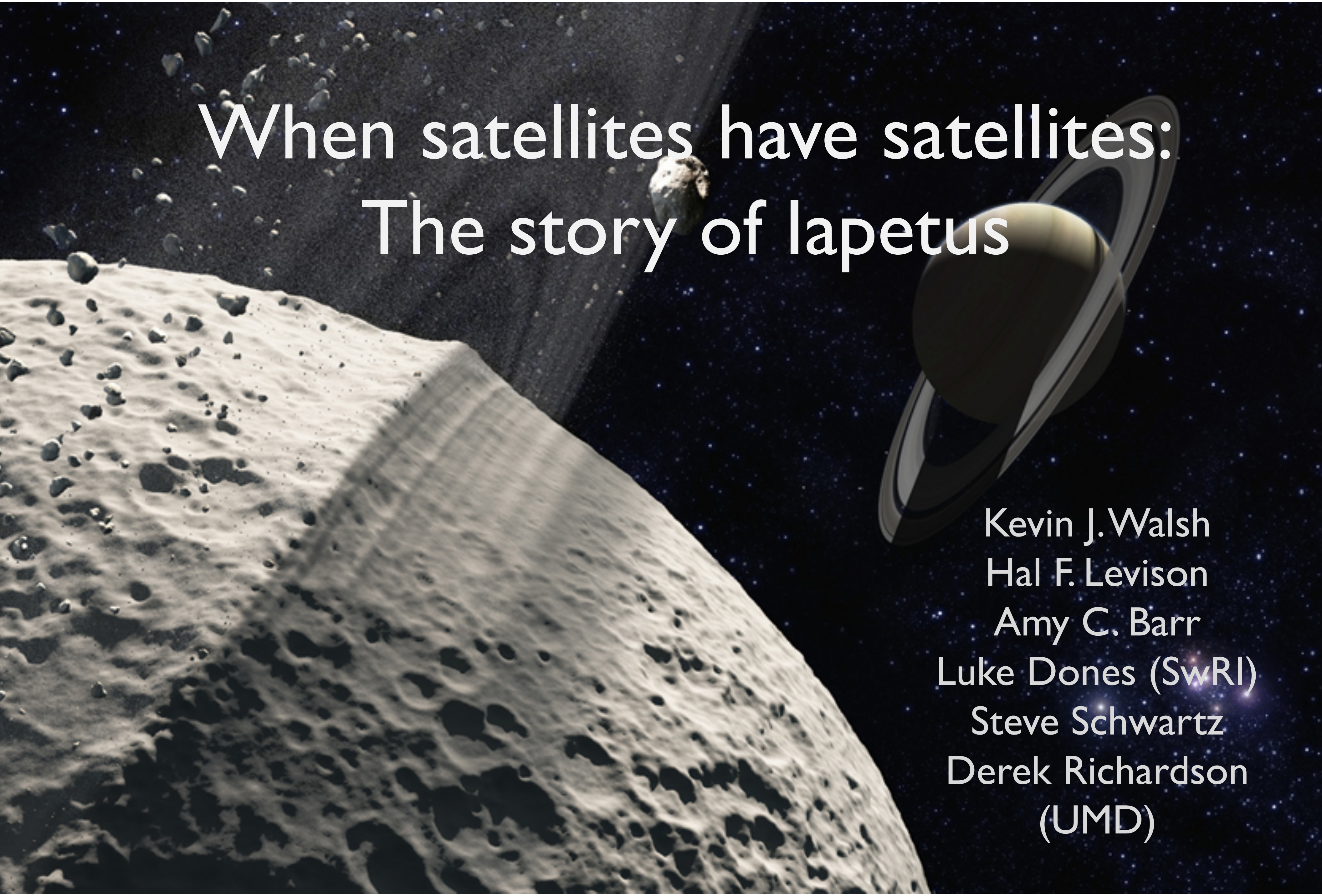

When satellites have satellites: The story of Iapetus

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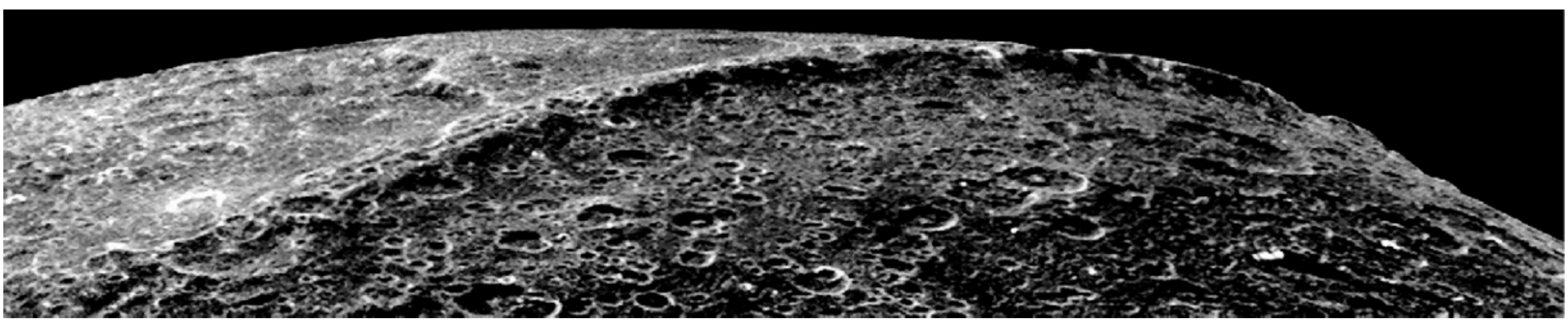
Iapetus oddities

- It appears that Iapetus has de-spun significantly in its lifetime,
  - Iapetus is currently rotating with a 79.3 day period, synchronous with its orbital period.
- Its global shape is not in hydrostatic equilibrium,
  - It has the shape of a body at 16 h rotation – this is the "fossil bulge".
- The "equatorial ridge", ~15 km tall and ~50 km wide, covers at least 110° of the equator.



Problems

de-spinning Iapetus

- Saturnian tides fail when operating on a rigid, cold Iapetus,
  - De-spinning takes > 10 Gyrs
- Saturnian tides can only succeed with the aid of an extra energy source,
  - Frequently modeled as Short-/Long-lived radioactive isotopes (i.e. ^{26}Al)

Equatorial ridge

- Ridge formation by an endogenic process is challenging,
  - Stresses frequently are in the wrong direction
  - Thermal bouyancy stress makes it hard to lift such a large ridge
- It appears to be one of oldest features on the surface
  - The timing of its formation must be considered.

What if Iapetus had a (sub-)satellite?

Tidal de-spinning

- A satellite with $\boldsymbol{n} > \Omega_{lap}$ of Iapetus evolves outward…
  - An outwardly evolving satellite (due to tides) de-spins Iapetus.
  - Larger sub-satellites take more angular momentum from Iapetus, de-spinning it faster
  - Smaller sub-satellites take longer, affecting Iapetus less

Equatorial ridge

- A small satellite is likely to form from a debris disk straddling the Roche limit,
  - Similar to Earth-Moon system
- Debris inside the Roche limit/ Synchronous limit,
  - tidally evolves inward and,
  - gets pushed to the surface by the satellite.
- The in-falling ring could form an equatorial ridge (Ip 2006).

Where could a satellite come from?

