Constraining the strength of 100-m scale asteroids through: **craters on Bennu's boulders** and **NEO population estimates**

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Planetary Defense Conference 2021

Session 4: OSIRIS-REx

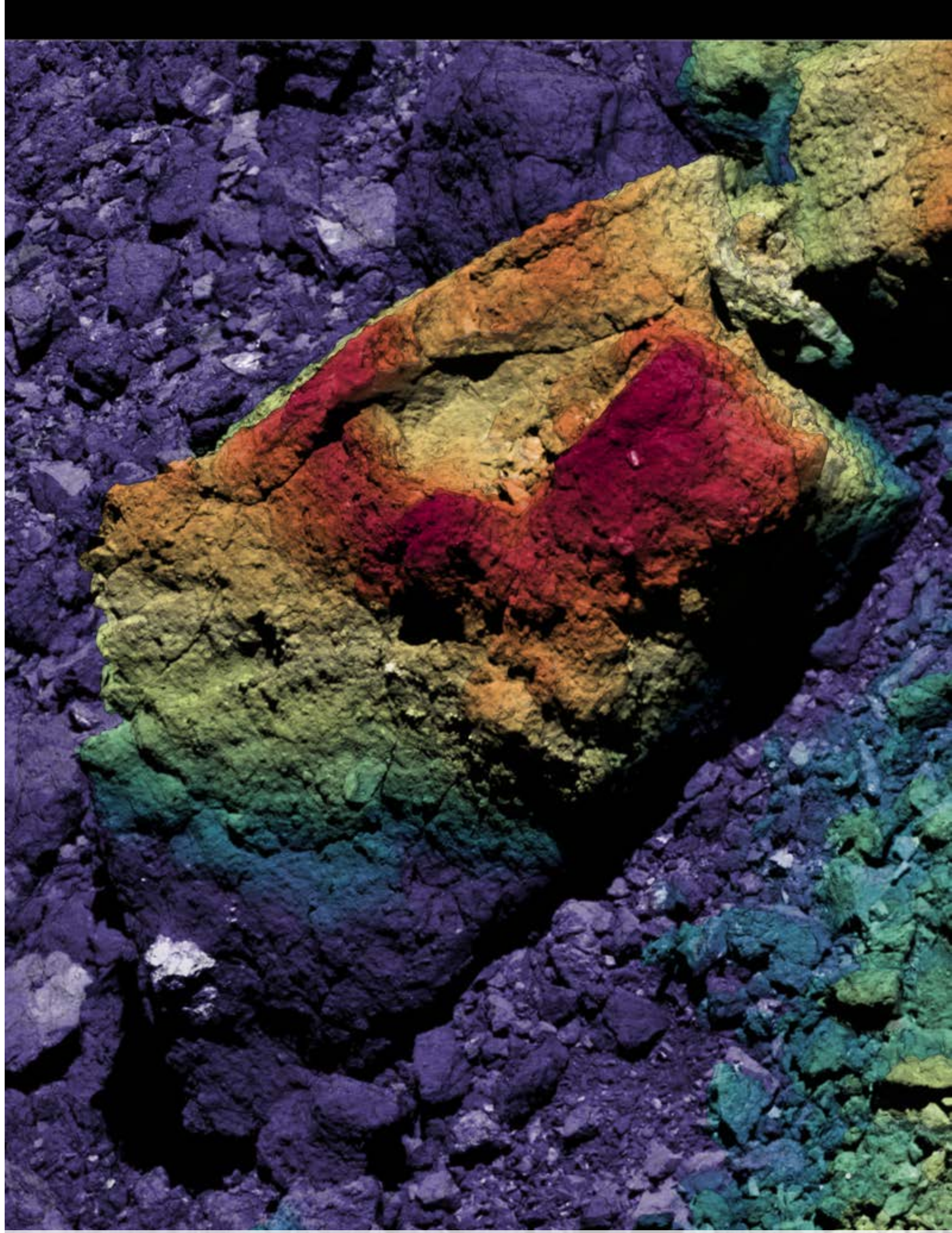


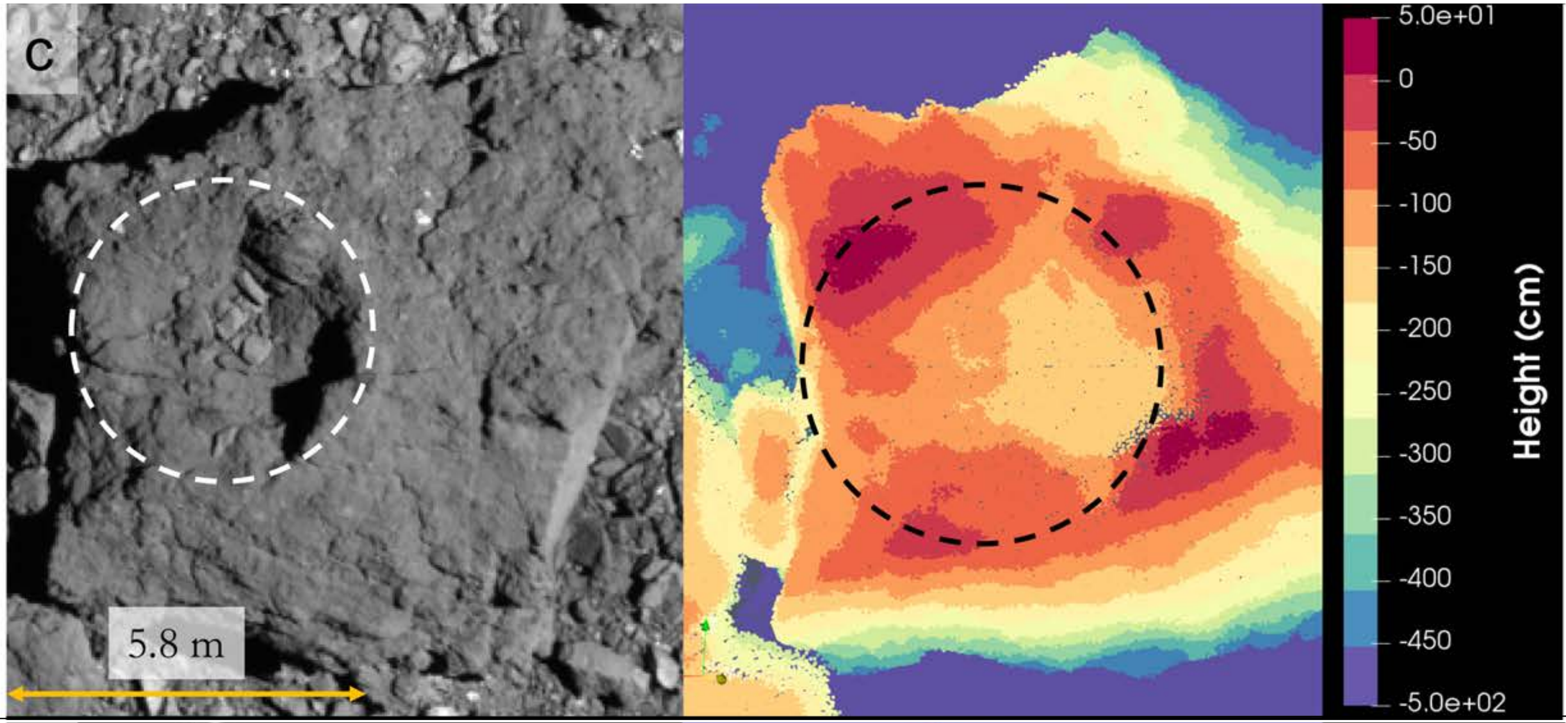
Image & LIDAR data of crater on 10 m boulder
OSIRIS-REx/OCAMS/OLA/UA/NASA

