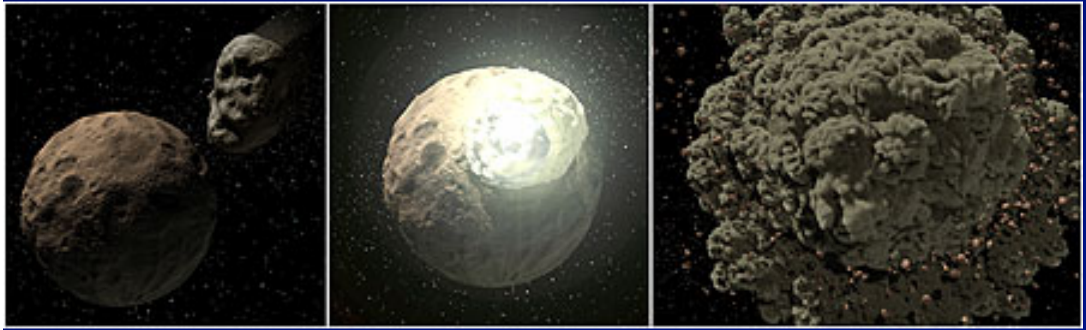
2011 Interdisciplinary Summer School: Granular Flows

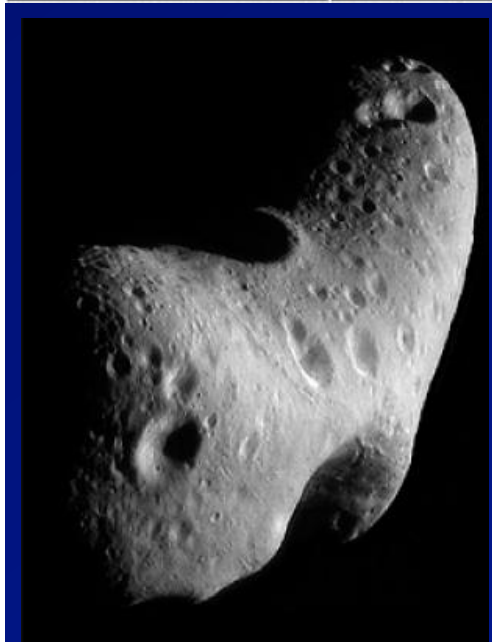


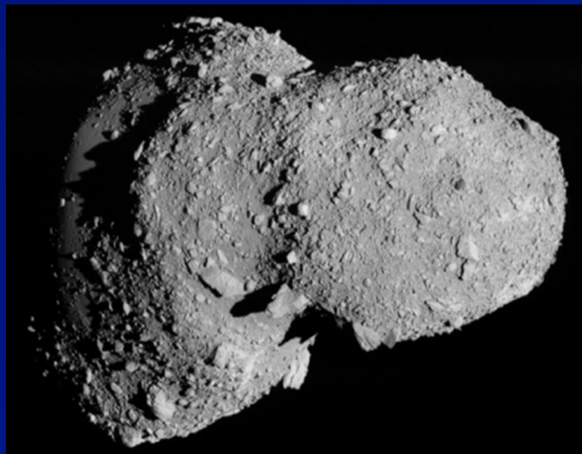
Astrophysical Applications

Patrick Michel

Leader of the group of Planetology

Laboratory Cassiopée



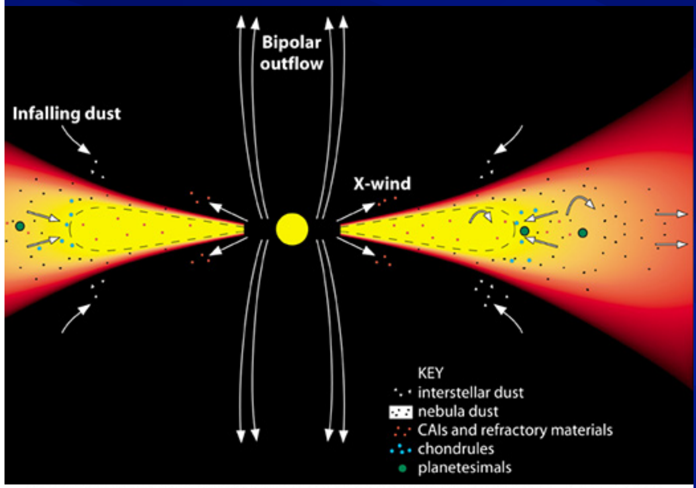


Granular Materials, Planetology and Space Missions

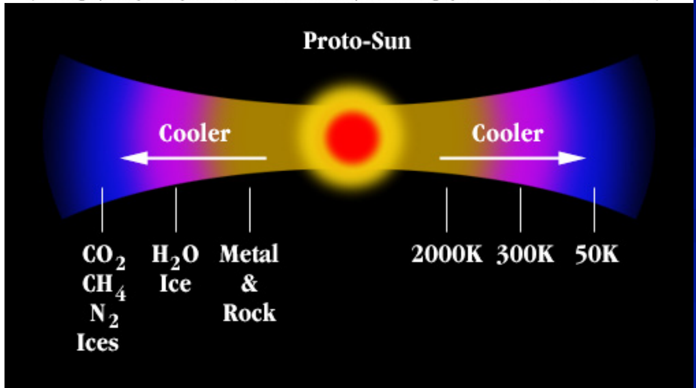
- Interpretation of celestial body surfaces covered with regolith (what are the properties of the regolith that explain surface features, how does the regolith behave under the different stresses undergone?)
- Cratering on regolith surfaces, momentum transfer
- Efficiency of sampling devices for extra-terrestrial material
- Risks posed for landing and/or anchoring on small bodies, the Moon and Mars, especially for humans!

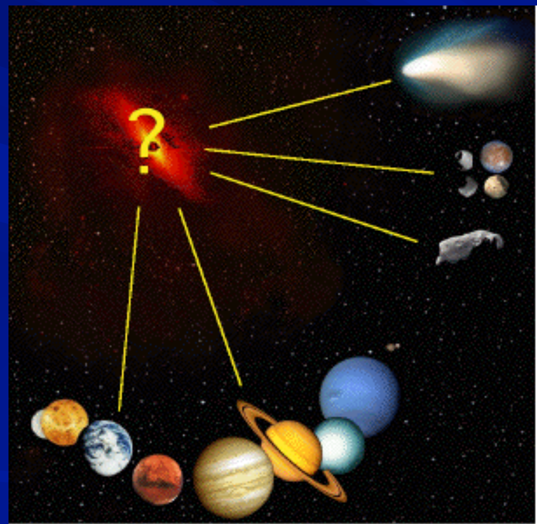
Small bodies= DNA of the Solar System

Asteroids are remnant of solids of the protoplanetary disk in which planets were formed

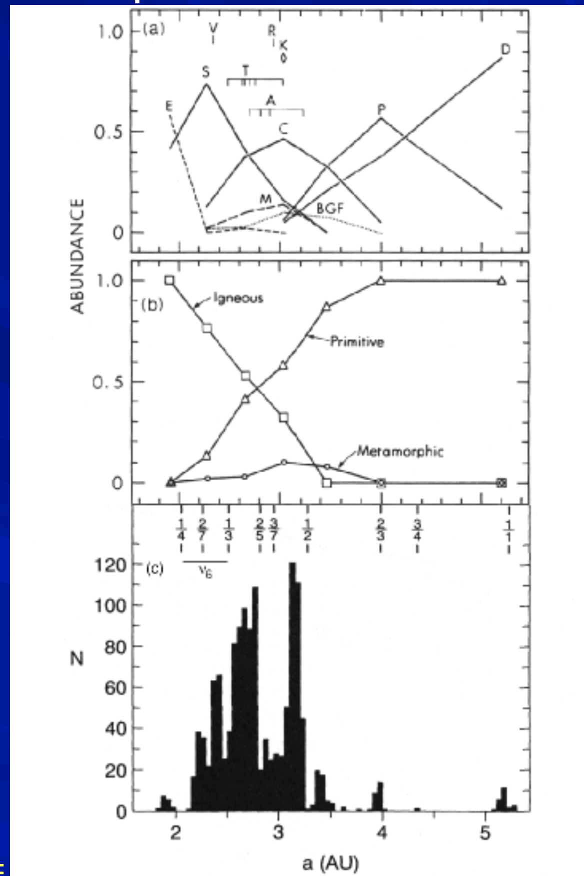


(PSRD graphic by Nancy Hulbirt, based on a conceptual drawing by Edward Scott, Univ. of Hawaii.)





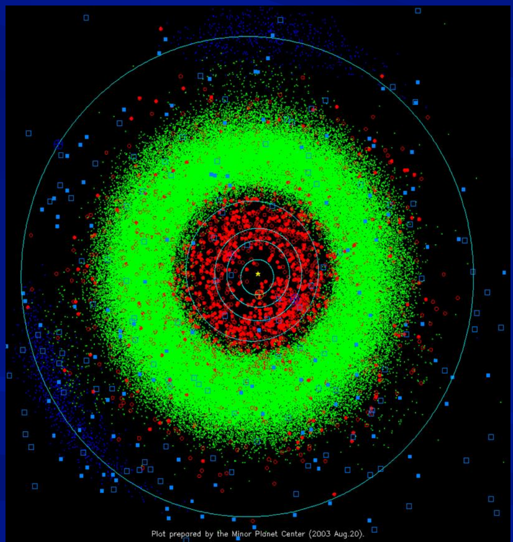
Asteroid Spectra, Composition and number

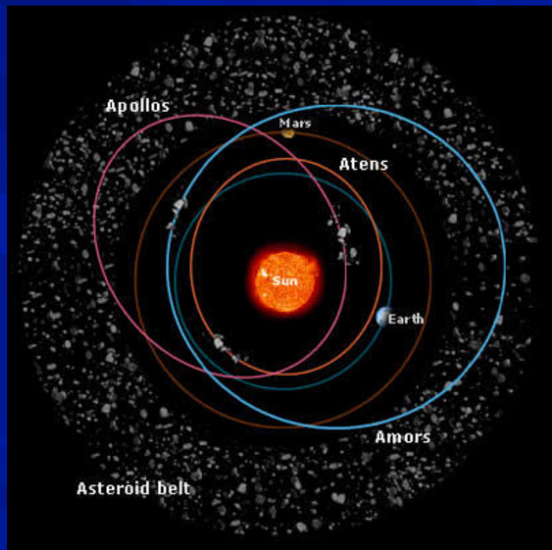


Dark (C, D) type asteroids ⇐ are the most primitive

Mean distance to Sun

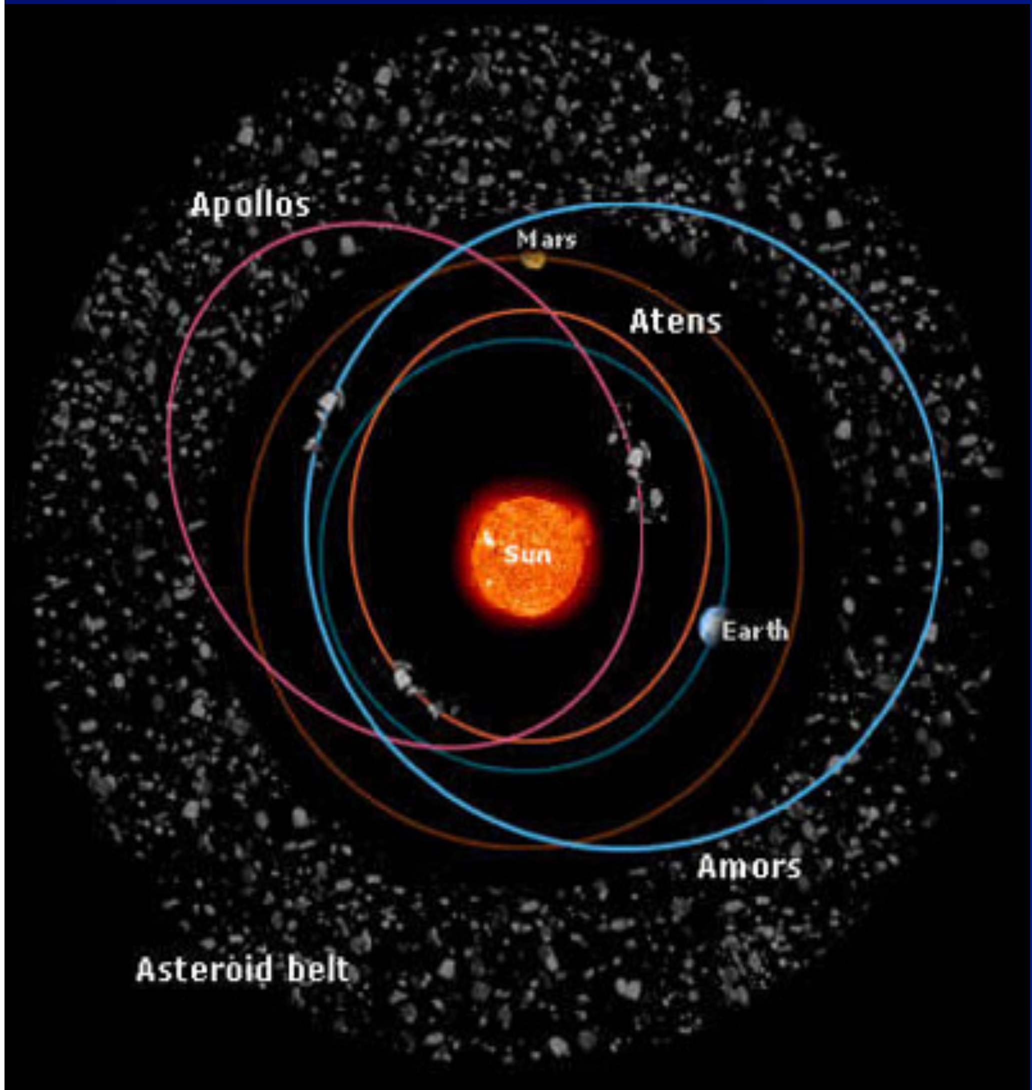
Current structure of the Solar System





Asteroids and comets: remnants of planetary bricks

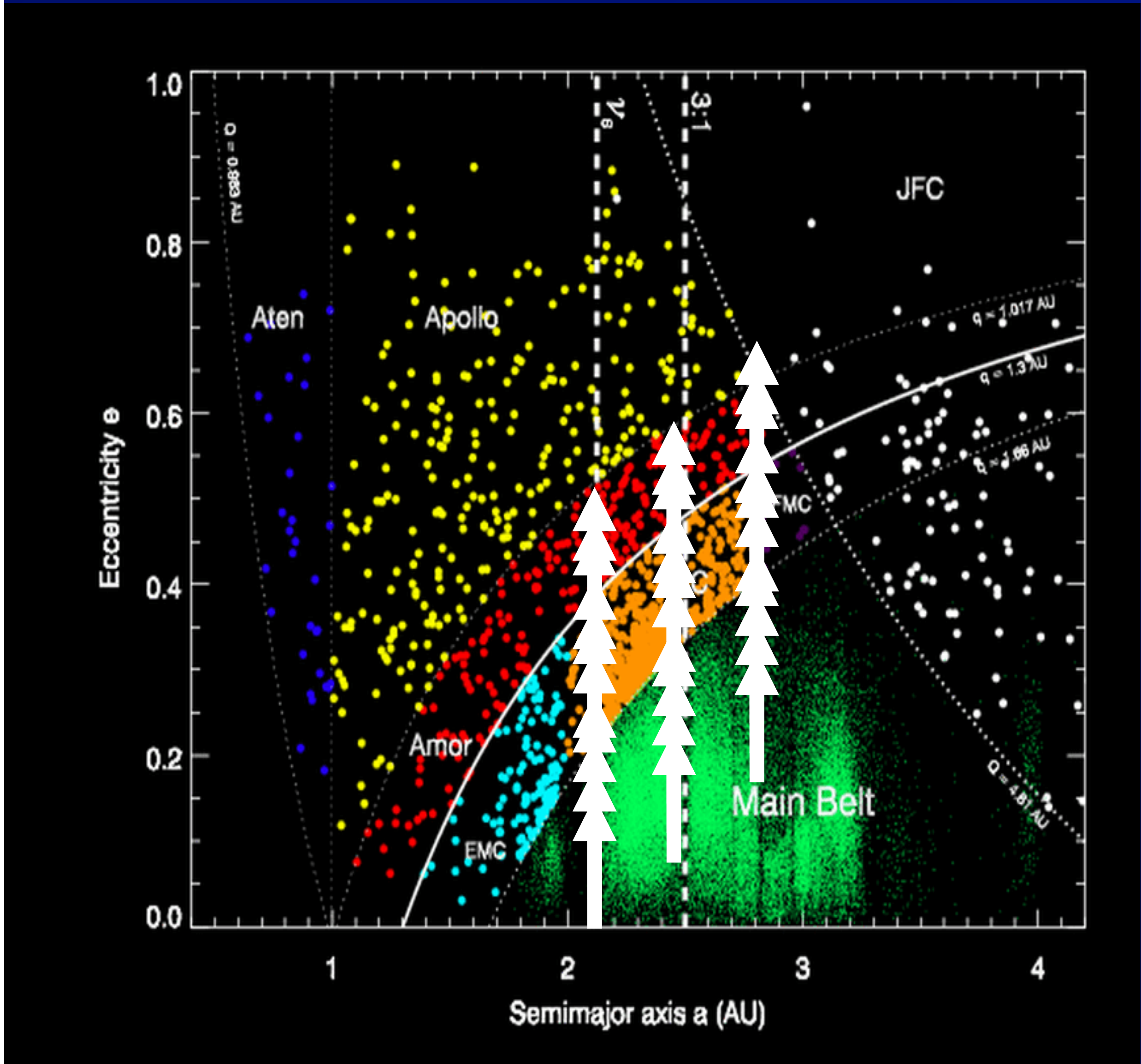
The NEO population



NEOs have many interesting characteristics:

