OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

OSIRIS-REx and Near-Earth Asteroid Bennu – Returning a Sample of the Early Solar System

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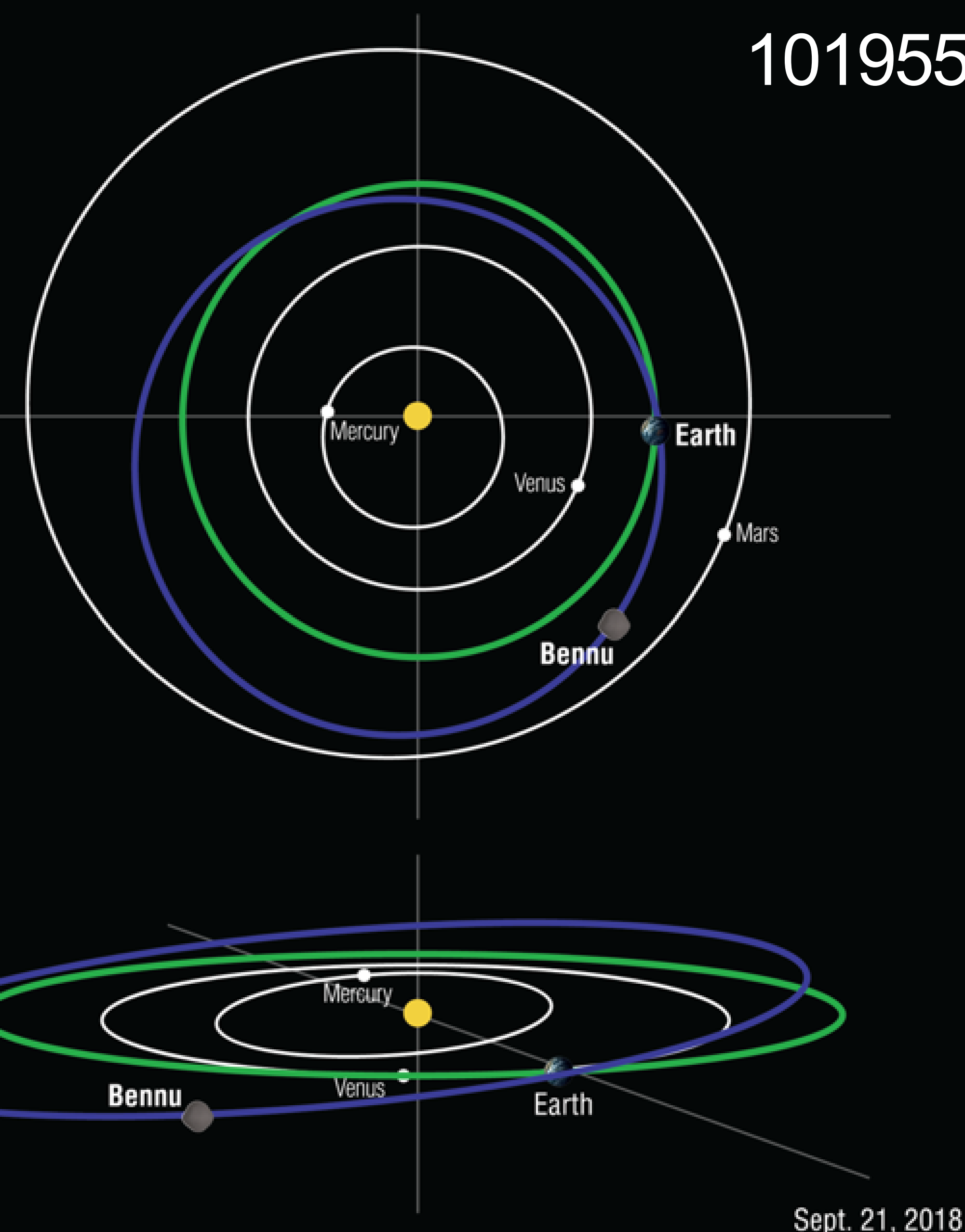
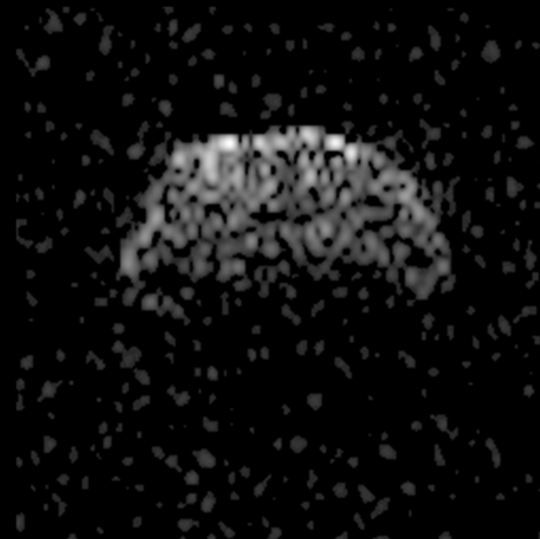
UNIVERSITY OF ARIZONA • NASA'S GODDARD SPACE FLIGHT CENTER • LOCKHEED MARTIN

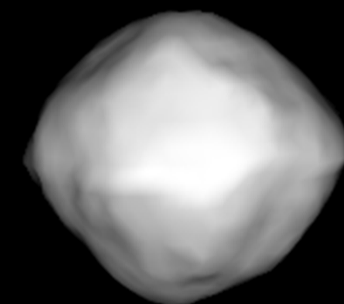
OSIRIS-REx Defined

- **O**rigins
  - Return and analyze a sample of pristine carbonaceous asteroid regolith
- **S**pectral **I**nterpretation
  - Provide ground truth for telescopic data of t entire asteroid population
- **R**esource **I**dentification
  - Map the chemistry and mineralogy of a primitive carbonaceous asteroid
- **S**ecurity
  - Measure the Yarkovsky effect on a potentia hazardous asteroid
- **R**egolith **Ex**plorer
  - Document the regolith at the sampling site a scales down to the sub-cm

101955 BENNU PRE-ENCOUNTER KNOWLEDG







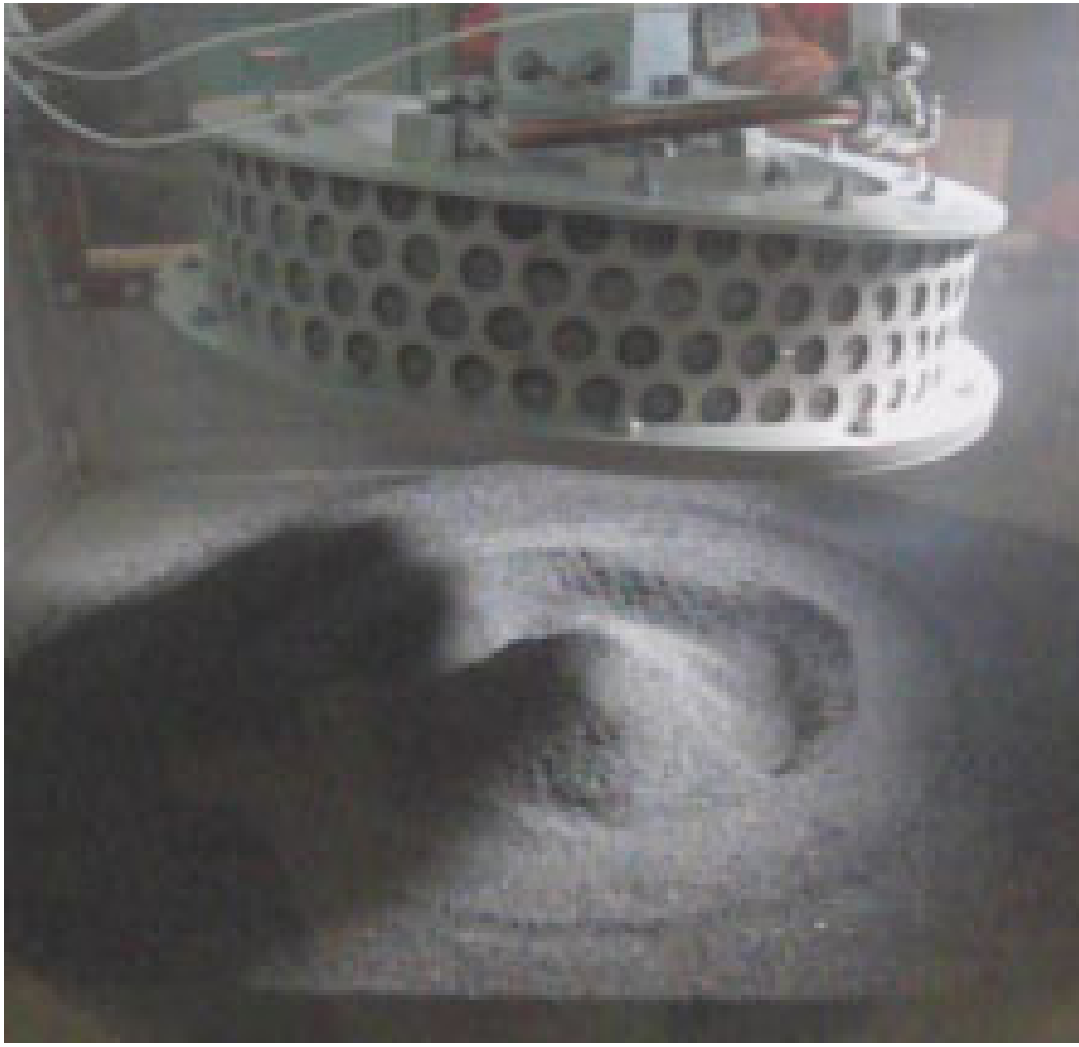
- **Size =** 492-m (±20 m, mean diameter)
- **Shape =** spheroidal "spinning top"
- **Rotation state =** 4.3 hr period, 180±5º obliquity
- **Bulk Density =** 1260 ± 60 kg/m3
- **Geometric Albedo =** 4.5 ± 0.5
- **Spectral Type =** B (Carbonaceous chor

Sample Return is the Primary Objective of the Missio

Key Requirements

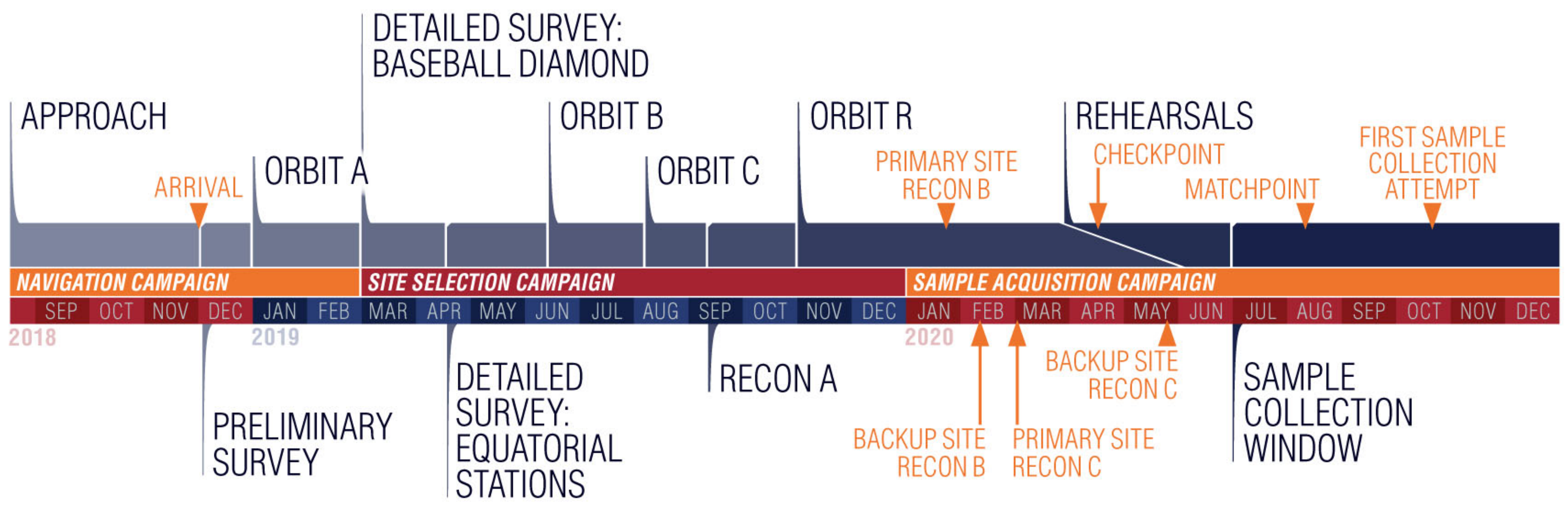
- Return **≥60 g of pristine bulk sample** from Bennu

- Contact **≥26 cm^2 of surface material** from Bennu and return the TAGSAM contact surface



