Celestial and Spaceflight Mechanics Laboratory

Orbital Dynamics Around Asteroids

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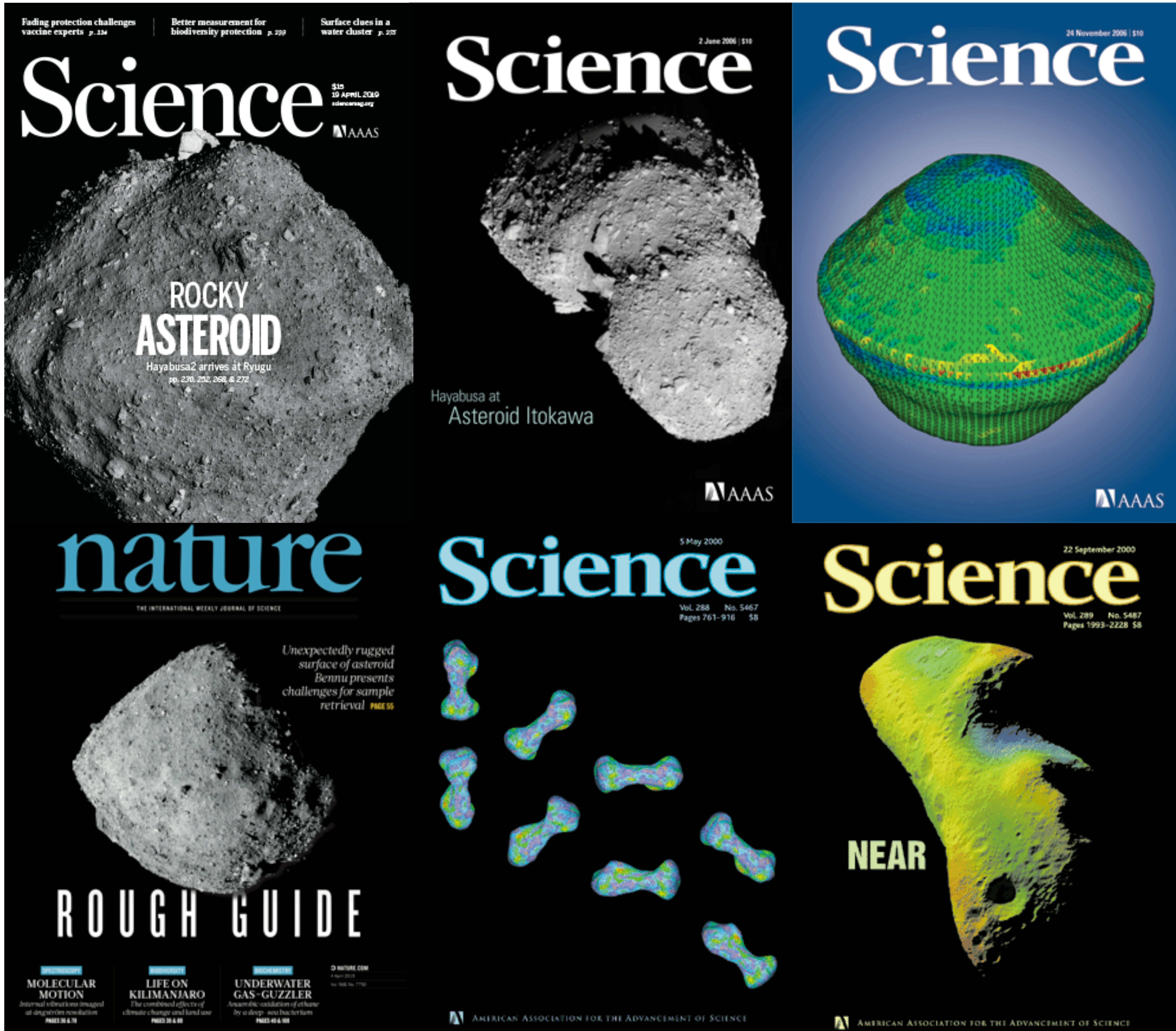
Why are we interested?

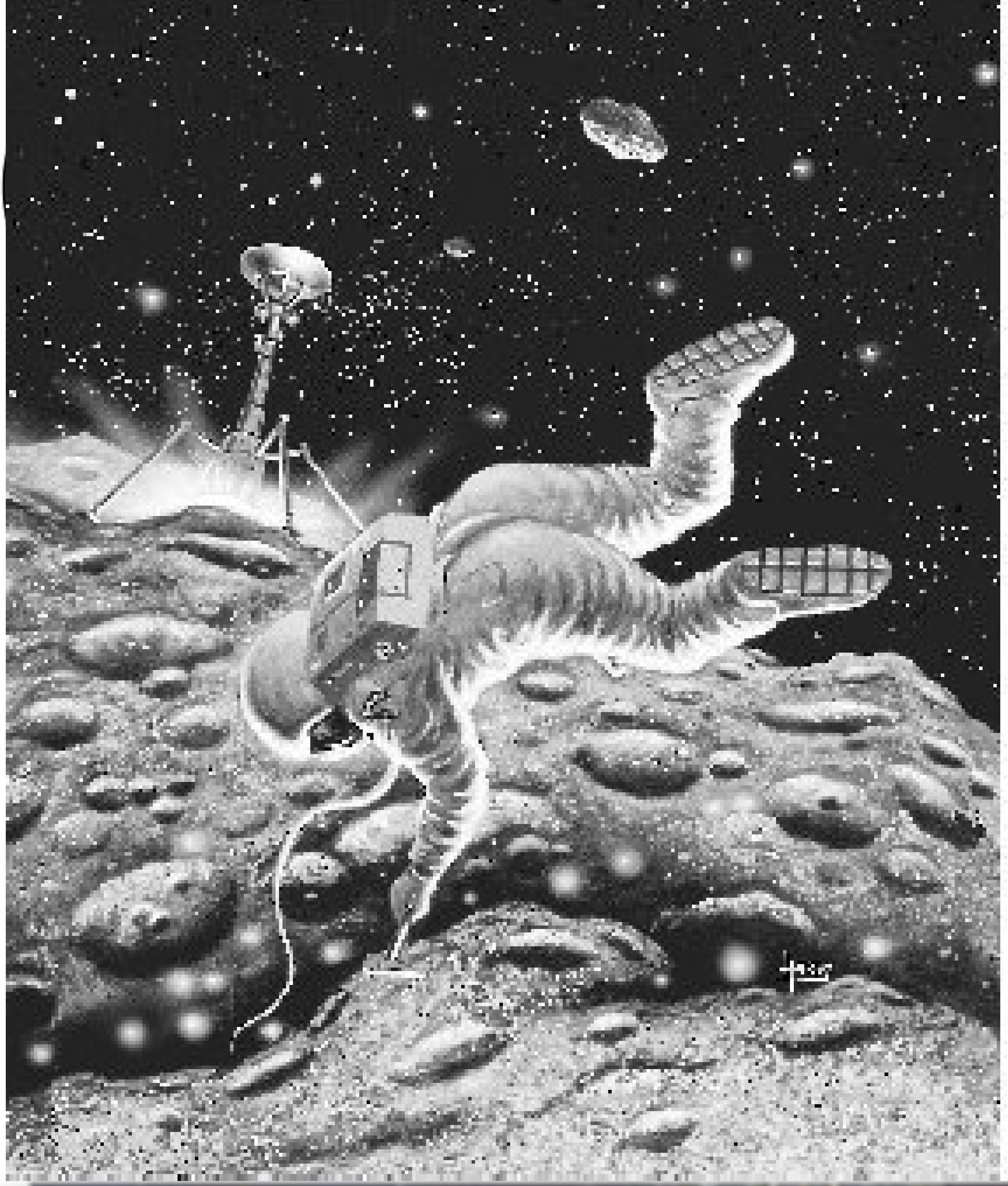
Why are we interested? *Science*

– Small bodies are “remnants” of the early solar system.
  - Their retain material that dates back to the solar system’s formation.
  - They act as “tracer particles” that record how the major planets move over time.

– They have shaped life on Earth.
  - By delivering water and minerals in the early history of the Earth.
  - By causing occasional wide-spread extinctions due to their impact.

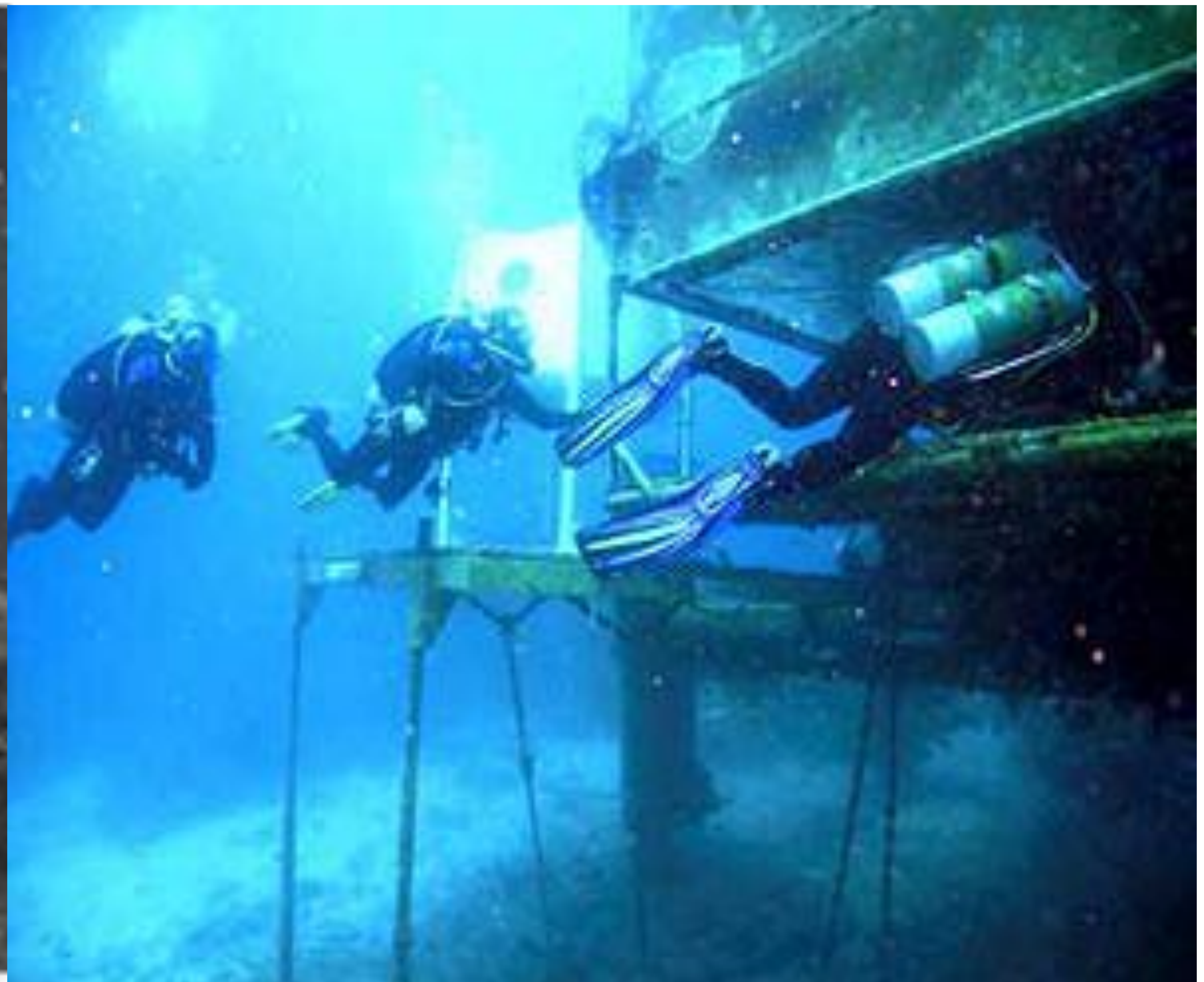
– They are a unique form of matter.
  - Their physics is controlled by a balance of gravity, molecular and inertial forces.
  - Their study can lead to new insights on planetary rings, protoplanetary discs, and other extreme types of matter.

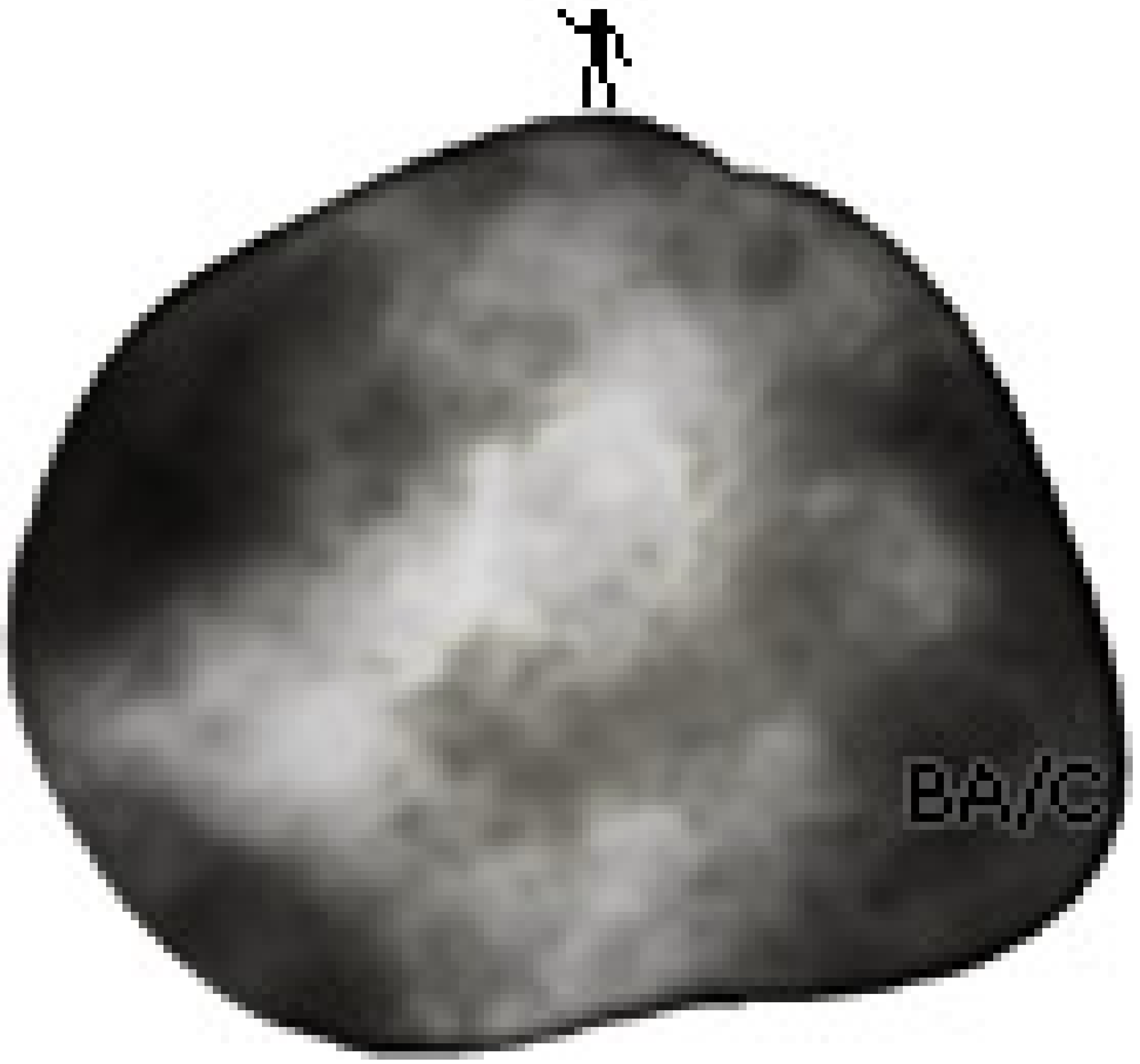




Why are we interested?
Human Exploration

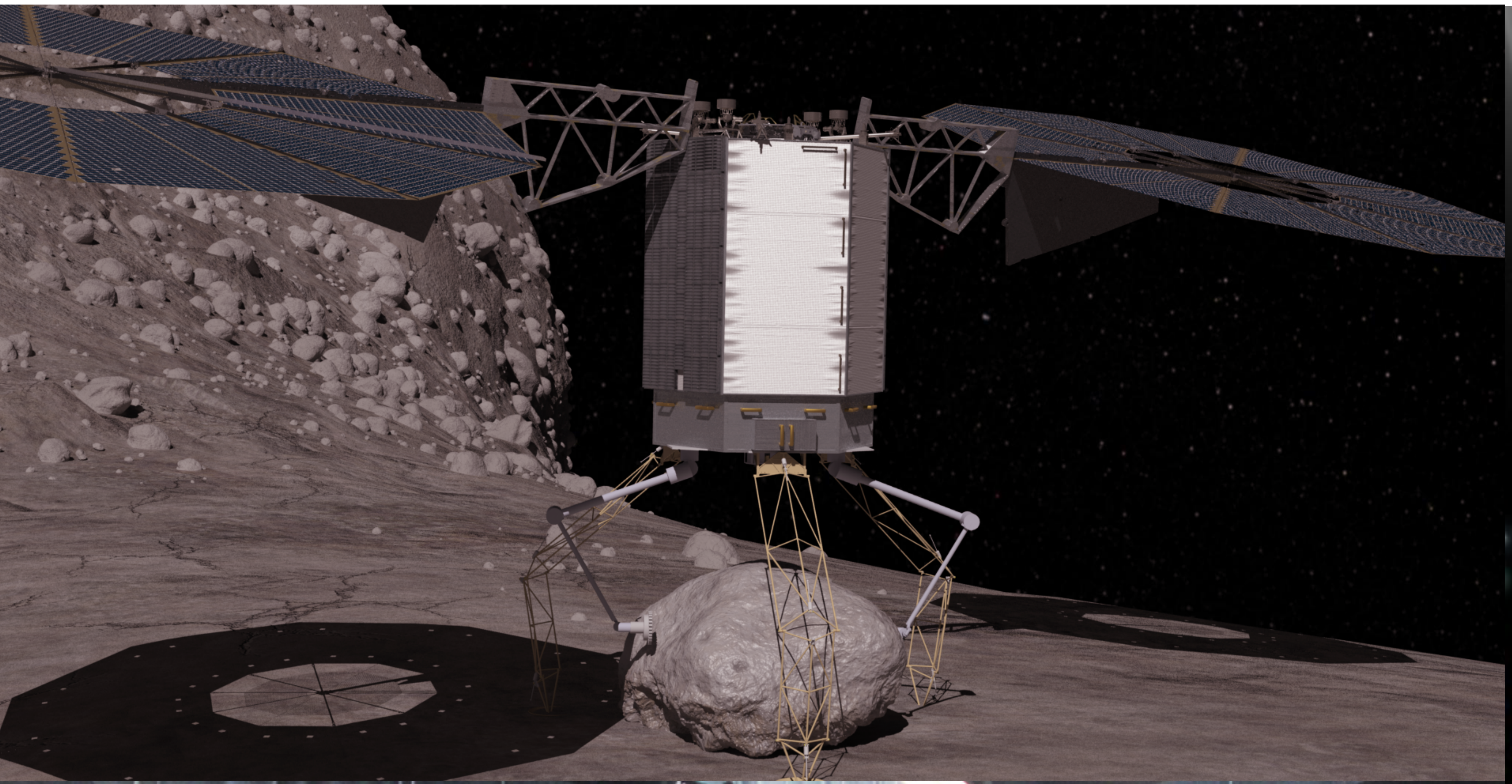
- Near Earth Asteroids are a natural destination for future human exploration missions.
- A human mission to an asteroid can be a “test run” for a Mars mission.
- Have been seriously considered by NASA for human exploration.

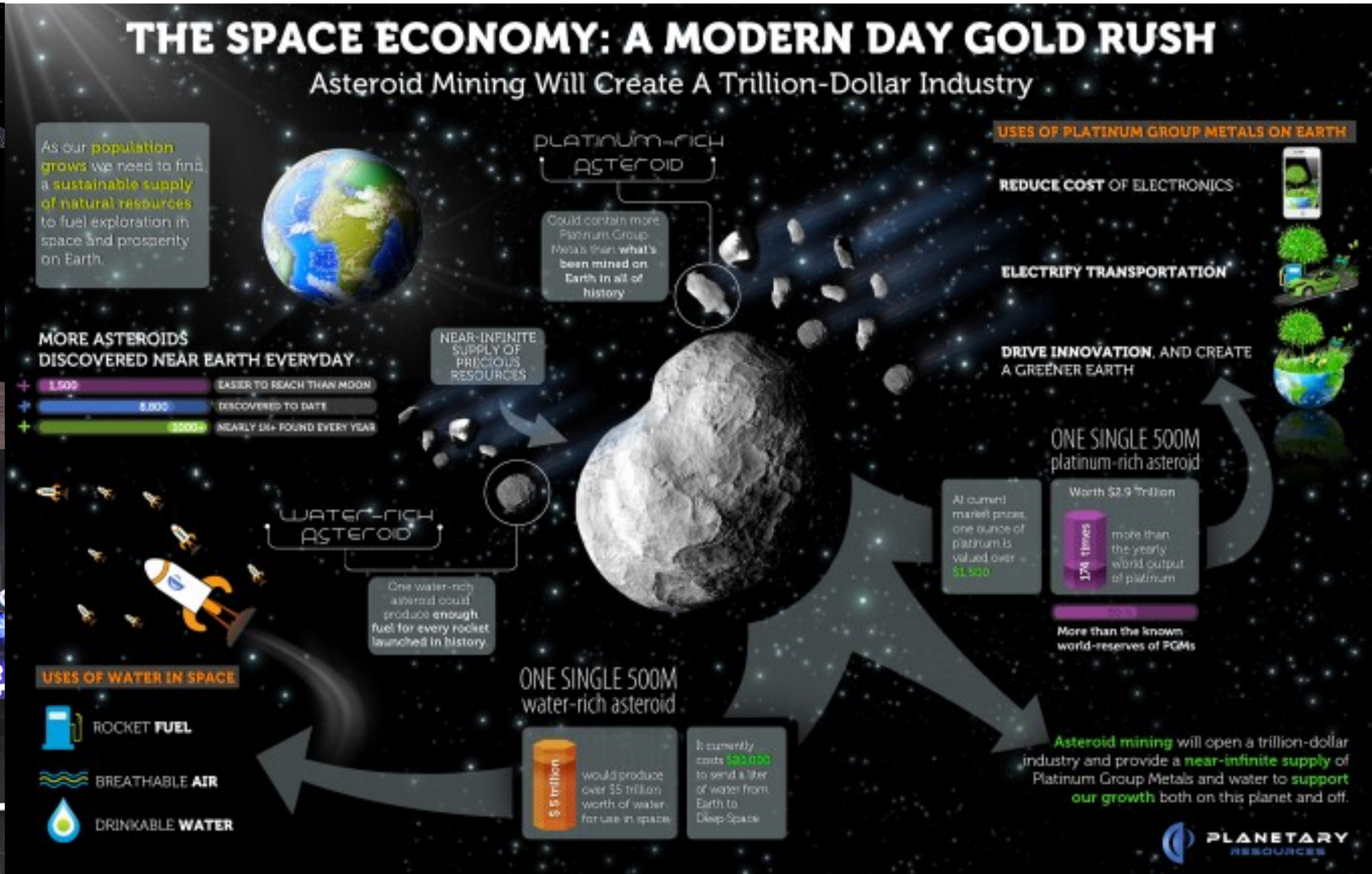




Why are we interested?
Resource Exploitation

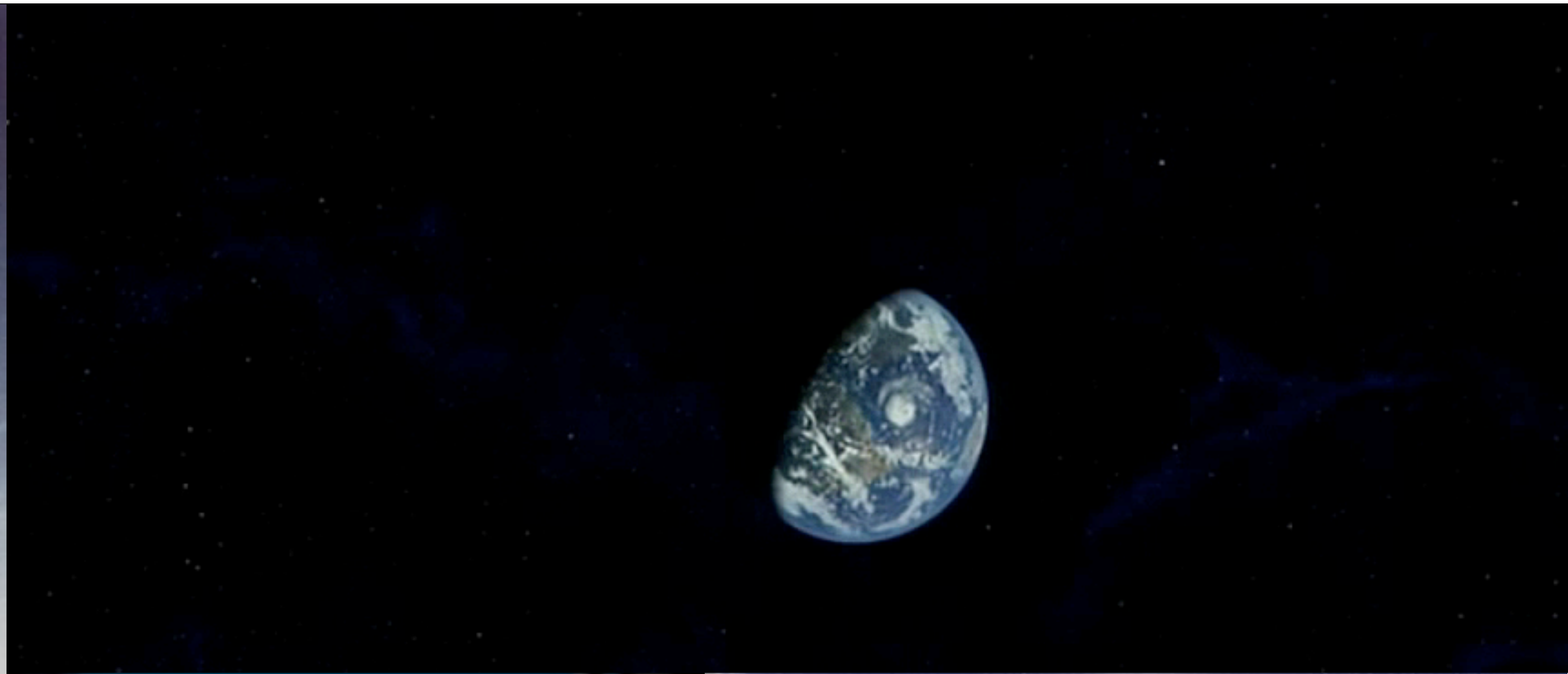
- Has been considered as Sci-Fi for years… but has recently spawned new industries and interest in NASA.



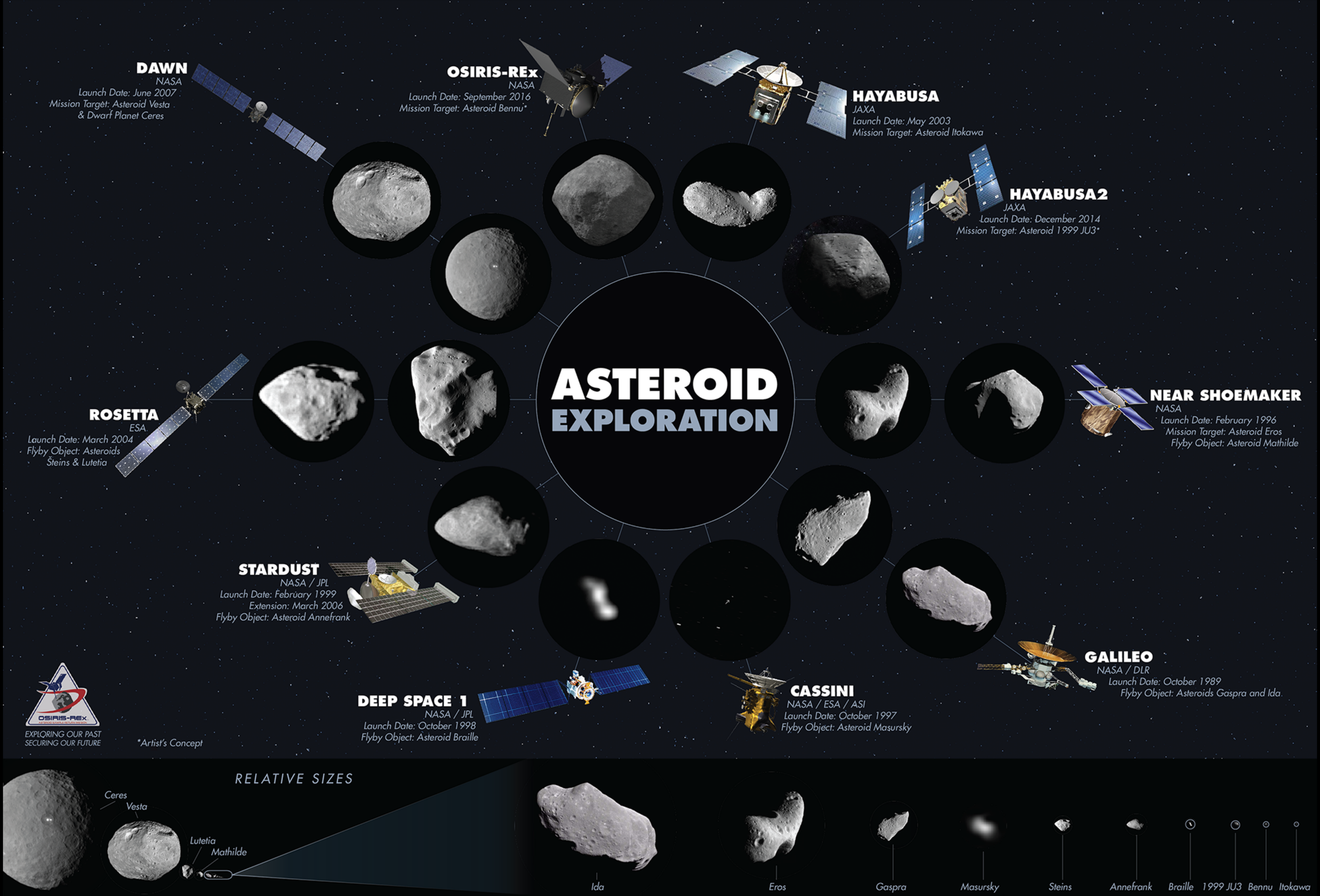


Why are we interested? *Society*

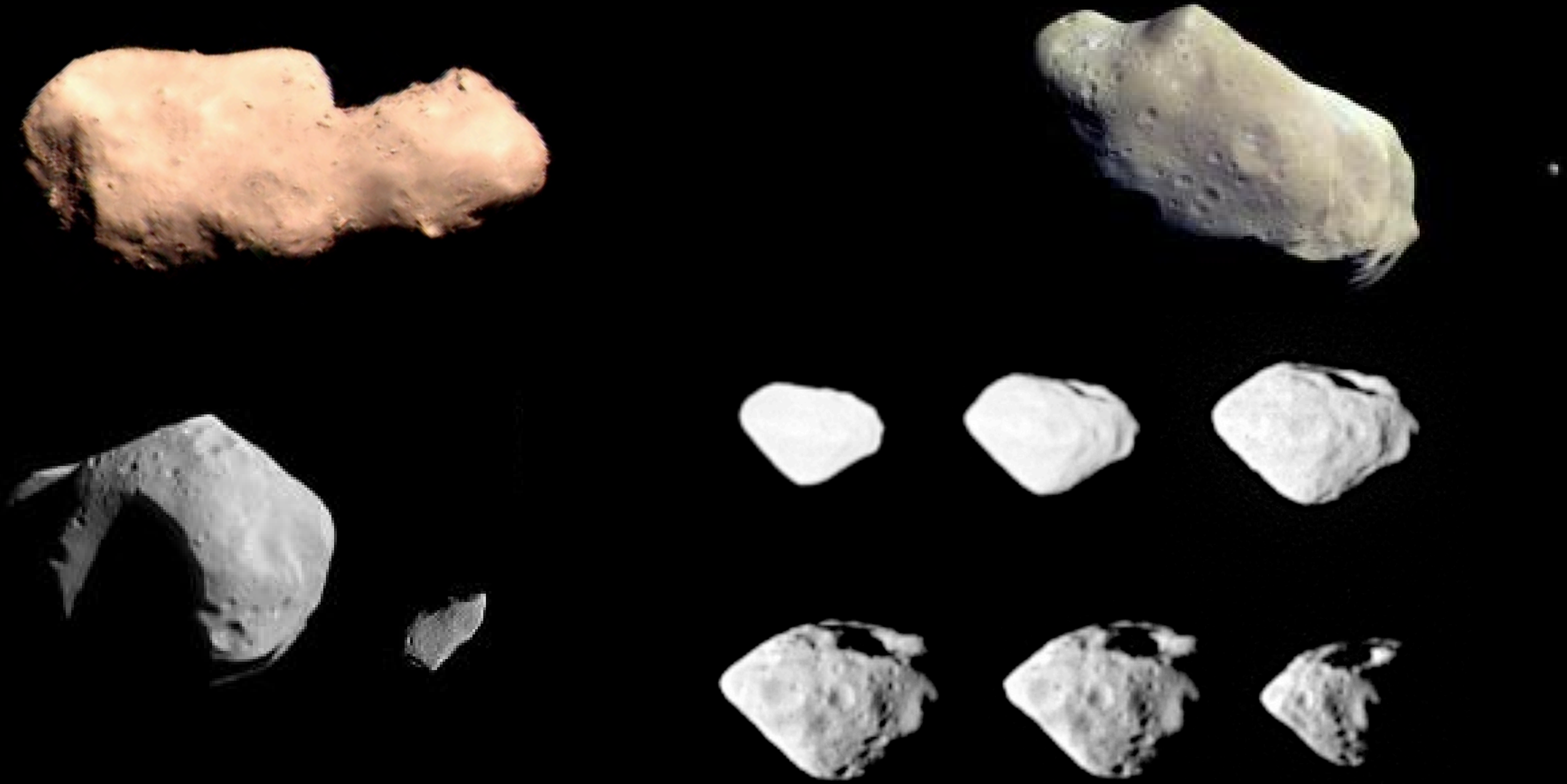
- Small bodies continually impact the Earth (e.g., shooting stars, Chelyabinsk)
- Have caused large-scale extinctions in the past (e.g., the dinosaurs)
- If one were detected on a collision course, could we stop it?



