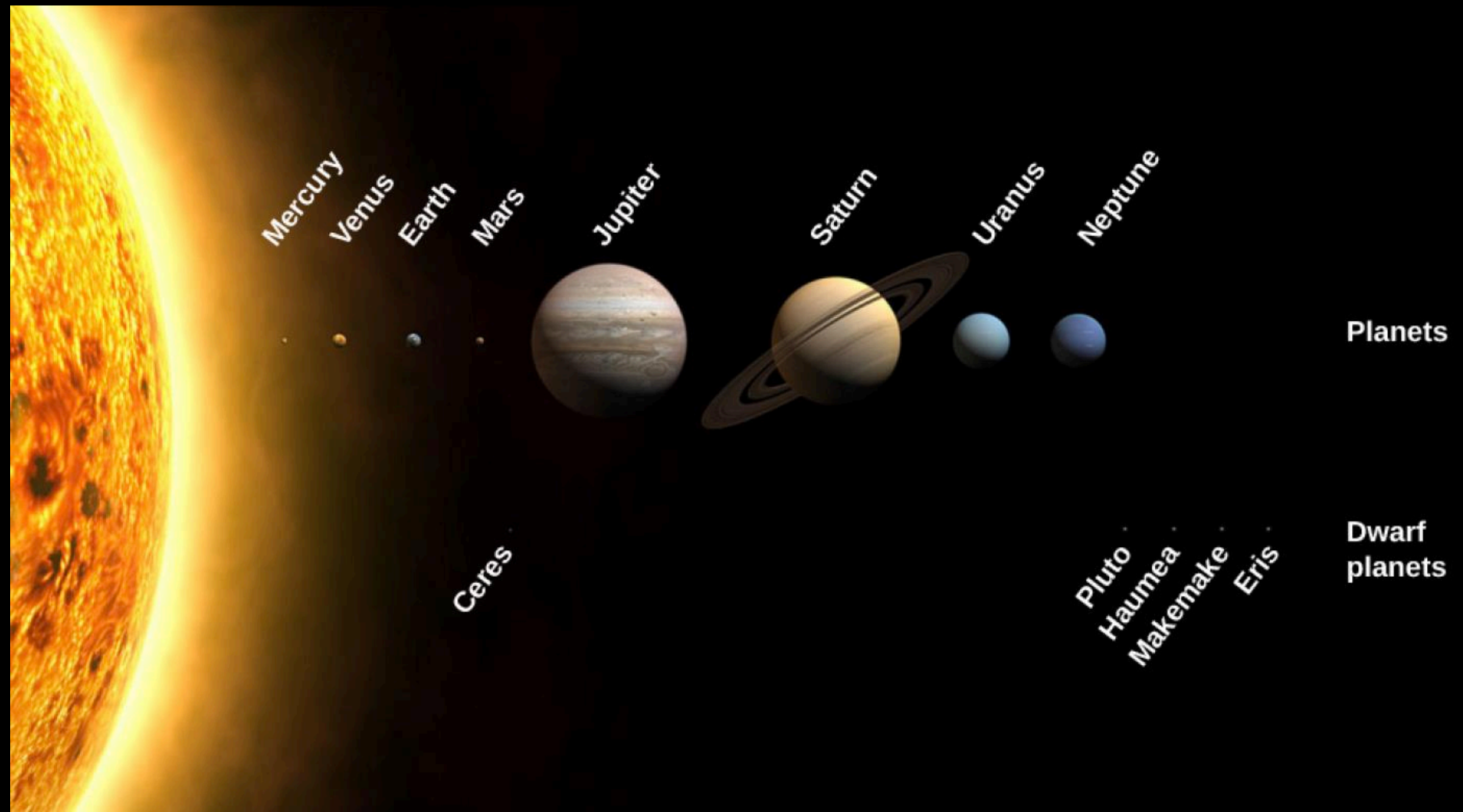
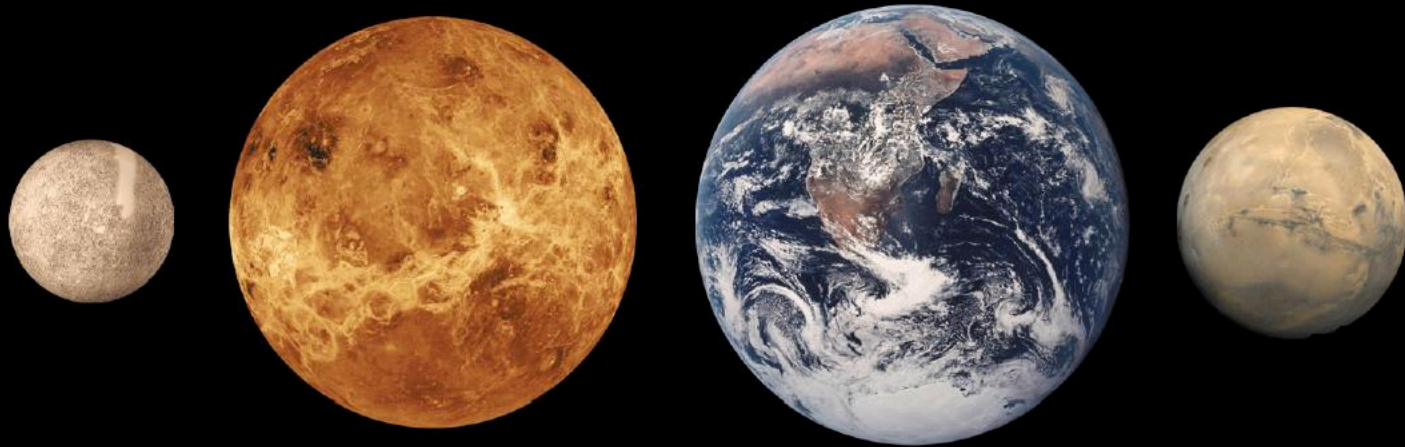


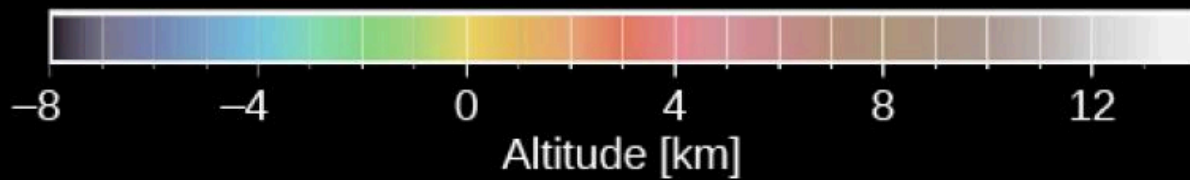
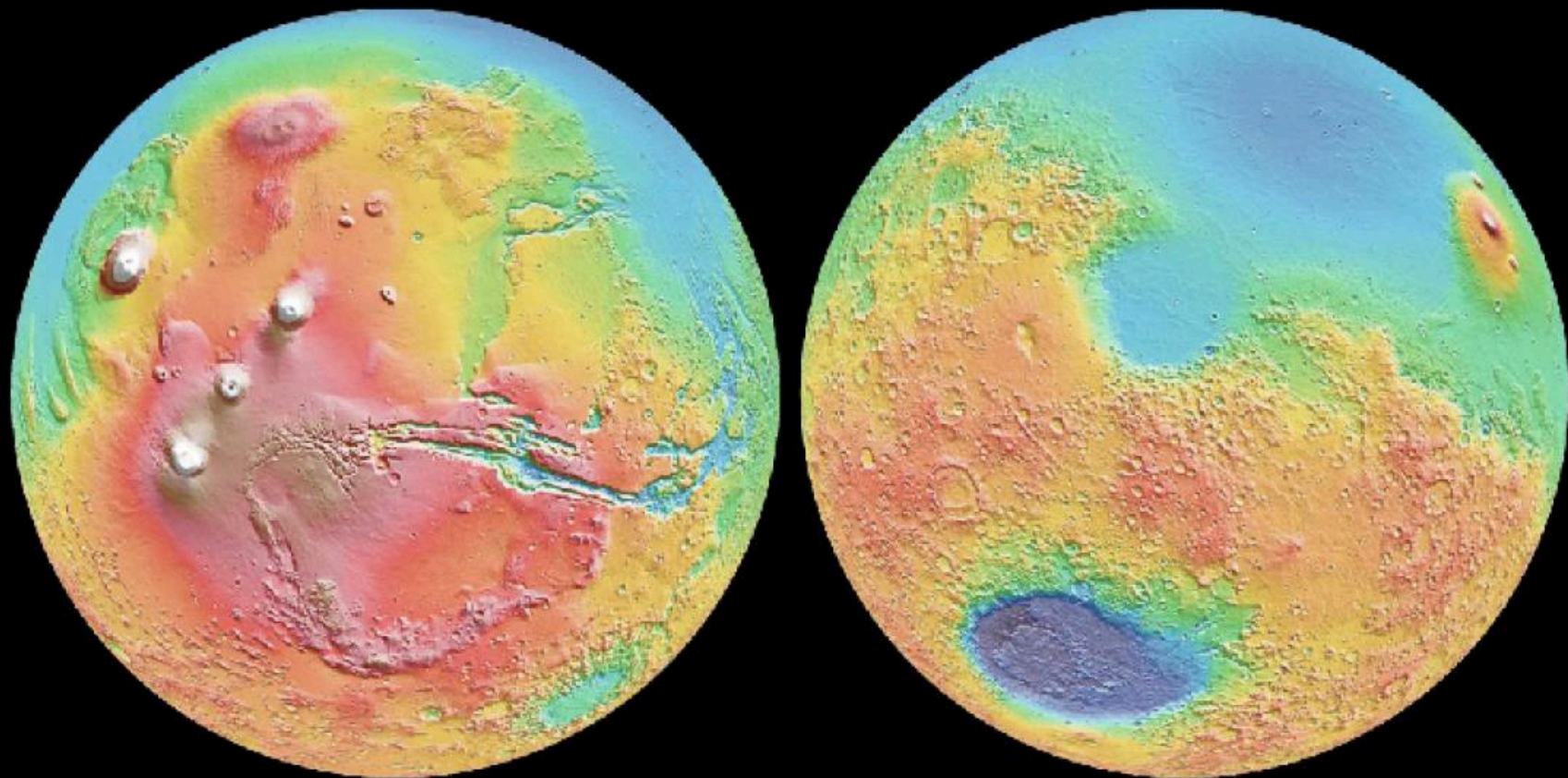
Our solar system: Moons and debris



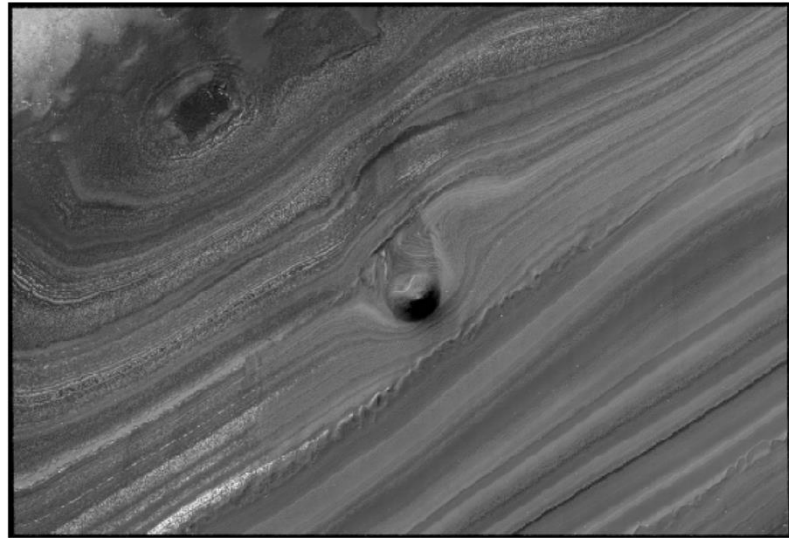
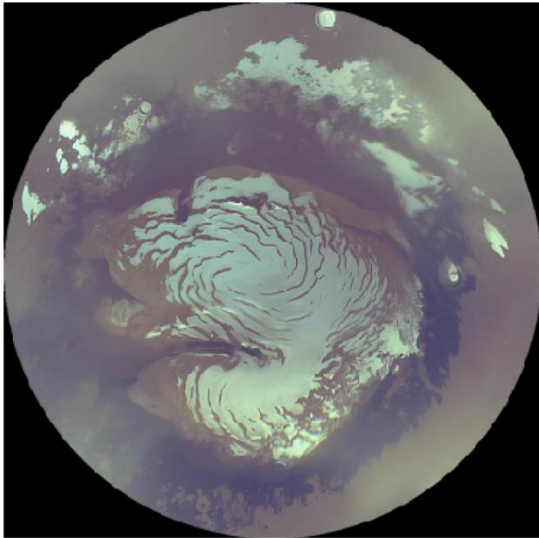
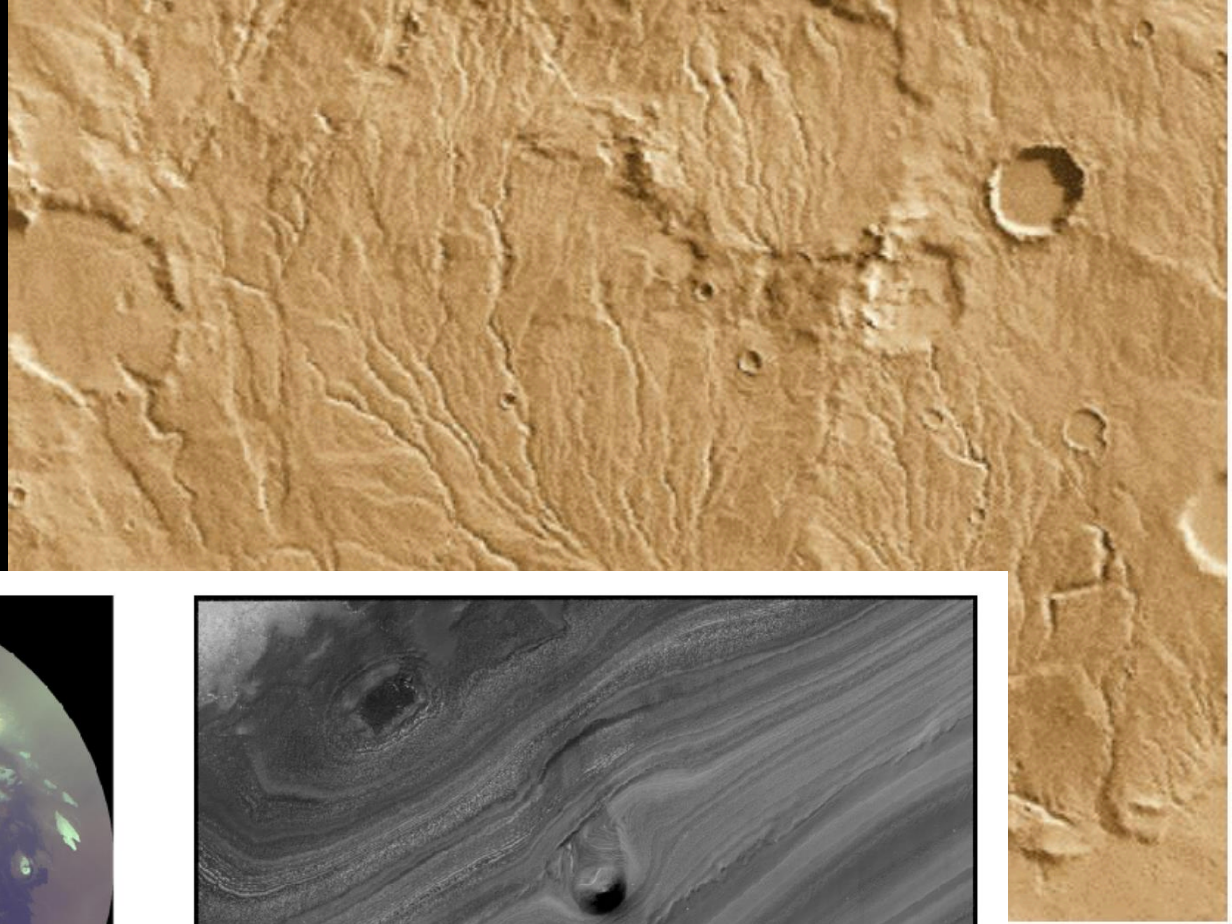
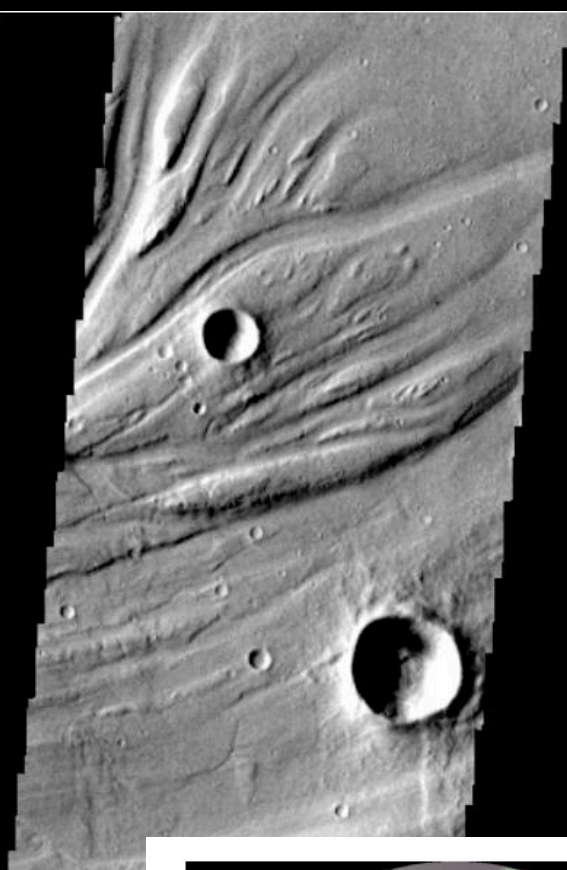
The terrestrial planets

– *rocky worlds*



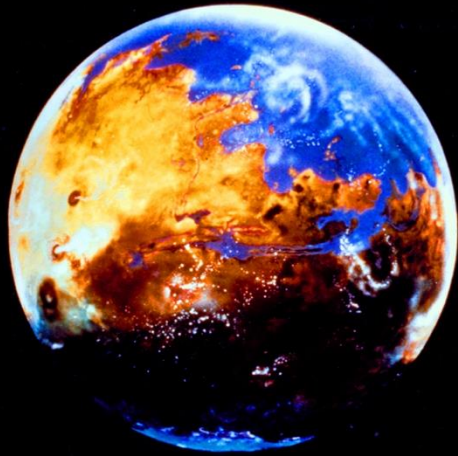


Water?



HISTORY OF WATER ON MARS

Billion years ago



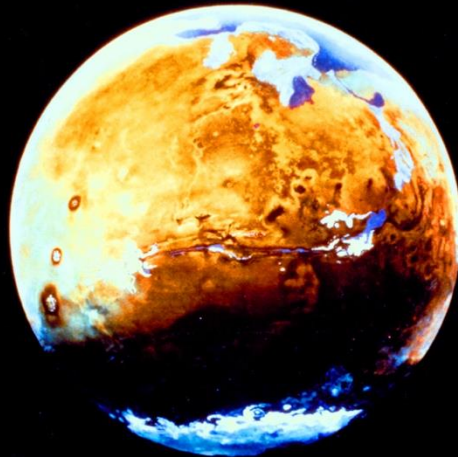
4.0



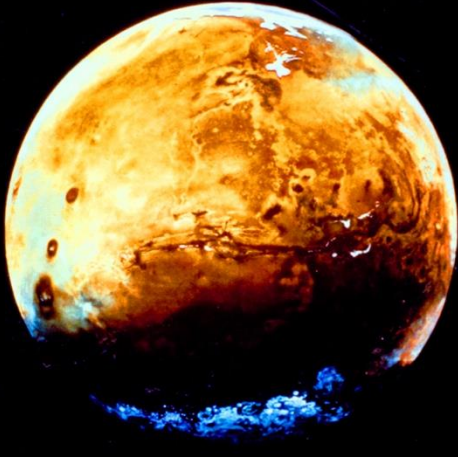
3.8



3.5



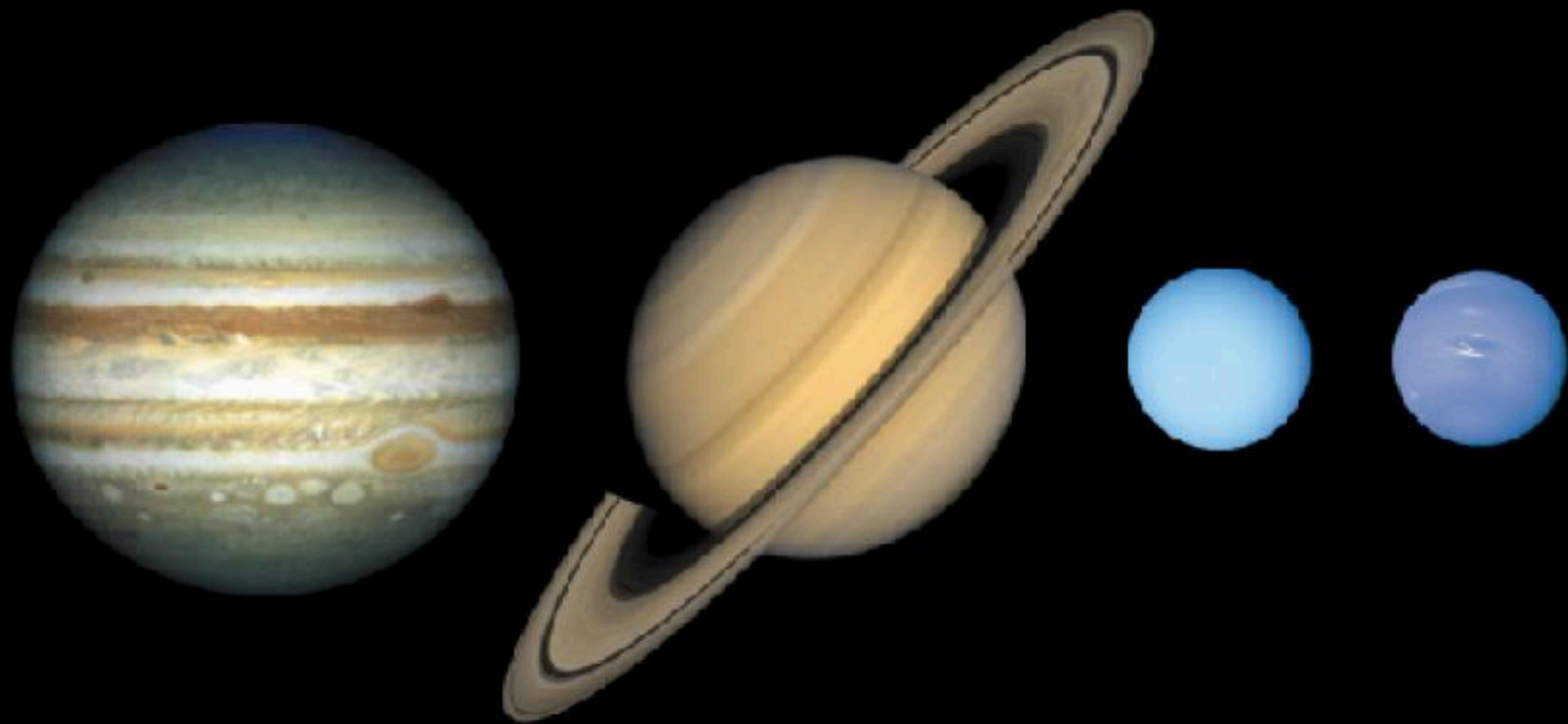
2.0




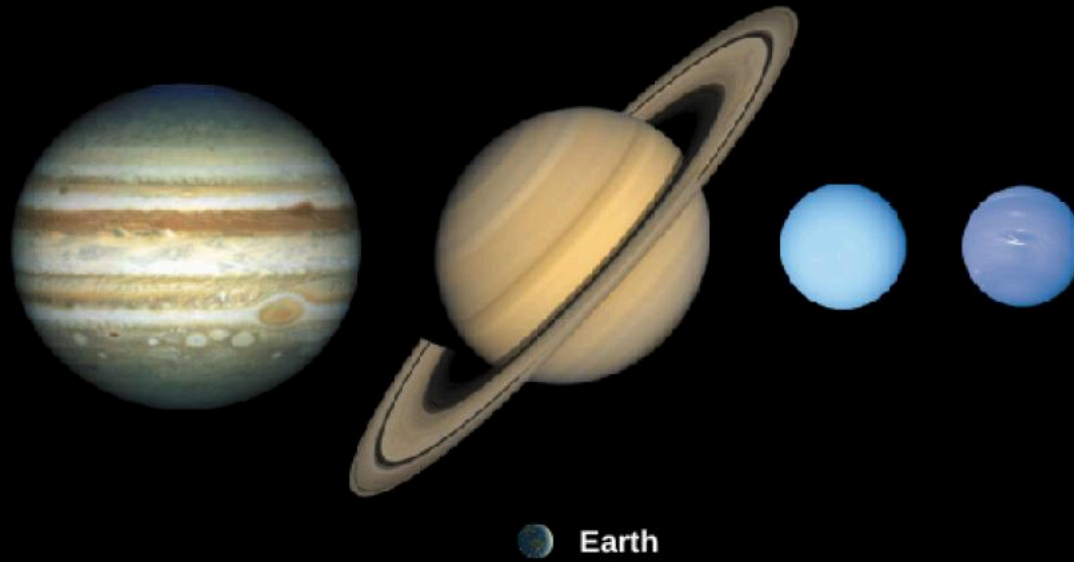
1.0



Now



 Earth



Gas giants

Jupiter, Saturn

Much more massive

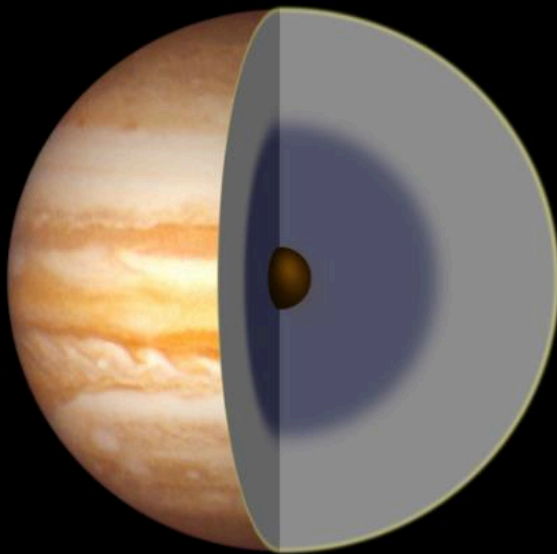
Abundances similar
to sun

Ice Giants

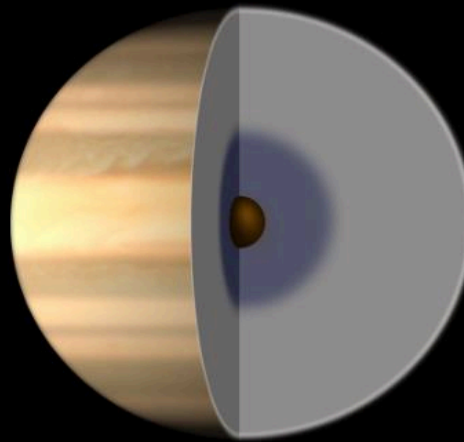
Uranus, Neptune

Much less massive

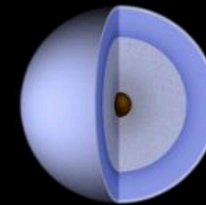
Similar cores as gas
giants



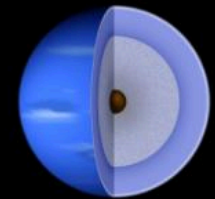
JUPITER



SATURN





URANUS






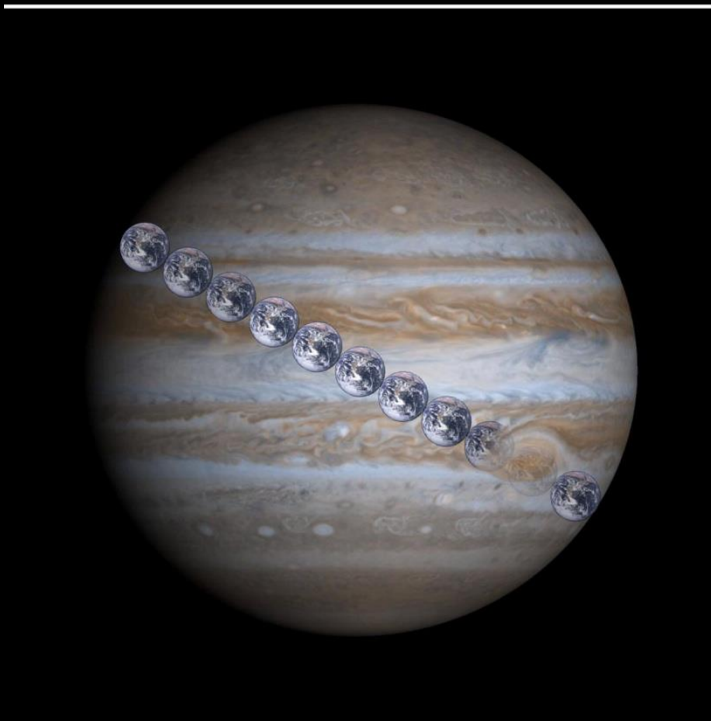
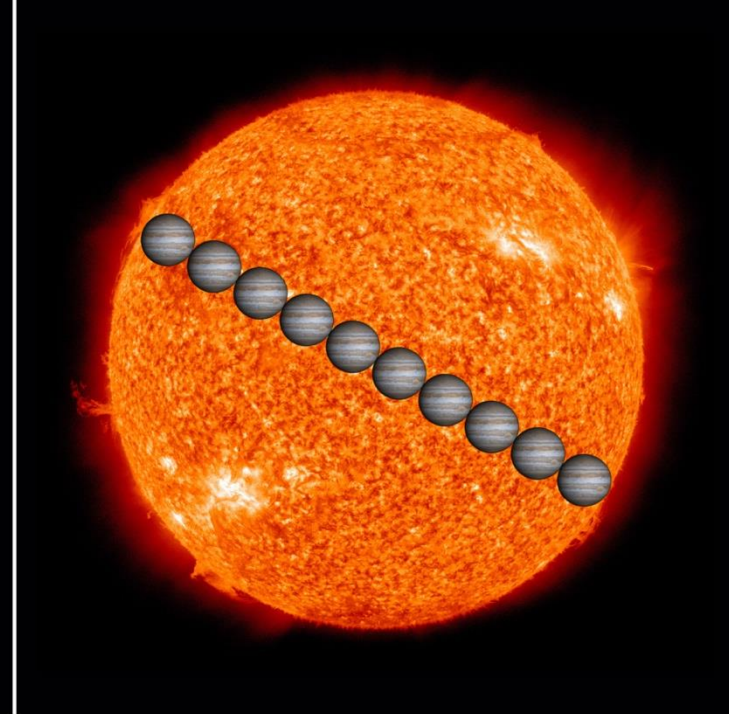
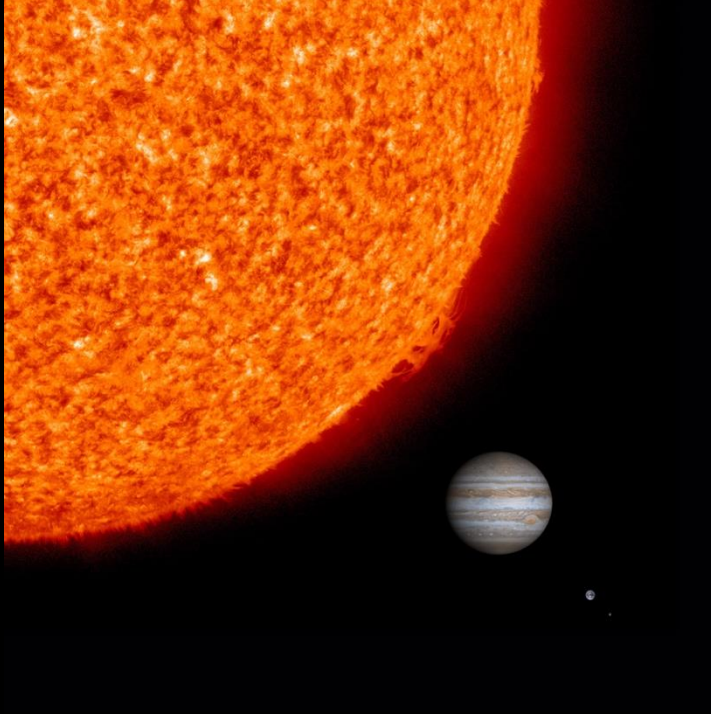
NEPTUNE

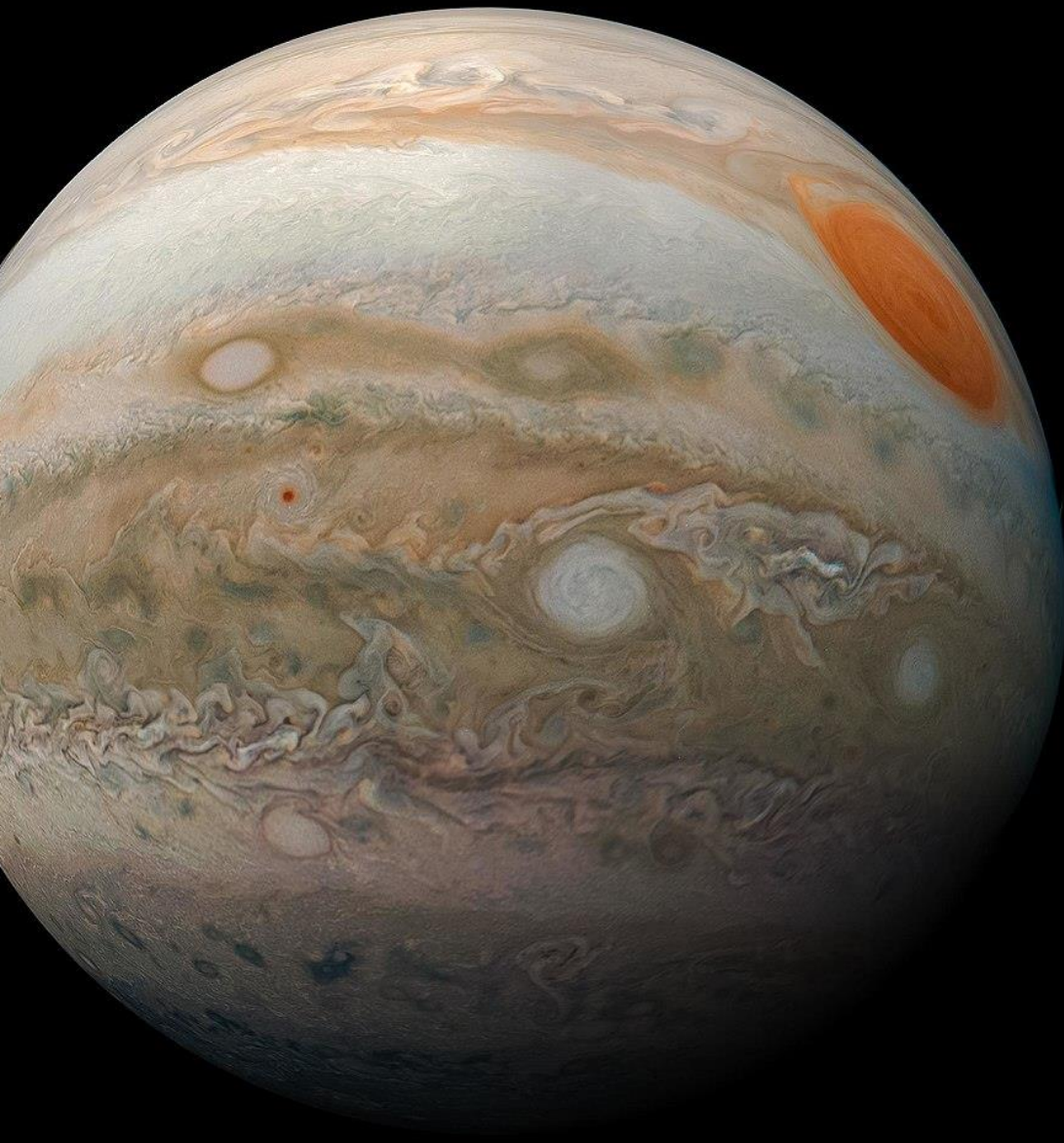


EARTH

-  Molecular hydrogen
-  Metallic hydrogen

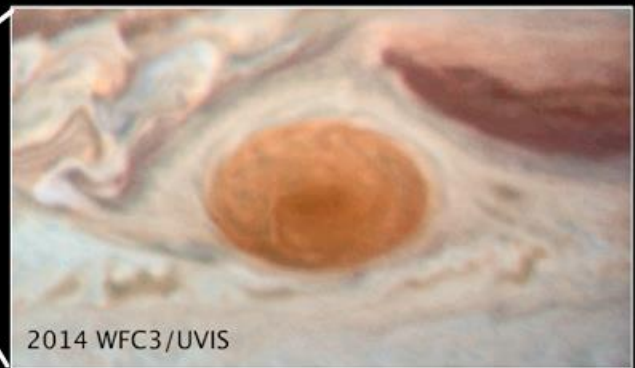
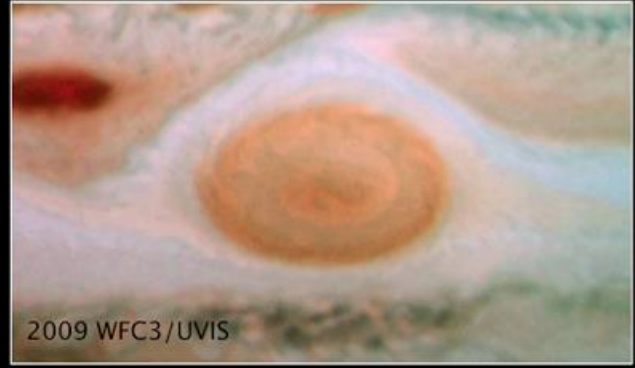
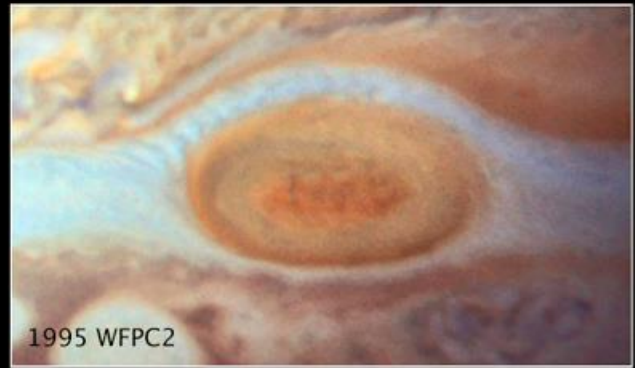
-  Hydrogen, helium, methane gas
-  Mantle (water, ammonia, methane ices)
-  Core (rock, ice)