OSIRIS-REx at Asteroid (101955) Bennu

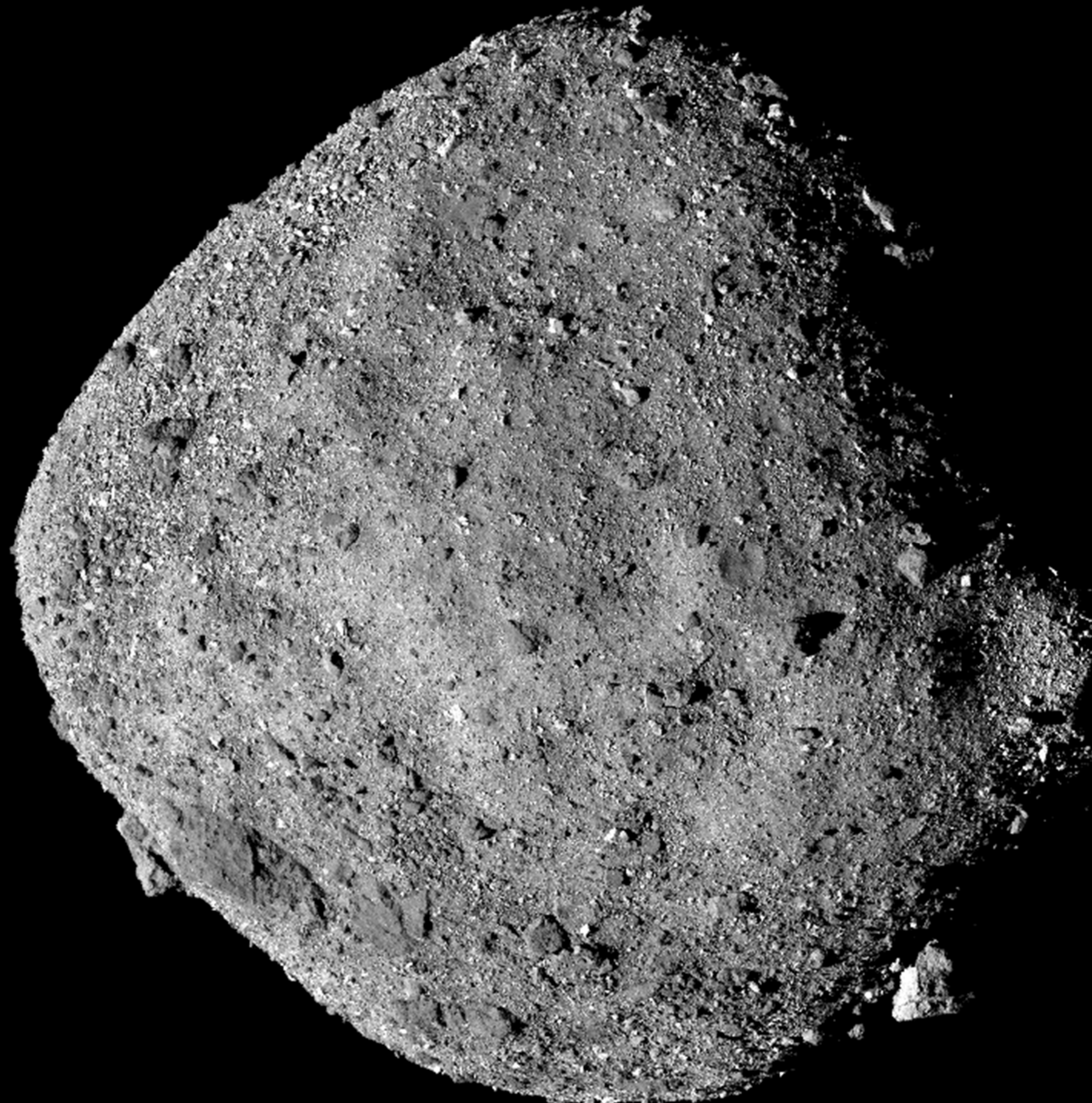
xtensive campaign to characterize Bennu and select sample site culminate
sample acquisition on October 20, 2020

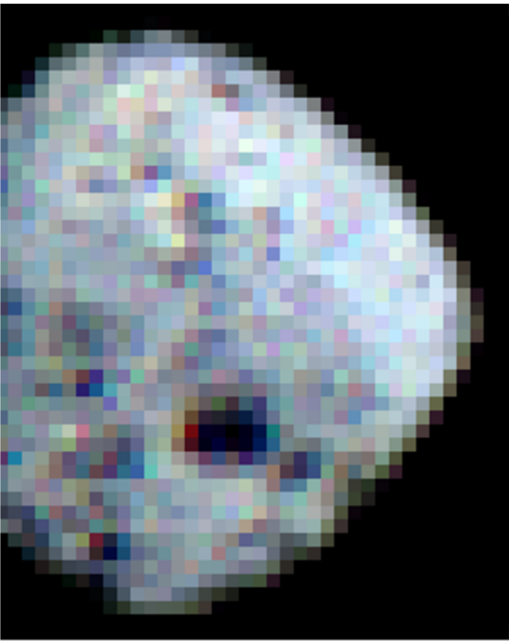


olyCam Image Mosaics
December 2, 2018
33 centimeters/pixel

4.3 hr rotation period

Phase angle ~48°
mphasizes terrain/reflief

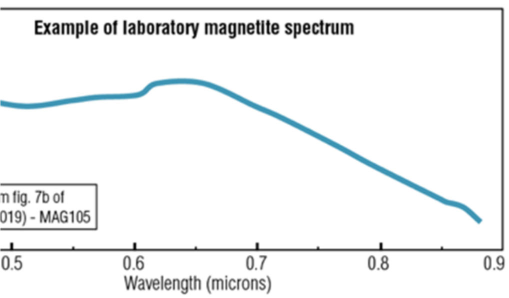


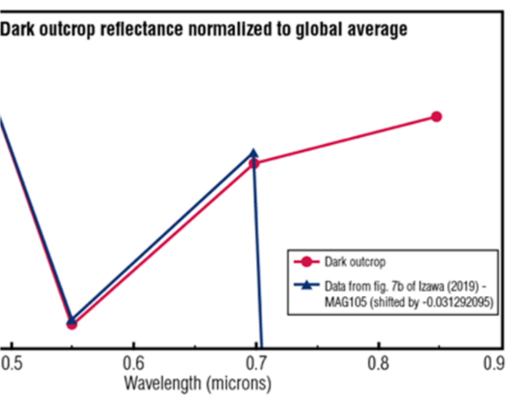


Abundant Hydrated Minerals and Magnetit

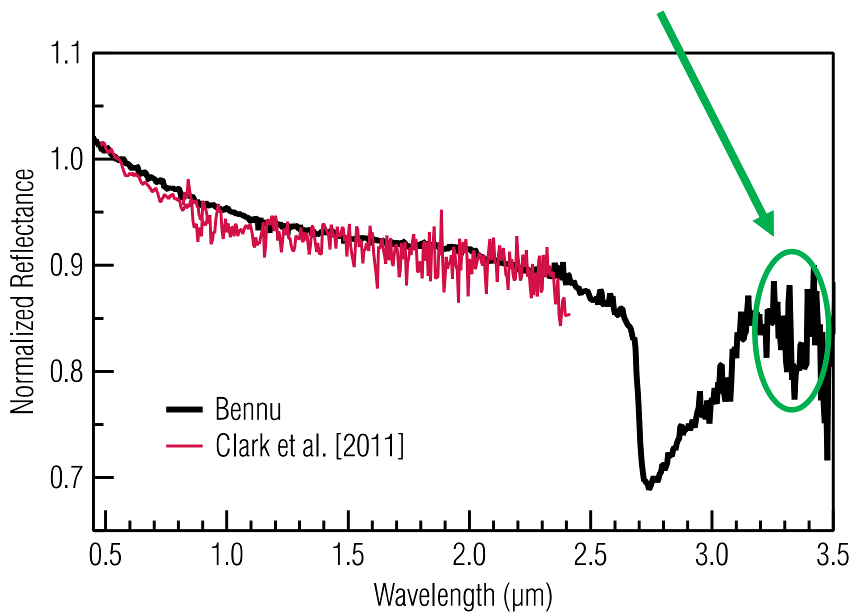
- The VIS-NIR spectrum has a blue (negative) slope, confirming the B-type taxonomy. A 2.7-μ spectral absorption band is present, consistent with the hydrated phyllosilicates
- Thermal emission spectra contain a spectral feature at 23 μm, also consistent with phyllosili and CM1 chondrites
- The darkest material show a spectral absorption at 0.55 μm, suggestive of magnetite (Fe_3O
- This interpretation is consistent with OTES spectra, which show features at 18 μm and 29 μ may be due to magnetite

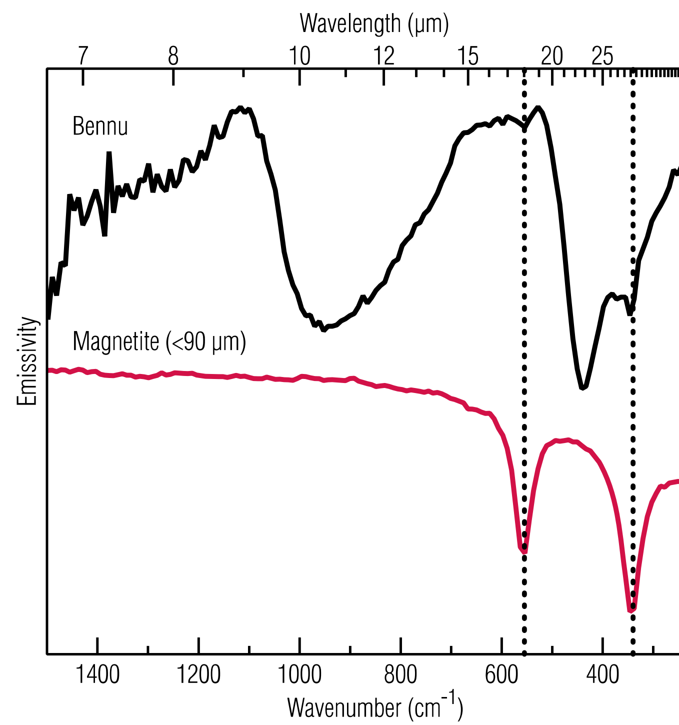
Lauretta et al. 2019a – Nature; Hamilton et al. 2019 - Nature





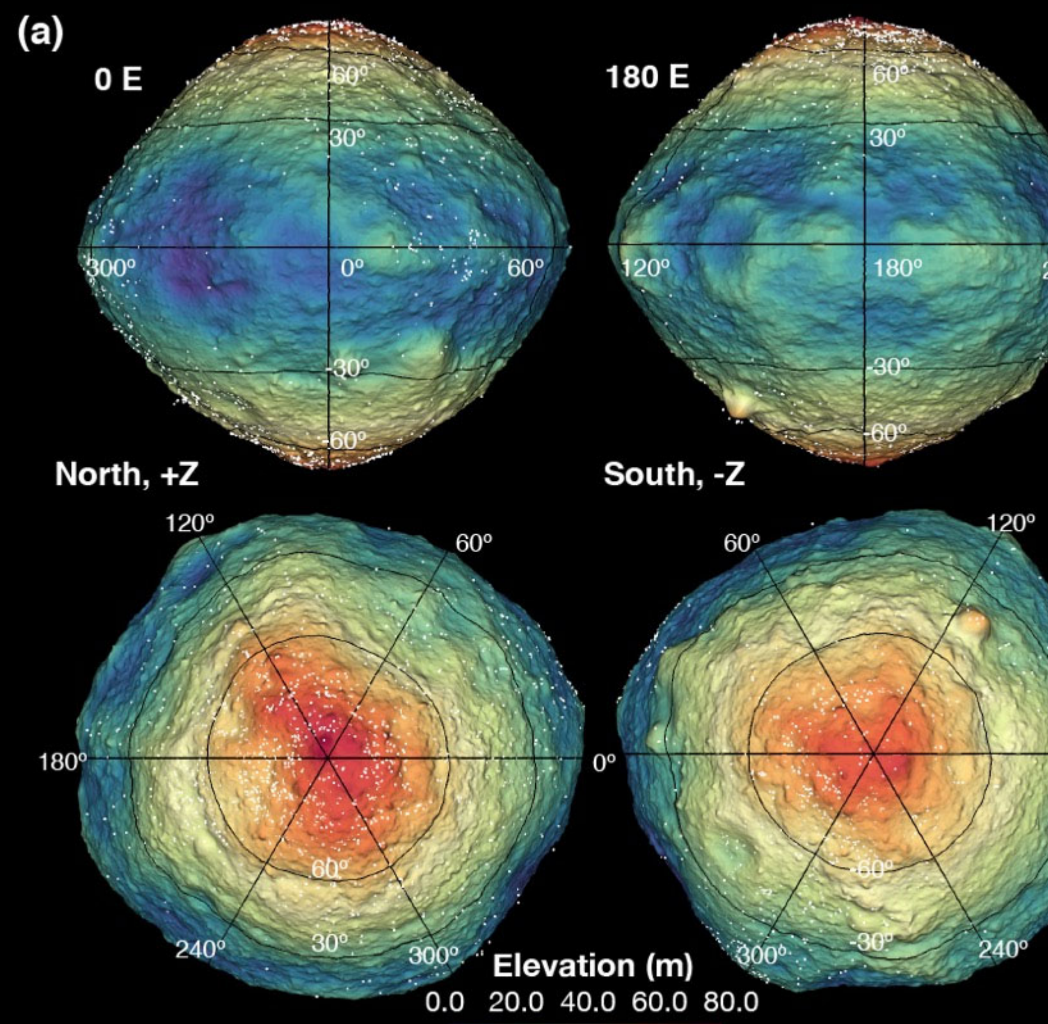
Organics/Carbonates!





