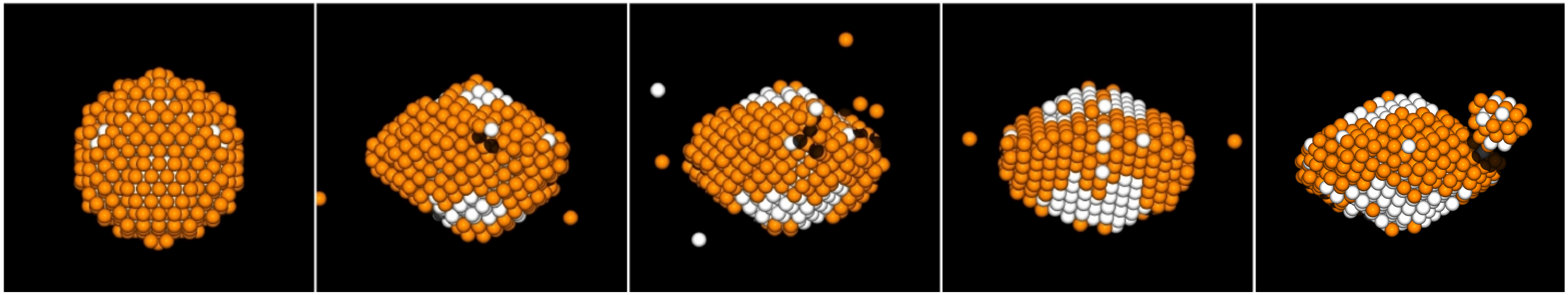
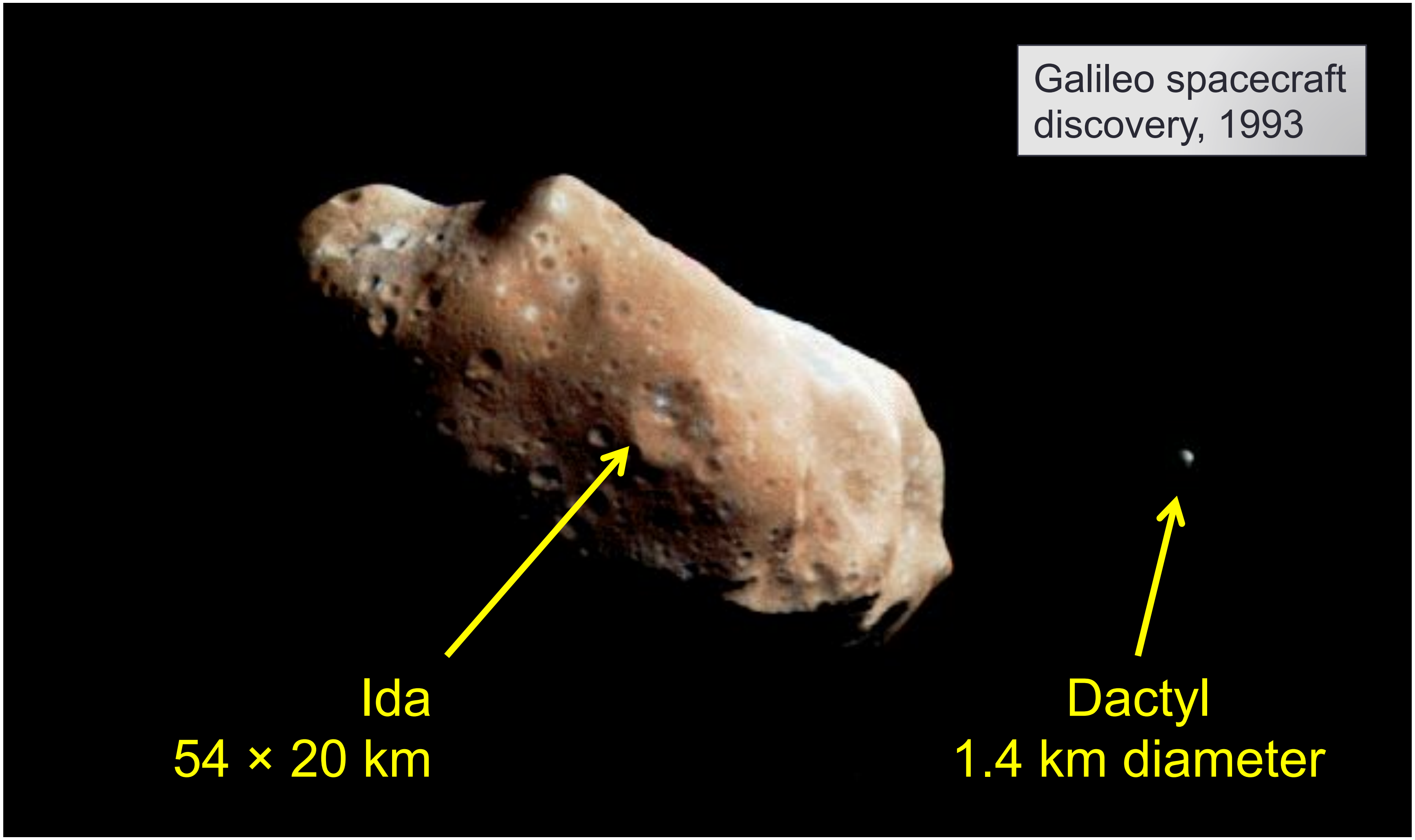
NUMERICAL SIMULATIONS OF SMALL SOLAR SYSTEM BINARY FORMATION

Derek C. Richardson (U Maryland)

Patrick Michel (OCA) • Kevin J. Walsh (SwRI)

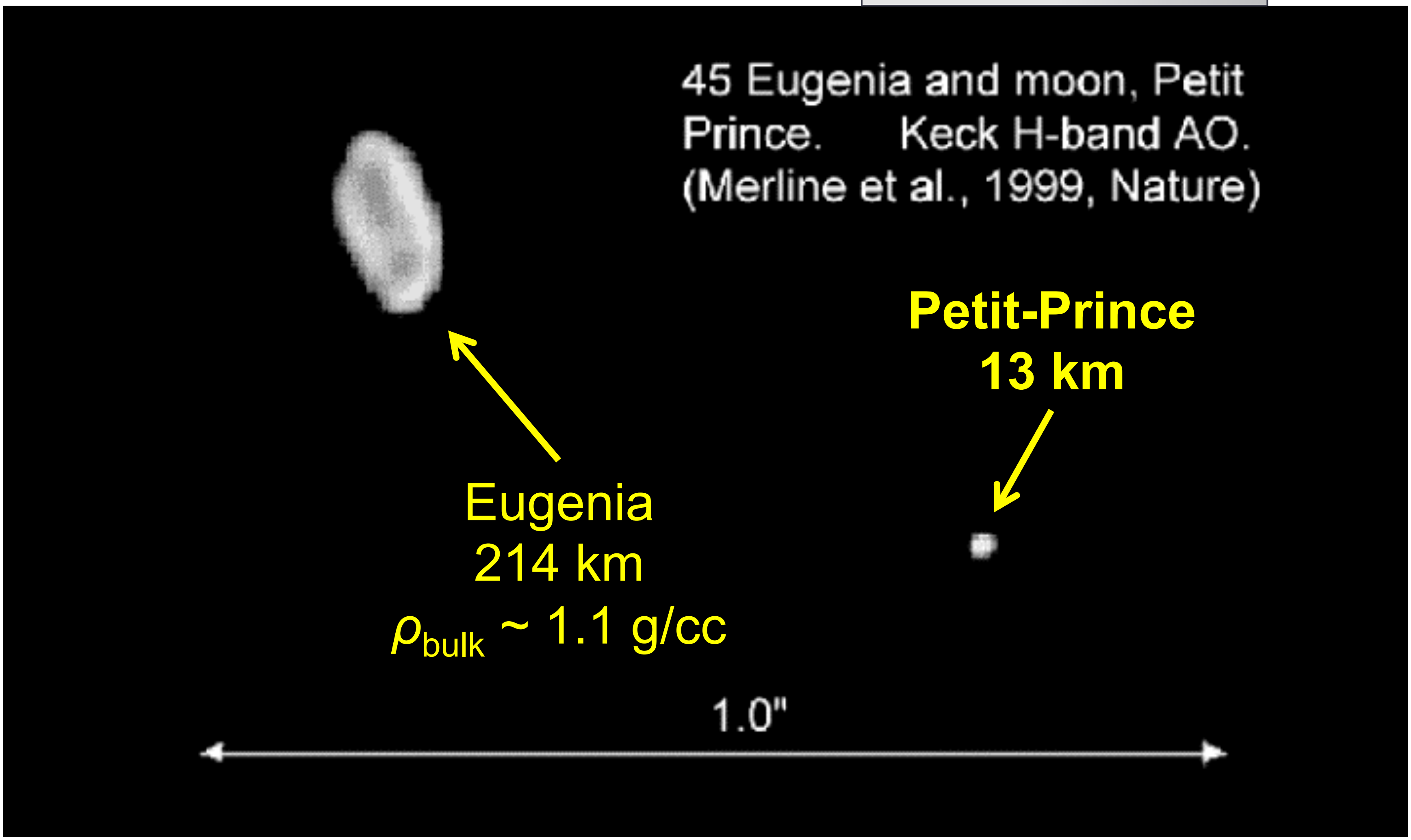


First Asteroid Binary: Ida-Dactyl



Eugenia-Petit Prince

Second moon found!
(Marchis et al. 2007)



SSSB System Demographics

Confirmed or probable detections as at June 14, 2012:

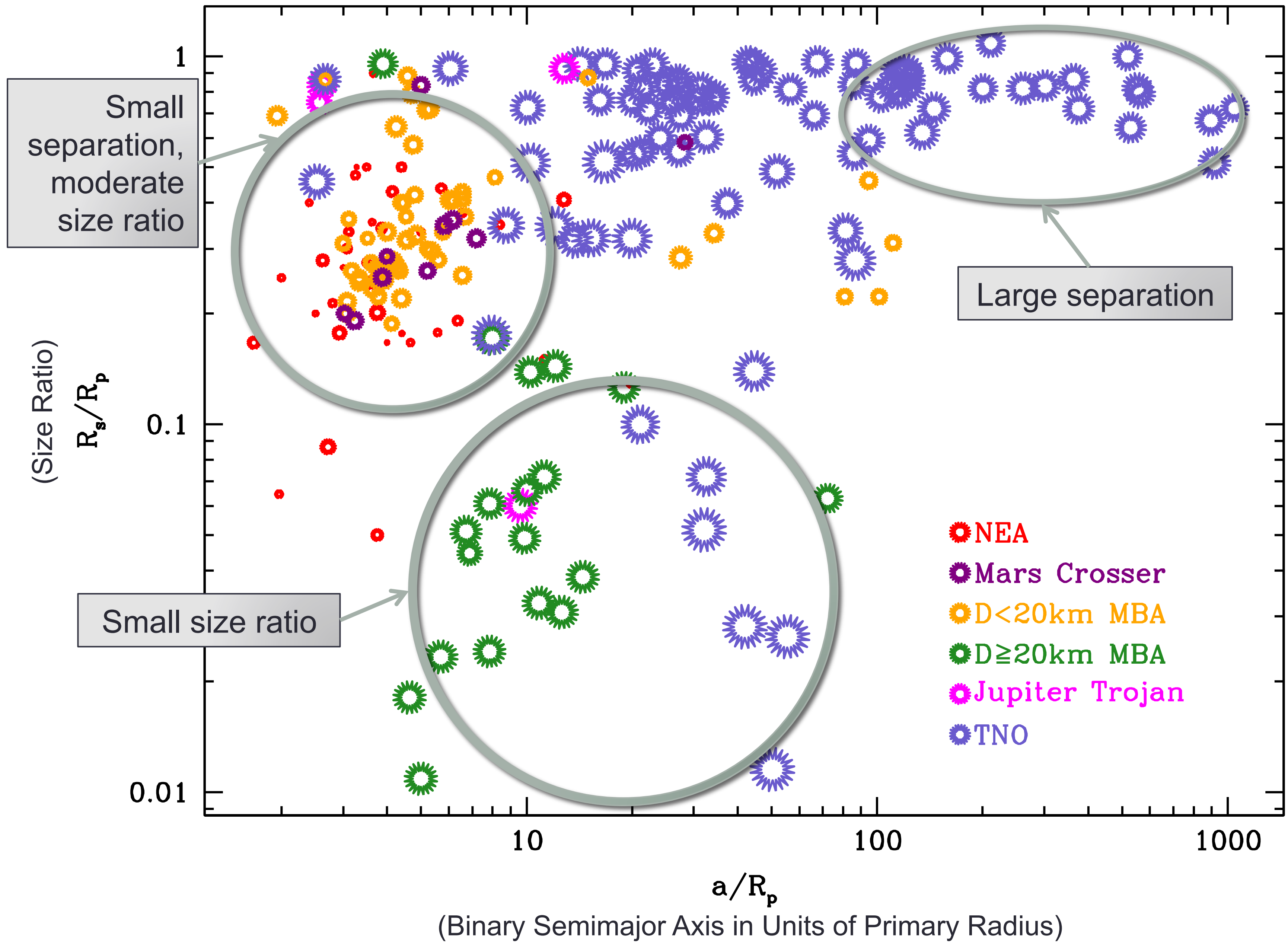
- 39 near-Earth asteroids (2 with two satellites each);
- 14 Mars-crossing asteroids;
- 76 main-belt asteroids (5 with two satellites each);
- 4 Jupiter Trojan asteroids; and
- 76 trans-Neptunian objects* (2 with two satellites, 1 with four satellites).

*Includes Pluto, Haumea, & Eris (dwarf planets).

Data from Johnston's Archive:

http://www.johnstonsarchive.net/astro/asteroidmoons.html

SSSB Companions: Separation *vs.* Size Ratio



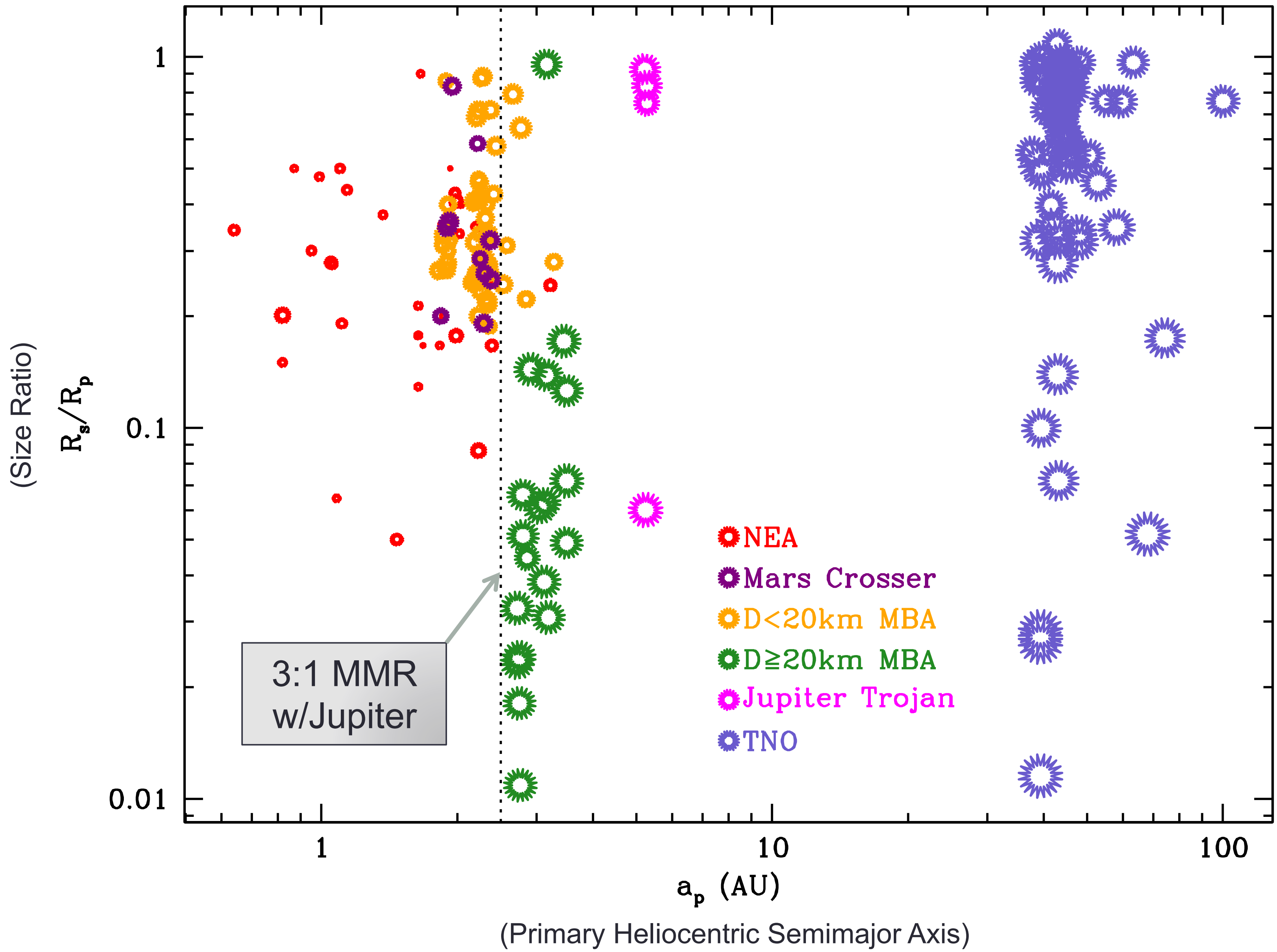
Properties of Binaries (out of date)

Primaries tend to be small, spherical, fast-rotating…

- 37 binary NEAs.
  - Mean size ratios ~4.2:1 (median 3.5).
  - Mean separations ~4.5 $R_{primary}$ (median 4).
  - ~15% of NEAs are binaries.
- 53 binary MBAs (incl. 2 Trojans).
  - Mean size ratio ~ 9.8:1 (4.4).
  - Mean separation ~ 24 $R_{primary}$ (11).
  - ~2–3% of MBAs are binaries.
- 49 binary TNOs (incl. Pluto/Charon).
  - Size ratios ~ 2:1–1:1.
  - Separations ~ 10–1000 $R_{primary}$.