Collisional origin

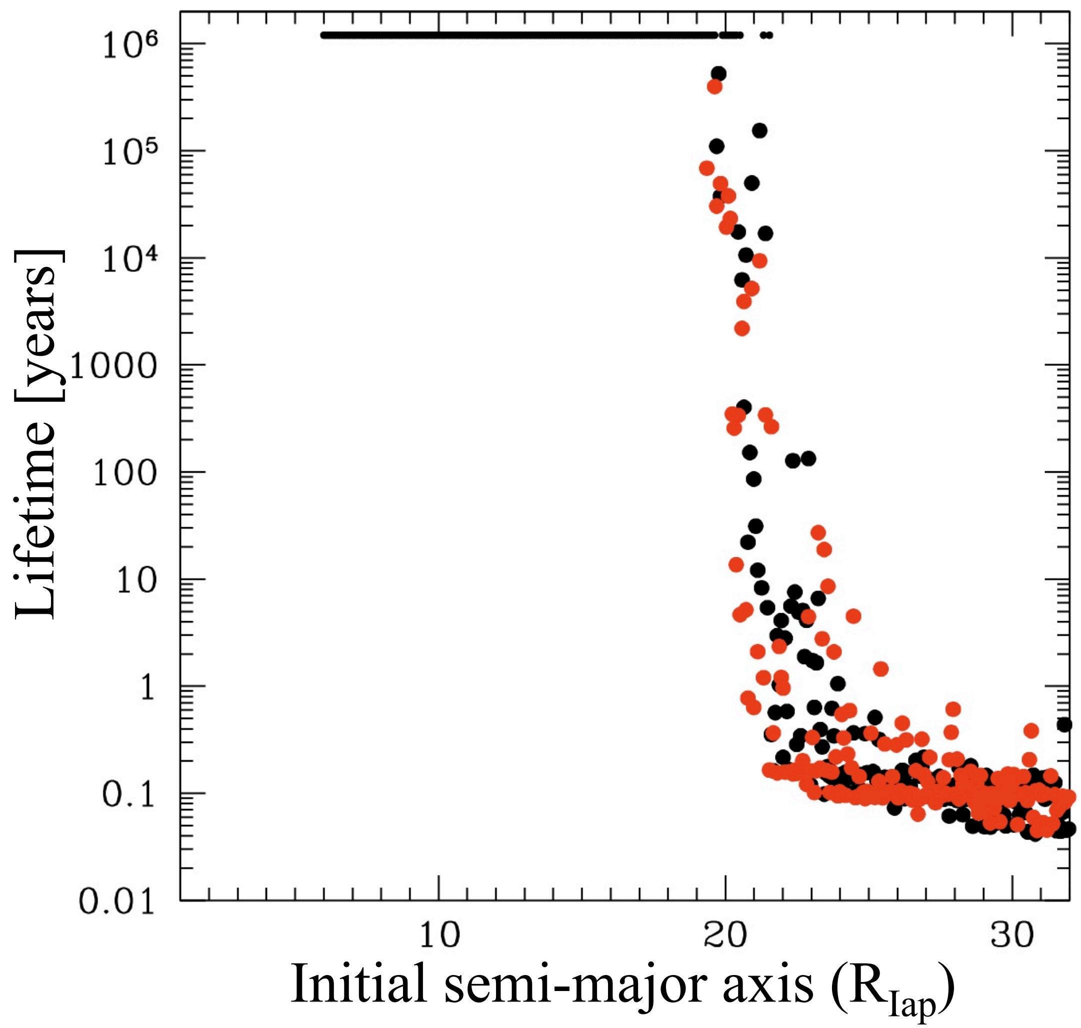
- Levison et al. (2010) propose that a large impact into Iapetus ejects significant debris into orbit
- The disk quickly collisionally damps to a disk.
- Disk straddles the Roche limit, producing a satellite outside, leaving debris inside,
- The collision would leave Iapetus with a rotation rate ≤ 16h

Intact capture

- Dombard et al. (2011) propose the capture of a satellite, following a collision.
- The proposed event would require a ~100km satellite (0.1% Iapetus' mass),
- Follow Canup (2005,2011) to suggest orbits of:
  - $a = 3.7\text{-}21\ R_{Iapetus}$
  - $e = 0.1\text{-}0.8$

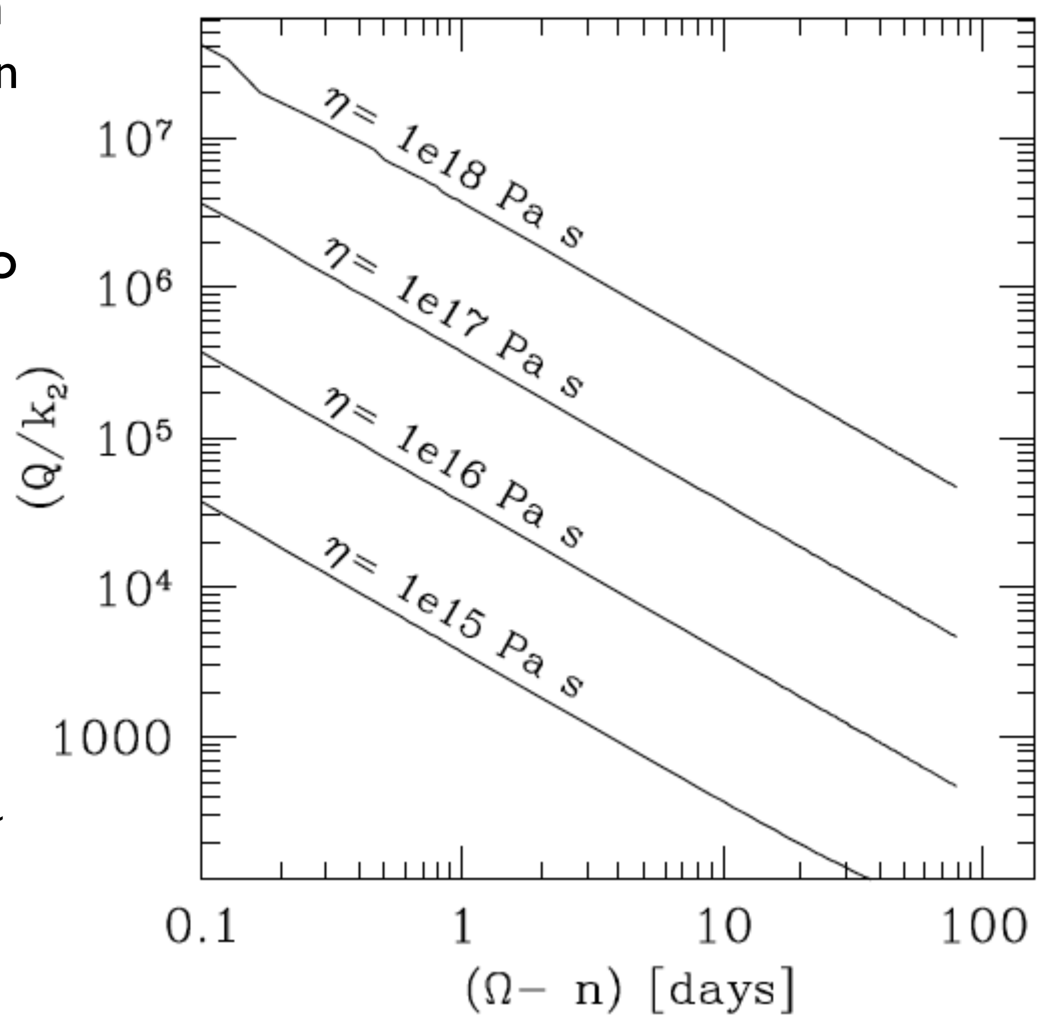
Tidal evolution with a sub-satellite

- As the sub-satellite evolves to larger semi-major axis it will eventually get stripped by Saturn.
- We found that sub-satellite lifetimes drops precipitously beyond $a \sim 21\ R_{lap}$
- Orbital period at $a \sim 21\ R_{lap}$ is ~12 days.
- For all following calculations we consider this endpoint of tidal evolution.



