ASTR695: DCR's Research '11

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

(Particle) Gravity + Collisions

- Equations of motion for gravity:

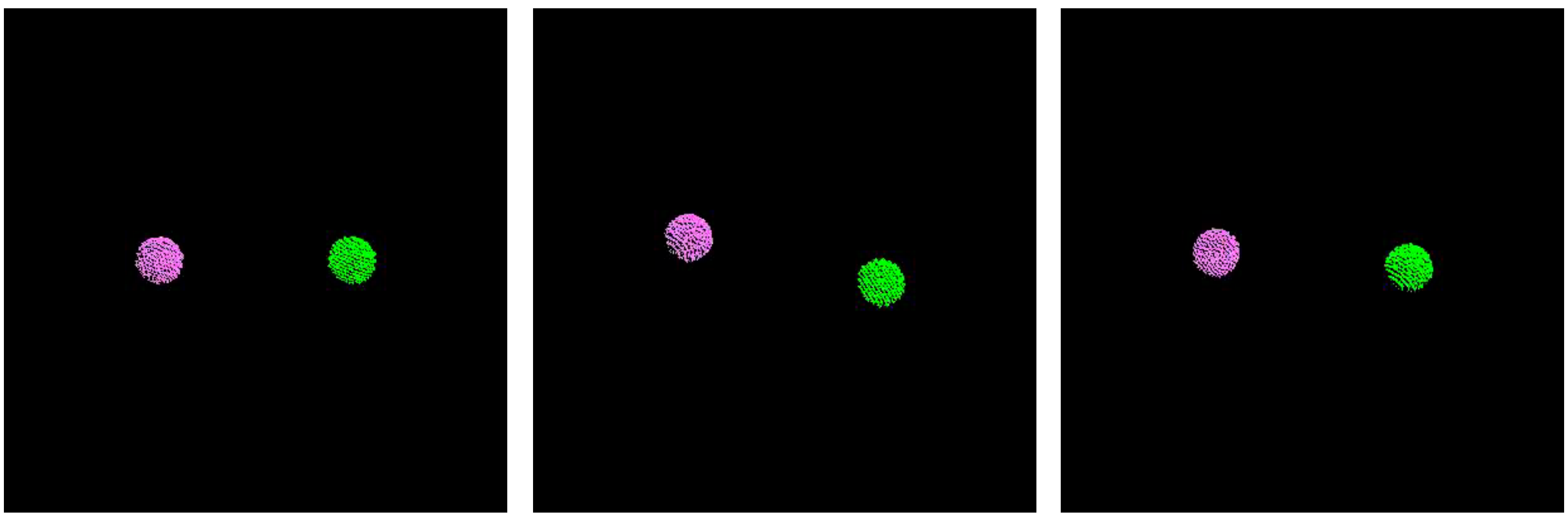
$$\ddot{\mathbf{r}}_i = -\sum_{j \neq i} \frac{G m_j (\mathbf{r}_i - \mathbf{r}_j)}{|\mathbf{r}_i - \mathbf{r}_j|^3}$$

- Collision condition:

$$|\mathbf{r}_i - \mathbf{r}_j| = s_i + s_j.$$

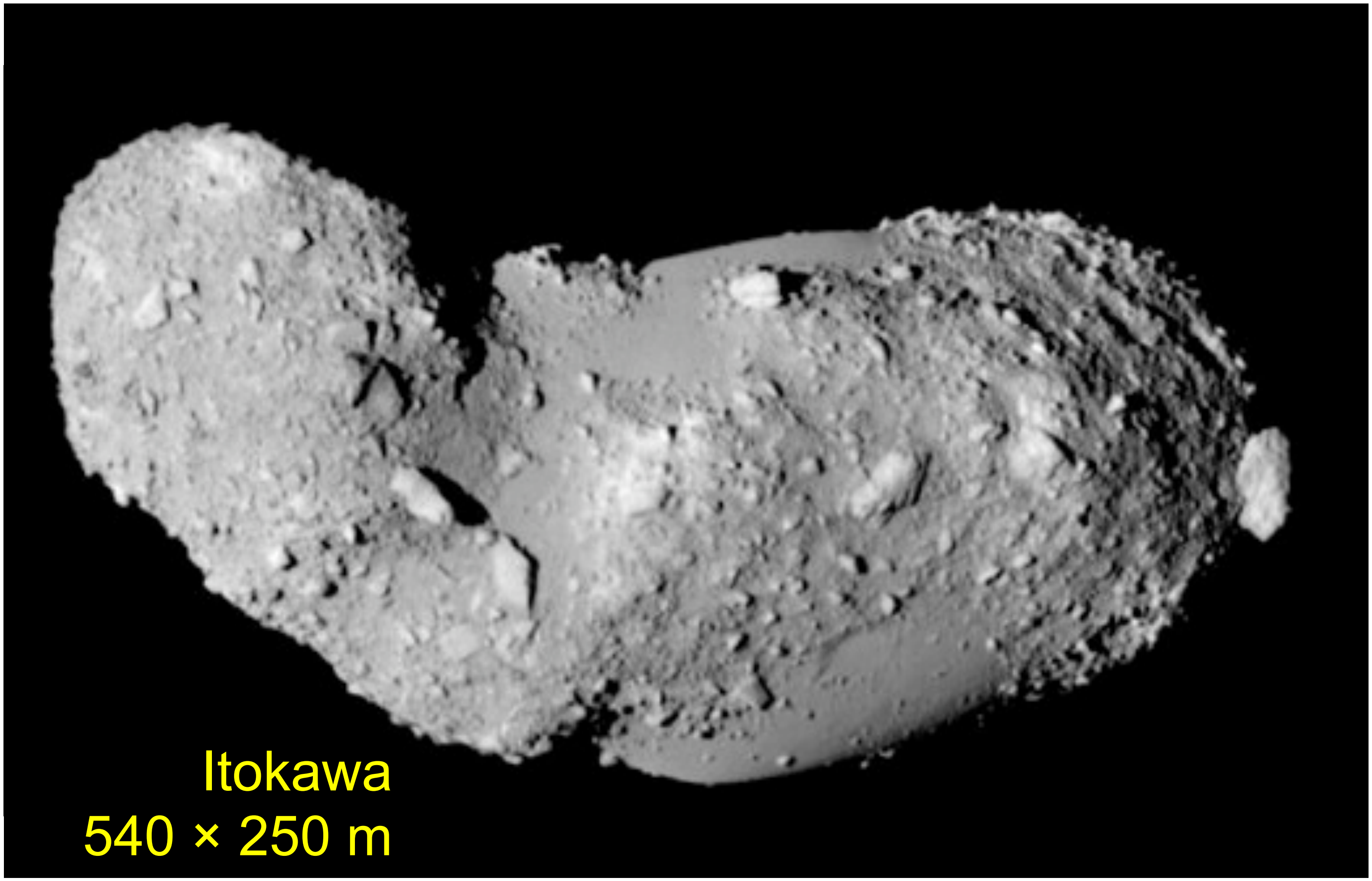
Example: Planet Formation

- Planetesimal accretion
  - Gravity + collisions involving rigid particles or groups of rigid particles with some dissipation law and possible fragmentation, etc.



