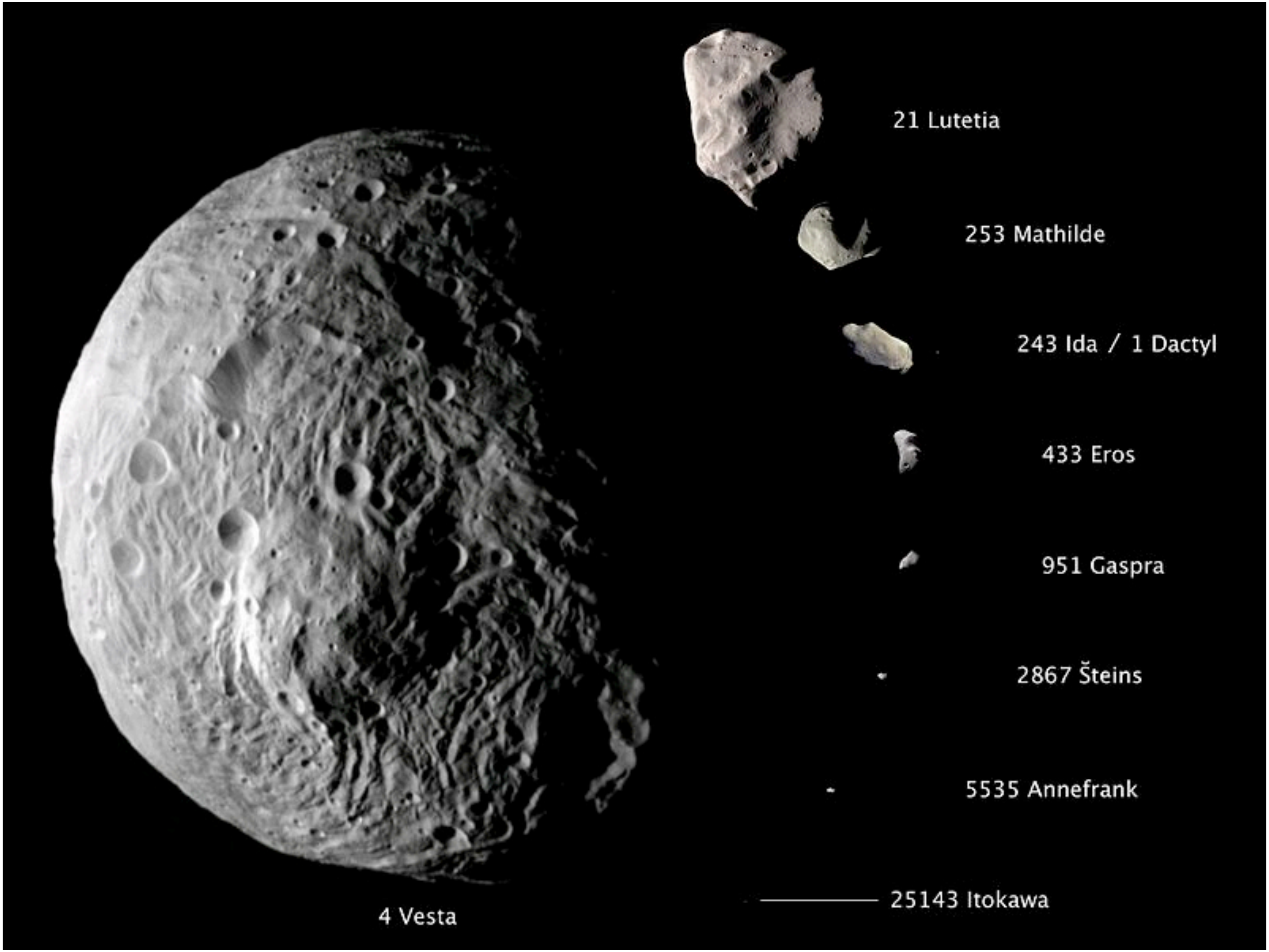
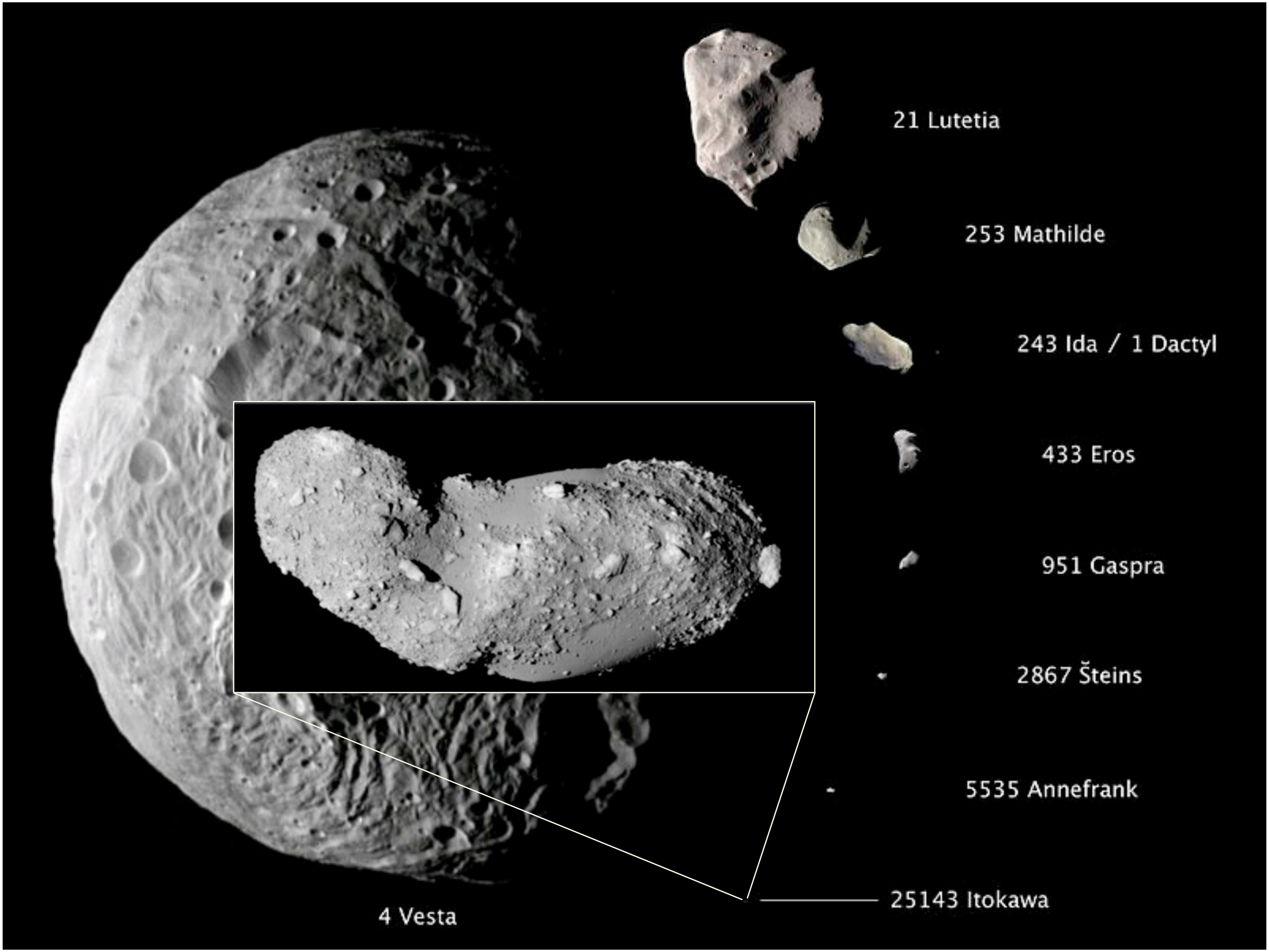
ASTR695: DCR's Research '12

- Theme: High-performance computation of many-particle gravitational systems.
- Applications (planetesimal dynamics):
  - Planet formation.
  - Planetary ring dynamics.
  - Small body satellite formation.
  - Granular dynamics. ← Biggest focus right now…
- Tools:
  - PKDGRAV (*N*-body code) & support code.
  - Commodity clusters & supercomputers.

Granular Dynamics Group

- **Ron Ballouz (U Maryland, grad).**
- Soko Matsumura (U Maryland, postdoc).
- Patrick Michel (Obs. Côte d'Azur, senior scientist).
- Brett Morris (U Maryland, undergrad).
- **Stephen Schwartz (U Maryland, grad).**
- Michael Sheaffer (TJHSST, high school senior).
- Eric Spieglan (U Maryland, undergrad).
- Kevin Walsh (SwRI Boulder, postdoc).
- **Yu Yang (U Maryland, grad).**
- …and others…


21 Lutetia
253 Mathilde
243 Ida / 1 Dactyl
433 Eros
951 Gaspra
2867 Šteins
5535 Annefrank
25143 Itokawa
4 Vesta


21 Lutetia
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433 Eros
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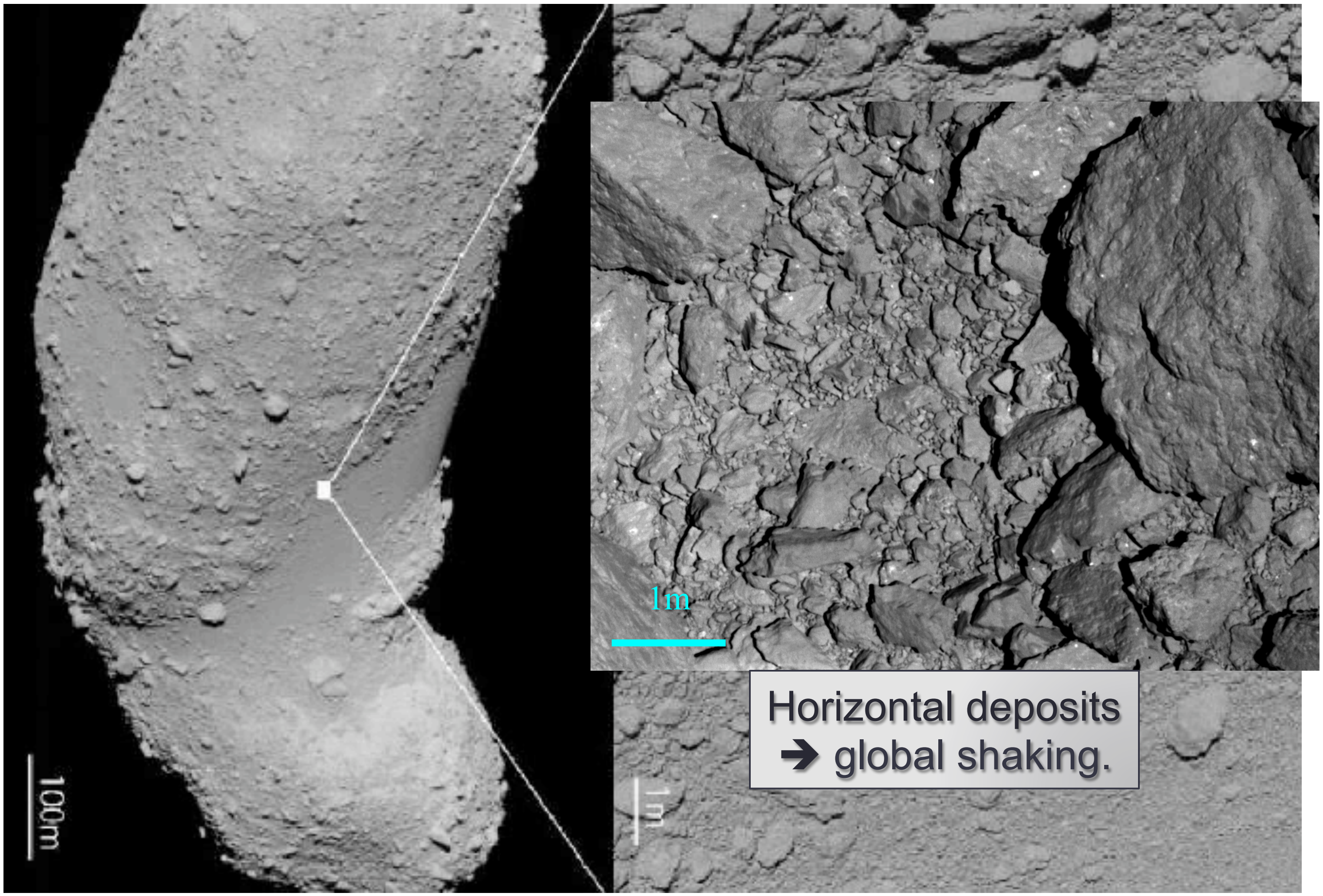
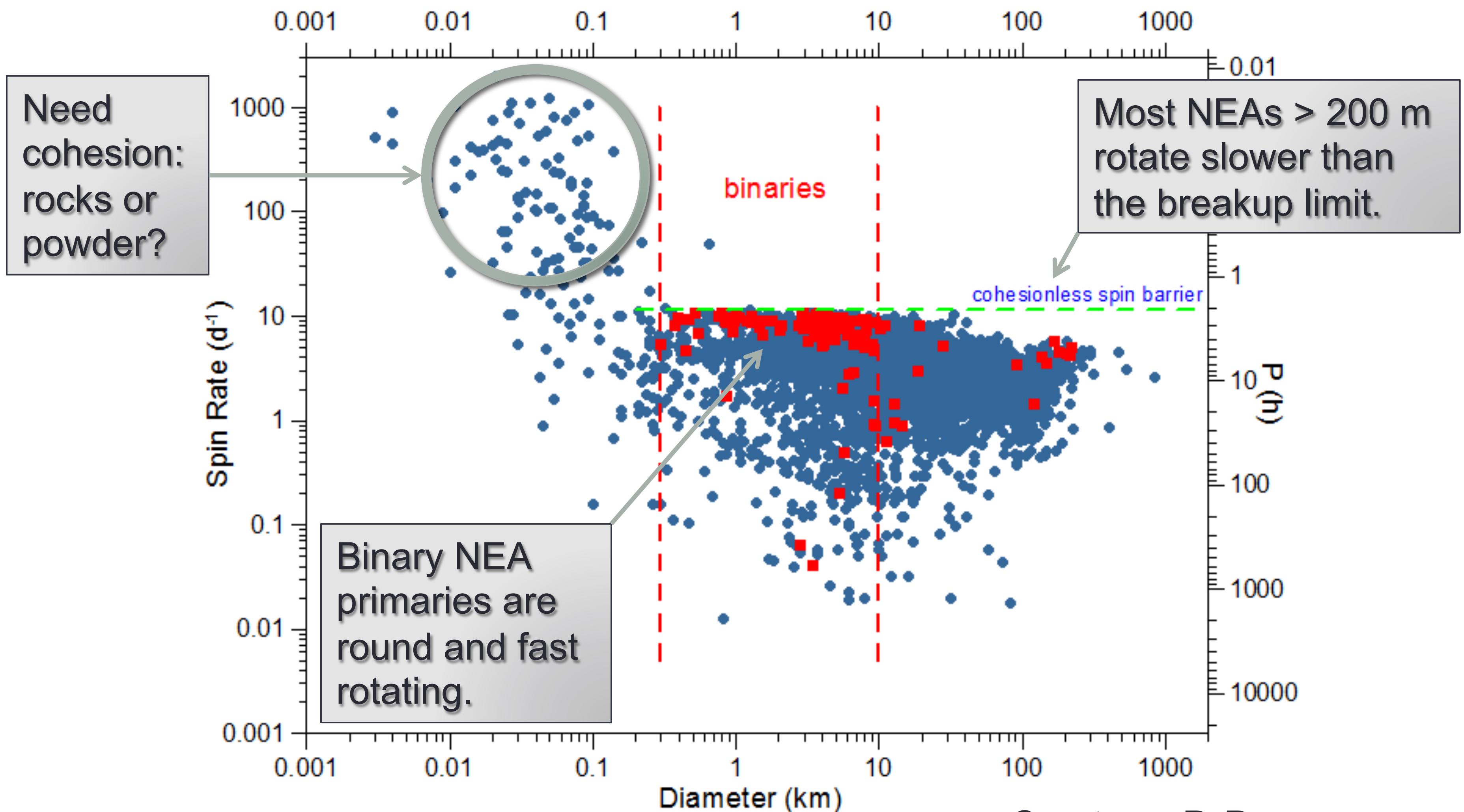
25143 Itokawa
4 Vesta

