with rocks and metals
* 10 times Earth's mass but in the same volume than the Earth
* At such temperatures and pressures, those are not regular "solids"



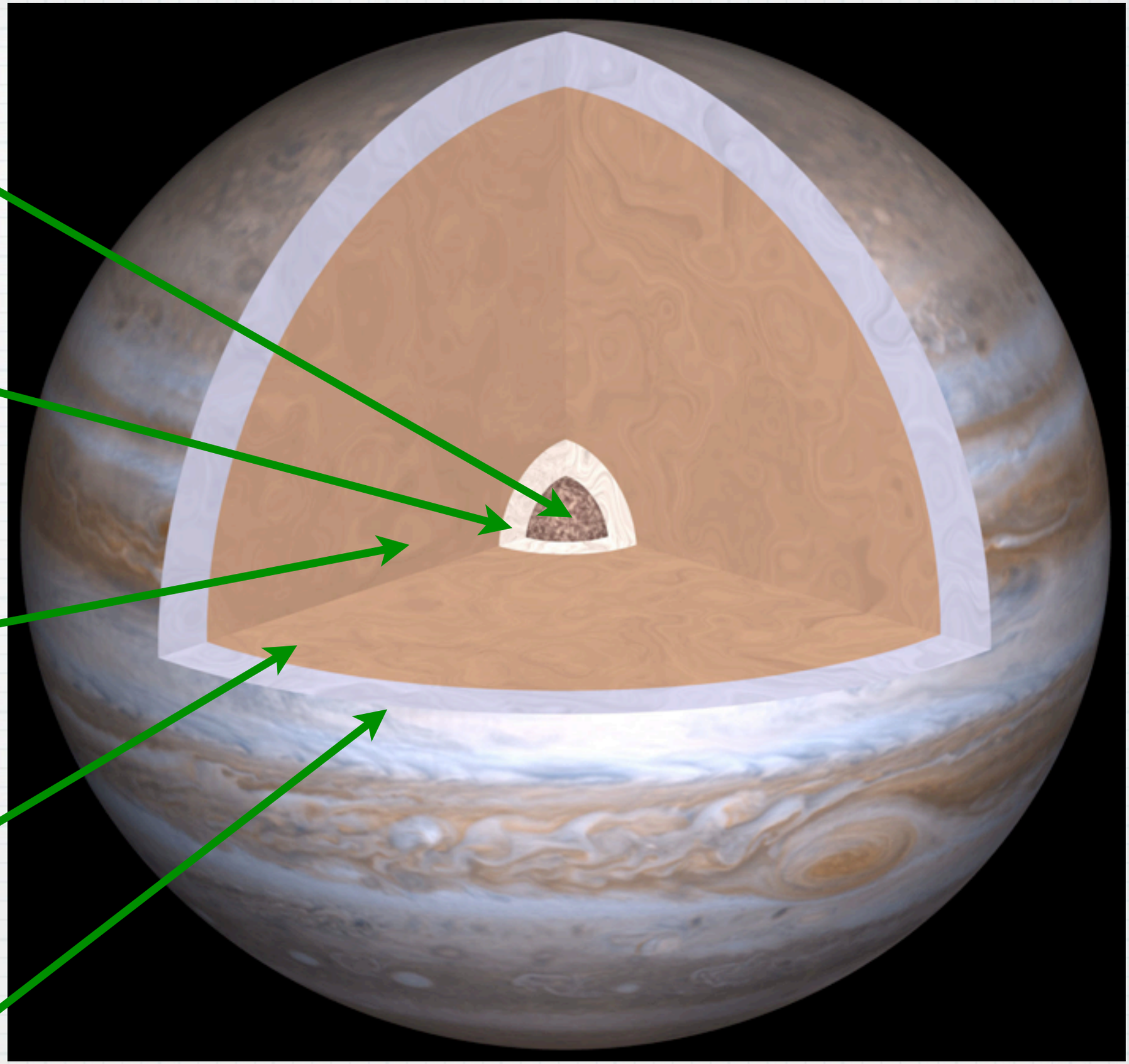
rock/metals compound core

ionized fluid mixture of water, ammonia & methane

fluid metallic hydrogen & atomic helium

fluid molecular hydrogen and atomic helium

hydrogen & helium atmosphere



Jupiter: 71,500 km radius

Comparing Jovian Interiors

* All four Jovian planets have similar sized cores (the original planetesimals...)
* The main differences are the amount of hydrogen and helium they have captured
* Hence we assume Saturn has a similar structure than Jupiter due to its mass

The Interior of Saturn

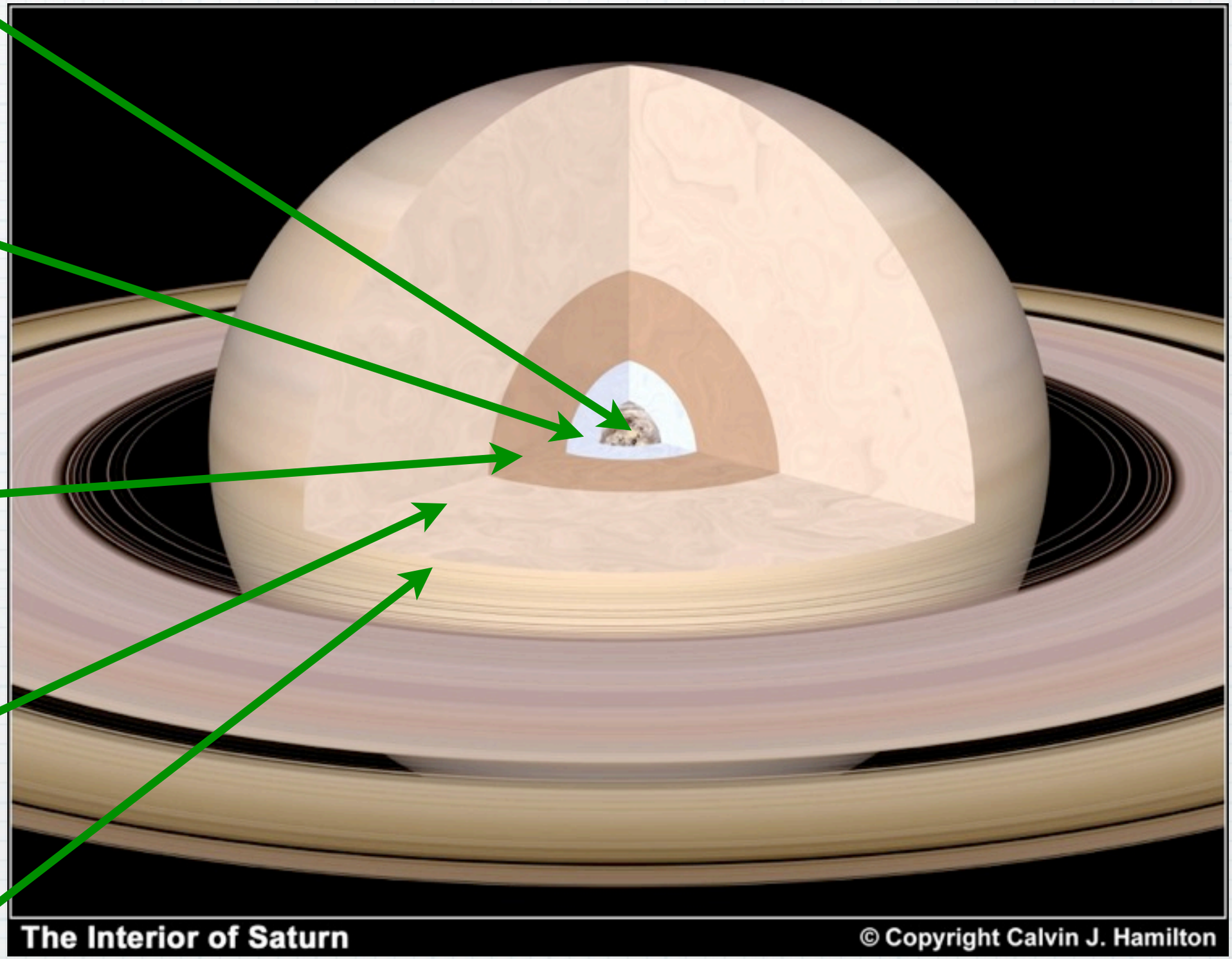
rock/metals
compound
core

ionized fluid
mixture of water,
ammonia &
methane

fluid metallic
hydrogen &
atomic helium

fluid molecular
hydrogen and
atomic helium

hydrogen &
helium
atmosphere



Comparing Jovian Interiors...

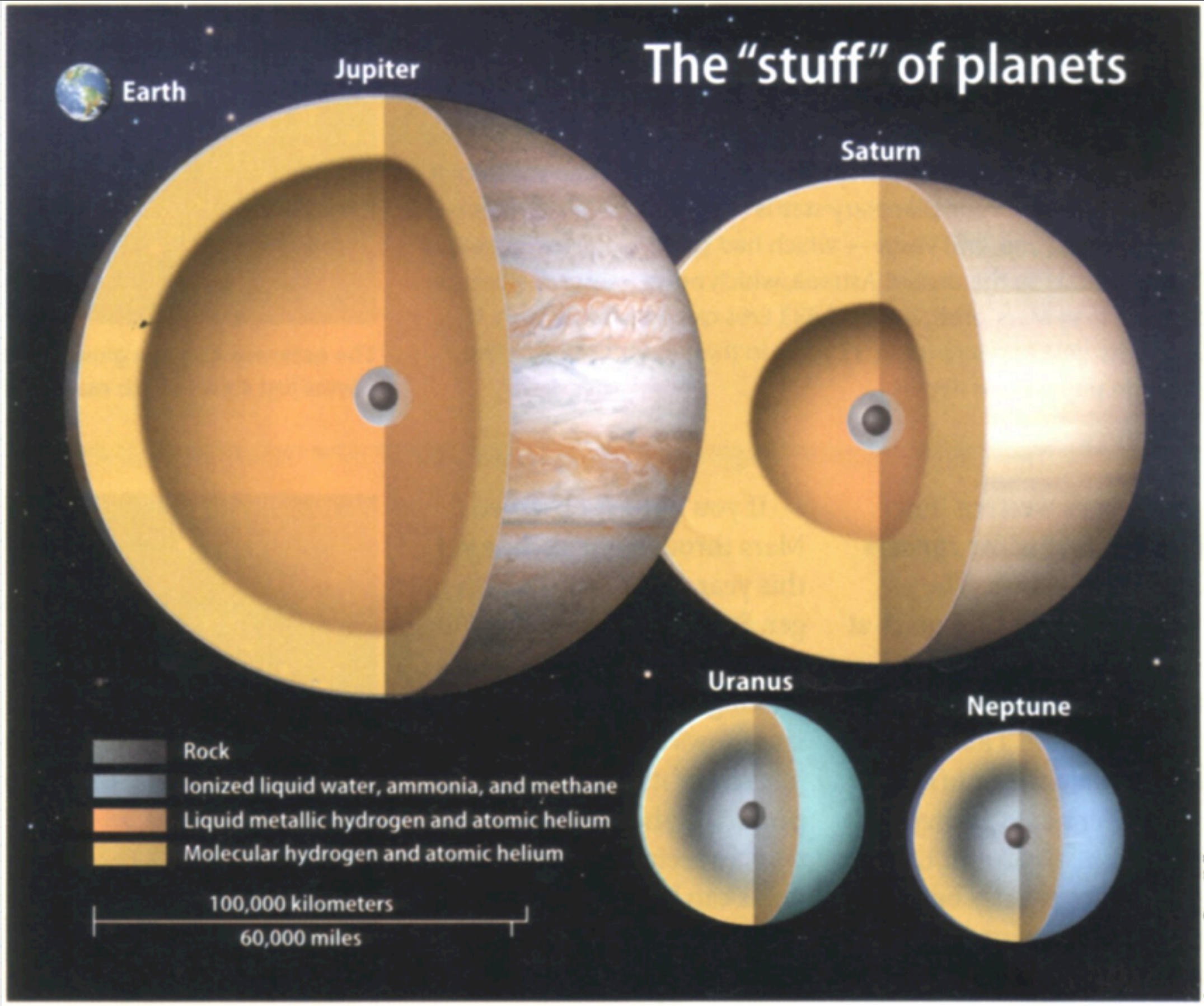
* But the pressures within Uranus and Neptune are not high enough for the hydrogen/helium mix to undergo a liquid state

➡ no liquid state

➡ hence, no metallic state

Comparing Jovian Interiors...

* Both Uranus and Neptune have a thick layer of gaseous hydrogen/helium mix surrounding a core of hydrogen compounds, rocks and metals
* These cores may have some liquid zones (needed to explain their magnetic field generation)



The gas giant planets are made up of layers of gas and liquid that surround probable solid rocky cores.

Magnetic Fields

- Earth's magnetic field is powered by the movement of charged particles in the liquid outer core
- Jupiter and Saturn's are generated in the metallic hydrogen layer
- Uranus and Neptune's are thought to be generated in their ionized fluid mixture of water, ammonia & methane

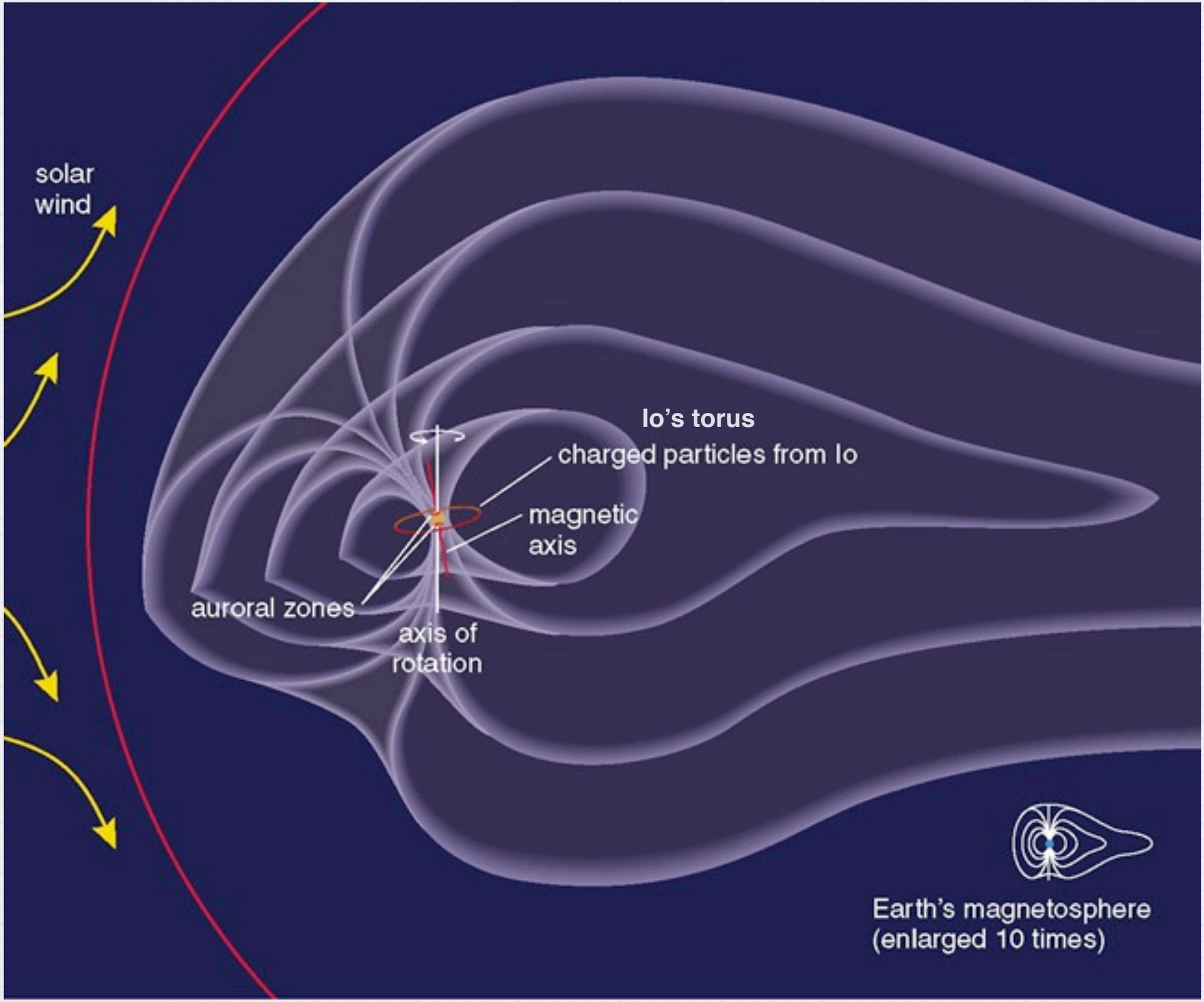
Jupiter's Magnetosphere

* Jupiter's magnetic field is 20,000 times stronger than Earth's due to its thick hydrogen metallic layer
* Its magnetosphere is enormous
* From Earth, the angular size of that magnetosphere is that of a full Moon

Jupiter's Magnetosphere...

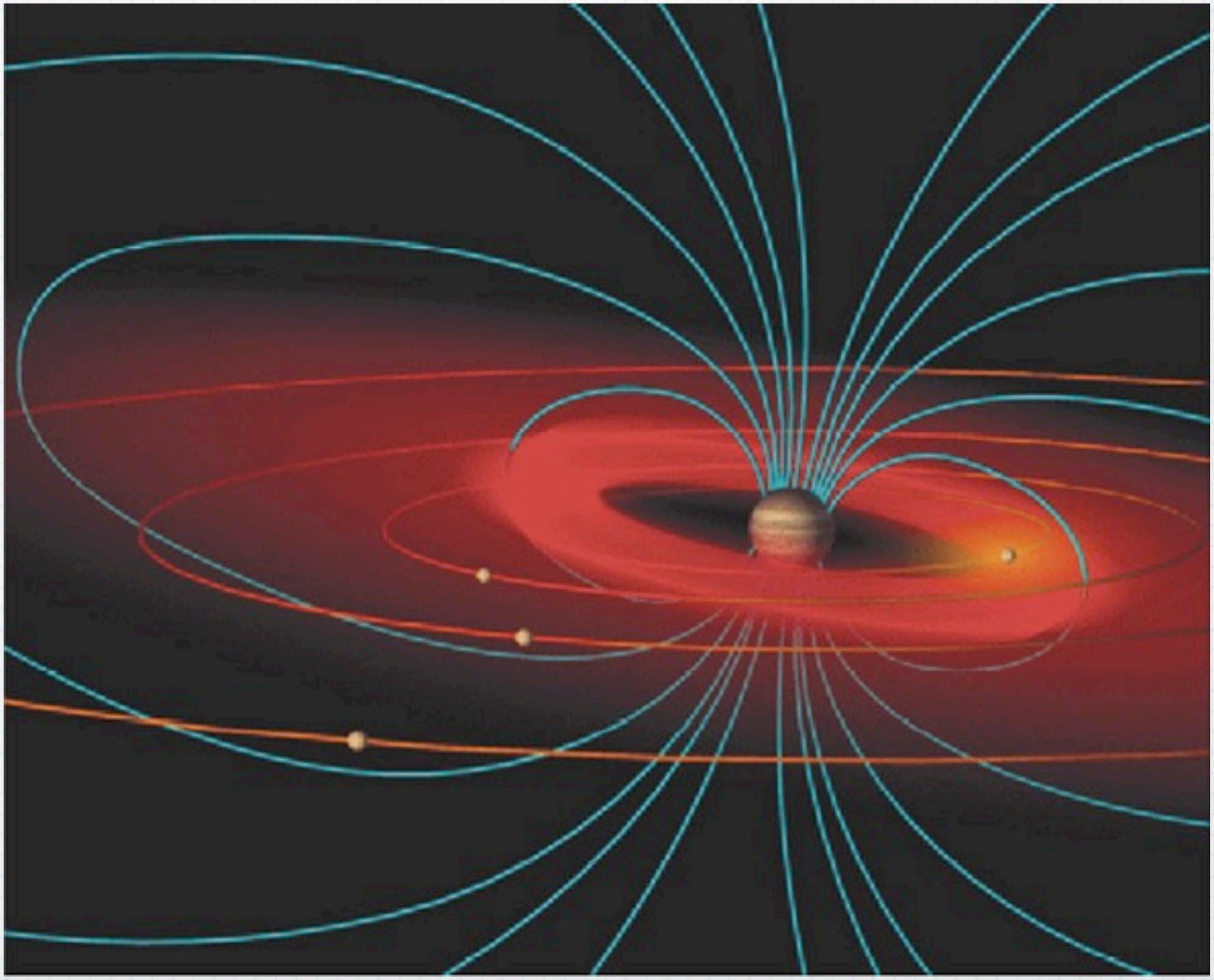
* As such, Jupiter has auroras
* The magnetosphere also creates belts of intense radiation around Jupiter from using charged particles emanating from Io's volcanic eruptions

➡ This radiation zone is called **Io's torus**

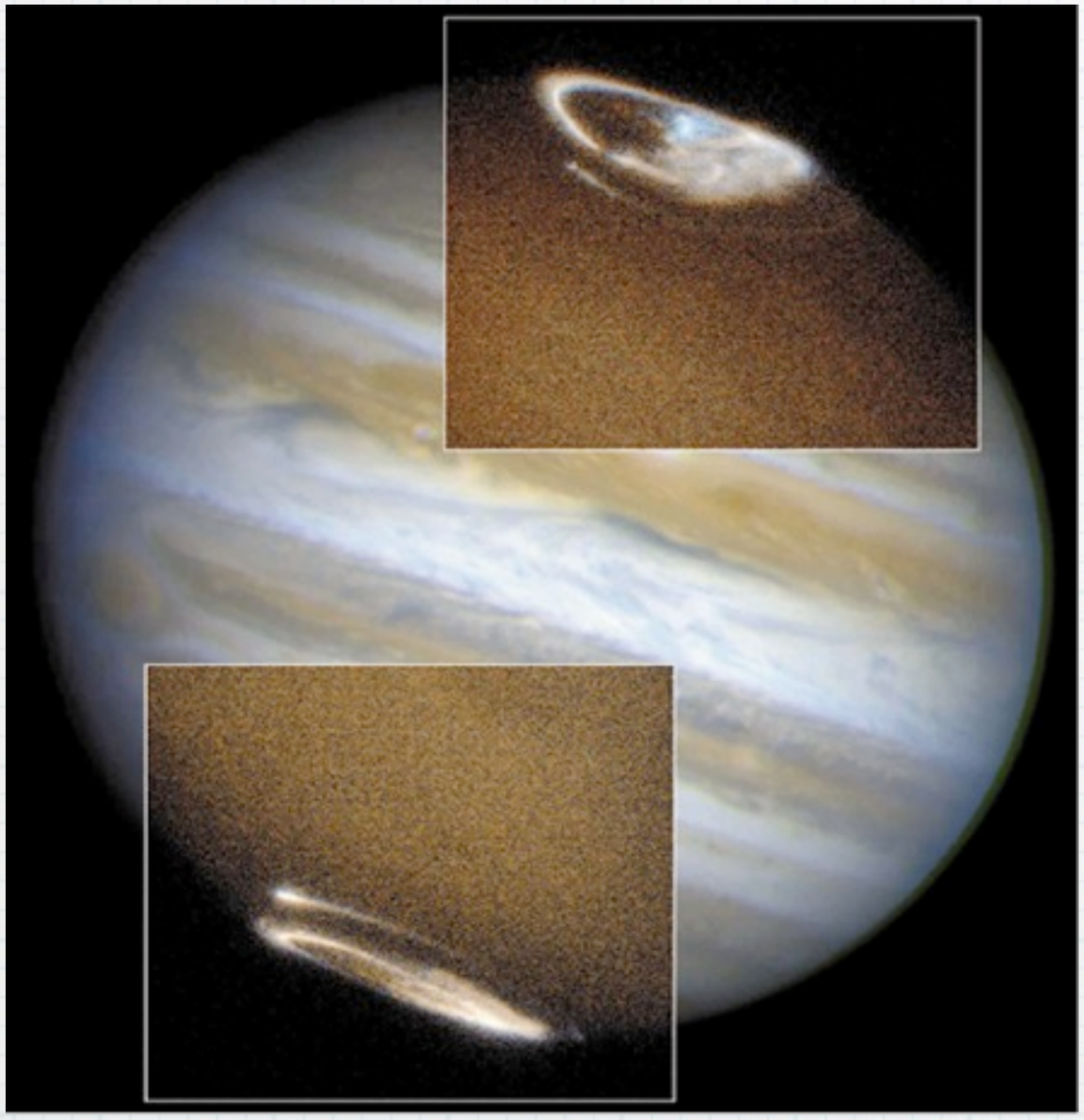


Io's Torus

Drawing of the charged particle belt (the torus of Io) emanating from ionized gasses from Io's volcanoes



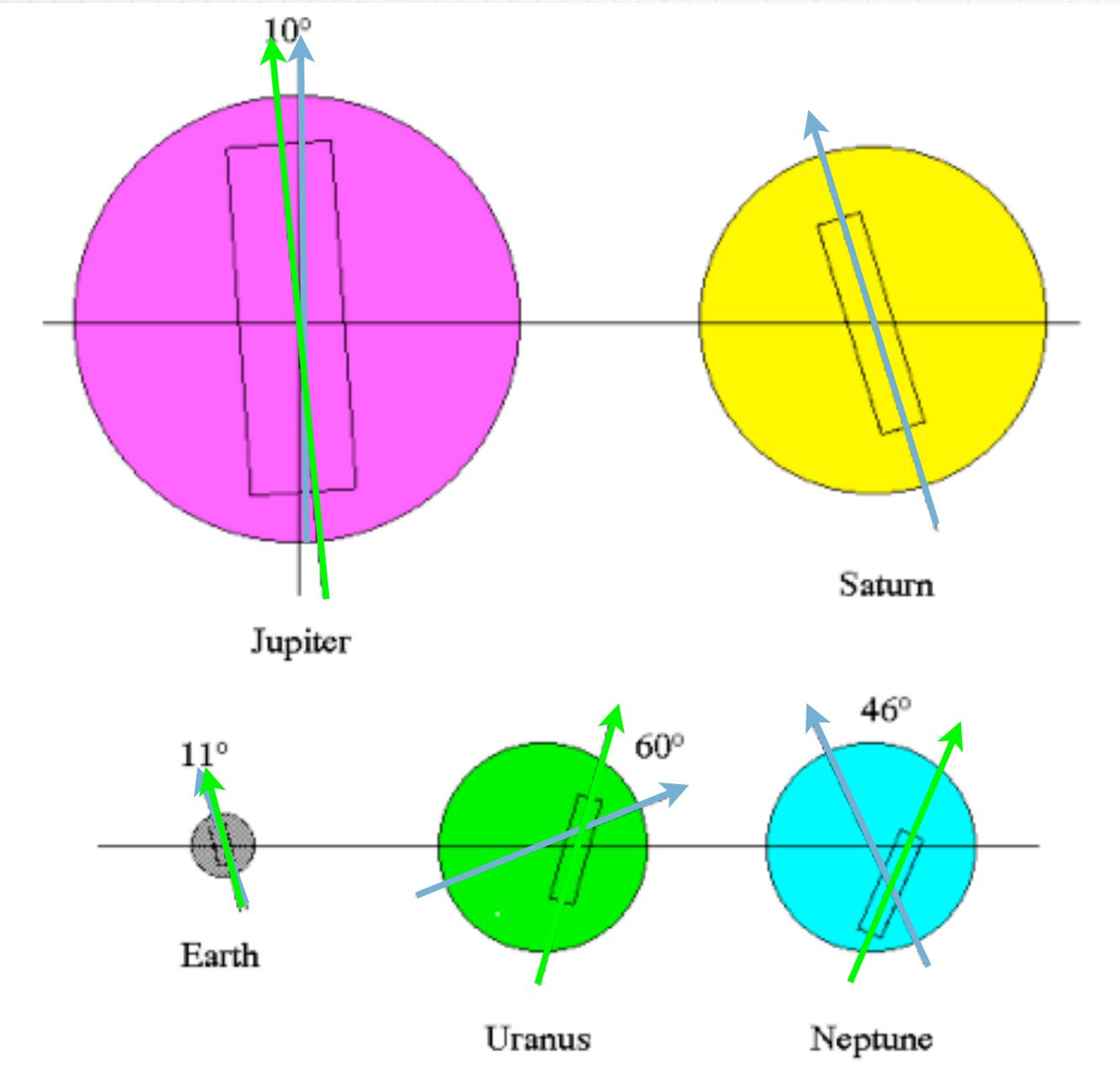
Jupiter Auroras



Saturn Auroras

Auroras seen in UV light overlaid on each photos

Magnetic & Rotational Axis for Jovian Worlds



rotational axis magnetic axis

Jupiter, Saturn and Earth's magnetic fields are roughly aligned with their planet's rotational axis

Not the case with Uranus and Neptune: they are not aligned nor centered. The fields are probably generated by local events in the icy mantles and may be unstable

Jovian Atmospheres

* Jovian weather has dynamic winds, colorful clouds, and enormous long-lived storms

* This weather is driven by
  1. energy from the Sun
  2. heat generated within the planets' themselves

Clouds & Colors

* Earth's clouds are made of water and reflect the visible light from the Sun
* The jovian planets have several types of clouds and they reflects different colors
* A cloud is formed when a gas condenses to make tiny liquid droplets or solid flakes

Clouds & Colors...

