A Brief Tour of Asteroid Exploration

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COMET-ORB

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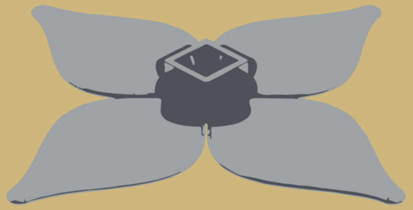
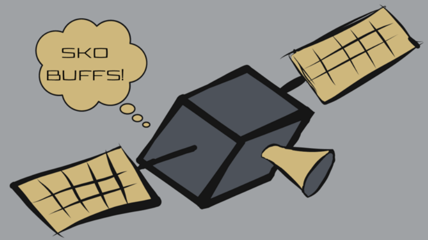
Space Robotics

Exploring innovative ways to combine robotics and autonomy for enabling low cost yet complex space exploration missions.

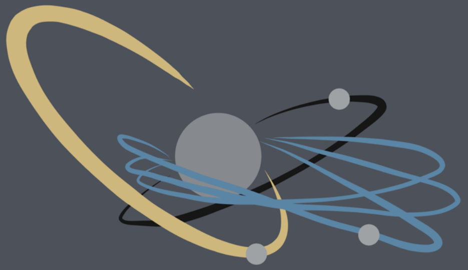


Autonomy and GNC

Developing robust and novel techniques to enable space vehicles to safely and efficiently reach and operate at their desired targets.

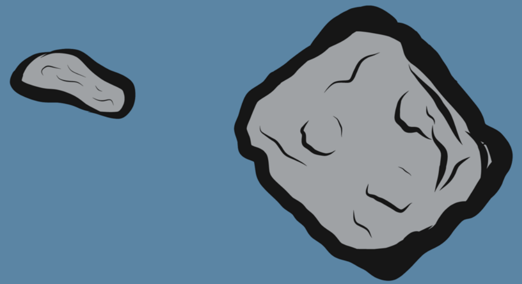


Astrodynamics



Using theoretical approaches to improve mission design and enhance our understanding of complex orbital regimes.

Planetary Science



Understanding the Solar System - in particular, asteroids, comets, and moons - using spacecraft data and celestial mechanics.

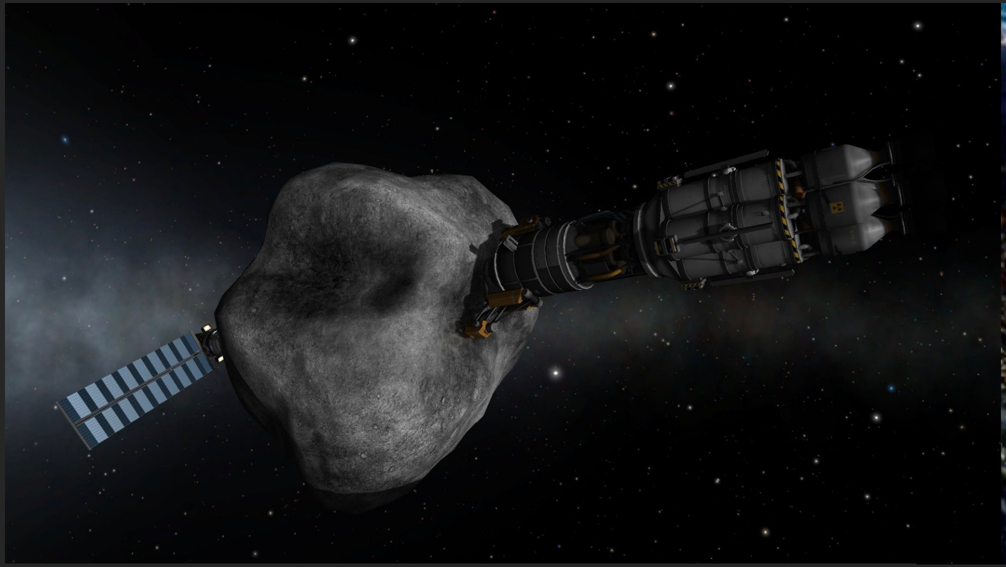
ASTEROID MISSIONS

Why asteroids?

Science

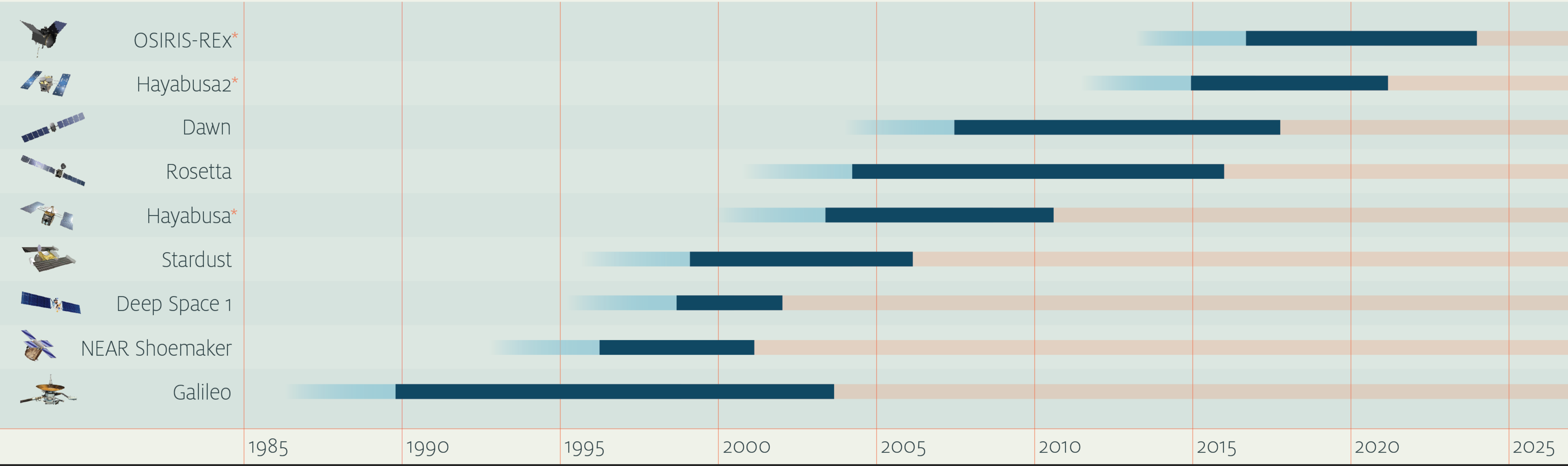
Economics

Planetary Defense



ASTEROID EXPLORATION: MISSIONS TIMELINE

MISSION DURATION
PLANNING PHASE
CONTINUED DATA ANALYSIS
* ASTEROID SAMPLE RETURN MISSION



OSIRIS-APEX
H2+
MMX
Other Apophis mission?

Lucy (2021 – 2033)
DART (7/21 – 9/22)
Psyche (2023 – 2028)
Hera (2024 – 2026)
Destiny+ (2025 ~ 2029)
EMA (2028 – 2036)

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nature
THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE
Unexpectedly rugged surface of asteroid Bennu presents challenges for sample retrieval
ROUGH GUIDE
MOLECULAR MOTION
LIFE ON KILIMANJARO
UNDERWATER GAS-GUZZLER


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
ASTEROID EXPLORATION
ROSETTA
ESA
Launch Date: March 2004
Flyby Object: Asteroids
Steins & Lutetia
NEAR SHOEMAKER
NASA
Launch Date: February 1996
Mission Target: Asteroid Eros
Flyby Object: Asteroid Mathilde
STARDUST
NASA / JPL
Launch Date: February 1999
Extension: March 2006
Flyby Object: Asteroid Annefrank
GALILEO
NASA / DLR
Launch Date: October 1989
Flyby Object: Asteroids Gaspra and Ida
DEEP SPACE 1
NASA / JPL
Launch Date: October 1998
Flyby Object: Asteroid Braille
CASSINI
NASA / ESA / ASI
Launch Date: October 1997
Flyby Object: Asteroid Masursky
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
Science
AAAS
ROCKY ASTEROID
Hayabusa2 arrives at Ryugu

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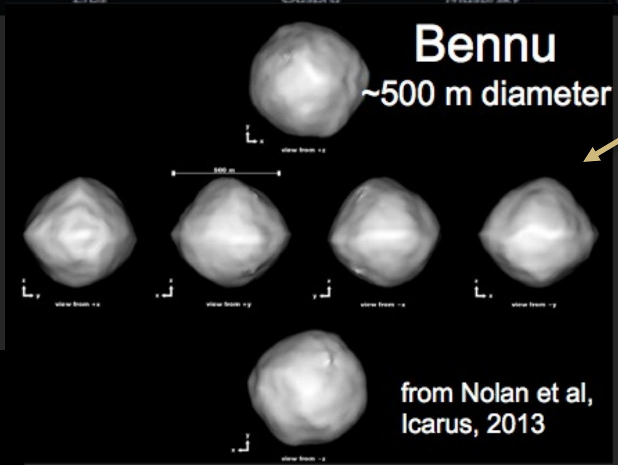
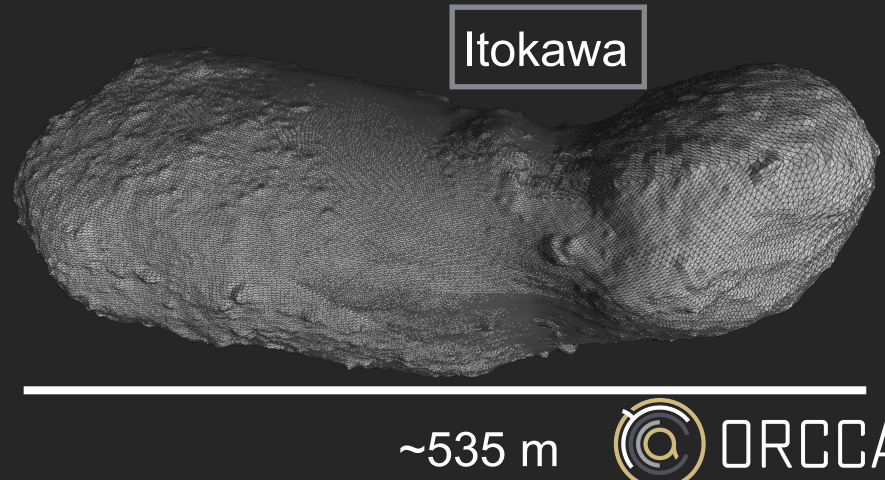
Asteroids are all shapes and sizes…





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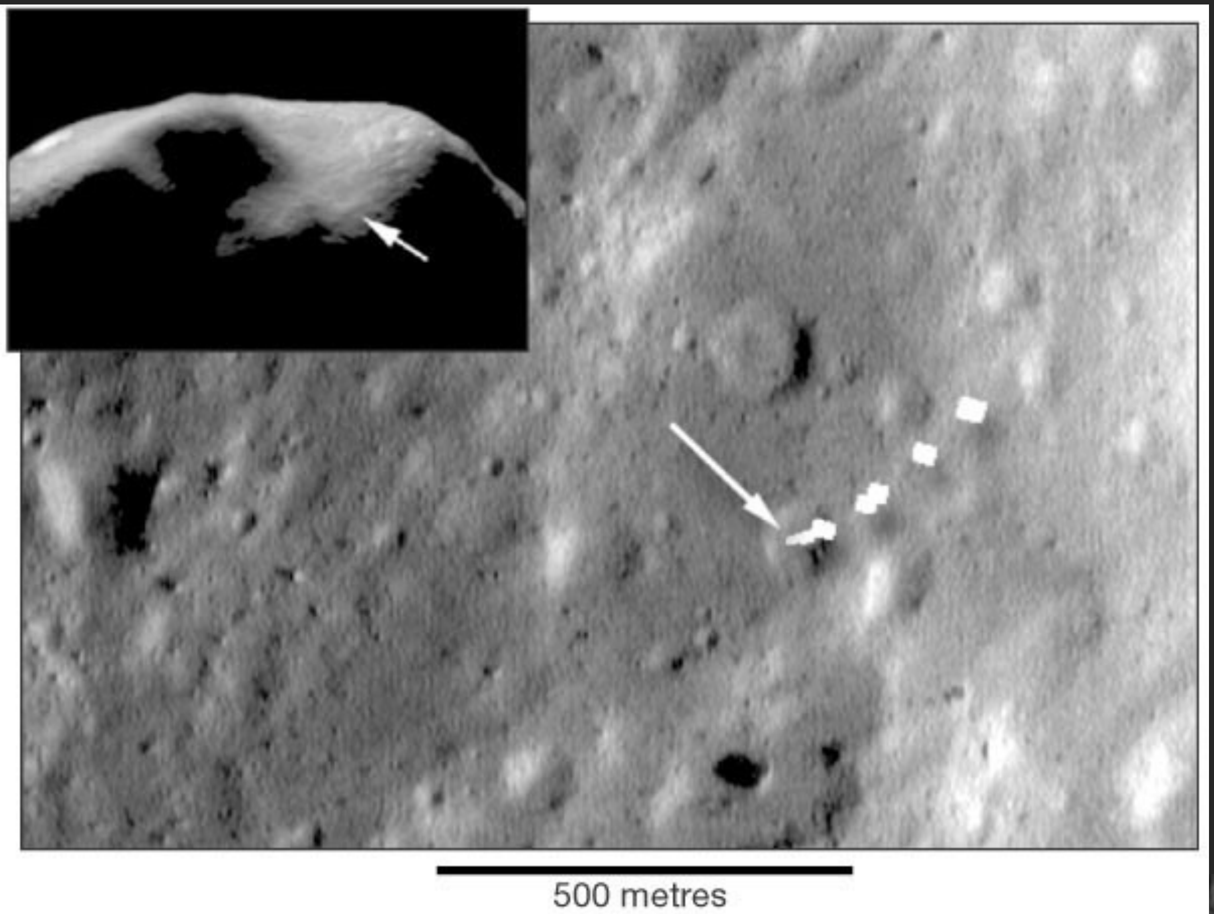
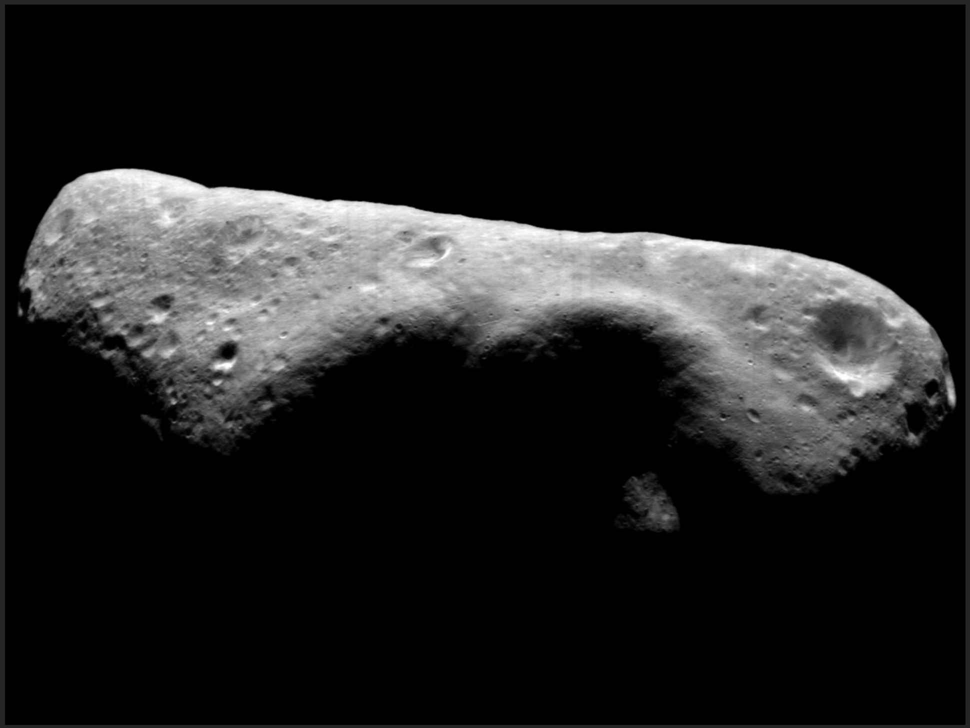
NEAR (NASA)

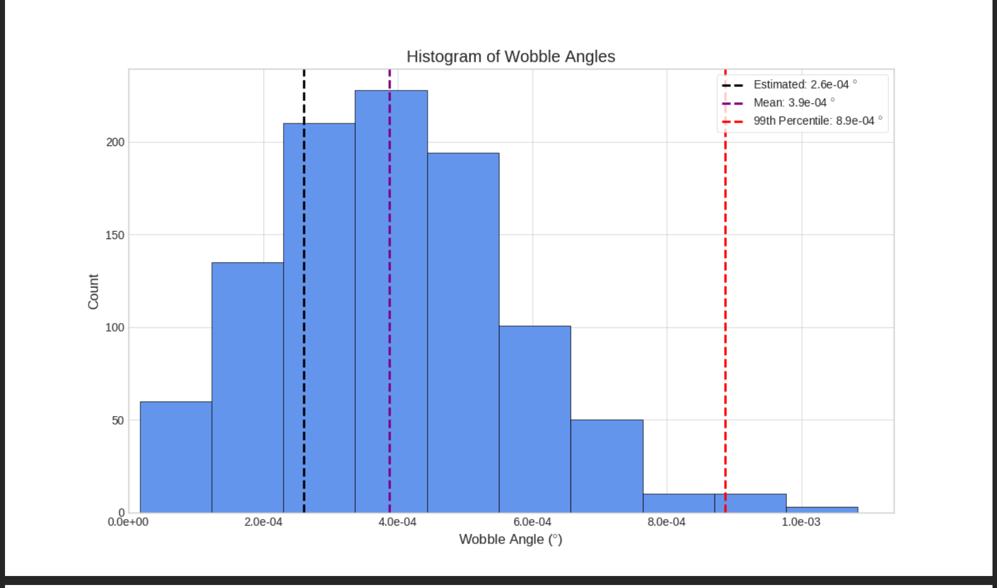
Feb. 17, 1996: Launch
June 27, 1997: Flyby of asteroid Mathilde
Jan. 23, 1998: NEAR flew by Earth for a gravity assist
Dec. 23, 1998: Spacecraft flew by Eros for the first time
Feb. 14, 2000: NEAR entered orbit around Eros becoming the first human-made object to orbit an asteroid
Feb. 12, 2001: NEAR touched down on Eros – the first time a U.S. spacecraft was the first to land on a celestial body

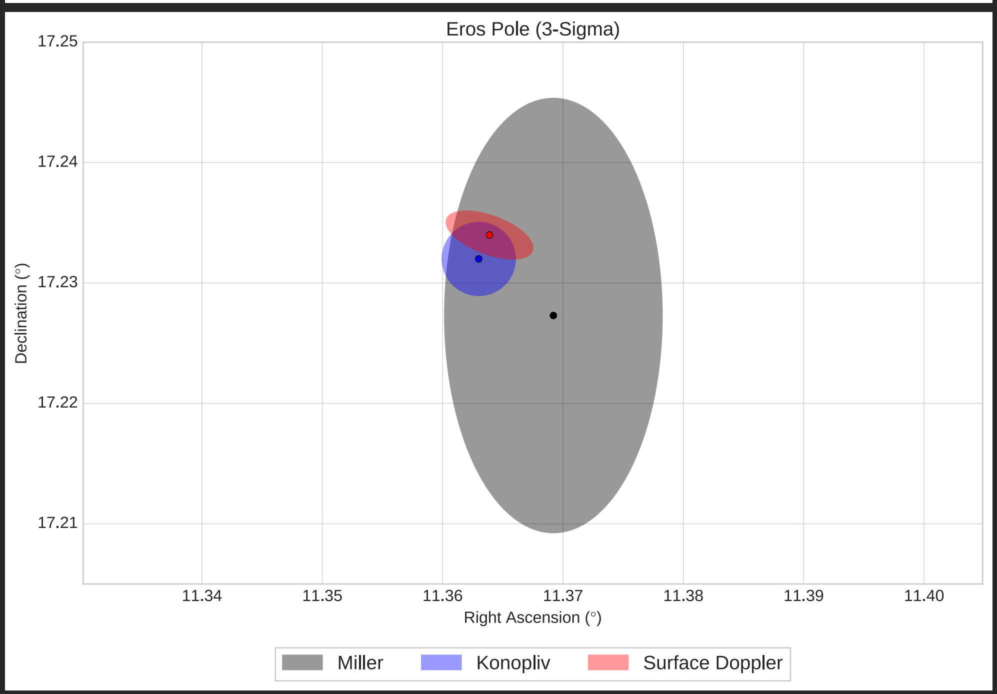


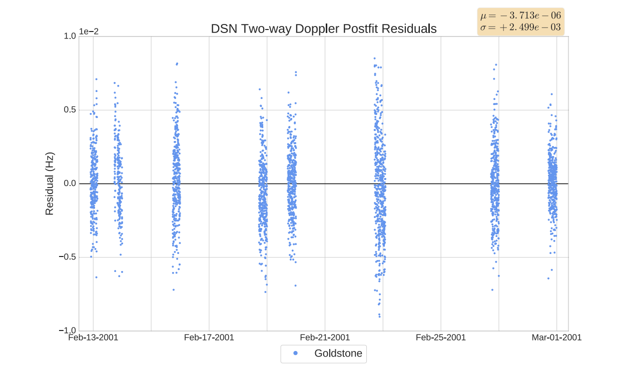


Spin State Estimation Using Landed Transponders

- Reprocessed NEAR mission data
  - 16 days of landed two-way Doppler
  - First time this has been used for spin state estimation
  - Applied altitude constraint to latest SPC shape model
- Estimate is consistent with both the nav (Miller) & radio science (Konopliv) solutions
  - Konopliv's had >130,000 landmark observations
- We also find Eros to be in PA rotation
  - We reduced the uncertainty in the maximum wobble angle by a factor of ~20

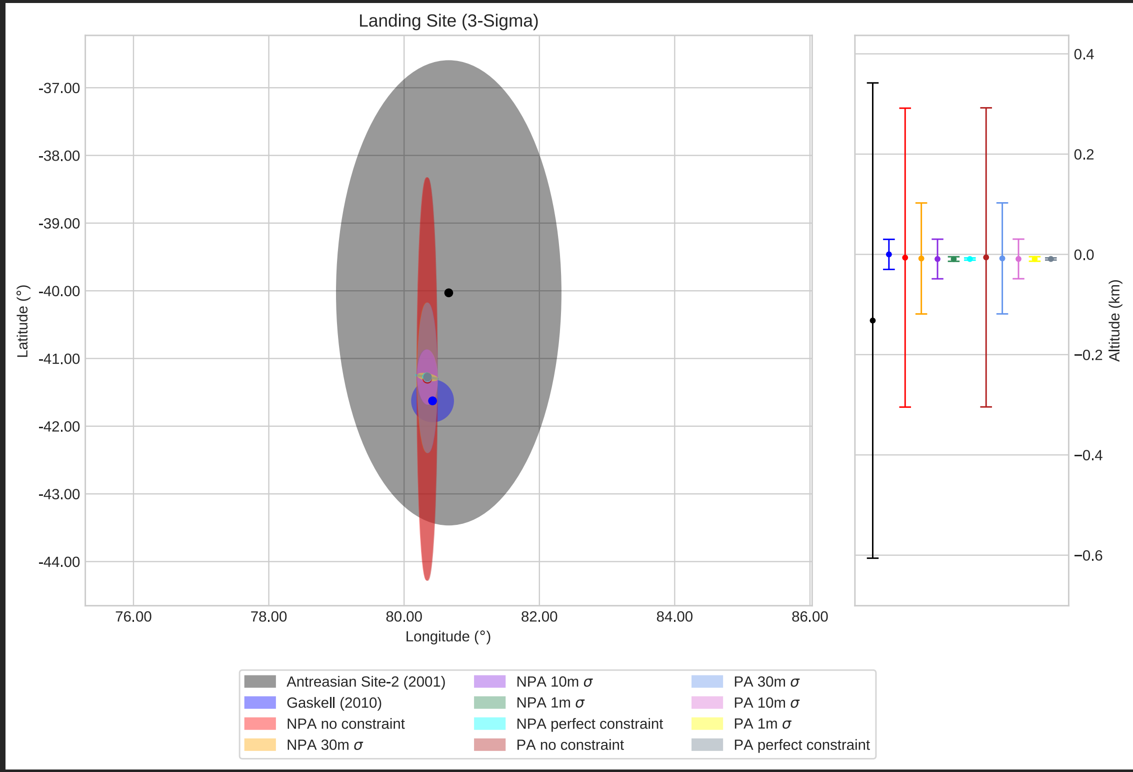


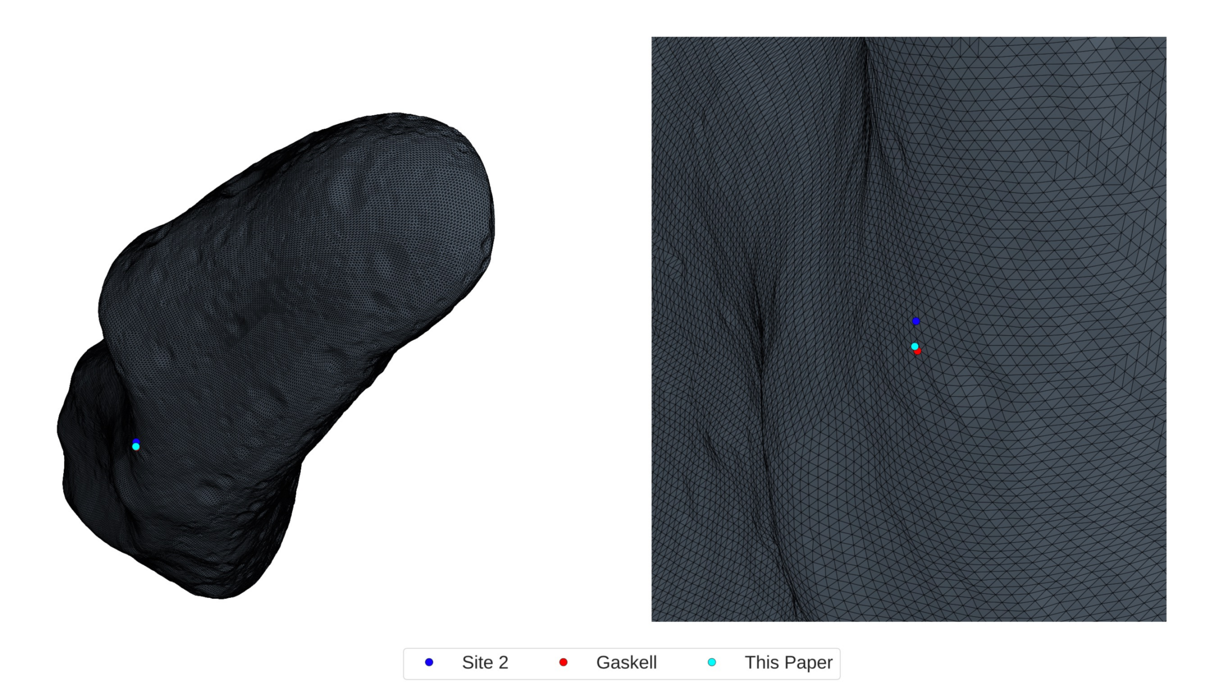




Reconstructed Landing Site

- Nav team published two potential landing sites, both determined via surface Doppler
  - Site-2 showed better agreement with the descent imagery
- Gaskell refit the landing trajectory in 2010 using new SPC landmarks and LIDAR data
  - His solution agreed well with site-2
- Our solution agrees well with both solutions, and places a tighter formal constraint on its longitude