Itokawa: A "Rubble Pile"



Courtesy: JAXA

More Evidence for Fragile Asteroids



Courtesy: P. Pravec

Simulating Gravity and Collisions

- PKDGRAV: "Parallel *k*-D tree GRAVity code"
  - Combine parallelism and tree code to compute forces rapidly.
- Started as pure cosmology code written at U Washington.
- PKDGRAV solves the equations of motion for gravity (point masses):

$$\ddot{\mathbf{r}}_i = -\sum_{j \neq i} \frac{G m_j (\mathbf{r}_i - \mathbf{r}_j)}{\left|\mathbf{r}_i - \mathbf{r}_j\right|^3}$$

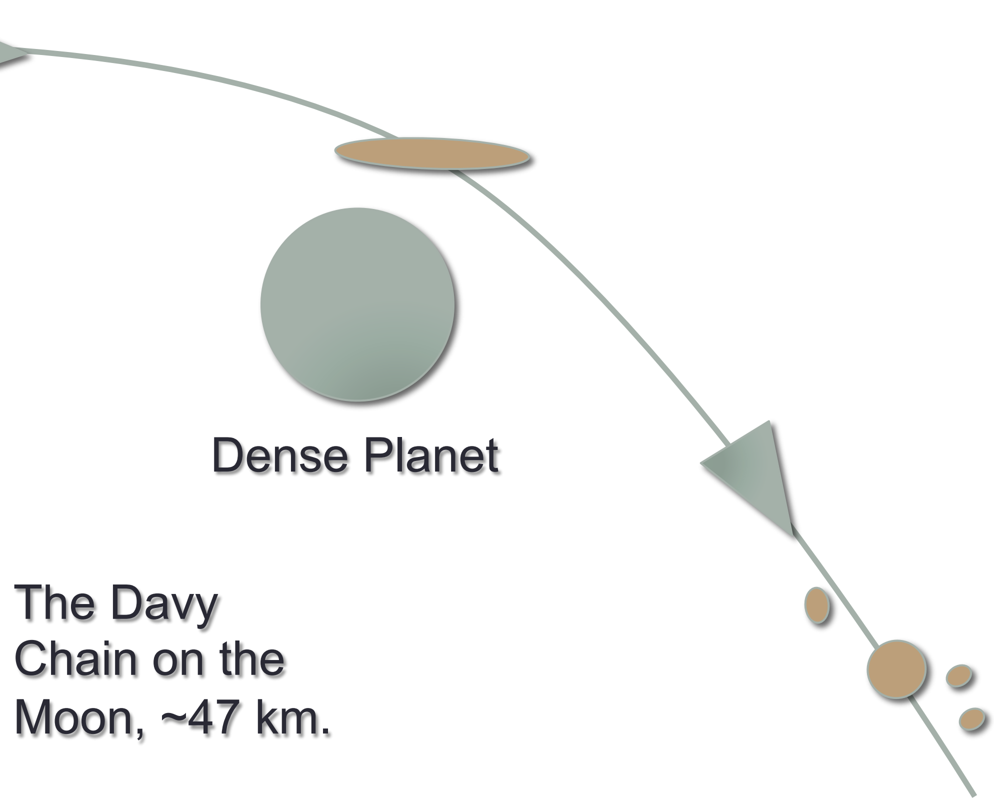
m = mass
r = vector position

- Introduce collision constraint (hard-sphere model):

Separation → $\left|\mathbf{r}_i - \mathbf{r}_j\right| = s_i + s_j.$ ← Sum of radii

Tidal Disruption of Asteroids

- If asteroids are fragile, they can be broken up like SL9.



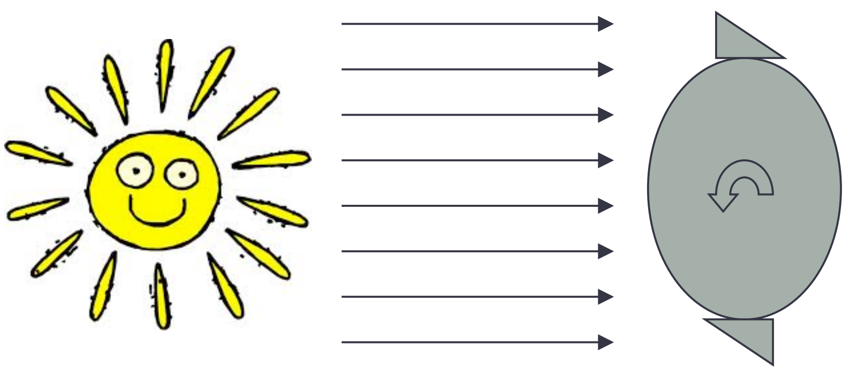
The Davy Chain on the Moon, ~47 km.

Binary Asteroids from Rotational Breakup

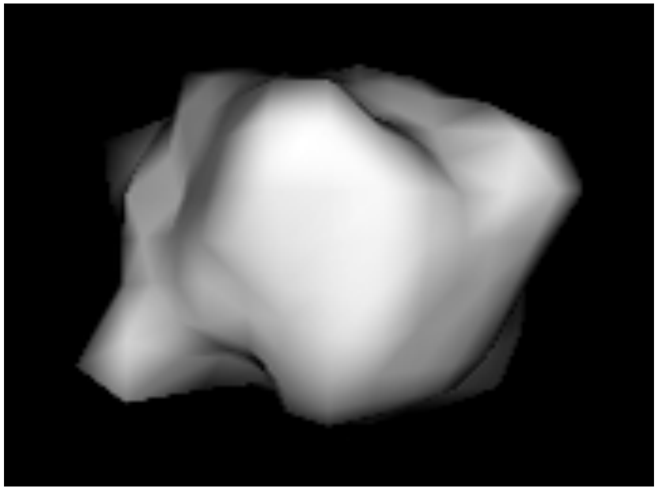
- Tidal disruption by Earth or Venus of fragile near-Earth asteroids (NEAs) accounts for only a few binaries (Walsh & Richardson 2008).
- Need a different mechanism to explain the 15% binary NEA population—YORP!

Spin-up by YORP

- Even sunlight, such as the "YORP" effect, can spin-up and disrupt asteroids.
- Depends on body size and distance from Sun.
- Spin-up timescale ~Myr.



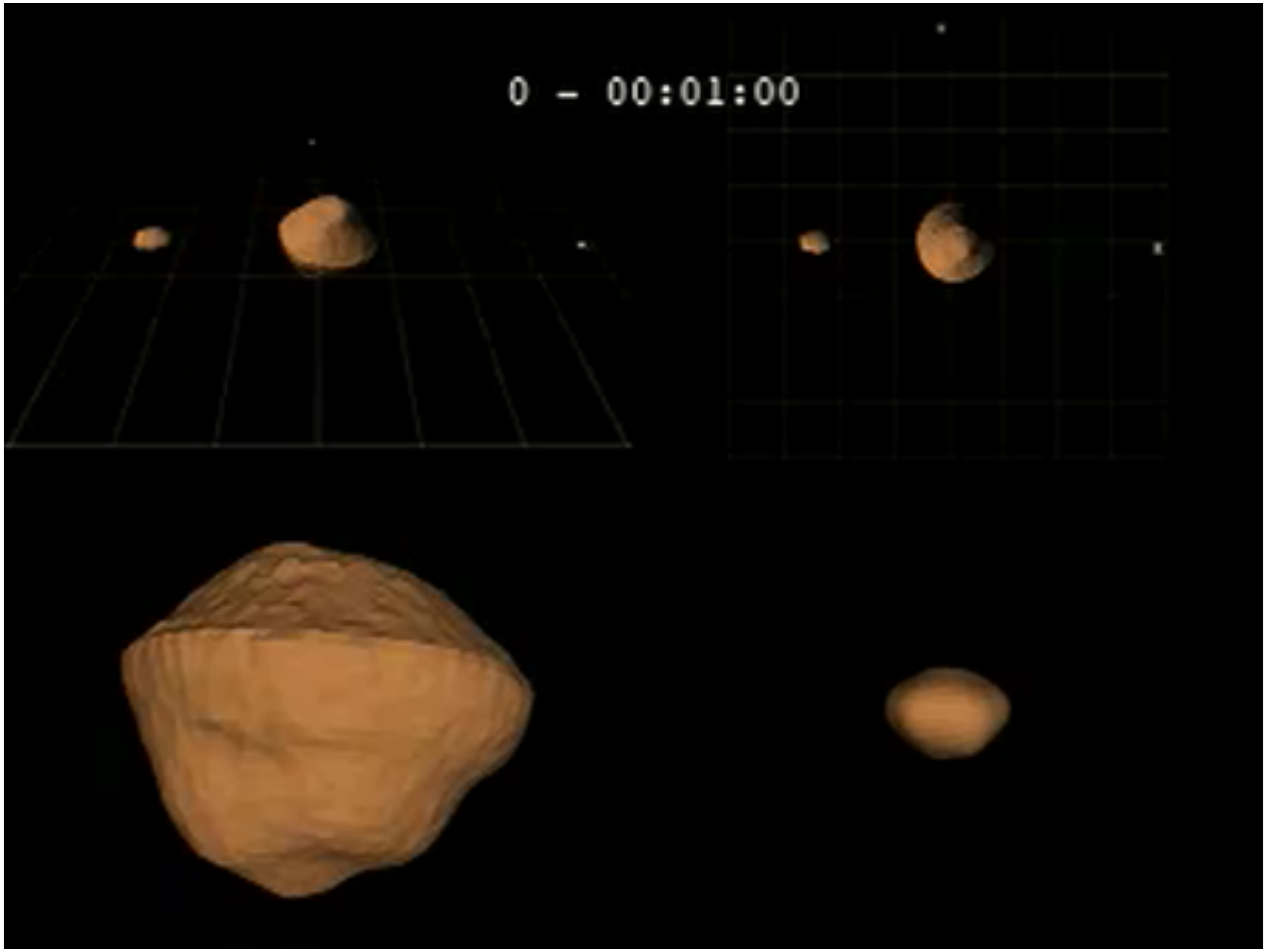
Taylor et al. (2007)



54509 YORP: 12.2-minute rotation and speeding up!

Asteroid must be nearly strengthless to disrupt.

1999 KW_4: Radar-derived Model



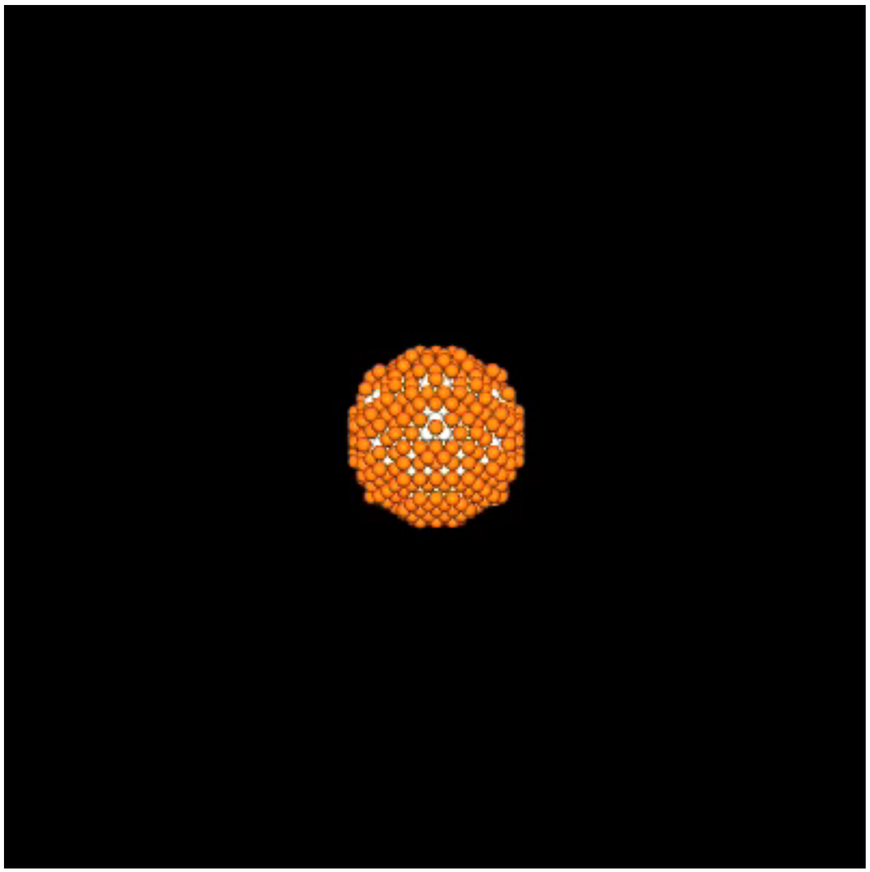
Ostro et al. (2005)

Simulating KW_4

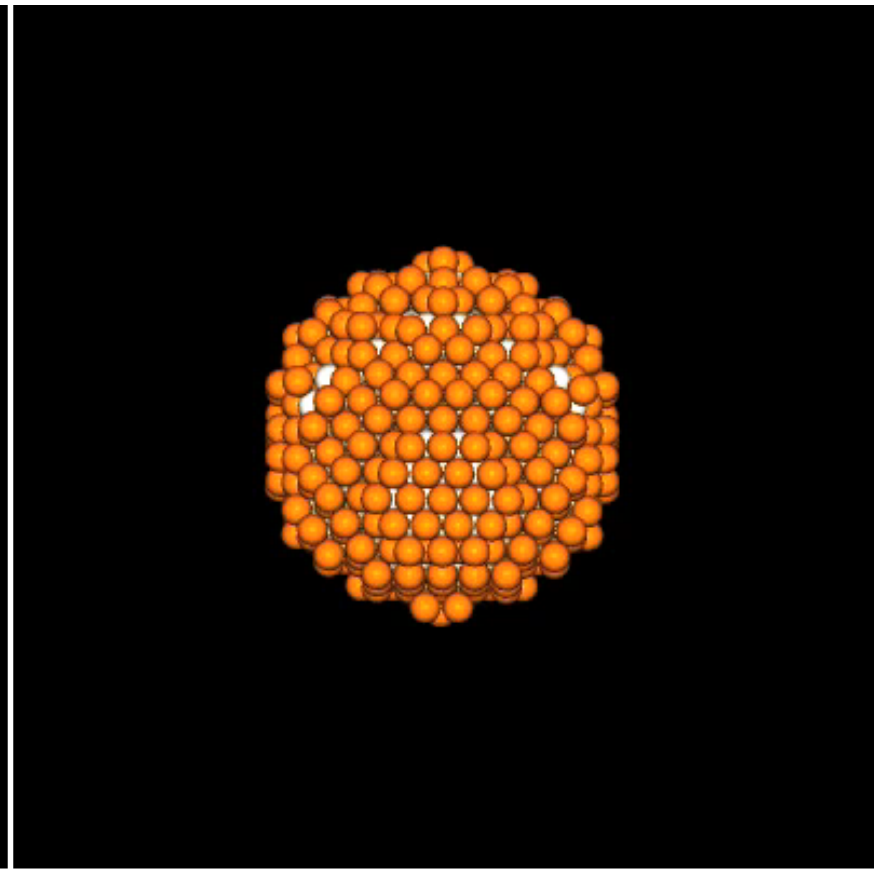
nature International weekly journal of science LETTERS
Vol 454 | 10 July 2008

