7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Session 4: OSIRIS-REx

Chairs: Terik Daly | Christian Koeberl

Presenters: A. Simon, NASA/GSFC |
R. Ballouz, Univ. of Arizona | B. Bierhaus, Lockheed Martin |
M. Nolan, Univ. of Arizona

OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

Overview and Highlights of the OSIRIS-REx Mission

A.A. Simon
(NASA Goddard Space Flight Center)

& all of the OREx team!

UNIVERSITY OF ARIZONA   NASA'S GODDARD SPACE FLIGHT CENTER   LOCKHEED MARTIN

Mission Overview

Origins

Return and analyze a sample of pristine carbonaceous asteroid regolith

Spectral **I**nterpretation

Provide ground truth for telescopic data of the entire asteroid population

Resource **I**dentification

Map the chemistry and mineralogy of a primitive carbonaceous asteroid

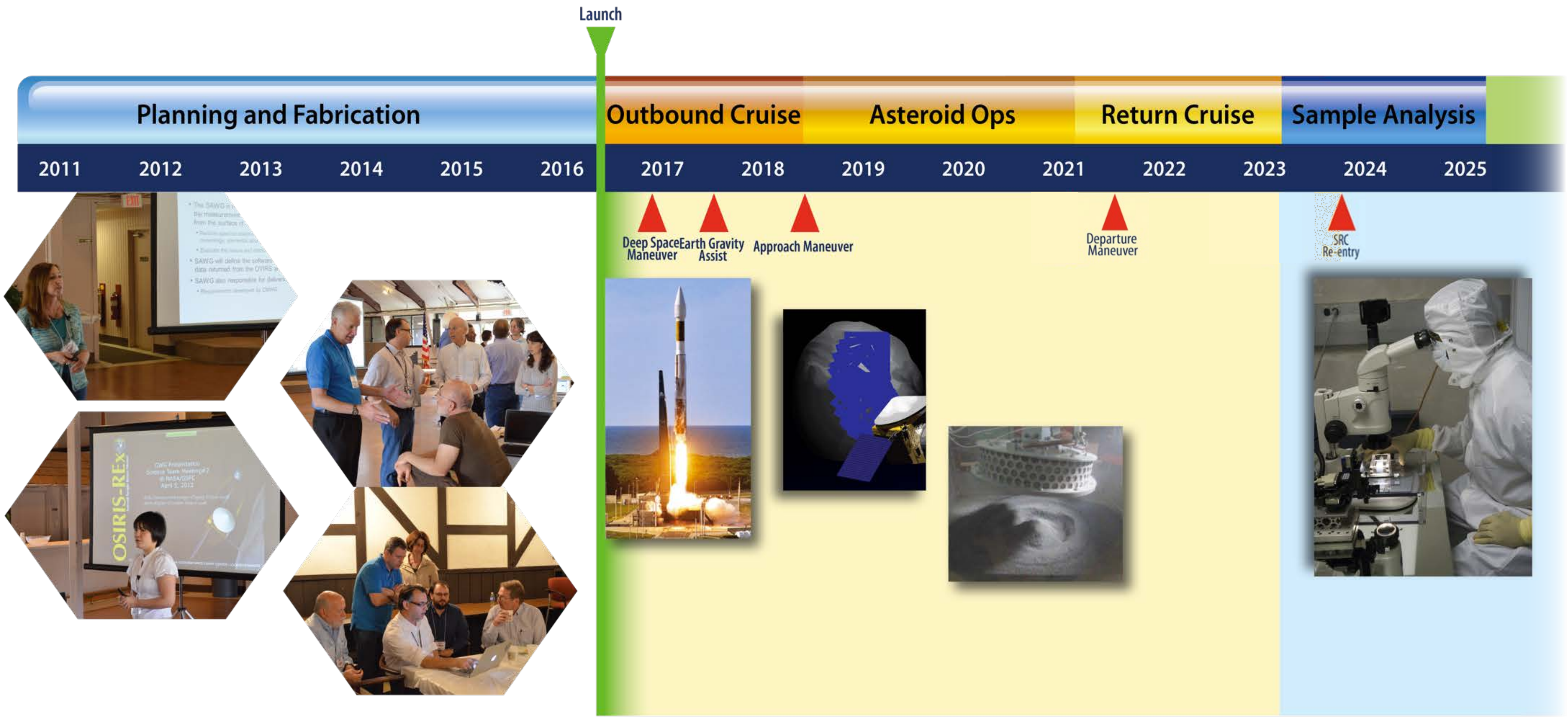
Security

Measure the Yarkovsky effect on a potentially hazardous asteroid

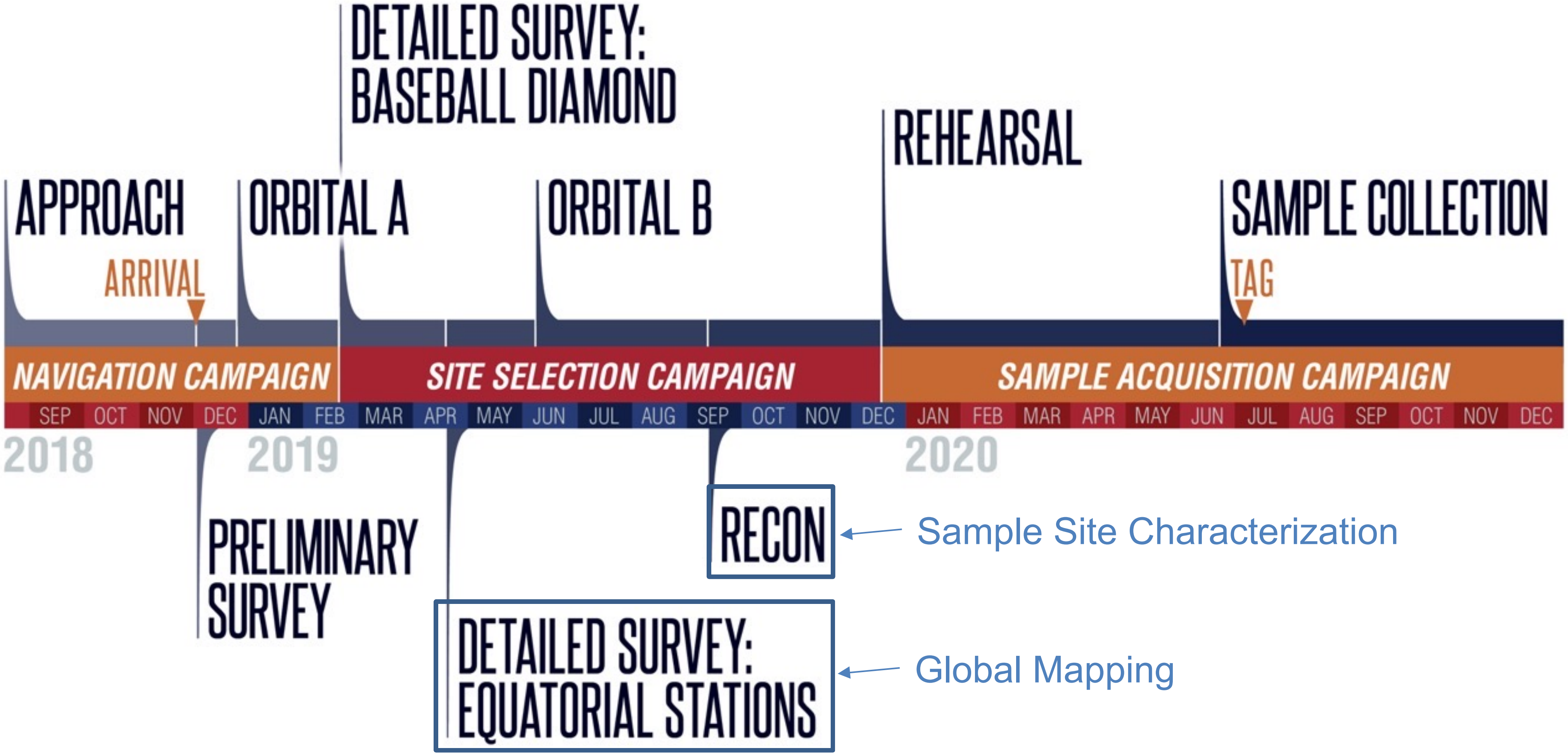
Regolith **Ex**plorer

Document the regolith at the sampling site at cm scale

Mission Timeline



Asteroid Operations Plan

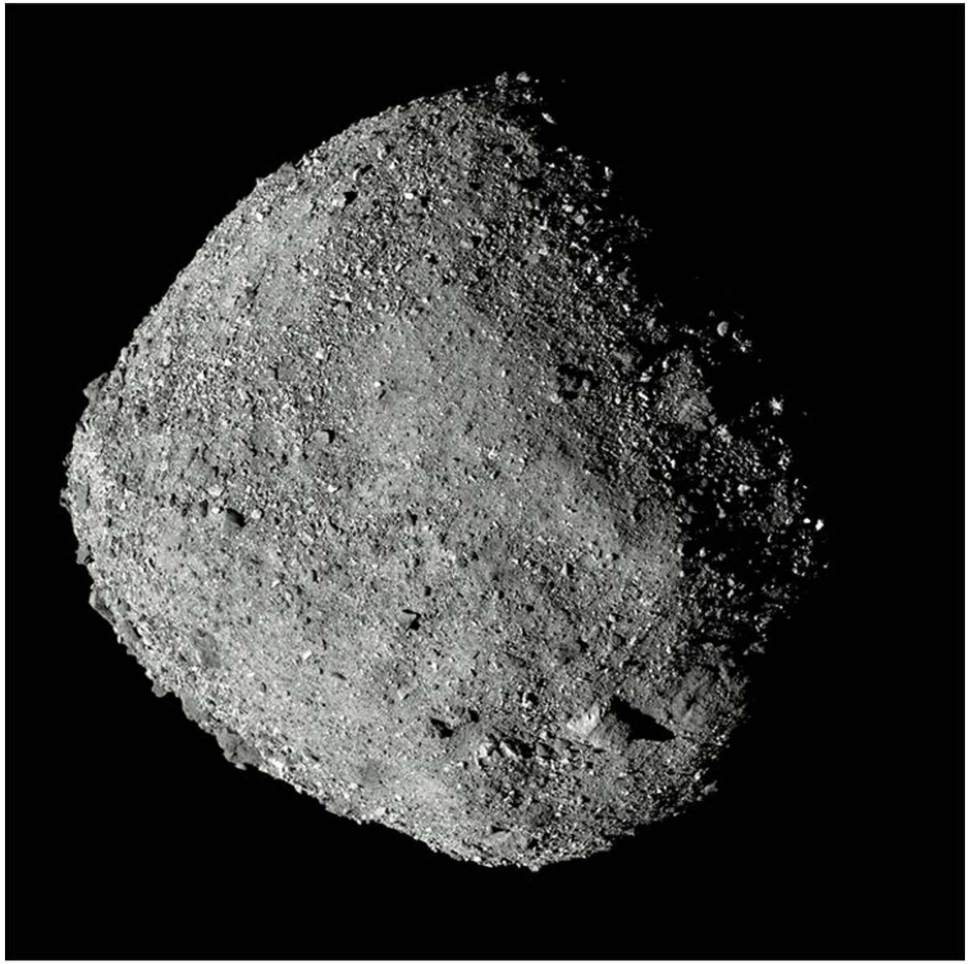


Sample Site Characterization

Global Mapping

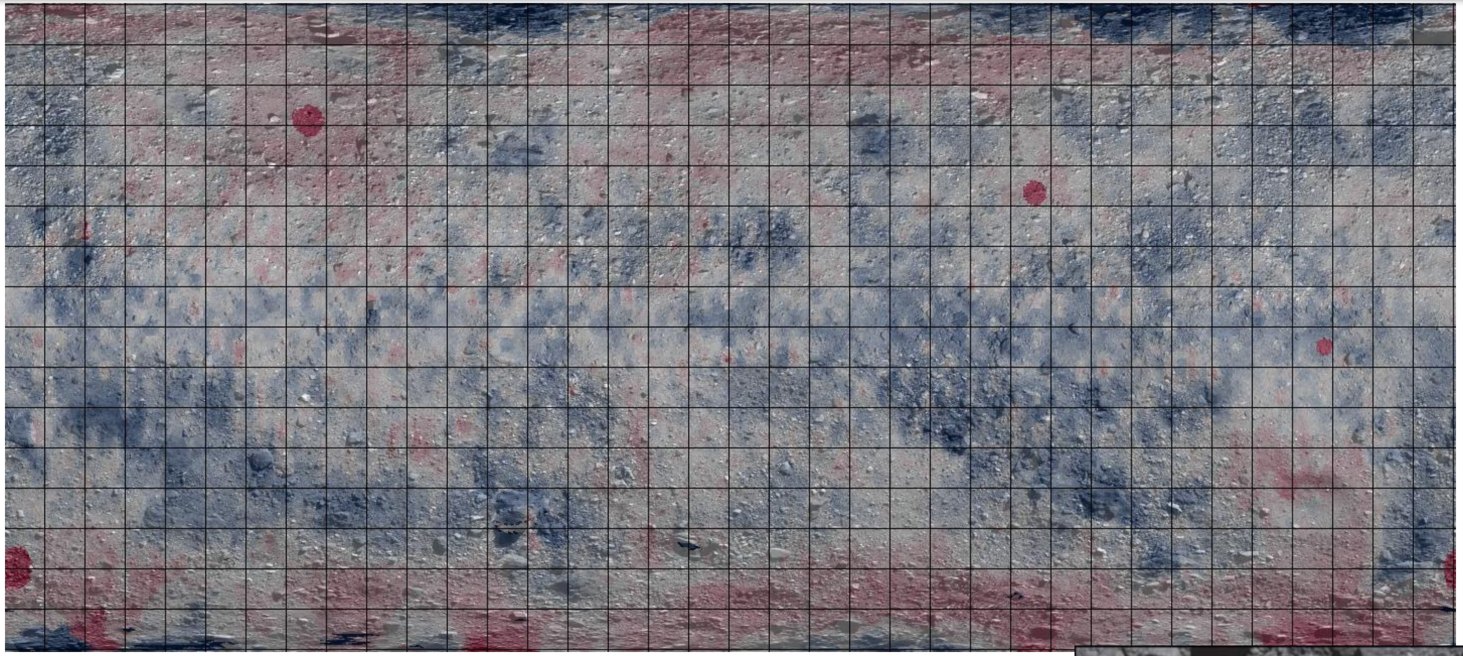
Discoveries on Approach

Boulders, boulders, more boulders



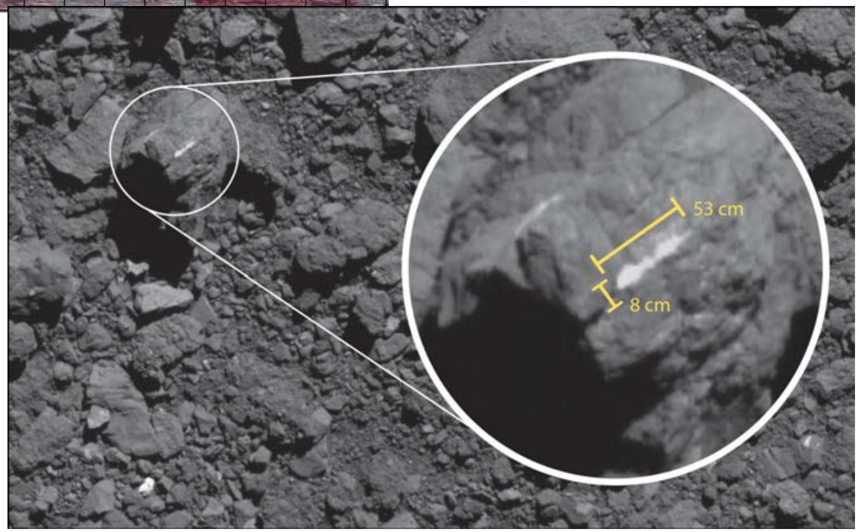
Mission Highlights: Composition

- Global maps:
  - Blue spectral slope
  - Carbon-bearing materials and hydrated phyllosilicates everywhere
  - Iron oxides present
- Small amounts of exogenous material
  - pyroxene



1.05-micron band depth map

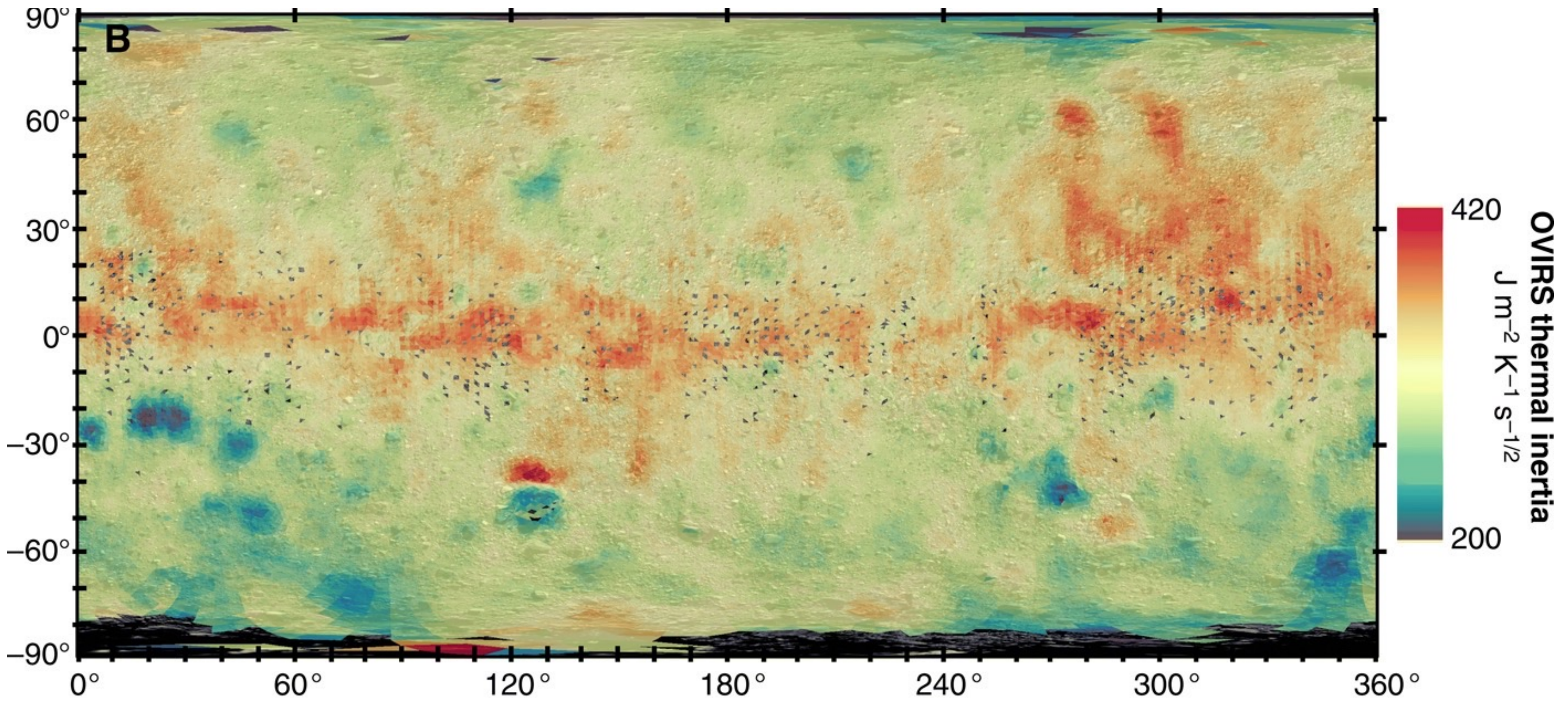
Veined boulders



DellaGiustina et al. *Nat. Astro.* 2020,
Kaplan et al. *Science* 2020,
Simon et al. *Science* 2020

