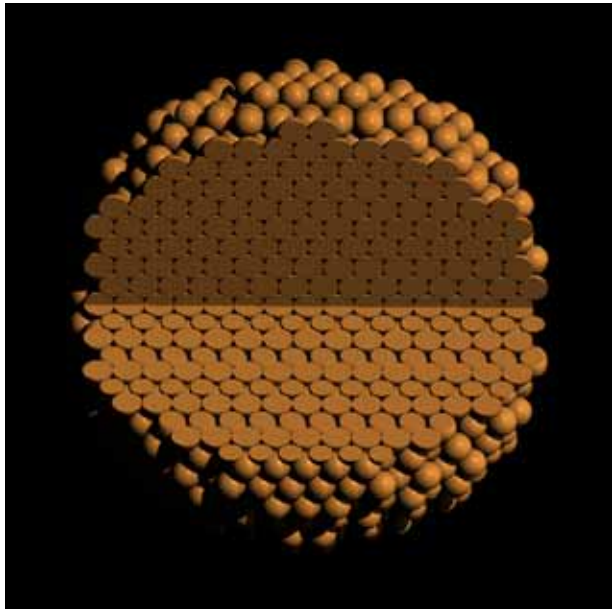
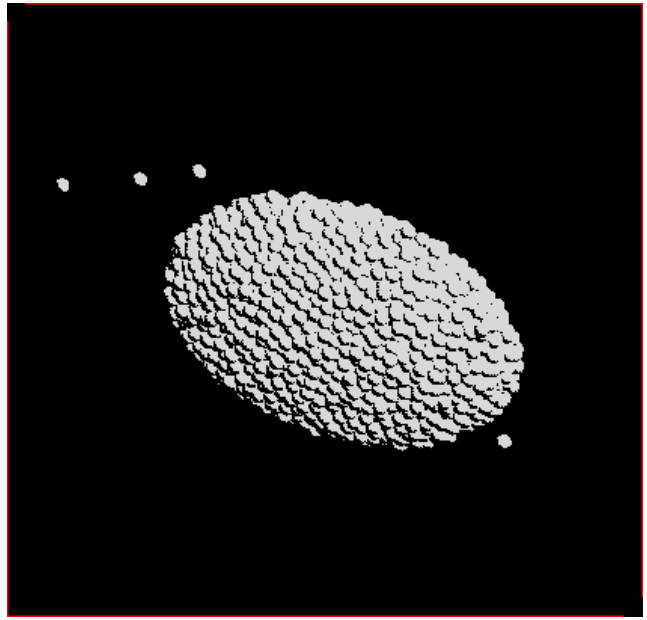
Equilibrium states for rubble piles





P. Tanga, C. Comito

Observatoire de la Côte d'Azur

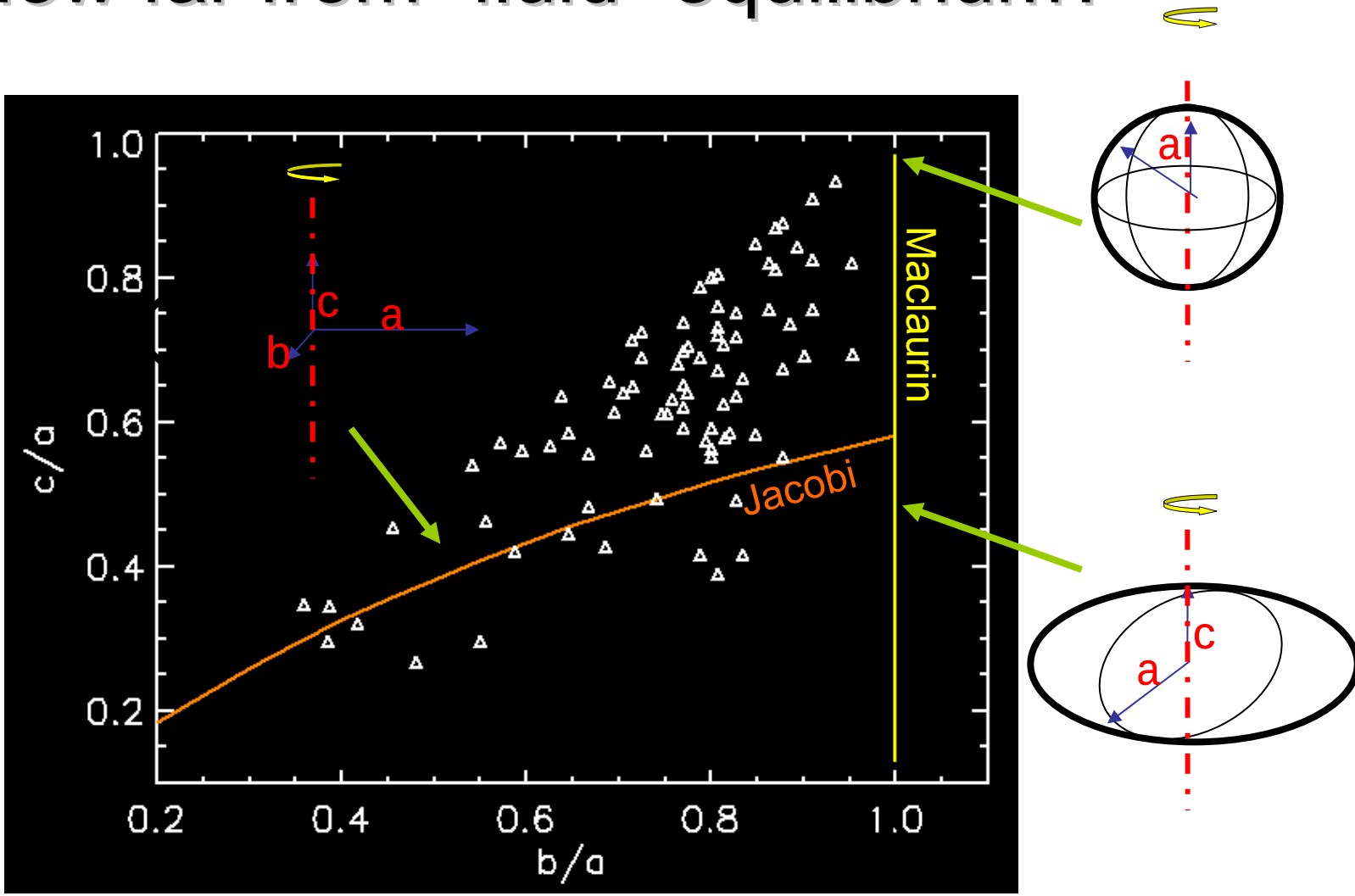
General context: how much is (not) known

Property	status
« good » orbits	~ 50%
rotation periods	4000
global shapes,	
+ pole directions	~300
spectral type	~ 1800
masses, σ < 60%	~ 40
size , σ < 10%	~ 500 (+ 10^5 WISE)
satellites	~ 200

Context

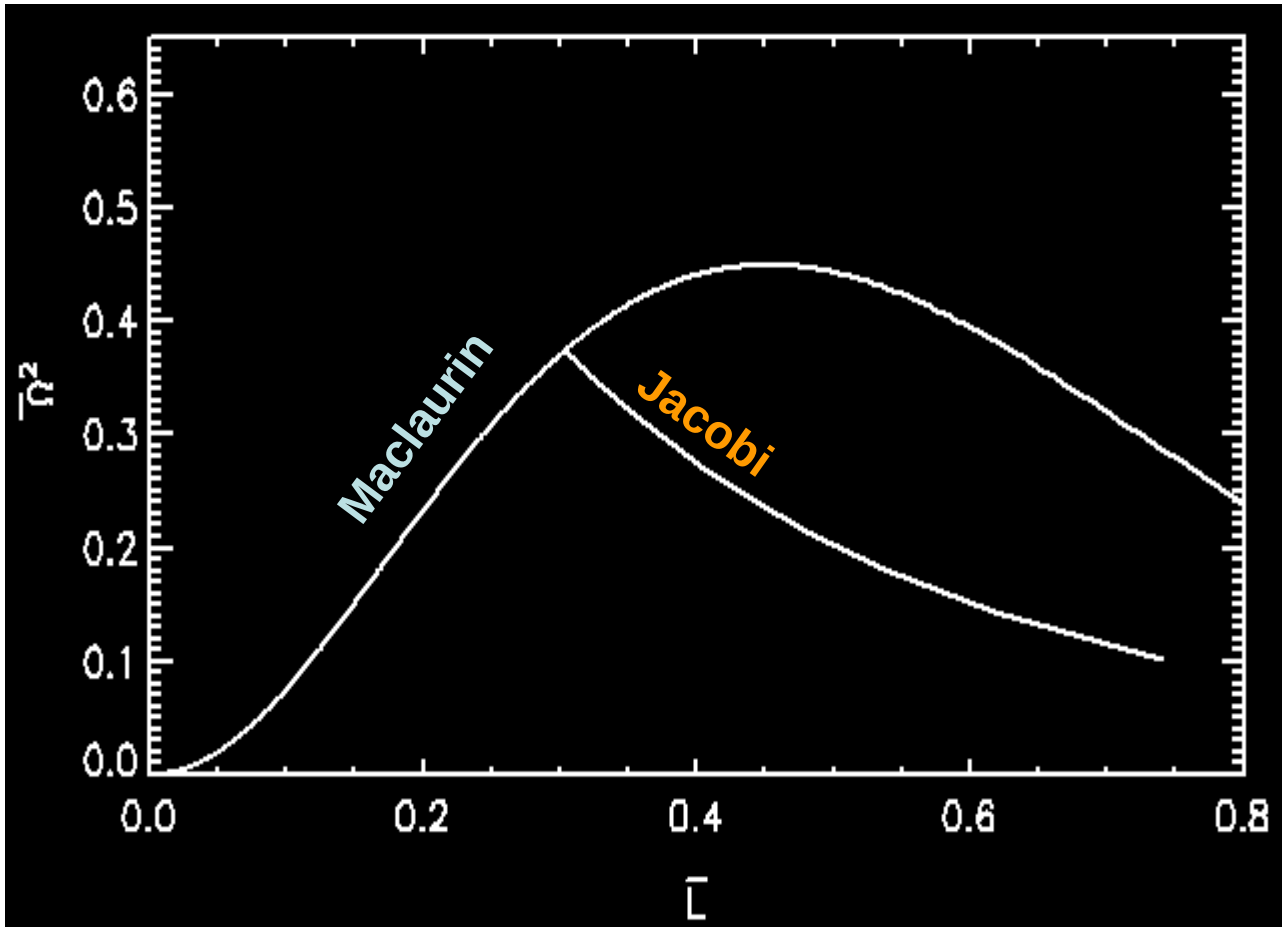
- Asteroid shapes compared to three axis ellipsoids
  - For explaining observed brightness variations
- Easy comparison to fluid equilibrium theories
- Can we model observed shapes with our method and rubble pile structures?
  - Their evolution?
  - Binary asteroids?