Leinhardt et al. 2000, Icarus 146, 133

Rubble is out there…



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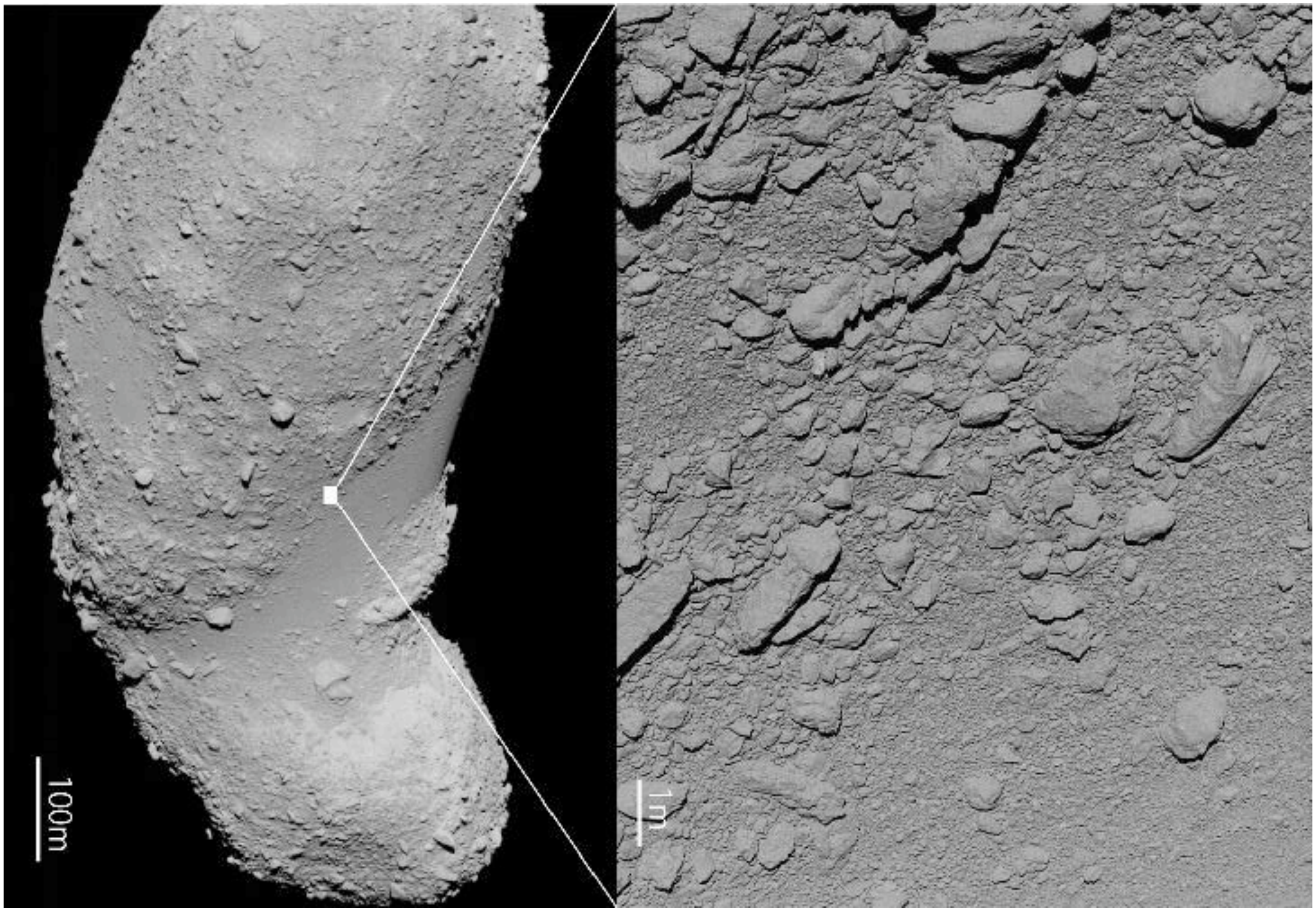
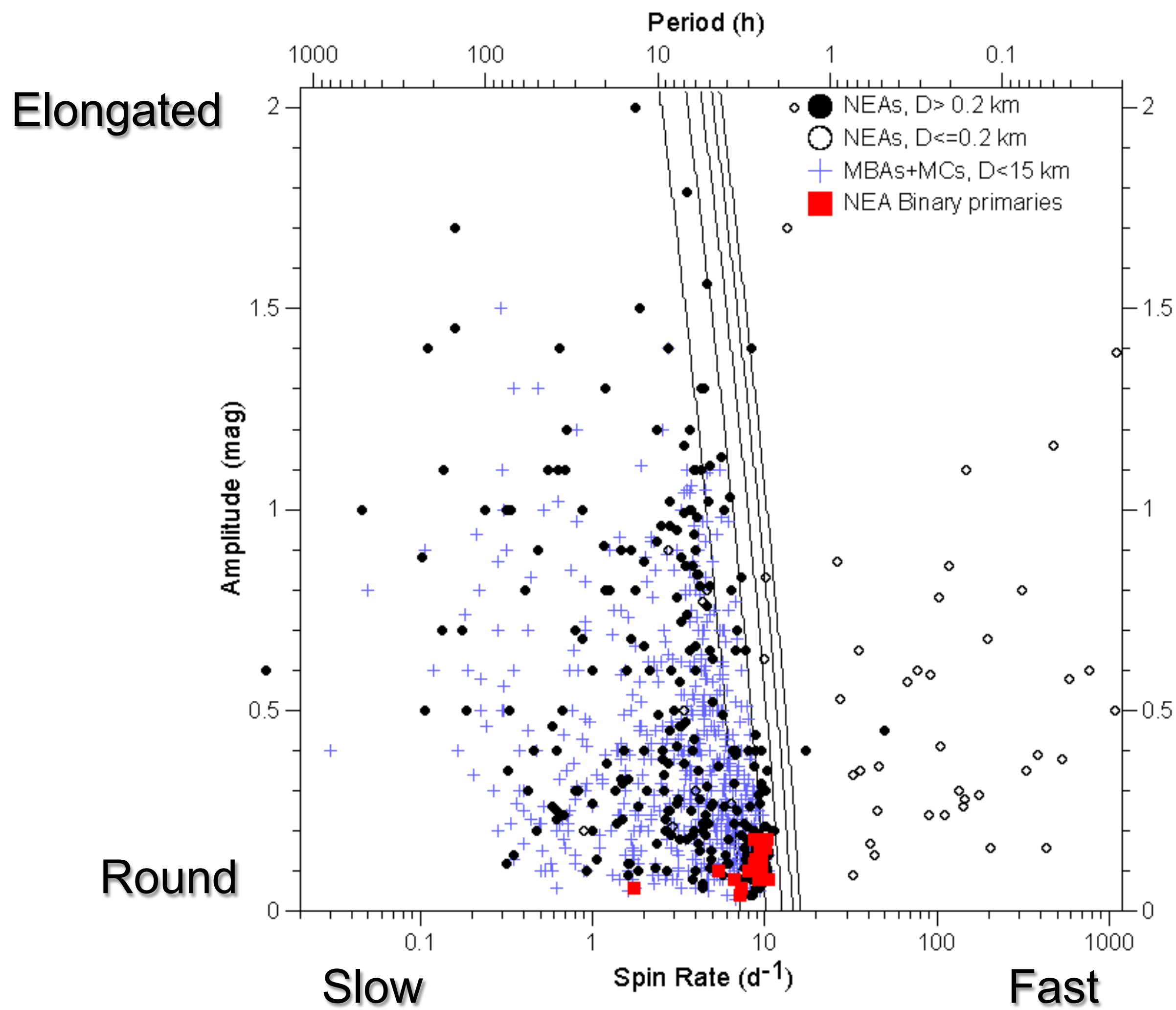