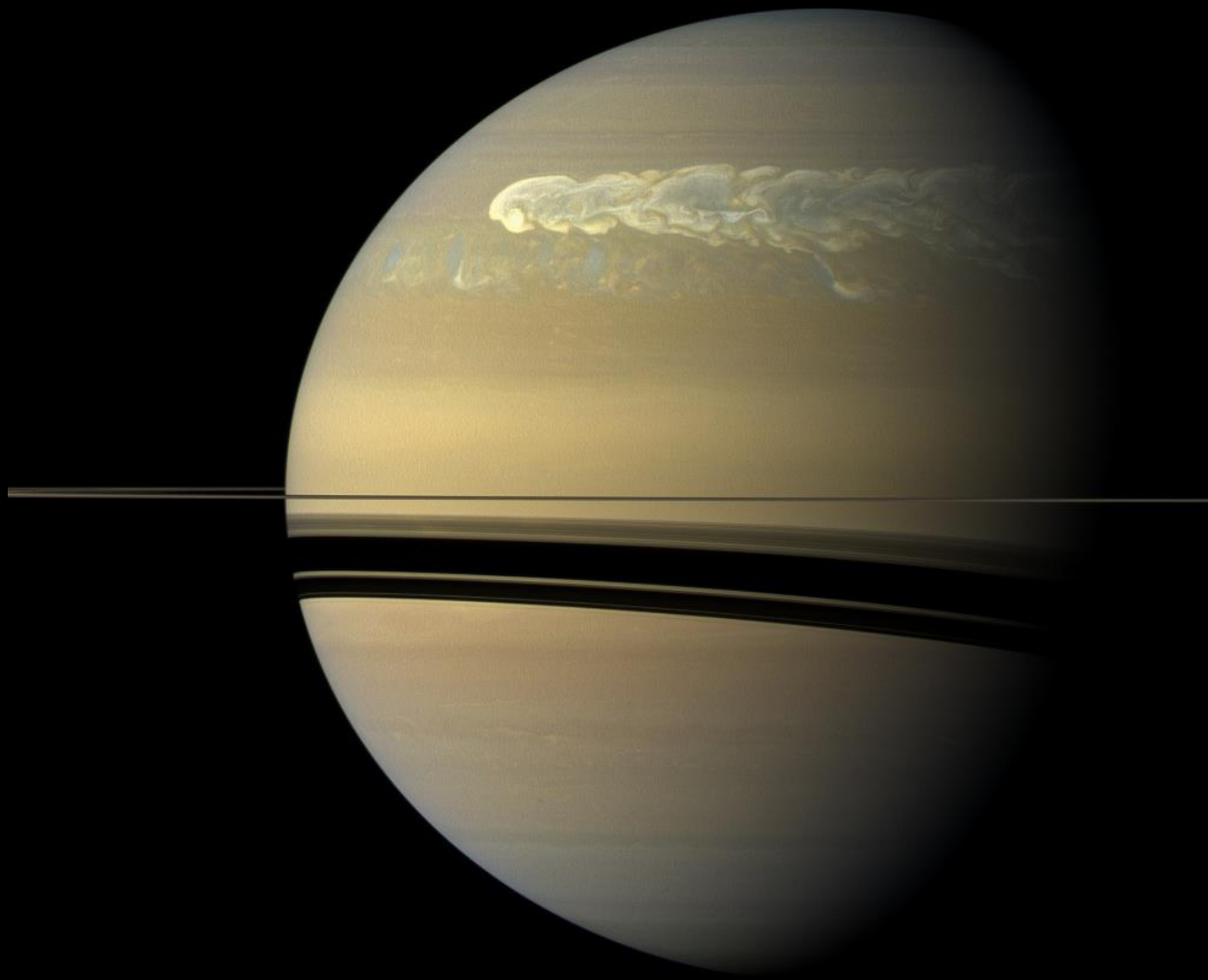
Bands of clouds

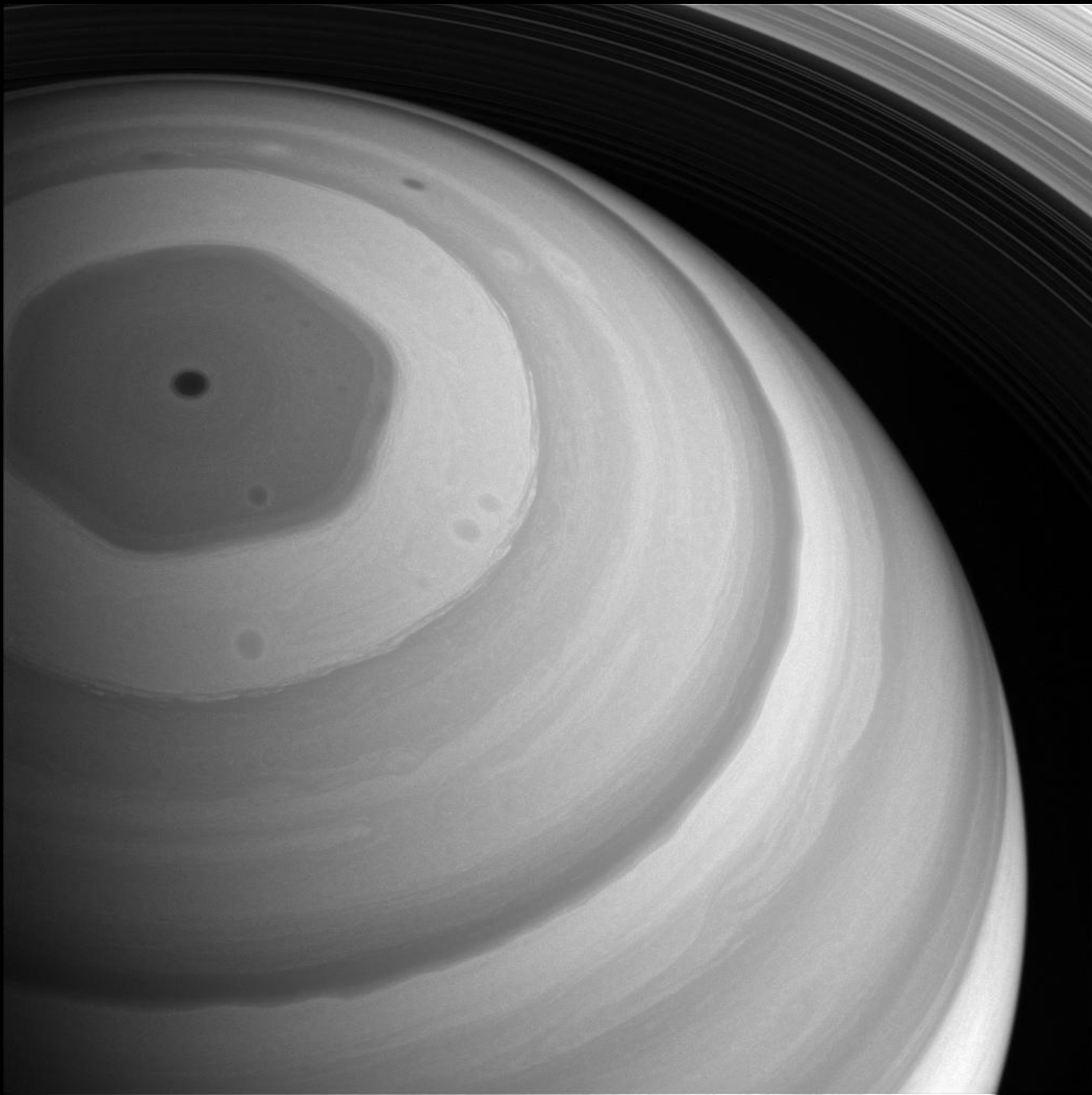
Great Red Spot:
high-pressure
storm

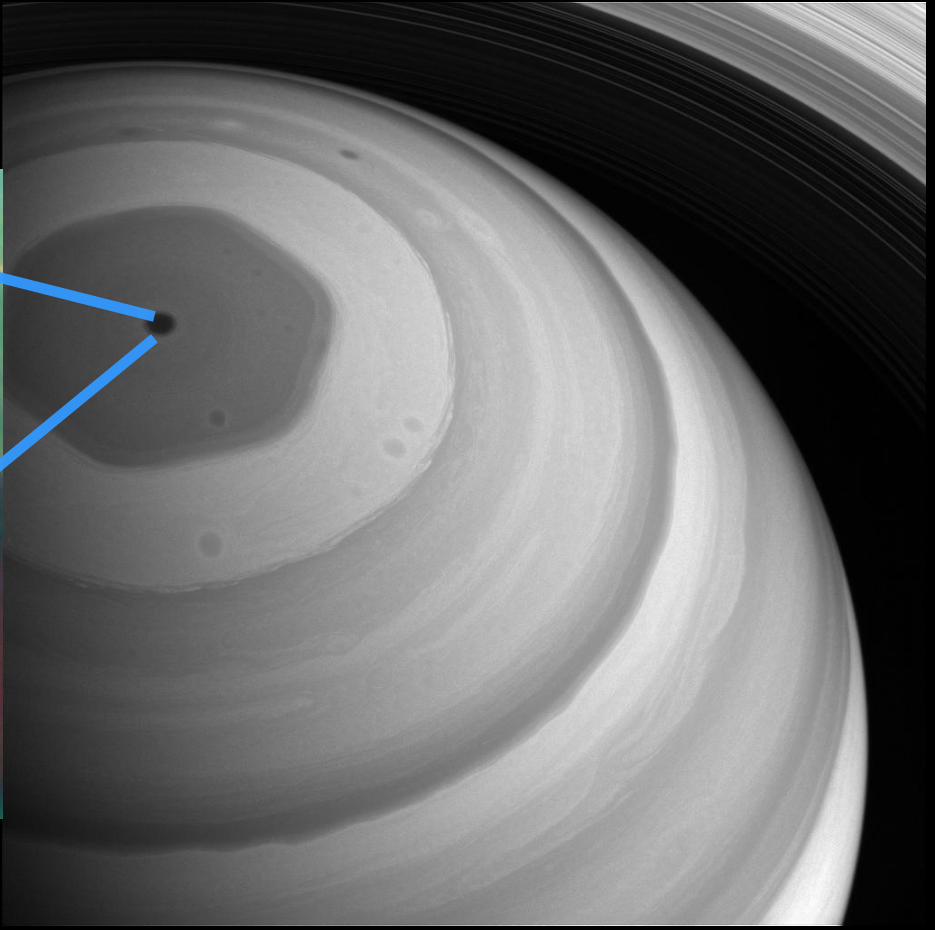
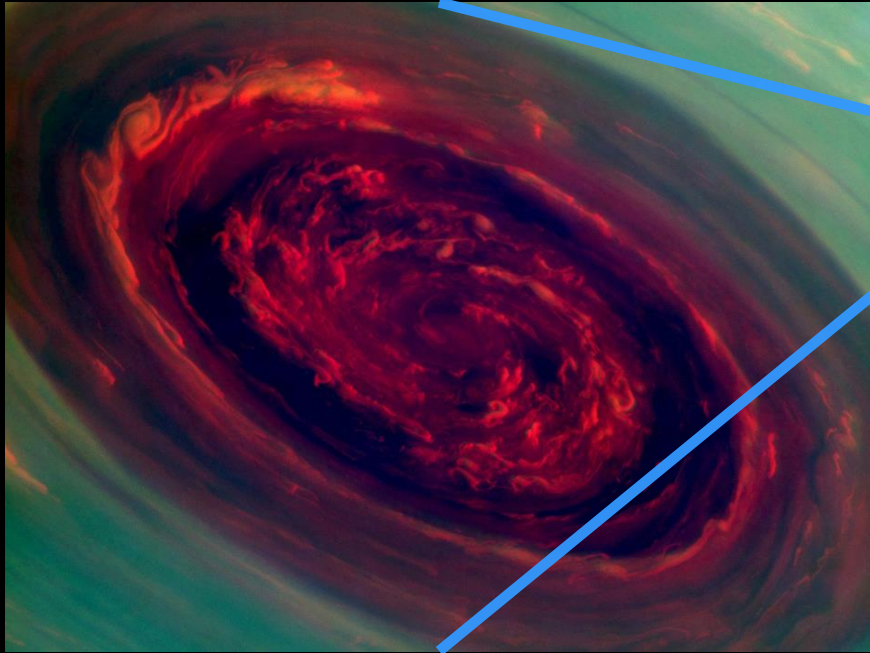


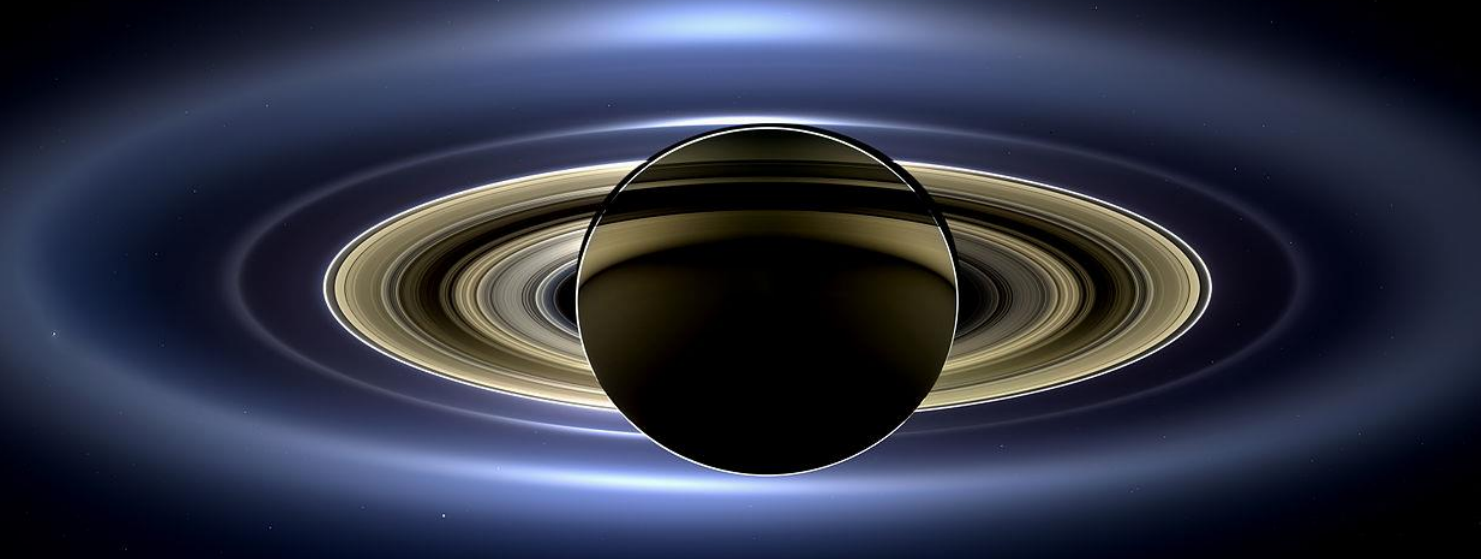
Red spot is shrinking!











Rings: water ice a few m across
remnants of a moon

Thousands of km across; ~10 m thick!
<100 million years old

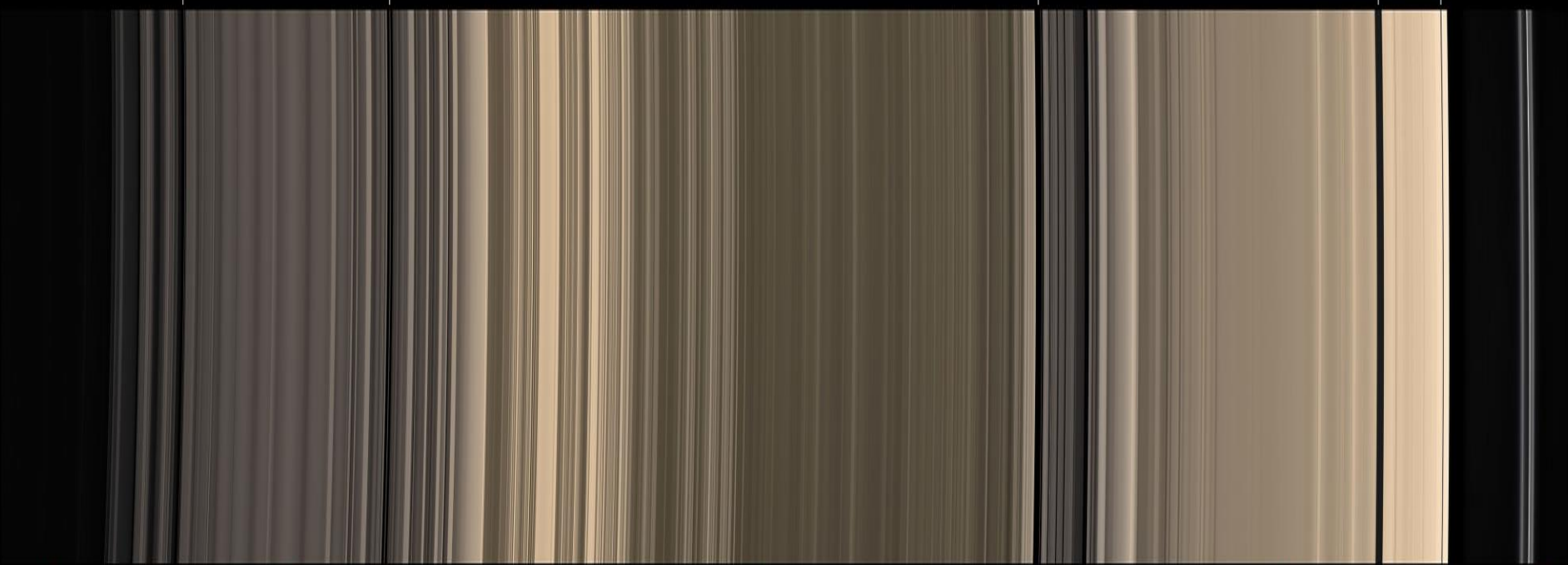
Colombo Gap

Maxwell Gap

Huygens Gap

Encke Gap

Keeler Gap



D Ring

C Ring

B Ring

Cassini
Division

A Ring

F Ring

74,500 km

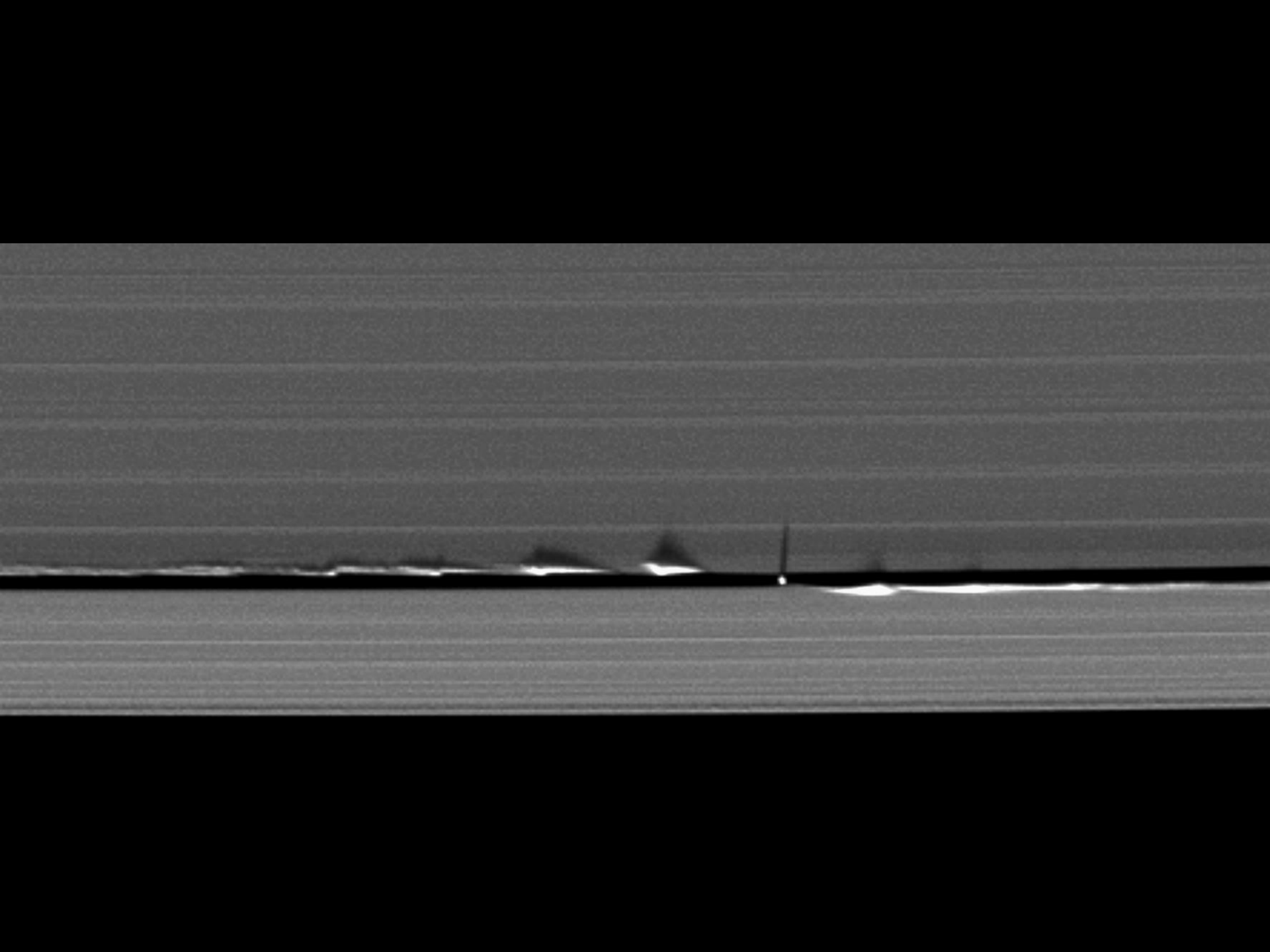
92,000 km

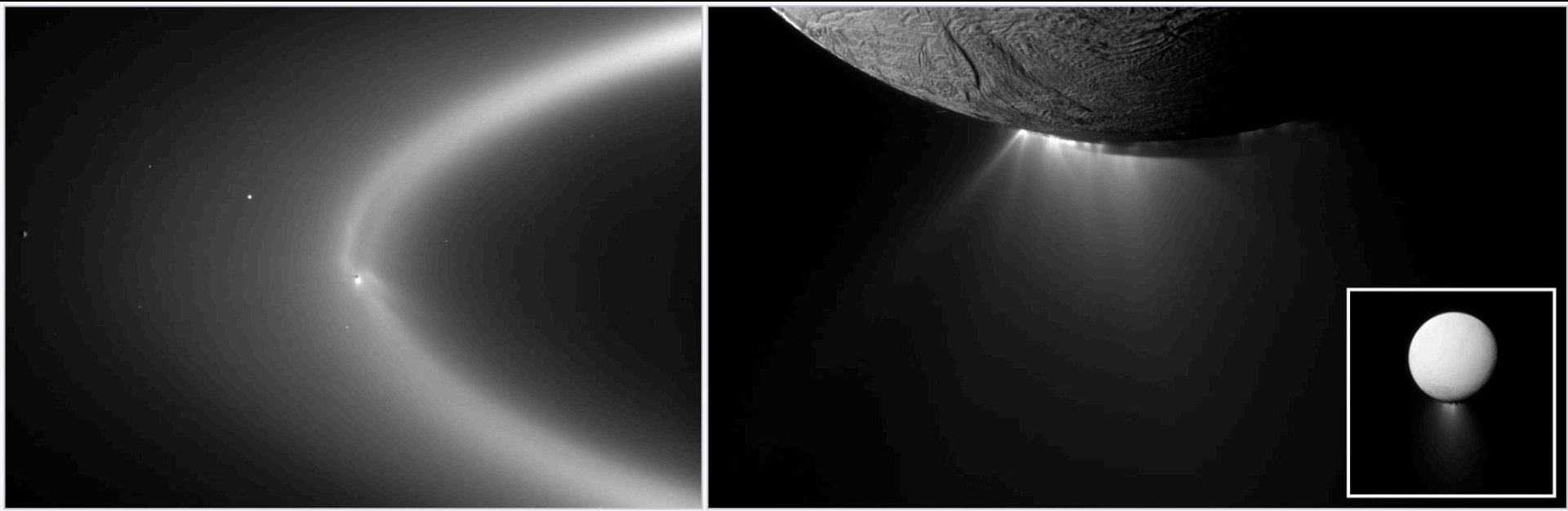
117,500 km

122,300 km

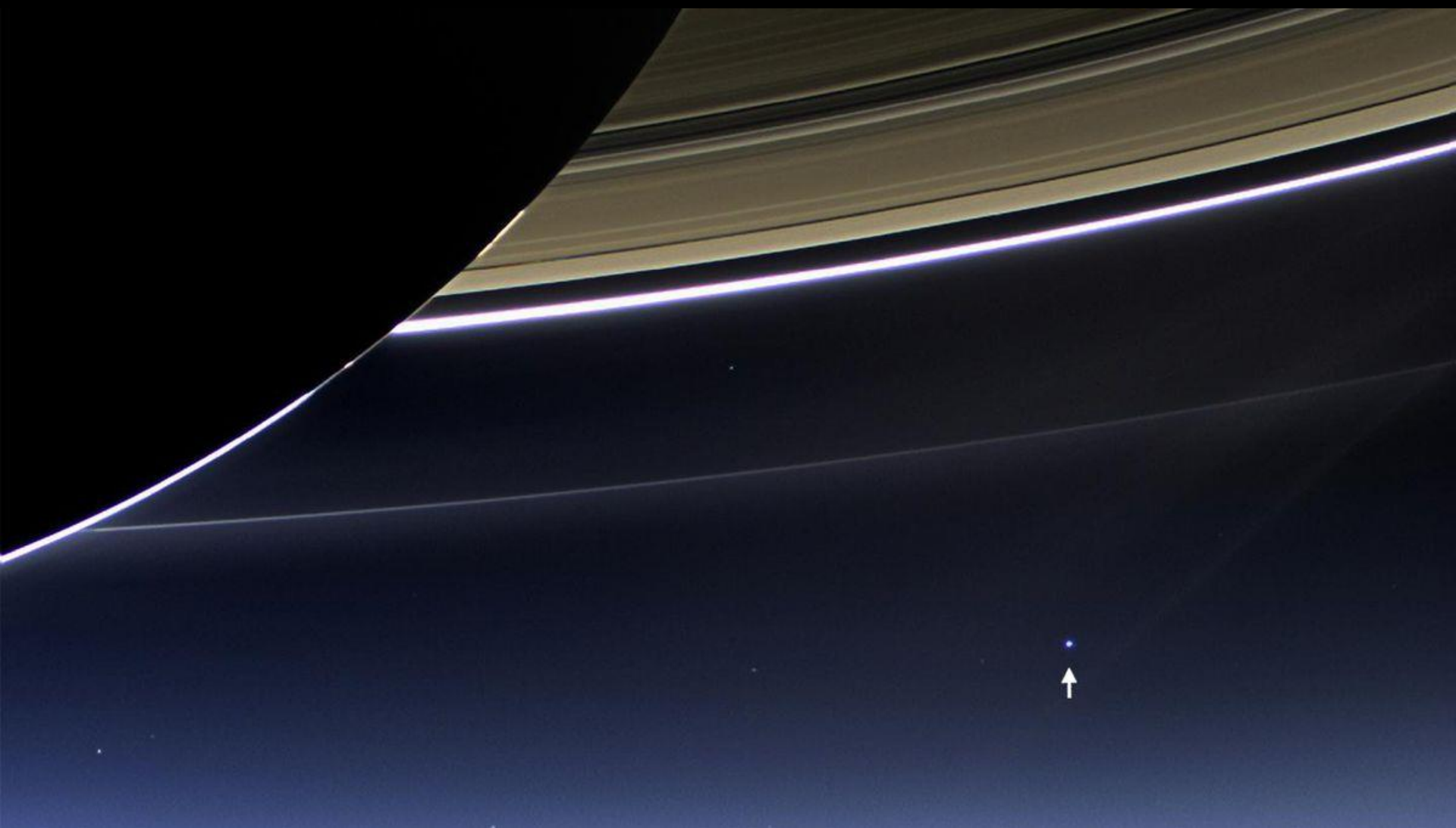
138,780 km

140,220 km





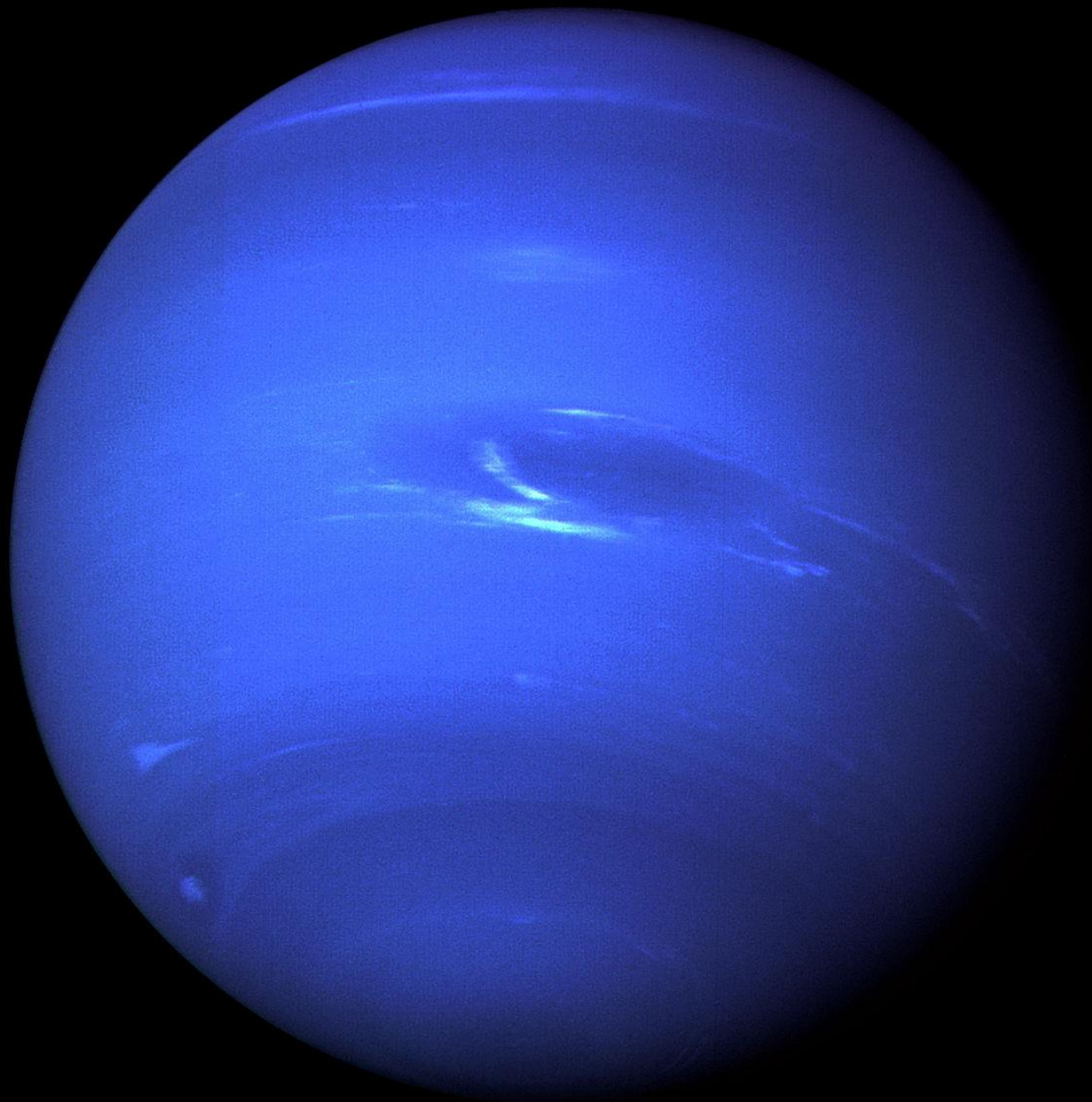
E ring: thousands of m thick
Water from geysers on the moon Enceladus



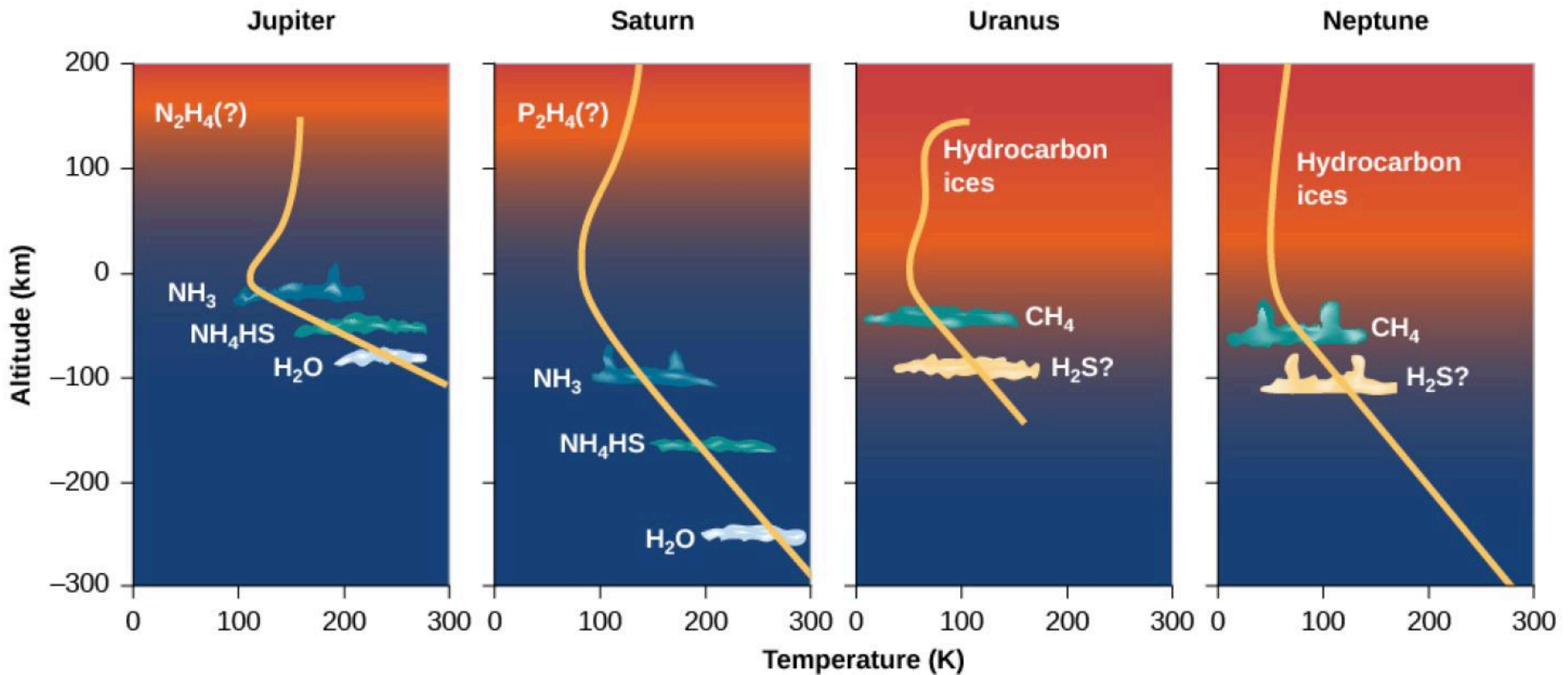
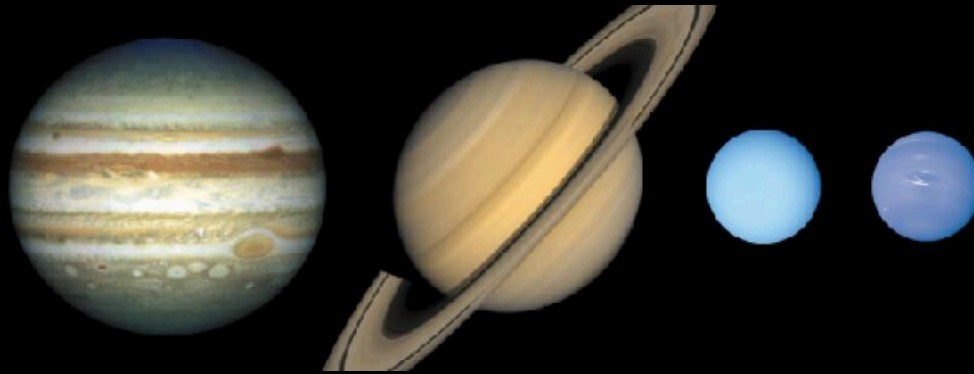
Uranus



Neptune



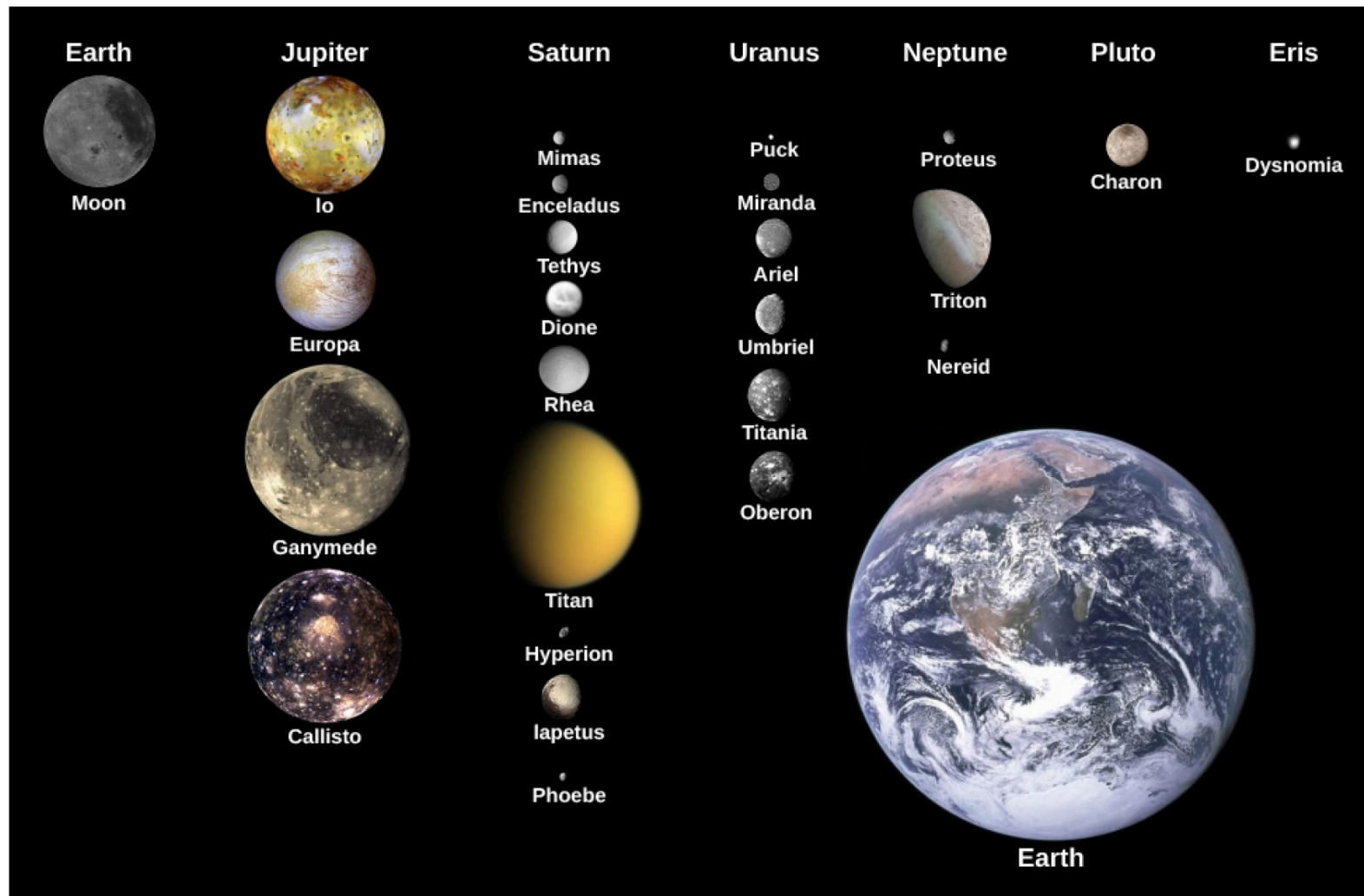
Clouds: scattering prevents detections of structure



Summary – number of moons

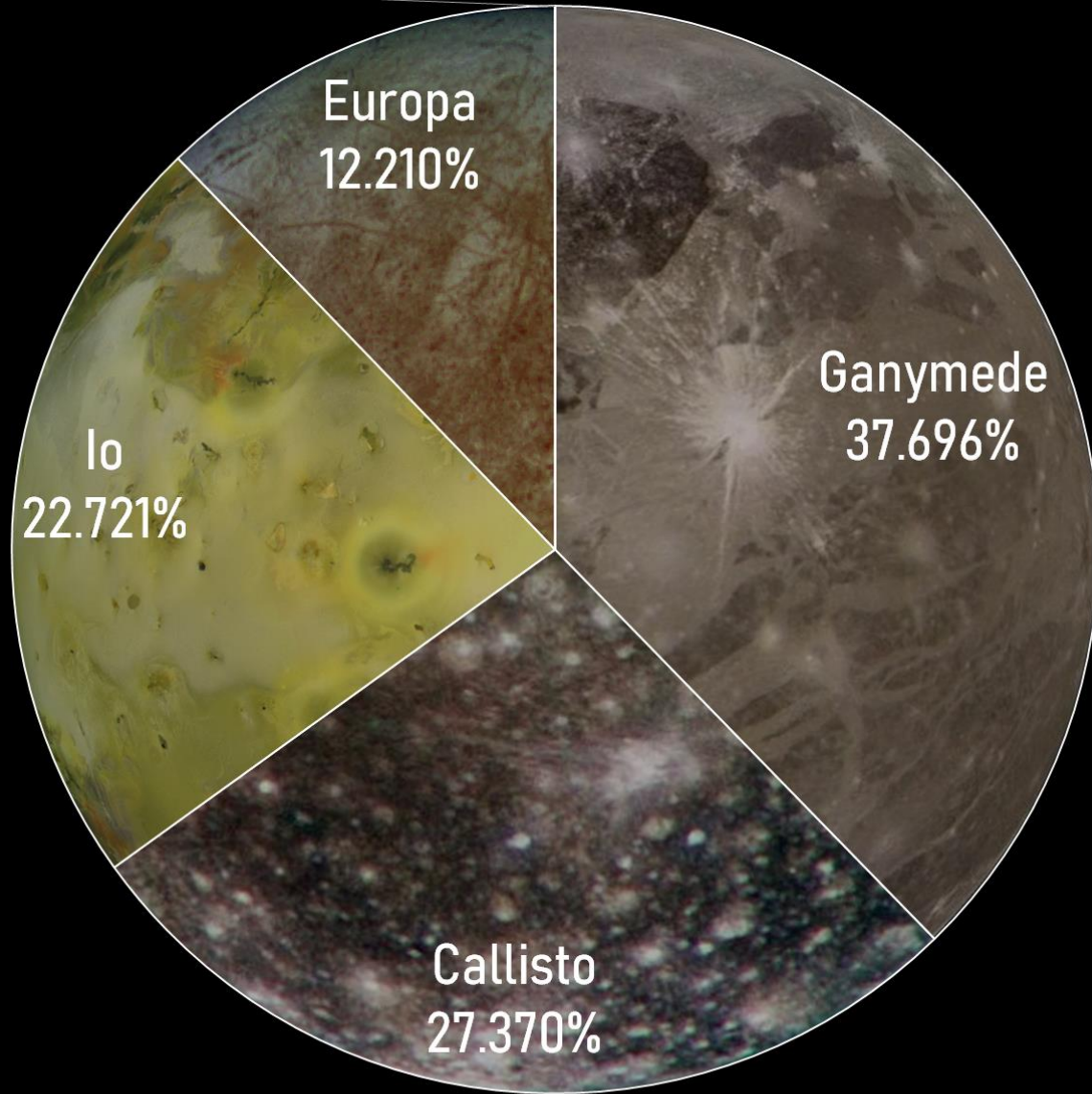
Planet	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Number of moons	0	0	1	2	79	62	27	14

Dwarf planet	Ceres	Pluto	Haumea	Makemake	Eris
Number of moons	0	5	2	1	1

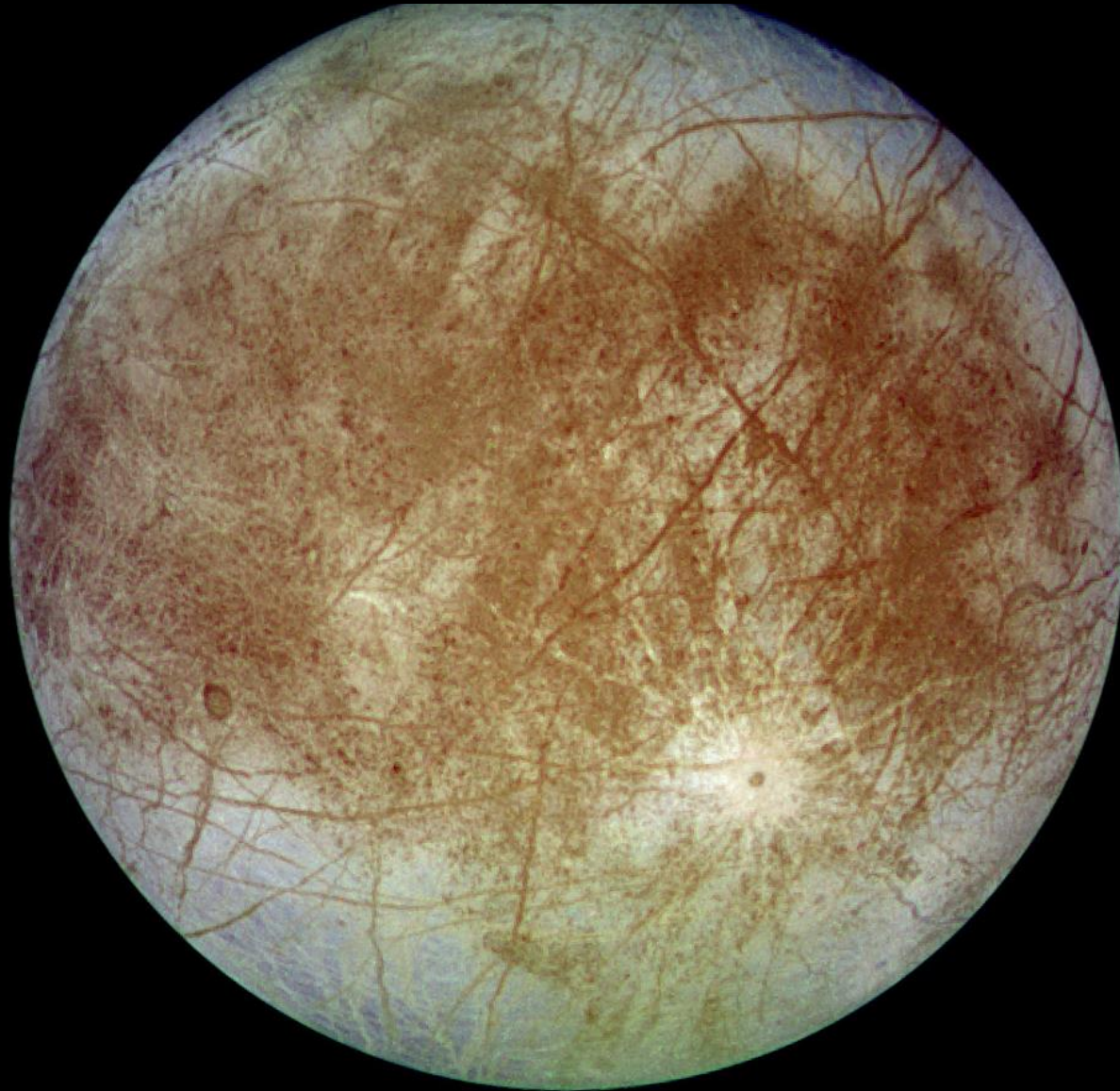


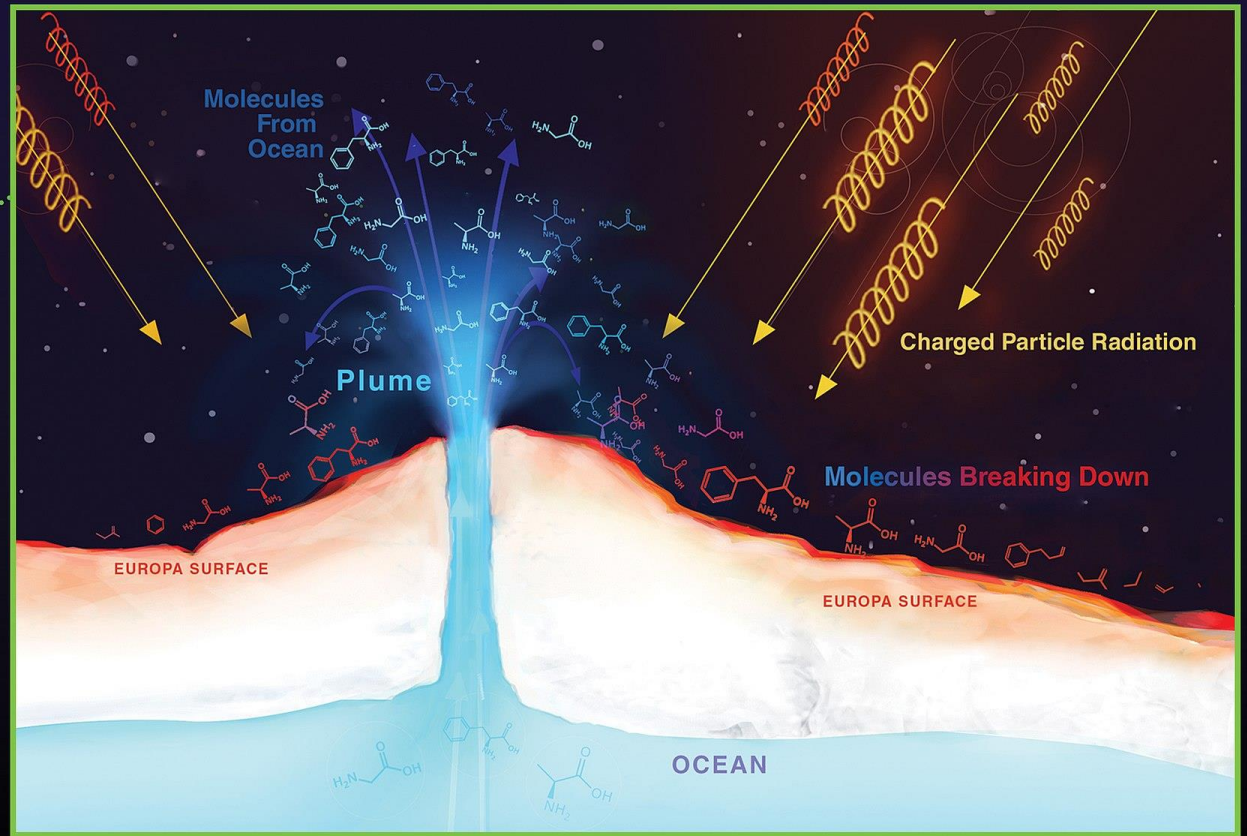
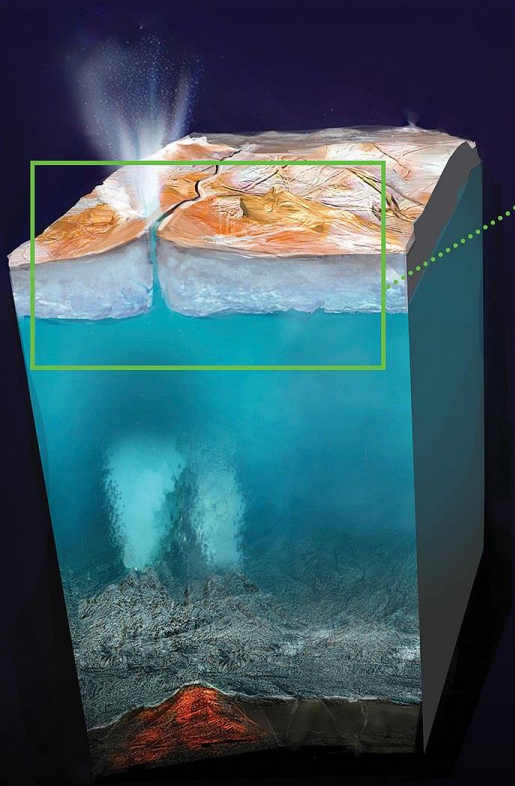
Relative Masses of Jovian Satellites

