Celestial and Spaceflight Mechanics Laboratory

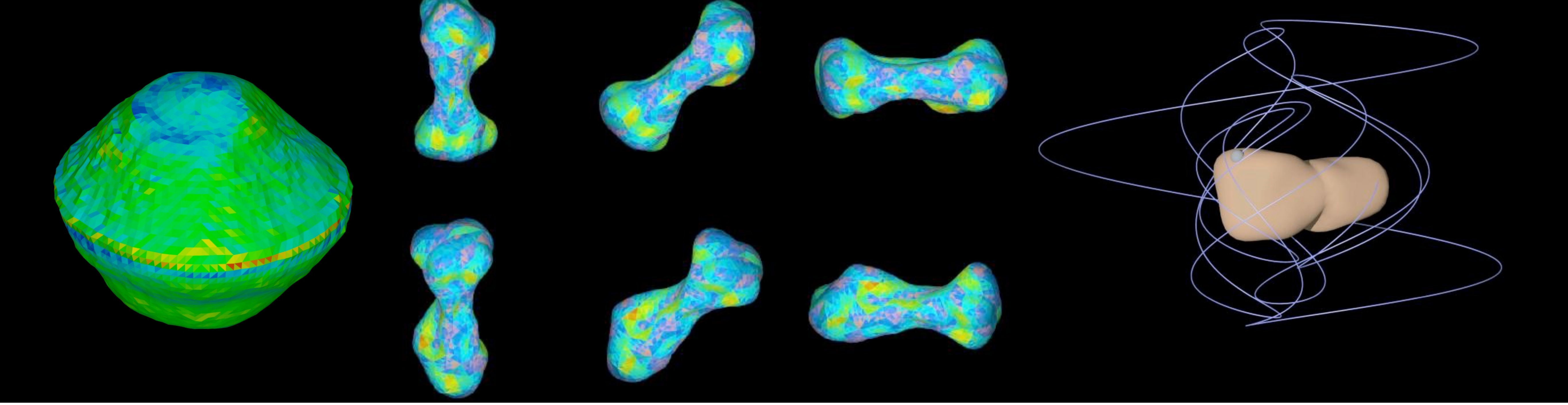
The Mechanics of Asteroid Exploration: OSIRIS-REx and Future Missions

D.J. Scheeres

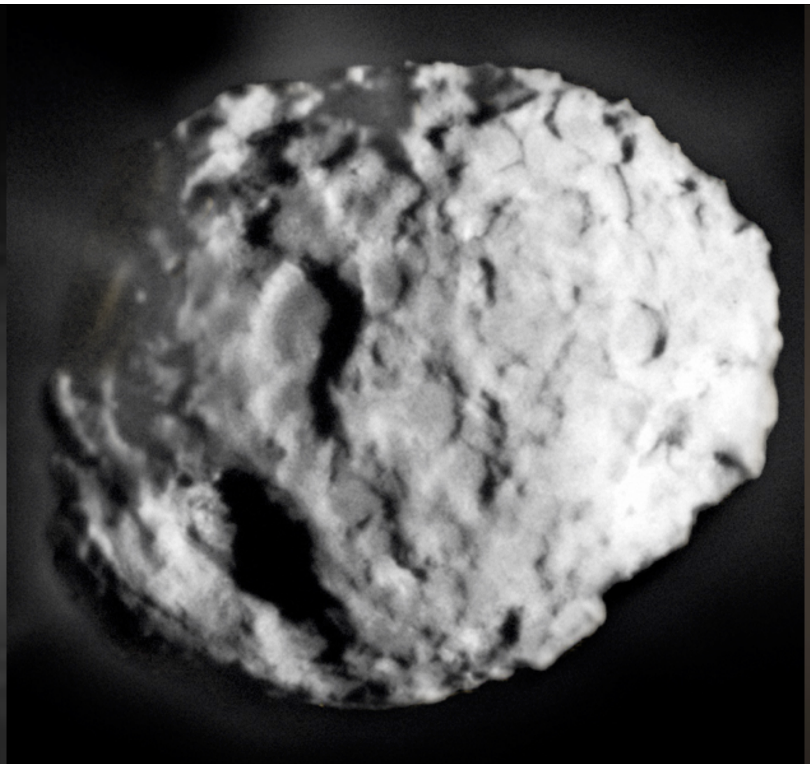
CCAR Colorado Center for Astrodynamics Research

Smead Department of Aerospace Engineering Sciences

The University of Colorado at Boulder



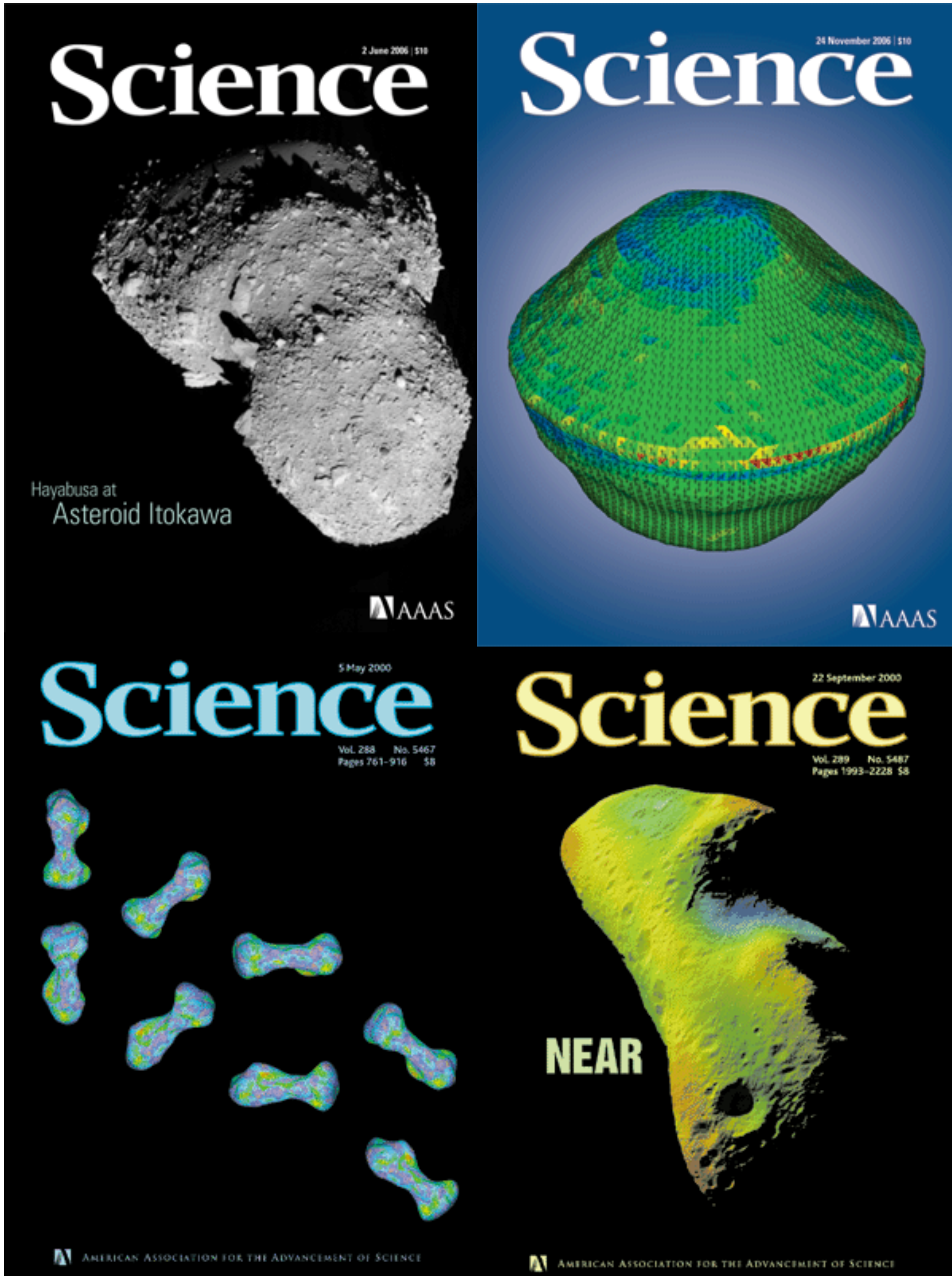
Why are we interested in Small Bodies?


Why are we interested? *Science*

- Small bodies are “remnants” of the early solar system.
  - They retain material that dates back to the solar system’s formation.
  - They act as “tracer particles” that record the orbital evolution of the major planets.
  - Their study probes the formational epoch of the solar system.

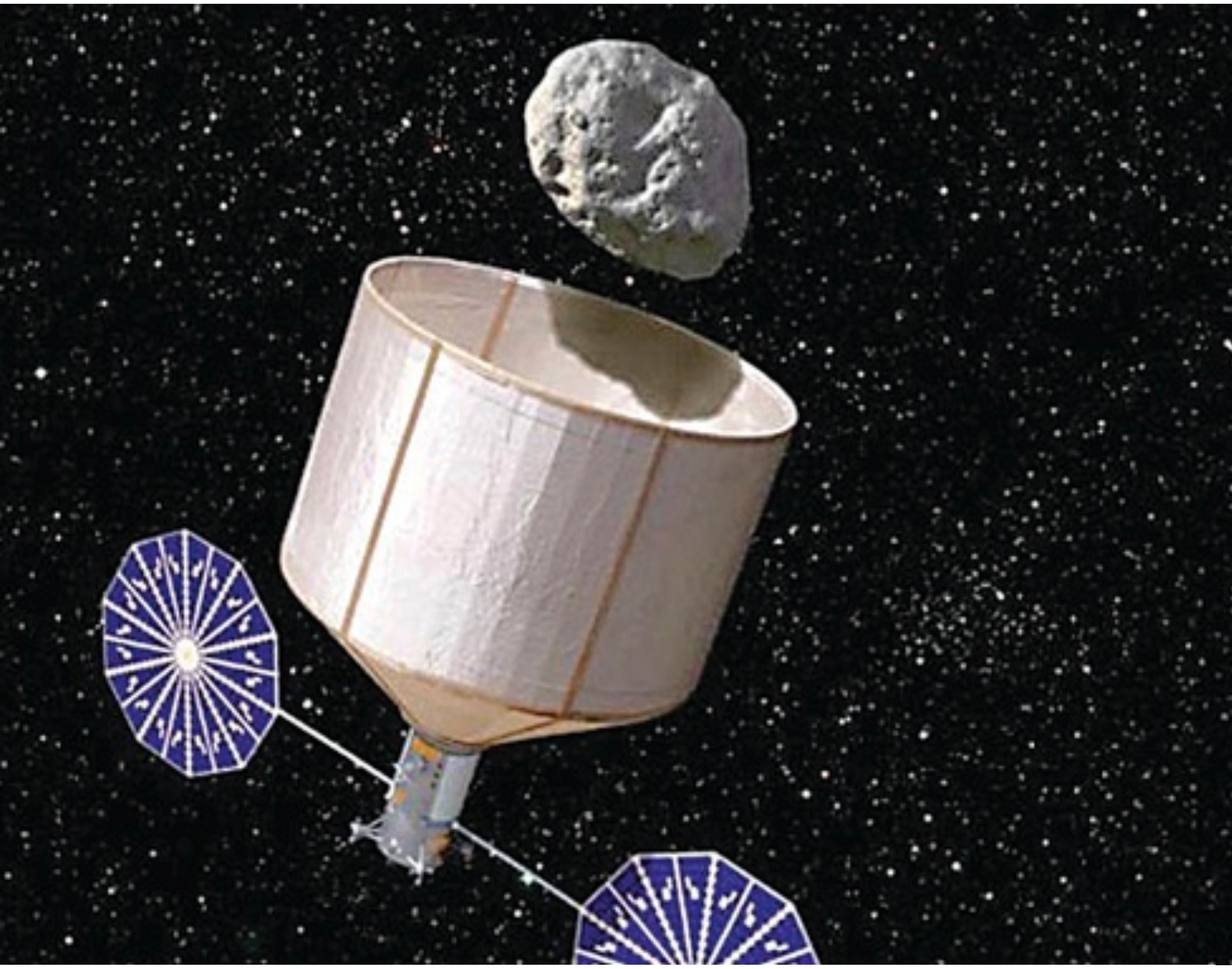
- They have shaped life on Earth.
  - By delivering water and minerals in the early history of the Earth.
  - By causing occasional wide-spread extinctions due to their impact.



Why are we interested?
Exploration

- – Near Earth Asteroids are a possible destination for future human exploration missions.
- – As we explore our solar system, they are the easiest bodies to rendezvous with.
- – Have been seriously considered by NASA for human exploration.

Why are we interested?
Resource Exploitation



- Asteroids are full of valuable minerals and water
- Technologies for their extraction and use in space are currently being developed

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COMMERCIAL SPACE

Luxembourg to Invest $227 Million in Asteroid Mining

Why are we interested? *Society*

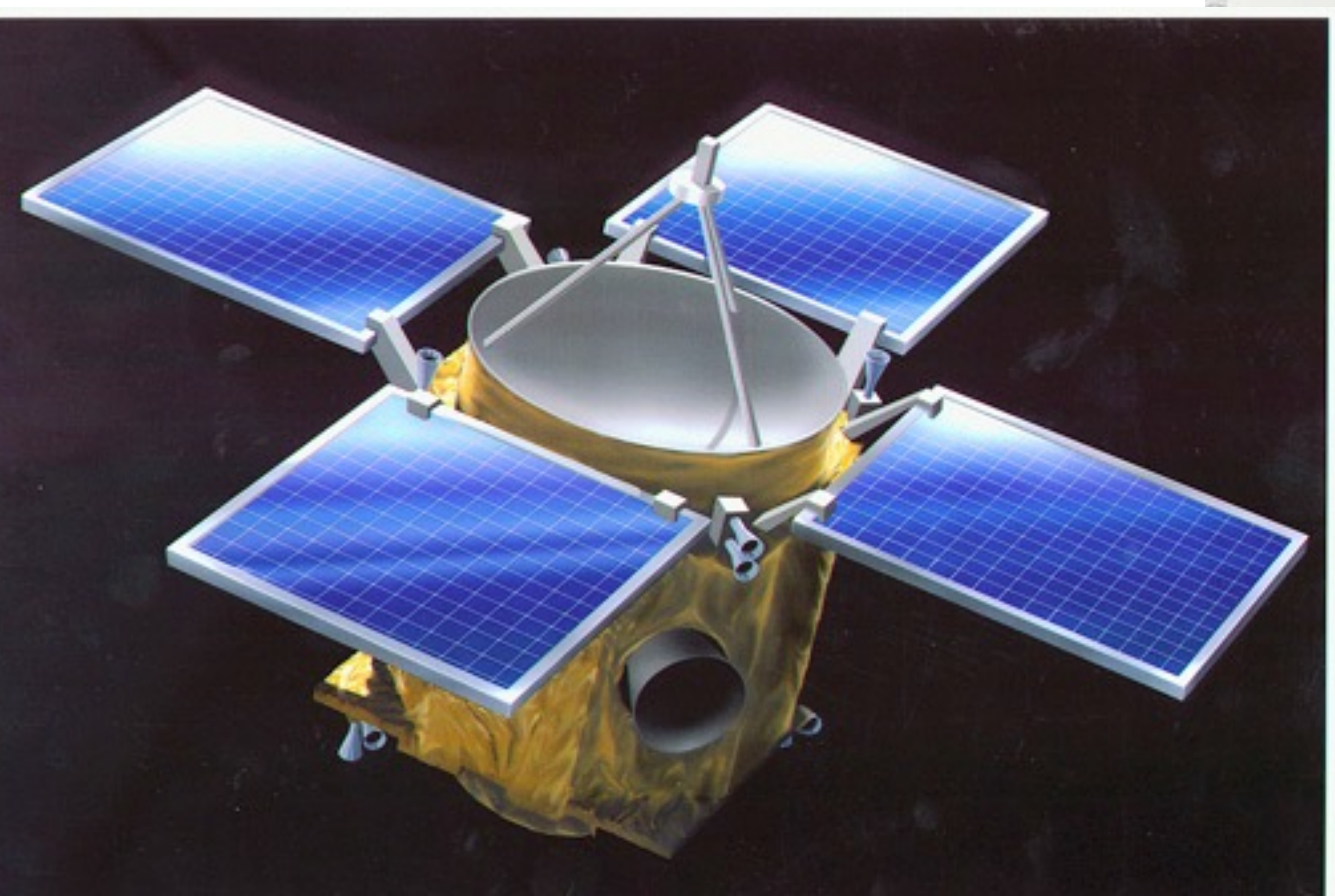
- Small bodies continually impact the Earth (e.g., shooting stars, Chelyabinsk)
- Have caused large-scale extinctions in the past (e.g., the dinosaurs)
- If one were detected on a collision course, could we stop it?

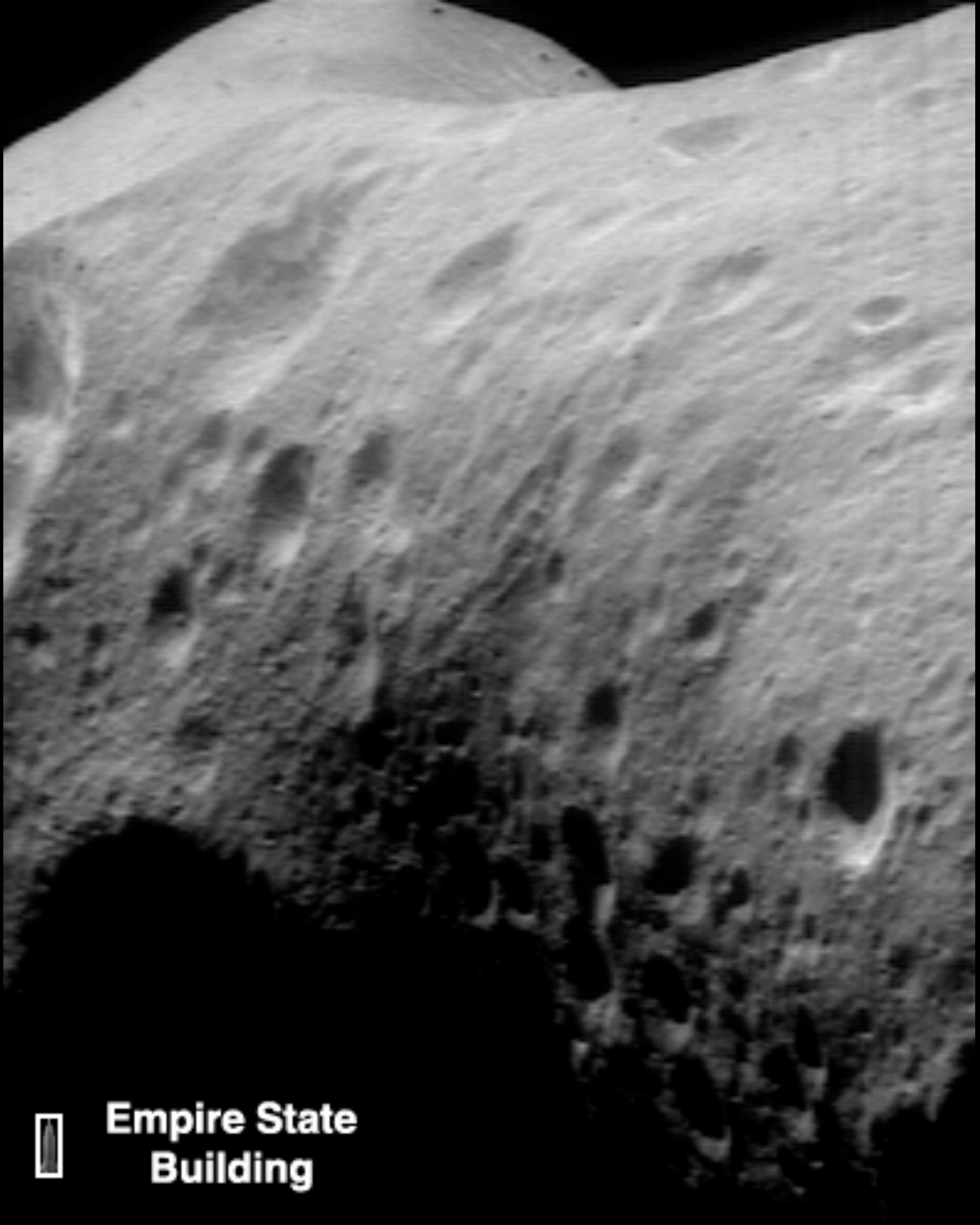

Asteroid Exploration: Past and Present

Flyby Observations

Near Earth Asteroid Rendezvous

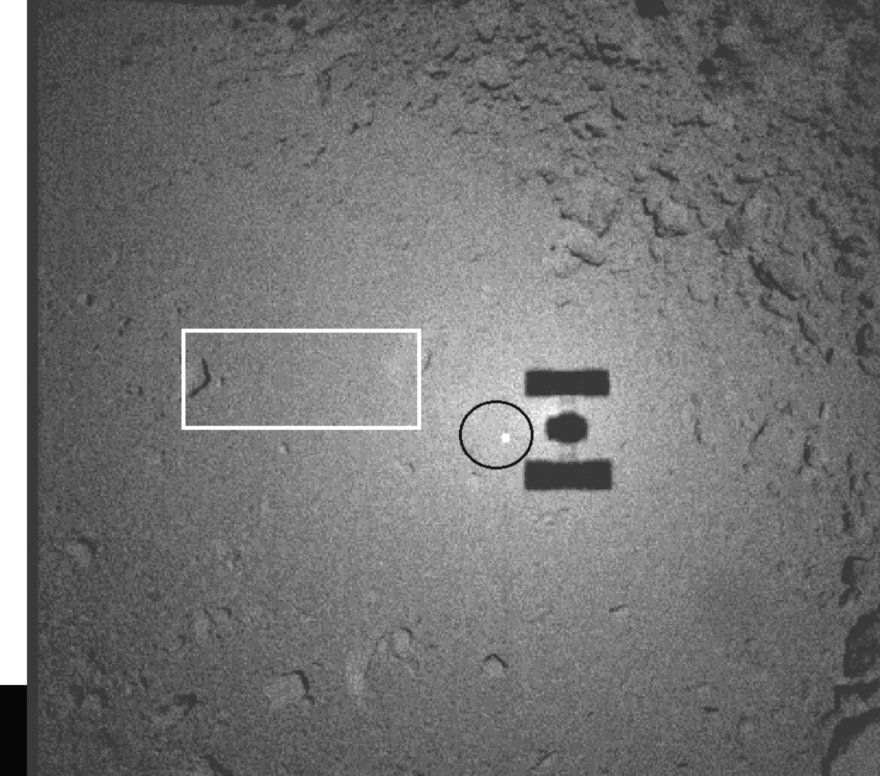
- NASA space science missio
- Visited the asteroid Eros
- Launched 1996
- Arrived at asteroid 2001
- Landed on asteroid 2002

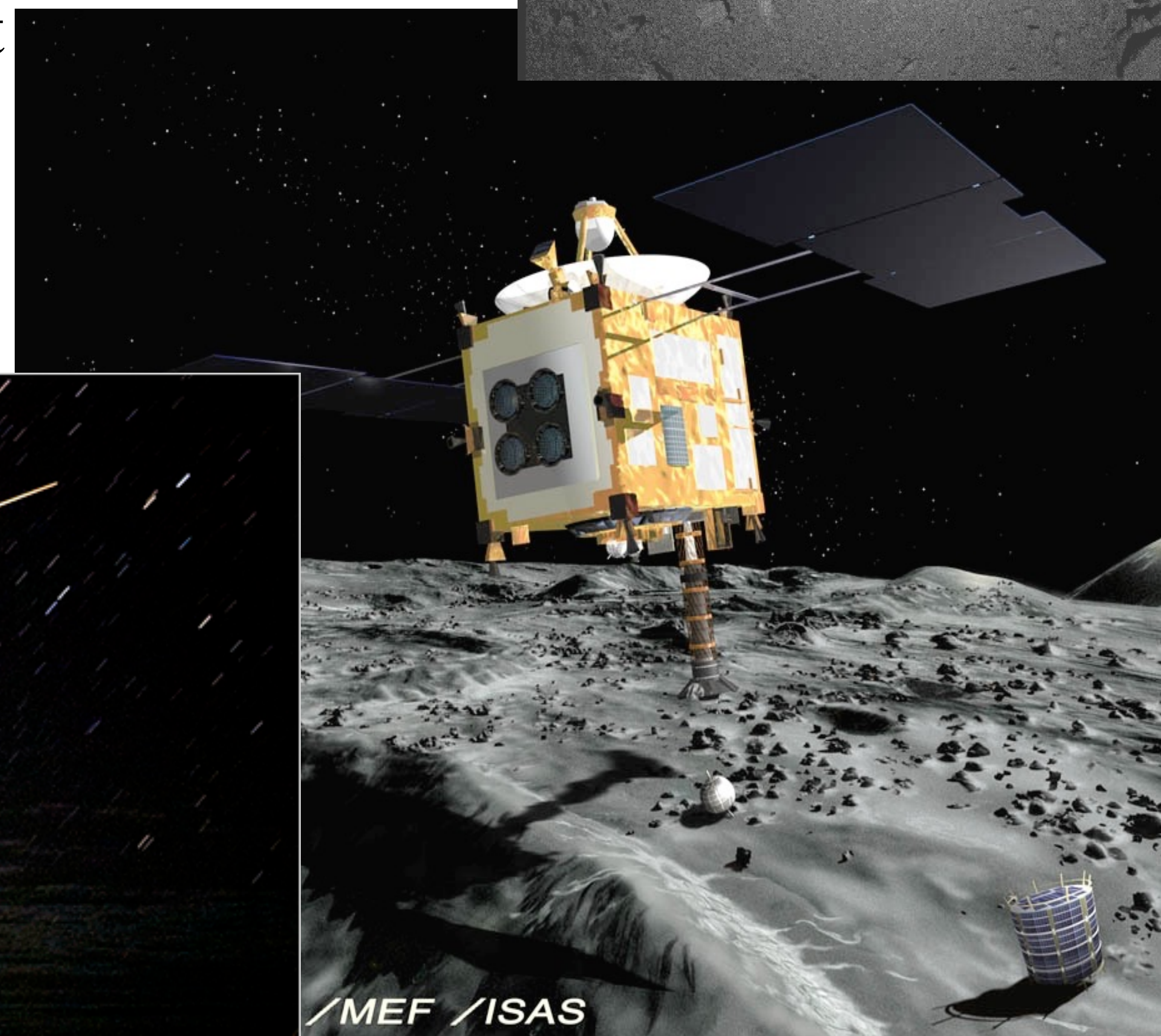



Empire State
Building

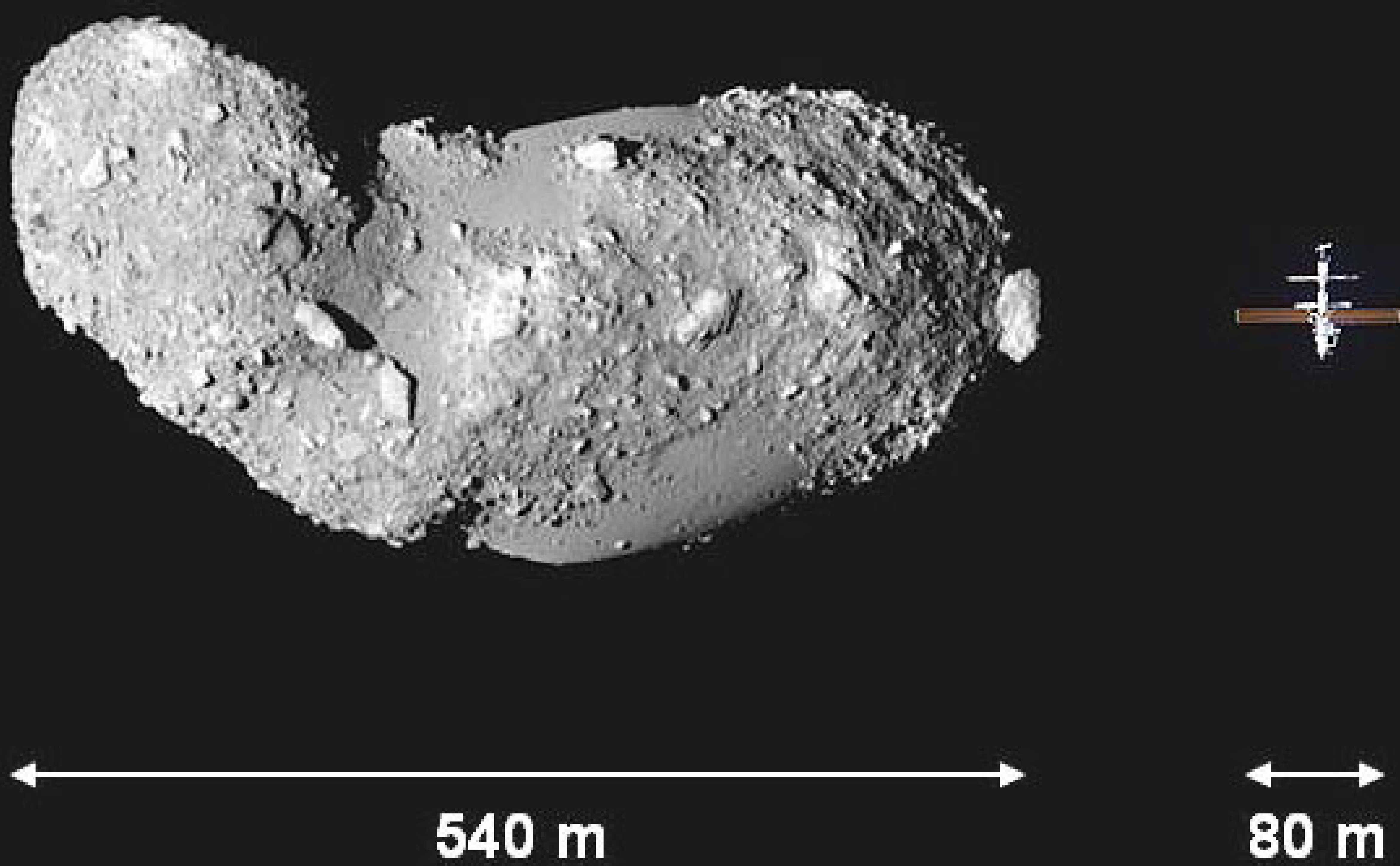
Hayabusa Mission

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

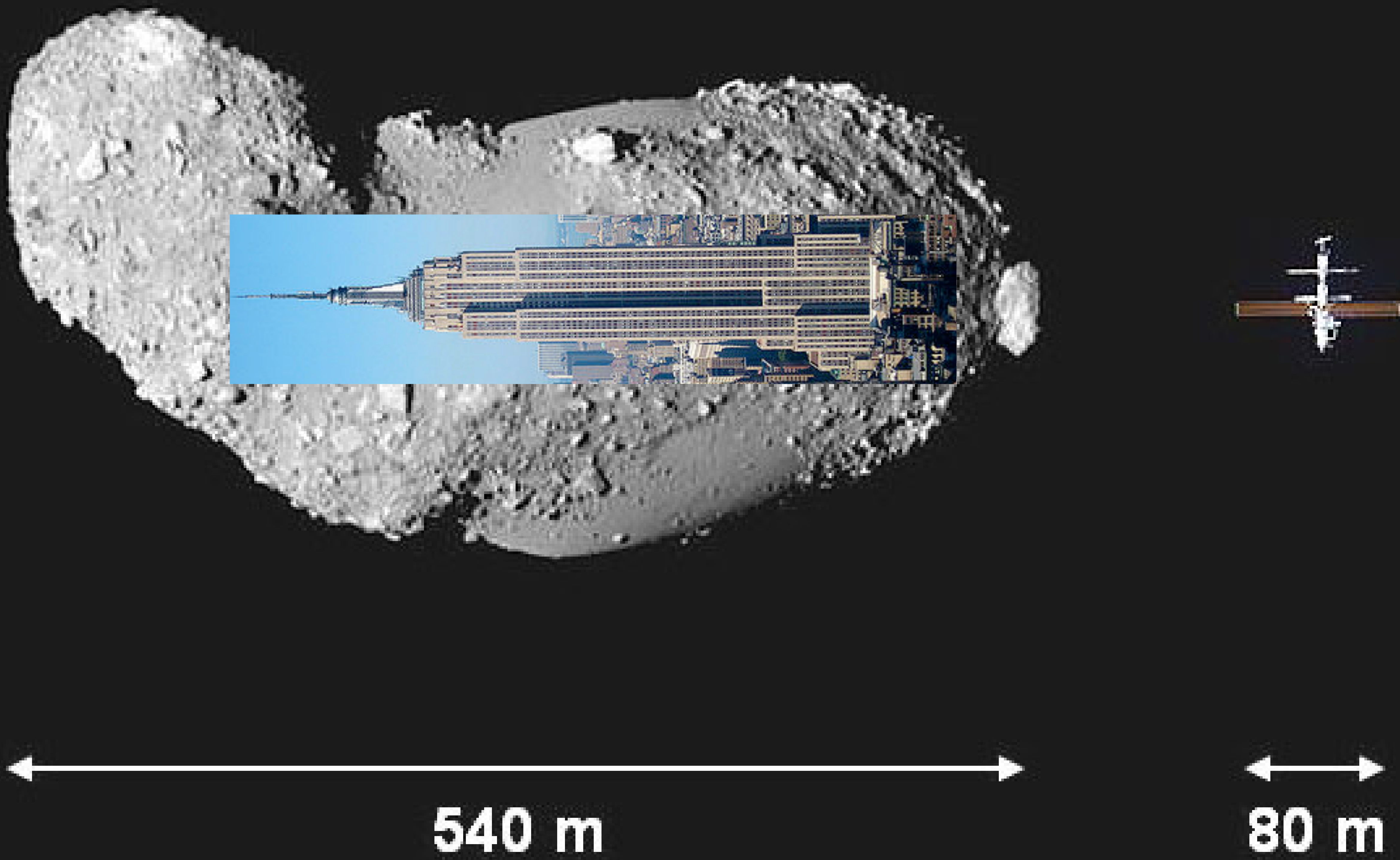




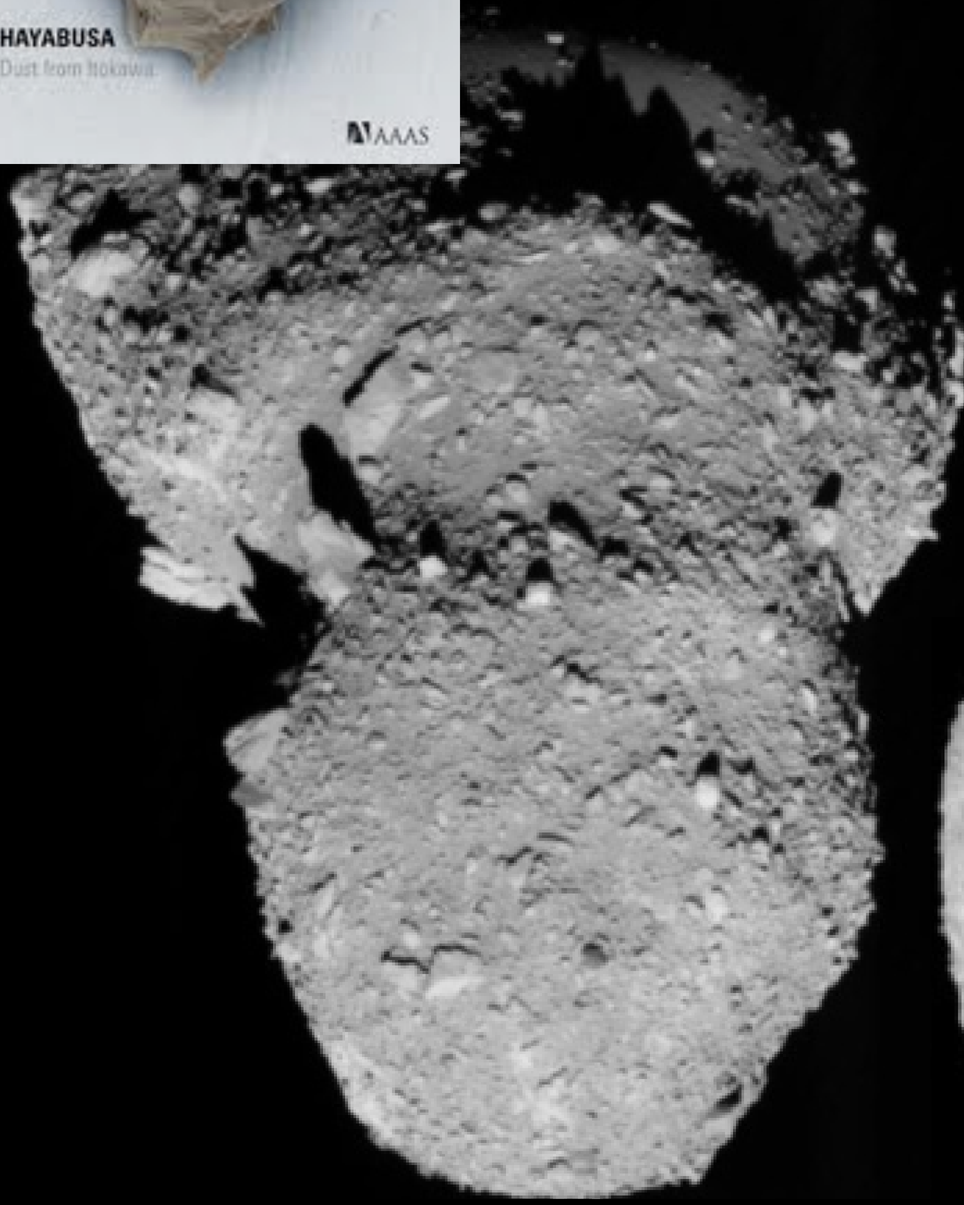
Asteroid Itokawa *vs* ISS



Asteroid Itokawa *vs* ISS

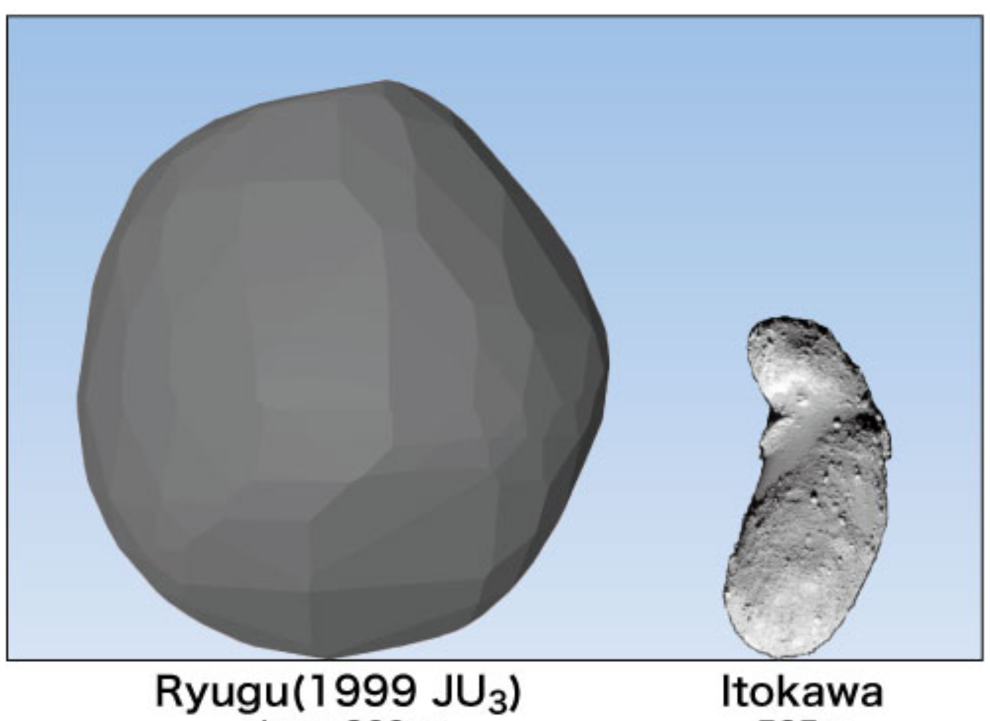


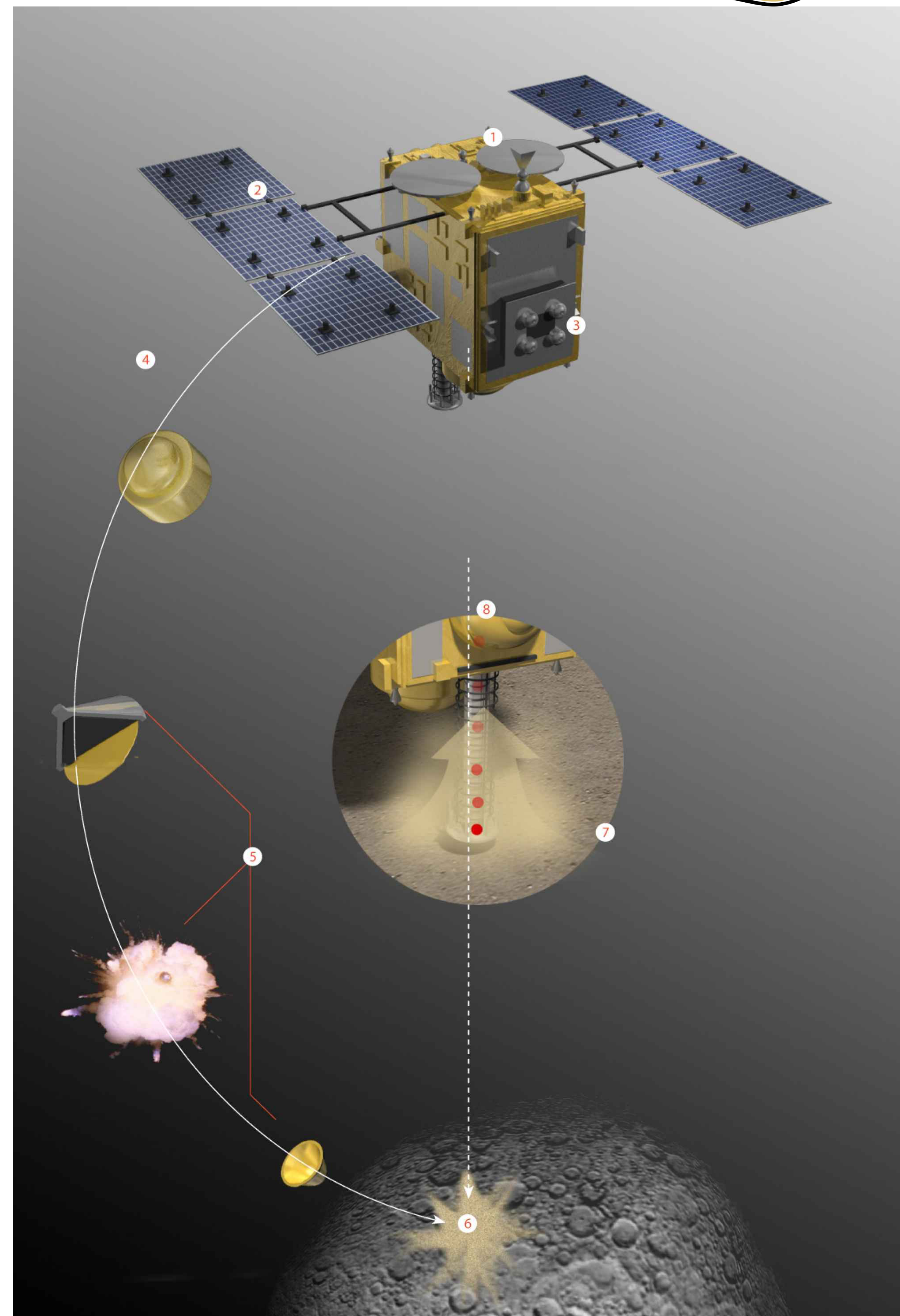

Science
HAYABUSA
Dust from Itokawa
AAAS



Hayabusa2

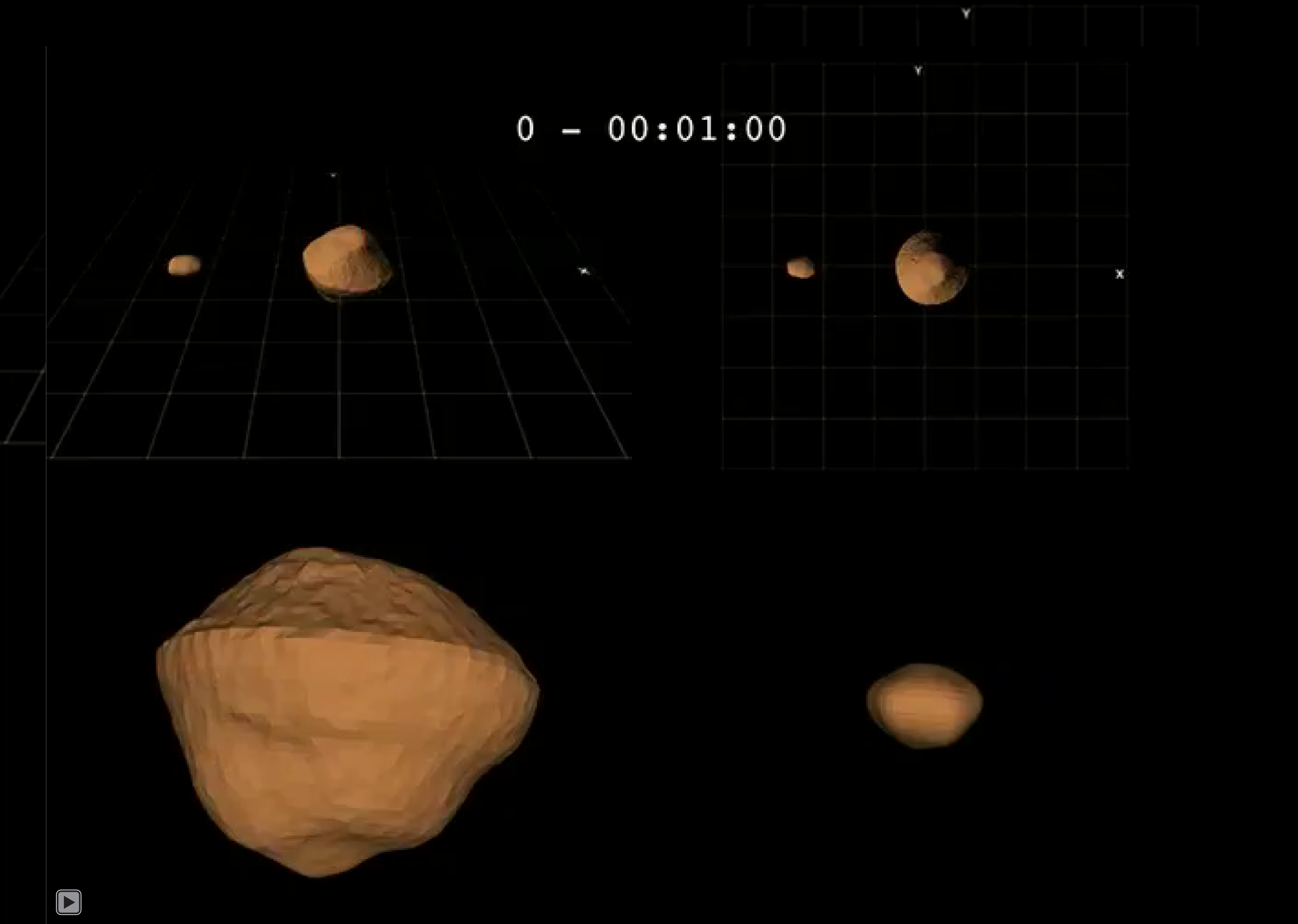
- Japanese sample return mission to Asteroid Ryugu
- Will carry out extended operations, deploy surface rovers, and create a crater on the asteroid’s surface
  - Launched in 2014
  - Scheduled to arrive at its target in 2018
  - Sample return in 2020





What are the Challenges?