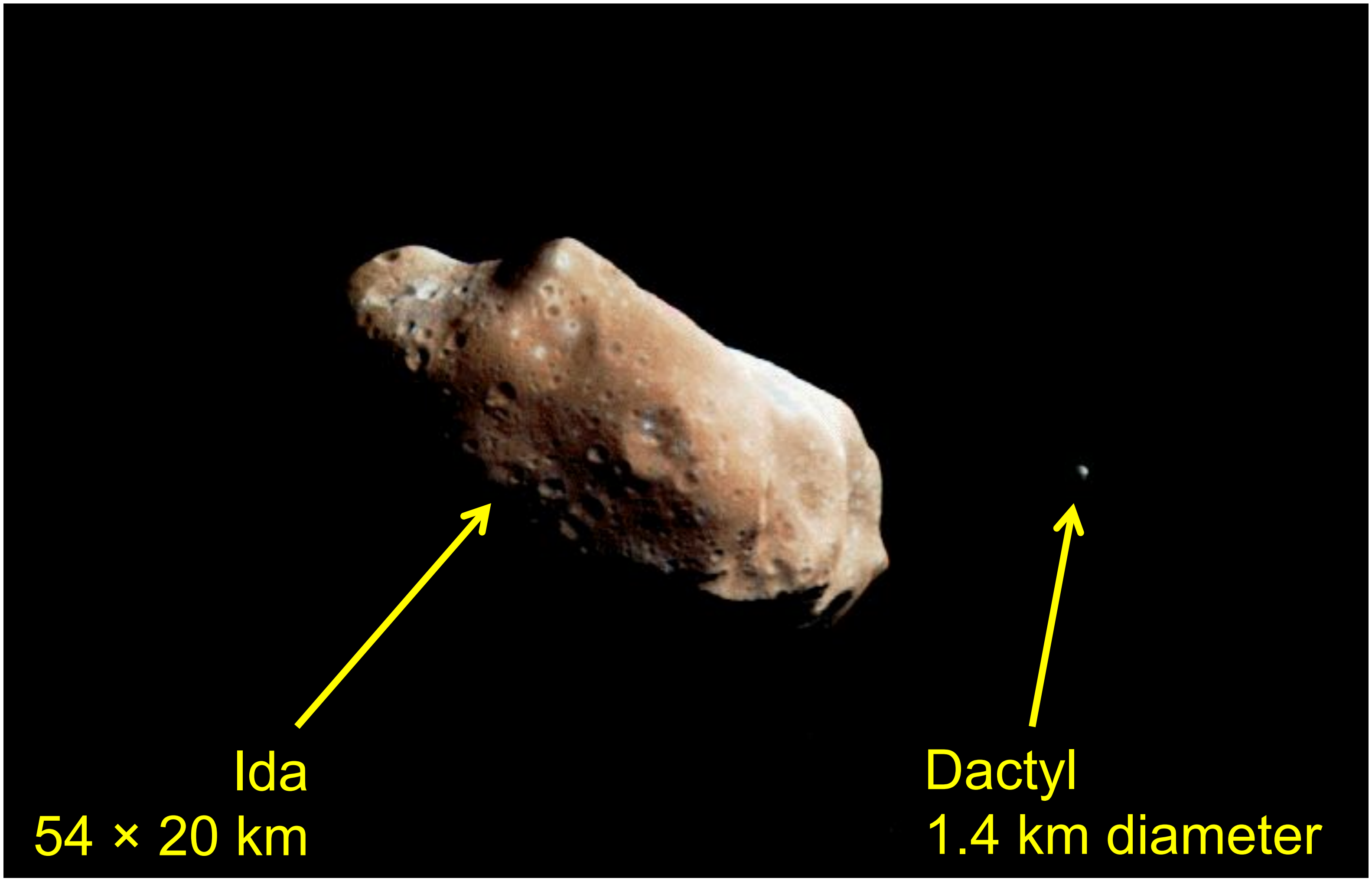
Rubble is out there…

Image courtesy JAXA/ISIS

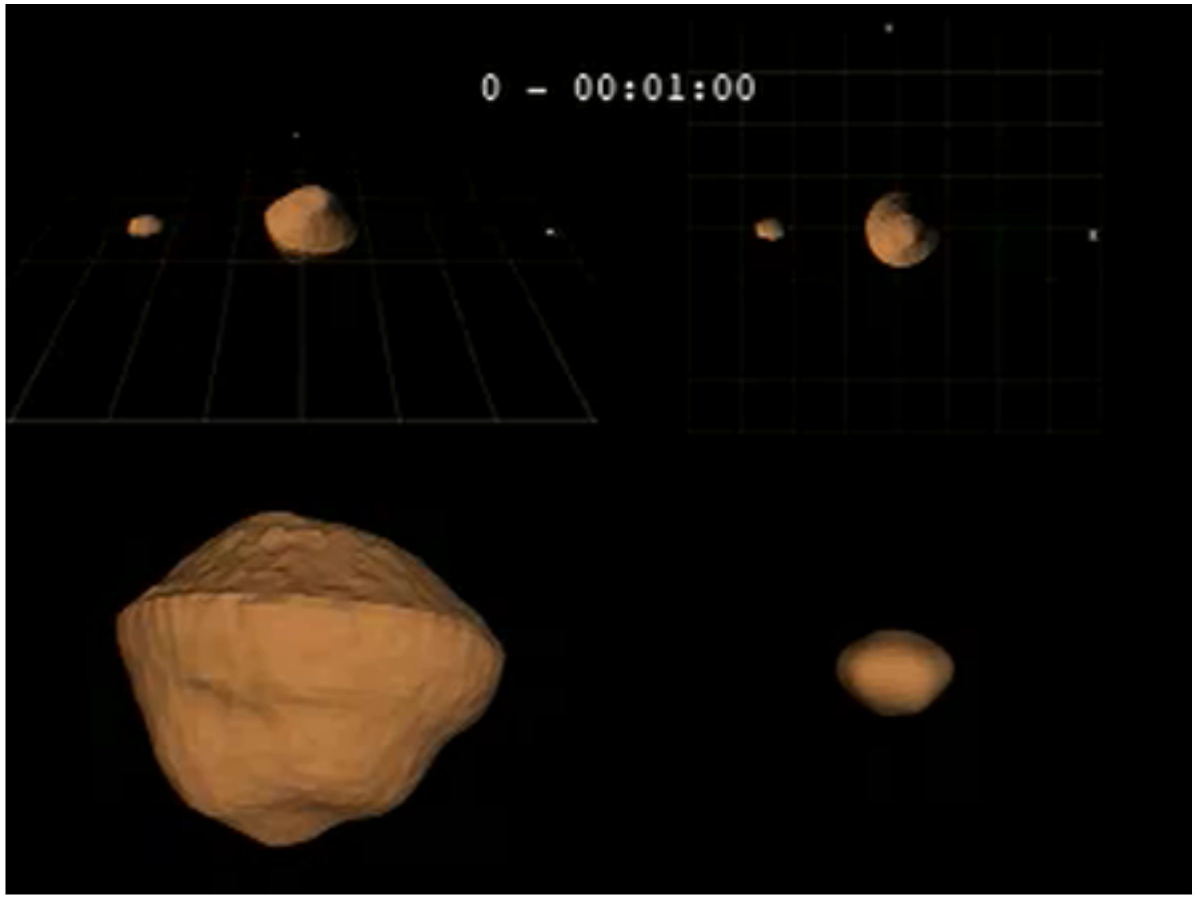
Evidence for Gravitational Aggregates



Binary Asteroids

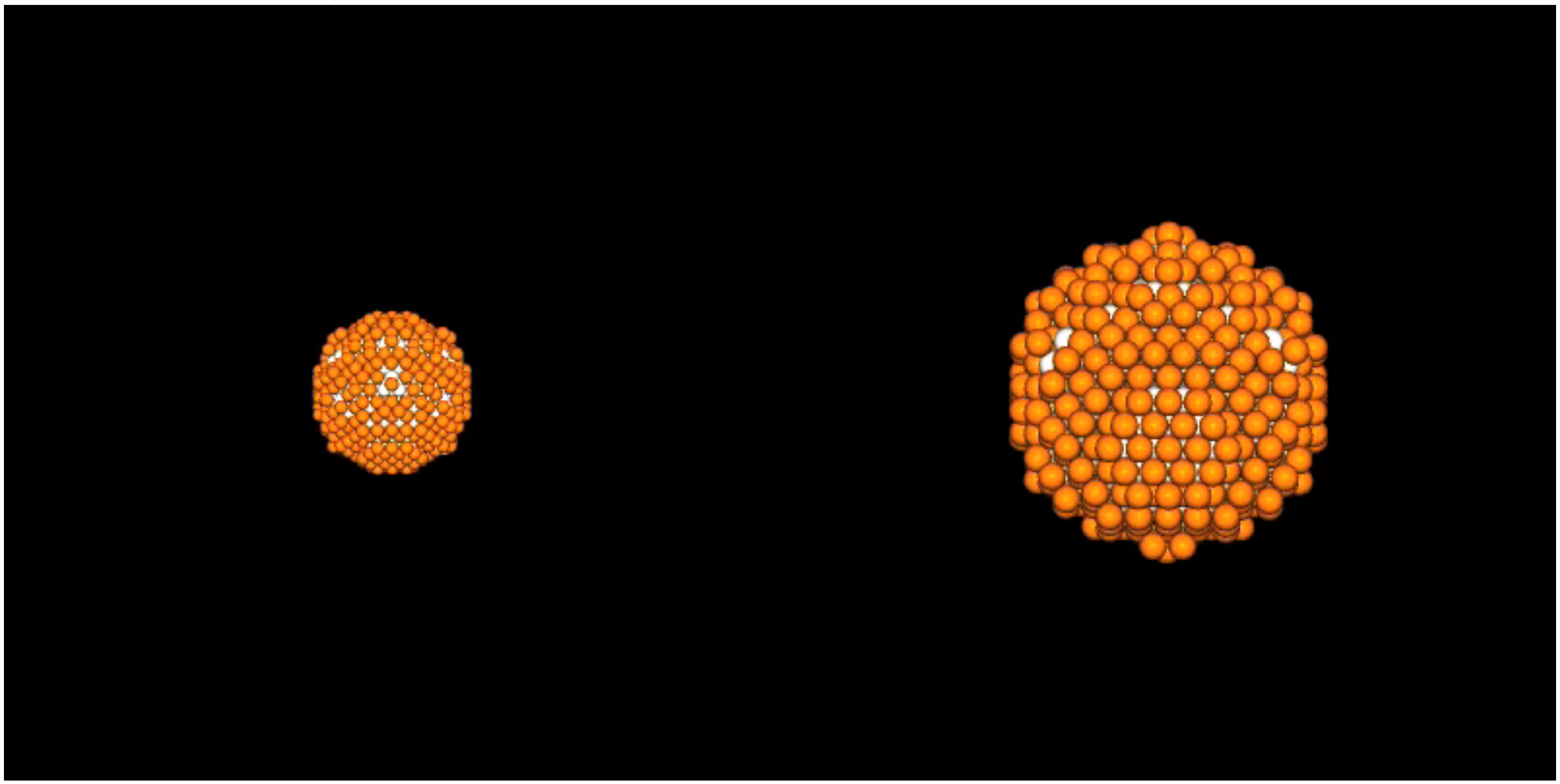


1999 KW_4



Simulating KW_4

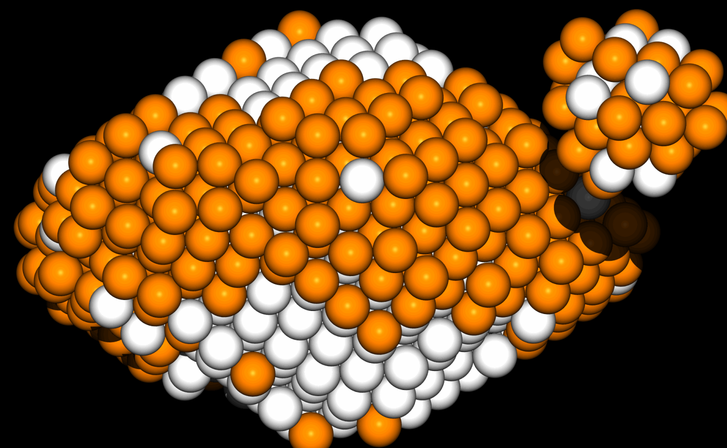
Top View Side

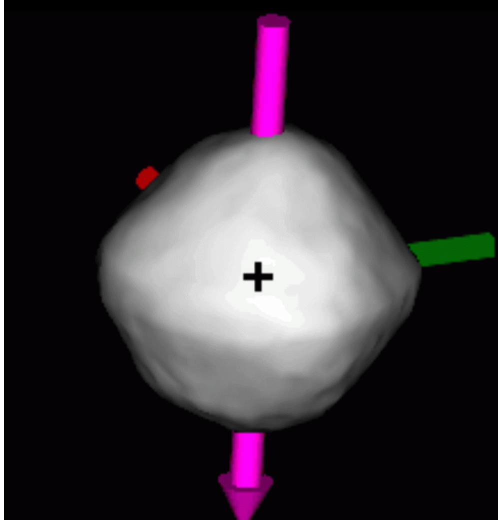


Top-shapes

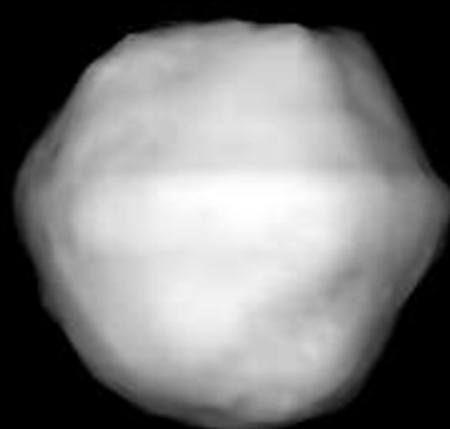
1999 KW4 Radar model, Ostro et al. 2005

YORP Spinup sims, Walsh et al. 2008





Single Asteroid RQ36
Howell et al. 2008, ACM



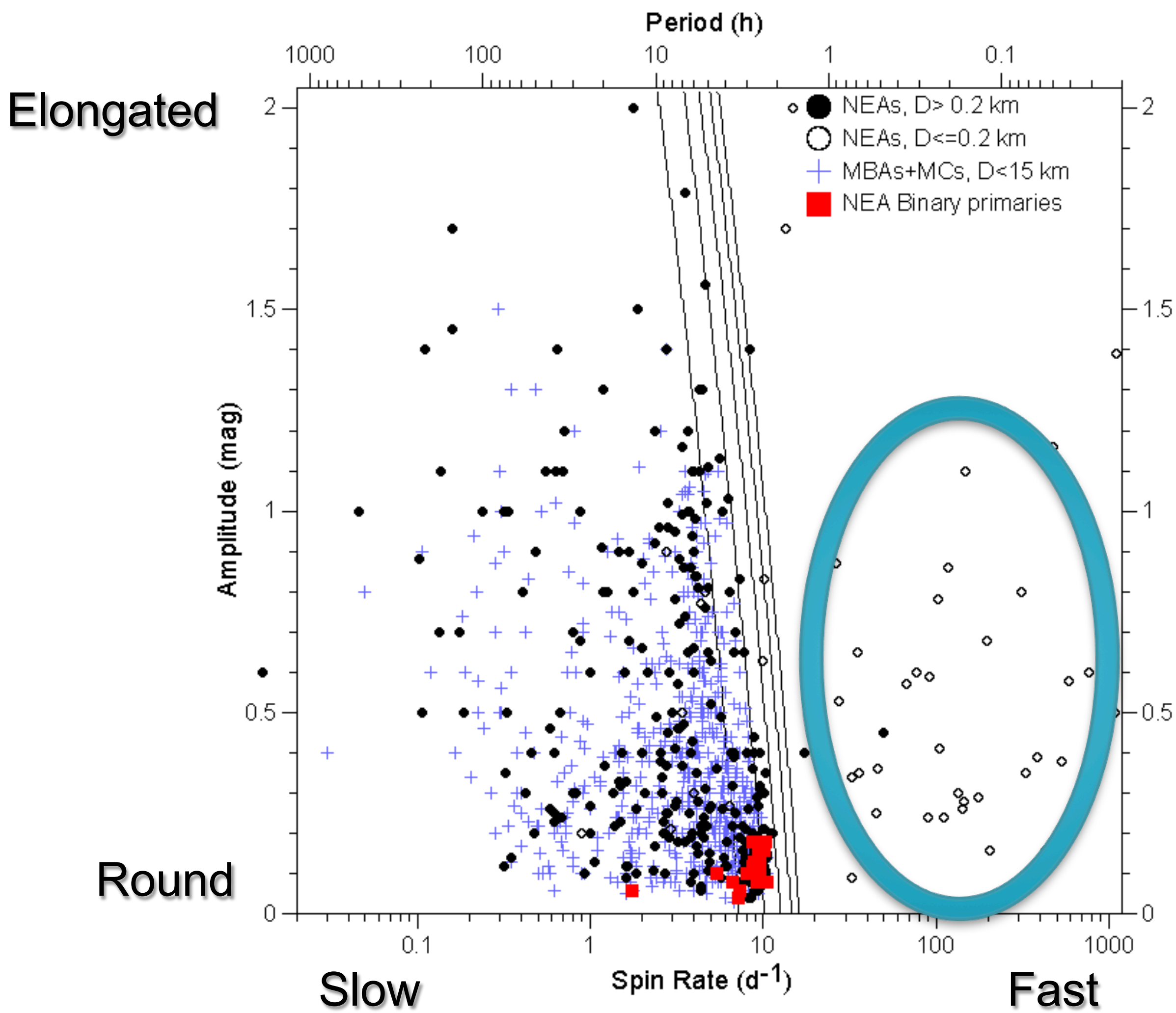
Binary 2004 DC
Taylor et al. 2008, ACM

Šteins from Rosetta Images

What about cohesion?