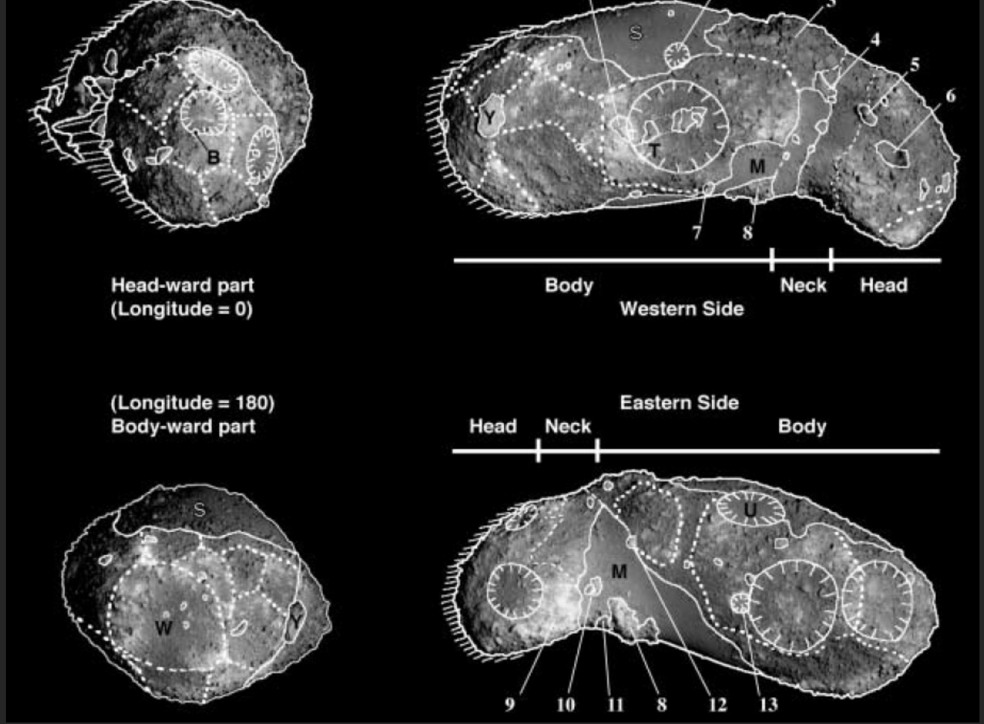


Hayabusa (JAXA)

First asteroid sample return mission to NEA Itokawa (S-type)

Overcame technical failures but returned a sample successfully…
and spawned feature films in Japan!

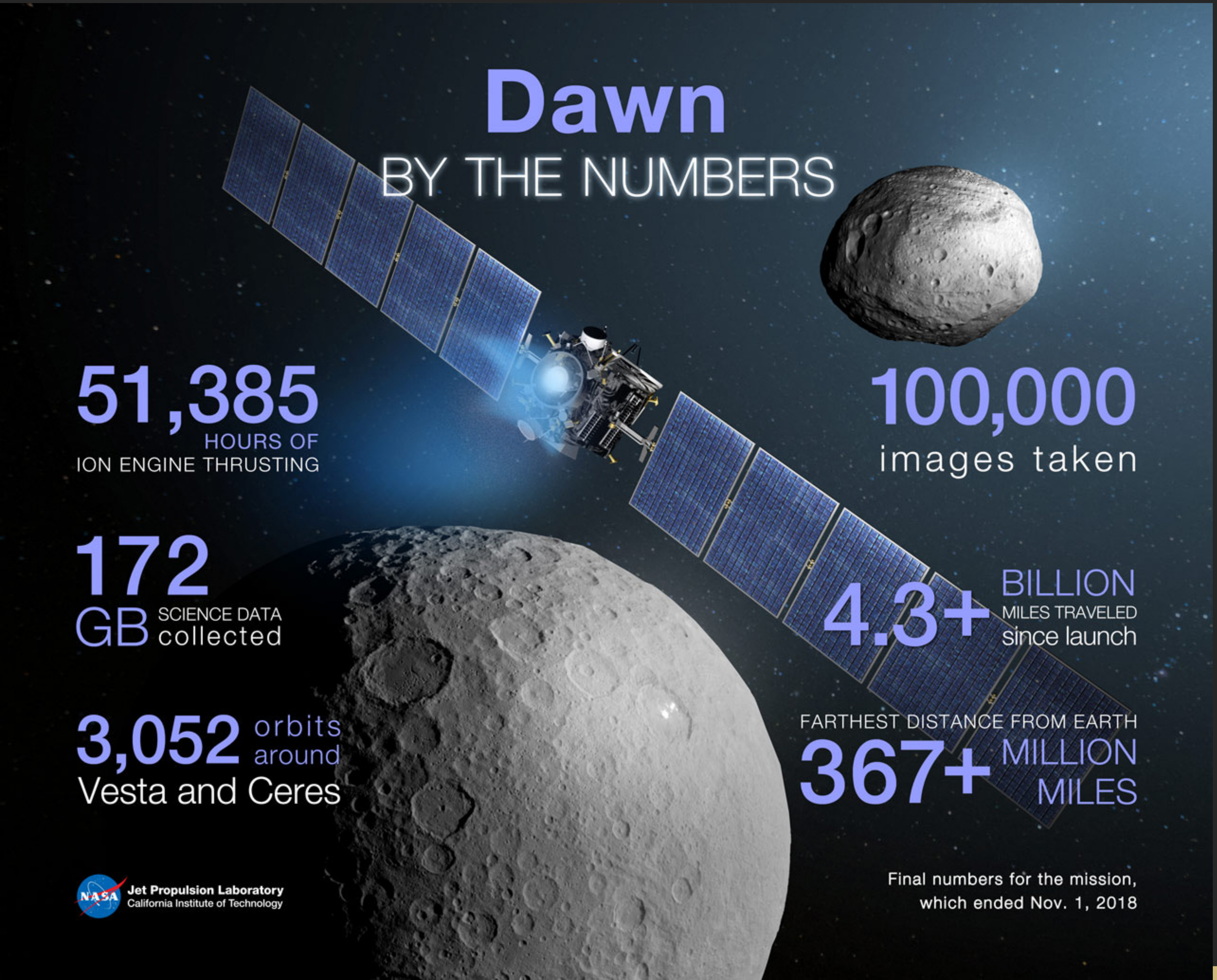
Demura, *Science*, 2006

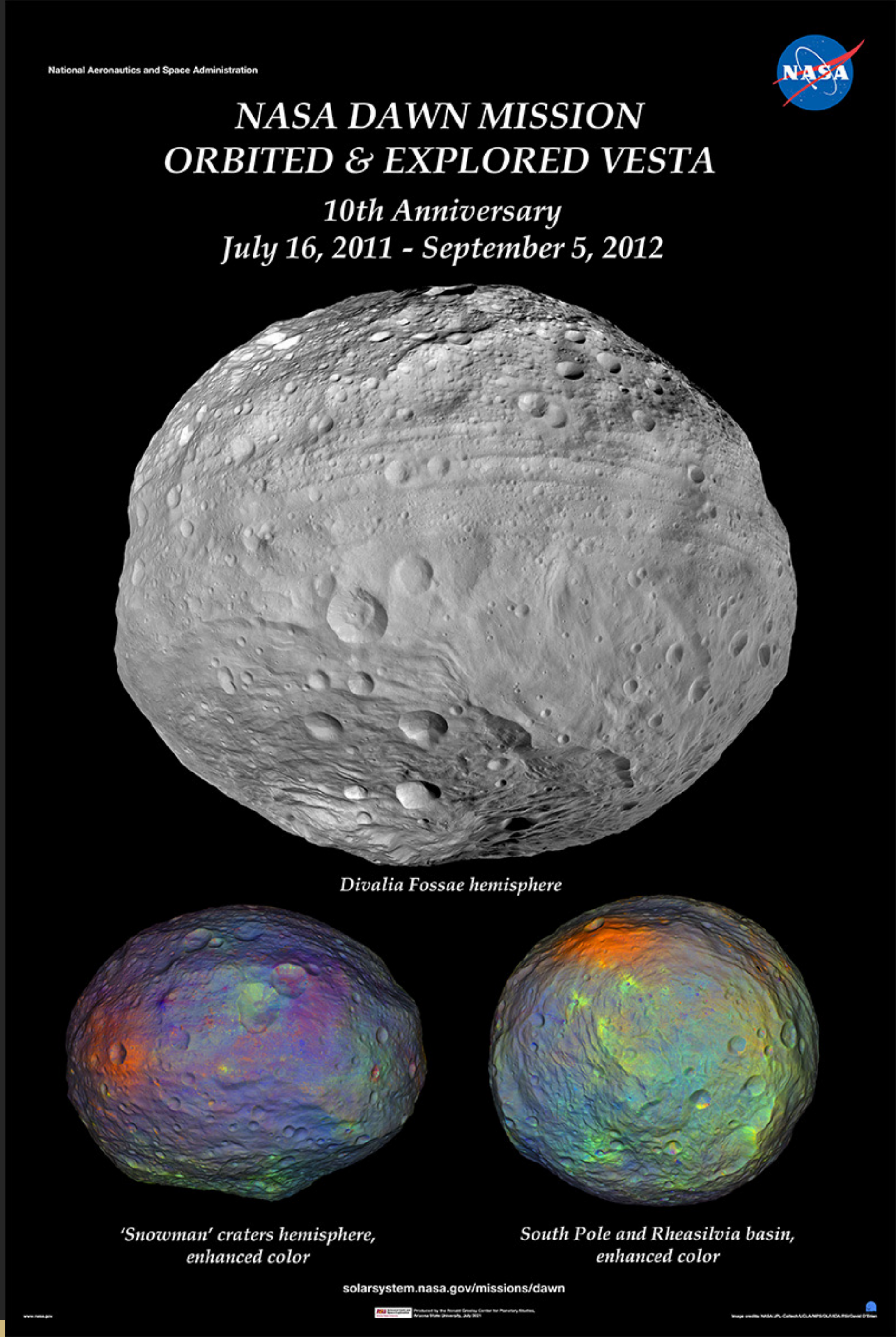


Itokawa – long axis 535 m

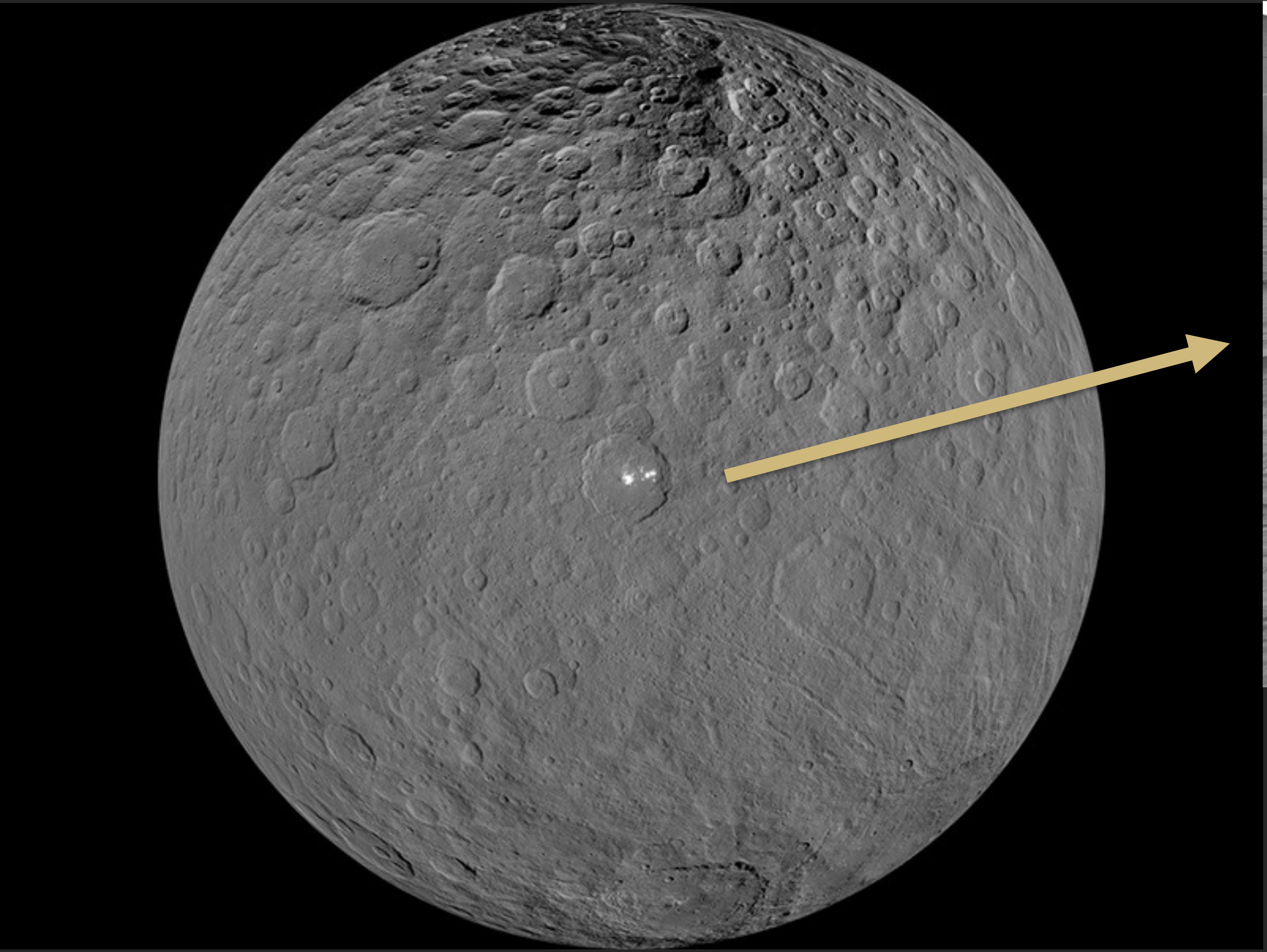
JAXA

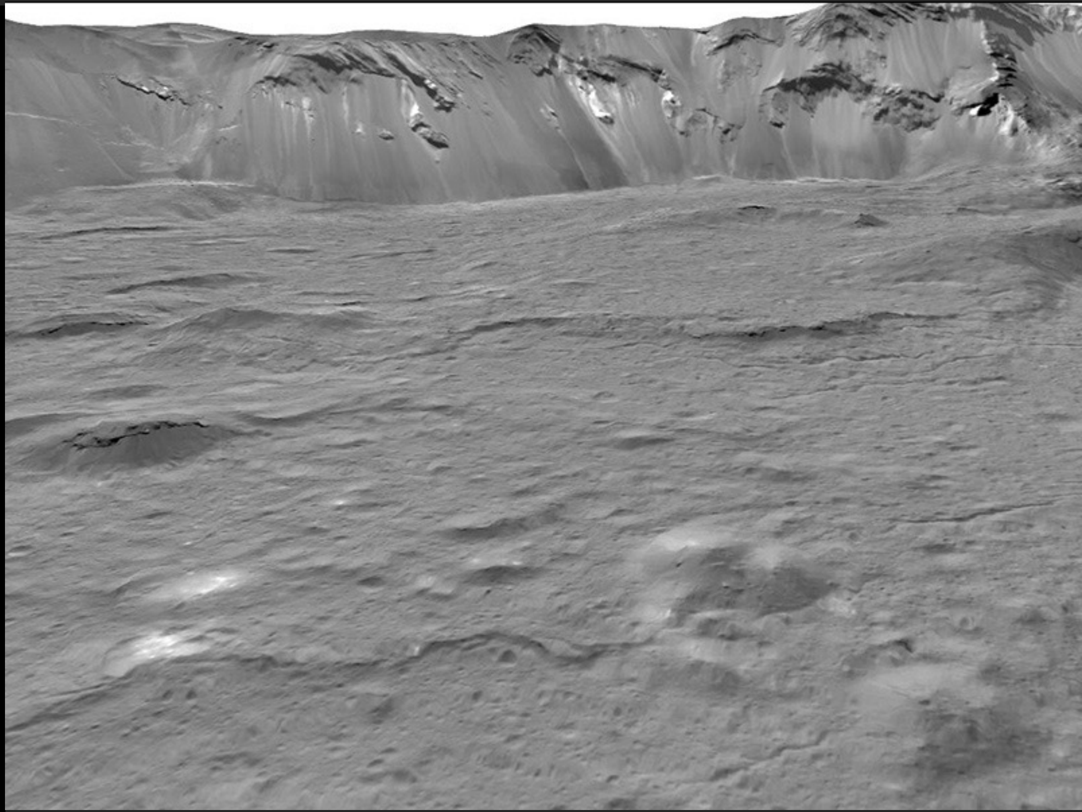
Dawn (NASA)


Dawn
BY THE NUMBERS
51,385
HOURS OF
ION ENGINE THRUSTING
100,000
images taken
172
GB SCIENCE DATA collected
4.3+
BILLION
MILES TRAVELED
since launch
3,052 orbits around
Vesta and Ceres
FARTHEST DISTANCE FROM EARTH
367+ MILLION MILES
Final numbers for the mission, which ended Nov. 1, 2018
NASA
Jet Propulsion Laboratory
California Institute of Technology


National Aeronautics and Space Administration
NASA
NASA DAWN MISSION
ORBITED & EXPLORED VESTA
10th Anniversary
July 16, 2011 - September 5, 2012
Divalia Fossae hemisphere
'Snowman' craters hemisphere, enhanced color
South Pole and Rheasilvia basin, enhanced color
solarsystem.nasa.gov/missions/dawn

Dawn (NASA)

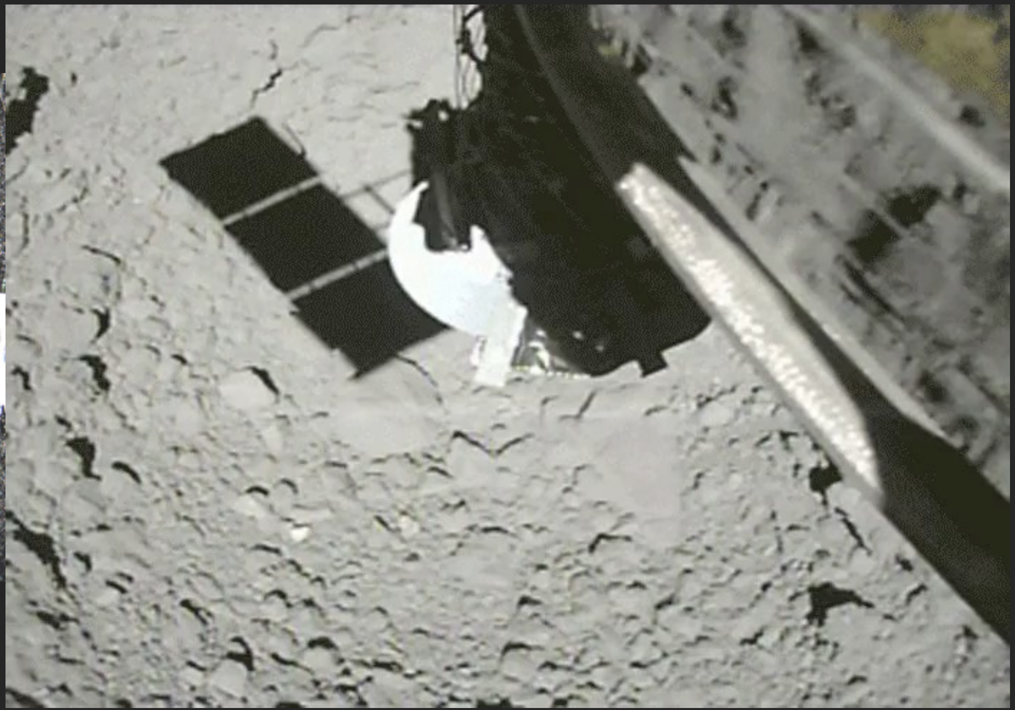


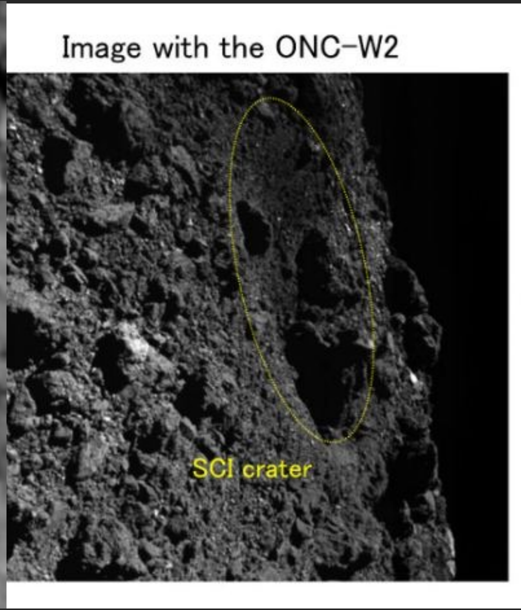


Occator Crater is 57 miles (92 kilometers) across. Bright pits and mounds in the foreground were formed by salty liquid released during the freezing of the water-rich floor, following the crater-forming impact about 20 million years ago.

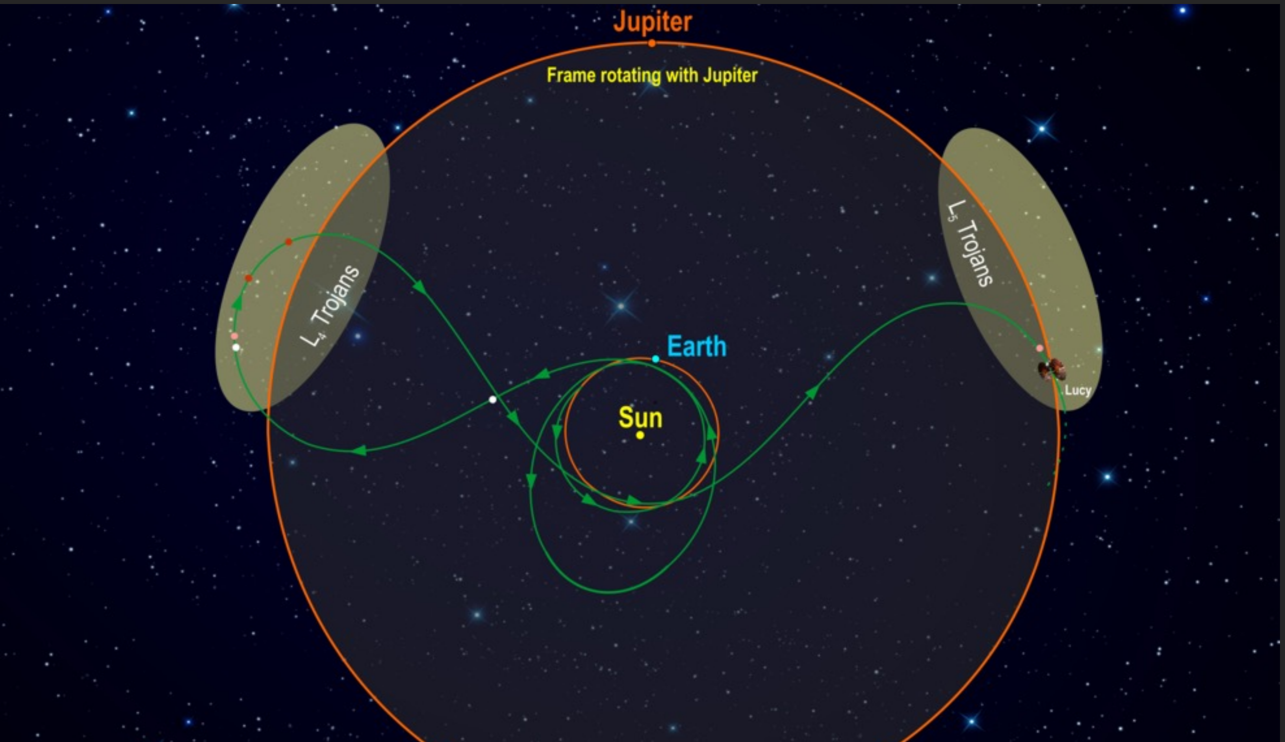
Hayabusa2 (JAXA)

5.4g returned to Earth!