All Other
Moons
0.003%



Europa: smallest of inner moons; ice world





Ganymede and Callisto



Europa Clipper

- Launched on 2024.10.14 by NASA (US)
- To arrive at Europa in 2030.04
- Cost: \$2B USD
- 9 instruments

Objectives:

Confirm liquid water between ice and ice-ocean exchange

Composition and chemistry

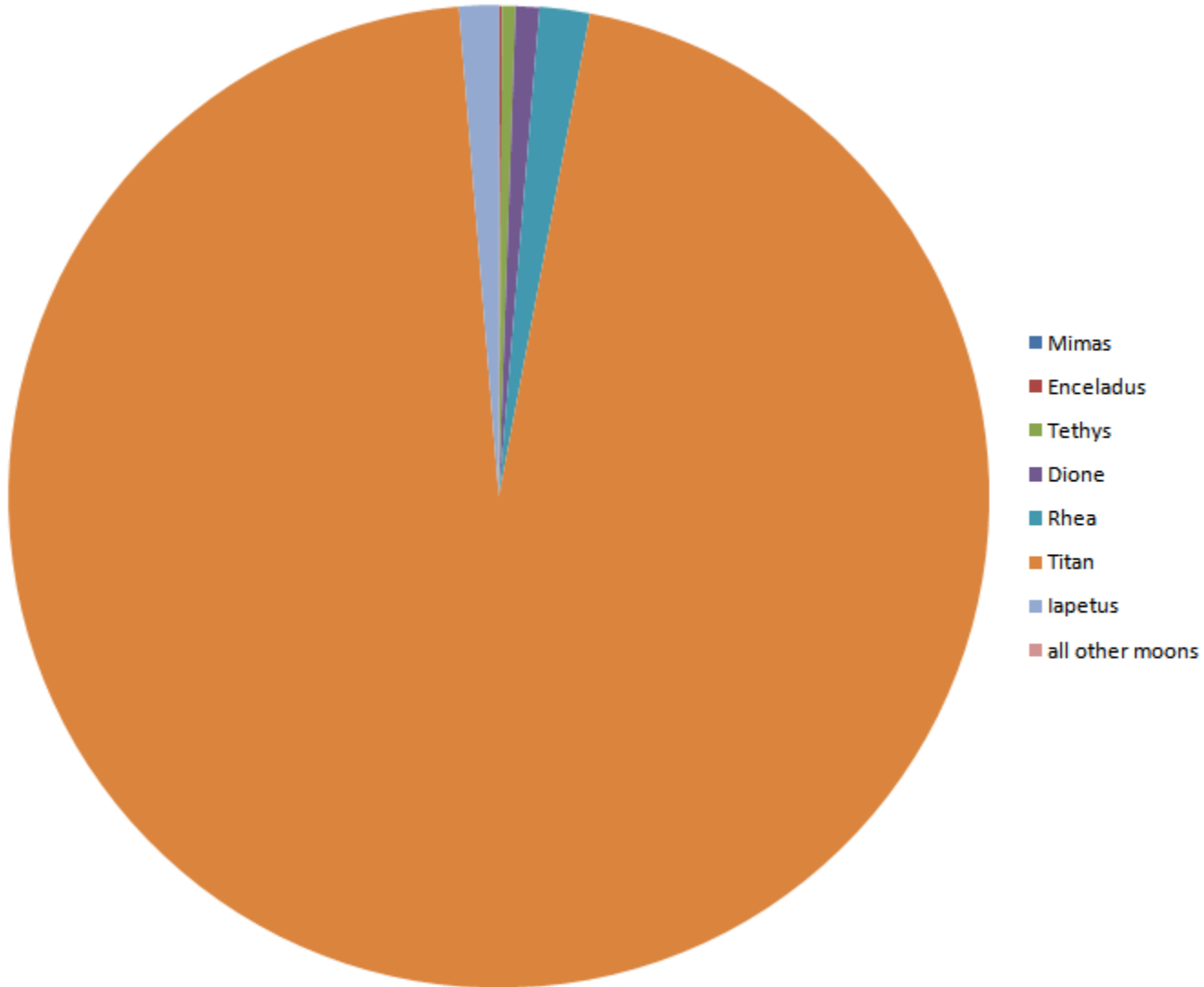
Geology of surface features

JUICE: Jupiter Icy Moons Explorer

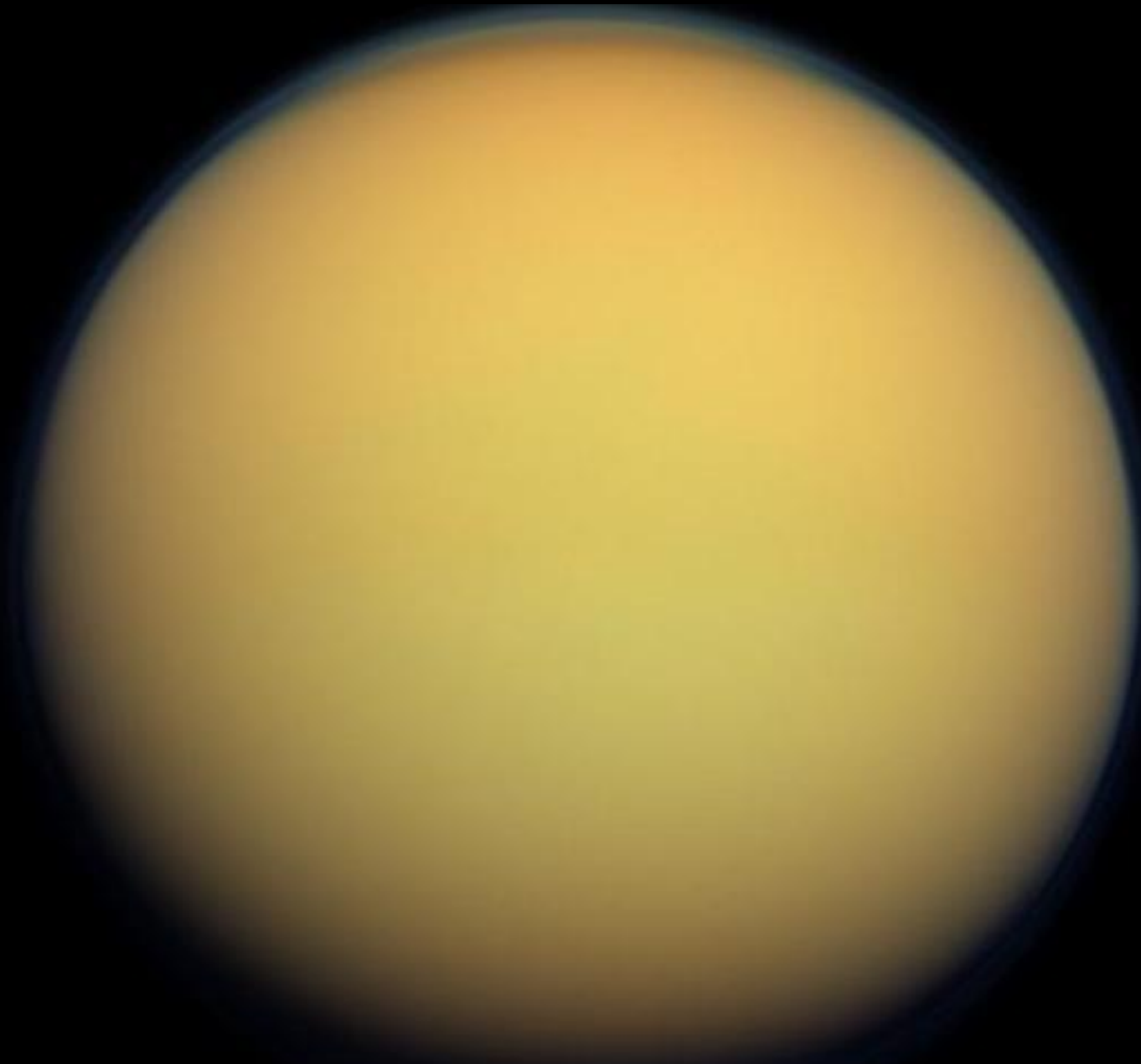
- Launched on 2023.04.14 by ESA (Europe)
- Arrive in 2031.07
- \$1.6B USD
- Will enter orbit around Ganymede
 - With flybys of Europa and Callisto

Similar science goals, but for Ganymede

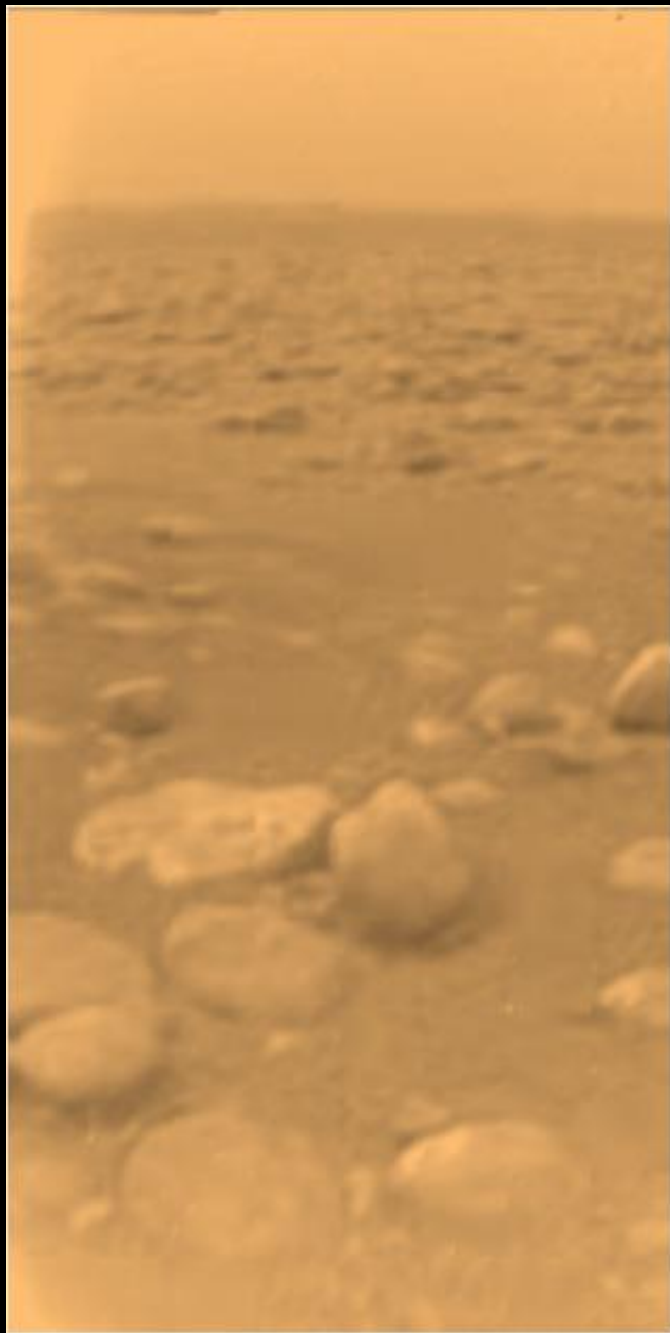
Moons of Saturn



Titan: the main moon of Saturn



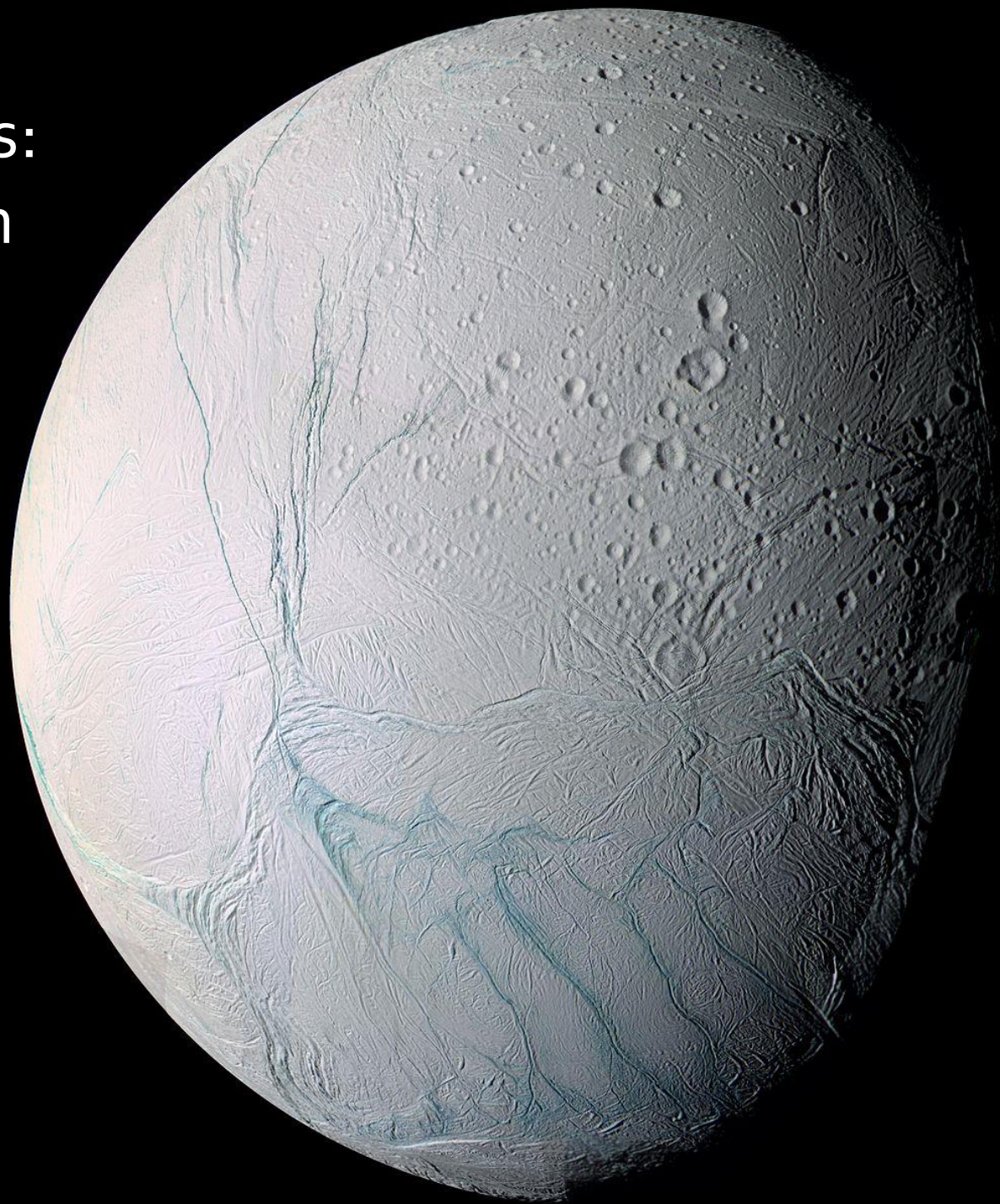


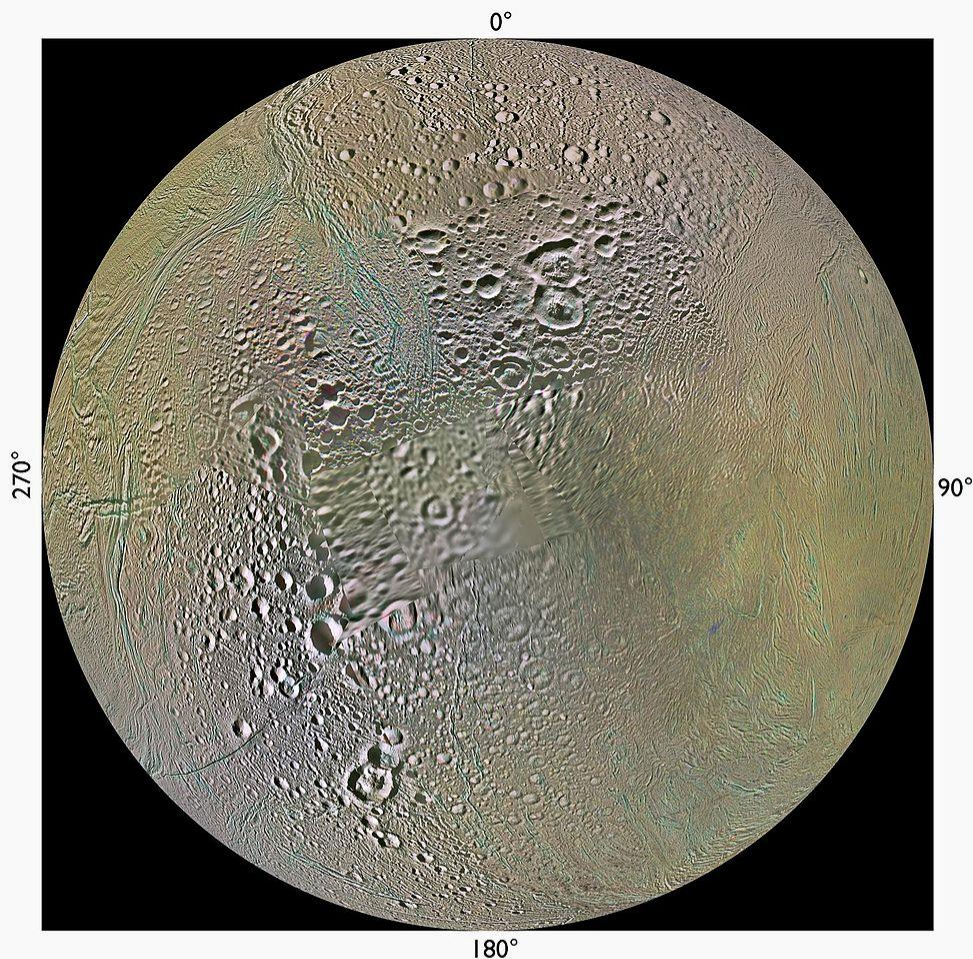




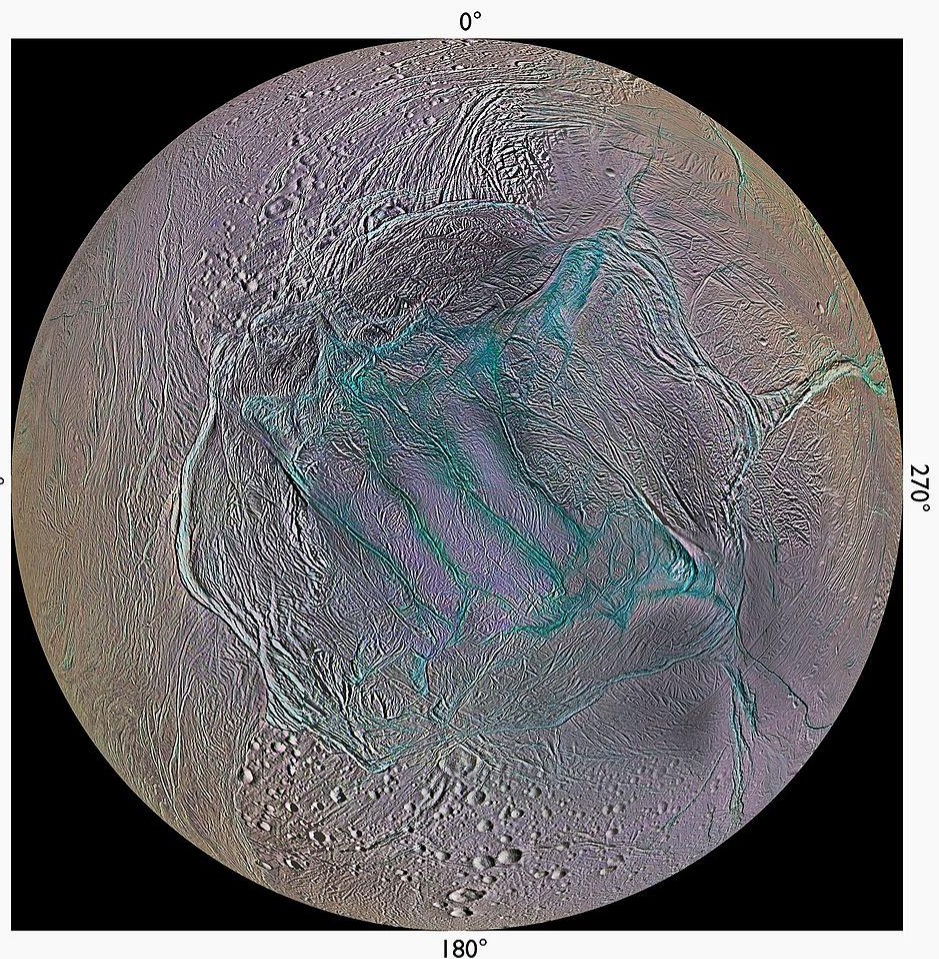
**NASA/Dragonfly Mission:
drone to Titan!**

Enceladus:
ice moon





Northern Hemisphere
Orthographic map projection at 100 meters/pixel

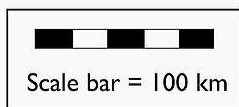


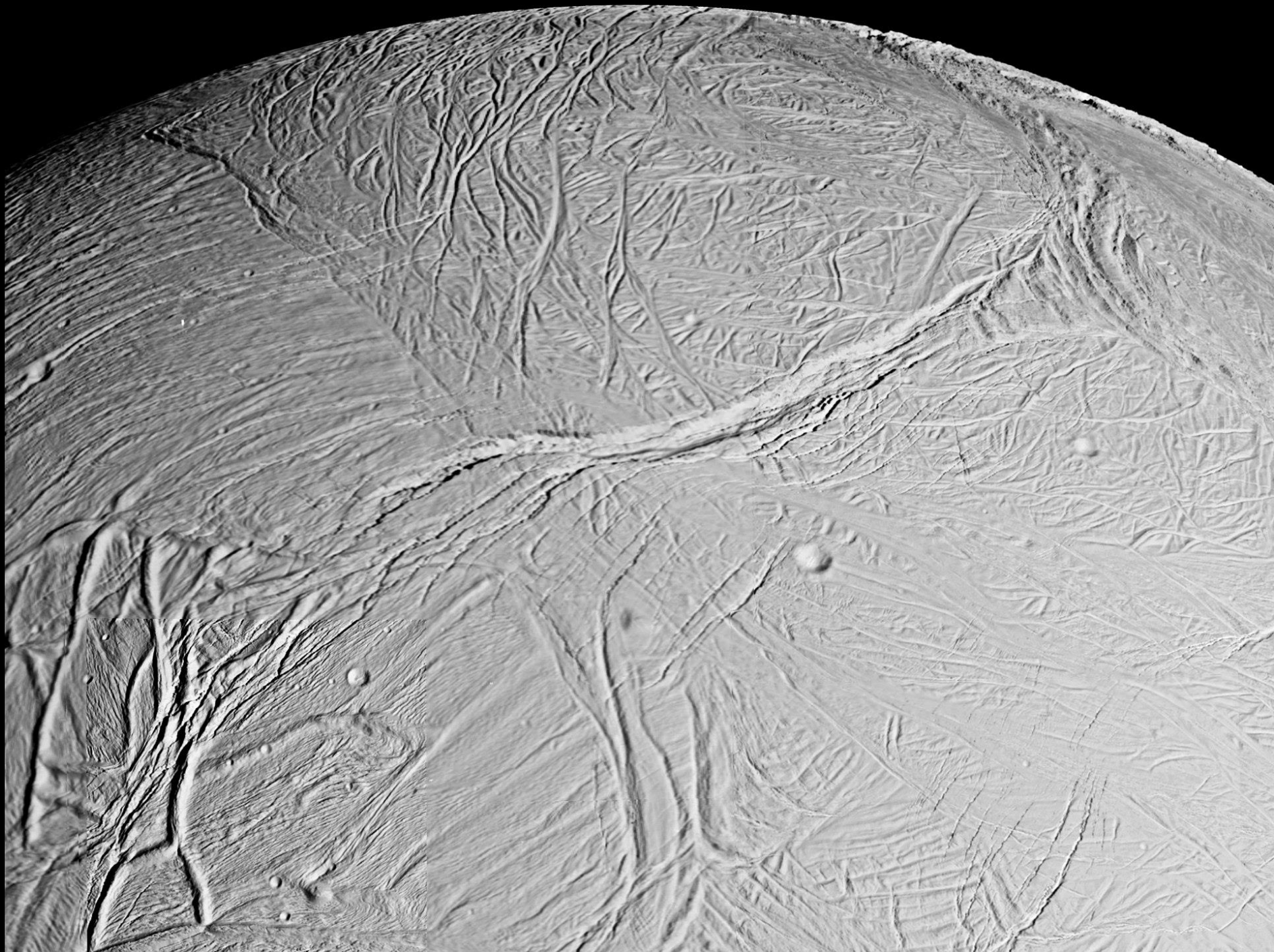
Southern Hemisphere
Orthographic map projection at 100 meters/pixel

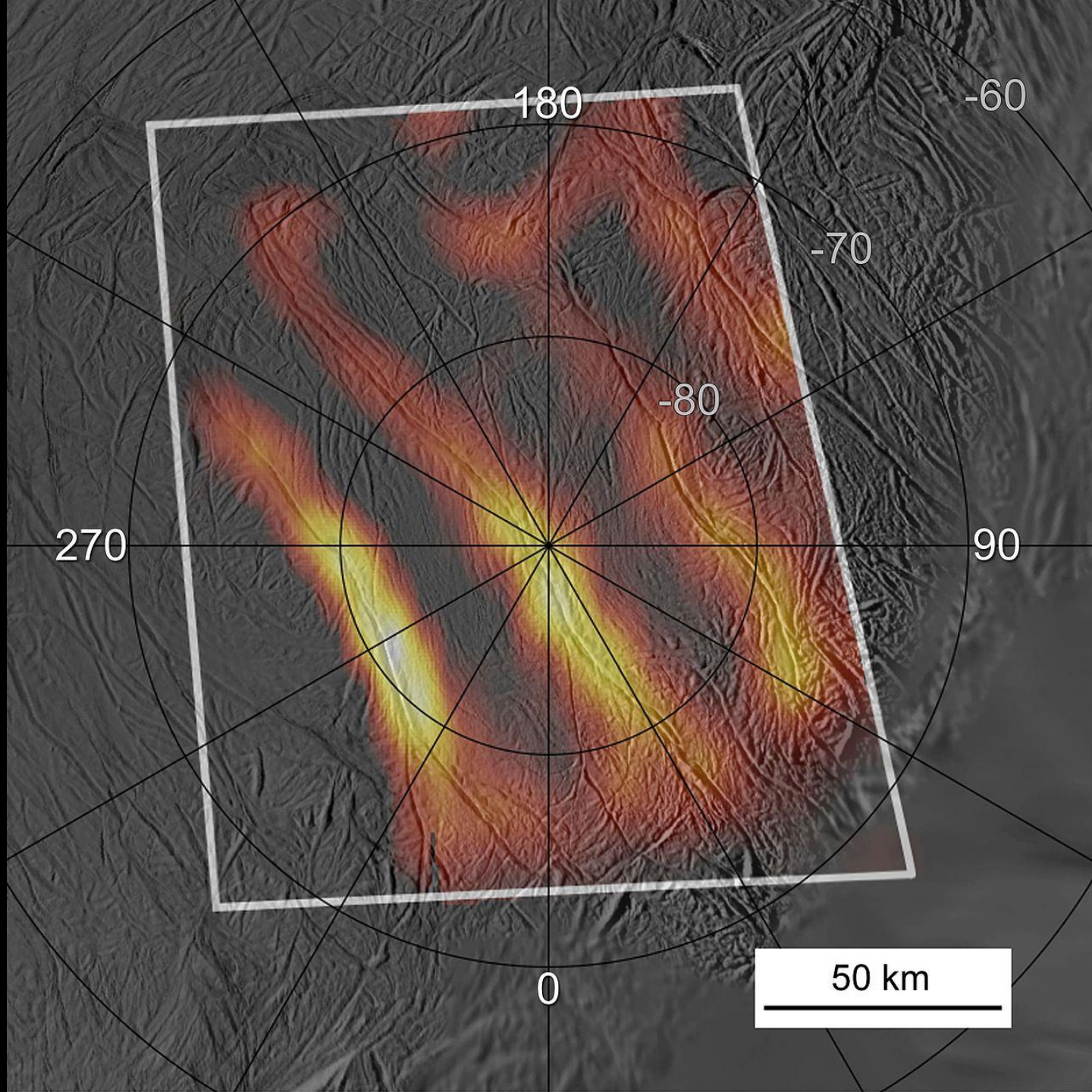
Global 3-Color Map of Enceladus (IR3-GRN-UV3)

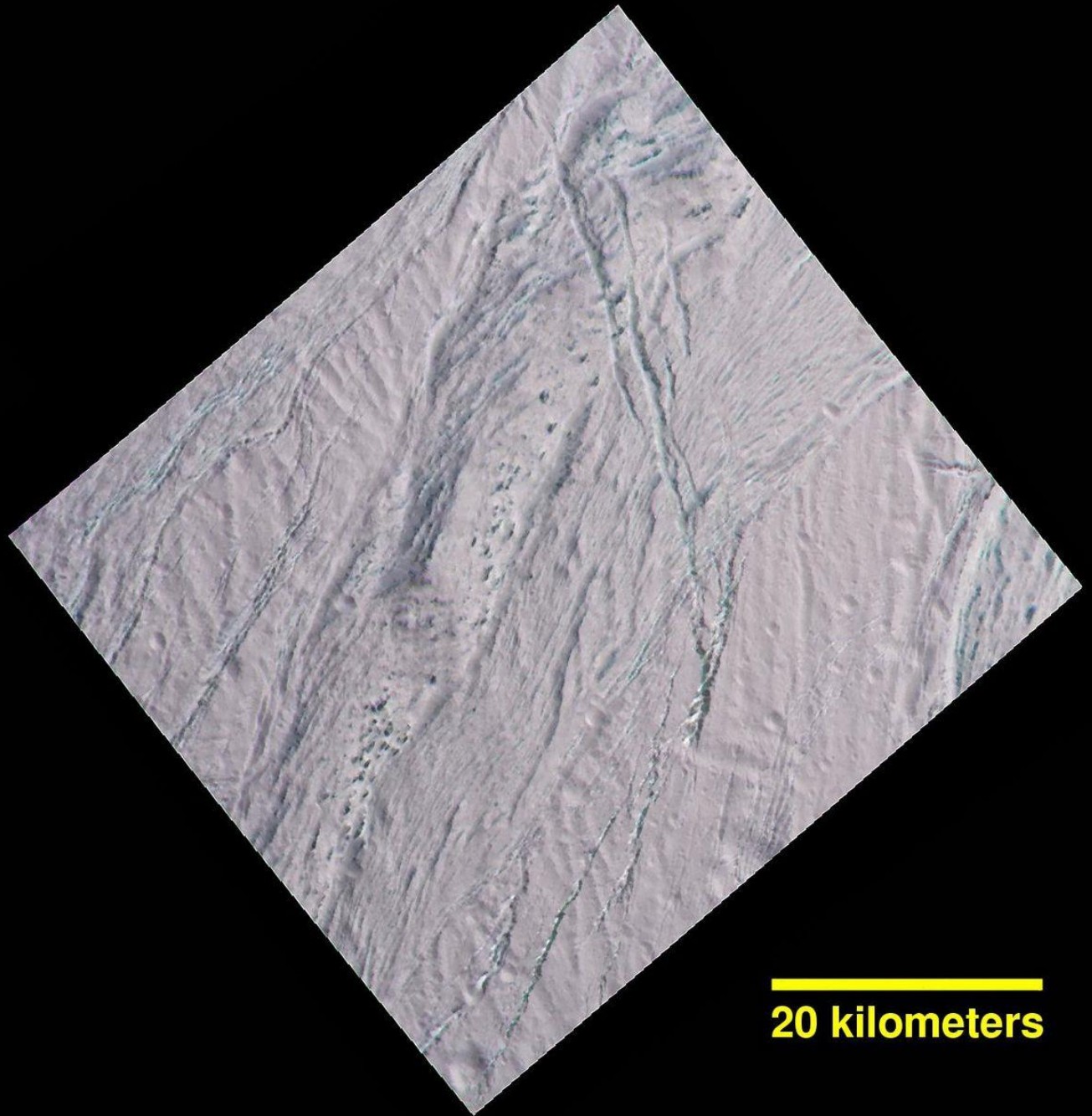
April 2014

Cartographic control and digital mosaic construction by Dr. Paul Schenk (LPI, Houston)
Cassini ISS images acquired 2004-2014





