The Strength of Small Rubble Pile Asteroids

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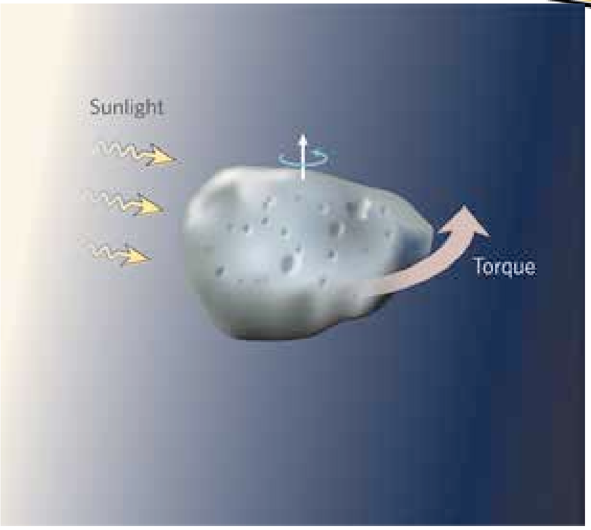


- This talk focuses on "small asteroids" of size less than ~ 10 km
  - These bodies are susceptible to the YORP effect:
    - Sunlight causes them to spin up and/or down
    - Can undergo extreme variations in their spin rate over their lifetime
  - Of most interest is what happens when their spin rates get large
- Fundamental Question:
- ***Are these small asteroids "monolithic rocks" or "rubble piles"?***

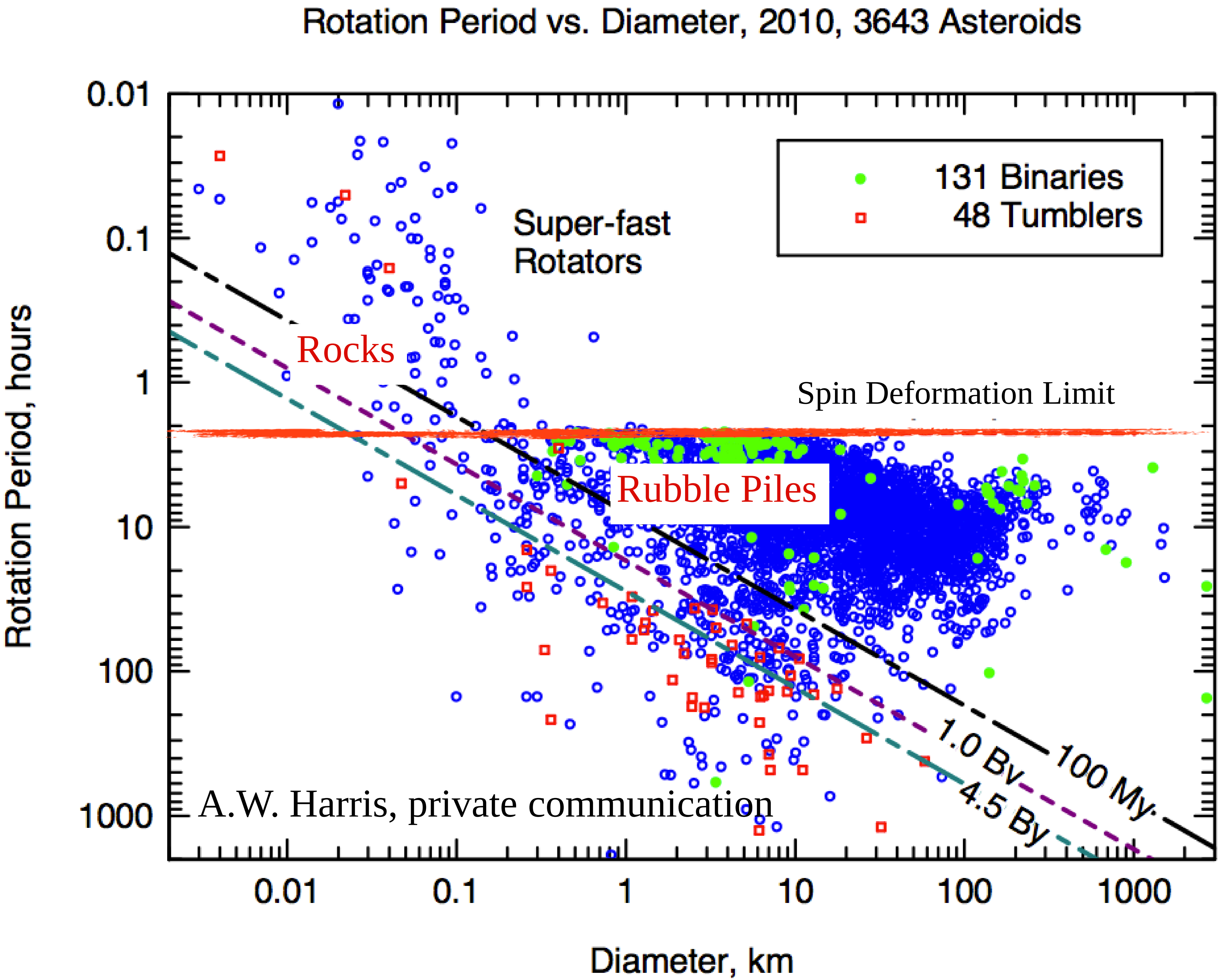
- Monolithic rocks:
  - Clean of surface material (regolith)
  - Rapid rotation = Strong, monolithic structure
  - Relatively high density

- Rubble piles:
  - Collections of rocks and gravels resting on each other
  - Low density / high porosity asteroids
  - Cannot spin very fast

  - ***We will argue that these simple distinctions may not be appropriate***

Spin / Size Relation

- The increase in asteroid spin rates with decreasing size has been well established since Pravec and Harris 2000.
- The spin limit for larger bodies is consistent with the spin disruption limit for spheres of density ~2-3 g/cm^3.
  – A simple interpretation is that the maximum block size from which asteroids are built is ~100+ meters and that asteroids spun beyond this limit “disassemble” into smaller pieces.



