Sampling the Solar System: Insights from the OSIRIS-REx Mission

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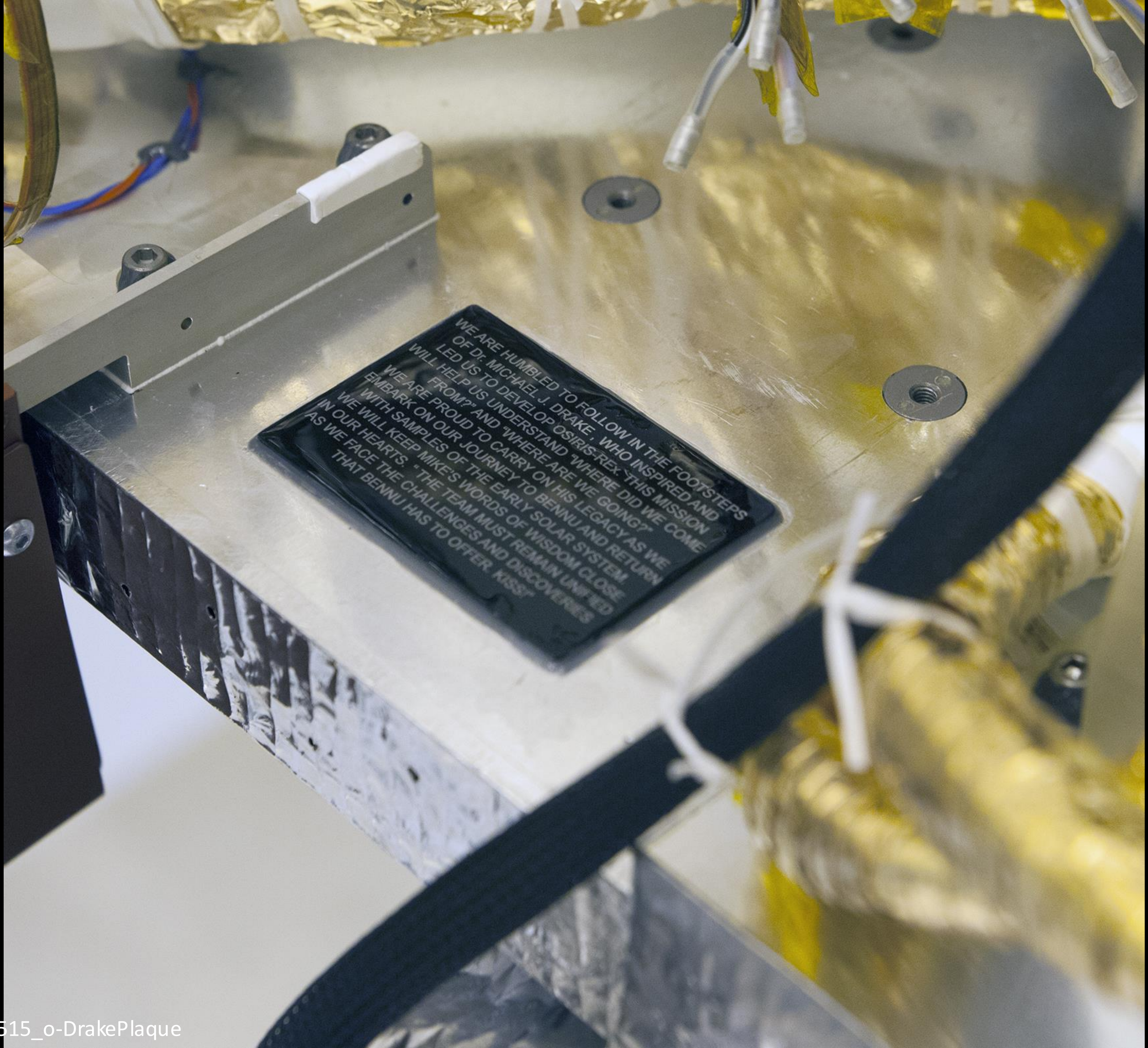
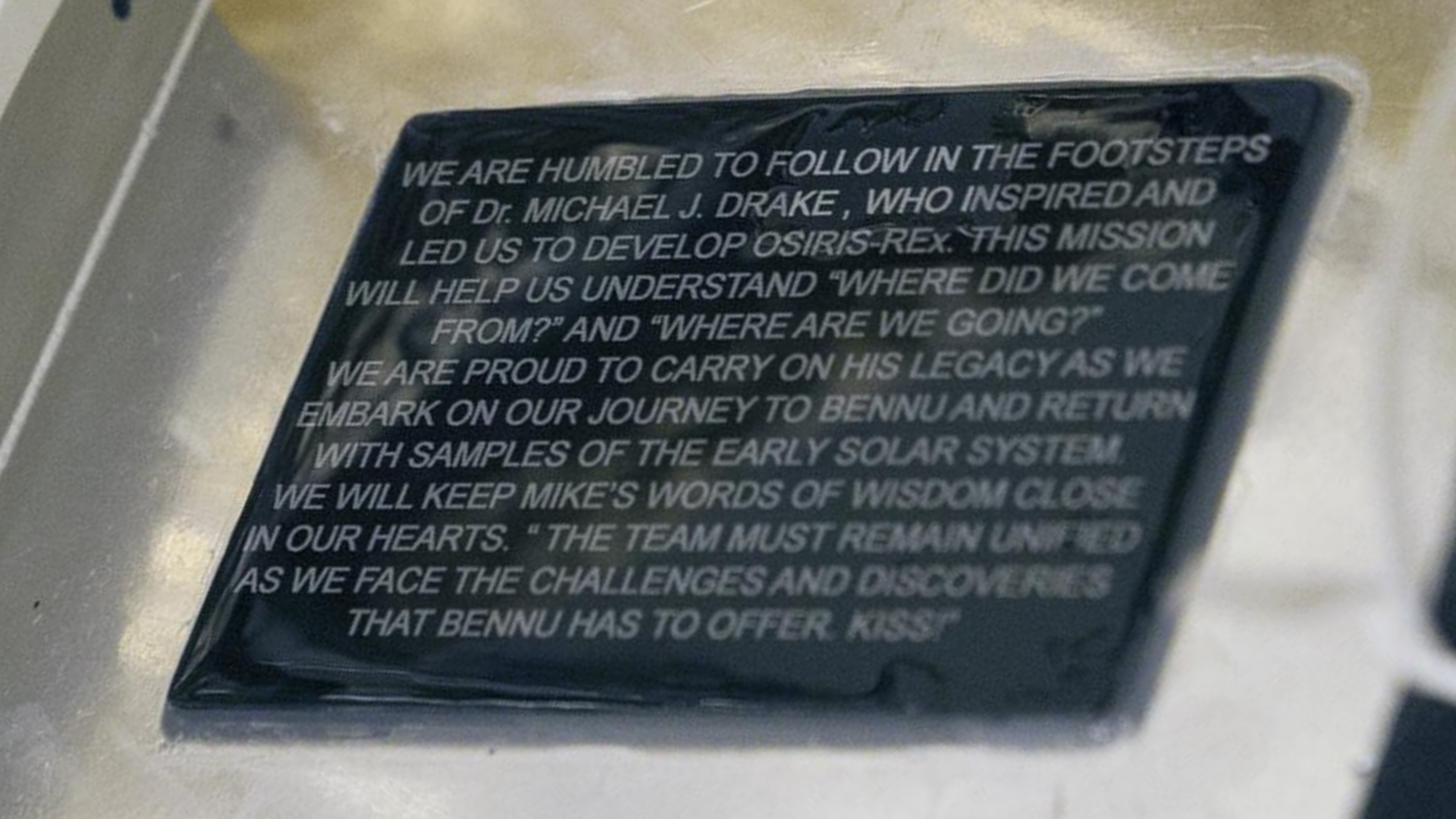
OSIRIS-REx Project Scientist
NASA's Goddard Space Flight Center