Which Asteroids have we explored?

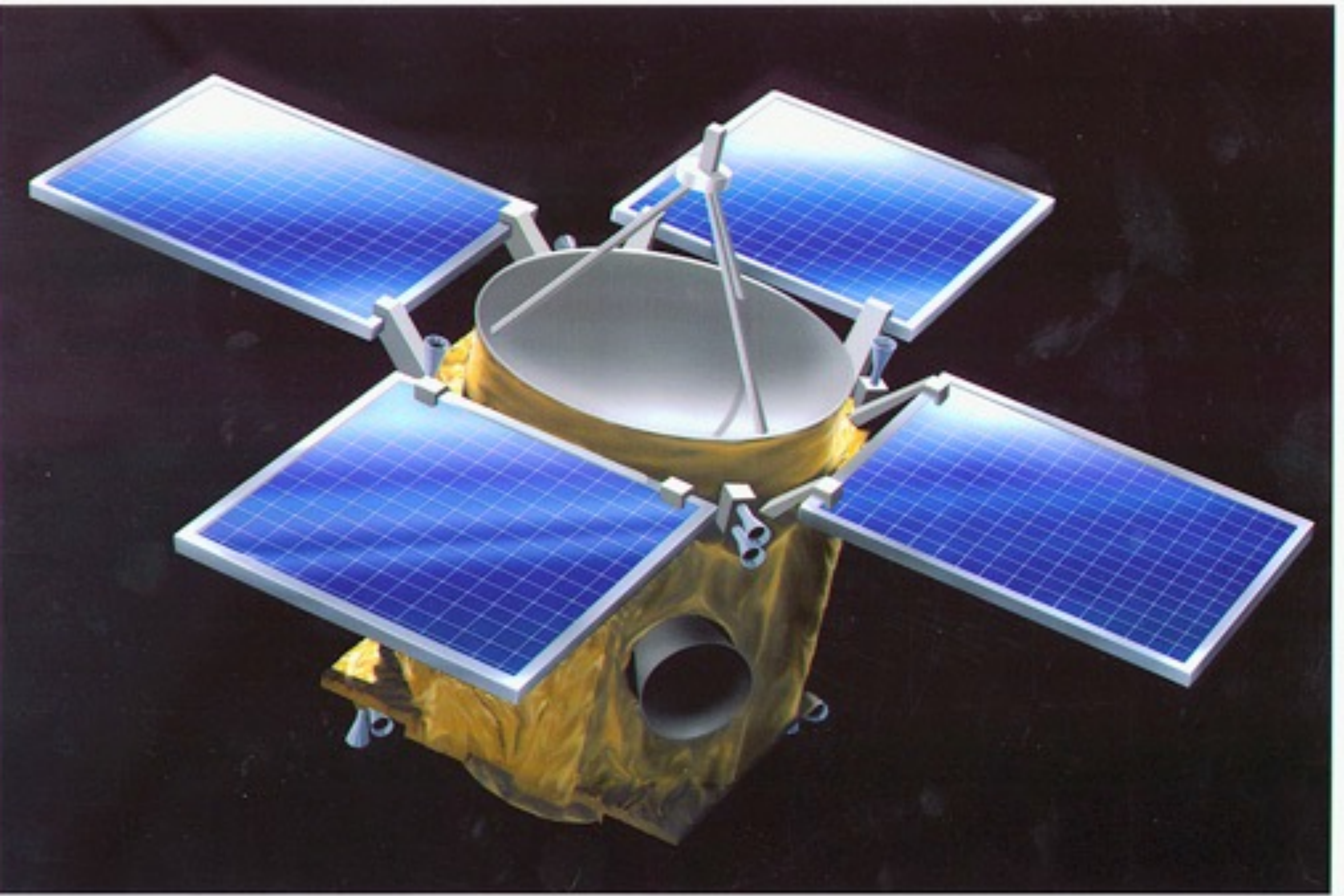

ASTEROID
EXPLORATION
DAWN
NASA
Launch Date: June 2007
Mission Target: Asteroid Vesta
& Dwarf Planet Ceres
OSIRIS-REx
NASA
Launch Date: September 2016
Mission Target: Asteroid Bennu*
HAYABUSA
JAXA
Launch Date: May 2003
Mission Target: Asteroid Itokawa
HAYABUSA2
JAXA
Launch Date: December 2014
Mission Target: Asteroid 1999 JU3*
NEAR SHOEMAKER
NASA
Launch Date: February 1996
Mission Target: Asteroid Eros
Flyby Object: Asteroid Mathilde
GALILEO
NASA / DLR
Launch Date: October 1989
Flyby Object: Asteroids Gaspra and Ida
CASSINI
NASA / ESA / ASI
Launch Date: October 1997
Flyby Object: Asteroid Masursky
DEEP SPACE 1
NASA / JPL
Launch Date: October 1998
Flyby Object: Asteroid Braille
STARDUST
NASA / JPL
Launch Date: February 1999
Extension: March 2006
Flyby Object: Asteroid Annefrank
ROSETTA
ESA
Launch Date: March 2004
Flyby Object: Asteroids
Šteins & Lutetia
OSIRIS-REx
EXPLORING OUR PAST
SECURING OUR FUTURE
*Artist's Concept
RELATIVE SIZES
Ceres
Vesta
Lutetia
Mathilde
Ida
Eros
Gaspra
Masursky
Steins
Annefrank
Braille
1999 JU3
Bennu
Itokawa

Flyby Observations



Near Earth Asteroid Rendezvous

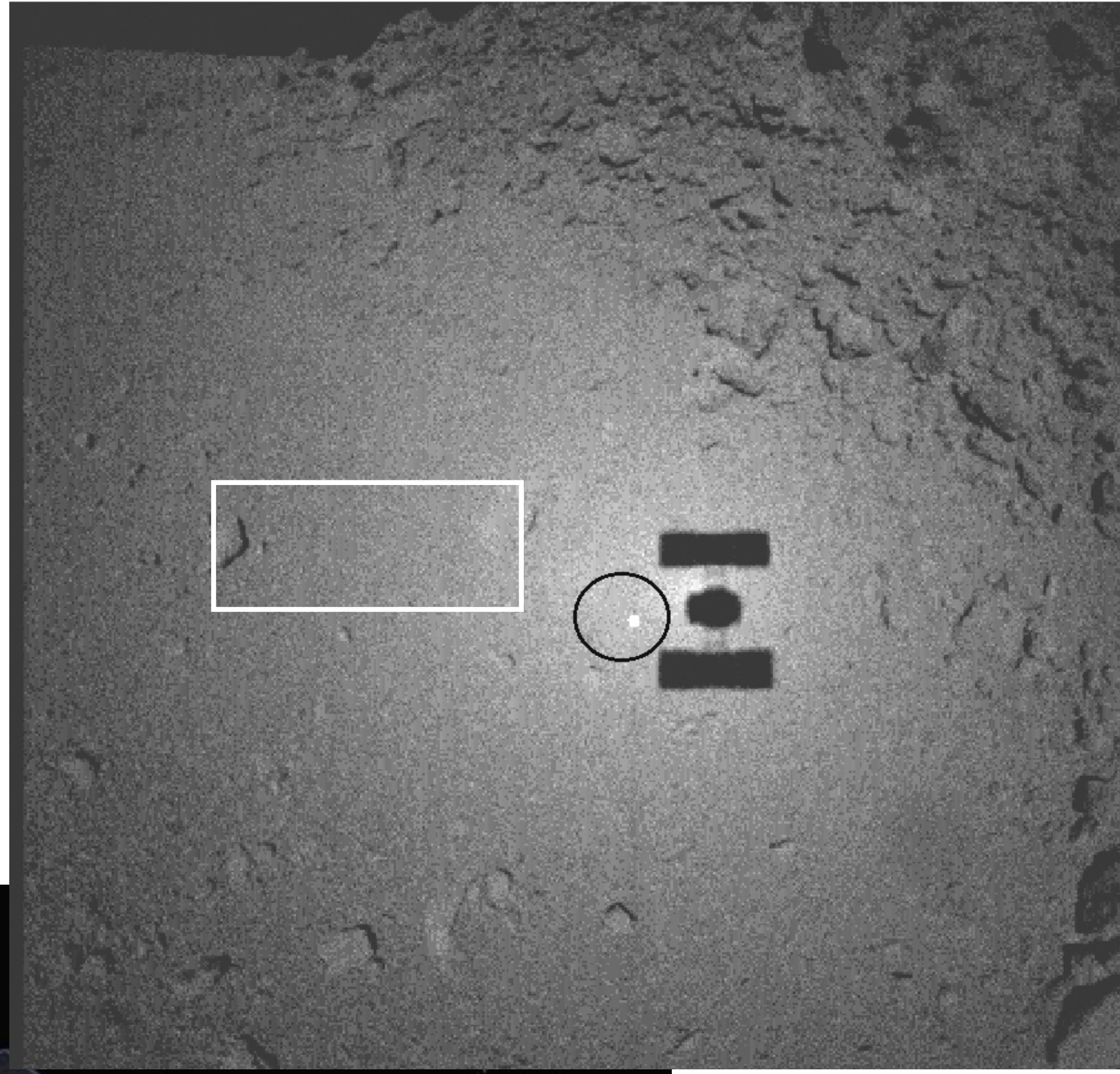
- NASA space science mission
- Visited the asteroid Eros
- Launched 1996
- Arrived at asteroid 2001
- Landed on asteroid 2002

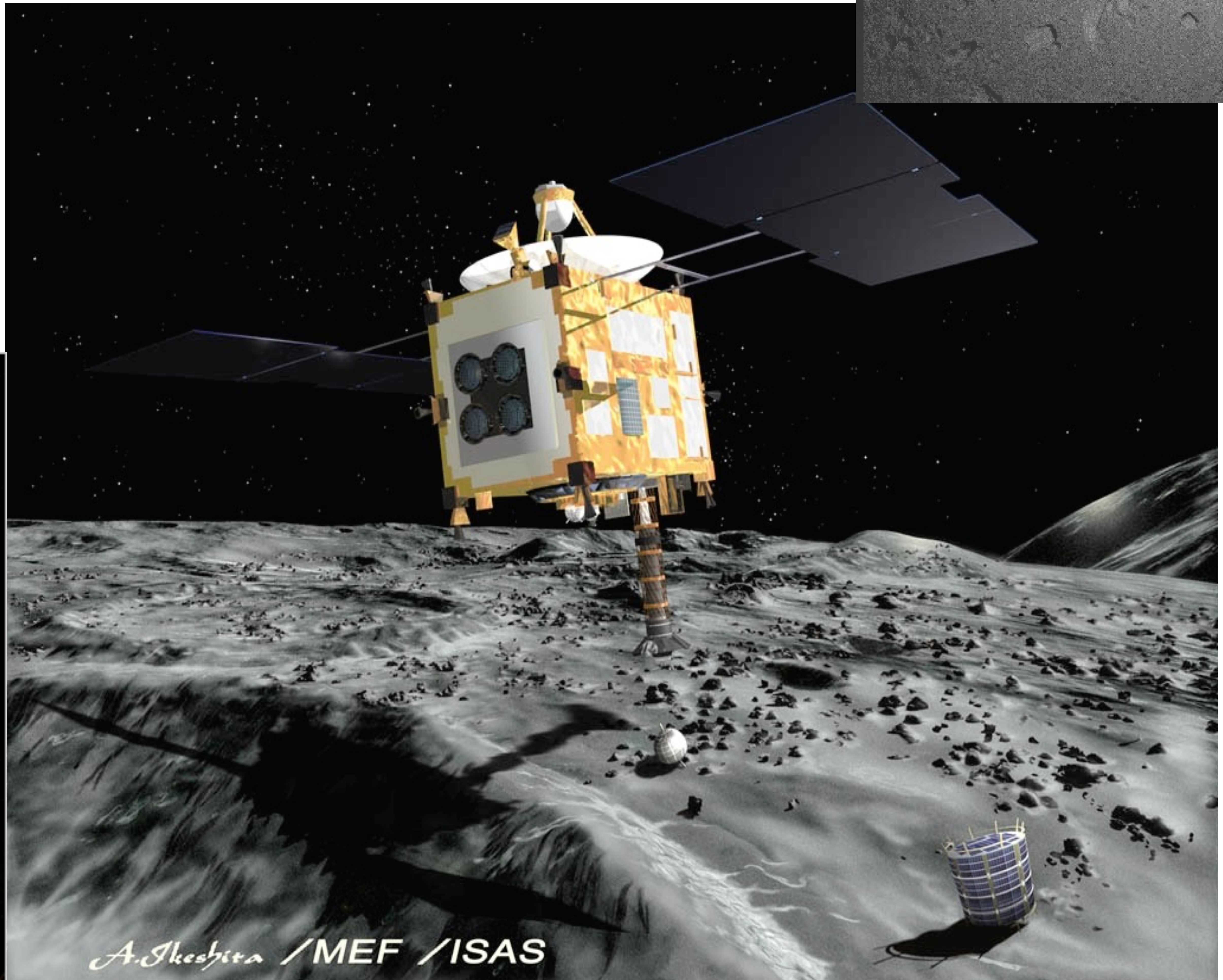



Empire State
Building

Hayabusa Mission

- Japanese sample return mission to asteroid Itokawa
- Launched 2003, arrived at asteroid in 2005, returned to Earth in 2010 after a long odyssey.

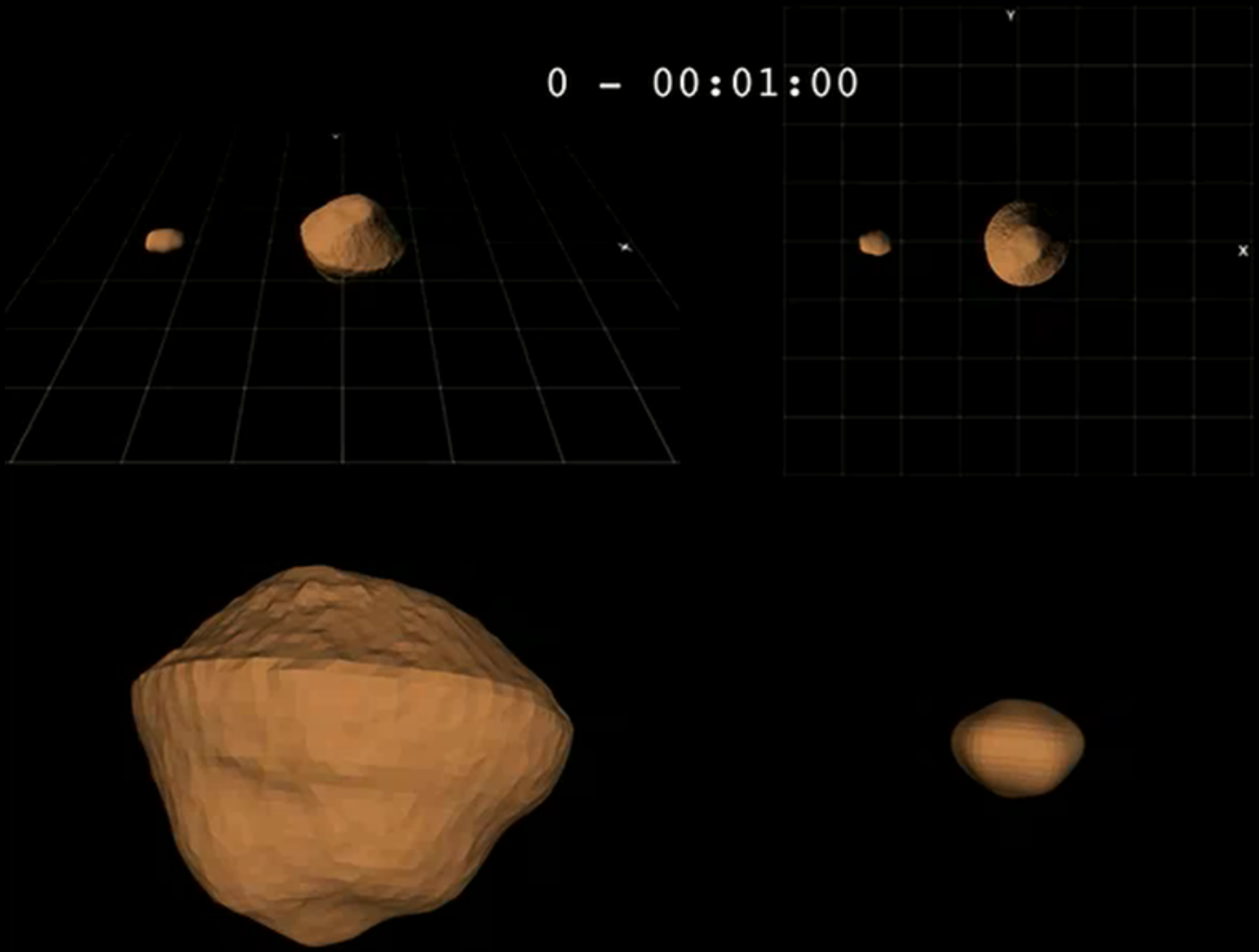





Science
HAYABUSA
Dust from Itokawa
AAAS

What are the Challenges for Exploration?

- The small body dynamical environment is ***one of the most perturbed orbital environments found in the solar system***
  - Asteroids present extreme exploration environments.
  - Gravity and rotational effects can destabilize an orbit, causing impact or escape on time scales of less than a day.
  - Solar radiation pressure perturbations can strip a spacecraft out of orbit or cause an impact.
  - Coupled effects from perturbations can cause chaotic orbit dynamics.
  - Asteroids present complex morphologies and surface environments
- Examples of extreme environments include…
  - Asteroid morphologies
  - Strong gravitational and non-gravitational perturbations
  - Complex resonant interactions


0 – 00:01:00
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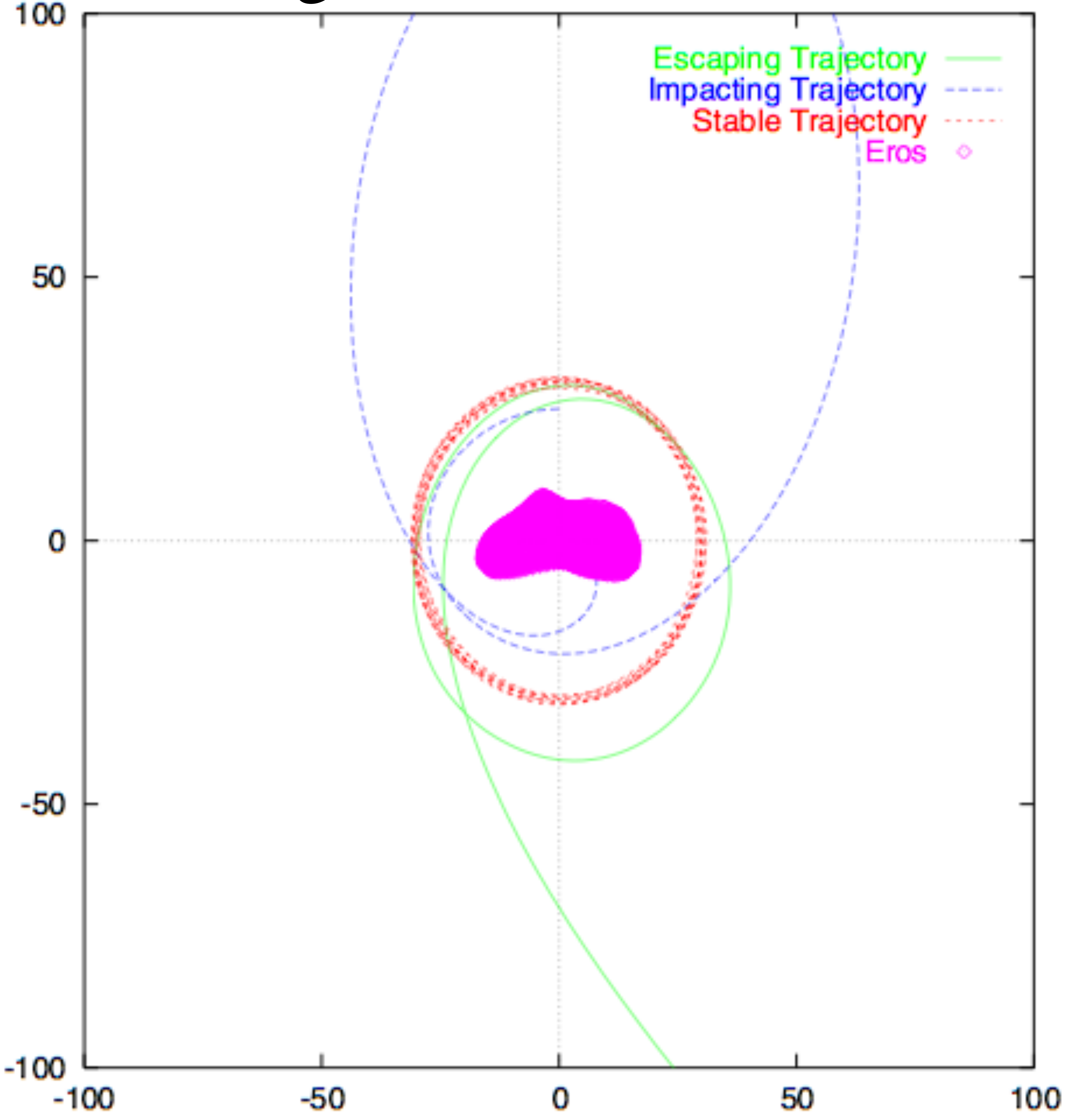
Challenge: Gravitational Effects

Simulation of spacecraft orbits at 433 Eros.

Stable Orbit

Impacting Orbit

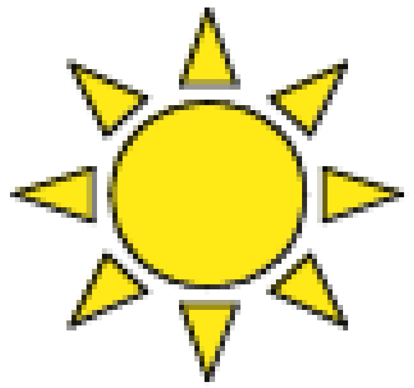
Escaping Orbit



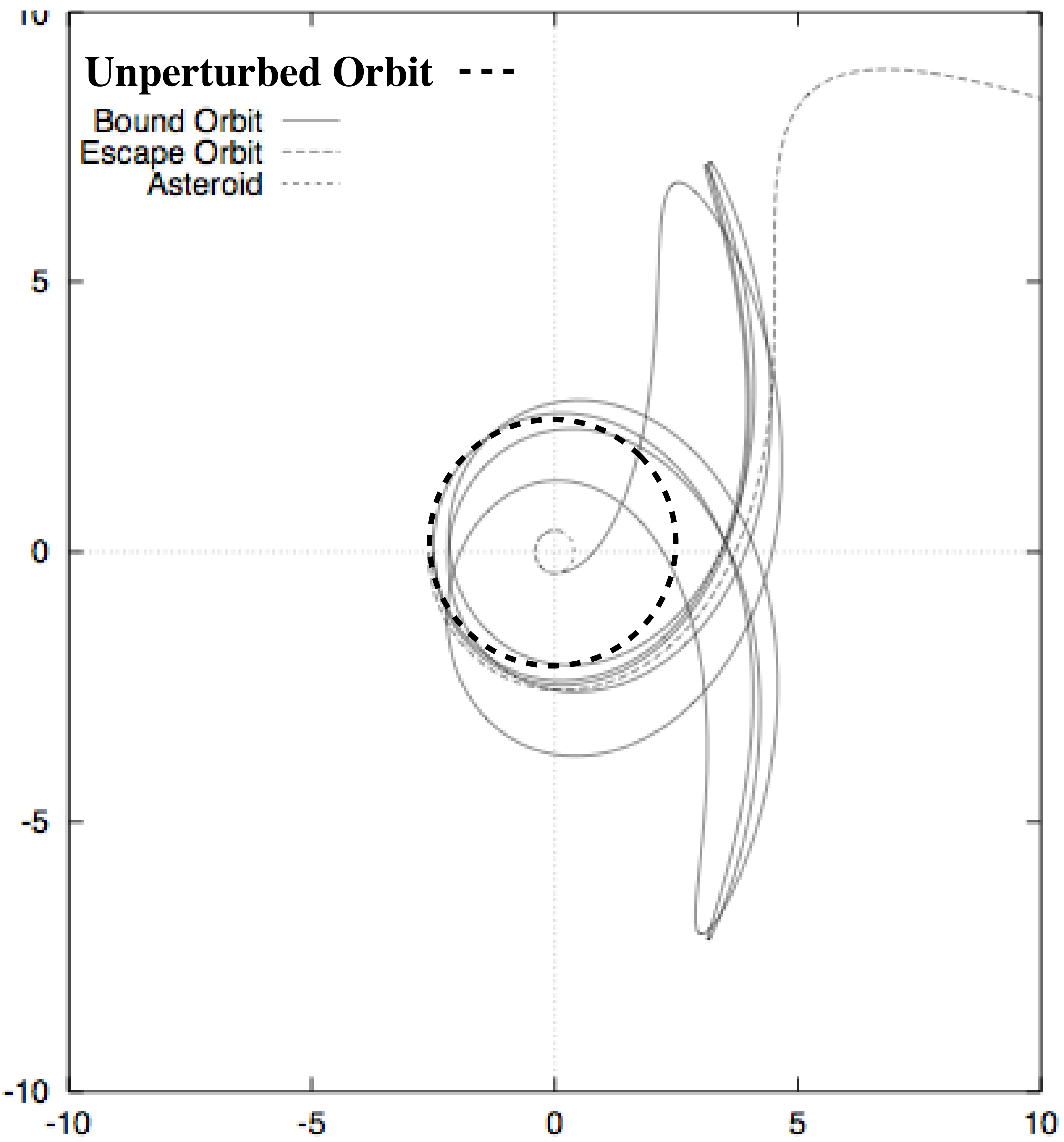
Small changes in initial conditions yield large variations in outcome.