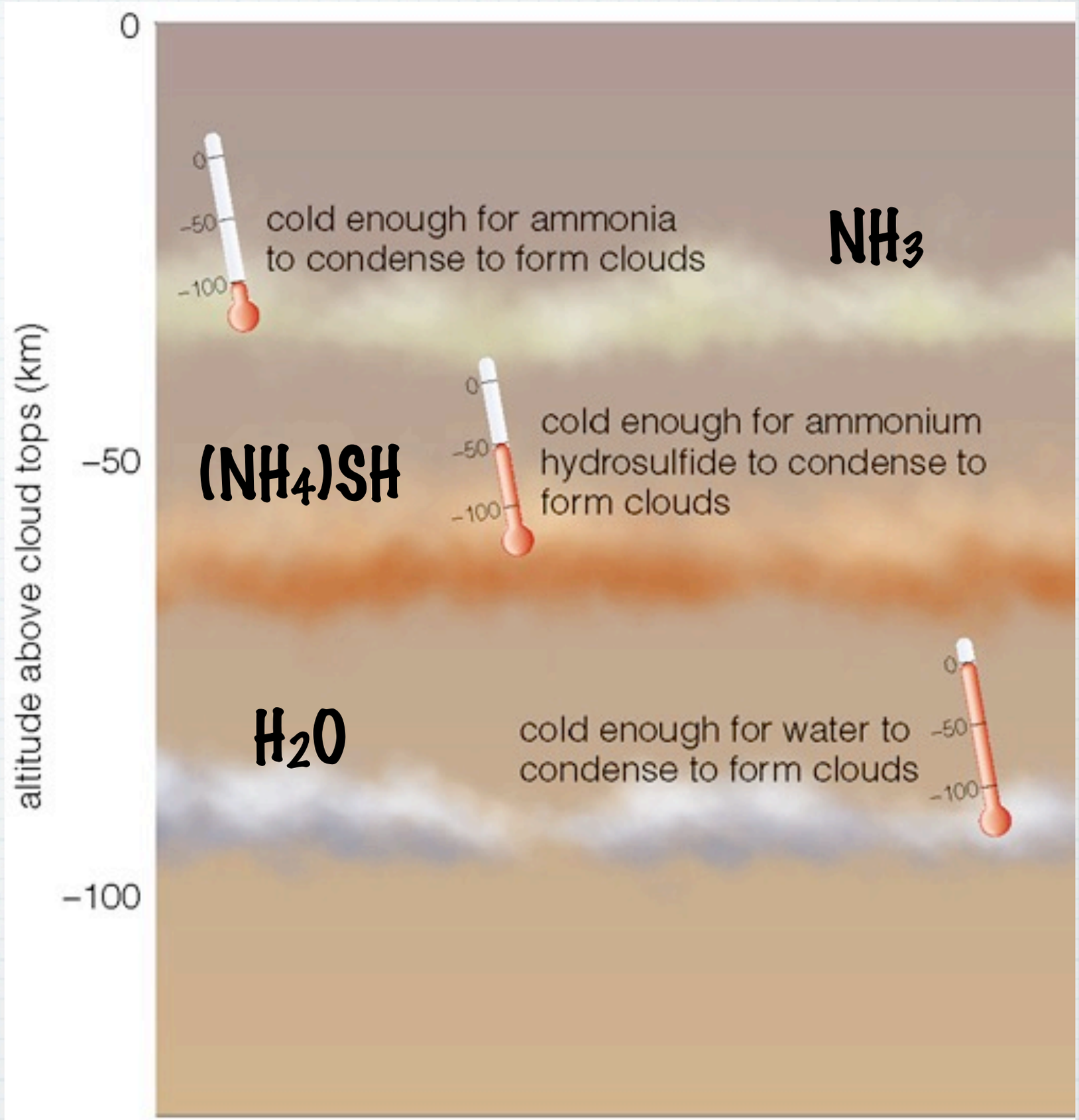
* On Earth, water vapor is the only gas that condenses in the atmosphere
* The Jovian planets have several such gasses and they each condense at different altitudes/temperatures

Clouds & Colors ...

* Saturn has the same set of clouds but they are deeper in the planet's atmosphere as it is colder
* If Uranus & Neptune have the same set, they are buried so deep that they can't be seen
* Rather Uranus & Neptune's color (blue) comes from methane gas which absorbs red light and the **blue light is reflected by the condensed methane gas**

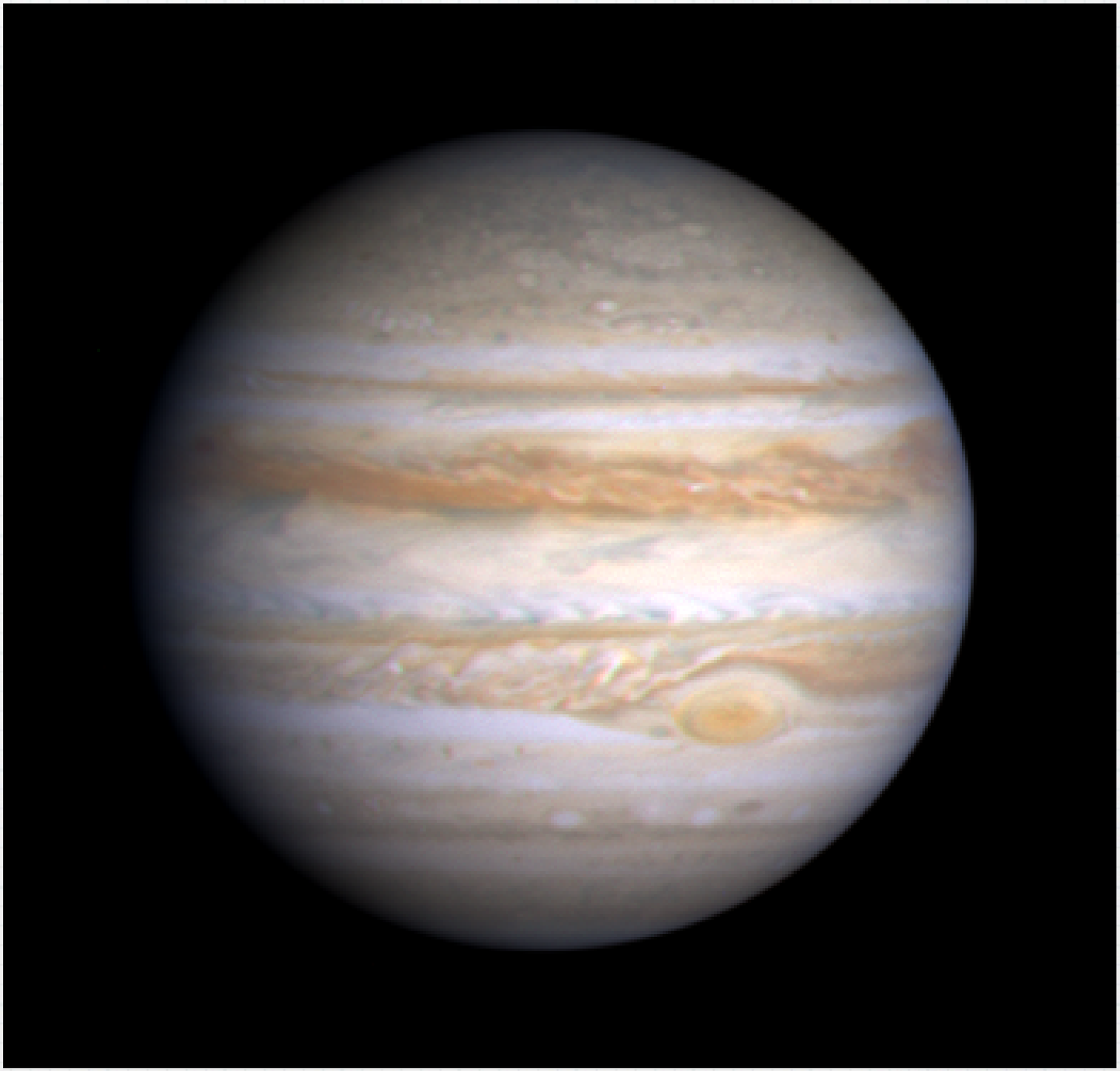
Jupiter has three primary cloud layers

Saturn has the same set of three clouds but they are deeper in Saturn's atmosphere as it is colder



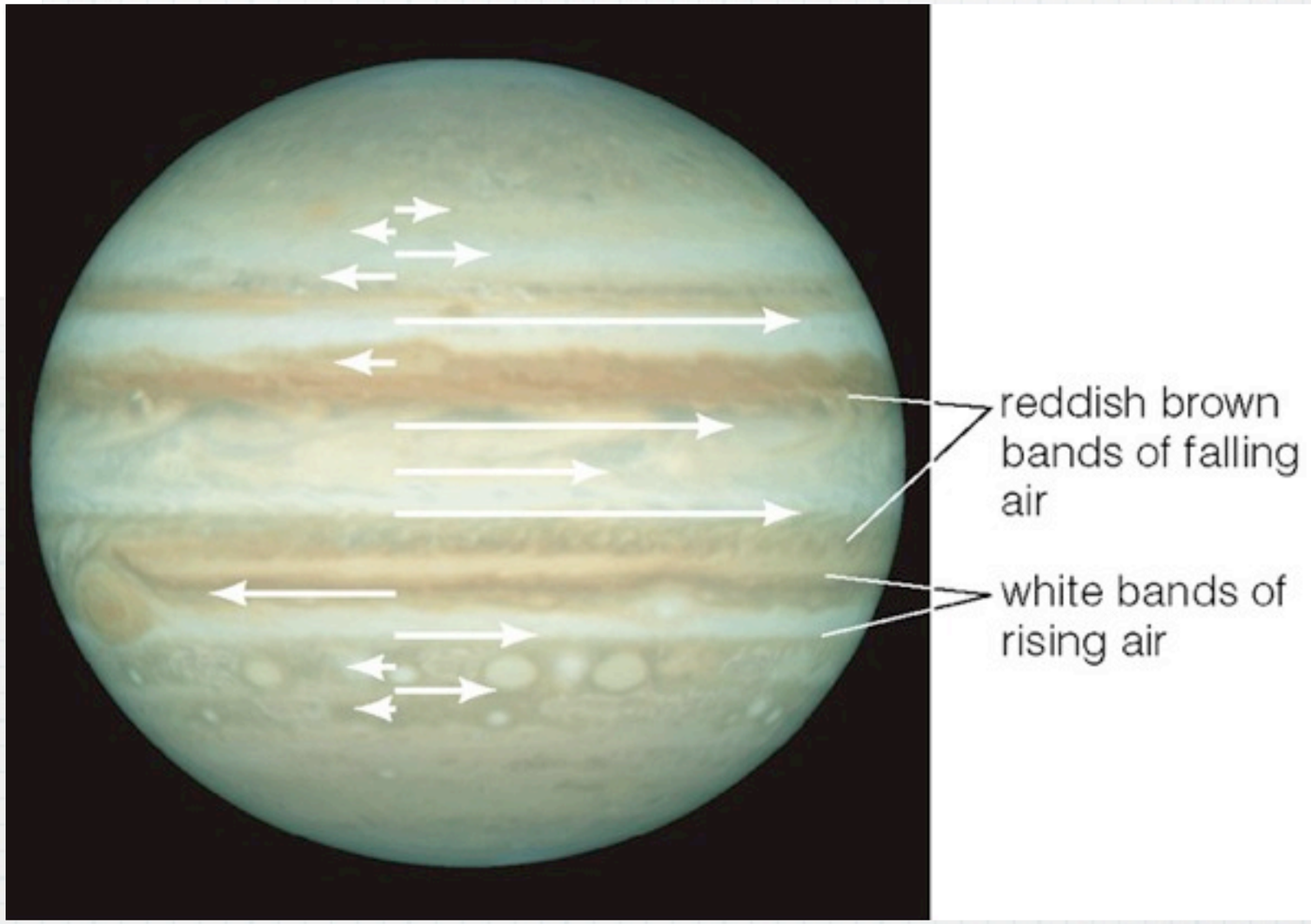
Jupiter

Notice the clouds: they surround the planet in thin horizontal bands



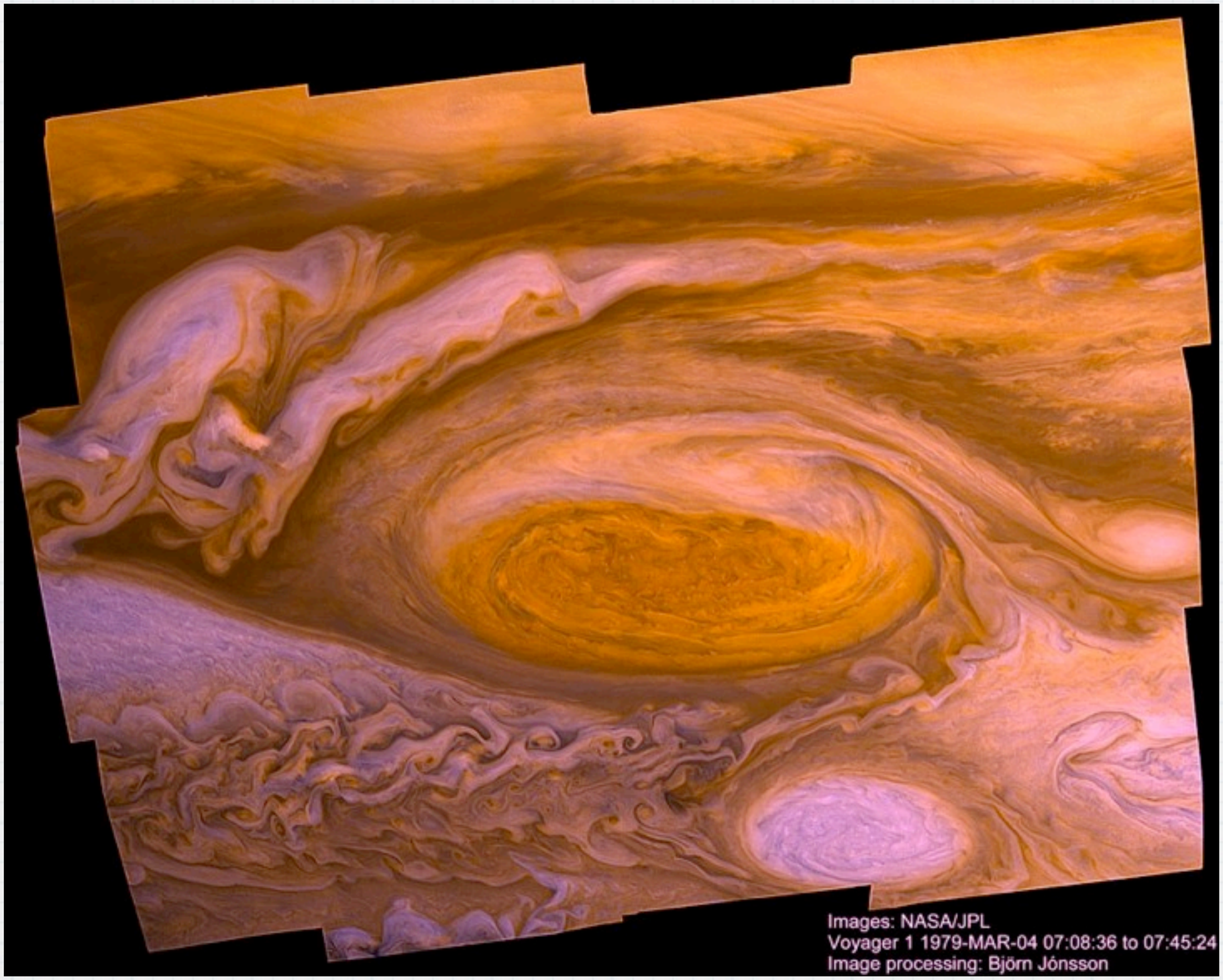
Earth's rotation causes the winds; storms circulate around low pressure regions

Jupiter's faster rotation are larger size stretch out the same circulation patters



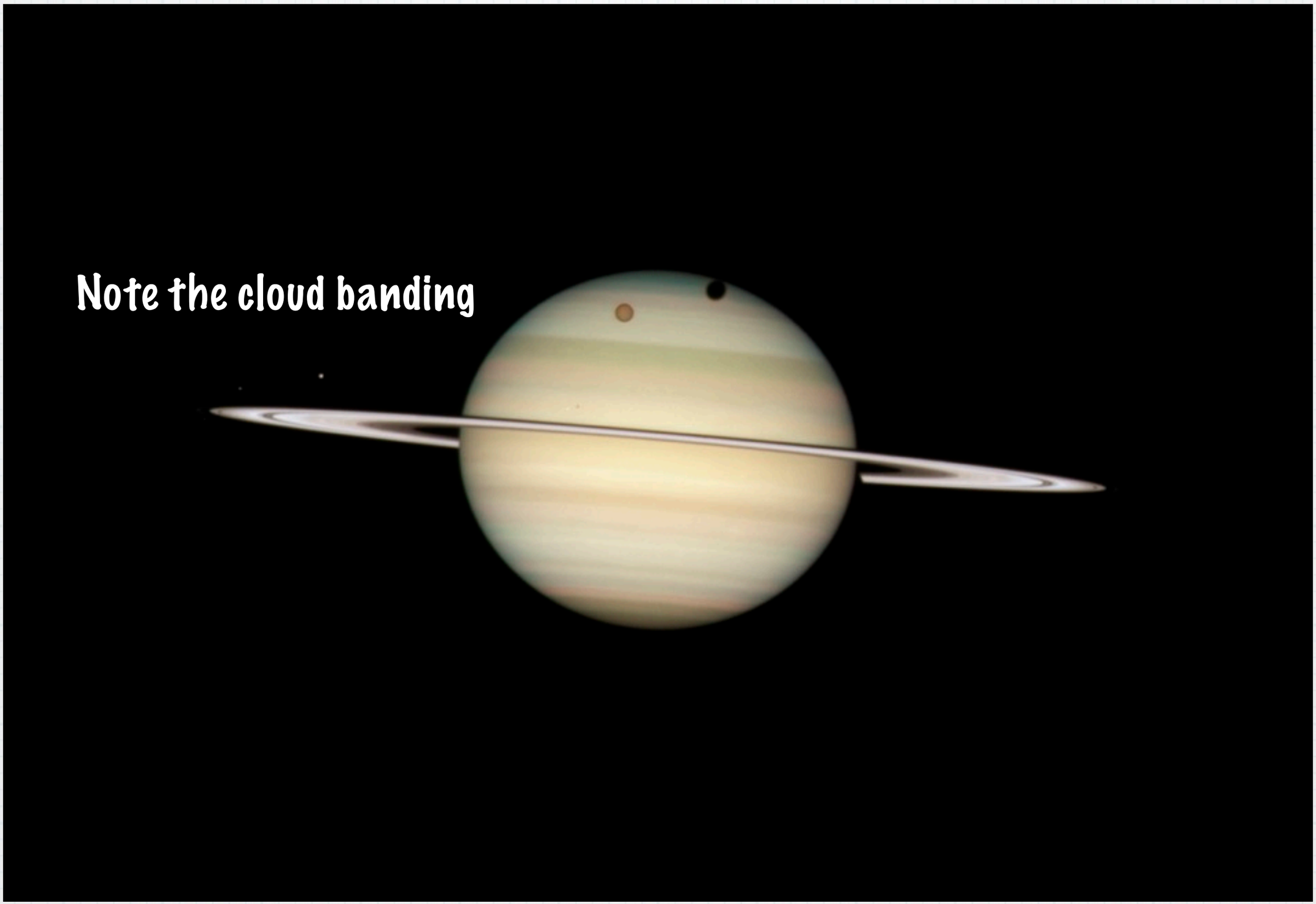
The Great Red Spot

Ammonium hydrosulfide clouds reflect reds, browns, yellows and oranges



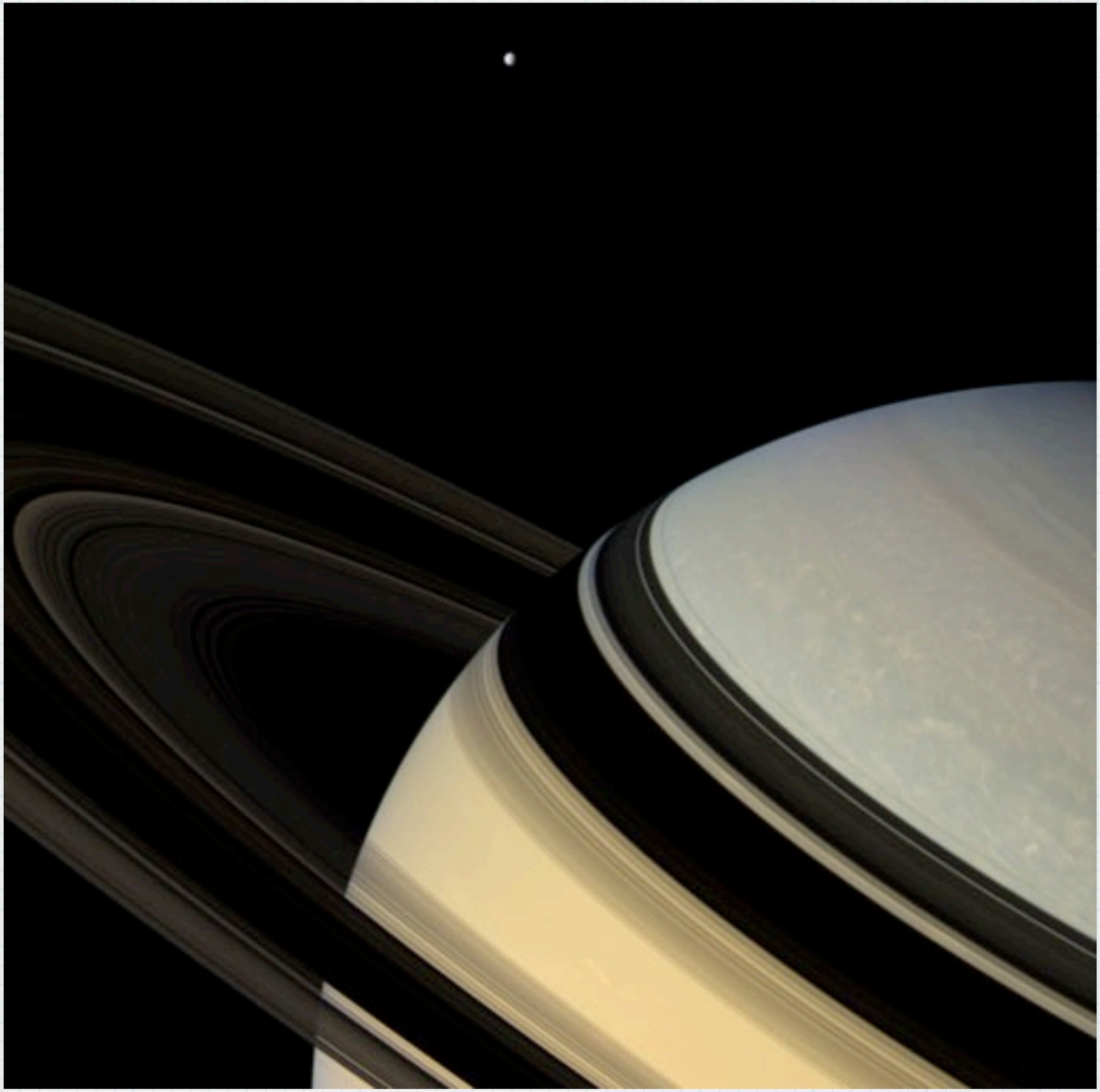
Ammonia, the highest coldest layer, reflects greyish-white