How far from “fluid” equilibrium?



Triangles: three axial shape ratios from Kryszczynska et al., 2007

On the other plane…



$$\bar{\Omega} = \frac{\Omega}{\sqrt{G\pi\rho}}$$

$$\bar{L} = \frac{L}{\sqrt{GM^3R}}$$

Common (dangerous) practice

- How to compute density when no information on the absolute size of a body is known

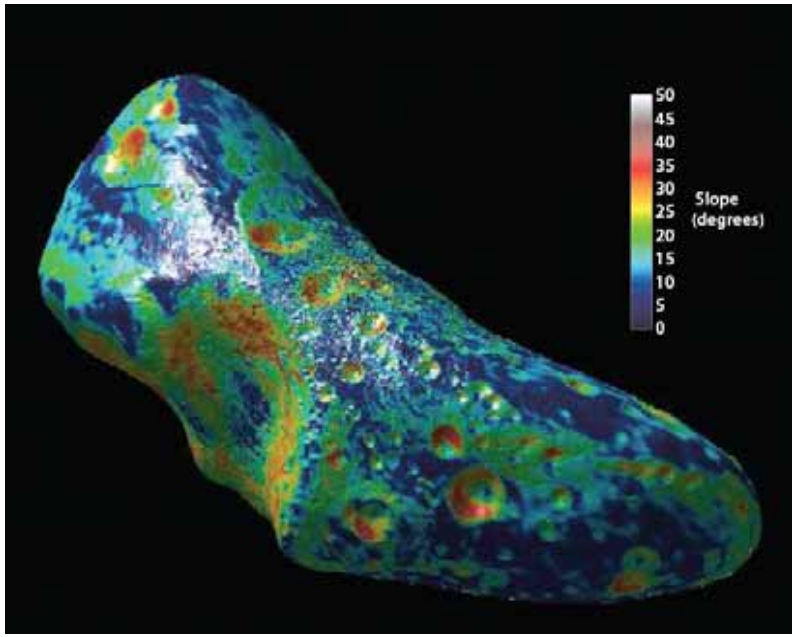
- Photometry
  - rotation period
  - Lightcurve amplitude → axis ratio b/a

- Find corresponding normalized spin
- Deduce density!

Gravitational slopes are low (in general)

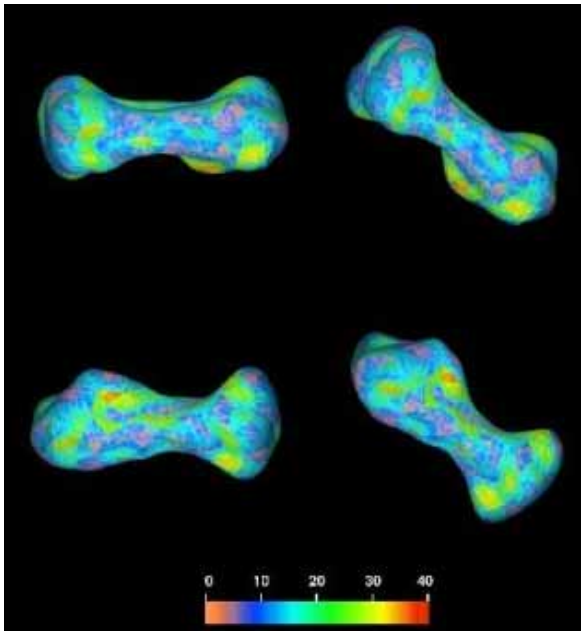
Eros

Asphaug et al 2002



…and Kleopatra

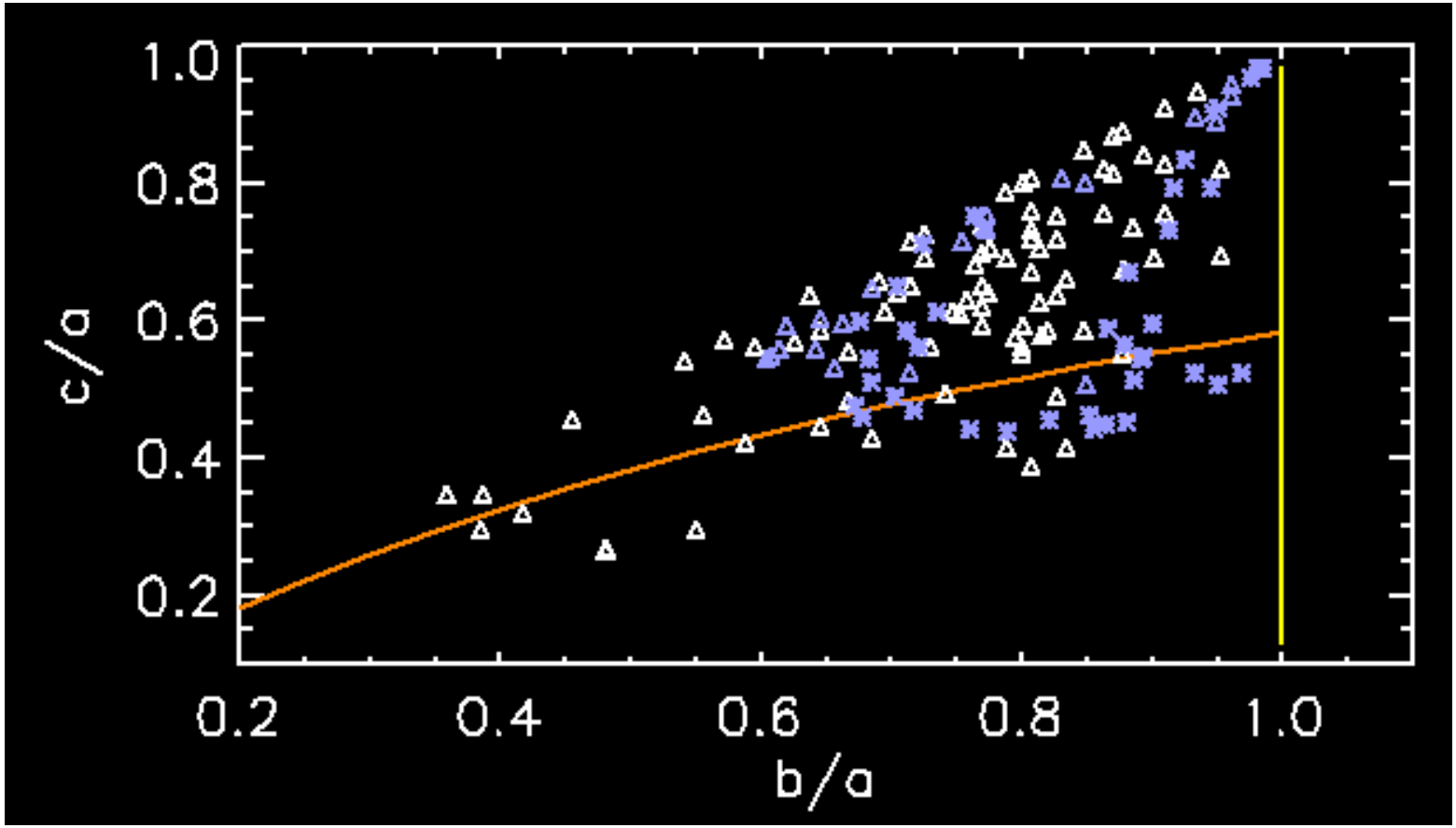
Ostro et al 2002



Are these shapes close to fluid??