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

Spin / Size Relation

- The increase in asteroid spin rates with decreasing size has been well established since Pravec and Harris 2000.
- The spin limit for larger bodies is consistent with the spin disruption limit for spheres of density ~2-3 g/cm^3.
  - A simple interpretation is that the maximum block size from which asteroids are built is ~100+ meters and that asteroids spun beyond this limit "disassemble" into smaller pieces.
- The real picture seems a bit more complicated, however...
  - Direct Observation of asteroid Itokawa and radar shapes
  - The existence of tumbling fast rotators in the small size population
  - The computed mechanics of asteroid fission
  - The predicted physics of rubble pile asteroid cohesive strength...

What is a Rubble Pile?

- A size distribution of boulders and grains.
  - Extends from ~ microns to a few 100 meters across
  - Measurements of Itokawa suggest:
    - $1/d^3$ from ~ millimeters to decameters
    - At least $1/d^2$ for microns to millimeters
- For either distribution, fines "dominate" in number and surface area over larger grains
  - Implies that larger boulders are emplaced in a matrix of finer grains
- What are the consequences of this?
  - Can these finer grains serve as a "matrix" that can hold larger blocks in place?
  - Can we apply basic properties of cohesive grains measured on Earth and the Moon to provide predictions for cohesive strength of a rubble pile?

What is the Strength of a Rubble Pile?

- For a "cohesionless" body, Drucker-Prager failure is only a function of self-gravity, internal stress, and friction angle:

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

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

s_c = Cohesive Shear Stress for Failure at 0 pressure

$$(\sigma_1,\sigma_2,\sigma_3)=\text{ Principal Stresses}$$

- "Strength" can be associated with cohesive shear stress, increasing the deviatoric stress needed to cause failure

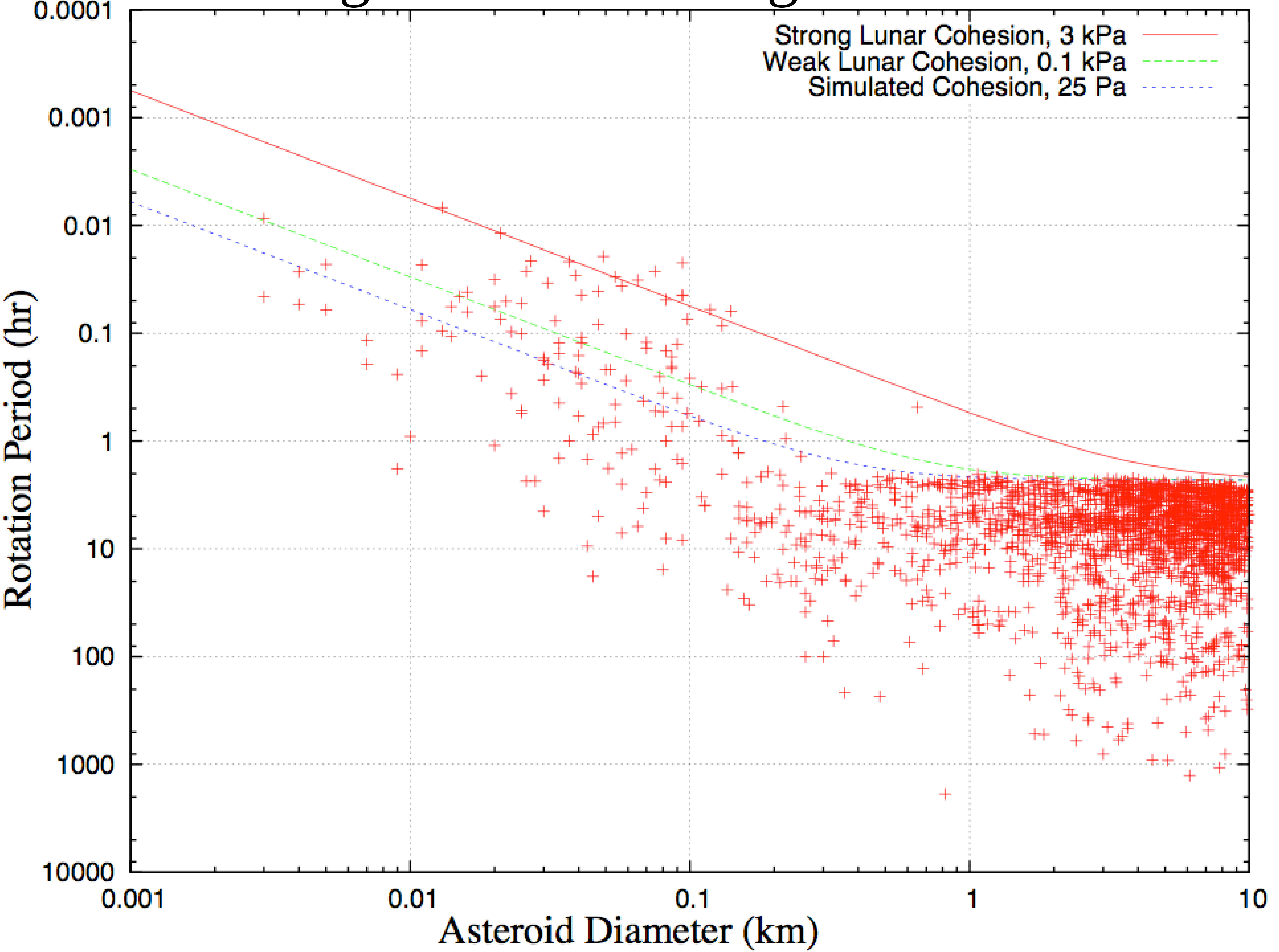
Is there a simple model for strength of a cohesive rubble pile?