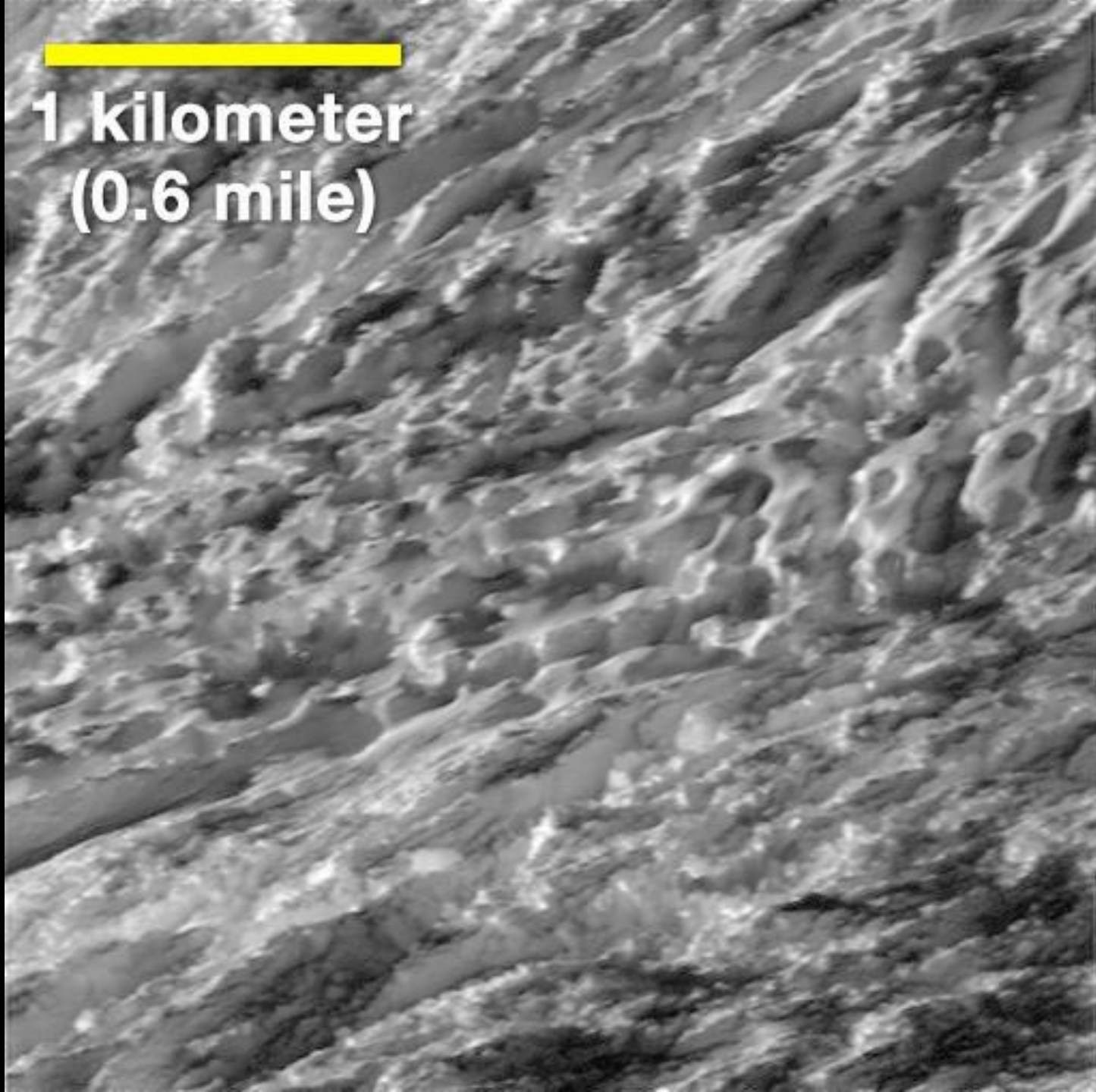




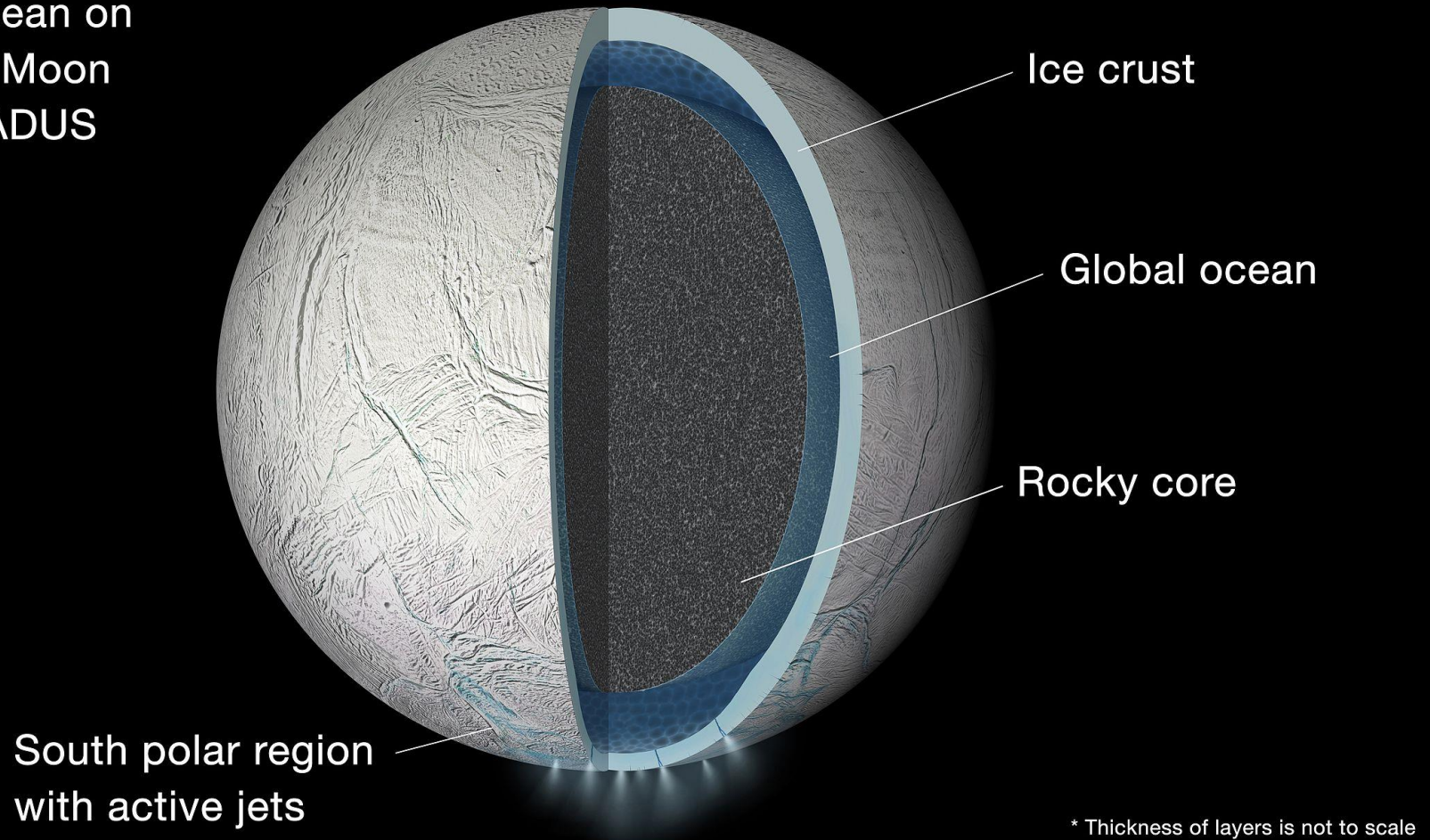
20 kilometers



**1 kilometer
(0.6 mile)**



Global Ocean on
Saturn's Moon
ENCELADUS



Ice crust

Global ocean

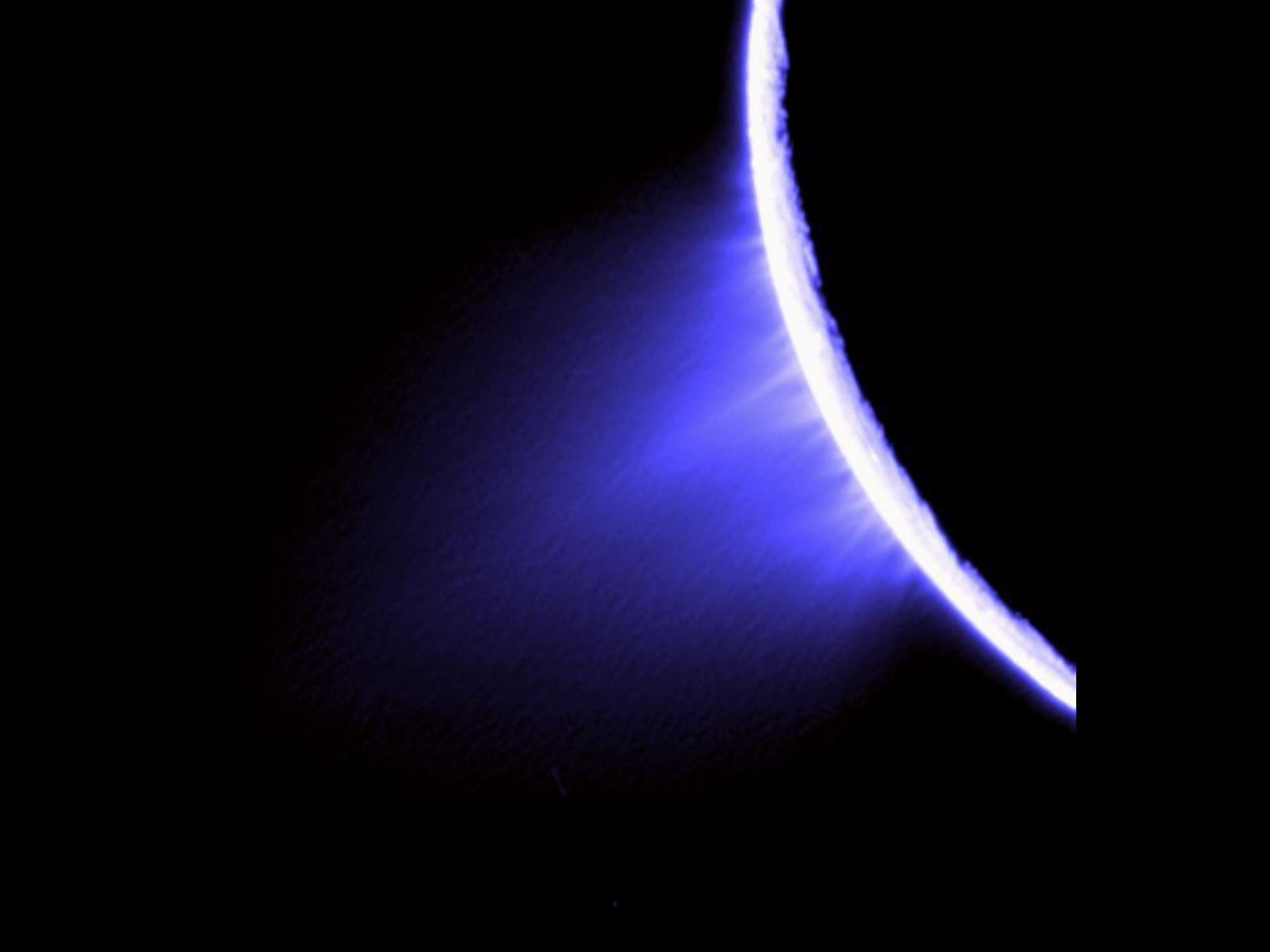
Rocky core

South polar region
with active jets

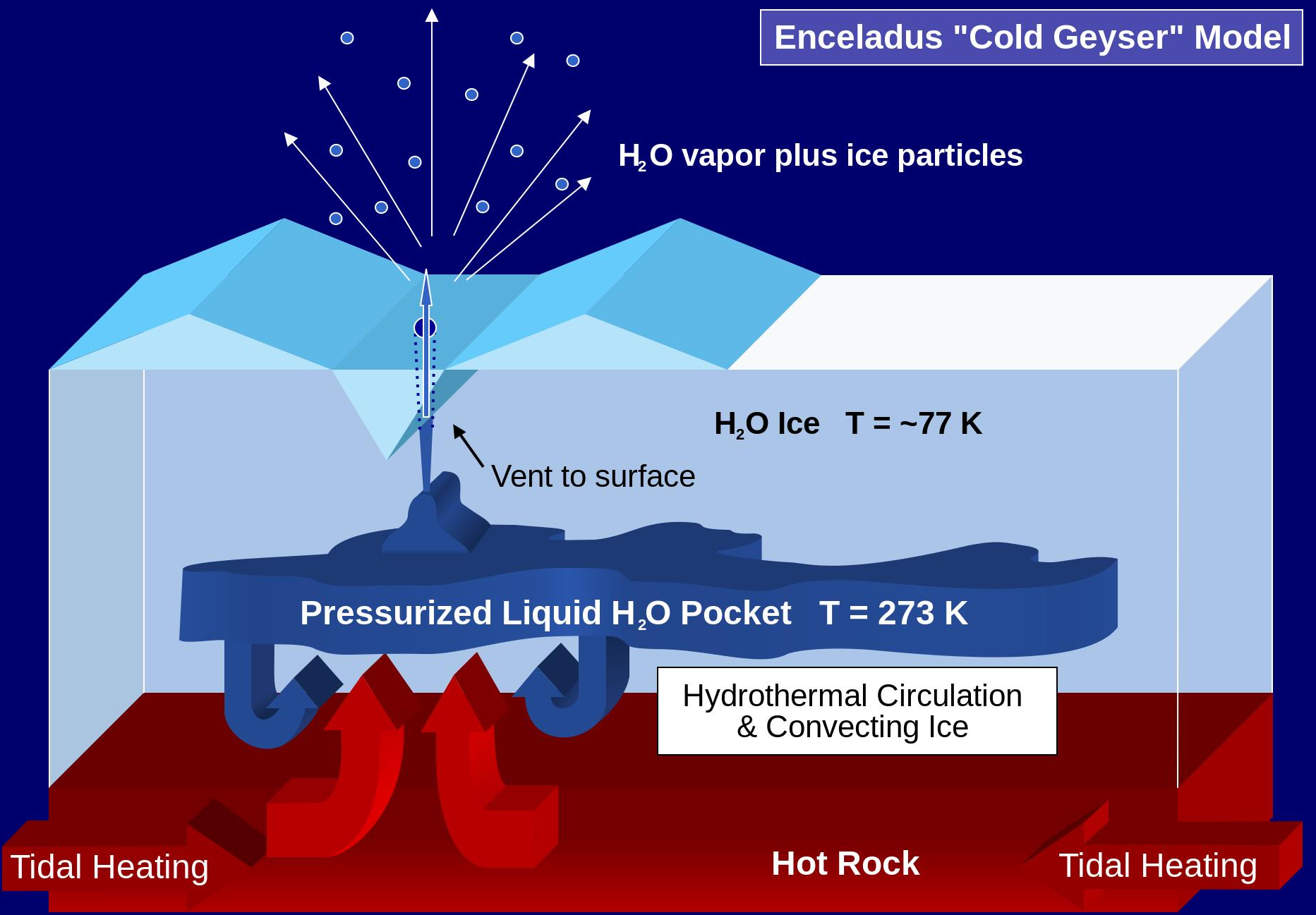
* Thickness of layers is not to scale

Enceladus:
geysers!

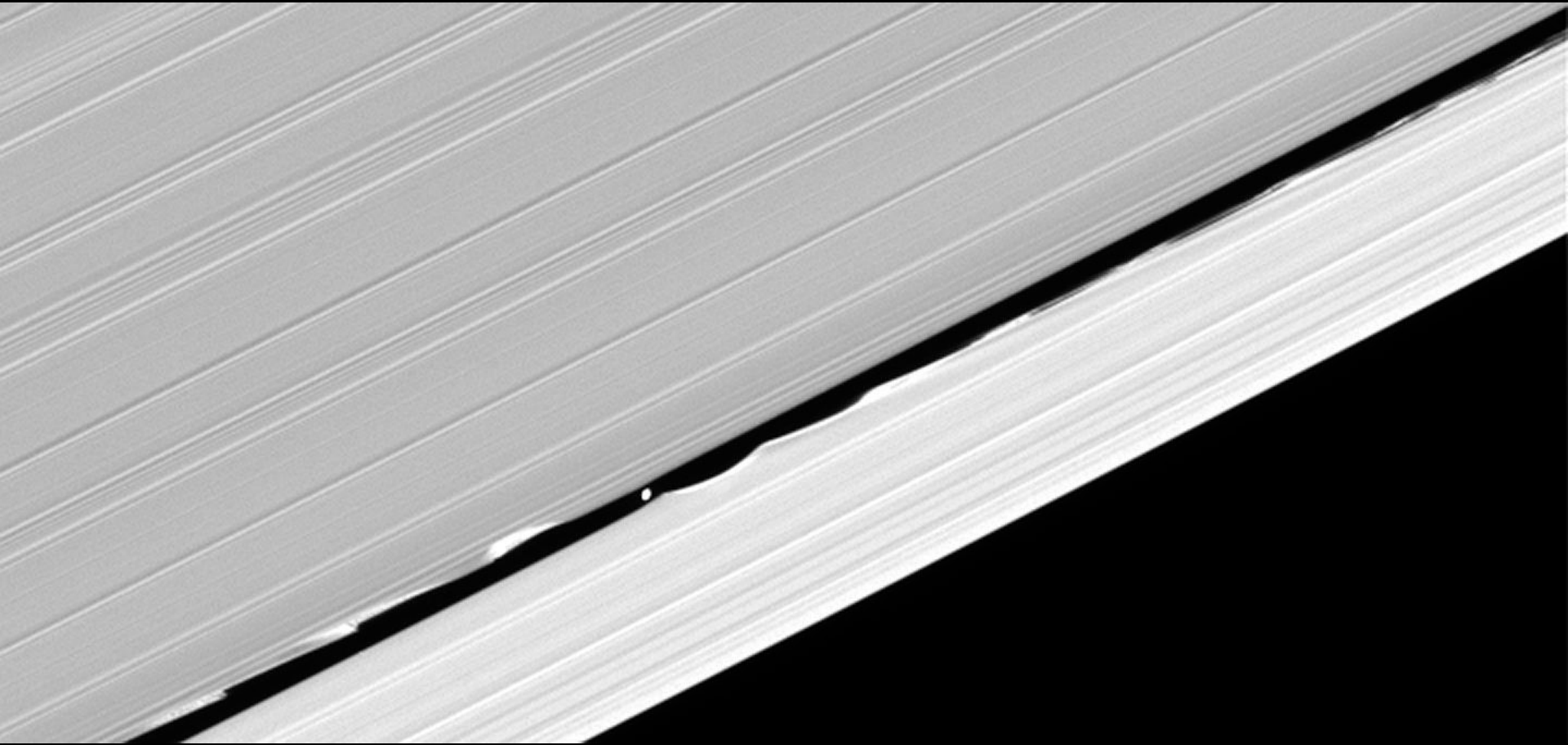




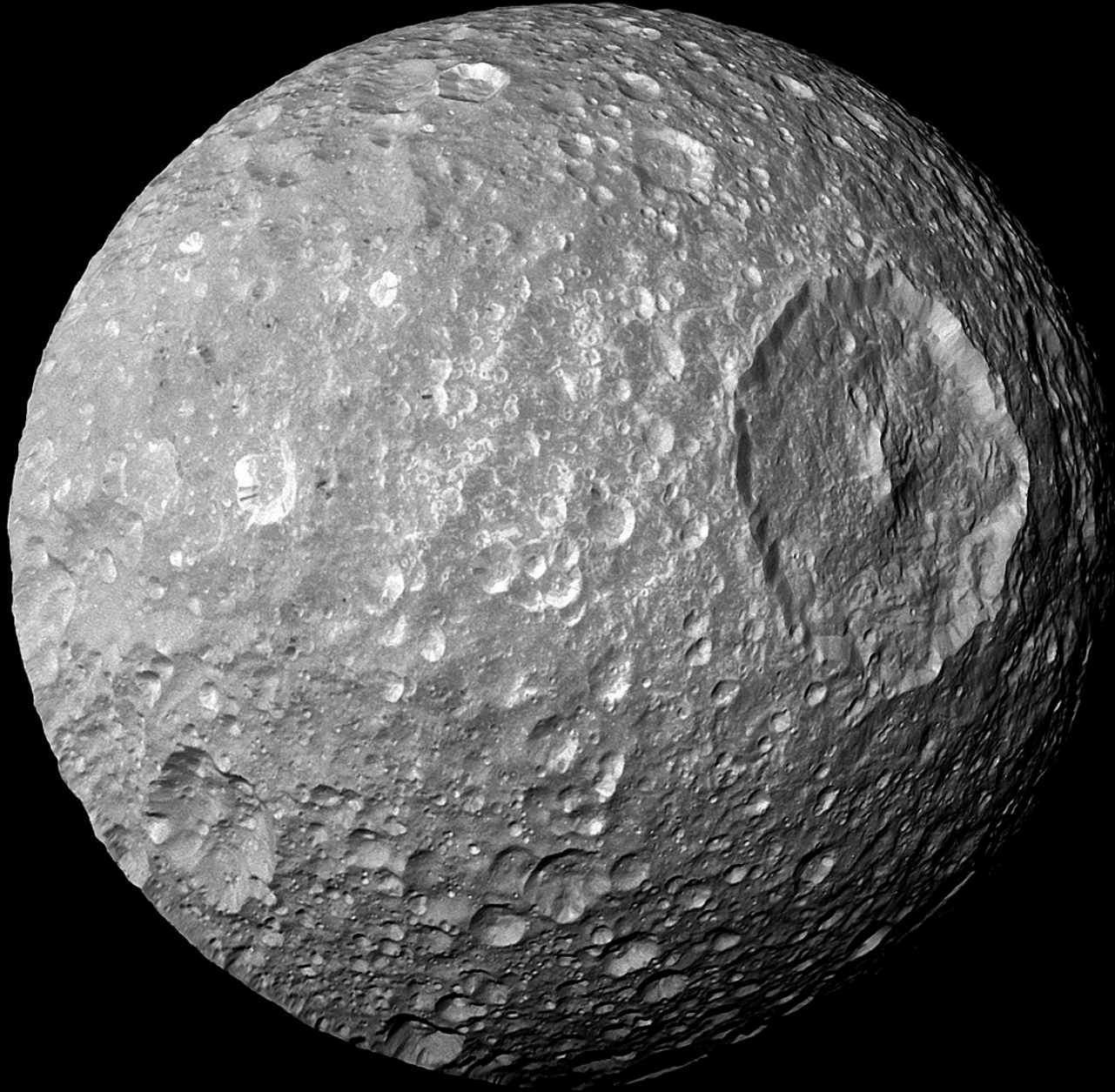
Enceladus "Cold Geyser" Model



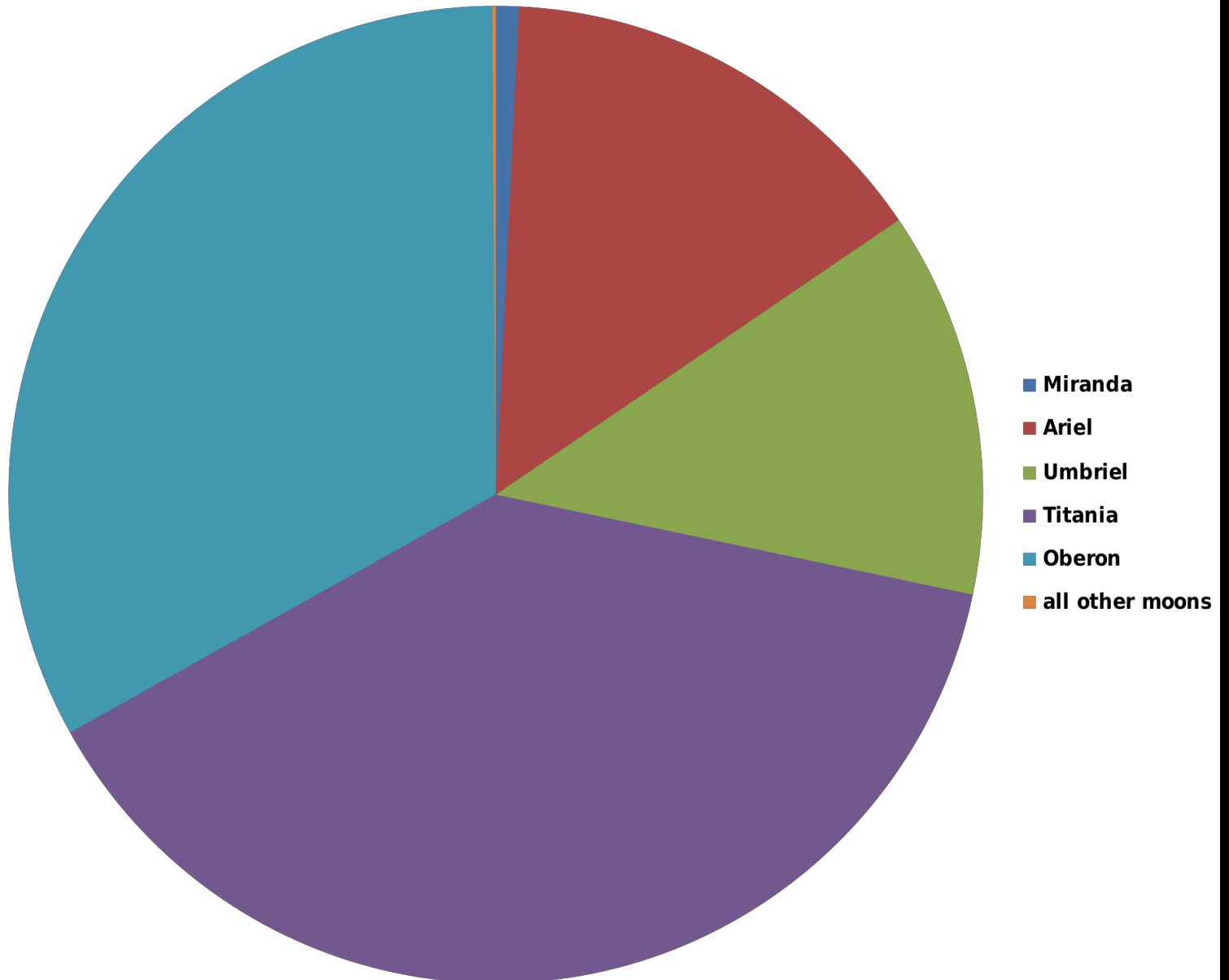
Daphnis: A shepherd moon

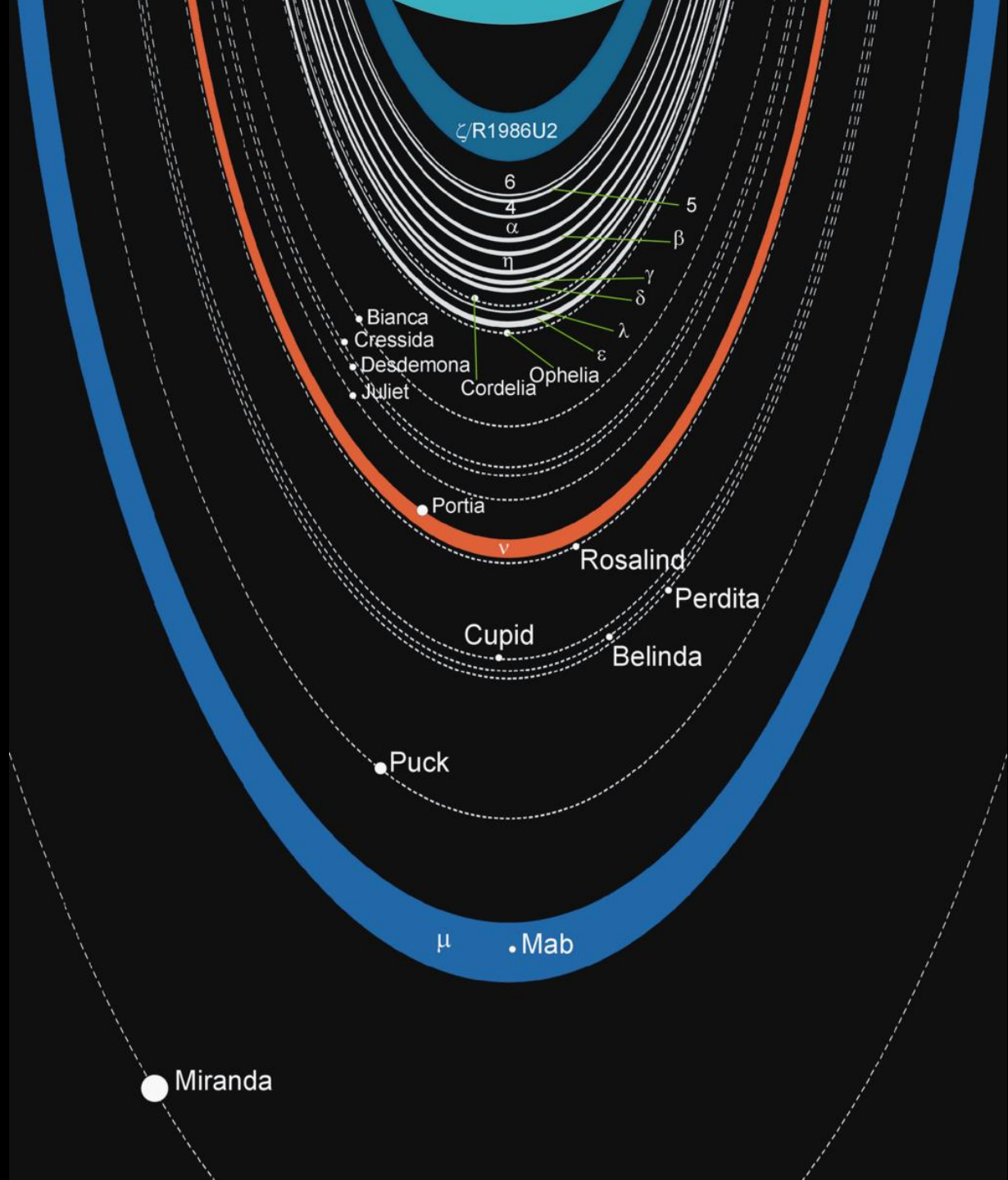


Mimas: the death star moon



Moons of Uranus





$\zeta/R1986U2$

6

4

α

η

5

β

γ

δ

λ

ϵ

Bianca
Cressida
Desdemona
Juliet

Cordelia
Ophelia

Portia

Rosalind

Perdita

Cupid

Belinda

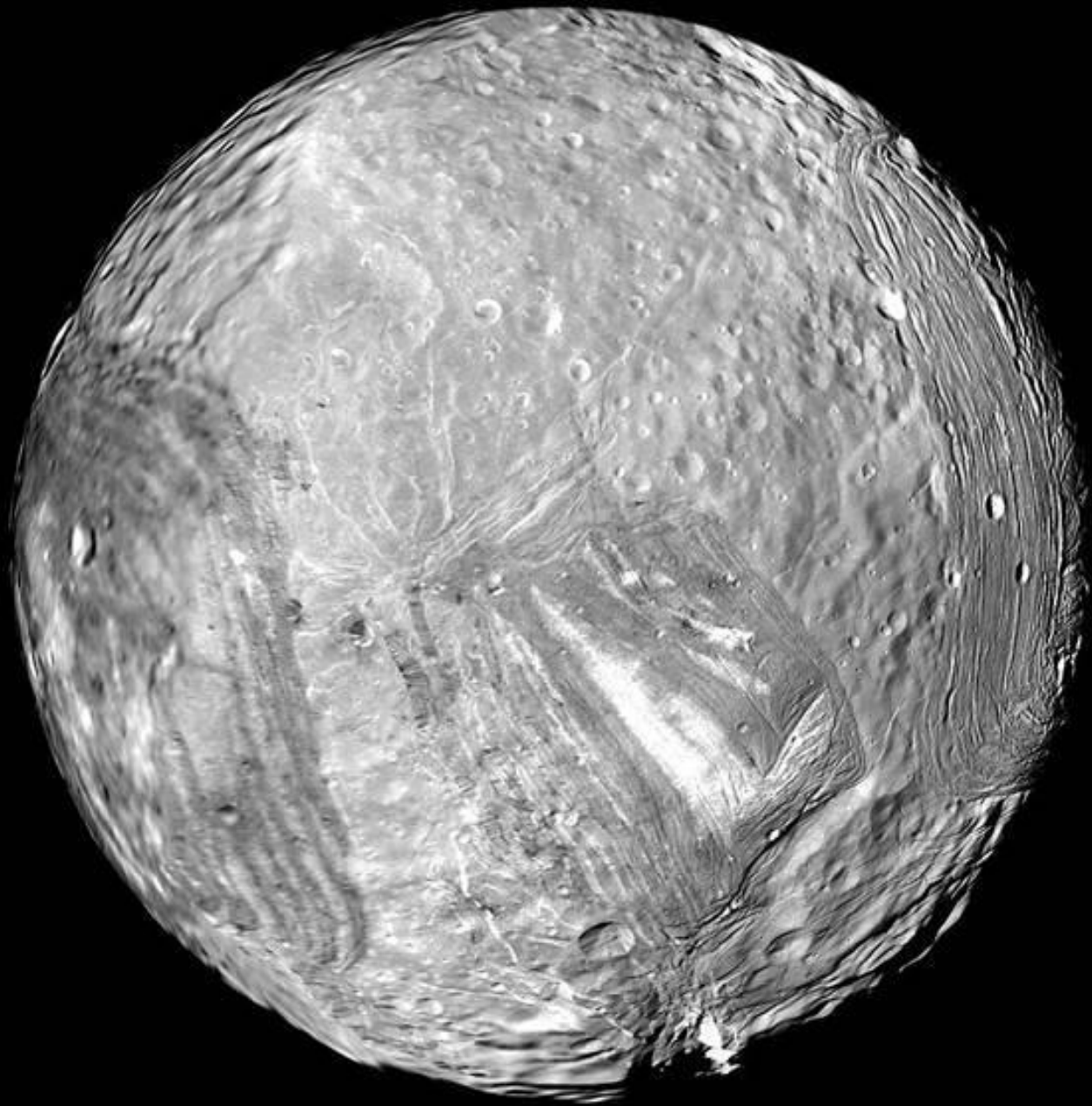
Puck

μ

Mab

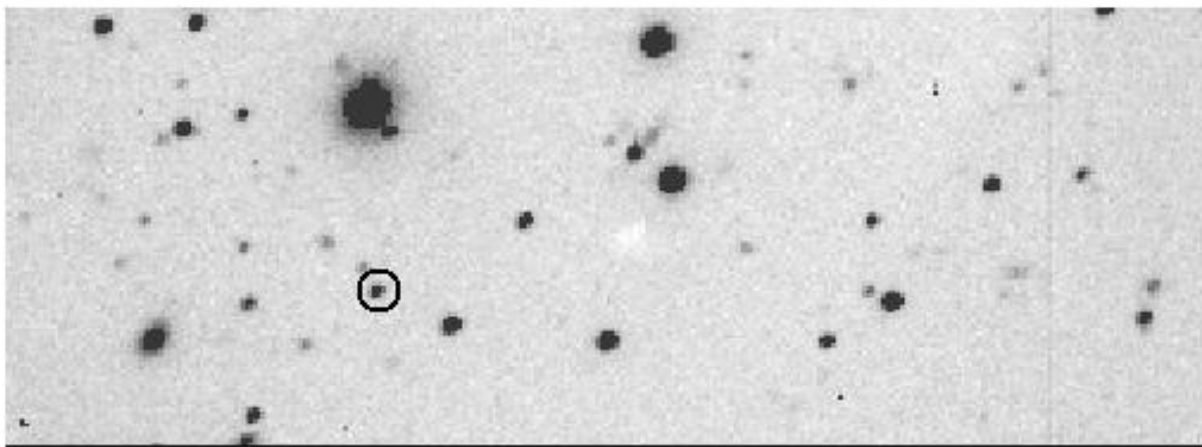
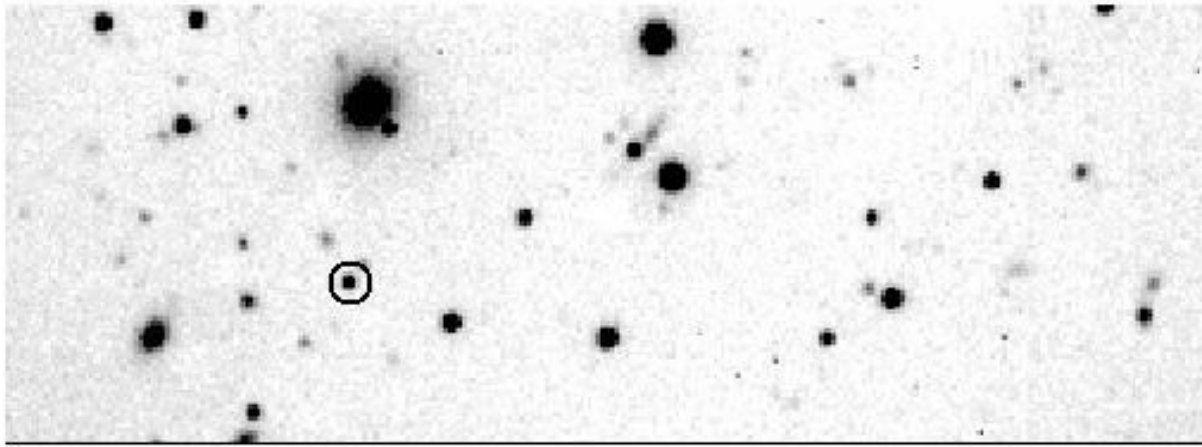
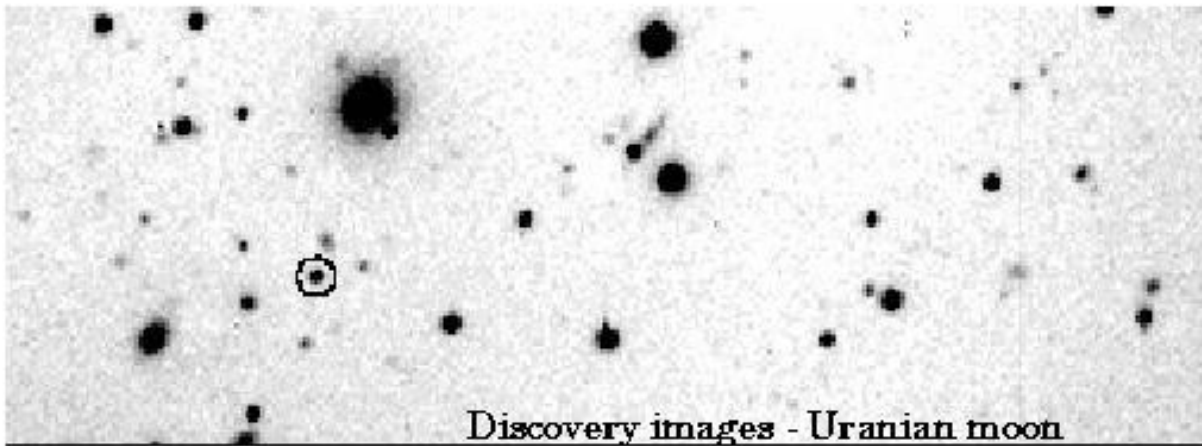
Miranda

Miranda: an ice world?



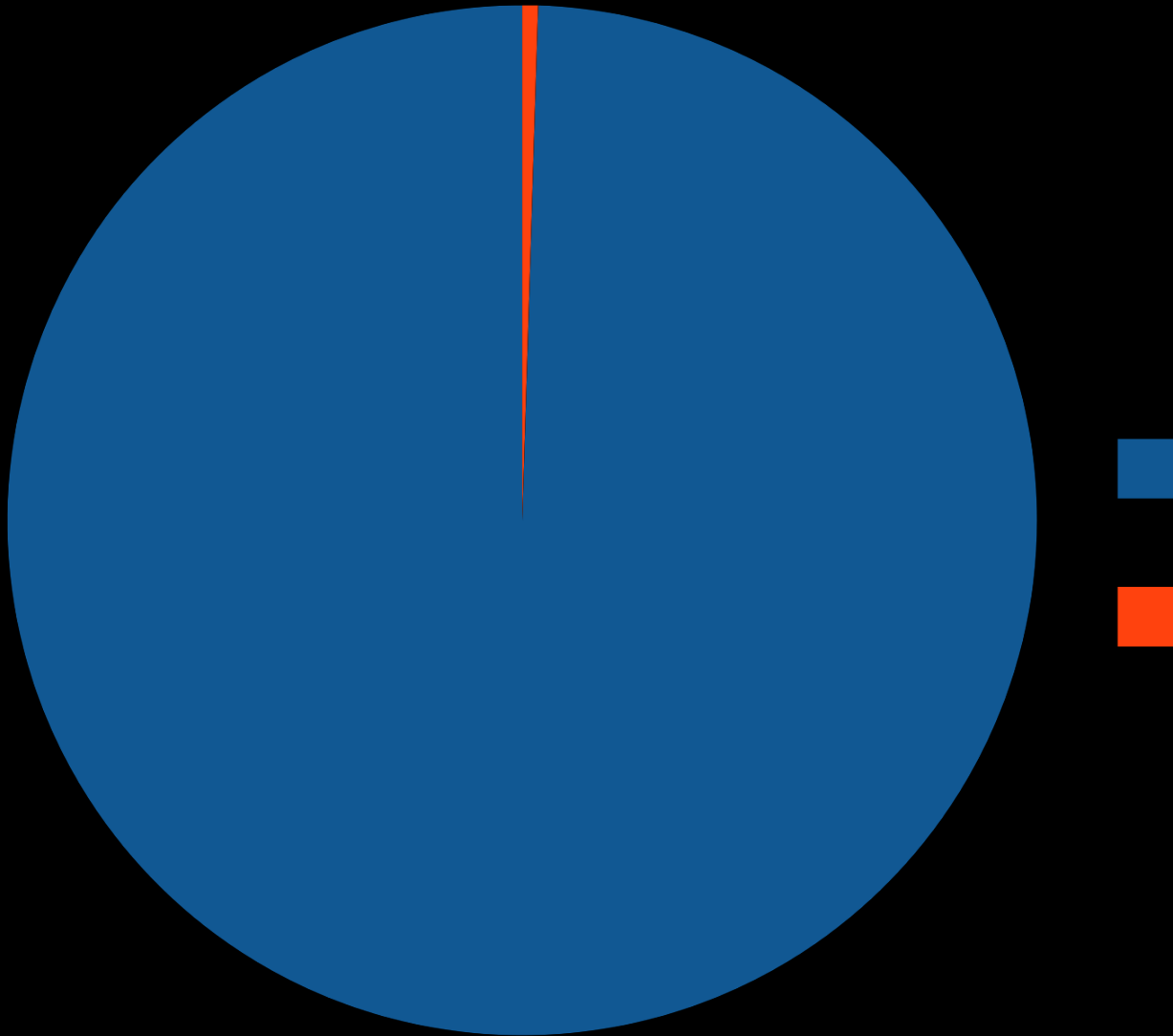
Umbriel: weird ring at the top



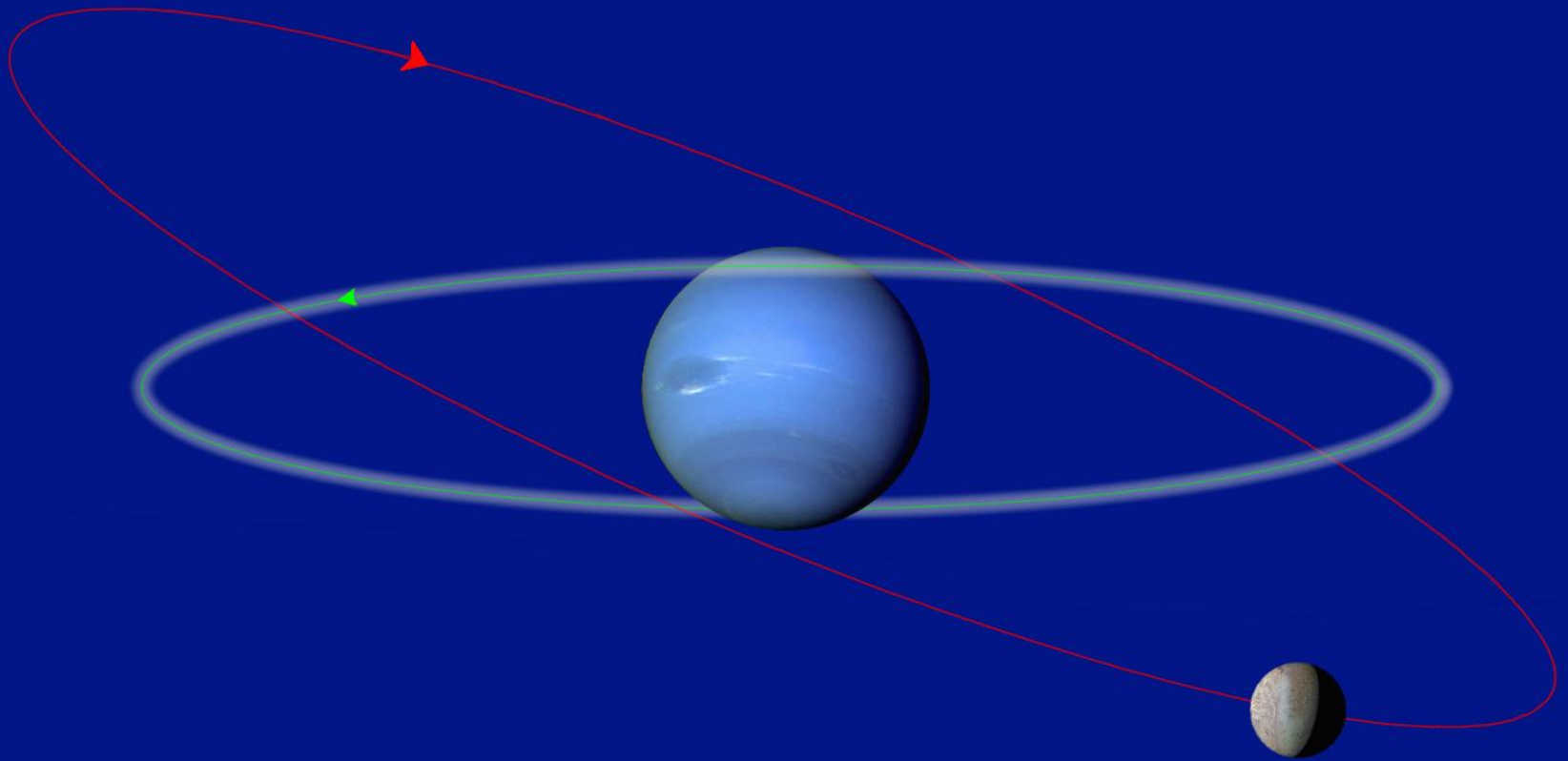


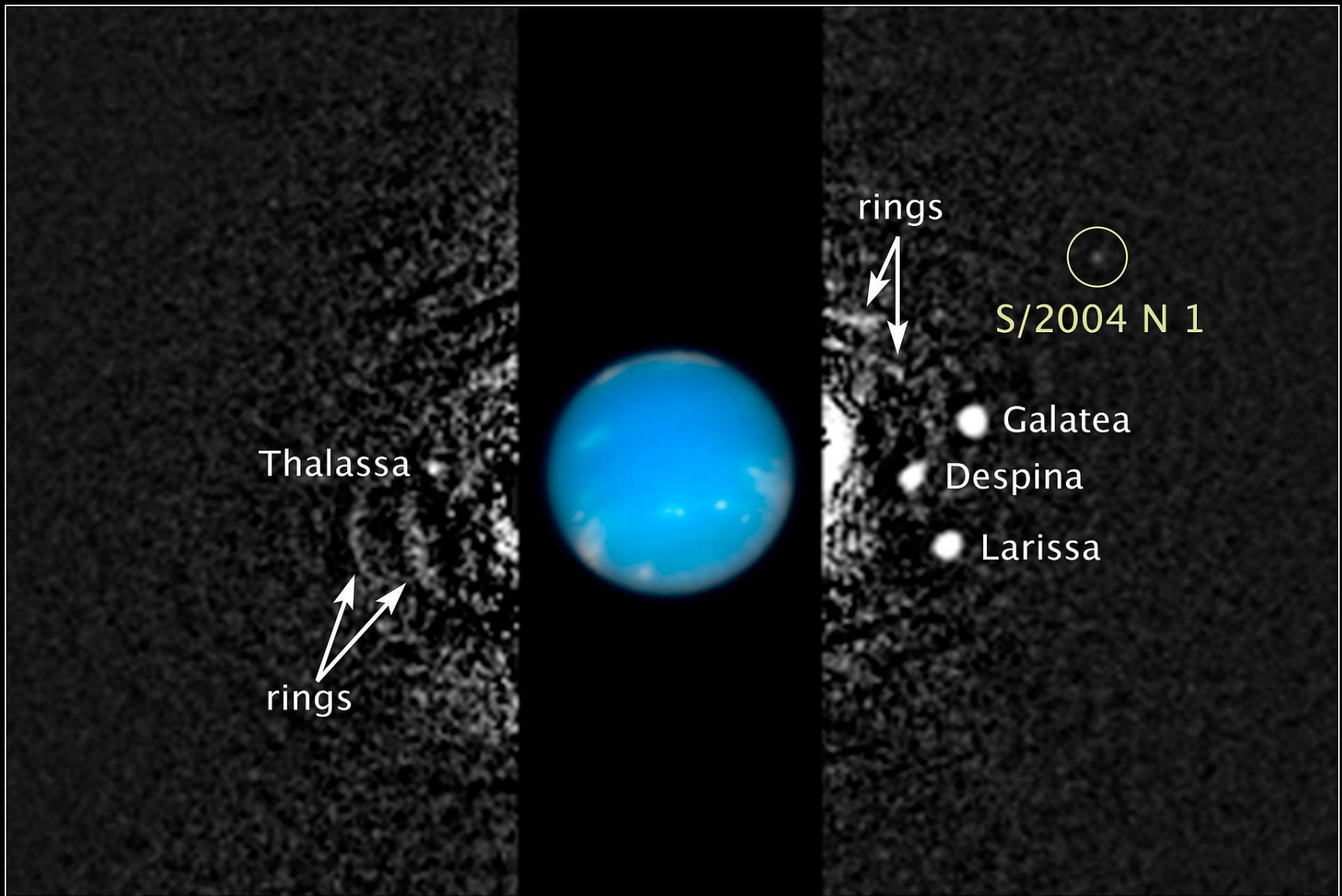
Sycorax:
example of how
the moons are
found

Moons of Neptune

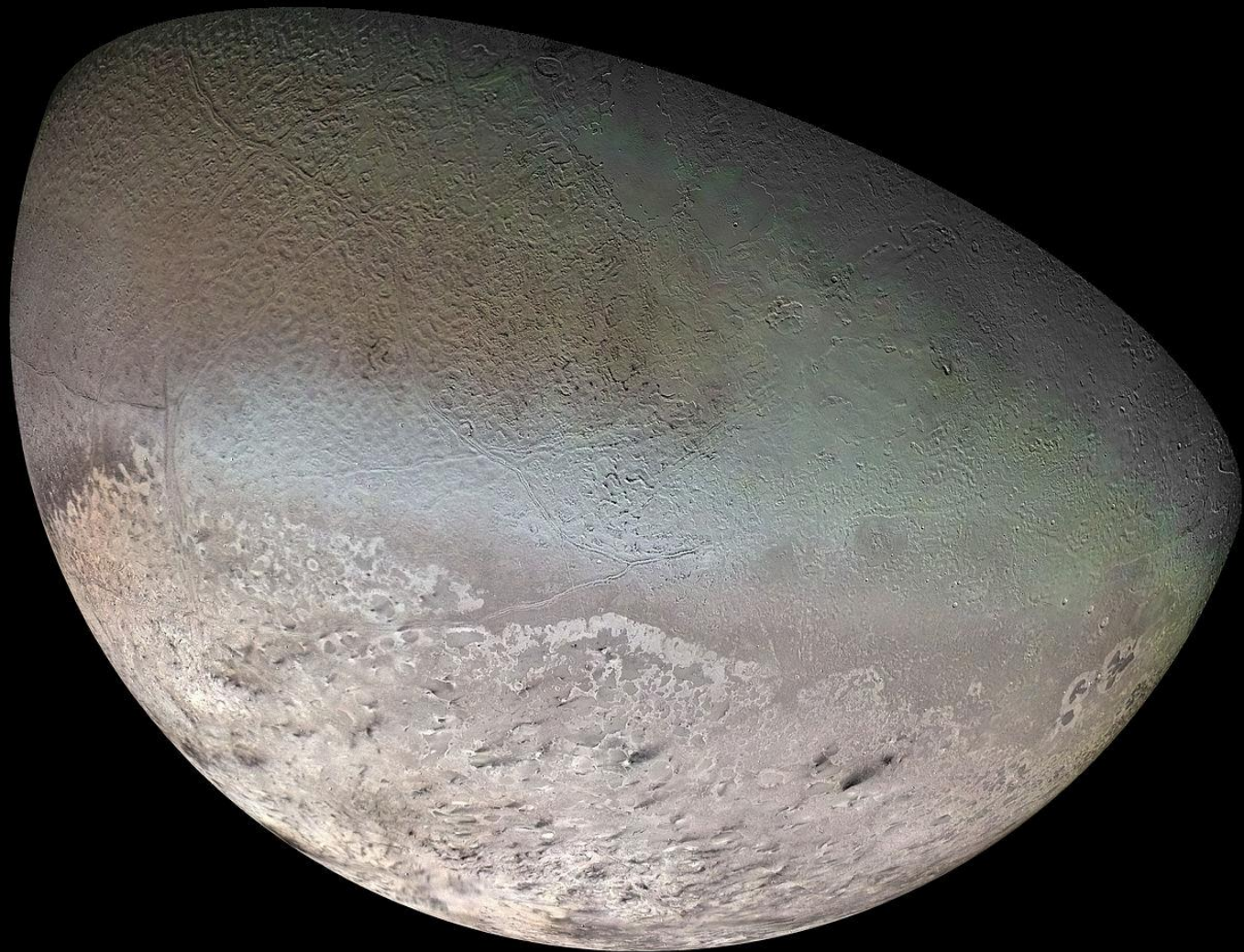


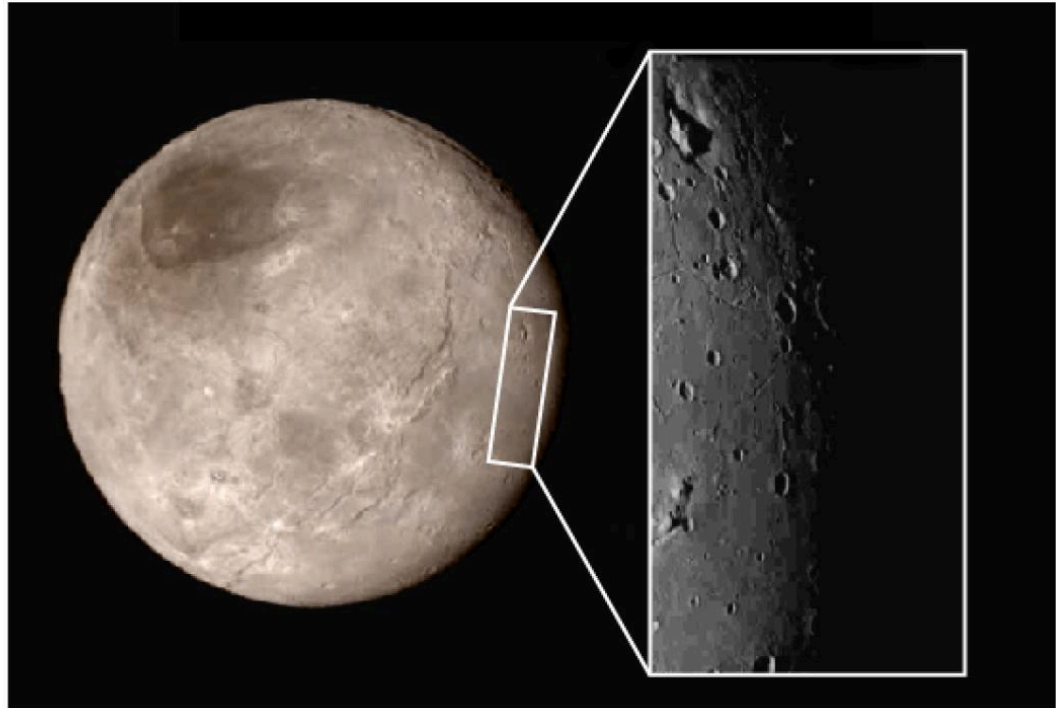
Triton: going in the wrong direction!
captured Kuiper Belt Object?