Definitely more among <u>small</u> MBAs…

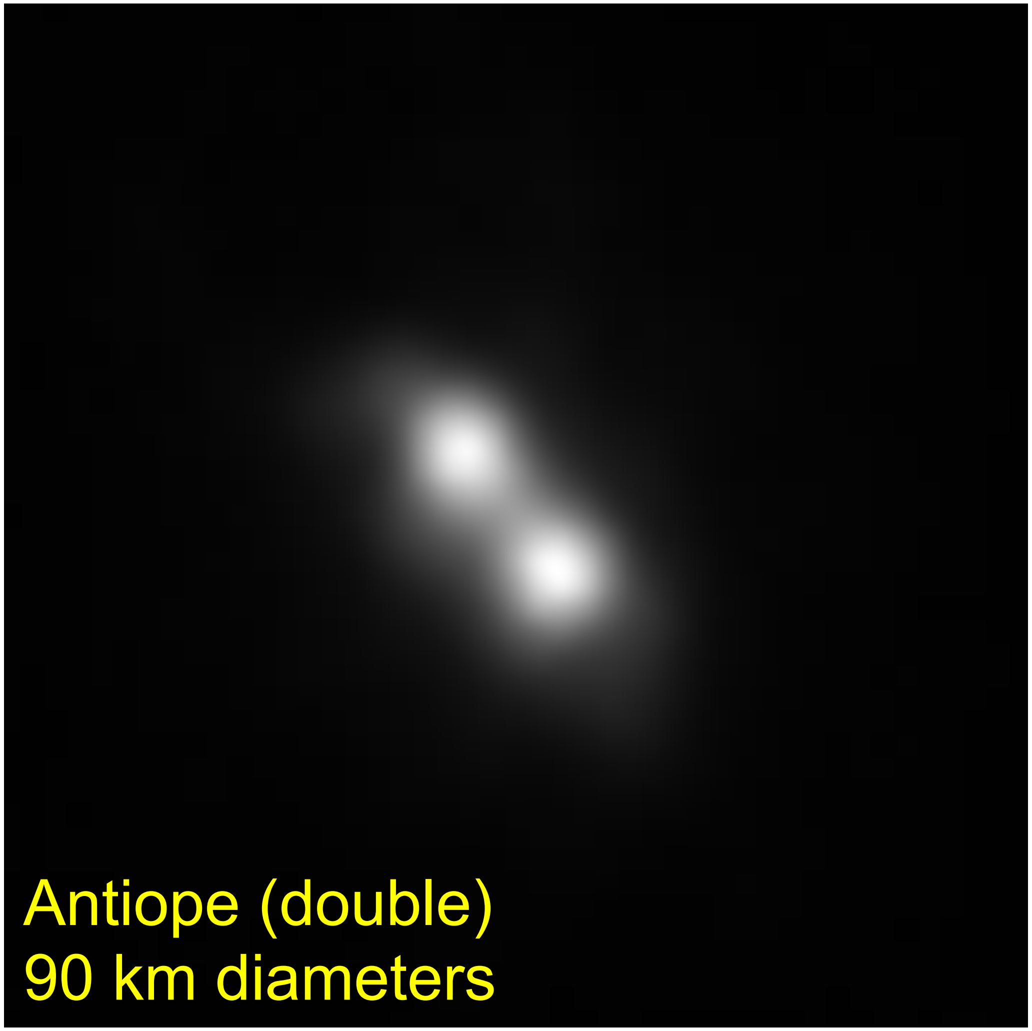
Heliocentric Distance *vs.* Size Ratio



Small Solar System Bodies with Satellites

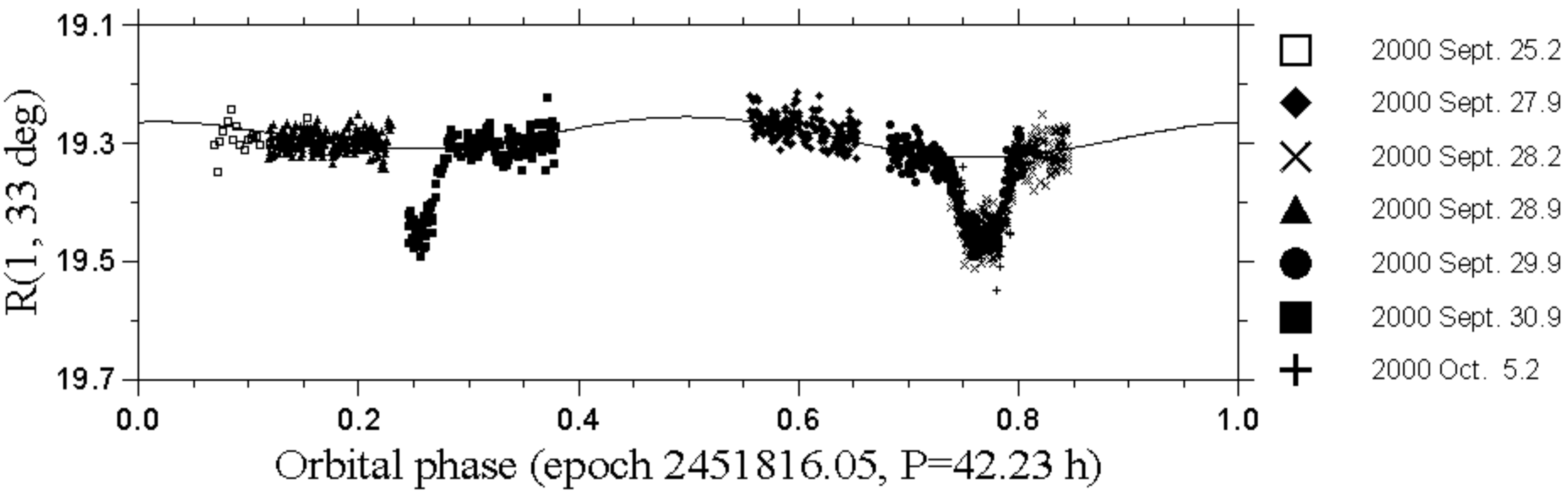
- Over 200 binary or multiple asteroids (and other small solar system bodies) discovered.
- Detection techniques include:
  - Direct imaging (33 ground, 64 space, mostly MBAs & TNOs).
  - Photometric lightcurves (86, mostly MBAs).
  - Radar (25, all NEAs, from Arecibo and Goldstone).

Detection by Direct Imaging

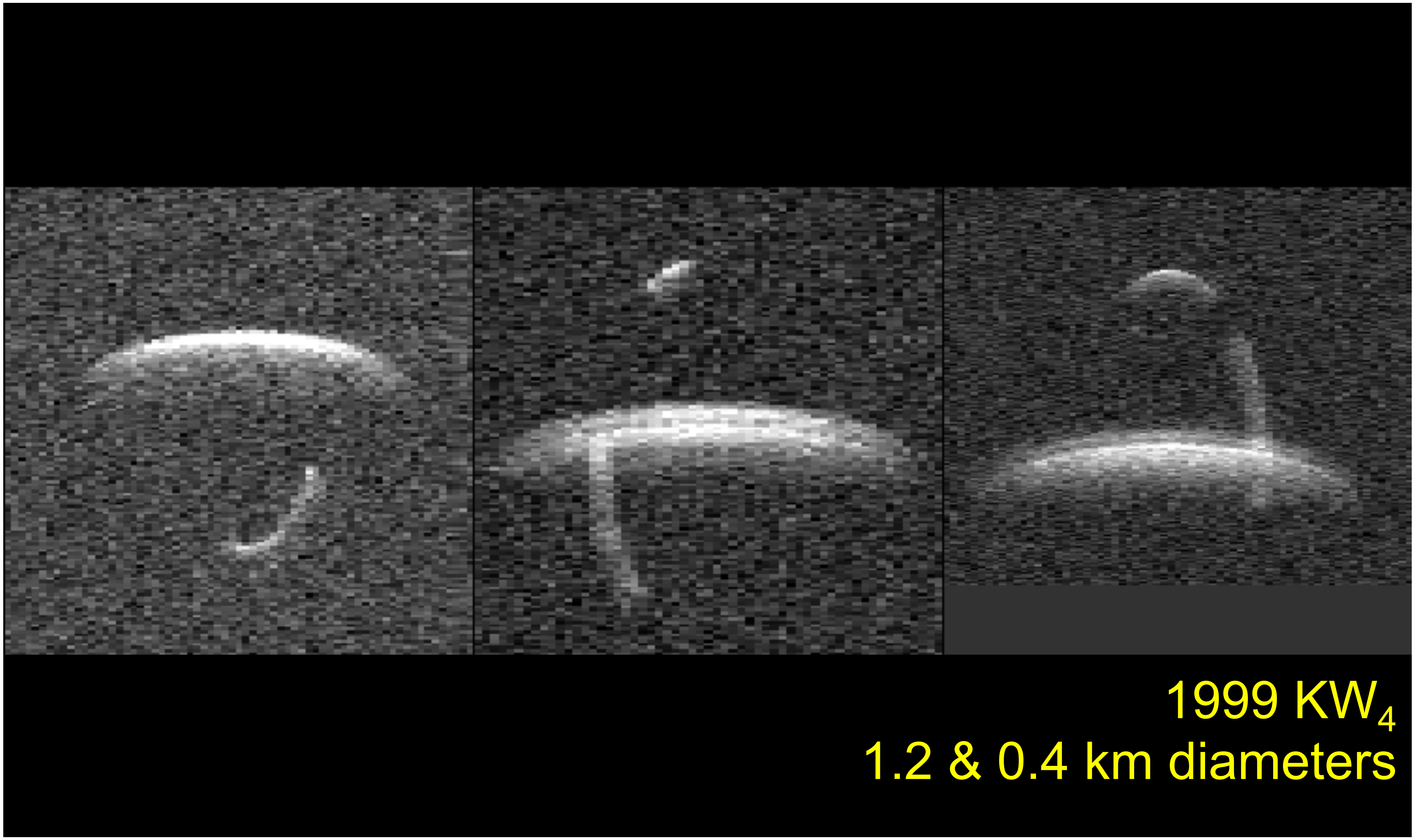


Detection by Lightcurves

2000 DP107
0.8 & 0.3 km diameters



Detection by Radar



Origins of Binaries

1. Direct capture during “close” approach.
   - Variants invoked to explain “primordial” Kuiper Belt binaries.
2. Capture of ejecta following impact.
   - Orbital reaccumulation of debris.
   - Most important in Main Belt.
3. Rotational disruption.
   - Includes tidal disruption and (mostly) YORP effect.
   - Applies to near-Earth and small, inner Main Belt asteroids.

Binary Trans-Neptunian Objects

- May be primordial.
  - Size ratios near unity and large separations energetically prohibited by collisions in present-day Kuiper Belt.
  - No large, dense bodies for tidal disruption to be efficient; YORP far too weak.
- Several models:
  - Weidenschilling (2002): two bodies collide and merge near third body ➔ capture.
  - Goldreich et al. (2002): dynamical friction on two larger bodies ➔ mutual capture.
  - Funato et al. (2004): binary exchange reactions.
  - Nesvorný et al. (2010): direct collapse from spinning cloud.

Binary Main Belt Asteroids

- Capture of collisional ejecta most likely (outer belt).
  - High collision frequency.
  - No bodies capable of tidal disruption.
  - Encounter speeds too fast for capture.
- Collisions that make asteroid families also make satellites.
  - Gravitational reaccumulation explains family size and velocity distributions.
- YORP effect plays a role in (at least) the inner Main Belt.

Numerical Methods

- Impacts: carry out fragmentation phase using hydrocode, then reaccumulation phase using *N*-body code.
  - Hydrocode: solve equations of fluid mechanics with a crack propagation model and suitable equation of state—short timescale. E.g., Lagrangian SPH or Eulerian grid codes with AMR.
  - *N*-body code: solve gravity equations of motion with low-speed collision constraint—long timescale. E.g., PKDGRAV (parallel hierarchical tree code with explicit treatment of particle collisions).
- Rotational disruption: model encounter or thermal spin-up using *N*-body code.
  - Construct "rubble pile" of self-gravitating particles in contact.
  - Outcome determined by angle of friction and any cohesion among components. E.g., monodisperse spheres ➔ friction angle ~40°.

Example Code Details

SPH Code

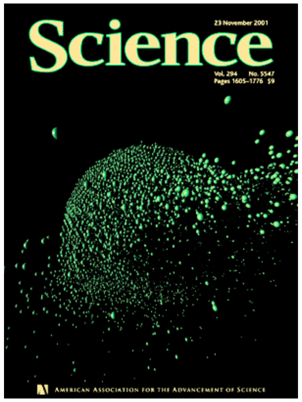
- Lagrangian method.
- Tillotson equation of state for basalt.
- von Mises yielding relation → plasticity.
- Nucleation of incipient flaws → brittle failure.

N-body Code

- Parallel hierarchical tree code (PKDGRAV).
- Second-order leapfrog integrator.
- Collision detection by fast neighbor search.
- Perfect sticking.

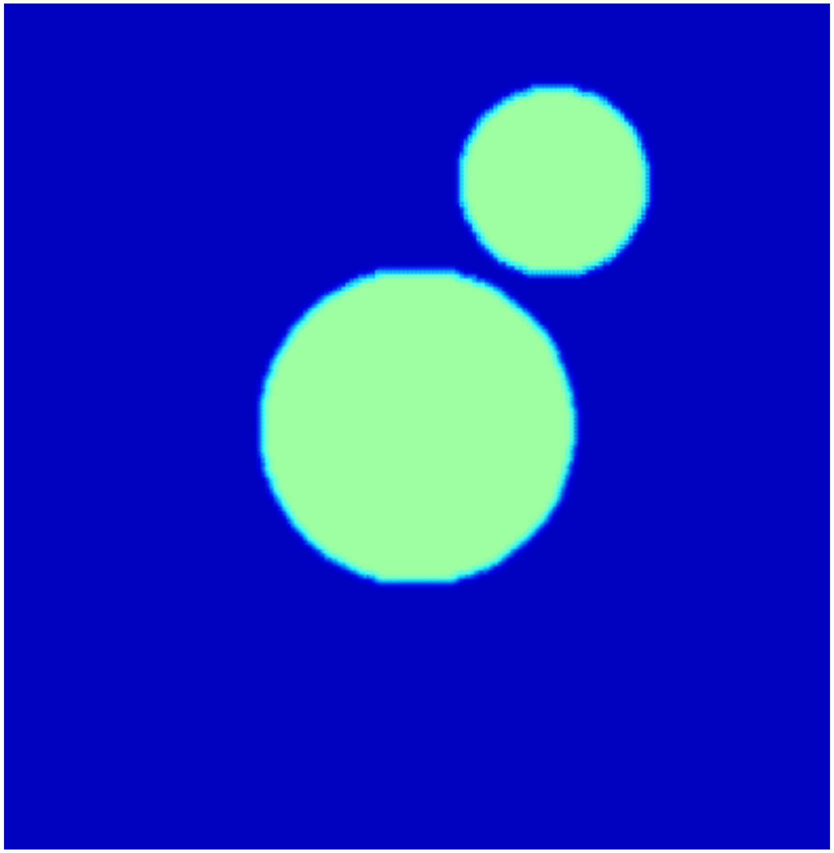
Impacts Make Families and Satellites

- Asteroids reaccumulate debris after big impacts.
- Explains velocity and size distributions of asteroid families, and satellites.
- Implies rubble structures.



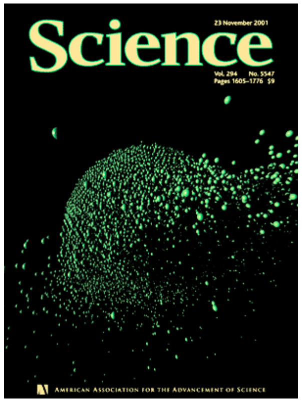
Michel et al. 2001, 2003

SPH Fragmentation Phase



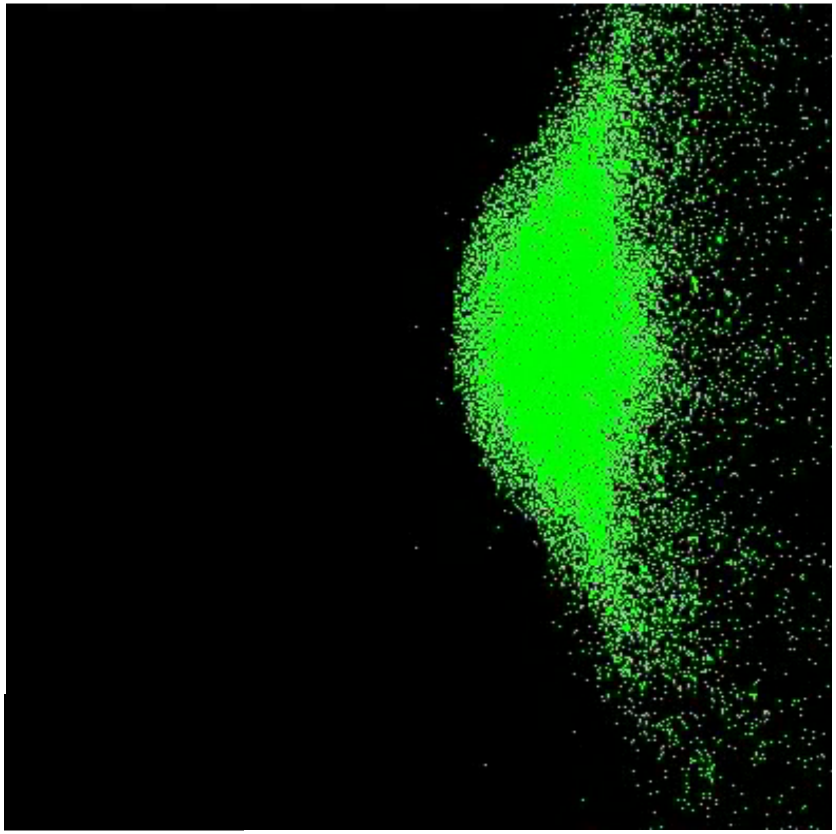
Impacts Make Families and Satellites

- Asteroids reaccumulate debris after big impacts.
- Explains velocity and size distributions of asteroid families, and satellites.
- Implies rubble structures.

