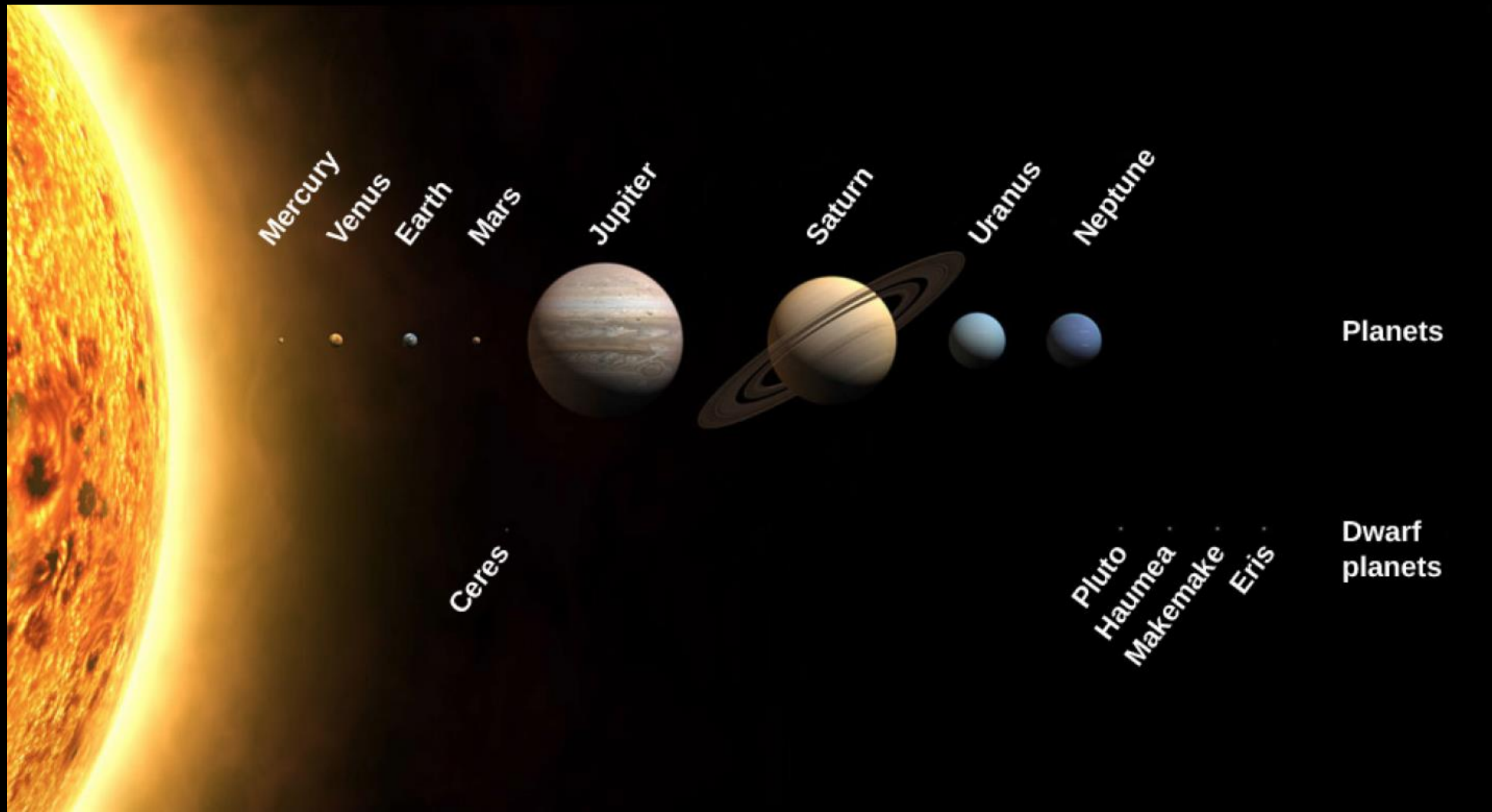
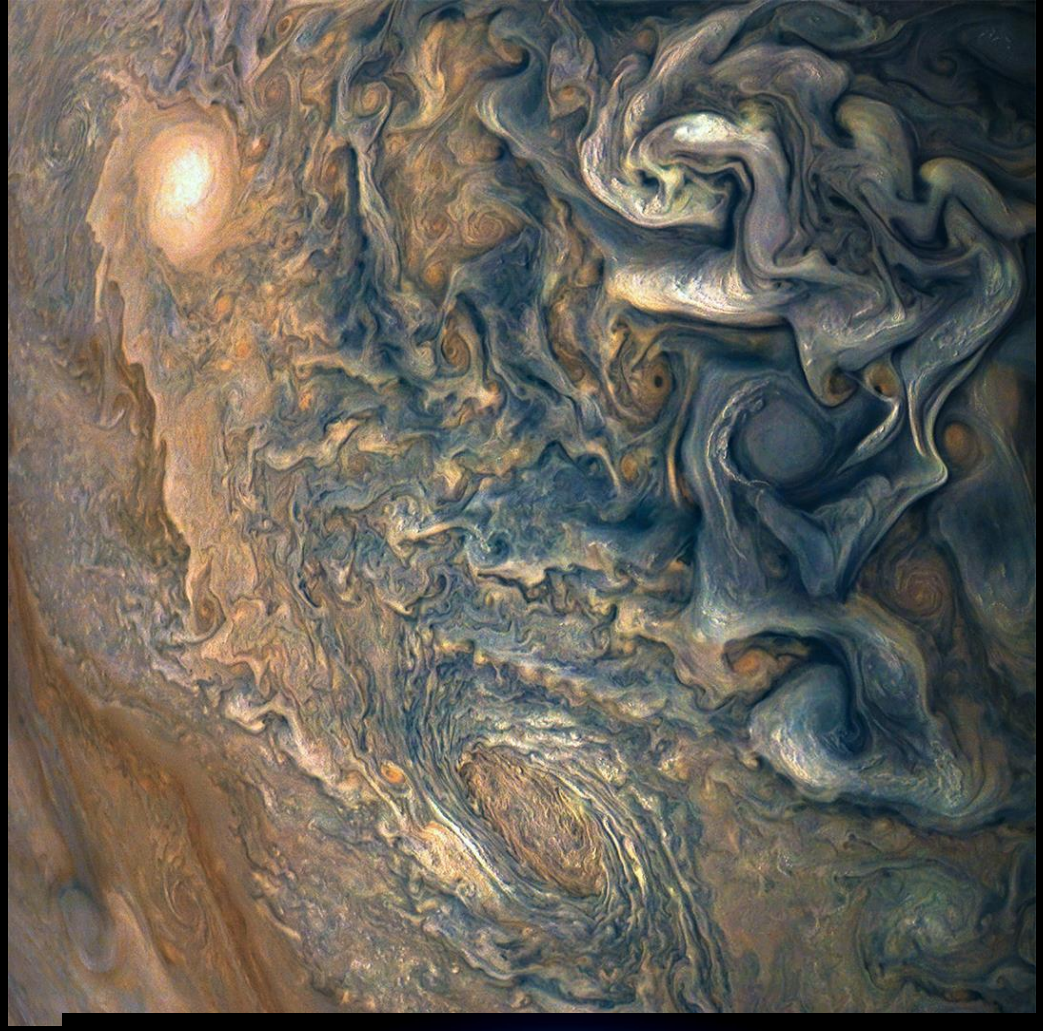
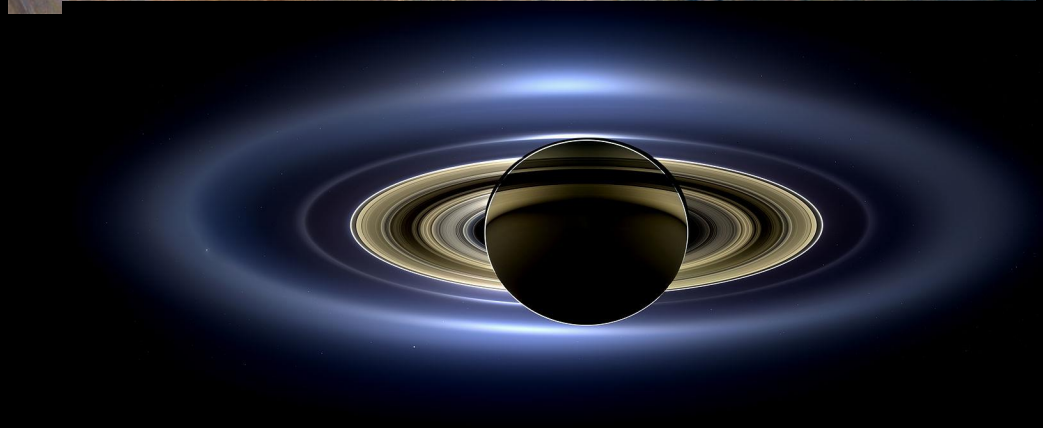
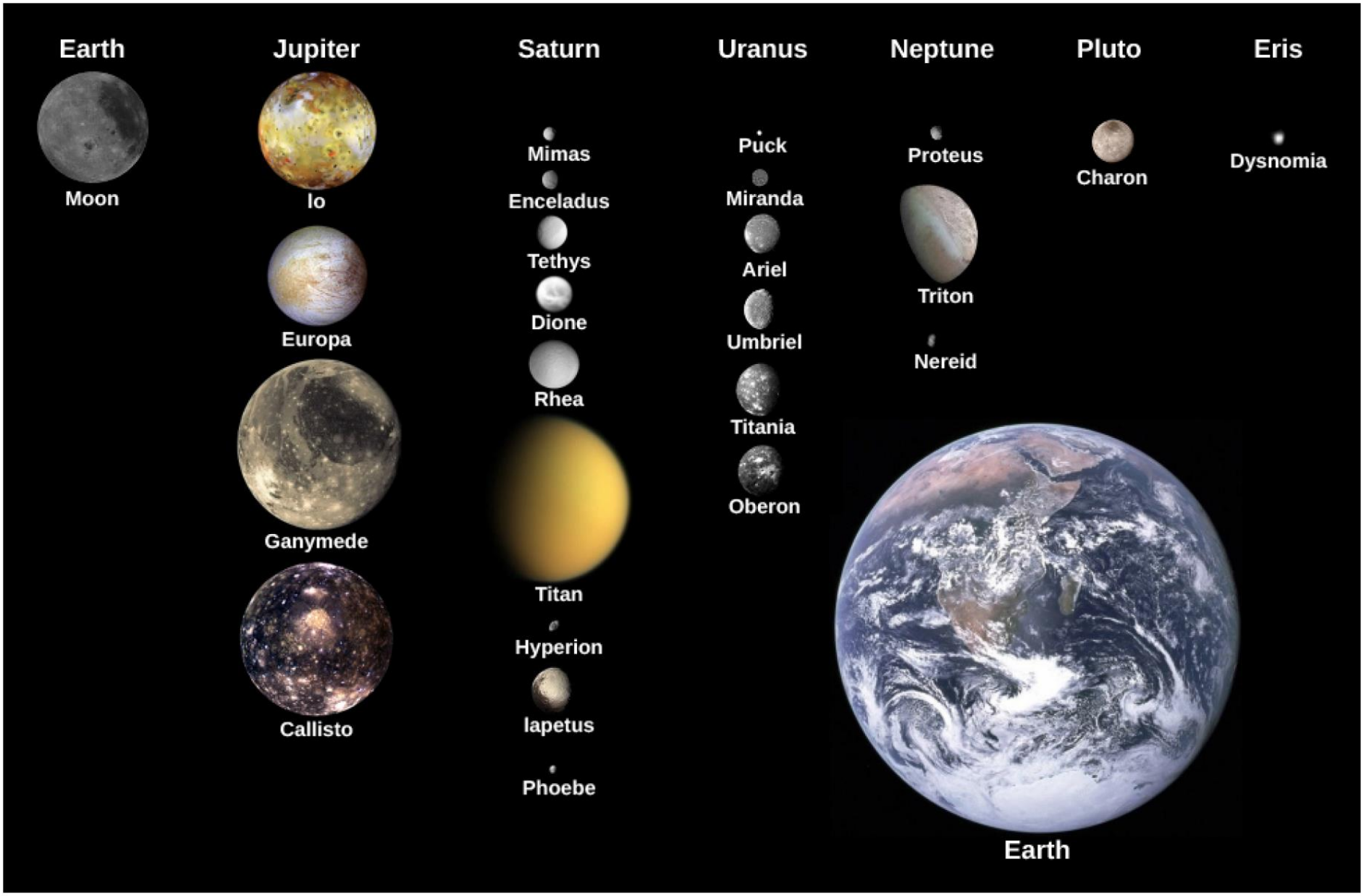
Our solar system: Moons and other debris

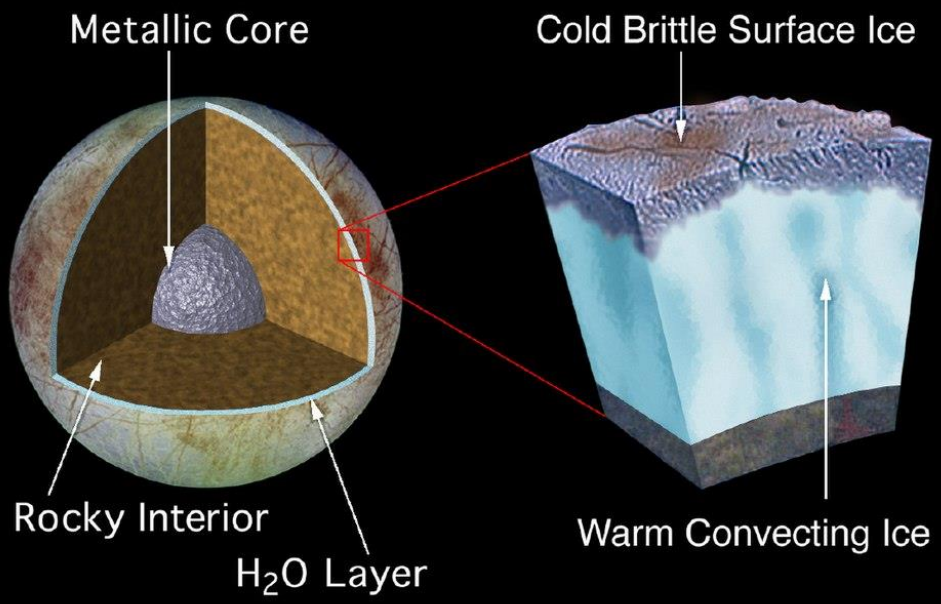


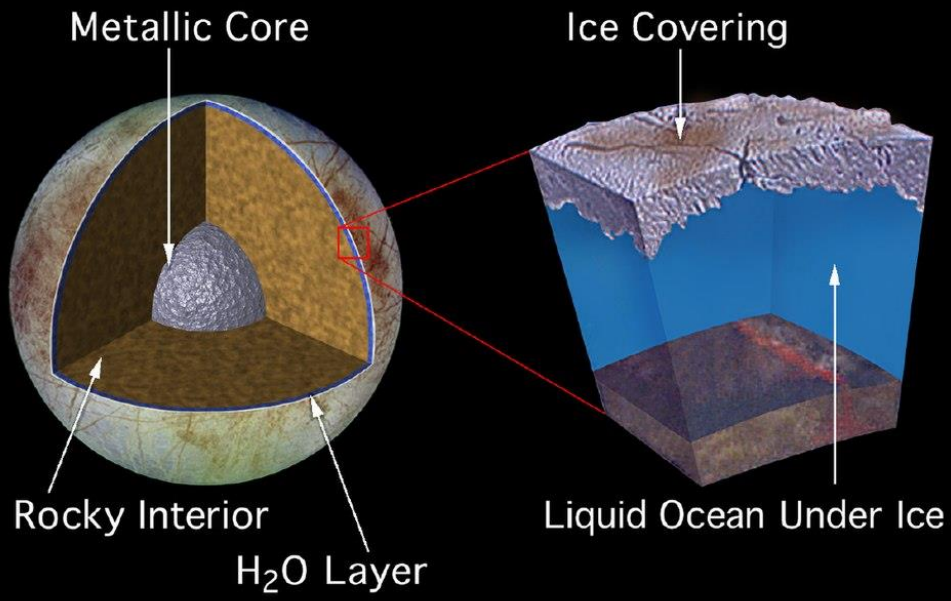




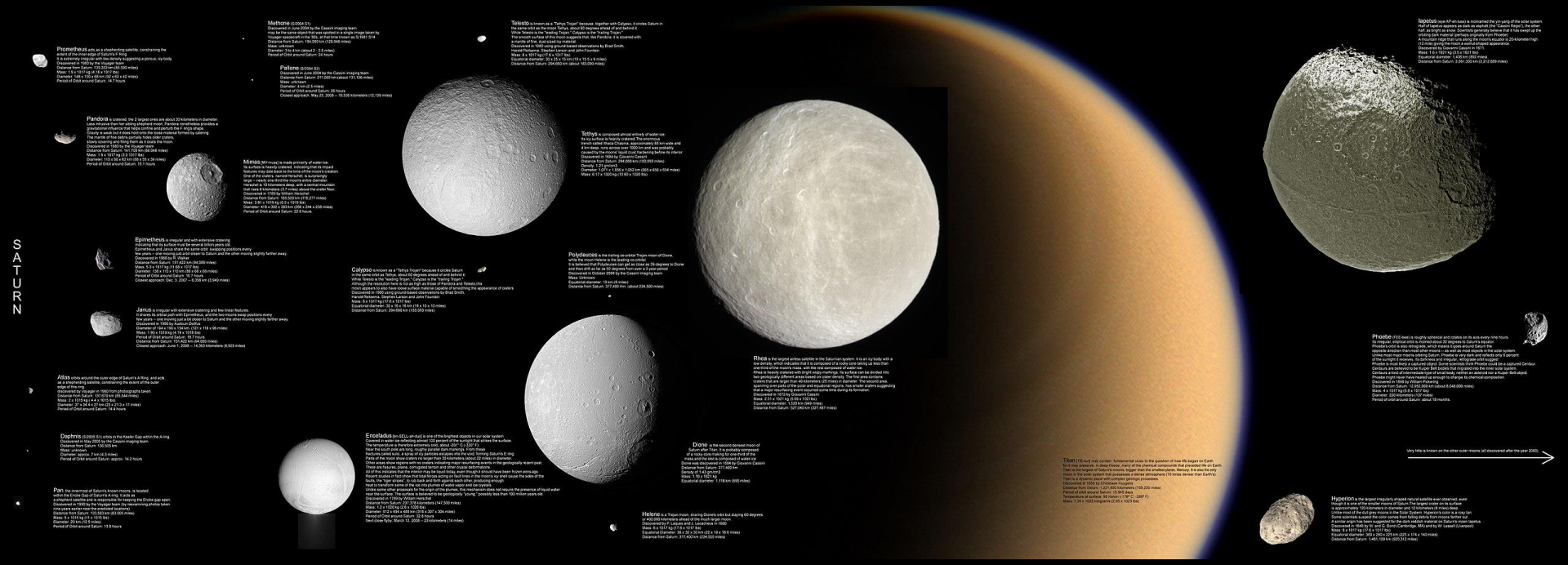

Earth
Moon
Jupiter
Io
Europa
Ganymede
Callisto
Saturn
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Hyperion
Iapetus
Phoebe
Uranus
Puck
Miranda
Ariel
Umbriel
Titania
Oberon
Neptune
Proteus
Triton
Nereid
Pluto
Charon
Eris
Dysnomia
Earth

Galilean satellites of Jupiter

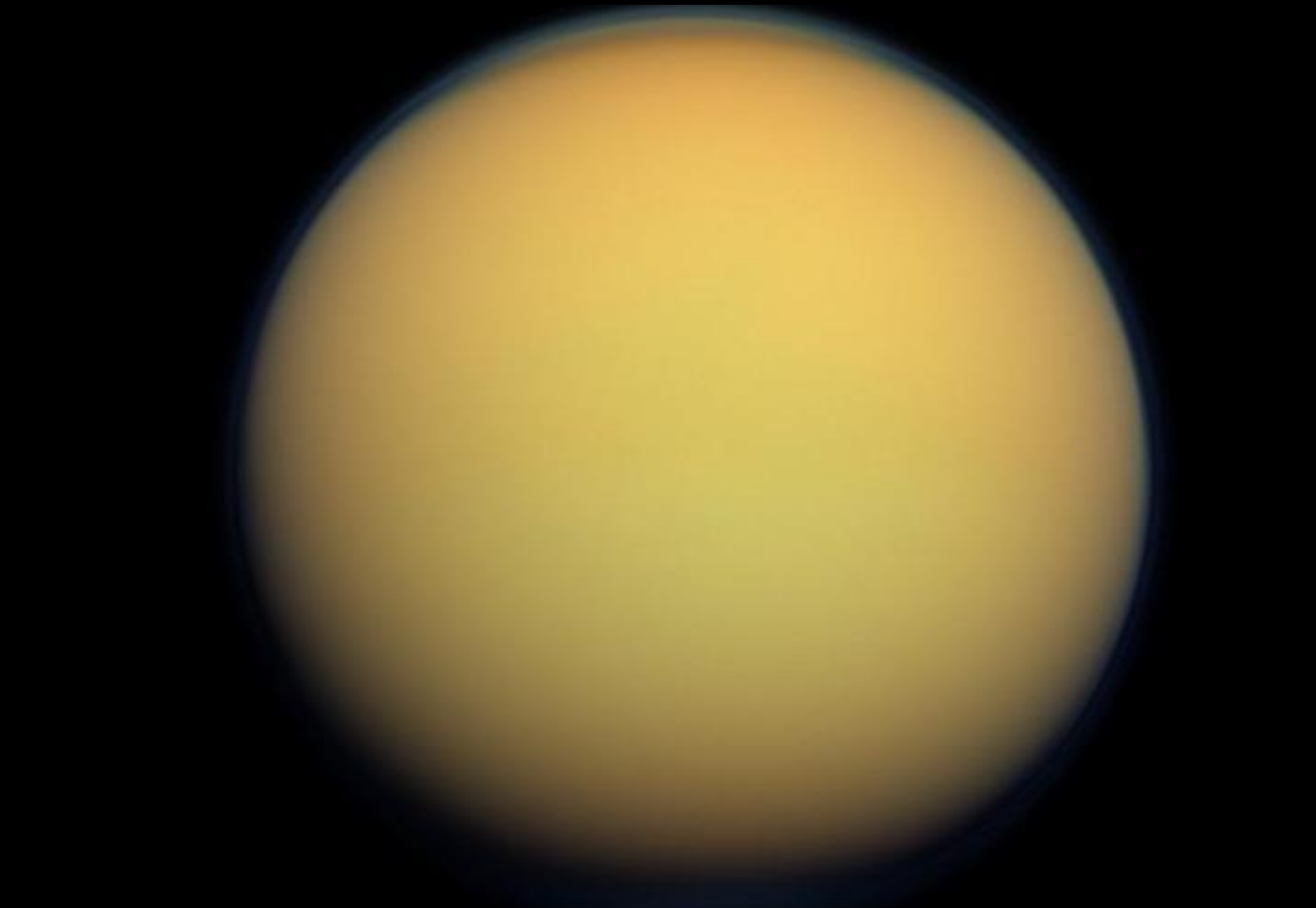

Metallic Core
Cold Brittle Surface Ice
Rocky Interior
H_2O Layer
Warm Convecting Ice

