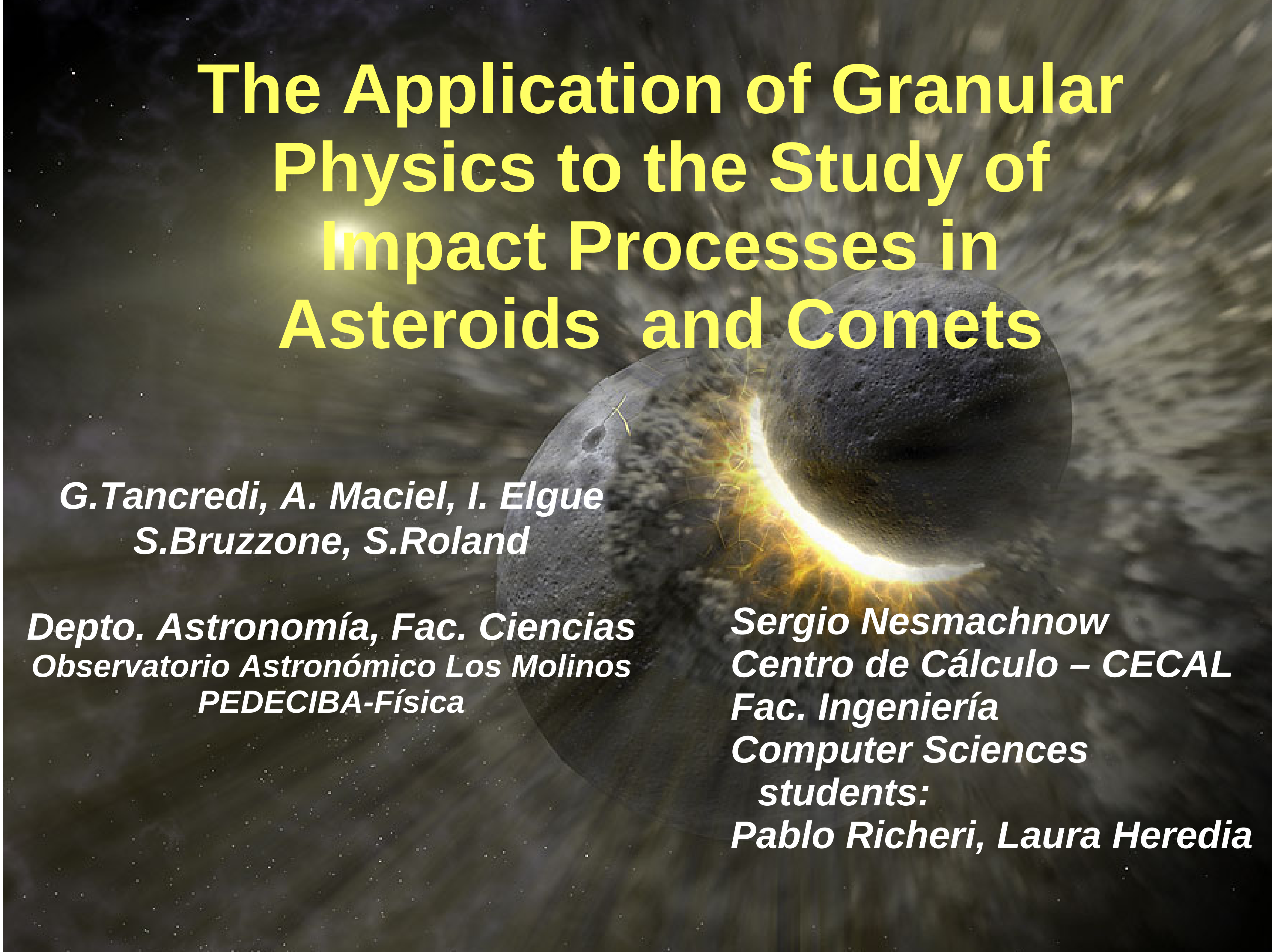

The Application of Granular Physics to the Study of Impact Processes in Asteroids and Comets

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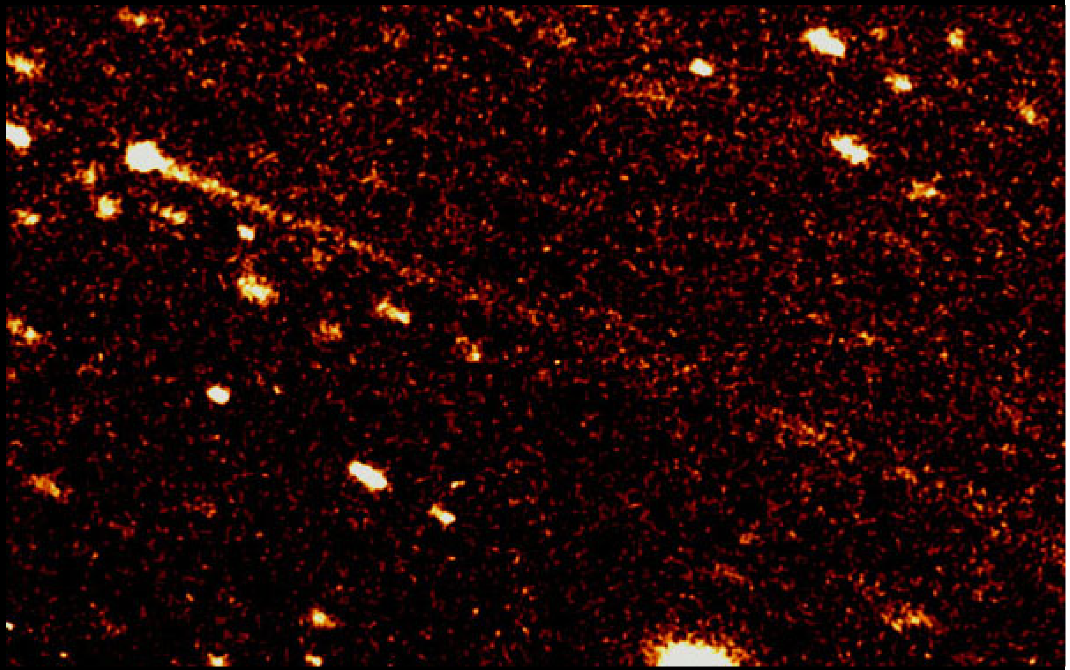
¿How to explain these observation?

Asteroid Itokawa

Big rocks on the surface, mainly on the extreme of the object

Objects in the region of the Asteroid Main Belt

which presents tails and comaes of cometary appearance.
Named “Main-Belt Comets”



Asteroid structures

Solid with surface craters

Solid with big cracks

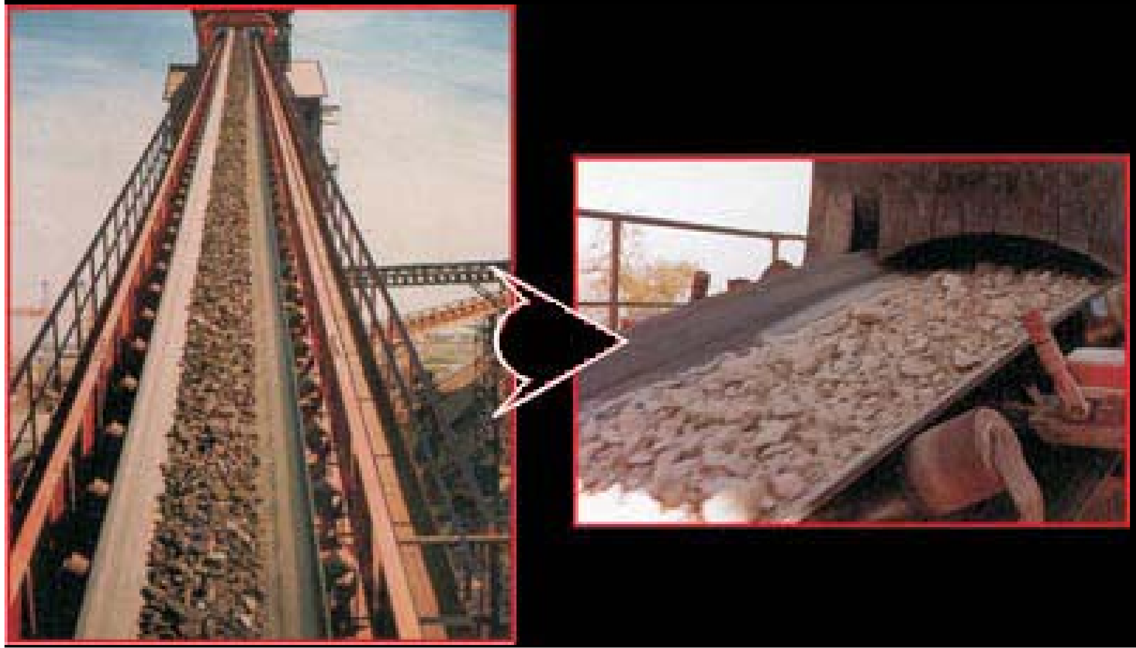
Rubble-piles covered by dust

Agglomerate of small boulders

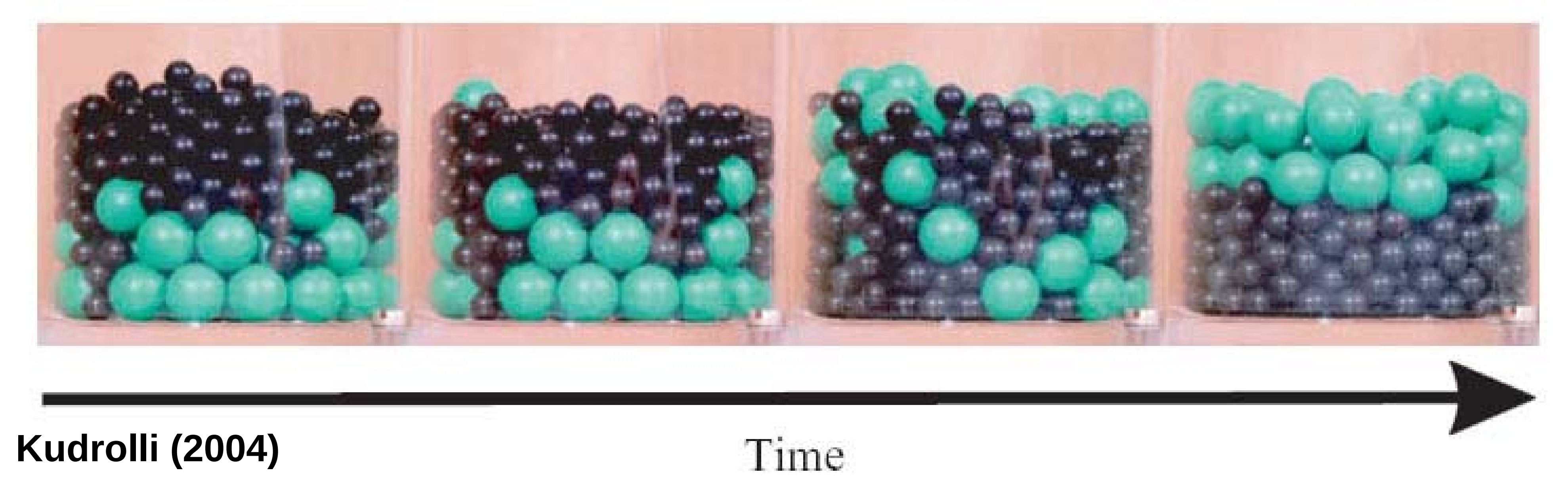
Granular Physics

Granular media reveals different behavior under diverse circumstances:

- Granular media can present fluidization similar to the behavior of fluids: transport of grains trough pipes.
- It behaves like a solid: a heap of sand and dunes