Tidal evolution with a sub-satellite

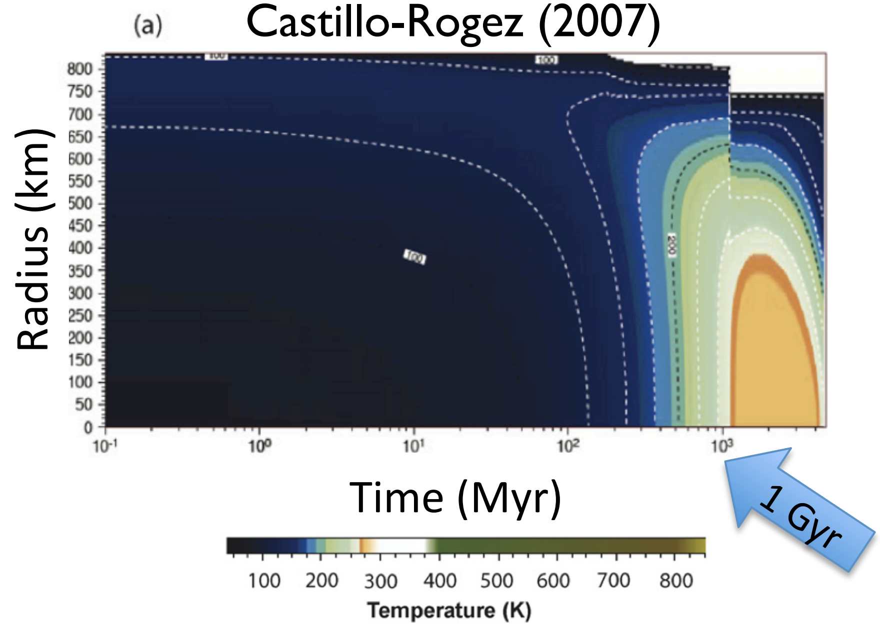
- de-spinning and orbit expansion rates depends on
  - the internal tidal dissipation (Q/k_2),
- Q/k_2 is not static – this ratio depends on
  - The internal state (Temperature, lithosphere thickness…)
  - Tidal frequency
- We need to consider the internal state of Iapetus as a function of time.



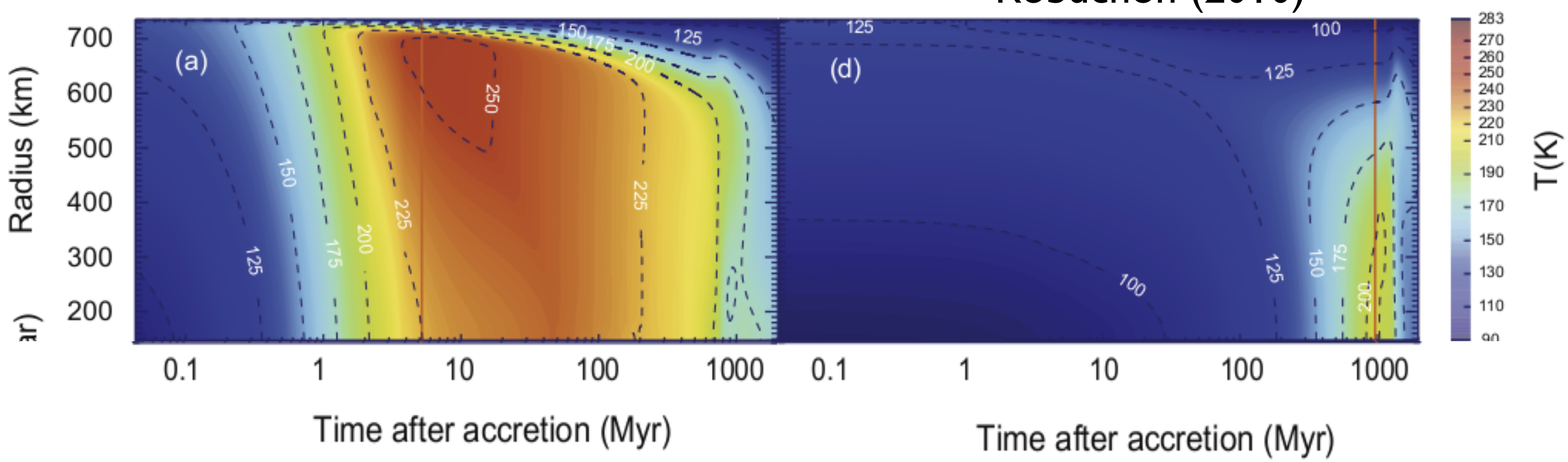
Internal evolution of Iapetus

- Castillo-Rogez (2007) and Robuchon (2010) modeled the internal evolution of Iapetus under many effects
    - Initial porosity
    - Short-live radioactive isotopes
    - Long-lived radioactive isotopes
    - Convection (Robuchon only)

Castillo-Rogez (2007)

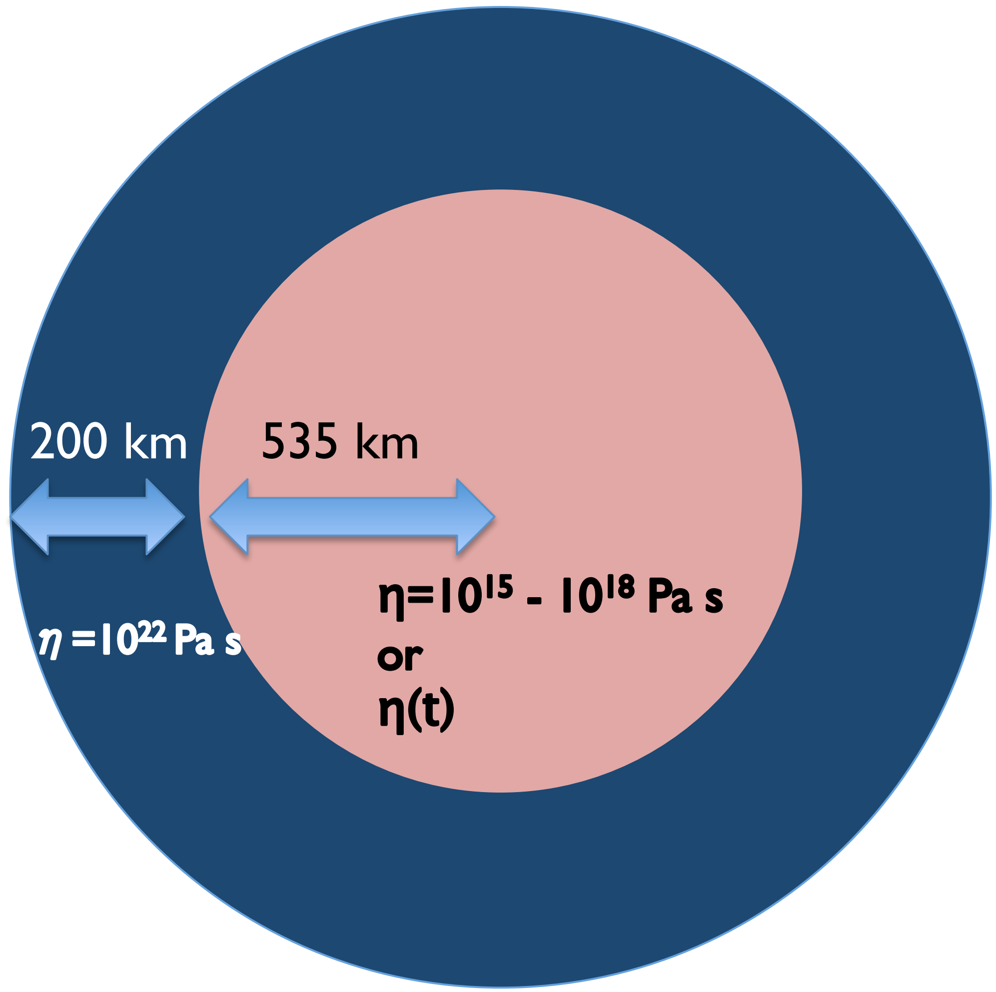


Robuchon (2010)