Numerical approach

- *pkdgrav* code using « Hard spheres »
- Optimized gravity computation
  - Tree code
    - Used also for collision detection
- Parallelized
- Tested in a variety of situations
  - Disperse systems (rarefied rings/disks)
  - Compact objects (« rubble pile »)
    - Close packing
    - Random packing
  - Monodispersed particles
  - Polydispersed particles (→ « fluid-like » behavior)



- Observed objects (white)
- Simulation results (blue)

Why?

- Is this a consequence of the gravitational collapse?
- …or an after-collapse reshaping?
- Are the objects really « far » from fluid equilibrium?

On the tracks of equilibrium shapes

Total energy

- A gravitational aggregate tends to minimize

$$\tilde{E} = E_{grav} + E_{rot}$$

- Simplest hypothesis: evolution shall follow

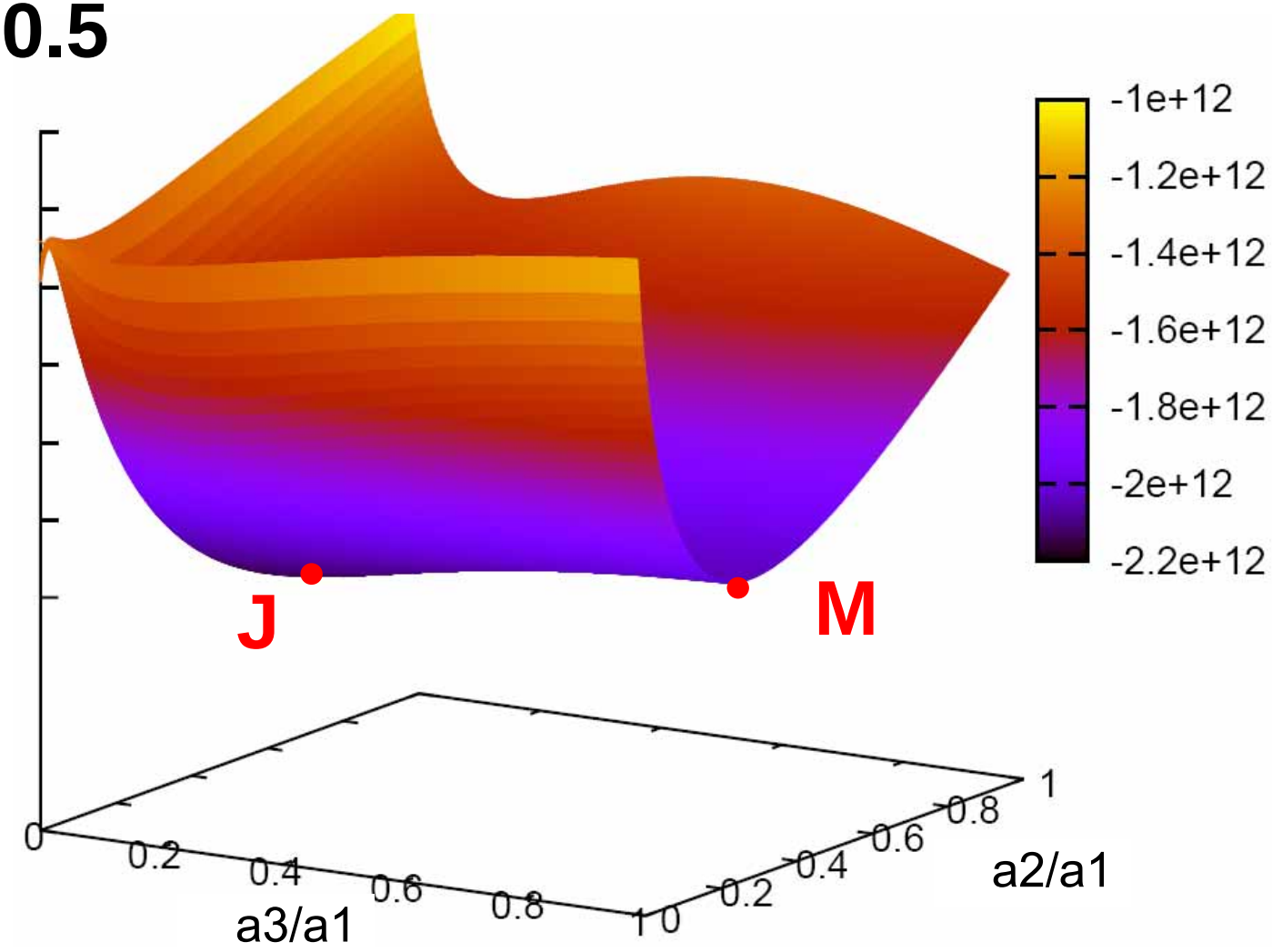
$$-\vec{\nabla}\,\tilde{E}$$

at constant angular momentum

…even for fragmented, non-fluid bodies

Flatness of the potential

L = 0.5



Simulations

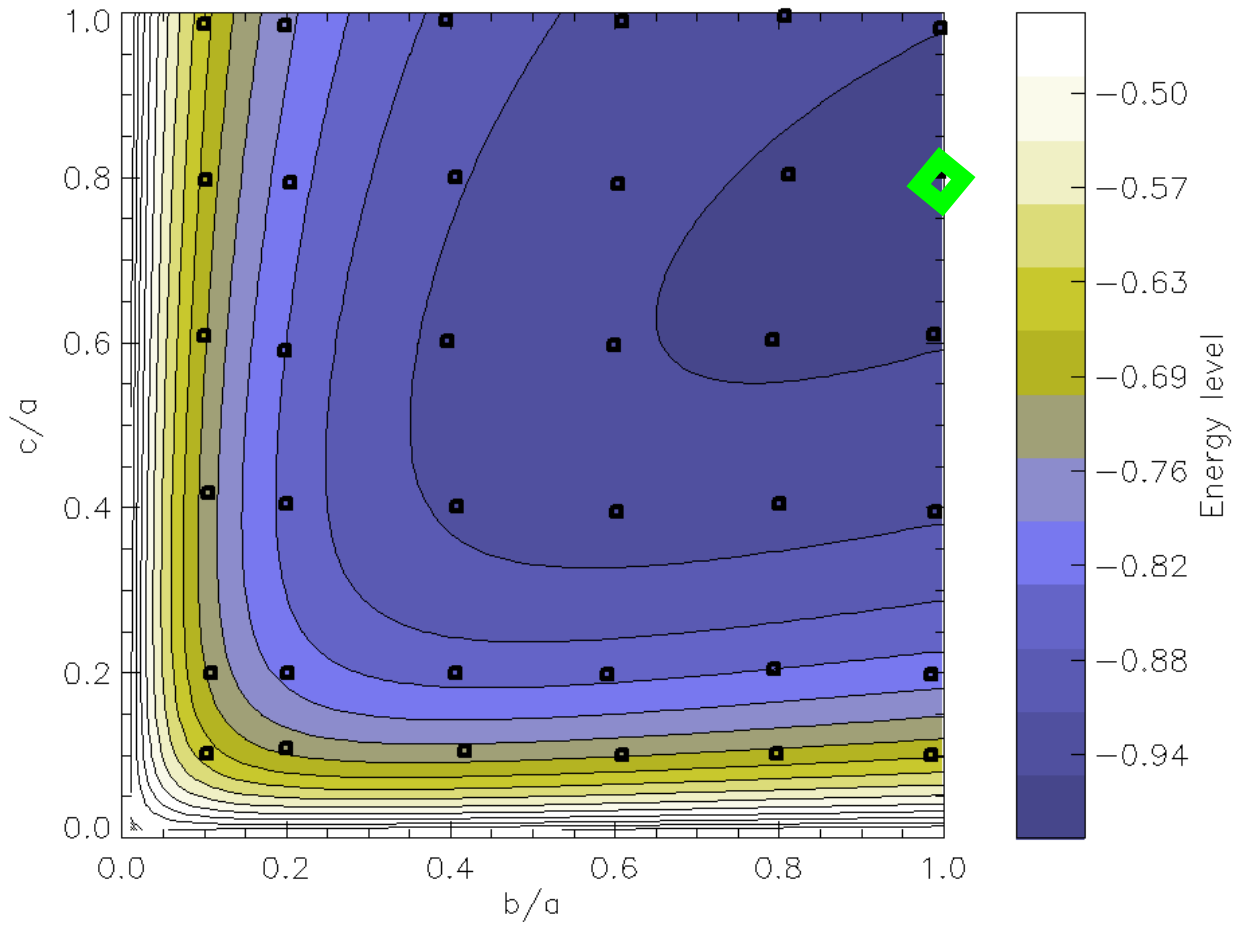
- We want to verify the simple « relax to fluid » hypothesis
- Initial conditions created by collapse of particle clouds
  - Self-gravity driven
  - Random packing

