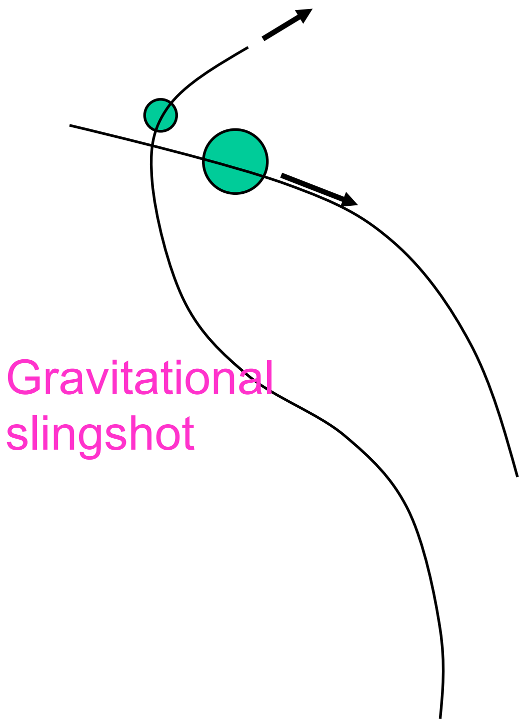
Lecture L15 – ASTC25

Minor Bodies

1. **Clearing stage: Oort cloud formation**
2. **Comets**
3. **Asteroids**
4. **Planetoids**
5. **Zodiacal light**
6. **IDPs (Interplanetary dust particles)**
7. **Chondrites and chondrules**

Clearing the junk left at the construction site:

- Oort cloud formation
- Kuiper belt and ‘planetoids’
  (dwarf planets like Pluto, Sedna, Eris)
- Comets
- Asteroids



Two-body interaction: a small planetesimal is scattered by a large one, nearly missing it and thus gaining an additional velocity of up to ~v_{esc} (from the big body with mass M_p)

The total kinetic energy after encounter, assuming that initially both bodies were on nearly-circular orbits is

$$E_K = \frac{v_K^{\,2} + v_{esc}^{\,2}}{2}$$

(we neglect the random part depending on the angle between the two components of final velocity).

If the total energy of the small body after encounter, $E = E_k + E_{pot}$, is positive, then the planetesimal will escape from the planetary system.

$$v_{esc}^2 = \frac{2GM_p}{R_p}, \quad v_K^2 = \frac{GM}{r}$$

$$E_{pot} = -\frac{GM}{r} = -v_K^2,$$

$$E_k = \frac{v_K^2 + v_{esc}^2}{2},$$

$$E = E_{pot} + E_k = \frac{v_{esc}^2 - v_K^2}{2}.$$

$$E > 0 \quad \Rightarrow \quad escape$$

Condition of escpe:

$$\frac{v_{esc}^2}{v_K^2} = \frac{2M_p}{M}\frac{r}{R_p} > 1$$

Planet	$\frac{v_{esc}^2}{v_K^2}$
Earth	0.14
Mars	0.04
Jupiter's core	5
Jupiter	21
Saturn	14
Uranus	10
Neptune	19

Terrestrial planets cannot eject planetesimals out of the solar system.

Giant planets (even cores) **can** eject planetesimals out of the solar system.

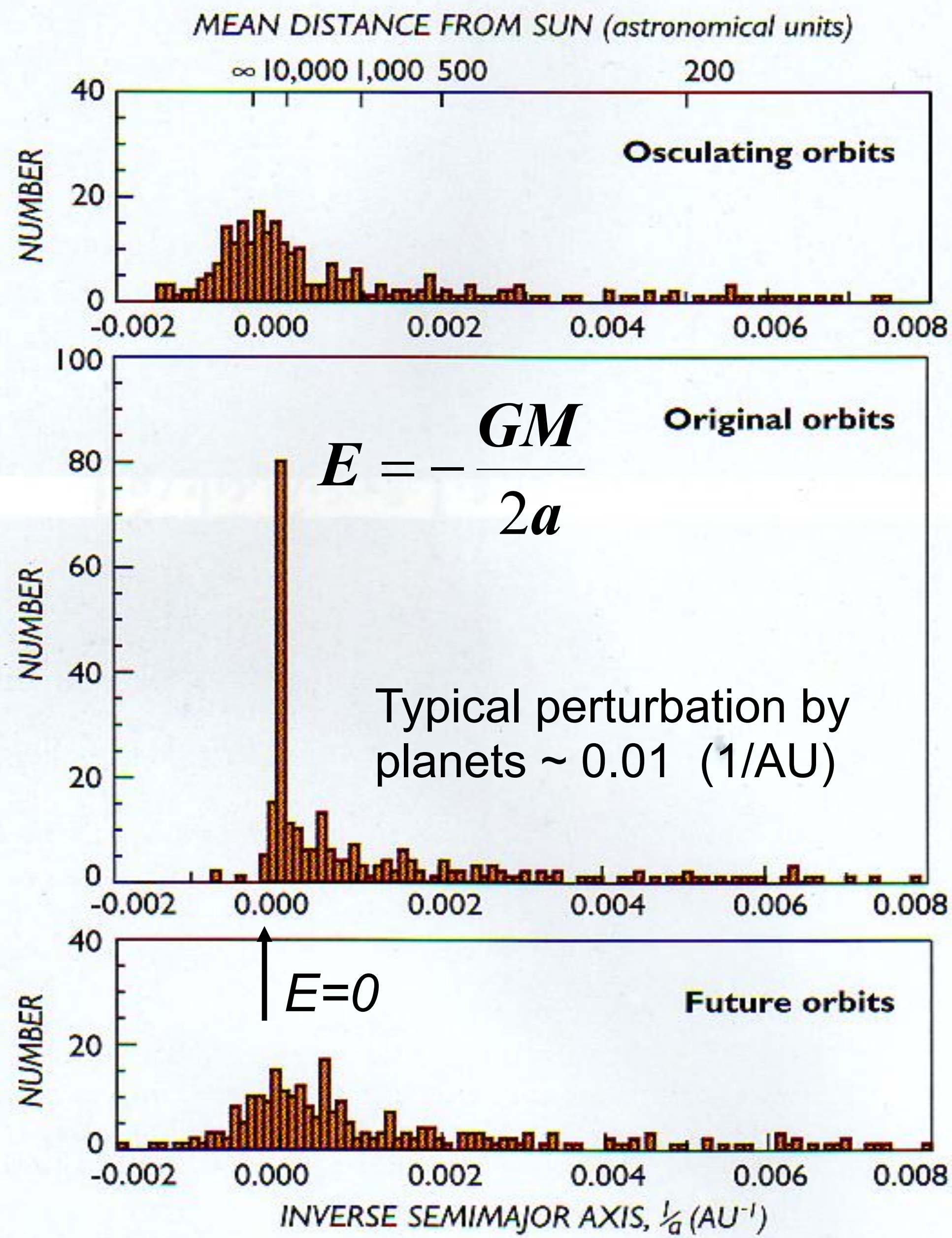


Figure 3. Dynamicists gauge the orbital energy of a long-period comet using the parameter 1/*a*, where *a* is the semimajor axis of the orbit. As seen in the upper panel, about one-third of these objects' osculating orbits (their apparent orbits while passing through the planetary system) have negative values, implying that they are arriving from interstellar space. But note the distribution of "original" orbits for the same group of comets (middle panel), which have been integrated backward in time and referenced to the solar system's center of mass. The spike of comets coming from the Oort cloud is easily visible at very small positive values of 1/*a*. These comets are all members of the solar system. A few apparently interstellar comets (negative values) are likely the result of small errors in observation or computation. "Future" orbits (lower panel) track comets as they leave the planetary region, again referenced to the solar system's center of mass. The gravitational pull of the planets alters these trajectories, and very few dynamically "new" comets return to the Oort cloud. Comets with negative values of 1/*a* are ejected into interstellar space and will not return.

Jan Oort
(1902-1992)

found that
a~ (2-7) 10^4 AU for
most new comets.

Figure 3. Dynamicists gauge the orbital energy of a long-period comet using the parameter 1/*a*, where *a* is the semimajor axis of the orbit. As

Oort cloud of comets: the source of the so-called ***new comets***

size ~ Hill radius of the Sun in the Galaxy ~ 260,000 AU

$$\mu = 10^{-11}, \quad r_L \cong r_\circ \sqrt[3]{\mu/3} \sim 8500\,pc\ \sqrt[3]{3}\,10^{-4} \sim 1.3\,pc$$

Q: $P_{orb} = ?$

inner part flattened, outer elliptical

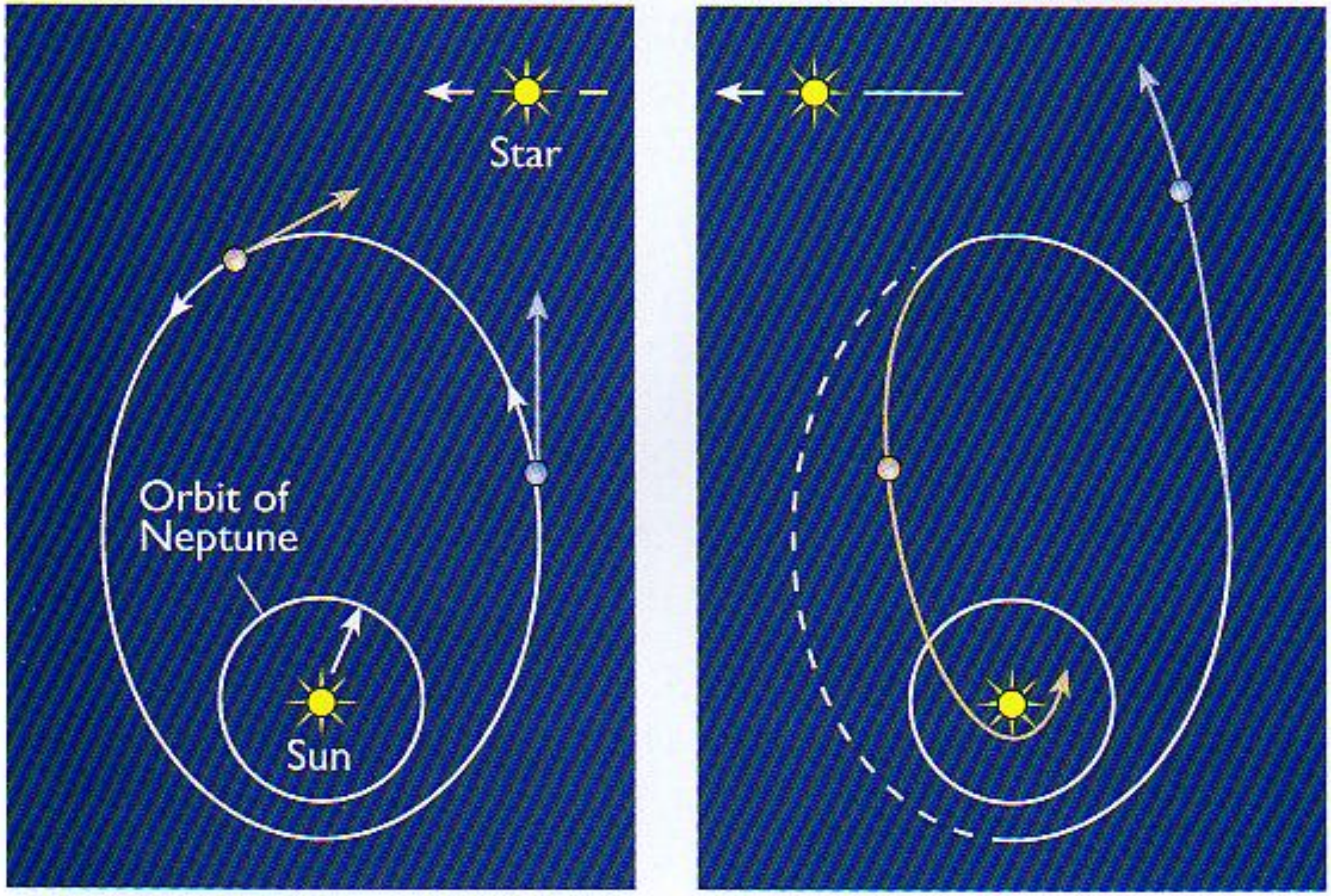


Figure 5. When a star passes close to the solar system, its gravitational attraction causes some comets in the outer Oort cloud to lose orbital angular momentum and "fall" into the planetary region (red); others gain energy and angular momentum and escape to interstellar space (blue). Meanwhile, many comets in the denser inner Oort cloud (not shown) are perturbed as well, and some of these migrate outward to replace those comets lost during the stellar encounter.

Out of
152 new comets

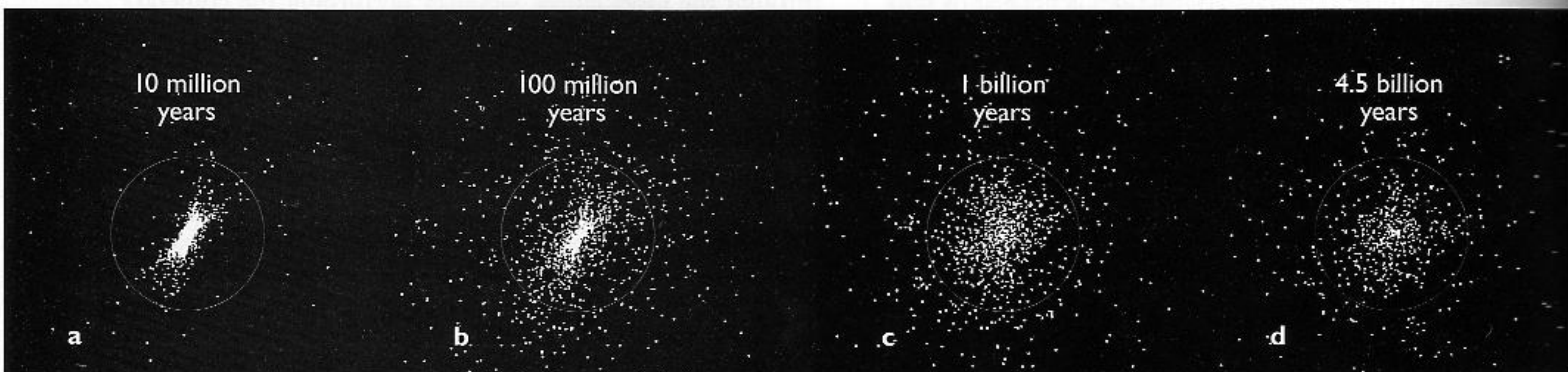
~50 perturbed
recently by 2 stars
(one slow, one fast
passage)

excess of retrograde
orbits,
aphelia clustered on
the sky

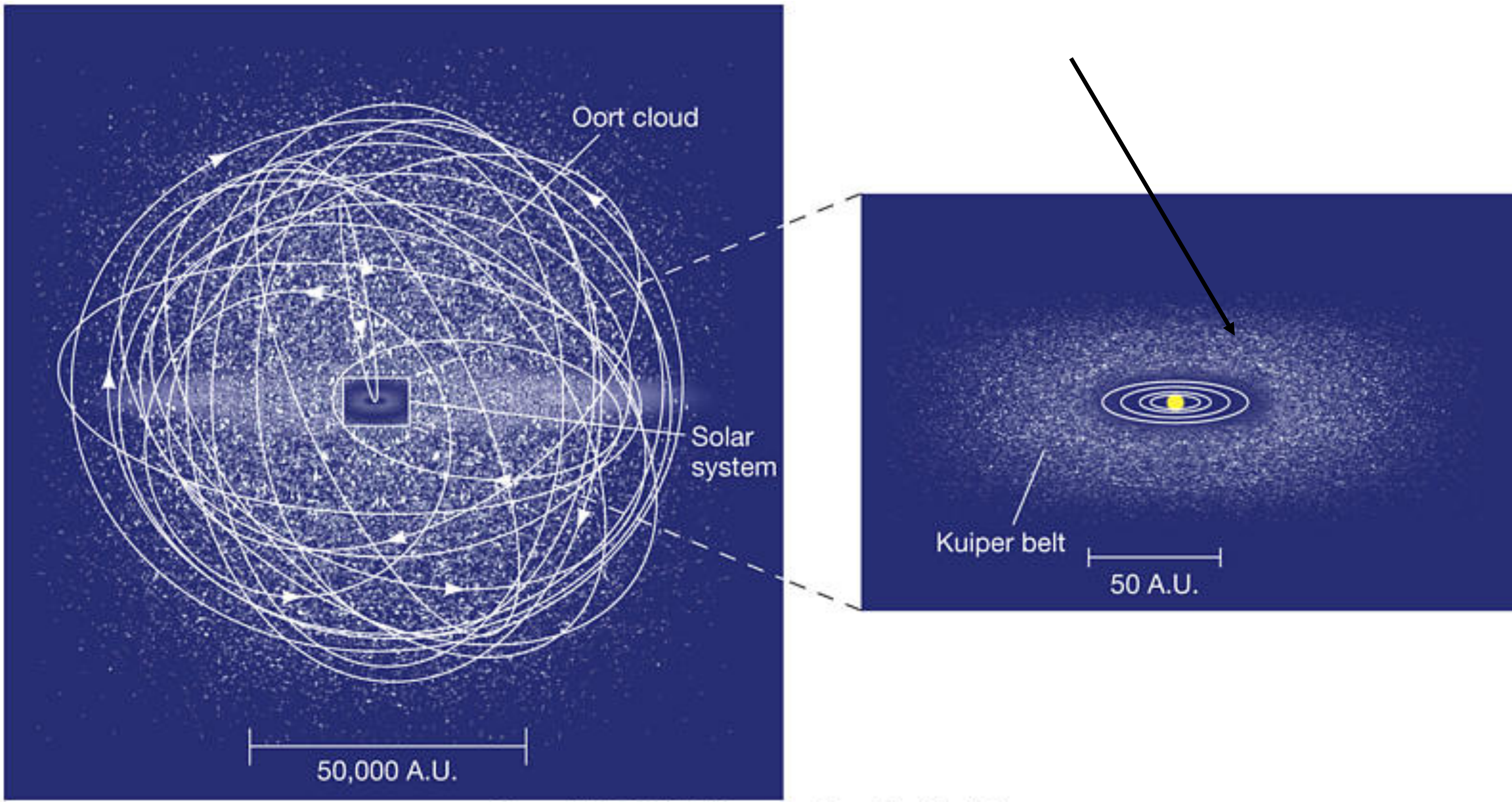
Fomation of Oort cloud

Figure 6. Early in solar-system history comets moved in the ecliptic plane among the outer planets *(a)*. Gravitational interactions with these planets pumped the comets into ever larger orbits *(b)*, after which the gravitational attraction of random passing stars, giant molecular clouds, and the galactic tide randomized their orbital inclinations and made the Oort cloud more spherical *(c,d)*. The circles are 20,000 AU from the Sun — the distance beyond which Oort-cloud comets can be thrown back into the planetary system by stellar and GMC perturbations and become visible as long-period comets.

However, that same year Fred Whipple suggested that com were icy conglomerates ("dirty snowballs"). This meant th comets must have formed much further from the Sun, in loca tions cold enough for water ice to condense. Later dynami studies suggested that the Oort cloud comets probably cam from the Uranus-Neptune zone. Because Jupiter and Saturn a so massive, they would have ejected any icy bodies in their zon beyond the Oort cloud and into interstellar space. Uranus an Neptune, with smaller masses, could not easily throw so man



Kuiper belt, a theoretical entity since 1949 when Edgeworth first mentioned it and Kuiper independently proposed it in 1951, was discovered (1st object) by D. Jewitt and J. Lu in 1993 who estimated that 30000 asteroid-sized (typically 100 km across) super-comets reside there.



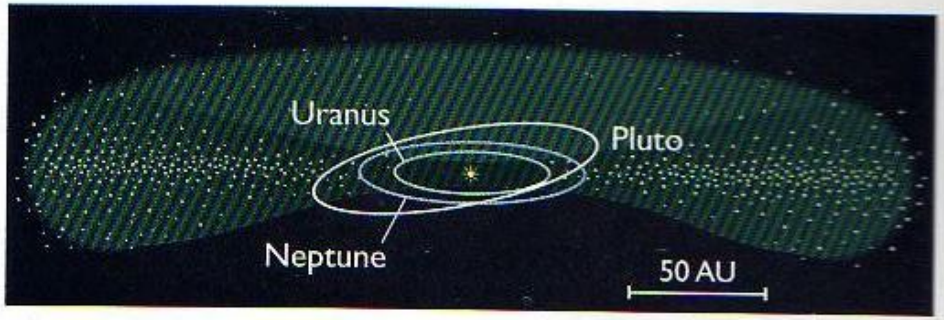


Figure 7. In 1949 and 1951 two astronomers independently proposed the existence of a band of comets closer to the Sun, objects left over from the solar system's formation. Known today as the Kuiper belt, this distant reservoir is the dominant source of short-period comets, whose orbits preferentially lie near the ecliptic plane.

Gerard Kuiper (1905-1973)

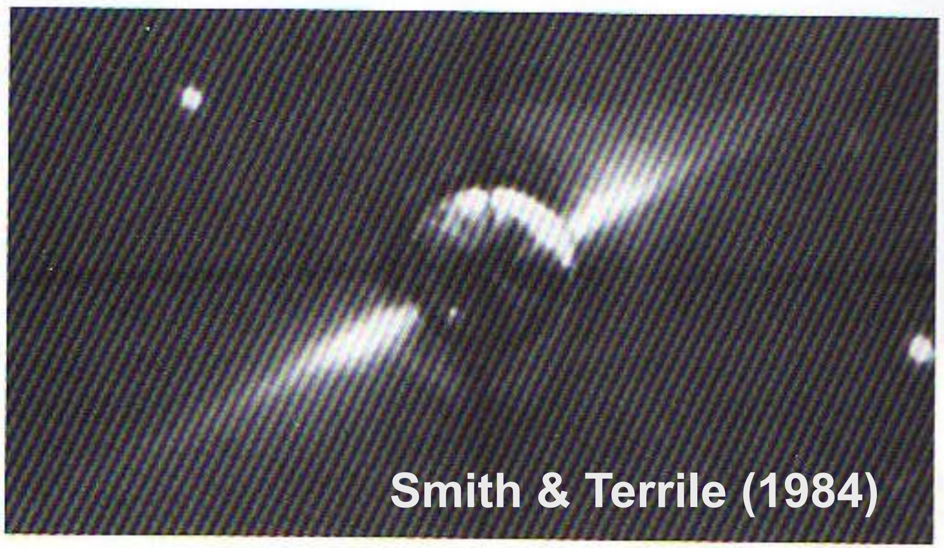
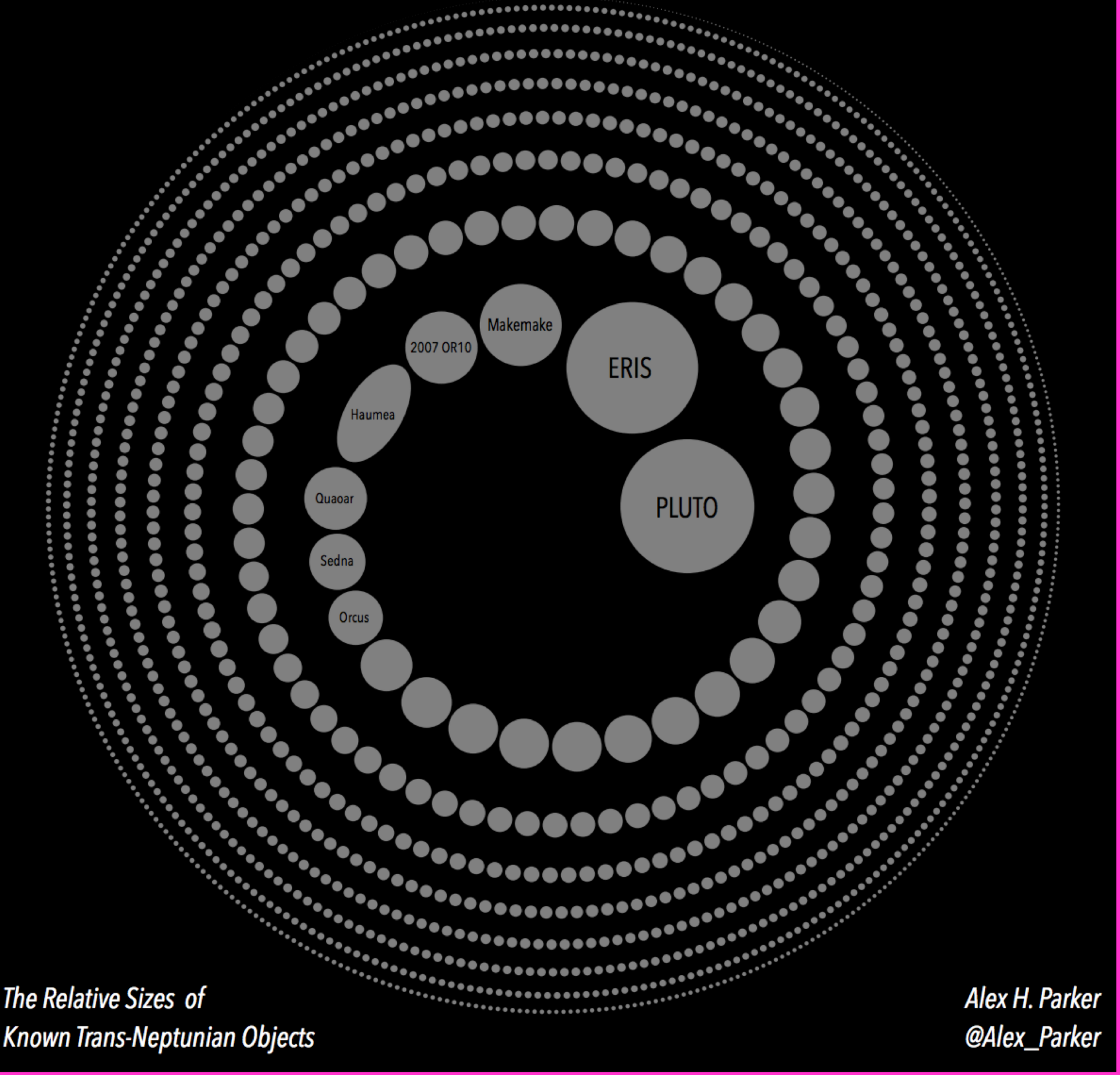


Figure 8. The edge-on disk of material around the star Beta Pictoris extends out about 900 AU to either side. (The star itself is blocked out by a small occulting disk placed in the telescope's optical path.) With an estimated mass of tens or even hundreds times that of Earth, this disk of matter is similar to what astronomers think the Kuiper belt might look like if viewed from far outside our solar system.

Planetoids

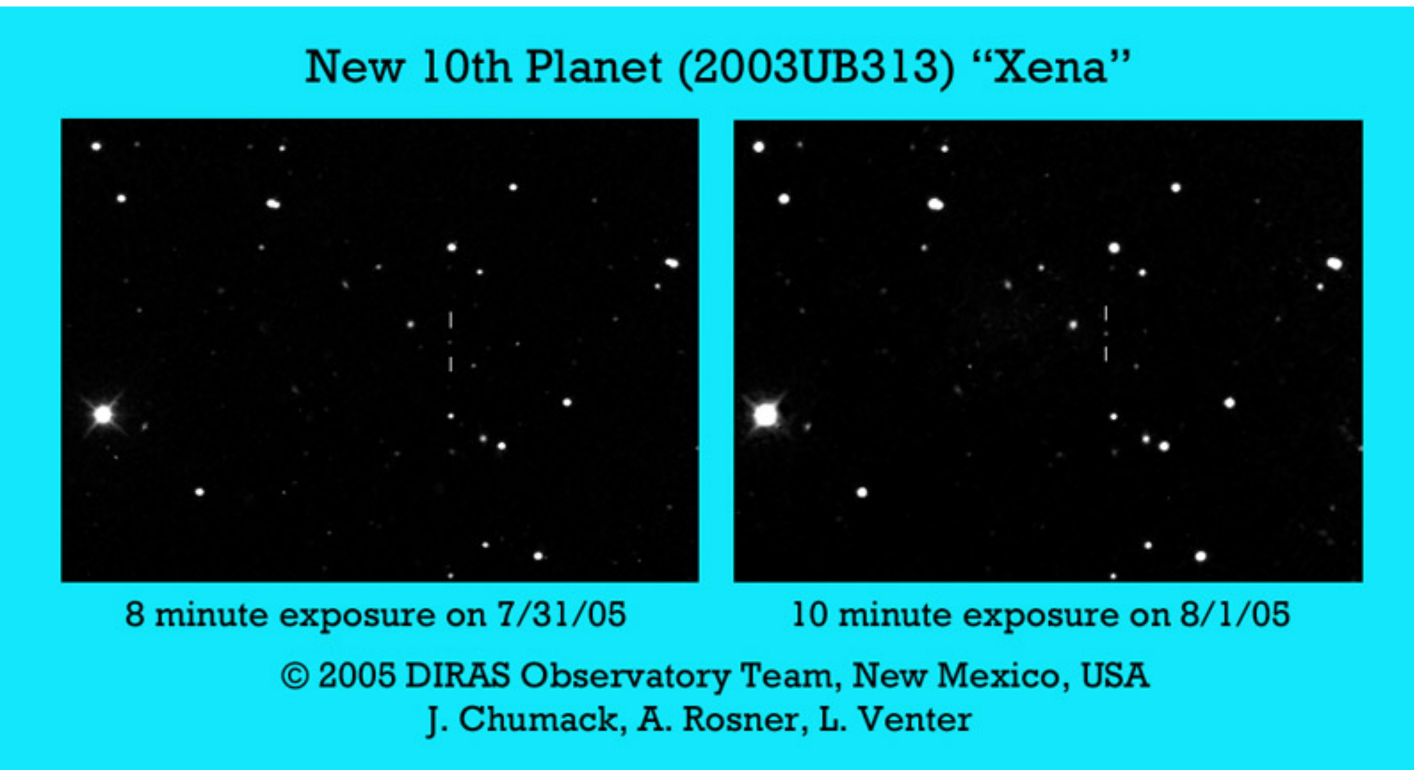


Outer solar system is inhabited by plutinos and dwarf planets

10th planet(s):

super-Pluto's: Sedna, "Xena"

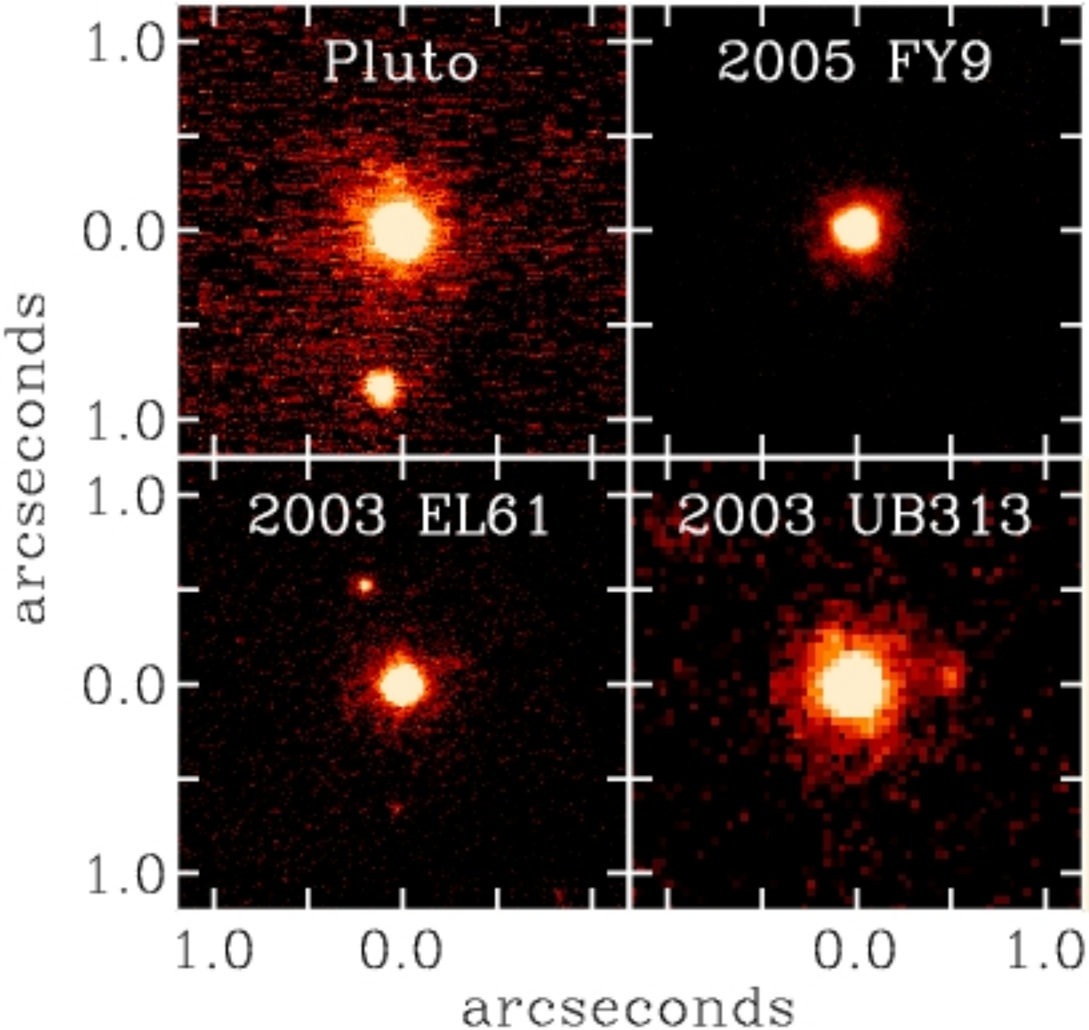
such bodies are called Plutinos



← *it's hard to see! Don't worry… Better image on the next slide.*

The **10th planet Sedna** (or UB313) first seen in 2003.
And it has a moon! (announced in Sept. 2005)

See the home page of the discoverer of planetoids, Michael Brown
http://www.gps.caltech.edu/~mbrown/



Images of the four largest Kuiper belt objects

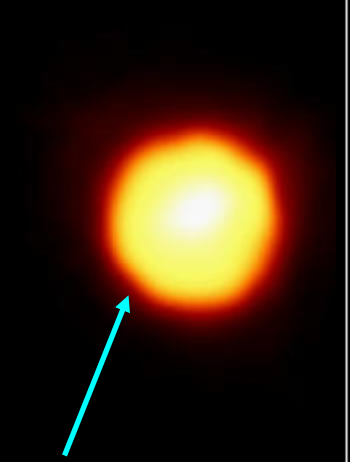
from the Keck Observatory Laser Guide Star Adaptive Optics system.