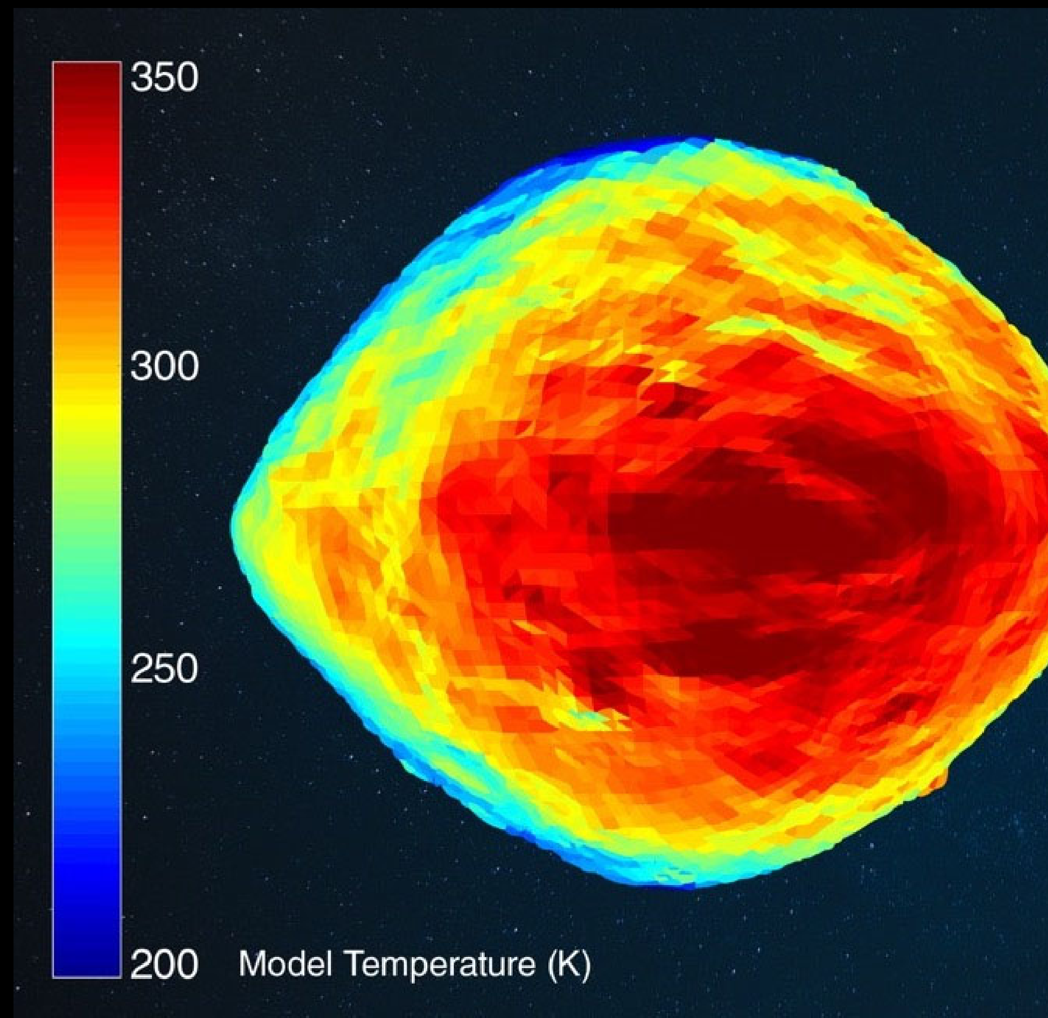
Mass, Shape, and Density – A Rubble Pile with Macroporos

- ennu exhibits the expected spinning-
op shape
- he shape and topography indicate low
evels of internal shear strength or
ohesion (Barnouin et al. 2019 – Nature Geosciences)
- mass determination from radio
cience yields a density of 1190 ± 13
g/m^3 (Scheeres et al. 2019 – Nature Astronomy)
- he low density of Bennu is consistent
vith a rubble-pile structure containing
0% macroporosity
  - Assuming a particle density characteristic of the CM chondrites



Low Thermal Inertia ≠ Fine Particulate Regolith

- hermal inertia (TI) of asteroid surfaces is often anslated into a characteristic particle size using odels that assume uniform particulates
- re-launch, we acquired disk-integrated and otationally resolved measurements of Bennu's ermal radiance
- or Bennu, we predicted a surface dominated by 5- to 5-cm-diameter particles
- /e confirm a global average TI of 350 ± 20 J m^{-2} $^{-2}$ $s^{-1/2}$
- esolved images of the asteroid's surface show at it is dominated by >1-m boulders
- ennu's TI may result from
  - Low thermal inertia of boulders
  - Dust cover on boulders
  - Mixture of particulate regolith and boulders
  - Combination of these effects



DellaGiustina and Emery et al. 2019 – Nature Astronomy esolved images of the teroid's surface show that it dominated by >1-m boulders

wo distinct reflectance values

ennu's TI may result from

- Low thermal inertia of boulders
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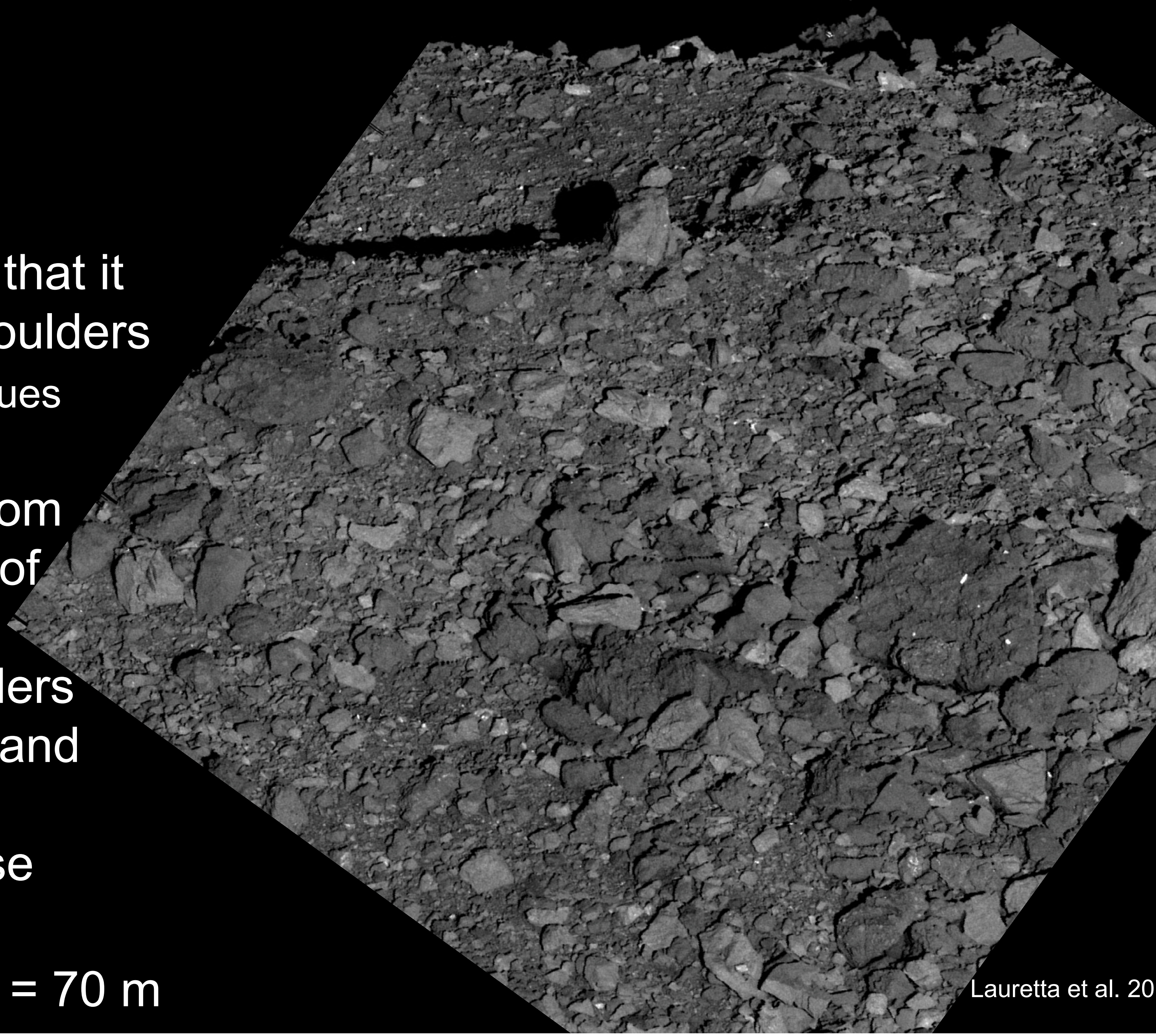
- Combination of these effects



FOV = 70 m

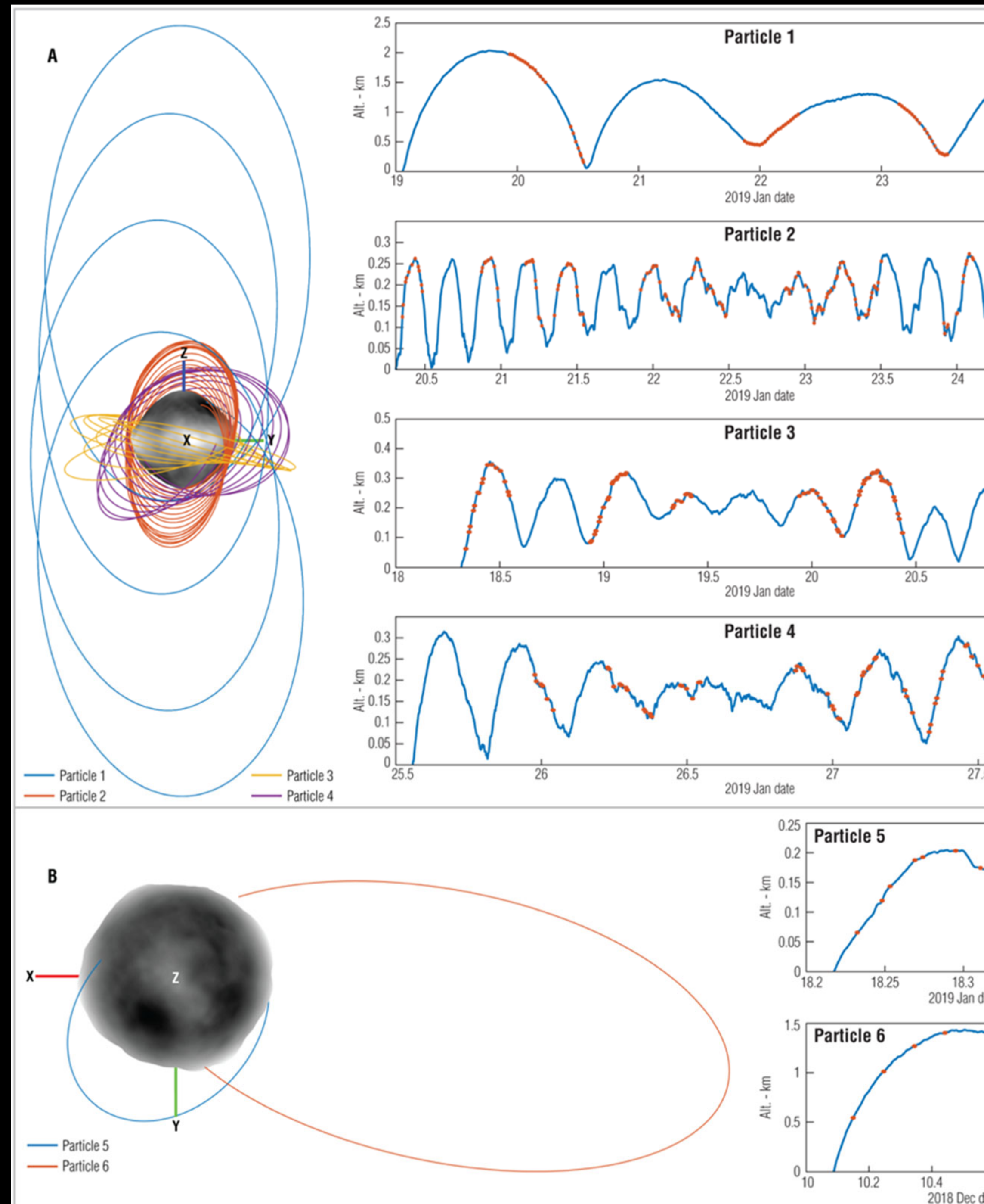
Lauretta et al. 20

The Biggest Surprise – Bennu is an Active Asteroid!