Brazilian Nut effect

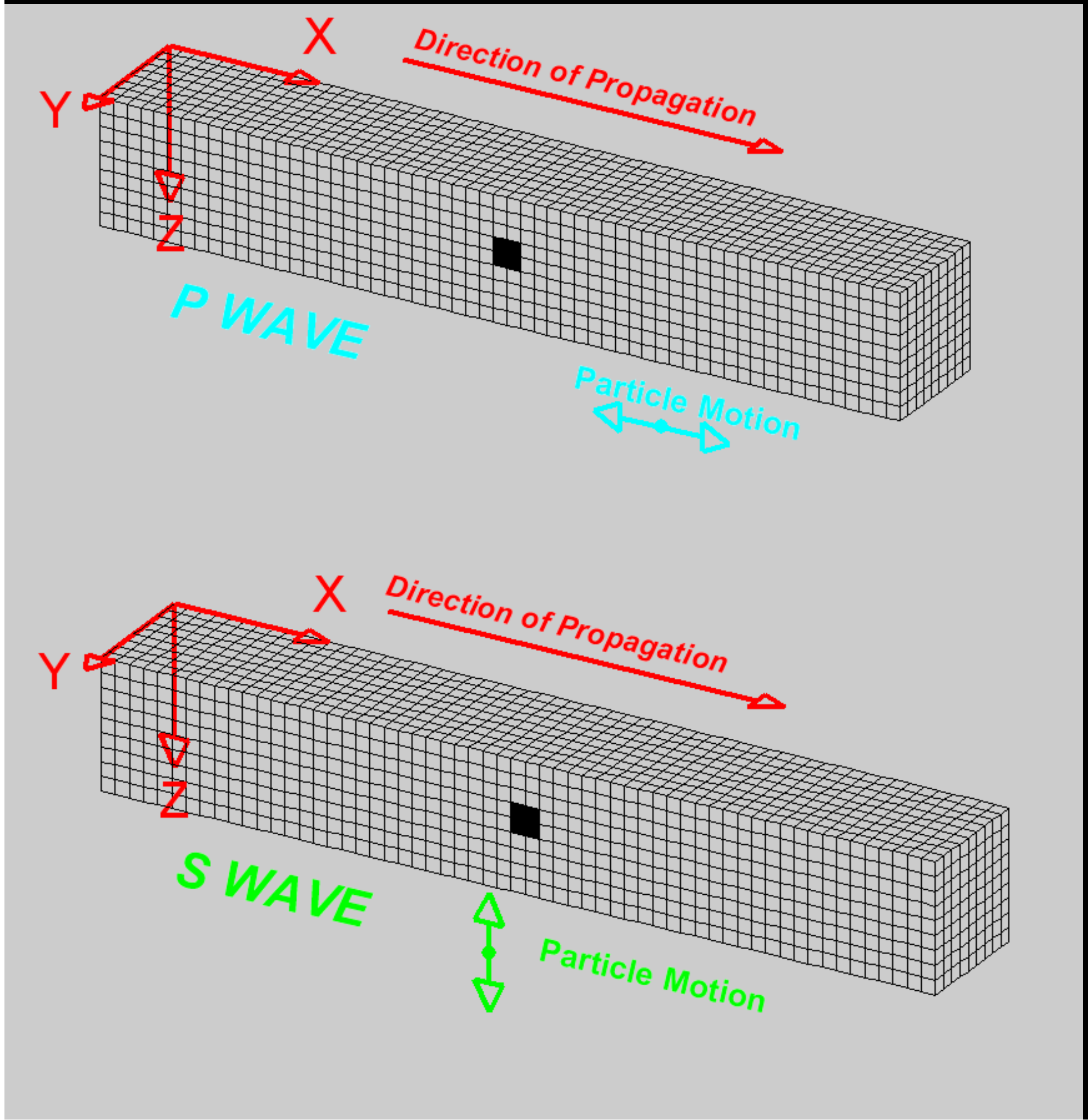


Kudrolli (2004)

Well known phenomenon in the physics of granular media and rock mechanics.

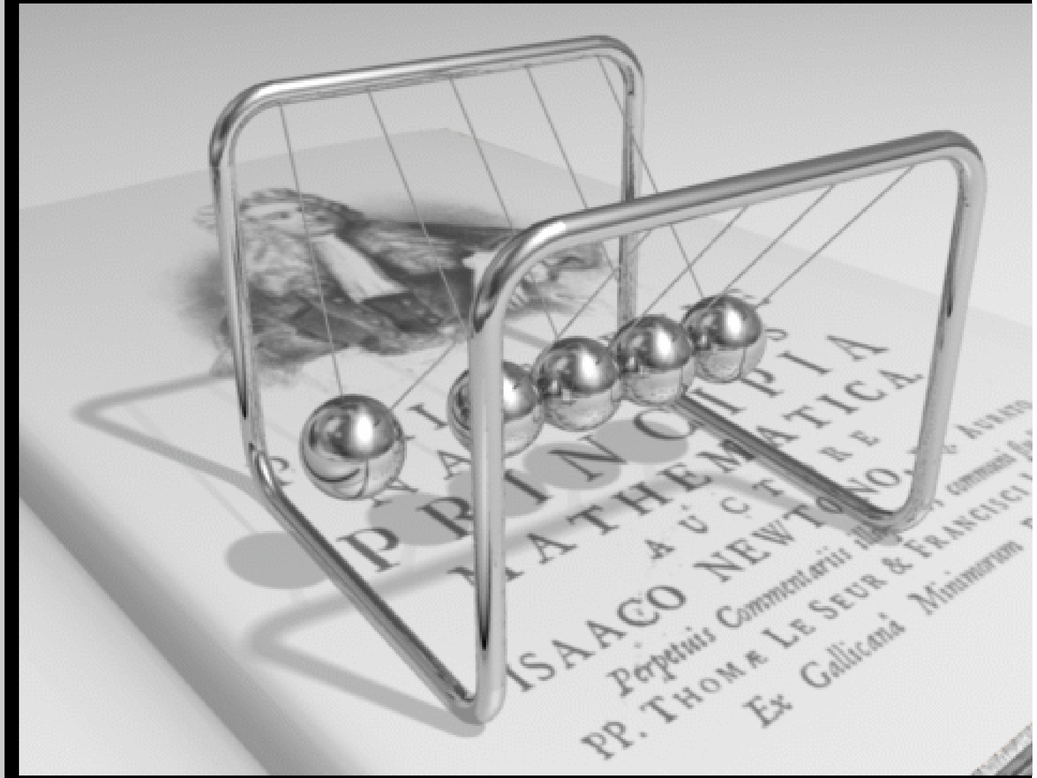
Solid objects

Propagation of seismic waves P and S



Granular media

Transfer of linear momentum



Newton Cradle

Discrete Element Methods (DEM) Molecular Dynamics (MD)

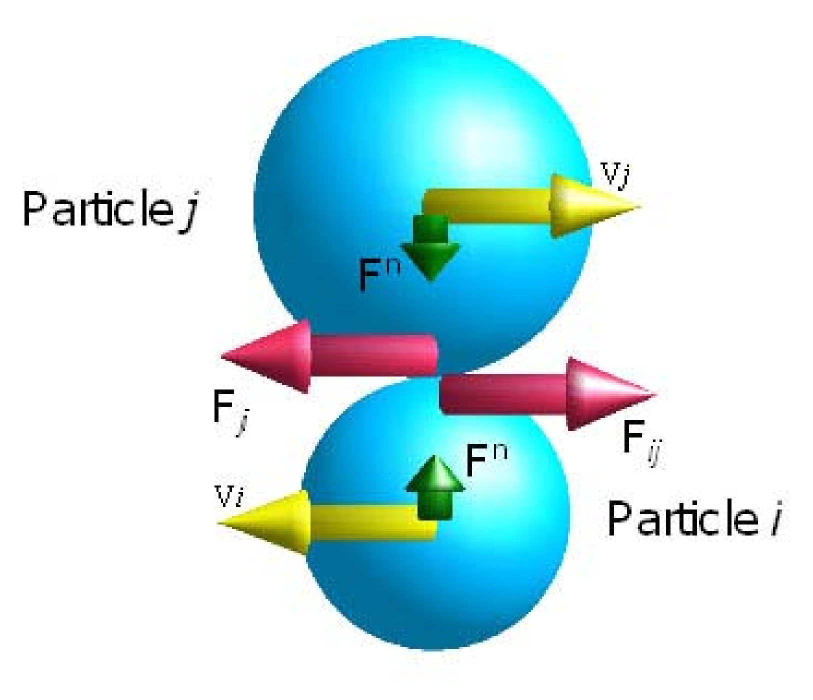
- The numerical simulation of the evolution granular materials has been done recently with the *Discrete Element Method* (DEM).
- DEM is a family of numerical methods for computing the motion of a large number of particles like molecules or grains under given physical laws.
- *Molecular Dynamics* (MD), is a particular case of a DEM, when the particles are spherical molecules.

Interactions between contacting particles

Contact force between particles: Normal + Tangential

$$\vec{F}_{ij} = \begin{cases} \vec{F}^{\mathrm{n}}_{ij} + \vec{F}^{\mathrm{t}}_{ij} & \text{if} \quad \xi_{ij} > 0 \\ 0 & \text{otherwise}\,. \end{cases}$$

ξ – Deformation $\quad \xi_{ij} \equiv R_i + R_j - |\vec{r}_i - \vec{r}_j| > 0$



Model of Viscoelastic Spheres with Friction

Normal Force

$$F^{\mathrm{n}} = \frac{2Y\sqrt{R^{\mathrm{eff}}}}{3\left(1-\nu^2\right)}\left(\xi^{3/2} + A\sqrt{\xi}\,\frac{\mathrm{d}\xi}{\mathrm{d}t}\right)$$

Y –Young modulus

ν – Poisson ratio

A – Disipation constant

R^{eff} – Efective Radius

$$\frac{1}{R^{\mathrm{eff}}} = \frac{1}{R_i} + \frac{1}{R_j}\,.$$

Tangential force or friction
(model of Cundall & Stark 1979)

$$F^{\mathrm{t}} = -\mathrm{sign}\left(v^{\mathrm{t}}_{\mathrm{rel}}\right) \cdot \min\left(\left|\kappa^{\mathrm{t}}\zeta\right|, \mu\left|F^{\mathrm{n}}\right|\right)$$

Static Friction

Dynamic Friction

Main Limitations of DEM simulations

Computational costs:

- Number of particles (N>10^4-10^5)

  “Bottle neck” of the method: Computation of the interacting forces for each particle at each timestep.

  - Simple approach: $\propto N(N-1)/2$ operations per time step.
  - But if the particles are equal spheres, each one interact with at most 6. The number of operations should be $\propto 3N$

- The timestep should be:

  Δt << duration of collisions (typically 1/10-1/20 of duration of collisions)

  - Based on the Hertzian elastic contact theory the duration time of contact is $\tau \propto V^{-1/5}$
  - Typically $\tau \sim 10^{-5}$ sec $\Delta t \sim 10^{-6}$ sec !!

