Why are Asteroids Interesting?

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And what did we learn from the first spacecraft to orbit and land on an asteroid?

OSSE/GET-WISE G. Consolmagno
5 March 2001

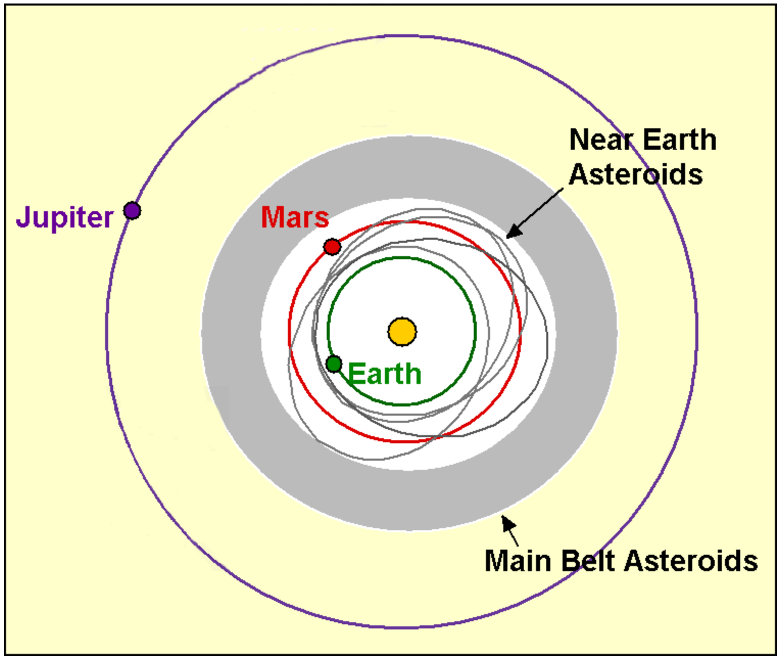
NEAR
Near Earth Asteroid Rendezvous

- What are near Earth asteroids and why are we interested in them?

- What did the instruments on NEAR tell us about Eros?

What are near Earth asteroids?

- **What are asteroids?**
  - Rocky objects more than 50 meters in size
  - Some are left over from the formation of the planets
- **Where are they and how many are there**
  - Most are between Mars & Jupiter
  - >400,000 larger than 1 km
  - Total mass < Moon

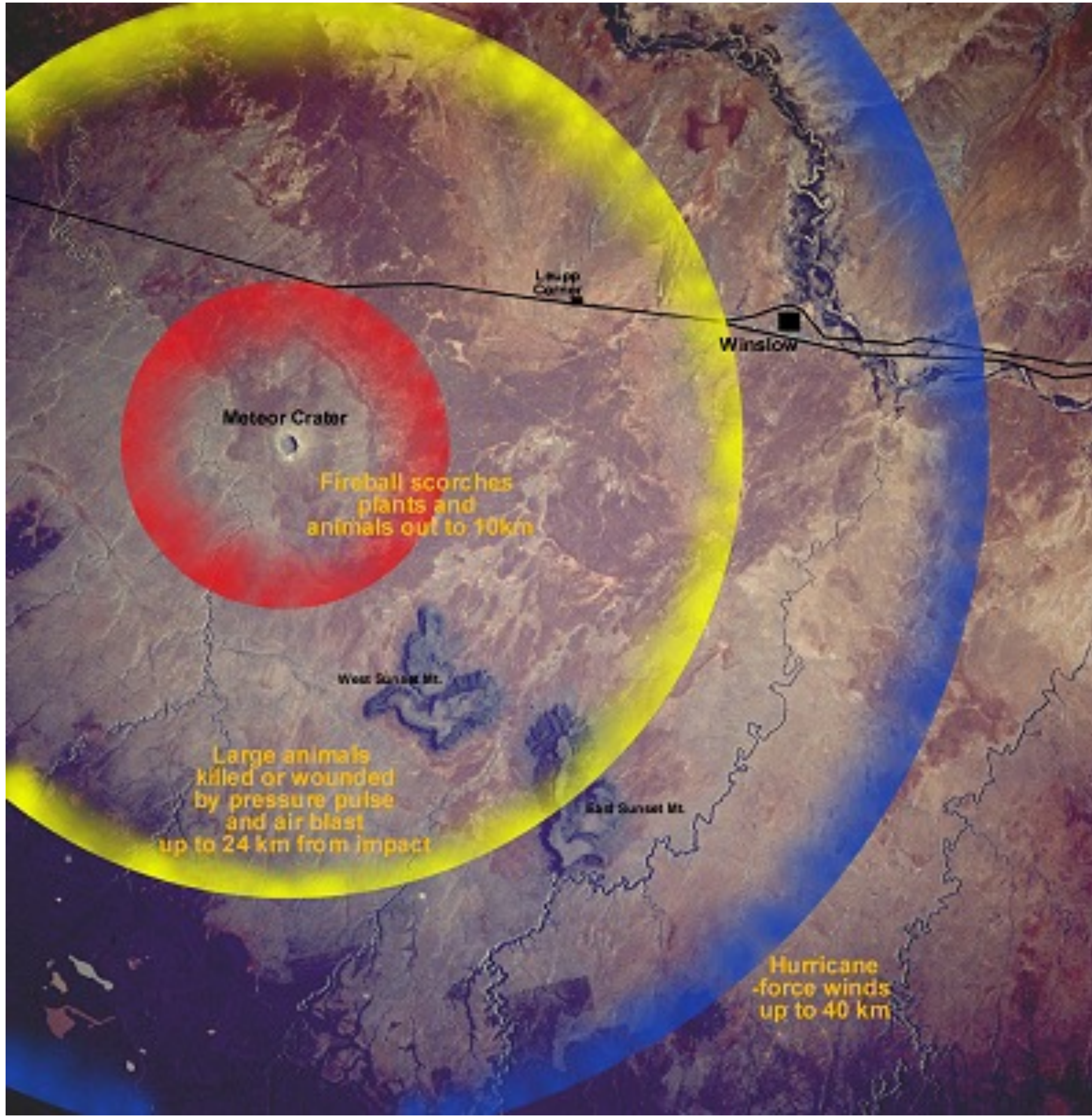


Why are we interested in near Earth asteroids?

- Near Earth asteroids could be related to meteorites, which tell us about the origins of the solar system.
- Mass extinctions can be caused by asteroid impacts.
  - They got rid of the dinosaurs for us!
  - In a few million years Eros may be able to impact Earth.
- It may prove profitable to “mine” asteroids.

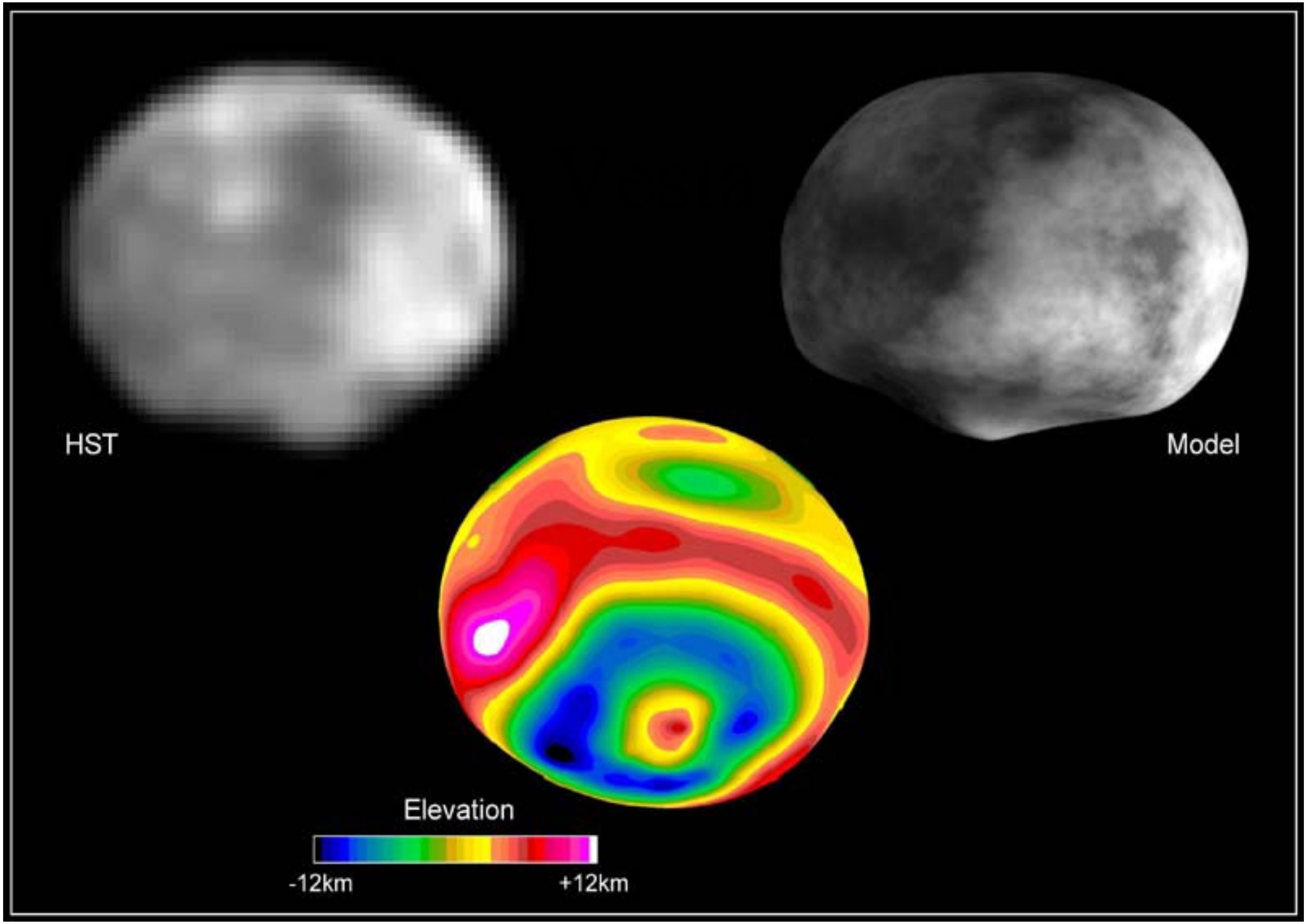
The most famous impact site on Earth is Meteor Crater in Arizona, evidence that asteroids do hit Earth from time to time.

When the meteorite that formed Meteor Crater in Arizona hit, it devastated much of the surrounding area.

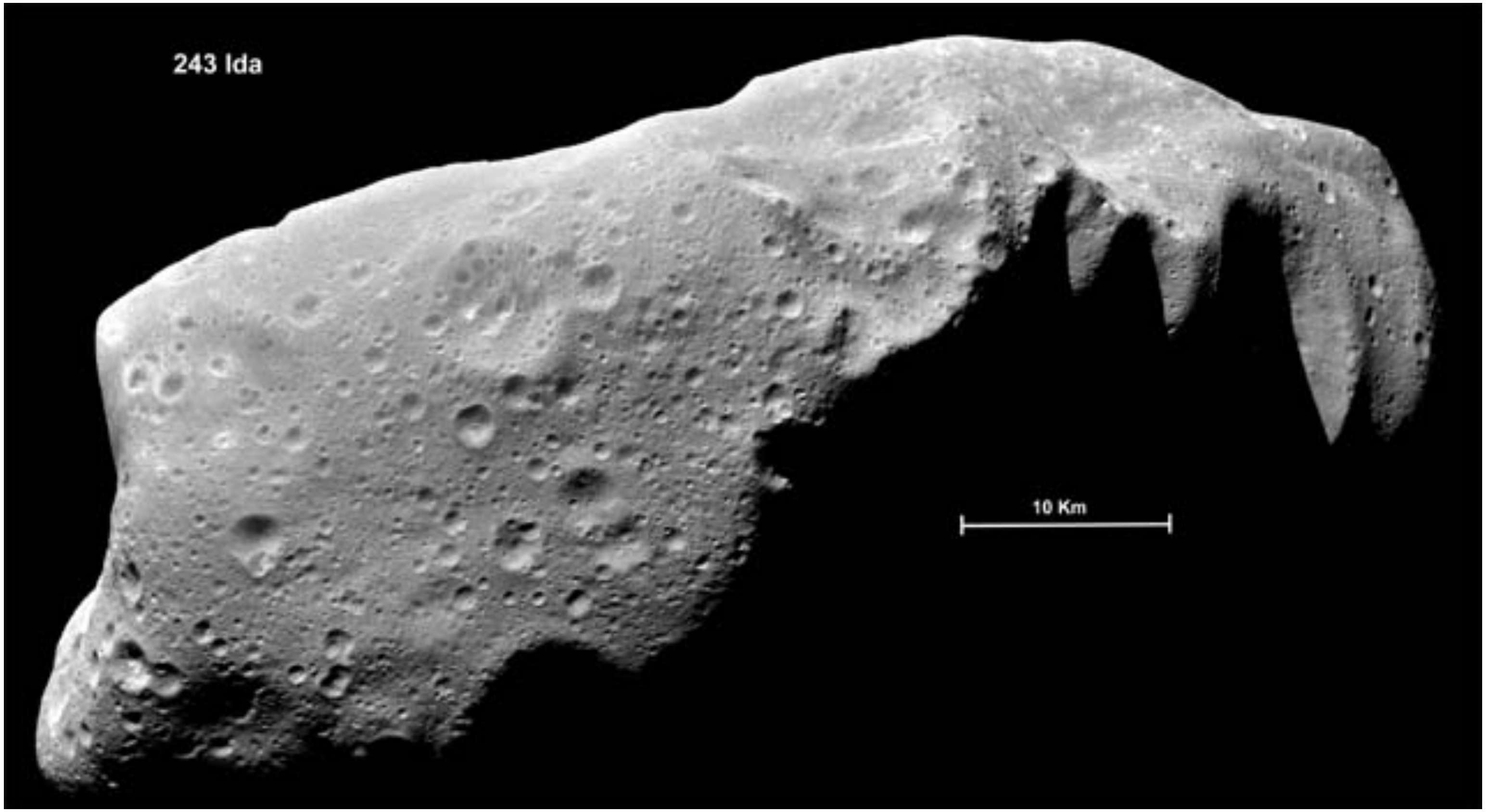


The metal in even a small Near Earth Asteroid could be worth a hundred trillion dollars!