Rotational breakup as the origin of small binary asteroids

Kevin J. Walsh[1,2], Derek C. Richardson[2] & Patrick Michel[1]



Top view

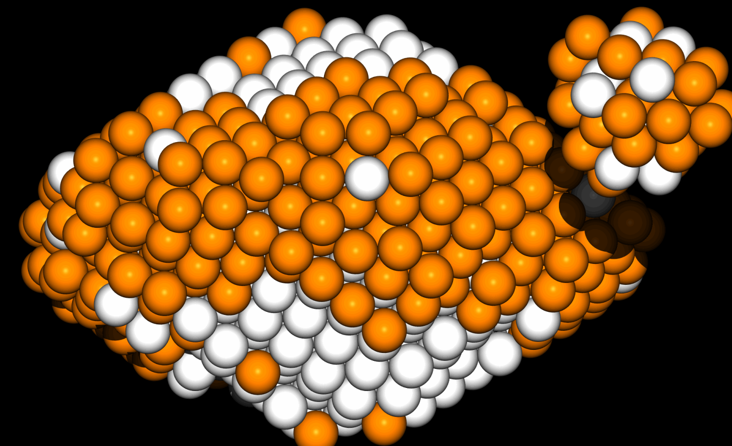


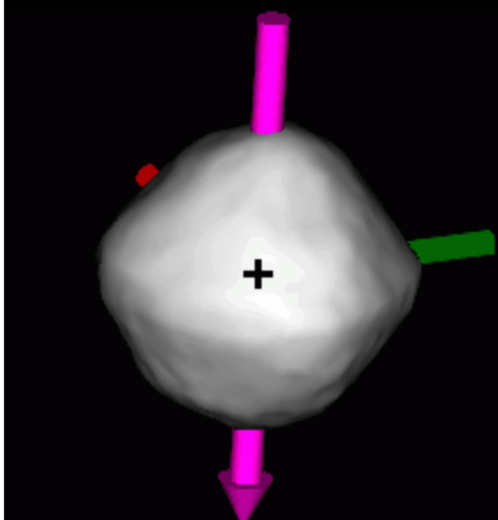
Side view

Top Shapes and Ridges

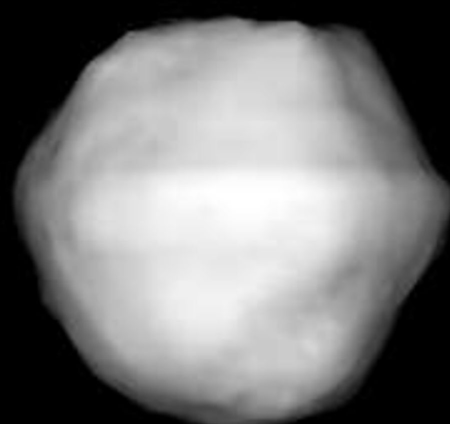
1999 KW_4 radar model, Ostro et al. 2005

YORP spinup sims, Walsh et al. 2008





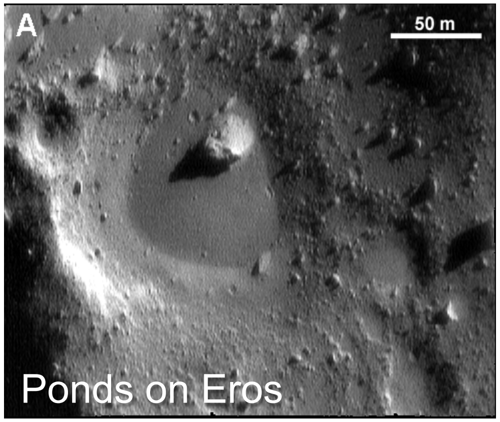
Single asteroid 1999 RQ_{36}
Howell et al. 2008, ACM

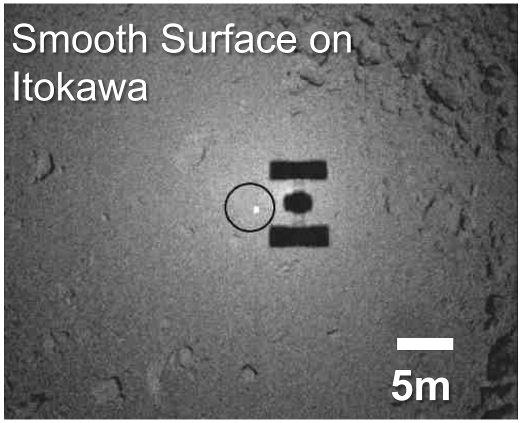


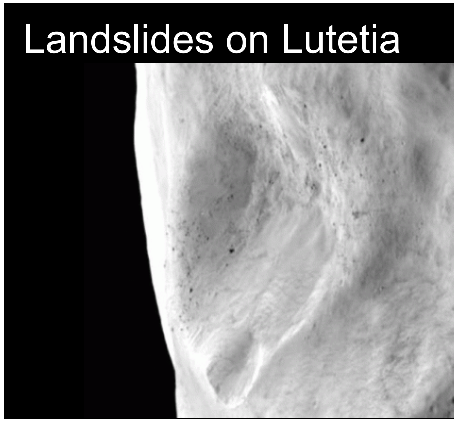
Binary 2004 DC
Taylor et al. 2008, ACM

Šteins from Rosetta Images

Why investigate granular material?







- Surfaces of planets and small bodies in our solar system are often covered by a layer of granular material.
- Understanding dynamics of granular material under varying gravitational conditions is important in order to:
  1. Interpret the surface geology of small bodies.
  2. Aid in the design of a successful sampling device or lander.

Asteroid Sample Return Missions

Marco Polo-R

- ESA proposed mission to binary asteroid.

http://www.oca.eu/MarcoPolo-R/

OSIRIS-REx

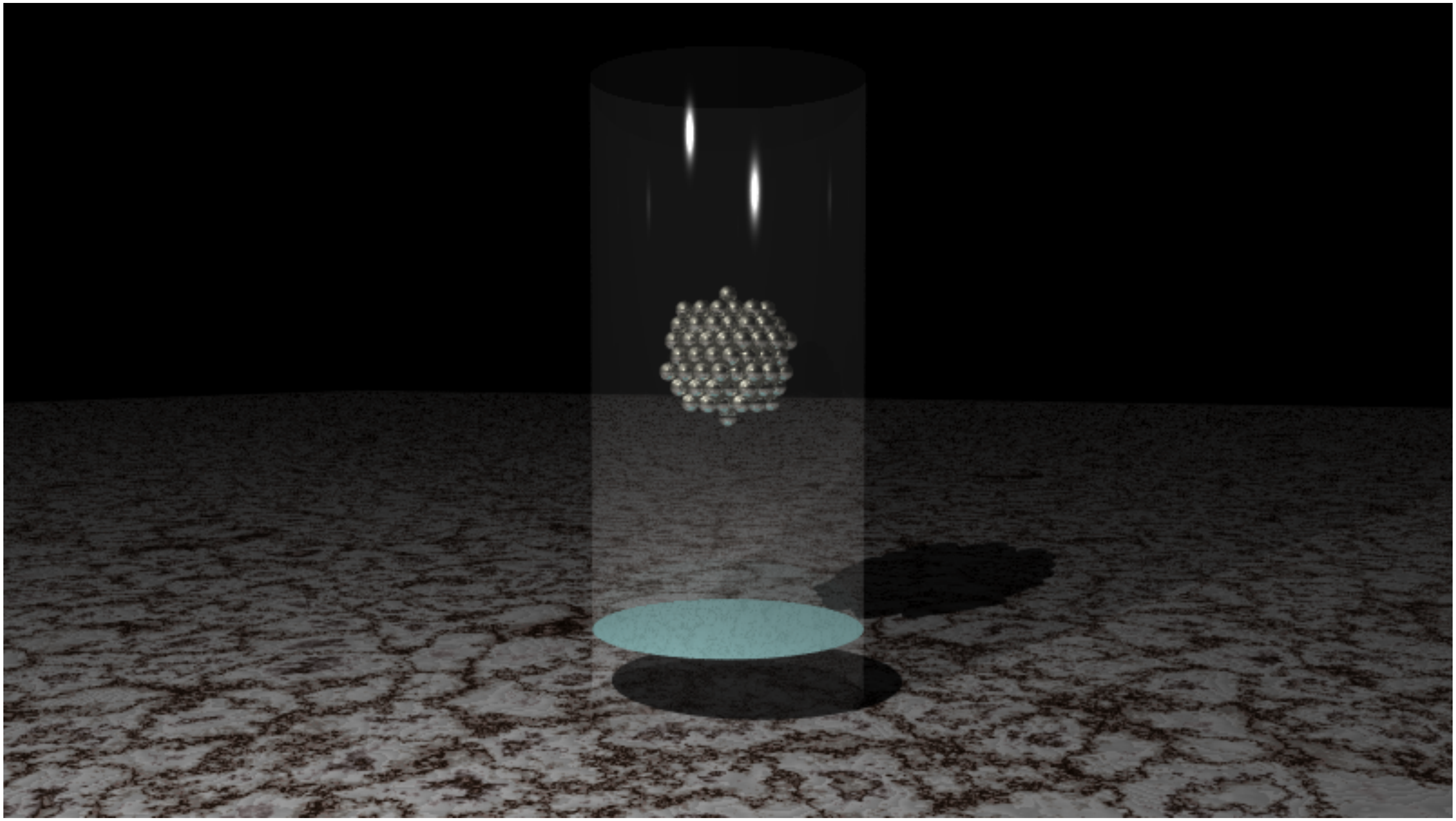
- NASA funded mission to primitive asteroid.

VIDEO

http://osiris-rex.lpl.arizona.edu/

Hayabusa 2 Mission Concept

Simulating Granular Dynamics



Soft-sphere Discrete Element Method

- HSDEM fails in dense and/or near-static regimes.
- In soft-sphere approach, allow particles to overlap, then apply restoring forces with optional damping/friction.
- Disadvantage: need small timesteps to resolve forces.
- Summary equations:

Restoring force

Friction force

Force $\rightarrow$ $$\mathbf{F}_p = \mathbf{F}_N + \mathbf{F}_T,$$

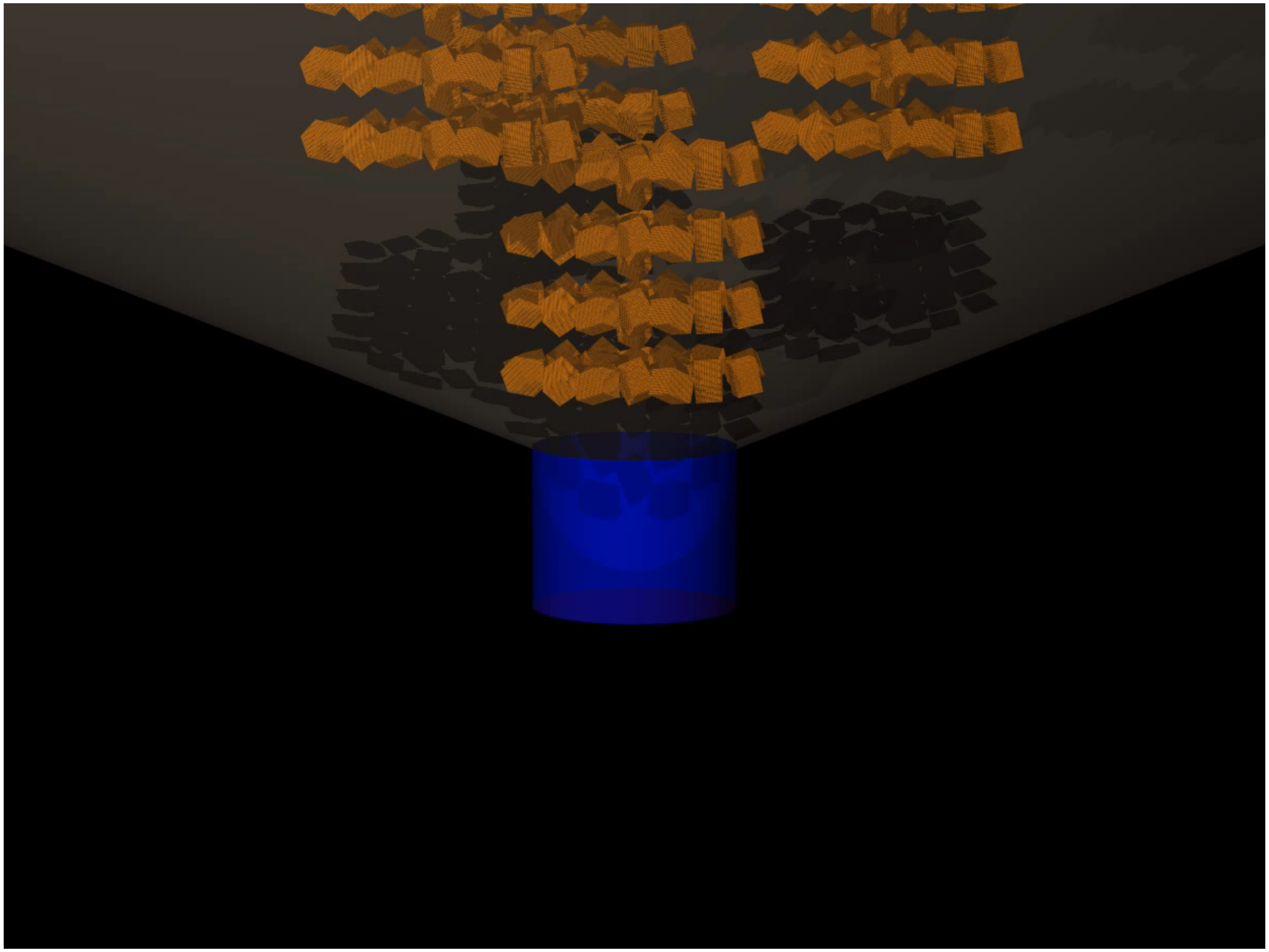
Torque $\rightarrow$ $$\mathbf{M}_p = l_p(\hat{\mathbf{n}} \times \mathbf{F}_T) + \mathbf{M}_{\text{roll}} + \cdots.$$

