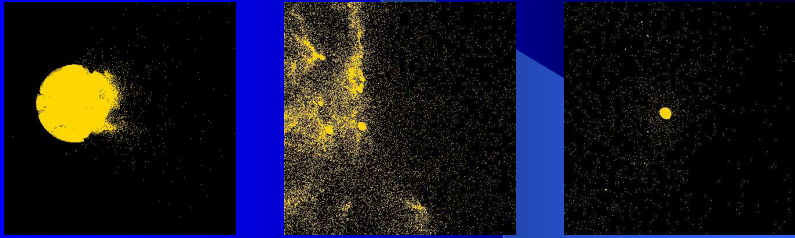


Gravitational Reaccumulation in the Solar System

Derek C. Richardson (U Maryland)



KITP 2004

The slide features three square panels illustrating the stages of gravitational reaccumulation. The first panel on the left shows a bright yellow protoplanet surrounded by a dark, diffuse cloud of particles. The middle panel shows a collision between two protoplanets, with bright yellow sparks and debris being ejected from the impact site. The third panel on the right shows a single, larger planet with a bright yellow core and a dark, diffuse cloud of particles around it, representing the final stage of reaccumulation.

Collaborators

E. Asphaug UCSC	W. Benz U Bern	W. F. Bottke Jr. SwRI
D. D. Durda SwRI	B. L. Enke SwRI	D. P. Hamilton U Maryland
Z. M. Leinhardt U Maryland	H. J. Melosh LPL	P. Michel Obs. Cote d'Azur
T. Quinn U Washington	D. J. Scheeres U Michigan	J. Stadel U Zurich
P. Tanga Obs. Cote d'Azur	K. J. Walsh U Maryland	P. R. Weissman JPL

Overview

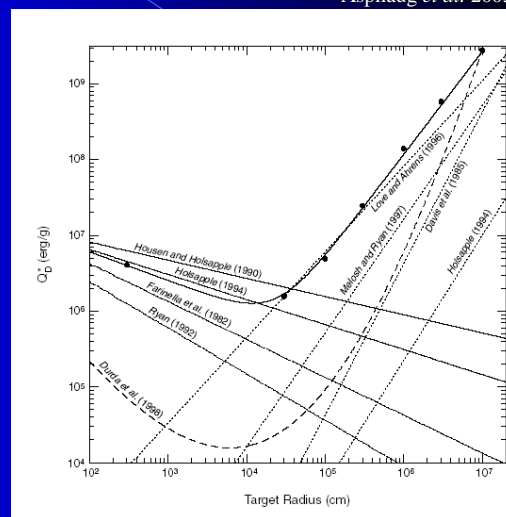
- Gravitational Reaccumulation
 - Important on scales of ~ 100 m and larger.
 - Explains asteroid family properties.
 - Plays a role in binary asteroid formation.
 - Better model for planetesimal fragmentation.
- Gravitational Aggregates
 - Modern-day planetesimals.

Cf. Leinhardt *et al.* 2000, 2002 (*Icarus*),
 Michel *et al.* 2001 (*Science*), 2003 (*Nature*),
 Richardson *et al.* 2003 (*Asteroids III*).

Strength vs. Gravity

Asphaug *et al.* 2003

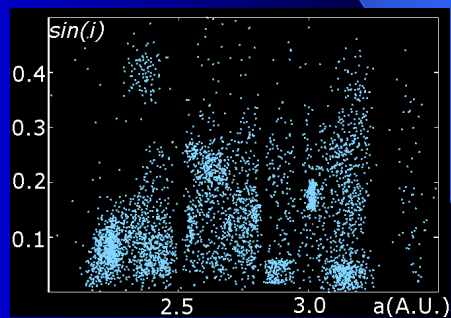
- Gravity dominates over strength for bodies as small as 100 m in radius.
- Bodies larger than this limit will be shattered before being dispersed.
- Gravitational dynamics important even for such small bodies.



Asteroid Families

- Evidence for past catastrophic collisions.
 - Groups of small bodies that share certain orbital and spectral properties.

More than 20 families have now been identified.