Mission Highlights: Thermal Inertia

We expected large boulders with high thermal inertia and dusty areas with low thermal inertia, but found the opposite: could be due to compacted material and/or porous boulders



Rozitis et al. *Science Advances* 2020

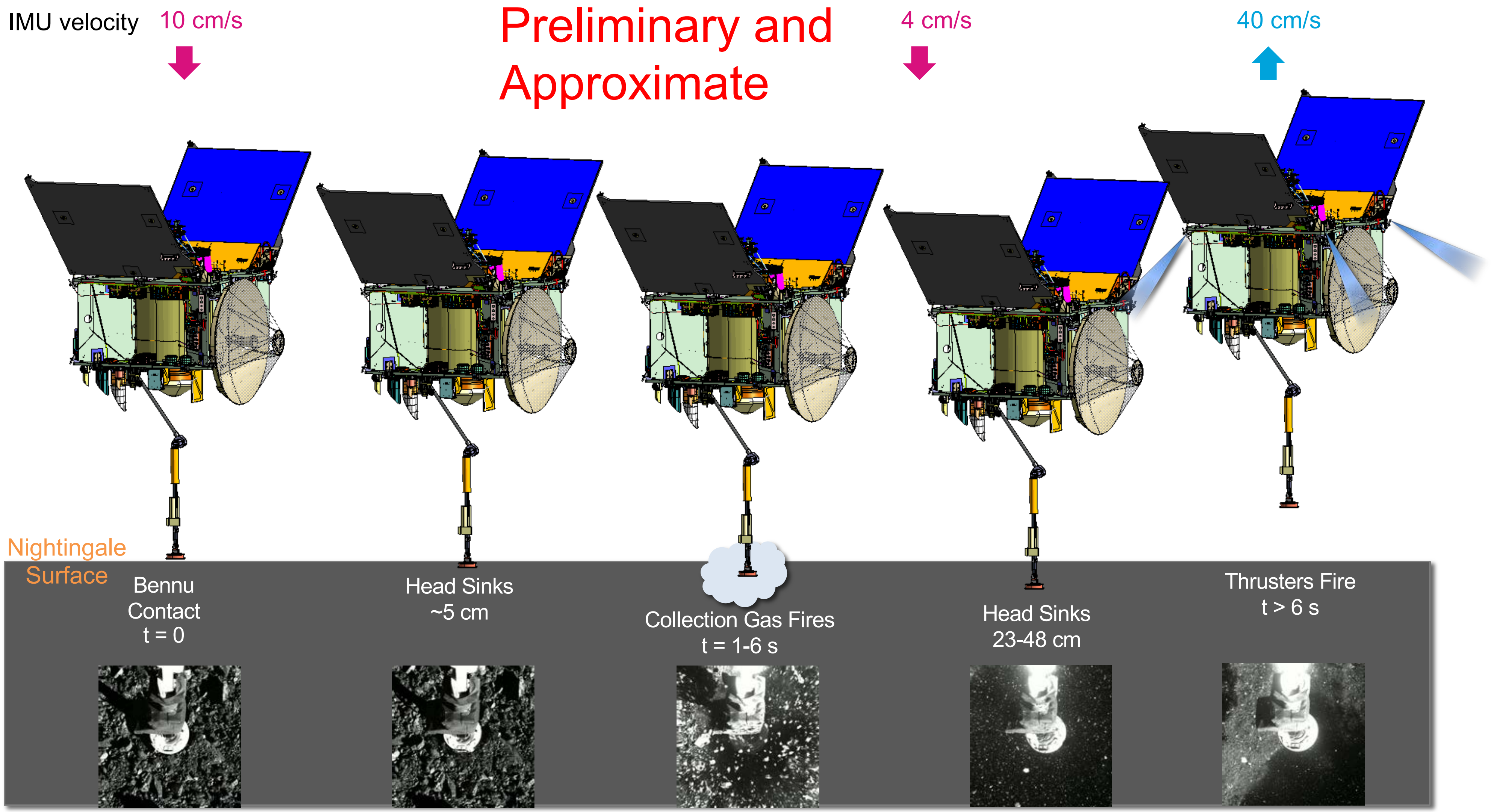
TAG

Contact!

Gas firing

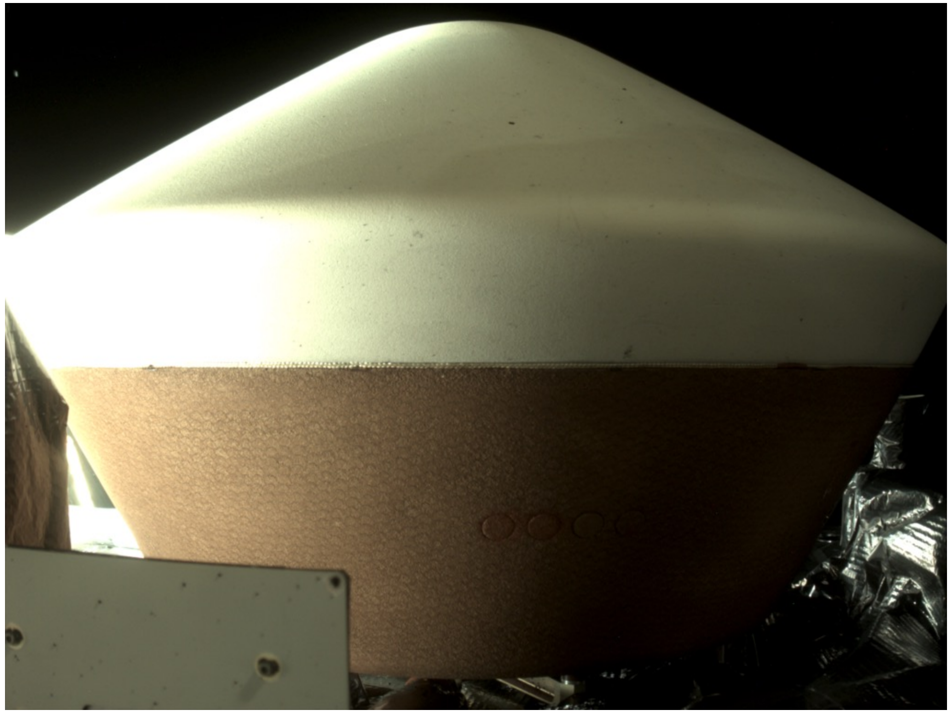
TAG Sequence

Preliminary and Approximate



Summary

- Asteroid Bennu held surprises for us!
  - Lots of loose rubble, no obvious regolith “ponds”
  - Composition and spectral slope are fairly uniform across the surface
    - ~90% of the surface is blue (a few redder boulders and craters)
    - Small variation in absorption band depths or band identification
  - Some exogenous material
    - Discrete bright boulders of pyroxene
  - Ample evidence of past aqueous alteration
    - Hydrated phyllosilicates present
    - Evidence of “veins”, possibly carbonates
    - Iron oxides



- What’s Next?
  - Finished final Bennu farewell views in April
  - Depart the asteroid in May
  - Earth return in September 2023

Visit AsteroidMission.org

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

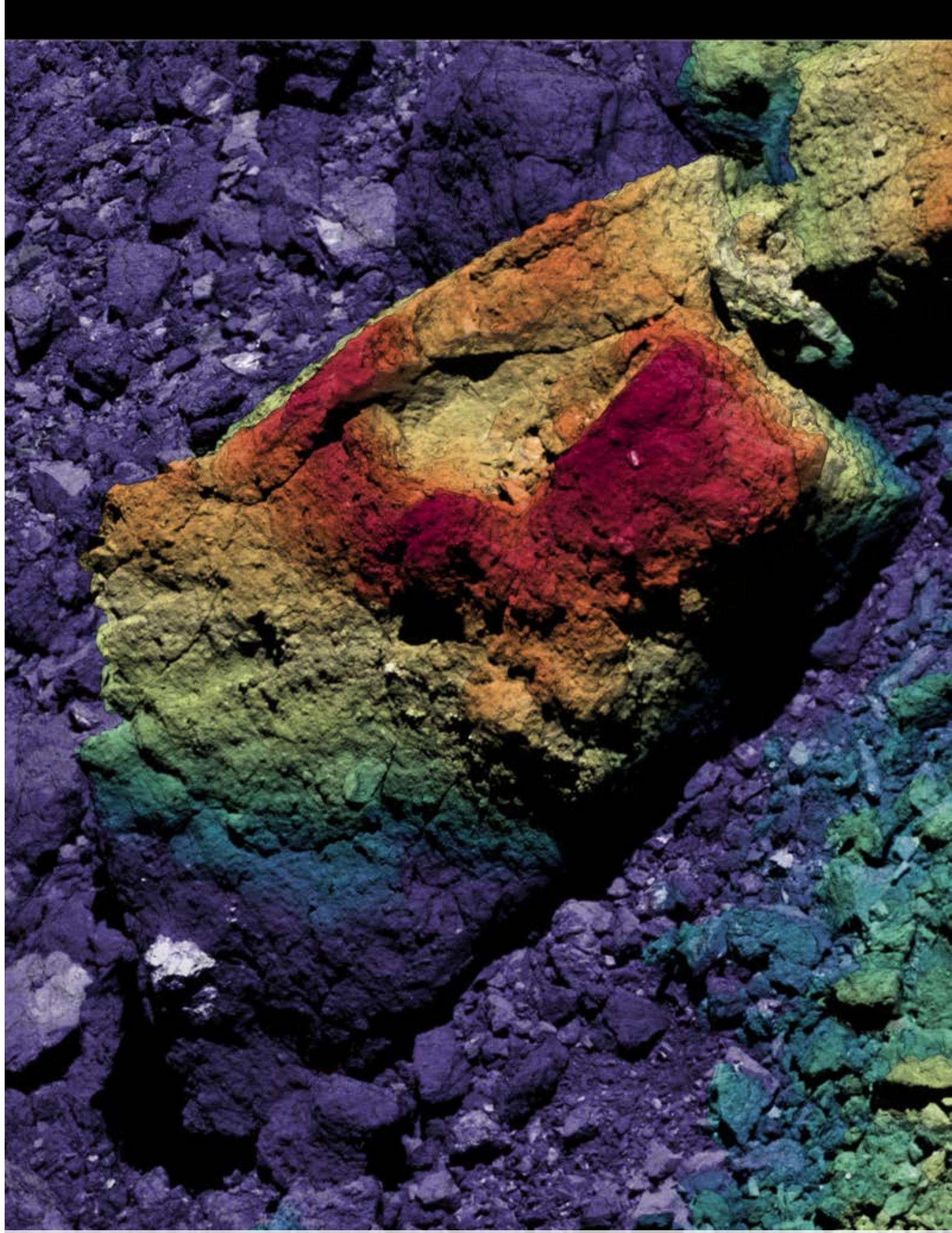


Image & LIDAR data of crater on 10 m boulder
OSIRIS-REx/OCAMS/OLA/UA/NASA

Outline

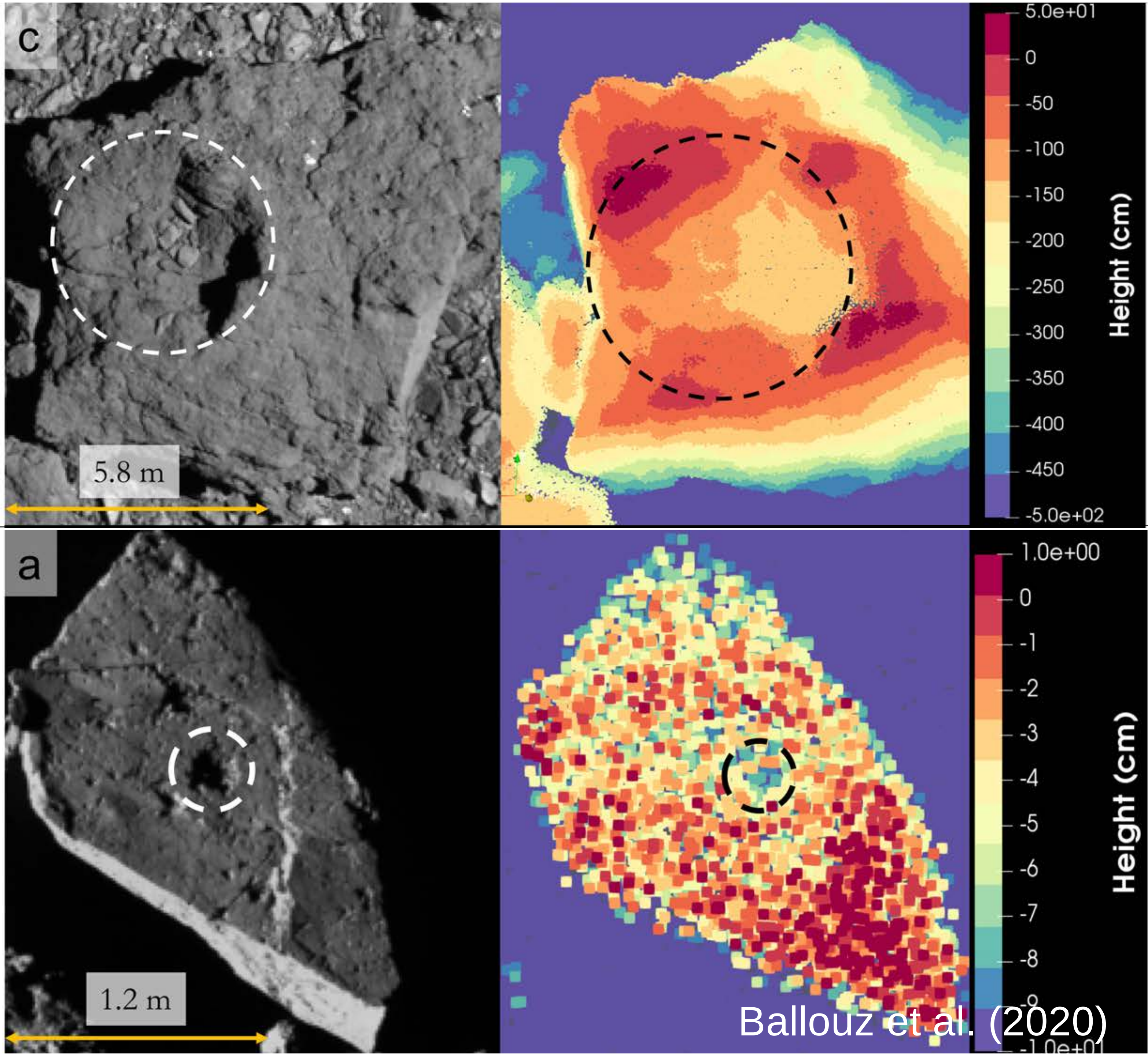
- Observations: Craters on Bennu’s Boulders
- Model: The strength of monolithic C-types
- Constraints from NEO Population Estimates
- Summary and Outlook:

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.

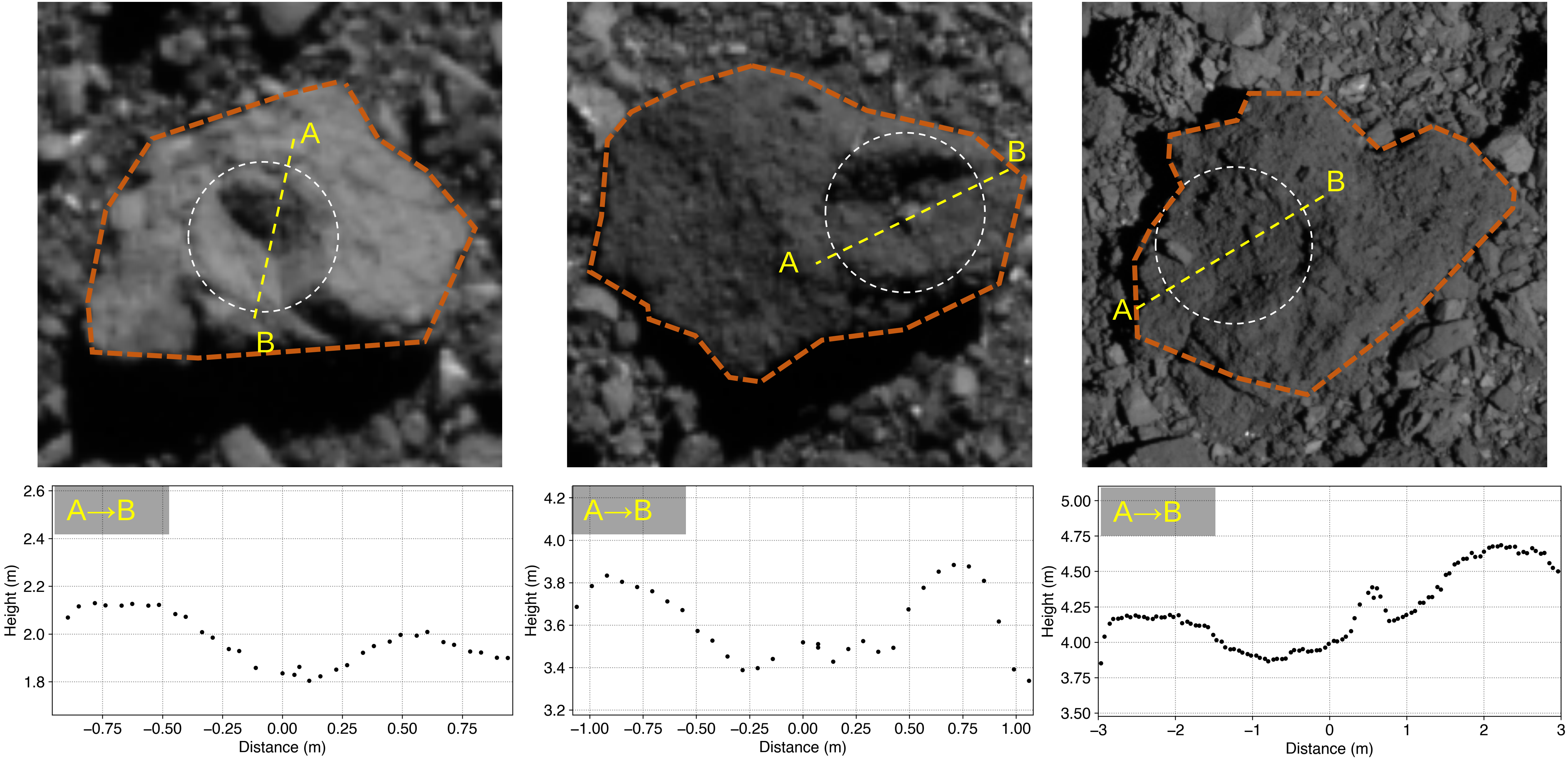
Crater dimensions of a subset were measured with OSIRIS-REx Laser Altimeter (OLA) data (right panels)



Ballouz et al. (2020)

OLA measurements of crater dimensions:

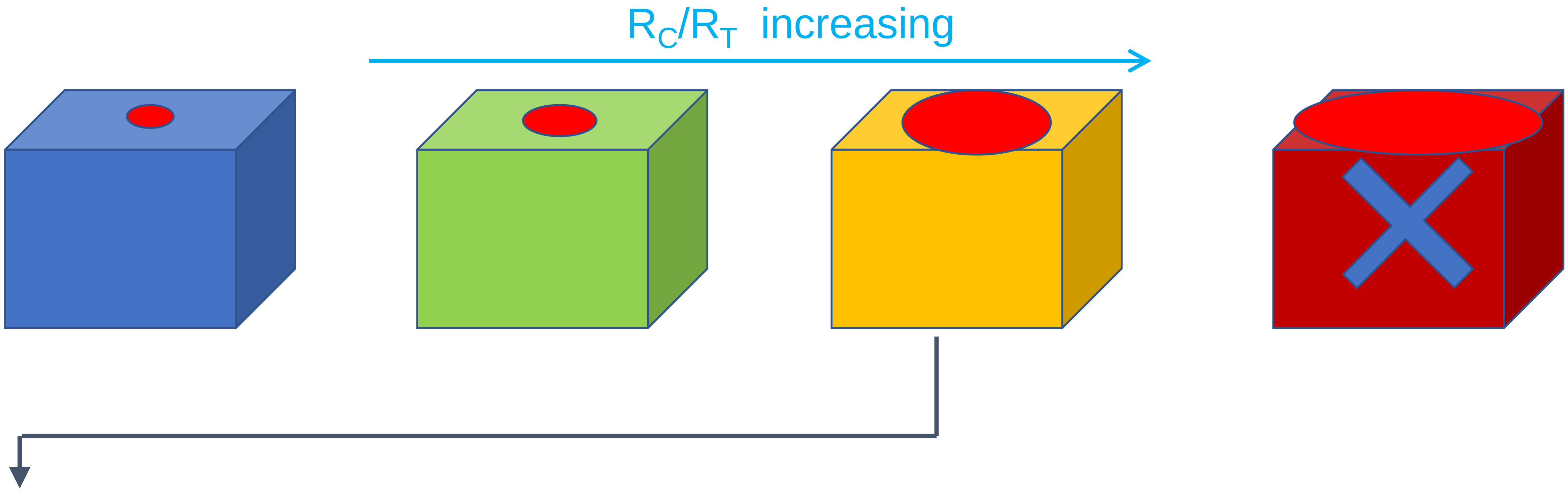
For 7 craters, *d/D* = 0.33 +/- 0.08 (relatively high compared to Bennu's craters, Daly et al. 2020)



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

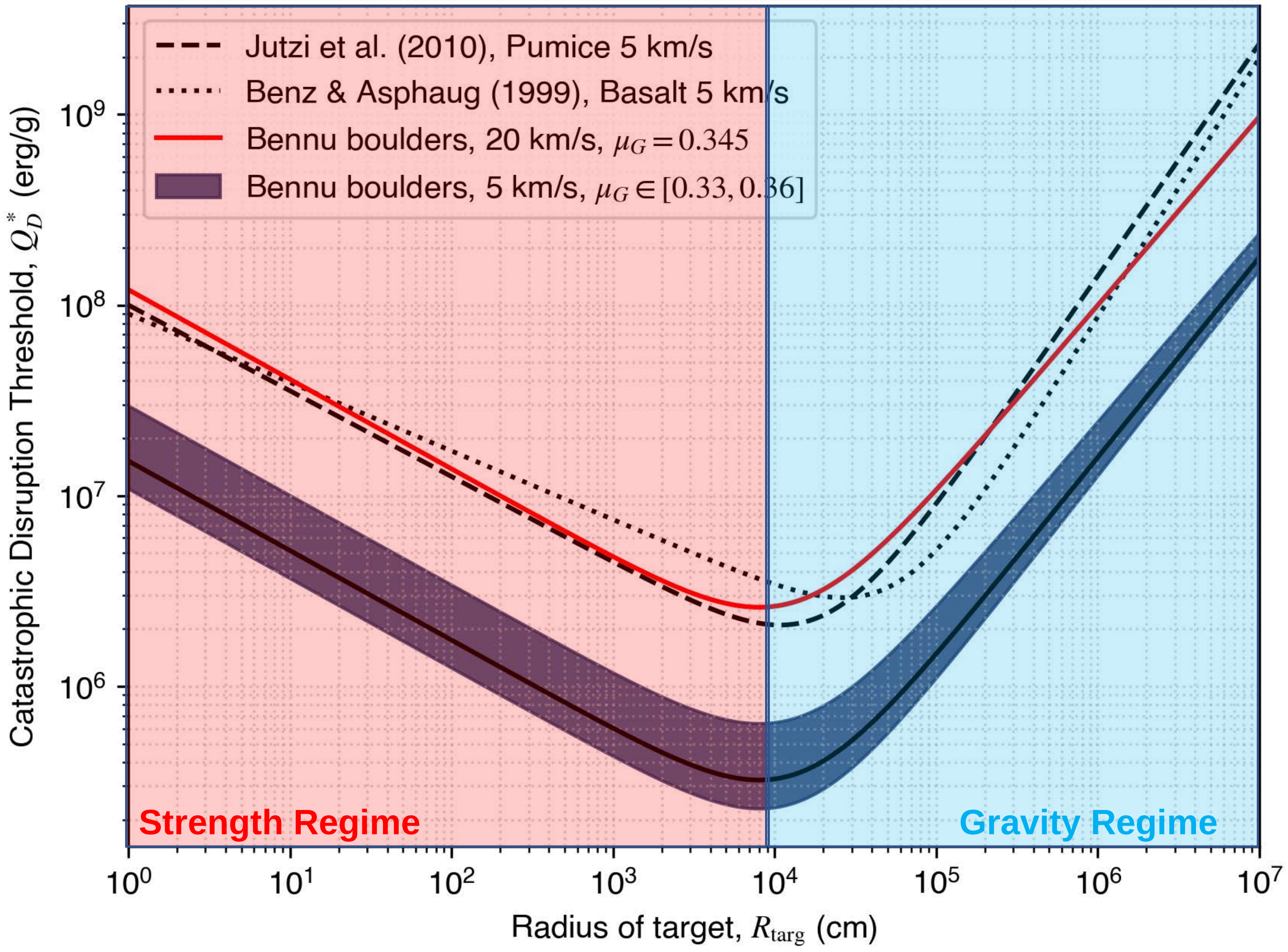
Q: How do we obtain a strength measurement from observations of craters?

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:

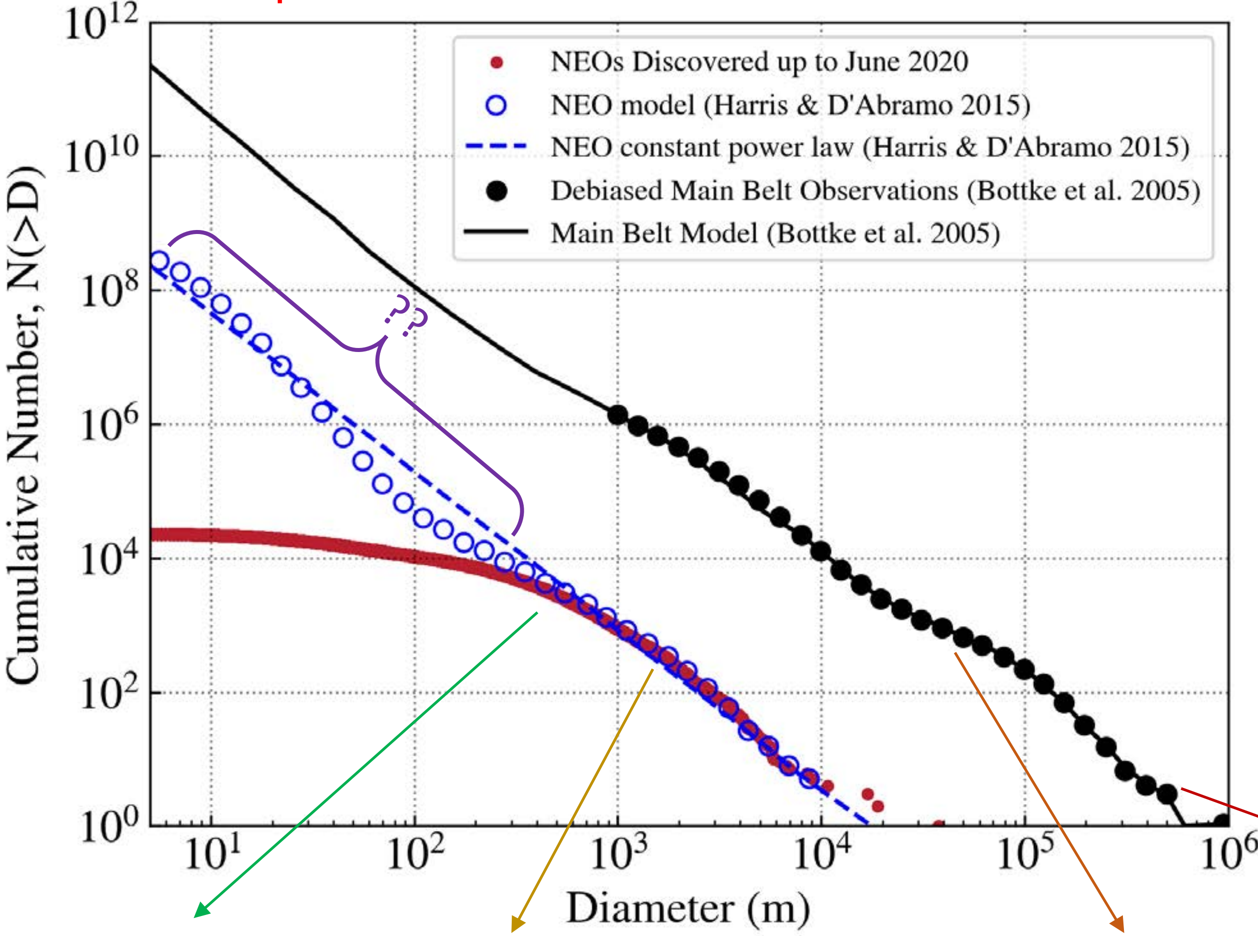
$\boldsymbol{Y}$ **= 0.44 to 1.70 MPa**
$\boldsymbol{Q_D^* \sim 200 - 300\ \mathrm{J/kg}}$ (5 km/s impact)

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)

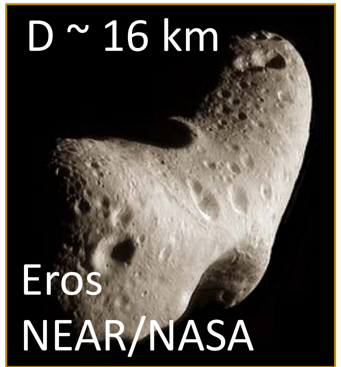
The NEO Population at 140 m

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



D < 0.2 km

??

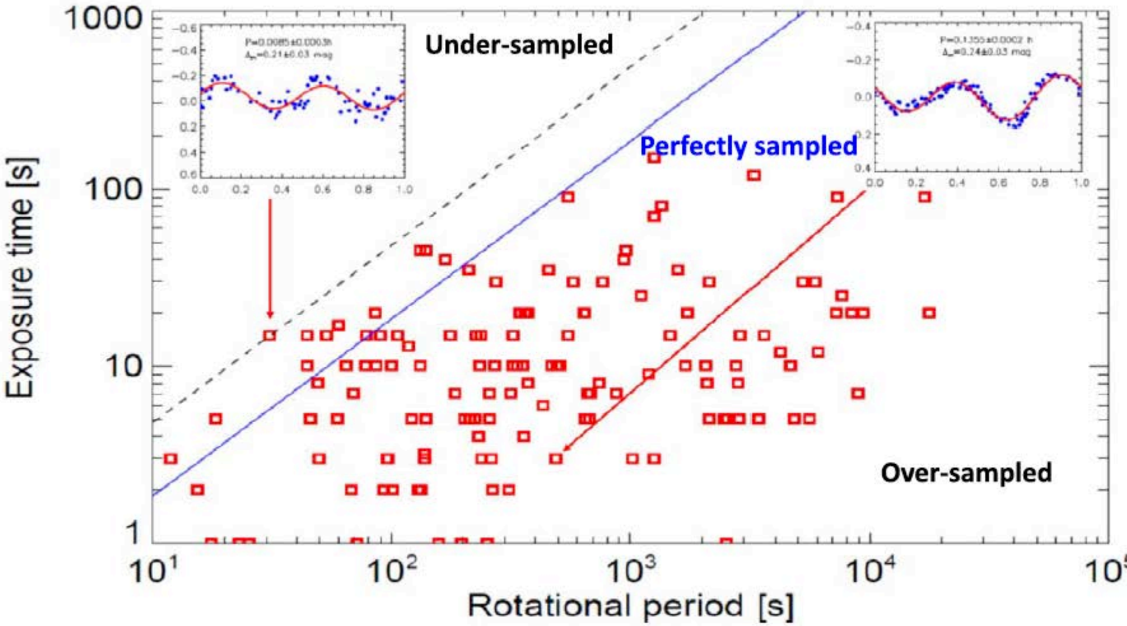


The Spin Limit of Asteroids

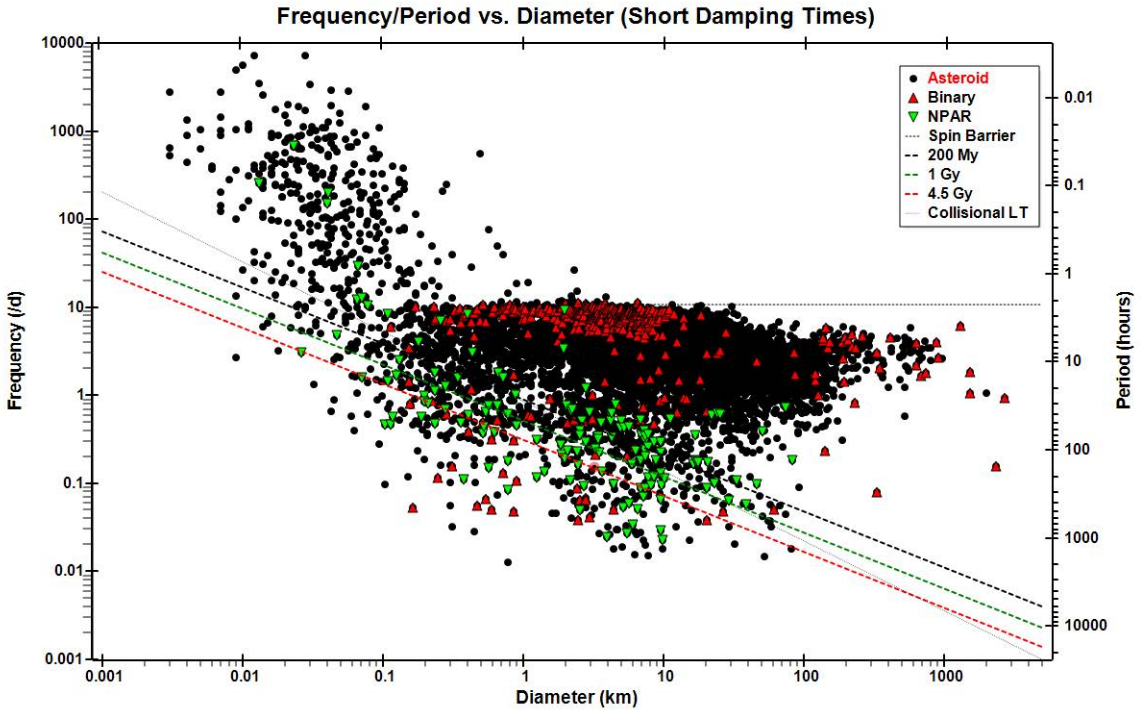
Open Question:

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

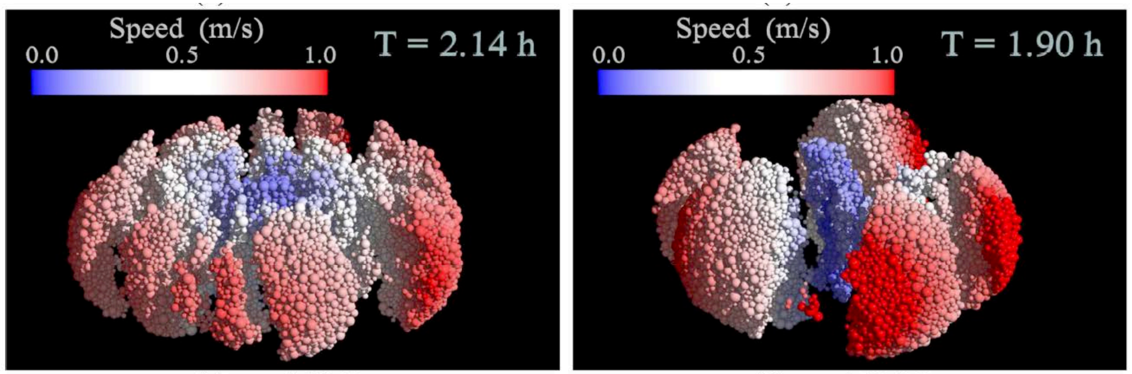
- The majority of asteroids ≳ 200 m do not have P_{spin} ≲ 2.2 h.
- This is the cohesionless spin barrier: rubble-pile interior for small NEAs where $t_{spin\text{-}up} < t_{dyn}$, their dynamical lifetime.
- Rubble Piles with inter-boulder cohesion can achieve high spin periods (~3 kPa for fastest spins,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



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



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

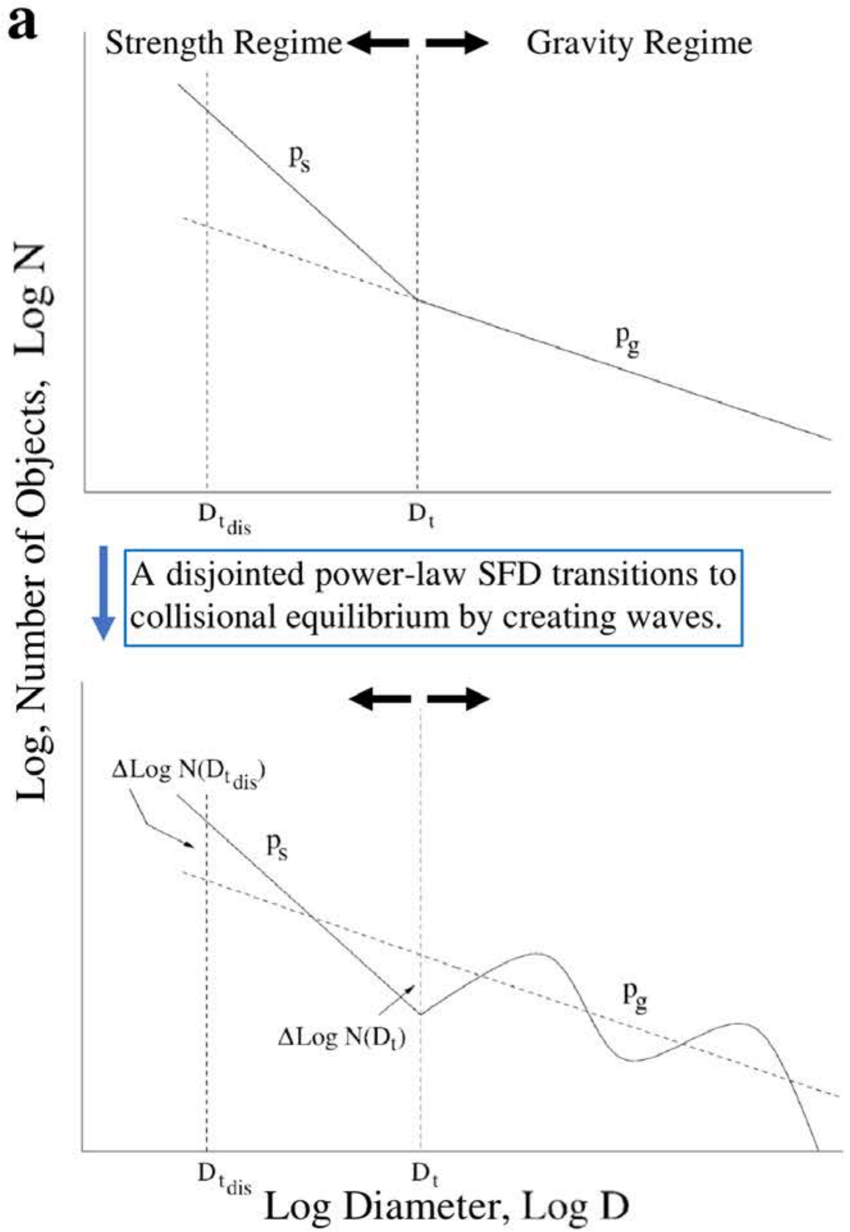


(e) c = 800 Pa

(f) c = 1600 Pa

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

Constraints from NEOs population Estimates



$\Delta\ log\ N\ (D_t)$:
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:

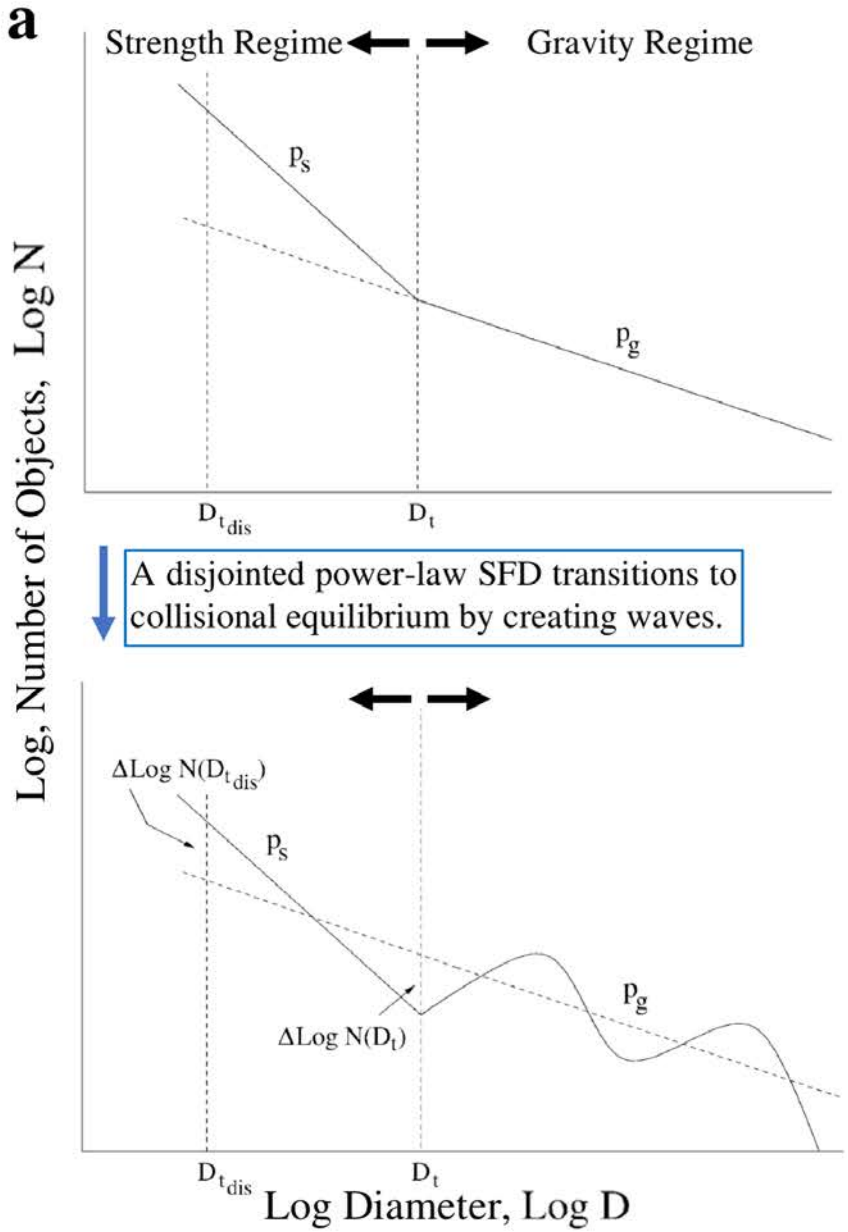
1) Impact Speed

Strength properties:

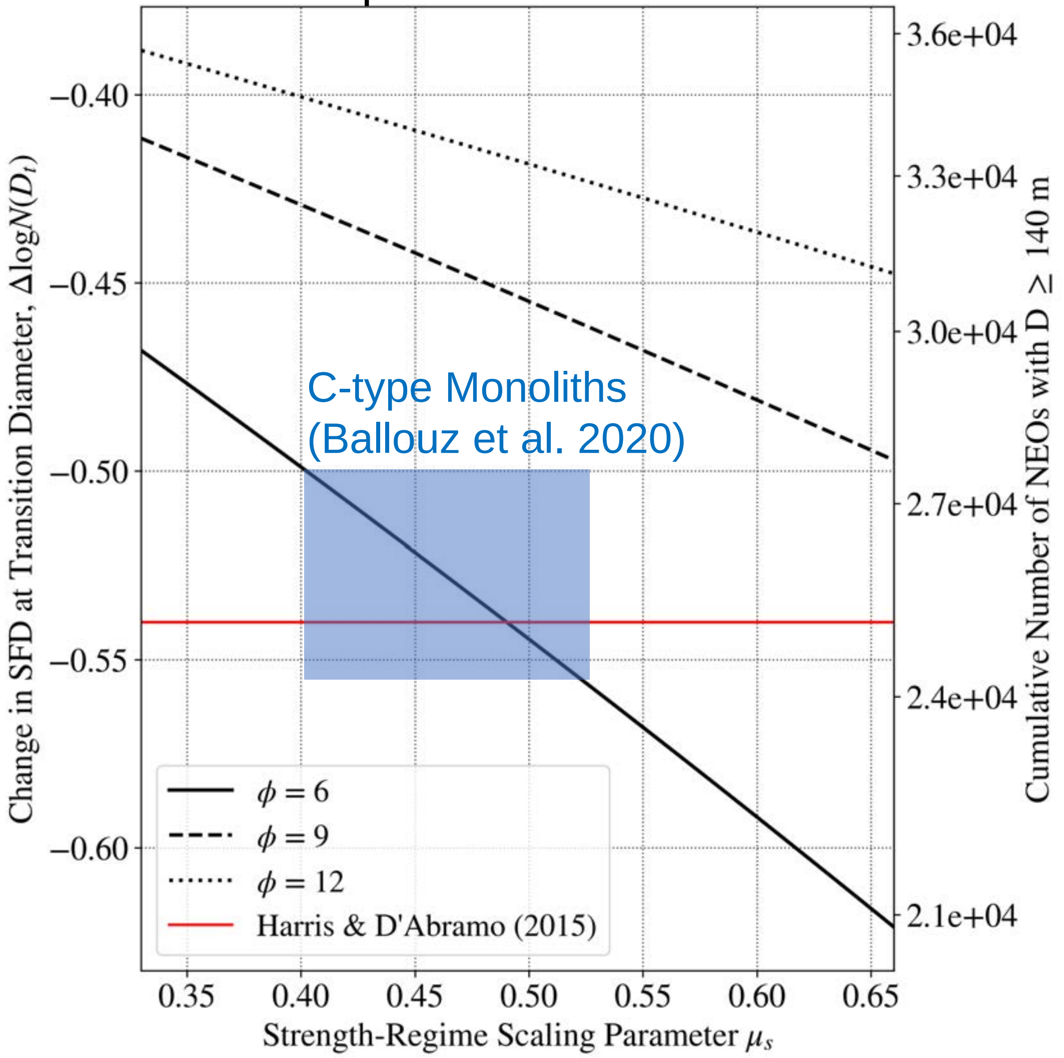
2) disruption threshold, $\boldsymbol{Q_D^*}$ = 30 J/kg (Ballouz et al. 2020)
3) strength regime scaling constant, $\boldsymbol{\mu_s}$ = 0.47±0.07 (Ballouz et al. 2020)
4) gravity-regime scaling constant, $\boldsymbol{\mu_g}$ =0.33-0.36 (Leinhard & Stewart 2012)
5) the strain-dependent strength parameter, ϕ (assumed).

Adapted from: O'Brien & Greenberg (2005)

Constraints from NEOs population Estimates

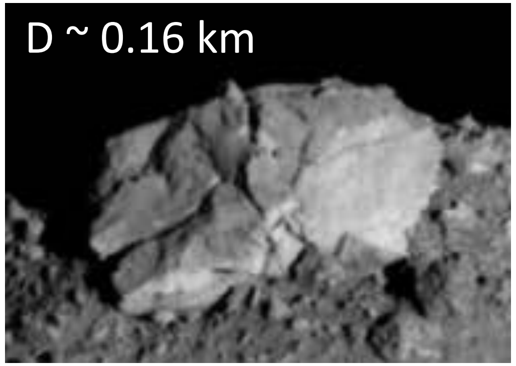


Δ $log\ N$ (D_t):
Vertical Axes:
Amplitude of the inflection point = # of NEOs ≳140 m NEOs

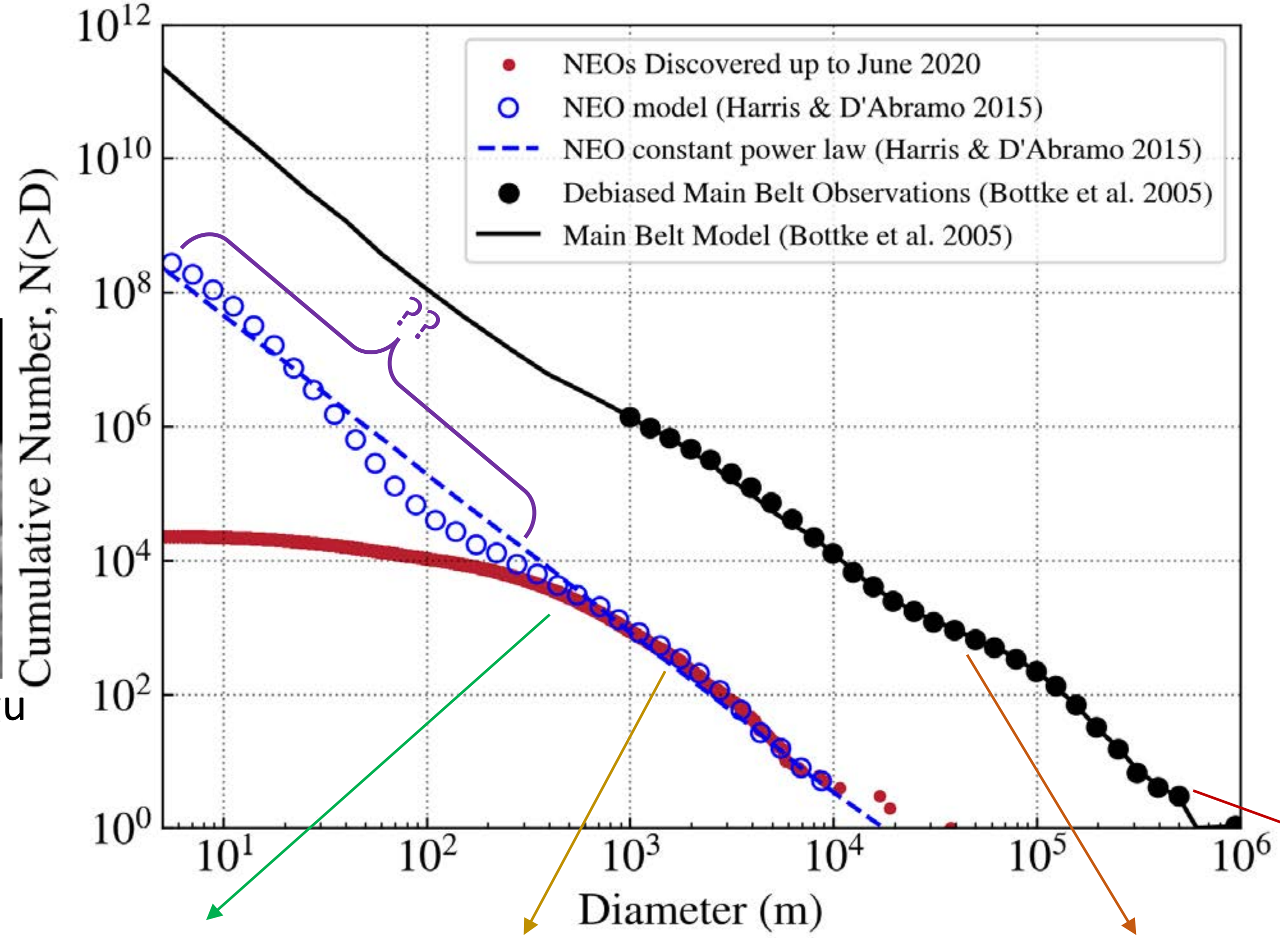


Adapted from: O’Brien & Greenberg (2005)

The strength of 100-m scale asteroids



Otohime Boulder on Ryugu
Hayabusa2/JAXA

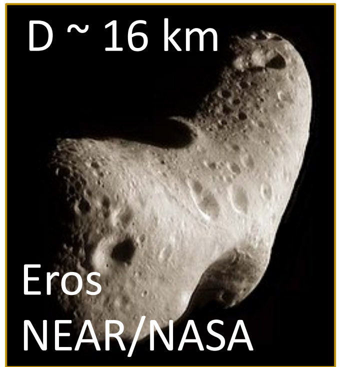


for 100-m C-type asteroid:

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

D < 0.2 km

??



Summary & Outlook : Heterogeneity

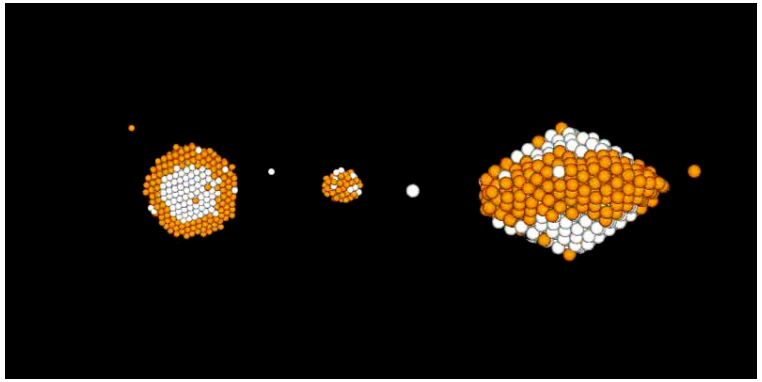
- Measured > 600 craters on Bennu's Boulders, and used population limits to estimate strengths and develop scaling relationships.
- Collisional equilibrium of NEO population can also place constraints on strength properties.
- Current estimates of NEO population ≳ 140 m are consistent with our strength 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.

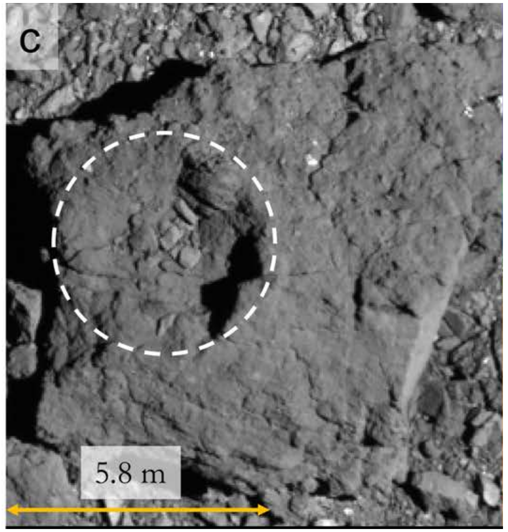
Outlook:

- 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.



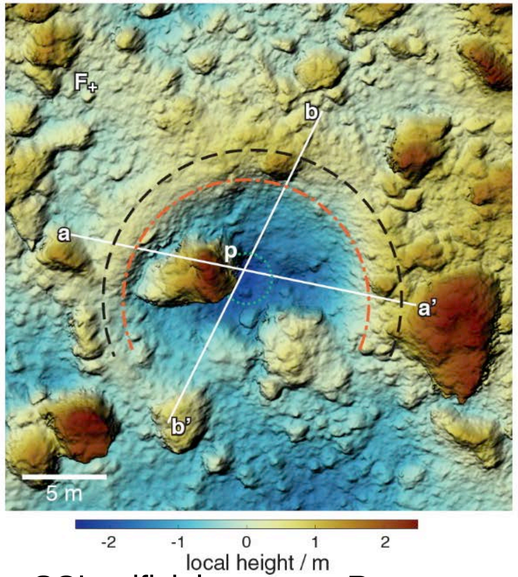
Binary Asteroid Formation via YORP: Walsh et al. (2008)

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

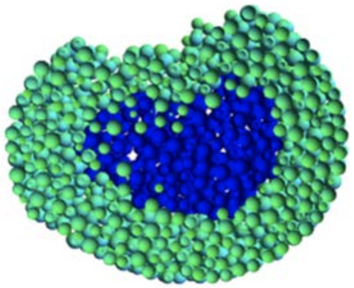


Crater on Bennu Boulder:
Ballouz et al. 2020

~ 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

OSIRIS-REx
Activity Presentation

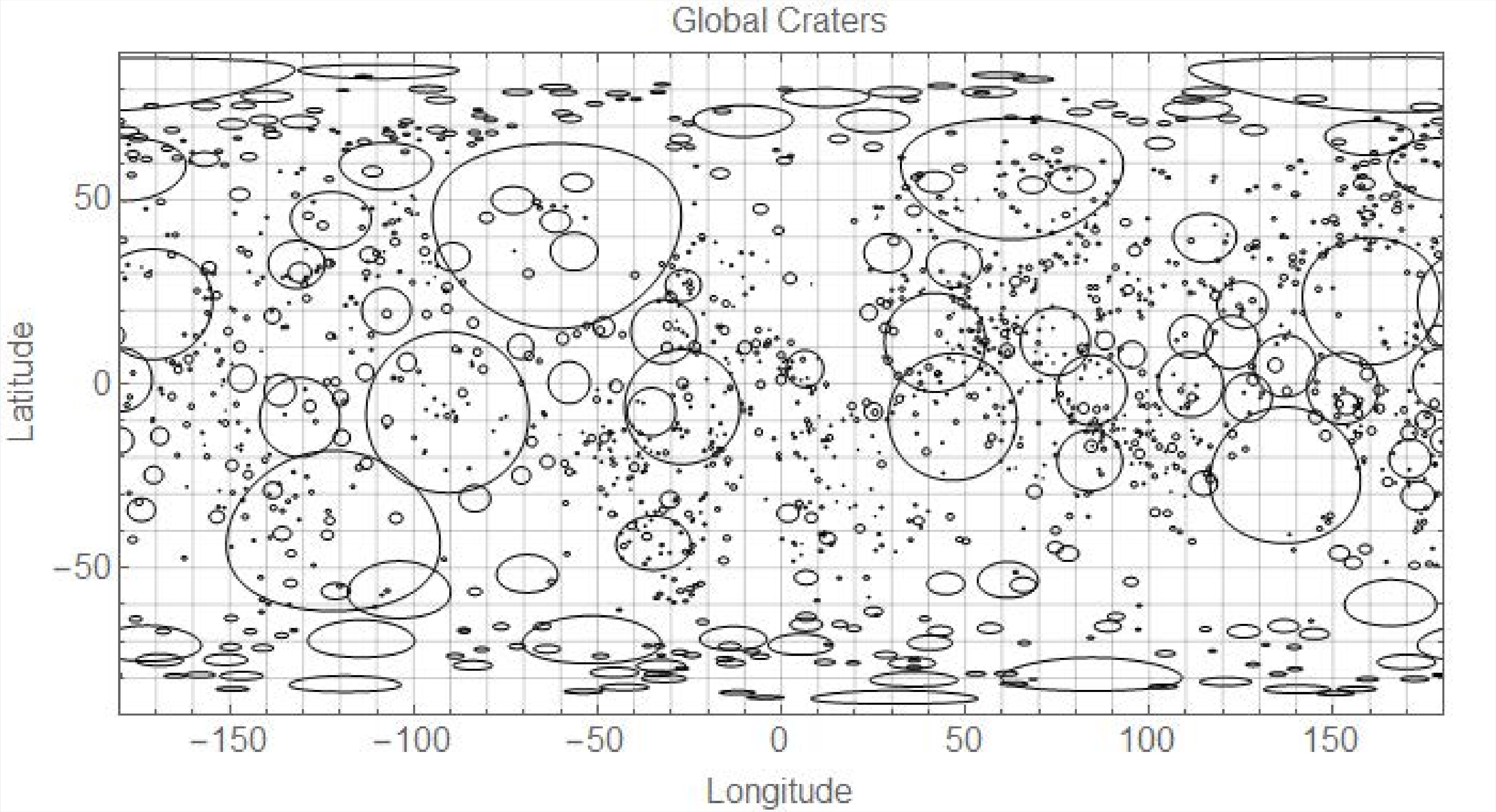
Bennu craters in the context of planetary defense