- 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…



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Y
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X

Challenge: Gravitational Effects

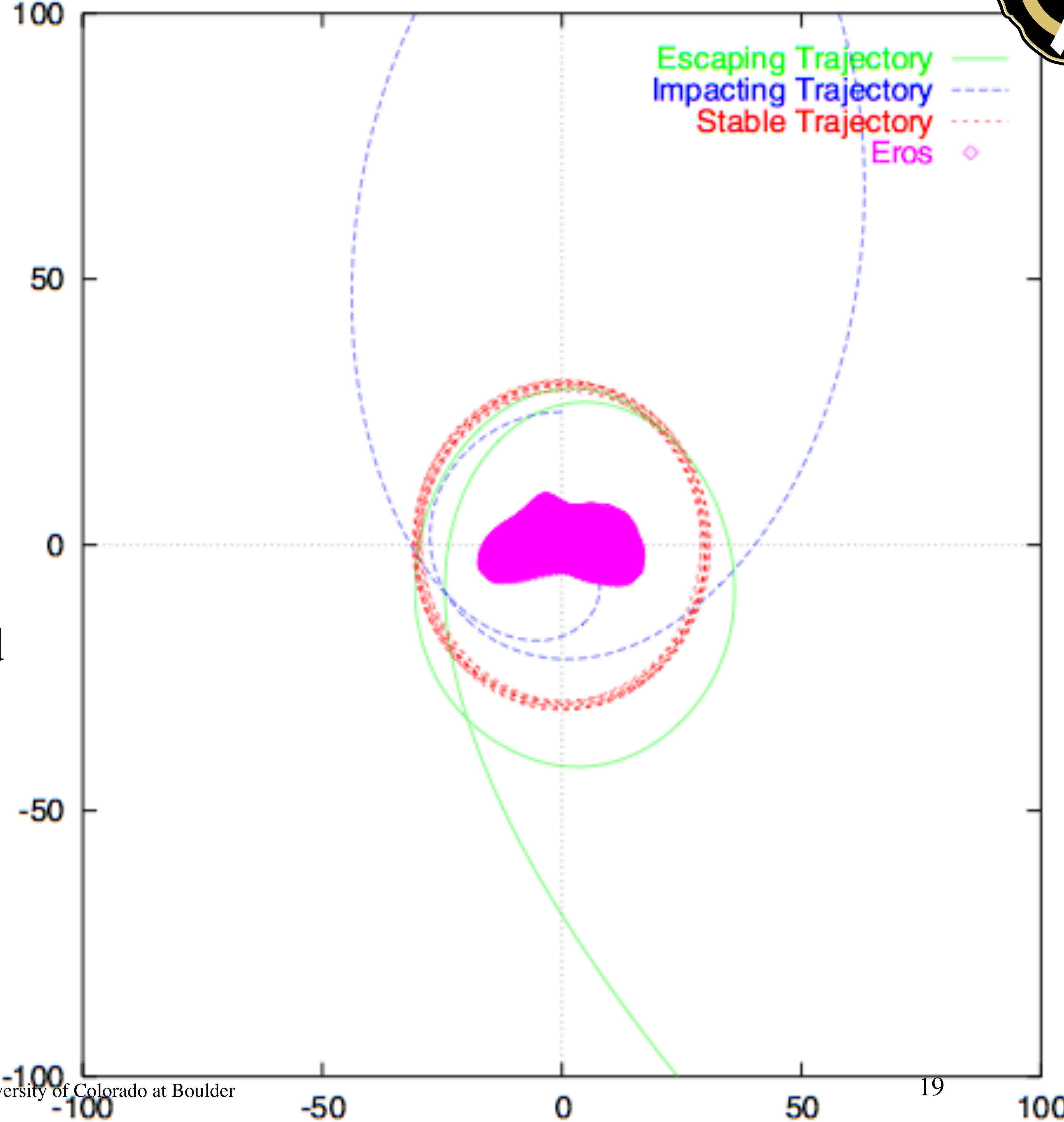
Simulation of spacecraft orbits at 433 Eros.

Stable Orbit

Impacting Orbit

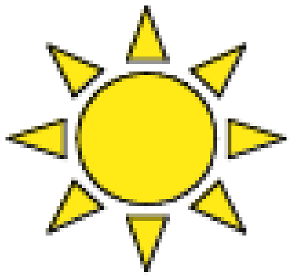
Escaping Orbit

Small changes in initial conditions yield large variations in outcome.

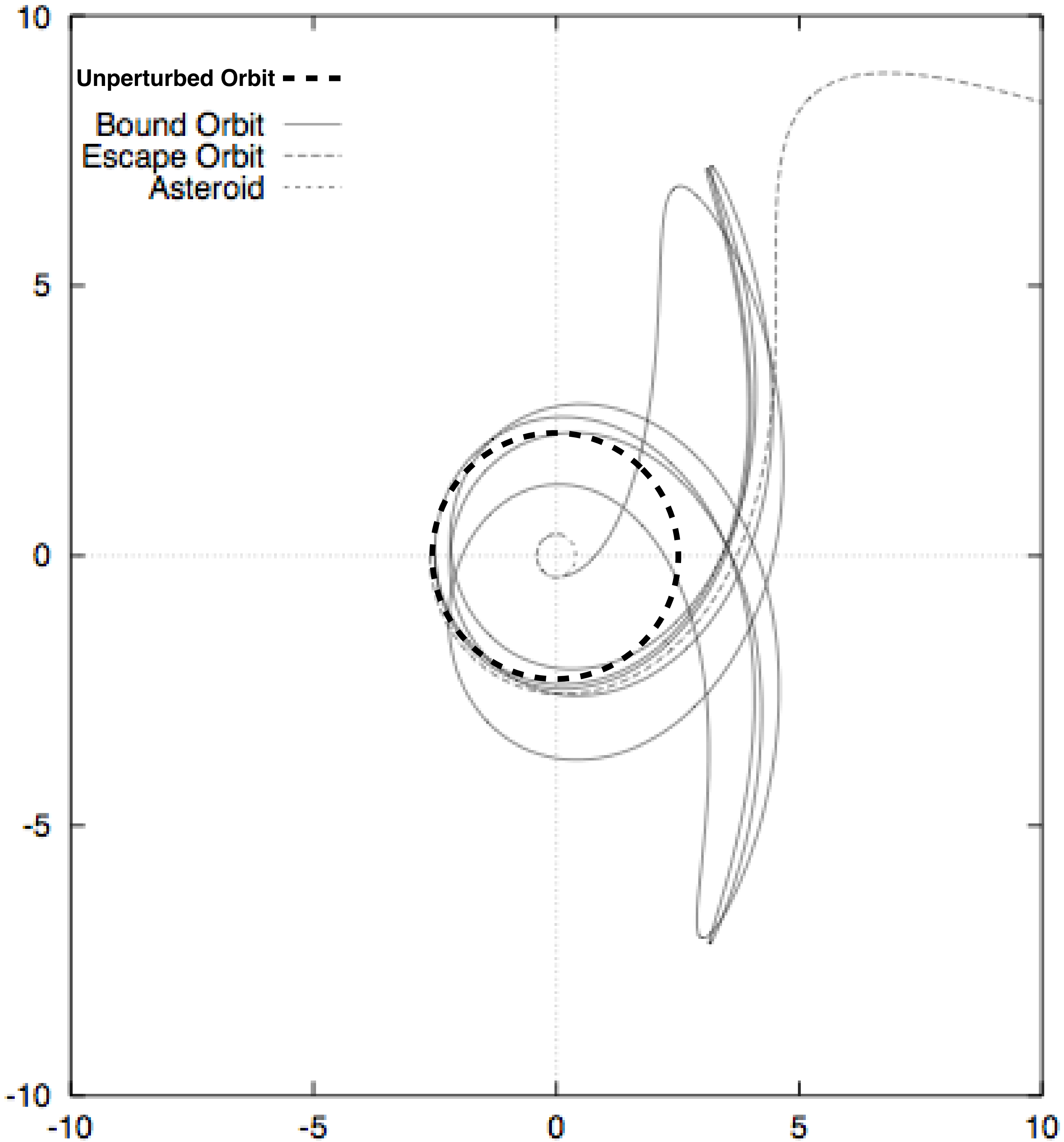


Challenge: SRP Effects

S/C orbits about a small point mass

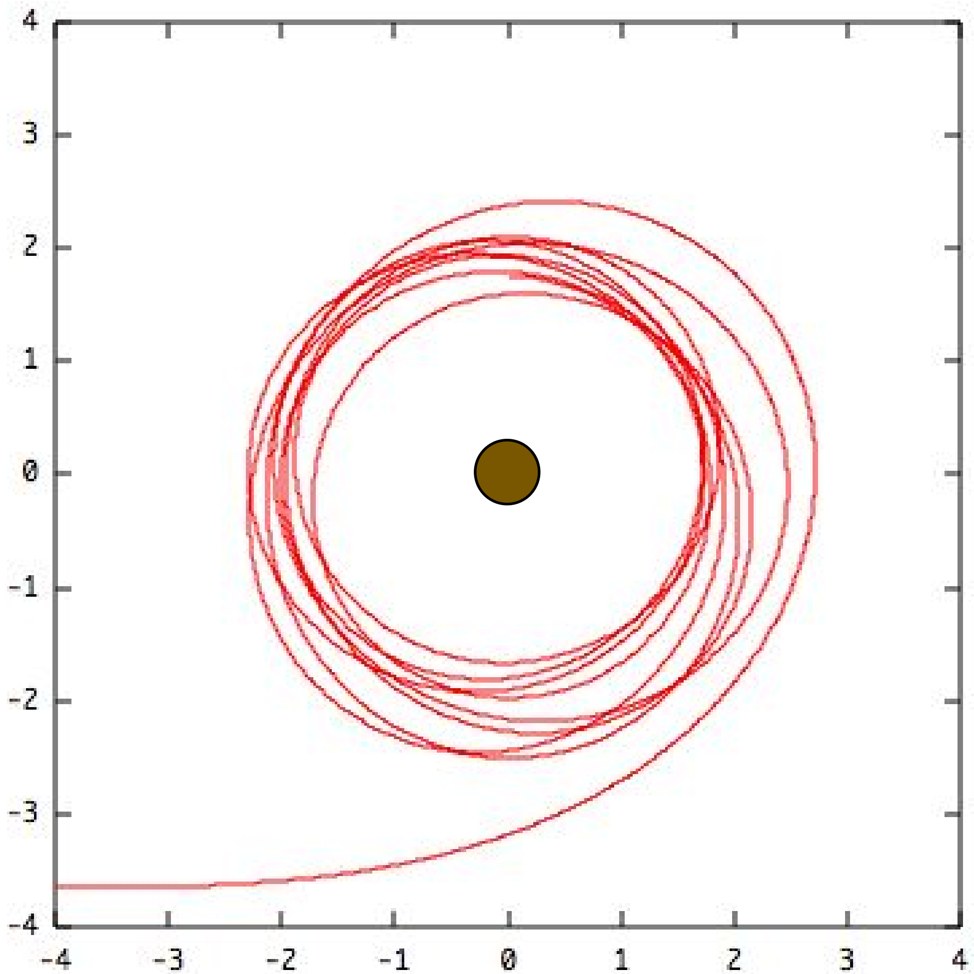


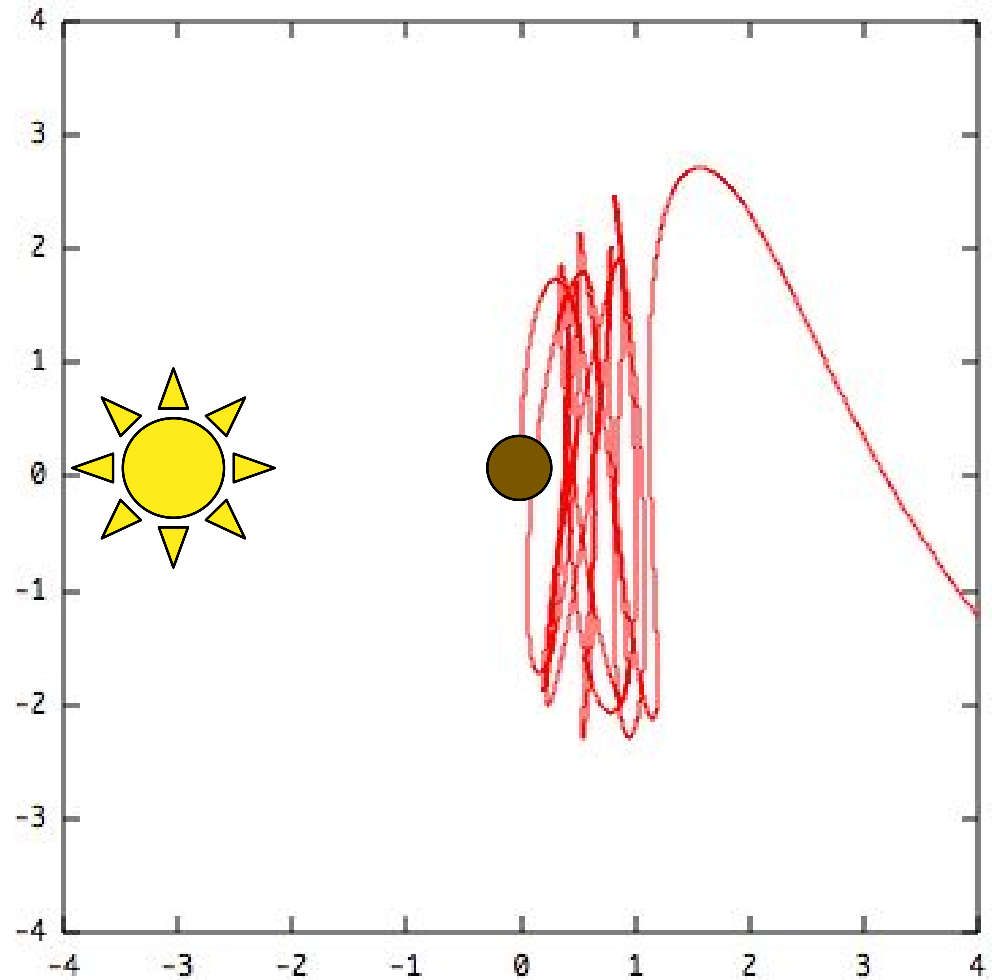
A 100 meter difference in initial conditions can change escape to impact



Challenge: SRP Effects

Escape due to SRP





View from the Sun

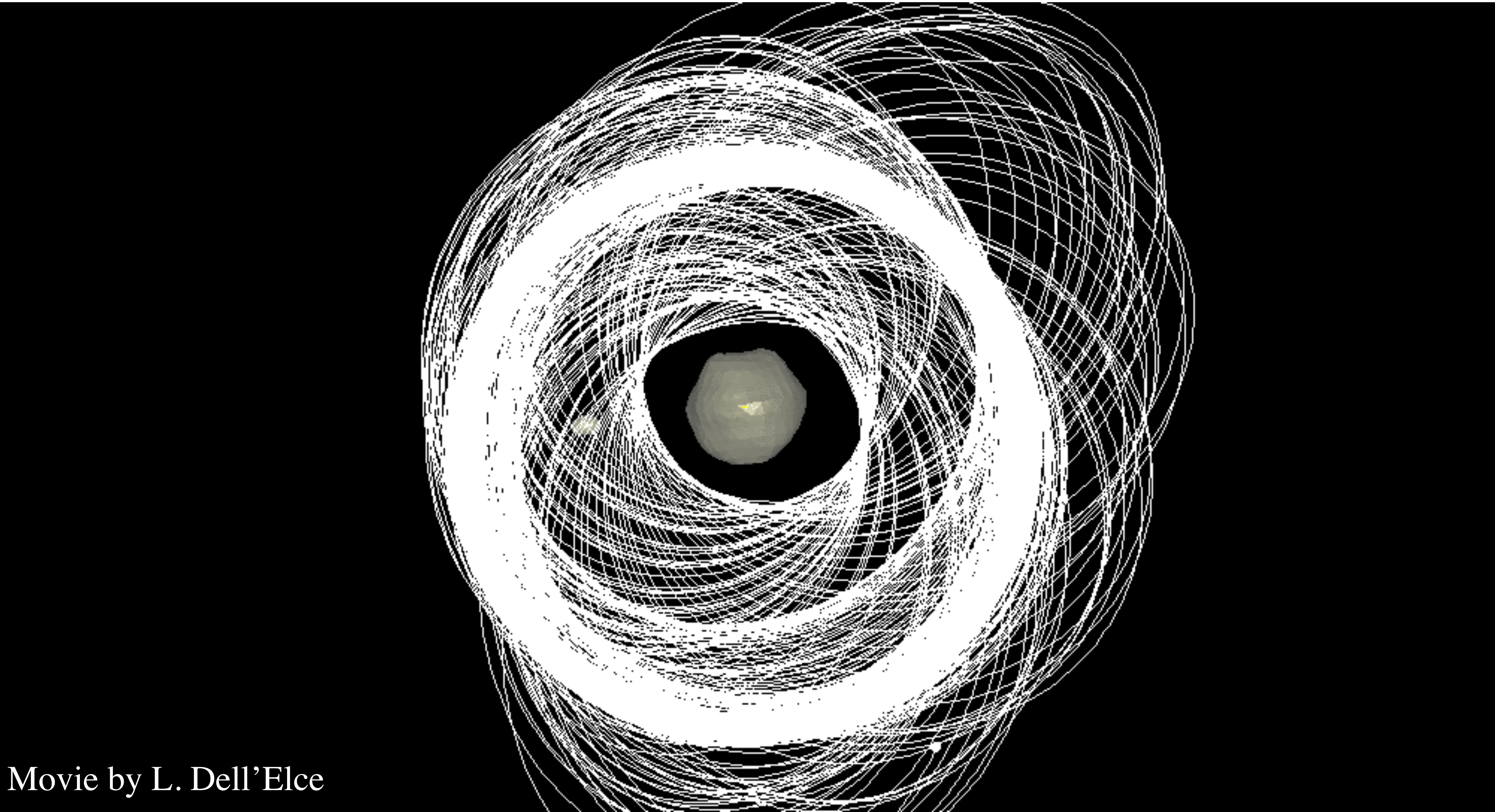
View in the terminator plane

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

Challenge: Complex gravitational environments

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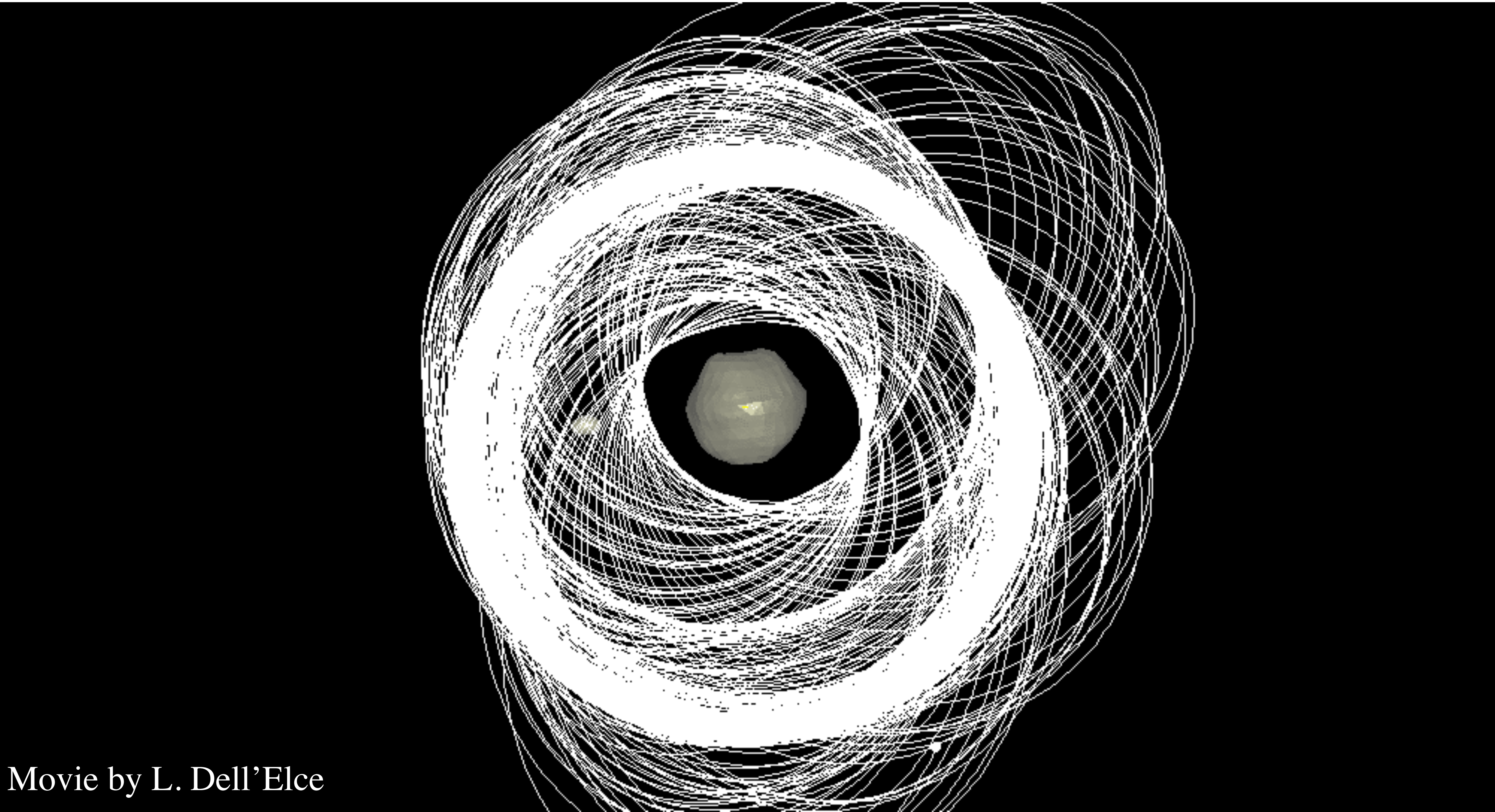

Movie by L. Dell'Elce

How to deal with such Challenges?

- Small bodies present a range of challenges that change 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 aspects are also of interest, but not discussed here:
  - Cometary outgassing effects
  - Controlled / hovering motion
  - Surface deployment and motion
- **Despite challenges, stable orbits for exploration can be found about *any* asteroid — but what works changes from body to body**

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robes to minor Solar System
d comets. This new field of
d on by the discovery of many
Kuiper Belt objects. However,
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ISBN 978-3-642-03255-4

PRAXIS

Scheeres

ORBITAL MOTION IN STRONGLY PERTURBED ENVIRONMENTS

PRAXIS

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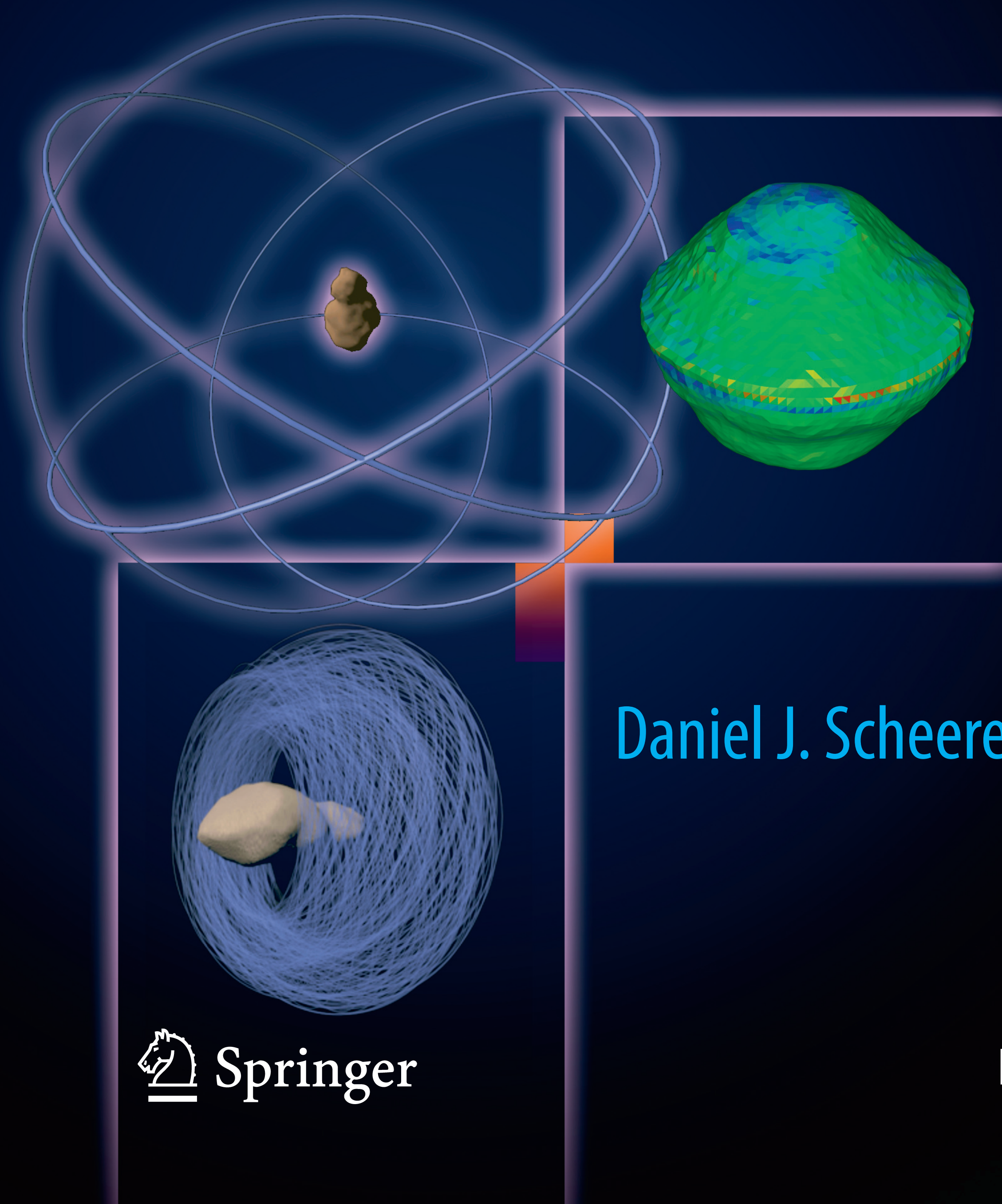
Applications to Asteroid, Comet and Planetary Satellite Orbiters



Daniel J. Scheeres

Springer

PRAXIS

OSIRIS-REx and Future Missions

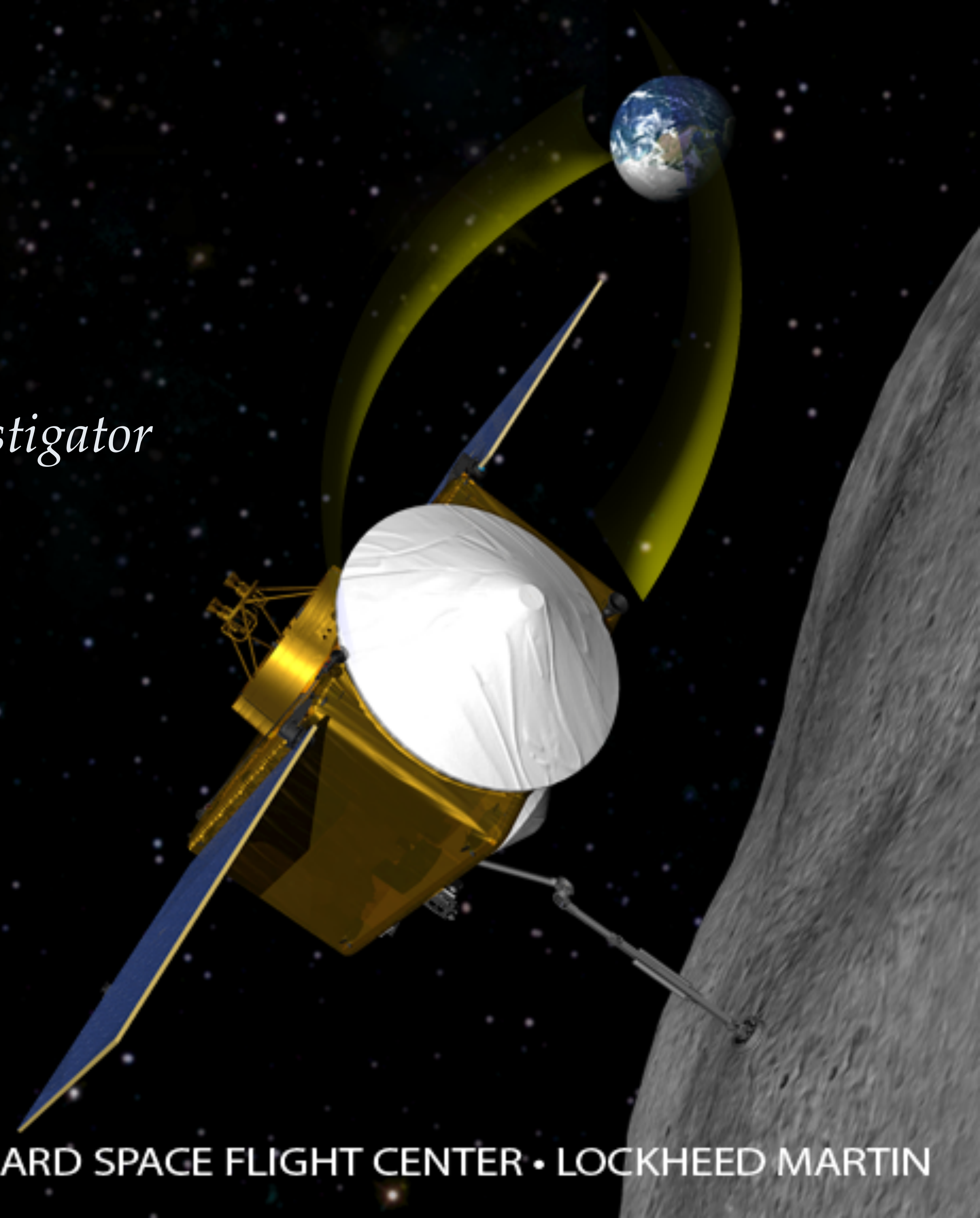
Future Exploration

OSIRIS-REx

Asteroid Sample Return Mission

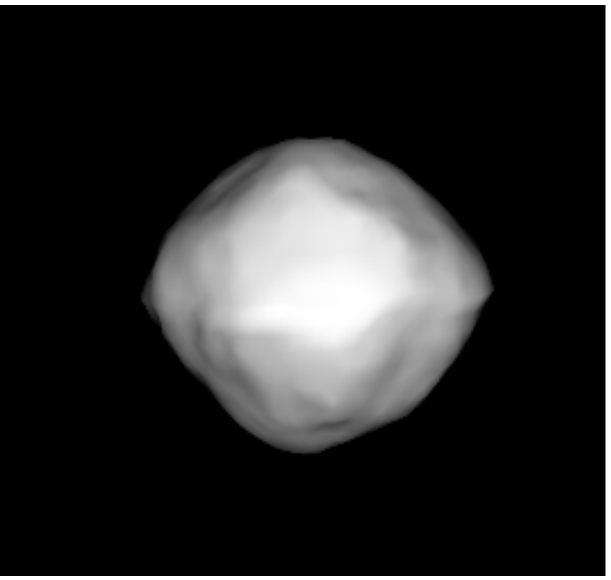
OSIRIS-REx Asteroid Sample Return Mission

Dante S. Lauretta – Principal Investigator



What is OSIRIS REx?

- **OSIRIS REx is a sample return mission** that returns at least 60 g (and as much as 2 kg) of **pristine carbonaceous regolith** from Asteroid Bennu



- Currently in transit to Bennu:
  - Launch in September 2016
  - Rendezvous with Bennu in 2019
  - Sampling in mid-2020
  - Return to Earth in 2023

Launch from KSC on September 8, 2016

- **Origins**
  - provide pristine sample to reveal the origin of volatiles and organics that led to life on Earth
- **Spectral Interpretation**
  - provide ground truth for ground-based and space based spectral observations of B-type carbonaceous asteroids
- **Resource Identification**
  - identify carbonaceous asteroid resources that we might use in human exploration
- **Security**
  - quantify the Yarkovsky Effect on a potentially hazardous asteroid, providing a tool to mitigate future asteroid impacts
- **Regolith Explorer**
  - Explore the regolith at the sampling site *in situ* at scales down to sub-millimeter

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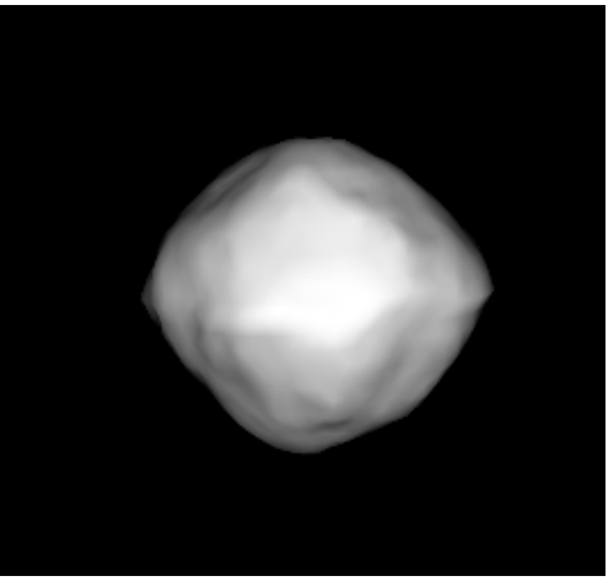

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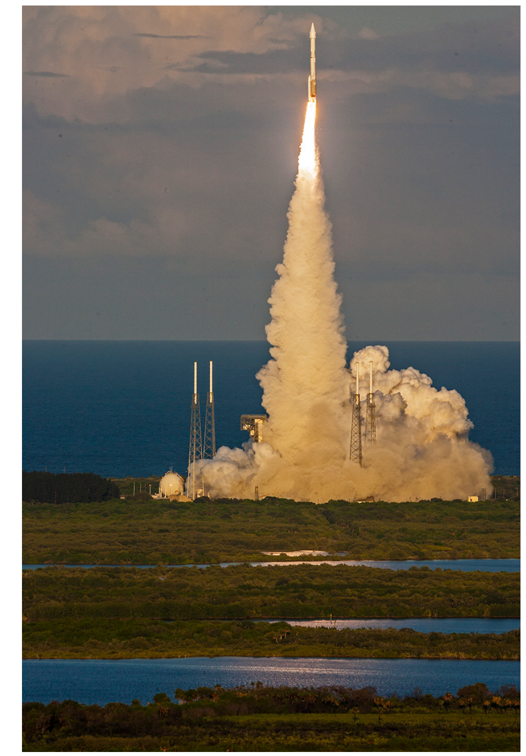

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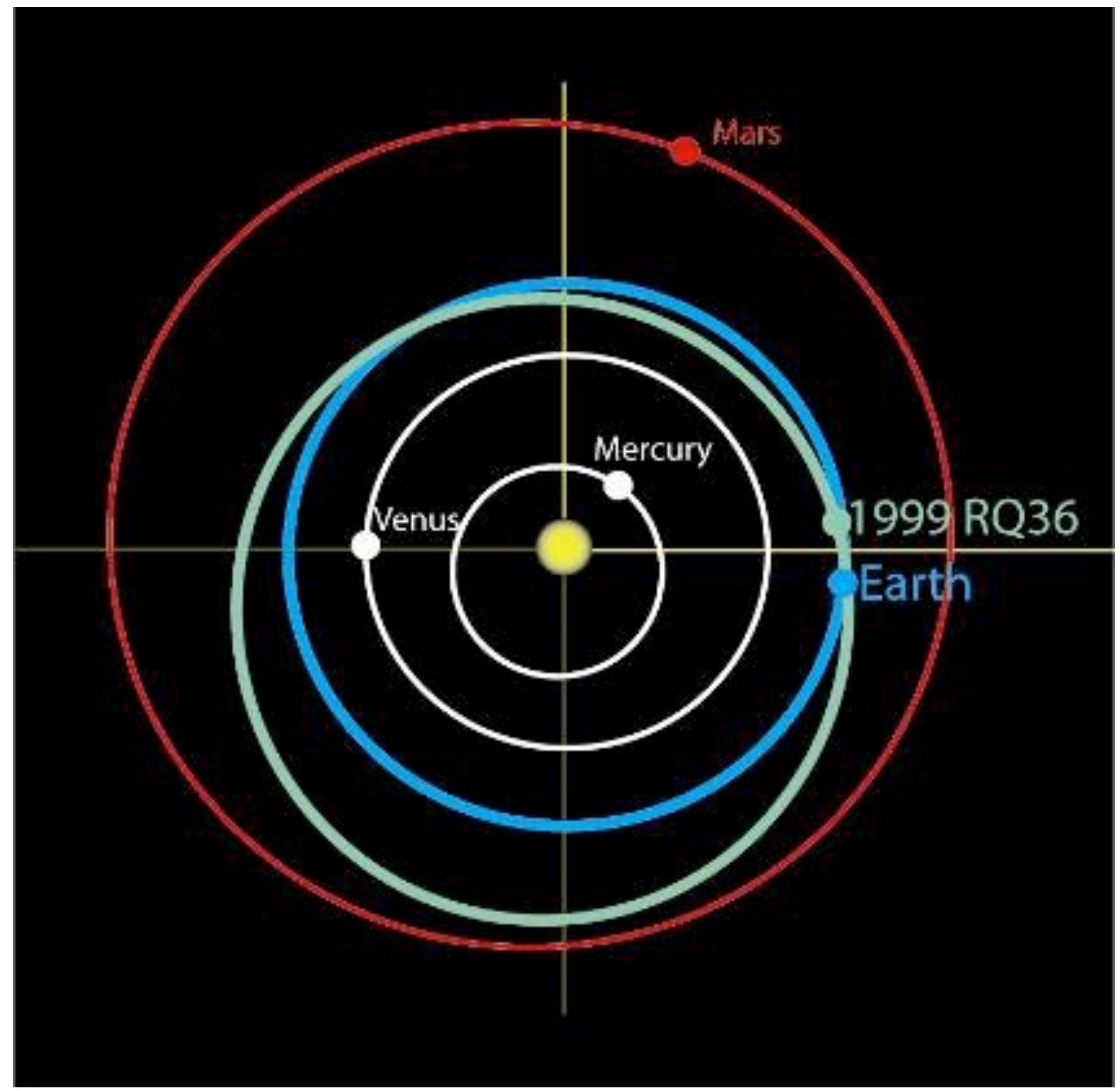
OSIRIS-REX ADDRESSES THE IMPACT HAZARD

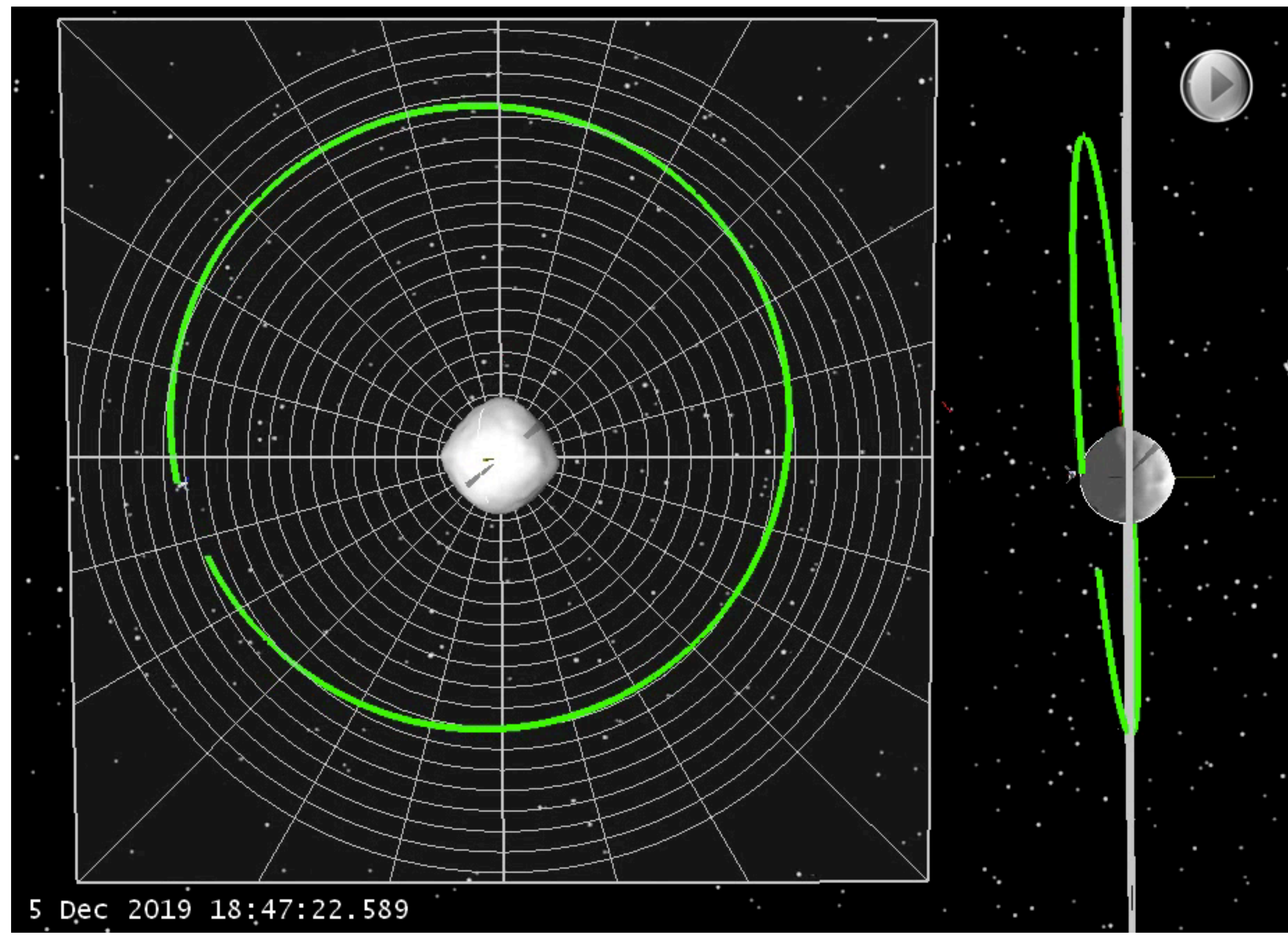
- Bennu is the ***most* Potentially Hazardous Asteroid known**.
- It is not particularly hazardous now, but…
  - Its orbit evolves to intersect Earth ~150 years from now
  - **Impact odds are 1 in 1800** in 2182
- OSIRIS-REx serves as a "**transponder mission**."
- It has the dual objectives of refining the orbit to ascertain whether an impact is impending and characterizing the object to facilitate a possible deflection mission.