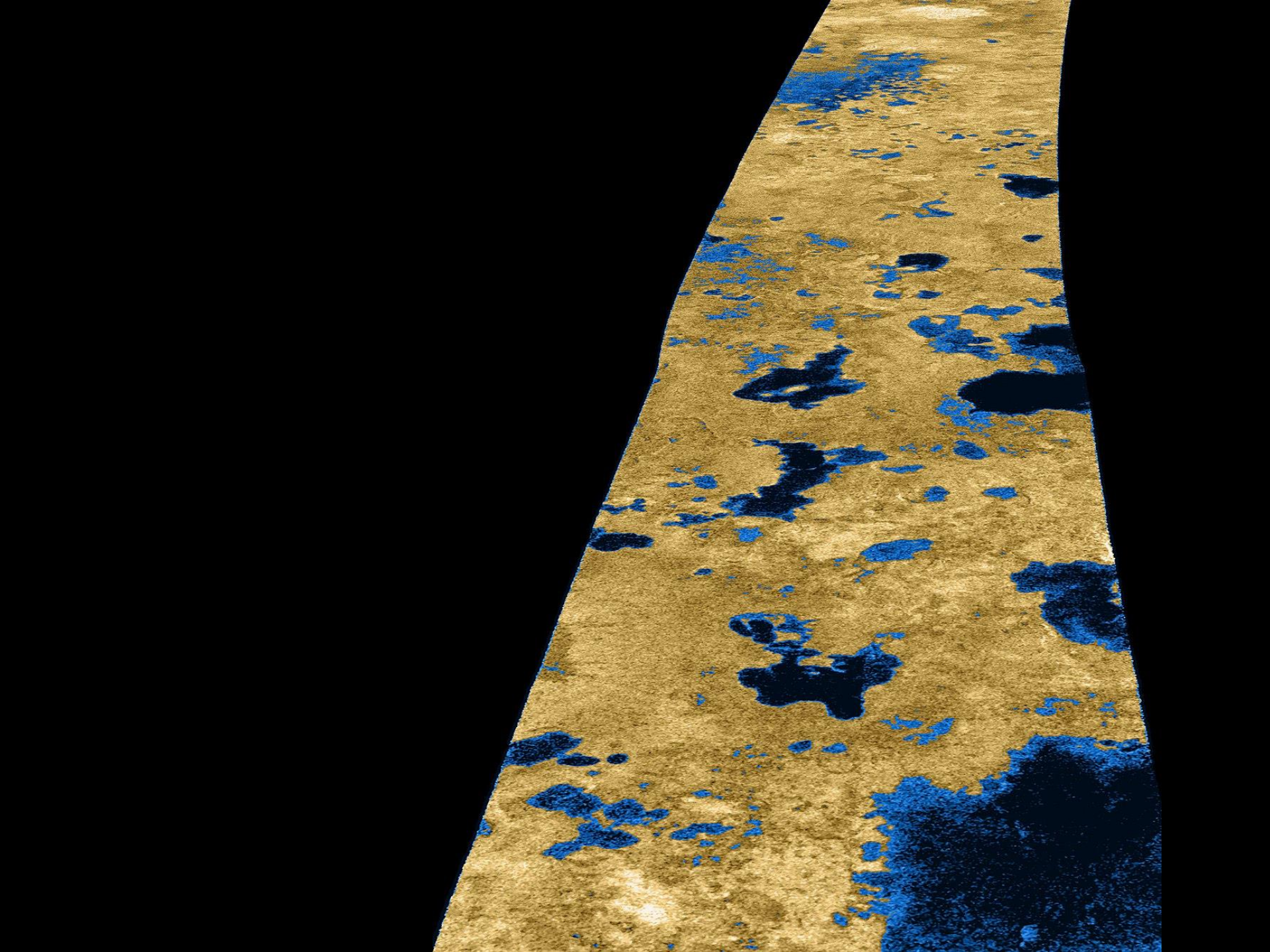

Metallic Core
Ice Covering
Rocky Interior
H_2O Layer
Liquid Ocean Under Ice

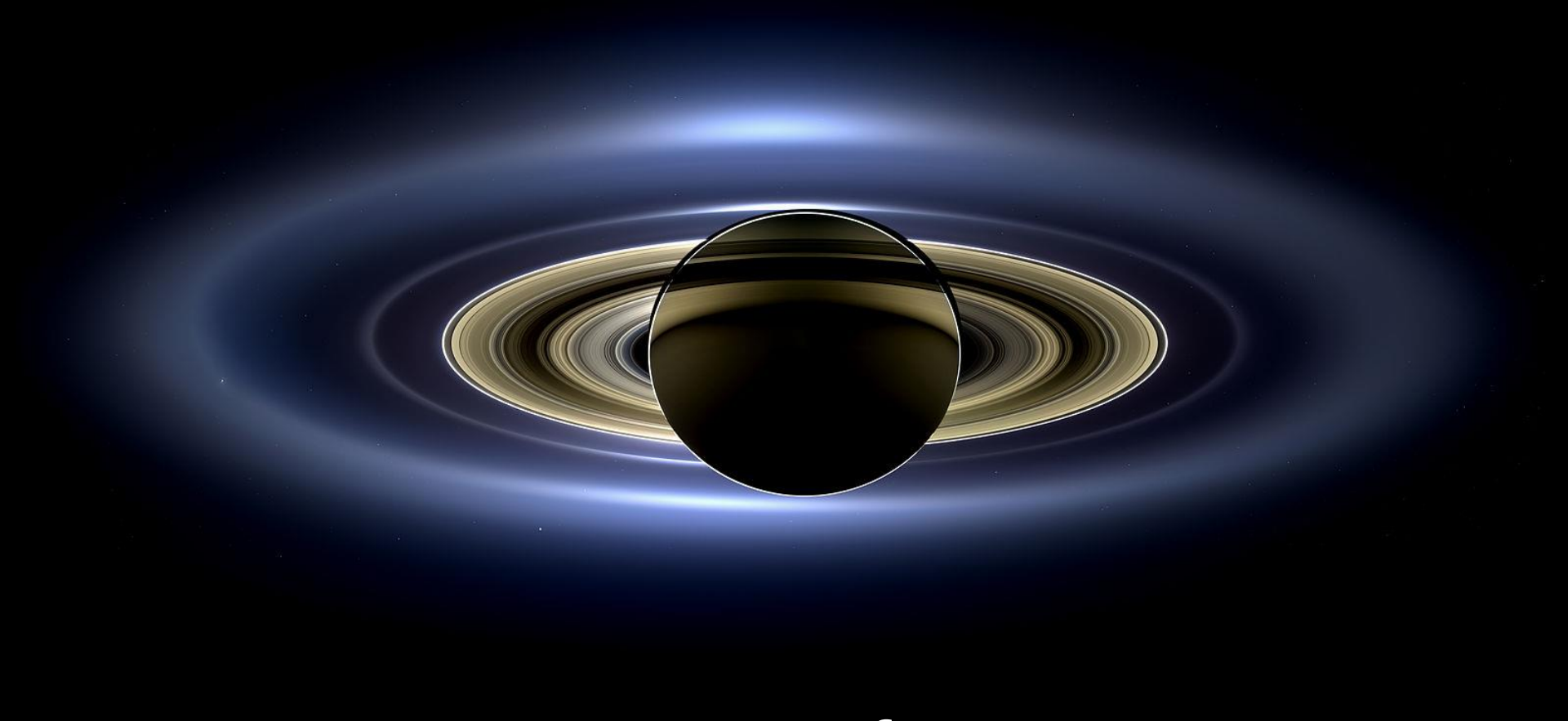
Moons of Saturn



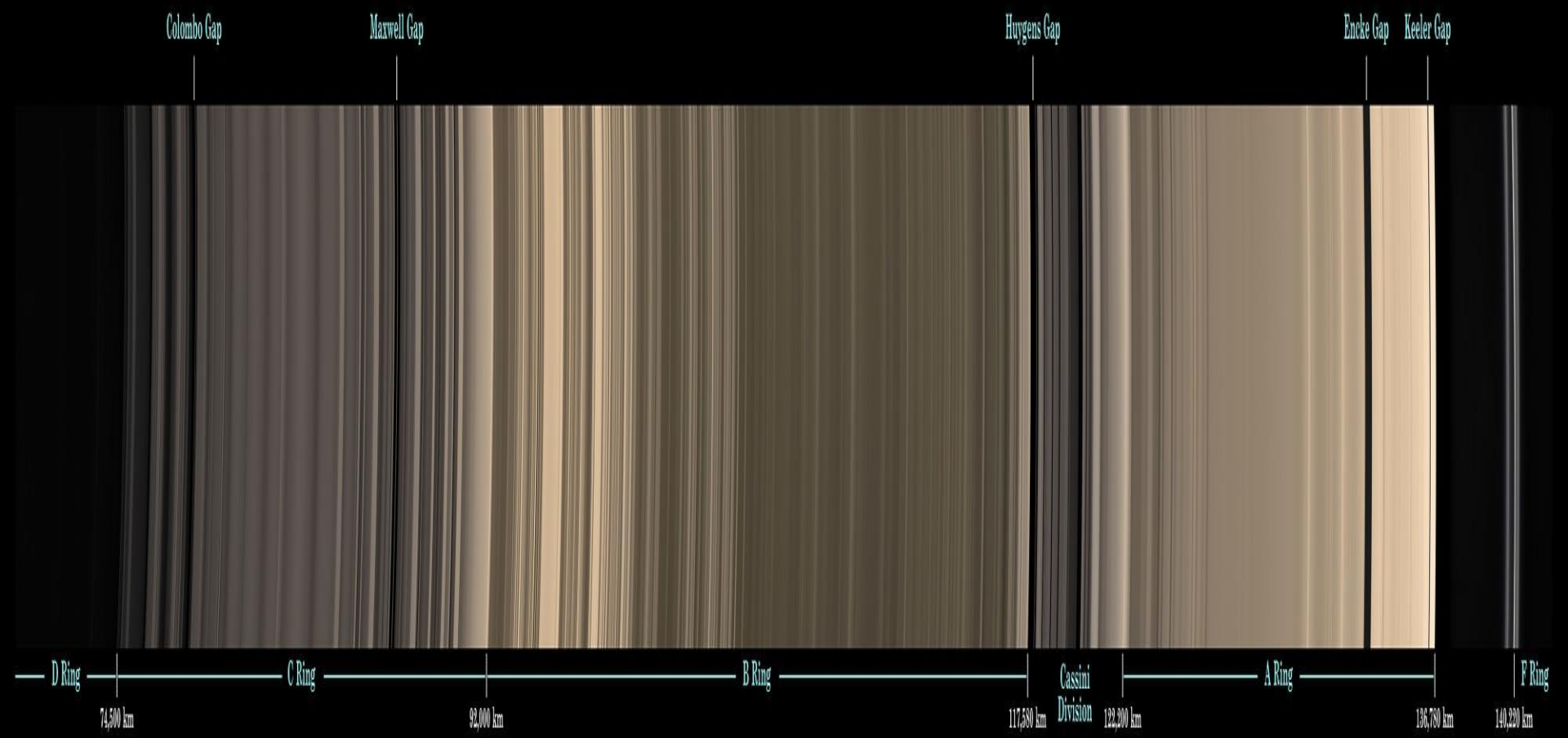
Titan: the main moon of Saturn



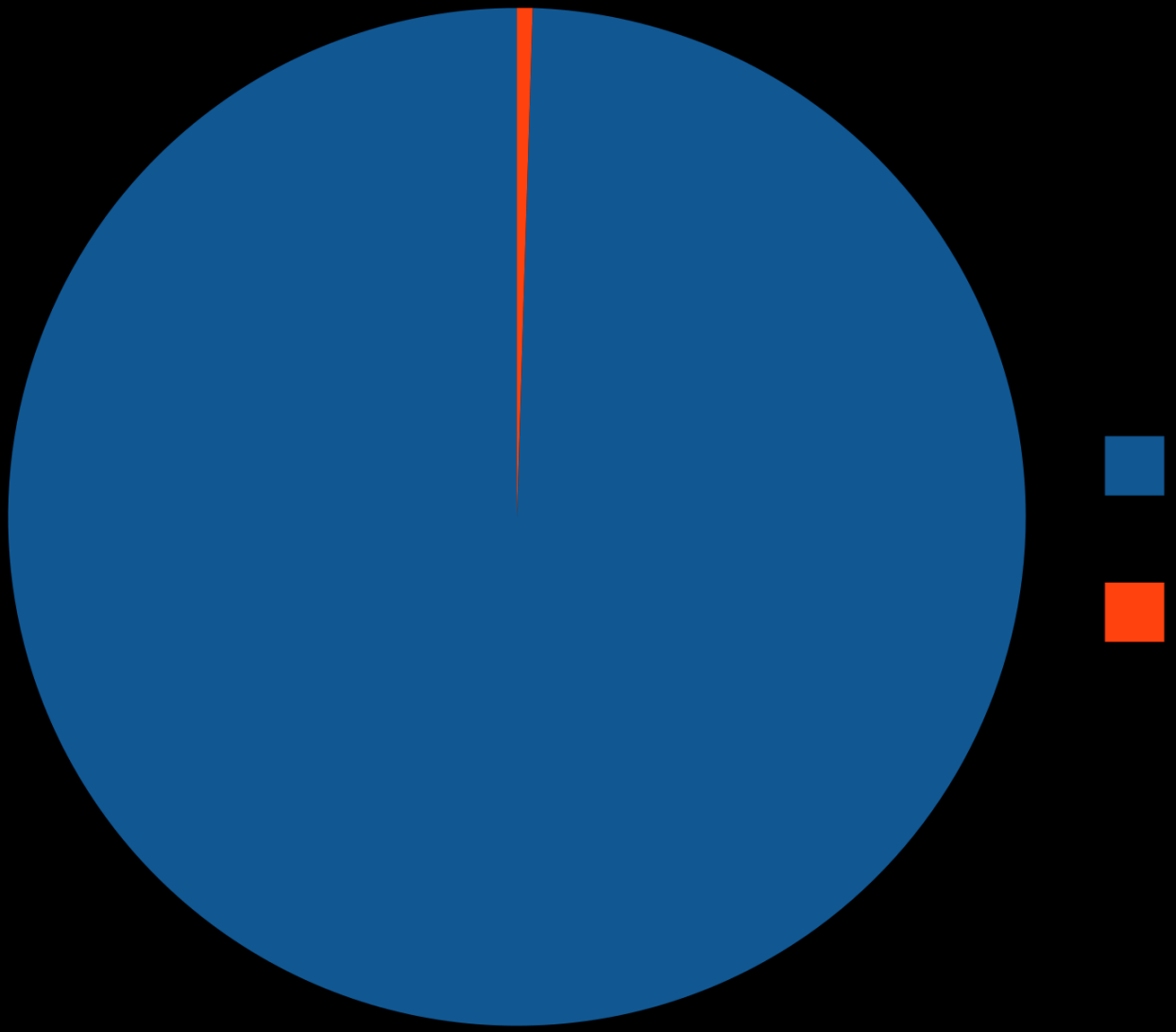




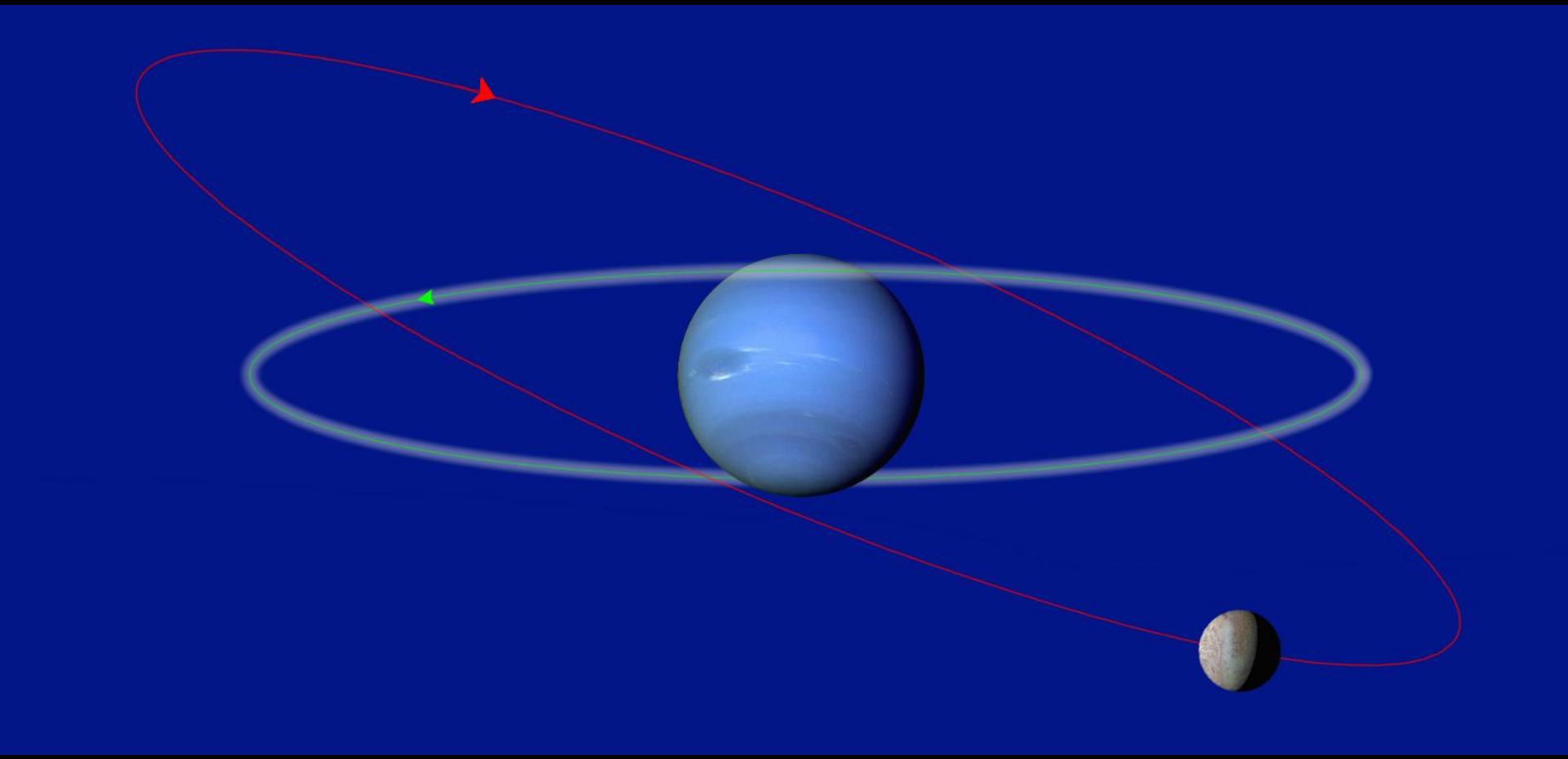
Rings: water ice a few m across
remnants of a moon
Thousands of km across; ~10 m thick!
<100 million years old

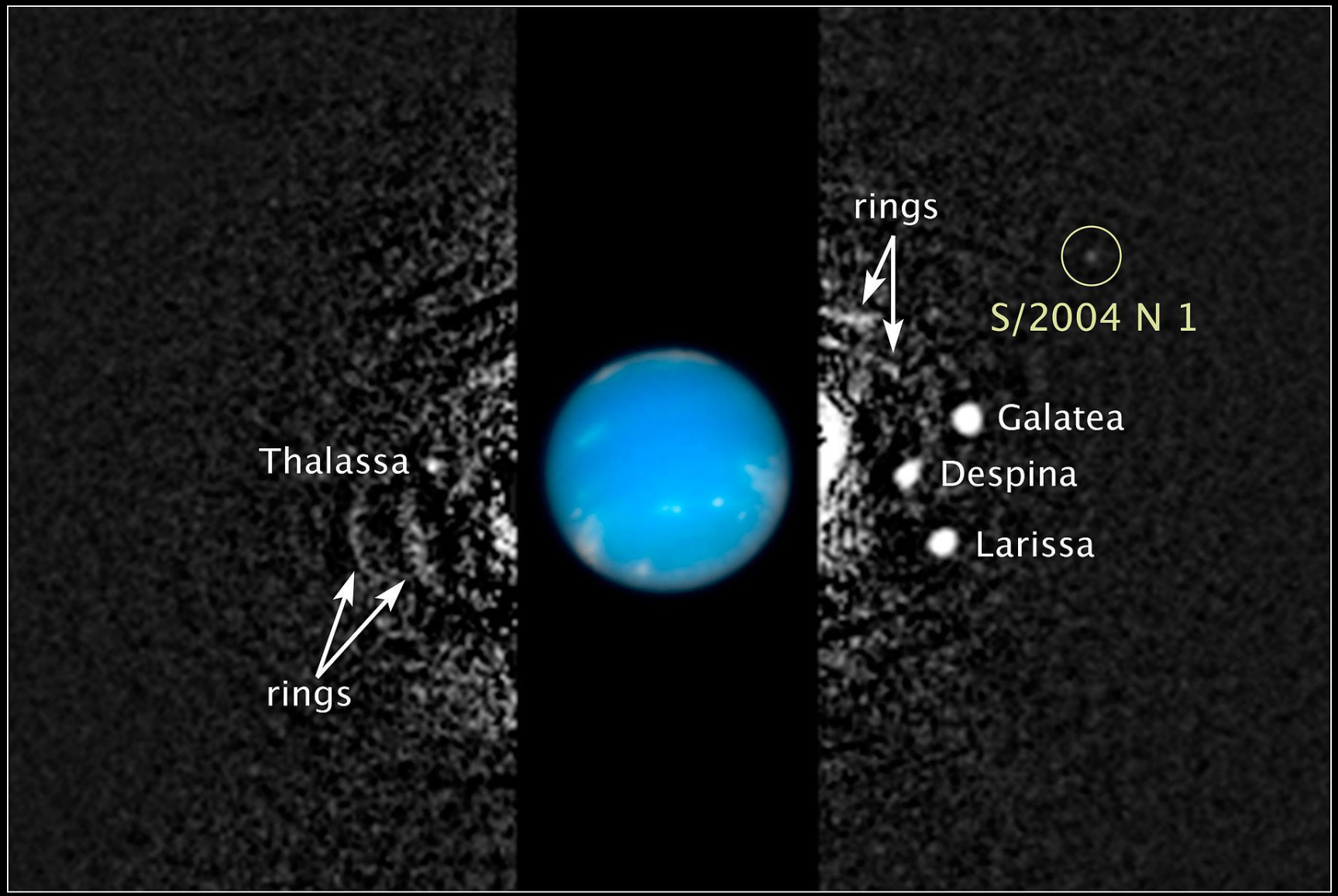

Colombo Gap
Maxwell Gap
Huygens Gap
Encke Gap
Keeler Gap
D Ring
C Ring
B Ring
Cassini Division
A Ring
F Ring
74,500 km
92,000 km
117,580 km
122,200 km
136,780 km
140,220 km

Moons of Neptune



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





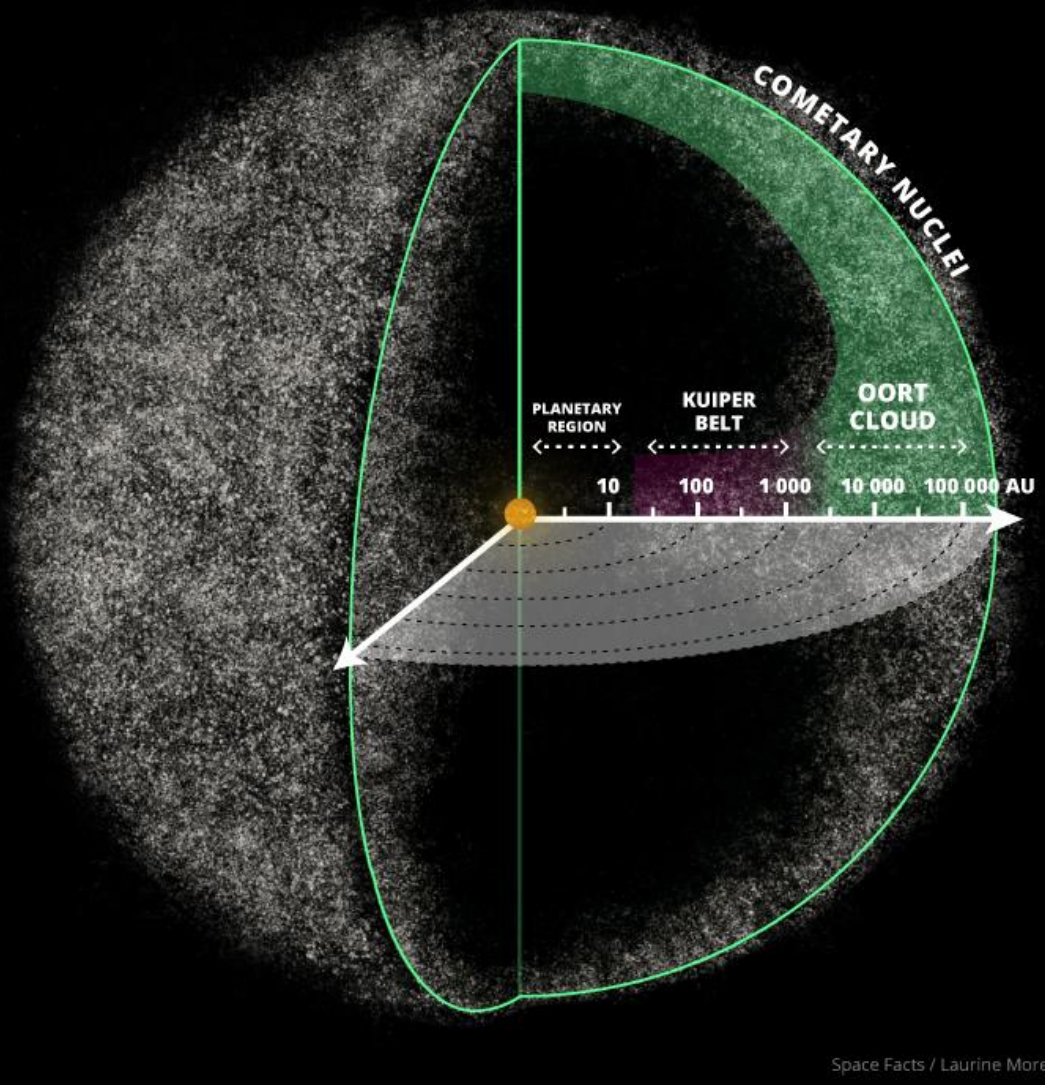
Neptune Satellites and Ring Arcs

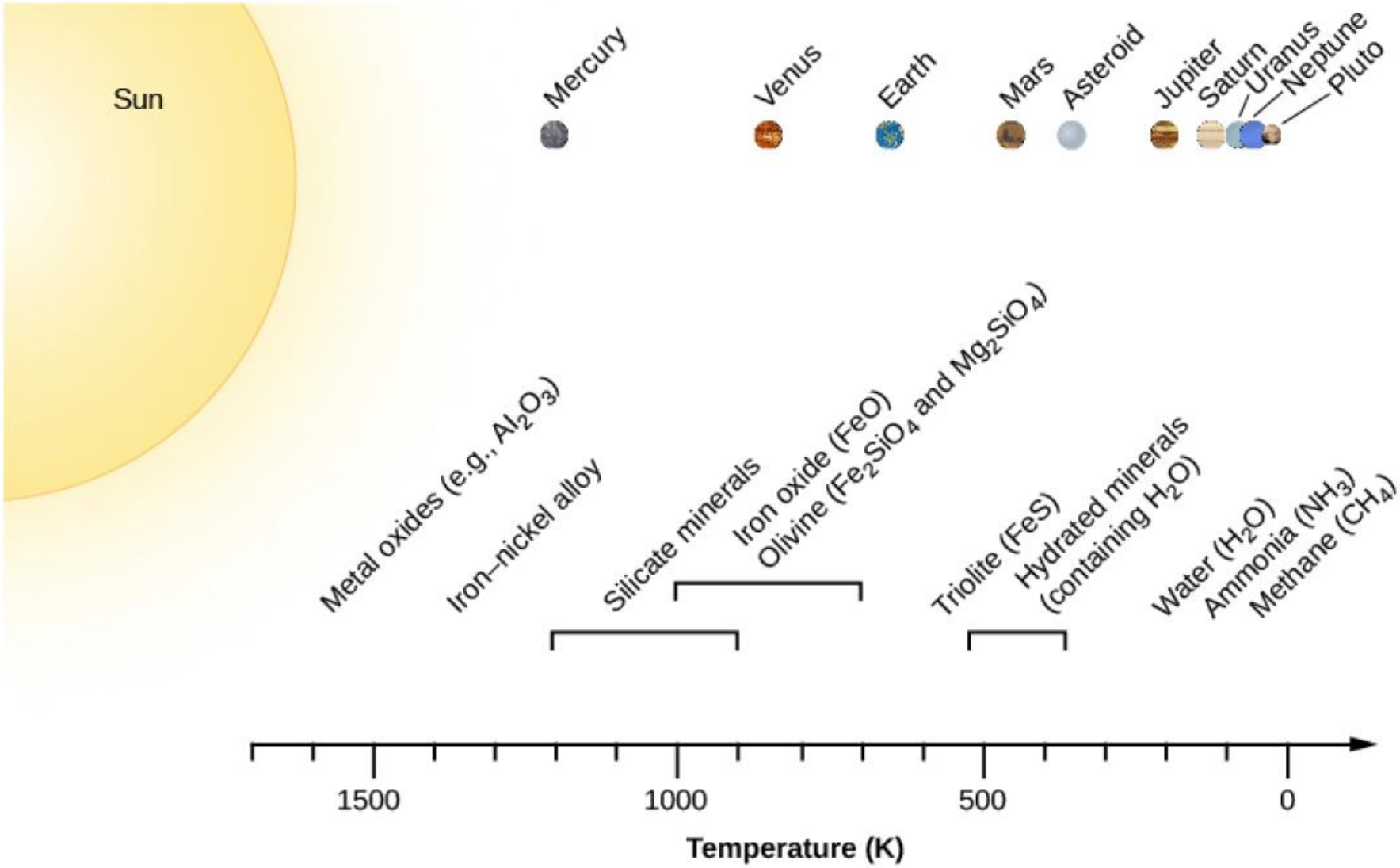
Hubble Space Telescope ▪ WFC3/UVIS

NASA and ESA

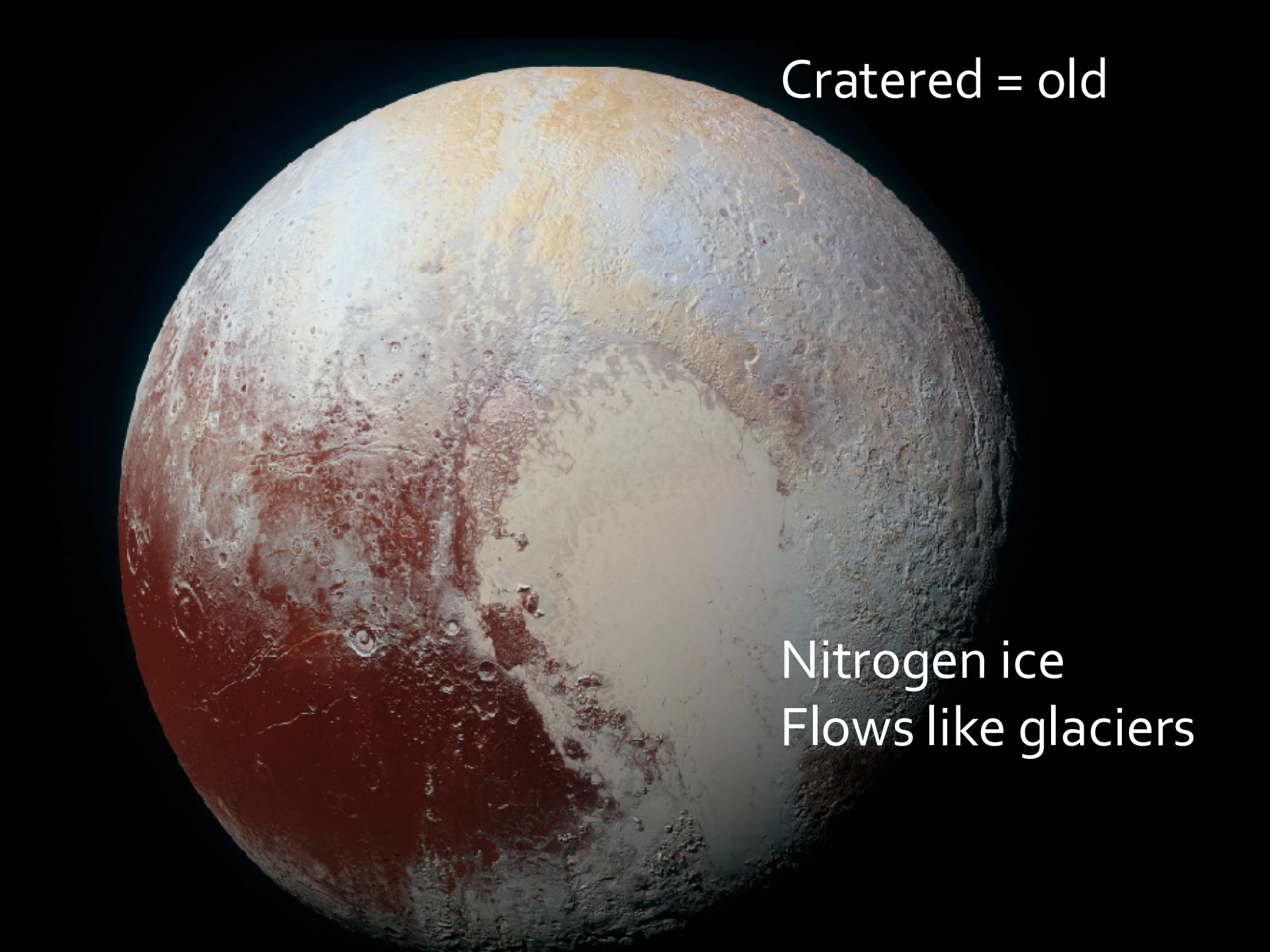
STScI-PRC13-30a

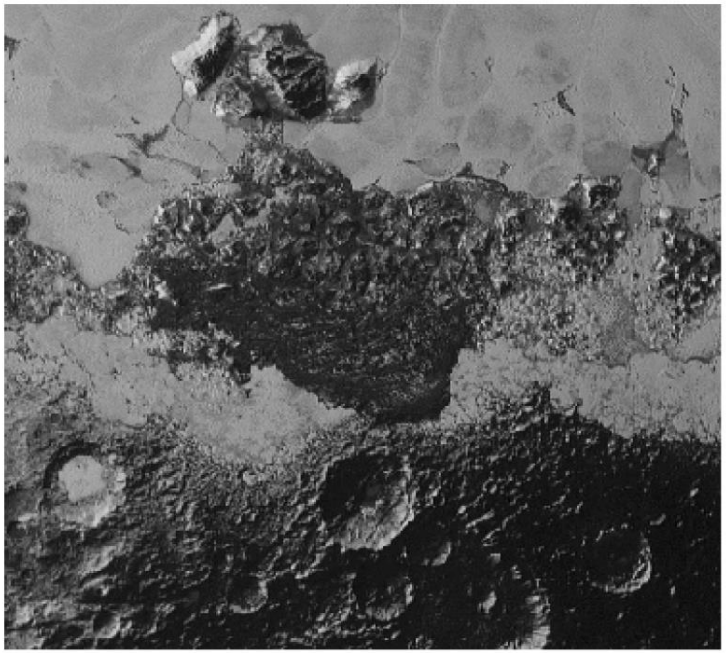
Debris from the solar system: asteroids, comets, Kuiper Belt Objects