- Accessibility
- Identified links to other small body populations
- DNA of the Solar System
- Great diversity of physical and compositional properties
- Hazard
- Great laboratory for studies of granular materials in micro-g

Origin of NEOs



Mean distance to the Sun (AU)

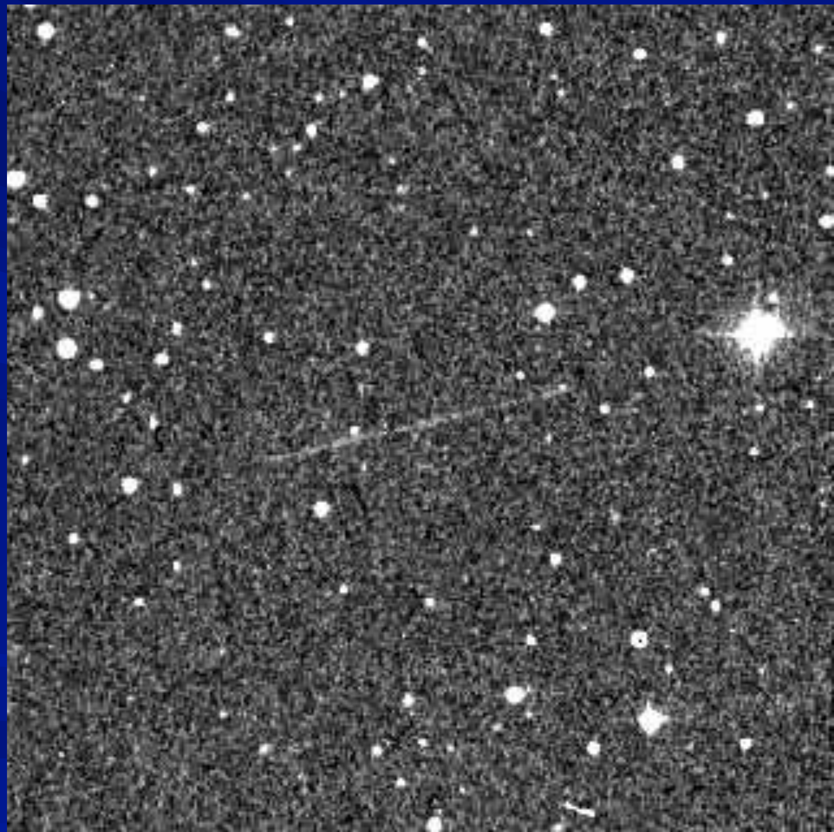
Asteroids from different regions of the Main Belt (MB) are injected into resonances which transport them on Earth-crossing orbits

A small fraction (6-8%) of NEOs come from Jupiter-family comets

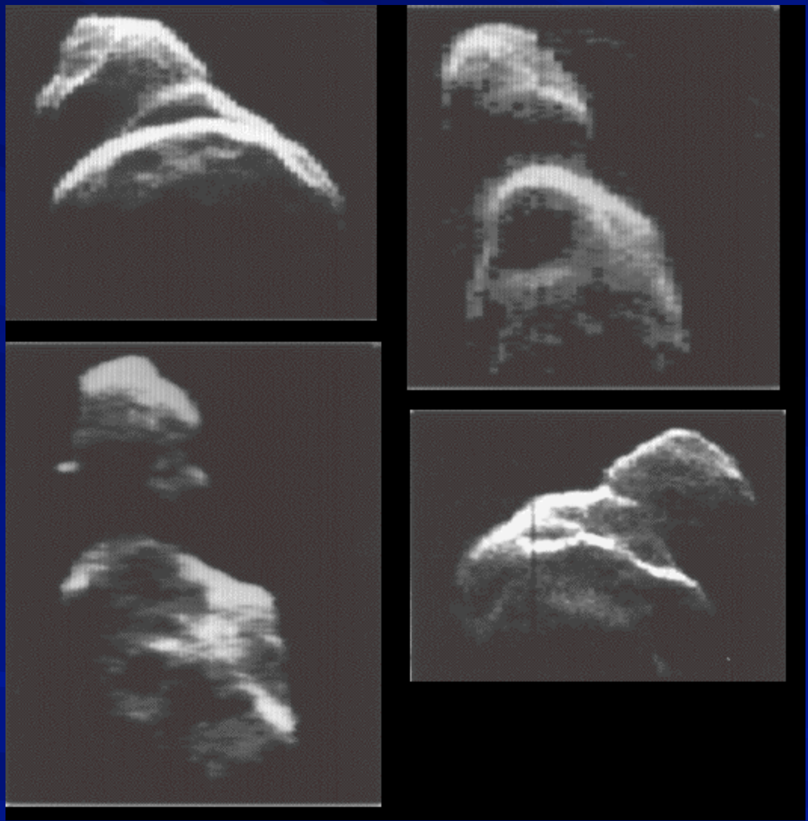
Consequences

- Collisions (accretion, disruption, cratering) play a major role in the Solar System history:
  - NEOs are the by-products of catastrophic disruptions
  - Most current asteroids < 50 km in size are at least of second generation => aggregates
  - All celestial body surfaces are covered with craters whose ejecta may fall back and form a regolith layer
- We should expect a lot of granular material to be present on bodies in the Solar System
- Understanding the dynamics of granular material is crucial to characterize those bodies and their geological evolutions

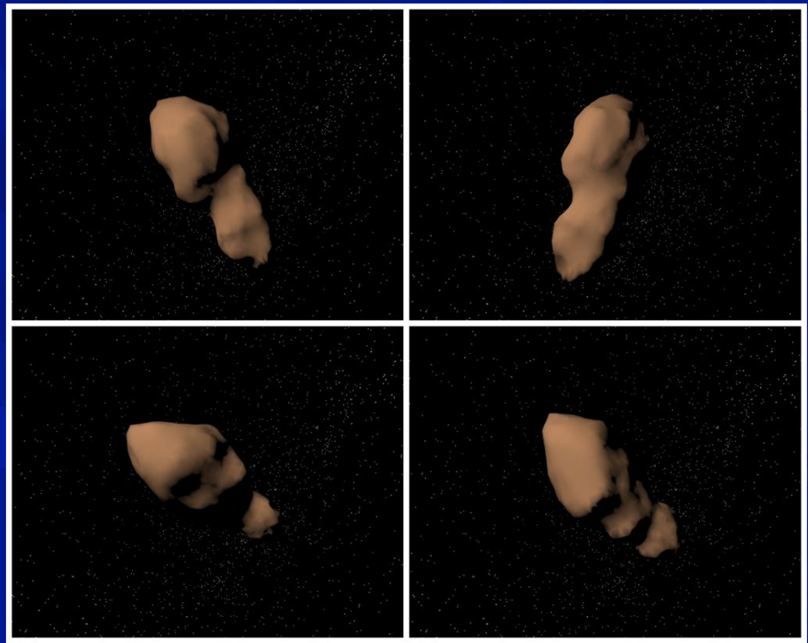
Detection of asteroids from the ground



Radar observations of Toutatis (discovered in Nice in 1989)

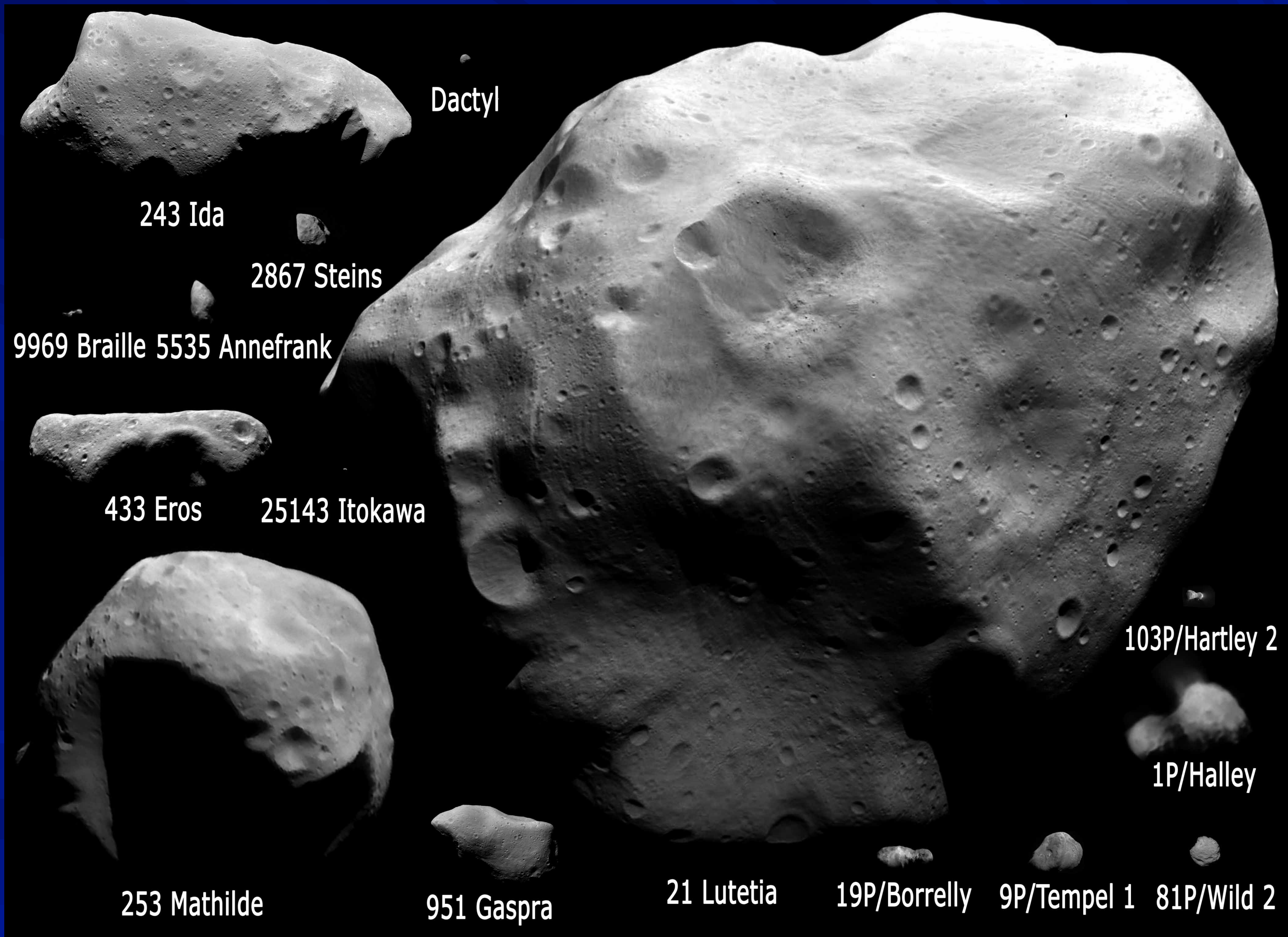


Images from radar echo: two rocky lobes (4 and 2 km of diameter)



Model
(S. Ostro)

A great diversity of sizes, shapes, rotational and surface properties



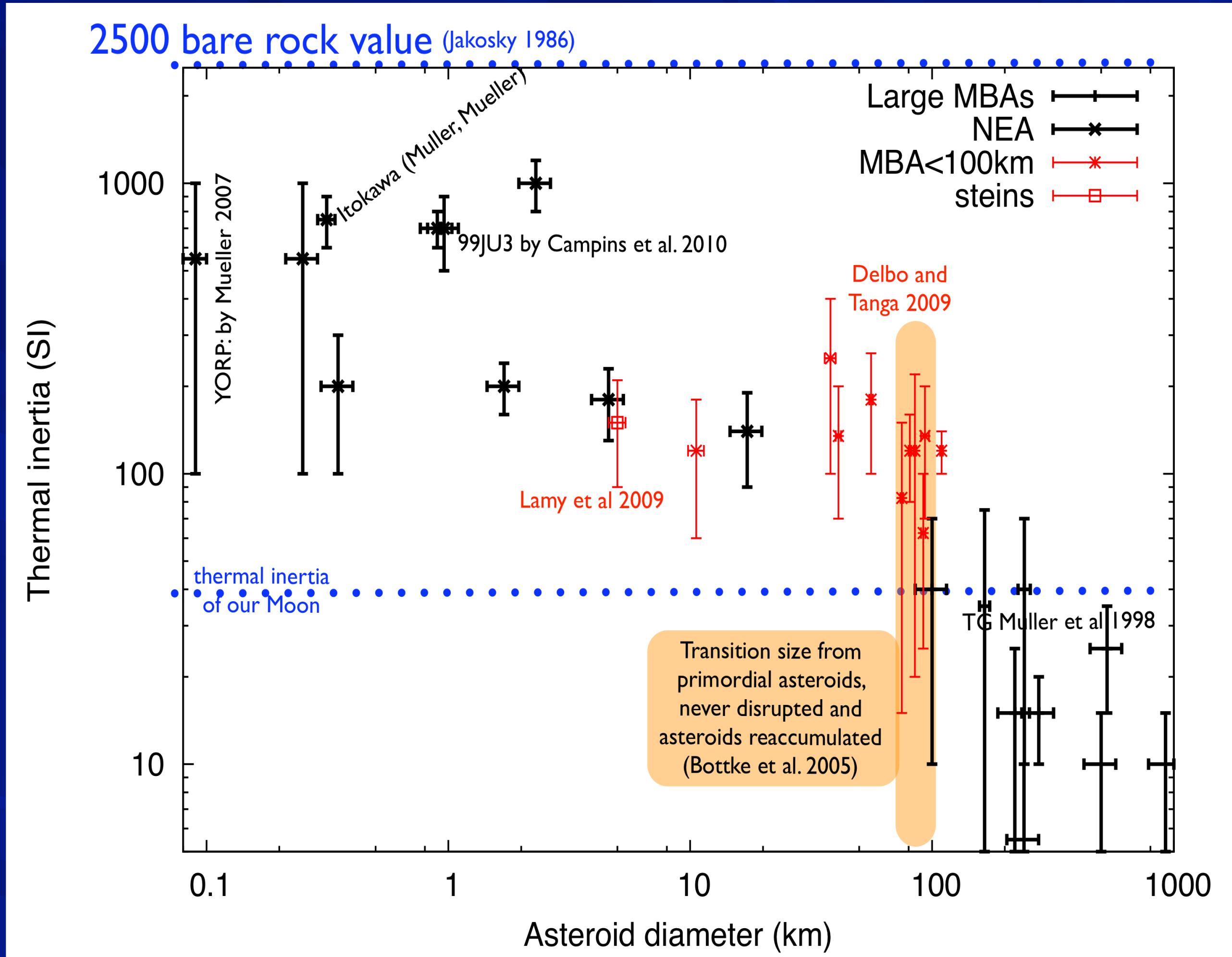
Note: only two asteroids have been visited so far, and are of the same type (S)
No such information exist for a primitive (dark type) asteroid

Surface conditions: Thermal IR data indicate the presence of regolith

Correlation (inverse) between thermal inertia and size
(Delbo et al. 2007, Mueller, 2007)

Larger asteroids have a finer regolith than small ones

Very small asteroids including fast rotators have low thermal inertia!!