- Initial conditions on a grid of axis ratios
  - At given angular momentums

The energy field is « flat » on the axis ratio plane

L = 0.2

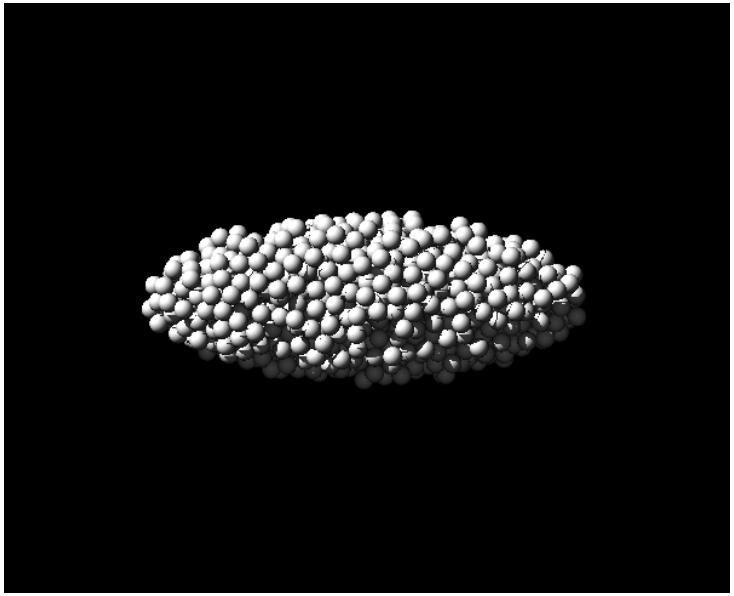
$$\overline{L} = \frac{L}{\sqrt{GM^3R}}$$



Let's try with aggregates made by spheres

- Pkdgrav (hard spheres, dissipative collisions)

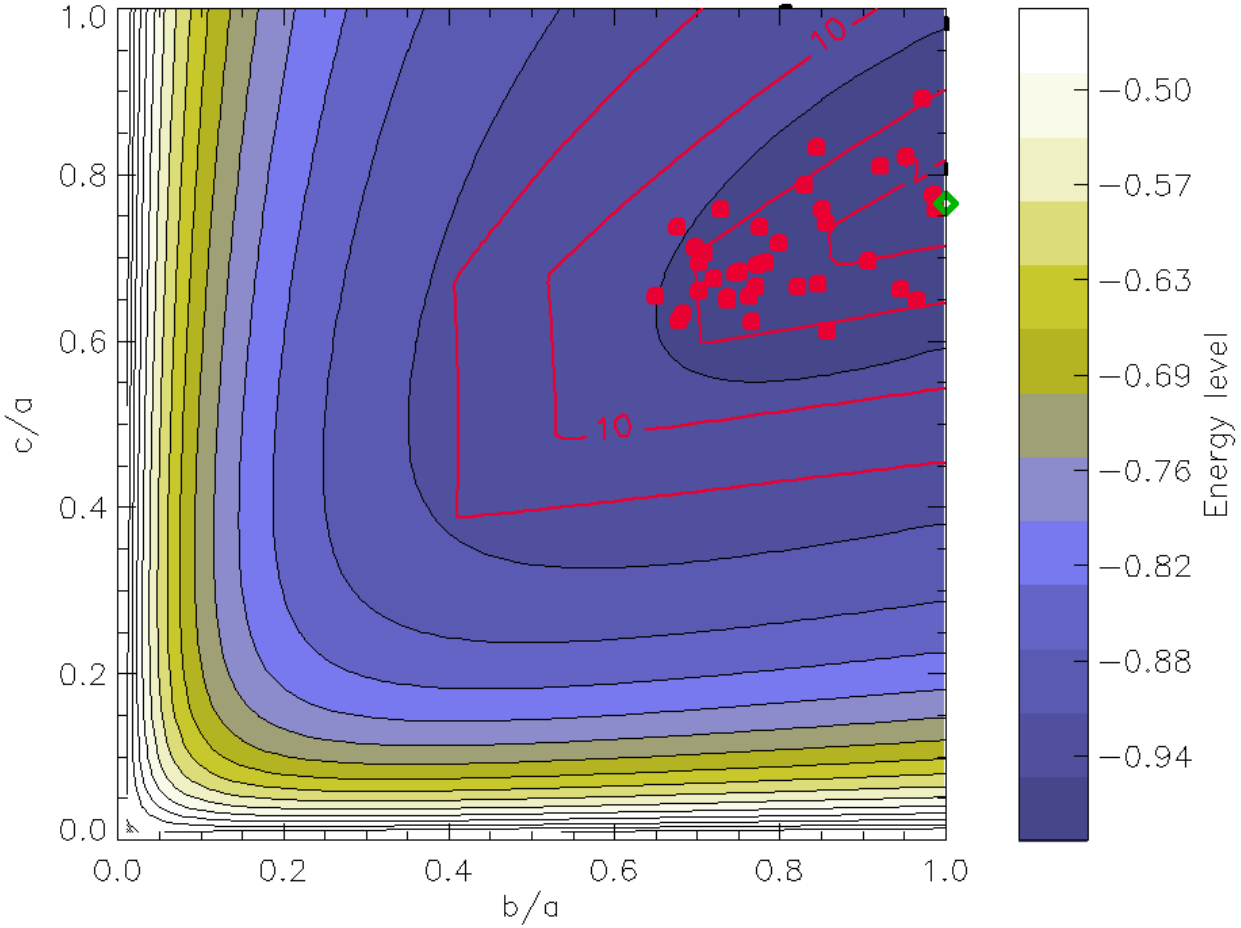
…we start from a variety of shapes (b/a, c/b) not at equilibrium