- A simple, approximate model can be constructed for the failure of an elongate asteroid:
  - Volume averaged stress is largest along the long-axis $\sigma_1 \gg \sigma_2, \sigma_3$
  - Stress balanced between gravitational and inertial forces
  - A conservative bound on spin rate for plastic deformation is

$$\omega^2 \leq \omega_\alpha^2 + \frac{5}{s(\phi)} \frac{\sigma_c}{\rho \alpha^2}$$

  - This models the effect of a "constant yield strength"
  - For large bodies (a >> 1 km) controlled by bulk density: $\omega_\alpha^2 \propto \rho$
  - For small bodies (a << 1 km) controlled by cohesive strength: σ_c

Cohesive Strength: Drucker-Prager Yield Criterion

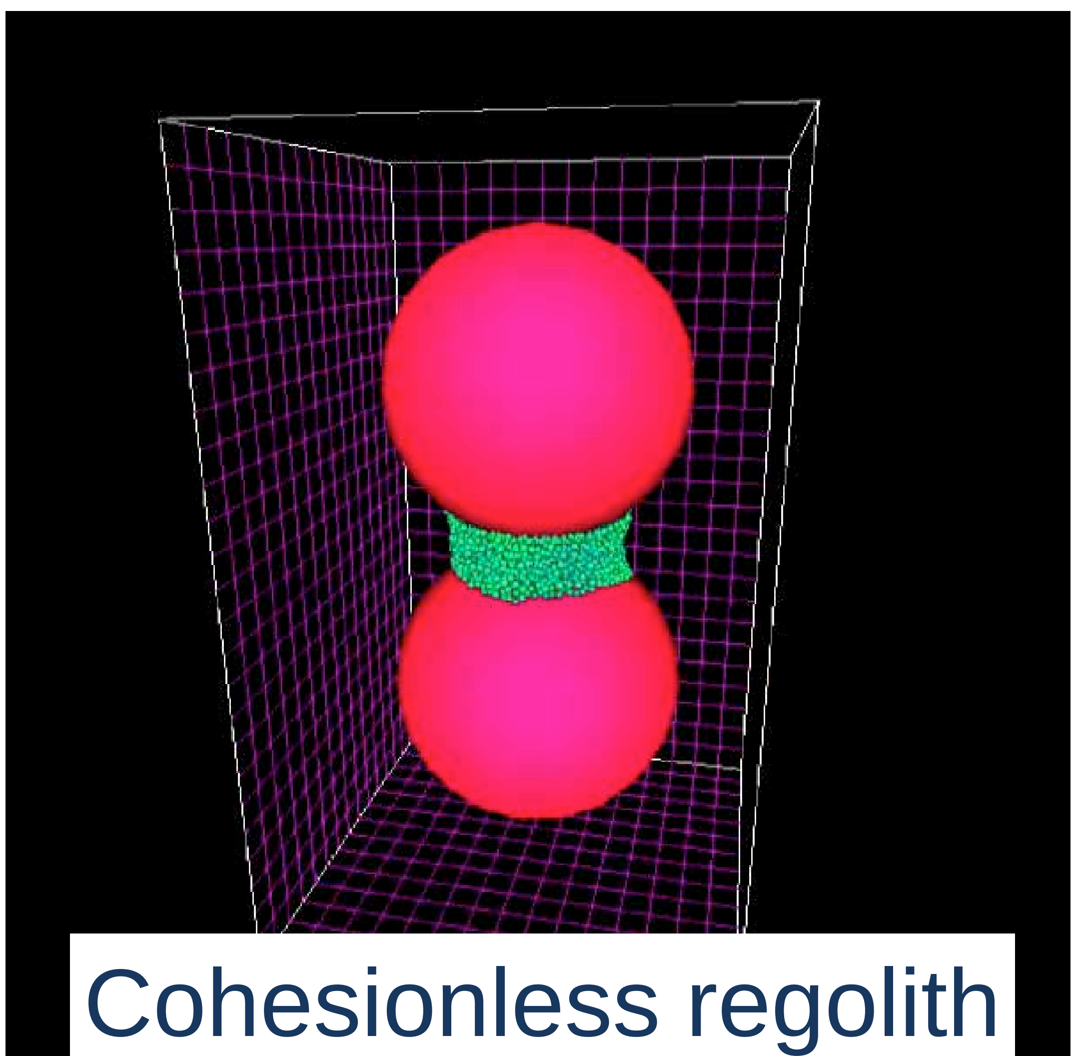


Physics of Micro-Gravity Bodies

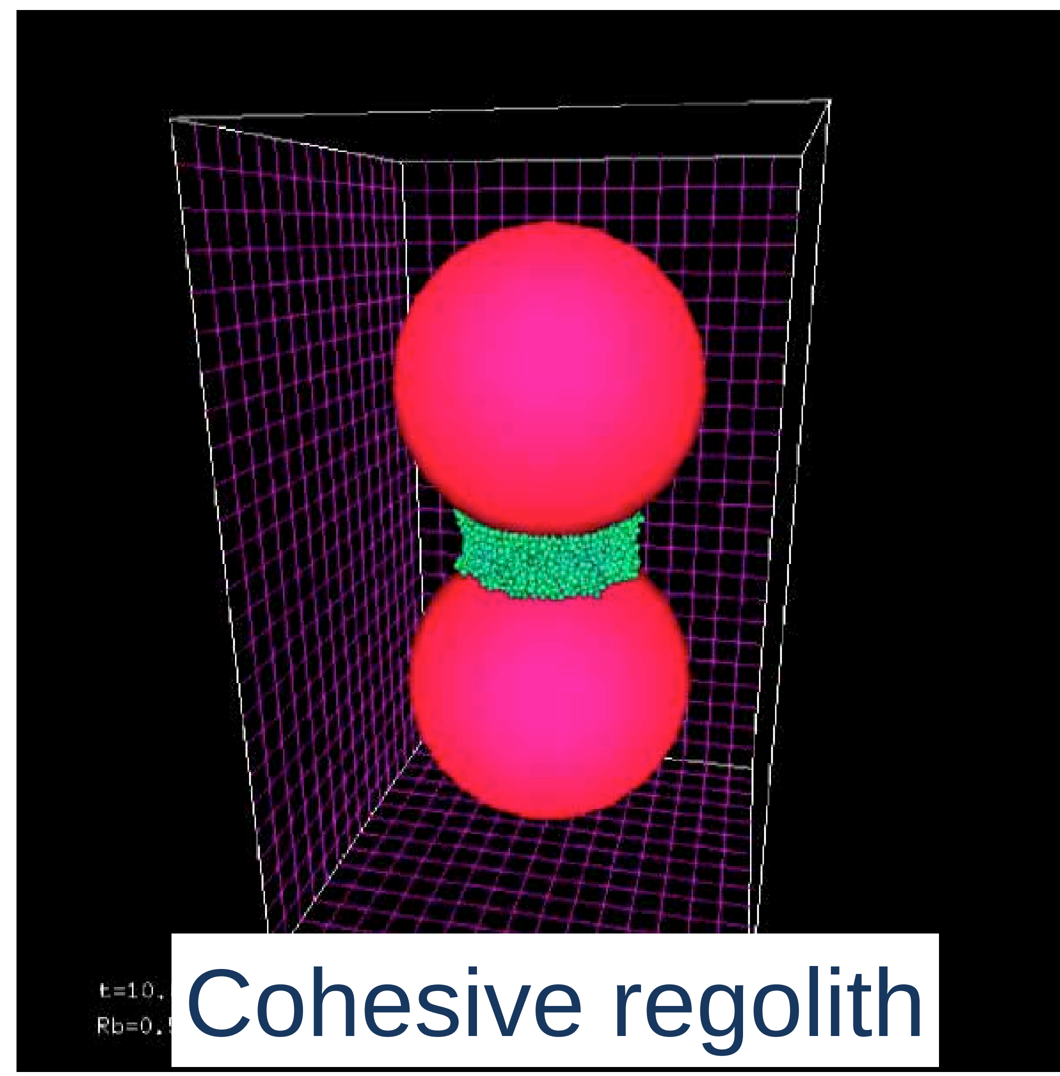
- Where does the cohesive strength arise?
- Chemical bonds?
  - Are very strong and can sustain extremely high spin rates
  - Are not relevant for cohesion ***<u>between</u>*** gravels/rocks
- van der Waals forces?