Challenge: SRP Effects

S/C orbits about a small point mass

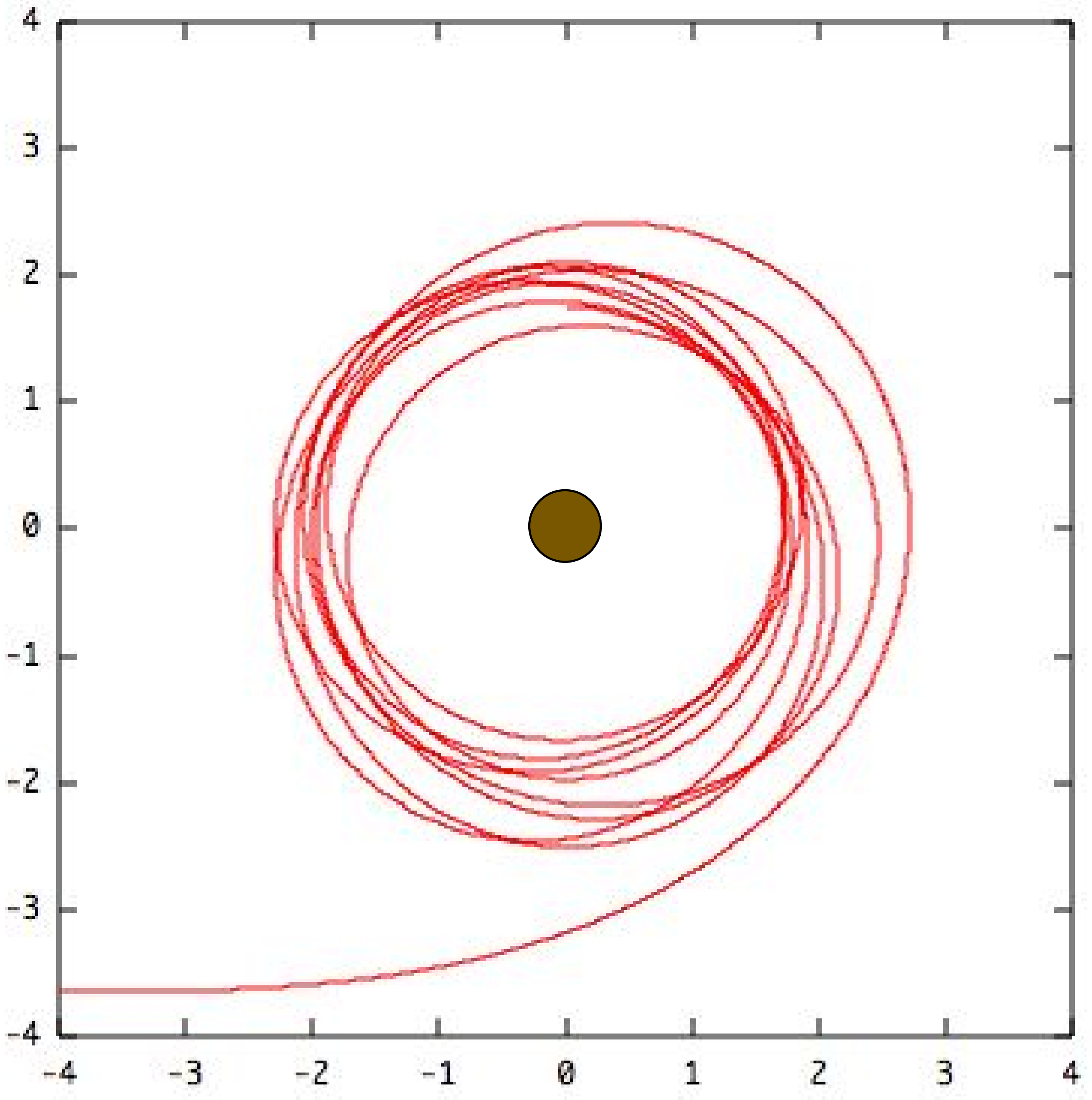


A 100 meter difference in initial conditions can change escape to impact

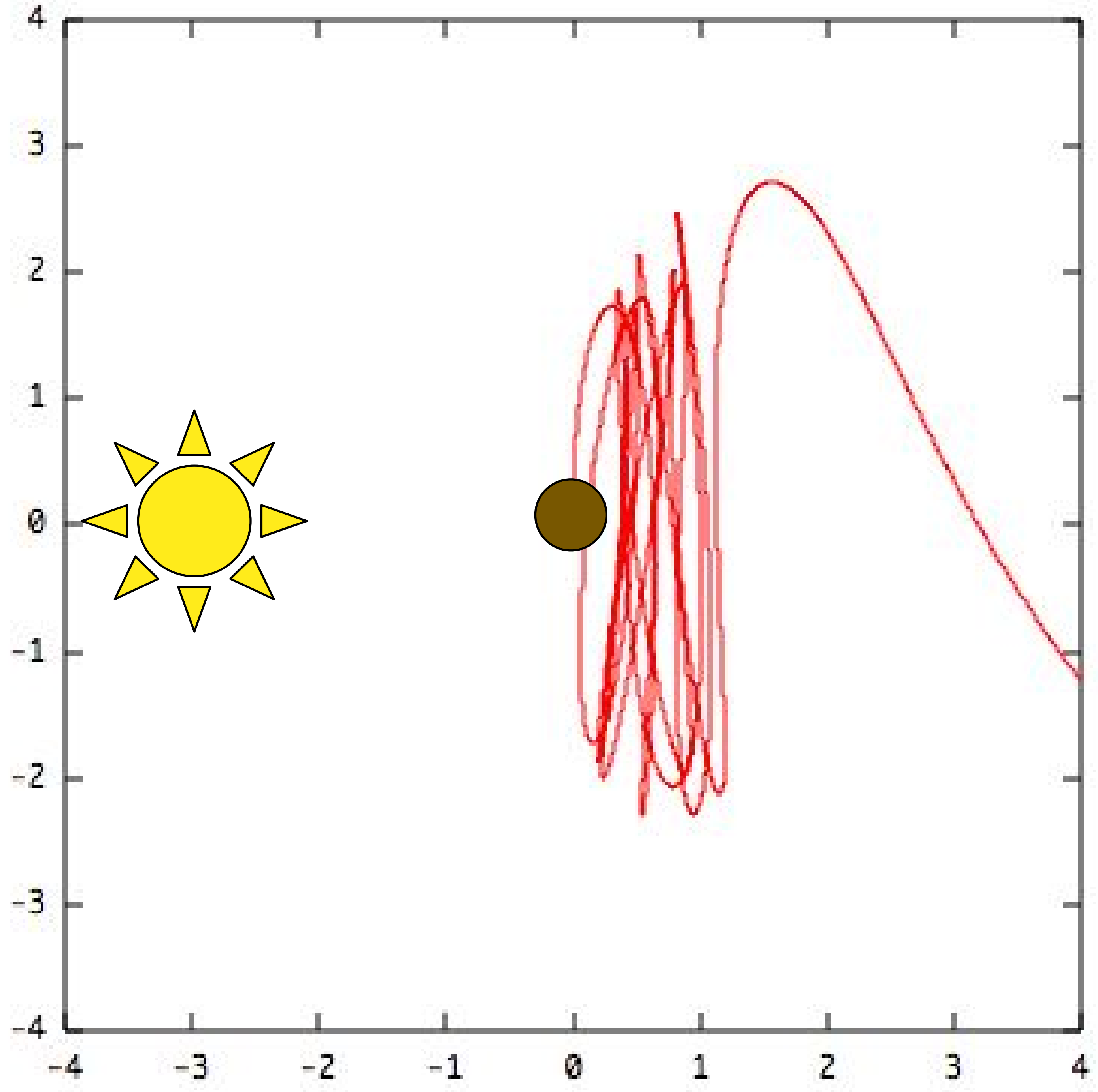


Challenge: SRP Effects

Escape due to SRP



View from the Sun



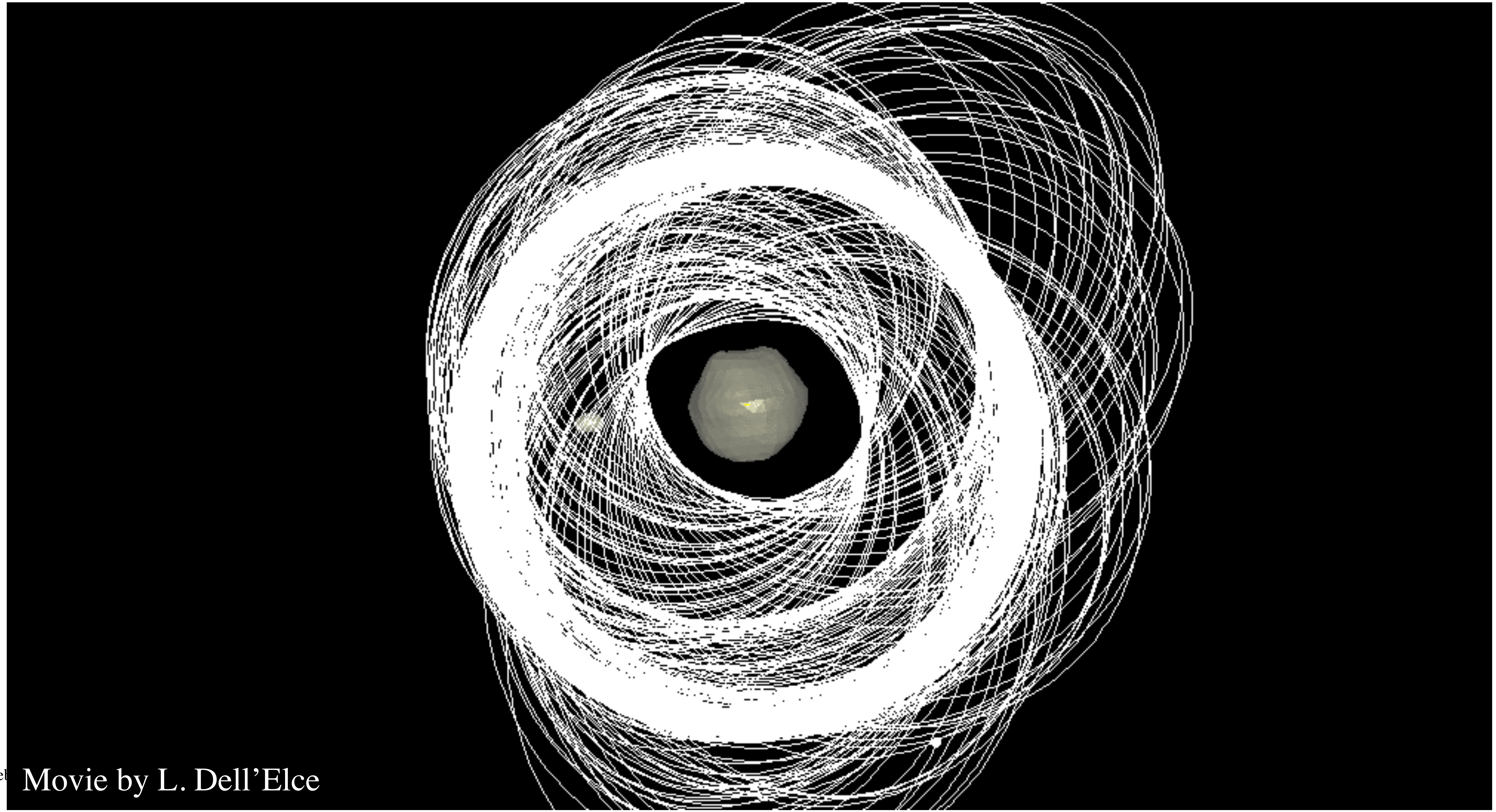
View in the terminator plane

a ~ constant in orbit perturbed only by SRP

S/C escapes once body travels too close to the sun

Challenge: Complex gravitational environments

Resonant interactions with a time varying system can cause chaos



Movie by L. Dell'Elce

How to deal with such Challenges?

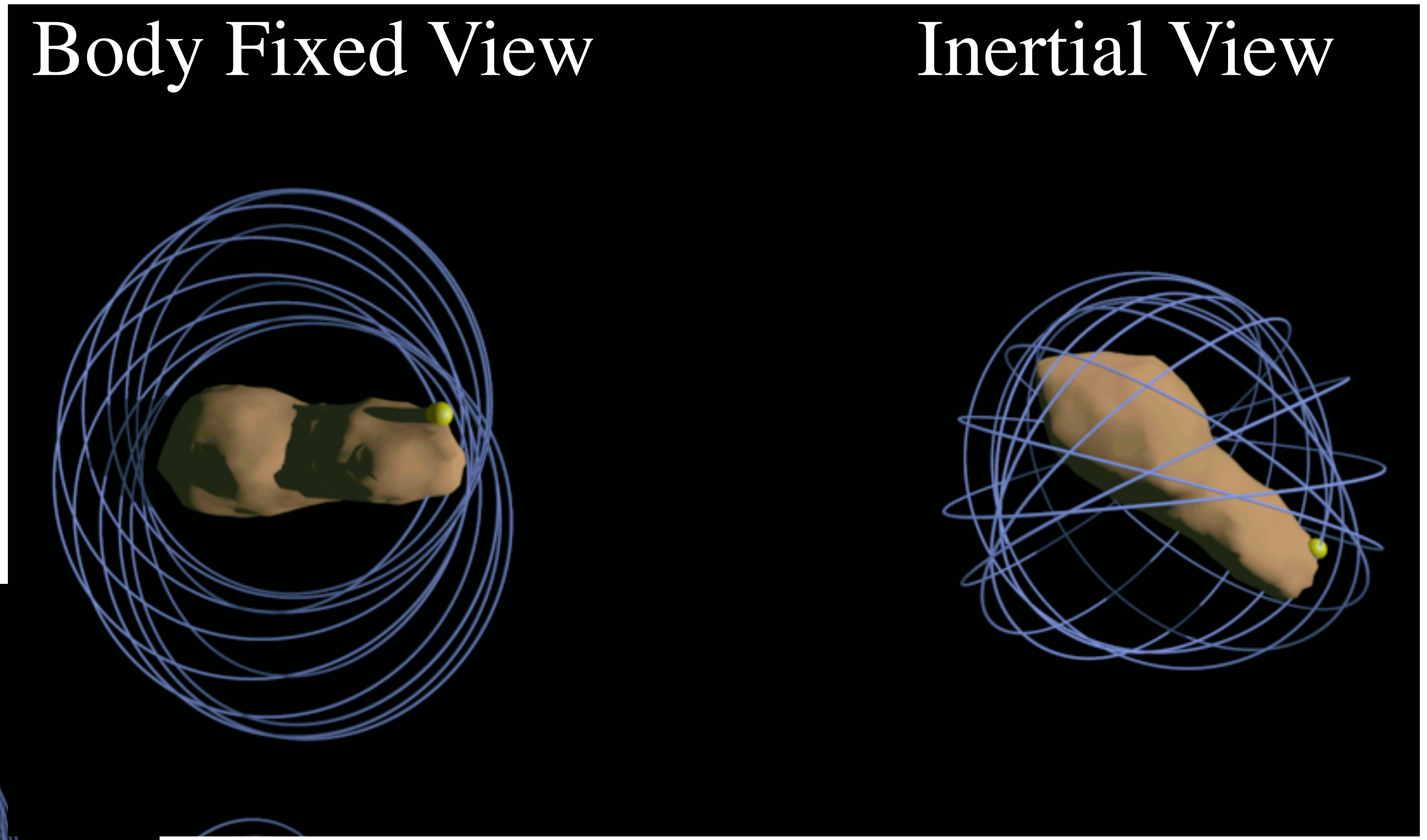
- Proximity operations about small bodies present challenges that vary across the population with size, shape and spin state.
- For orbital motion there exist regimes of special interest:
  - **Gravity Regime**: Orbital Mechanics are controlled by the mass distribution and rotational dynamics of the central body.
  - **Solar Radiation Pressure Regime**: Orbital Mechanics are controlled by the radiation pressure and tidal perturbations from the sun.
  - **Mixed Regime**: Orbital Mechanics are simultaneously perturbed by gravity and solar effects.
- Other modes of operations are also of interest:
  - Controlled / hovering motion
  - Surface deployment and motion
- **Despite challenges, safe approaches for exploration can be found about *any* asteroid — but change from body to body**

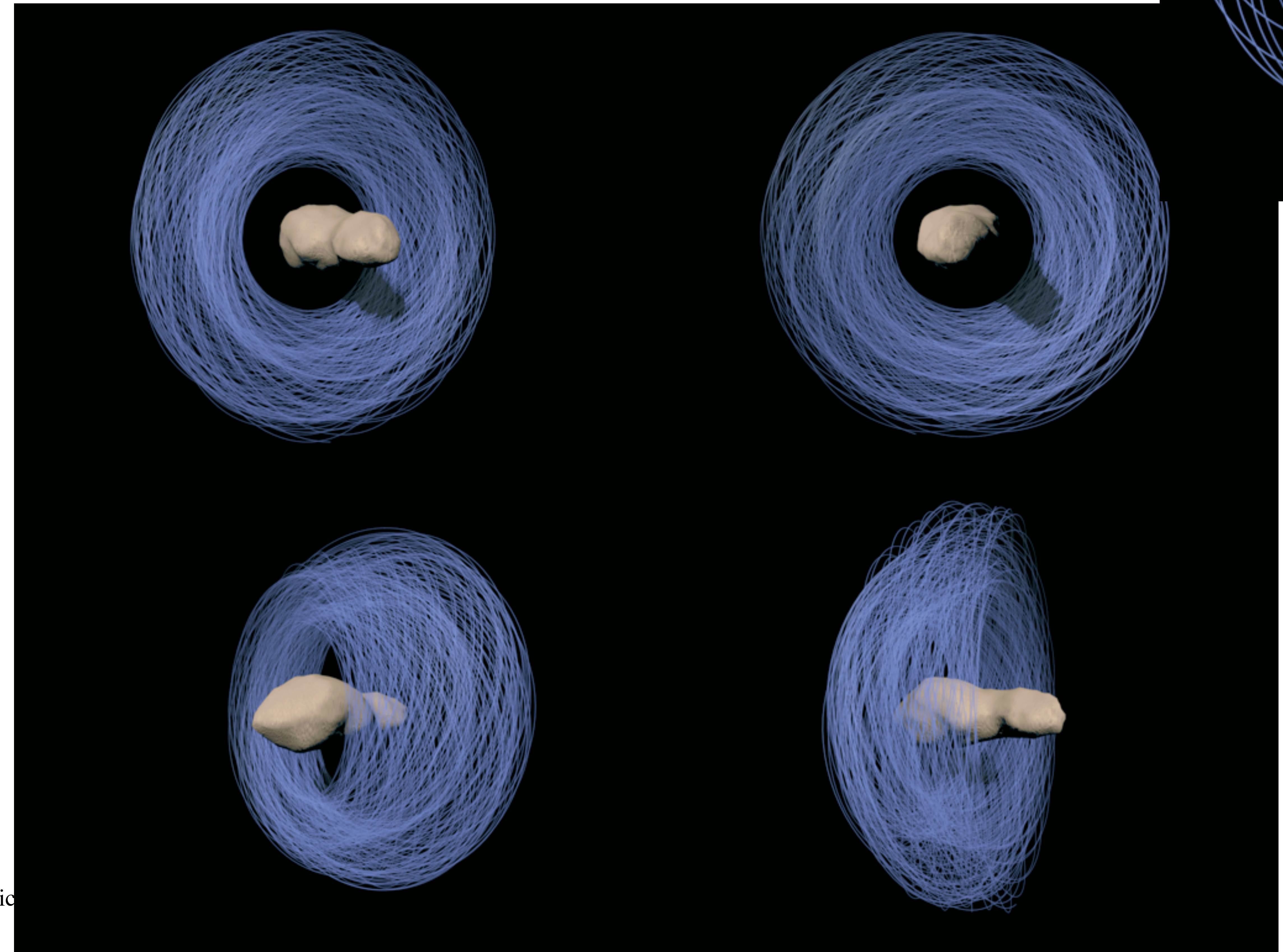
Gravity Regime

- Mass distribution and rotation state dominates motion.
- Use of classical analytical theories is challenging:
  - At Eros, the secular effect of J_2 is ***200*** times stronger than at Earth, high order zonal and tesseral coefficients are relatively even larger.
  - Convergent series for analytical descriptions must extend to much higher orders, incorporate many more effects.
  - Resonant interactions with the rotating gravity field causes orbital motion to become chaotic – cannot be described by analytical theories.
- Alternate tools for stable orbit design are needed and include:
  - Averaging to identify first-order effects
  - Periodic orbits to delineate regions of stability
  - Hill stability to guarantee no-impact with the body (Lagrange stability)
  - Semi-analytic evaluations to identify conditions for instability

Averaging for understanding

First-order averaging analysis suggests stable orbit designs and identifies the controlling, fundamental dynamical effects.





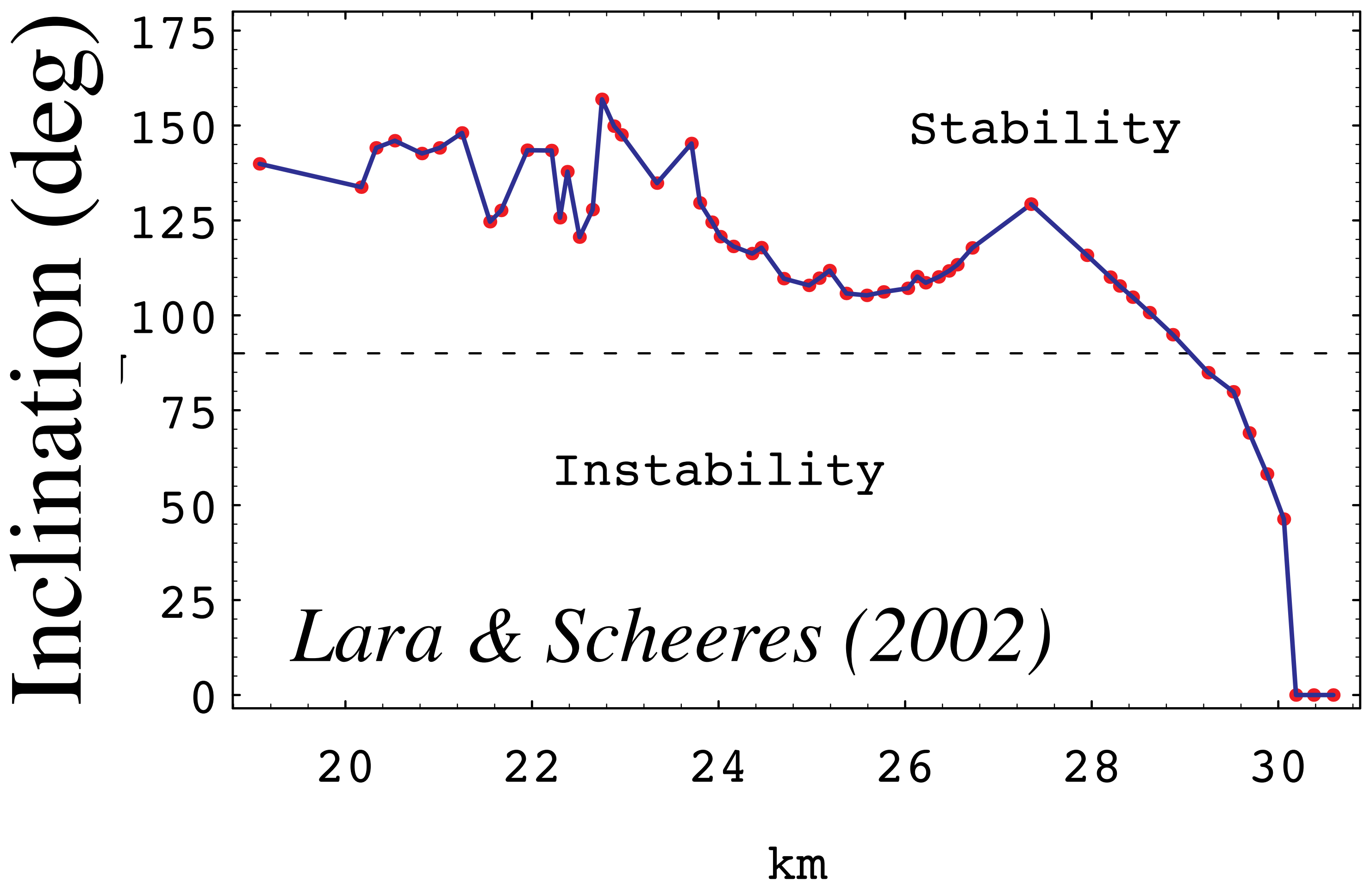
Orbit plane "dragging" by mass distribution, predicted by averaging theory.

Stable orbit viewed in asteroid-fixed frame, identified using averaging analysis for motion about a non-uniform rotator.

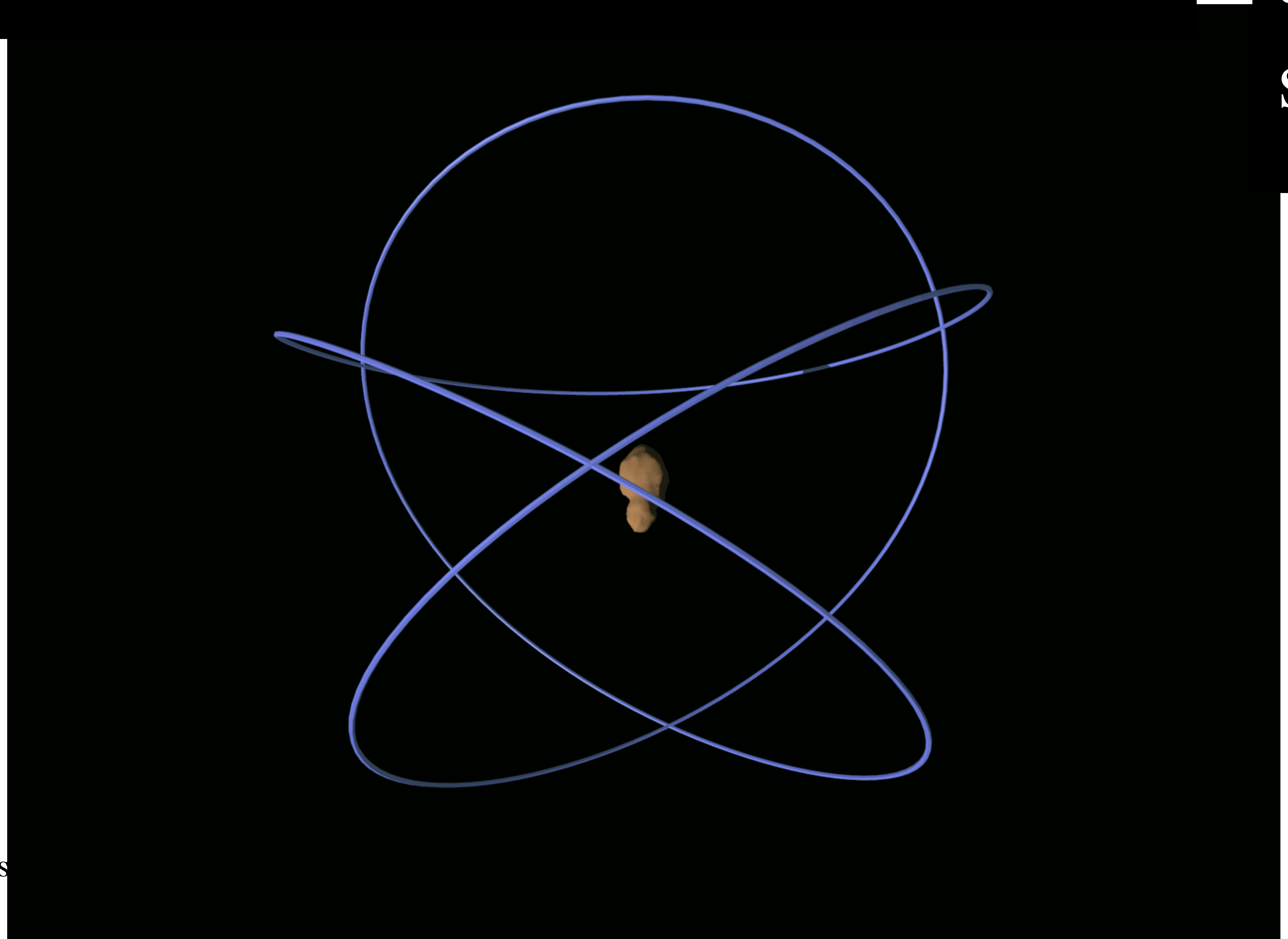
Periodic Orbits as Stability Probes

Stable Periodic Orbit about Didymos

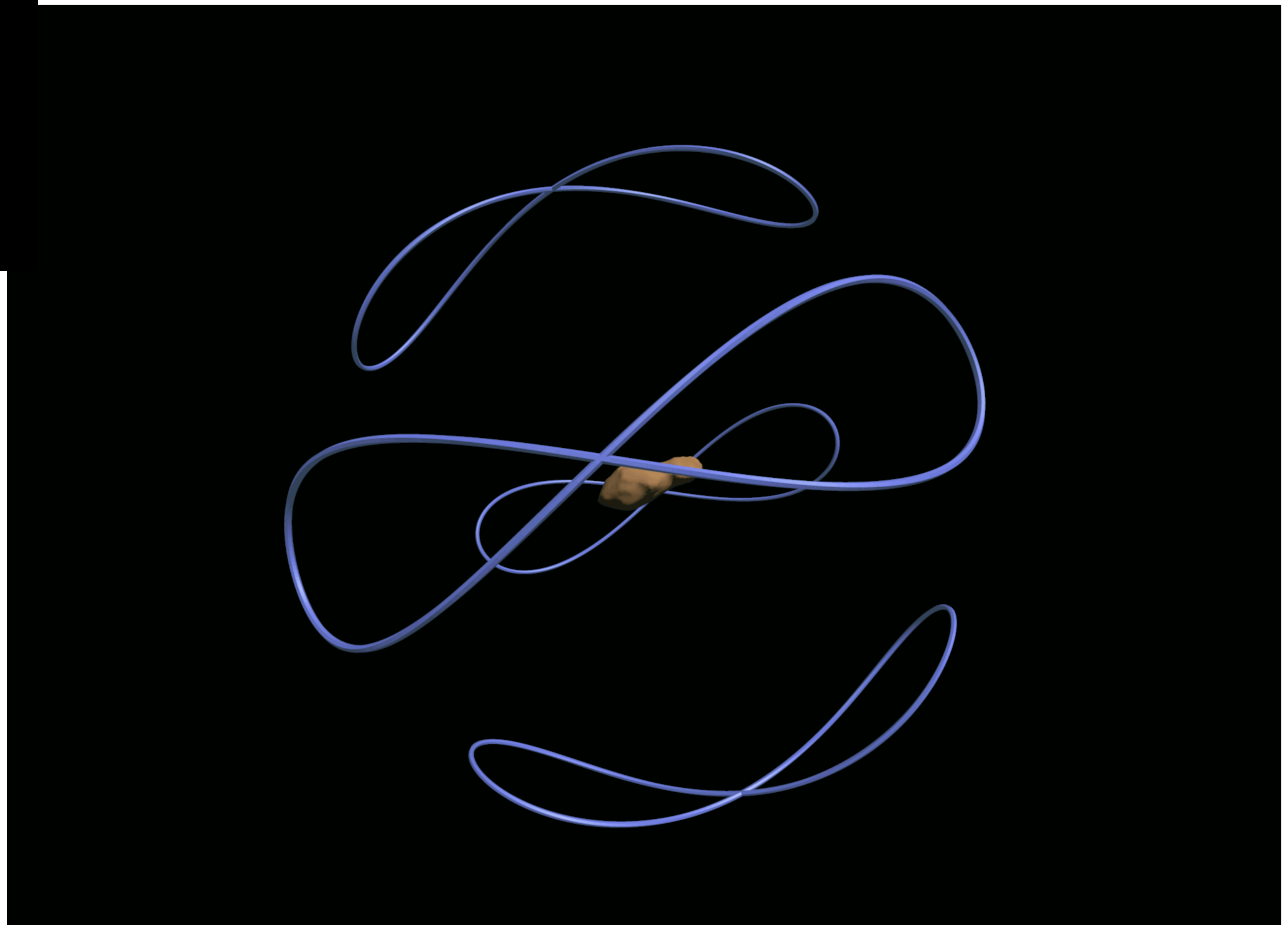
Eros Stability Zones



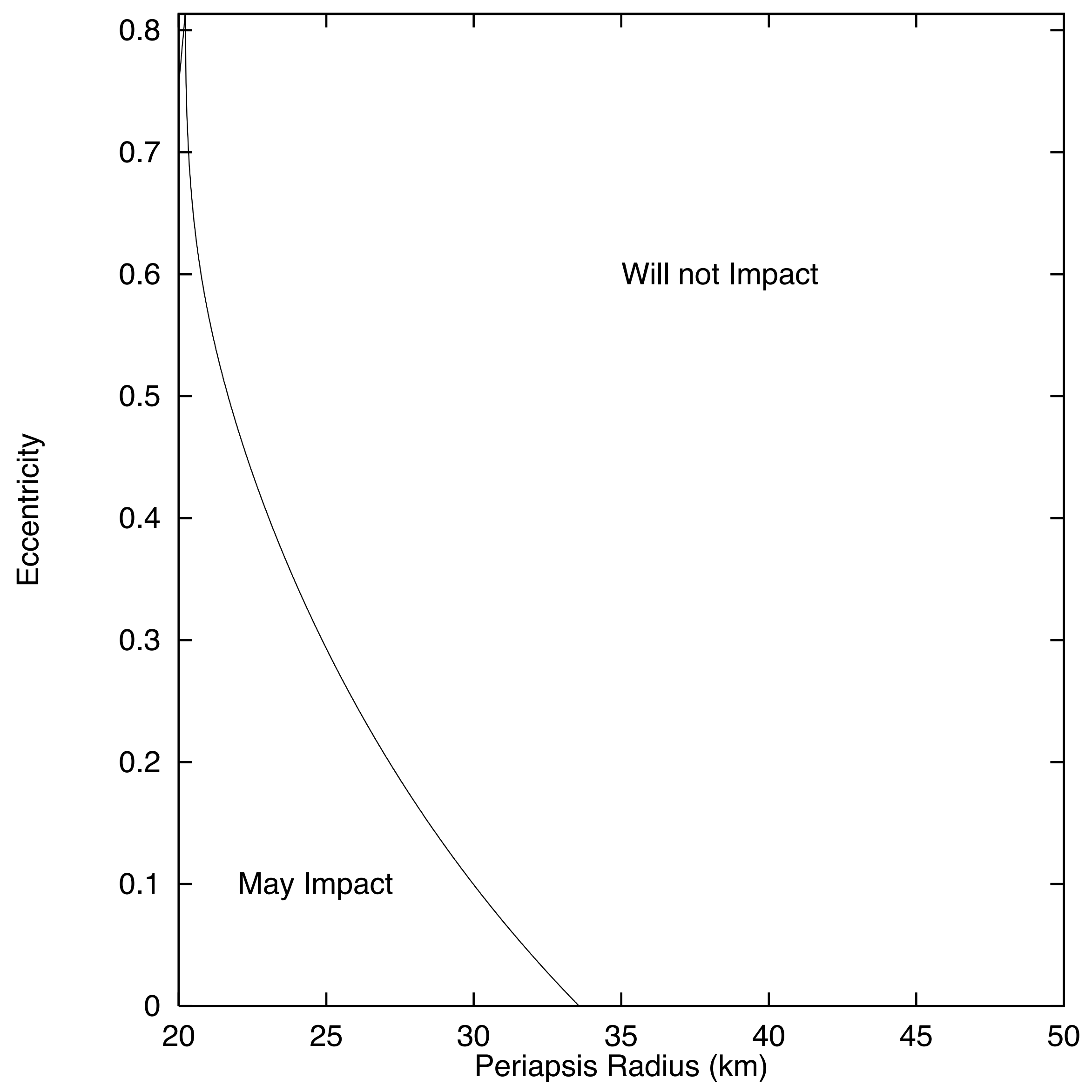
Periodic Orbit Family Stability Maps Stable and Unstable phase space regions