Outline

- Observations: Craters on Bennu’s Boulders
- Model: The strength of monolithic C-types
- Constraints from NEO Population Estimates
- Summary and Outlook:

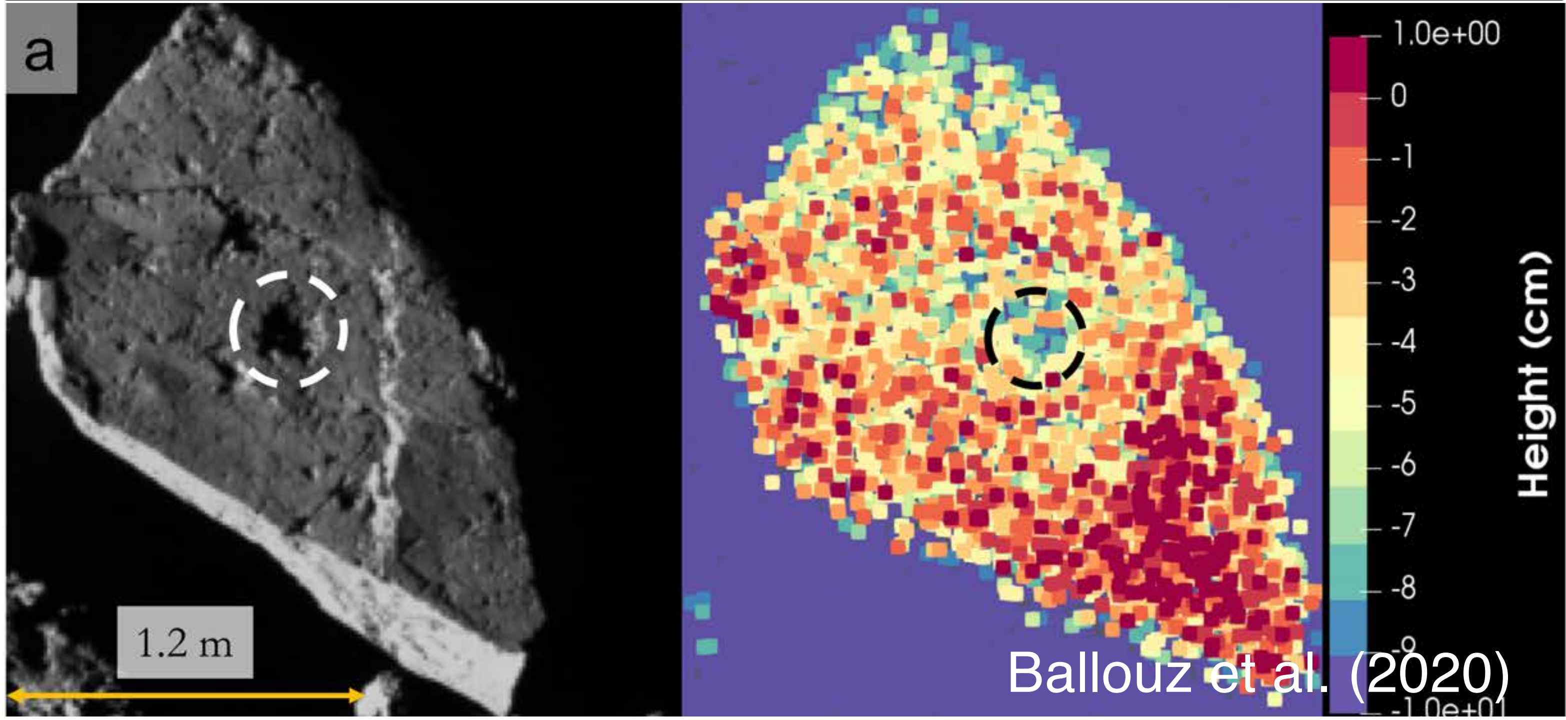
Observation:
Craters on Bennu's Boulders

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



Crater and boulder dimensions were measured using images from OSIRIS-REx PolyCAM.

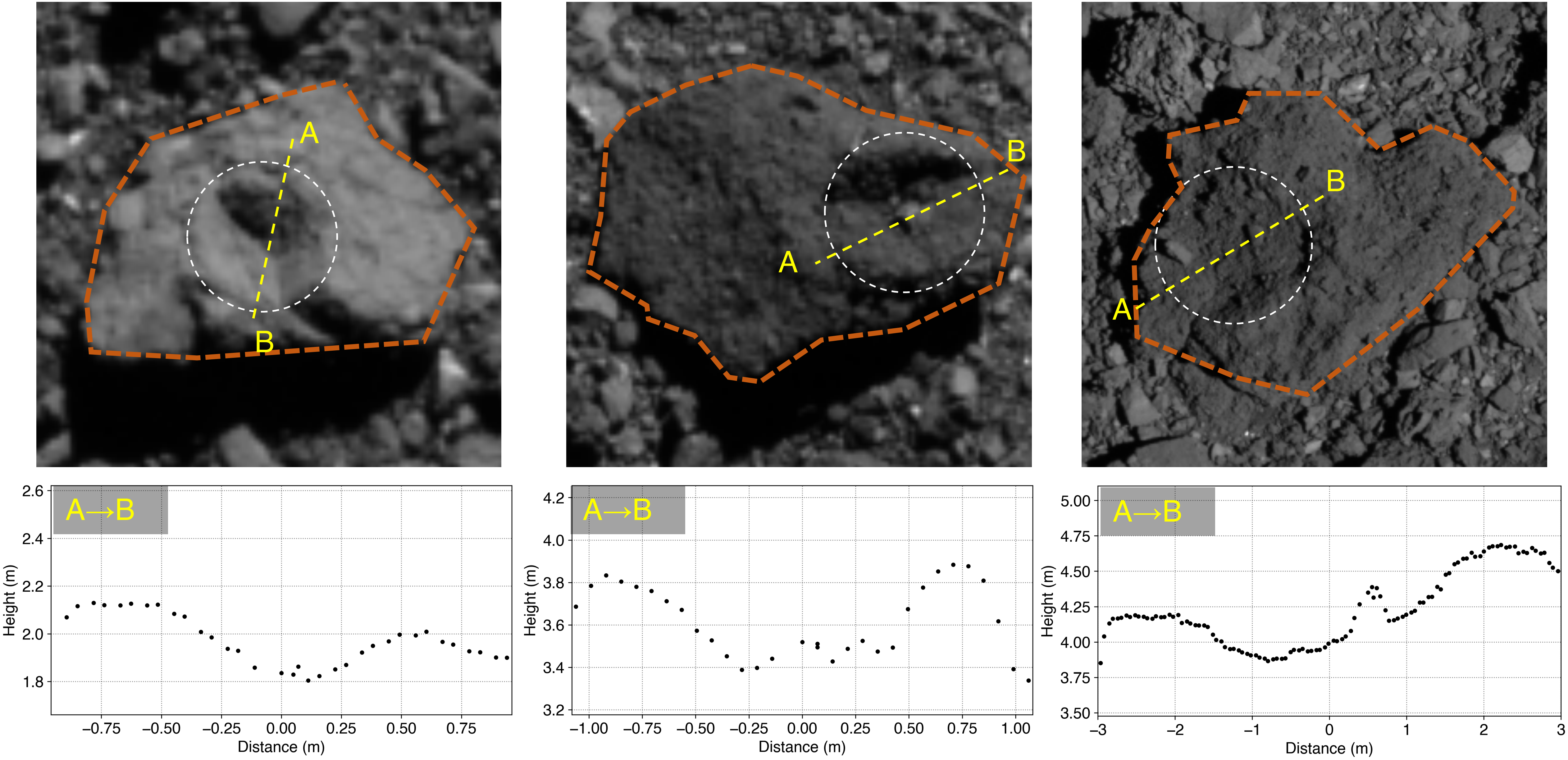
Crater dimensions of a subset were measured with OSIRIS-REx Laser Altimeter (OLA) data (right panels)