Saturn with Titan and Dione



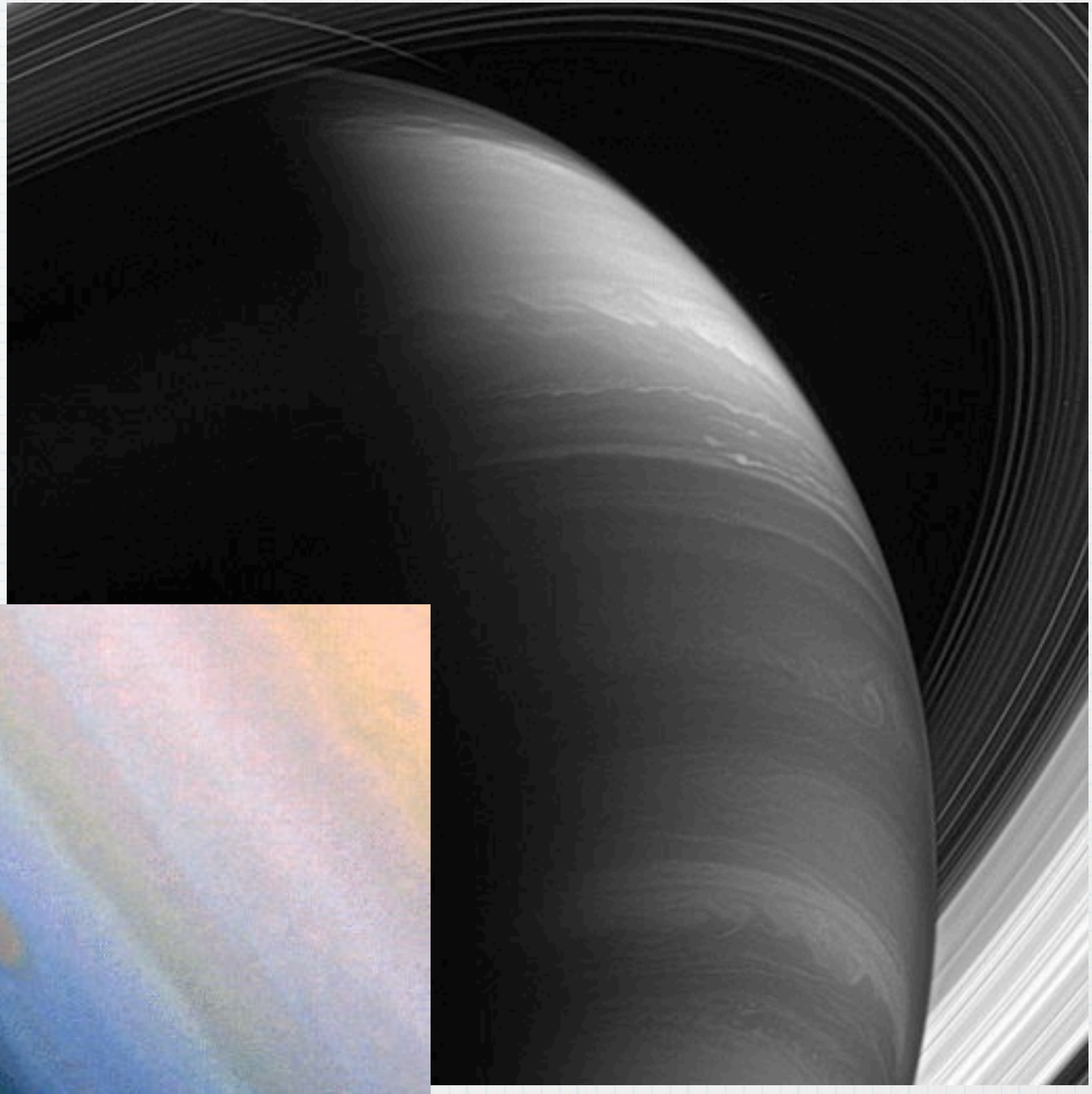
Hubblesite.org picture

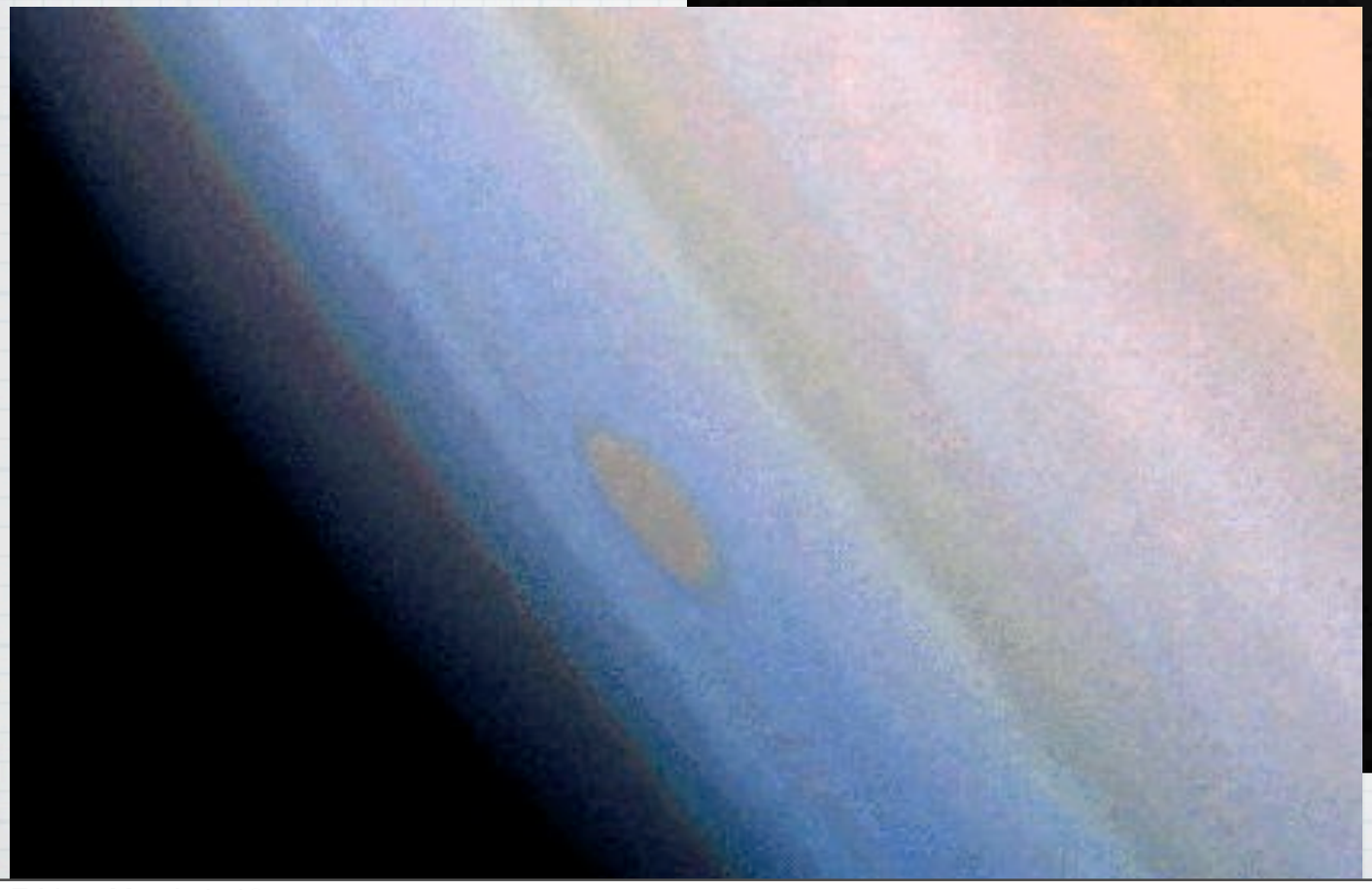
Rings and rings shadows



More rings

Red oval cloud in Saturn's southern hemisphere



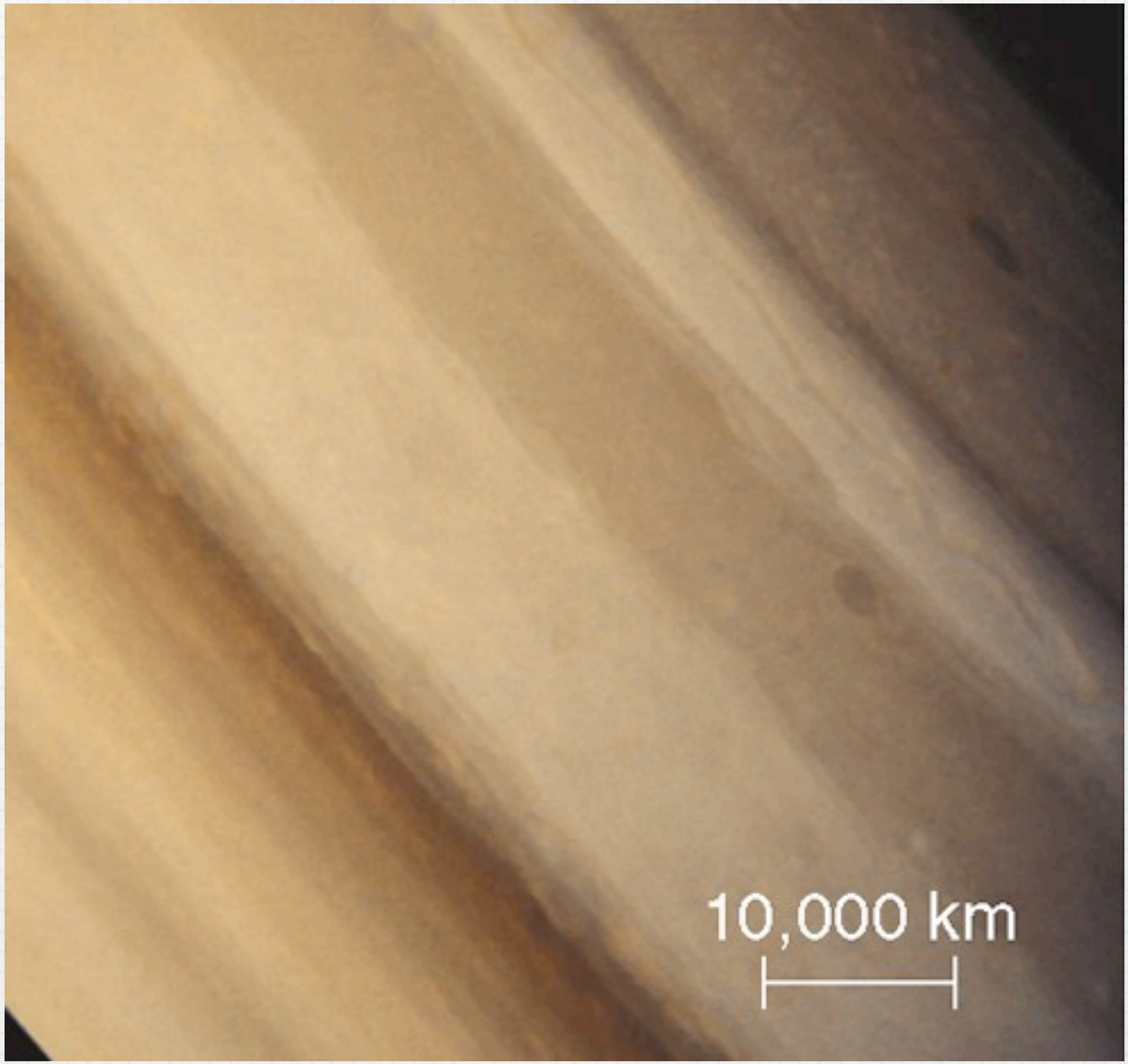


Close-up of Saturn

Its banded appearance is similar to Jupiter's

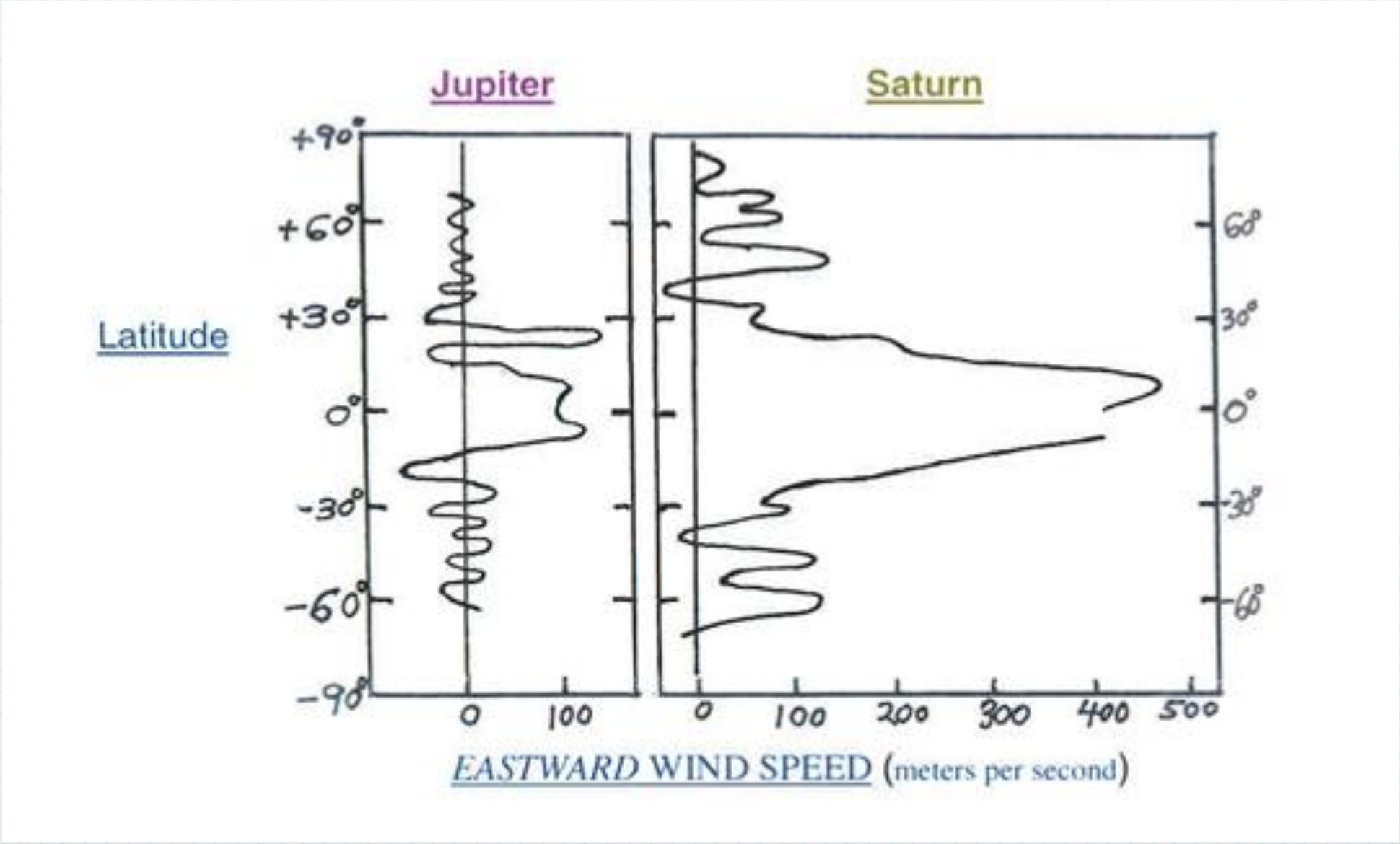
Saturn's winds are much faster than Jupiter's

Scientists do not have an explanation why



Winds on Jupiter and Saturn

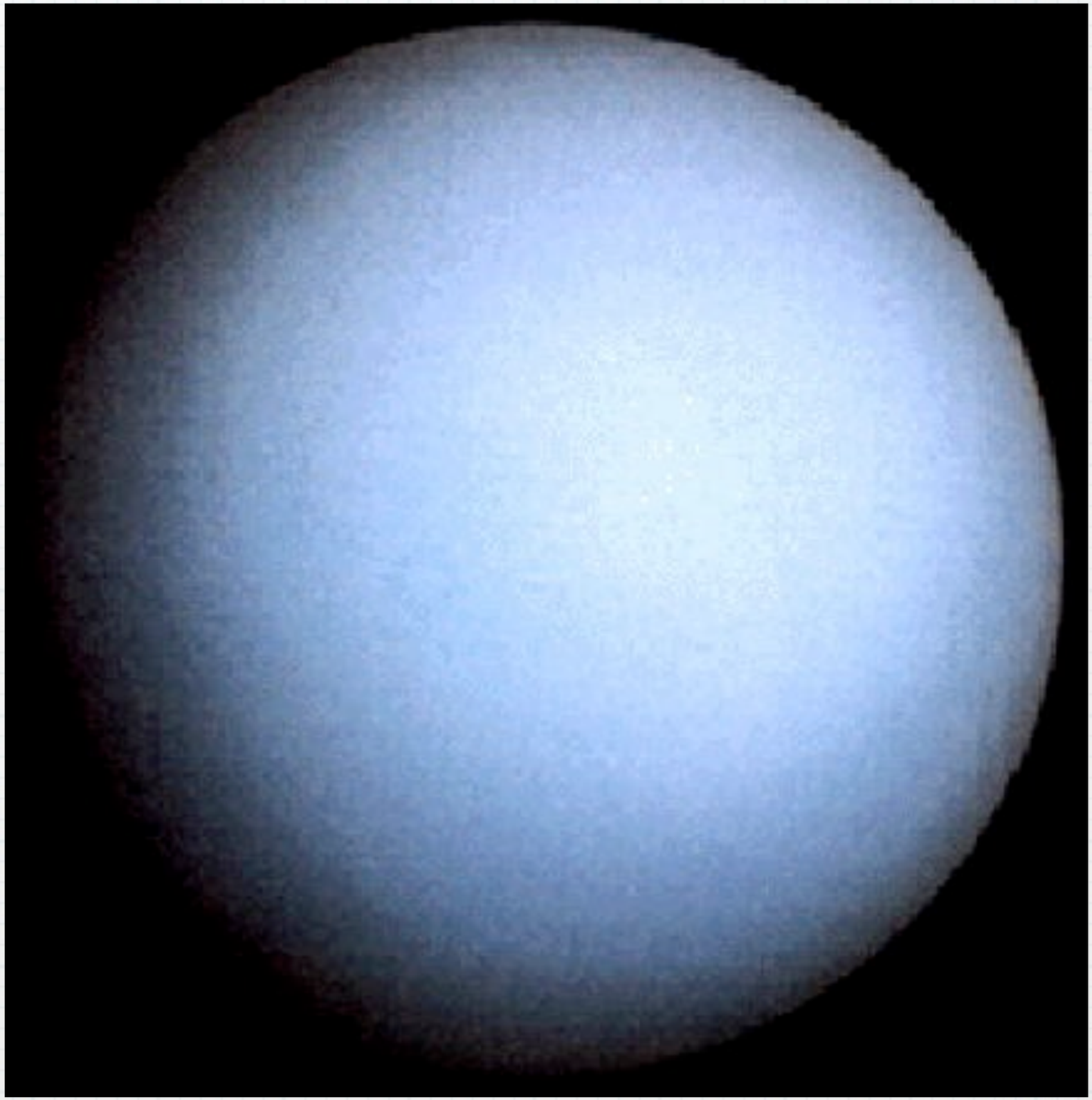
Max winds:
Jupiter: 430 km/hr
Saturn: 1700km/hr

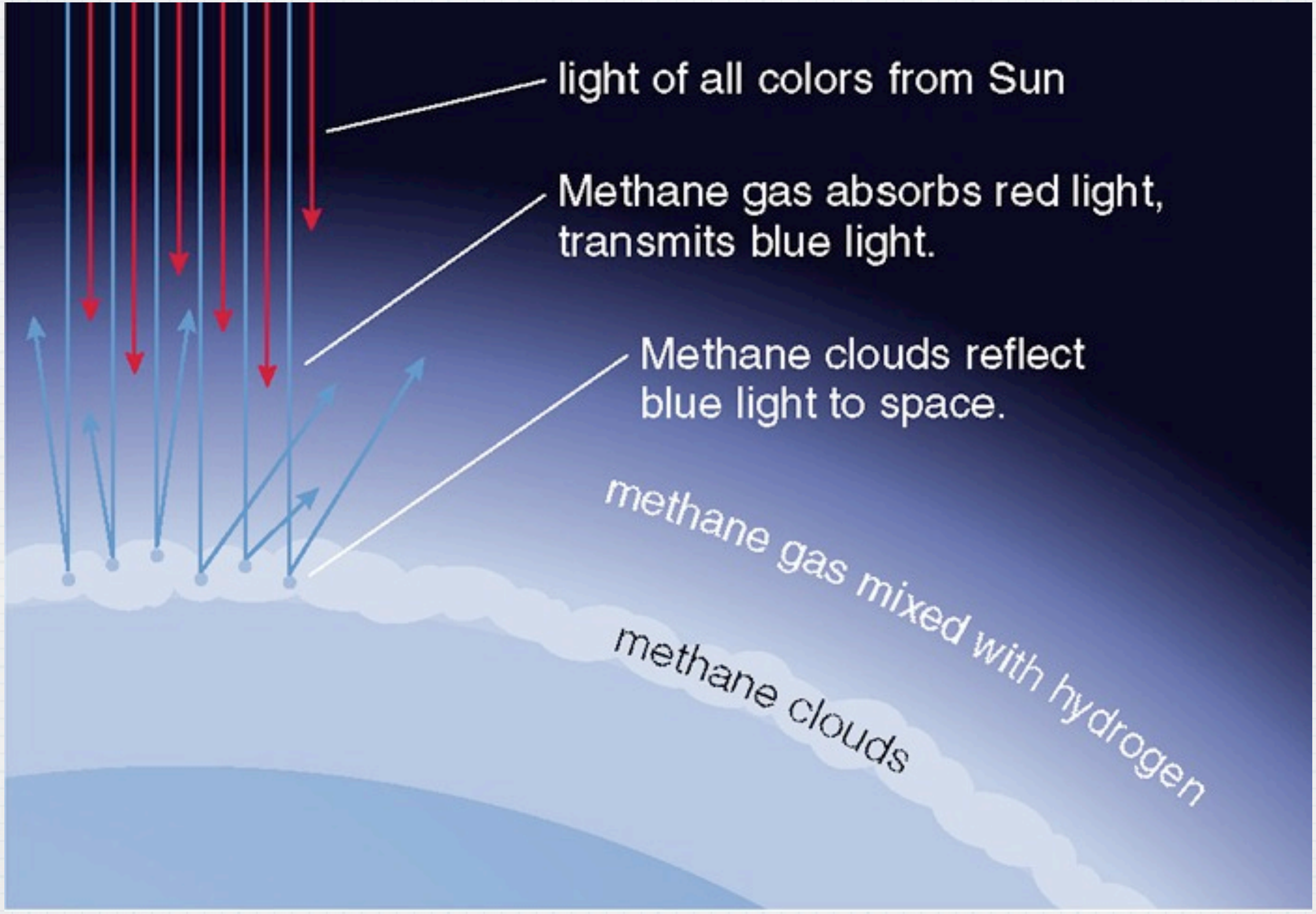


Uranus

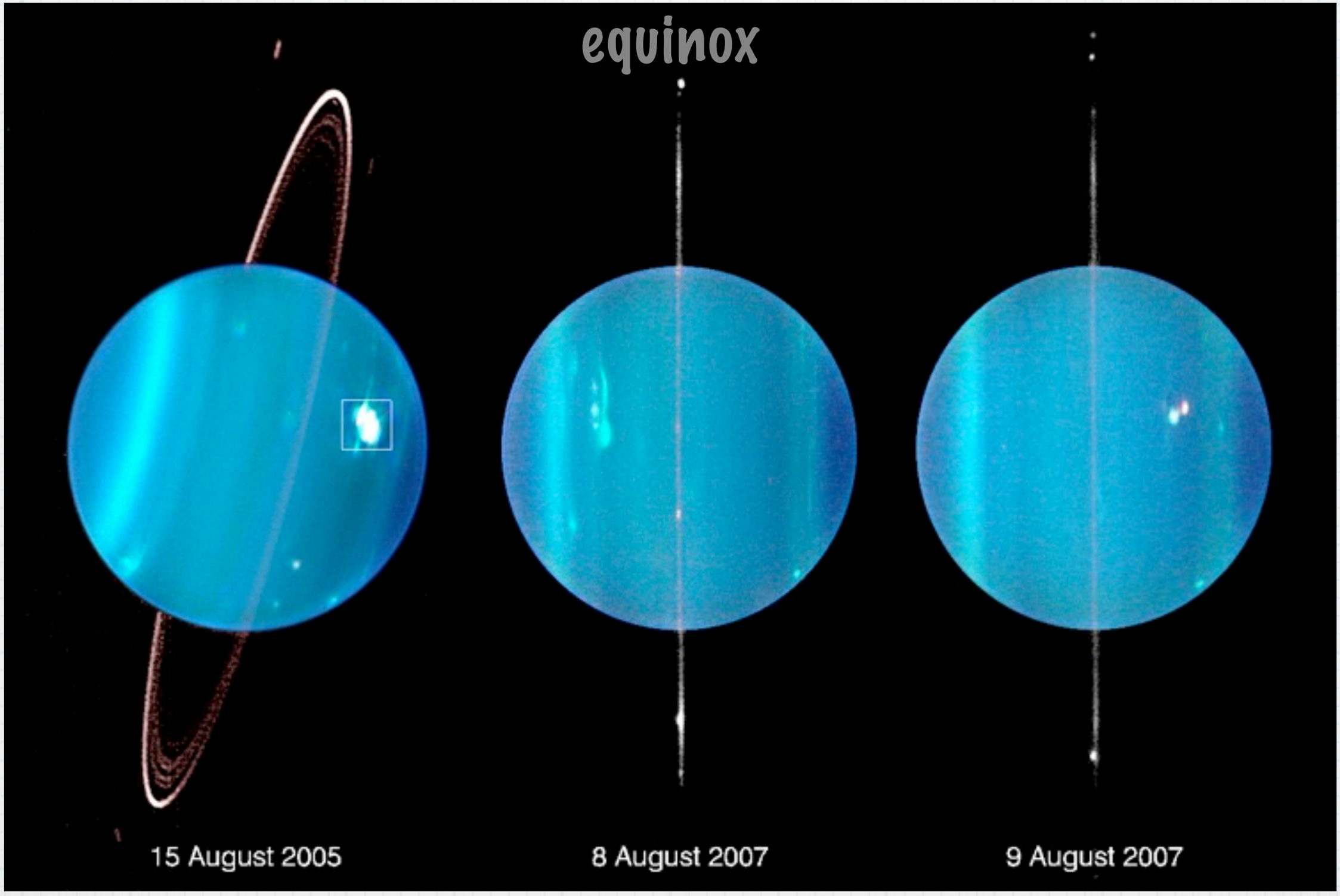
This picture was taken along its rotational pole

Hence the cloud banding is unseen

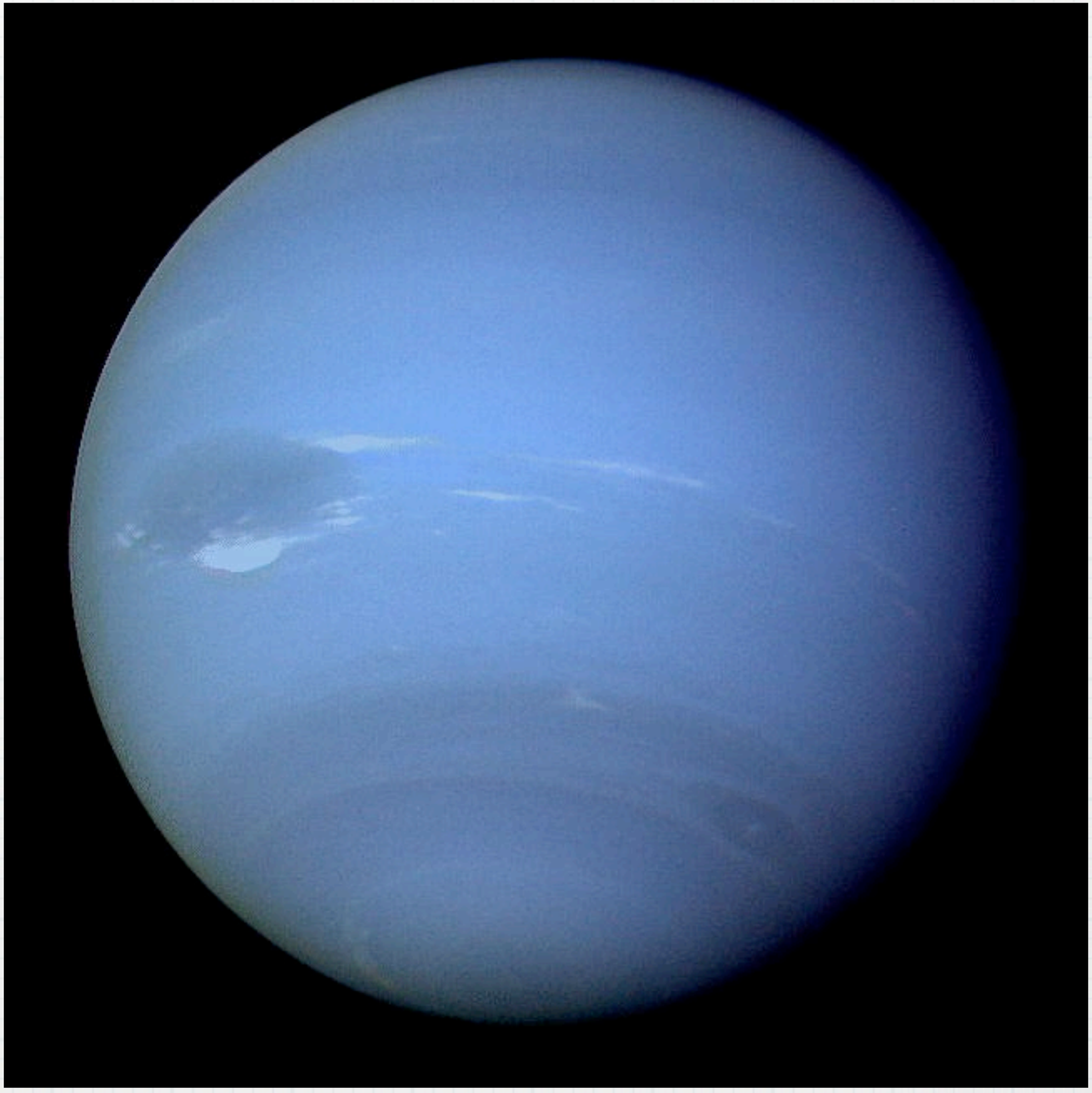




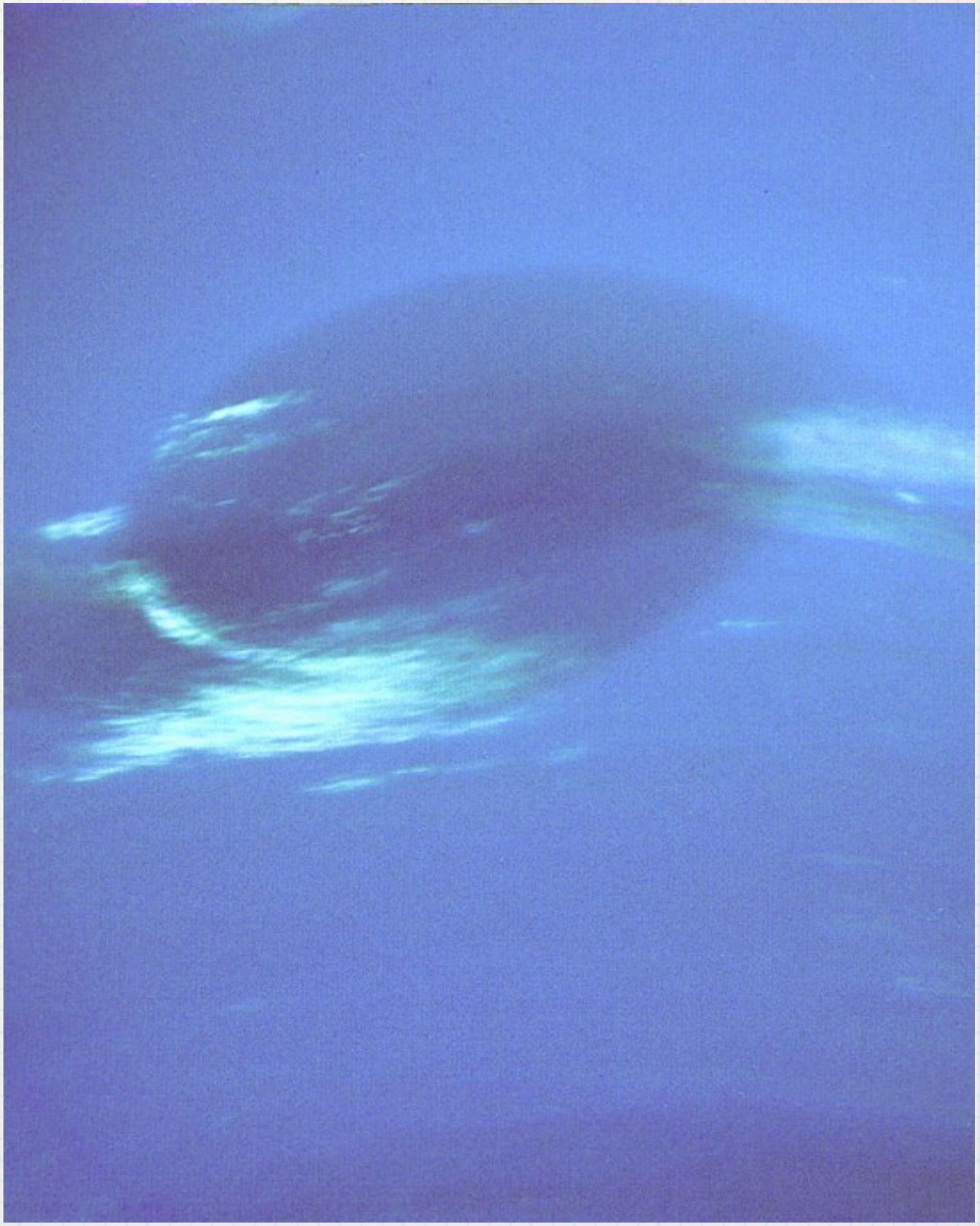
near-IR shot of Uranus from Keck II telescope



Neptune and two of its four oval cloud features



The Great Dark Spot on Neptune



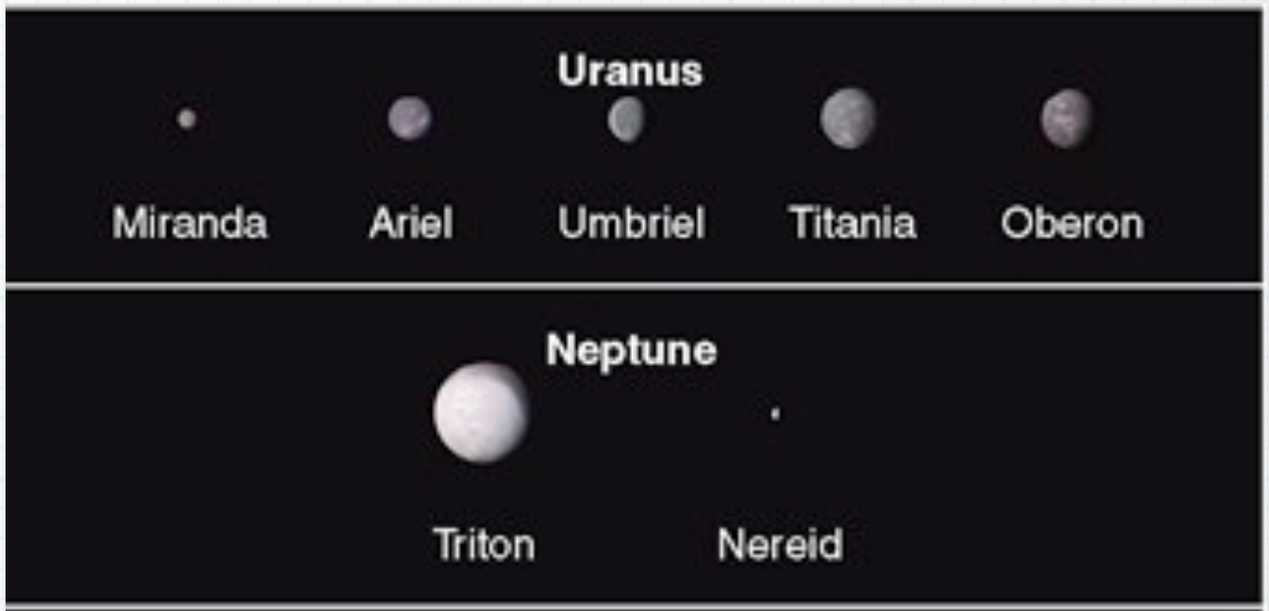
Jovian Satellites

* So many... 164 and counting!
* So diverse... in size and characteristics
* So little time... so...
* Let's look at them in 3 broad categories, ordered by size

Jovian Satellites...

1. **Large moons**: > 1,500 km diameter
2. **Medium moons**: between 300 & 1,500 km diameter
3. **Small moons**: < 300 km diameter

Moons shown to scale



Ganymede & Titan > Mercury

Callisto & Io > Moon

Medium & Large Jovian Moons

* They resemble terrestrial planets in many ways:

1. spherical
2. solid surface
3. unique geology for each
4. some even possess atmospheres, hot interiors and even magnetic fields

Medium & Large Jovian Moons...

* However they differ from their terrestrial cousins in their compositions

* They natively possess substantial amounts of hydrogen compound ices in additions to rocks & metals

* They formed in place accreting materials which surrounded each jovian planet

Medium & Large Jovian Moons...