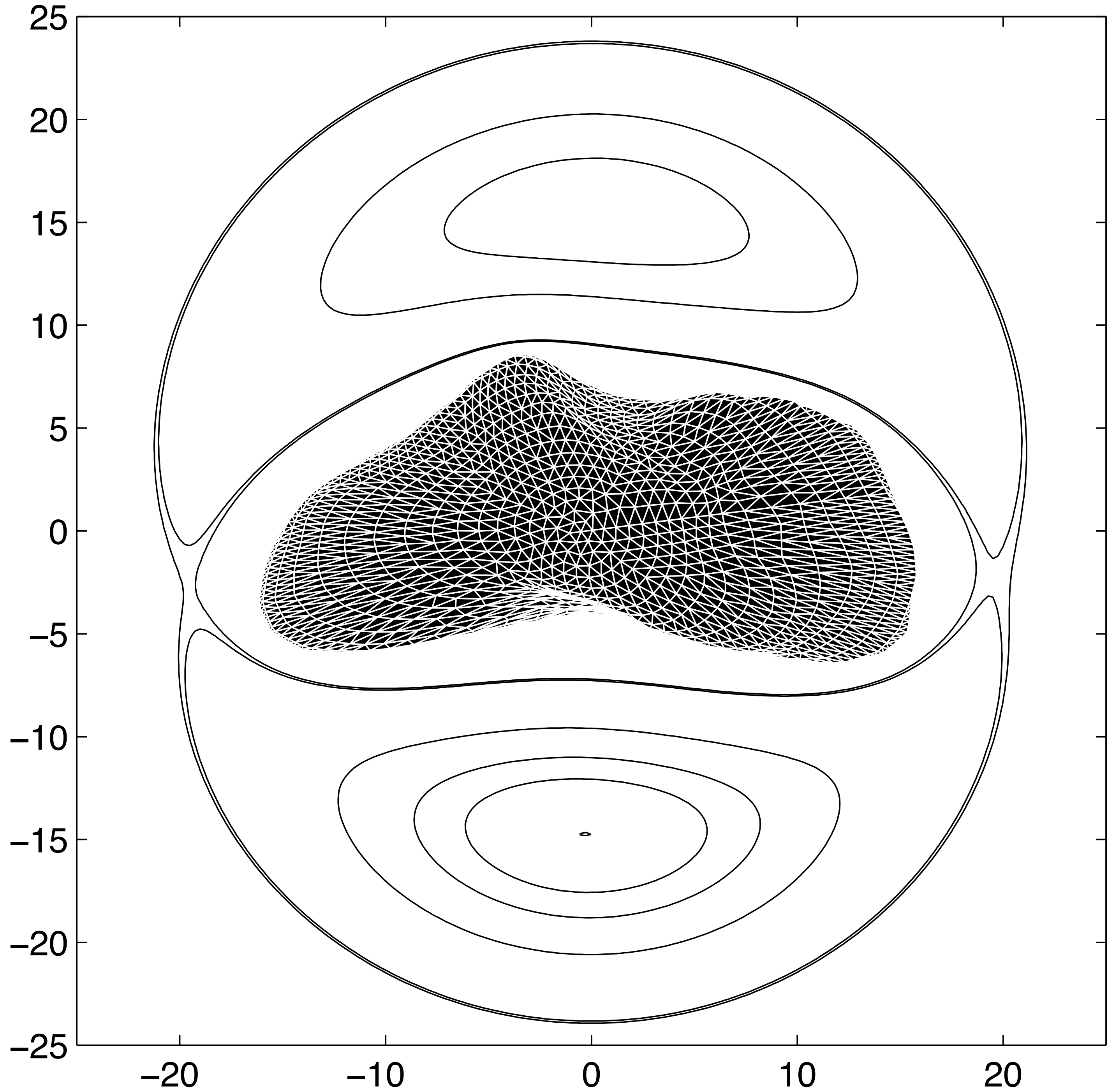
Stable Periodic Orbits at Toutatis

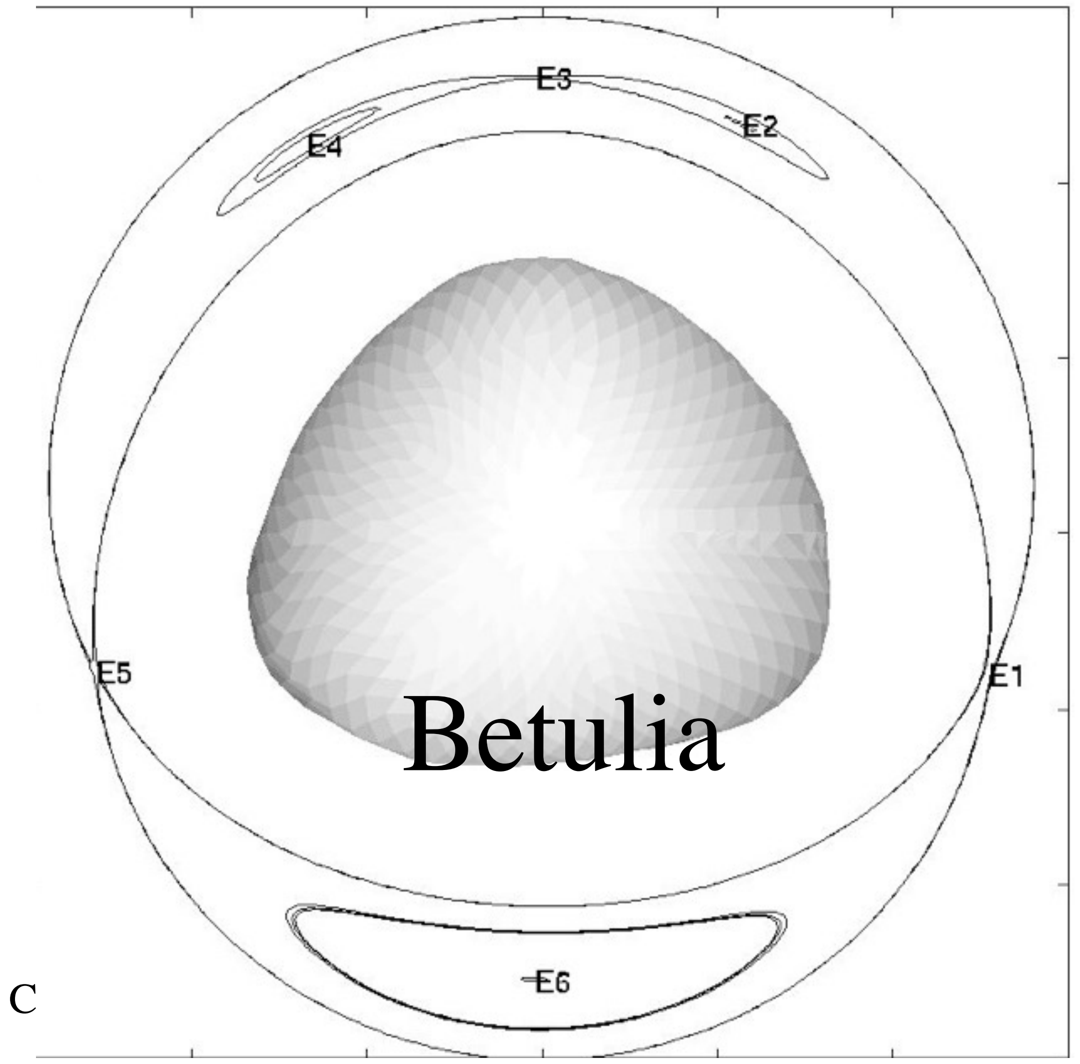


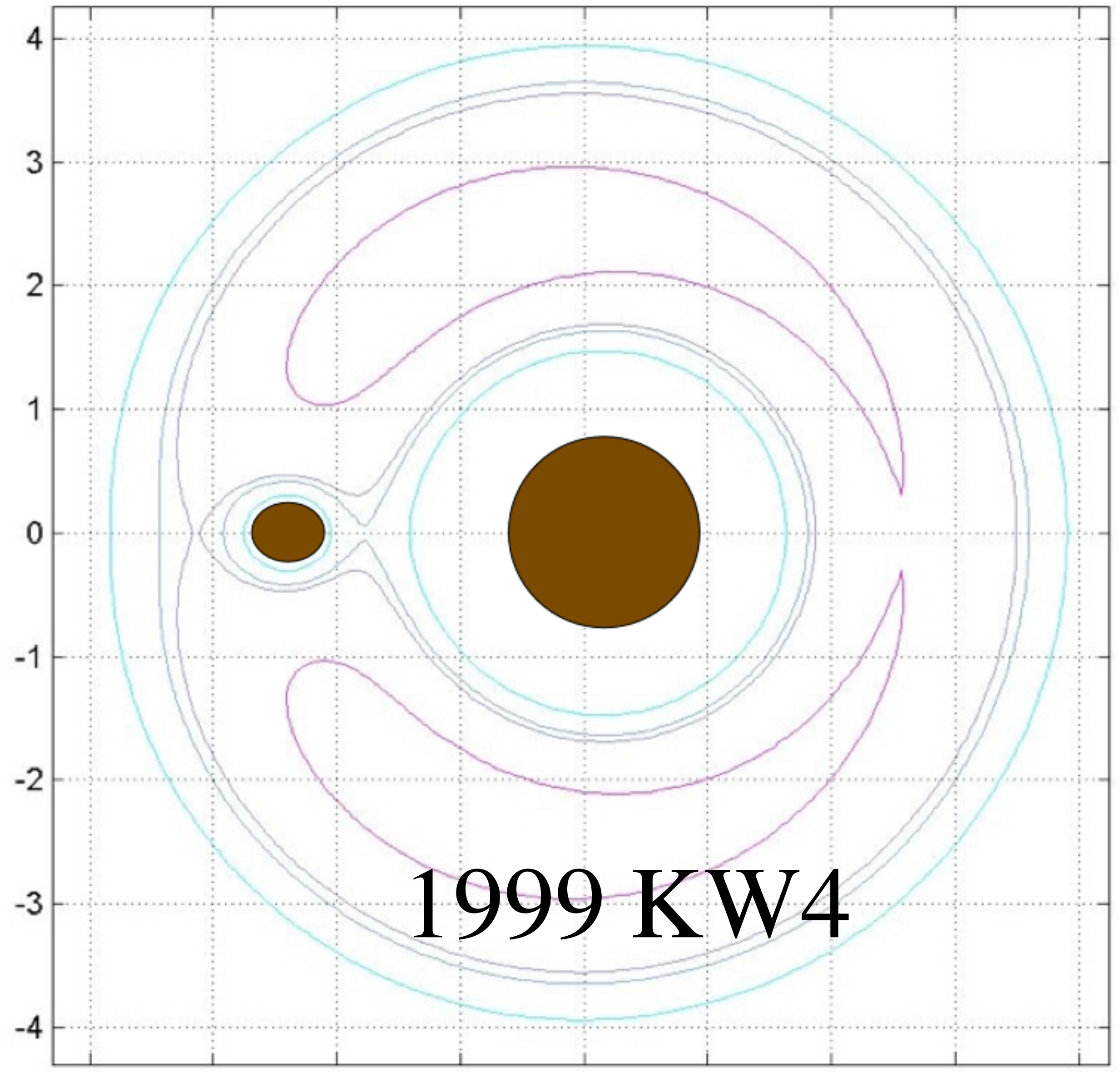
Zero-Velocity Curves to Define Impact-Free Orbits or Captured Rovers

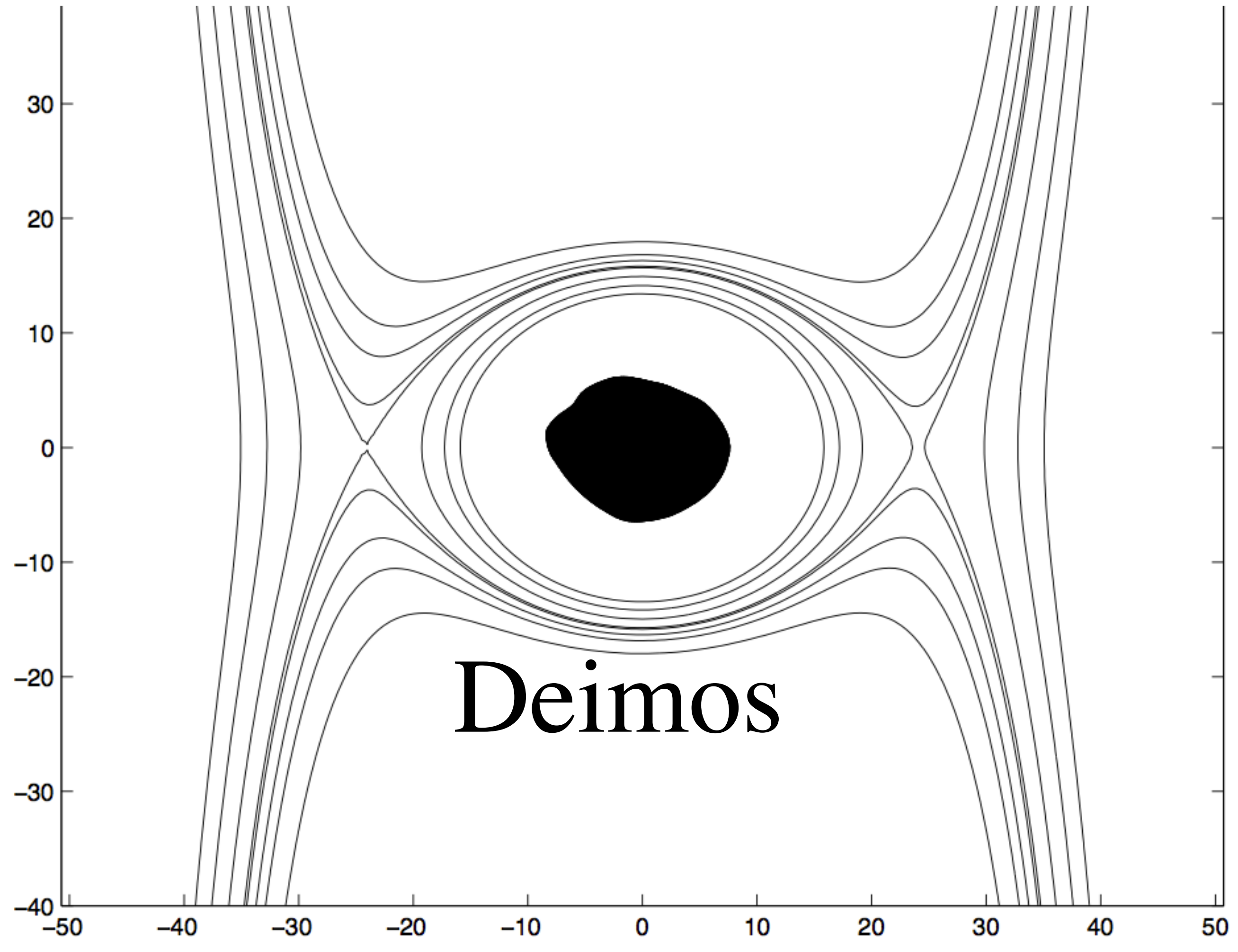


Eros Zero-Velocity Curves and resultant sharp limits on non-impacting orbits



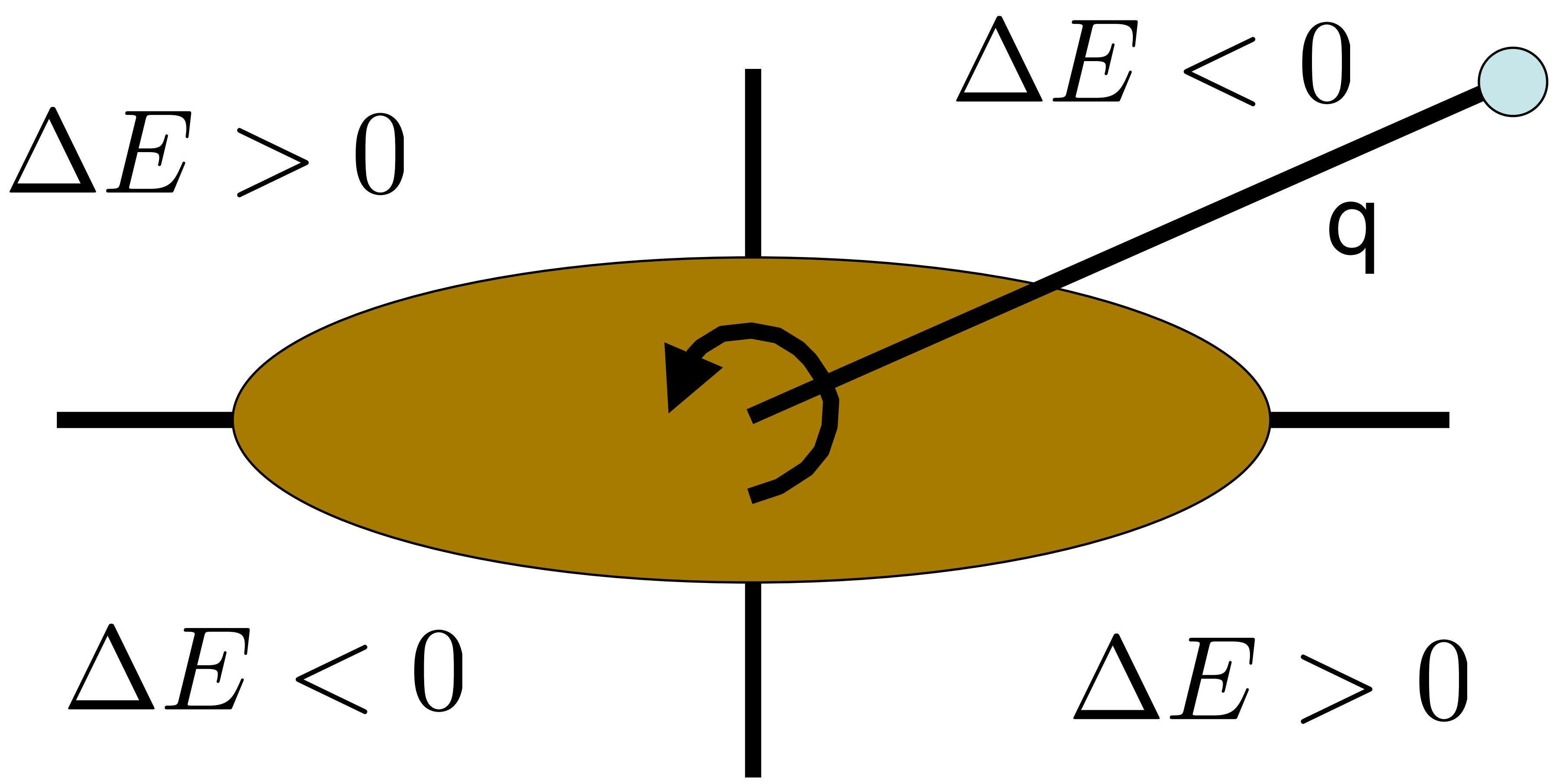




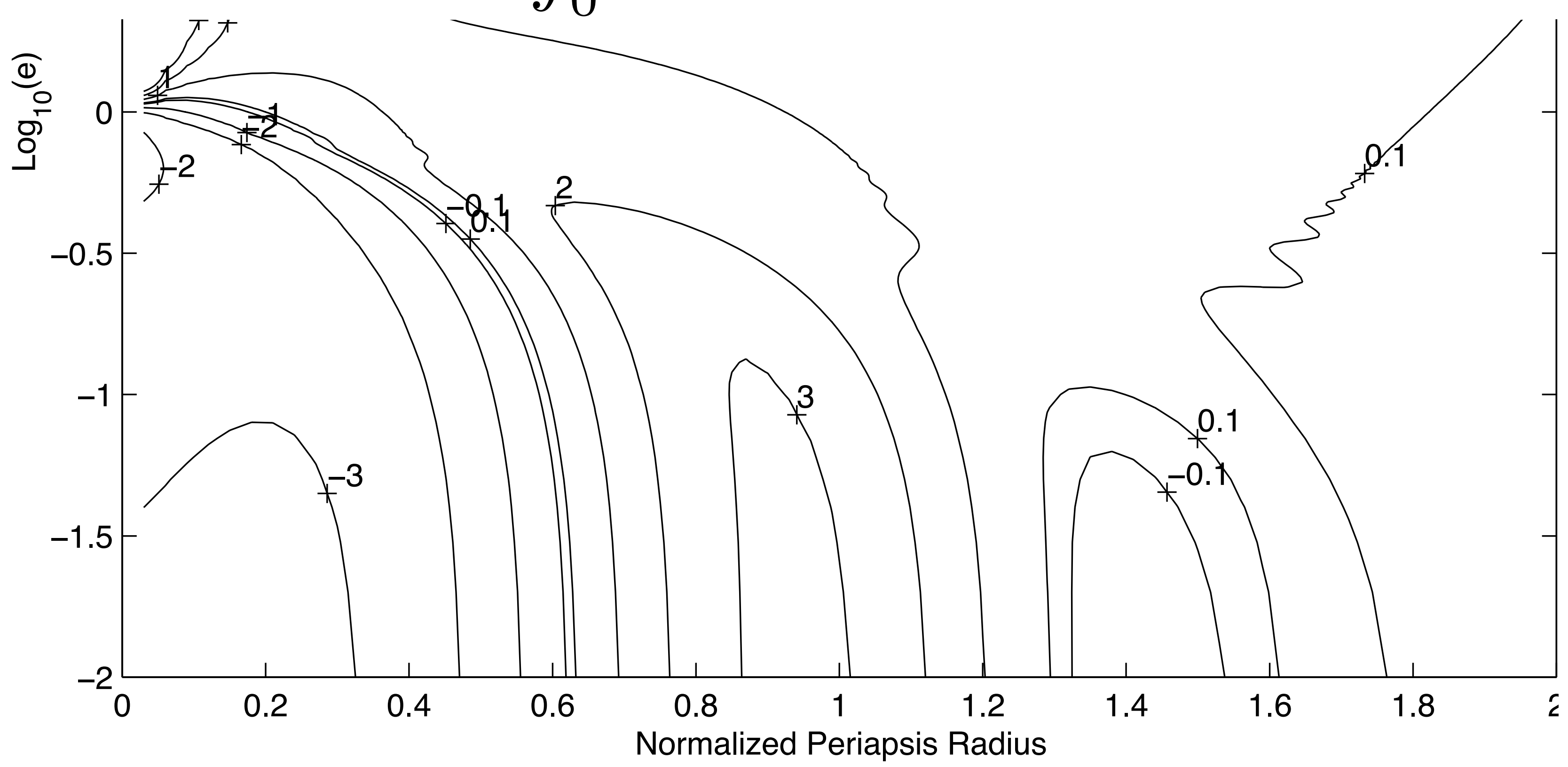


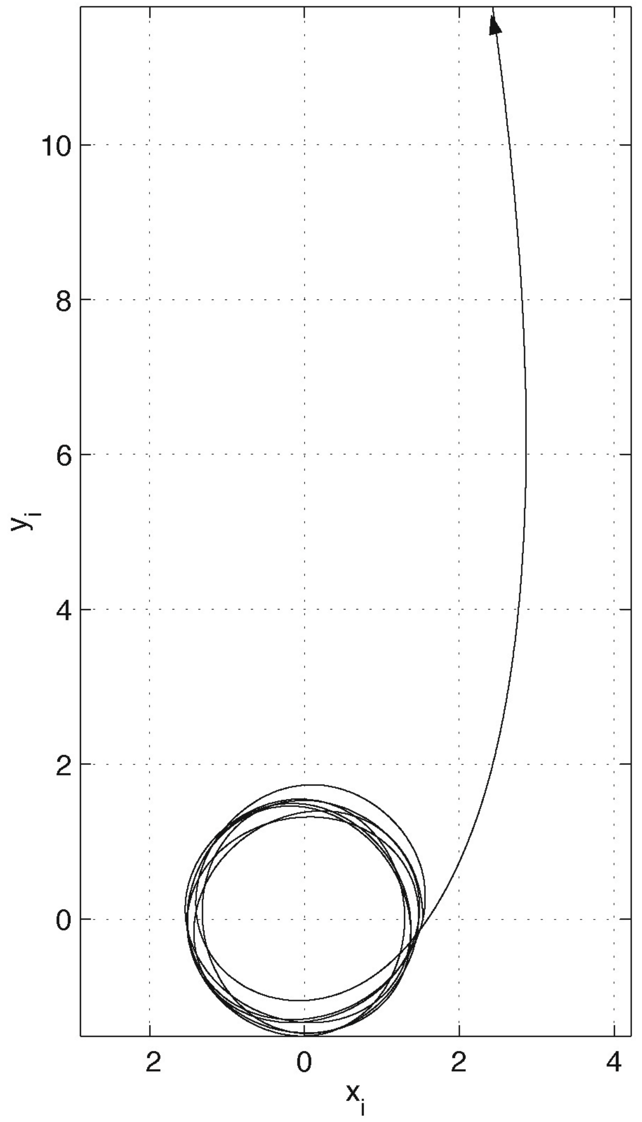
Semi-Analytical Results

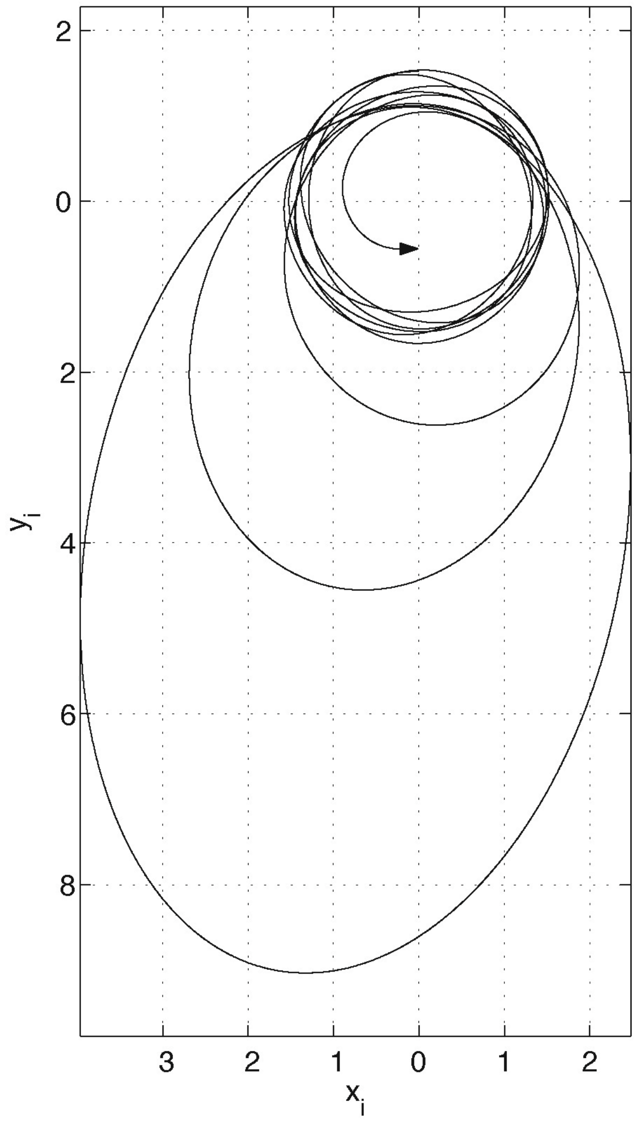
$$\Delta E = -6\omega C_{22} R^2 \sqrt{\frac{\mu}{p^3}} \cos^4(i/2) \sin 2(\theta) I_2^1(r_p, e)$$



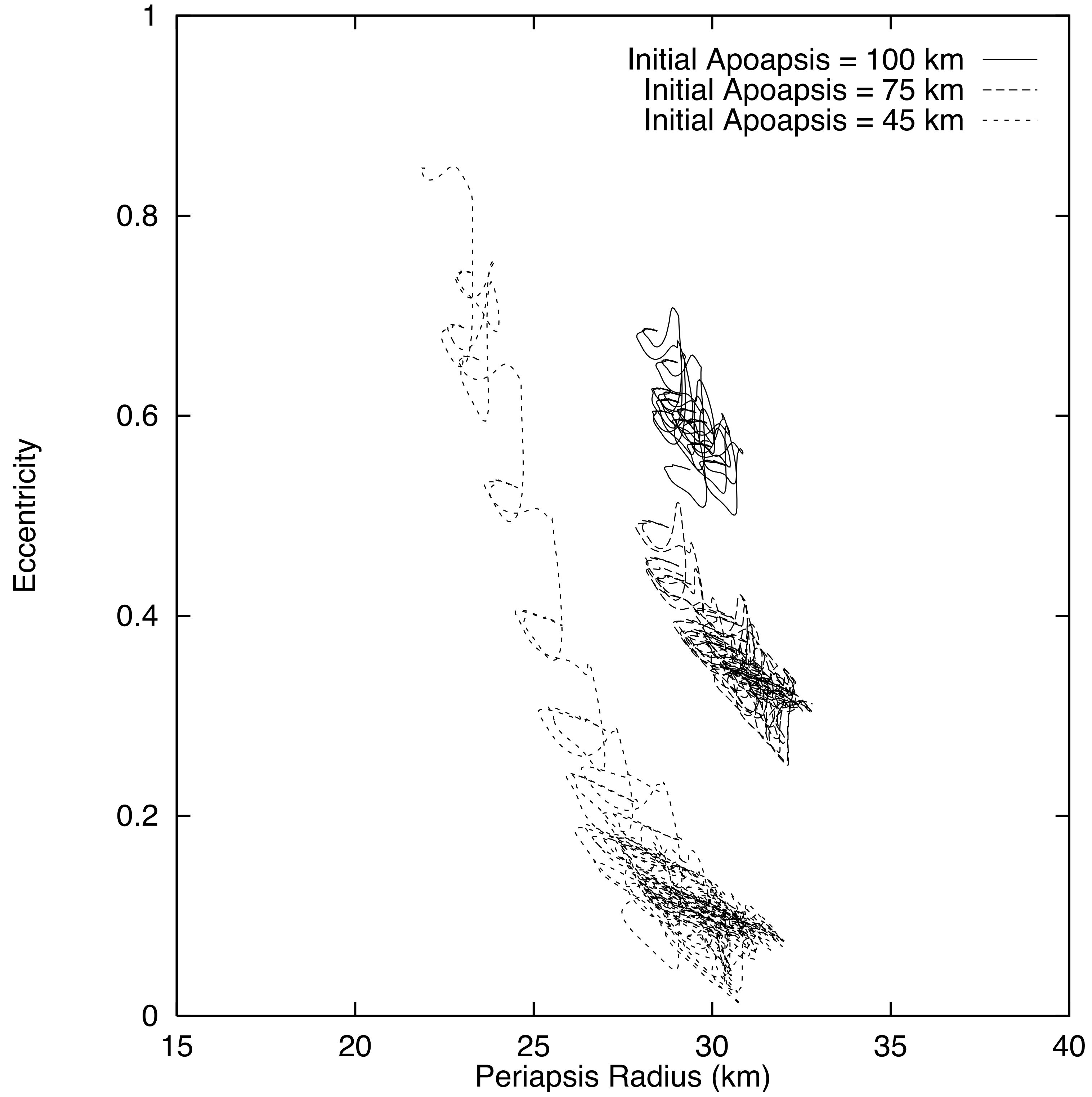
$$I_2^1(r_p, e) = 2 \int_0^{\pi} (1 + e \cos f) \cos(2f - 2\omega t) df$$







Placement of periapsis controls energy gain/loss. High inclination orbits suffer less perturbation



