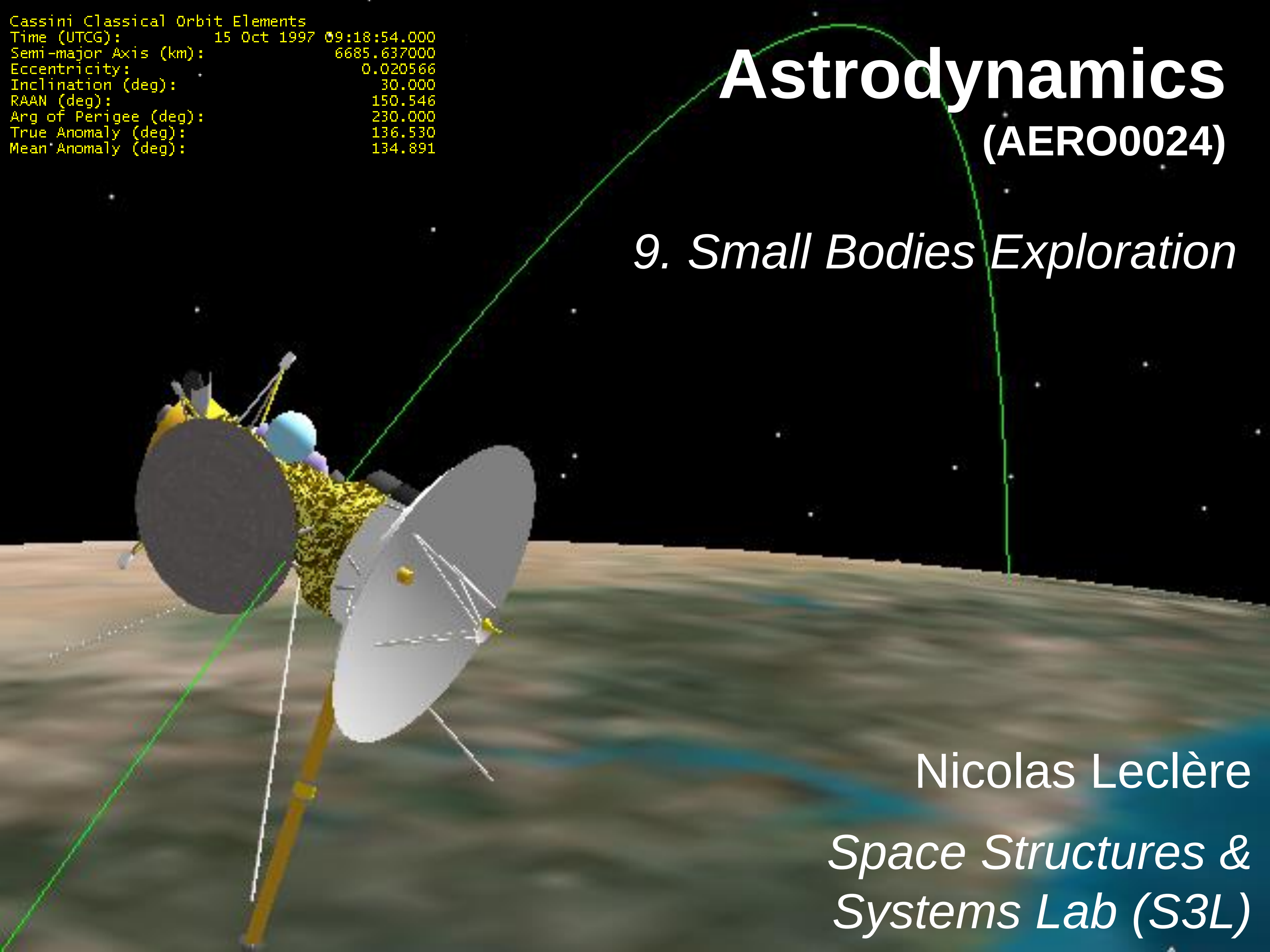
Astrodynamics
(AERO0024)

9. Small Bodies Exploration



Nicolas Leclère

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Small bodies in the Solar system

Asteroids

Asteroids are small rocky celestial objects. They are much smaller than planets, between 100m and 1000km.

Most of them are situated in the main asteroid belt between Mars and Jupiter.

There are more than 1,000,000 asteroids in the Solar system.

Small bodies in the Solar system

Comets

Frozen bodies composed of dust, rock and ices.

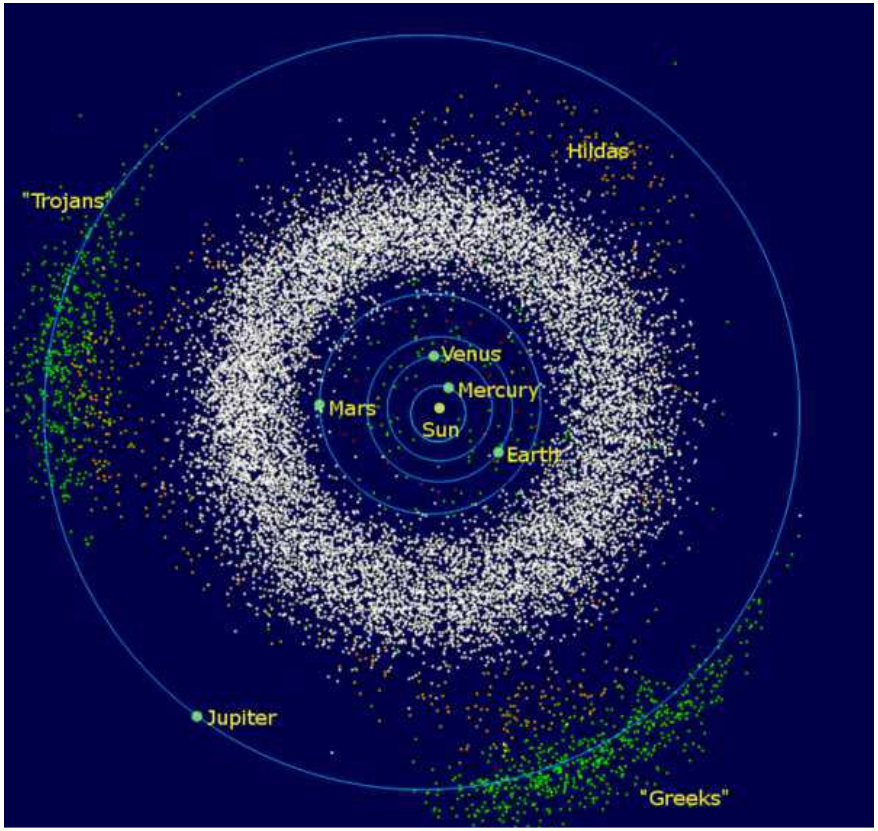
When they orbit close to the Sun, they heat up and form a tail made of gases and dust.

Comets dimension varies between 100m and 30km.

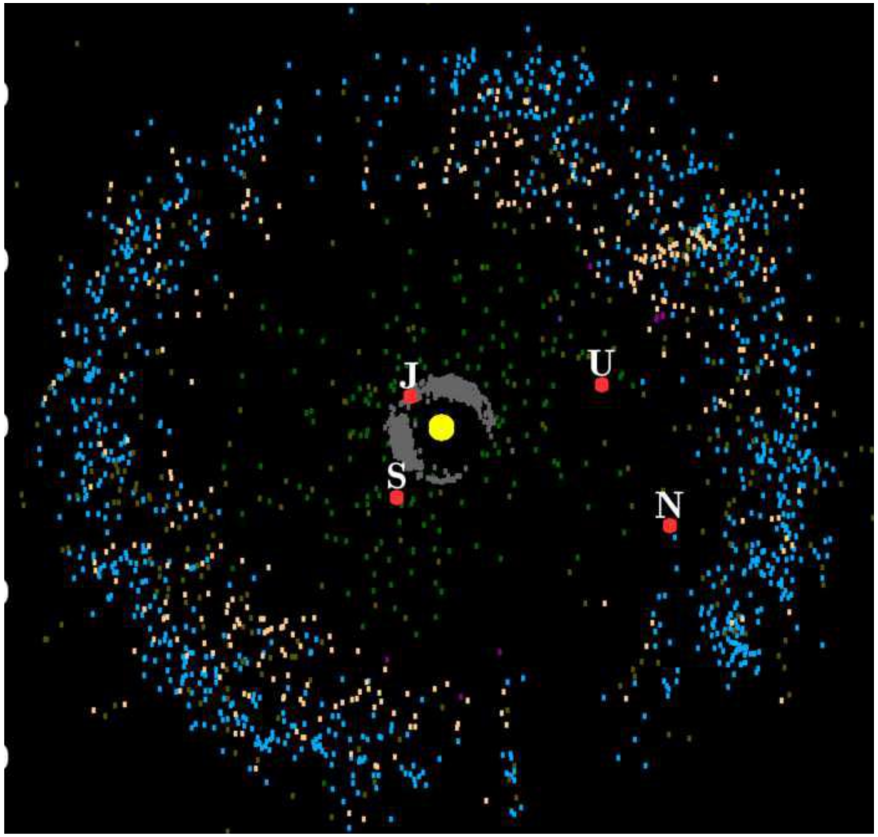
The current number of known is over 3500

Small bodies in the Solar system

Inner solar system

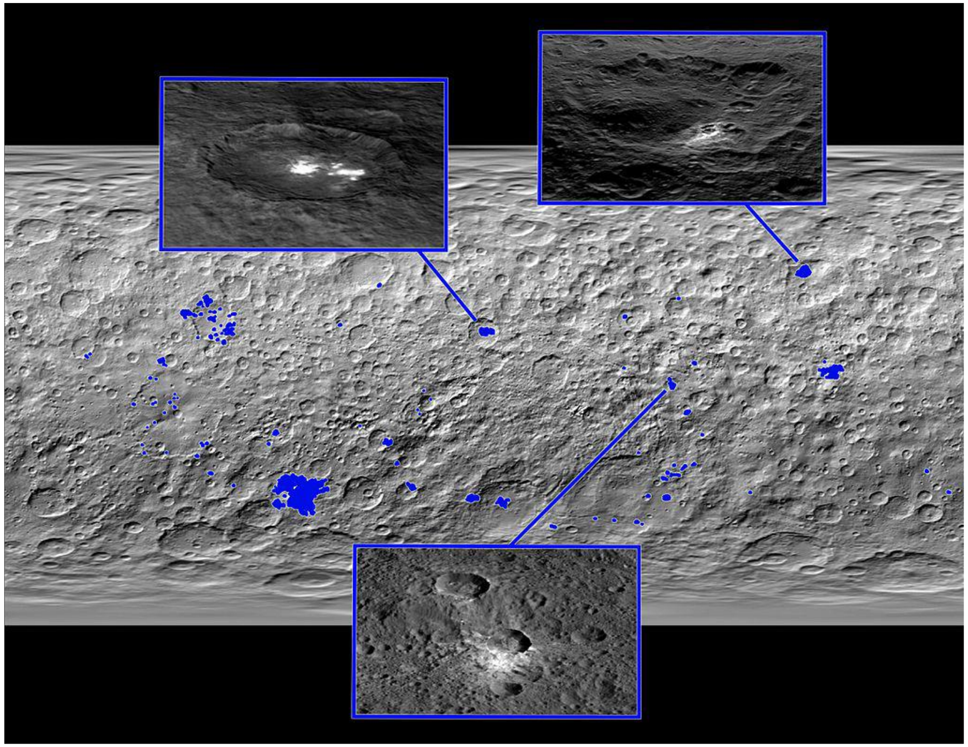


Outer solar system



Small bodies exploration, why?

