Interior Structure of Asteroids: Inferences from impact processes*

A discussion with the Small solar system bodies panel of the National Academies' decadal survey on planetary science and astrobiology

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*mostly

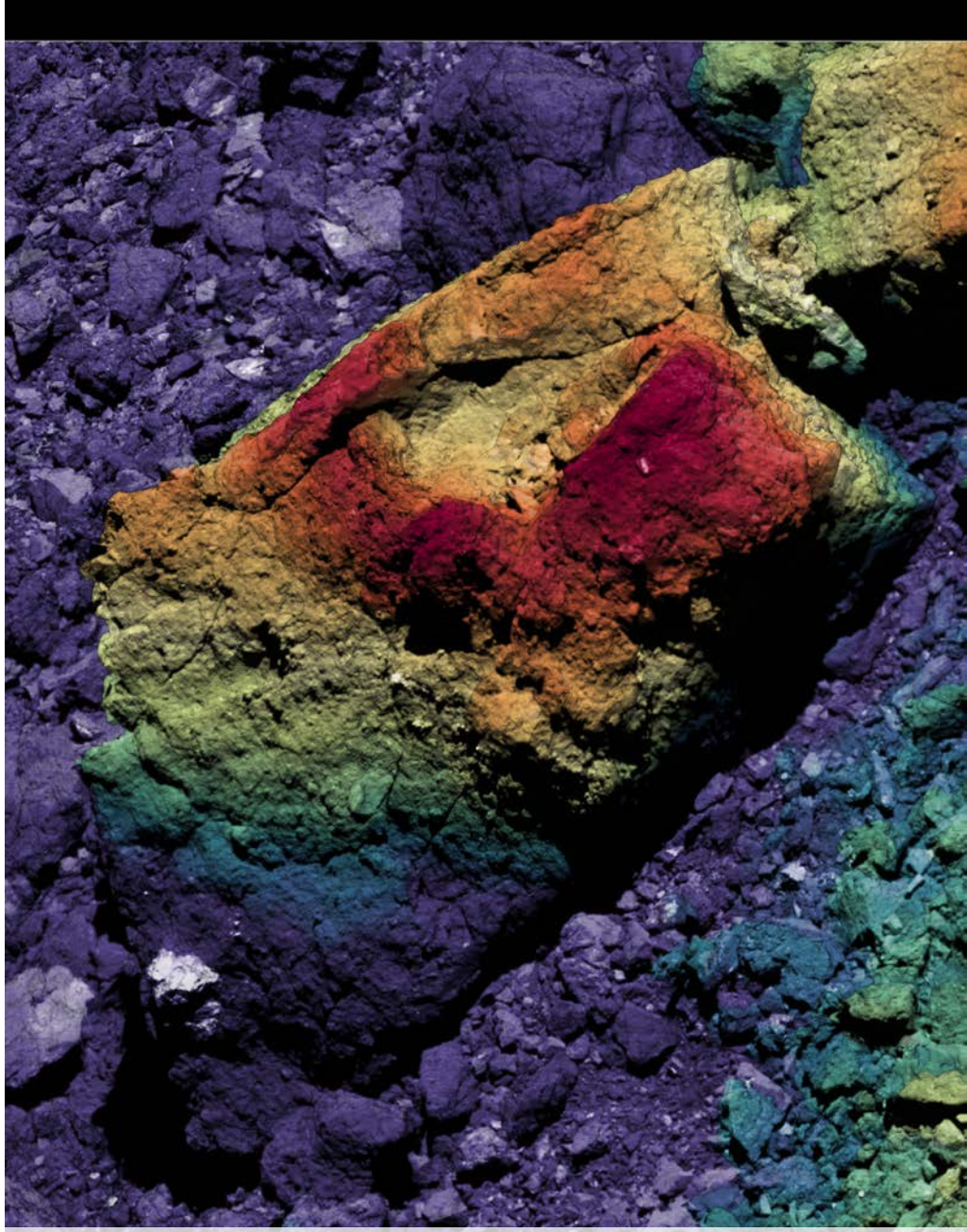
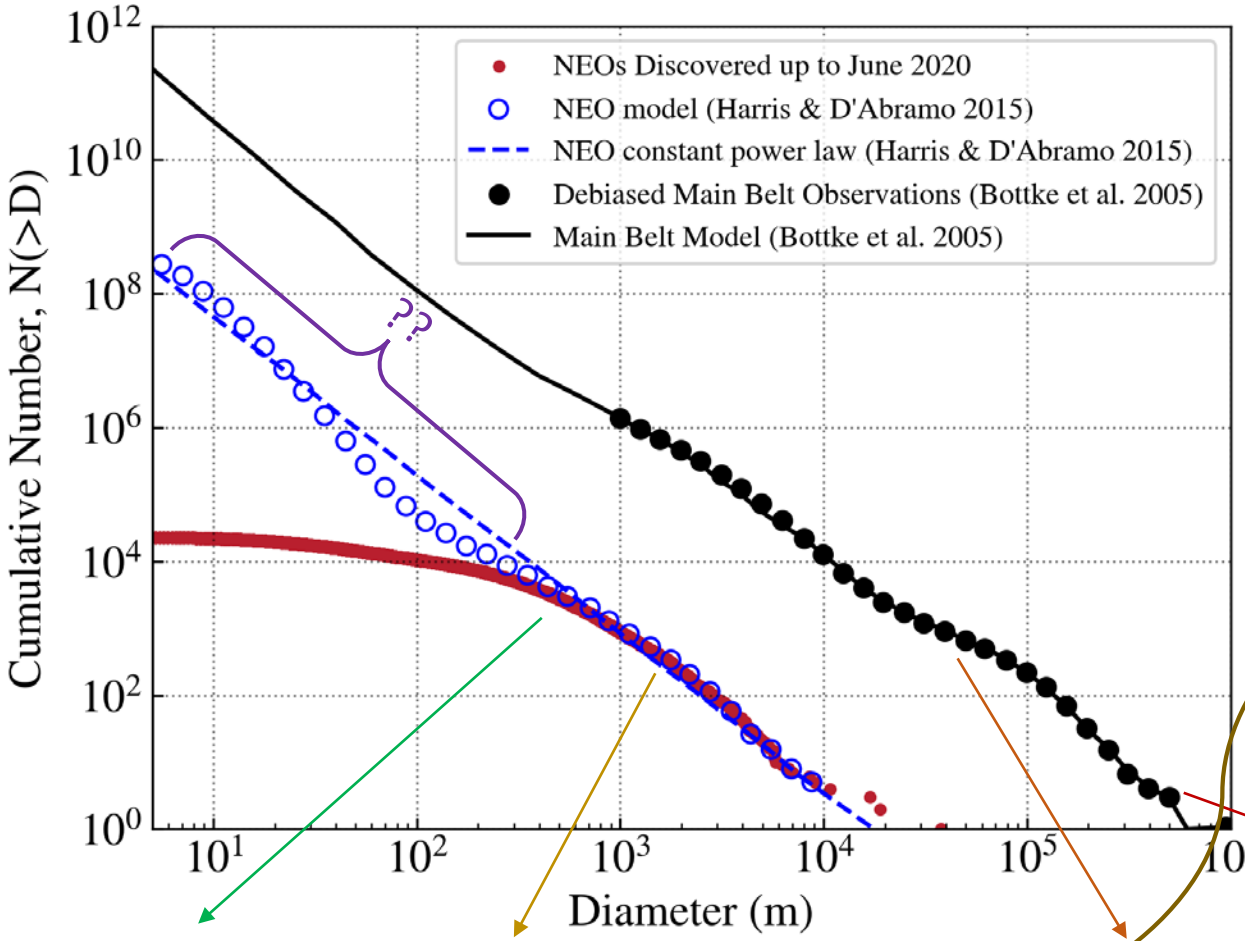


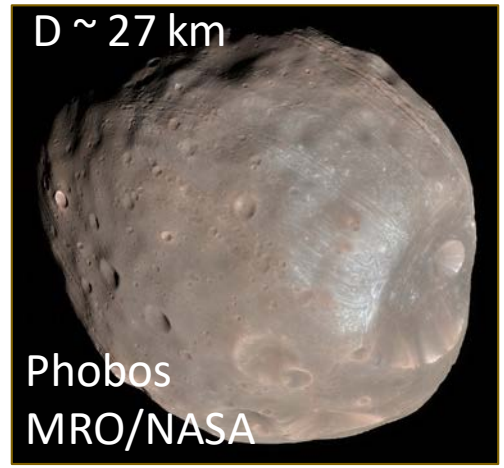
Image & LIDAR data of crater on boulder, OSIRIS-REx/UA/NASA

Outline

- Overview: one model for all sizes?
- Inference of Asteroid Interiors: Impact Processes
- Have we already observed Asteroid Interiors?
- Planetary Defense: Monoliths or Rubble Piles at 140 m?
- Summary:
  - Open Questions
  - Recommendations

Overview of “Asteroid” Interiors: one model for all sizes (?)