Friction torque

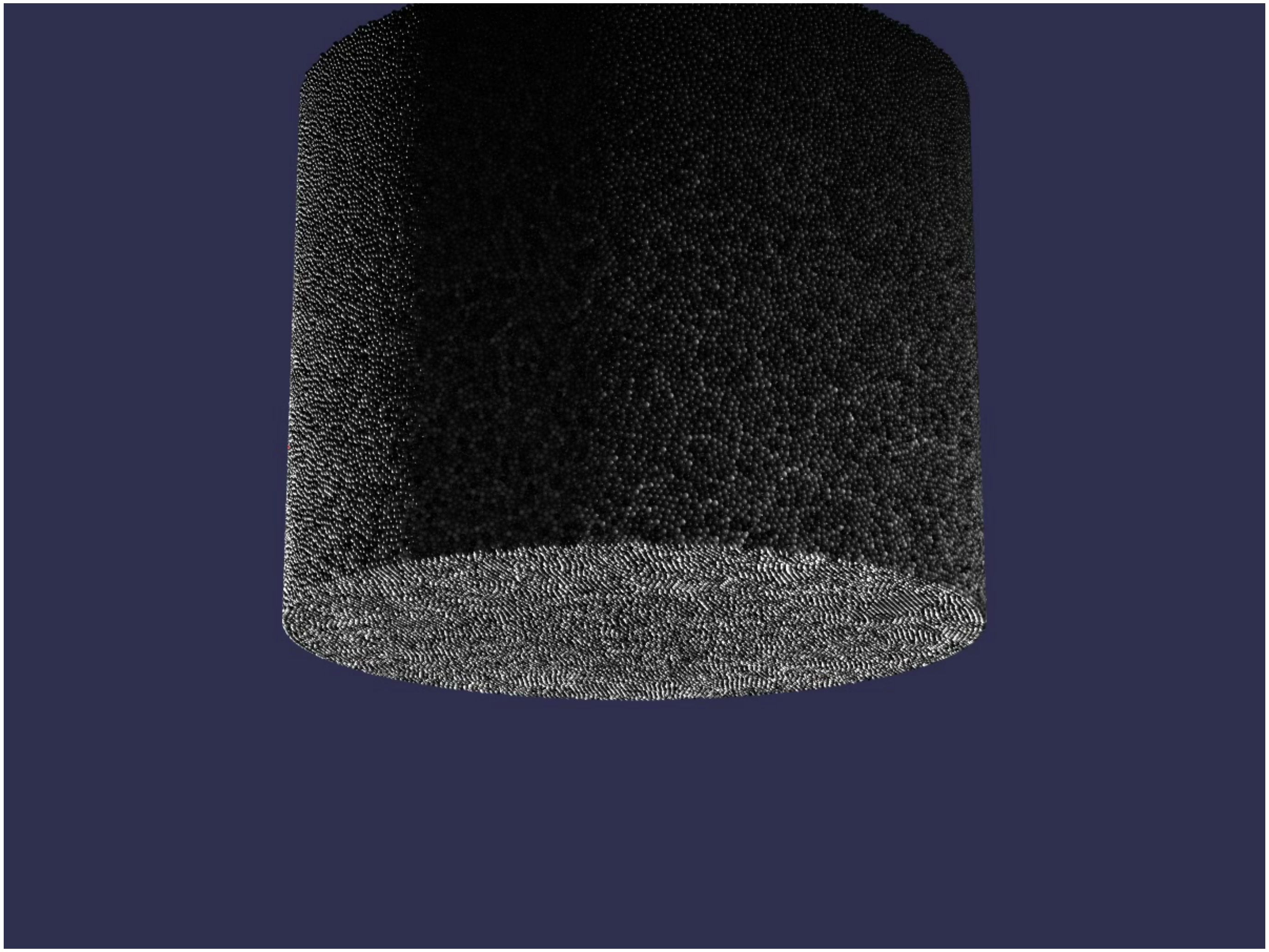
Rolling friction, etc.

Schwartz et al. (2012), *Granular Matter* 14, 263.

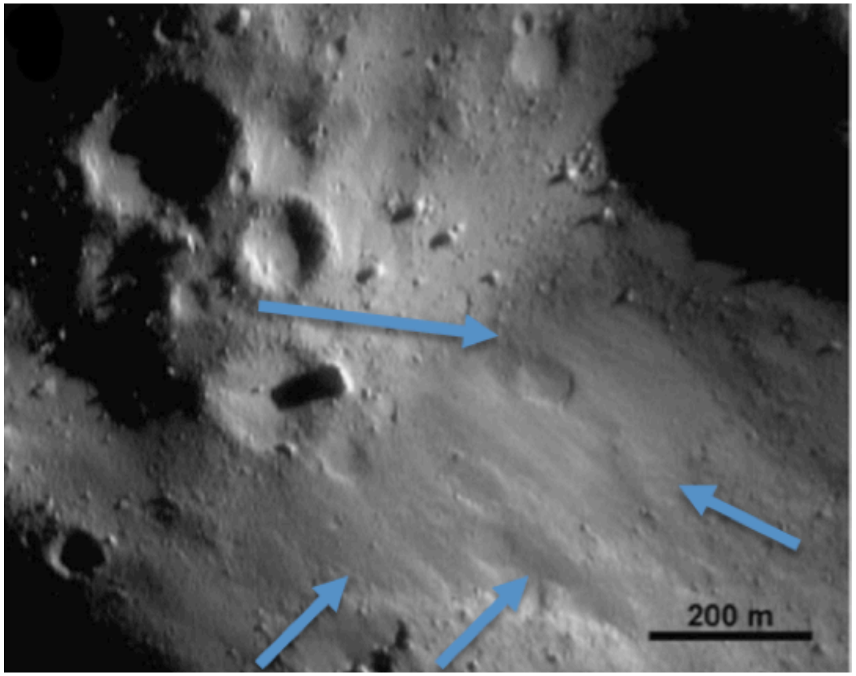
SSDEM Test: Hopper ($N = 1.5 \times 10^6$!)



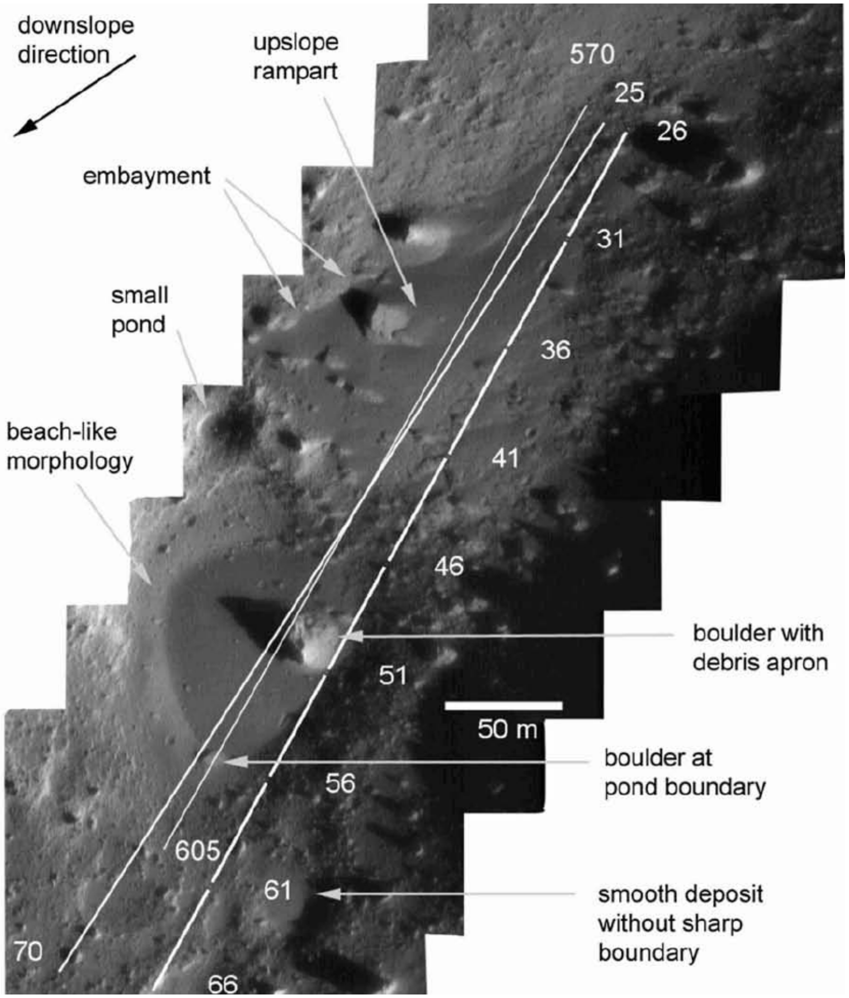
Hopper: Force Networks (Real Time!)



Eros: Evidence of Surface Flow

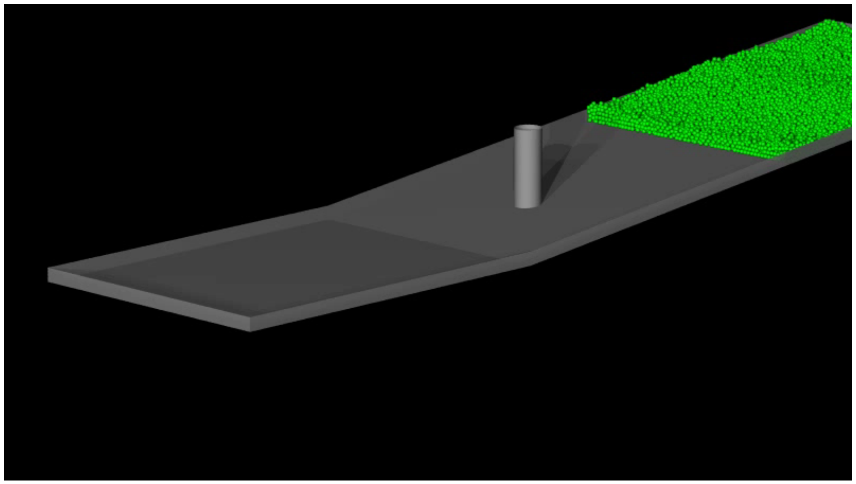


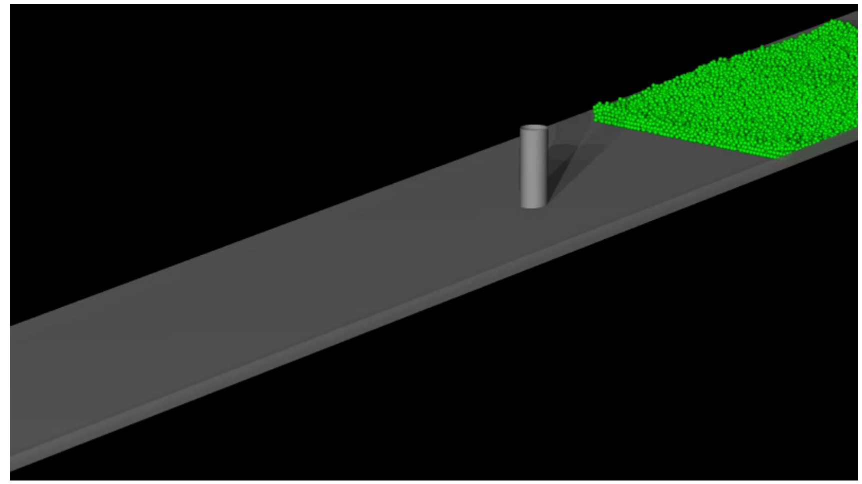
(arrows mark boundary of flow region)