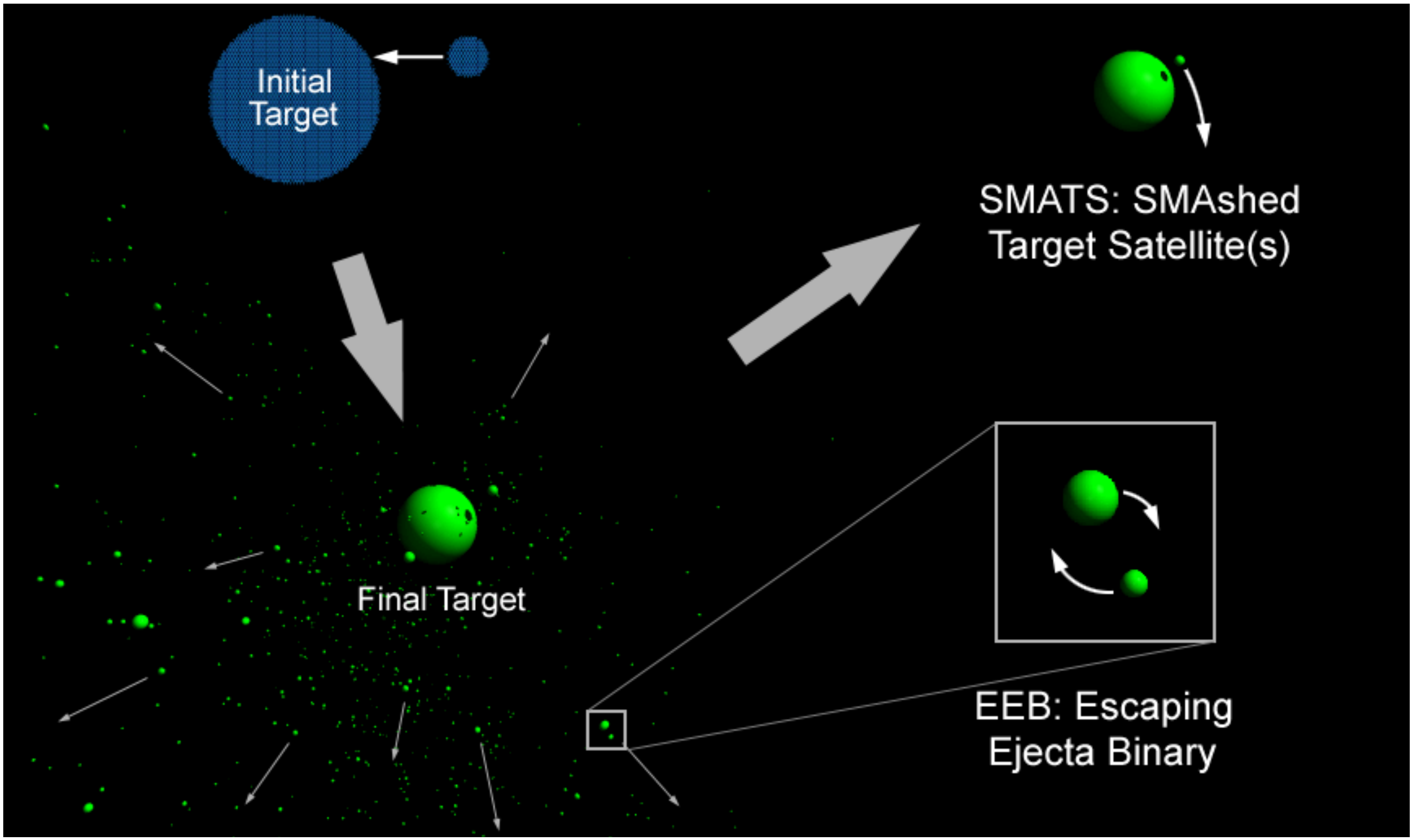


Michel et al. 2001, 2003

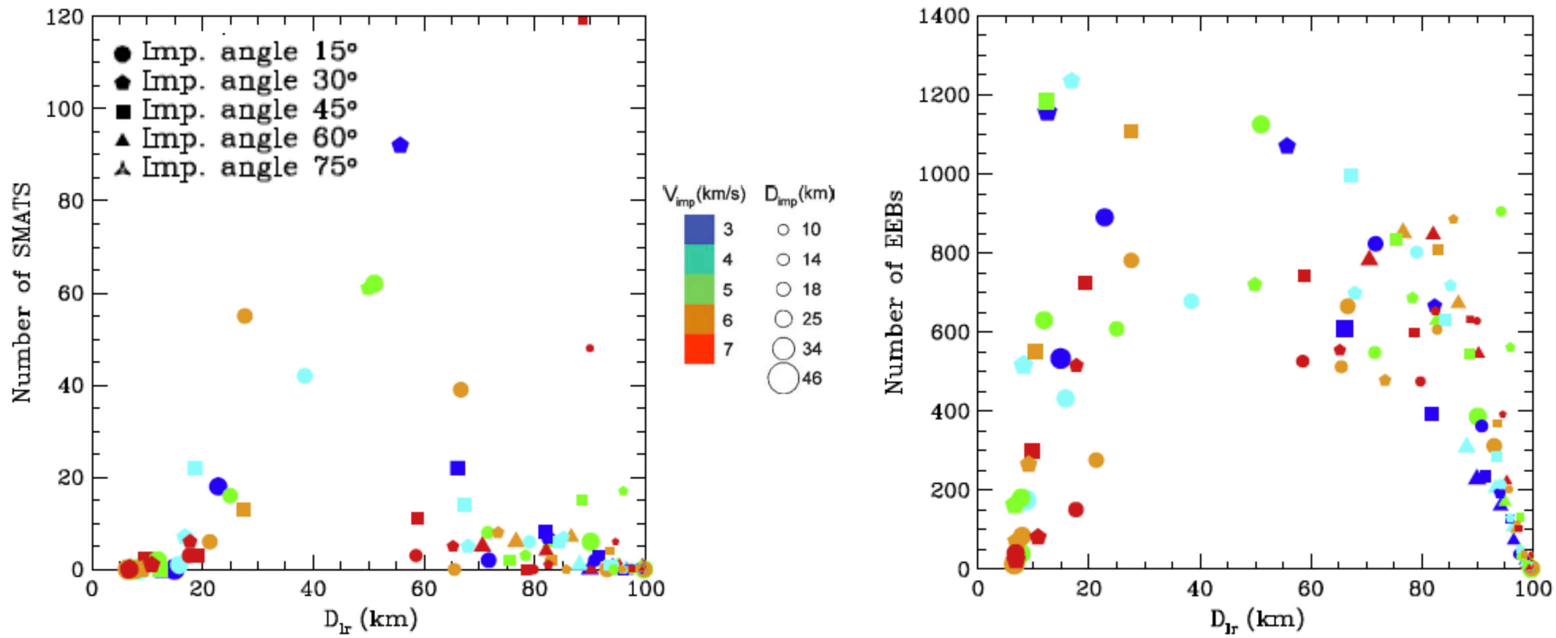
PKDGRAV Reaccumulation Phase



Ejecta Capture (Durda et al. 2004)



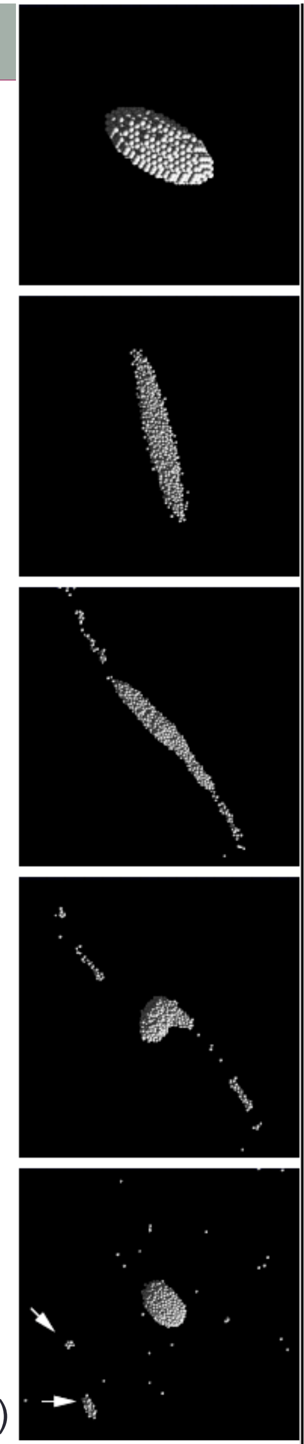
Lots of Impact-generated Binaries…



- Good match to size ratio but no shape/spin info (reaccreting particles become larger spheres).
- Benavidez et al. (2012): rubble pile targets give similar results, but fewer overall binaries compared to monolithic.

Binary NEAs

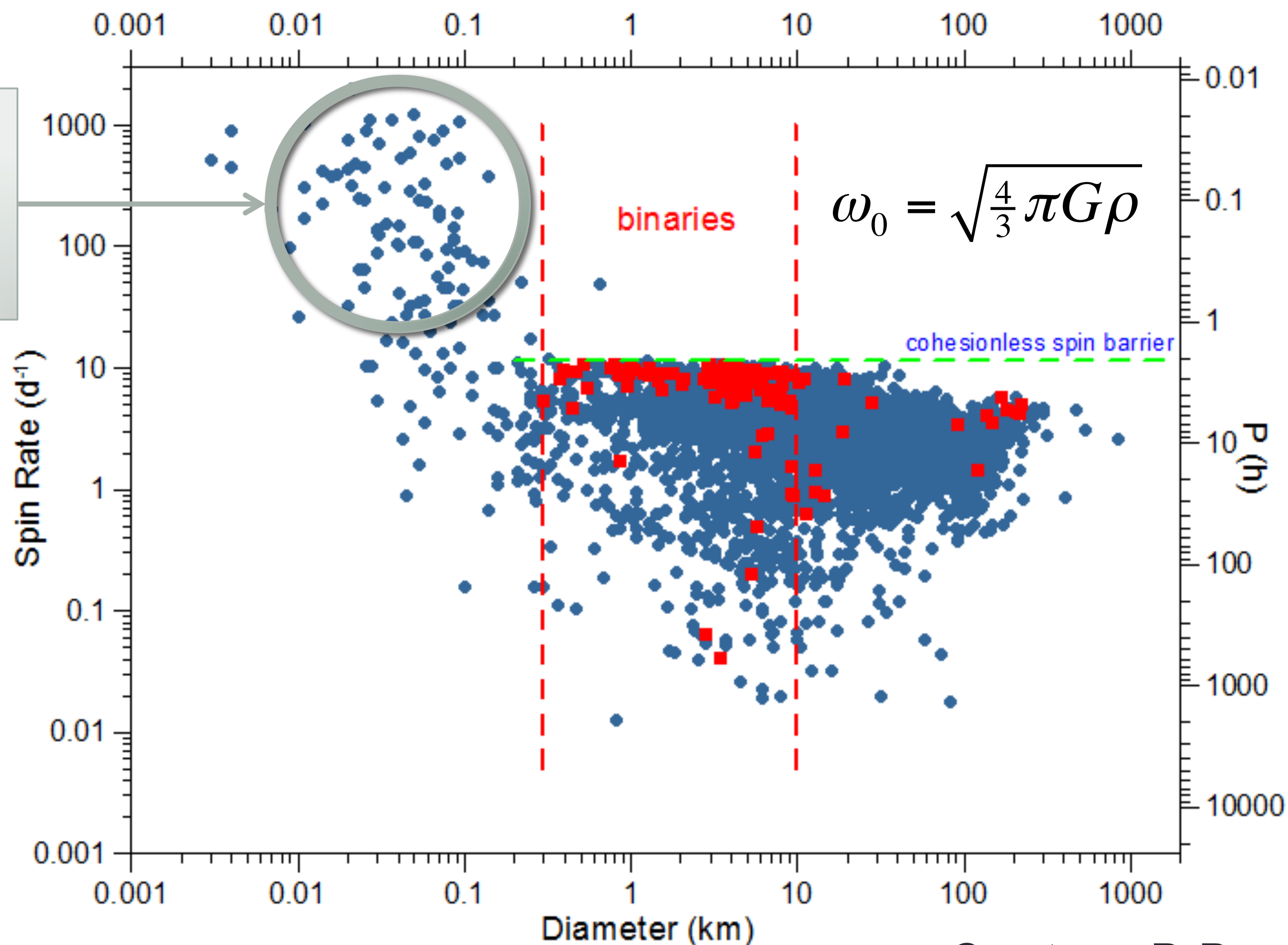
- Binary NEAs are common (~15%), and have properties suggestive of rotational disruption.
  - Rapidly rotating primaries (2–4 h periods).
  - Small (20–50% R_p) secondaries.
  - Close secondaries (a = 2–5 R_p).
  - Primary lightcurves have low amplitude < 0.3 mags.
  - Satellites have low eccentricity.
- Tidal disruption and YORP spin-up are favored for making such binaries.
  - Need *fragile* progenitor: low strength/cohesion.



Richardson et al. (1998)

Evidence for Fragile Asteroids

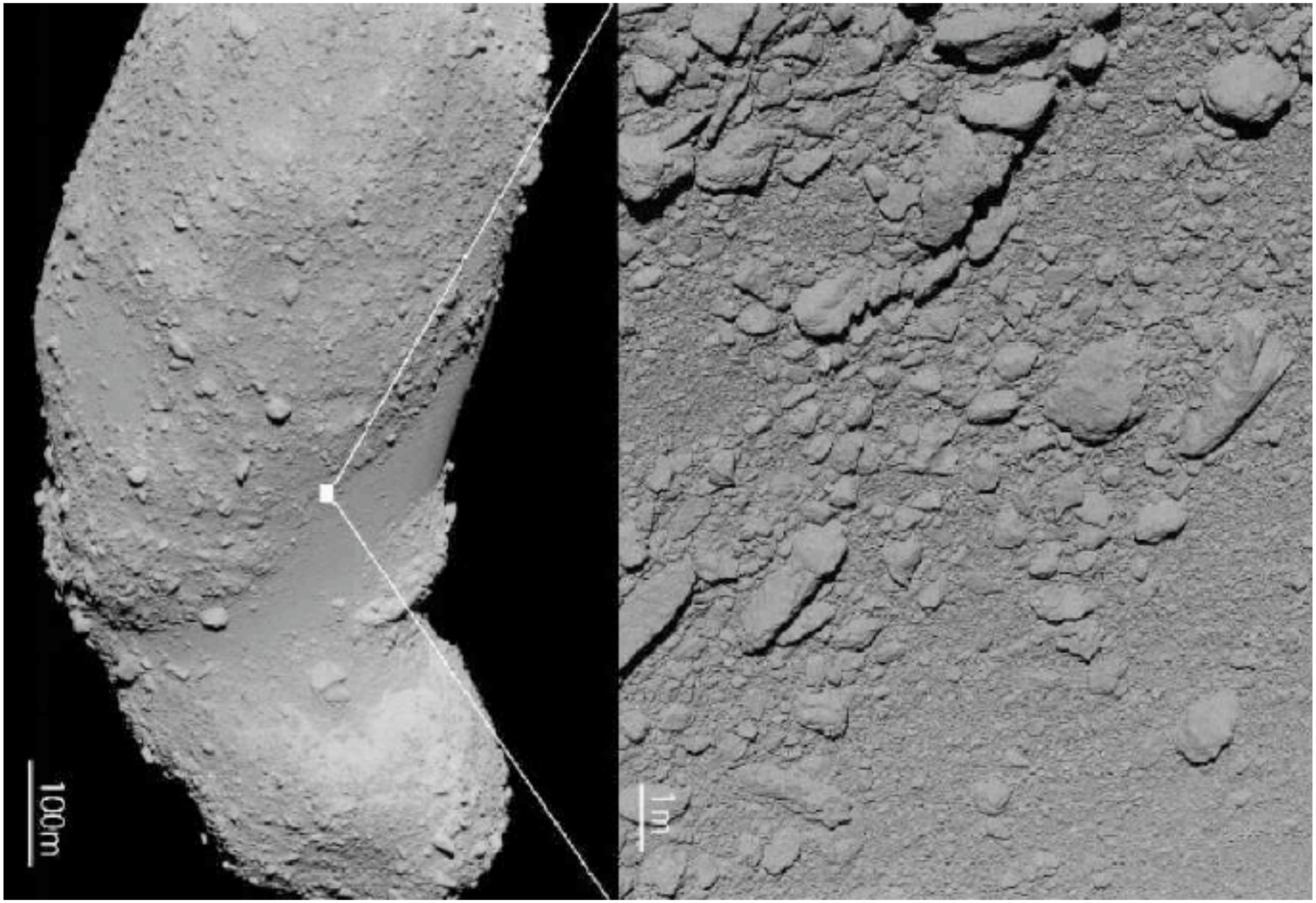
Need cohesion: rocks or powder?



Courtesy: P. Pravec

Evidence for Fragile Asteroids

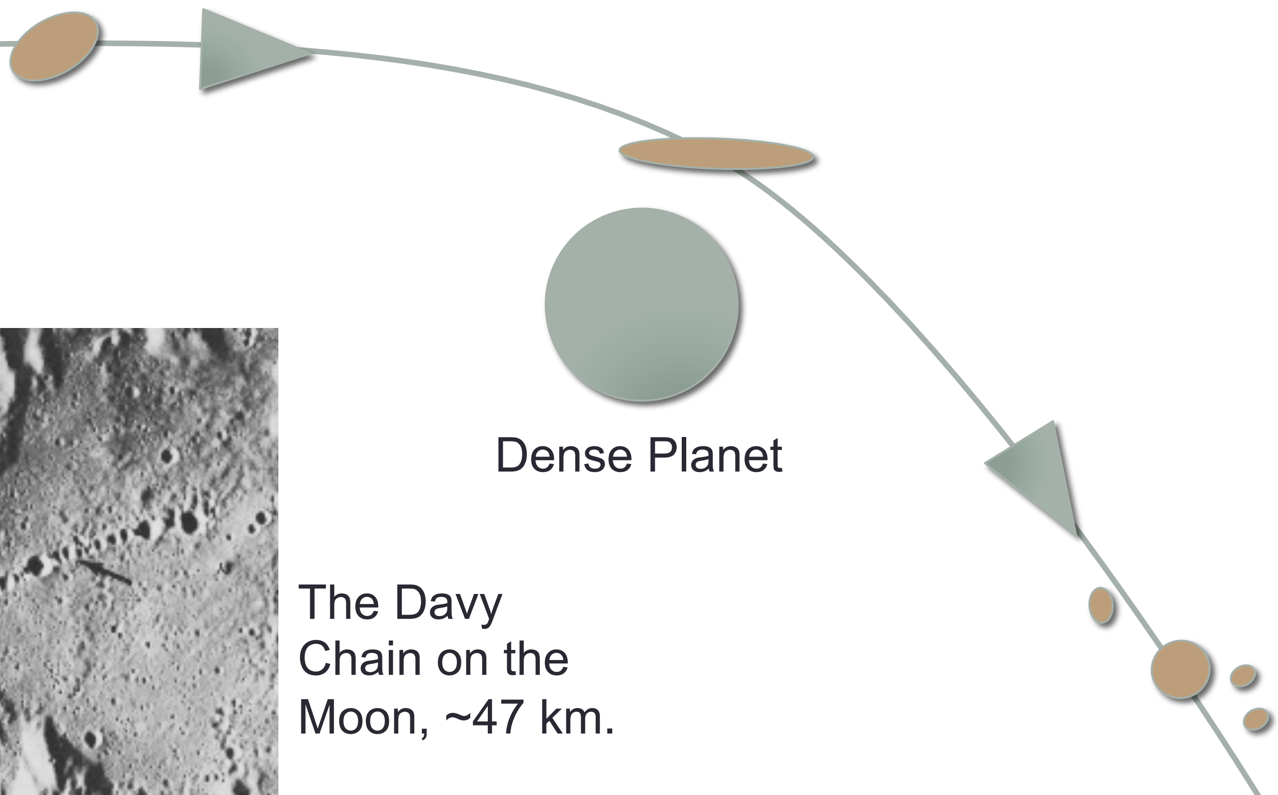
Itokawa: A Gravitational Aggregate



Courtesy: JAXA

Tidal Disruption of Asteroids

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



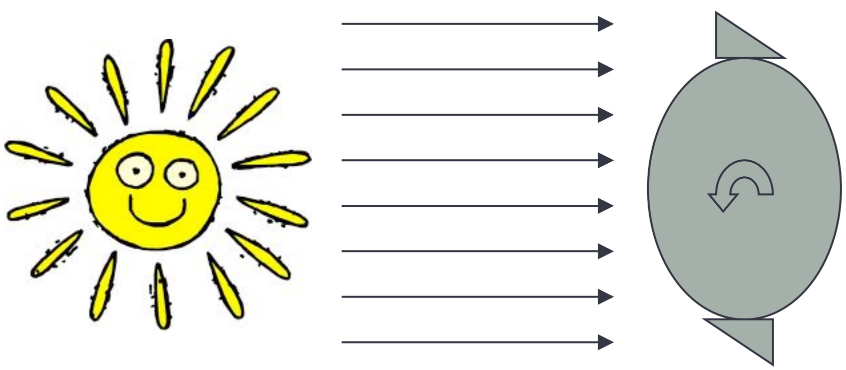
The Davy Chain on the Moon, ~47 km.

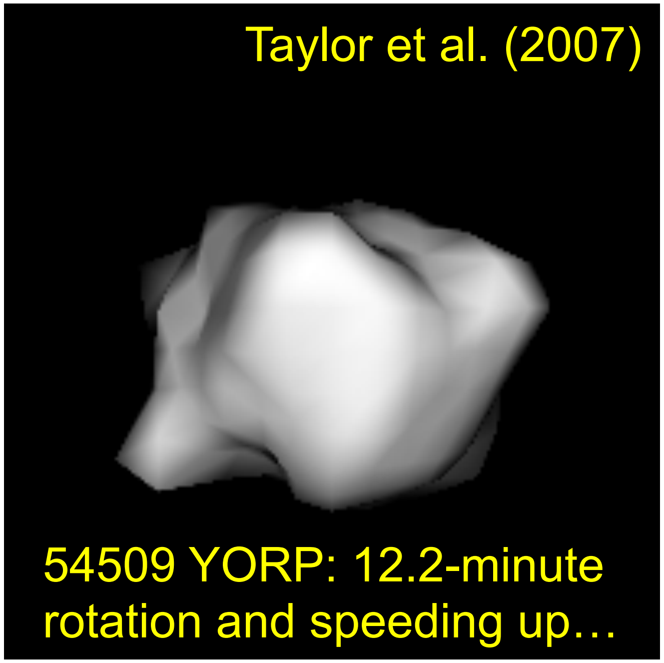
Binary Asteroids from Tidal Disruption

- Tidal disruption of NEAs makes ~1–2% binary population (Walsh & Richardson 2008).
  - Binaries are high-*e*, primaries elongated.
  - Subsequent encounters often disrupt binary system.
- Need a different mechanism to explain the 15% binary NEA population—YORP!

