Scaling Forces to the Asteroid Surface: The role of cohesion

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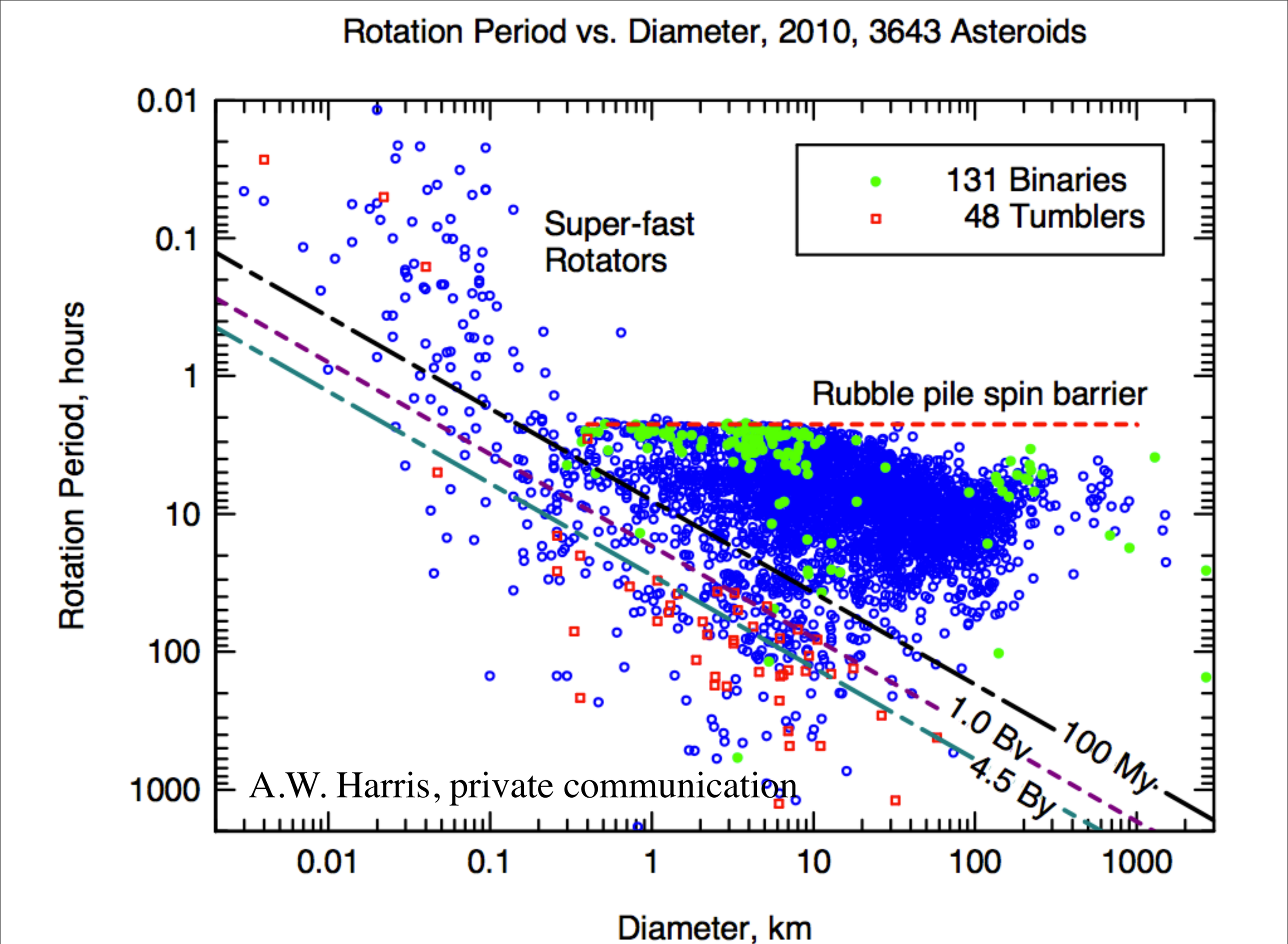
Theory

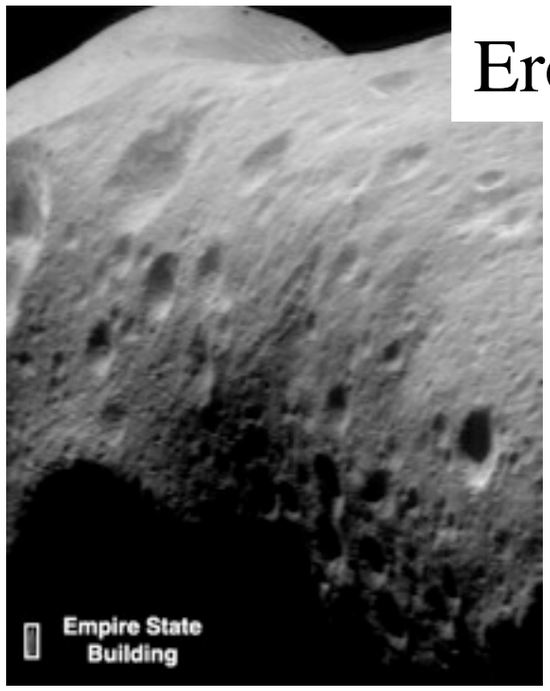
Formation model of Itokawa / small asteroids proposed in Fujiwara et al., Science 2006.

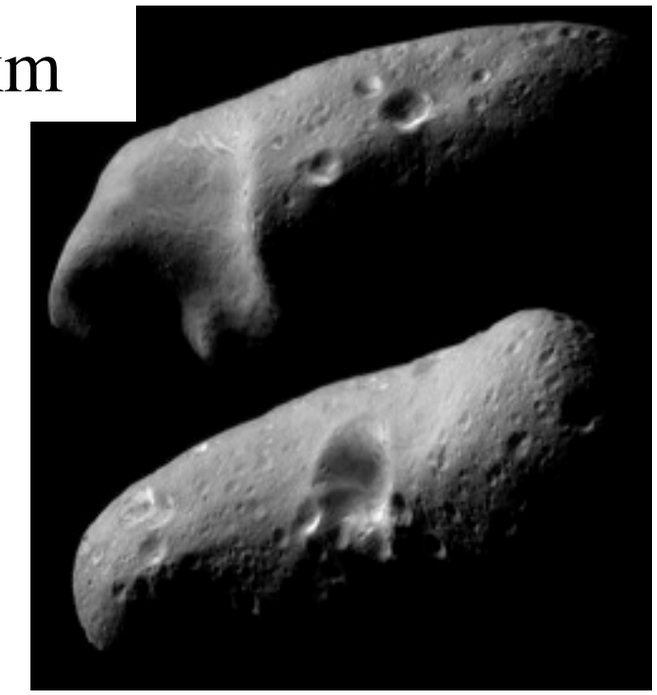

Rotation Period vs. Diameter, 2010, 3643 Asteroids
Rotation Period, hours
0.01
0.1
1
10
100
1000
131 Binaries
48 Tumblers
Super-fast
Rotators
Rubble pile spin barrier
100 My.
1.0 By
4.5 By
A.W. Harris, private communication
0.01
0.1
1
10
100
1000
Diameter, km

The best data we have on NEA: Eros, Itokawa and 1999 KW4

– Eros and Itokawa, visited by S/C, represent small and large NEA

Eros ~ 10 km





Itokawa ~ 0.1 km

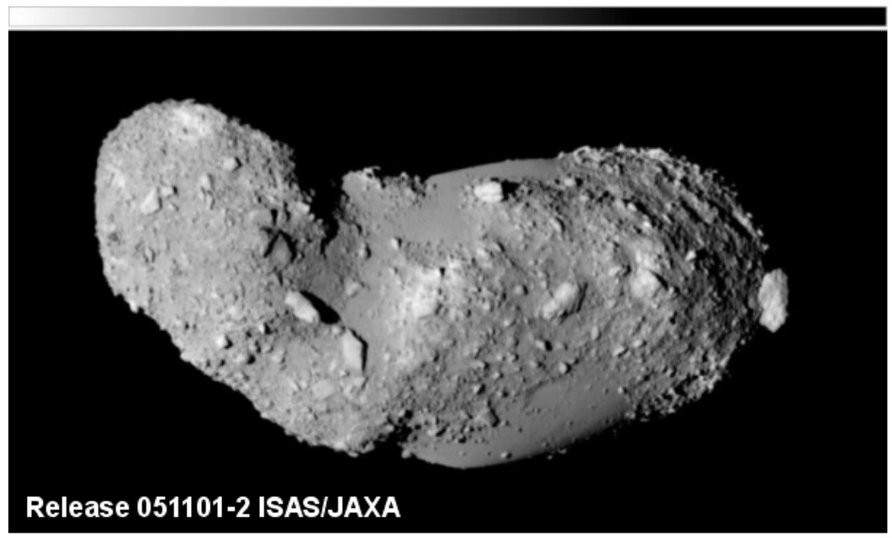
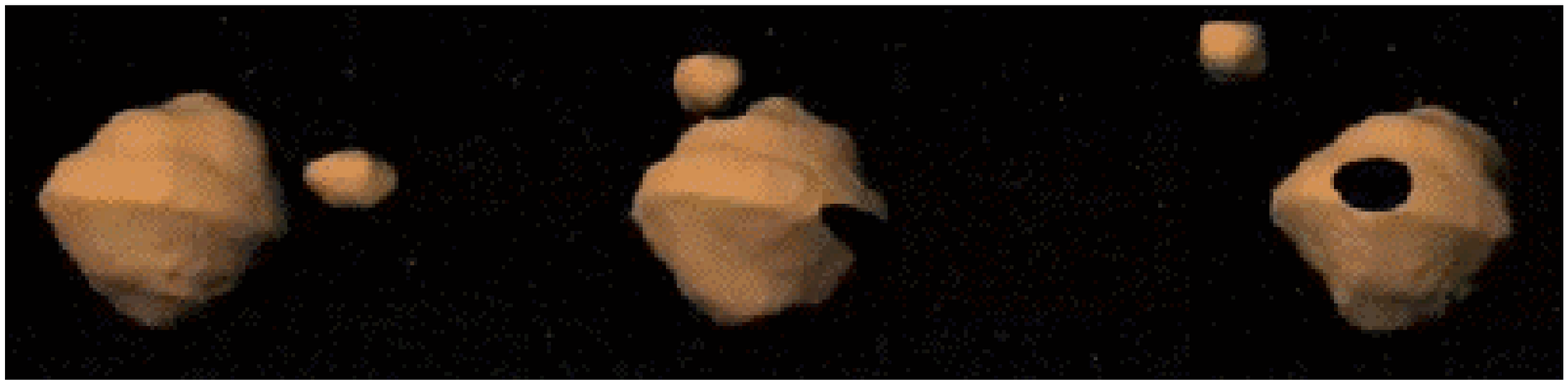


図4 イトカワの +270 度面

– 1999 KW4, observed using Arecibo Radar, represents the recently discovered NEA binary population, ~1.5 km primary



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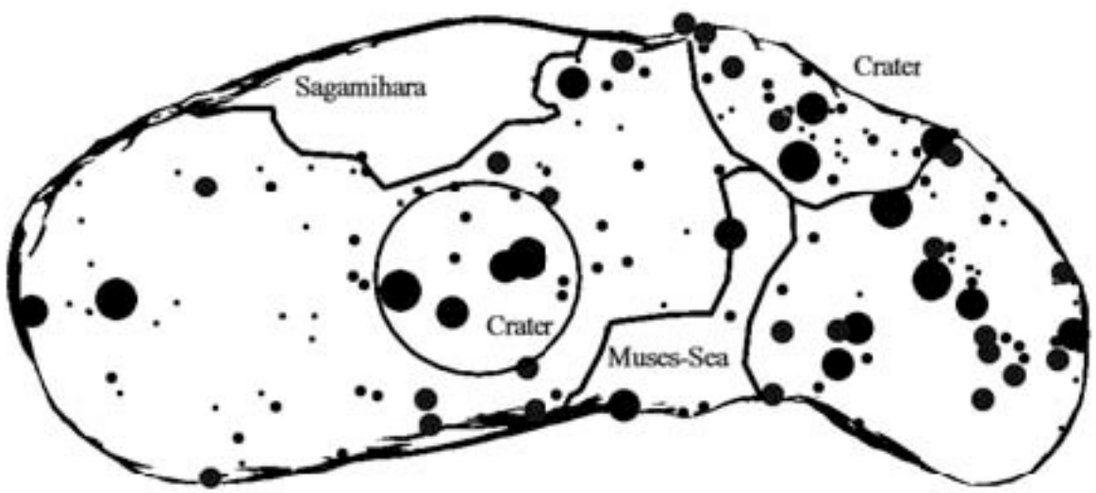
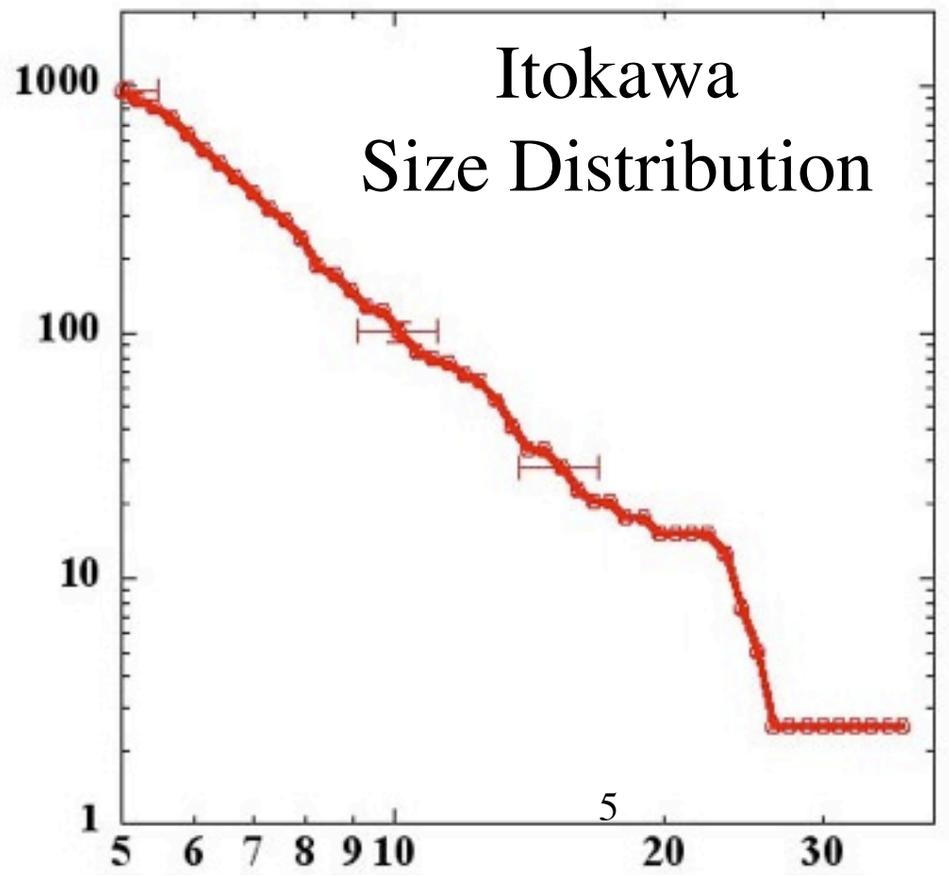
Itokawa

- Itokawa remains the poster child of rubble pile asteroids.
- Clearly comprised of a collection of boulders and grains:
  - Maximum size on the order of 10's of meters
  - Minimum size on the order of 10's of microns (Hayabusa Sample)
  - Measured distribution size has a slope on the order of ~ -3 (Michikami et al. 2008)

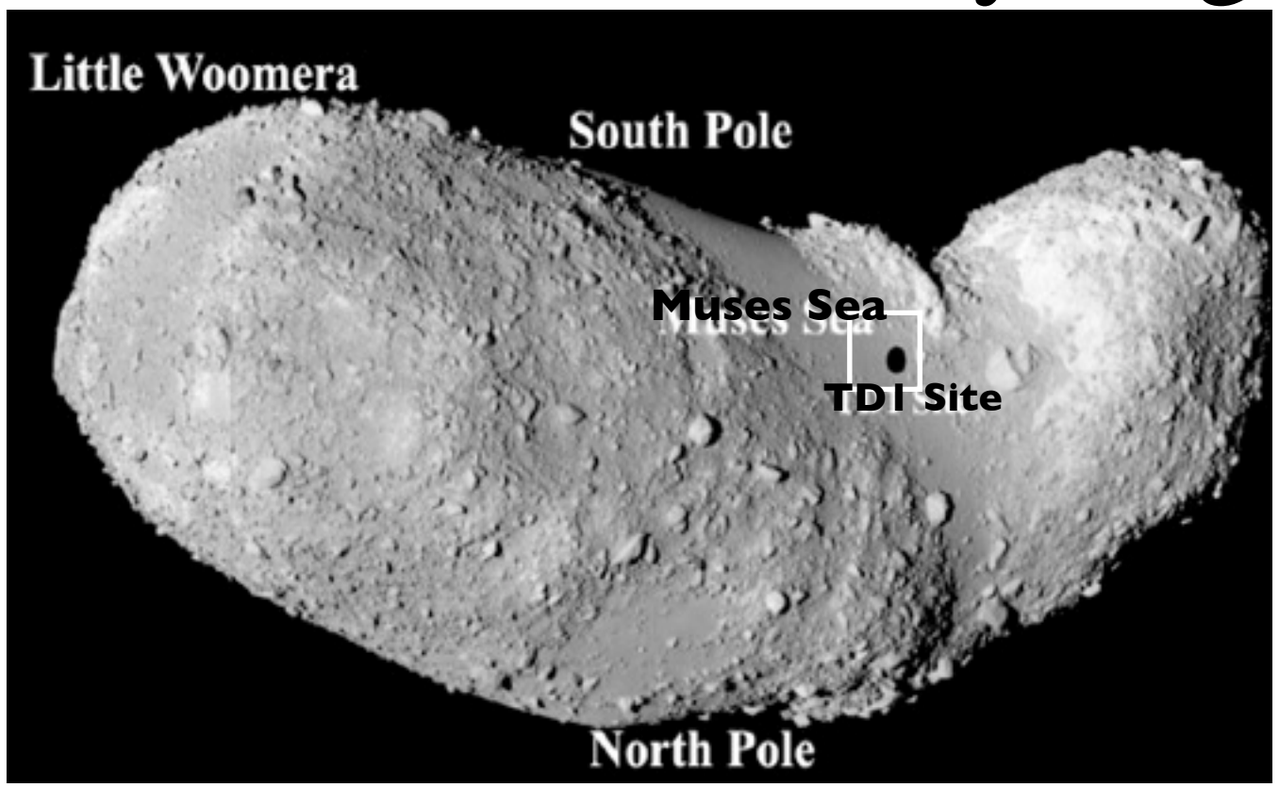


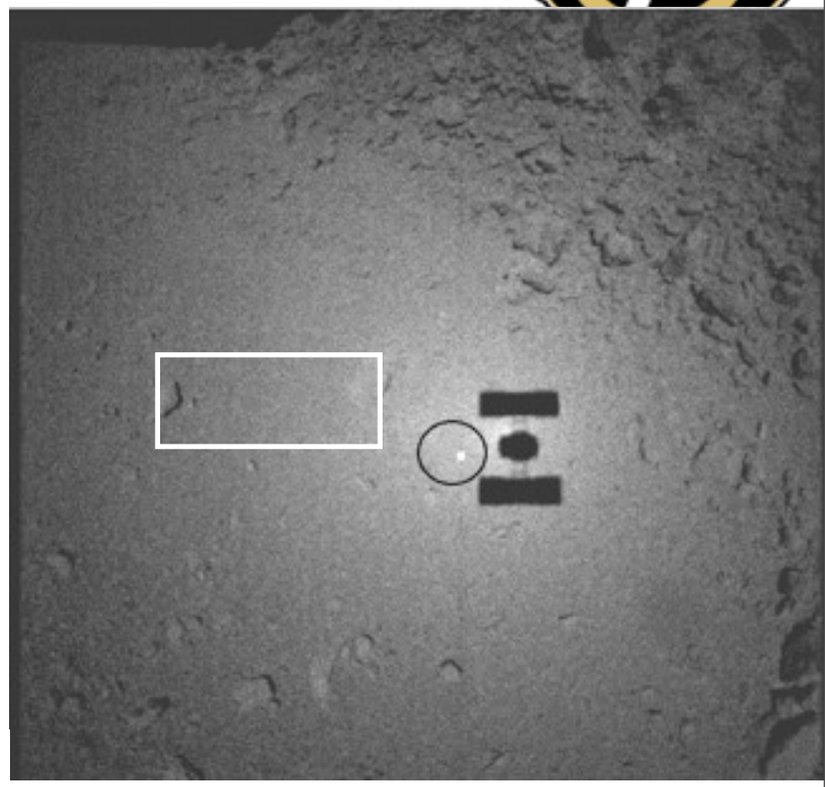


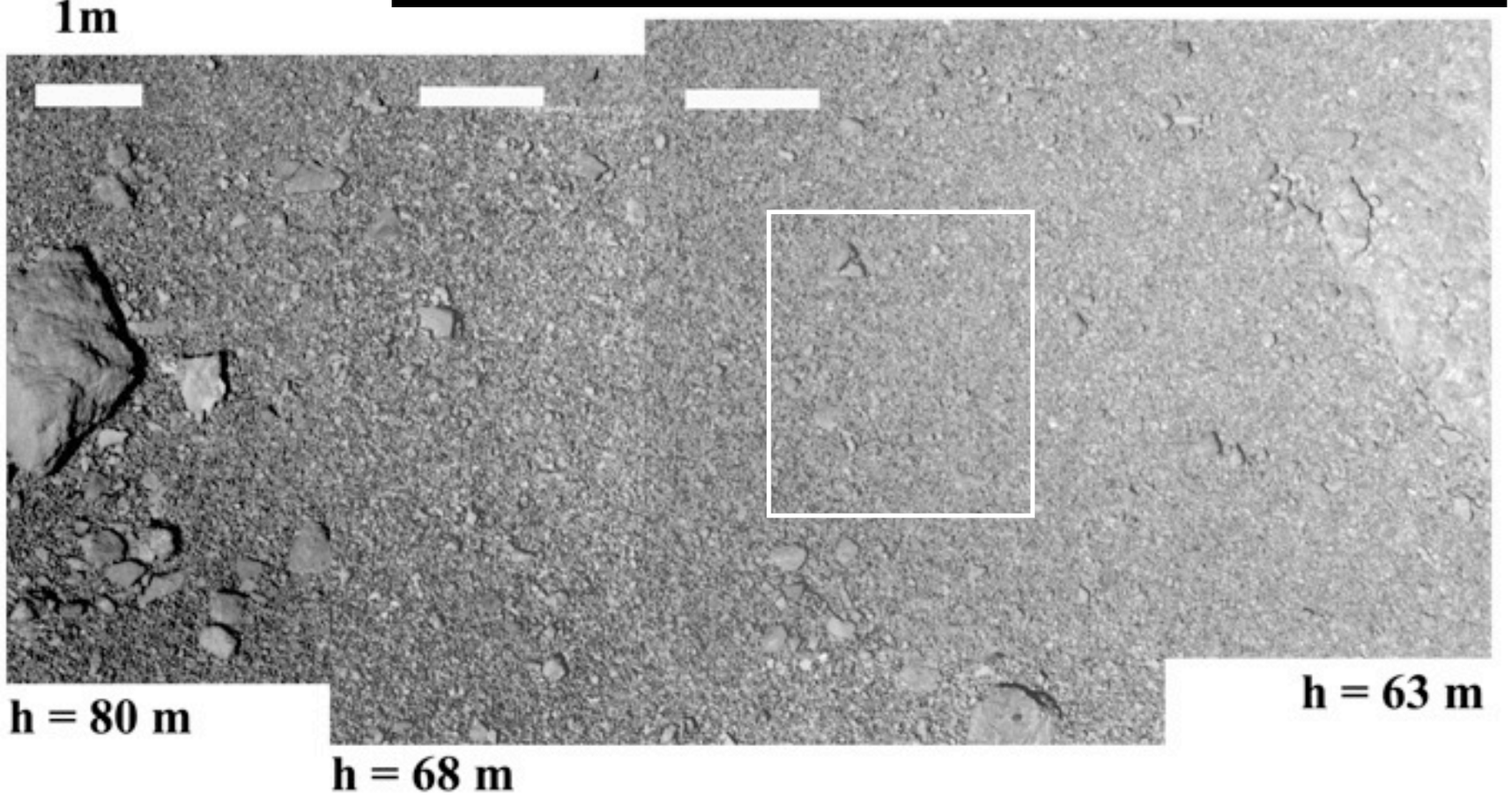
Science
HAYABUSA
Dust from Itokawa
AAAS

Smooth and Rocky Regions

All images courtesy JAXA/ISAS







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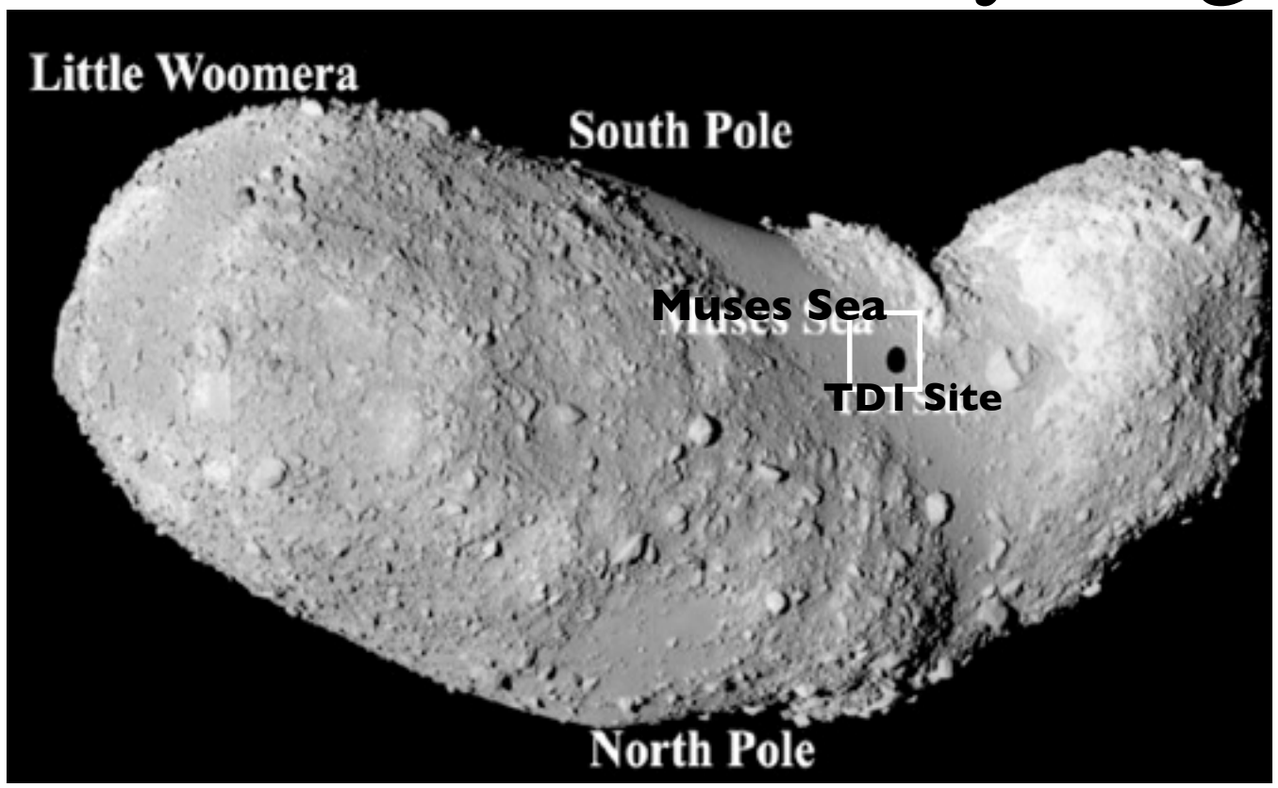