* This explains why

1. their orbits are circular

2. they are in the equatorial plane of their parent planet

3. they orbit in the same direction than their planet's spin (one exception however: Triton of Neptune - most likely captured)

The Smaller Jovian Moons

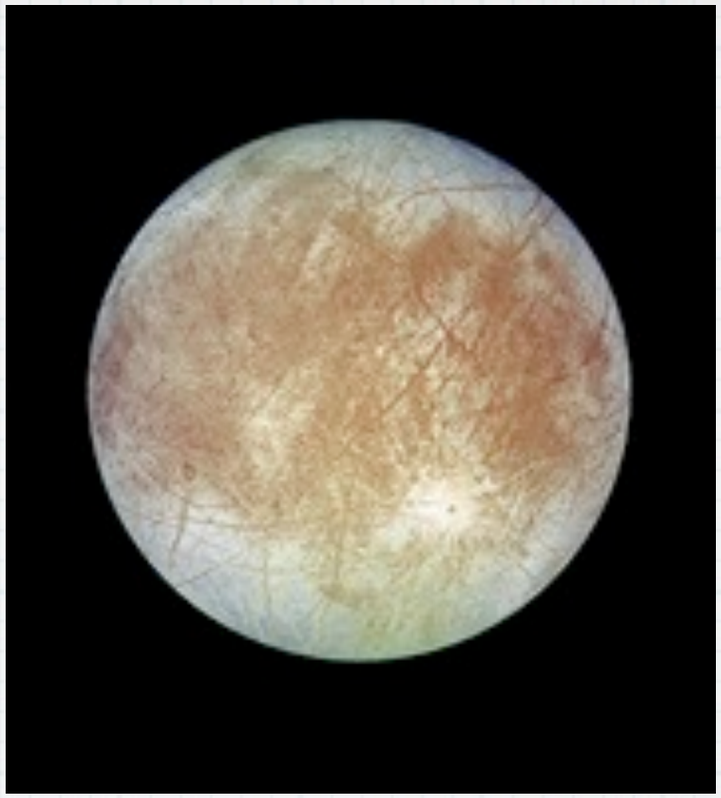
* They far outnumber their bigger siblings
* They consists of captured asteroids and comets:
* Their orbits do not follow a pattern
* They are not big enough to be spherical
* We expect them to be geologically dead

Jupiter's Biggest Moons

* All four were discovered by Galileo and are called the Galilean moons
* They would count as planets if they were to orbit the Sun as opposed to orbiting Jupiter

Io

Europa



Ganymede

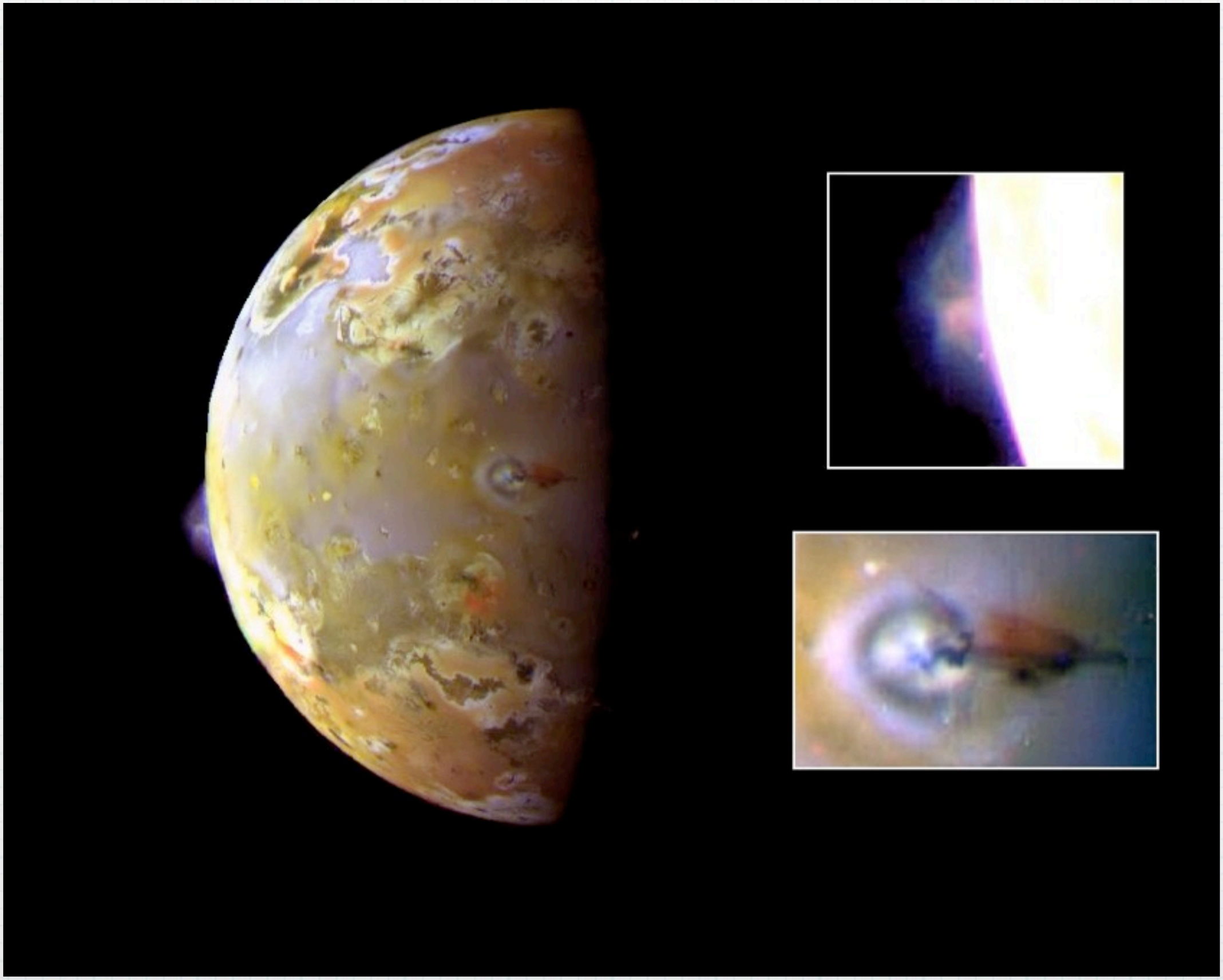
Callisto

Io

* The most volcanically active world in the Solar System to this day
* Not a single impact crater can be seen as the surface is constantly renewed
* Rather than impact craters, the surface is pockmarked with large volcanoes

Io

Io



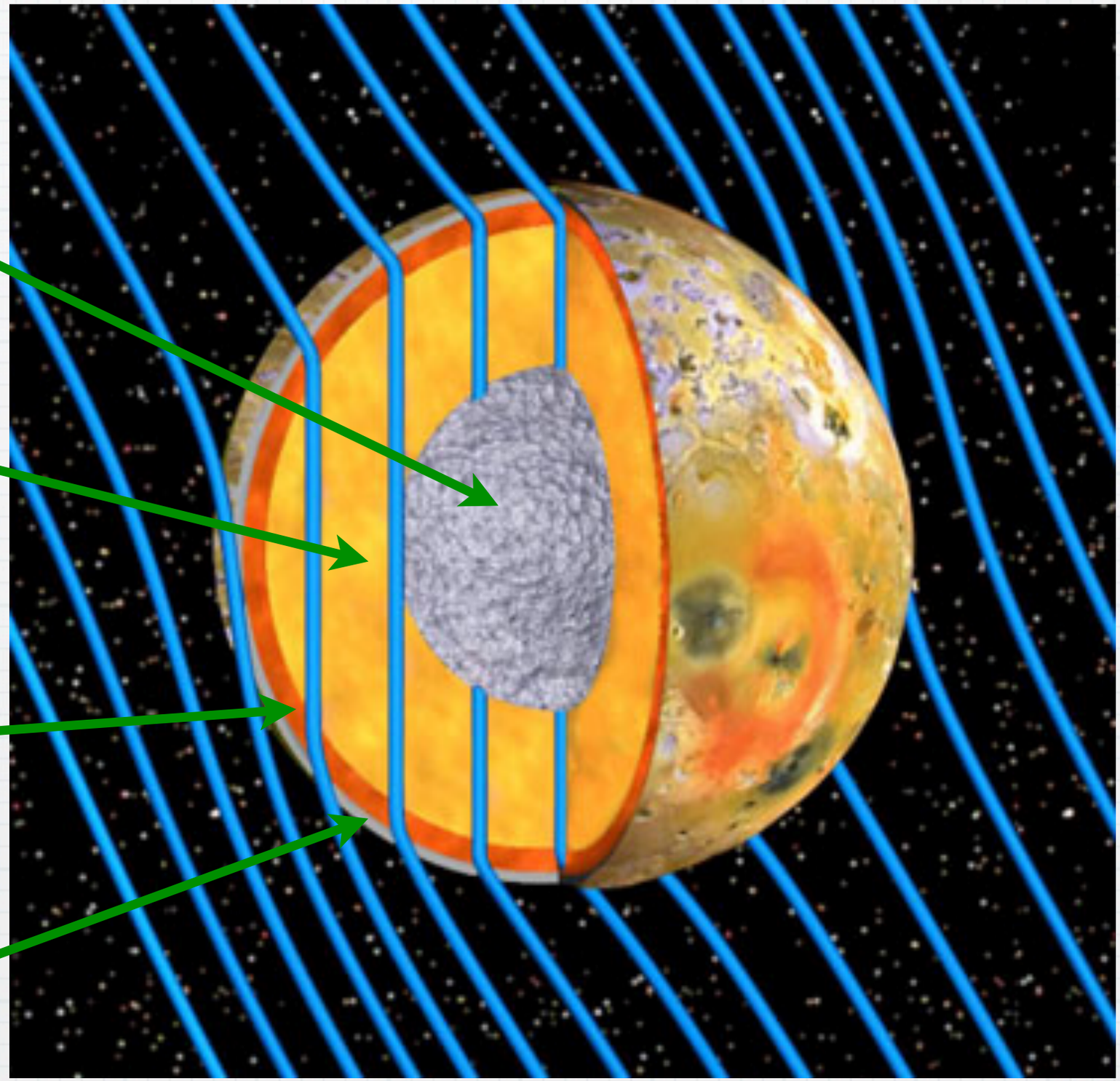
Io produces about 100 times more lava each year than all the volcanoes on Earth

iron core

molten silicate rocks

magma ocean

crust (20 to 30 miles)



Io: 1821 km radius

NASA:Galileo data

Io...

* Io is about the size of our Moon
* Io should be geologically dead as it lost its "natural" internal heat a long time ago (due to its size and time passed) but it is not dead
* Io is quite hot inside
* Scientists suggest this is due to tidal heating

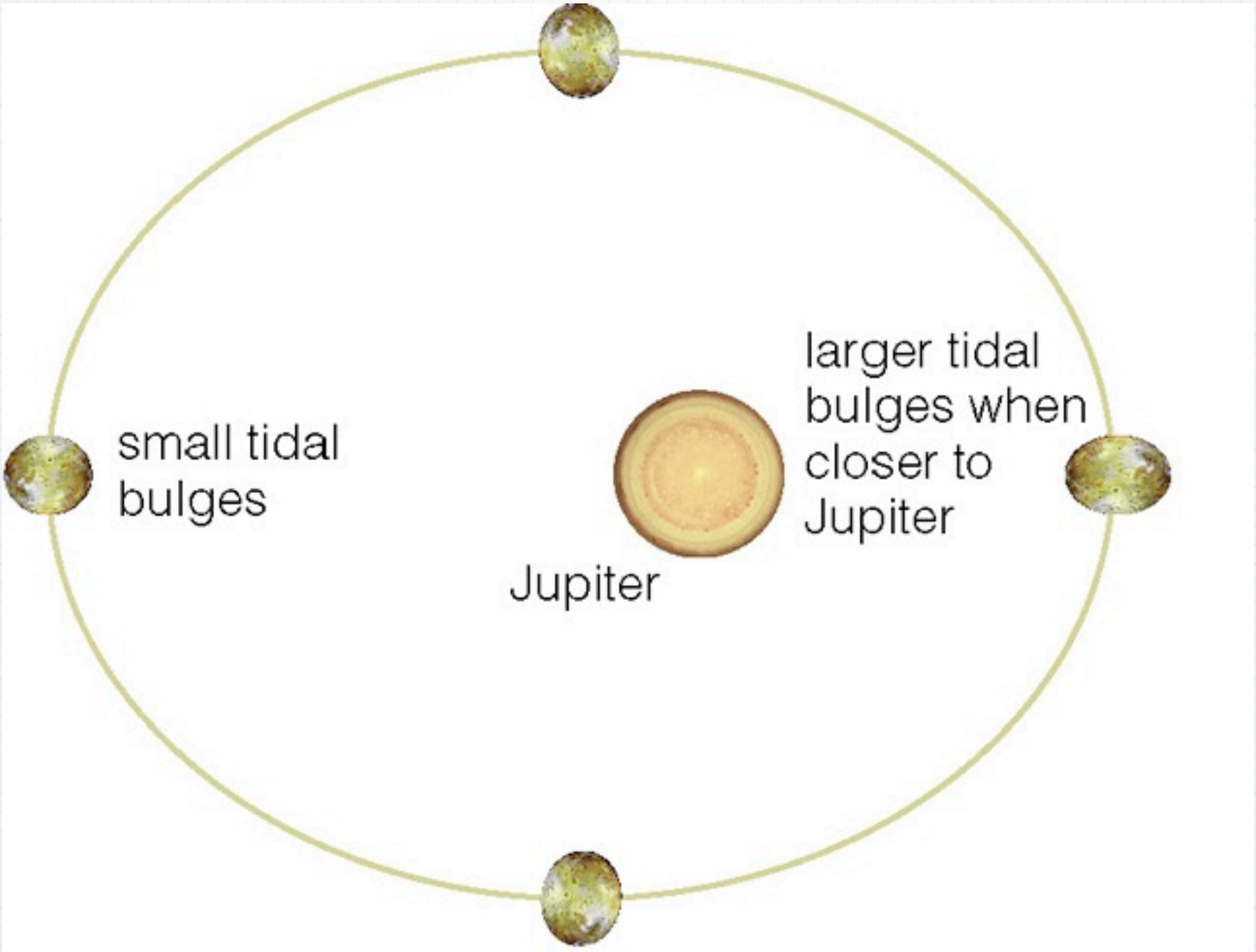
Io and Tidal Heating

1. Jupiter's huge mass exerts a far larger tidal force on Io than the Earth does on the Moon
2. Like the Moon, Io is synchronously locked with its parent planet
3. Io's orbit is slightly elliptical so its orbital speed and distance varies as it orbits Jupiter

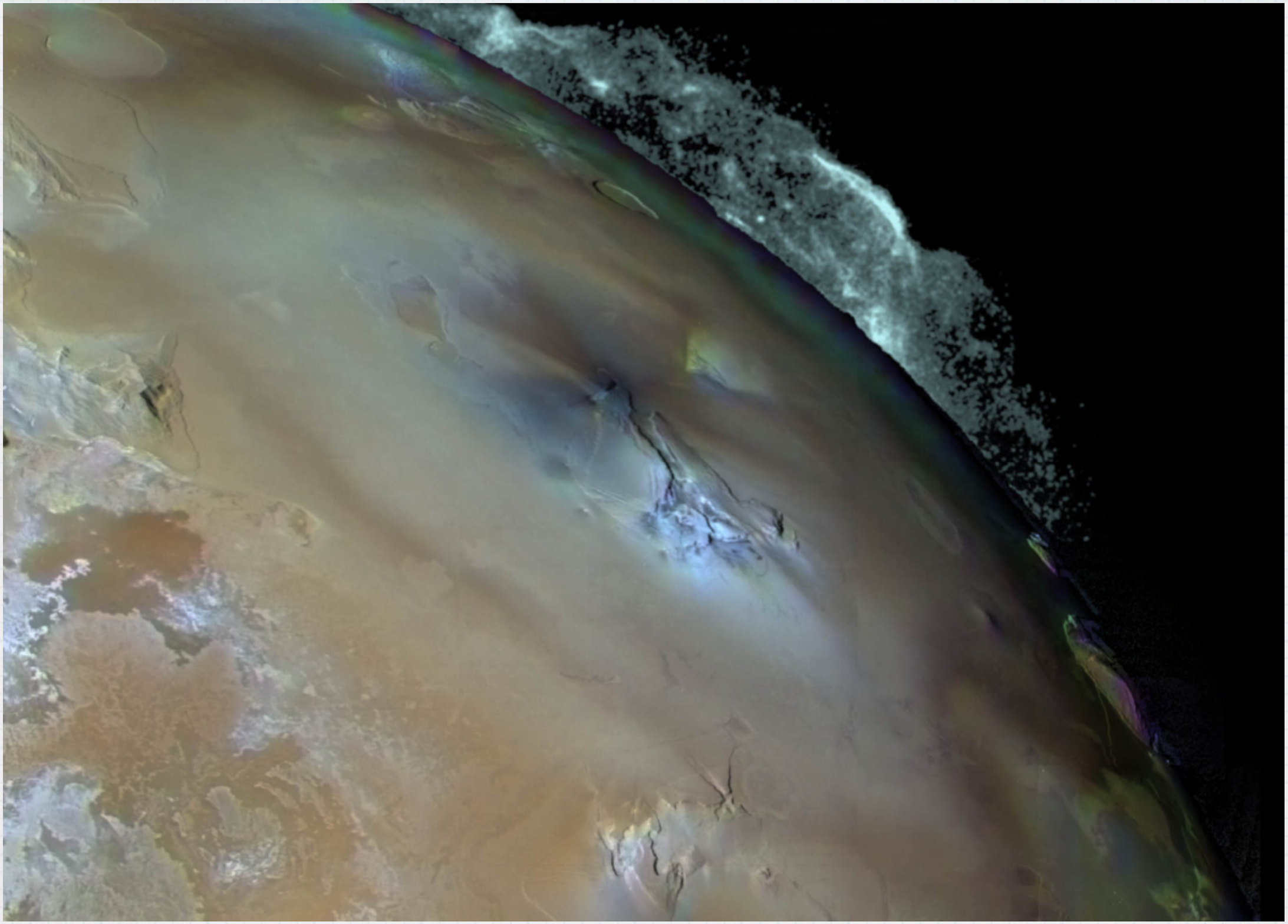
Io and Tidal Heating...

- This affects the size and orientation of Io's tidal bulges
- As a result, Io is being continuously flexed inside and this causes internal frictions which then generates the intense internal heat which drives its volcanic activity

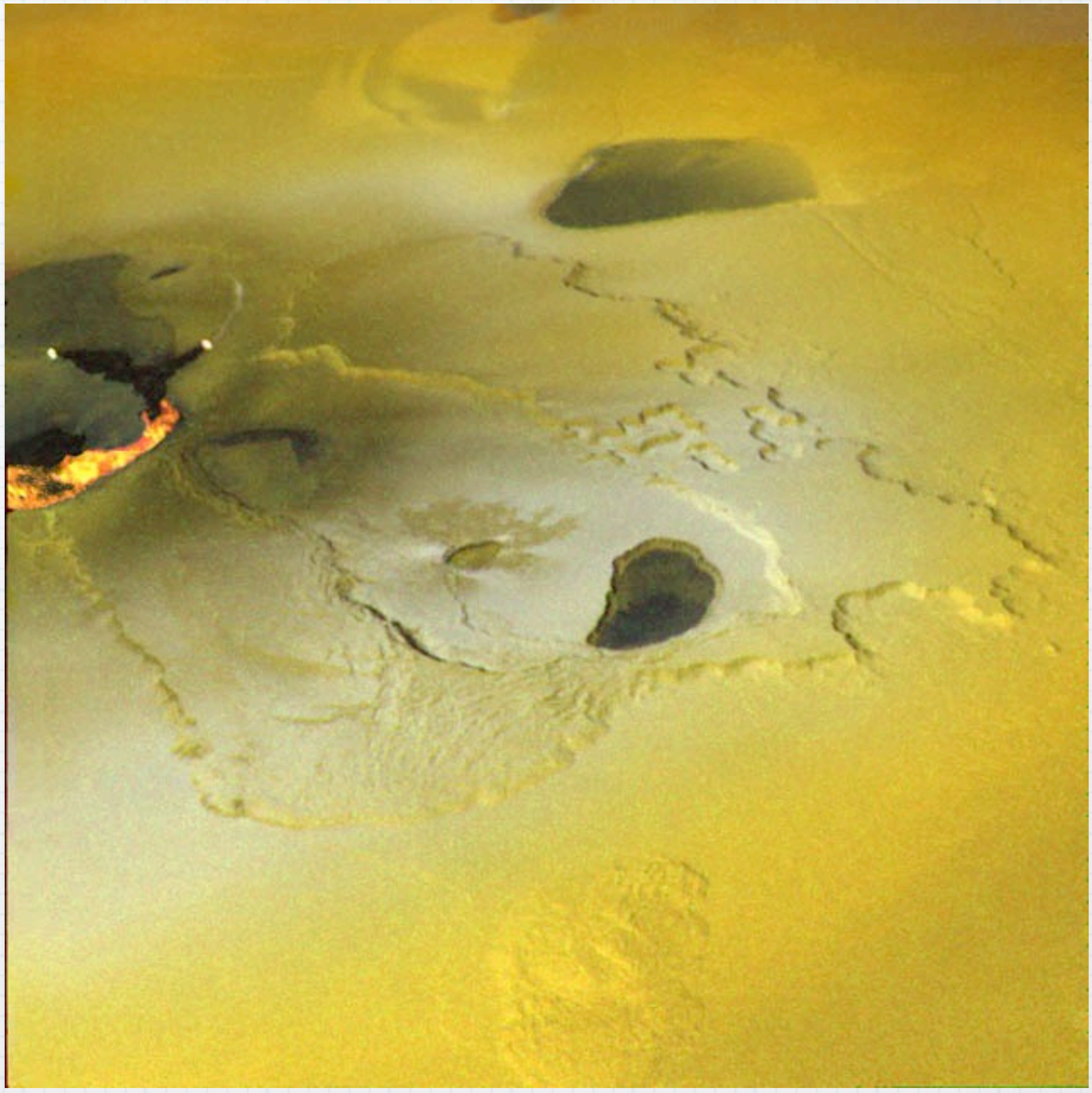
Exaggerated elliptical orbit of Io



Eruption of Pele on Io



An active volcanic eruption on Io



Io's Elliptical Orbit

* But why is the orbit of Io slightly elliptical? Why isn't virtually circular?

* The answer lies with Io's neighboring moons, Europa and Ganymede
* They are in orbital resonance with one another

Orbital Resonance

* When Ganymede has orbited Jupiter **once**
  i. Europa has orbited it **twice**
  ii. Io has orbited it **four times**

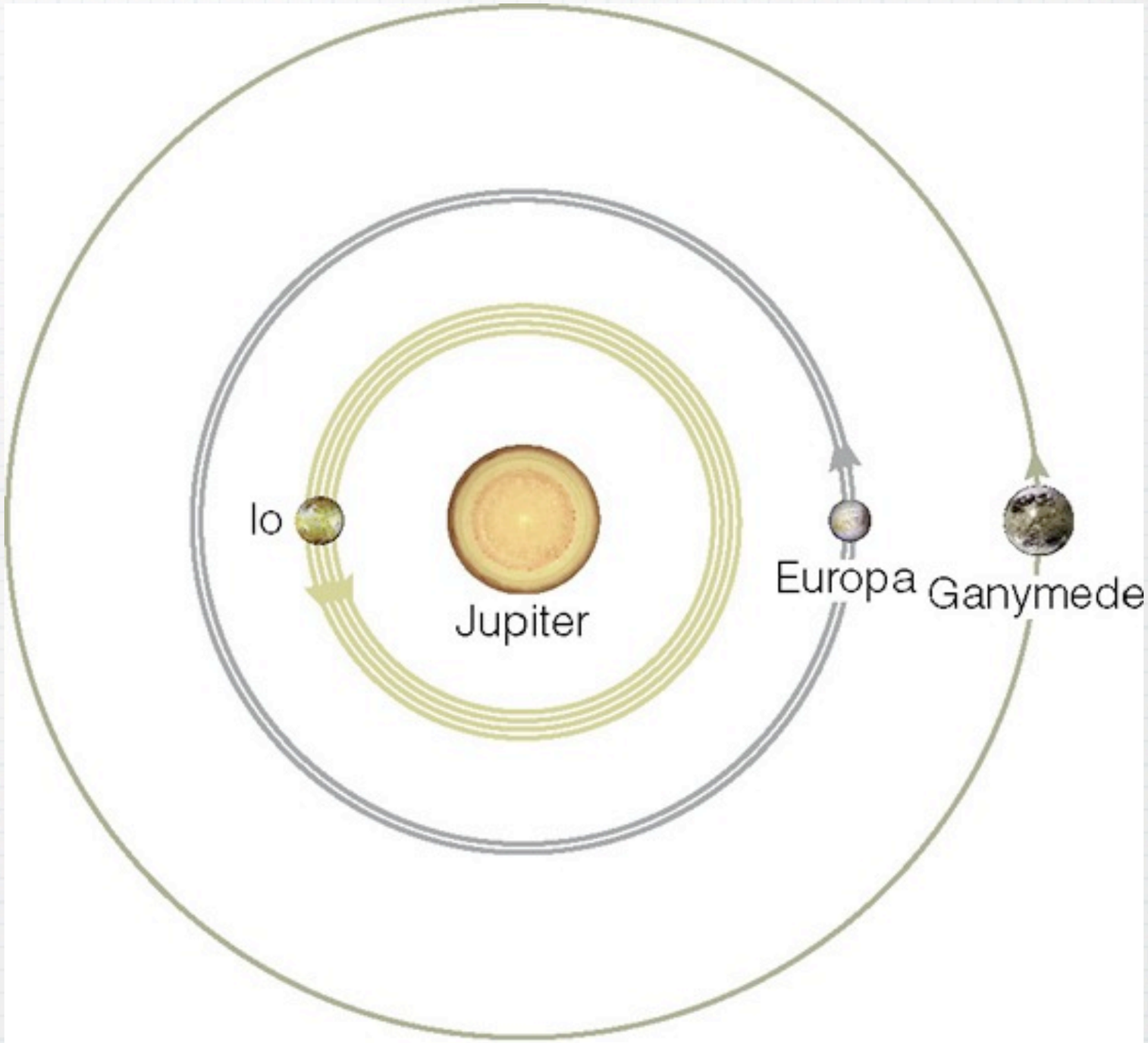
➡ This means that the moons line up often

➡ This alignment creates a gravitational tug on all three moons and they all have slightly eccentric orbits and tidal heating

Orbital Resonance

Every four Io orbits, the three moons are in this alignment which creates a small gravitational tug

This tug adds up over time and all 3 moons have elliptical orbits



Europa, a Water World

* Also suffers from a case of tidal heating but it is weaker as Europa is farther than Io from Jupiter

* Rather than showing a hellish face, **Europa is covered with (dirty) water ice!**

* **Few impact craters show**, as its surface gets renewed by ice

Europa, a Water World...

* Ongoing geological activity is suspected to have covered the past impacts

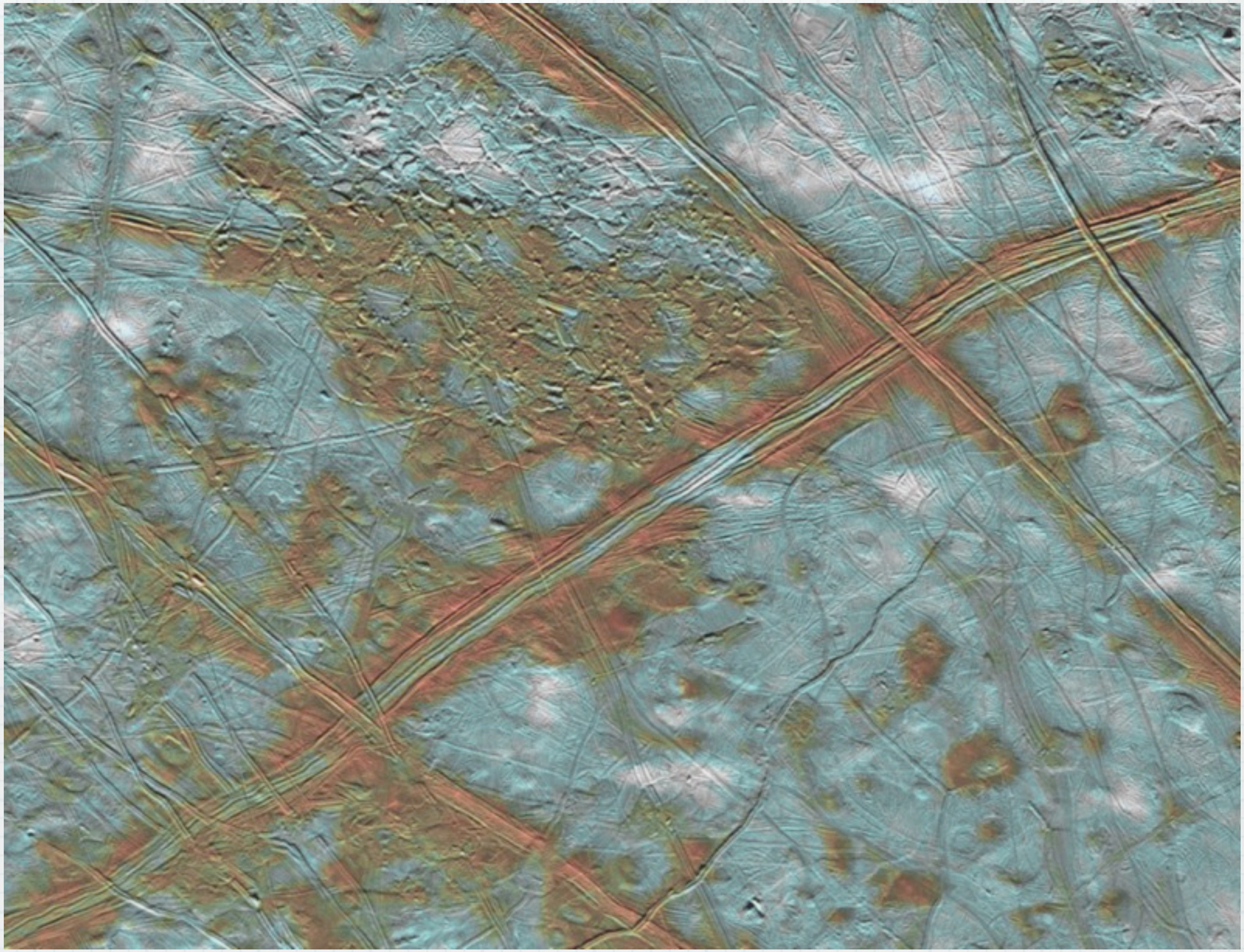
* Planetary scientists think that the ice is soft enough to convect or that the ice is not very thick and water can flow to the surface

Europa

Surface features of Europa

200x250 km

Domes, ridges, and crustal plates



Europa's Interior

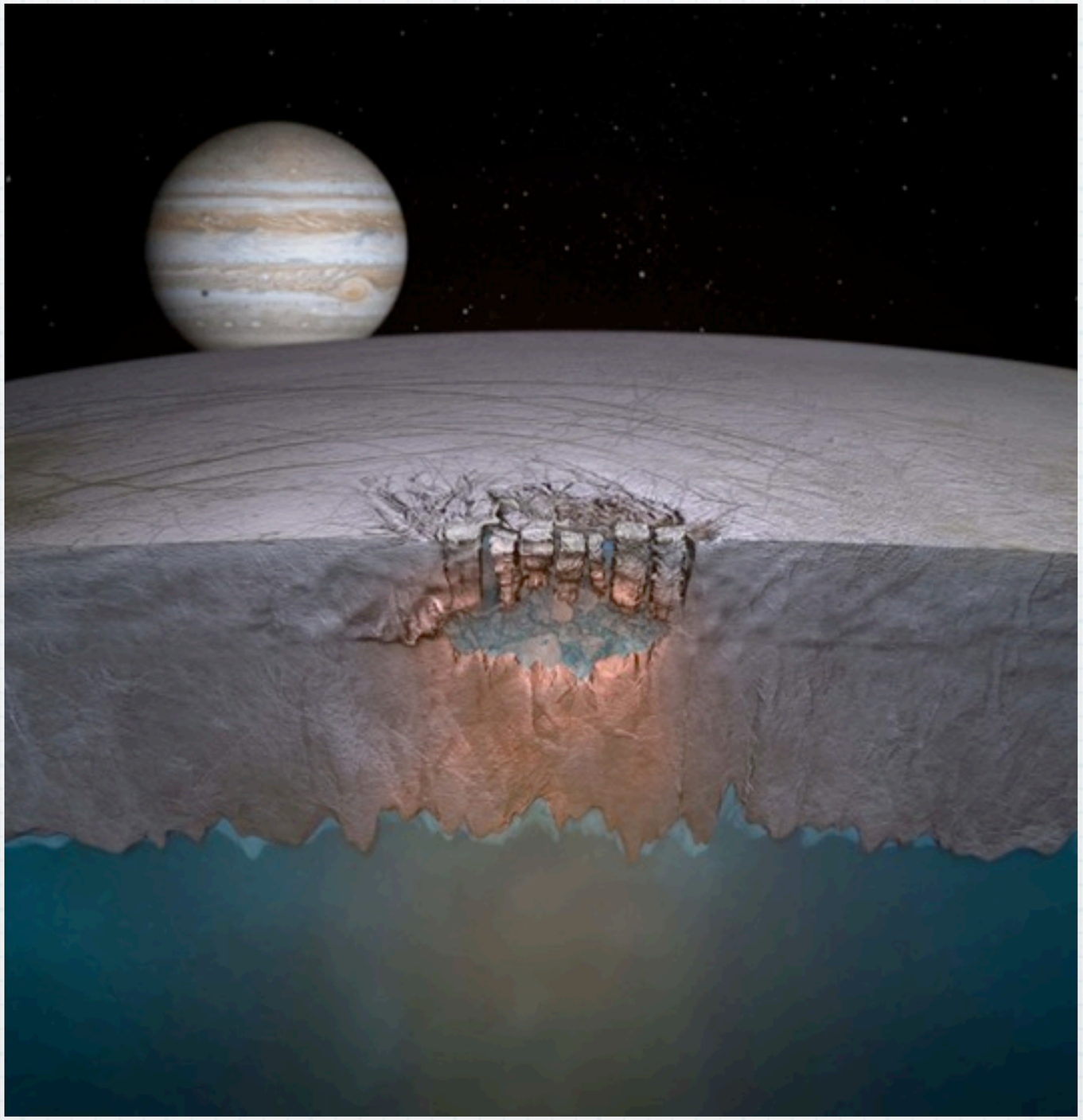
* Recent data suggest that Europa has

  i. a metallic core,

  ii. a rocky mantle,

  iii. and is surrounded by a layer of water 100 km (60 miles) thick!