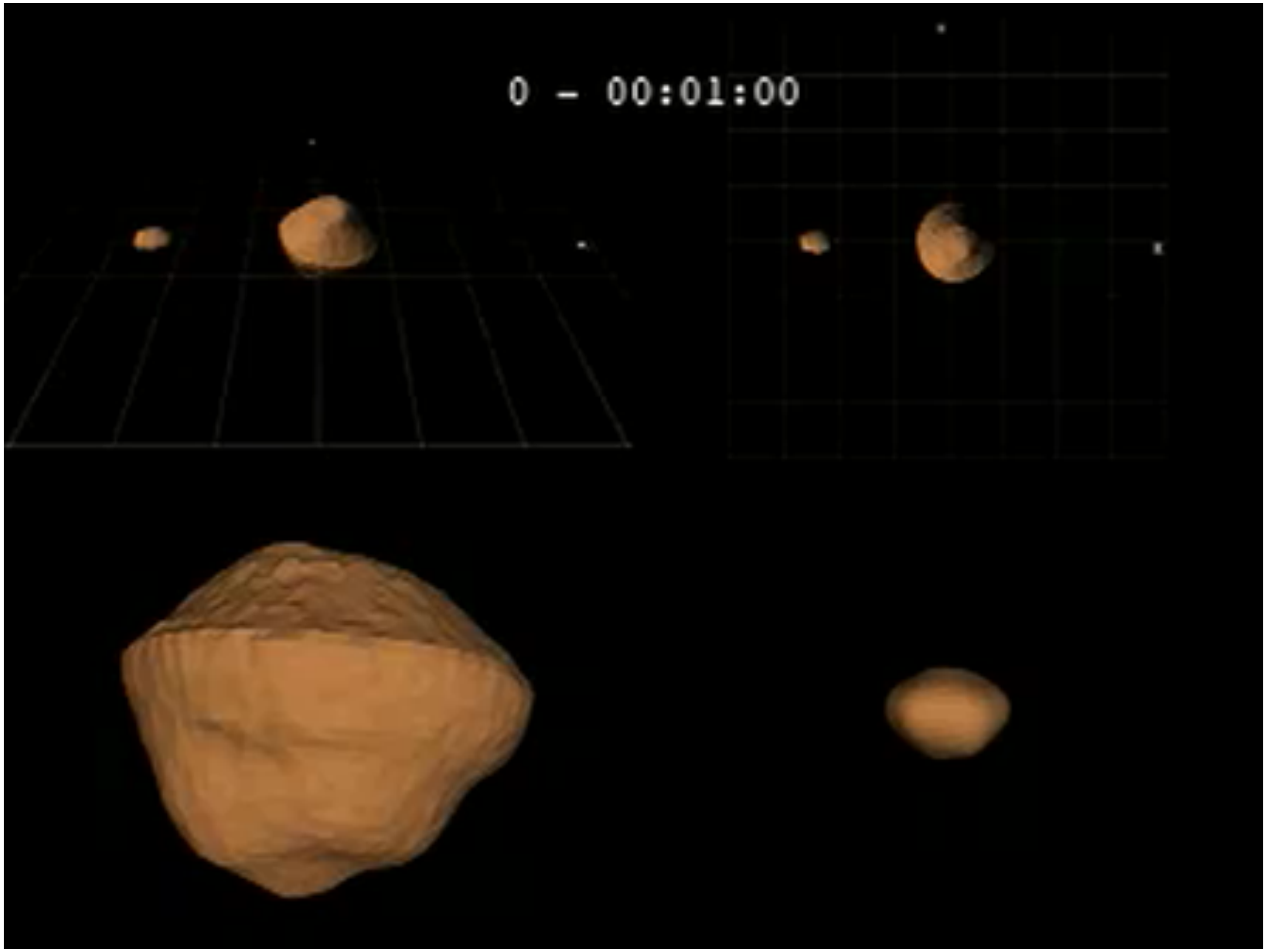
Spin-up by YORP

- Spin state change due to reflectance/re-emission of absorbed solar radiation.
- Depends on body size and distance from Sun.
- Spin-up timescale ~Myr.



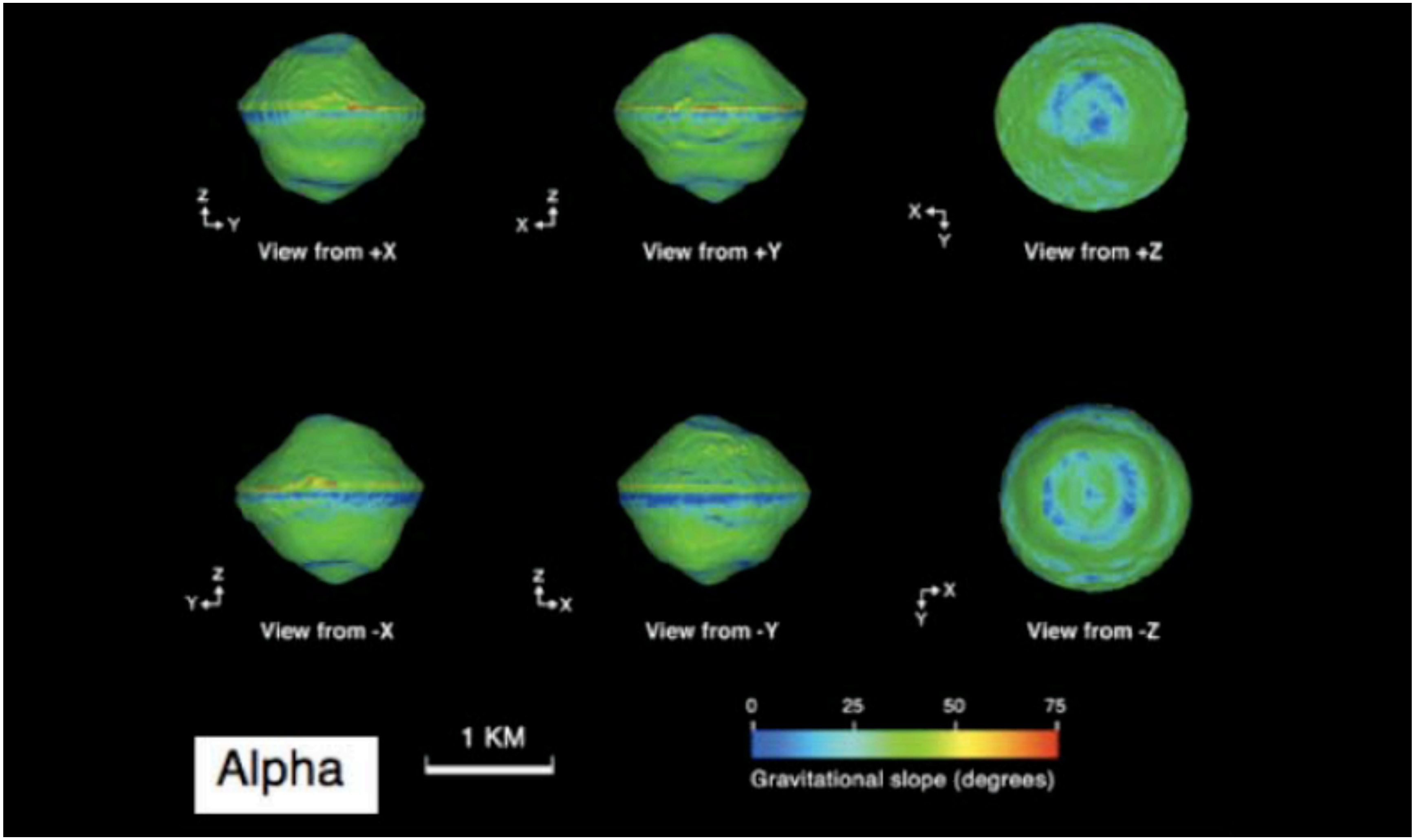


1999 KW_4: Made by YORP?



Ostro et al. (2005)

1999 KW_4: Made by YORP?

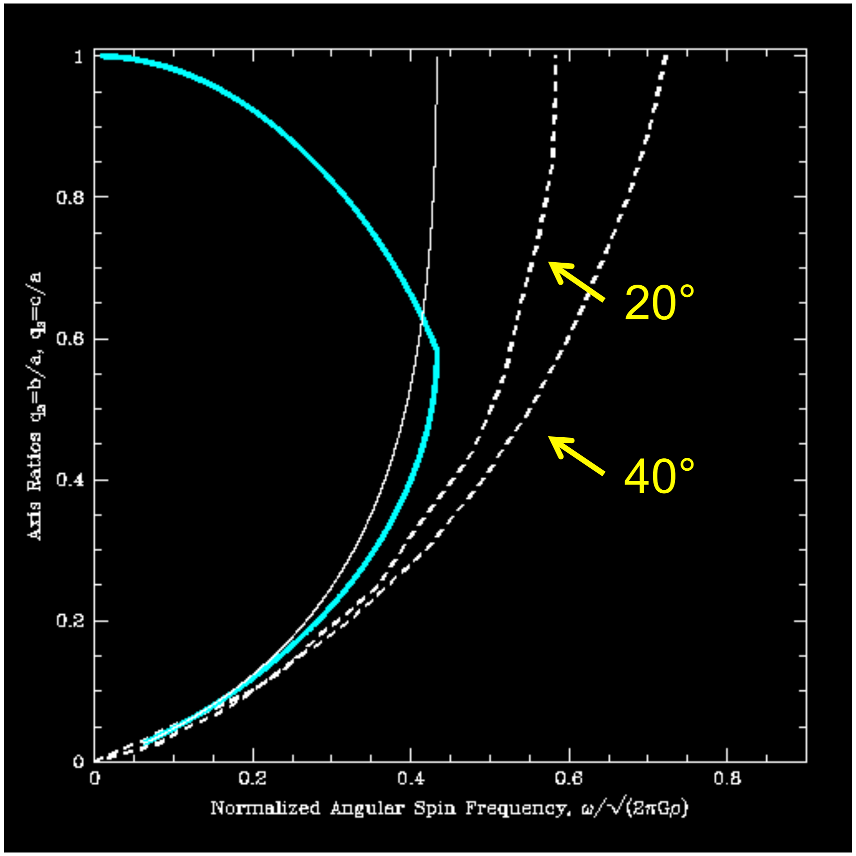


Simulating KW_4

- Start with arbitrary-shape rubble pile, with angle of friction determined by (spherical) particle size distribution.
  - Cases: fluid-like; 20° angle of friction (sand); 40° (typical rubble?).
- Largest body spun up periodically to mimic YORP effect, with pauses in between to allow system to equilibrate.
- Only gravity and collisions modeled; no cohesion.
- Energy loss parameterized by coefficients of restitution.
  - *Some* dissipation required to ensure secondary accretion.

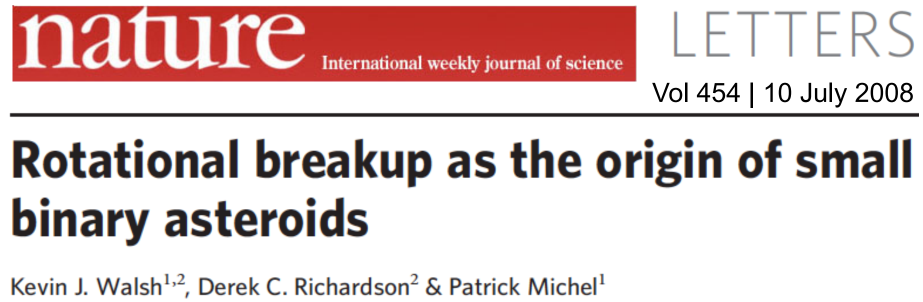
Determining the Angle of Friction

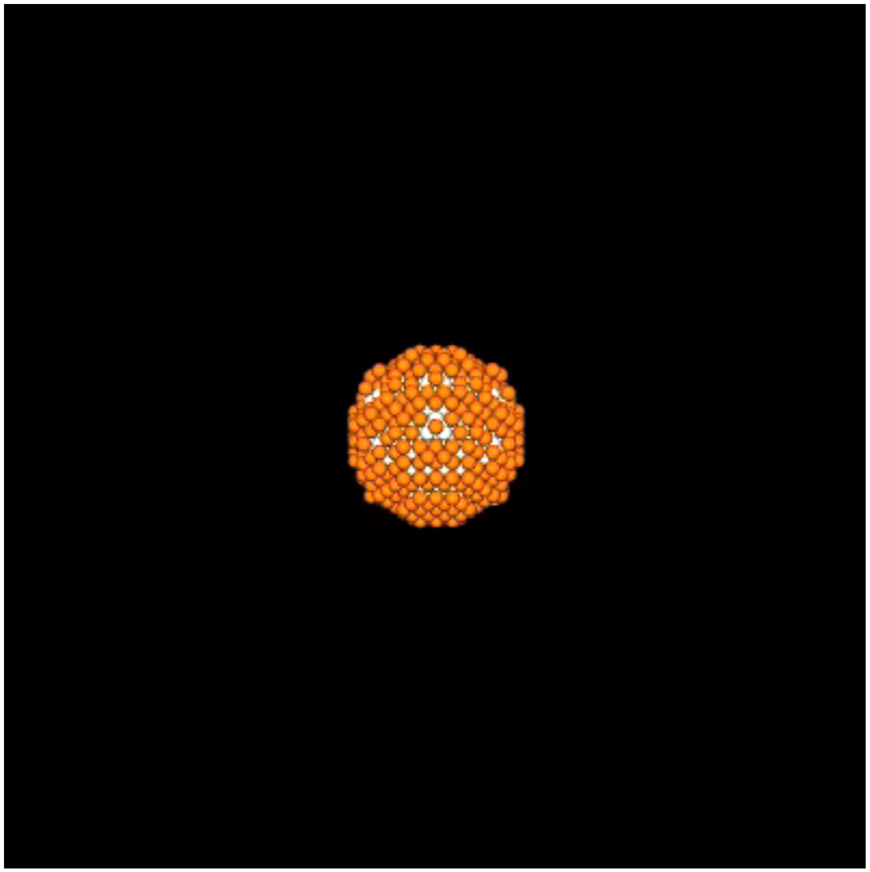
- The angle of friction of a material can be inferred by the equilibrium shape it adopts under rapid spin.
- Fluids follow the Jacobi/ Maclaurin curves exactly.
- Granular materials can occupy any region to the left of the limiting curves.



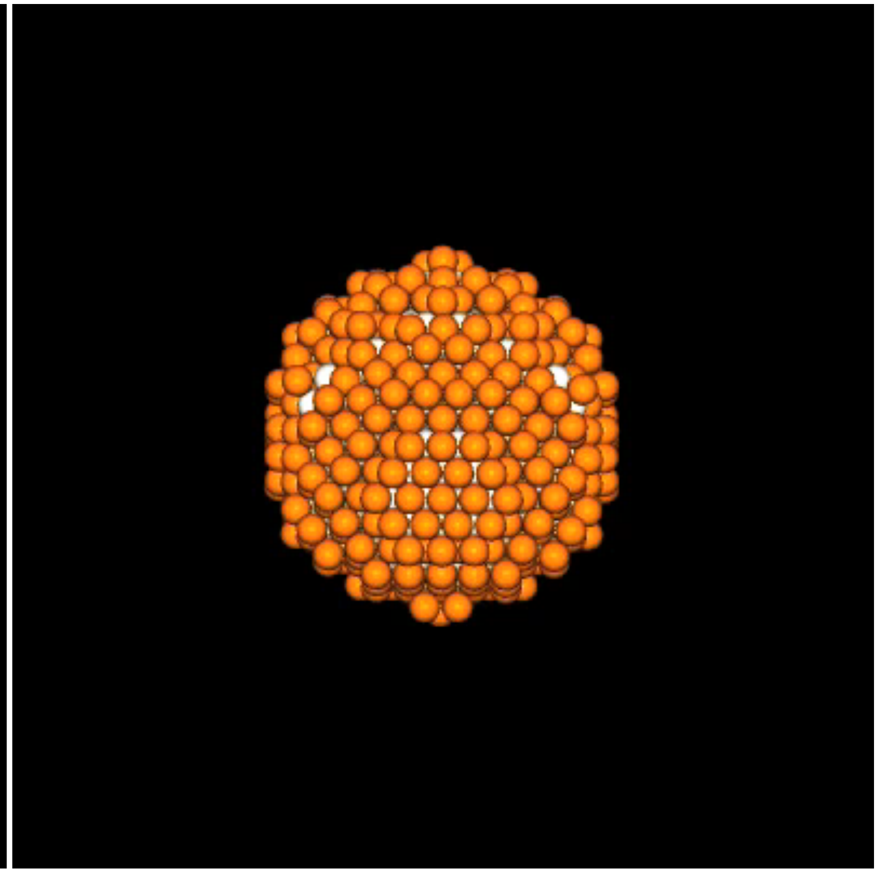
Simulating KW_4

(High angle of friction case)