Solar Radiation Pressure Regime

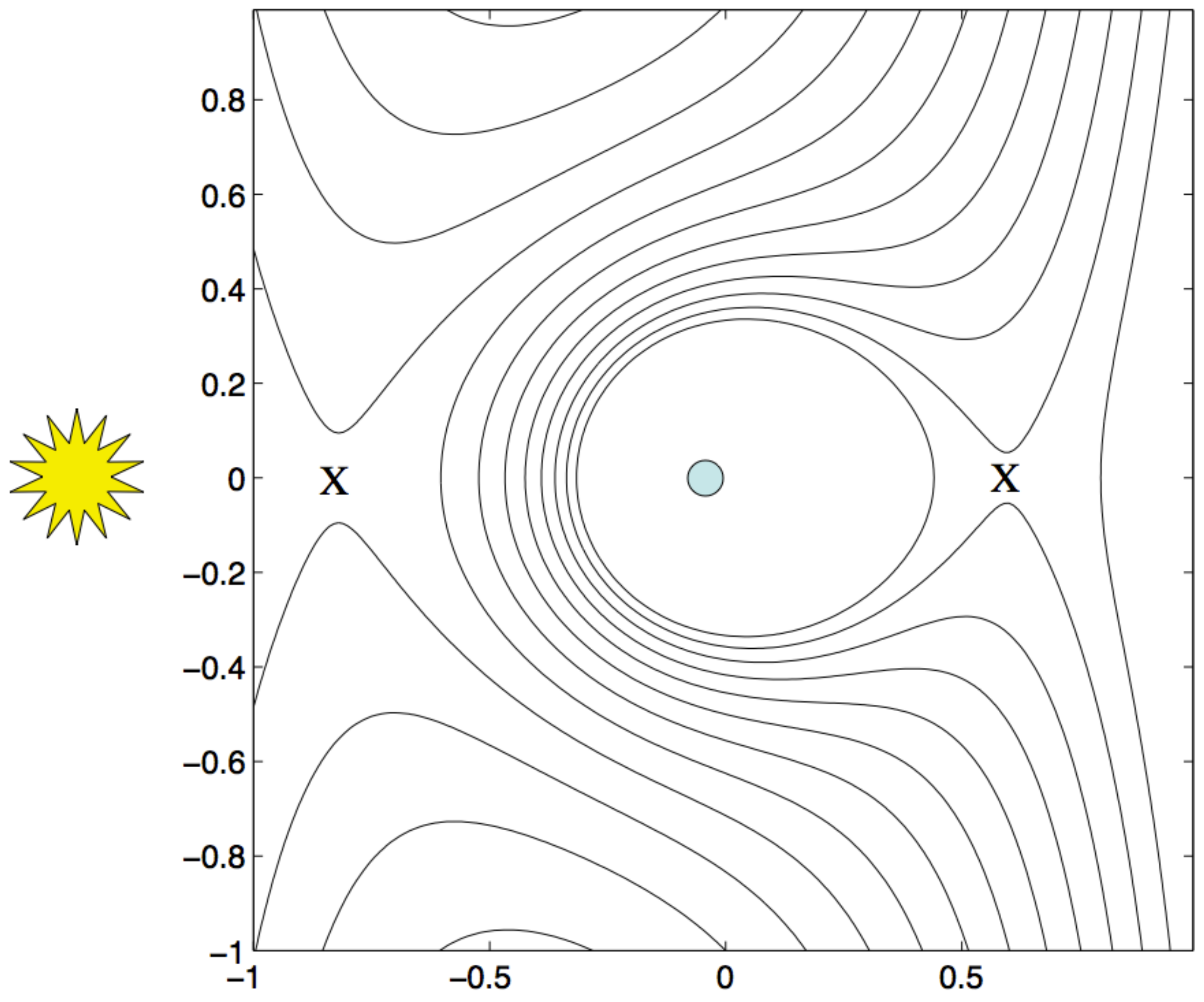
- For small asteroids, the primary perturbation acting on Spacecraft arise from Solar Radiation Pressure (SRP)
  - Area to mass ratio of typical S/C at small bodies are on the order of cm-sized rocks
- SRP controls escape and places limits on semi-major axis for bound motion
- Once bound, averaging solutions accurately describe the S/C motion and suggest mission design solutions
  - Eccentricity and inclination are strongly perturbed by SRP
  - For strong SRP effects, only terminator orbits will be robustly stable
  - Joint effects between SRP and gravity can be strongly destabilizing

Escape Limits

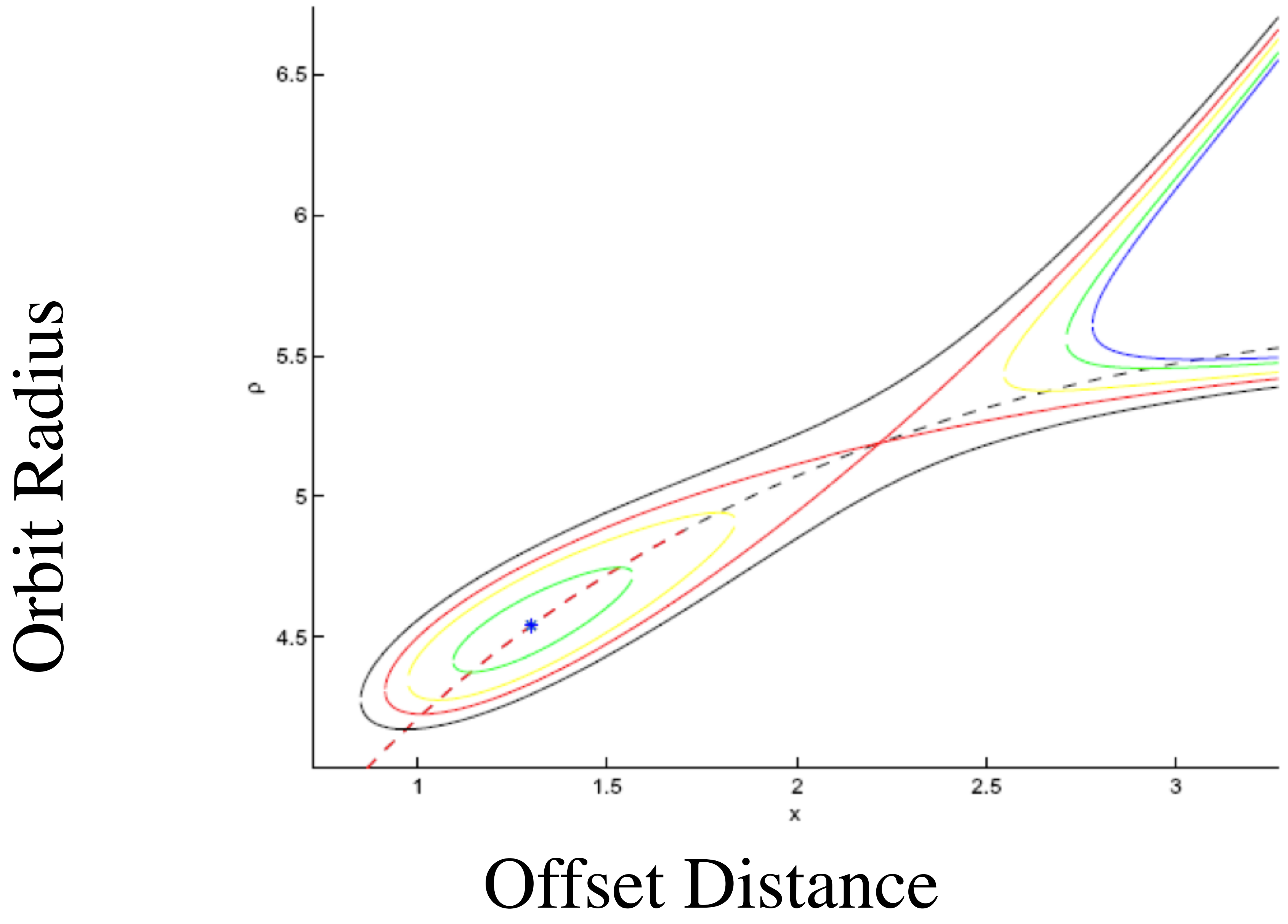
Maximum semi-major axis for bound orbits: $a_{max} \sim \frac{\sqrt{3}}{4}\sqrt{\frac{\mu}{(A/m)P_\Phi}}d$

Semi-major axis remains constant until $a > a_{max}$ and then escapes.

Orbiter traveling towards perihelion can be lost as d decreases.



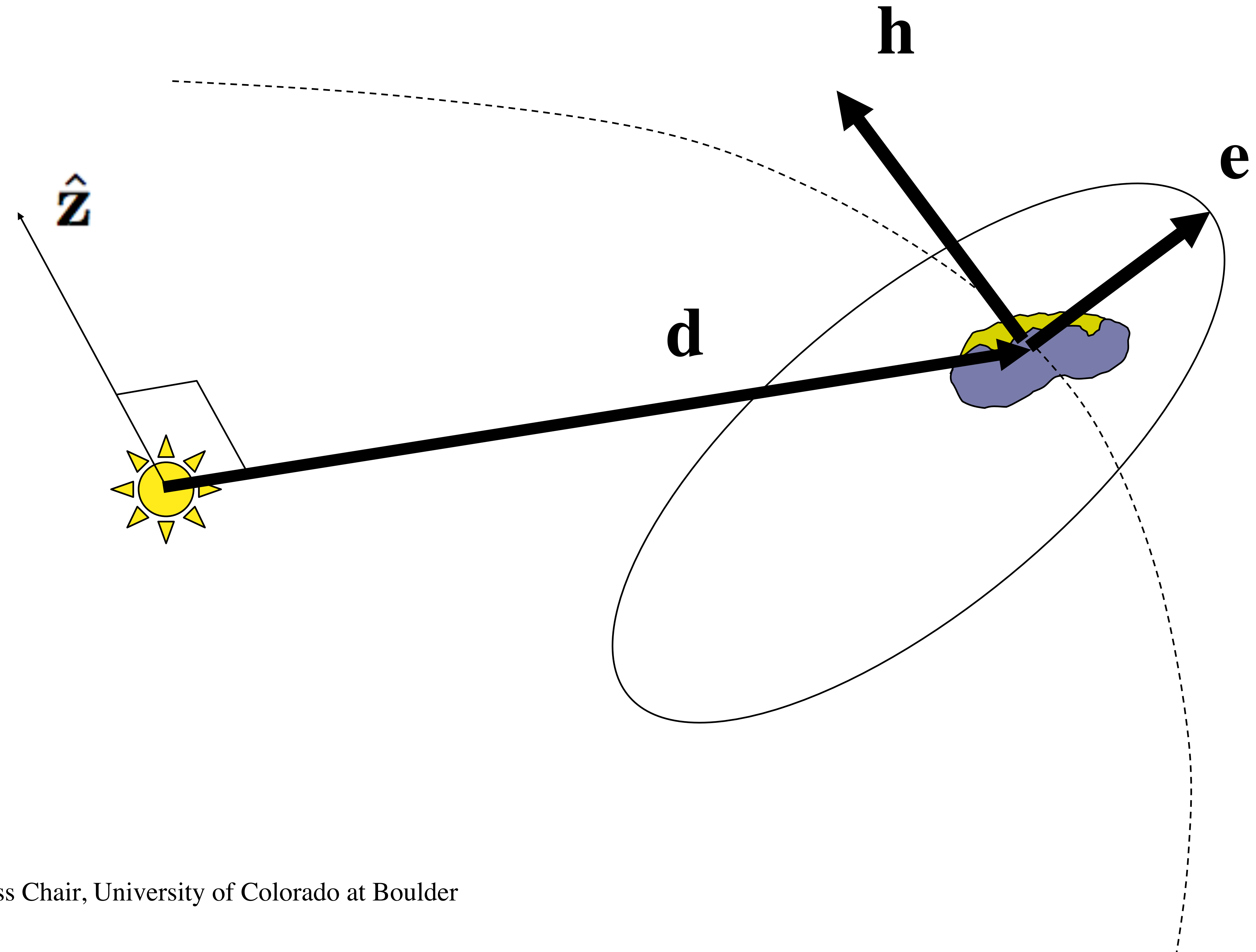
Zero-Velocity Curves in the Elliptic-Restricted SRP Problem



Zero-Velocity Curves in the Non-Rotating SRP Problem

Averaged Orbit Mechanics for SRP

- If $a < a_{max}$ averaging can be applied
  - Semi-major axis a is constant on average
  - Solution is simplest to state using the osculating eccentricity and angular momentum vectors
  - Dynamics of the eccentricity and angular momentum are described by a 6x6 orthonormal rotation



$$\begin{aligned} a &= \text{Constant} \\ |\mathbf{h}| &= \sqrt{1-e^2} \\ |\mathbf{e}| &= e \\ \mathbf{e}\cdot\mathbf{h} &= 0 \\ \mathbf{e}\cdot\mathbf{e}+\mathbf{h}\cdot\mathbf{h} &= 1 \end{aligned}$$

Averaged SRP Equations

- In a frame rotating with the sun-line, with the heliocentric orbit true anomaly as the independent parameter:

$$\begin{bmatrix} \mathbf{e}' \\ \mathbf{h}' \end{bmatrix} = \left[\begin{array}{ccc|ccc} 0 & 1 & 0 & 0 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 & -\tan\Lambda \\ 0 & 0 & 0 & 0 & \tan\Lambda & 0 \\ \hline 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & -\tan\Lambda & -1 & 0 & 0 \\ 0 & \tan\Lambda & 0 & 0 & 0 & 0 \end{array}\right] \begin{bmatrix} \mathbf{e} \\ \mathbf{h} \end{bmatrix}$$

$$\tan\Lambda = \frac{3P_\Phi(A/m)}{2}\sqrt{\frac{a}{\mu\mu_{sun}a_{sun}(1-e_{sun}^2)}}$$

  - For a strong perturbation, $\Lambda \to \pi/2$
  - For a weak perturbation, $\Lambda \to 0$
  - OSIRIS-REx at Bennu, $\Lambda \sim 87°$
  - NEAR at Eros, $\Lambda \sim 13°$

Solution to the SRP Eqns

- A Linear, Time Invariant System, its solution can be expressed as:

$$\begin{bmatrix} \mathbf{e} \\ \mathbf{h} \end{bmatrix} = \Phi(\nu / \cos\Lambda) \begin{bmatrix} \mathbf{e}_o \\ \mathbf{h}_o \end{bmatrix}$$

– Φ is a 6x6 orthonormal rotation matrix, periodic with period $2\pi/\cos(\Lambda)$

$$\begin{aligned} \Phi(\psi) &= \cos(\psi) I_{6\times 6} + \\ & [1-\cos(\psi)] \begin{bmatrix} \cos^2\Lambda \hat{\mathbf{z}}\hat{\mathbf{z}} + \sin^2\Lambda \hat{\mathbf{d}}\hat{\mathbf{d}} & -\sin\Lambda\cos\Lambda\left(\hat{\mathbf{z}}\hat{\mathbf{d}} + \hat{\mathbf{d}}\hat{\mathbf{z}}\right) \\ -\sin\Lambda\cos\Lambda\left(\hat{\mathbf{z}}\hat{\mathbf{d}} + \hat{\mathbf{d}}\hat{\mathbf{z}}\right) & \cos^2\Lambda \hat{\mathbf{z}}\hat{\mathbf{z}} + \sin^2\Lambda \hat{\mathbf{d}}\hat{\mathbf{d}} \end{bmatrix} \\ & + \sin(\psi) \begin{bmatrix} -\cos\Lambda \tilde{\hat{\mathbf{z}}} & \sin\Lambda \tilde{\hat{\mathbf{d}}} \\ \sin\Lambda \tilde{\hat{\mathbf{d}}} & -\cos\Lambda \tilde{\hat{\mathbf{z}}} \end{bmatrix} \end{aligned}$$

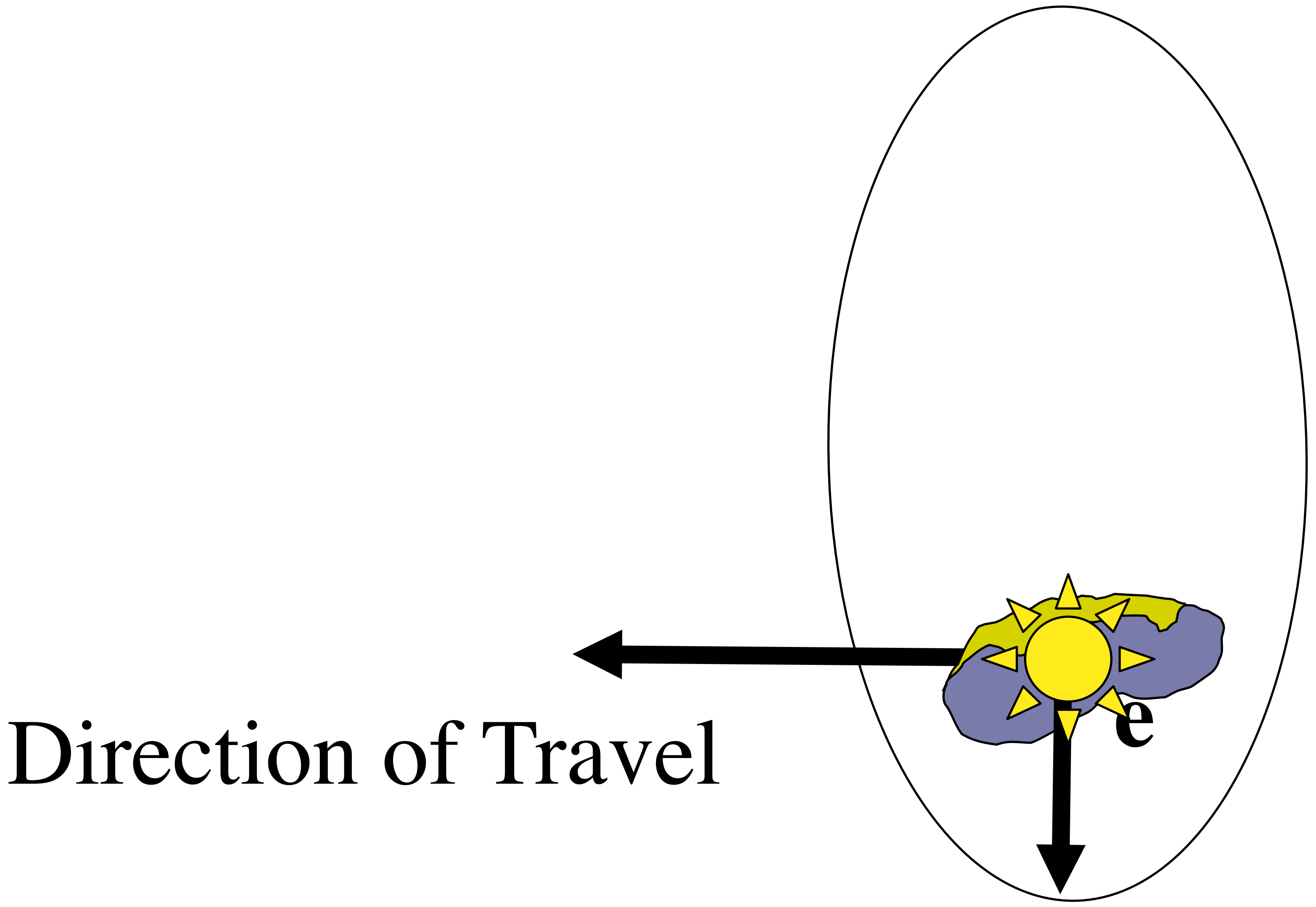
– Secular motion is periodic in true anomaly with period $2\pi/\cos(\Lambda)$

– Orbital evolution changes drastically as a function of Λ

– Application of this simple result has provided deep insight into previously unexplained orbital phenomenon in GEOsynchronous orbit, applies to the motion of ejected particles at Bennu

Solar Plane-of-Sky / Terminator Orbits

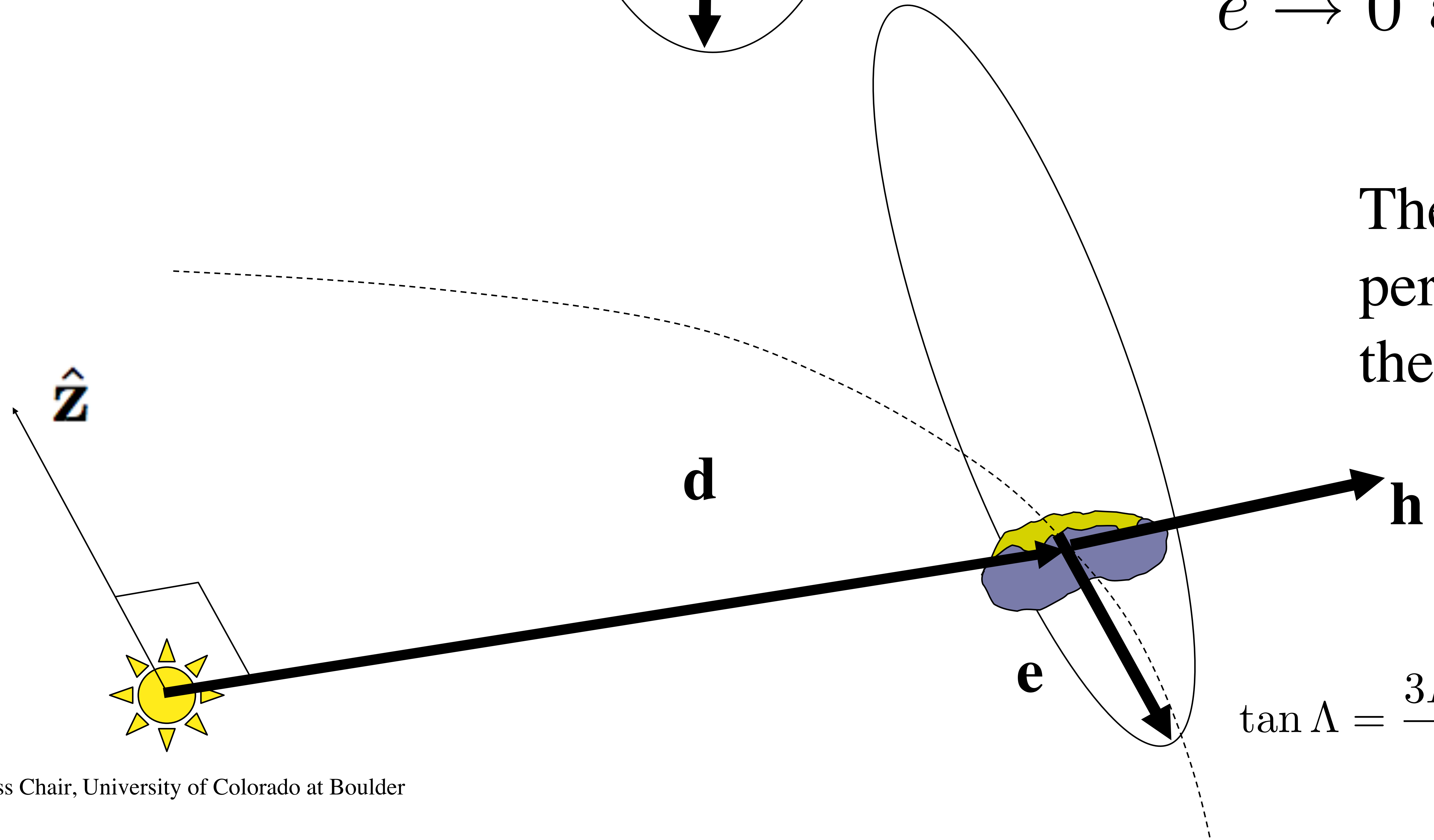
A particularly useful "frozen orbit" solution to these equations are the terminator orbits with properly chosen argument of periapsis and eccentricity.



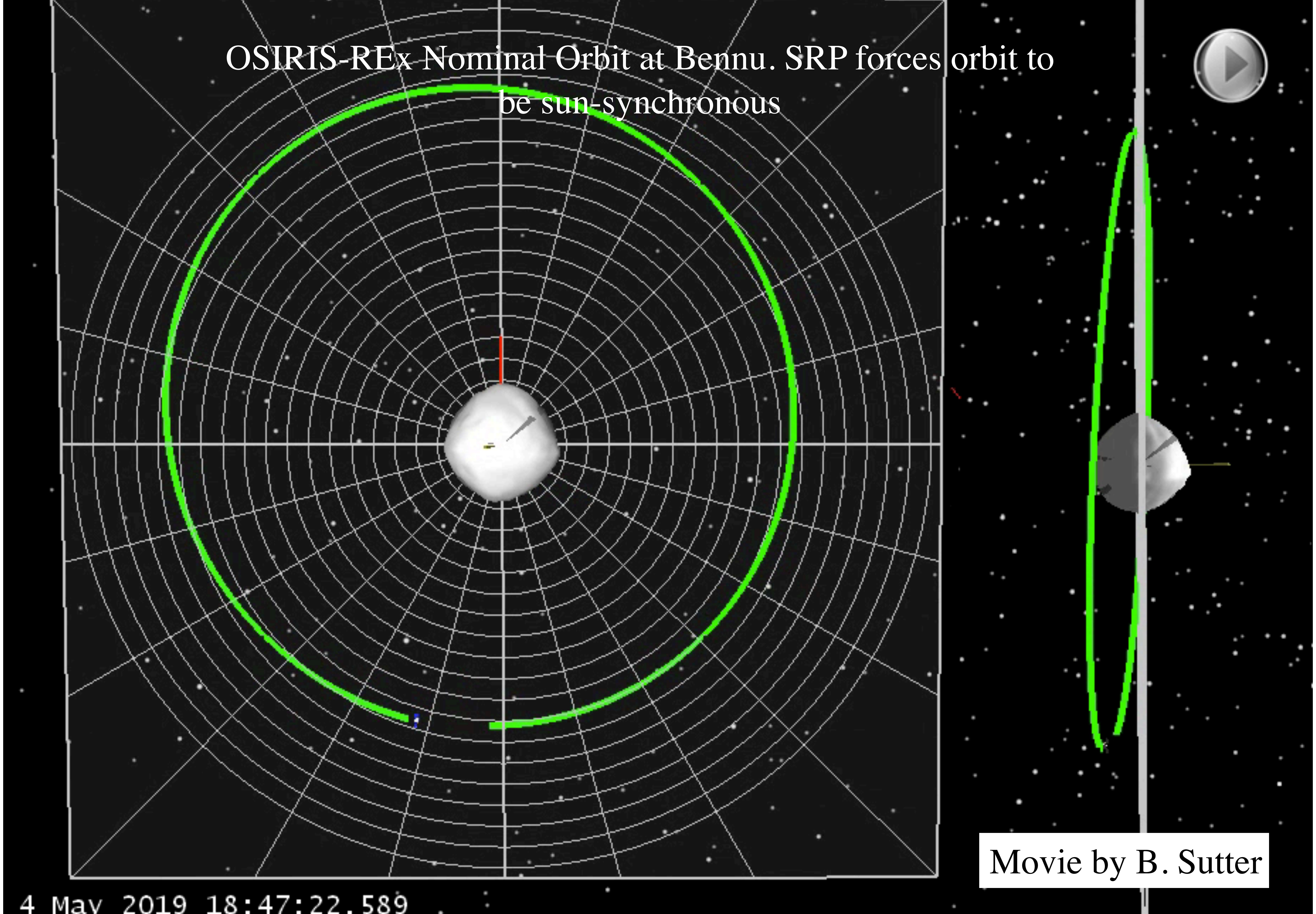
$$e = \cos \Lambda$$

$$e \rightarrow 0 \text{ as } \Lambda \rightarrow \pi/2$$

The stronger the SRP perturbation, the more circular these frozen orbits become.



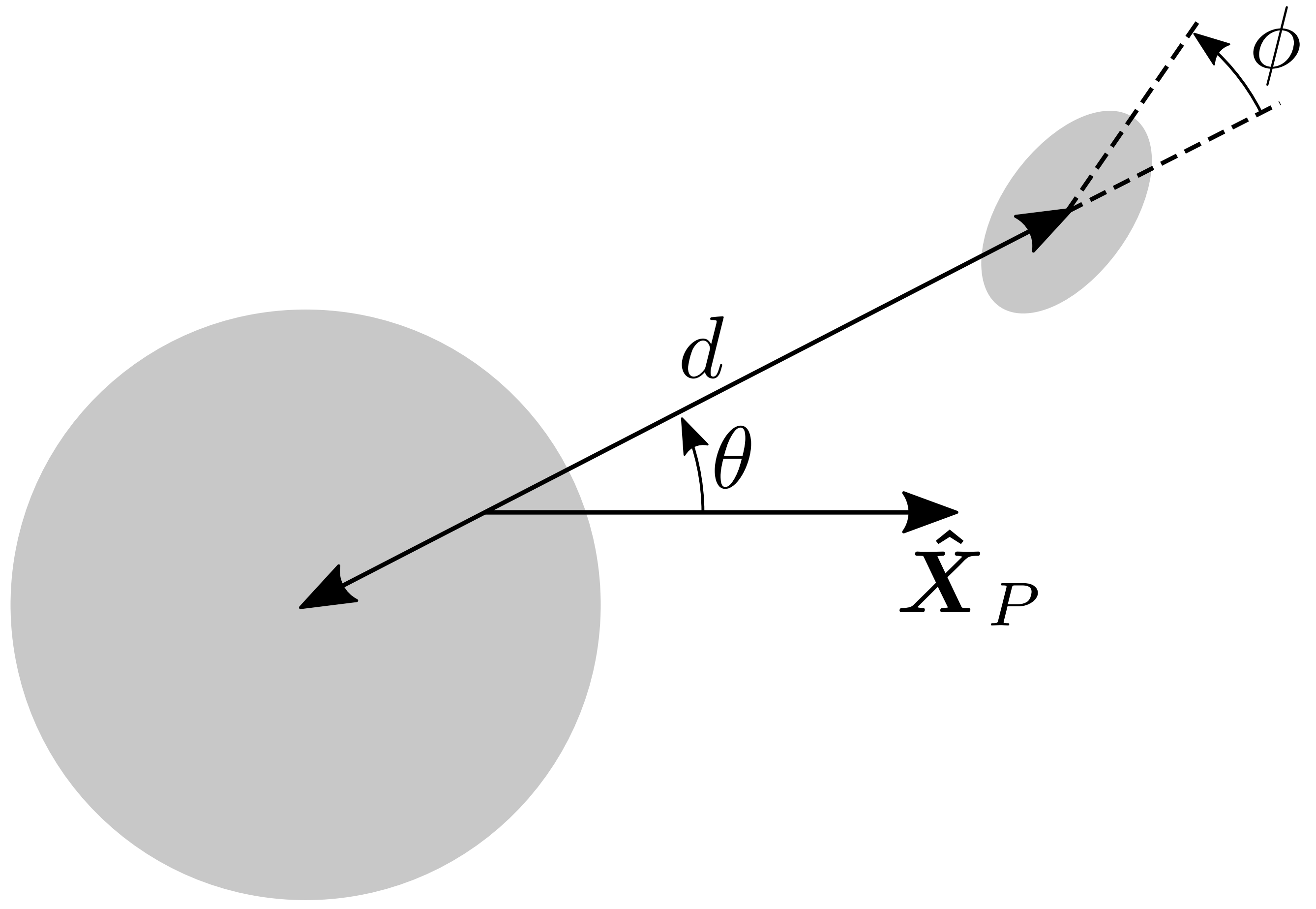
$$\tan \Lambda = \frac{3P_\Phi(A/m)}{2}\sqrt{\frac{a}{\mu\mu_{sun}a_{sun}(1-e_{sun}^2)}}$$