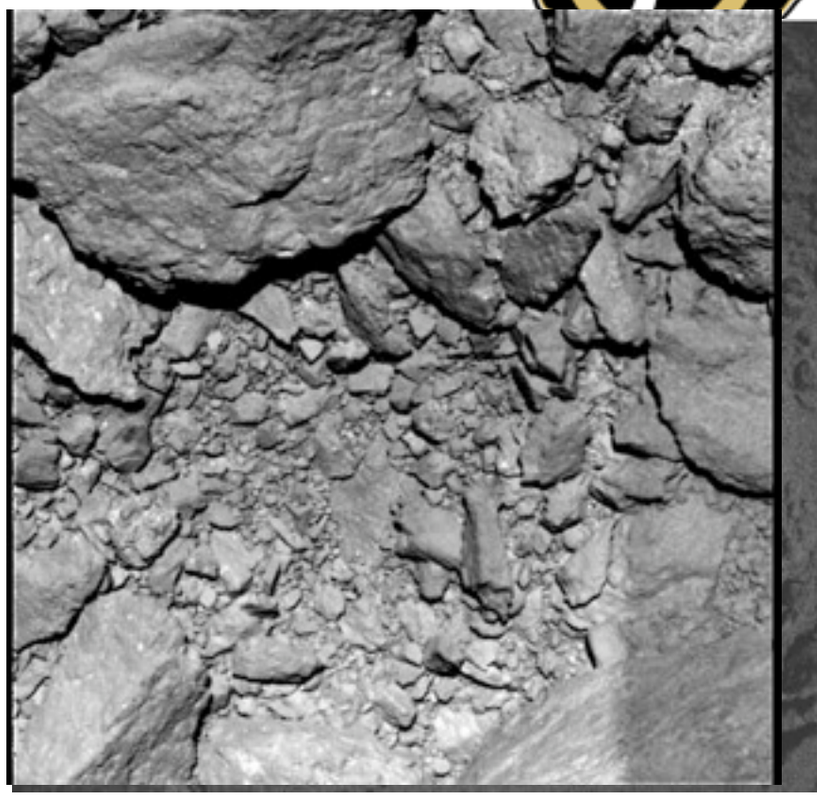

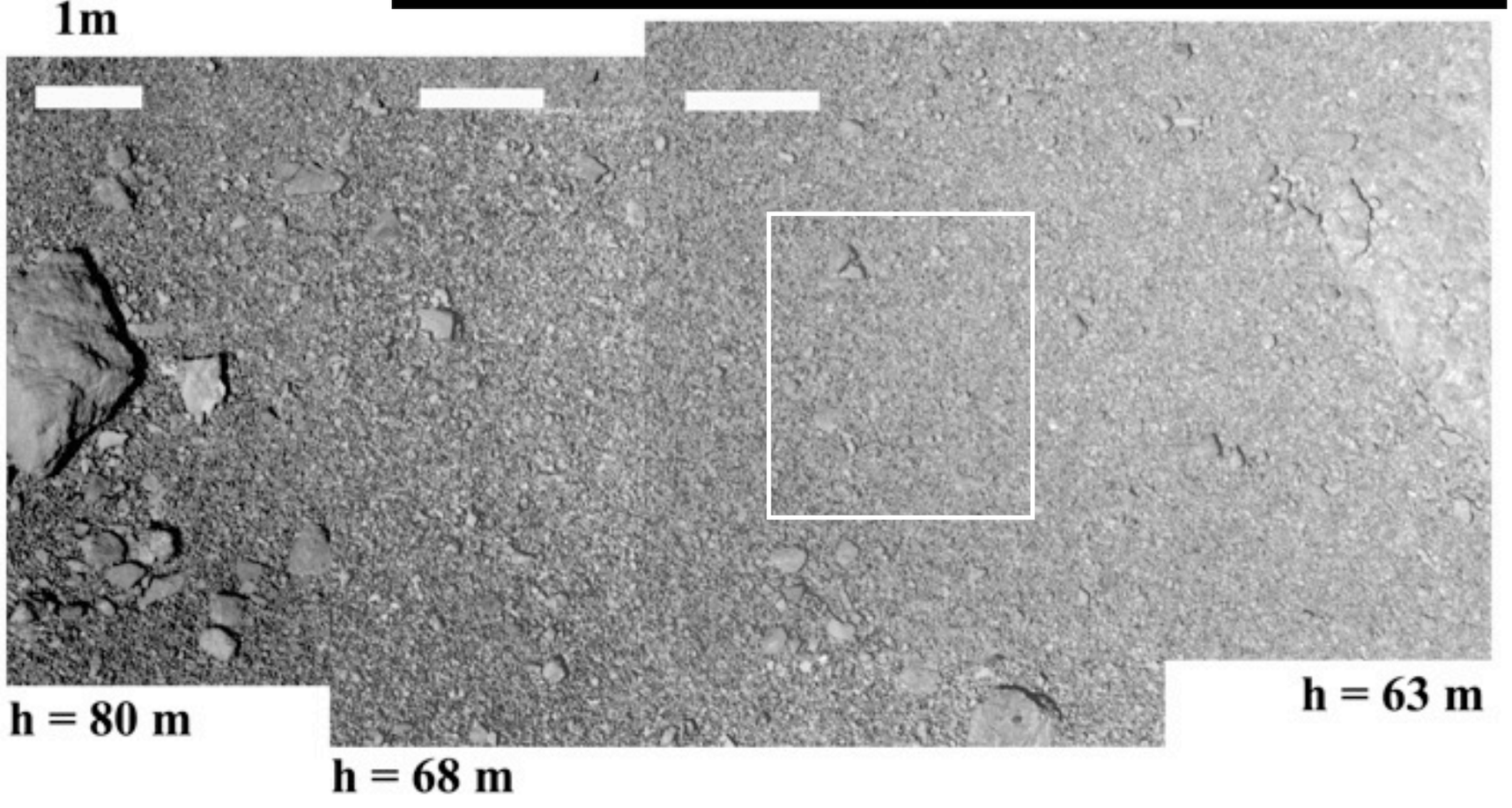

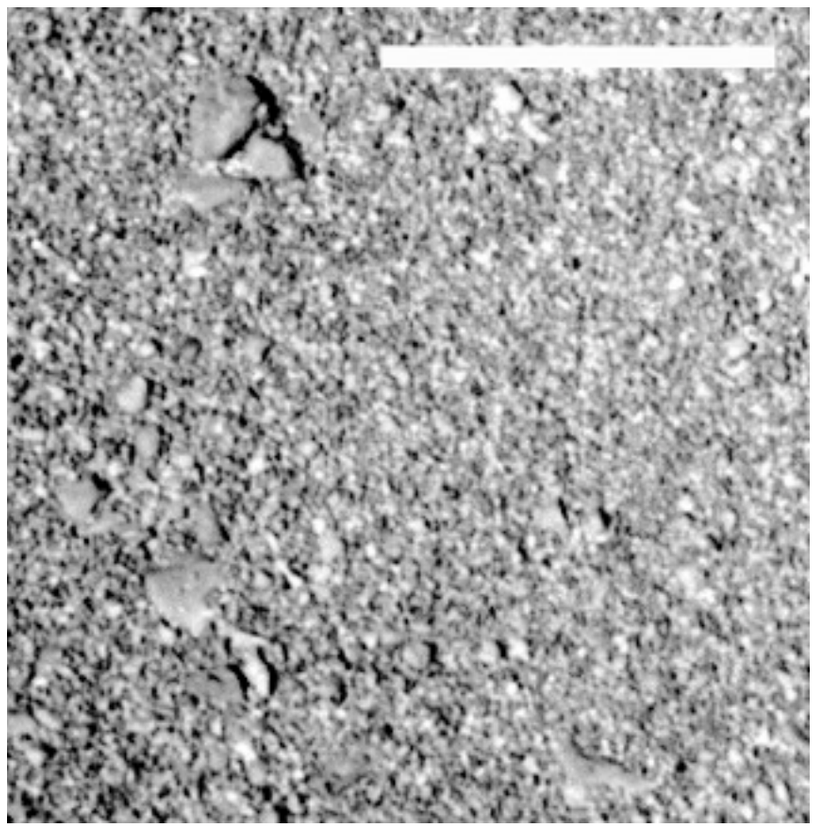

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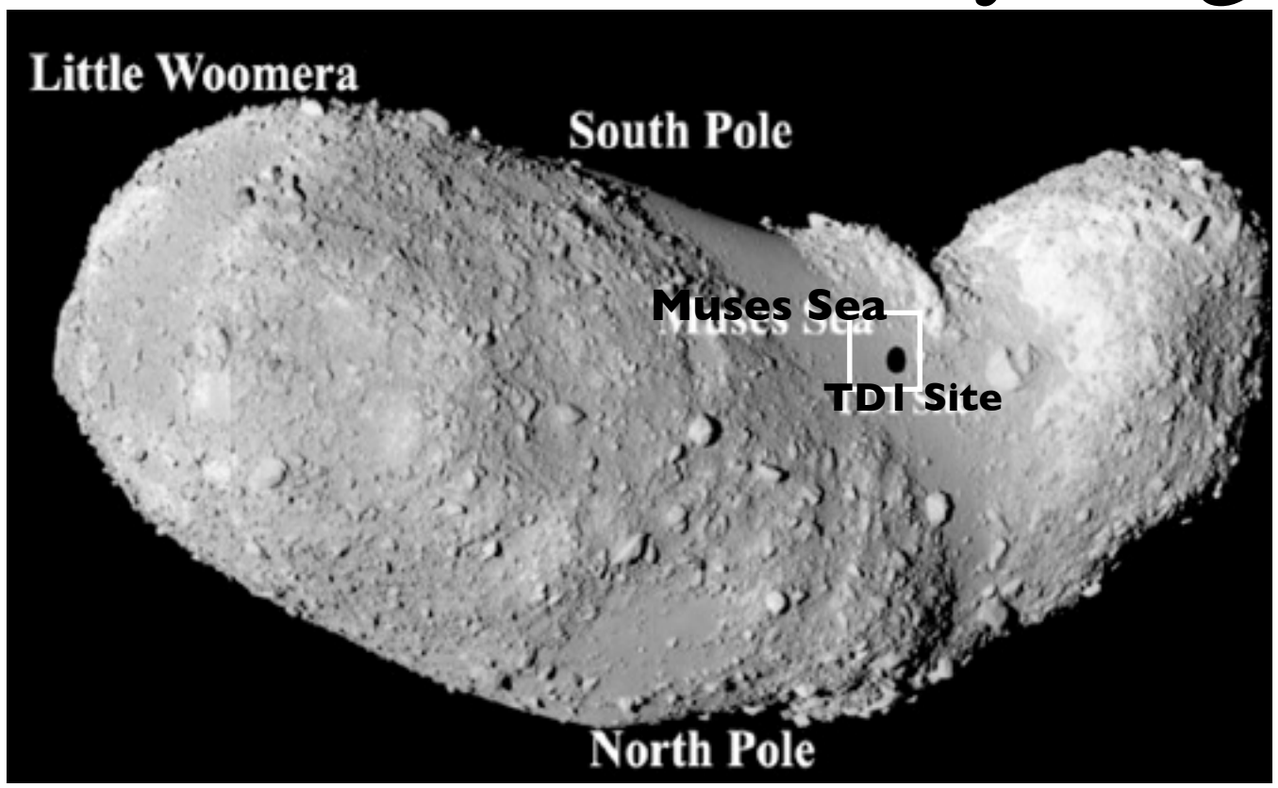

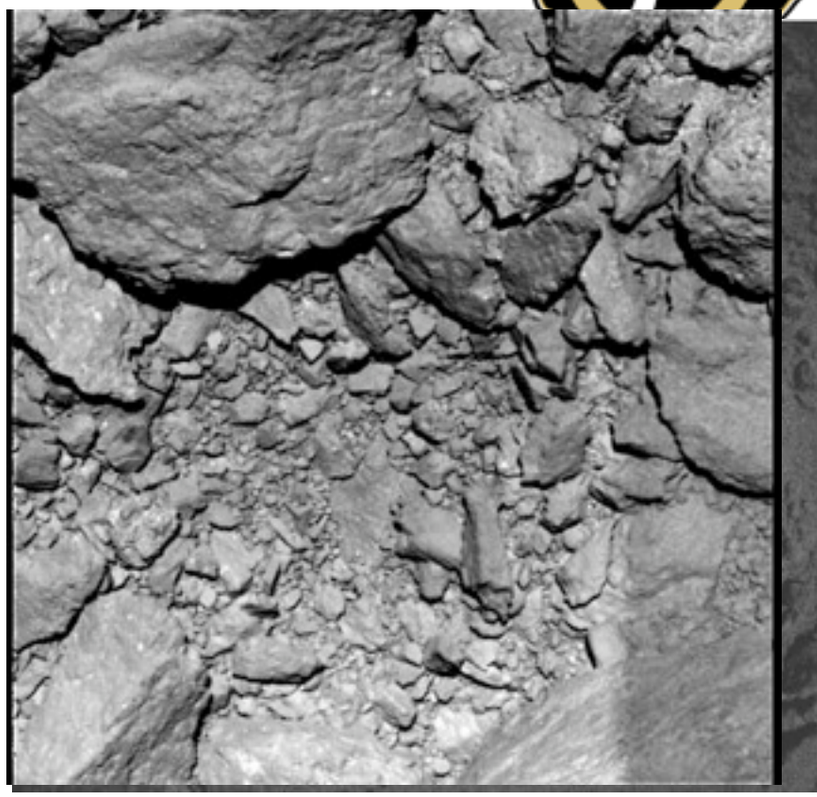

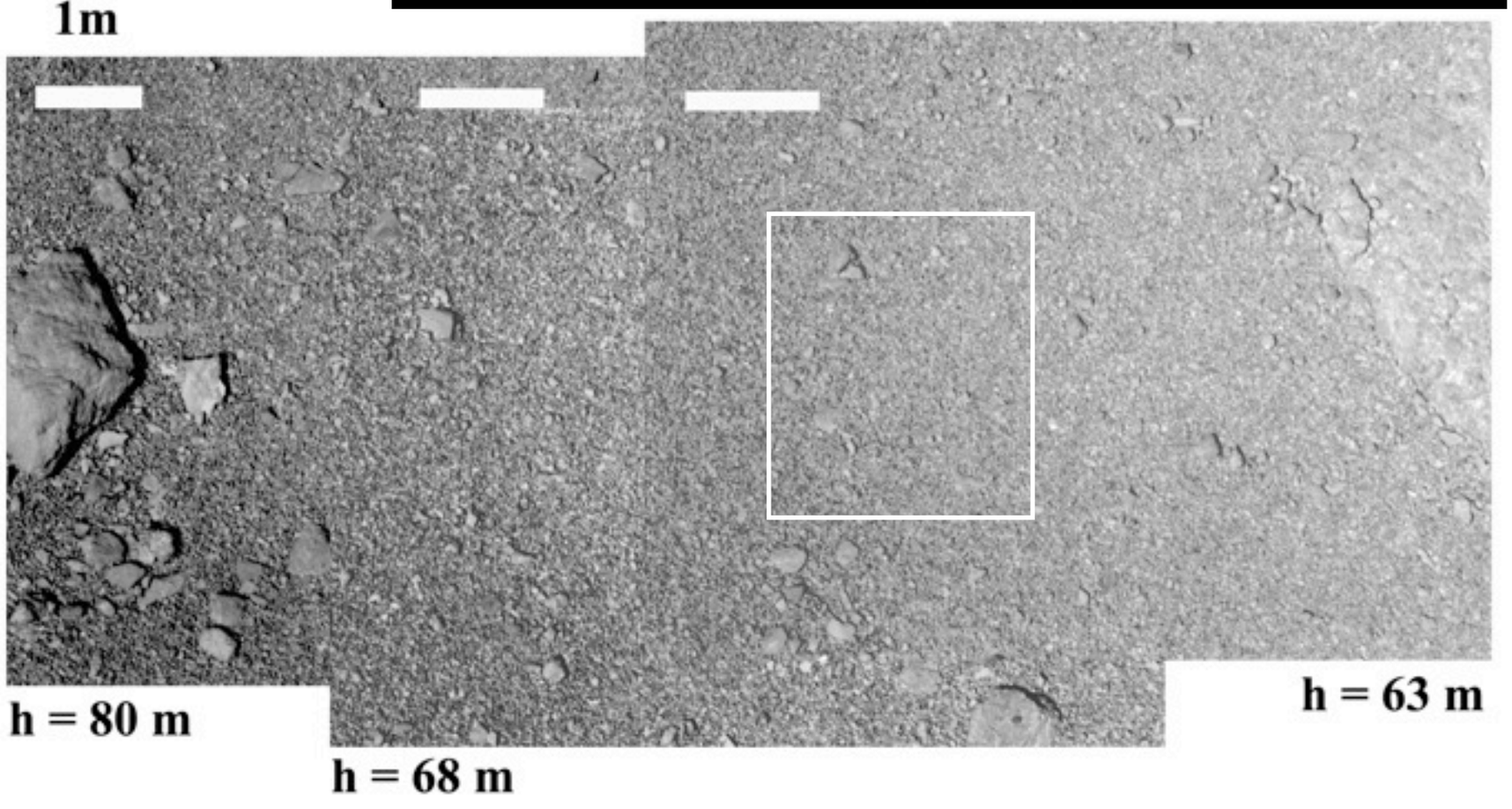

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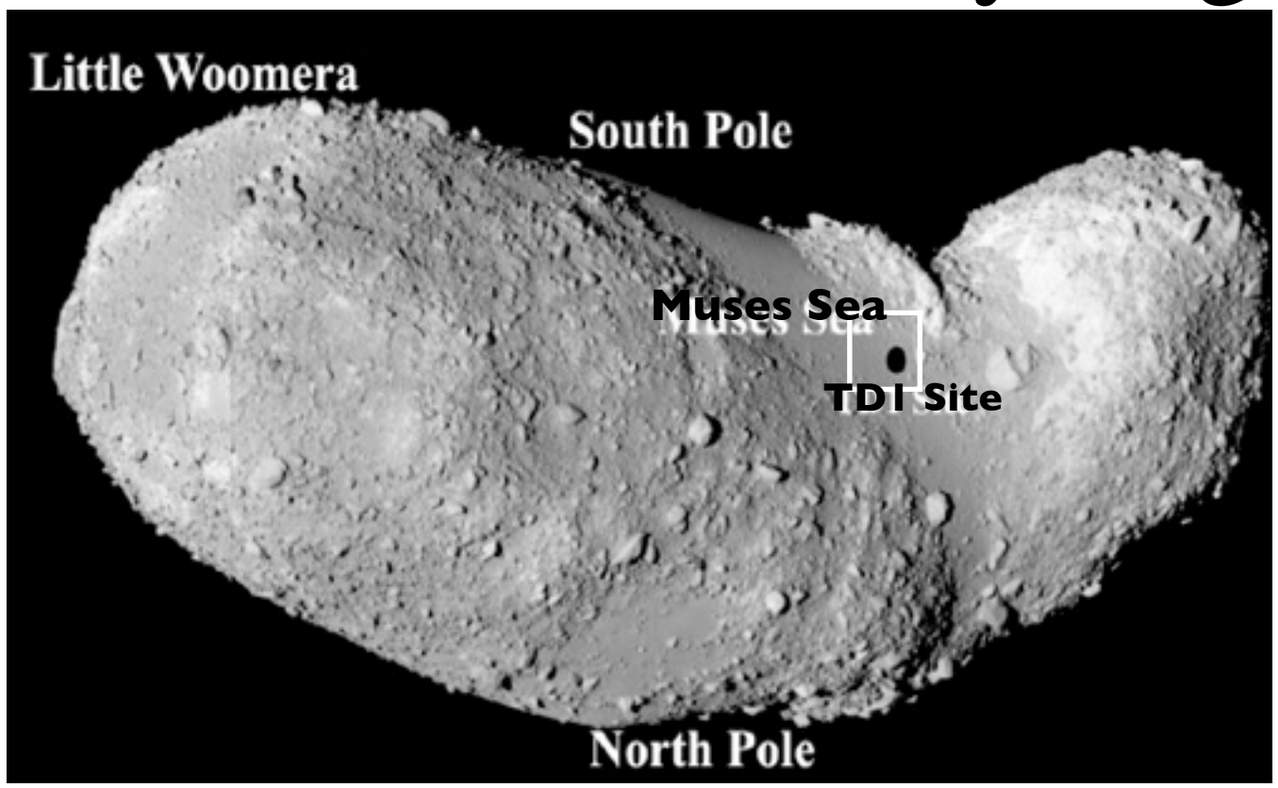

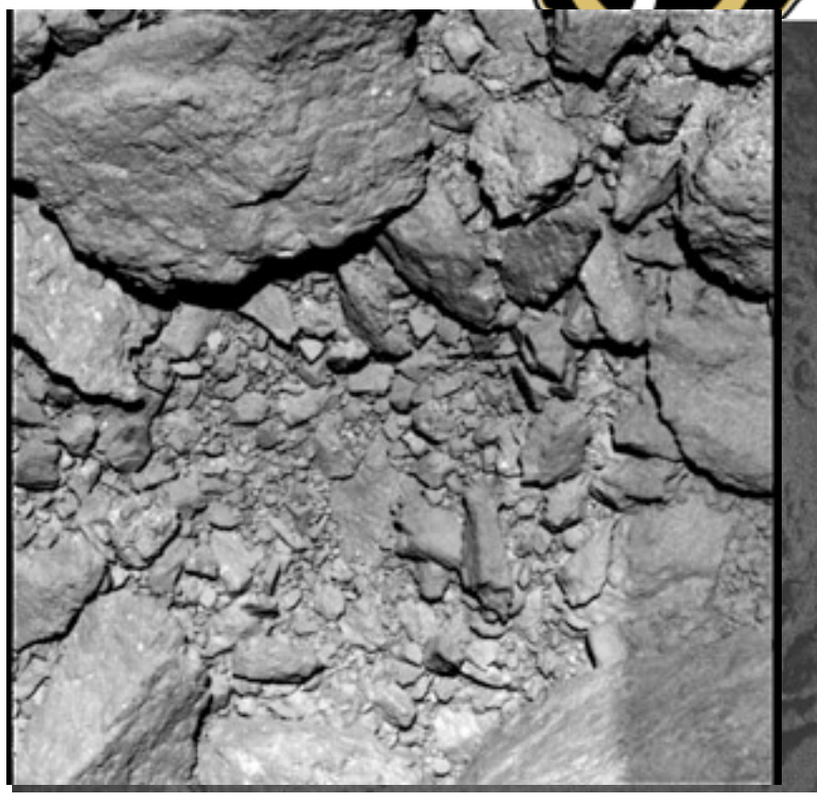

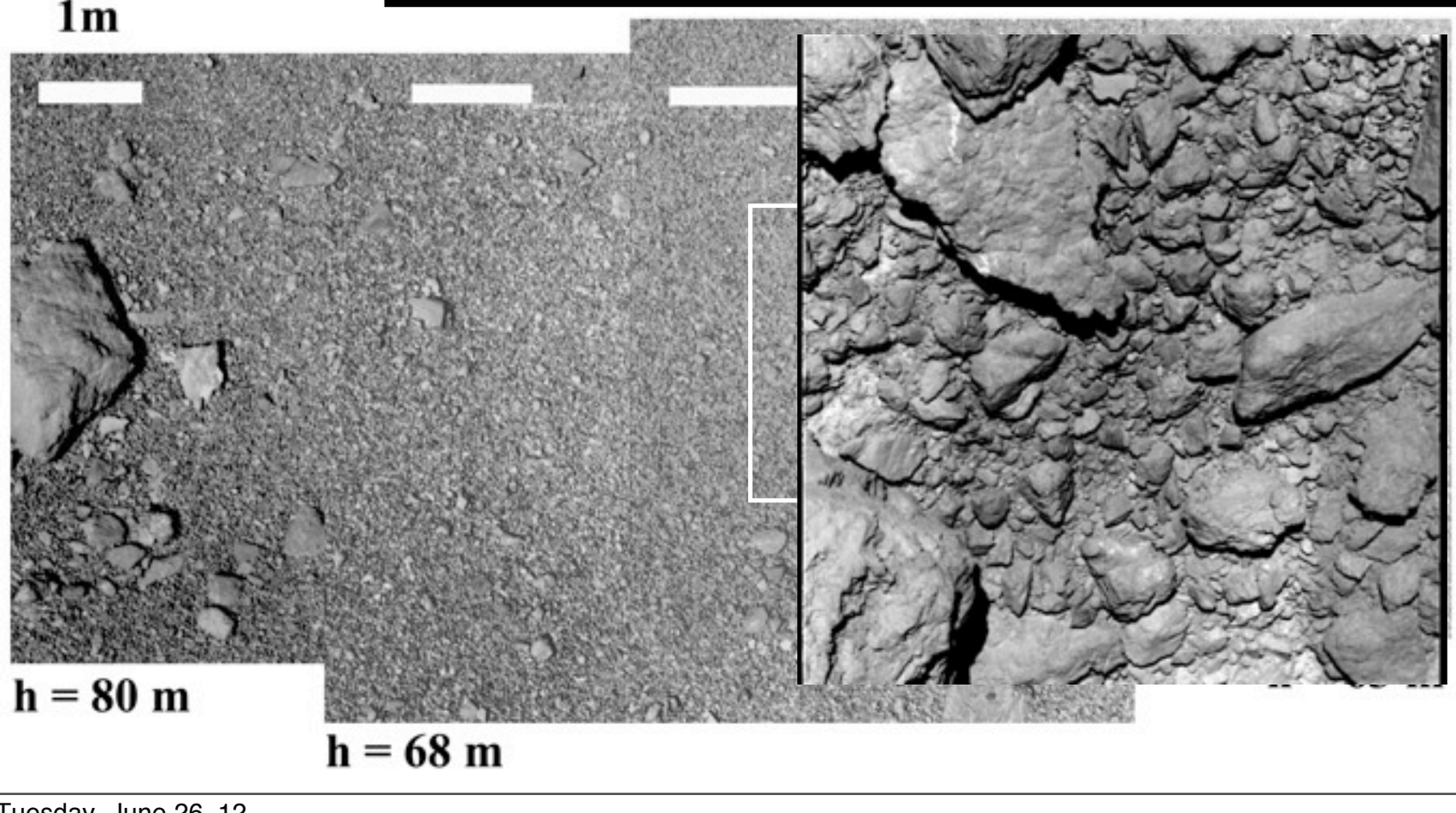

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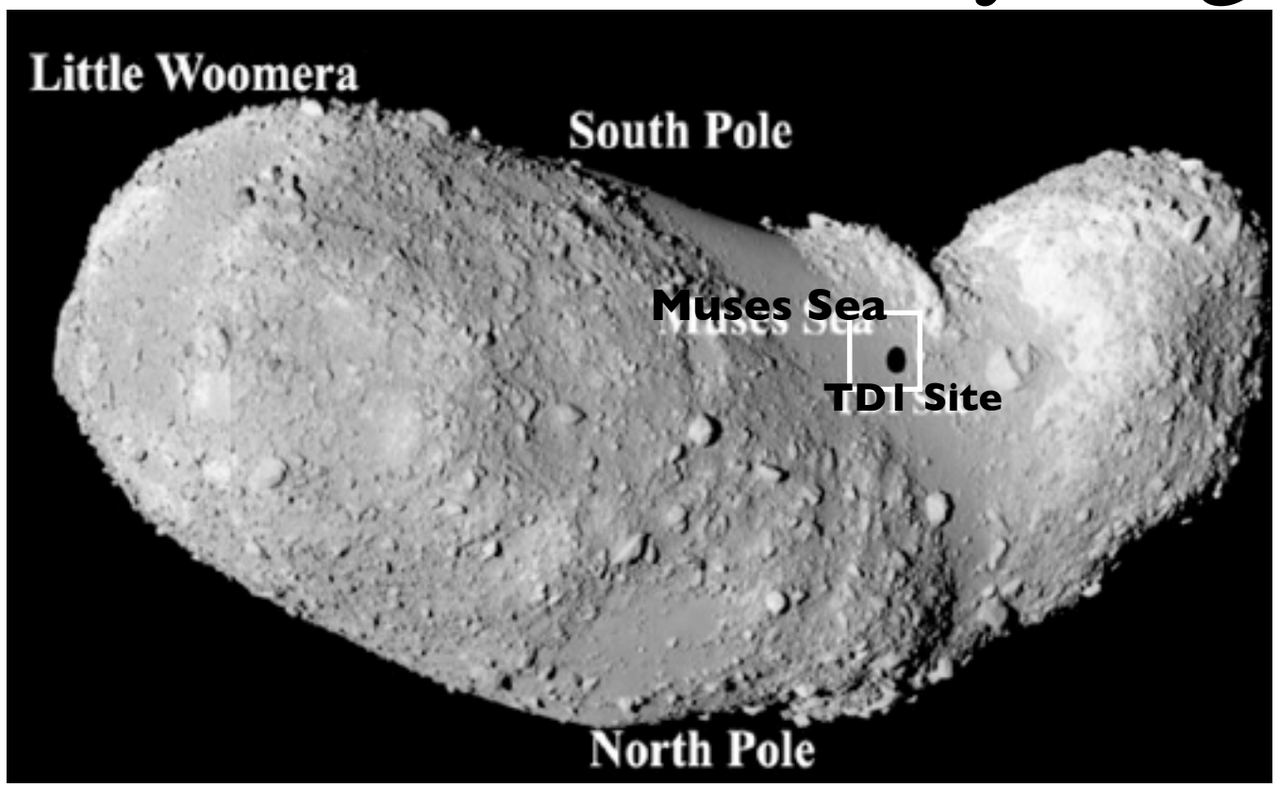
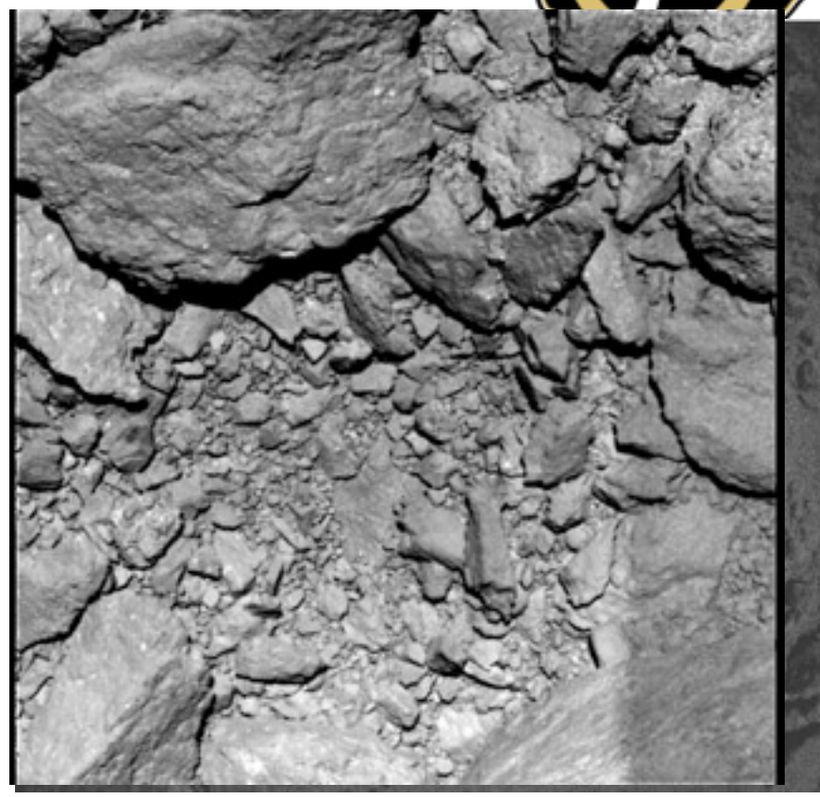
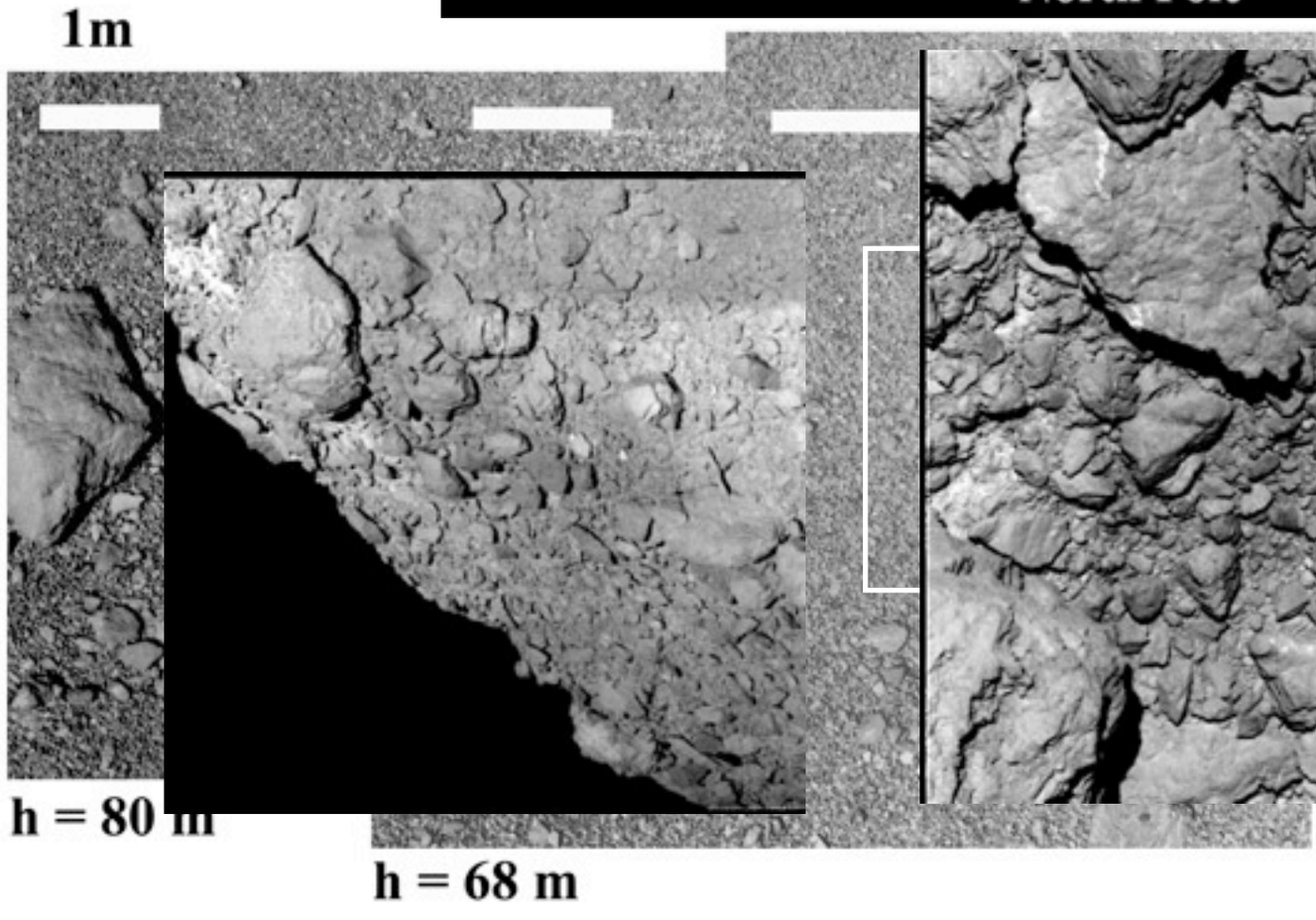
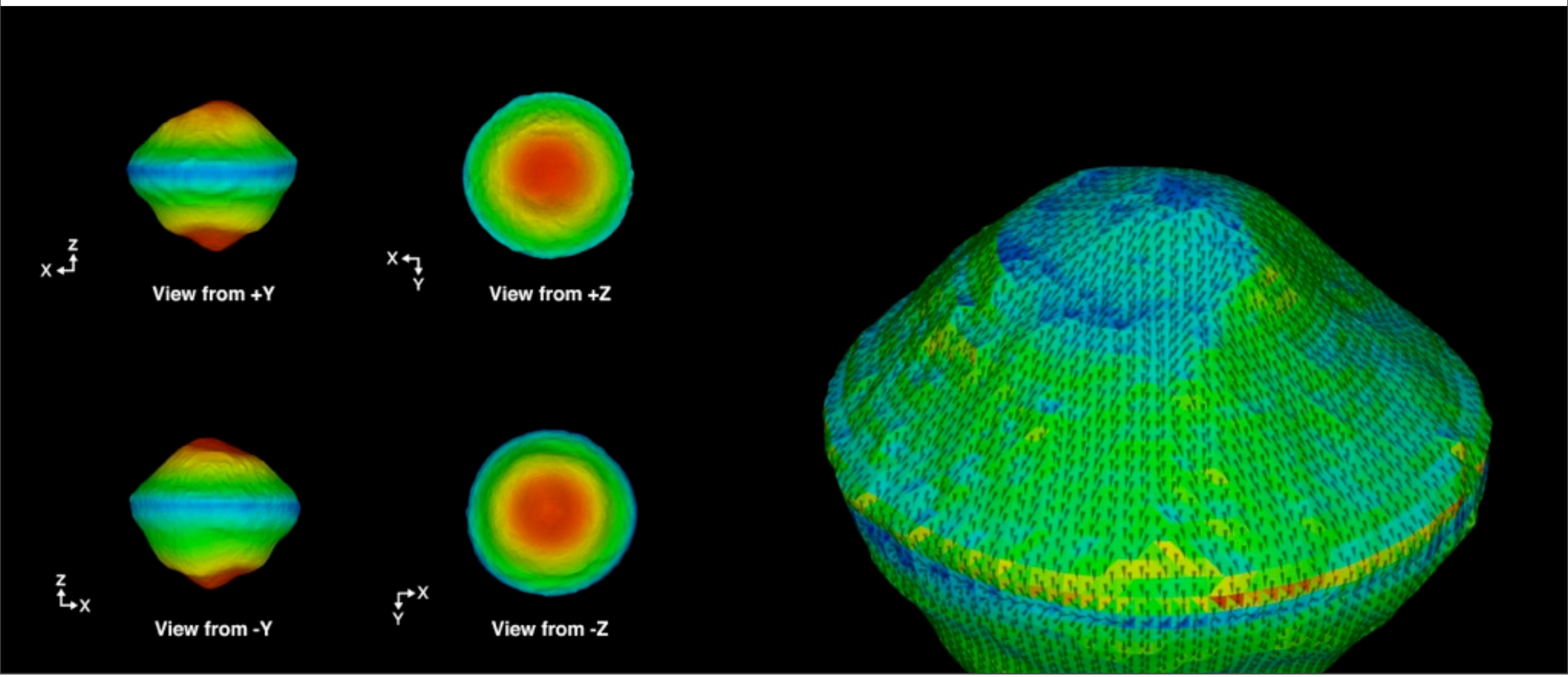