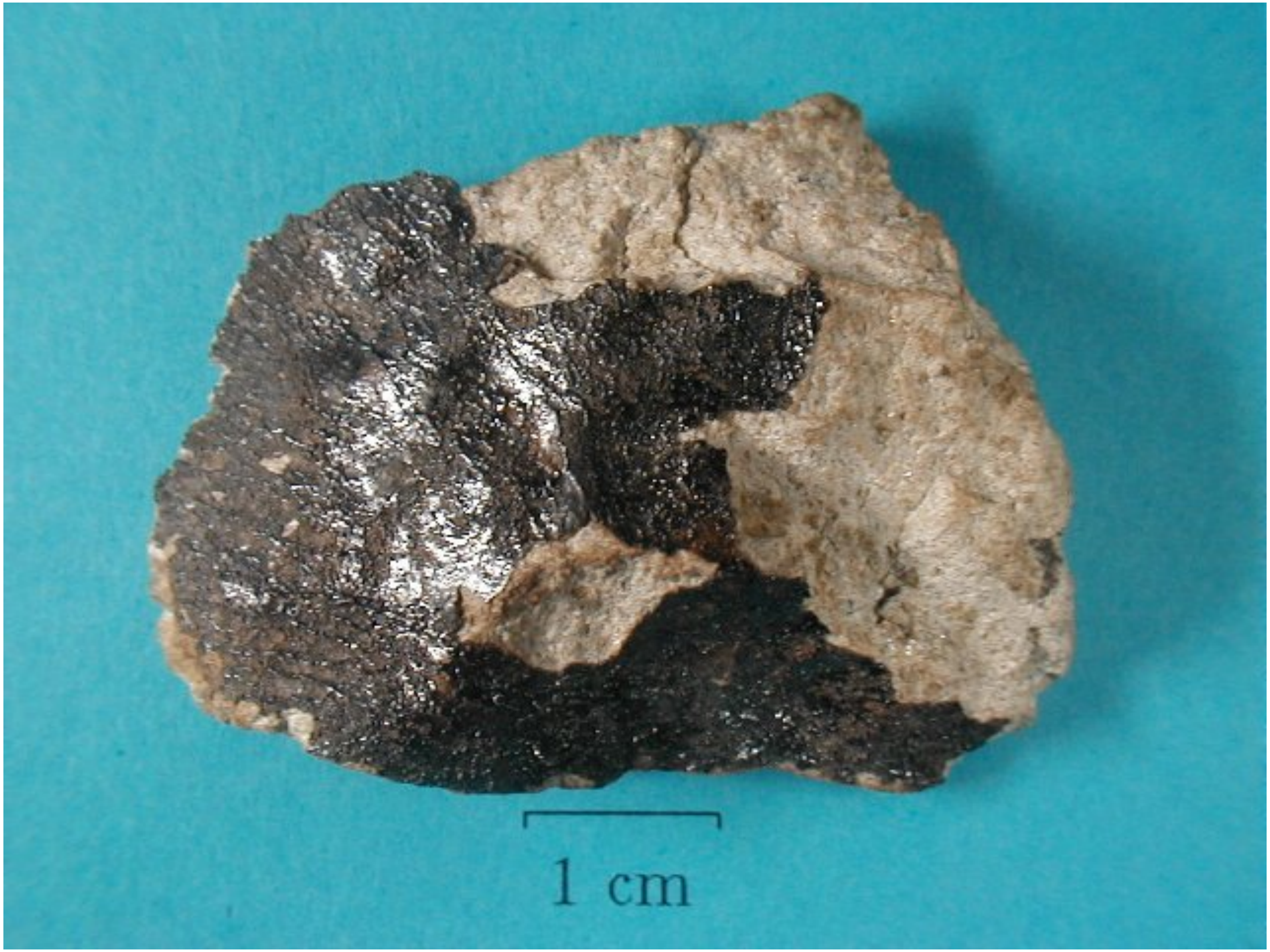
This meteorite, Ibitira, is a basalt made from a molten lava. (note the holes, called “vesicles”, made by gas bubbles expanding in the molten lava from which this rock was crystallized) and probably comes from Vesta, the only large basaltic asteroid.



Hubble images of Asteroid Vesta show a large crater near the south pole; perhaps meteorites were ejected here.



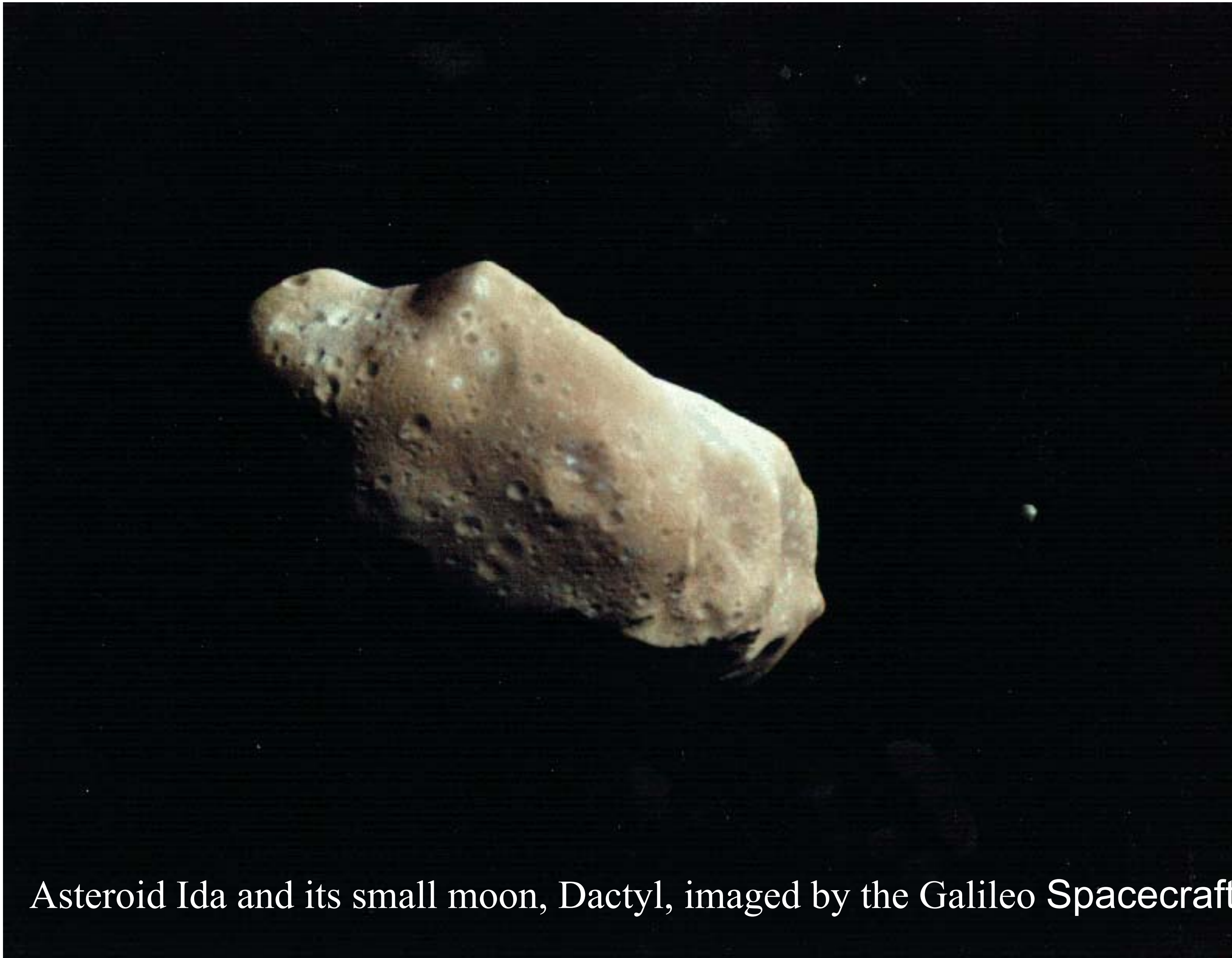
Asteroid Ida is *not* covered with basalts; its rock looks more like ordinary, unmolten, meteorite material.



A typical meteorite has a black, glassy “fusion crust” where the rock melted while travelling through the Earth’s atmosphere; but the inside of the meteorite, the gray part, remains unmelted.

This meteorite, Soko Banja, is an example of the most common type of stony meteorite, called an “ordinary chondrite”. It is a collection of loose bits of stone, packed together without having been melted.

Note in this image many “rust” spots. These meteorites can be ten or fifteen percent metallic iron, which will rust once the meteorite reaches Earth’s warm, moist atmosphere.



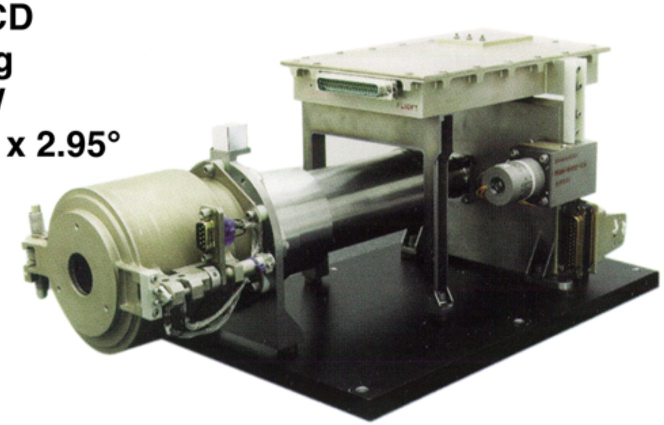
Asteroid Ida and its small moon, Dactyl, imaged by the Galileo Spacecraft

By exaggerating the colors, we can see different types of material on the surface of an asteroid. The parts that look “blue” here are freshly exposed parts of Ida, and look much like an ordinary chondrite meteorite. The parts that look “red” here appear to have been “weathered” by high energy particles and impacts.

What do the instruments on NEAR tell us about Eros?

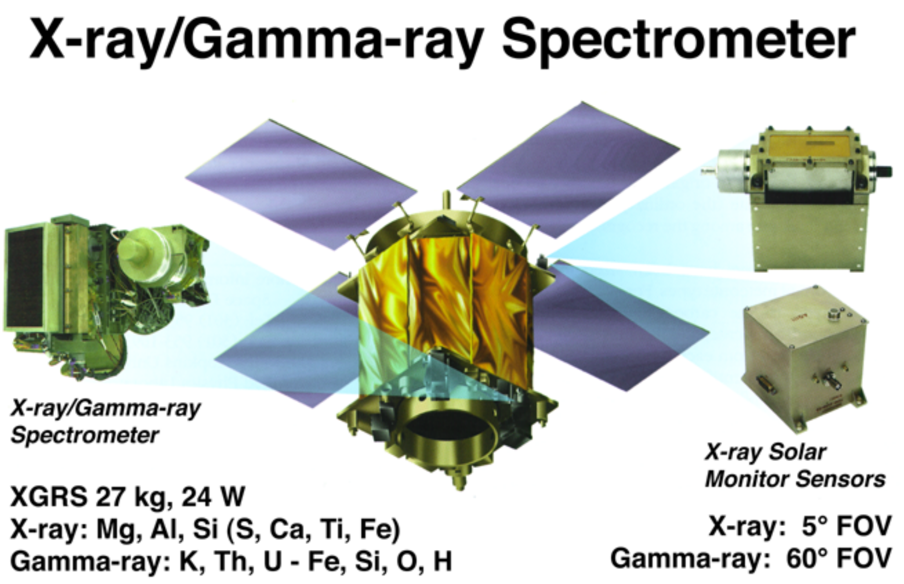
- Multi-Spectral Imager: MSI
  - **Resolve features a few yards across: Cratering tells us how old the surface is and provides clues about whether Eros is made of hard or soft material.**

- **Color pictures: How does the surface of Eros compare with those of planets? Is Eros a uniform object? (*Yes!*)**



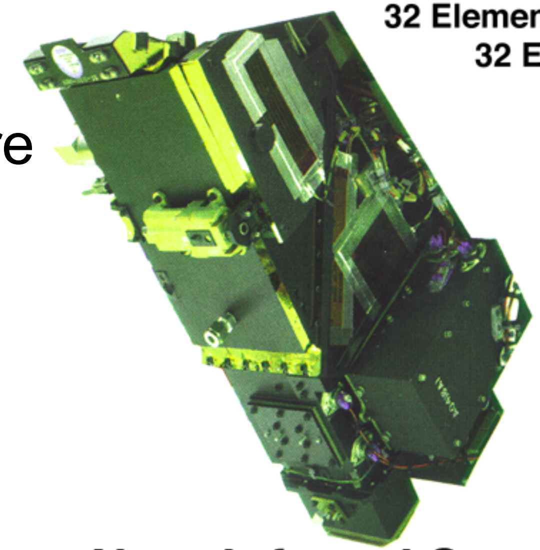
What do the instruments on NEAR tell us about Eros?