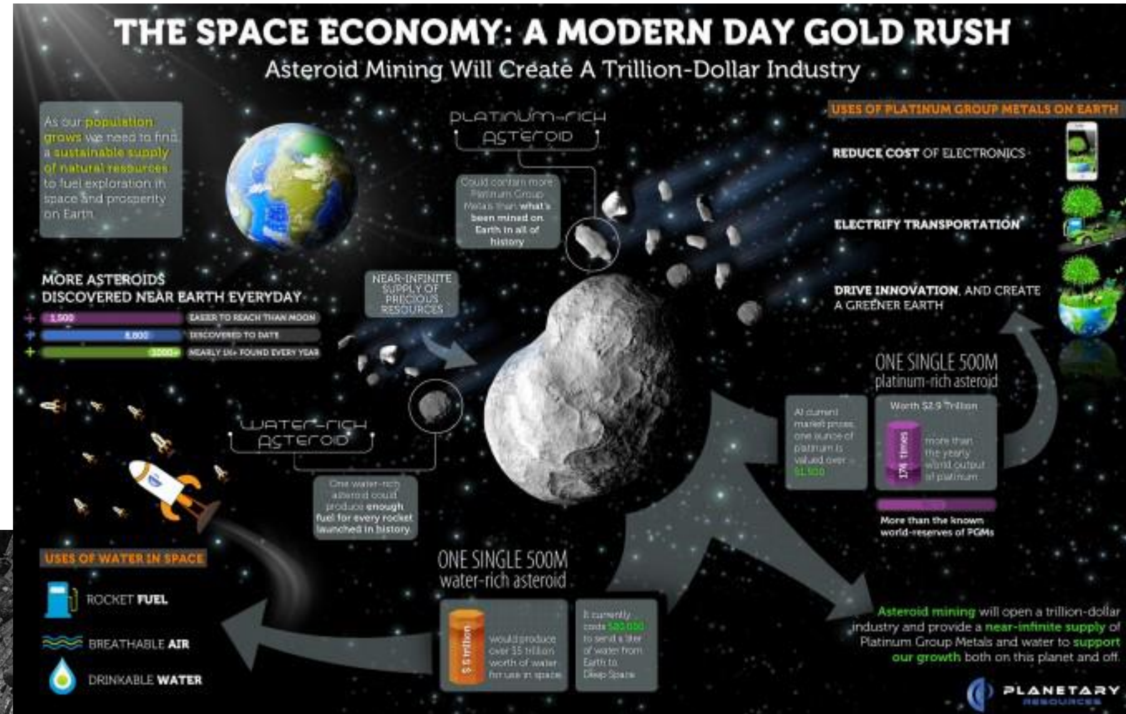
Science

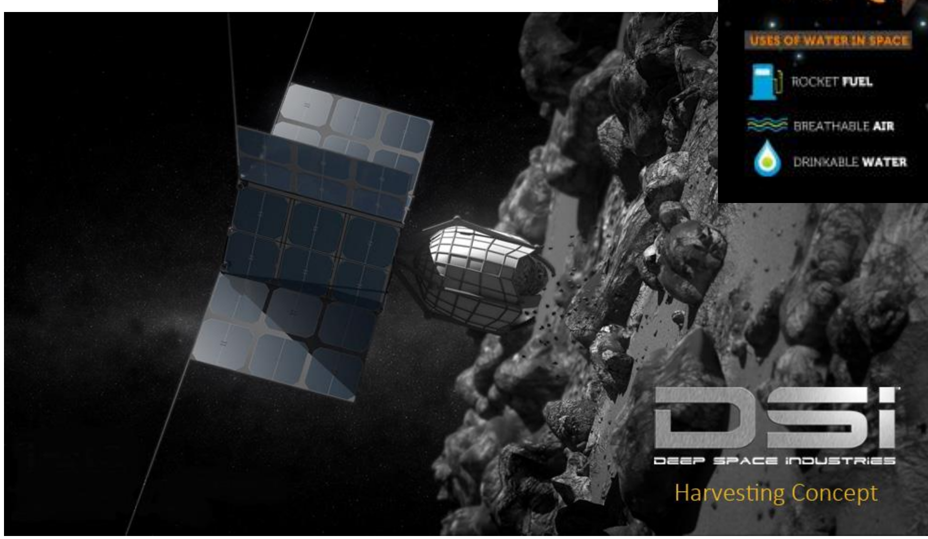


- Better understanding of the early solar system.
- Fuel, oxygen and water storehouses
- Early trace of chemical components of life

Small bodies exploration, why?

Economical

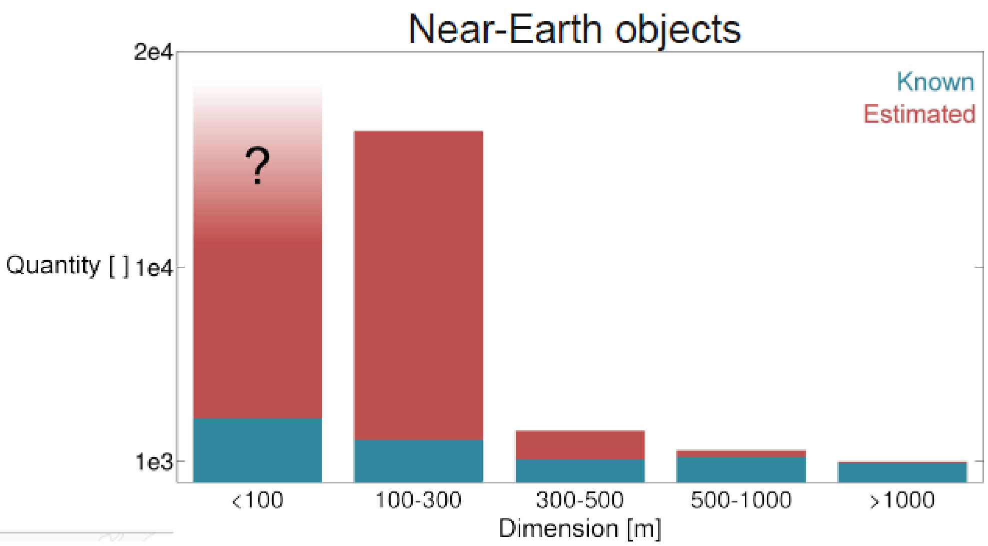


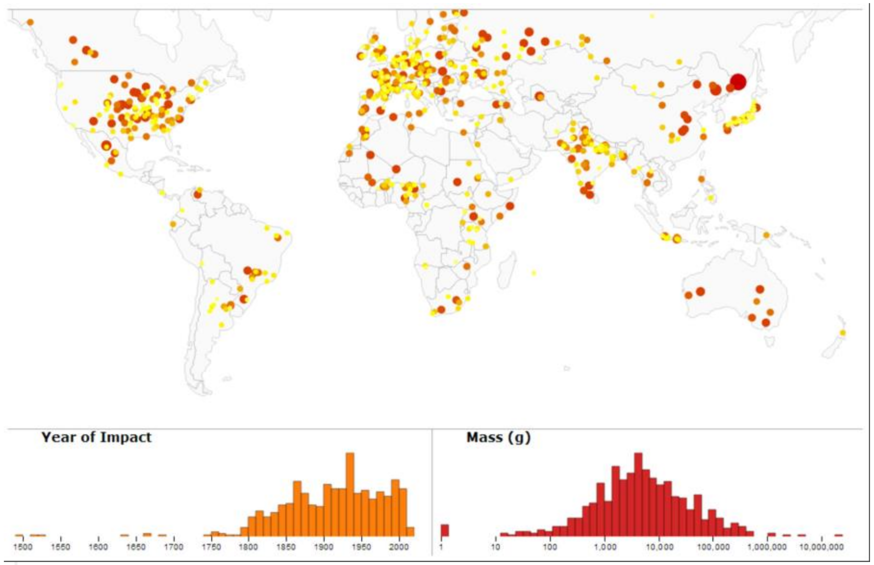


Small bodies exploration, why?

Defence

- There are less large asteroids than small ones
- It is important to monitor their positions for impacts





Small bodies exploration, why?

Defense

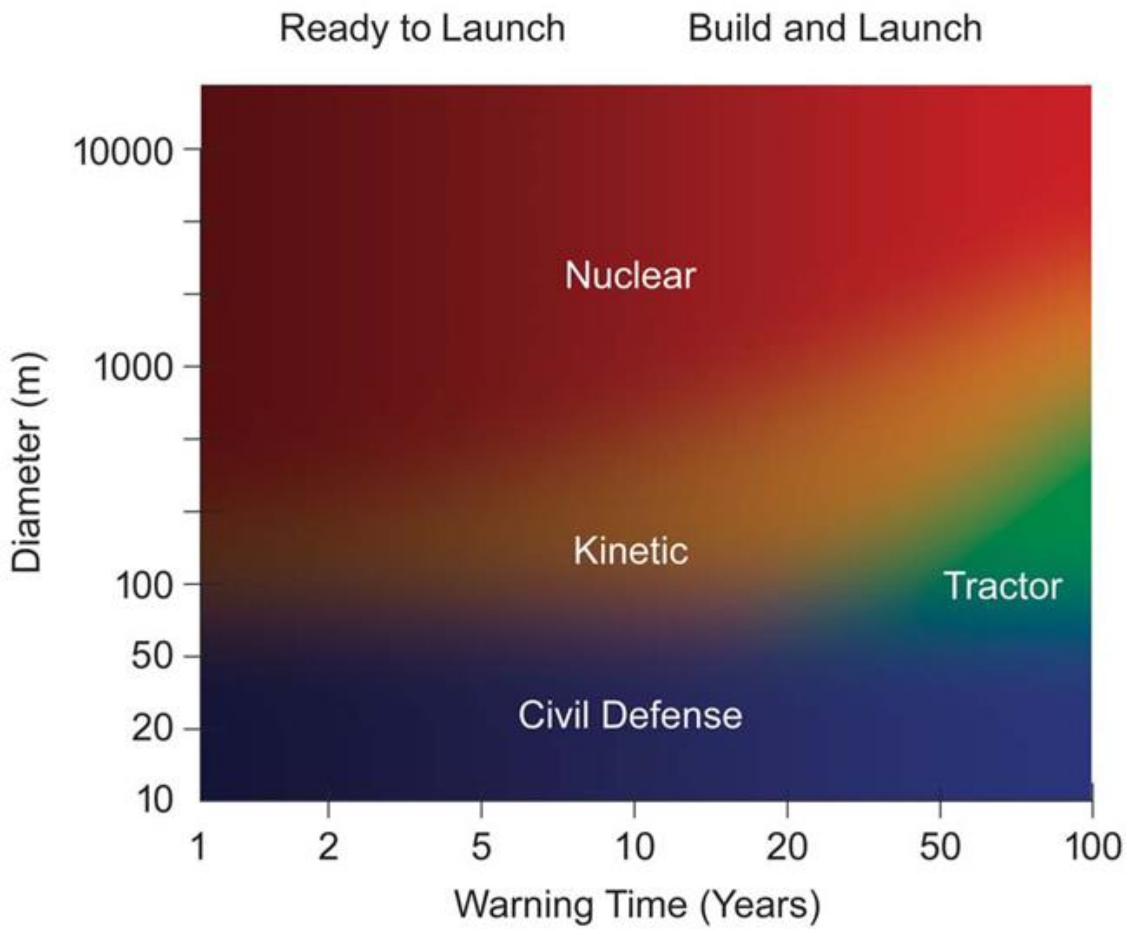
10m impacting body
1/50 years

50m impacting body
1/100 years

10km impacting body
1/100 million years

Small bodies exploration, why?