NavCam1 images
(combined long and
short exposures)
January 19, 2019

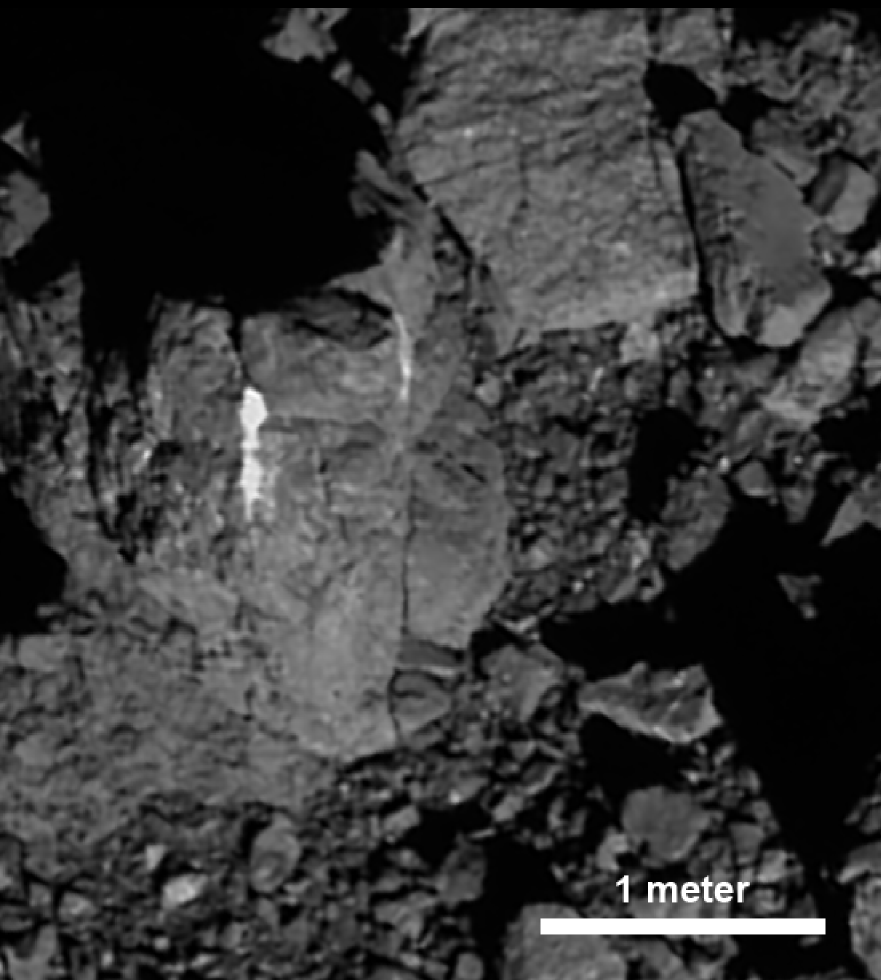
Lauretta et al. 2019b – Scienc

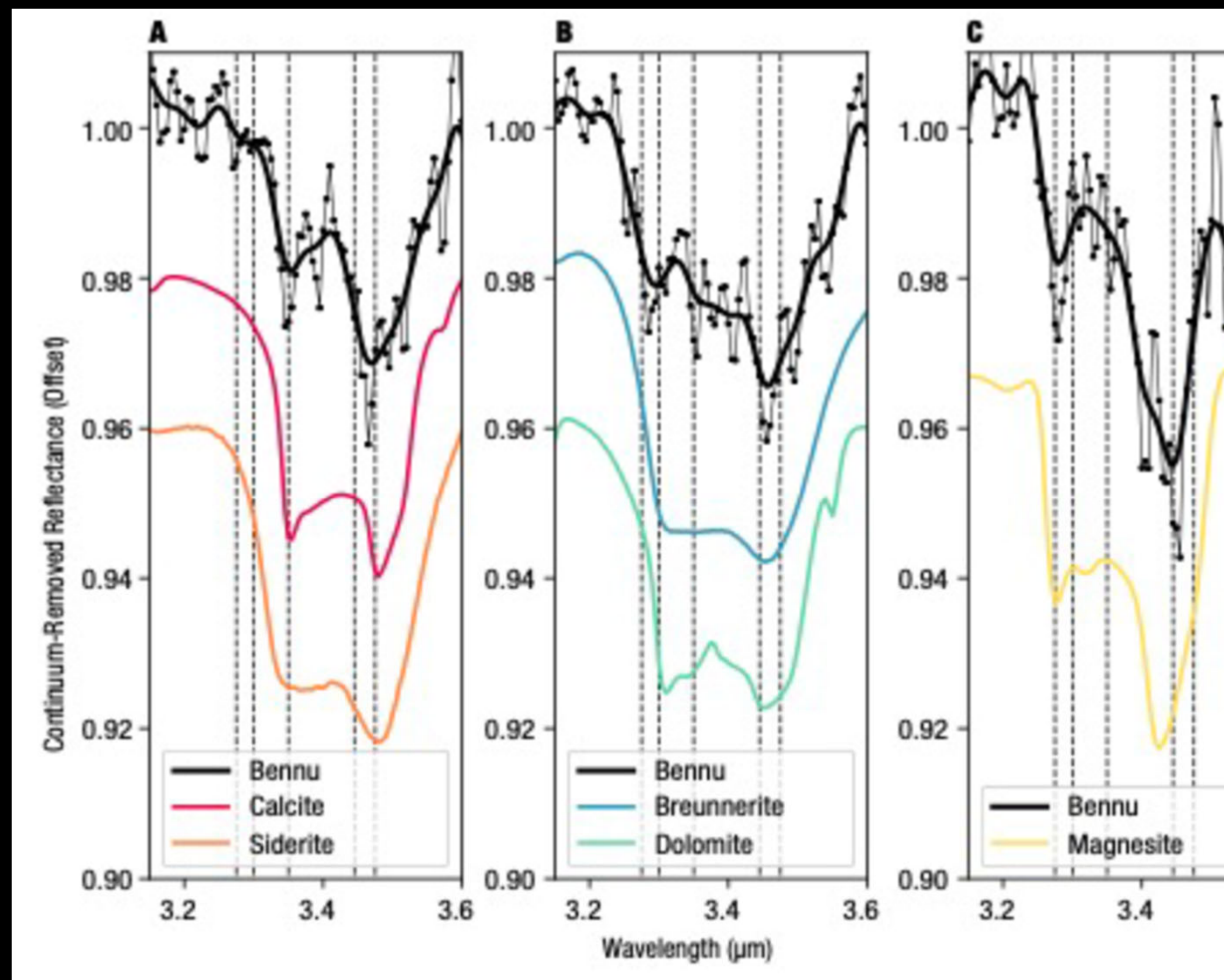
dividual particle detections
nked to determine orbital
trajectories



Lauretta et al. 2019b – Science

Images of boulders show centimeters-thick, roughly meter-long bright vein suggesting that fluid flow and hydrothermal deposition on Bennu's parent body occurred on km scales for thousands to millions of years.

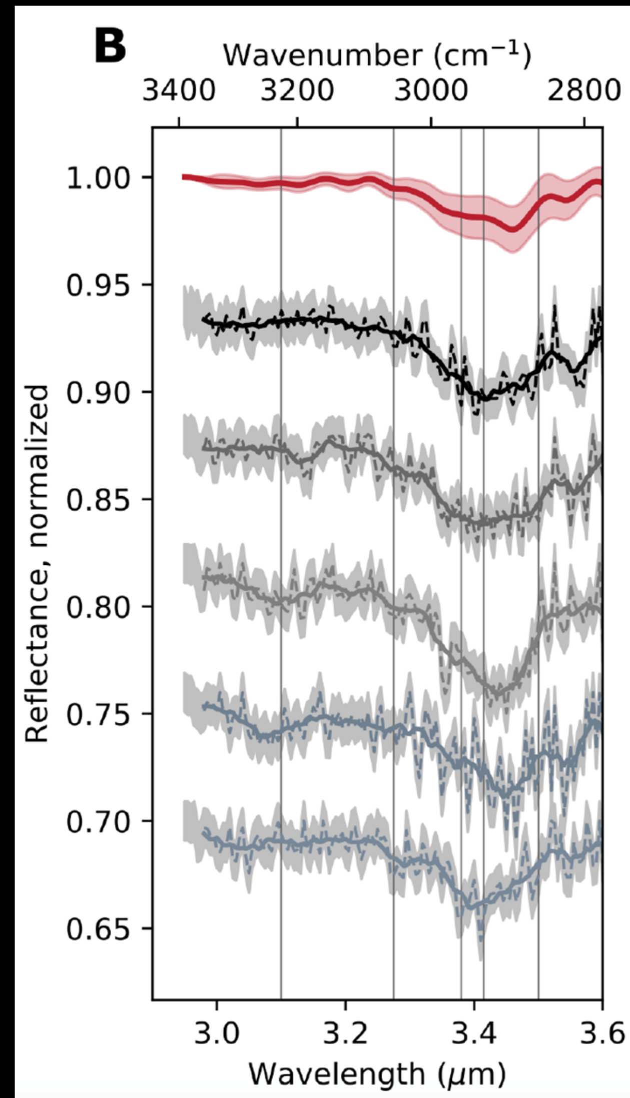




Kaplan et al. 202

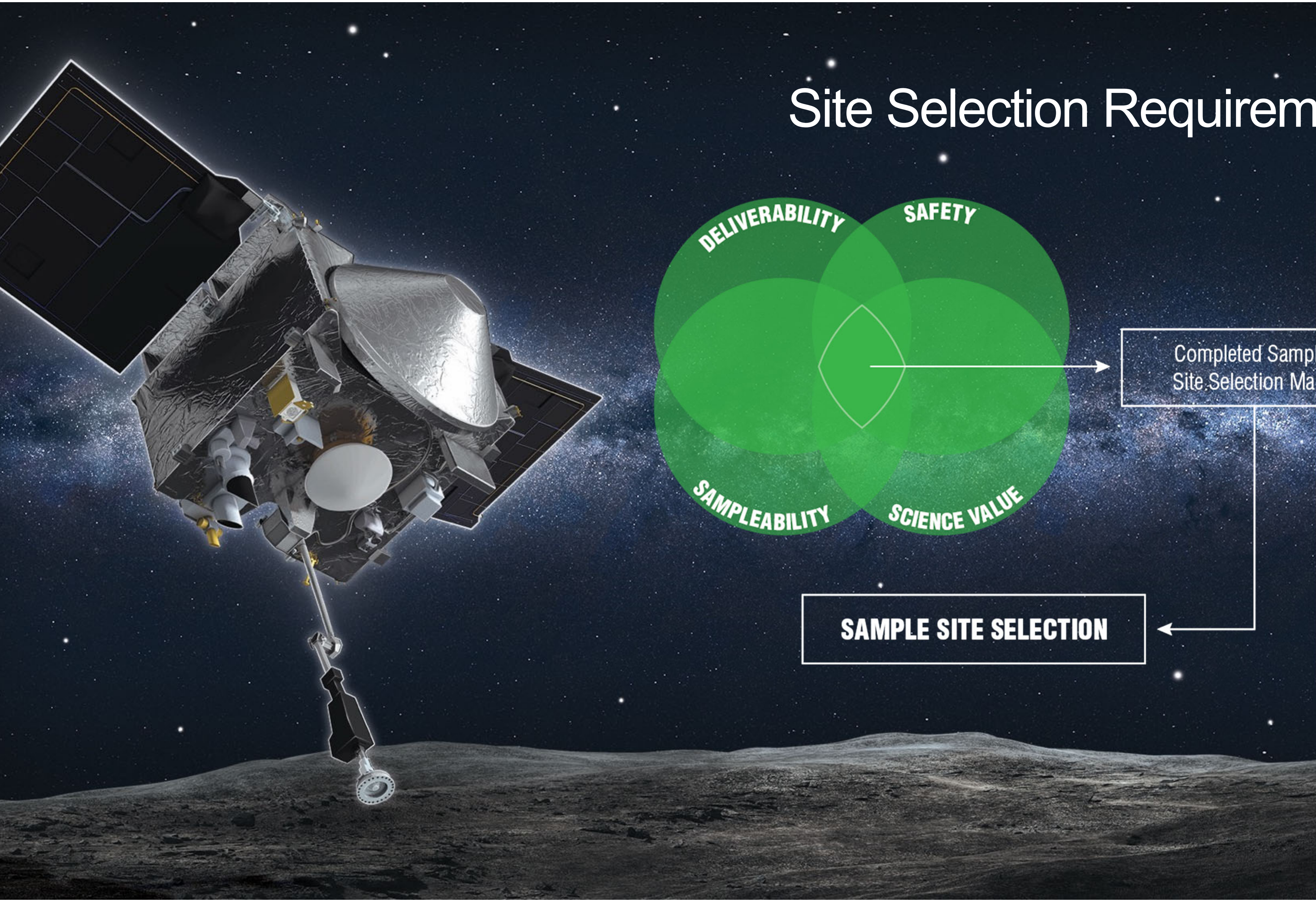
Organics on Bennu

- Ve find spectral evidence of aromatic nd aliphatic CH bonds.
- The absorptions are broadly consistent n shape and depth with those ssociated with insoluble organic matter n meteorites.
- Given the thermal and space veathering environments on Bennu, it is kely that the organics have not been xposed for long enough to substantially lecrease the H/C and destroy all liphatic molecules.

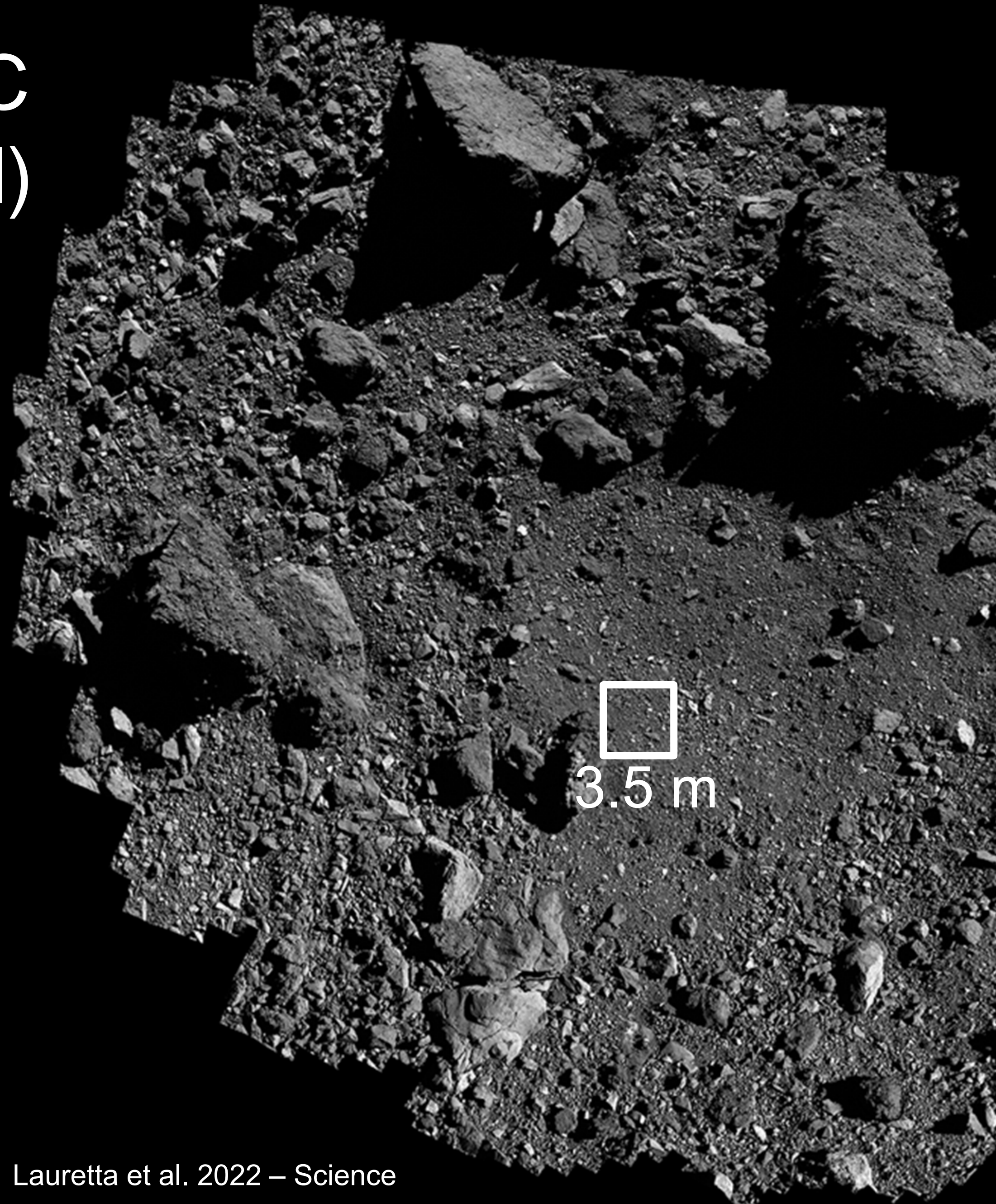


Vertical lines i
positions of po
absorption fea
from C-H bond

Kaplan et al. 2021 - Astronomy & Astrophysics


Site Selection Requirem
DELIVERABILITY
SAFETY
SAMPLEABILITY
SCIENCE VALUE
Completed Sampl
Site Selection Ma
SAMPLE SITE SELECTION