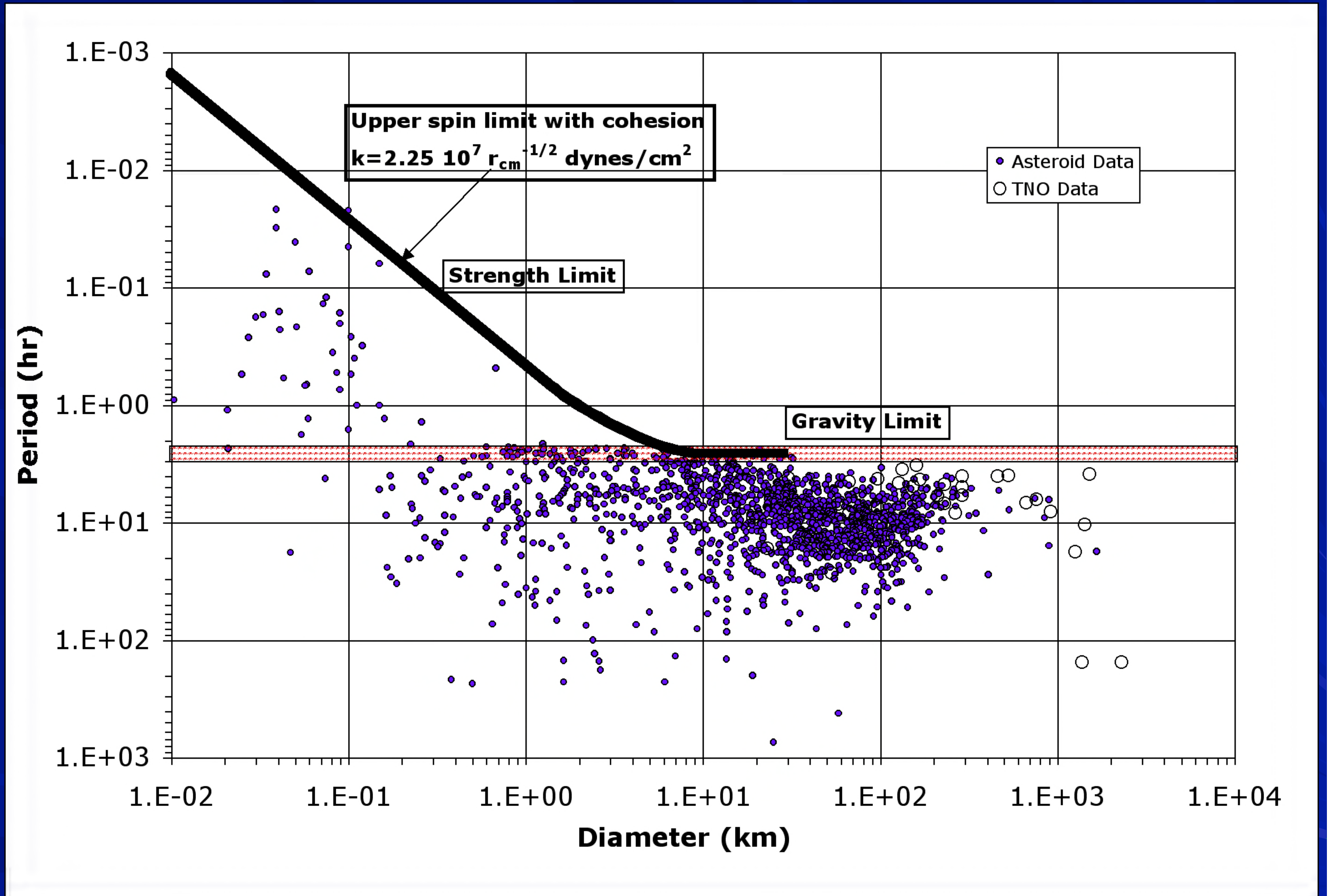
Thermal inertia < 2500 $Jm^{-2}s^{-0.5}K^{-1}$ (bare rock value) in all cases
→ presence of regolith on all studied asteroids

Spin limits of small bodies

Small asteroids (<100 m) can have fast spin rates

2009 BF2:
D= 27 m
Period: 58 s

2008 HJ:
Period: 42.7 s



From Holsapple and Michel, Icarus 193, 2008

Ground based vs. Space-based observations

- Absolute magnitude
- Albedo (size) if thermal infrared observations, polarimetry, and/or radar
- Basic shape estimate (light curve, interferom., radar)
- Spin rate
- Very rough knowledge of surface conditions (regolith presence), but no detailed properties
- Global spectral properties

- Accurate shape (volume)
- Mass (radio science)
- Bulk density
- Accurate surface topography (slopes, boulders, craters)
- Regolith, thermal properties
- Spectral, gravitational inhomogeneities
- Internal structure (radar tomography)
- Composition, mineralogy (lander, sample return)

Asteroid Mathilde (50 km)

1.3 g/cm^3

C-type
low albedo
(<0.1)

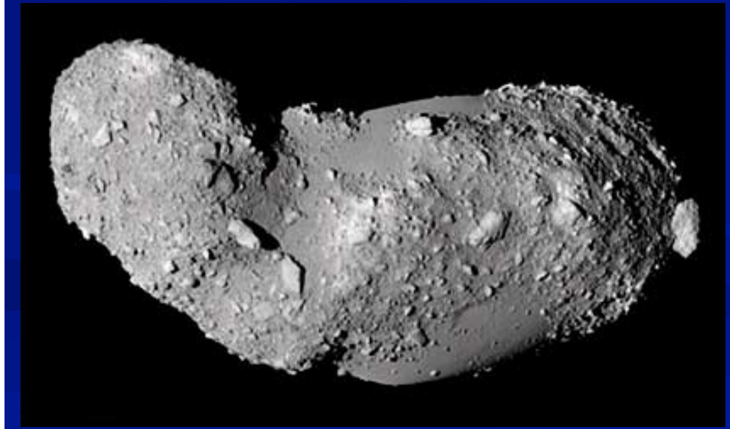
Asteroid Eros (23 km)

2.7 g/cm^3

S-type
high albedo
(> 0.15)

Note: even two bodies of
same spectral type
can be very different!

Asteroid Itokawa (350 m)



S-type

1.9 g/cm^3

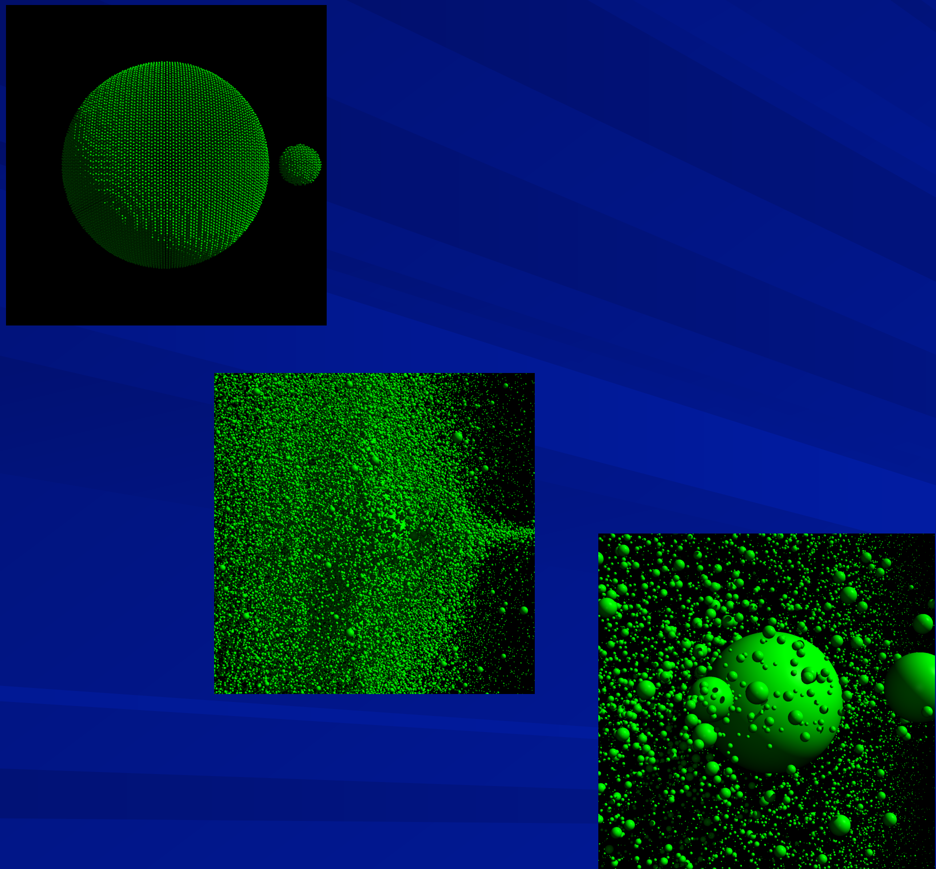
Great diversity of structures

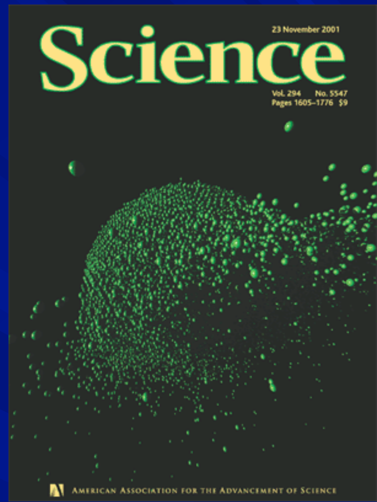
$\Rightarrow$bulk density:
smaller for lower albedo objects

Presence of regolith on all these bodies

Internal structure:
Current knowledge from both observations and modeling suggest that NEOs > 200 m are rubble piles

Gravitational phase of a disruption



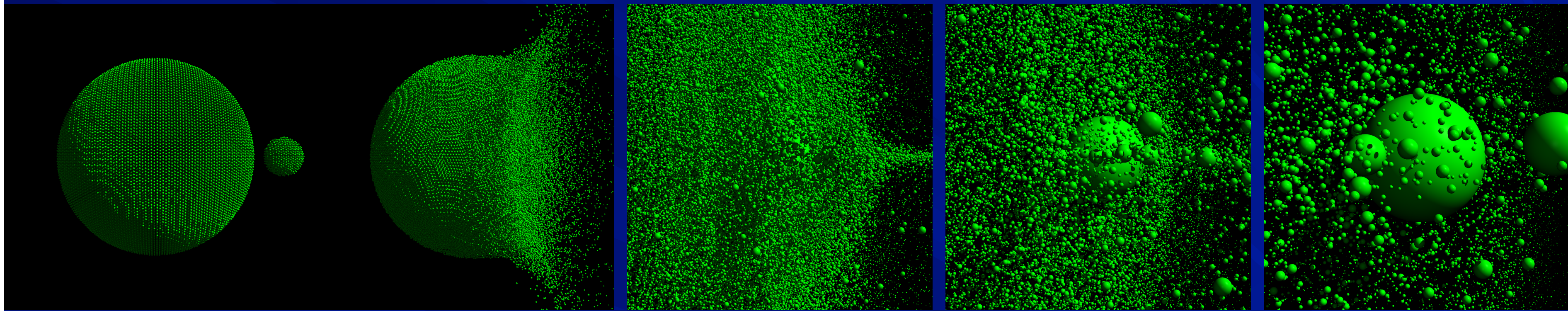


Michel et al., 2001, Science 294
Michel et al., 2003, Nature 421

Michel P., Benz W., Richardson D.C. 2001. 2002, 2003, 2004a, b
Michel P. 2006, Lecture Notes in Physics
Michel P. 2009, Lecture Notes in Physics

Collision and gravitational reaccumulation

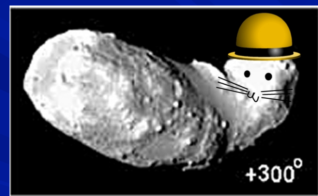
Michel P. et al. 2001. 2002, 2003, 2004
Michel P. 2006, Lecture Notes Physics
Michel P. 2009, Lecture Notes in Physics

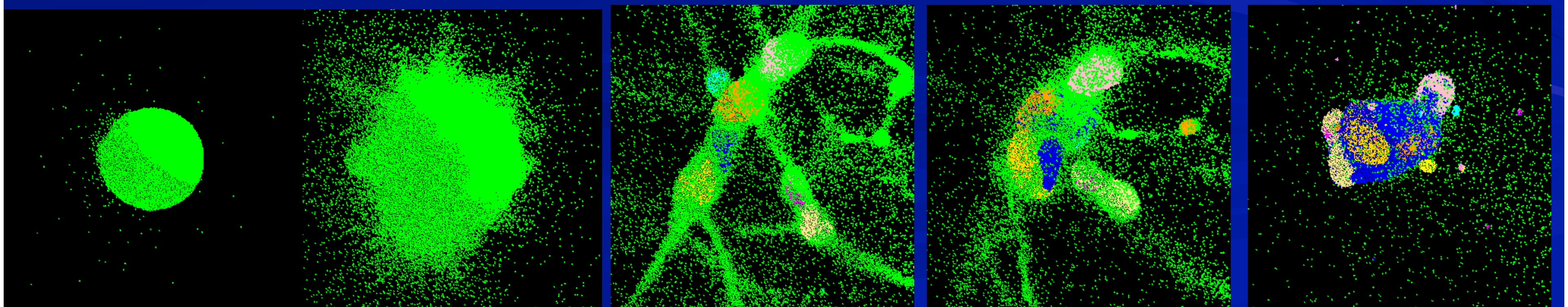


Snapshots centered on the largest fragment from t=0 to 84 minutes

Increase of realism of simulations: model of rigid body accounting for
The shapes of aggregates formed in a collision
(Richardson, Michel et al. 2009, PSS 57):

Itokawa





Mission NEAR (NASA)

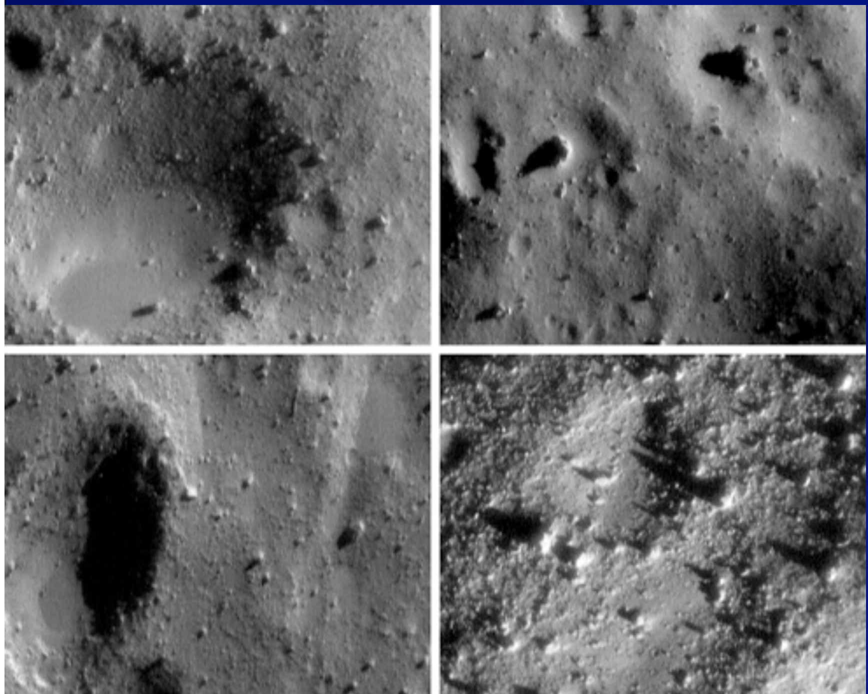
Un an en orbite

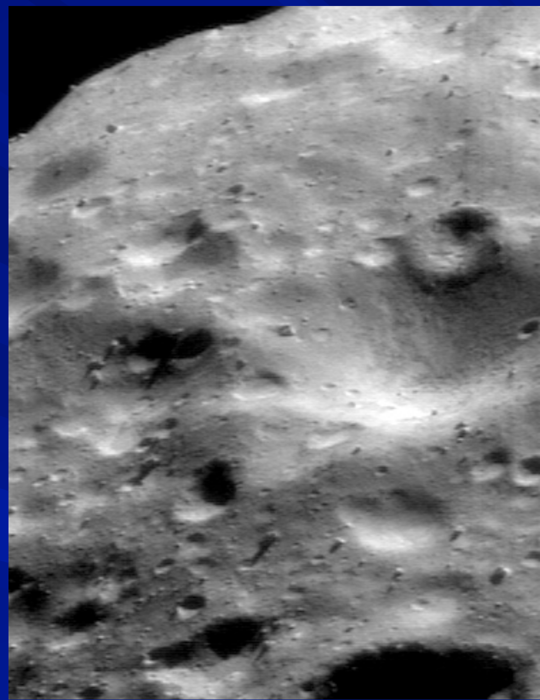
Autour d'Eros

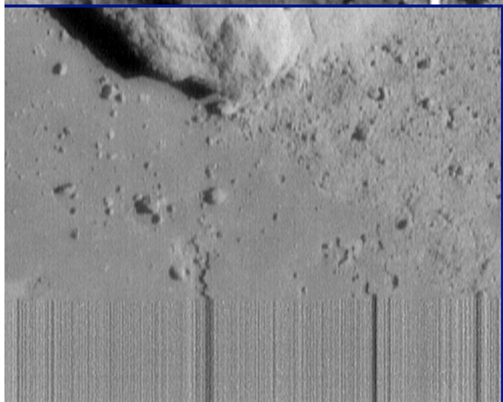
2000-2001

Astéroïde Eros: dimension= 23 km
2e plus gros croiseur de la Terre !!
Découvert à Nice en 1898

First detailed images of an asteroid (Eros, NEAR mission, NASA)