- Lightcurve and radar data show some very small solar system bodies must have tensile strength/cohesion.

What about cohesion?



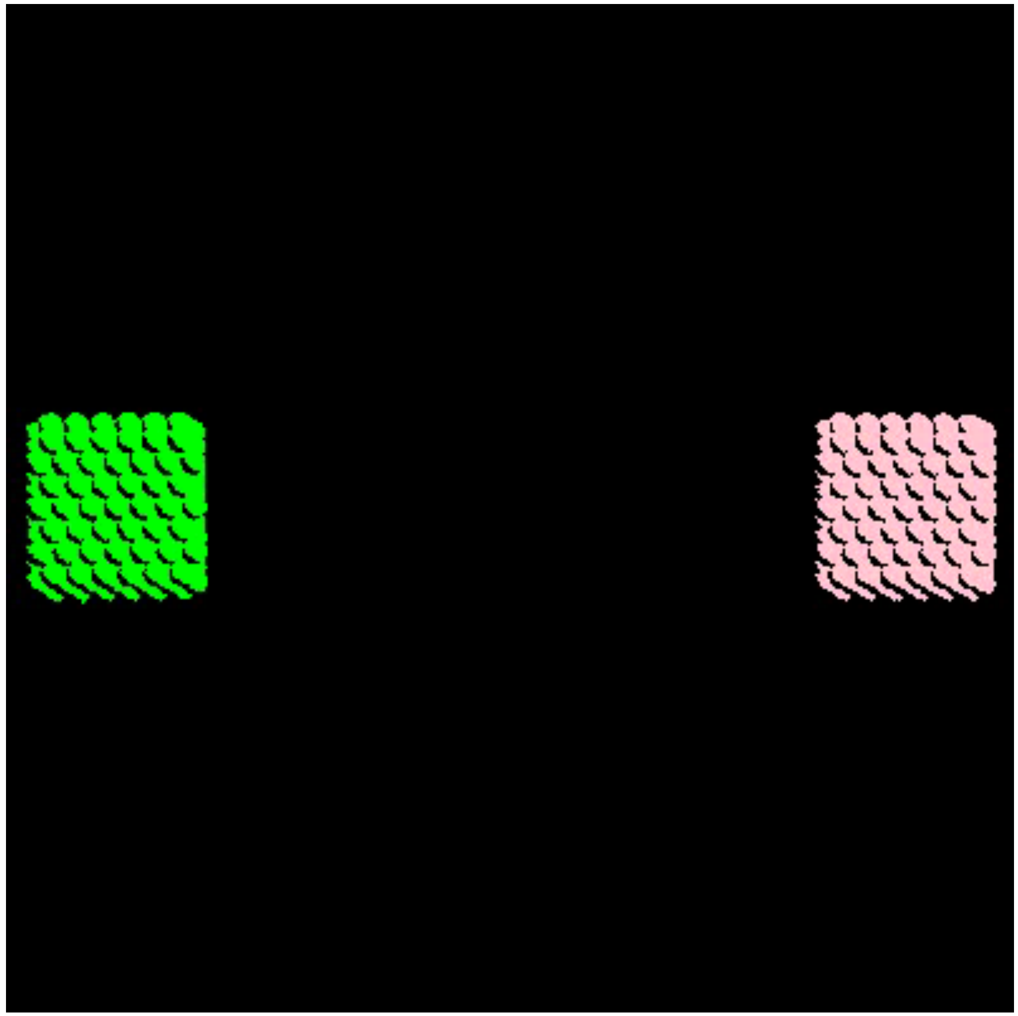
What about cohesion?

- Upper limits from comets SL9 & Tempel 1 ~100 Pa. Essentially no data for asteroids.
- How to model this?
- What is the effect?

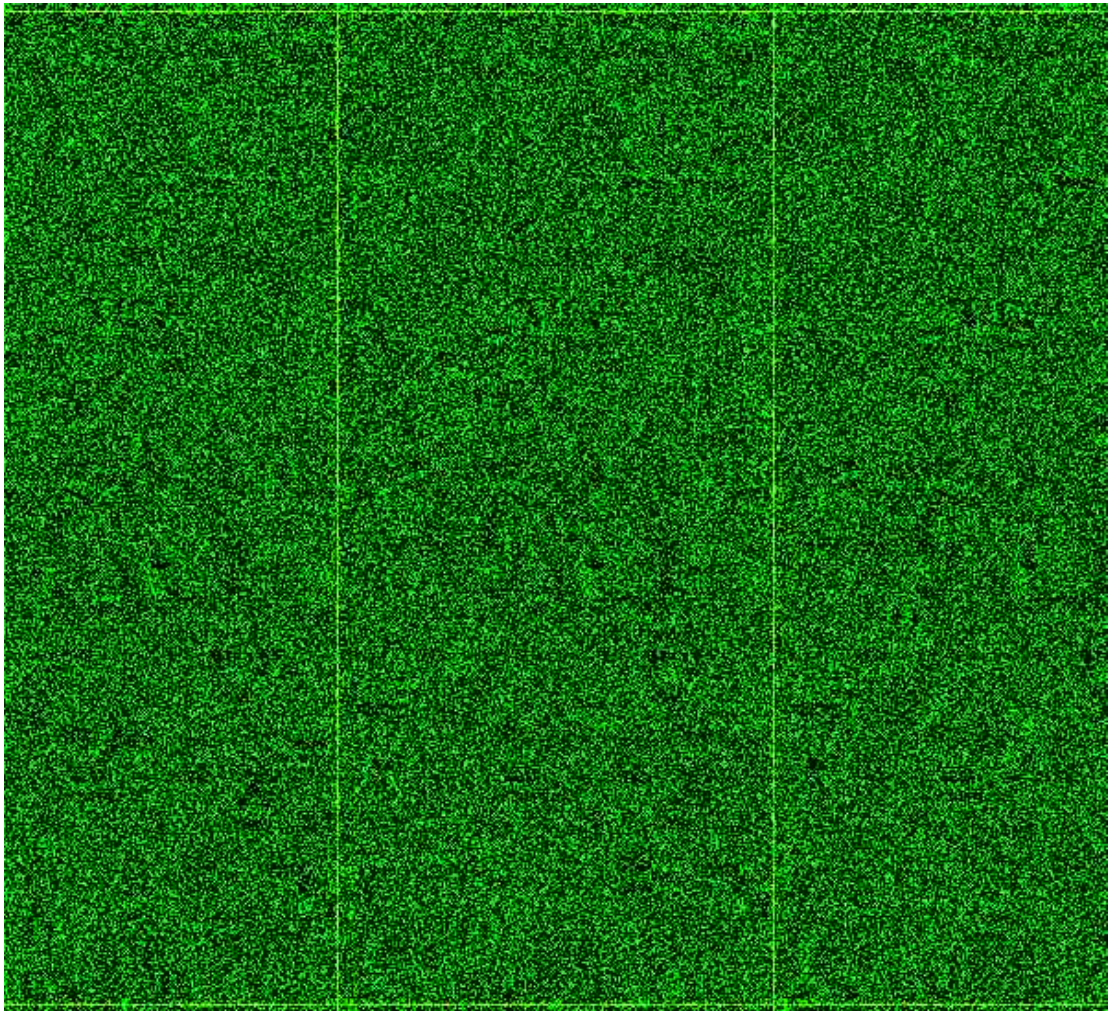
NSF grant: "Effect of Internal Structure on the Formation of Binary Near-Earth Asteroids" 7/15/10–6/30/13

NASA OPR grant: "Numerical Modeling of Cohesion in Planetary Rings" 8/4/10–8/3/12

Bouncing Cubes!

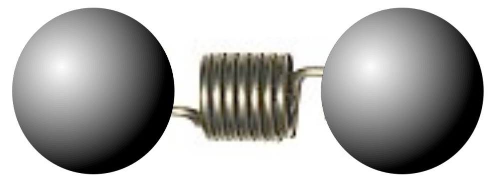


Bonded Aggregates in Rings



Modeling Weak Cohesion

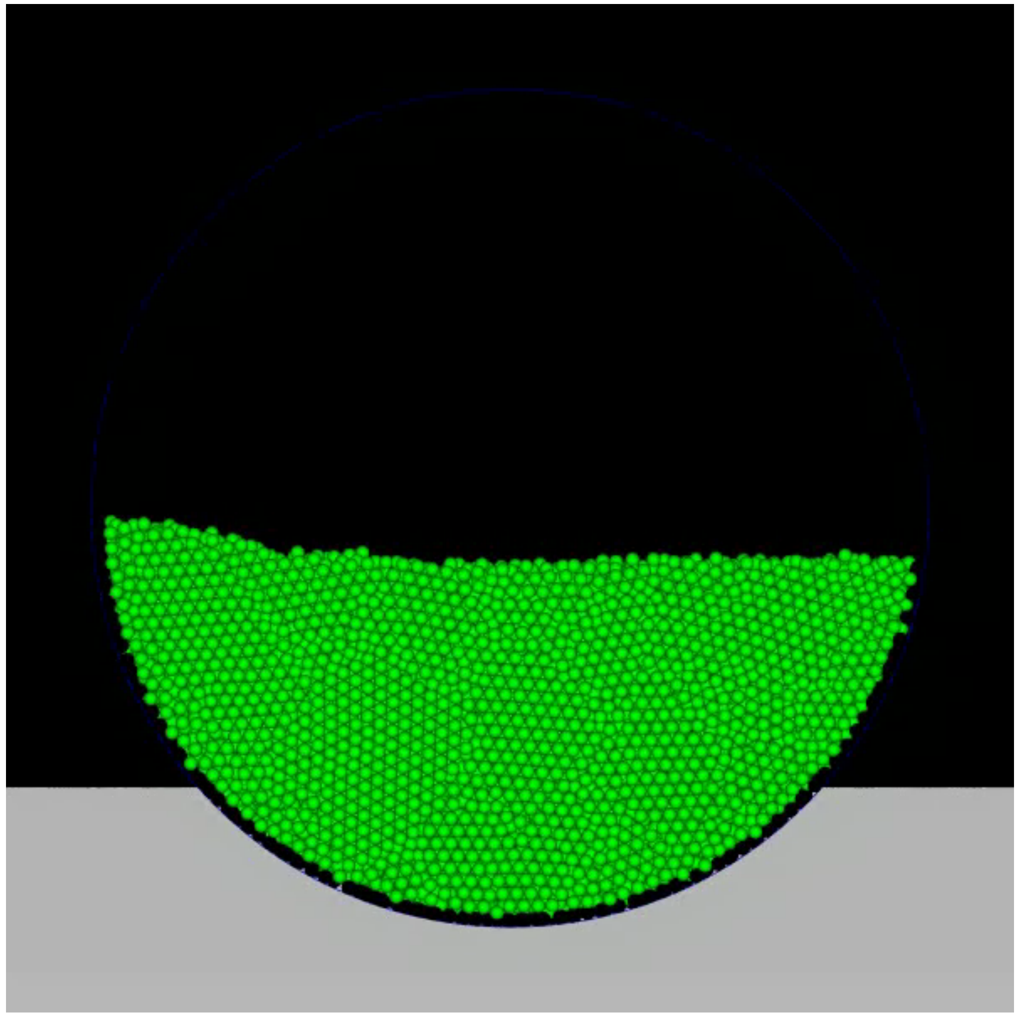
- Add simple Hooke's law restoring force between nearby particles.