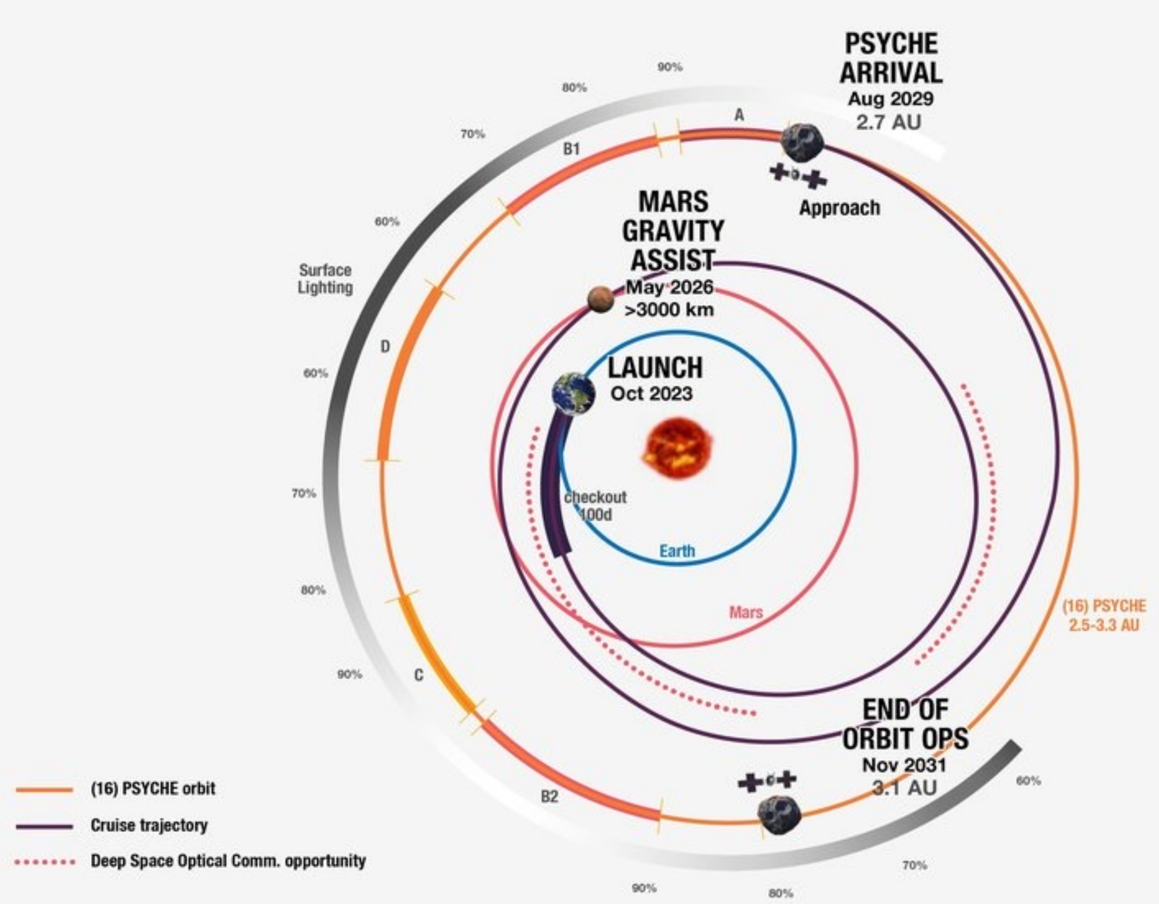


Lucy (NASA)



Credits: Southwest Research Institute
https://www.nasa.gov/mission_pages/lucy/overview/index

In the L4 cloud Lucy will fly by (3548) Eurybates (white) and its satellite, (15094) Polymele (pink), (11351) Leucus (red), and (21900) Orus (red) from 2027-2028.
After diving past Earth again Lucy will visit the L5 cloud and encounter the (617) Patroclus-Menoetius binary (pink) in 2033.
In 2025, Lucy flies by a small Main Belt asteroid, (52246) Donaldjohanson (white), named for the discoverer of the Lucy fossil.



https://www.jpl.nasa.gov/images/pia24930-psyches-mission-plan

Psyche is a metallic (M-type) main belt asteroid

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Dinkinesh & Selam flyby

- Lucy flew by main belt asteroid Dinkinesh on November 1, 2023 and discovered it is a binary!
- 431 km close approach
- Dinkinesh ~720 m
- Selam two lobes ~210 and 230 m
  - It orbits Dinkinesh at a distance of ~3.1 km with an orbital period of about 53 hr, and is tidally locked

Levinson preprint; https://doi.org/10.21203/rs.3.rs-3911173/v1

https://www.nasa.gov/image-article/nasas-lucy-spacecraft-discovers-2nd-asteroid-during-dinkinesh-flyby/

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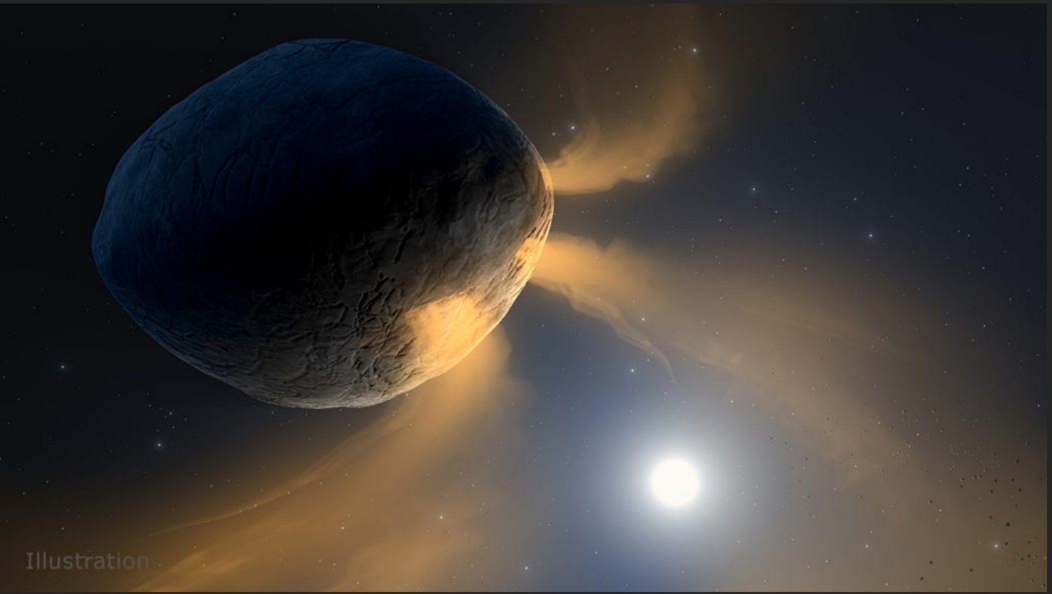
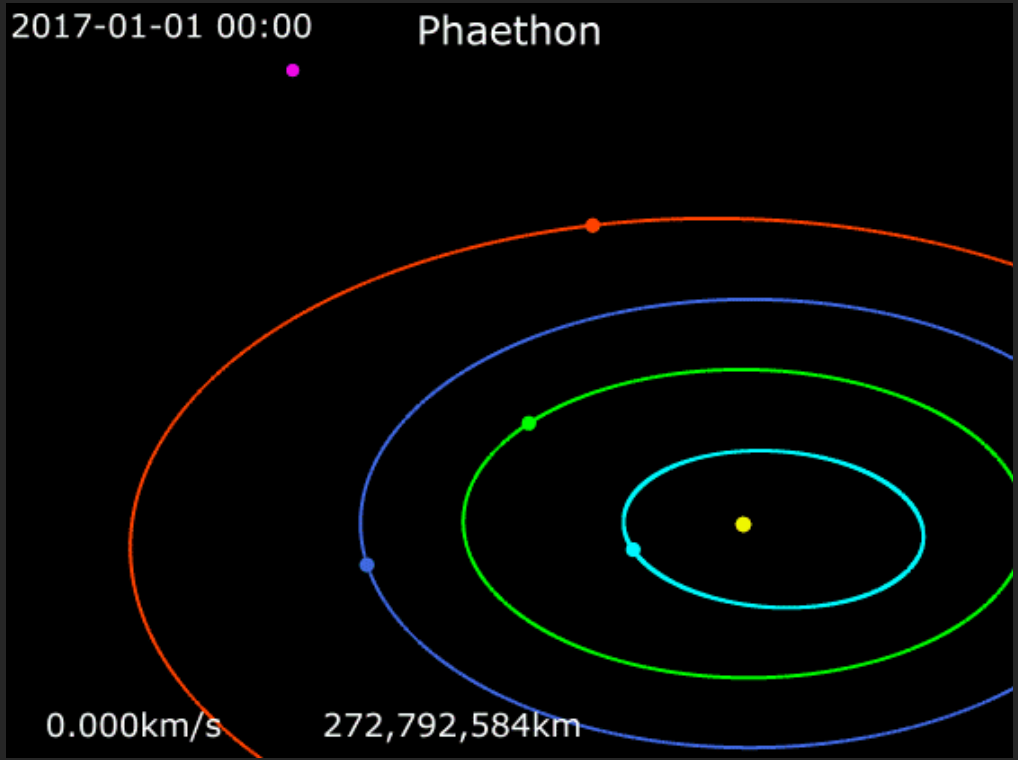
Destiny+ (JAXA + DLR)



DESTINY+ is a science and technology demonstration mission to asteroid (3200) Phaethon, the parent body of the Geminids meteor shower. It will explore the asteroid during a flyby, and conduct scientific observations of cosmic dust, which is considered to be a source of the organic matter on Earth.

Scheduled to launch in 2025 and flyby Phaethon in 2029

Driven by sodium "fizzing"? [Masiero 2024]



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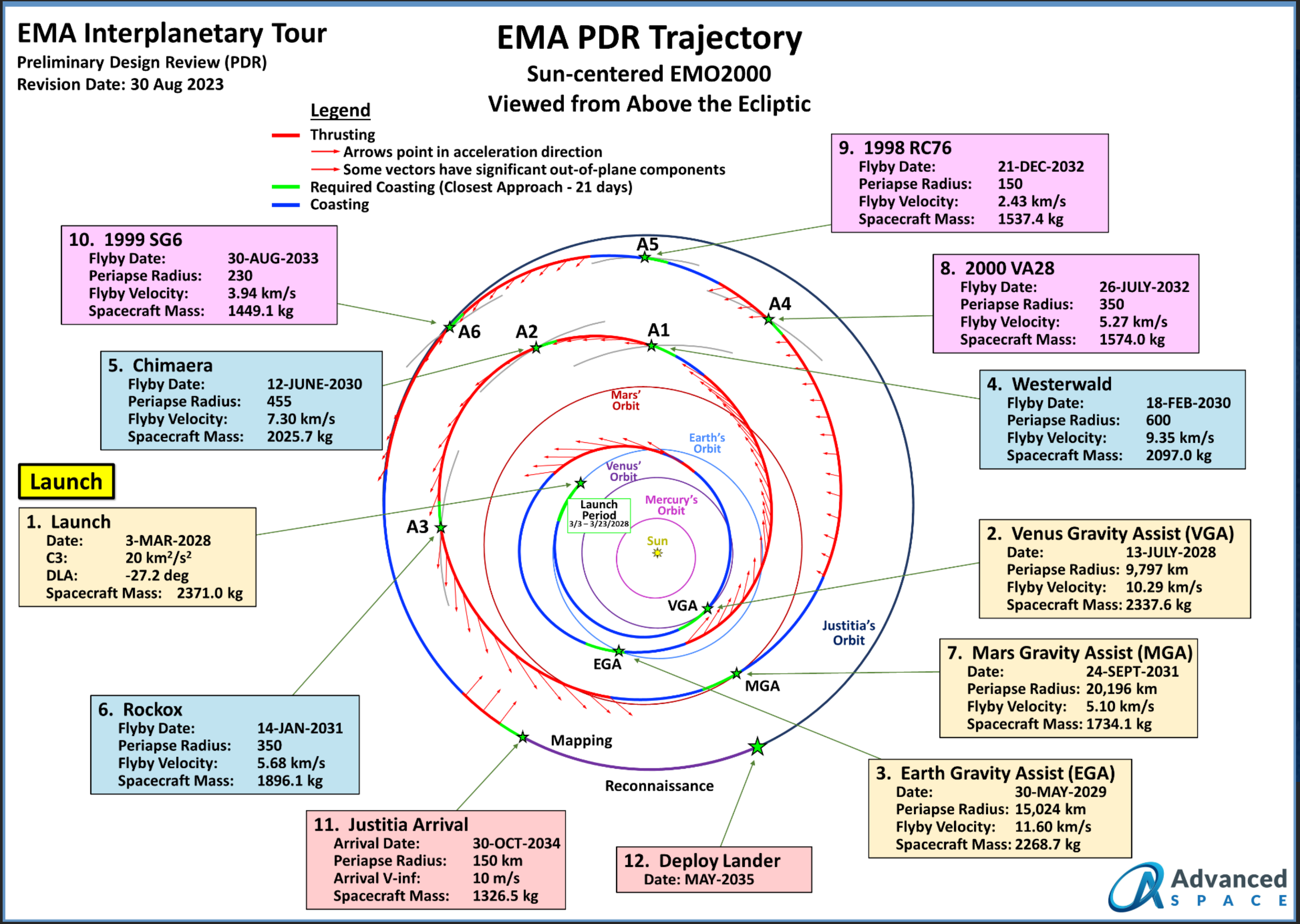
Emirates Mission to Explore the Asteroid Belt (UAE + LASP)

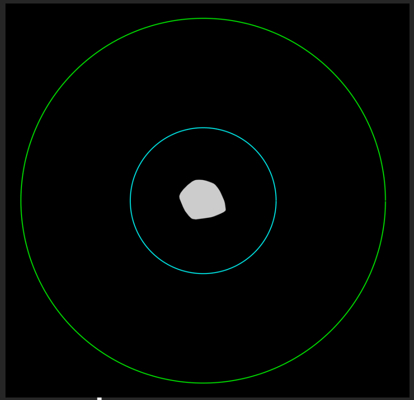
Justitia?

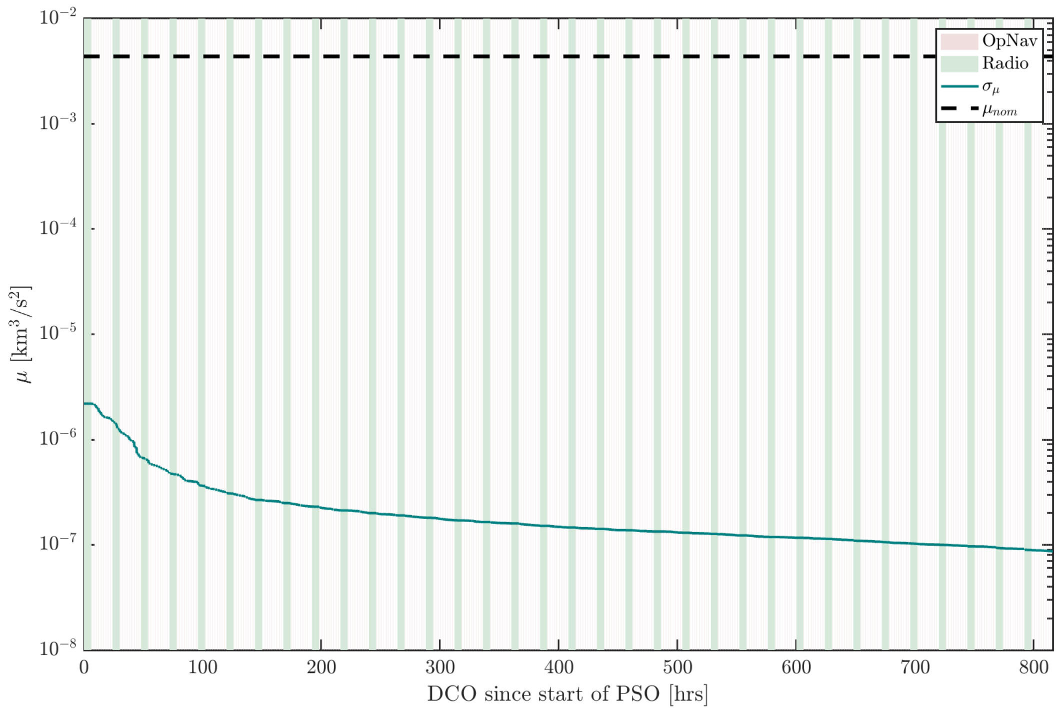
- Planned launch in 2028
- Flyby: 10253 Westerwarld (2116 T-2)
- Flyby: 623 Chimaera (A907 BC)
- Flyby: 13294 Rockox (1998 QC105)
- Flyby: 88055 (2000 VA28)
- Flyby: 23871 (1998 RC76)
- Flyby: 59980 (1999 SG6)
- Rendezvous: 269 Justitia (A887 SA)

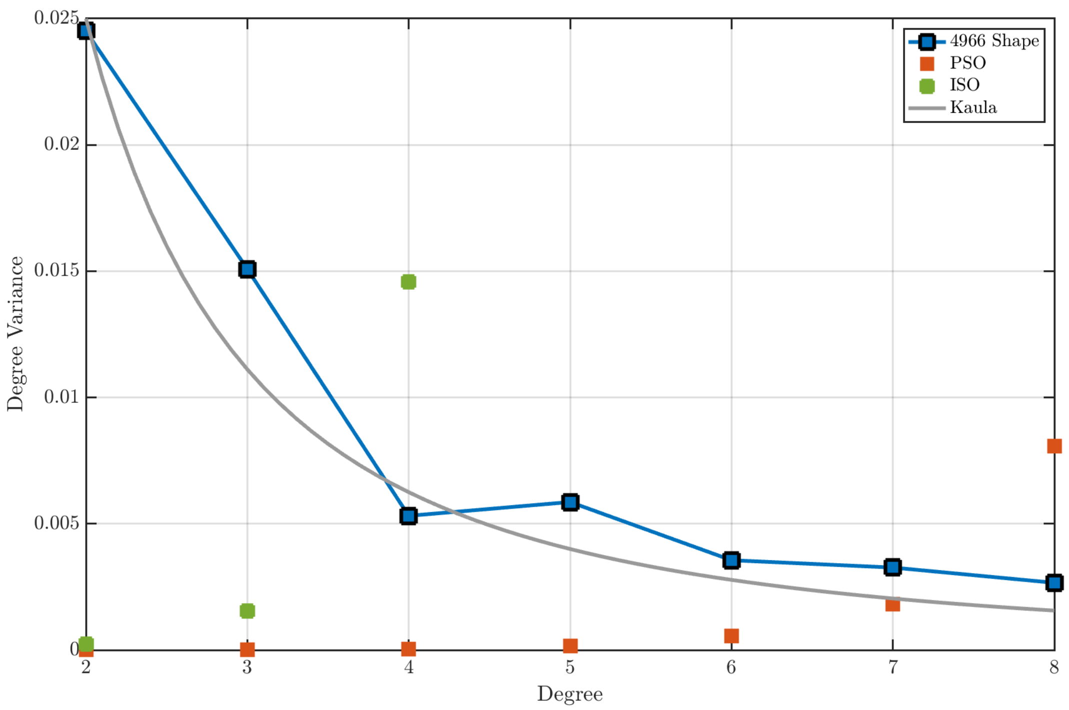


Justitia Radio Science

- Initial analysis shows Radio science should determine up to a 7th degree field
- Will get some stronger data from lower orbits for lander deployment