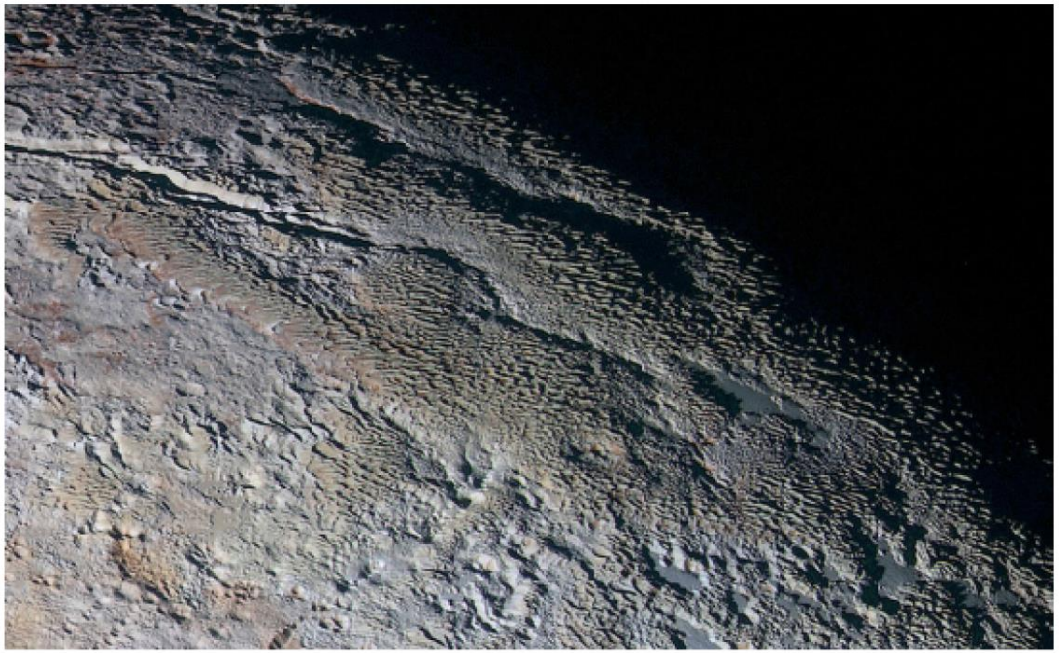



Sun
Mercury
Venus
Earth
Mars
Asteroid
Jupiter
Saturn
Uranus
Neptune
Pluto
Metal oxides (e.g., Al_2O_3)
Iron–nickel alloy
Silicate minerals
Iron oxide (FeO)
Olivine (Fe_2SiO_4 and Mg_2SiO_4)
Triolite (FeS)
Hydrated minerals (containing H_2O)
Water (H_2O)
Ammonia (NH_3)
Methane (CH_4)
1500
1000
500
0
Temperature (K)

Pluto from
New Horizons Mission

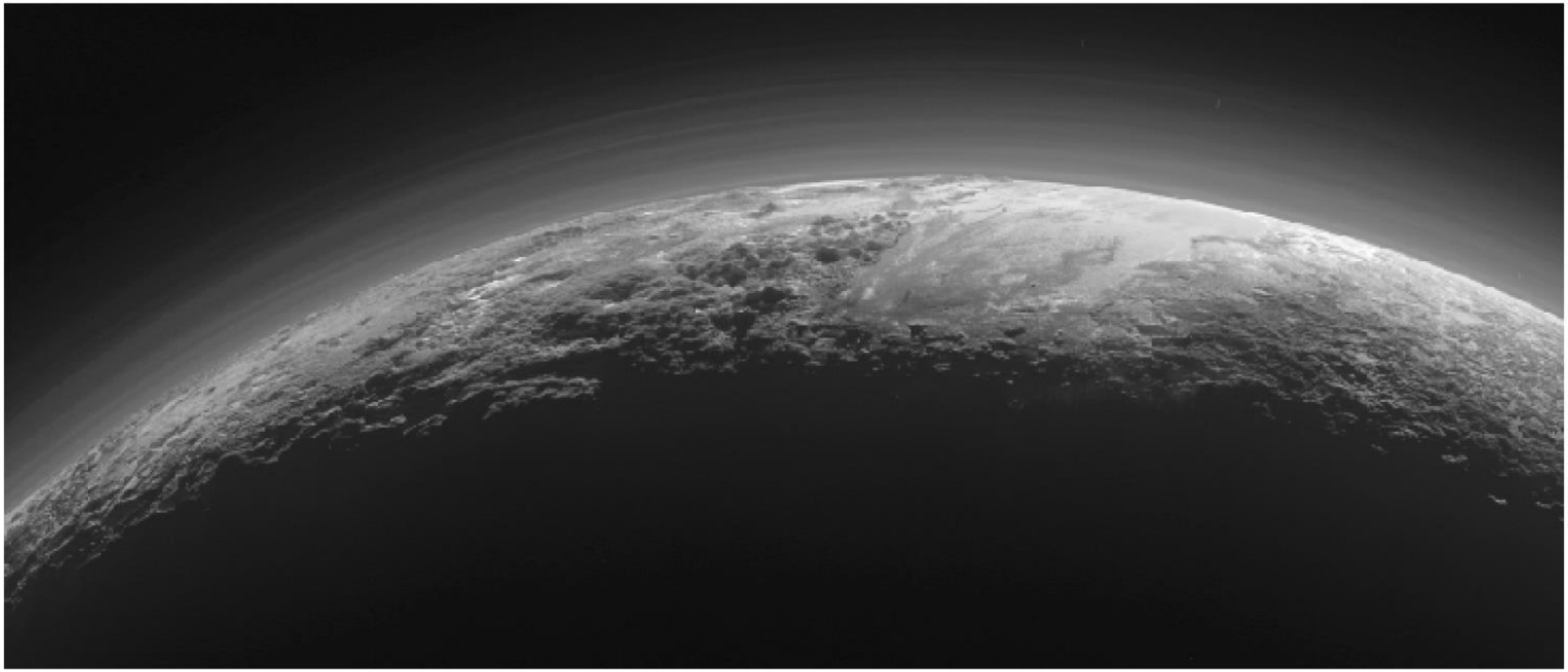

Cratered = old
Nitrogen ice
Flows like glaciers

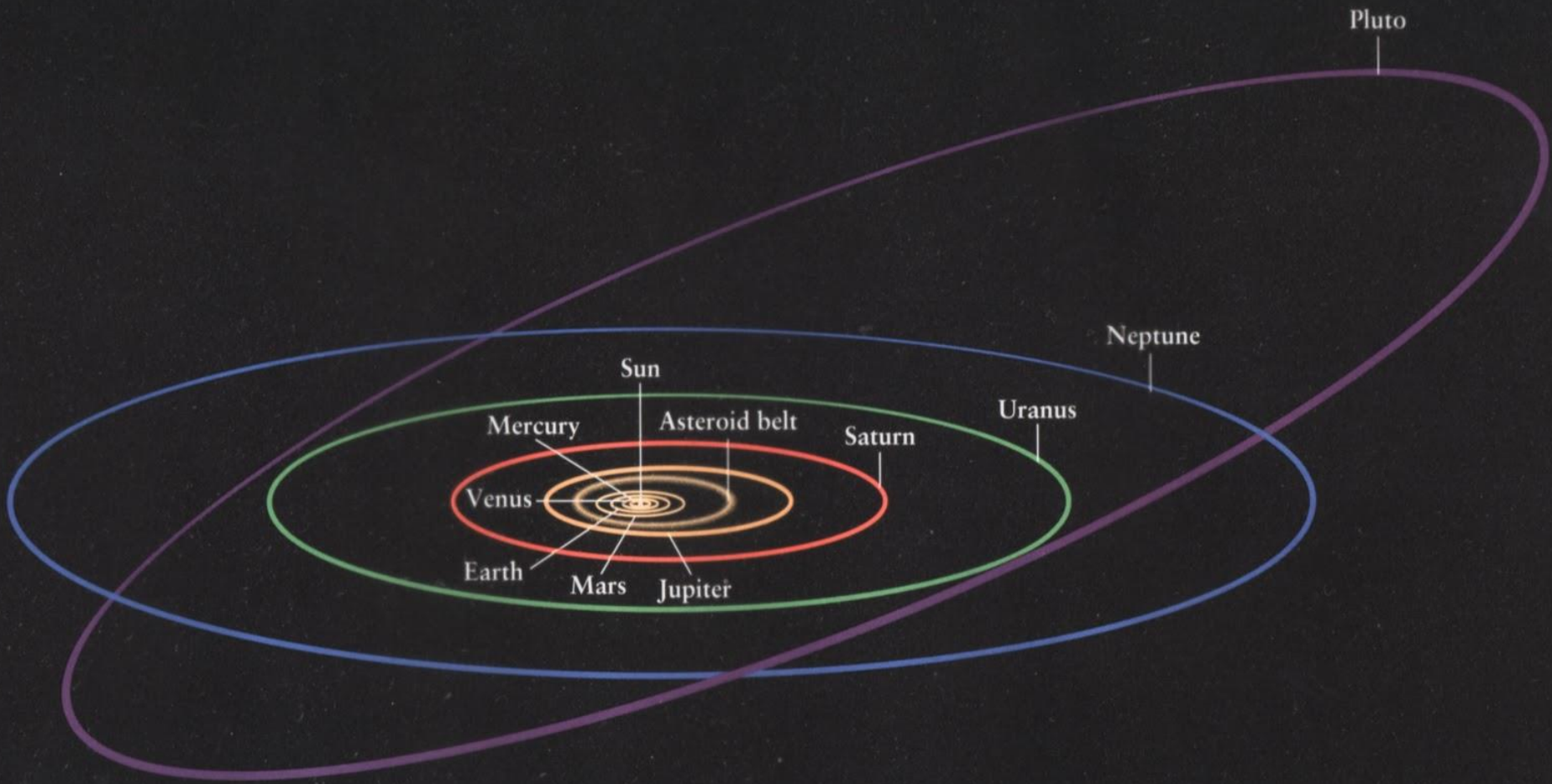




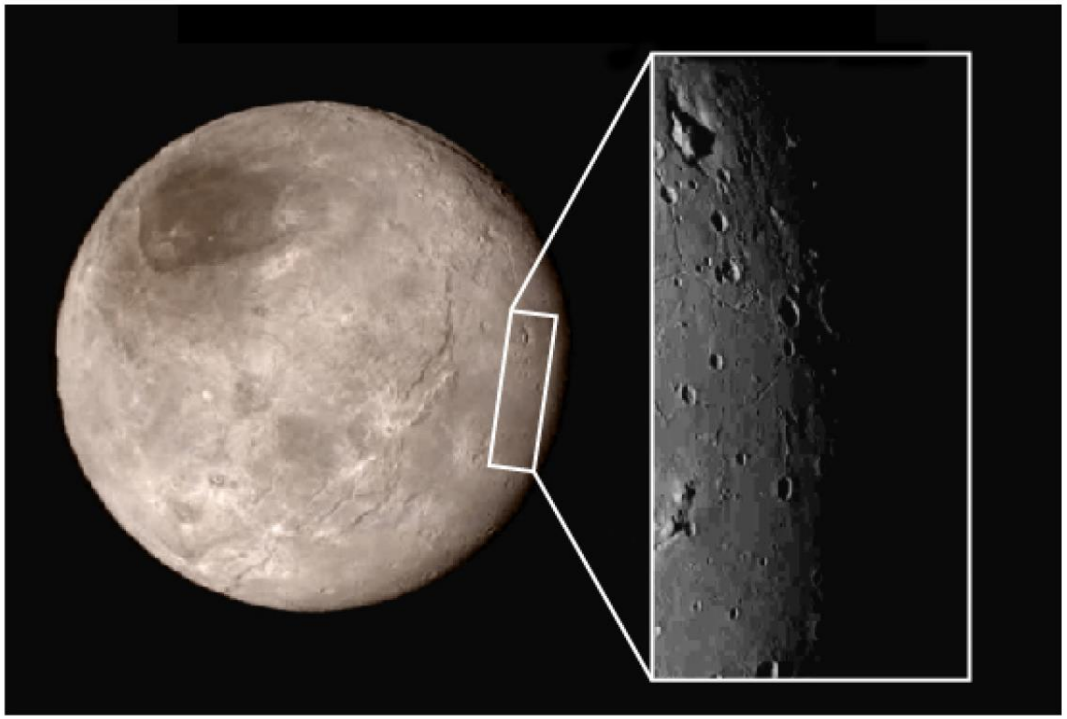
Ice mountains, 3 km high

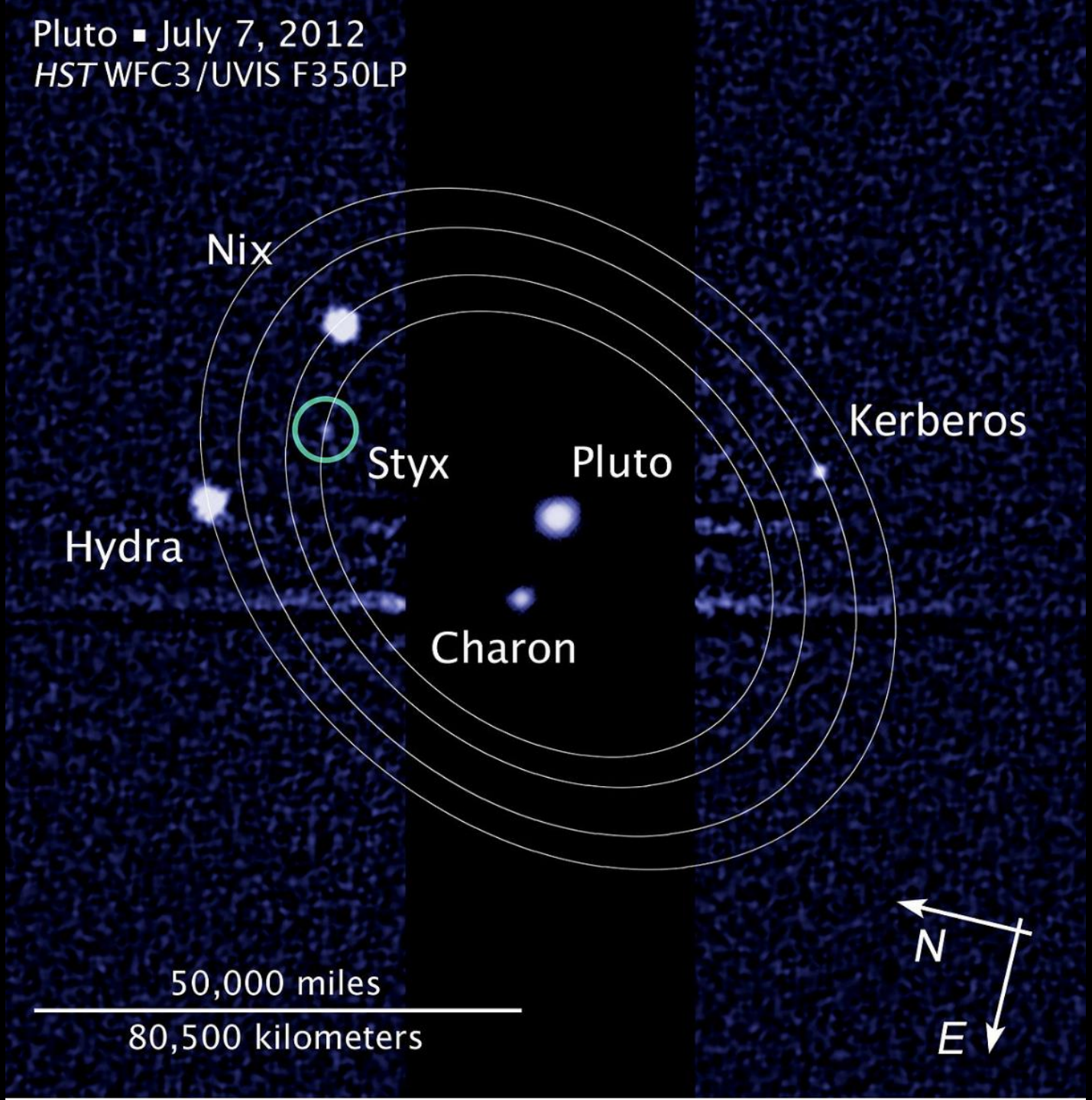
Haze! Pluto has an atmosphere
Likely from solar radiation, will disappear when Pluto is farther from the Sun

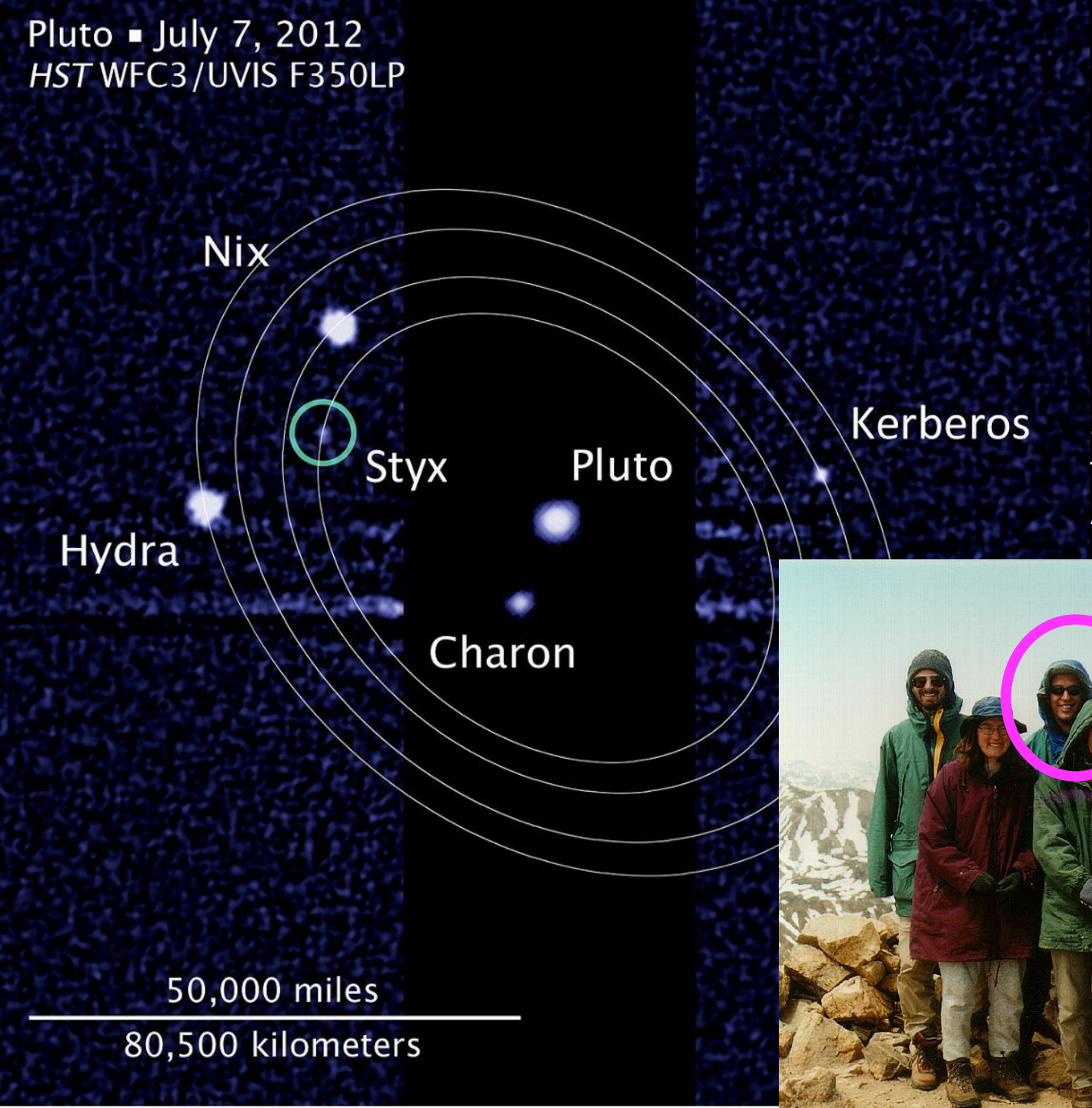



Pluto
Neptune
Sun
Uranus
Mercury
Asteroid belt
Saturn
Venus
Earth
Mars
Jupiter

Pluto's moons: largest moon Charon

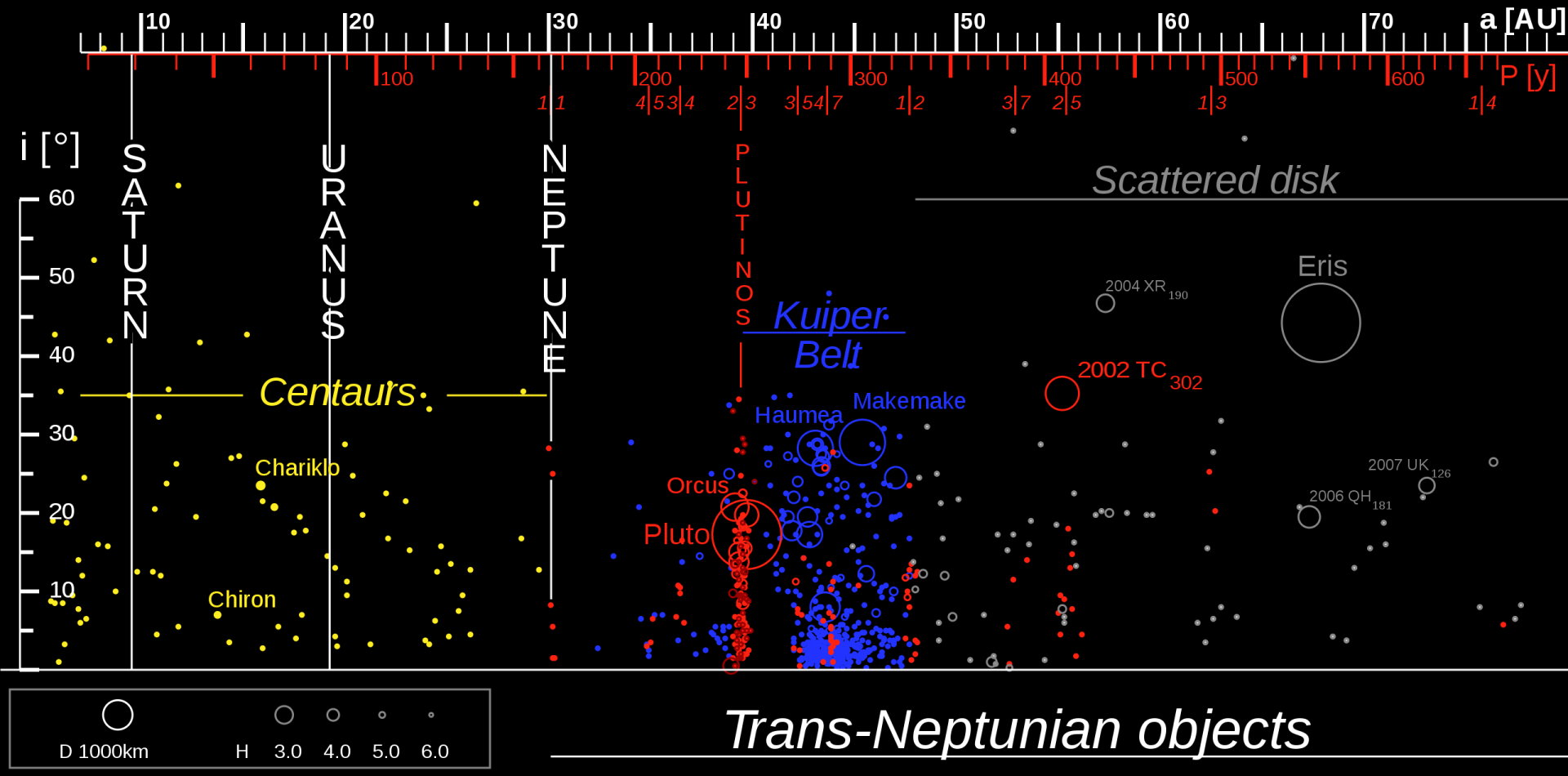



Pluto ▪ July 7, 2012
HST WFC3/UVIS F350LP
Nix
Styx
Pluto
Kerberos
Hydra
Charon
50,000 miles
80,500 kilometers
N
E