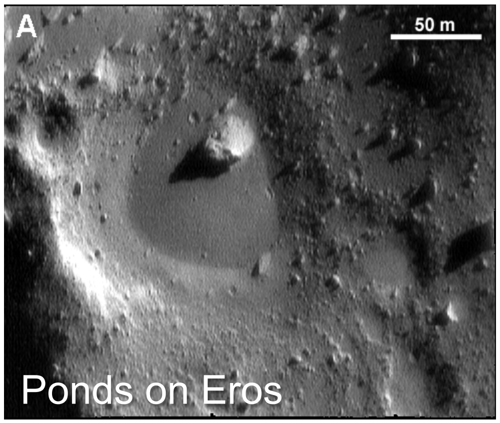
- Deform elastically up to maximum strain (spring rigidity set by Young's modulus).
- Particles act as *tracers* of a continuum solid.

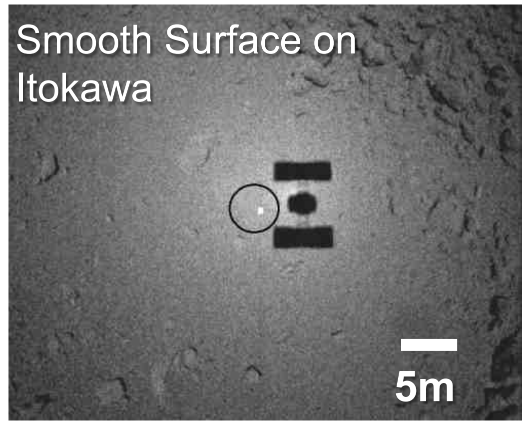
These are NOT bonded aggregates!

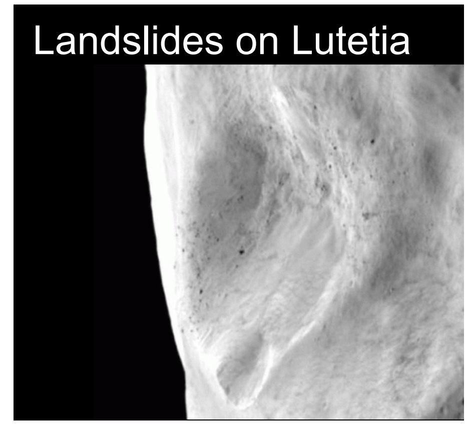
Weak Cohesion in Granular Fluids



Why investigate granular material?







Understanding dynamics of granular material under varying gravitational conditions is important: 1) to interpret the surface geology of small bodies; and 2) to aid in the design of a successful sampling device or lander.

➔ Need to combine granular physics and complex gravitational fields.
➔ Need to validate numerical approach.

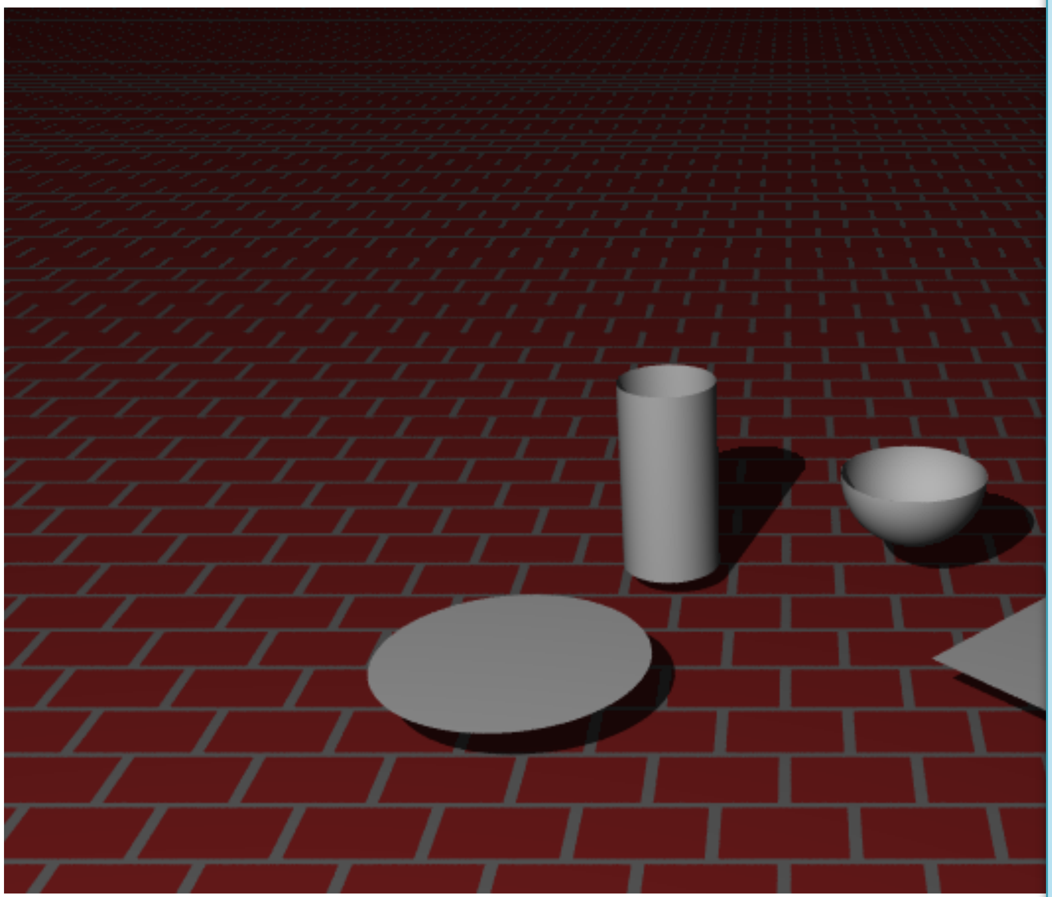
Walls

Numerical simulations of granular dynamics: I. Hard-sphere discrete element method and tests (Richardson et al.)

- Collision condition: $|\mathbf{r}_{\text{impact}} - \mathbf{c}| = s$, where **c** is the point of contact on the wall, which depends on the wall geometry.
- Following geometries supported:

Geometry	Unique Parameters	Degenerate Cases
Plane (infinite)	none	none
Triangle (finite)	*vectors to 2 vertices*	*point, line*
Rectangle (finite)	vectors to 2 vertices	point, line
Disk (finite)	radius	point
Cylinder (infinite)	radius	line
Cylinder (finite)	radius, length, *taper*	point, line, ring
Spherical shell (finite)	*radius, opening angle*	*point*

Walls



```
wall type plane
  transparency 1

wall type disk
  origin -1 0 0.2
  orient 0 0 1
  radius 0.5

wall type cylinder-finite
  origin -0.5 1 0.5
  radius 0.2
  length 0.8

wall type shell
  origin 0.5 1 0.5
  radius 0.3
  open-angle 90

wall type rectangle
  origin 0.5 0 0.2
  vertex1 -0.6 0.6 0
  vertex2 0.6 0.6 0
```