Ballouz et al. (2020)

OLA measurements of crater dimensions:

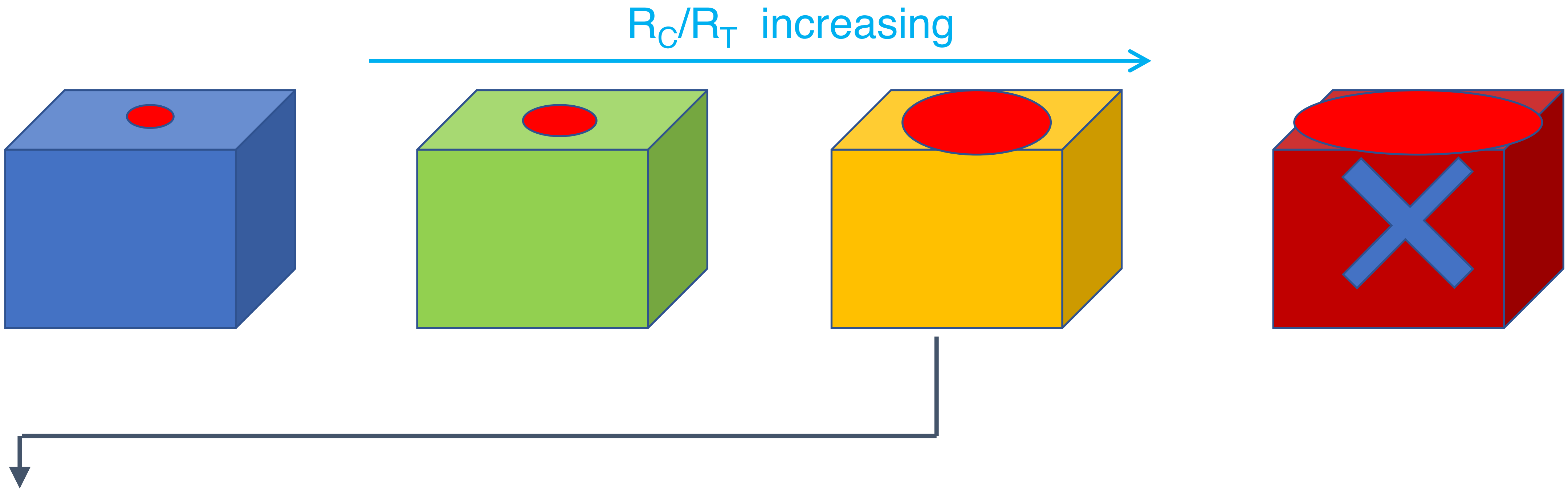
For 7 craters, *d/D* = 0.33 +/- 0.08 (relatively high compared to Bennu's craters, Daly et al. 2020)



The strength of Bennu's boulders and monolithic C-complex objects.

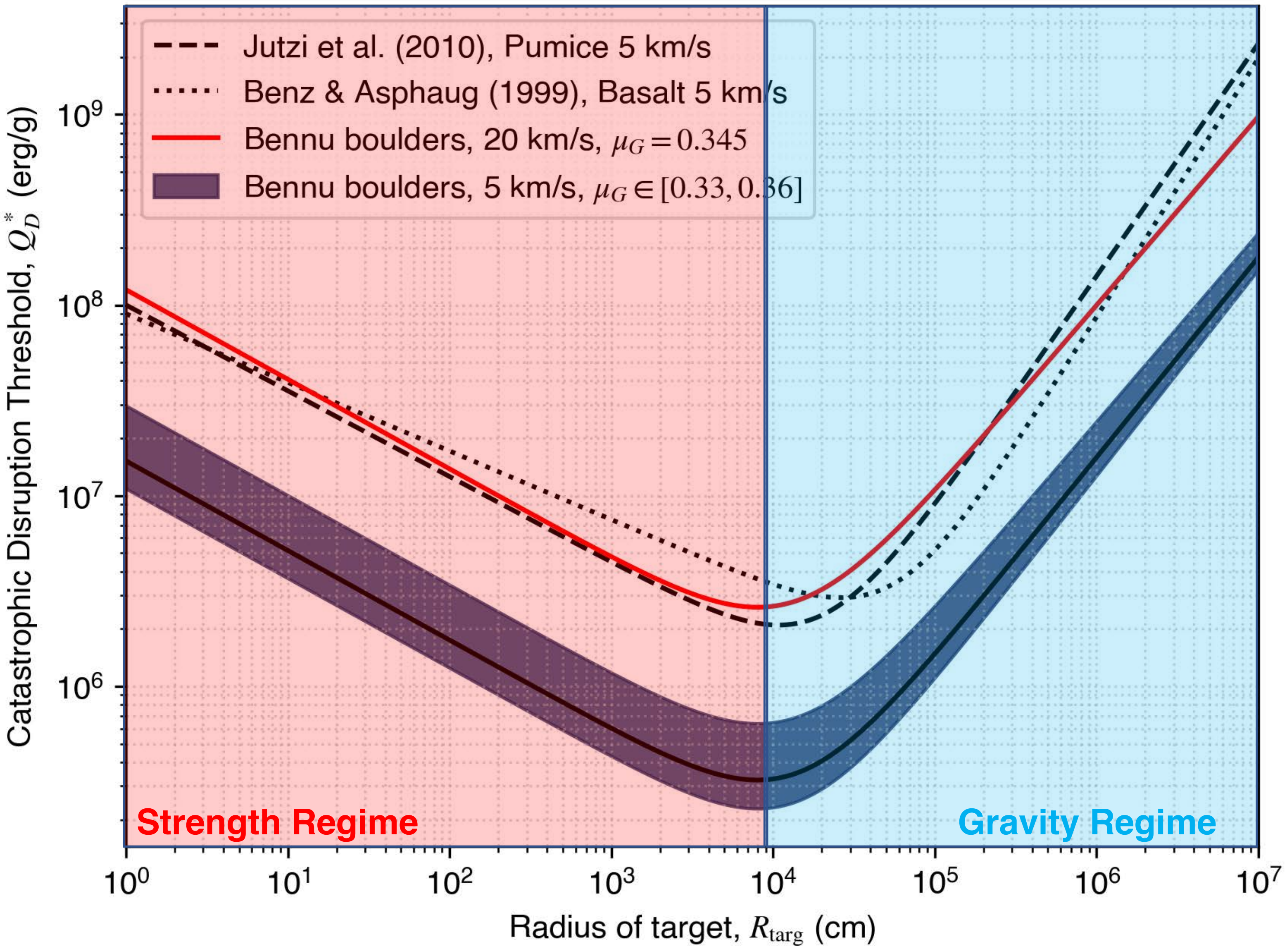
Q: How do we obtain a strength measurement from observations of craters?