ESyS-Particle

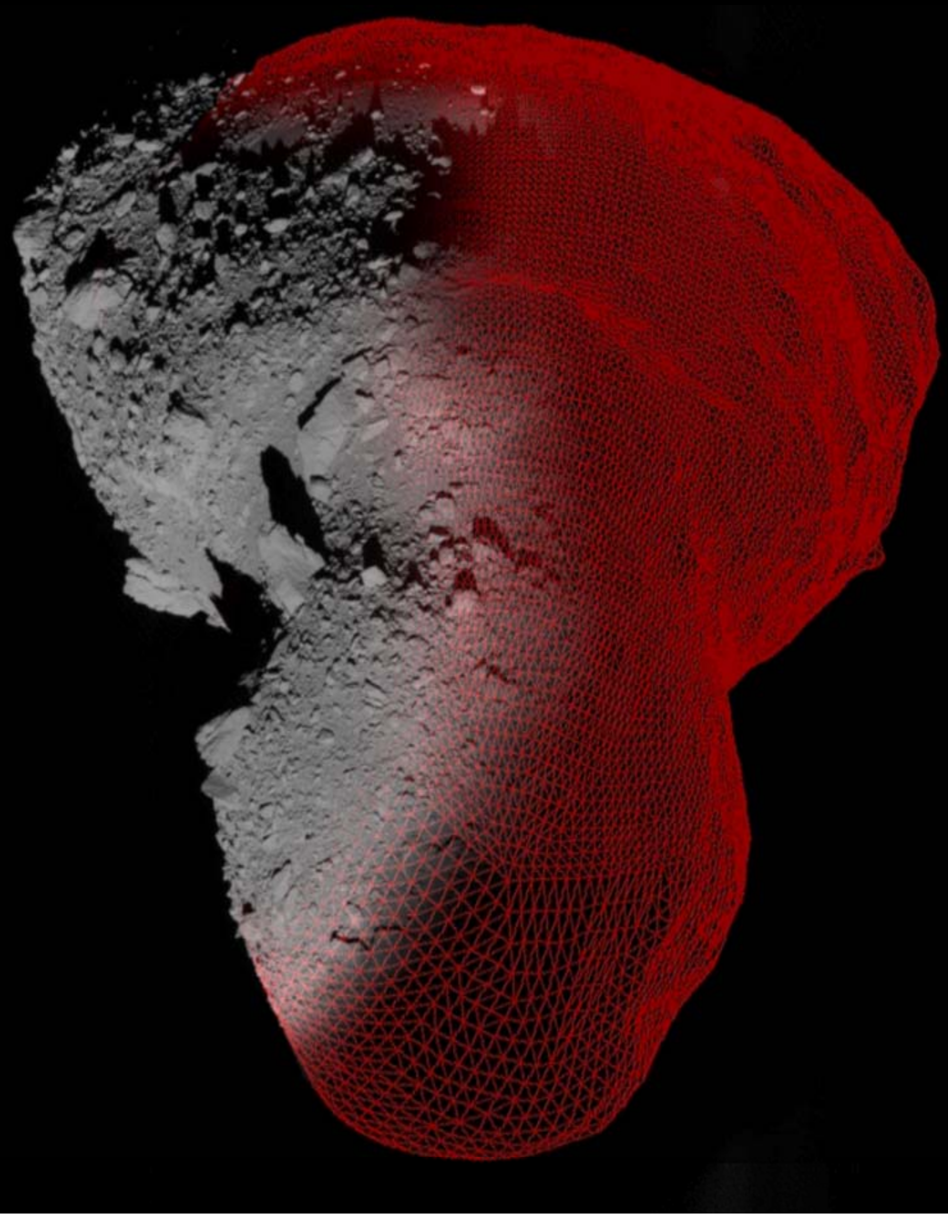
https://launchpad.net/esys-particle

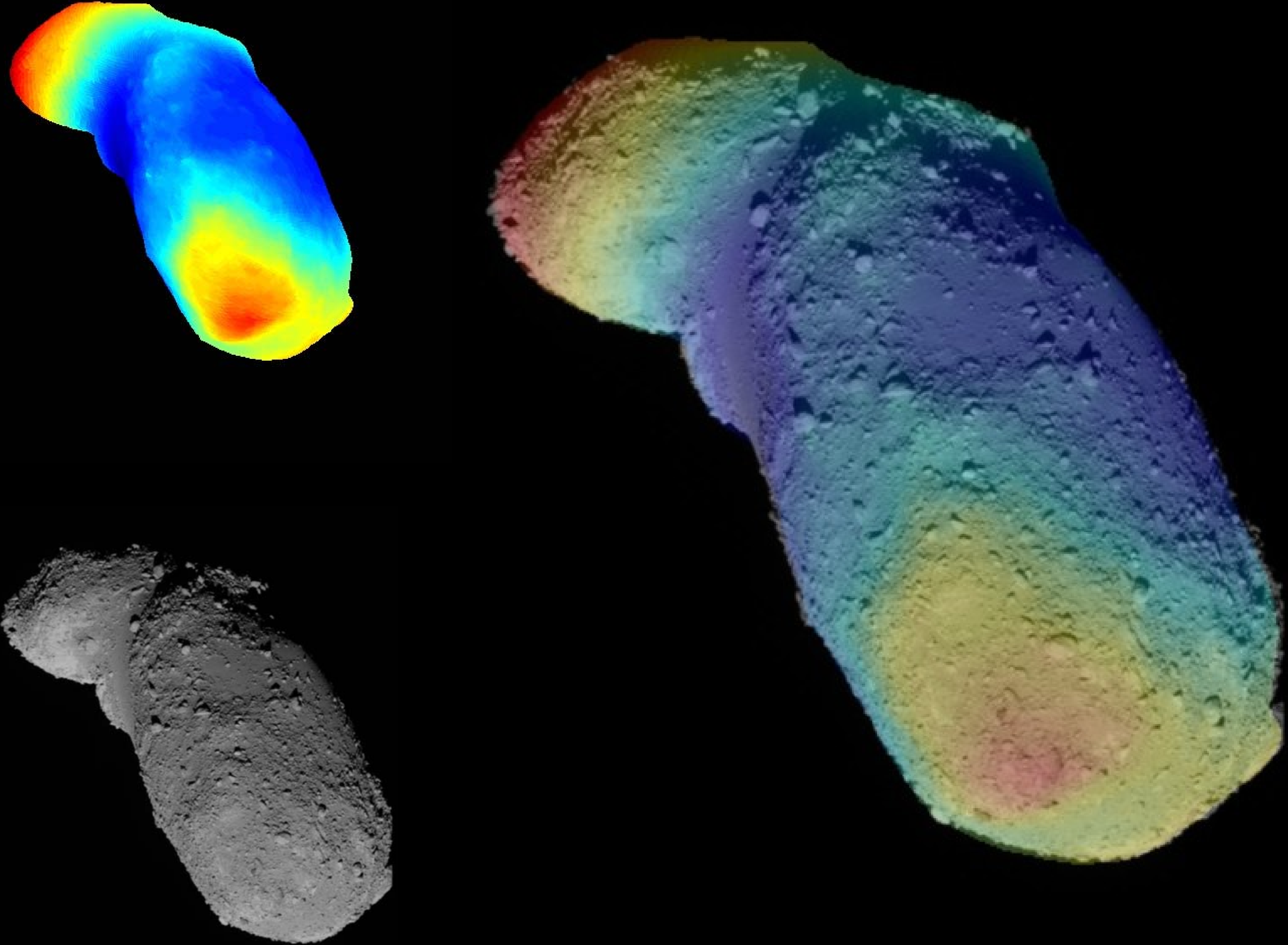
Initiated by Earth Systems Science Computational Centre (ESSCC), University of Queensland (Brisbane, Australia)

ESyS-Particle is an implementation of the Discrete Element Method which is

- Open Source
  - Freely available
  - Can be modified & extended
  - A user community is starting to emerge
- Fully Parallellized
  - Distributed memory parallelisation using MPI
  - runs on commodity hardware from Desktop PC to large clusters (under Linux)
  - Good scaling to large number of CPUs/Cores
    - As long as the problem size is scaled with the number of Cores, scaling is close to linear
  - Very large models possible
    - 1-2Million particles routinely in application
    - 10M+ particles in tests