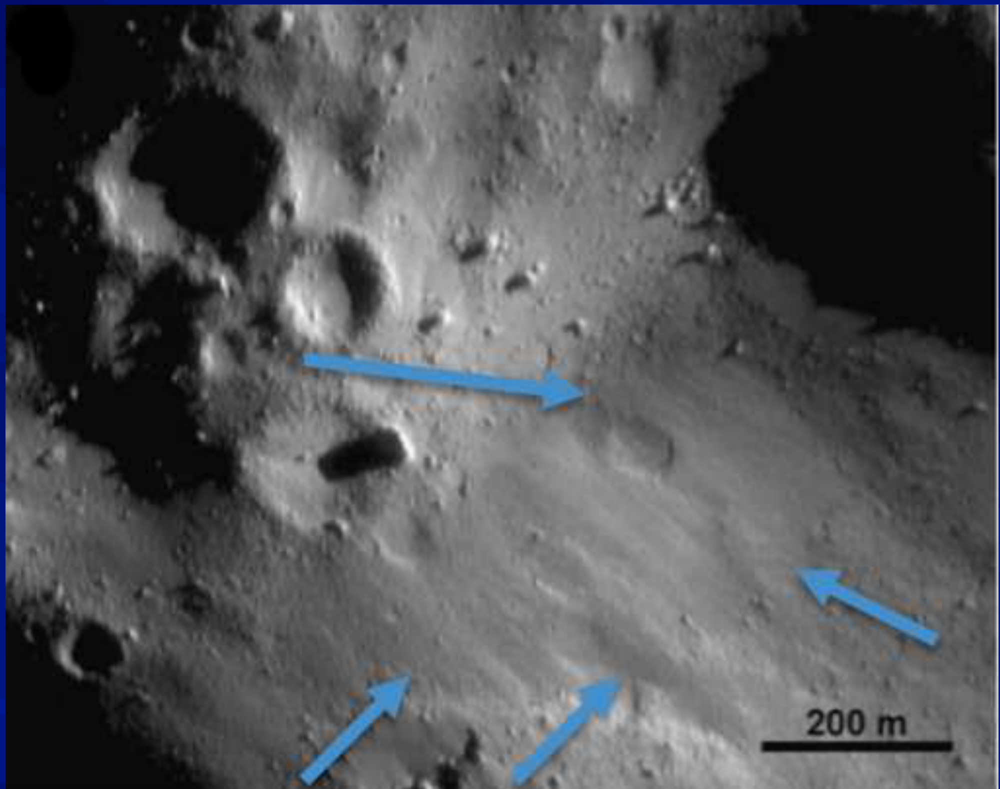


Presence of fine regolith (10-100 m depth)

Craters and ponds

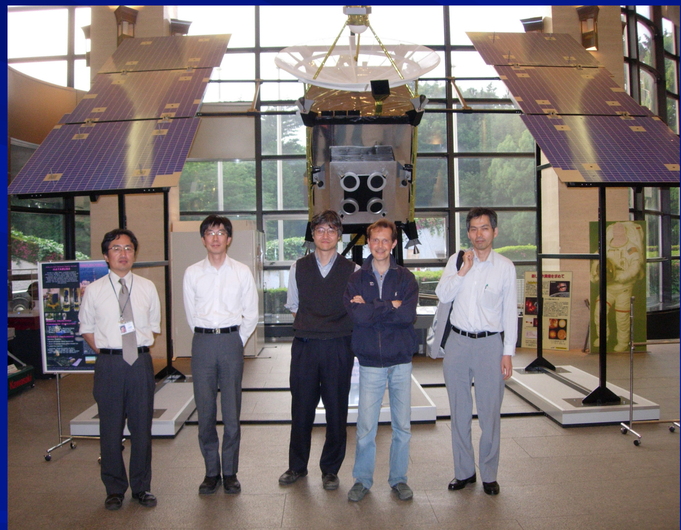
Last image (altitude: 120; width: 6 m)

Regolith migration on Eros



- Arrows mark the boundaries of the affected region
- Candidate for extended characterization (slope, length, etc ..)

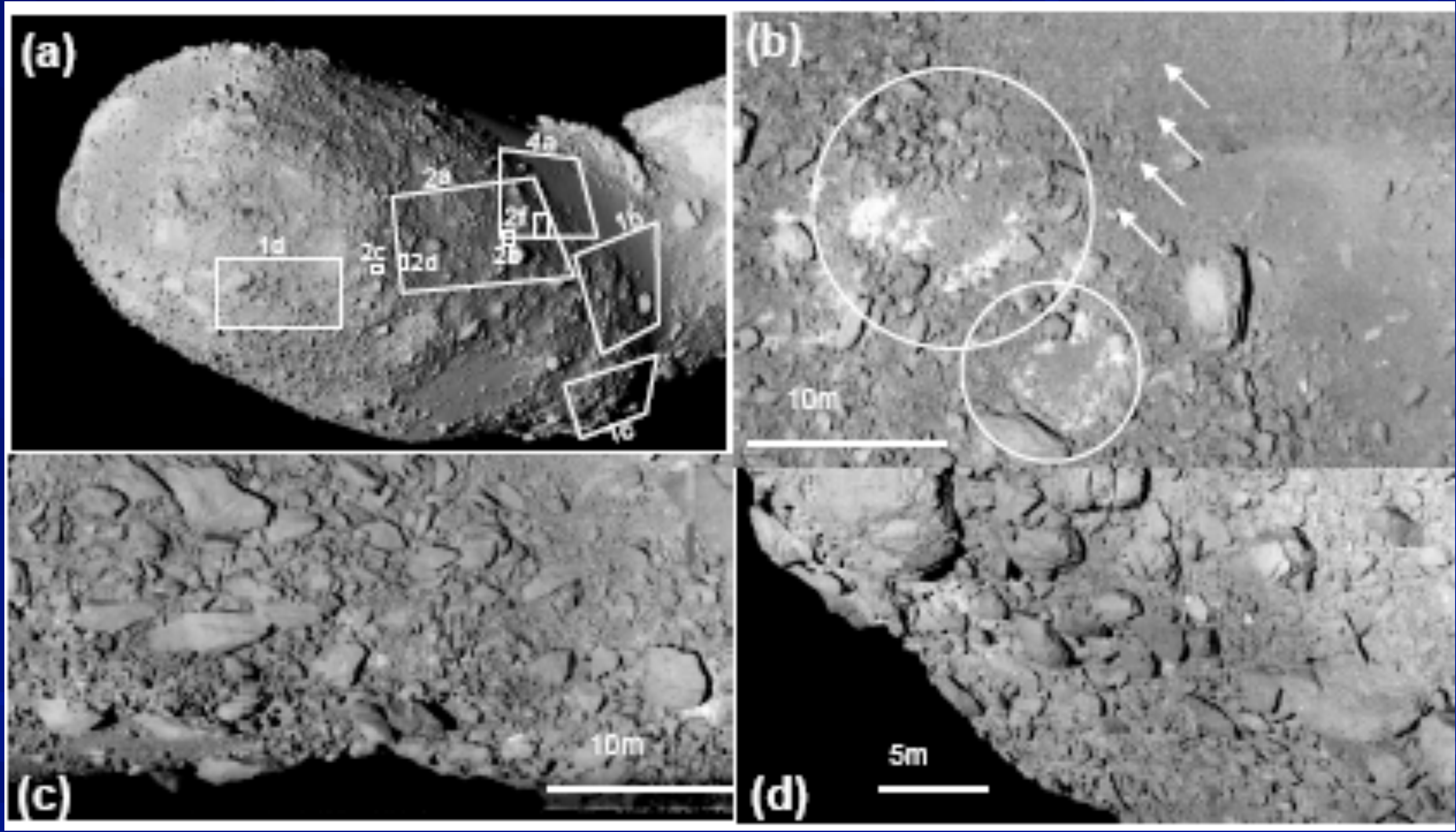
Mission Hayabusa: sample collect in Novembre 2005, returned in June 2010!




Mission Hayabusa (JAXA, Japan)
540m
243m

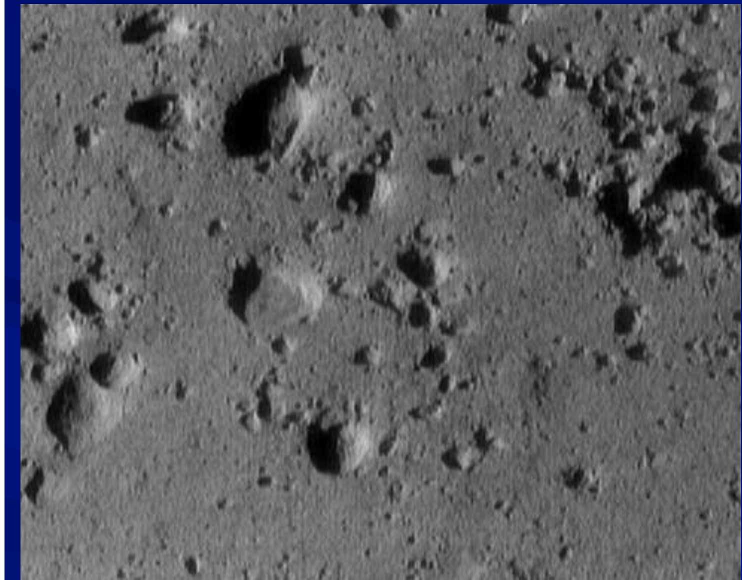
Itokawa: gravels, pebbles, …

Miyamoto et al. Science 2007



Constraints on navigation for landing: Hayabusa accuracy was a few tens of meters

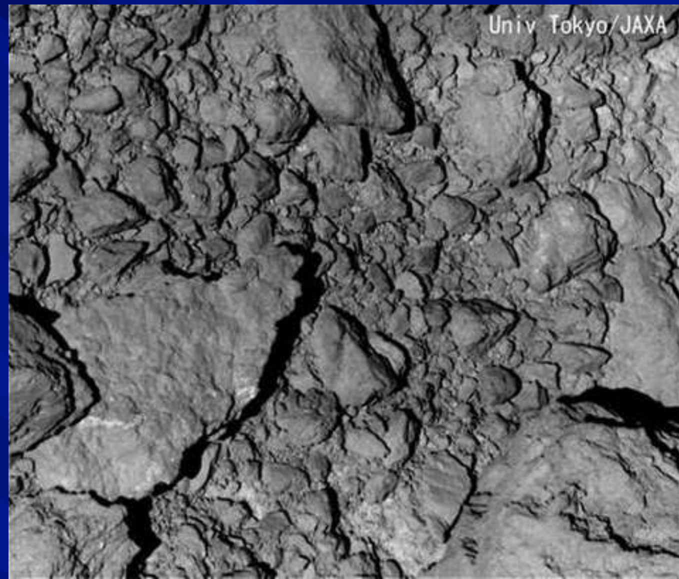
Eros surface taken from 823 feet (NEAR)

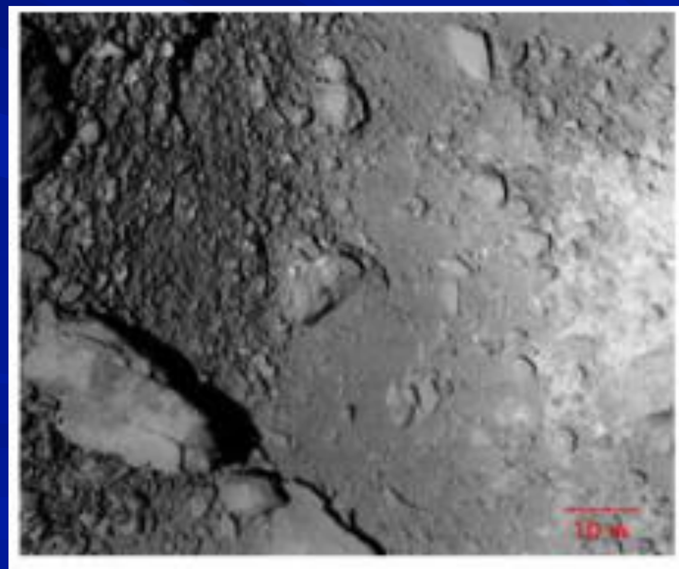


Layer of fine regolith, 10-100 m depth
1 m to 100 m-size boulders

The two visited asteroids:
both S taxonomic type and
totally different surface
Properties.
What about a dark type??

Itokawa surface: gravel, pebbles (Hayabusa)





Outer regolith layer with mean depth about 44 cm

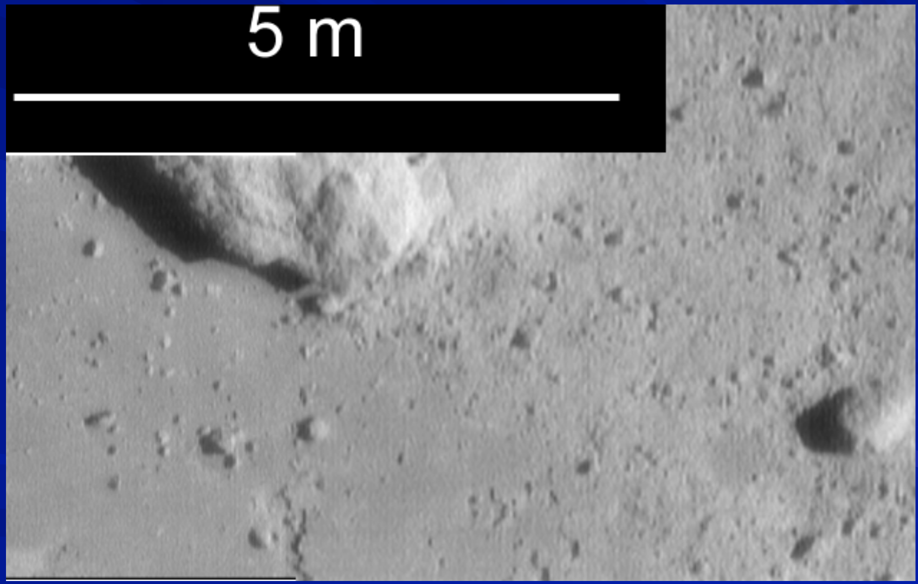
Itokawa vs. Eros

Smooth areas on Eros (*below*) and Itokawa (*left*); absence of fines on Itokawa

Itokawa

Images at same scale

Eros



Escape velocity on Eros: 10.3 m/s
Escape velocity on Itokawa: 15 cm/s

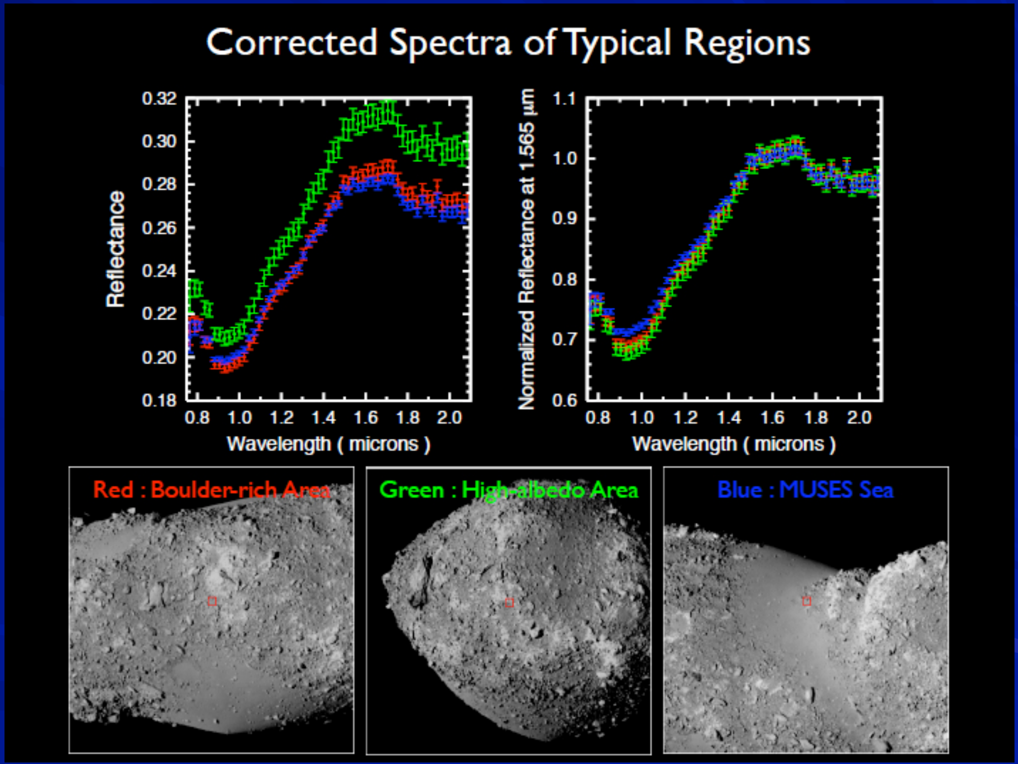
Recall: gravity conditions are extremely different

NIRS

Apparent Difference in Spectra May Due to Grain Size and Space Weathering: All Surfaces Indicate Similar Minerals

M.Abe, et al., *Science* (2006)

Spectra of three typical regions are different each other in the depth of the 1-micron band. This disagreement is a result of different grain size as well as degrees of space weathering. Otherwise all the spectra suggest basically the same mineralogical materials all over the surface of Itokawa.