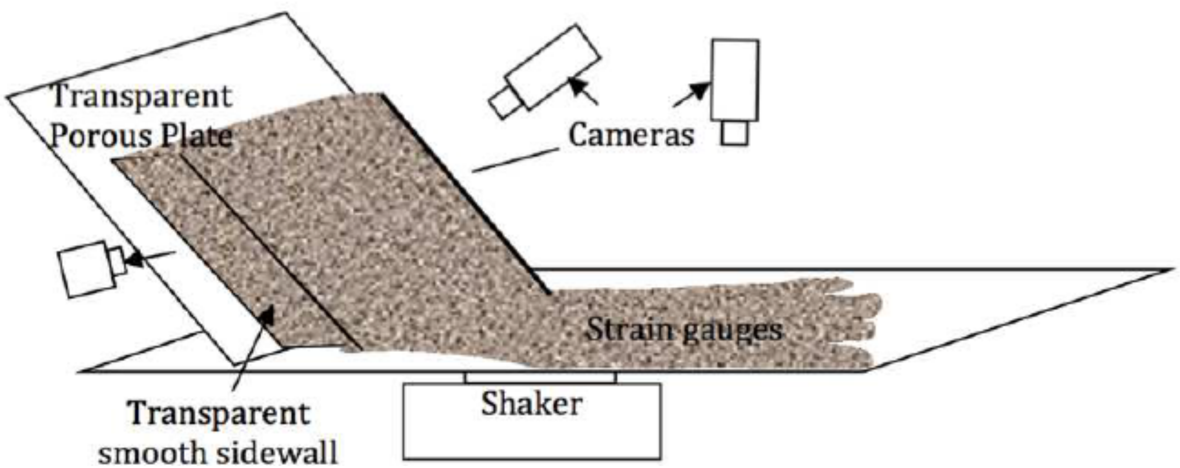


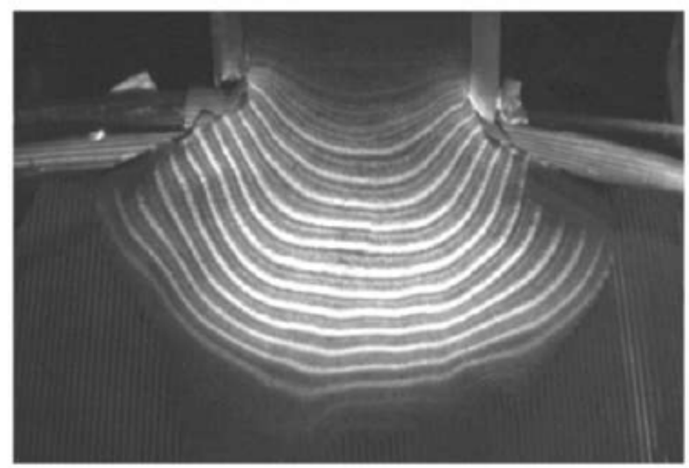
Courtesy: A. Cheng

Landslides: Simulations





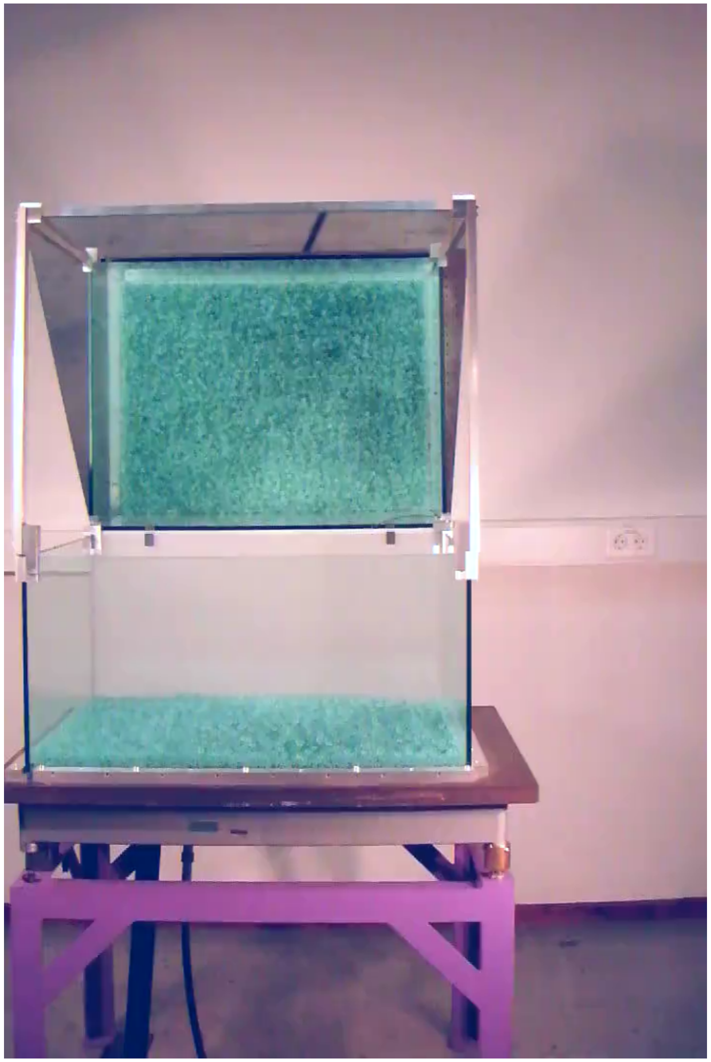




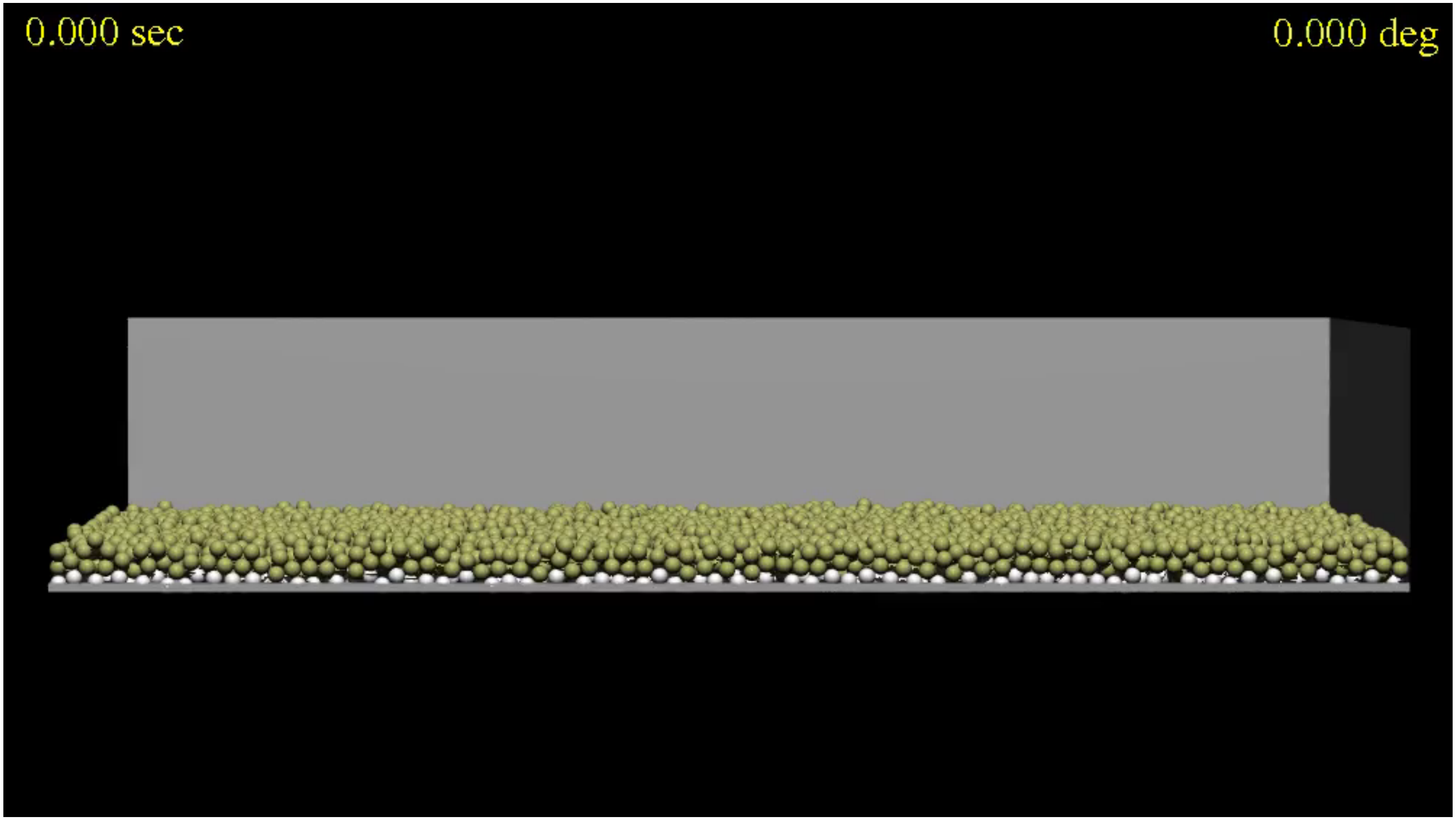
Losert lab apparatus (U Maryland Physics)

Granular Avalanches

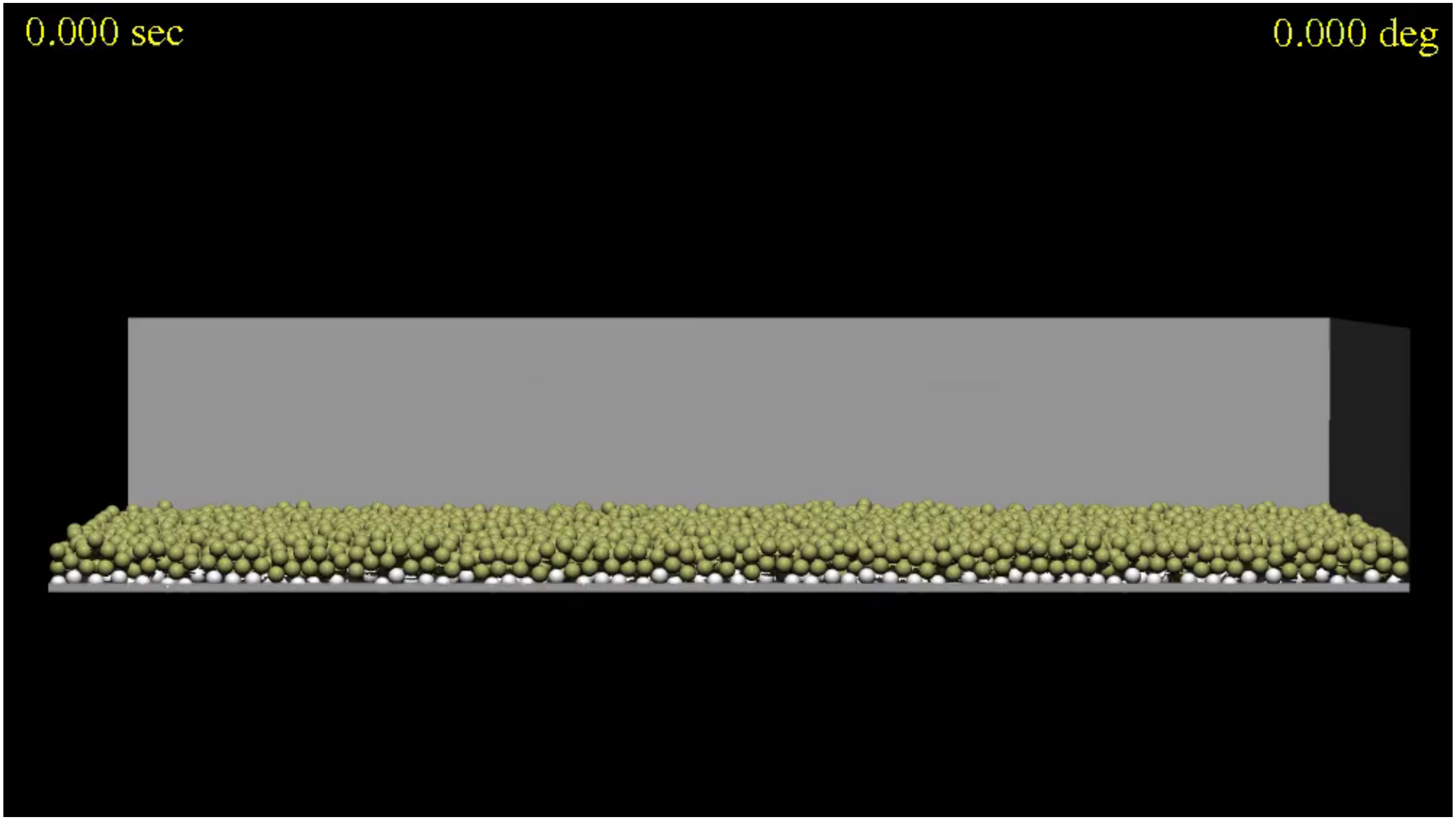
- Start with loose particles on bed of glued particles.
- Gradually incline bed and measure avalanche angle.
- Bed dimensions: 80 cm × 60 cm; polished & etched glass beads (1.3 g/cc).
- Sims: R = 0.5 cm, N = 14,040; ε_n = 0.95, ε_t = 1.0; vary μ_s, μ_r.



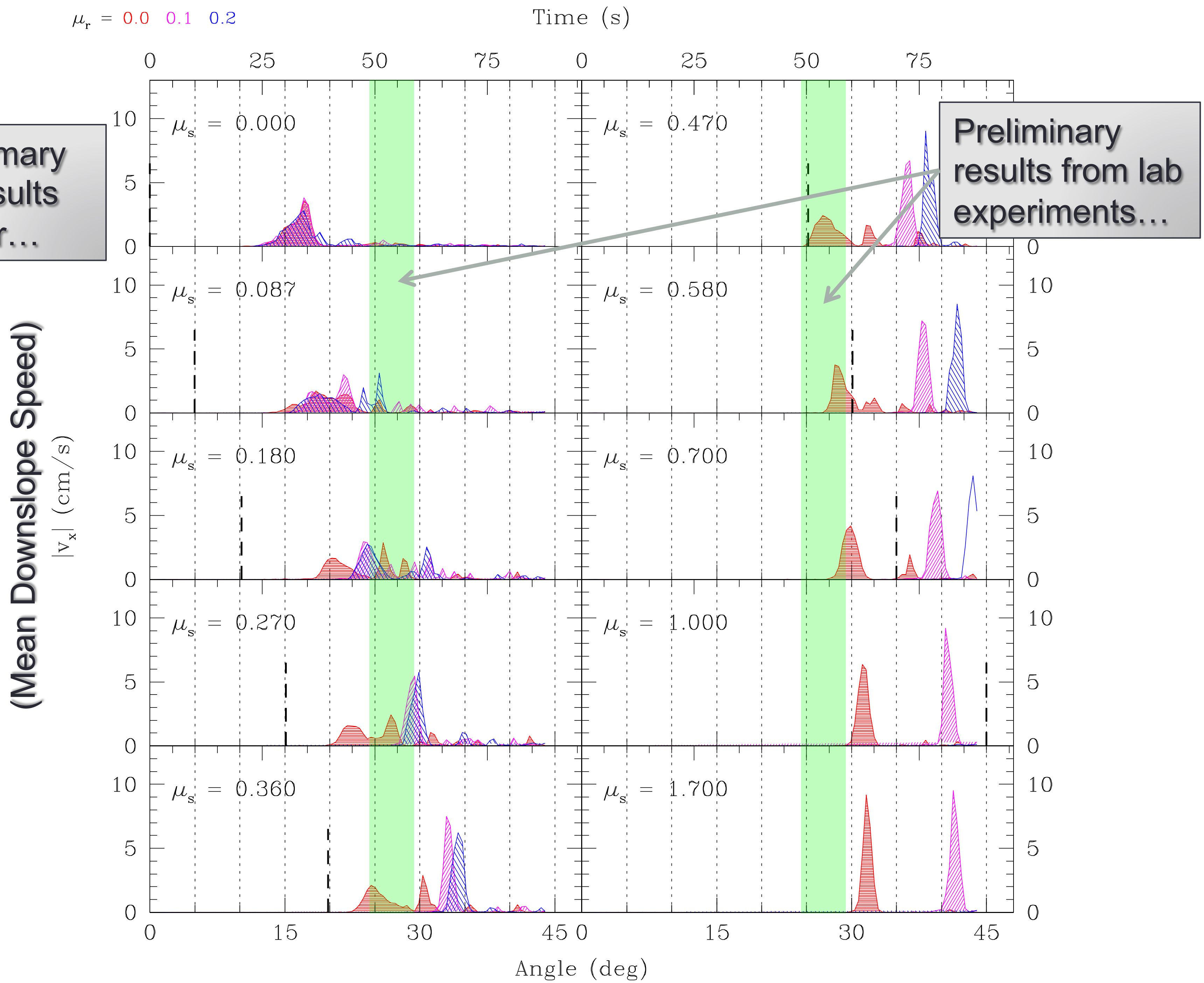
$\mu_s = 0.000$ (static), $\mu_r = 0.0$ (rolling)…