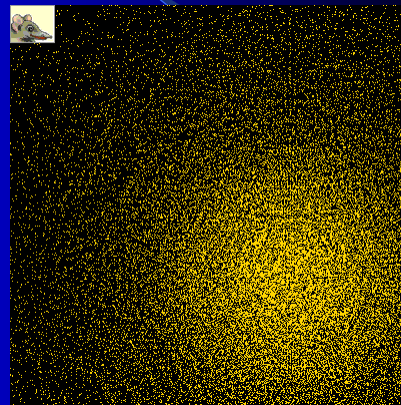


- The size and velocity distributions of family members provide important constraints on understanding asteroid collisions...
 - Size distribution \Leftrightarrow range of fragment sizes.
 - Velocity distribution \Leftrightarrow range of ejecta energy.
- Until recently, numerical simulations could not reproduce *simultaneously* the dynamical properties and mass spectra of families.

- **ASSUMPTION:** Asteroid family members are monolithic fragments.
- **REQUIREMENT:** To disperse family members, impact energy must be HIGH.
- **PROBLEM:** Laboratory experiments (extrapolated) and numerical simulations imply fragments must all be shattered!

Solution: Gravity!

- Impacts that completely shatter a target are followed by gravitational reaccumulation of debris.



Simulation of Koronis formation

Simulations of Family-forming Impacts

- SPH hydrocode → crack propagation through the target
(short timescale)
- *N*-body code → gravitational interaction between intact fragments
(long timescale)

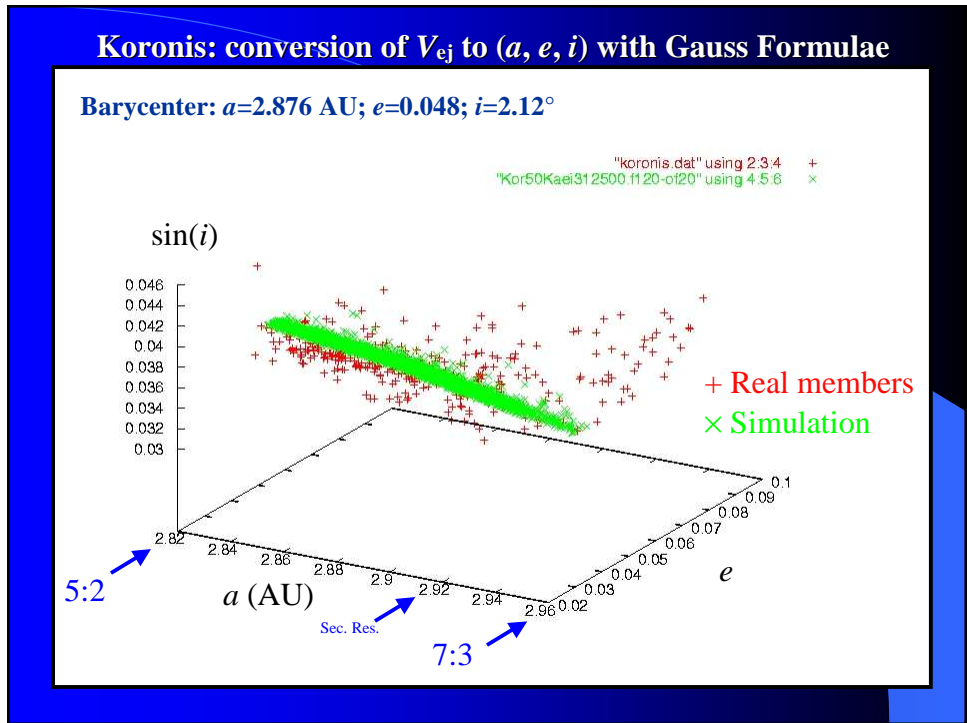
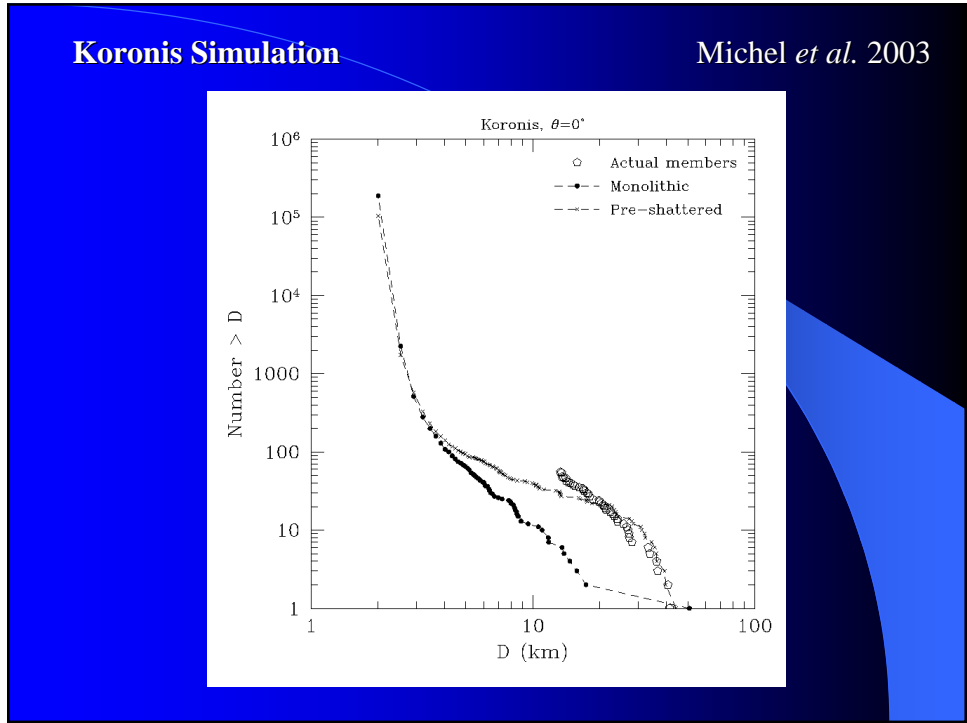