NIRS

Albedo Map (NIR)

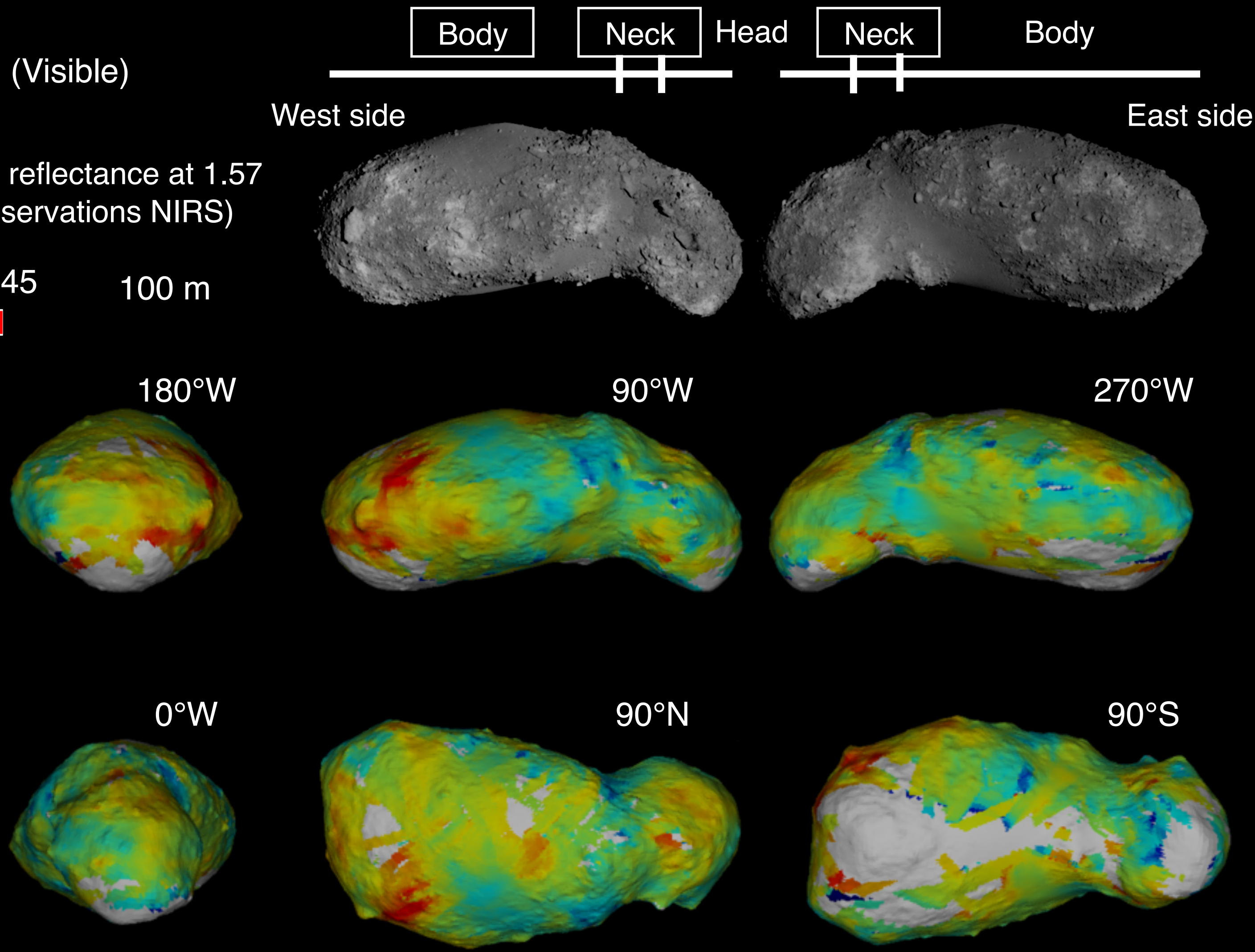
K. Kitazato, et al. 2008

▶ Images (Visible)

▼ Standard reflectance at 1.57 µm (observations NIRS)

0.126 0.145

100 m



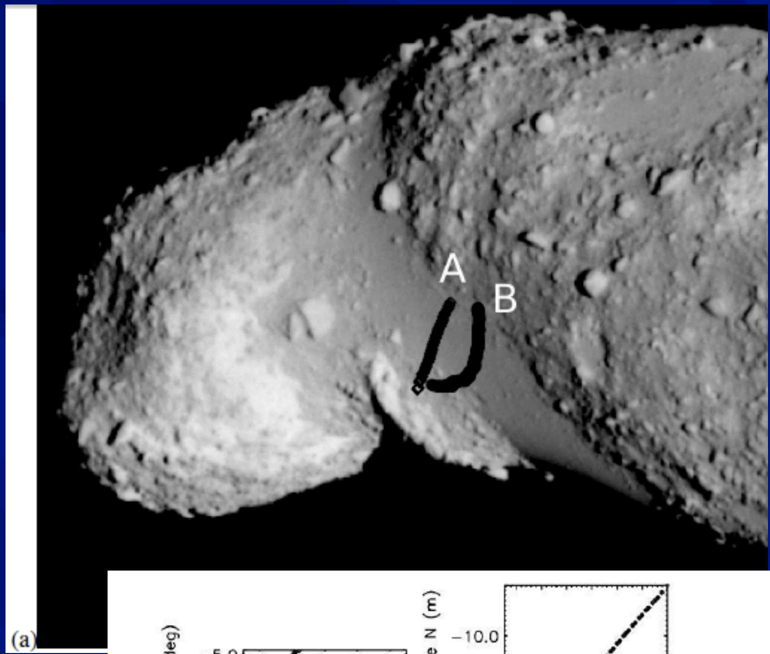
Surface roughness measurements

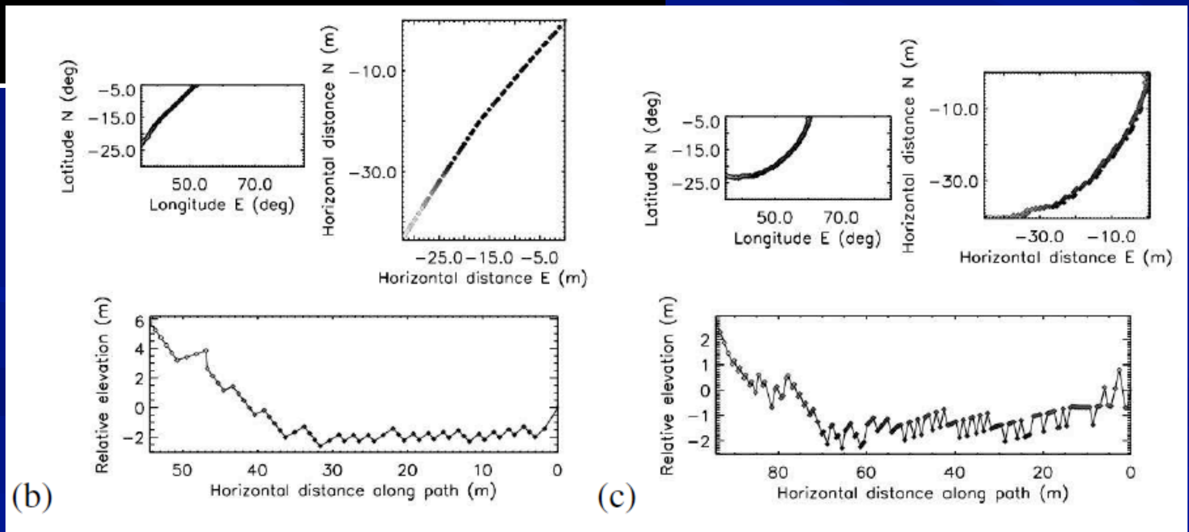
LIDAR

O.S. Barnouin-Jha et al. (2008)

LIDAR transects across the MUSES-C region

indicating a very smooth surface: (a) AMICA image with the two profiles A and B shown in plots (b) and (c). All the point to point scatter seen in the elevation plots are due to the quantization of the ranges measured by the LIDAR at ±0.5m, implying a very smooth surface, especially compared to all the previous plots where the elevation axes are larger.



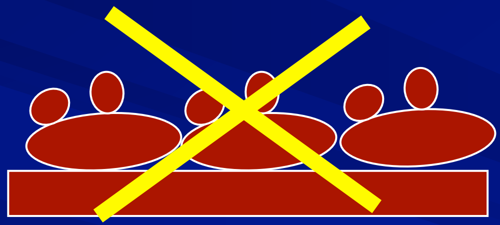


Global-scale particle migrations

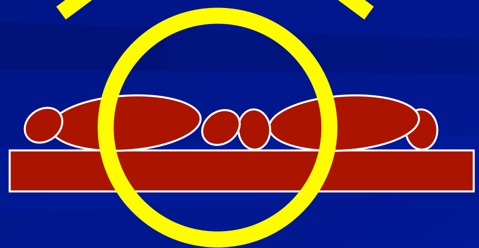
Miyamoto et al. *Science* 2007

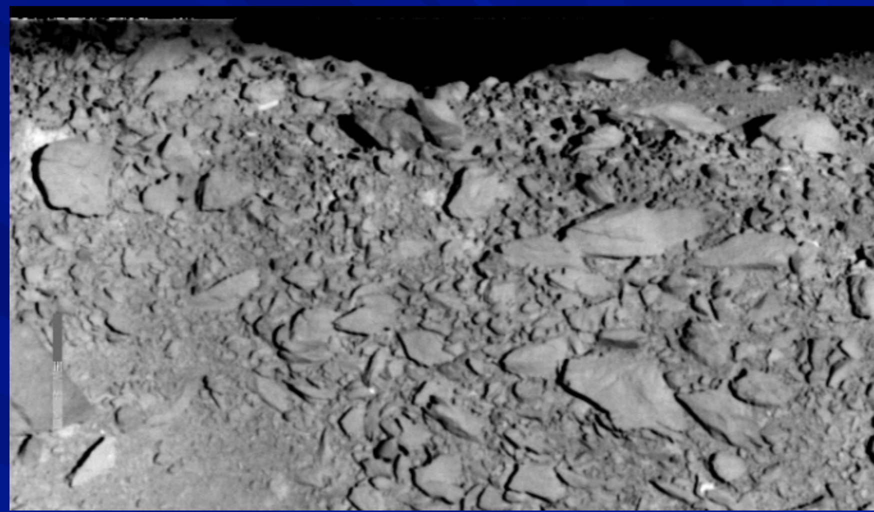
Two important characteristics:

1. None of the smaller gravels are isolated on top of boulders



2. The position and orientation of gravels are stable against local gravity

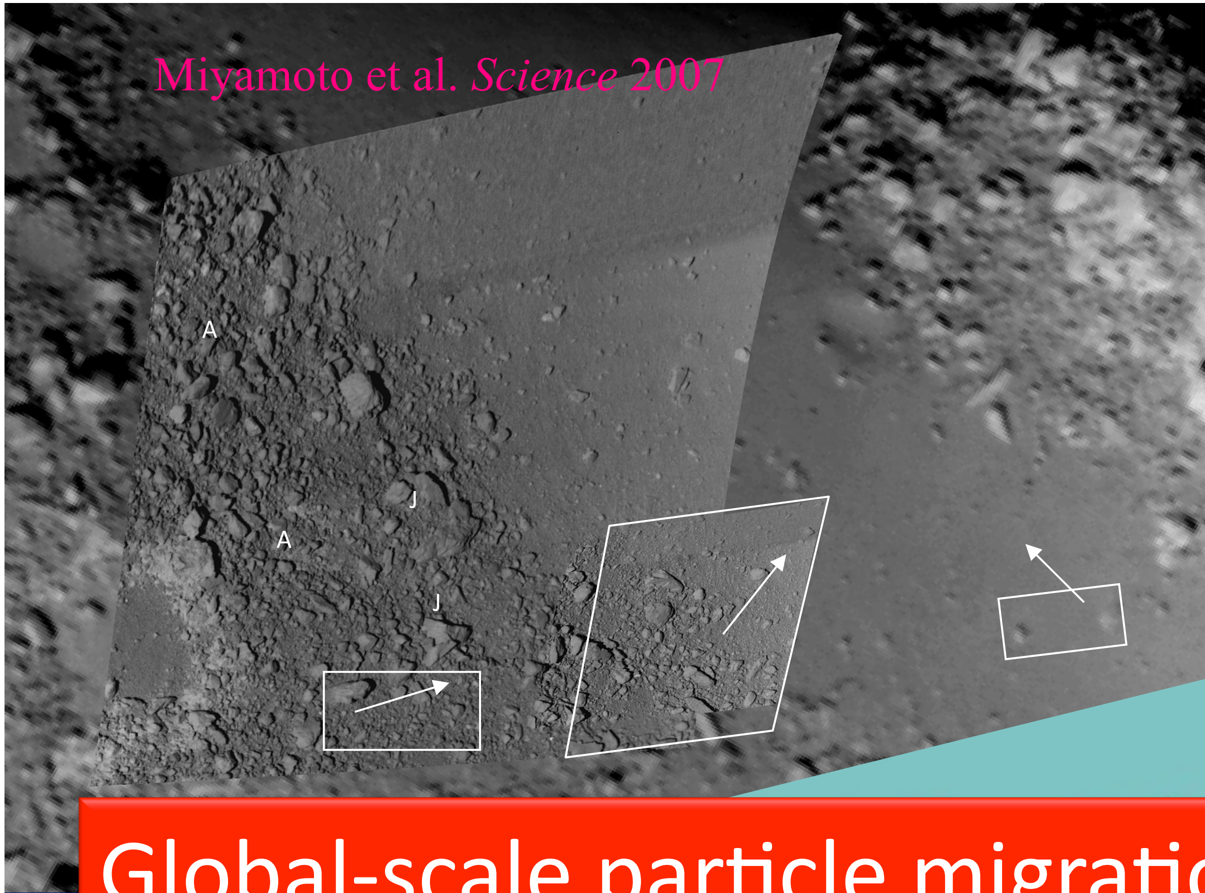




"Gravels on Itokawa were reallocated after deposition"