What will OSIRIS-REx do at Bennu?

Arrival in late 2018, then…

- Reconnaissance
- Map the surface in detail
- Measure Bennu's
  - mass and gravity field
  - shape and spin state
- Choose "Touch and Go" site
- Prepare for TAG surface sampling in 2019
- Return to Earth with sample in 2023



Movie by B. Sutter

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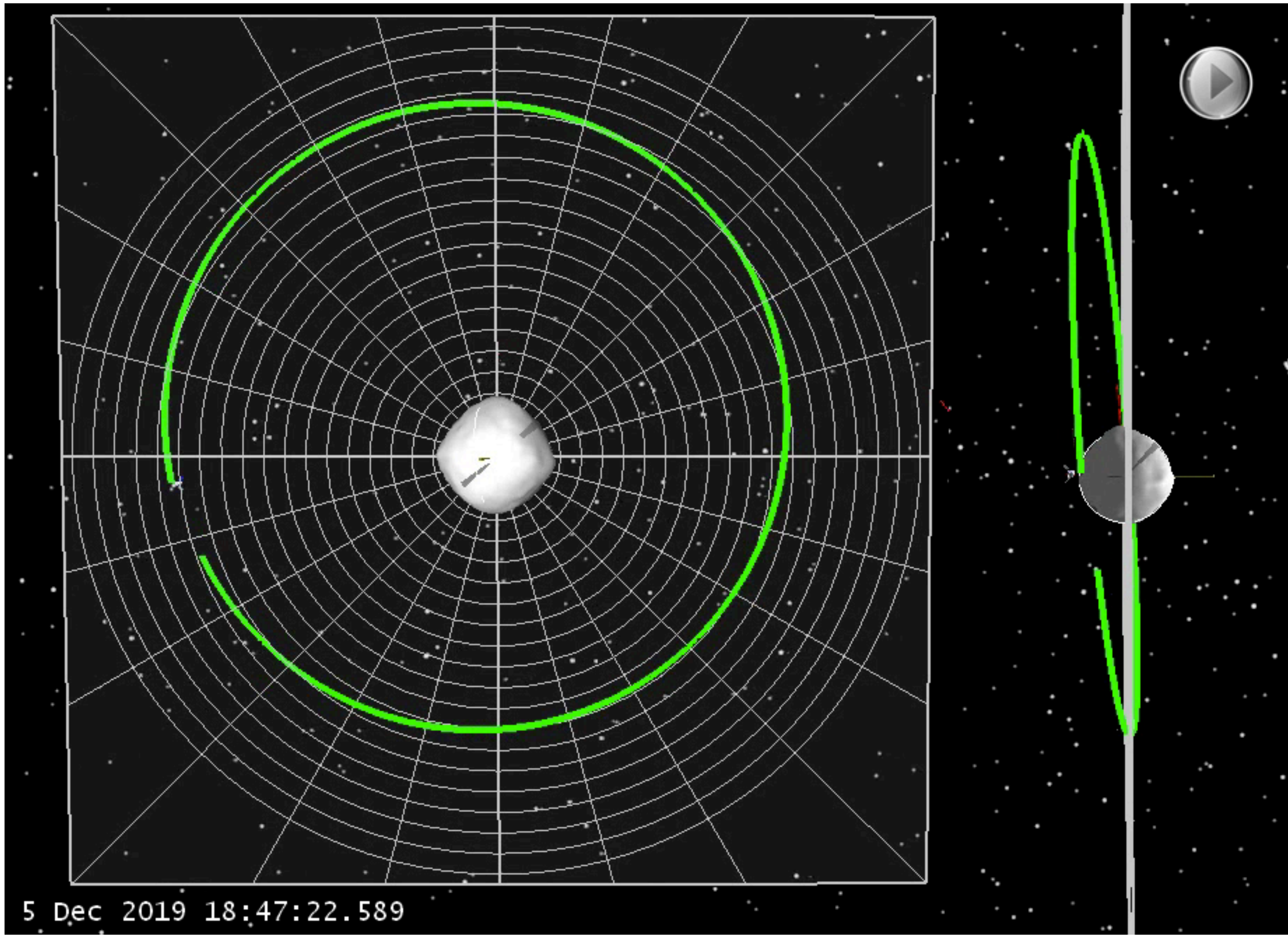
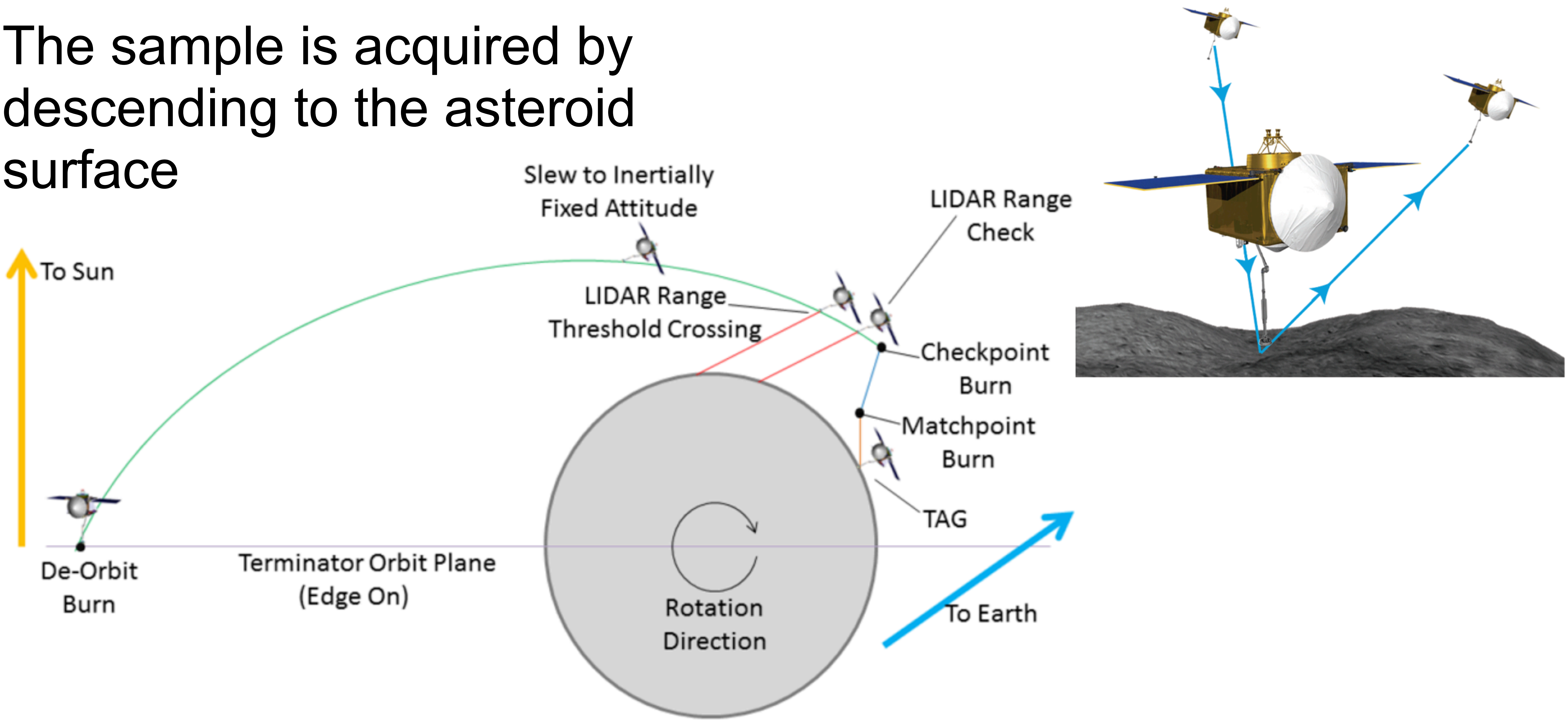


Movie by B. Sutter

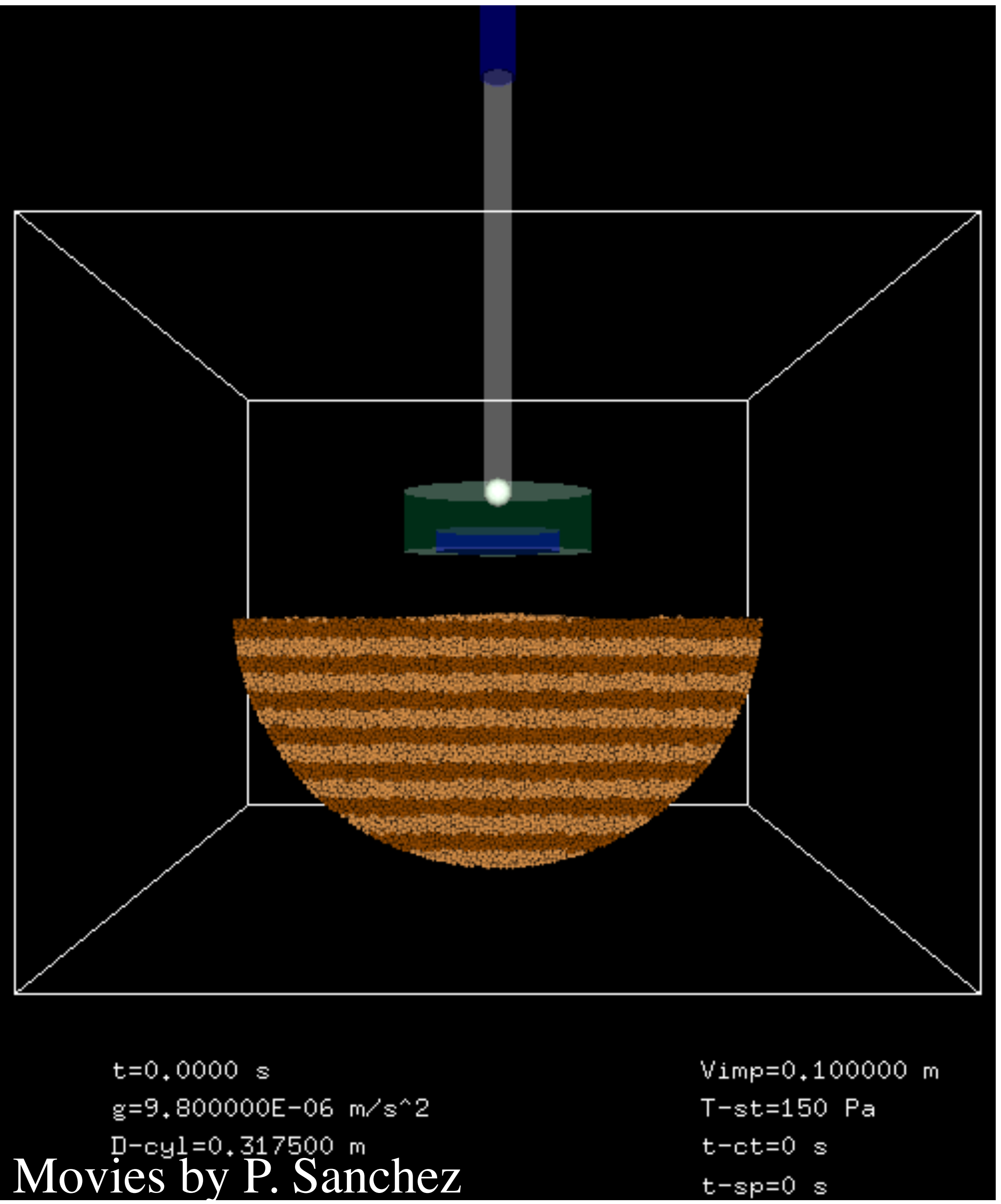
What will OSIRIS-REx do at Bennu?

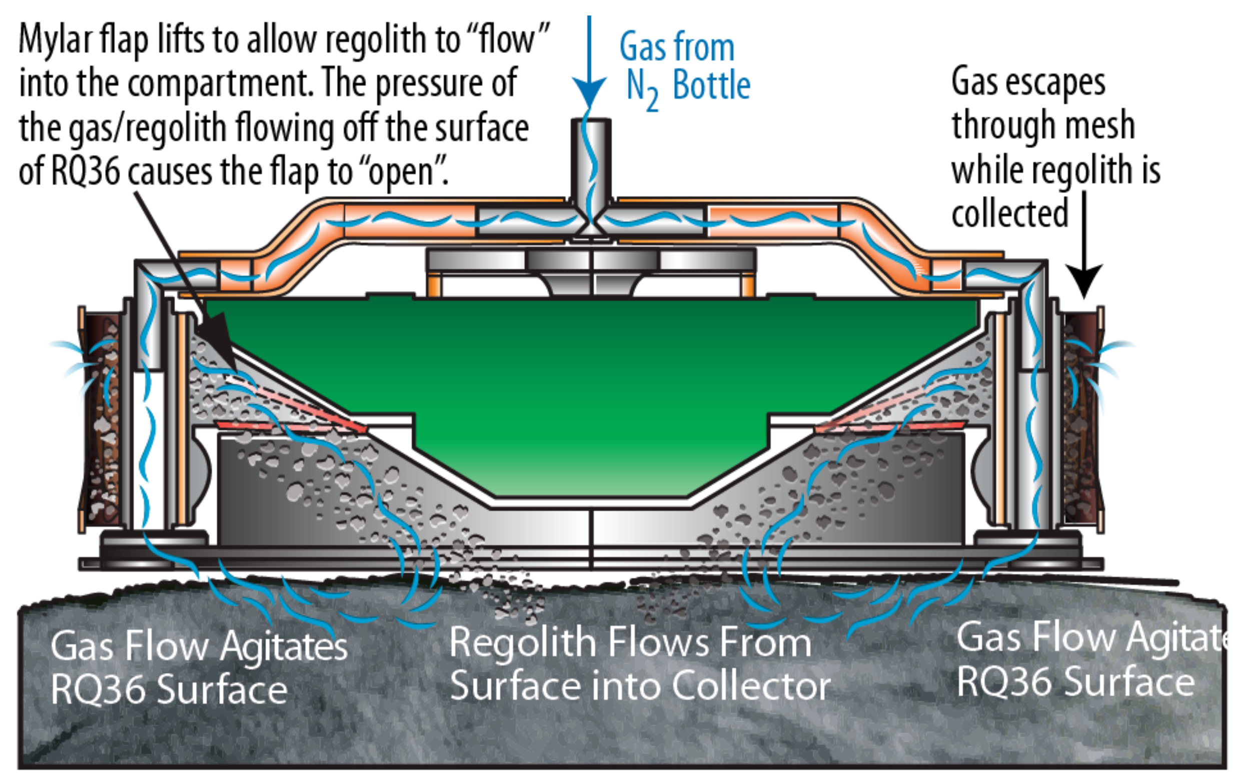
The sample is acquired by descending to the asteroid surface



What will OSIRIS-REx do at Bennu?

Sampling involves touching the surface for a few seconds with the TAGSAM device and capturing “regolith” using nitrogen gas and a “reverse vacuum cleaner” design





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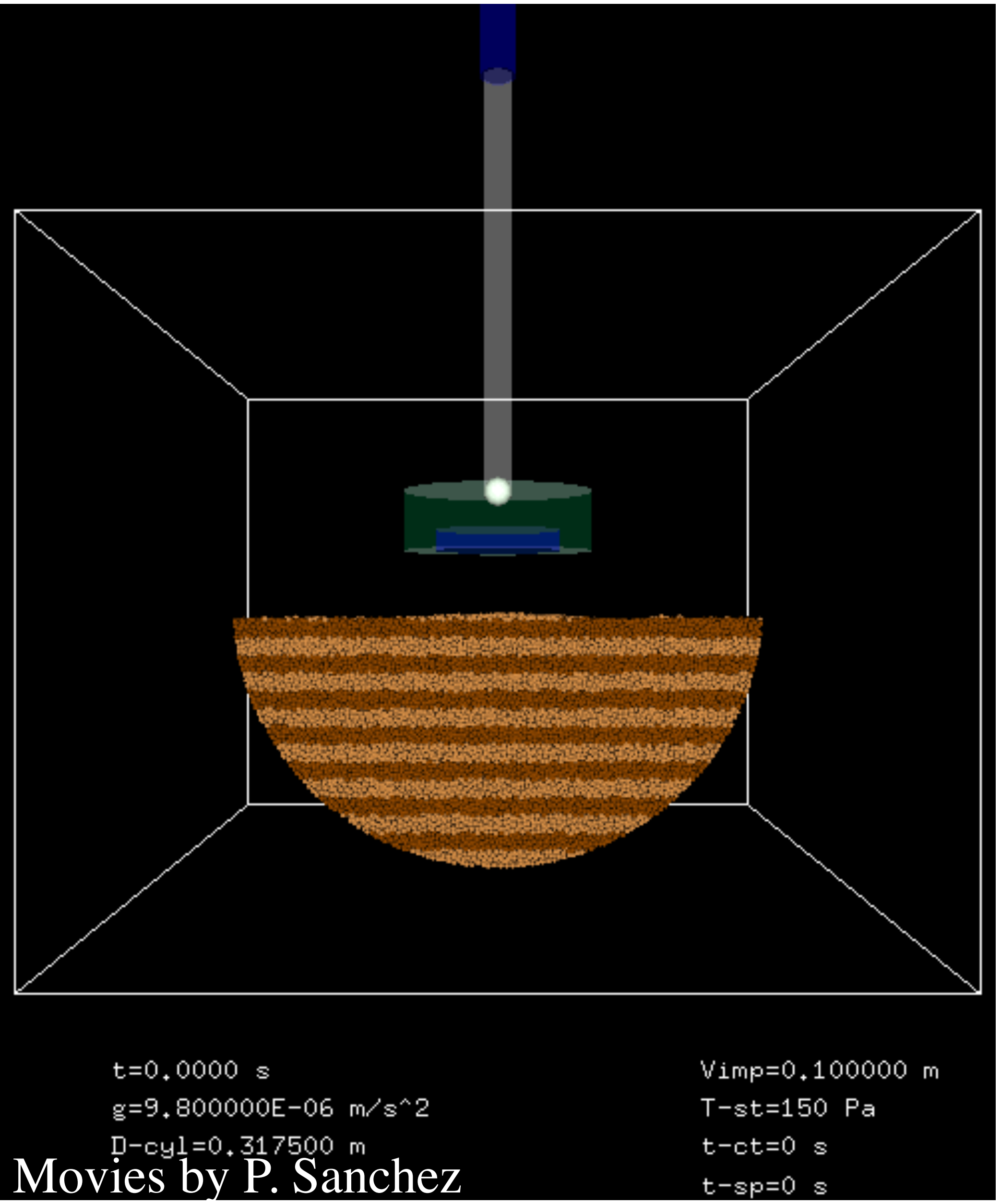
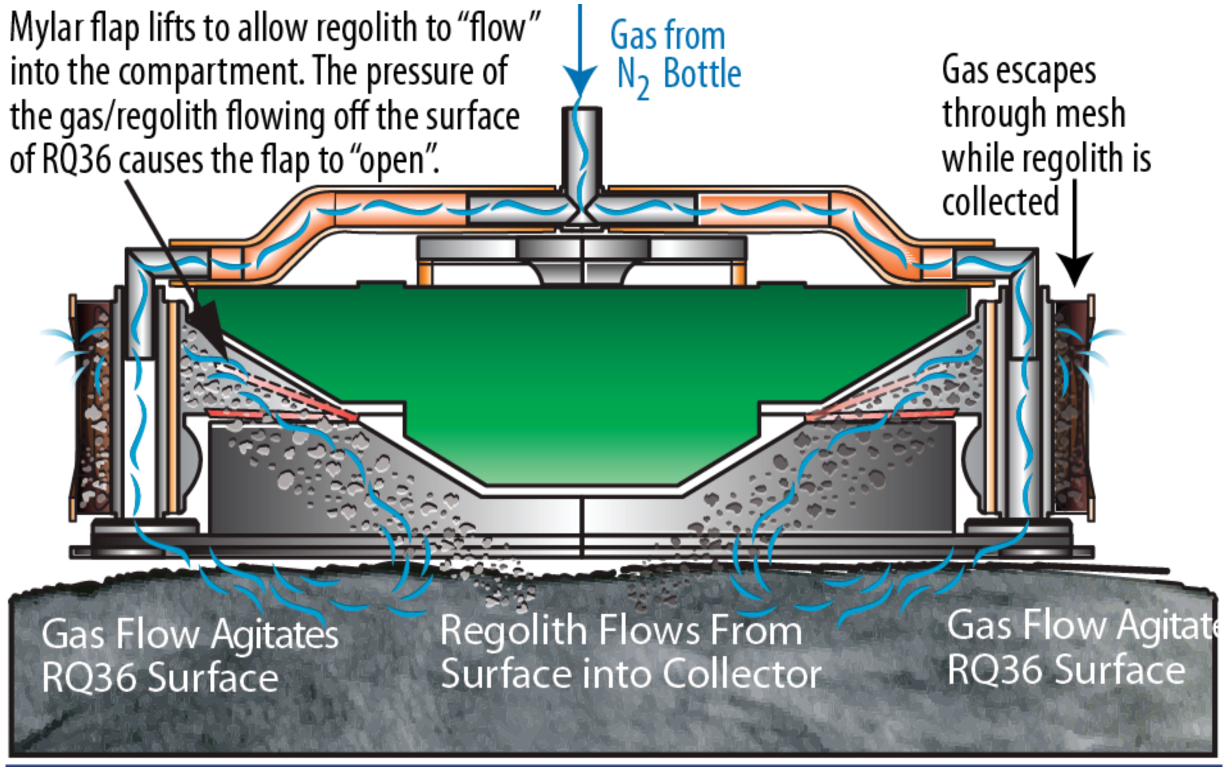
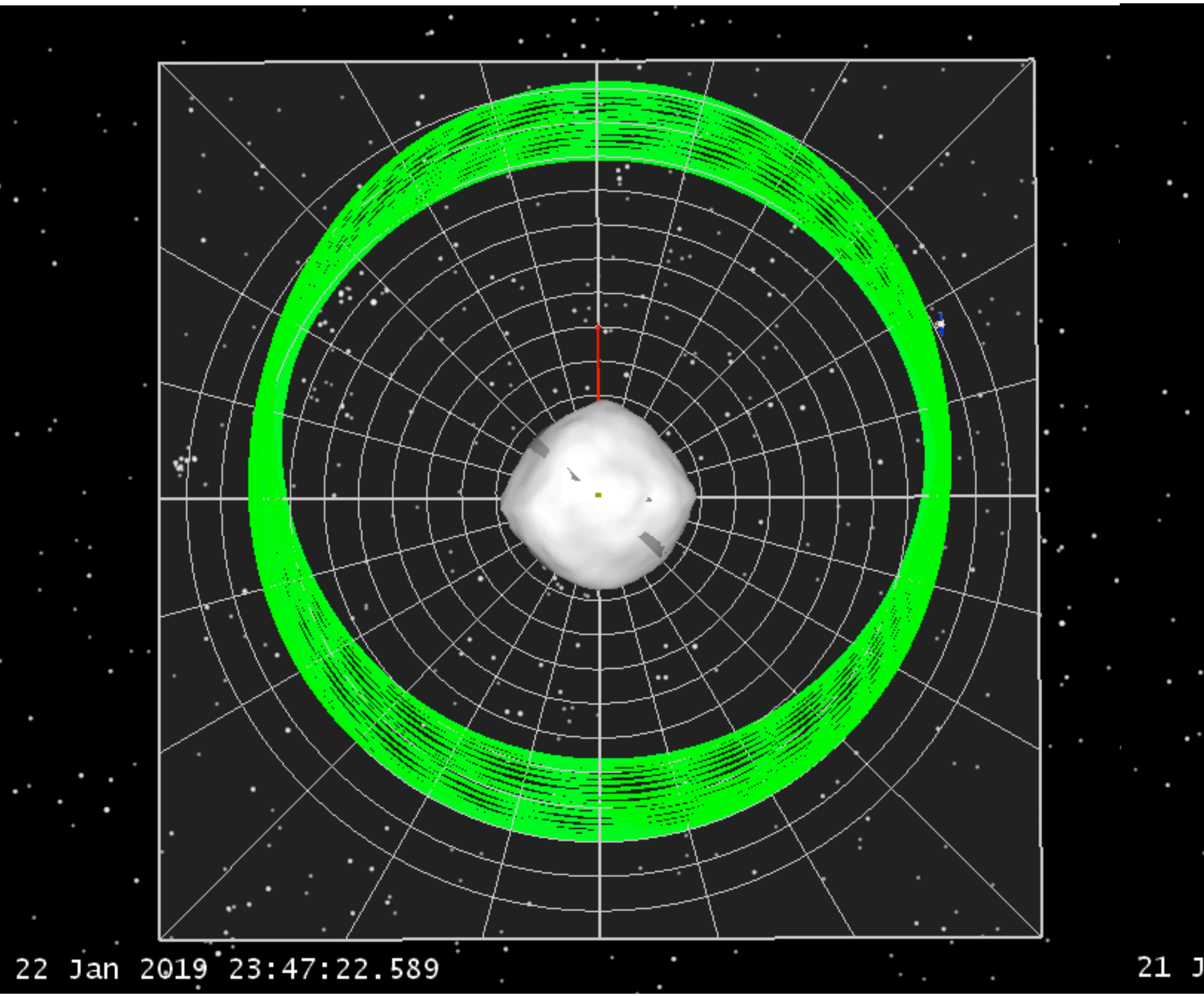


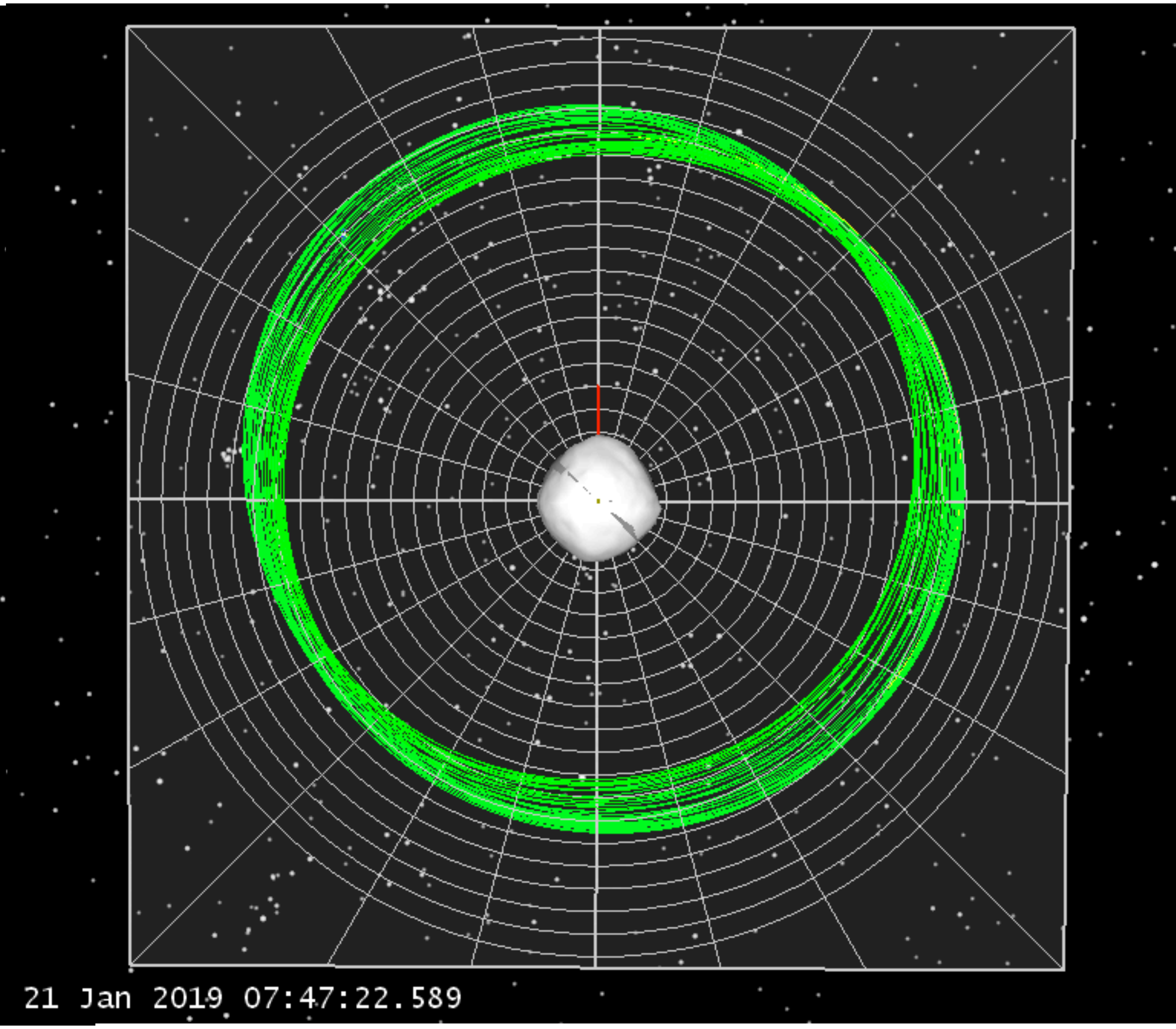
Movies by P. Sanchez



A key component of the mission are Orbit Phases A and B where important scientific observations and gravity field measurements occur



Orbit Phase B: 1 km Orbit



Orbit Phase A: 1.5 km Orbit

OSIRIS-REx is in the Solar Regime

- Primary perturbations 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
- Clear lower limits on semi-major axis also appear
  - Joint effects between SRP and gravity can be strongly destabilizing

Spacecraft Model

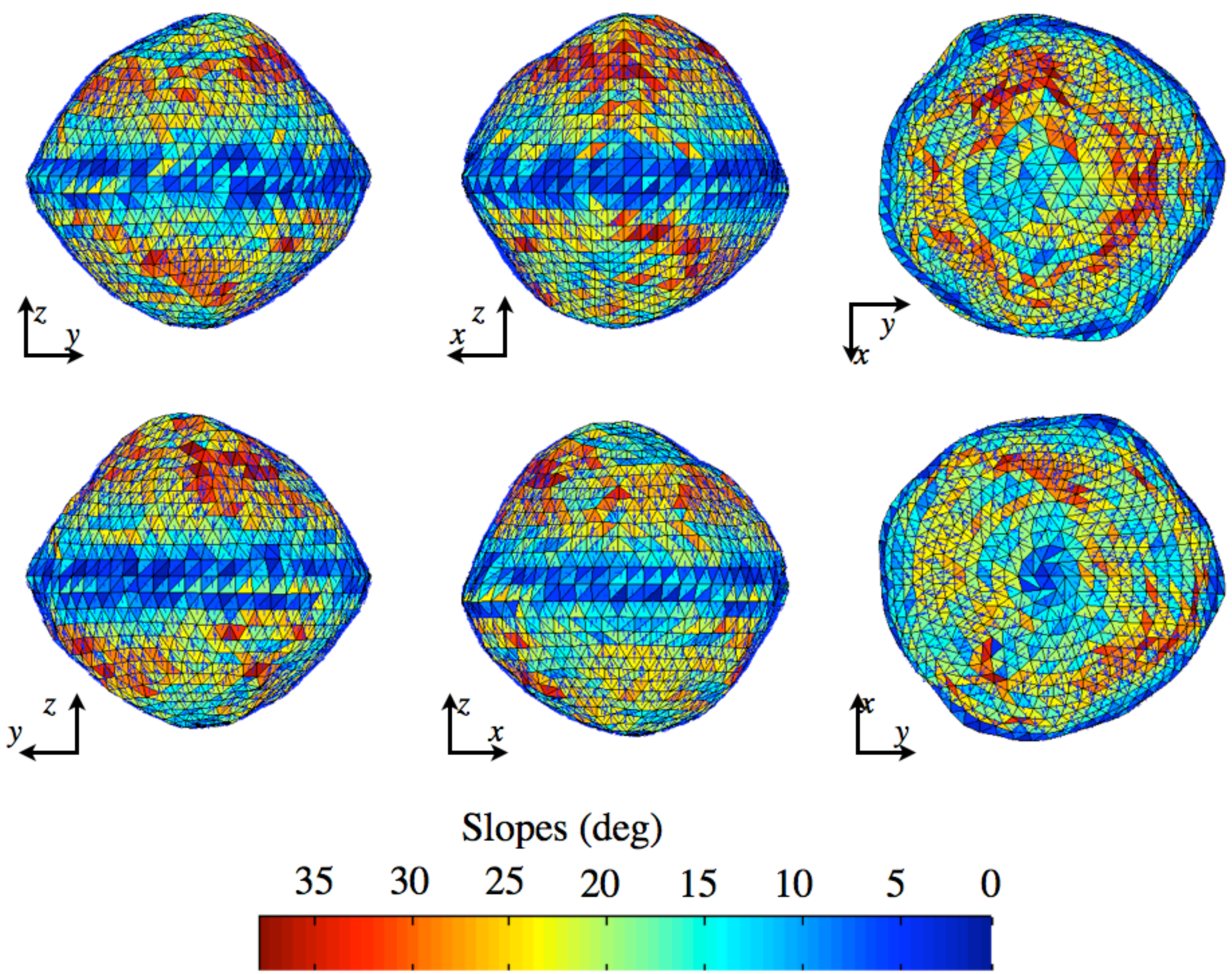
- We use a simple SRP model based on the usual characteristics of a small body orbiter
  - Constant area oriented towards the sun
  - S/C Mass to Area ratio: $B = M/A = 62$ kg/m^2 for OSIRIS-REx
  - Reflectance of $\rho = 0.4$

$$\mathbf{a}_{SRP} = \frac{(1+\rho)P_\Phi}{Bd^2}\hat{\mathbf{d}}$$

  - $P_\Phi \sim 1 \times 10^8 \text{ kg km}^3/\text{s}^2$
  - $\mathbf{d}$ is the sun-asteroid position vector (km)
- Asteroid orbit: $a = 1.126$ *AU*, $e = 0.2037$, $T = 1.19$ years

Environment Model

- Asteroid 1999 RQ36:
  - Diameter ~ 500 meters
  - Density ~ 1 ± 0.15 g/cm^3
  - Asteroid GM ~ 4.0 m^3/s^2
  - Uniform rotator with period ~ 4.3 hours

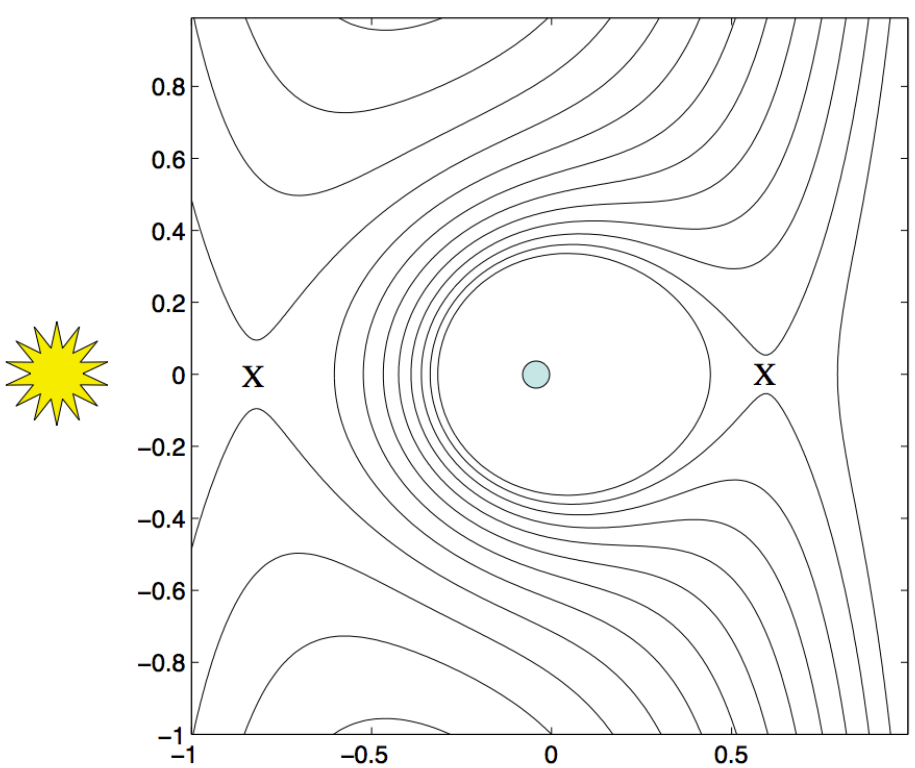


Escape Limits

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

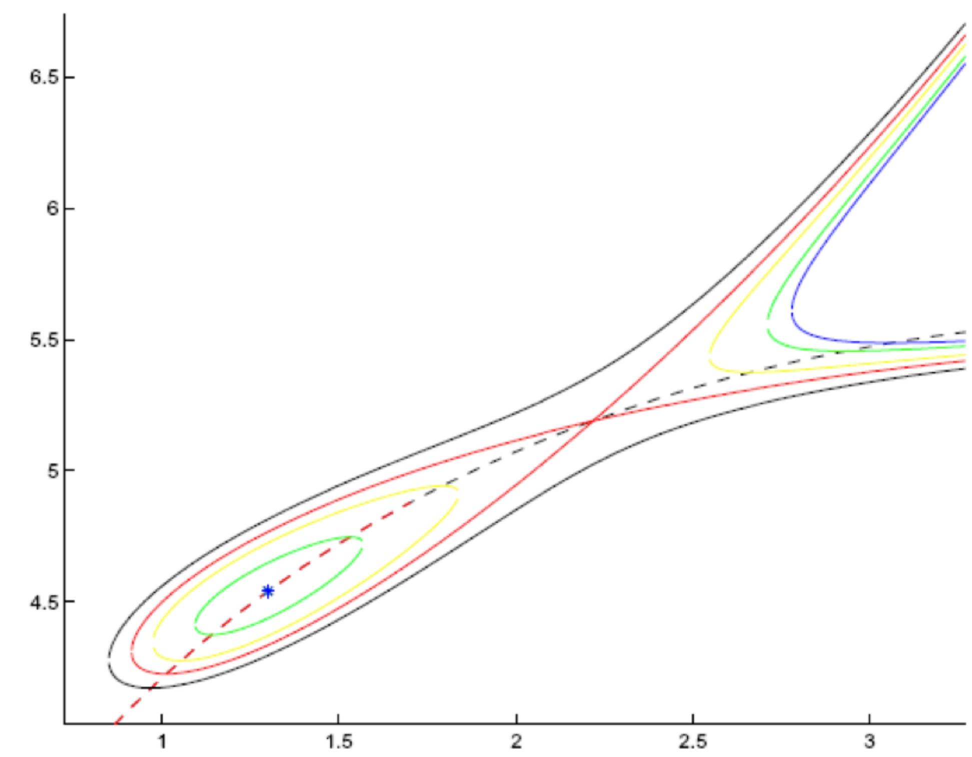
Semi-major axis remains constant until $a > a_{max}$ and then escapes.

Orbiter traveling towards perihelion can be lost as d decreases.