Size segregation
The case of Itokawa

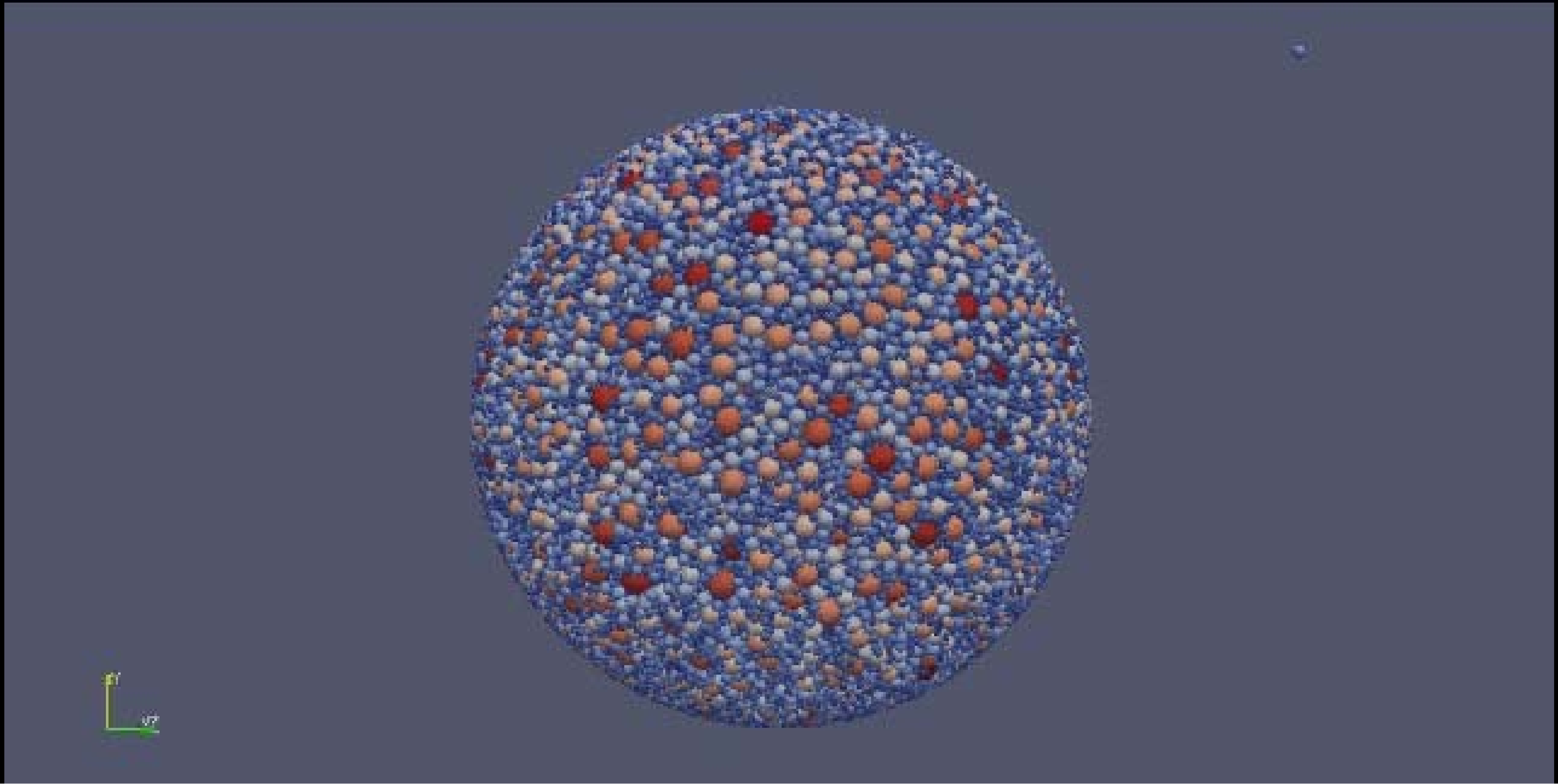




Impact simulations

Diameter asteroid 500m
~90.000 particles of 2.5-12.5 m
without selfgravity

Projectile 10m
Vel. impact 5 km/s



Diameter 500m

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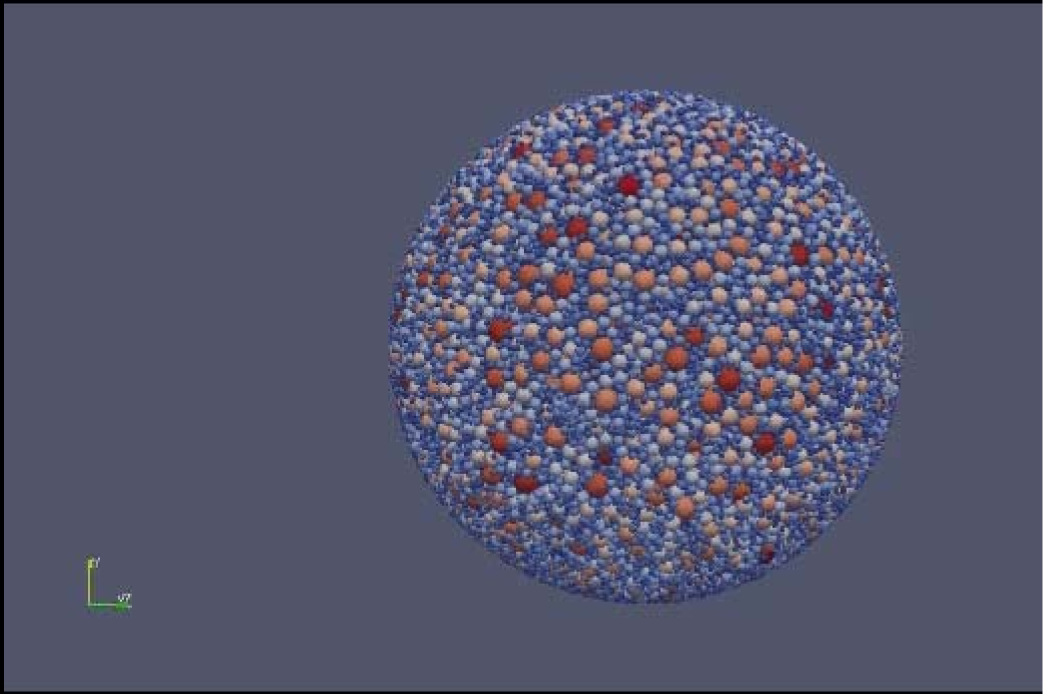
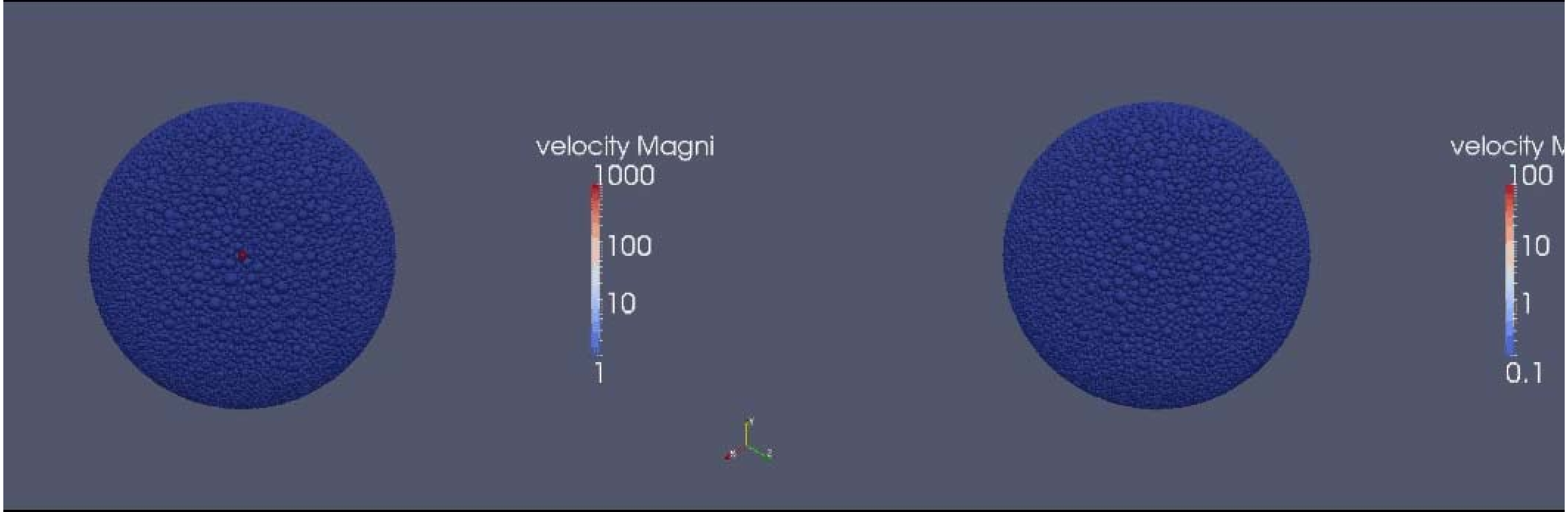
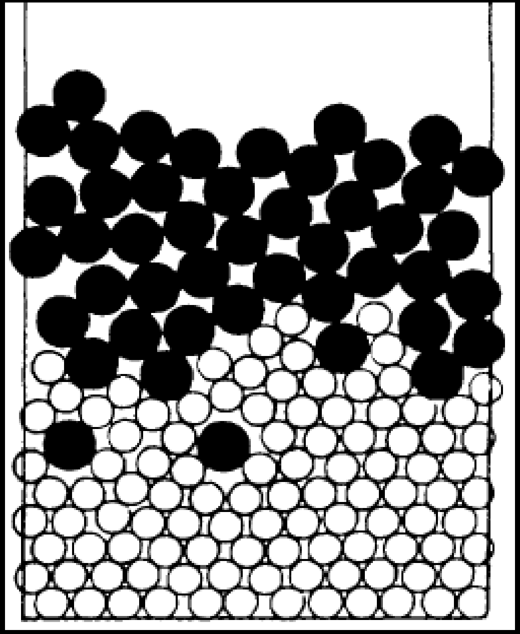
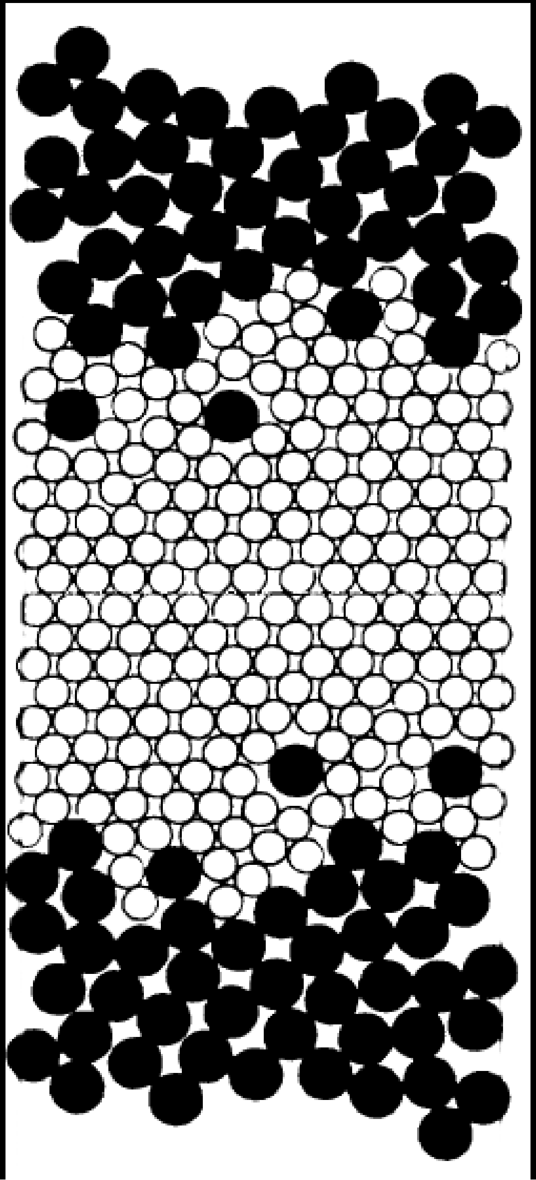




Brazilian nut effect in asteroids

It was proposed by Ausphaug et al. (2001) to explain the size-sorting of Eros' regolith; motions driven by surface gravitational slopes.

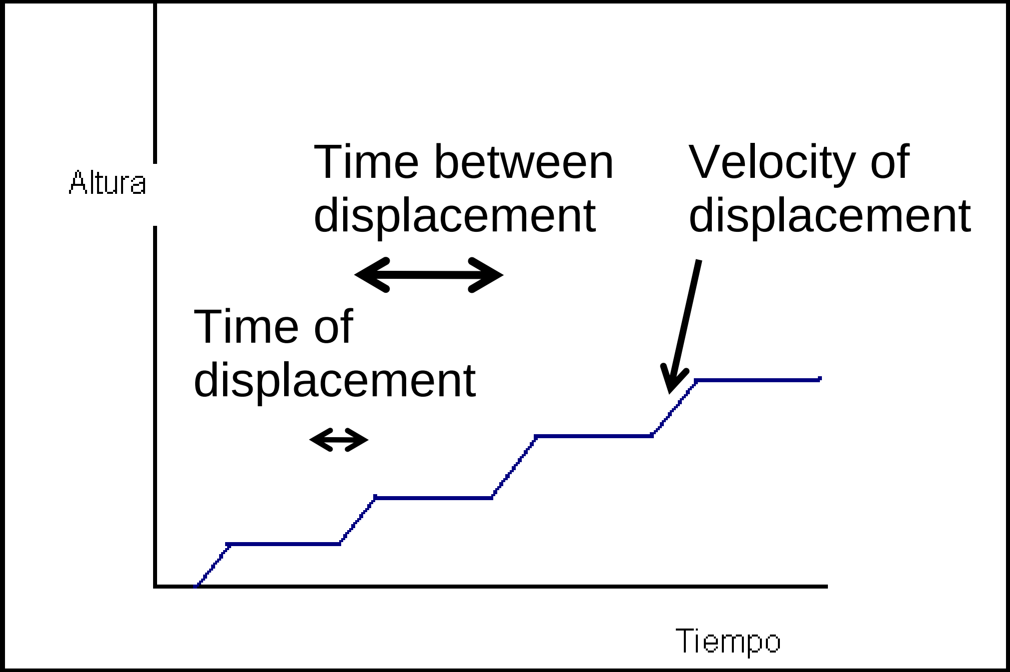




Global shaking could produce a Brazilian Nut effect in Itokawa's entire body.