Simulation of target shattering + fragment dispersion and/or reaccumulation

Matching Observations

- Perfect match to observations not expected:
 - Different collision scenarios give similar results but differ in the details.
 - Families will evolve...
 - Collisional erosion → shallower size distribution.
 - Gravitational perturbations/Yarkovsky → dispersal.

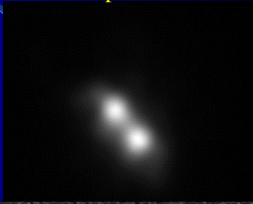
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Binary Asteroids

- 32+ confirmed or suspected binaries found.
- Techniques include:
 - Direct imaging
 - Lightcurve analysis
 - Radar imaging

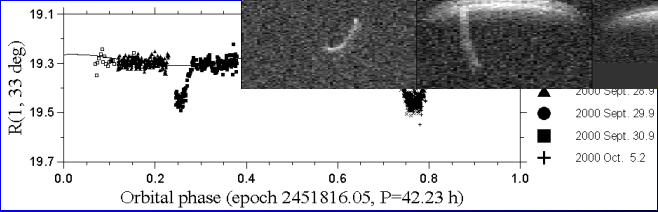
90 Antiope



KW4




DP107



Symbol	Date
▲	2000 Sept. 26.9
●	2000 Sept. 29.9
■	2000 Sept. 30.9
+	2000 Oct. 5.2

NEA Binaries

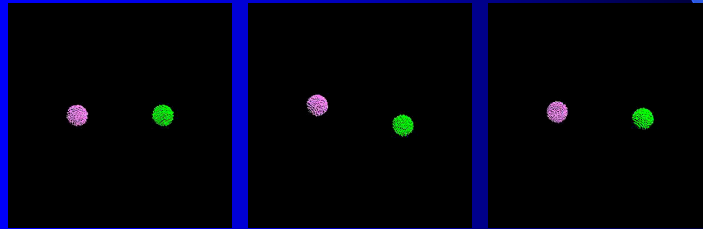
- Reaccumulation following tidal disruption could form NEA binaries.
- Need reaccumulated (or shattered/fragile) body to start with...



Planetesimal Evolution

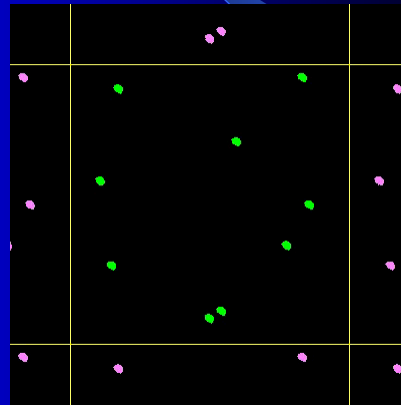
- Evolutionary models based on laboratory experiments may be inadequate.
 - Outcomes determined by gravitational reaccumulation.

Leinhardt *et al.* 2000



Incorporating Collision Models

- Based on individual test cases, collision outcomes can be incorporated into large-scale sims of planet formation.