  - In microgravity, can van der Waals forces supply enough cohesion? (Asphaug, *LPSC 2009*; Scheeres et al., *Icarus 2010*)
  - For asteroid sizes less than ~ 1 km, van der Waals attraction between gravel-sized grains can become as significant as their weight
  - The amount of cohesion needed to keep a fast-spinning rubble pile together is very small (Holsapple, *Icarus 2007*)

How could this work?

- Cohesive van der Waals forces between smaller grains can hold larger boulders in place
- Validated with detailed granular mechanics simulations
  - 1-meter boulders with cohesive interstitial regolith van der Waals forces
  - Equal pull forces applied to each... very different outcomes



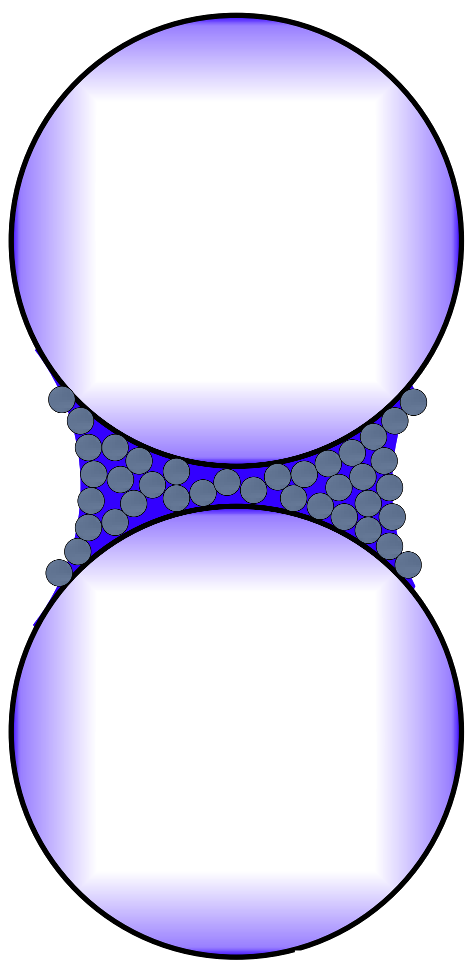
Cohesionless regolith



Cohesive regolith

How Strong is it?

- Predicts a cohesive strength model for asteroids dependent on fundamental physical properties and mean grain size
  - Model is consistent with measured cohesive strength properties of the upper lunar regolith: 25Pa – 150Pa