Simulating repeated seisms

- 3D box with many small particles and 1 big.
- Physical and elastic parameters are typical of rocks. The box is under a given surface gravity.
- The floor is vertically displaced according to a staircase-like function, like:



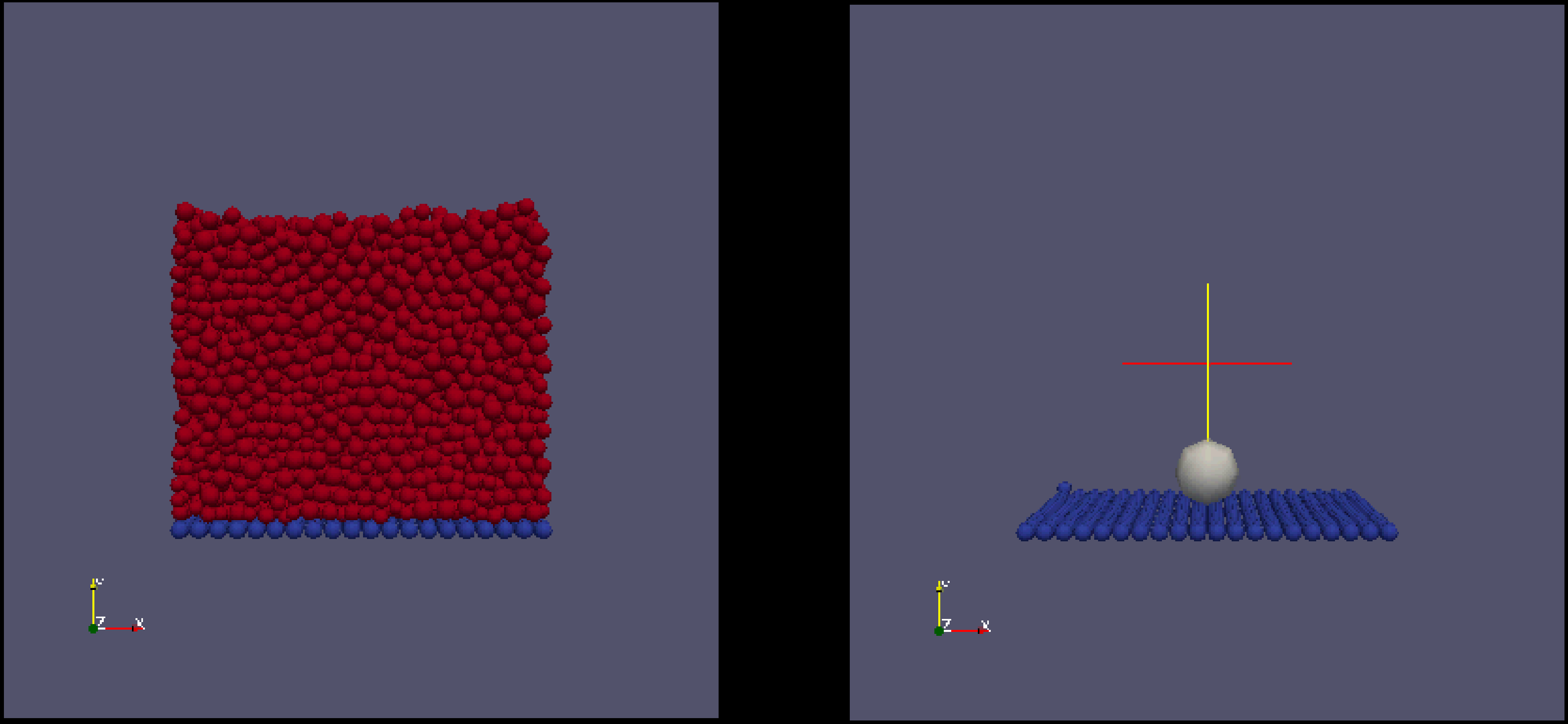
- The process is repeated every given number of seconds, which depends on the settling time given by the surface gravity.
- The simulation typically requires 1 day of CPU-time for a few hundred seconds of simulation.

Earth

$g=9.8$ m/s^2
Vel=5m/s

Time of displacement = 0.1 s
Time between displacement s = 2s
Total integration: 100sec.

The camera is moving with the floor

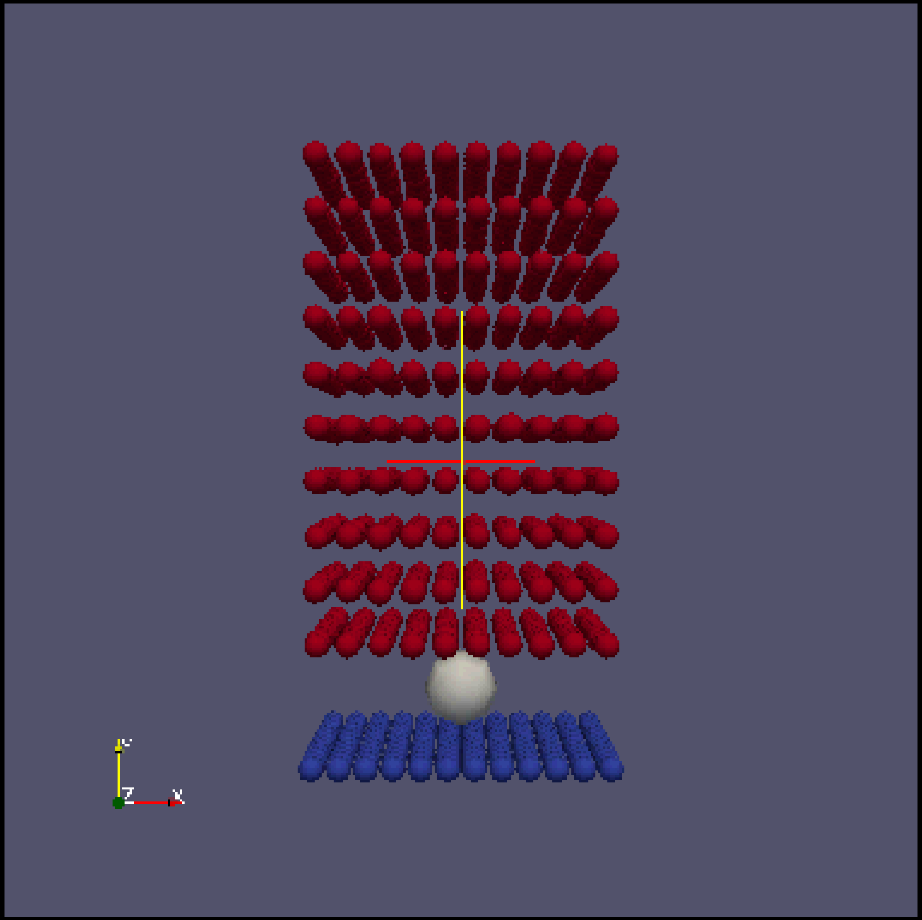


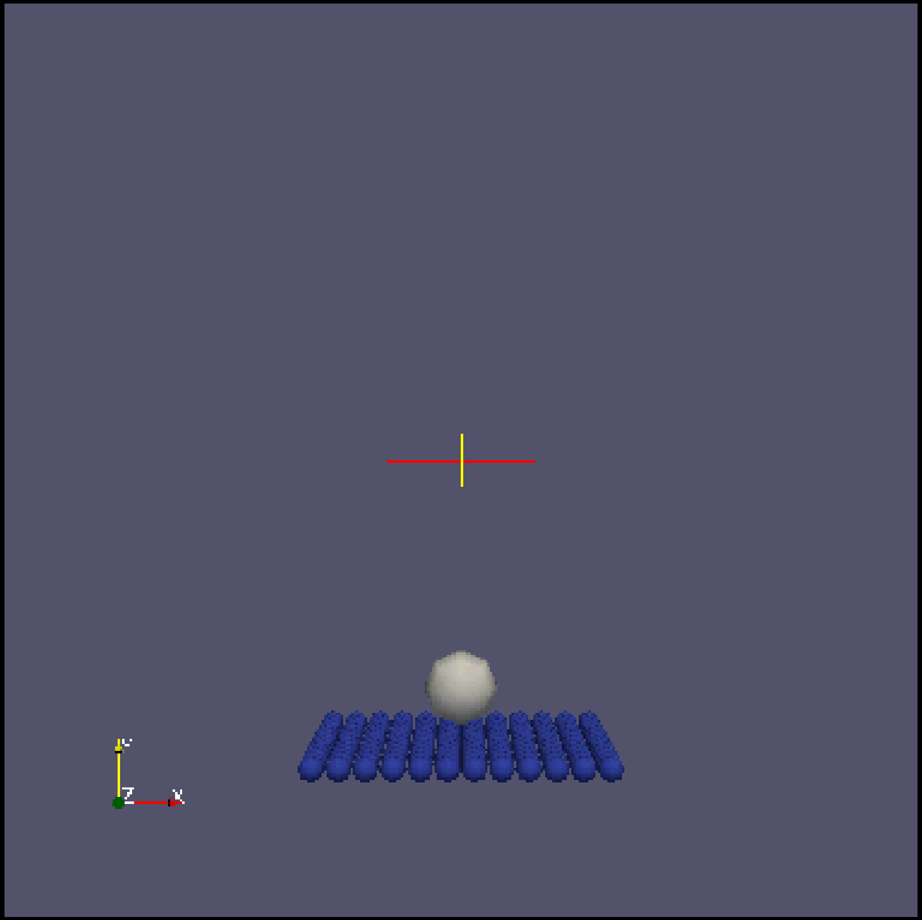
Itokawa

$g=10^{-4}$ m/s^2
Vel=0.02m/s

Time of displacement = 0.1 s
Time between displacement s = 15s
Total integration: 10000 sec.