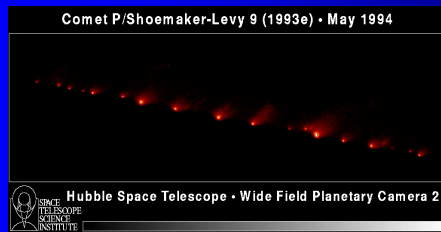


Gravitational Aggregates

- Present-day planetesimals (asteroids and comets) may be gravitational aggregates.
- Evidence includes:
 1. Tidal disruption.
 2. Low bulk densities.
 3. Spin rate limits.

Tidal Breakups

- Require low tensile strength.



Comet breakups like D/SL9 can make crater chains.

Asteroid breakups may explain a few catenae seen on the Moon.

Davy Chain, ~47 km



Low Densities

- Many asteroids appear underdense, particularly C-class asteroids.

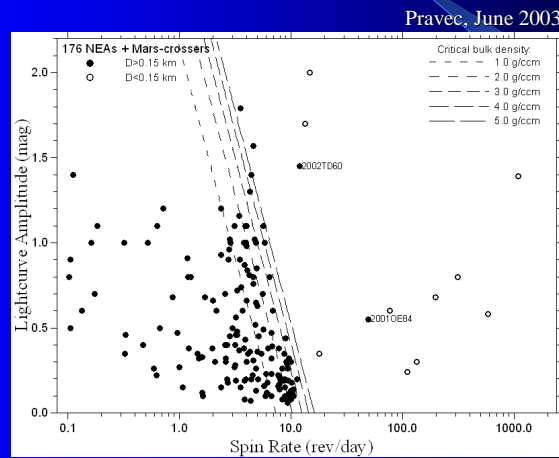


Large craters and low density of Mathilde imply high porosity.

← ~59 km → NEAR

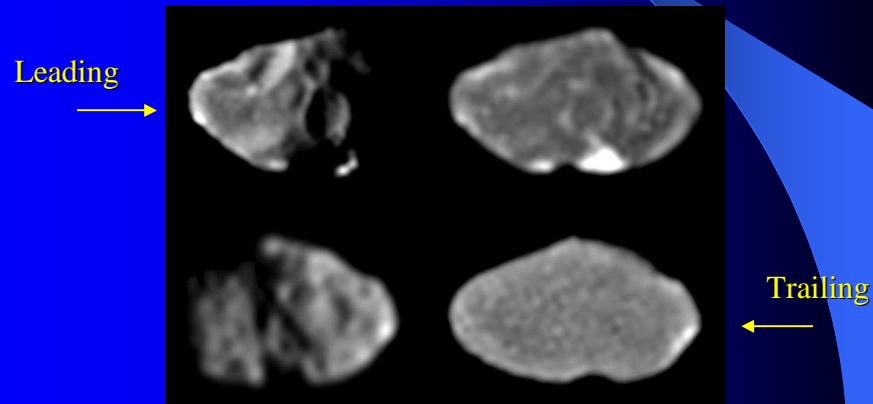
Asteroid Spins

- Nearly all large ($D > 200$ m) asteroids spin slower than the rubble breakup limit.



Latest Evidence

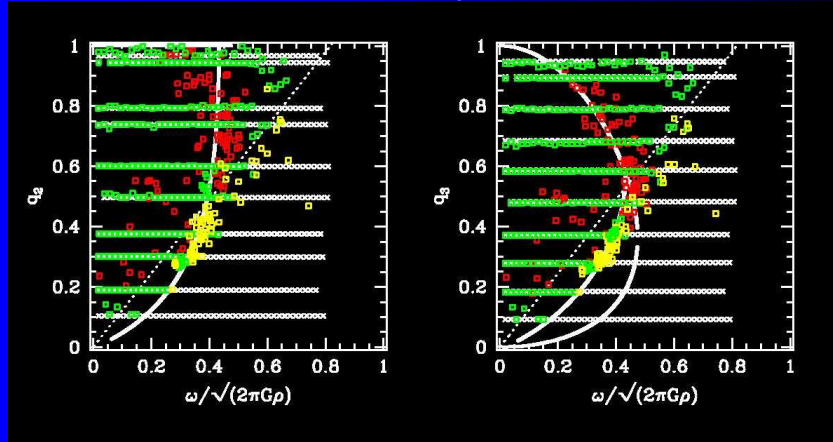
- Galileo flyby of Amalthea revealed bulk density of just 1 g/cc for this 270 km moon.



A Word About Rubble Piles

- Rubble piles are low-tensile-strength, medium-porosity gravitational aggregates.
- In simulations, rubble piles consist of perfectly smooth spheres; some dissipation.
- Used in a variety of contexts: planetesimal collisions, tidal disruption, spin-up.
- How do they differ from perfect fluids?