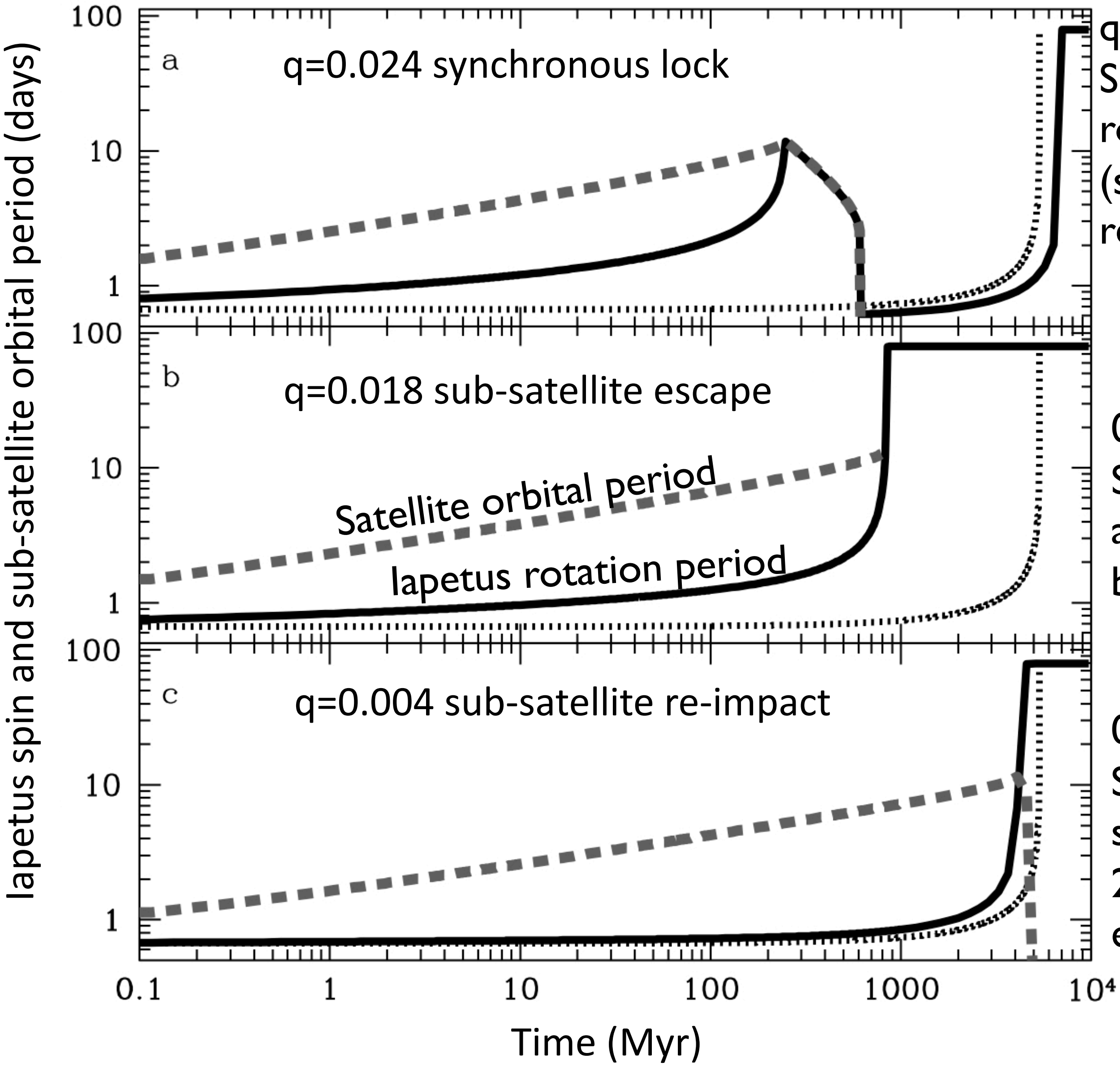


A simple model of Iapetus

- We needed a simple model of Iapetus to calculate Q/k_2 at each tidal frequency.
- 200 km lithosphere with high viscosity.
- The rest of the interior is either
  - Static η $=10^{15} - 10^{18}$
  - η (t) according to Castillo-Rogez (2007) or Robuchon (2010)
- We calculate Q/k_2 values for this body as a function of the internal η



Tidal evolution for $\eta=10^{16}$ Pa s



$q > 0.021$
Sub-satellite slows Iapetus rotation to < 12 days (synchronous), before reaching $a>21\ R_{lap}$

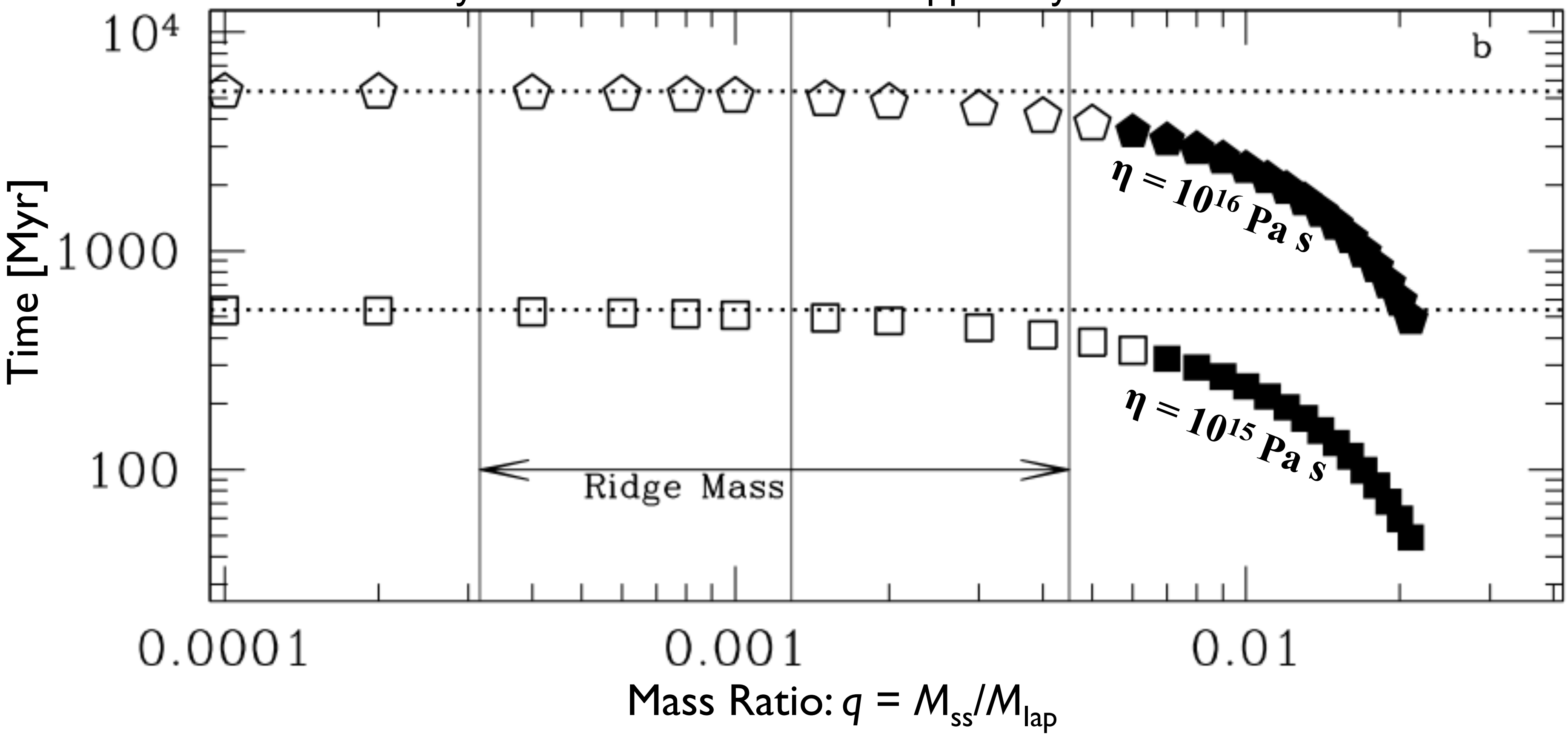
$0.006 < q < 0.021$
Sub-satellite evolves to $a>21\ R_{lap}$, and is stripped by Saturn.

$0.006 > q$
Sub-satellite evolves too slowly and never reaches $21\ R_{lap}$. It eventually evolves back to Iapetus.