Defense

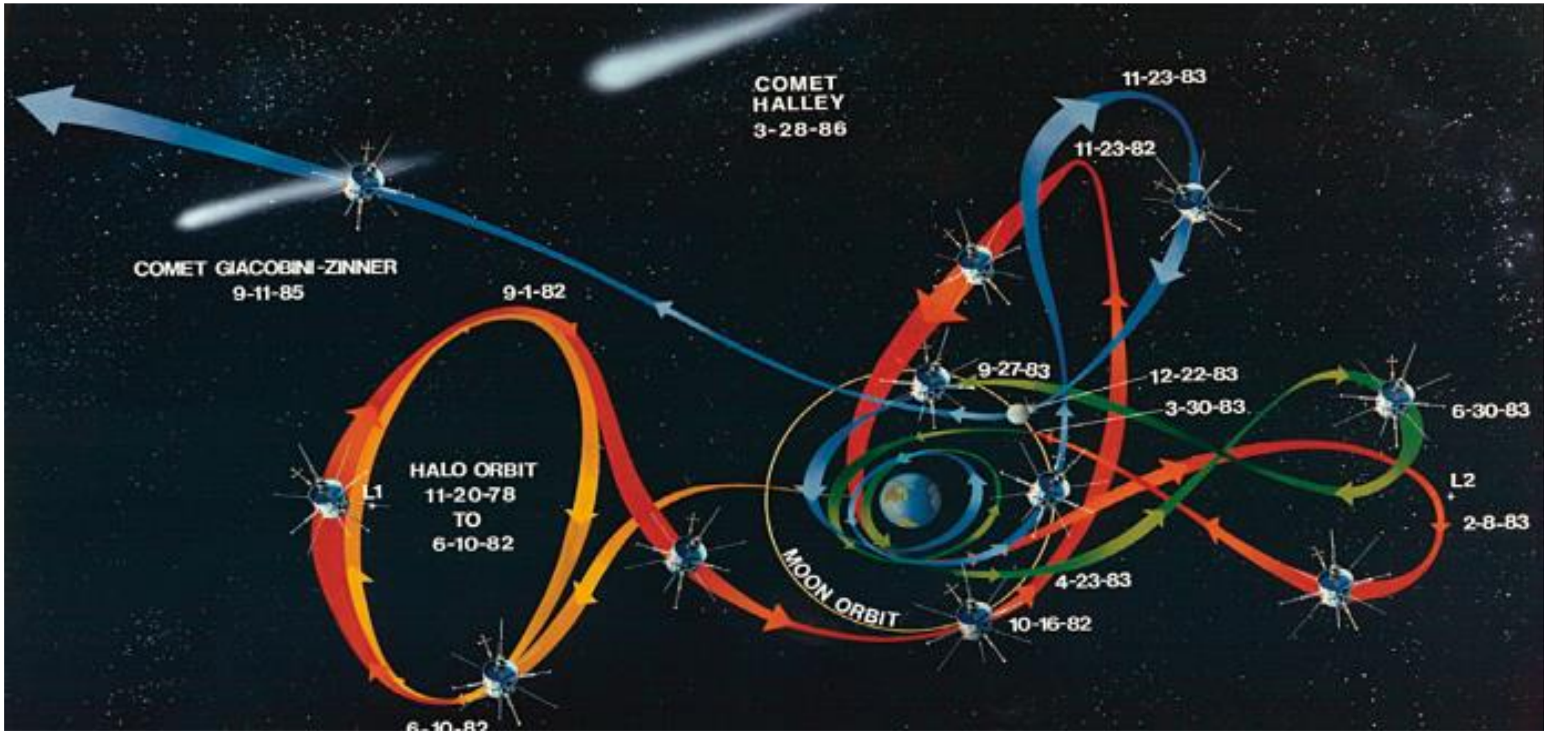


Milestones of small bodies exploration

1985	Fly-by of a comet (ISEE-3)
1991	Fly-by of an asteroid (Galileo)
1998	Orbit around the asteroid 433 Eros (NEAR Shoemaker)
2001	Landing on 433 Eros (NEAR Shoemaker)
2006	Sample return from a comet (Stardust)
2010	Sample return to Earth (Hayabusa)
2014	Orbiting and soft landing on a comet (Rosetta & Philae)
2015	Most distant object visited (New Horizons)
2016	Sample return from Bennu (Osiris-Rex)
2022	Asteroid Deflection (Dart)
2023	Orbit around Psyche in the main belt (Psyche)

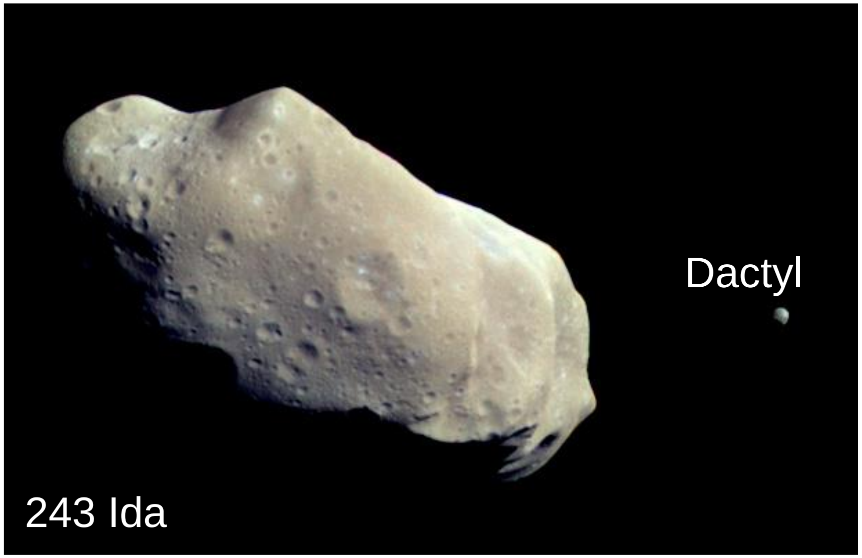
International Sun-Earth Explorer-3 (1978-1997)

1985



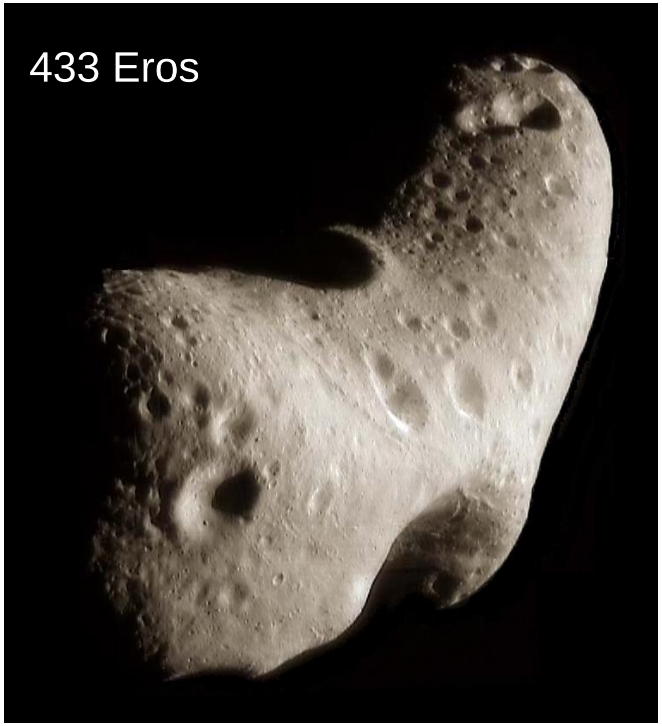
Galileo (1989-2003)

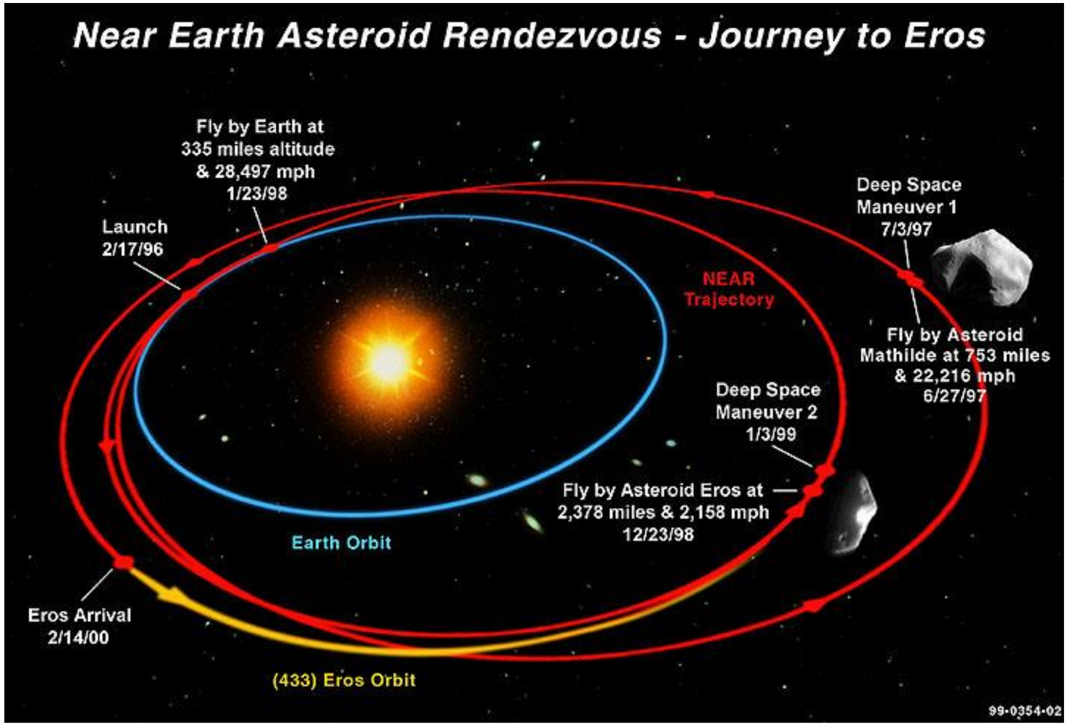
1991



NEAR Shoemaker (1996-2001)