D < 0.2 km

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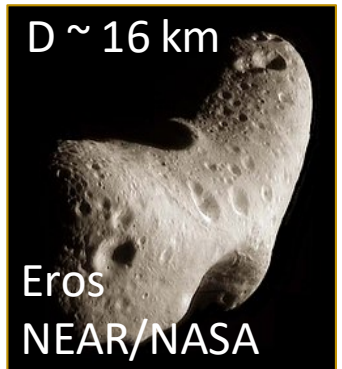
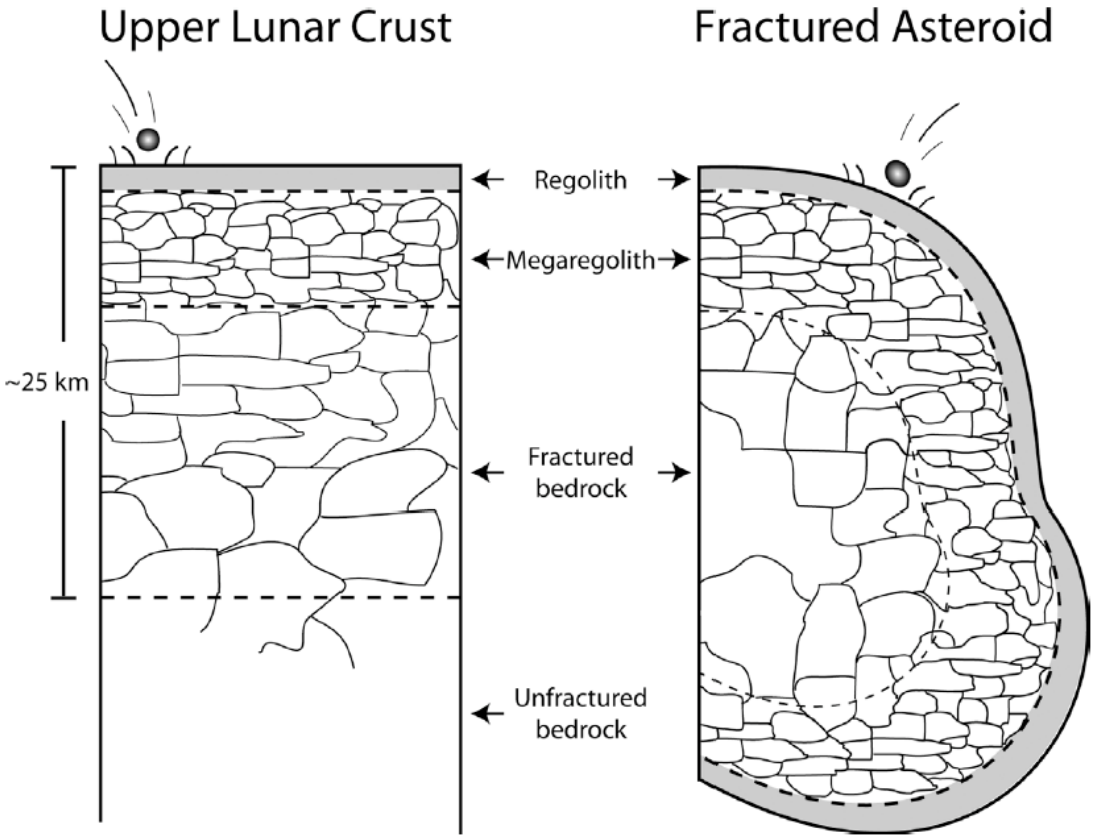


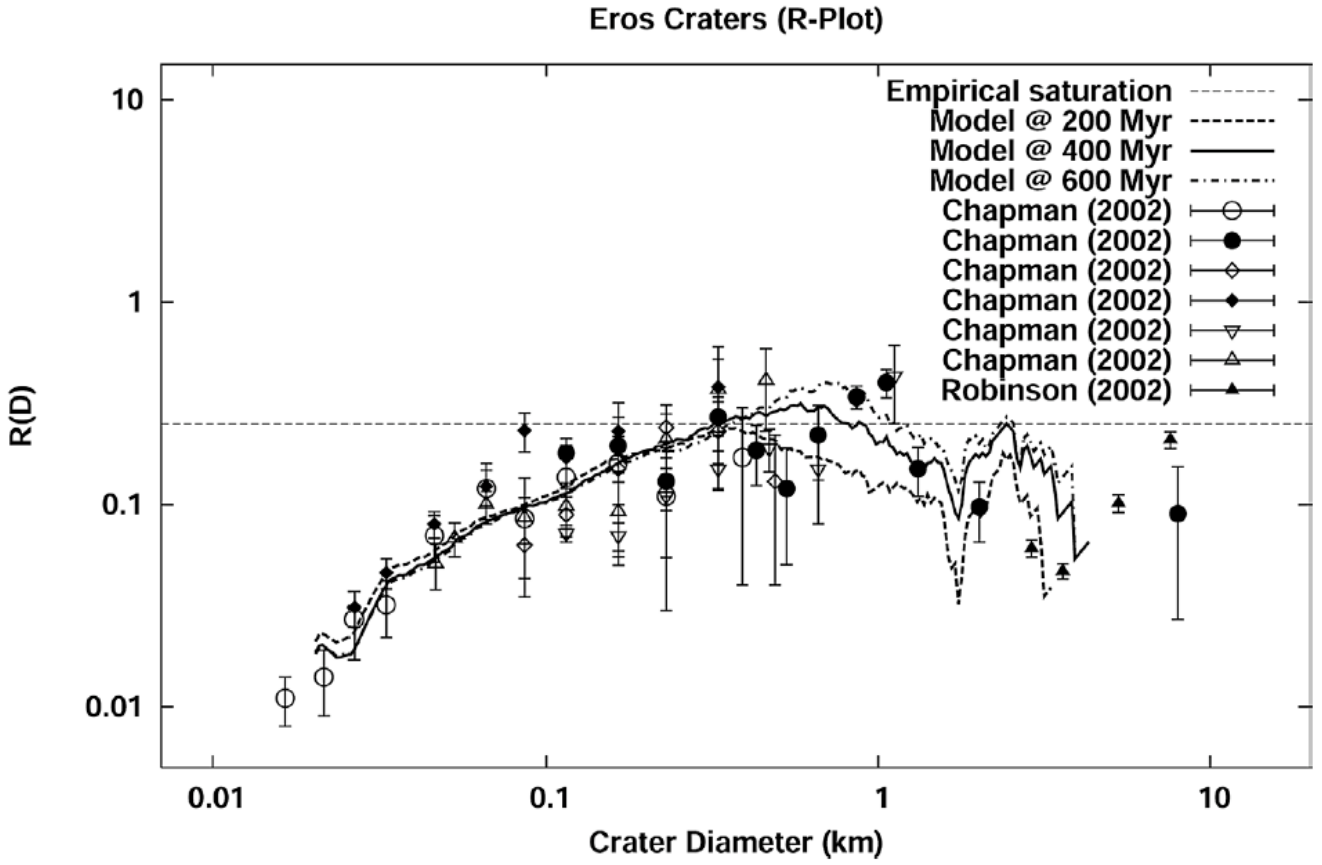
Inferences of Asteroid Interiors: Surface Evolution through impact processes

Crater Erasure through impact-induced seismic shaking (Richardson et al. 2005)

Interior model was a fractured asteroid with interior similar to upper 10's of km of moon.



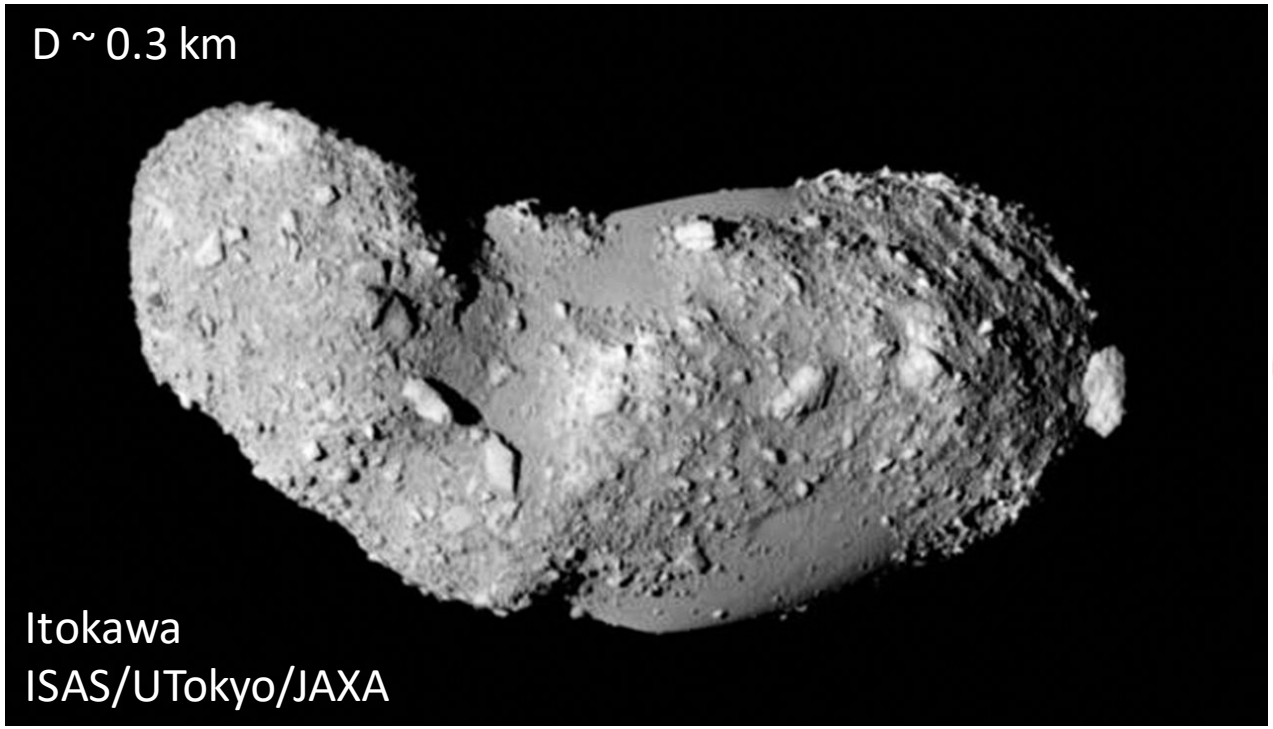
(Richardson et al. 2005)