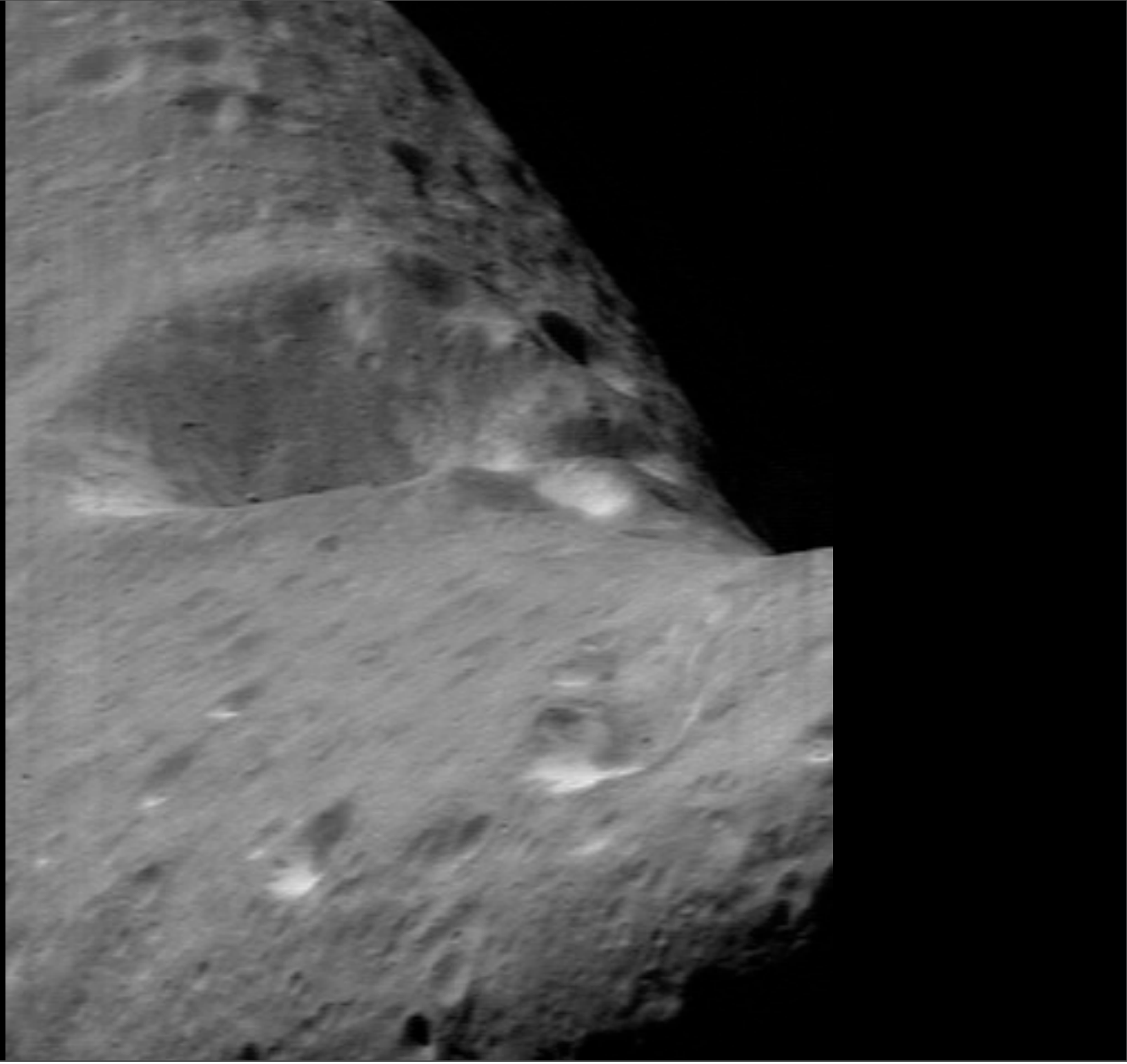


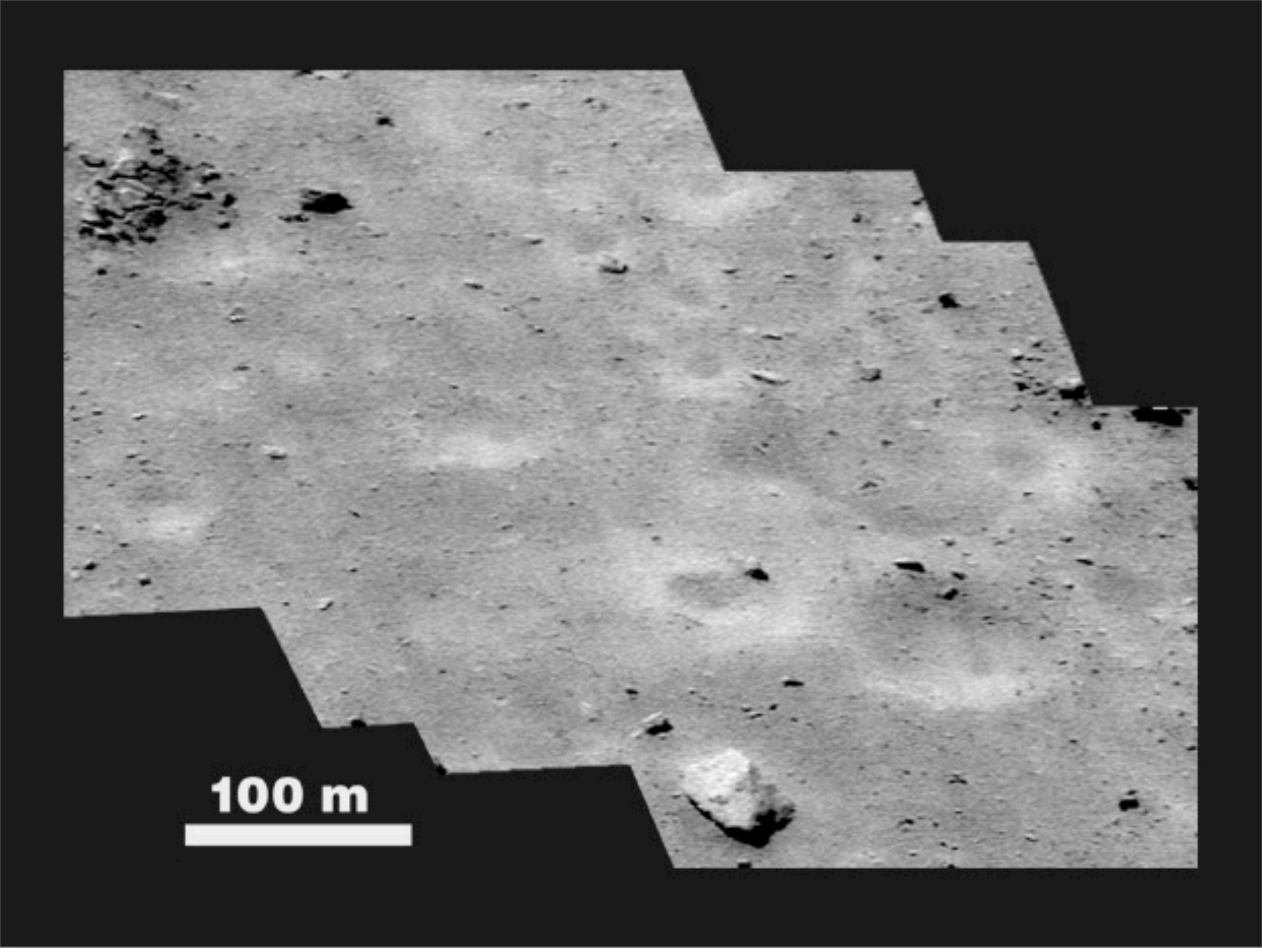
Binary Asteroid 1999 KW4 ...

- ... is consistent with being a rubble pile
- The “lowest” point on Alpha is at its equator, causing loose regolith to settle there and forming the characteristic bulge
- Spins so fast the equator has a near-zero surface acceleration

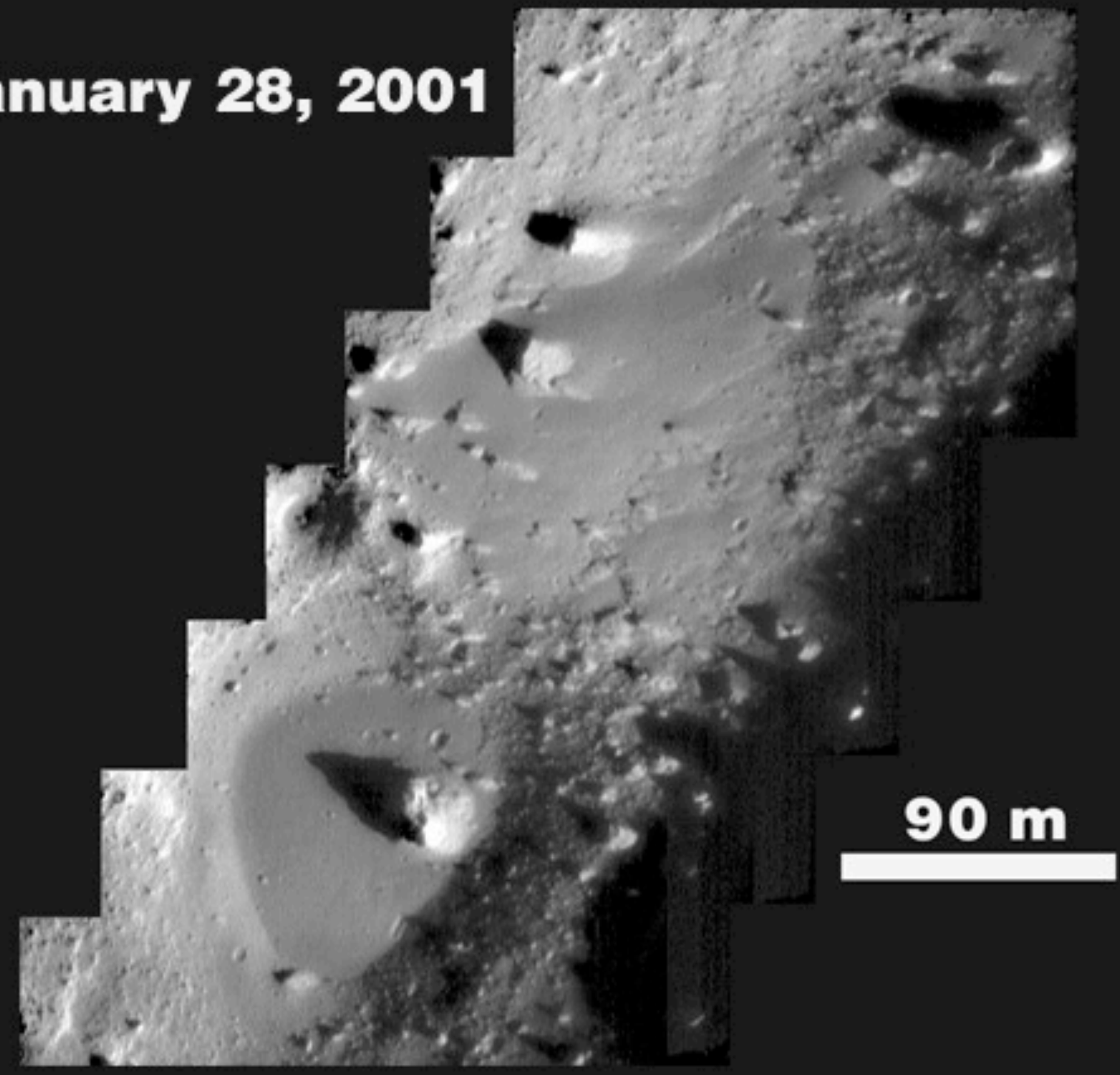


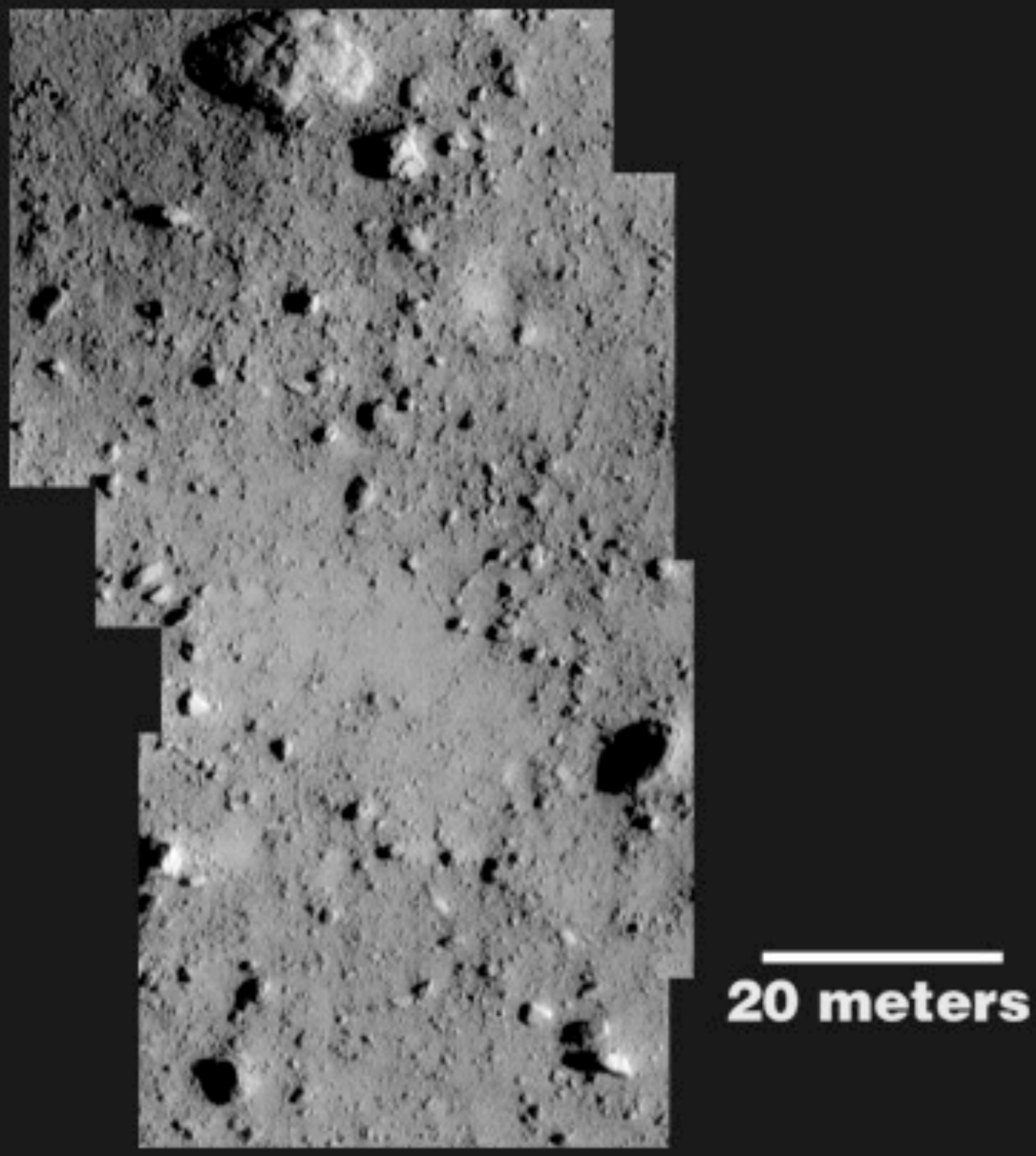
Eros shows a changing surface as a function of resolution

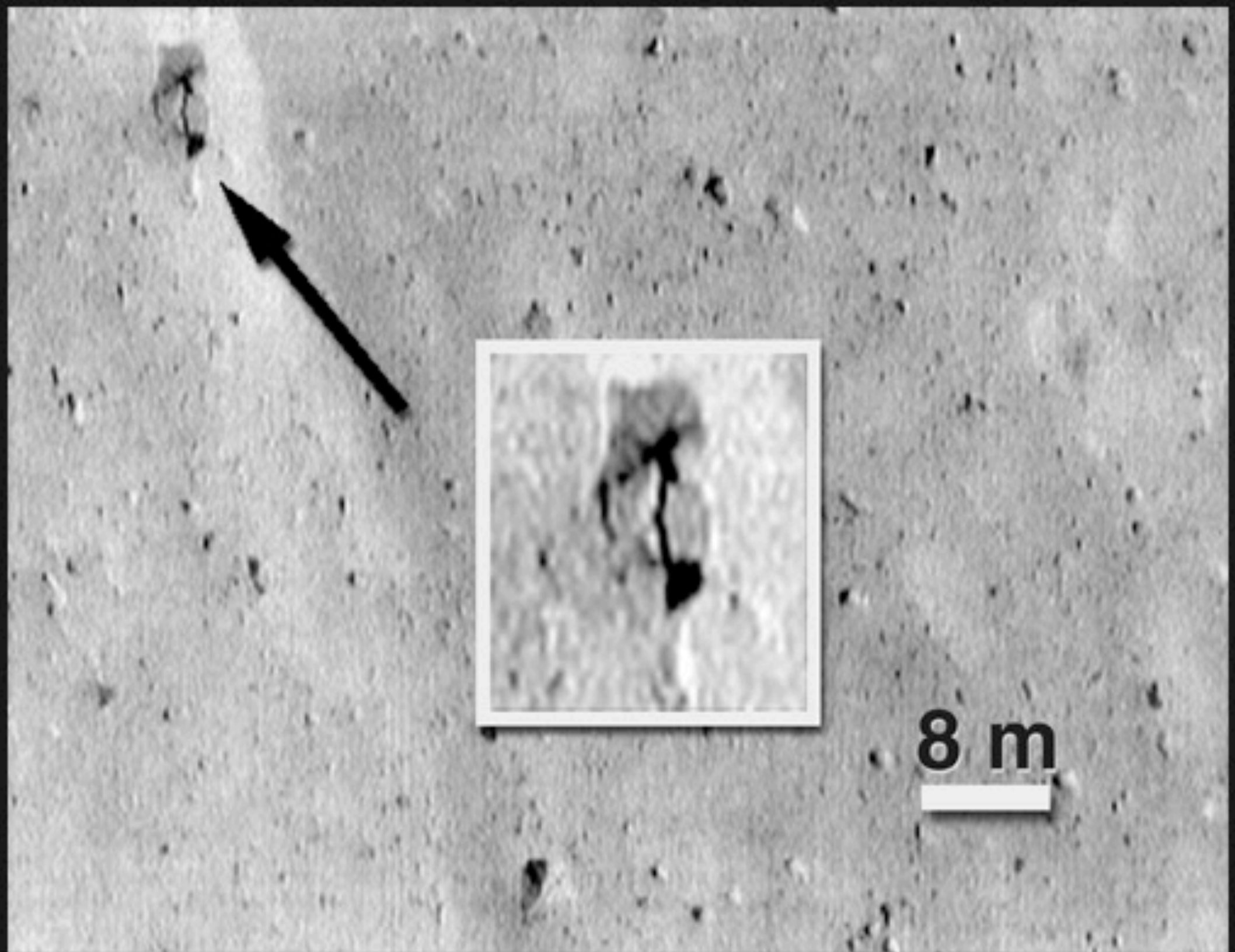


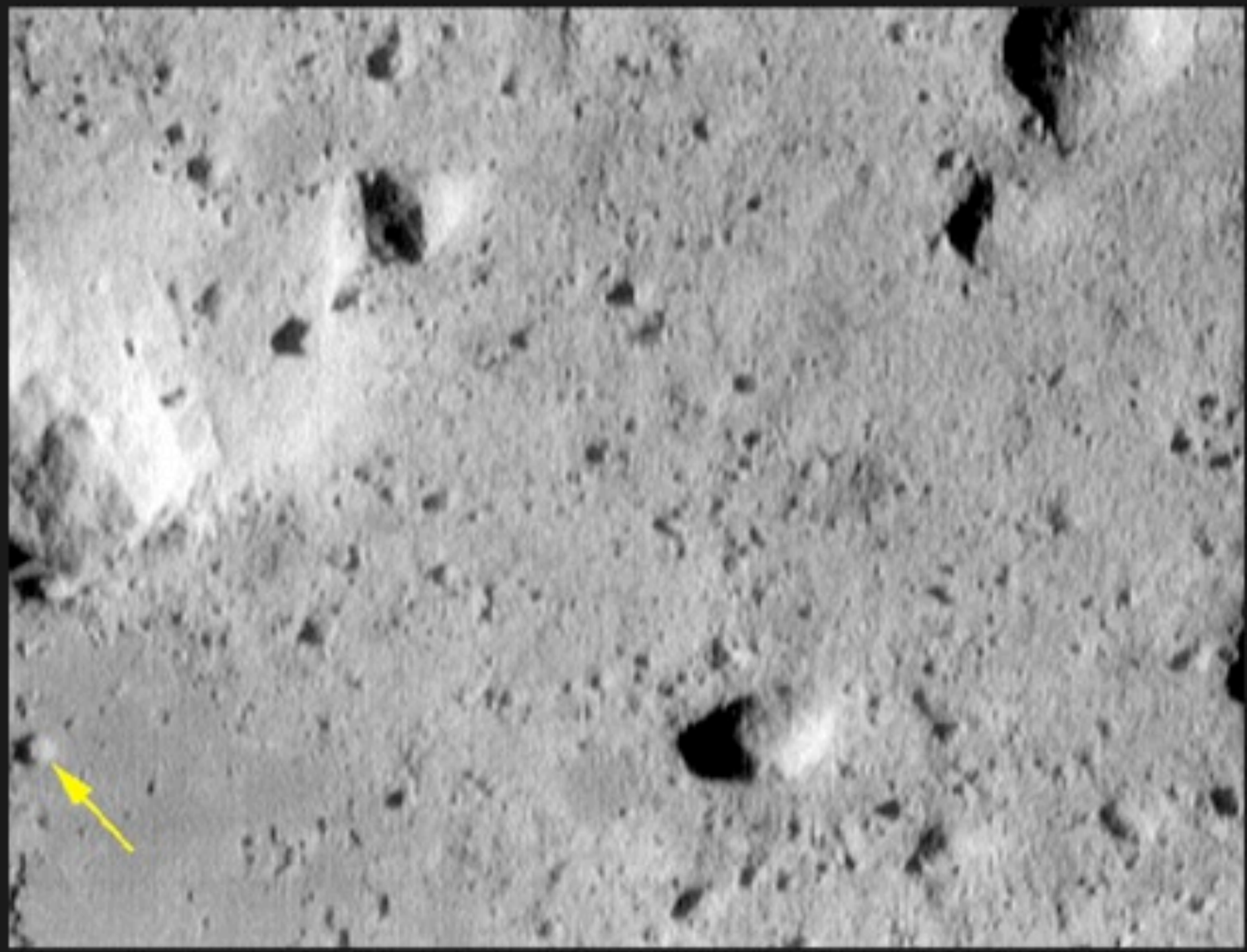

100 m

January 28, 2001




20 meters


8 m


2 meters

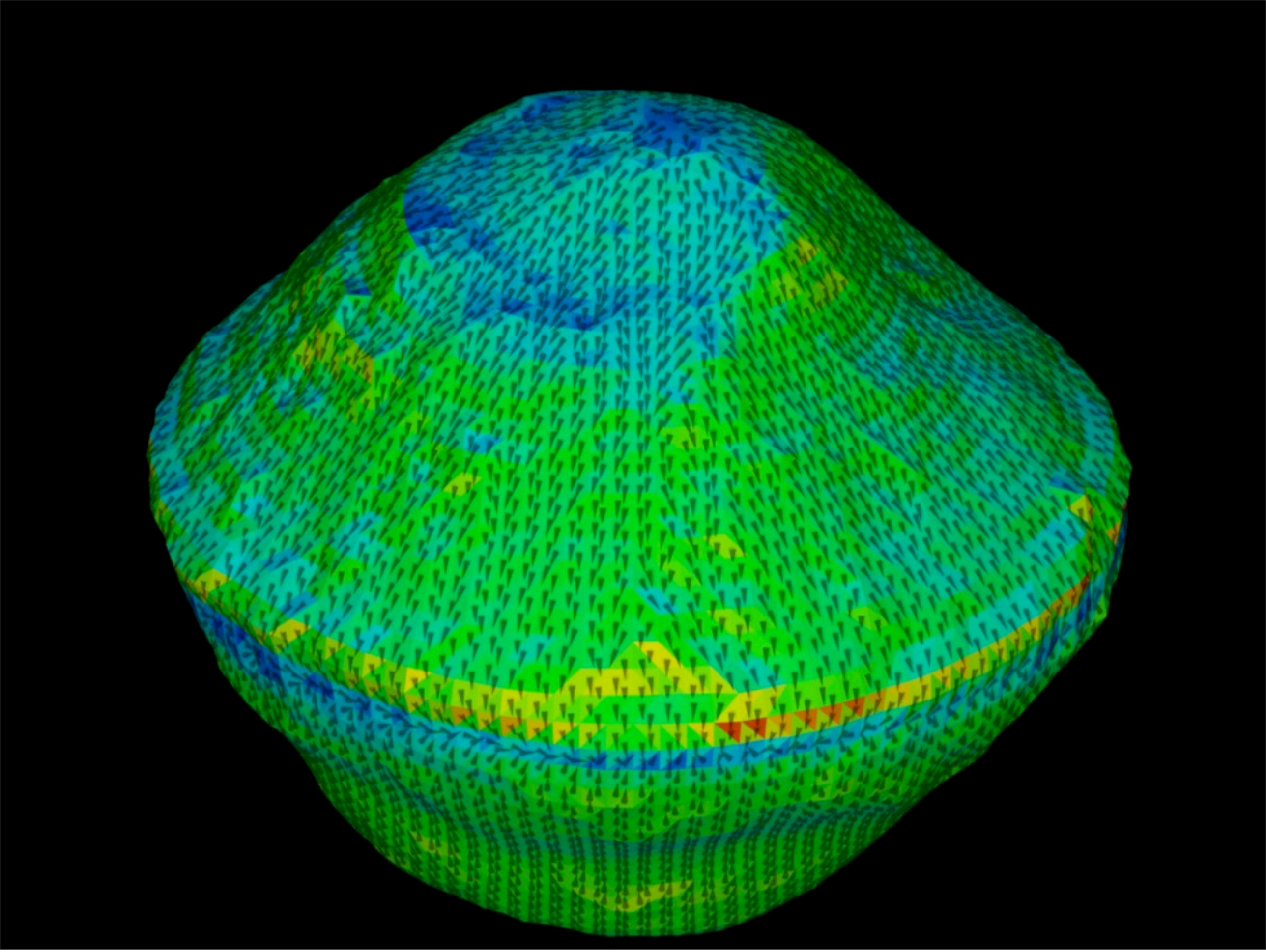
Classical View of Rubble Pile Asteroids

- Asteroids are composed of a distribution of boulders down to small scale gravels (dust?)
  - Maximum size may be on the order of ~100 meters (largest blocks seen on Eros, largest size of fast spinners)
  - Minimum size should be ~ micron-sized dust
- Main mechanical effects for rubble pile asteroids arise from:
  - Mass and mass distribution
  - Shape and size of rigid constituents
  - Rotation of the body
  - Surface friction between components
- All these effects scale uniformly with mass, size and density
  - As long as material strength properties are not exceeded leads to scale invariant systems...