Beau Bierhaus

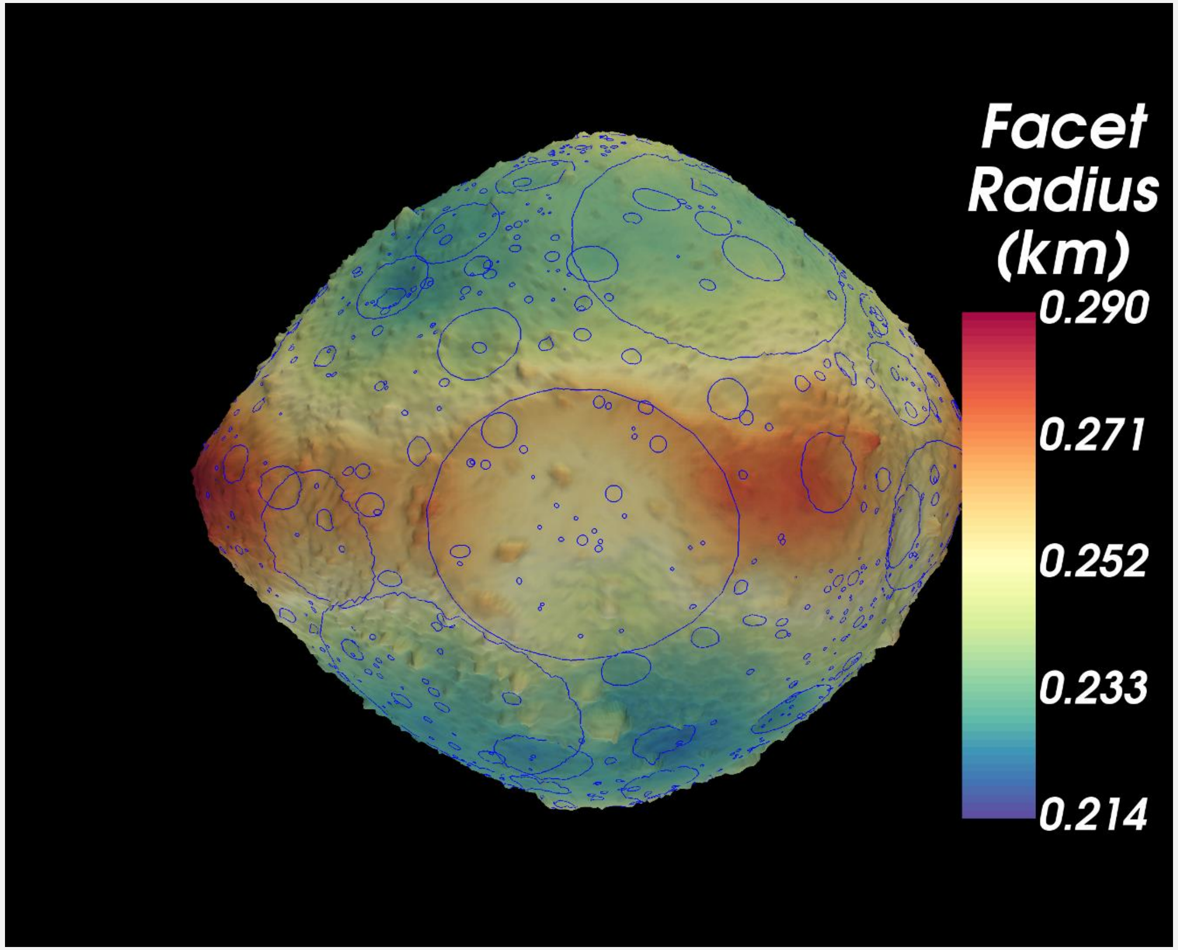
Lockheed Martin Space

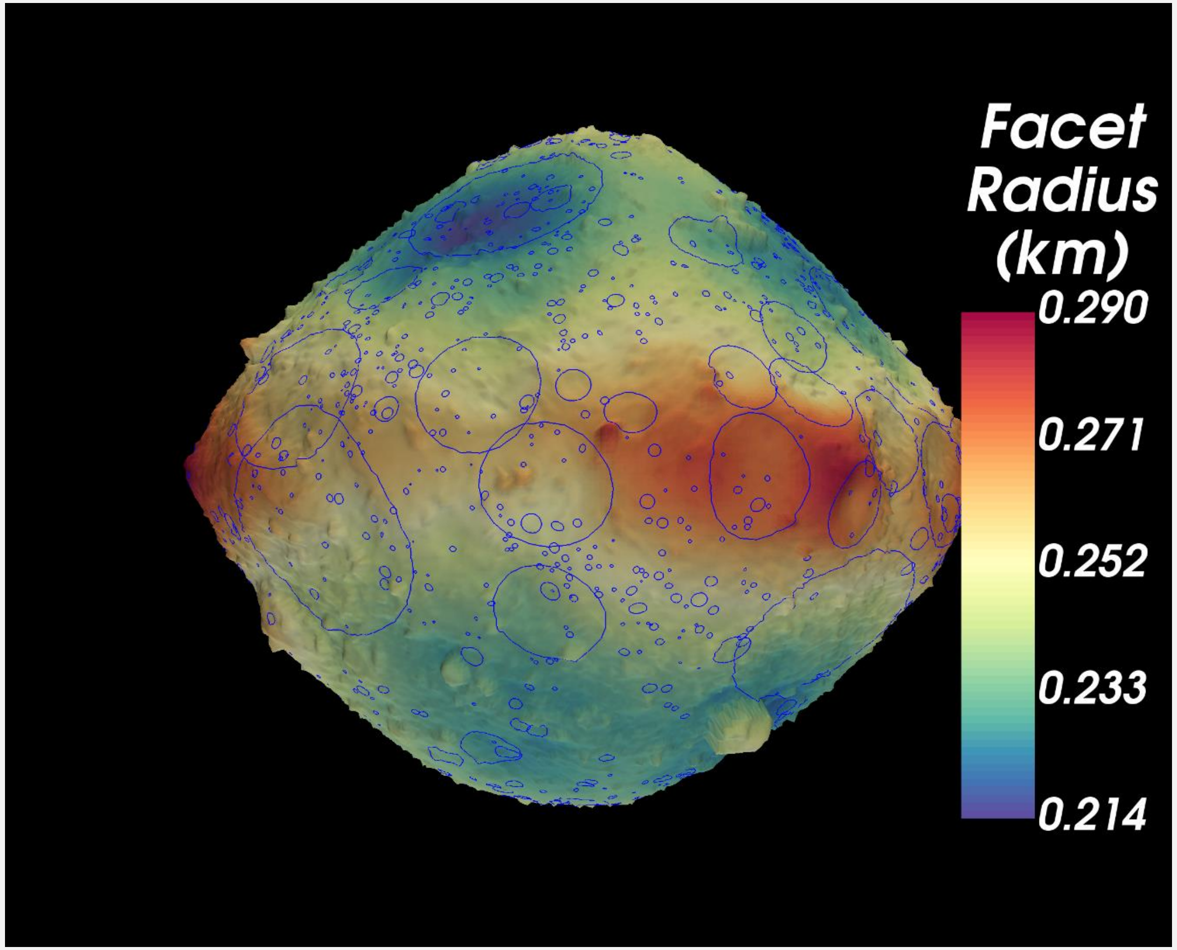
26 April 2021

Bennu’s craters

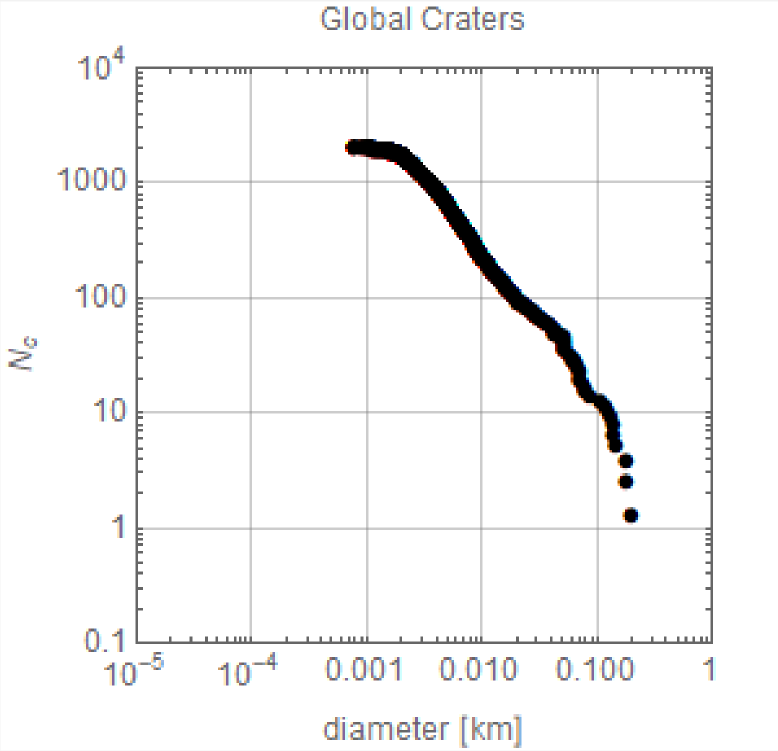


Projected on the shape model

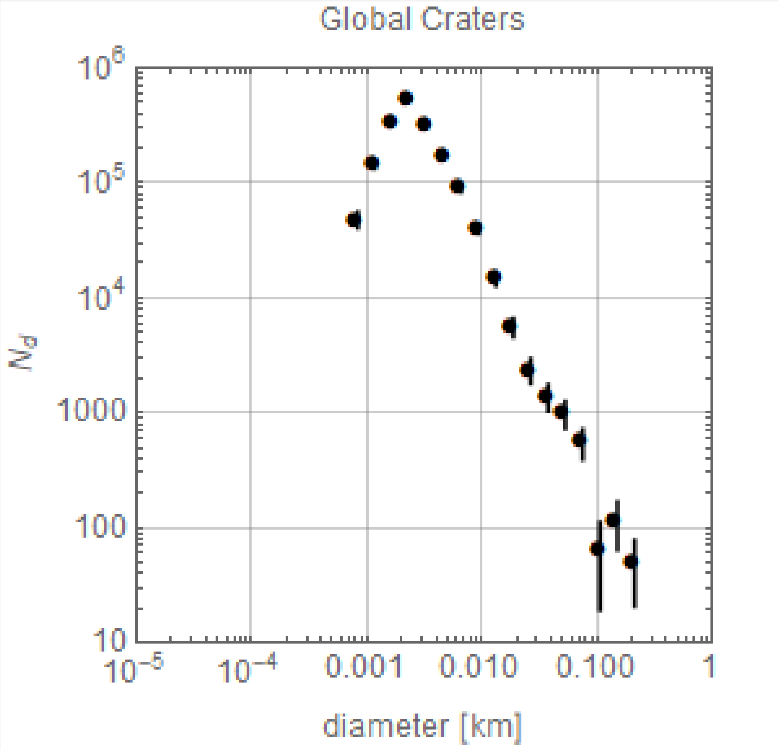




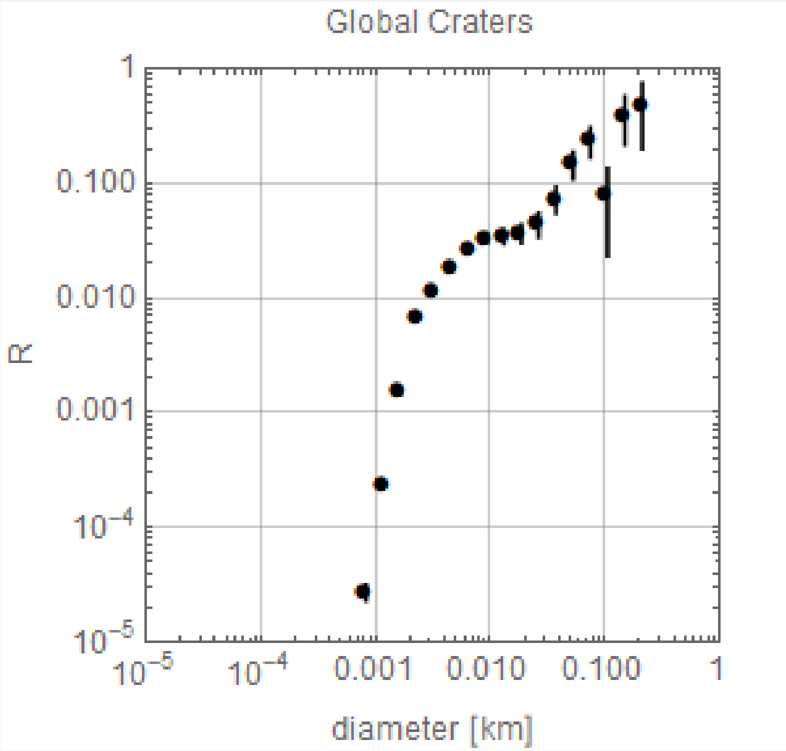
Crater SFD



cumulative



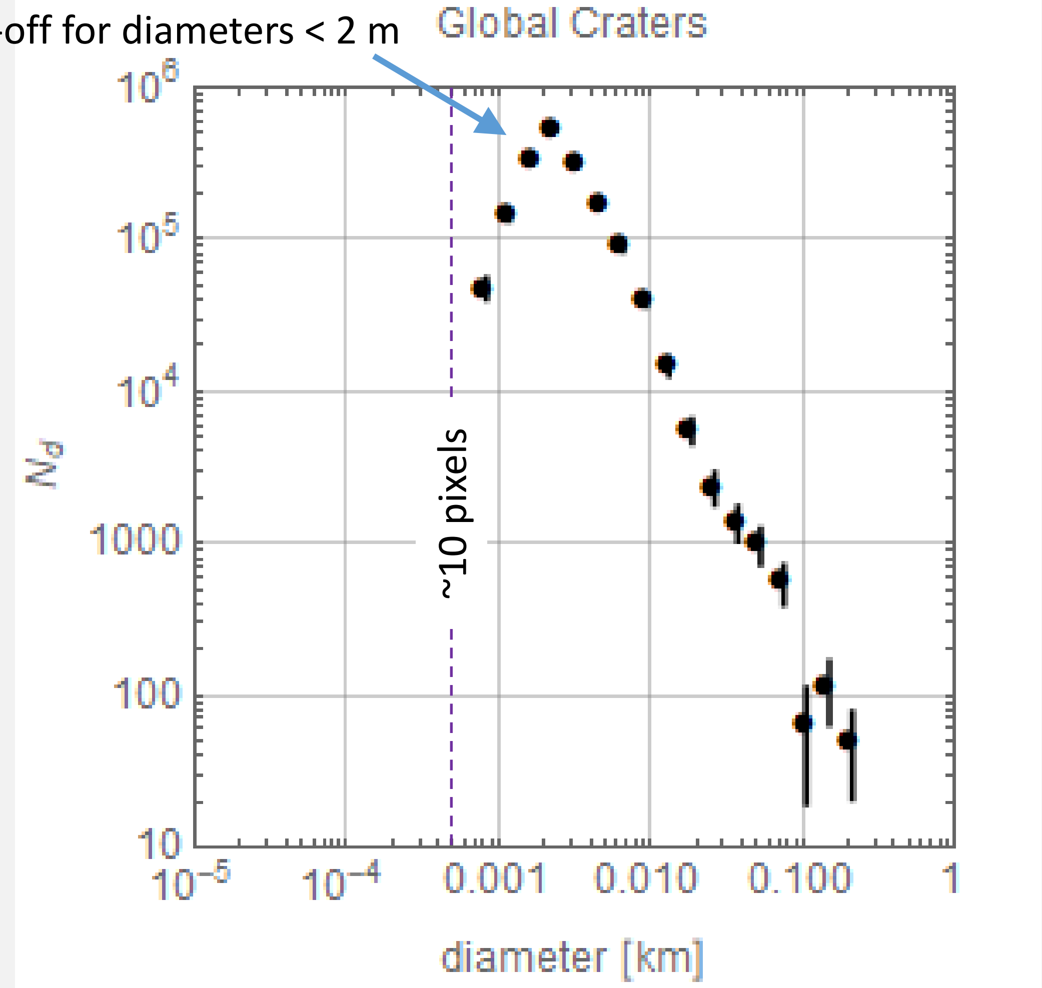
differential



Relative

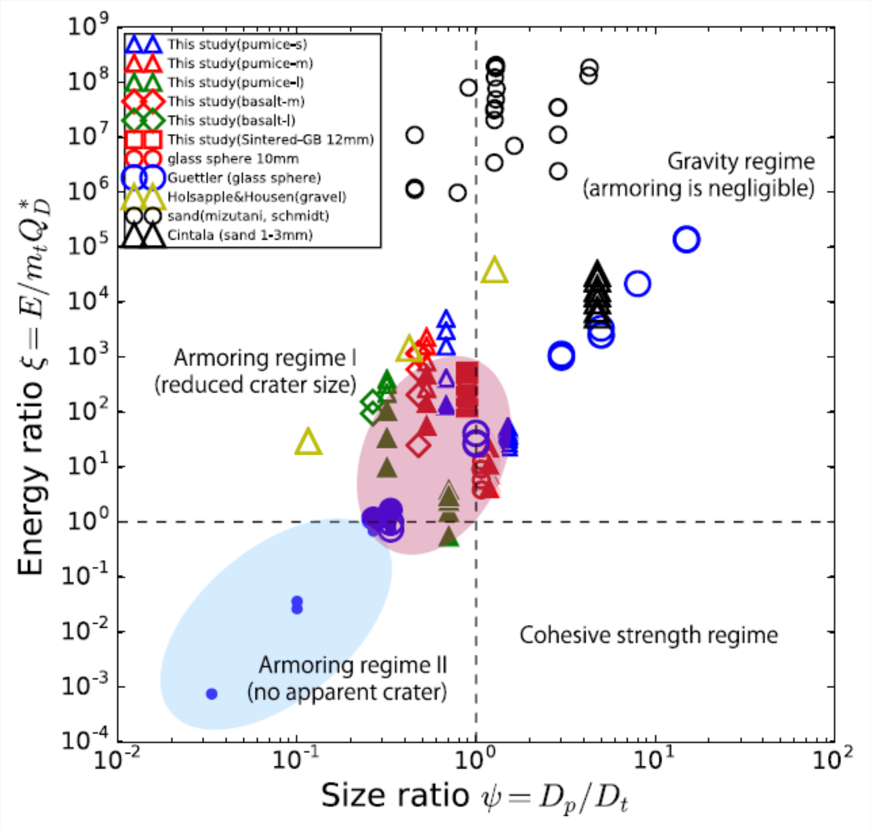
Completeness . . . or not ?!