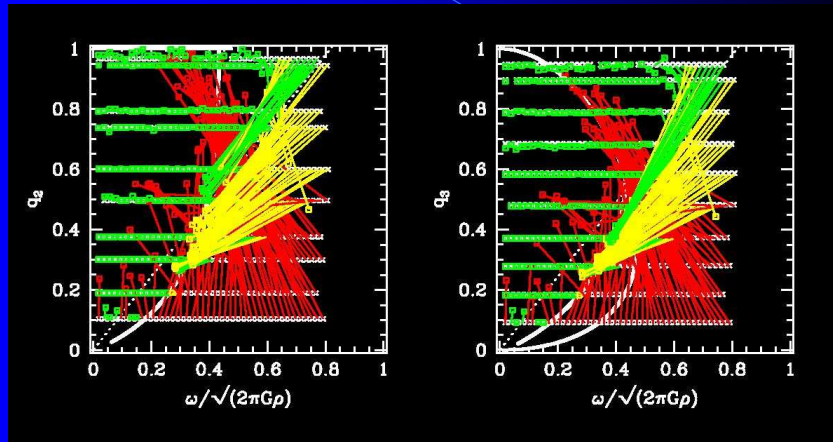
Equilibrium Shapes of Rubble Piles



Mass loss: 0% < 10% > 10% X = initial condition

Recall: $q_2 = a_2/a_1 \leq 1$; $q_3 = a_3/a_1 \leq q_2$

Equilibrium Shapes of Rubble Piles



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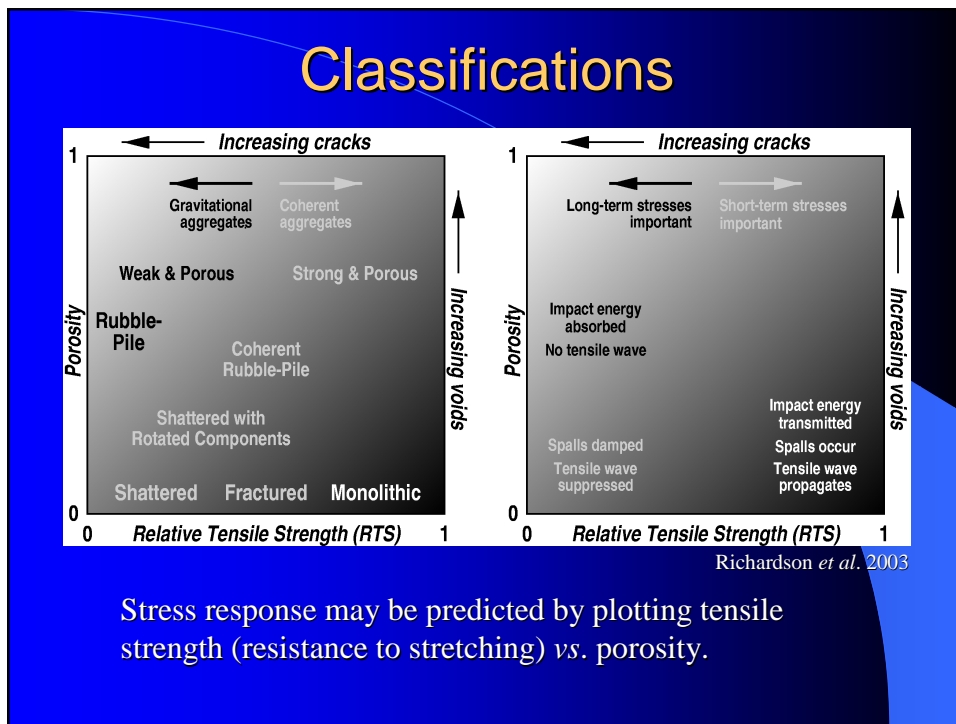
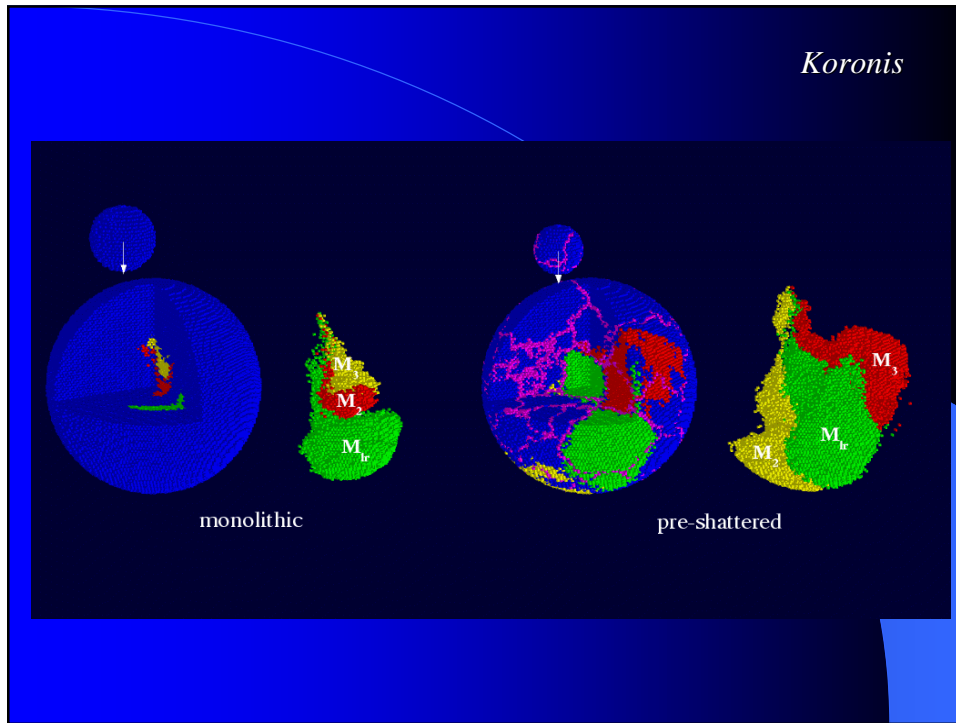
Conclusions