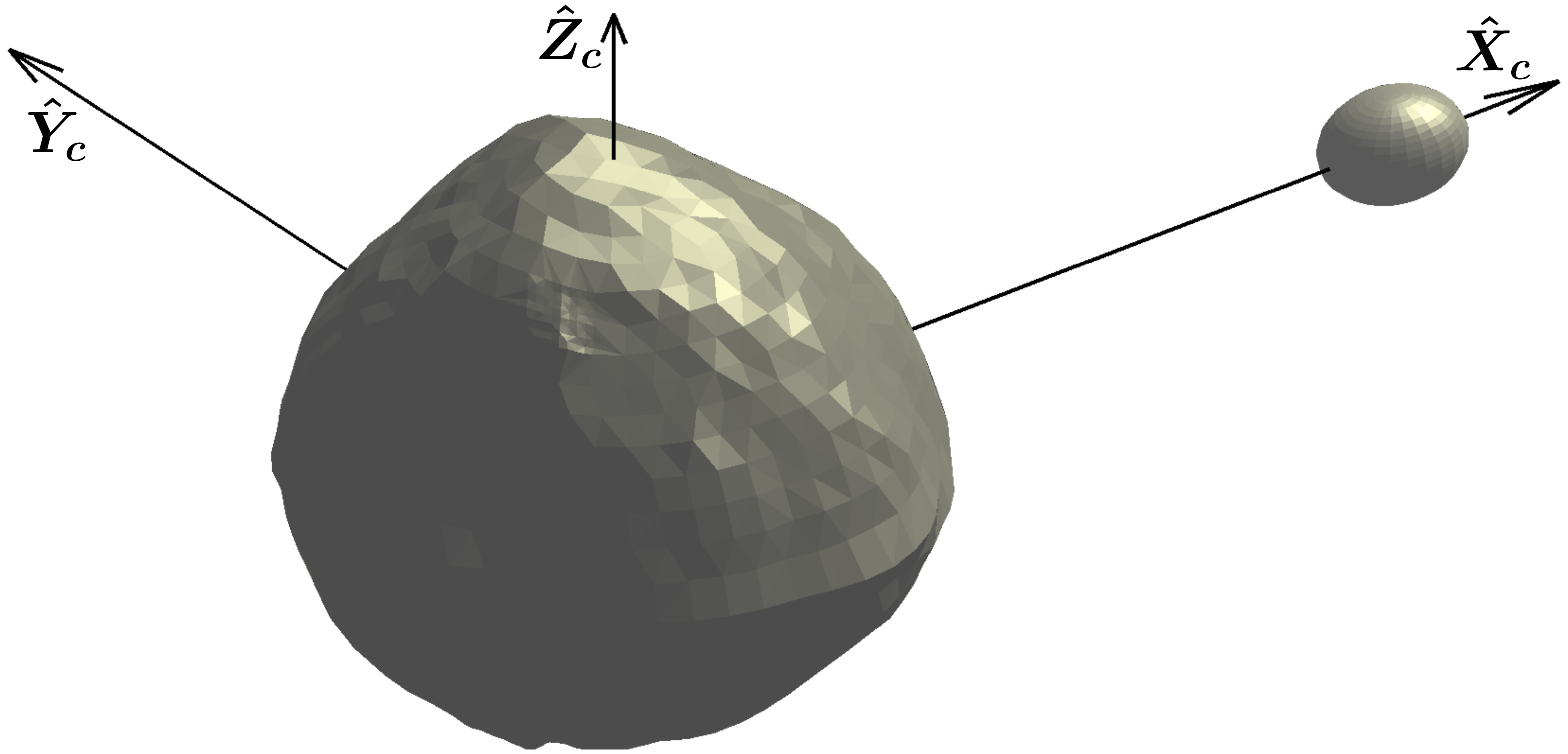

OSIRIS-REx Nominal Orbit at Bennu. SRP forces orbit to be sun-synchronous
Movie by B. Sutter
4 May 2019 18:47:22.589

Application to a Binary Asteroid System

Binary System Model

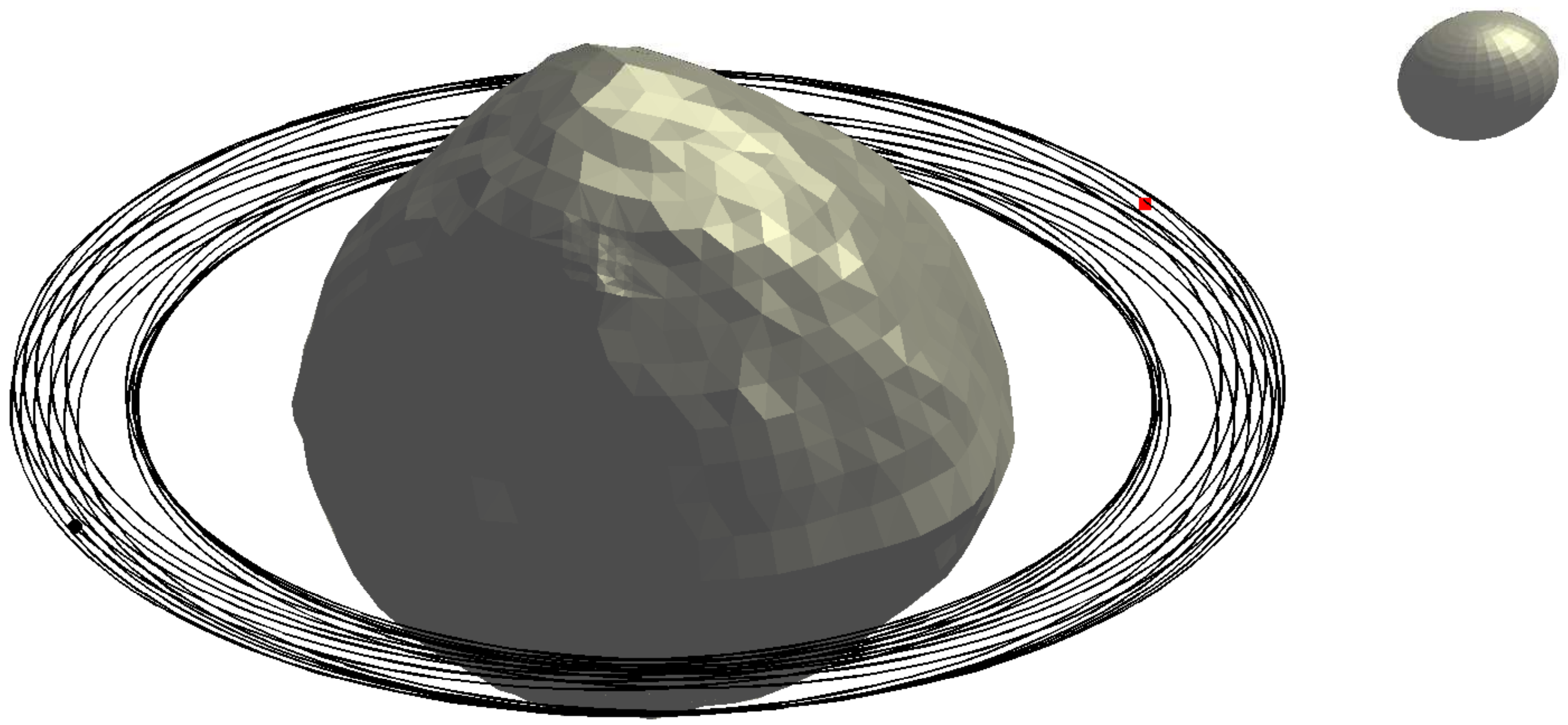
- We assume a fully-dynamic Didymos system
  - oblate Didymos primary
  - ellipsoidal Didymos secondary with zero inclination but non-zero libration
  - Full coupling between planar orbit and rotation of the Didymos system
  - Assumes:
    - a 180° obliquity of system
    - Current heliocentric orbit elements of Didymos





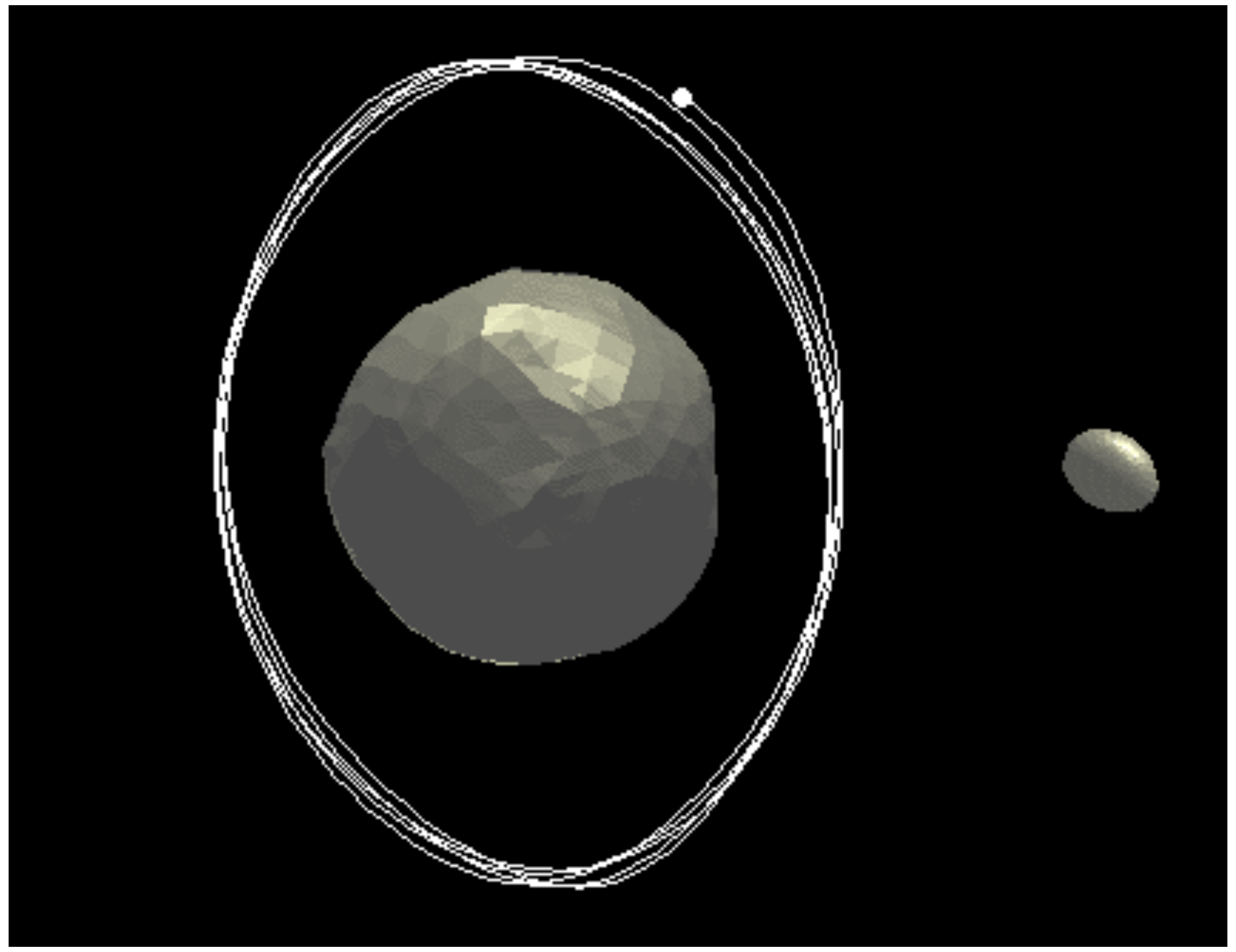
Spacecraft Dynamics Model

- Equations of motion about the binary asteroid system center of mass incorporating all relevant perturbations:
  - Full polyhedron shape model gravity of Didymos primary
  - Ellipsoidal gravity field model of Didymos secondary
  - Full dynamic coupling between the binary members
  - Solar Gravity and Didymos orbital motion
  - Solar radiation pressure on S/C (Mass to area ratio ~ 30 kg/m^2 similar to NEAR & Hayabusa)