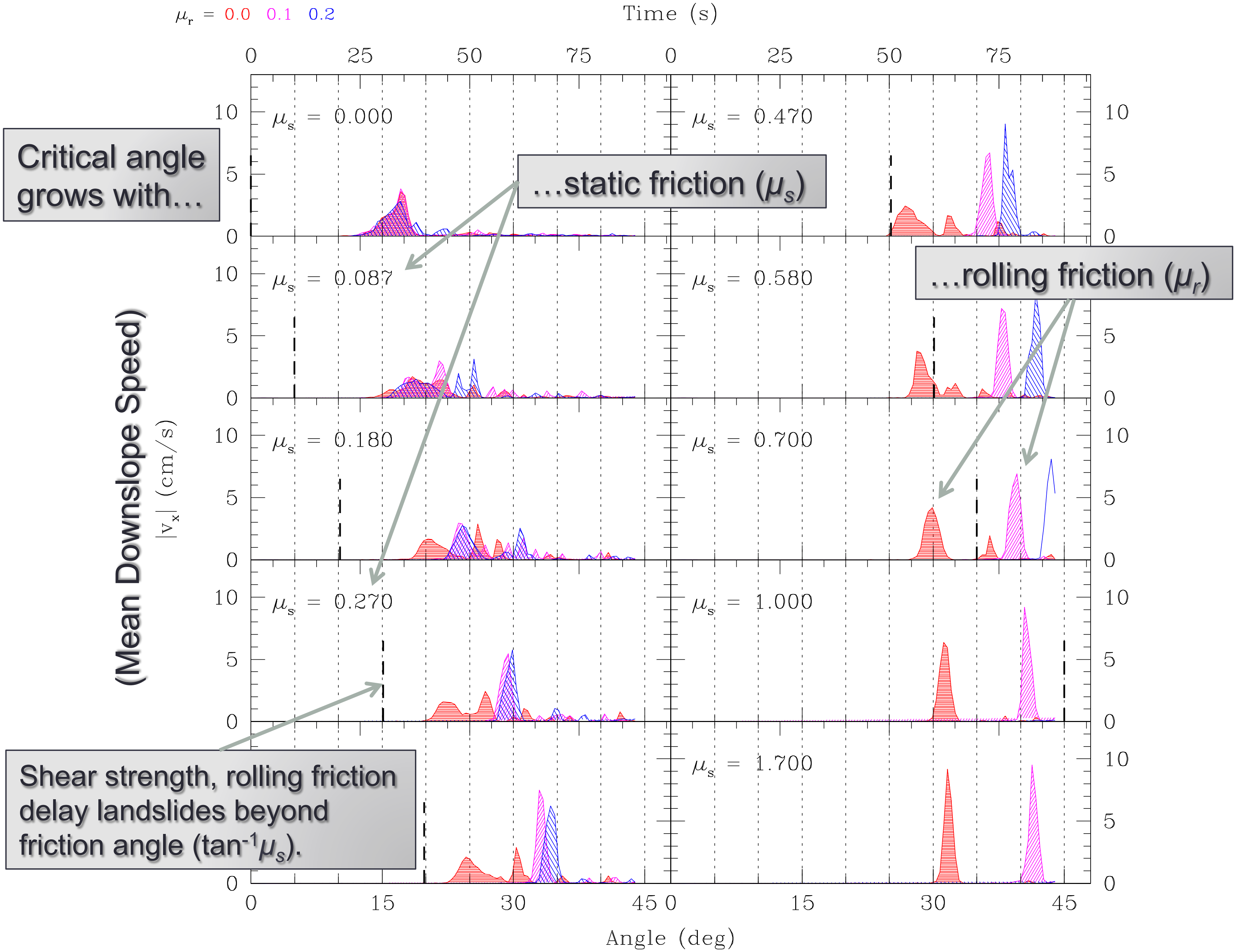


μ_s = 0.180 (static), μ_r = 0.2 (rolling)…



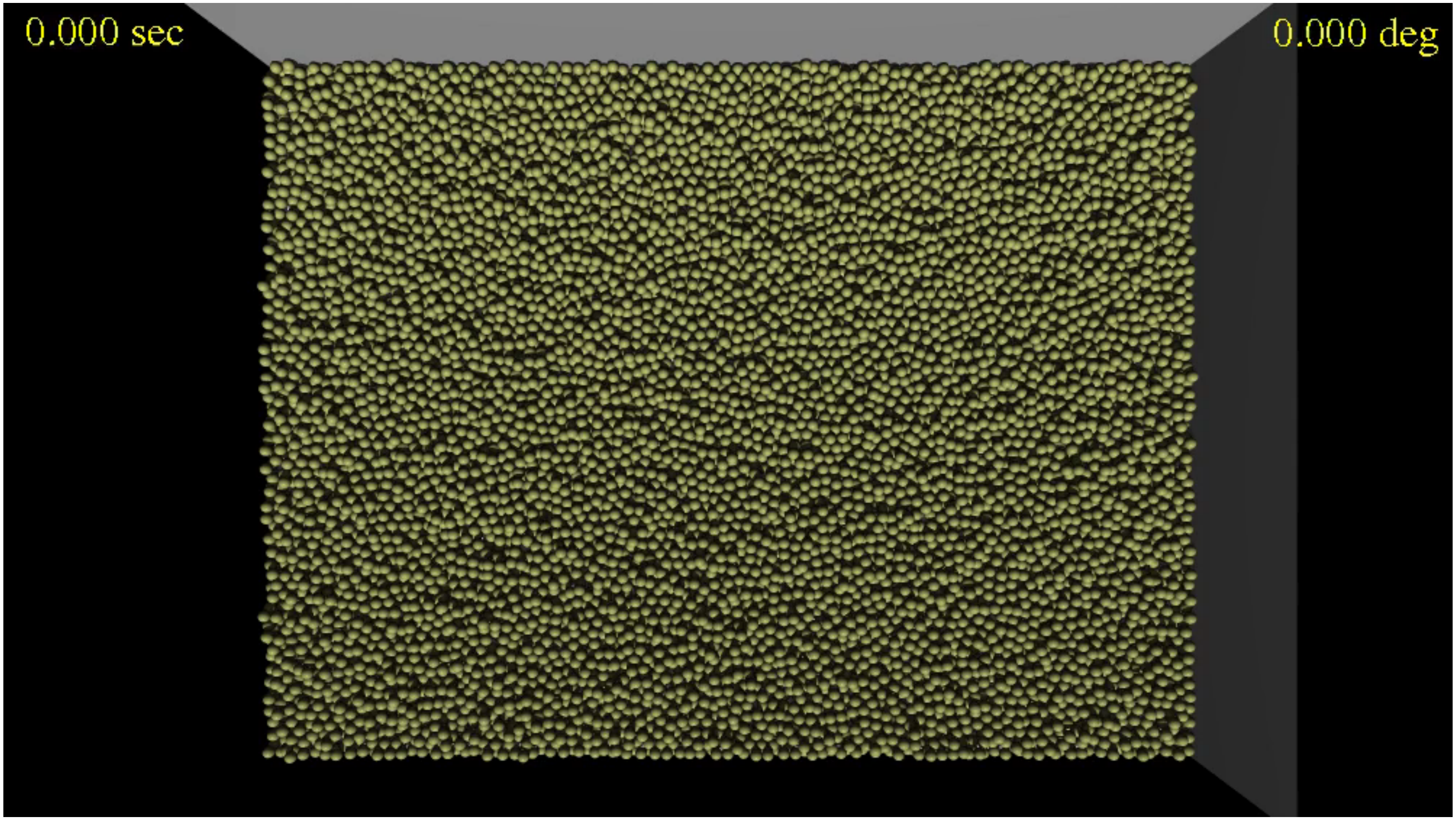
Summary of results so far…





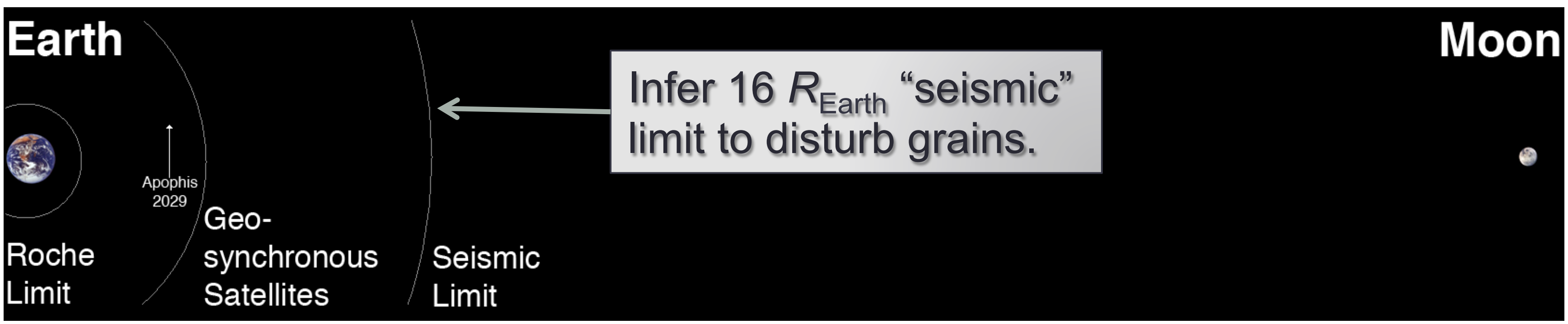
μ_r = 0.0 0.1 0.2
Time (s)
0 25 50 75 0 25 50 75
μ_s = 0.000
μ_s = 0.087
μ_s = 0.180
μ_s = 0.270
μ_s = 0.470
μ_s = 0.580
μ_s = 0.700
μ_s = 1.000
μ_s = 1.700
Critical angle grows with…
…static friction (μ_s)
…rolling friction (μ_r)
Shear strength, rolling friction delay landslides beyond friction angle ($\tan^{-1}\mu_s$).
(Mean Downslope Speed)
$|v_x|$ (cm/s)
0 15 30 45 0 15 30 45
Angle (deg)

$\mu_s = 0.180$, $\mu_r = 0.2$… (from above)

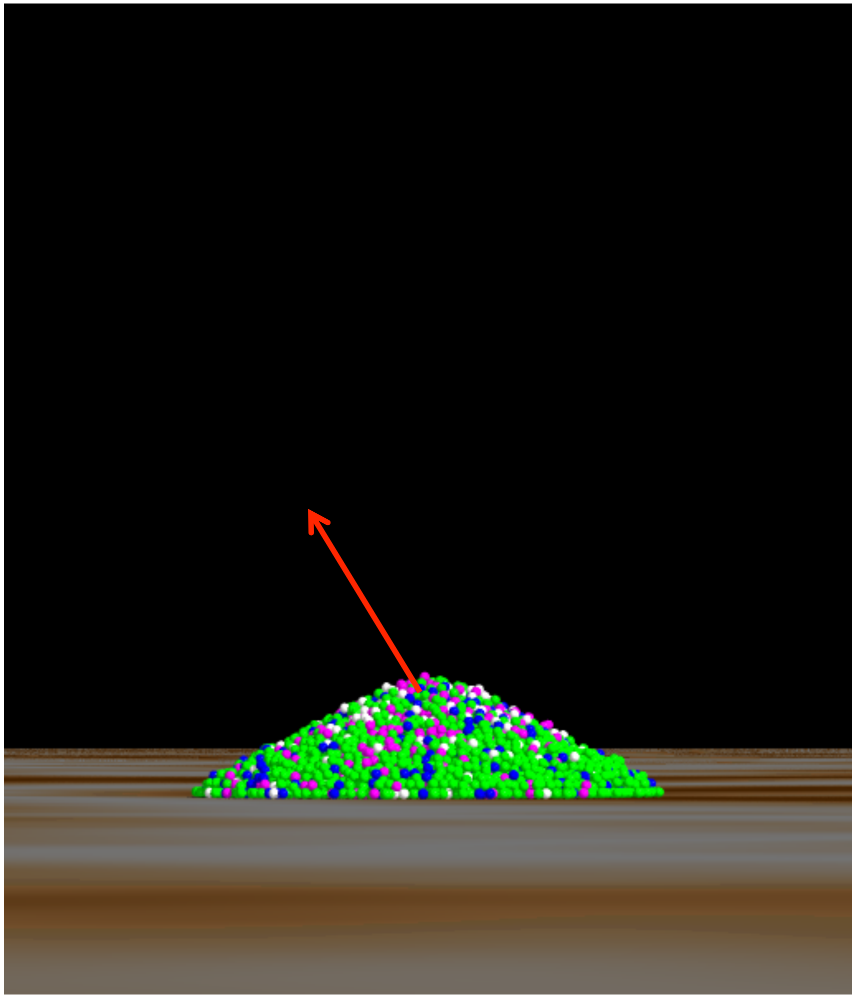


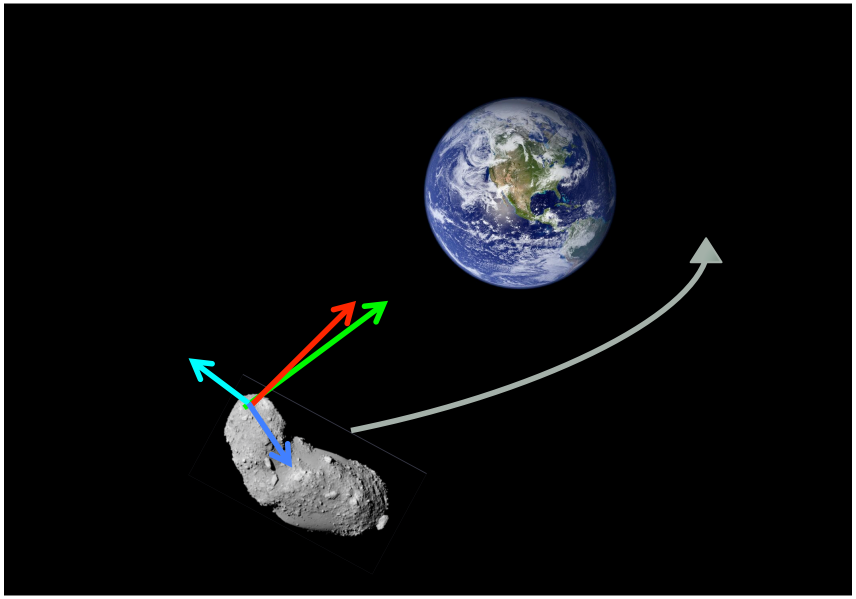
Space Weathering (Binzel et al. 2010)

- Find "fresh" (unreddened) Q-class asteroids have high probability of recent Earth encounters (within ~1 Myr).
- Can tides expose fresh grains, like landslides?



Local Simulations: Concept

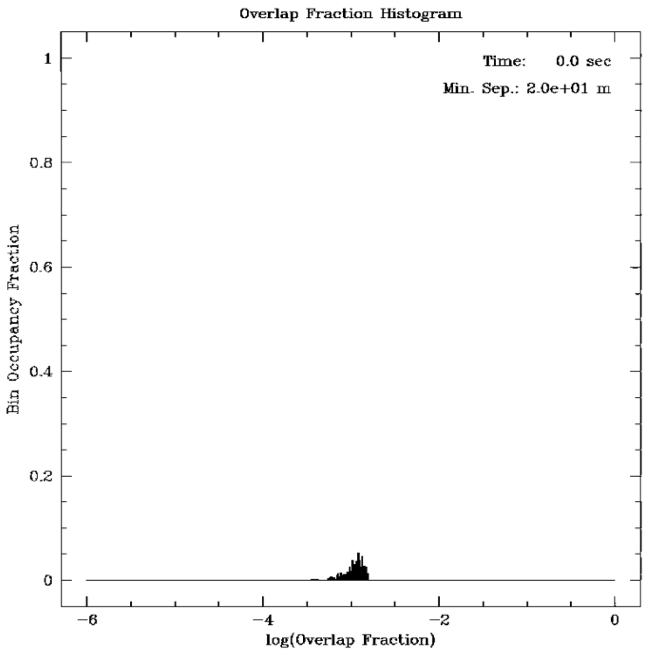




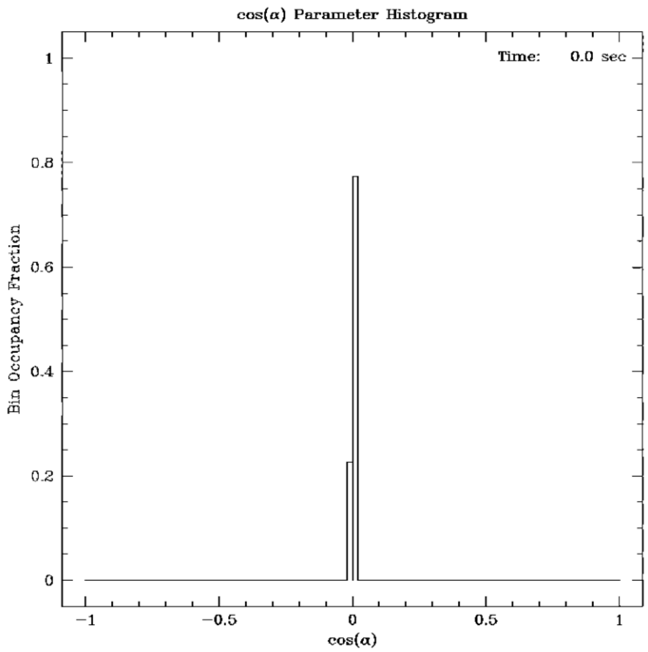
- Measure force at a point on asteroid during flyby.
- Apply to local environment.