10 October 2024

Derived from Flight Data



ksc-20160718-ph_csh01_0040_28767006515_o-DrakePlaque

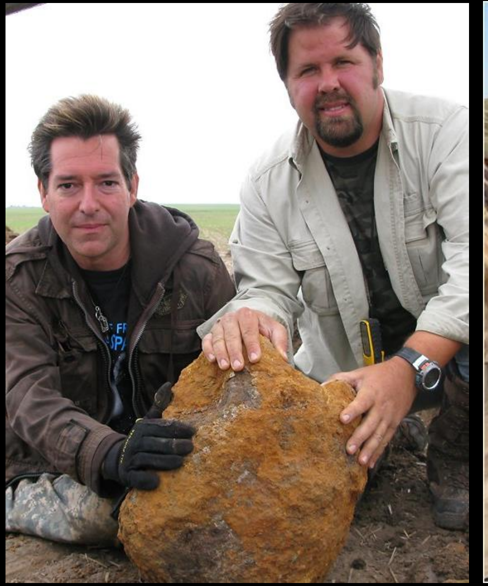

WE ARE HUMBLED TO FOLLOW IN THE FOOTSTEPS
OF Dr. MICHAEL J. DRAKE , WHO INSPIRED AND
LED US TO DEVELOP OSIRIS-REx. THIS MISSION
WILL HELP US UNDERSTAND "WHERE DID WE COME
FROM?" AND "WHERE ARE WE GOING?"
WE ARE PROUD TO CARRY ON HIS LEGACY AS WE
EMBARK ON OUR JOURNEY TO BENNU AND RETURN
WITH SAMPLES OF THE EARLY SOLAR SYSTEM.
WE WILL KEEP MIKE'S WORDS OF WISDOM CLOSE
IN OUR HEARTS. " THE TEAM MUST REMAIN UNIFIED
AS WE FACE THE CHALLENGES AND DISCOVERIES
THAT BENNU HAS TO OFFER. KISS!"

JWST Data Orion Nebula


Artistic Interpretation NASA's Goddard Space Flight Center Conceptual Image Lab

Geologists have a saying – rocks remember.

Extraterrestrial Samples



Geoff Notkin and Steve Arnold

“Alpha” Kansas, USA Brenham Strewn Field

Muawia Shaddad, Peter Jenniskens, and U. Khartoum students

Nubian Desert, Sudan. Almahata Sitta Fall

Scott Messenger and Danny Glavin with Dante Lauretta (background)

MacAlpine Hills, Antarctica ANSMET

NASA’s OSIRIS-REx mission collected 250±101gg of asteroid Bennu surface to return to Earth

More contaminated
Worse documented

Less contaminated
Better documented

Sample Return Missions: The gift that keeps on giving

Moon

NASA *Apollo* 11, 12, 14, 15, 16, and 17 (1969, 1971, 1972)
Soviet Luna 16, 20, and 24 (1970, 1972, 1976)
China Chang'e 5, 6 (2020, 2024)
NASA *Artemis III, etc.* (in development, 2026)

Solar wind

NASA Genesis (returned 2004)

Comet tail

NASA Stardust (returned 2006)

Stony Asteroid

JAXA Hayabusa (returned 2010)

Carbonaceous Asteroid

JAXA Hayabusa2 (returned 2020)
NASA OSIRIS-REx (returned 2023)

Phobos

JAXA MMX (in development, 2026-2030)

Mars

NASA/ESA MSR (in development, 2020-)

Astronauts

Robots

OSIRIS-REx

Origins

Return and analyze a sample of pristine carbonaceous asteroid regolith

Spectral Interpretation

Provide ground truth for telescopic data of the entire asteroid population

Resource Identification

Map the chemistry and mineralogy of a primitive carbonaceous asteroid

Security

Measure the Yarkovsky effect on a potentially hazardous asteroid

Regolith Explorer

Document the regolith at the sampling site at scales down to the sub-cm

TAGSAM (LM)
Collects the sample

REXIS (MIT) Student Experiment maps the elemental abundances

SRC (LM) Returns the sample

OCAMS (UA) **PolyCam** >500K-km range, high-resolution imaging of the surface, **SamCam** images the sample site and TAG, **MapCam** provides landmark-tracking, filter photometry.