Satellites are seen around all except for 2005FY9; in 75% of cases!

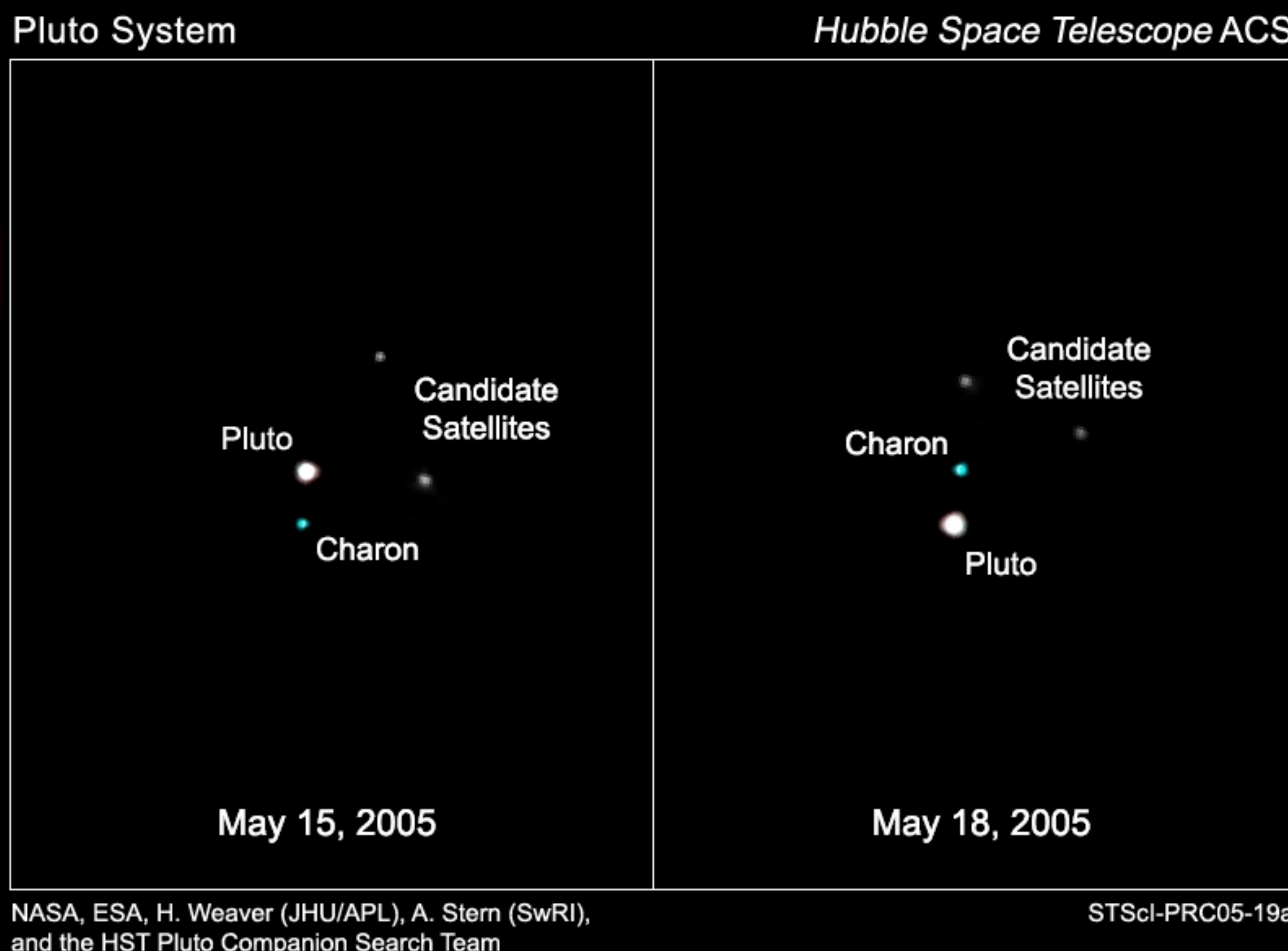
In comparison, only 1 out of 9 Kuiper belt objects, also known as TNOs (Trans-Neptunian Objects) have satellites.

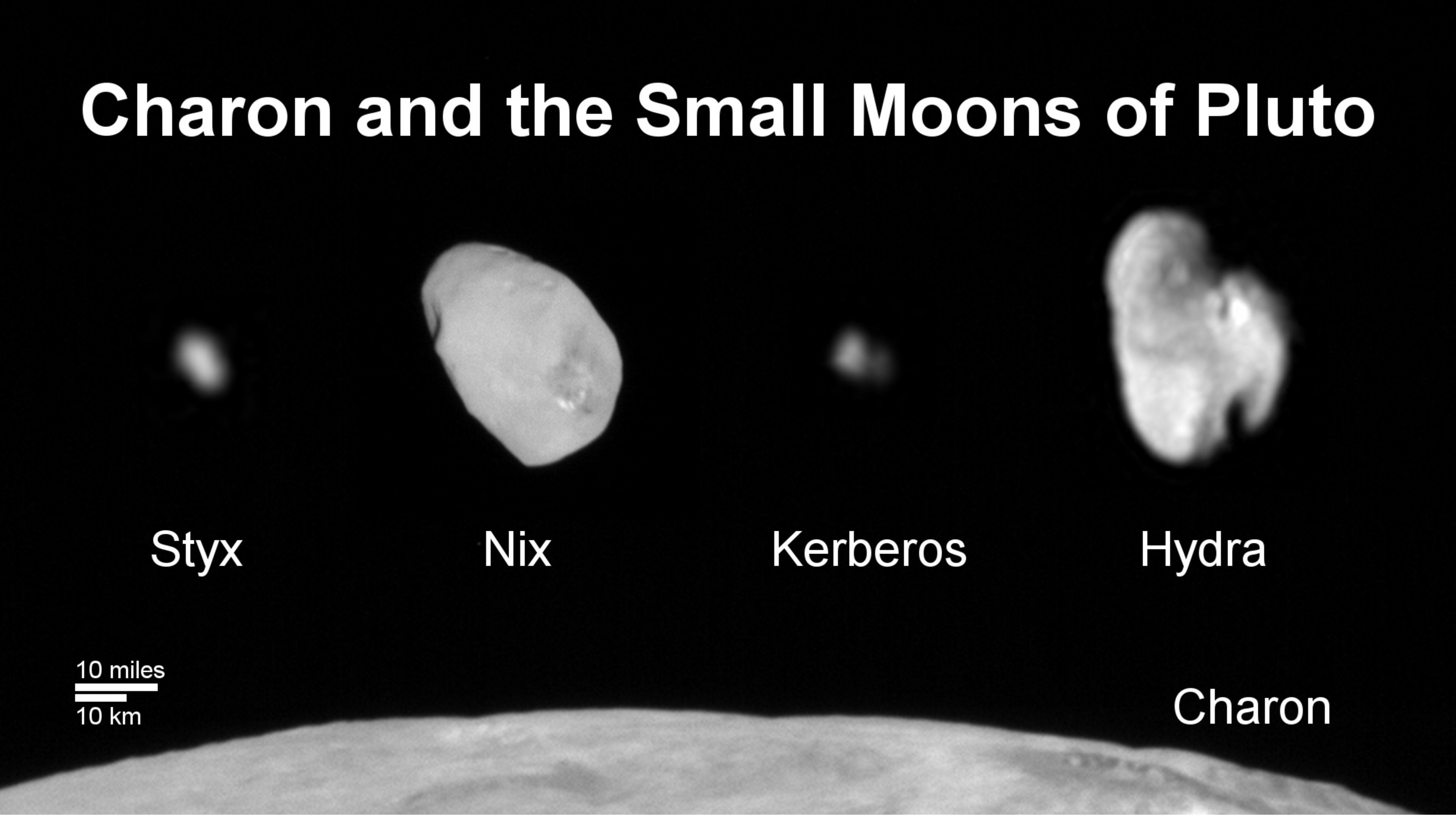
On October 31 2005, ***2 new moons of Pluto*** *have been found by the Hubble Space Telescope/ACS*

Charon



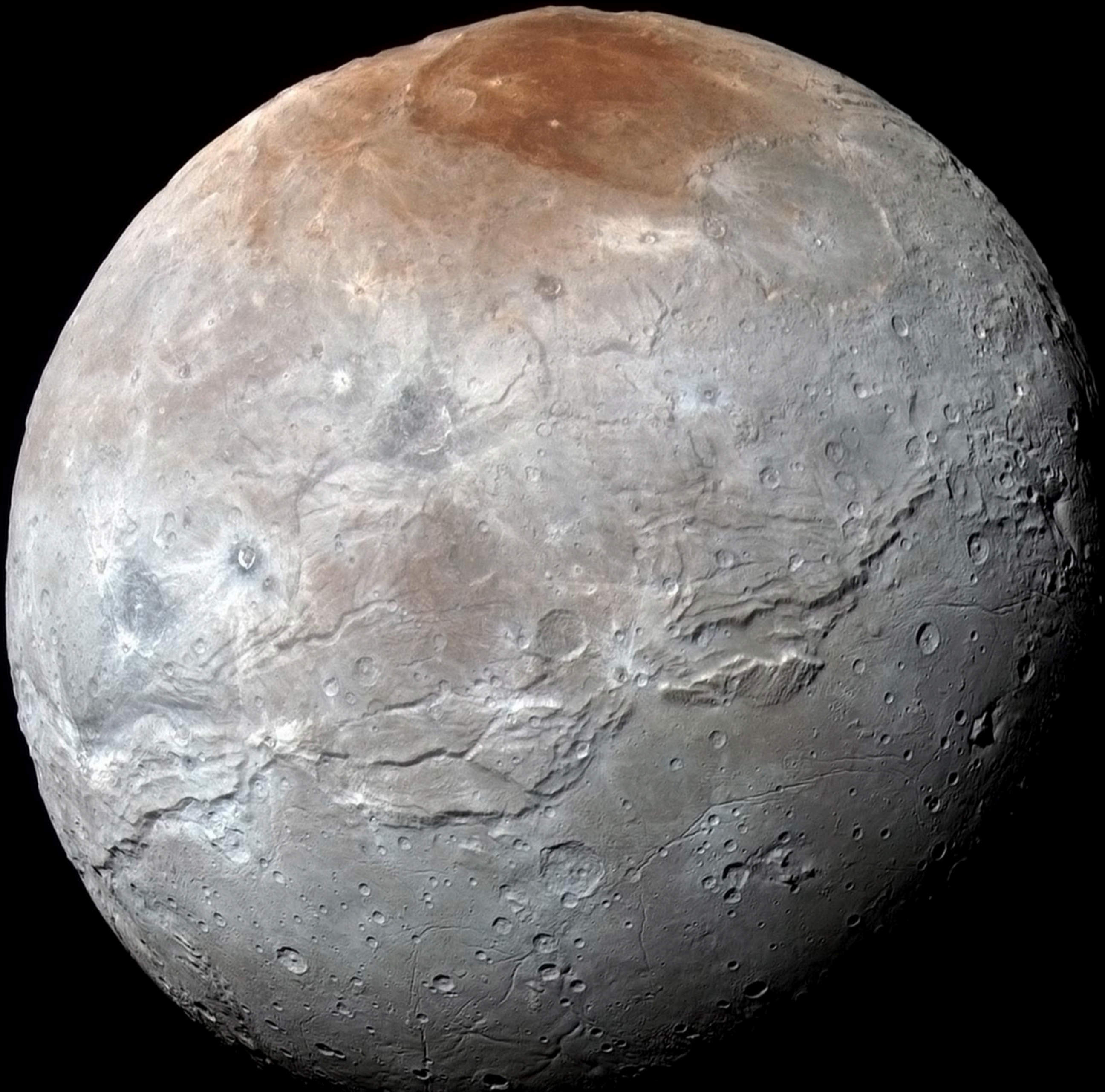
Pluto



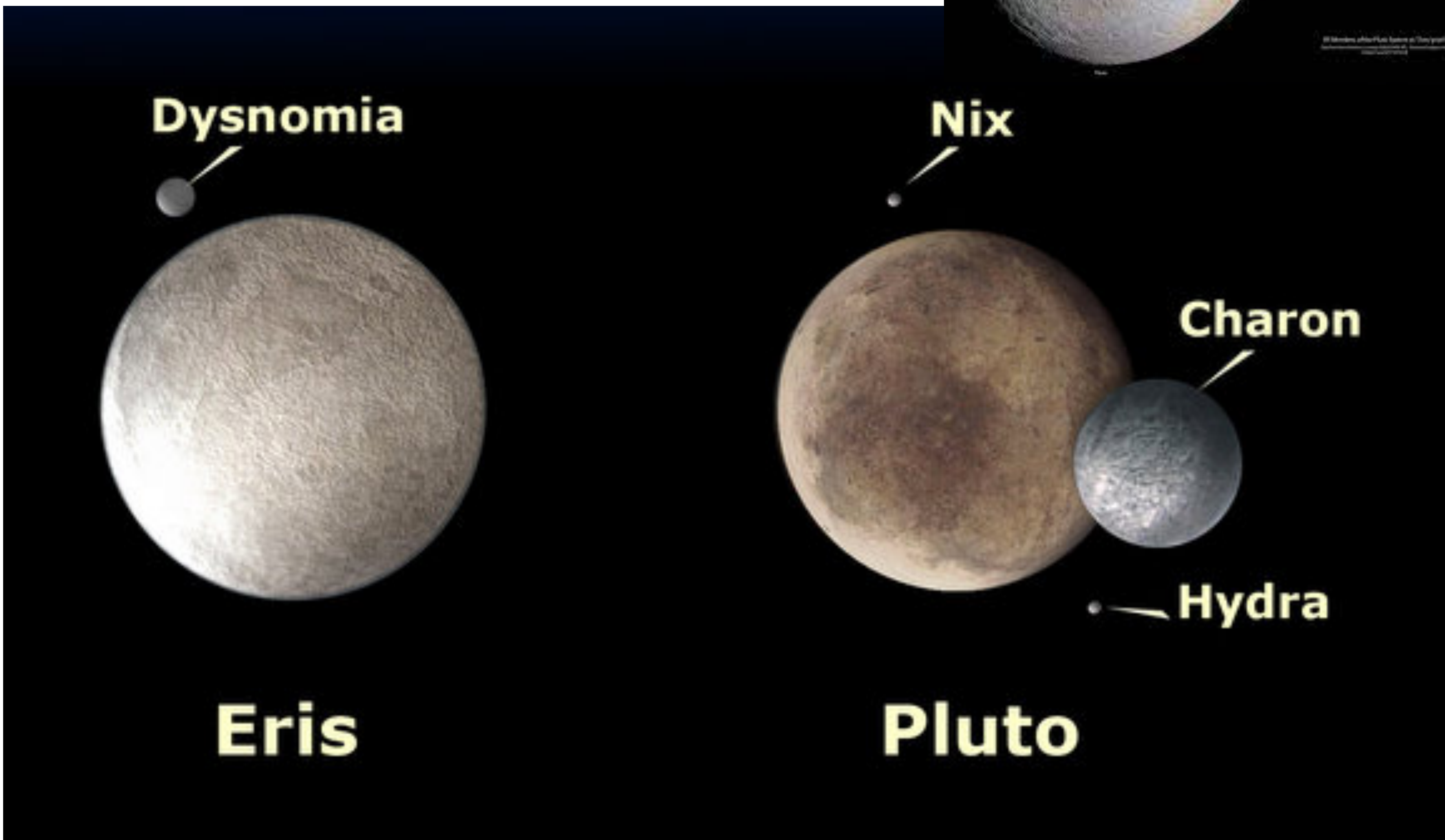


size 10...60 km

(cf. Charon’s R=606 km, Pluto’s R=1188 km)



= ?


Dysnomia
Nix
Charon
Hydra
Eris
Pluto

Charon – the side always facing Pluto.
Picture by New Horizons probe

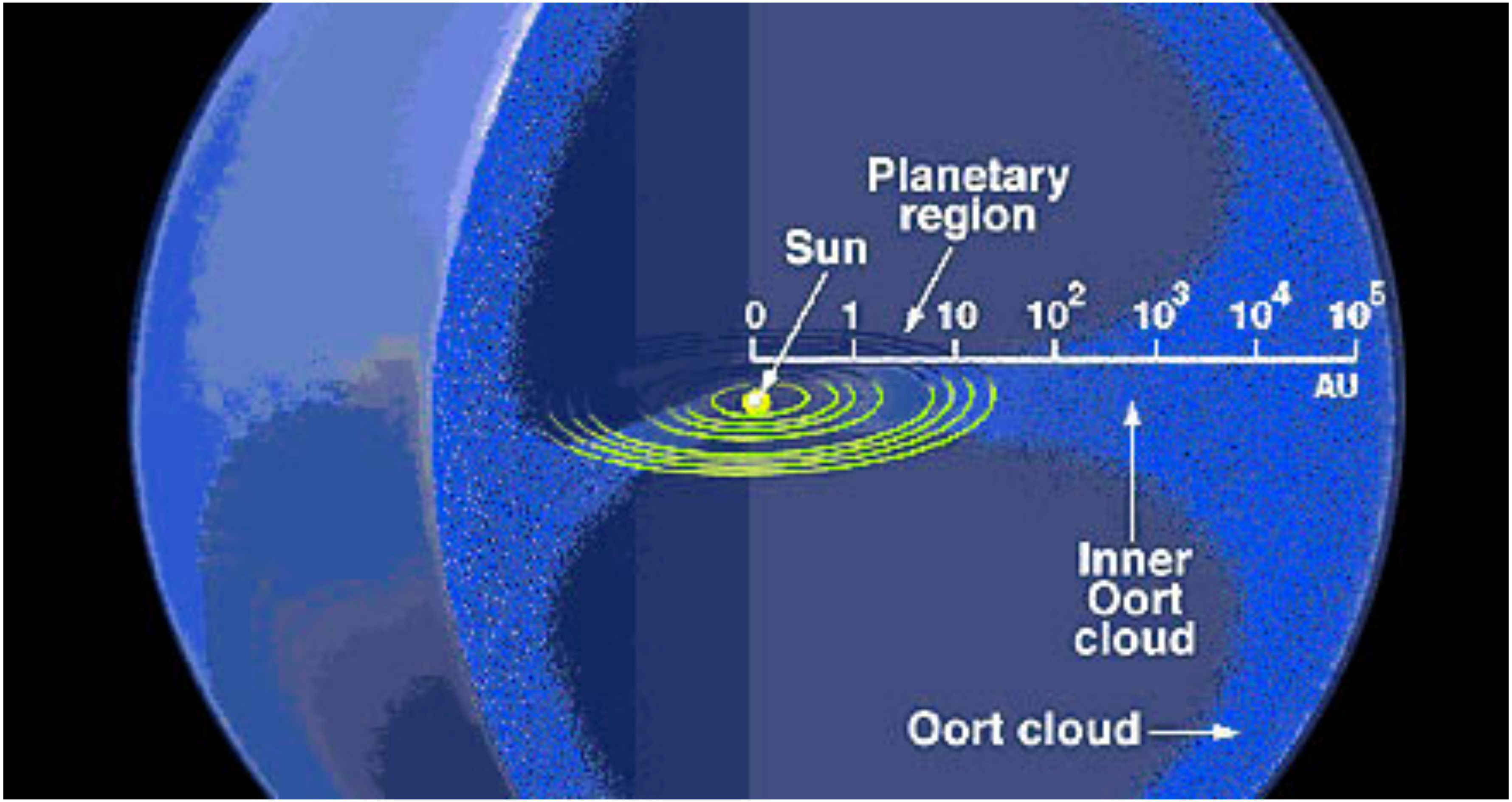
Comets

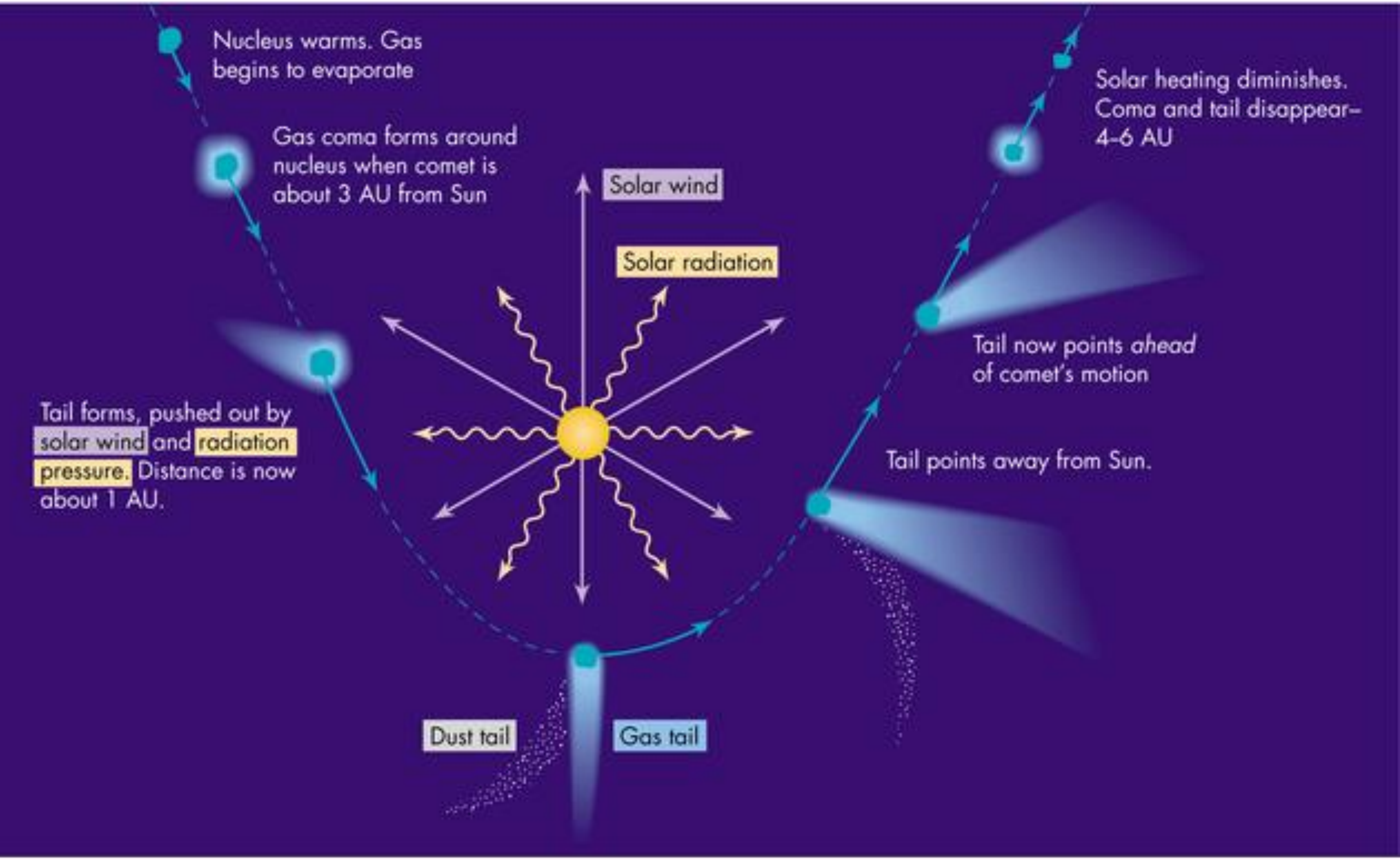
Required reading:

3 wikipedia articles on

- comet 1P/Halley (last apparition in 1986)
- comet Hyakutake (1996)
- comet Hale-Bopp (1997)

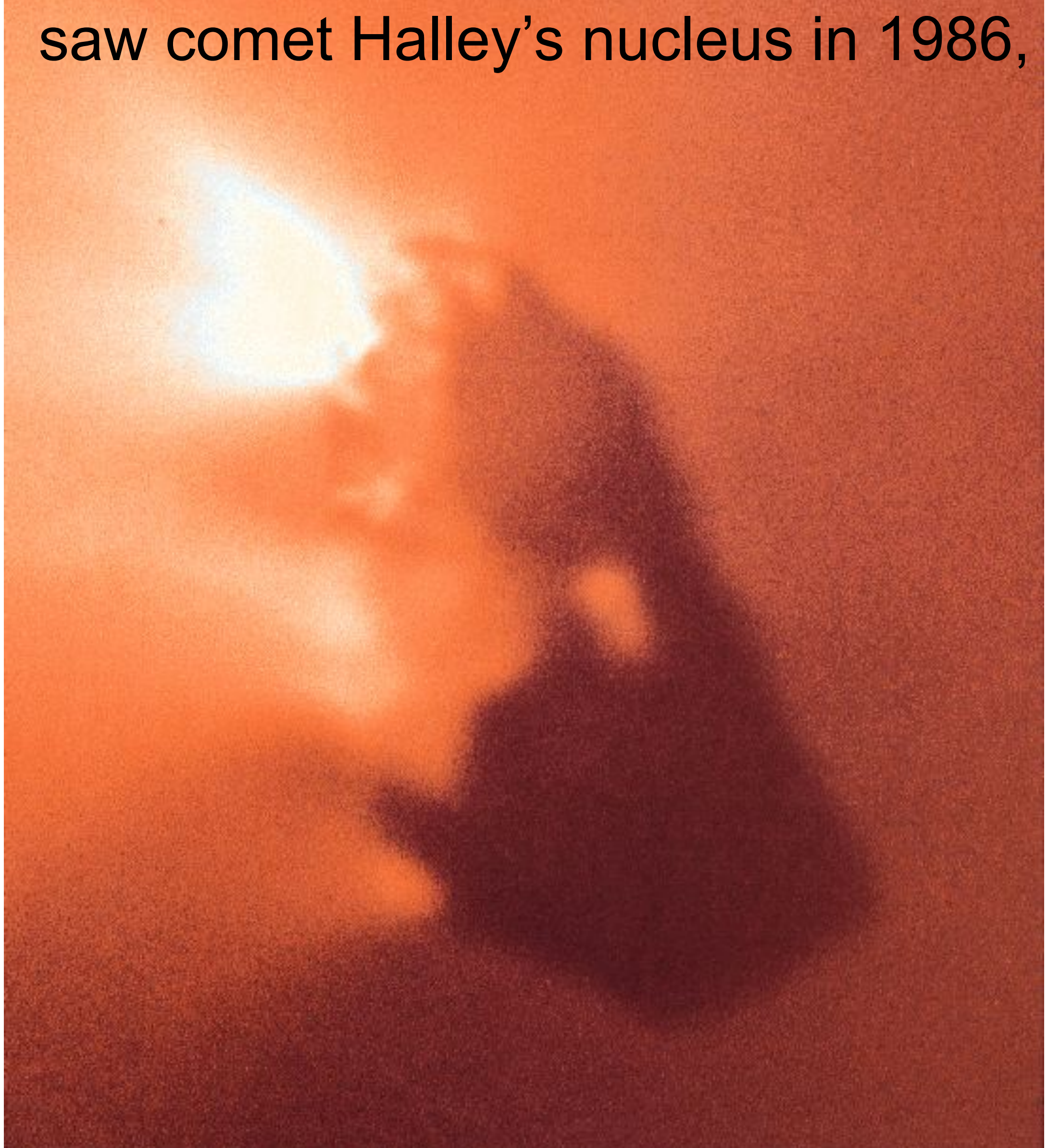
Why study comets?