- X-ray, Gamma-Ray Spectrometer: XGRS
- **Detects X-ray and gamma-ray "signatures" of atoms, which are emitted when radiation from the Sun and cosmic rays excite atoms in the surface.**
- **XGRS identifed which elements are present, <u>including</u> less abundant elements that provide crucial clues about Eros' origin.**



What do the instruments on NEAR tell us about Eros?

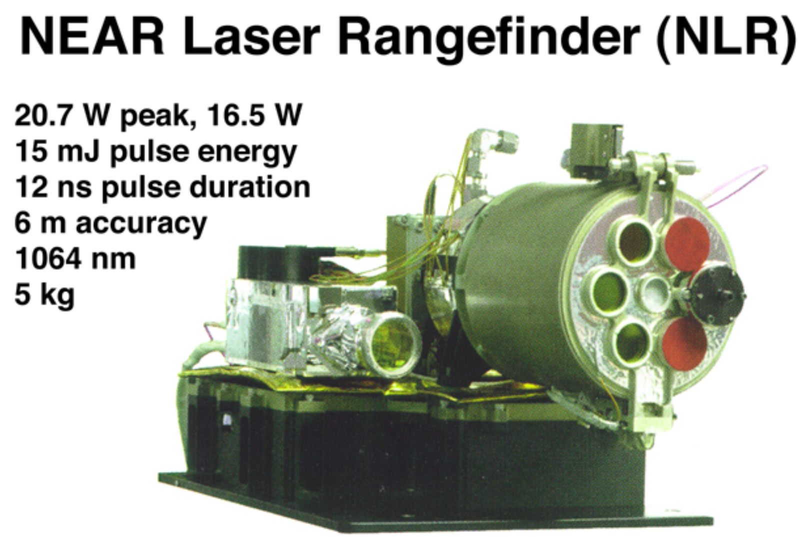
- Near Infrared Spectrometer: NIS
  - Looks at the spectrum of light just beyond the red end of the visible range. Different minerals have different "signatures" in the infrared.
  - Minerals form in specific ways and which minerals are there will tell us where and how Eros originally formed.
  - Result: Eros appears to be similar to ordinary chondrite meteorites.



Near-Infrared Spectrometer (NIS)

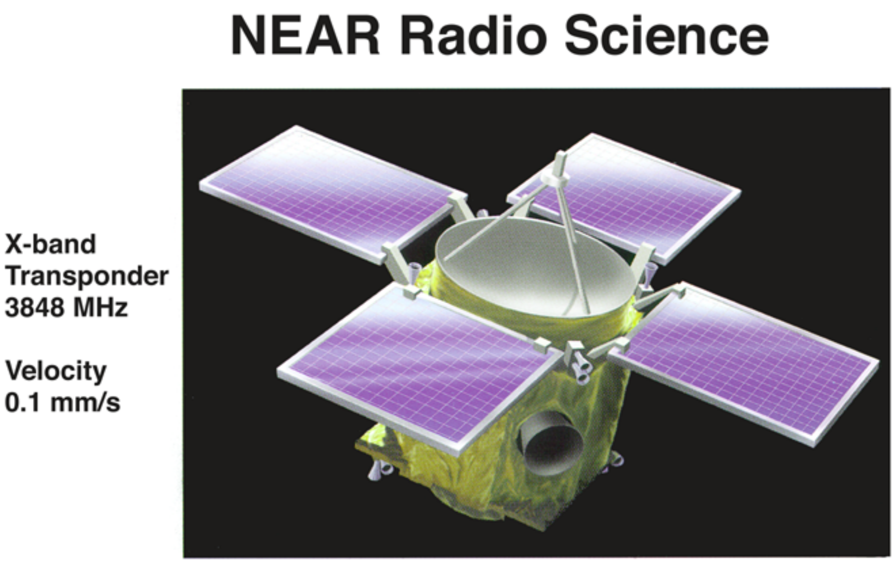
What do the instruments on NEAR tell us about Eros?

- NEAR Laser Rangefinder: NLR
  - **Measures the NEAR-Eros distance to within a meter by bouncing pulses of laser light off the surface and timing how long it takes the light to come back.**
  - **The topography tells us Eros' precise shape and helps us to understand what we see in pictures.**



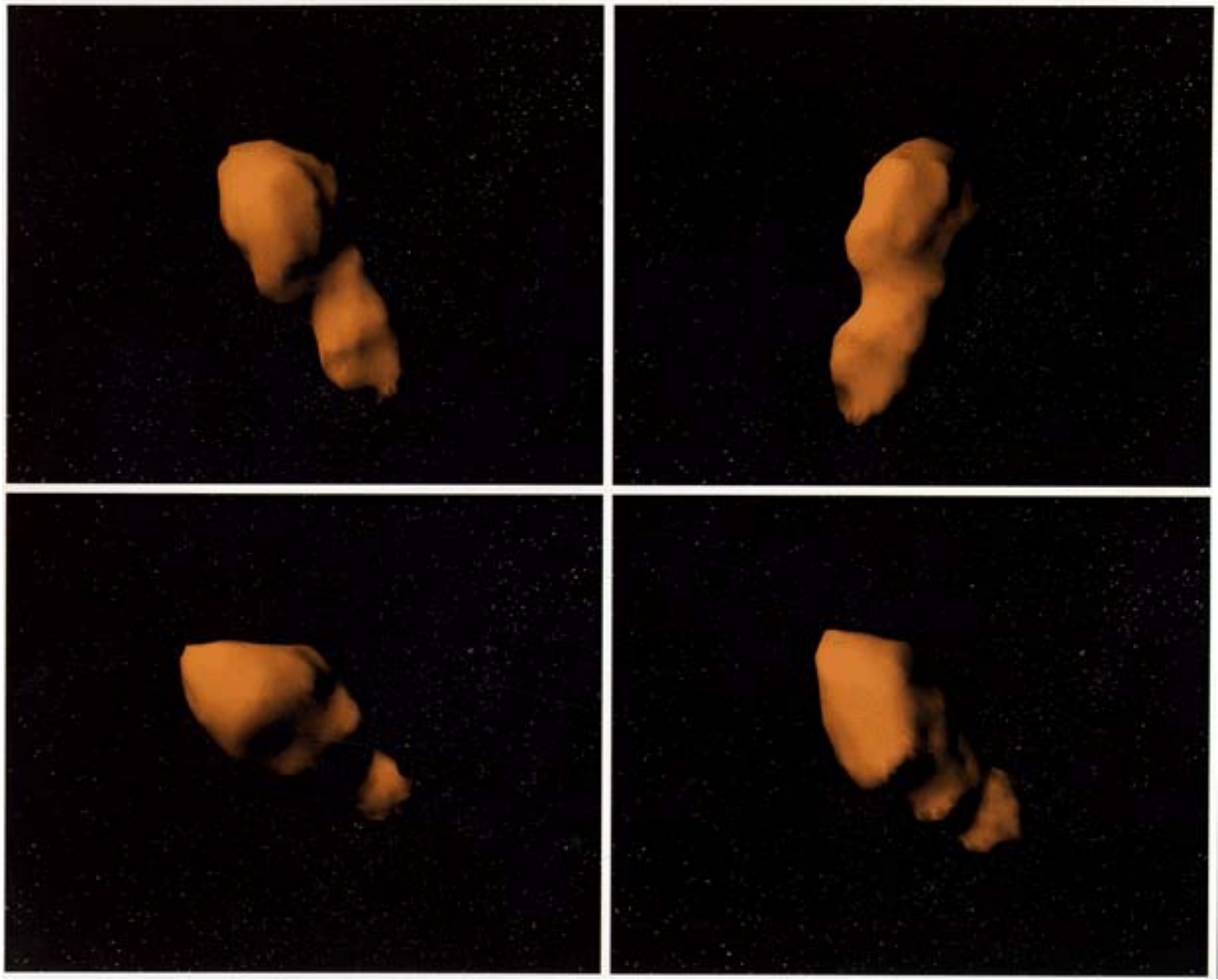
What do the instruments on NEAR tell us about Eros?

- Radio science: doppler tracking
- **NEAR's carrier frequency rises and falls due to the Doppler shift. These shifts can be used to detect velocity changes as small as 0.1 mm/s!**
- **By reconstructing NEAR's actual motion we deduce Eros' gravity field. That tells us how much mass it has, and how that mass is distributed.**



Now we know that asteroids like Eros are made of material much like ordinary meteorites.

But how are asteroids put together? Are they solid rocks, or piles of sand?



Asteroid Toutatis was imaged by radar as it passed close by Earth. Its irregular shape is evidence that it is made of weak material, which was pulled apart by the tidal forces of Earth’s gravity.

The odd shape of asteroid Geographos, also imaged by radar as it passed close by Earth, indicates that it was very weak, and probably passed very close to Earth some time in the recent past.

Why is Bulk Density Important?

- Many asteroids appear to be very weak, implying that they may be porous…maybe even extremely porous.
- Knowledge asteroid bulk density combined with meteorite *microporosity* (cracks in the rocks) allows us to set limits on asteroid *macroporosity* (gaps in the asteroid). This provides insight on asteroid internal structure.

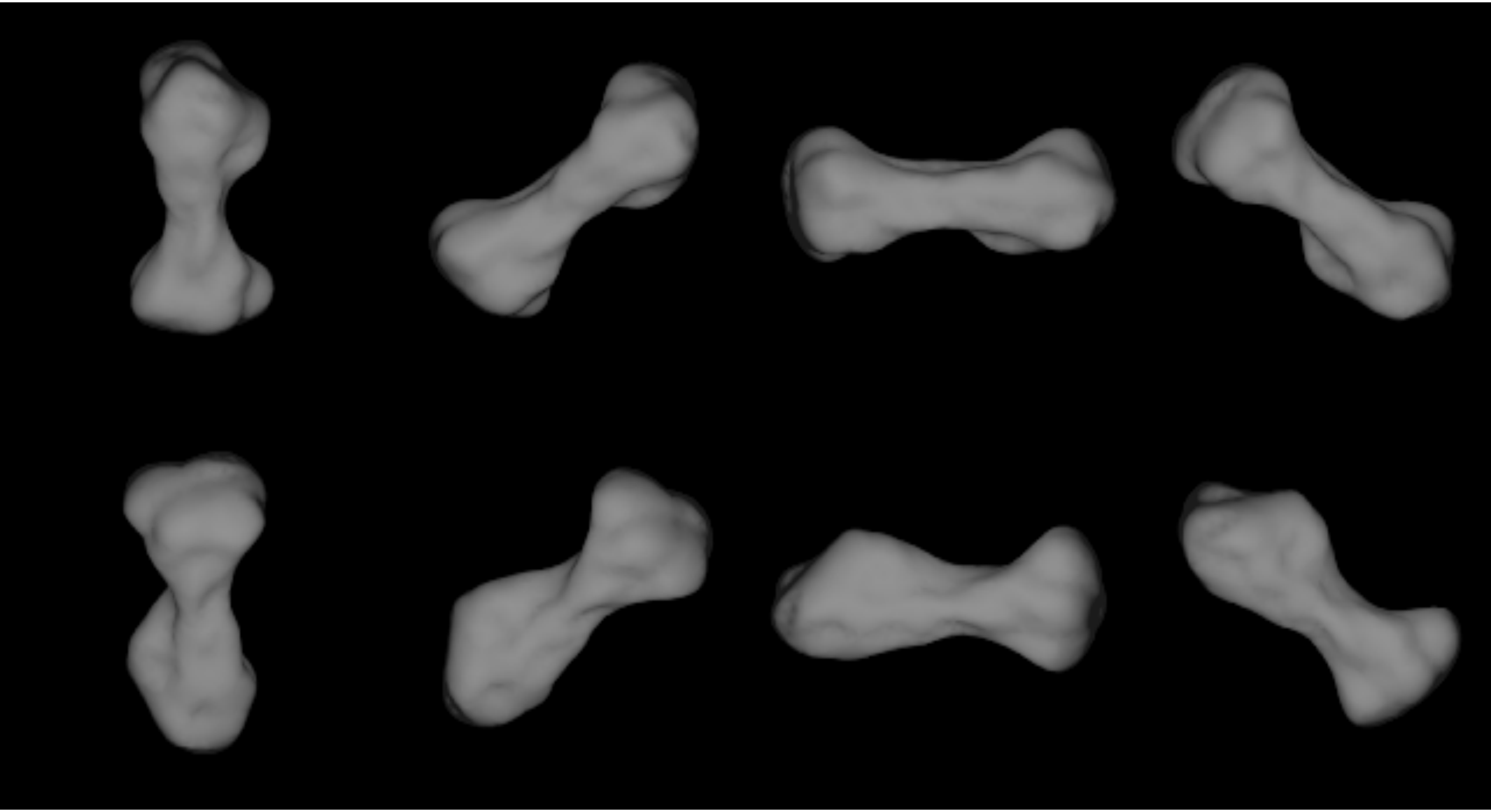
Bulk Density = Mass / Volume

- Mass is determined by observations of gravitational interactions.
  - Spacecraft motions near the asteroid (Mathilde, Eros, Phobos, Deimos)
  - Orbits of satellites (Eugenia, Ida)
  - Observing how the asteroids pull on one another and on the other planets (especially Mars).