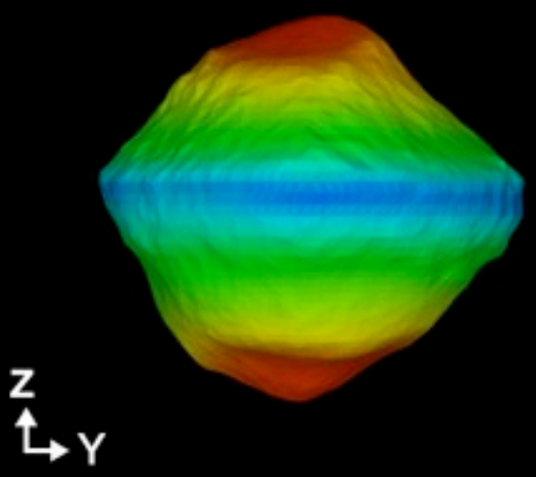
- ... but asteroids exist in a realm of milli to micro-G physics, where we have no intuition...
- What are the relevant physics of interaction in this regime?

Gravity (Gs)	Body
1	Earth
0.1	Moon
0.01	Vesta (180 km)
0.001 (milli G)	Eros (18 km)
0.0001	Toutatis (1.8 km)
0.00001	Itokawa (0.18 km)
0.000001 (micro G)	(0.018 km)
< 0.0000001 (100 nG)	KW4 Equator

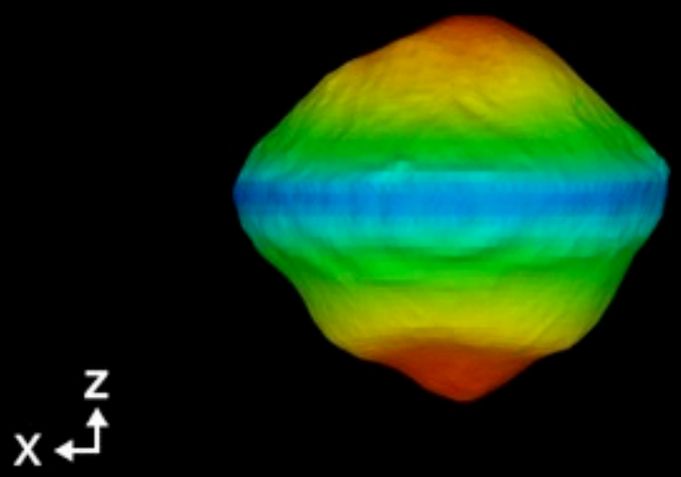
Approximate surface G asteroid relations



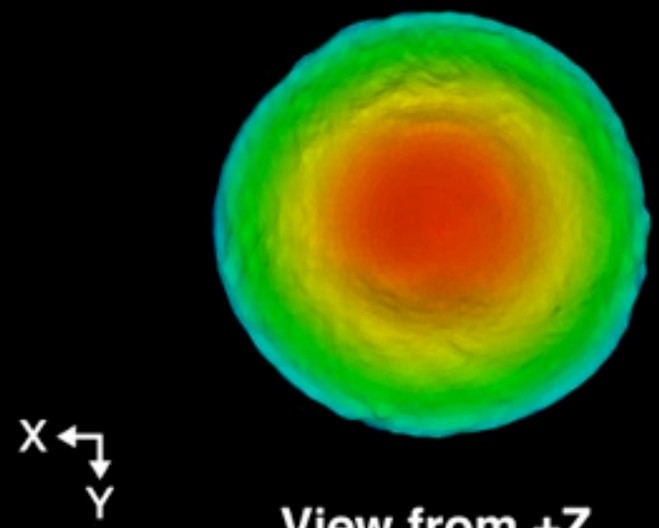
1999 KW4 Alpha



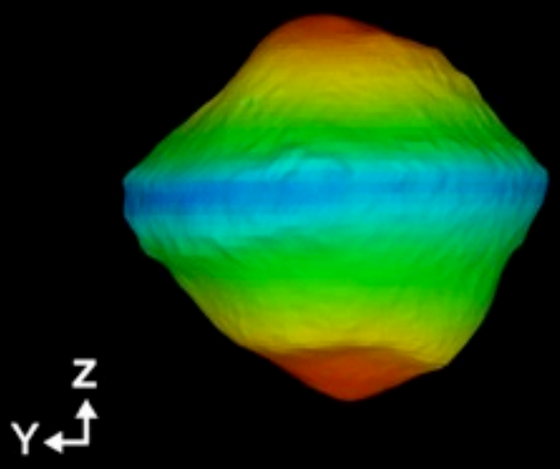
View from +X



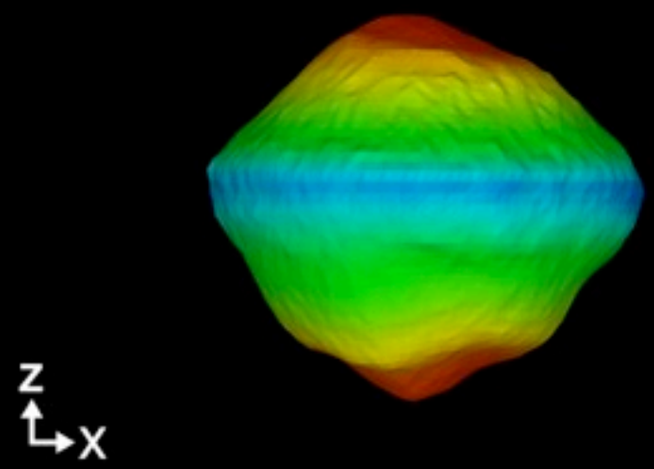
View from +Y



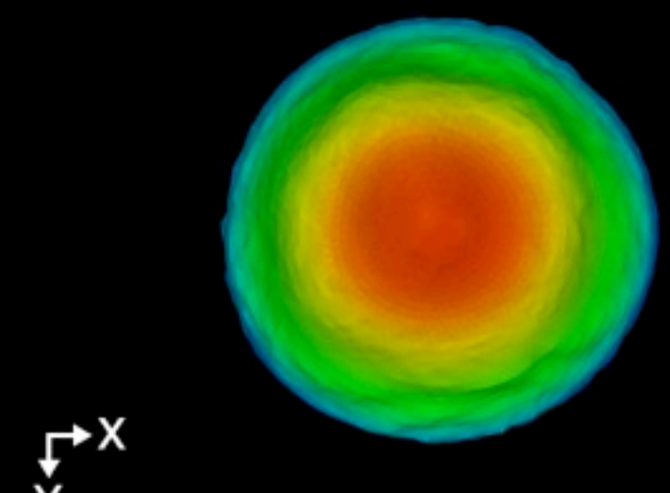
View from +Z



View from -X

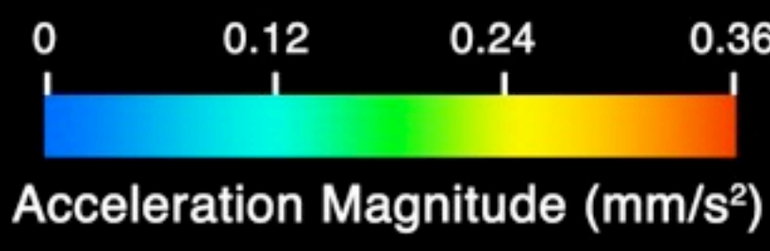


View from -Y



View from -Z

1 KM



~ 40 µG

What Forces are relevant?

- Gravitational Forces:
  - Gravitational attraction
  - Inertial effects
- Classical Contact Forces:
  - Coulomb Friction
- Non-Gravitational Forces:
  - Solar Radiation Pressure
  - Electrostatics
  - van der Waals Cohesion

- *Forces* are not generally considered in studying rubble pile asteroids, usually only *accelerations*
  - Arises from primacy of gravitation, rotation and friction, allowing masses to scale out
  - Inclusion of non-gravitational forces changes the picture

Forces as a Function of Particle Size

– **Gravity & Rotation**:

$$F_{gr} = m\left|\omega^2 r - g\right| = \frac{4\pi\rho}{3}R^3 g_a$$

– **Friction**:

$$F_F = \mu\left[m g_a + F_{ng}\right]$$

On surface, controlled by ambient weight and non-gravitational forces

– **Electrostatics**:

$$F_{es} = C_{es}R^2$$

$$C_{es} = \left[10^{-8}, 10^{-1}\right]$$

Transient, with max value for localized regions at the terminator

– **Solar Radiation Pressure**:

$$F_{srp} = C_{srp}R^2$$

$$C_{srp} = 10^{-5}/d^2$$

$d =$ Asteroid distance from sun in AU

– **Cohesion (due to van der Waals attraction)**:

$$F_{vdw} = C_{vdw}R$$

$$C_{vdw} = 4 \times 10^{-2}$$

Derived for lunar regolith in (Perko et al. 2001)

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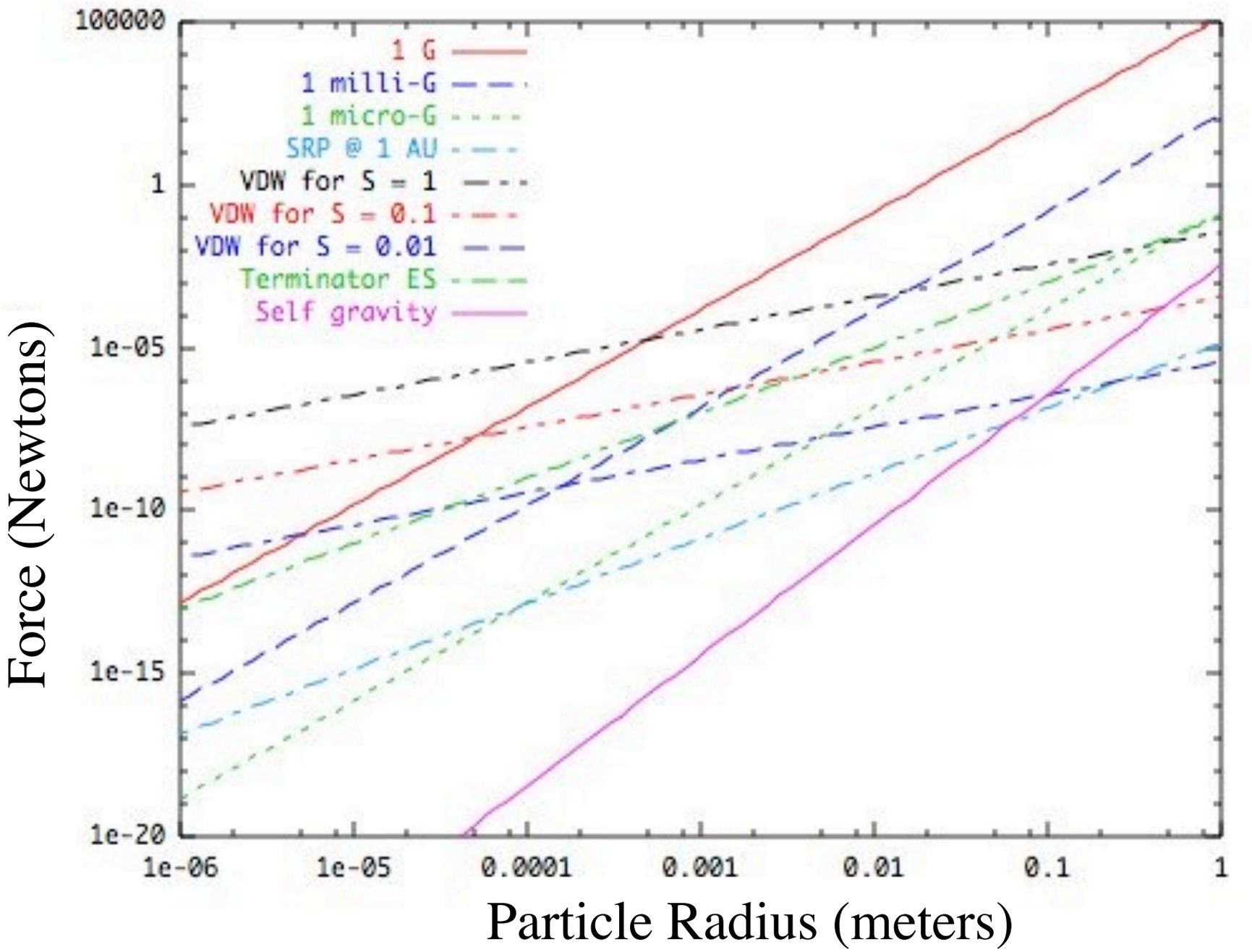
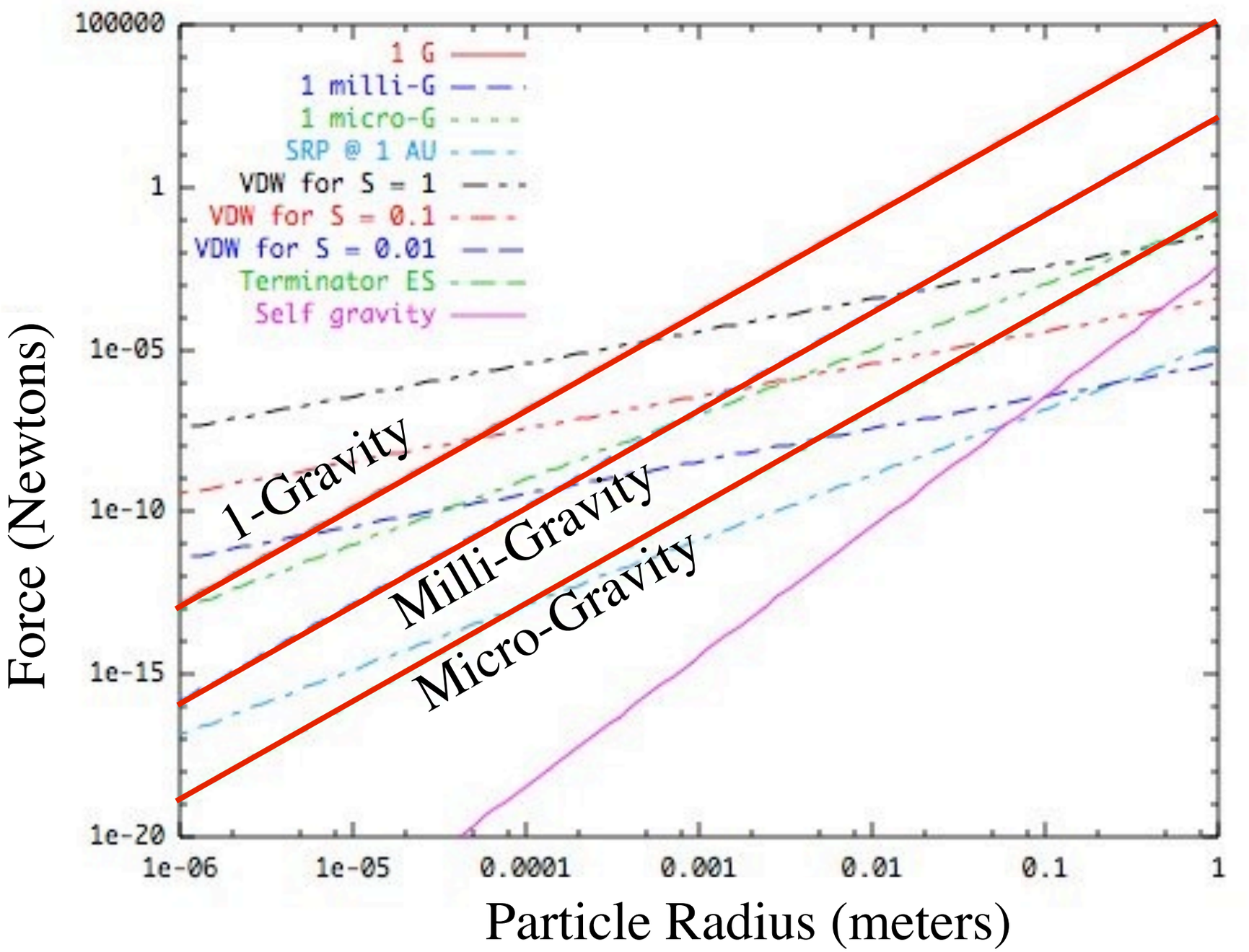
Comparisons of Forces/Sizes



Inter-particle cohesion forces are relevant for centimeter-sized particles in milli-G and larger particles in micro-G environments

Comparisons of Forces/Sizes



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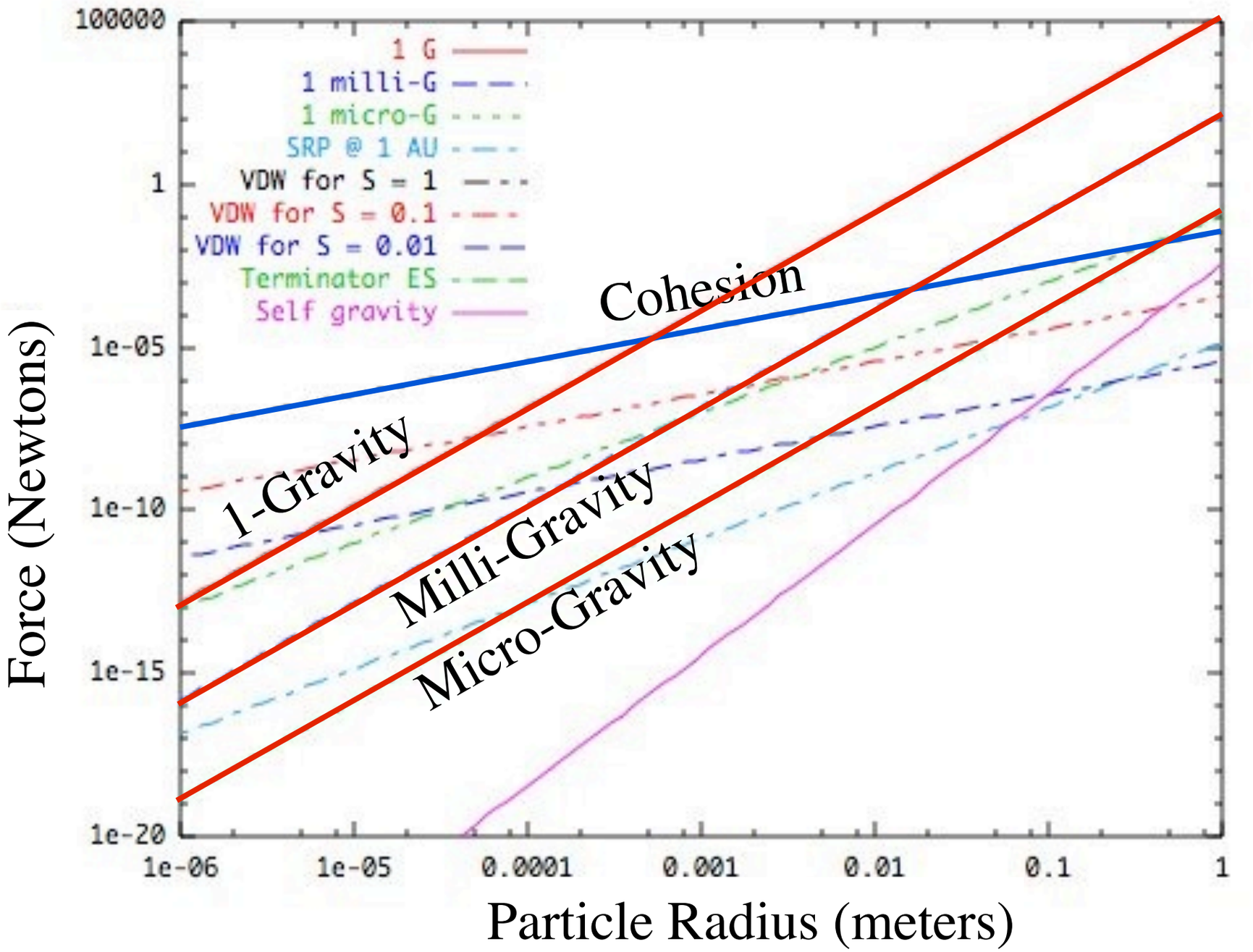

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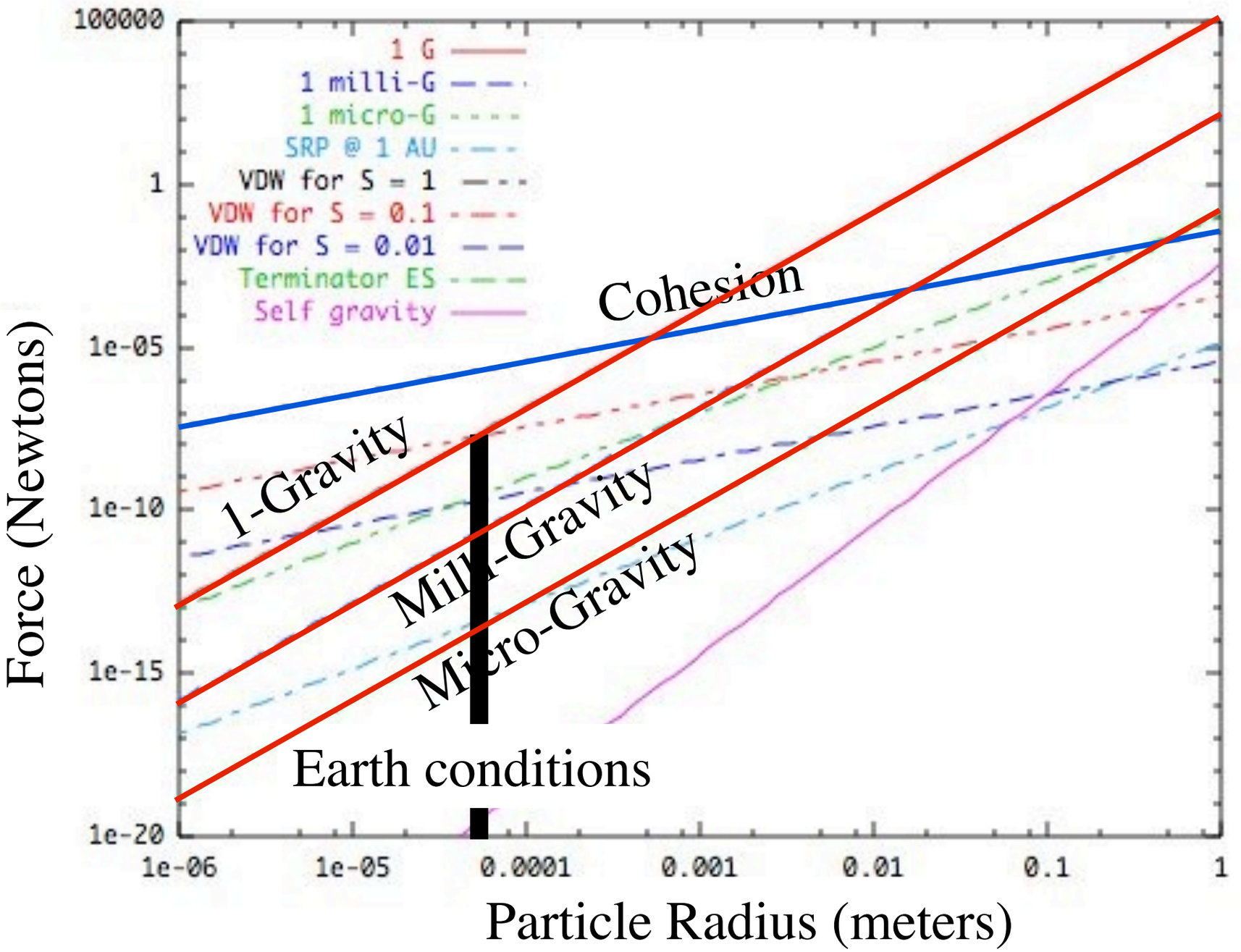

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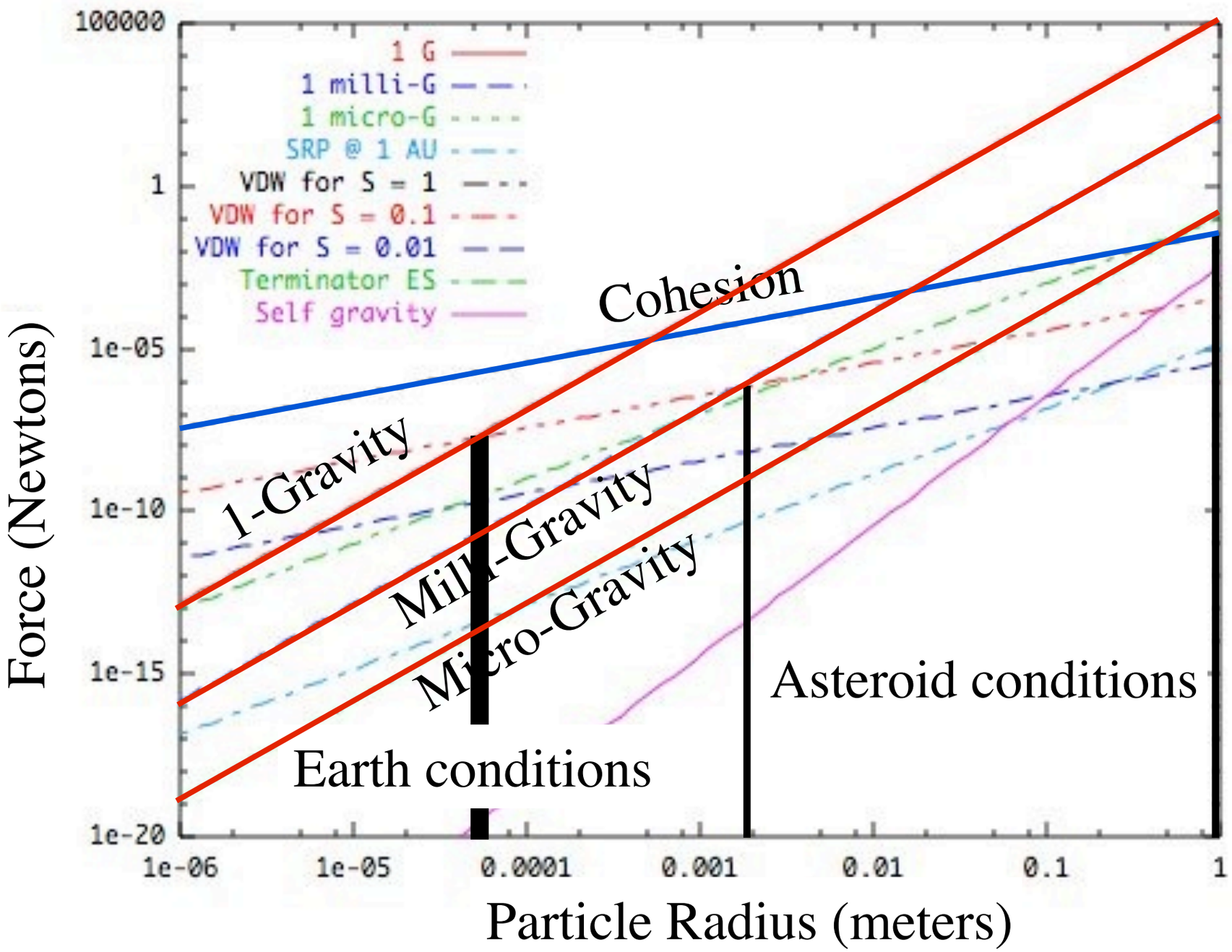

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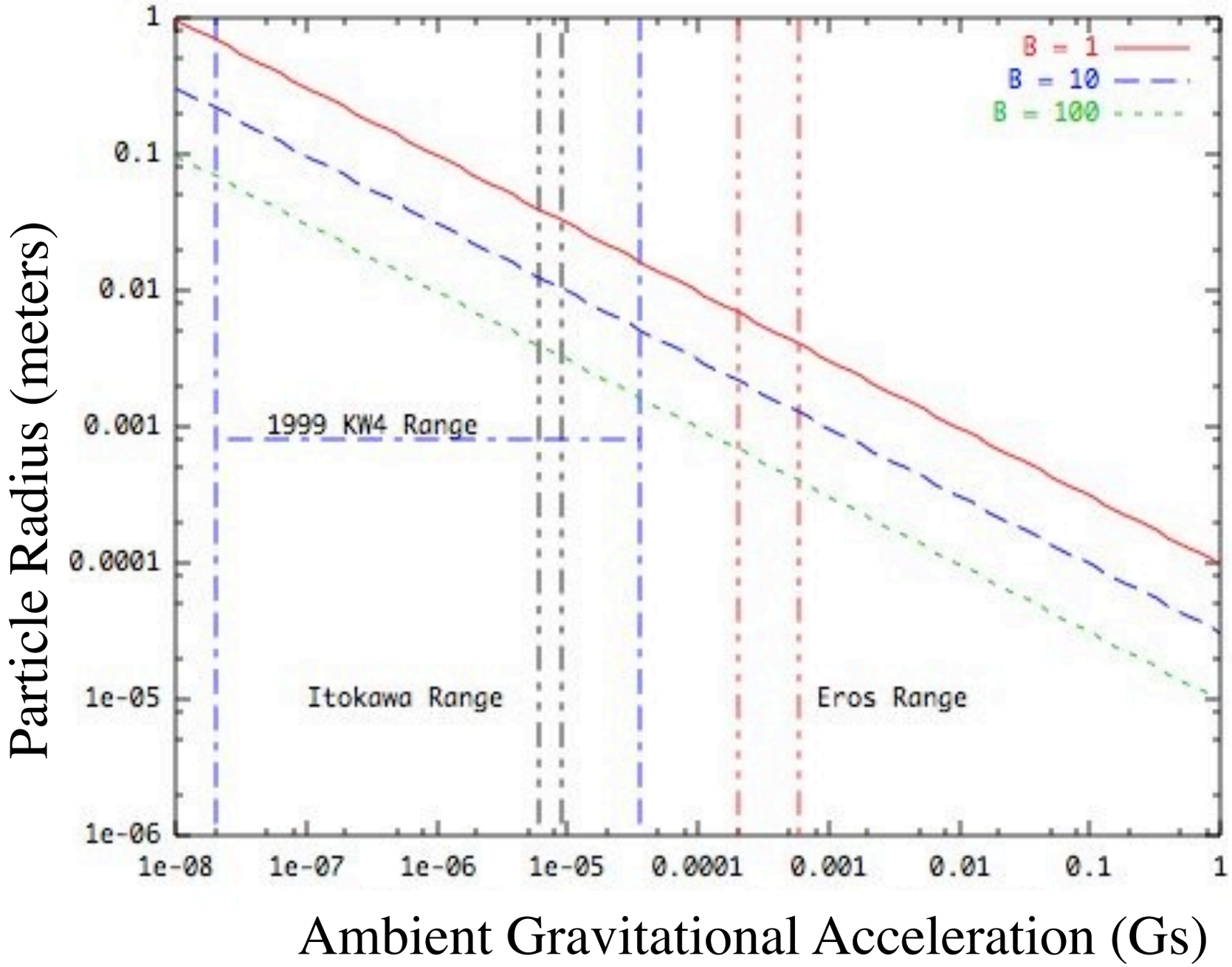
Cohesion Bond Numbers