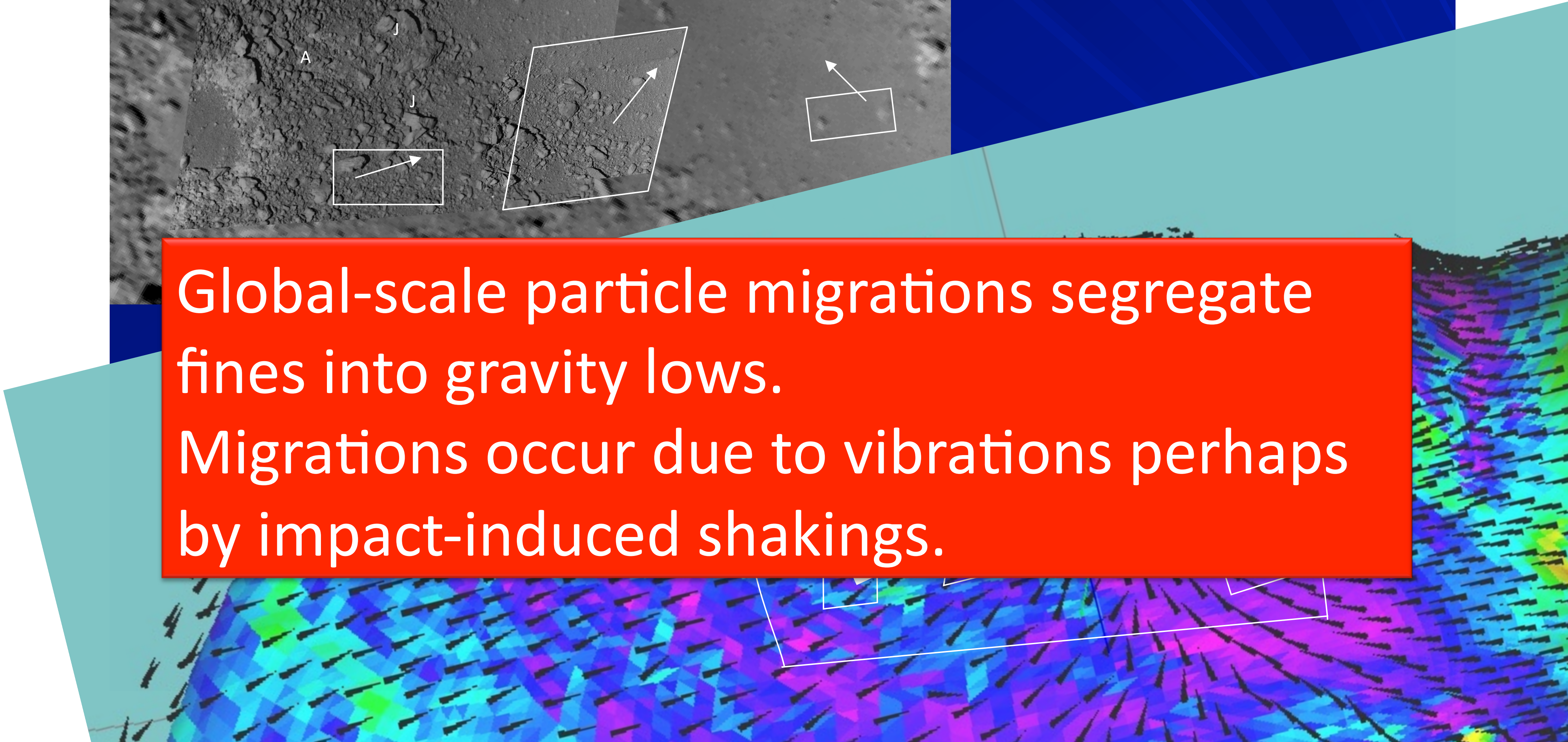
The surface has been subject to

global vibrations



Critical morphological evidences of gravel migrations

- Imbrications
- Hampered fines
- Jig-saw fit structures
- Boulder alignments

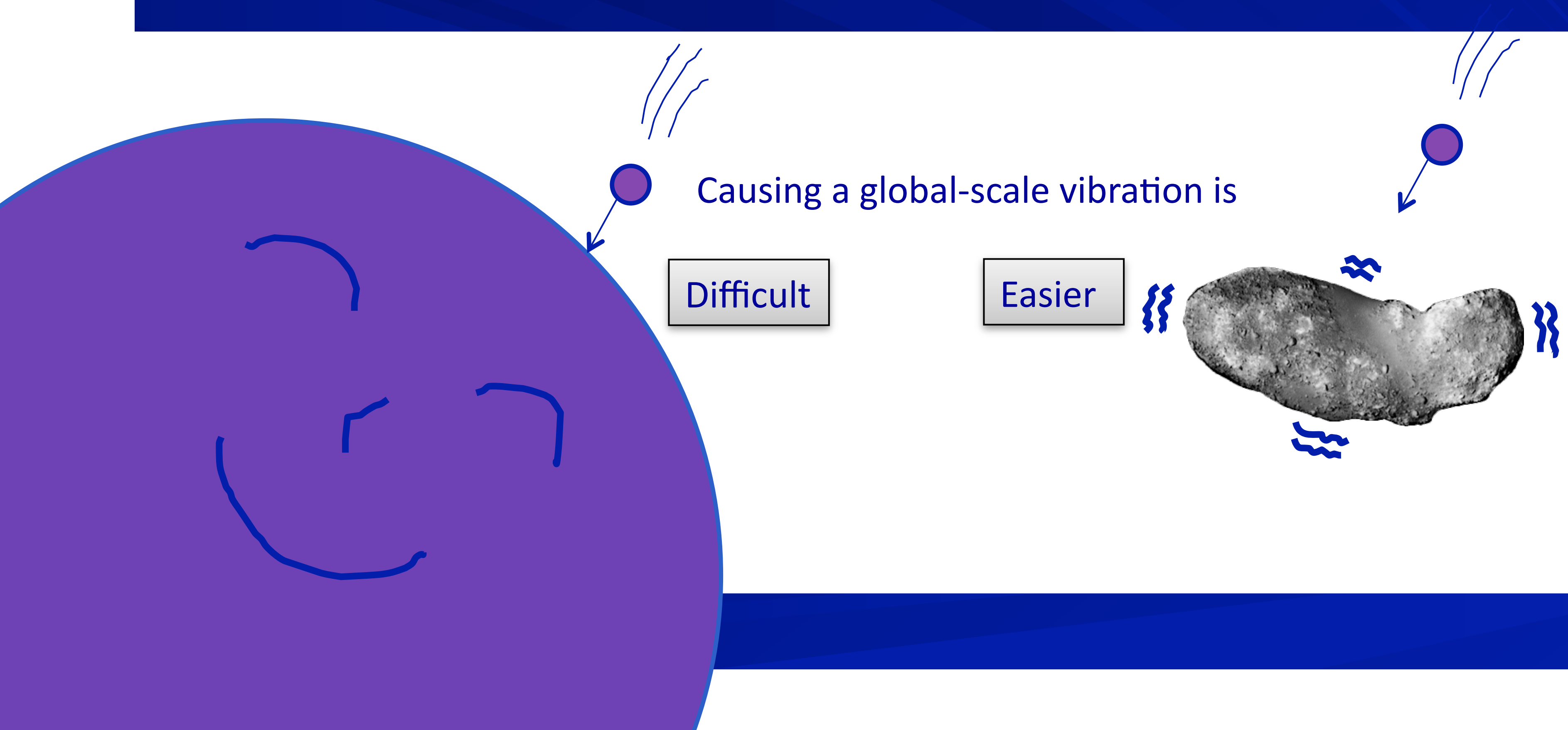


Global-scale particle migrations segregate fines into gravity lows.
Migrations occur due to vibrations perhaps by impact-induced shakings.

Why this process found only on Itokawa?

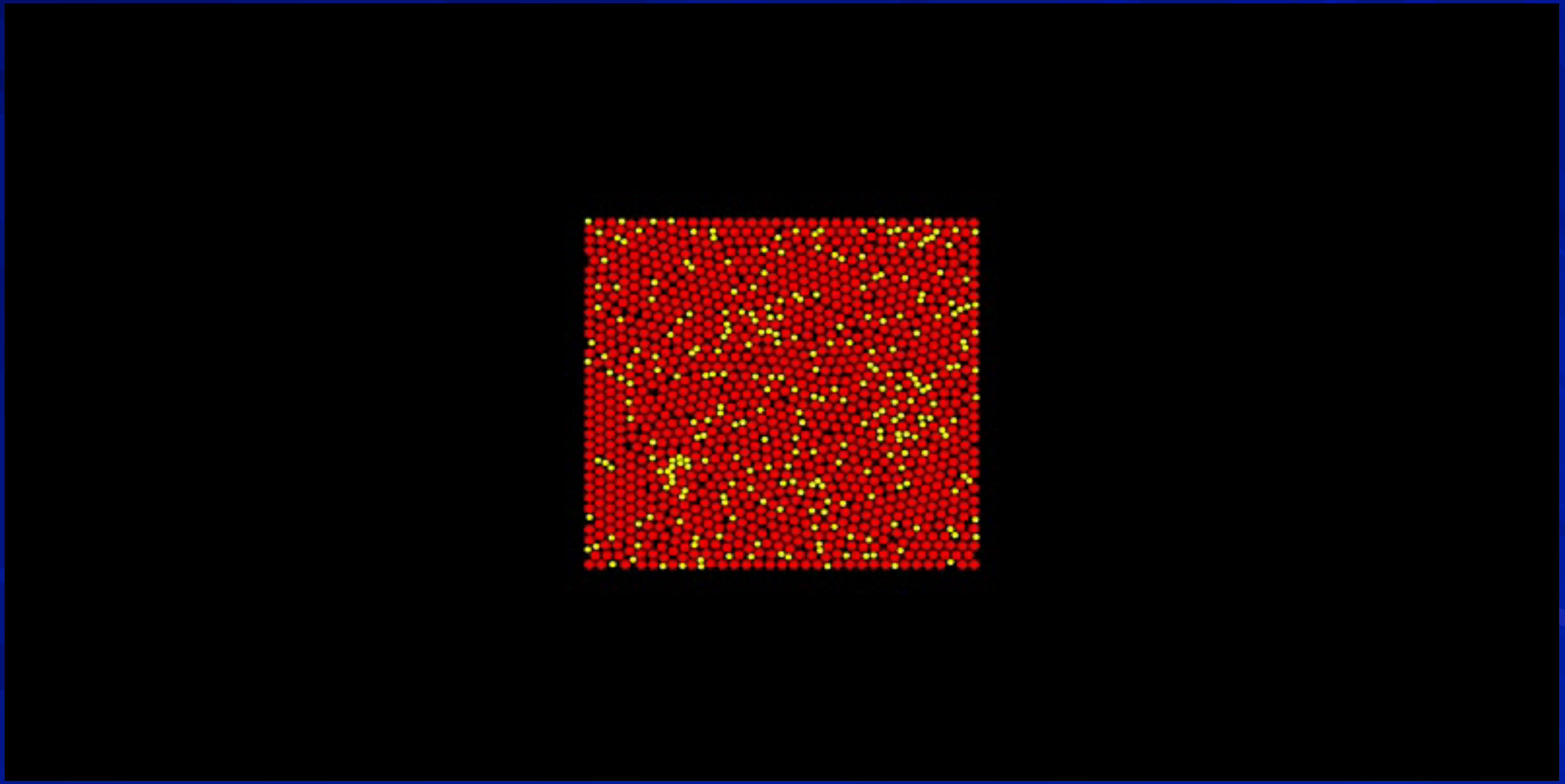
Miyamoto et al. *Science* 2007

- Distance from the source of seismic energy is generally short at any locations, resulting in effective fluidizations of particles
- A small body keeps the seismic energy, which supports particle fluidizations for a sufficiently long time
- A small body generally has steeper slopes that provides gravitational driving force for particle migrations.



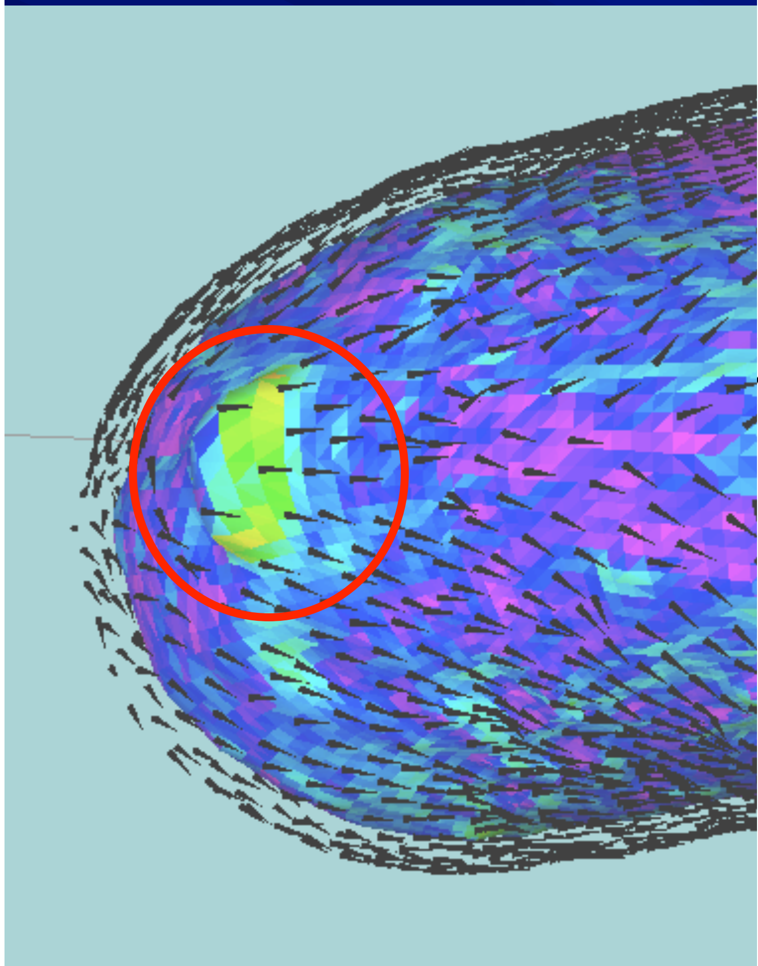
Shaking of granular material in various gravity conditions:

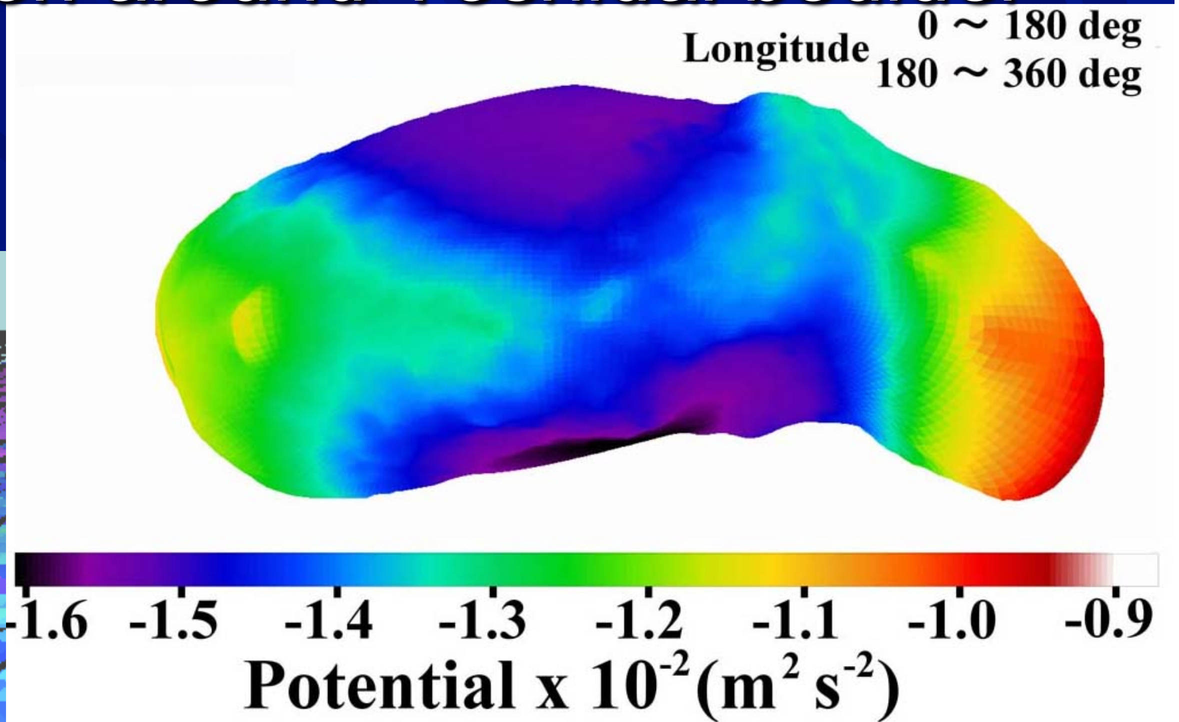
Numerical simulations can help to investigate this process over a wide parameter space (size distribution of grains, …)

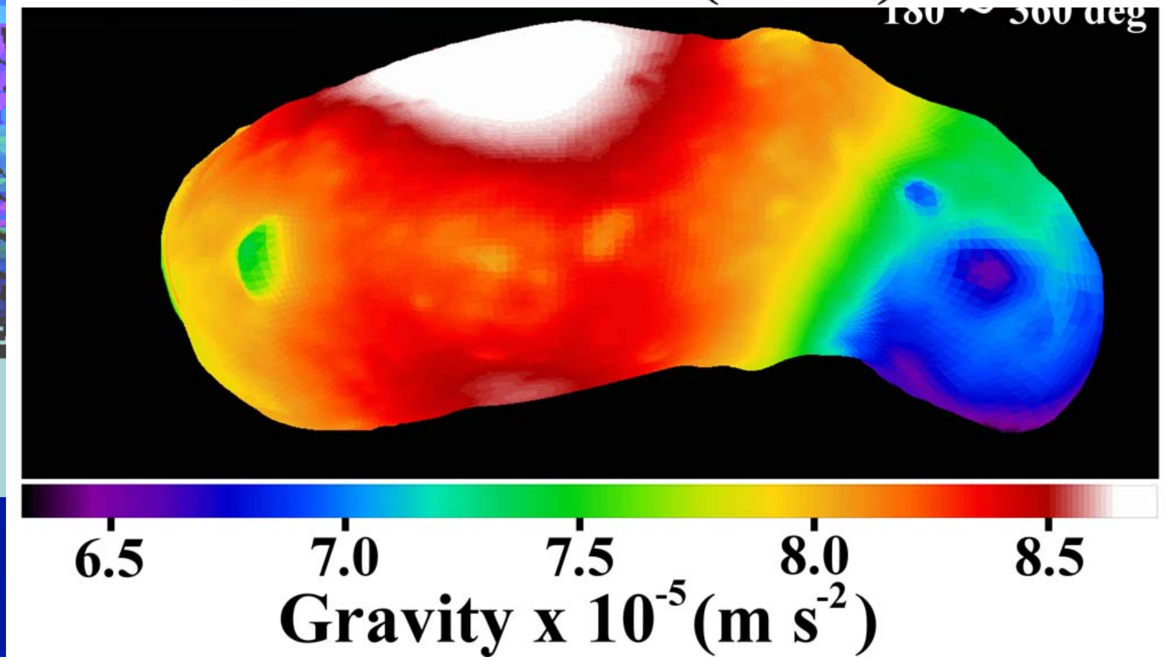


Simulations by Naomi Murdoch, using pkdgrav code

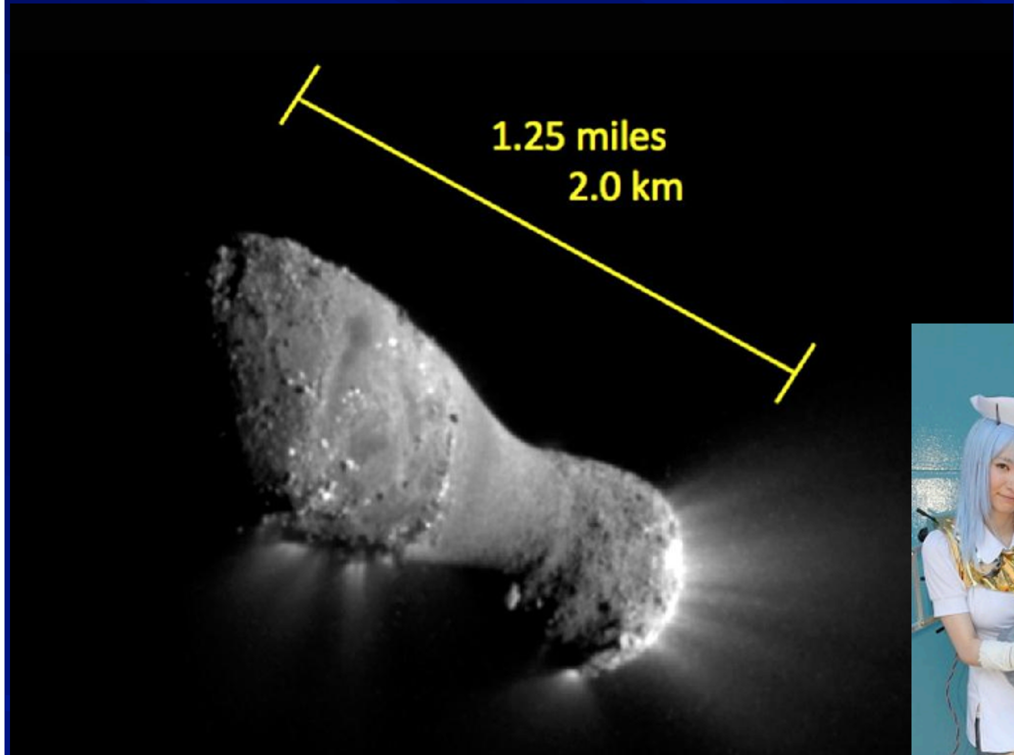
Physical condition around Yoshidai boulder