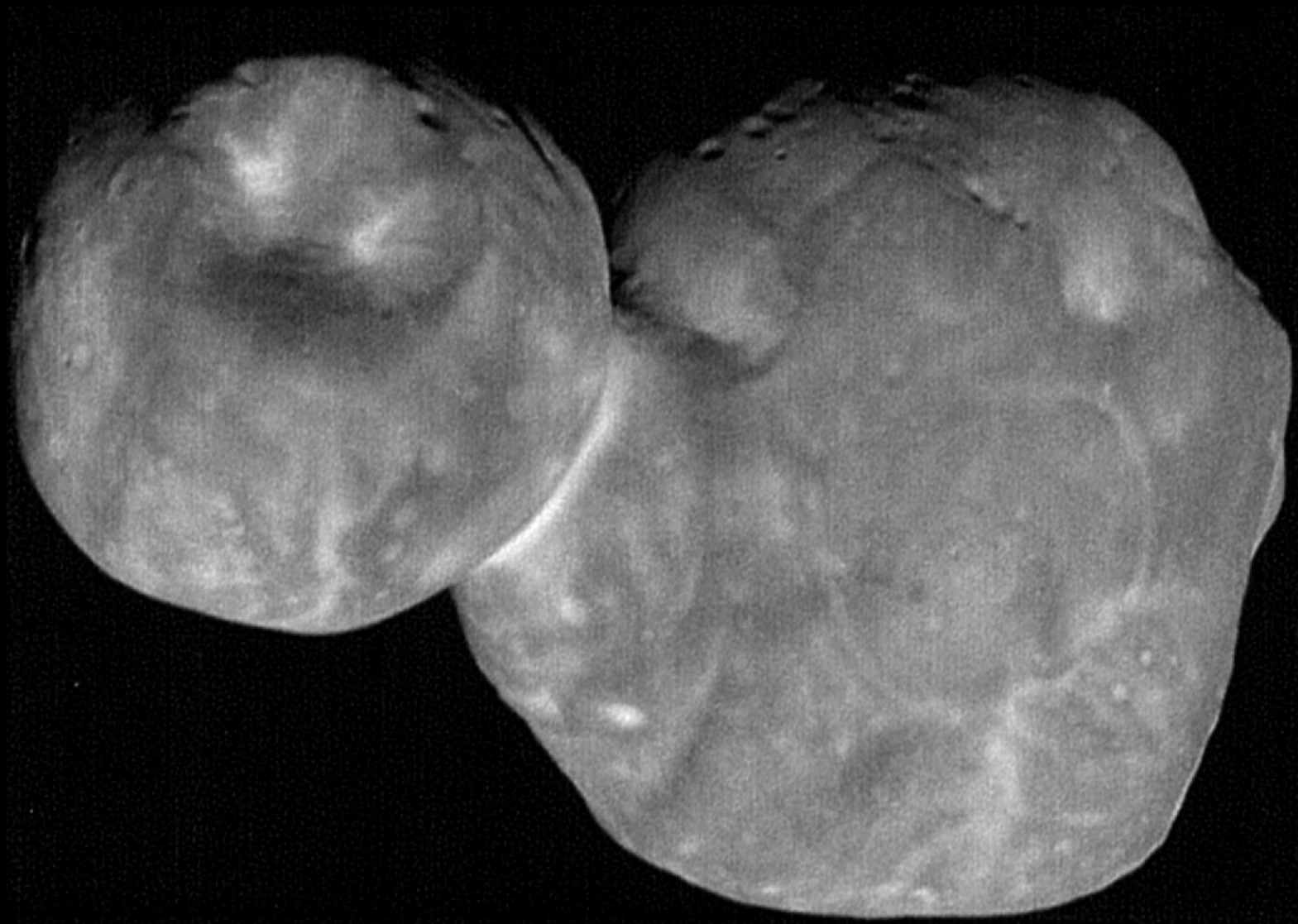


Some moons of Pluto found by team including Andrew Steffl

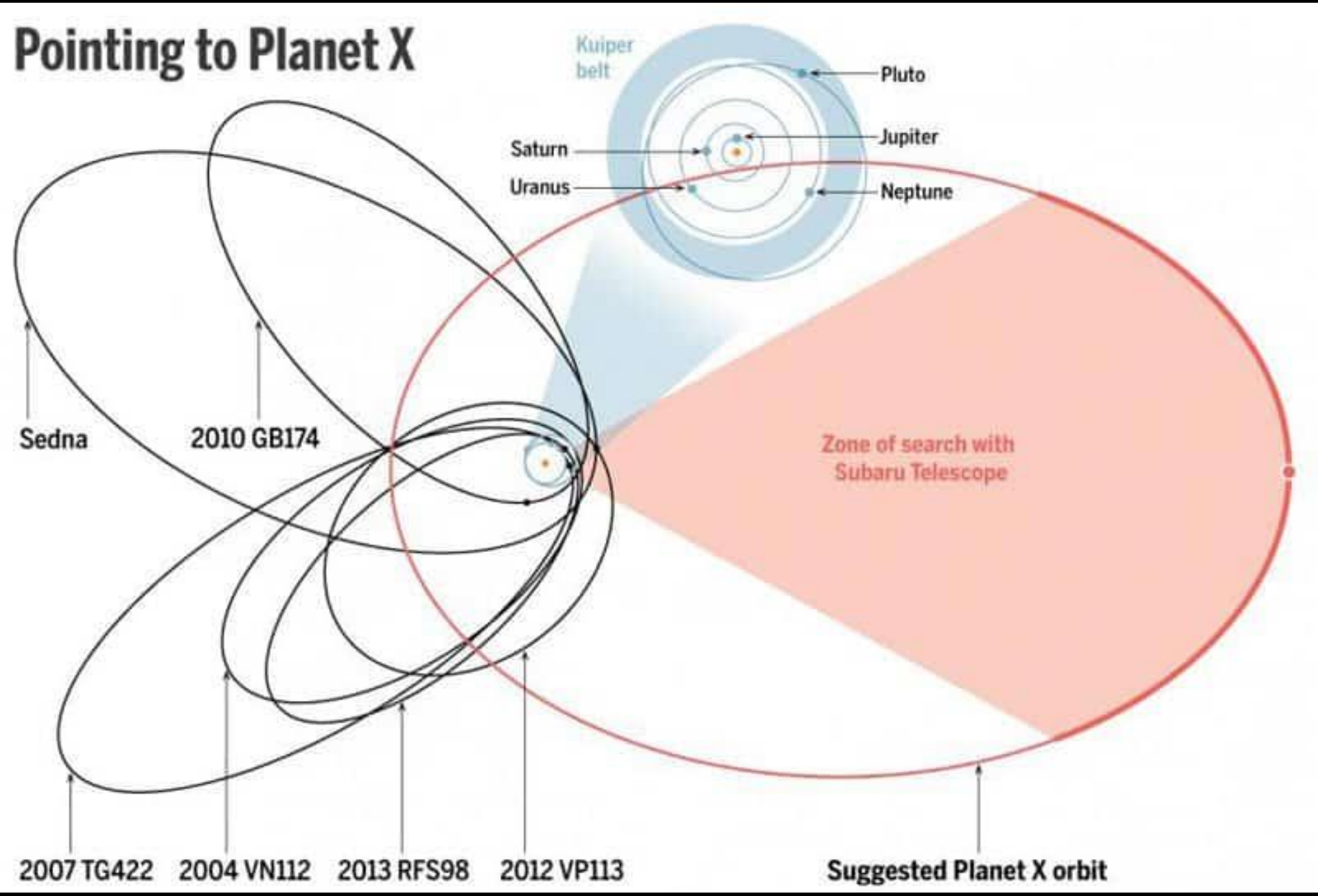
Trans-Neptunian Objects



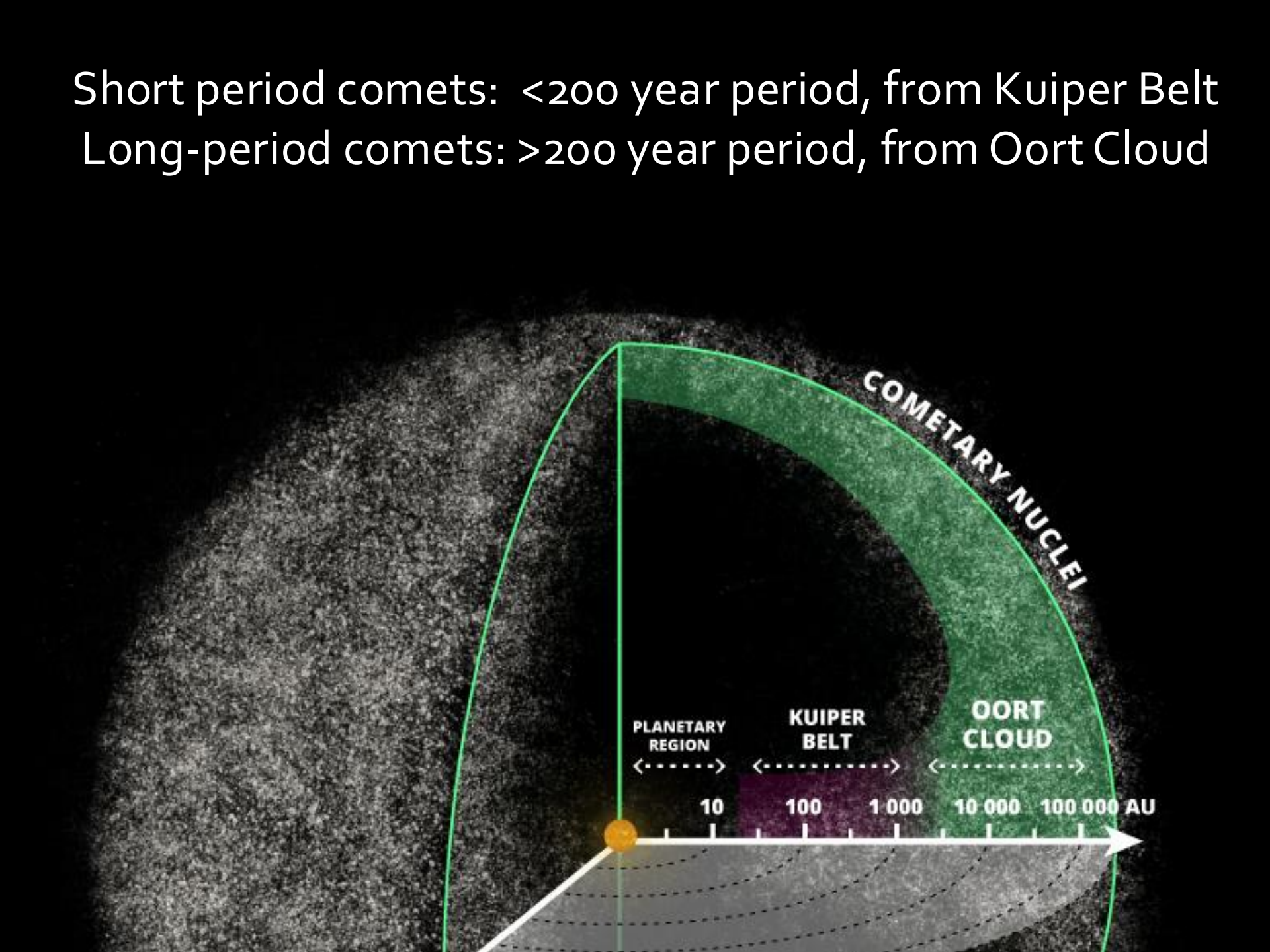
Largest known trans-Neptunian objects (TNOs)



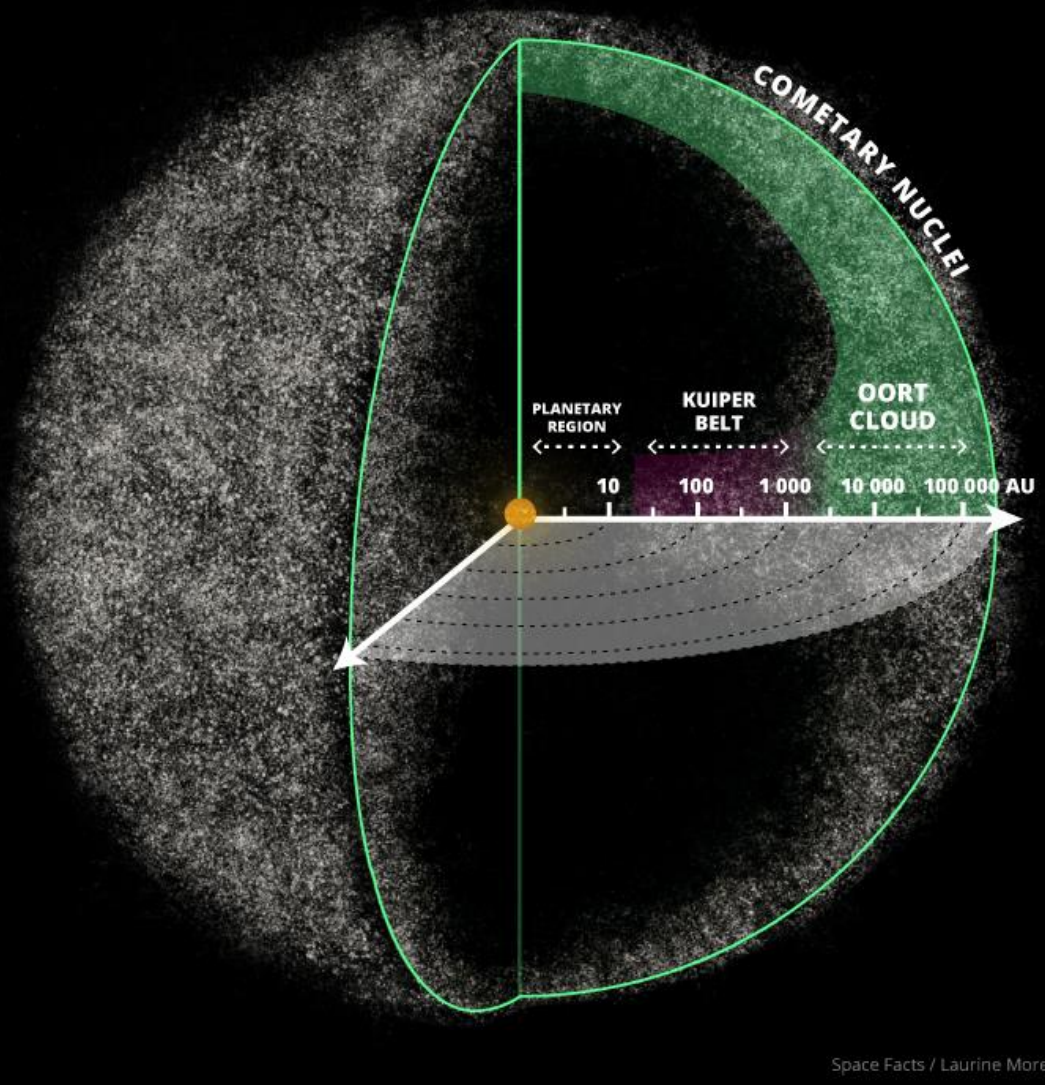
New Horizons flyby of Kuiper Belt Object MU-69
36 km across

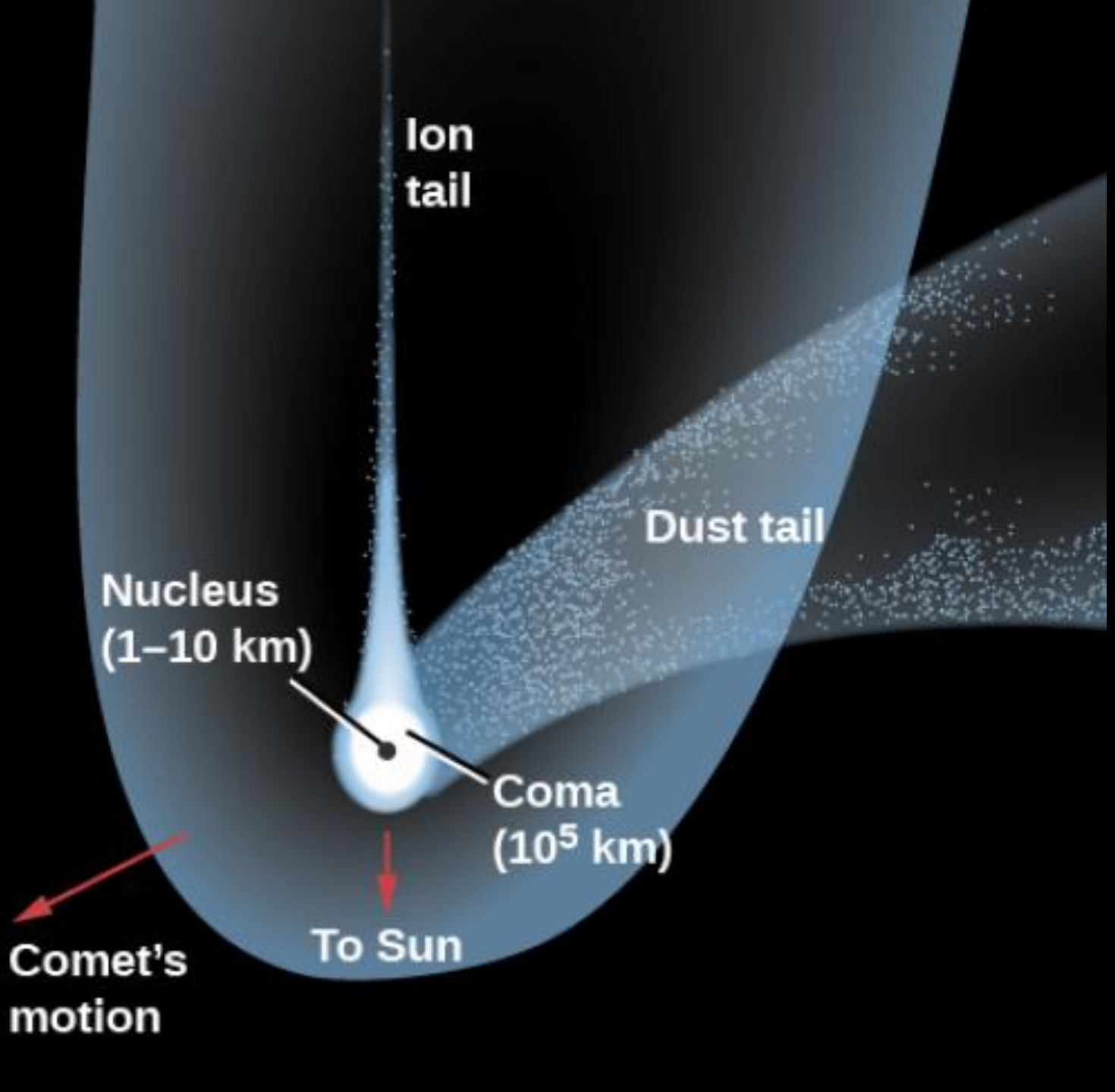

Pointing to Planet X
Kuiper belt
Pluto
Jupiter
Saturn
Uranus
Neptune
Sedna
2010 GB174
Zone of search with Subaru Telescope
2007 TG422
2004 VN112
2013 RFS98
2012 VP113
Suggested Planet X orbit

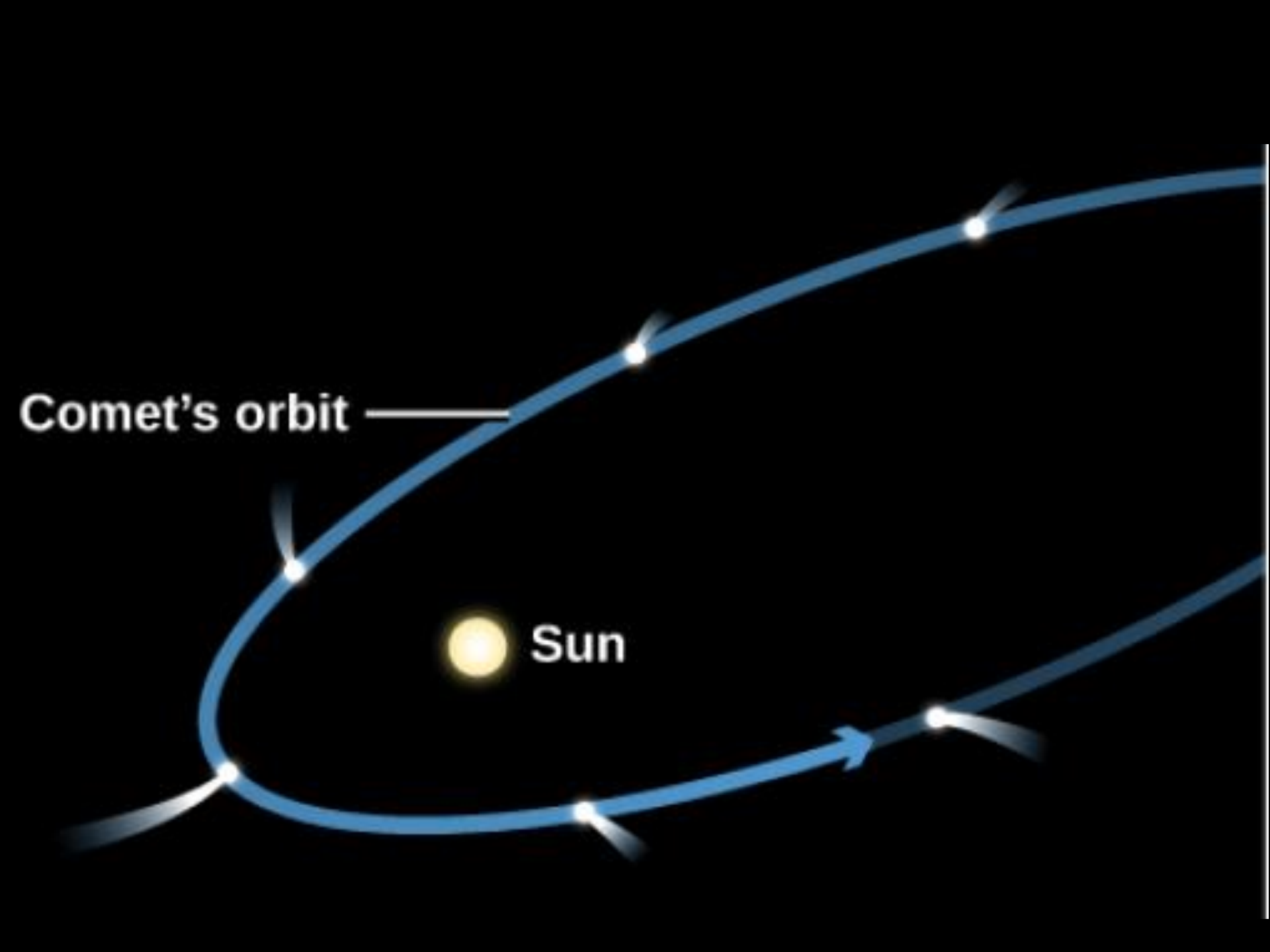
Short period comets: <200 year period, from Kuiper Belt
Long-period comets: >200 year period, from Oort Cloud

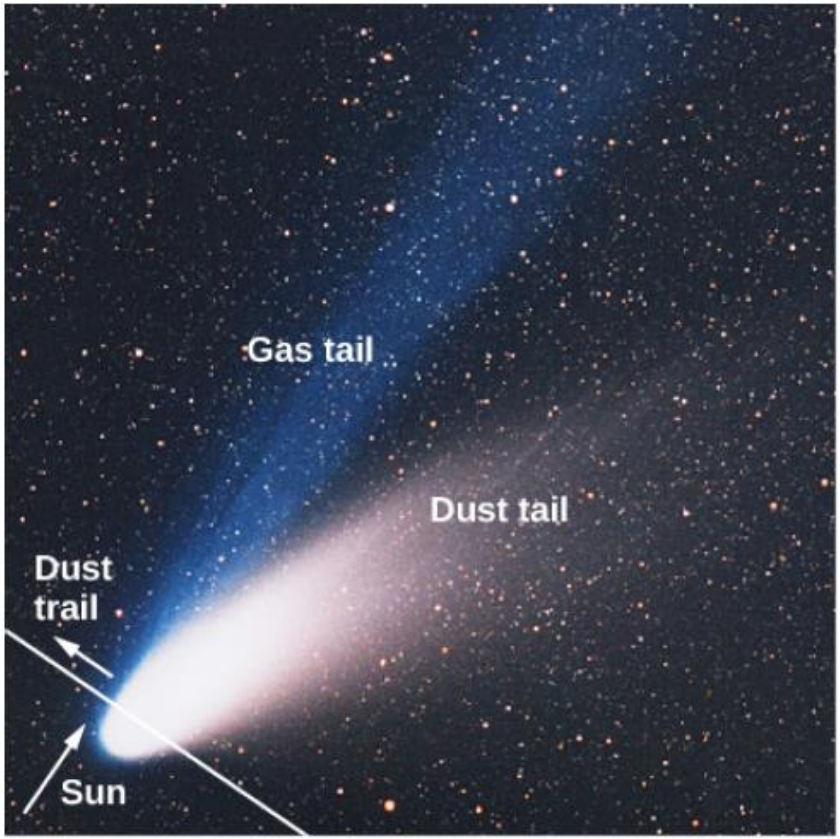


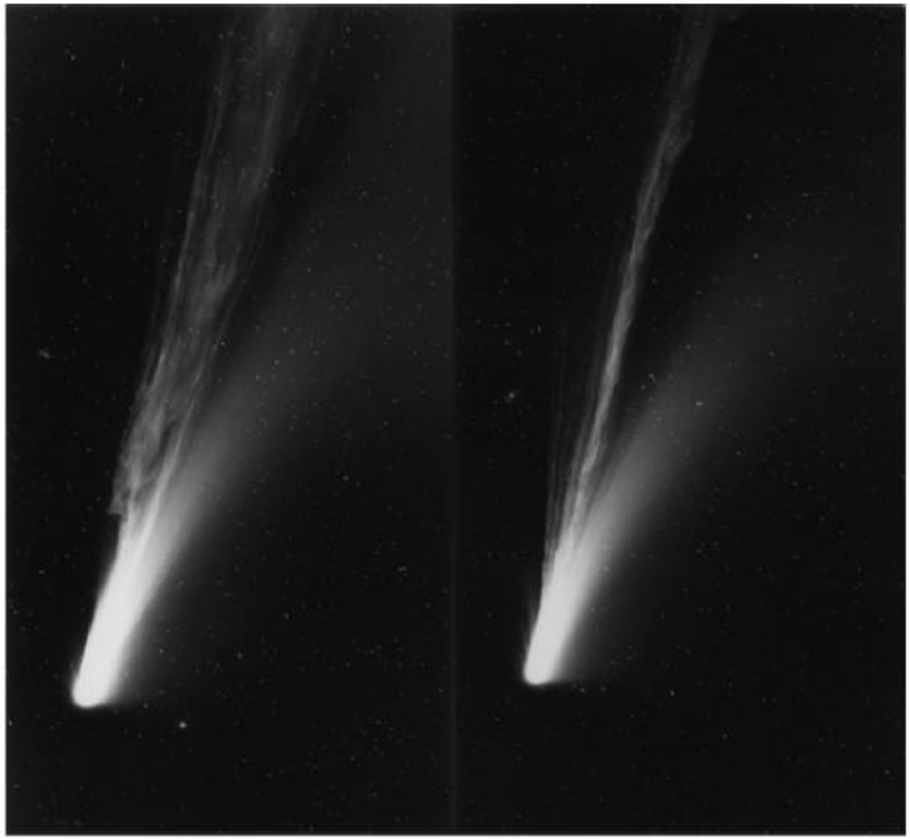
Debris from the solar system: asteroids, comets, Kuiper Belt Objects



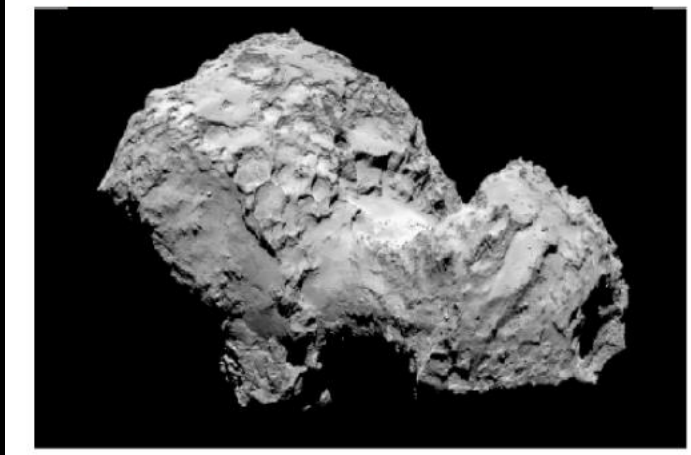

Ion
tail
Dust tail
Nucleus
(1–10 km)
Coma
(10^5 km)
To Sun
Comet's
motion

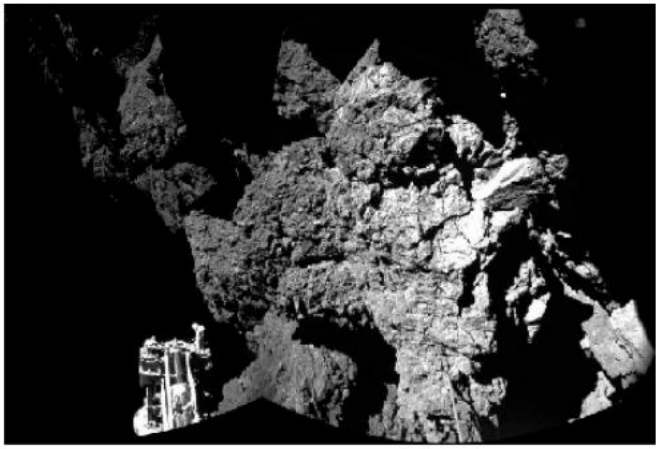

Comet's orbit
Sun

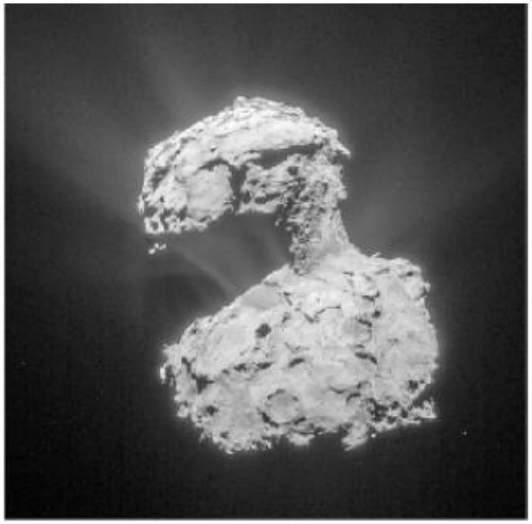

Gas tail
Dust tail
Dust
trail
Sun



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



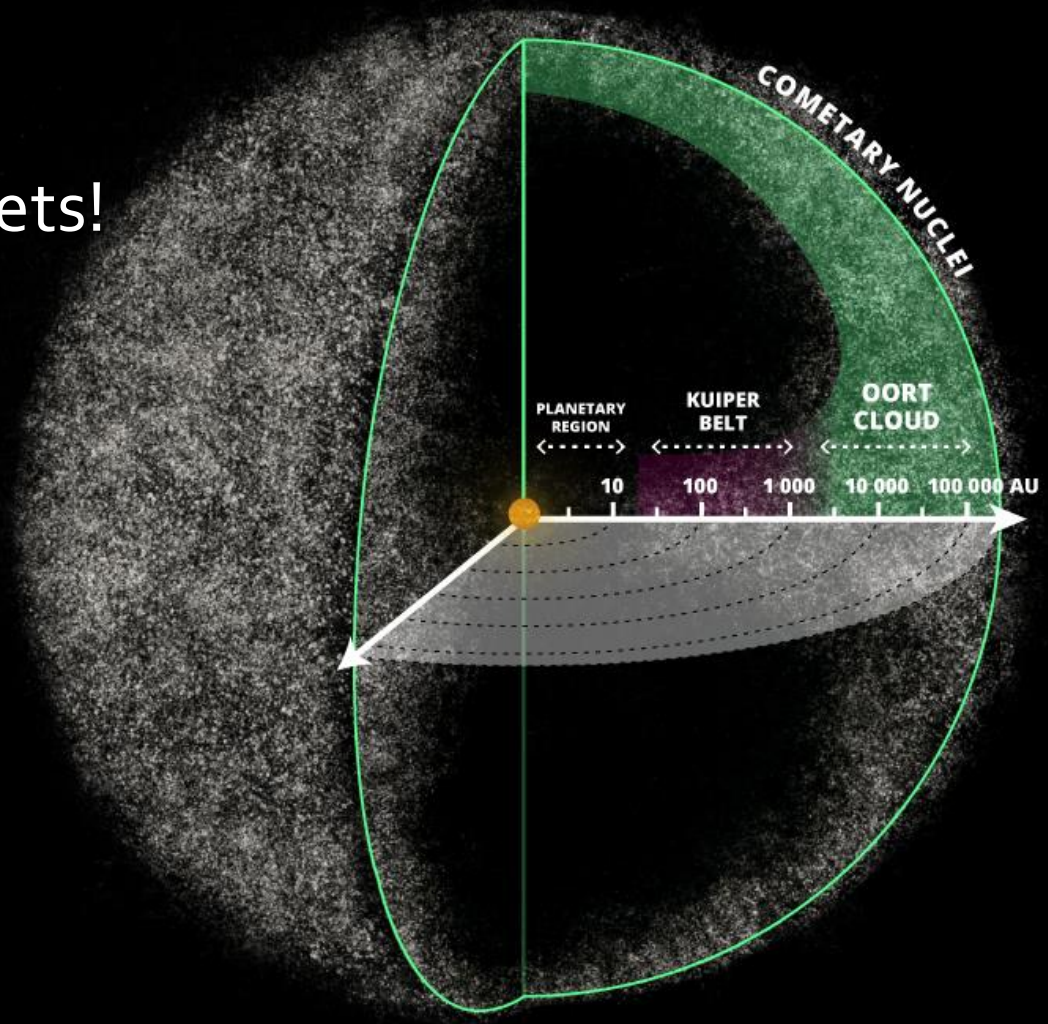




How did they get there?