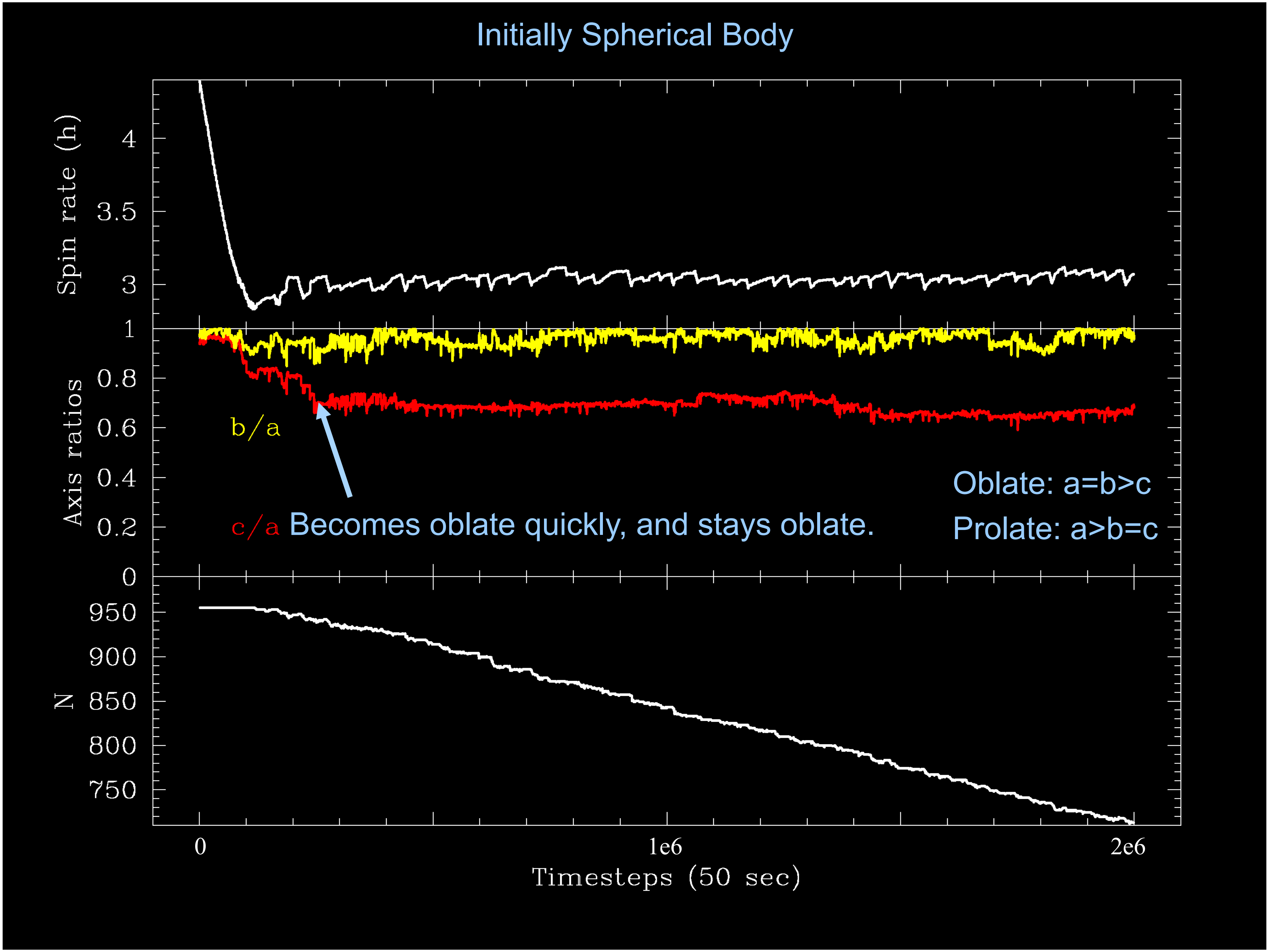




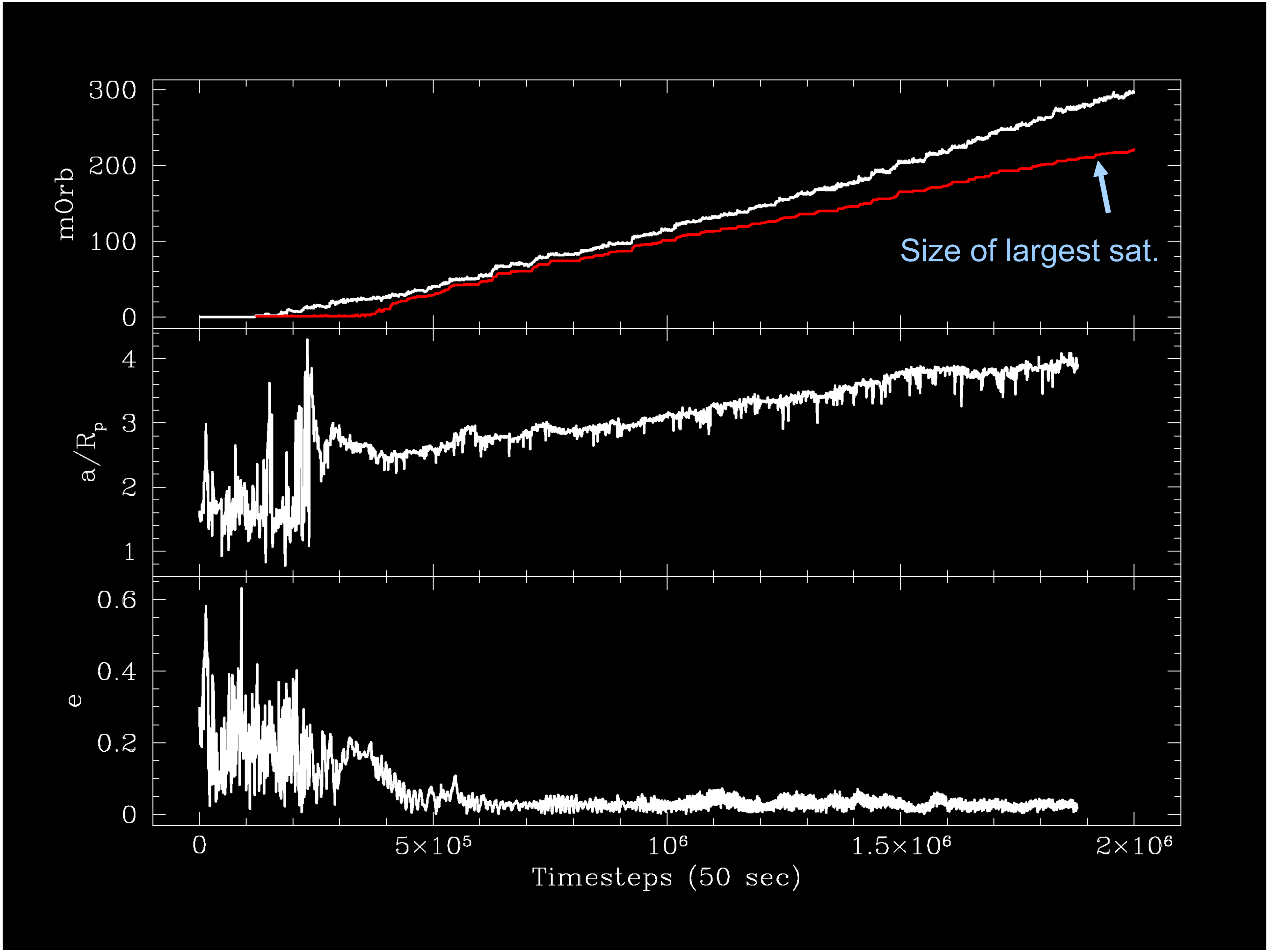
Top view



Side view

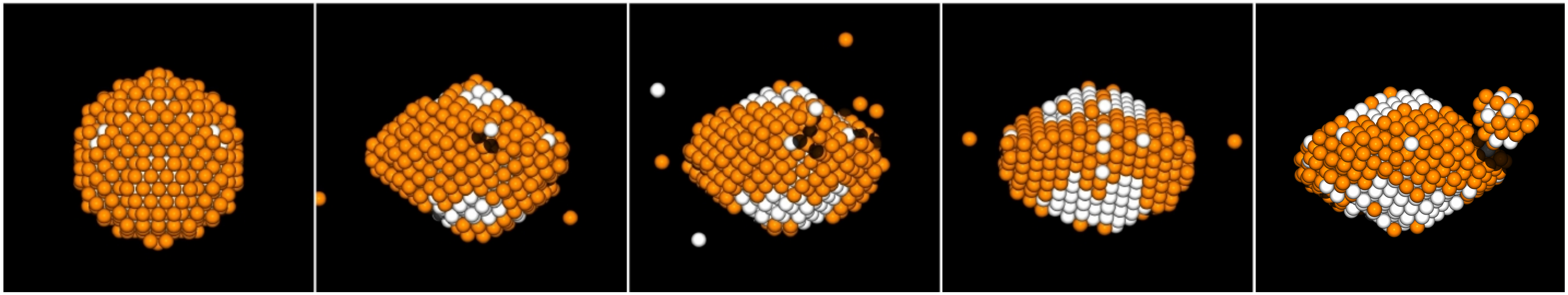


Initially Spherical Body
Spin rate (h)
4
3.5
3
1
0.8
0.6
0.4
0.2
0
Axis ratios
b/a
c/a
Becomes oblate quickly, and stays oblate.
Oblate: a=b>c
Prolate: a>b=c
950
900
850
800
750
N
0
1e6
2e6
Timesteps (50 sec)


300
200
100
0
mOrb
Size of largest sat.
4
3
2
1
a/R_p
0.6
0.4
0.2
0
e
0
5×10^5
10^6
1.5×10^6
2×10^6
Timesteps (50 sec)

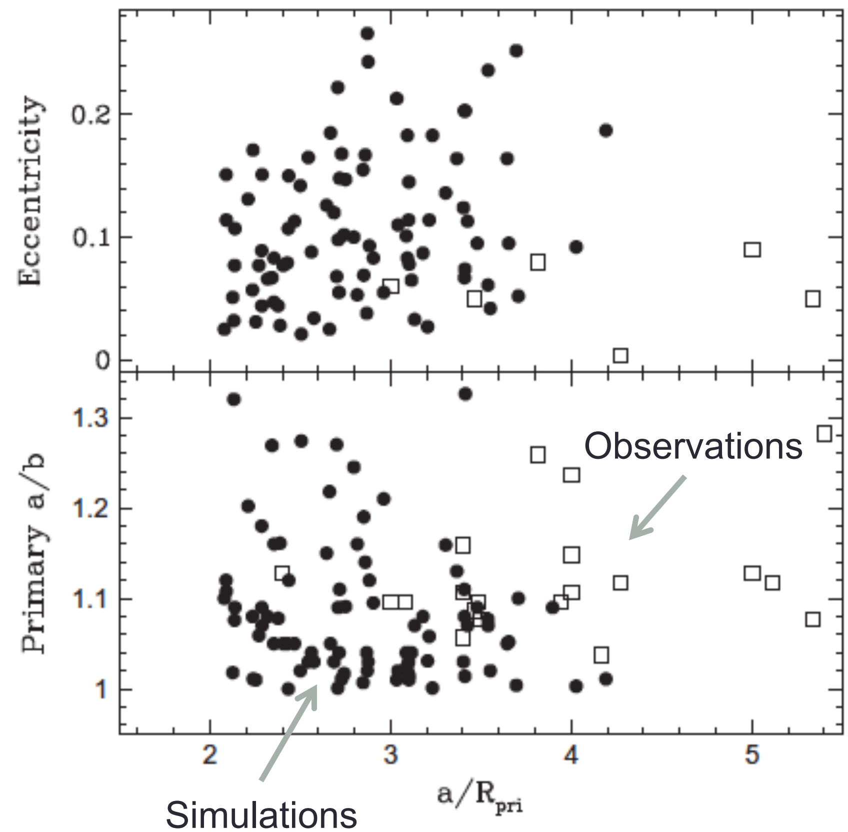
Simulating KW_4 (High angle of friction case)

- As body spins up, it bulges at equator (becomes oblate), mass moves down from the poles, and a satellite forms from material shed from ridge in equatorial plane.
- Satellite has low eccentricity and gradually moves away.
- Explains shape, fast rotation rate, and KW_4 satellite.



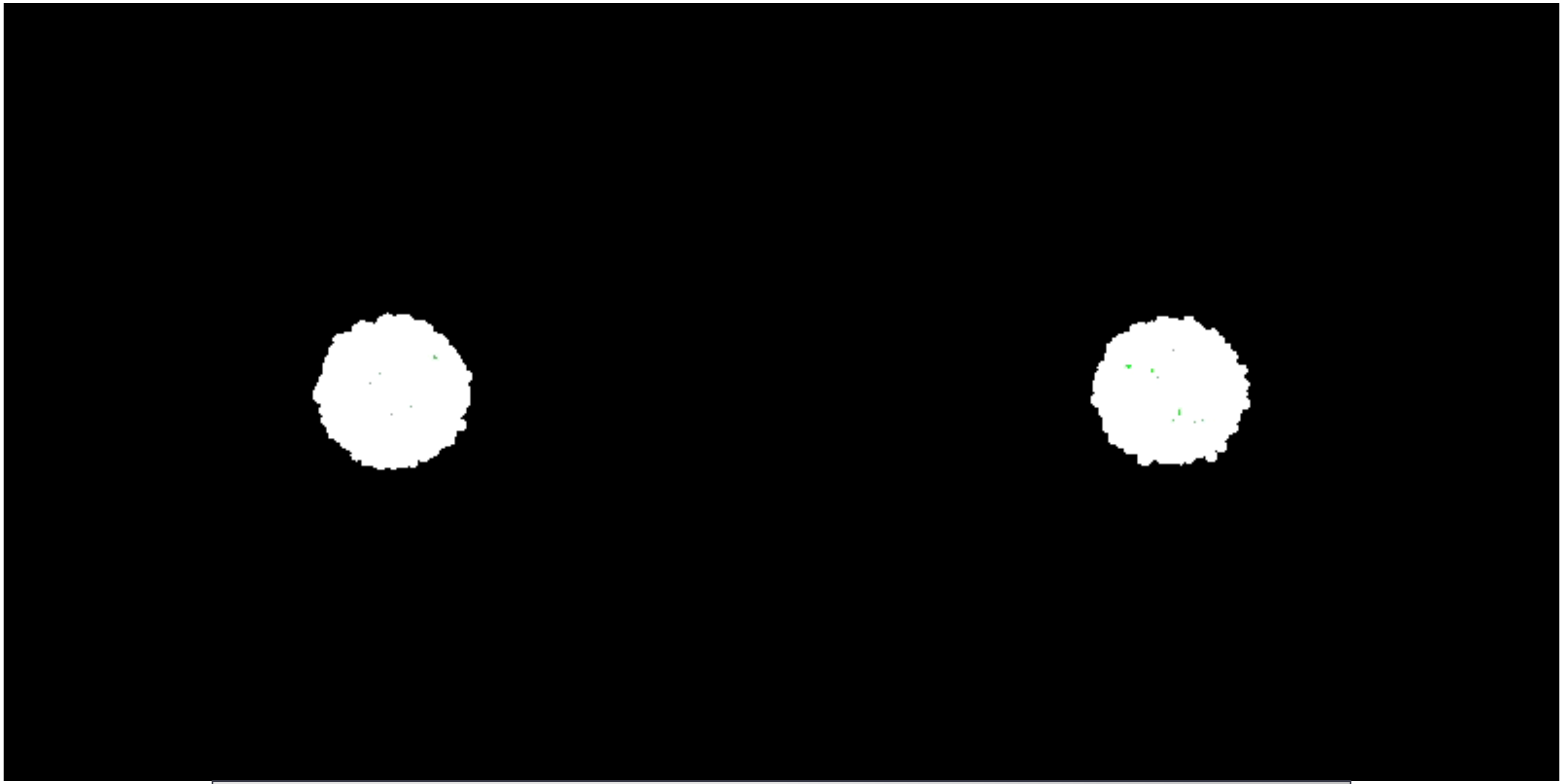
General Properties from Simulations

- YORP binaries enabled by:
  - High angle of friction (e.g., monodisperse spheres, or large rigid core).
  - Moderate dissipation.
- Resulting systems have:
  - Oblate primaries.
  - Low-*e* secondaries.
  - Moderate size ratios.



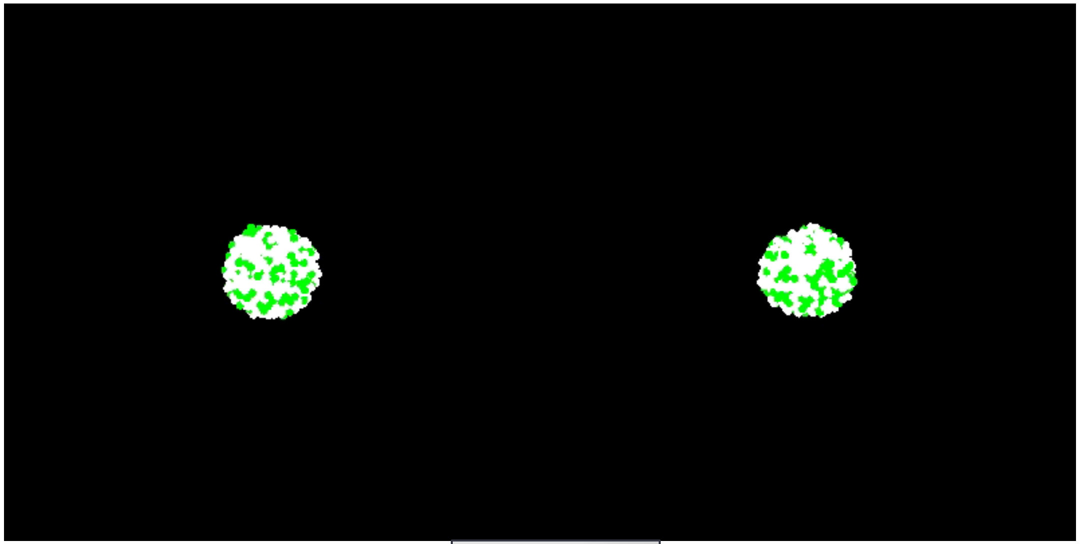
Walsh et al. (2012)

Core Model: Binary Formation



Rigid core (green) surrounded by smaller particles (white)

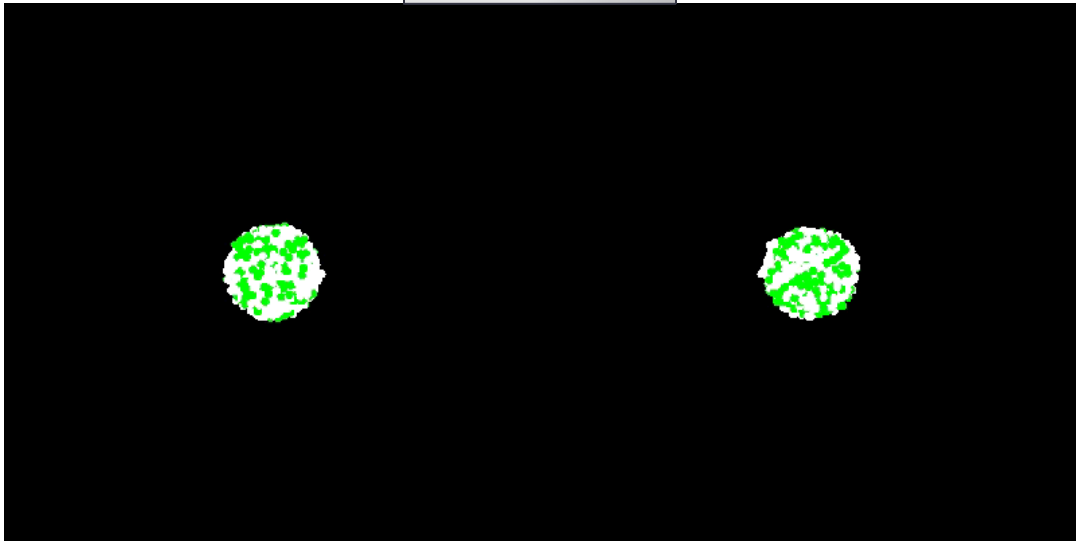
Marginal Binary Formation



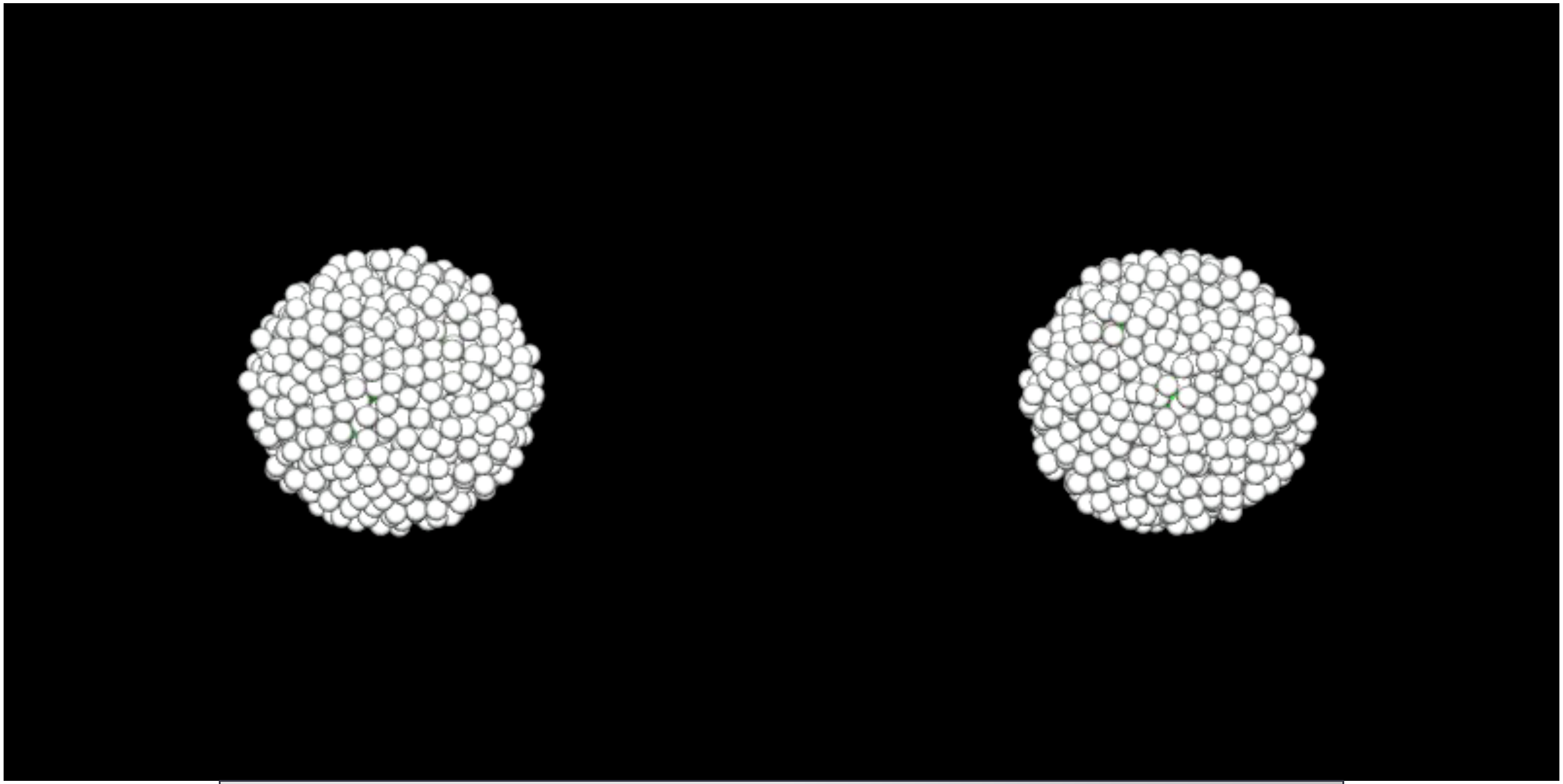
Binary

Two randomized cases with friction angle ~20°.