Random packing

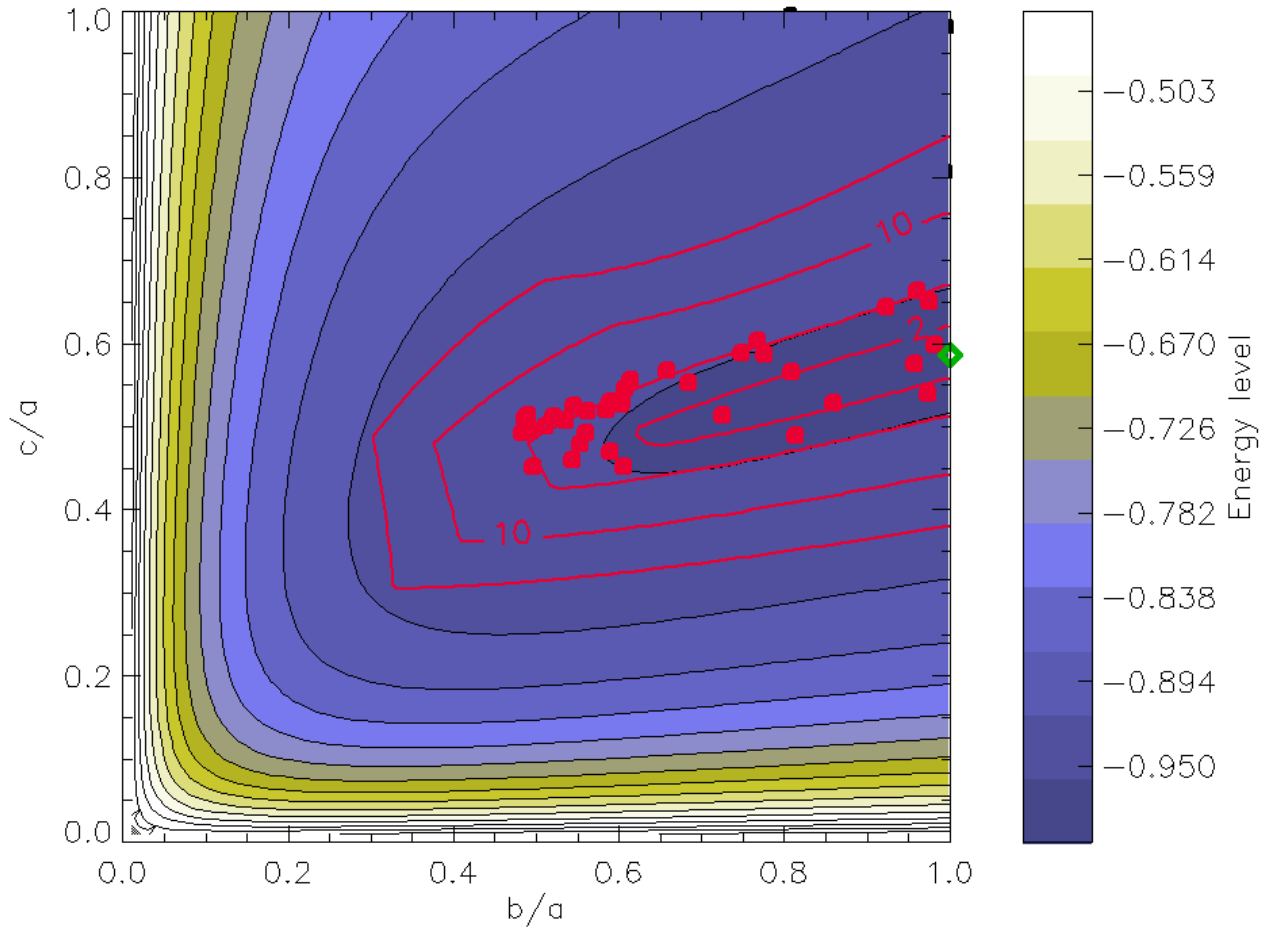
Shape evolution - 1

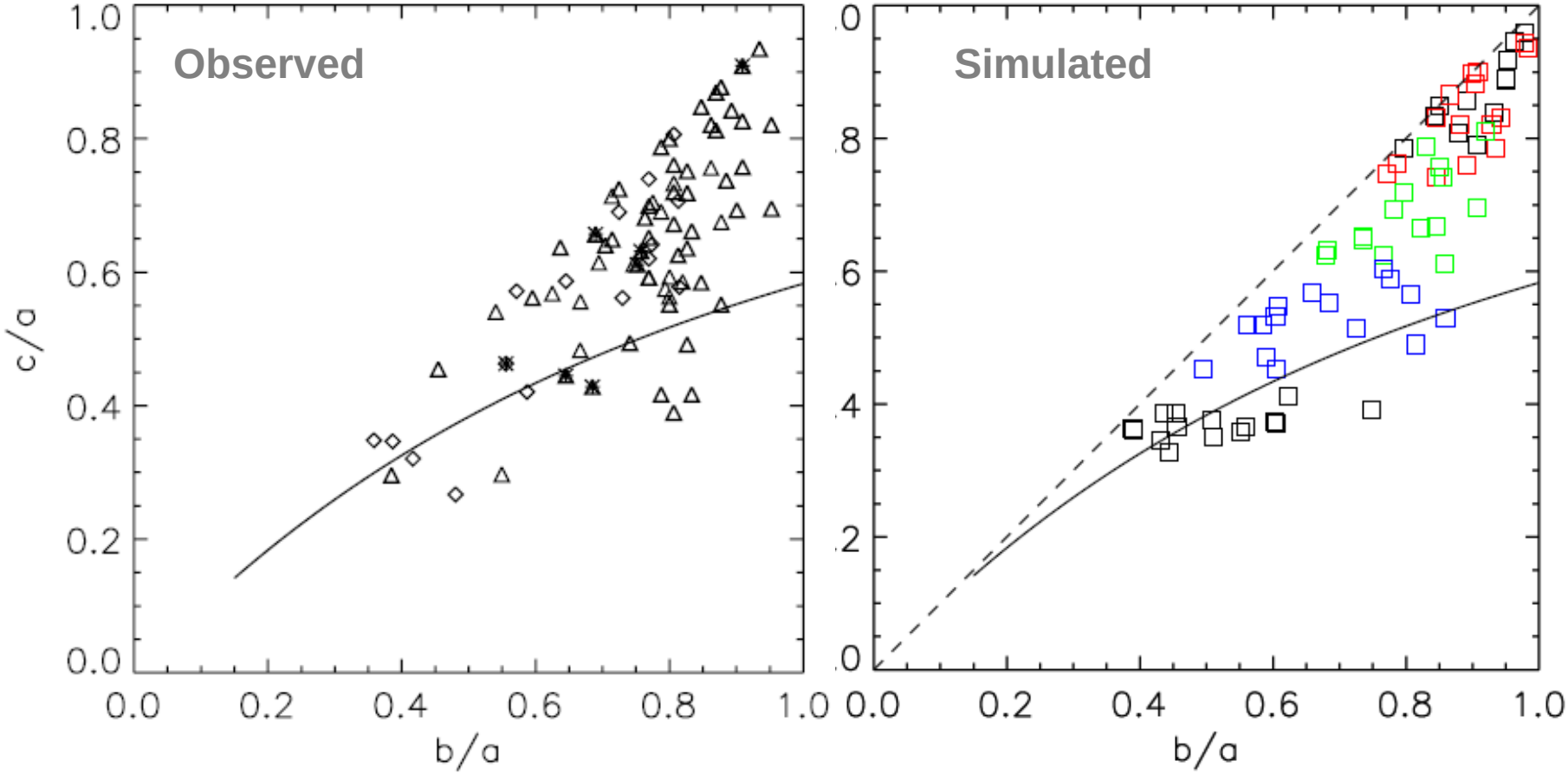
L = 0.2



Shape evolution - 2

L = 0.3





P. Tanga et al. ***Rubble-pile reshaping reproduces overall asteroid shapes***, ApJ (Letters) 706 (2009)

A general scenario

- Non disruptive seismic events, impacts, tides… « shake » asteroids
- They allow the fragments to displace
- Shapes follow energy gradient toward minimum
- They stop their evolution following the pattern of the energy field
- The resulting shape distribution is in agreement with the observations

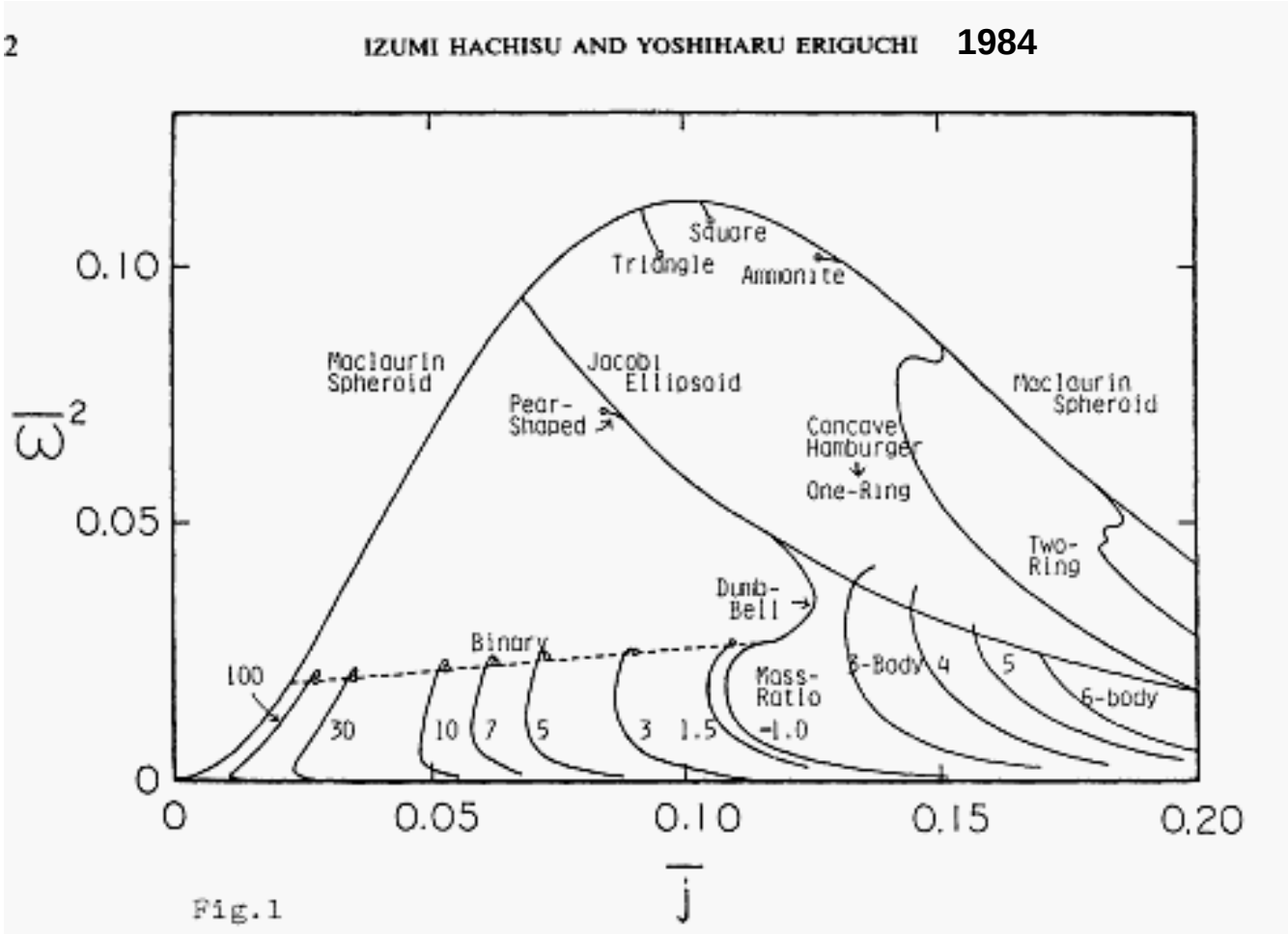
Consequences

- The energy field is « flat » → most observed shapes are probably « close » to fluid equilibrium
  - …even if they not appear as ellipsoidal!

- …as such, a small friction angle is sufficient to explain the observed distribution of macroscopic shapes

- The other way around: overall shape is not very informative on the internal strength of a body
  - Don't derive density by assuming equilibrium!