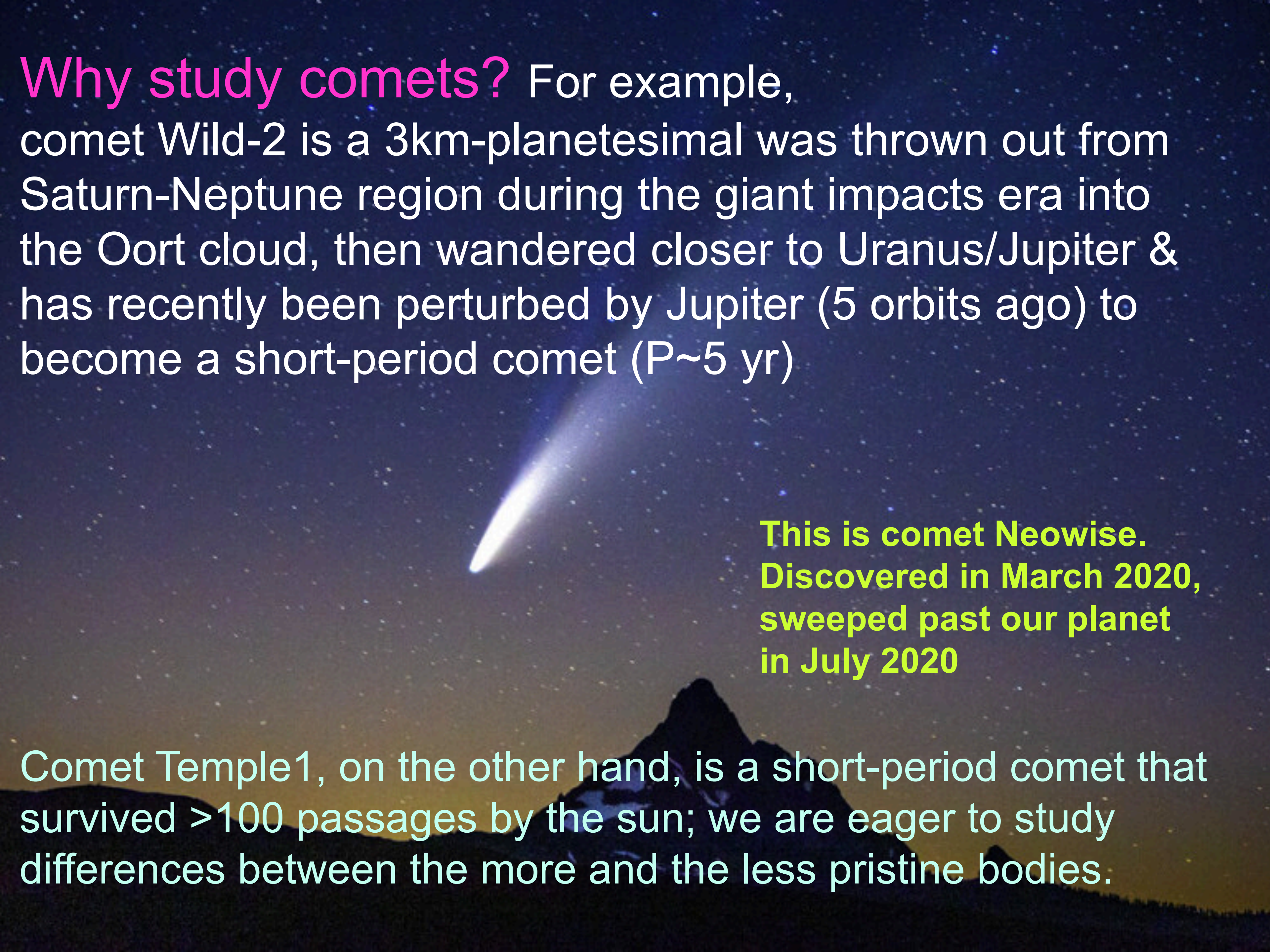
Nucleus warms. Gas begins to evaporate
Gas coma forms around nucleus when comet is about 3 AU from Sun
Solar wind
Solar radiation
Solar heating diminishes. Coma and tail disappear–4-6 AU
Tail now points *ahead* of comet's motion
Tail forms, pushed out by solar wind and radiation pressure. Distance is now about 1 AU.
Tail points away from Sun.
Dust tail
Gas tail


Gas tail
Dust tail
This is comet Hale-Bopp in 1997



European (ESA) Giotto mission saw comet Halley's nucleus in 1986, confirming the basic concept of comet nucleus as a few-km sized chunk of ice and rocks stuck together (here, in the form of a potato, suggesting 2 collided "cometesimals")

The bright jets are from the craters or vents through which water vapor and the dust/stones dragged by it escape, to eventually spread and form head and tail of the comet.



Why study comets? For example,

comet Wild-2 is a 3km-planetesimal was thrown out from Saturn-Neptune region during the giant impacts era into the Oort cloud, then wandered closer to Uranus/Jupiter & has recently been perturbed by Jupiter (5 orbits ago) to become a short-period comet (P~5 yr)

This is comet Neowise. Discovered in March 2020, sweeped past our planet in July 2020

Comet Temple1, on the other hand, is a short-period comet that survived >100 passages by the sun; we are eager to study differences between the more and the less pristine bodies.

Comet 2I/Borisov, the first interstellar comet & 2nd interstellar body was discovered by Gennadiy Borisov, a Russian technician doing maintenance on scientific telescopes for work, and building his own telescopes as a hobby. He found to comet in 2019 from his backyard in the town of Nauchnyi, Crimea. The comet passed the perihelion at the distance 2.000669 AU from the sun covering 42.882 km/s, from which you can derive eccentricity e=3.357 >> 1

2I/Borisov will slow down to 32.3 km/s when far-away from sun.

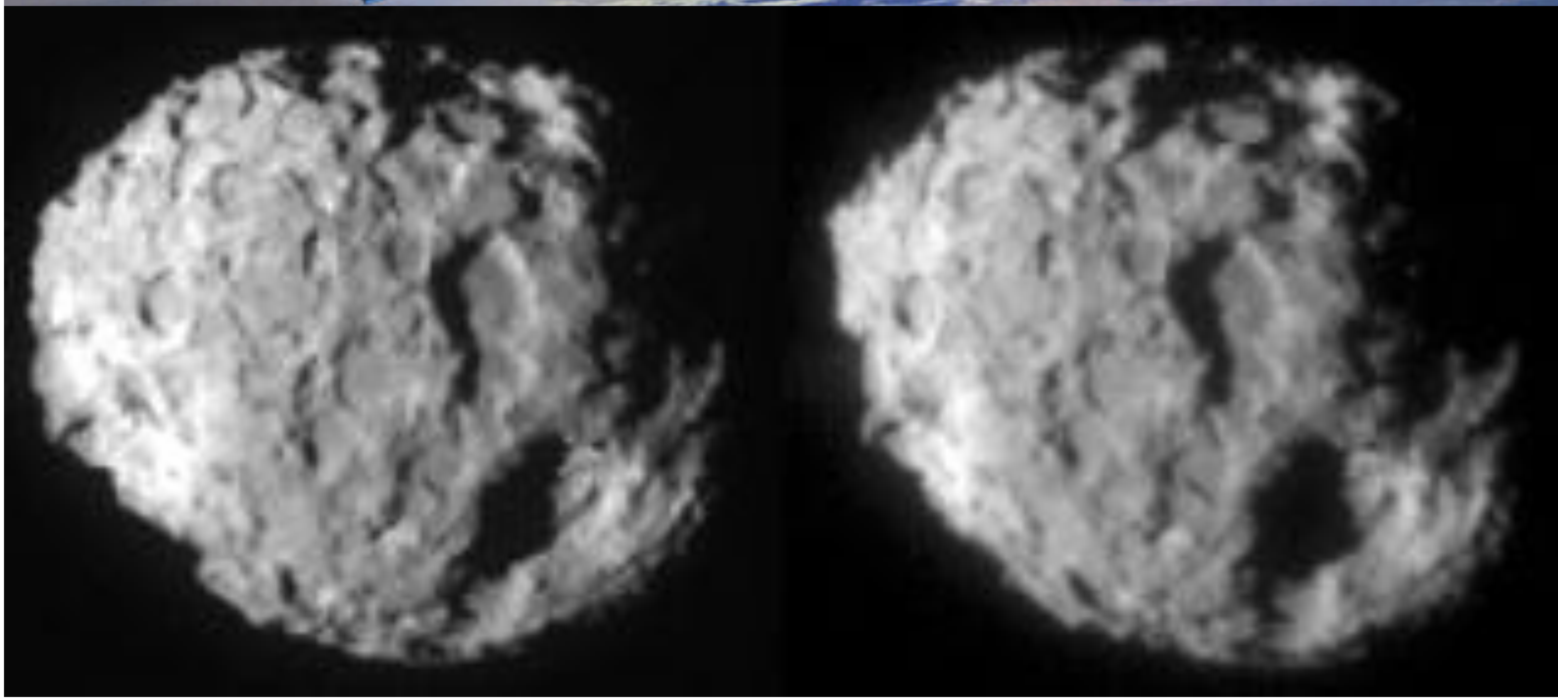
2I/Borisov - viewed by Hubble Space Telescope as it quickly passes a di
background galaxy.

In 2020 the comet underwent multiple events of 2x brightening, suggesting possib
fragmentation caused by solar heating of ices under its surface.

Can we orbit and sample a comet's nucleus?

Borrely-1   imaged by NASA in 2001

Stardust NASA mission - reached comet Wild-2 in 2004



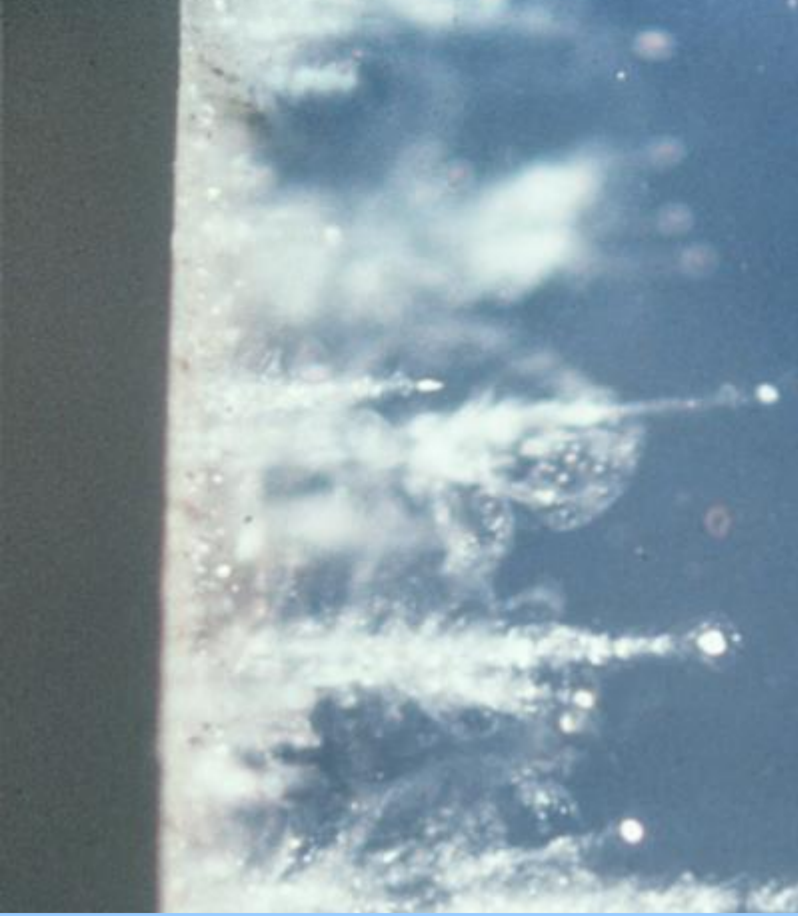
Storeoscopic view of comet Wild-2 captured by Stardust

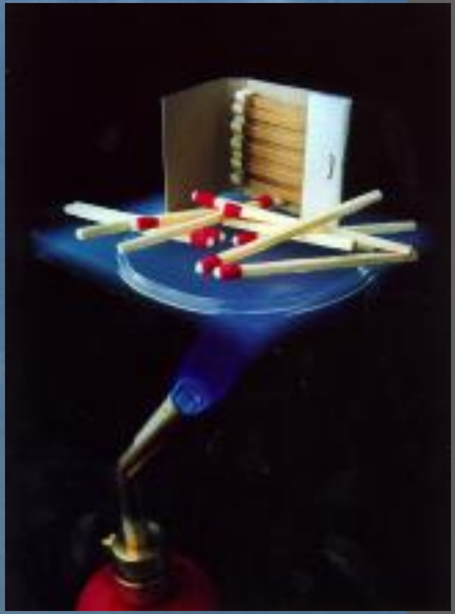
http://stardust.jpl.nasa.gov/index.html and in particular:
http://stardust.jpl.nasa.gov/mission/index.html
http://stardust.jpl.nasa.gov/science/details.html


STARDUST
NASA's COMET SAMPLE RETURN MISSION


Proposed October 14, 1994
Launched February 7, 1999
Encountered Wild 2 January 4, 2004
Earth Returned January 15, 2006
$200M Including Launch Vehicle

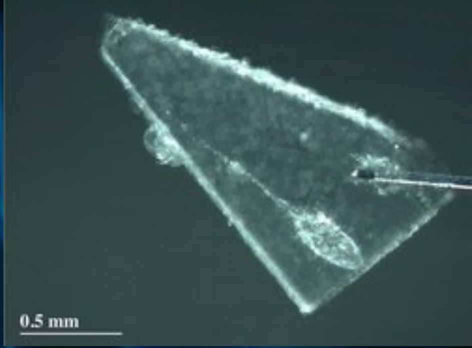
Stardust NASA mission - reached comet Wild-2 in 2004





The probe also carried aerogel - a ghostly material that NASA engineered (like a transparent, super-tough styrofoam, 2 g of it can hold a 2.5 kg brick - see the r.h.s. picture).
Aerogel was used to capture cometary particles (l.h.s. picture) which came back and landed on Earth in Jan. 2006.

Particle Track Profiles

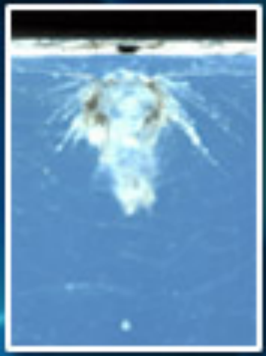


8.5 & 11mm

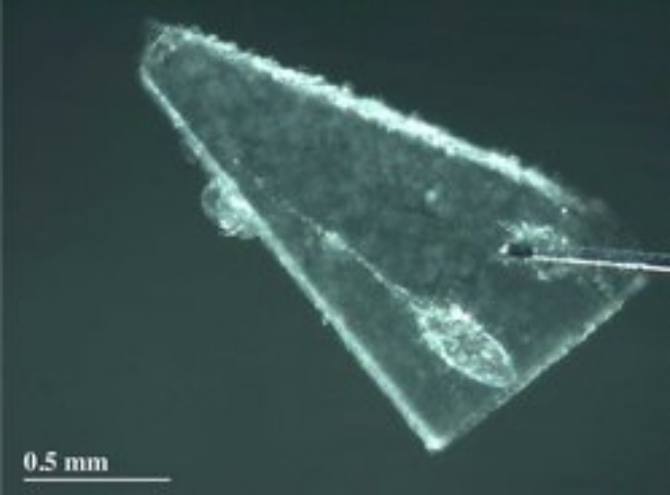
11.7mm

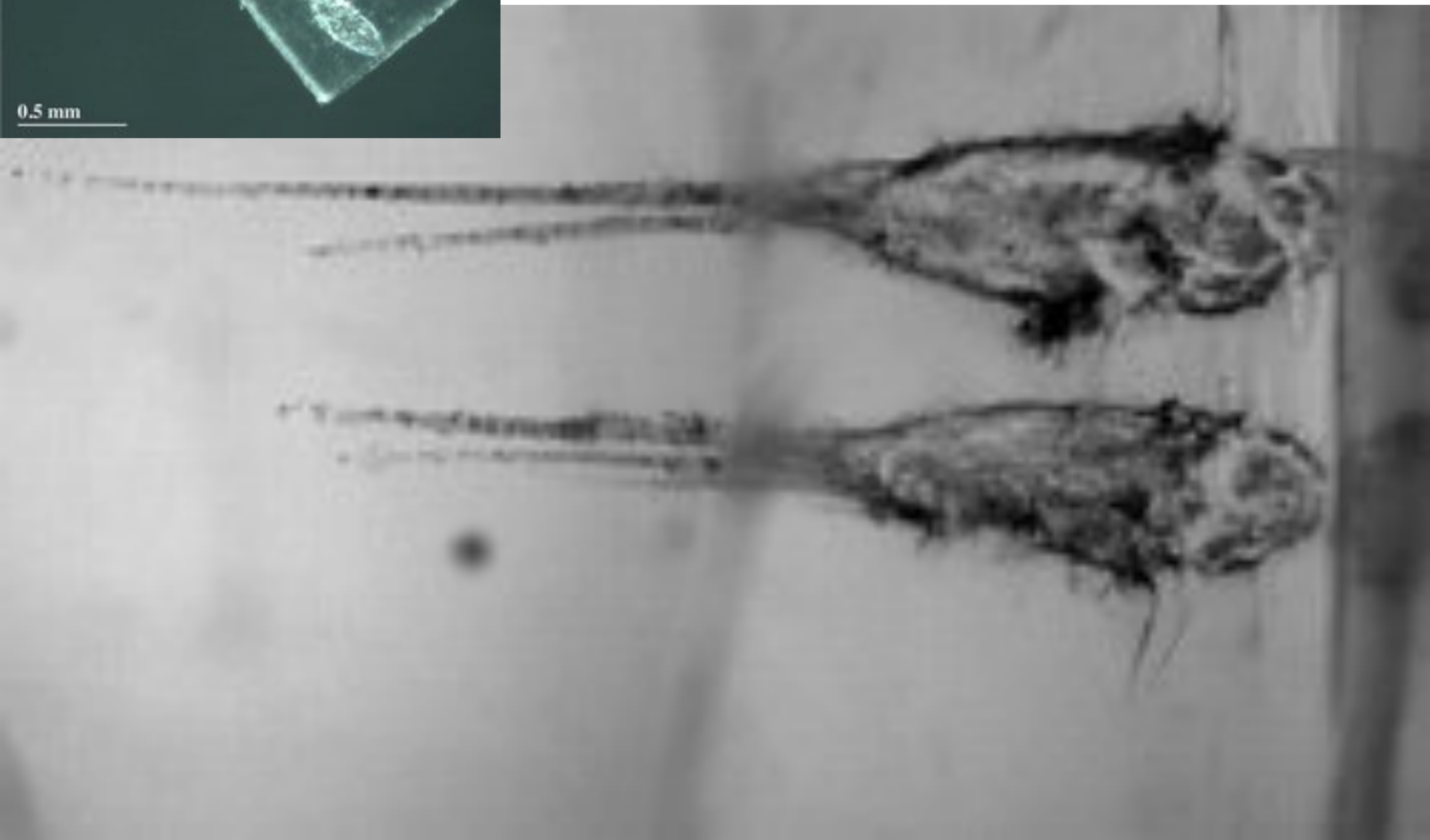
8mm

6mm



3.6mm

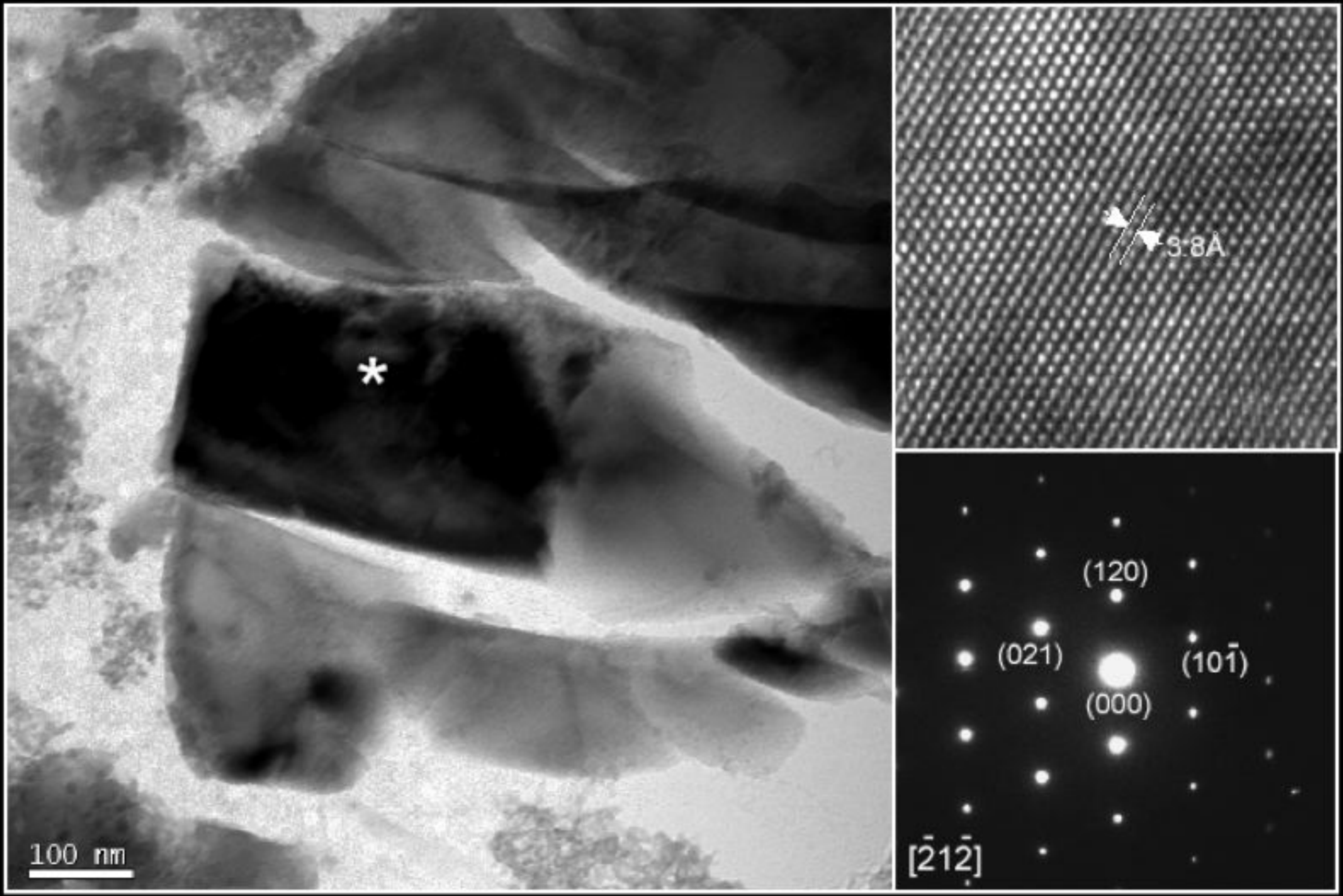




Tracks in aerogel, Stardust sample of dust from comet Wild 2. That comet was residing in the outer solar system until a close encounter with Jupiter in 1974.

Stardust sample 7-10-9c-(1-4) LICE forsterite

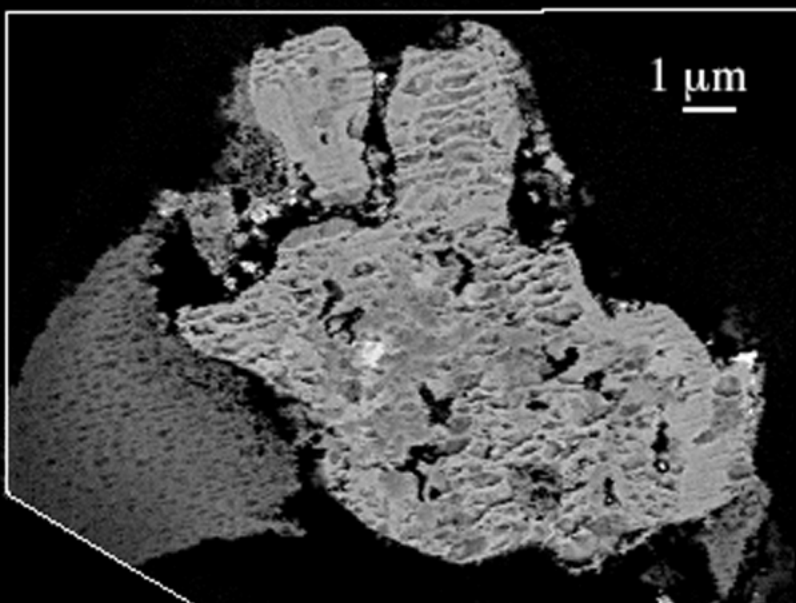
crystal structure verification



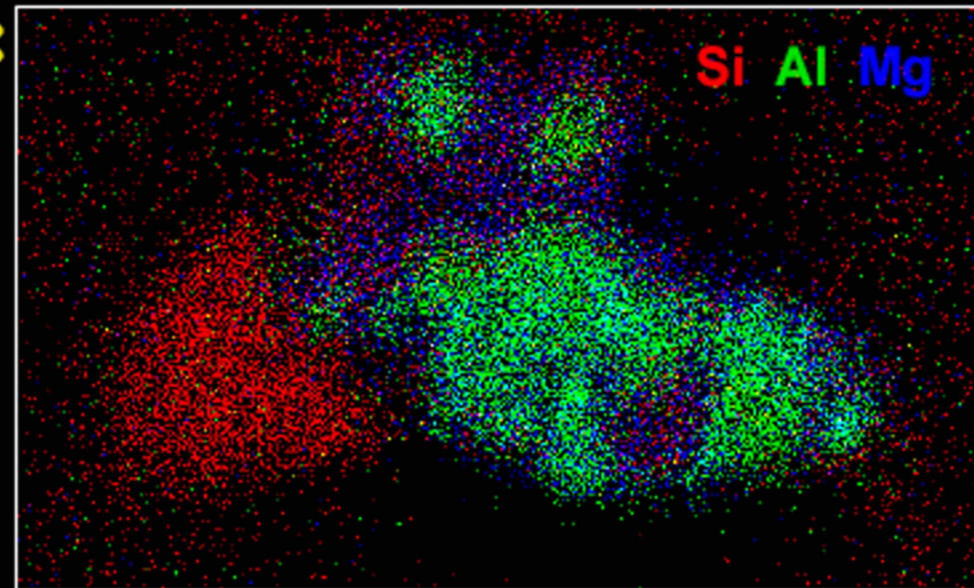
Crystal structure - orthorhombic *Pbnm (62)* a = 4.753Å, b = 10.190Å, c = 5.978Å

SEM-EDS X-ray Maps: overlay maps

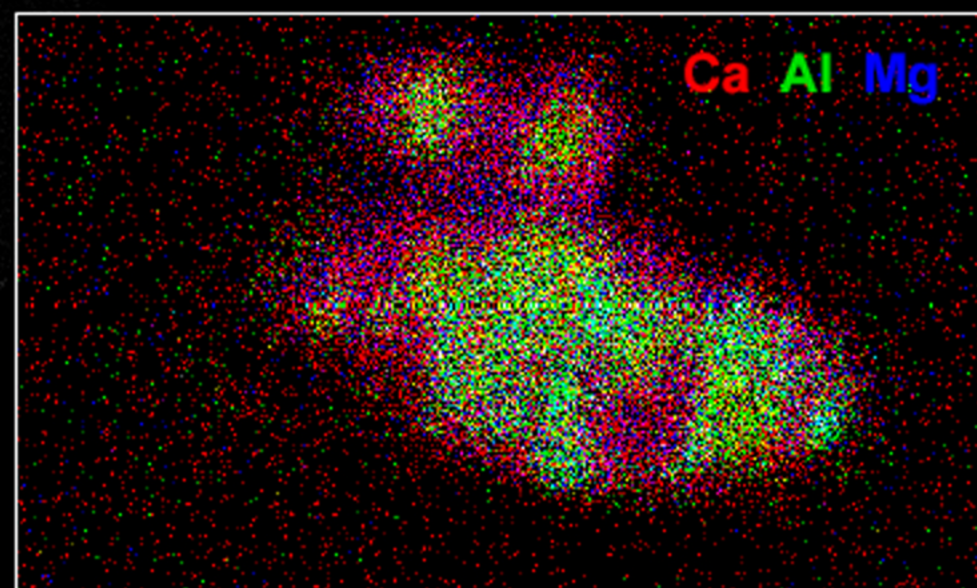
"Easter" C054.4.25.0
potted butt in acrylic



BSE image, 4.0 kV, high contrast



EDS X-ray maps, 10 kV



OLIVINES, Mg-Fe silicate solid state solutions (also found by Stardust) are the dominant building material of both our and other planetary systems.

Forsterite, Mg_2SiO_4

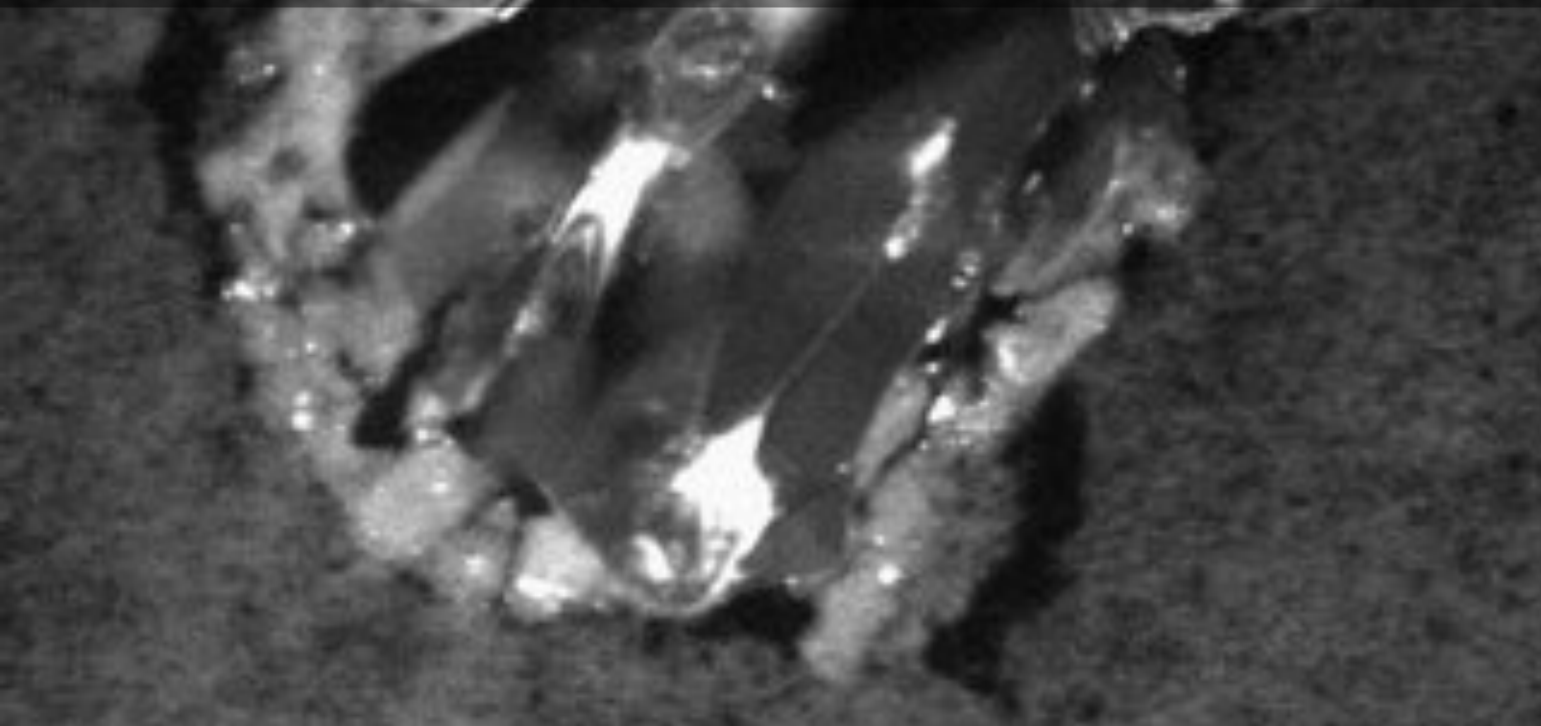
Fayalite, Fe_2SiO_4

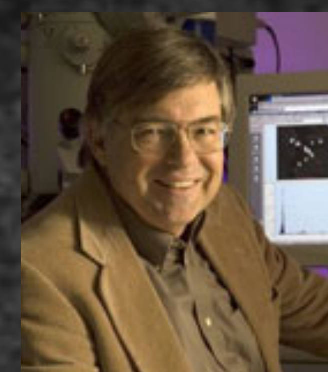
Evidence of outward migration of dust in the solar nebula?