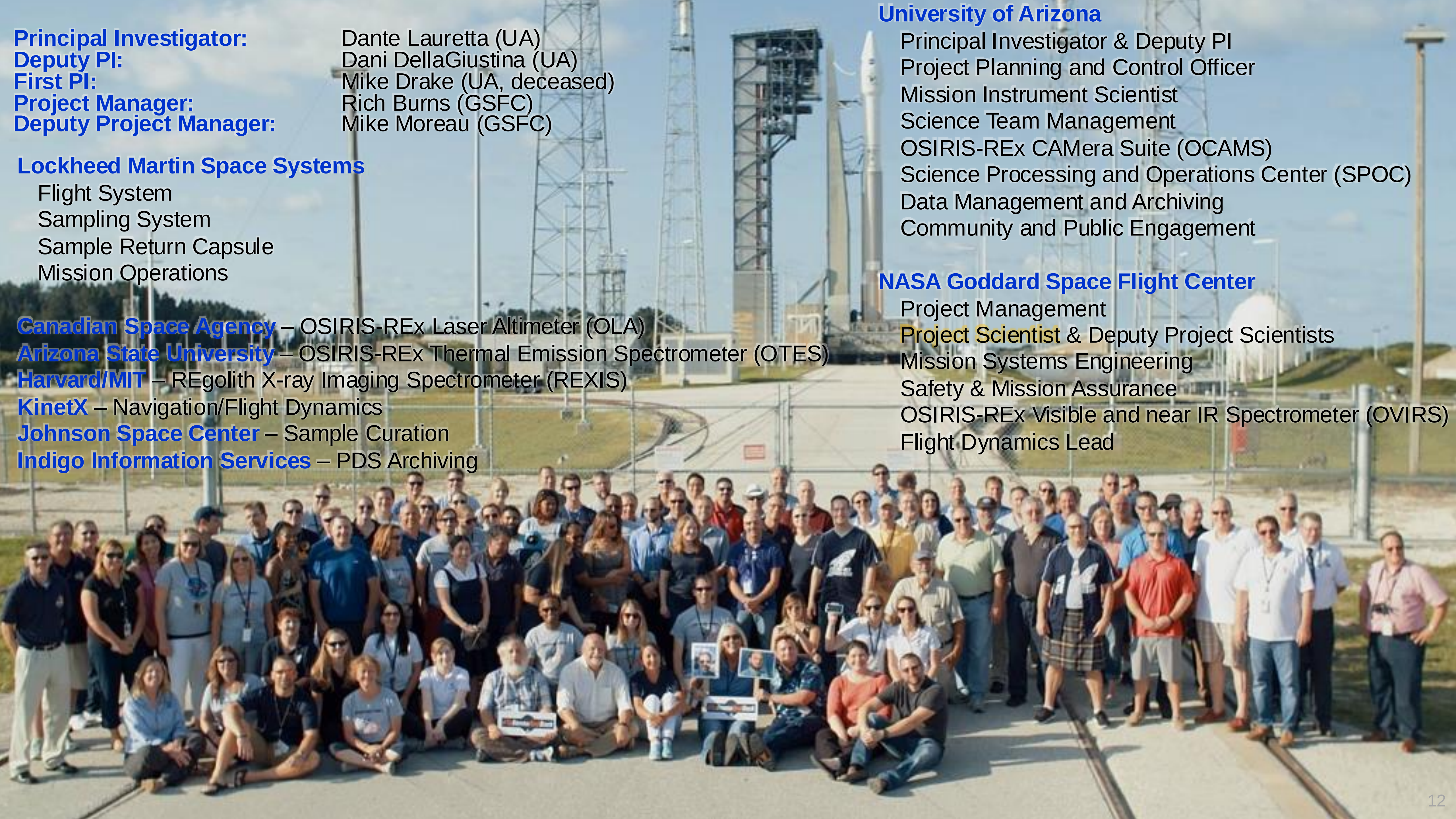
OLA (CSA) ranging to 7 km and maps the asteroid shape and surface topography

OTES (ASU) maps the thermal flux and spectra from 5 – 50 µm

NavCams (MSSS) navigates the surface of Bennu

OVIRS (GSFC) maps the reflectance albedo and spectra from 0.4 – 4.3 µm

Highly capable, nimble spacecraft



Principal Investigator: Dante Lauretta (UA)
Deputy PI: Dani DellaGiustina (UA)
First PI: Mike Drake (UA, deceased)
Project Manager: Rich Burns (GSFC)
Deputy Project Manager: Mike Moreau (GSFC)