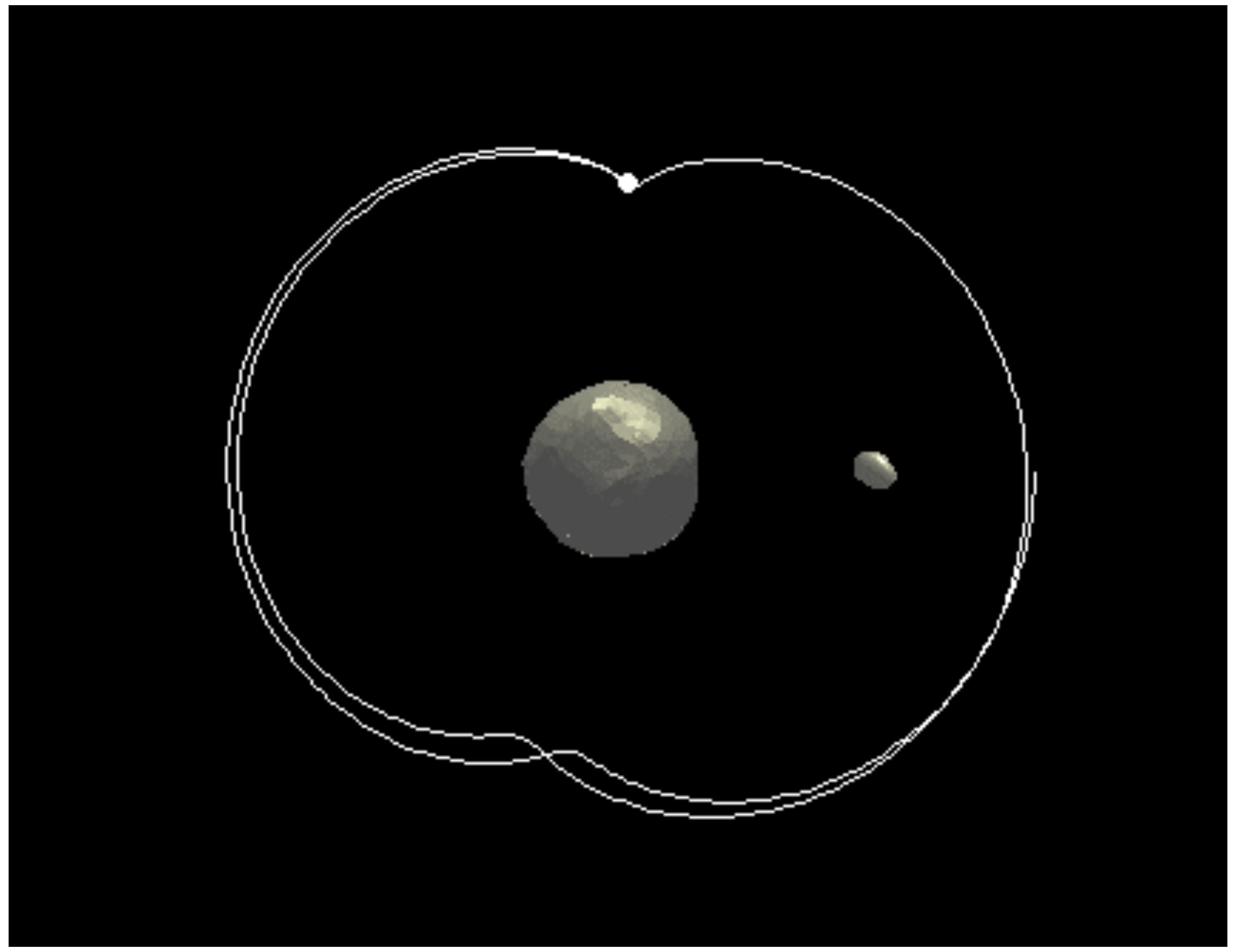


We surveyed many possible orbits…

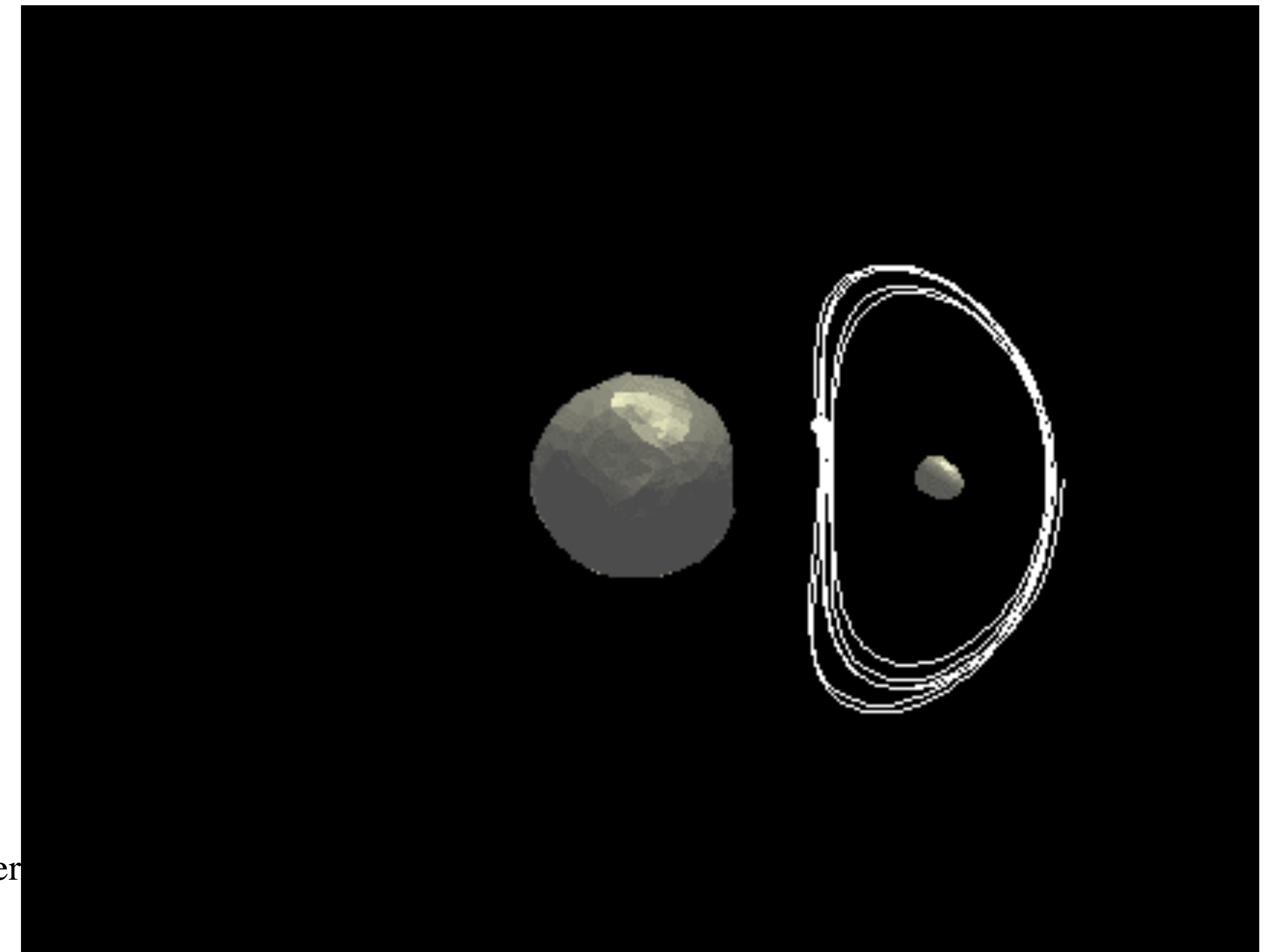
Direct Interior



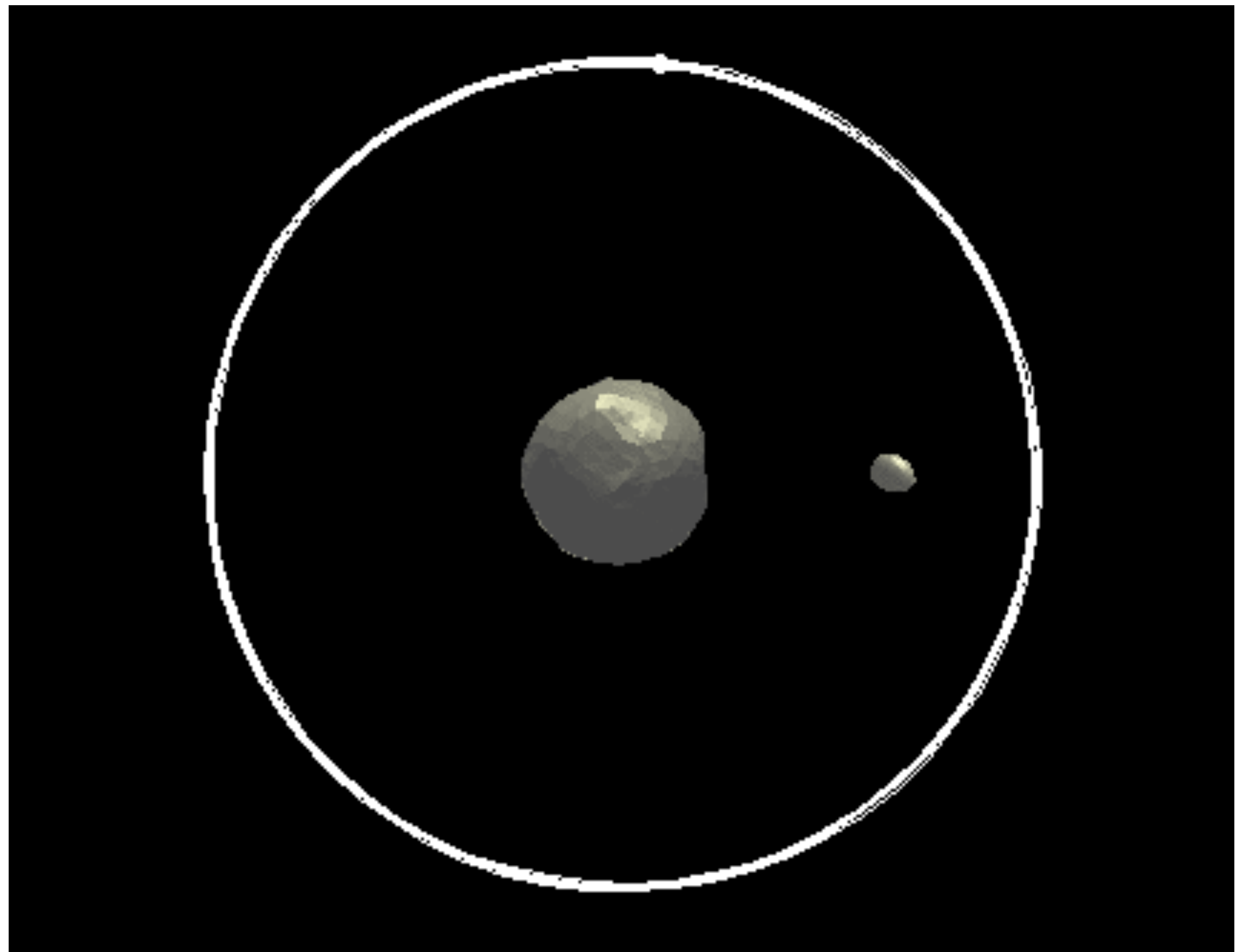
Direct Exterior



Retrograde Secondary

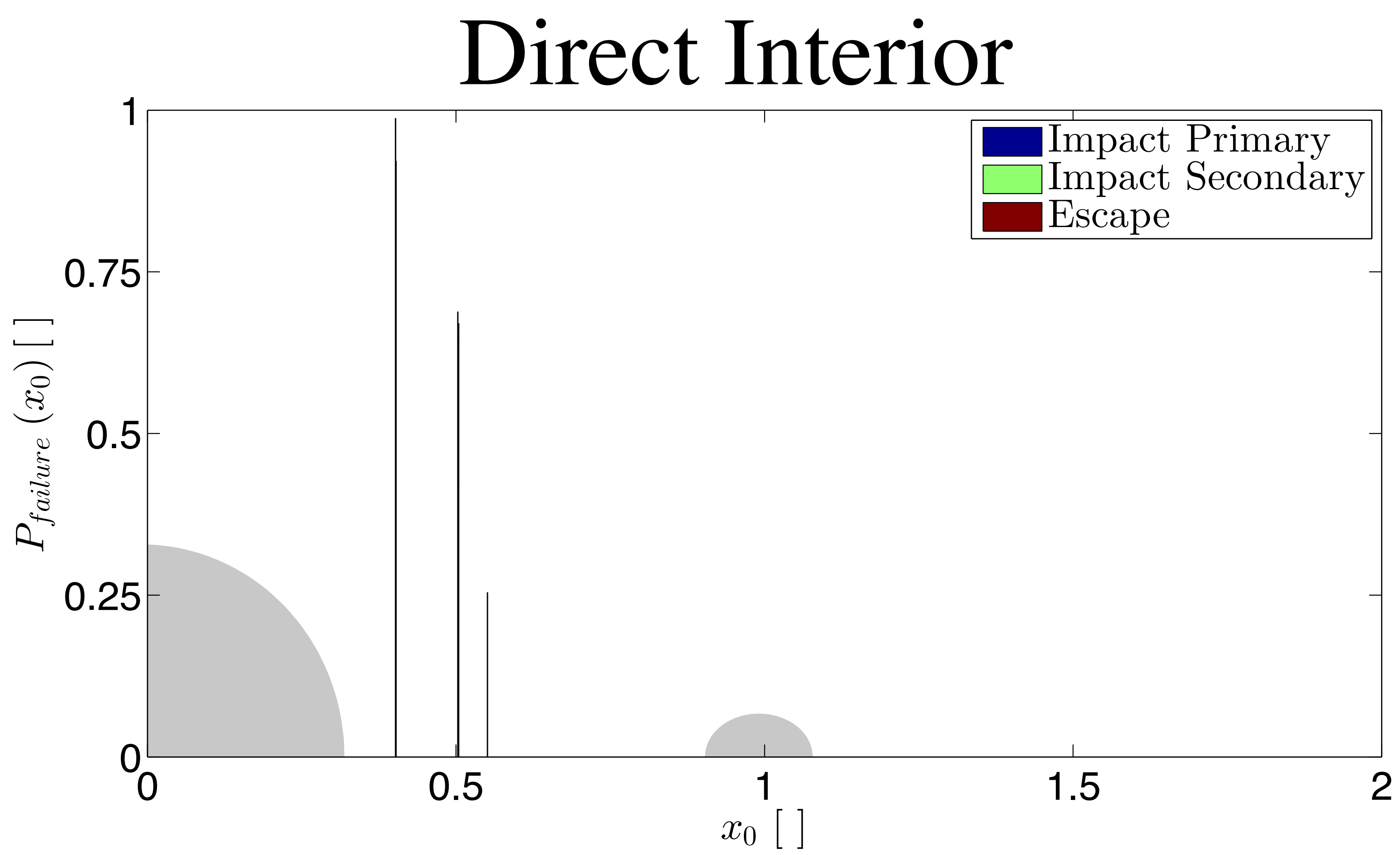


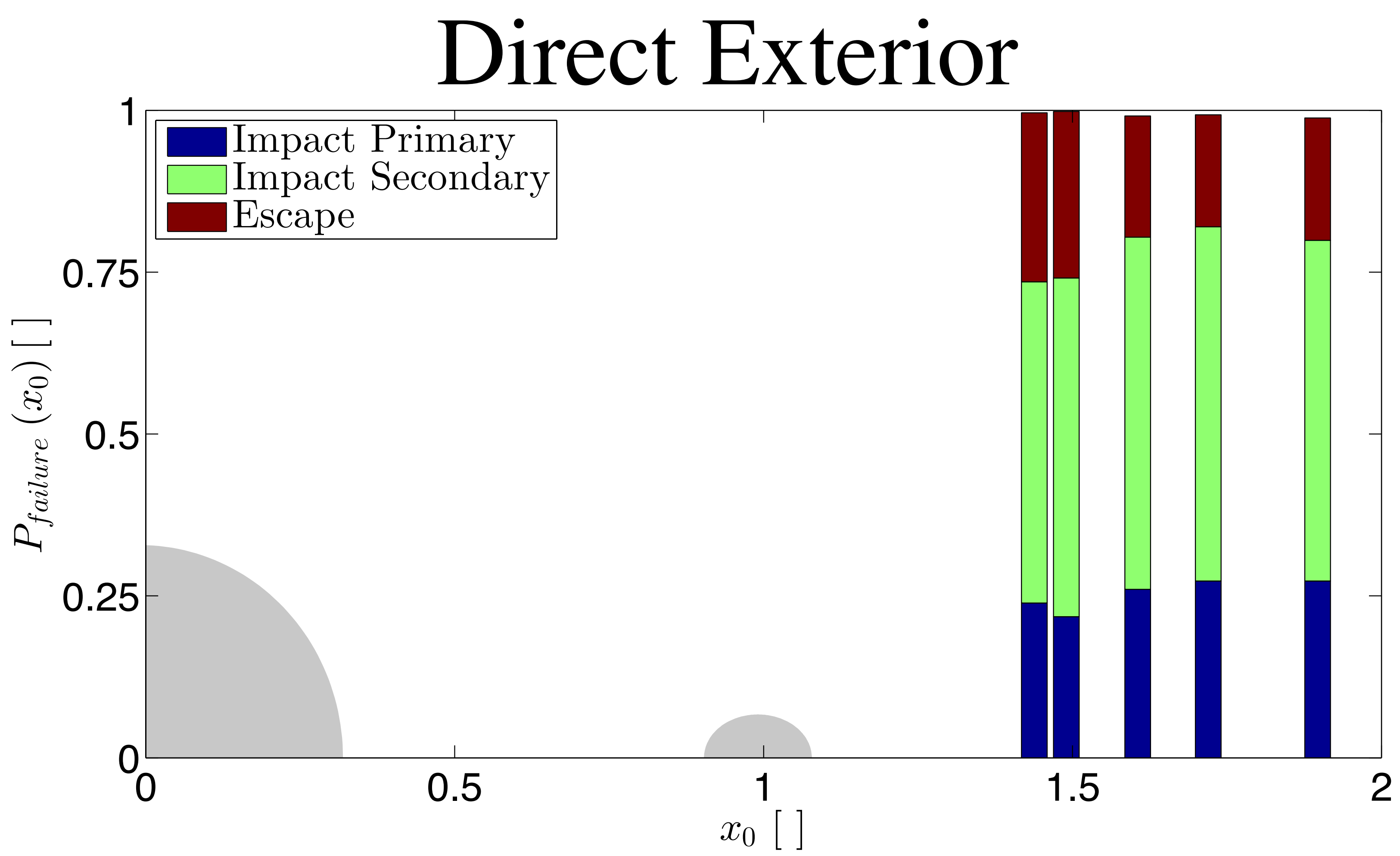
Retrograde Exterior

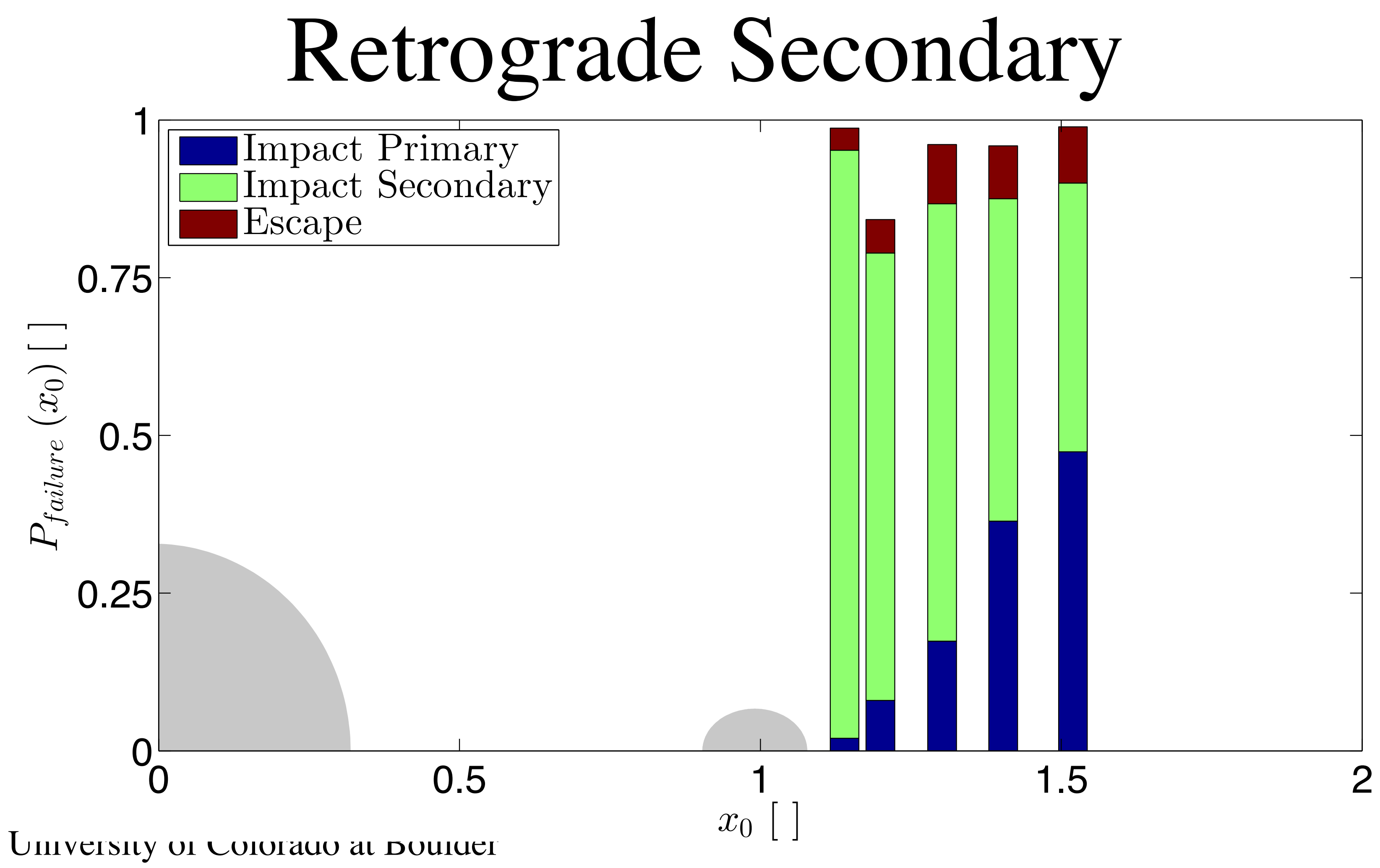


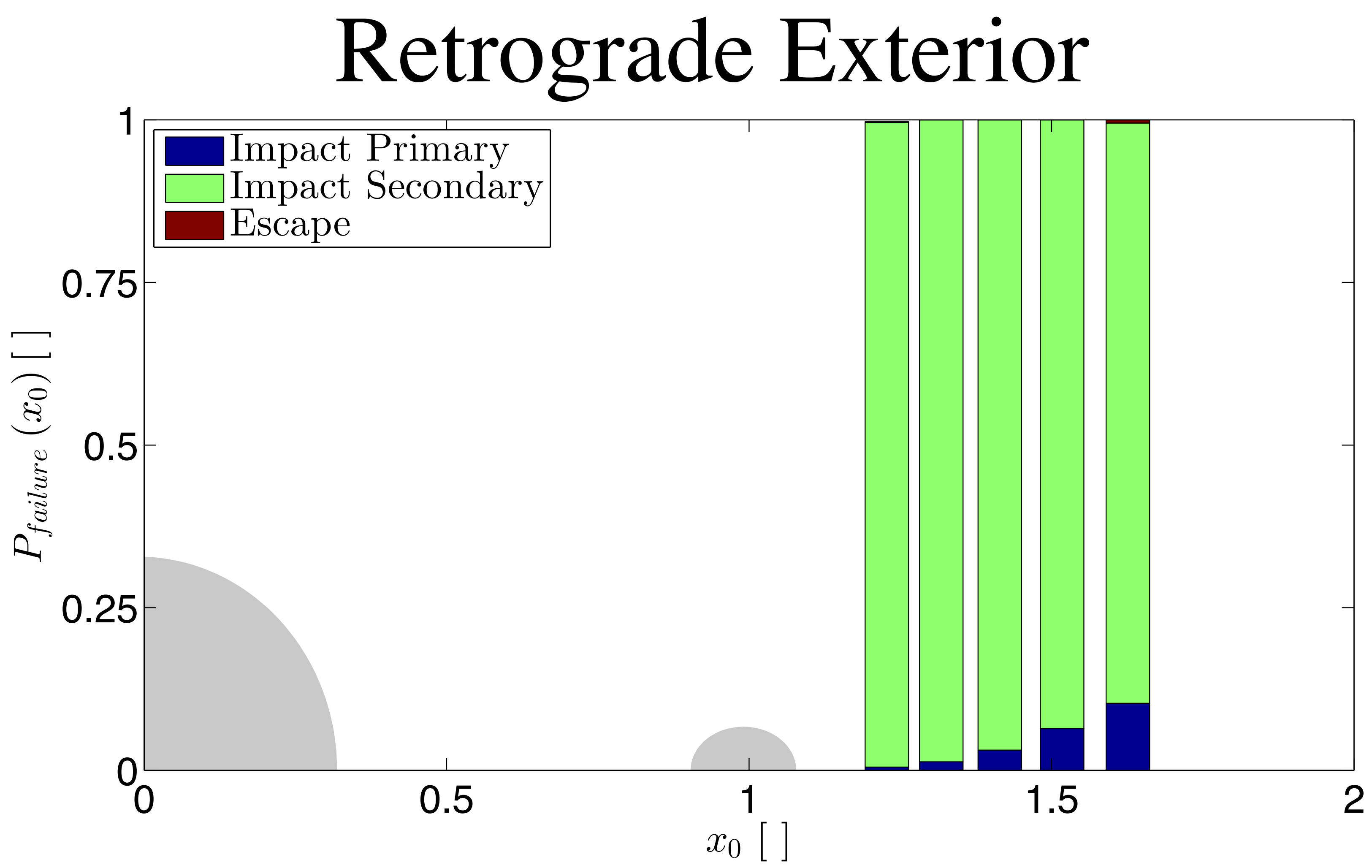
… but most were not suitable or safe

- All other in-plane orbits perform poorly with most impacting or escaping



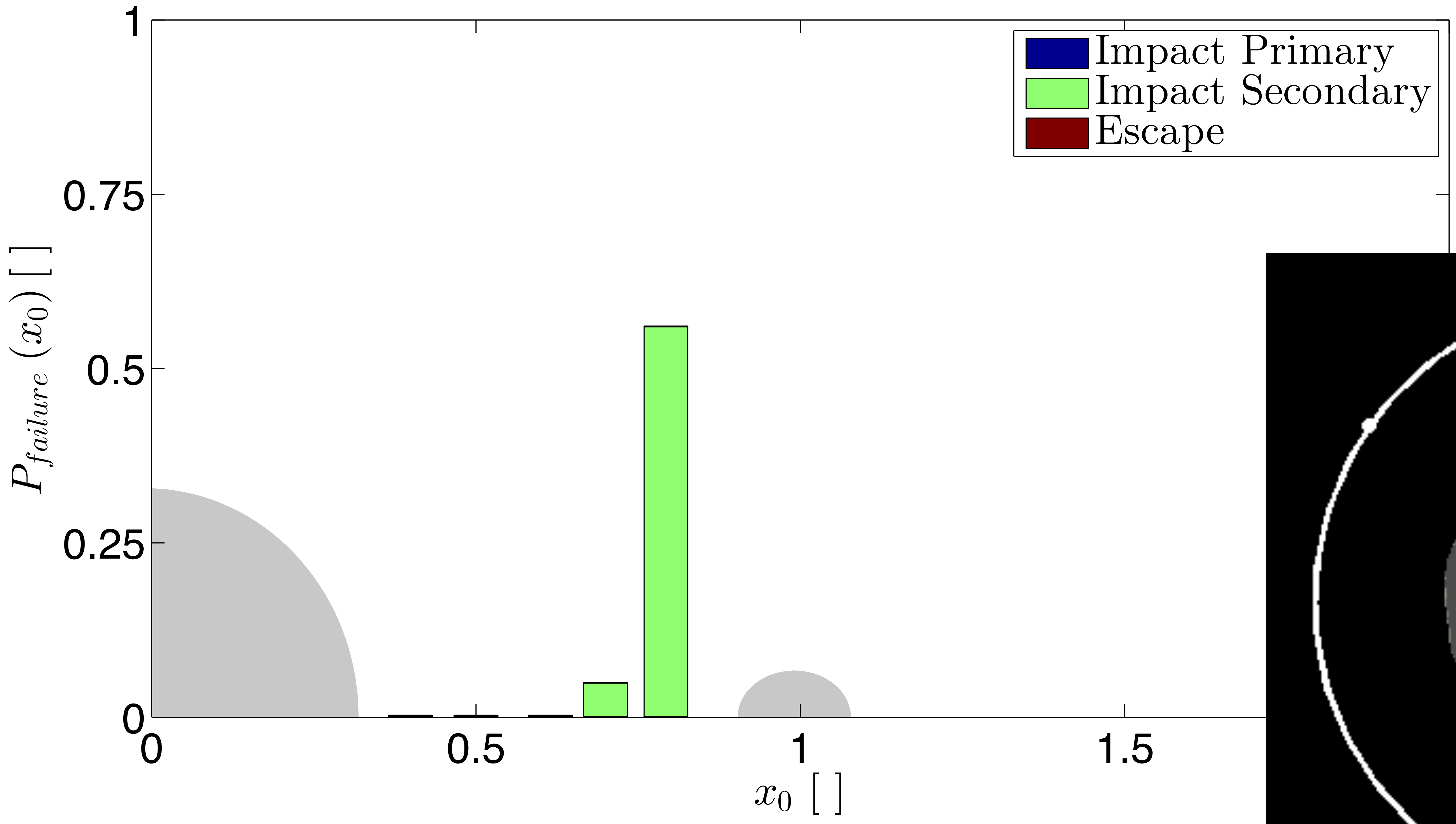


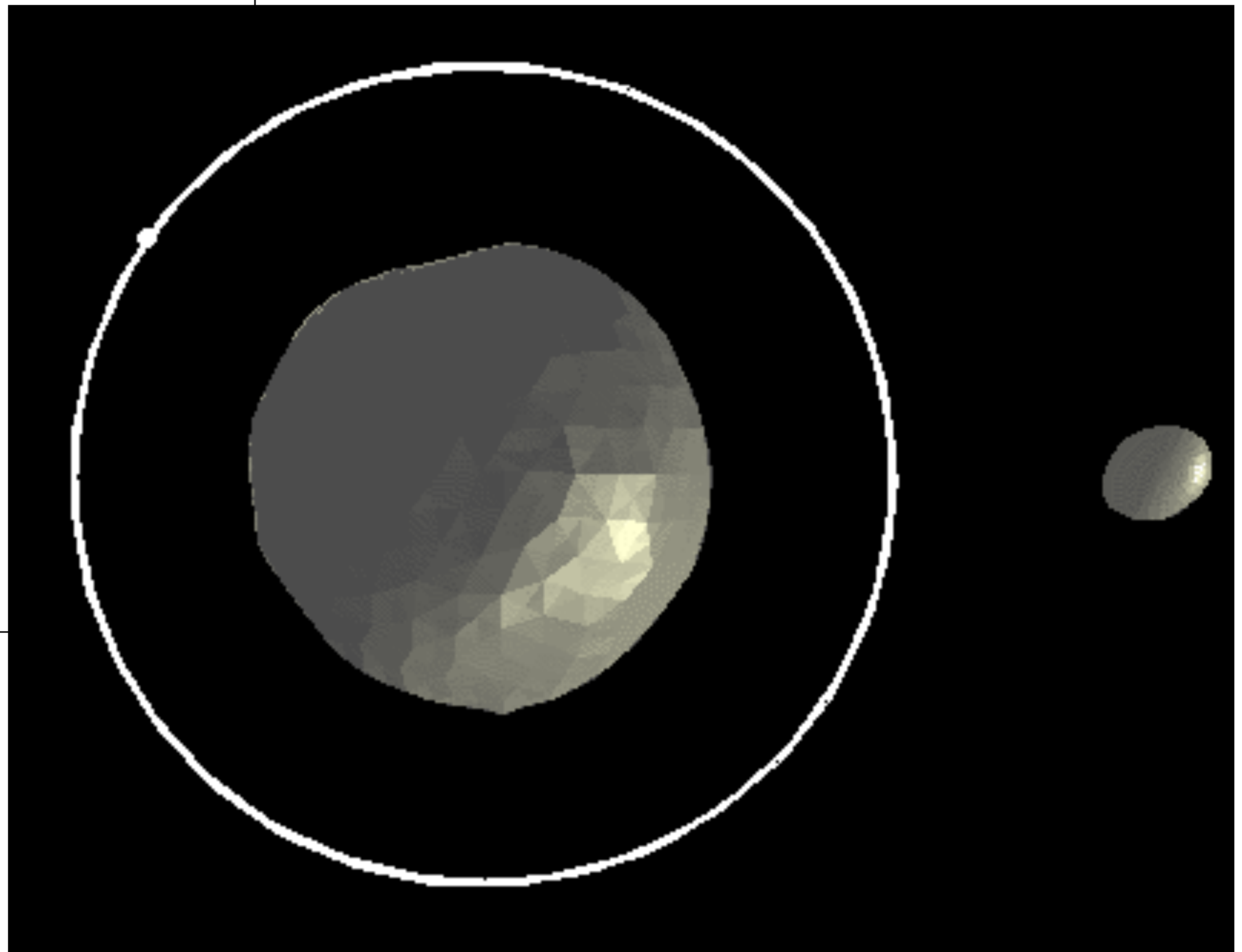




Best Planar Orbits

- Interior, Retrograde:
  - Issues include limited viewing angles, periods of shadow
  - Advantages include robust stability, close-in dynamical sensitivity to gravity field





Best Terminator Orbits

- Terminator orbits between ~1.75 and 6.25 km are stable
  - Orbits naturally track the sun (i.e., are sun synchronous) due to SRP
  - Similar to the OSIRIS-REx terminator orbits, but cannot get as close
  - Provide a safe / stable observing platform, enable gravity science
  - Do not require correction maneuvers to maintain stability

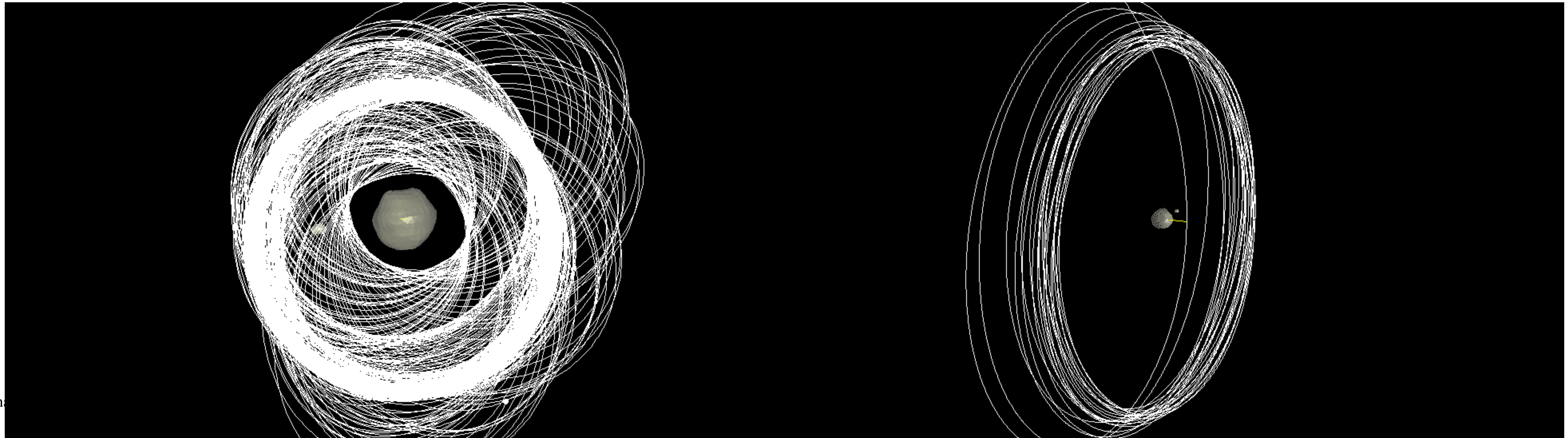
1.75 km orbit 3.5 km orbit

Too close or too far terminators…

- Terminator orbits can also be destabilized by:
  - Resonant interactions with the system gravity field
  - Too close to the system, leading to strong perturbations from the secondary and primary gravity field
  - Too large orbits can be stripped out of orbit during perihelion passage

2:1 Mean Motion Resonance
Semi-Major axis ~ 1.95 km

7 km orbit



In recent years there has been a considerable increase in interest in sending space probes to minor Solar System bodies such as asteroids and comets. This new field of investigation has been spurred on by the discovery of many binary asteroid systems and Kuiper Belt objects. However, the motion of spacecraft about such small Solar System bodies is not only extremely complex, but is a challenging problem that spans the fields of celestial mechanics, dynamical astronomy and astrodynamics.

Orbital Motion in Strongly Perturbed Environments

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- brings together in a single volume a wide range of mathematical, scientific and engineering material;
- shows how a particular practical problem in orbital mechanics may only be solved through careful consideration of all the major classical problems and techniques in astrodynamics;
- discusses a range of space mission design problems and uses case studies to demonstrate the practical solutions for some specific small body missions.

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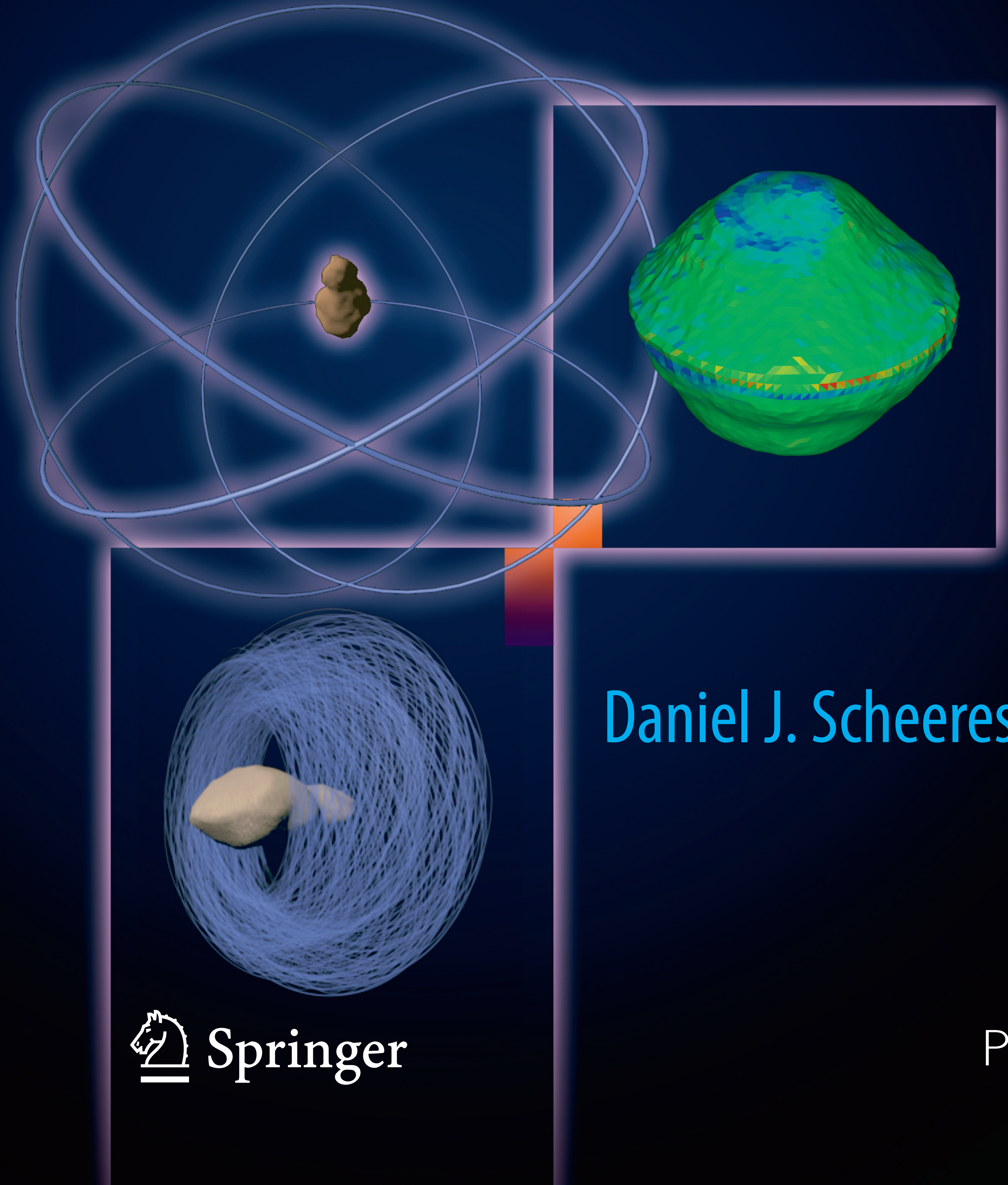
Applications to Asteroid, Comet and Planetary Satellite Orbiters



Daniel J. Scheeres

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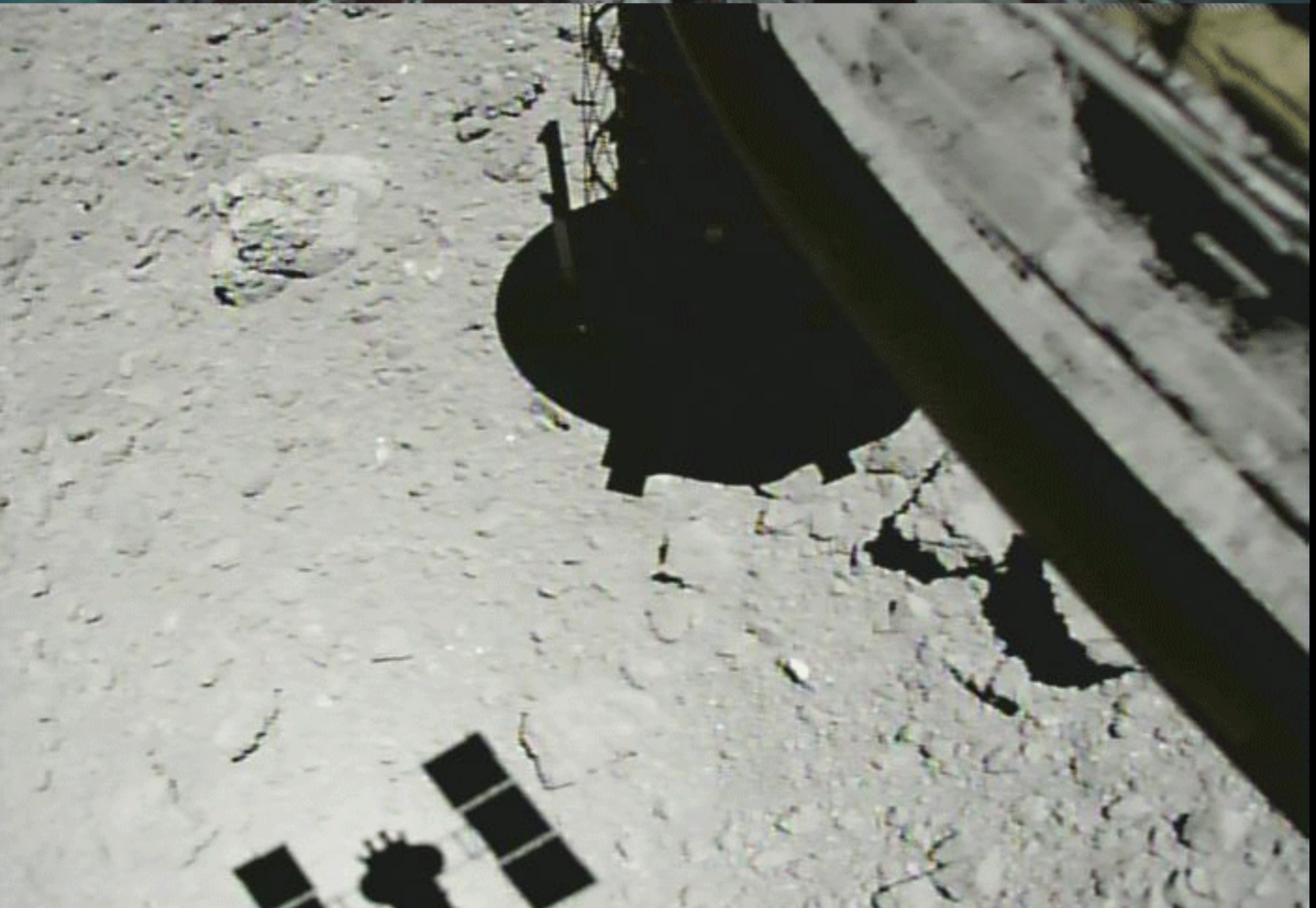
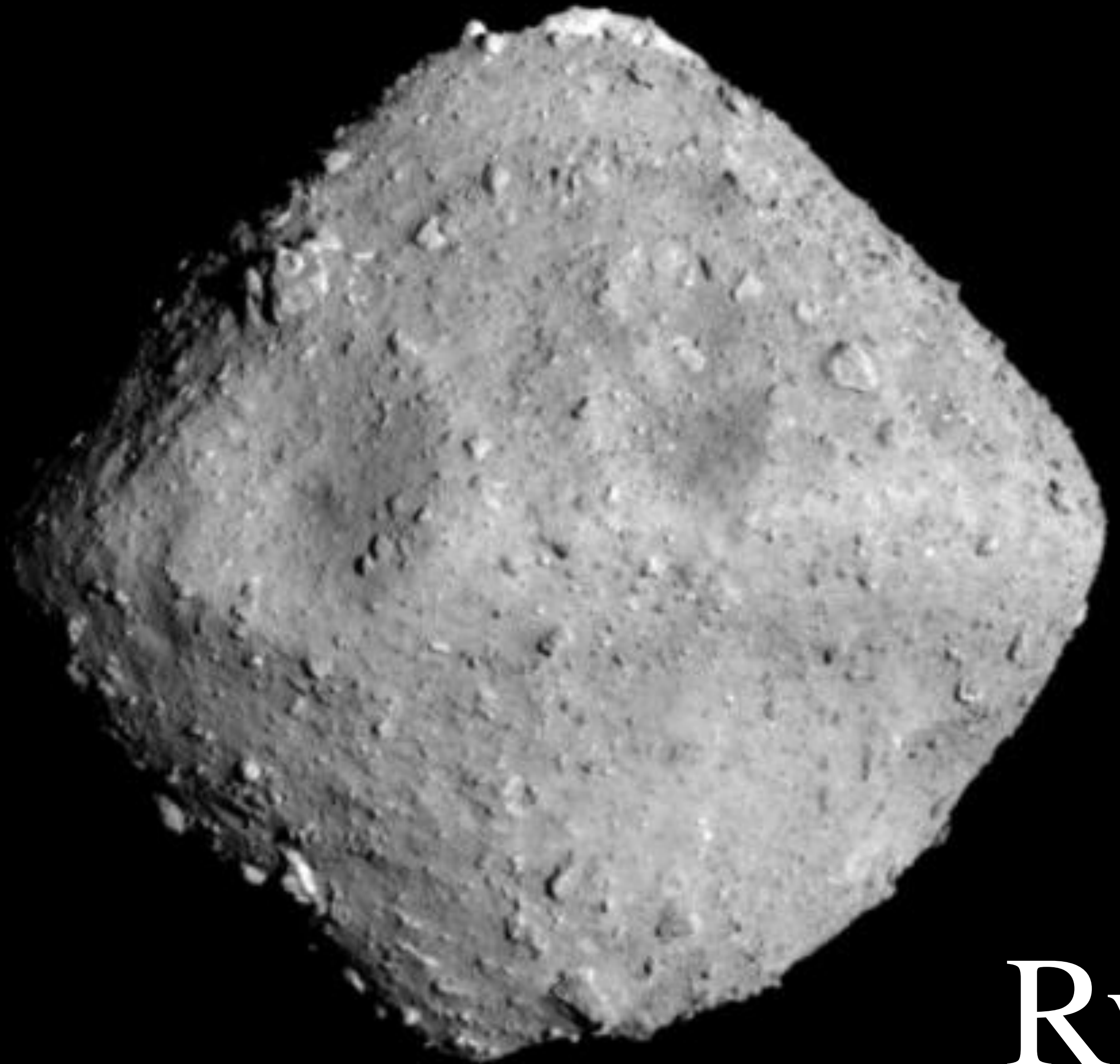
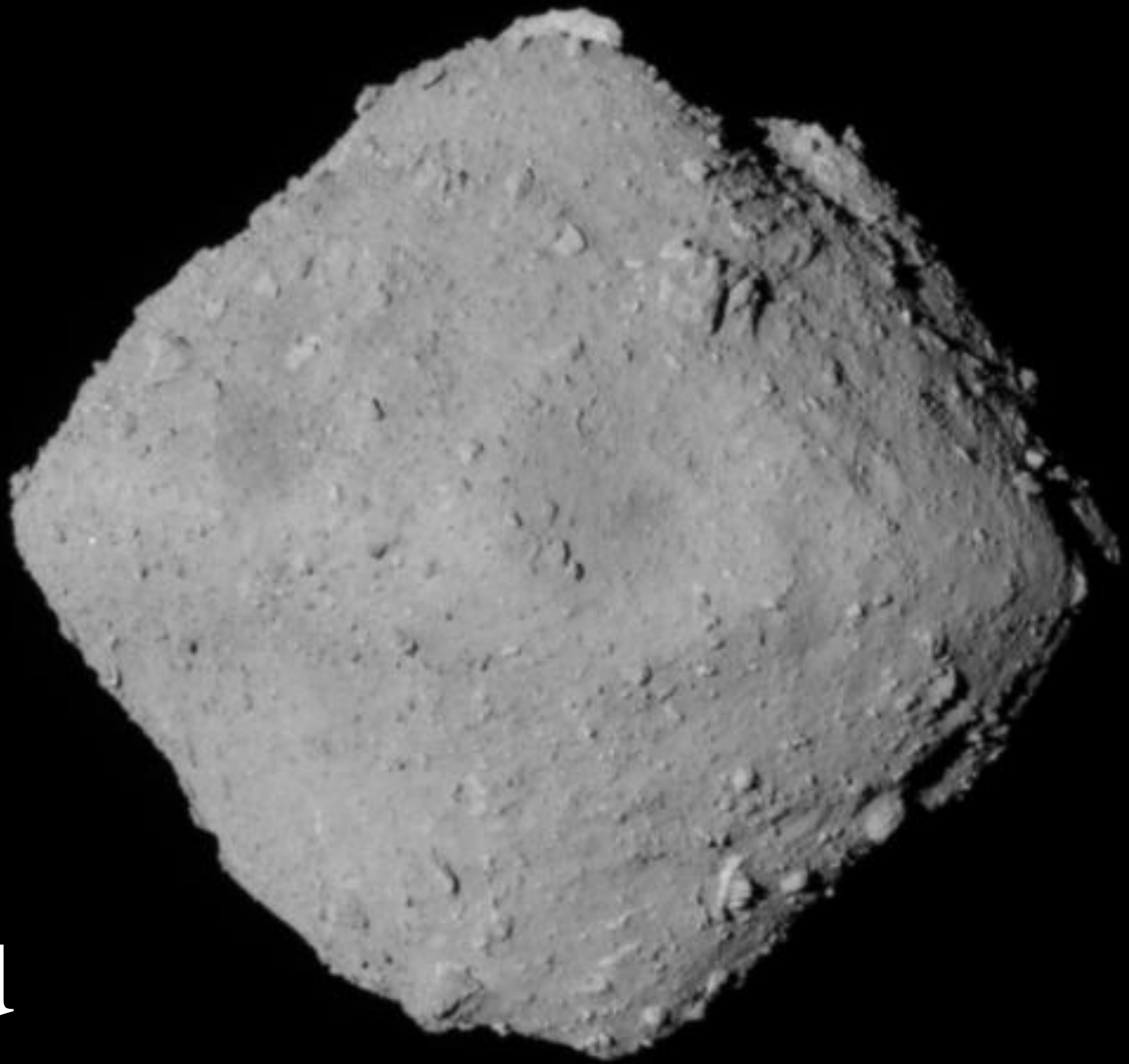
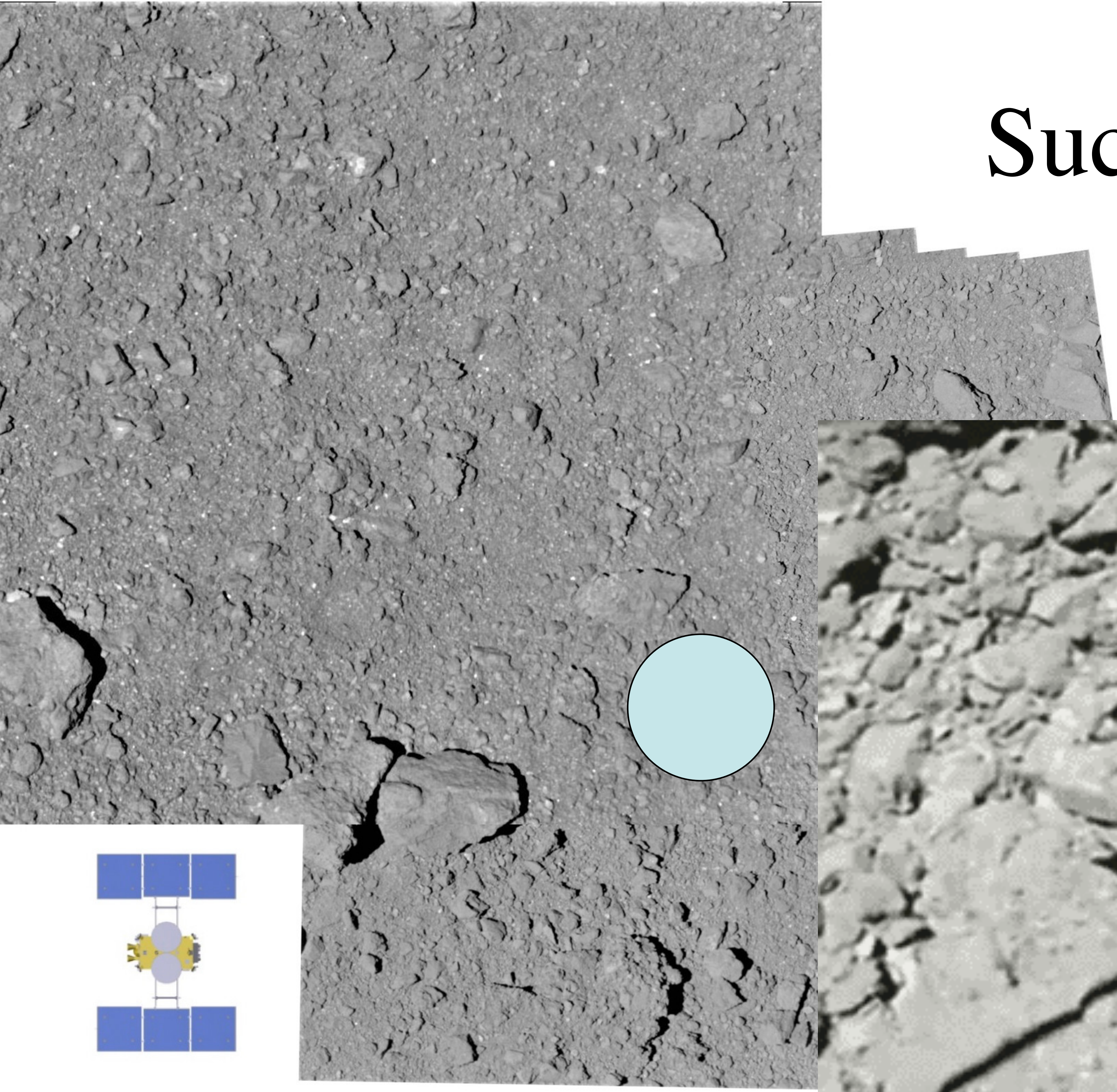
Ryugu Images from Hayabusa2