"I would say these materials came from the inner, warmest parts of the solar system or from hot regions around other Stars.

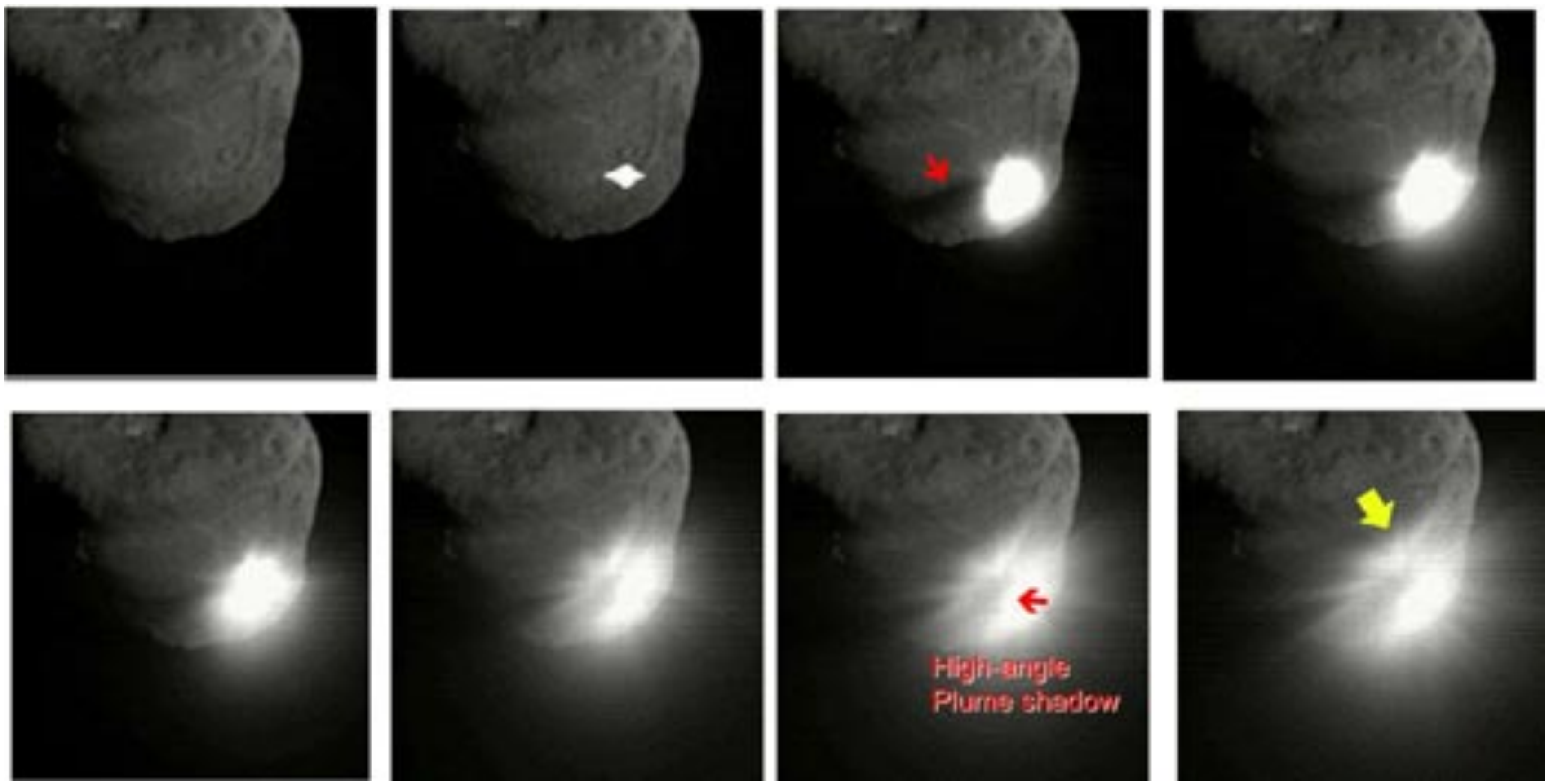
The issue of the origin of these crystalline silicates recovered from Wild 2 still must be resolved. "

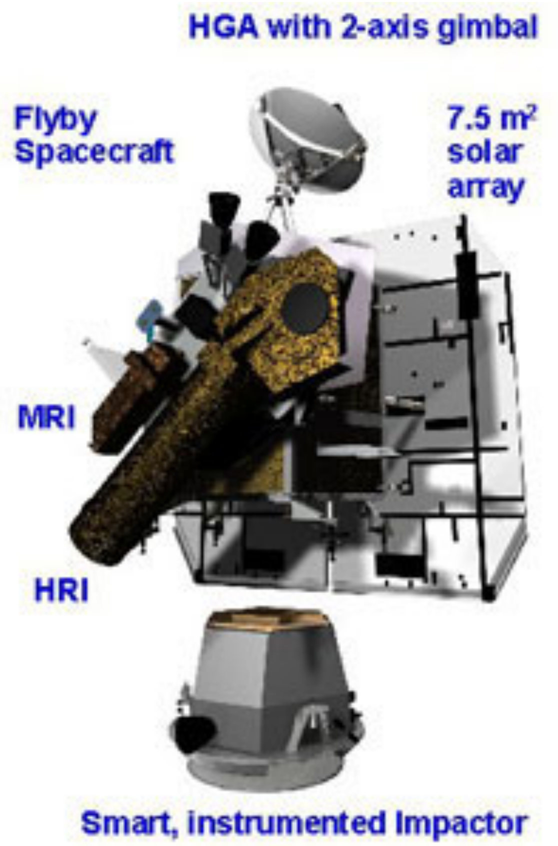
D. Brownlee (2006)





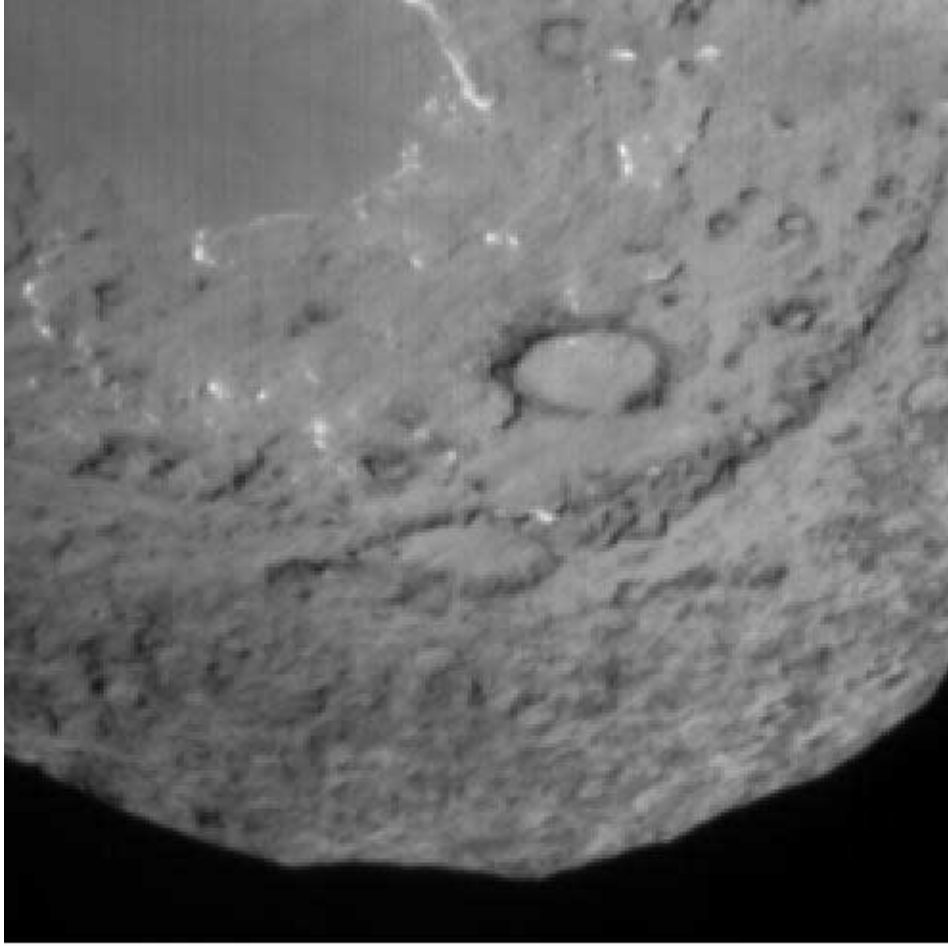
Deep Impact NASA probe - impacted comet Tempel1 on July 4, 2005 (v =10.2 km/s) - *see the movie frames of the actual impact of the probe taken by the main spacecraft, taken 0.83s apart. The study showed that Temple1 is porous: the impactor dug a deep tunnel before exploding.*





Comet Temple 1 nucleus

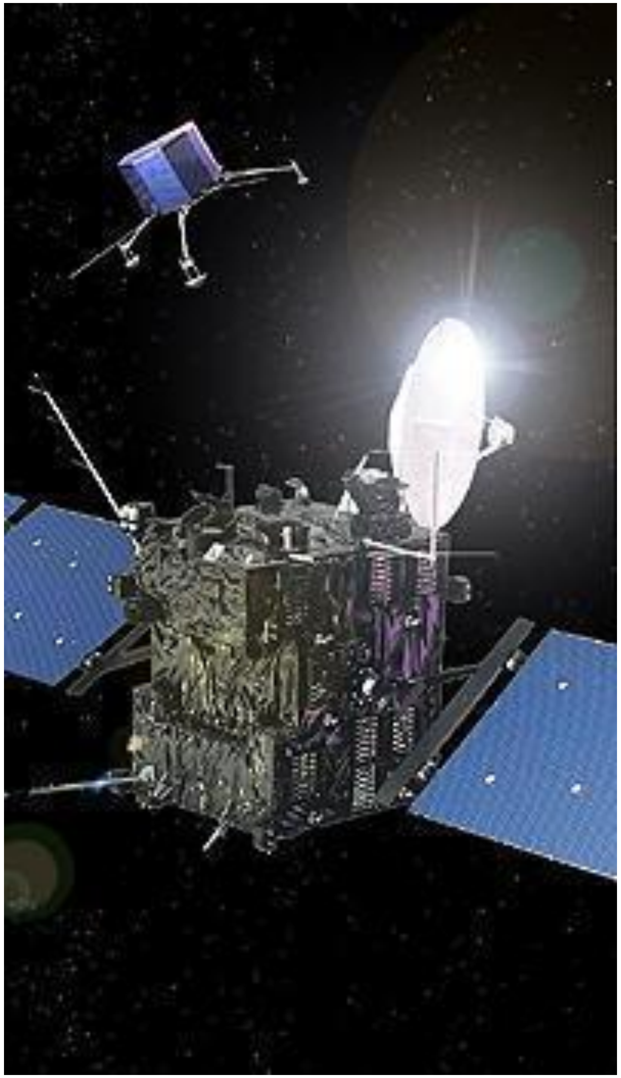
~10m resolution



Here is the Deep Impact description (cut & paste URL)
http://deepimpact.jpl.nasa.gov/home/index.html

See http://stardust.jpl.nasa.gov/science/feature001.html on the differences between comets Wild-2 and Temple 1.

http://rosetta.esa.int



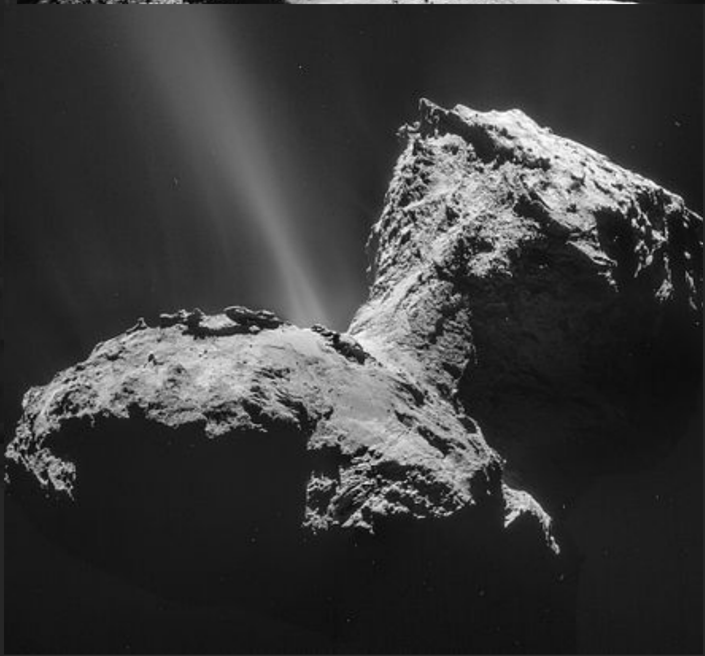
Rosetta mission by ESA (European Space Agency)

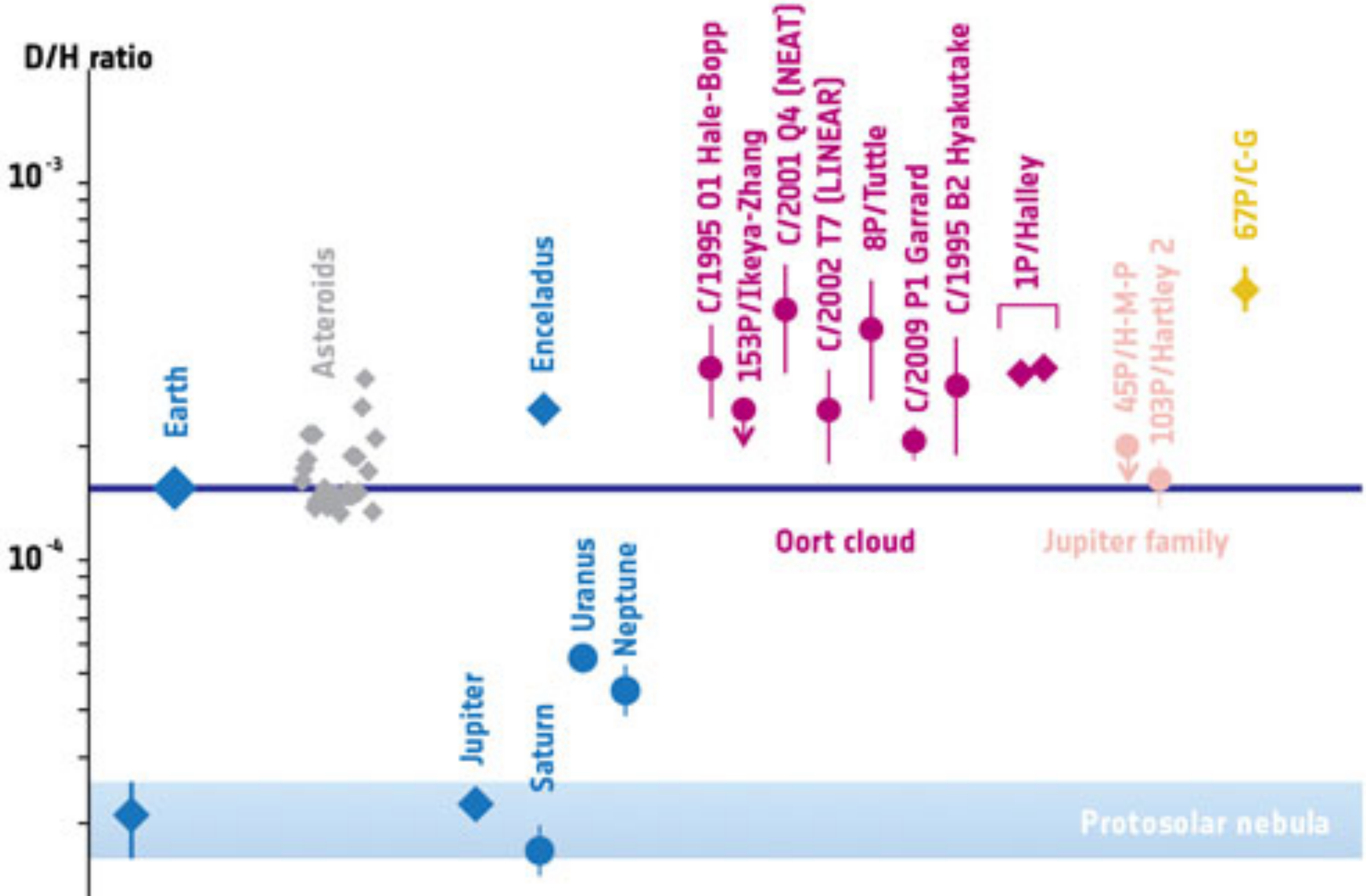
In the vicinity of Mars Rosetta flew by asteroids Steins and Lutetia

After the arrival at the comet Churyumov-Gerasimenko in 2014, the spacecraft *entered an orbit* around the comet and continued the journey together.

A lander *descended* onto the surface.

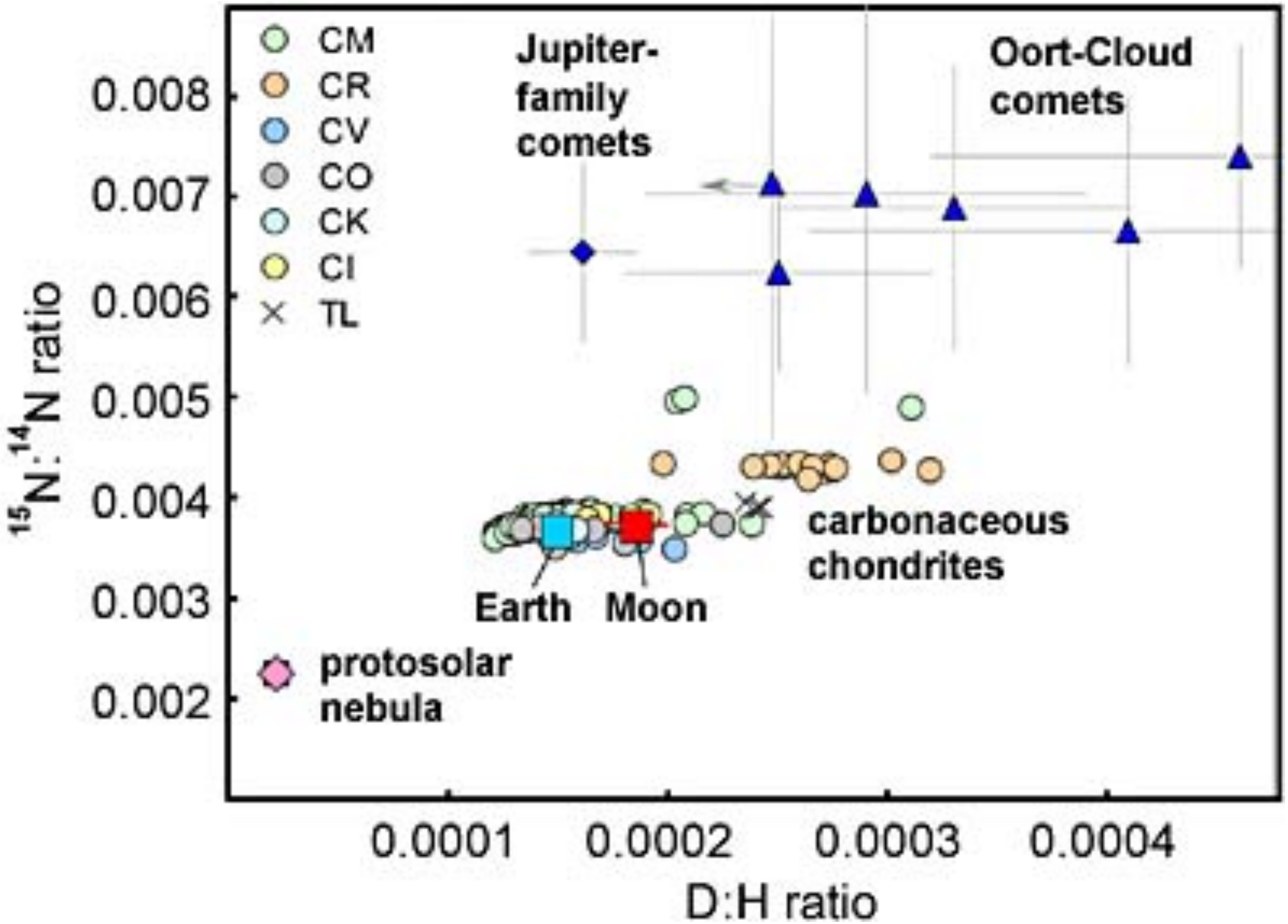
Comet 67P/Churyumov-Gerasimenko *seen in 2014 by Rosetta space probe from the distance of only 198 km down to 10 km*



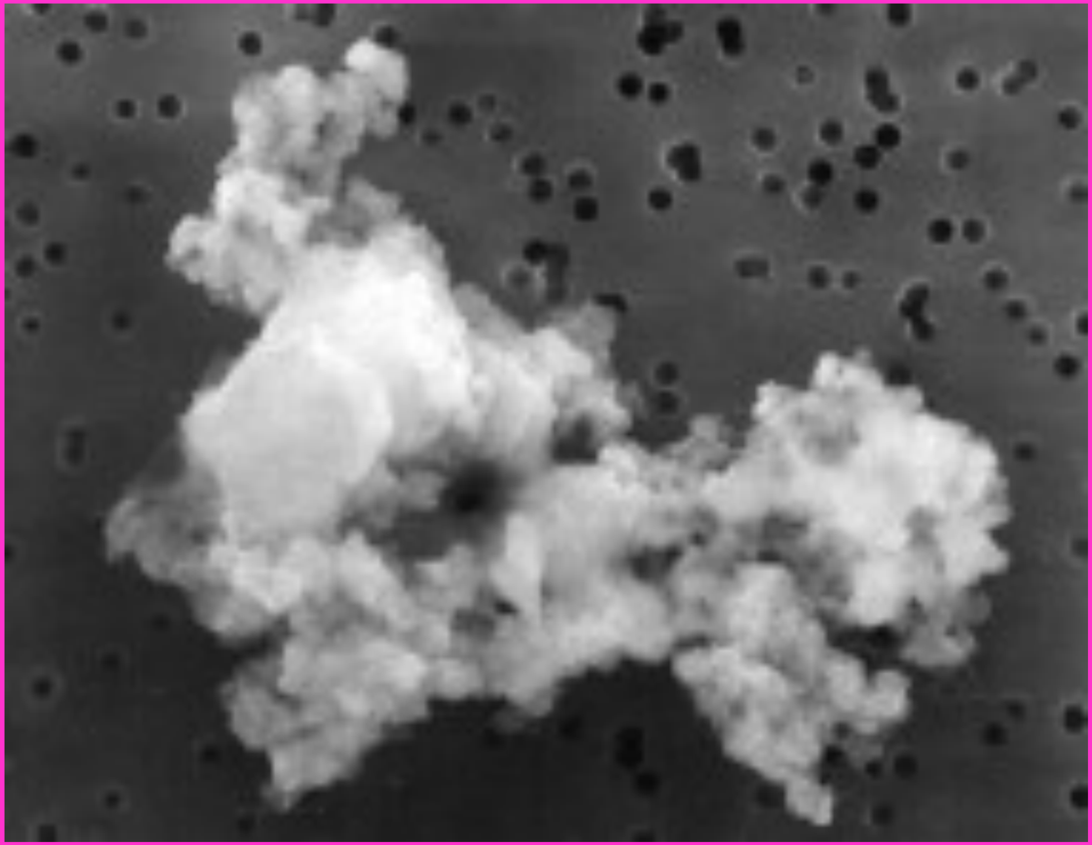


Q: Where does water on Earth come from?

Q: Where does water on Earth come from?



IDPs
Interplanetary Dust Particles



10 µm

From:Ch.2, textbook

IDP (cometary origin?)

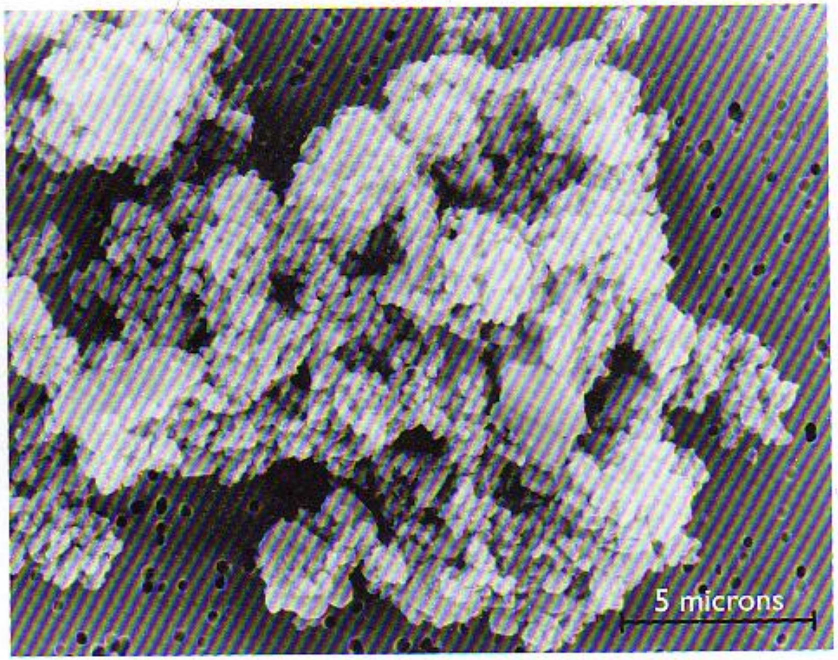


Figure 6. In this scanning electron microscope image, all the minerals, organic compounds, and amorphous materials in an interplanetary dust particle look the same. However, isotopic analysis reveals that some components of this dust actually solidified in interstellar space long before our Sun and its planets formed.

Chonditic meteorite

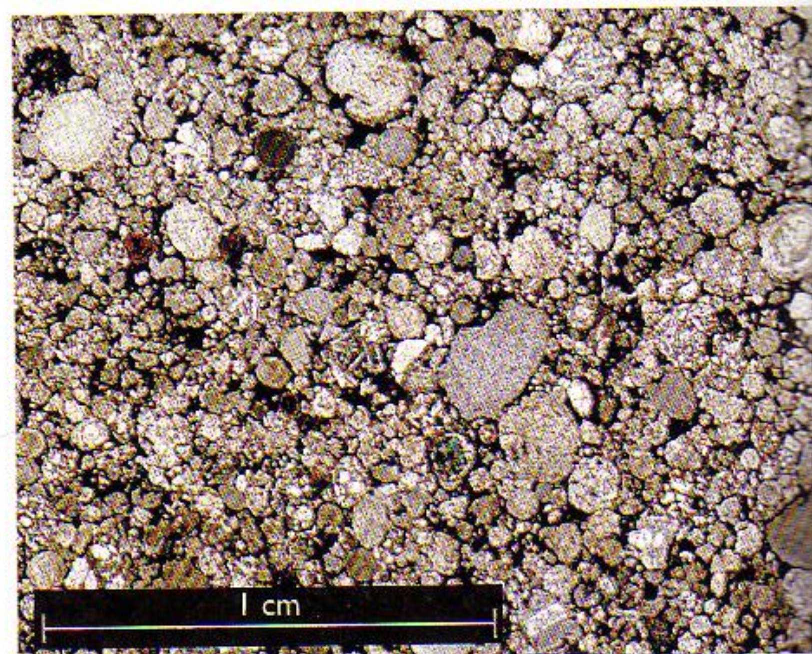
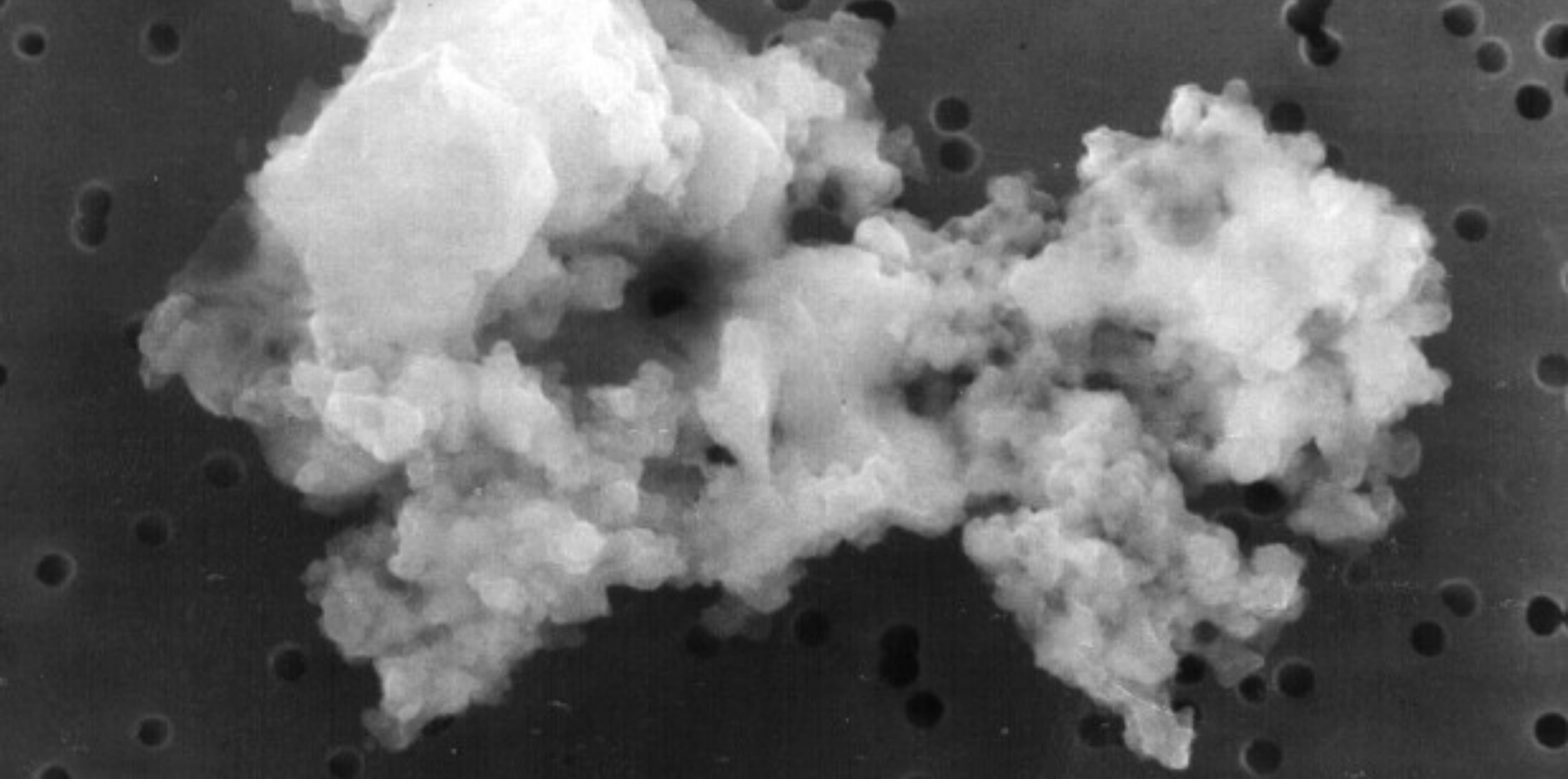


Figure 7. A 2-cm-wide section of the Mezö-Madaras chondrite, a tightly compacted mass of spheroidal and more irregular chondrules that fell near Harghita, Romania in 1852. Each chondrule formed as an independent igneous system. The sectio has been ground so thin, about 30 microns, that most of its minerals appear transparent when light shines through it.