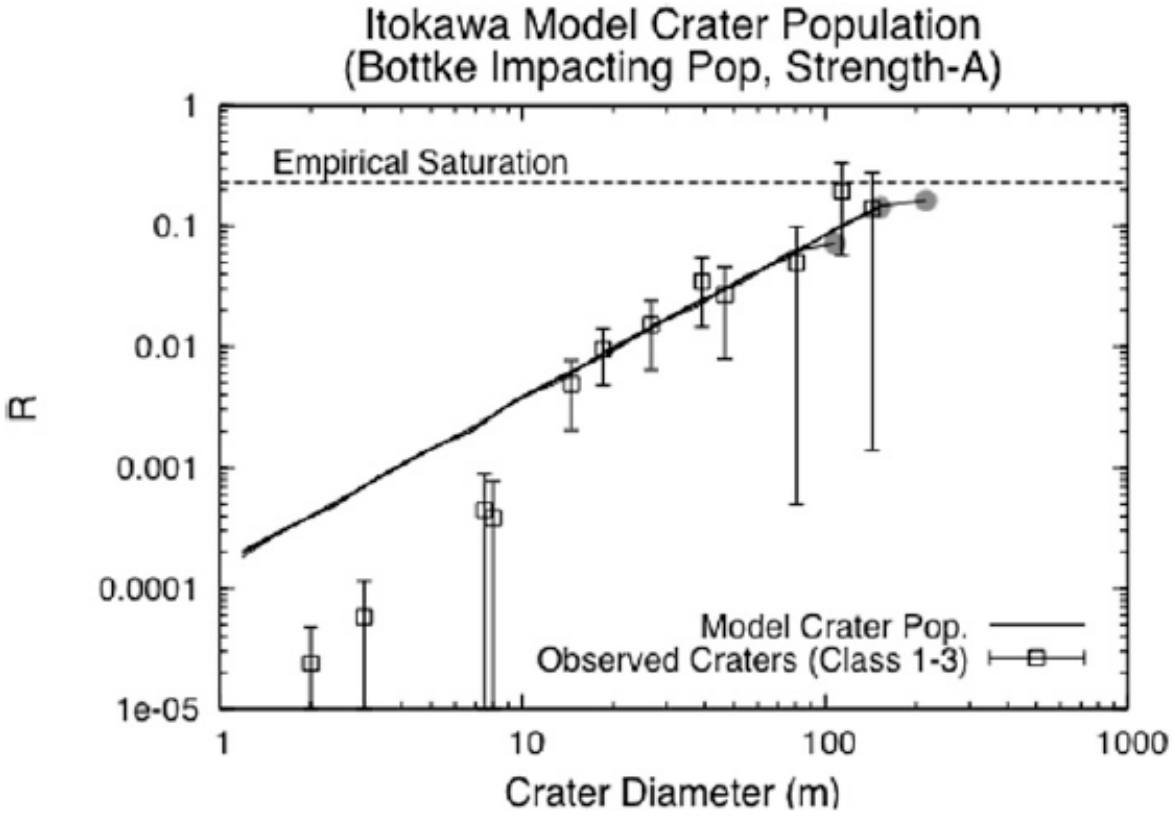


(Richardson et al. 2005)

Inferences of Asteroid Interiors: Surface Evolution through impact processes

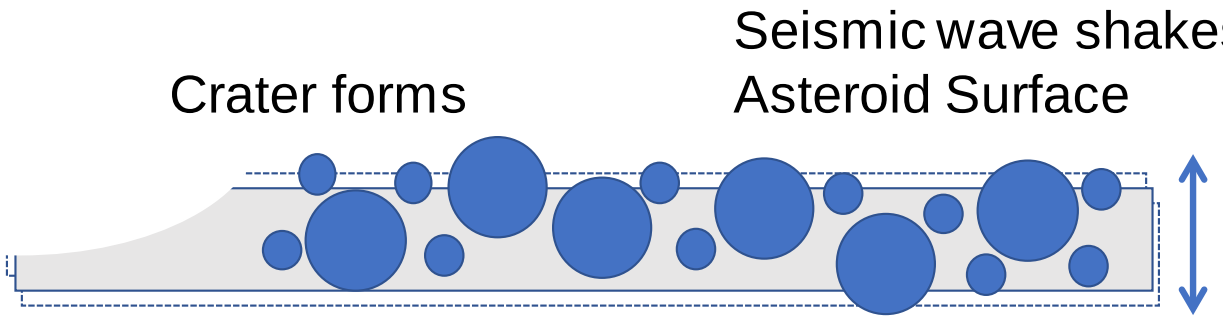
Also seen on Itokawa (Hirata et al. 2009. Michel et al. 2009).
Impact-induced seismic shaking model can explain some observations on Itokawa, not all..
How does specifics of interior fit into modeling?





Michel et al. (2009)

Seismicity depends on interior structure

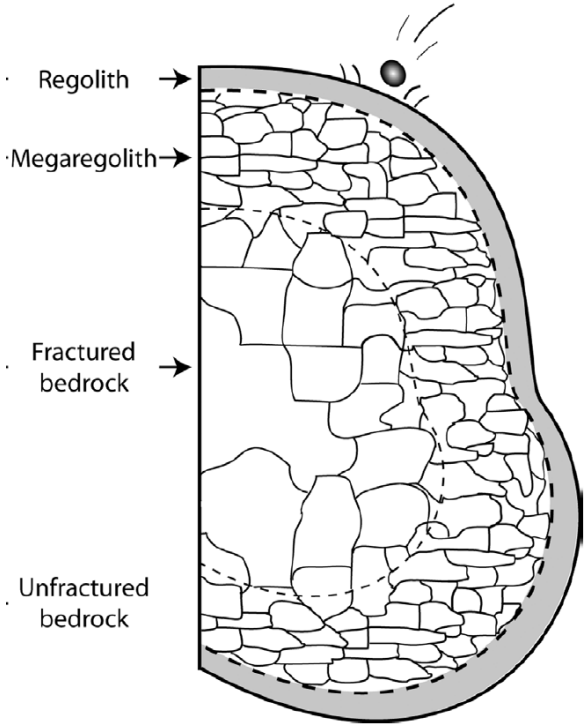


$$\frac{a}{g} = \frac{3 f v_i}{G} \sqrt{\eta \frac{\rho_i}{\rho_a^3} \frac{D_i^3}{D_a^5}} \cdot \exp\left(- \frac{f D_a^2}{K \pi Q} \right)$$

(Richardson et al. 2005)

a / g : surface acceleration compared to local gravity
D_i , D_a : diameter of impactor, asteroid
ρ_i , ρ_a : density of impactor, asteroid
***K, Q, η* : seismic diffusivity, quality, efficiency**
f : characteristic frequency
v_i : impact speed

Fractured Asteroid



(Richardson et al. 2005)

Rubble Pile

(Goldreich & Sa'ri 2007)

Characteristic frequency, *f*, determines efficiency of seismic shaking,
but this depends on unknown interior structure of the asteroid.

Inferences of Asteroid Interiors: Surface Age

2018: Hayabusa2 and OSIRIS-REx arrive at Bennu and Ryugu.

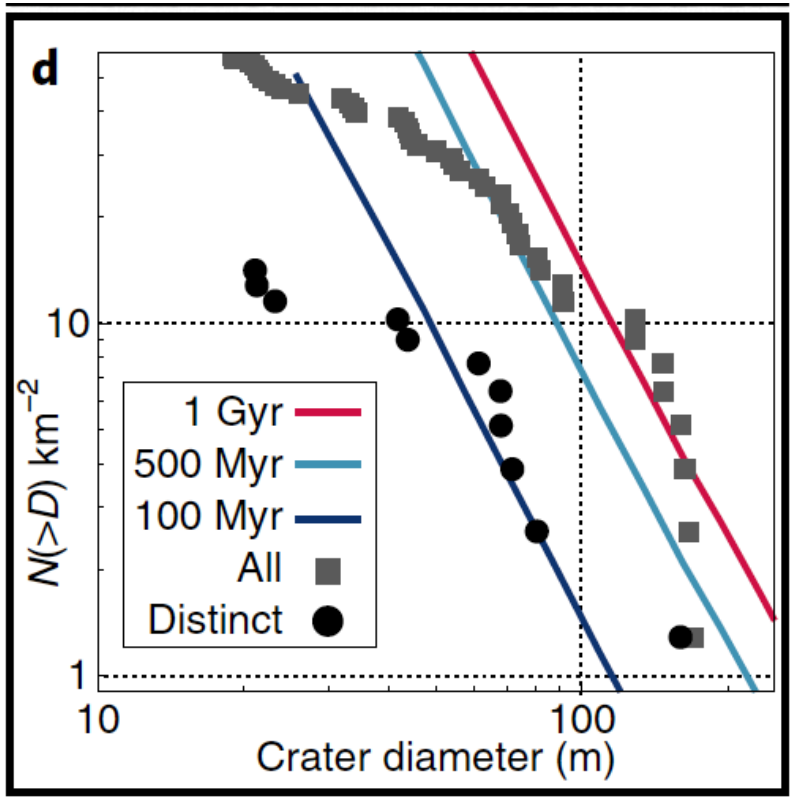
Crater erasure evident.