Planetessimals that never formed into planets

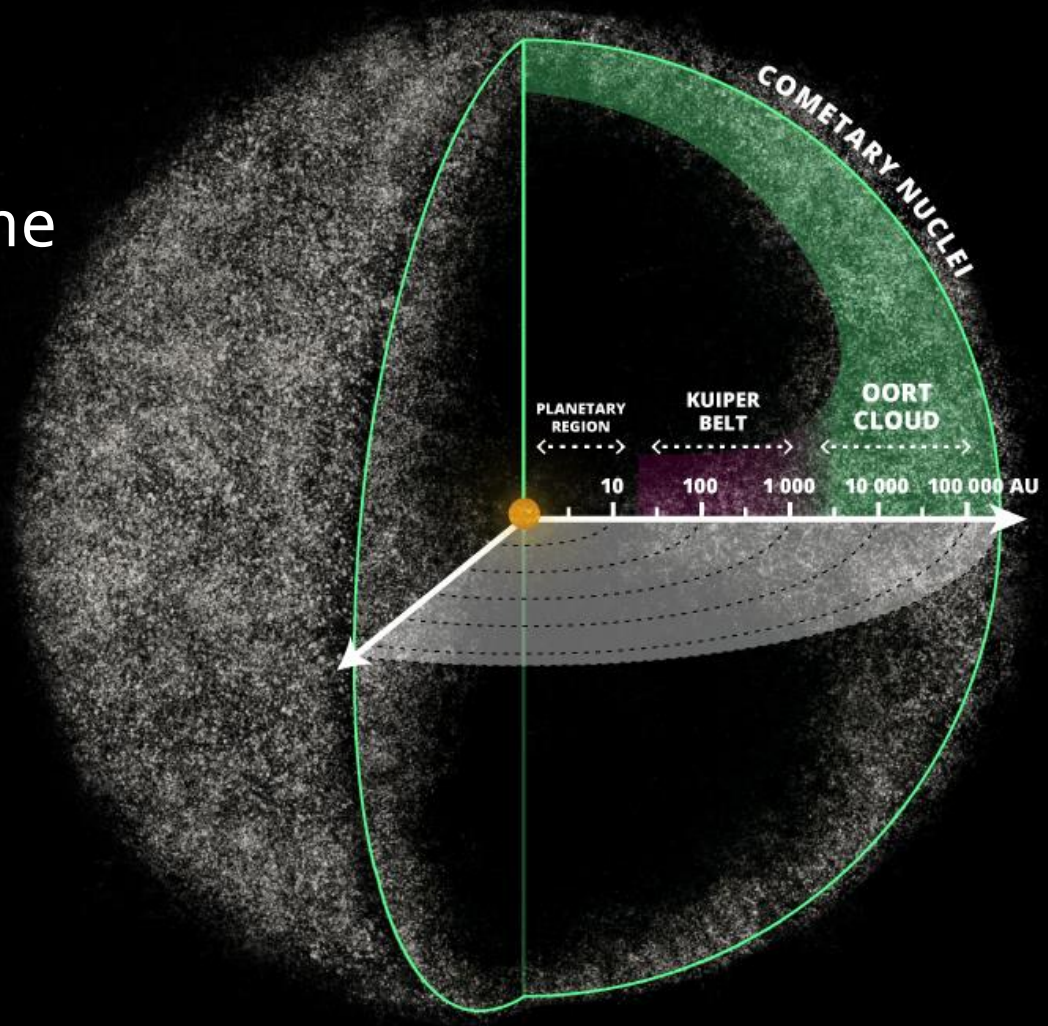
Scattered by giant planets!



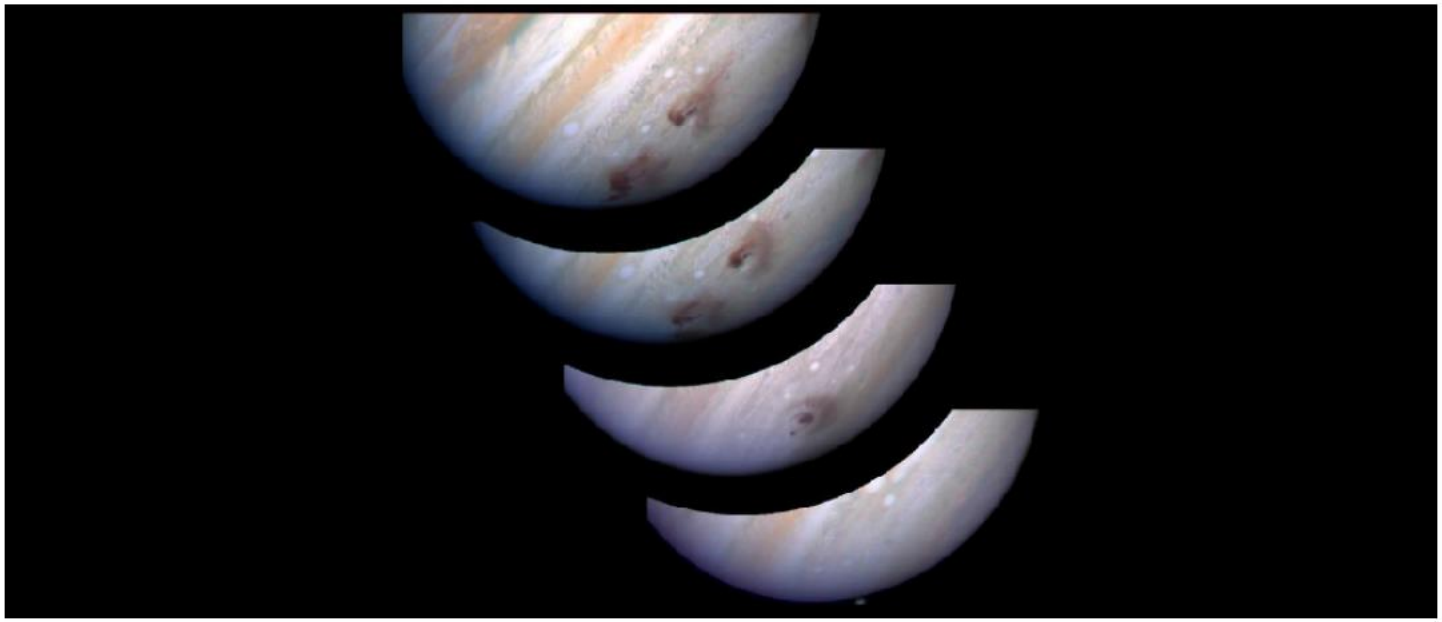
How did they get here?

Dynamical interactions in Oort cloud:

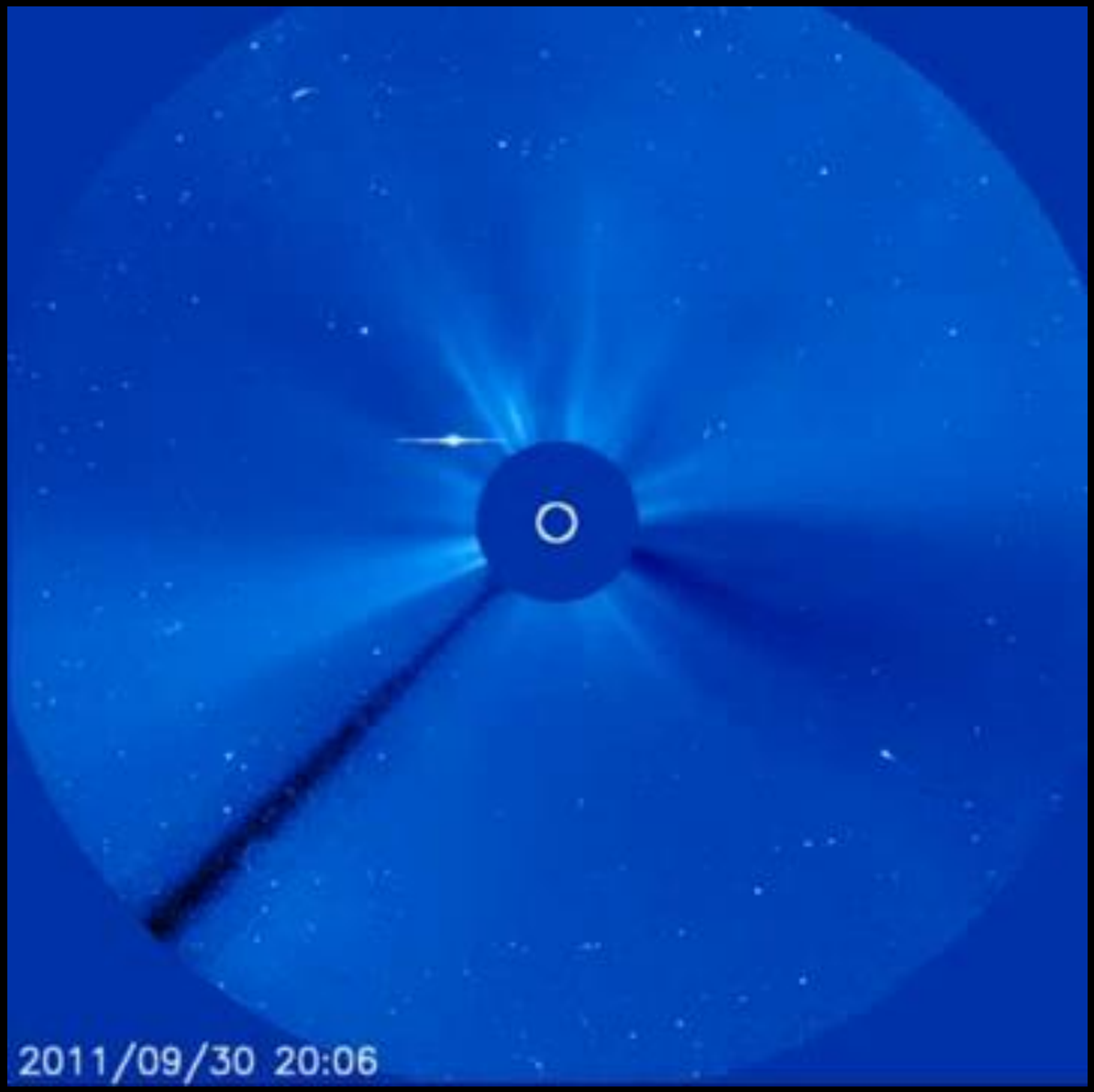
Unstable, sometimes one heads to inner solar system



Shoemaker-Levy 9:
comet that crashed into Jupiter



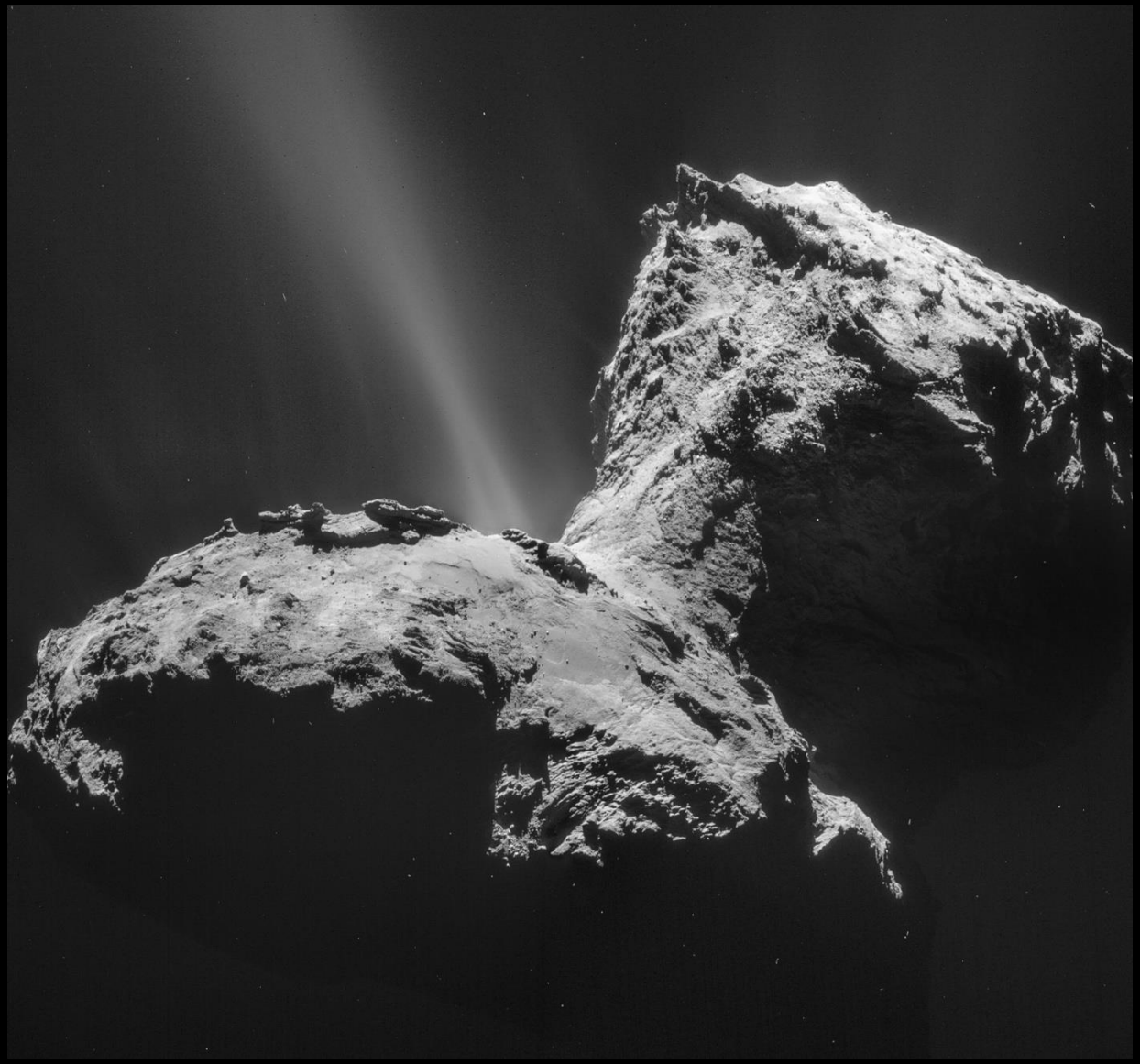
Into the sun!

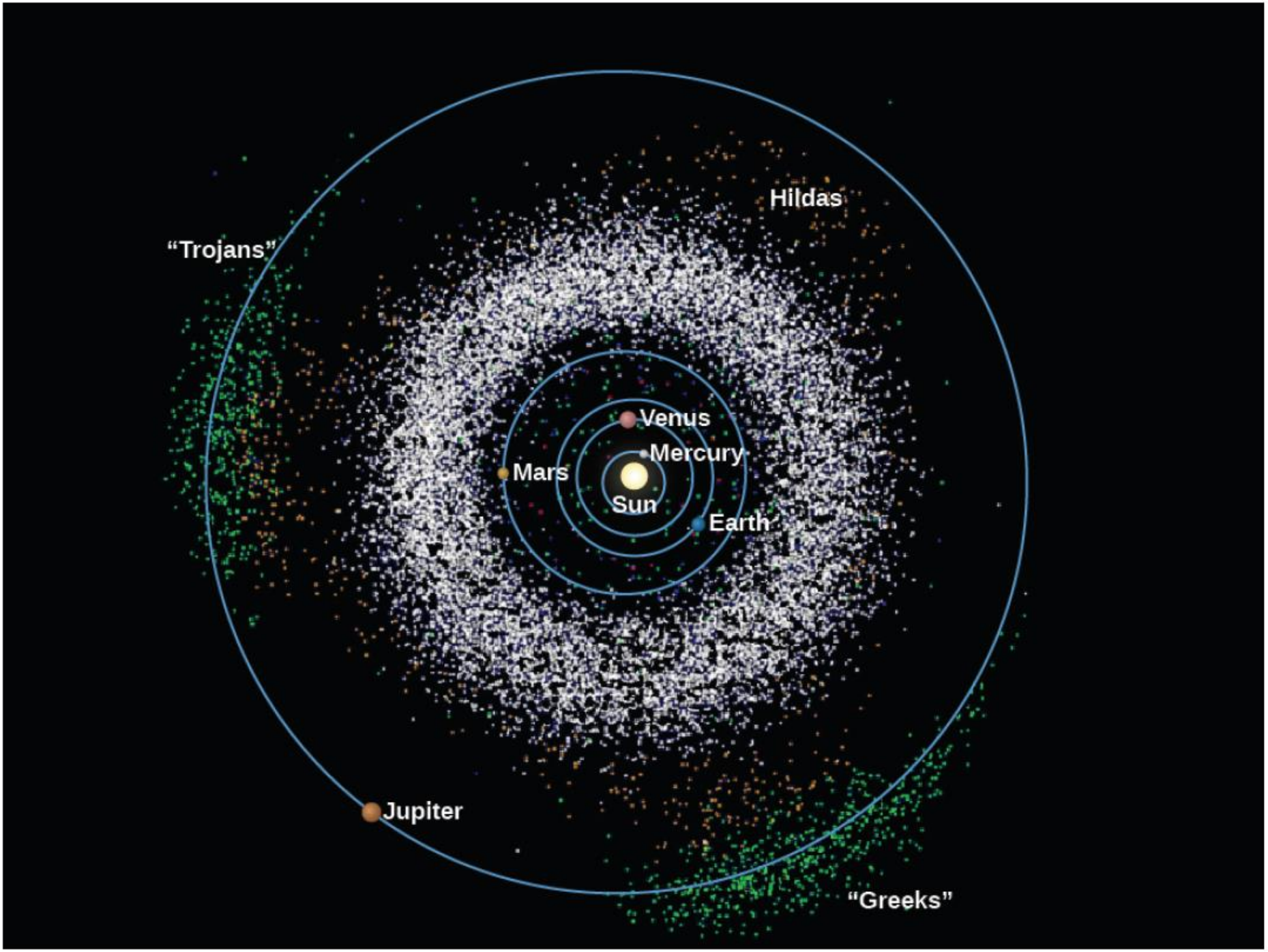


Leaving a trail of dust

Major Annual Meteor Showers

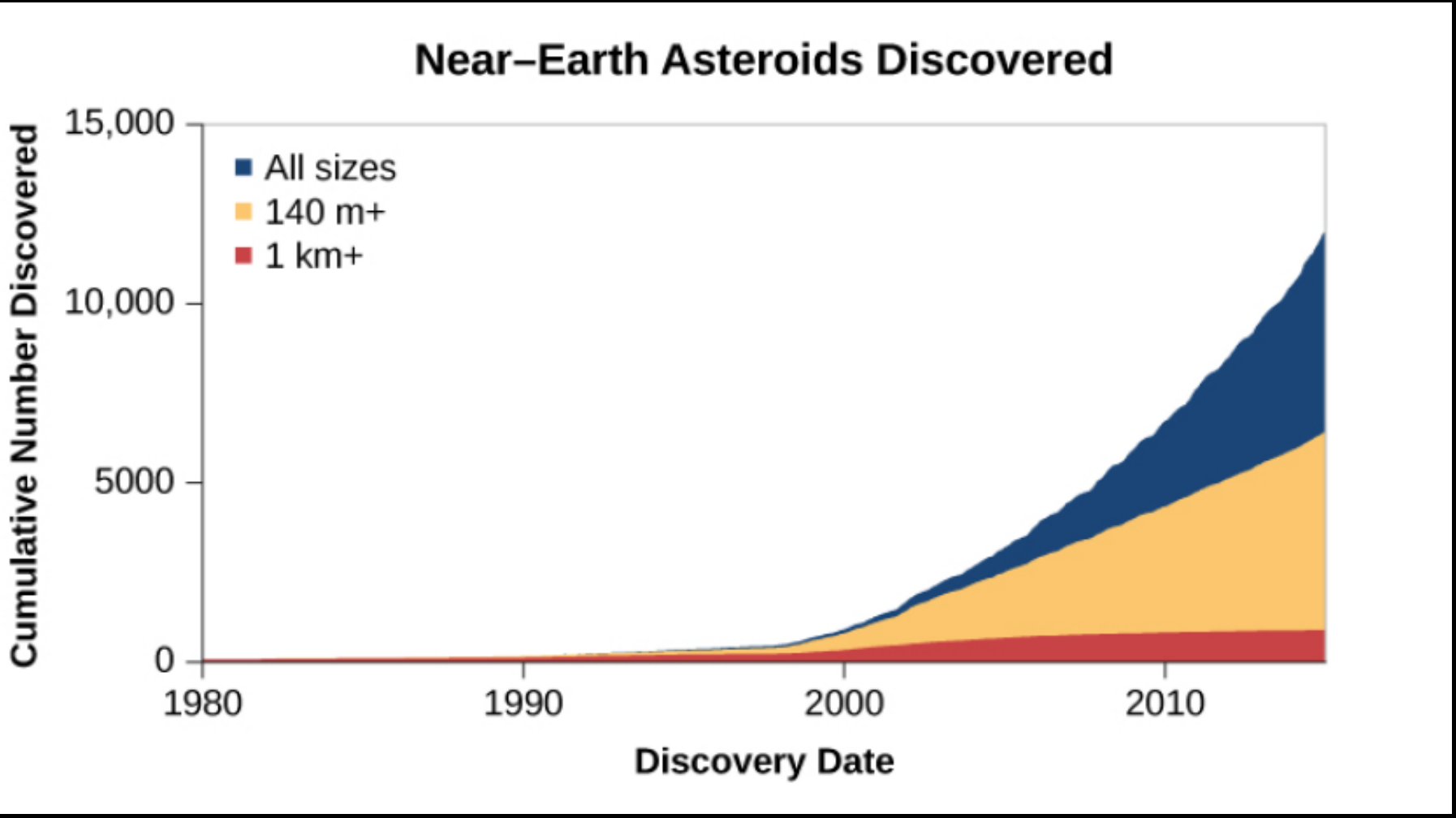
Shower Name	Date of Maximum	Associated Parent Object	Comet's Period (years)
Quadrantid	January 3–4	2003EH (asteroid)	—
Lyrid	April 22	Comet Thatcher	415
Eta Aquarid	May 4–5	Comet Halley	76
Delta Aquarid	July 29–30	Comet Machholz	—
Perseid	August 11–12	Comet Swift-Tuttle	133
Orionid	October 20–21	Comet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