A: There should be a maximum crater size for a given boulder size:
a more energetic impact will catastrophically disrupt the boulder.



$R_C = R_{C,MAX}$: Cratering Equation = Catastrophic Disruption Equation

Scaling to monolithic C-types



In the Strength Regime

$Q_D^* \propto R_T^{-\mu_S}$
μ_S = 0.47±0.07 (measured from Boulders)
$Y = Y_0 R_T^{-1/4}$

for 1-m boulder:

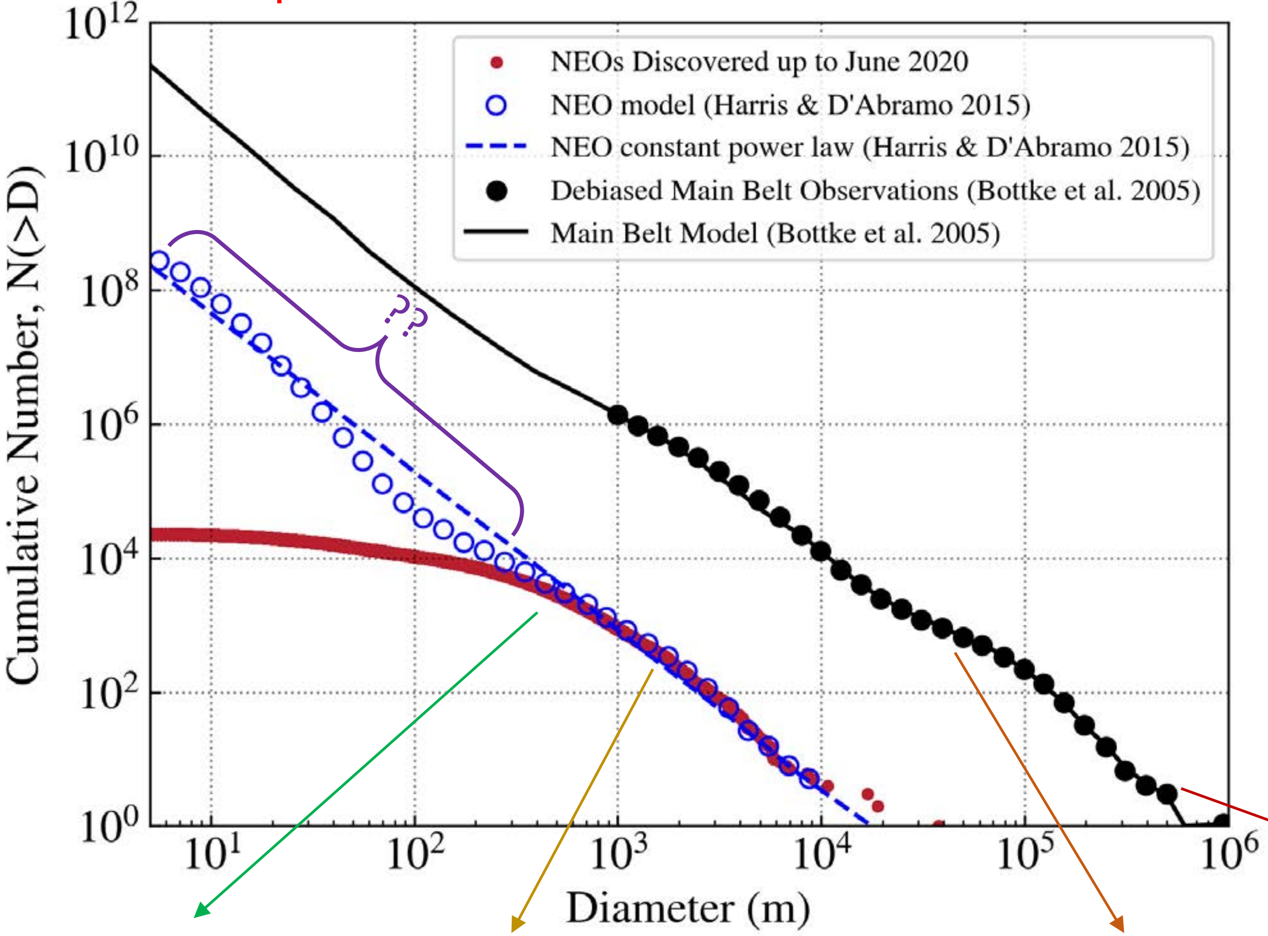
$\boldsymbol{Y}$ **= 0.44 to 1.70 MPa**
$\boldsymbol{Q_D^* \sim 200 - 300}$ **J/kg** (5 km/s impact)

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

Meteoritic Analogs, CI/CM have Y =
0.2 MPa (Tagish Lake, Brown et al. 2002) to
85 MPa (Sutter's Mill, Jennsikens et al. 2007)

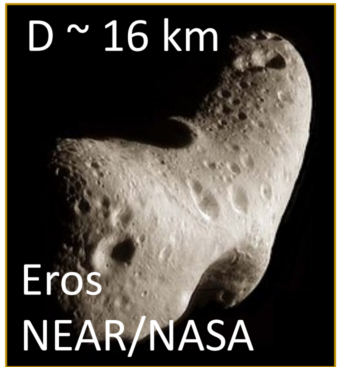
The NEO Population at 140 m

Are NEAs ≲ 200 m cohesive rubble-piles or monoliths?



D < 0.2 km

??