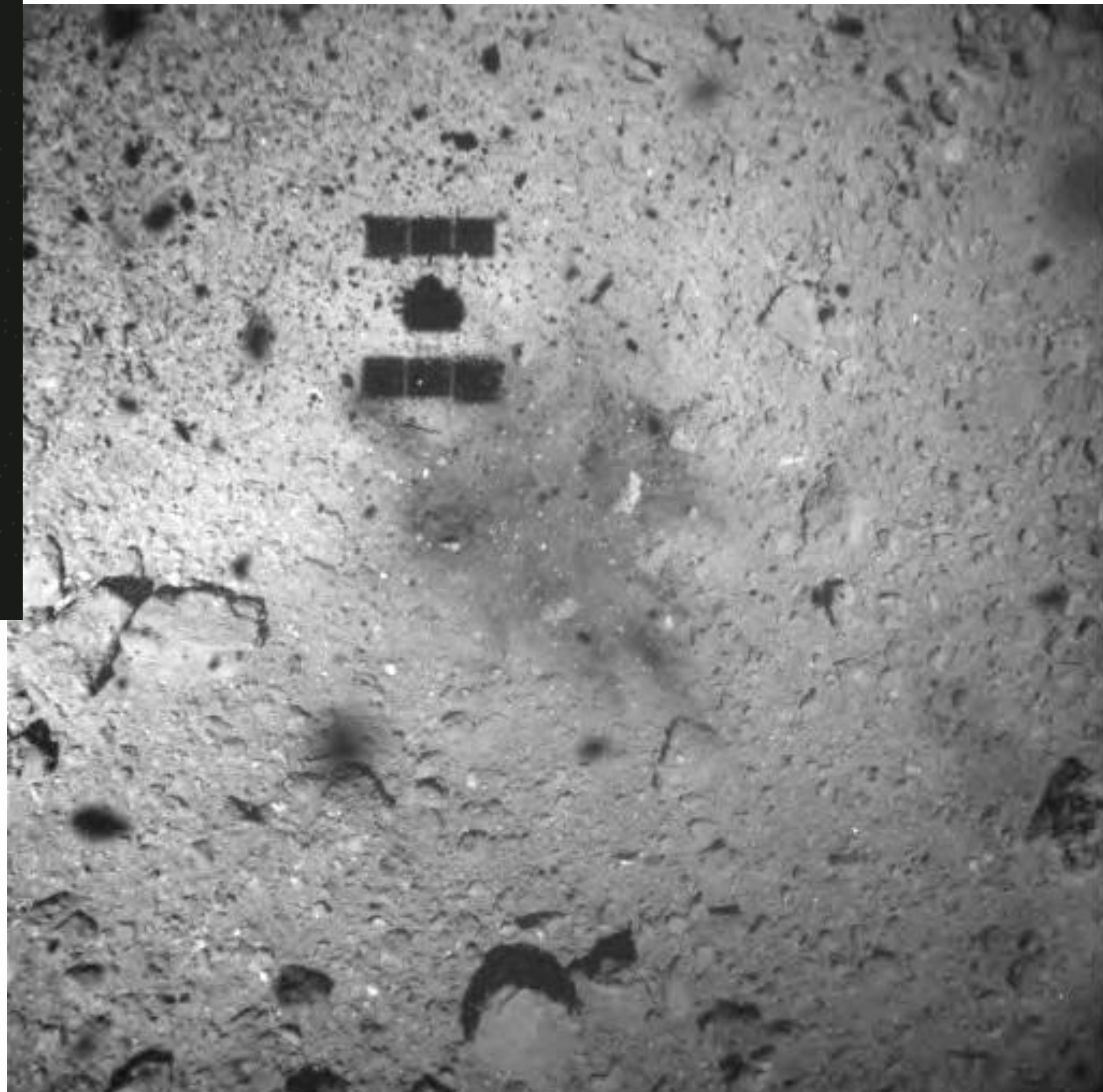


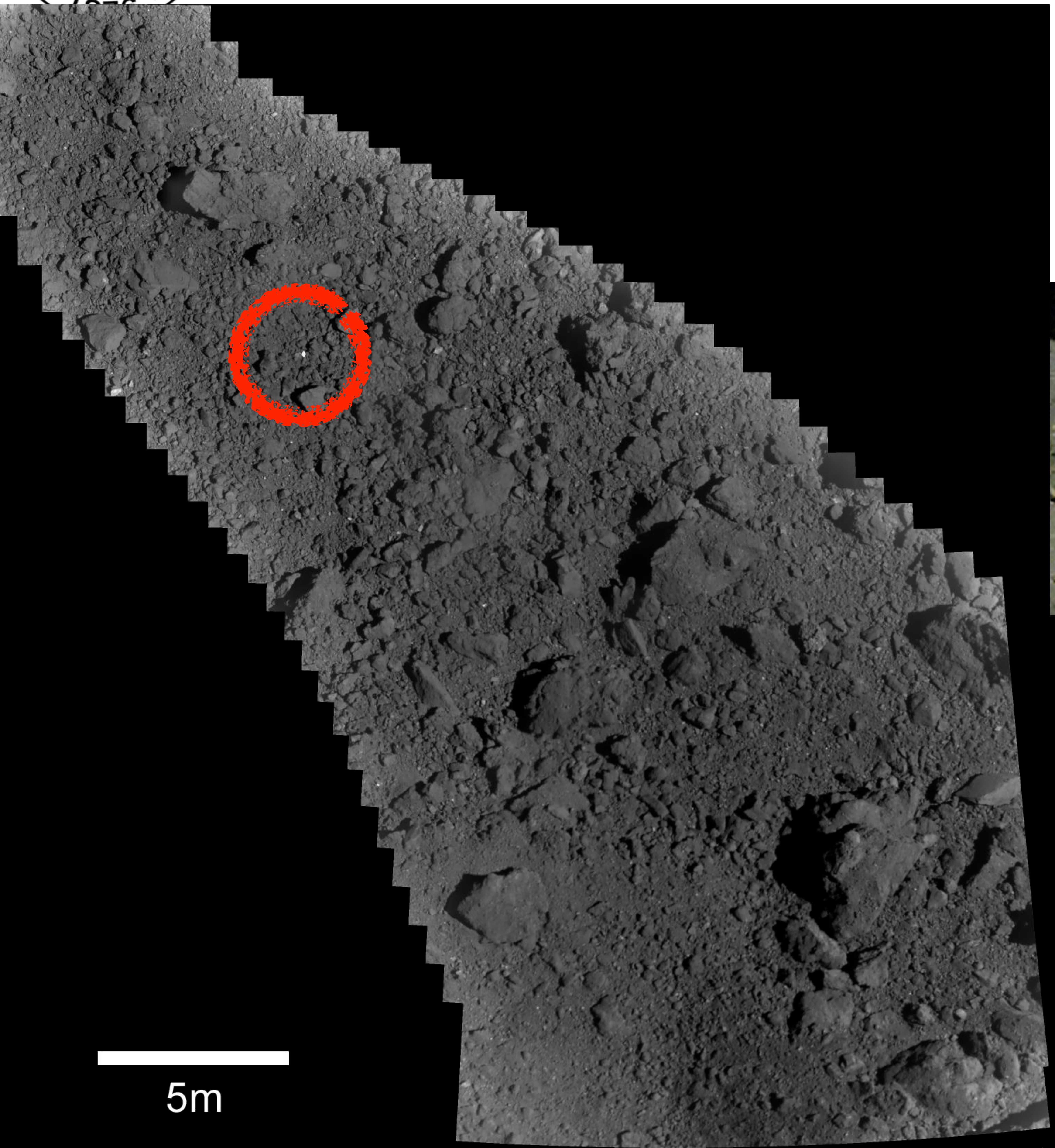
Ryugu

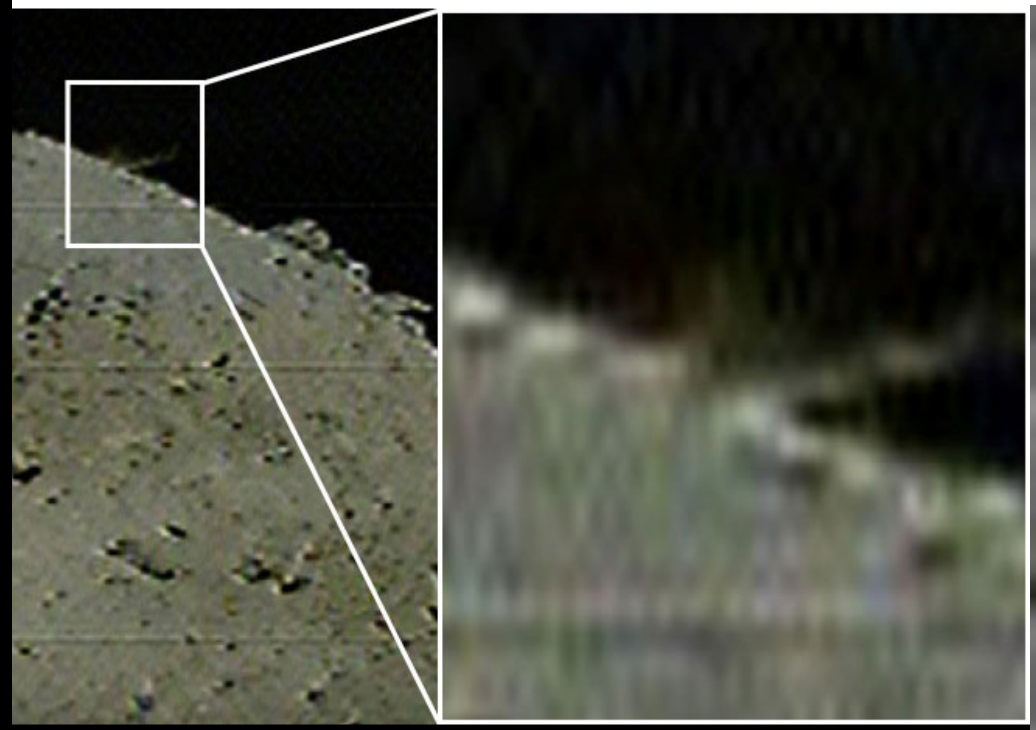
Successful Sampling!

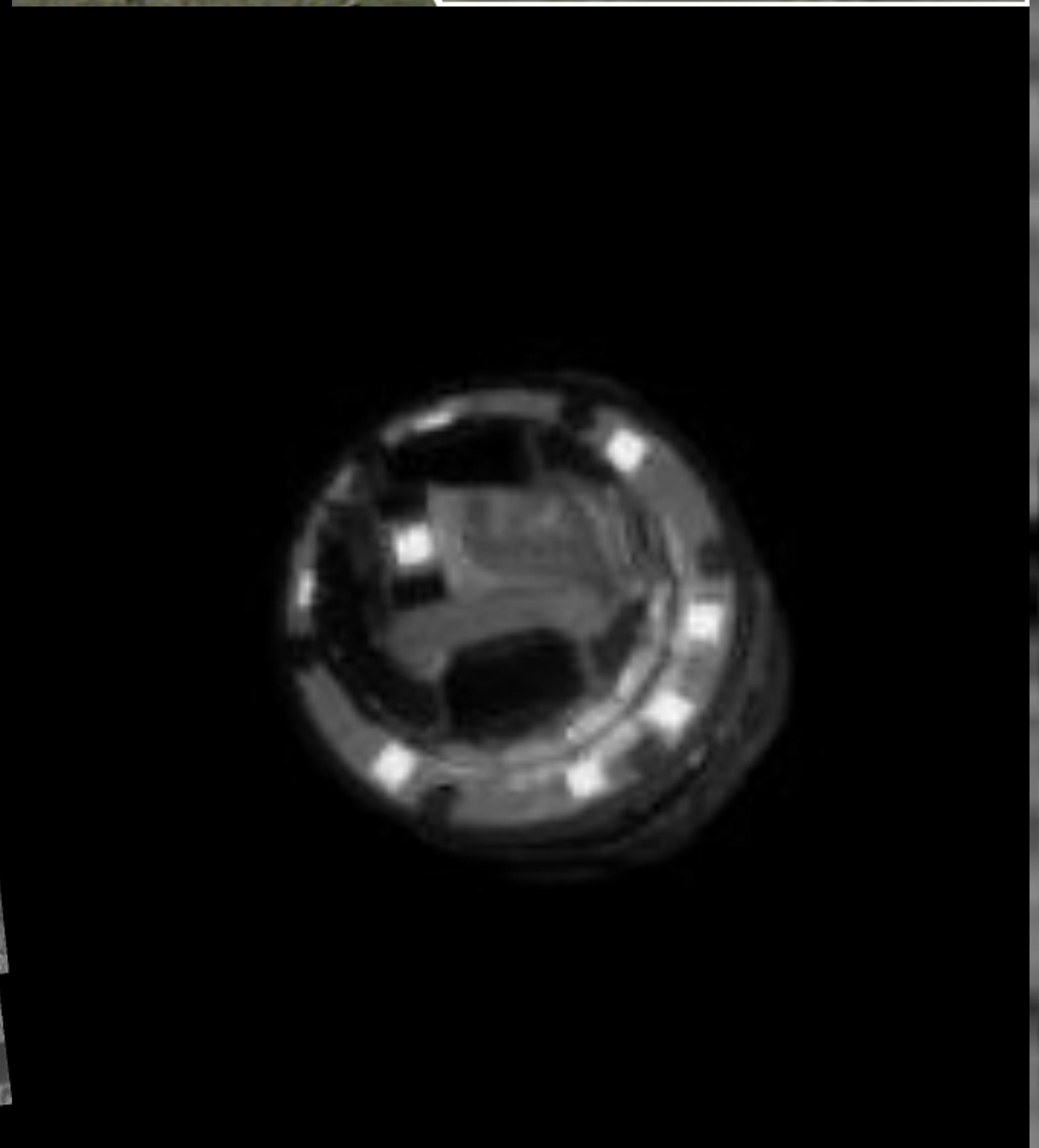




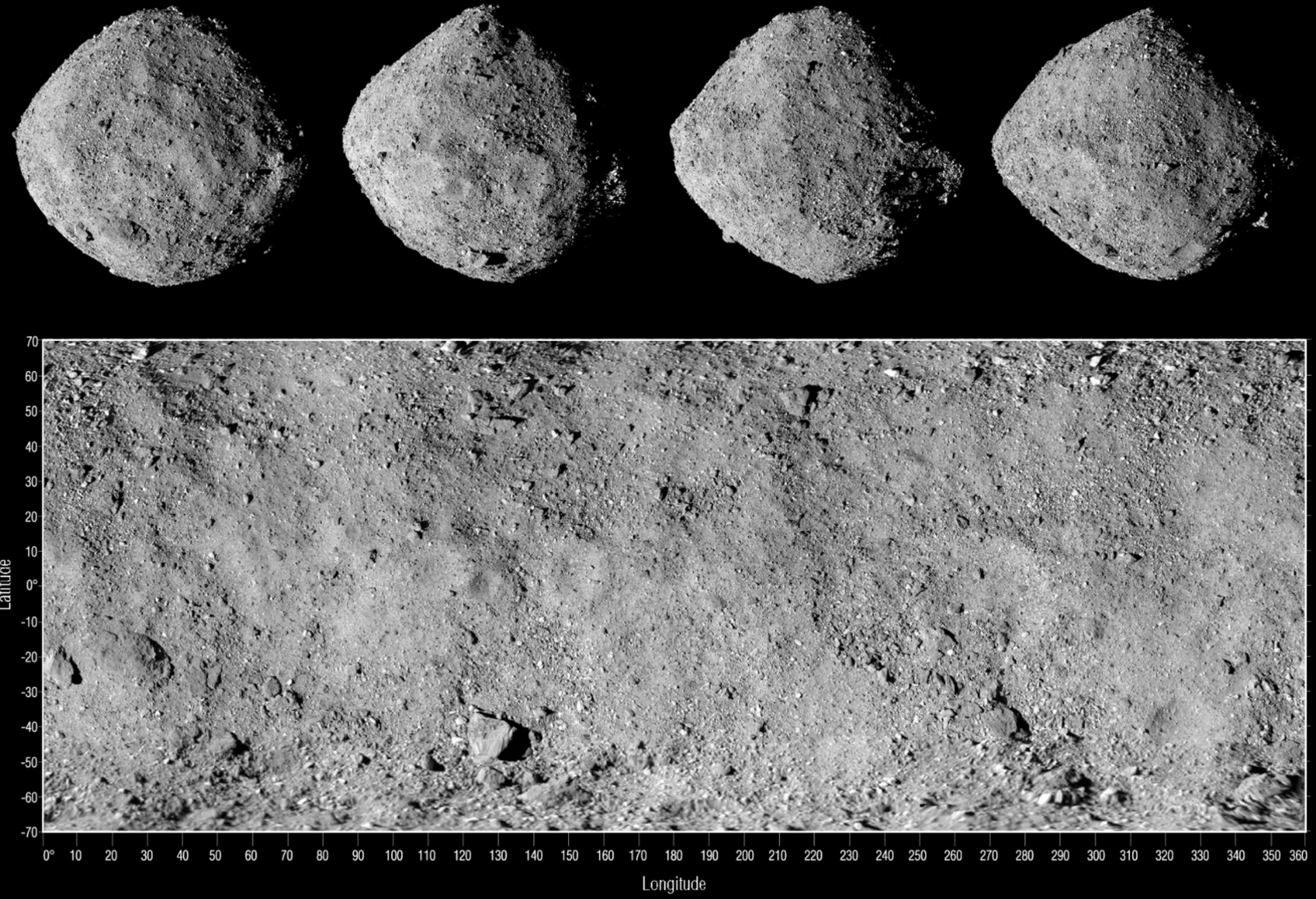
… and Cratering Experiment!







Bennu Images from OSIRIS-REx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60
50
40
30
20
10
0°
-10
-20
-30
-40
-50
-60
-70
0°
10
20
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80
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110
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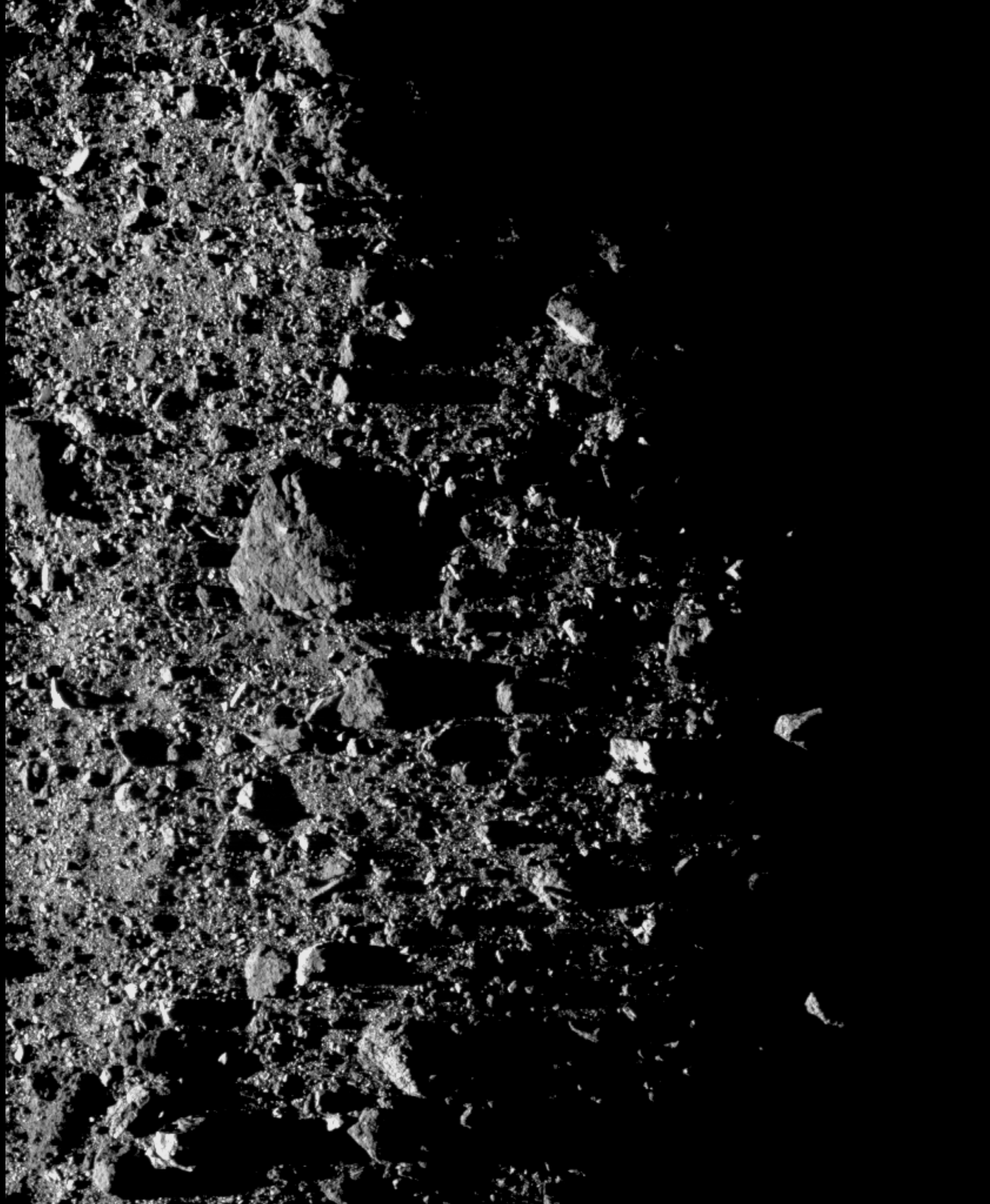
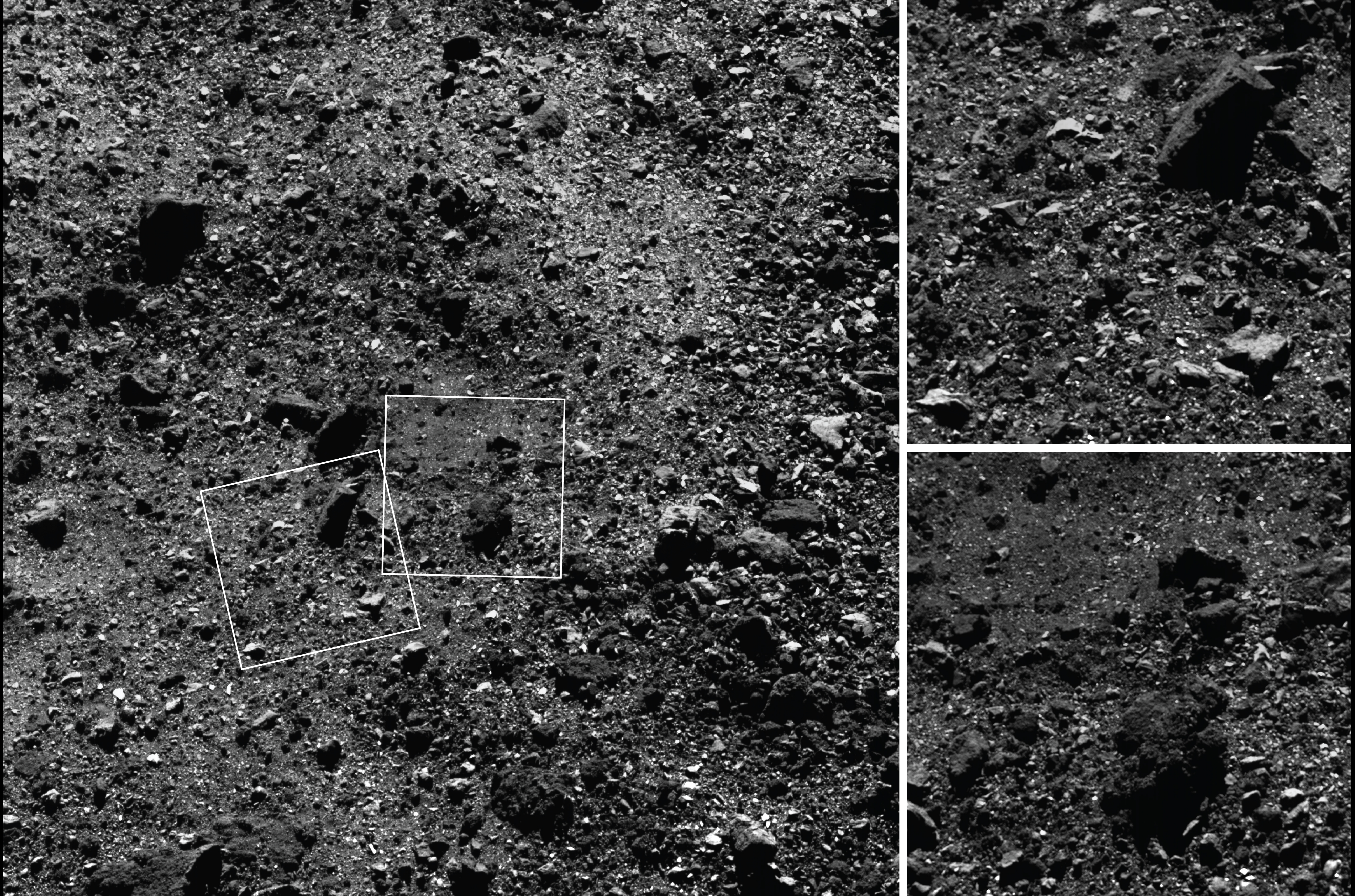
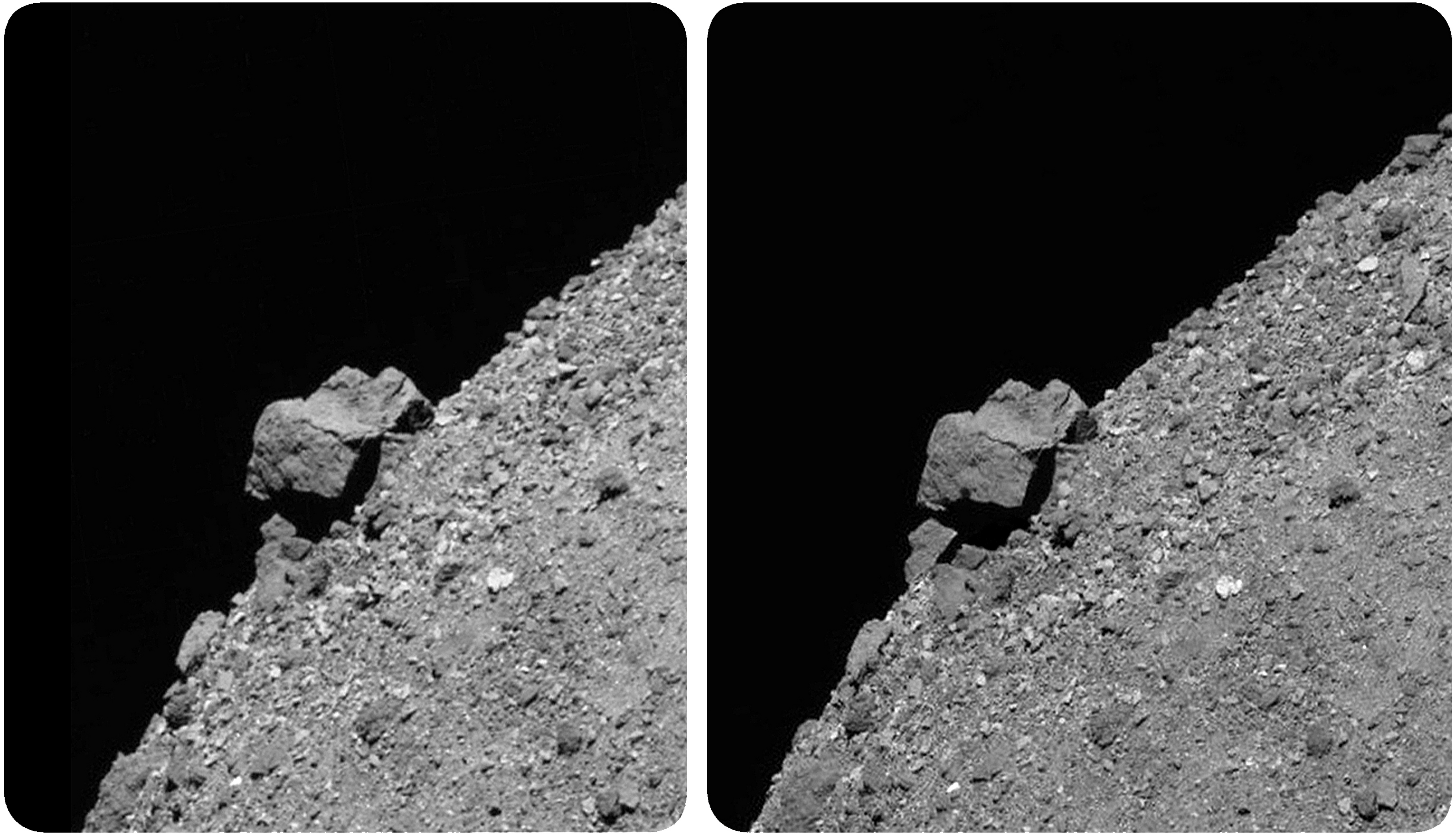
330
340
350
360
Longitude





“Cross-Eyed” Stereo Image of “Benben”

Summary

- We are living in a "golden age" of asteroid exploration!
- Many missions are deepening our understanding of these bodies
- We are developing new techniques and capabilities for the exploration of these bodies.
- Exploration close-proximity *solutions* exist across the full range of asteroid/comet size and morphology and include:
  - ***Orbiting solutions***, with specific limits on orbit radius and plane
  - ***Hovering solutions***, to enable surface sampling
  - ***Surface solutions***, to explore the these bodies at close range
- Development of new exploration approaches goes beyond astrodynamics and demands advances across many fields, including *autonomy, astronomy and astrodynamics*
  - Fundamental questions are motivated by this topic
  - Resolution of these questions are crucial for moving beyond the ***exploration*** of small bodies towards their ***utilization*** and ***mitigation***