Cohesive forces scaling factor

Coordination number

Packing fraction

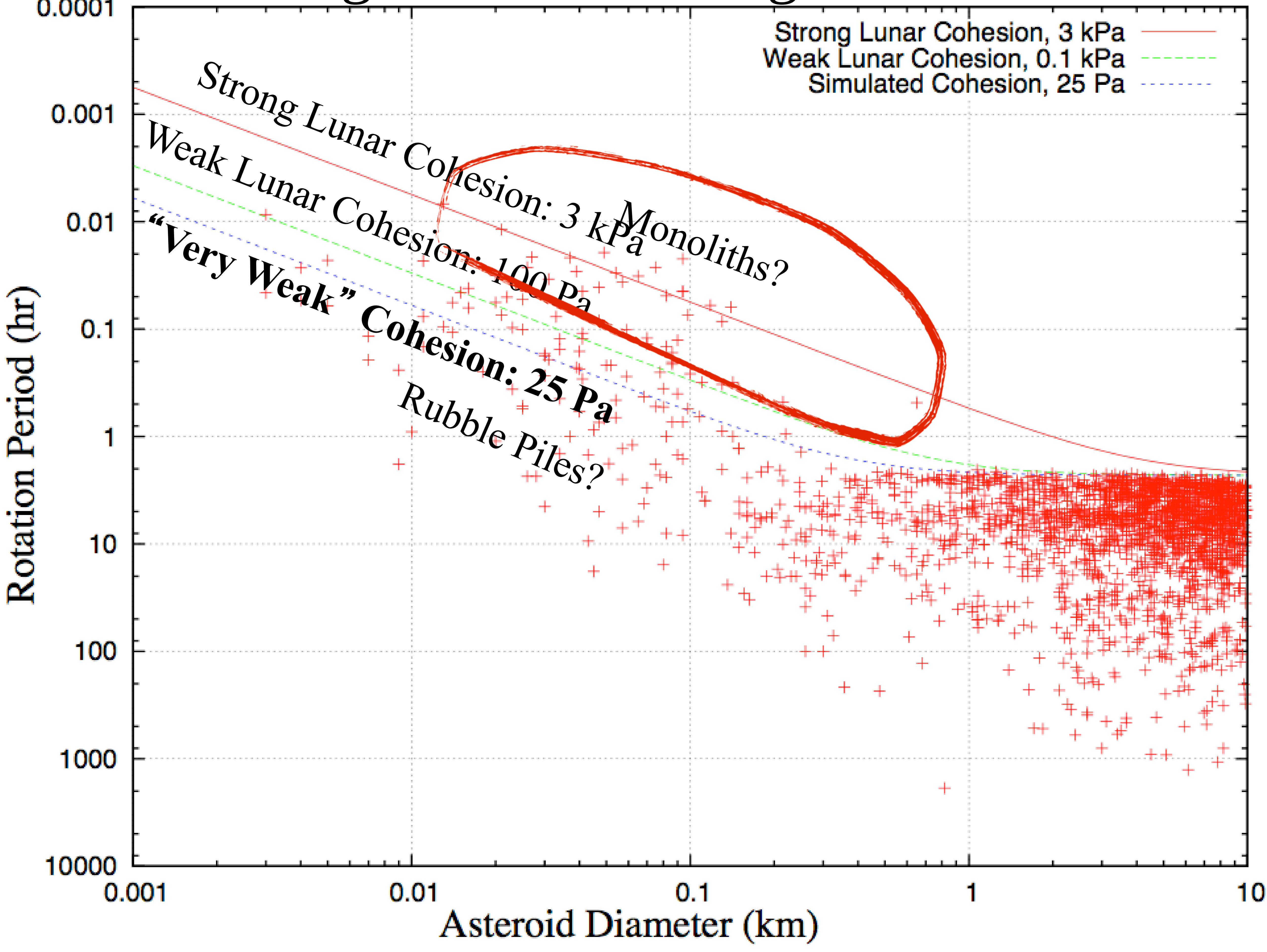
Modified Hamaker constant

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

Mean particle radius - regolith

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

Cohesive Strength: Drucker-Prager Yield Criterion