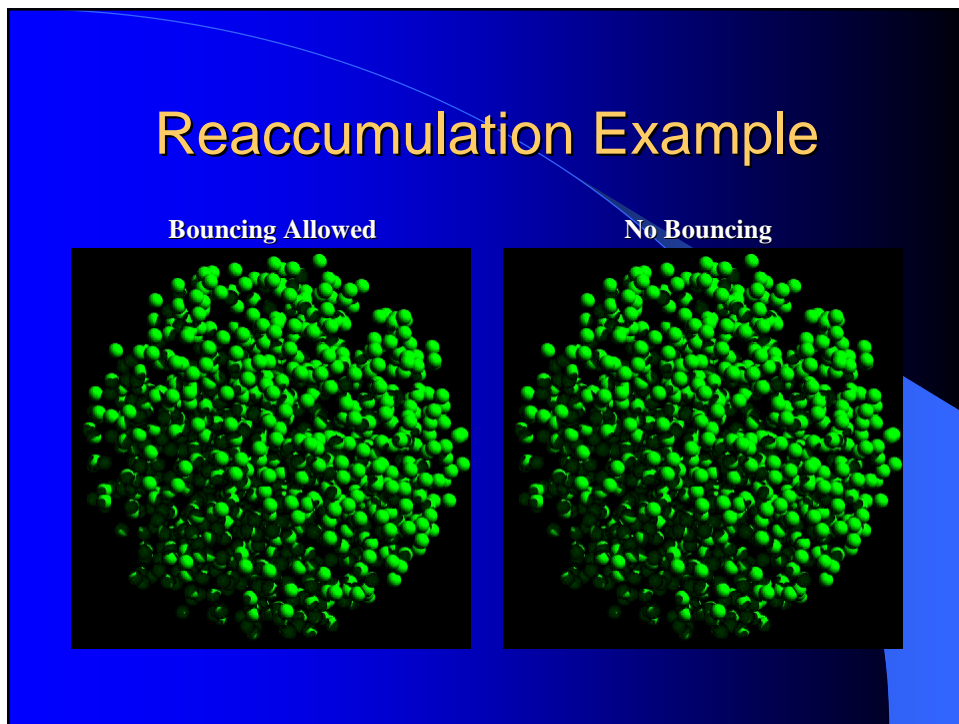
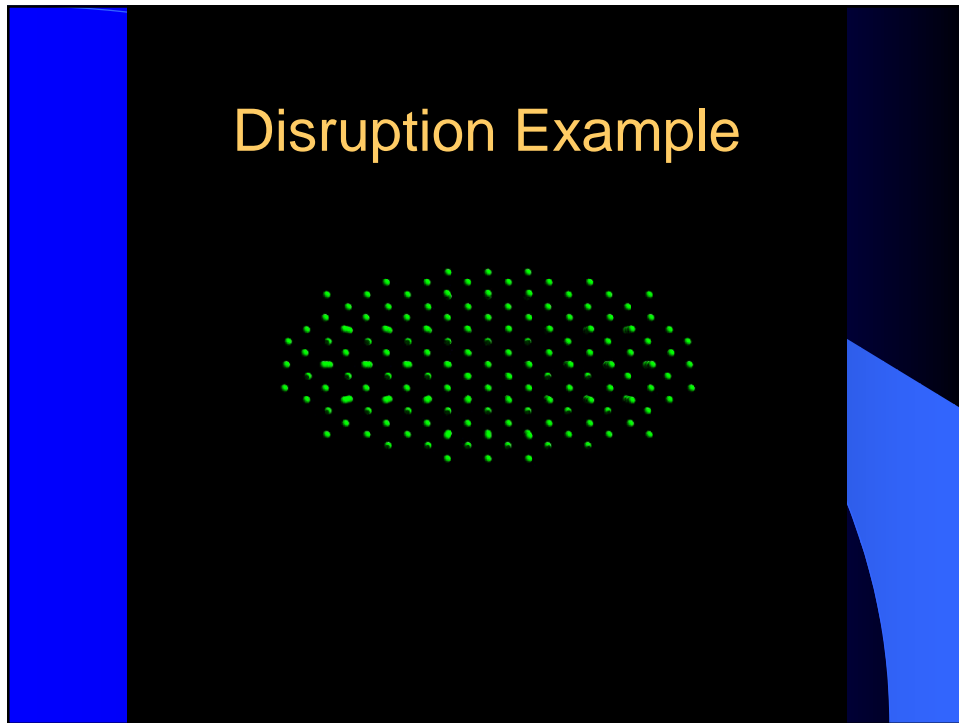
- Gravitational reaccumulation explains present-day asteroid families.
 - May also explain **asteroid binary formation**, from collisions or tidal disruption.
- It is likely the same processes were important during planet formation.
 - Simulation methods that extrapolate from **laboratory experiments** may need revising.