Brownlee particles collected in the stratosphere are IDPs

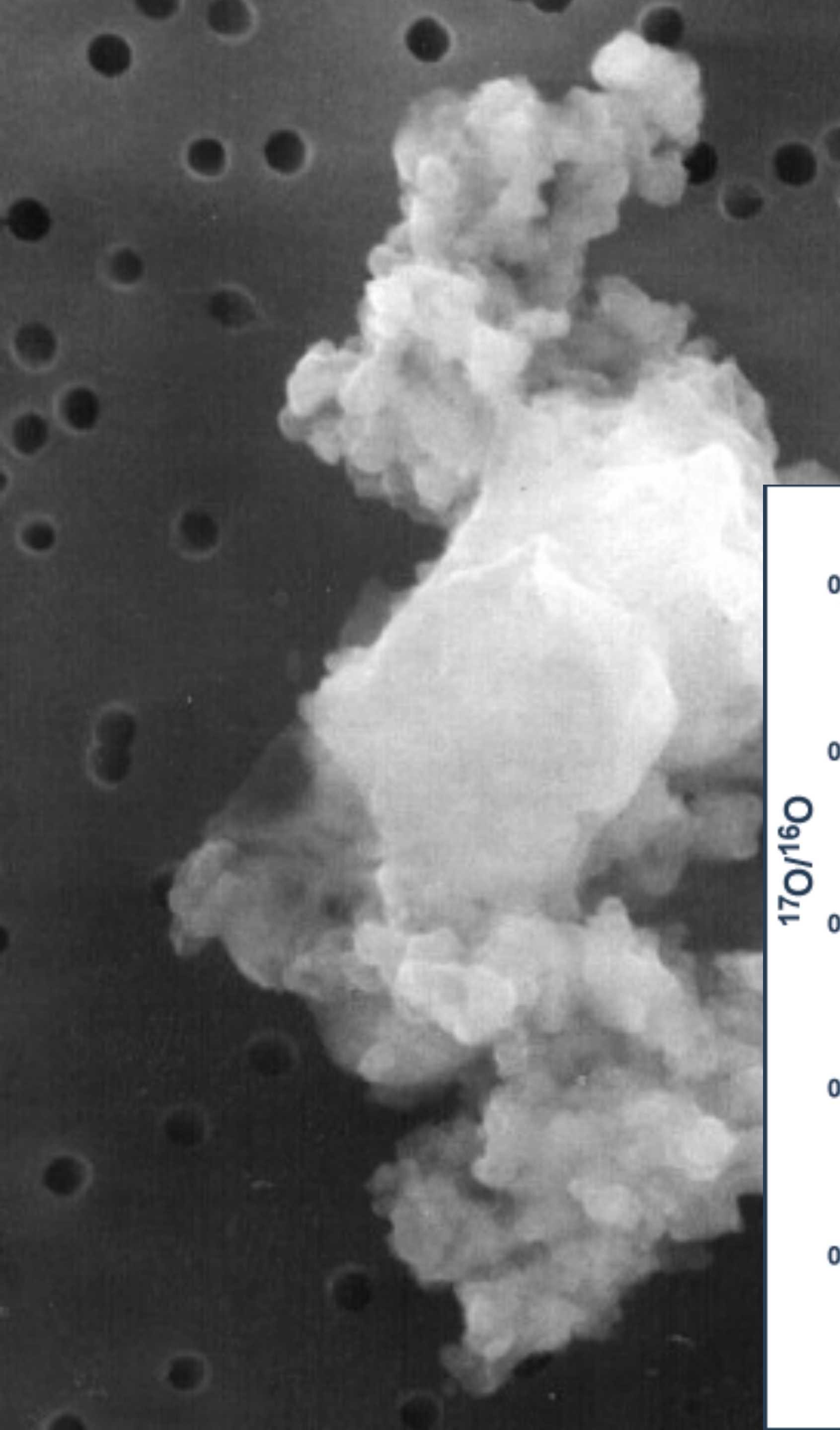
Donald Brownlee, UW

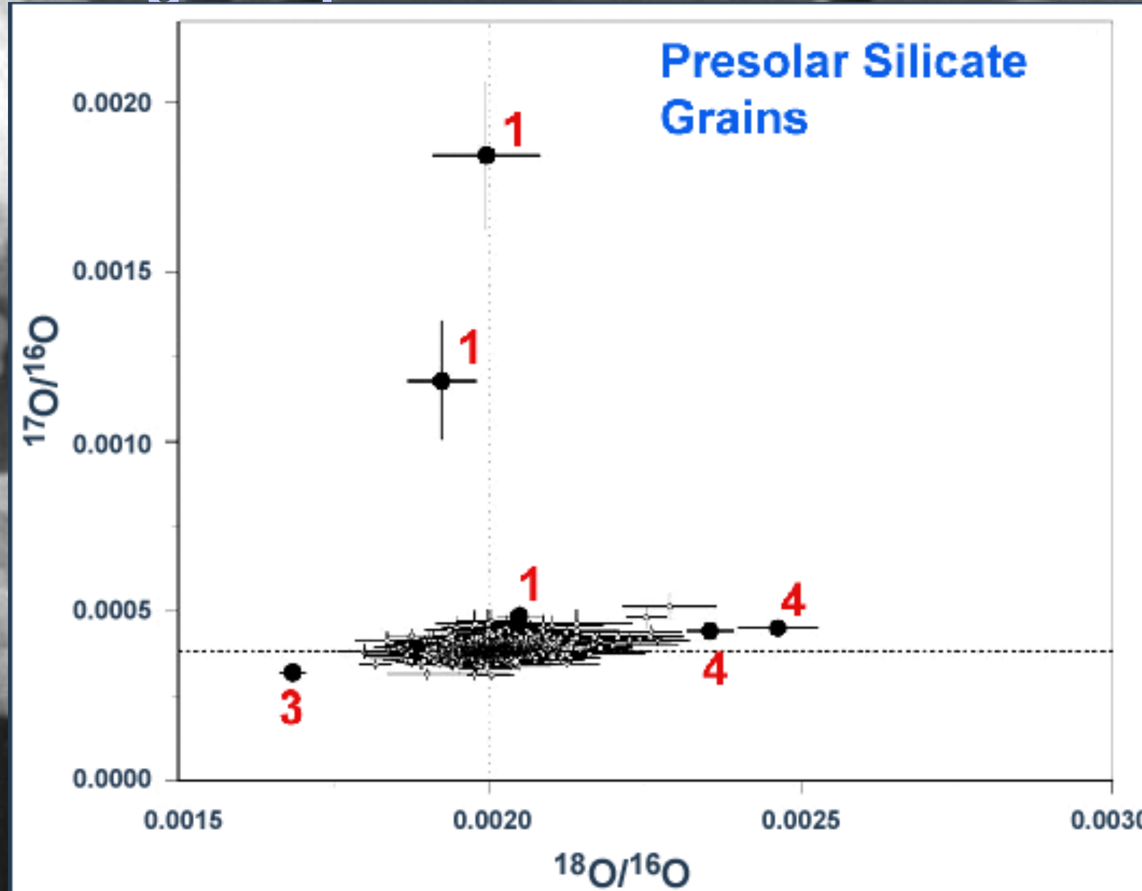
Brownlee particle



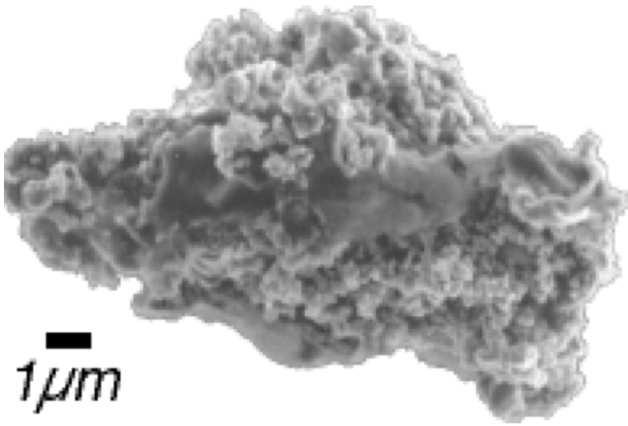
Brownlee particle

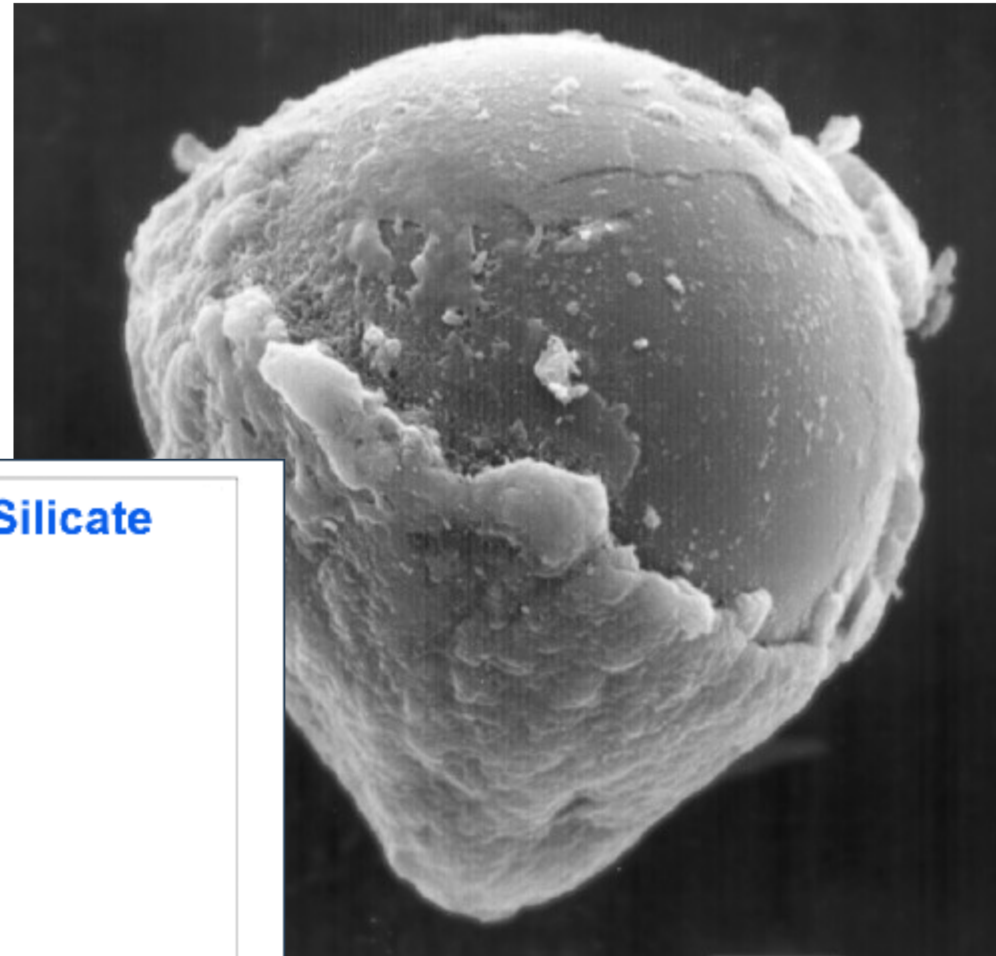
A few out of a thousand subgrains shows isotopic anomalies, e.g., a O(17) to O(16) isotope ratio 3-5 times higher than all the rest - a sign of pre-solar nature.

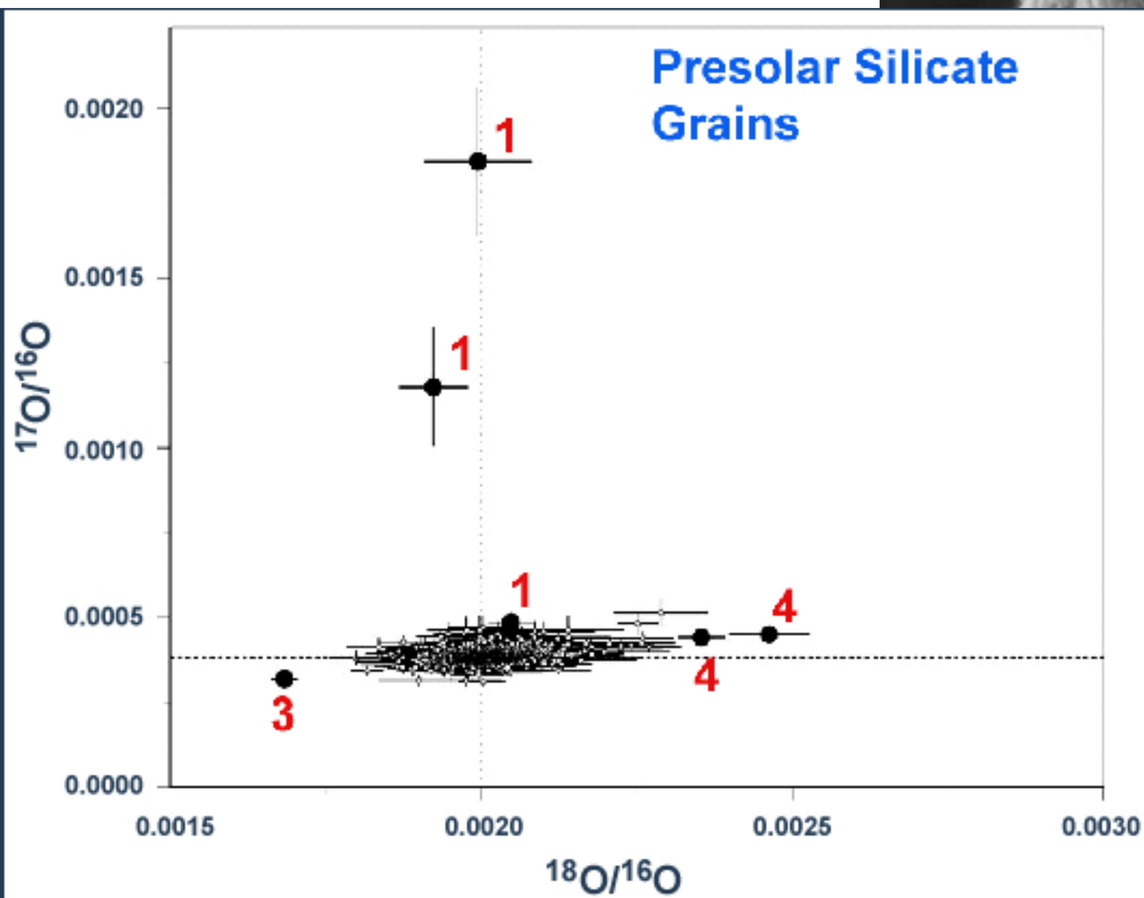




(From Messenger *et al.*, 2003, *Science*, v. 300, p. 105-108.)

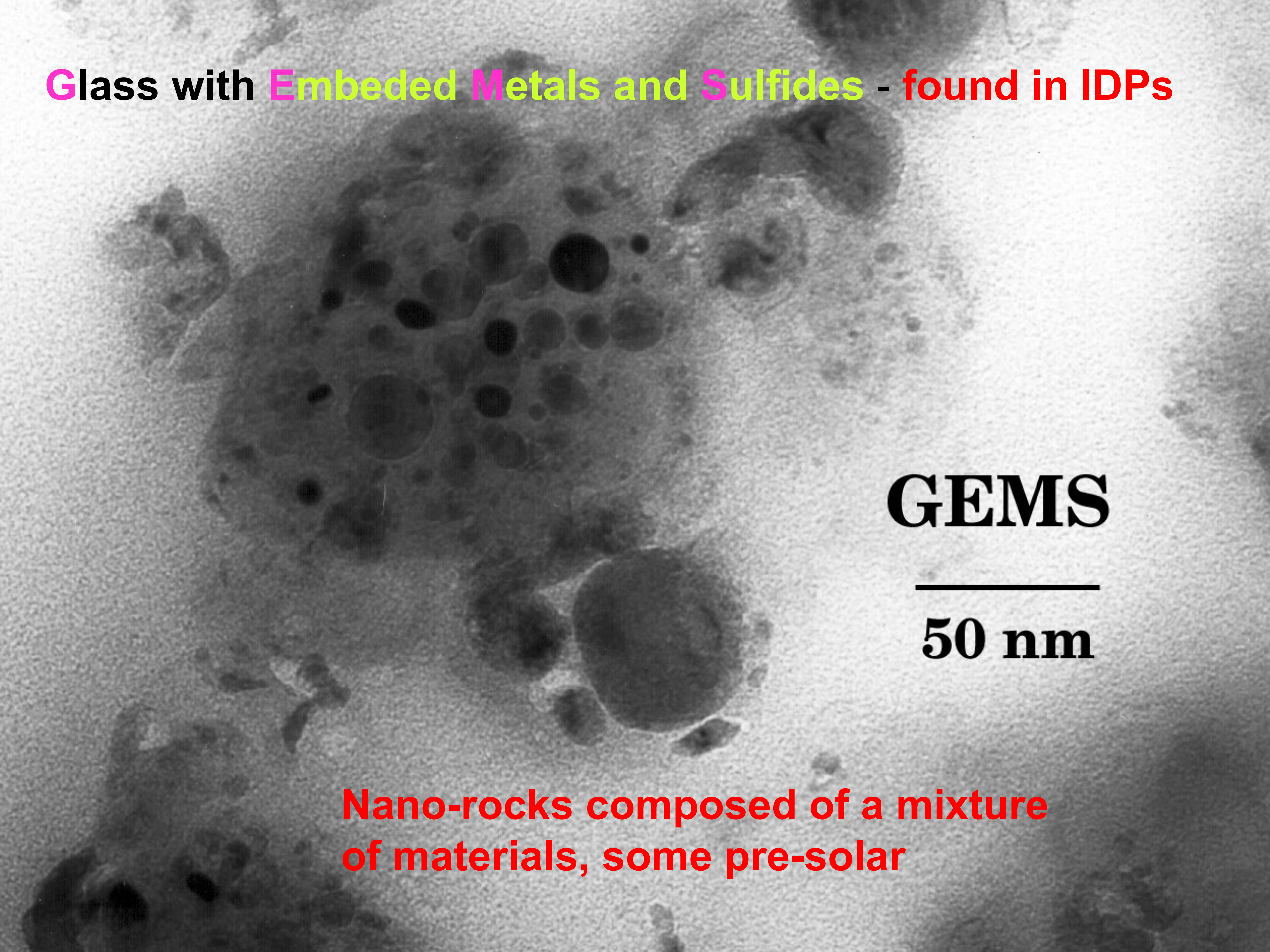




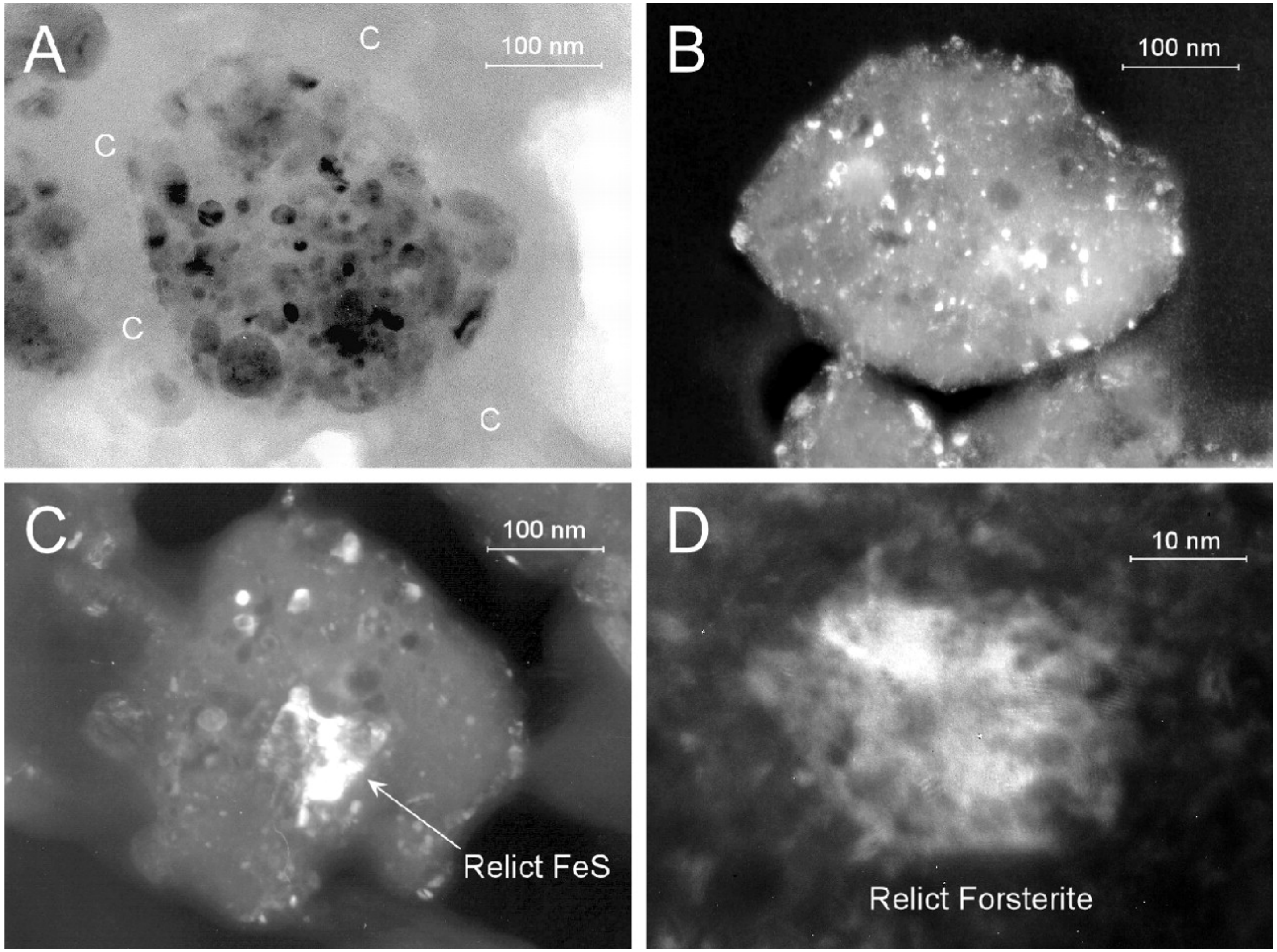


(From Messenger *et al.*, 2003, *Science*, v. 300, p. 105-108.)

Glass with Embeded Metals and Sulfides - found in IDPs



Nano-rocks composed of a mixture of materials, some pre-solar



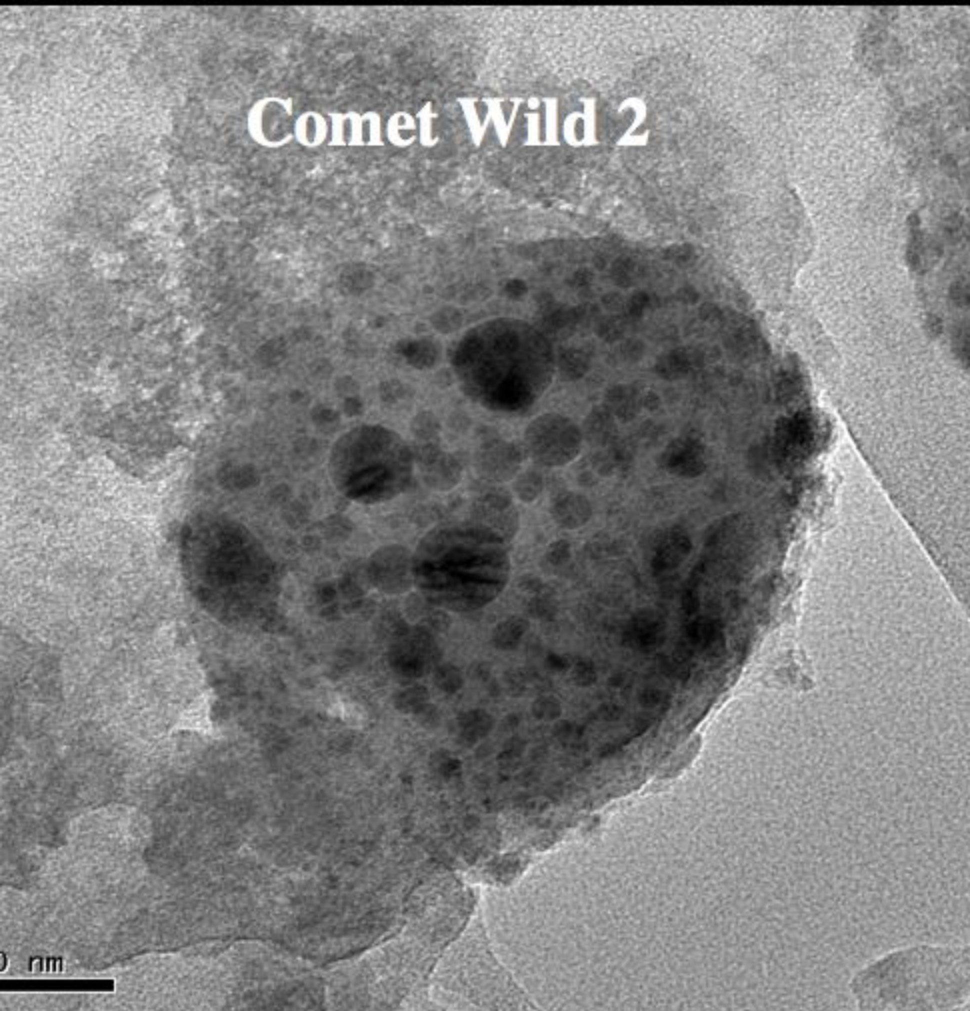
Out of this world

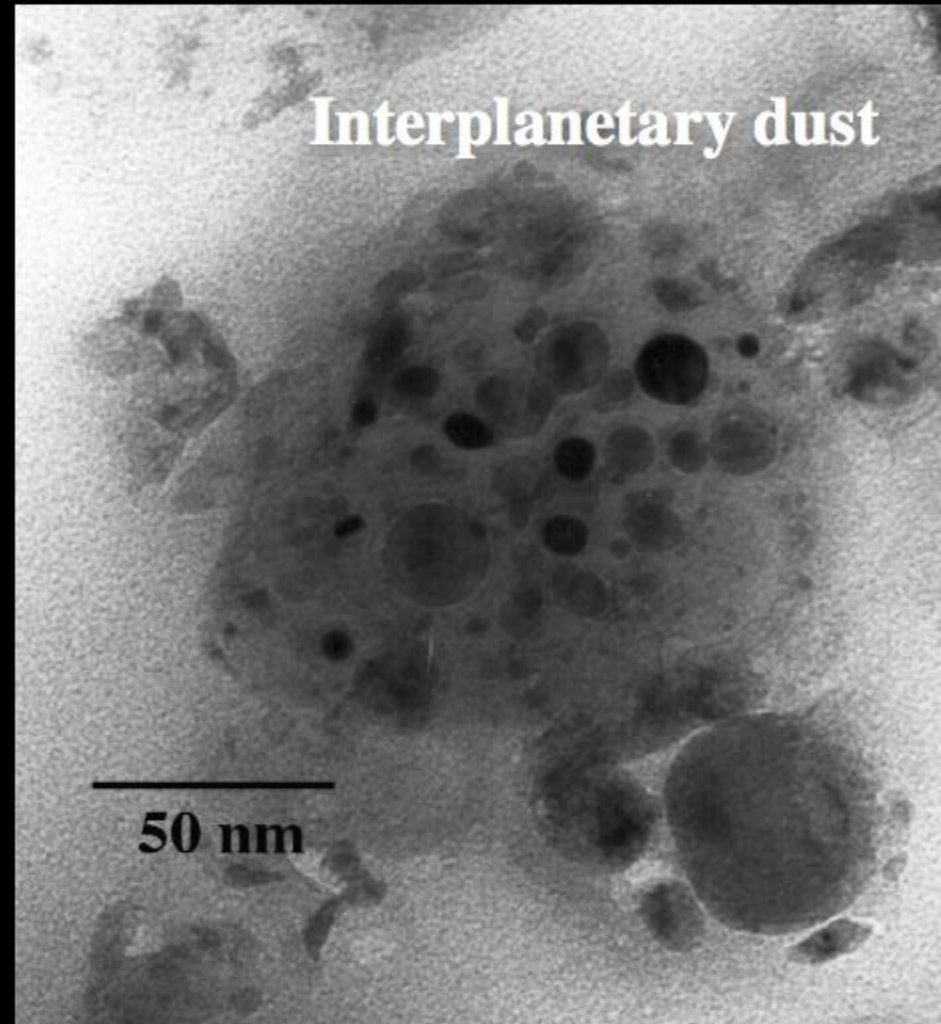
(pre-solar isotopes, composition of GEMS)

Figure 1. Transmission electron micrographs of GEMS within thin sections of chondritic IDPs. (**A**) Bright-field image of GEMS embedded in amorphous carbonaceous material (C). Inclusions are FeNi metal (kamacite) and Fe sulfides. (**B**) Dark-field image. Bright inclusions are metal and sulfides; uniform gray matrix is Mg-rich silicate glass. (**C** and **D**) Dark-field images of GEMS with "relict" Fe sulfide and forsterite inclusions.

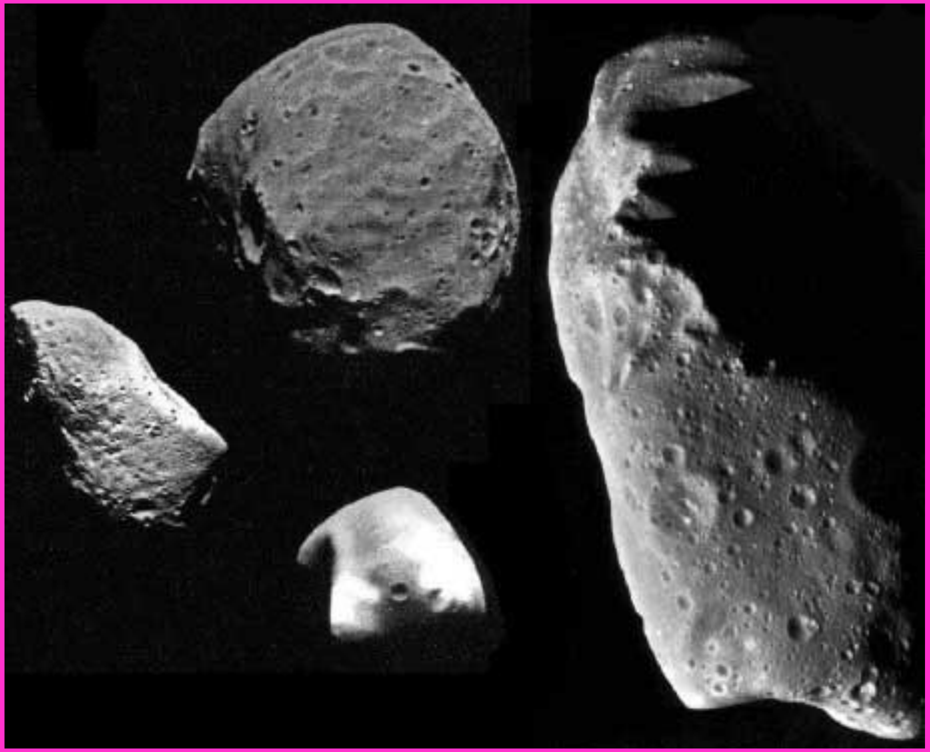
GEMS ?