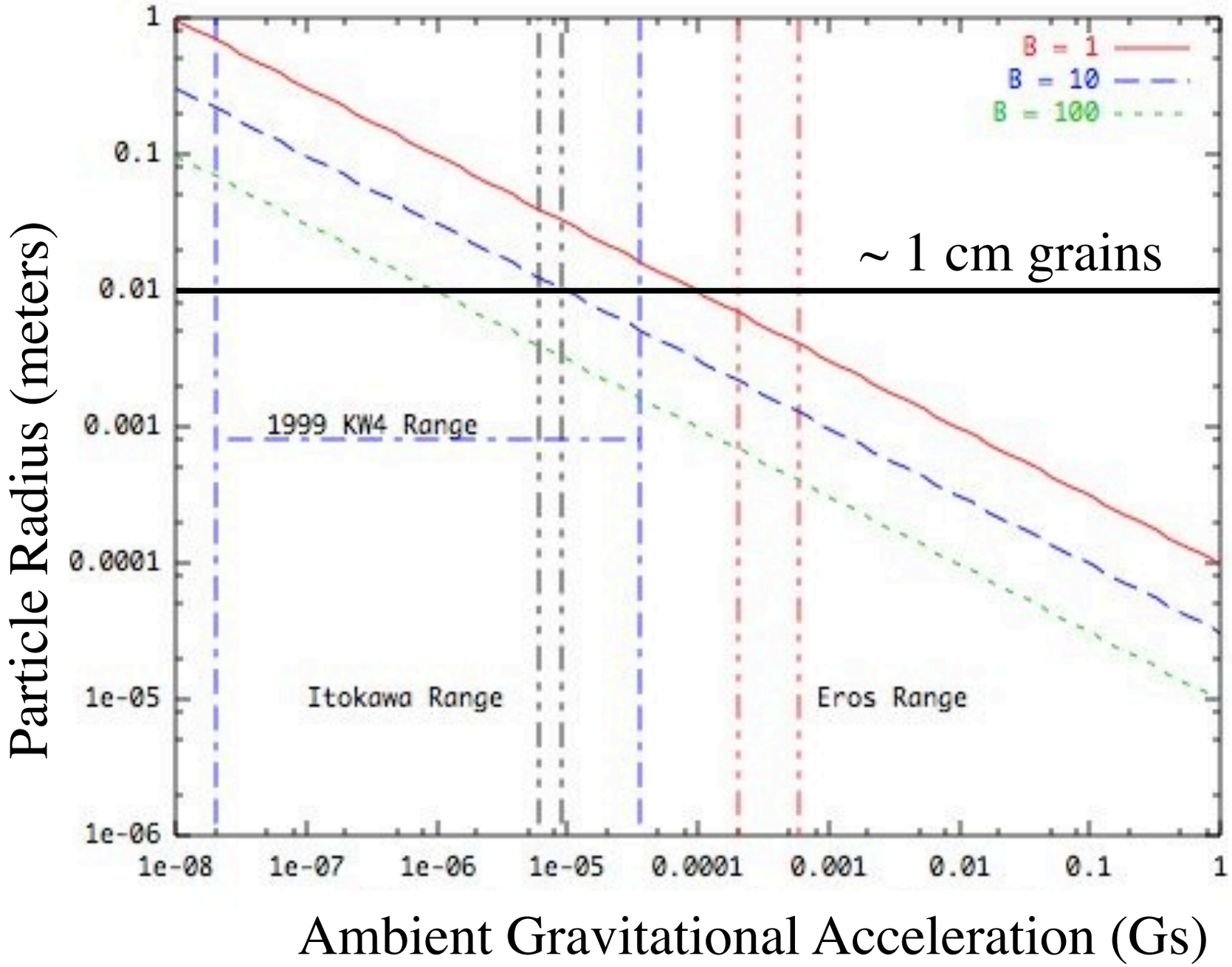
Bond Number = Ratio of Cohesion Force with Weight

= 1 for equality

= 10-100 for macroscopic granular effects

> 100 leads to formation of larger-sized aggregates

Cohesion Bond Numbers



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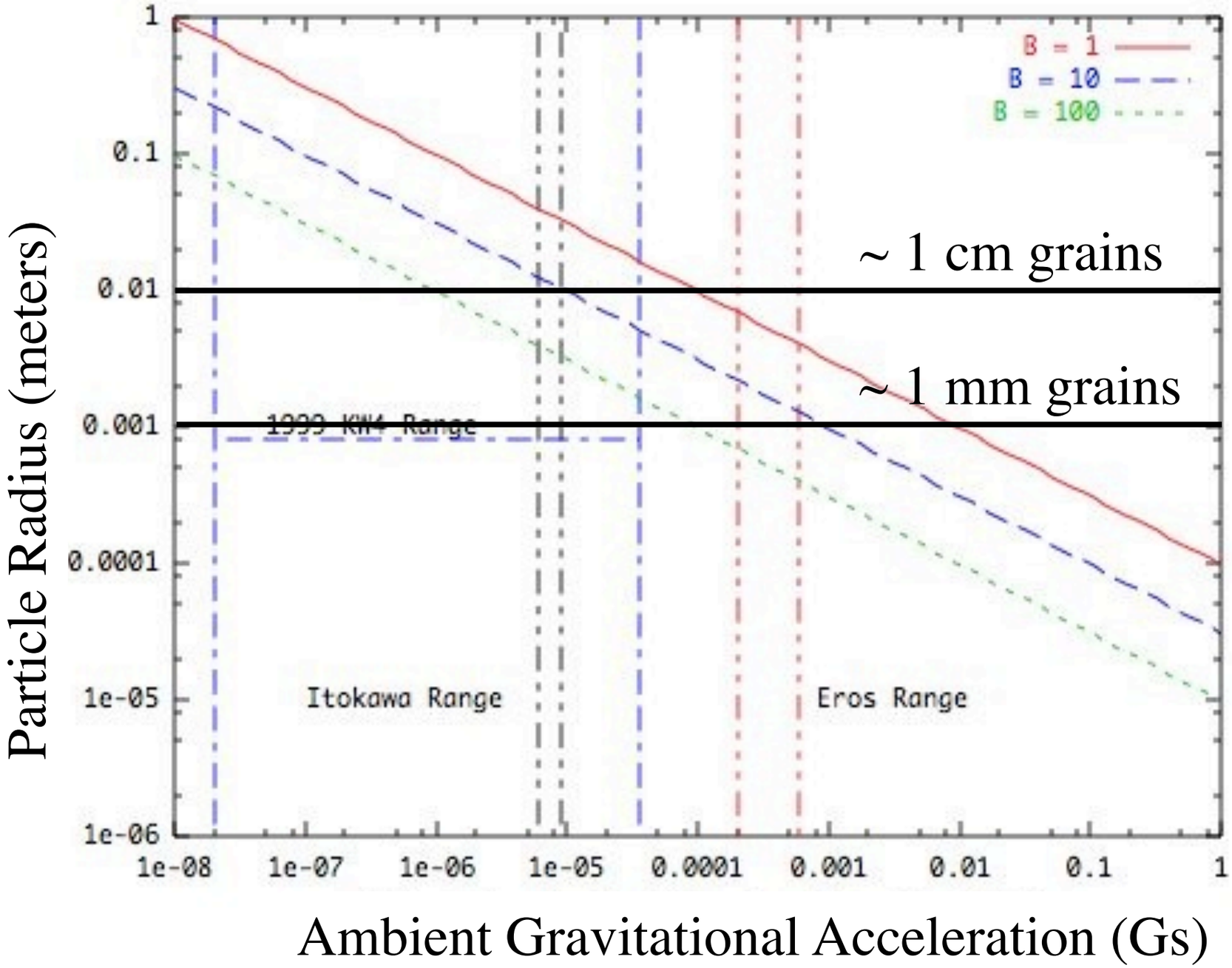

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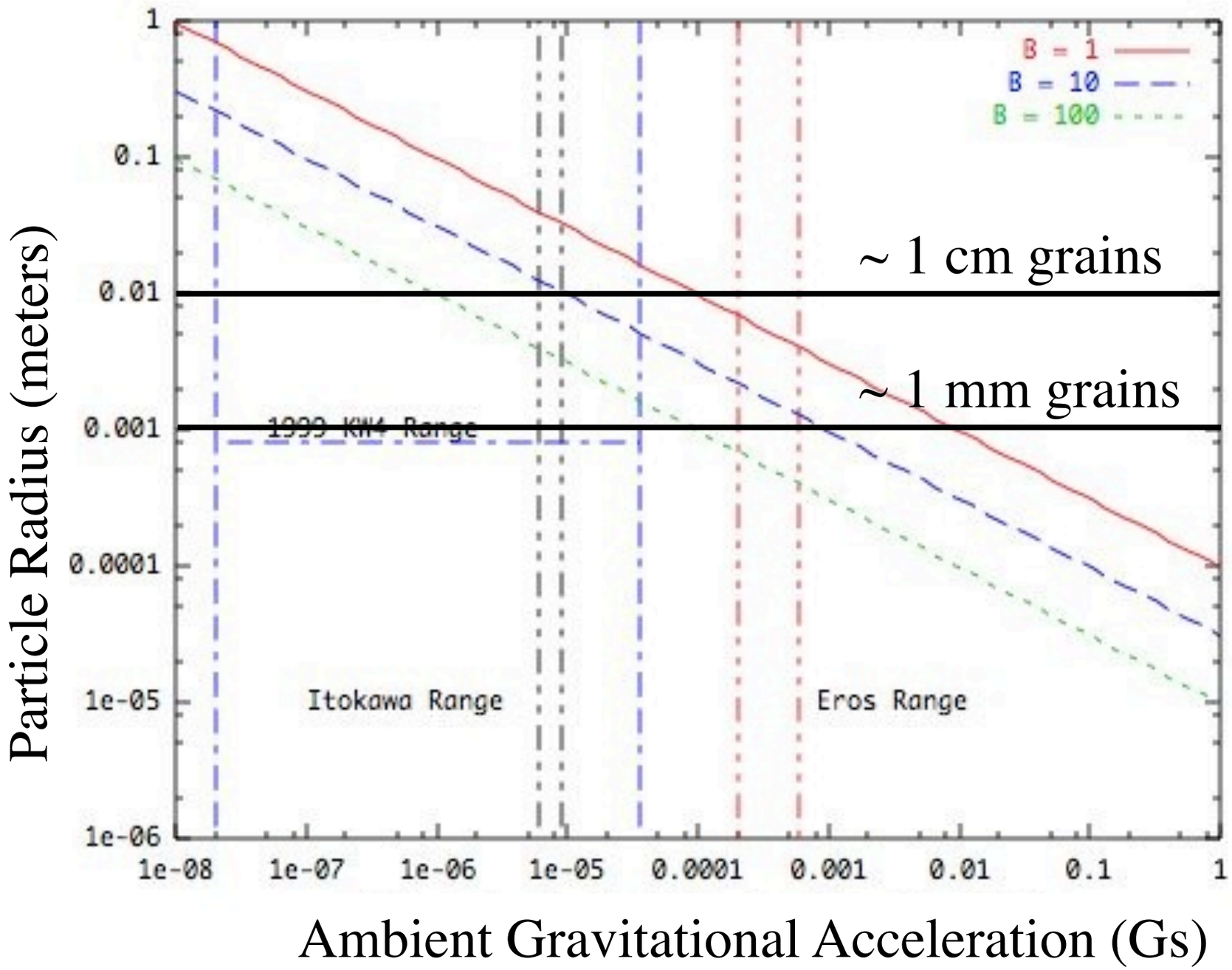
Cohesion Bond Numbers

Asteroid Regolith is Analogous to Cohesive Powders on Earth



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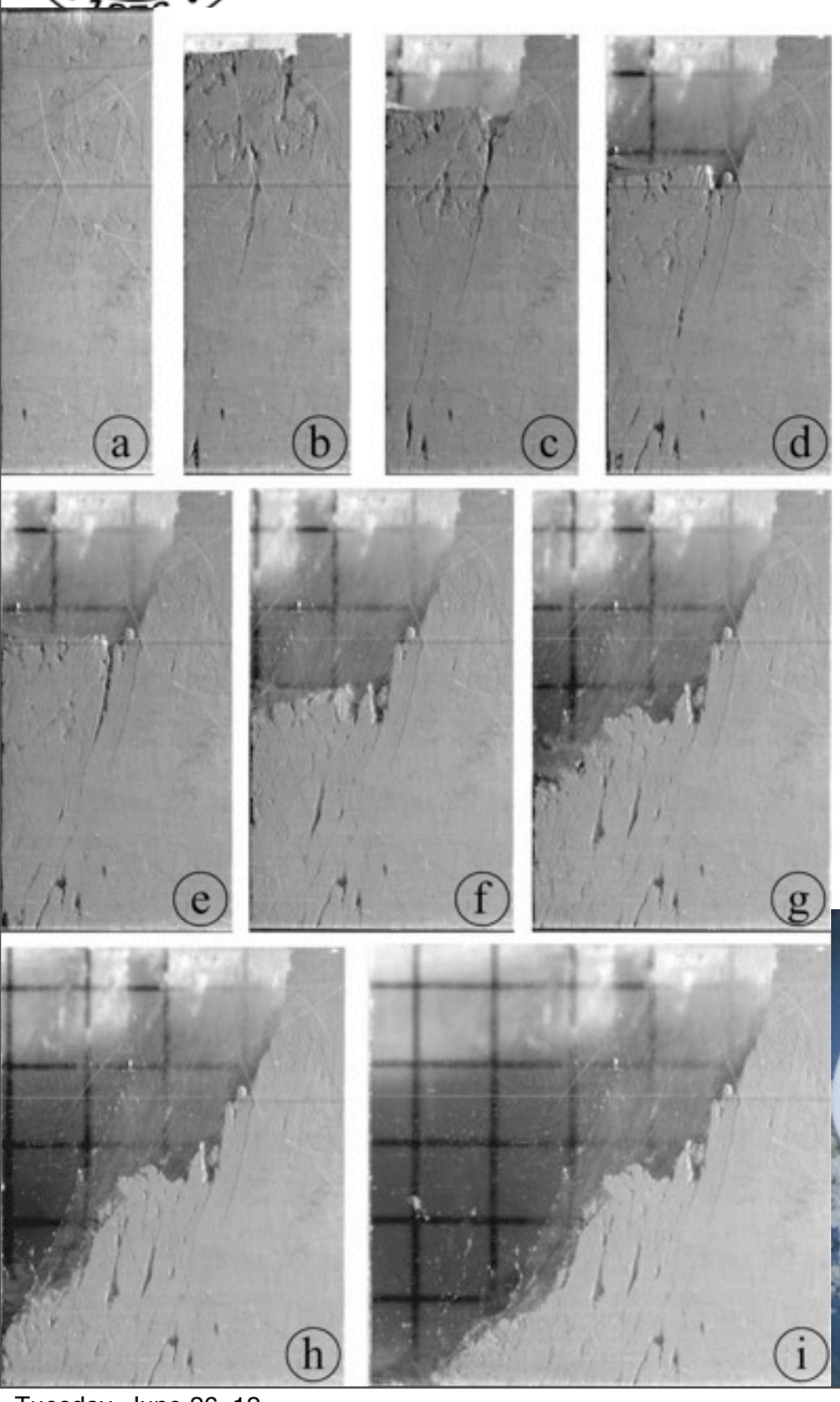
Mechanics of Cohesive Powders



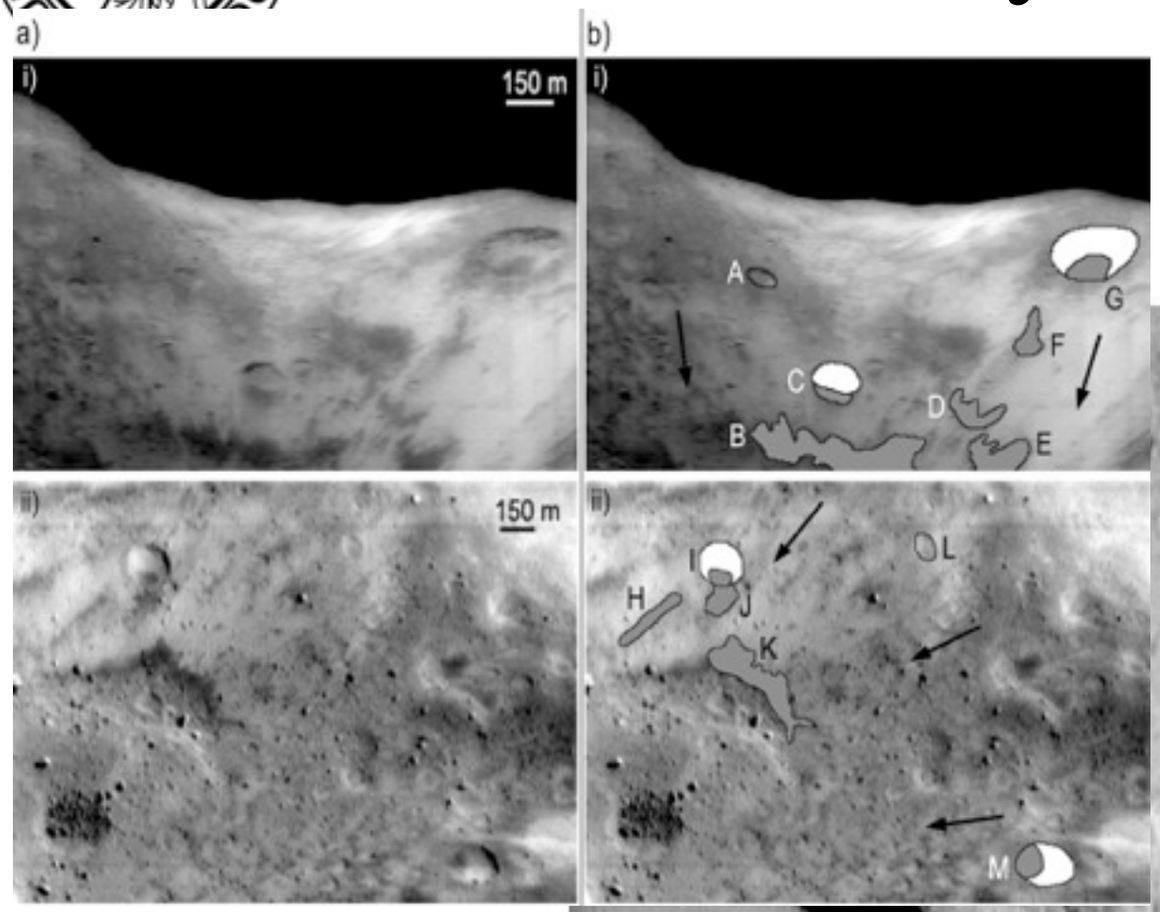
On Earth: Stress fractures occur along planes of weakness, clumping of grains, ability to support high slopes at small scales

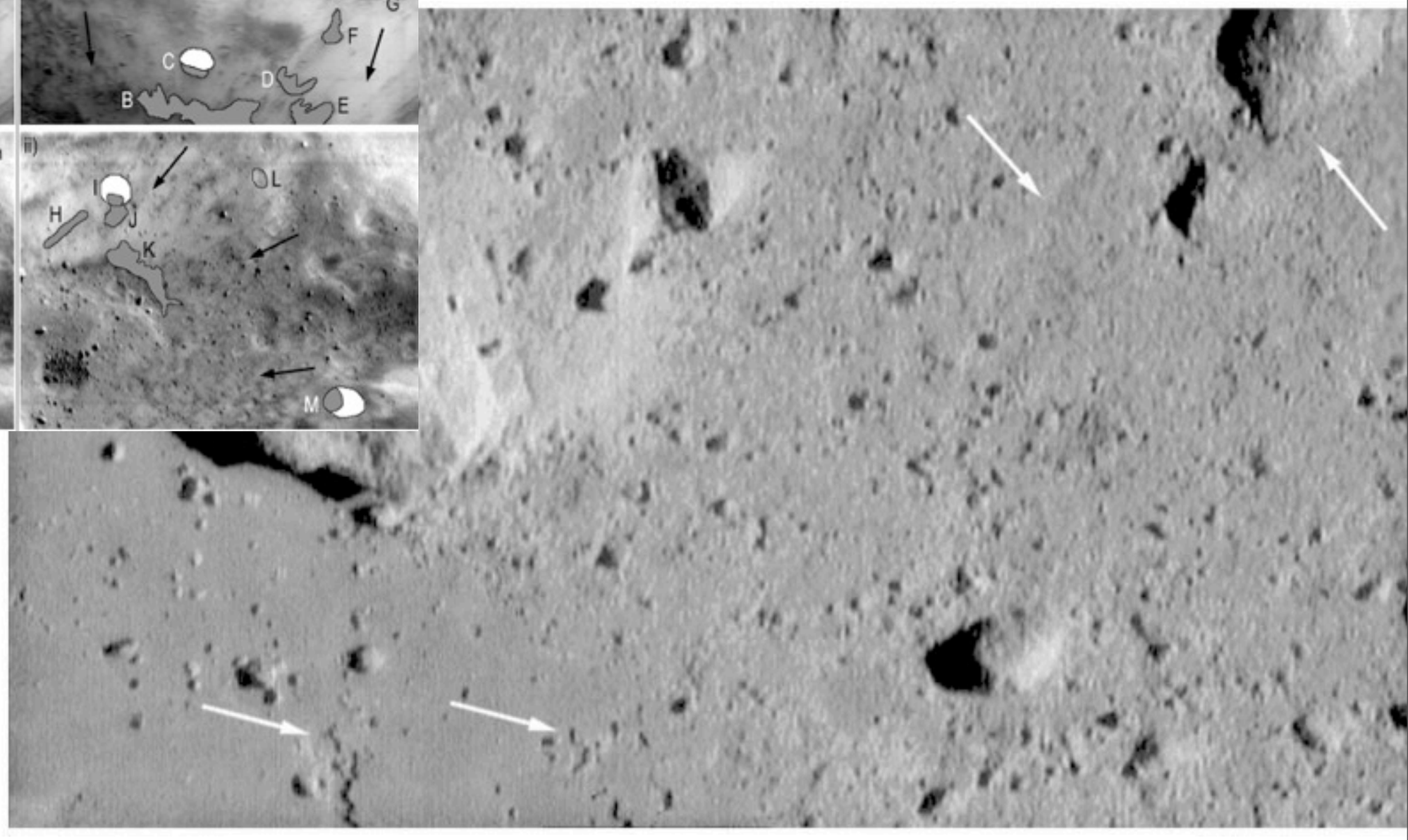
On Asteroids: Scaled effects of cohesion predict similar properties for sizes up to ~ mm-cm sized grains. Implications include greater strength at small scales, different geophysical responses, and an ability to spin much faster than cohesionless gravity limits.

D.J. Scheeres, C.M. Hartzell, P. Sanchez, M. Swift. 2010. "Scaling forces to asteroid surfaces: The role of cohesion," *Icarus* 210: 968-984, 2010.

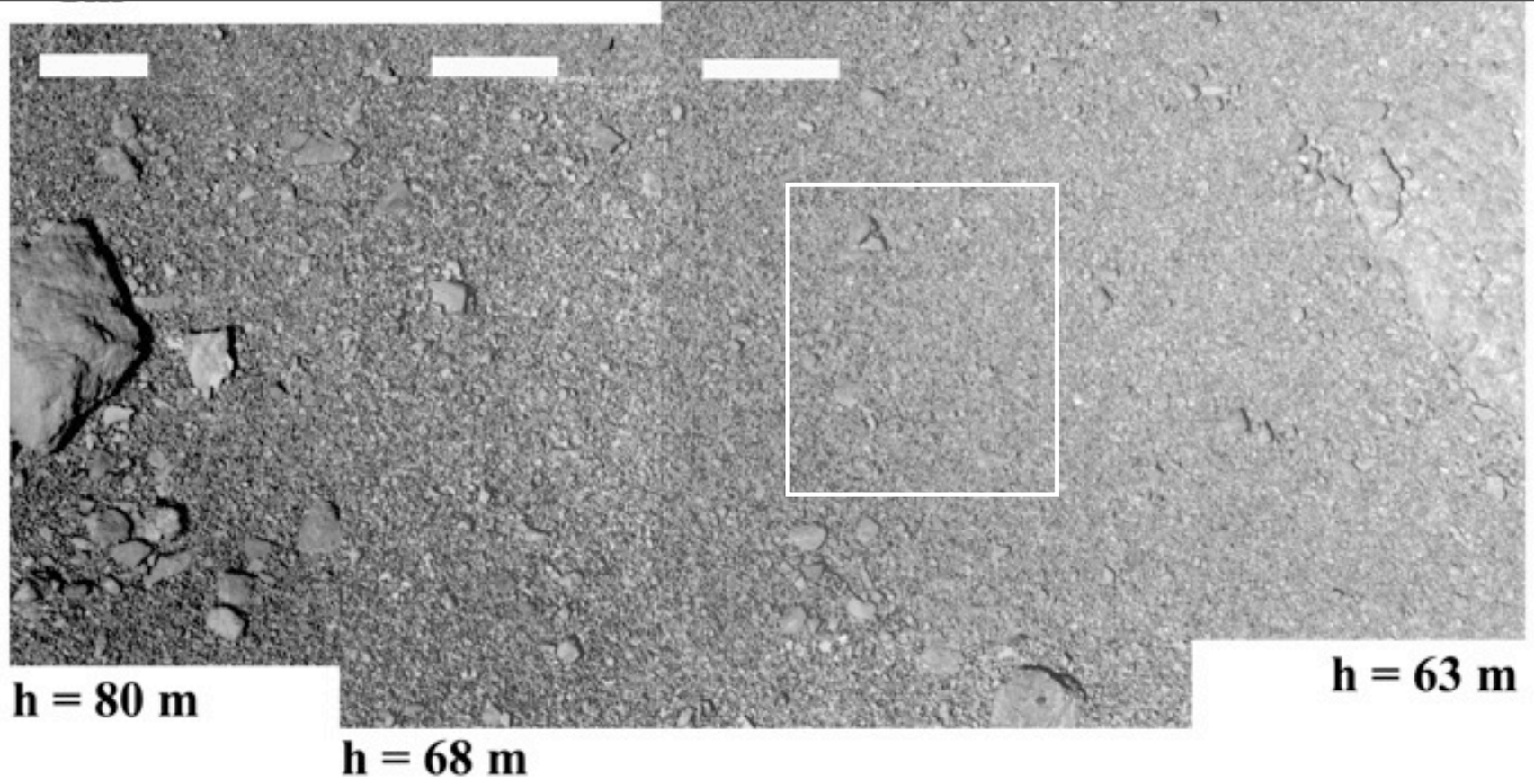
Consistency with Observations

Regolith Migration on Eros fits cohesion model (Mantz et al. 2004)