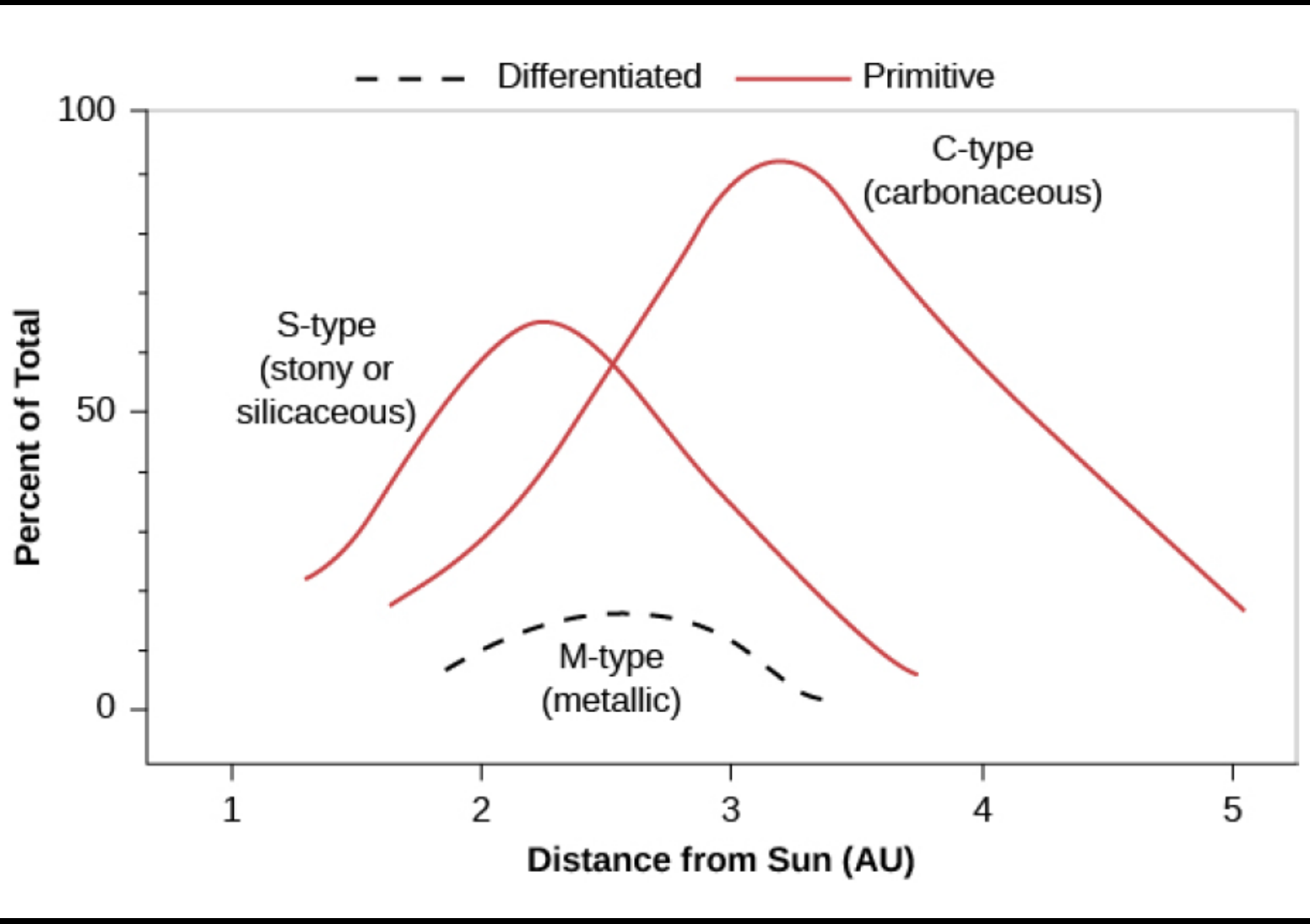


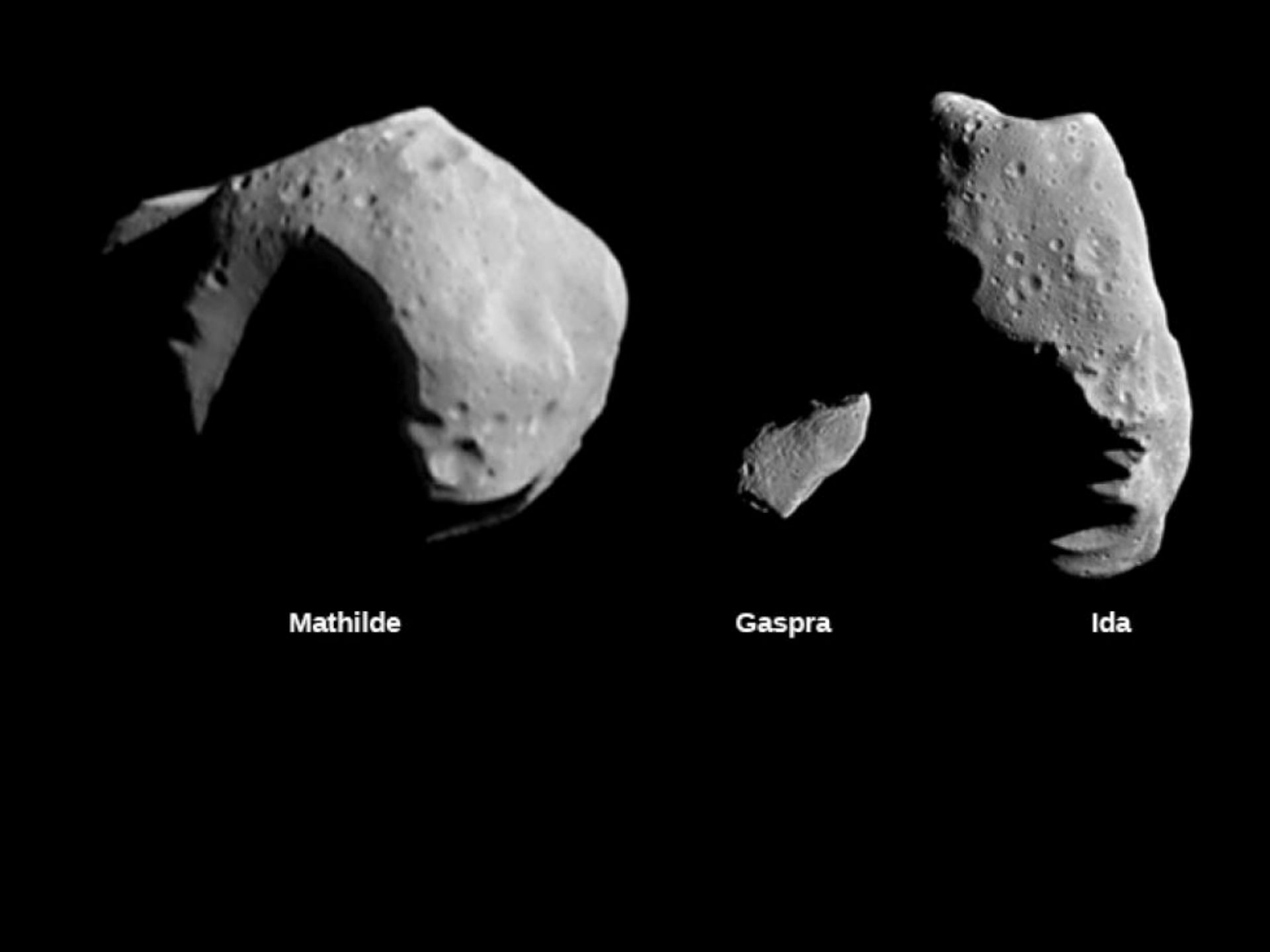

Hildas
"Trojans"
Venus
Mercury
Mars
Sun
Earth
Jupiter
"Greeks"

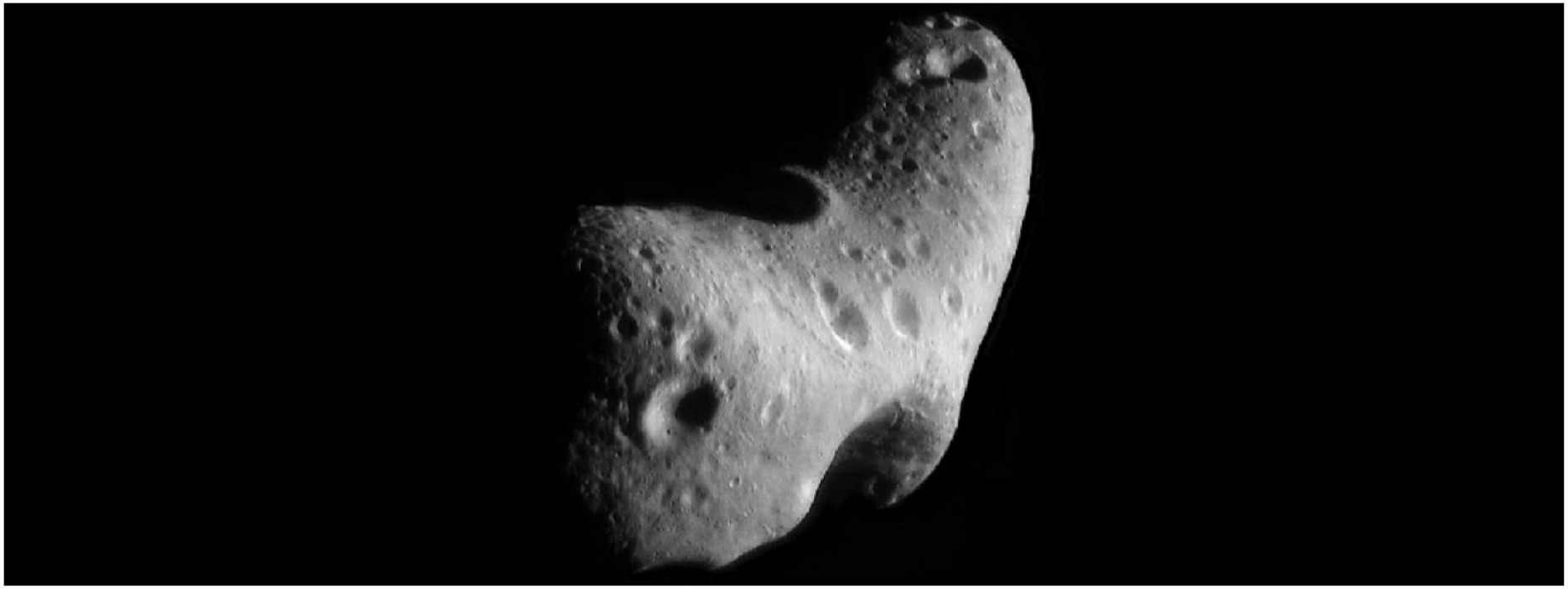
The Largest Asteroids

#	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)

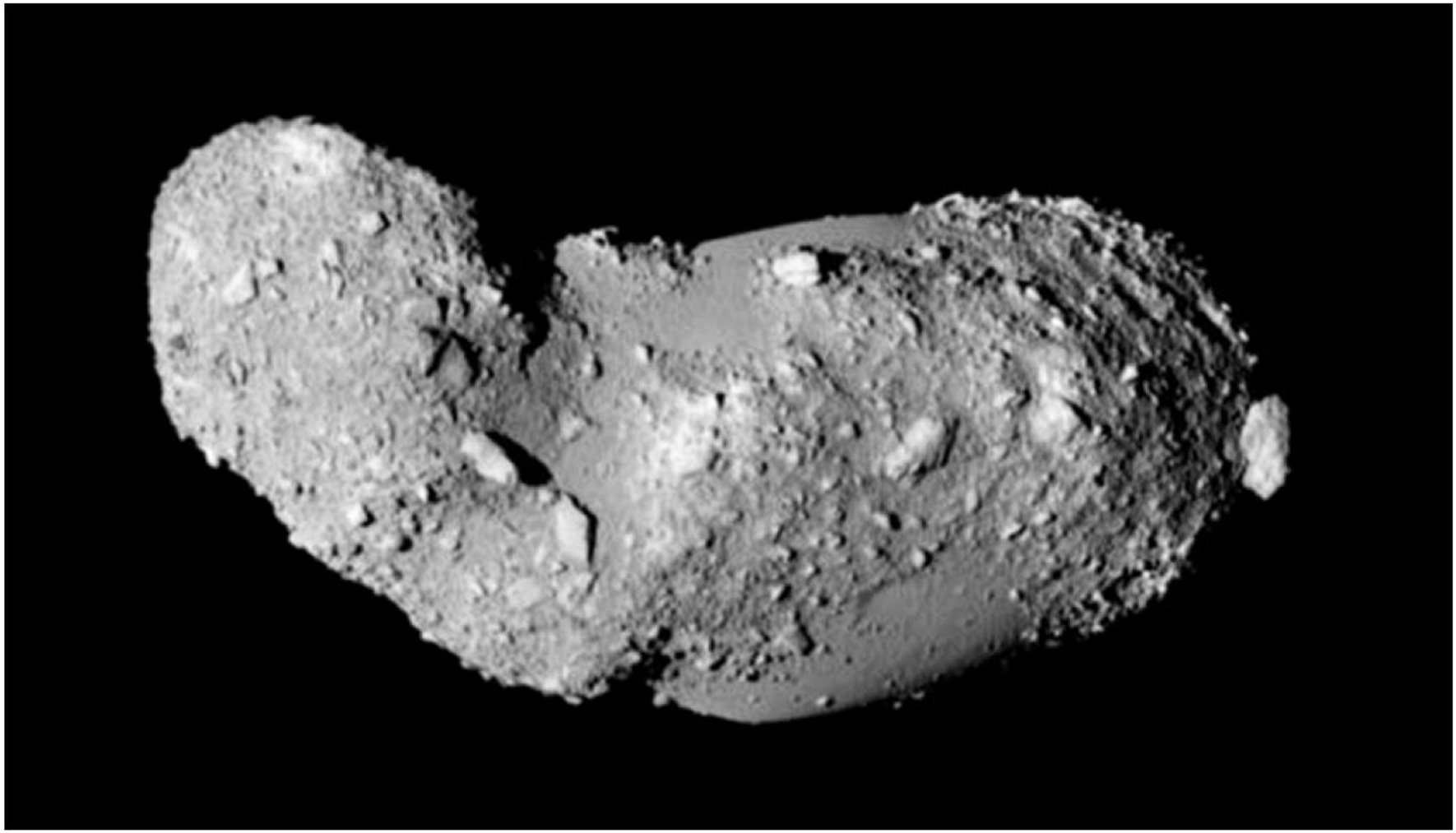

Near–Earth Asteroids Discovered
Cumulative Number Discovered
15,000
10,000
5000
0
All sizes
140 m+
1 km+
1980
1990
2000
2010
Discovery Date


Differentiated
Primitive
100
50
0
Percent of Total
C-type
(carbonaceous)
S-type
(stony or
silicaceous)
M-type
(metallic)
1
2
3
4
5
Distance from Sun (AU)


Mathilde
Gaspra
Ida

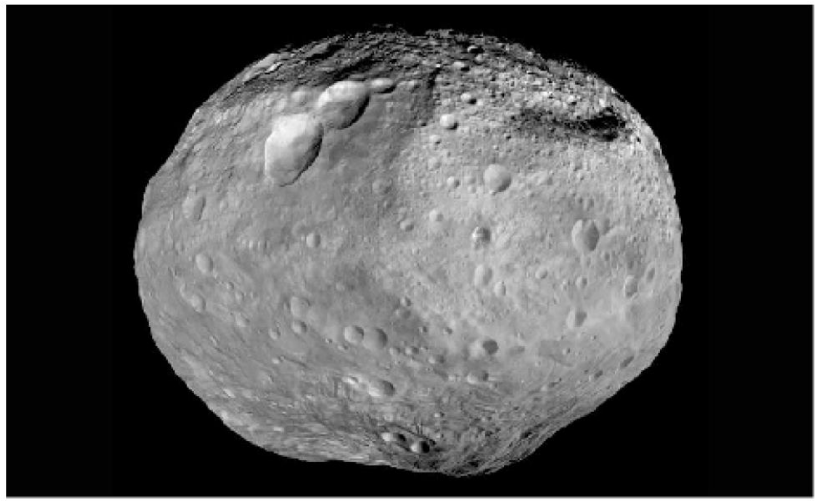


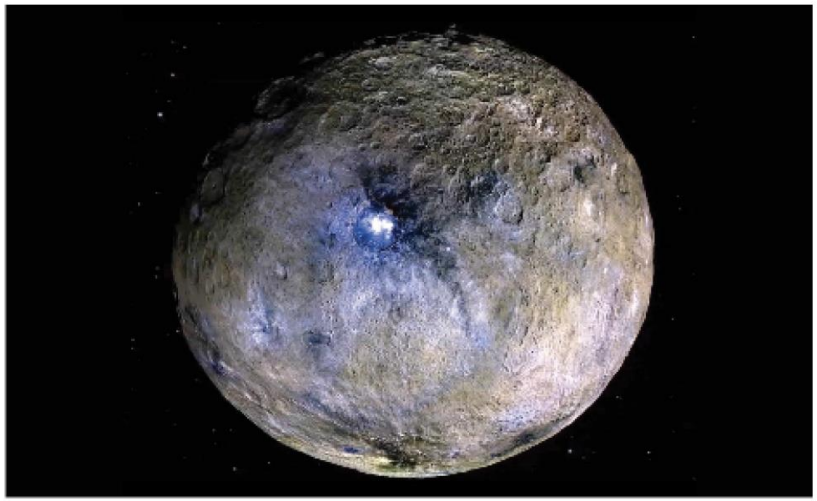
Asteroid Itokawa



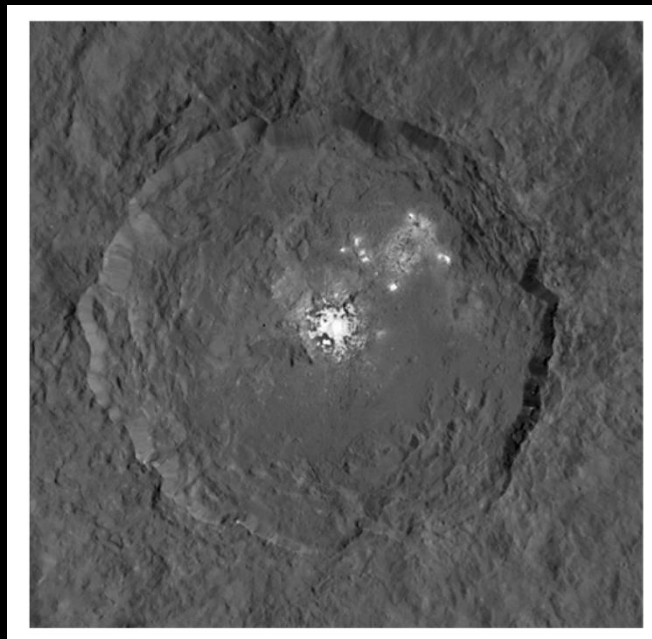
Hayabusa mission:
Landed on the asteroid and sample return!

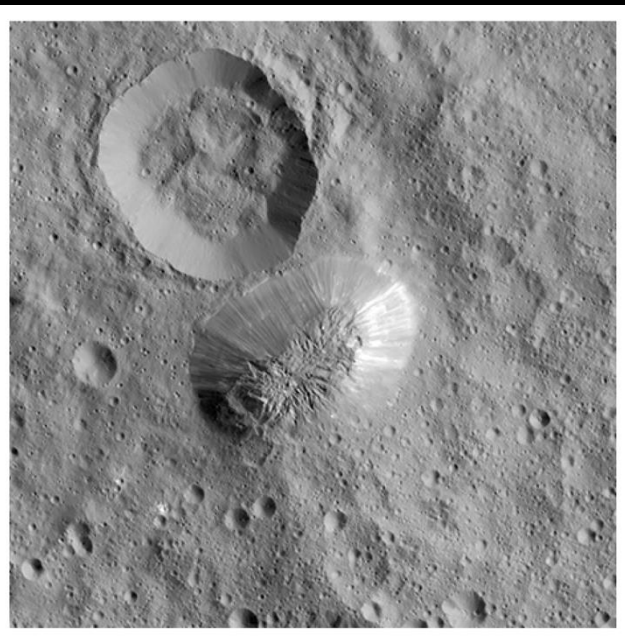
Asteroids Vesta (left) and Ceres (right)



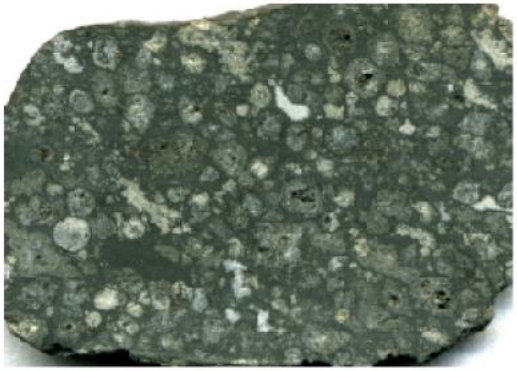


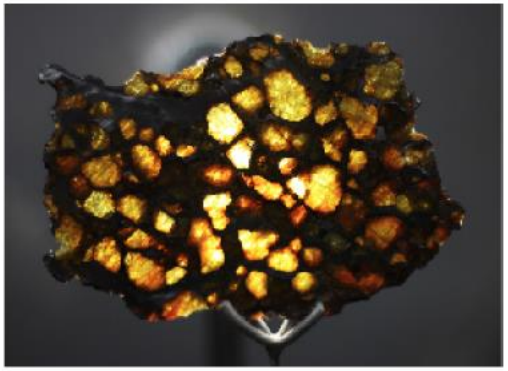
Ceres





Meteors: asteroids that hit the Earth

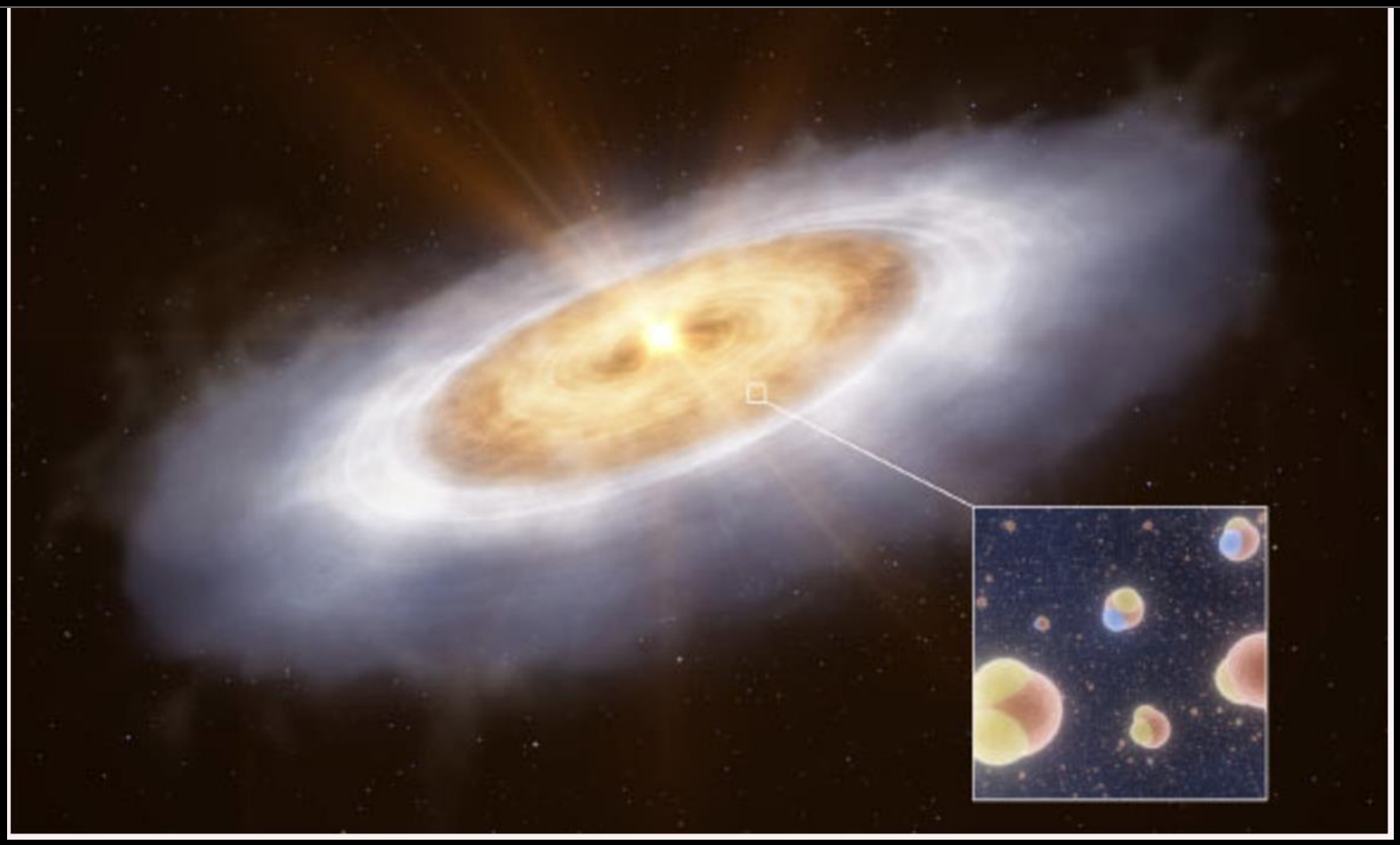




Frequency of Occurrence of Meteorite Classes

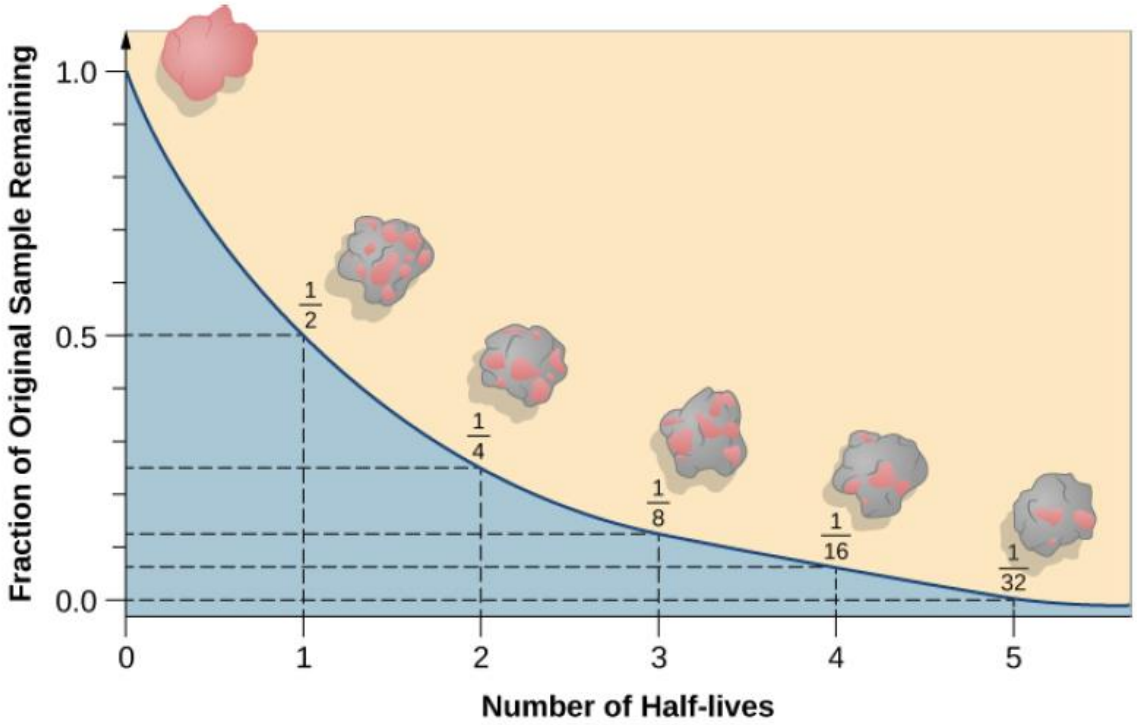
Class	Falls (%)	Finds (%)	Antarctic (%)
Primitive stones	88	51	85
Differentiated stones	8	2	12
Irons	3	42	2
Stony-irons	1	5	1

Origins of our solar system

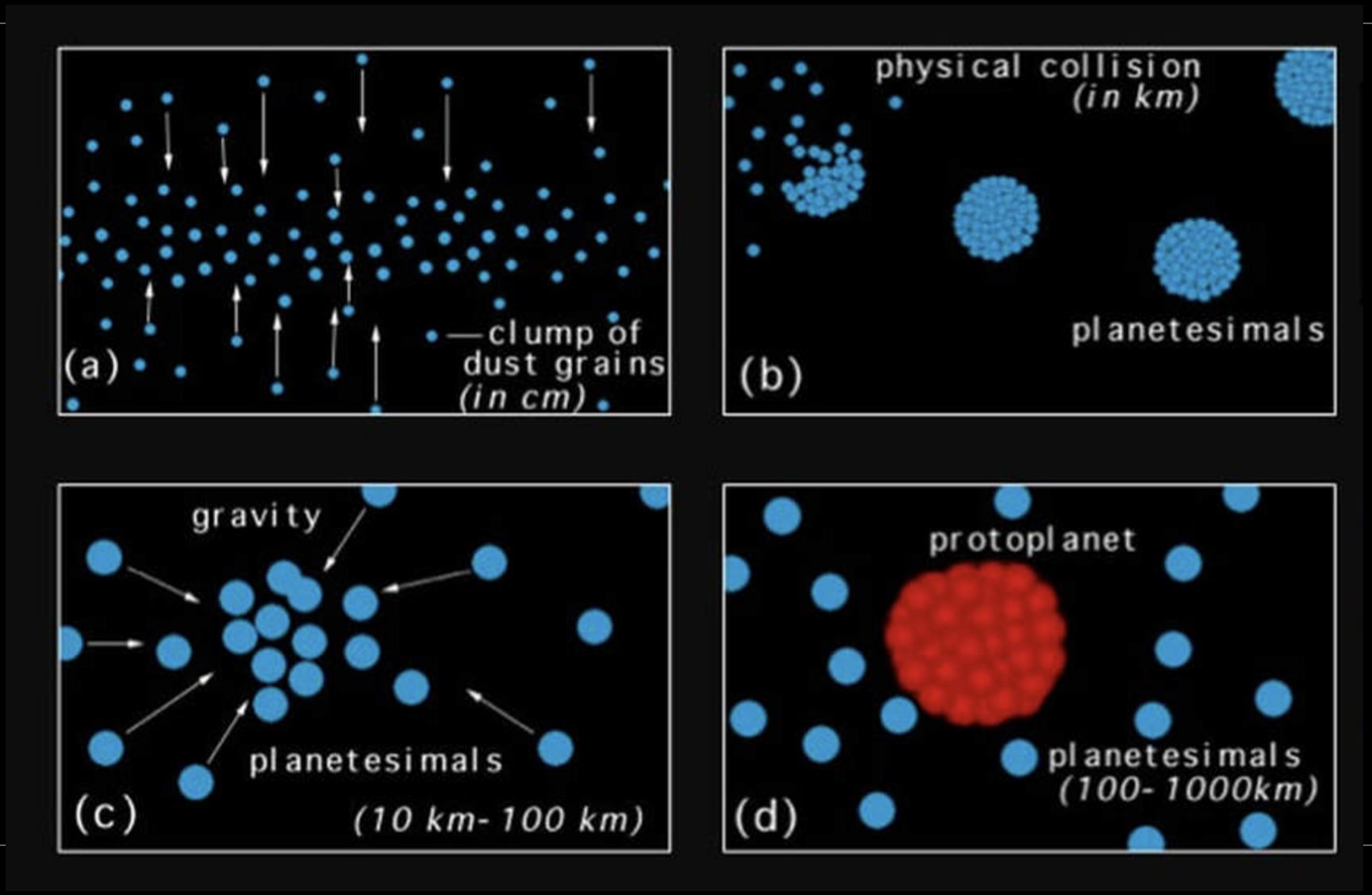


Radioactive Decay Reaction Used to Date Rocks[4]