Zero-Velocity Curves in the Elliptic-Restricted SRP Problem

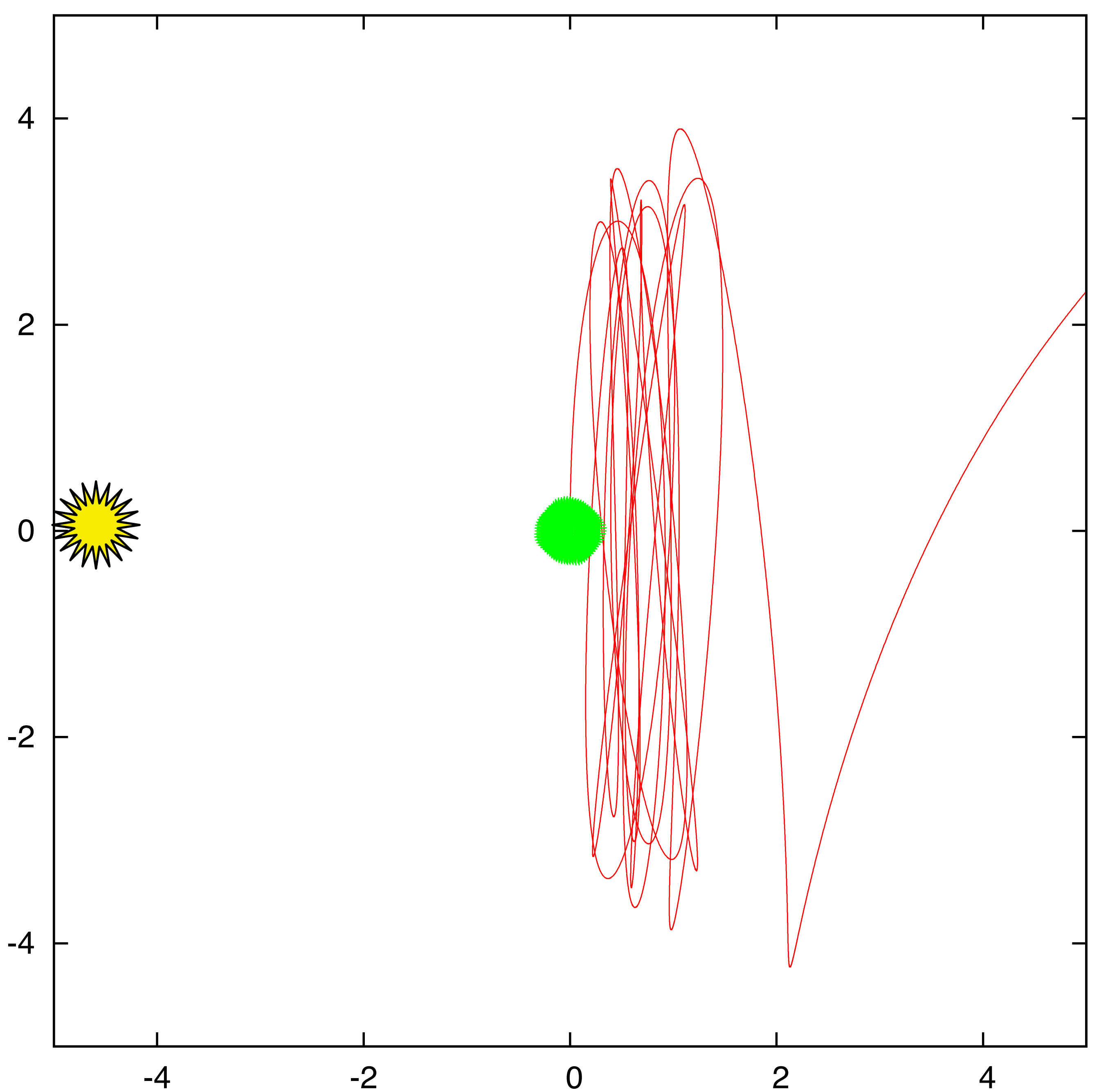
Orbit Radius



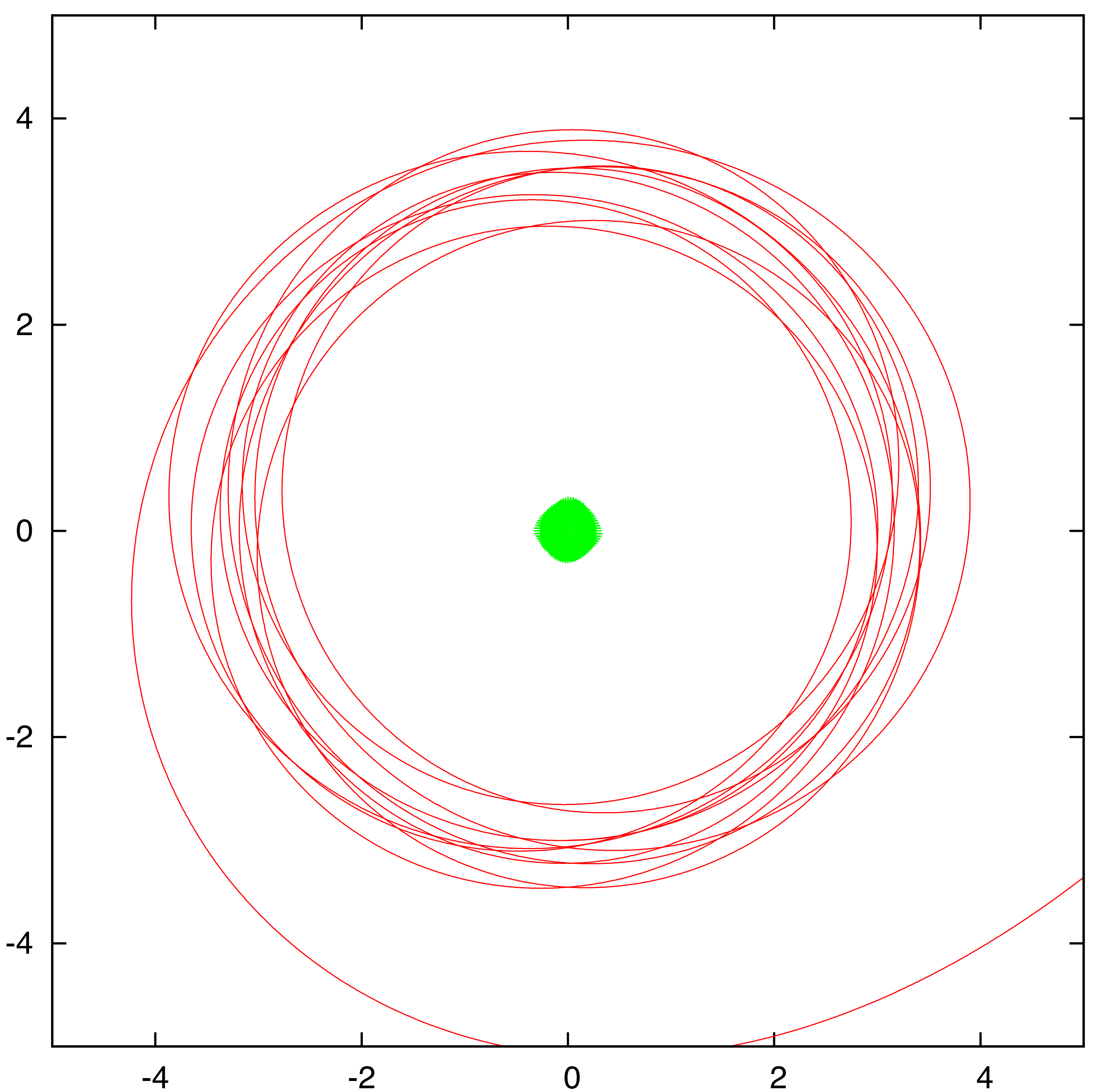
Offset Distance

Zero-Velocity Curves in the Non-Rotating SRP Problem

Maximum semi-major axis for bounded motion ~ 2.5 km



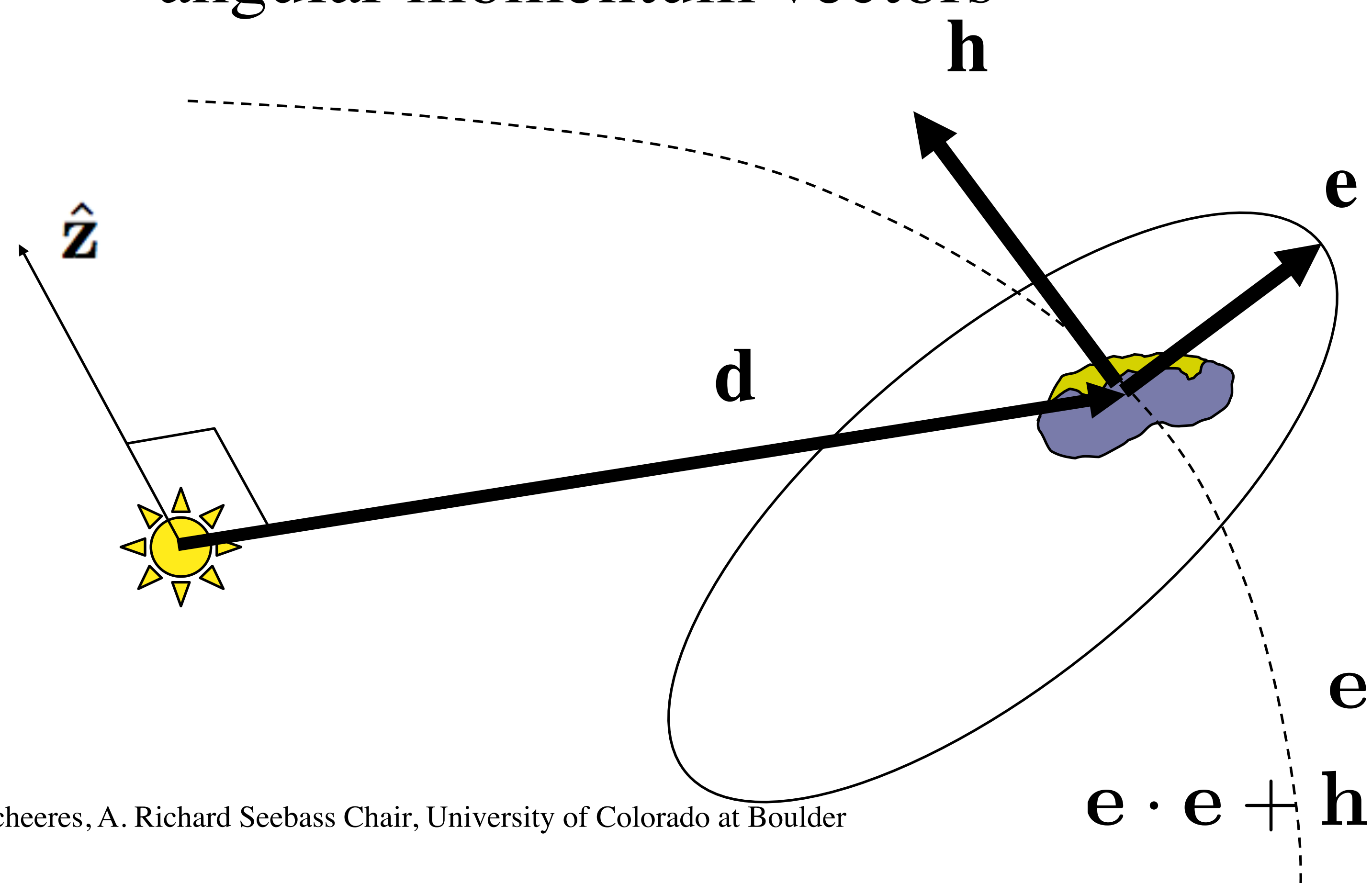
View looking down on the asteroid orbit plane



View looking from the sun

Averaged Orbit Mechanics for SRP

- If $a < a_{max}$ averaging can be applied
  - Semi-major axis a is constant on average
  - The secular equations can be solved in closed form, assuming a point mass (Mignard and Henon, 1984 and Richter and Keller, 1995), and generalized to the case of an asteroid orbiting the sun on an elliptic orbit (Scheeres 2009).
  - Solution is simplest to state using the osculating eccentricity and angular momentum vectors



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

Milankovitch Orbit Elements

- The orbit elements of eccentricity vector, angular momentum, and true longitude are non-singular
  - Introduced early in the 20th century by Milankovitch for propagating the orbit of the Earth to understand natural fluctuations in climate change
- After averaging take on a simple, symmetric form:

$$\dot{\mathbf{h}} = \tilde{\mathbf{h}} \cdot \left(\frac{\partial \overline{R}}{\partial \mathbf{h}} \right) + \tilde{\mathbf{e}} \cdot \left(\frac{\partial \overline{R}}{\partial \mathbf{e}} \right)$$

$$\dot{\mathbf{e}} = \tilde{\mathbf{e}} \cdot \left(\frac{\partial \overline{R}}{\partial \mathbf{h}} \right) + \tilde{\mathbf{h}} \cdot \left(\frac{\partial \overline{R}}{\partial \mathbf{e}} \right)$$

$$R = \frac{(1+\rho)P_\Phi}{Bd^2} \hat{\mathbf{d}} \cdot \mathbf{r}$$

$$\overline{R} = -\frac{3}{2} a \frac{(1+\rho)P_\Phi}{Bd^2} \hat{\mathbf{d}} \cdot \mathbf{e}$$

Averaged SRP Equations

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

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

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

- For a strong perturbation, Λ -> π/2
- For a weak perturbation, Λ -> 0
- Hayabusa at Itokawa, Λ ~87°, NEAR at Eros, Λ ~13°, OREX at RQ36 ~ 85°

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Solution to the Eqns

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

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

– $\mathbf{\Phi}$ is a 6x6 orthonormal rotation matrix, periodic in true anomaly: $2\pi/\cos(\Lambda)$

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

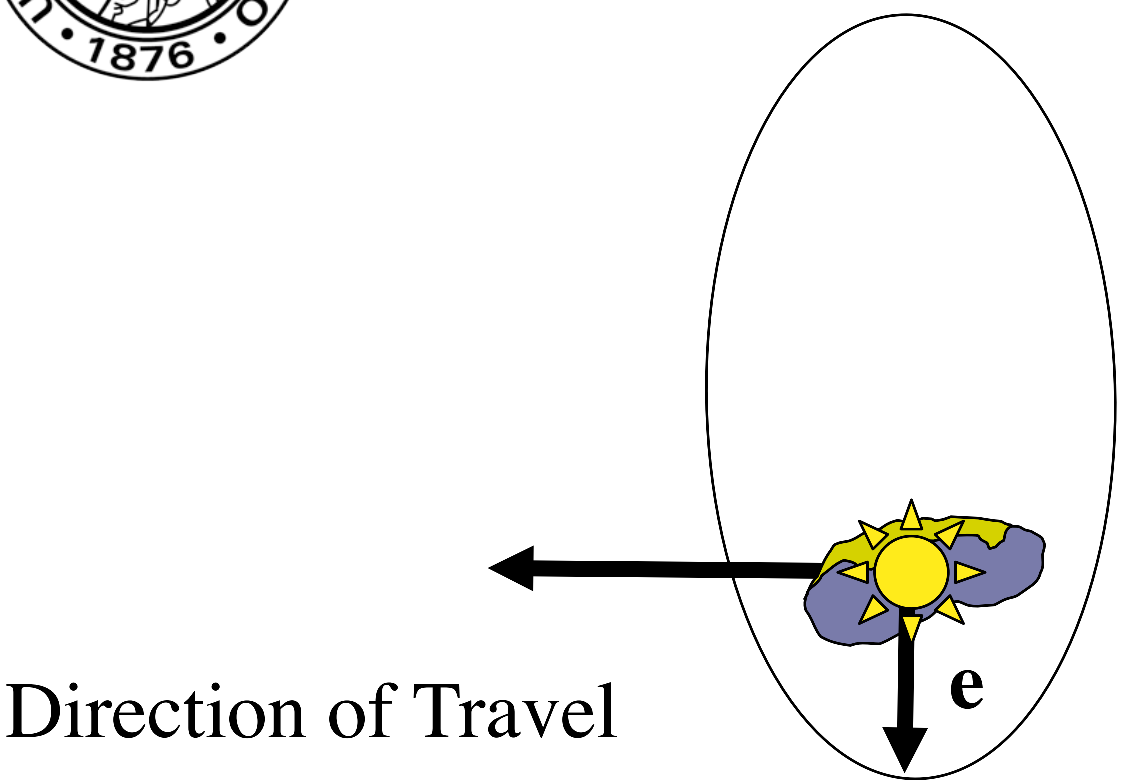
– Defined as a function of scaled true anomaly: $\psi = \nu/\cos(\Lambda)$

– OSIRIS-REx has a perturbation angle of $\Lambda \sim 85°$

– A 1 km orbit has a secular period of ~ 38 days on average (faster at perihelion, slower at aphelion)

Solar Plane-of-Sky / Terminator Orbits

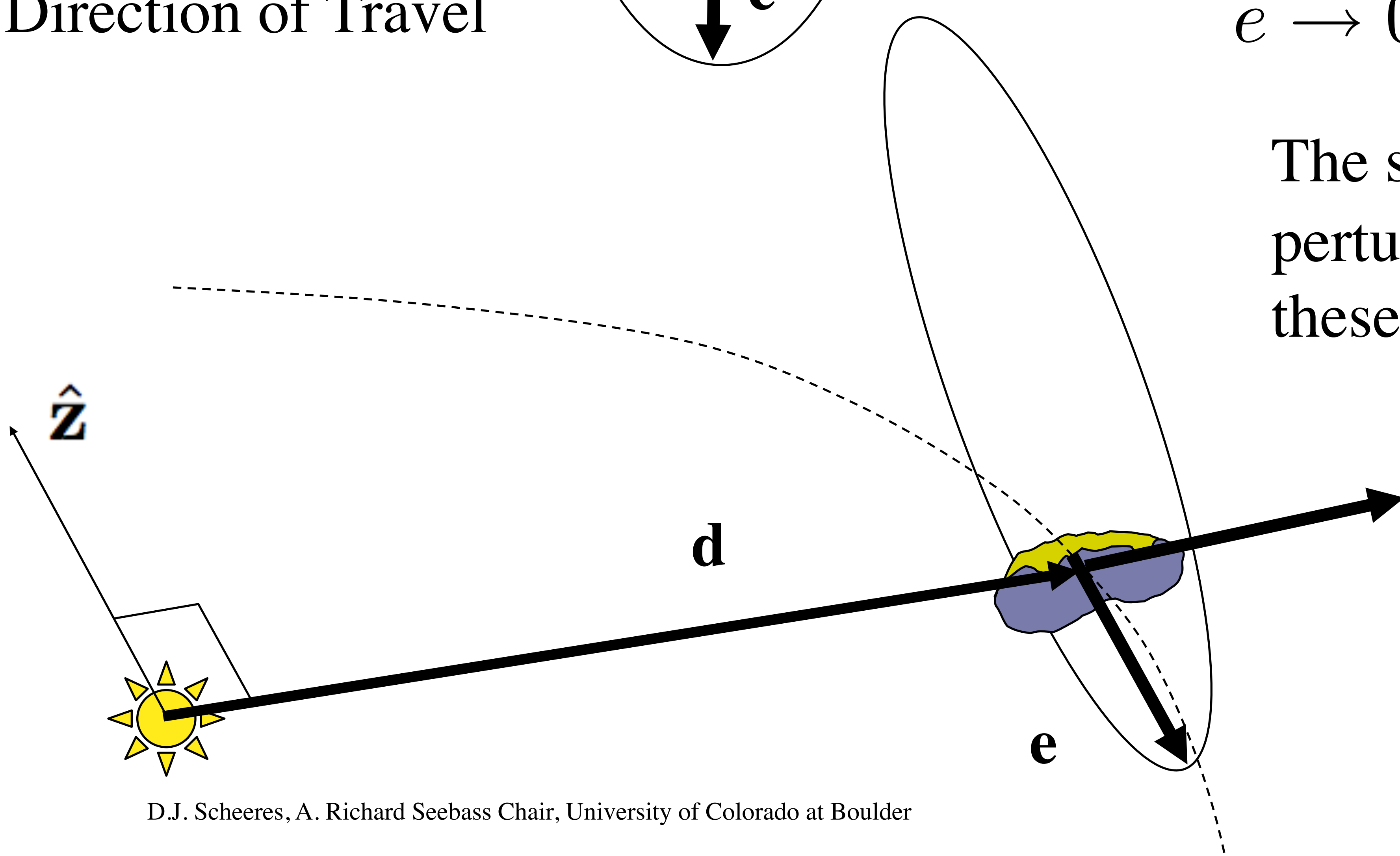
A particularly useful "frozen orbit" solution to these equations are the terminator orbits with properly chosen argument of periapsis and eccentricity.



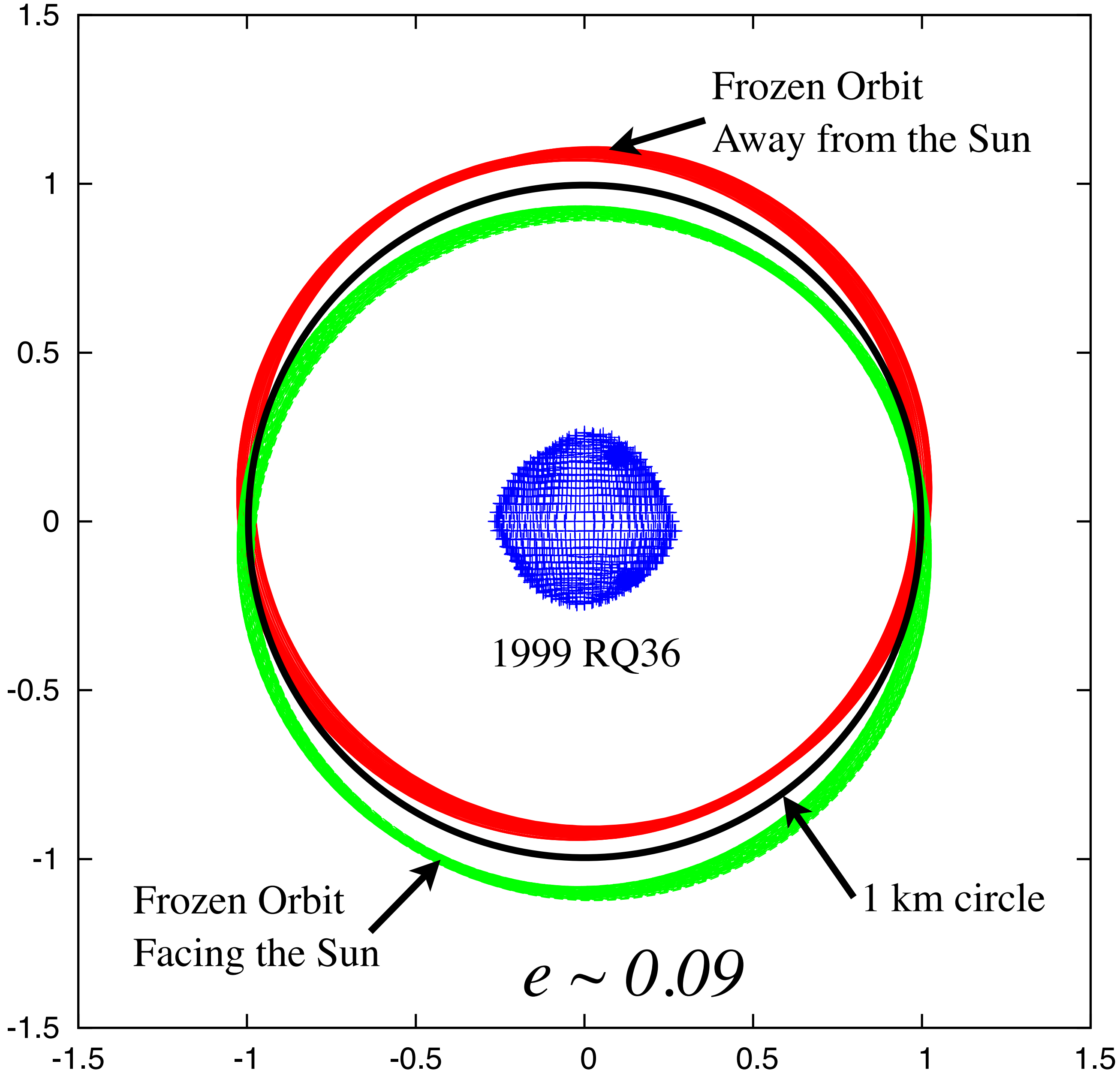
$$e = \cos \Lambda$$

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

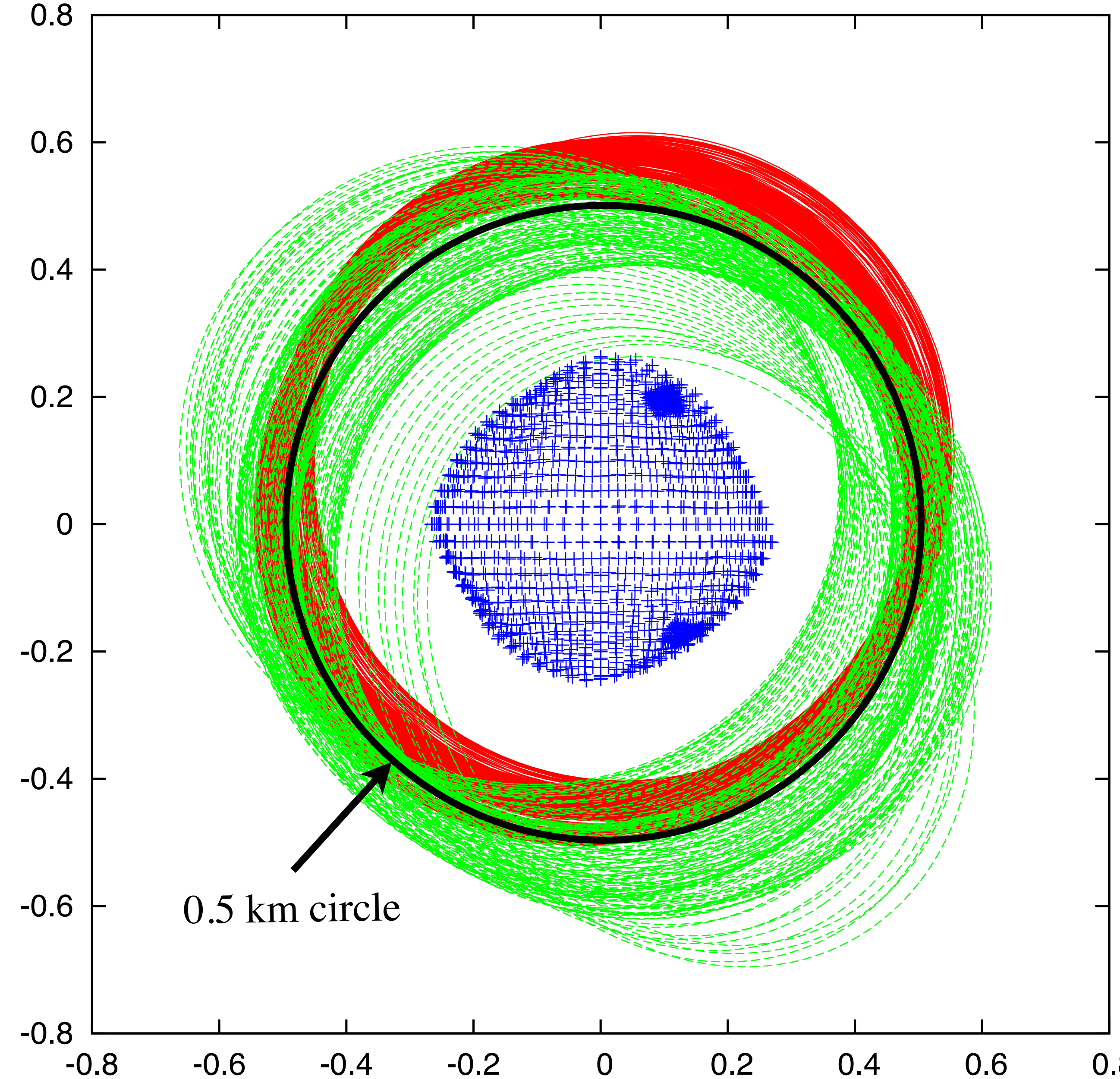
The stronger the SRP perturbation, the more circular these frozen orbits become.



For orbits much closer than ~ 0.7 km semi-major axis, the gravity field destabilizes motion



Orbit Phase B: 1 km Orbit



0.5 km Orbit

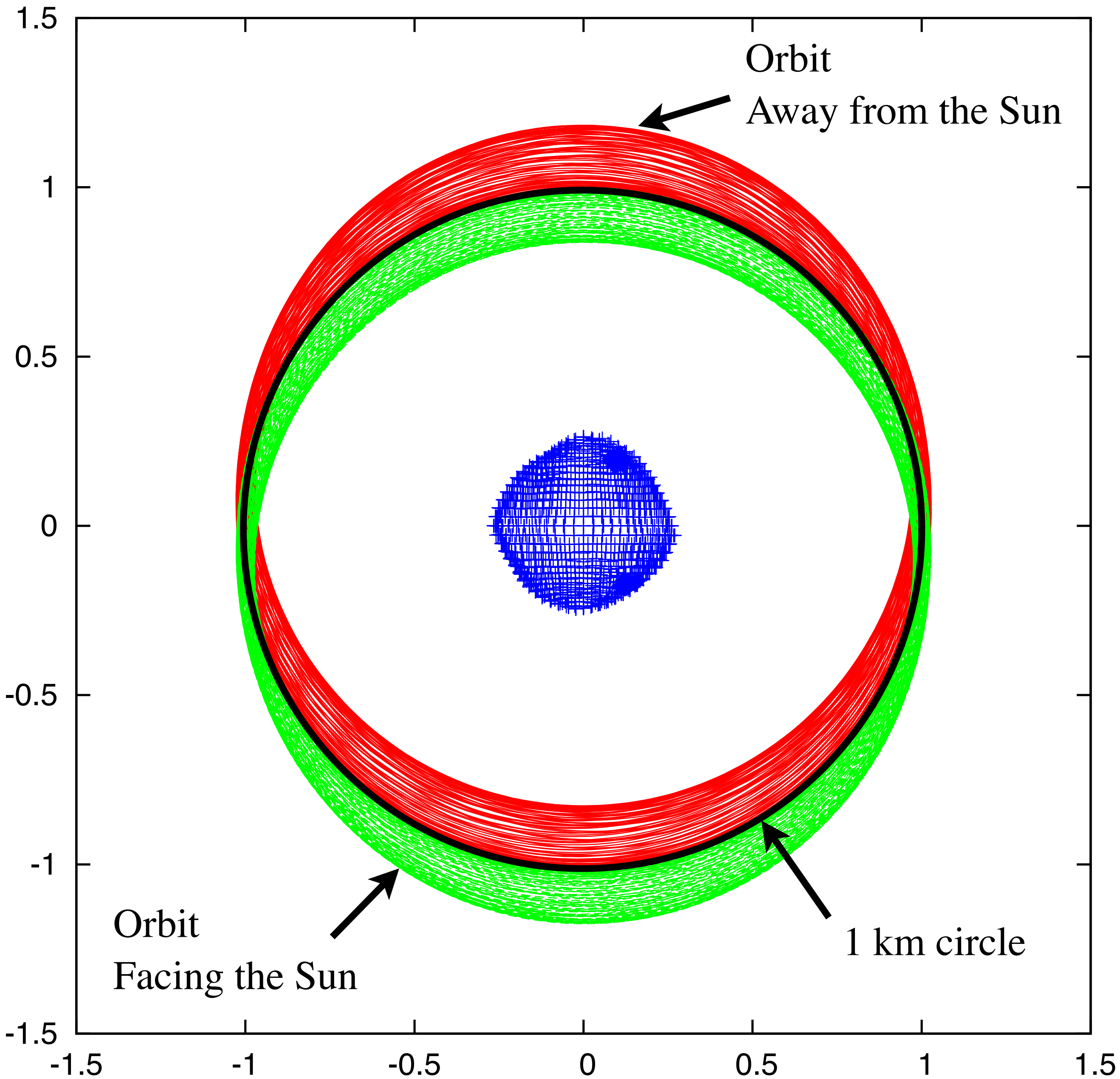
Initially Circular Orbits

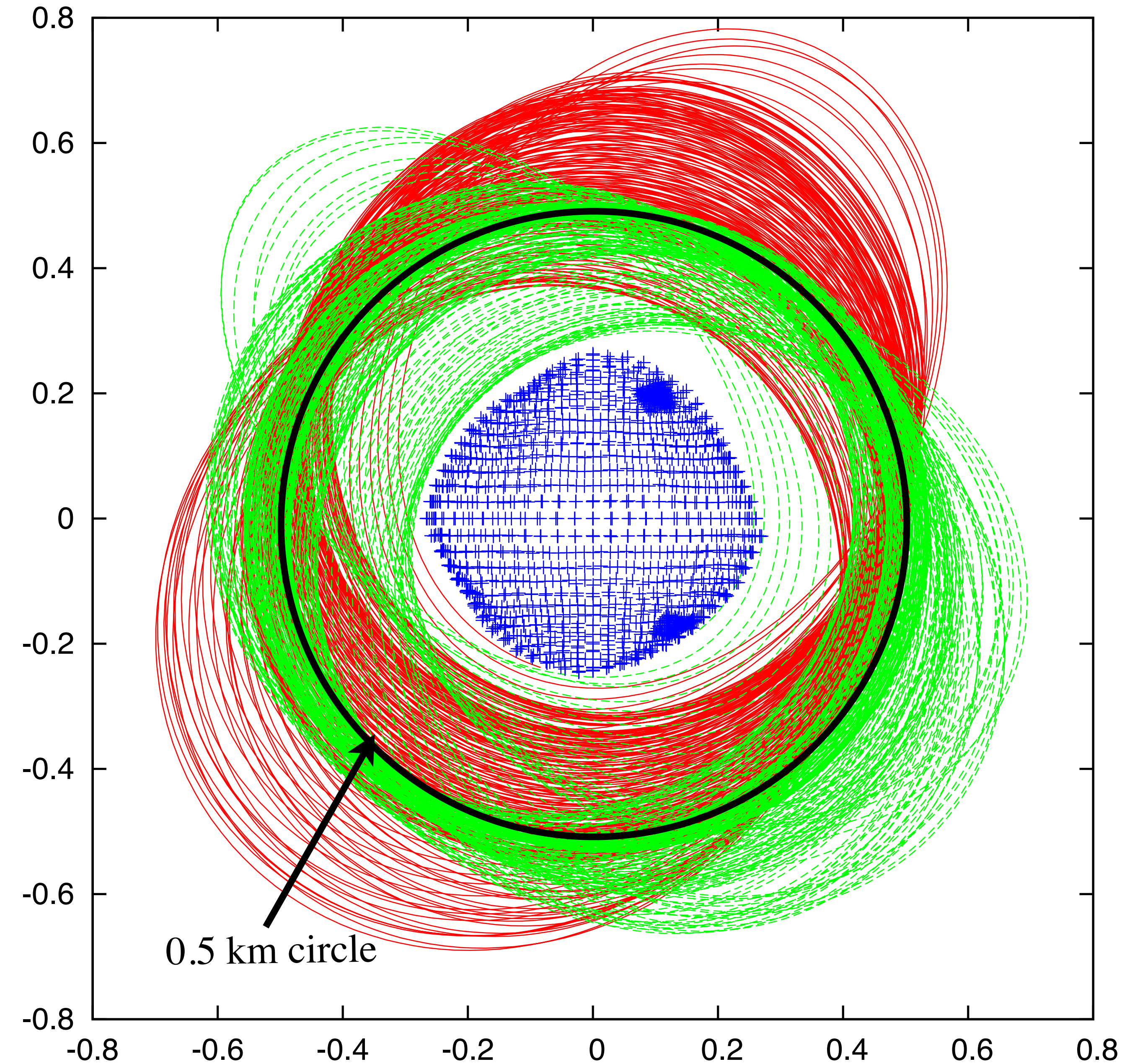
- As the secular orbits are periodic, any orbit that becomes circular at one point can be modeled as an initially circular orbit
  - Initial conditions are $\mathbf{e}_0 = \mathbf{0}, \;\; \mathbf{h}_0 = \hat{\mathbf{h}}_0$
- Solution can be worked out in detail and analyzed:

$$\begin{aligned}
\mathbf{e}(\psi) &= -(1-\cos\psi)\sin\Lambda\cos\Lambda\left[\hat{\mathbf{z}}\hat{\mathbf{d}} + \hat{\mathbf{d}}\hat{\mathbf{z}}\right]\cdot\mathbf{h}_0 + \sin\psi\sin\Lambda\tilde{\hat{\mathbf{d}}}\cdot\mathbf{h}_0 \\
\mathbf{h}(\psi) &= \cos\psi\mathbf{h}_0 + (1-\cos\psi)\left[\cos^2\Lambda\hat{\mathbf{z}}\hat{\mathbf{z}} + \sin^2\Lambda\hat{\mathbf{d}}\hat{\mathbf{d}}\right]\cdot\mathbf{h}_0 - \sin\psi\cos\Lambda\tilde{\hat{\mathbf{z}}}\cdot\mathbf{h}_0
\end{aligned}$$

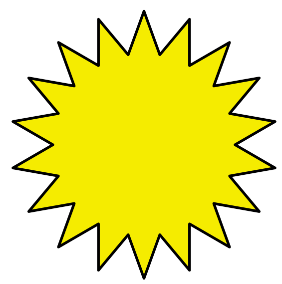
  - Note, it is impossible to have a constant zero eccentricity solution.

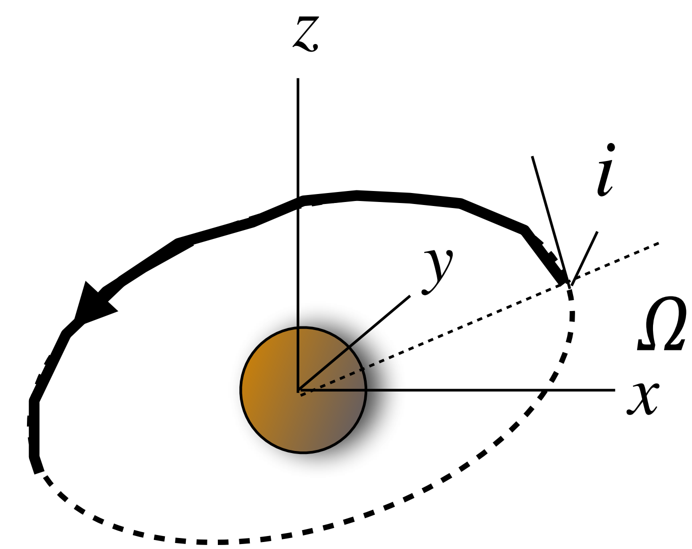
Initially circular orbits in the terminator plane have one-sided oscillations in eccentricity coupled with out of plane oscillations.

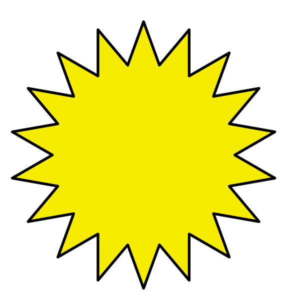


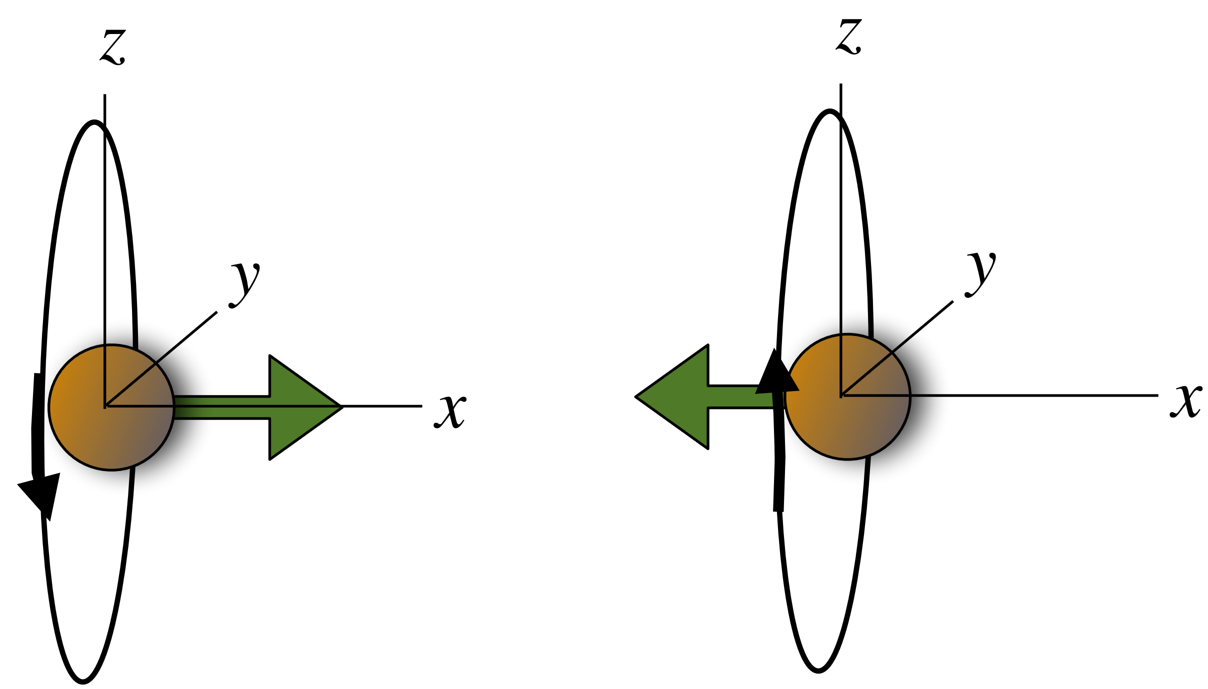


Orbit Geometry



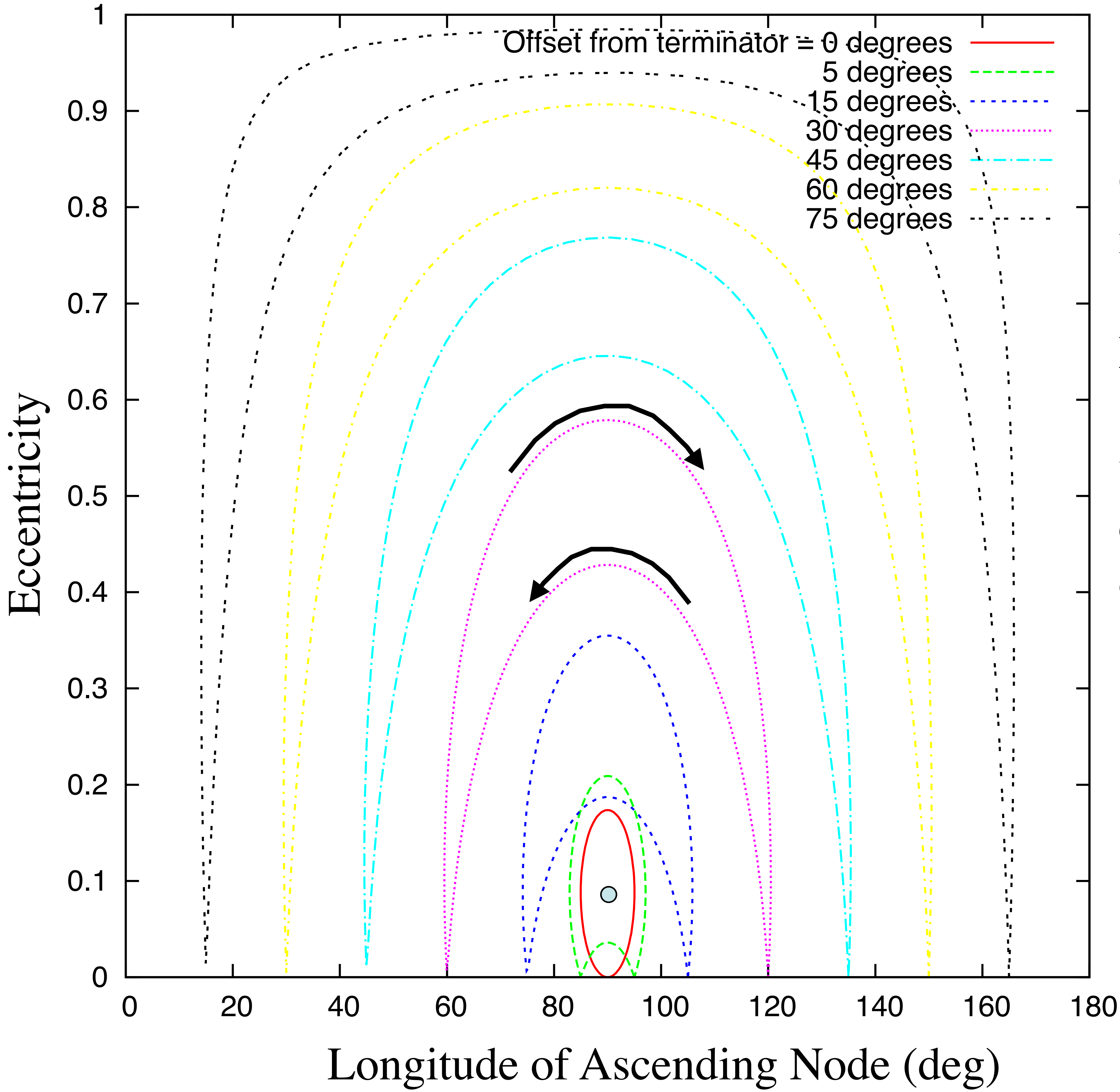






Node is at ± 90°

Oscillations around a node of 90°



Constant Period for all motion of ~38 days

Maximum eccentricity at terminator crossing, with two different extreme values at crossing