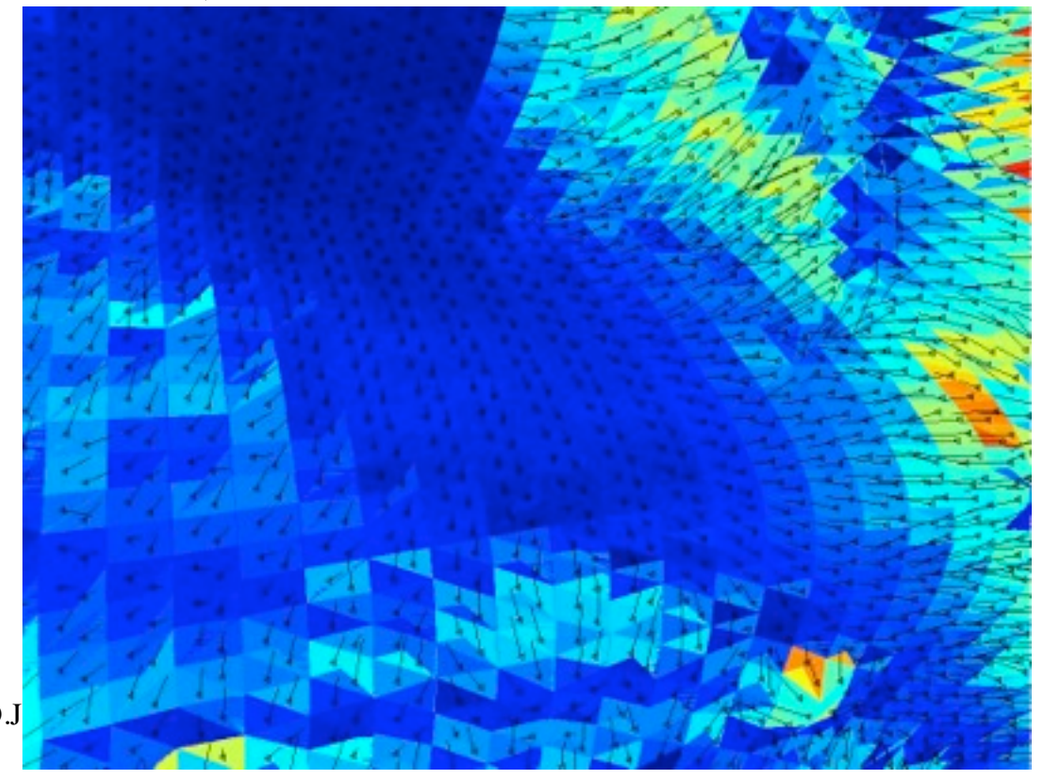


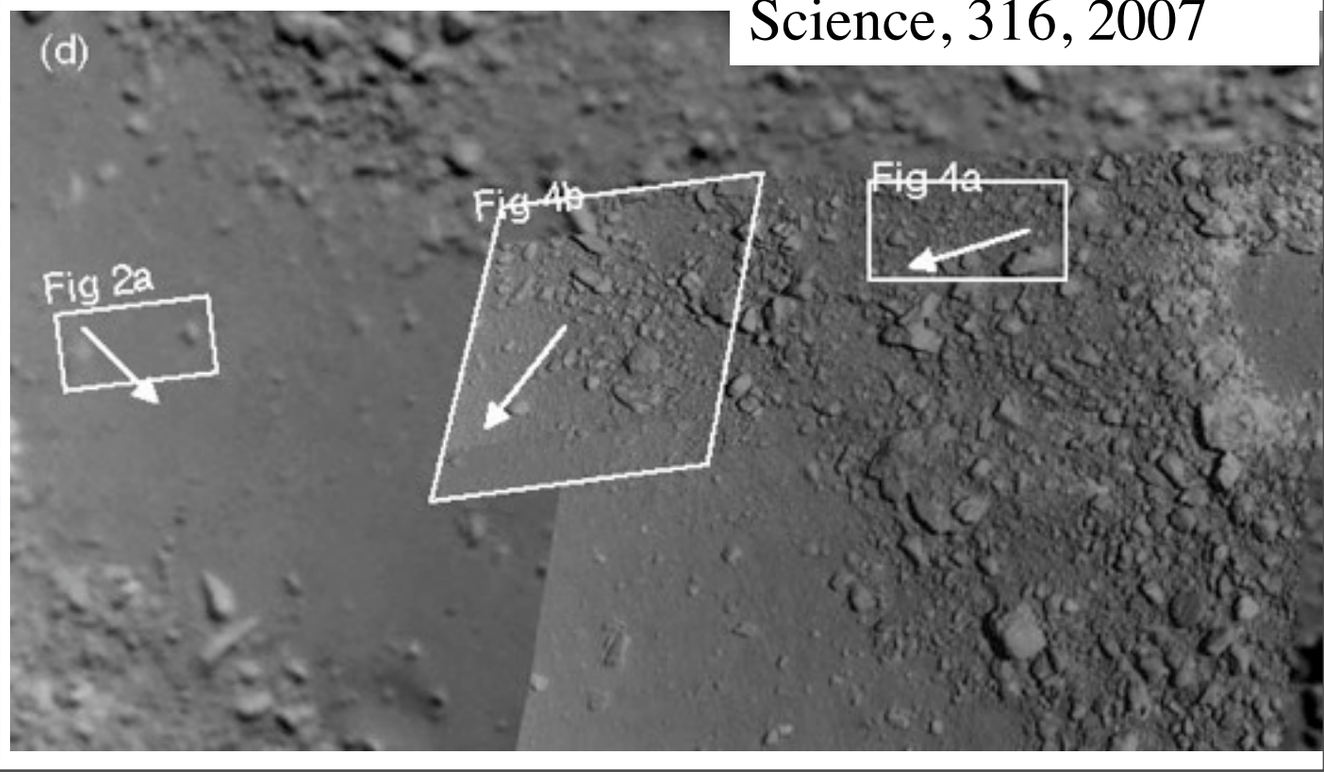
Surface dominated by particles that should have Bond numbers > 1



Itokawa's Sea region has compacted surface (high COE, Yano et al. 2006) and possible evidence of increased density (Scheeres & Gaskell 2008)

From Miyamoto et al., Science, 316, 2007





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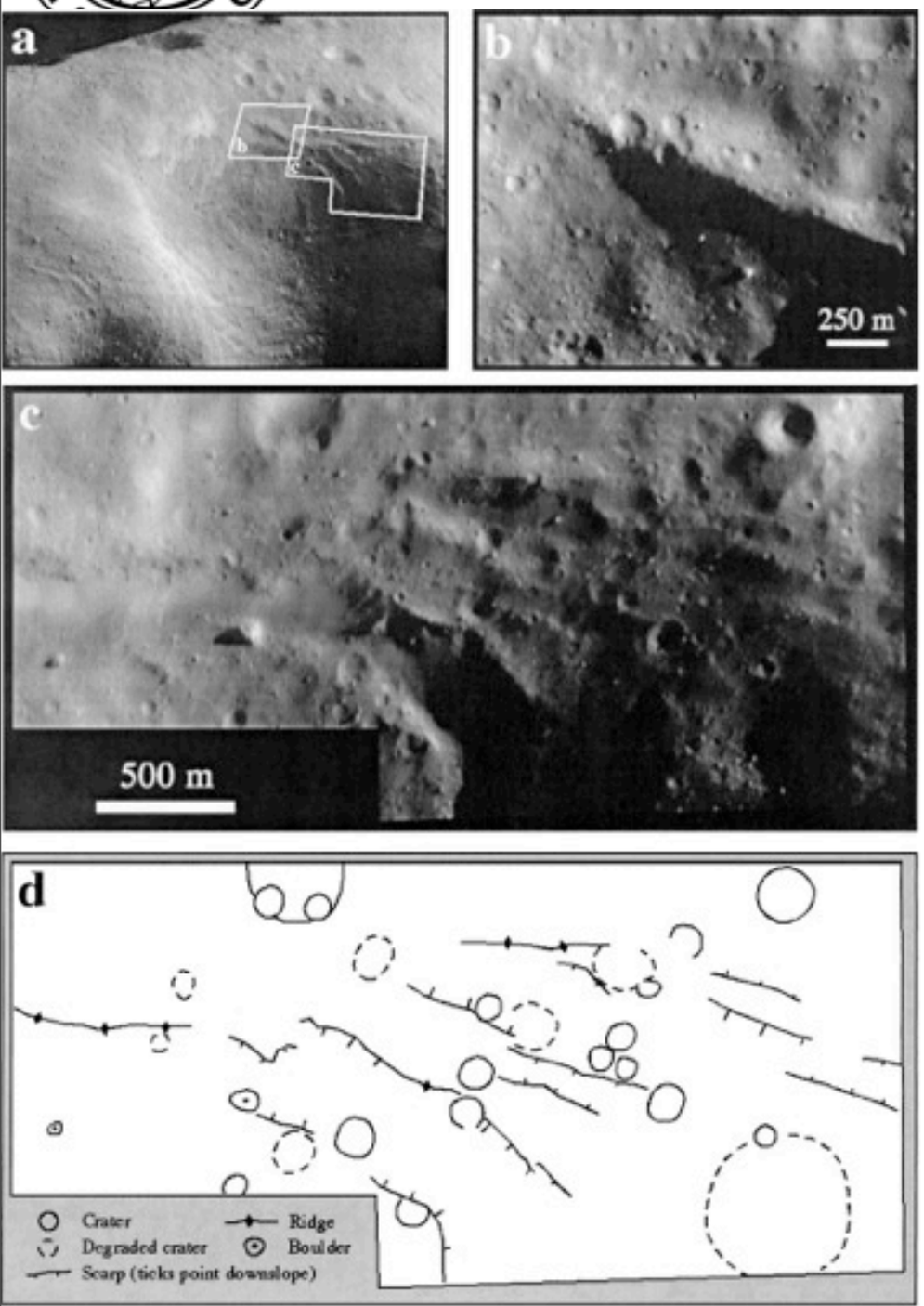
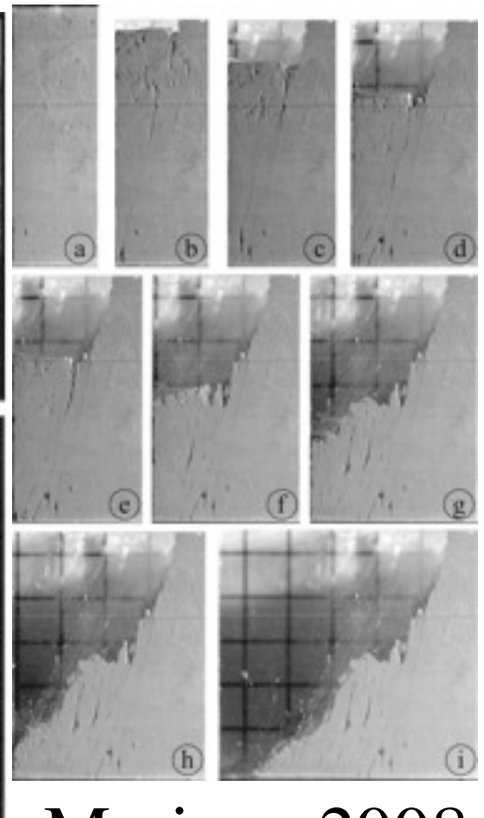




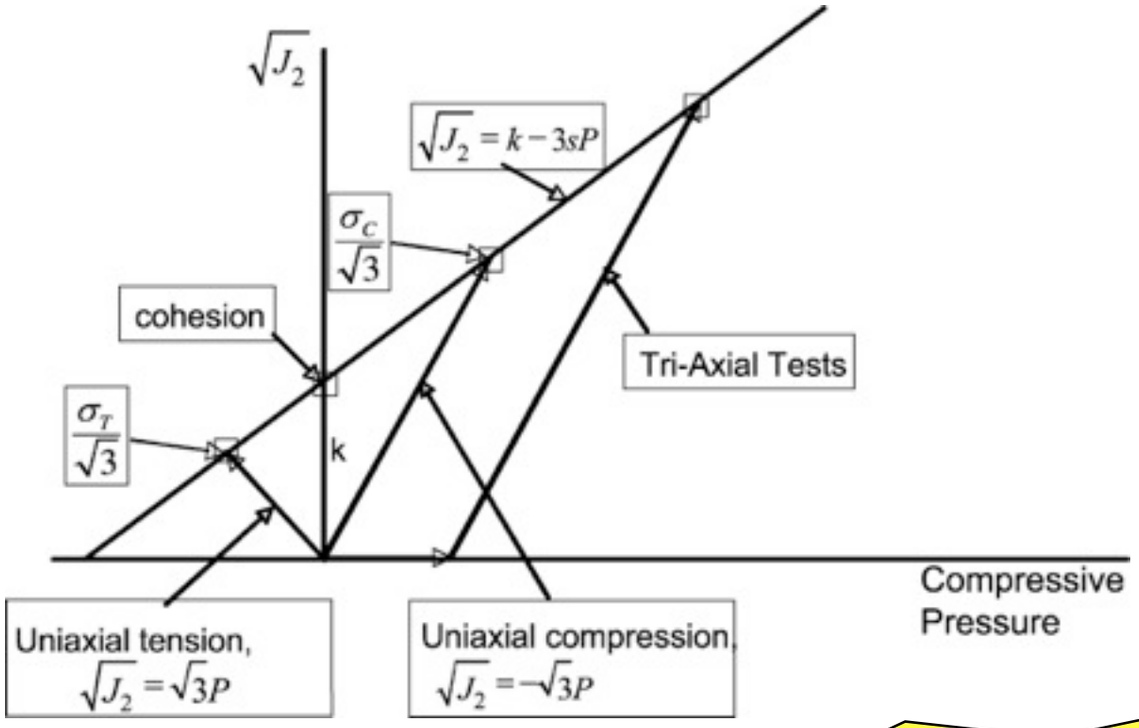
Meriaux 2008

Structural features on Eros and Phobos may be expressions of stress fractures in a cohesive granular material (Asphaug 2009)

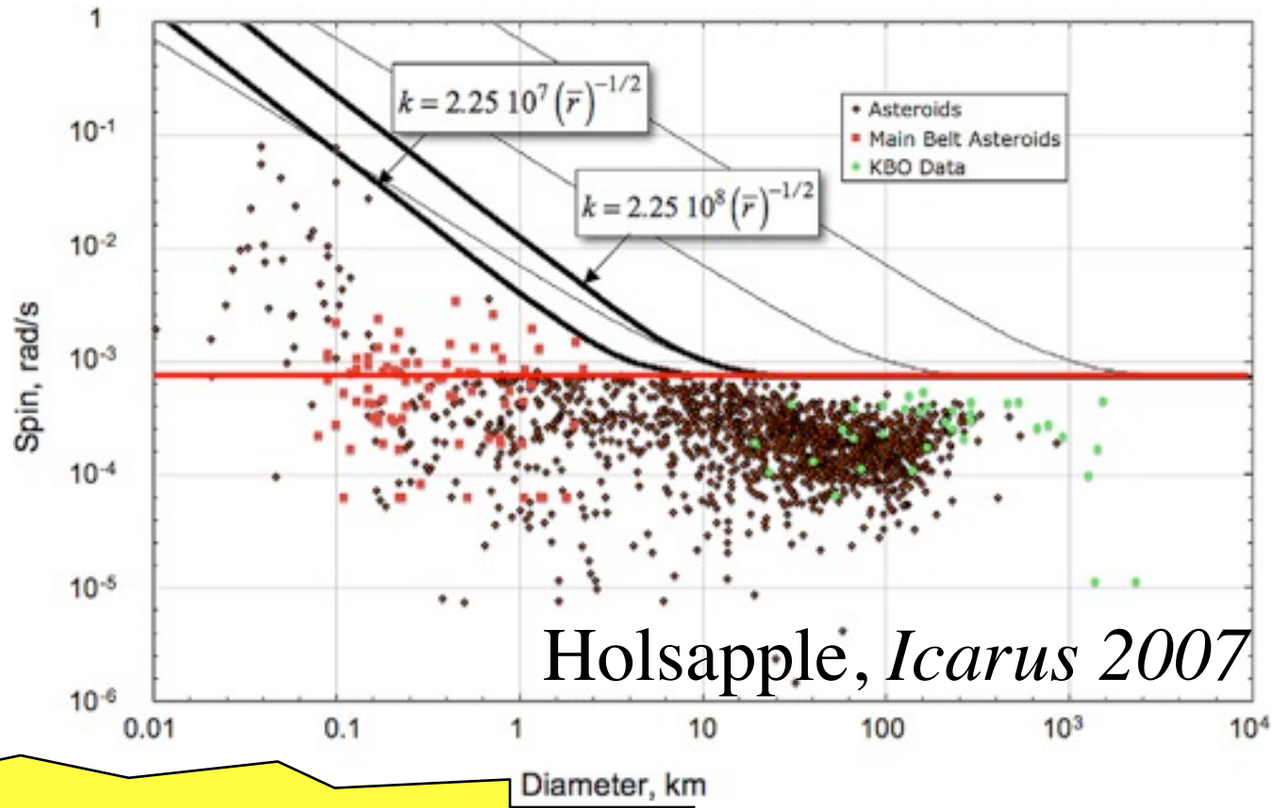
Effect on Asteroid Strength

- How is the strength of an asteroid affected by cohesion?
- To accurately understand and analyze the interiors of rubble piles requires:
  - Stress models and failure criteria
  - Flow rules for motion during failure
  - Specification of internal friction models
  - Cohesion and the physical basis for cohesive strength
- Seminal studies of this effect by Keith Holsapple have shown that minimal “cohesive strength” can keep fast rotating rubble-pile asteroids together
  - Physical basis for this cohesion has not been identified
  - Drives our study of the strength of asteroids

Failure Stress States



Cohesion with Volumetric Weakening



Holsapple, *Icarus 2007*

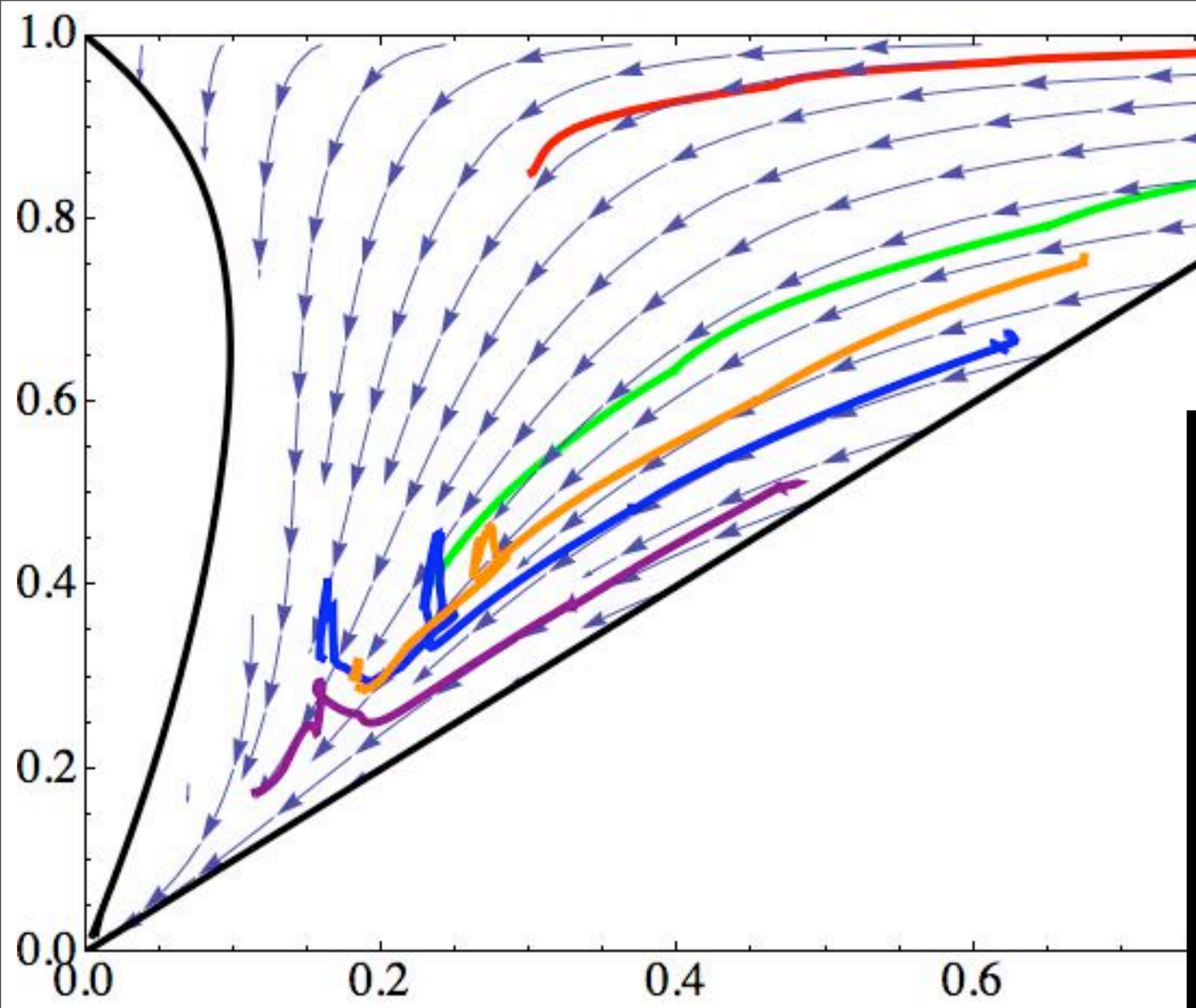
Drucker-Prager Failure Criterion

$$\sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{6}} + s(\sigma_1 + \sigma_2 + \sigma_3) \leq k$$

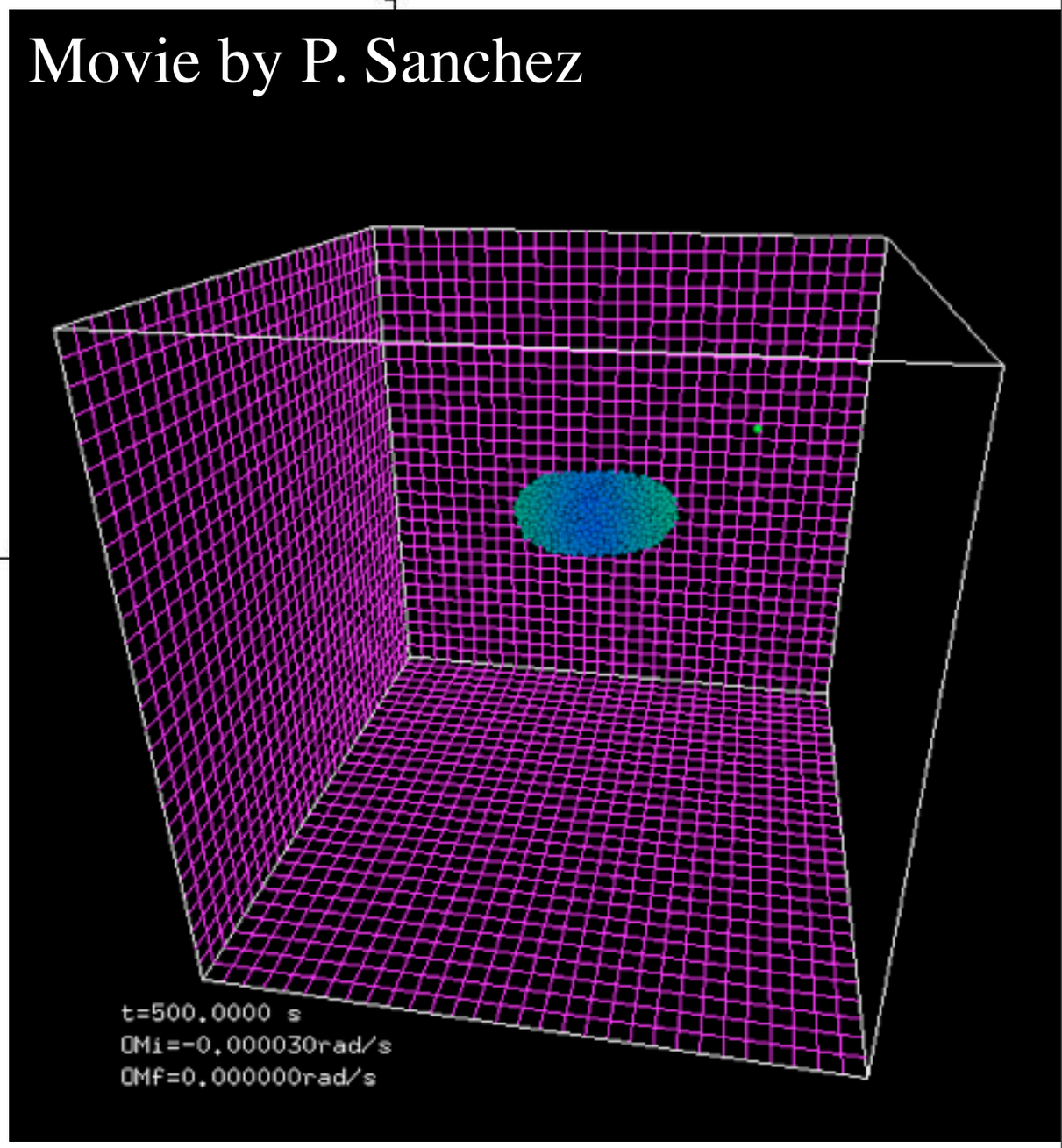
$$s = \frac{2\sin\phi}{\sqrt{3}(3 - \sin\phi)}$$

k = Cohesive Shear Stress for Failure at 0 pressure

$(\sigma_1, \sigma_2, \sigma_3) =$ Principal Stresses



Sanchez & Scheeres, *Icarus 2012*
comparisons with
Holsapple, *Icarus 2007*



As spin rate increases, internal stresses increase to the point where the DP failure criterion is violated, leading to reshaping and, in some cases, fission of the body.

Sanchez & Scheeres, *Icarus 2012*

Physics of Micro-Gravity Bodies

- But what about the extremely fast spinners? Can they be rubble piles?
  - The amount of cohesion needed to keep a fast-spinning rubble pile together is very small (Holsapple, *Icarus 2007*)
  - In microgravity, van der Waals forces can apparently supply enough cohesion (Asphaug, *LPSC 2009*; Scheeres et al., *Icarus 2010*)
    - For asteroid sizes less than ~ 1 km, cohesive attraction between small grains can become as significant as their weight
    - Rubble pile asteroids become effectively stronger as they become smaller
- Mechanism for this effect:
  - Larger boulders embedded in a matrix of finer regolith are held in place by cohesion between fine regolith
  - Fine regolith forms a “van der Waals concrete”
  - Specific predictions for how fast rotating rubble pile asteroids will fail, consistent with some observations

A typical simulation

Cohesionless regolith

- Boulders (red):1m
- Regolith (green): 1-3 cm
- Forces: gravity, friction, cohesion, normal contacts.
- Boulders are pulled apart with equal, but opposite forces.
- Pull is incremented by 10% of the total gravitational attraction every 5 seconds.

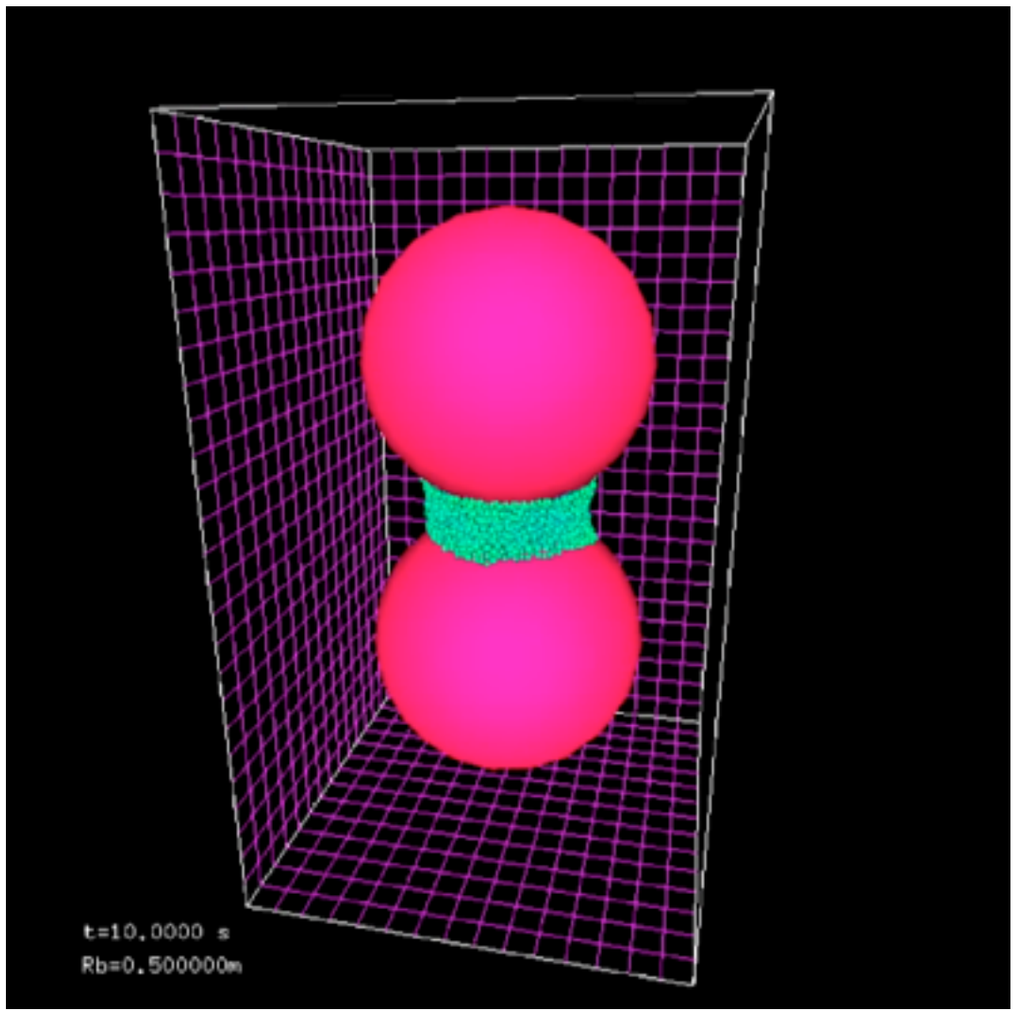
Simulations and movies by P. Sanchez

University of Colorado Boulder

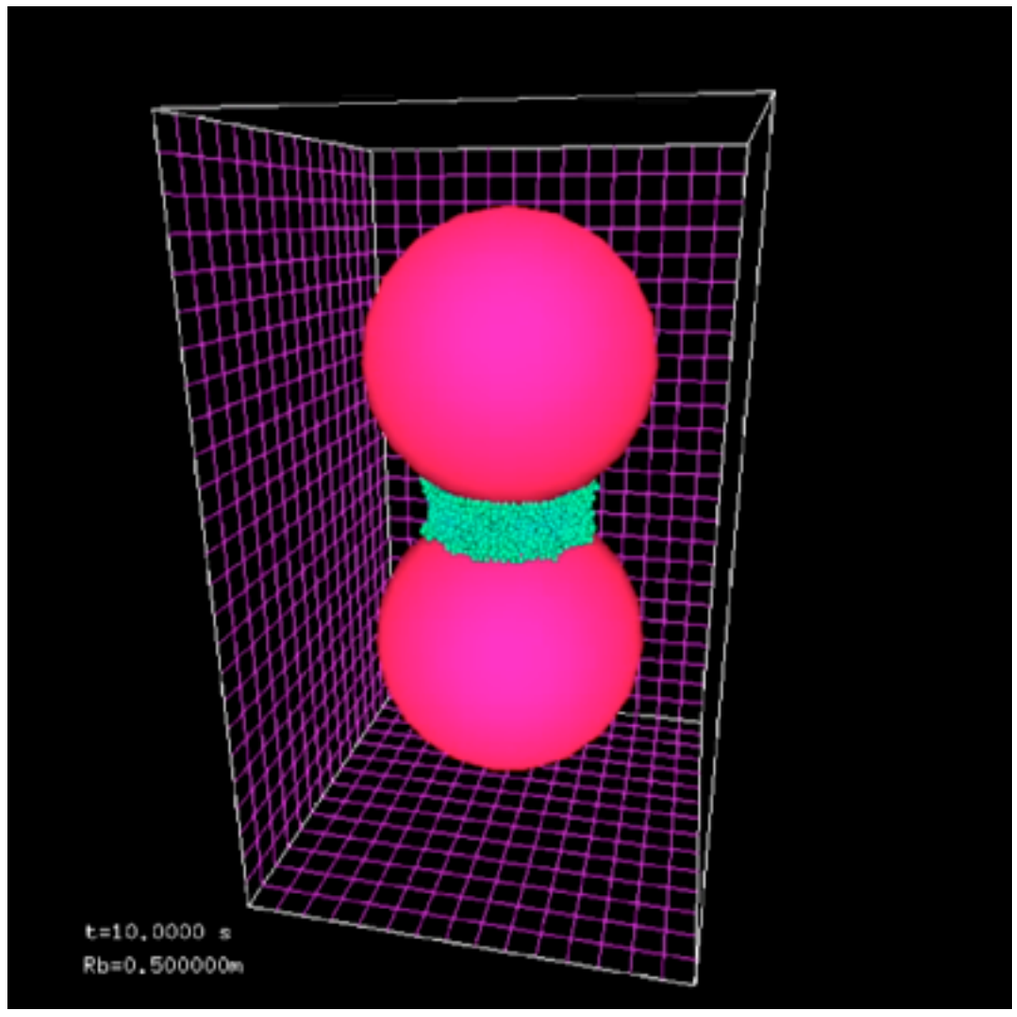
Celestial and Space Flight Mechanics Laboratory