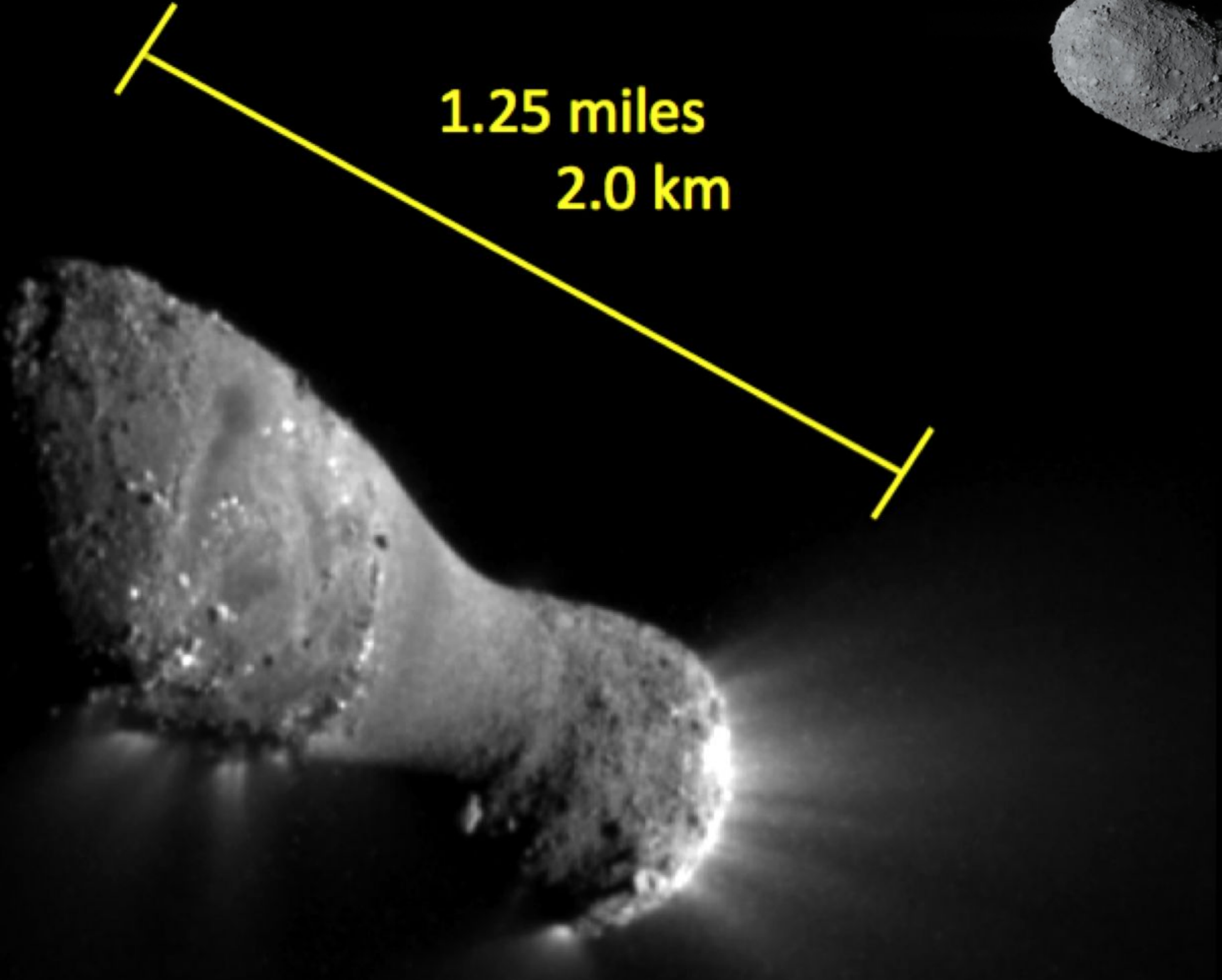
The camera is moving with the floor





103P/Hartley 2 recently visited by NASA's EPOXI

103P/Hartley 2



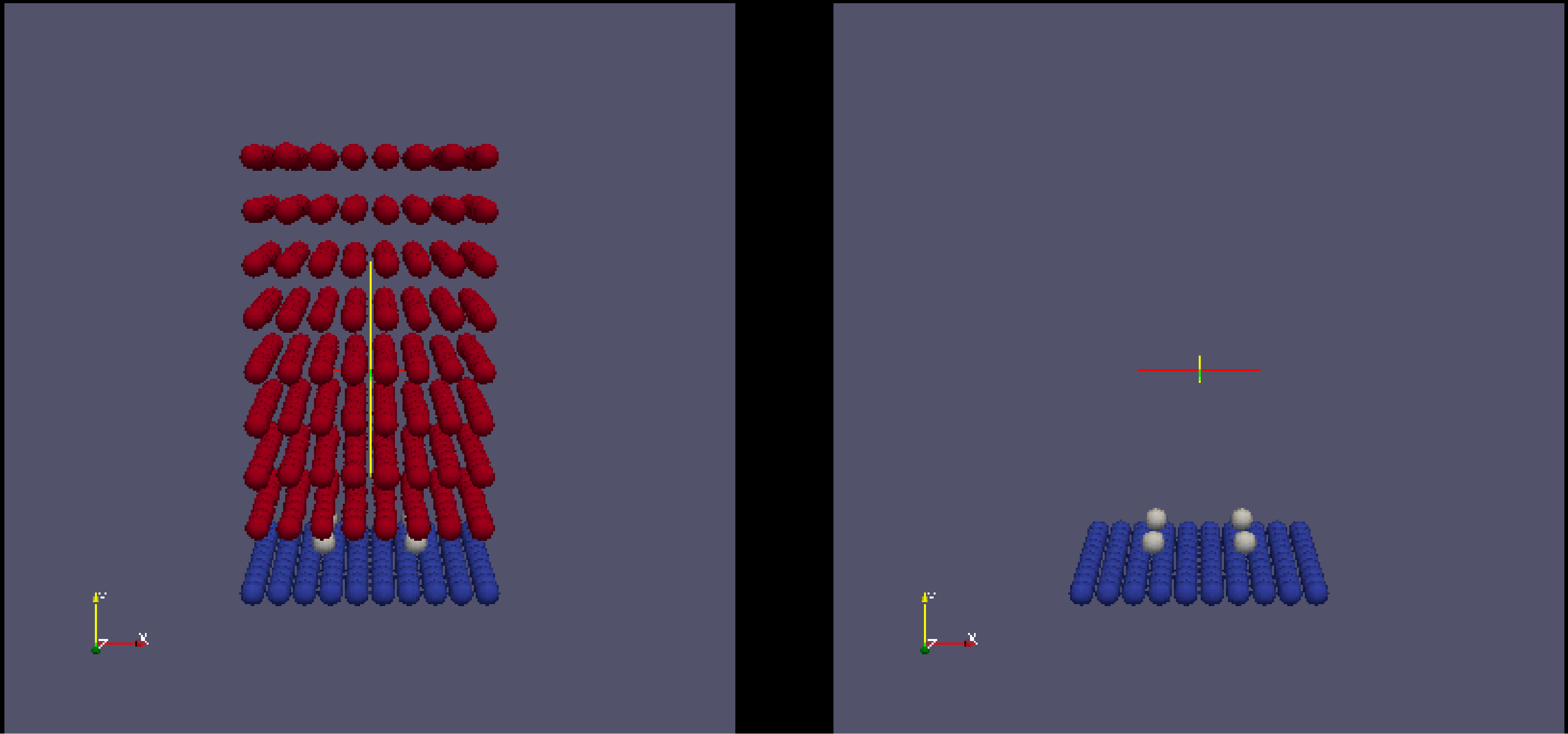
Itokawa

Segregation among icy and rocky boulders

~ 1000 rocky particles (ρ=2 gr/cm^3) and
4 icy particles at the bottom (ρ=0.5 gr/cm^3)

g=10^{-4} m/s^2
Vel=0.02m/s

Time of displacement = 0.1 s
Time between displacement s = 15s
Total integration: 50000 sec.



How does the neck form?

Mixed particles

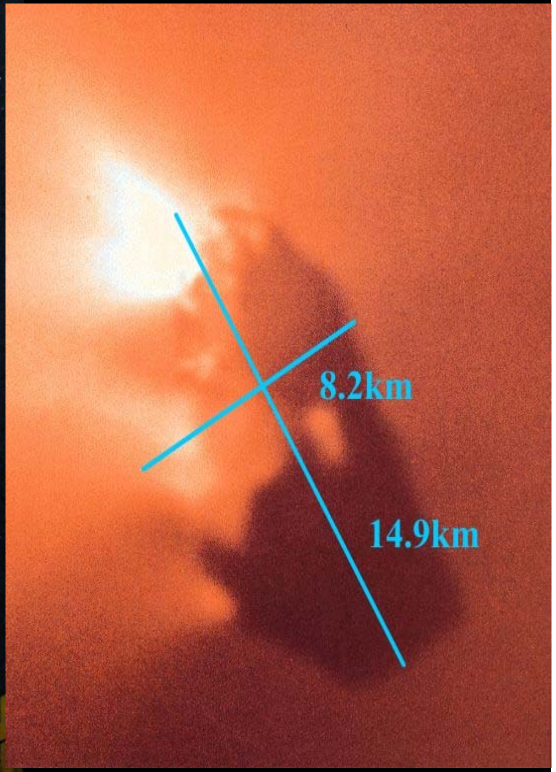
After shaking,
size segregation

Compaction after
more shaking,
and neckle
squeezing

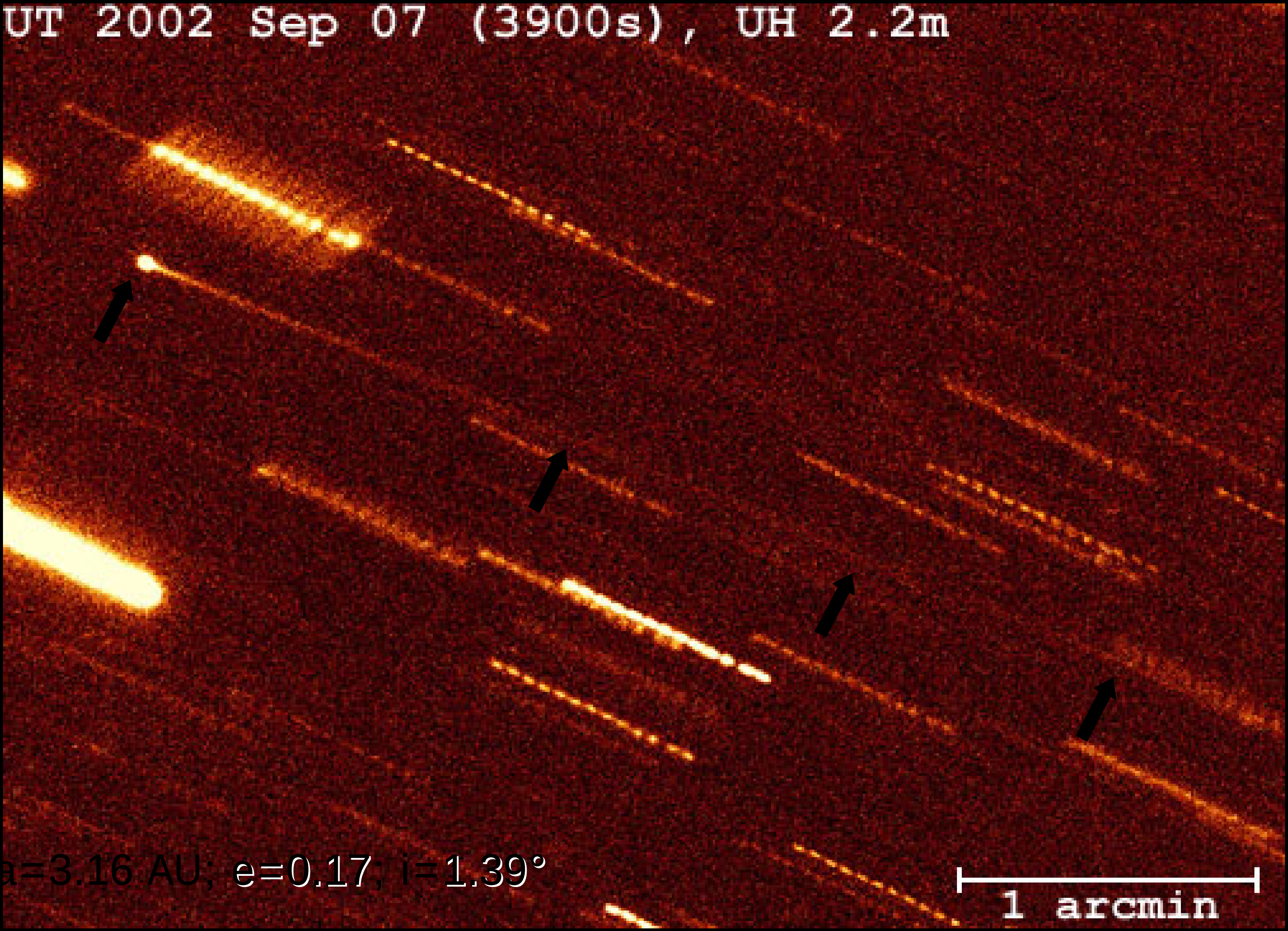
Asteroids versus Comets
Physical distinction