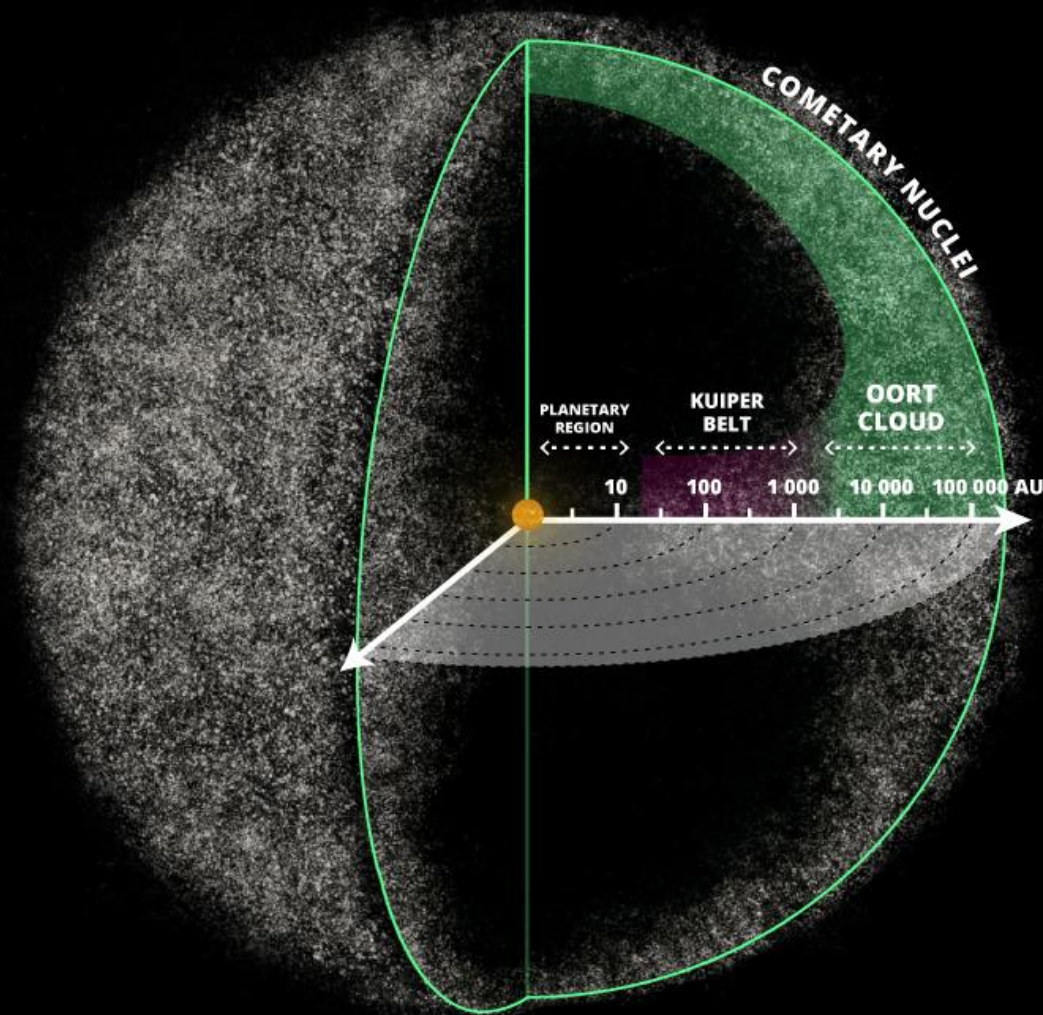


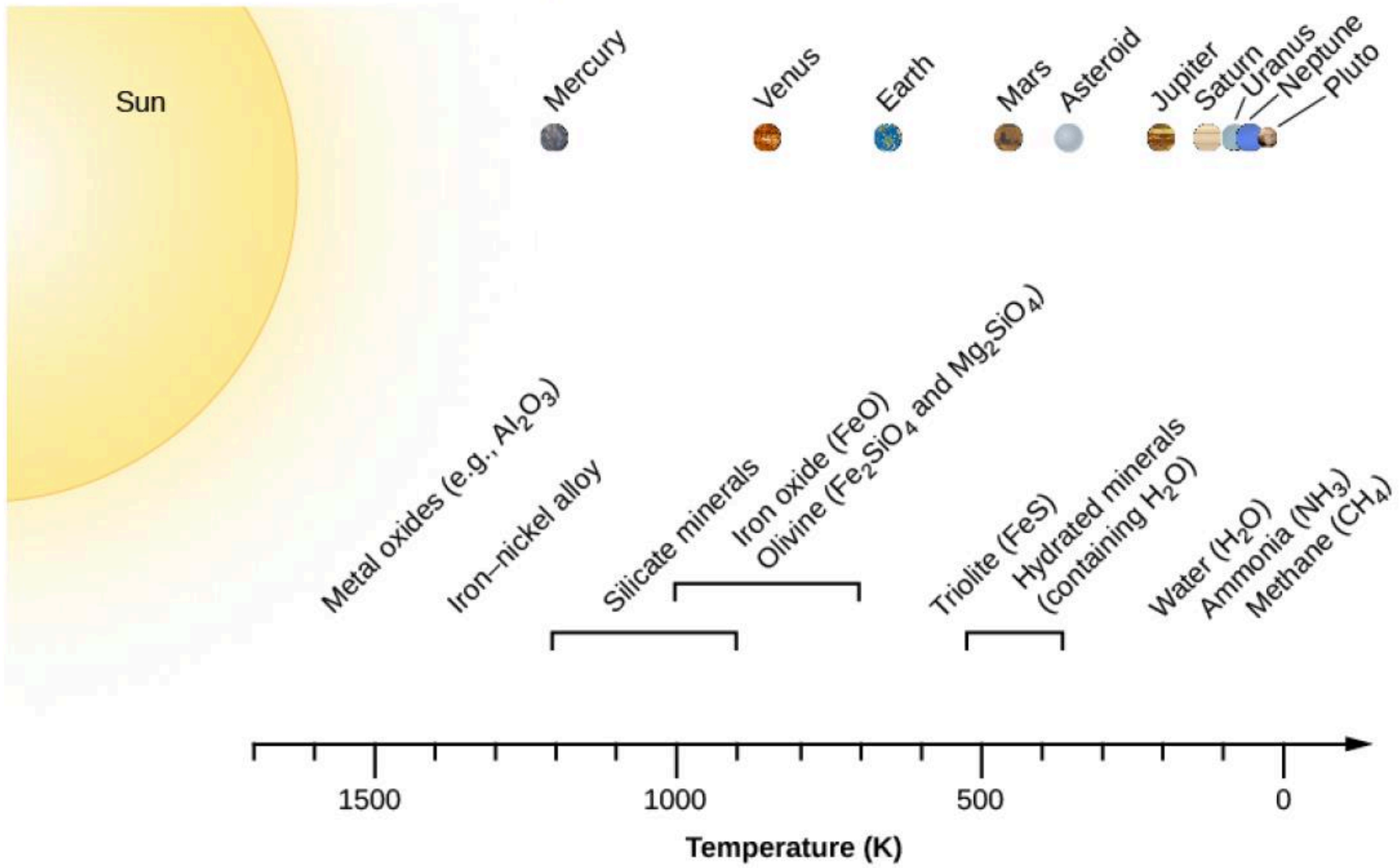
Neptune Satellites and Ring Arcs
Hubble Space Telescope ■ WFC3/UVIS





Debris from the solar system: asteroids, comets, Kuiper Belt Objects





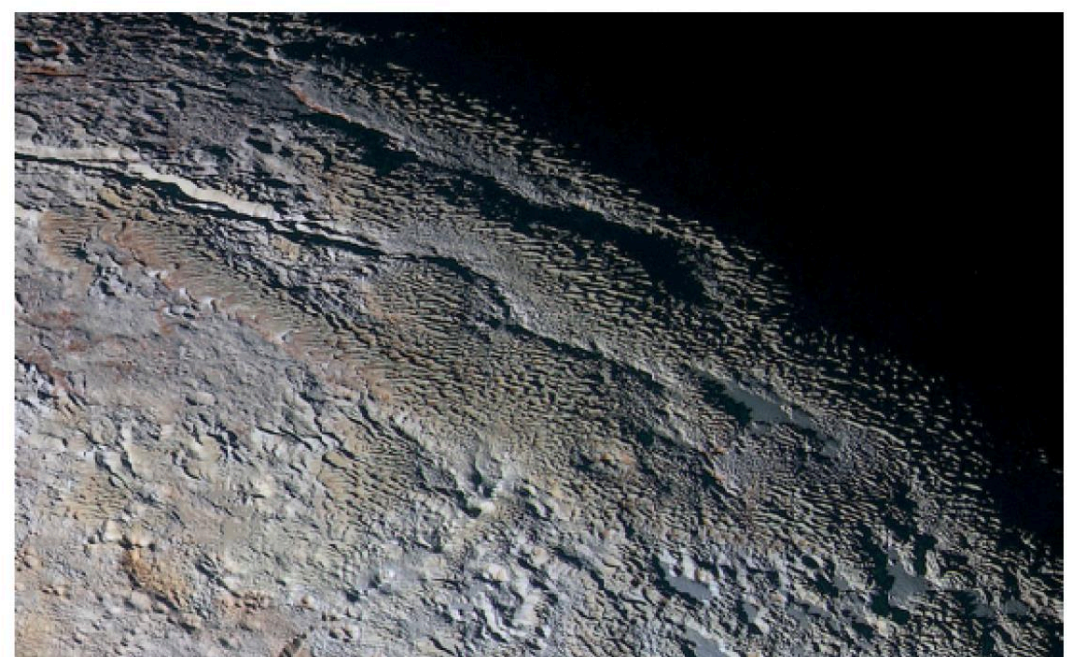
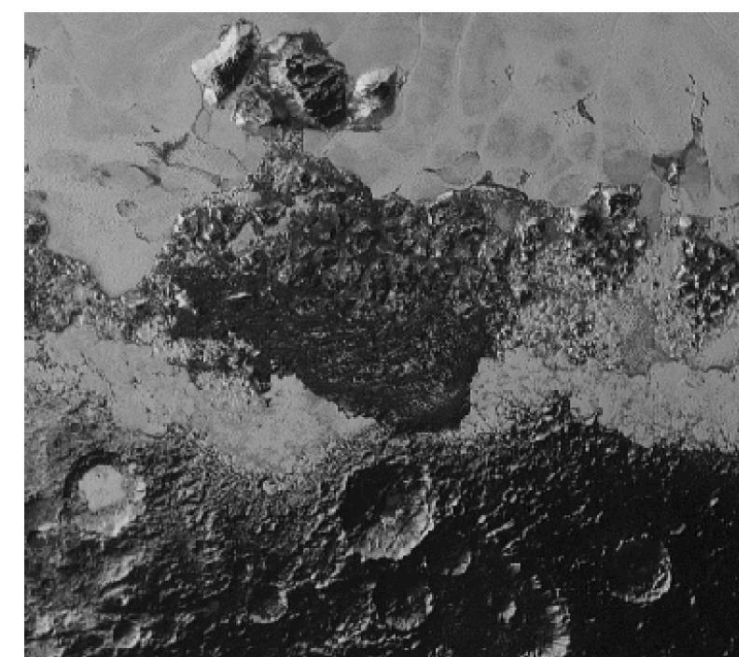
Pluto from New Horizons Mission





Cratered = old

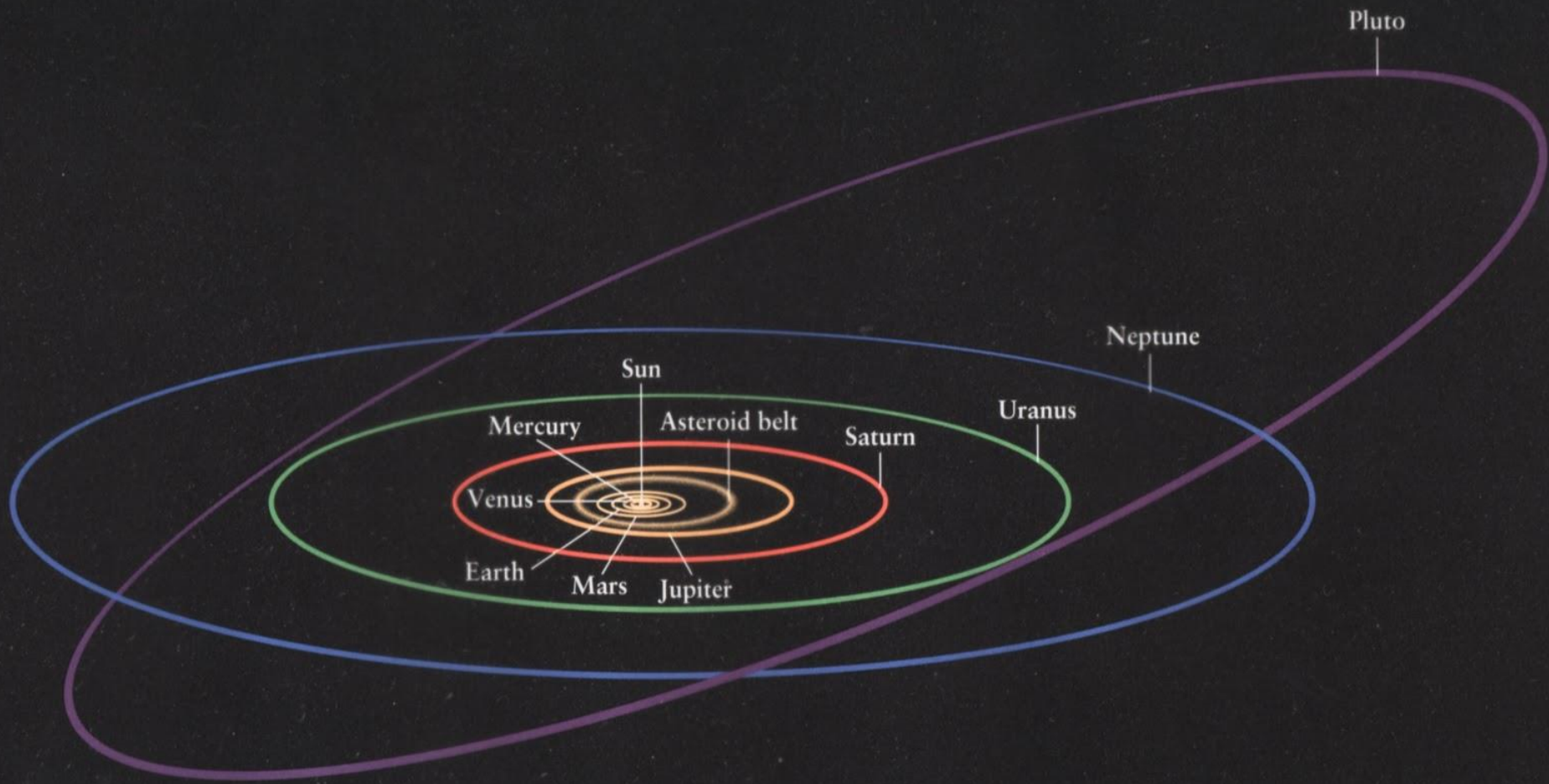
Nitrogen ice
Flows like glaciers



Ice mountains, 3 km high

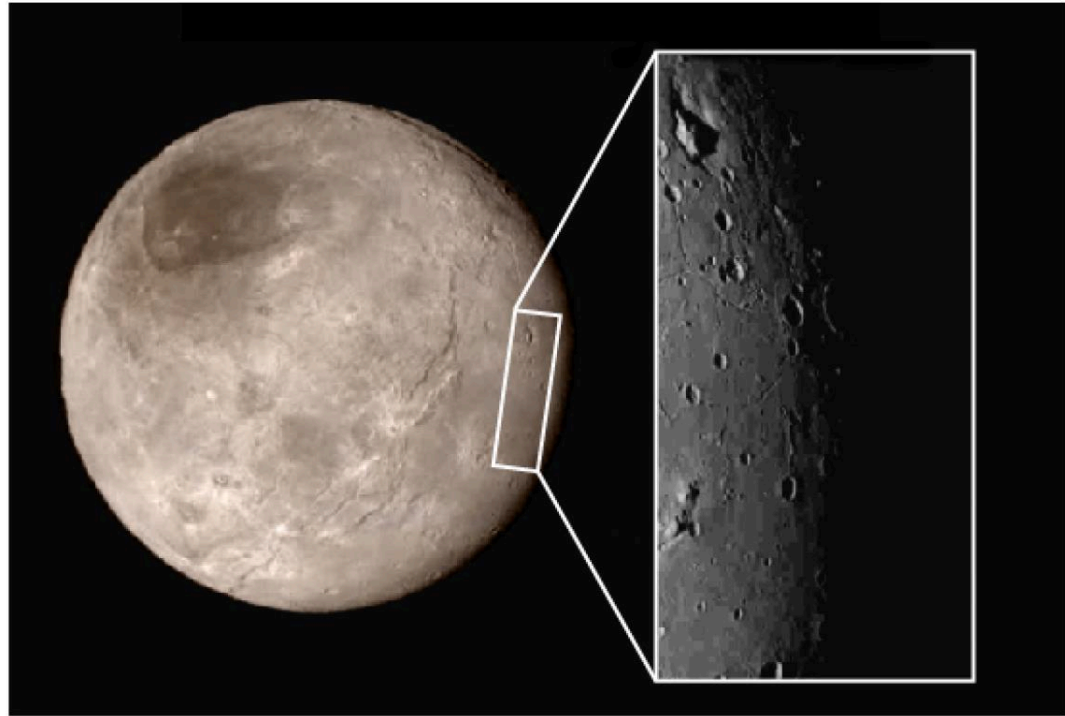
Haze! Pluto has an atmosphere
Likely from solar radiation, will disappear when
Pluto is farther from the Sun



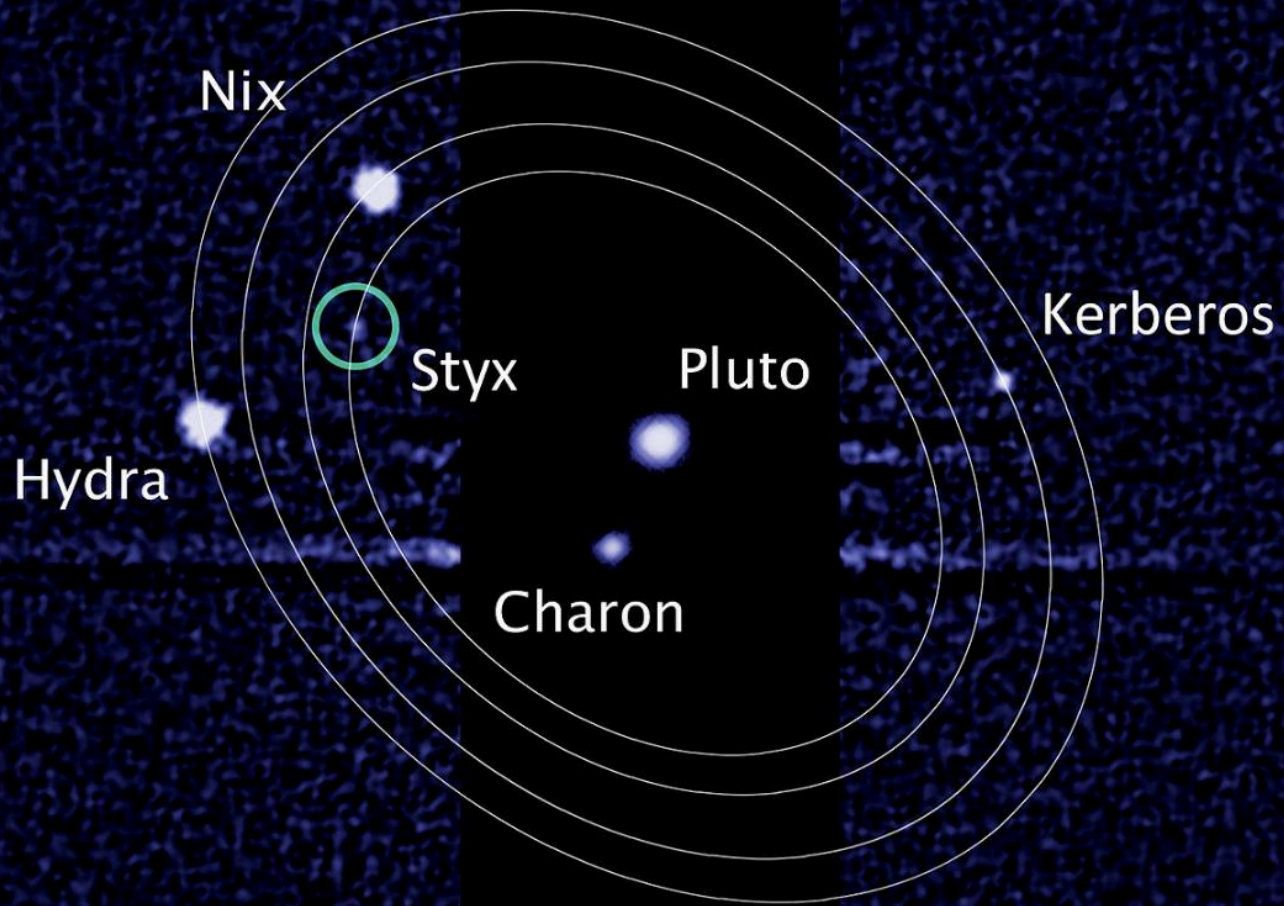




Pluto's moons: largest moon Charon



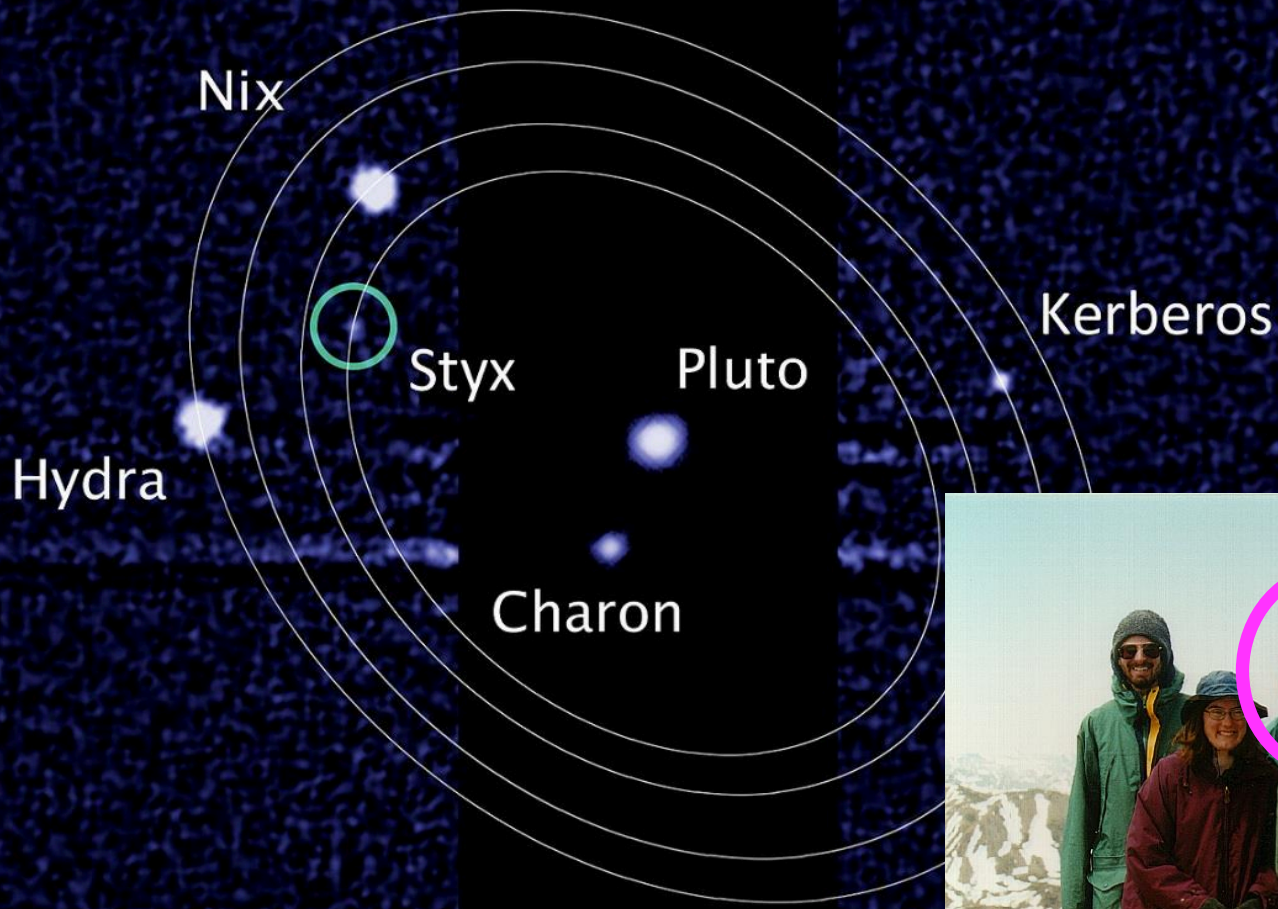
Pluto ■ July 7, 2012
HST WFC3/UVIS F350LP



50,000 miles
80,500 kilometers



Pluto ■ July 7, 2012
HST WFC3/UVIS F350LP

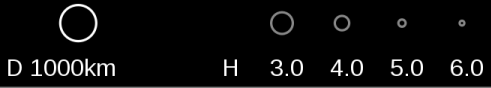
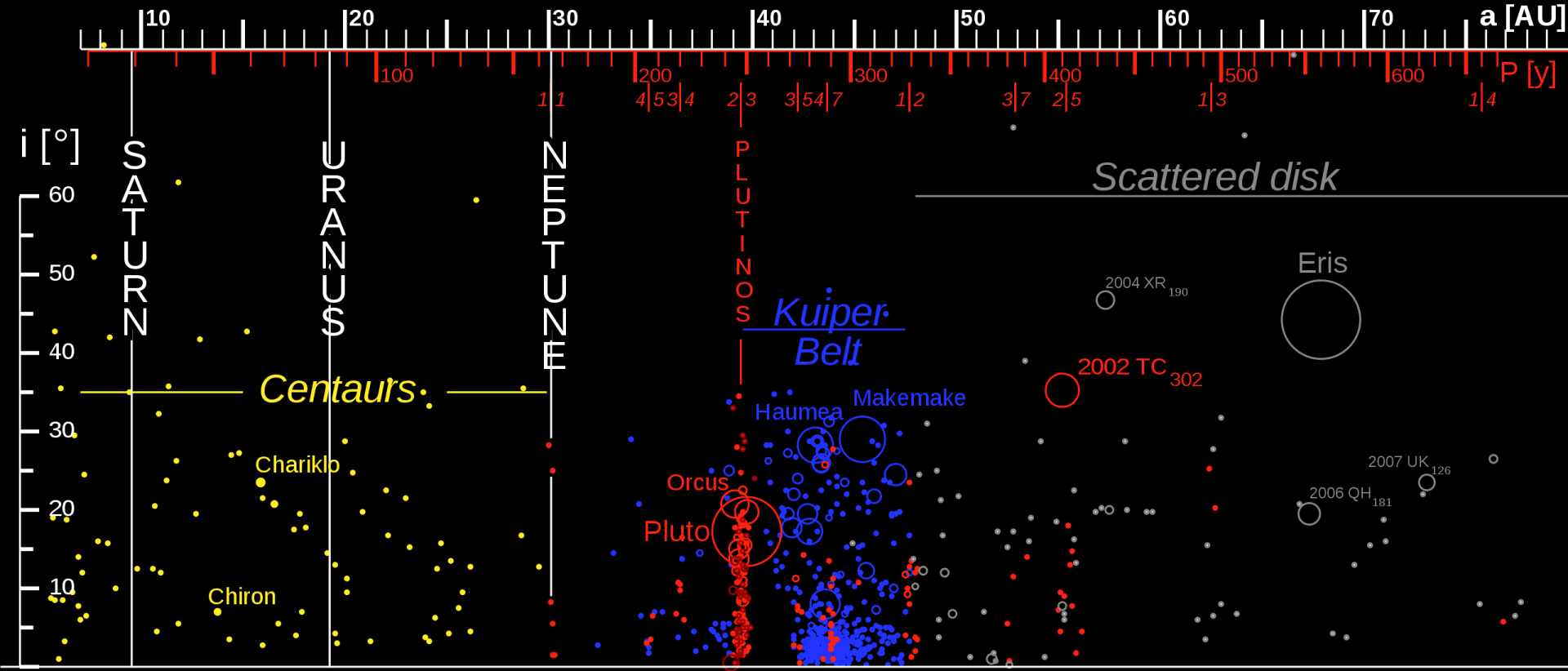


Some moons of Pluto found by team including Andrew Steffl

50,000 miles
80,500 kilometers



Trans-Neptunian Objects



Trans-Neptunian objects

Largest known trans-Neptunian objects (TNOs)

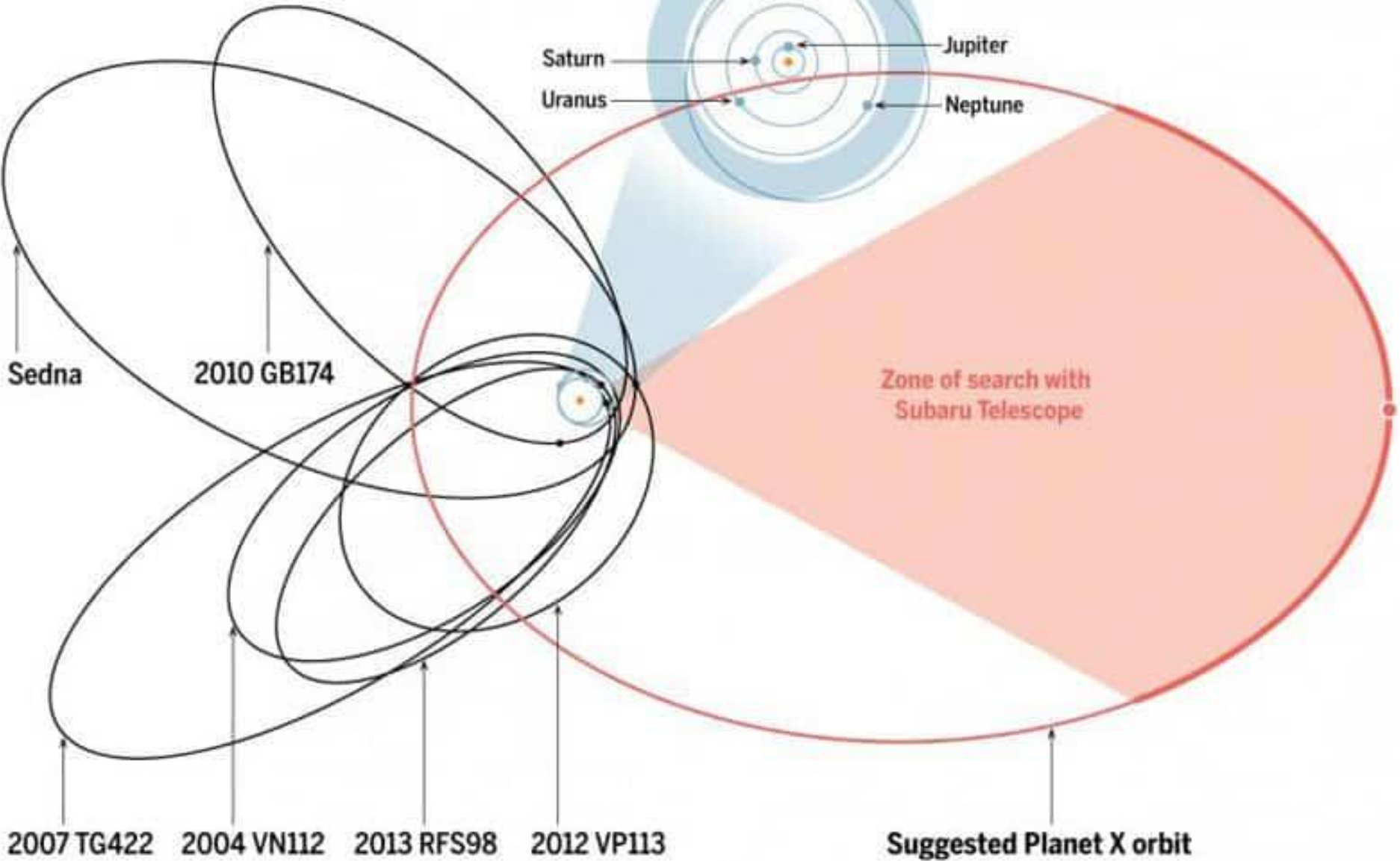


2000 km

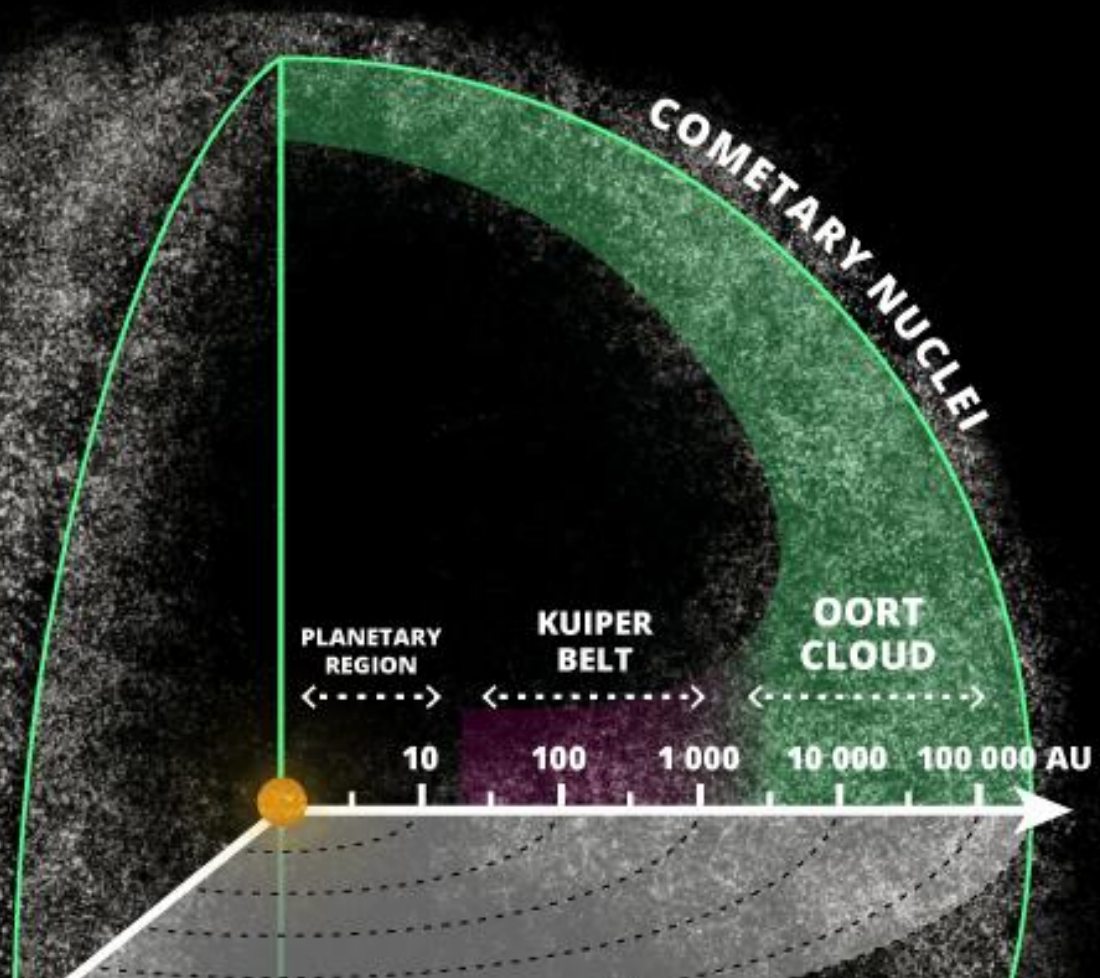


New Horizons flyby of Kuiper Belt Object MU-69
36 km across

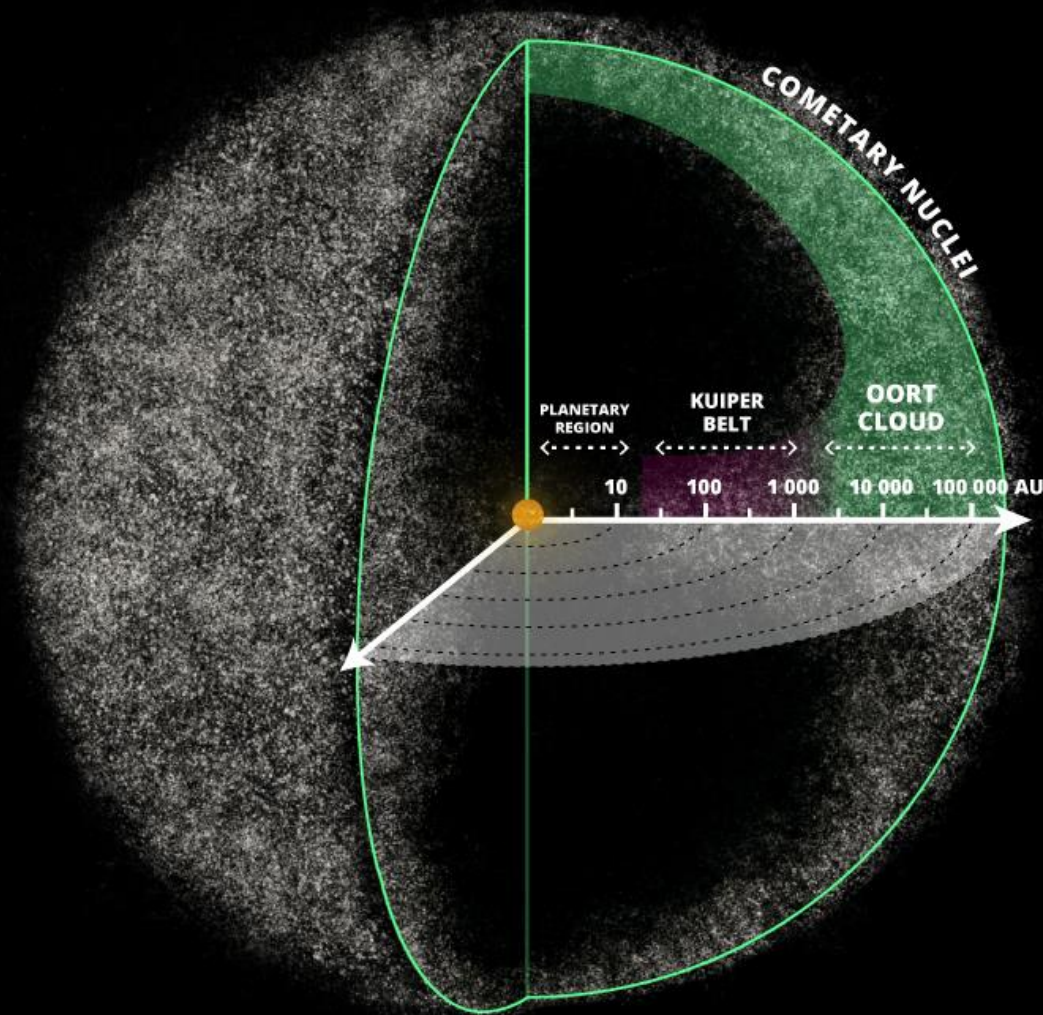
Pointing to Planet X



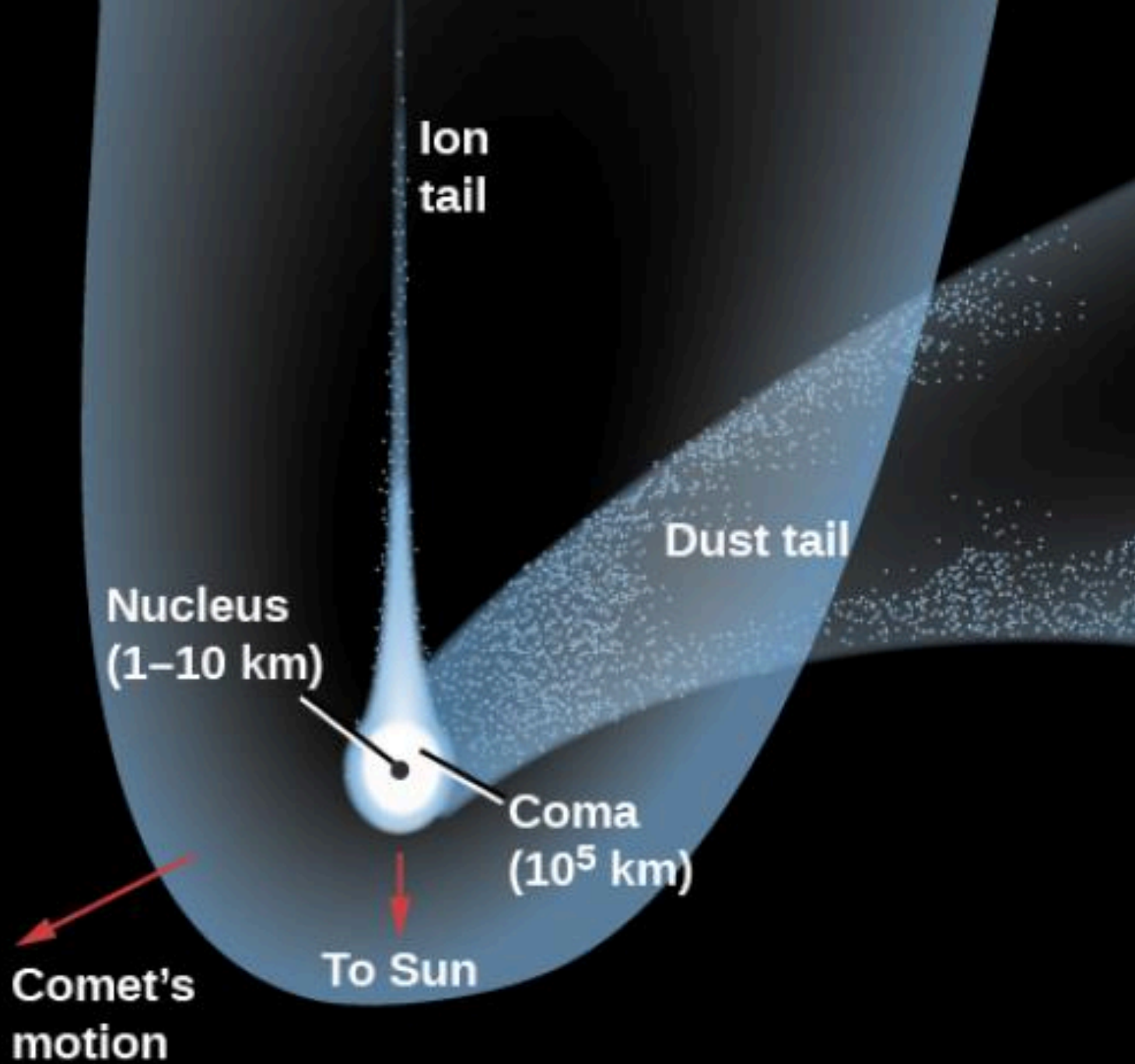
Short period comets: <200 year period, from Kuiper Belt
Long-period comets: >200 year period, from Oort Cloud