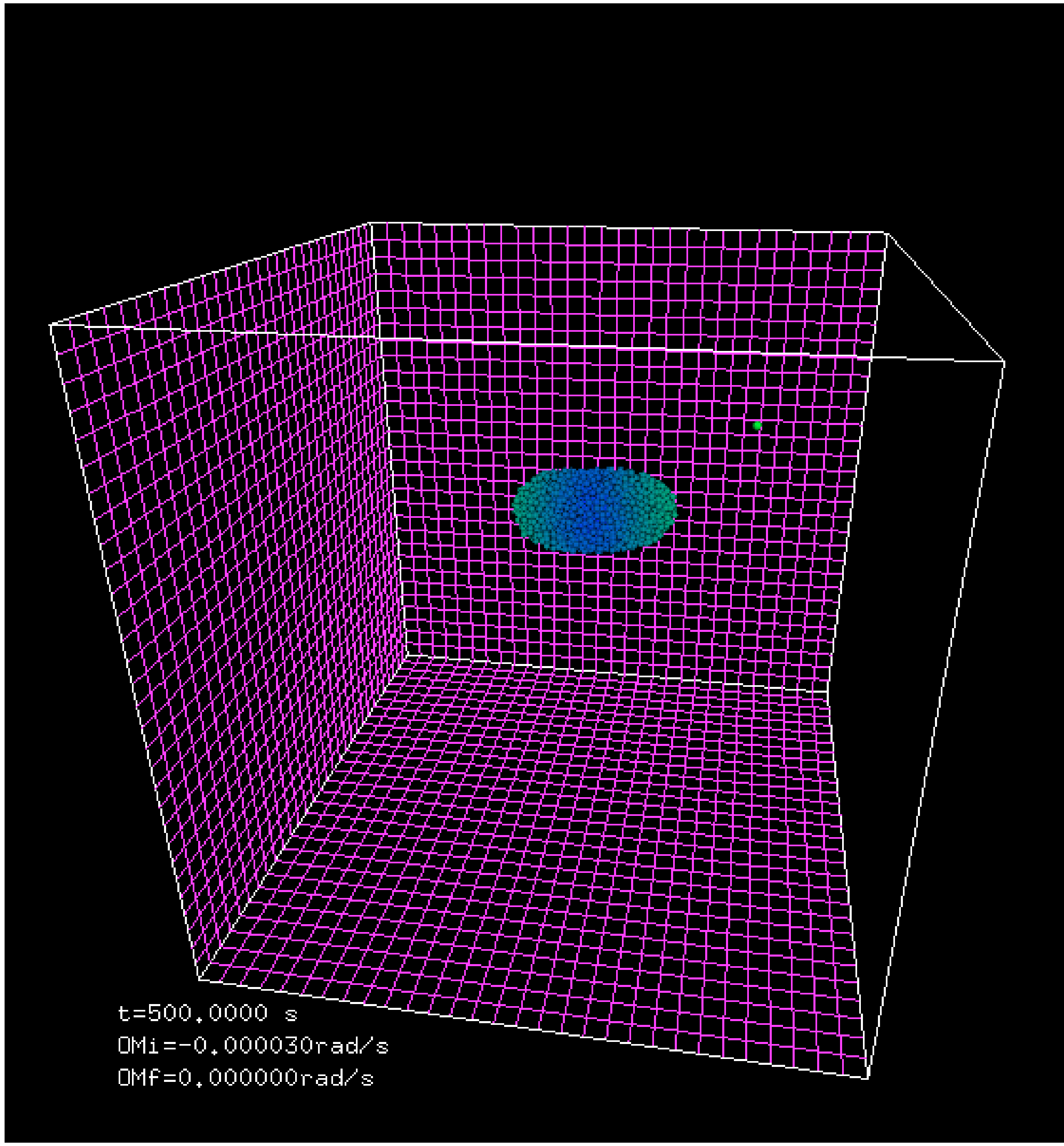


Minimum Binary Size

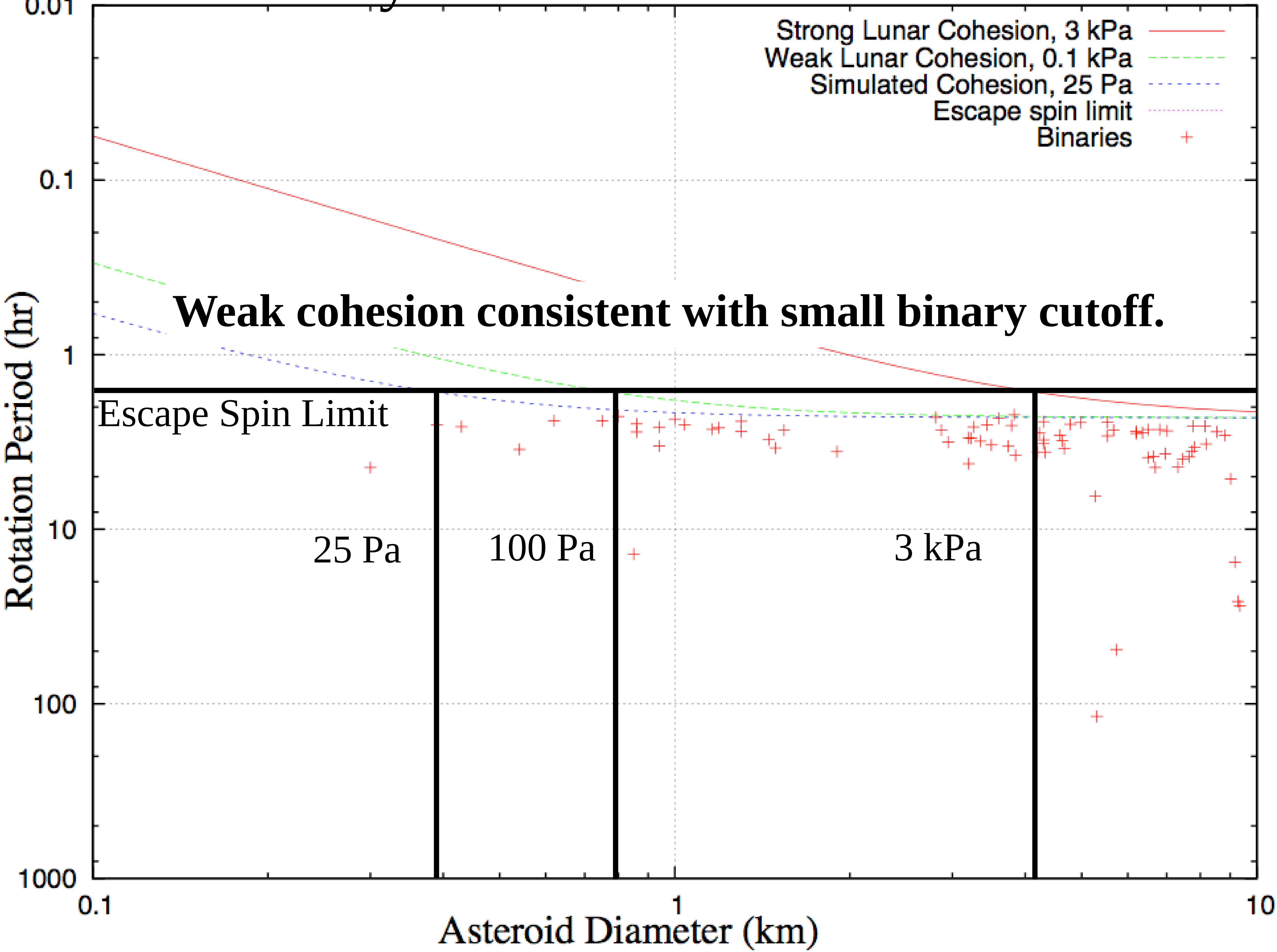
Binary asteroids have a statistically significant cut-off in size below a few hundred meters (Margot et al., 2002).

If a rubble pile has enough cohesive strength, it must spin faster than "escape speed" before it fails