NASA probe data show evidence of liquid water on icy Europa

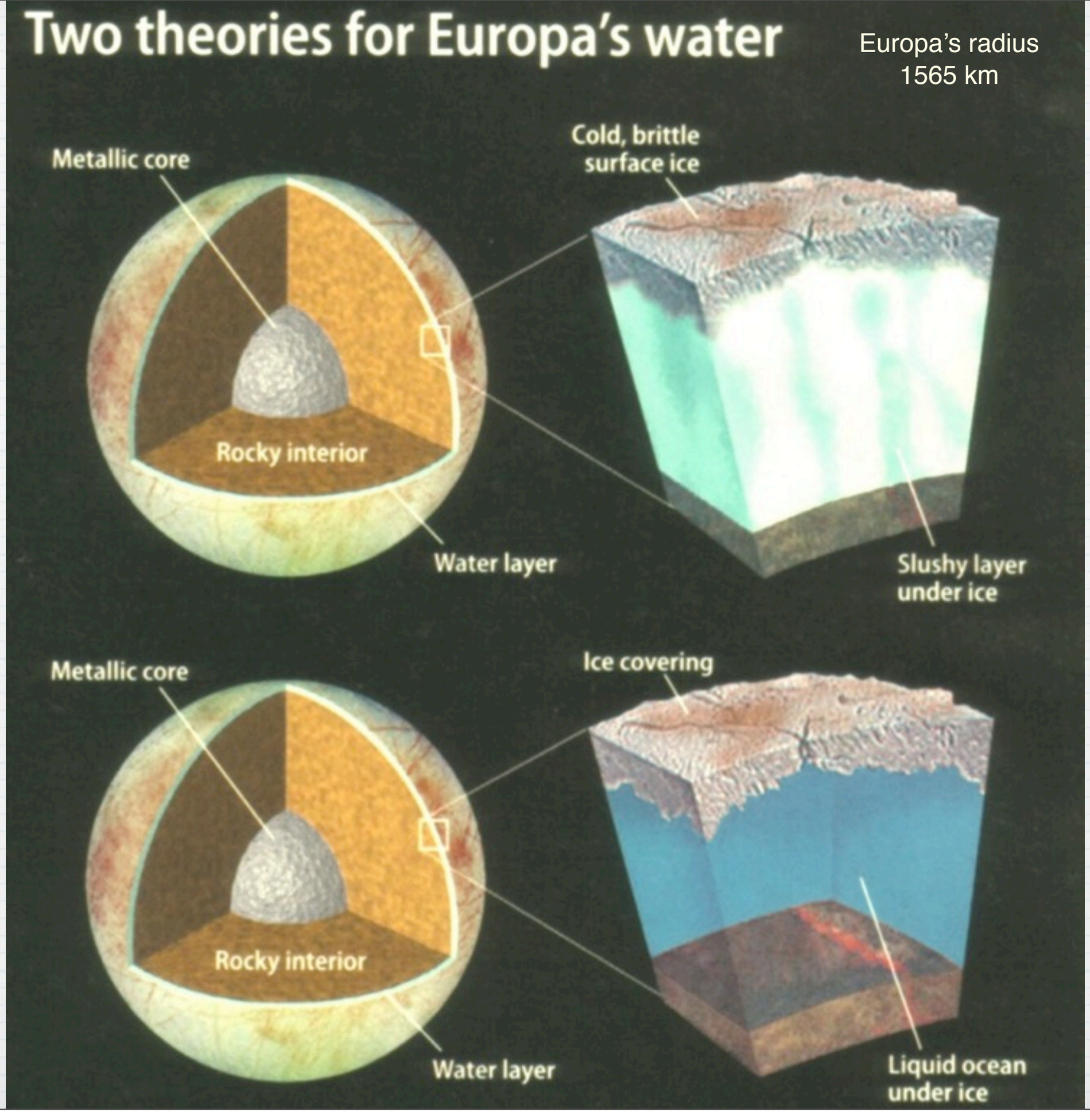


Europa's "Great Lake." Researchers predict many more such lakes are scattered throughout the moon's icy shell

Britney Schmidt/Dead Pixel VFX/Univ. of Texas at Austin

Two theories for Europa's water

Europa's radius
1565 km

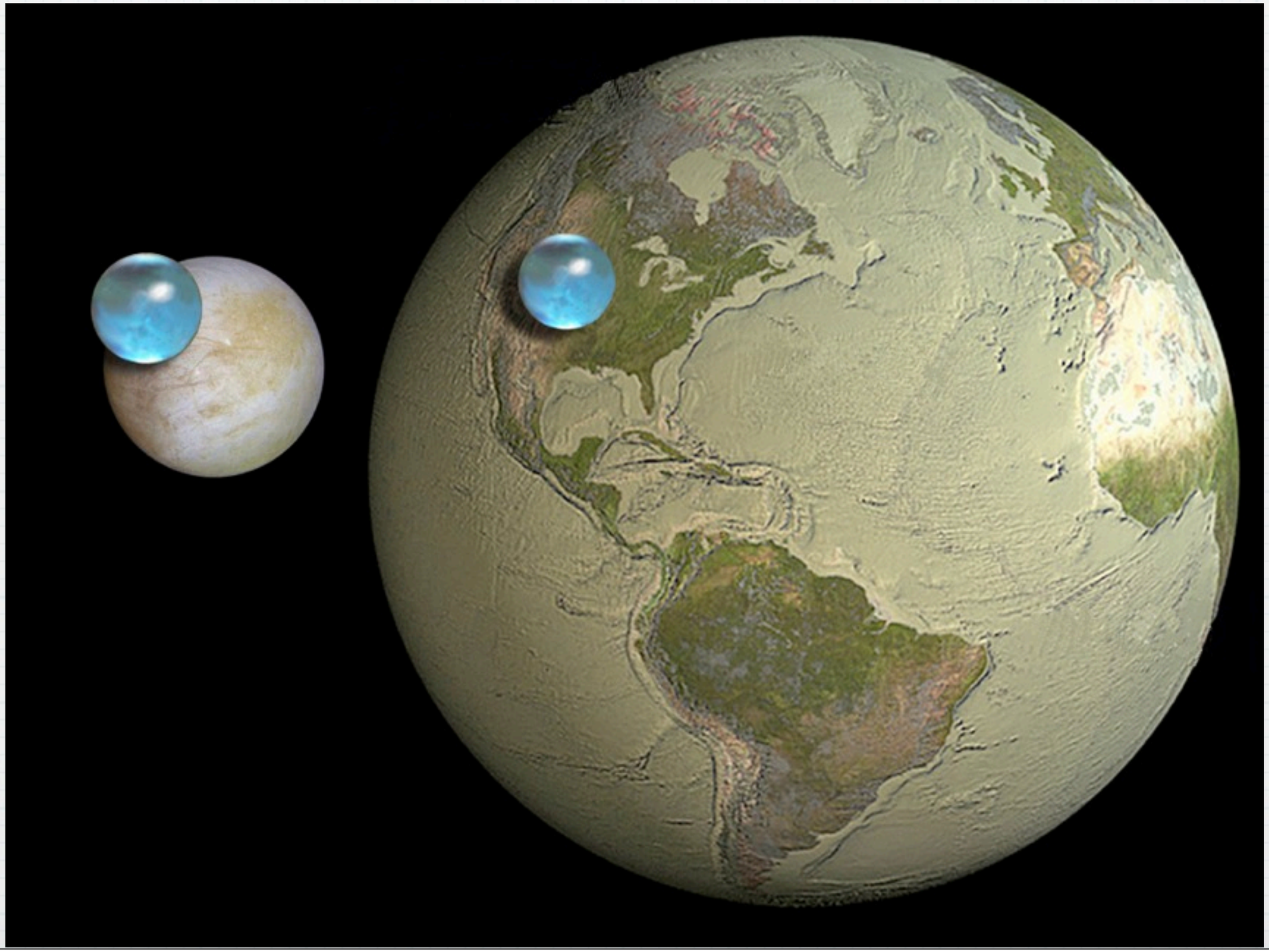


So Much Water

* Europa may contain twice as much more water than Earth

* Just as there is primitive life on Earth under the oceans near the volcanic vents, maybe Europa too is home to some similar lifeforms

Twice as much more water than Earth ??



Ganymede

* Like Europa, Ganymede has surface water ice
* But some regions are dark and are billions of years old while others appear much younger covered with water that surfaced and refroze recently
* Tidal heating is not strong enough for a liquid ocean underneath the thick icy surface
* So perhaps ongoing radioactive decay is present...

Ganymede

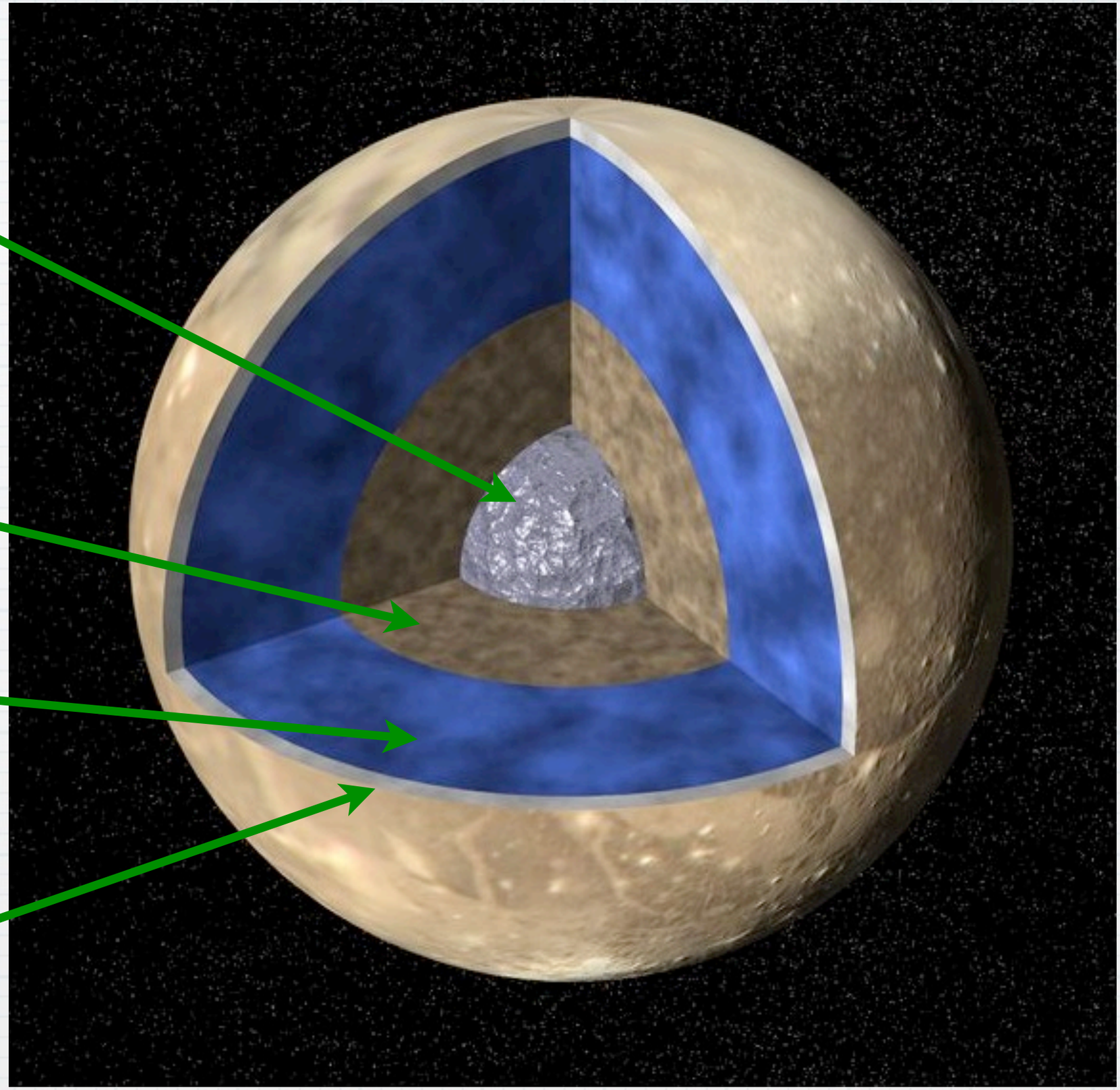
Ganymede

iron/sulfur core

rock shell

deep layer of warm soft ice

water ice crust



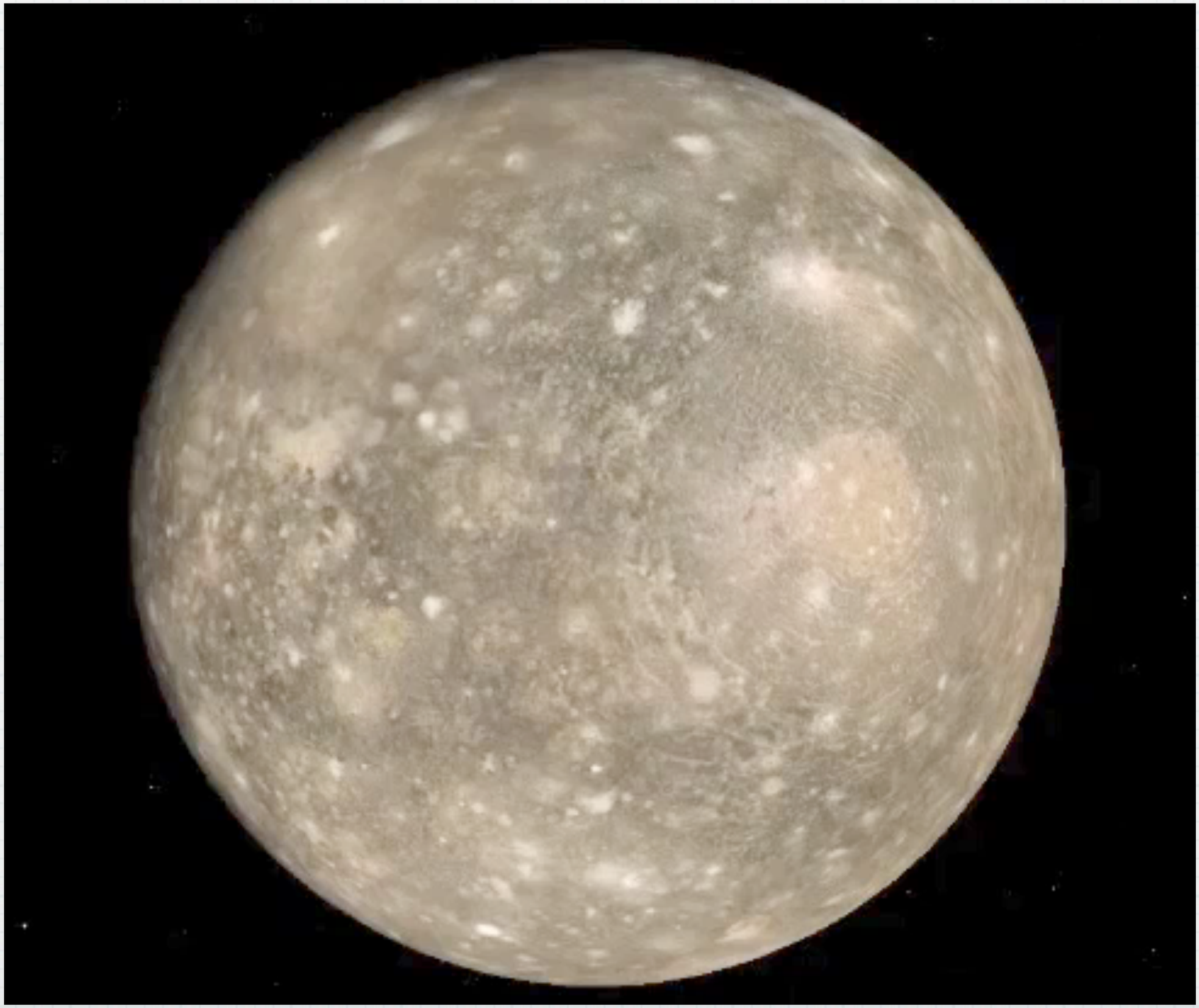
Ganymede: 2631 km radius

Callisto

* Callisto is a heavily cratered ice ball, just as scientists expected for a satellite of an outer Solar System gas planet
* Nevertheless, magnetic data shows that Callisto too could hide a subsurface ocean

Callisto

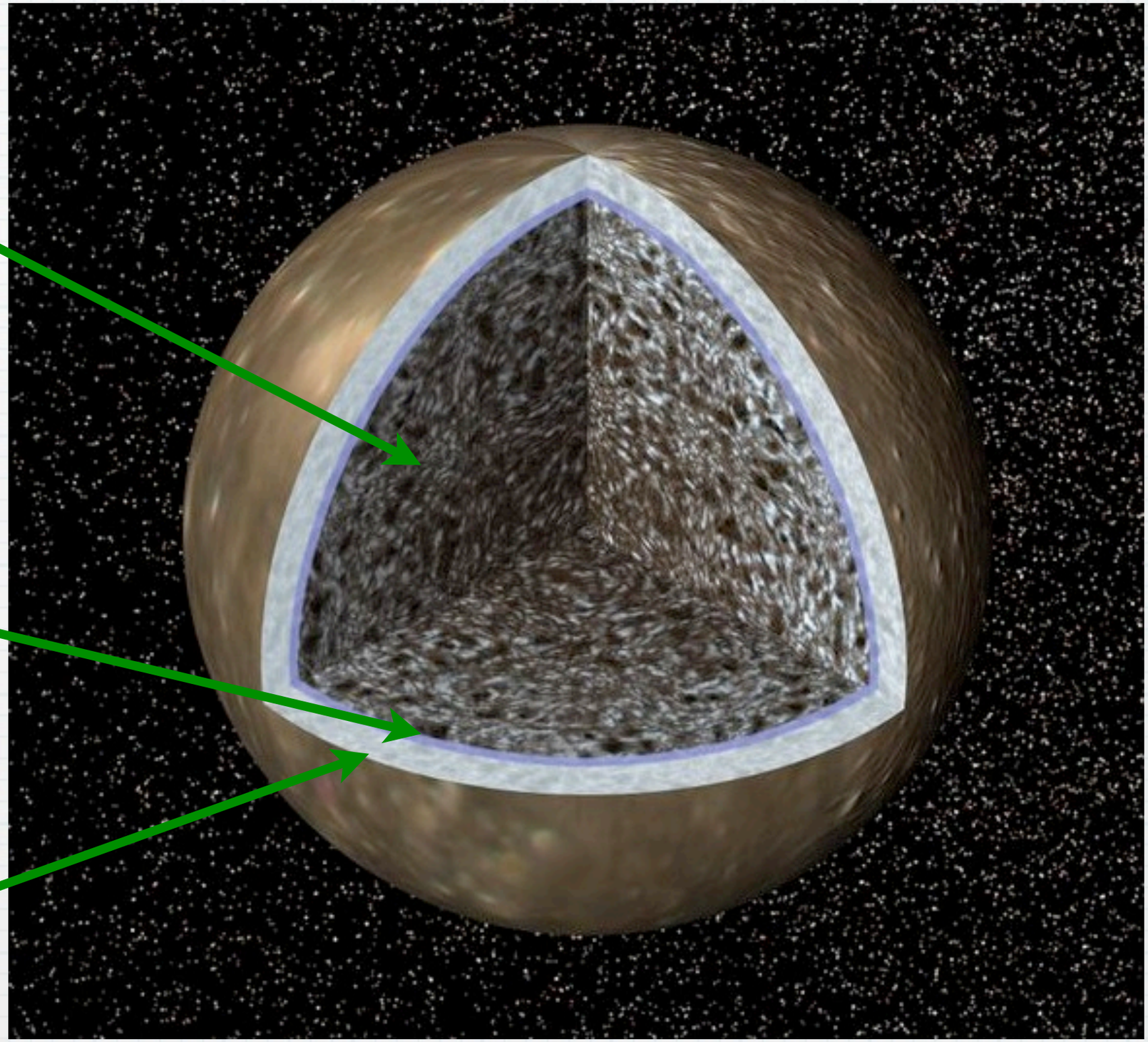
Callisto



compressed rocks and ice

salty water shell

water ice crust



Callisto: 2410 km radius

Saturn's Moons

* One large moon: Titan
  * second largest moon in Solar System
* Six medium-sized moons
* Five of which show sign of past geological activity

Titan

* It is unique in that it has a thick atmosphere which hides the surface from view (like Venus)

* The atmosphere is 90% nitrogen with argon, methane and ethane and other hydrogen compounds filling the rest

* Titan's atmosphere is smoggy!

Titan...

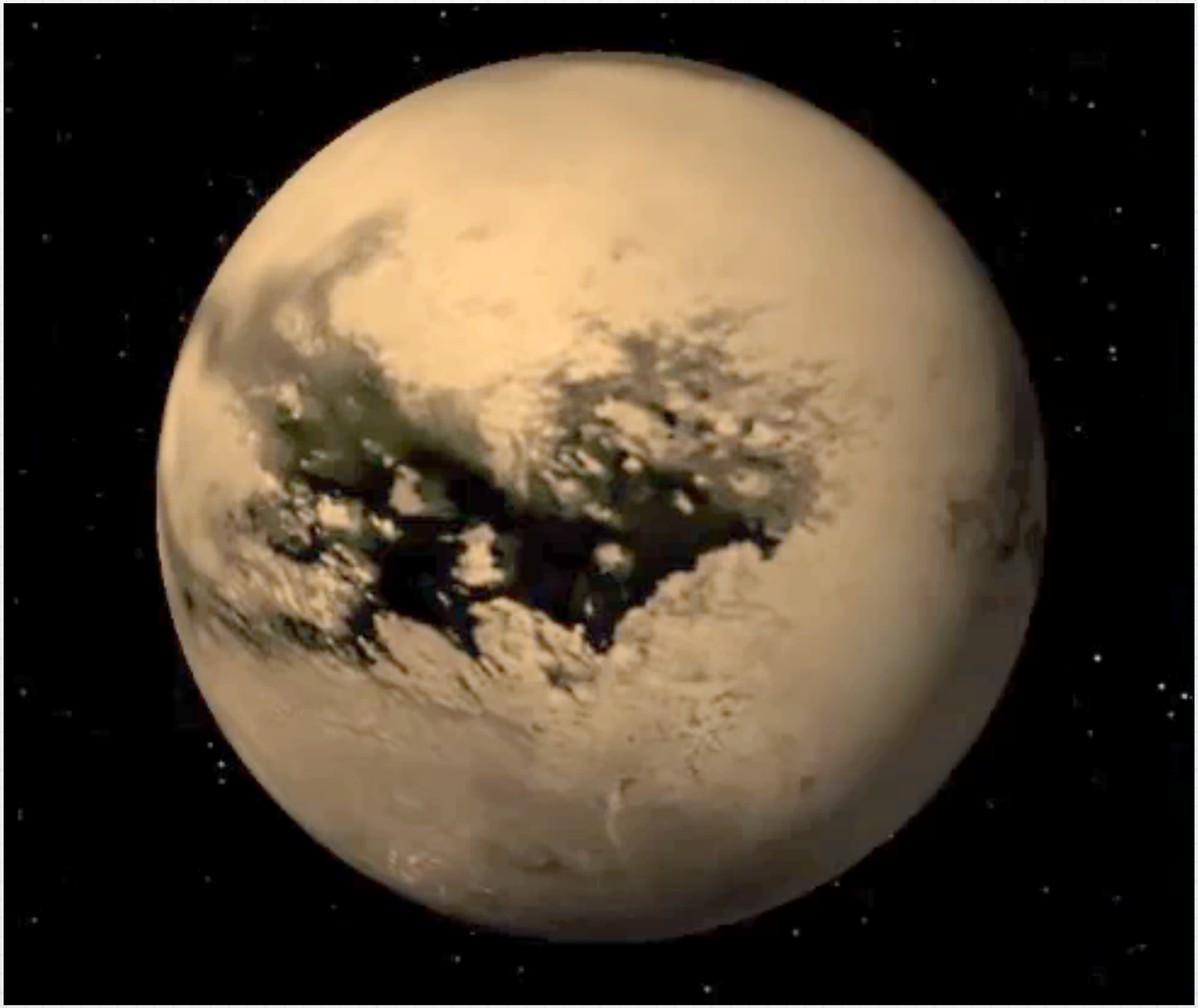
* Methane (CH_4) and ethane (C_2H_6) are both greenhouse gasses
* Its surface however is still frigid by human standards (93 K, or -180°C)
* Surface pressure is 1.5 times that on Earth
* If it were not for the lack of oxygen and the temperature, it could be comfortable for us

Titan...