Future Work

- The details of breakup and reaccumulation depend sensitively on the **internal structure** of the original body, but the exact relationship remains to be determined.
 - See next figure...
- Other applications: planet formation, planetary rings, etc.

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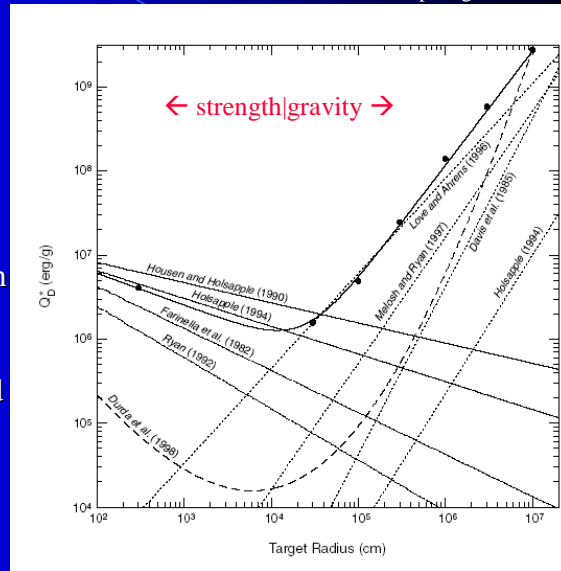




Morphological Evolution

Asphaug *et al.* 2003

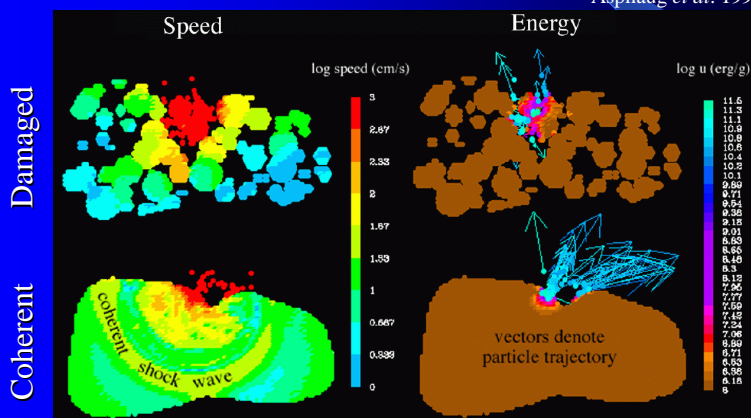
- Collisions are the dominant geologic process affecting large main-belt asteroids.
- Expect collisionally evolved population in gravity regime to consist of shattered and/or reaccumulated bodies.