Asteroids: Rocky

Comets: Ice + dust



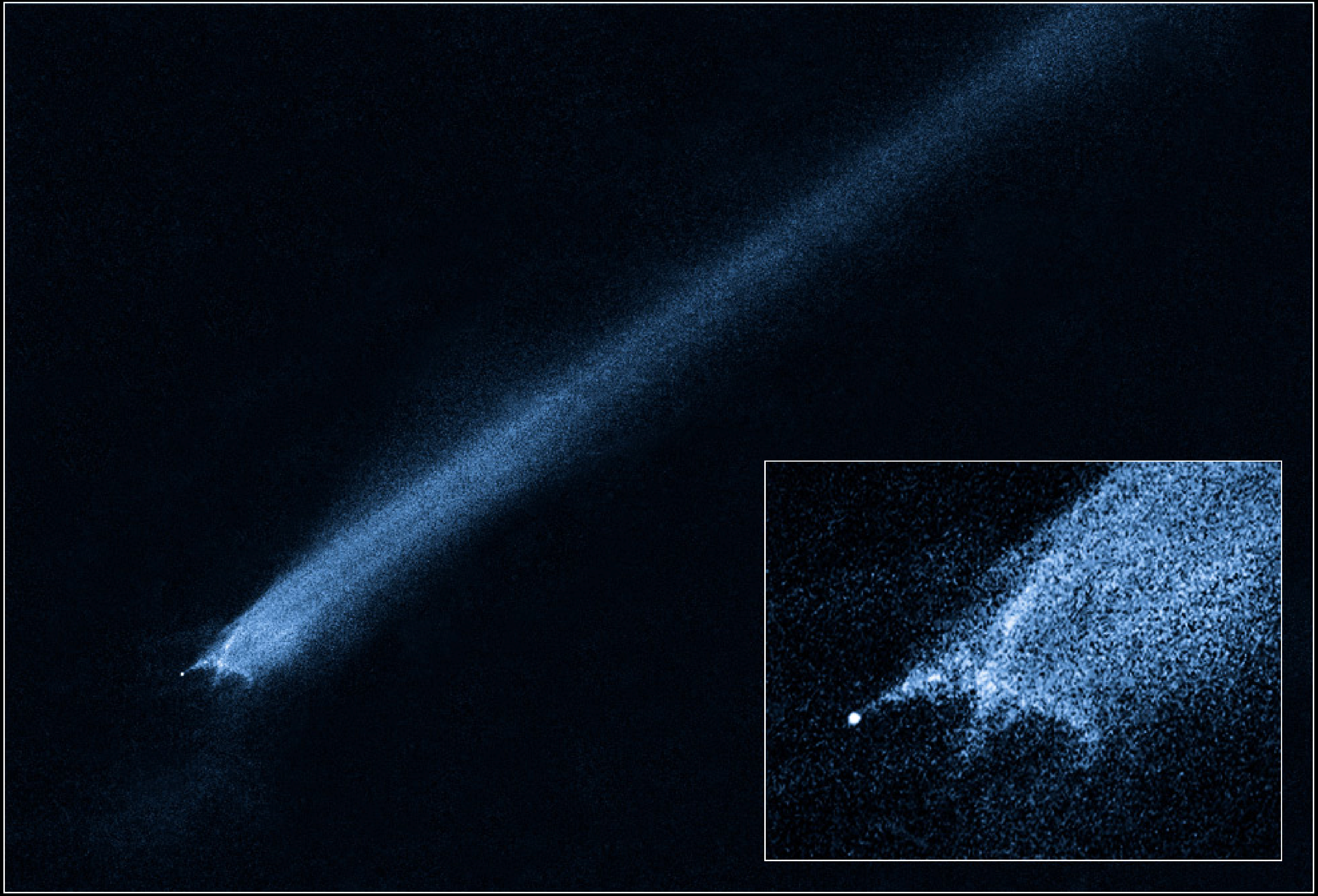
133P/(7968) Elst-Pizarro



a=3.16 AU; e=0.17; i=1.39°

P/2010 A2

Comet-like Asteroid P/2010 A2 • January 29, 2010 *Hubble Space Telescope* • WFC3/UVIS



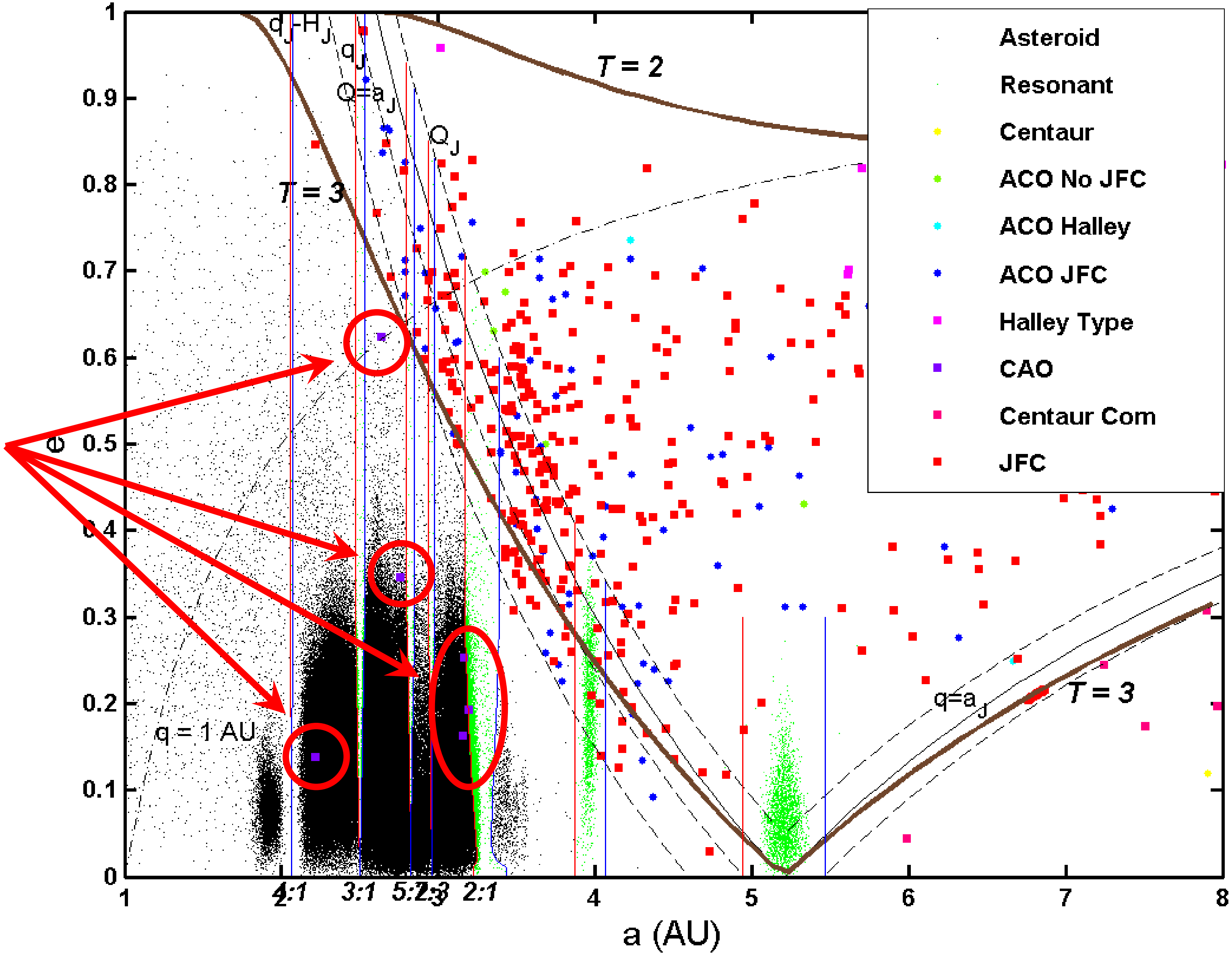
NASA, ESA, and D. Jewitt (UCLA) STScI-PRC10-07

Asteroids versus Comets Dinamycal distinction

Asteroids in Cometary Orbits or Main Belt Comets

7 Objetcs:
3 Themis
1 Flora

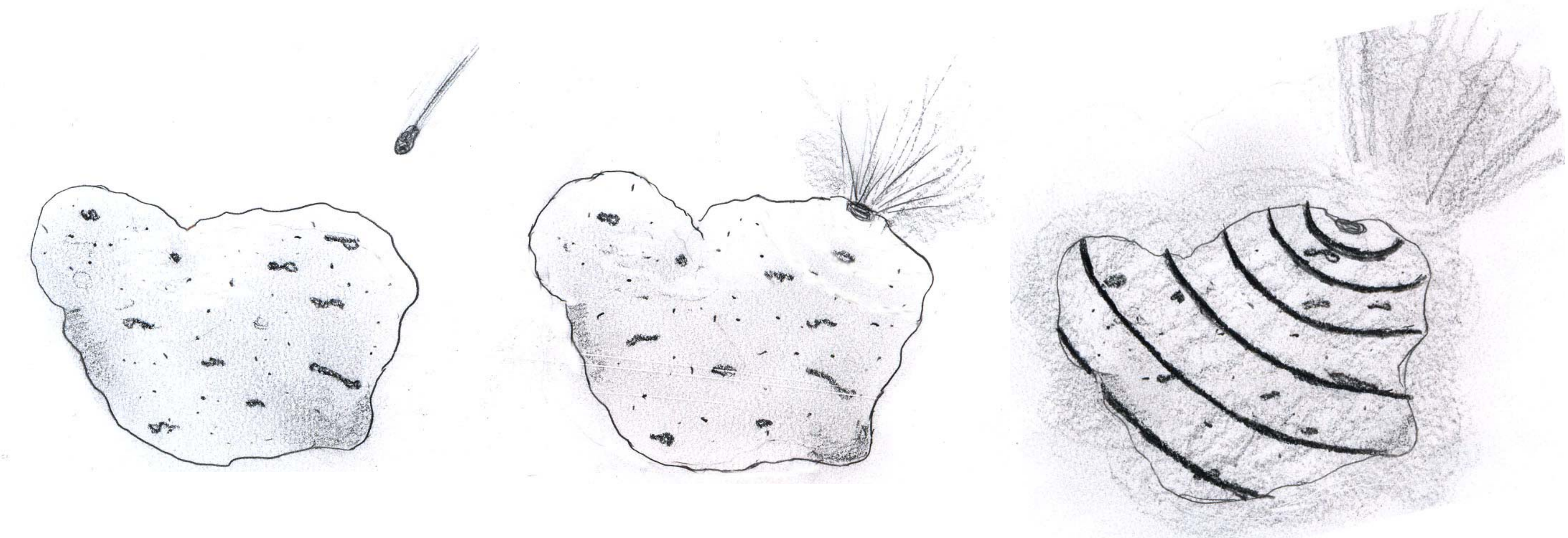
5 con inc<3º
3 con q<2 UA



¿How is the activity produced?

Alternatives:

- Cloud generated by the ejected material after the formation of an impact crater. Problem: The material is rapidly dispersed
- Ice Sublimation on the surface – Problem: how to keep ice on the surface for very long time. Solution: A recent impact expose sub-surface ice. Problem: Is the subsurface ice stable over the age of the Solar System?
- Production of dust cloud at low velocities as a consequence of the shaking produced after a seism generated by an impact and the propagation of the shockwave.