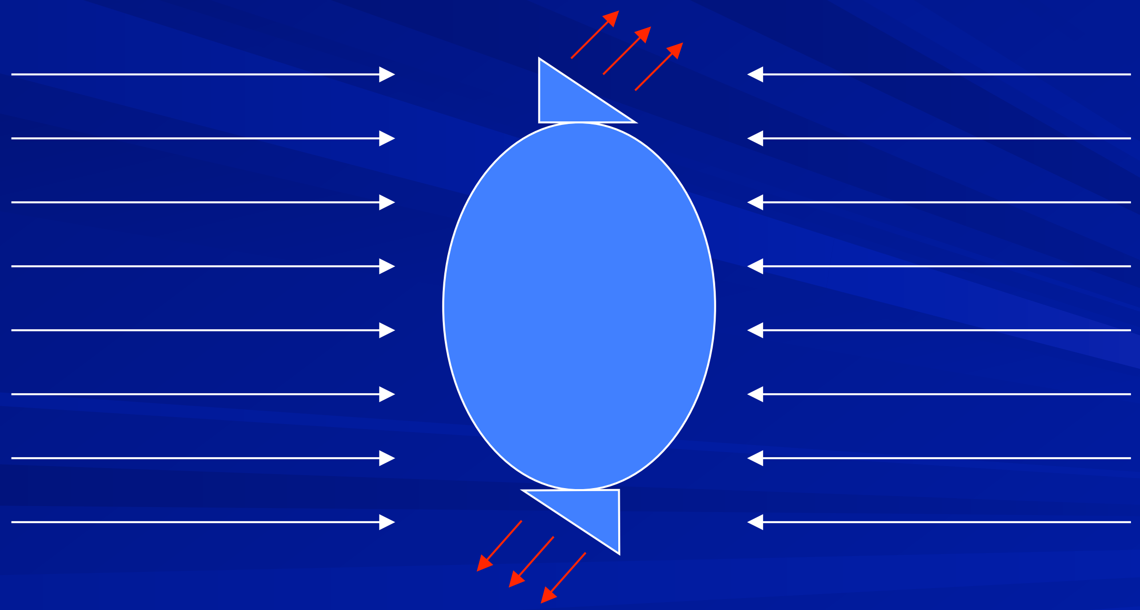
Fly-by of Comet Hartley 2
(EPOXI, NASA,11/3/2010)
Strange similarity with Itokawa



The YORP effect, regolith migration and the formation of binary asteroids

(Walsh, Richardson, Michel, 2008, Nature 454)

- Effect Yarkovsky-O'Keefe-Radzievskii-Paddack
- Irregularly shaped bodies receive/re-emit solar photons in different directions: net torque ➔ spin up/down

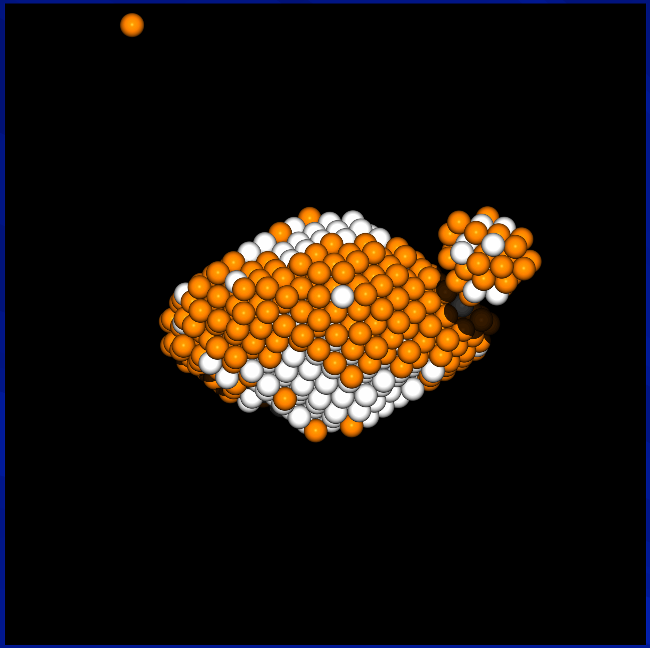


This effect was measured by observations for at least 2 objects (publications in Science et Nature)

A rubble pile structure also explains binary formation by YORP spin-up (15% of NEOs are binaries)

Last image of simulation of YORP spin-up of a rubble pile

Granular matter migrated from the pole to the equator, then escaped to form a satellite



Walsh, Richardson, Michel, Nature 454, 2008

1999KW4, Ostro et al.

Initial surface particles are in orange, core ones are in white

The surface of the primary consists of fresh material

Make them great targets for sample return space missions:

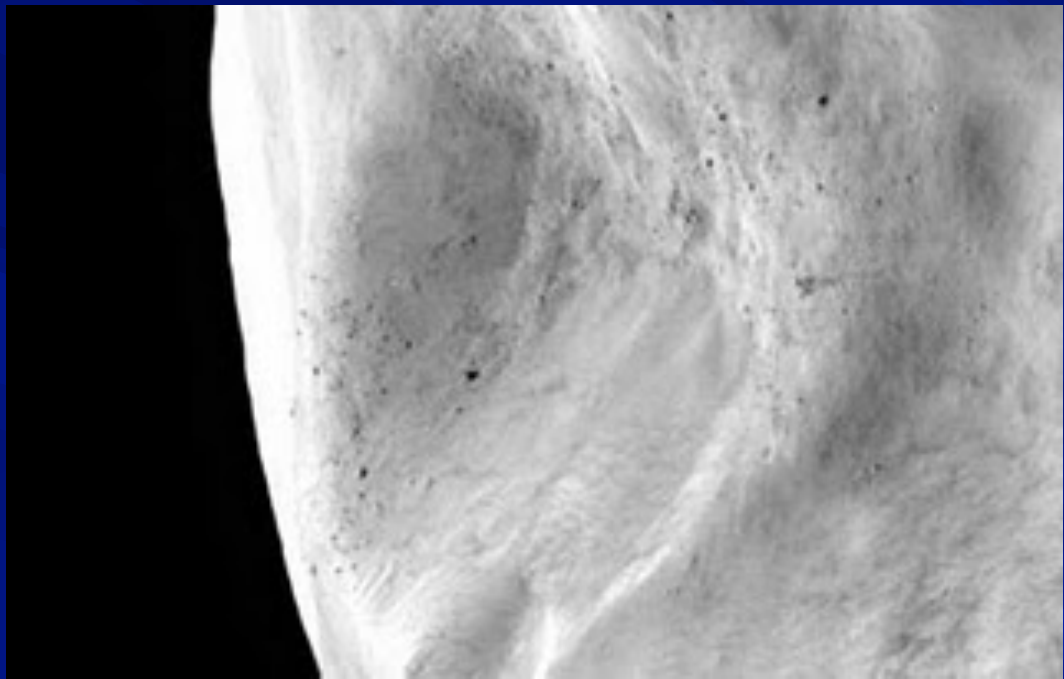
1- mass determination facilitated by the presence of a secondary

2- sampling at the pole allows getting fresh material (from previous interior)

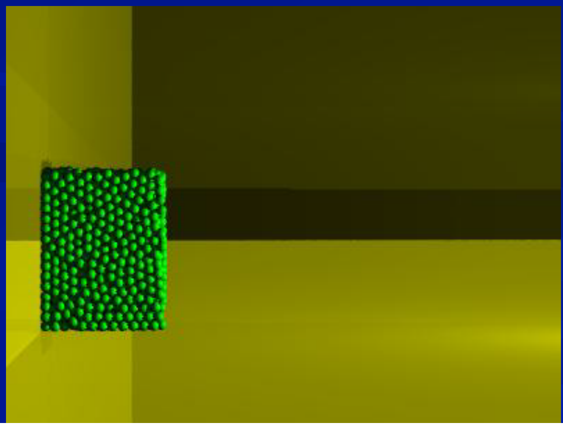
The baseline target of MarcoPolo-R is a binary!

Avalanches

- Landslides on the 100 km-size asteroid Lutetia



Mission Rosetta ©ESA



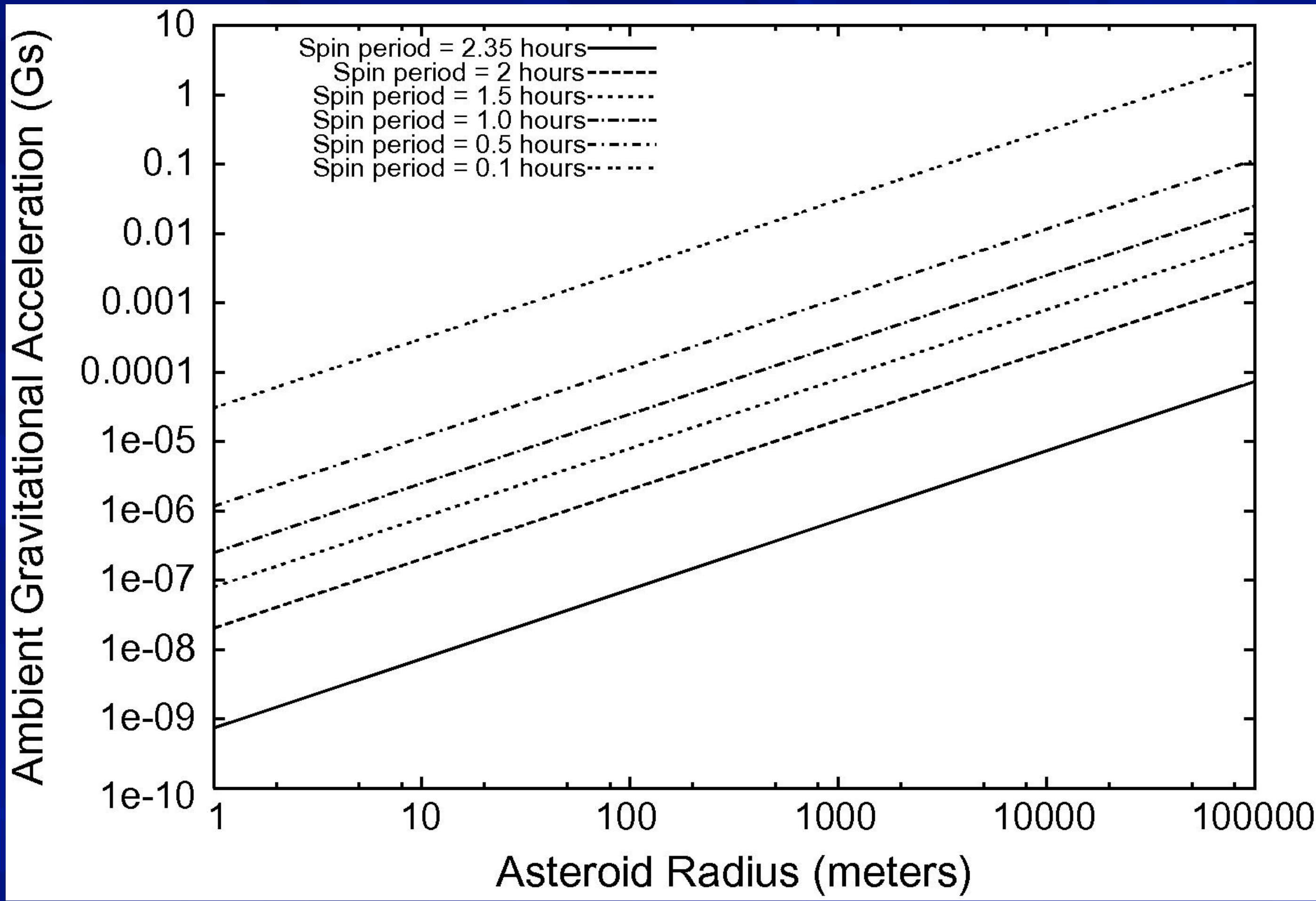
Simulation by Naomi Murdoch,
Kevin Walsh
Code pkdgrav

Surface gravity vs. Size

From Scheeres et al., 2010

Amount of “cohesive acceleration” necessary to keep a grain on the surface of an asteroid.

Milli-G’s necessary for a 100 m asteroid rotating with a 6 min period or a 10 m asteroid rotating with a period on the order of tens of seconds.



Escape velocity on Eros: 10.3 m/s
Escape velocity on Itokawa: 15 cm/s

Cohesion at different G levels

- Radius at which ambient weight and cohesion forces are equal (assuming lunar regolith properties and cleanliness ratios of unity), along with parent body sizes.

Gravity (Gs)	Grain radius (m)	Analog body
1	6.5×10^{-4}	Earth
0.1	2×10^{-3}	Moon
0.01	6.5×10^{-3}	(180 km)
0.001 (milli-G)	2×10^{-2}	Eros (18 km)
0.0001	6.5×10^{-2}	Toutatis (1.8 km)
0.00001	2×10^{-1}	Itokawa (0.18 km)
0.000001 (micro-G)	6.5×10^{-1}	(0.018 km)
0.0000001	2×10^{0}	KW4 equator

From Scheeres et al., 2010, Icarus 210, 968

We need more data (in-situ investigations)

Detailed in-situ investigation are needed

- To know the geophysical properties on low-G bodies
  - Regolith properties and their dynamics (seismic shaking, gardening, spin up, impacts)
  - Crater morphology and environment (presence of ejecta)
  - Albedo variations and implications on space weathering
  - Thermal properties and measurement of YORP/Yarkovsky
- To determine the internal properties of a body (by e.g. radar tomography, seismic experiment)
  - Indication on the past collisional history (reaccumulation)
  - Important information for mitigation strategies

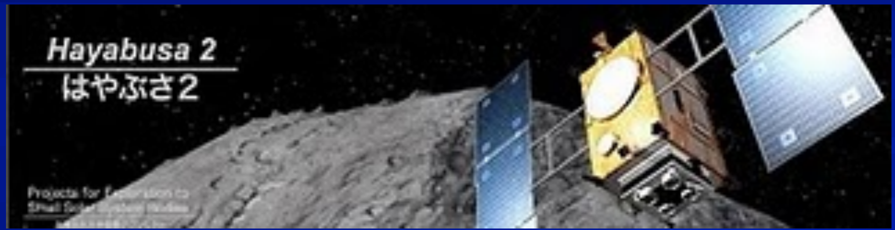
Sample return would then allow analysing the very material taken on site with great details in the lab

Understanding primitive NEOs: designing an efficient sampling tool

- Mission MarcoPolo-R: selected for the assessment study phase of M3-class missions of the Programme Cosmic Vision 2015-2025 of ESA in Feb. 2011
- On-going selected projects:

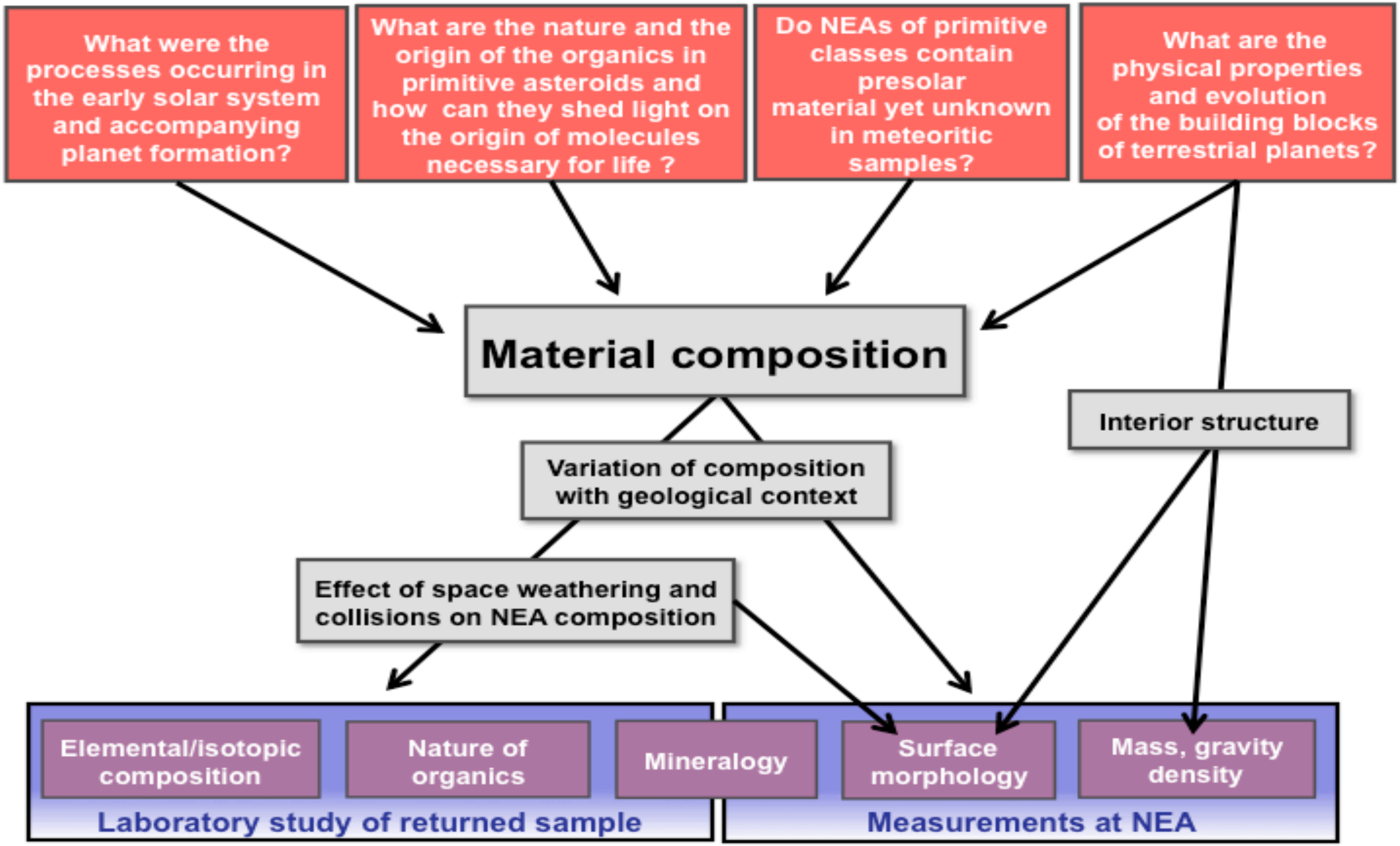
OSIRIS-Rex: selected in NASA New Frontiers, launch in 2016

Hayabusa 2: phase B at JAXA, launch in 2014

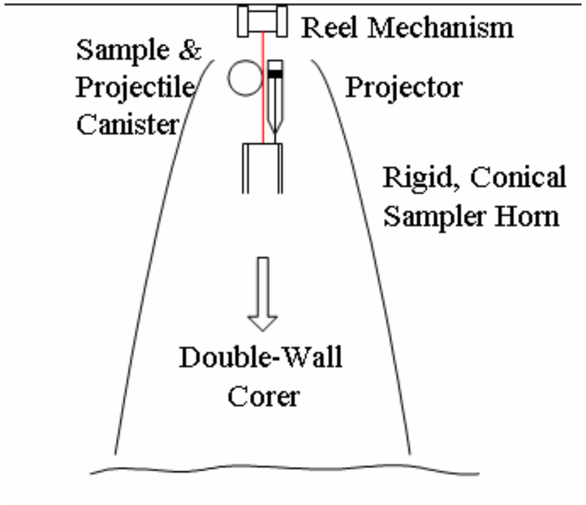


Proposed by:
A. Barucci (Obs. Paris, Lead)
P. Michel (OCA, co-Lead),
Supported by > 560 European scientists

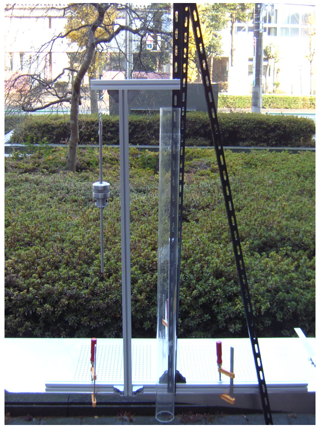
Origin and evolution of the Solar System, origin of life, hazard


What were the processes occurring in the early solar system and accompanying planet formation?
What are the nature and the origin of the organics in primitive asteroids and how can they shed light on the origin of molecules necessary for life ?
Do NEAs of primitive classes contain presolar material yet unknown in meteoritic samples?
What are the physical properties and evolution of the building blocks of terrestrial planets?
Material composition
Interior structure
Variation of composition with geological context
Effect of space weathering and collisions on NEA composition
Elemental/isotopic composition
Nature of organics
Mineralogy
Surface morphology
Mass, gravity density
Laboratory study of returned sample
Measurements at NEA

Sample mechanism (Hayabusa)



Experimental Tests

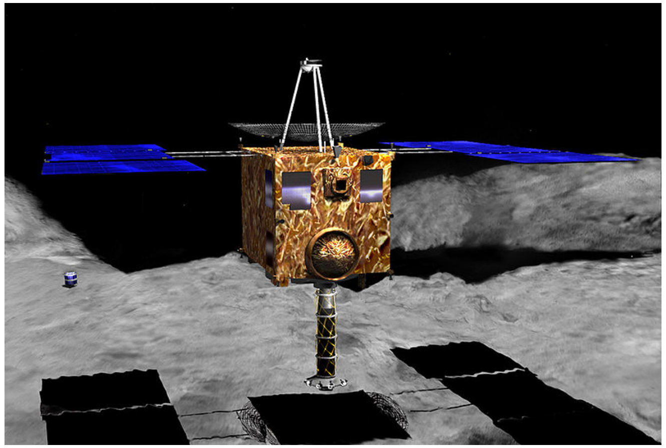


Asteroid material analogues

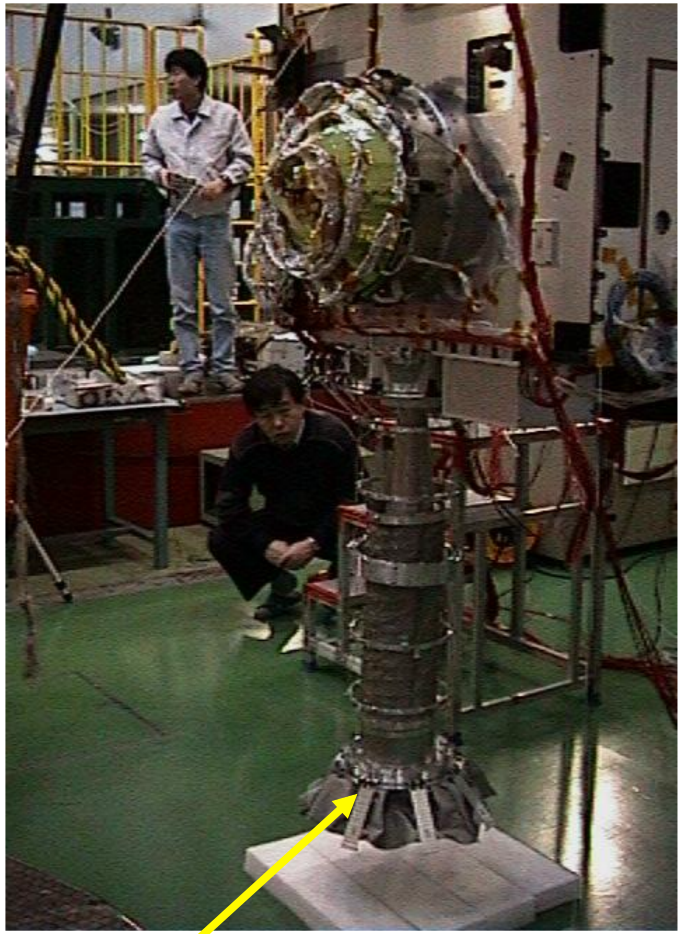

Sand


Pumice


Pumice Table

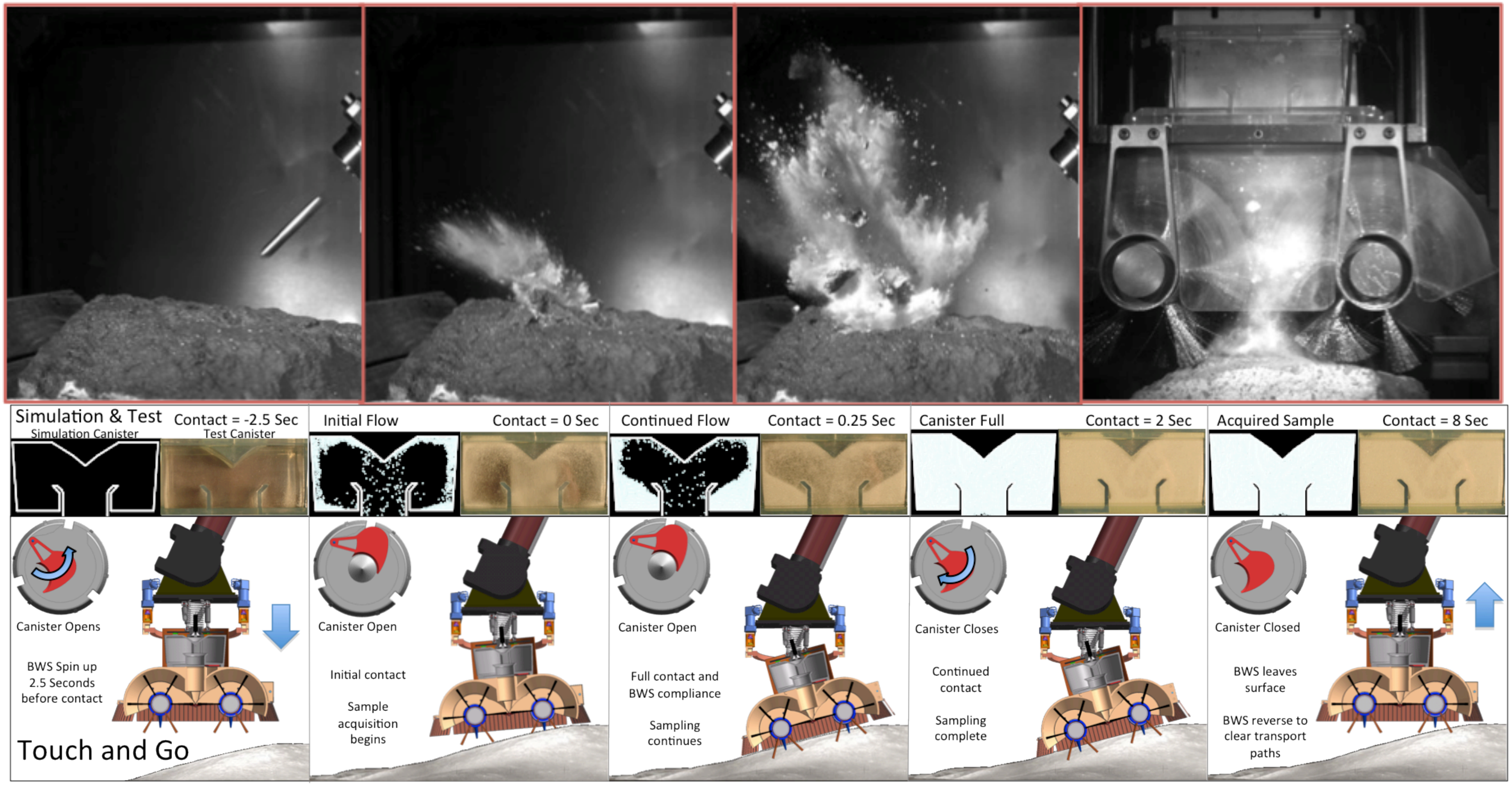


Sampling in a few seconds



Sample device

Test with BWS (Brush Wheel Sampler) and tuff rocks
BWS collecting lunar regolith simulant (APL-JPL-NASA)



The BWS has been designed and tested to collect the sample (0.350-2.1 kg) in <1 sec

Impact cratering on the Moon, Mars … (higher-G environments)

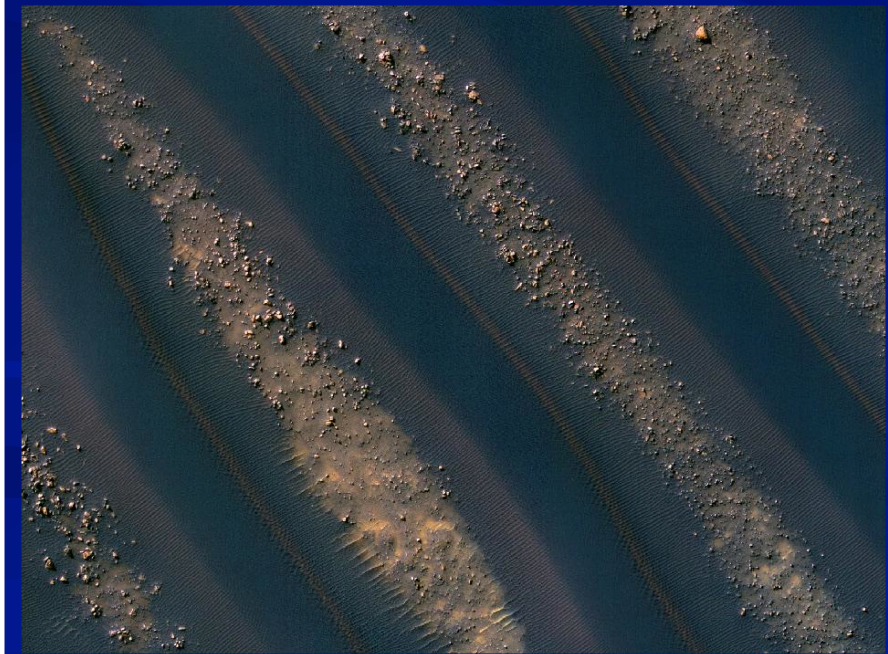
- Part of a large mass of layered rock in Galle Crater, in the southern cratered highlands of Mars

The ridge-forming layers may be weak, but separated by material with virtually no cohesion.

Polygonal fracture patterns in the dark regolith between distinct layers could be due to ground ice, or regional tectonic stresses.

Other observed processes on planetary surfaces

- **Wind induced grain detachment on Mars:** what's the wind shear allowing entrainement as a function of granular material properties? Behavior of granular material in rough wheel contacts
- **Dynamics of dunes:** dunes of ice on Earth and Mars seem to migrate in opposite direction to the wind that form them and to that of dunes of silico-clastits: maybe due to ice specific properties (cohesion, sublimation)

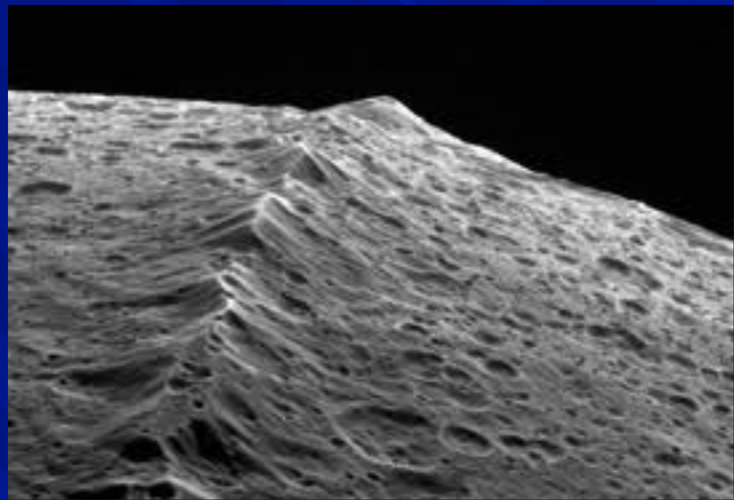


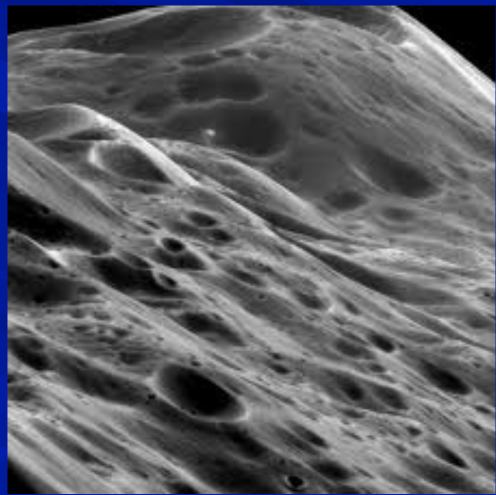
© NASA

Dunes of sand-sized materials have been trapped on the floors of many Martian craters. This is one example, from a crater in Noachis Terra, west of the giant Hellas impact basin. The High Resolution Imaging Science Experiment (HiRISE) camera on NASA's MRO captured this view on Dec. 28, 2009.

The dunes here are linear, thought to be due to shifting wind directions. Large angular boulders litter the floor between dunes.

And on satellites
Ridge on Iapetus
(Third largest Saturn's satellite)





20 km wide
13 km high
1300 km long

Maybe formed by the impact of a satellite debris disk

Understanding the dynamics of granular material

- Is fundamental to interpret images obtained by those in-situ investigations, e.g.:
  - Can we infer the mechanical properties of the regolith from its observed behavior (landslide slopes, crater properties)?
  - Can we predict the evolution of those surfaces based on their observed properties and the different processes they are submitted to?
- To prepare the next missions aimed at interacting with such surfaces

This needs experimental and modeling work!

Welcom to this exciting field, folks!