De-spinning time-savings

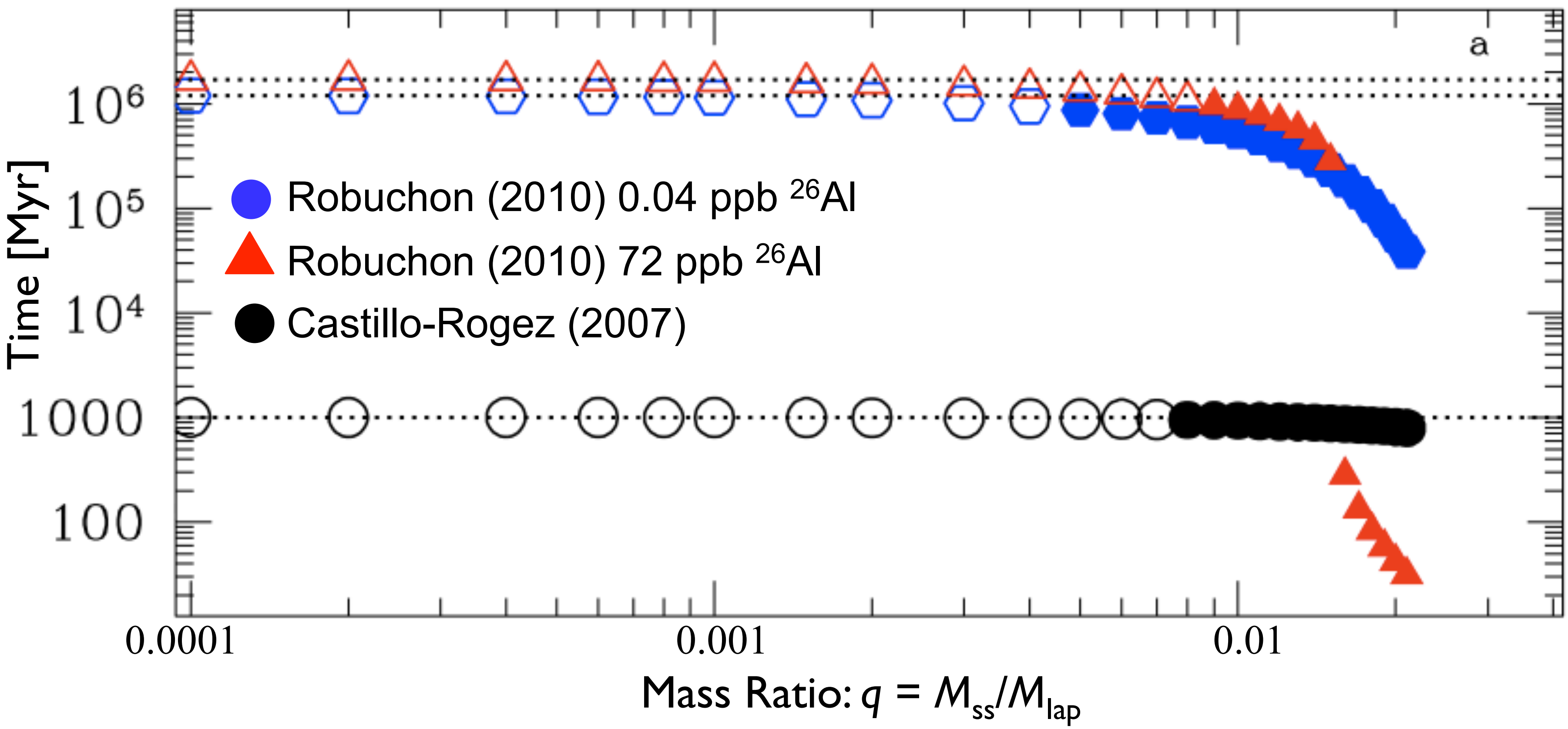
• For the simple cases with static internal viscosities sub-satellite mass ratio $q = M_{ss}/M_{iap} = 0.021$ de-spins 10x faster than by Saturn alone.

Open symbols: sub-satellite is too small – is never stripped
Closed symbols: sub-satellite is stripped by Saturn



De-spinning time-savings

- For the Robuchon models with 72 ppb and 0.04 ppb ^{26}Al (SLRI)
  - $q= M_{ss}/M_{iap}$=0.021 <u>de-spins > 10x faster</u> than by Saturn alone.
- For Castillo-Rogez (2007) model with LLRI and initial porosity
  - q=M_{ss}/M_{iap} =0.021 only de-spins 20% faster



A stripped sub-satellite

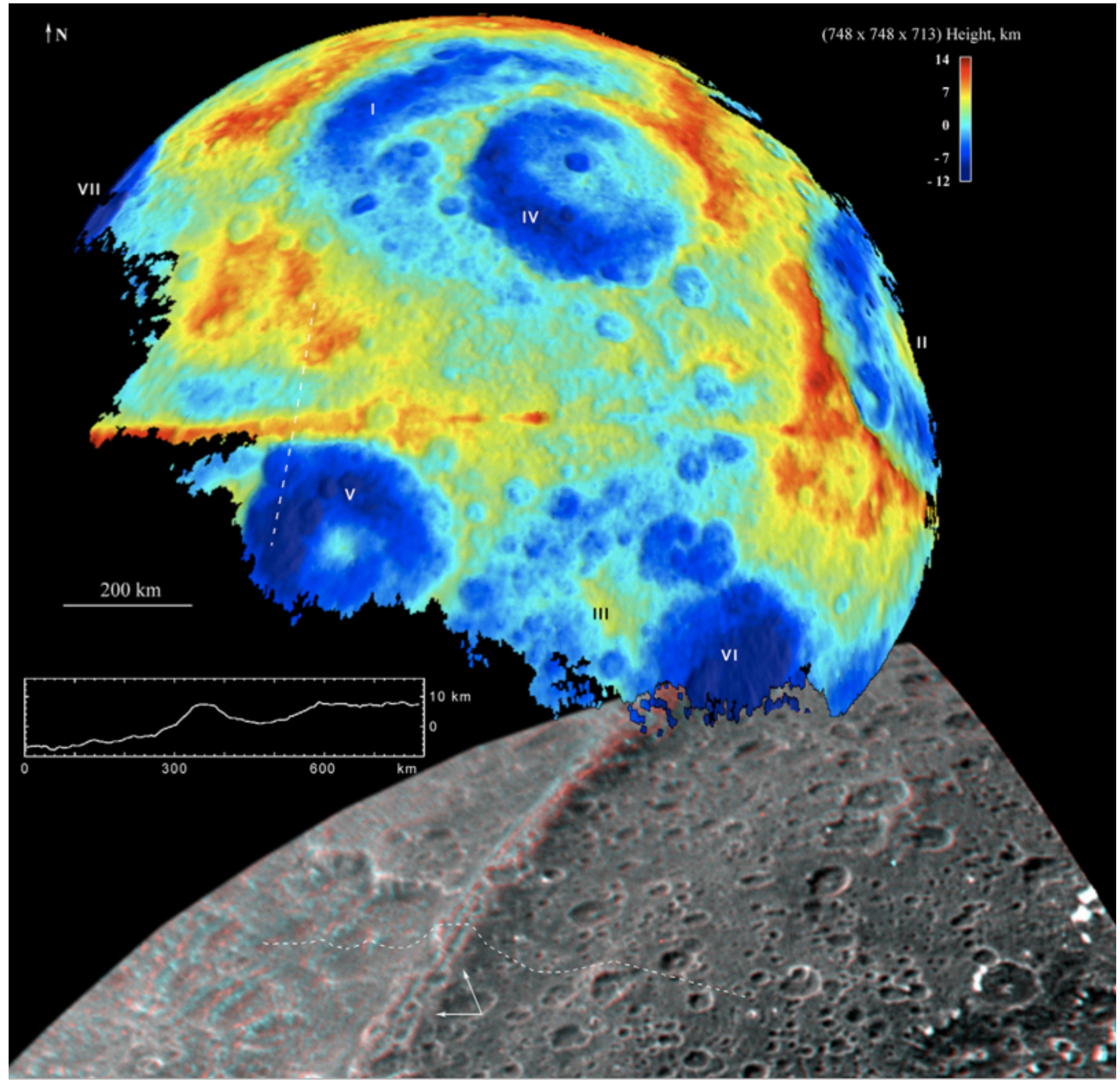
- For the mass ratios which produce the largest time-savings in de-spinning, q=0.06—0.021, the sub-satellite is stripped by Saturn.