Simple Demo: Apophis at 2 R_E

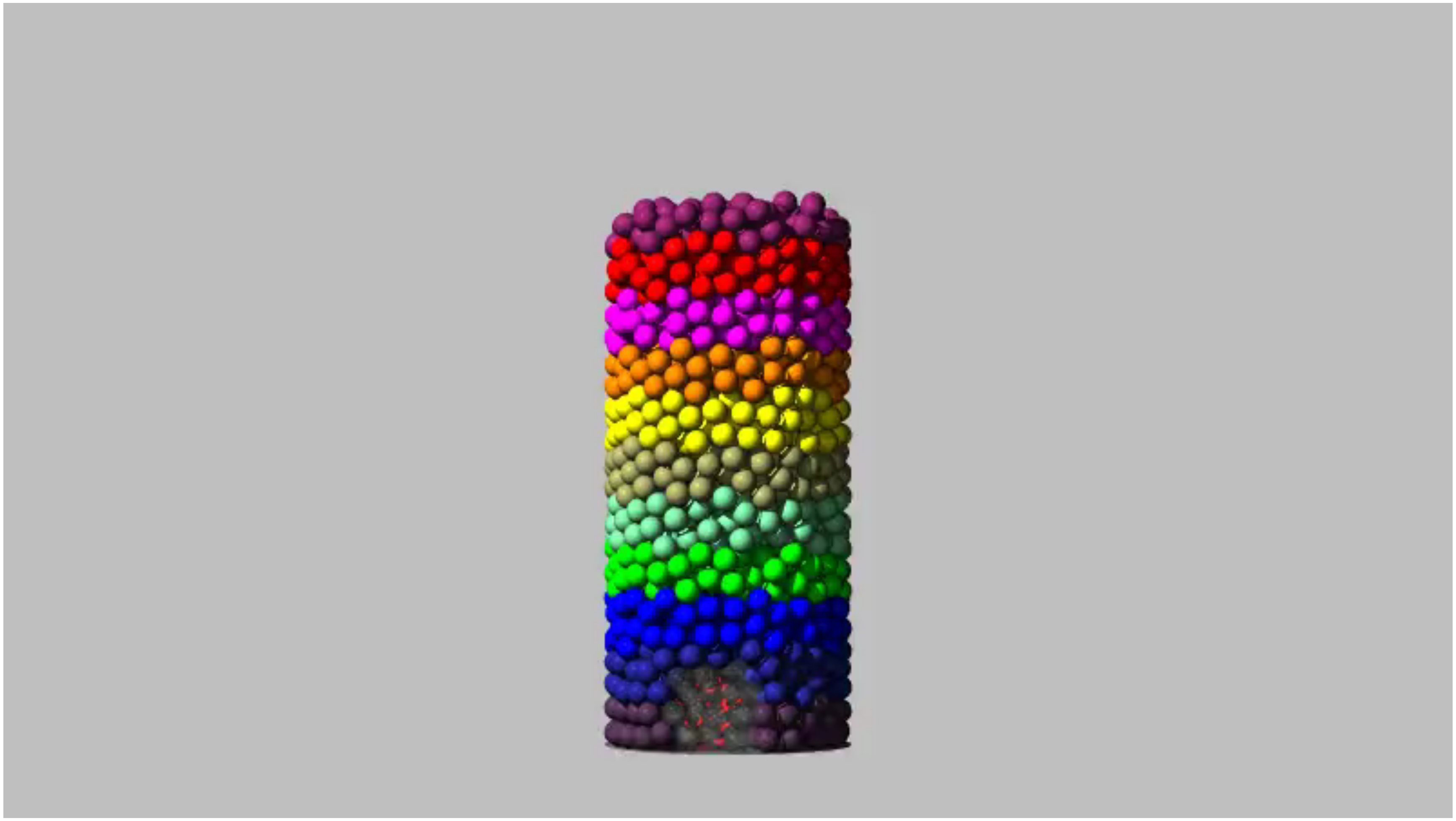
Overlaps: Measure of Pressure



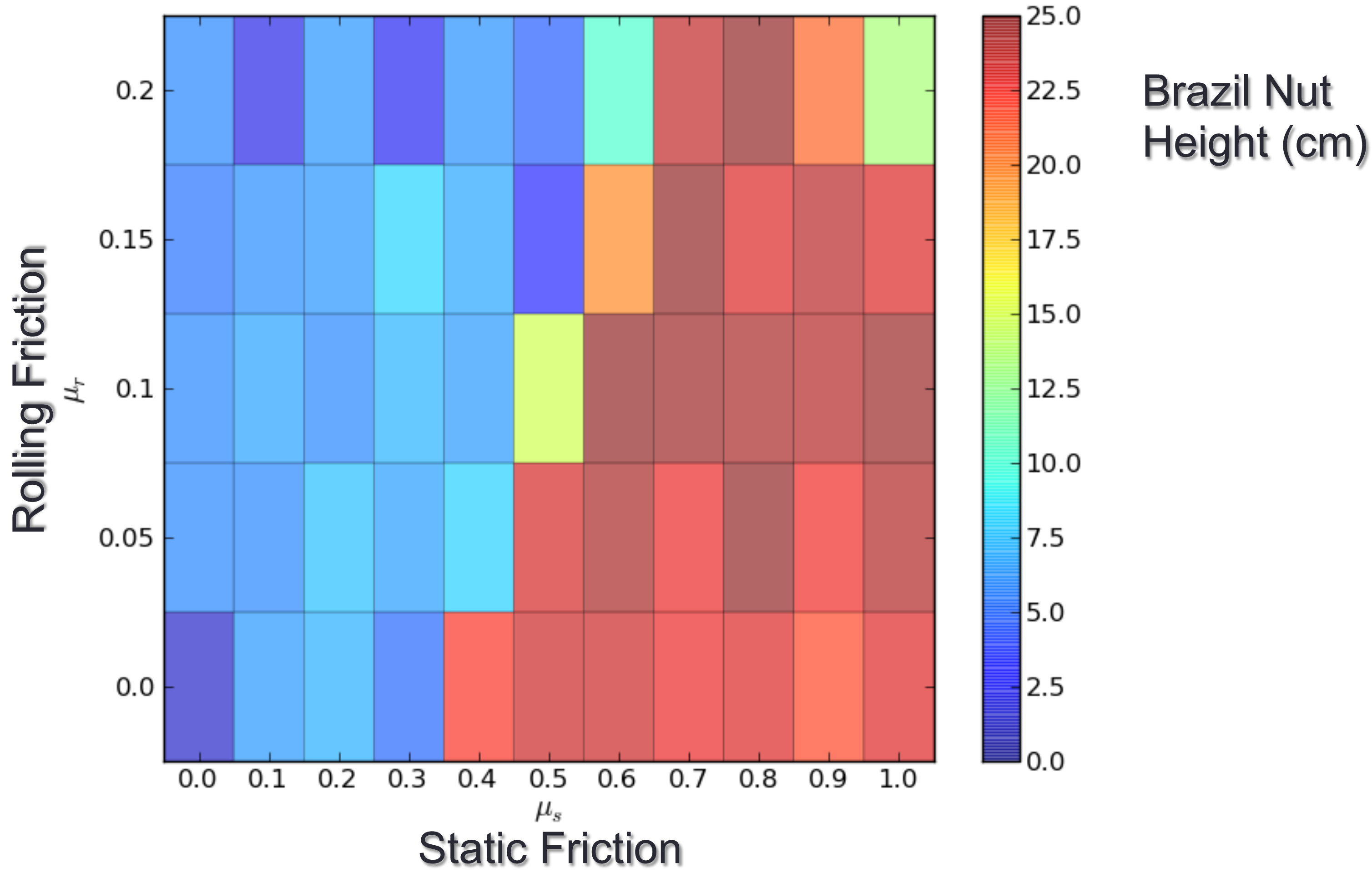
cos α: Measure of Distortion



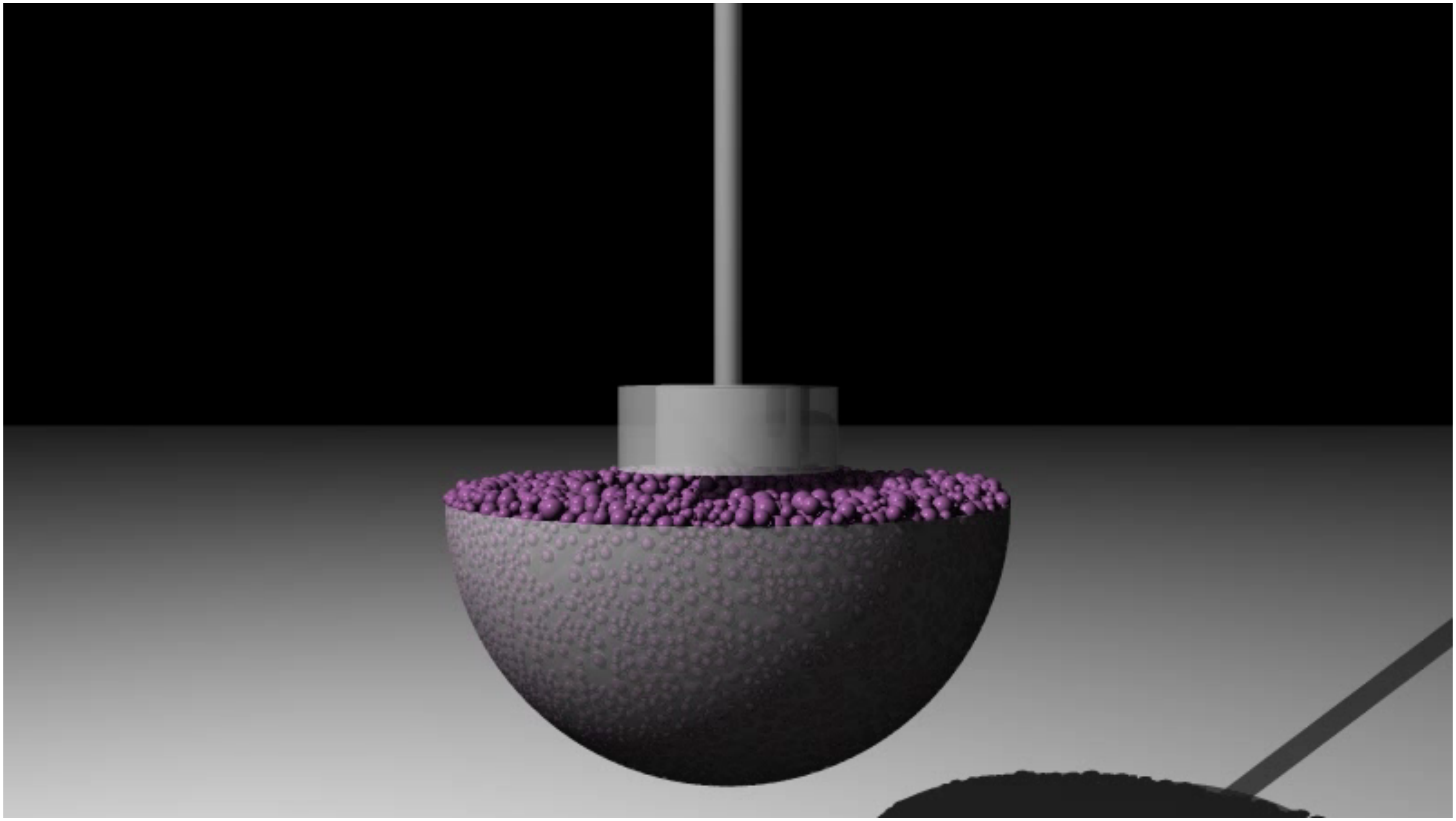
Brazil Nut Effect



Brazil Nut Effect



OSIRIS-REx Compliance Test



Yorp & Deepthought

- Yorp: mini cluster for department use.
  - 160 cores, 213 GB RAM, 32 TB disk.
  - http://www.astro.umd.edu/twiki/bin/view/AstroUMD/YorpCluster
- Deepthought: campus HPC.
  - Over 3000 cores, high-performance network and disk.
  - CTC has guaranteed time.
  - I'm on the advisory committee and TAC.
  - http://www.it.umd.edu/hpcc

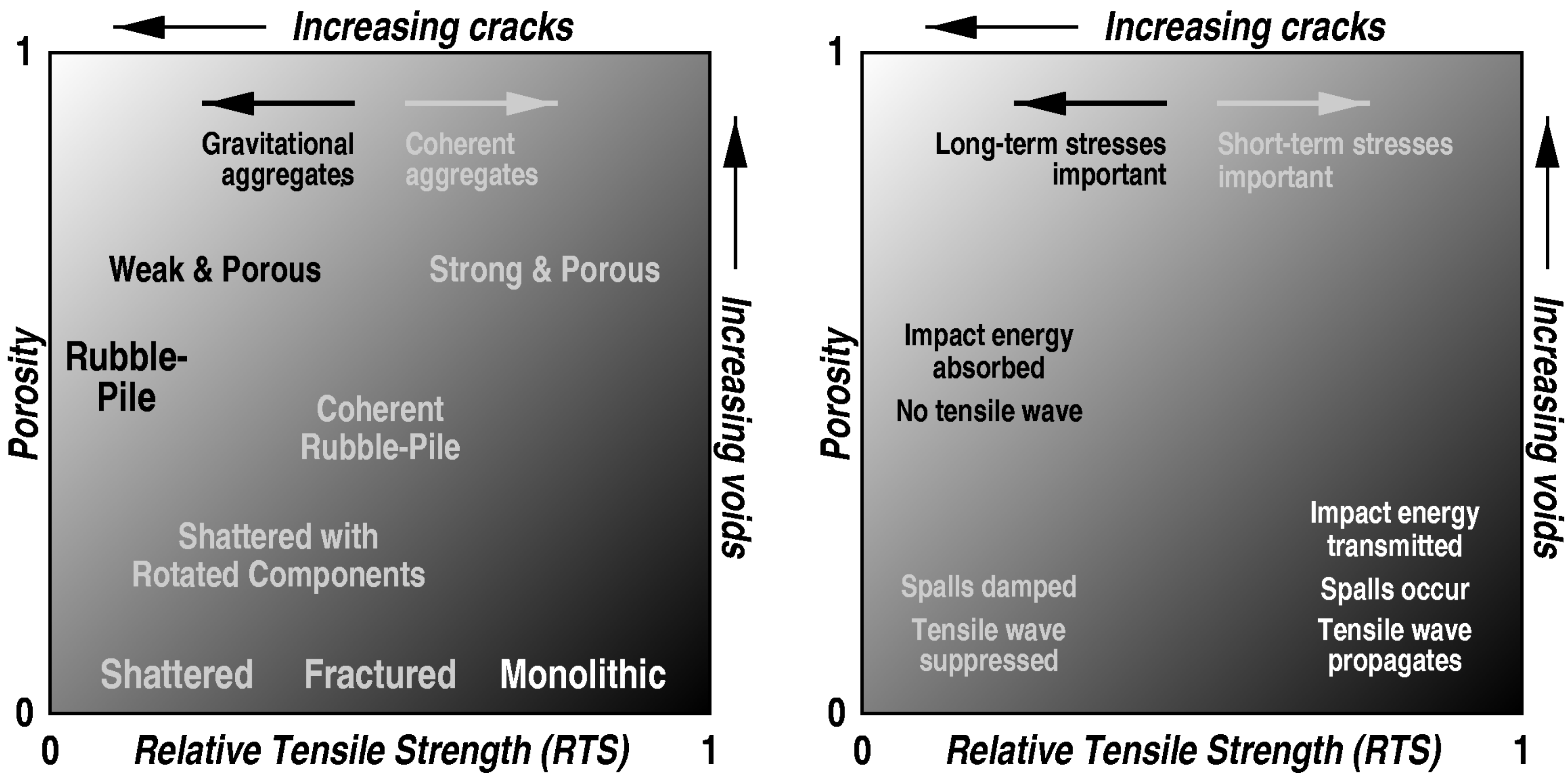
Projects

- Ongoing
  - Impacts into sintered glass beads (Steve).
  - Rubble pile collisions with rotation (Ron).
  - OSIRIS-REx surface compliance (Ron).
  - Impact cratering into granular media (Steve).
  - Others: rigid body dynamics, Brazil nut effect, tidal resurfacing, avalanches, charged granular media.
- Open
  - Tumblers (dynamic angle of repose).
  - Spin-up of cohesive asteroids.
  - Surface reddening via impacts.
  - SSDEM in rings.