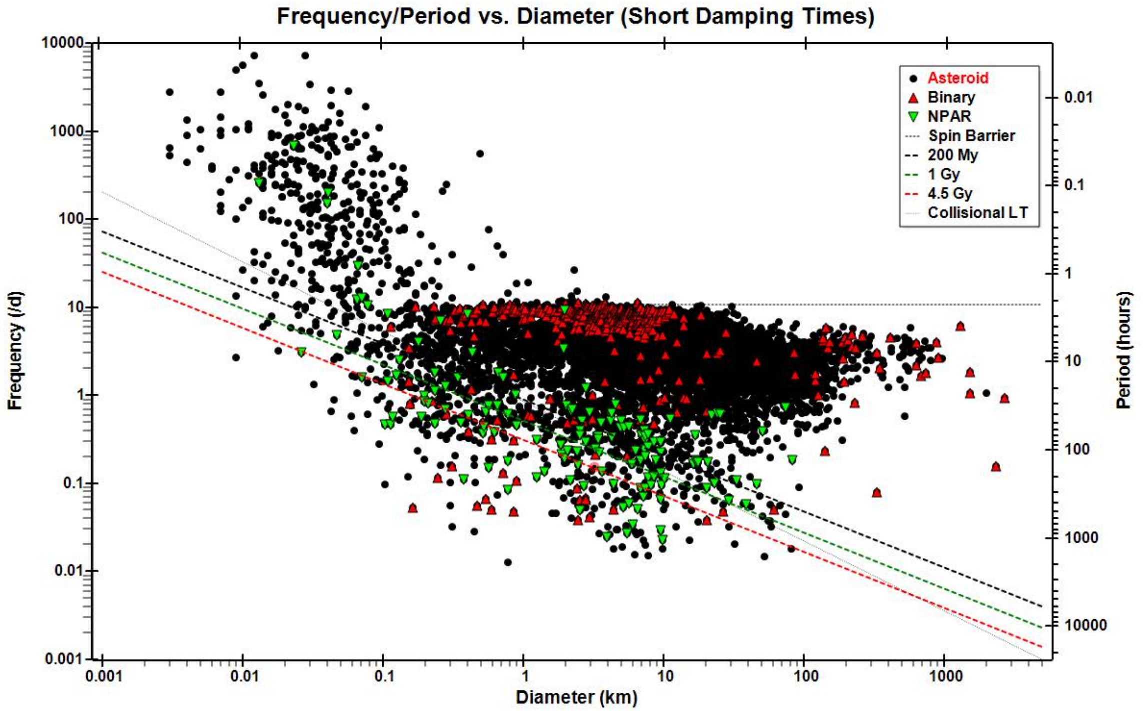


The Spin Limit of Asteroids

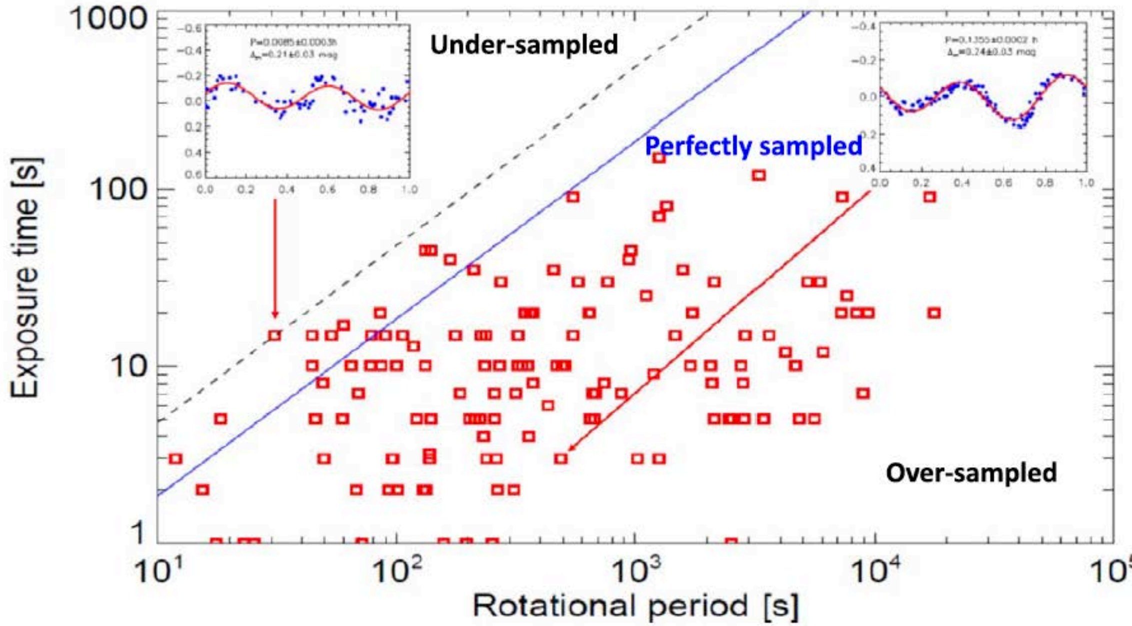
Open Question:

Are NEAs ≲ 200 m cohesive rubble-piles or monoliths?

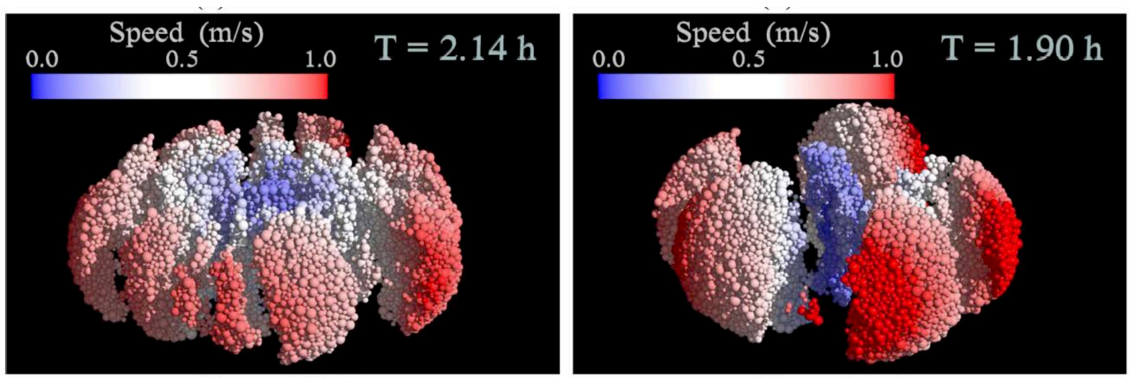
- The majority of asteroids ≳ 200 m do not have P_{spin} ≲ 2.2 h.
- This is the cohesionless spin barrier: rubble-pile interior for small NEAs where $t_{spin\text{-}up} < t_{dyn}$, their dynamical lifetime.
- Rubble Piles with inter-boulder cohesion can achieve high spin periods (~3 kPa for fastest spins, Sànchez & Scheeres 2014)
- Objects ≲ 200 m, can have high spins, but observations are limited by exposure times (Thirouin et al. 2018).