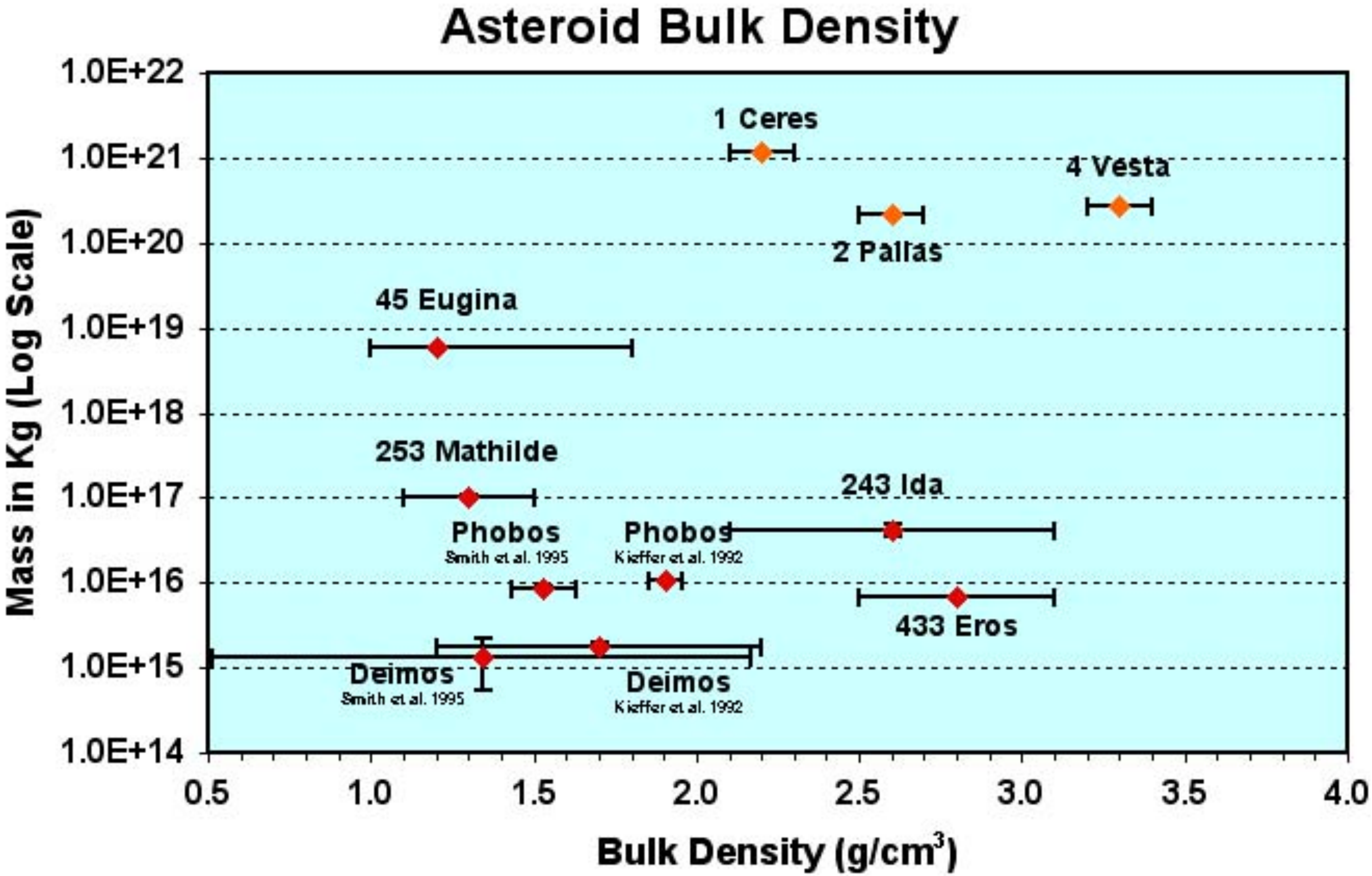
Volume Determination

- Shape models
  - Laser Rangefinder: Requires orbiting spacecraft.
    - Very accurate, but only done once so far (NEAR @ Eros)
  - Spacecraft images
    - Accuracy depends on imaging coverage (can't model what you can't see)
  - Radar and lightcurve measurements
    - Accurate and getting better

- Estimating diameters from brightness
  - Models the diameter of an object using visible and infrared light.
  - Accurate to 10%…..with caveats.



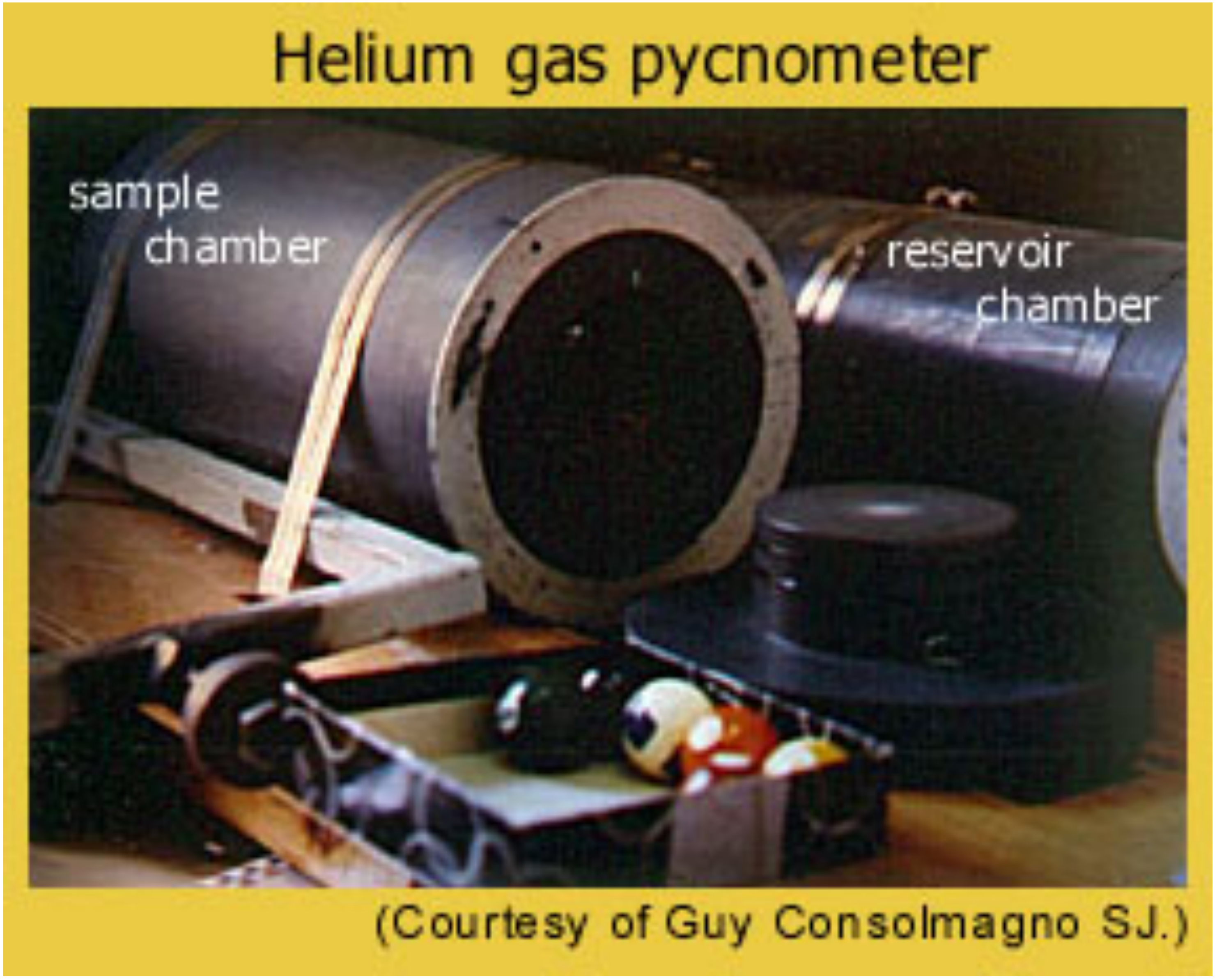
Asteroid Kleopatra is VERY irregular in shape (as seen by radar during a close pass by Earth), demonstrating the difficulty of guessing the volume of an asteroid from its brightness.



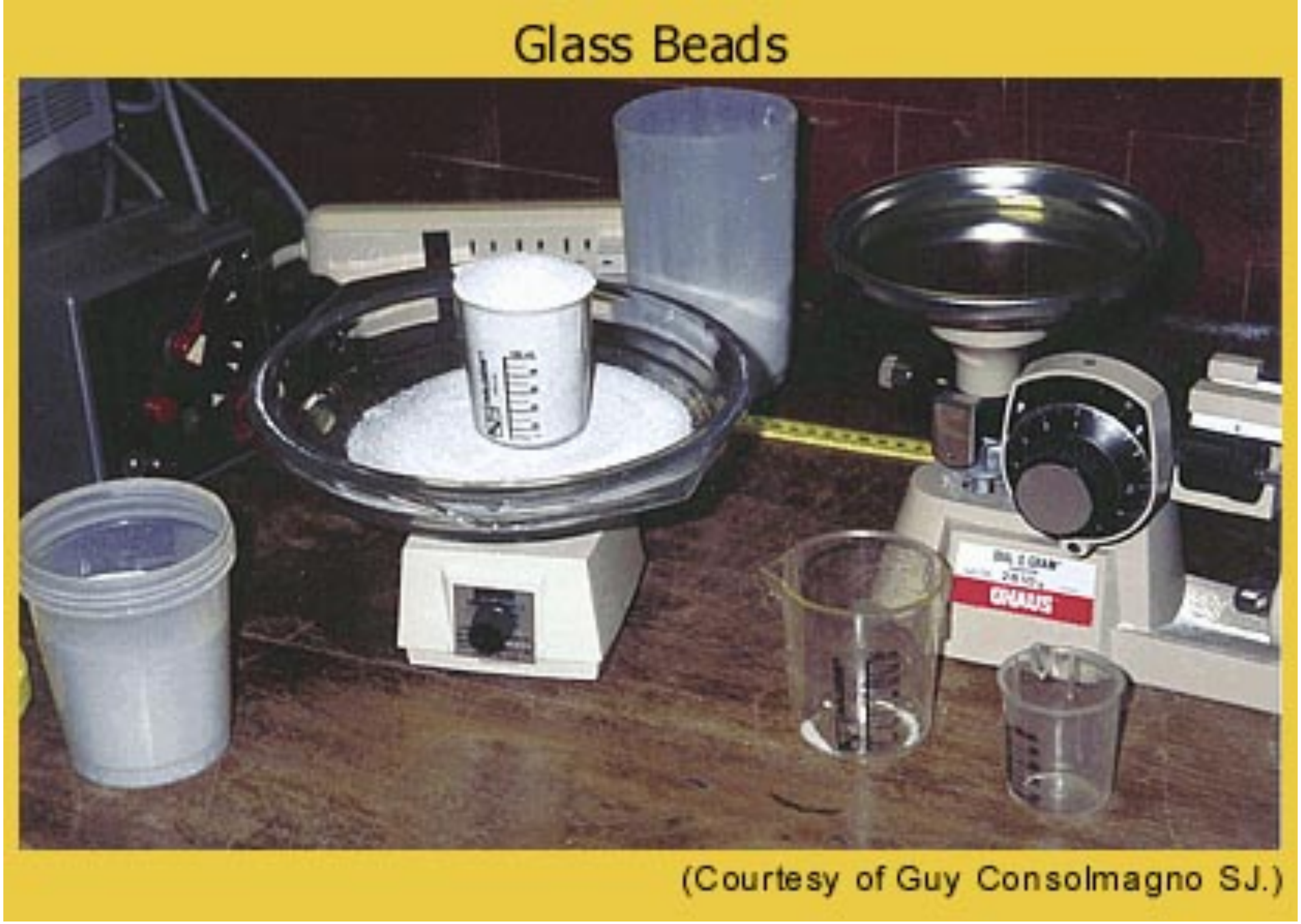
Only a few asteroids have had their mass and volume measured; and some (like Phobos and Deimos) have been measured two different ways, with two different results!