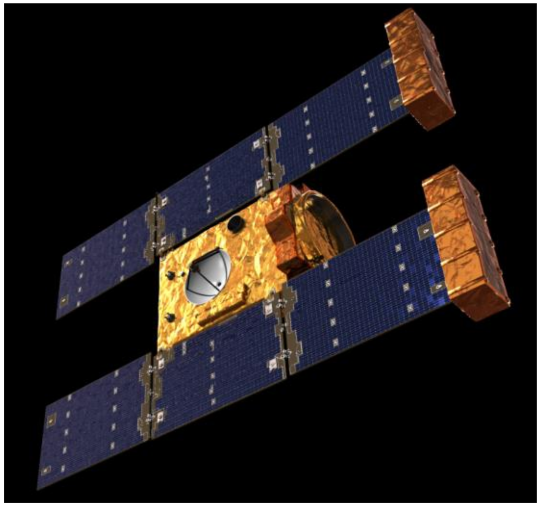
1998

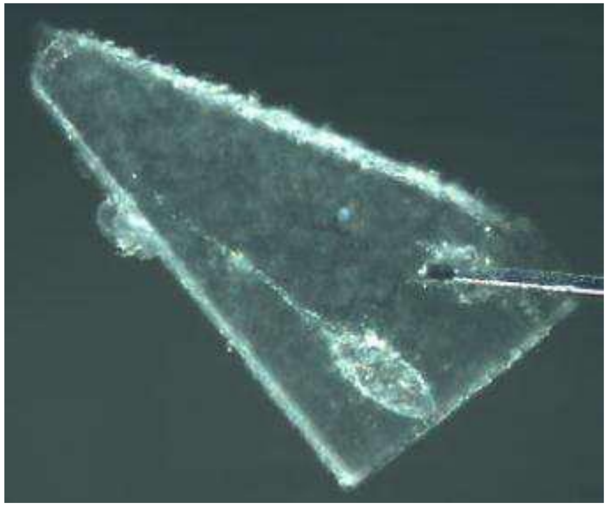




Stardust (1999-2006)

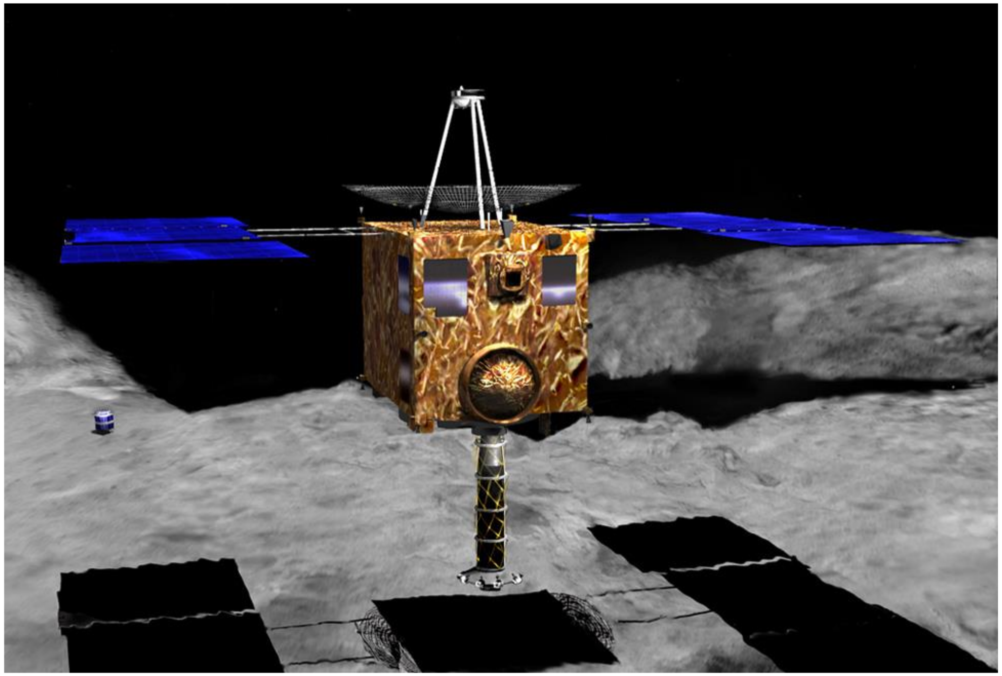
2001





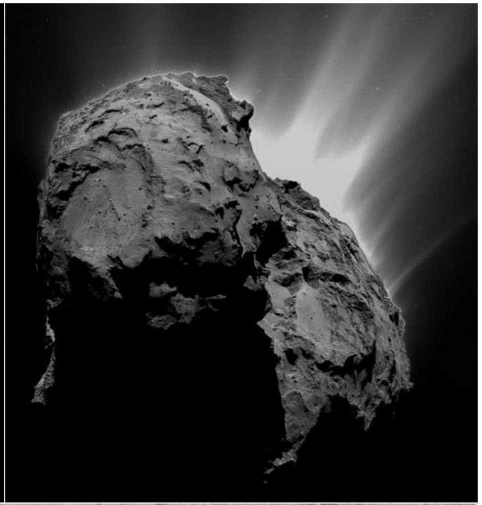
Hayabusa (2003-2010)

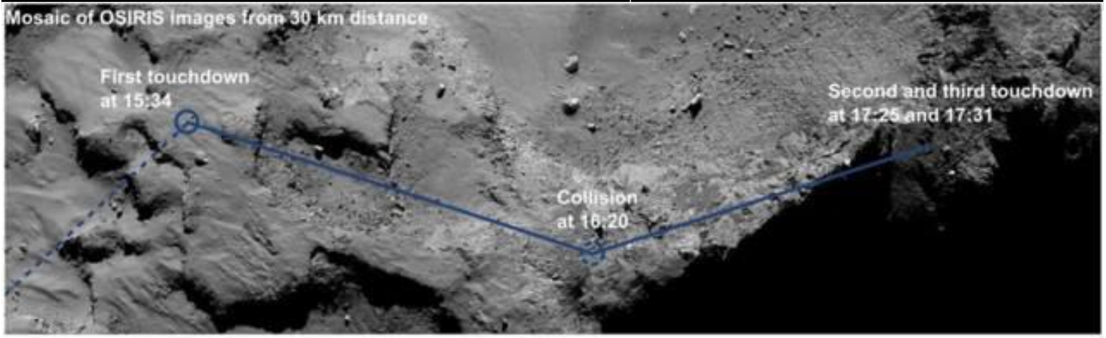
2006

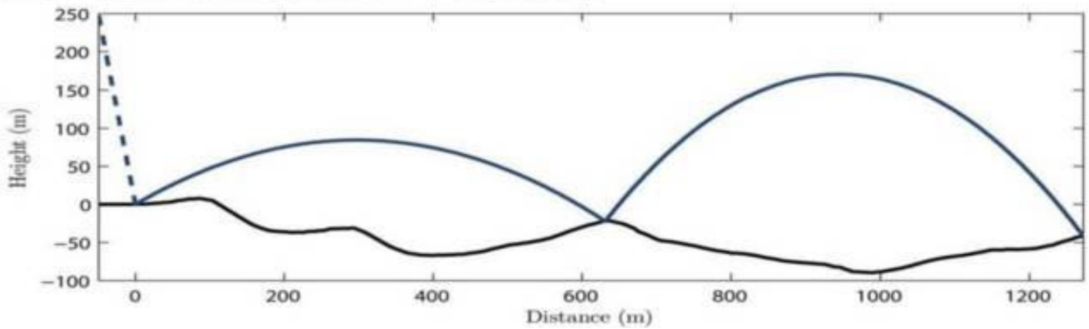


Rosetta (2004-2016)

2010

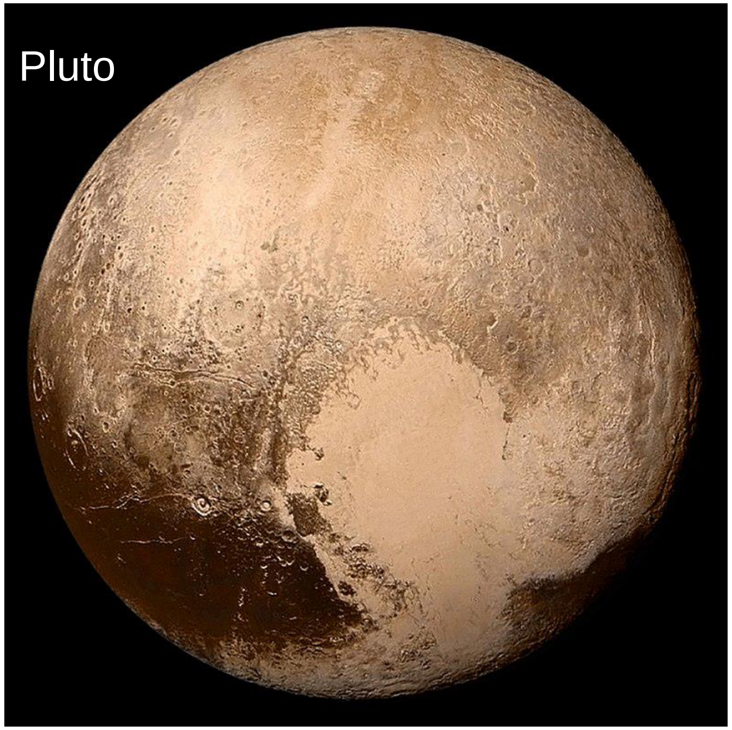


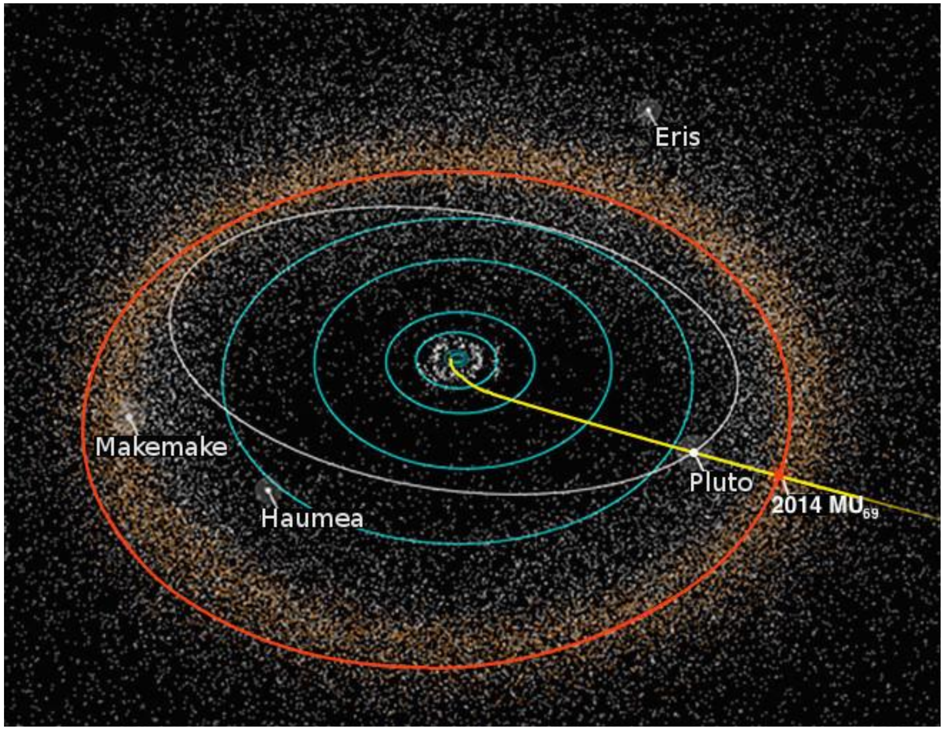




New Horizons (2006-now)