Splitting rubble-piles


2
IZUMI HACHISU AND YOSHIHARU ERIGUCHI
1984
Square
Triangle
Ammonite
Maclaurin Spheroid
Jacobi Ellipsoid
Pear-Shaped
Concave Hamburger
One-Ring
Maclaurin Spheroid
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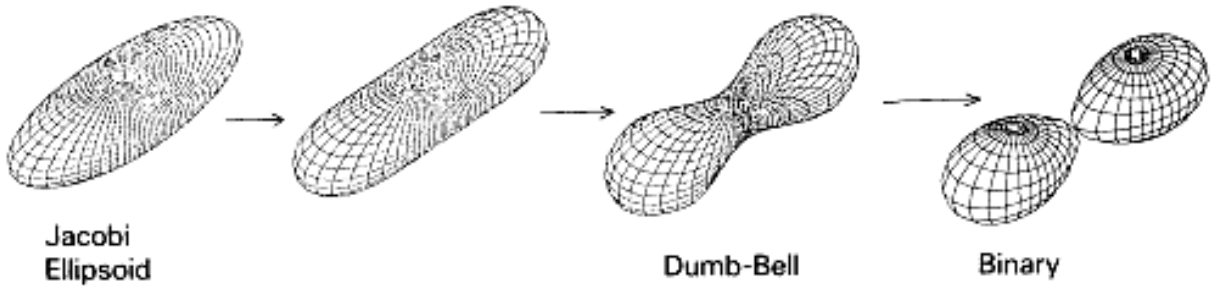
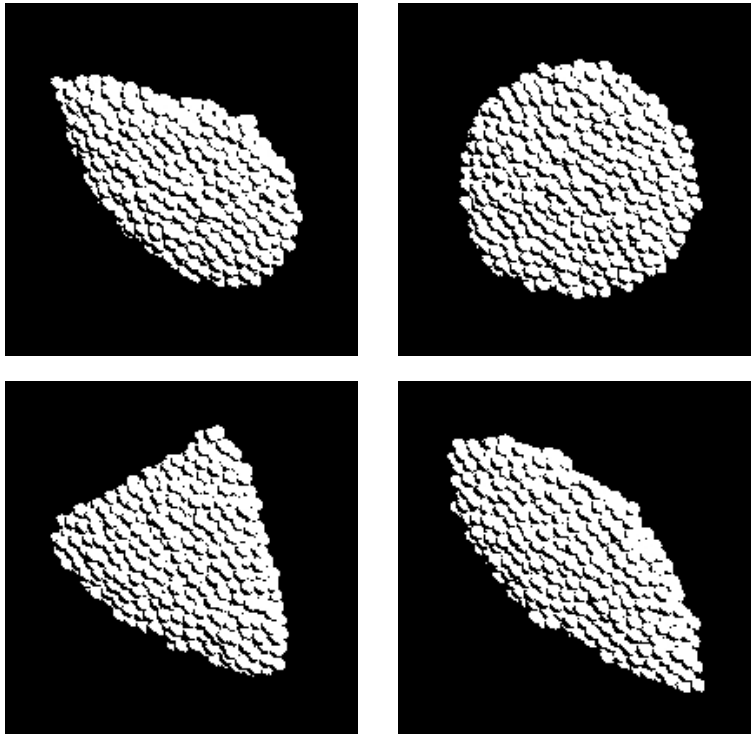
Dumb-Bell
Binary
100
30
10
7
5
3
1.5
Mass-Ratio =1.0
3-Body
4
5
6-body
0.10
0.05
0
0.05
0.10
0.15
0.20
Fig.1


Jacobi Ellipsoid
Dumb-Bell
Binary

Aims

- Explore shape evolution in proximity of the breakup barrier
- Investigate the role of initial shapes
- Application to satellite formation?

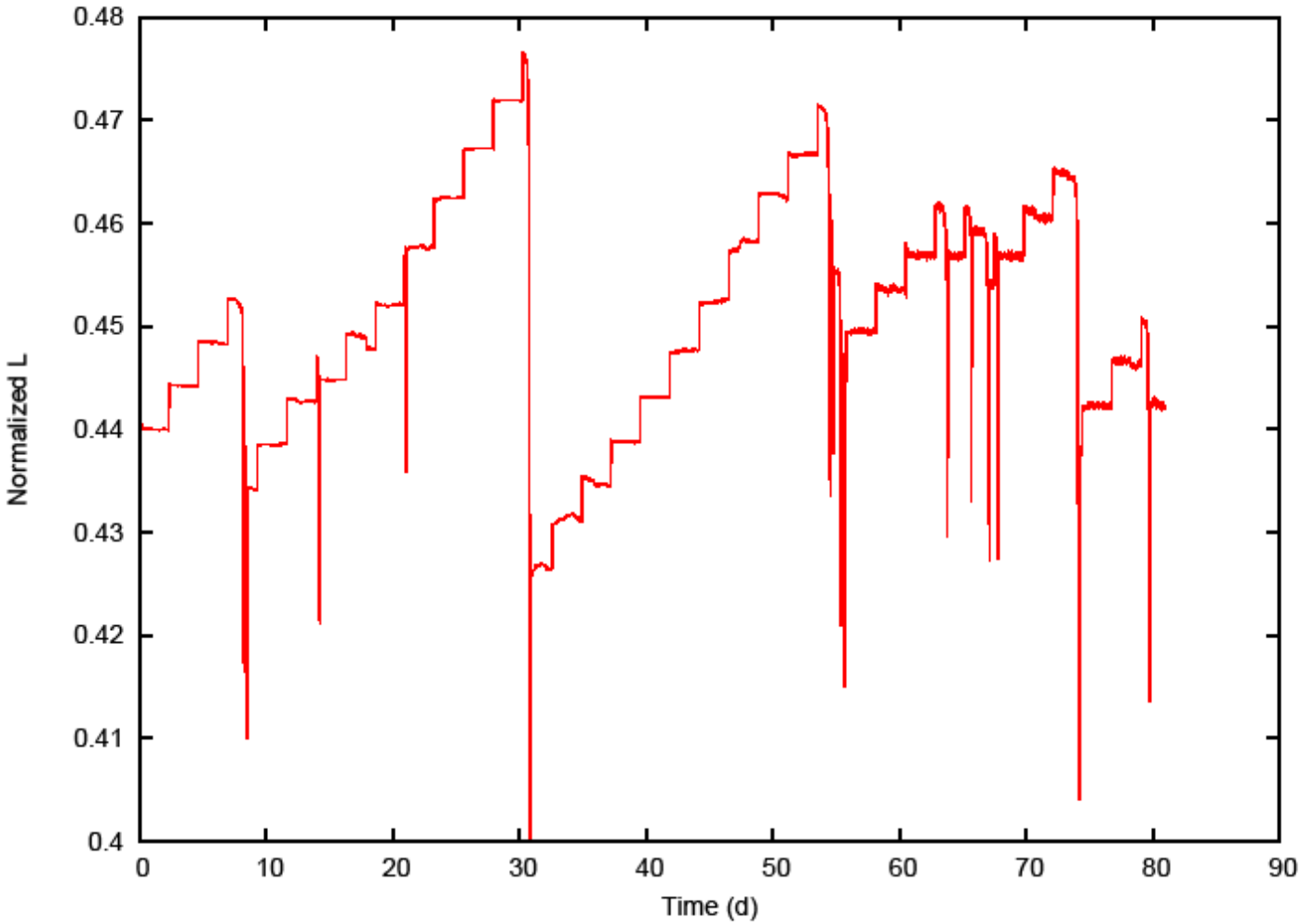


Method

- pkdgrav: N-body gravitational code – hard spheres and collisions
- no friction
  - but restitution coeff. = 0.8 (both radial and tangential)
- "asteroids" of 1000 equal spheres (50 m) and 3 g/cm^3 density (but also variations of those parameters)

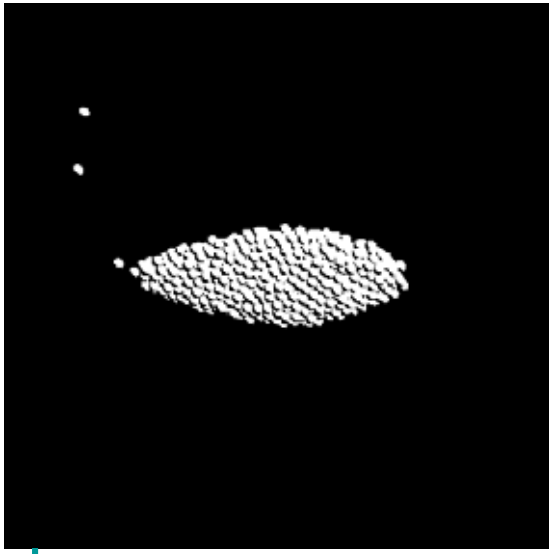
- Getting close to the spin barrier:
  - Spin-up by "kicks" (rigid rotation added)
  - 0.01%-1% in angular momentum increase
  - check reshaping and wait for stability before the subsequent kick (→ very similar to Walsh et 2008 for satellite formation)