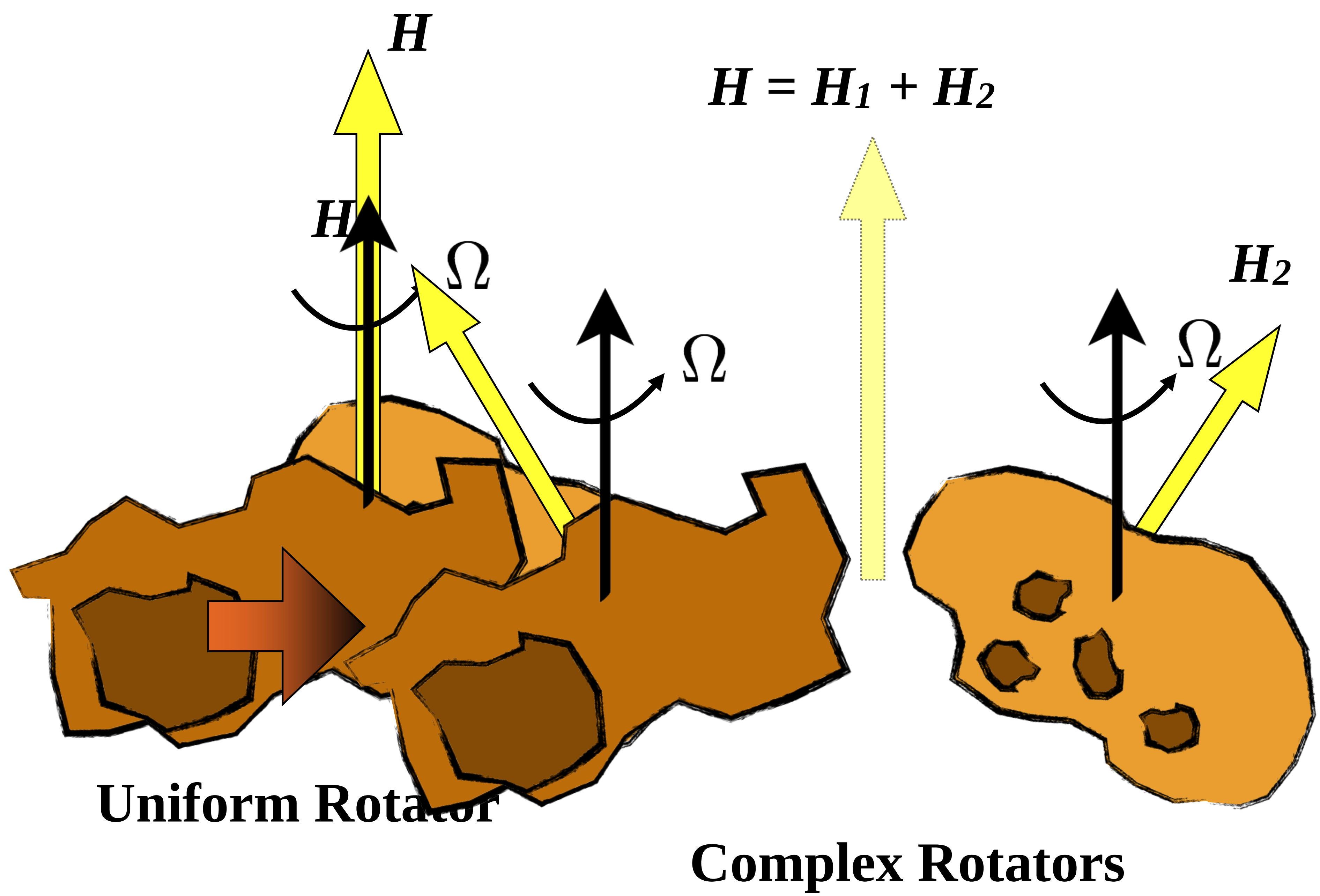
This would shut down binary creation by fission.



Binary Cutoff at Small Sizes

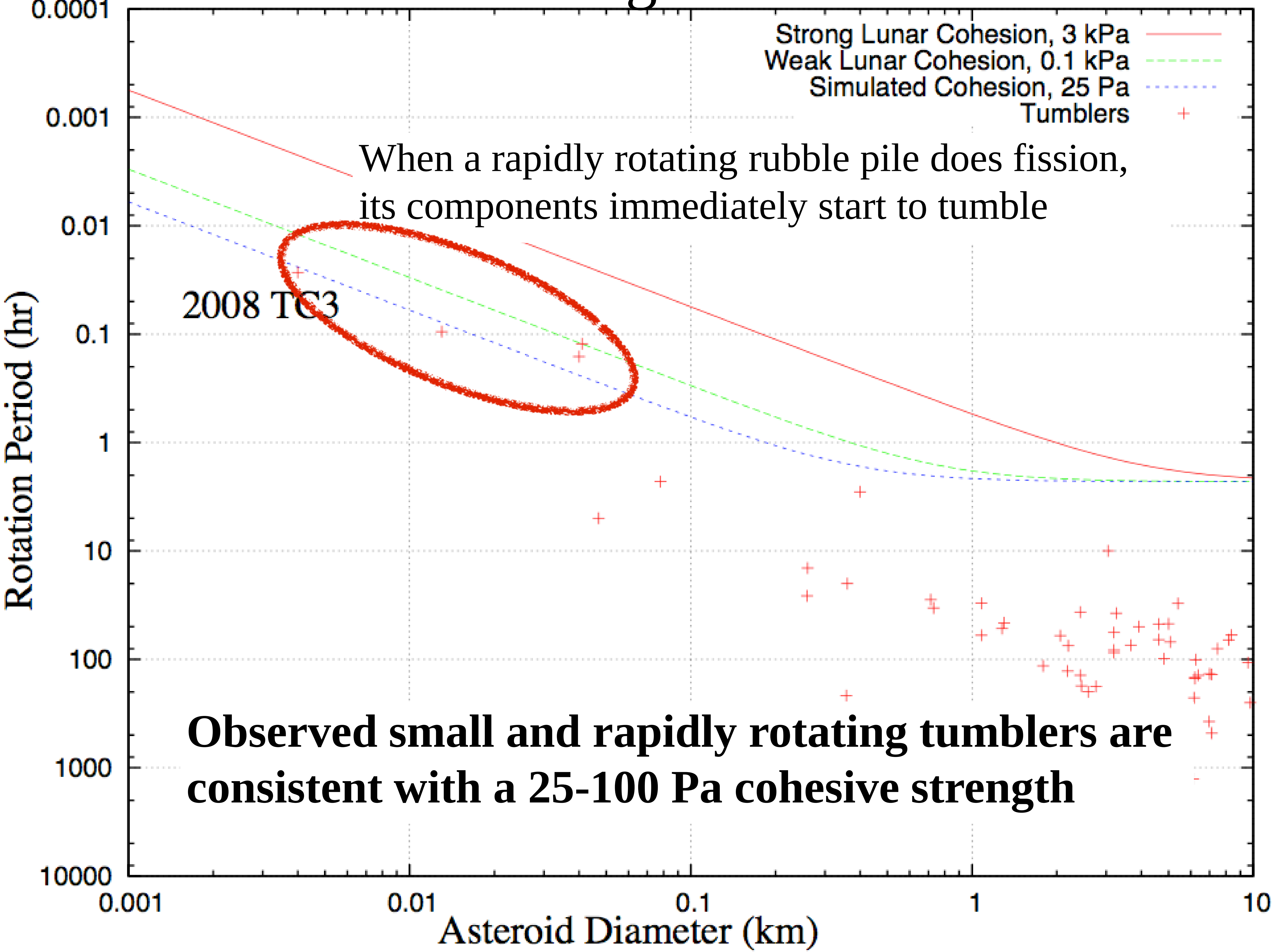


Fission Leads to Fast Rotating Tumblers



Smaller Bodies are more stable against spin fission, can be further rotationally accelerated...