- The rapid fall-off at diameters < 2 m typically would be a sign of the completeness limit (decreasing ability to sample population because of finite image resolution)
- However . . .
- 2 m corresponds to 40 pixels (!) in the detailed survey images, which are typically ~5 cm/pix
  - This is well above typical completeness limit values of 5-10 pixels
- **The roll-over is a real observation, and not a completeness-limit effect!**



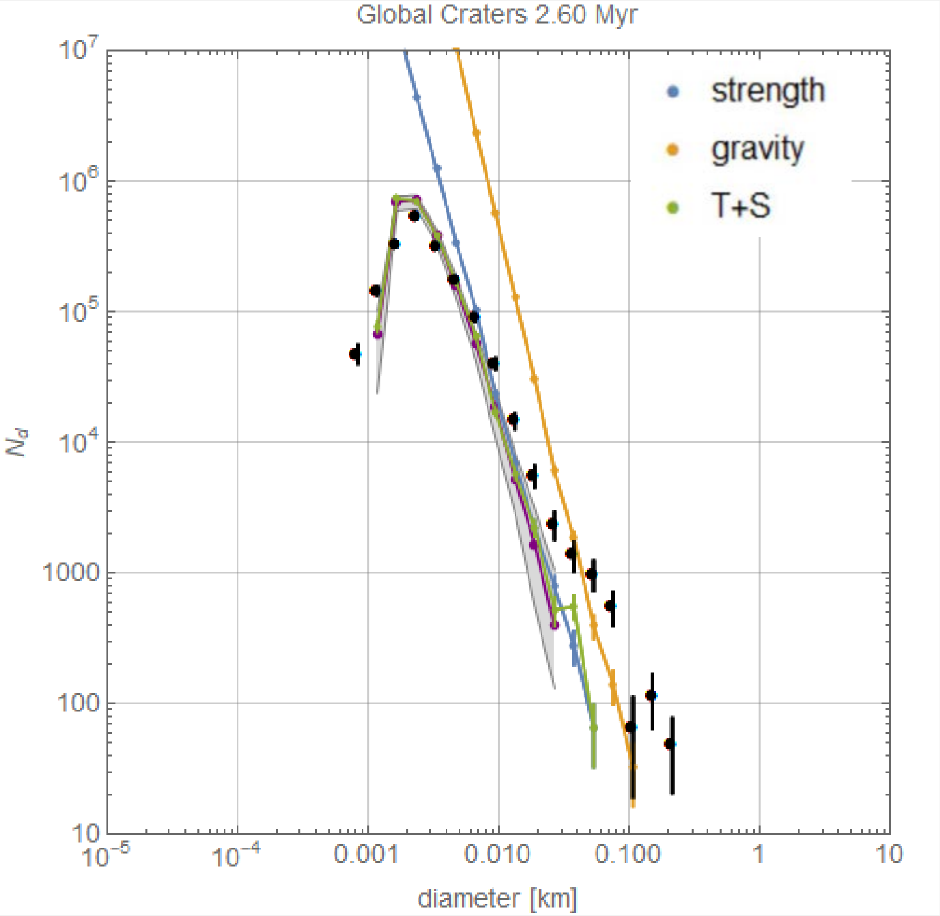
Impact armoring

- Tatsumi and Sugita (2018) [TS2018] conducted a series of experiments that elucidated an "impact armoring" behavior
- Occurs when the impactor size is comparable to the average grain size of the target surface
- They updated standard crater-scaling relationships to include this armoring effect
- We implemented simulations to apply TS2018 scaling to Bennu



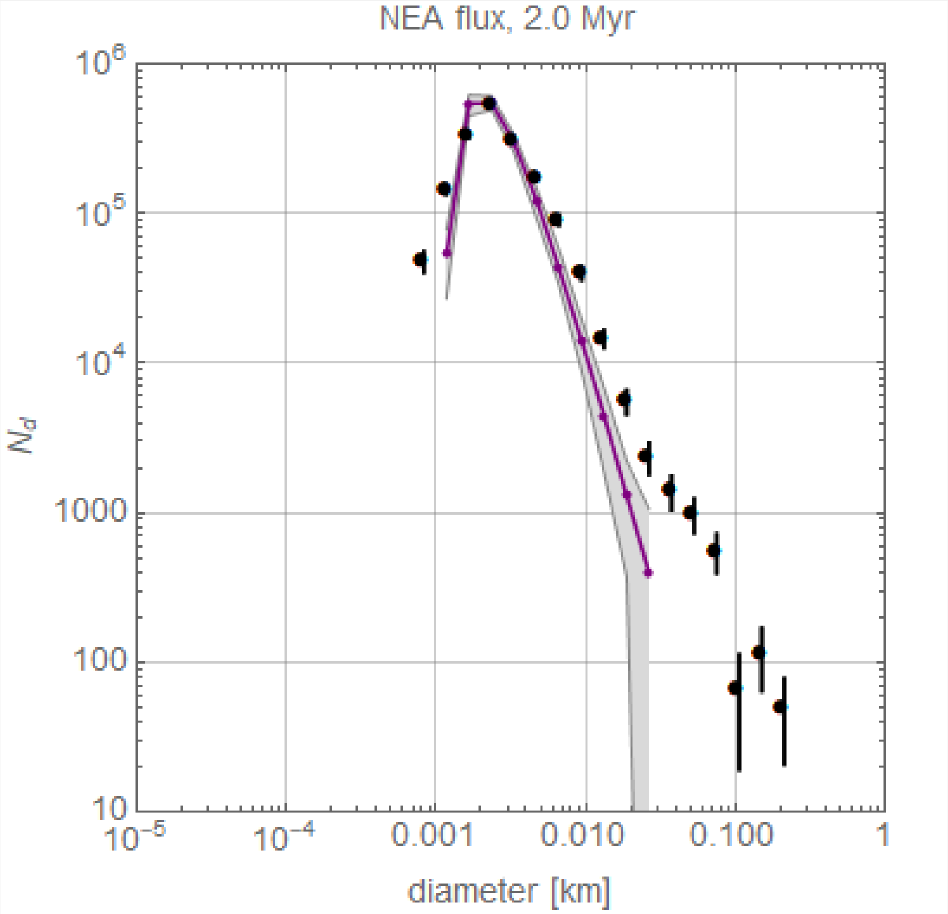
Tatsumi and Sugita (2018), Figure 17

Model results compared with the observations



- **Black** data = Bennu observations
- **Purple** data = median of 100 simulations for 2.6 Myr NEA flux, using TS2018 scaling
- **Gray** band = 99% range of modeled outcomes
- **Orange** = gravity scaling
- **Blue** = strength scaling
- **Green** = a single run of TS2018 scaling
- TS2018 scaling matches the “fish hook” of the differential SFD

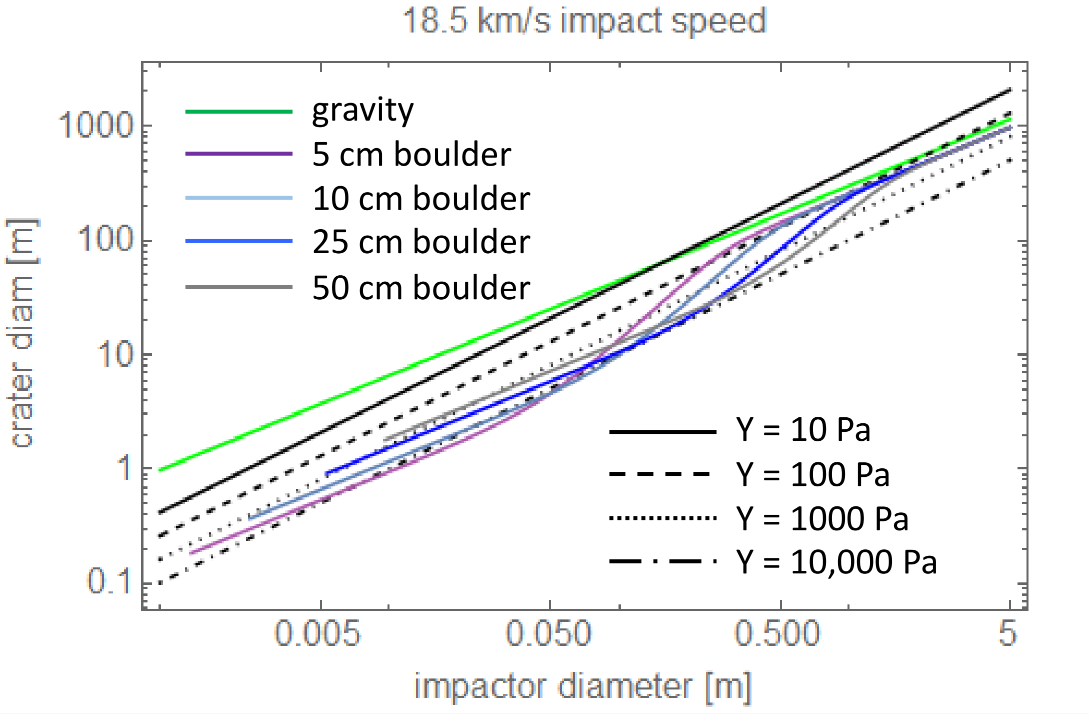
Another look, comparison with TS2018 only



- **Black** data = Bennu observations
- **Purple** data = median of 100 simulations for 2.6 Myr NEA flux, using TS2018 scaling
- **Gray** band = 99% range of modeled outcomes

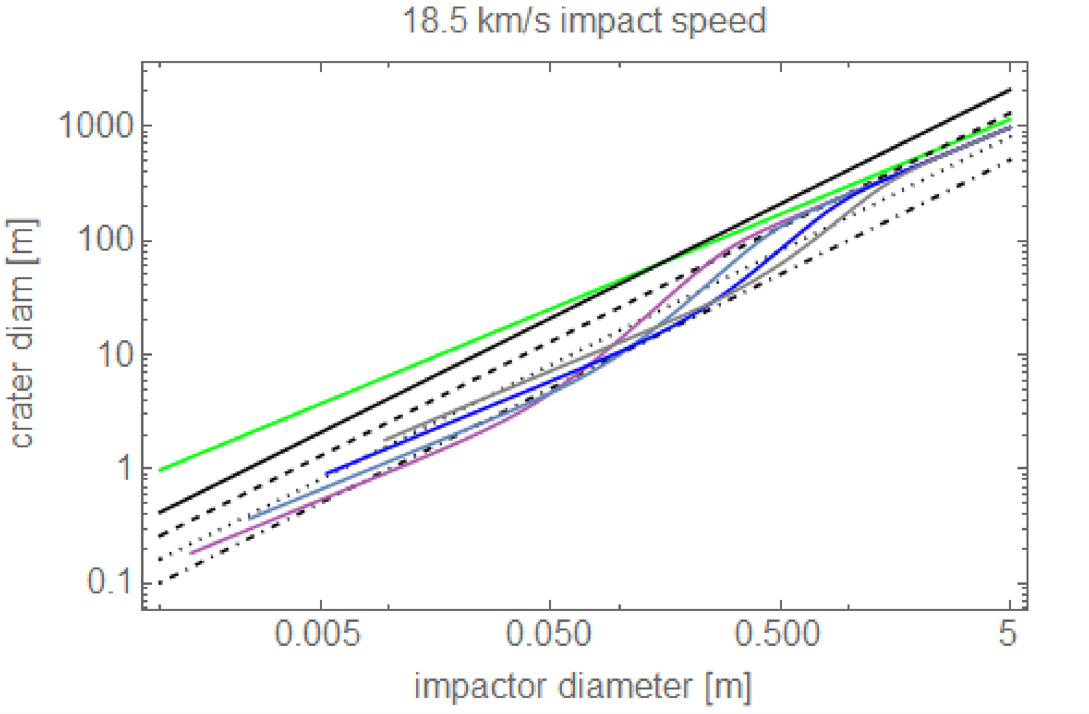
Armoring is like a strength value in crater-scaling relationships for smaller impacts

- Plot is crater size vs. impactor size for strength, gravity, and TS2018 scaling
  - Single **green** line for gravity
  - **Black** lines are different strength values
  - Other colors are TS2018 for different target boulder sizes
- TS2018 results span a range of 10^3 Pa in strength for small impactor sizes and boulder sizes



Consequences for planetary defense

- On a rubble-pile asteroid the same projectile will have different outcomes depending on the size of the target boulder
  - The impact energy may be transmitted to the bulk object efficiently, or
  - The impact energy may be dissipated largely by disrupting a boulder
- An important consideration for the DART mission: is it possible to determine the size of the boulder(s) that reside at the impact point?
- Any impact-deflection mission should consider the outcome variability introduced by the size of the target boulder



OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

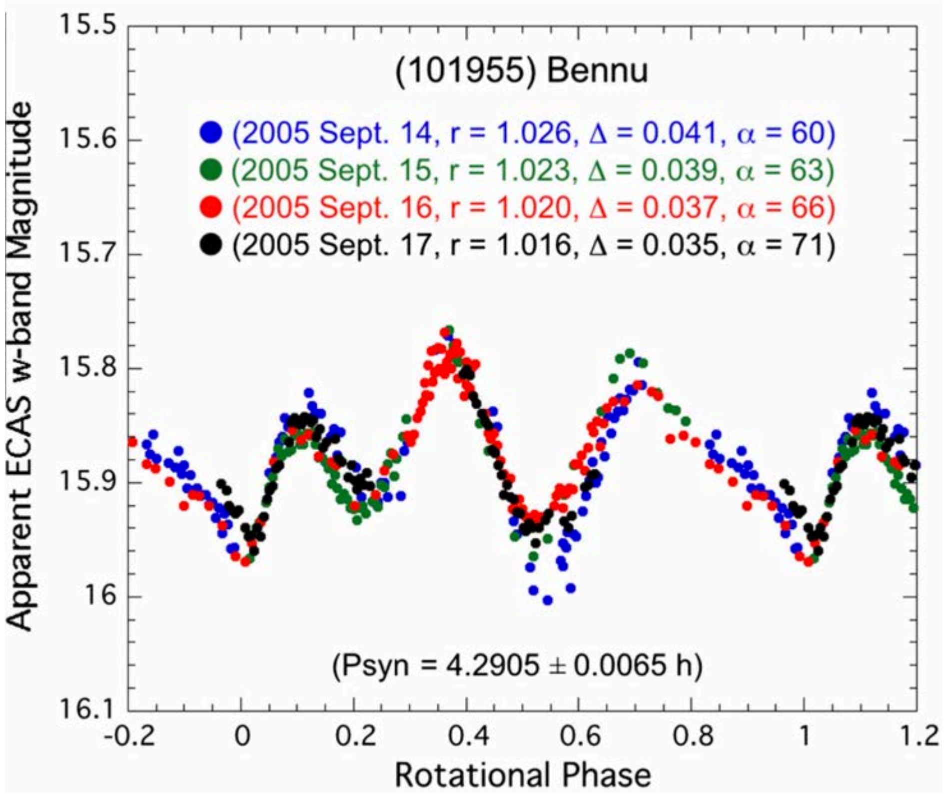
Observations of Bennu's Increasing Rotation Rate, YORP, and Implications for Bennu's Evolution

Michael C. Nolan, Jason M. Leonard,
Daniel J. Scheeres, Jeroen L. Geeraert,
Peter G. Antreasian, Steven R. Chesley,
Ellen S. Howell, Keith S. Noll, Joshua P. Emery,
Carl W. Hergenrother,
Jay W. McMahon, Dante S. Lauretta

UNIVERSITY OF ARIZONA NASA'S GODDARD SPACE FLIGHT CENTER LOCKHEED MARTIN

Rotation State of Bennu

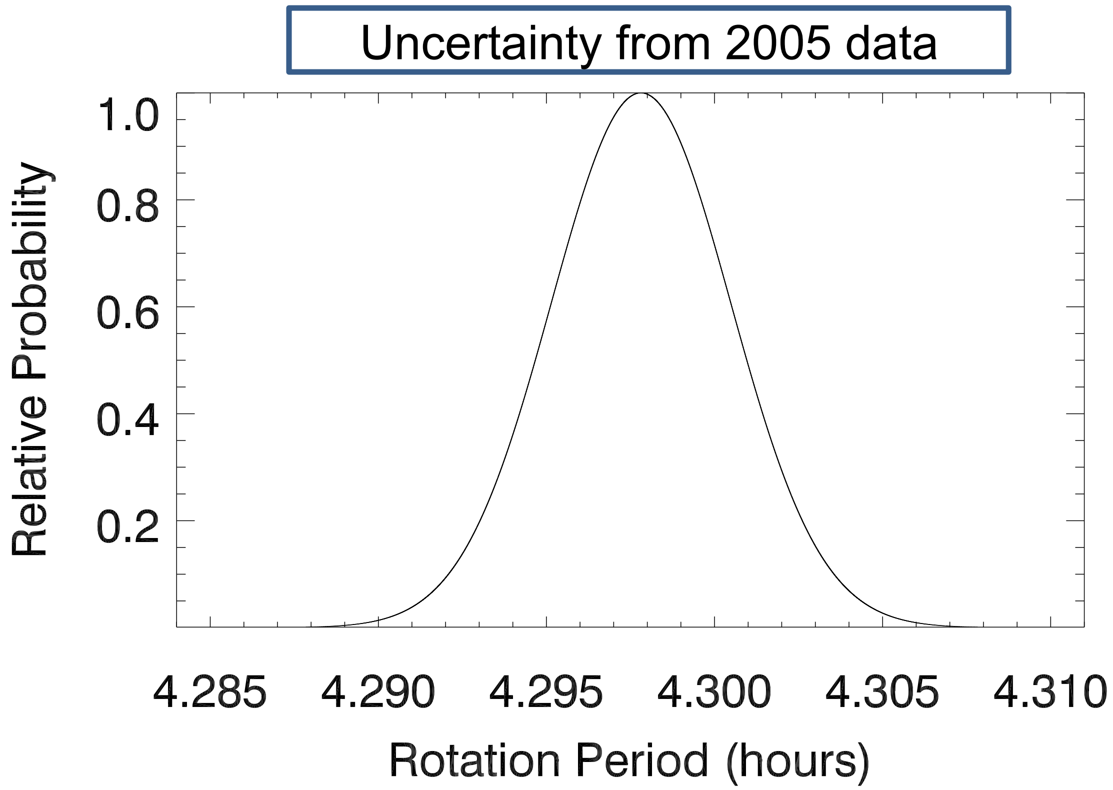
- Ground-based visible lightcurves of Bennu were obtained in 1999 and 2005, before Bennu (then 1999 RQ36) was a spacecraft target.
- As is common, lightcurves were taken for a few days each time, resulting in a rotation period accurate to about 0.1%: Fine for physical description, but not to maintain phase over apparitions.
- Bennu has a low-amplitude 3-peaked lightcurve consistent with its round shape.