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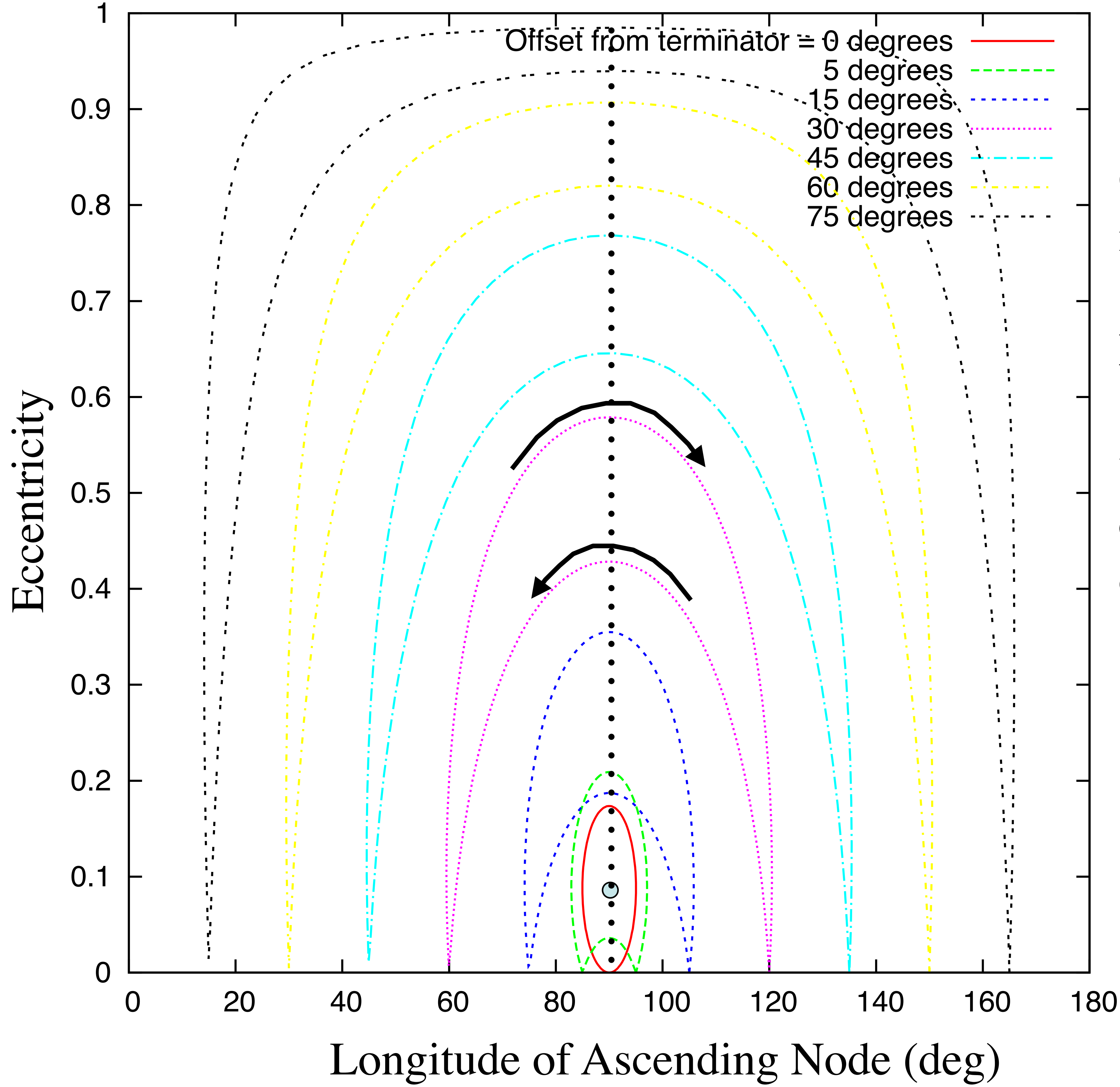

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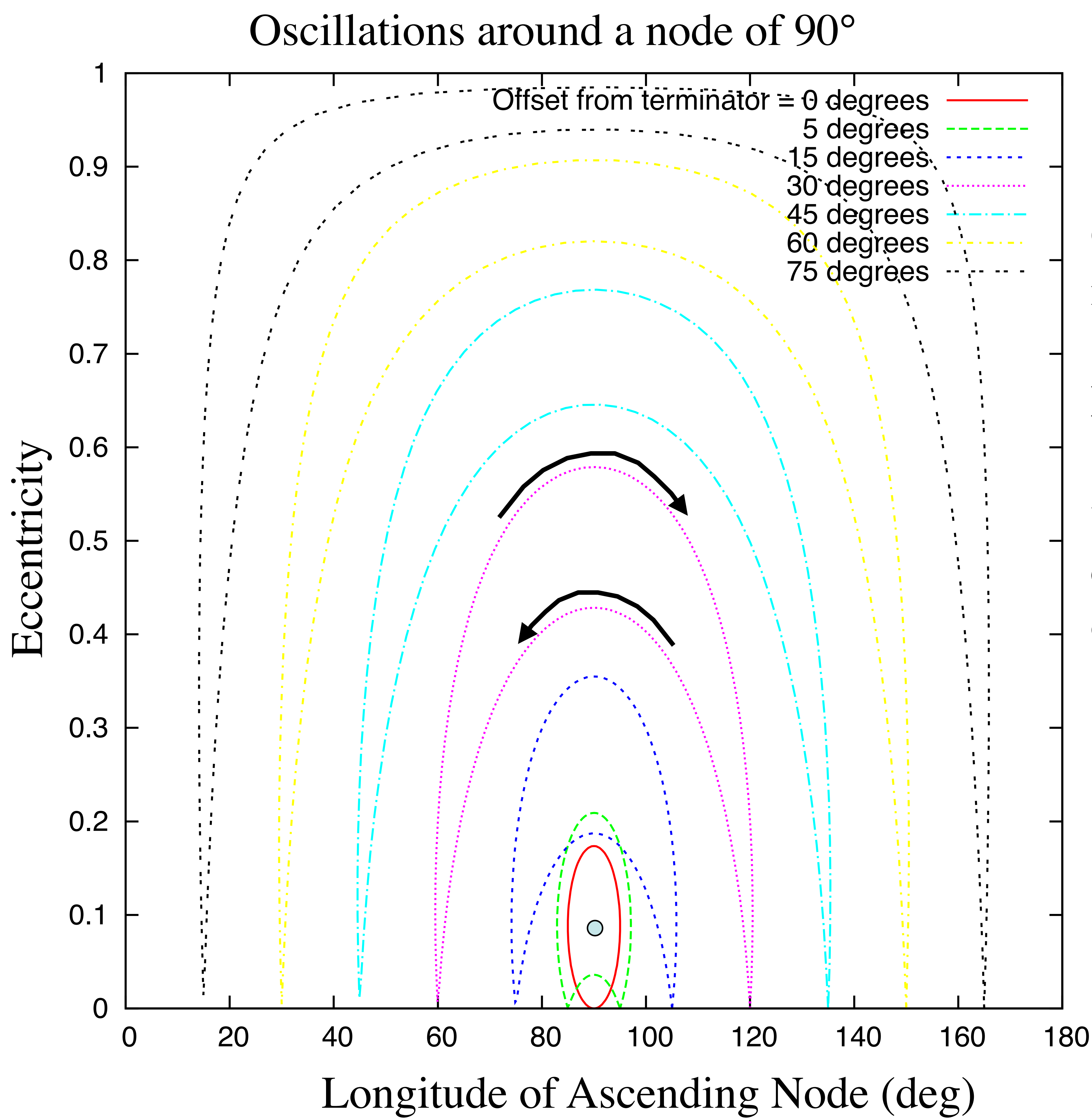

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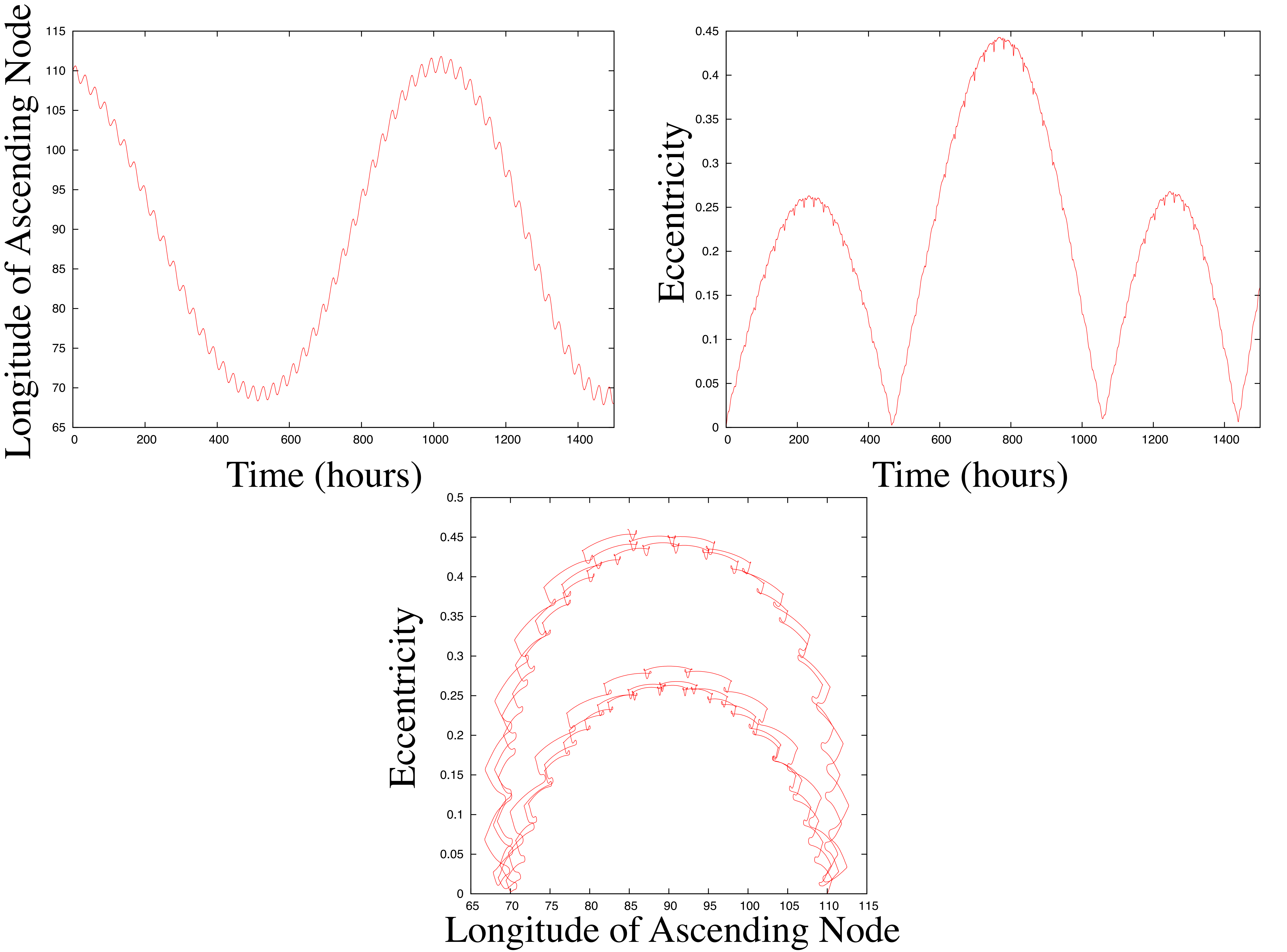
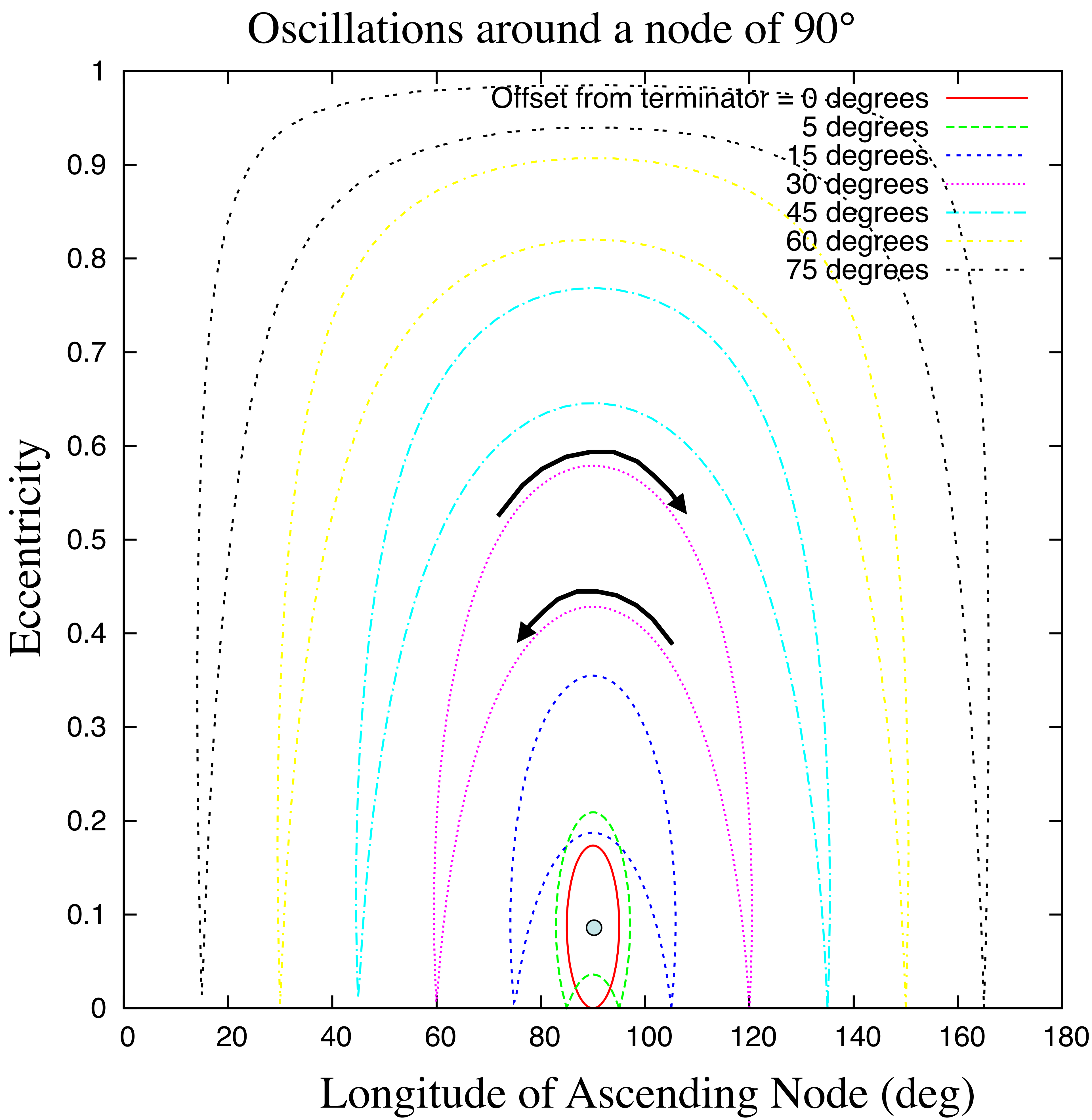
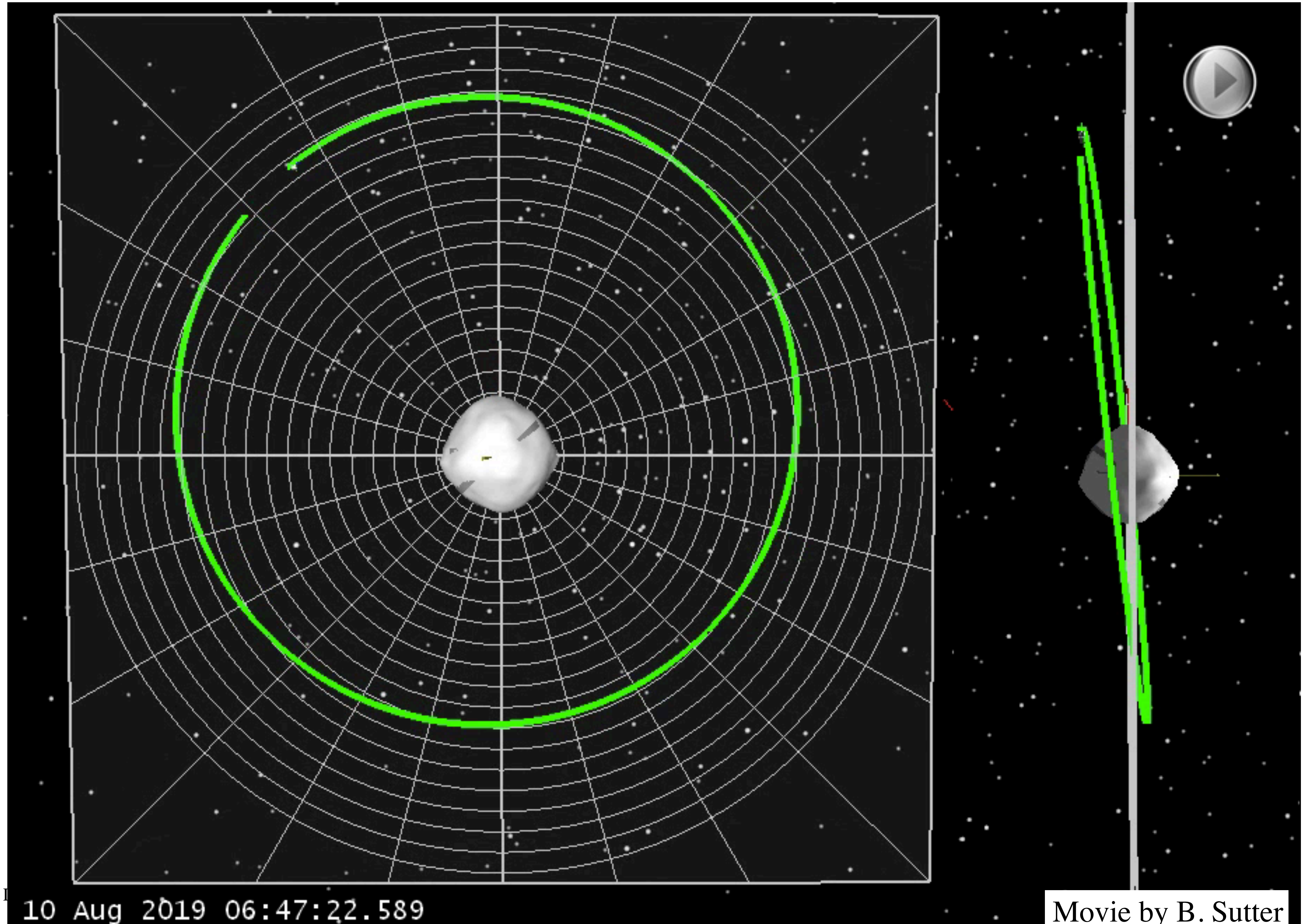

Longitude of Ascending Node
115
110
105
100
95
90
85
80
75
70
65
0 200 400 600 800 1000 1200 1400
Time (hours)
Eccentricity
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0 200 400 600 800 1000 1200 1400
Time (hours)
Eccentricity
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
65 70 75 80 85 90 95 100 105 110 115
Longitude of Ascending Node



Oscillations around a node of 90°
Offset from terminator = 0 degrees
5 degrees
15 degrees
30 degrees
45 degrees
60 degrees
75 degrees
Eccentricity
Longitude of Ascending Node (deg)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
20
40
60
80
100
120
140
160
180

Initially Circular Terminator Orbit



Orbit Dynamics about Didymos

D.J. Scheeres

Lamberto Dell'Elce

Nicola Baresi

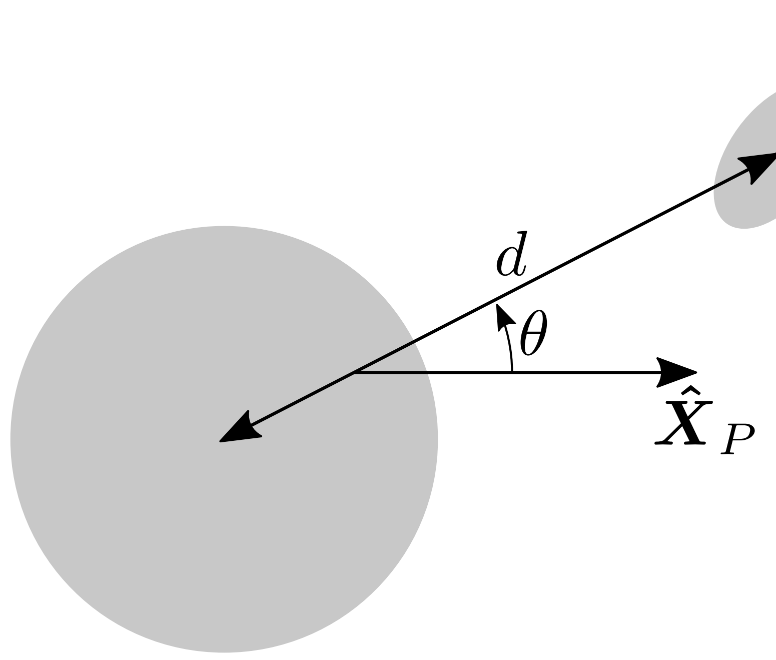
Department of Aerospace Engineering Sciences

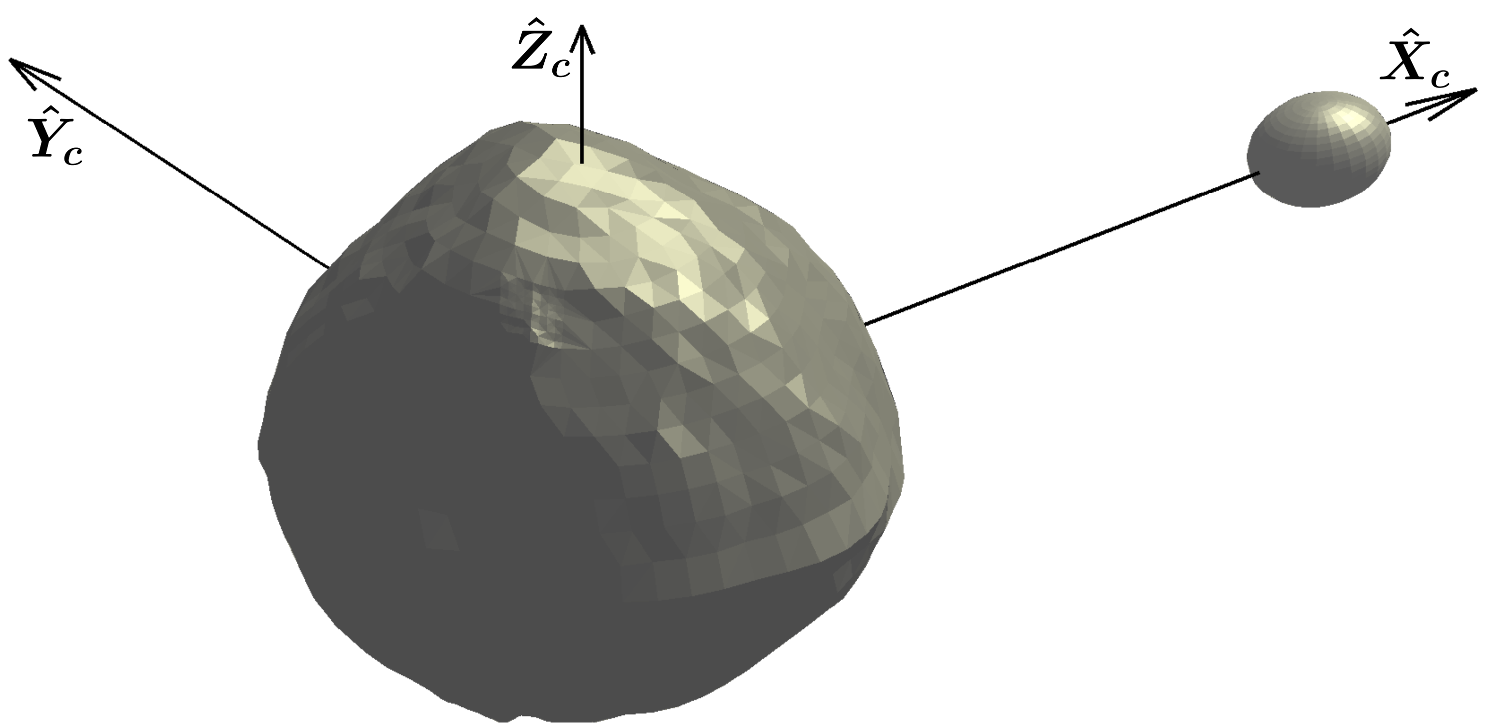
The University of Colorado Boulder

L. Dell'Elce, N. Baresi, S. Naidu, L.A.M. Benner and D.J. Scheeres. 2017. "Numerical investigation of the dynamical environment of (65803) Didymos," *Advances in Space Research* 59(5): 1304-1320.

Binary System Model

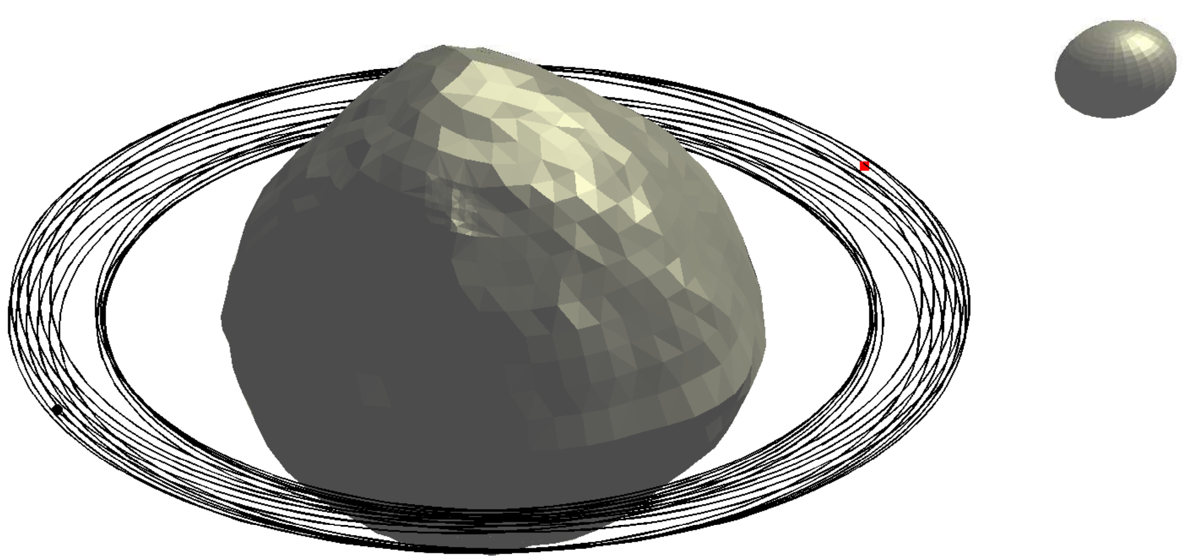
- We assume a fully-dynamic Didymos system
  - oblate Didymos primary
  - ellipsoidal Didymos secondary with zero inclination but non-zero libration
  - Full coupling between planar orbit and rotation of the Didymos system
  - Assumes:
    - a 180° obliquity of system
    - Current heliocentric orbit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

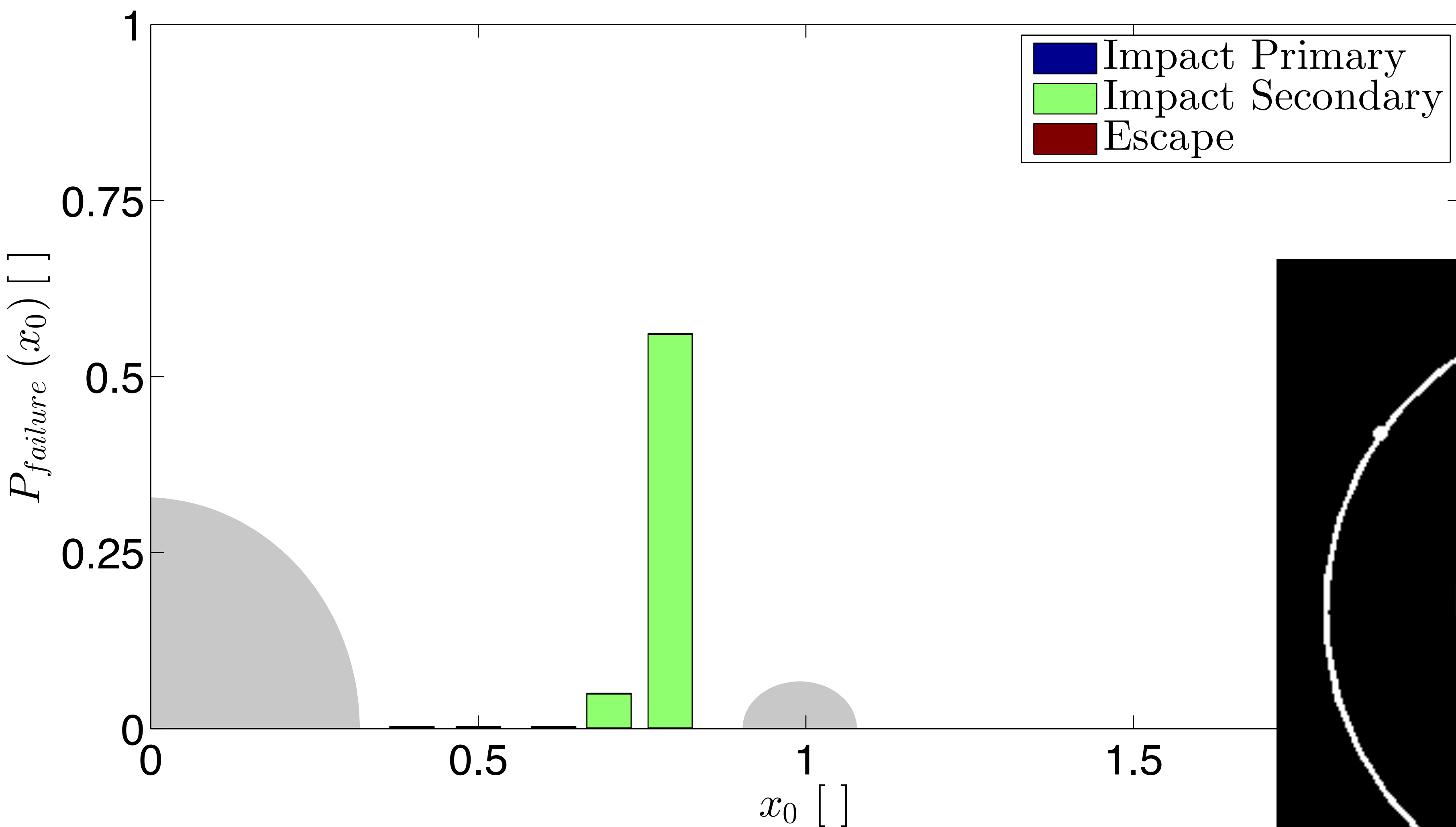


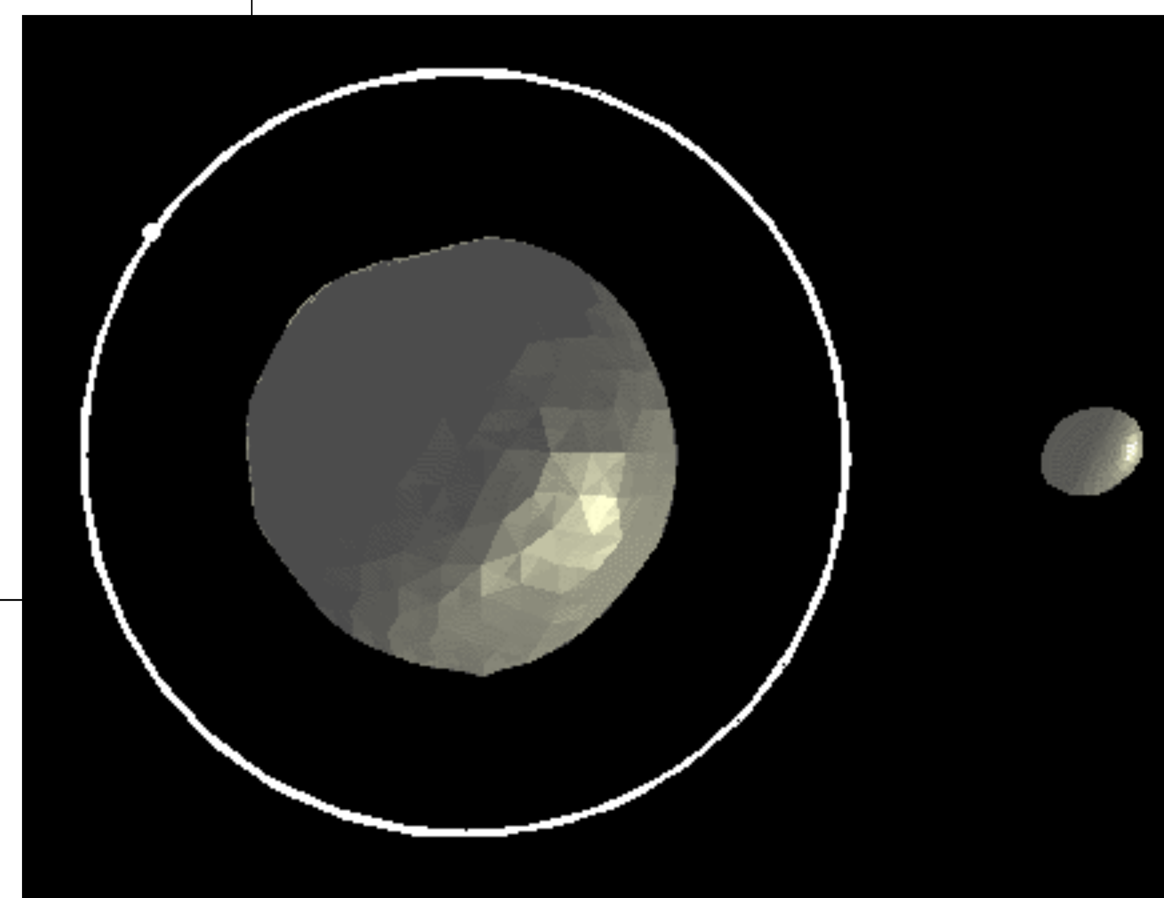
Orbit Design and Evaluation

- We use two approaches to find and test orbits in the system
- Planar Orbits:
  - We compute planar periodic orbit families in the "ideal" problem of Didymos circular motion and no libration
  - The robustness of stable members of these families are tested by running MC runs with the system in eccentric orbit with libration and mis-modeled SRP
  - Most of these orbits only have very narrow stability ranges
  - Only interior retrograde orbits have good performance
- Terminator Orbits:
  - We compute captured "frozen terminator orbits"
  - Orbit periods are chosen to avoid mean motion resonances with the system
  - These orbits perform very well and can provide attractive orbital options for monitoring the Didymos system over arbitrarily long timespans

Best Planar Orbits

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





D.J. Scheeres, A. Richard Seebass Chair, University of Colorado at Boulder

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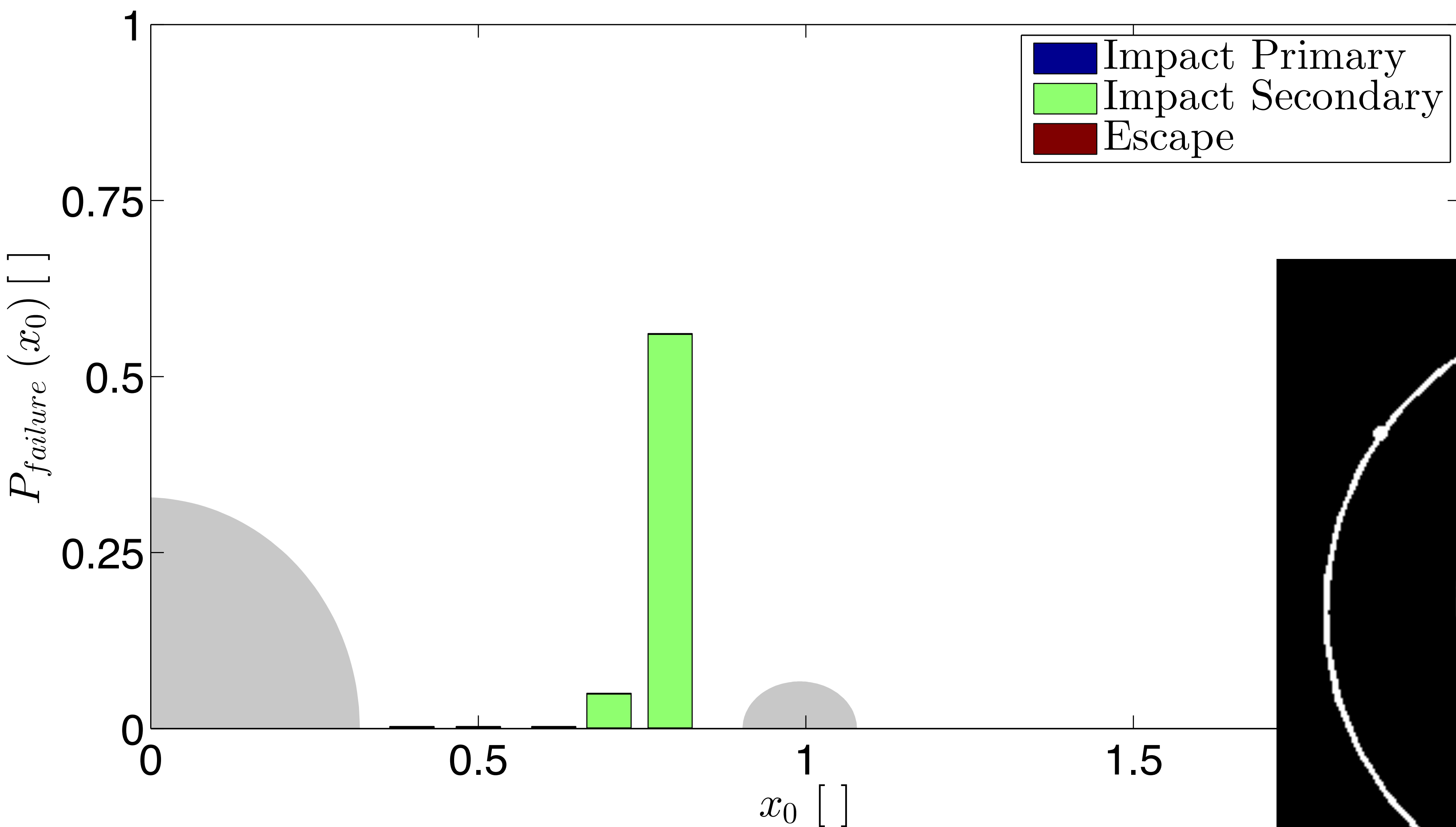
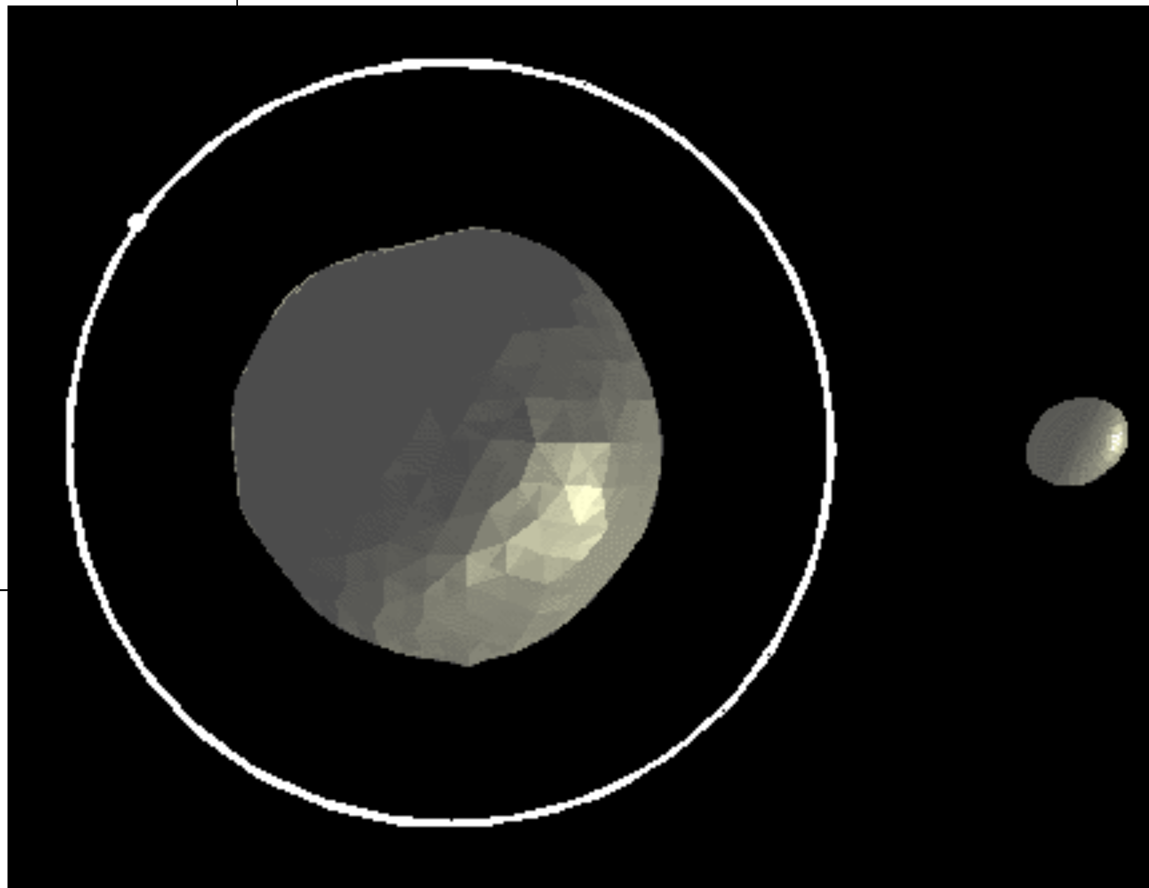
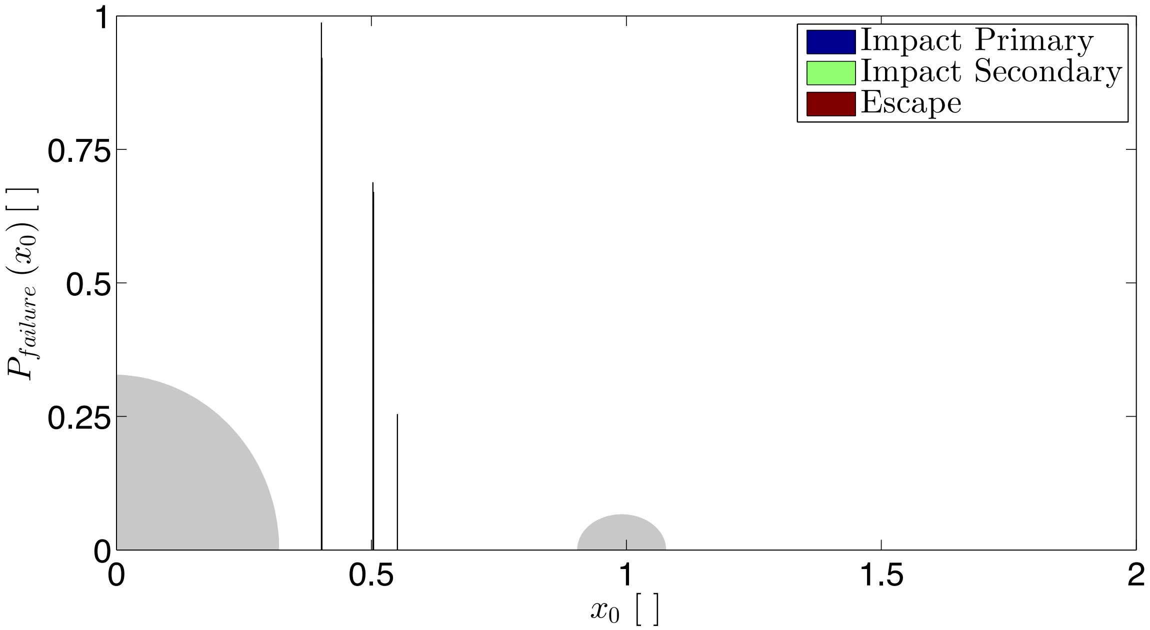