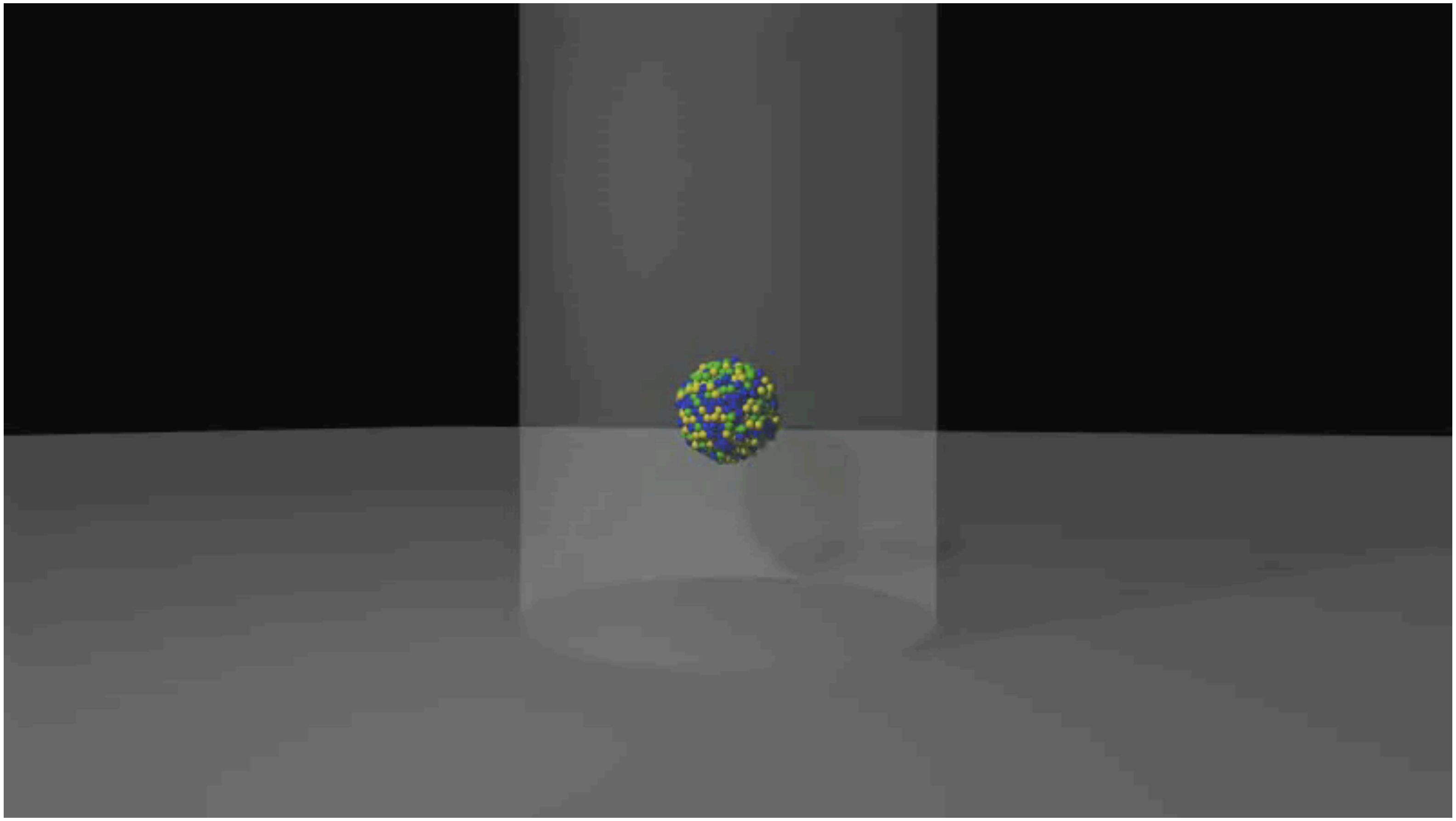
Test: Model Atmosphere

- Drop ~1000 particles in cylinder.
- NO dissipation (walls or particles).
- Particle masses 1, 3, 10 (all same radius).
- Expect energy equipartition, leading to a vertical probability distribution:

$$P_m(z) \sim \exp(-z/h_m),$$

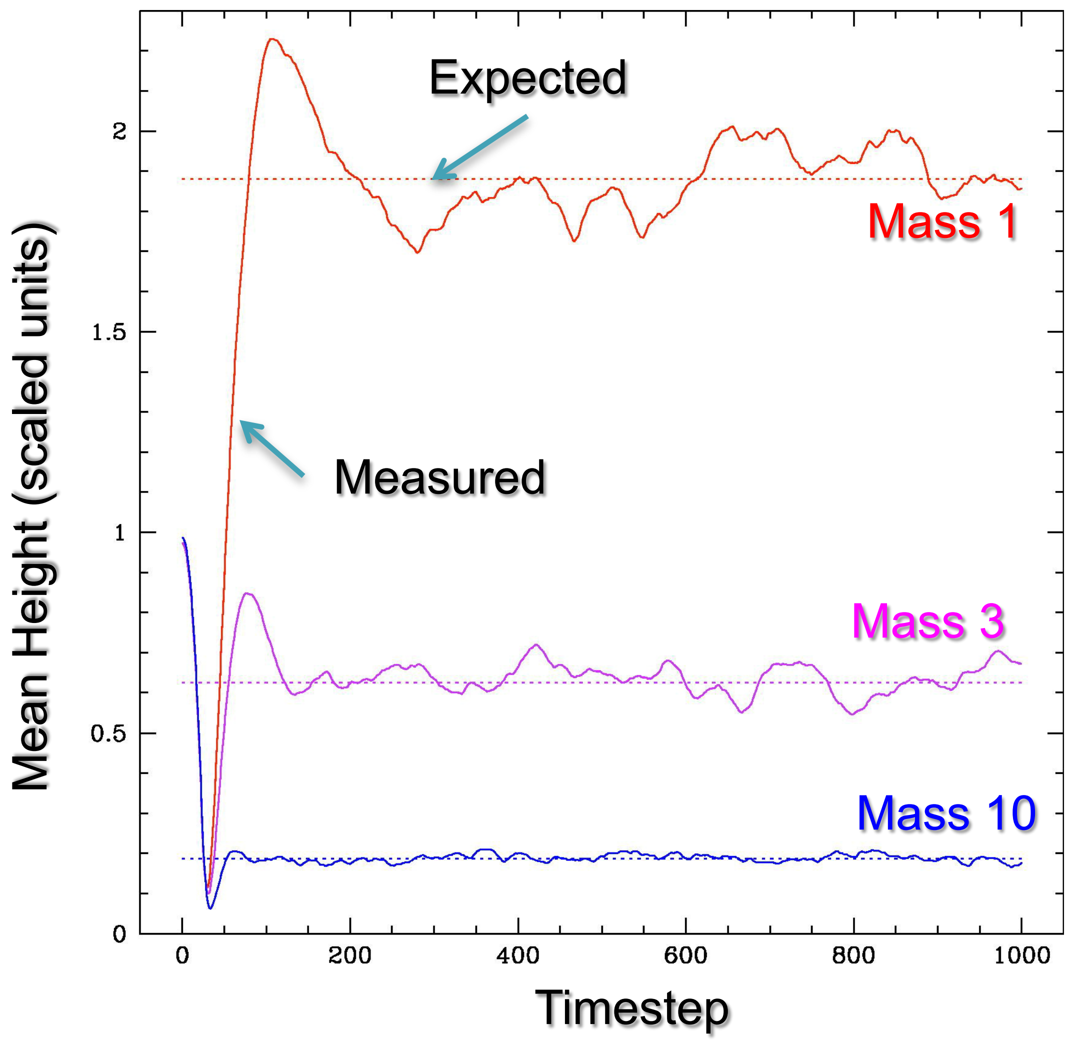
where $h_m = (2/5) \langle E \rangle / mg$, and $\langle E \rangle = E/N$ is the mean particle energy (KE + PE).

Test: Model Atmosphere

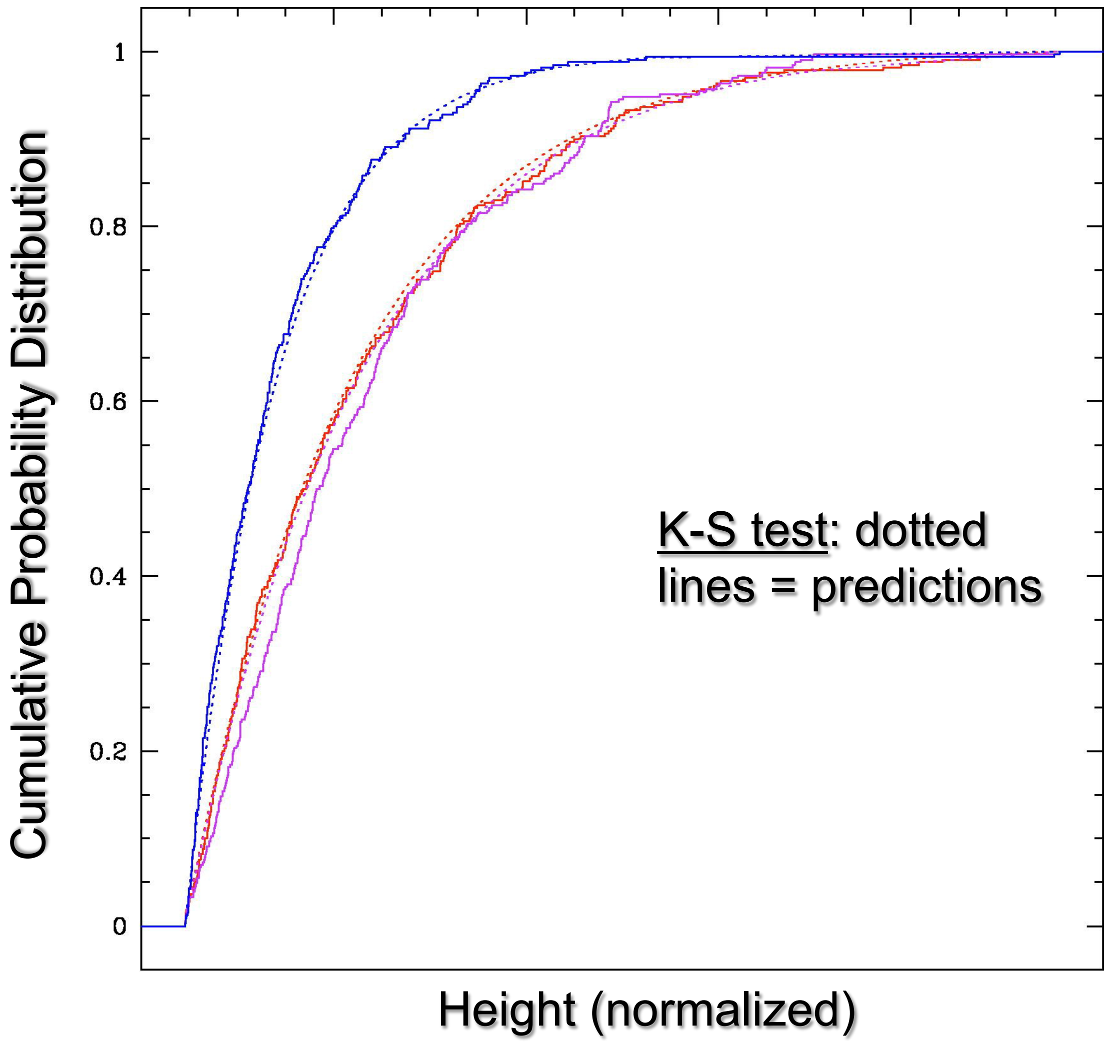


Green, blue, yellow = mass 1, 3, 10. Only bottom portion shown.