Walsh et al. (2019) got ages between 100-1000 Myr for Bennu based on a surface strength of ~ 400,000 Pa.

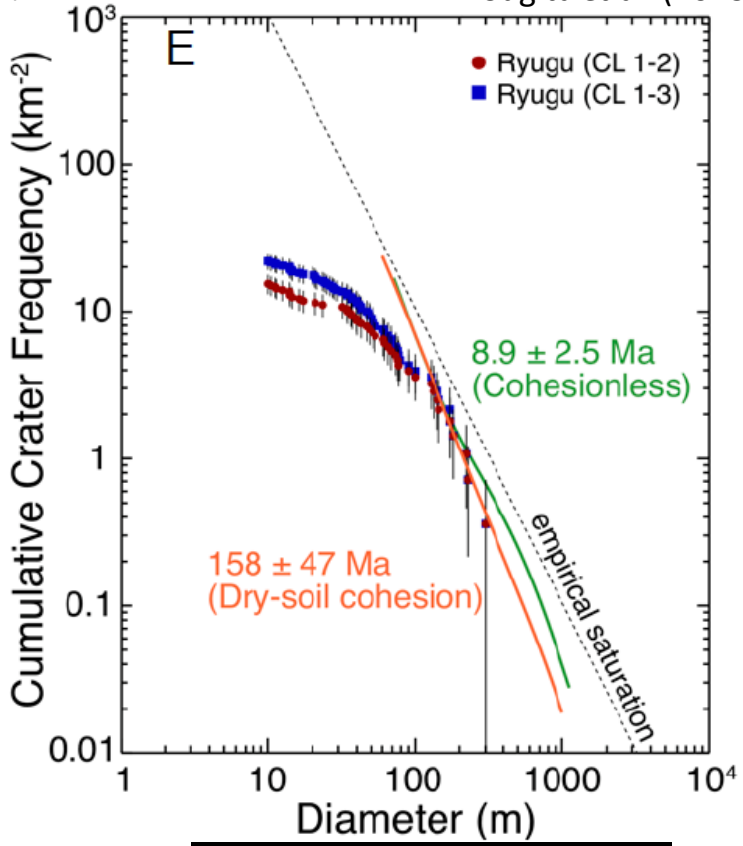
Sugita et al. (2019) showed that the surface of Ryugu can be as old as 158 Myr – if the surface is ”strong”.

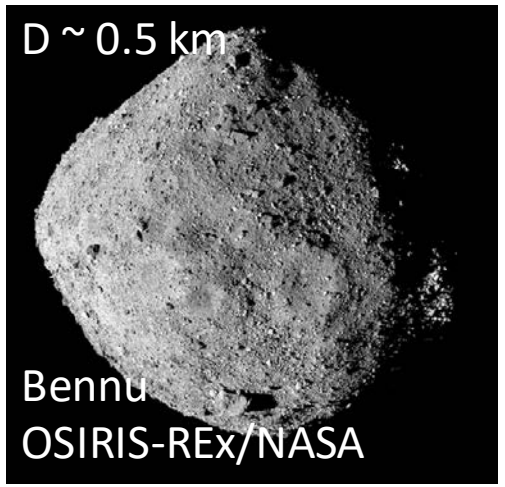
-- but could be much younger (8.9 Myr) if the surface was “strength-less”

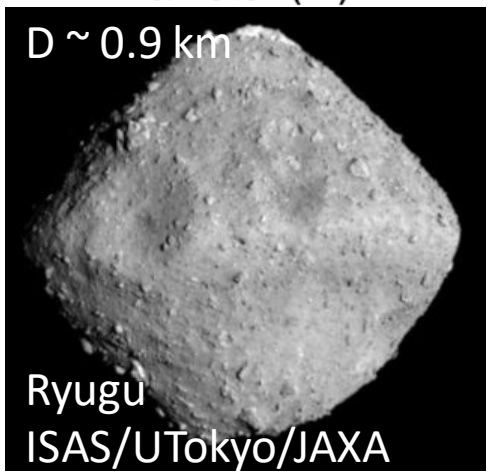
Walsh et al. (2019)



Sugita et al. (2019)

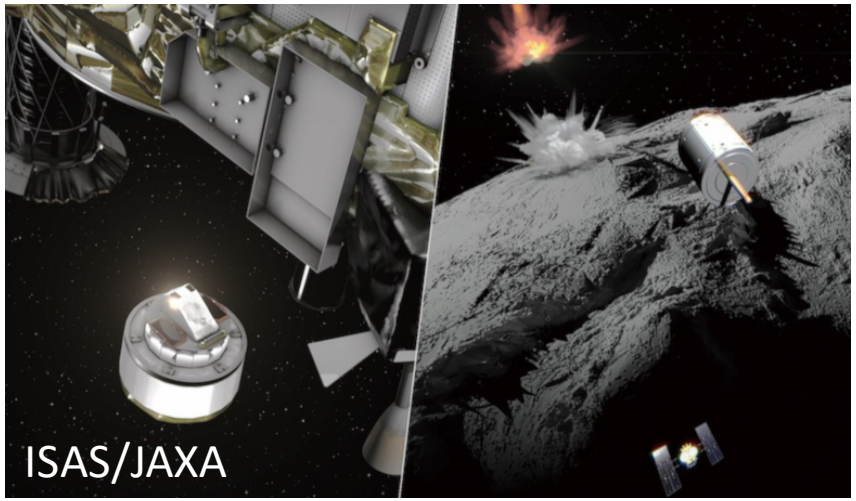


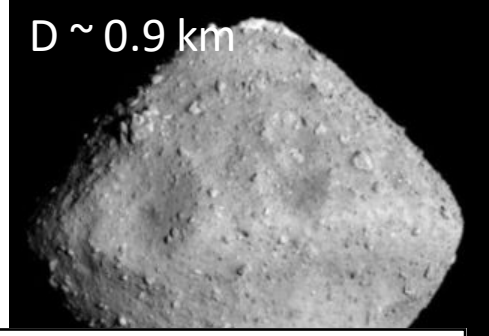




Inferences of Asteroid Interiors: Surface Age

Small Carry-On Impactor (SCI) on Hayabusa 2





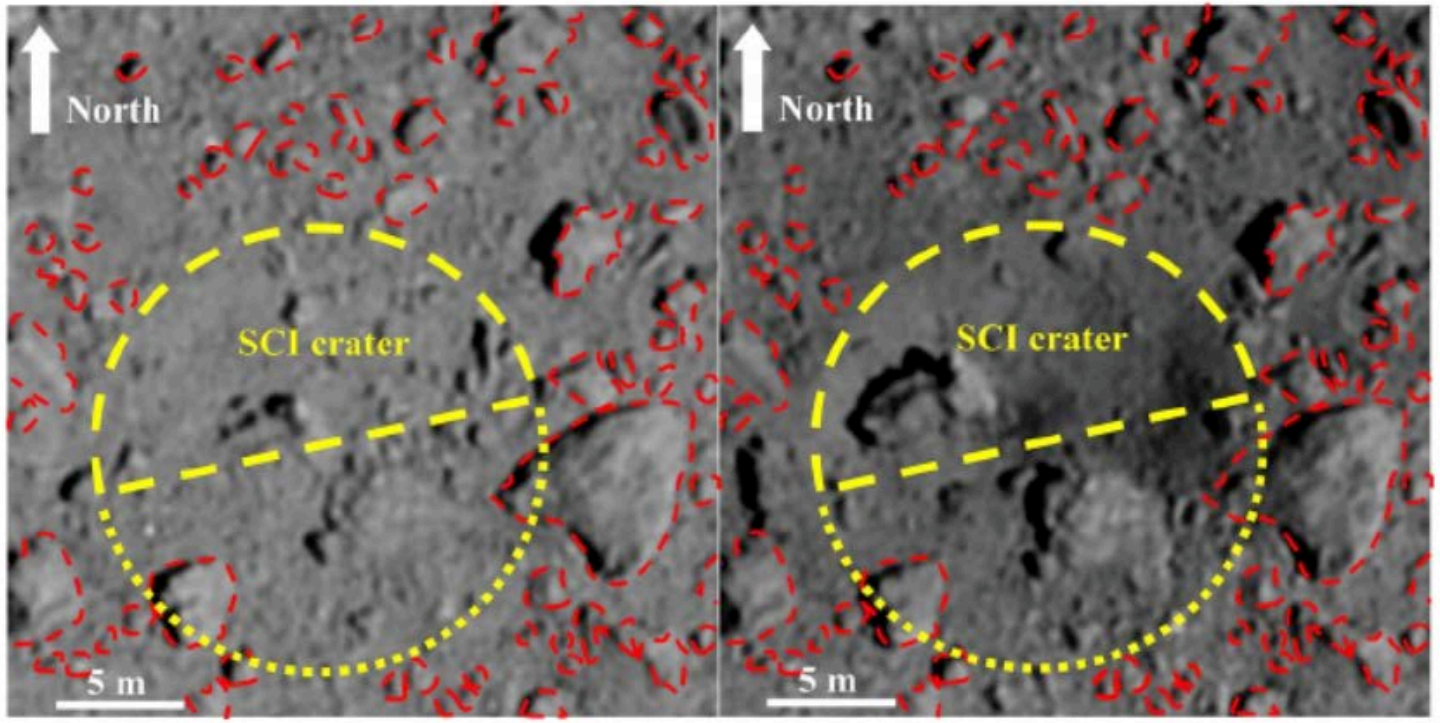
2 kg copper projectile at a velocity of 2 km s−1, to form an artificial impact crater