EXTRA SLIDES

Real, Practical Experiments…

Gravitational Aggregates



Non-gravitational Forces as a Function of Particle Size

Courtesy: D. Scheeres

- Gravity & rotation:

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

- Friction:

$$F_f = \mu\left(mg_a + F_{ng}\right)$$

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

- Electrostatics:

$$F_{es} = C_{es} R^2, \; C_{es} = \left[10^{-8}, 10^{-1}\right]$$

Max value, for localized regions at the terminator; not verified.

- Solar radiation pressure:

$$F_{srp} = C_{srp} R^2, \; C_{srp} = 10^{-5} / d^2$$

d = distance from Sun in AU.

- Cohesion (due to van der Waals attraction):

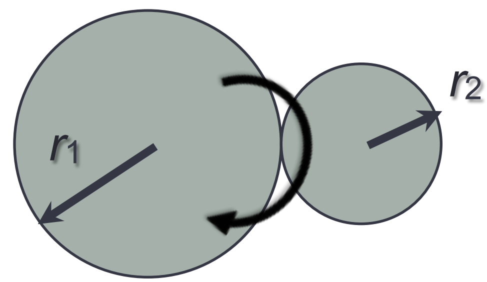
$$F_{vdw} = C_{vdw} R, \; C_{vdw} = 5 \times 10^{-2}$$

Derived from lunar regolith (Perko et al. 2001).

Van der Waals Cohesion

- Perko et al. (2001): lunar regolith $F_C \sim 0.05\, r_1 r_2/(r_1+r_2)$ N.
- Scheeres et al. (2010): ~cm-sized grains can stick to surface of 100-m asteroid with up to 6-min rotation period.

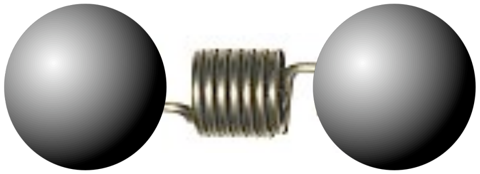
$$\Omega_{g,\max} = \sqrt{\frac{G 4\pi\rho(r_1^3 + r_2^3)}{3(r_1 + r_2)^3}}$$



With cohesion: $$\Omega_{g+c,\max} = \Omega_{g,\max}\sqrt{1 + \frac{Q}{G(\frac{4\pi}{3}\rho)^2}\frac{(r_1 + r_2)}{r_1^2 r_2^2}}$$

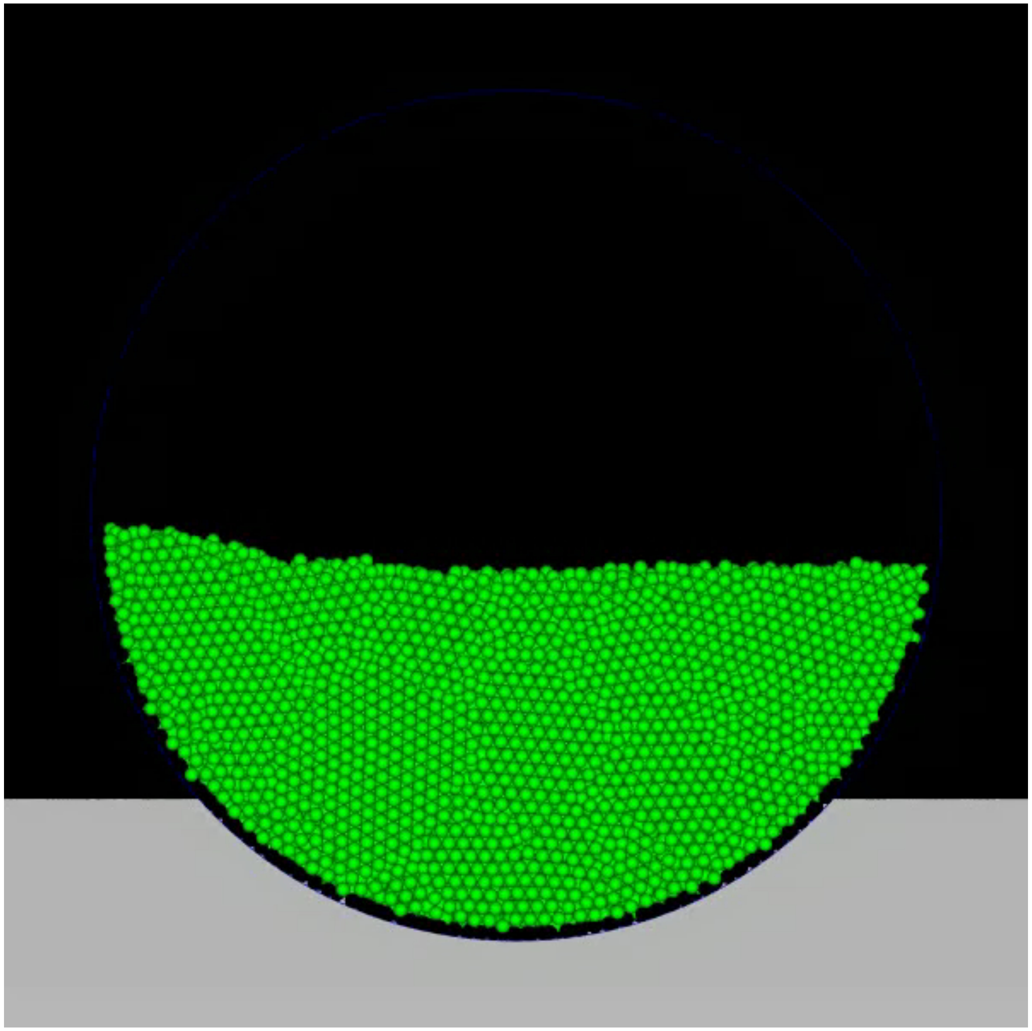
Modeling Weak Cohesion

- Add simple Hooke's law restoring force between nearby particles.



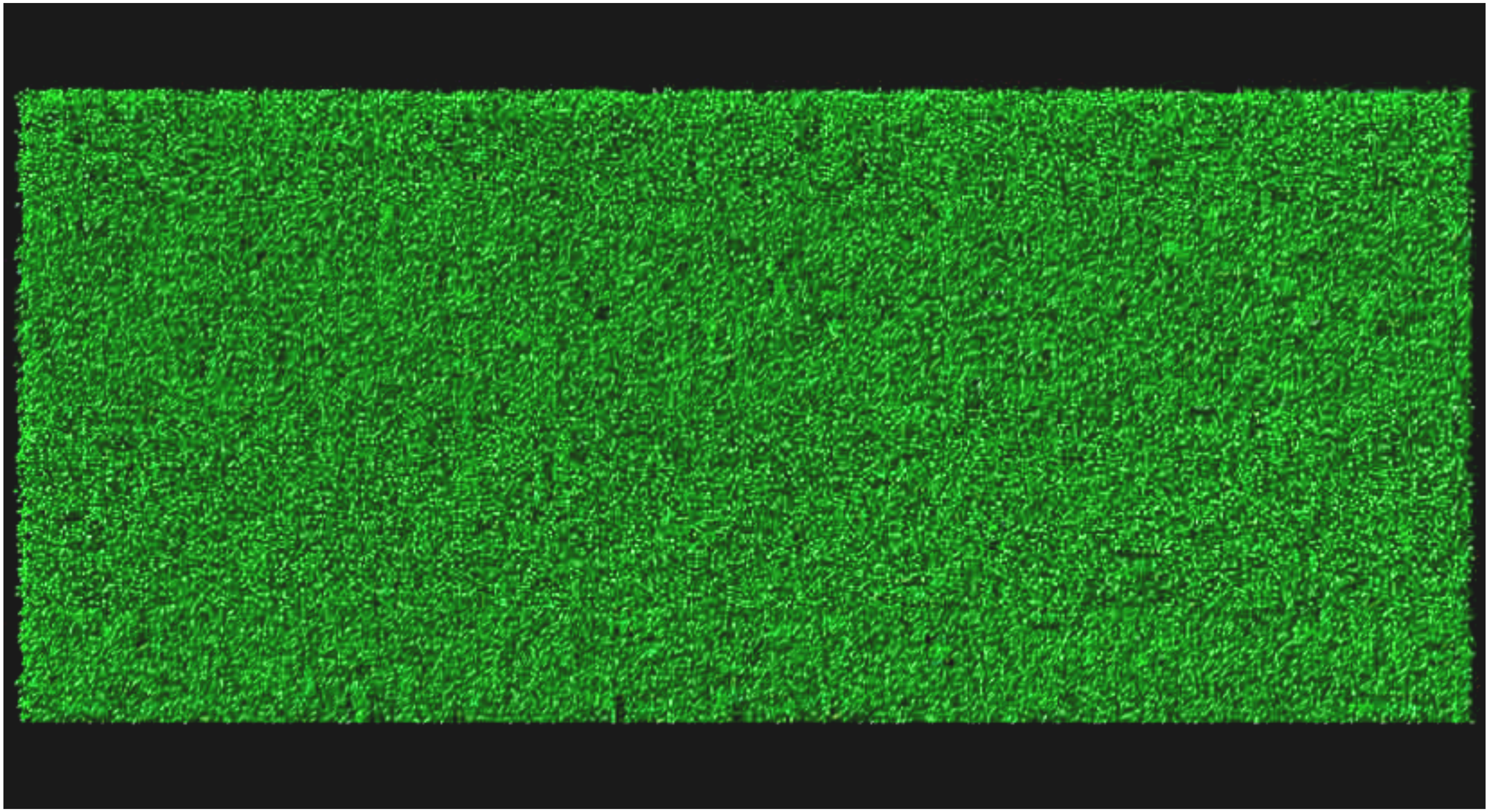
- Deform elastically up to maximum strain (spring rigidity set by Young's modulus).
- Other force laws can be implemented, e.g., van der Waals.

Weak Cohesion in Granular Fluids

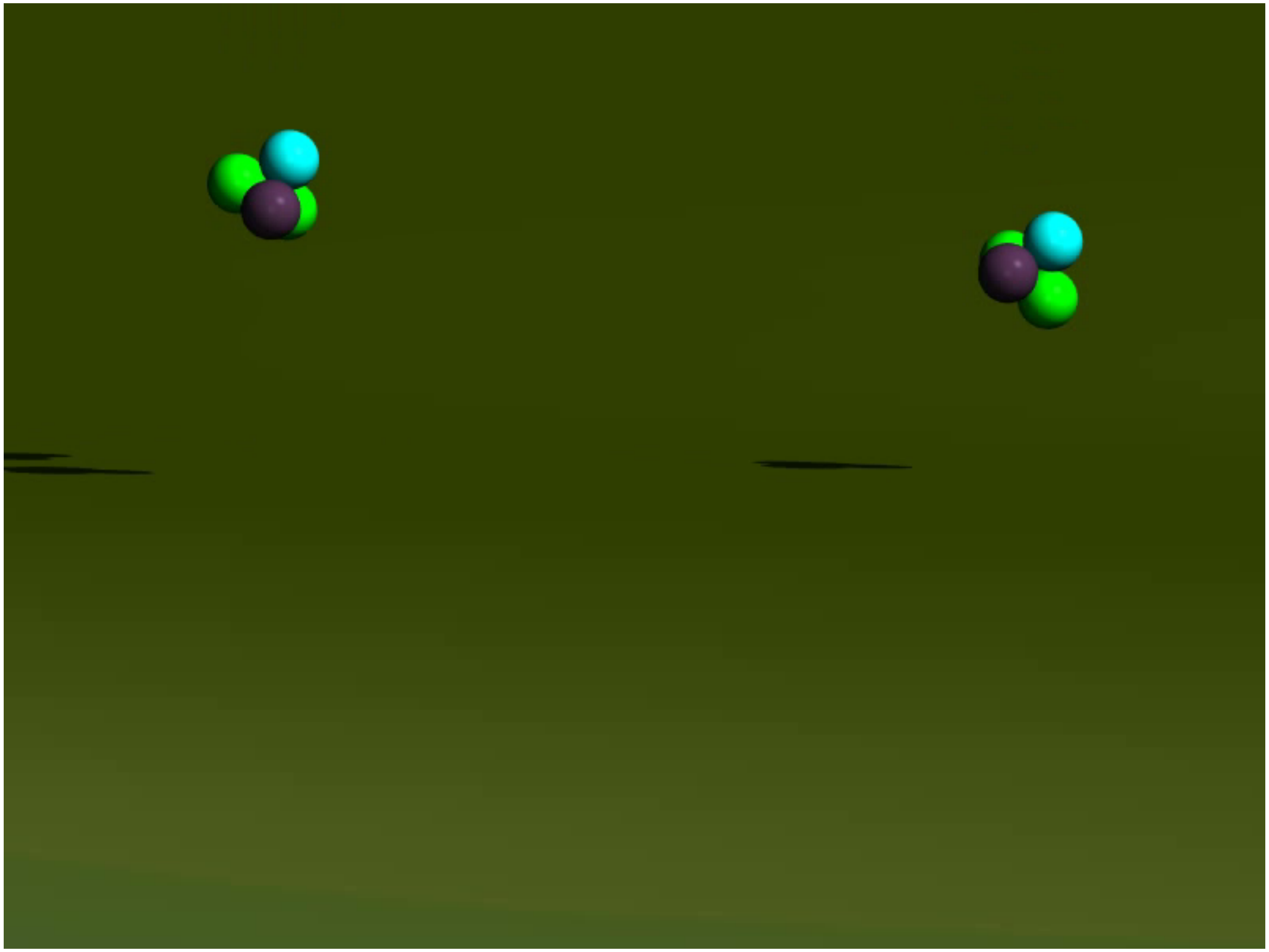


Cohesion in Planetary Rings?

Perrine et al. (2011), Perrine & Richardson (2012)



SSDEM + Springs



Asteroid Family Formation