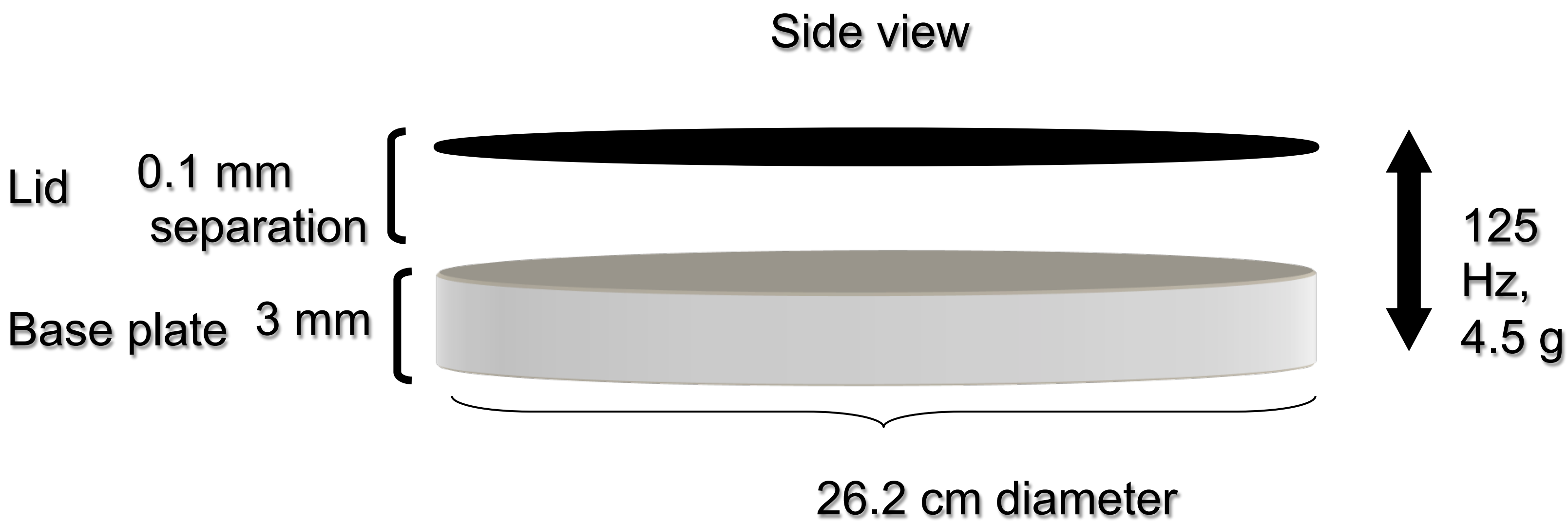
Test: Model Atmosphere



Test: Model Atmosphere



Numerical simulations of granular dynamics: II. Particle dynamics in a shaken granular material (Murdoch et al.)



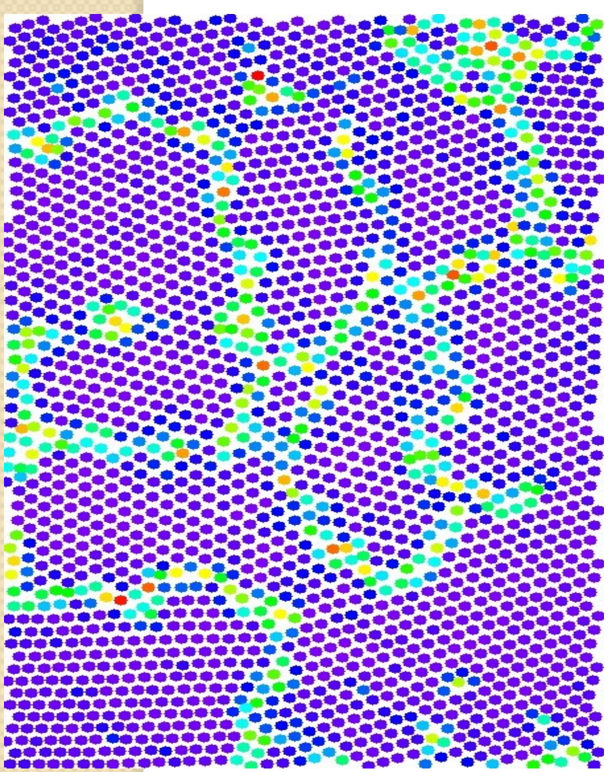
Berardi *et al*. 2010: vibrate densely packed layer of particles (3mm and 2mm) at nearly close packing (~85%).

Note: Figure not to scale.

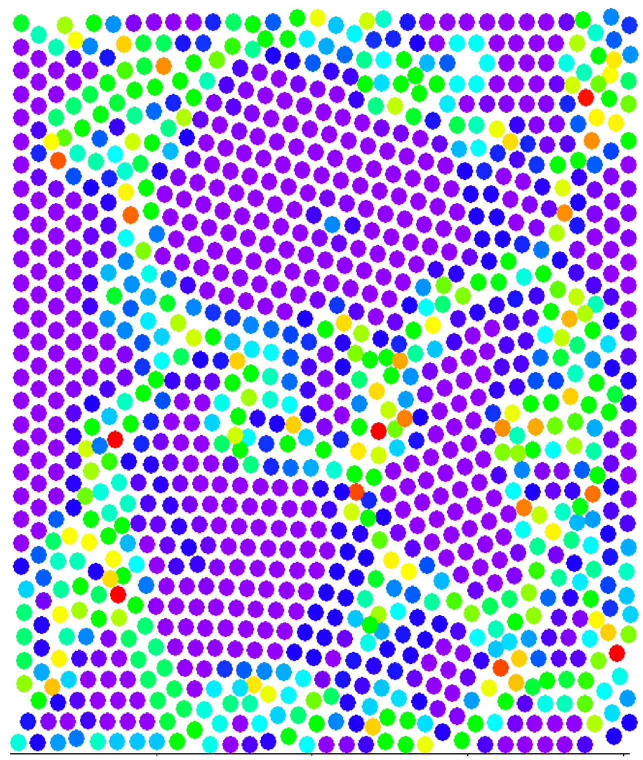
Grains, Boundaries, & Strings

We correctly model grains, grain boundaries, and "strings."

85% total coverage and 3% small particle additives.



Experiment†



Simulation*

Purple: near hexagonal particle packing.

Red: more disordered packing (i.e. GB regions).

† Berardi *et al.*, 2010

* Murdoch *et al.*, 2010 (in preparation)

Test: Tumbler

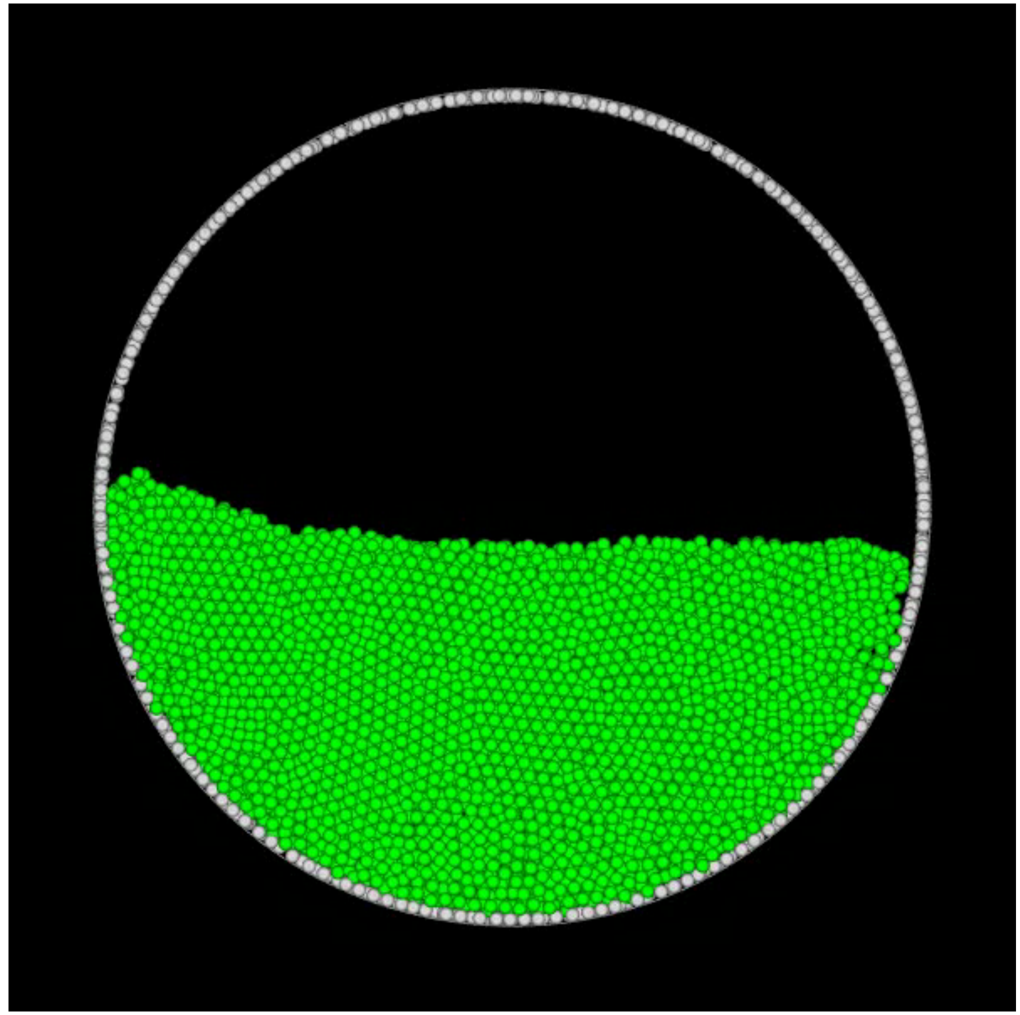
- Attempt to replicate lab experiments of Brucks et al. (2007).
- Idea: rotate short cylinder (radius *R*, half-filled with beads) at various rates. Measure dynamical angle of repose.
- Theory: response is a function of the "Froude" number Fr = $\Omega^2 R/g$.
  - E.g. Fr = 1.0 ➔ centrifuging.