Asteroid Bulk Densities

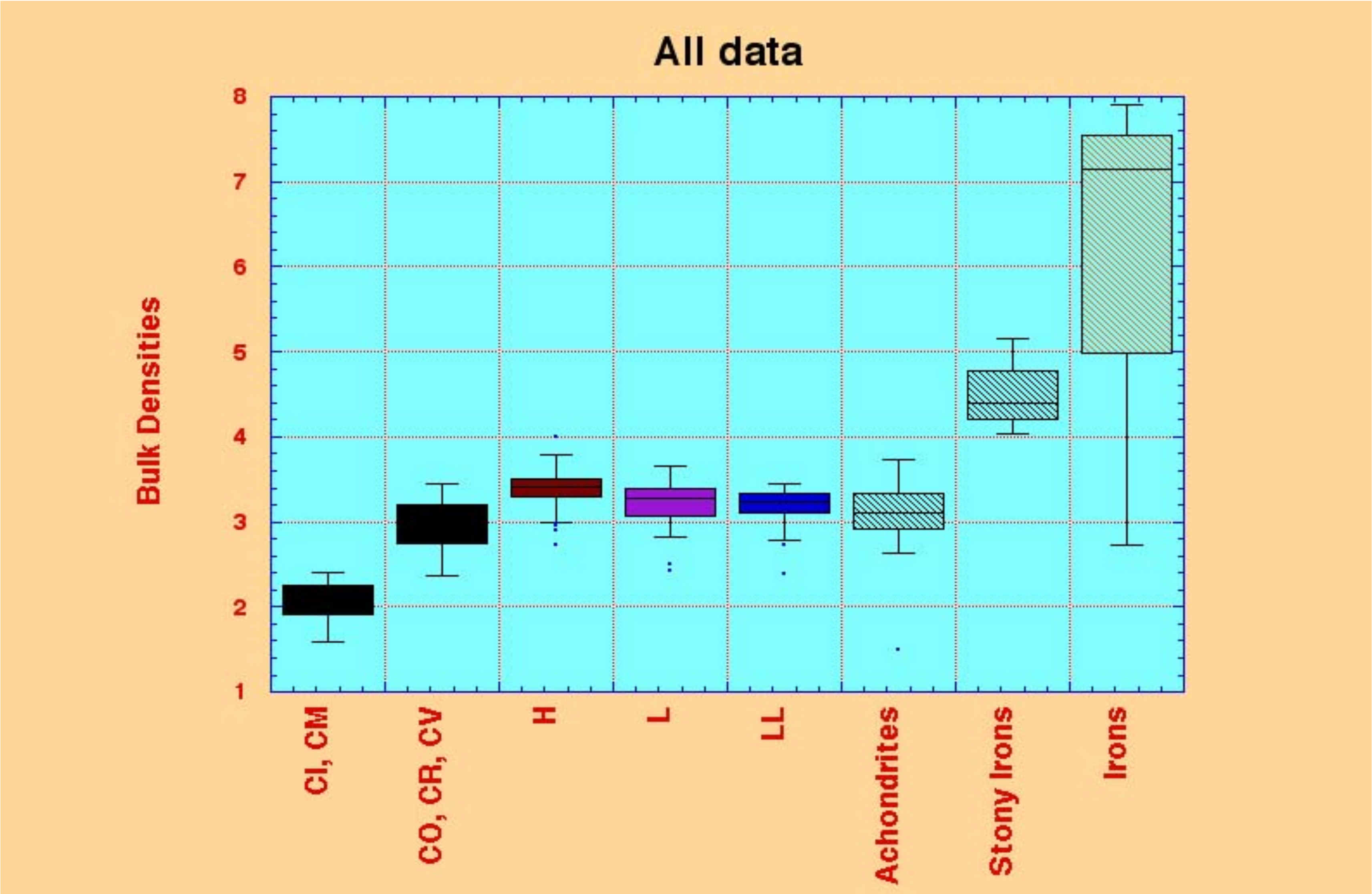
Object	BulkDensity	Object	Bulk Density
1 Ceres	2.2 ± 0.1	Average C	1.3 ± 0.1
2 Pallas	2.6 ± 0.1	Phobos	1.53 ± 0.1
4 Vesta	3.3 ± 0.1	Deimos	1.34 ± 0.5
Average S	2.8 ± 0.1	253 Mathilde	1.3 ± 0.2
433 Eros	2.67 ± 0.03	45 Eugenia	$1.2^{+0.6}_{-0.2}$
243 Ida	2.6 ± 0.5	16 Psyche	1.8 ± 0.6
121 Hermione	1.8 ± 0.4		



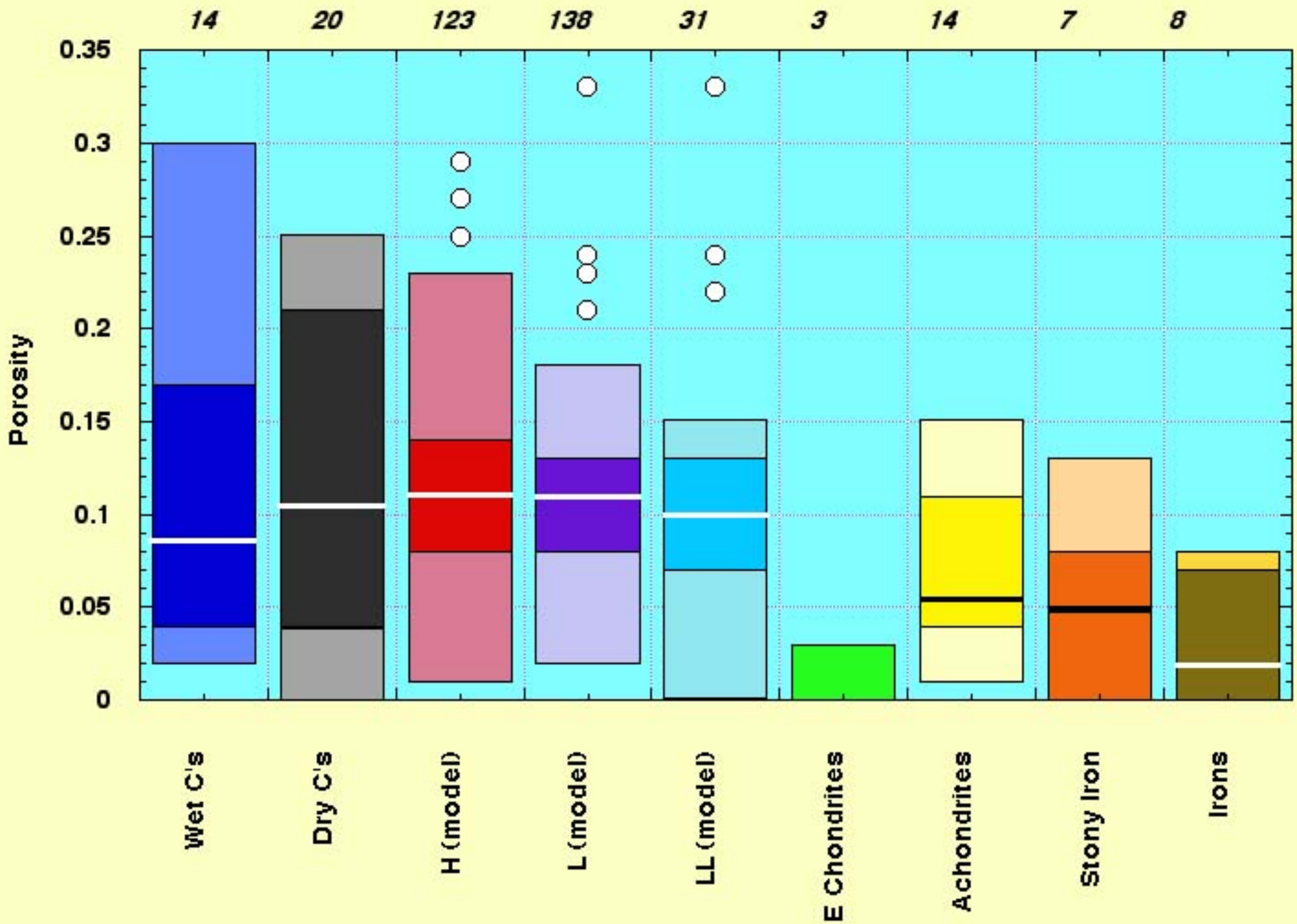
To measure the volume of rock in a meteorite, this device fills its pore spaces with Helium



To measure the bulk volume, glass beads are used; this sand will not penetrate the pore spaces. The difference between volume of the sand compared to the volume of the beaker measures the outside volume of the rock. Comparing this with the Helium measure tells us how much of the volume of the rock is empty “pore” space: the rock’s “porosity”.



Most meteorites have a bulk density of around 3 to 3.5 times the density of water. “C” meteorites are very dark; “H” “L” and “LL” meteorites are the ones grouped together as “ordinary chondrites”.



The white lines in the boxes show the average porosity; most ordinary meteorites are about 10% empty space, mostly in the form of cracks running through the rock.

When you subtract away the porosity in the rocks, the remaining porosity in an asteroid must be large empty spaces between the bits of rubble that make up the asteroid:

Estimated Macroporosity

Object	Estimated Porosity	Average Microporosity	Estimated Macroporsoity
1 Ceres	3.1% ± 4.4%	11%	0%
2 Pallas	4.1% ± 3.7%	12%	0%
Average S	25.3% ± 2.7%	10.8%	14.5%
433 Eros	28.8% ± 0.8%	10.8%	18%
243 Ida	30.7% ± 13.3%	10.8%	19.9%
121 Hermione	33.6% ± 14.8%	12%	21.6%
Average C	42.7% ± 4.4%	11%	31.7%
Phobos	43.5% ± 3.7%	12%	31.5%
Deimos	50.6% ± 30.6%	12%	38.6%
253 Mathilde	52.0% ± 7.4%	12%	40%
45 Eugenia	$55.7\%^{+22.1\%}_{-7.4\%}$	12%	43.7%
16 Psyche	75.0% ± 8.3%	0%	75%