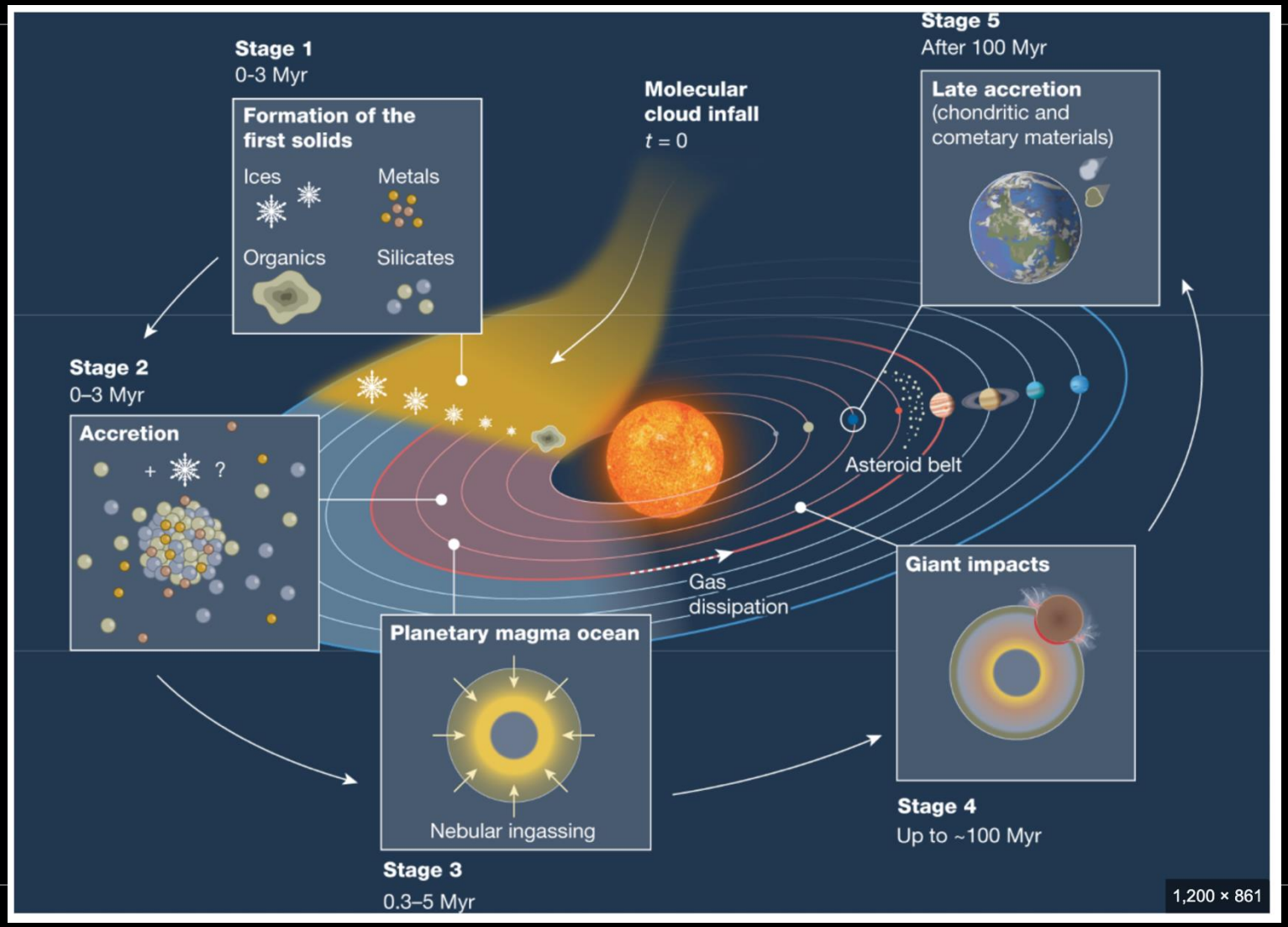
Parent	Daughter	Half-Life (billions of years)
Samarium-147	Neodymium-143	106
Rubidium-87	Strontium-87	48.8
Thorium-232	Lead-208	14.0
Uranium-238	Lead-206	4.47
Potassium-40	Argon-40	1.31



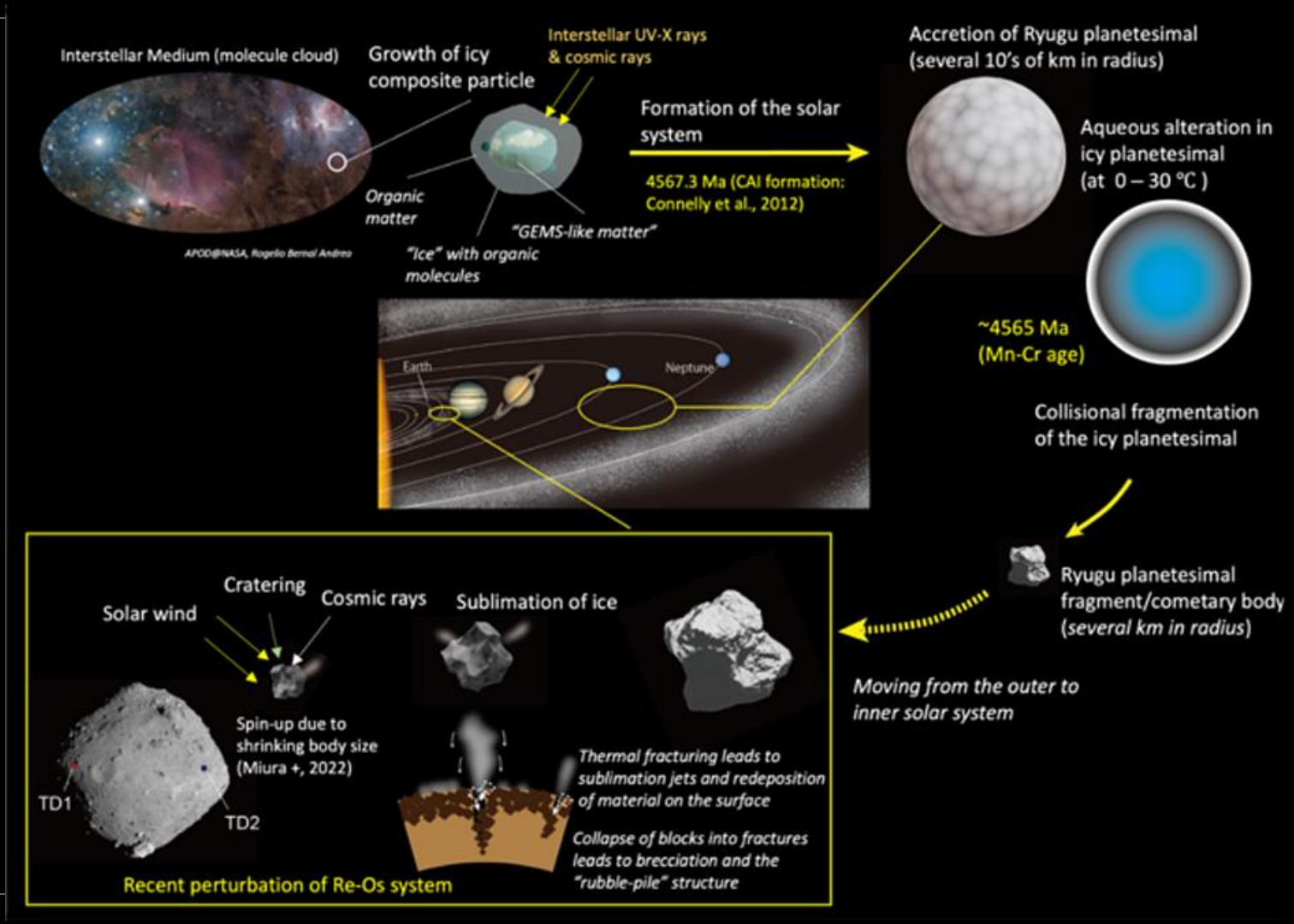
Origins of our solar system



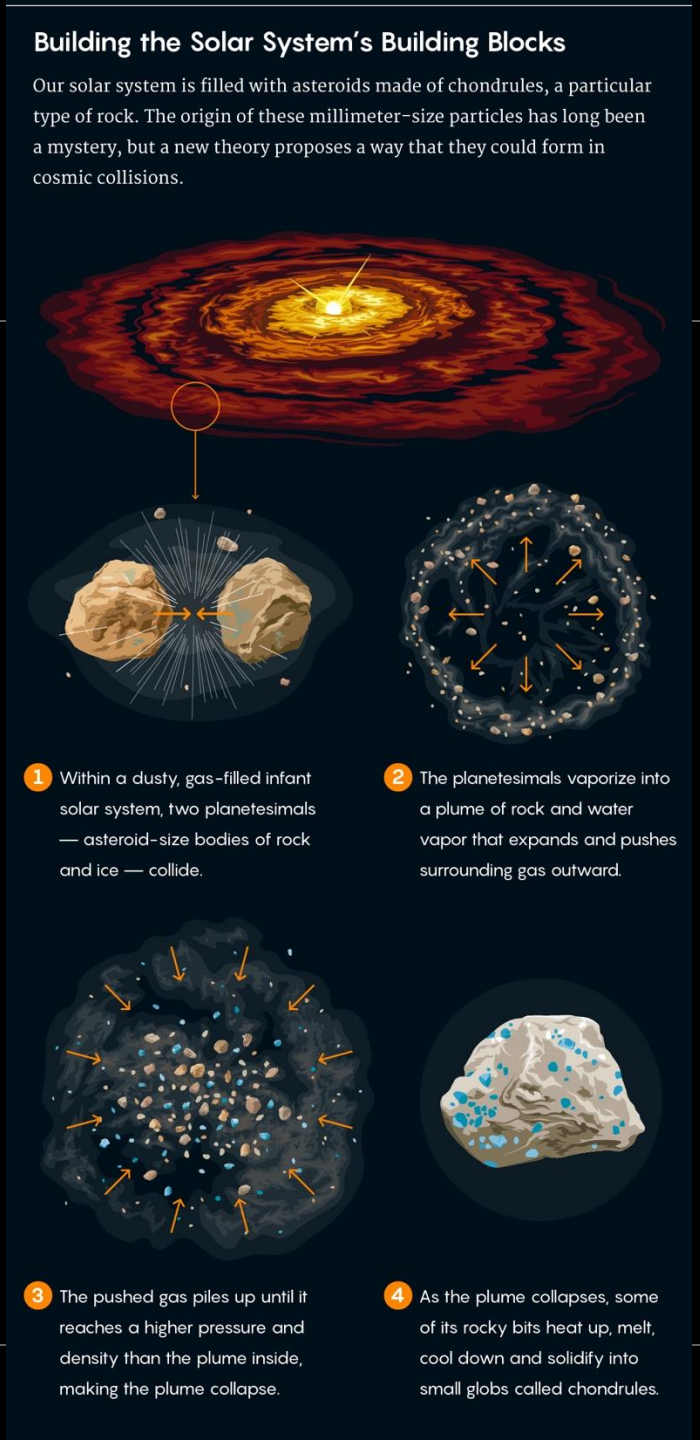
Origins of our solar system

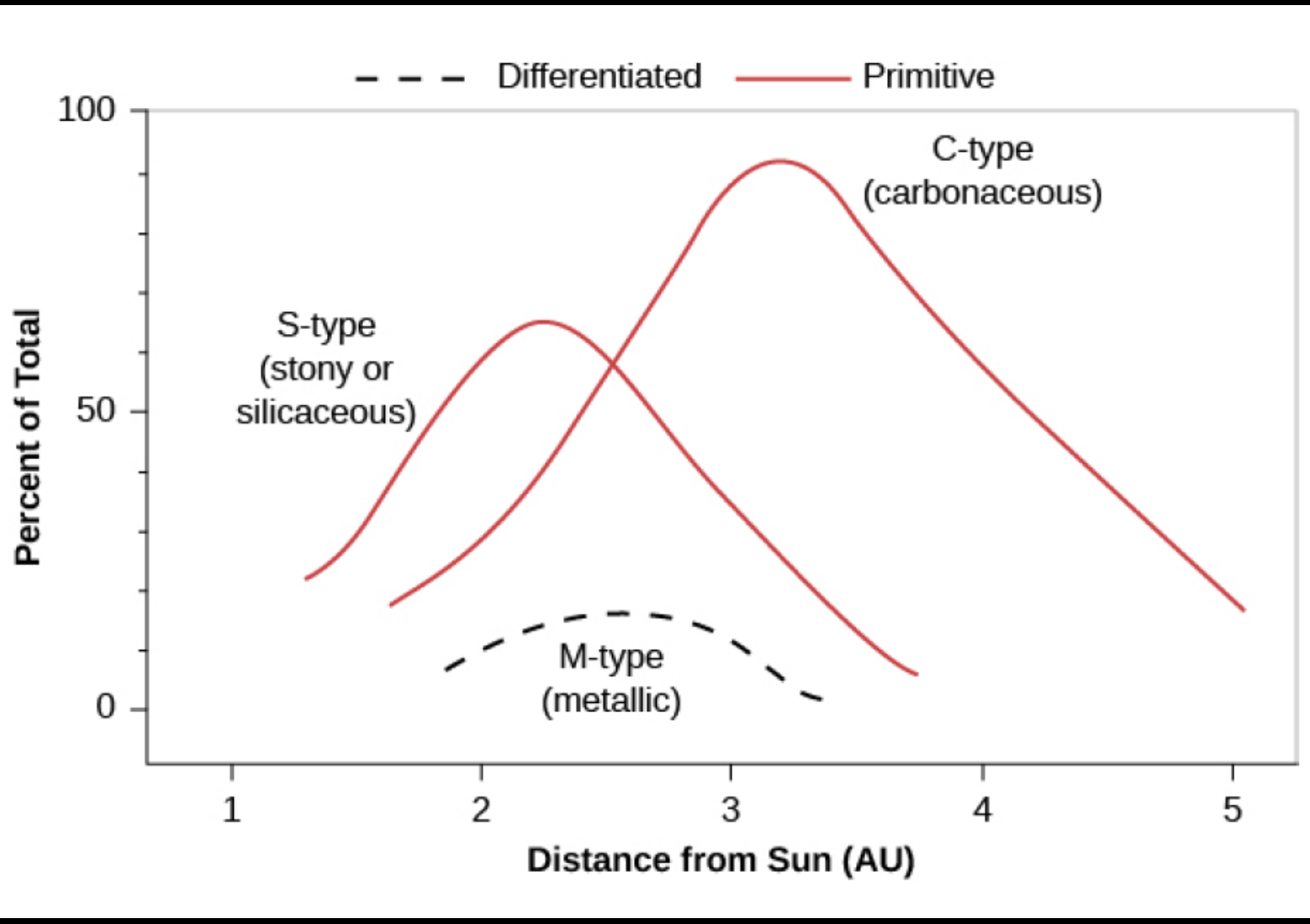


Origins of our solar system

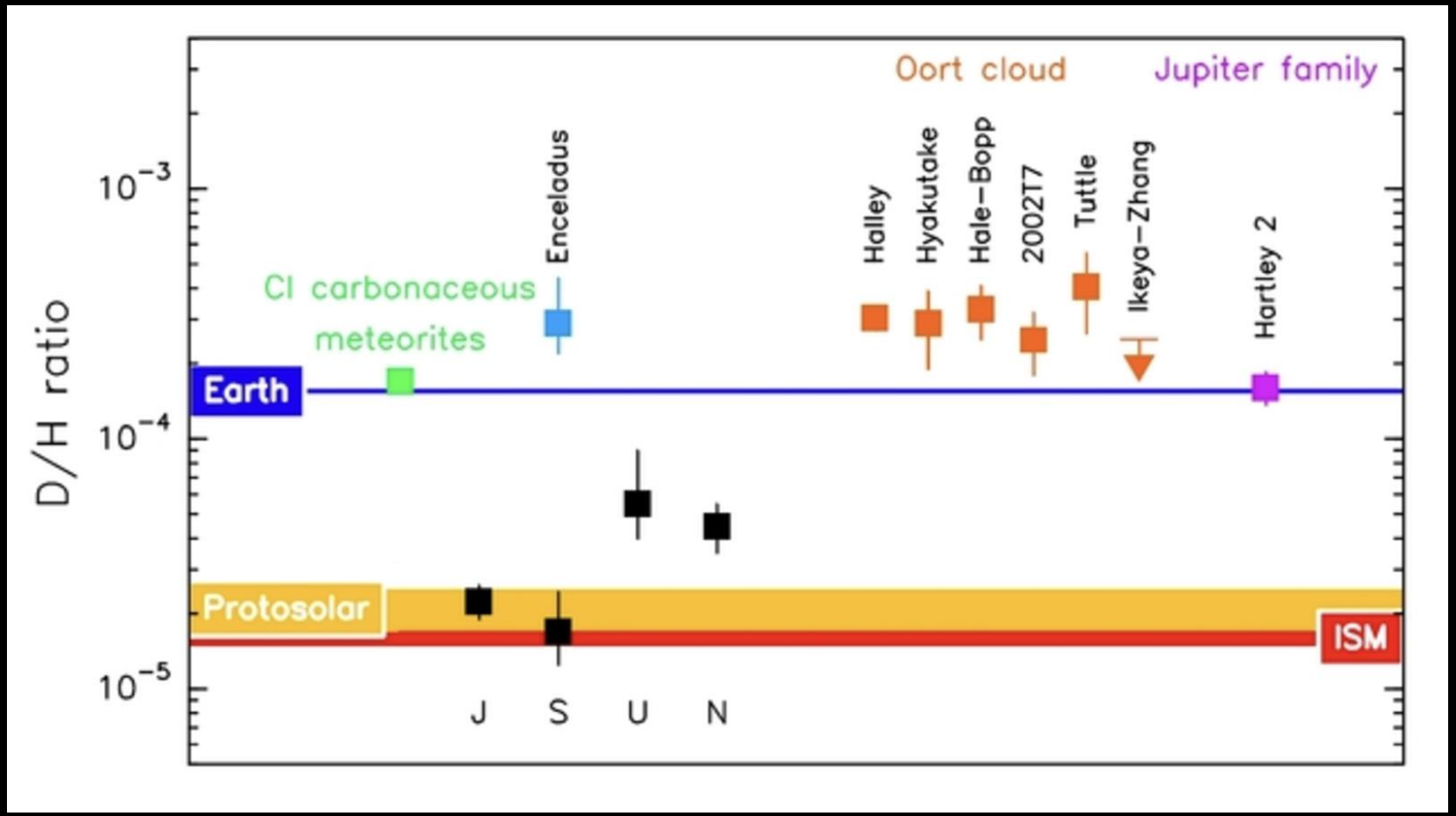


Origins of our solar system

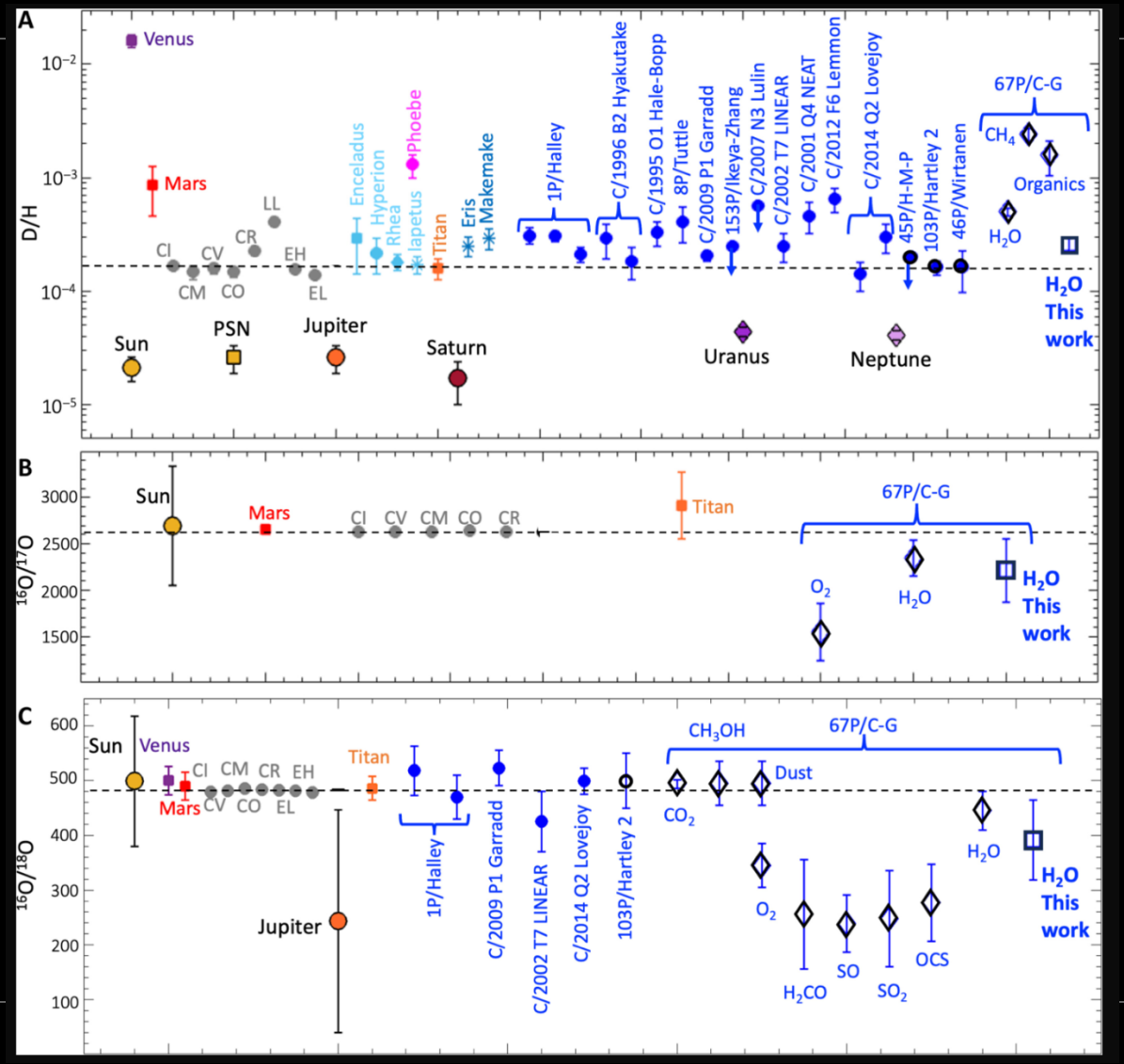



Differentiated
Primitive
100
50
0
Percent of Total
C-type
(carbonaceous)
S-type
(stony or
silicaceous)
M-type
(metallic)
1
2
3
4
5
Distance from Sun (AU)

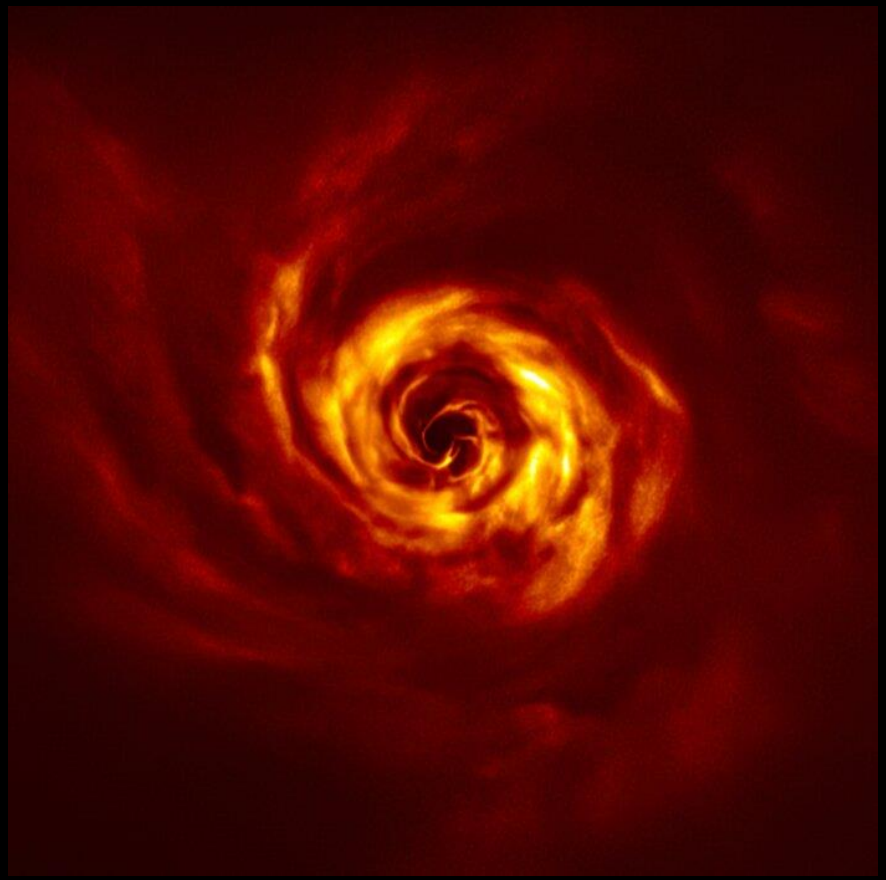
D/H ratio: water from comets?



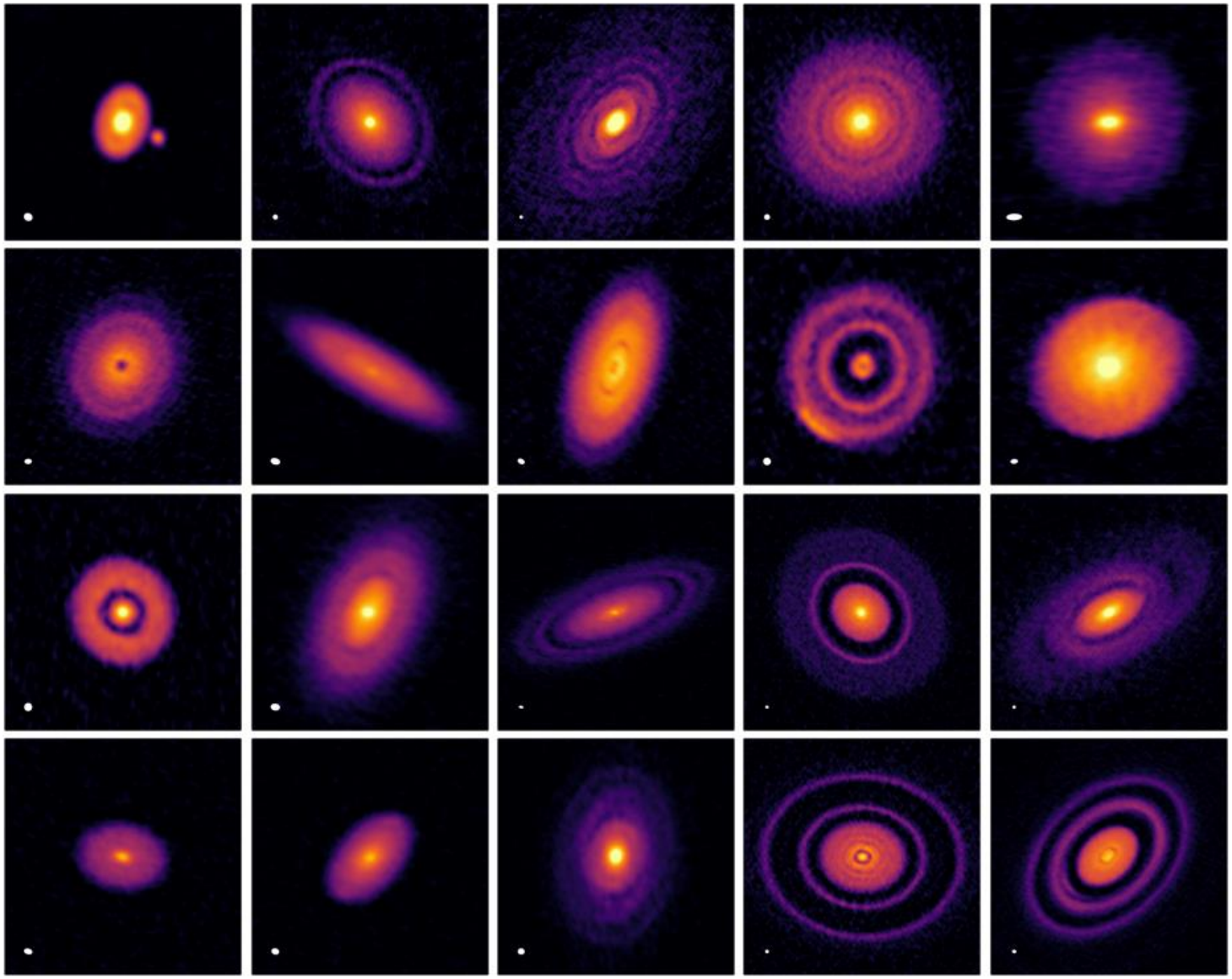
D/H ratio: water from comets?