* Titan's geology shows
  * impact cratering
  * winds creating erosional processes
  * river channels (carved by methane?)
  * faulting, tectonism, & volcanism
  * coastlines and lake-like features
  * bodies of surface liquid heavily suspected

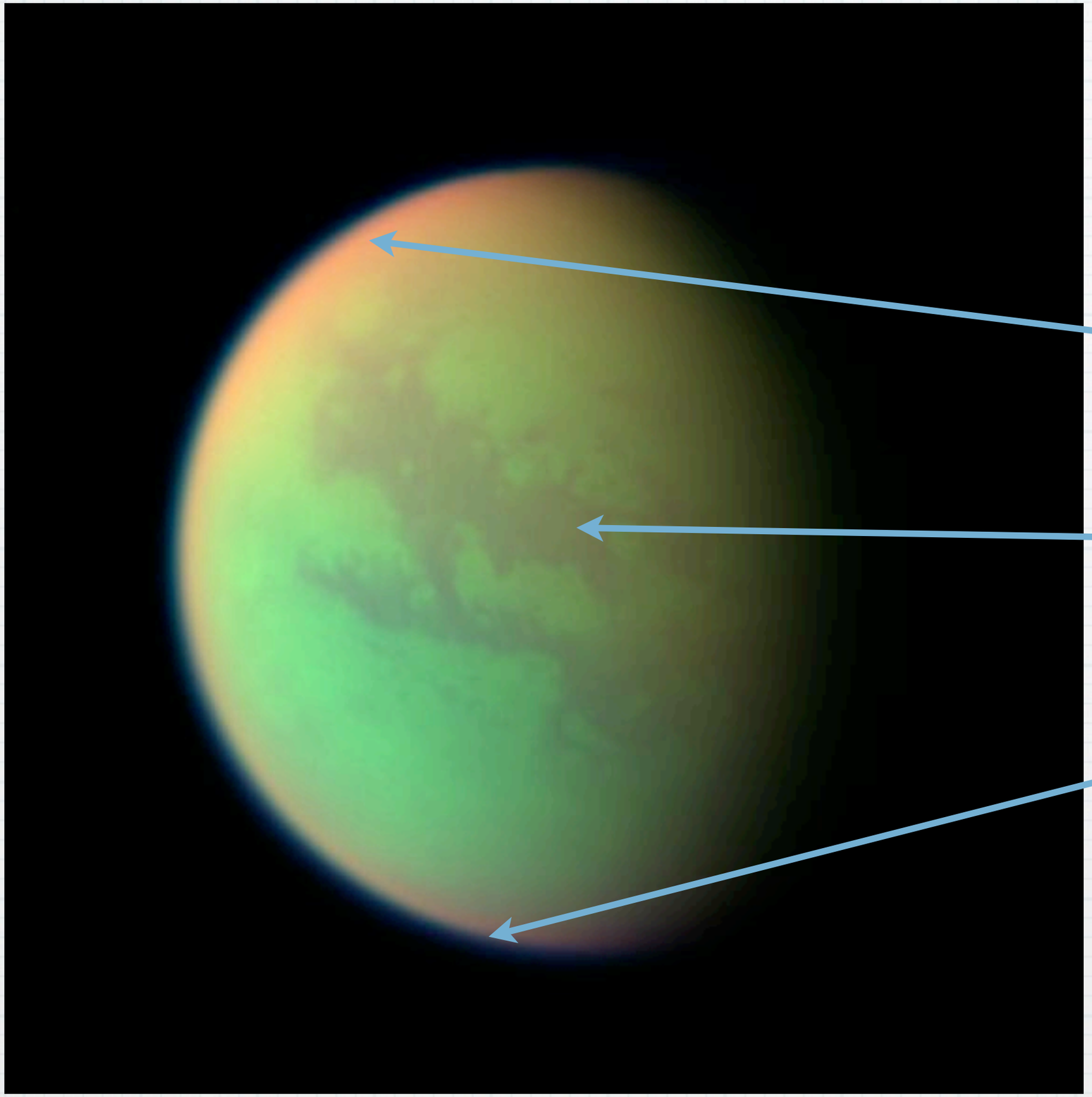
Titan

Titan



Titan

False color composite



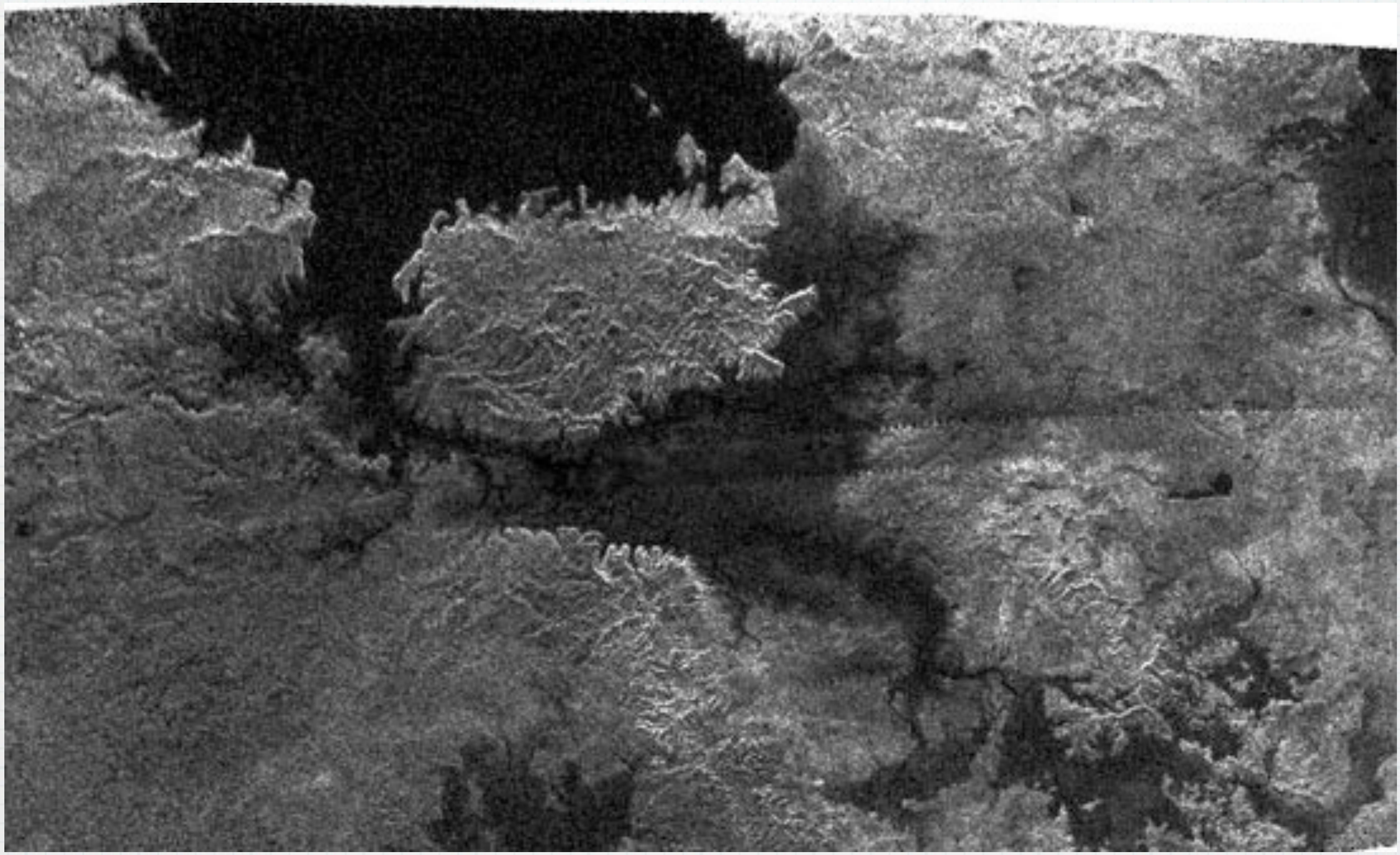
red
Atmospheric methane

green
Surface features

blue
Upper atmosphere
& haze

Mosaic of river channel and ridge area on Titan

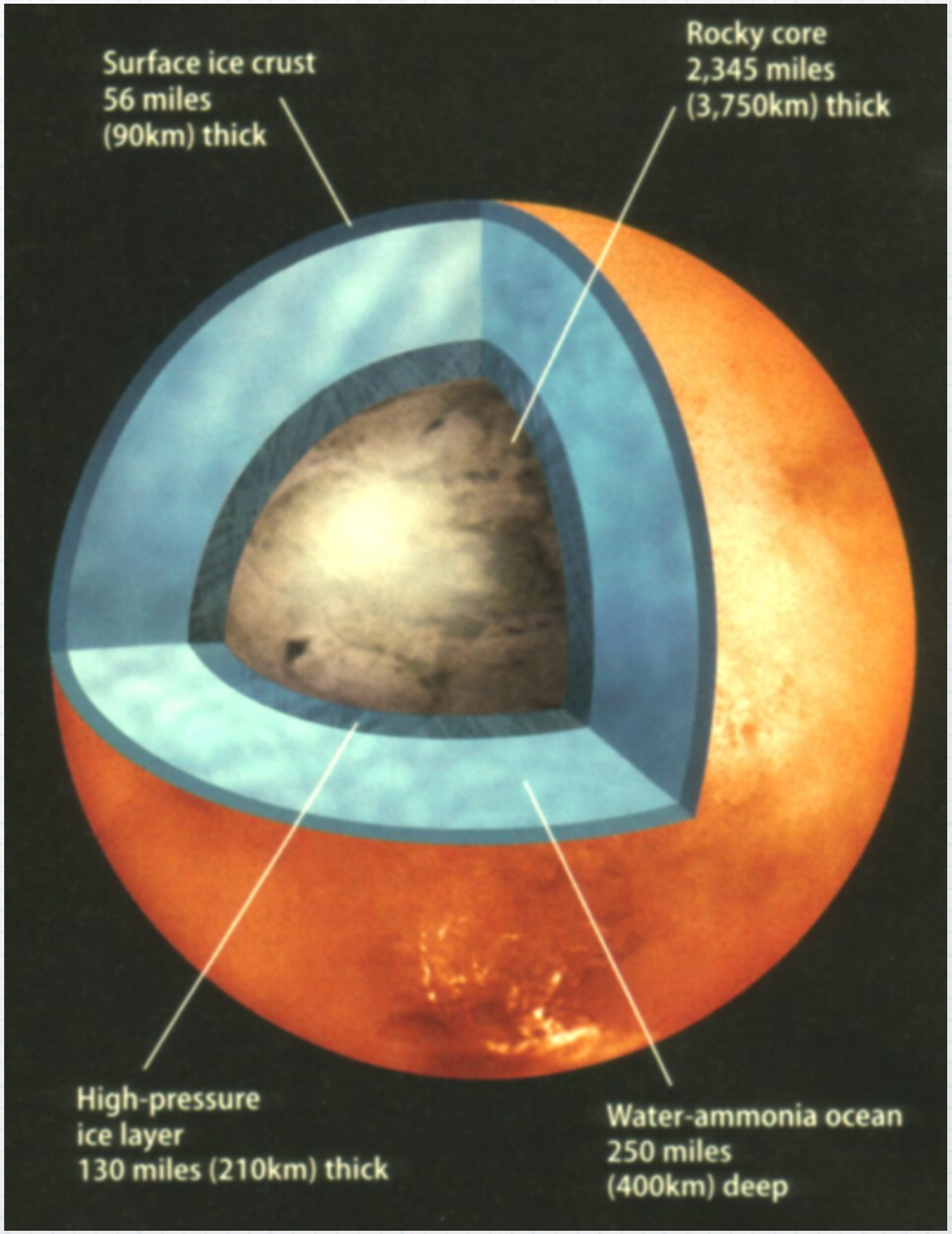
it is the only second body in the Solar System to possess liquids (methane lakes) on the surface



A model of Titan's interior

Large rocky core surrounded by layers of liquid and ice (mostly water)

Abundant ammonia which lowers the melting point of water producing a liquid zone despite the low temperature



Saturn's Medium-Sized Moons

* All six have heavily cratered surfaces
* They are far too small to have had significant past geological activities yet...
* Five of them show abundant evidence of past volcanism or/and tectonic activity

Saturn's Medium-Sized Moons...

* How is it possible that such small moons had heavy tectonic/volcanic activity in the past?

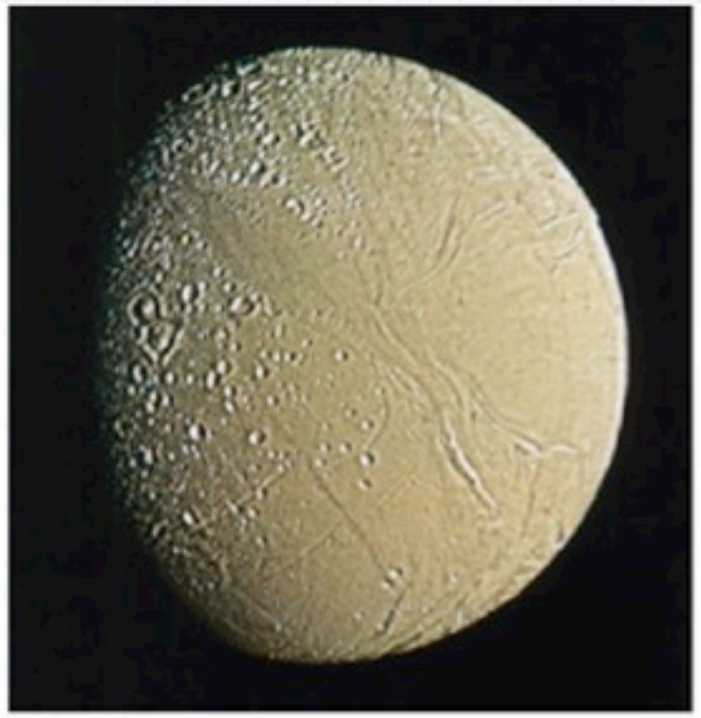
1. Because they are composed of ices as well as metals and rocks

2. And those ices can melt and deform at very low temperatures

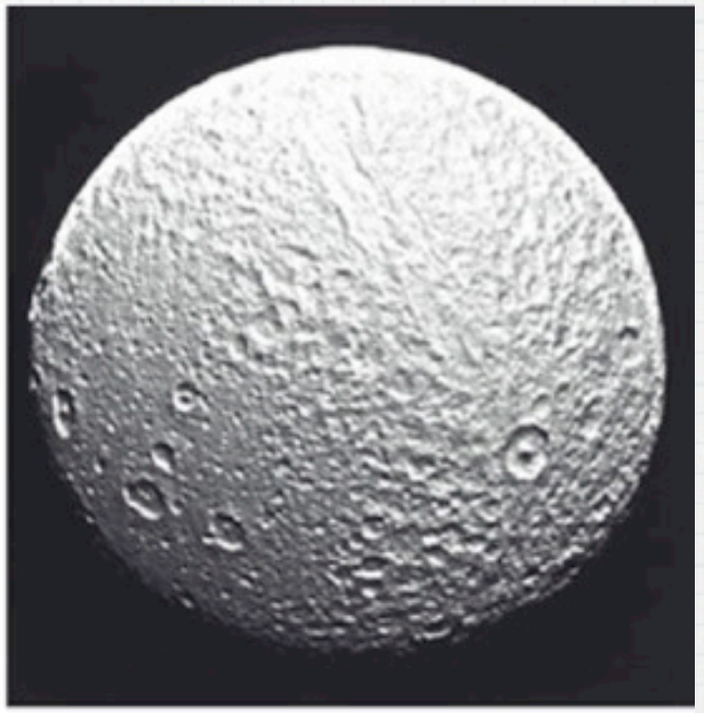
* We expect all these moons to have icy lava composed of water, methane and ammonia

Saturn's medium-sized moons

Mimas

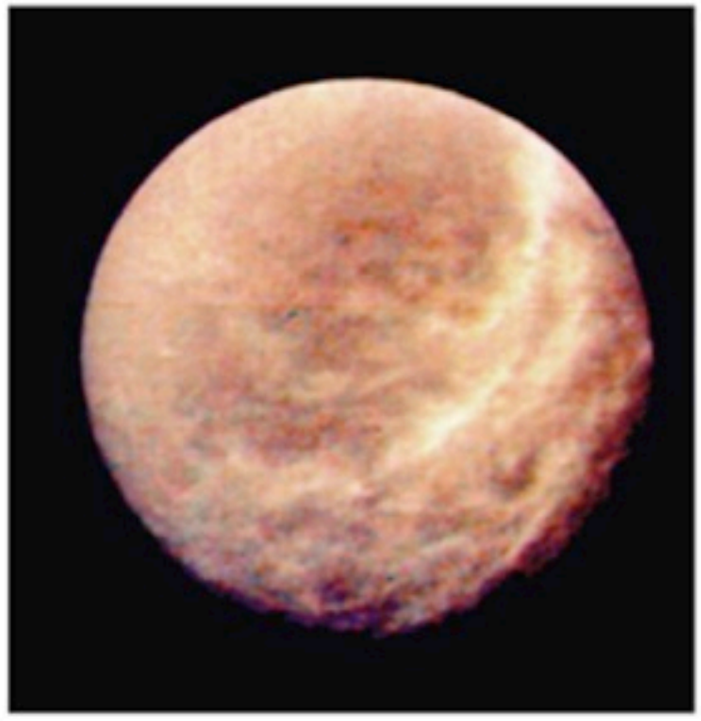


Enceladus

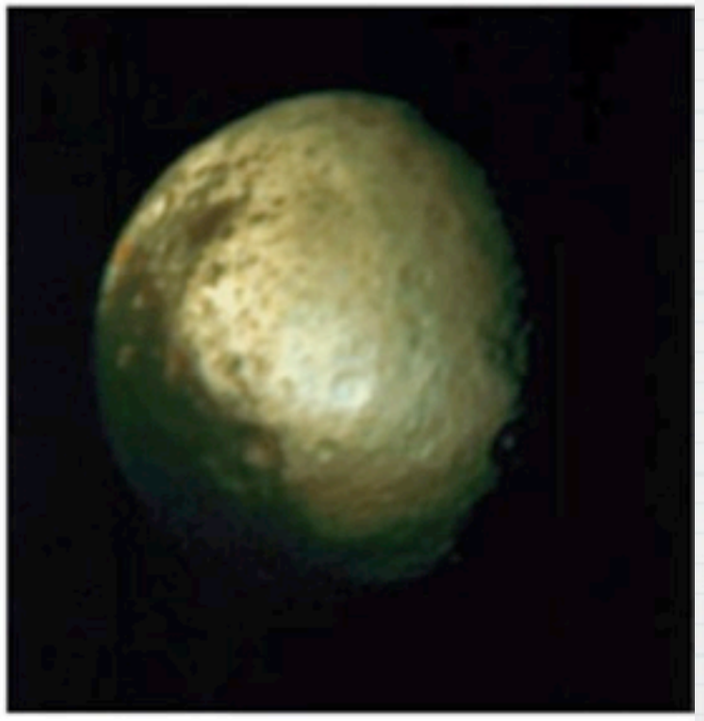


Tethys

Dione



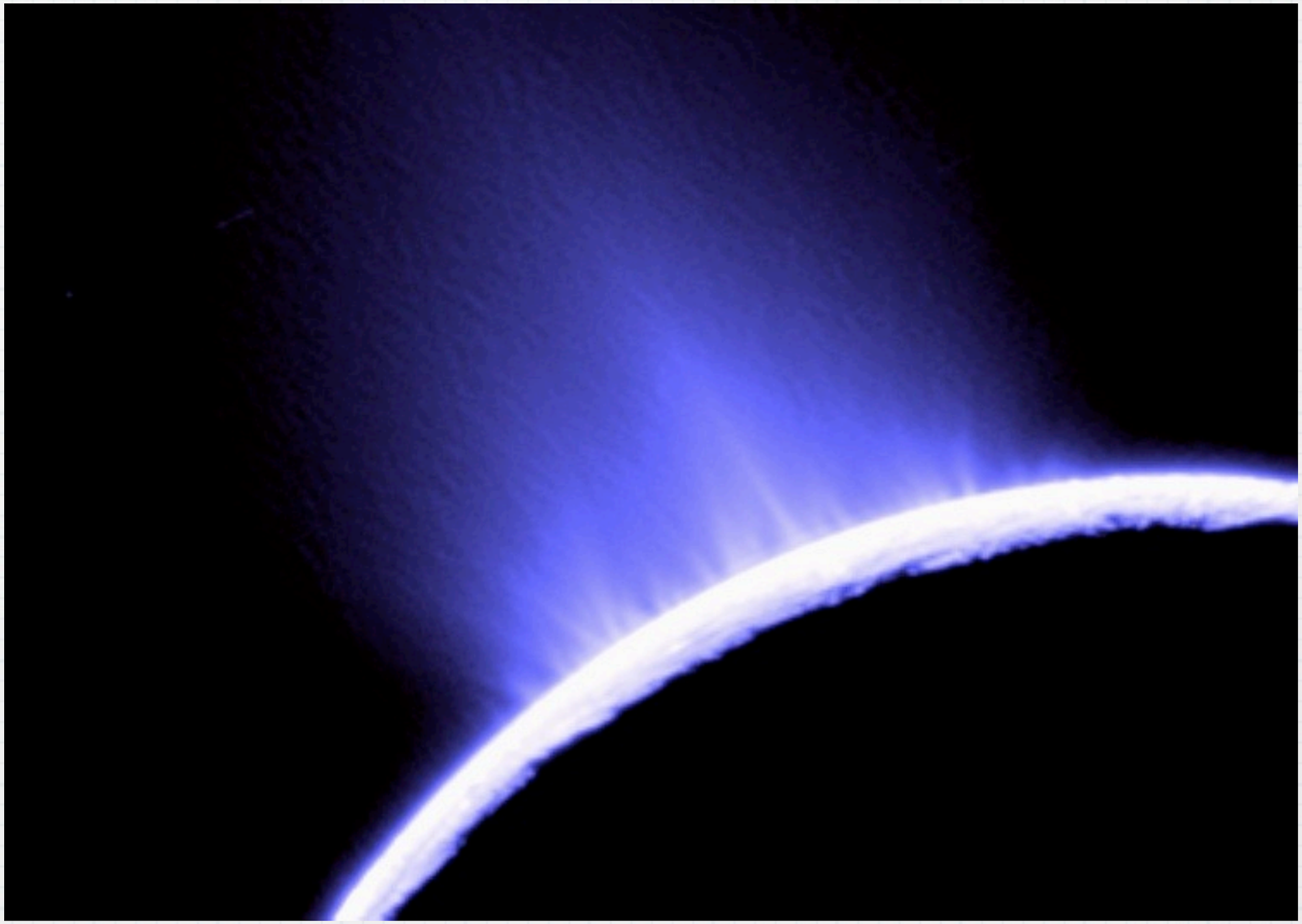
Rhea



Iapetus

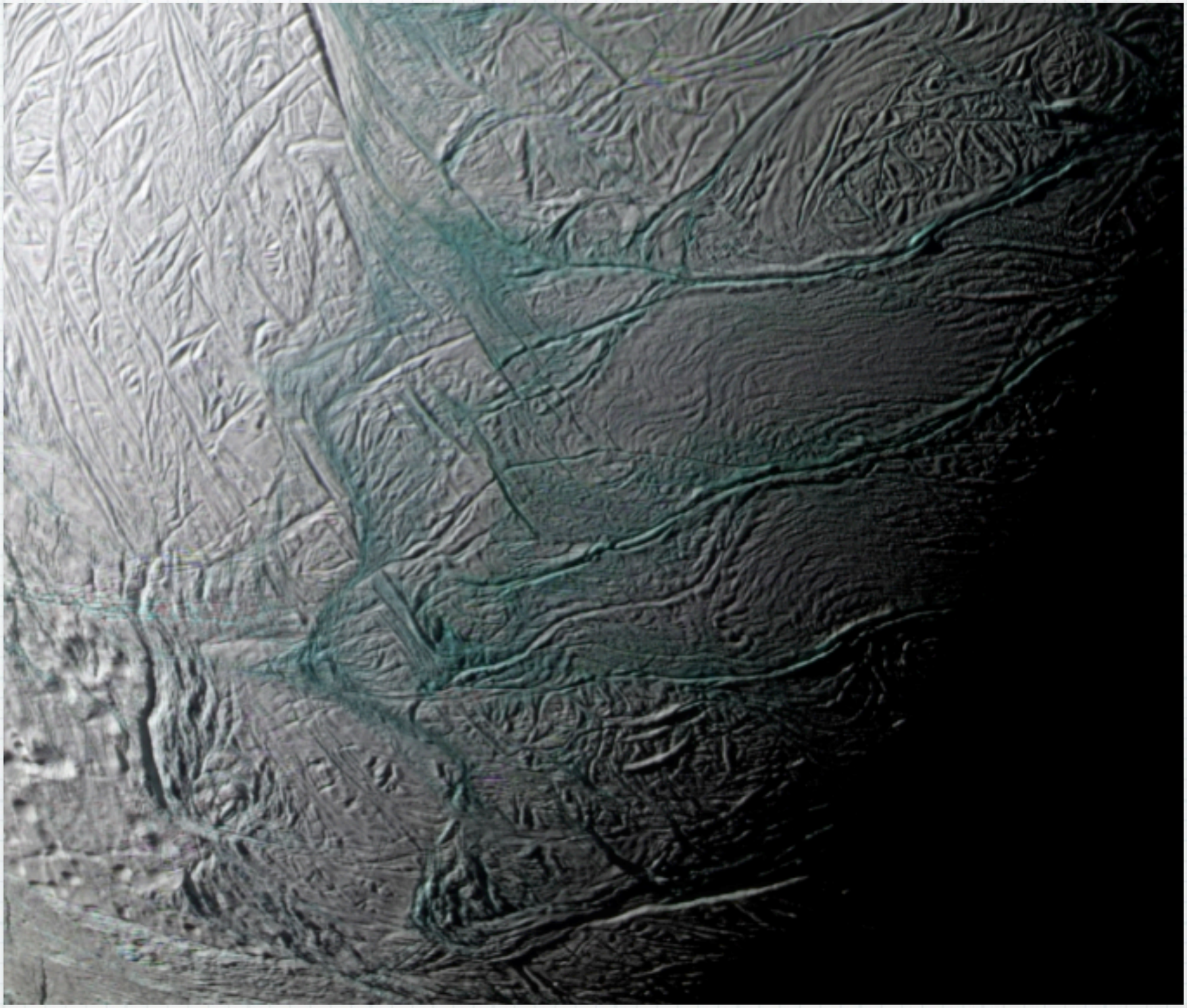
Enceladus Ice Geysers

Located along substantial surface fractures in the moon's south polar region



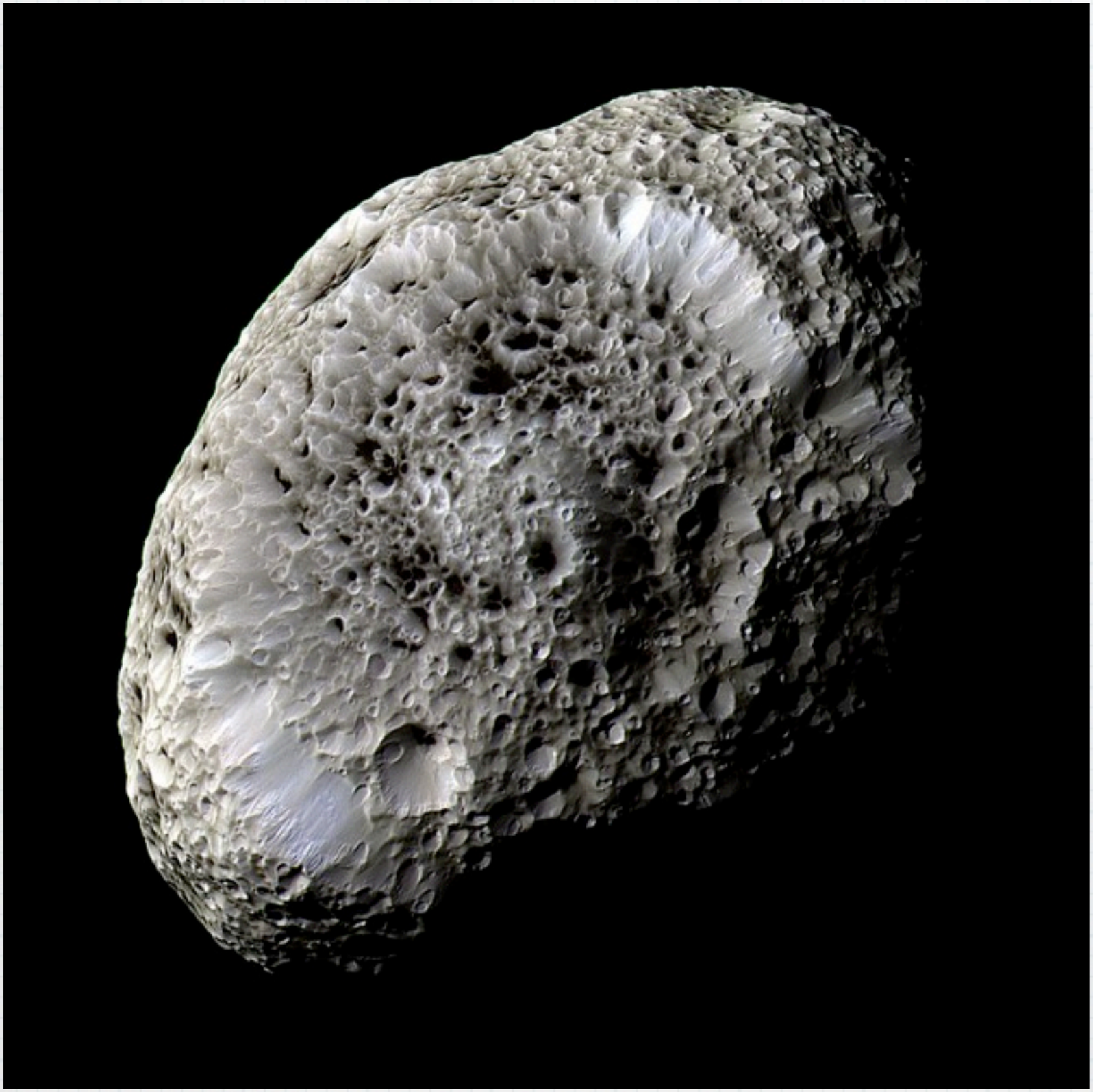
Source of Enceladus Ice Geysers

This sweeping mosaic of Saturn's moon Enceladus shows the cracks where the ice escapes from Enceladus' interior



Cassini spacecraft flew through the ice fountains

They are composed of water vapor laced with methane and organic molecules and escape via these cracks



Hyperion, a strange "spongious" moon of Saturn

Hyperion is the largest highly irregular (non-spherical) body in the solar system

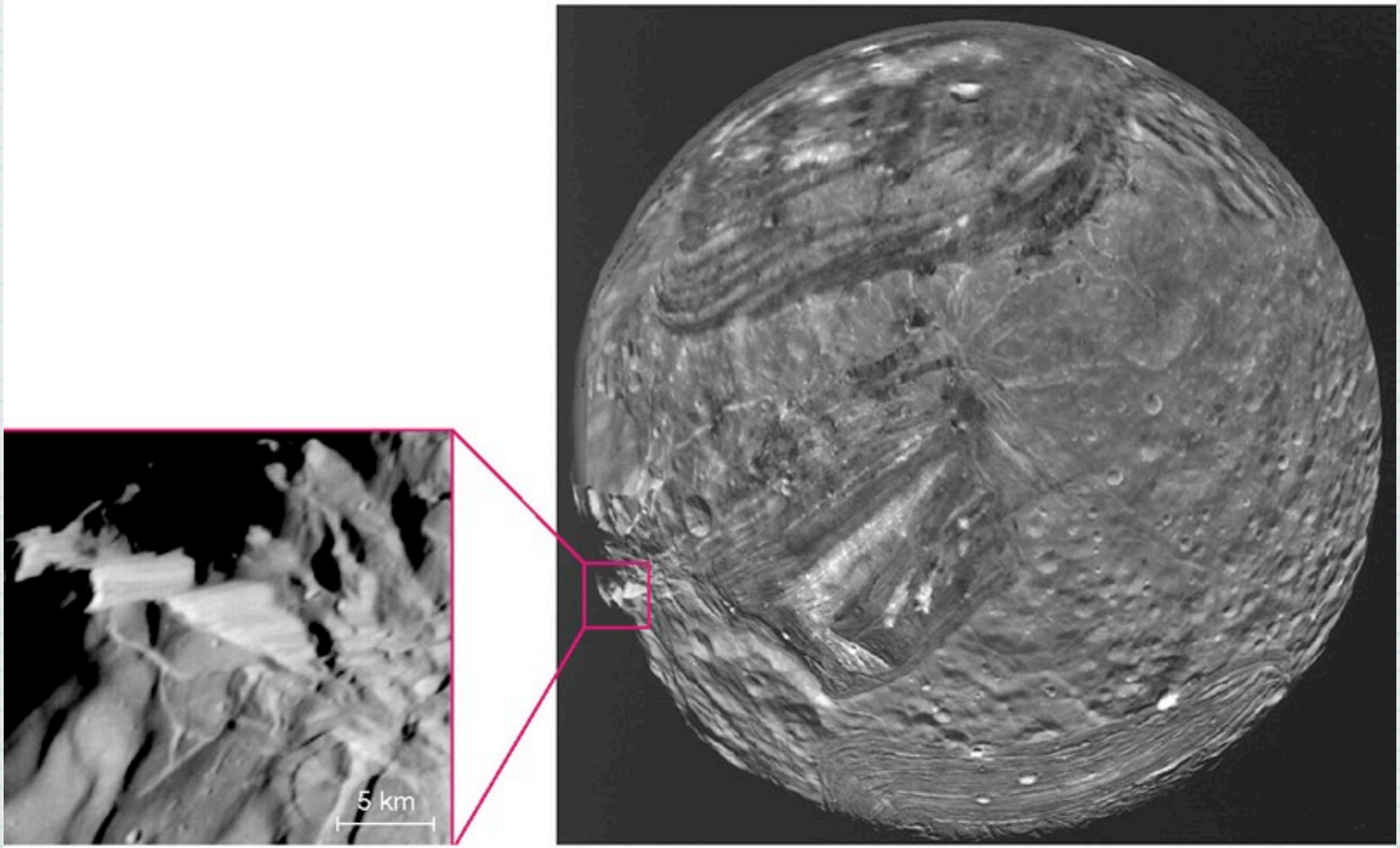
It is composed of water ice with only a small amount of rock and considerably porous

Uranus & Neptune's Moons

* They show further evidence of non-expected geological activity

* Uranus has five medium-size moons
  * at least 3 show such evidence
  * Miranda, the smallest of the 5 show tremendous tectonic features

Miranda, of Uranus, show cliff walls higher than those of the Grand Canyon on Earth



Uranus & Neptune's Moons...