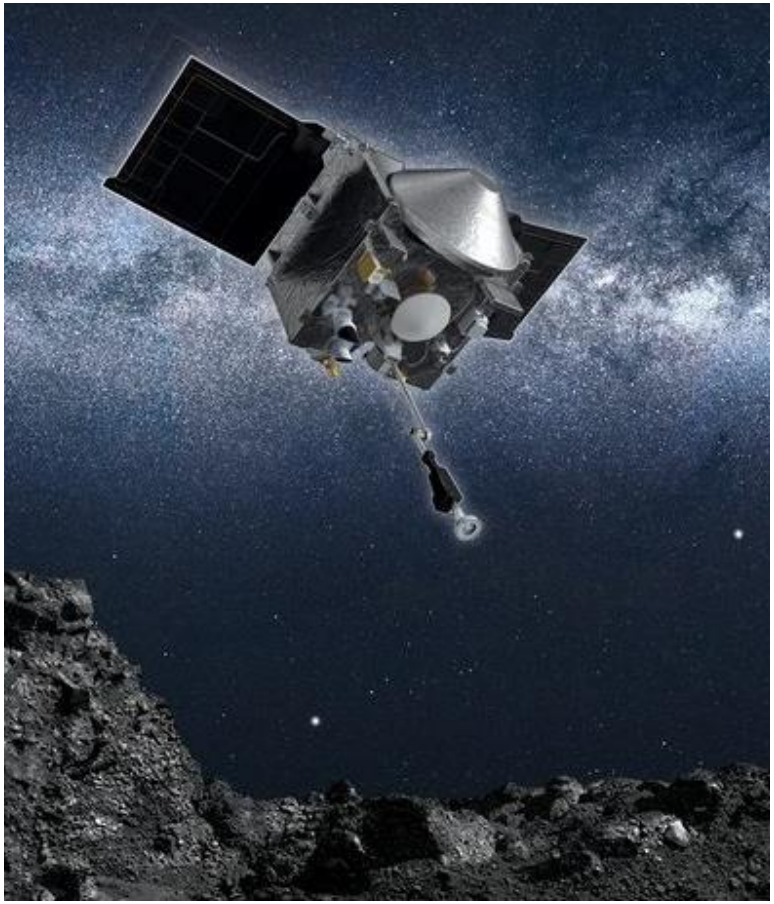
2014

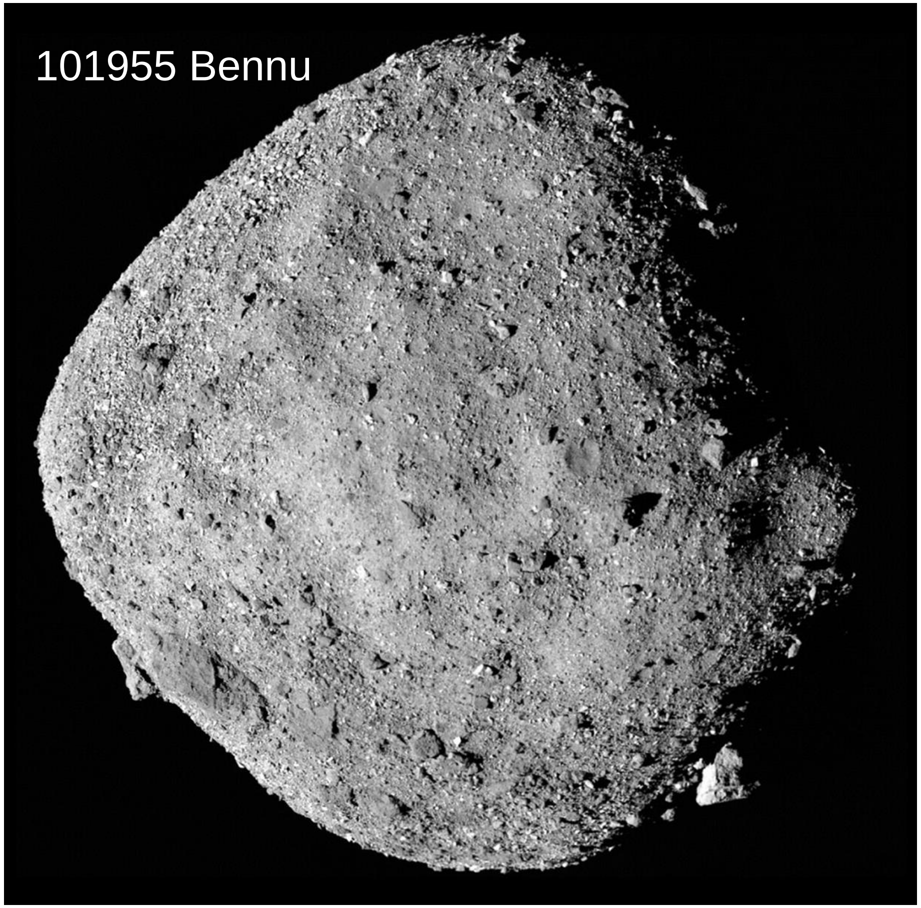




Osiris-REX (2016 – 2023)

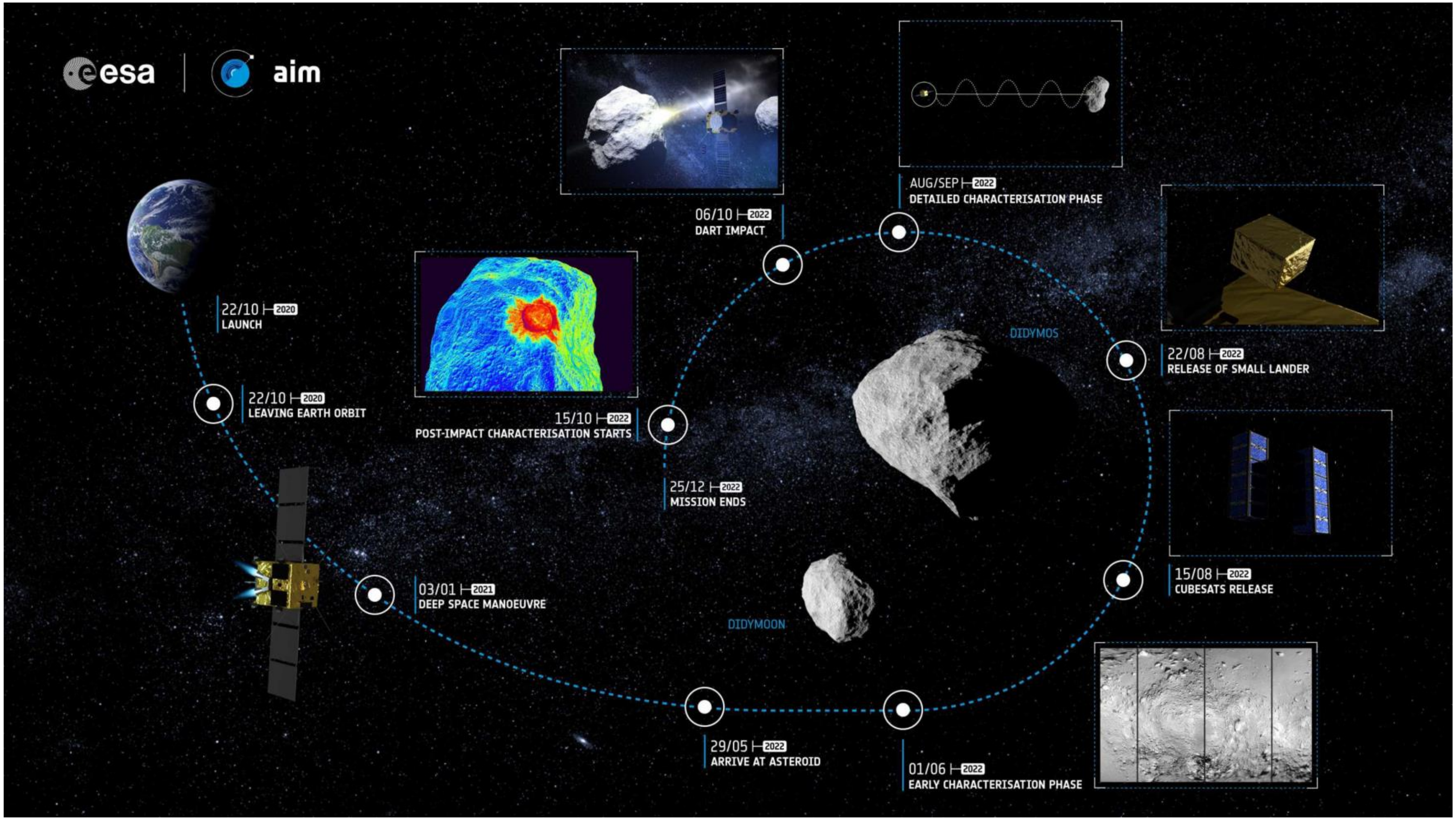
2016





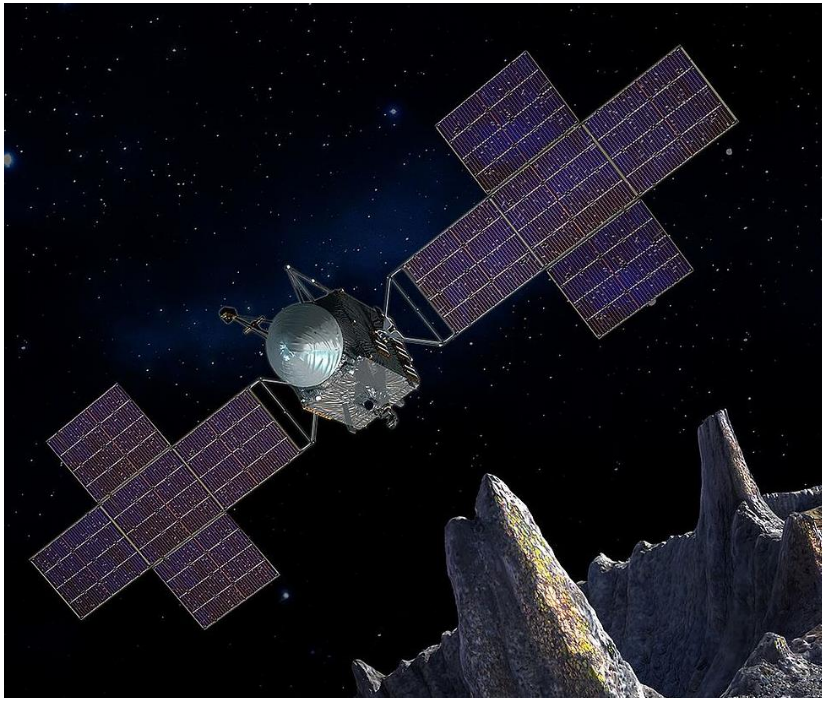
DART (2022-2024)