(Glass with Embedded Metal and Sulfides)





Asteroids

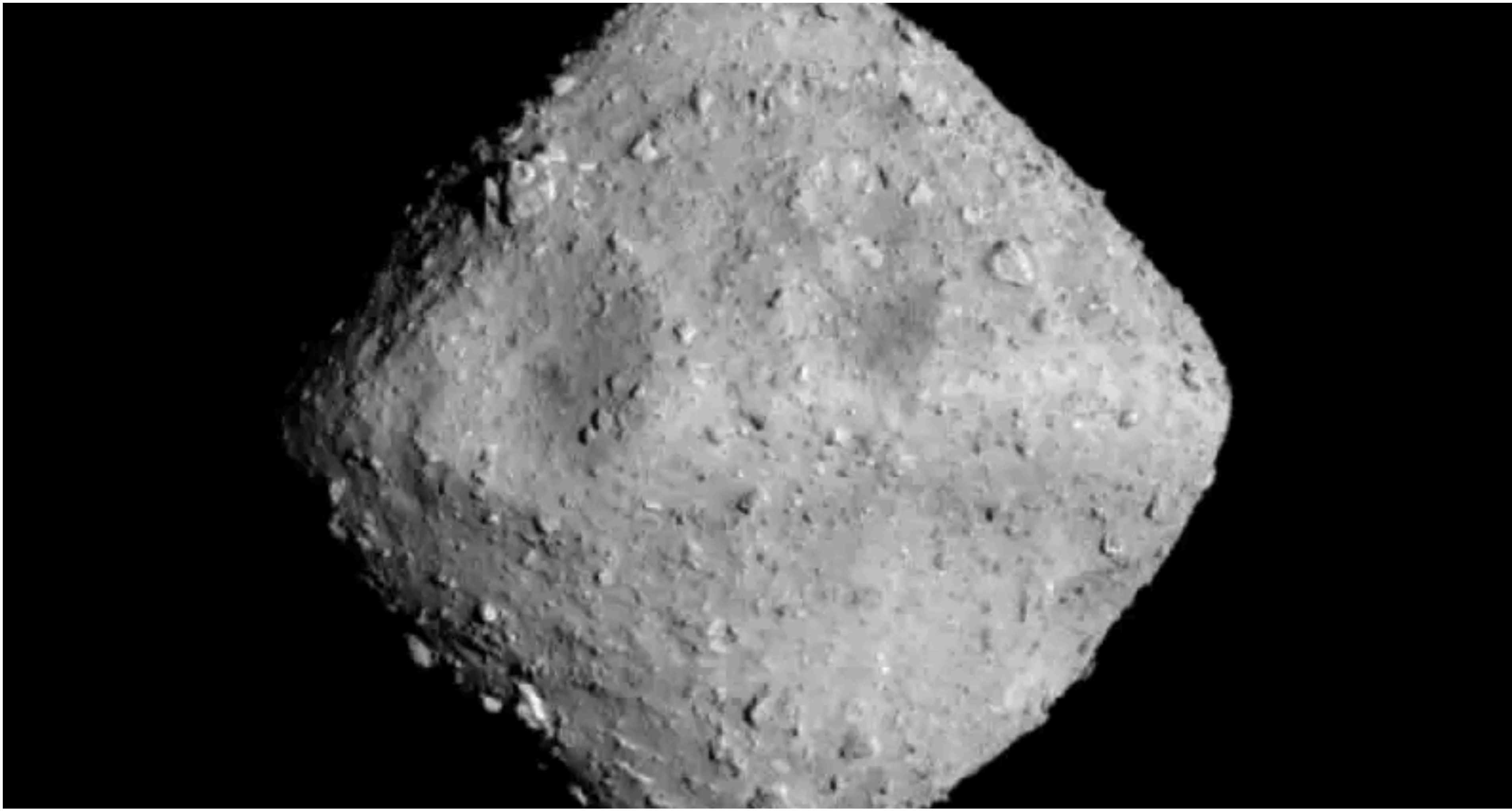


Additional reading:

1. **the Lissauer + dePater book**

2. See
http://www.nineplanets.org/asteroids.html

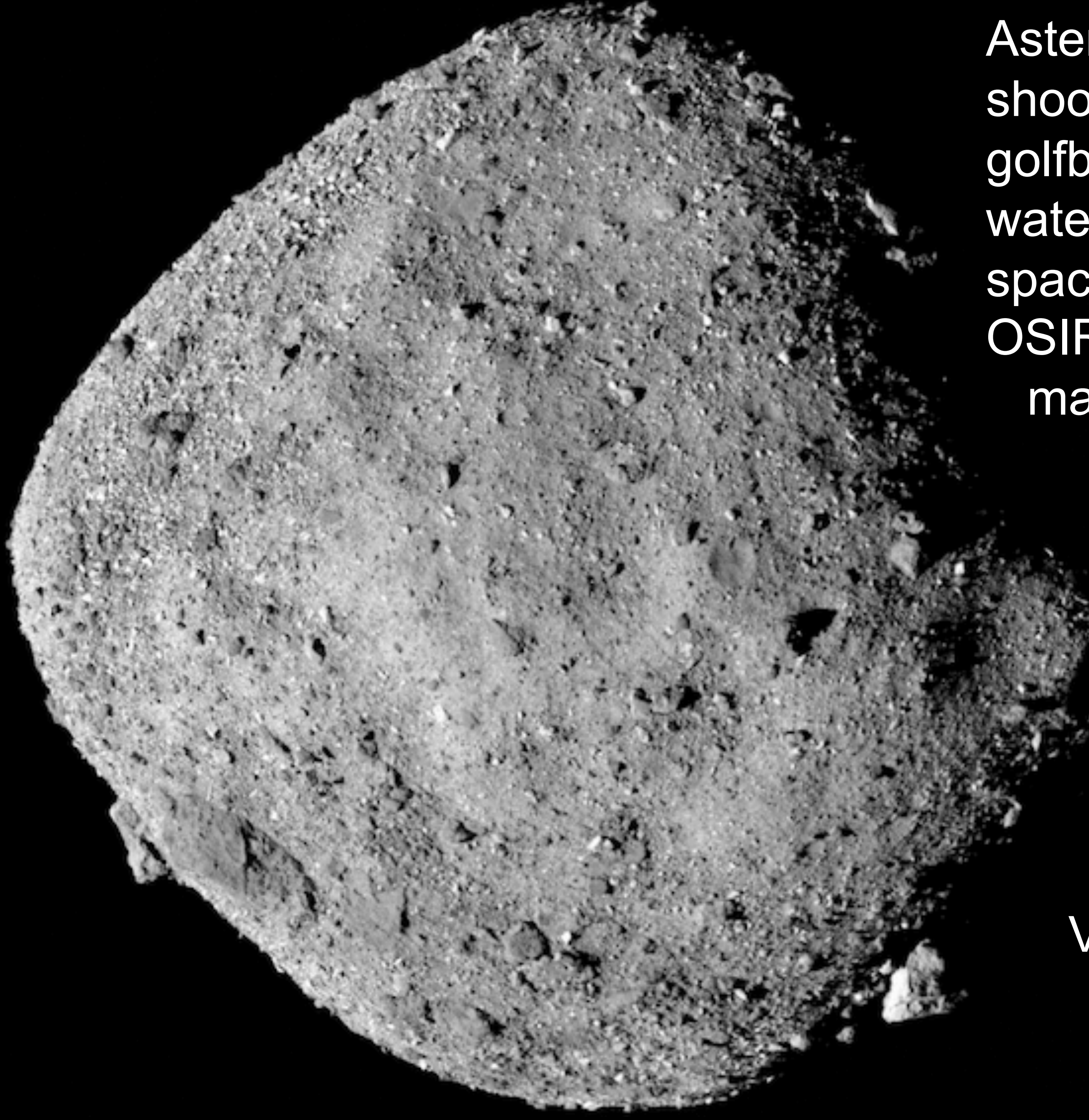
A Japanese spacecraft bombed an asteroid Ryugu and it barely flinched



Hayabusa 2 spacecraft shot it with a lump of copper in 2019 to create an artificial crater. This wasn't very successful.

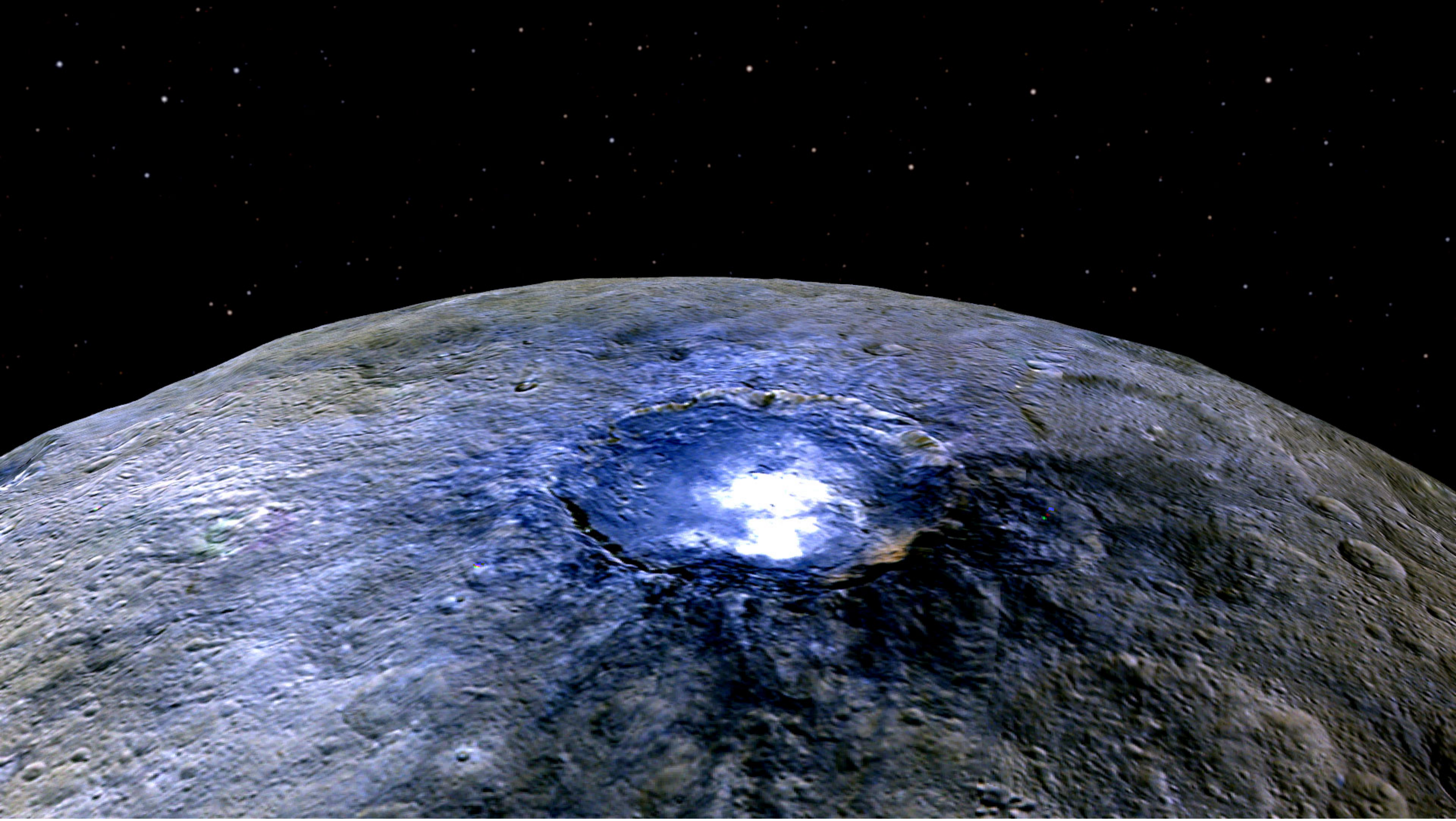
= ?

Hint:
Will fall
onto Mars



Asteroid Bennu shoots pebbles and golfballs of its water-rich rock into space. Spacecraft OSIRIS-REx (NASA) may bring some of them back to Earth.

V_{esc} = 20 cm/s



Ceres and Vesta are the largest, differentiated, asteroids.

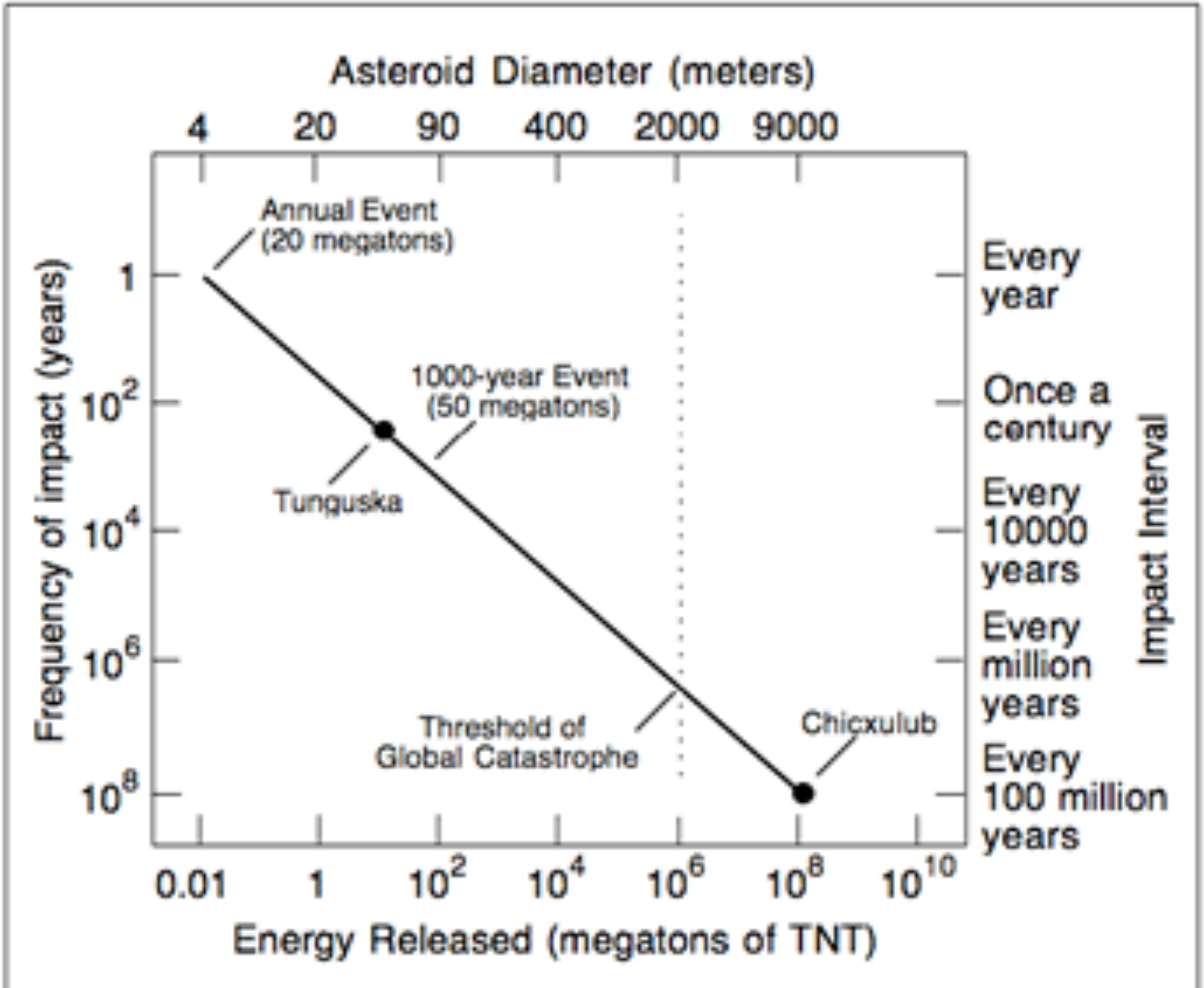
NASA Dawn mission visited both recently. Vesta is dry, but Ceres (show here with a crater Occator) has rocks andup to 25% of water inside, as well as ammonia. It probably formed beyond Jupiter and migrated inward.

Apophis

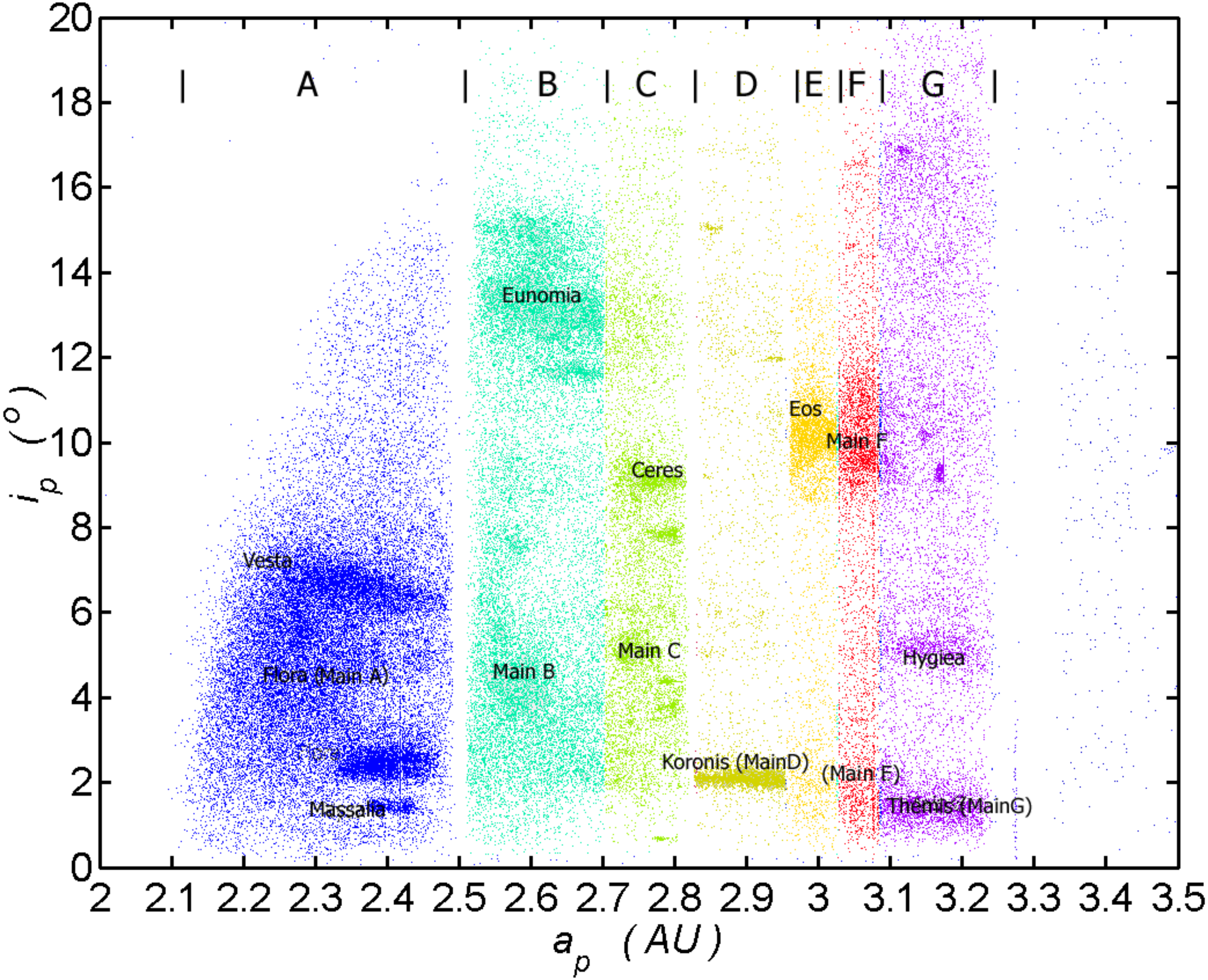
NEA (near-Earth asteroid, will make a close approach in 2029)

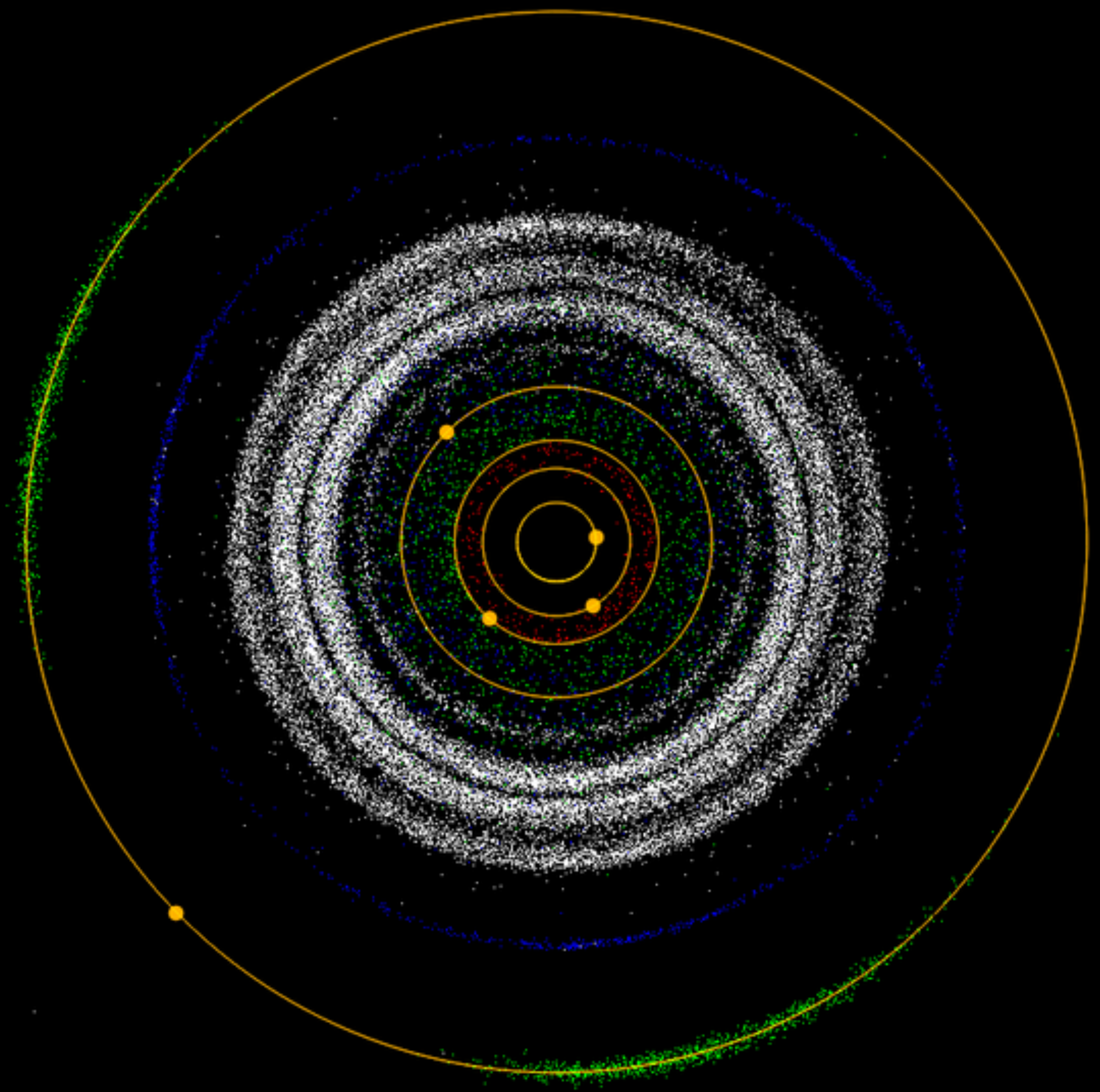
~400 m across

COLLISION PROBABILITY IS ~~SMALL ....~~ HUGE ... well it depends



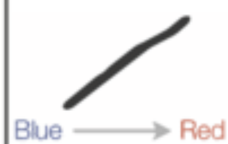
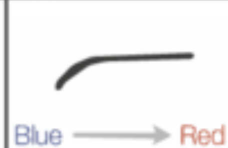
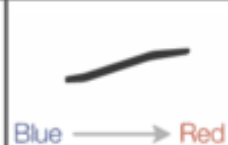
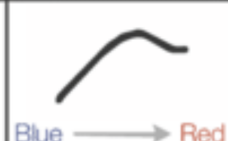
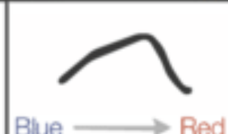
asteroid proper orbital elements **122 FAMILIES**





(a,ω) plot shows Kirkwood gaps + unevenly spread ω's (arguments of perihelium)

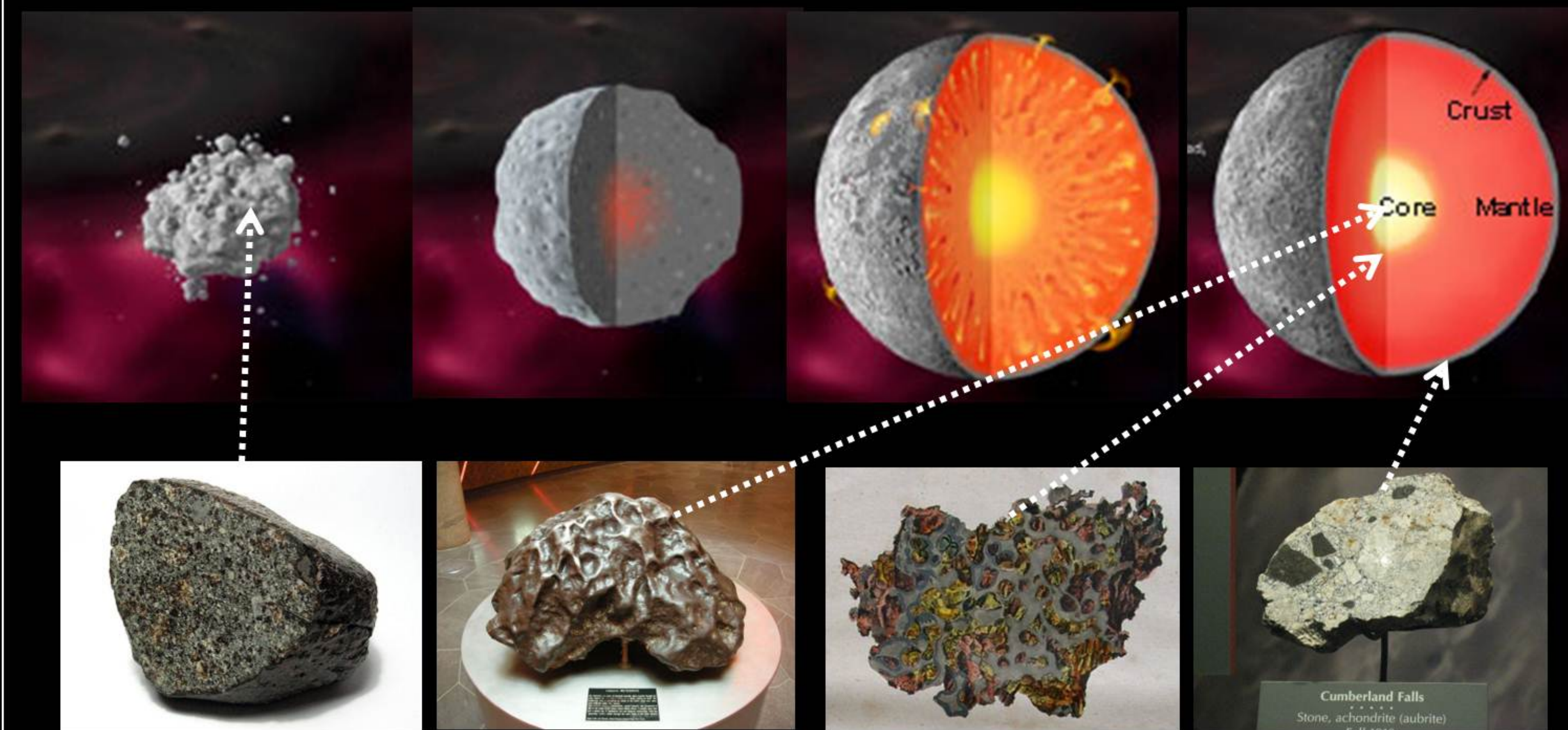
Asteroid and meteoroid classification

Major Taxonomic Types	Reflectance Spectrum (0.4-0.9 um)	Spectral Features	Visible Albedo	Suspected Composition
D (D,T)		Relatively featureless spectrum Steep red slope	0.02-0.06	Primitive carbonaceous Organic-rich compounds Hydrated minerals
C (C,B,F,G)		Slight bluish to slight reddish slope Shallow to deep absorption blueward of 0.5 μm Hydrated asteroids with absorption at 0.7 and 3.0 μm	0.03-0.10	Hydrated minerals Silicates Organics
X (E,M,P)		Slightly reddish spectrum E: absorption features at 0.5 and 0.6 μm	E: 0.18-0.40 M: 0.10-0.18 P: 0.03-0.10	E: Enstatite-rich M: metallic, Nickel-Iron P: Carbonaceous, Organics
S (S,Q,A,K,L)		Moderately steep red slope ($\lambda < 0.7$ μm) Shallow to deep absorption at 1.0 and 2.0 μm	0.10-0.22	Stony composition Magnesium Iron silicates
V		Moderate to steep red slope ($\lambda < 0.7$ μm) Very deep absorption at 1.0 μm	0.20-0.60	Volcanic basalts Plutonic rocks

75% asteroids are C-type (carbonaceous) - they reside in outer asteroid belt
The rest are mostly S-type, stony - they reside in the inner belt.
M = metallic (Fe, Ni) - less frequent but easier identified on Earth.
Pallasites are stony-iron mix (see the specimen!)
50000 asteroid pieces have been collected as meteorites on Earth