A typical simulation

Cohesionless regolith



Cohesive regolith



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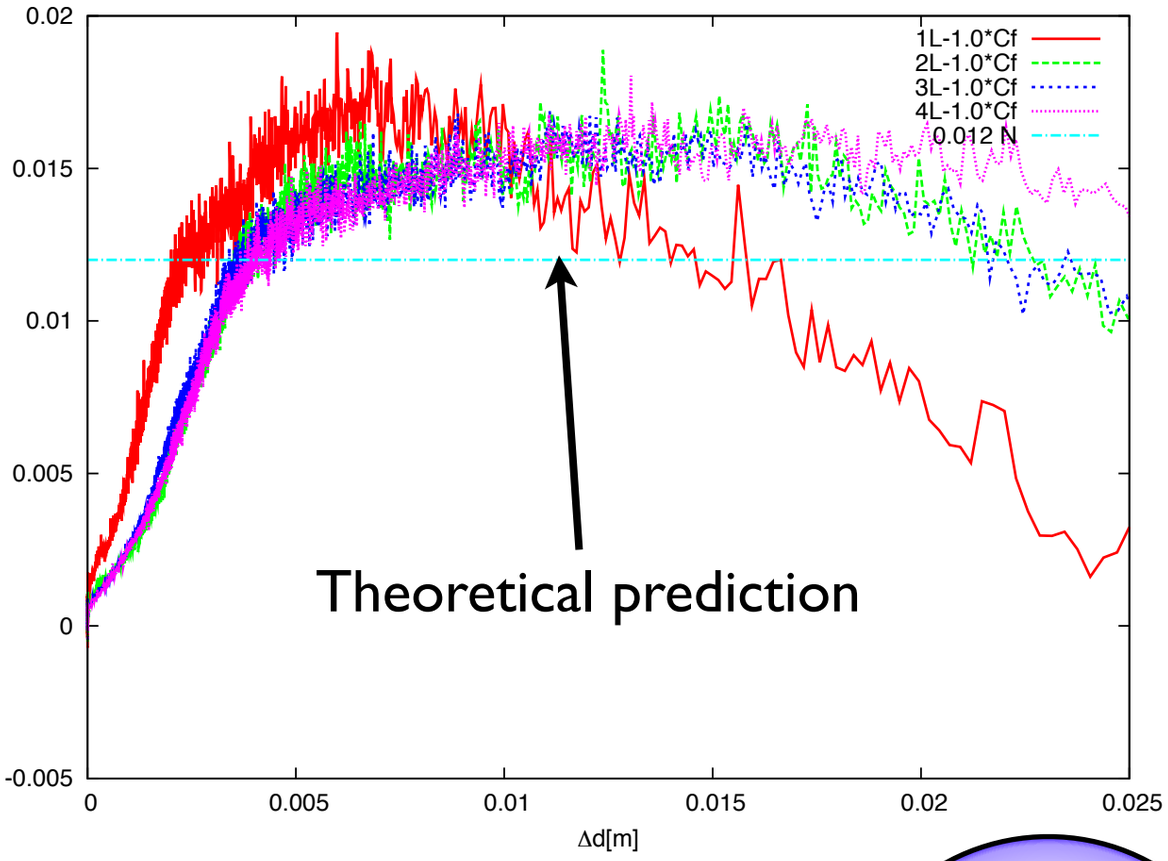
Mechanics Laboratory

Net Cohesive Force



Cohesive forces scaling factor

Coordination number

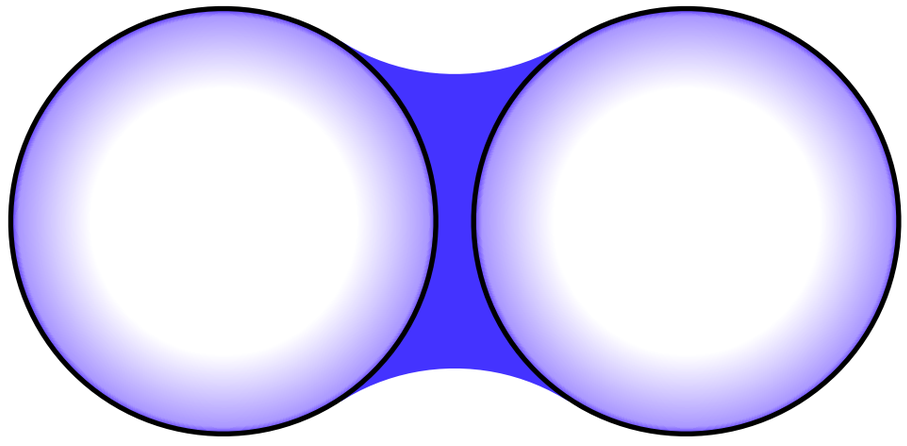
Modified Hamaker constant

Packing fraction

$$\sigma_{yy} = 1.73 \times 10^{-2} \left[\frac{A'_h C_\# C_s \phi}{\pi^2} \right] \frac{1}{\bar{r}_p}$$

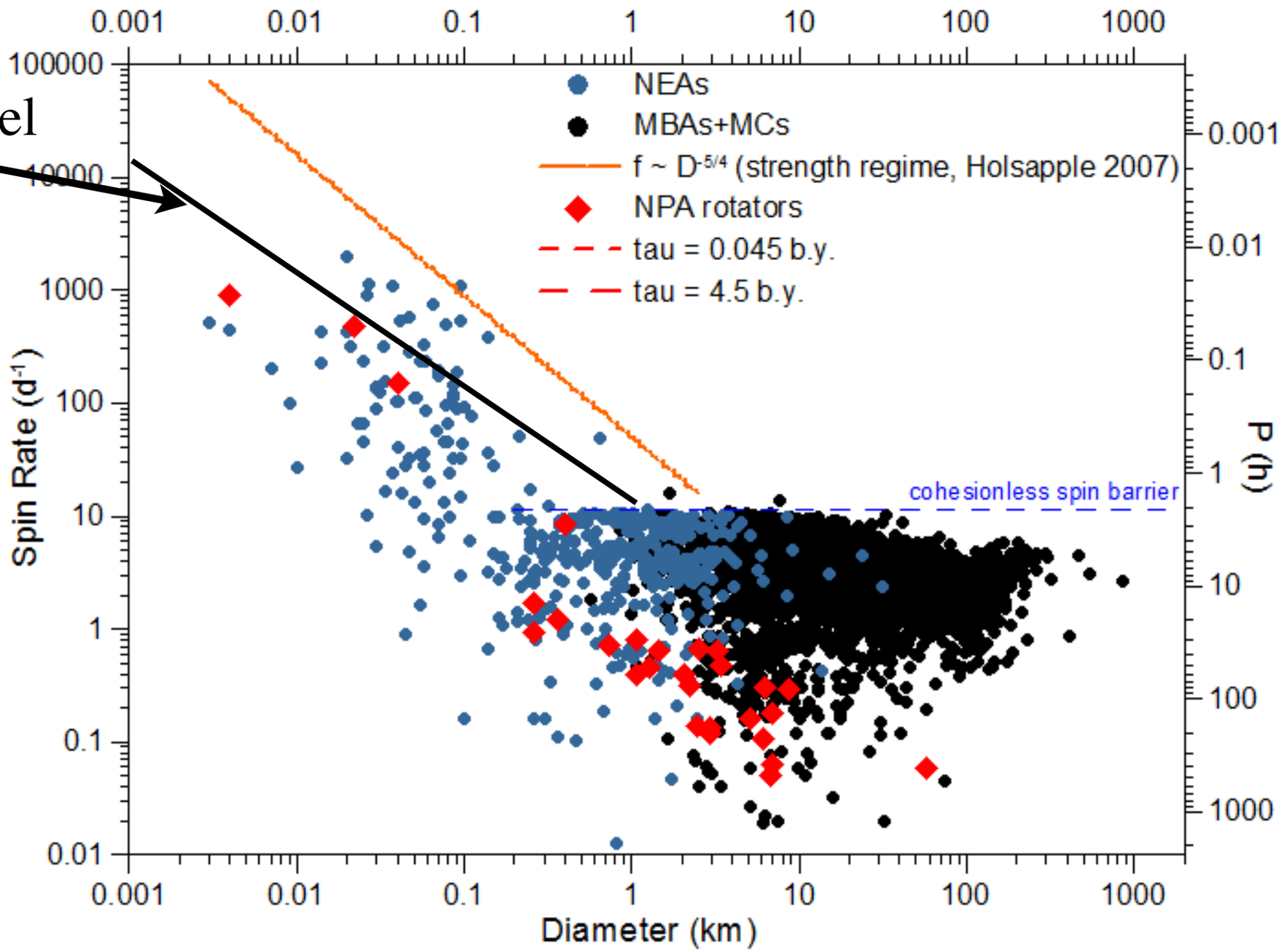
Mean particle radius - regolith

Modifications due to: orientation of the contacts, fraction of contacts in tension and magnitude distribution of cohesive forces.

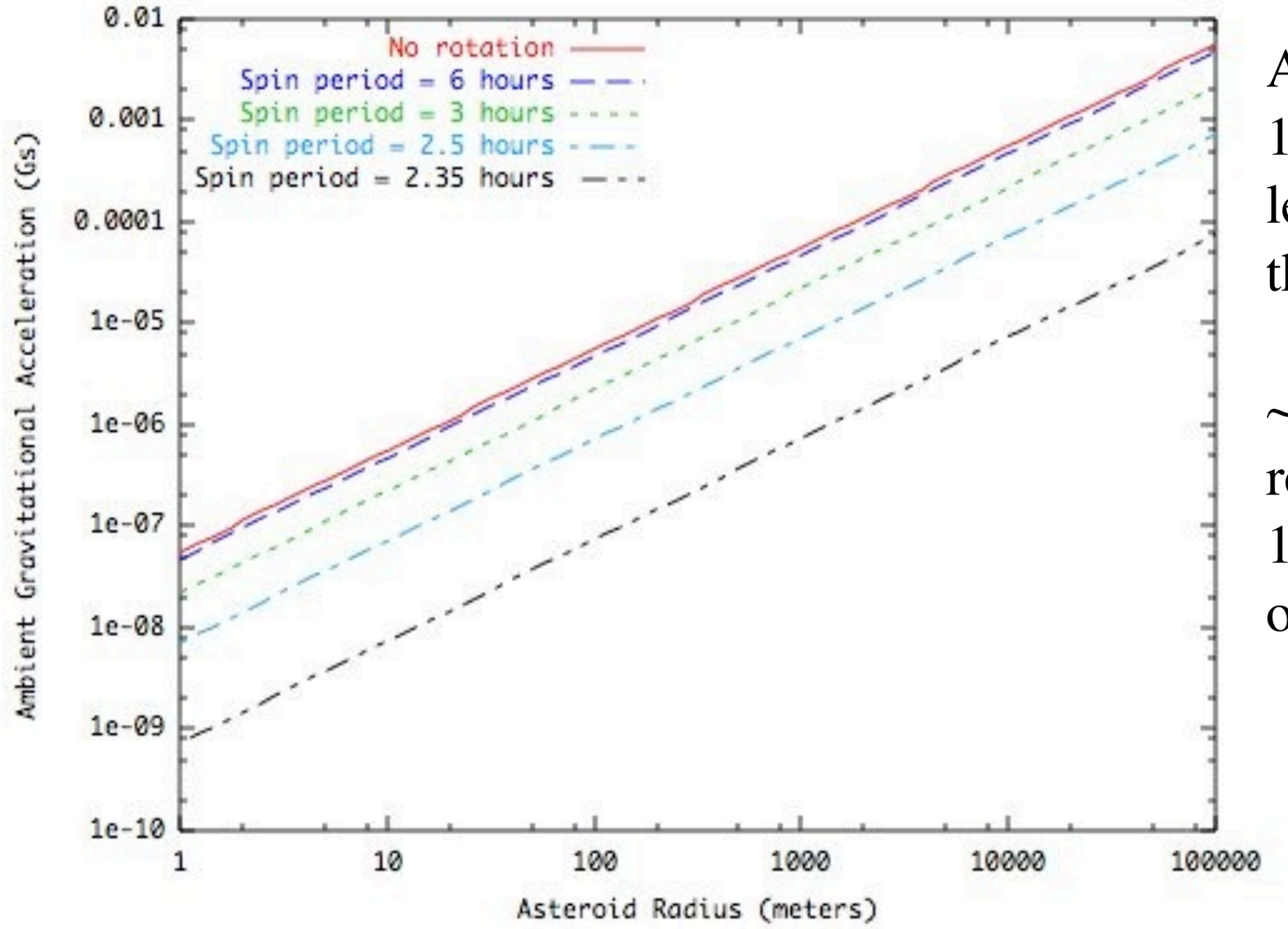


van der Waals Cohesion will strengthen rubble pile asteroids in the < ~100 meter regime, and could be the physical basis for Holsapple's cohesive strength.

Naive vdW cohesive stress model



Asteroid Surface Gravity



All asteroids less than 10 km have milli-G or less ambient gravity on their surface.

~ centimeter-sized regolith scales as 10-100 micron powders on Earth.

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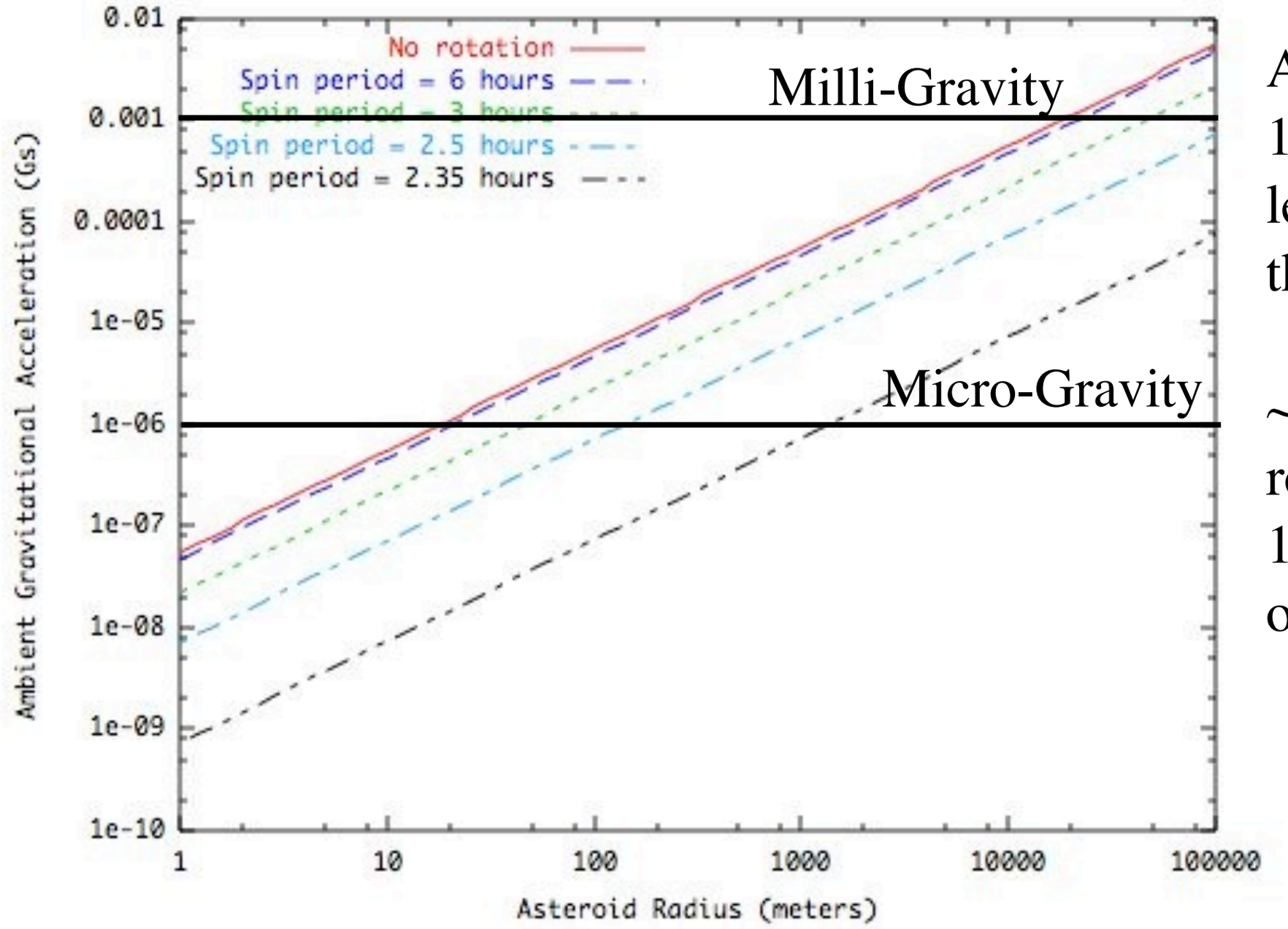

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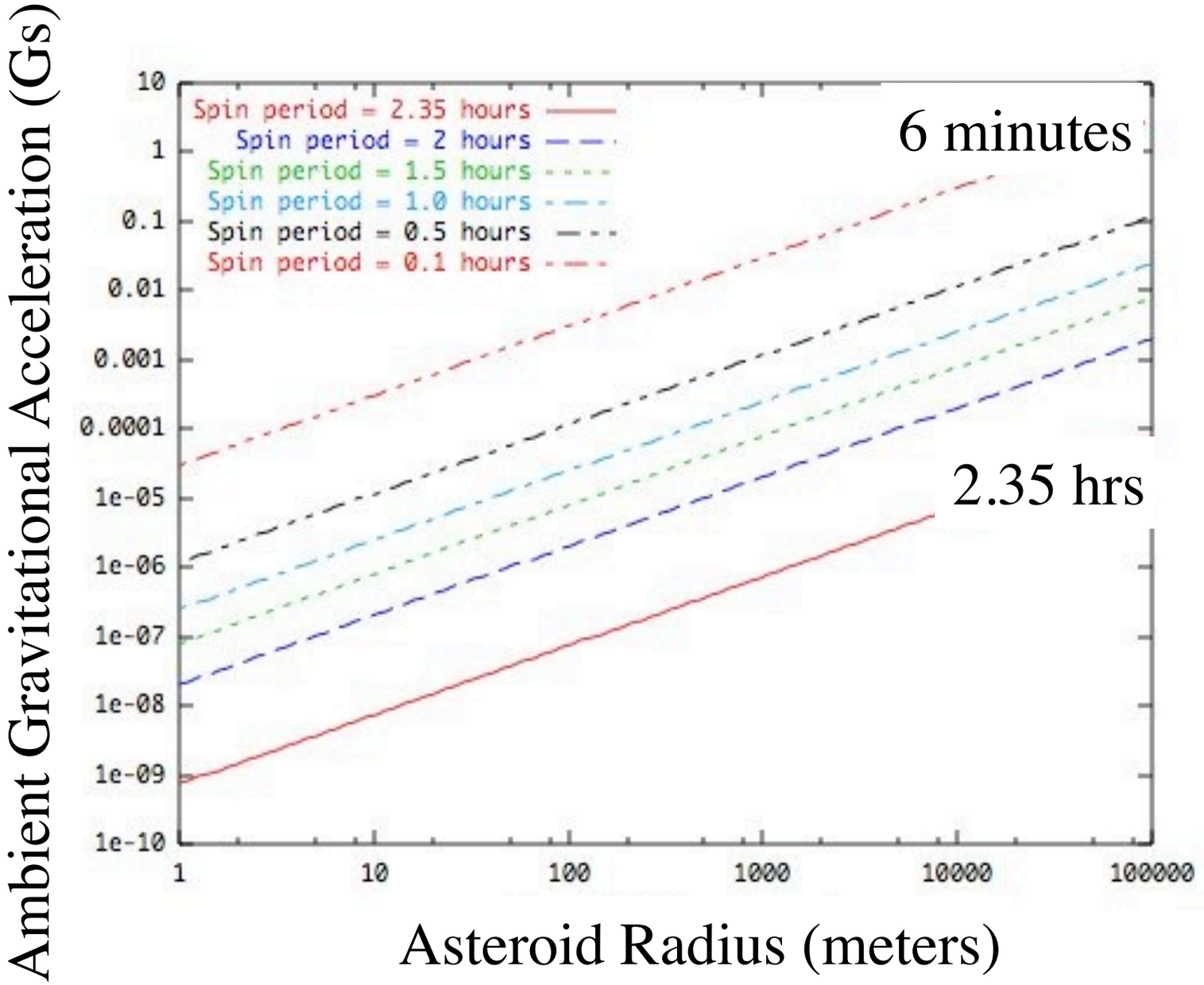
Surface structure of "Rapidly Rotating Monoliths"



Surfaces of rapidly rotating asteroids of size ~ 100 meters can be held together by cohesion forces between ~ mm -> cm sized grains.

Cohesion force required decreases with asteroid radius

Are some rapid rotators the end product of an asteroid progressively shedding its largest boulders, leaving a cohesive gravel pile?

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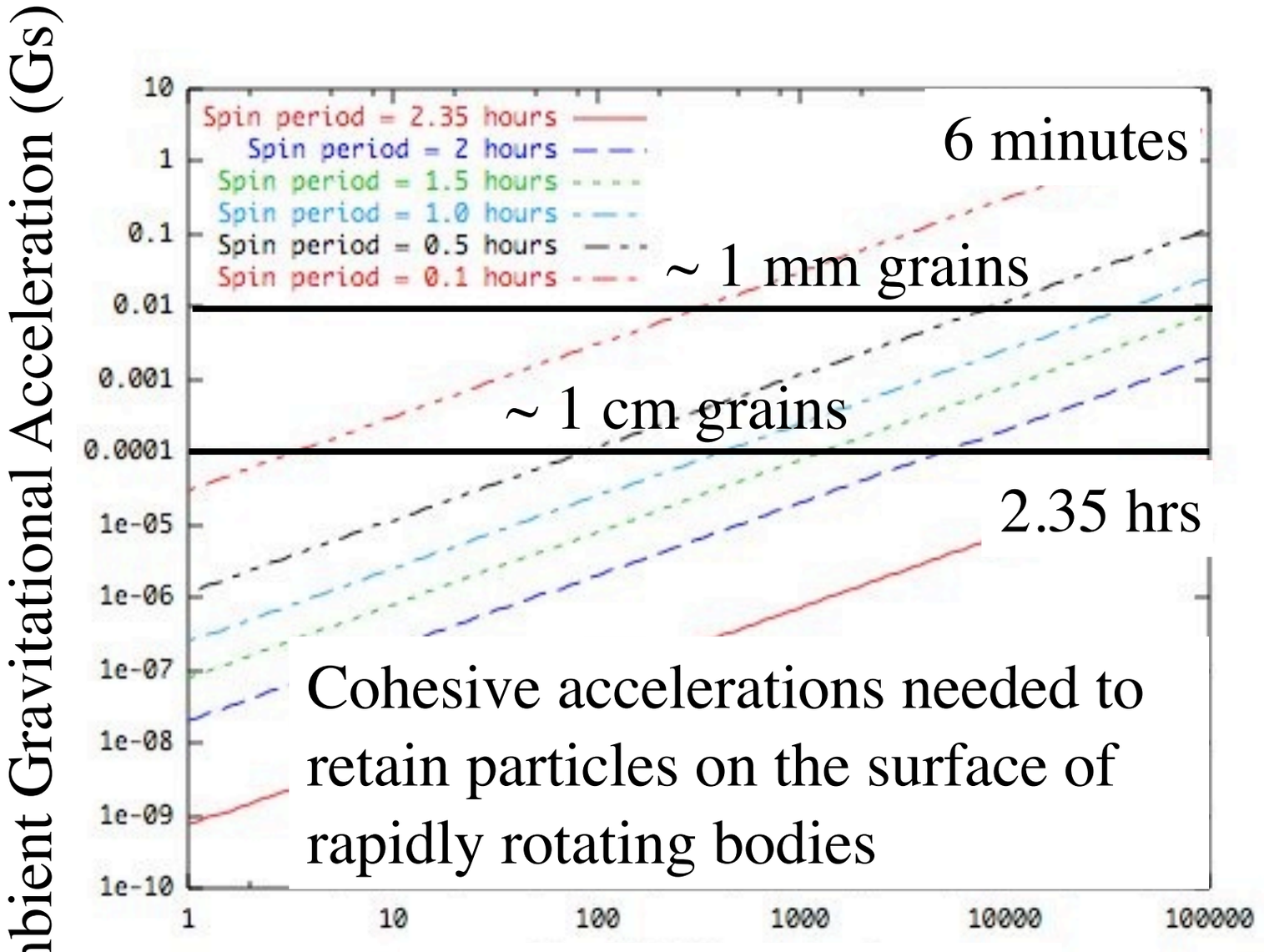

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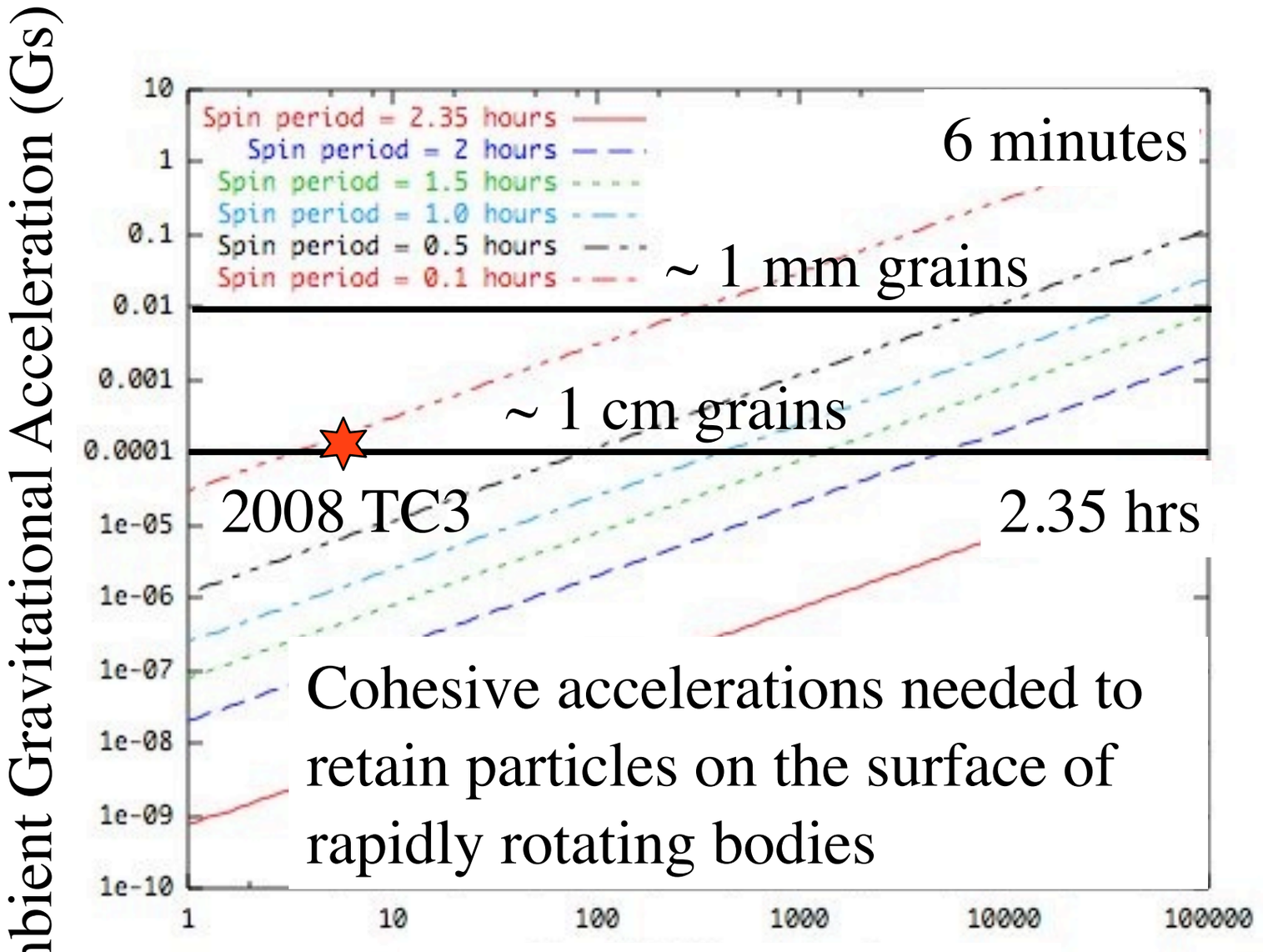

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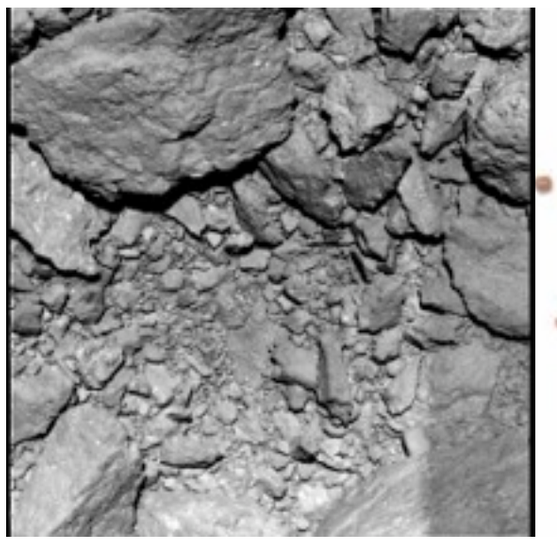
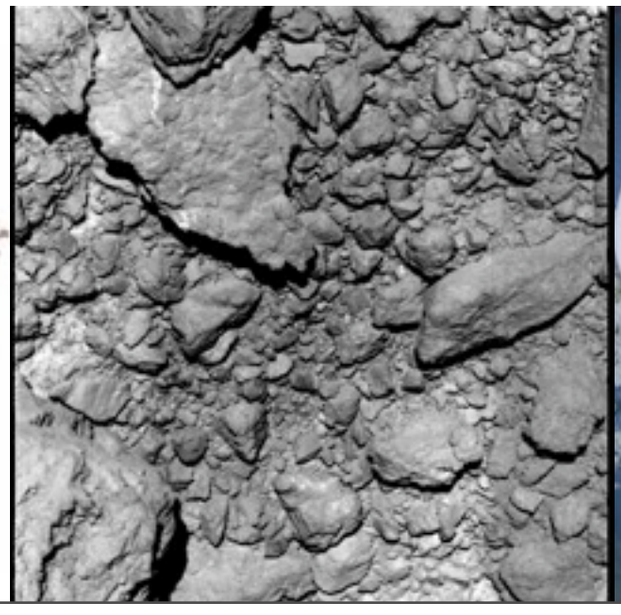
Conclusions / Summary