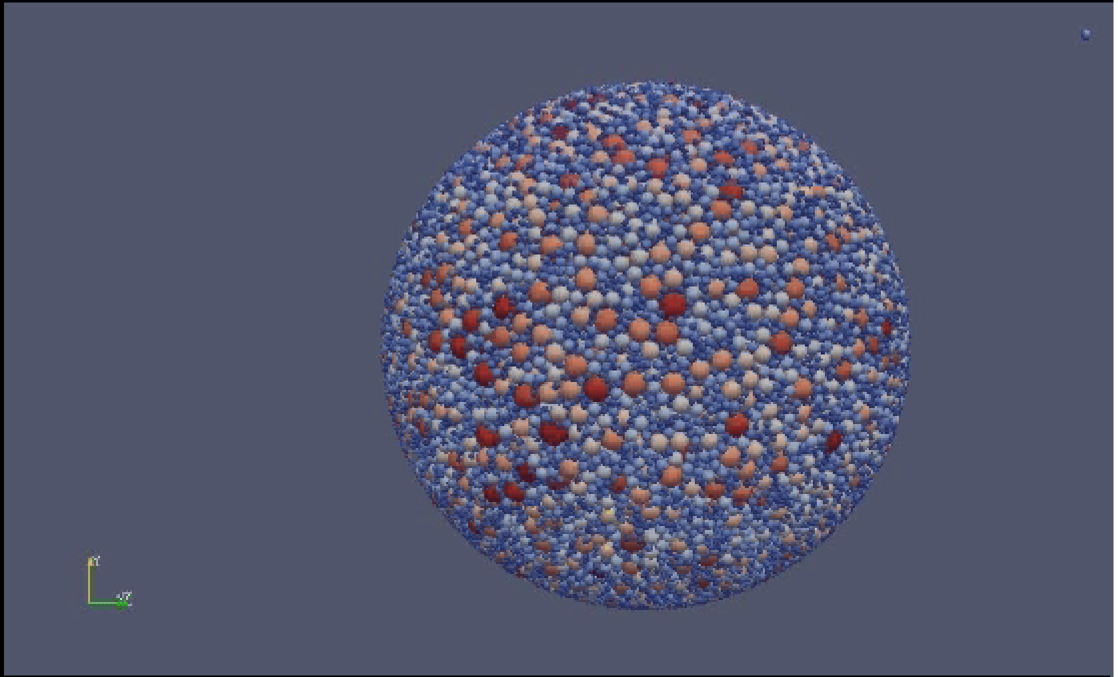


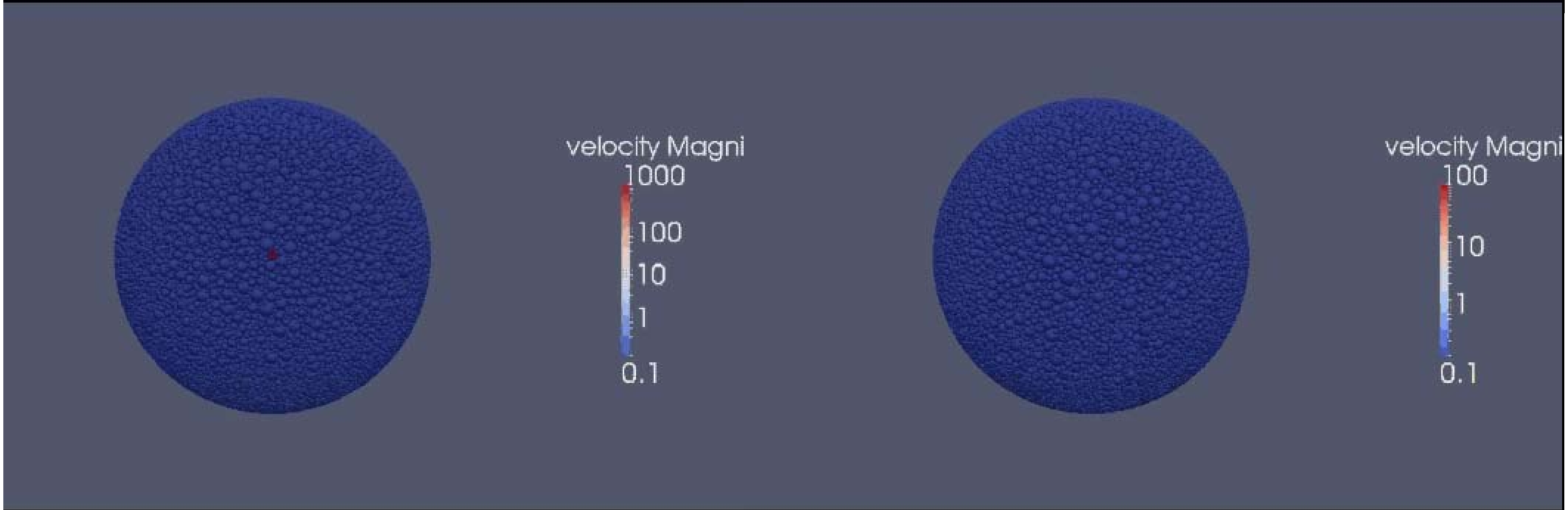
Processes to be considered

- Passage of the shock wave generated by the impact through a granular media
- Ejection of fine particles from the surface
- Formation of a narrow tail from the ejected particles at vel.~ vel. Escape and the action of the solar radiation pressure.

Diameter 2000m
~90.000 particles 10-50m
v escape = 1m/s

Projectile 20m
Vel. impact 5 km/s





Other relevant processes in Granular Media

- The “Cocoa or Flour Effect”

Laboratory of Planetary Geophysics

The Falling Box - Caja Que Cae – CQC : to simulate the production of dust clouds due to seismc Shaking.

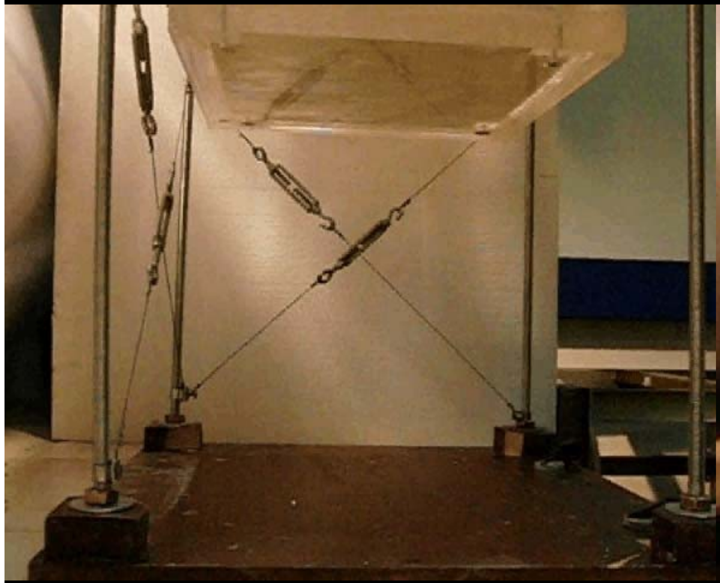
Acrylic box with different type of grains inside.

We vacuum the box down to ~1/10 atm.

The box free fall from a height of ~40cm, impacting the floor at a vel. ~ 2.4 m/s.

The experiment is recorded with high-speed cameras.

Lab experiments with 3 types of grains



Talc

10-100 μm

Fine Sand

100-500 μm

Coarse Sand

500-1000 μm

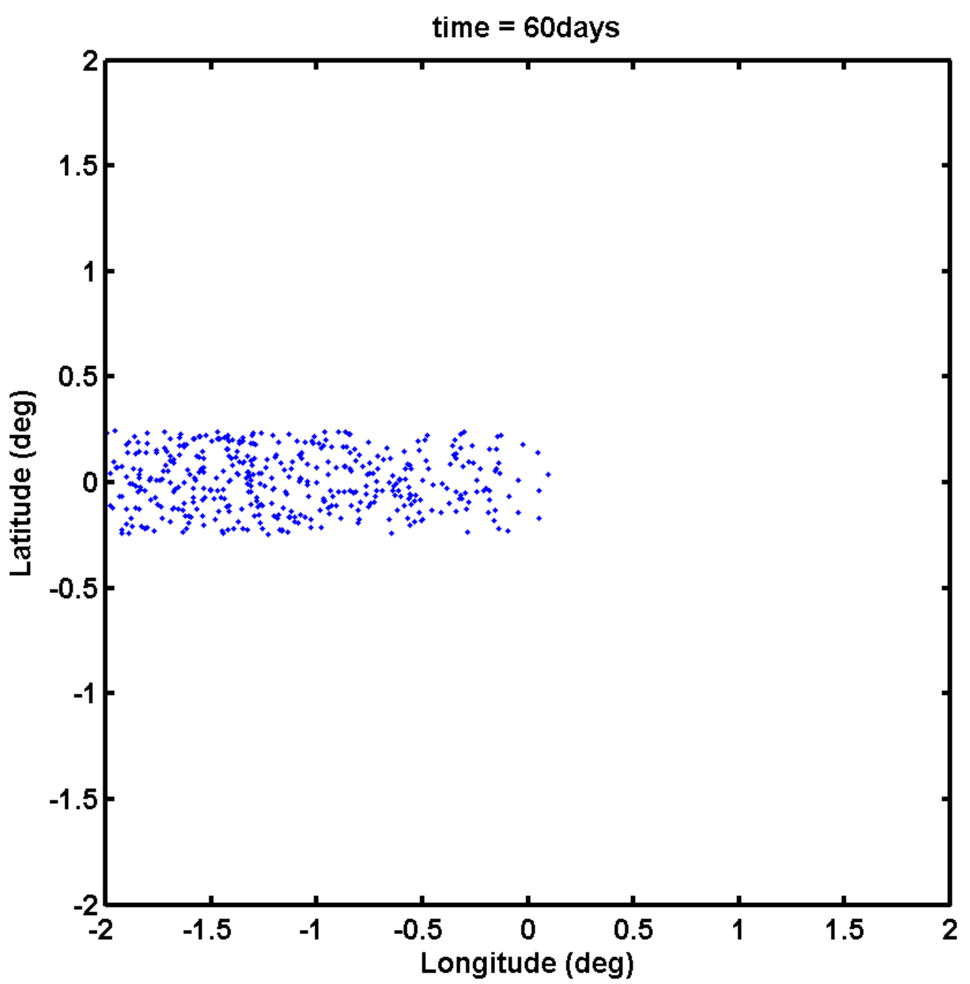
★ For talc, the particles are ejected from the upper surface at velocities up to 2m/s.
The ejection velocity depends on the particle sizes.

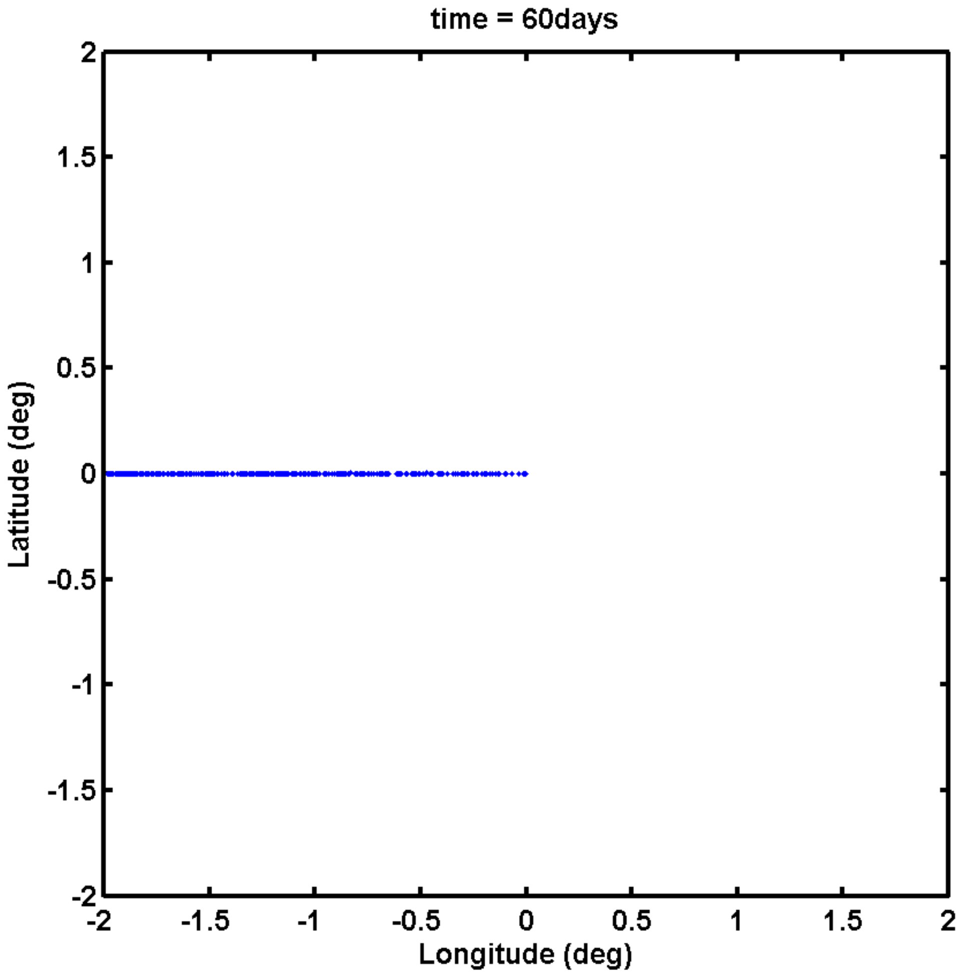
Orbital evolution of a cloud

under the action of the gravitational force of the body and the Sun and the solar radiation pressure

Particles ejected at 100m/s

Particles ejected at 1m/s





Conclusions

- Seismic shaking due to impacts of *m* to 10*m* size projectiles is a relevant effect for objects of a few *kms*
- Size segregation works even in low-gravity conditions **– Itokawa can be explained**
- Density segregation also works in low-gravity conditions **– Hartley 2 can be explained**
- Seismic shaking could produce the ejection of particles from the surface at velocities comparable to the escape velocity **– “Main-Belt Comets” can be explained without ice sublimation: blowing regolith**

Future Plans

- Implement new simulations with mutual gravitational attraction among the interacting particles
- We require great computational capacity

Other applications

- Formation of planetesimals
- Deflection of an asteroid on an impact trajectory to the Earth
- Passage of an agglomerated asteroid through the atmosphere – Bajada del Diablo crater field