Different Asteroid & Meteorite Types

Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html



Chondritic Stony Meteorite

Iron Meteorite

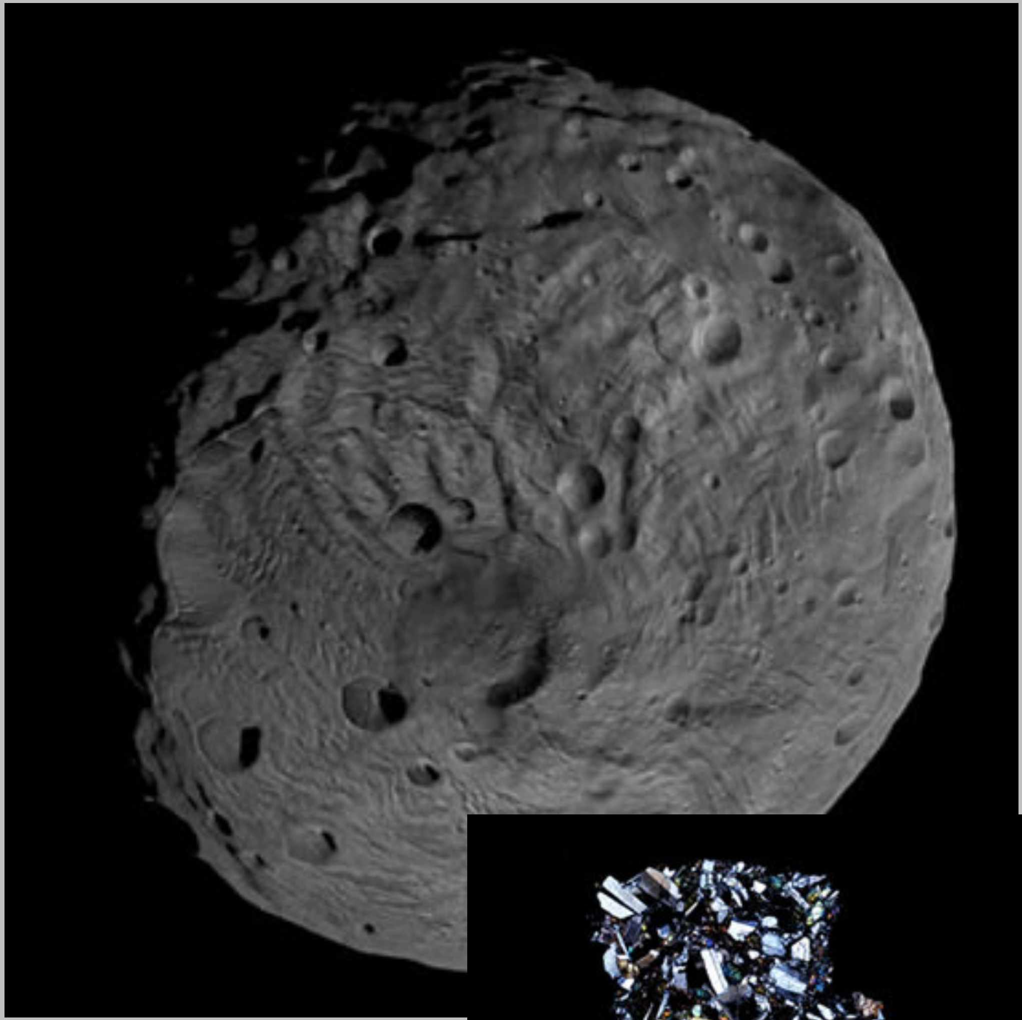
Pallasite Meteorite

Achondritic Stony Meteorite

Asteroid Type C

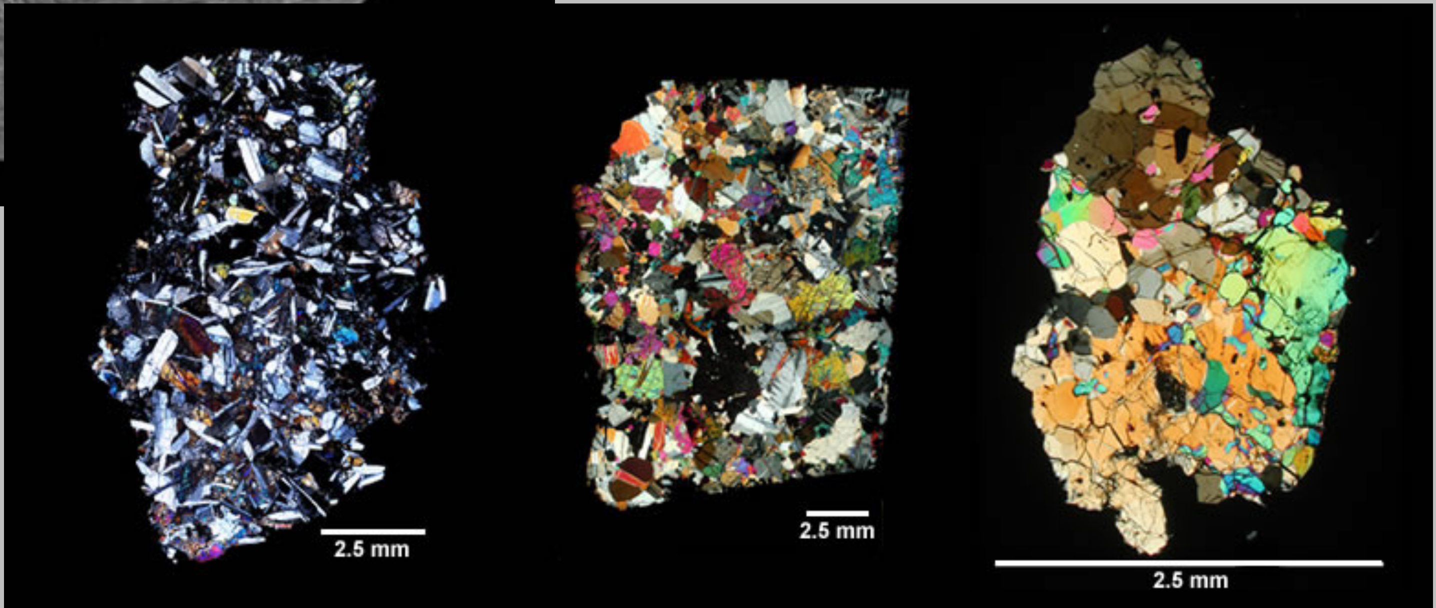
Asteroid Type M

Asteroid Type S



One in 20 meteorites found on Earth are from asteroid Vesta

Vesta has 500 km diameter and 9% of the asteroid belt mass



Chondrites:

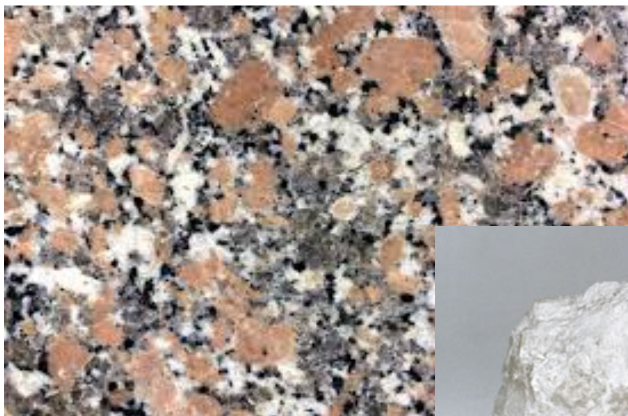
An abundant class of stony meteorites with chemical compositions similar to that of the Sun and characterized by the presence of chondrules in a silicate matrix.

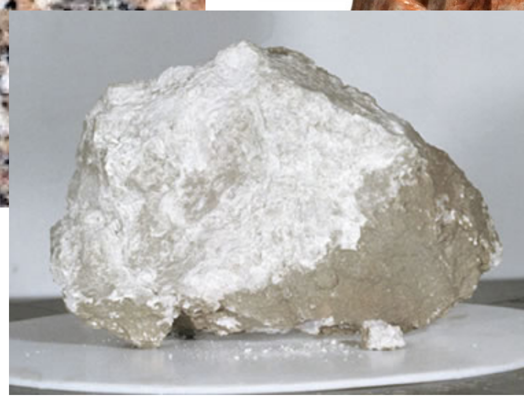
Chondrites come from unfractionated asteroids that never melted.

- The L chondrites are composed of olivine $(Mg,Fe)_2SiO_4$ and pyroxene $(Ca,Mg,Fe)SiO_3$. Olivines range from forsterite (pure Mg_2SiO_4)

to fayalite (pure Fe_2SiO_4) in solid solution.

Pyroxene ranges from mineral enstatite $MgSiO_3$, through augite, bronzite, diopside, hypersthene and eulite to ferrosilite (pure $FeSiO_3$), but also contains feldspar $(K,Ca,Al)Si_3O_8$ [41% of Earth's crust],





Killarney, ON

metallic Ni-Fe, and iron sulfide FeS (called troilite).

Most L chondrites are severely shocked, probably by a large impact on the asteroid in which they formed.

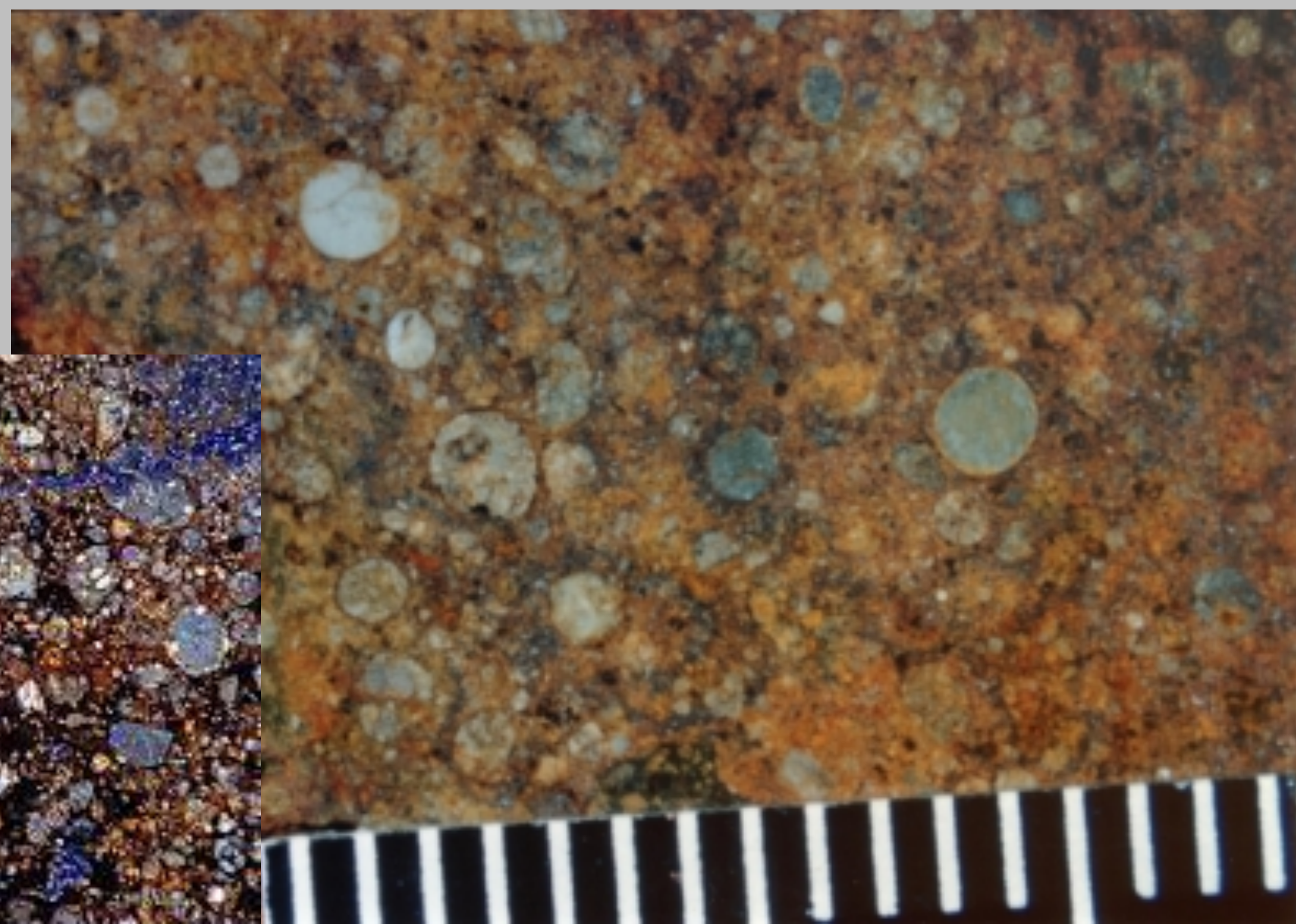
E Chondrites:

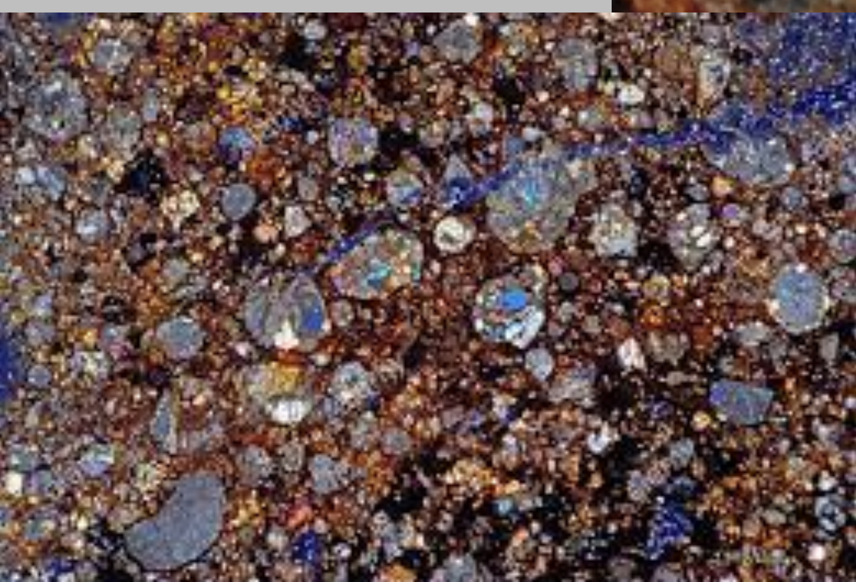
◆The E type = Enstatite chondrites, $MgSiO_3$, a rare type that formes under very reducing conditions (oxygen-poor)

C-type Chondrites:

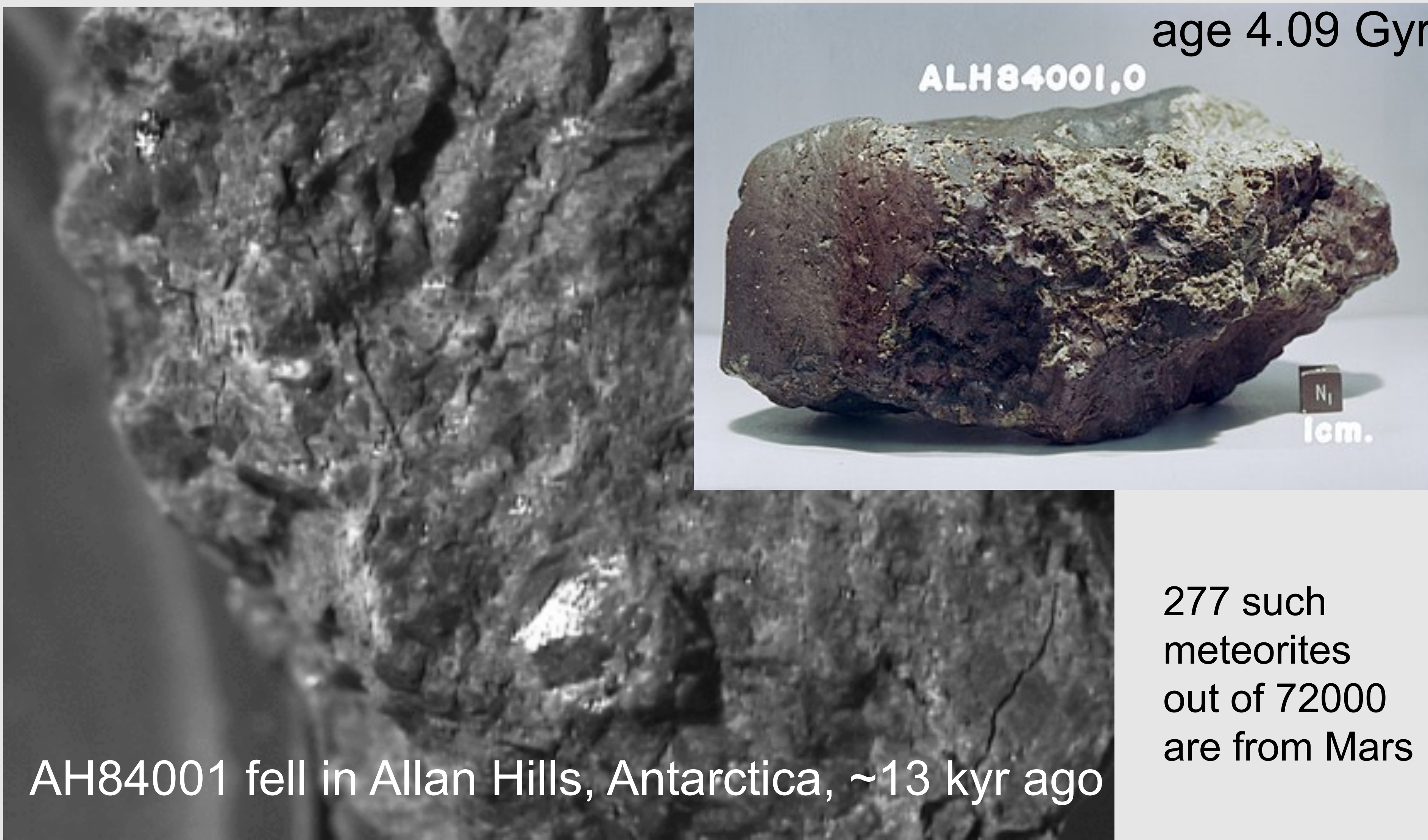
C – carbonaceous chondrites – contain clay-like, water-bearing minerals and carbon compounds including a variety of organic molecules such as amino acids.

Carbonaceous chondrites CI are the most primitive meteorites - closest in composition to sun's photosphere.





Pyroxene $(Mg,Fe,Ca)SiO_3$ is a major part of Earth's basaltic crust.
It also makes up most of this Martian meteorite called Allan Hills 84001, which is an igneous rock (solidified lava) from Mars, dislodged & thrown into space 17 Myr ago in a major impact of a comet or asteroid with Mars.

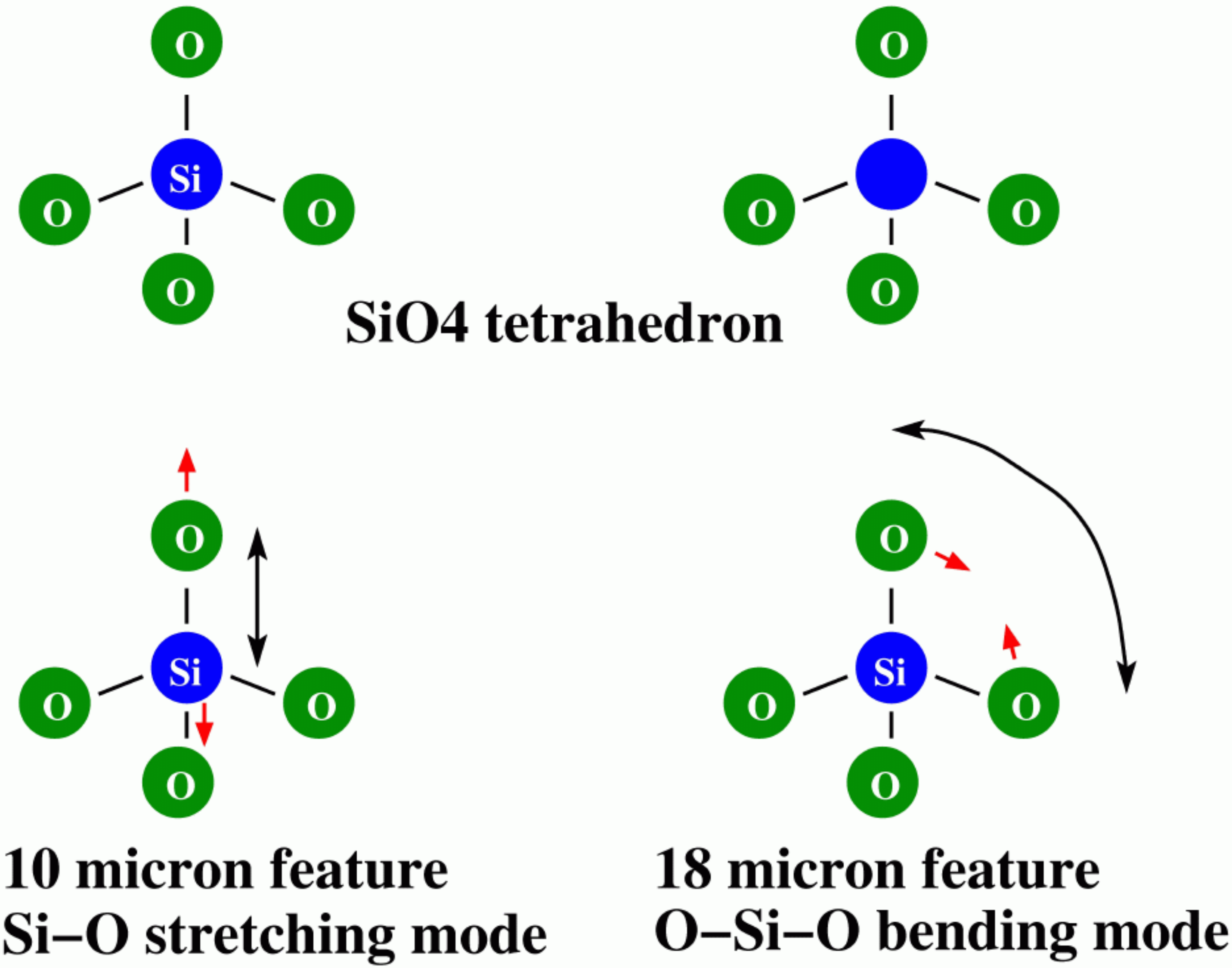


age 4.09 Gyr

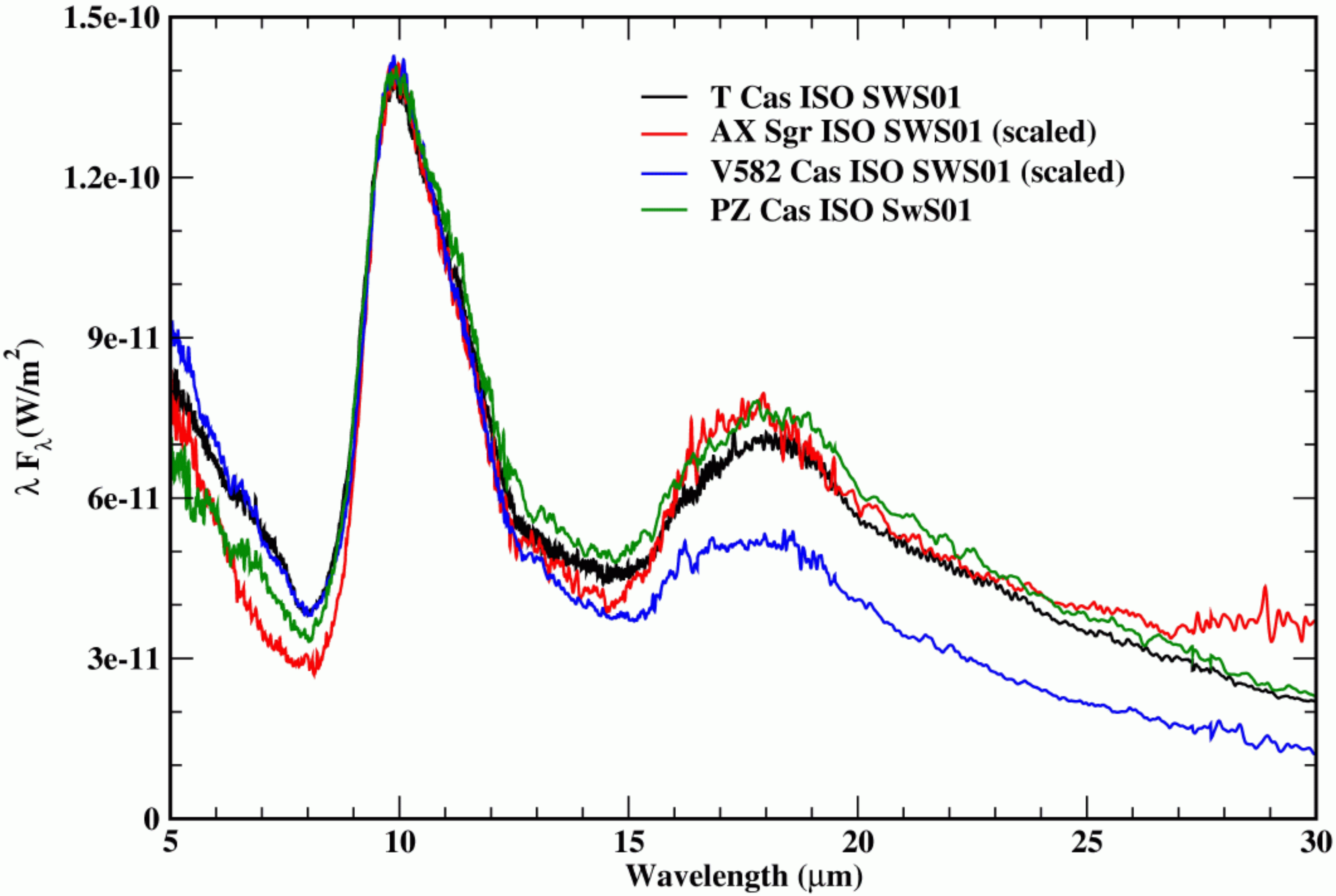
AH84001 fell in Allan Hills, Antarctica, ~13 kyr ago

277 such meteorites out of 72000 are from Mars

Minerals can be identified remotely by spectroscopy



The 10 µm and 18µm features in spectra of four planetary system disks



Comparison of the 10-μm Si-O stretch bands of a "GEMS-rich" IDP and astronomical silicates.

Objects:

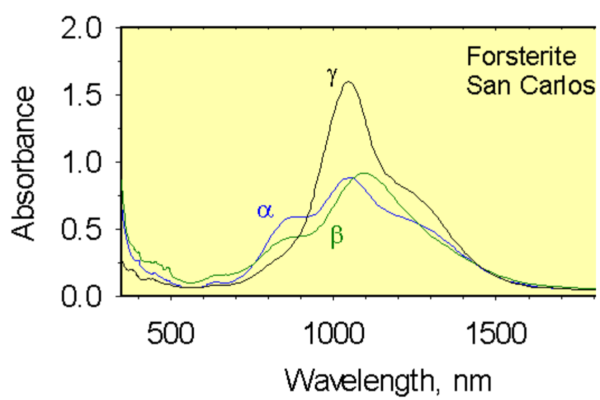
(A) Chondritic IDP L2008V42A. Profile derived from transmittance spectrum.

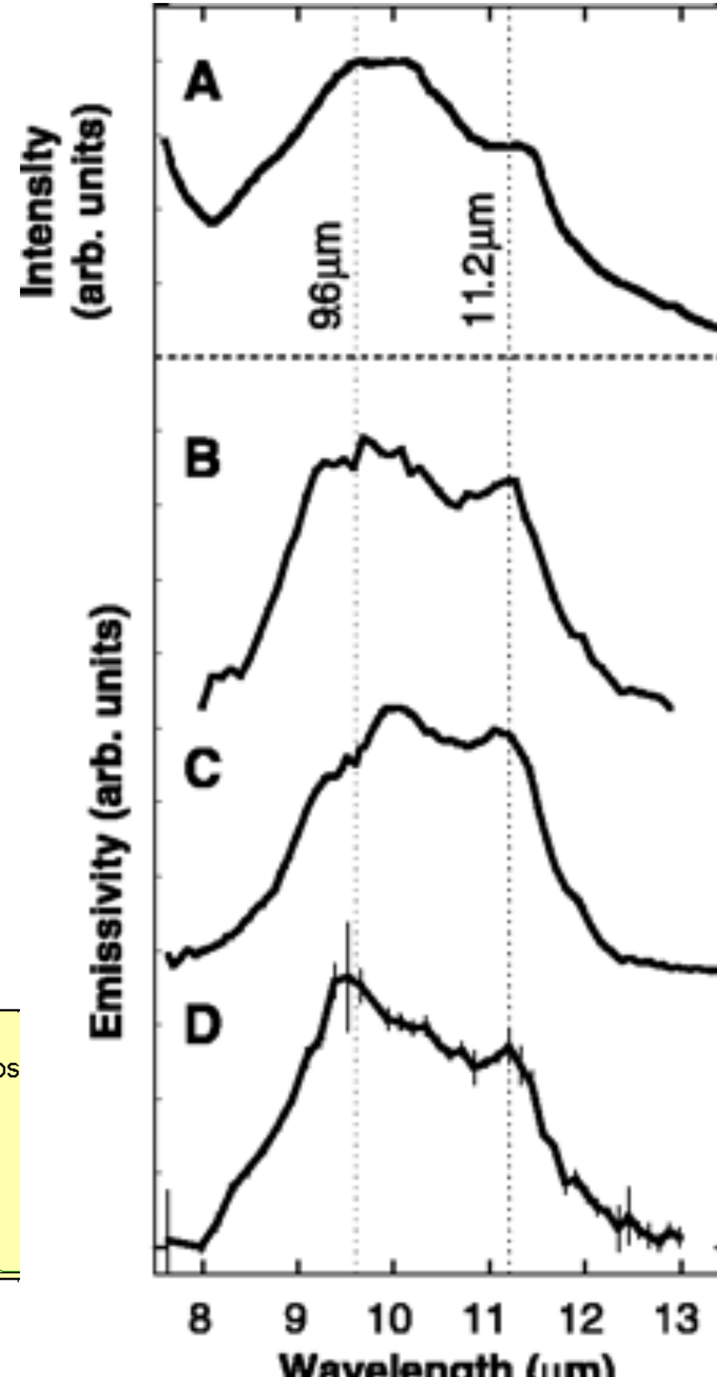
(B) Comet Halley (15).

(C) Comet Hale-Bopp (16).

(D) Late-stage Herbig Ae/Be star HD163296 (17).

The structure at 9.5 μm in (B), (C), and (D) is due to terrestrial O_3.





Comparison of the 10-µm Si-O stretch bands of GEMS with astronomical silicates.