Debris from the solar system: asteroids, comets, Kuiper Belt Objects

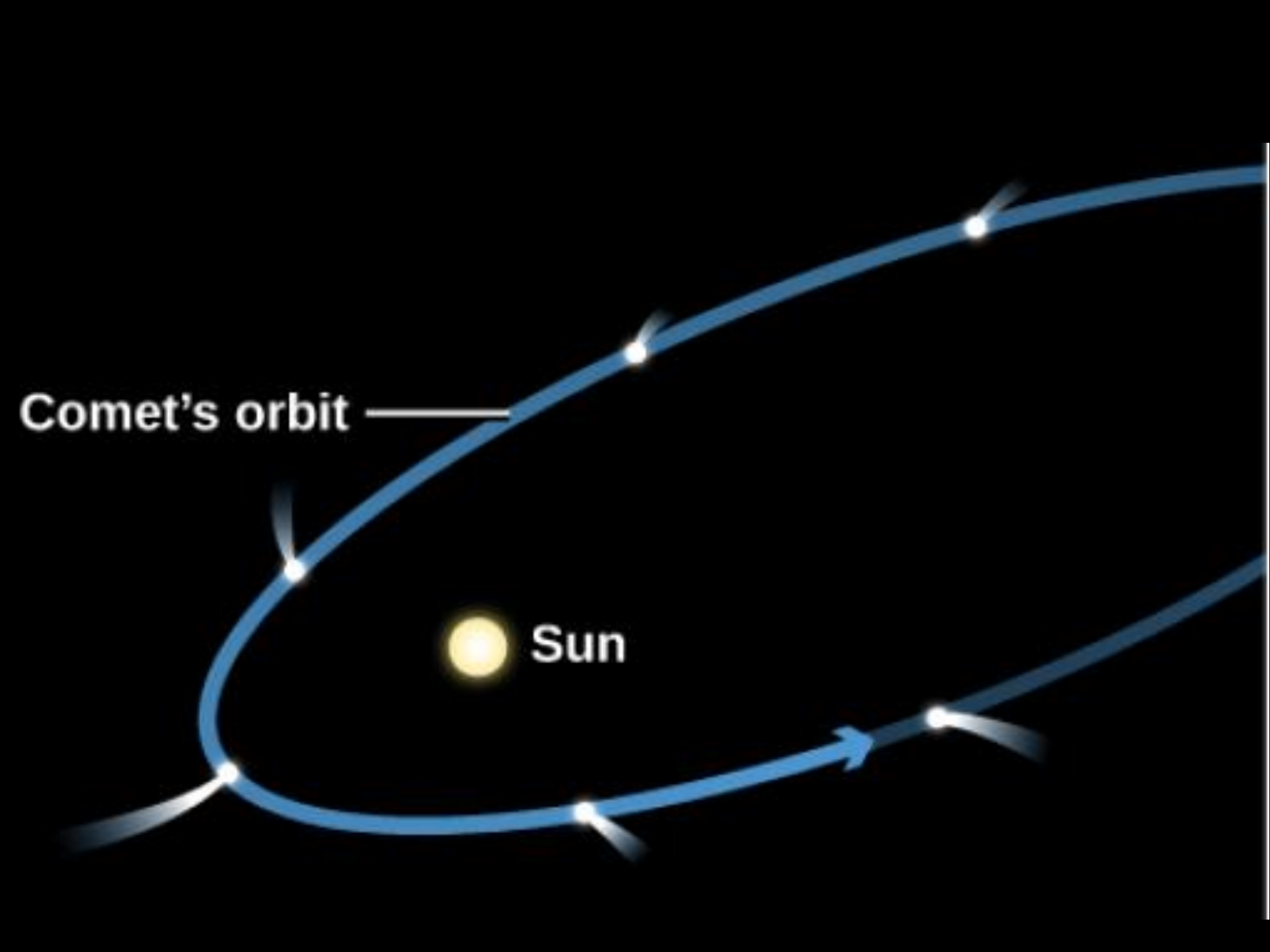


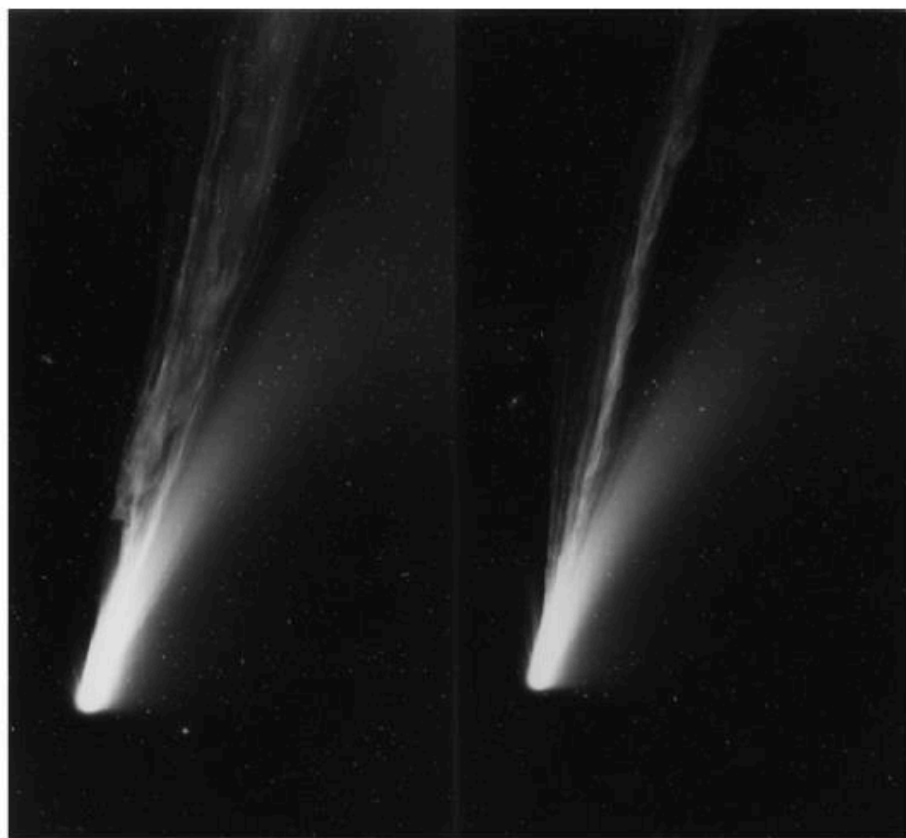
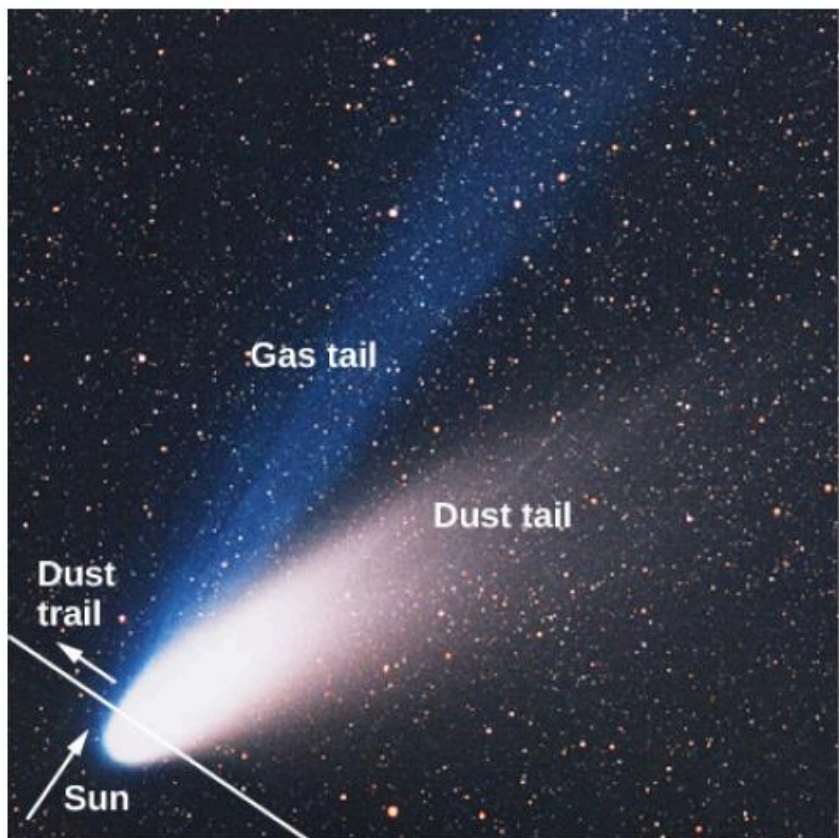




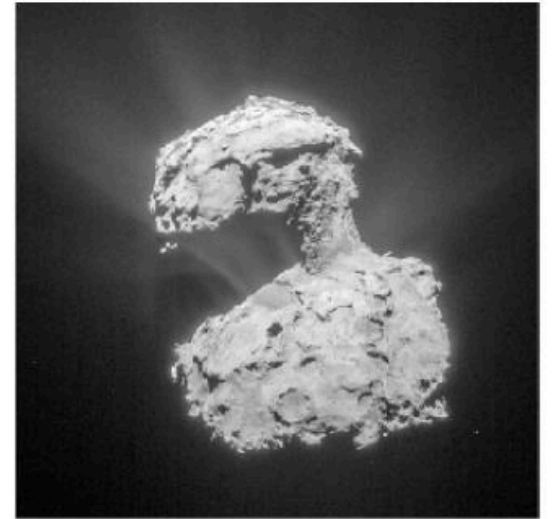
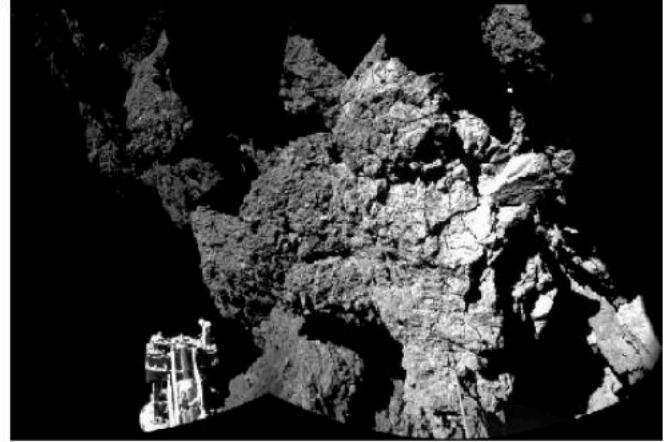
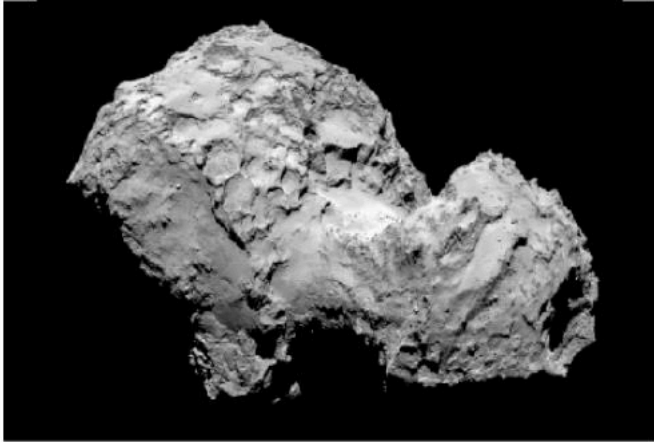
Comet's orbit

Sun





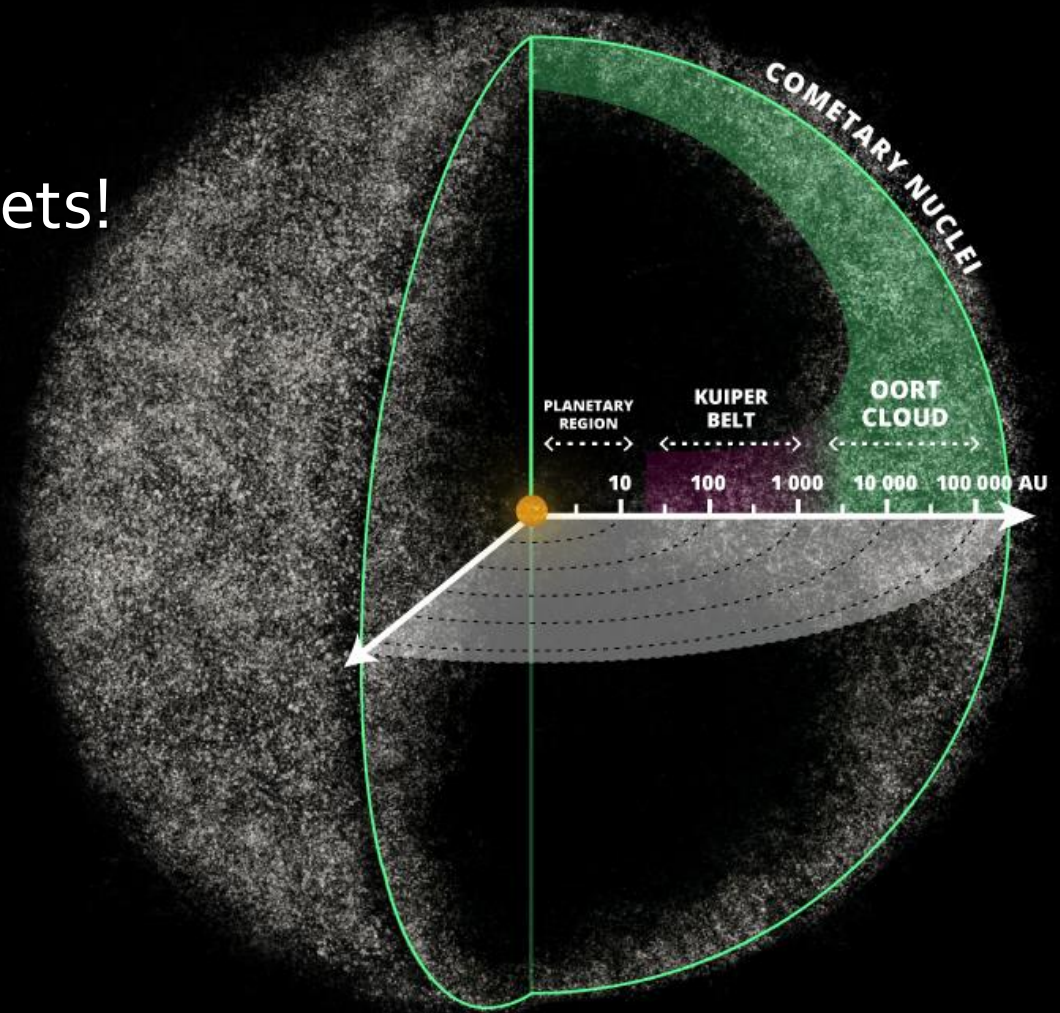
Rosetta Mission: landed on Comet 67P (!!!)



How did they get there?

Planetessimals that never
formed into planets

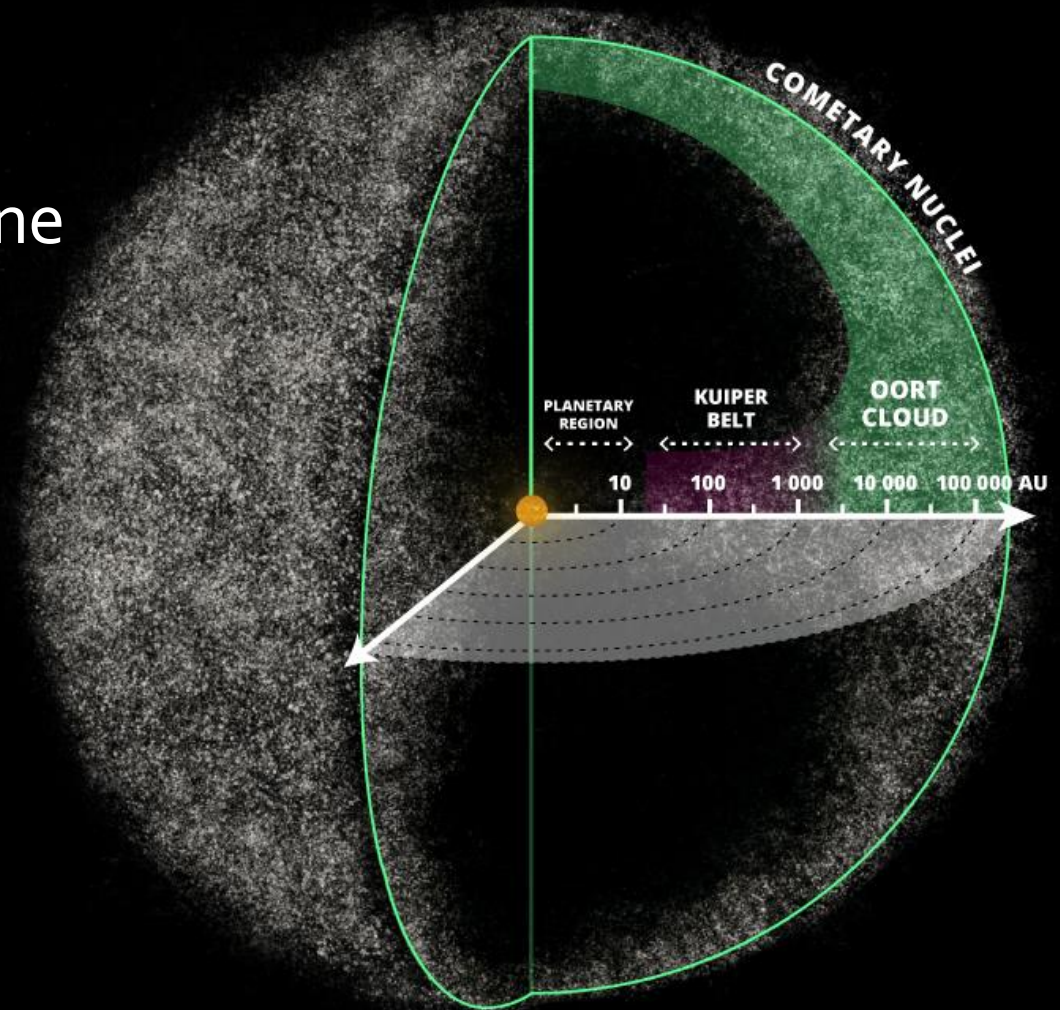
Scattered by giant planets!



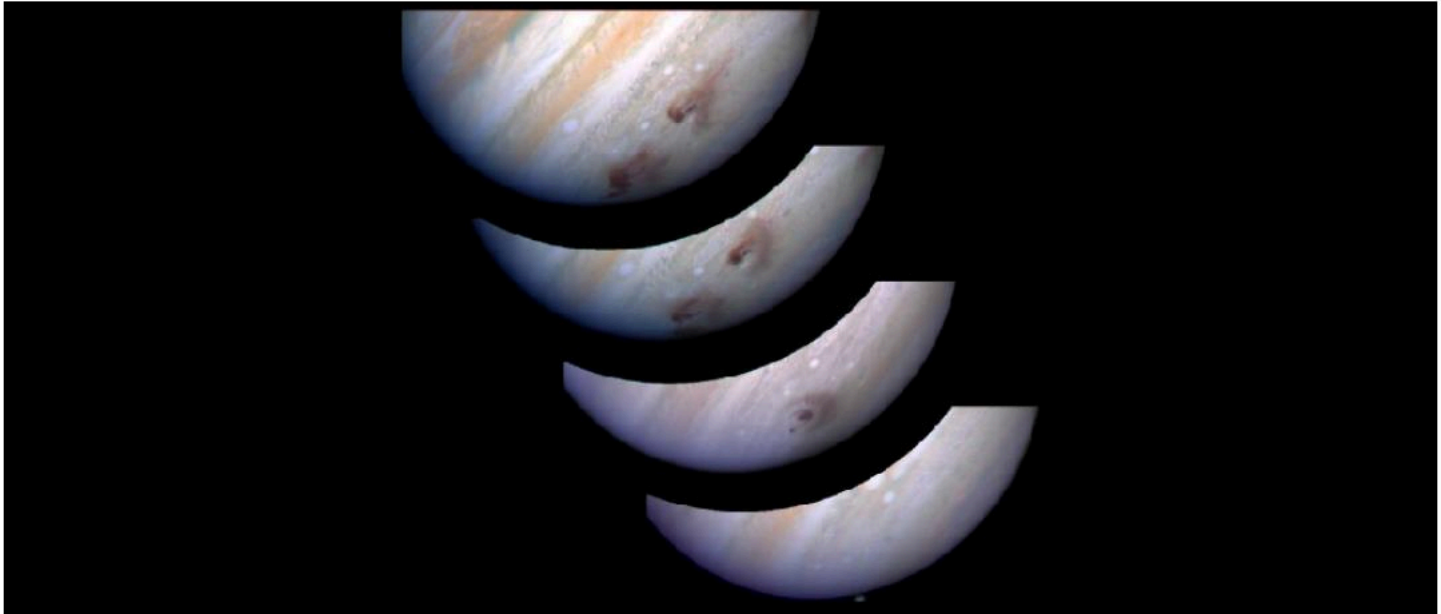
How did they get here?

Dynamical interactions in
Oort cloud:

Unstable, sometimes one
heads to inner solar
system



Shoemaker-Levy 9: comet that crashed into Jupiter



Into the sun!

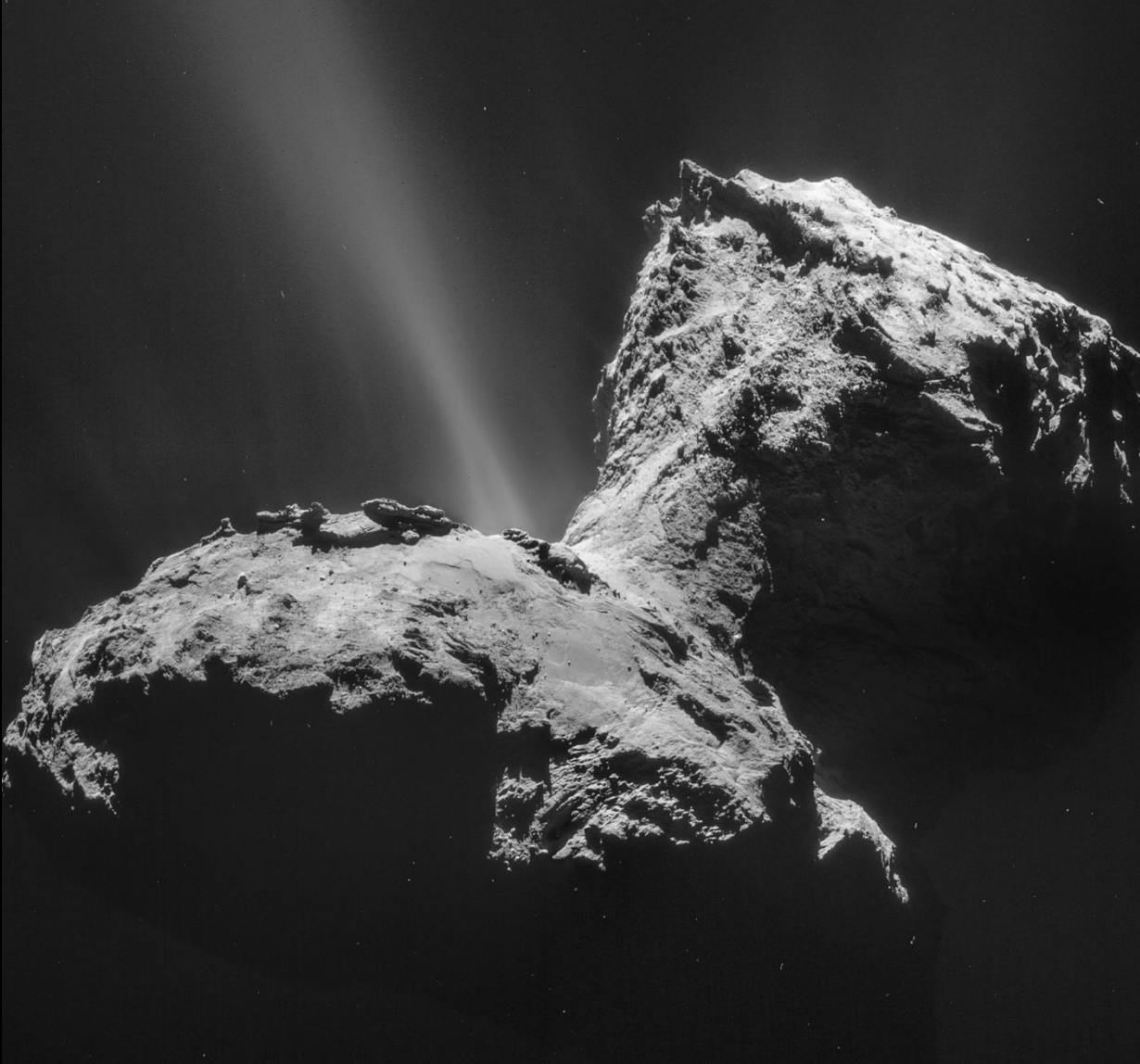


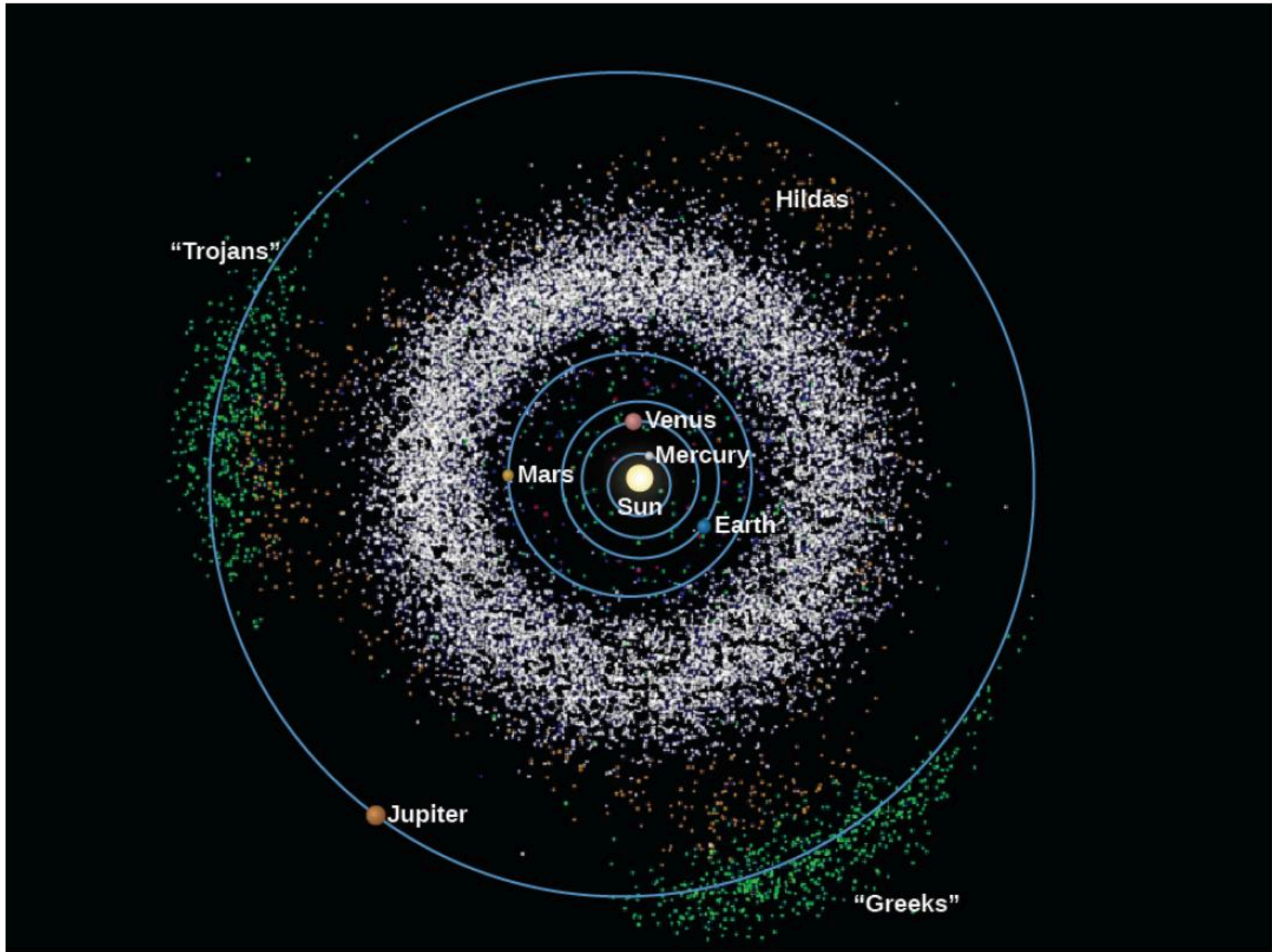
2011/09/30 20:06

Leaving a trail of dust

Major Annual Meteor Showers

Shower Name	Date of Maximum	Associated Parent Object	Comet's Period (years)
Quadrantid	January 3-4	2003EH (asteroid)	—
Lyrid	April 22	Comet Thatcher	415
Eta Aquarid	May 4-5	Comet Halley	76
Delta Aquarid	July 29-30	Comet Machholz	—
Perseid	August 11-12	Comet Swift-Tuttle	133
Orionid	October 20-21	Comet Halley	76
Southern Taurid	October 31	Comet Encke	3
Leonid	November 16-17	Comet Tempel-Tuttle	33
Geminid	December 13	Phaethon (asteroid)	1.4

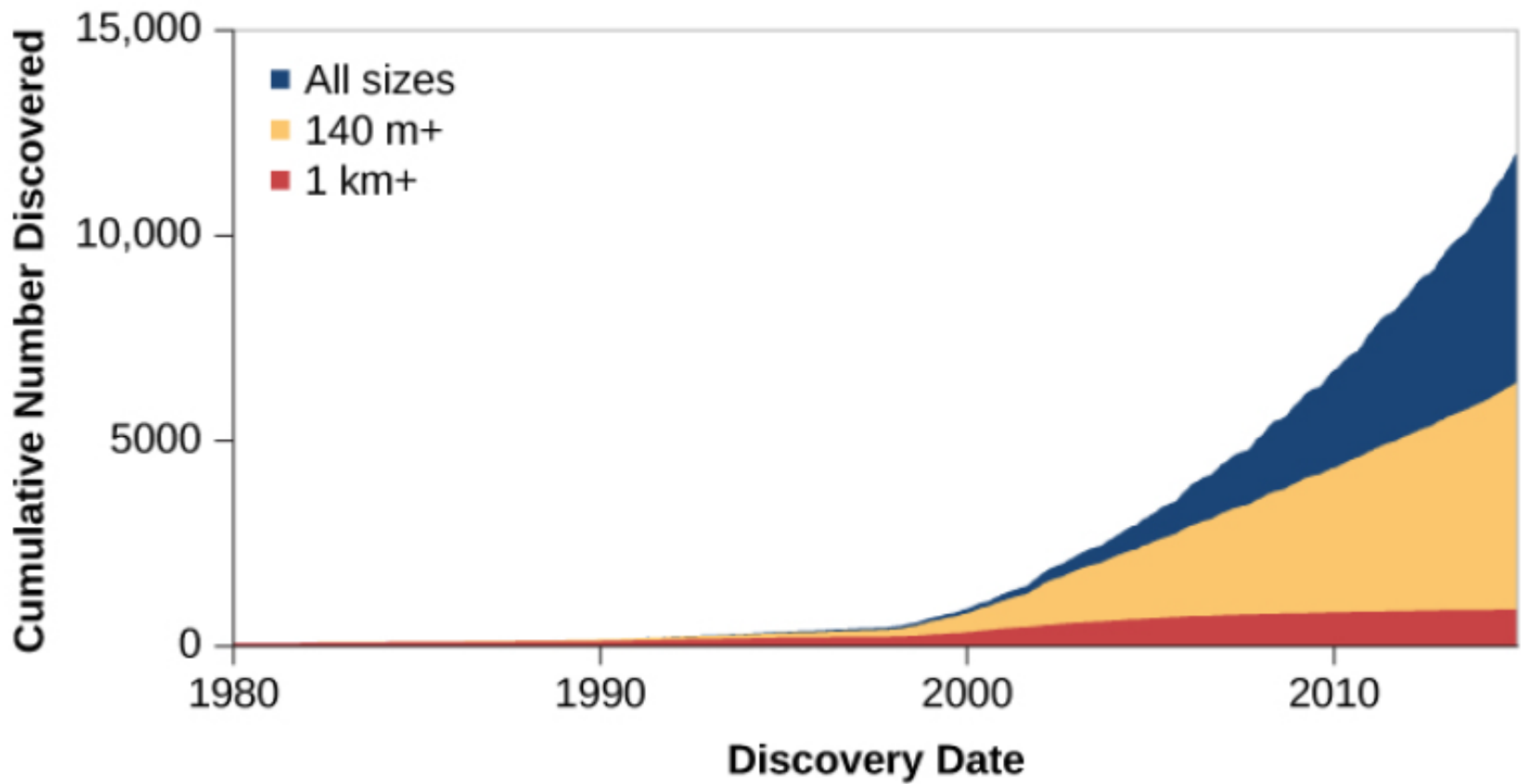


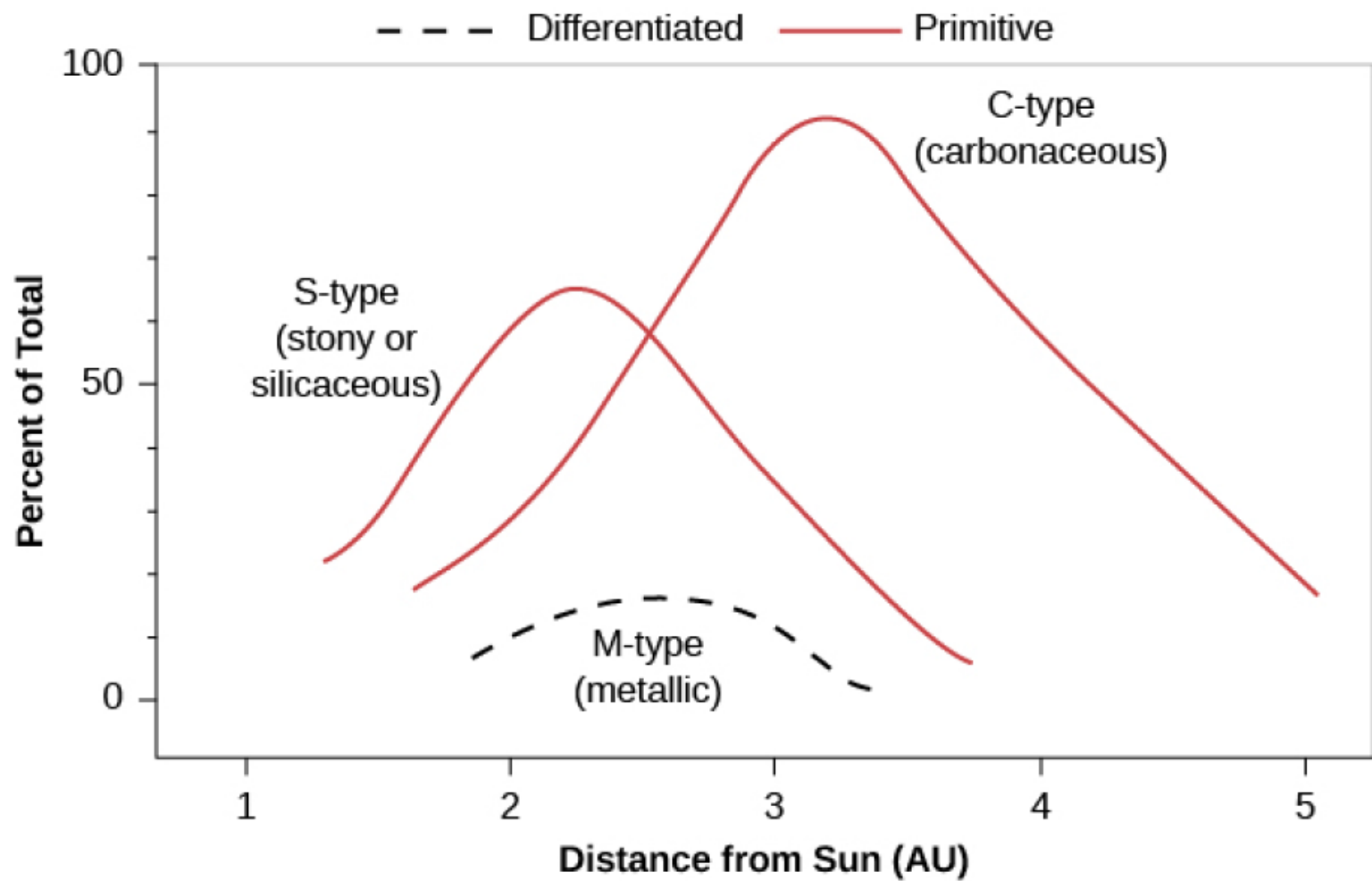


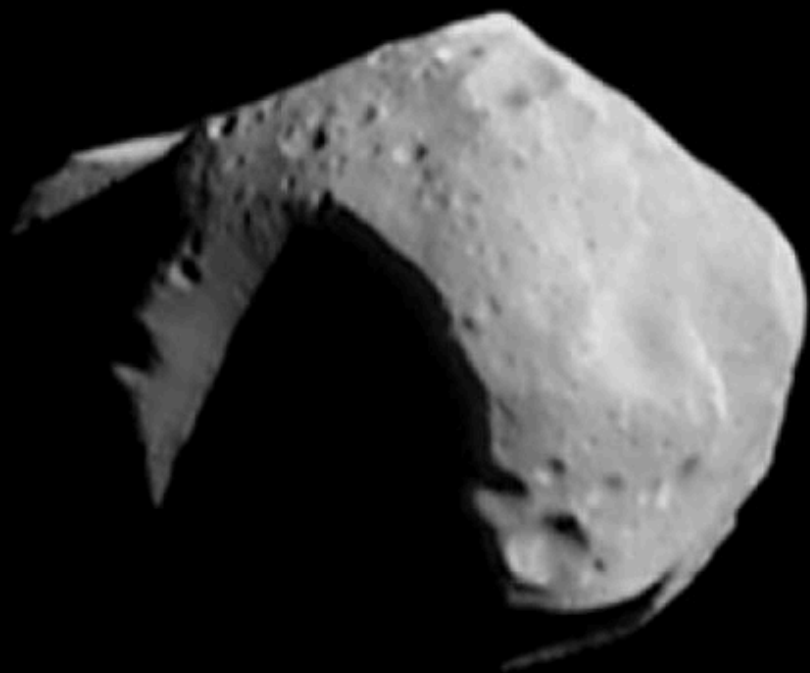
The Largest Asteroids

#	Name	Year of Discovery	Orbit's Semimajor Axis (AU)	Diameter (km)	Compositional Class
1	Ceres	1801	2.77	940	C (carbonaceous)
2	Pallas	1802	2.77	540	C (carbonaceous)
3	Juno	1804	2.67	265	S (stony)
4	Vesta	1807	2.36	510	basaltic
10	Hygiea	1849	3.14	410	C (carbonaceous)
16	Psyche	1852	2.92	265	M (metallic)
31	Euphrosyne	1854	3.15	250	C (carbonaceous)
52	Europa	1858	3.10	280	C (carbonaceous)
65	Cybele	1861	3.43	280	C (carbonaceous)
87	Sylvia	1866	3.48	275	C (carbonaceous)
451	Patientia	1899	3.06	260	C (carbonaceous)
511	Davida	1903	3.16	310	C (carbonaceous)
704	Interamnia	1910	3.06	310	C (carbonaceous)