No binary

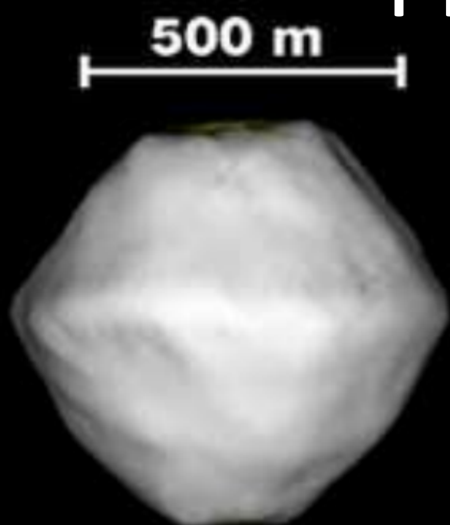


No Binary: Small Core of Larger Particles

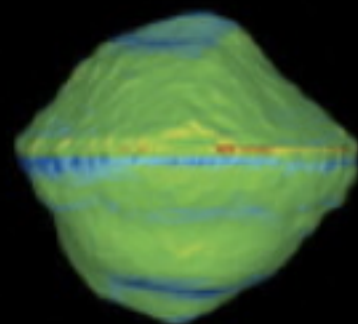


When the core is too small, the body becomes too elongated and binary formation is suppressed.

Prevalence of Top Shapes

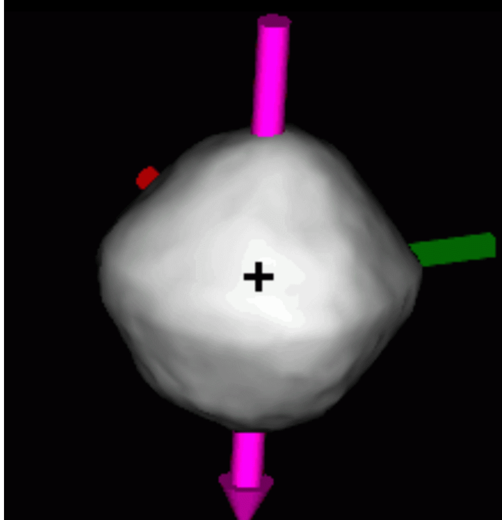


Triple Asteroid 1994 CC
Brosovic et al. 2011

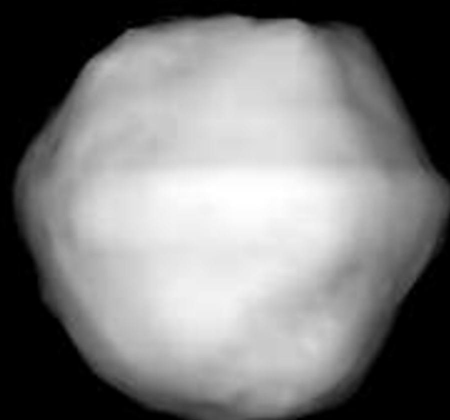


Binary Asteroid 1999 KW4
Ostro et al. 2005

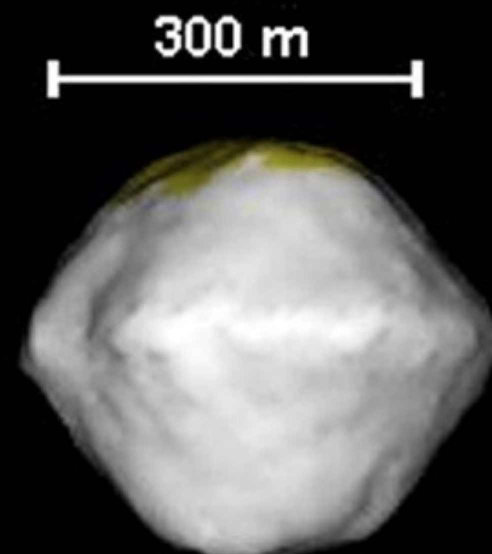
Triple Asteroid 1996 SN263
Becker et al. 2008



Single Asteroid RQ36
Howell et al. 2008, ACM

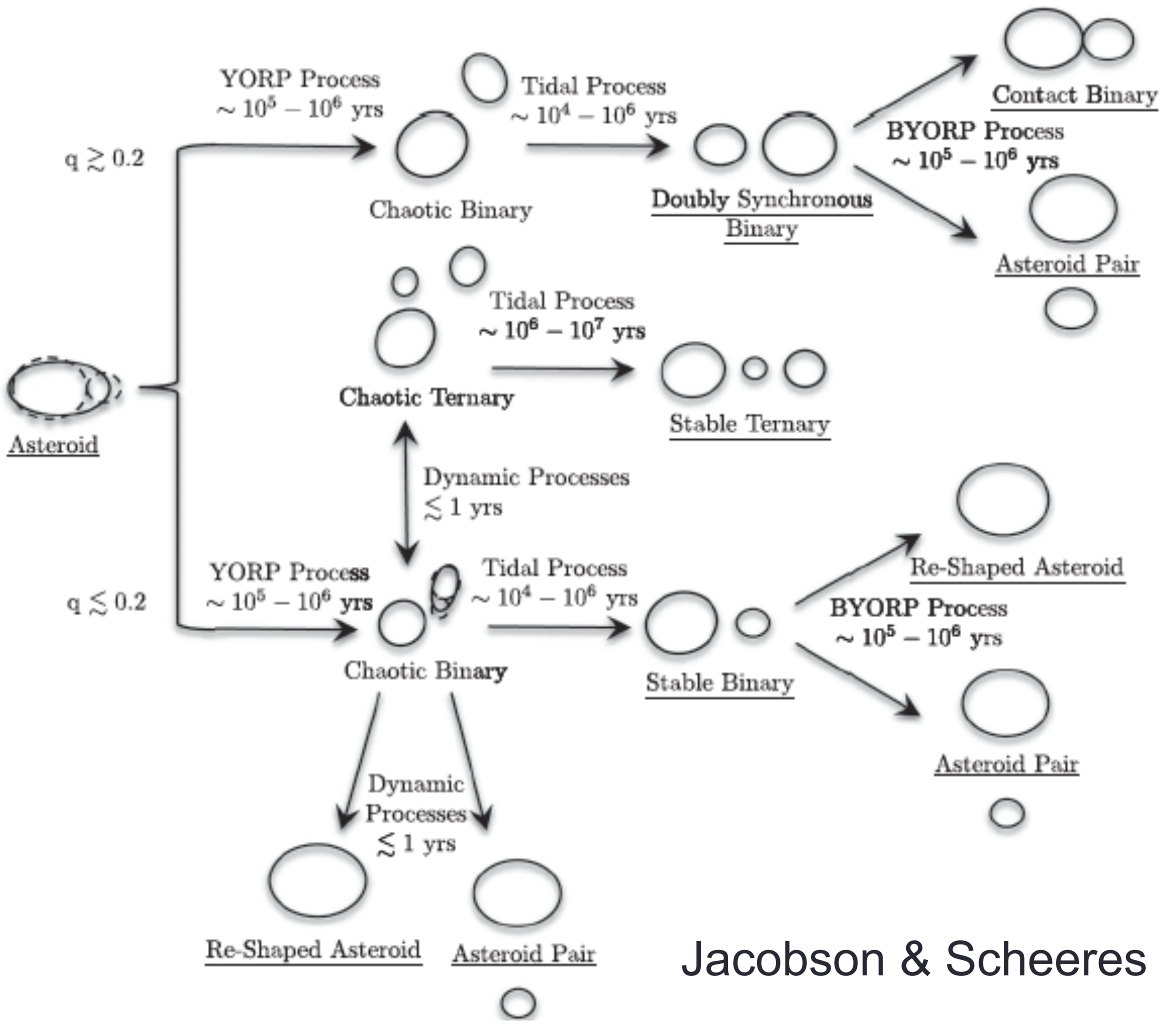


Binary Asteroid 2004 DC
Taylor et al. 2008, ACM



Single Asteroid 2008 EV5
Busch et al. 2011

Fission Model (Conceptual)



Jacobson & Scheeres (2011)

Two Different Models

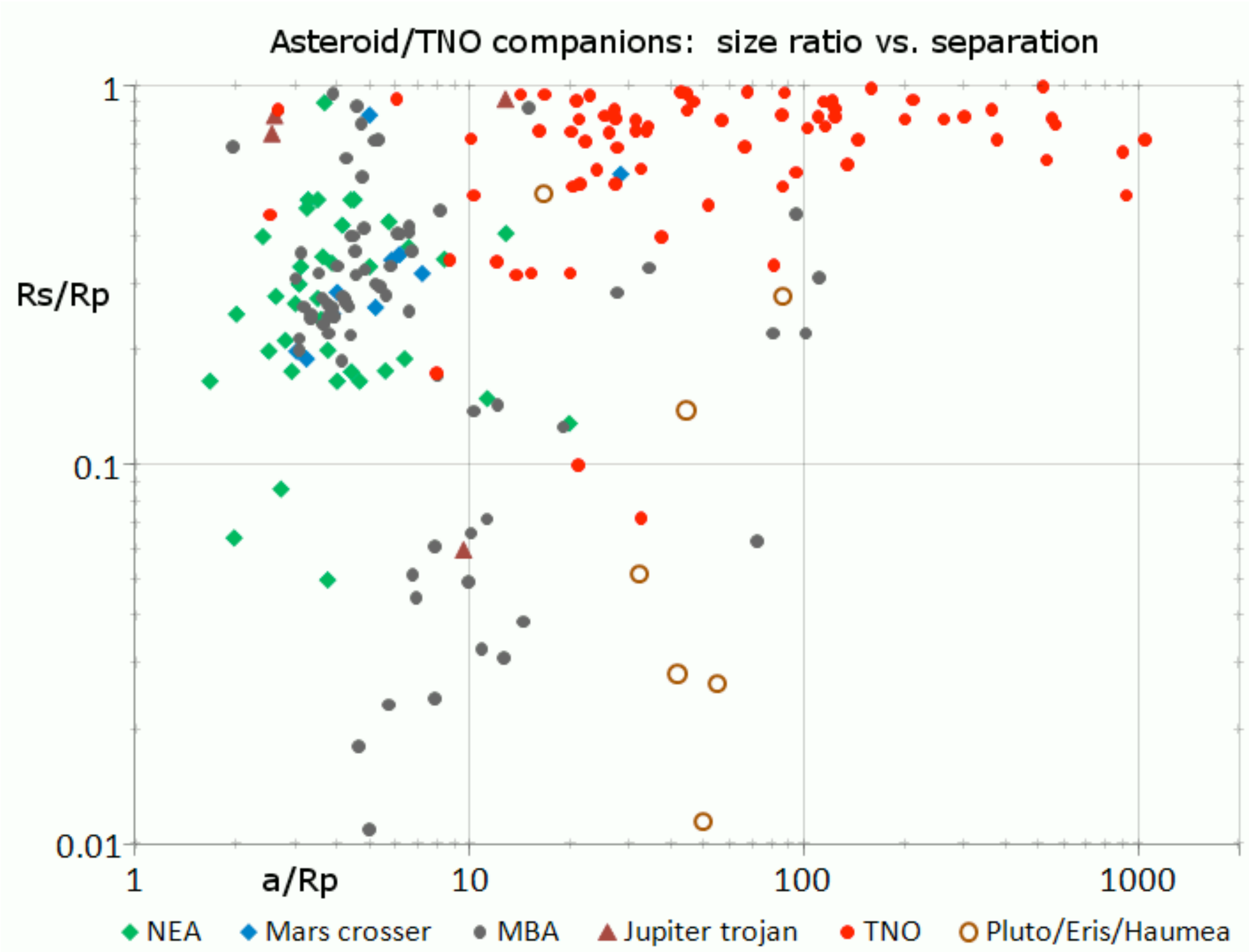
- Walsh et al.: binary via mass shedding from primary.
  - Requires high angle of friction (moderate reshaping resistance).
  - Secondary accretes in orbit; primary shape & ridge from shedding.
  - Fresh material exposed at primary poles.
- Jacobson & Scheeres: binary via fission from primary.
  - Requires fluid-like body (no resistance/low shear strength)—or contact binary—followed by dynamical evolution of components.
  - Primary shape/equatorial ridge formed after secondary breakup.
- The two models predict different internal structures.
  - Walsh et al.: moderate shear strength, e.g., crystallization, rigid core, and/or irregular blocks; porous material to reaccrete?
  - Jacobson & Scheeres: near-zero shear strength, e.g., free-flowing material; shape adopts global minimum energy configuration.*

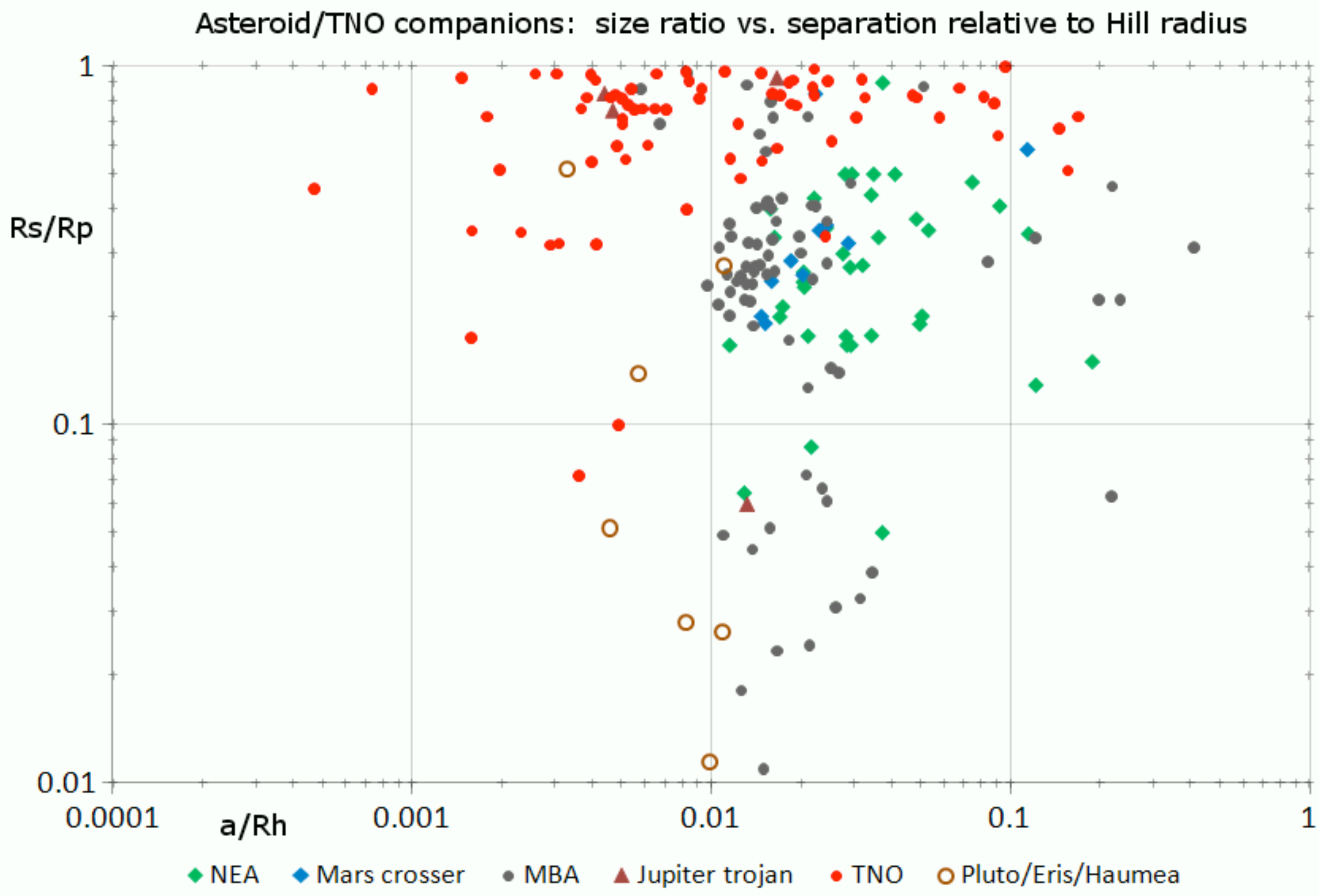
Inconsistent with present KW_4 shape—need friction (Cf. Holsapple).

Conclusions & Future Work

- Numerical simulations of SSSB binary formation show good match to Main Belt and NEA binaries via impacts and rotational disruption.
- Need to preserve shape & spin for impact simulations.
- Is YORP torque self-reinforcing or self-defeating (how does shape change/mass loss after torque)? Is it a random walk (so it takes much longer to evolve)?
- New SSDEM codes needed to better model rubble pile contact physics (landslides instead of individual particle loss?), and investigate effect of weak cohesion.
- Marco Polo-R mission to FG_3 will distinguish between binary formation models.

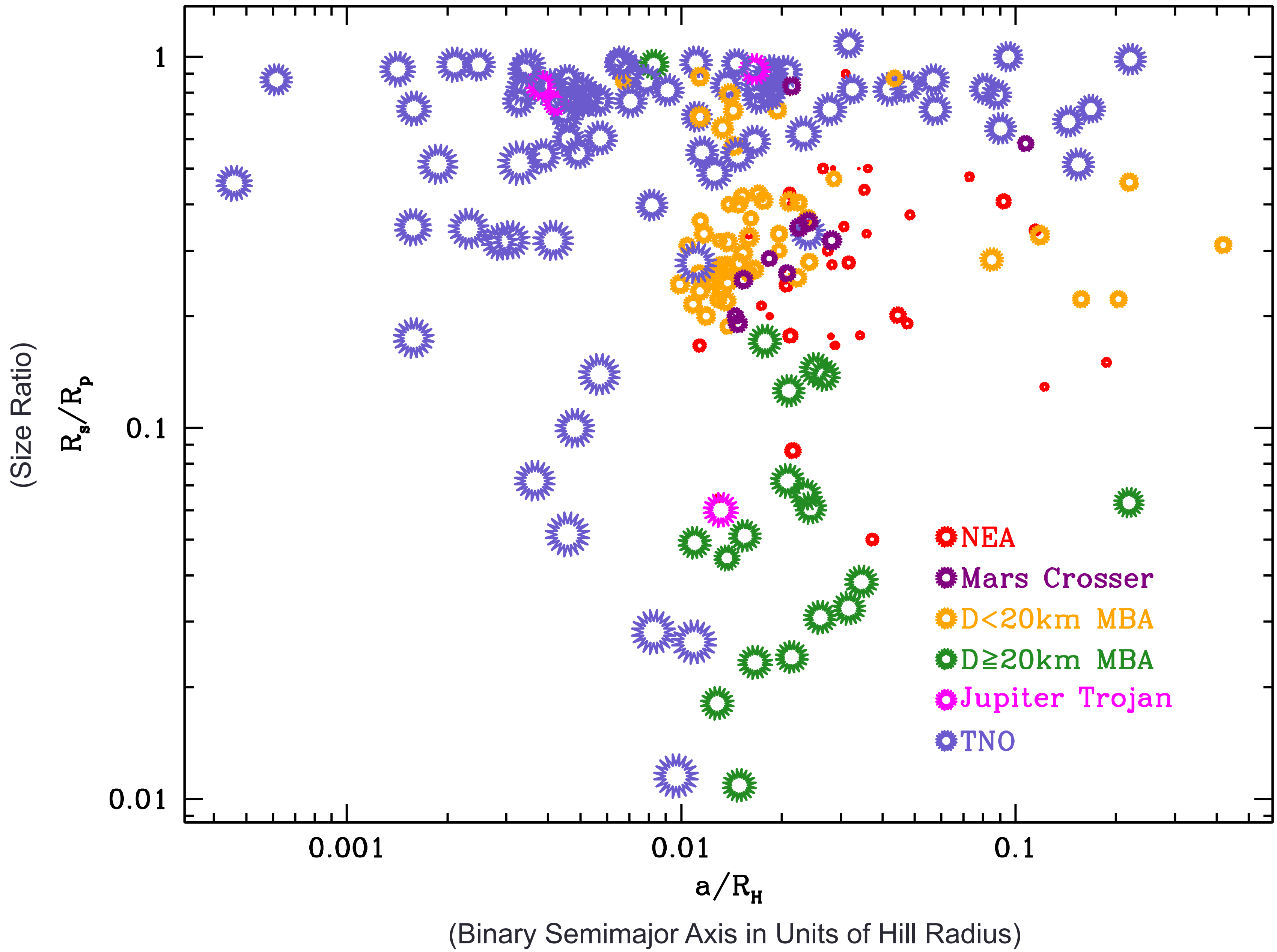
EXTRA SLIDES


Asteroid/TNO companions: size ratio vs. separation
Rs/Rp
1
0.1
0.01
1
10
100
1000
a/Rp
NEA
Mars crosser
MBA
Jupiter trojan
TNO
Pluto/Eris/Haumea