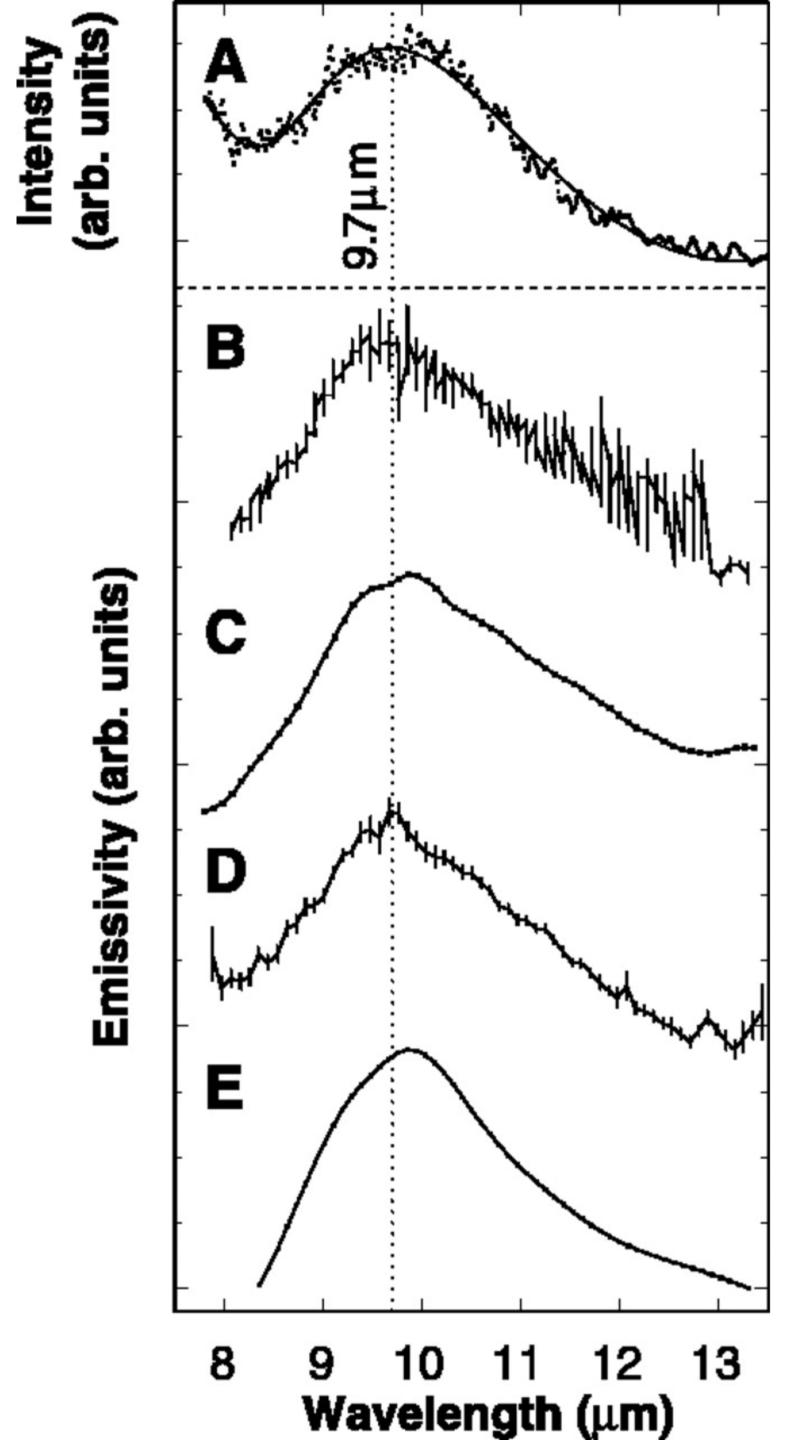
(A) GEMS (in IDP L2011*B6).

(B) Elias 16 molecular cloud.

(C) Trapezium molecular cloud.

(D) Pre–main sequence T Tauri YSO DI Cephei

(E) Post–main sequence M-type supergiant µ-Cephei (21)

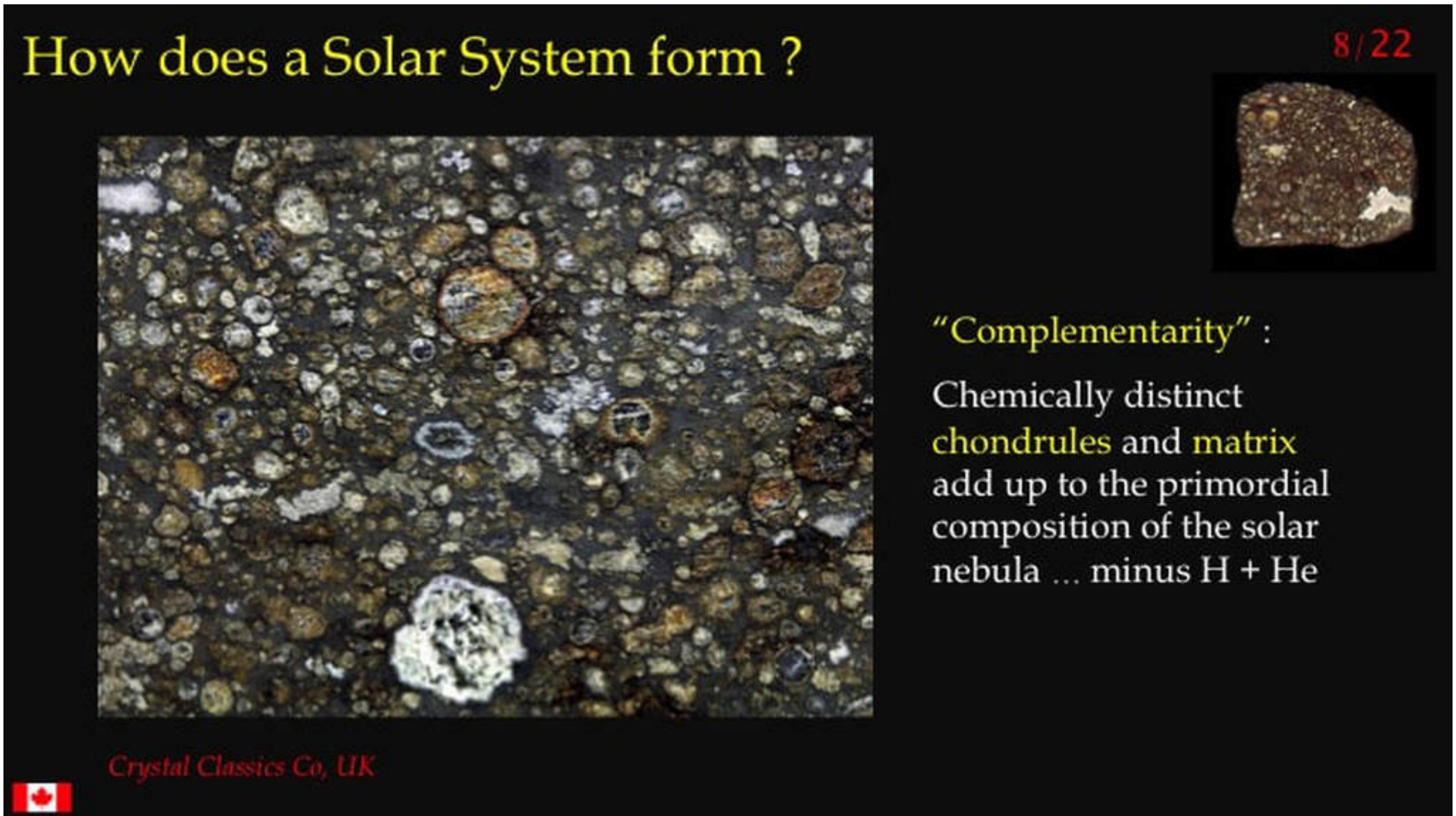


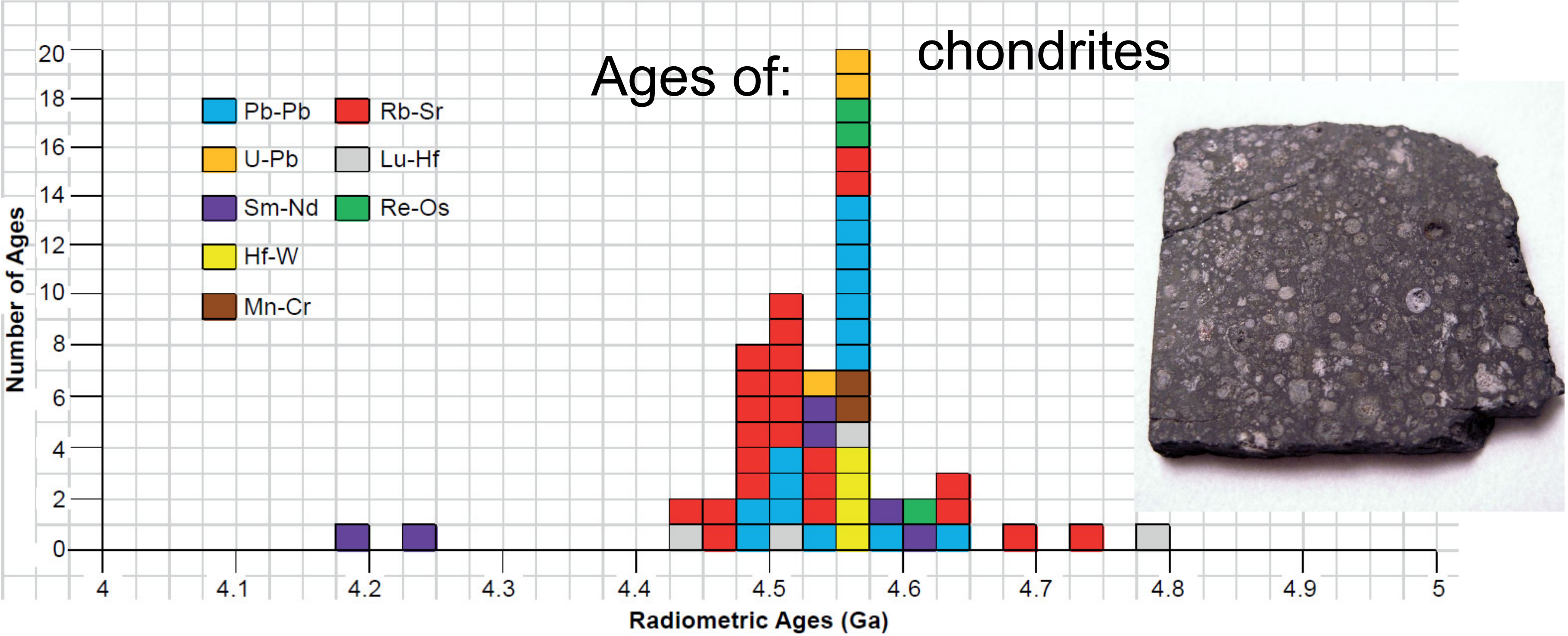
Chondrule: Roughly spherical rock pieces found in chondrites. Most chondrules are 0.5 to 2 millimeters in size and are composed of olivine and pyroxene, with smaller amounts of glass and iron-nickel metal.

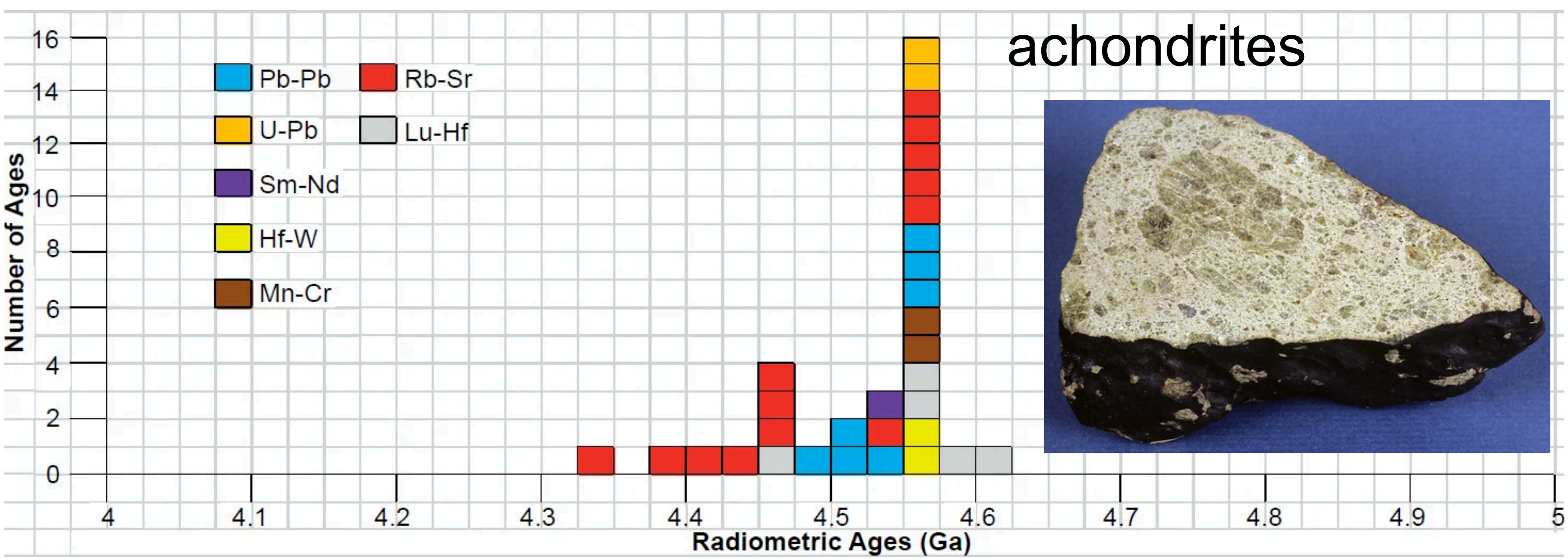
Some (Type I) contain MgO and only small amounts of FeO; olivine crystals in them contain only about 2% percent of the iron-rich-olivine fayalite (Fe_2SiO_4) end member.
Other (Type II chondrules) contain much more FeO; olivine crystals in them typically contain 10-30% fayalite.

Their isotopic analysis shows a large-scale mixing of material in the solar nebula during the formation of meteorites.
They formed from a variety of materials, some refractory CAI inclusions from the inner solar system. Calcium-Aluminum Inclusions (CAI) formed first, then migrated outwards and were included in chondritic matter. Even the formation of Jupiter did not apparently stop the mixing of inner and outer solar system.

Chondrules: The rounded shapes of the mineral grains in them indicate that chondrules were once molten droplets floating freely in space. Some have double rims and were repeatedly re-heated by short bursts of energy, maybe electrical discharges or gas shock waves inside the accretion disk. Chondrules are very common, yet still a bit puzzling.



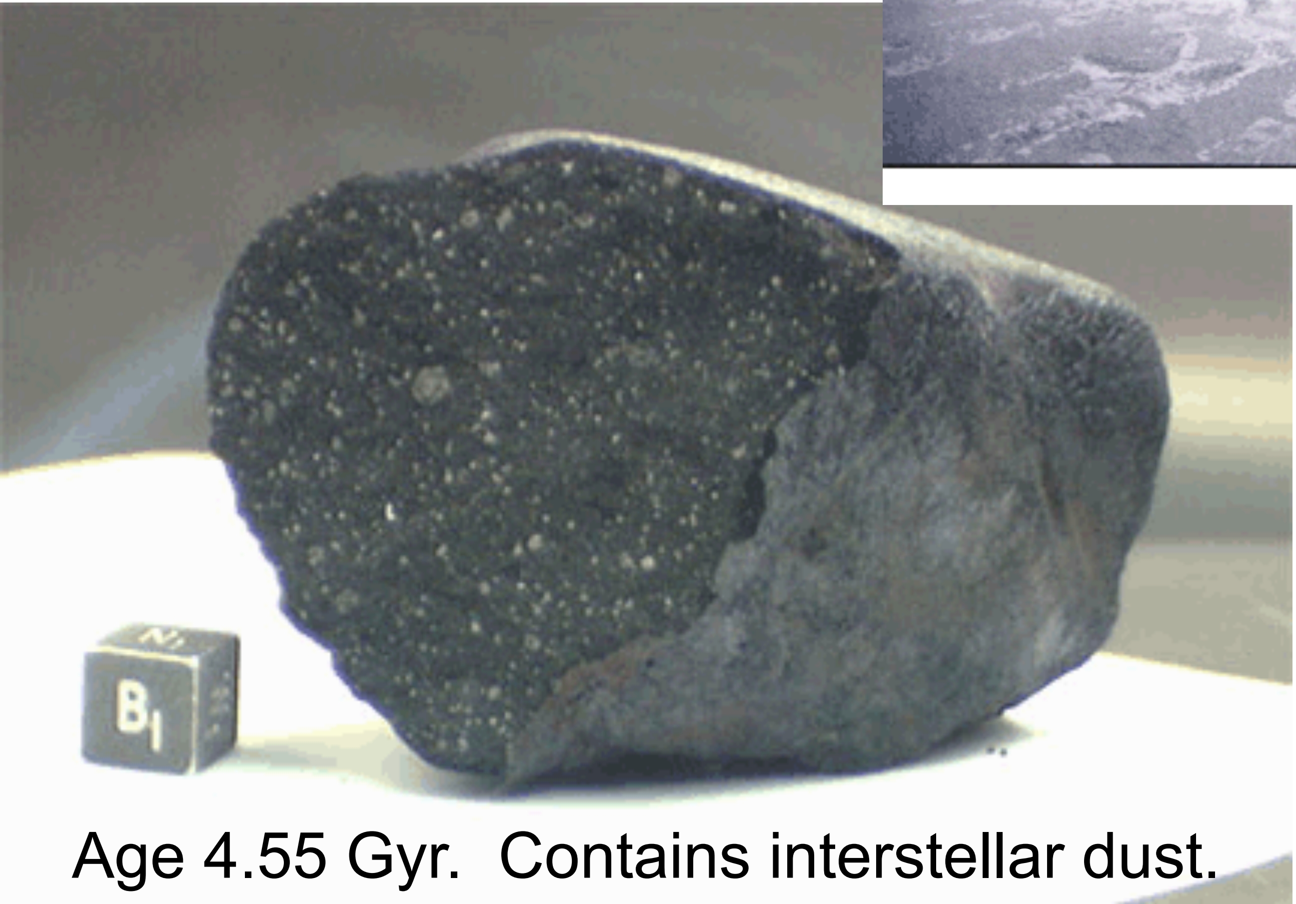

Ages of:
chondrites
Pb-Pb
Rb-Sr
U-Pb
Lu-Hf
Sm-Nd
Re-Os
Hf-W
Mn-Cr
Number of Ages
0
2
4
6
8
10
12
14
16
18
20
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5
Radiometric Ages (Ga)


achondrites
Pb-Pb
Rb-Sr
U-Pb
Lu-Hf
Sm-Nd
Hf-W
Mn-Cr
Number of Ages
0
2
4
6
8
10
12
14
16
4
4.1
4.2
4.3
4.4
4.5
4.6
4.7
4.8
4.9
5
Radiometric Ages (Ga)

In 2000, on Tagish Lake, B.C., Canada, a fireball was seen and a carbonaceous meteorite fell. Original size was 4 m, 97% volume has burned off.

Kinetic energy 1.7 kiloton TNT.

(University of Western Ontario, University of Calgary)

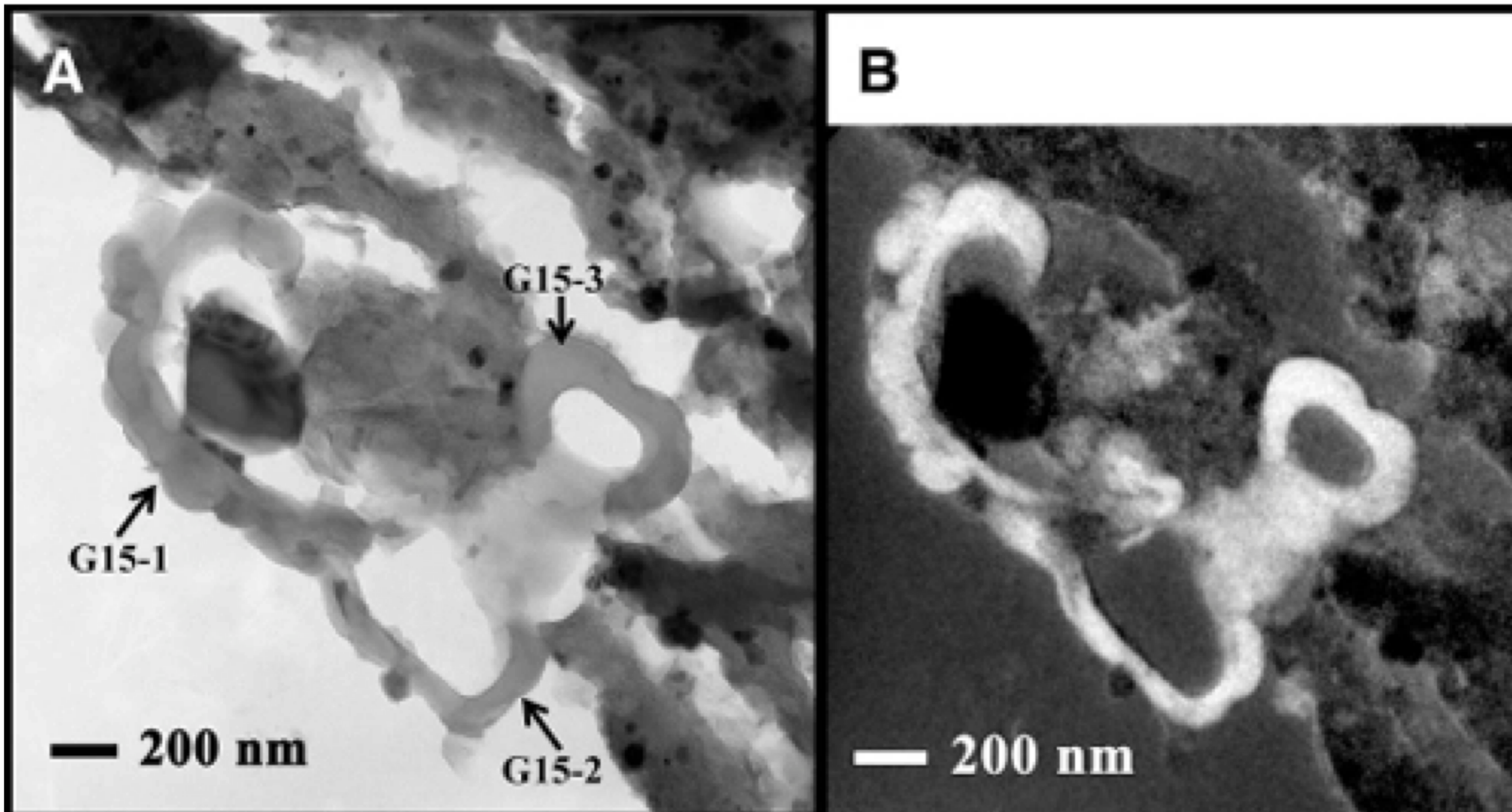


Age 4.55 Gyr. Contains interstellar dust.

In 1992 Peekskill, NY, meteorite (ordinary chondrite) hit a teenage girl's car parked in a driveway. The car was a $400 gift from grandmother; it was sold to a museum for $20k.

Olivine grains are enclosed in a gooey organic stuff. Tagish meteorite contains water in clay-like materials. It is not Earth's water though... isotopic ratios are not terrestrial. The trajectory traces back to outer asteroid belt. This meteorite is probably a piece of a reddish asteroid 773 Irmintraut at 2.6-3.1 AU from the sun, and has H_2O.

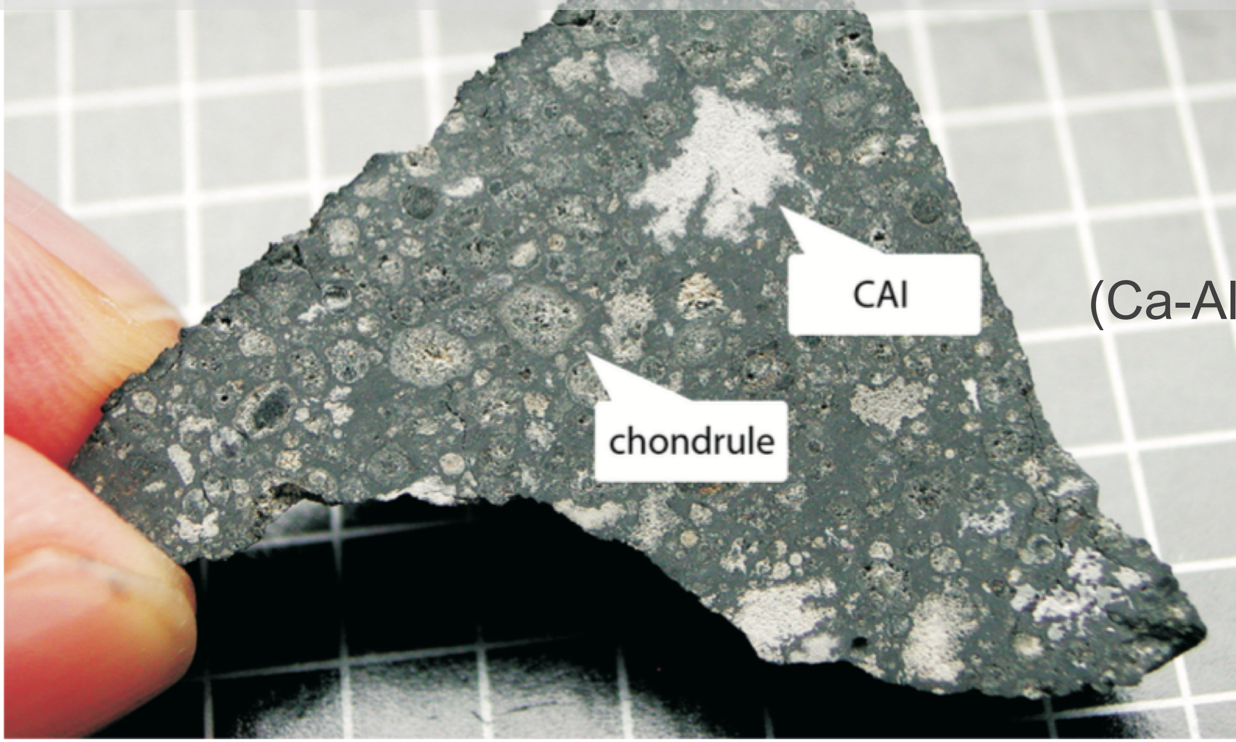
Organic Globules in the Tagish Lake Meteorite



(From Nakamura-Messenger *et. al.*, 2006, *Science*, v. 314, p. 1439-1442, Fig.1.)

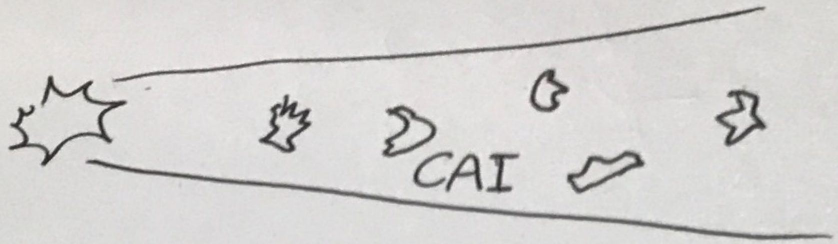
sions were discovered only in the late '60s (Christophe Michel-Levy 1968). The technology nowadays helped to estimate precise age of these pieces by Pb-Pb dating, especially with the use of secondary ionization mass spectrometry (SIMS also called an ion microprobe). Now we estimate Allende's CAIs age to be
→ 4567.72±0.93 Myr (see Fig. 3) (Connelly et al. 2008). To compare, CAIs of Efremovka CV3 chondrite are 4567.2±0.6 Myr old (Amelin 2002).

Allende meteorite fragment (type CV3, carbonaceous chondrite 2+ tons of fragments fell in Mexico in 1969 over Pueblito de Allende)

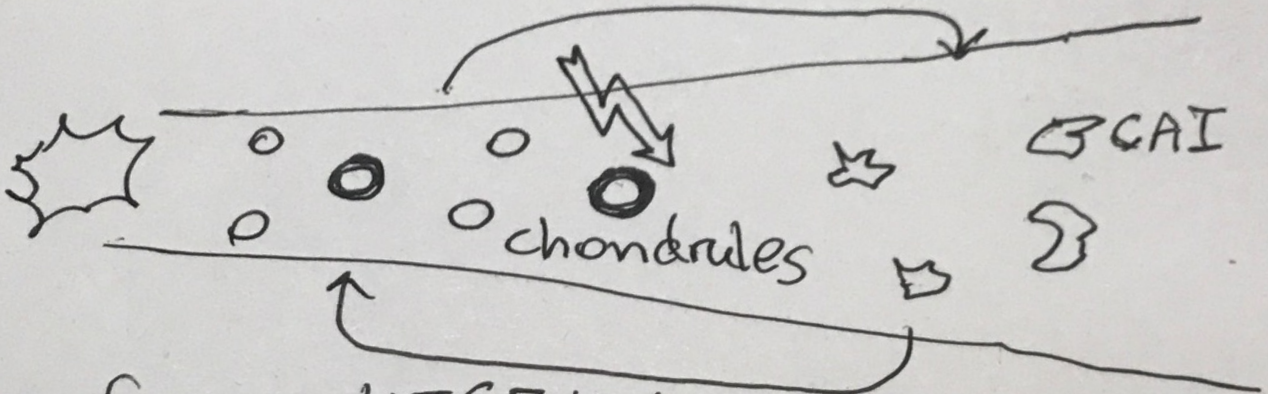


(Ca-Al-Inclusions)

Fig. 2. Allende's CAIs and chondrules. The grid behind is 1×1 cm (courtesy of Jan Woreczko).

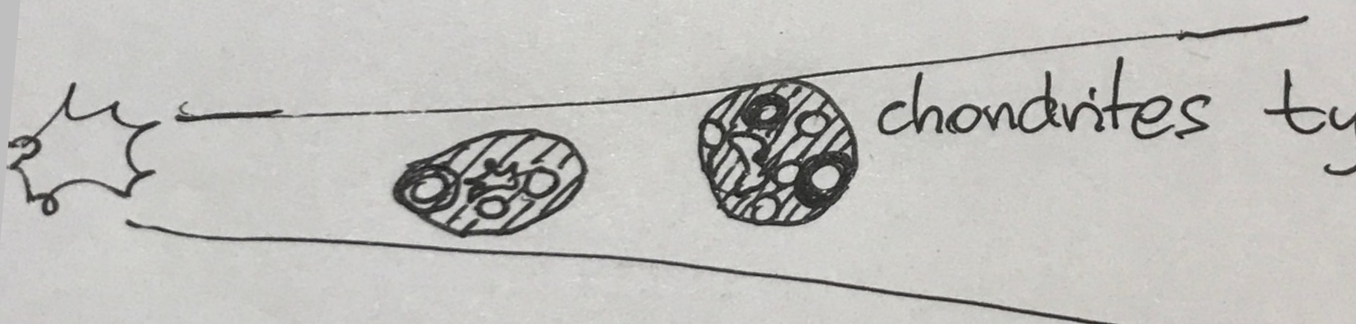


Calcium-Aluminum Inclusion form 4567.72 ± 0.98 Myr ago



[re-melting episodes of chondrules]

form 4565.4 ± 0.50 Myr ago and are included in meteorite matrix:



chondrites type CV3

In 2020 a research group from Harvard laboratory claimed a discovery of the first extraterrestrial protein in carbonaceous chondrites Allende and Acfer 086 (both category CV3).

Protein hemolithin has not been independently confirmed in Allende https://en.wikipedia.org/wiki/Hemolithin

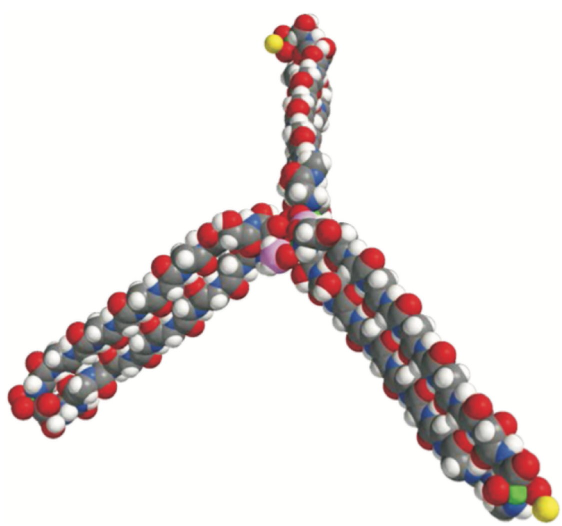


Fig. 4. Model of the hemoglycin molecule, a probable meteoritic protein. White = H; grey = C; blue = N; red = O; pink = Si; yellow = Na and green = Fe (McGeoch et al. 2020).


We don't yet have any scientifically proven facts, but seem to be getting closer and closer to the discovery of extraterrestrial life.