Spin Period Distribution: Waner et al. (2009) (LCDB, Oct 2020)



Sampling Light Curve limited by exposure time: Thirouin et al. 2018

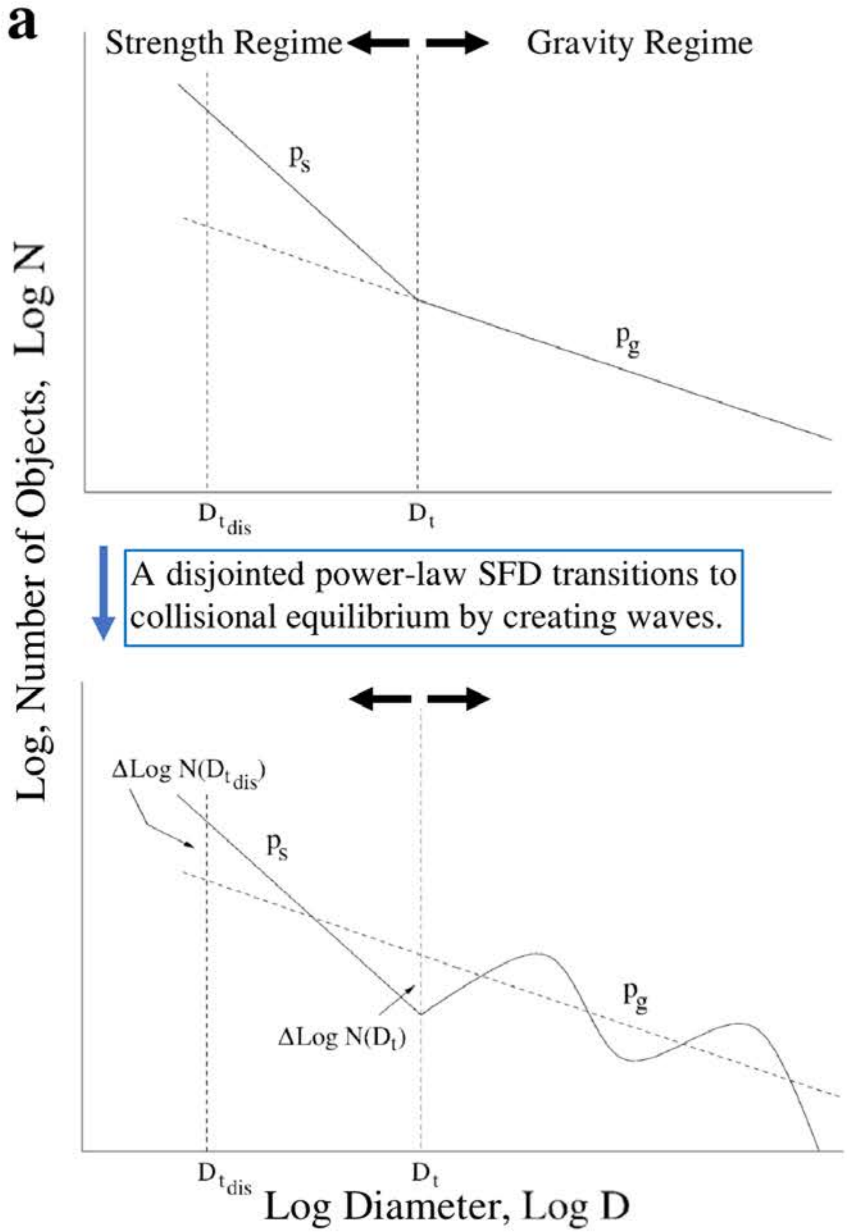


(e) c = 800 Pa

(f) c = 1600 Pa

Cohesive rubble piles can spin faster than the fluid limit: Zhang et al. 2018

Constraints from NEOs population Estimates

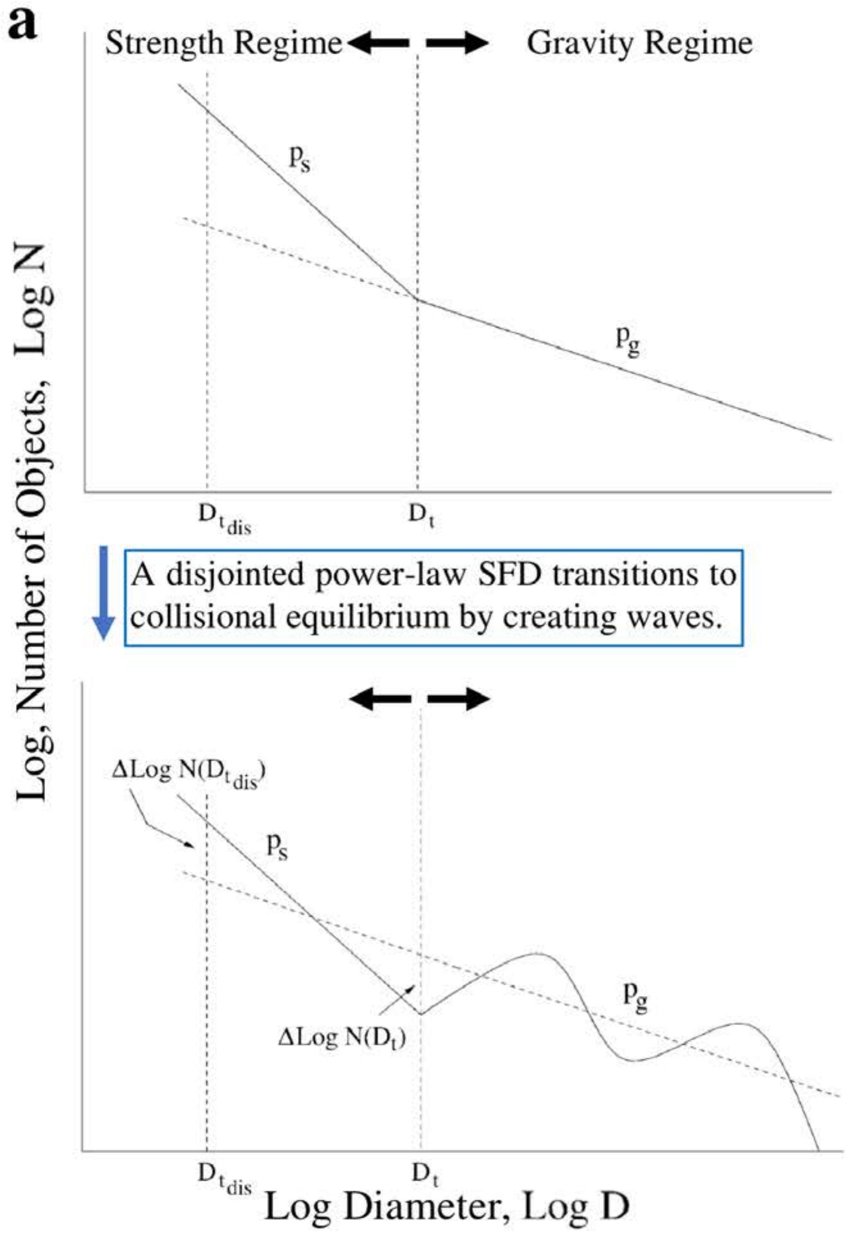


$\Delta\ log\ N\ (D_{\mathrm{t}})$:
Amplitude of the inflection point = # of ~ 140 m NEOs
Will be measured by next generation of NEO surveys