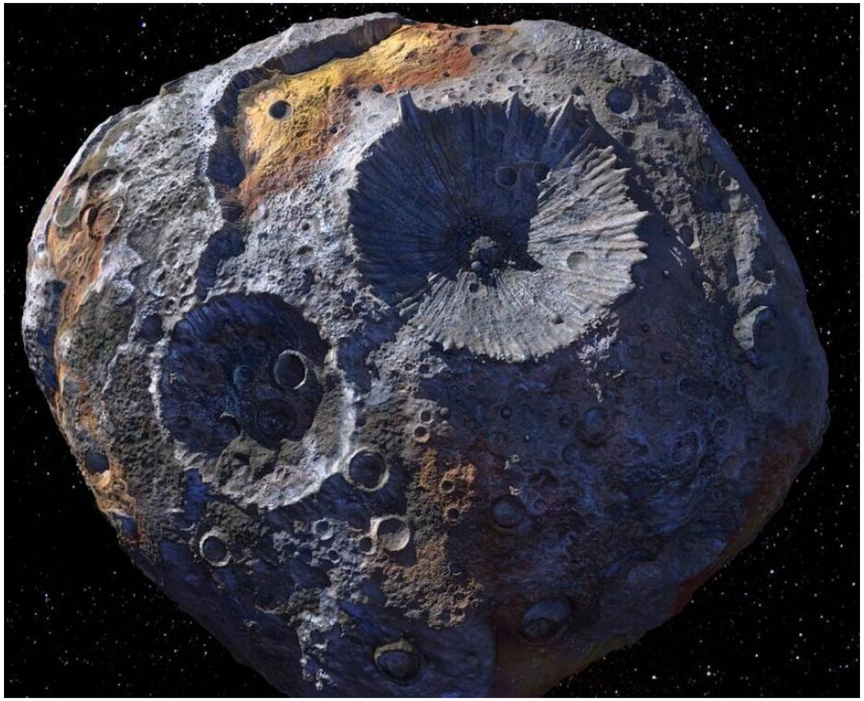
2015



Psyche (2023-…)

2022



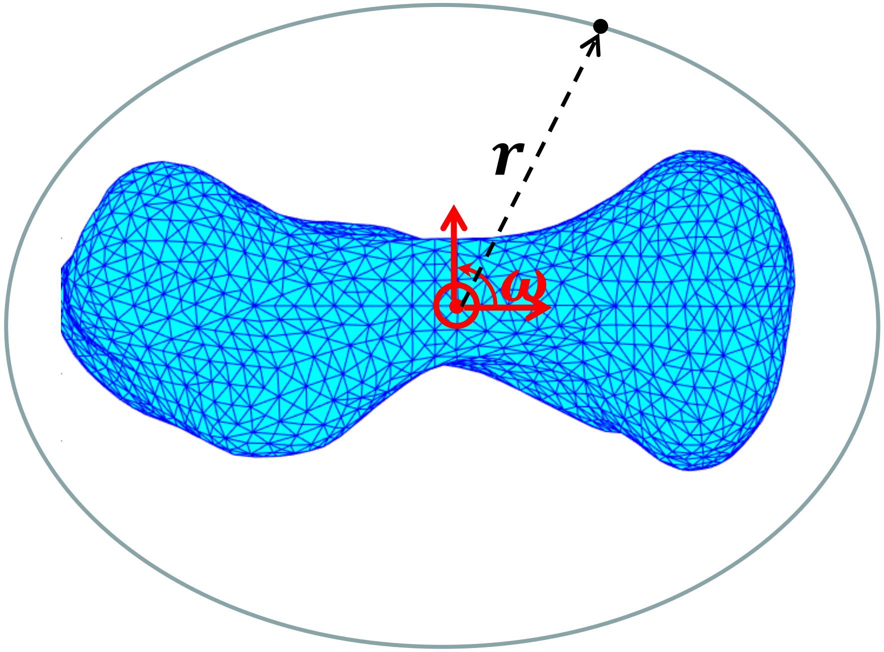


Orbiting an irregular body

The position of a mass-less point, $\boldsymbol{r}$, with respect to the center of mass of an irregular body in space depends of 2 factors.

The angular velocity of the body around its main inertia axis.

And the gravity potential of the body which is directly linked to its mass.



Equations of motion

$$\ddot{\boldsymbol{x}} + 2\boldsymbol{\omega_A} \times \dot{\boldsymbol{x}} + \boldsymbol{\omega_A} \times (\boldsymbol{\omega_A} \times \boldsymbol{x}) + \nabla U(x) = \mathbf{0}$$

$\ddot{\boldsymbol{x}}$ = the acceleration

$2\boldsymbol{\omega_A} \times \dot{\boldsymbol{x}}$ = Coriolis force

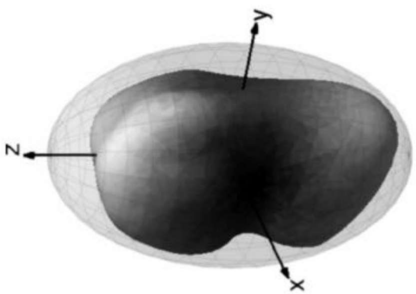
$\boldsymbol{\omega_A} \times (\boldsymbol{\omega_A} \times \boldsymbol{x})$ = centrifugal force

$\nabla U(x)$ = the gradient of the gravity potential

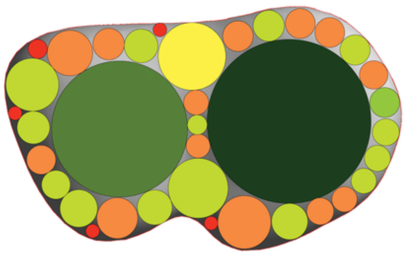
Gradient of the potential

$$\ddot{\boldsymbol{x}} + 2\boldsymbol{\omega}_A \times \dot{\boldsymbol{x}} + \boldsymbol{\omega}_A \times (\boldsymbol{\omega}_A \times \boldsymbol{x}) + \nabla U(x) = \mathbf{0}$$

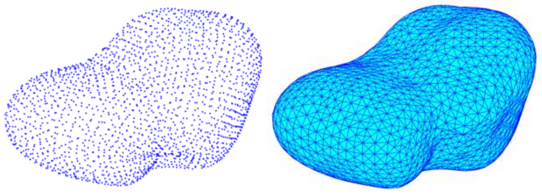
Spherical harmonic model



Mass concentration

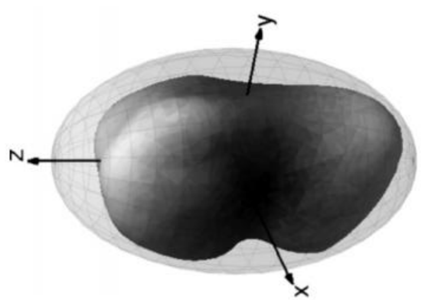


Polyhedrons



Spherical harmonic

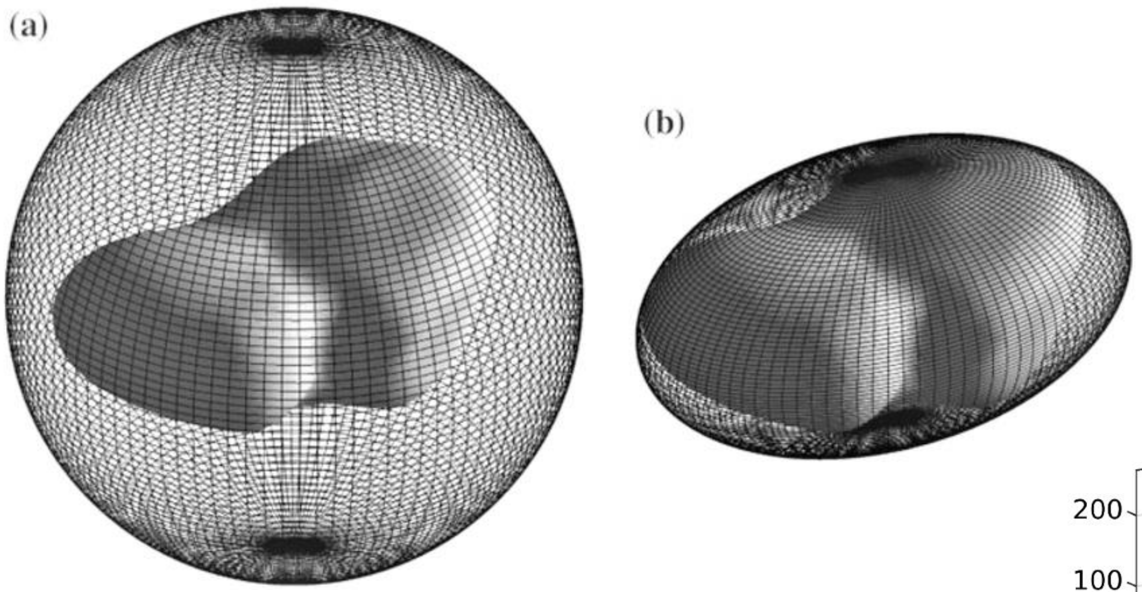
Spherical harmonic model

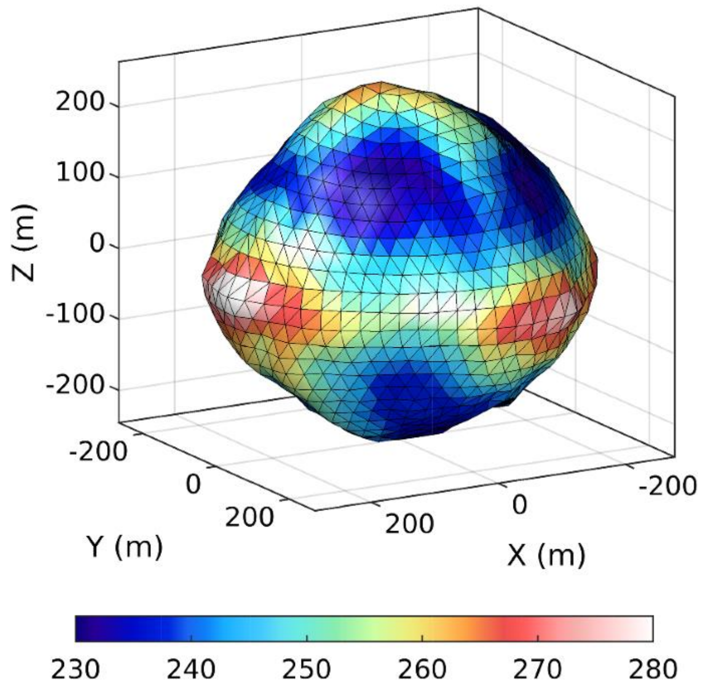


Spherical harmonics are straightforward and not computationally demanding but not very accurate for irregular bodies.