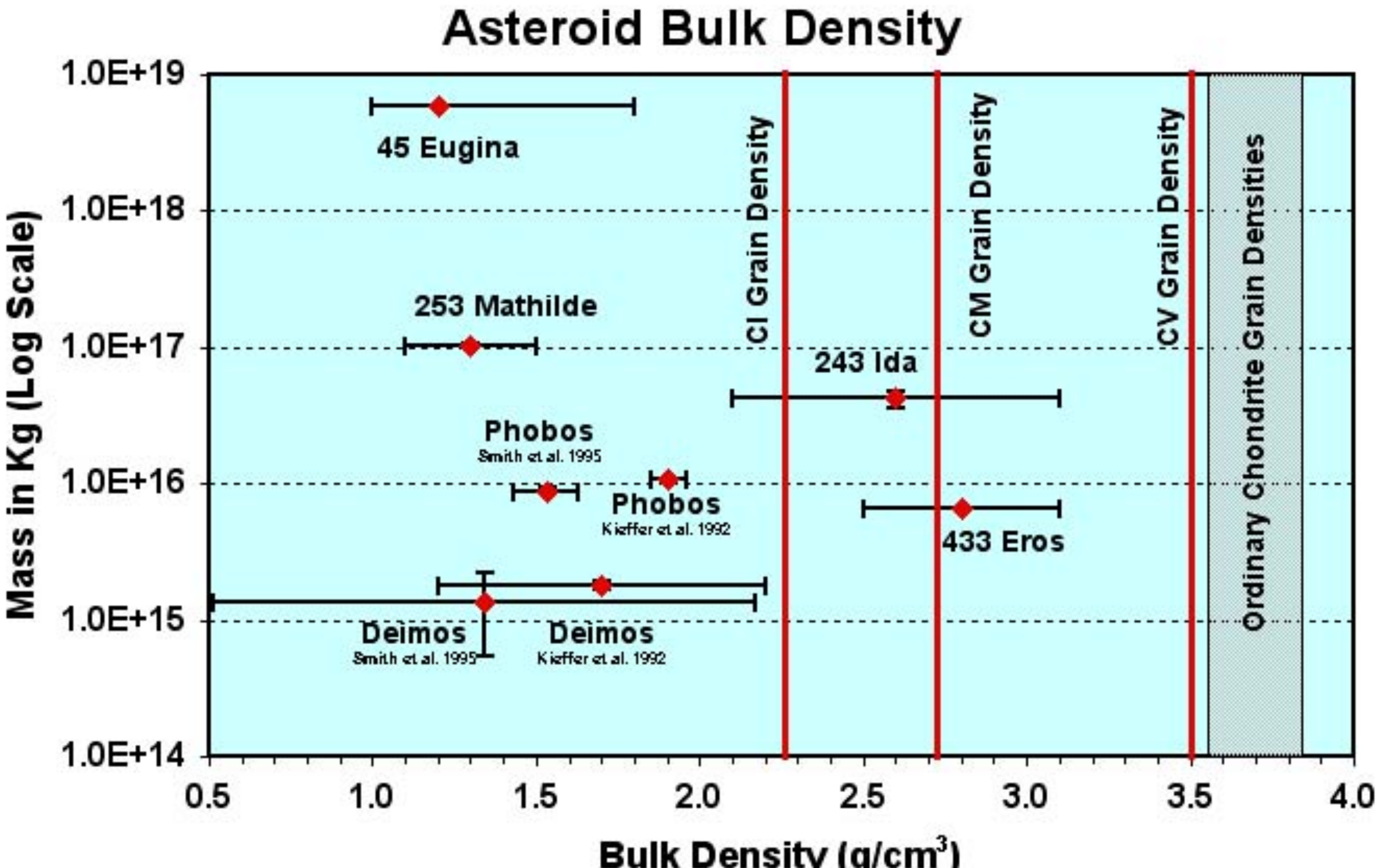
Trends in the Data

- We can estimate macroporosity using these bulk porosity estimates and what we know about meteorite porosity.
- Once an asteroid gets up to about 30% macroporosity, it is hard to believe that it is a coherent object
  - From terrestrial experience, 30% porosity is about the upper limit for a coherent rock.
- We suggest that these data can be divided into two groups.
  - Some objects have as estimated macroporosity below 20%. These are probably coherent asteroids.
  - Some objects have an estimated macropososity above 30%. These are probably rubble piles.
  - This is not a hard an fast rule. As will all classifications, there is a gray zone in the middle.

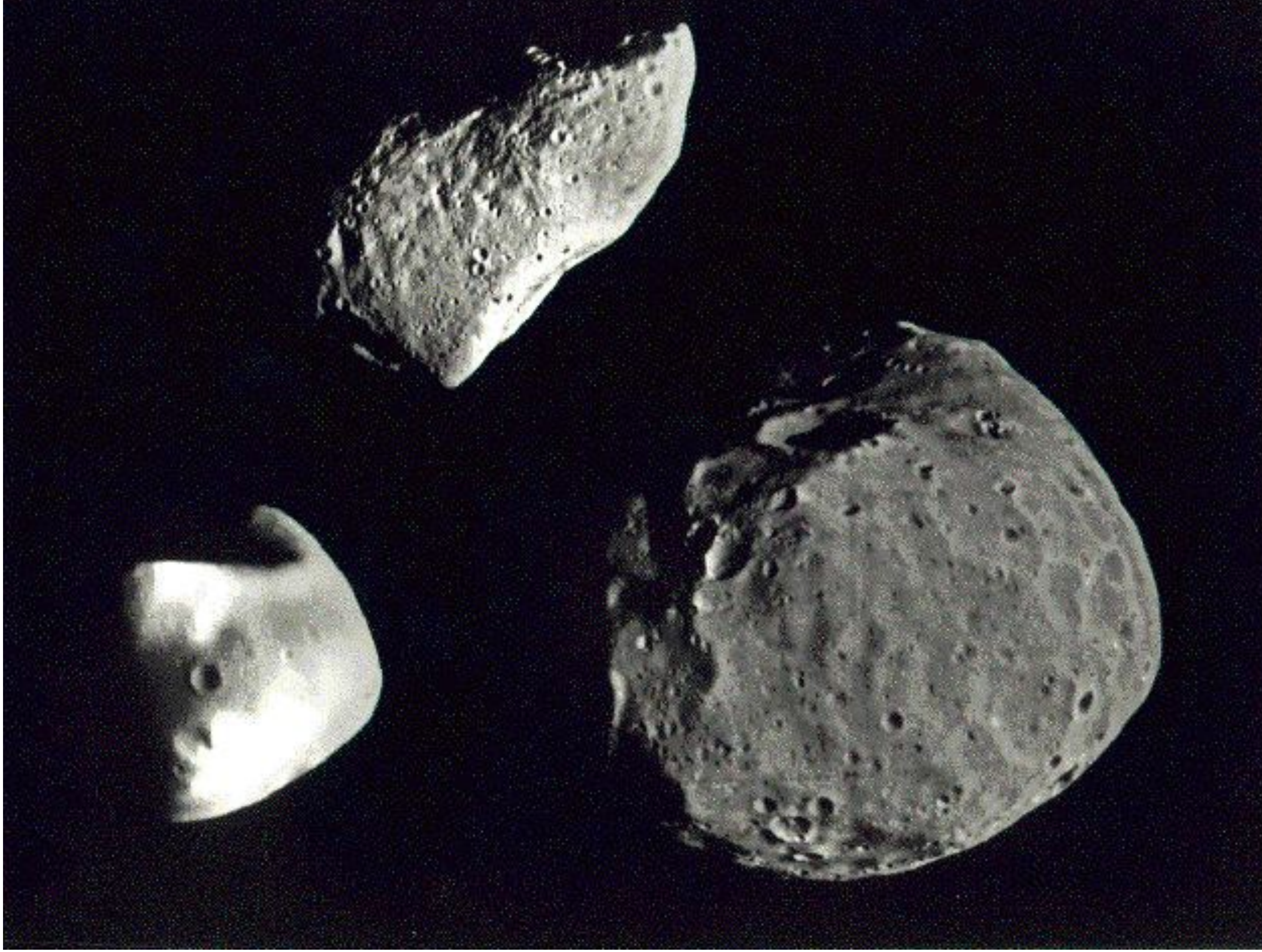
What Does it Mean?

- We can interpret the bulk density numbers by looking at the densities of the meteorites we think come from these asteroid.
  - Meteorite/asteroid connection determined by spectroscopy
  - This allows the estimation of asteroid bulk porosity.
- The large asteroids, 1 Ceres, 2 Pallas, and 4 Vesta, have bulk densities close to those of their presumed analogues. These objects are probably coherent and have low bulk porosity.
- The “smaller” asteroids (and this includes 16 Psyche with a diameter of 264 km) appear to have substantial porosity.

Ida and Eros are asteroids that look like Ordinary Chondrites; the others look like dark C type meteorites. In all cases, the asteroids are less dense than the meteorite types, implying they are full of void spaces.



Can we see evidence of void spaces in the asteroids imaged by spacecraft to date?



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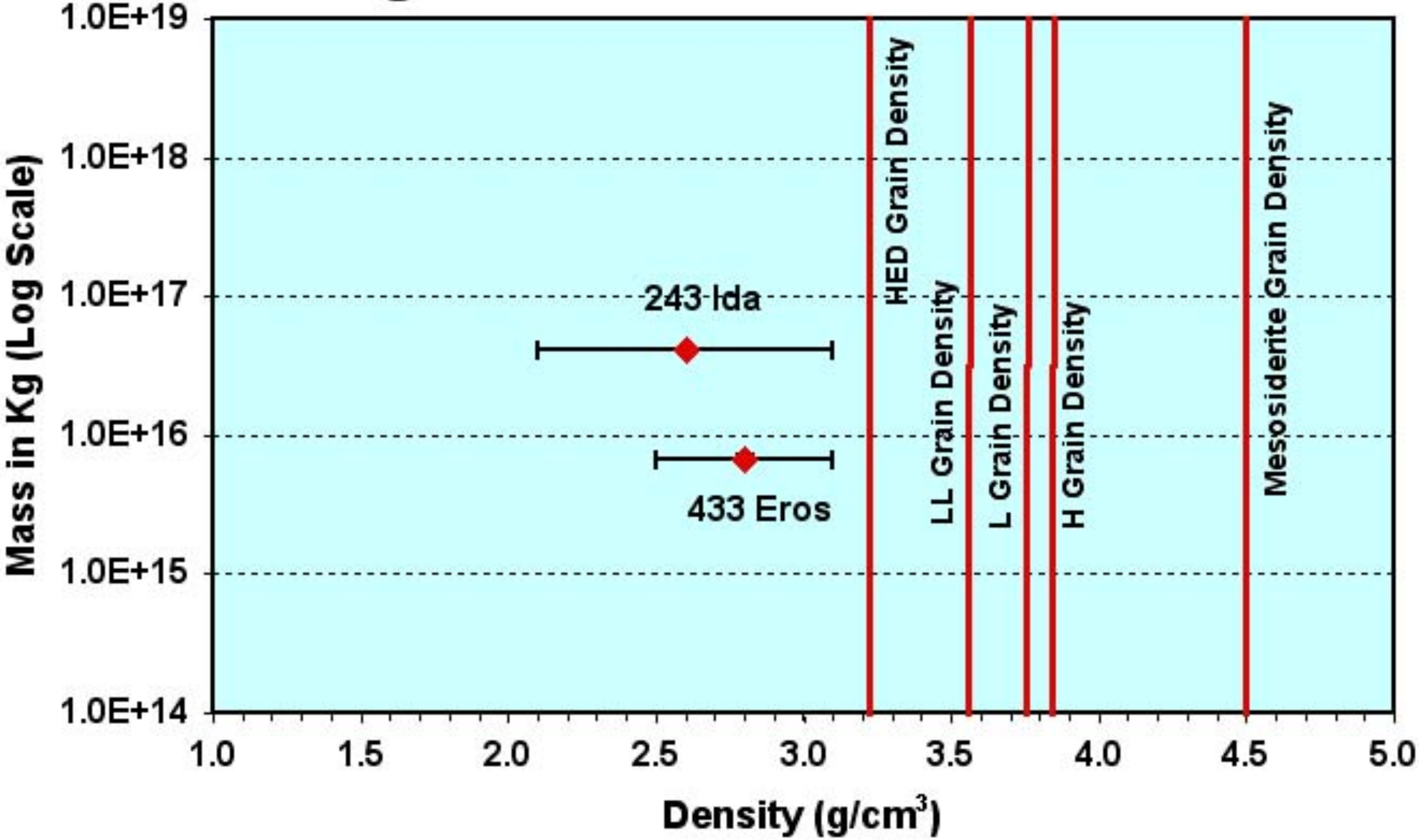
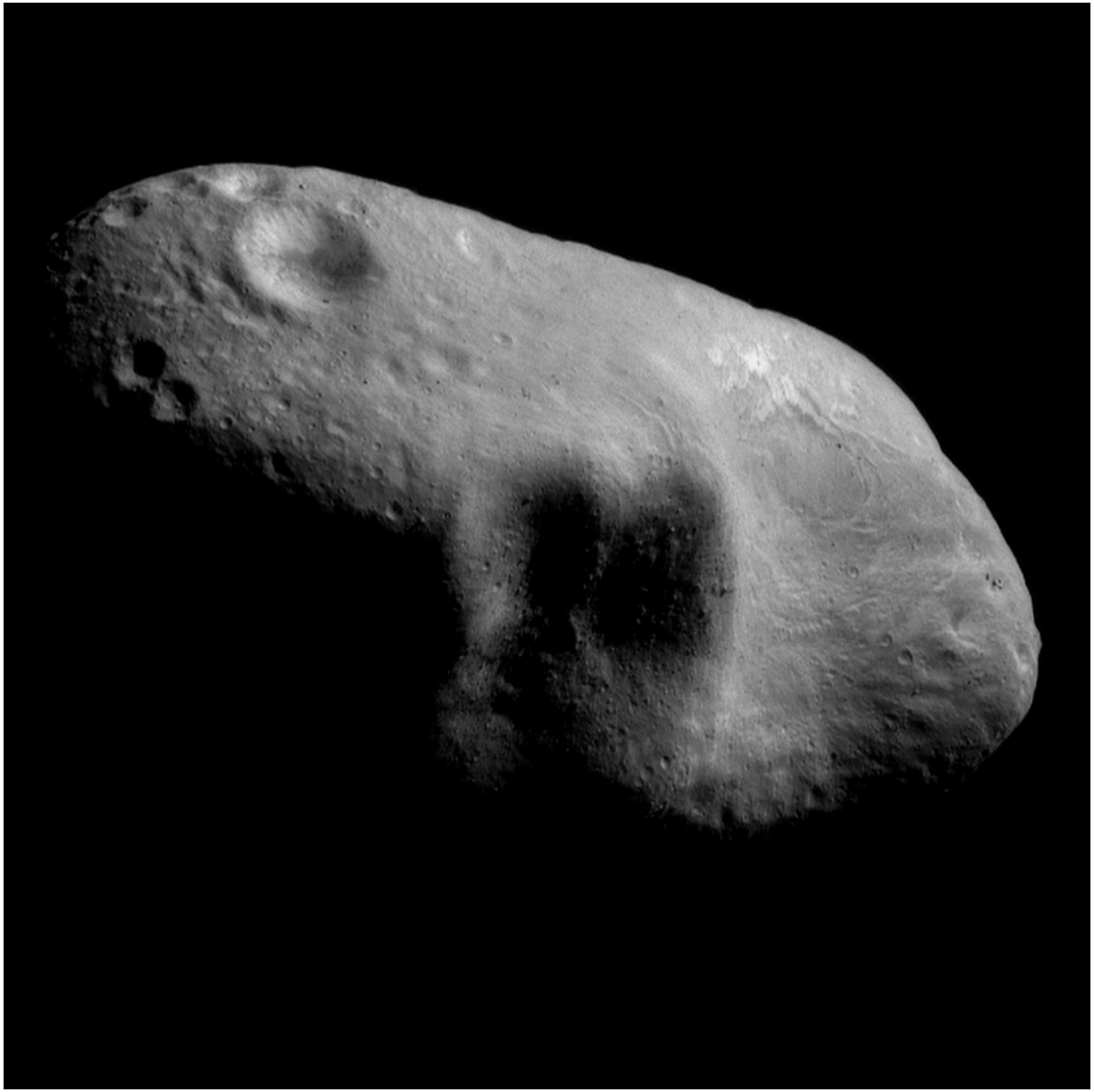
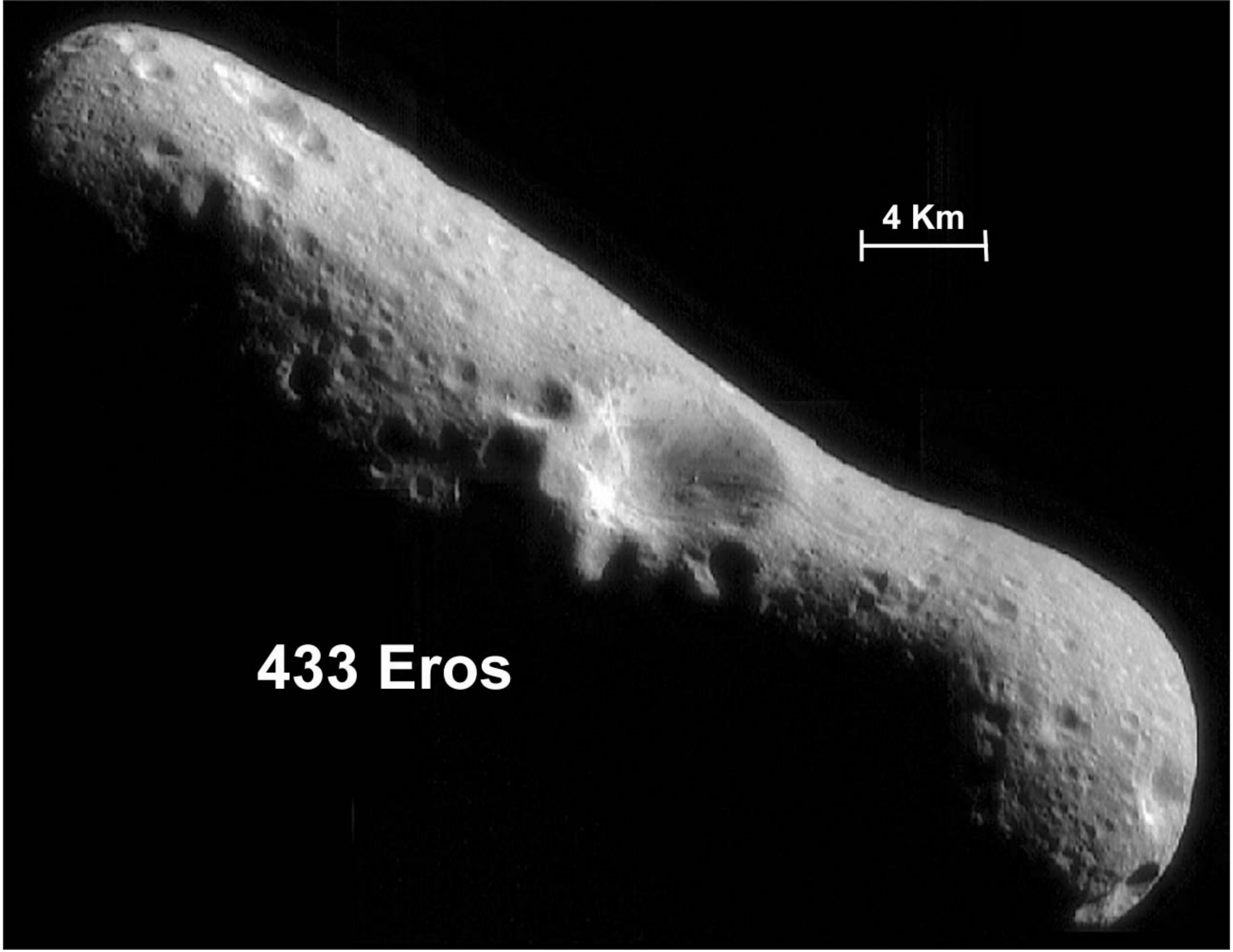
Light Asteroids and Meteorites