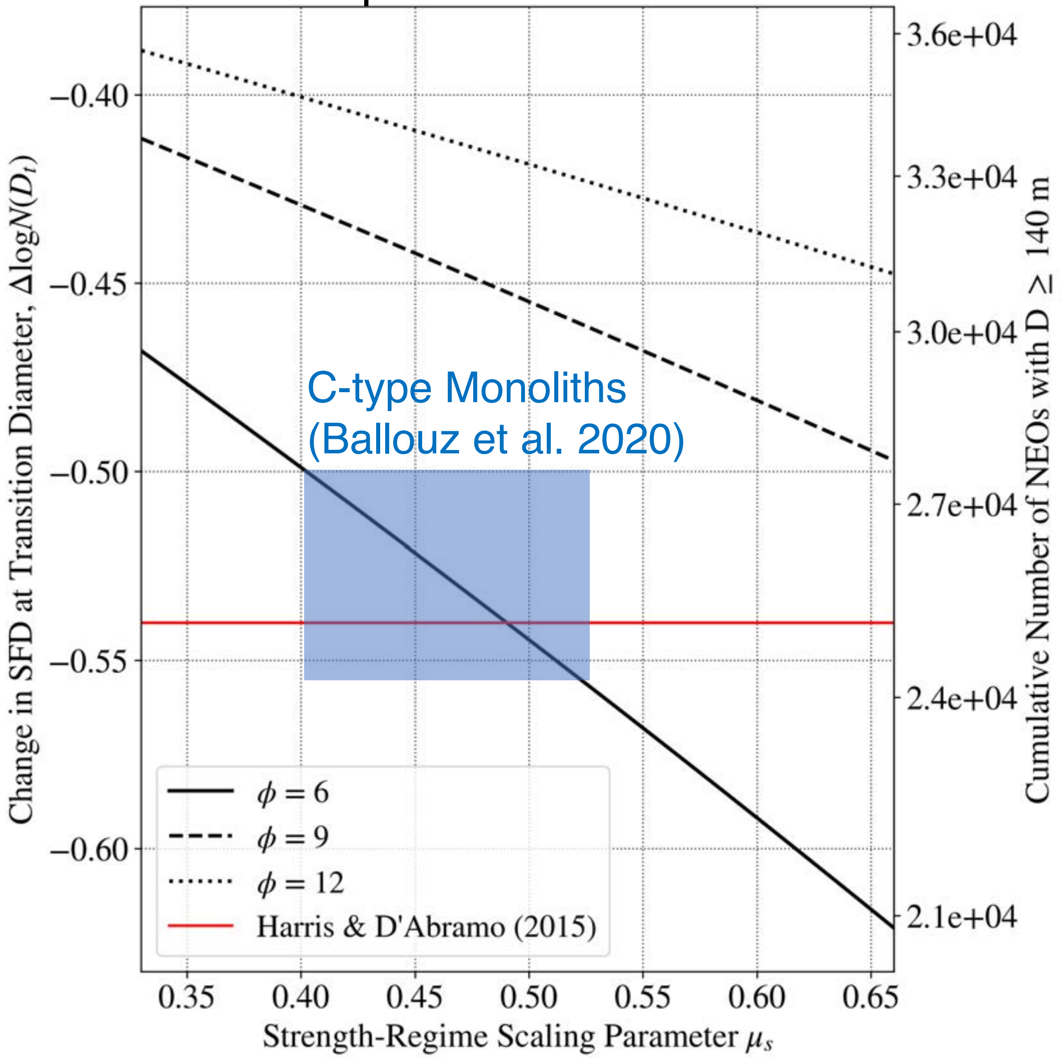
For collisional equilibrium, can be calculated for known:
Impact properties:
1) Impact Speed
Strength properties:
2) disruption threshold, Q_D^* = 30 J/kg (Ballouz et al. 2020)
3) strength regime scaling constant, μ_s = 0.47±0.07 (Ballouz et al. 2020)
4) gravity-regime scaling constant, μ_g =0.33-0.36 (Leinhard & Stewart 2012)
5) the strain-dependent strength parameter, ϕ (assumed).

Adapted from: O'Brien & Greenberg (2005)

Constraints from NEOs population Estimates

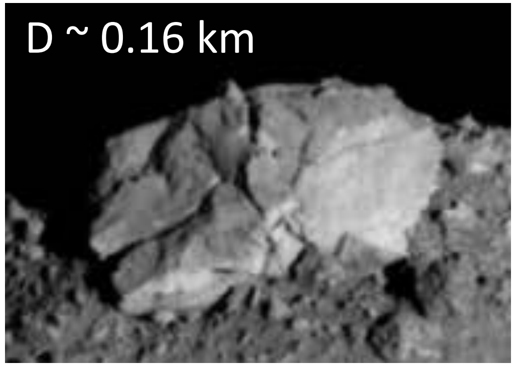


$\Delta\ log\ N\ (D_t)$:
Vertical Axes:
Amplitude of the inflection point = # of NEOs ≳140 m NEOs