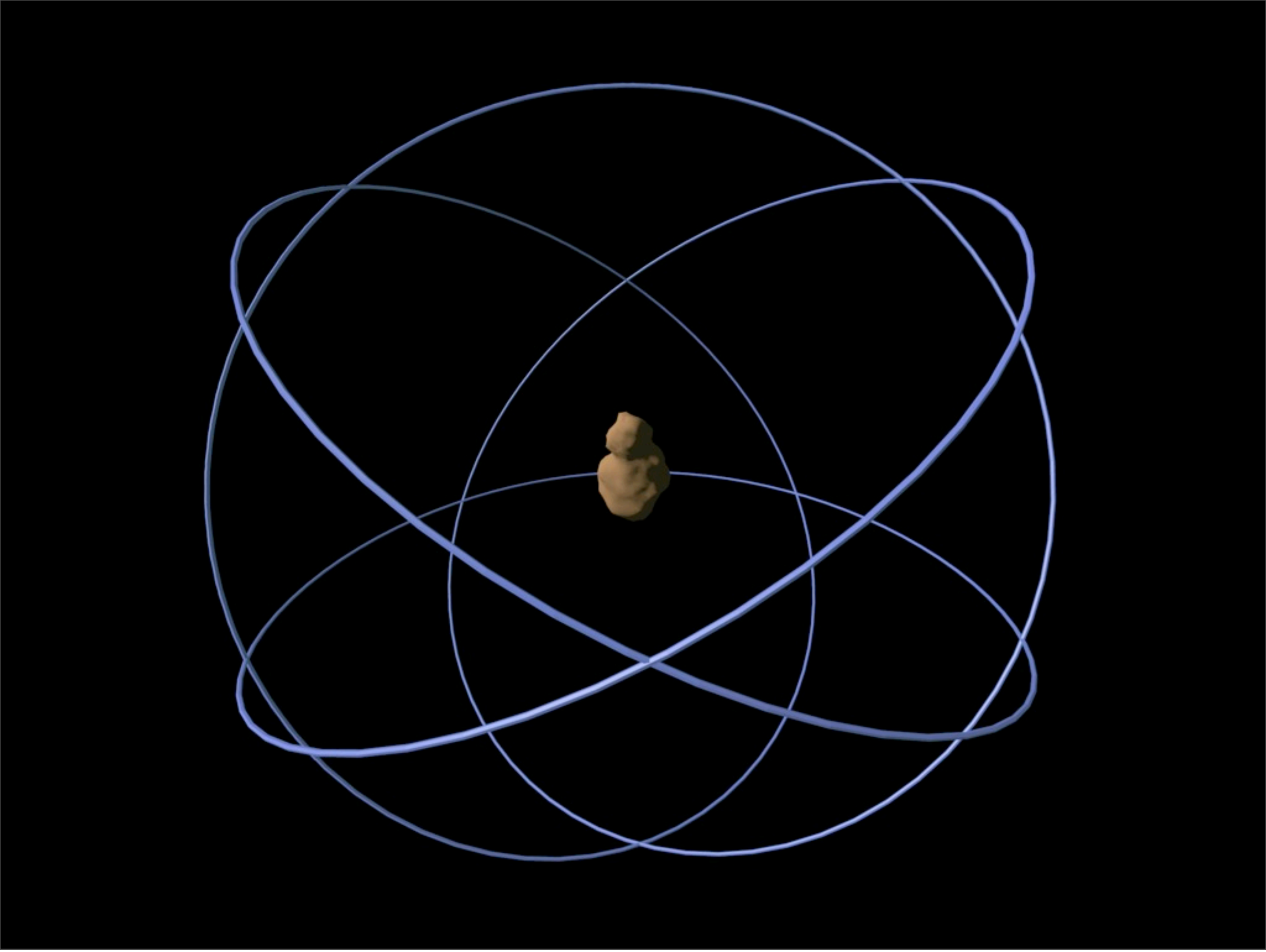
- Evidence for Rubble Pile asteroids is reviewed
- A survey of relevant forces/physics predicts that:
  - van der Waals cohesion between ~mm-cm sized grains can dominate over weight
  - Asteroid regolith on small bodies may act as a cohesive powder
  - Smaller grains can serve as a “concrete” to hold larger boulders together, even at fast spin rates
  - Asteroid observations have consistency with this theory, but still require further testing

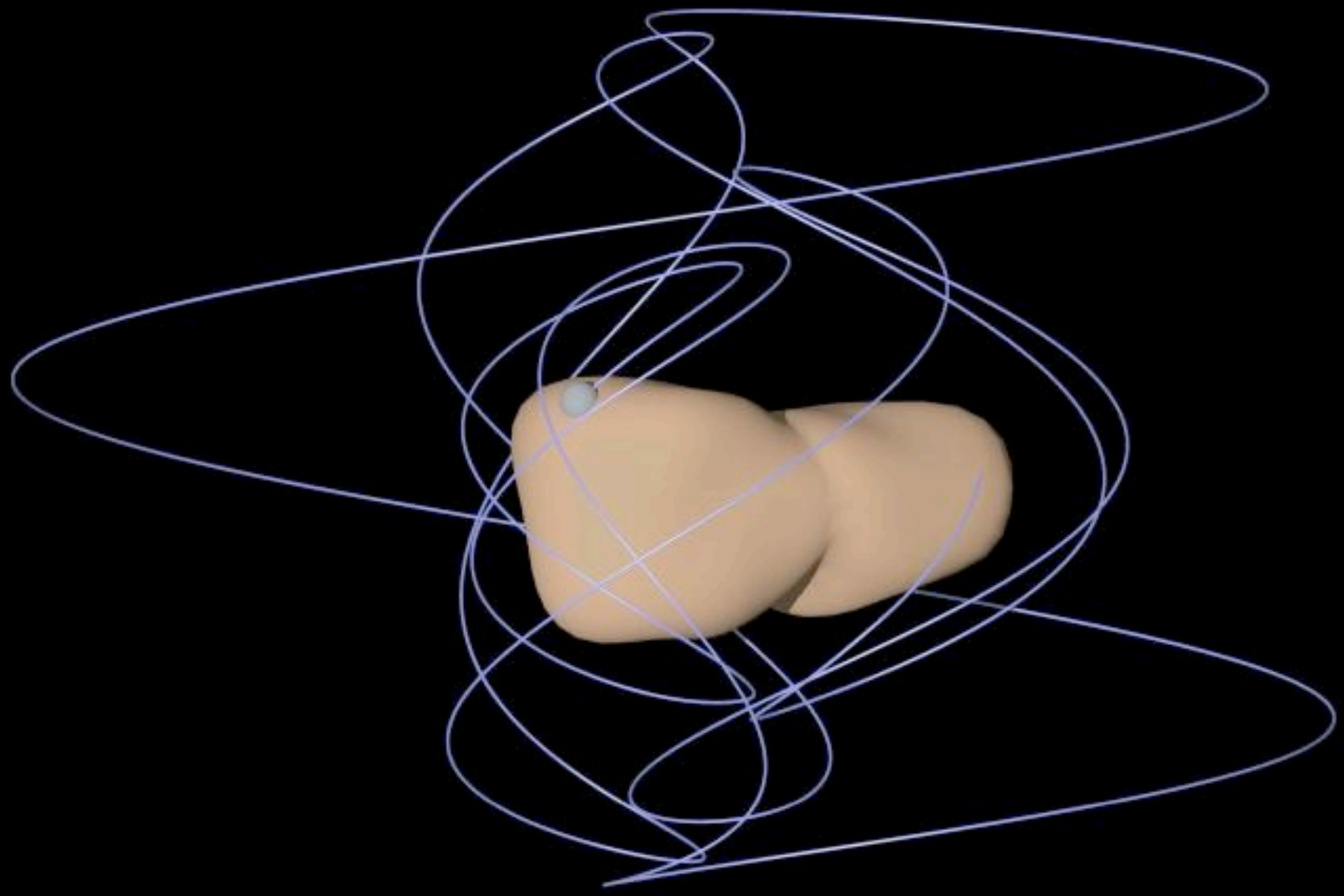


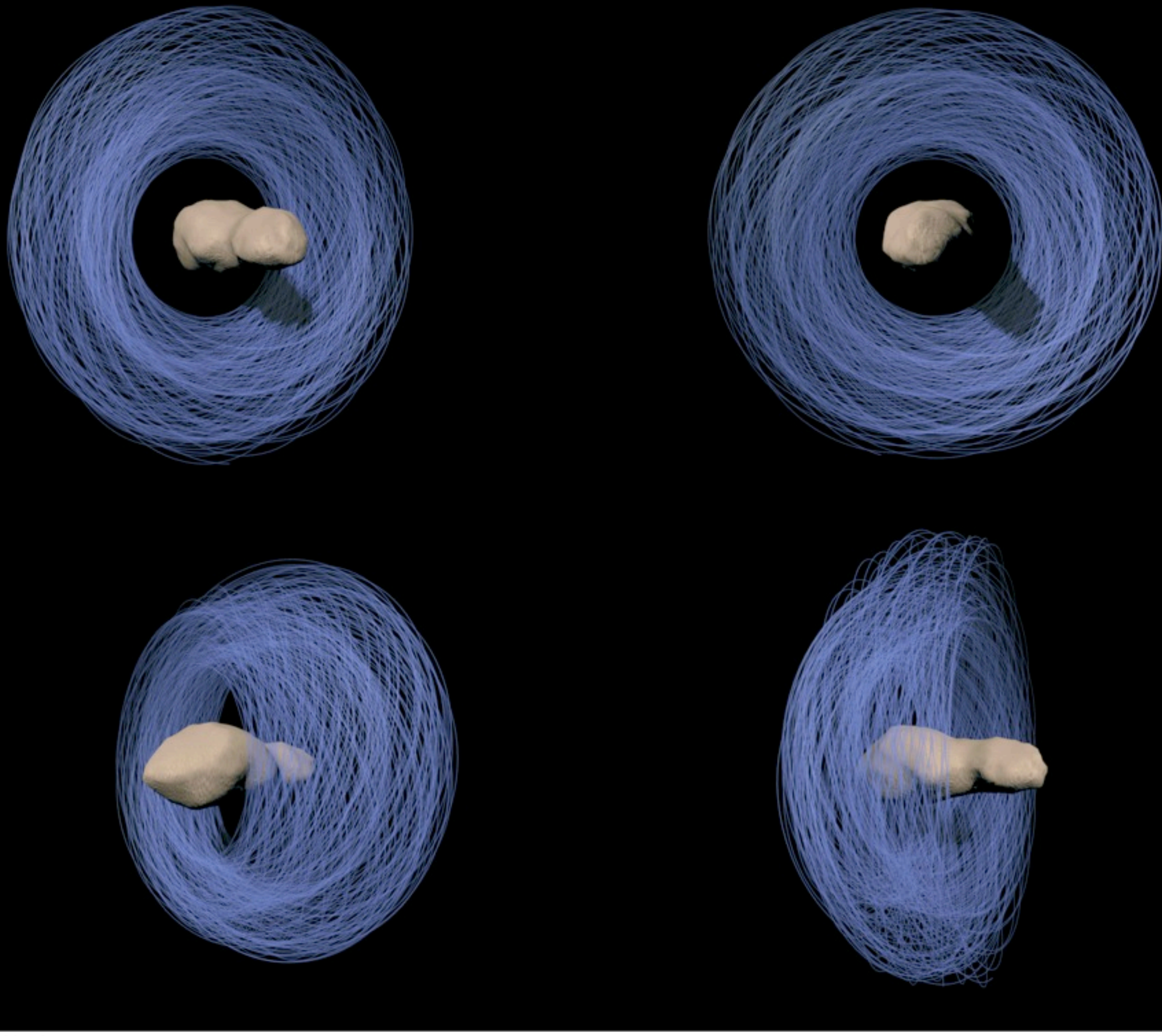


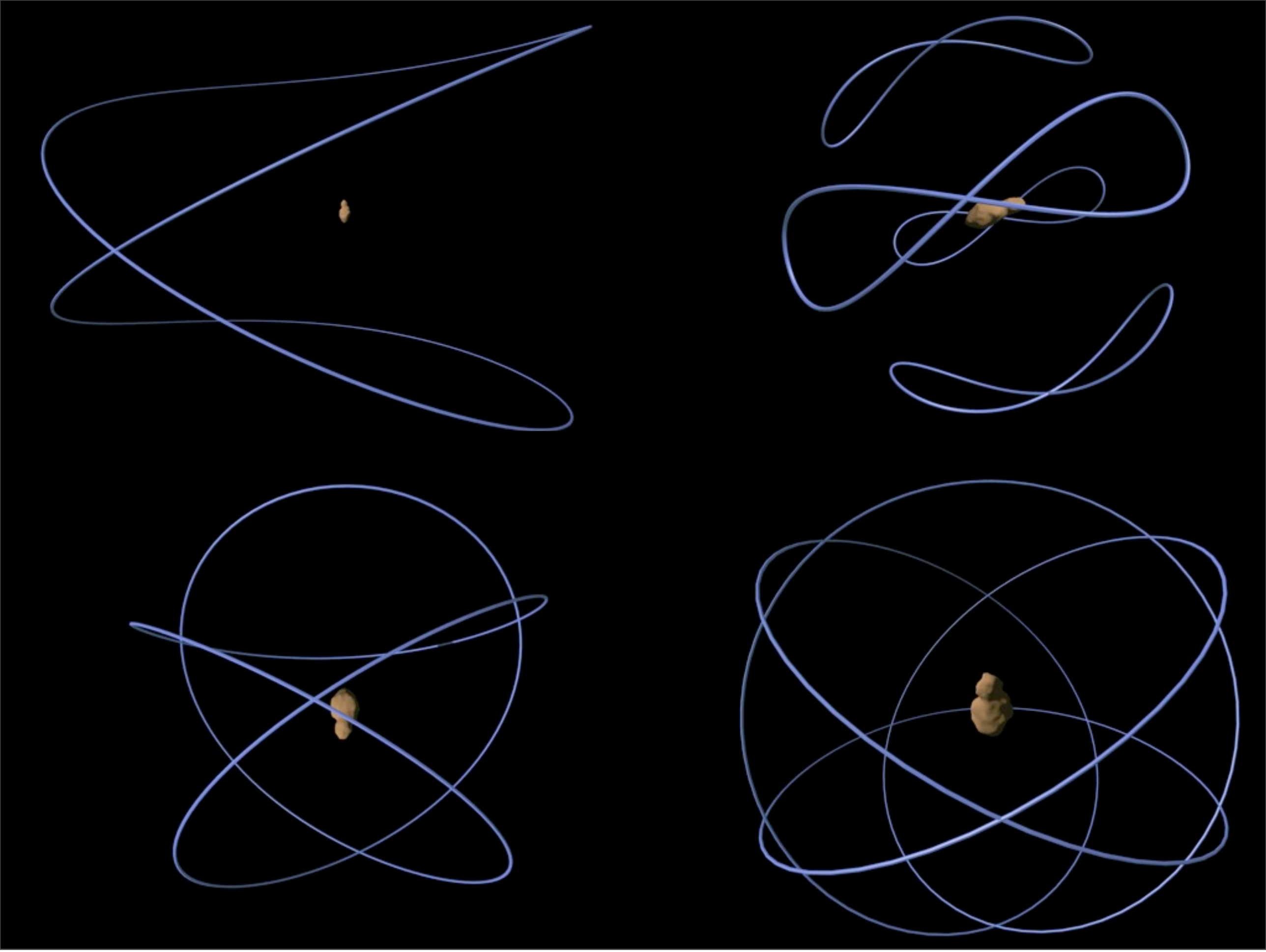
Proposed Experimental Investigations

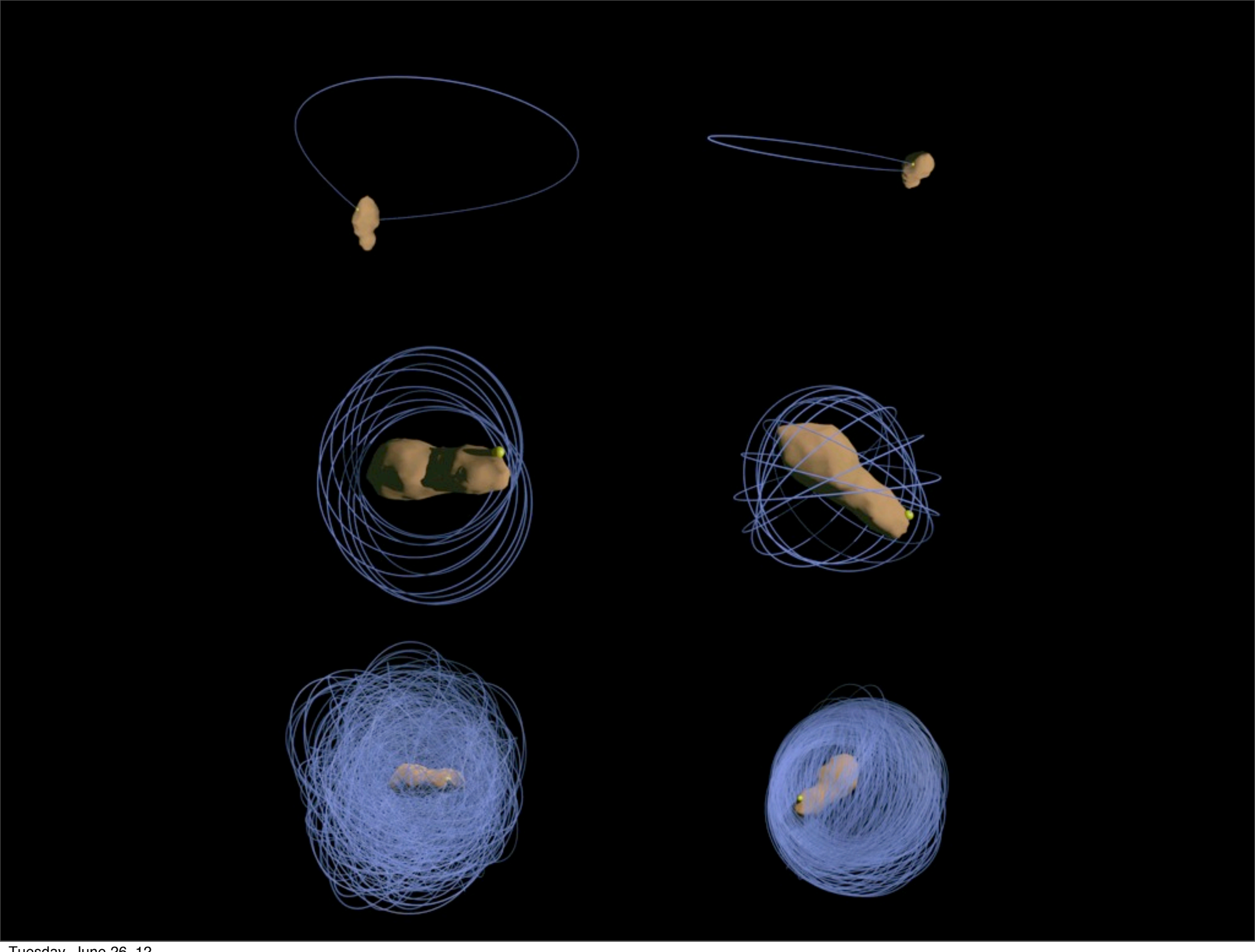
- Study of cohesive powders on Earth for understanding asteroid surfaces in space:
  - Vacuum to remove air effects
  - High temperature to remove adhered gas molecules and enhance cohesion
  - Development of appropriate analogs, such as lunar regolith
- Specific properties of interest:
  - Seismic properties, do S-waves cause dilation?
  - Response of cohesive grains to repeated impacts
  - Avalanche mechanics and resulting surface structure
  - Role of electrostatics
  - etc…

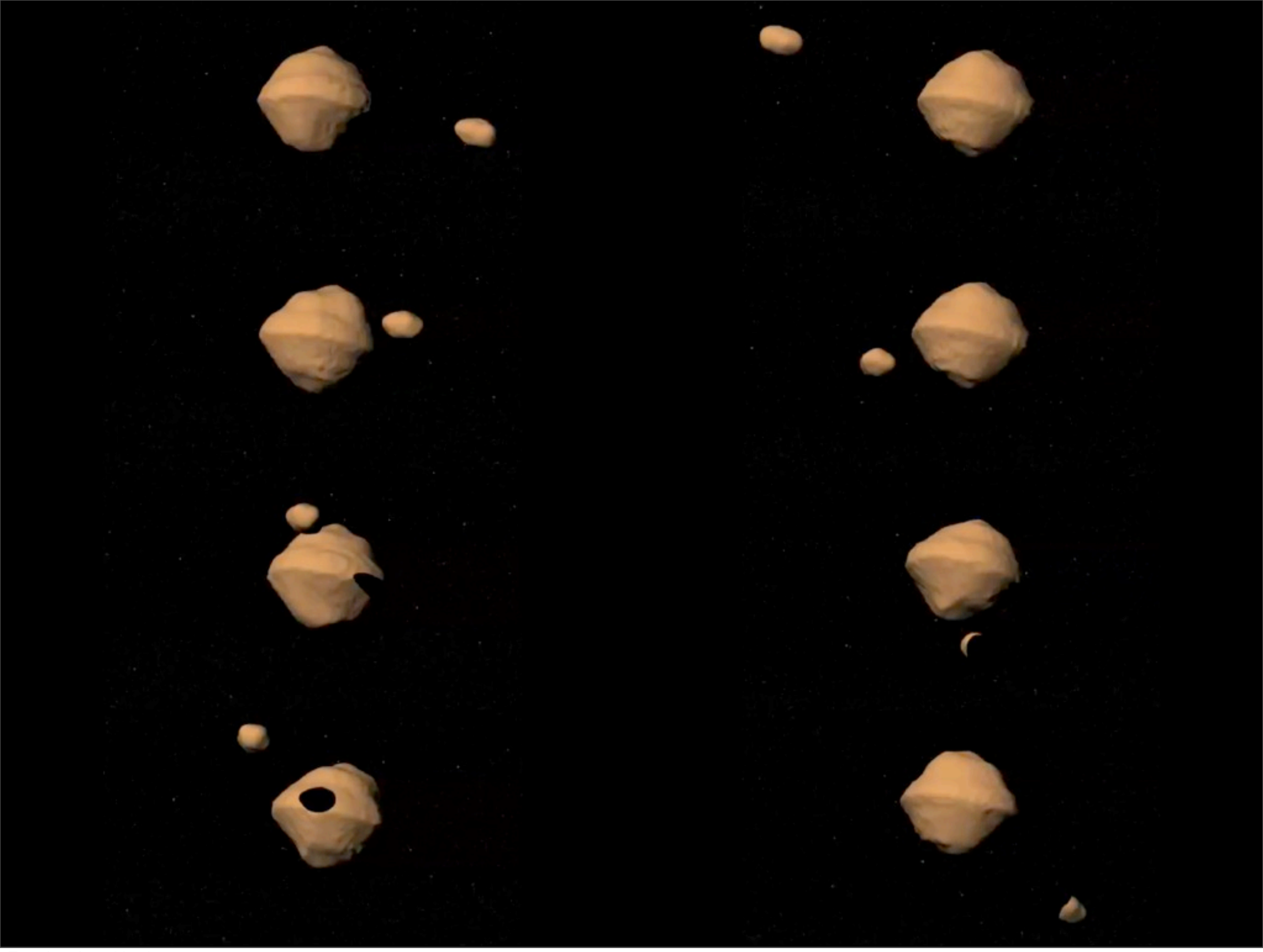








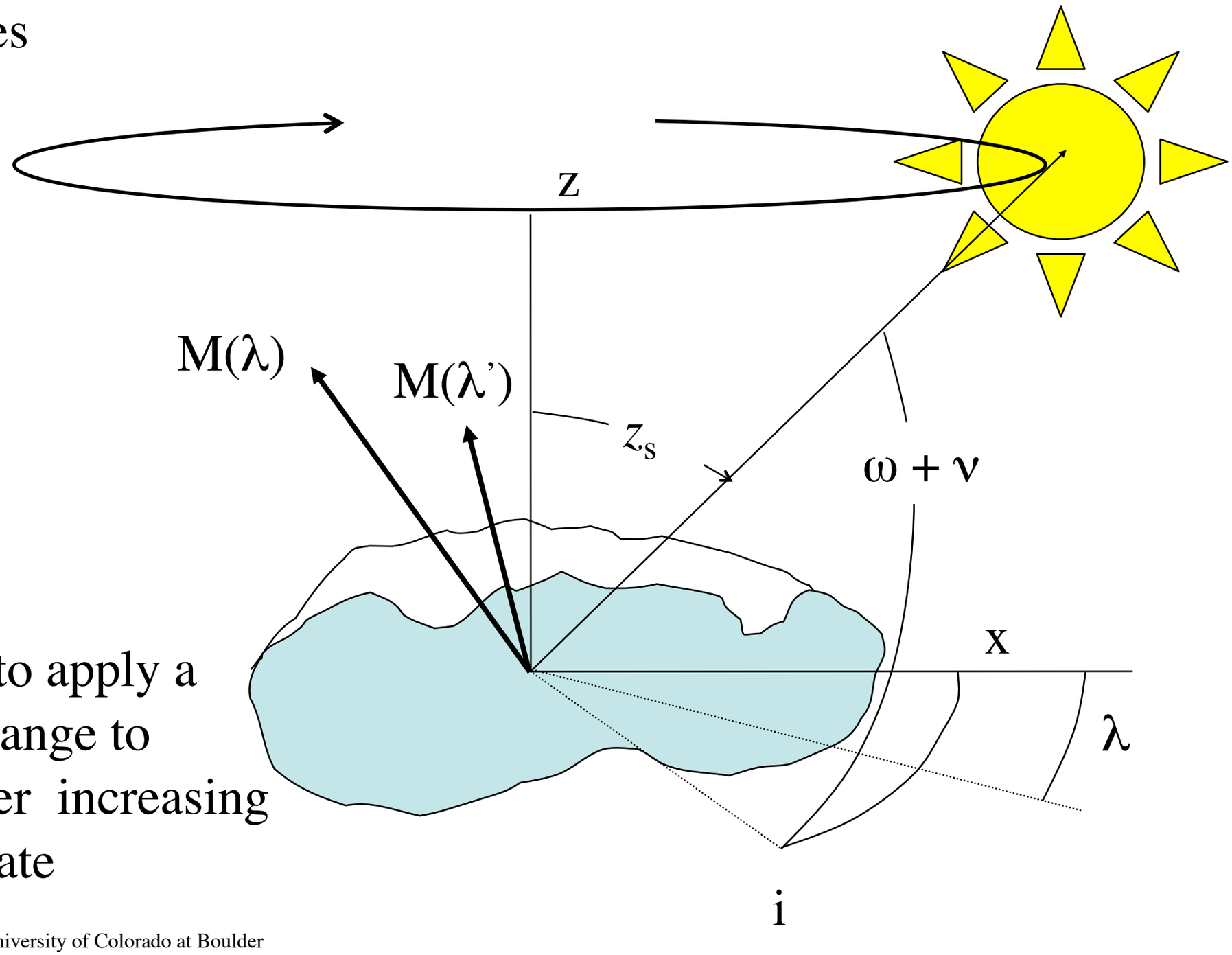




What is YORP?

Yarkovsky-O'Keefe-Raszievskii-Paddack (YORP) Effect:
Photon reflection and re-radiation from a non-symmetric body can induce net torques

Verified for two NEA in 2007



YORP's main effect is to apply a near-constant rate of change to asteroid spin rates, either increasing or decreasing rotation rate

What effect does YORP have?

- YORP rotational acceleration is inverse-squared with asteroid semi-major axis (a) and size (D)

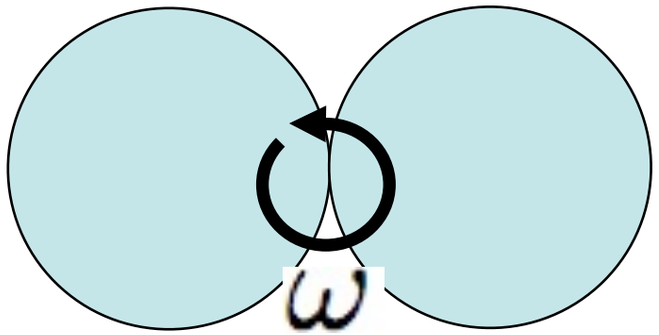
$$\frac{d\omega}{dt} \propto \frac{1}{a^2 D^2}$$

  – Bodies much larger than 10 km are relatively insensitive

- Asteroid Obliquity also evolves under YORP, which modifies the spin acceleration rate
- For populations of bodies this yields a uniform distribution of spin rates between $\omega \sim 0$ and ω_{max}
  – The maximum rotation rate will vary for each body and plays a key role in what follows
  – Significant changes in rotation rate occur over 100Kyr timespans for most NEA

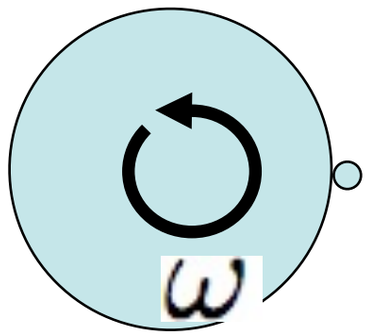
Fission of Asteroids

- Fission occurs when two portions of the body attain orbital rates relative to each other
- The fission spin rate is a strong function of "shape"



$$\omega > \sqrt{\frac{\pi G \rho}{3}}$$

Simple examples of "fission"



$$\omega > 2\sqrt{\frac{\pi G \rho}{3}}$$

For a density of $\rho = 2$ g/cm^3

~ 4.7 hour rotation period

~ 2.3 hour rotation period

Fission occurs at half the spin rate for the equal mass distribution

Fission Conditions

- For fission of an arbitrary rubble pile split into two collections I and J the general condition becomes:

$$\boldsymbol{R}_{IJ} \cdot \tilde{\boldsymbol{\omega}} \cdot \tilde{\boldsymbol{\omega}} \cdot \boldsymbol{R}_{IJ} \quad \geq \quad -\frac{M_I + M_J}{M_I M_J} \frac{\partial U}{\partial \boldsymbol{R}_{IJ}} \cdot \boldsymbol{R}_{IJ}$$

  - Applying a weak form of Euler's Theorem of Homogenous functions this reduces to

$$T_{IJ} + \alpha U_{IJ} \geq 0$$

  - which is equivalent to

"the two components with the largest separation between their centers of mass will fission first at the lowest spin rate"

Scheeres, Planetary & Space Science (2009)