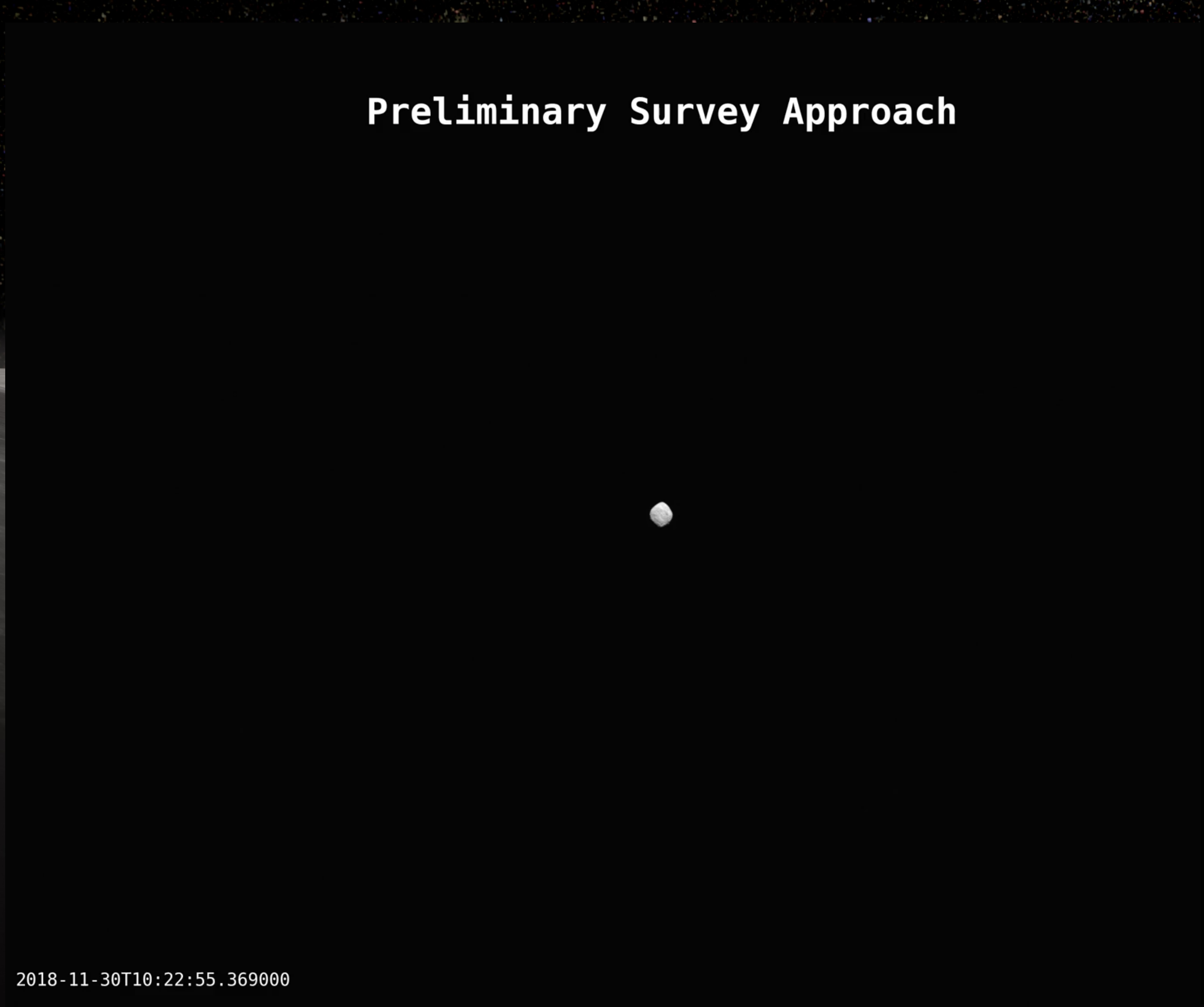


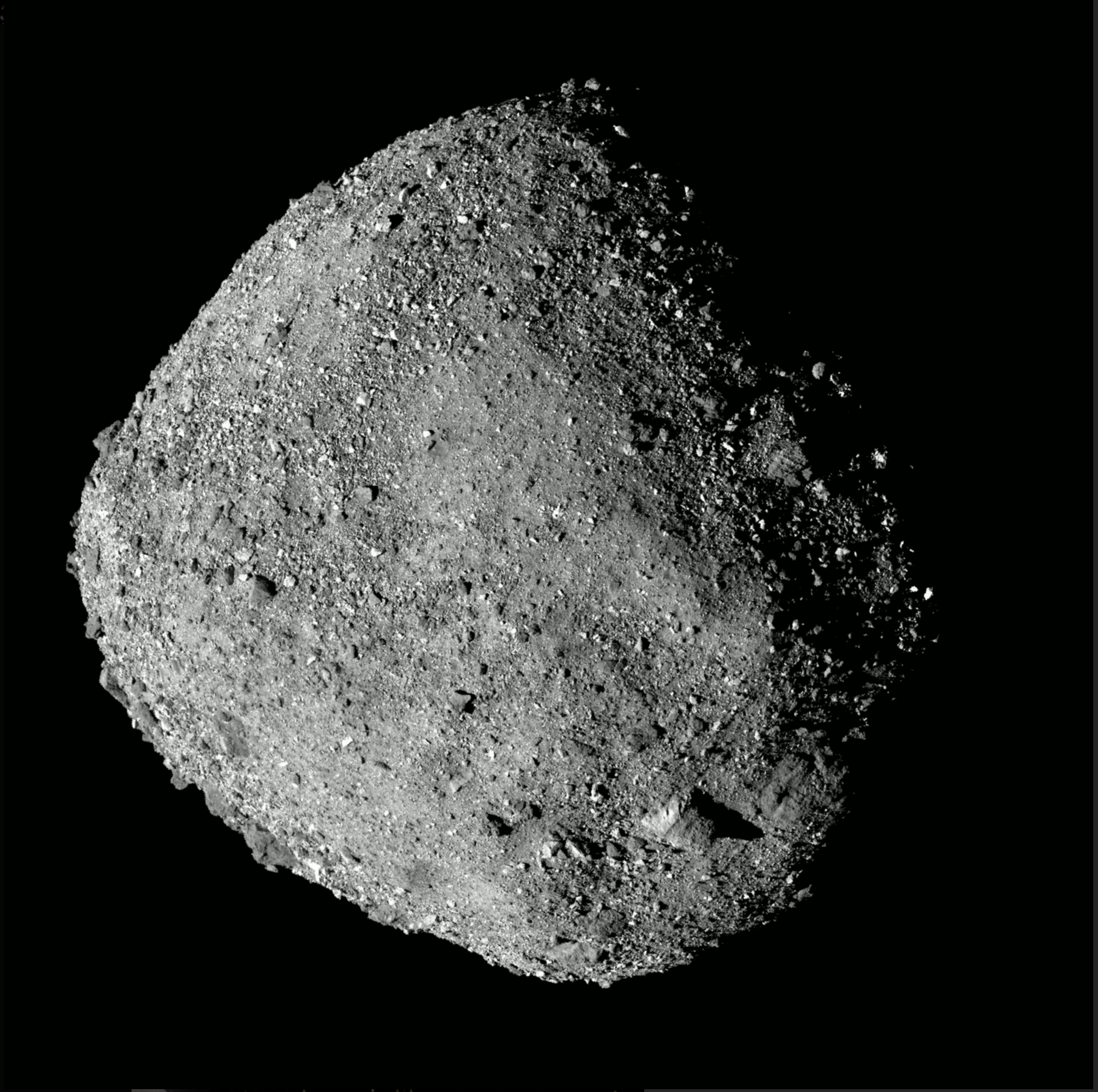


OSIRIS-REX

Work of Dr. Andrew French shown

Exploration today: OSIRIS-REx





More information at: www.asteroidmission.org

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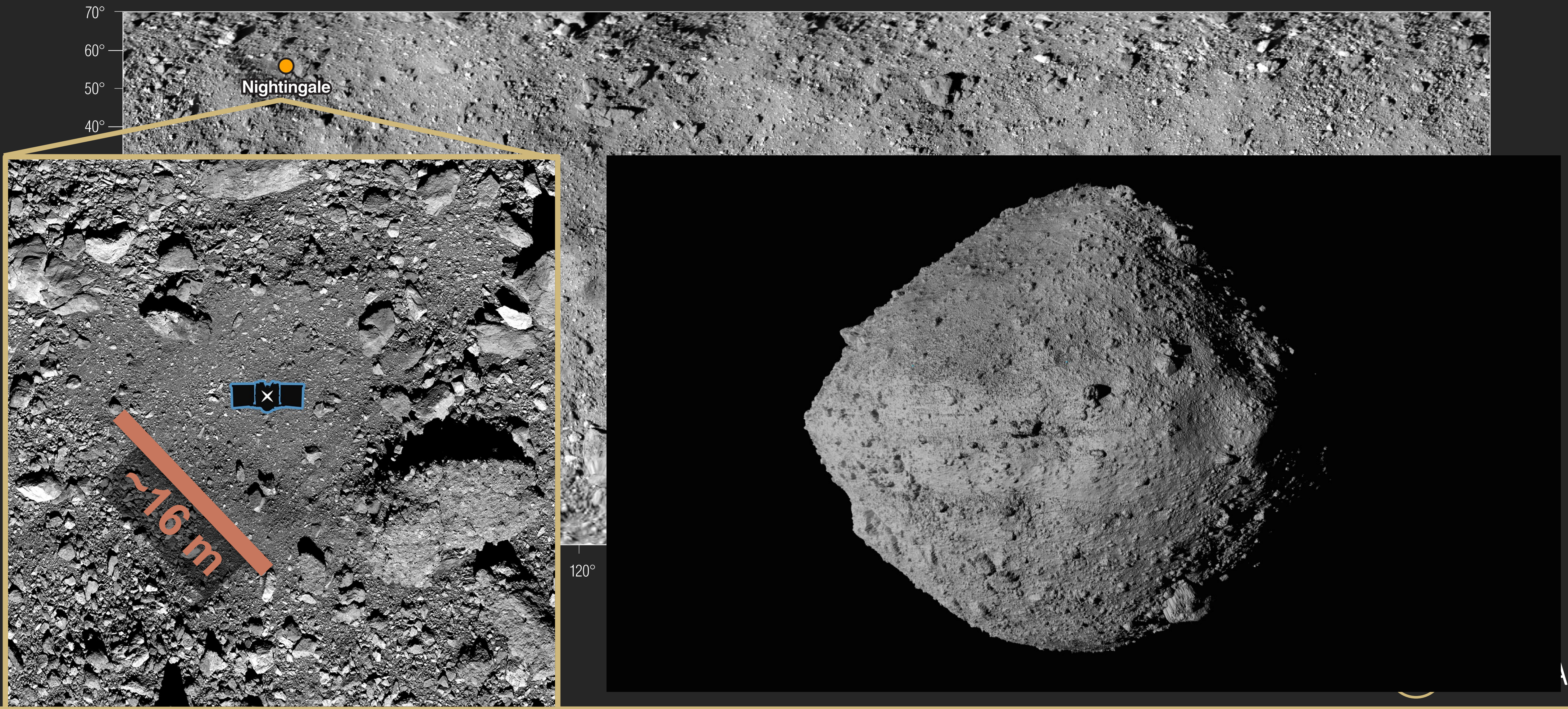
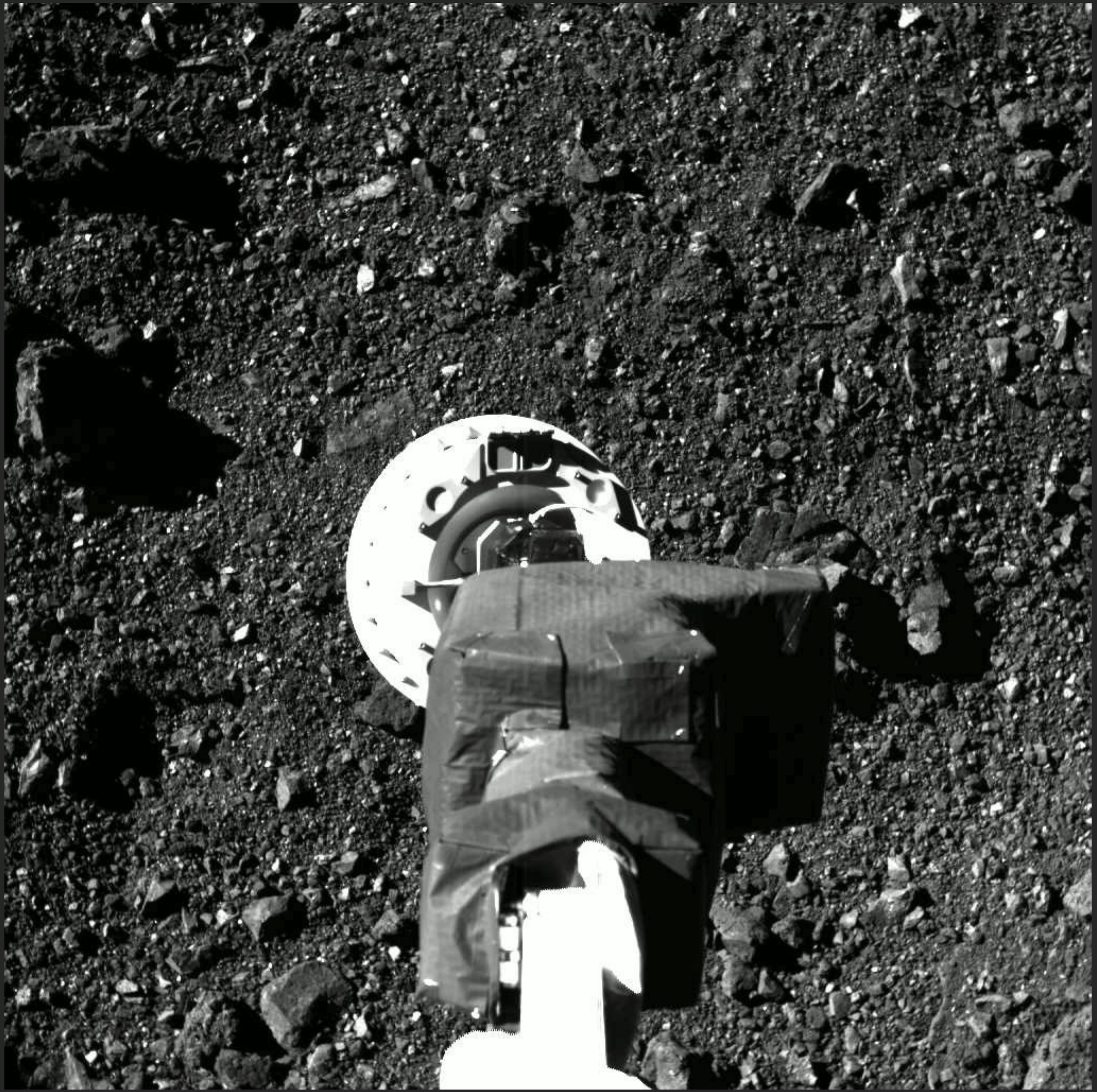
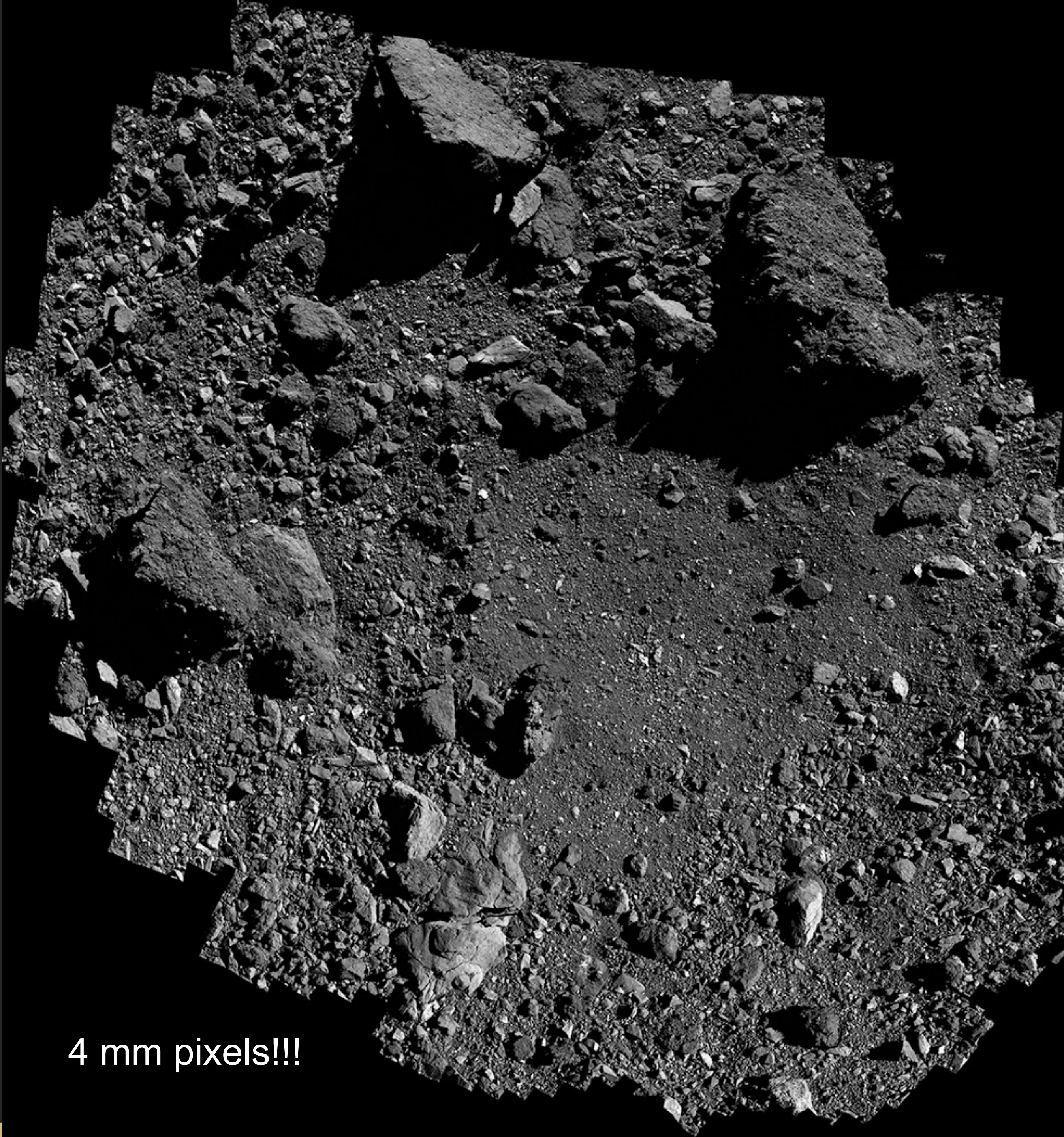
OSIRIS-REx Touch-and-Go (TAG) Sampling



OSIRIS-REx TAG Sampling





4 mm pixels!!!

Bennu's Particles – January 19, 2019 Event

What happens to these particles?
Can they stay in orbit?

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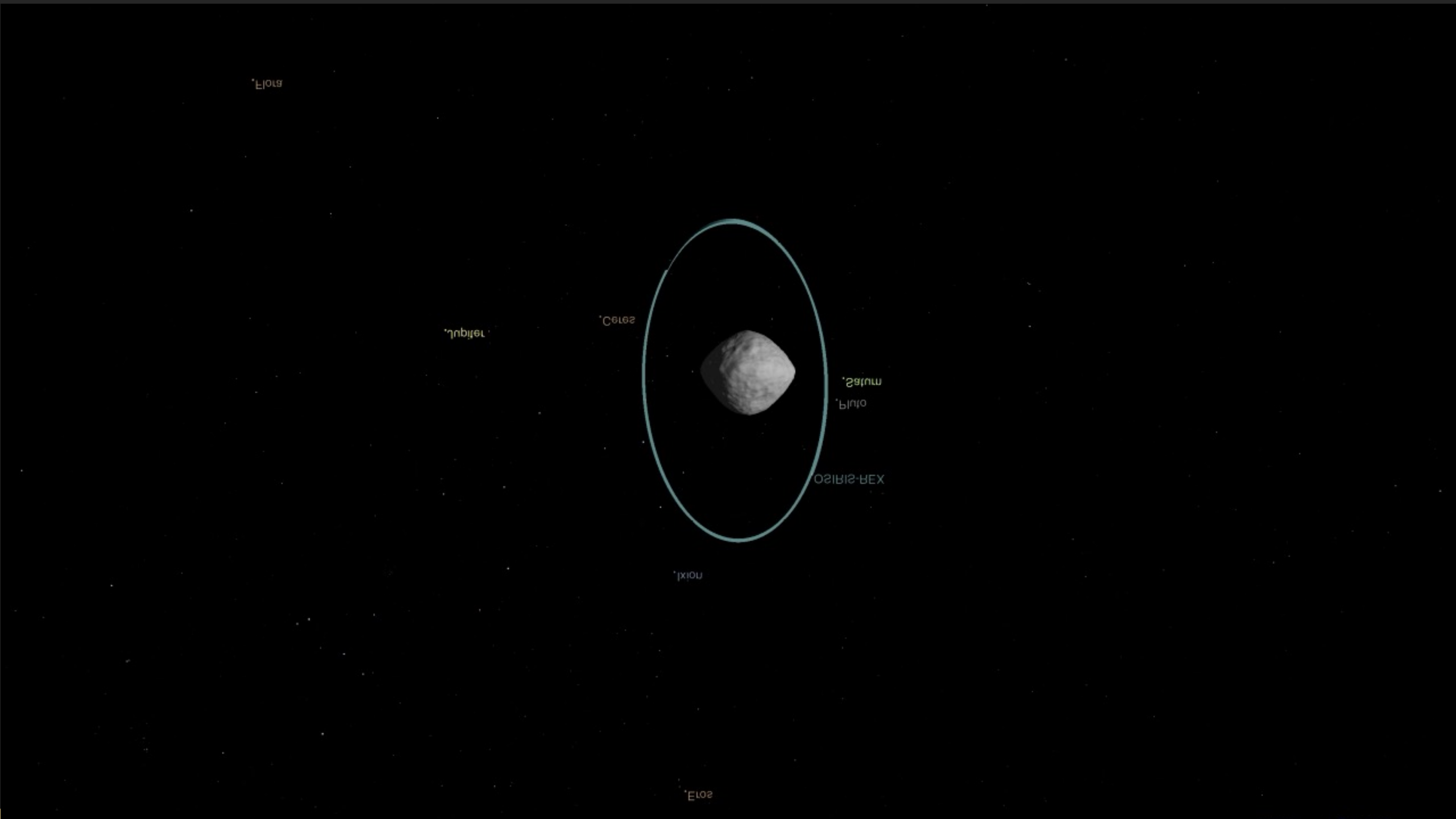
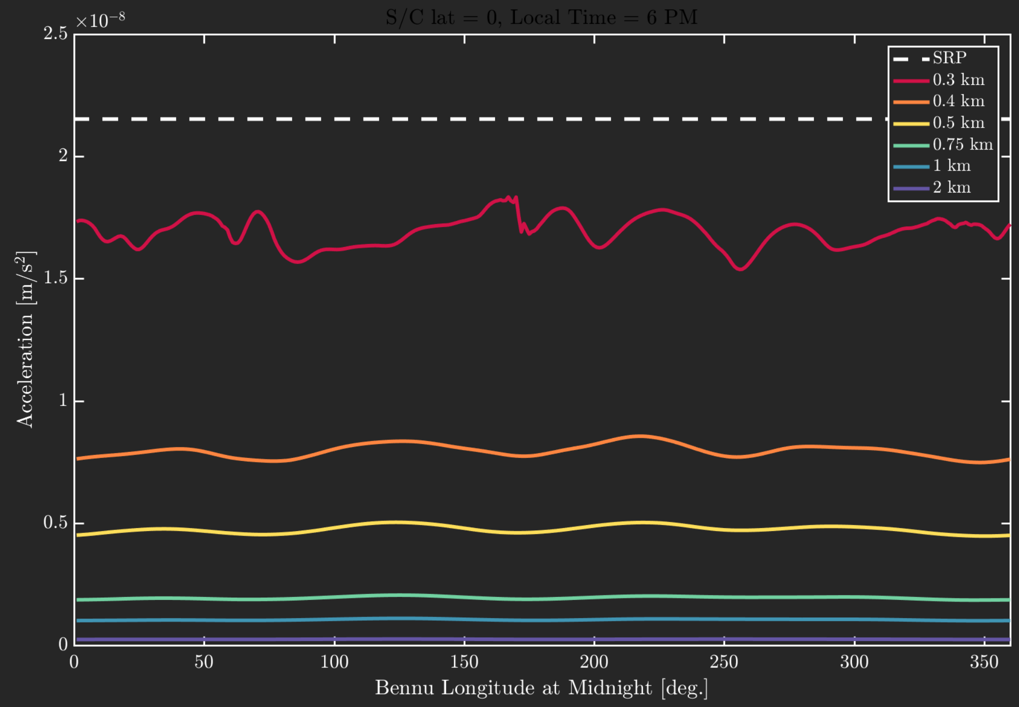

Flora
Jupiter
Ceres
Saturn
Pluto
OSIRIS-REX
Ixion
Eros

Dynamics Assumptions/Caveats

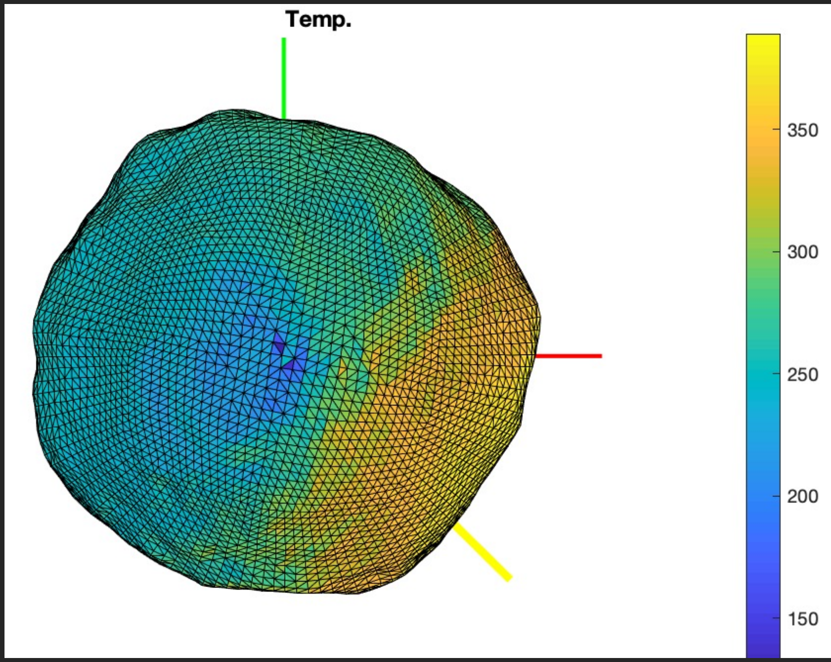


- Modeling assumptions
  - Cannonball SRP with constant A/m
  - Shape-based shadowing
  - Constant density polyhedron gravity model
  - 3^{rd} body effects from Sun
  - Bennu thermal/albedo force model

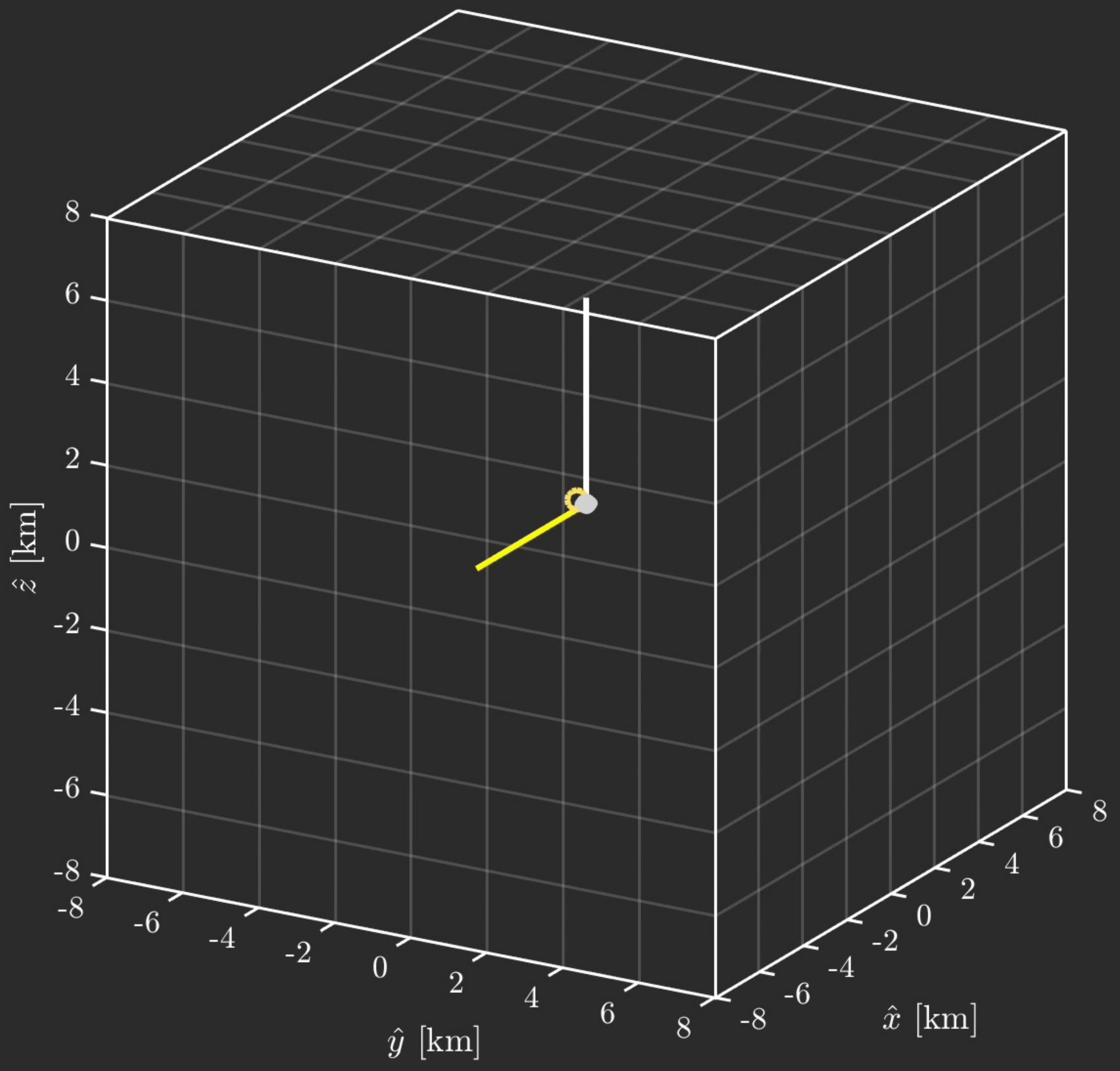
$$\mathbf{a}_{SRP} = -\frac{(1+\rho)P_0 A}{m}\frac{(\mathbf{d}-\mathbf{r})}{|\mathbf{d}-\mathbf{r}|}$$

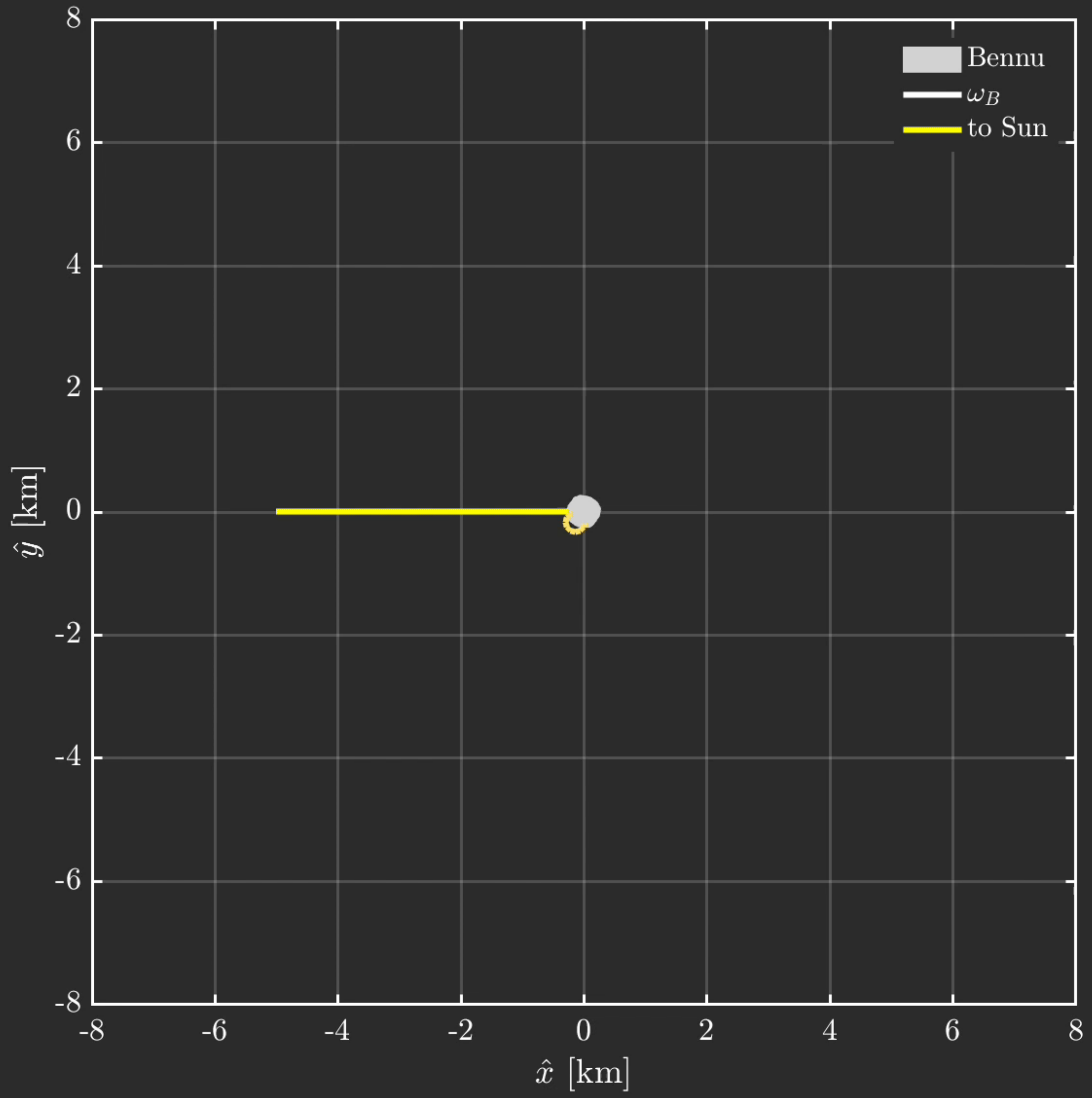
$$\mathbf{a}_{th} = -\frac{(1+\alpha)A}{m}\sum_{i\in F}^{N_F} P_i \frac{(\mathbf{r}-\mathbf{r}_i)}{|\mathbf{r}-\mathbf{r}_i|}$$

$$P_i = (\tau * a G_R \cos\Theta + \epsilon\sigma_B T_i^4)\frac{\cos\phi A_i}{c\pi|\mathbf{r}-\mathbf{r}_i|^2}$$