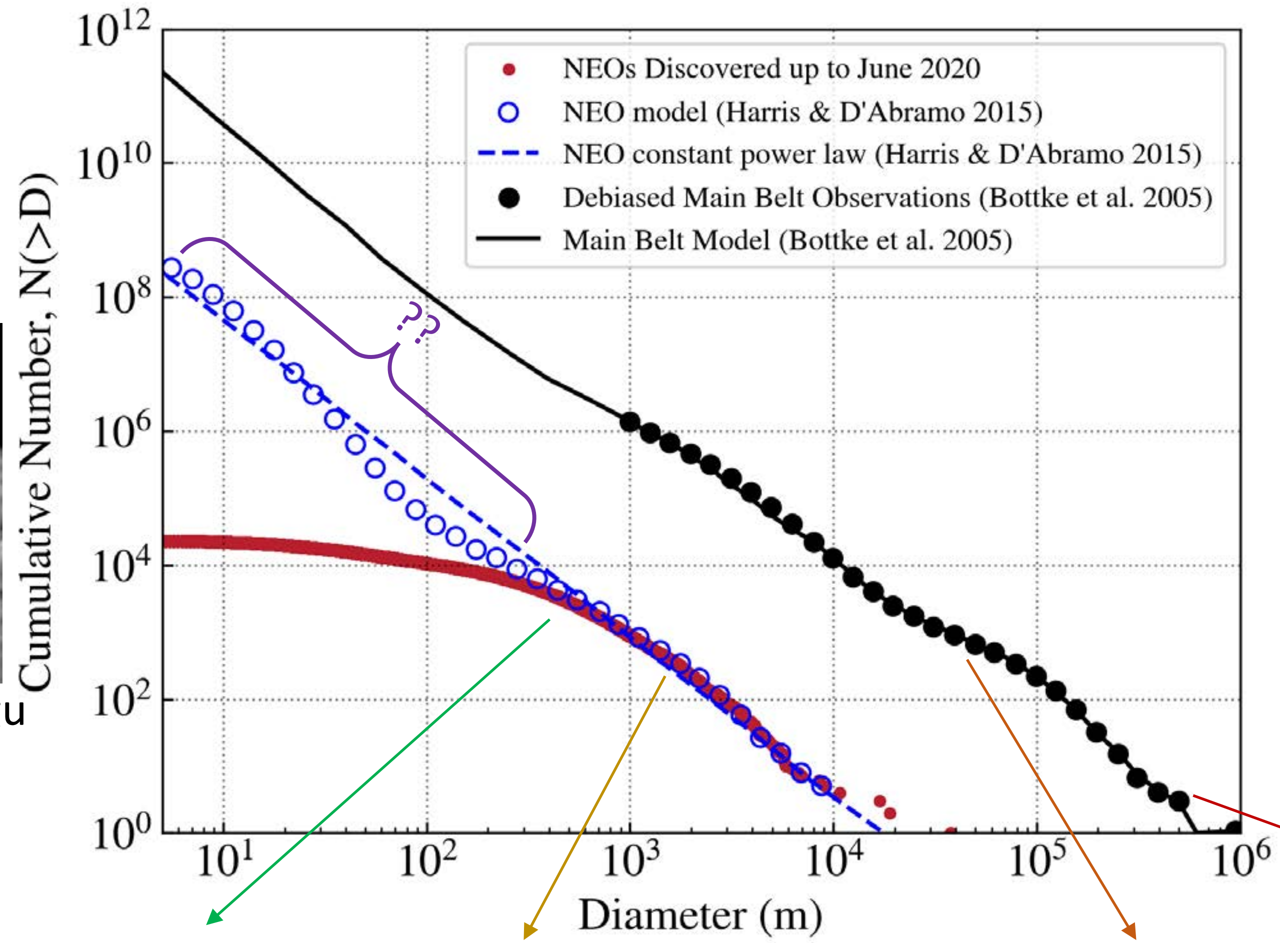


Adapted from: O'Brien & Greenberg (2005)

The strength of 100-m scale asteroids



Otohime Boulder on Ryugu
Hayabusa2/JAXA



for 100-m C-type asteroid:

$Y \sim$ **0.13 MPa**
$Q_D^* \sim \mathbf{30\ J/kg}$ (5 km/s impact)

D < 0.2 km

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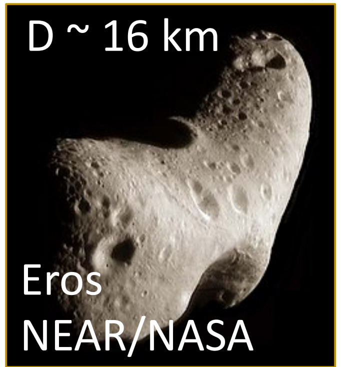


Summary & Outlook : Heterogeneity

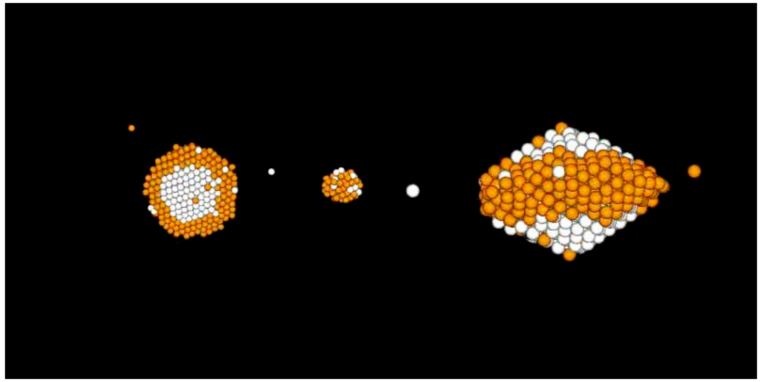
- Measured > 600 craters on Bennu's Boulders, and used population limits to estimate strengths and develop scaling relationships.
- Collisional equilibrium of NEO population can also place constraints on strength properties.
- Current estimates of NEO population ≳ 140 m are consistent with our strength estimates: this population may be dominated by monoliths.
- Using our scaling relationships, 100-m C-type asteroids have:

$$Y \sim 0.13 \text{ MPa and } \boldsymbol{Q_D^*} \sim \mathbf{30\ J/kg} \text{ (5 km/s impact)}$$

- Hypotheses testable with next generation surveys and sample return.

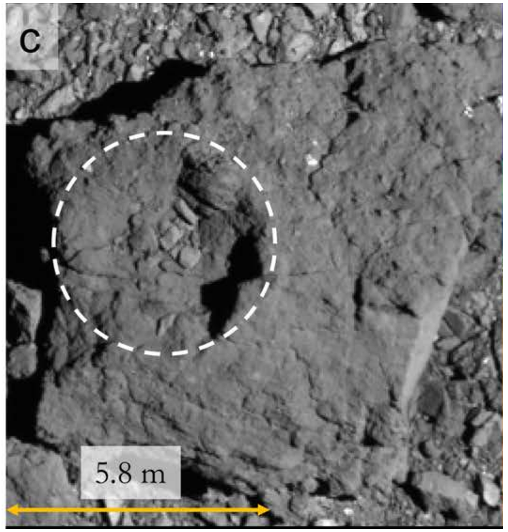
Outlook:

- Impact on the surface of a rubble-pile can have very different outcomes.
- DART will be impacting the ~170 m secondary of an NEA Binary:
- may have diversity in strengths of 100-m scale NEOs.



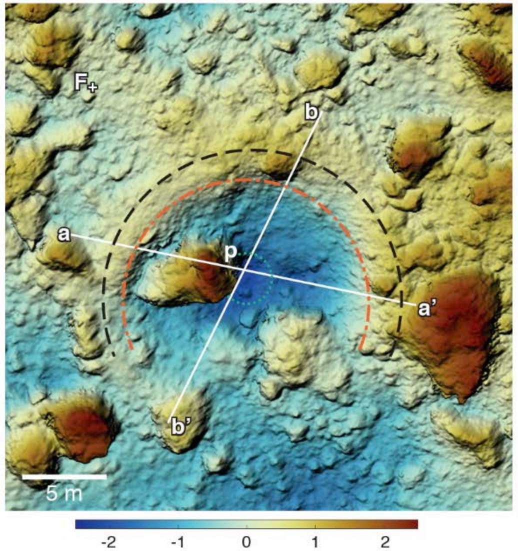
Binary Asteroid Formation via YORP: Walsh et al. (2008)

~ 50 cm impactor
5 km/s, 5 m crater

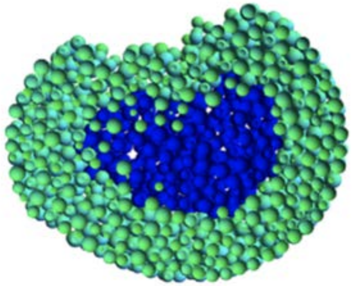


Crater on Bennu Boulder:
Ballouz et al. 2020

~ 20 cm impactor,
2 km/s, 15 m crater



SCI artificial crater on Ryugu
Arakawa et al. 2020



Fast-spinning rubble-piles can be held together by cohesion:
Sànchez & Scheeres (2018)

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