* Triton, a moon of Neptune, has an orbit which is opposite (retrograde) to Neptune's own rotation and has a high inclination
* So it must have been captured, especially since
* its composition is likely a primordial mixture of ice, rock and carbon-containing compounds similar in many ways to material seen in Pluto

Triton, Neptune's largest moon

A thin atmosphere and evidence for **ice volcanoes**

Most likely, Triton is a captured comet

Terrestrial vs. Jovian Moon Differences

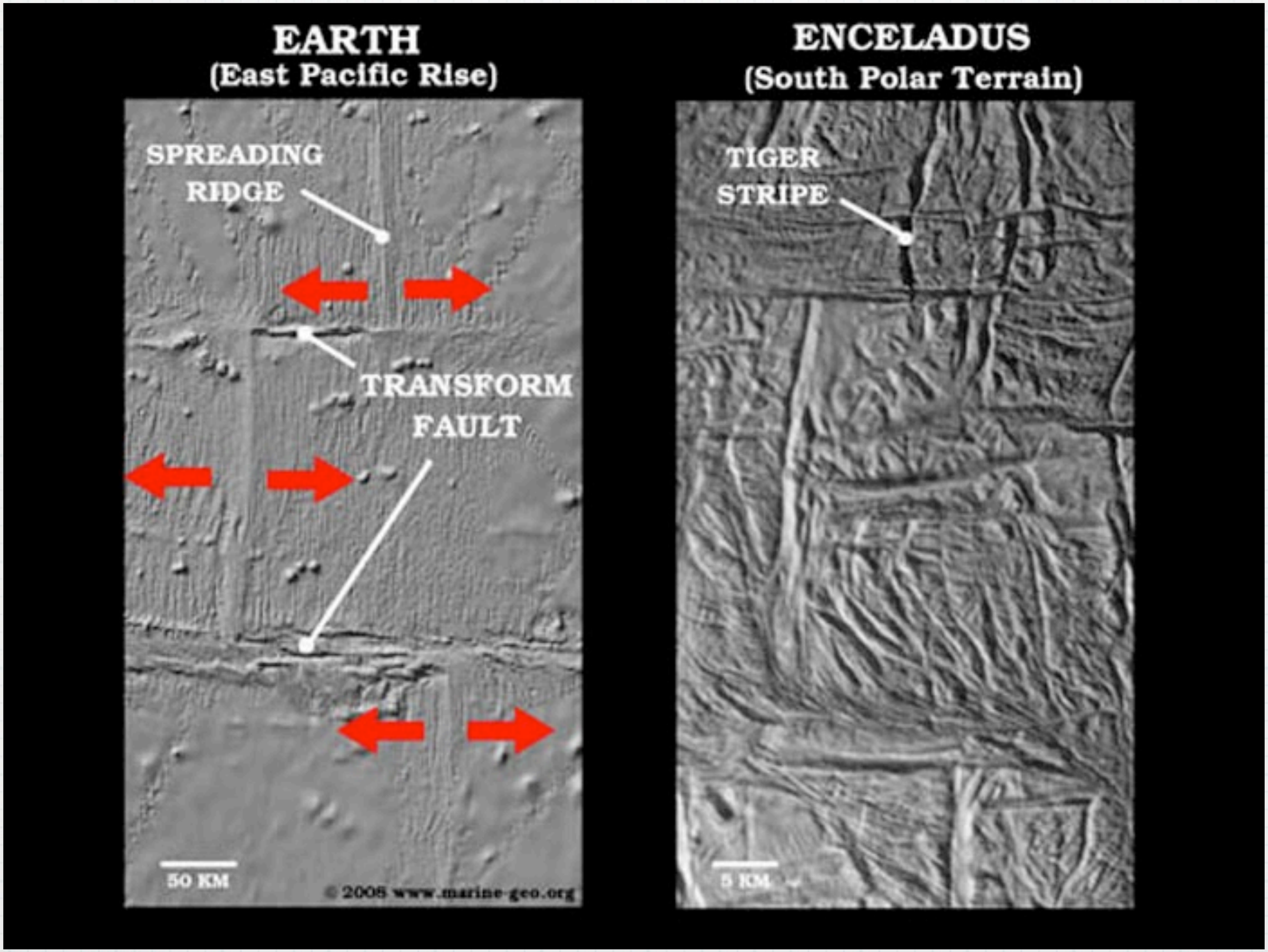
	Terrestrial	Jovian
Internal heat	radioactive decay	tidal heating
Constituents	metals, rocks	metals, rocks & hydrogen compounds

Terrestrial vs. Jovian Moon Differences...

* The hydrogen compounds help form icy materials

1. They deform at much lower temperatures than rocks
2. They permit geological activity on much smaller moons

Enceladus of Saturn shows signs of an active world



earthlike spreading of the icy crust

Rings

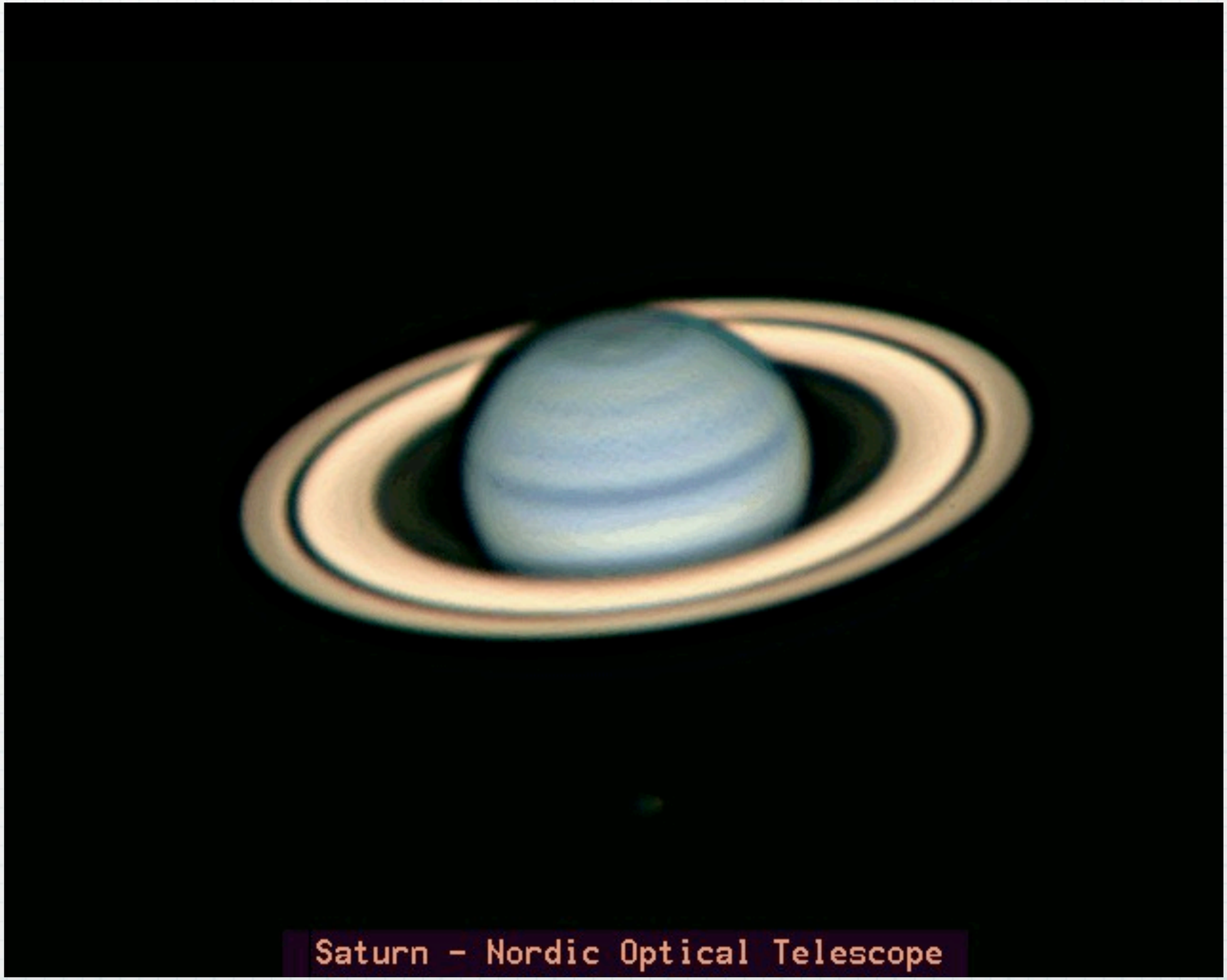
* Saturn's are the most spectacular and can be seen from Earth with binoculars

* Jupiter, Uranus and Neptune have rings too but they are much smaller and they were only discovered when Voyager I and II explored them

Saturn's Ring Composition

* From Earth, they look thin and solid, made of concentric sheets of material
* There is a large gap called the Cassini division

The Cassini division is easily seen



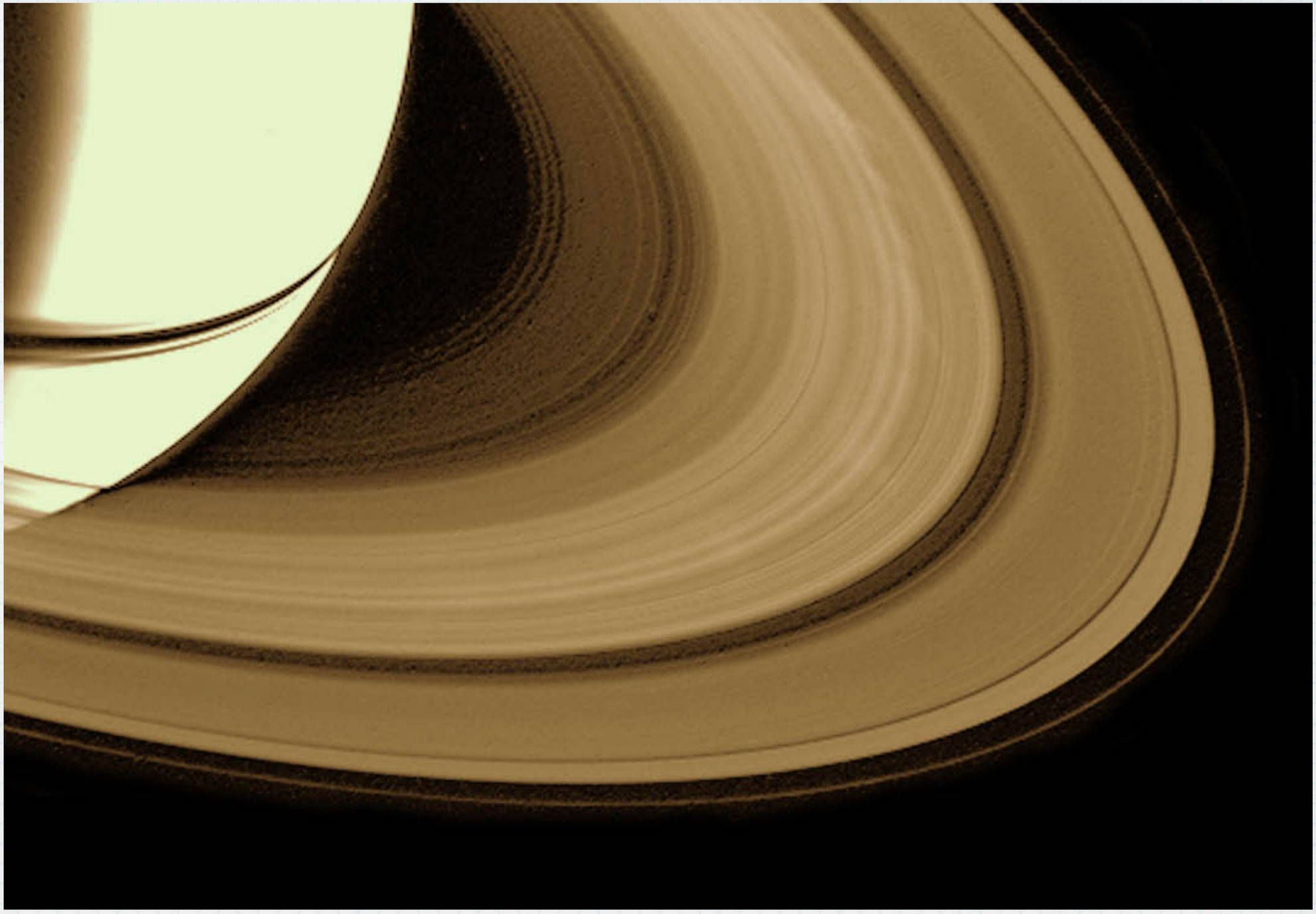
Cassini crossing the rings

Saturn's Ring Composition...

* From Saturn's itself, the rings become more numerous, each separated by narrow gaps
* They are composed of countless icy particles ranging in size from dust grains to large boulders
* They are a few tens of meters thick

The many more rings of Saturn

Even the Cassini division has rings inside

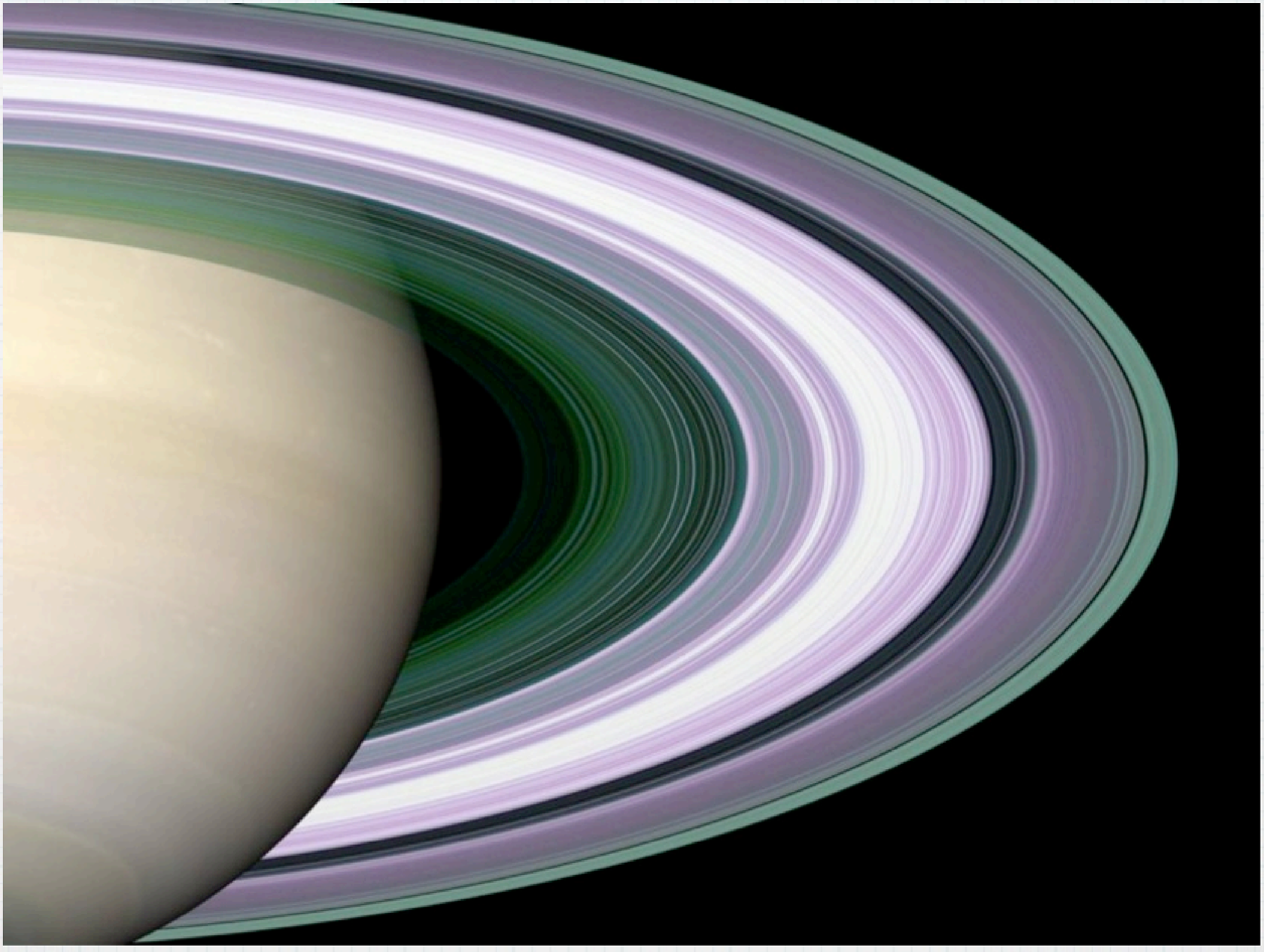


A radio picture: 1 cm, 3.5 cm, and 13 cm wavelengths

green:
< 1 cm

purple:
> 5 cm

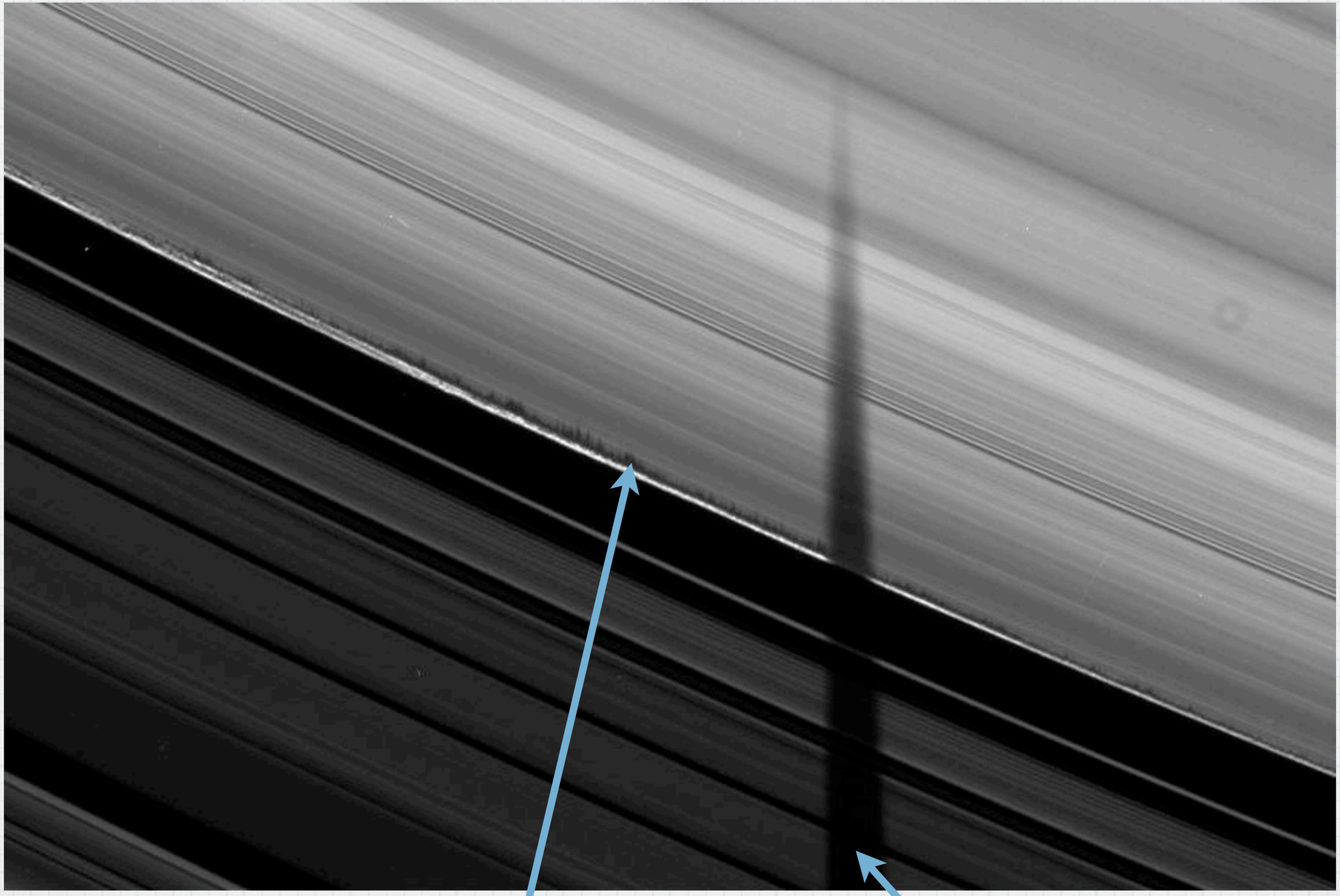
white:
cannot
tell



Saturn's Ring Composition...

* Spectroscopic analysis show that the rings are made of water ice
* Each ring orbits Saturn independently
* Some are so close to one another that they frequently collide with one another

Jagged Shadows May Indicate Particles of Saturn Ring



jagged shadows of transient groups of particles

shadow of Mimas

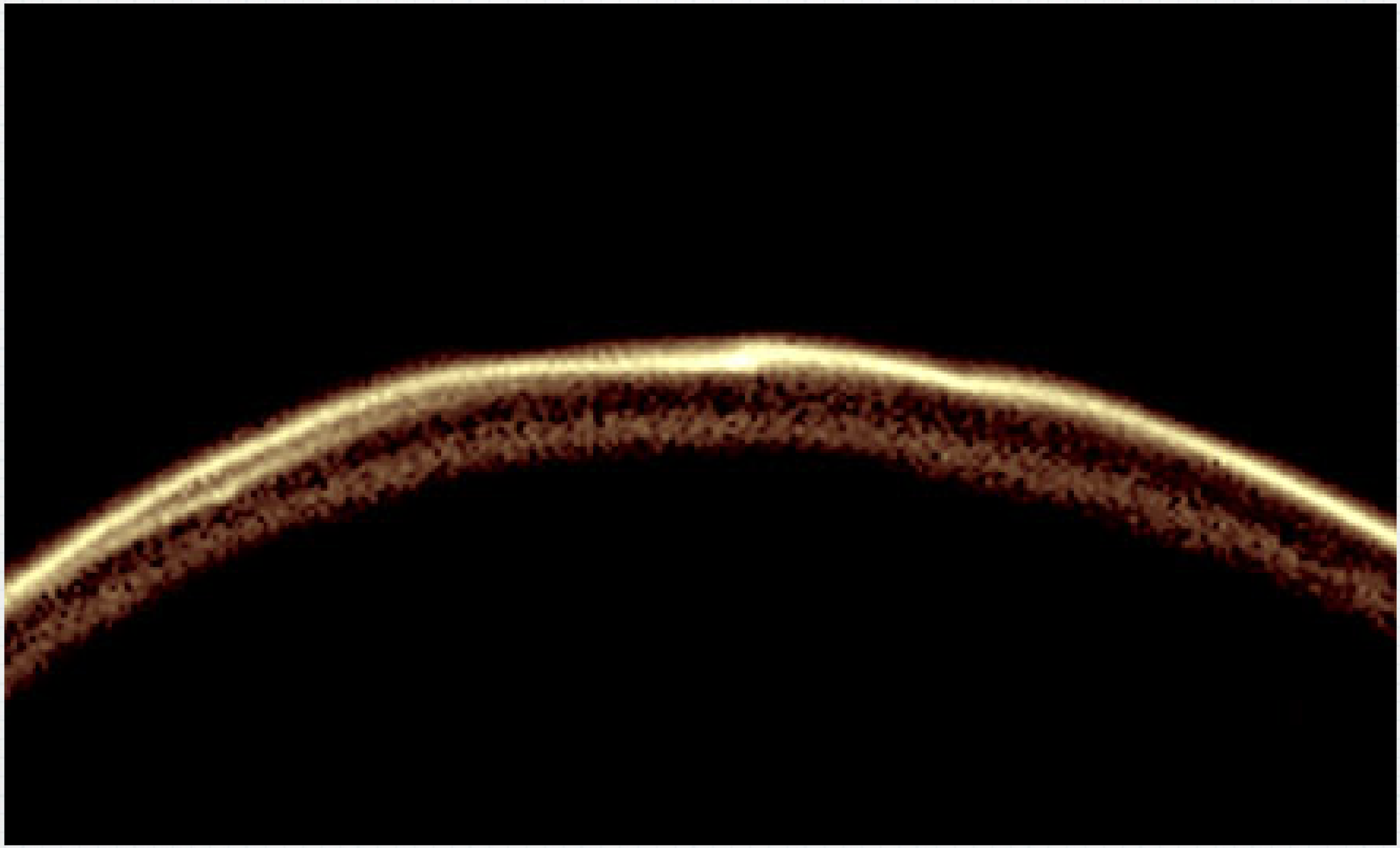
Credit: NASA, JPL, Space Science Institute

Other Ring Features

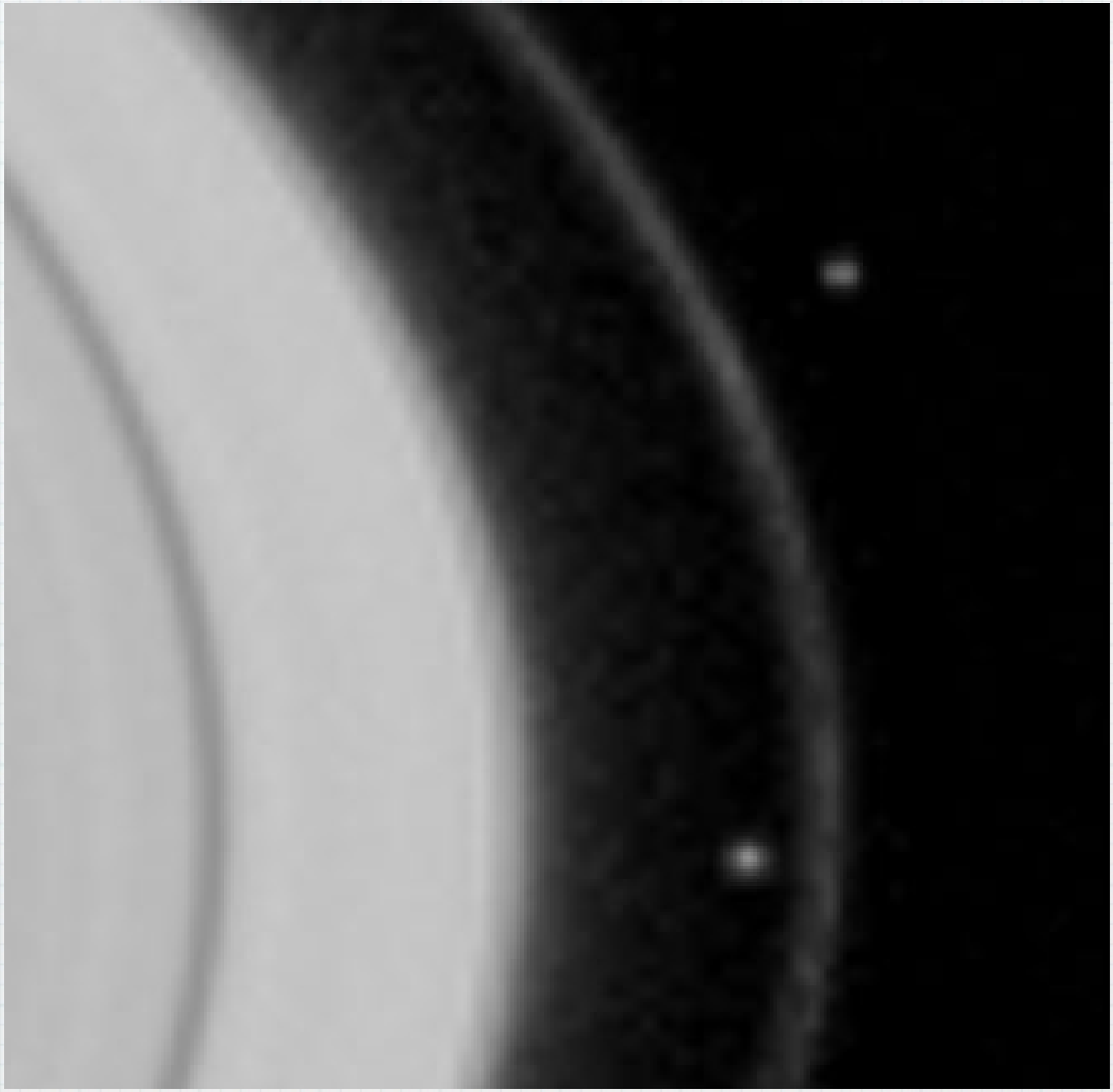
* Detailed observations show features such as
  * spokes
  * ripples
  * ondulations (kinks)
  * gap moons (keeps the gap clear)
  * shepherd moons (two close gap moons trap a ringlet)

Spokes may be created by electrostatic repulsion between ring particles

Ring Braids



Shepherd moons



Why do the Jovian Planets have Rings?

* Originally people thought that tidal forces had torn apart moons that had ventured too close to Saturn
* Then they thought that the rings were remnants of the planets' formation and that tidal forces kept them from aggregating into moons

Why do the Jovian Planets have Rings?...

* Now we know better. The particles which make the rings up cannot survive for billion of years

* They are continually being grounded down in size by colliding with themselves and meteorites

* By now they should all have been "dusted"

Why do the Jovian Planets have Rings?...

➡ So the rings are being continuously renewed!