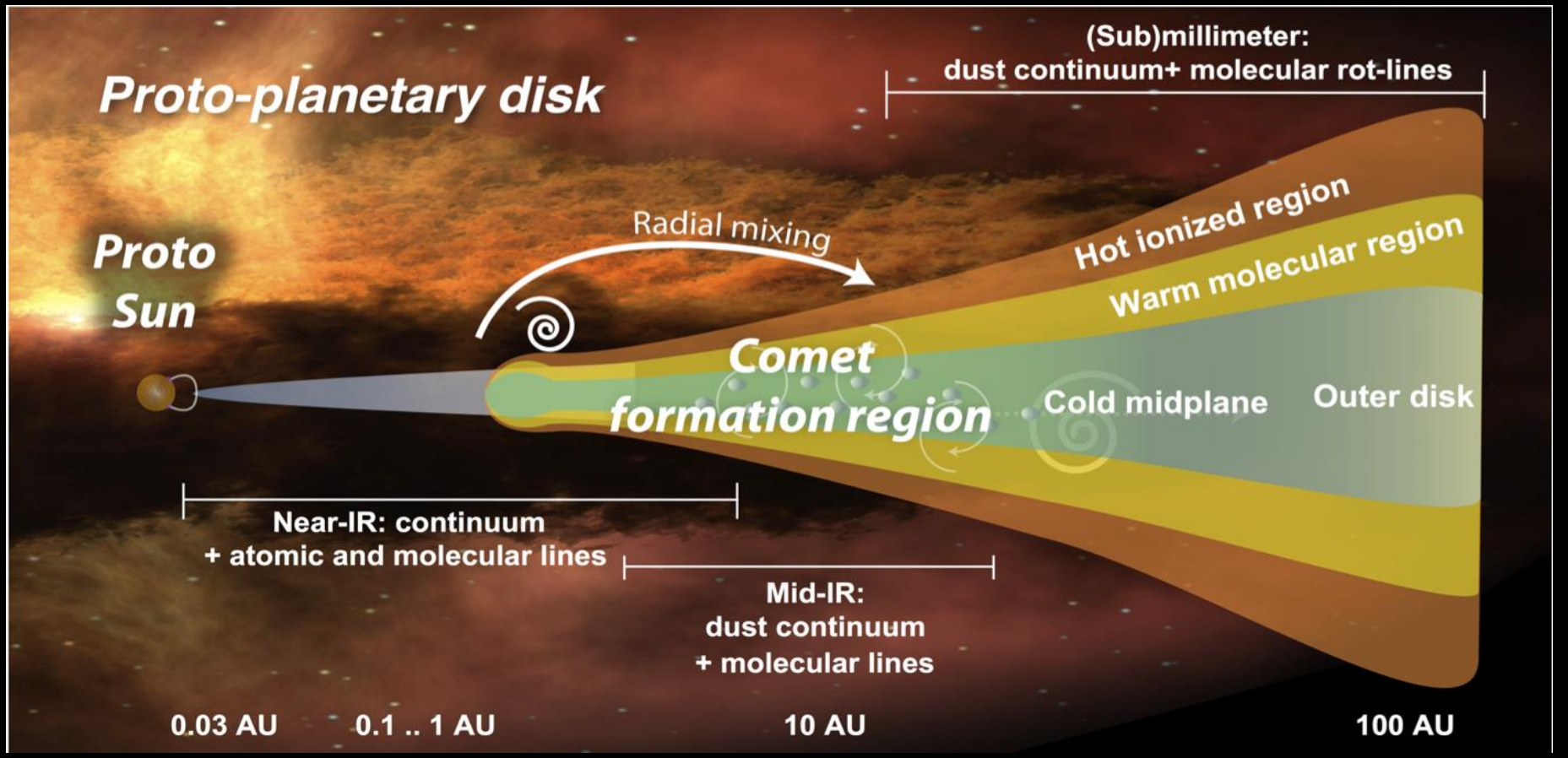


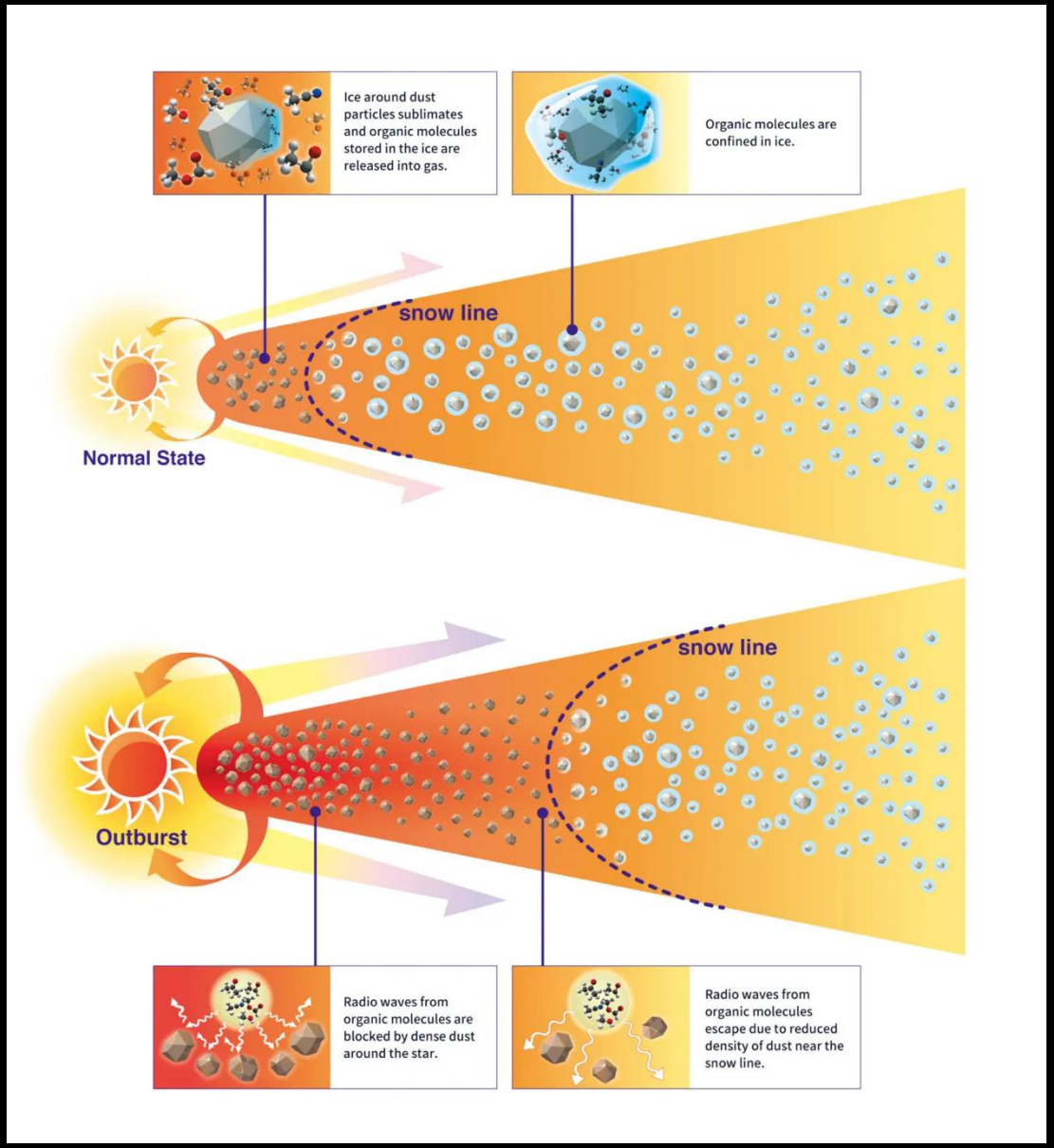
Connecting the solar nebula to planet formation



Connecting the solar nebula to planet formation



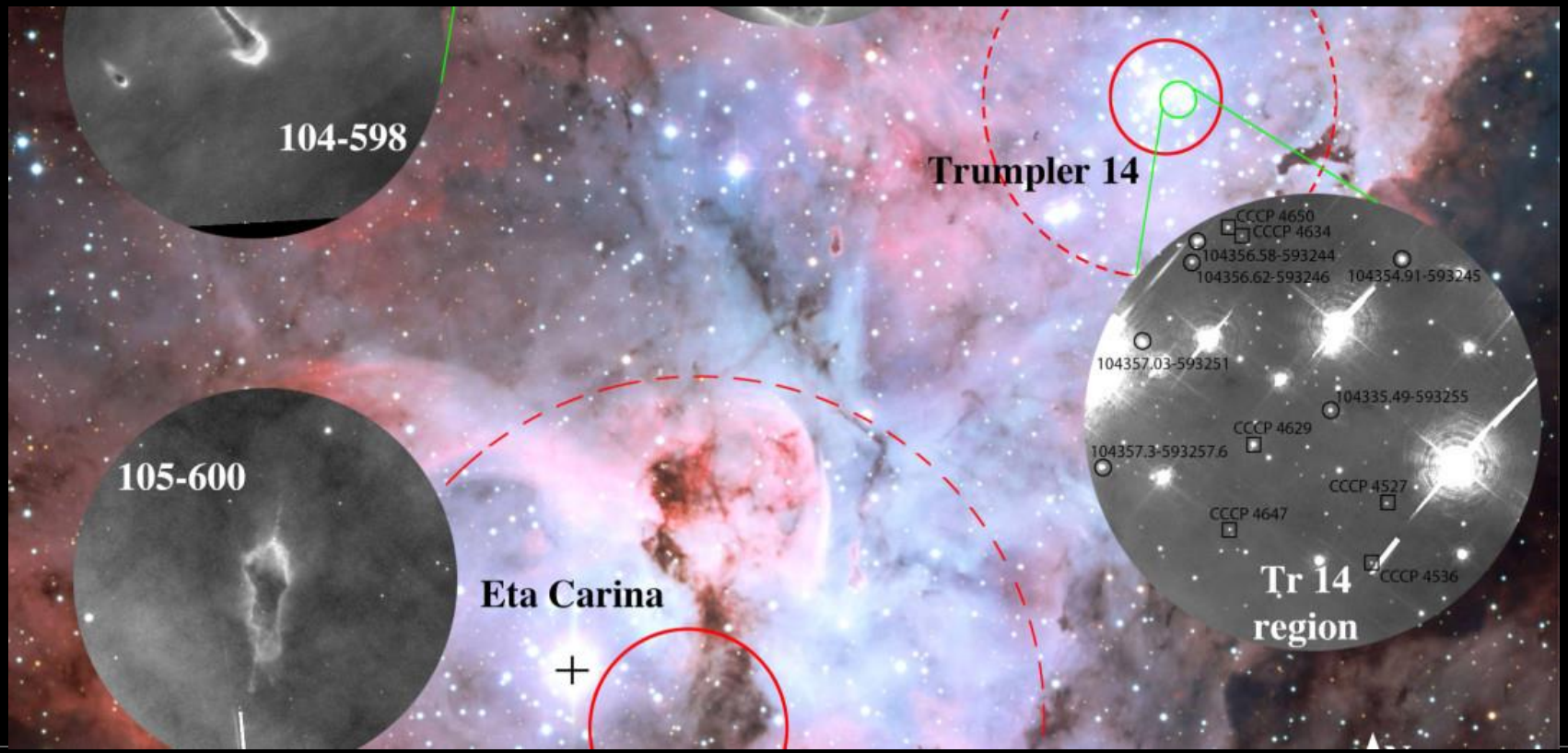

Proto-planetary disk
(Sub)millimeter:
dust continuum+ molecular rot-lines
Radial mixing
Proto
Sun
Hot ionized region
Warm molecular region
Comet
formation region
Cold midplane
Outer disk
Near-IR: continuum
+ atomic and molecular lines
Mid-IR:
dust continuum
+ molecular lines
0.03 AU
0.1 .. 1 AU
10 AU
100 AU



Very hot disk during a burst: chondrite heating?

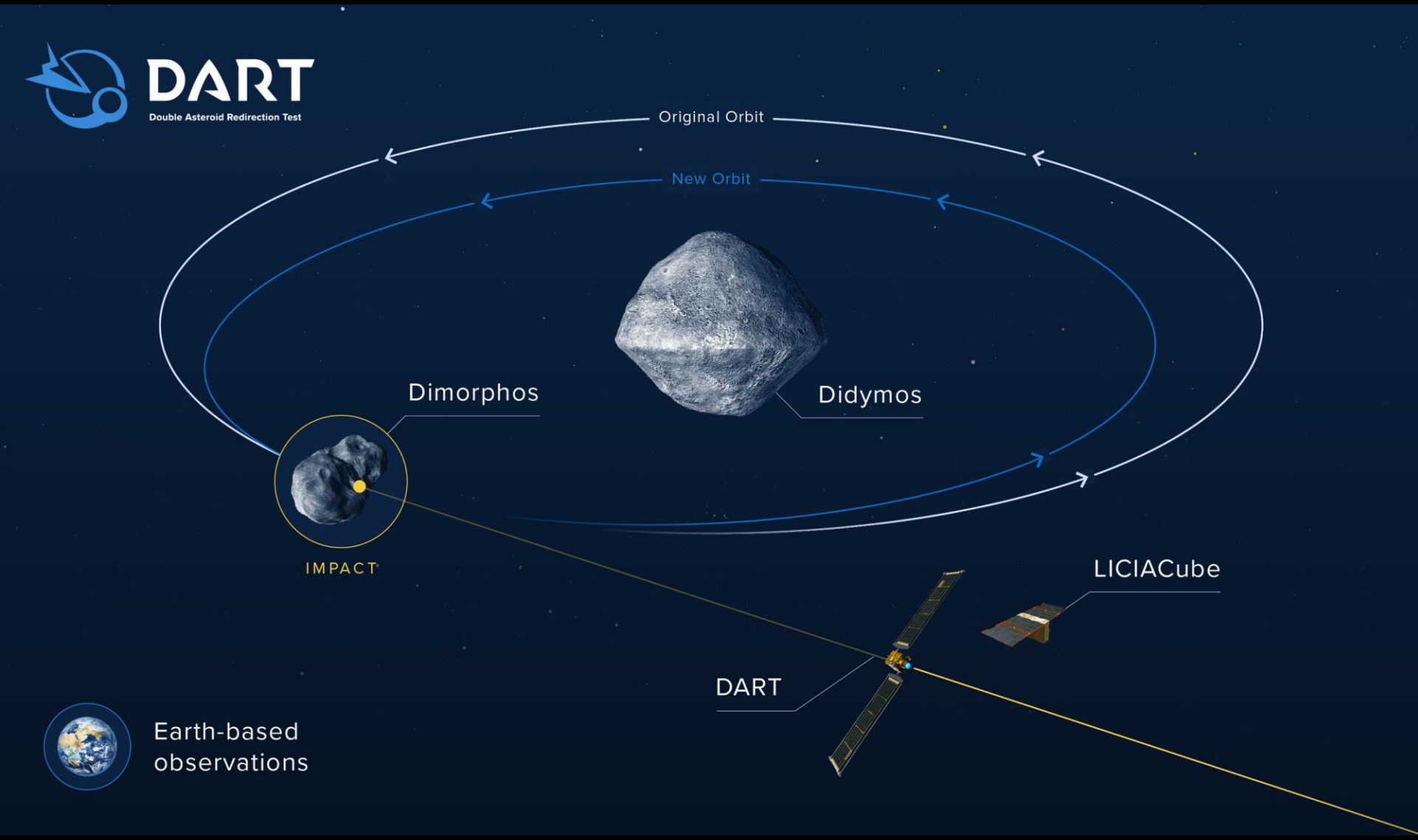
The sun formed in a massive star-forming region

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



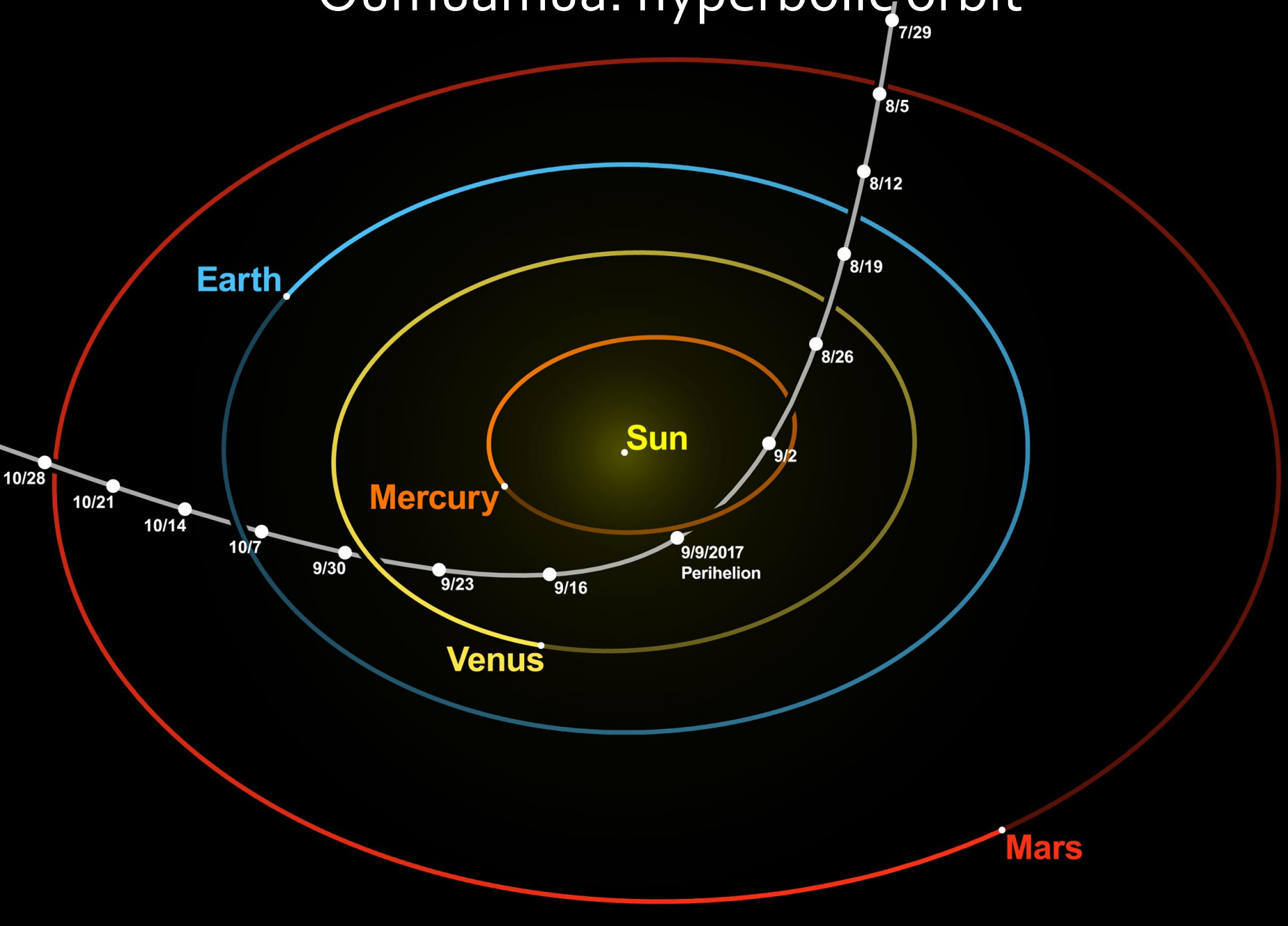
DART mission

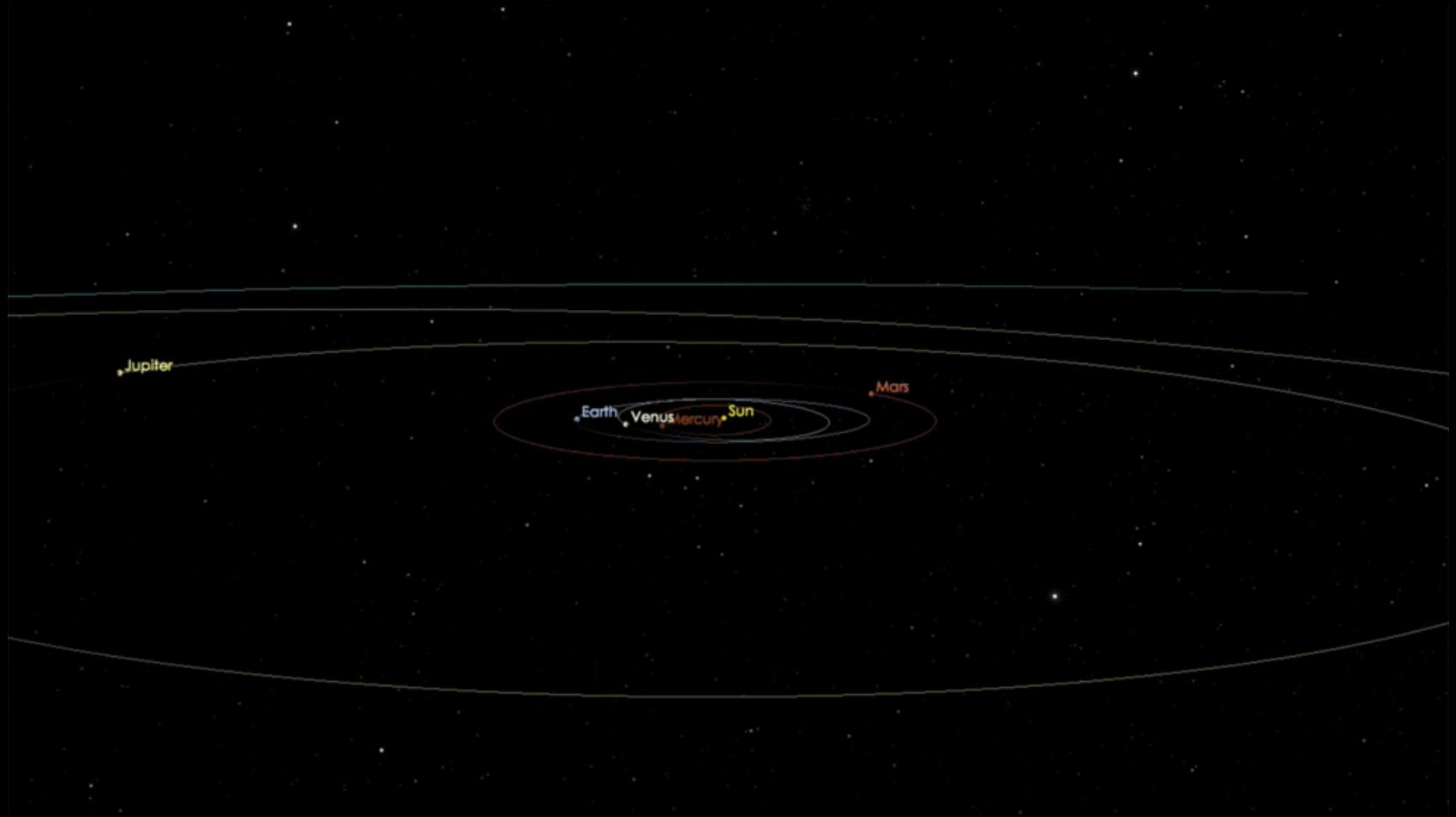
- Double Asteroid Redirection Test (DART) Mission


DART
Double Asteroid Redirection Test
Original Orbit
New Orbit
Dimorphos
Didymos
IMPACT
LICIACube
DART
Earth-based
observations

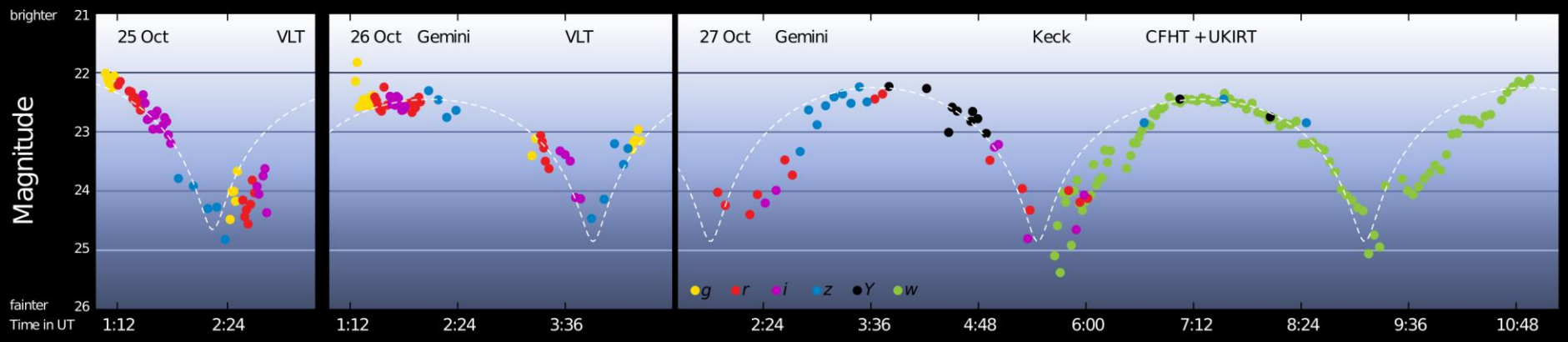
Oumuamua (and Borisov-2): interstellar visitors!

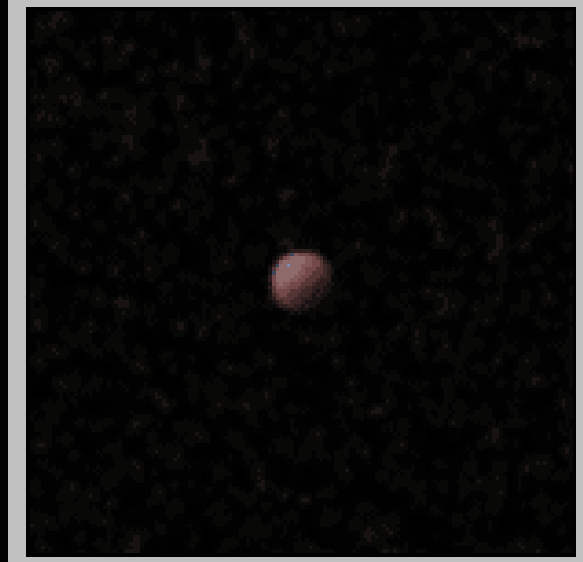
Oumuamua: hyperbolic orbit

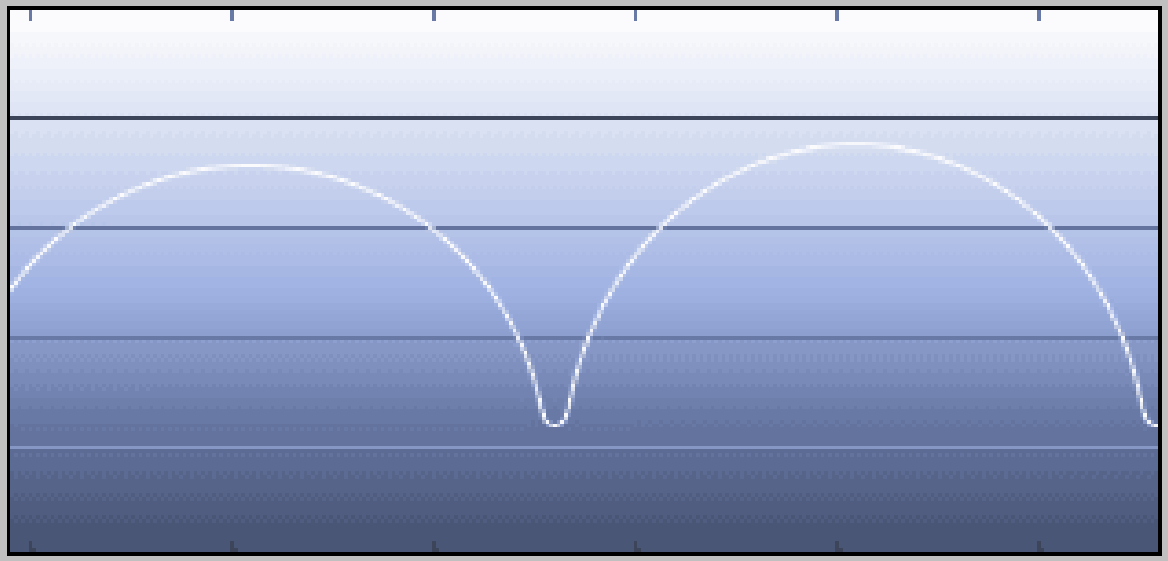



Jupiter
Mars
Earth
Venus
Mercury
Sun

Oumuamua lightcurve and shape







Artist's conception of Oumuamua

The Earth as a planet