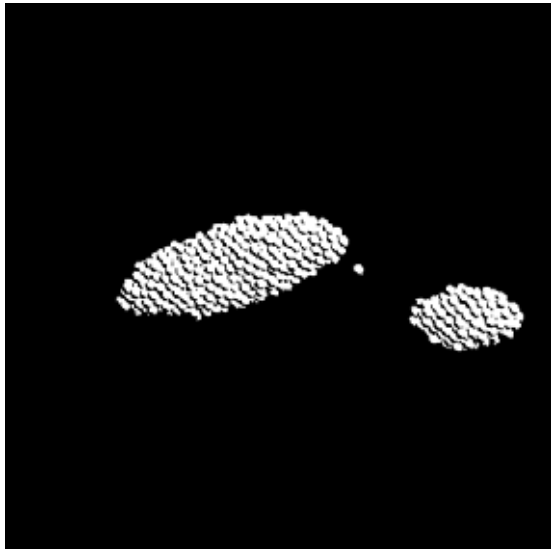
angular momentum evolution



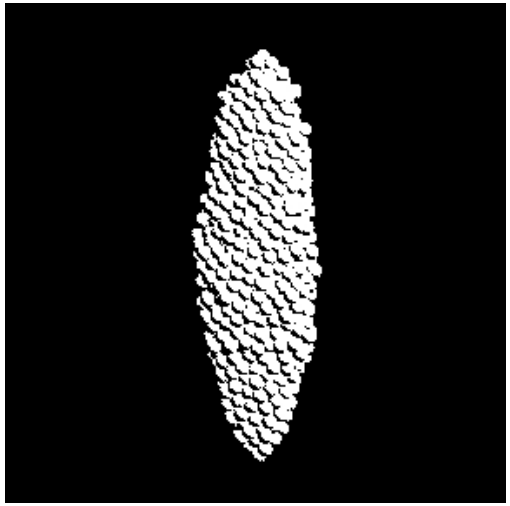
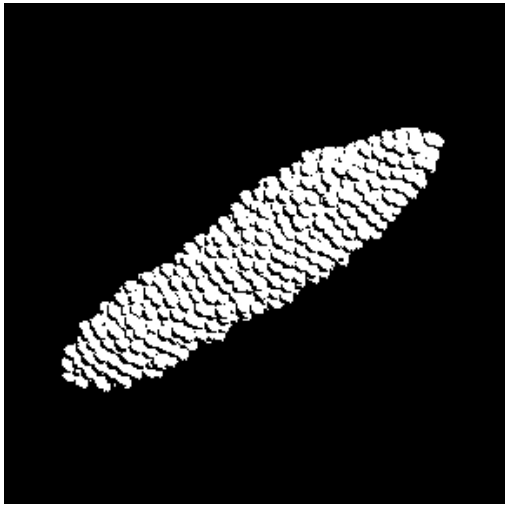
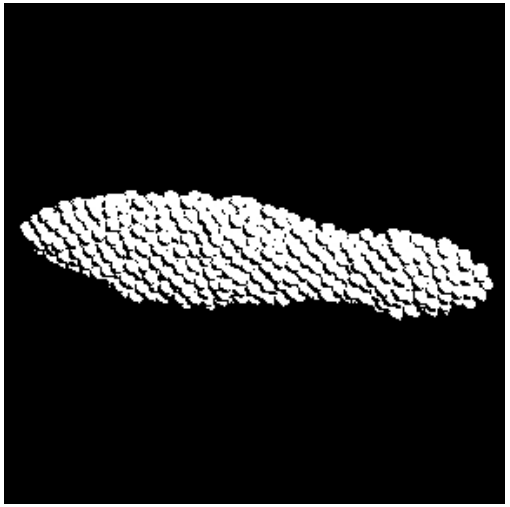
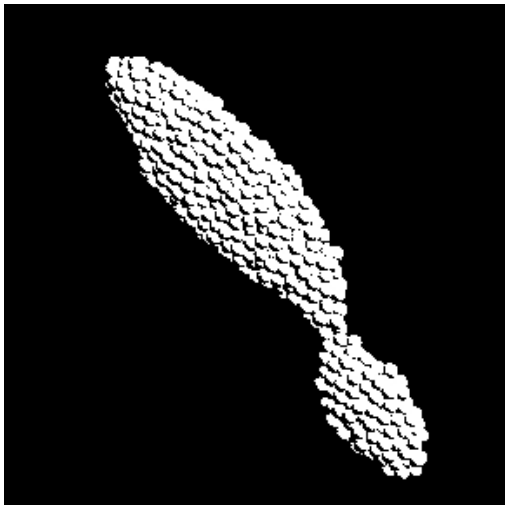
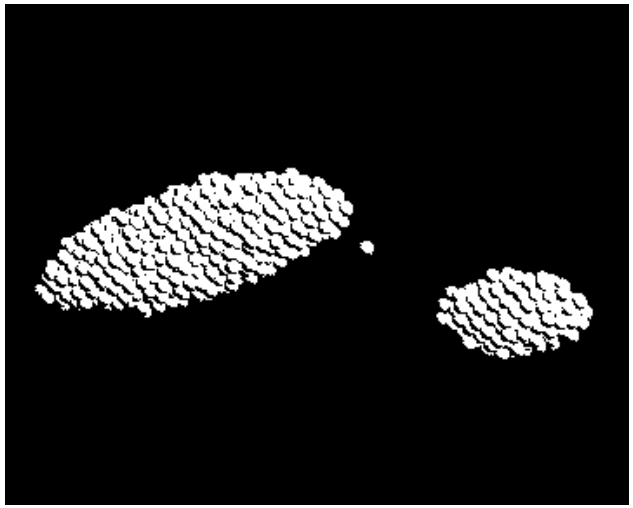
Typical evolution: mass losses

- Two typical situations not mutually exclusive:

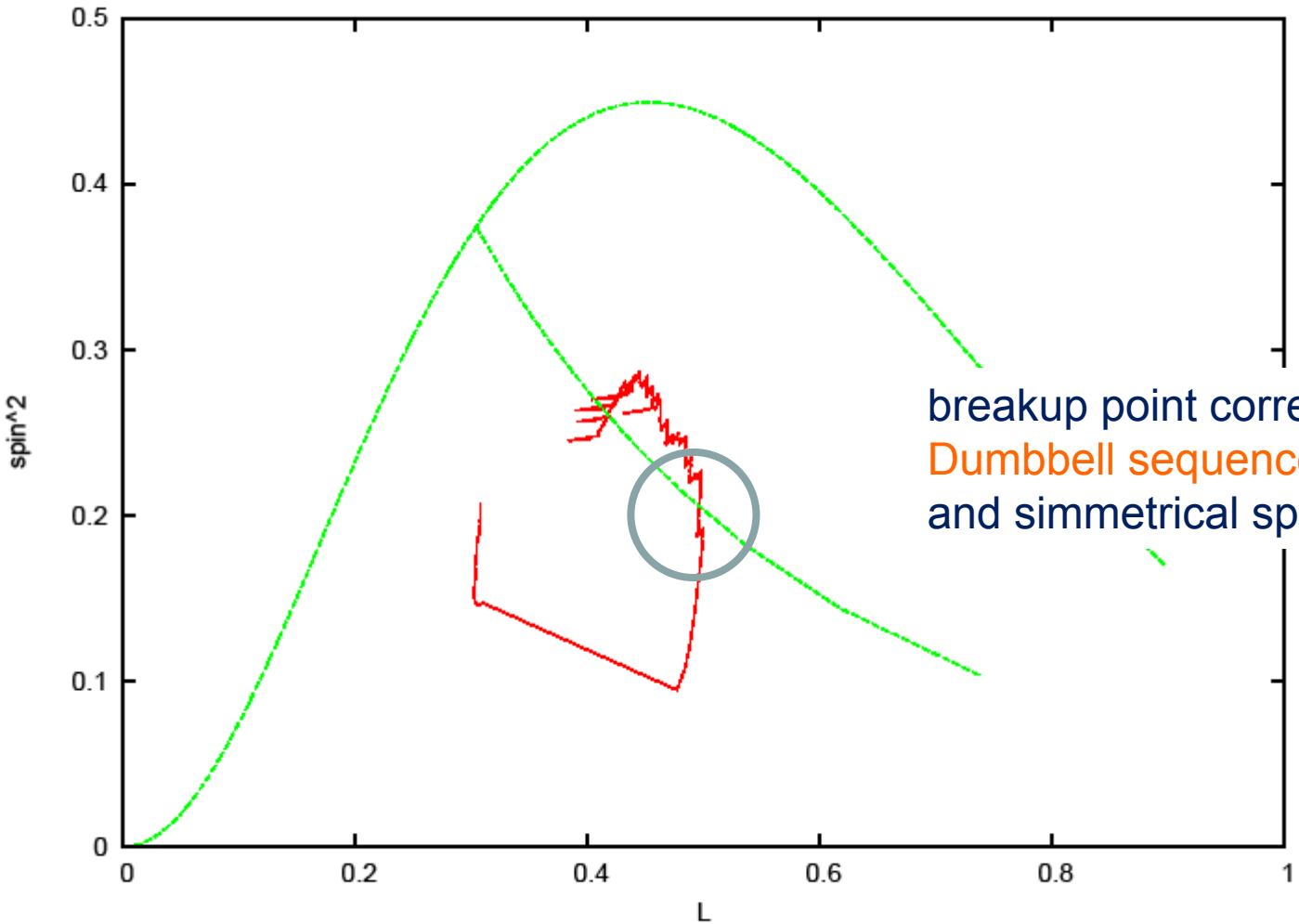




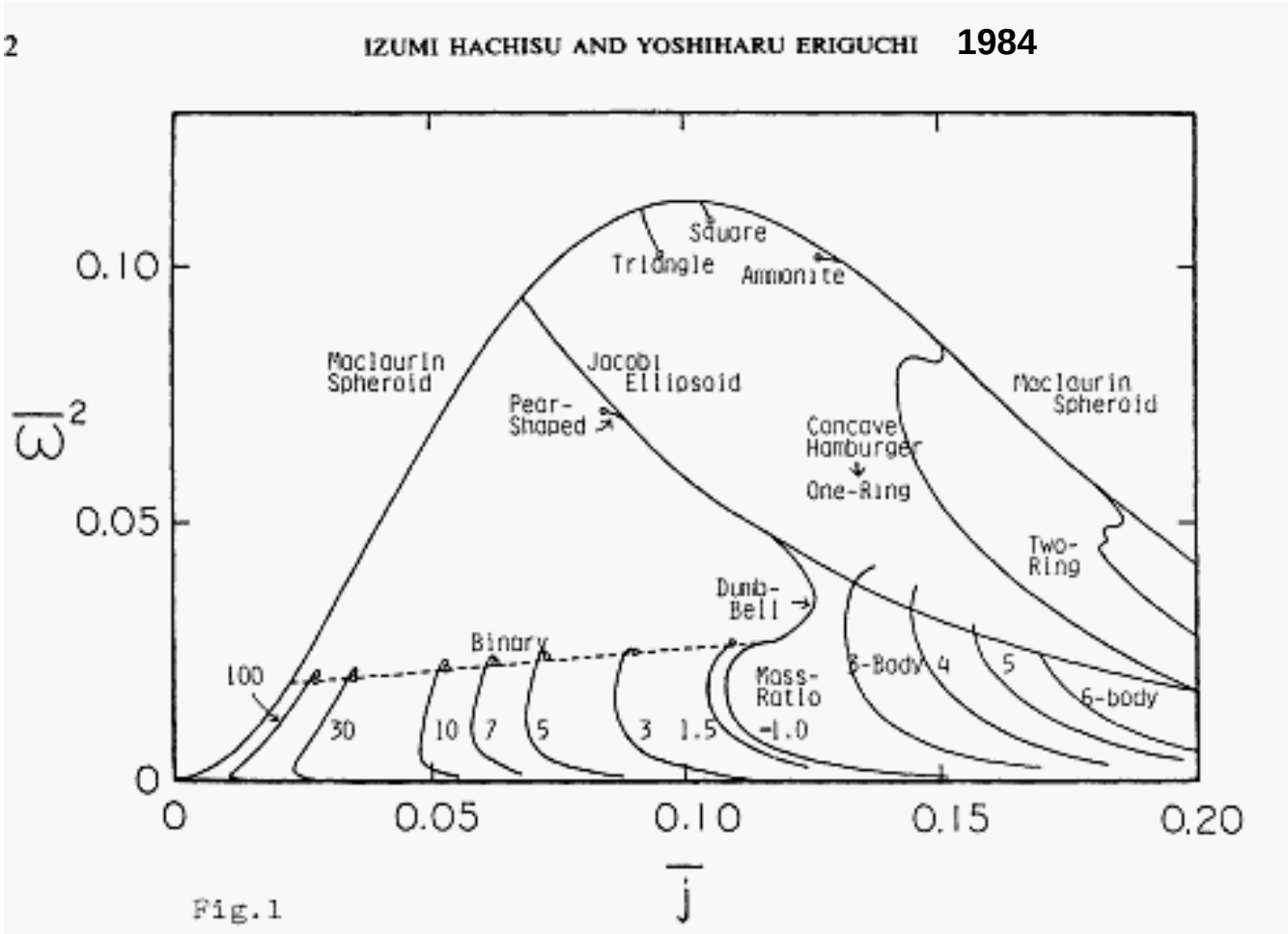
satellite formation by accretion of fragments (Walsh et al. 2008)

Evolution Sequence - L vs ω^2



breakup point corresponding to Dumbbell sequence (elongation and simmetrical splitting)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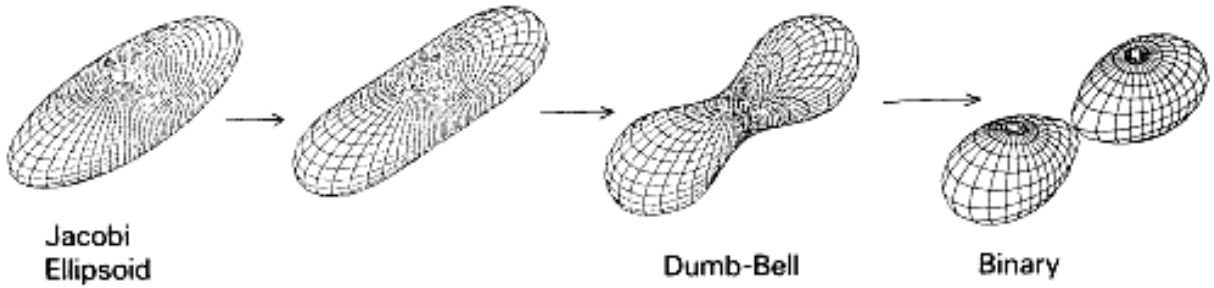

Jacobi Ellipsoid
Dumb-Bell
Binary

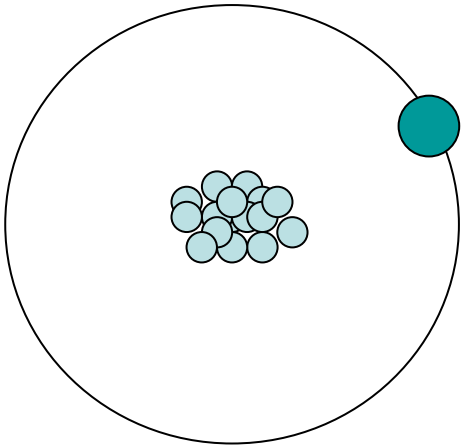
Summary

- Splitting occurs when/where expected by fluid theory
  - They are very close to fluid: repose/“friction” angle ~5°
- Shape evolution poorly/not sensitive to initial shape
  - in flattened spheroids small asymmetries develop into a pear-shaped body before splitting
- Obtained systems are moderately-to-highly chaotic
  - Small change in initial conditions → different evolution
- 40% of cases do form large satellites, regardless of dimension or density (15% - 50% primary mass)
  - Difference from Walsh et al. (~7% at most)
- not all satellites are stable (in a few orbits)
- biggest satellites (>≈20% primary mass) are more stable
  → Scheeres 2007, Pravec et al. 2010

Limitations

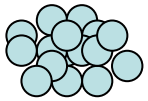
- The code is unable to follow long-term evolution of the couples
  - Approximate computation of gravity
  - Other approximations… (multiple collision handling…)

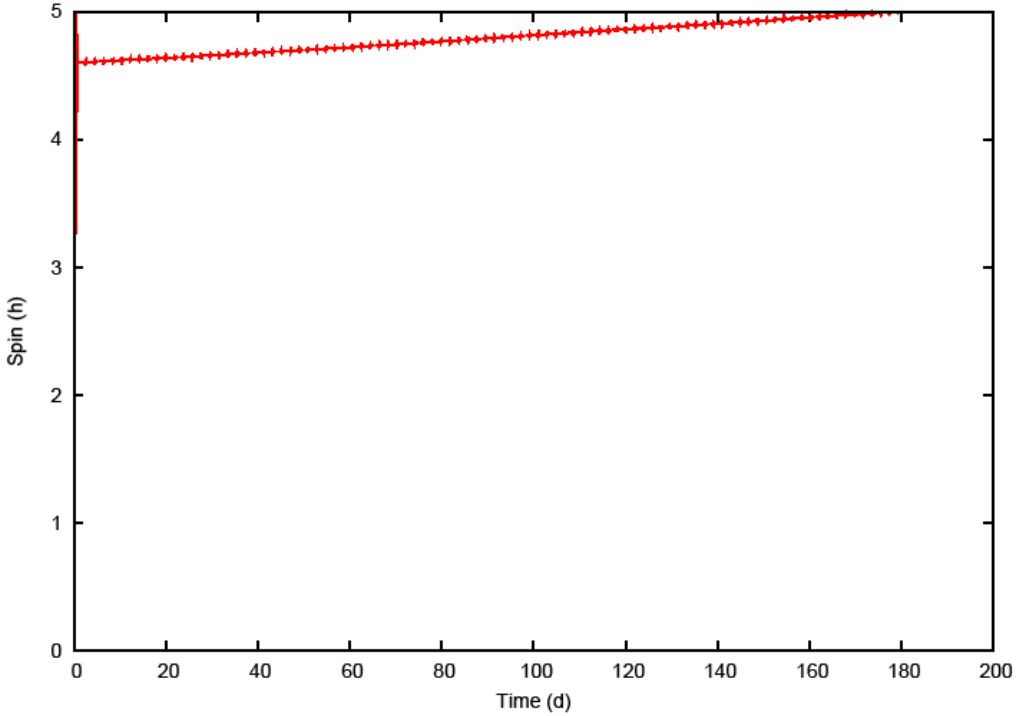
- Attempt to simulate a tidal effect on a satellite orbit:



Evolution of the system

0.6 x 0.4 x 0.8





initial relaxation followed by secondary tidal frictioning / spin-orbit coupling

we can "freeze" bodies into rigid rubble piles just after splitting ...