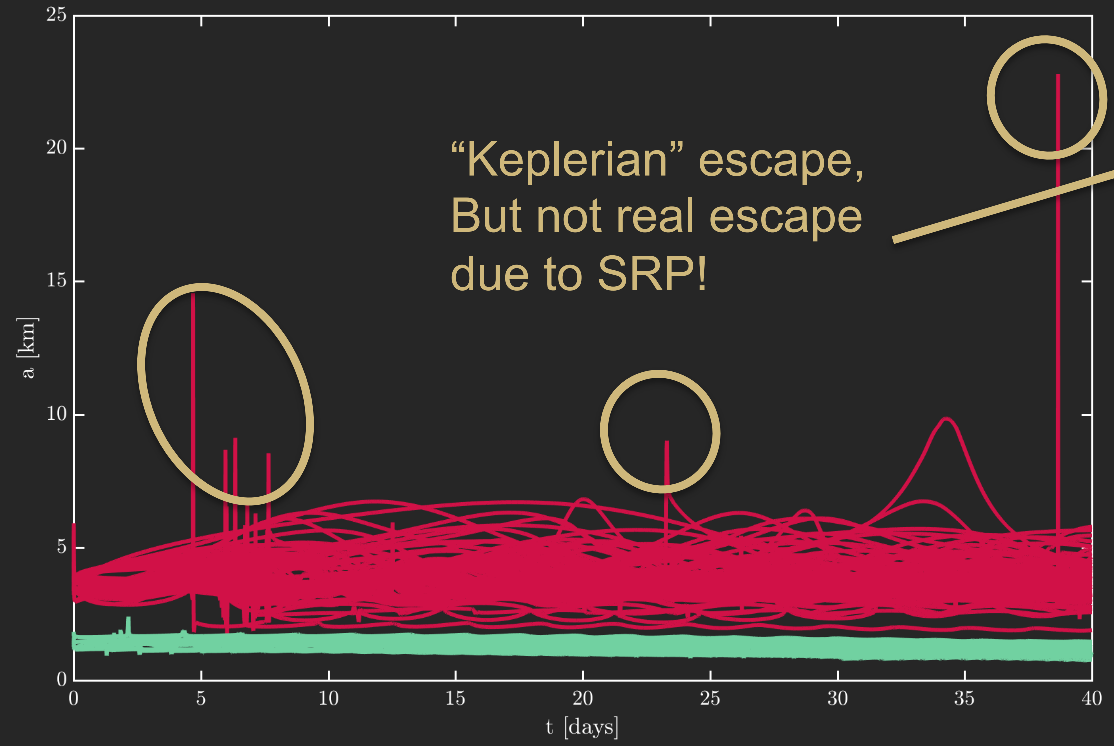
5 minute timesteps pictured
~8 day trails shown

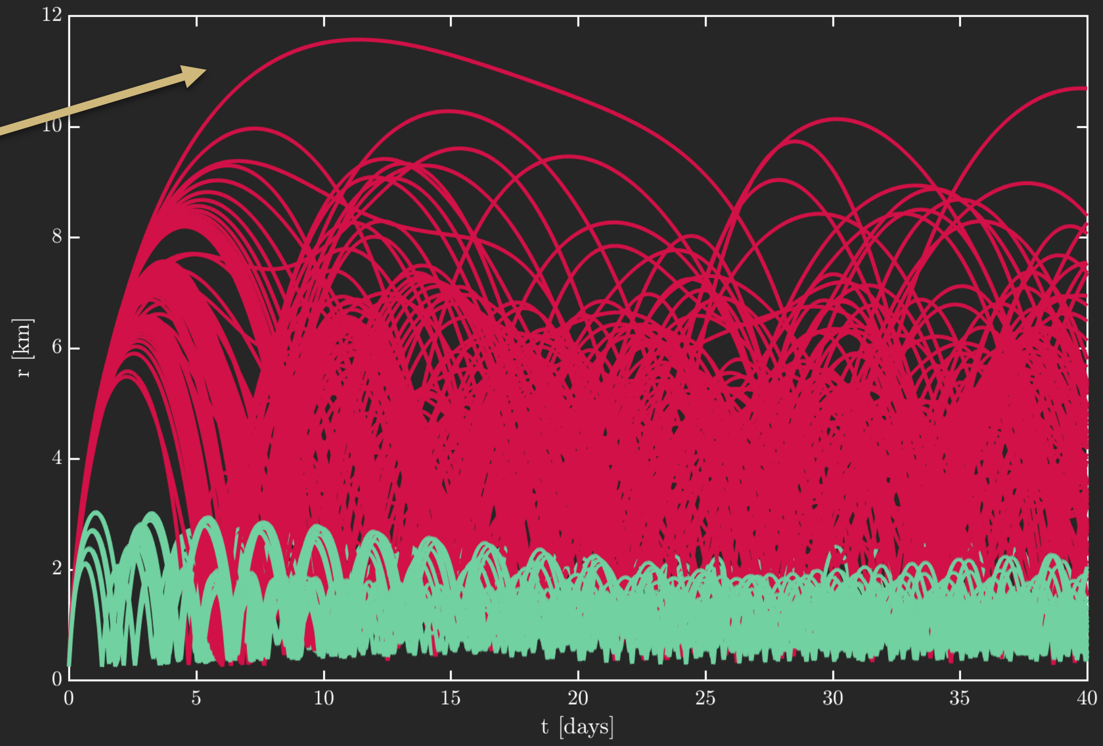




Two Families of Long-lived Orbiters Based on Semimajor Axis

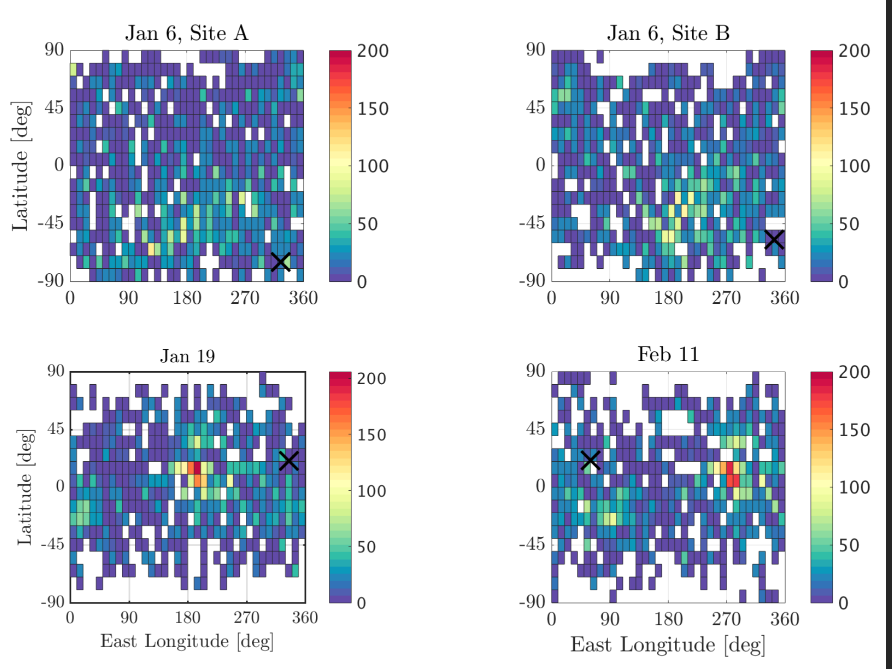
- High family doesn't come back near surface for 5+ days
- Only particles that stayed in orbit for the full 40 days are shown here

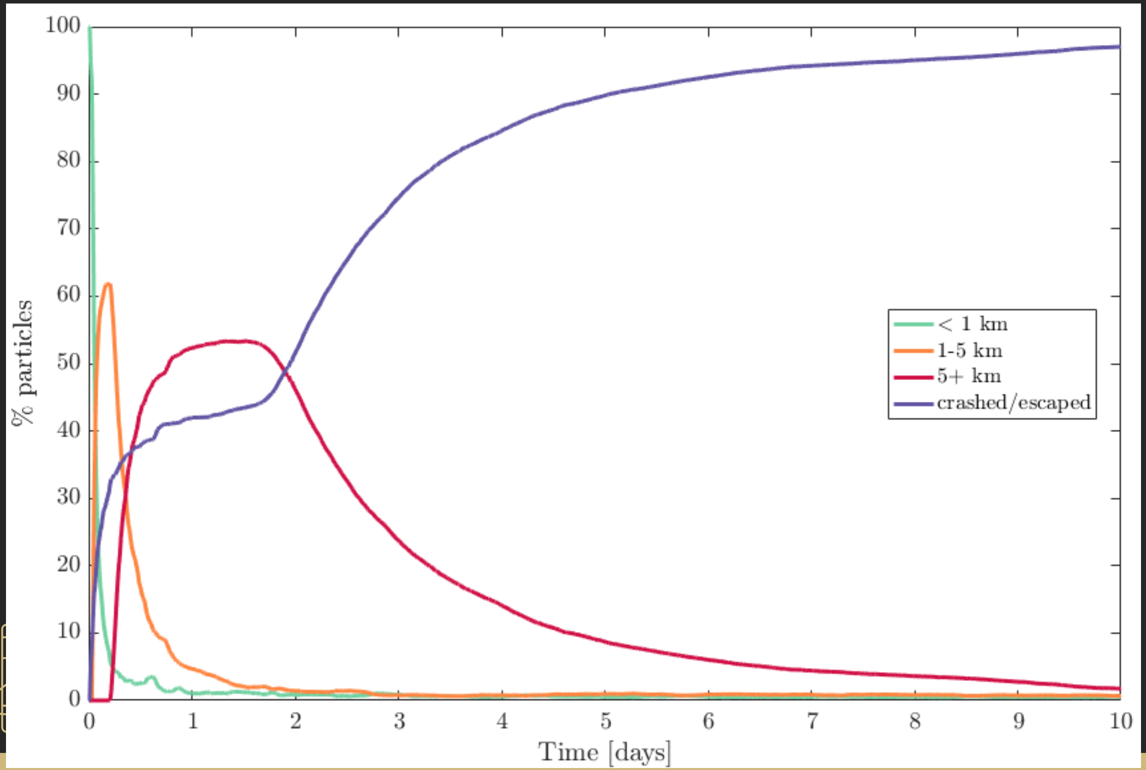


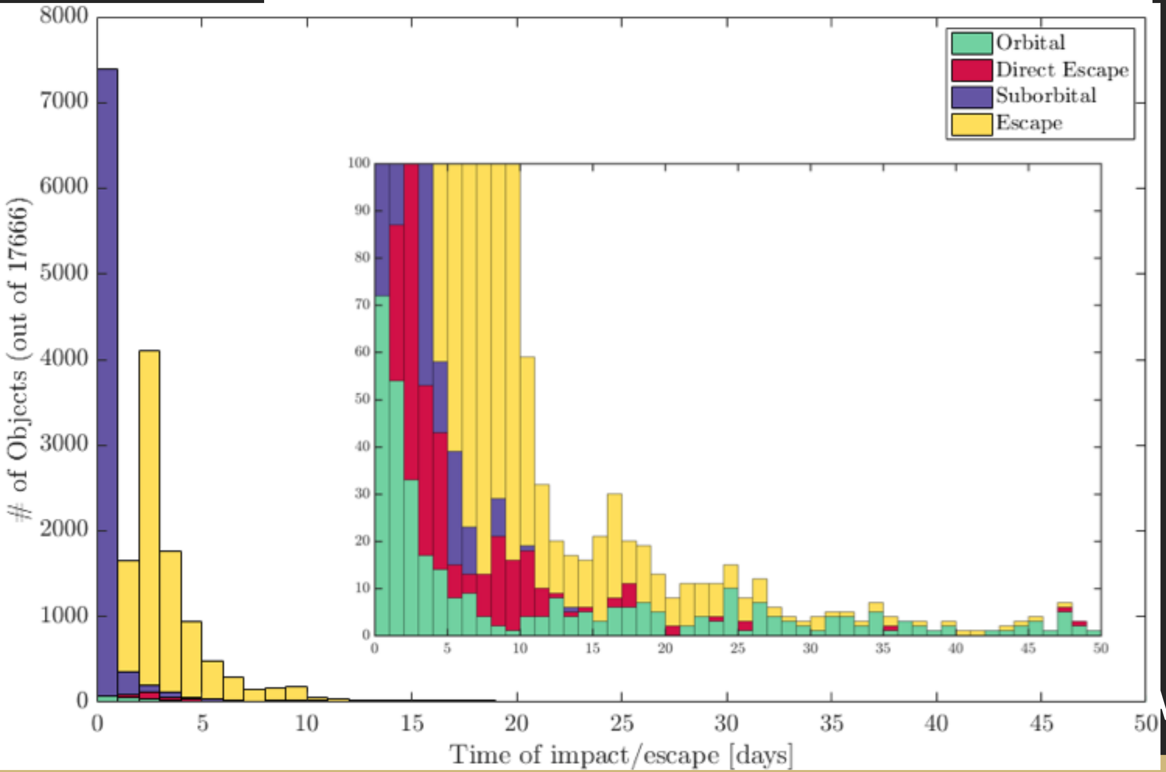


Population Behavior

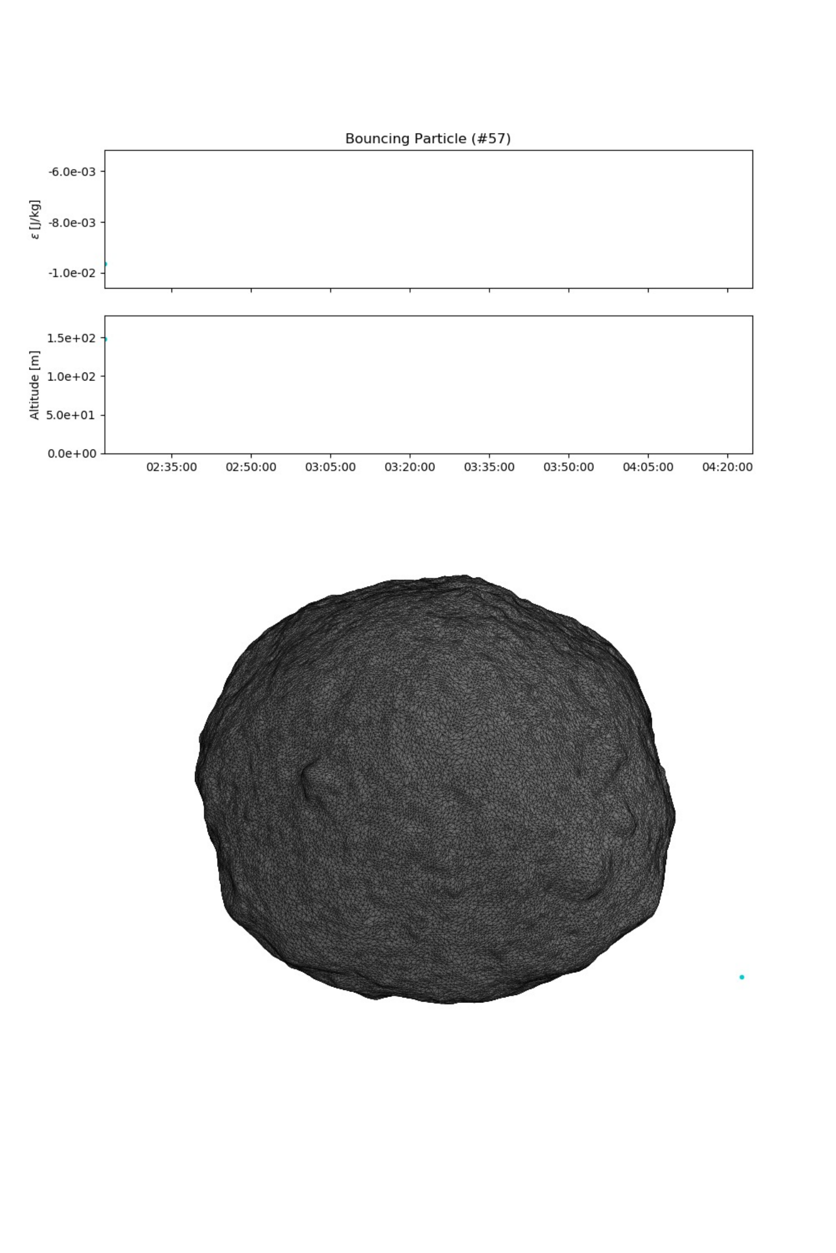
- Some particles can orbit for a long time!
- Small particles disappear preferentially, changing the surface PSD
- Material moves toward equator reinforcing equatorial bulge

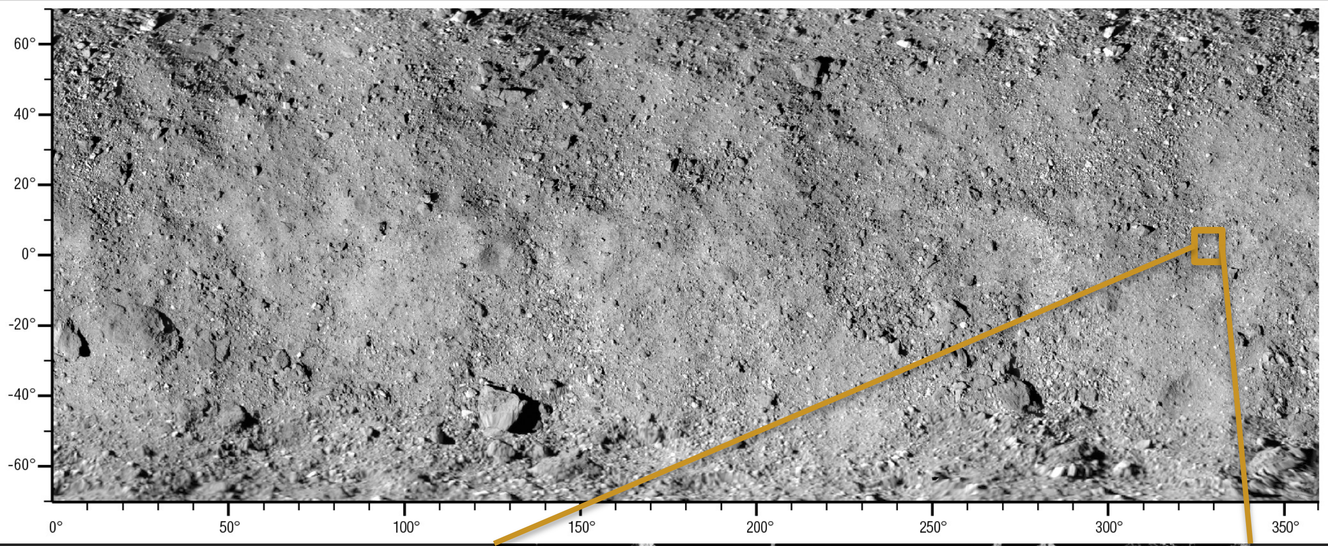


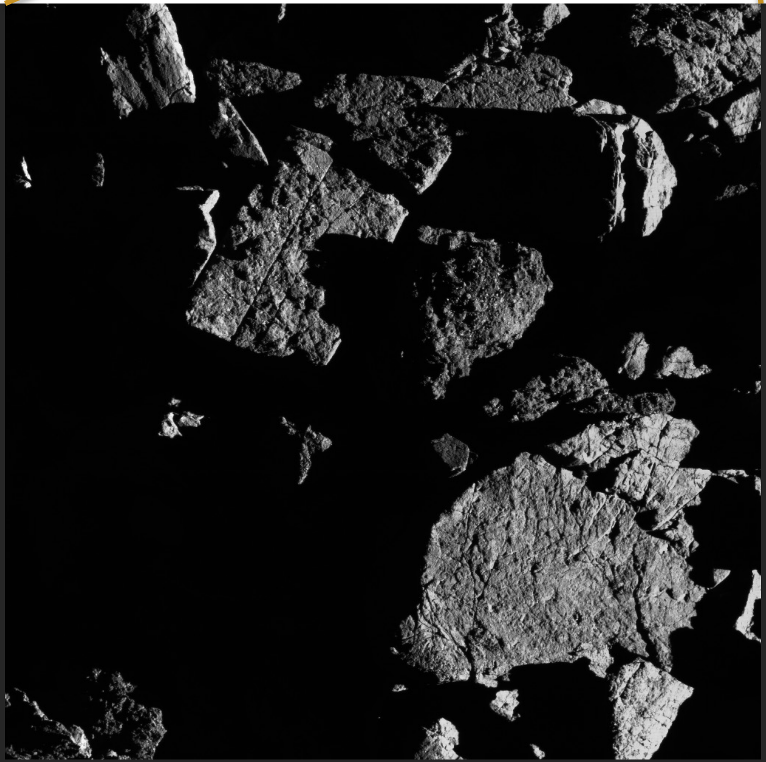




Bouncing Particle







- Discovered a particle ricocheting off Bennu's surface on February 13th, 2019
- Combination of traditional OD and MC analysis to determine bounce location & time

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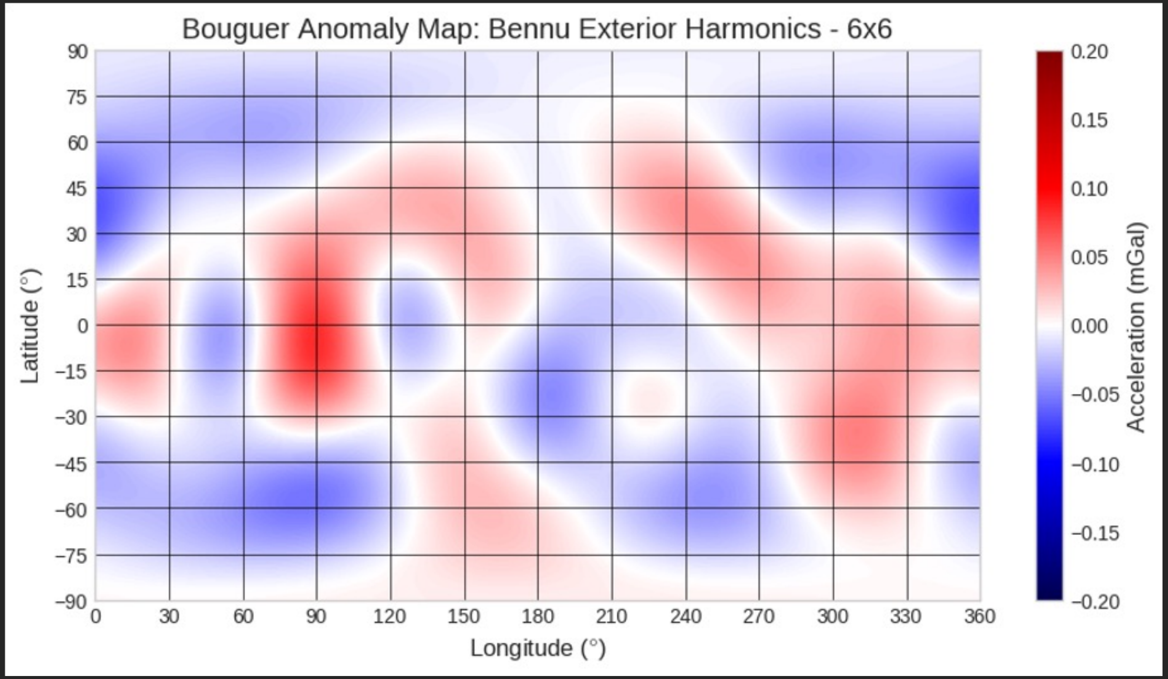
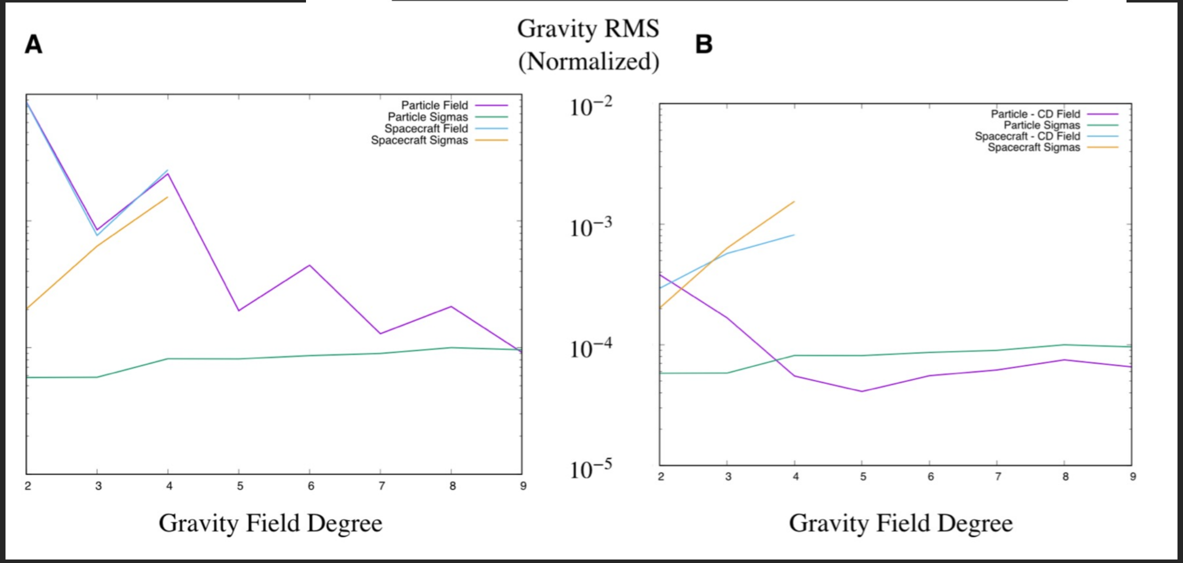
Particle Derived Gravity Field