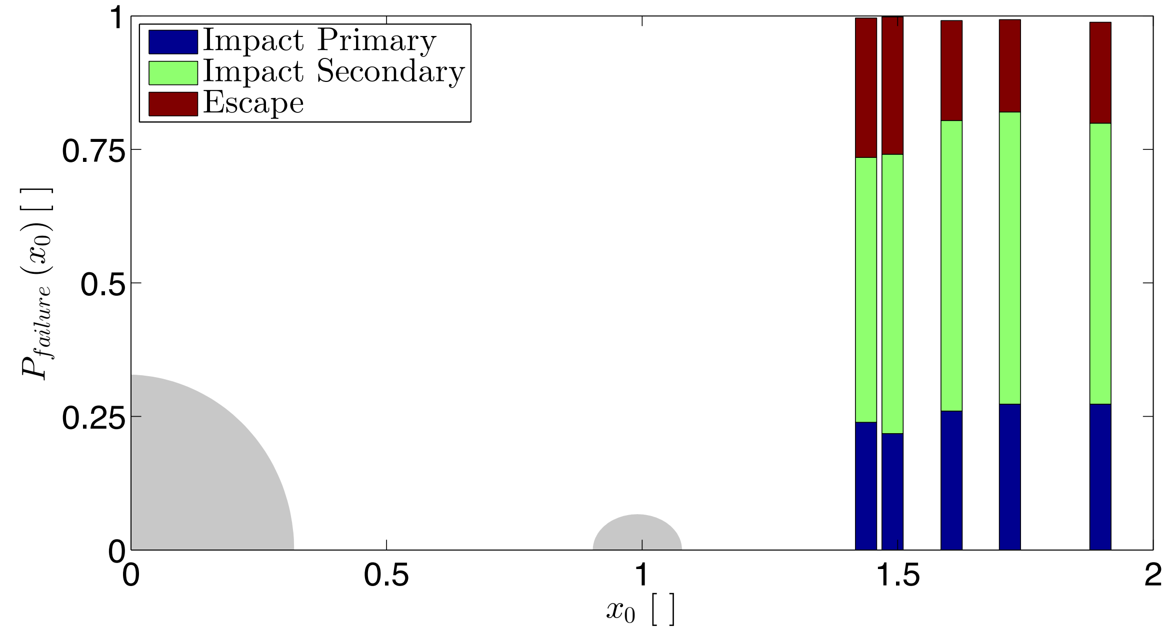
Other Planar Orbits are Worse

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

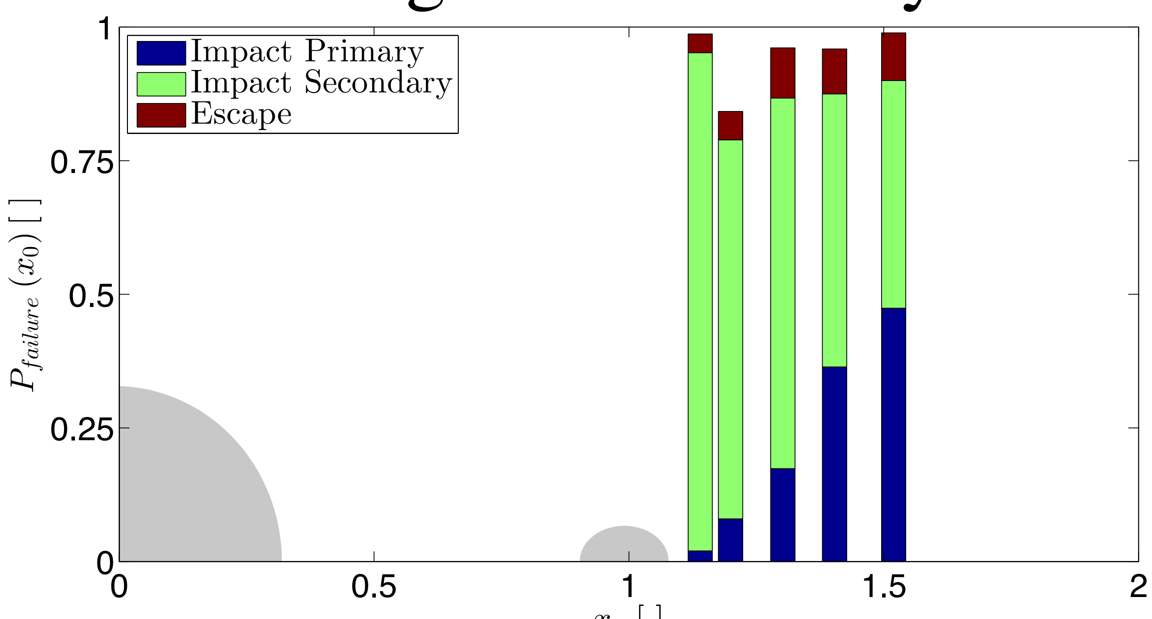
Direct Interior



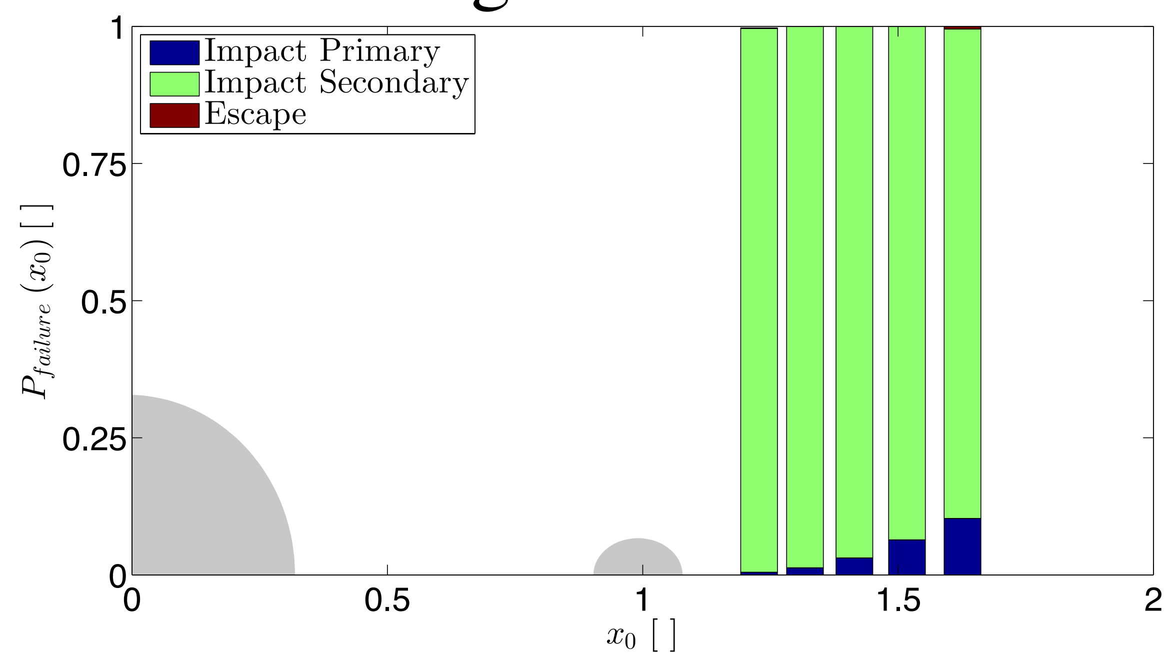
Direct Exterior



Retrograde Secondary

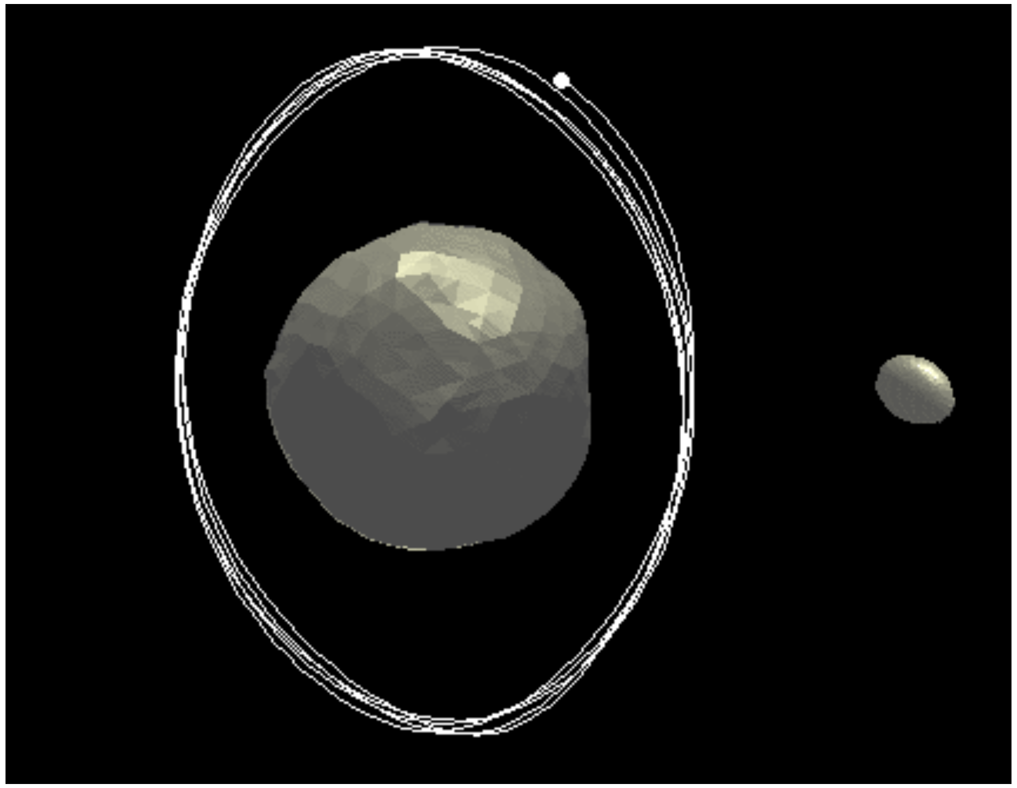


Retrograde Exterior

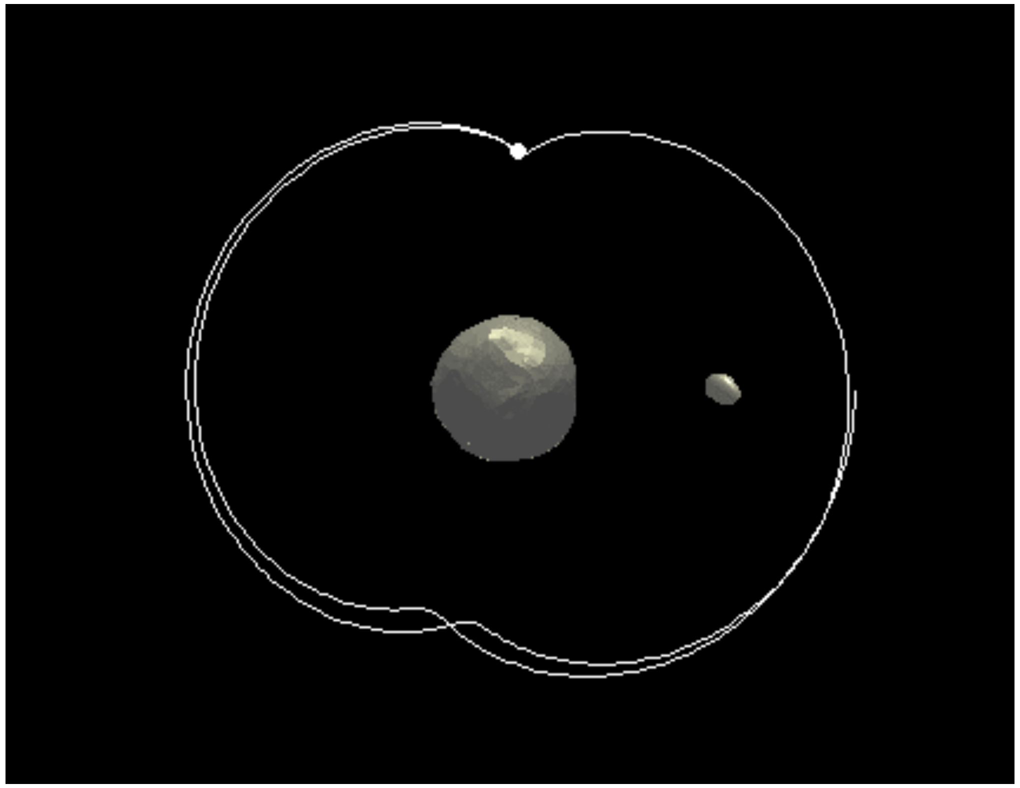


Other Planar Orbits…

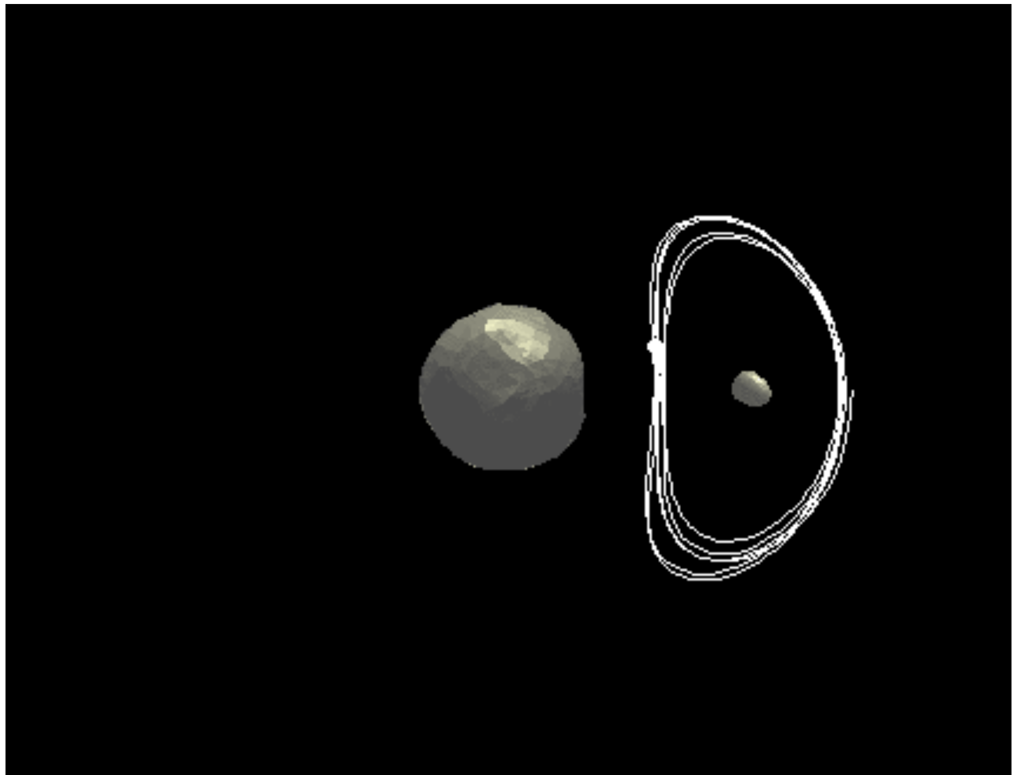
Direct Interior



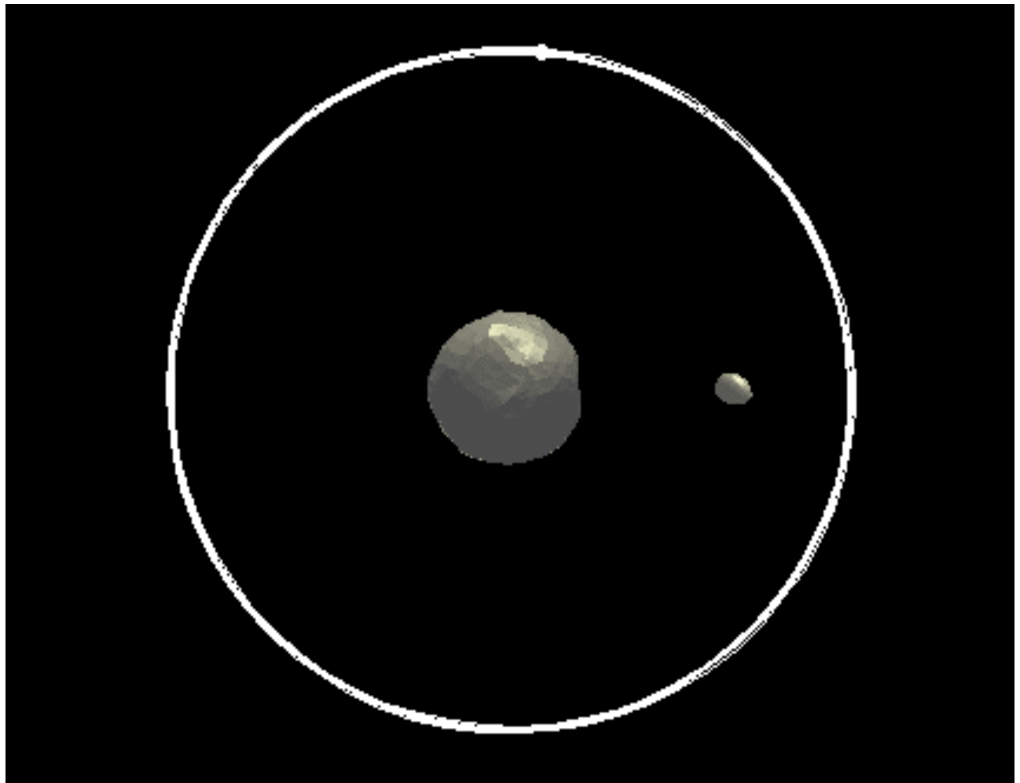
Direct Exterior



Retrograde Secondary



Retrograde Exterior



Other Planar Orbits…

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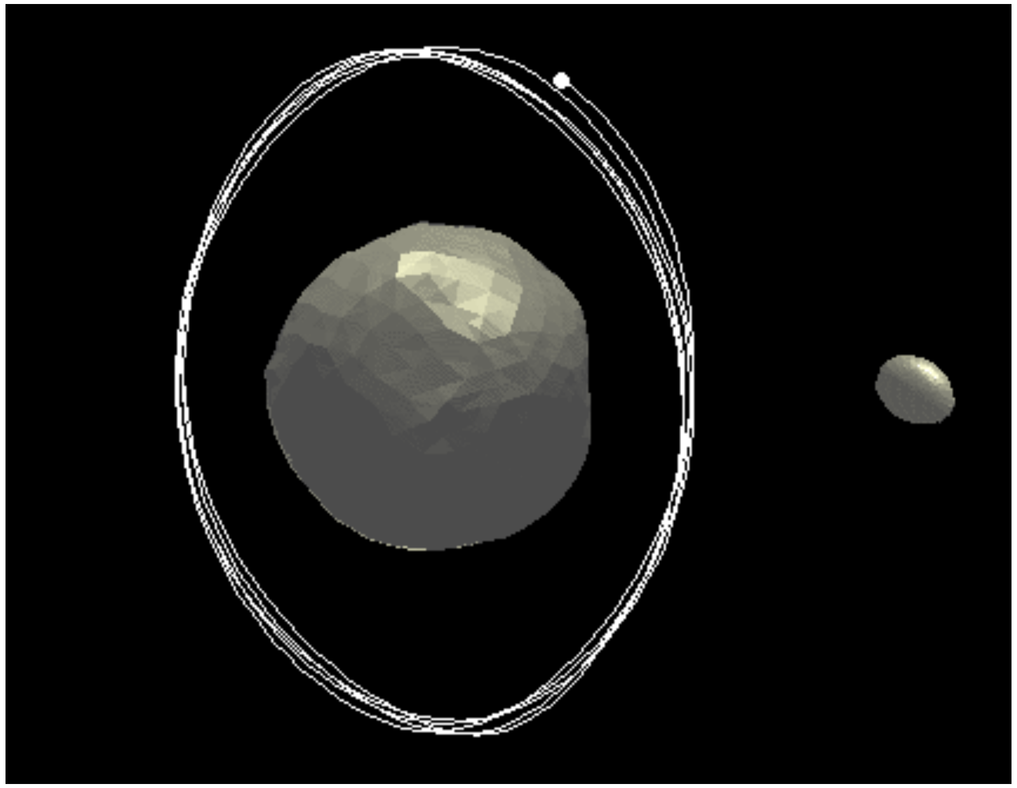

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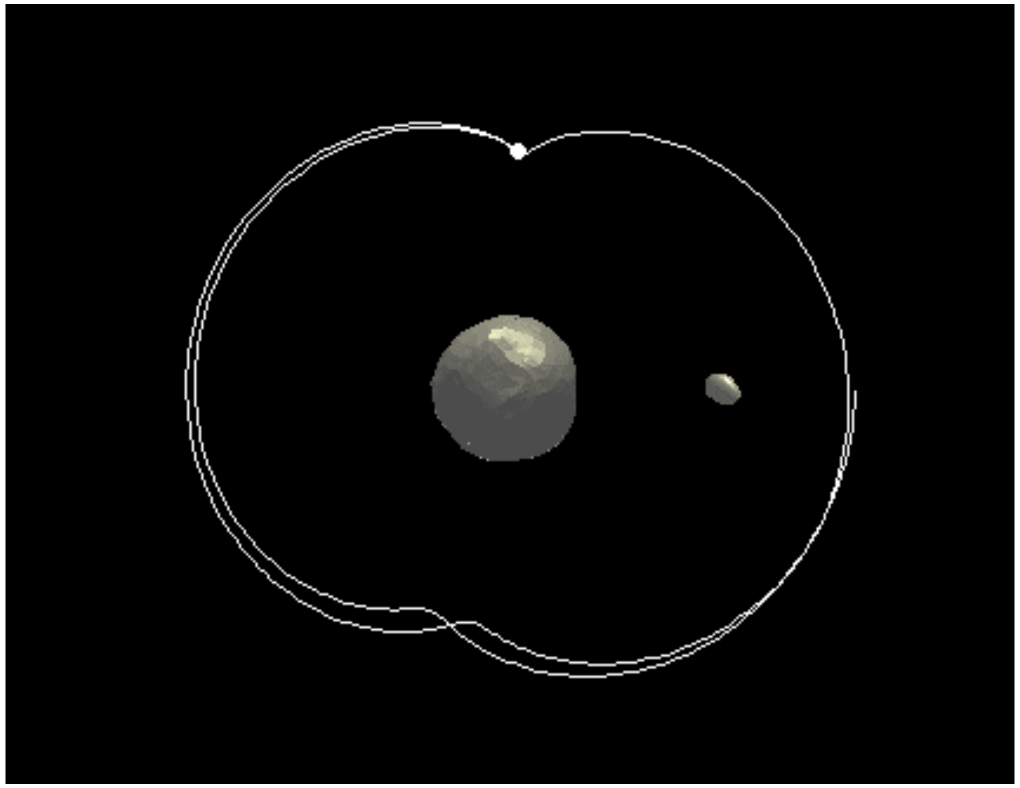
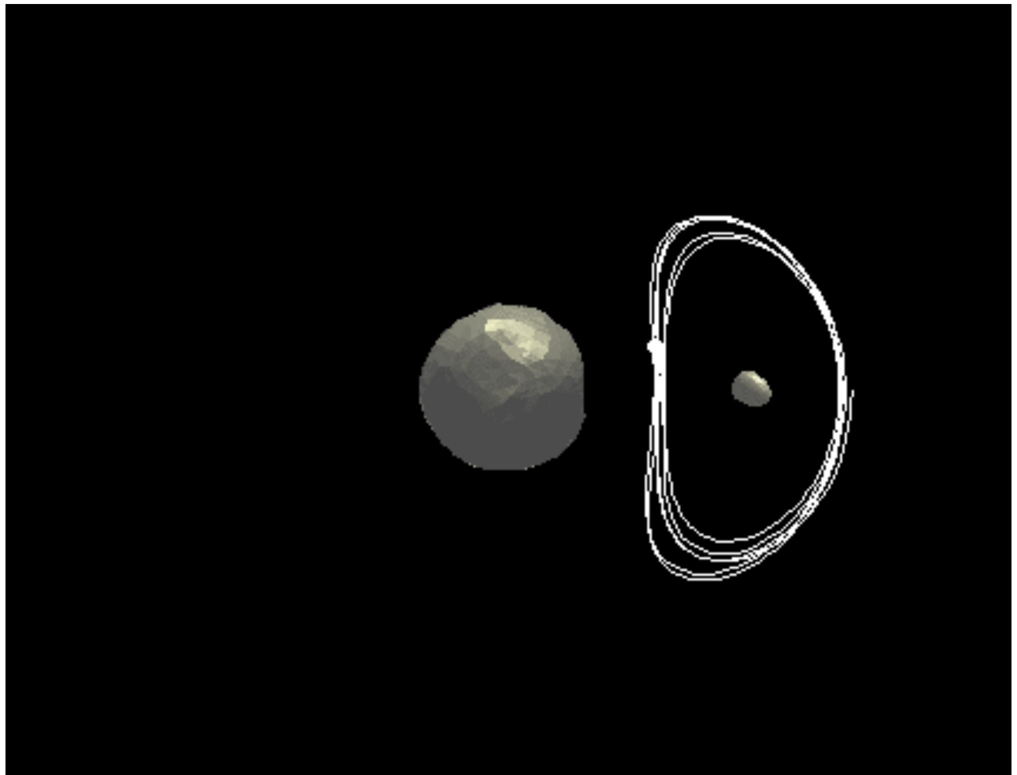
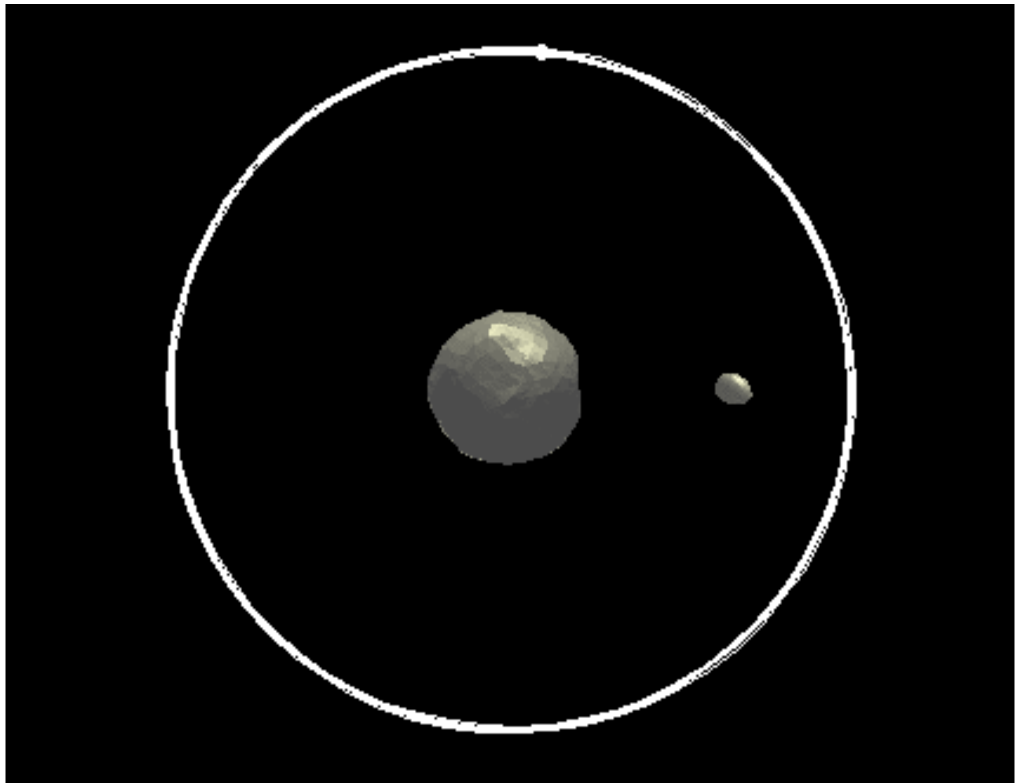


Retrograde Secondary



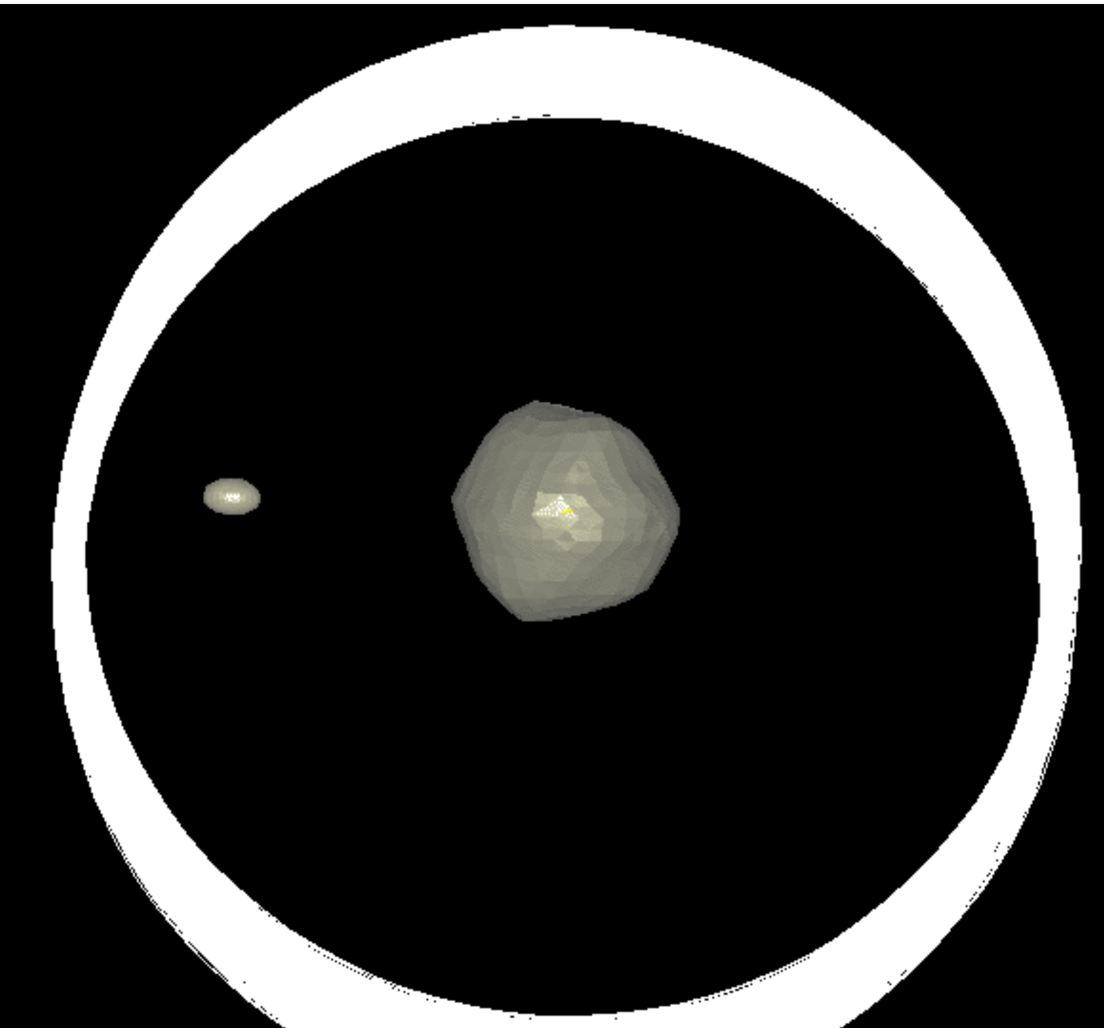
Retrograde Exterior



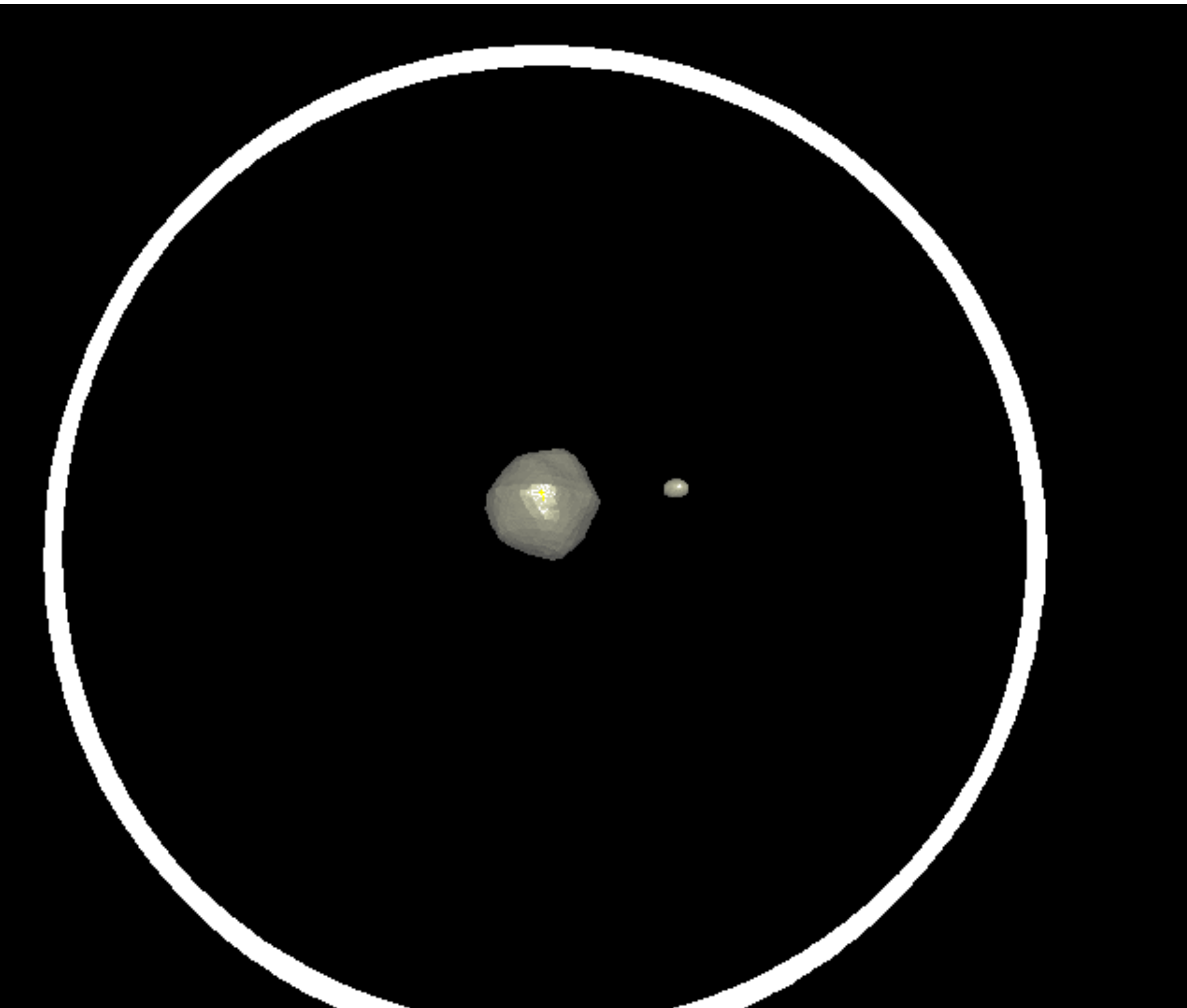
Best Terminator Orbits

- 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



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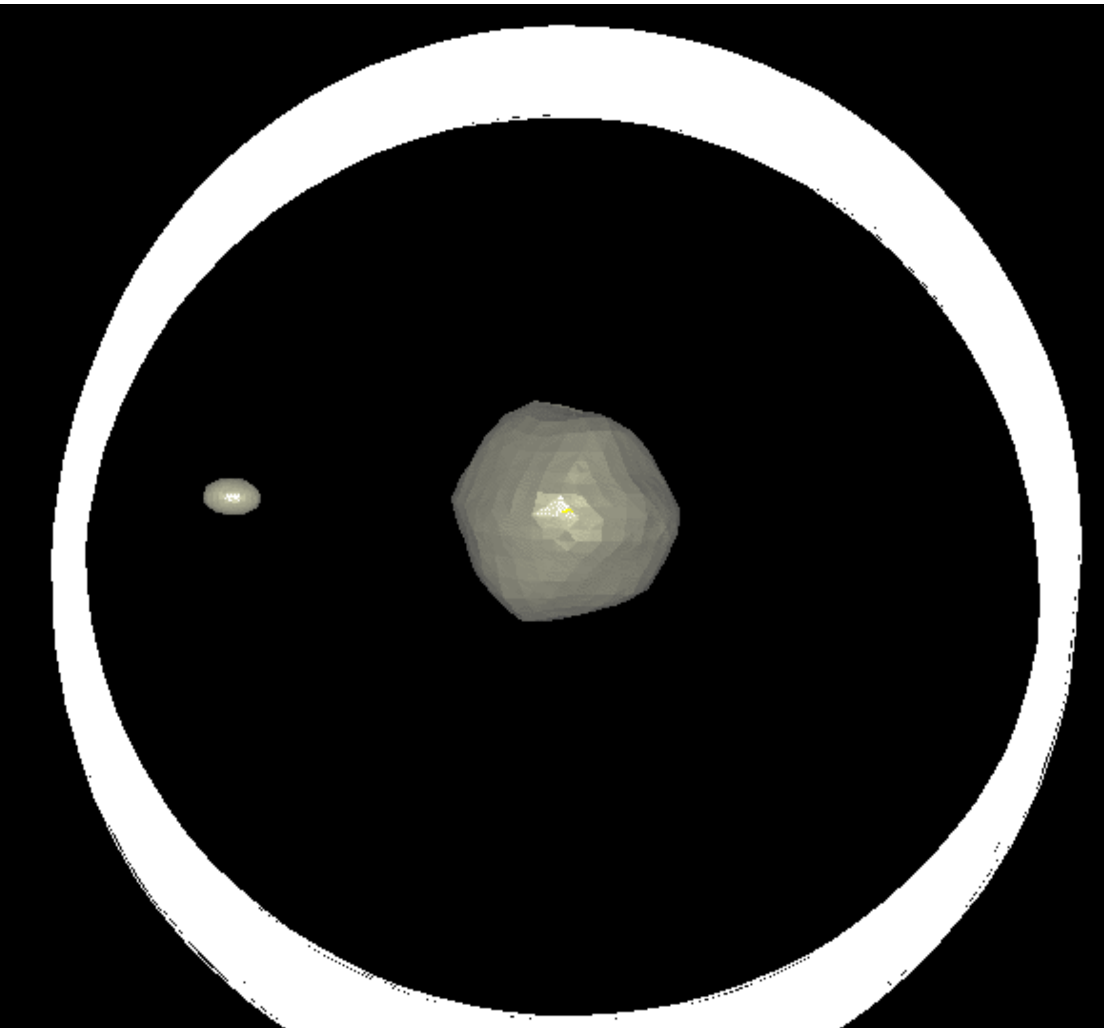

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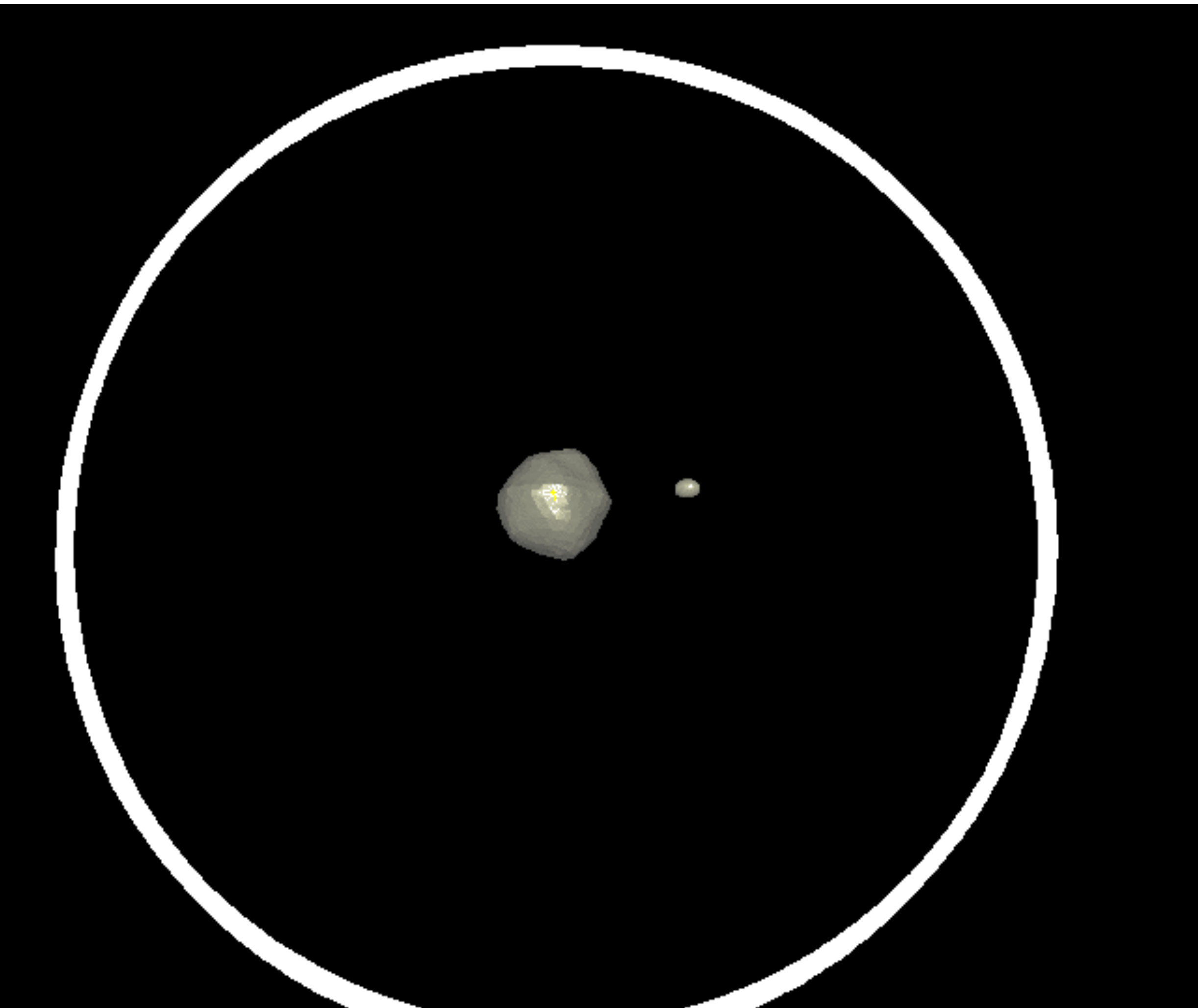
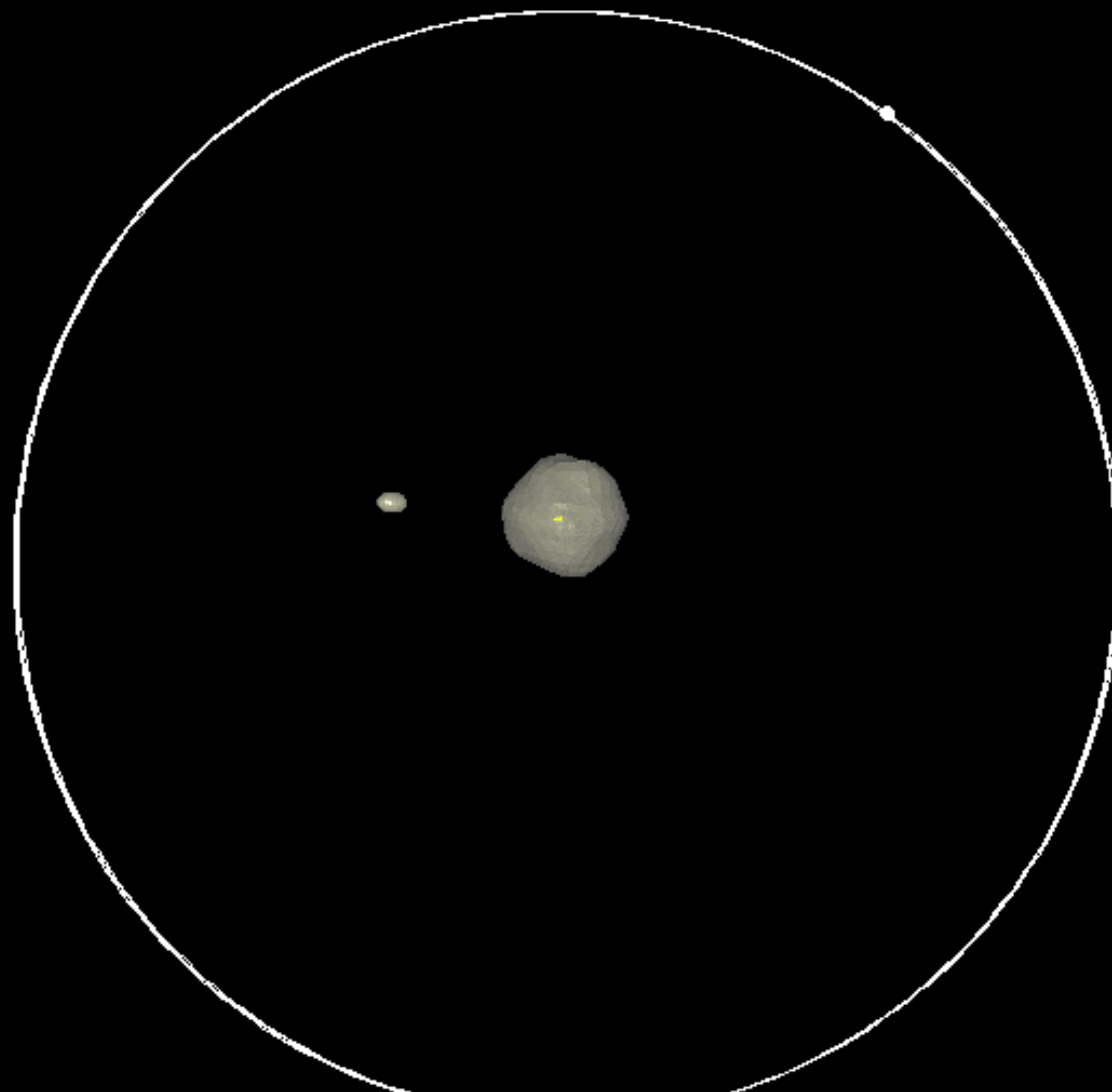
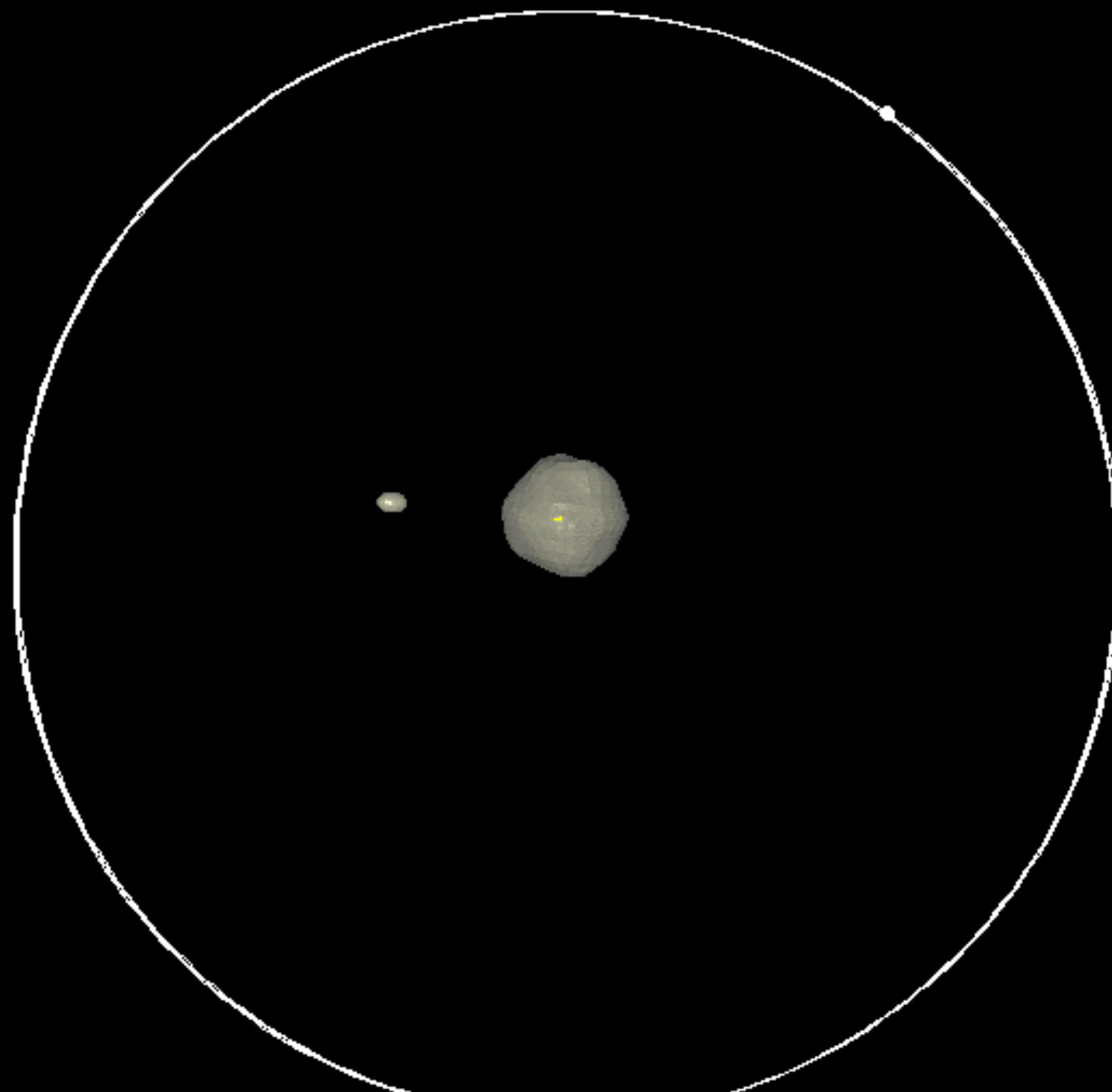