- What happens to the sub-satellite?
  - In 90% of the cases – it re-impacts Iapetus.

- Will this increase Iapetus' spin dramatically?
  - No. Likelihood is very small for impact to substantially increase the spin rate for most q.

Topography

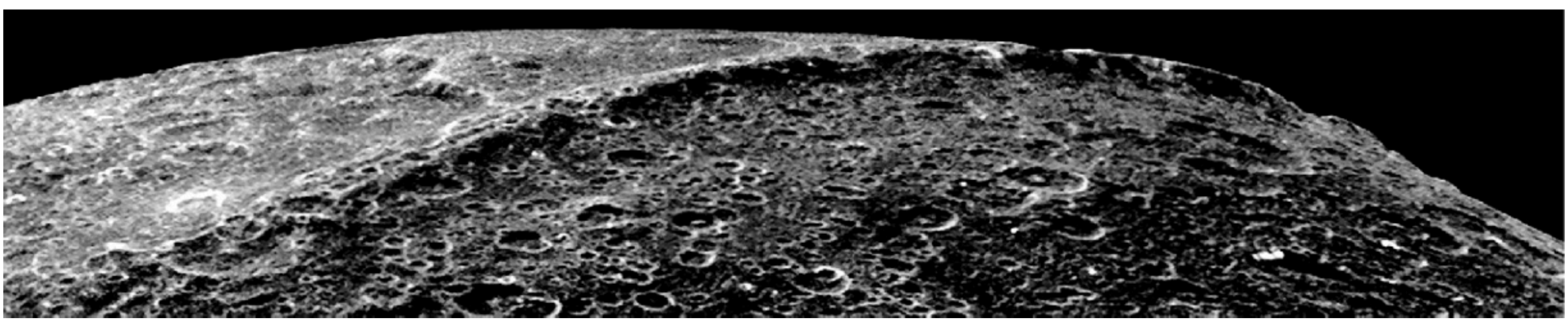
- Iapetus has at least 7 basins between 300-800 km.
- The sub-satellite re-impact would impact near escape velocity ~0.58 km/s.
- Impactors with q=0.005—0.021 match the basin sizes.



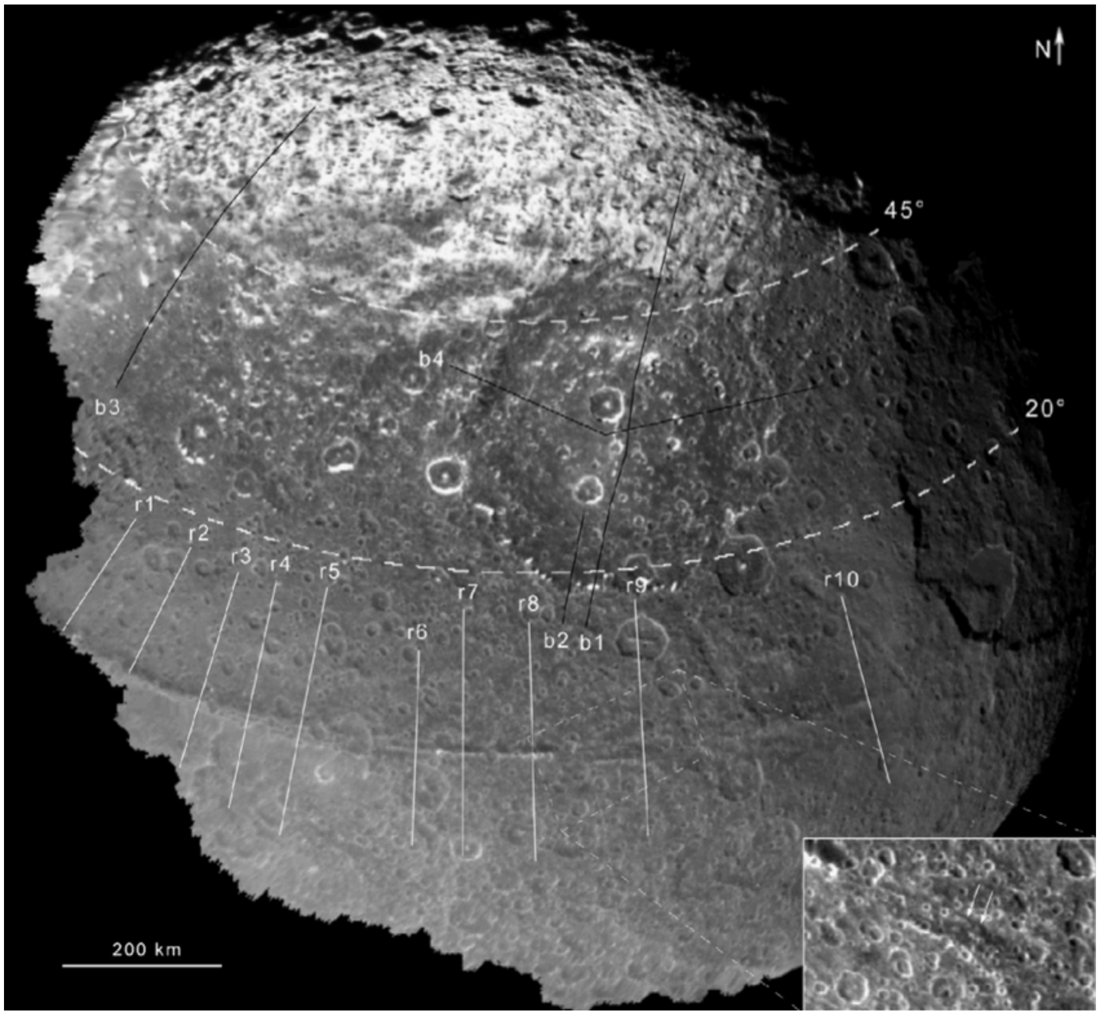
Giese et al. 2008

Building the ridge

- After accreting out of a ring of debris the sub-satellite can/will push the remaining debris to the surface.
  - Tidal spreading times of a ring due to an external perturber (sub-satellite) are very short ~10-1000's years
- The in-falling debris will have velocities nearly tangential to the surface at only 300 m/s.
- Will the morphology match all the details of the observed ridge? (current work)



The Ridge?