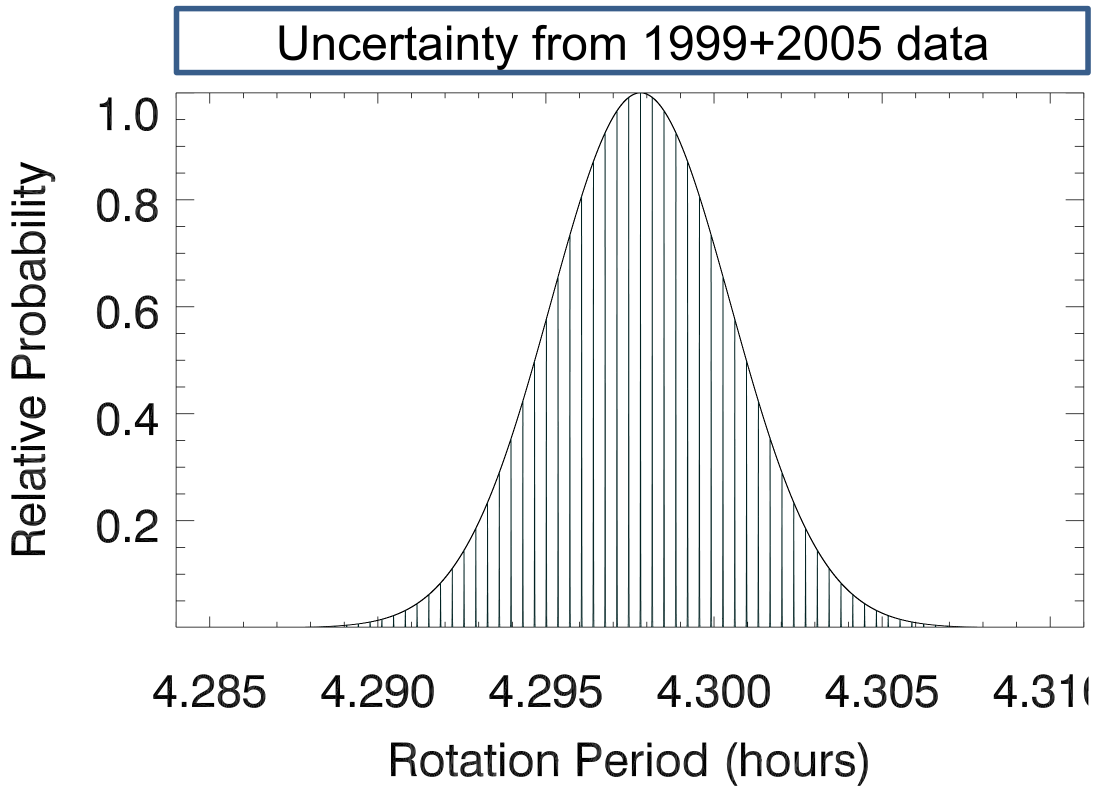


2005 lightcurve (Hergenrother et al 2013)

Rotation based on 1999 and 2005 data

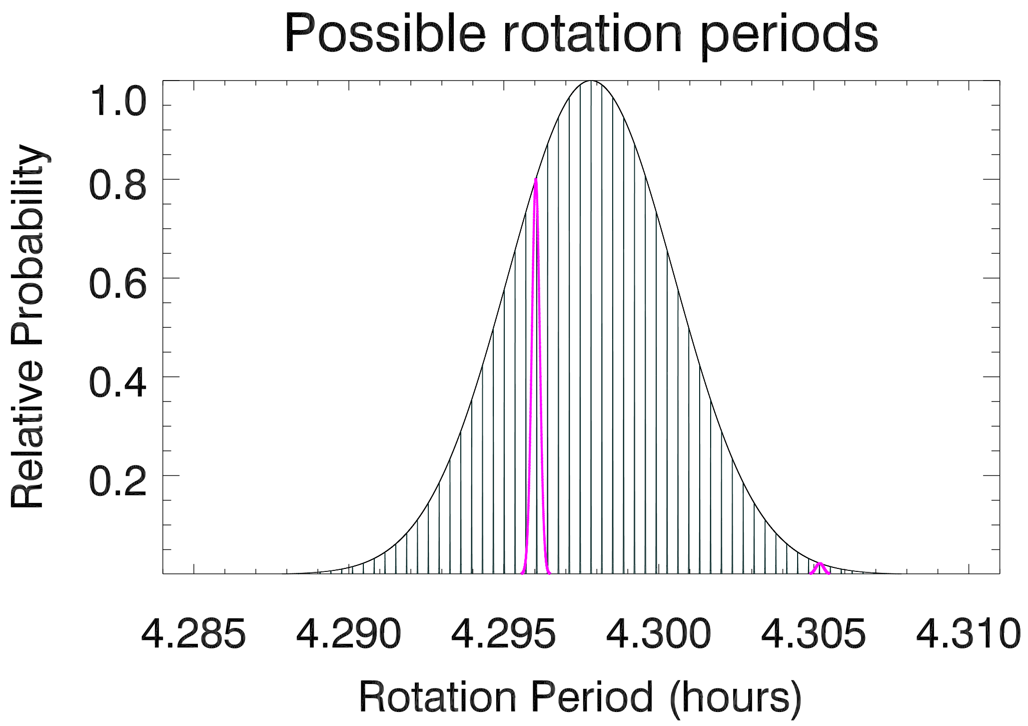
- Based on the 1999 and 2005 data, the rotation period was 4.297 h +/- 10 rotations /6 years (1-sigma).





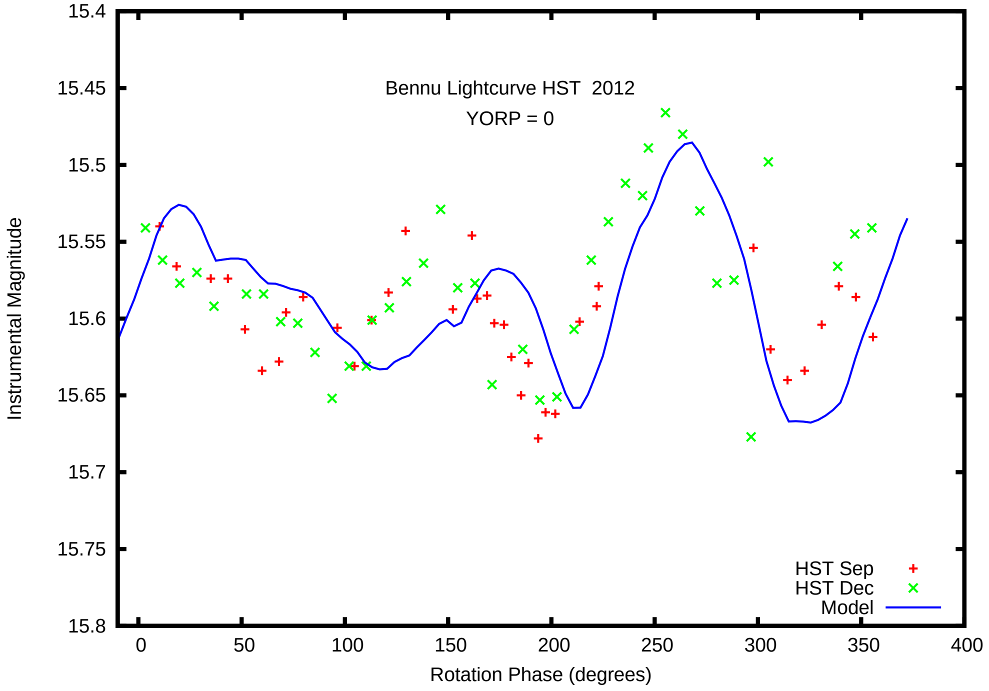
Added two epochs in 2012

- Ground-based campaign in 2011 unsuccessful.
- Two epochs of HST data ~ 3 months apart unambiguously determine period

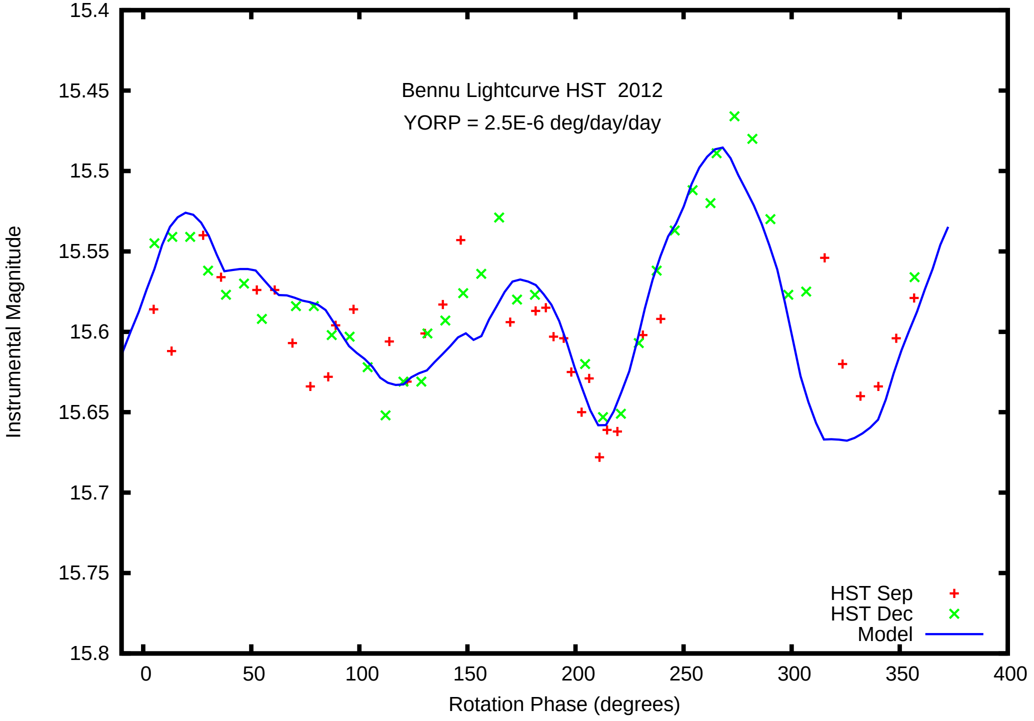


HST lightcurves compared to 2012 model with five extra rotations

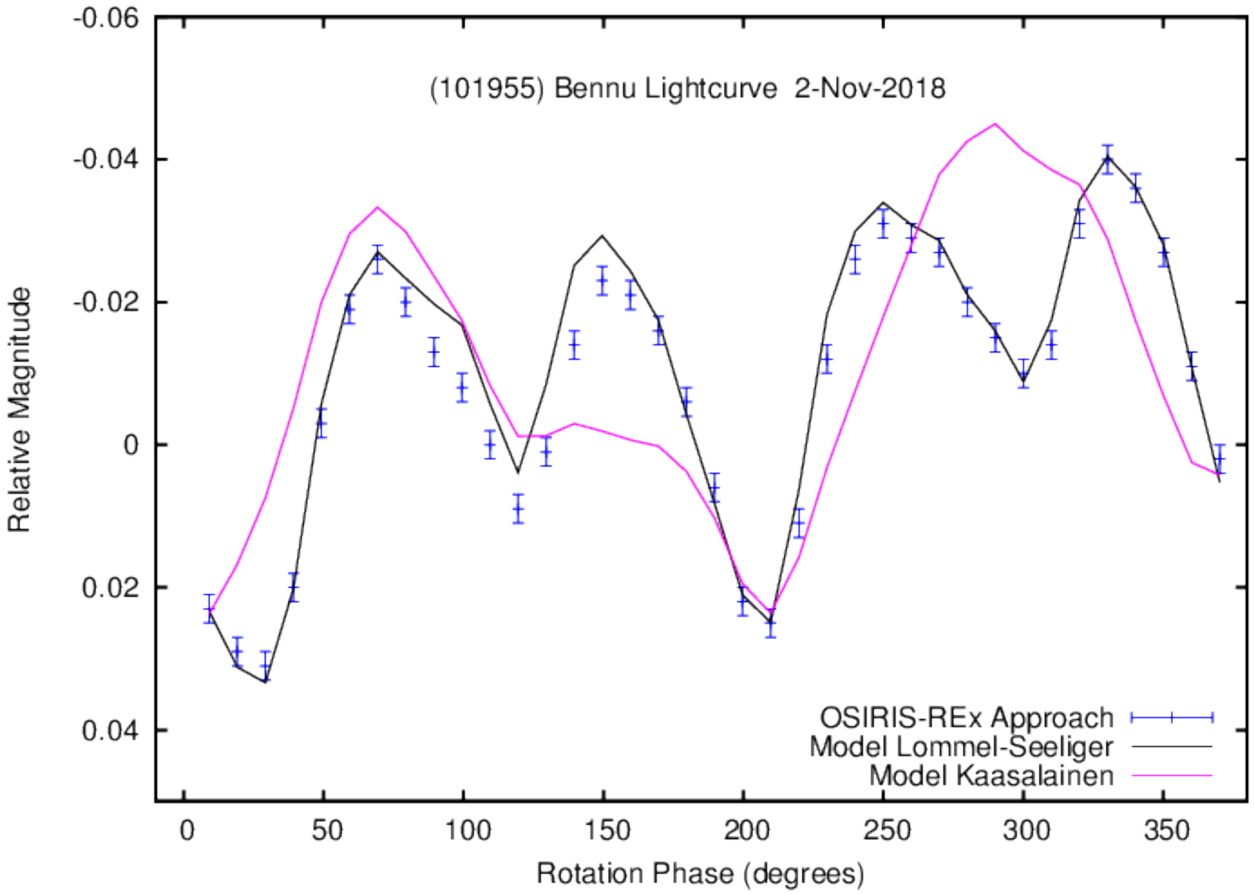
HST Data plotted against predicted lightcurve from radar shape model



Added small YORP acceleration

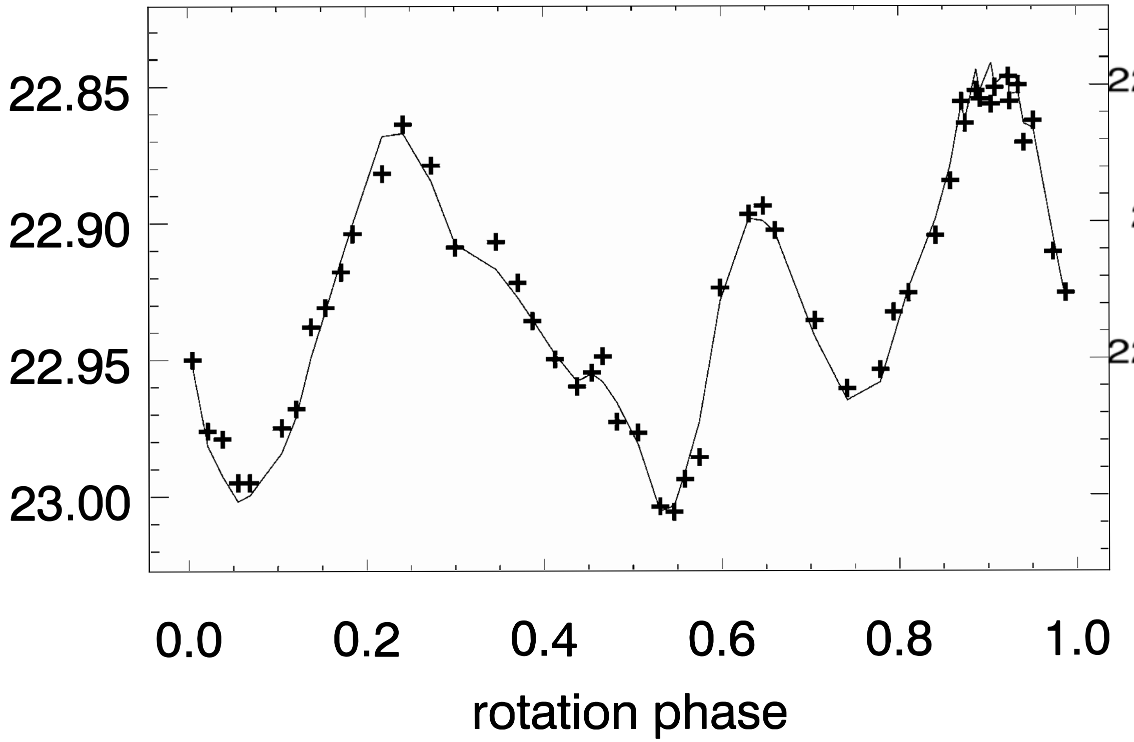


- As we approached Bennu, the lightcurve looked very different.
- Low phase angle (~ 10 degrees) and integrating resolved images.
- Scattering function is very important and not uniform
  - Adds uncertainty in comparing ground-based and proximity data.