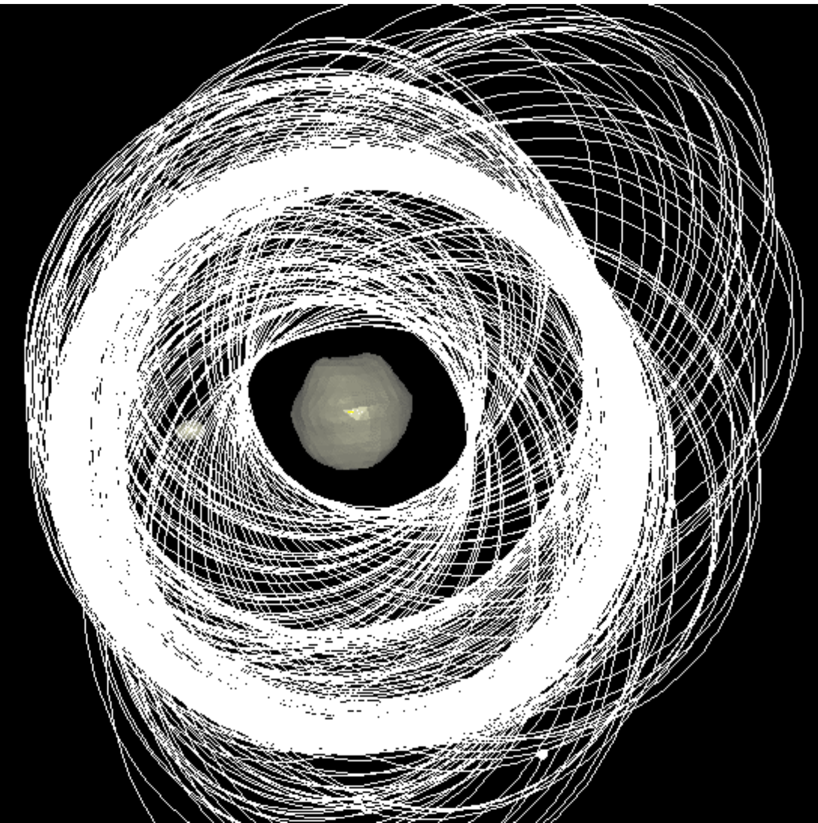




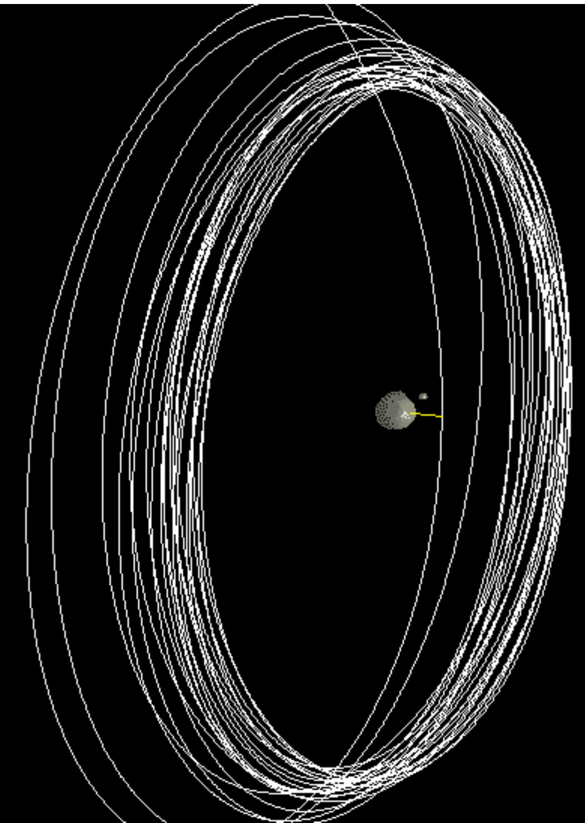
Too close or too far terminators…

- 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



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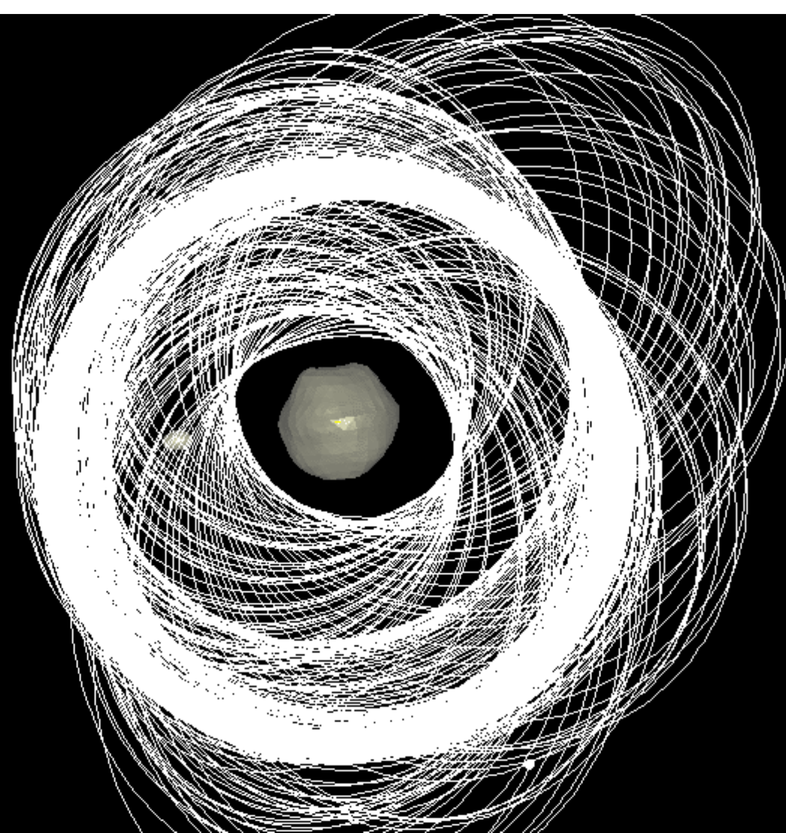
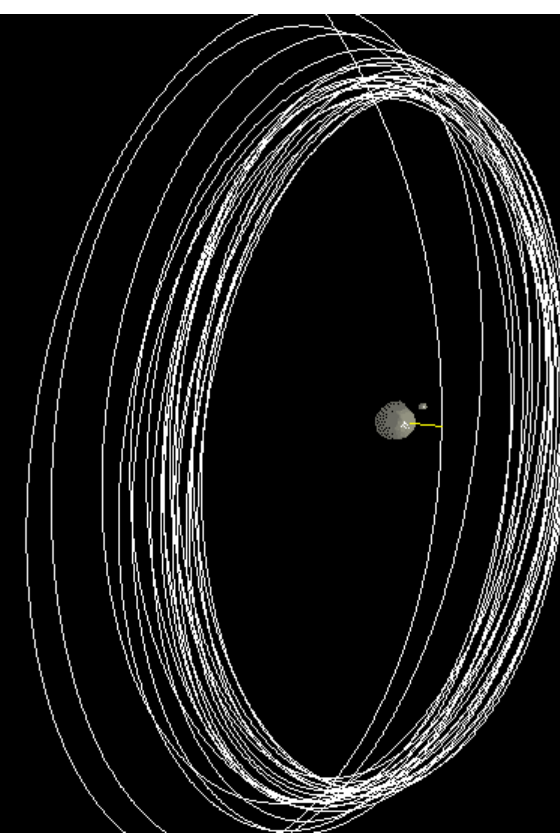


7 km orbit



Conclusions

- Stable orbits that are good for observations of the Didymos system exist and should be navigable
- Terminator orbits
  - Near-circular orbits perpendicular to the sun, remain perpendicular to the sun due to SRP perturbations
  - Stable semi-major axes exist from ~1.75 — 6.25 km
  - Are stable over long time periods and allow the entire system to be observed
- Interior retrograde orbits
  - Robustly stable orbits exist for radii from 0.4 to 0.6 km
  - Are subject to strong gravity field signals, could be of use for gravity science
  - But… they do not have a good vantage point for viewing the global asteroid system and suffer frequent eclipses

Celestial and Spaceflight Mechanics Laboratory

The Dynamical Environment For The Exploration Of Phobos

D.J. Scheeres, S. Van wal, Z. Olikara & N. Baresi

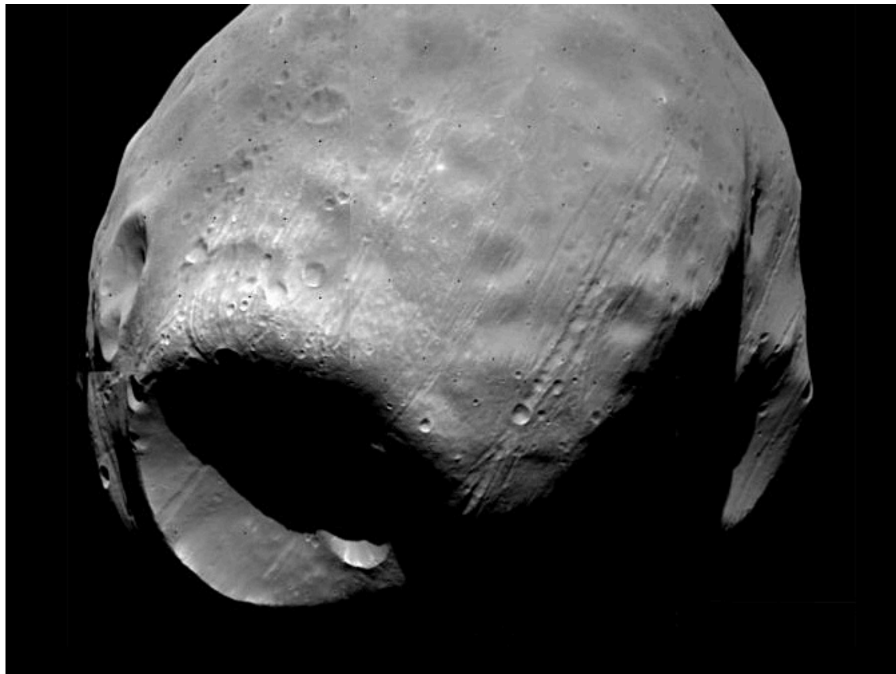
Smead Department of Aerospace Engineering Sciences

The University of Colorado

scheeres@colorado.edu

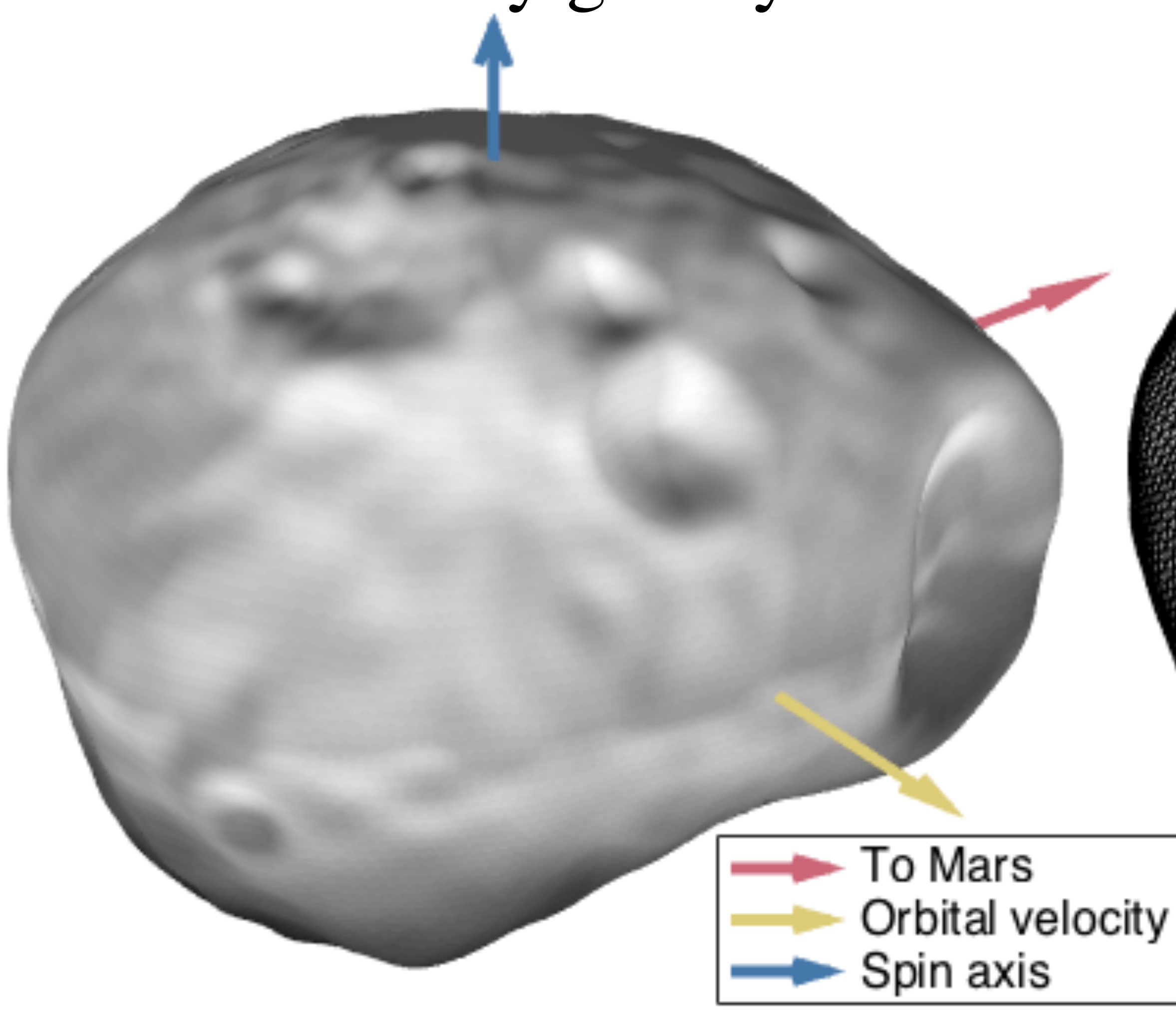
Motivation

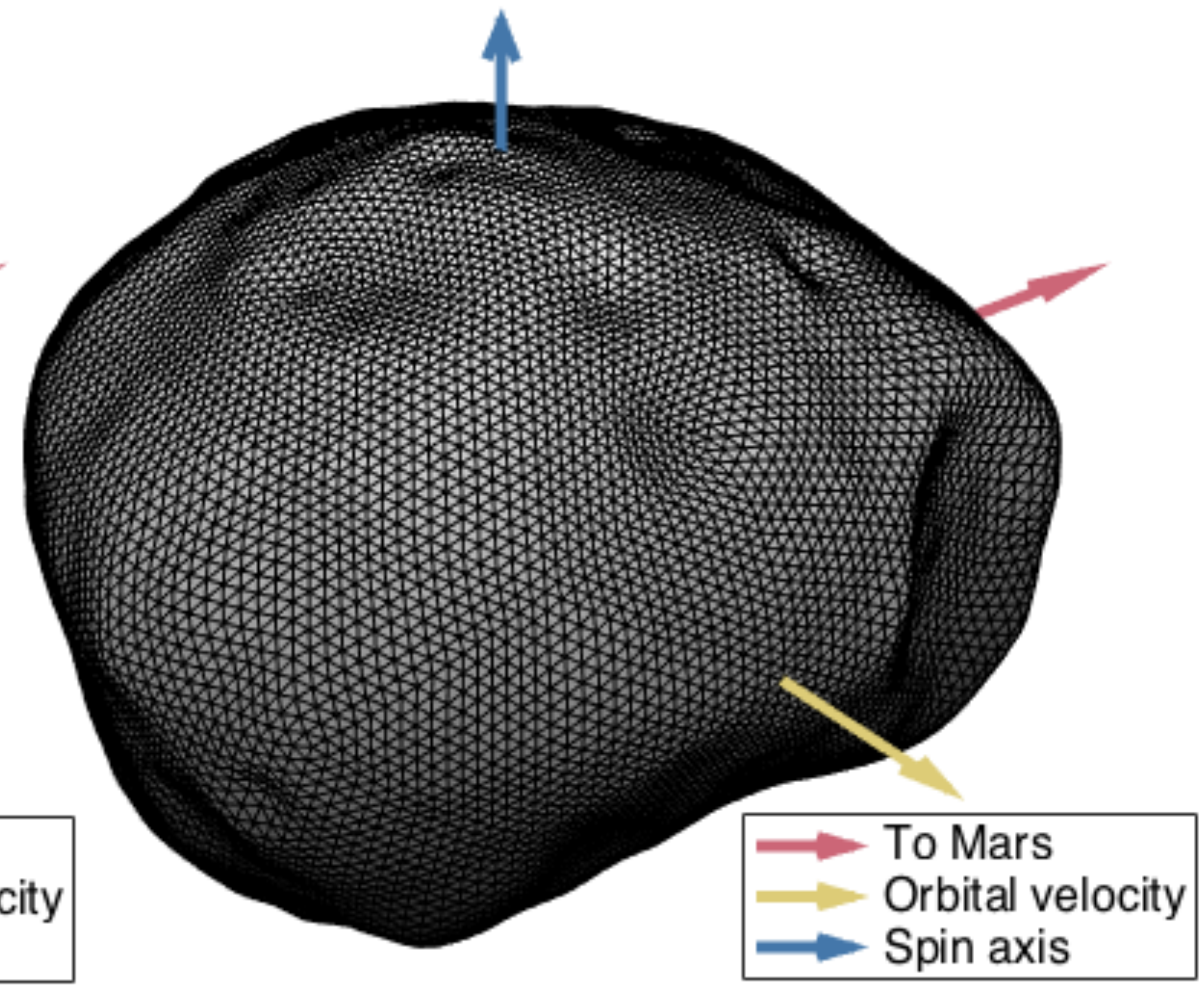
- Phobos has long been a target of space exploration
  - Many successful flybys have occurred providing a good estimate of the body's mass, shape, orbit and spin state
  - The physical exploration of Phobos has been less successful, with no sustained surface or close proximity operations occurring
- With the JAXA MMX mission and a host of proposed exploration missions over the last decade, the future prospect for a successful physical exploration of Phobos is high
- Our study's goal is to provide an accurate dynamical analysis of the Phobos exploration environment
  - Surface motion
  - Close proximity orbiting:
    - Synchronous (direct) orbits
    - Asynchronous (retrograde) orbits



Phobos Model

- Shape Model: Wilner et al. 2014.
  - Spherical harmonic expansion to degree and order 45 x 45
  - Converted into a polyhedron with 2562 facets
  - Exact constant density gravity field
- Spin/Orbit state:
  - Eccentricity 0.01515
  - Free and forced libration
  - Period of 7 hrs 39.2 min





Dynamical Equations

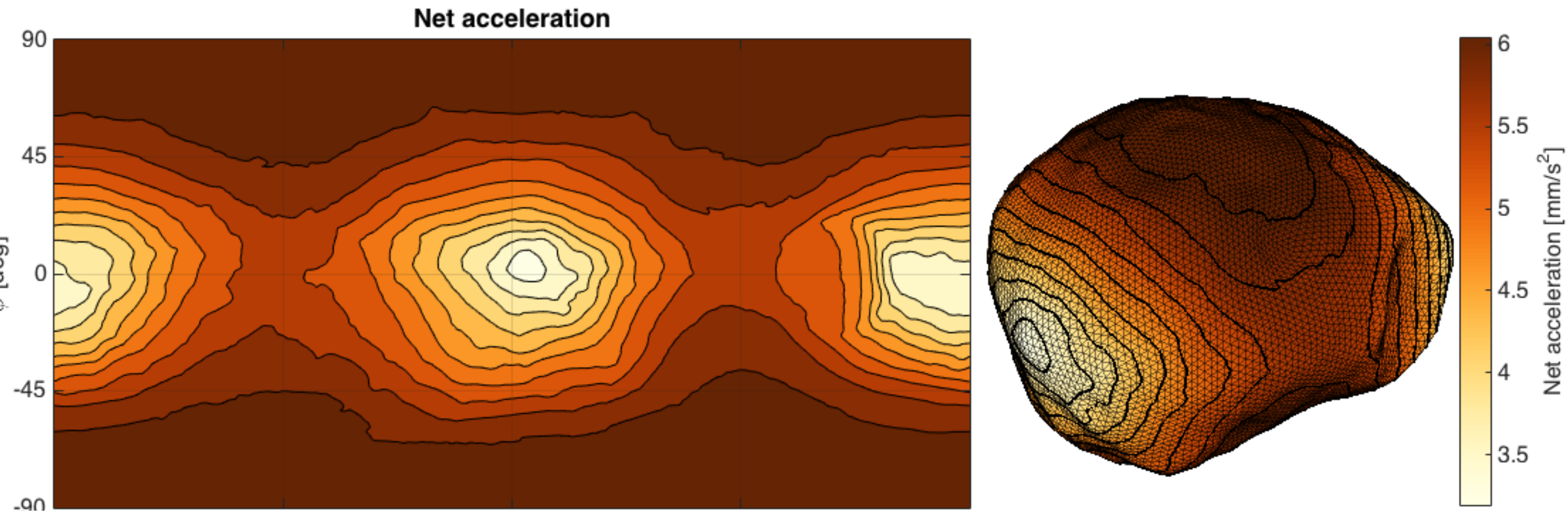
- Gravitational Attraction from Phobos' shape
  - Includes surface normal forces for surface motion
- Tidal forces from Mars
  - Combination of Mars gravity and Phobos' orbit
- Phobos librations
  - For eccentric orbit case, creates a time-periodic system
- General equations of motion:

$$\ddot{\mathbf{r}} = \nabla U(\mathbf{r}) - \omega \times \omega \times \mathbf{r} - 2\omega \times \dot{\mathbf{r}} - \dot{\omega} \times \mathbf{r} + \mu_{Mars} \cdot \left(\frac{\mathbf{r}_{Mars} - \mathbf{r}}{\left|\mathbf{r}_{Mars} - \mathbf{r}\right|^3} - \frac{\mathbf{r}_{Mars}}{\left|\mathbf{r}_{Mars}\right|^3} \right)$$

  - Used for surface and orbital motion
  - Both the circular orbit case (time invariant) and the more accurate eccentric orbit case (time periodic) are used

Surface Environment

– Total acceleration varies from 0.3 to 0.6 mGs



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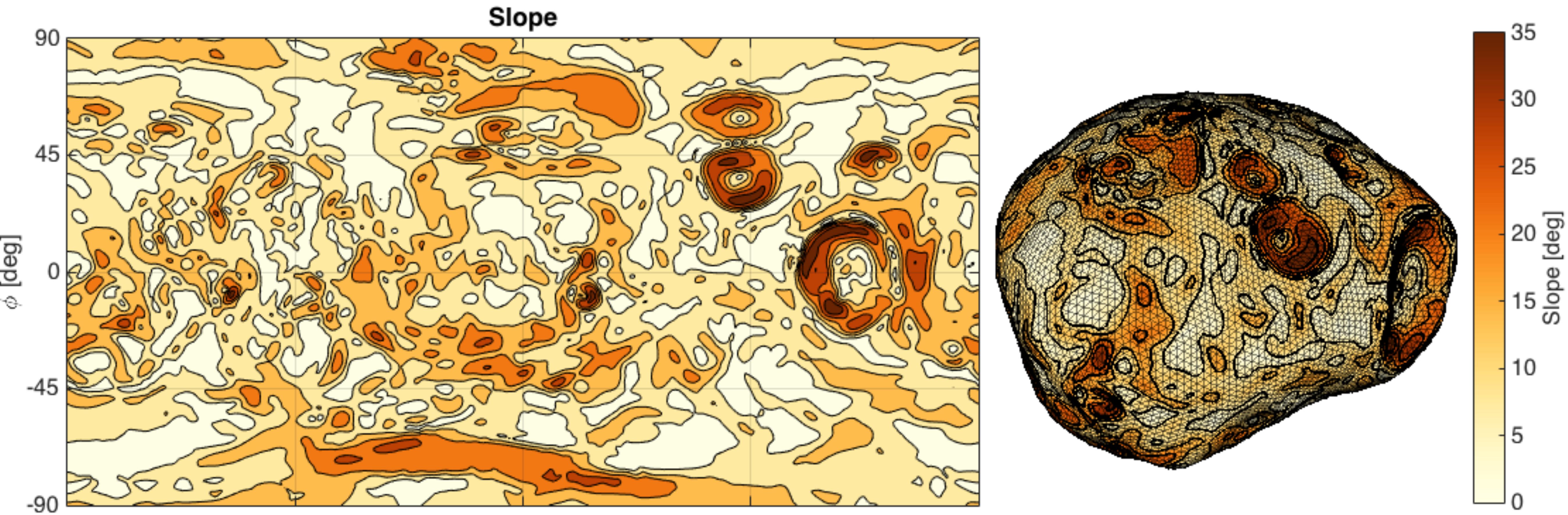

Surface Environment

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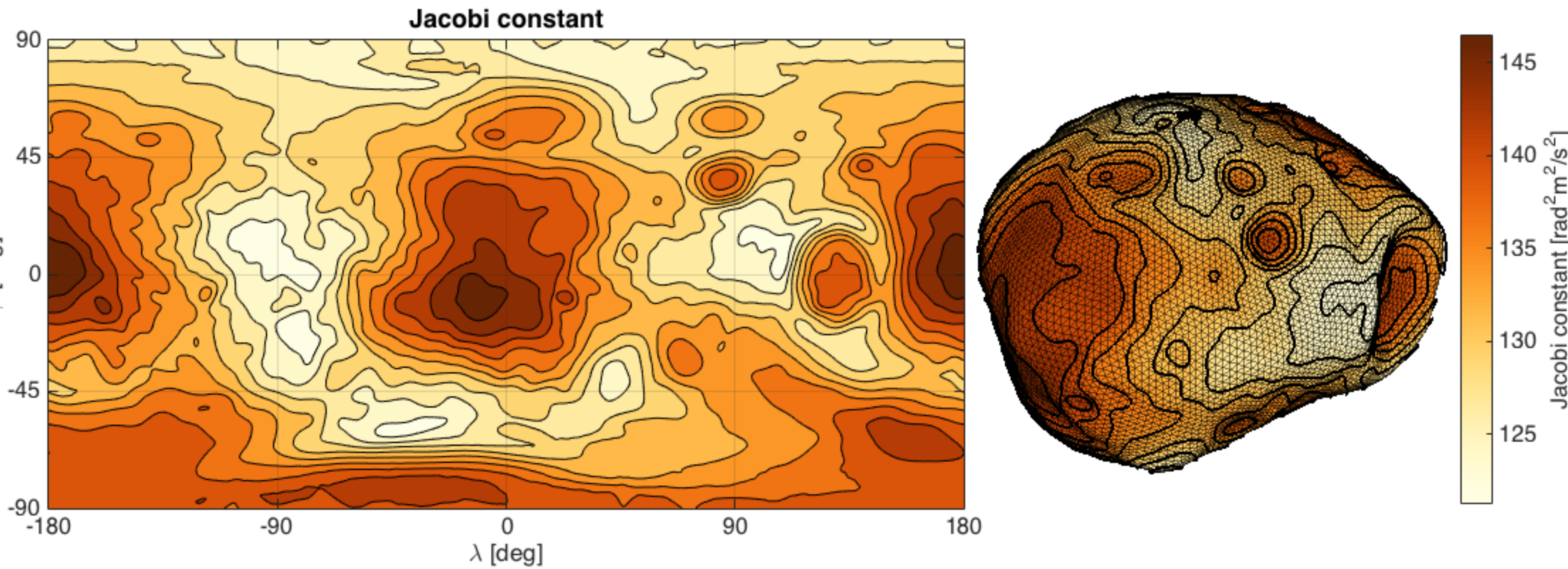
– Slope ranges up to 35°, our computations agree with Wilner et al. 2014.

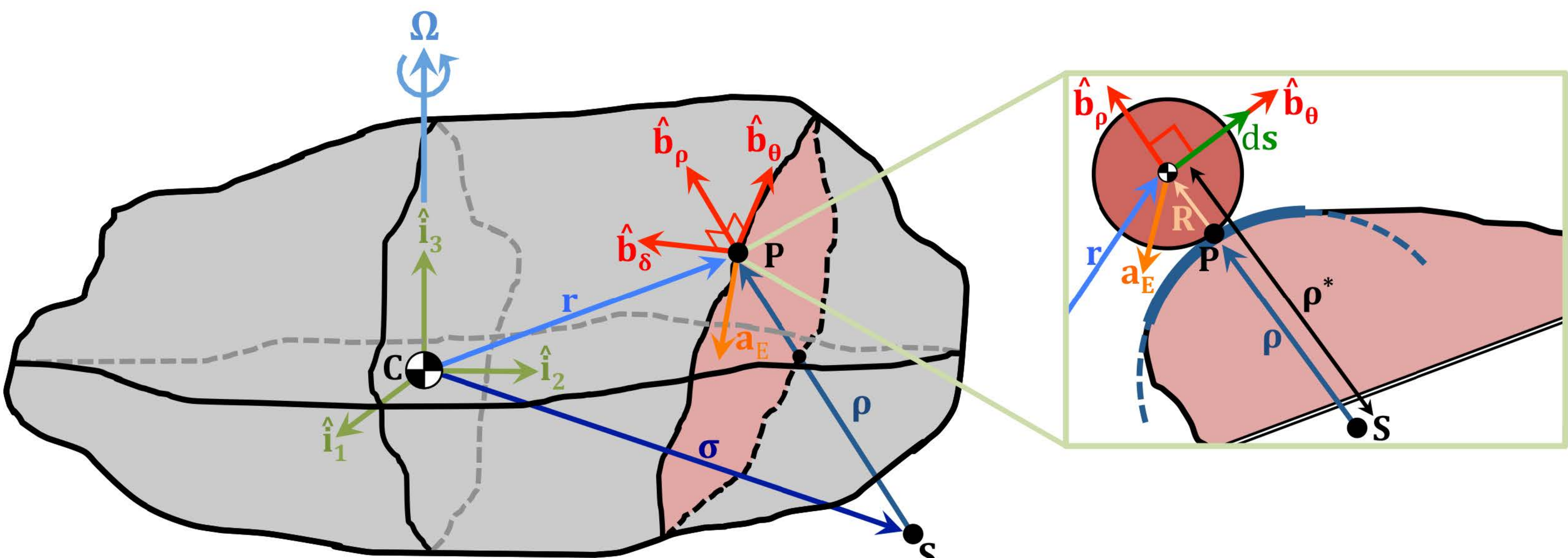
– Potential Energy on the surface ranges from 100 — 150 (m/s)^2

- Maximum speed gain on surface is ~7 m/s for a ball rolling from highest potential point to bottom of Stickney



Motion on the Surface

- Lift-off speed limits as a function of direction
  - As a function of the local gravity and surface radius of curvature, every body has a local "lift-off speed" that determines when a body transitions onto a ballistic orbital arc
  - Varies as a function of direction traveled and local body convexity
  - Traveling greater than this speed can lead to prolonged orbit or even escape from the body



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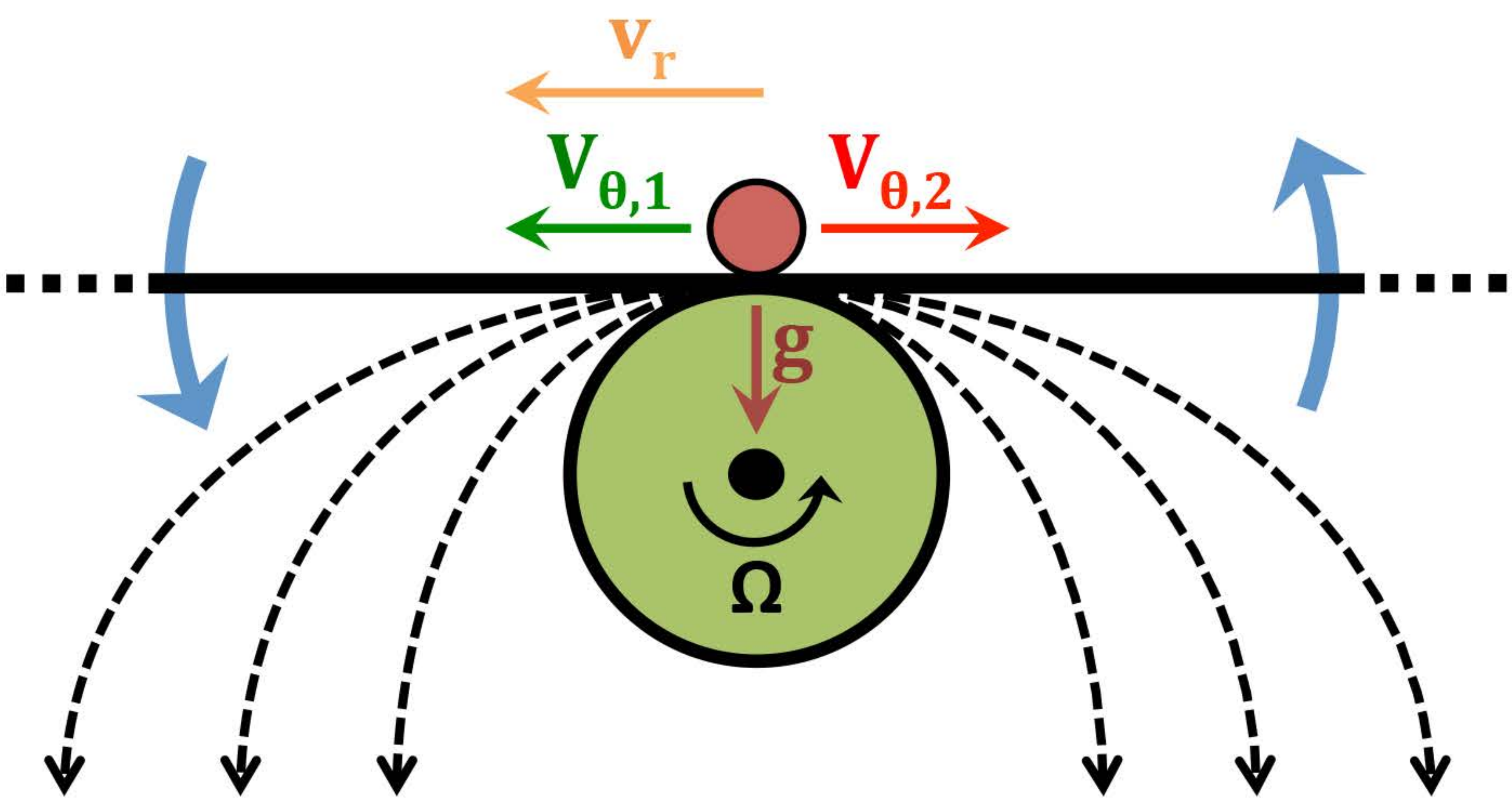

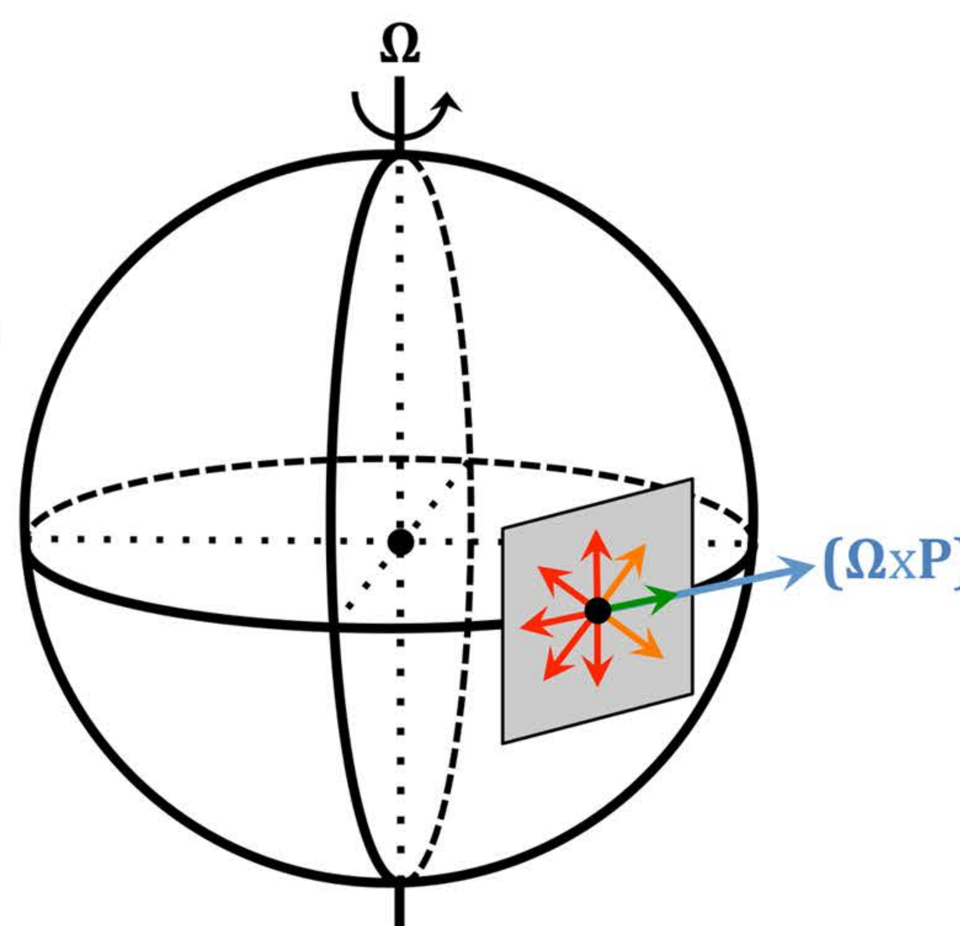

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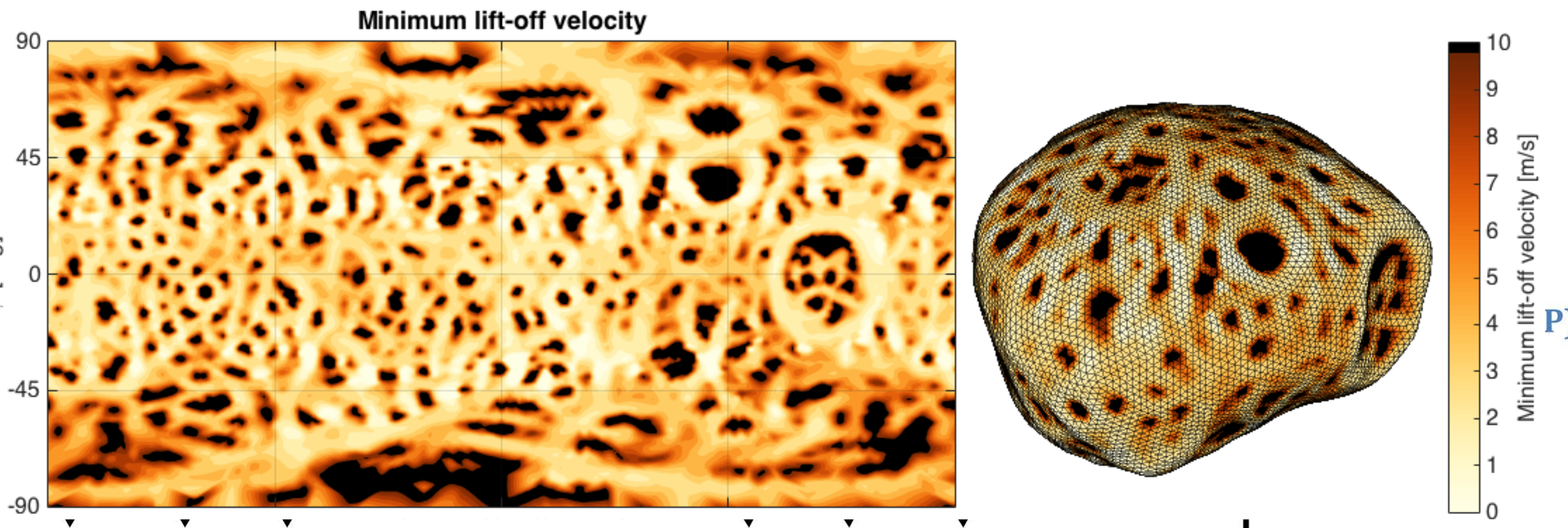