Test: Tumbler

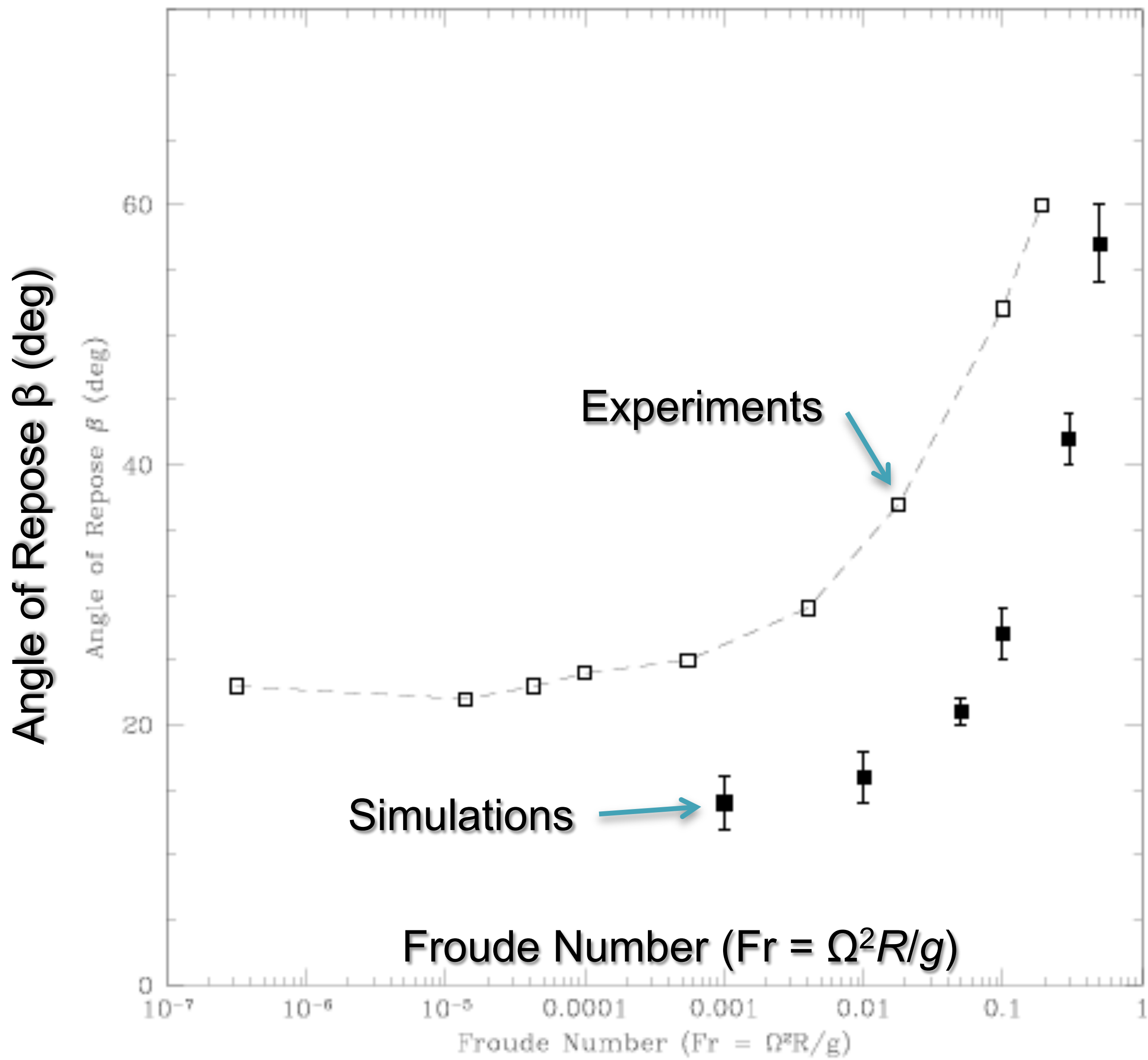
3-D simulation (cylinder is about a dozen particle diameters long).

Wall roughness provided by gluing particles to inner wall (experiments used sandpaper).

Movie: Fr = 0.5.

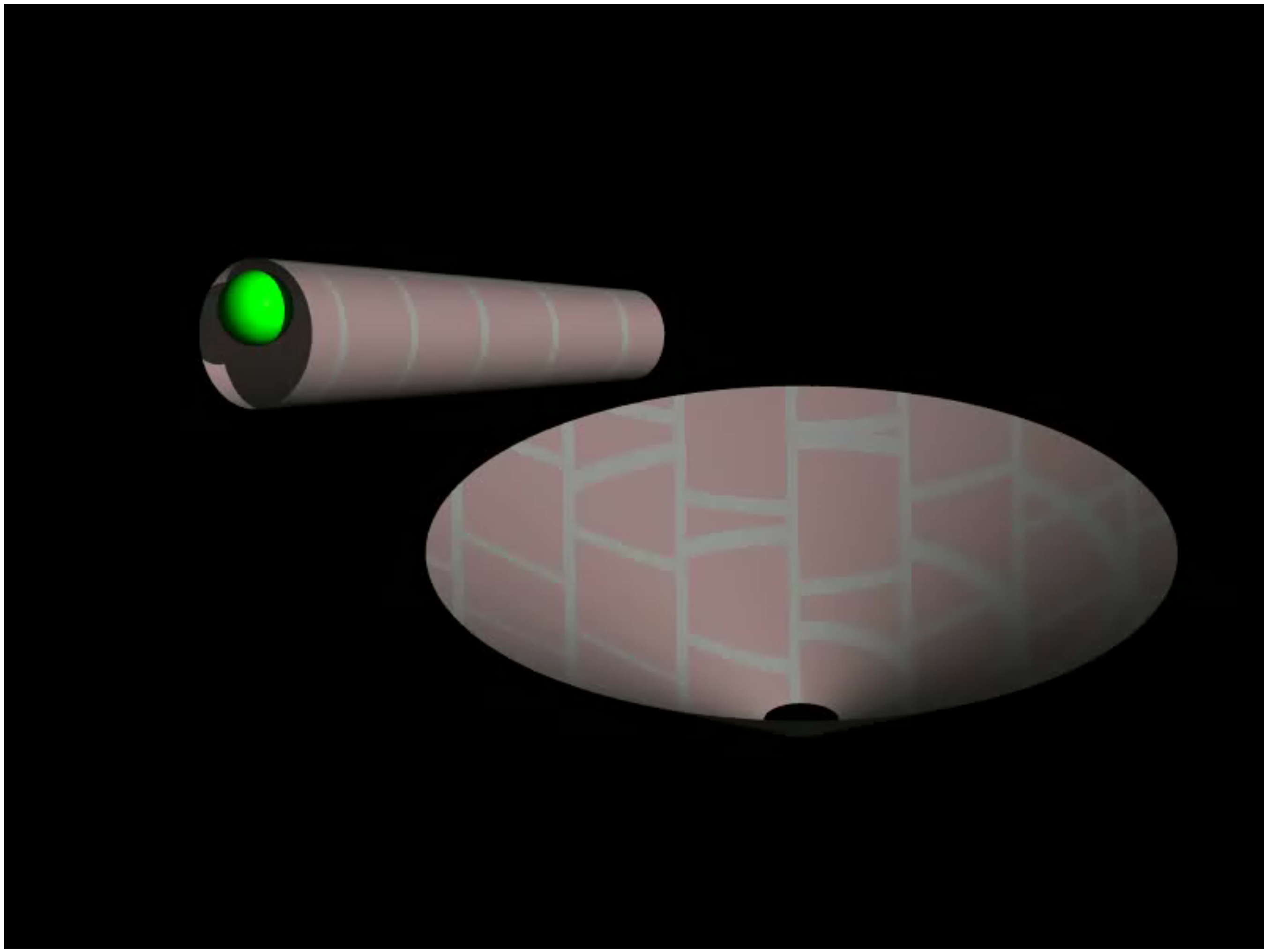


Test: Tumbler

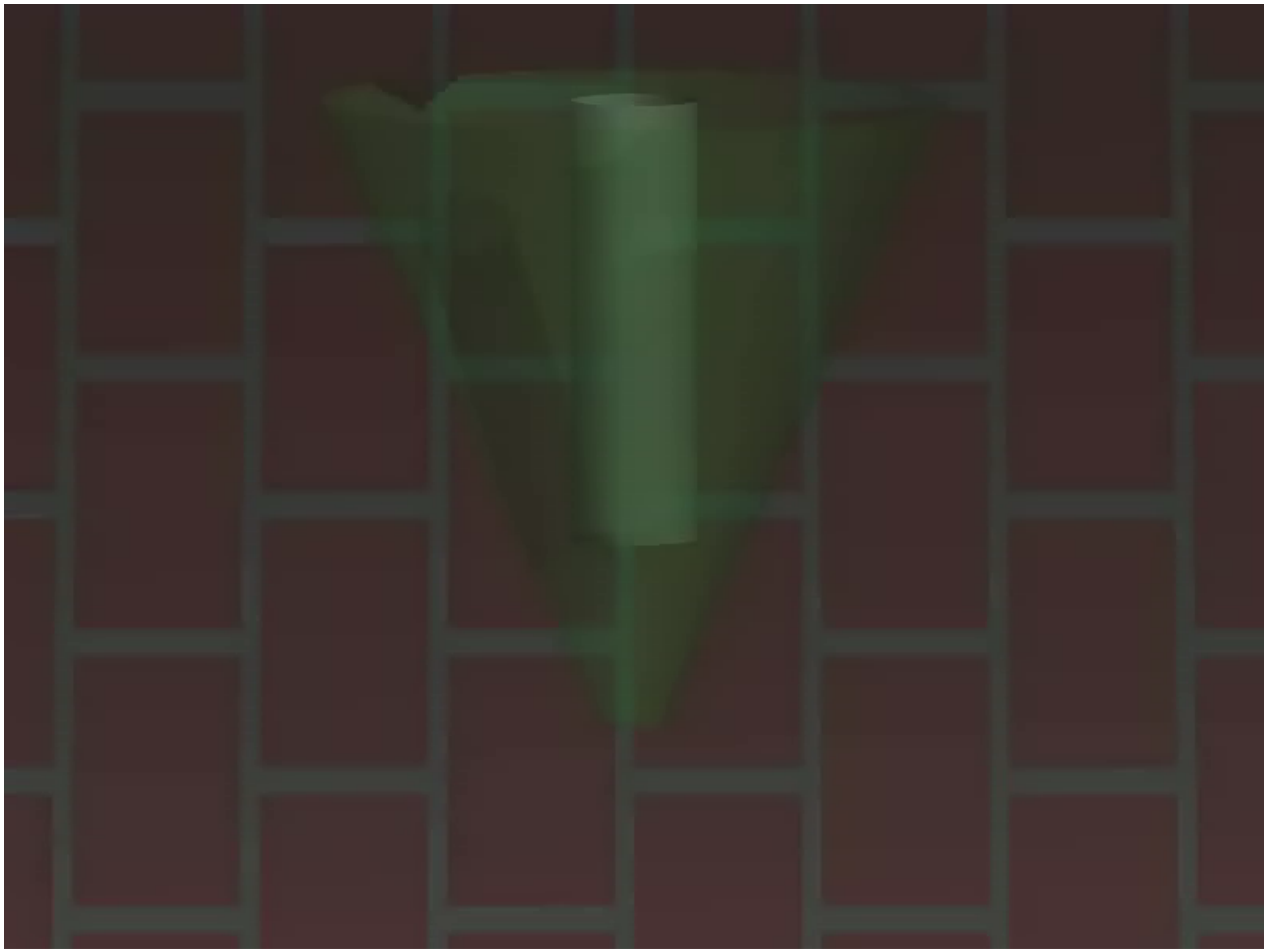


Soft-sphere DEM

NASA PG&G grant "Gravitational Aggregate Dynamics" 4/16/08–4/15/11



Soft-sphere DEM



The Code: PKDGRAV

- Originally designed for cosmology (large-scale structure simulations).
- Modified to handle particle collisions.
- Gravity computed using tree code.
- Can run in parallel across many nodes.
- Nearly 50,000 lines of code!!…

Yorp & Deepthought

- Yorp: mini cluster for department use.
  - 104 cores, 109 GB RAM, 12.8 TB disk.
  - http://www.astro.umd.edu/twiki/bin/view/AstroUMD/YorpCluster
- Deepthought: campus HPC.
  - Over 1000 cores, high-performance disk.
  - CTC has guaranteed time.
  - I'm on the advisory committee and TAC.
  - http://www.oit.umd.edu/hpcc