Asteroid Eros, as seen by NEAR



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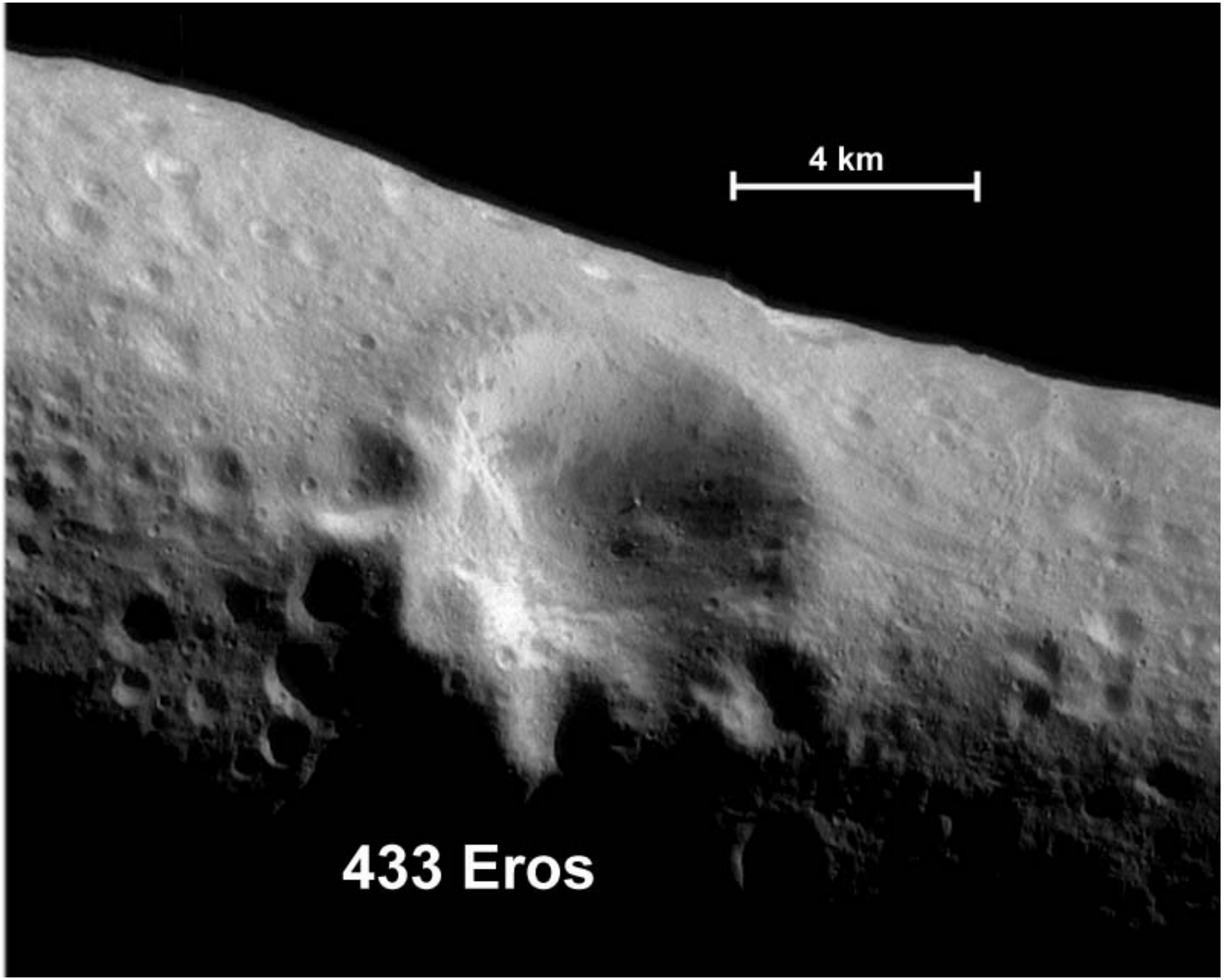
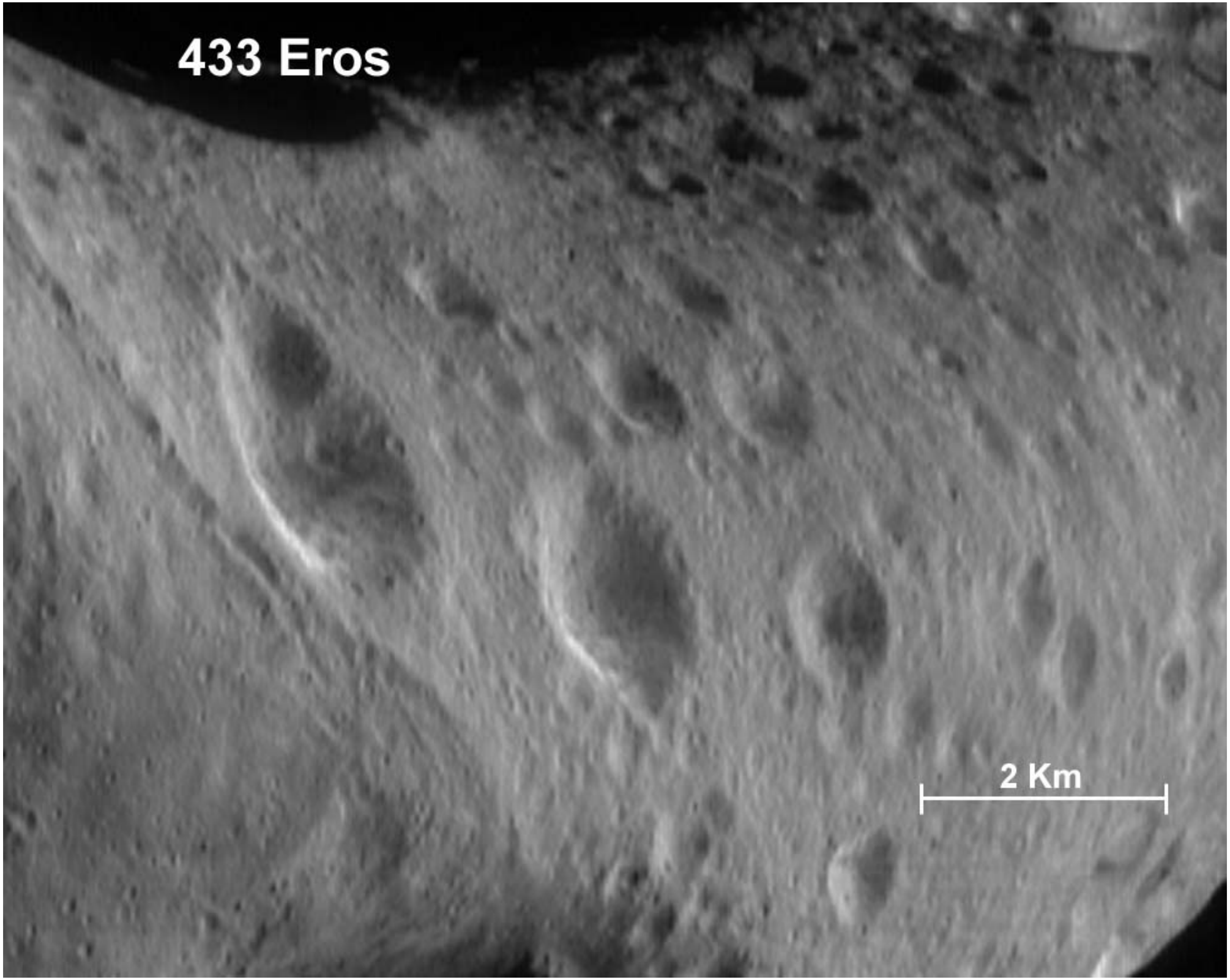


The craters on Eros imply that it has some cohesive strength, though it may be riddled with cracks. Note the boulder that has rolled towards the center of this crater.