Nightingale – Recon C images (0.35 cm/pixel)



Lauretta et al. 2022 – Science

Contact Location

ntacted at 55.8993˚, 41.8412˚

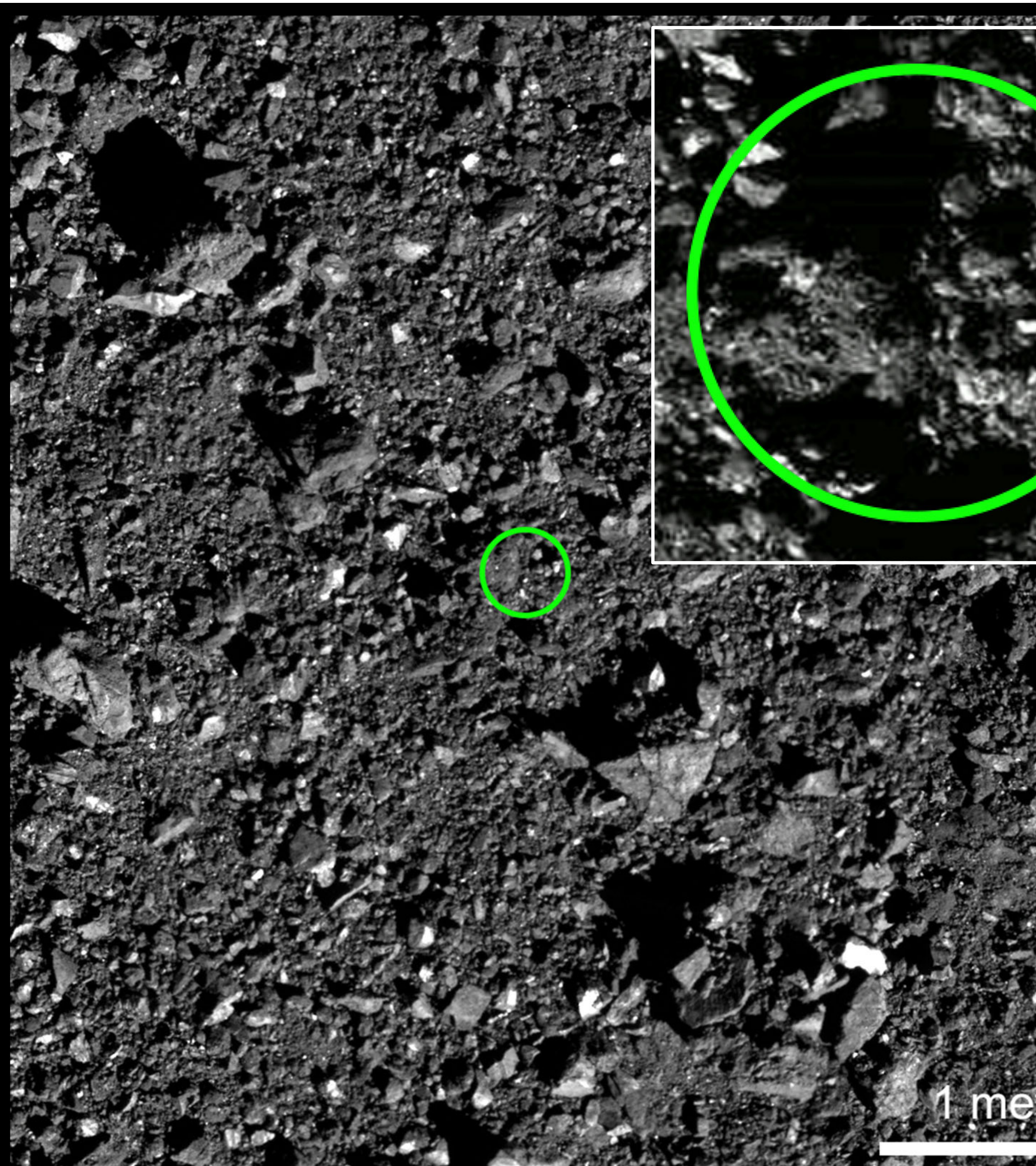
wnward velocity of 10.05 cm/s

hin 73 cm of the targeted location

t-and-pepper appearance indicates
nnu's two primary lithologies might
h be sampled
- dark with low thermal inertia
- brighter with higher thermal inertia

h abundance of surface particles <2
in diameter
- Size class ingestible by TAGSAM

Lauretta et al. 2022 – Science



ontact Dynamics

mera and IMU data indicate an initial
face contact force of between 10
d 15 N

dence of surface disturbance in all
ections around TAGSAM

GSAM partially disrupted a ~20-cm-
g boulder near the eastern edge of
contact point

other boulder, 40 cm long responded
e a rigid plate, tilting up and
nching small particles

pports the conclusion that Bennu’s
ulders have a range of strengths

Lauretta et al. 2022 – Science

Gas Firing

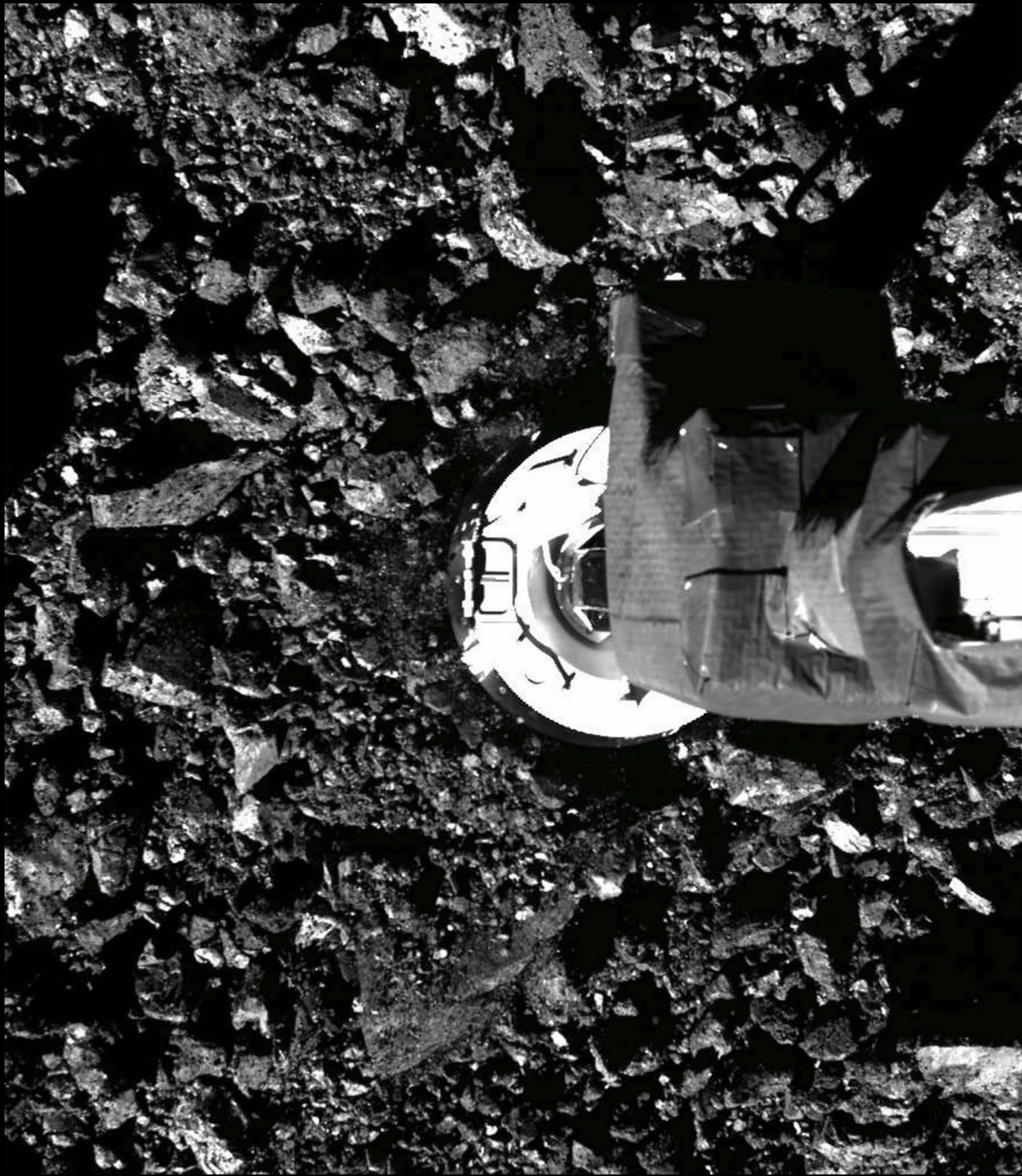
e second after contact, TAGSAM eased a jet of nitrogen gas to fluidize consolidated surface material and de it into the collection chamber.

out 6 s after contact, the spacecraft ained a downward velocity of ~4 /s

e velocity change of 6 cm/s is ibutable to TAGSAM gas release

e spacecraft then fired eight of its -N thrusters, initiating the back-away neuver.

Lauretta et al. 2022 – Science



Backaway

seconds of thruster firing arrested
residual downward velocity

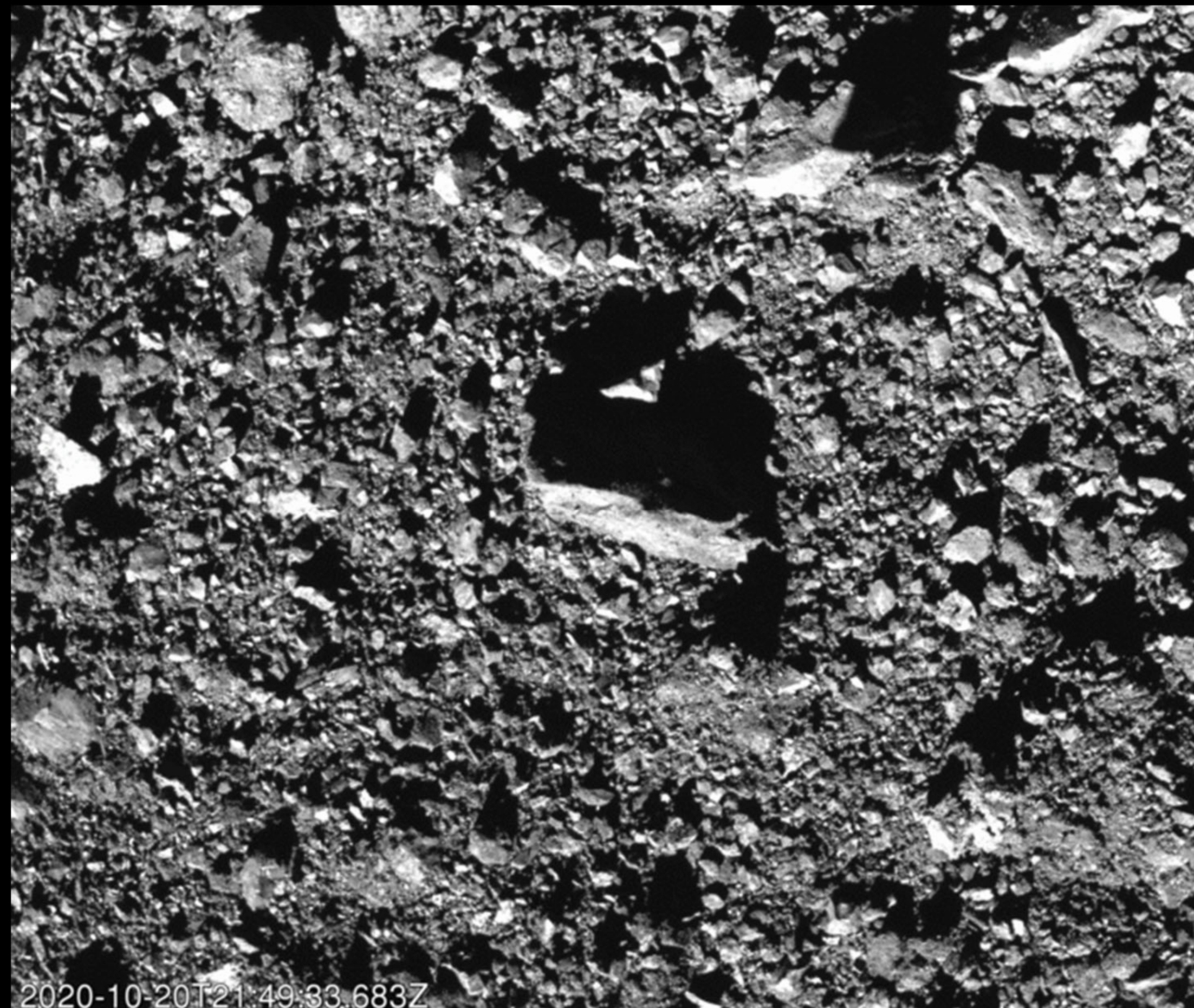
GSAM penetrated 48.8 cm

e thrusters fired for a total of 25.7 s

GSAM rose above the original
face height 16.6 s after contact

h-opacity debris plume with vertical
d lateral velocity relative to surface

rphology due to a combination of
GSAM gas and thruster pressure



Lauretta et al. 2022 – Science

Final Flyby

turned to Bennu on 7 April 2021 for
nal flyby at 3.7 km to characterize
newly exposed subsurface