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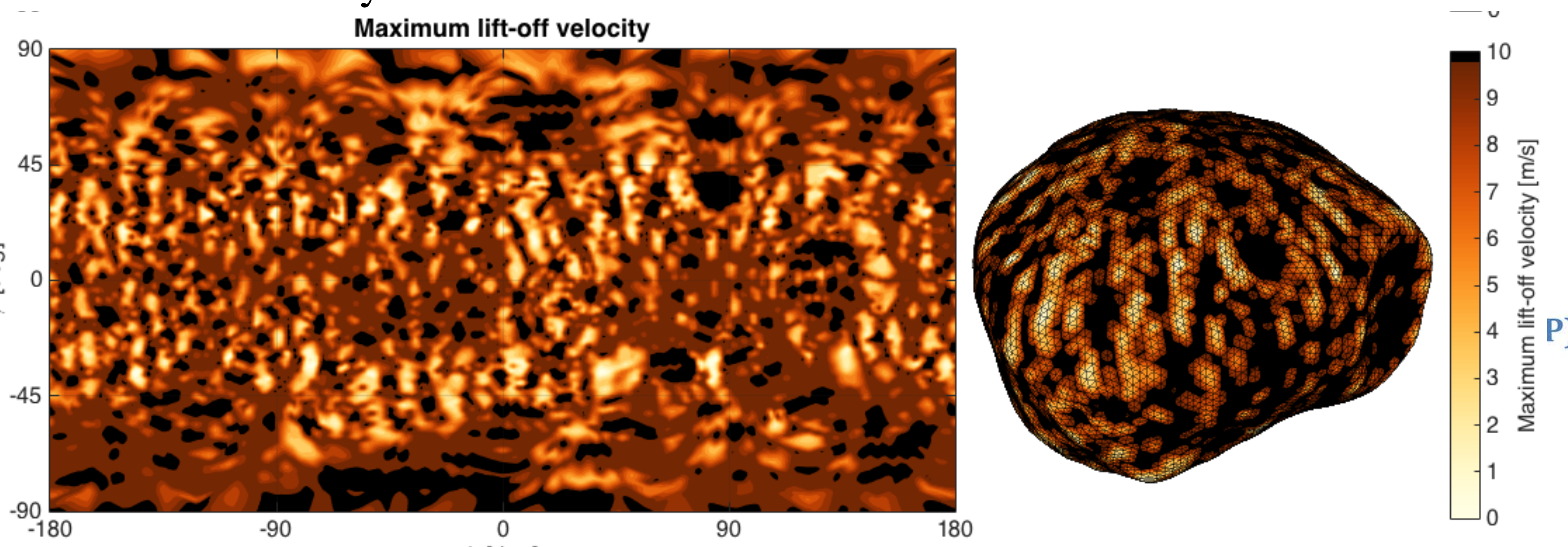
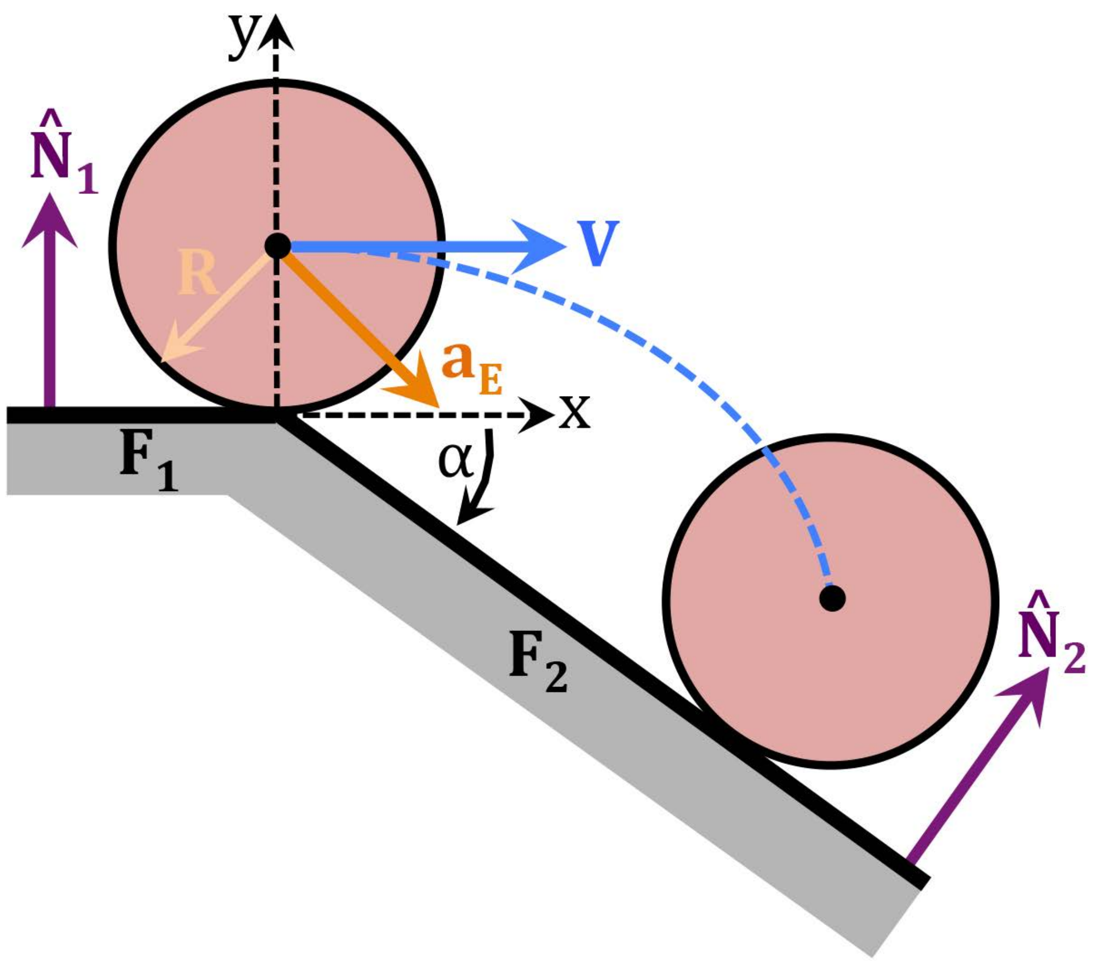


Motion on the Surface

- Effective "hop" speeds
  - For a wheeled vehicle with radius R, traveling faster than ~$0.05\sqrt{R}$ m/s can lead to loss of contact with the surface, and a significant decrease in traction
  - Defines a lower speed limit for efficient travel over the surface on the order of centimeters / second



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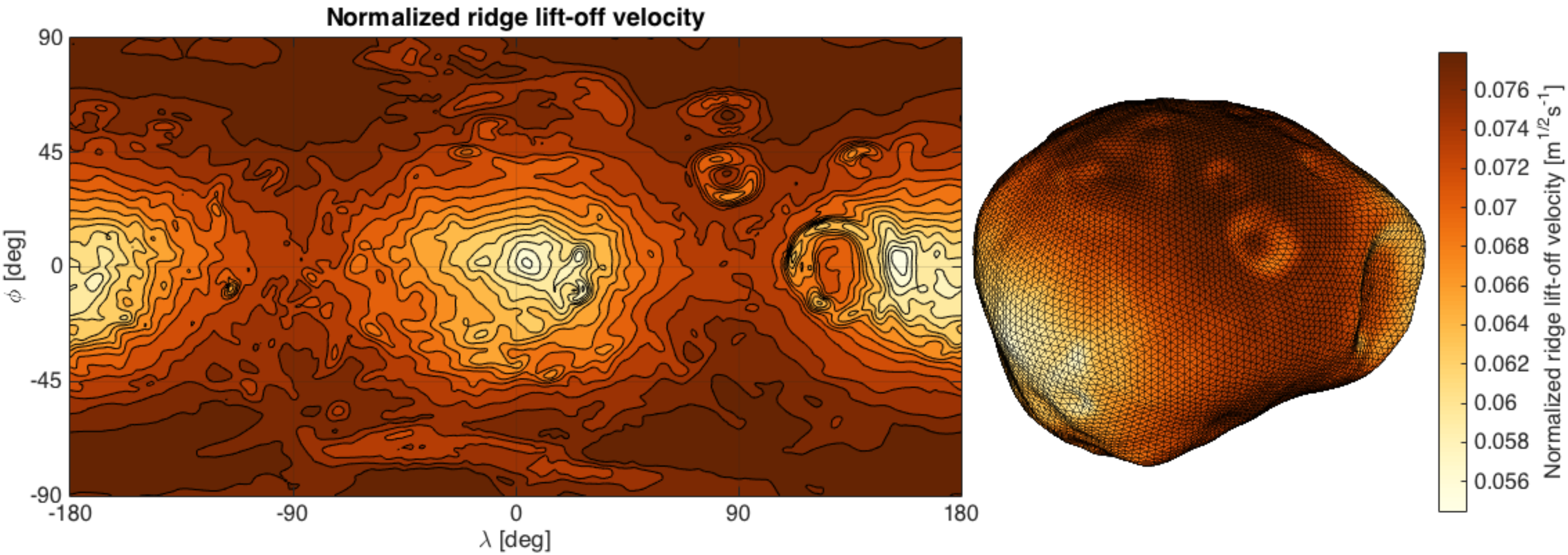
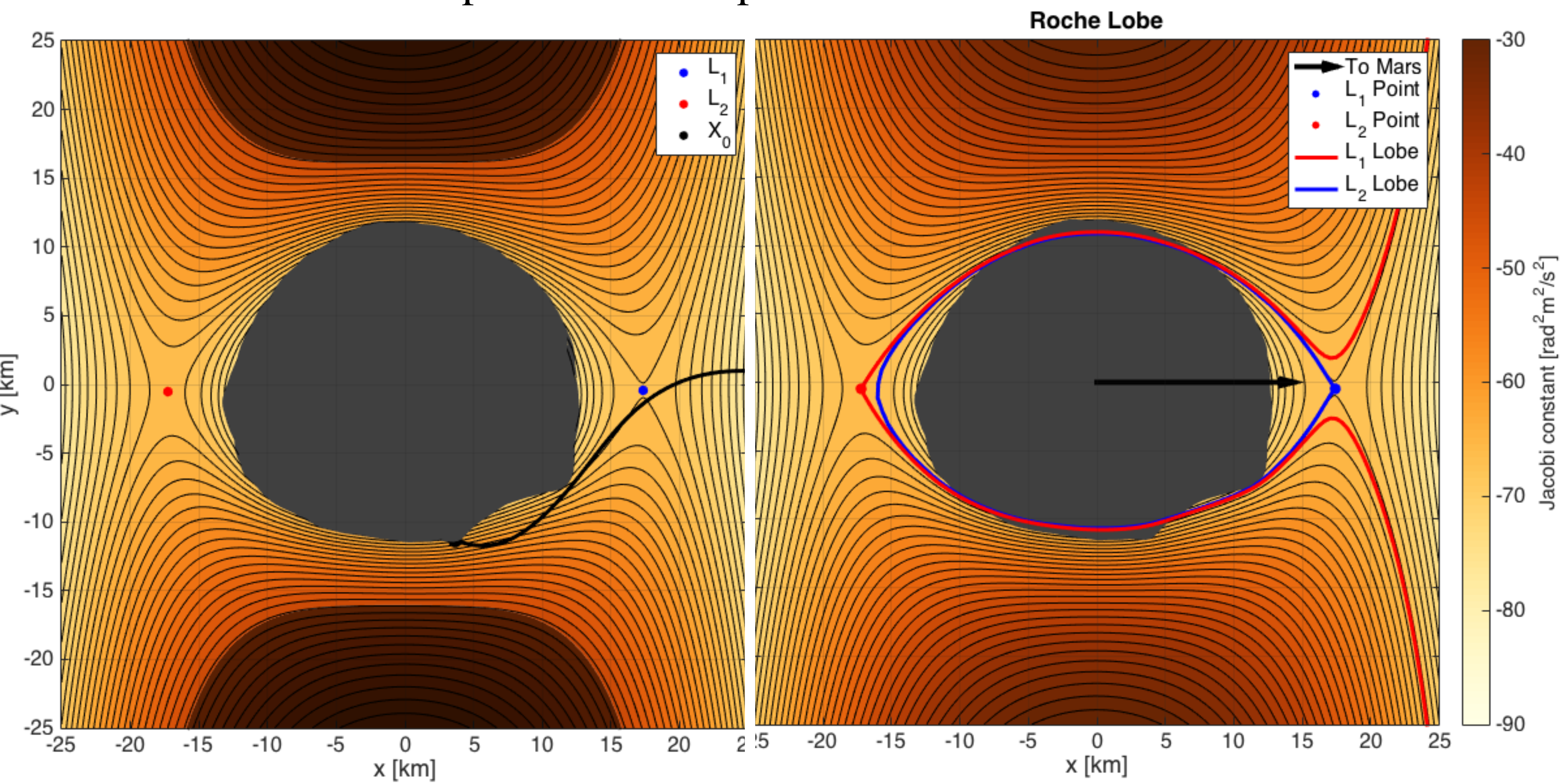


Motion in Close Proximity

- Energy to escape:
  - The "Roche Lobe" defines the level of energy / speed relative to Phobos for a particle to escape. Over much of the surface it is 0!



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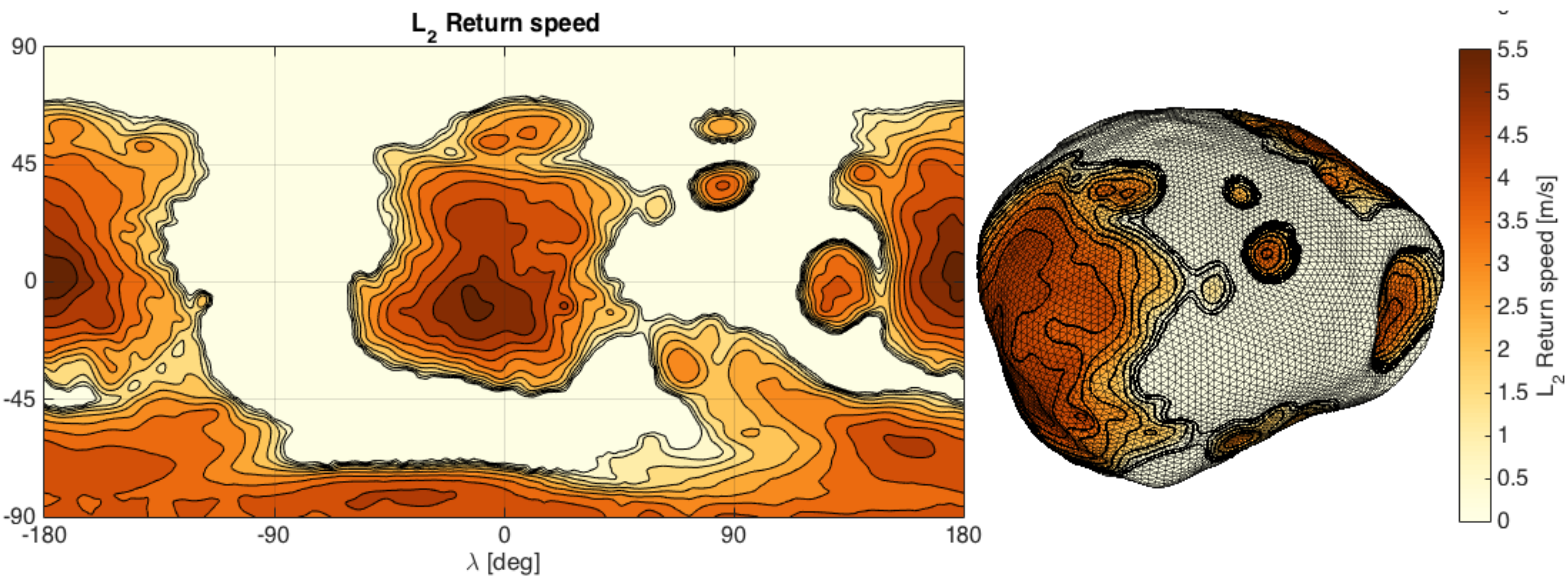
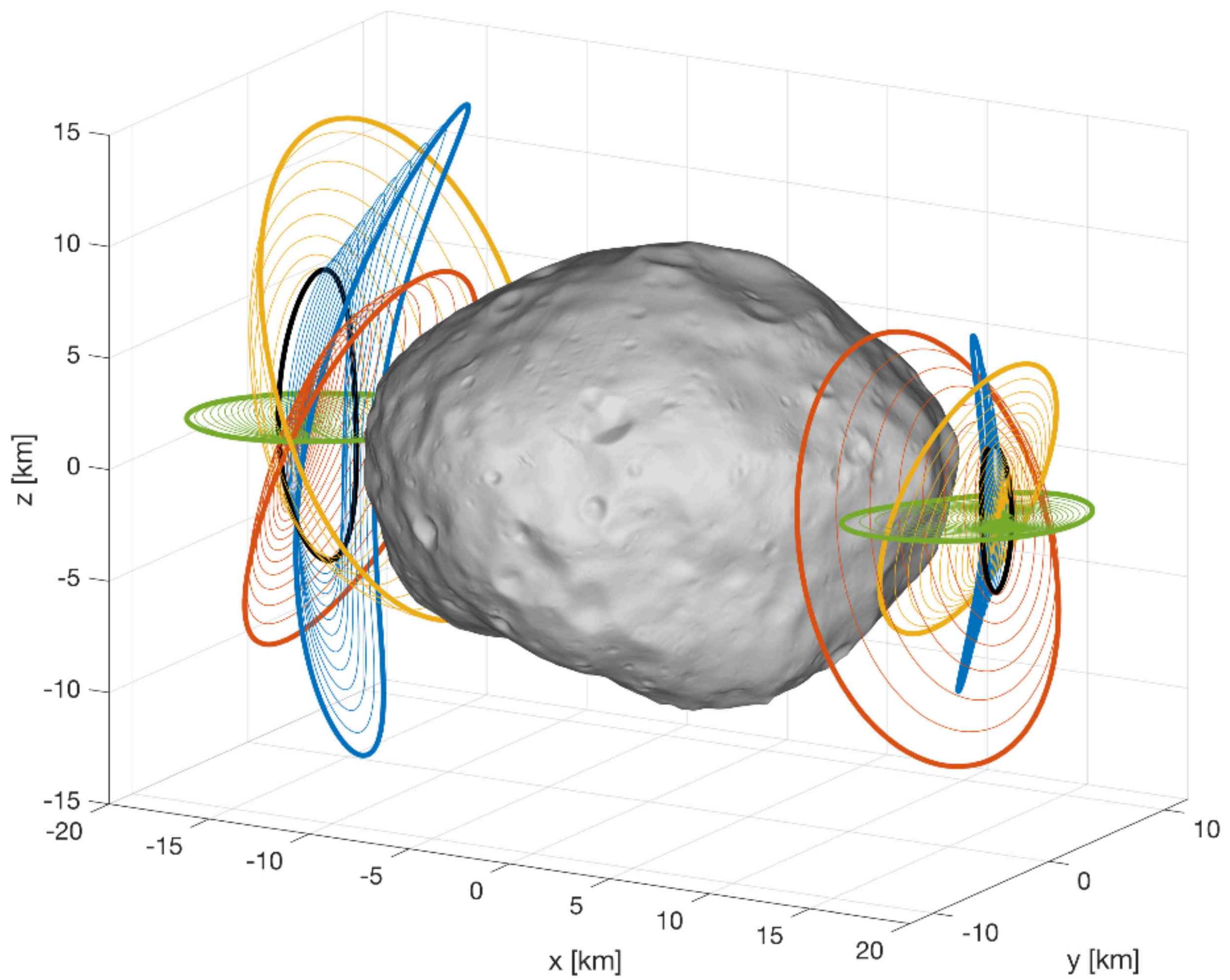
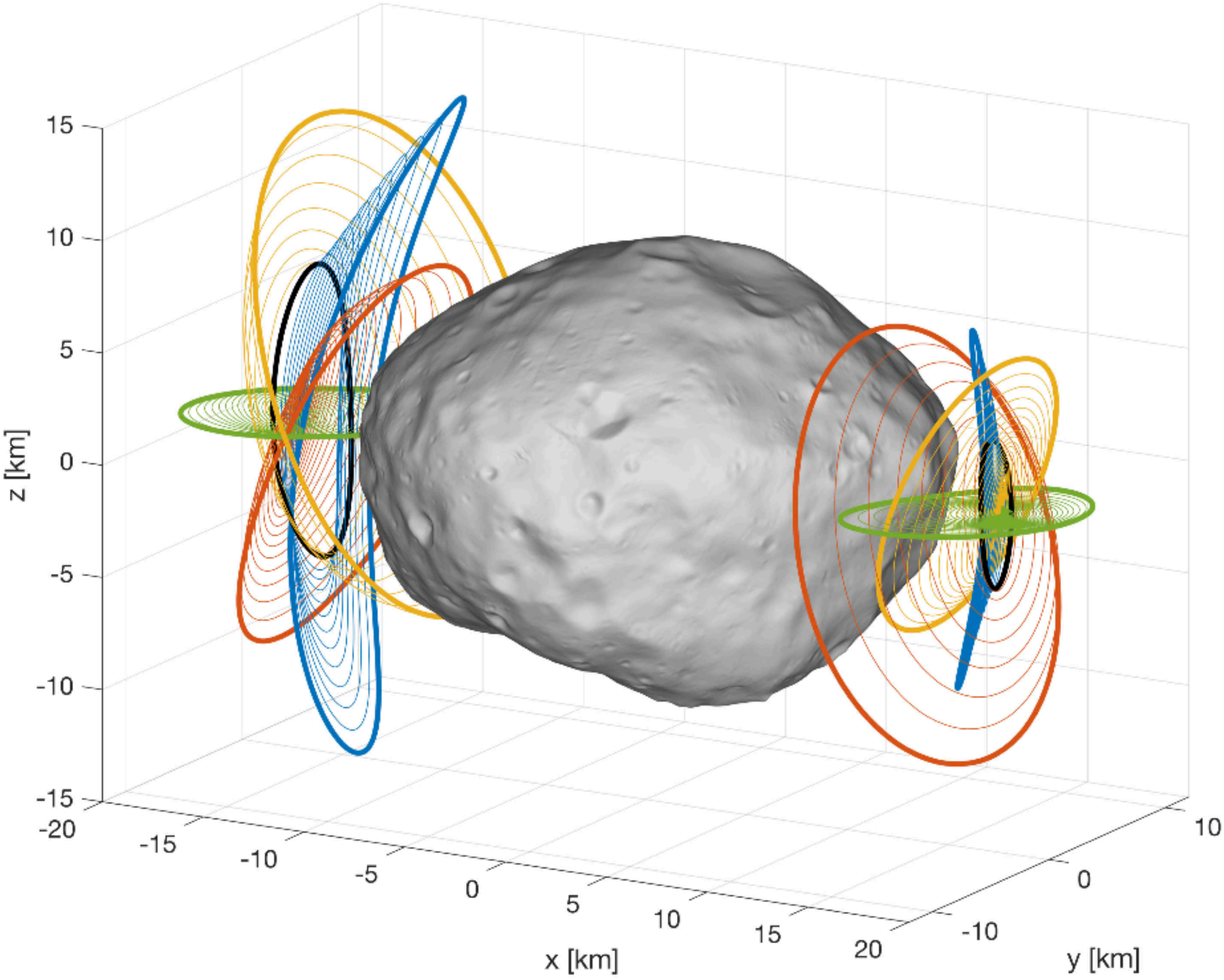


Motion in Close Proximity

- Structure of synchronous motion about L_1 and L_2
  - All families that arise in their vicinity are unstable, making their utility limited
  - Knowledge of them allows us to analyze motion in their vicinity
  - The family structure between Lyapunov, out of plane and halo orbits is much more complex

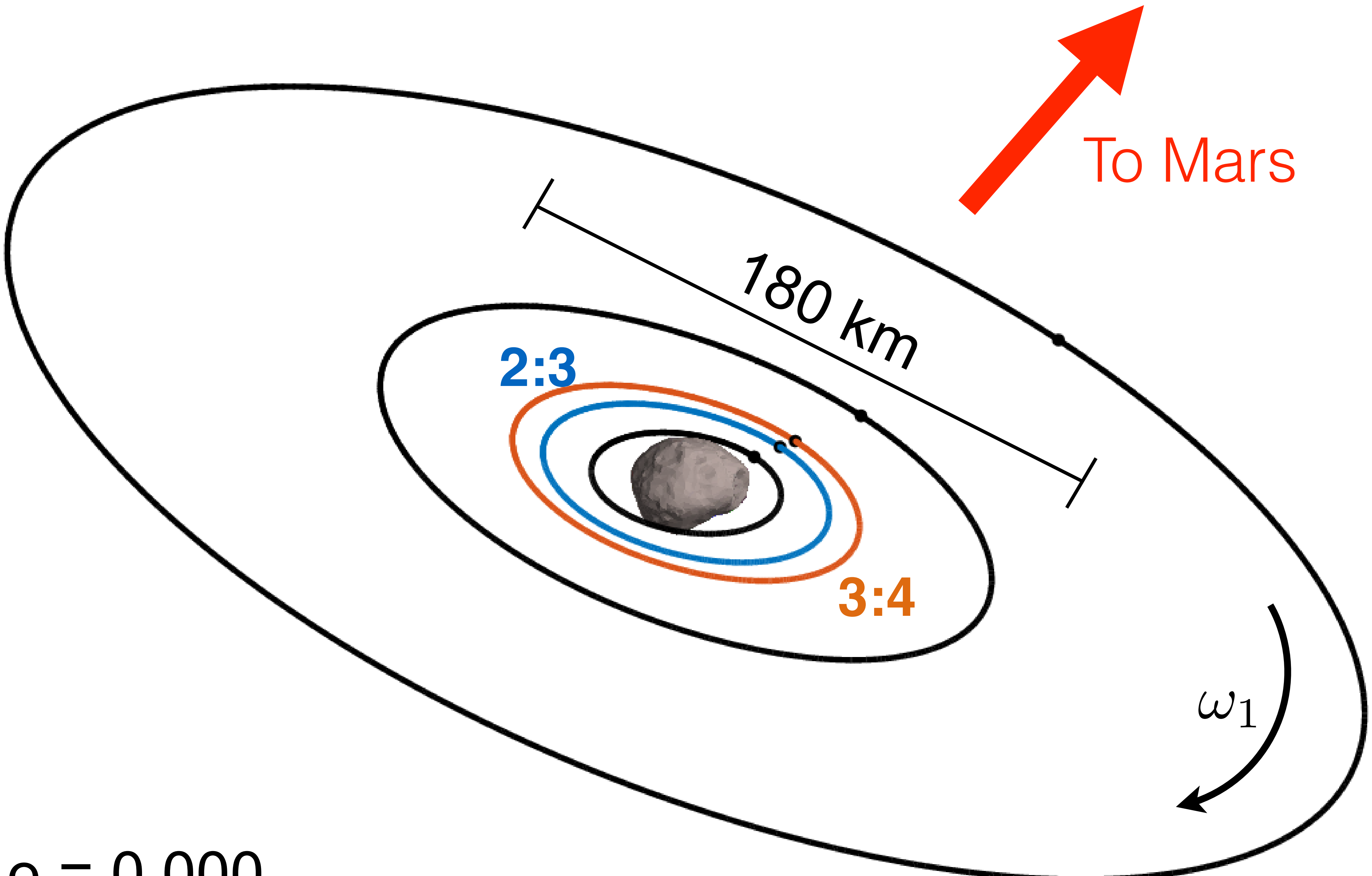




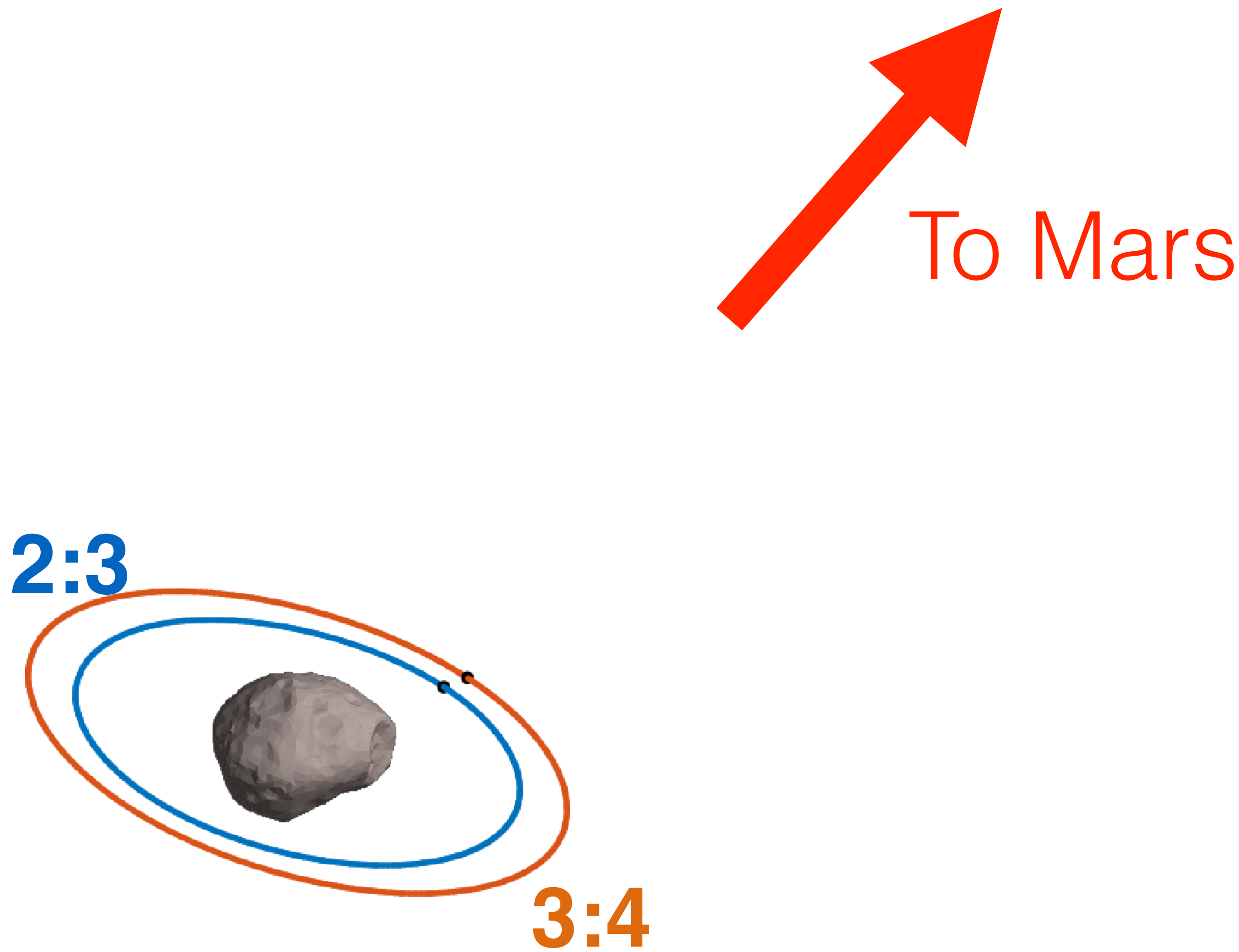
15
10
5
0
-5
-10
-15
z [km]
-20
-15
-10
-5
0
5
10
15
20
x [km]
10
0
-10
y [km]

Retrograde Motion

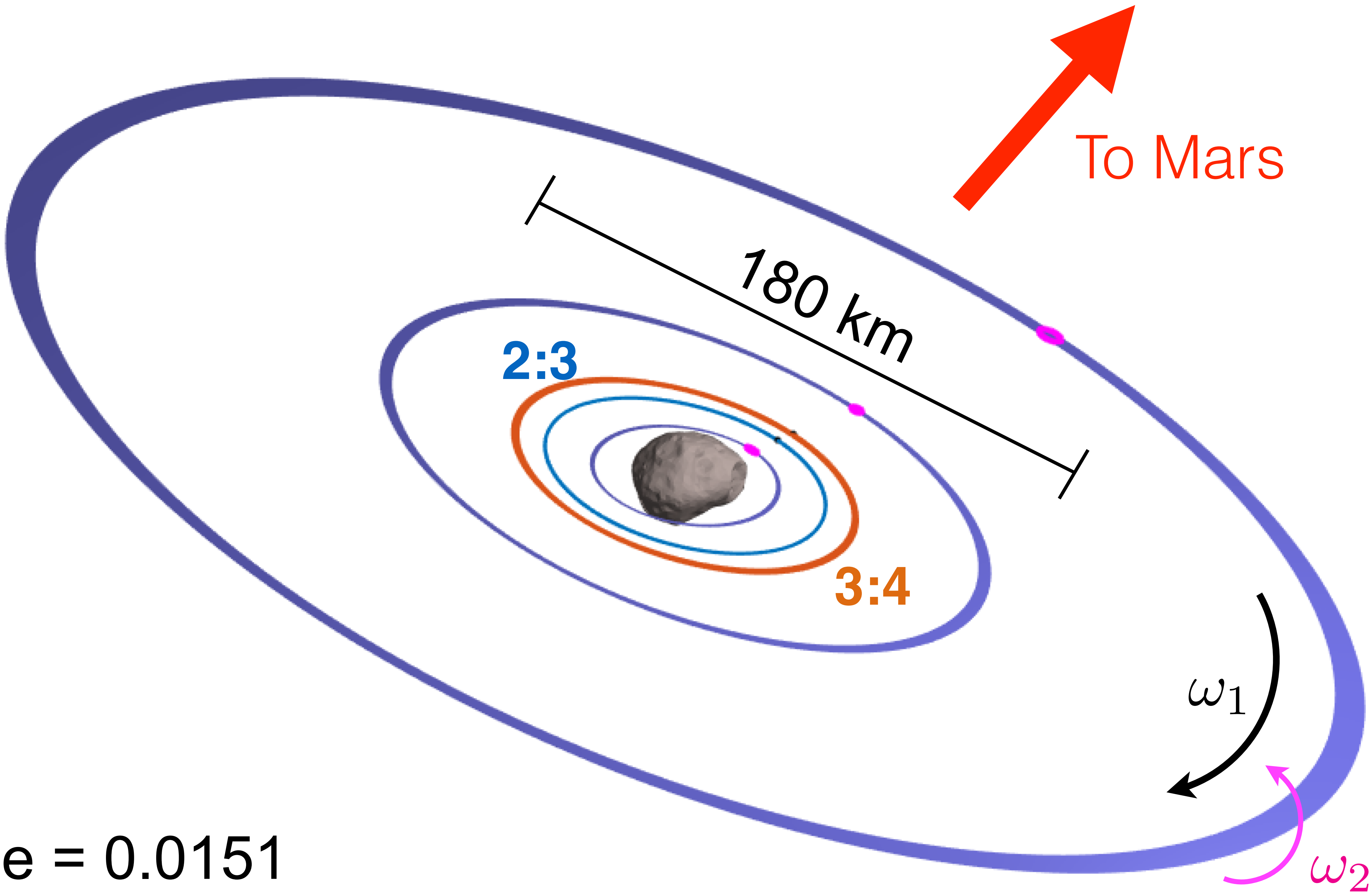
- Stability of retrograde motion
  - Retrograde orbits about Phobos are stable and exist down to the surface
  - At greater distance, they resemble 2:1 Clohessy-Wilshire ellipses, while close to Phobos they resemble near-circular, retrograde orbits
- Circular orbit case:
  - Periodic orbits exist as a continuous function of distance
  - Only resonant periodic orbits persist once ellipticity is accounted for
- Elliptic orbit case:
  - For elliptic Phobos orbit, instead we can find a continuous family of quasi-periodic orbits that exist at all distances
  - The stability of these orbits has been verified



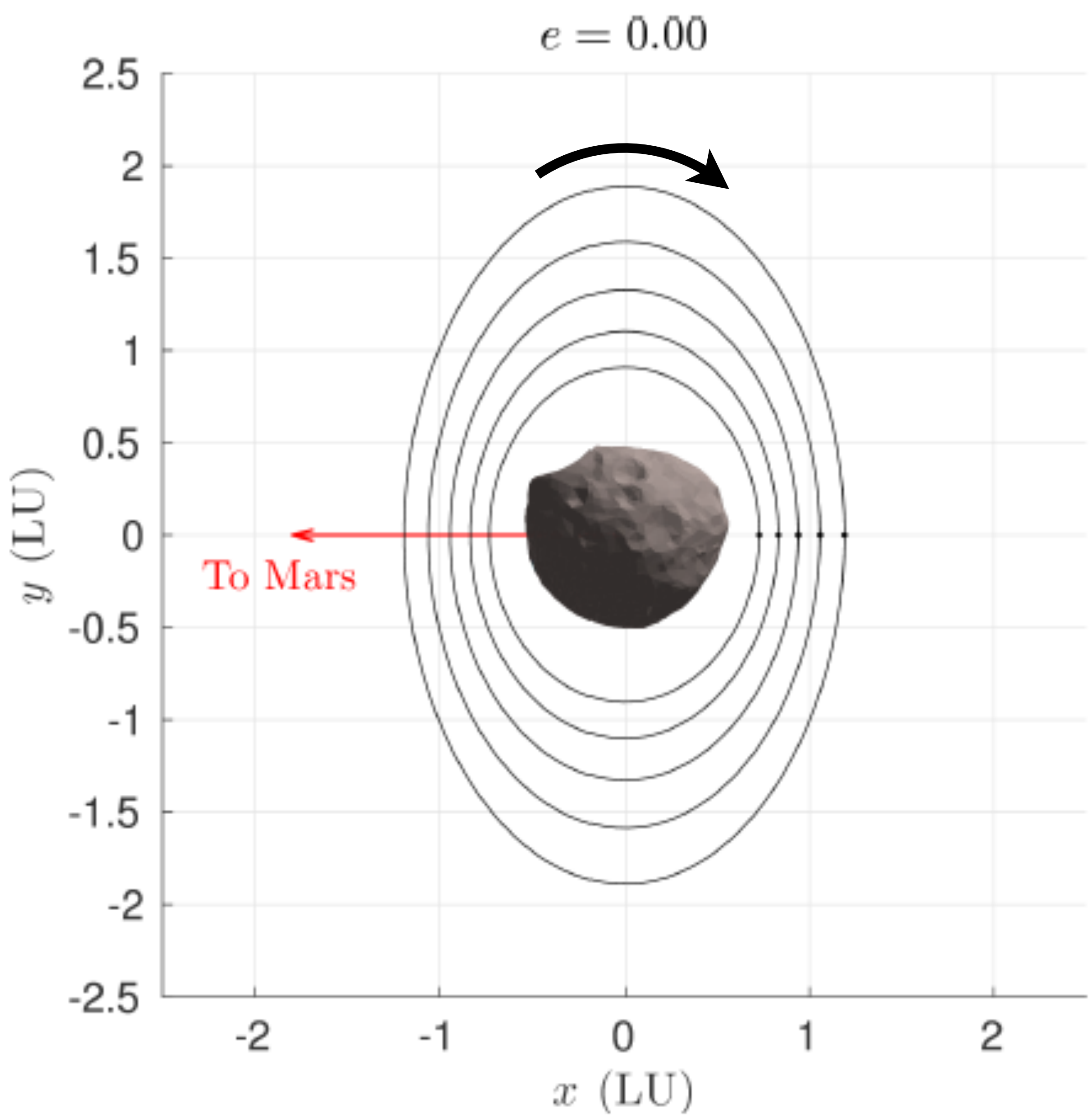
e = 0.000

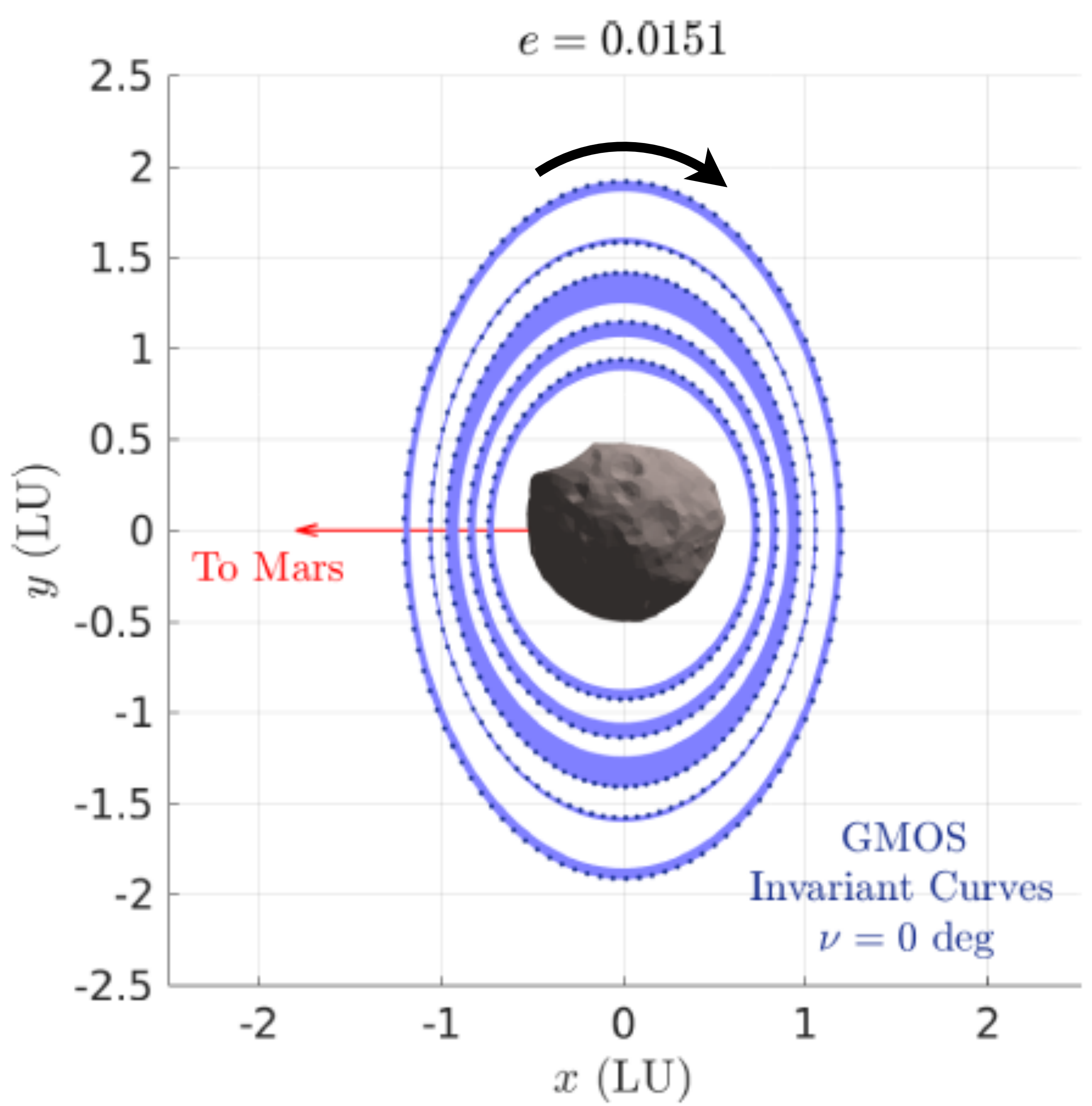


e = 0.0151



e = 0.0151





LU ~ 23.92 km

TU ~ 1.21 hr

Conclusions / Summary

- Detailed models of vehicle dynamics about Phobos are explored
- Results for surface and orbital motion are given
- There exist limits on the speed of vehicles on the surface
- Direct orbits associated with the libration points are unstable
- Retrograde periodic and quasi-periodic orbits are very stable down to the surface of the Phobos
  - These provide excellent options for orbital observations of the body
  - Naturally can be extended into the out-of-plane direction for better visibility of the polar regions
- Hovering dynamics are also possible, will be analyzed in the final paper

Challenges Beyond Orbital Dynamics

- The exploration of small bodies motivates fundamental questions across a range of fields
  - Astronomy & Astrophysics
  - Exploration technologies
  - Celestial Mechanics
  - Granular Mechanics
  - Control theory and planning
- To properly develop techniques for their exploration and utilization requires us to understand their...
  - Evolution in time
  - Geophysical properties
  - Formation circumstances
  - Responses to external stimuli

Conclusions

- Orbital Mechanics about small bodies *can* be analyzed and understood but require *non-conventional* techniques and analysis
- 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 *astrophysics, astronomy and celestial mechanics*
  - 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***