- The particles are our best source of gravity information
  - Can fit many particles simultaneously
  - High orbit diversity relative to S/C orbits → less biased gravity
  - Particle OD is not tied to shape-based OpNavs → less biased gravity

Particle No.	N_{det}	Data arc (d)	Lifetime (d)	a (km)	e	i (deg)
1	107	5.45	5.79	1.05	0.27	88
247	378	4.23	4.26	0.49	0.13	87
2	185	4.17	4.45	0.40	0.11	83
41	43	2.92	5.35	1.29	0.52	14
3	92	2.58	2.65	0.49	0.12	15
303	217	2.30	2.91	0.44	0.13	29
213	42	1.63	3.30	0.88	0.53	165
4	75	1.58	2.30	0.41	0.17	128
273	81	1.53	2.39	1.34	0.76	17
188	34	1.05	1.12	0.48	0.04	2
289	101	0.65	3.68	0.55	0.39	5
302	35	0.50	3.45	0.53	0.50	7
252	78	0.34	2.37	0.59	0.11	83
248	58	0.33	0.40	0.58	0.87	130
15	66	0.33	0.47	0.61	0.72	1
210	35	0.32	0.33	0.49	0.96	75
50	33	0.28	0.44	0.59	1.00	111
16	47	0.24	0.27	0.45	0.59	16
285	46	0.19	0.21	0.38	0.78	32
269	45	0.19	0.23	0.41	0.43	5





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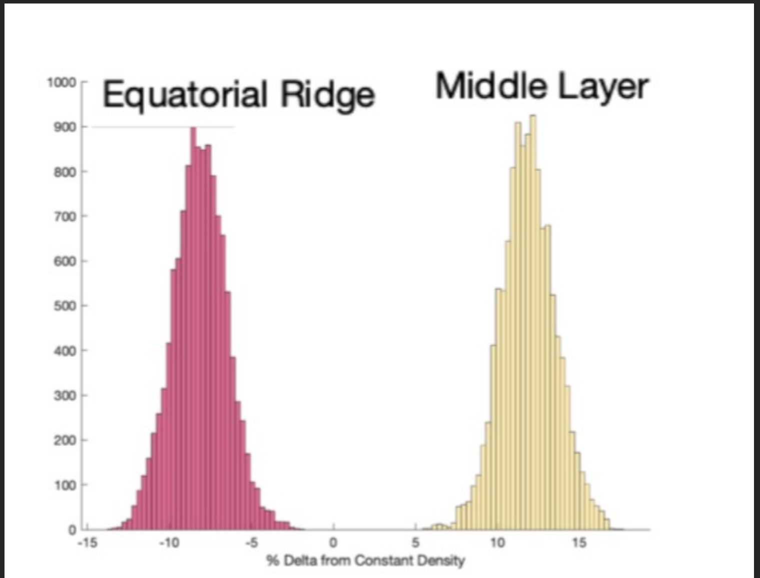
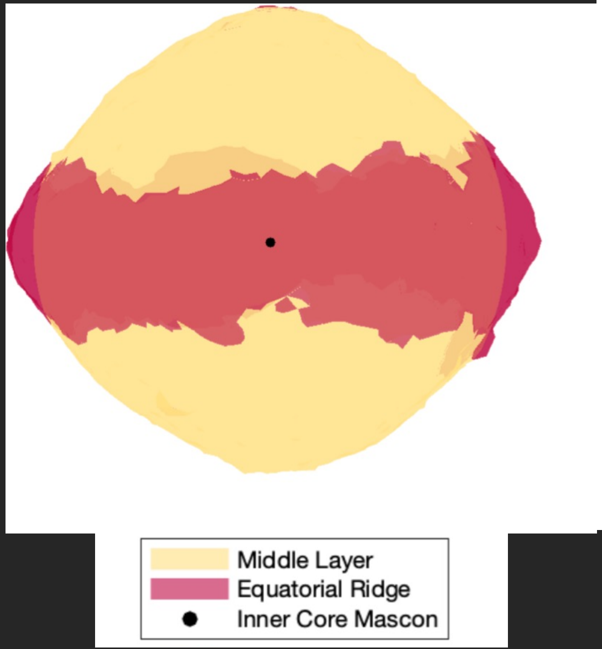
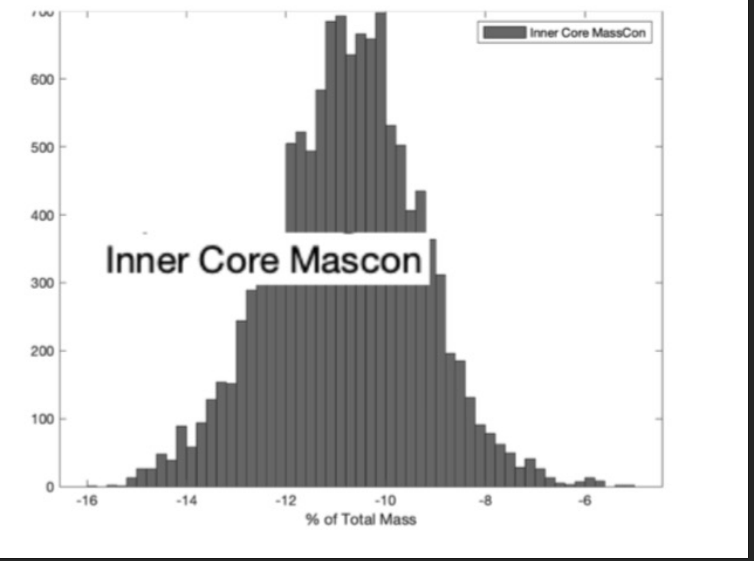
Evidence for a Heterogeneous Mass Distribution

- The initial geophysical characterization from the Navigation Campaign made the following gravity field predictions
  - 1) YORP cycling → interior failure → under-dense core
  - 2) YORP cycling → mantle failure → over-dense core
  - 3) Regolith accumulation at the equator → ridge with different density
- This provided the perfect chance to test our hypothesis driven algorithm
  - The under-dense core and under-dense ridge can be attributed primarily to J2 and J4 being larger than constant density
  - MCMC results are consistent with analytical results performed by Scheeres and Tricarico







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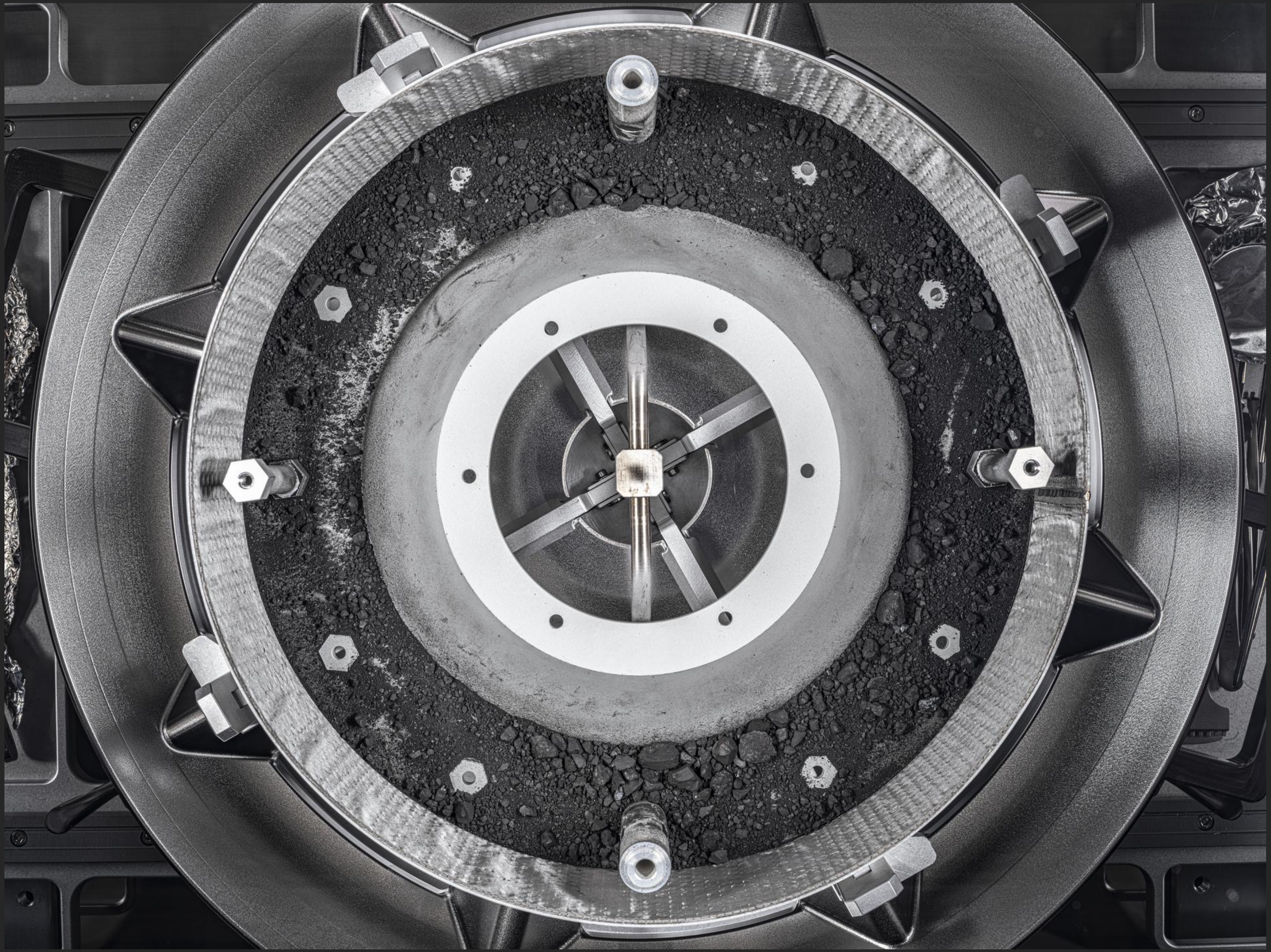
OSIRIS-REx Sample

- 120 grams of sample returned to Earth on September 24, 2023
- Over 1000 particles > 0.5 mm
- Largest individual sample is approximately 3.5 cm
- Initial analyses confirm Bennu age and composition from remote sensing
- Interestingly high concentration of magnesium phosphates
  - May tie to water rich parent body



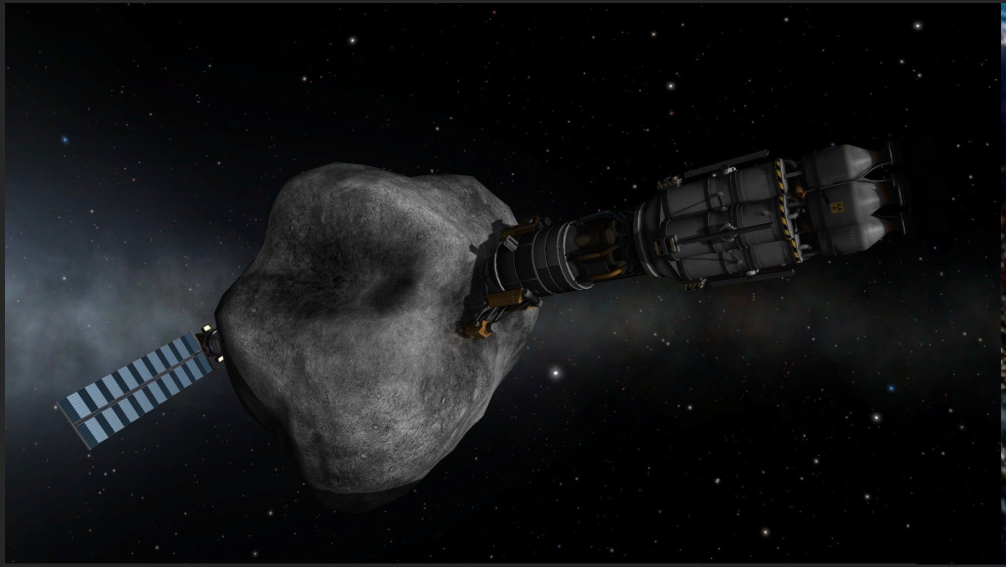
https://images.nasa.gov/details/jsc2024e006057

Why asteroids?

Science

Economics

Planetary Defense



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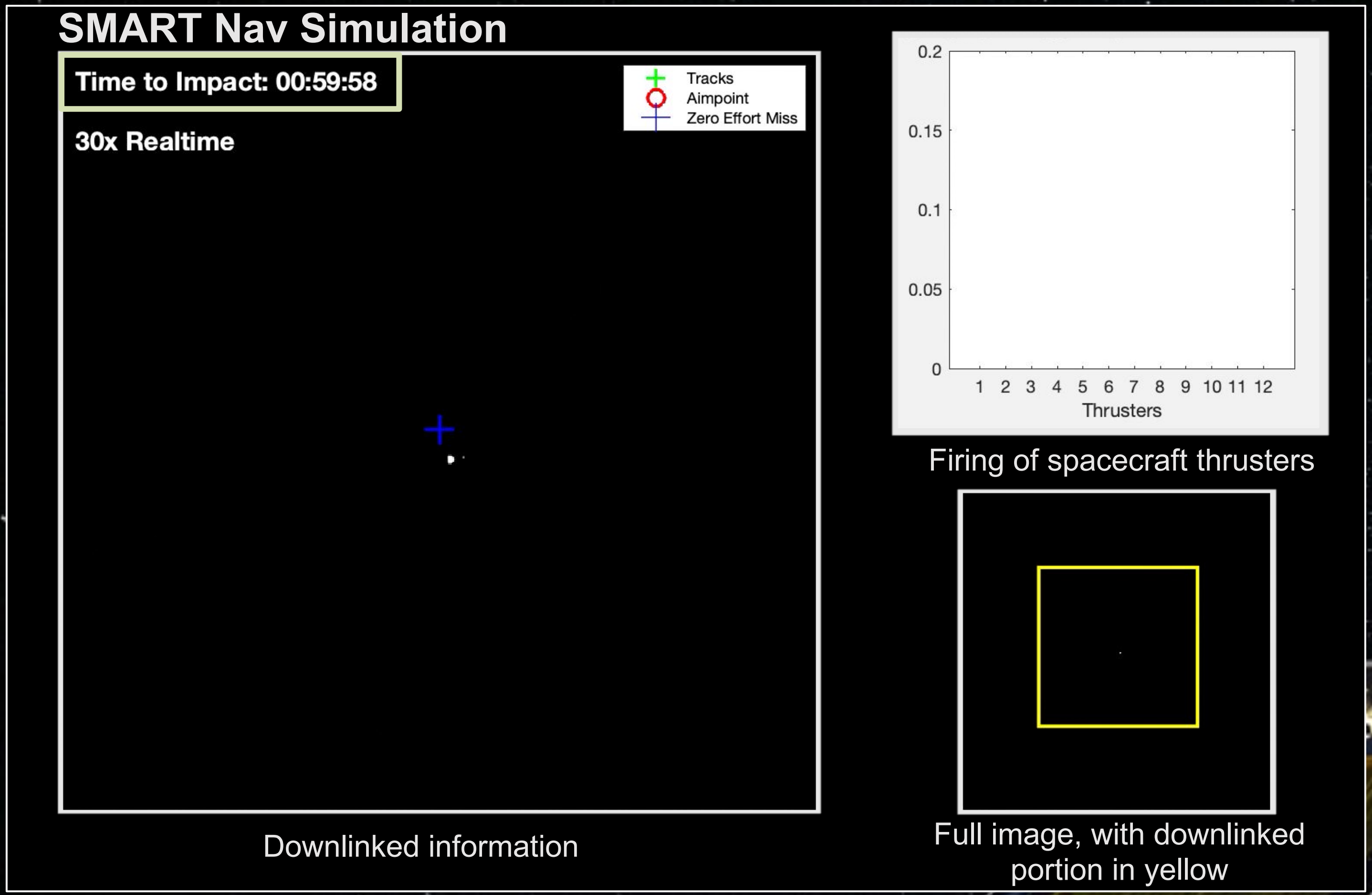
DART

Work of Rachel Cueva shown

DART Autonomous Navigation to Impact

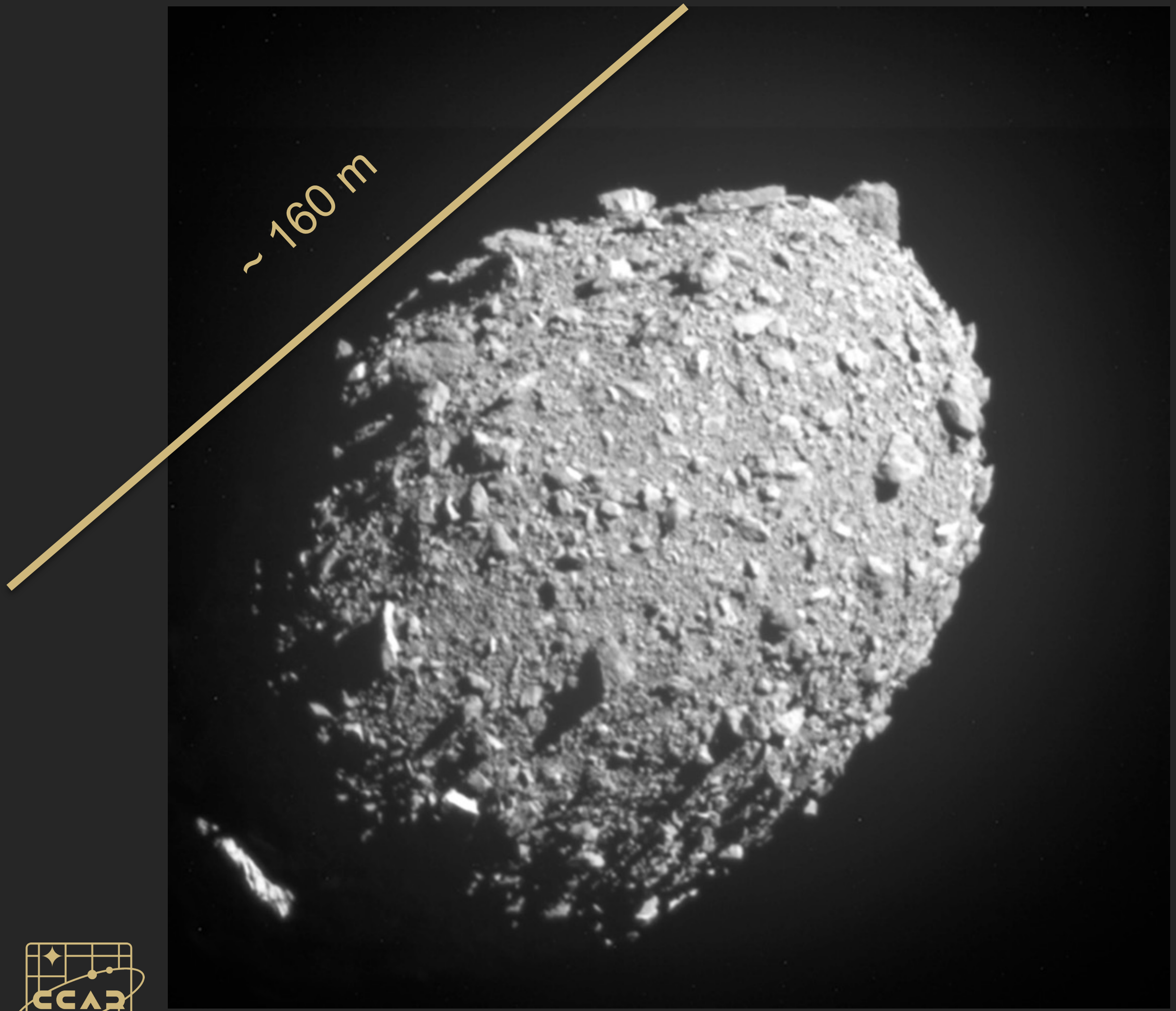
Final 5 ½ minutes of approach images from DART – 10x faster until last six images

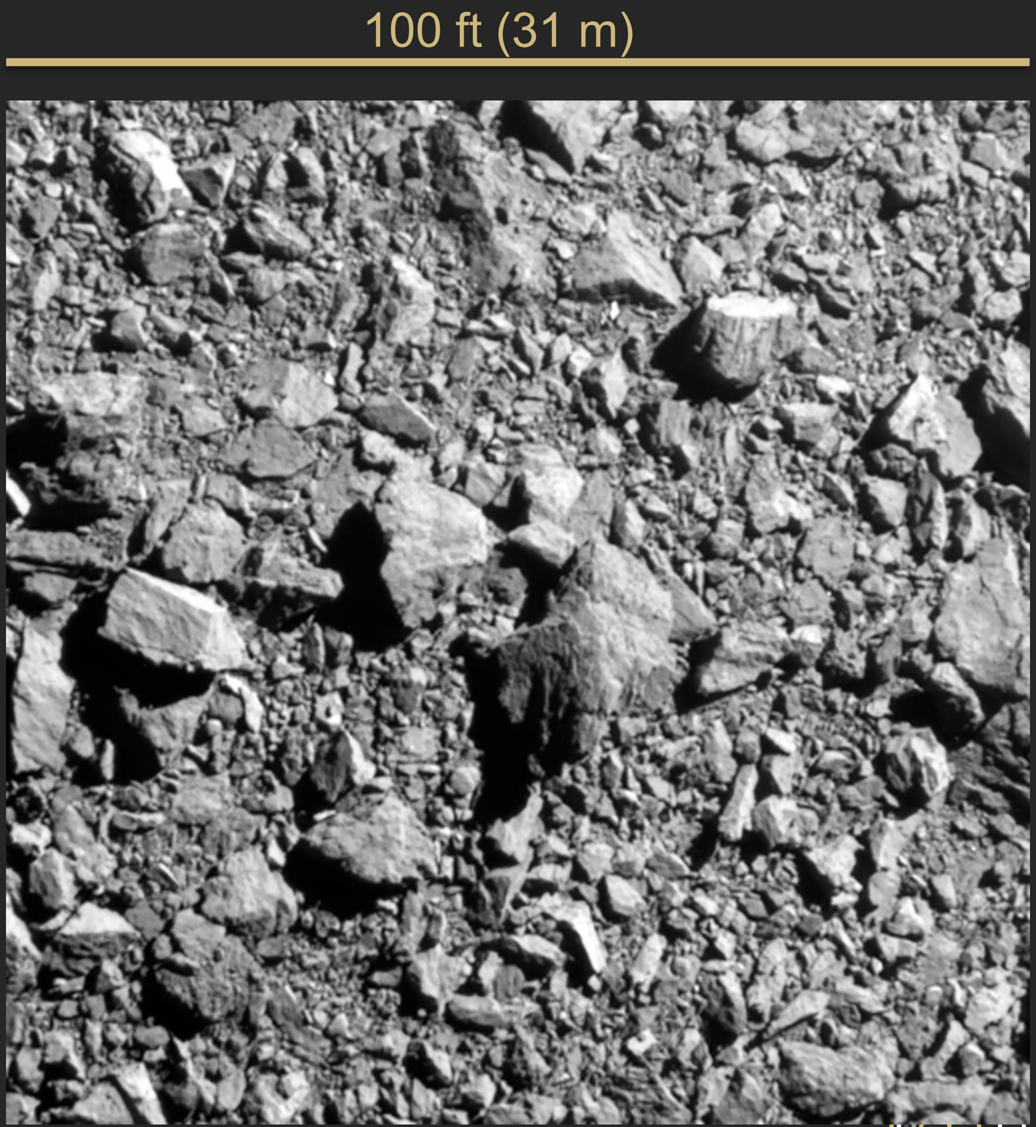


DRACO view of Didymos and Dimorphos one hour before impact

DART Autonomous Navigation to Impact

DART Final Images





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Background

DARTMission

- Impacted Dimorphos on September 26, 2022 as a kinetic impactor test
- Impact speed: 6.1449 km/s
- Changed orbital period by –33.0 min
- Mass loss of ~1,000,000 kg from impact/ejecta → definite surface reshaping
- β factor ~ 3.5

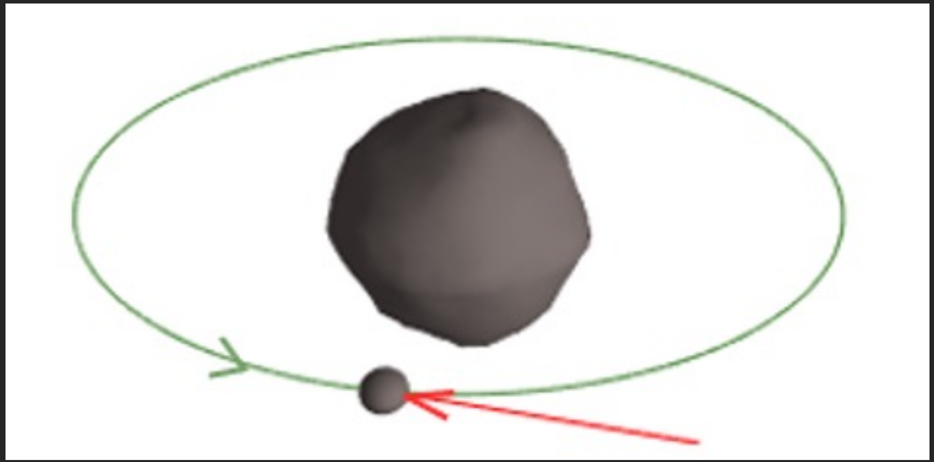
https://science.nasa.gov/missions/hubble/hubble-captures-movie-of-dart-asteroid-impact-debris/

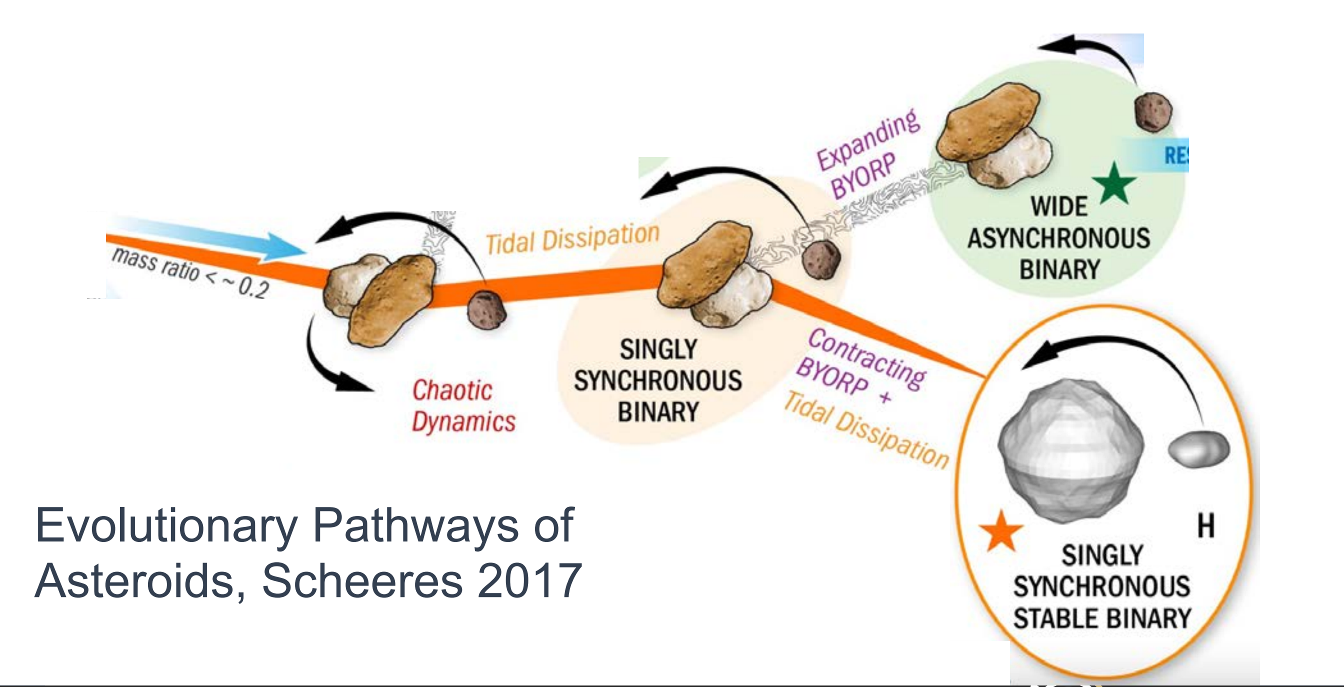
How will the long-term dynamical evolution of the Didymos binary system change post-DART impact?