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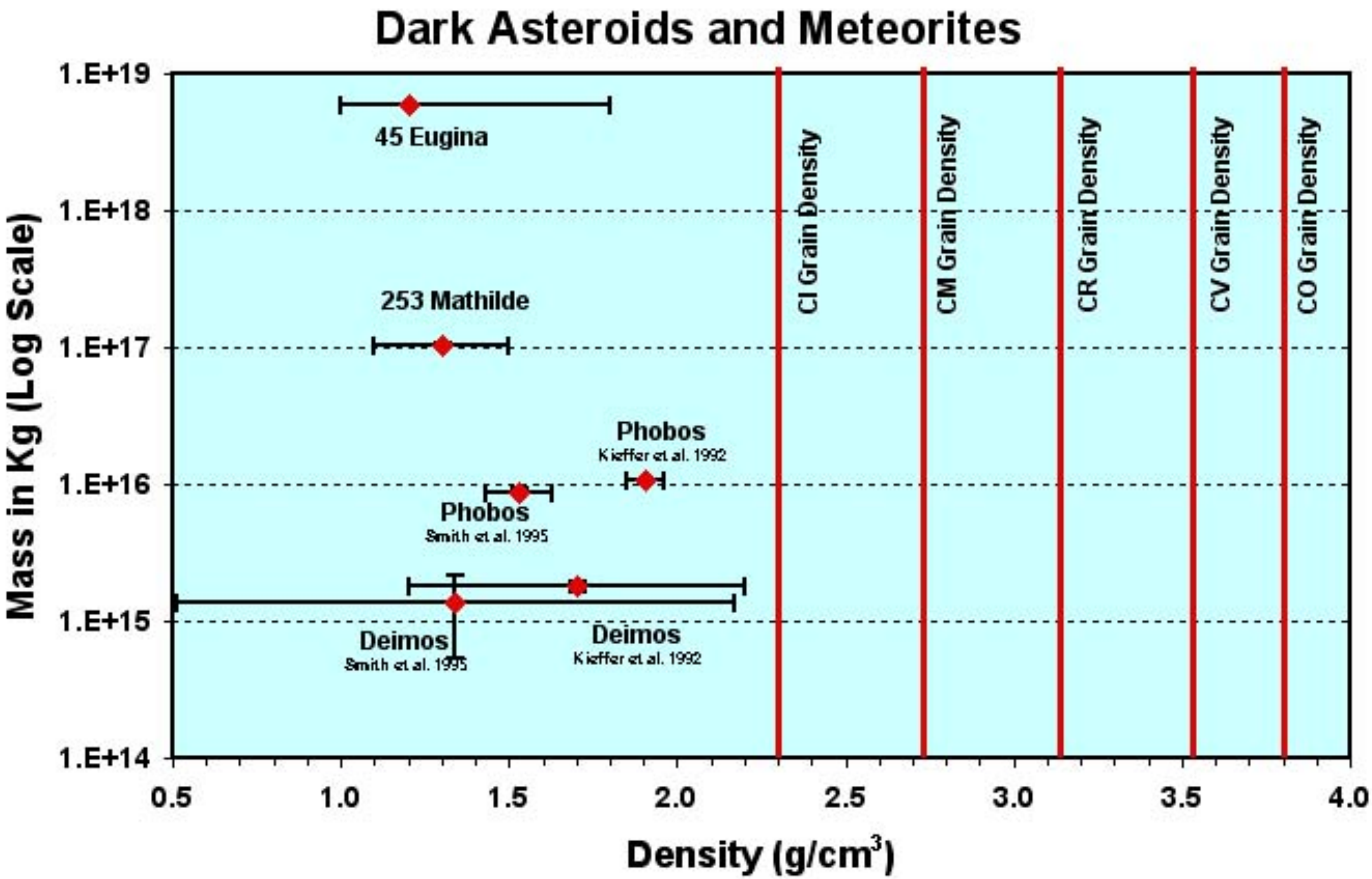
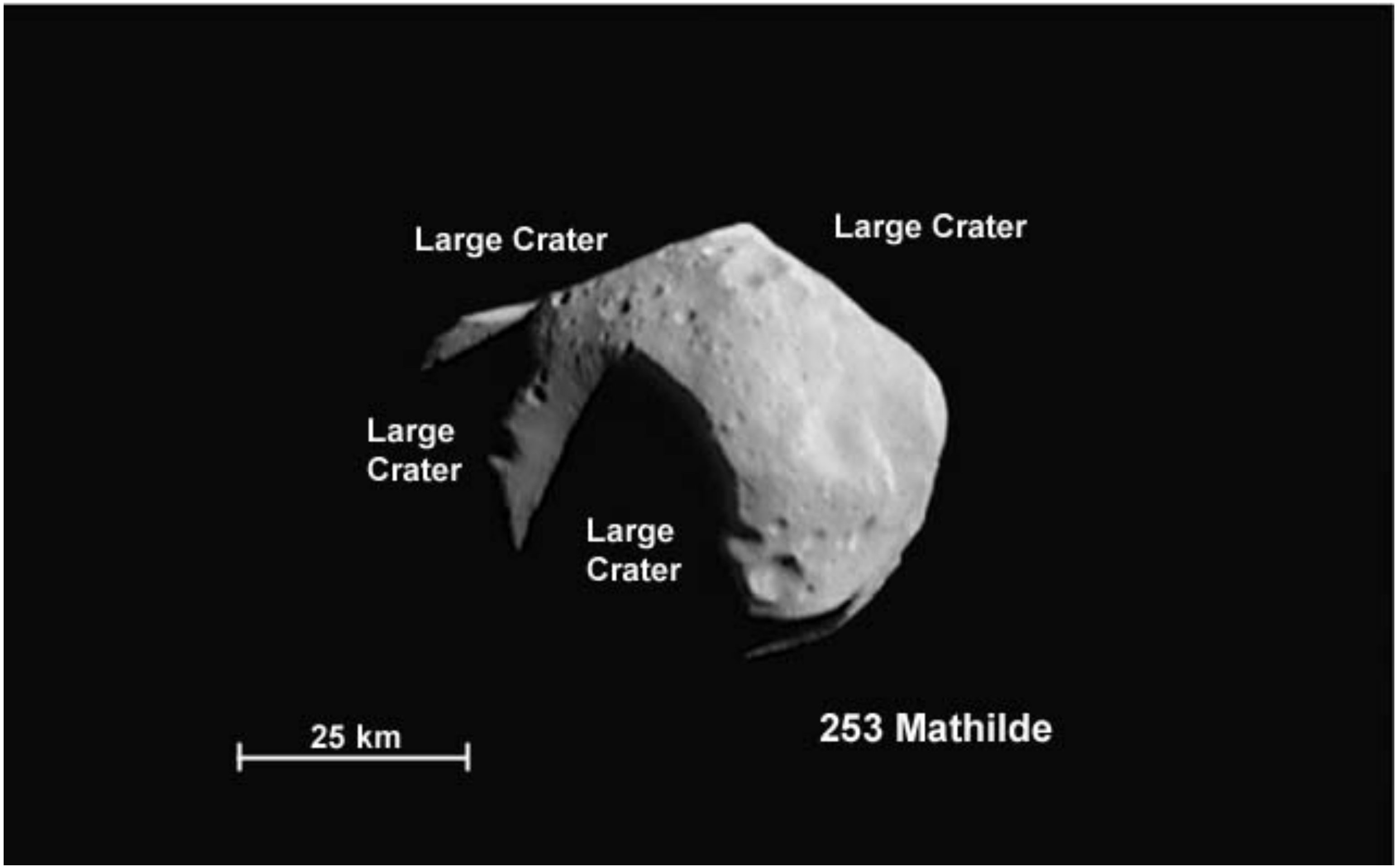
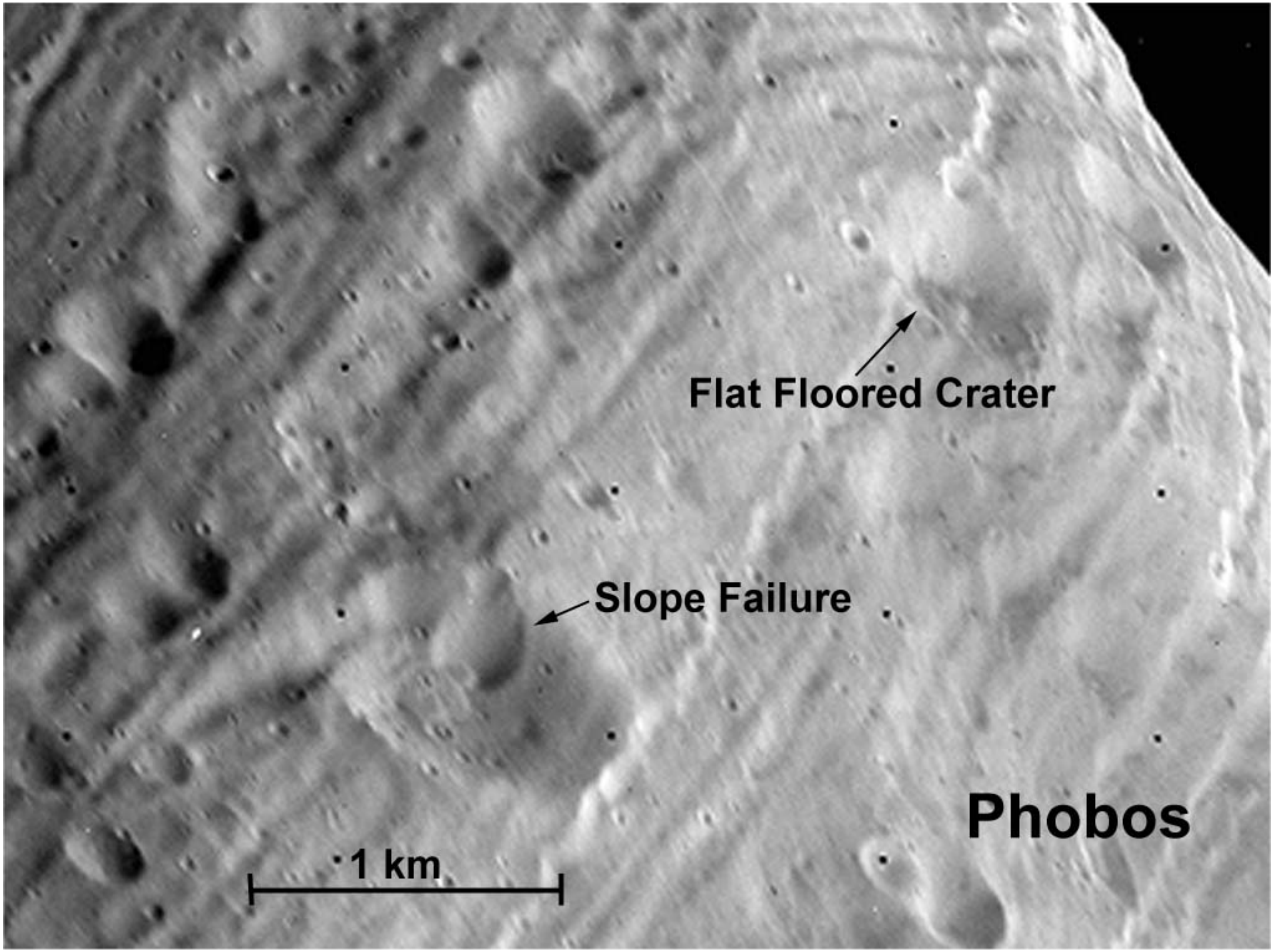

Dark Asteroids and Meteorites
1.E+19
1.E+18
1.E+17
1.E+16
1.E+15
1.E+14
Mass in Kg (Log Scale)
45 Eugina
253 Mathilde
Phobos
Kieffer et al. 1992
Phobos
Smith et al. 1995
Deimos
Smith et al. 1995
Deimos
Kieffer et al. 1992
CI Grain Density
CM Grain Density
CR Grain Density
CV Grain Density
CO Grain Density
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Density (g/cm3)



The many large craters on the dark asteroid Mathilde, imaged by NEAR, imply that it must be made of soft material that can absorb heavy blows without flying apart. Asteroids like this may be hard to destroy if they are on an Earth-impacting path. On the other hand, they may be very easy to mine for minerals!



The moon of Mars, Phobos, may be a captured asteroid. Notice the soft material making landslides on its surface, and the string of grooves that may be evidence of material falling into voids in its interior.

Conclusions

- The asteroid bulk density measurements often depend on difficult observations and models. Final numbers are very sensitive to small changes in model parameters. Healthily skepticism is encouraged.
- The largest asteroids, like Vesta, appear to have bulk densities similar to their meteorites. They are probably coherent objects with little porosity.
- For most of the other asteroids, the population can be roughly divided between rubble-pile (e.g. Mathilde) and coherent objects (e.g. Eros) at approximately 20-30% macroporosity.