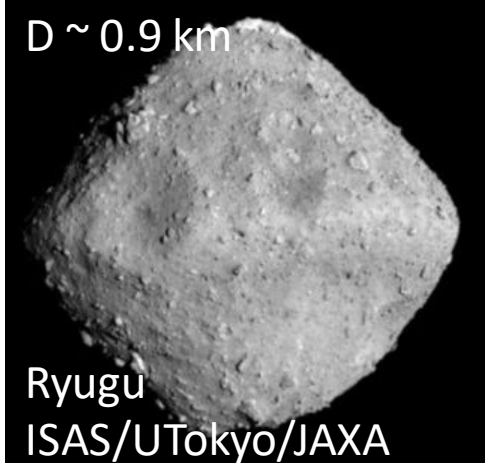
Using Digital Elevation Model, measured diameter of SCI crater, D = 14.5 ± 0.8 m.

The cohesive strength of this putative subsurface layer would be between **140 and 670 Pa.**

Scaling to larger sizes, infer surface age of Ryugu of < 10 Myr (Arakawa et al. 2020, Sugita et al. 2019).

Inferences of Asteroid Interiors: Surface Age





Nishiyama et al. (2020)

No obvious regolith hopping was identified even immediately outside of the crater formed by the SCI impact (< 1 m).

Open Questions:

- Can SCI-derived gravity scaling be used for much larger craters (>100 m) that excavate deeper?
- What are the seismic properties of rubble piles?
- Are rubble-pile interiors similar to rubble pile surfaces?

Have we already seen the inside of Asteroids?

- **Scaling to larger sizes, infer surface age of Ryugu of < 10 Myr (Arakawa et al. 2020, Sugita et al. 2019).**

- Simulation of Asteroid Family Forming Event: Catastrophic disruption.
  - Material from both interior and exterior reaccumulate to form small rubble piles.

- Putative Main Belt Families of Ryugu/Bennu formed > 800 Myr.

- Open Question: Rubble piles NEAs are (great)-grand-children (Walsh et al. 2019)?

Michel & Ballouz et al. (2020)

Have we already seen the inside of Asteroids?

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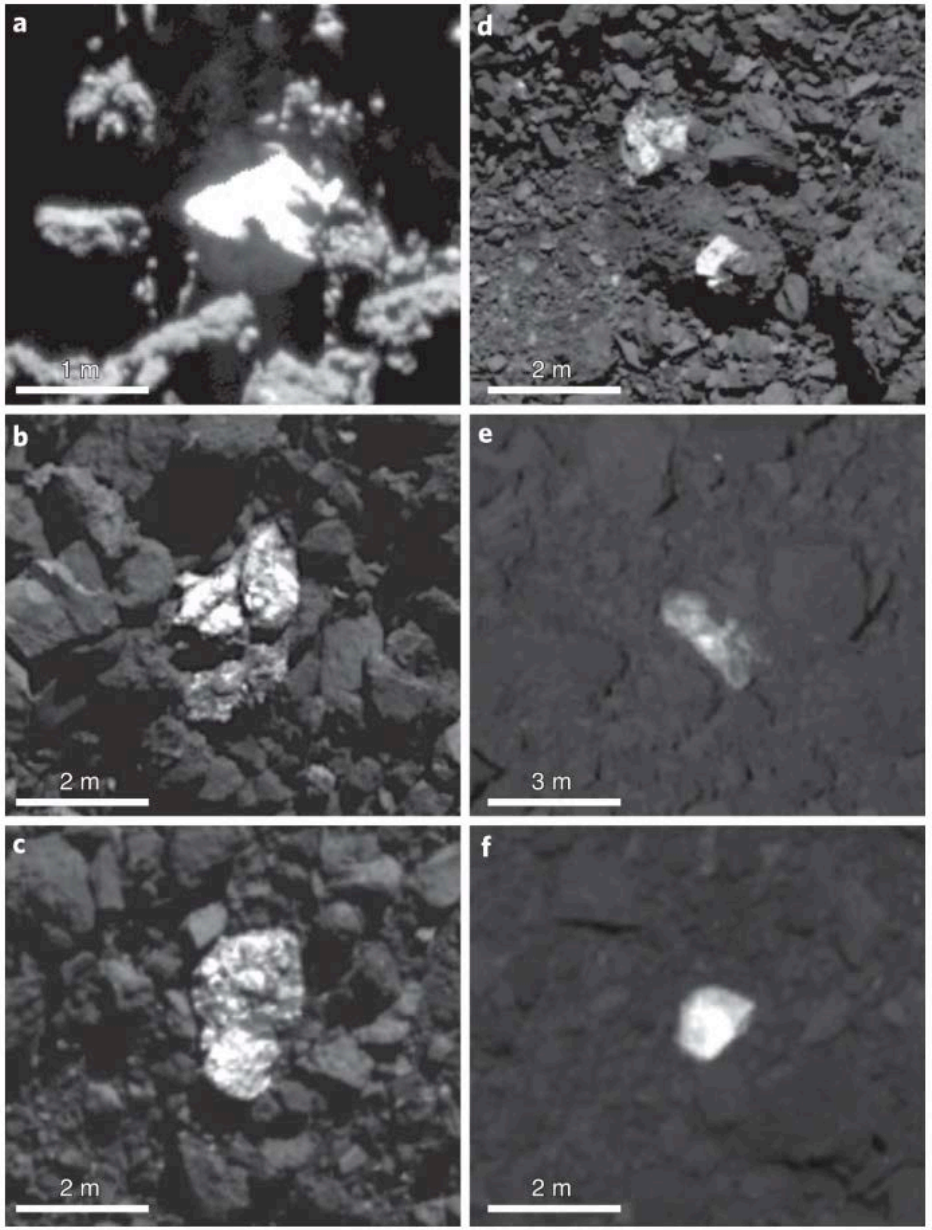
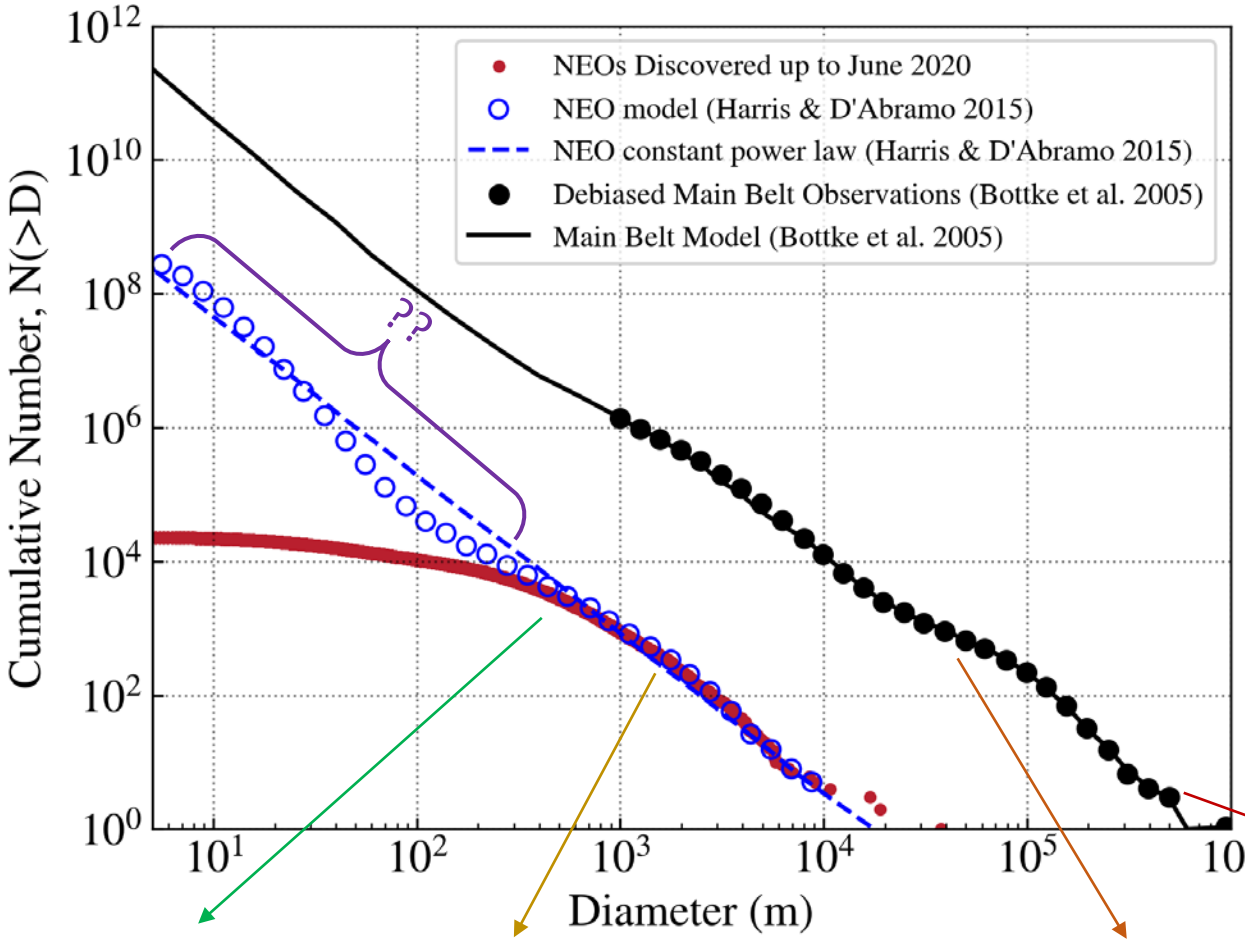
- Multiple Catastrophic Disruptions to explain contamination of Bennu/Ryugu (DellaGiustina et al. 2021, Tatsumi et al. 2021, Bottke et al. 2020)