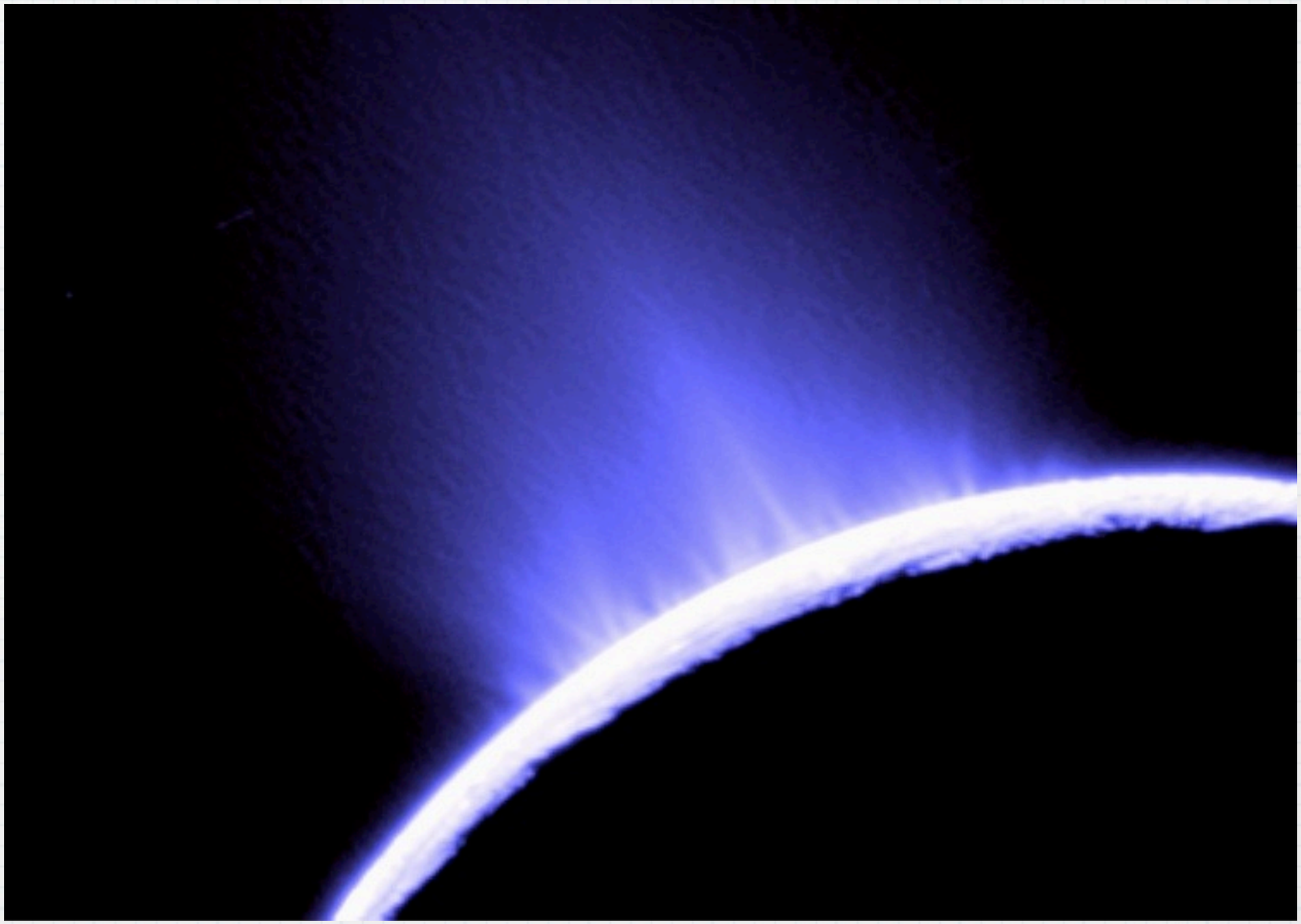
* The most likely source are the planets' moons (such as the gap moons - aka moonlets)

* These moons are being "sandblasted" by meteorites and occasional larger impacts create the boulder size objects

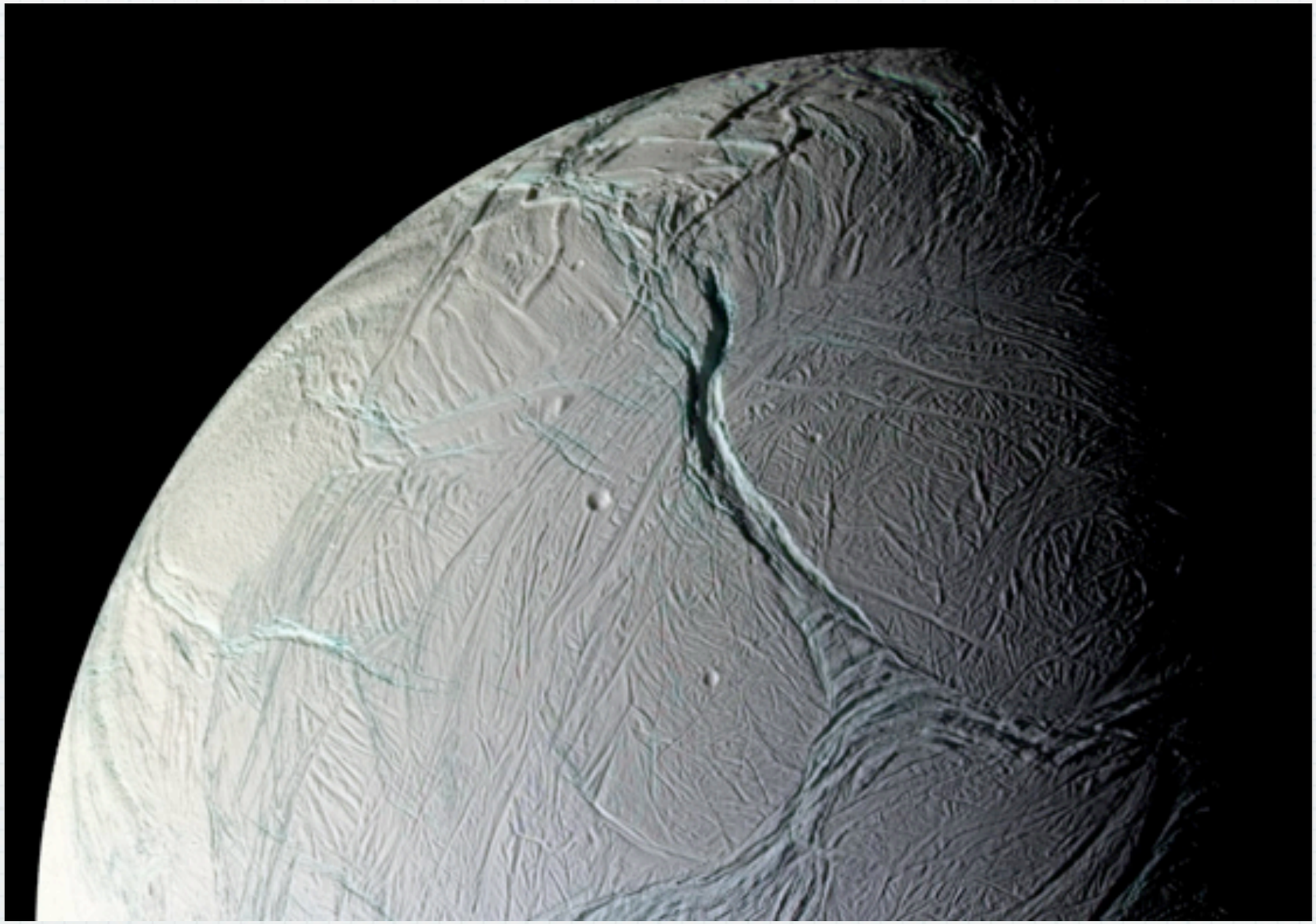
* ice is also released by icy geysers and ice volcanoes located on those moons

Enceladus Ice Geysers

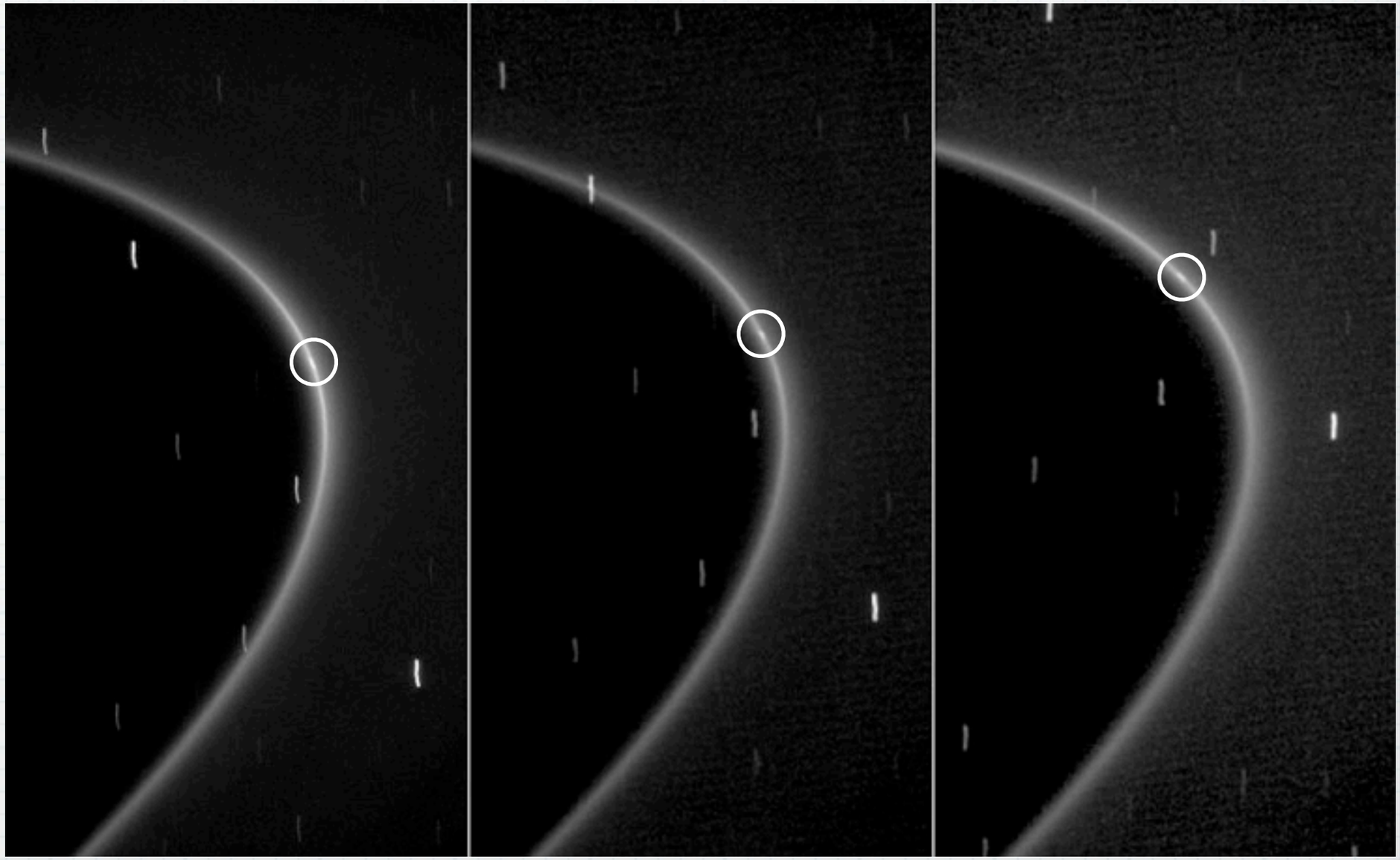
These ice geysers also likely produce Saturn's faint but extended E ring



The Sources of Enceladus Ice Geysers

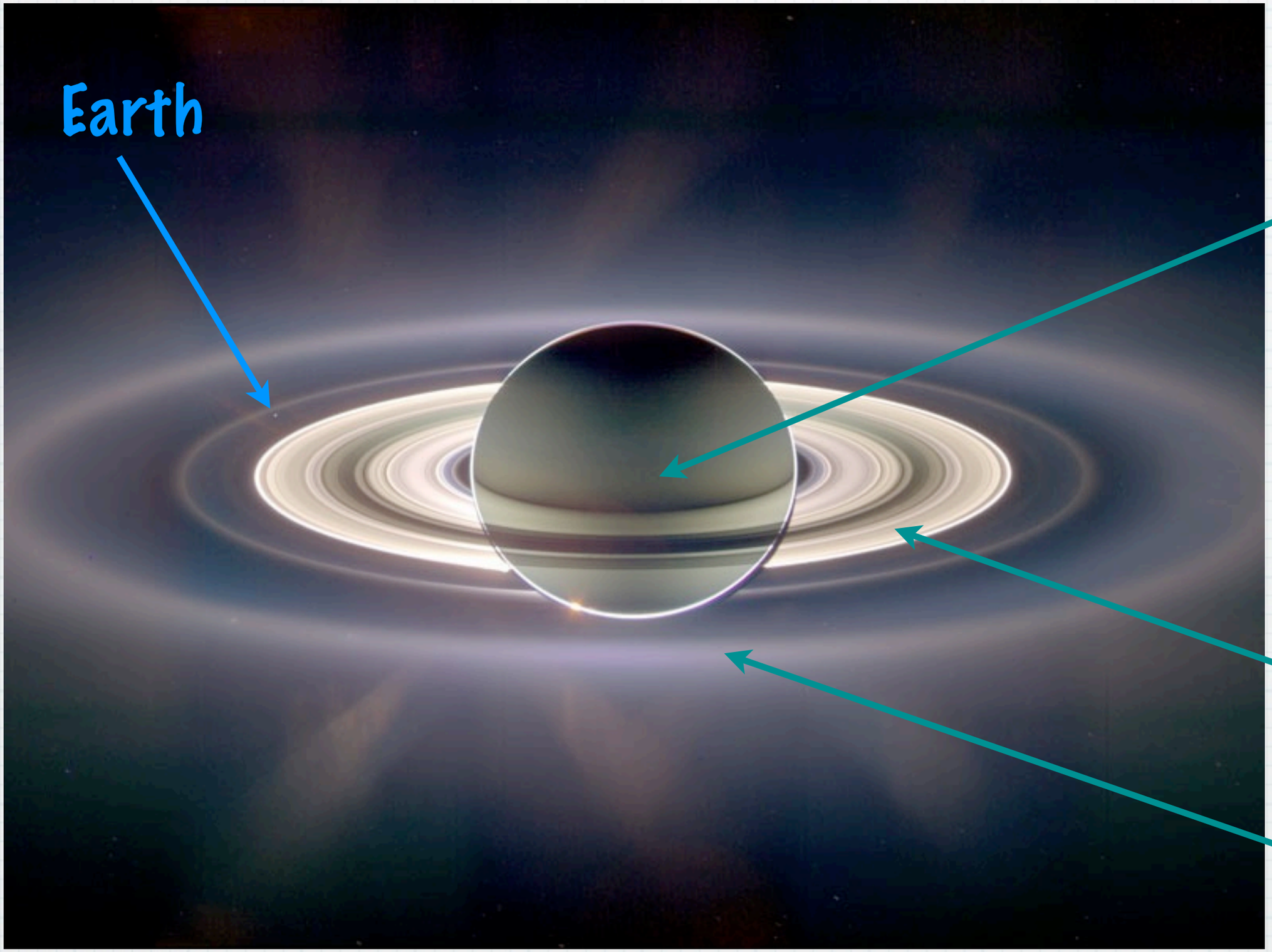


A newly discovered embedded moonlet appears as a faint, moving pinprick of light within Saturn's G ring

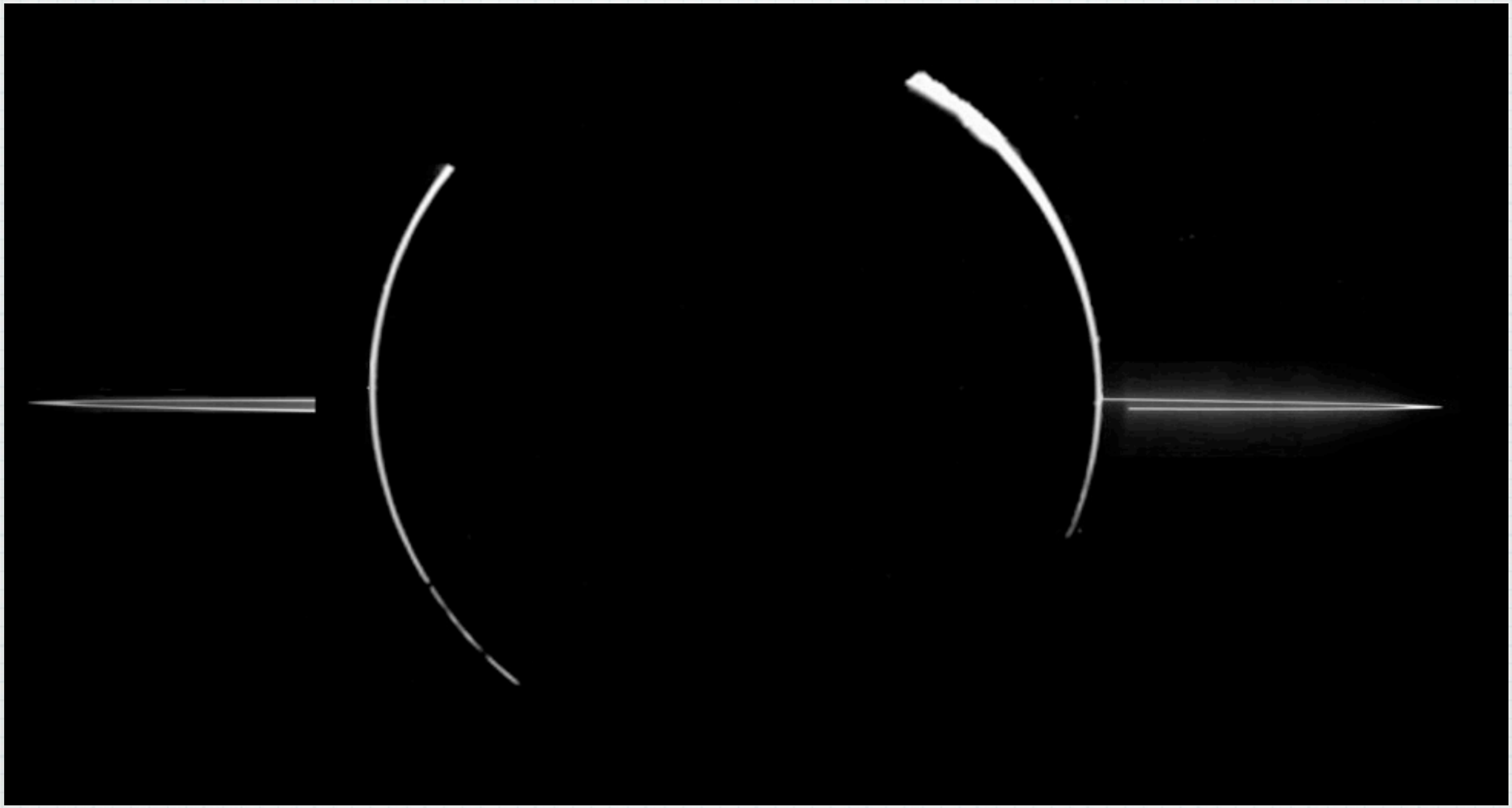


Scientists believe it is a main source of the G ring

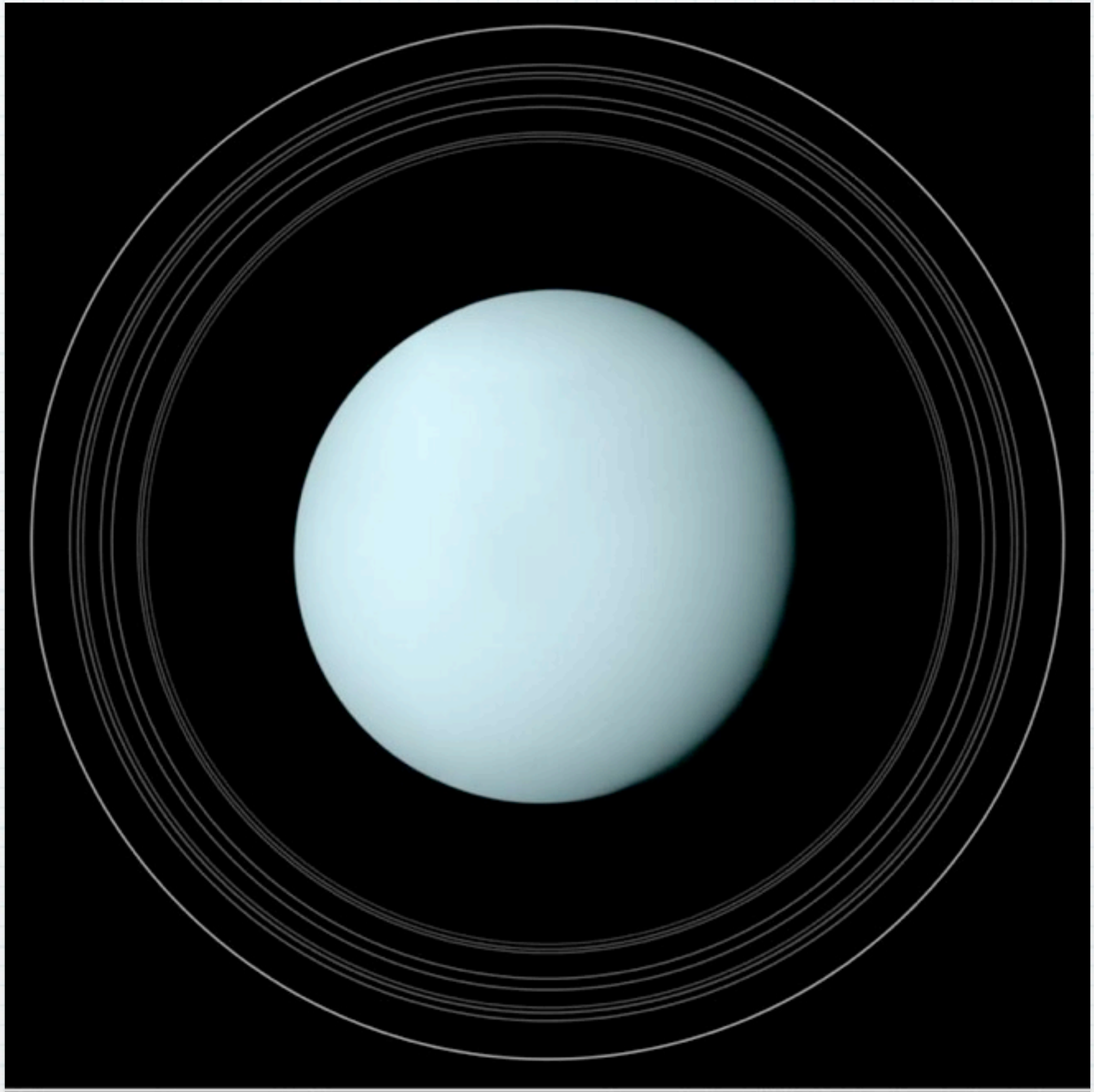
Saturn eclipsing the Sun



Rings of Jupiter



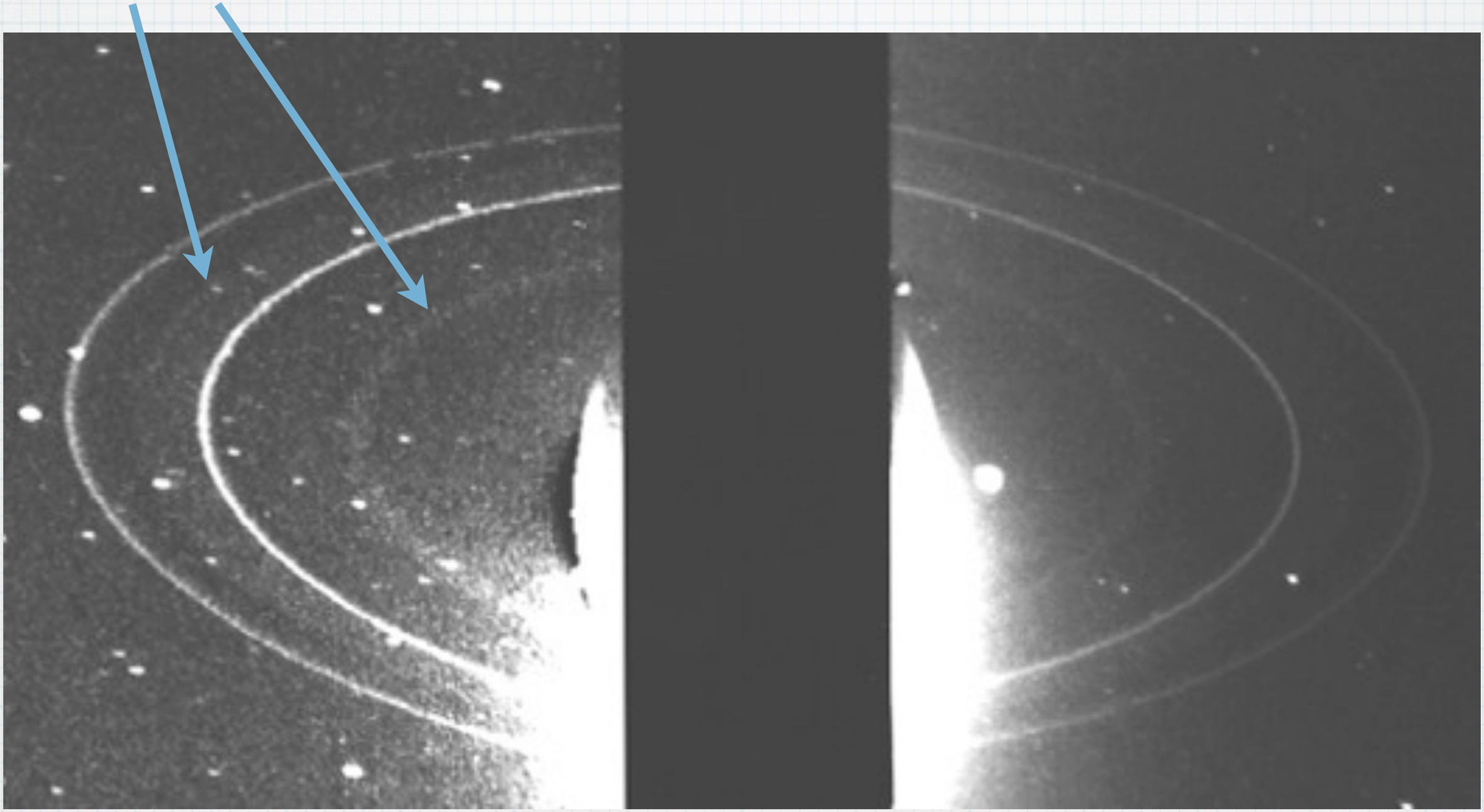
Rings of Uranus



Voyager Image of Uranus

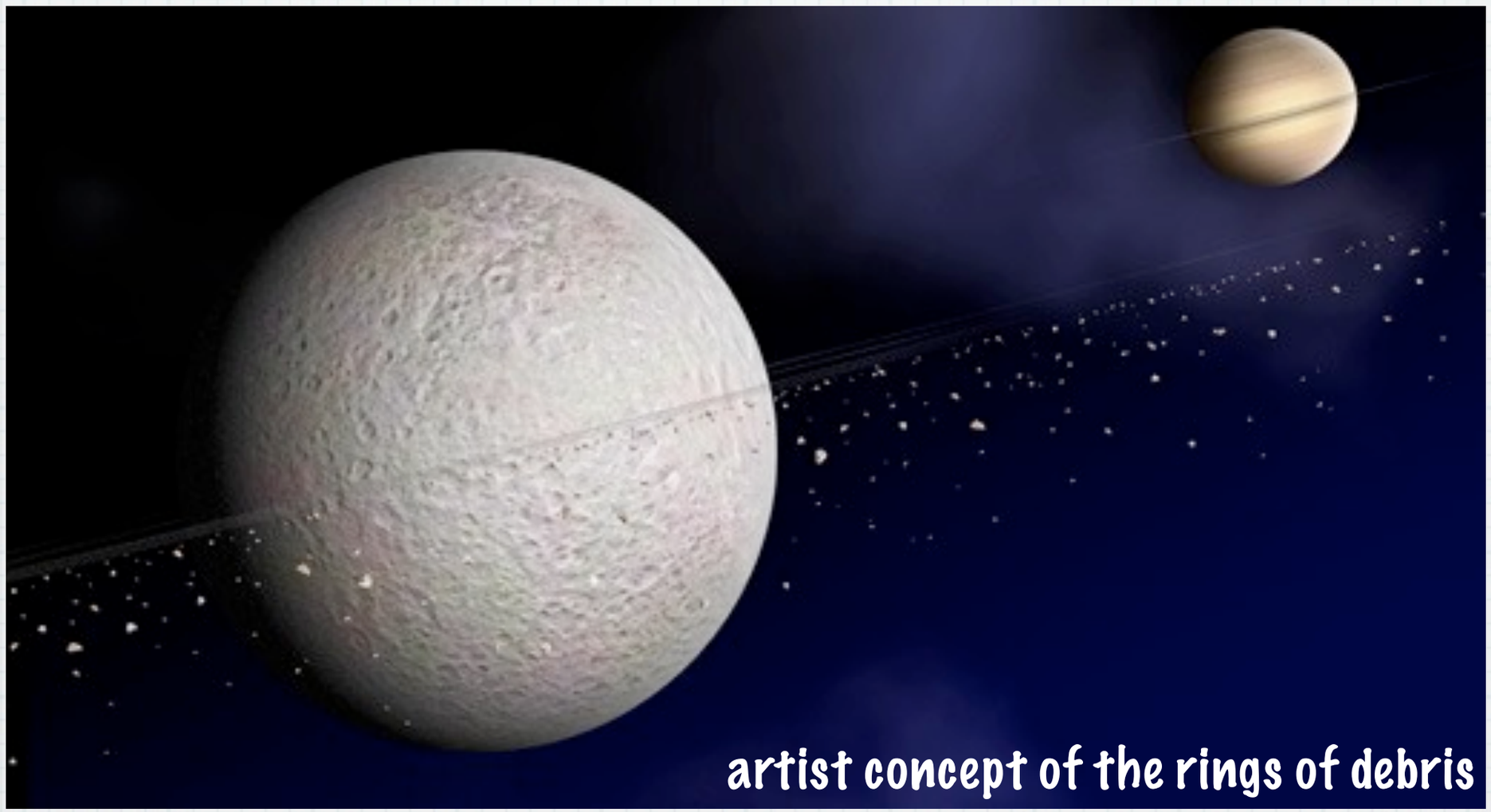
Rings of Neptune

Very faint and hard to detect, even in overexposed image



Rhea of Saturn may have a ring

NASA's Cassini spacecraft has found evidence of material orbiting Rhea, Saturn's second largest moon. This is the first time rings may have been found around a moon.



artist concept of the rings of debris