moved the edge of a pre-existing
bris apron at the base of the Hokioi
ter wall and replaced it with a small
ter (centered at 55.997˚, 44.971˚)
n several boulders at its bottom

rrounded by decimeter-scale rocks
nsported by the sampling event into
arc

.25-m boulder, which was directly
der one set of thrusters, was
nsported 12 m

Lauretta et al. 2022 – Science

TAG Crater

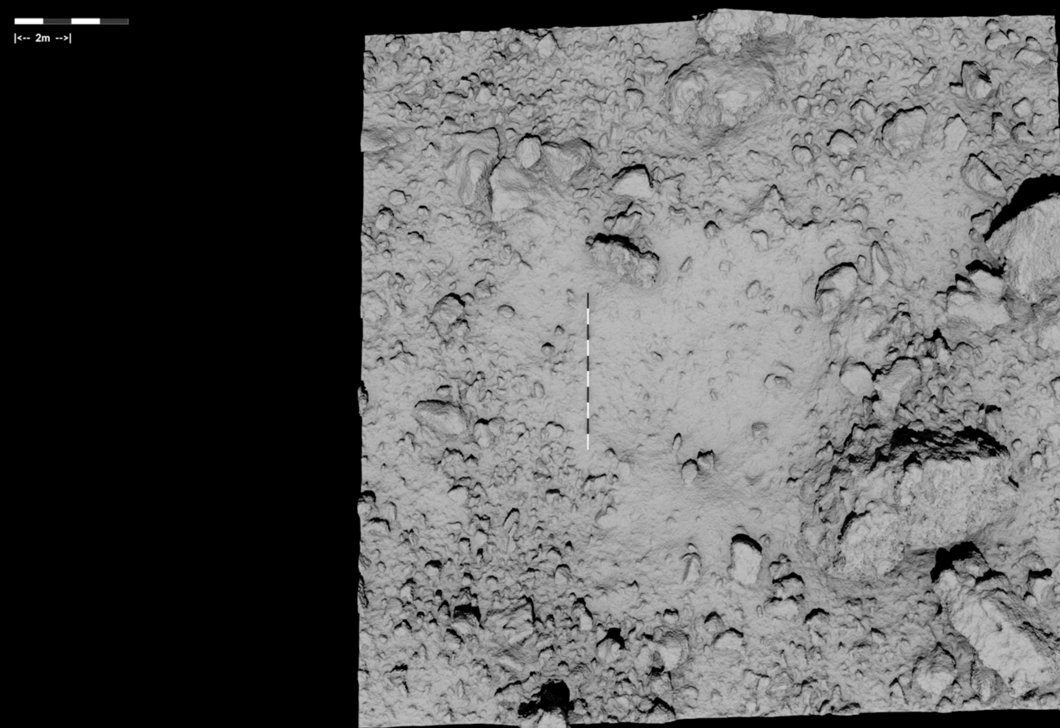
applied stereophotoclinometry to
nstruct a 5-cm GSD DTM

cavated crater is elliptical (9.0 ×
m), with its long-axis oriented
th to south

erage lateral dimension is 7.8 ±
m, and its depth is 0.68 ± 0.1 m

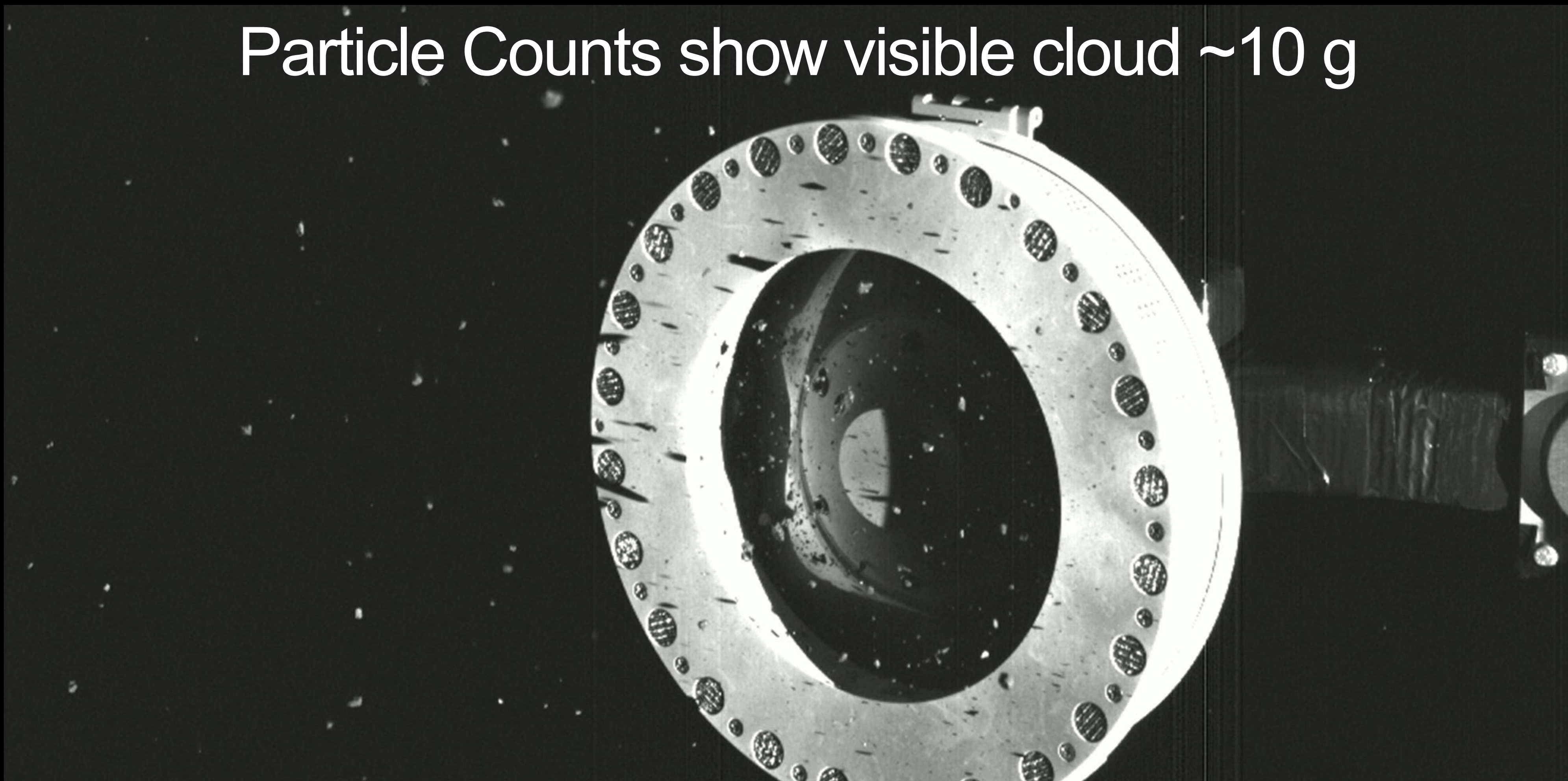
placed volume is 12.2 ± 0.9 m^3

applied crater scaling
ationships and energy of the gas
ease to assess physical properties
- Bulk density of 500 to 700 kg/m^3
- Nearly cohesionless (<0.001 Pa)
- granular material



Lauretta et al. 2022 – Science

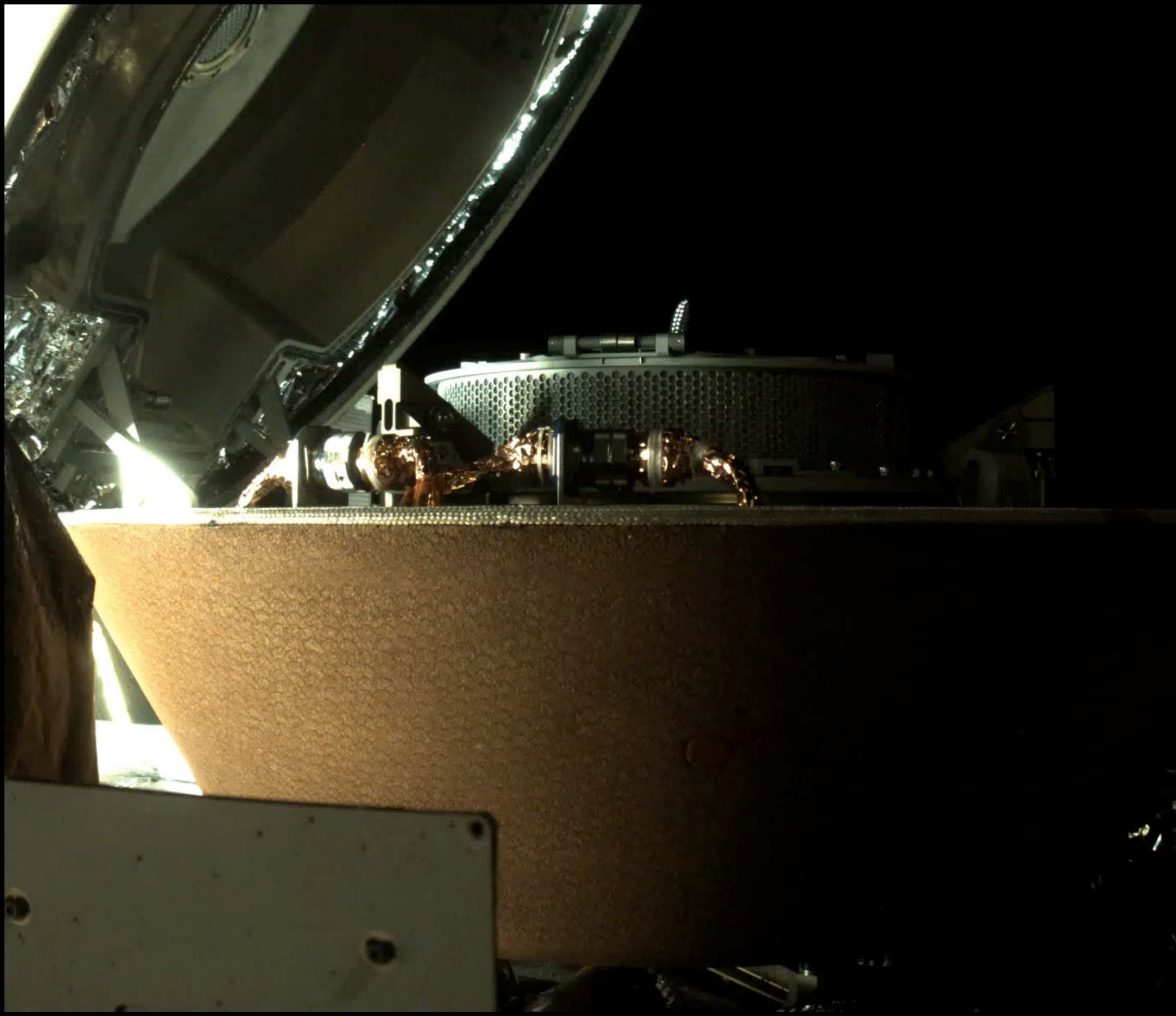
Contingency identified – mass loss during TAGSAM imaging



Sample Stowed

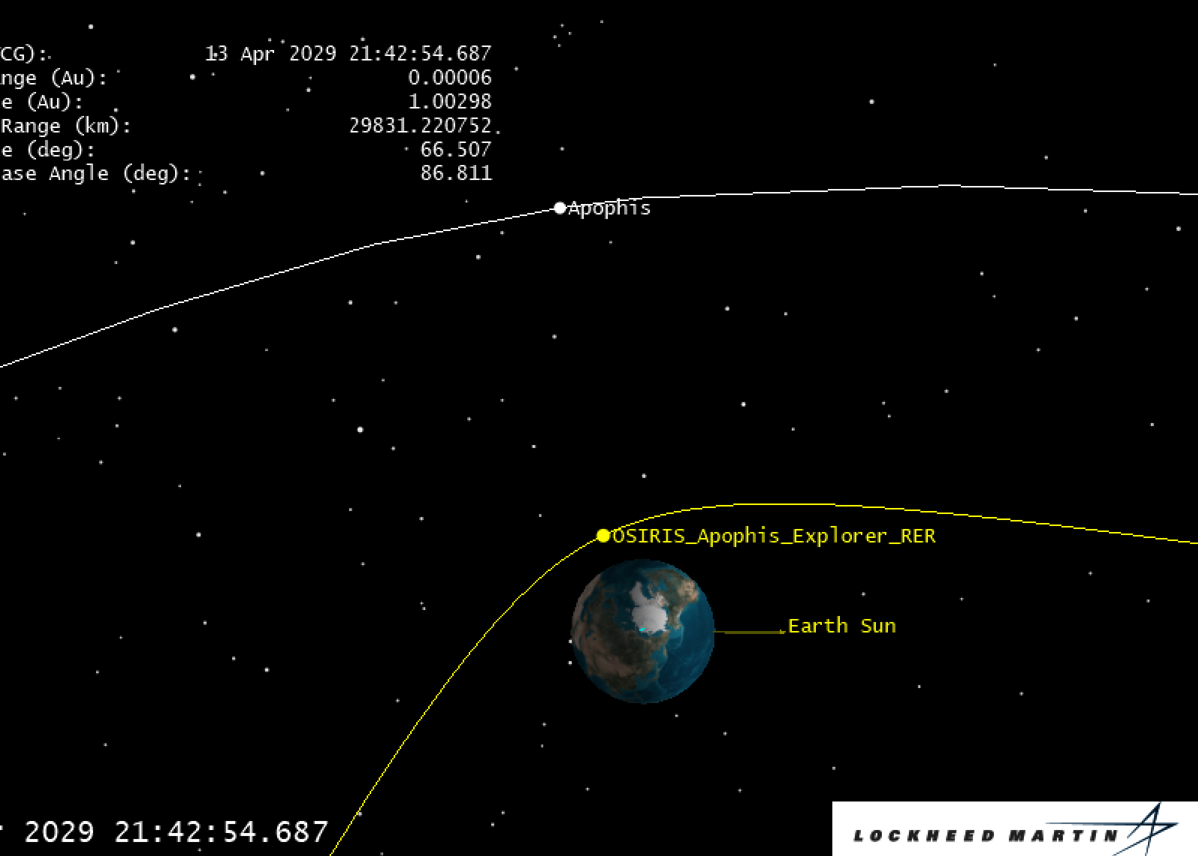
- ze range from sub-micron to 3 cm
- pected Mineralogy, :
  - Hydrated silicates
  - Organic compounds
  - Carbonates
  - Magnetite
  - Sulfides (not spectrally active – but inferred from analog meteorites)