Giese et al. 2008

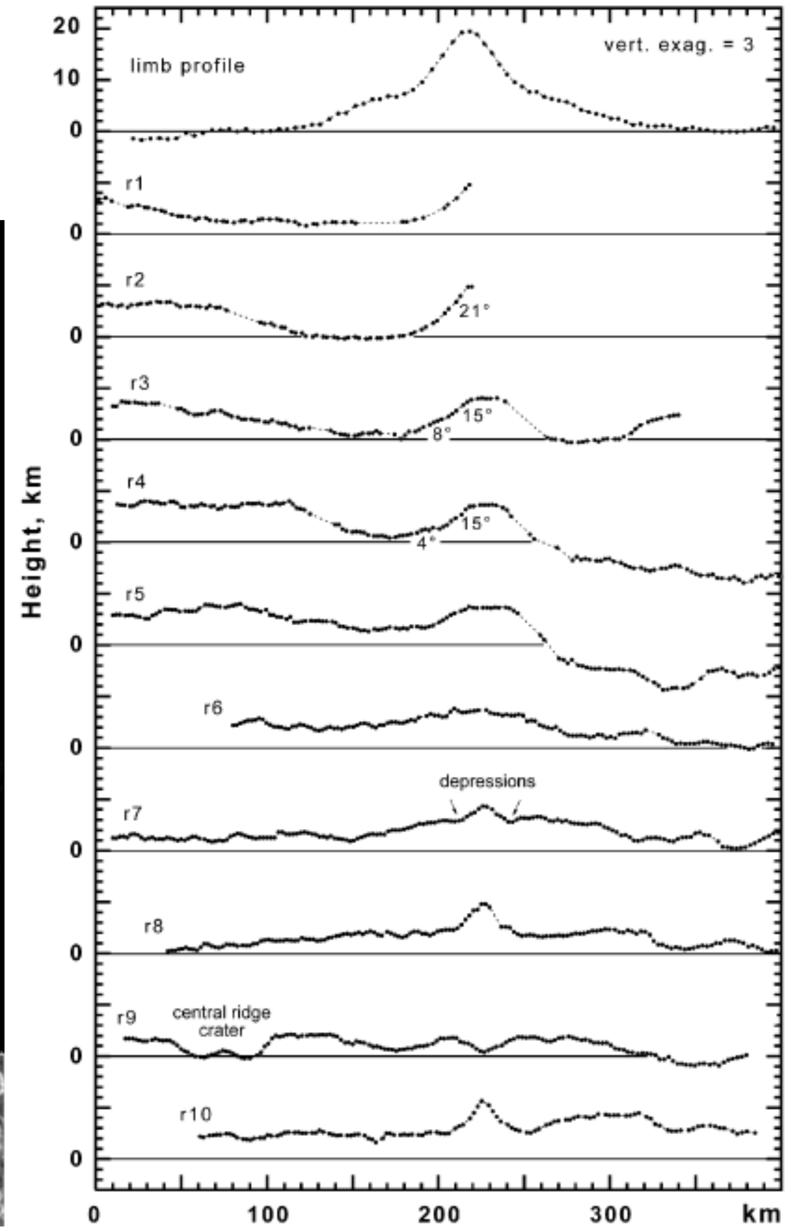
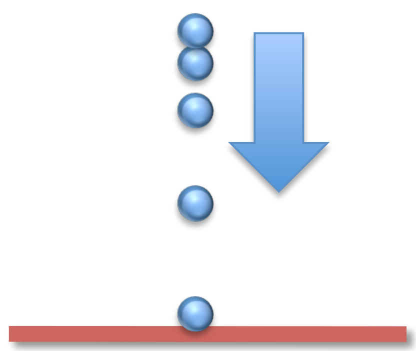


Fig. 5. Profiles across the equatorial ridge. Profile locations are shown in Fig. 6. The top profile is a section of limb profile N1482859953 (Thomas et al., 2008) showing ridge heights in a location distant from the area covered by the DTM.

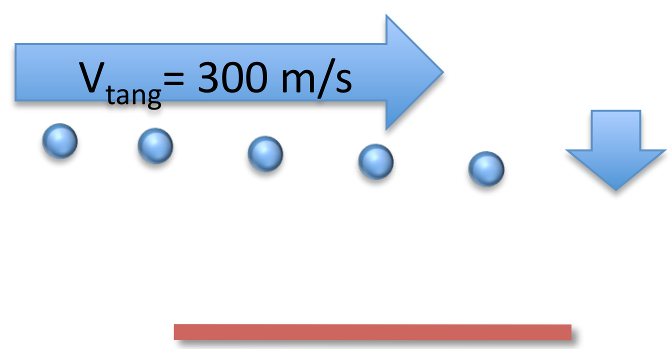
Building a sandpile…

- Where the particles fall with ONLY tangential velocity.

•This sandpile's properties will largely be governed by its granular properties

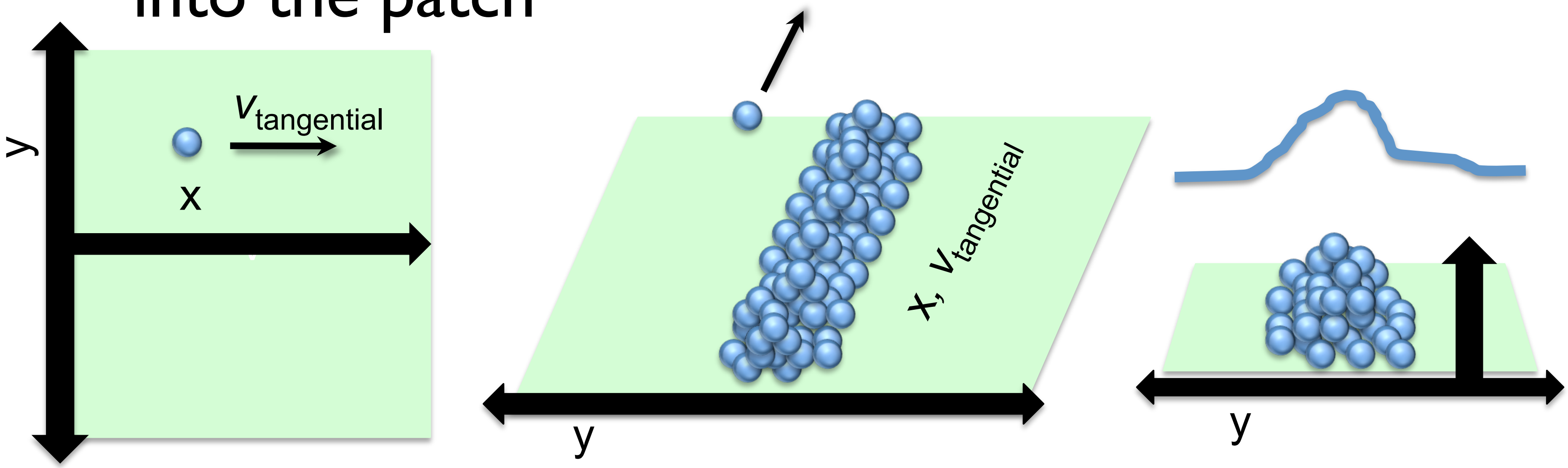


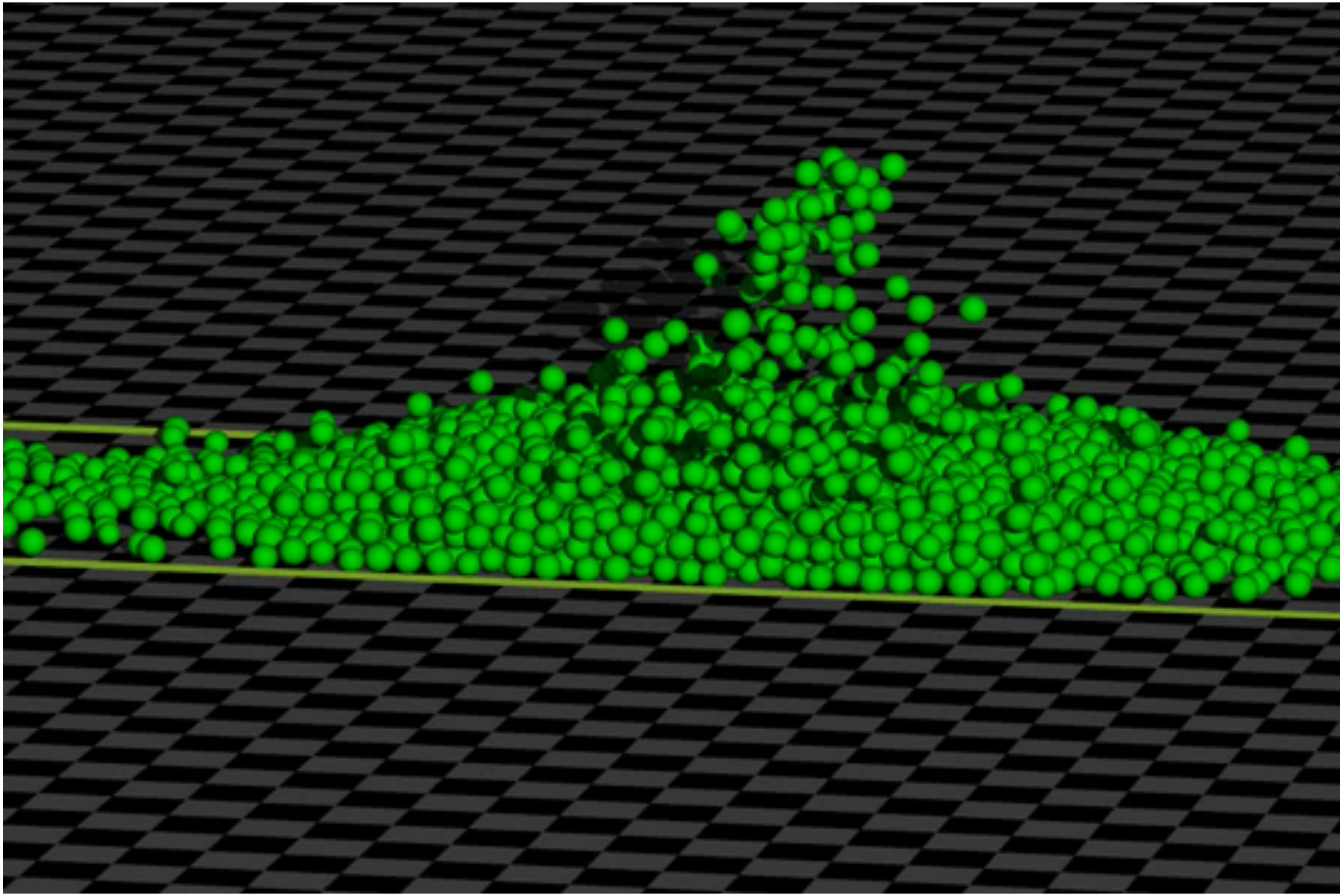
•What will govern the properties of this sandpile's properties????