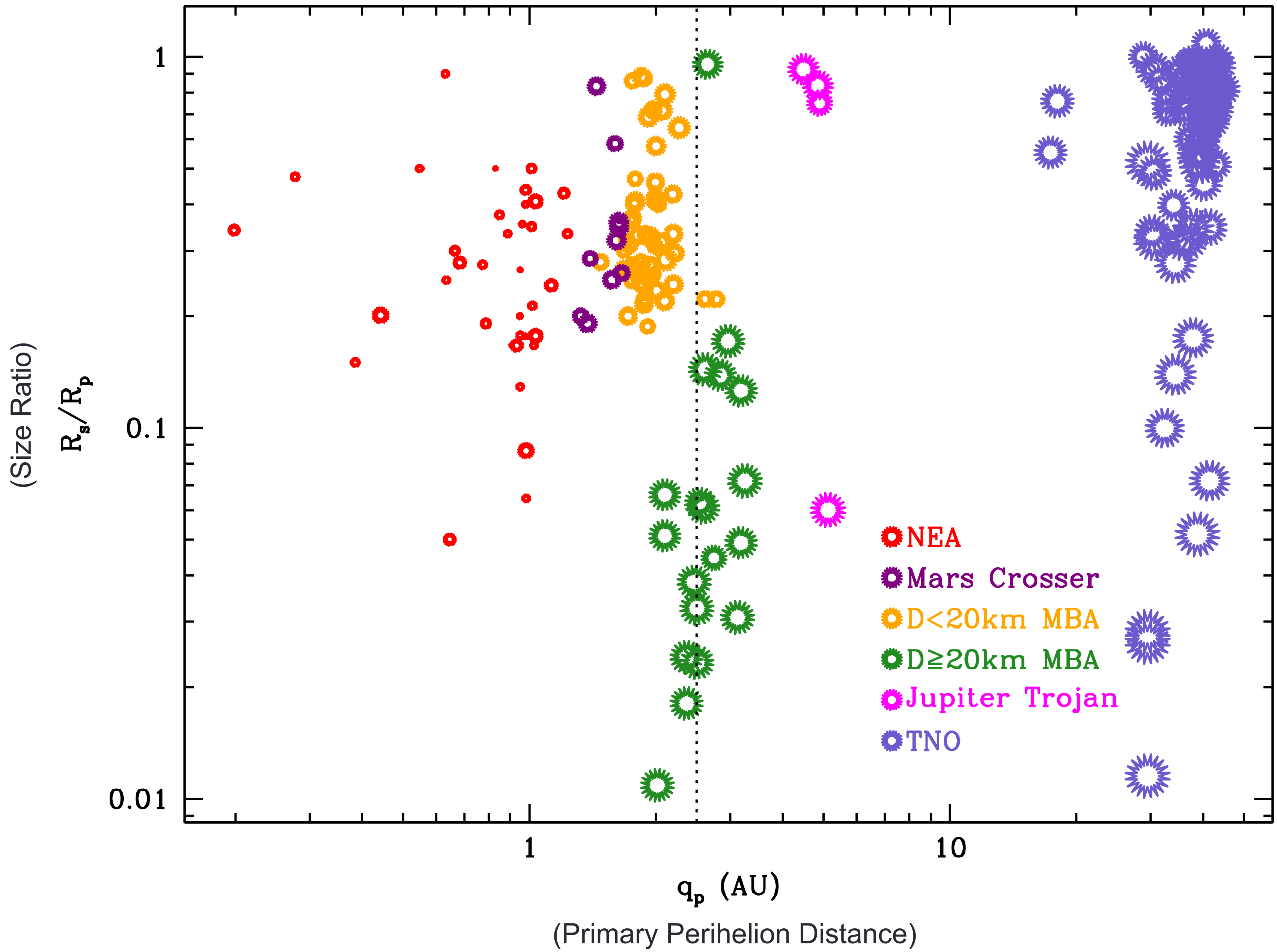


Asteroid/TNO companions: size ratio vs. separation relative to Hill radius
Rs/Rp
1
0.1
0.01
a/Rh
0.0001
0.001
0.01
0.1
1
NEA
Mars crosser
MBA
Jupiter trojan
TNO
Pluto/Eris/Haumea

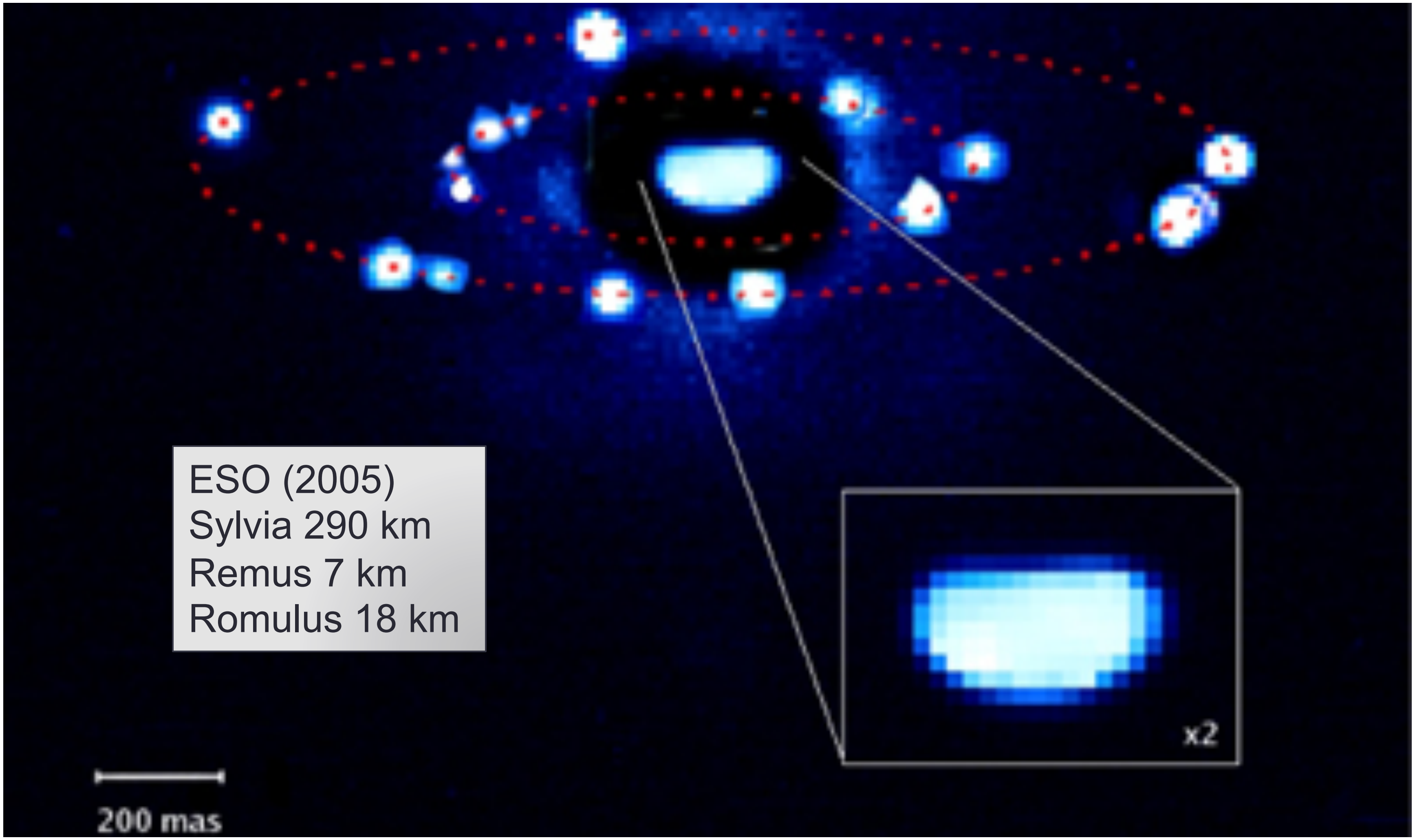
Separation in Hill Radii *vs.* Size Ratio



Perihelion Distance *vs.* Size Ratio

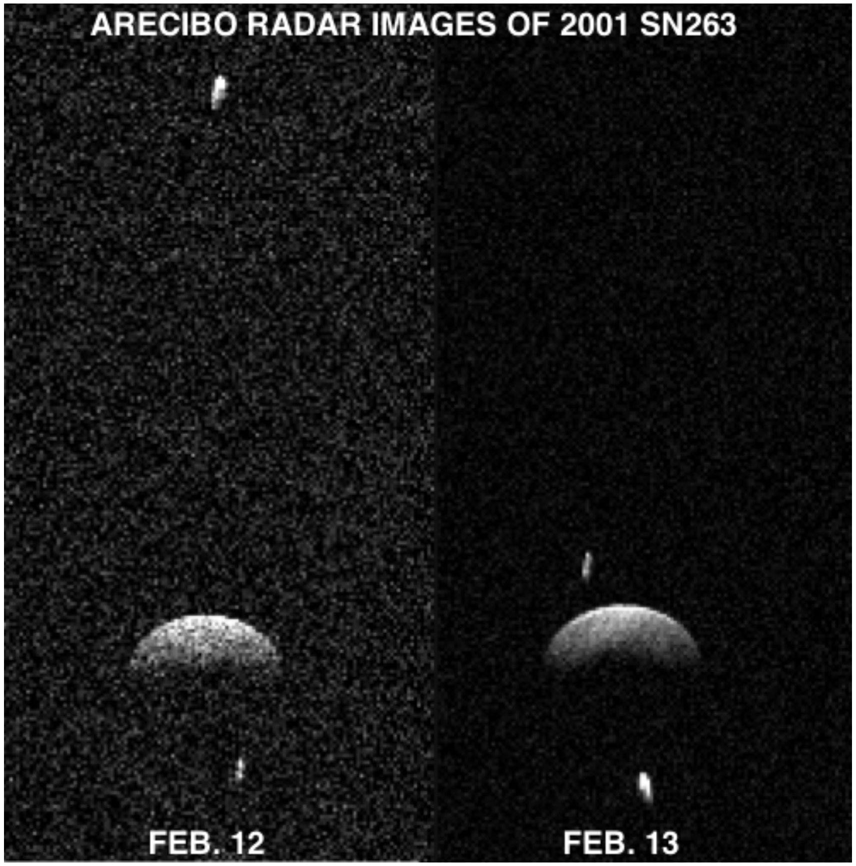


First Triple Asteroid: 87 Sylvia

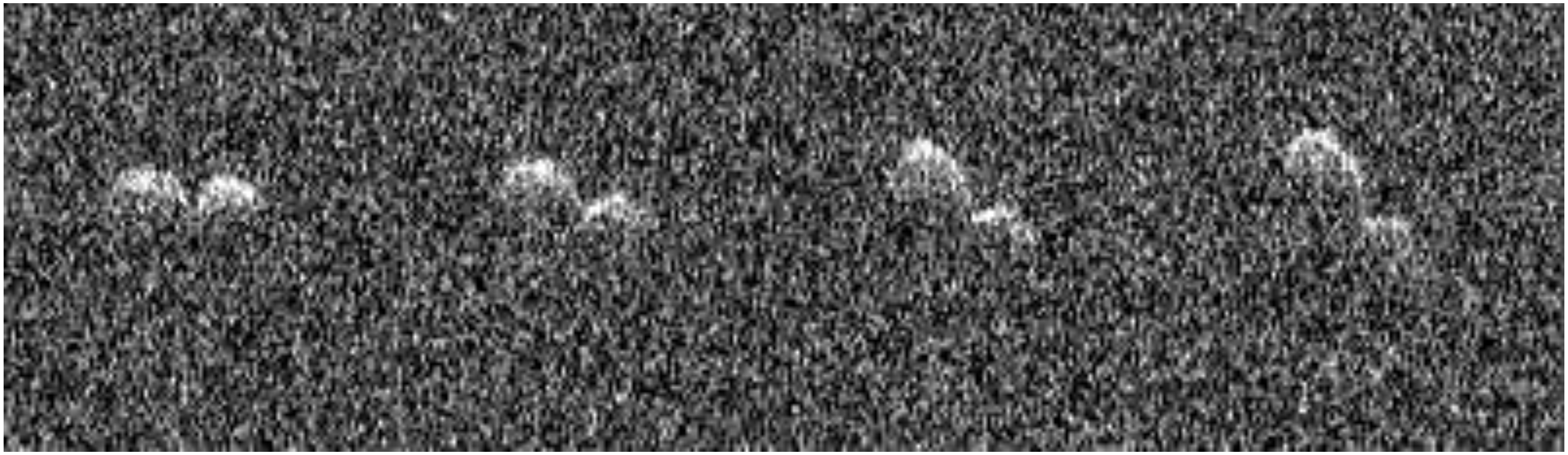


Recent Triple Asteroid

- 2001 SN_{263}.
- Companions found Feb. 12/13, 2008.
- 2 km primary.
- 75 m resolution.

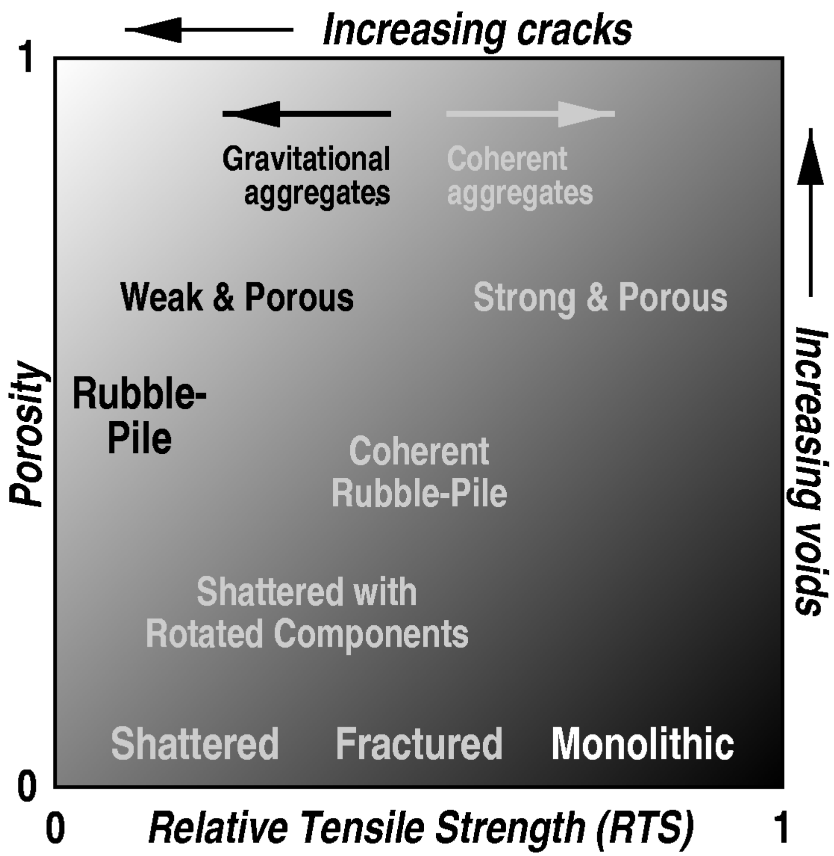


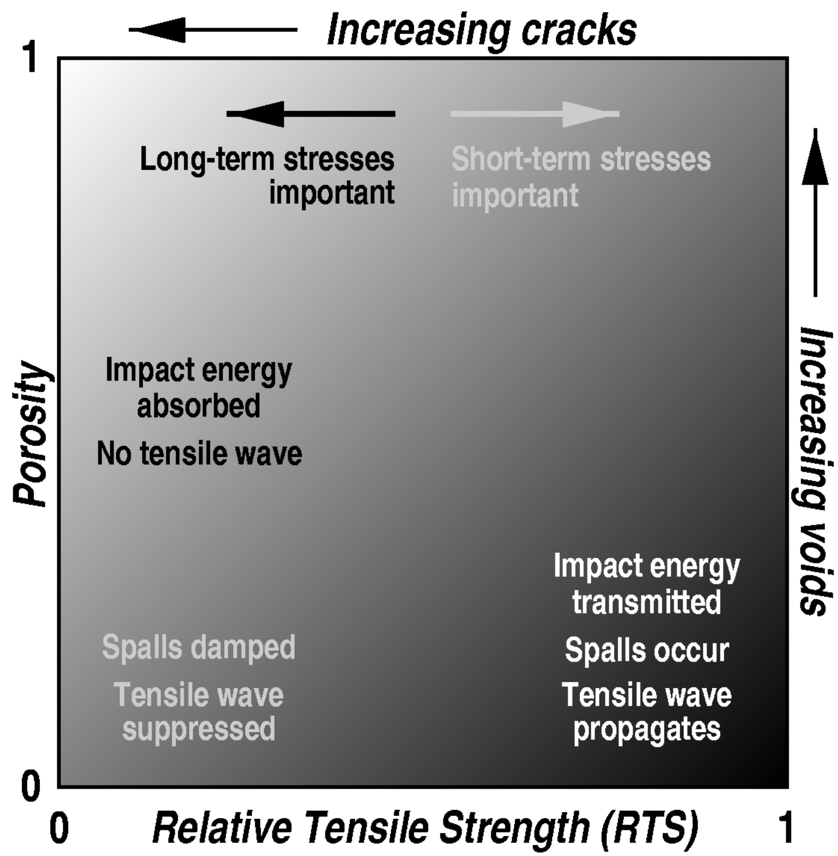
Comet 8P/Tuttle: Contact Binary?



- Arecibo Jan. 4, 2008.
- Spheres 3–4 km.
- Resolution 300 m.
- Rotation 7.7 h.

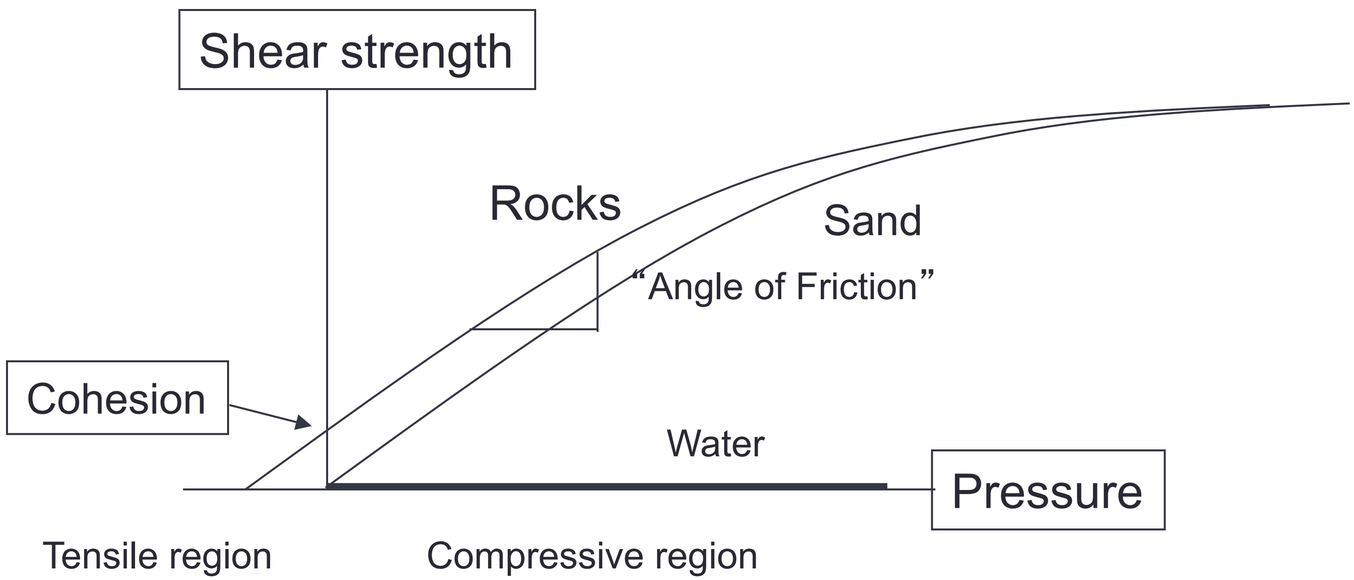
Gravitational Aggregates





Some Important Concepts About Strength

- The Mohr-Coulomb (or Drucker-Prager) model:



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 (requires collision search):

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

SSDEM Equations

Schwartz et al. 2012, *Granular Matter*, 14, 363.