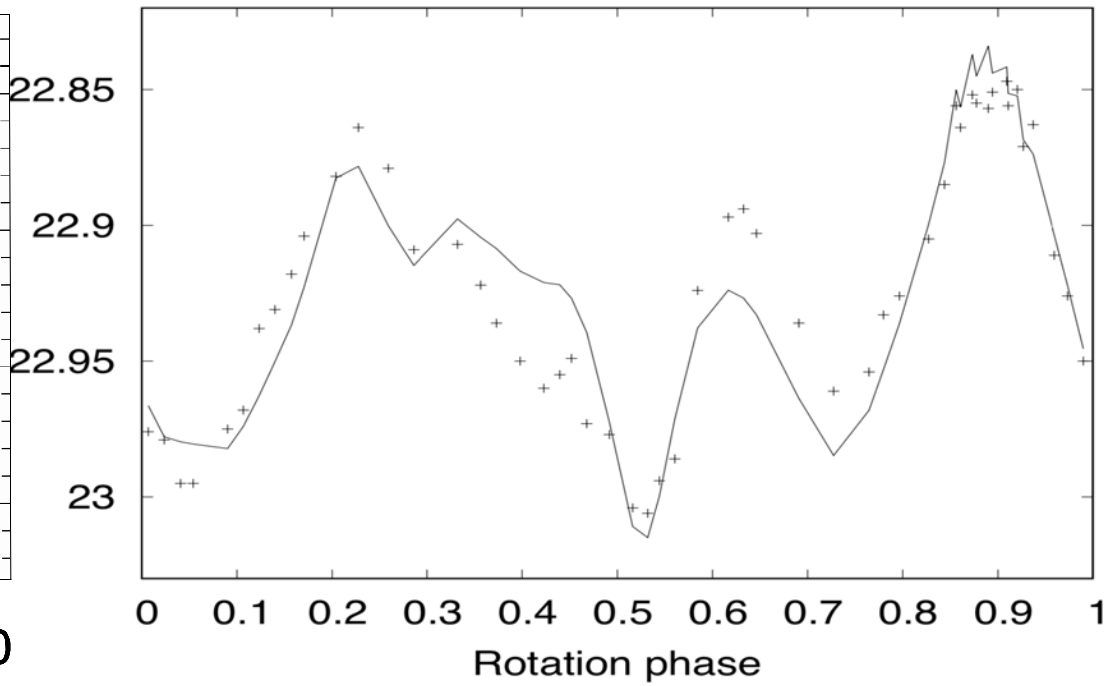


2005 Lightcurve

Radar Shape Model

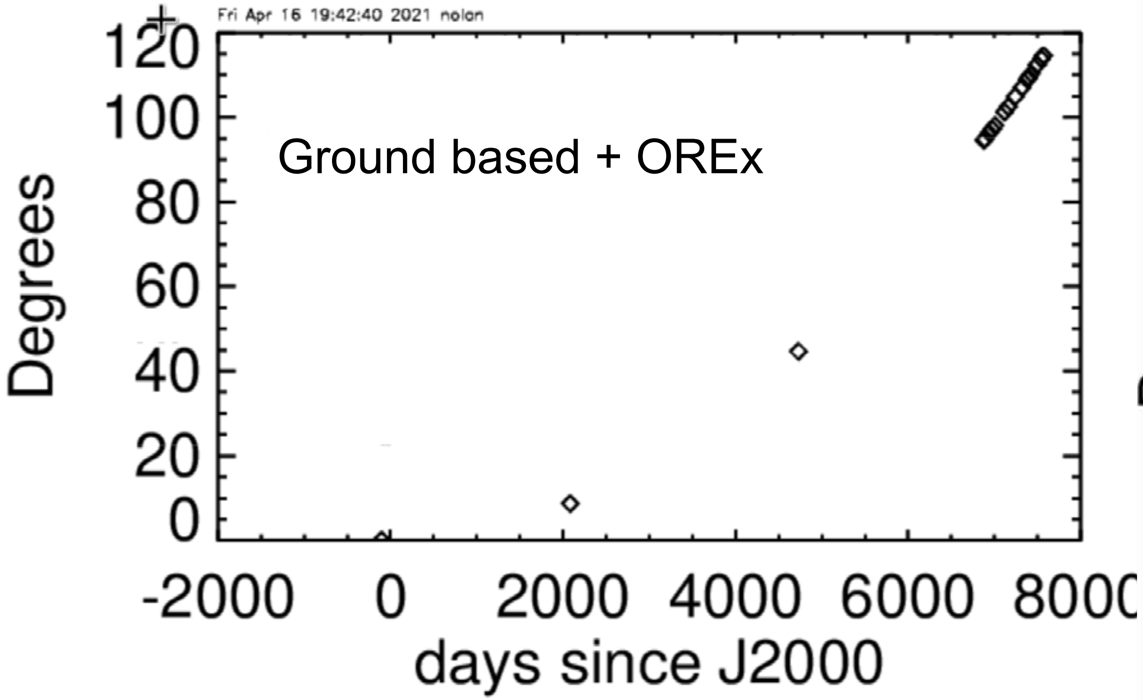


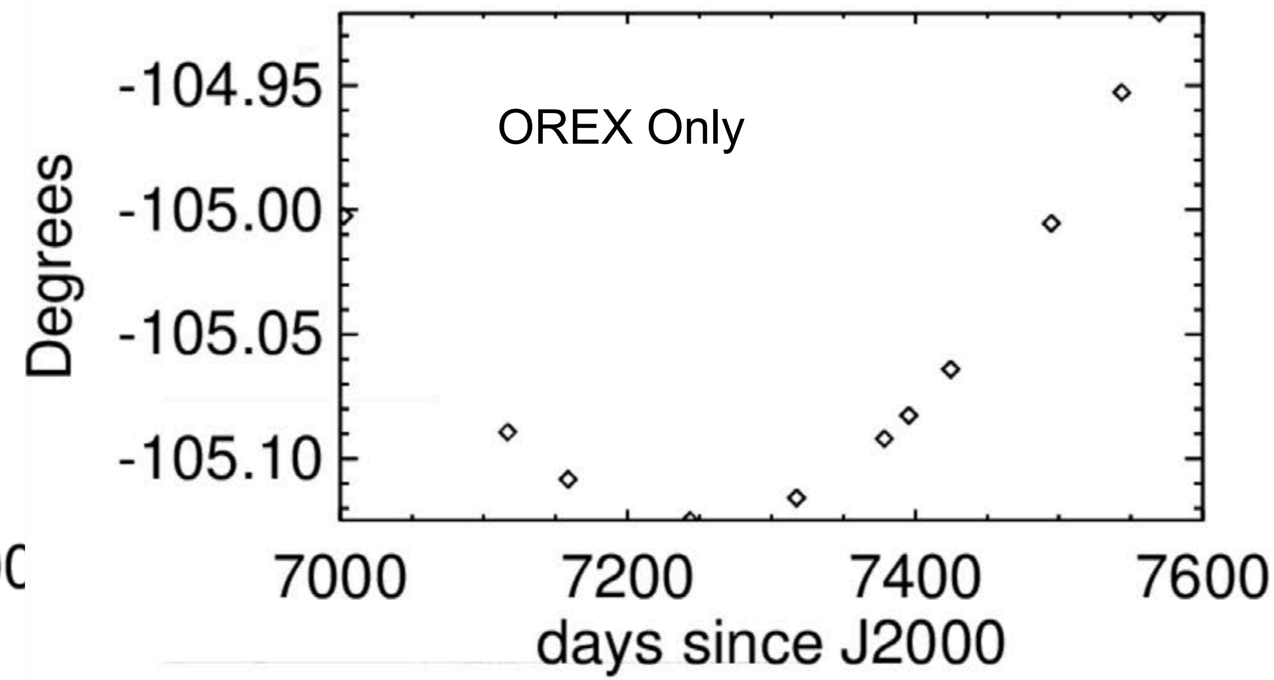
OSIRIS-REx Shape Model



Proximity Operations at Bennu

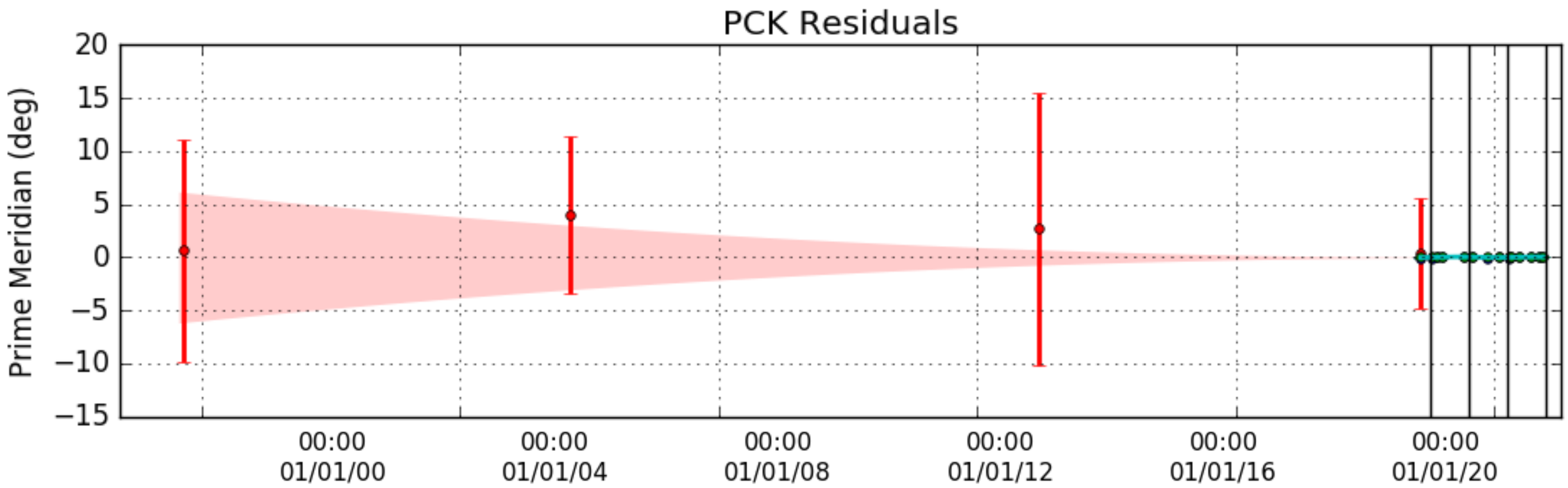
- The OSIRIS-REx Navigation team solves for the instantaneous rotation phase when solving for the spacecraft position.
  - Images as fine as 1 cm/pixel in orbit
  - Much more precise than the ground-based observations, but shorter baseline.
  - Clear YORP detection required ~ 1 year





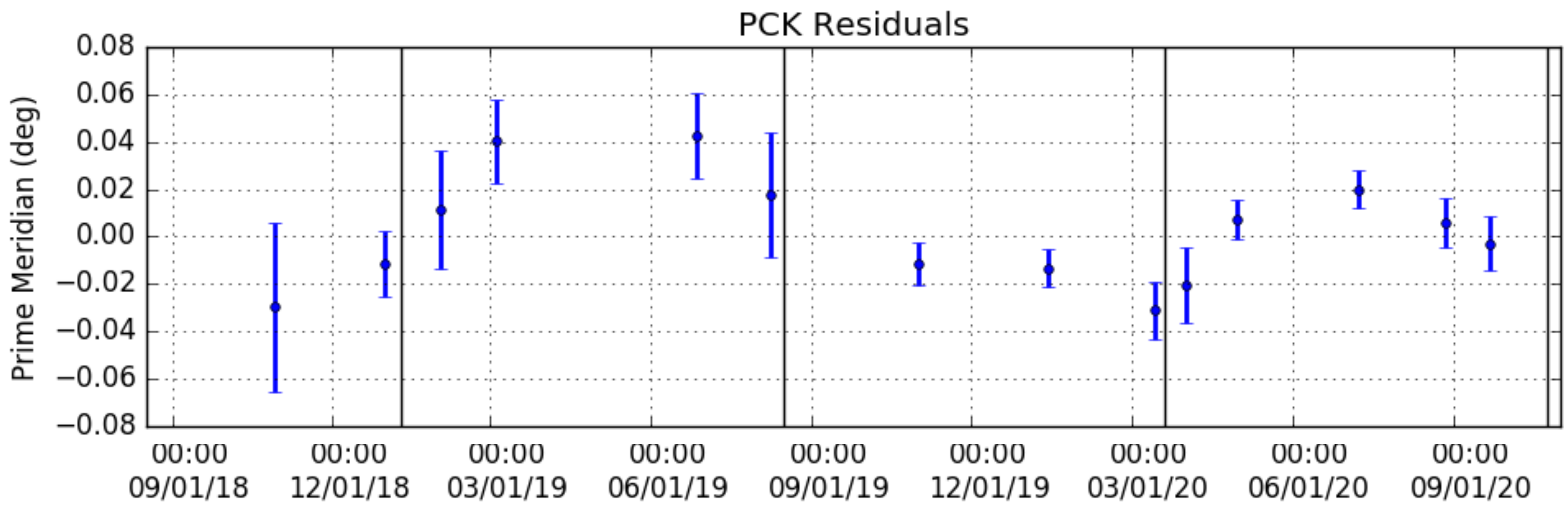
Rotation Solution Residuals w/ 3-sigma Uncertainty Bounds

- Removing the Average acceleration of 4 x 10^{-6} deg/day/day gives nearly flat residuals.
- Difficulty in comparing photometric regimes (OREx vs ground-based) increases phase uncertainty in ground-based data.
- Hint but no statistically significant change in acceleration rate.



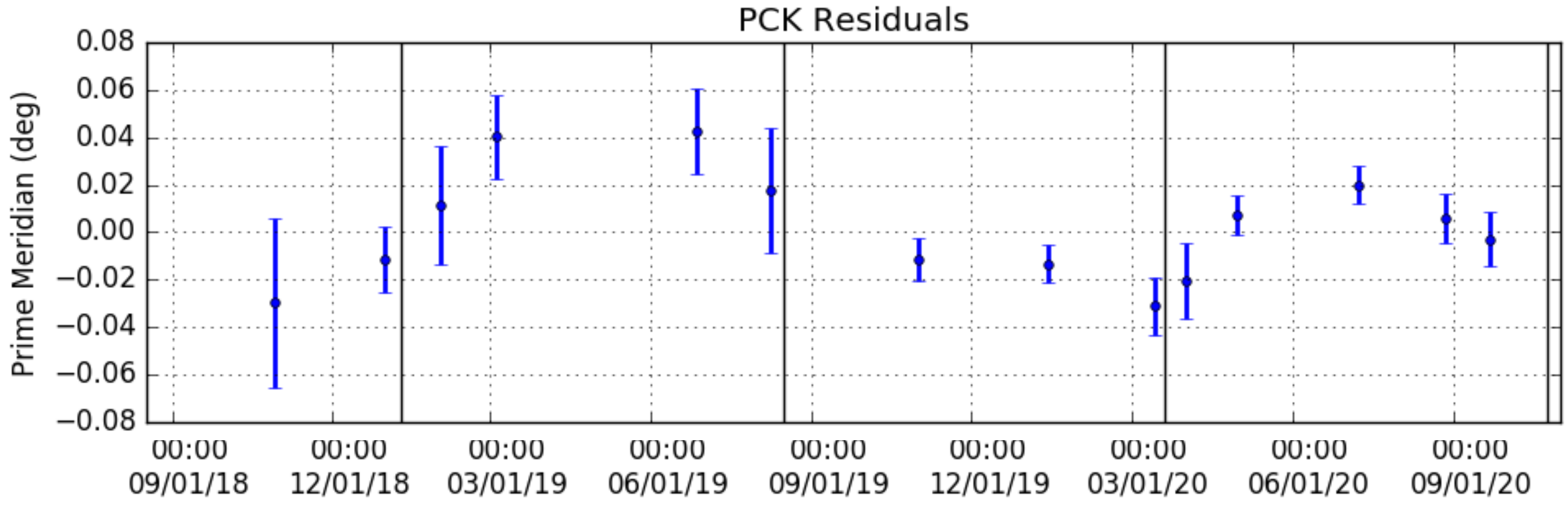
Rotation Solution Residuals

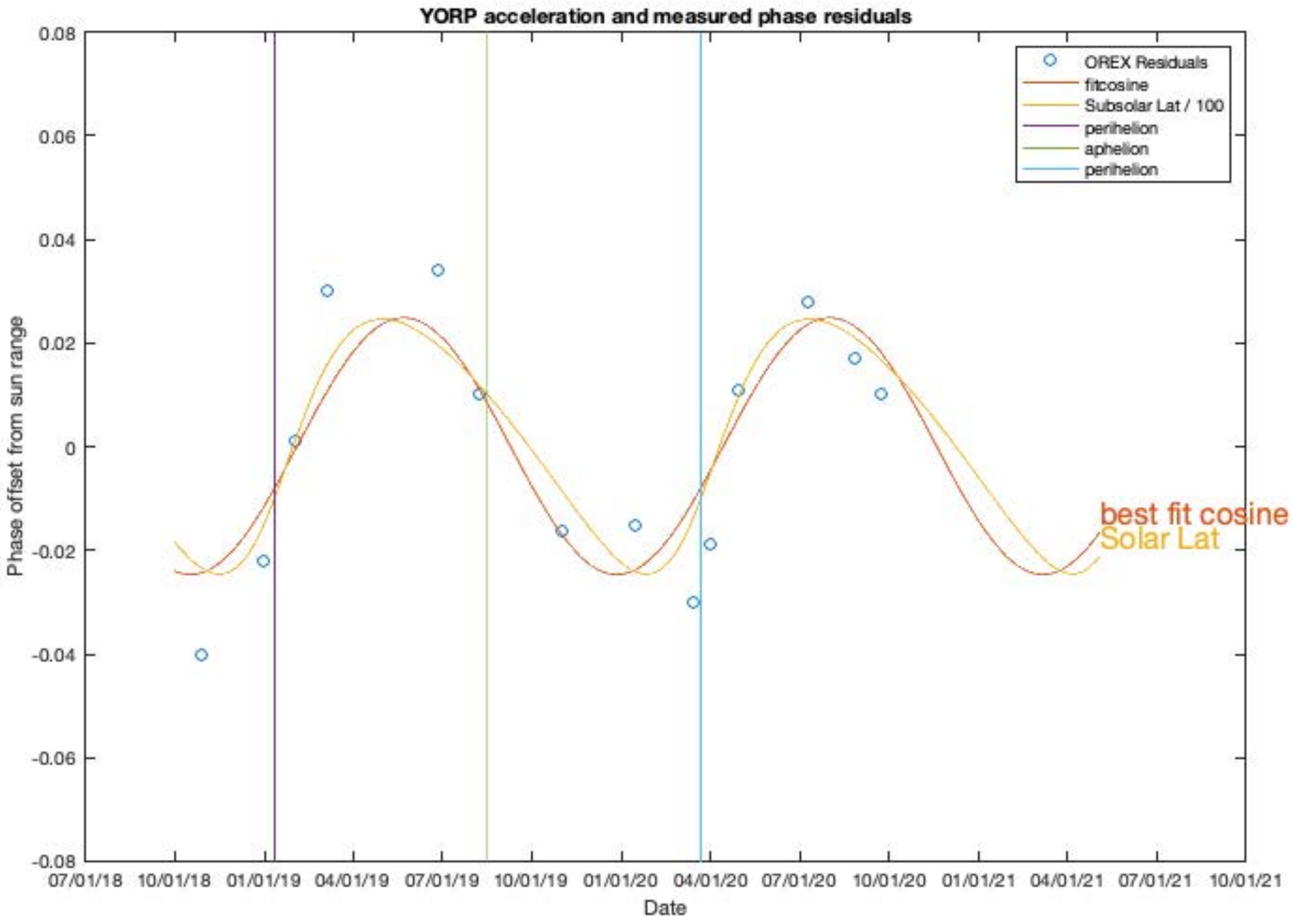
- Now blow up proximity operations.
- There appear to be ~ sinusoidal residuals with a period of 1 Bennu year



Rotation Solution Residuals

- Now blow up proximity operations.
- There appear to be ~ sinusoidal residuals with a period of 1 Bennu year
- Torque $= G/R^2[C_0 + C_1 \sin(i) \sin(\omega + f)]$
- $\Delta\theta = -\frac{(1-e^2)G}{n\,h\,l} C_1 \sin(i) \sin(\omega + E)$
- C_1 is differently dependent on shape / mass





YORP acceleration and measured phase residuals
OREX Residuals
fitcosine
Subsolar Lat / 100
perihelion
aphelion
perihelion
best fit cosine
Solar Lat
Phase offset from sun range
Date
0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
07/01/18
10/01/18
01/01/19
04/01/19
07/01/19
10/01/19
01/01/20
04/01/20
07/01/20
10/01/20
01/01/21
04/01/21
07/01/21
10/01/21

- Variation along orbit finally proves this is YORP
  - Or at least, something that depends on solar radiation.
- Torque $= G/R^2[C_0 + C_1 \sin(i)\sin(\omega + f)]$
- C_0 and C_1 depend differently on shape / mass
  - We will be examining those details soon.

Long Term Implications

- Bennu (and Ryugu) have obliquities very near 180 degrees, but are neither rotating near breakup nor stalled.
- Bennu’s rotation is accelerating fast enough that it would break up in about 1 million years.
  - Bennu has surface features that appear to be much older than 1 million years old, predating its history in near-Earth space, as well as some that could be driven by recent YORP-induced slope changes (e.g., Jawin et al., 2020).
  - No clear sign of body-wide mass movement
- It does not appear likely that it will accelerate to breakup.
- YORP is affecting the surface, but does not appear to drive the large-scale surface evolution.
  - Could be self-limiting (Cotto-Figueroa 2015)
  - Some similar objects **are** spinning near breakup.

7th IAA Planetary Defense Conference

26-30 April 2021, Online Event

Hosted by UNOOSA in collaboration with ESA

Q&A

Session 4 - OSIRIS-REx

End of Day 1

Thank you