- e sample will contain multiple hologies
  - Similar to type-1 CI and CM chondrites
  - Non-chondritic and igneous in nature, like HED meteorites
  - Some with properties distinct from known meteorites
  - Monomineralic cm-scale carbonates
  - Ejected cm-scale platy particles



Lauretta et al. 2022 – Science

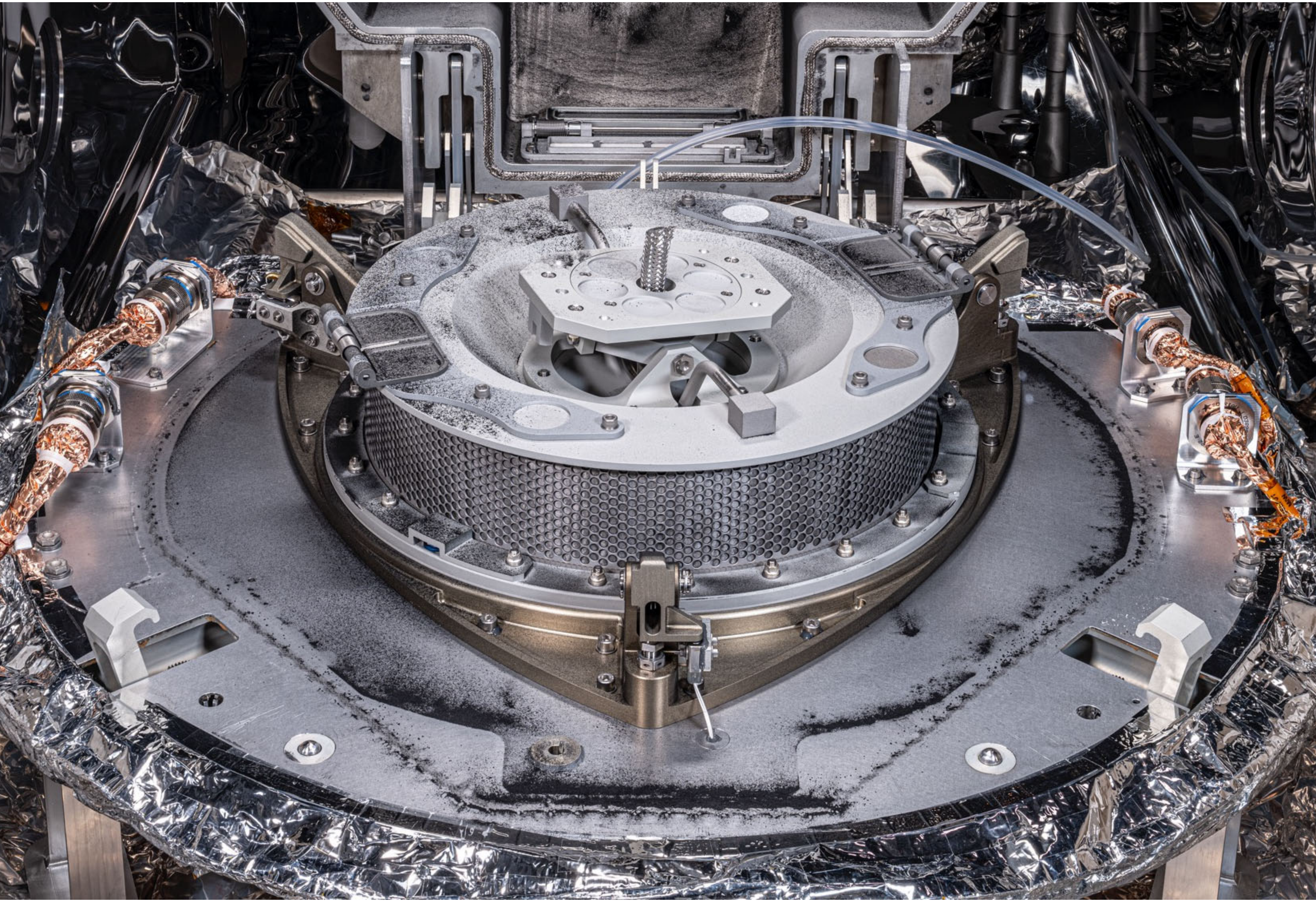
Extended Mission – Apophis Explorer (OSIRIS-APEX

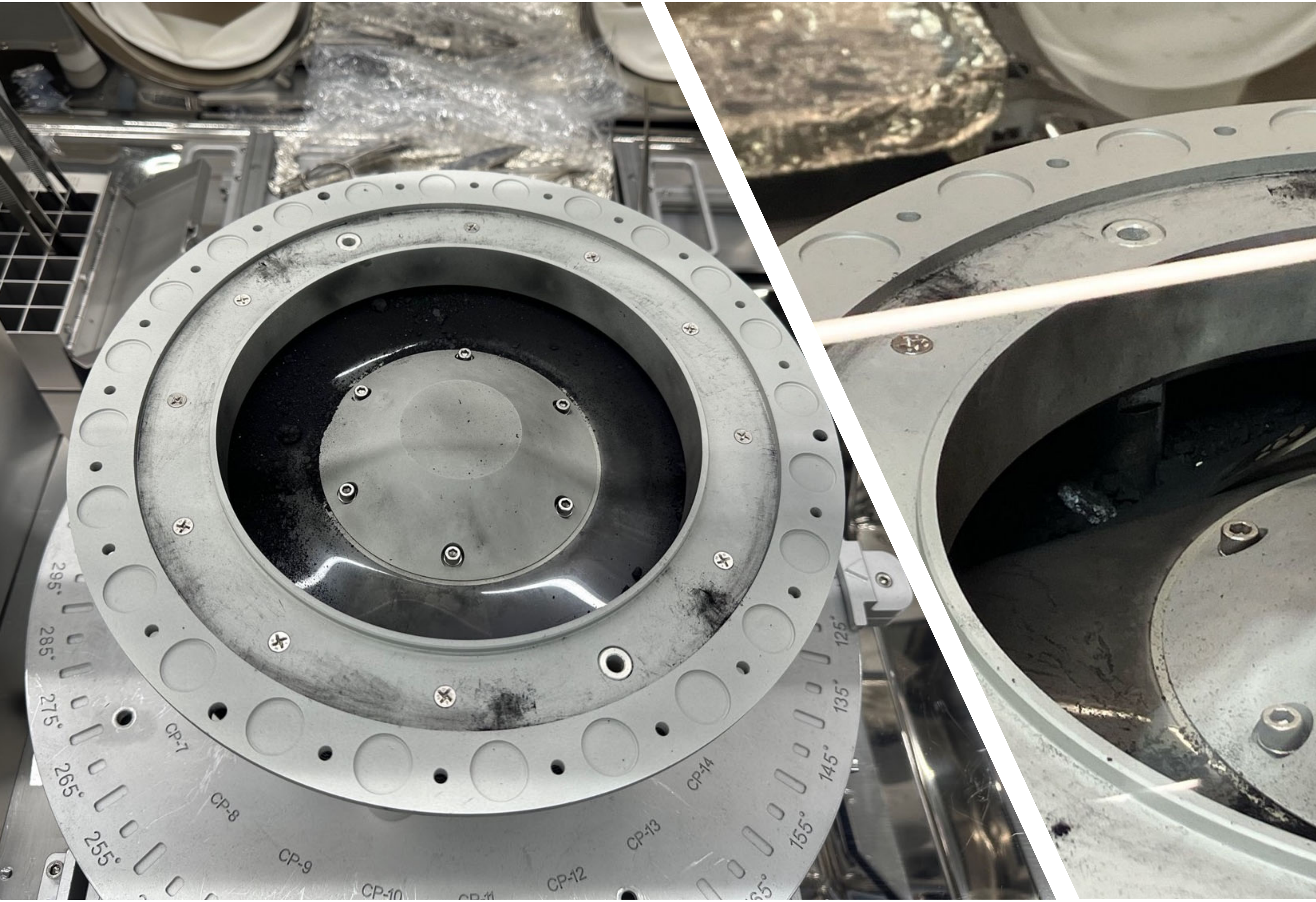


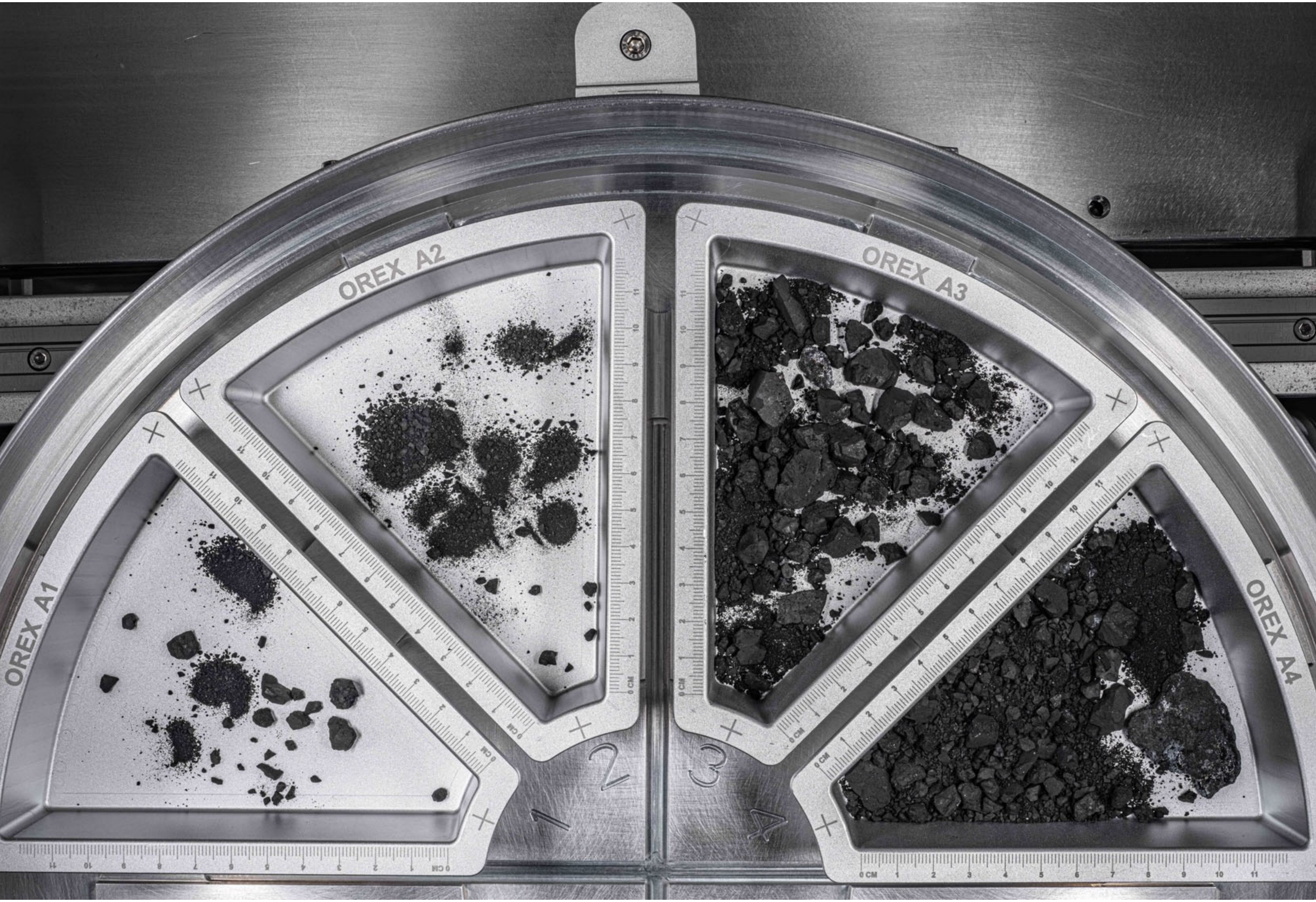
- EGA concurrent with Apophis close approach on April 13, 202
- Acquisition with PolyCam April 2029, prior to Apophis close approach
- Daily science and OpNav observations of Apophis until arrival later in April
- Global and regional characterization from orbit and hyperbolic flybys
- Focus on personnel developme and early career opportunities