Exogenic basalt on asteroid (101955) Bennu.
(DellaGiustina, Kaplan et al. 2021)

Overview of Asteroid Interiors: size dependence



D < 0.2 km

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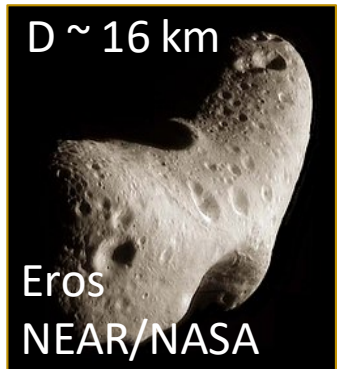


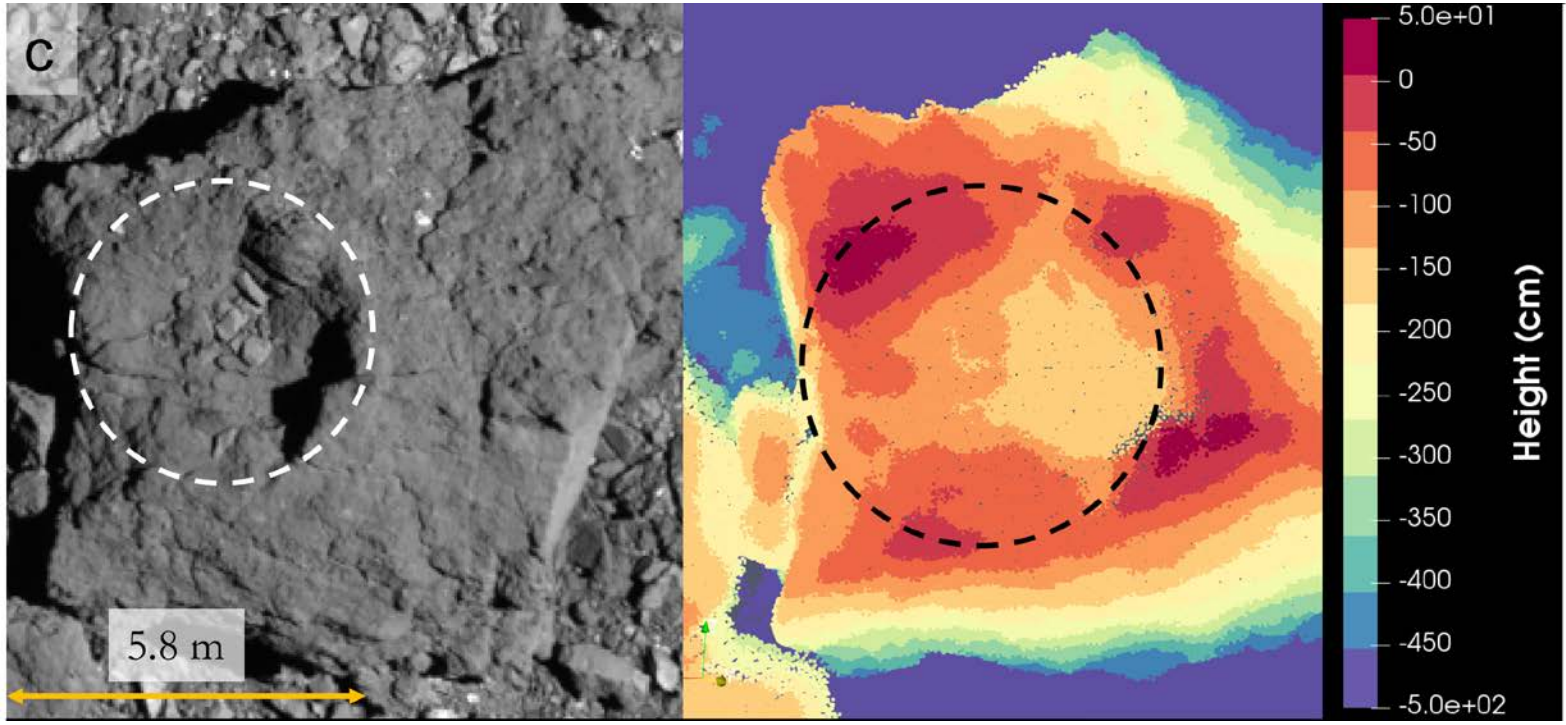
Strength-Dominated Objects on the Surface of Bennu

Measured the diameters of > 600 craters (D = 0.03 – 5 m) on Bennu's boulders (D = 0.5-50 m)

Y = 0.44 to 1.70 MPa for 1-m boulder (Ballouz et al. 2020)

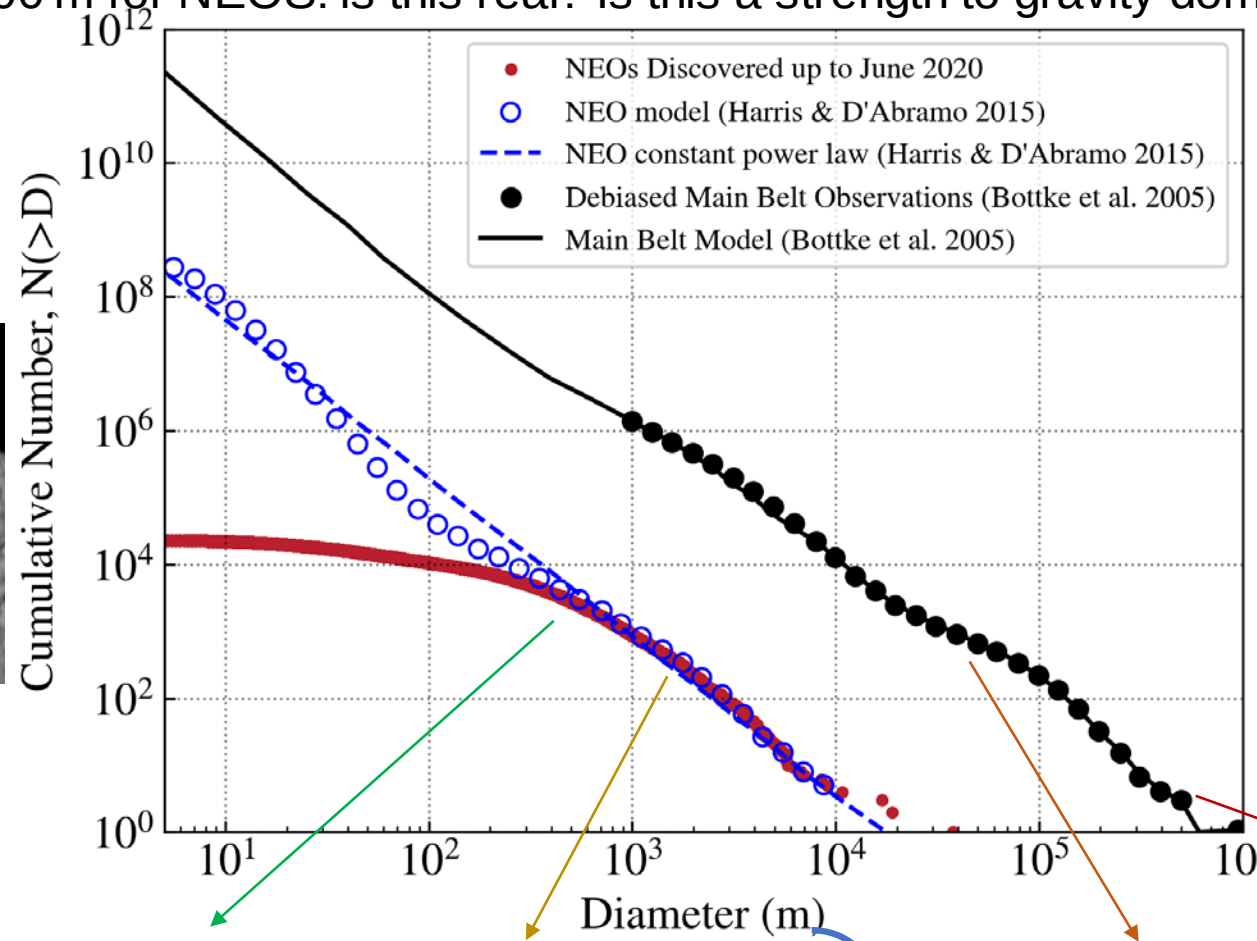
Thermal Inertia Measurement:
$Y \sim$ 0.2 MPa for boulder on Ryugu (MASCOT, Grott et al. 2019)

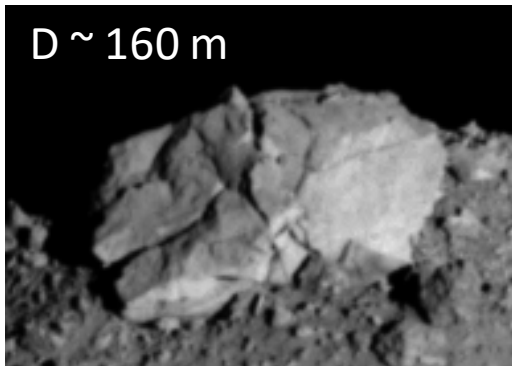
Meteoritic Analogs, CI/CM have tensile strength 0.2-85 MPa.