Near-Earth Asteroids Discovered







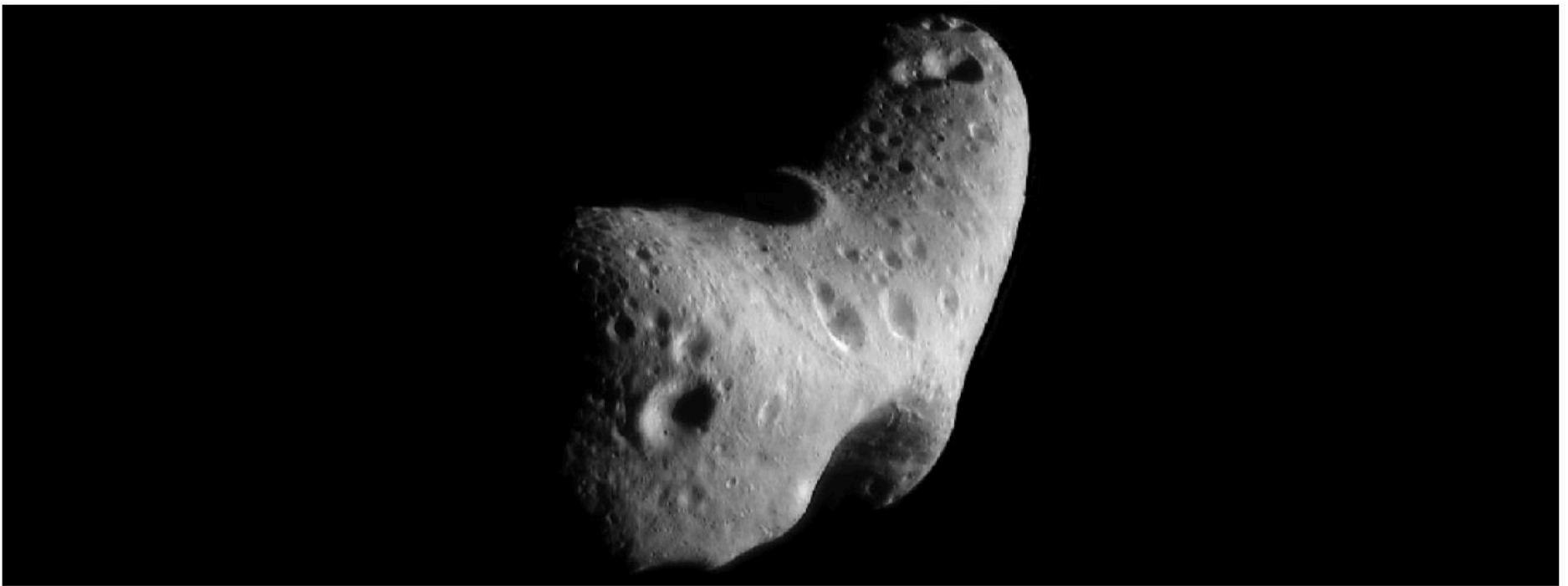
Mathilde



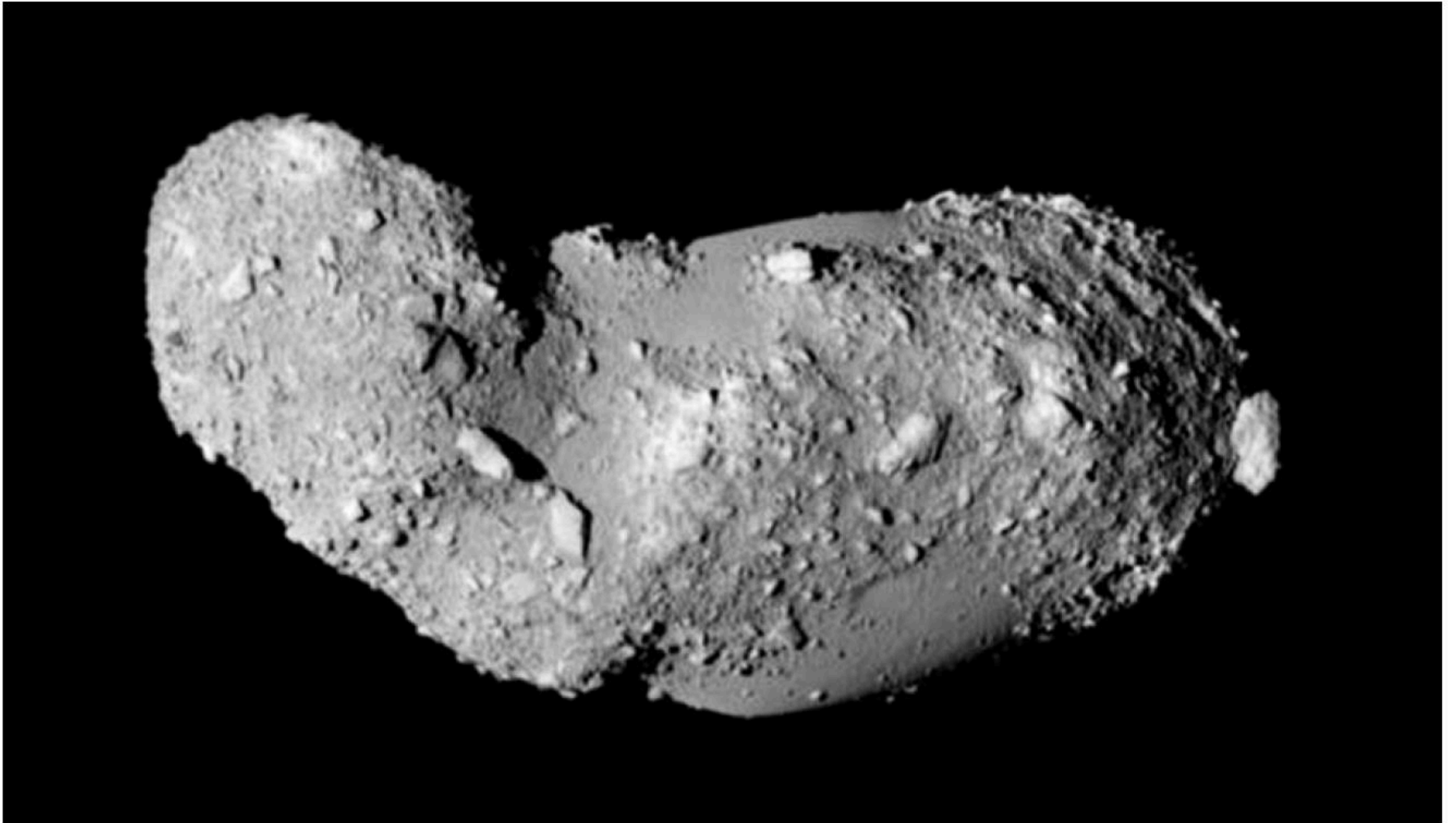
Gaspra



Ida



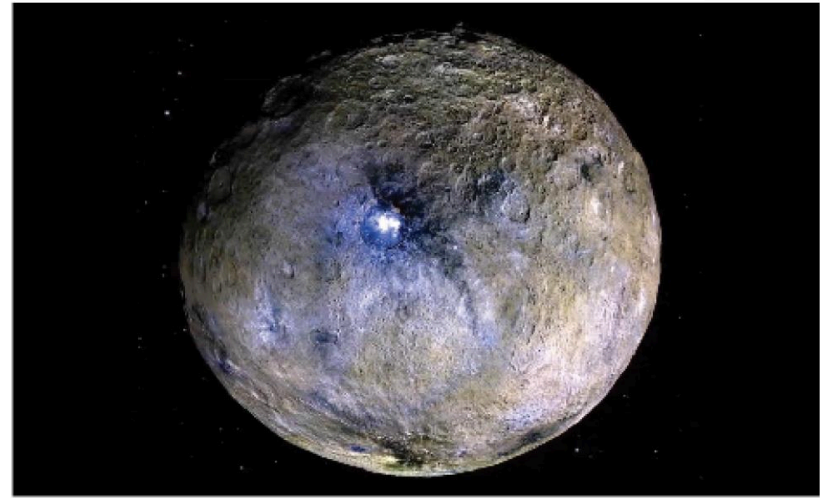
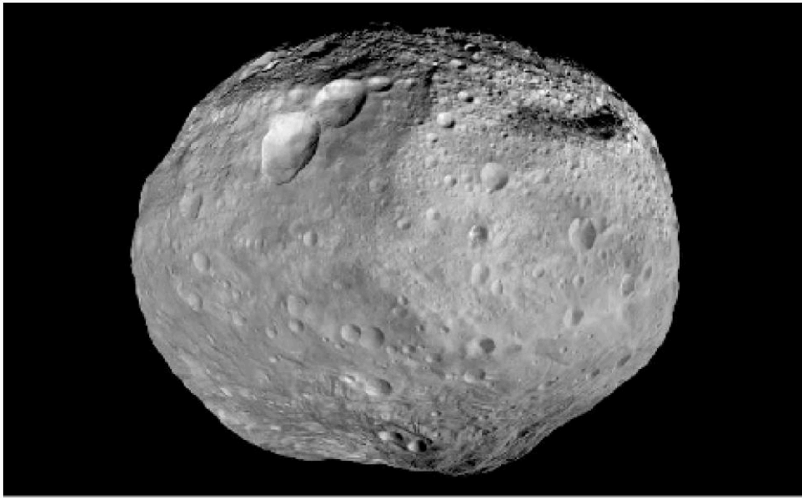
Asteroid Itokawa



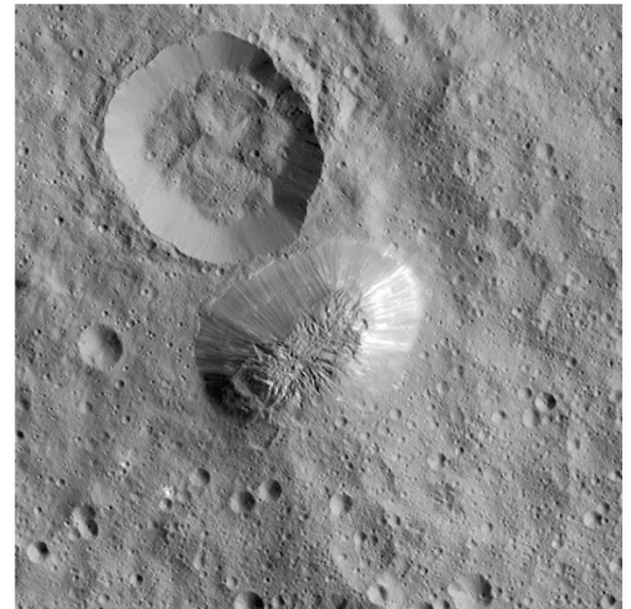
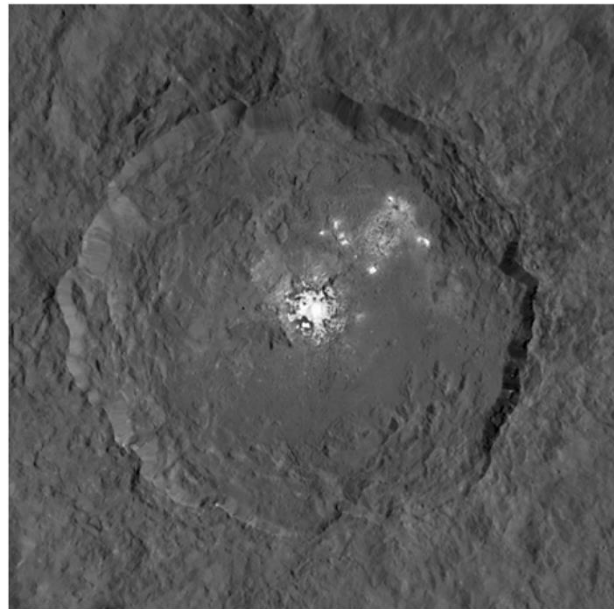


Hayabusa mission:
Landed on the asteroid and sample return!

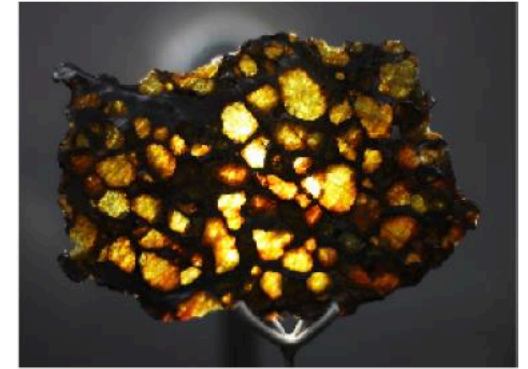
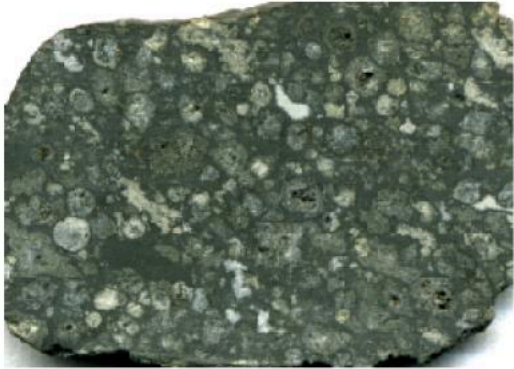
Asteroids Vesta (left) and Ceres (right)



Ceres



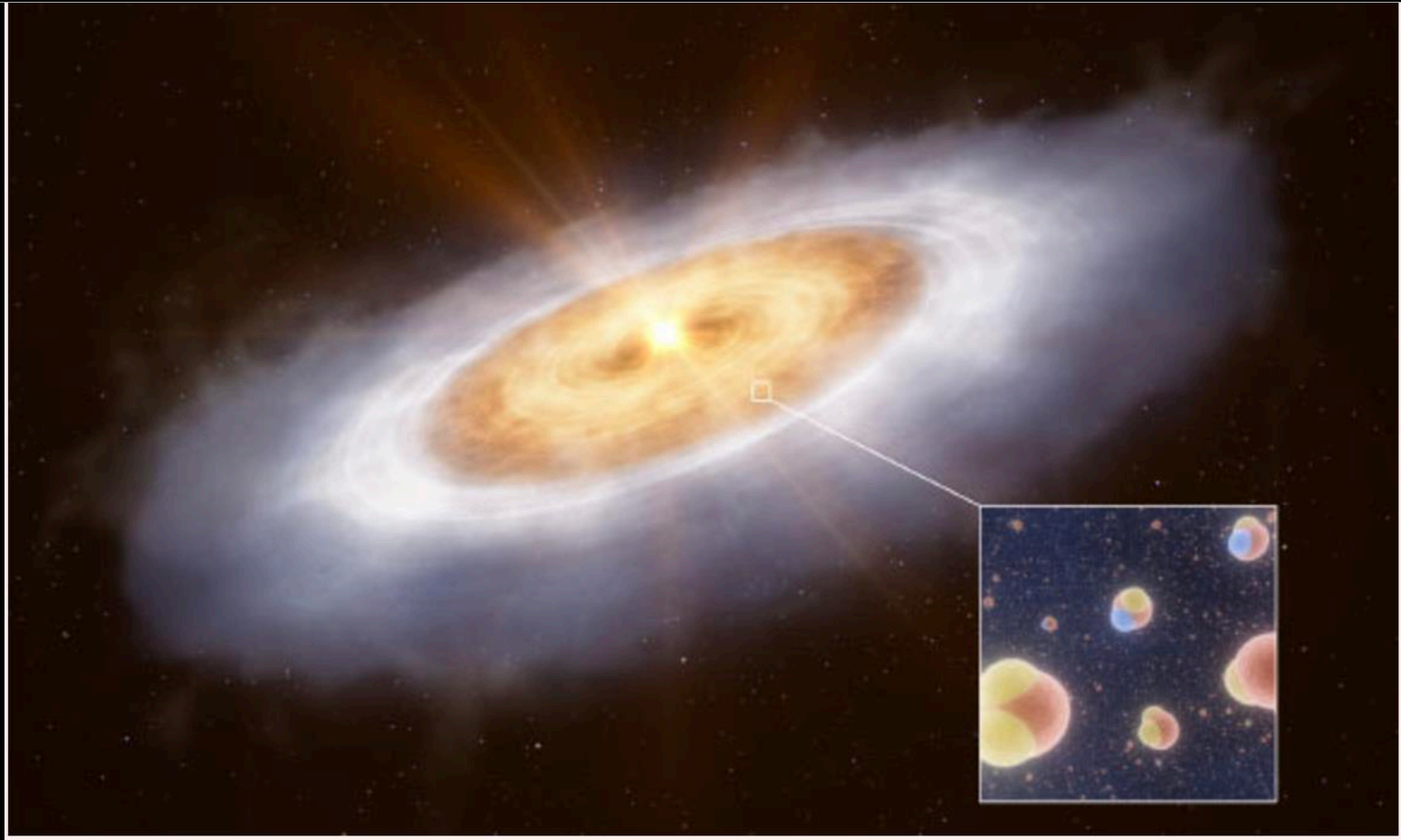
Meteors: asteroids that hit the Earth



Frequency of Occurrence of Meteorite Classes

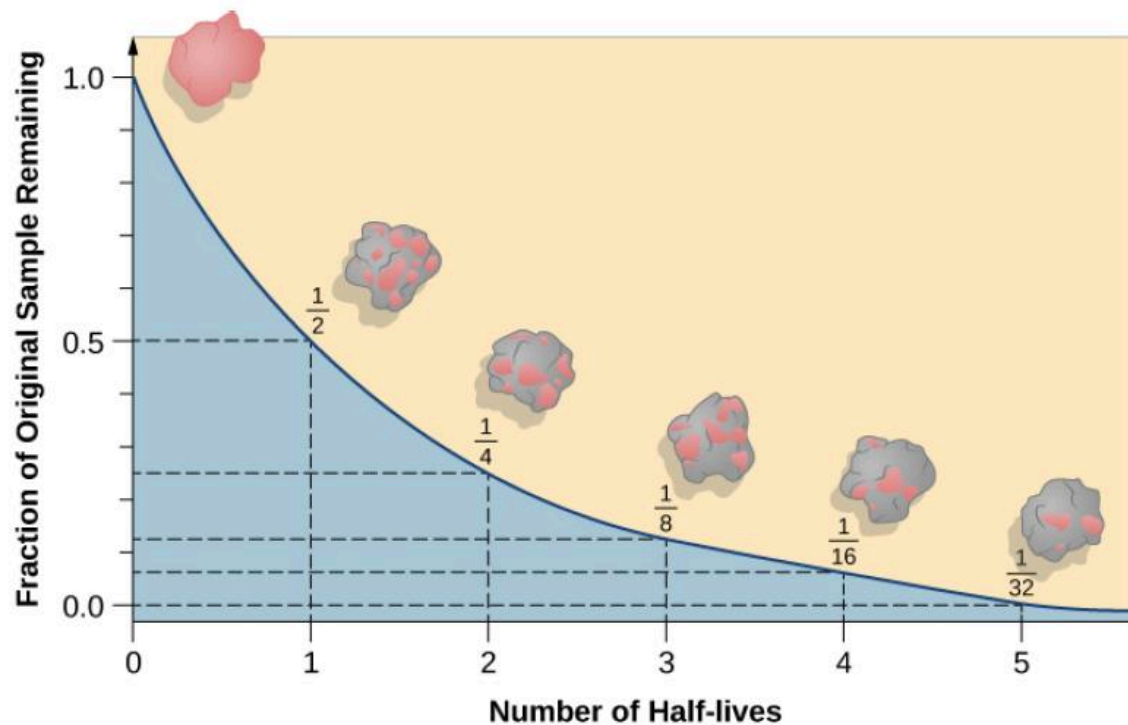
Class	Falls (%)	Finds (%)	Antarctic (%)
Primitive stones	88	51	85
Differentiated stones	8	2	12
Irons	3	42	2
Stony-irons	1	5	1

Origins of our solar system

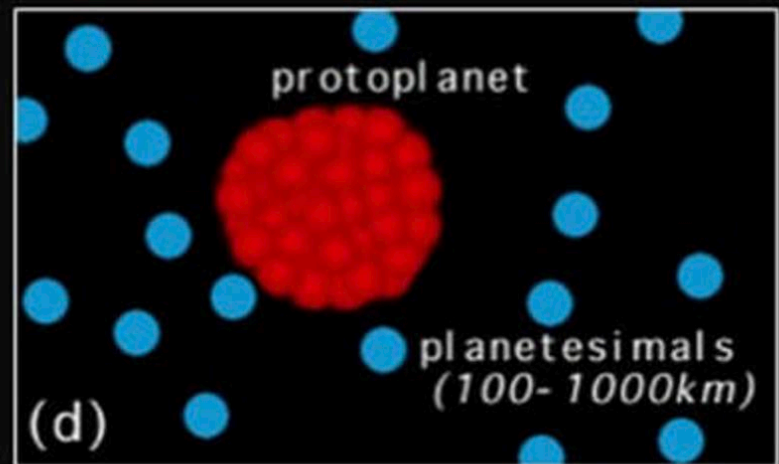
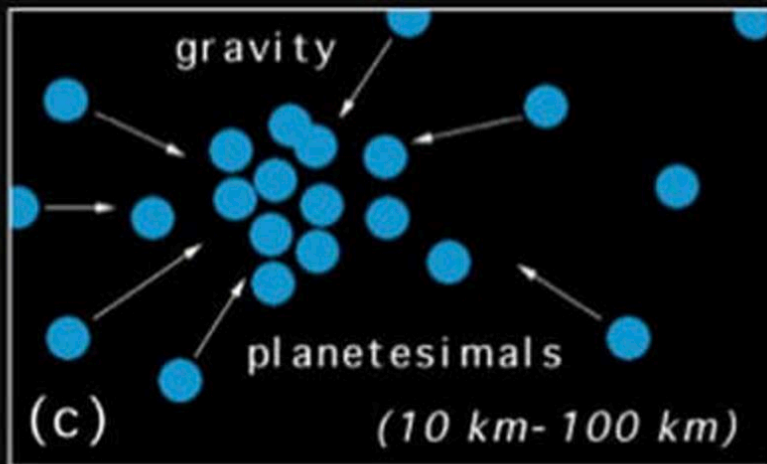
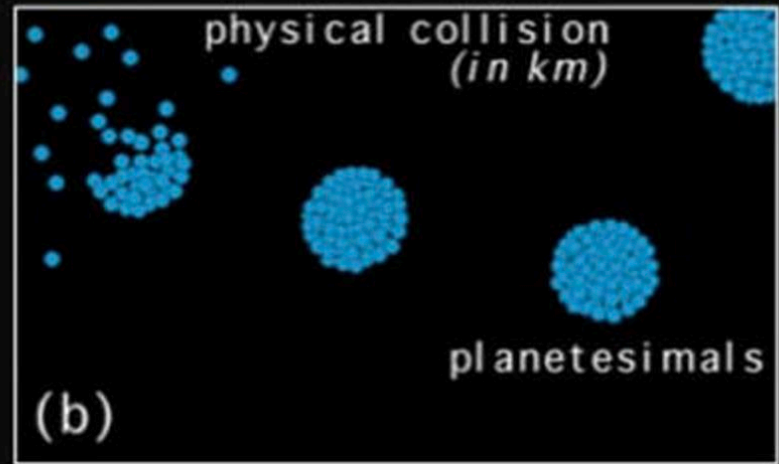
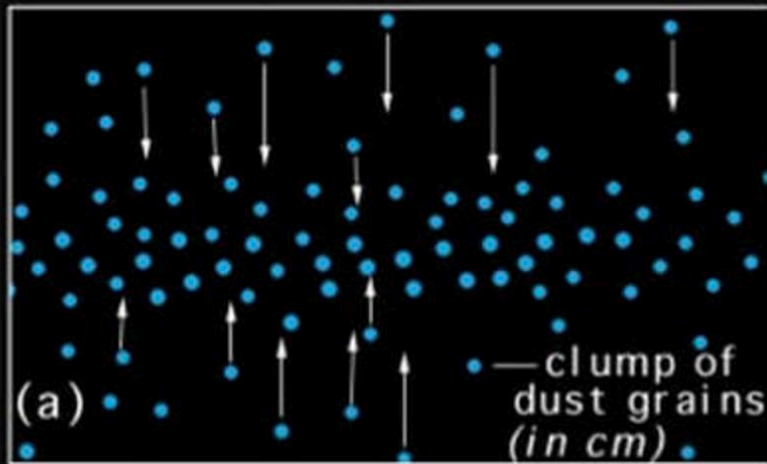


Radioactive Decay Reaction Used to Date Rocks^[4]

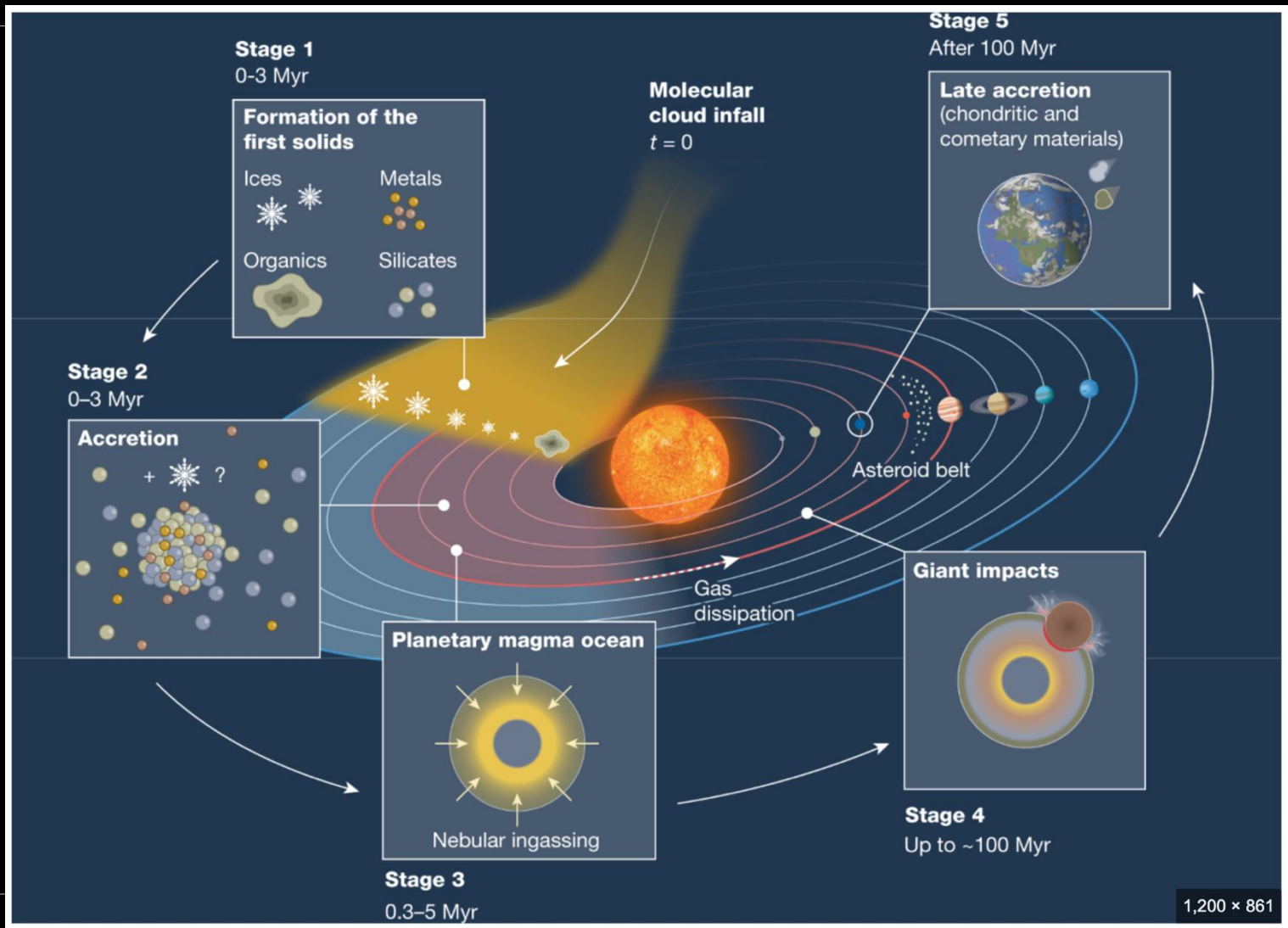
Parent	Daughter	Half-Life (billions of years)
Samarium-147	Neodymium-143	106
Rubidium-87	Strontium-87	48.8
Thorium-232	Lead-208	14.0
Uranium-238	Lead-206	4.47
Potassium-40	Argon-40	1.31



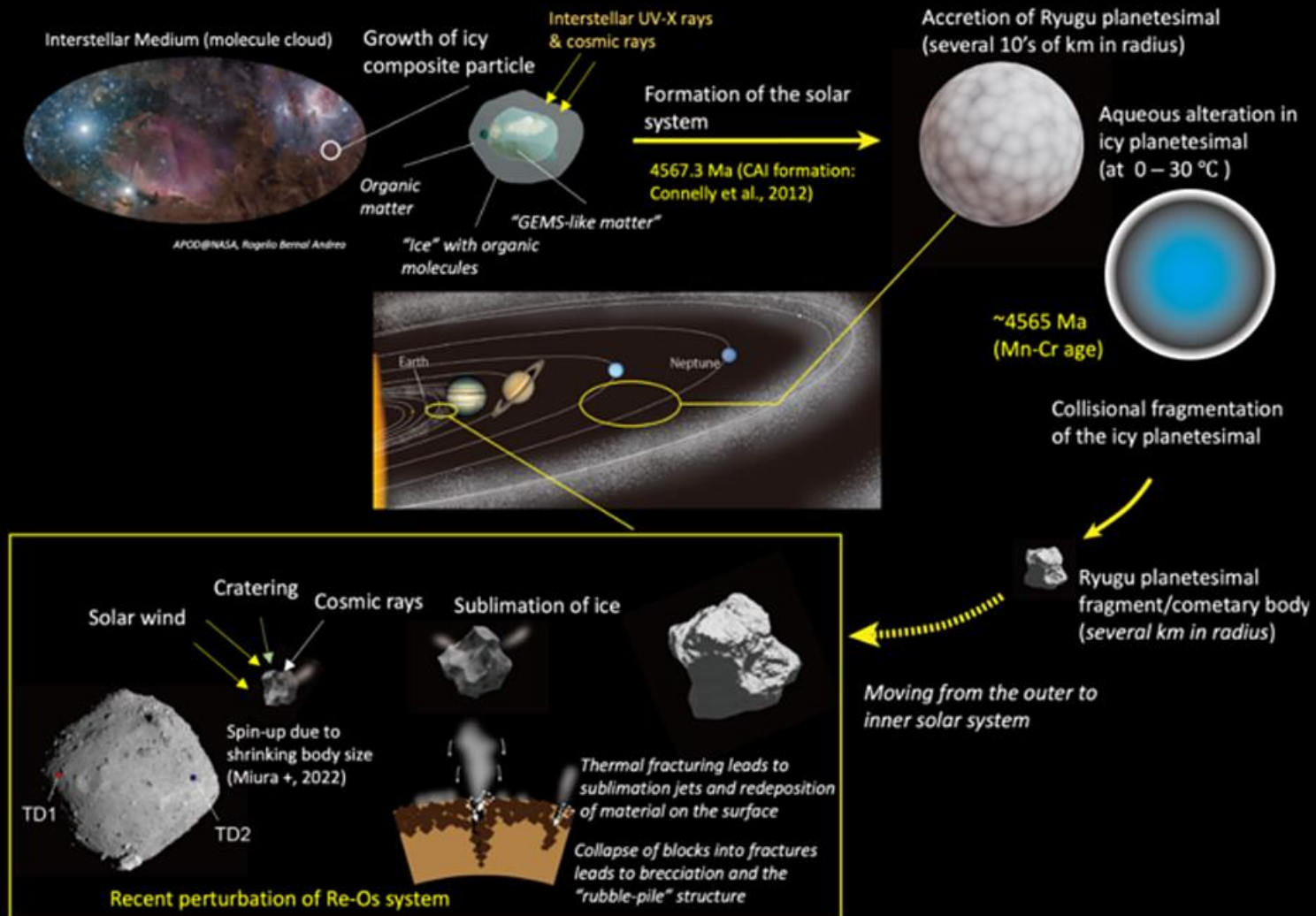
Origins of our solar system



Origins of our solar system

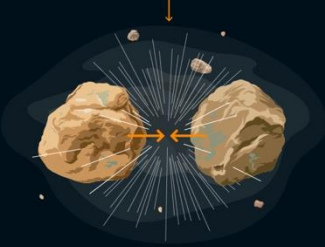
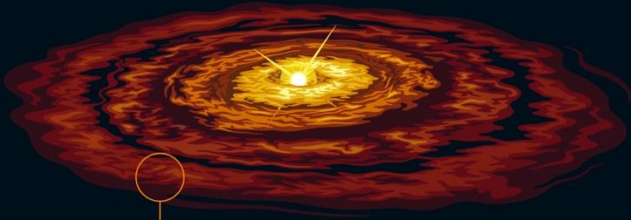


Origins of our solar system



Building the Solar System's Building Blocks

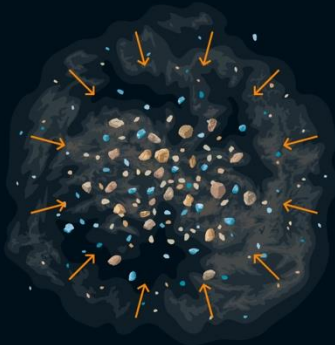
Our solar system is filled with asteroids made of chondrules, a particular type of rock. The origin of these millimeter-size particles has long been a mystery, but a new theory proposes a way that they could form in cosmic collisions.



- 1** Within a dusty, gas-filled infant solar system, two planetesimals — asteroid-size bodies of rock and ice — collide.



- 2** The planetesimals vaporize into a plume of rock and water vapor that expands and pushes surrounding gas outward.



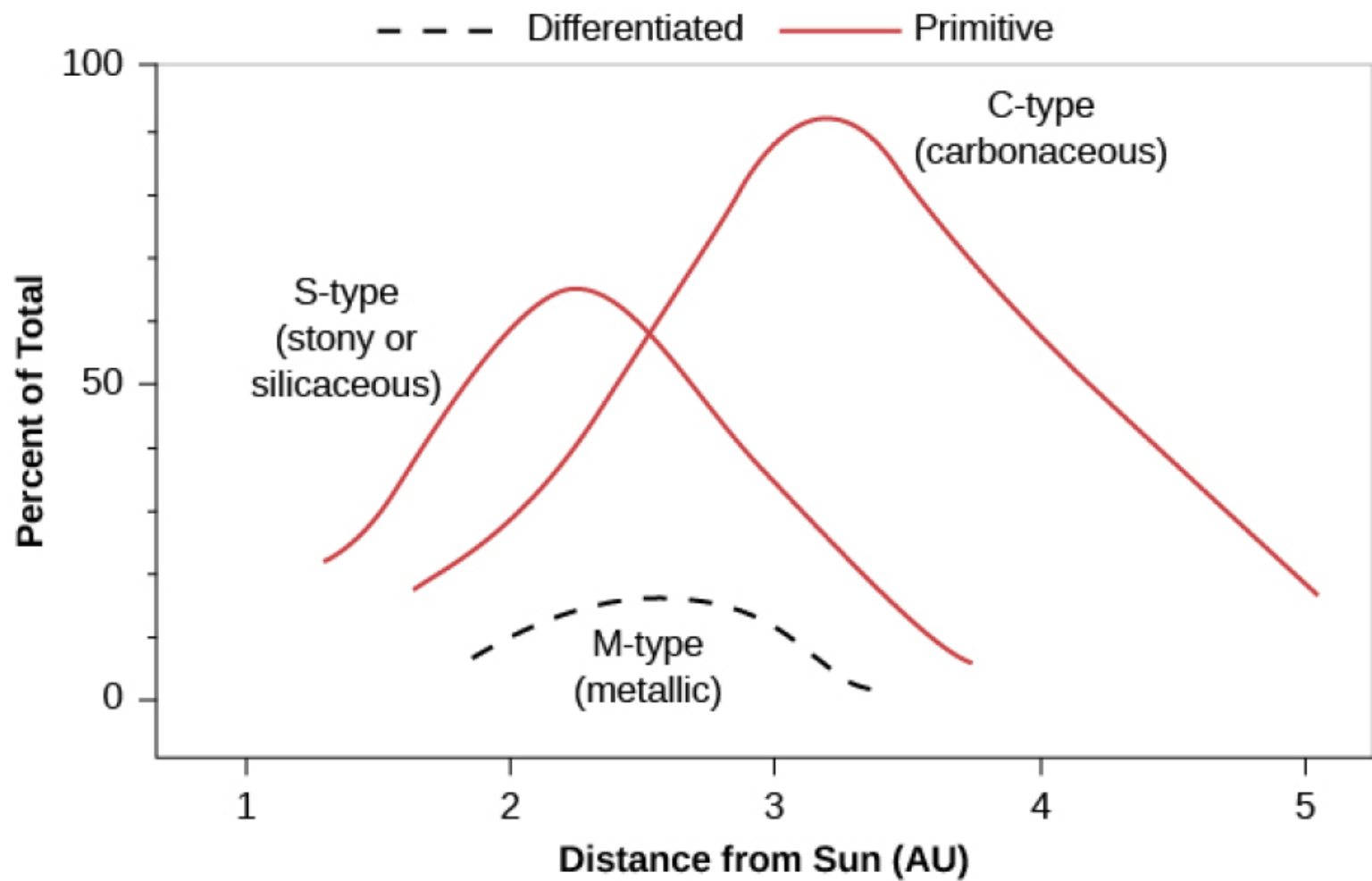
- 3** The pushed gas piles up until it reaches a higher pressure and density than the plume inside, making the plume collapse.



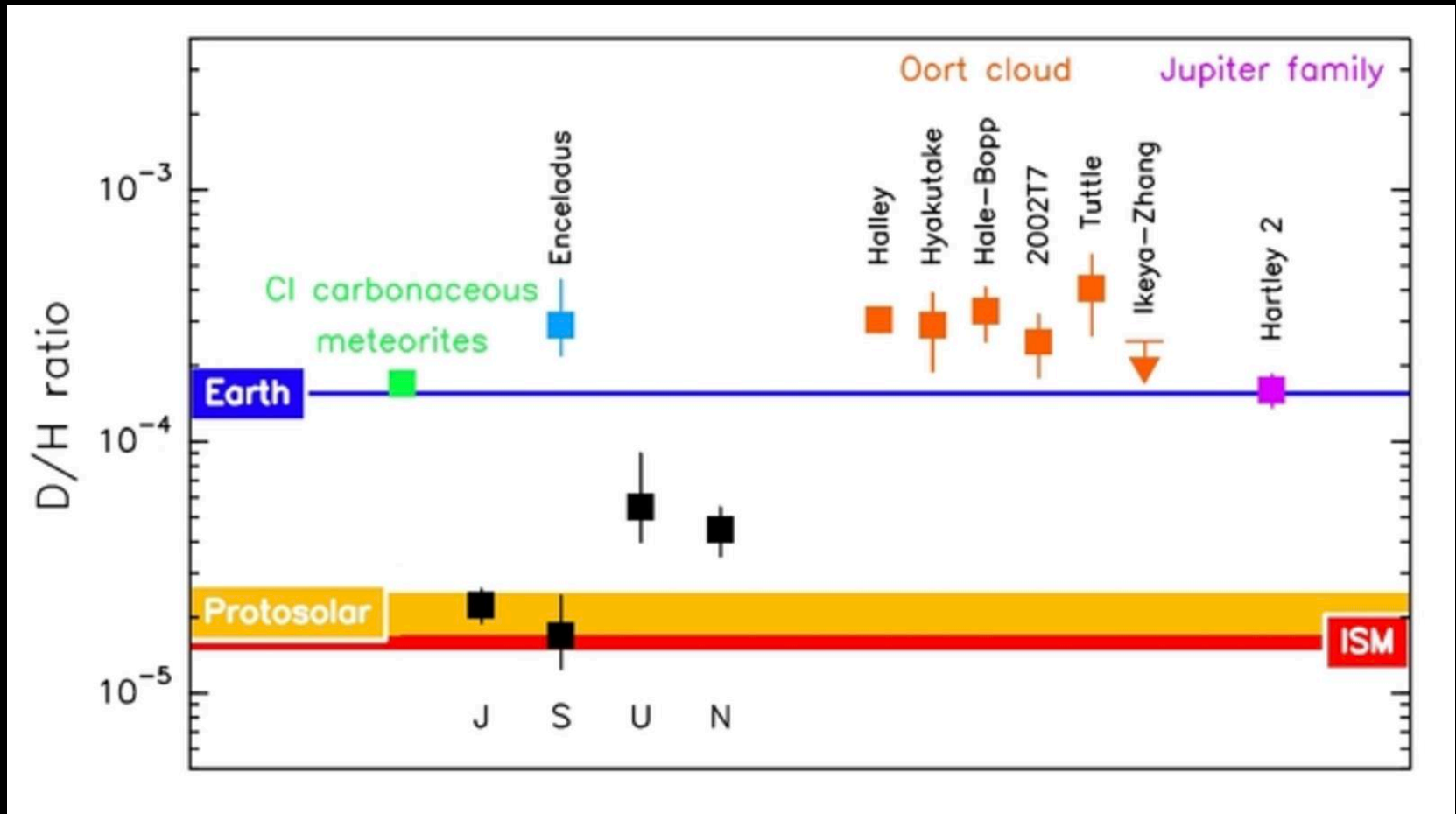
- 4** As the plume collapses, some of its rocky bits heat up, melt, cool down and solidify into small globs called chondrules.