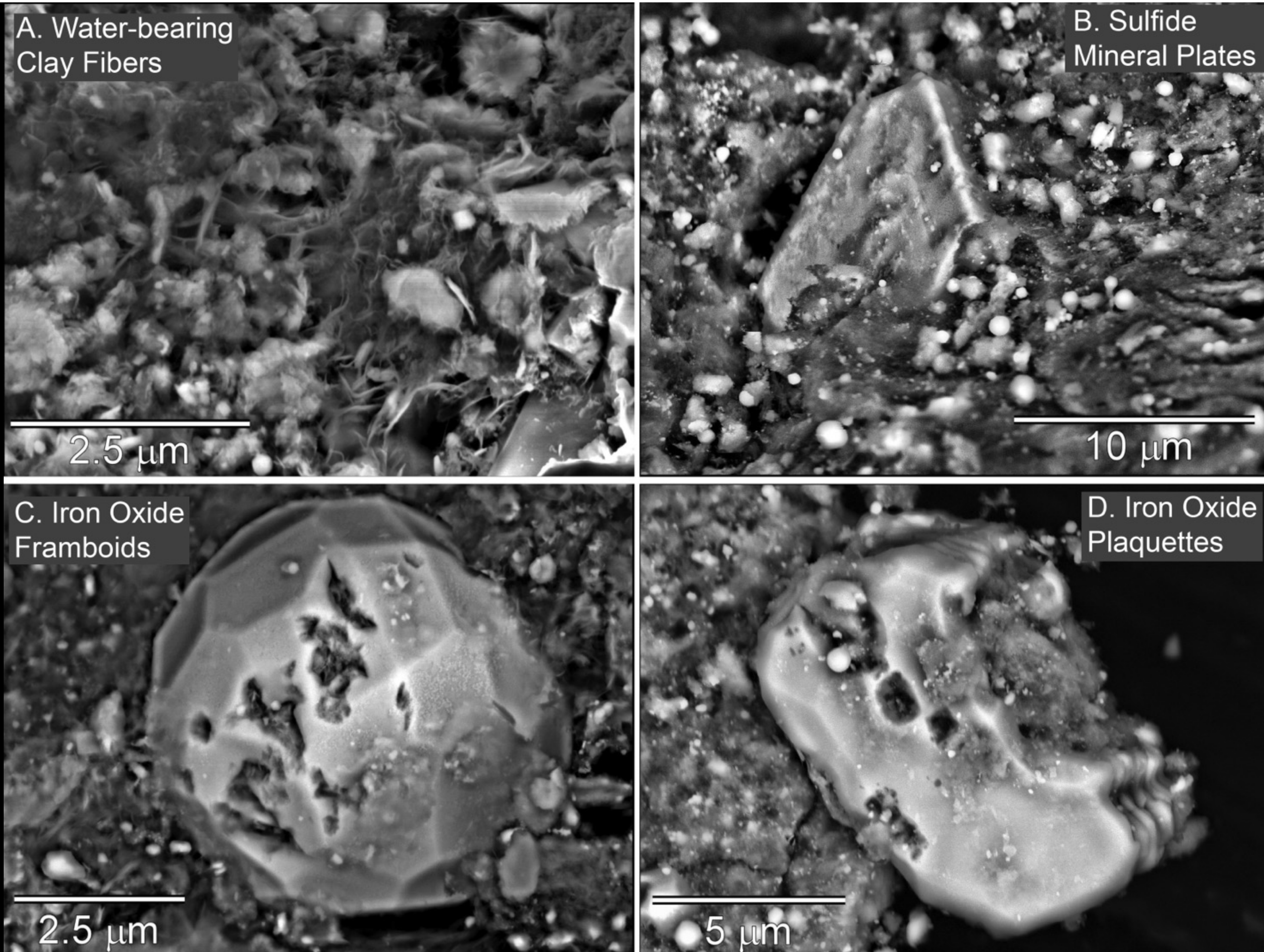

.8994
.3725
MSL
0
14:46
> ZOO
FOCUS
IRI
CI
CO
FO

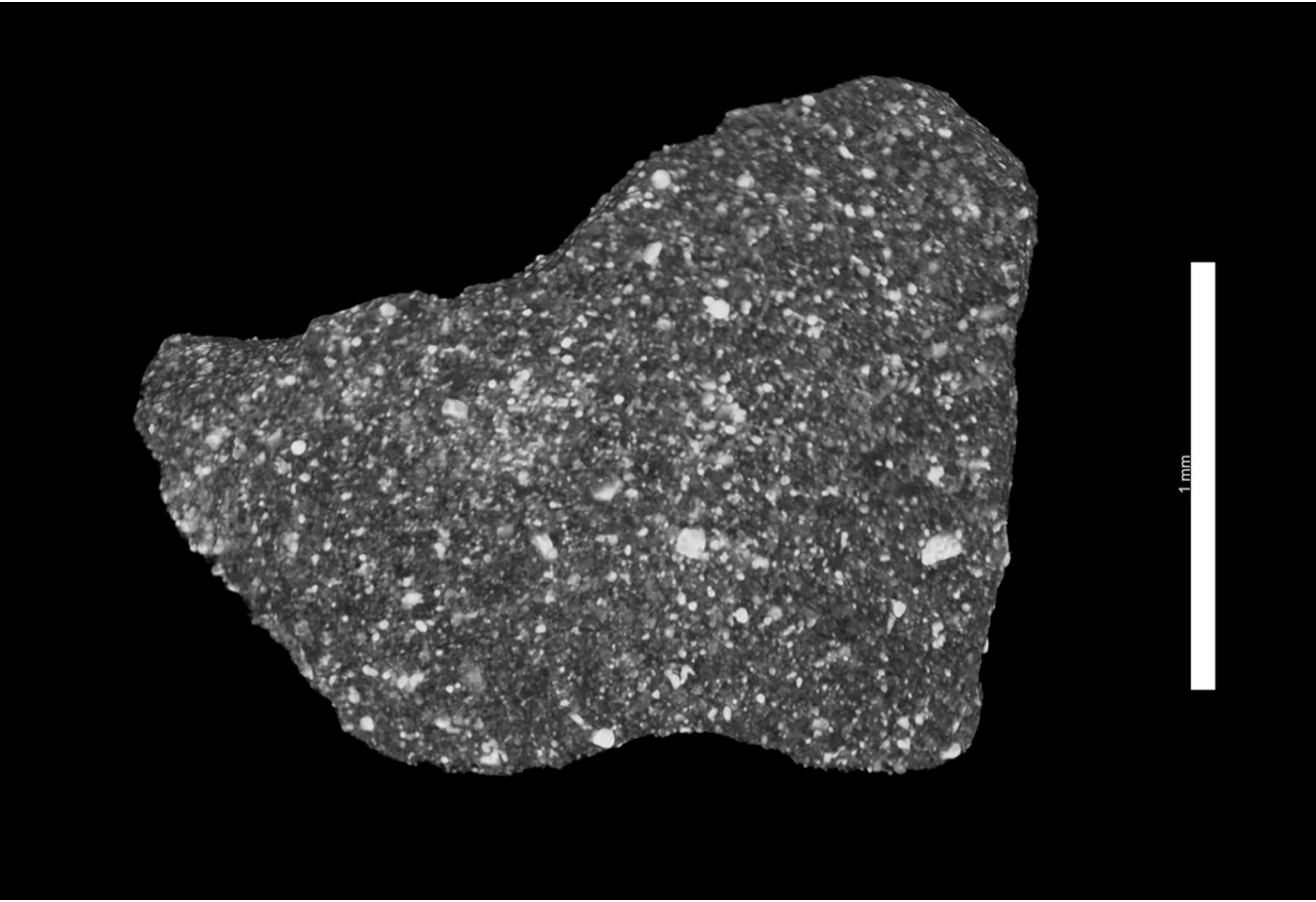

EXIT

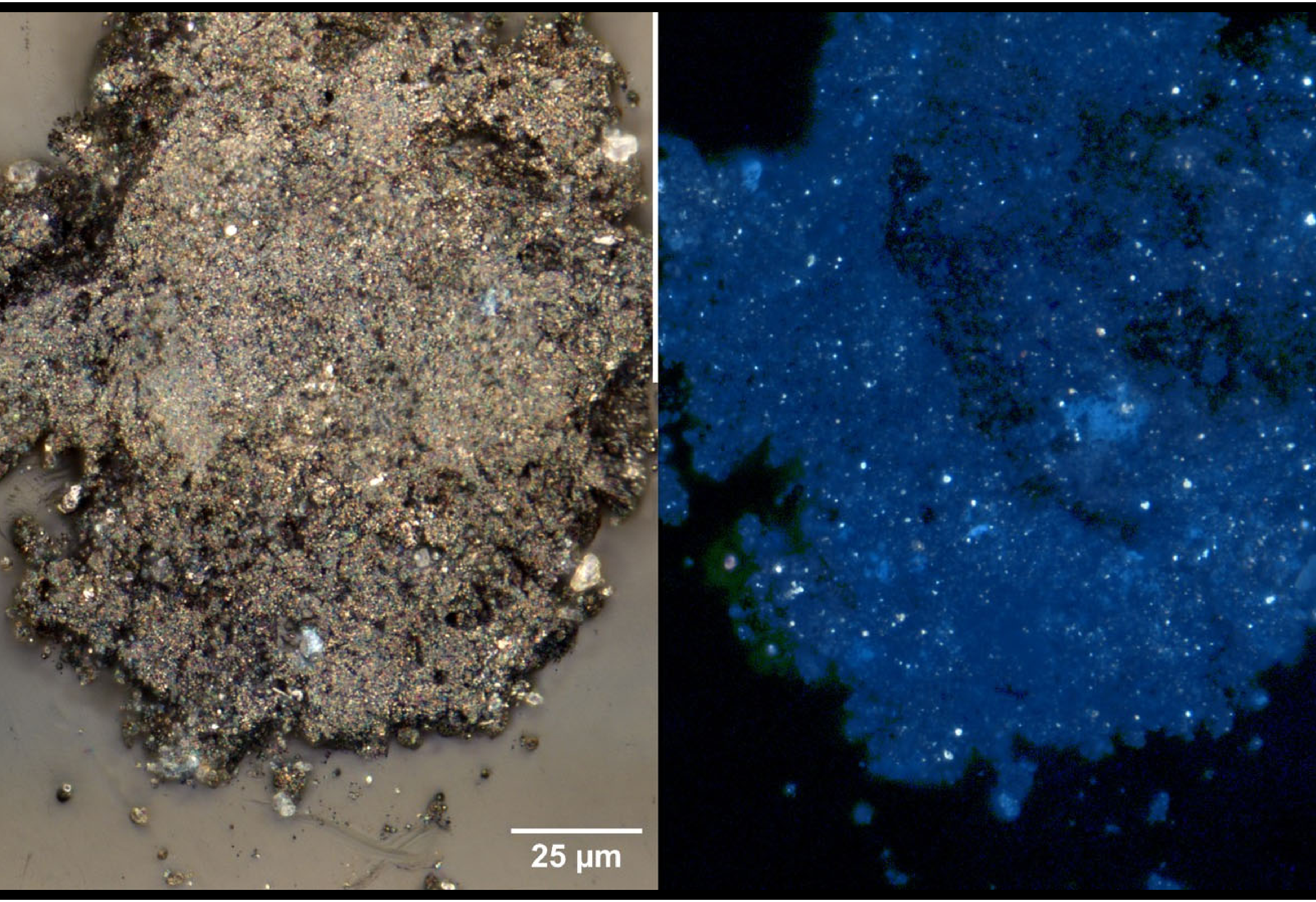



295°
285°
275°
265°
255°
CP-7
CP-8
CP-9
CP-10
CP-12
CP-13
CP-14
125°
135°
145°
155°


OREX A1
OREX A2
OREX A3
OREX A4


A. Water-bearing
Clay Fibers
2.5 μm
B. Sulfide
Mineral Plates
10 μm
C. Iron Oxide
Framboids
2.5 μm
D. Iron Oxide
Plaquettes
5 μm


1 mm


25 µm

Risk Areas – What Keeps the PI Up-At-Night?

Risk Area	Mitigations
Unique Aspects of a Sample Return Mission	• Established World Class Navigation Team • Developed detailed Design Reference Mission which guides the execution of careful & methodical asteroid operations and sample collection • Earth-return enveloped by Stardust Capsule and Entry
Preventing Mission Requirements Creep	• Detailed Phase A study completed • Well understood and stable requirements • Thorough cost estimate developed and independently validated • Incorporating lessons learned into baseline plan • Established PI Support Office • Established detailed SOW's for Science Team • PI & Management team are committed to deliver
Long-Term Continuity of Expertise	• Organization is optimized for success • Partner organizations are assigned responsibilities aligned with corporate strengths • Development of a multi-generational team • Phase A team provides continuity into Phase B

OSIRIS-REx Overall Costing Strategy

emonstrate Robust & Credible Cost Plan

- Clear understanding of the scope of work
- Work Breakdown Structure
- Methods & Rationale used for cost estimates
  - Basis of Estimates
  - List of quotes received
  - List and description of analogs
    - Quantify cost savings from heritage
  - Model assumptions & results
- Clear link to the project schedule
  - Identify interdependence
  - Identify margins
- Clearly identify Cost Risks & Mitigations
- Adequate reserves
  - Identify areas not adequate and associated risk

		CSR - April 2011		Departure - March 2021		
WBS #	Title	Total		Total		Delta
1	PM	$	35,353,804	$	46,097,900	$ 10,7
2	PSE	$	17,933,242	$	29,242,700	$ 11,3
3	SMA	$	11,764,035	$	10,469,927	$ (1,2
4	Science	$	65,022,833	$	106,298,021	$ 41,2
5	Payload	$	67,362,595	$	85,181,126	$ 17,8
6	Spacecraft	$	252,458,896	$	307,541,000	$ 55,0
7.3	MSA	$	31,971,823	$	72,082,800	$ 40,1
7.4	SPOC	$	34,753,662	$	25,164,100	$ (9,5
7.5	FDS	$	12,323,972	$	32,553,400	$ 20,2
7.6	EDL/Recovery	$	8,041,249	$	8,569,100	$ 5
7.7	DSN	$	19,882,728	$	5,014,400	$ (14,8
7.8	Curation	$	8,988,014	$	10,184,000	$ 1,1
9.3	MSA-Ops	$	9,327,464	$	10,072,000	$ 7
9.4	SPOC-Ops	$	25,860,567	$	25,243,000	$ (6
9.5	FDS-Ops	$	5,875,339	$	16,827,900	$ 10,9
9.6	EDL/Recovery	$	1,982,868	$	1,169,000	$ (8
9.7	DSN-Ops	$	2,471,508	$	1,839,300	$ (6
9.8	Curation	$	142,064	$	893,900	$ 7
10	ATLO	$	25,581,950	$	25,745,400	$ 1
11	EPO	$	10,519,409	$	743,000	$ (9,7
Total		$	647,618,022	$	820,931,974	
1.9	Reserves	$	163,601,770	$	7,863,000	$ (155,7
HQ	UFE	$	70,000,000	$	52,424,818	$ (17,5
Total		$	811,219,792	$	828,794,974	$ 17,5