$$U = \frac{GM}{R} \sum_{n=0}^{\infty} \sum_{m=0}^{n} \left(\frac{R}{r}\right)^{n+1} P_{nm}(\sin\theta) \begin{bmatrix} \cos(m\lambda) \\ \sin(m\lambda) \end{bmatrix} \cdot \begin{bmatrix} C_{nm} \\ S_{nm} \end{bmatrix}$$

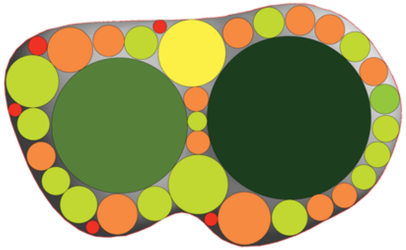
Spherical harmonic





Mascons

Mass concentration



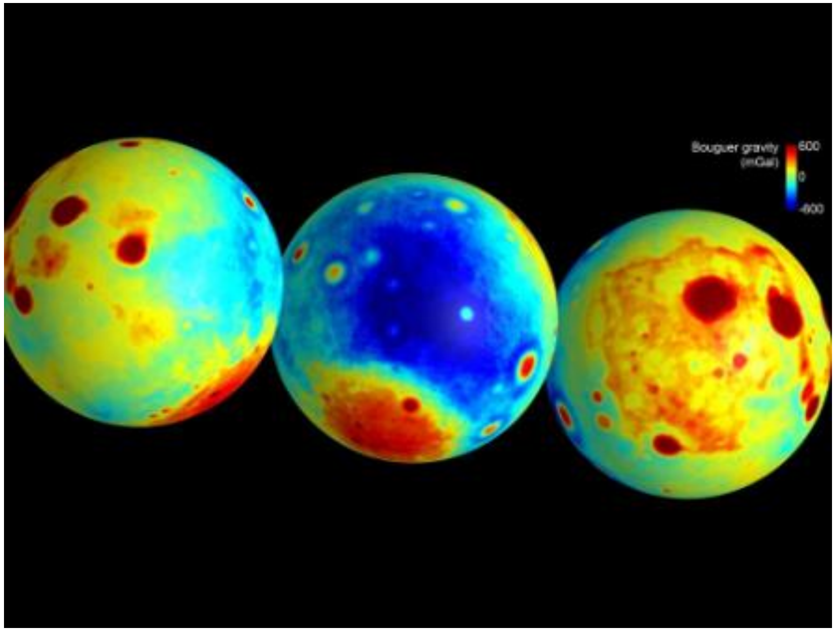
Simple representation but allows to represent the internal density distribution. The resolution depends on the number of masses considered.

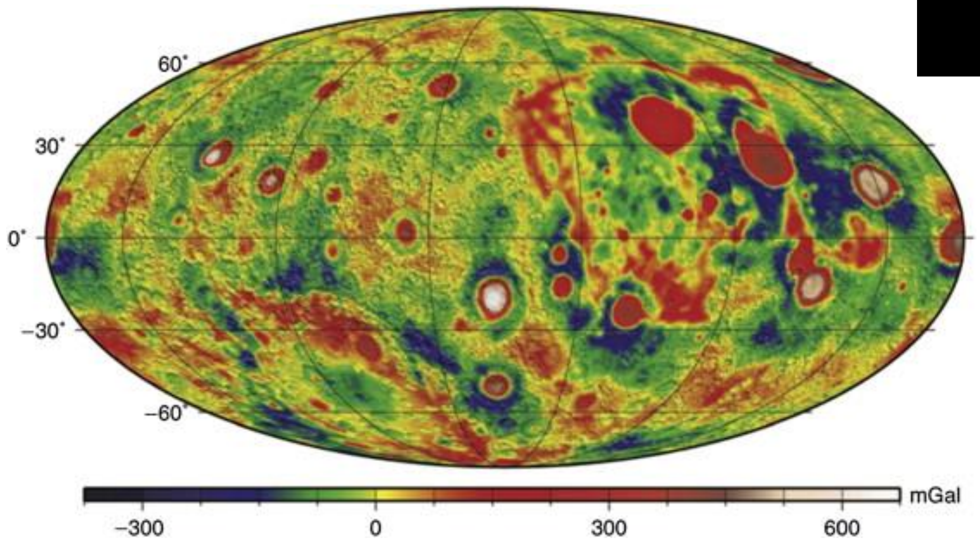
$$U = G \sum_{i=0}^{N} \frac{m_i}{|\boldsymbol{r} - \boldsymbol{r}_i|}$$

Moon’s Lumpy Gravity

Mascons were discovered during the planning for Apollo moon missions.

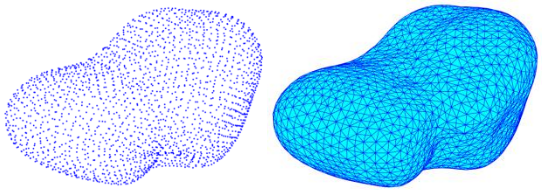
They are the results of asteroids impacts. The heat melt the moon rocks into denser parts.





Polyhedrons

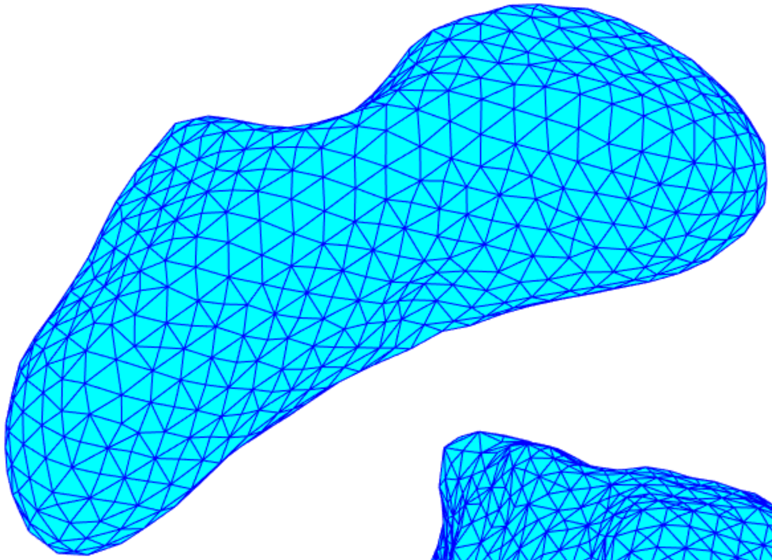
Polyhedrons

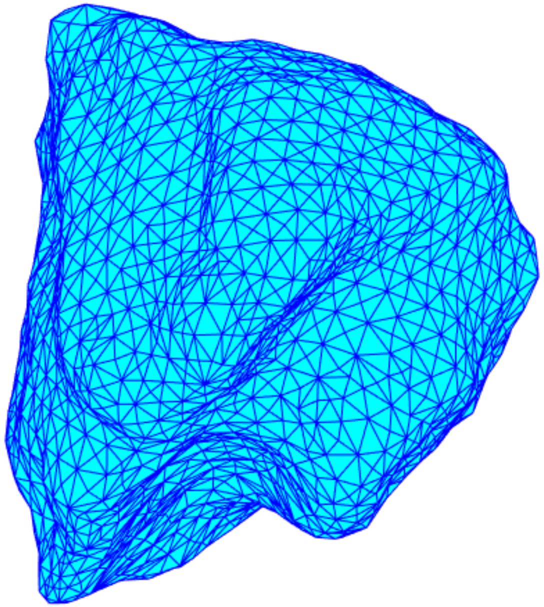


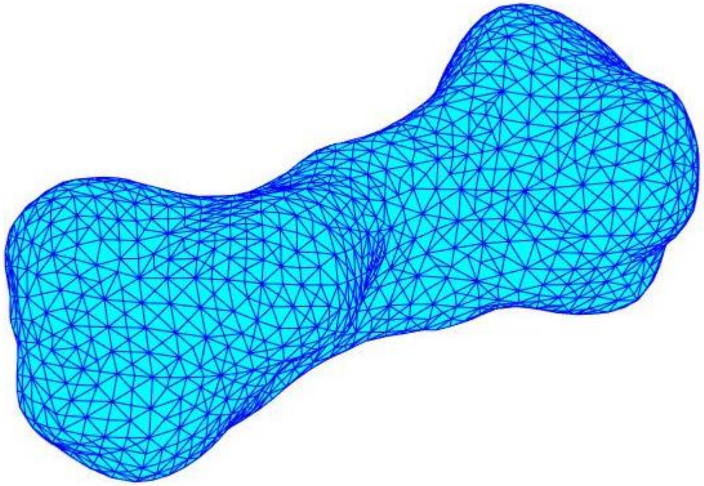
Analytical expression for the potential of an arbitrary polyhedron. Highly accurate but computationally intensive.

$$U = \frac{1}{2} G\rho \sum_{e} \boldsymbol{r}_e \cdot \boldsymbol{E}_e \cdot \boldsymbol{r}_e \cdot L_e - \frac{1}{2} G\rho f \sum \boldsymbol{r}_f \cdot \boldsymbol{F}_f \cdot \boldsymbol{r}_f \cdot \omega_f$$