Overview of "Asteroid" Interiors: size dependence

Inflection point at ~ 200 m for NEOS: is this real? Is this a strength to gravity dominated transition?

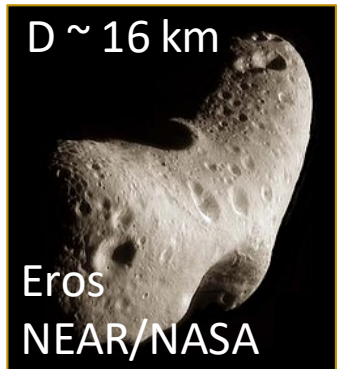




Otohime Boulder
Hayabusa2/Ryugu

D < 0.2 km

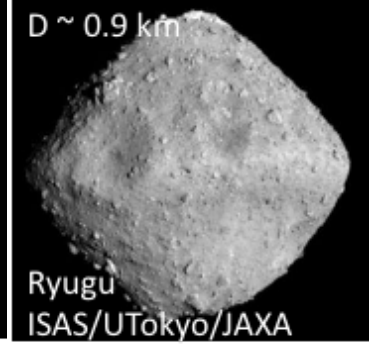
??



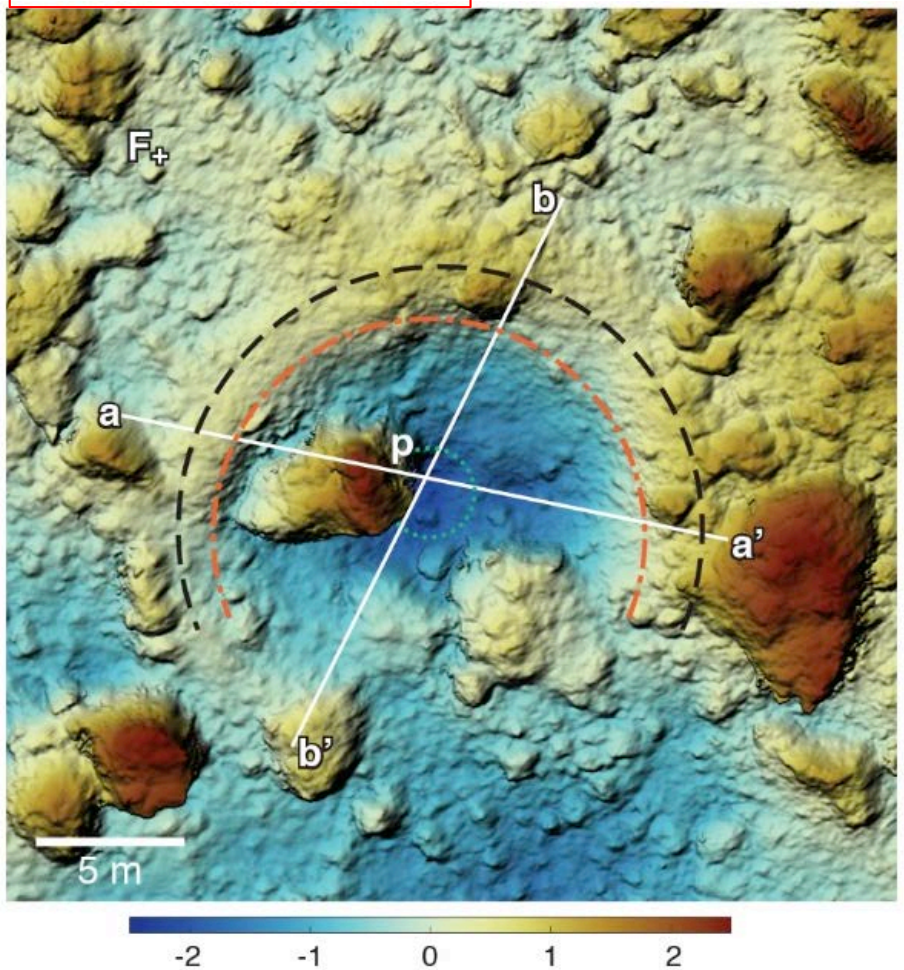
Planetary Defense: Heterogeneity

Impact can have very different outcomes for the same ~ target.

d ~ 50 cm impactor
v = 5 km/s
D = 5 m crater



d = 13 cm impactor,
2 km/s
D = 14.5 m crater



Ballouz et al. (2020)

Arakawa et al. (2020)

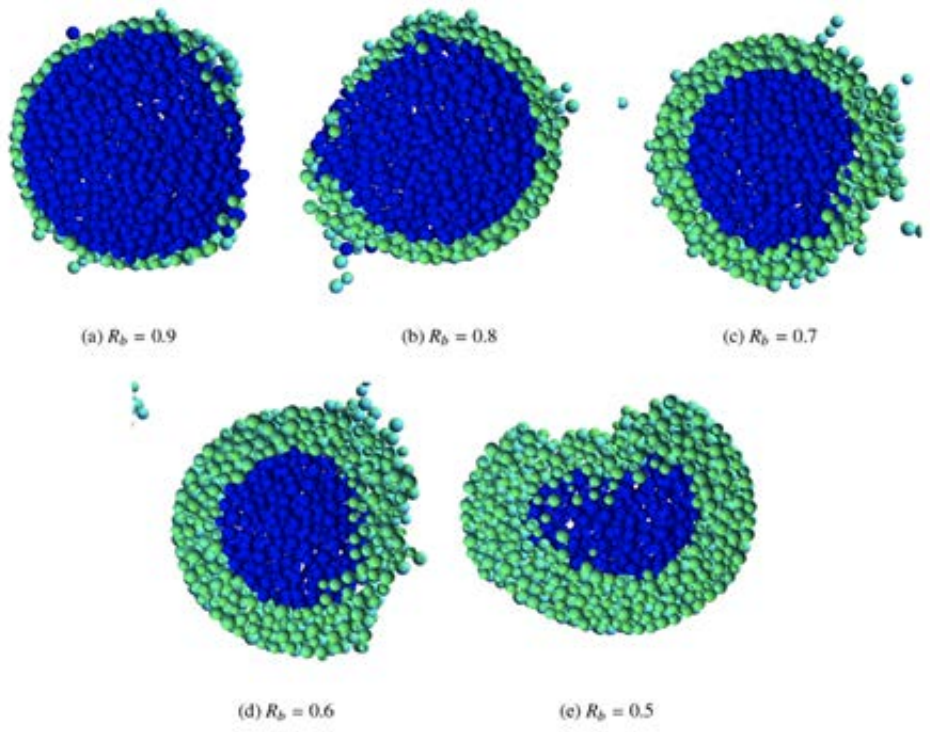
Open Question: Monoliths (Strength) or Rubble Piles (Gravity) at 140 m?

Bennu's 1-m boulders have a compressive strength of ~ 0.5 MegaPascals (MPa).

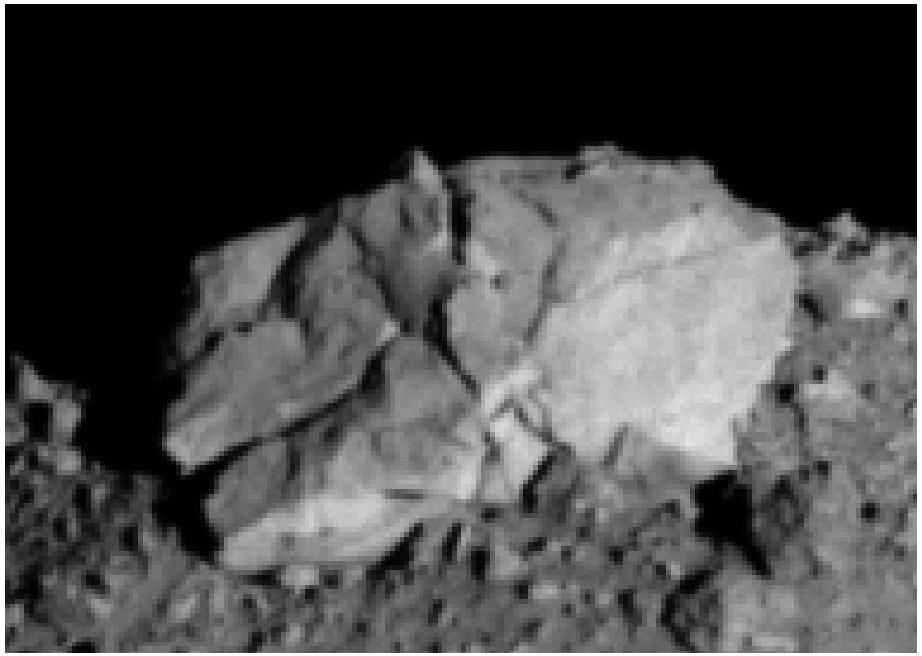
> "A catalog that is 90% complete for [Potentially Hazardous Objects] larger than 140 meters, which corresponds to characterizing 90% of the impact risk of sub-global effects" – Near-Earth Object Science Definition Team

True for all NEAs?