Fast Tumbling Asteroids



Surfaces of Monoliths

- If a rubble pile is “fractionated” into its constituent boulders and gravels, what happens to the finest regolith grains?
  - Assuming lunar regolith properties, the necessary spin rate of a boulder can be computed to detach a grain:

r_1 is the grain radius
r_2 is the boulder radius

$$F_{cohesion} = \mathcal{A} \frac{r_1 r_2}{r_1 + r_2}$$

$$F_{grav} = \mathcal{G} \left(\frac{4\pi\rho}{3} \right)^2 \frac{r_1^3 r_2^3}{(r_1 + r_2)^2}$$

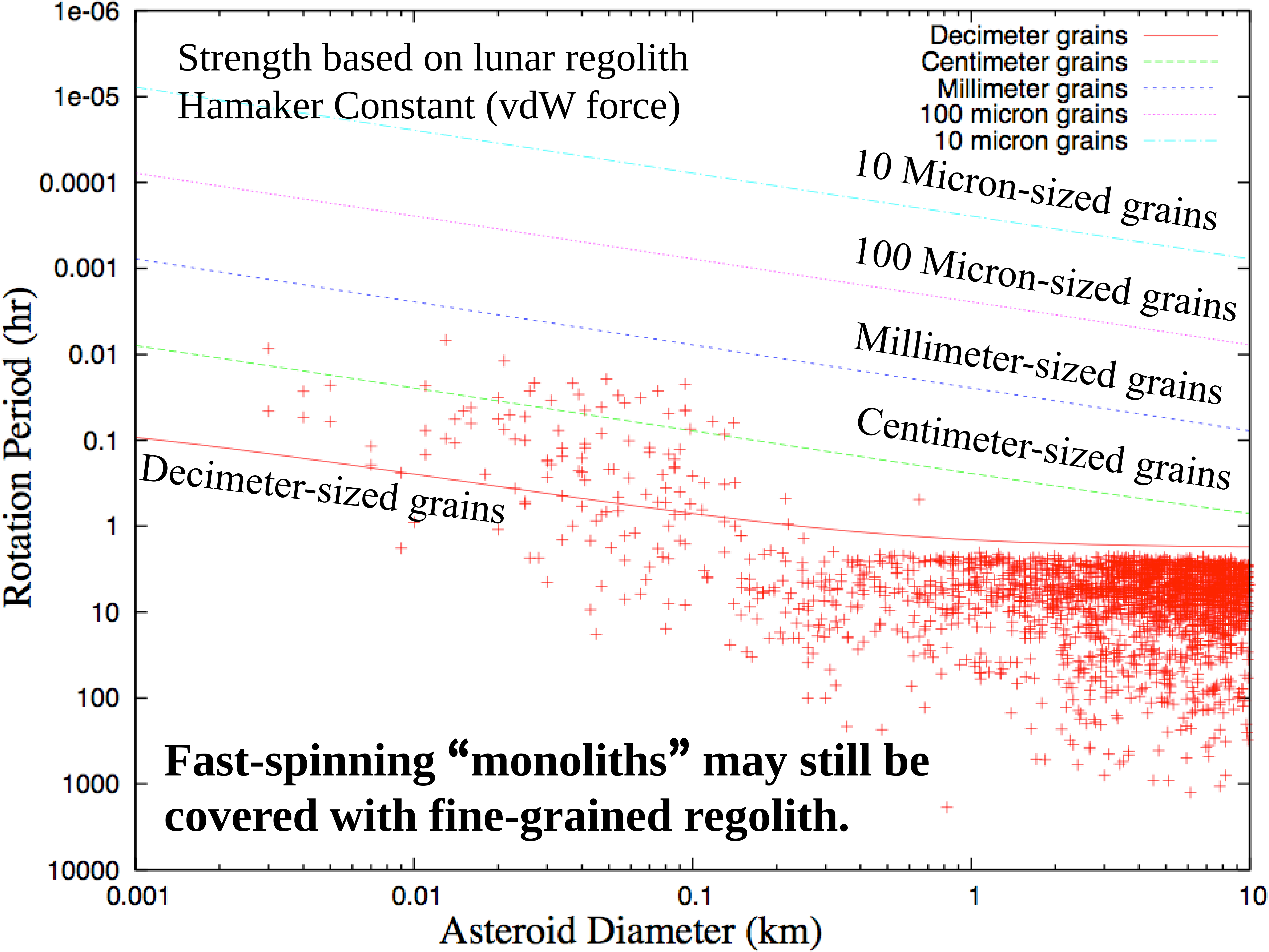
$$F_{inertial} = \frac{4\pi\rho}{3} \frac{r_1^3 r_2^3}{r_1^3 + r_2^3} (r_1 + r_2)\omega^2$$

$$F_{cohesion} > F_{inertial} - F_{grav}$$

If $r_1 \ll r_2$

Then $\omega^2 \leq \frac{3\mathcal{A}}{4\pi\rho} \frac{1}{r_1^2 r_2}$

Prediction: Surface Grains on Monoliths



Summary

- Rubble pile asteroids are strengthened by cohesive forces between the smallest grains in their size distributions
- Simulation and theoretical predictions are consistent with the measured strength of the upper lunar regolith
  - Fitting strength to the observed population assuming a Drucker-Prager Yield criterion predicts ~ 25-100 Pa
    - Based on: Overall spin/size curve, binary small size cut-off, small tumbling asteroids
- Implications of cohesive rubble piles:
  - The small asteroid population can continue to be “ground down” by YORP fission, with final state => coherent grains
- Details in:
  - Scheeres, Sánchez, Hartzell & Swift, *Icarus 2010*
  - Sánchez & Scheeres, *Icarus 2012*
  - Sánchez & Scheeres, *LPSC 2012*
  - Sánchez & Scheeres, submitted to *MAPS 2012*

Questions?