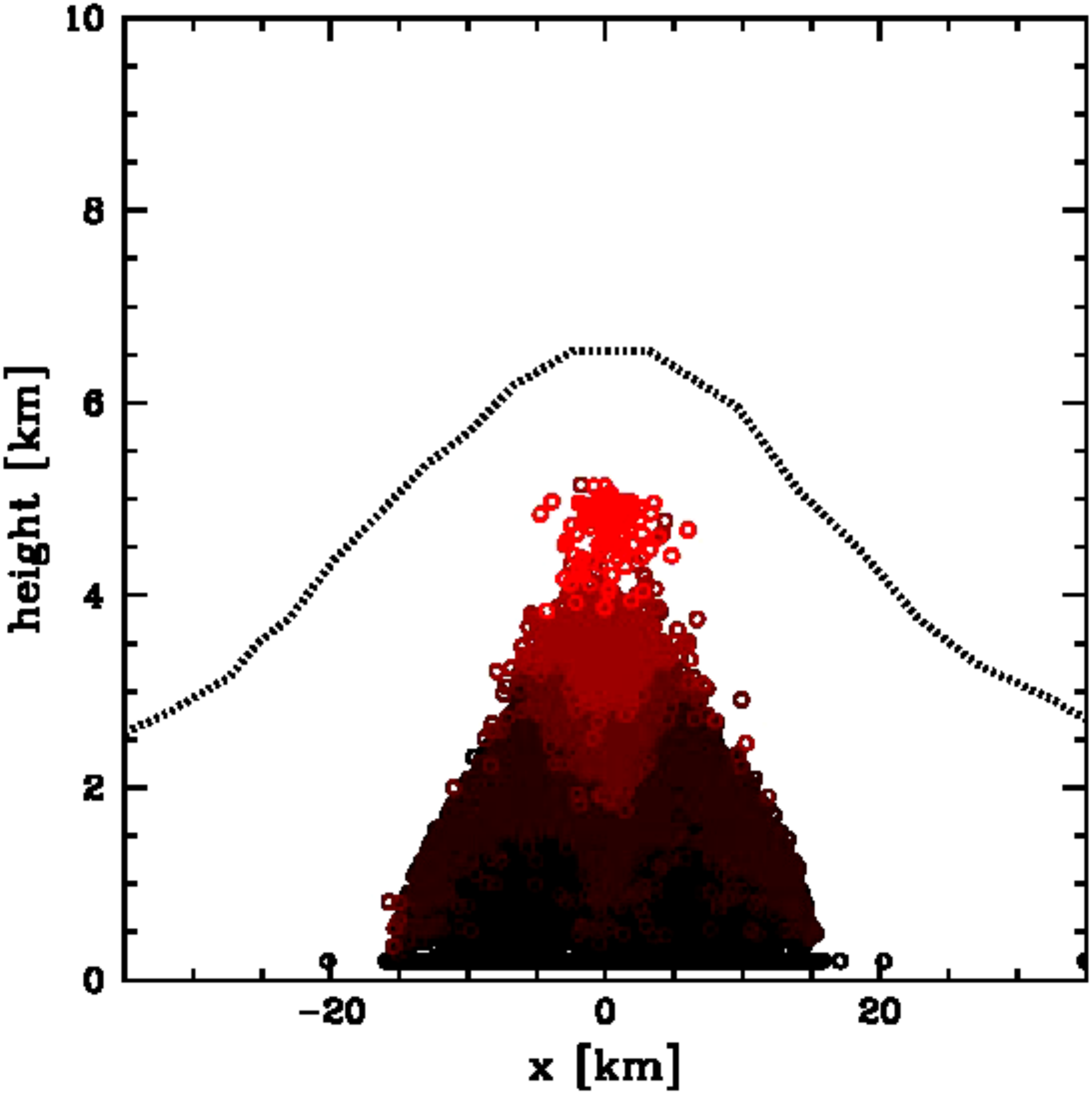


Methods

- We use `pkdgrav` to handle particle-particle interactions
- We model only a small patch of the surface with periodic boundary conditions
- Drop particles with 300 m/s tangential velocity into the patch







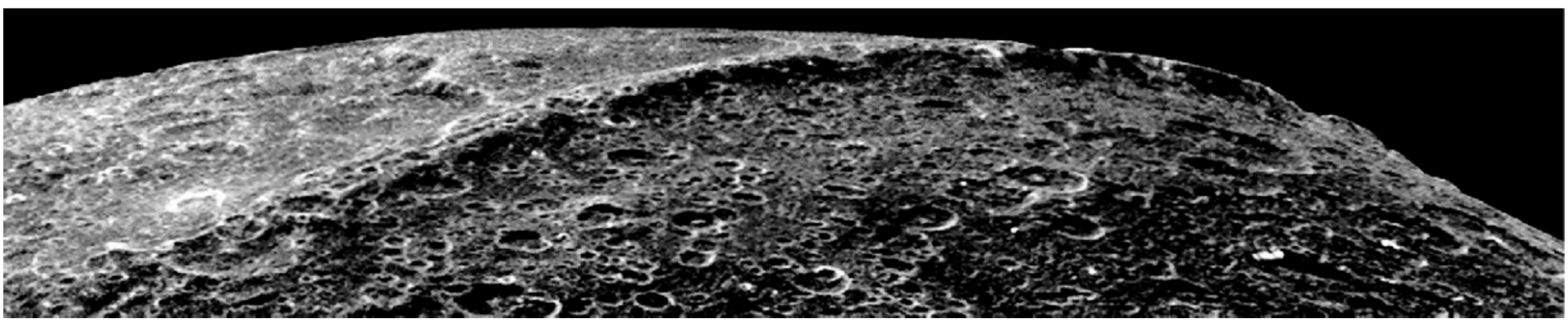
10
8
6
4
2
0
height [km]
−20
0
20
x [km]

Our experiment

- Relative effects of ridge/sandpile construction with tangential velocity
  - We really don't know the state of the in-falling material, or the surface material, or the particle size distribution, or the actual timescales….
  - Also, the numerical challenge of modeling a large static clump/pile/ridge AND in-falling particles with v=300m/s eliminates the possibility of modeling the entire thing – even in a patch.

Conclusions

- A sub-satellite around Iapetus can decrease de-spinning times by a factor of 10.
- Sub-satellites which are stripped by Saturn re-impact Iapetus 90% of the time.
- The remnants of the debris disk, out of which the sub-satellite forms, would be pushed to the surface, possibly explaining the ridge of Iapetus.



- 1. Impact forms a ring of debris out of which a satellite accretes
- 2. Ring gets pushed to the surface to form the ridge
- 3. Tidal interactions between satellite and Iapetus help to de-spin Iapetus, and push the satellite to an orbit large enough to be stripped by Saturn