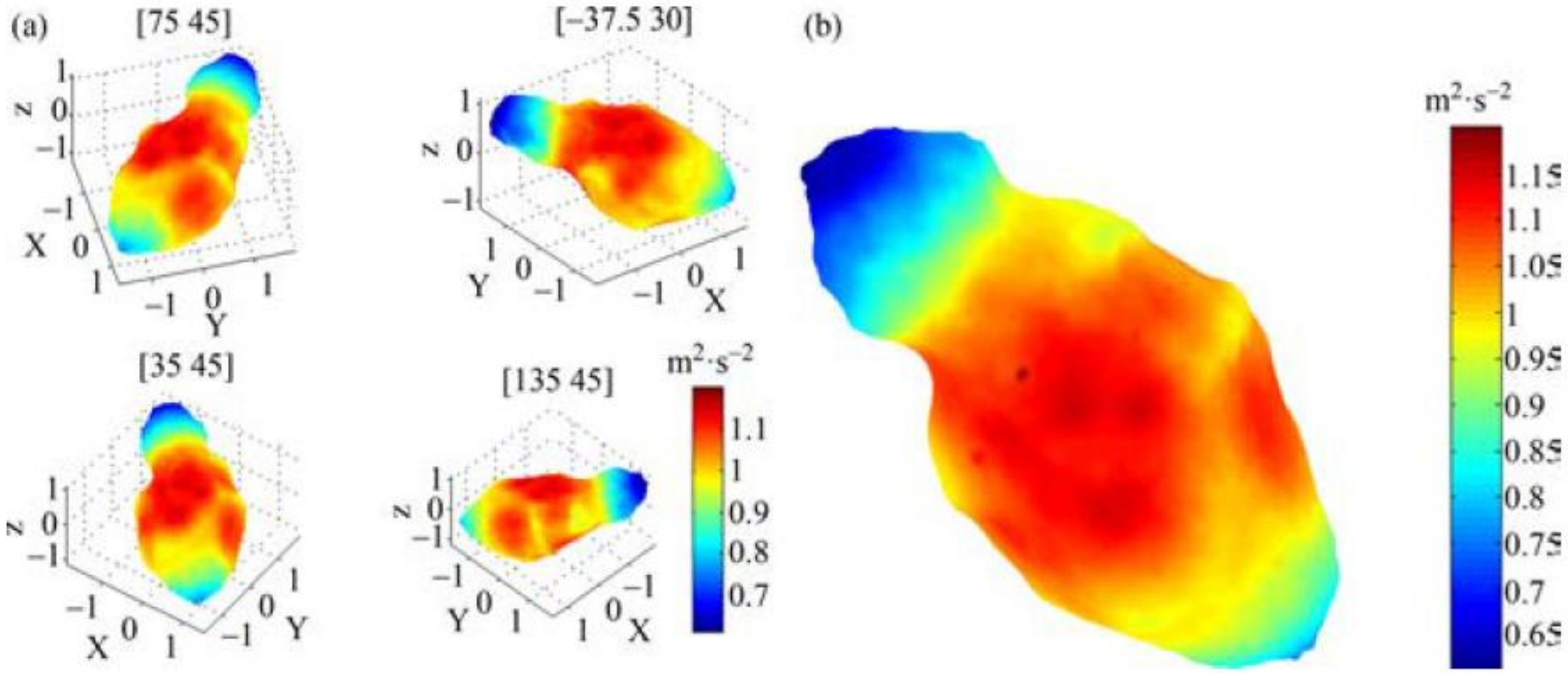
All kind of meshes



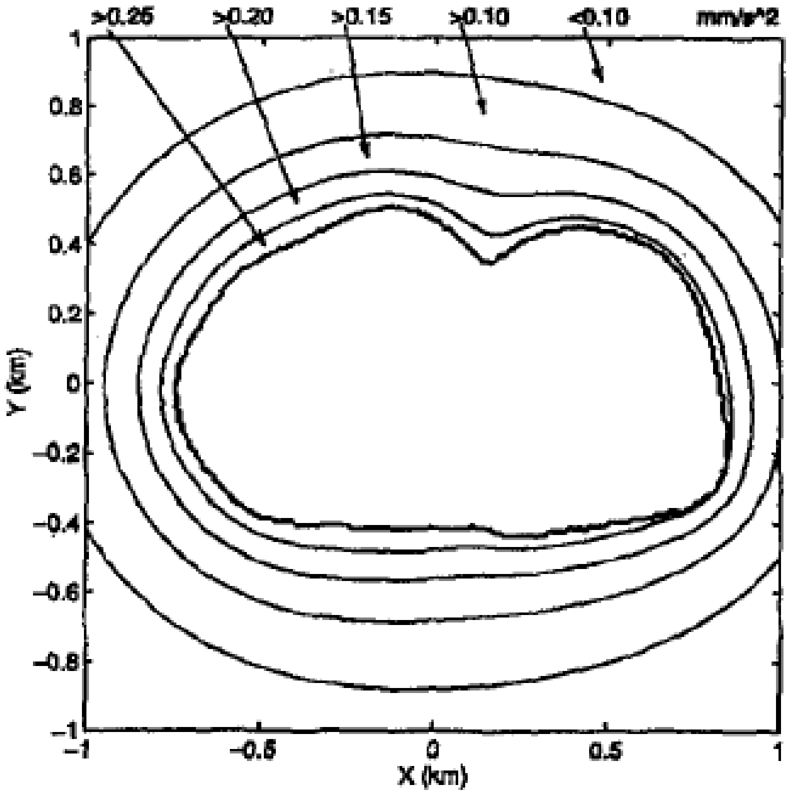


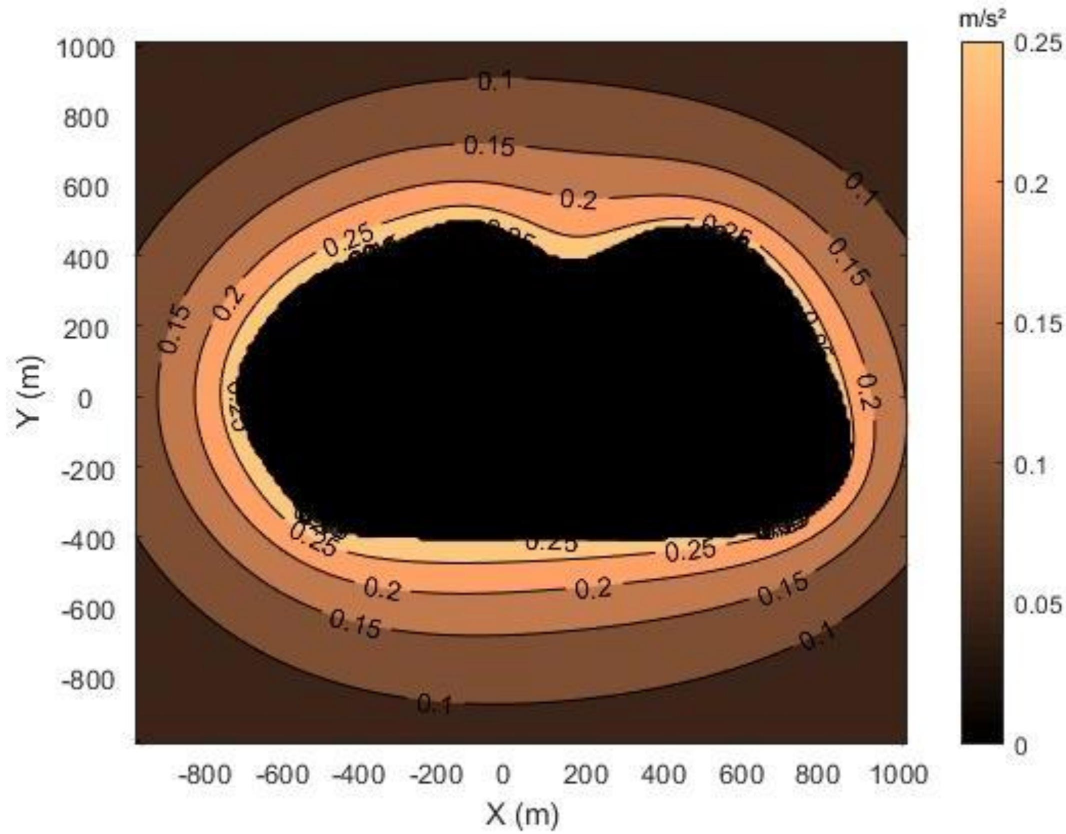


Surface potential

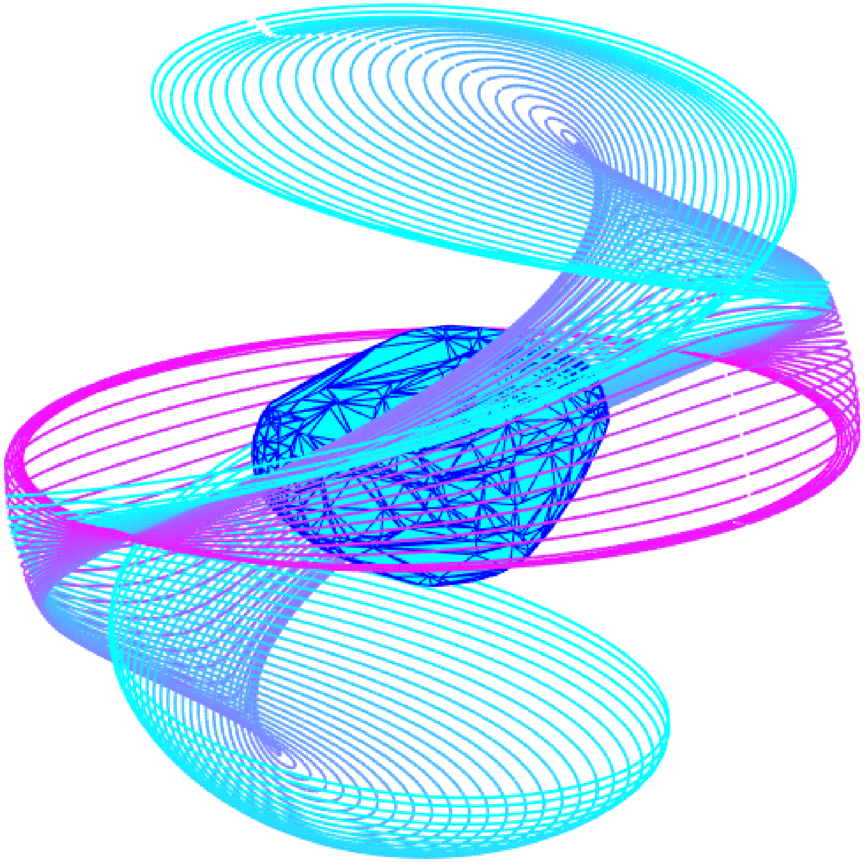


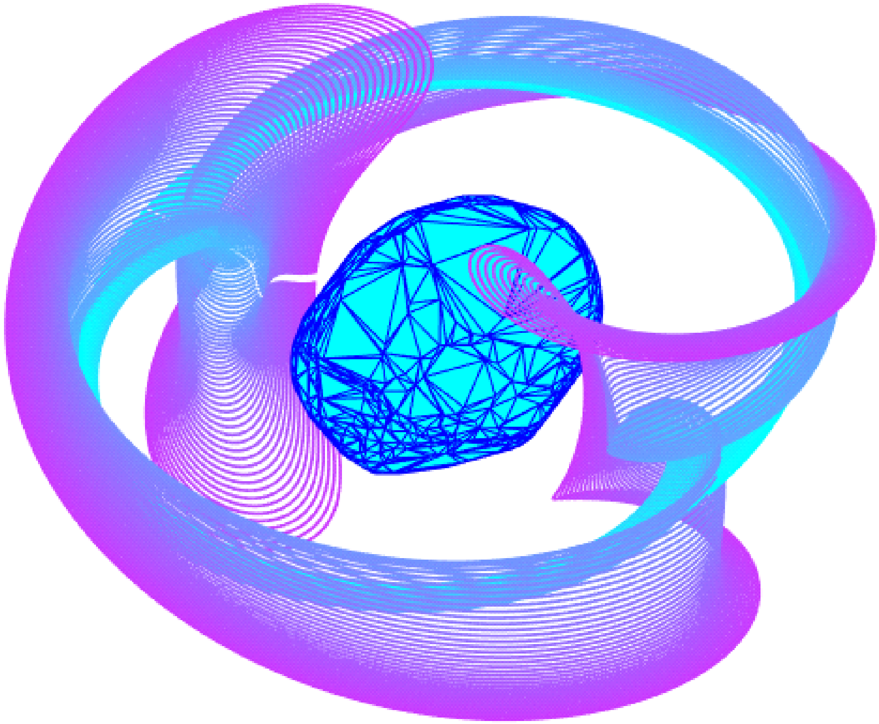
Gravity potential





Orbits shapes





Conclusions

Missions to small bodies are complex and challenging

Complex shape and weak gravity strongly perturb asteroid’s dynamical environment

Growing interest for asteroid missions and increasing ambitions for the future plans

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(AERO0024)

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