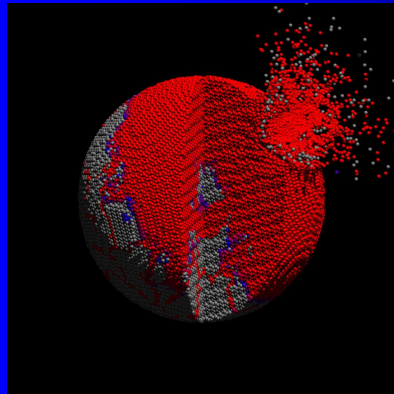
Aggregates Resist Disruption

Asphaug *et al.* 1998

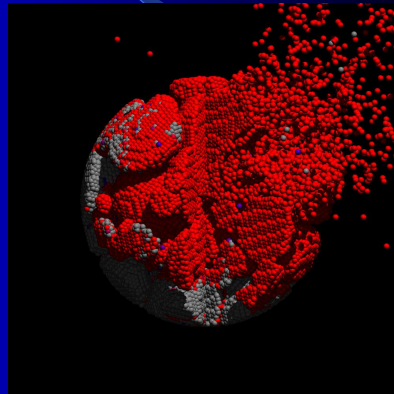
- Once shattered, impact energy is more readily absorbed at impact site.



Collision Target Models



Preshattered

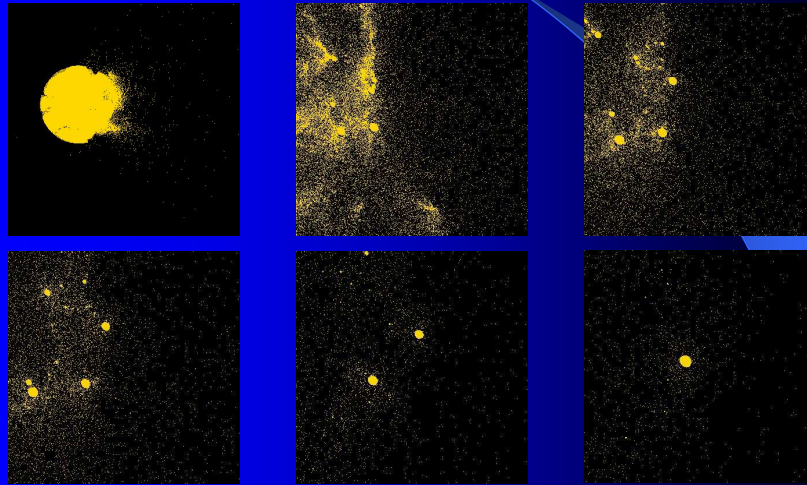


Rubble

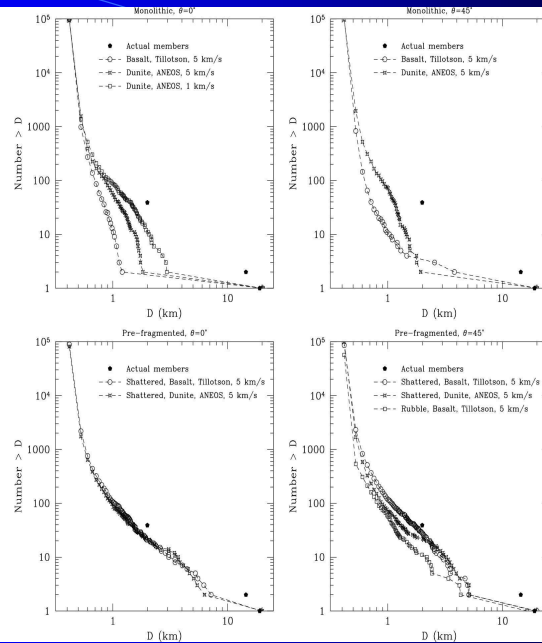
Recent Collision: Karin

- Nesvorný *et al.* (2002) found cluster inside Koronis that may have formed as recently as **5 million years ago** → little evolution.
- Our simulations (Michel *et al.* 2003) show that to reproduce the Karin cluster, the parent body must have been **pre-shattered**, consistent with being in the Koronis family.

Karin Formation



Karin Cluster



GRAVITATIONAL REACCUMULATION IN THE SOLAR SYSTEM