Origins of our solar system

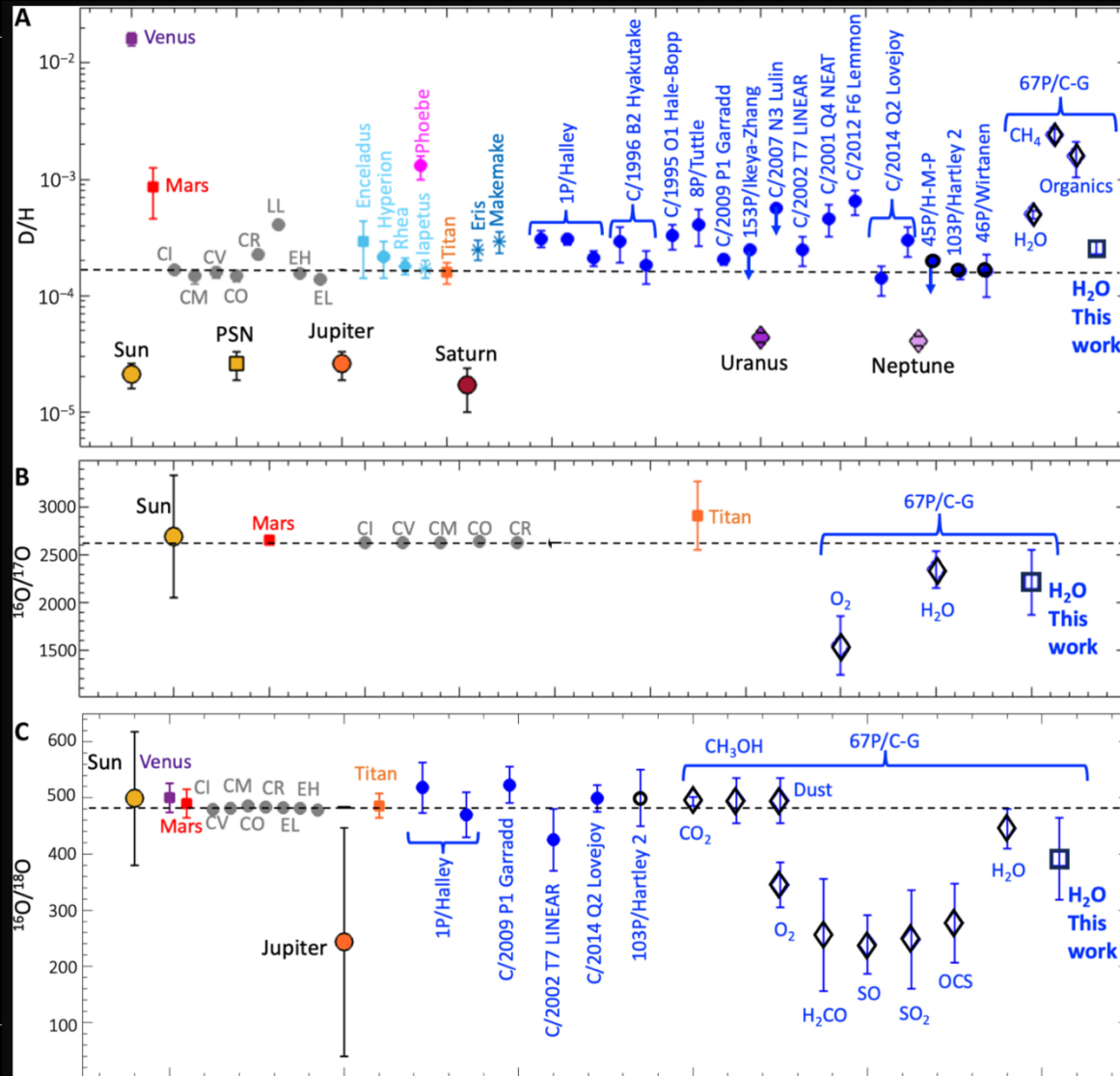




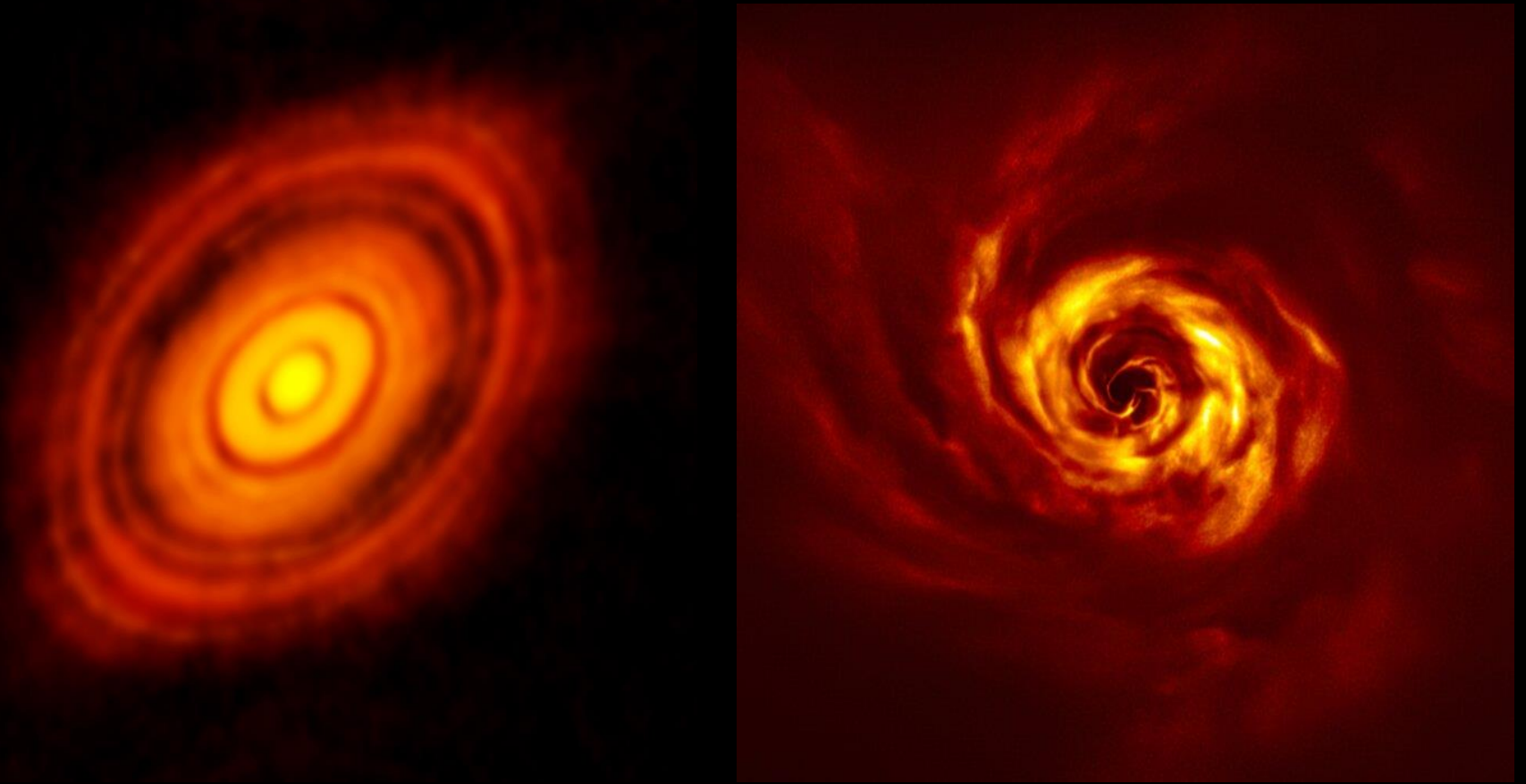
D/H ratio: water from comets?



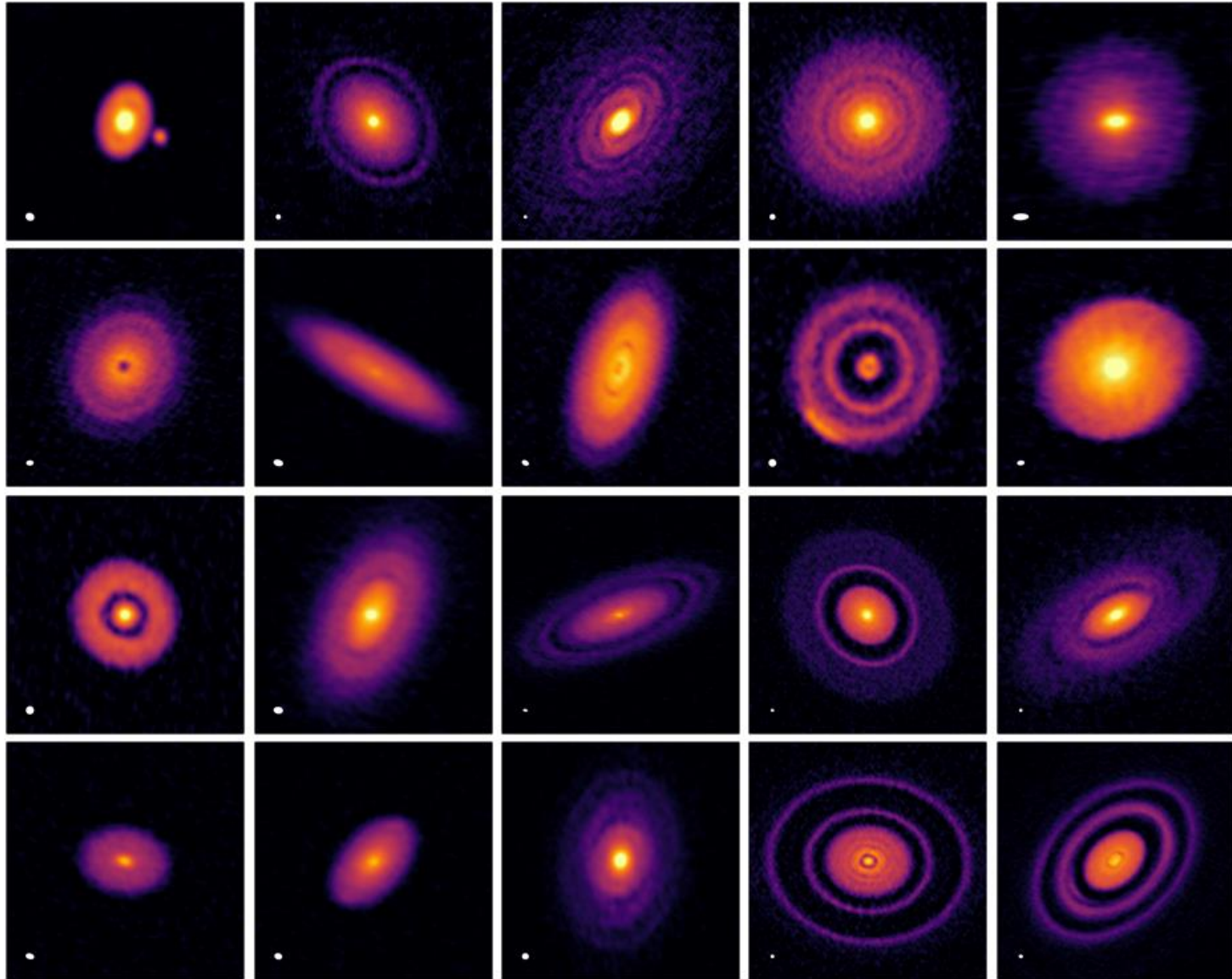
D/H ratio: water from comets?

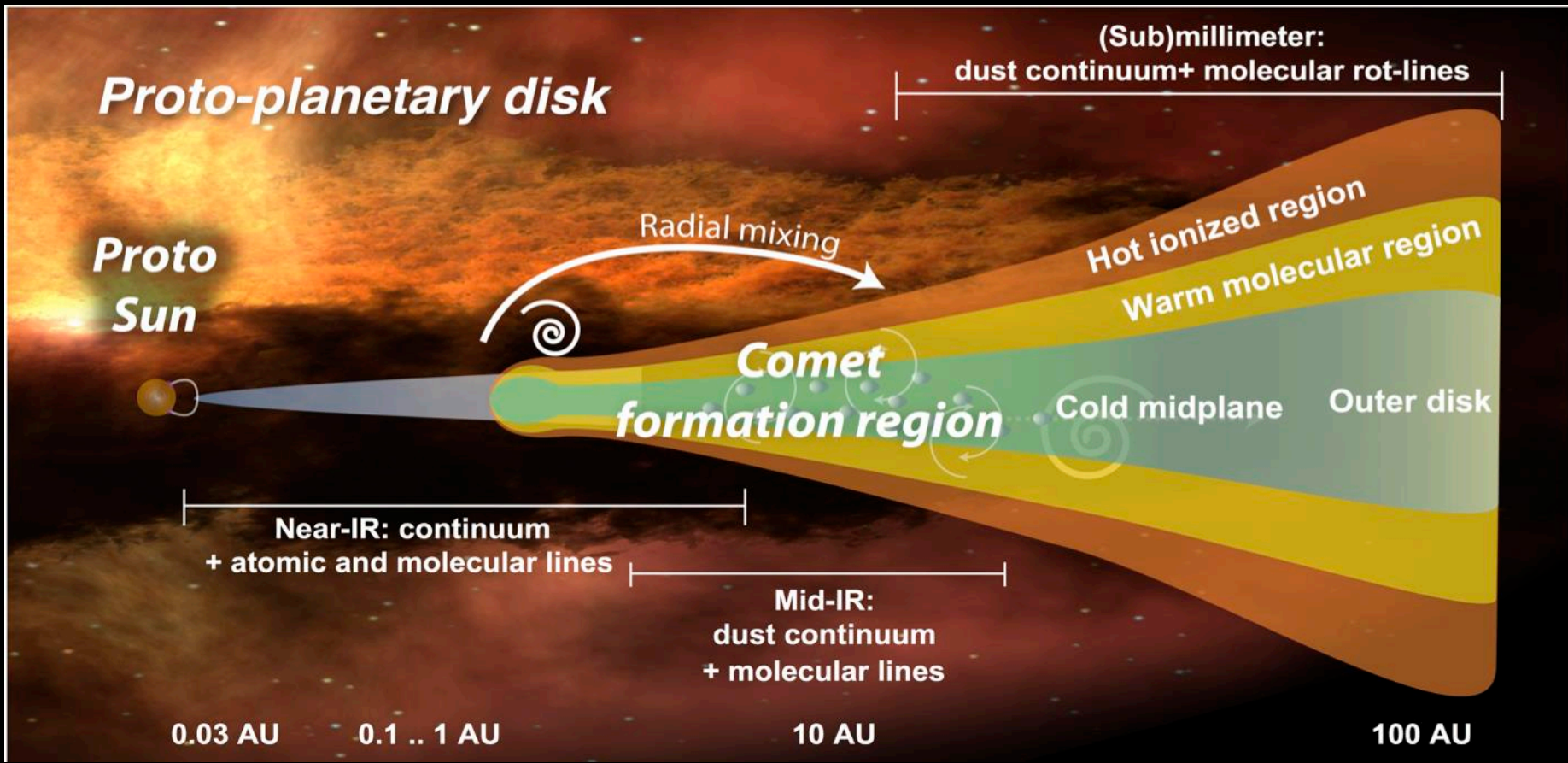


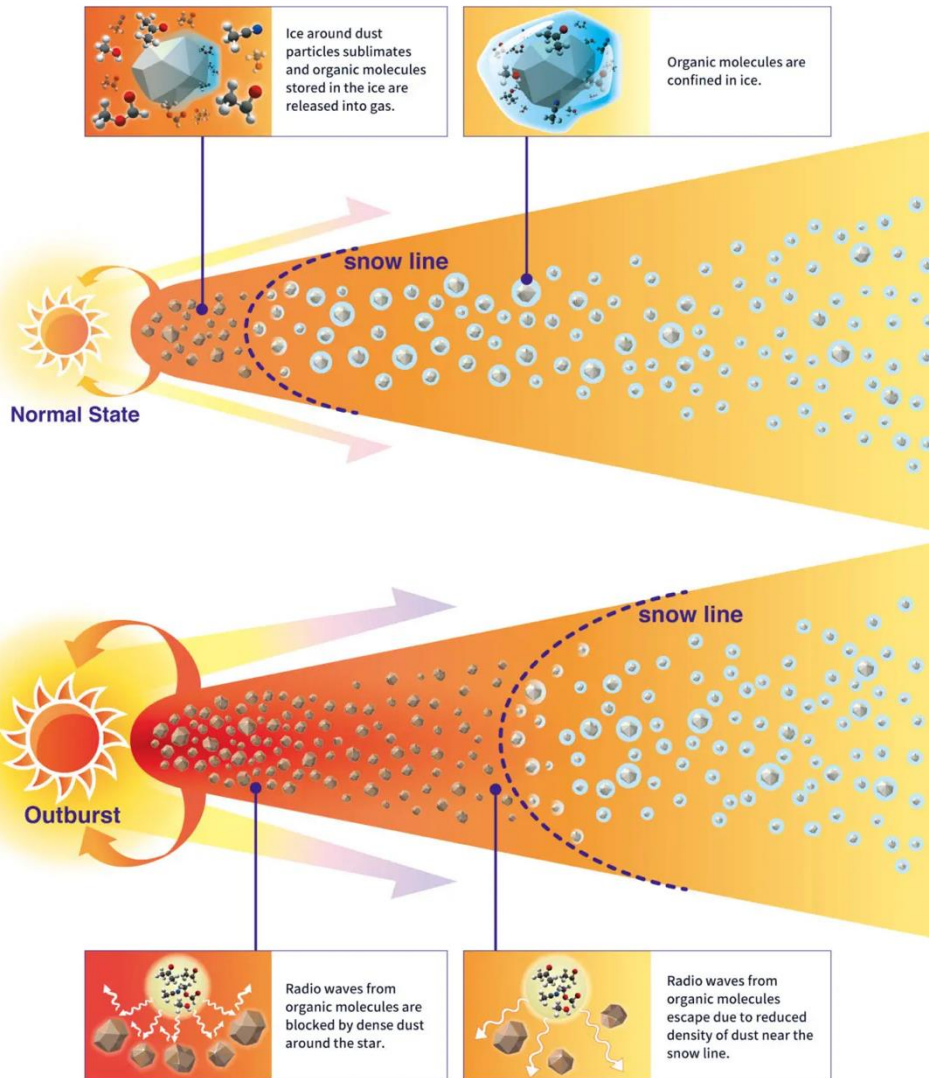
Connecting the solar nebula to planet formation



Connecting the solar nebula to planet formation



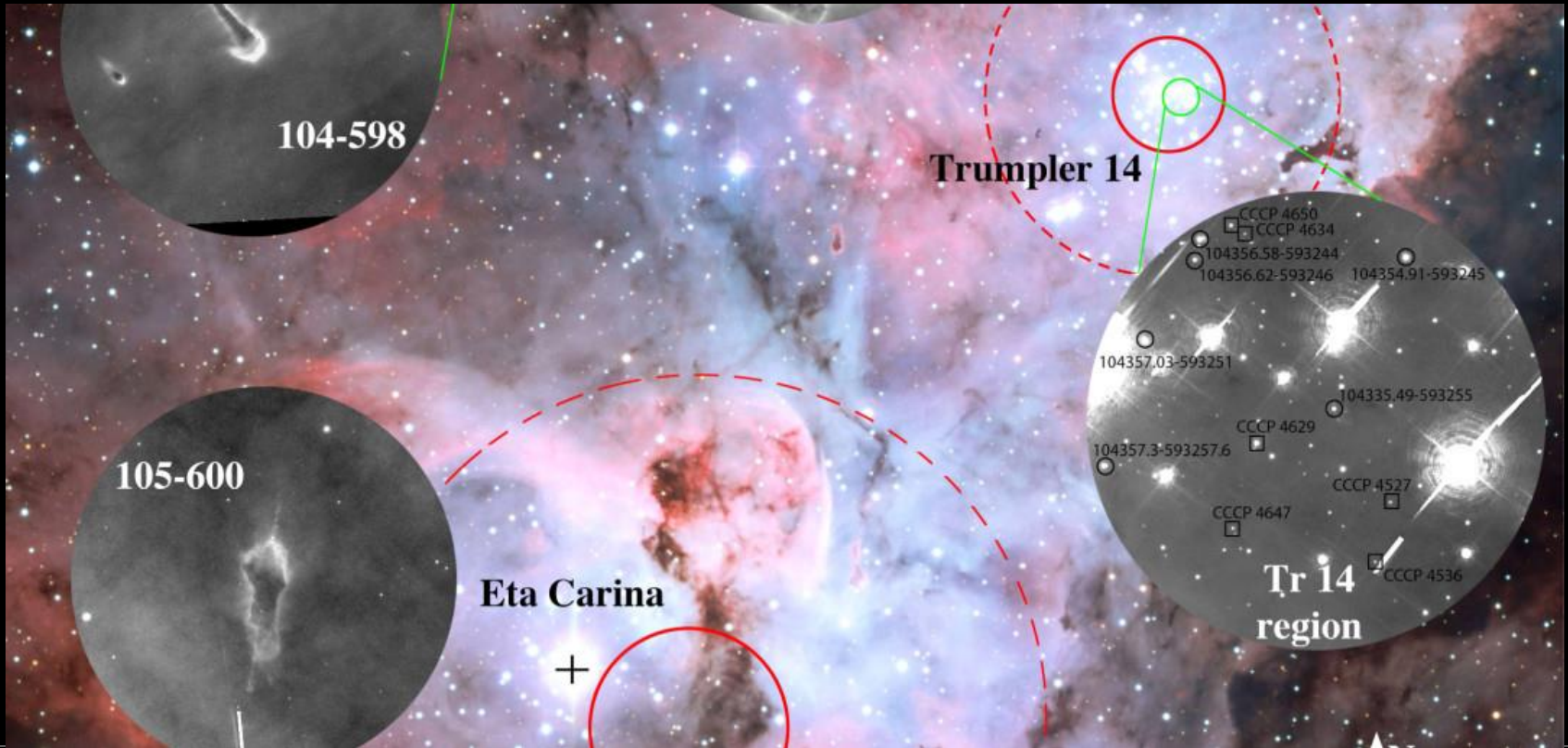




Very hot disk during a burst: chondrite heating?

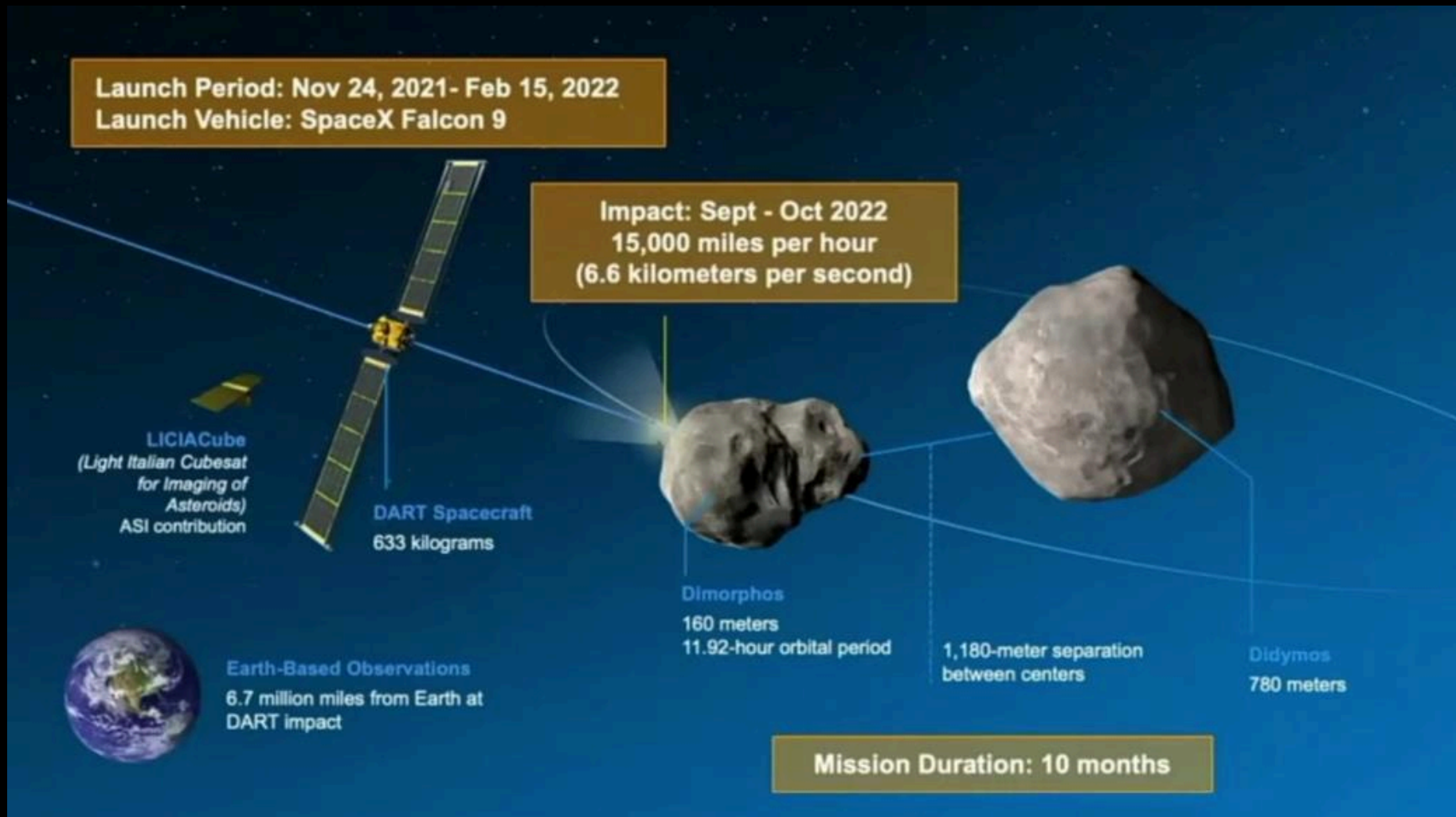
The sun formed in a massive star-forming region

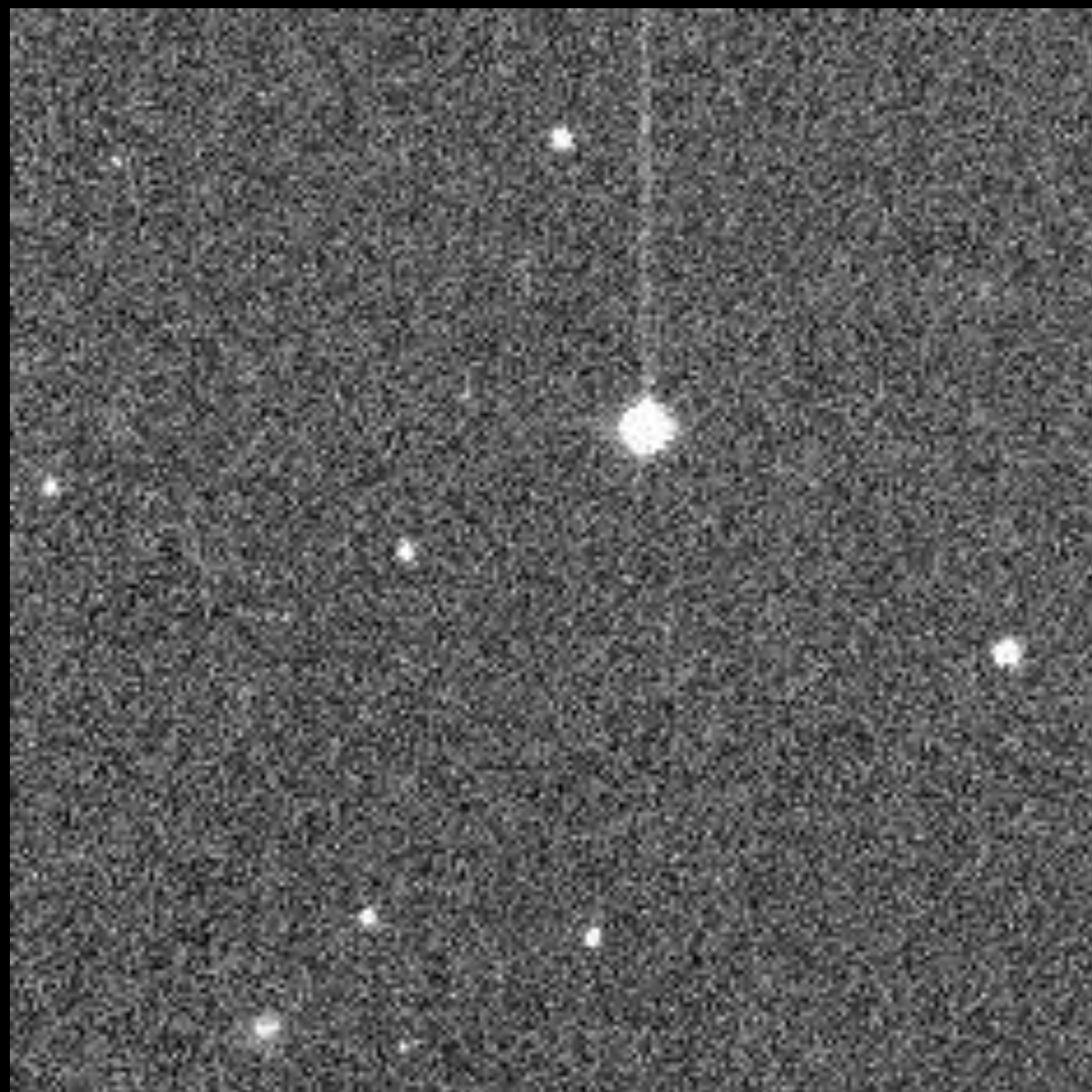
- Al-26 and Fe-60 abundances: solar material enriched by nearby supernova!

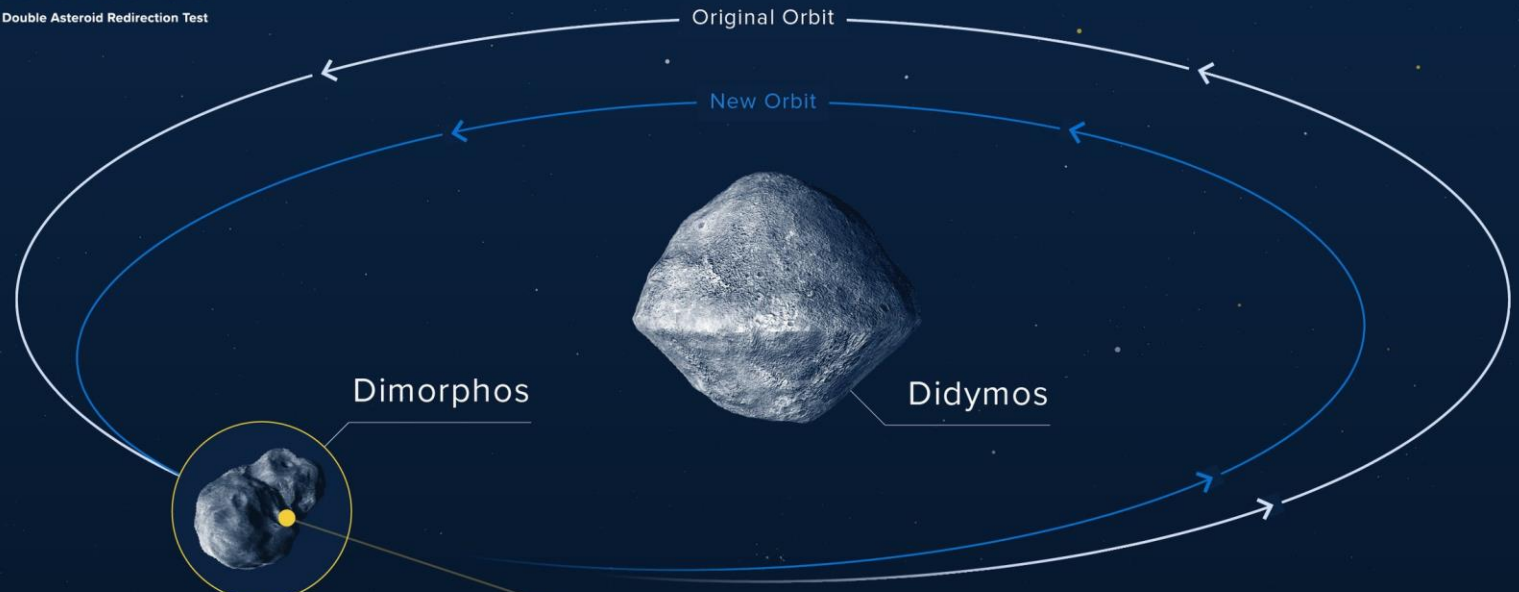


DART mission

- Double Asteroid Redirection Test (DART) Mission







Dimorphos

Didymos

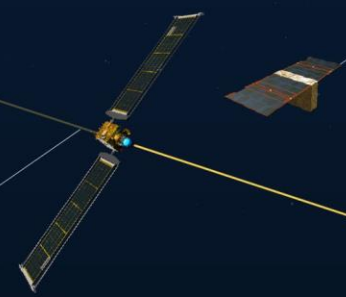
IMPACT

DART

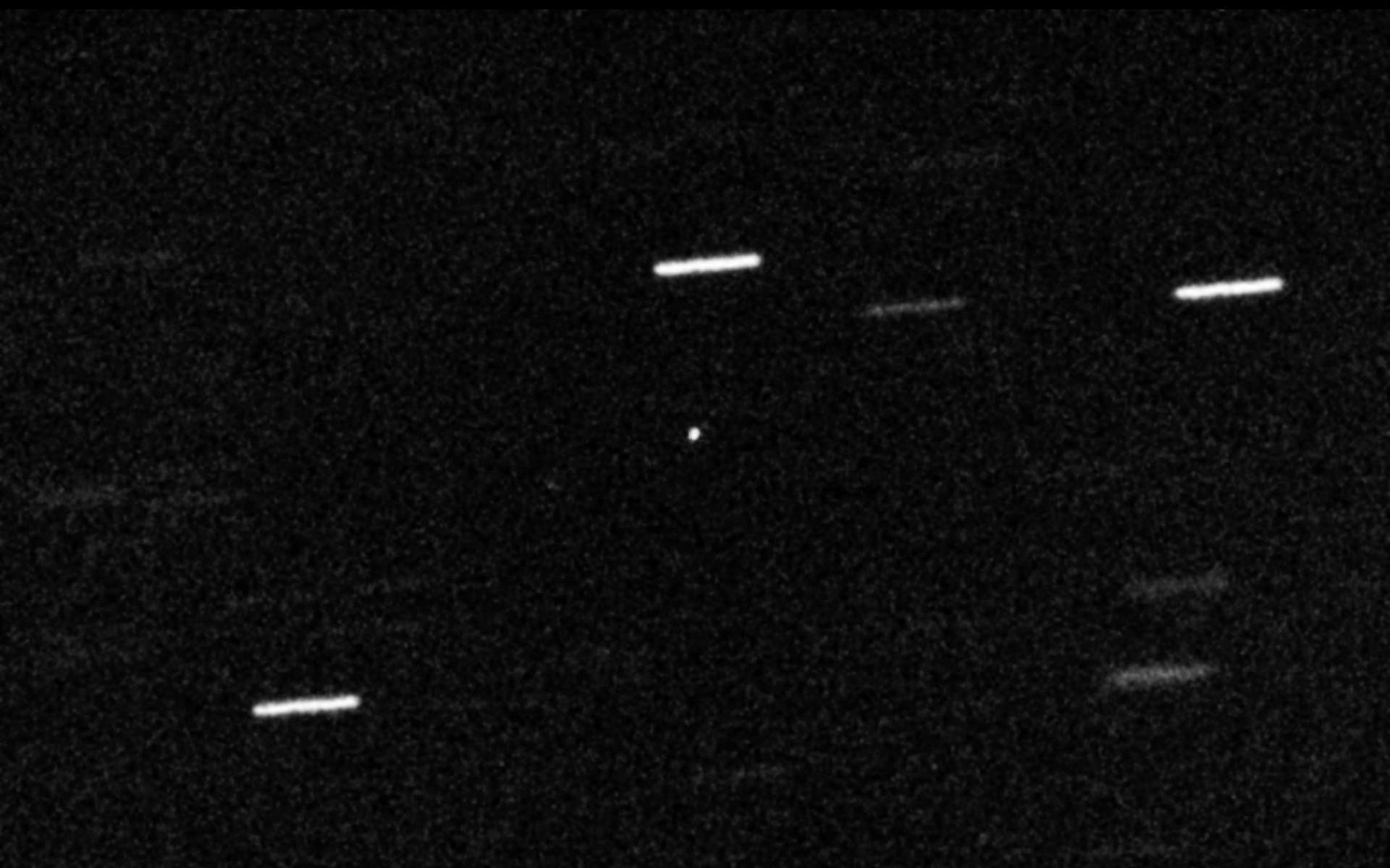
LICIACube



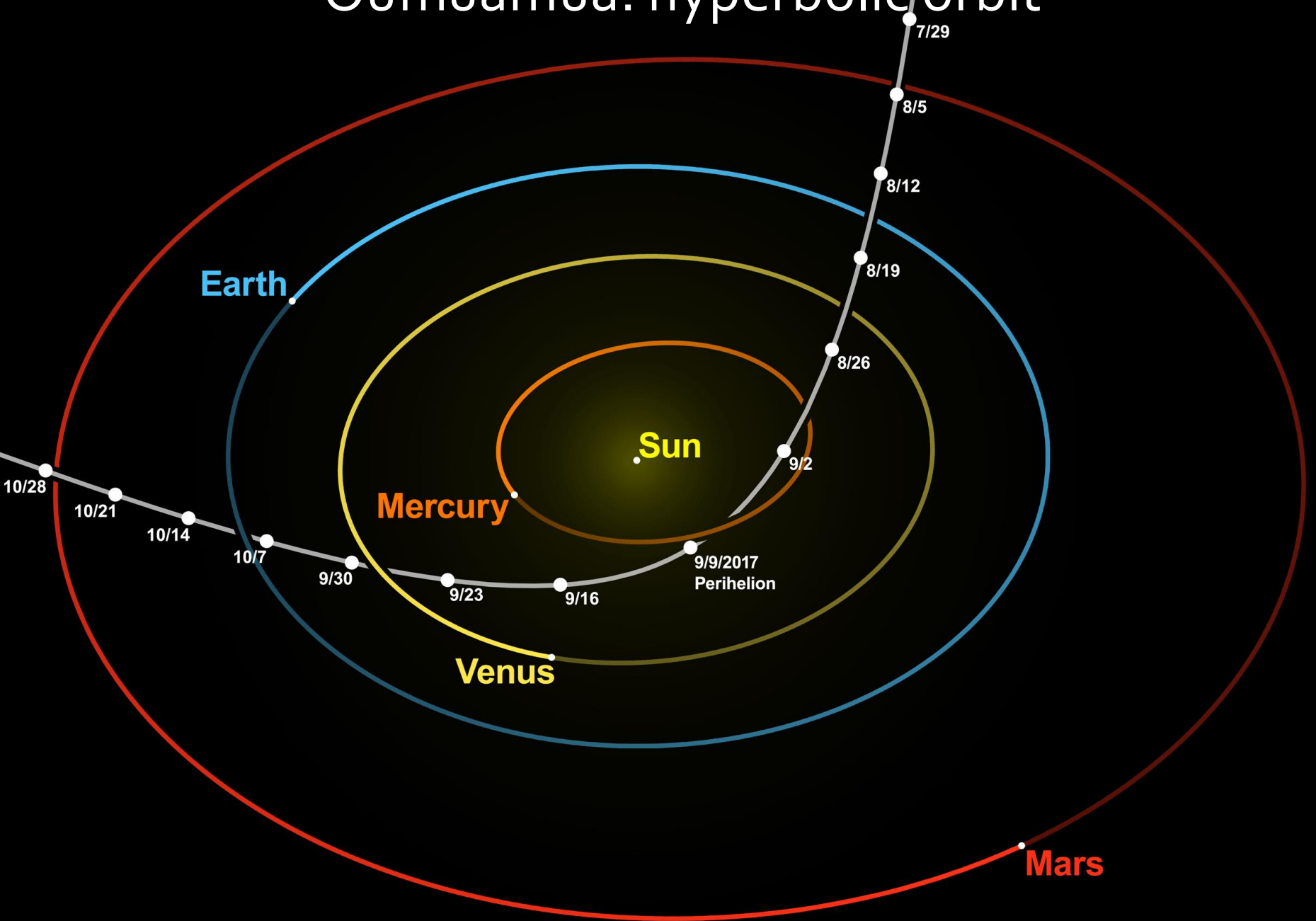
Earth-based observations



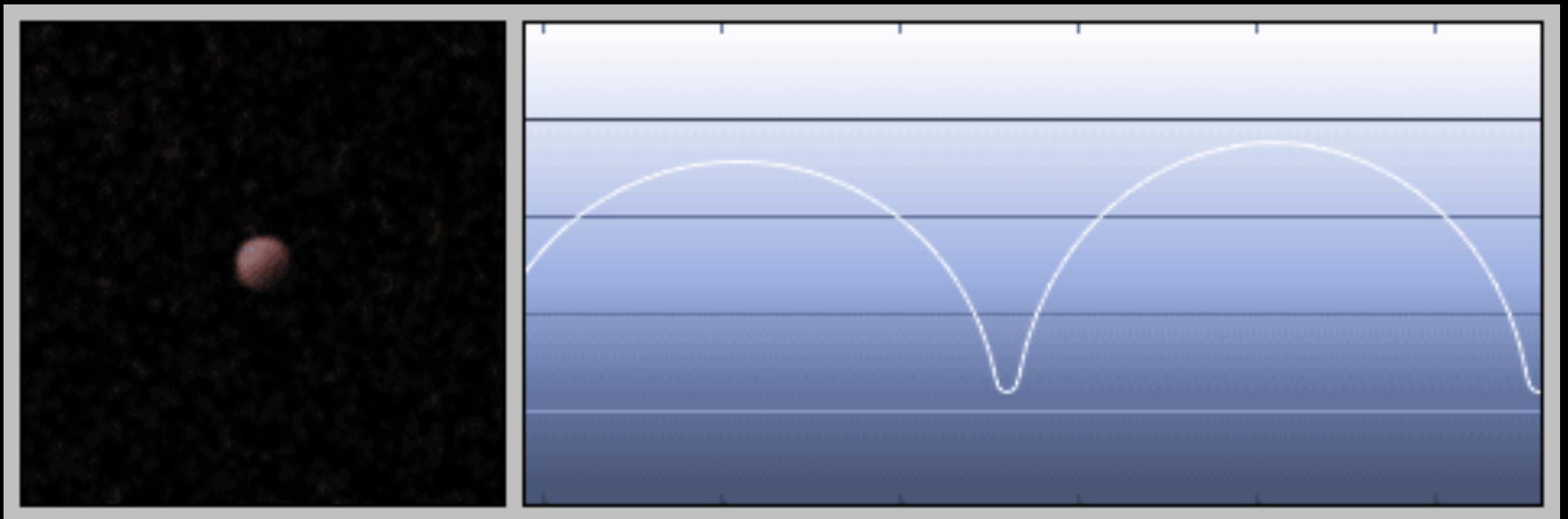
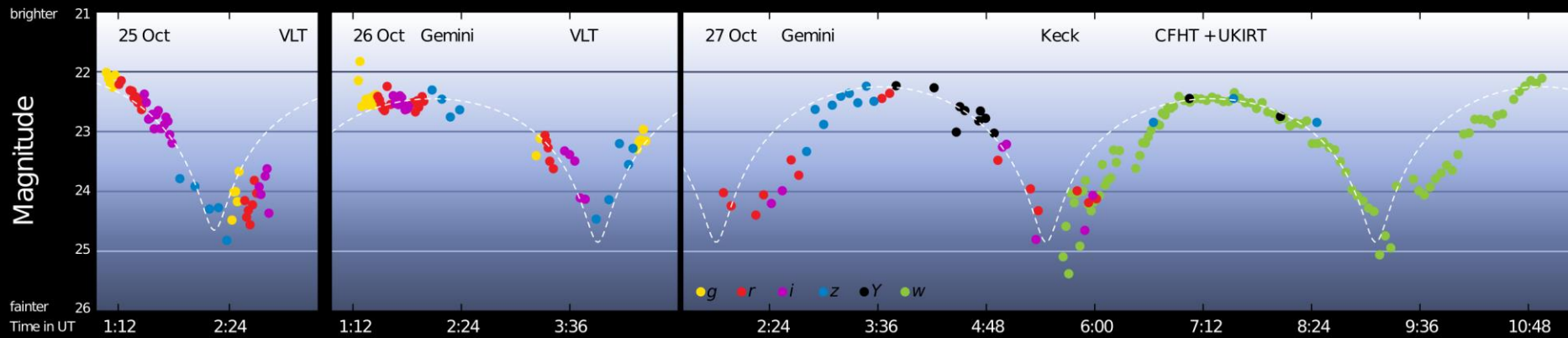
Oumuamua (and Borisov-2): interstellar visitors!



Oumuamua: hyperbolic orbit



Oumuamua lightcurve and shape



Artist's conception of Oumuamua



Density: likely icy body

The Earth as a planet