Tied to broader question of NEA delivery and survival (dynamics).



Sanchéz and Scheeres (2018)



Otohime Boulder on Ryugu (160 m)
Sugita et al. (2019)

Open Questions:

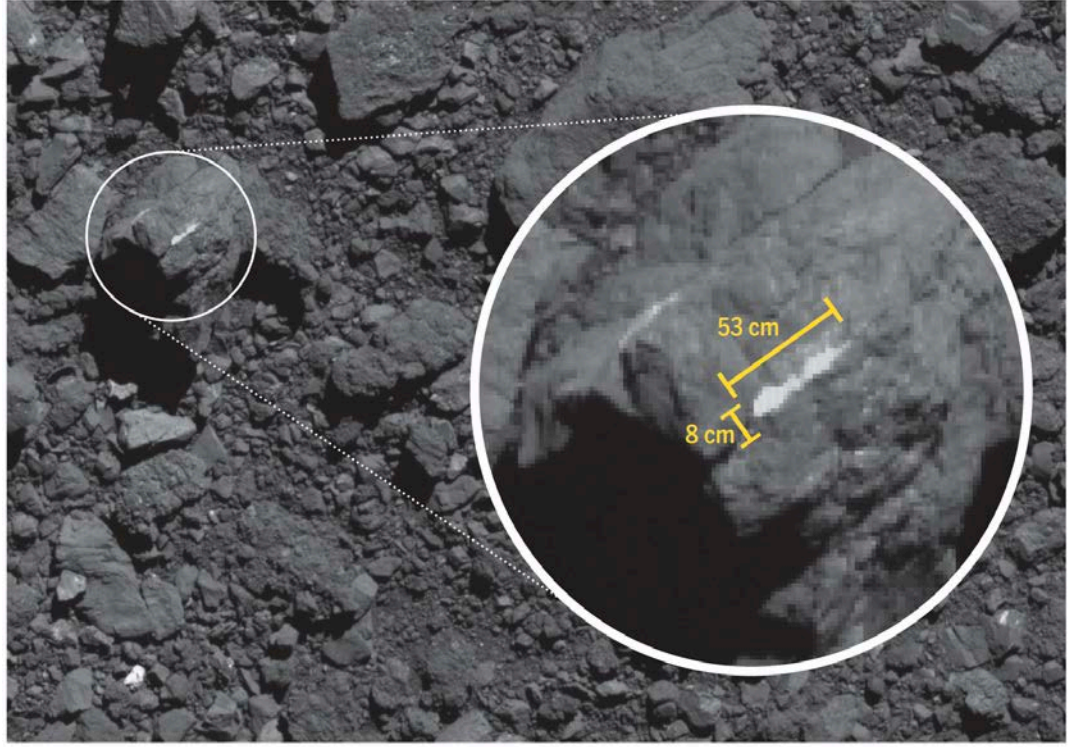
- What are the seismic properties of rubble piles? (DART/HERA)
- Can SCI-derived gravity scaling be used for much larger craters (>100 m) that excavate deeper? (DART/HERA Simulation)
- Are rubble-pile interiors similar to rubble pile surfaces? Have we already seen the inside of Asteroids? (Simulation)
- Are rubble piles NEAs the (great)-grand-children of main belt parent bodies? (Simulation/OREx/Hayabusa2)
- Are Monoliths or Rubble Piles at 140 m? (DART/HERA/Radar/ NEOSM/LSST)
- Is there an inflection point in the NEO SFD at ~ 200 m? Does this point to a strength-to-gravity dominated transition? (NEOSM/LSST)

Recommendations

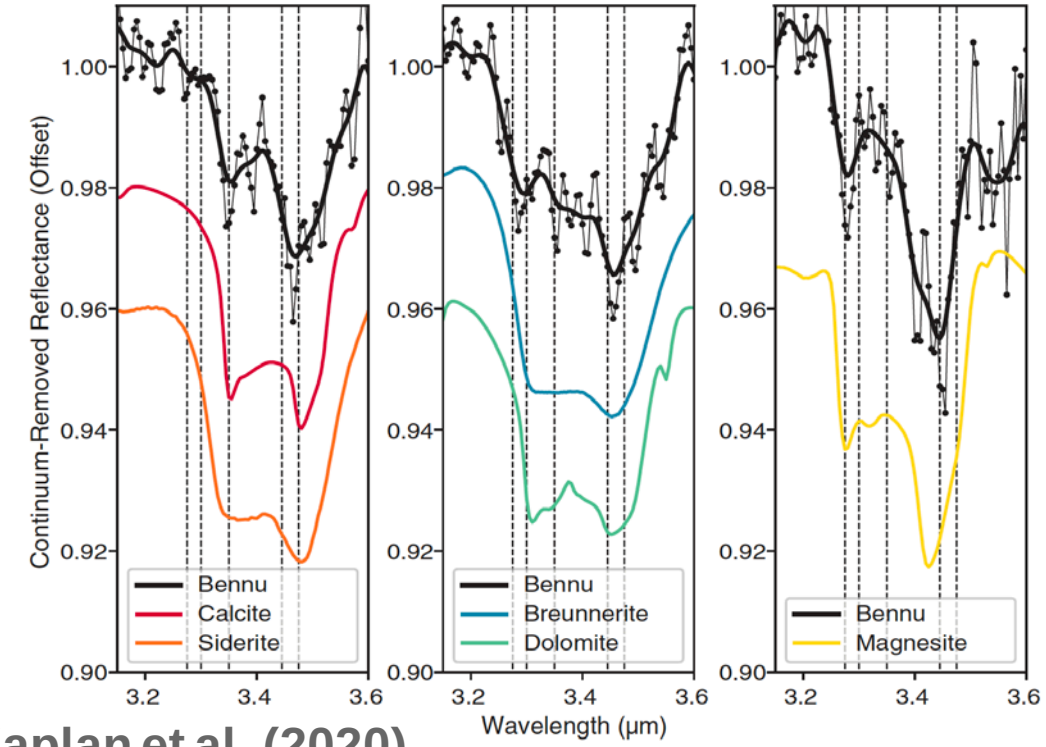
- Rendezvous missions: detailed images / high-spatial resolution spectral information of surface.
- Ride-along resources (CubeSats/SCI) can provide a lot of value: SCI, DCAM
- Mission to binary system: DART/HERA, JANUS (Scheeres et al. 2020).
- Passive Seismic Instrument to a rubble pile (particle ejection events, Lauretta & Hergenrother et al. 2019).
- Seismology from orbit: Laser Doppler Vibrometry (Sava & Asphaug 2019).

Giant convecting mud balls of the early solar system

Fluid flow on Bennu's parent body would have taken place over distances of kilometers for thousands to millions of years. We predict that the returned sample could contain carbonates with structure and scale distinct from those in the meteorites.



Kaplan et al. (2020)



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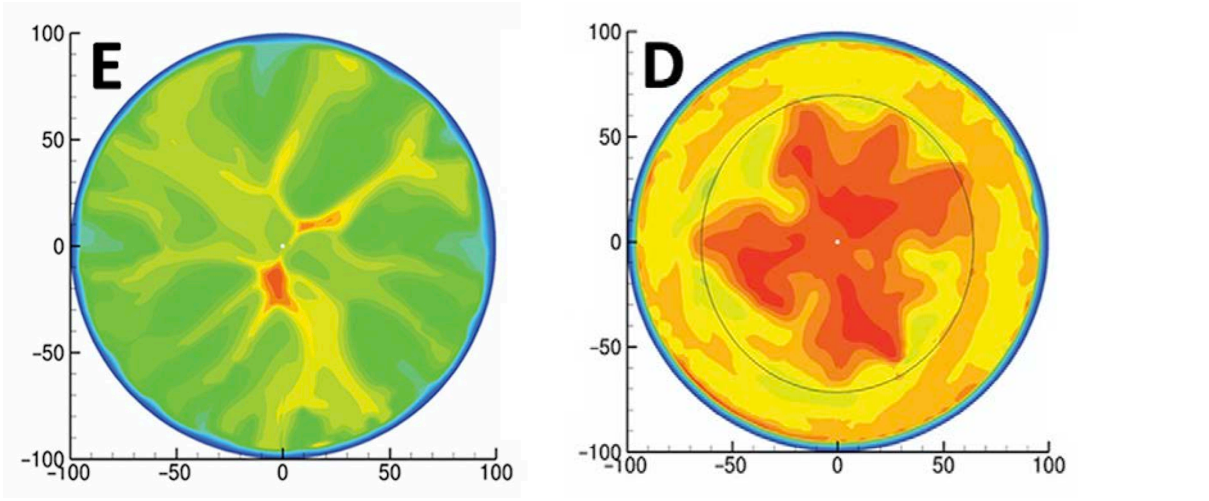

Giant convecting mud balls of the early solar system (Bland & Travis 2017)