ORCCA

Secular Evolution of Binaries

- Tidal-BYORP evolution
  - Cuk & Burns, McMahon & Scheeres BYORP theory
  - Jacobson & Scheeres tidal-byorp equilibrium
    - Can get BQ/k, if we know B, can get Q/k (or inverse)
  - Primary tides expand orbit
  - BYORP can expand or contract
  - Secondary tides torque the secondary and try to synchronize it
  - Resonances with sun tides can also play a role
- BYORP is determined by the shape, so adding a crater can change this
- How much can it change?
- What happens to the subsequent dynamical evolution?

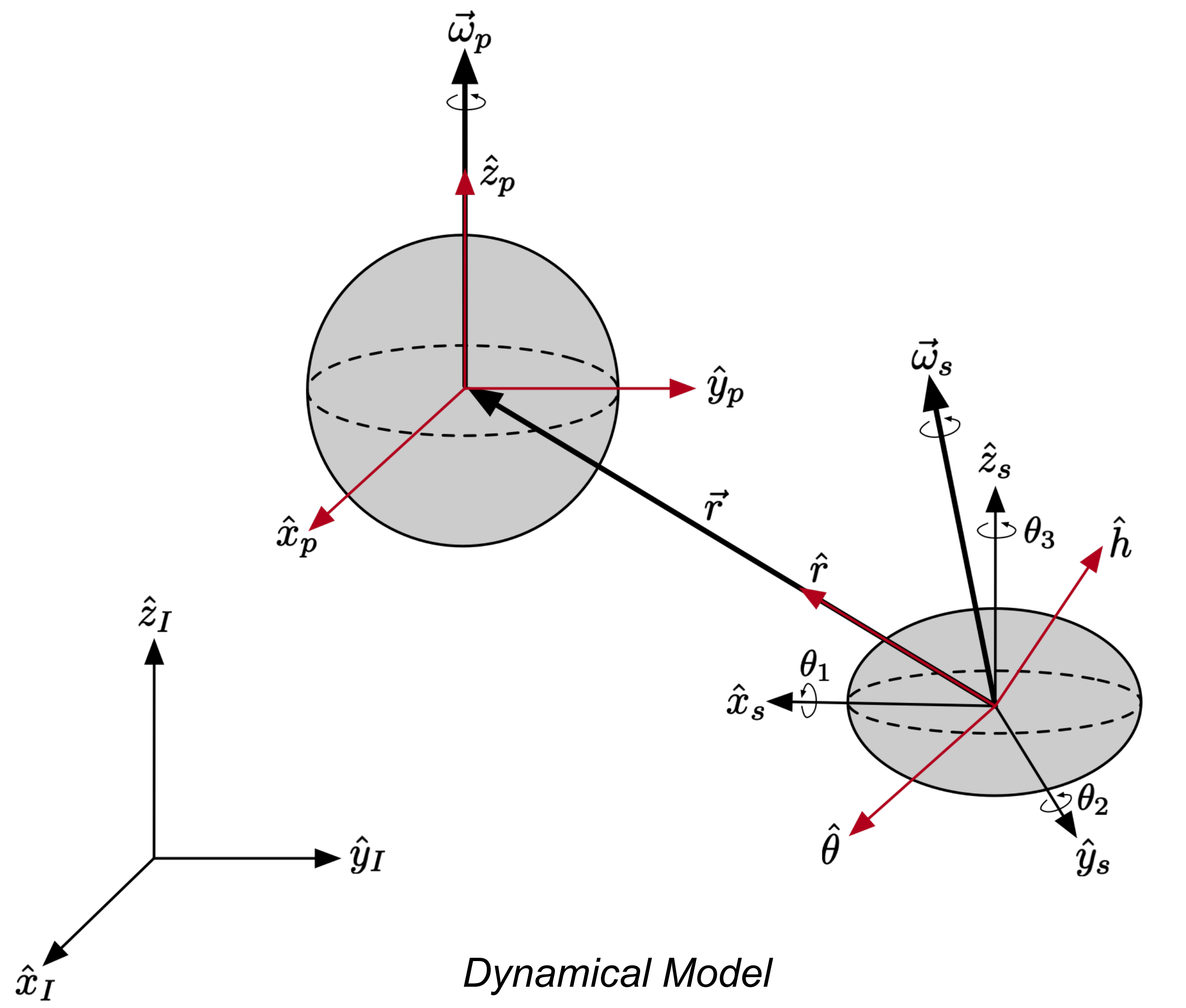




Evolutionary Pathways of Asteroids, Scheeres 2017

Dynamical Model

- Full 2-Body Problem (F2BP)
  - State vector: $\vec{X} = [\vec{r}, \dot{\vec{r}}, \vec{\omega}_s, \vec{\beta}_s, \vec{\omega}_p]^T$
  - $\dot{\vec{X}} = \begin{bmatrix} \dot{\vec{r}} \\ -2(\vec{\omega}_s \times \dot{\vec{r}}) - \dot{\vec{\omega}}_s \times \vec{r} - \vec{\omega}_s \times (\vec{\omega}_s \times \vec{r}) + \frac{M_p + M_s}{M_p M_s}\left(\vec{F} - \frac{\partial U}{\partial \vec{r}}\right) \\ [I_s]^{-1}\left(-\vec{\omega}_s \times [I_s]\vec{\omega}_s + \vec{r} \times \frac{\partial U}{\partial \vec{r}} + \vec{L}\right) \\ (1/2)[B(\beta)]\vec{\omega}_s \\ [I_p]^{-1}\vec{L} \end{bmatrix}$
  - Expressed in secondary's body-fixed frame
- Mutual Gravity Dynamics: Ellipsoidal Secondary and Spherical Primary (MacCullagh's formula)
  - $U = -\frac{GM_p M_s}{r} - \frac{GM_p(A+B+C-3\Phi)}{2r^3}$
  - $\Phi = \frac{Ax^2 + By^2 + Cz^2}{r^2}$
- Attitude of secondary with respect to rotating frame: 1-2-3 Euler angles $(\theta_1, \theta_2, \theta_3)$



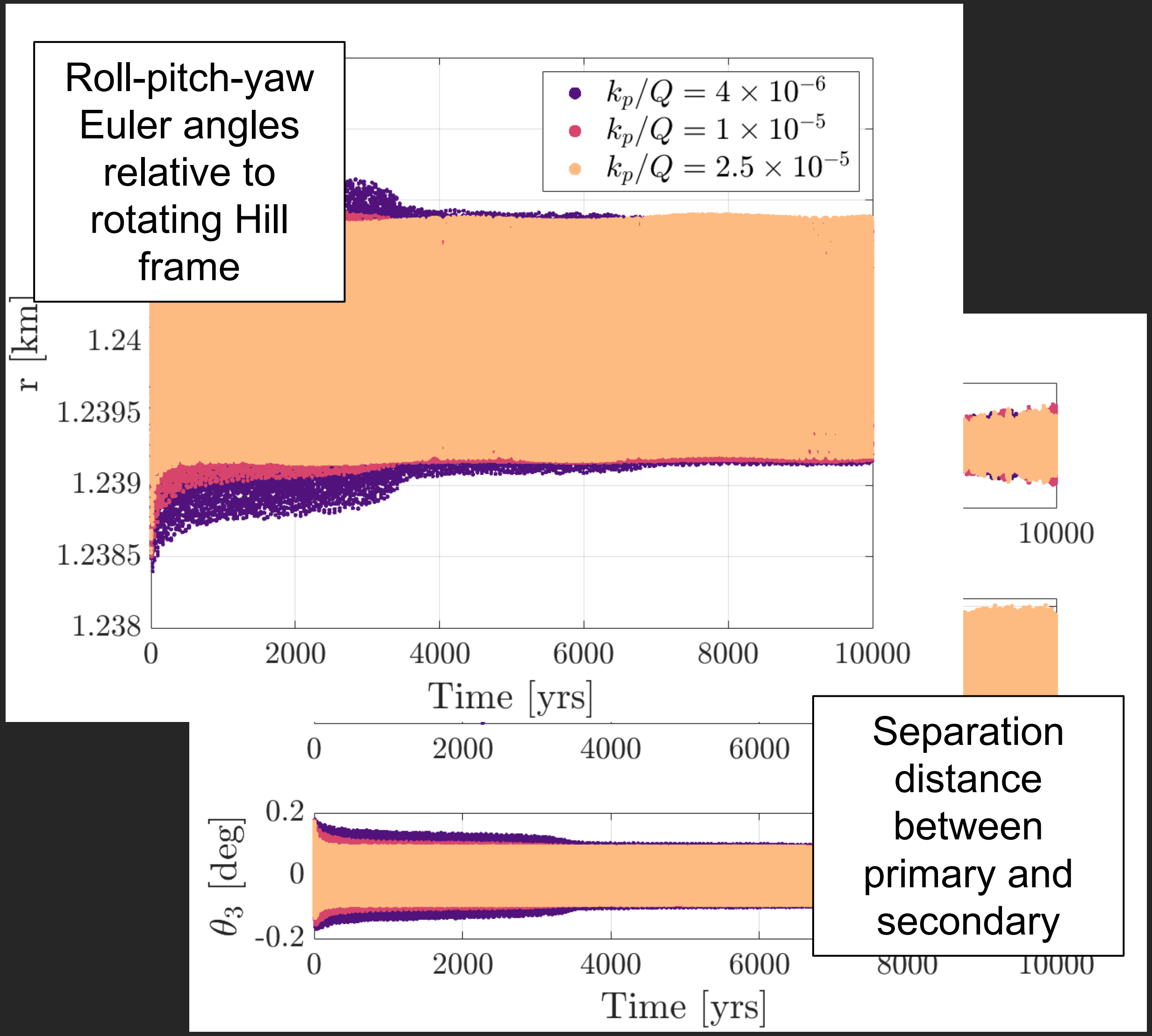
Dynamical Model

Tidal-BYORP Equilibrium

- Torques from contractive BYORP and tidal expansion cancel out → no secular evolution
  - $\frac{BQ}{k_p} = \frac{2\pi \omega_d^2 \rho R_p^2 q^{4/3}}{H_\odot a^7}$
  - $\omega_d = \sqrt{4\pi G\rho/3}$, $H_\odot = \frac{F_S}{a_\odot^2 \sqrt{1-e_\odot^2}}$
- Useful state b/c if *B* is known, can constrain tidal parameters (k_p/Q)
  - Currently don't know much about the strength of tides for rubble piles
- Didymos system likely in or near tidal-BYORP equilibrium prior to impact
  - May constrain the unseen side topography/shape

k_p/Q	B
4×10^{-6}	-1.59×10^{-3}
1×10^{-5}	-3.99×10^{-3}
2.5×10^{-5}	-9.97×10^{-3}

Pre-Impact B values for given tidal parameters



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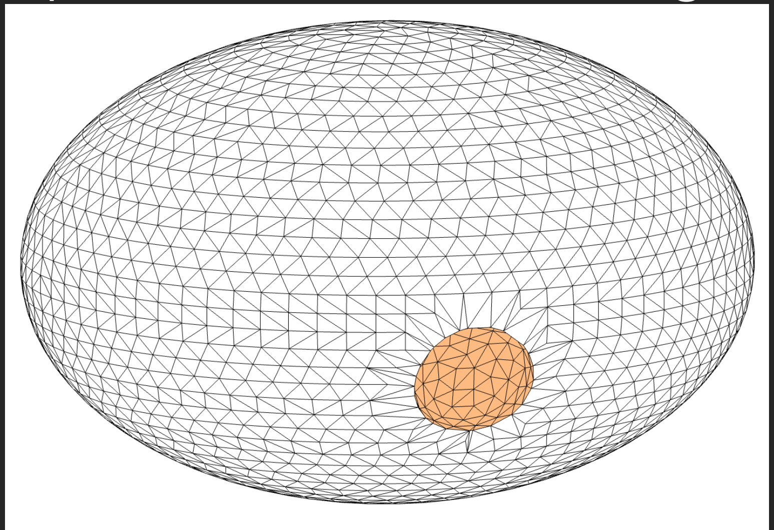
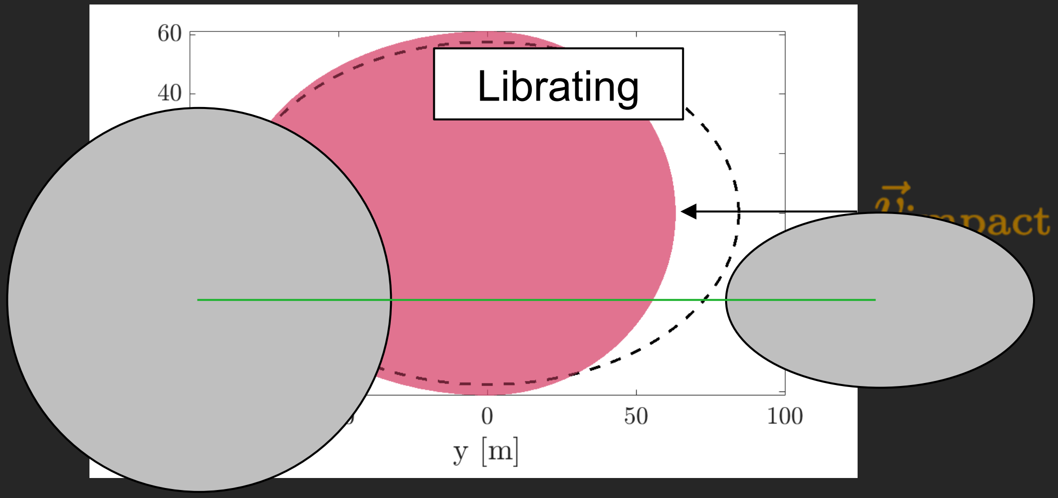
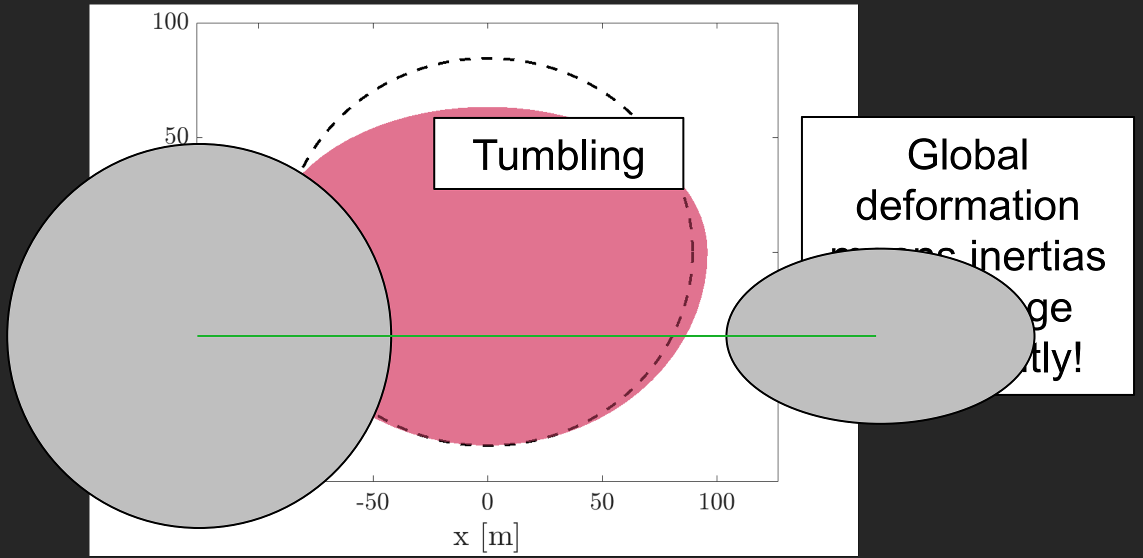
How Did DART Change Dimorphos?

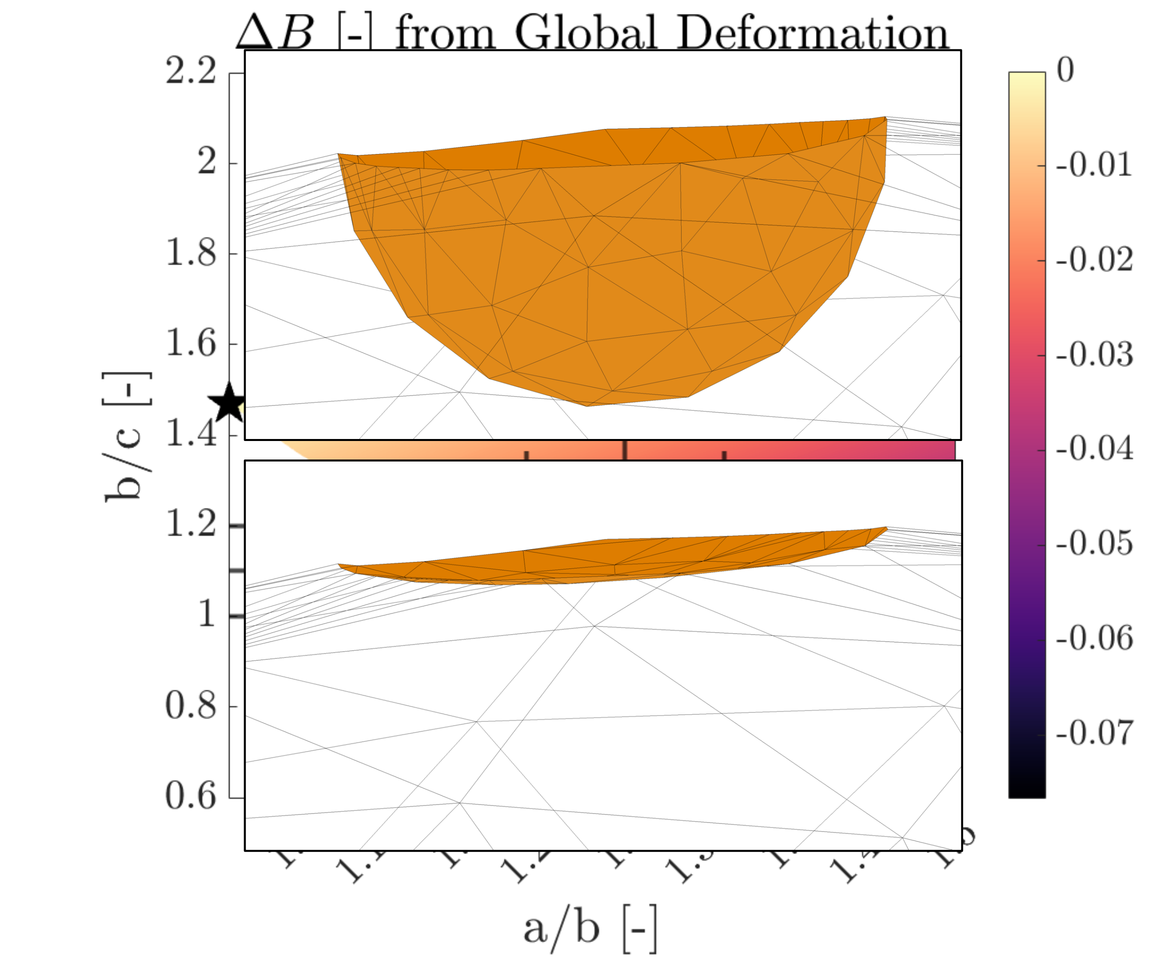
- Reduced orbit period by ~33 minutes → shrunk orbit
- Likely dynamically excited Dimorphos → librating on order of tens of degrees or tumbling?
- Most likely changed shape of Dimorphos → crater vs. elongation?