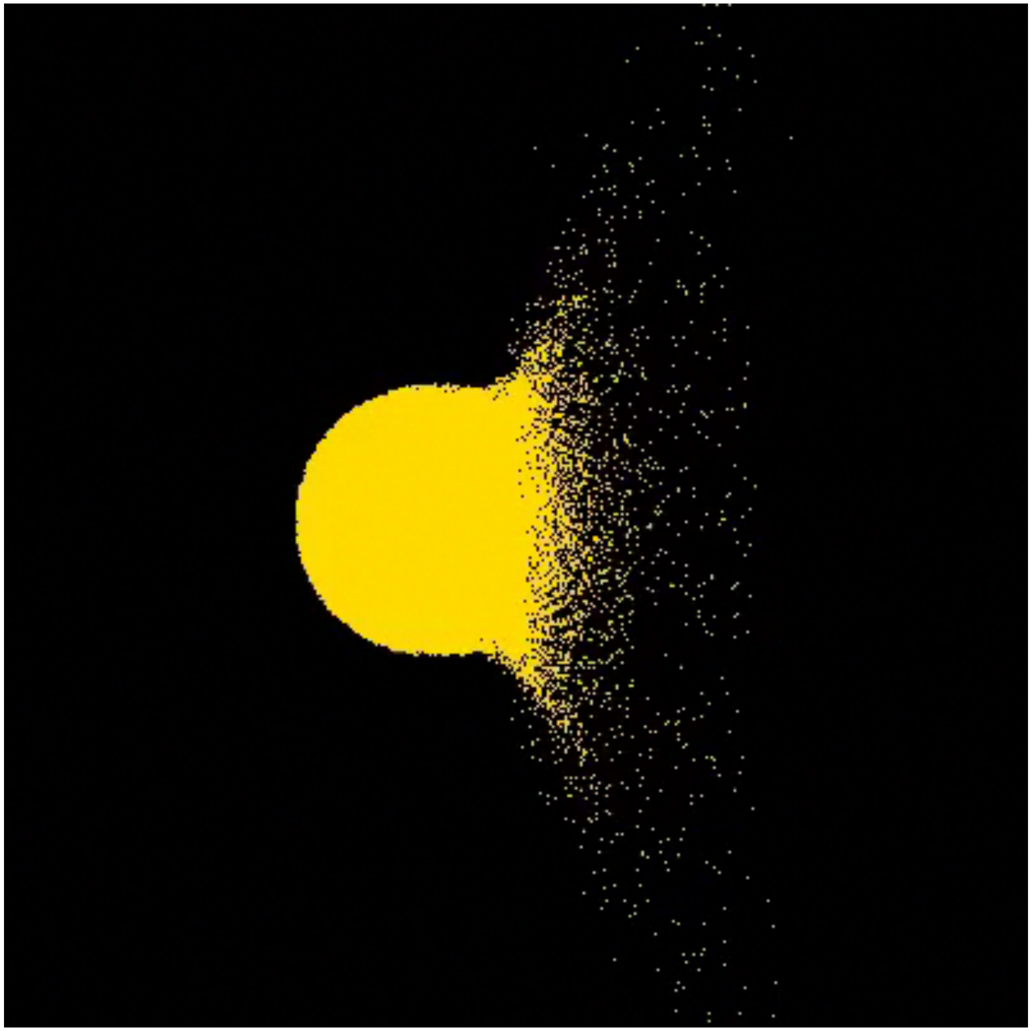
Force; Restoring force; Plastic friction forces; Static friction force

$$\overrightarrow{\mathbf{F_p}} = -k_n x\,\hat{\mathbf{n}} + C_n \cdot \overrightarrow{\mathbf{u_n}} + \min\{\mu_s|\overrightarrow{\mathbf{F_N}}|\hat{\mathbf{S}}\,;\ k_t\,\overrightarrow{\mathbf{S}} + C_t|\overrightarrow{\mathbf{u_t}}|\hat{\mathbf{t}}\}.$$

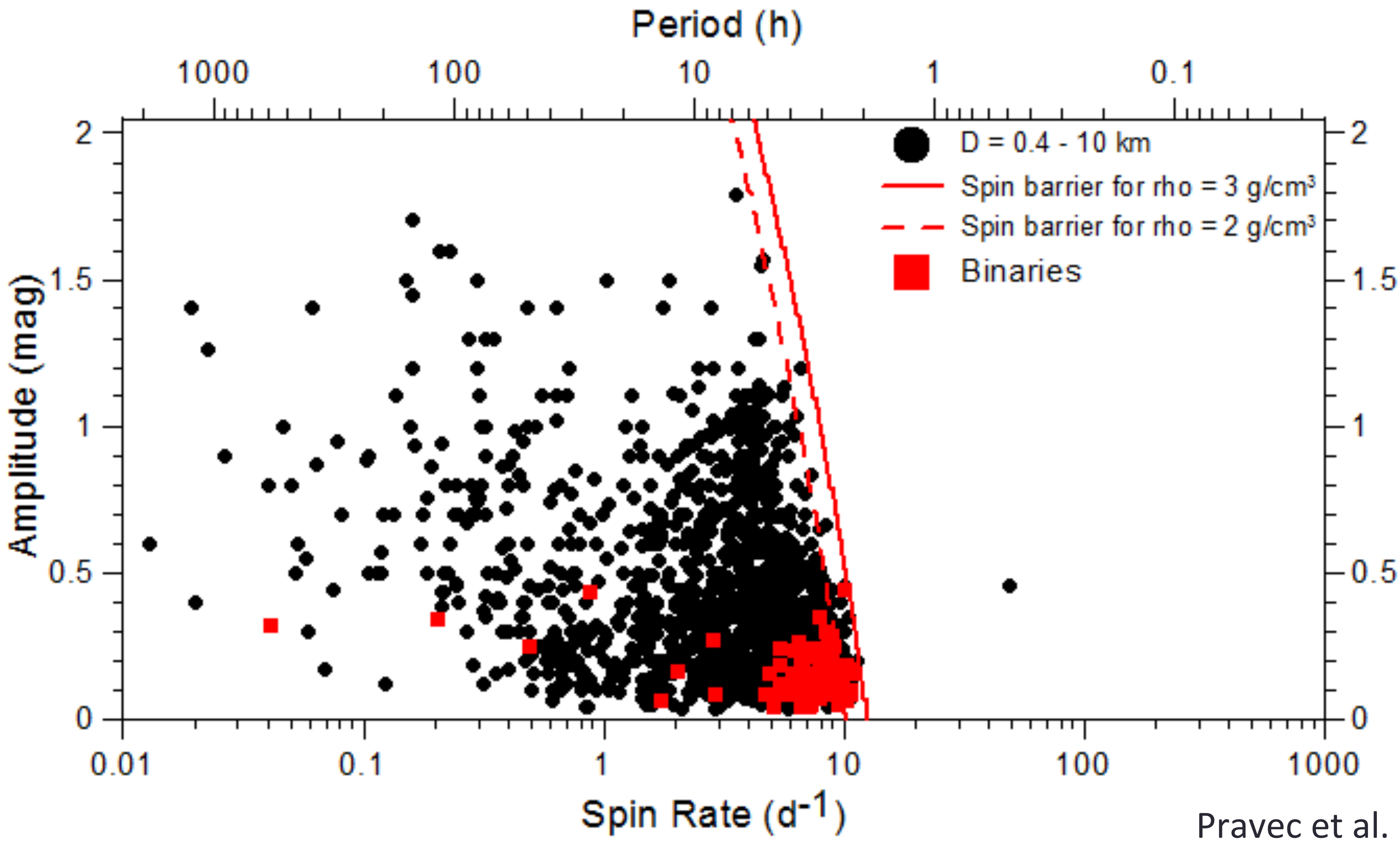
Tangential friction torque; Rolling friction; Twisting friction; Torque

$$\overrightarrow{\mathbf{M_p}} = -l_1\left[\min\{\mu_s|\overrightarrow{\mathbf{F_N}}|\hat{\mathbf{S}}\,;\ k_t\,\overrightarrow{\mathbf{S}} + C_t|\overrightarrow{\mathbf{u_t}}|\hat{\mathbf{t}}\} + \mu_r\frac{(\overrightarrow{\mathbf{F_N}}\times\overrightarrow{\mathbf{v_{rot}}})}{|\overrightarrow{\mathbf{v_{rot}}}|}\right]\times\hat{\mathbf{n}} - \mu_t\frac{r_c\left[(\overrightarrow{\omega_\mathbf{n}}-\overrightarrow{\omega_\mathbf{p}})\cdot\overrightarrow{\mathbf{F_N}}\right]}{|(\overrightarrow{\omega_\mathbf{n}}-\overrightarrow{\omega_\mathbf{p}})\cdot\hat{\mathbf{n}}|}.$$

EEB Example: Flora Impact



Spin Rate *vs.* Lightcurve Amplitude (Shape)

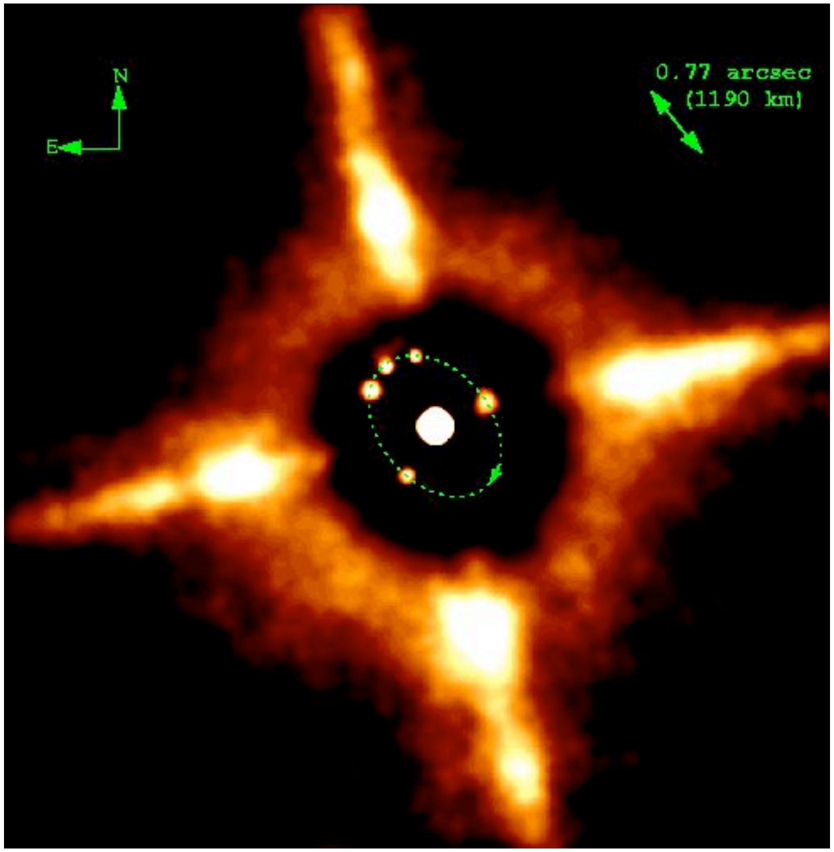


Pravec et al.

Low Bulk Densities Imply Porosity

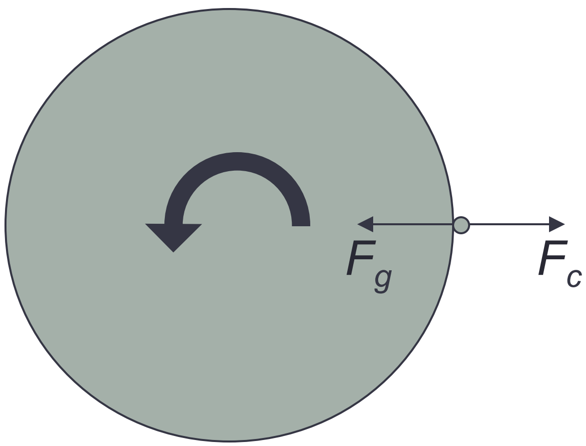
253 Mathilde (1.3 g/cc)

45 Eugenia (1.1 g/cc)



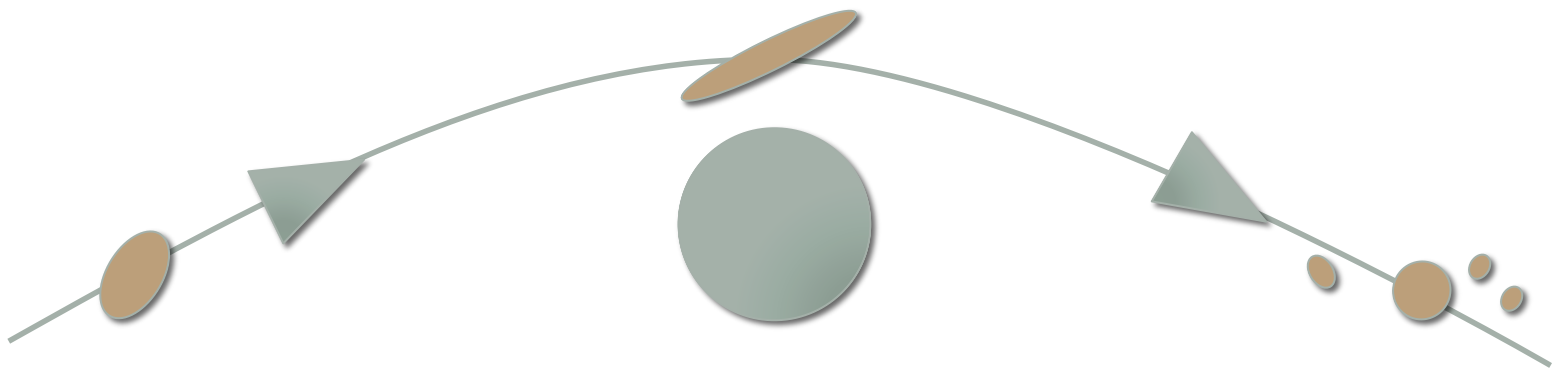
Rotational Disruption

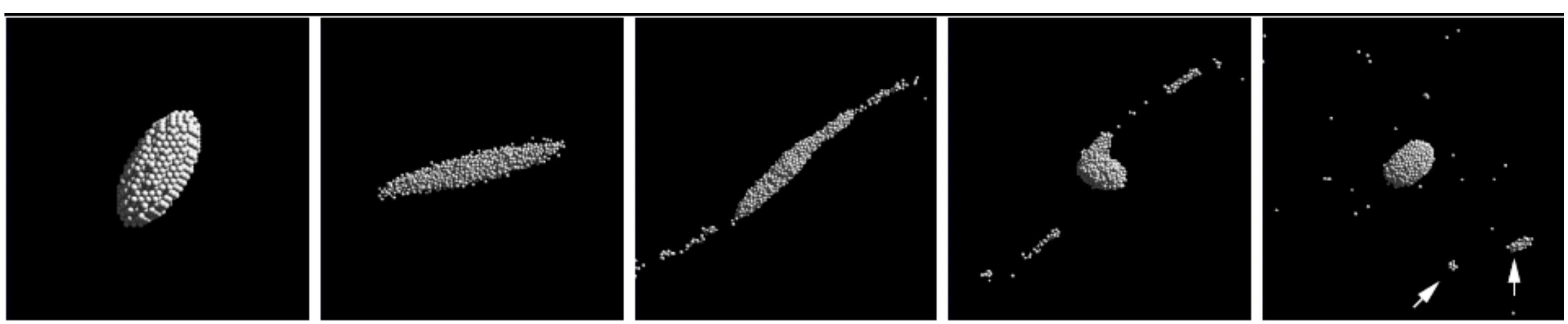
- Centrifugal force > gravitational force.



$$\frac{P_{\min}}{2.2\ \mathrm{h}} \approx \sqrt{\frac{2.2\ \mathrm{g/cc}}{\rho}}$$

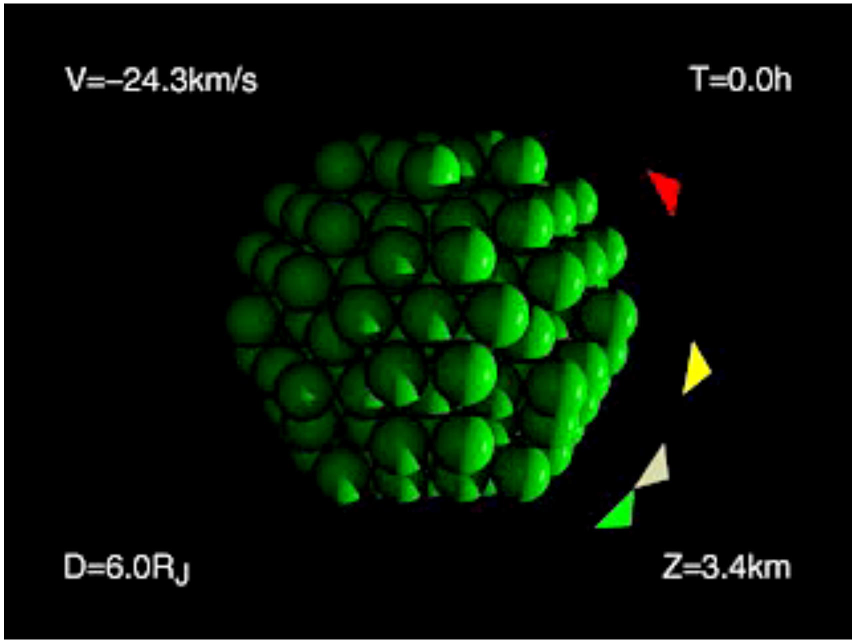
Tidal Disruption





Example: SL9 Breakup at Jupiter

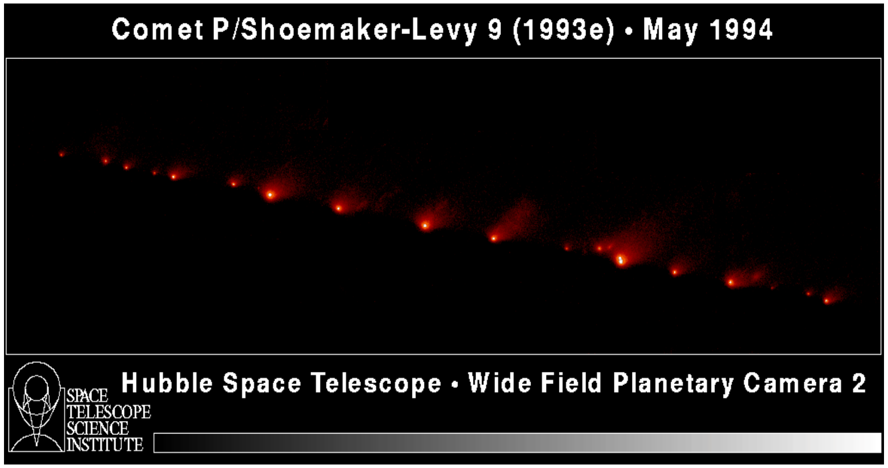
- Simplest explanation: Jupiter tides pulled comet into many pieces, which then reaccumulated.
- Implies weak structure.



Encounter in comet frame of reference.

Crater Chains (Catenae)

- Historical evidence of tidal disruption.



Comet breakups like D/SL9 can make crater chains on big moons.

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

Davy Chain, ~47 km