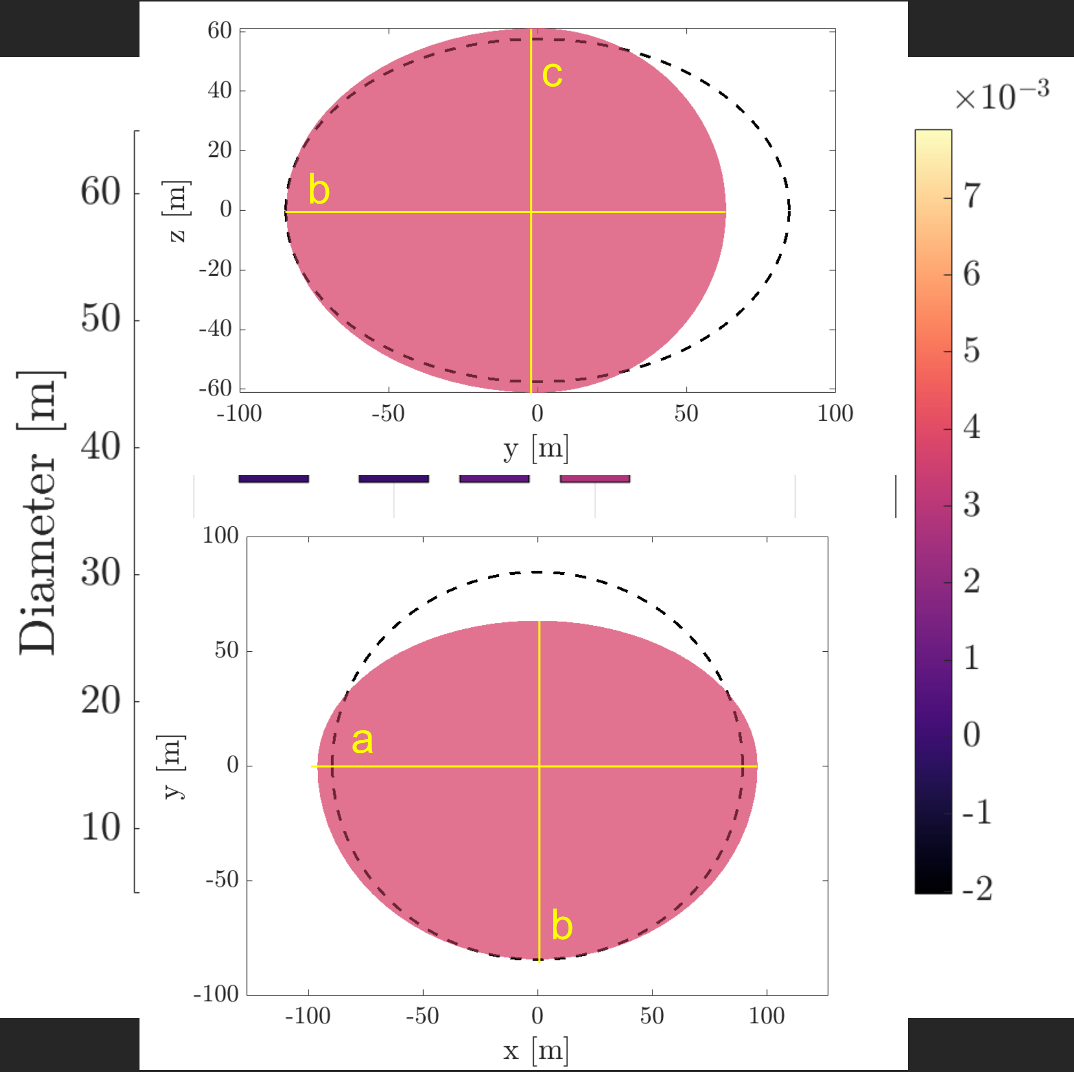






Effect of Shapes Changes on *B*





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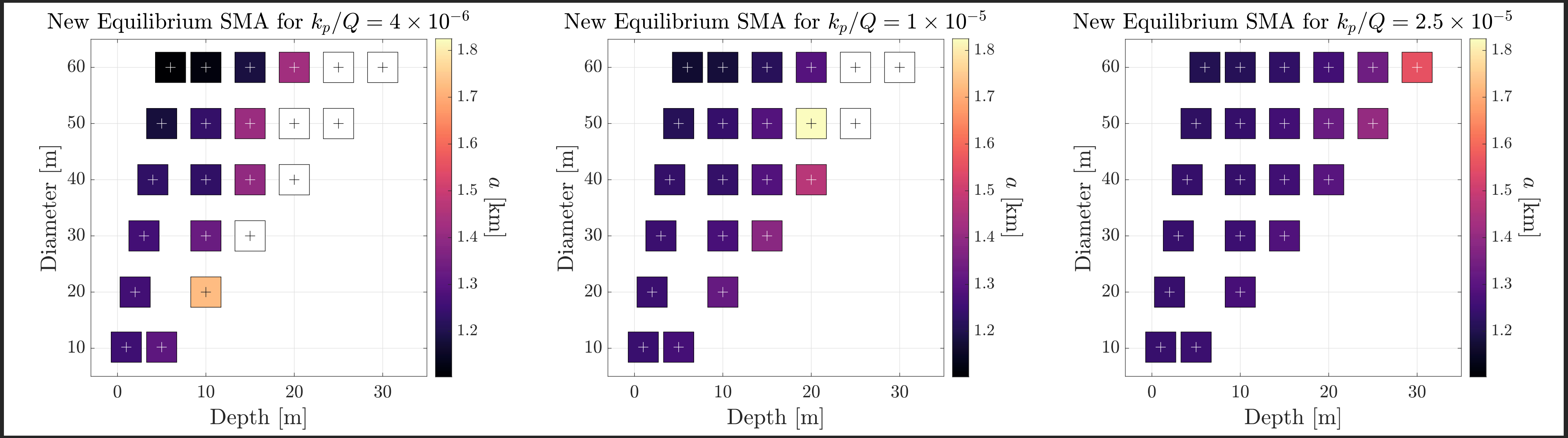
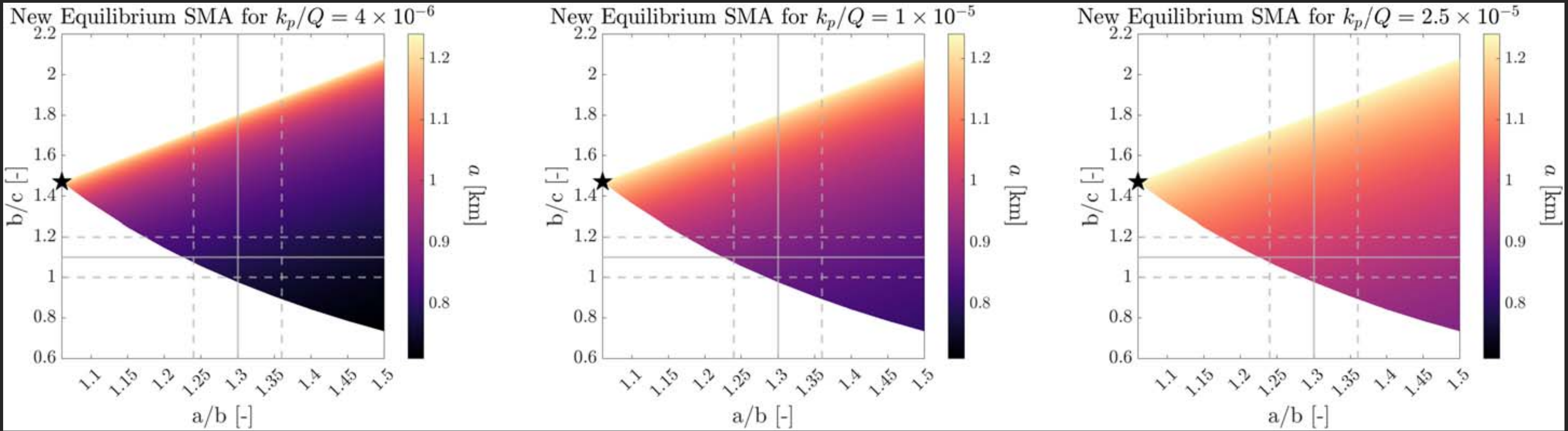
New Tidal-BYORP Equilibria

Craters
(white is unbounded expansion)



Reshaping
(all cases are negative)

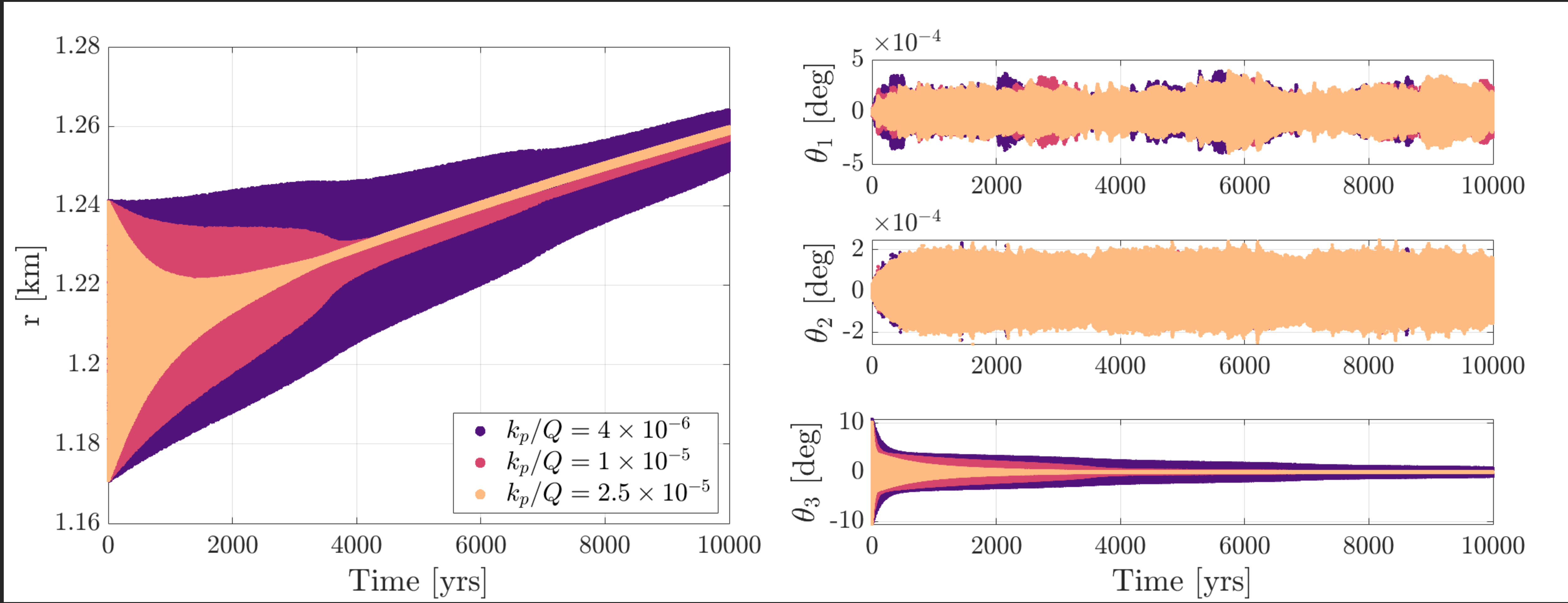


Recall initial orbit size (T-B equilibrium?) is ~1.2 km

Simulating Effect of Craters

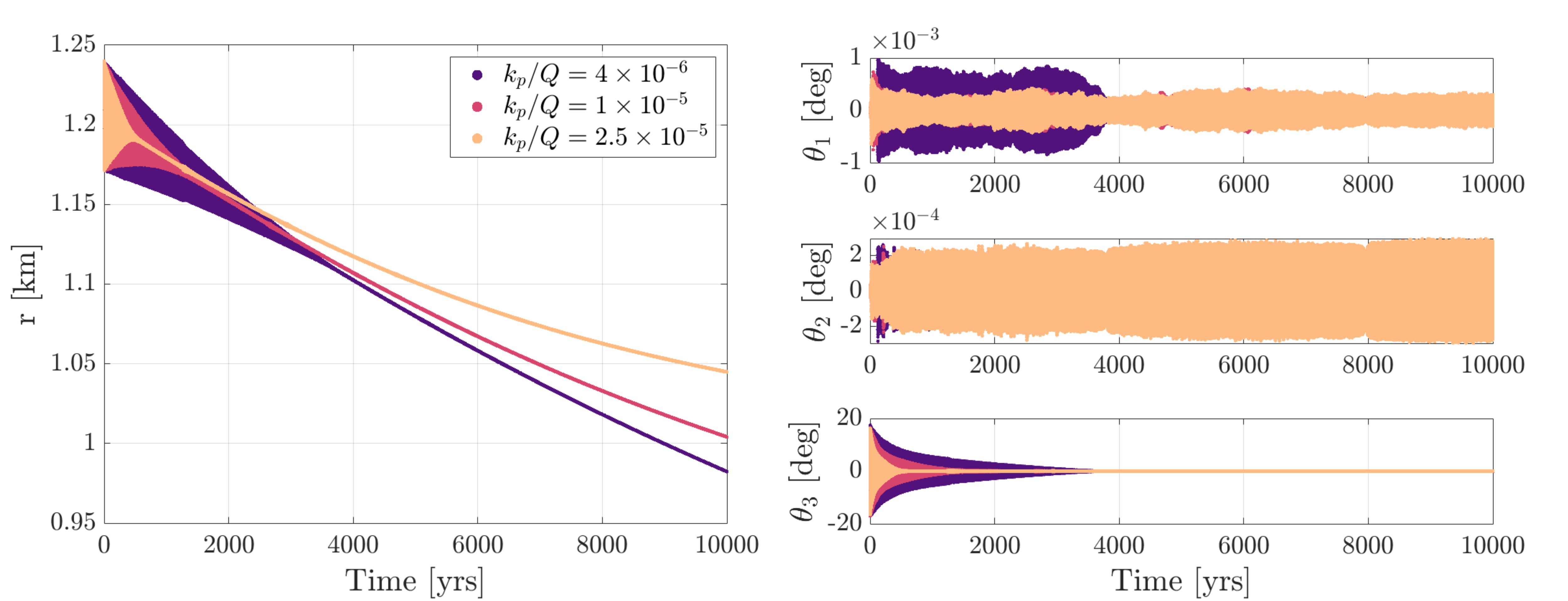
K_p/Q = 4e-6 or 1e-5 → Expansive

K_p/Q = 2.5e-5 → Contractive BYORP → higher equilibrium SMA



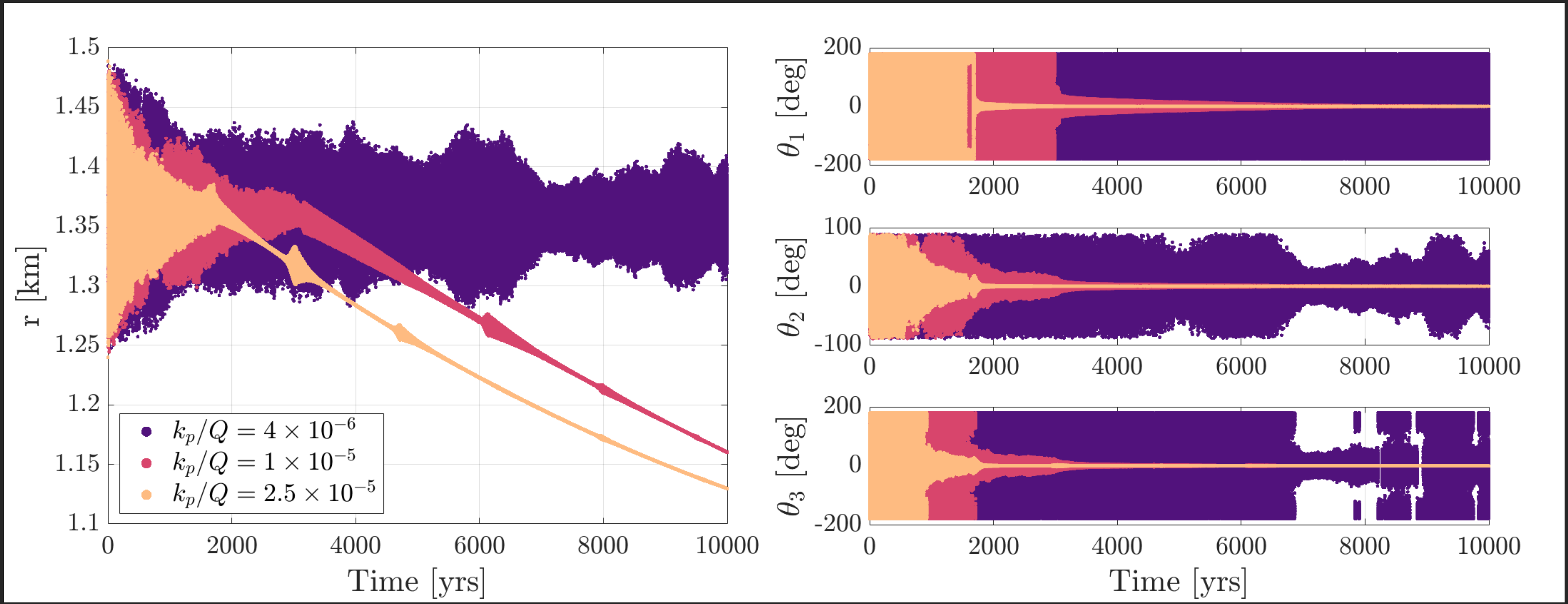
50 m radius, 25 m deep crater, ω_s

Simulating Effect of Global Deformation



***a/b* = 1.3, *b/c* = 1.1, ω_s**

Simulating Effect of Global Deformation

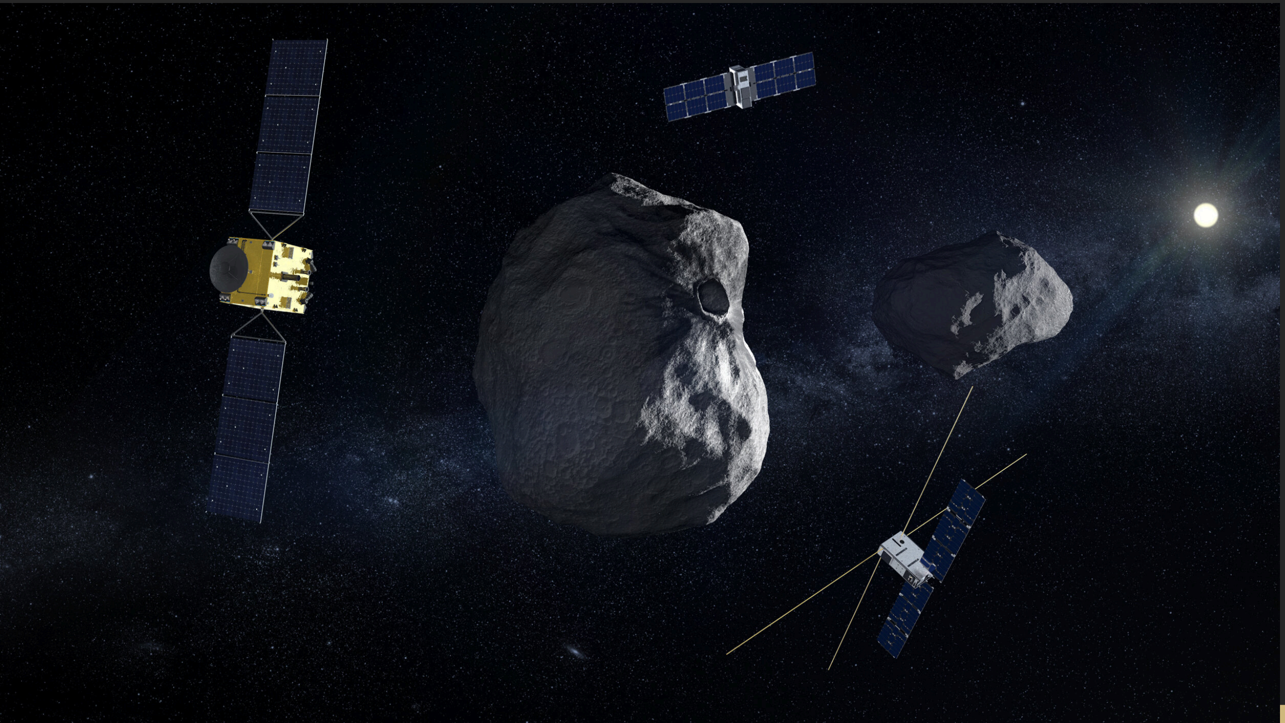


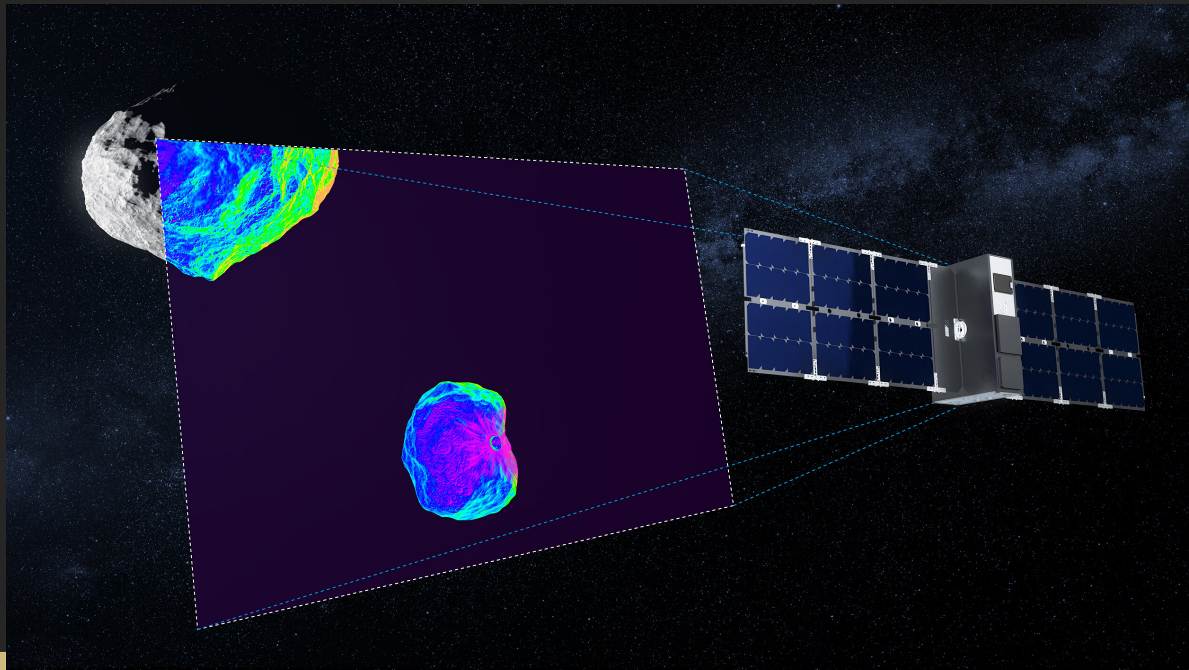
a/b **= 1.3,** ***b/c*** **= 1.1,** $\boldsymbol{\omega_c}$

How will we know what happened??

Hera

- ESA mission returning to Didymos
  - Launching October 2024
  - Arriving December 2026
- First rendezvous mission to an NEA binary asteroid
- Will help us solve all sorts of mysteries about binary asteroids and DART's impact… and certainly find new ones!





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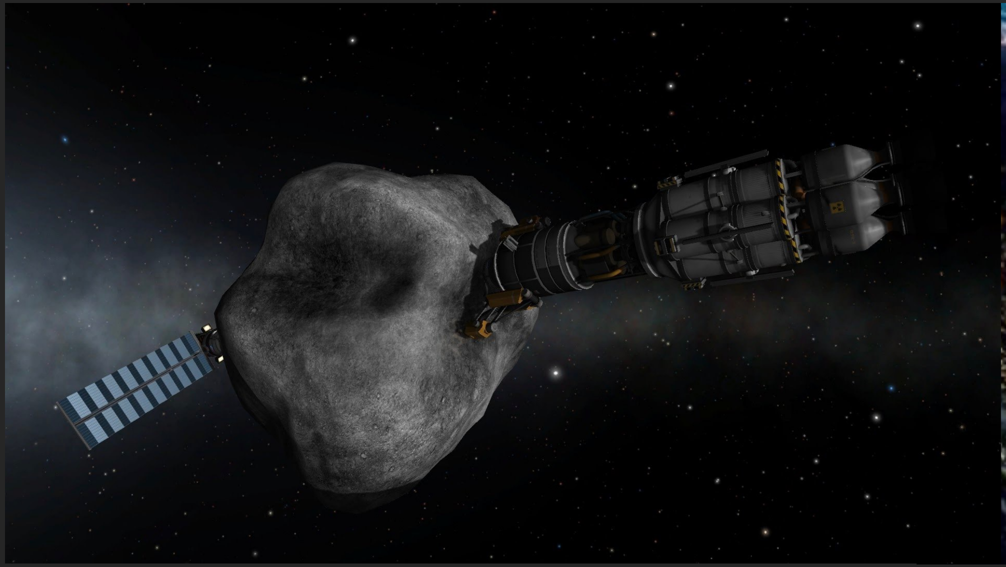

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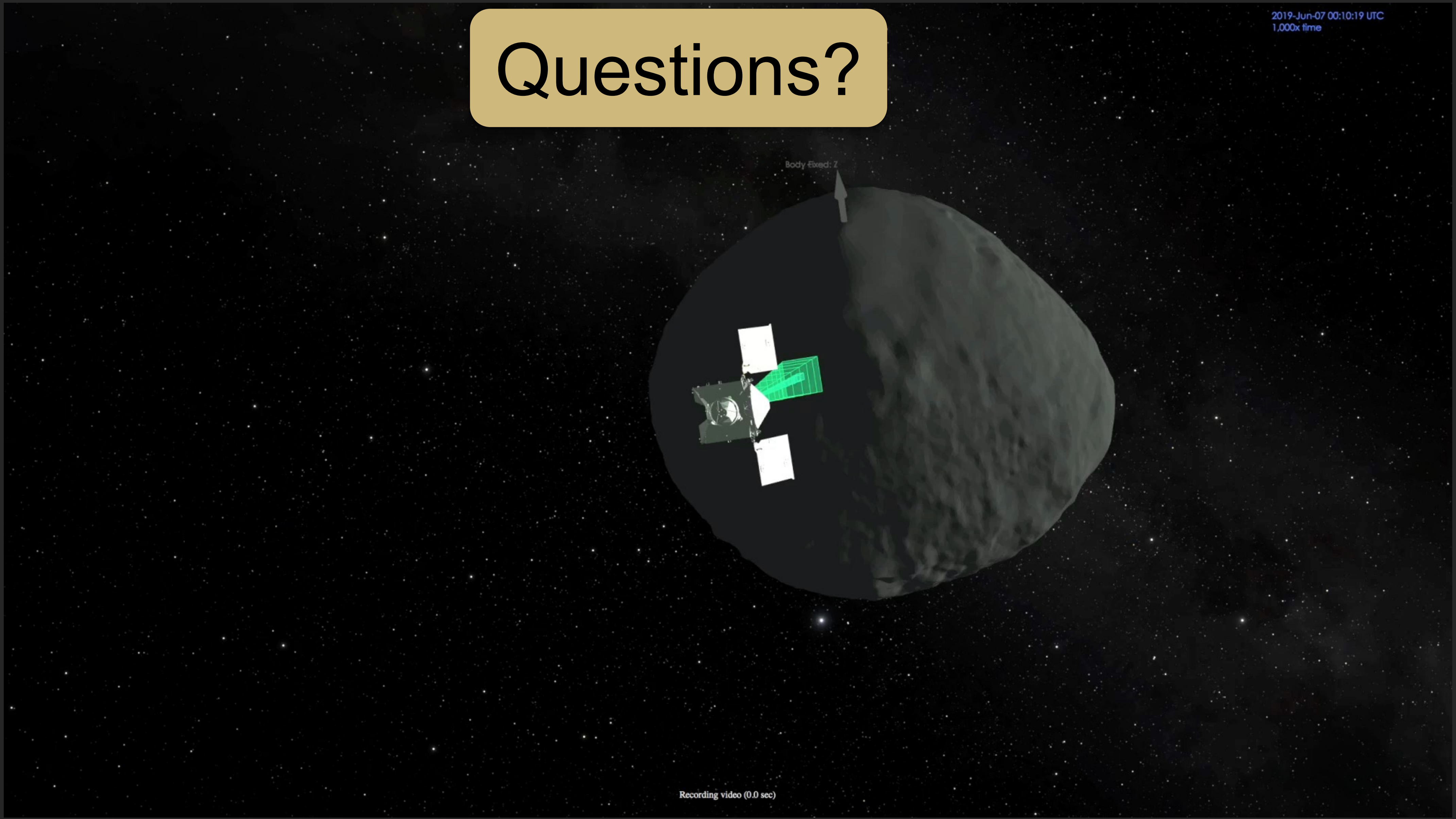
Questions?



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