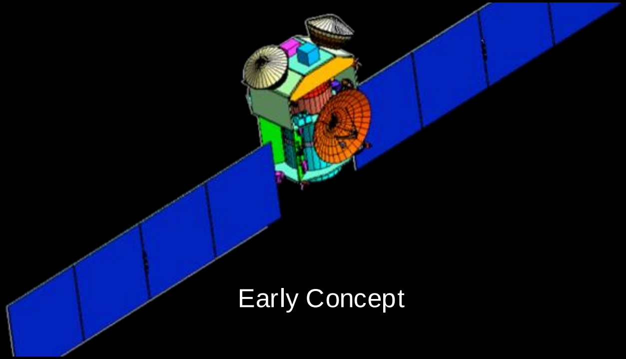
Lockheed Martin Space Systems
- Flight System
- Sampling System
- Sample Return Capsule
- Mission Operations

Canadian Space Agency – OSIRIS-REx Laser Altimeter (OLA)
Arizona State University – OSIRIS-REx Thermal Emission Spectrometer (OTES)
Harvard/MIT – REgolith X-ray Imaging Spectrometer (REXIS)
KinetX – Navigation/Flight Dynamics
Johnson Space Center – Sample Curation
Indigo Information Services – PDS Archiving

University of Arizona
- Principal Investigator & Deputy PI
- Project Planning and Control Officer
- Mission Instrument Scientist
- Science Team Management
- OSIRIS-REx CAMera Suite (OCAMS)
- Science Processing and Operations Center (SPOC)
- Data Management and Archiving
- Community and Public Engagement

NASA Goddard Space Flight Center
- Project Management
- Project Scientist & Deputy Project Scientists
- Mission Systems Engineering
- Safety & Mission Assurance
- OSIRIS-REx Visible and near IR Spectrometer (OVIRS)
- Flight Dynamics Lead

Path to Launch



Early Concept

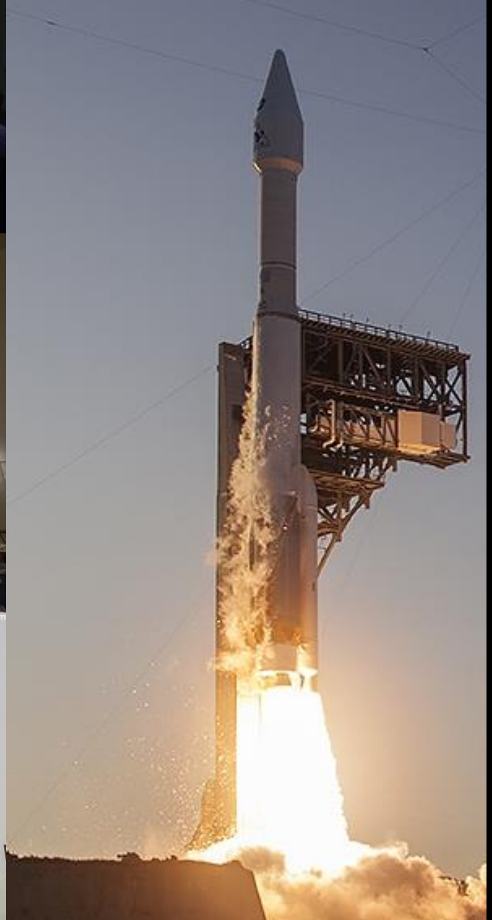
Volume 2 of the Step 2 Proposal

Discovery 11 Proposal	July 16, 2004
Non-selection	Feb 2, 2005
Discovery 12 Proposal	Mar 27, 2006
Down Select (KDP-A)	Oct 30, 2006
Step 2 Proposal	June 20, 2007
Site Visit	Aug 21, 2007
Non-selection	Dec 11, 2007
New Frontiers 3 Proposal	July 31, 2009
Down Select (KDP-A)	Dec 17, 2009
Step 2 Proposal	Jan 28, 2011
Site Visit	Apr 14, 2011
Selection (KDP-B)	May 25, 2011
MDR	May 8-10, 2012
PDR	Mar 4-8, 2013
Confirmation (KDP-C)	June 1, 2013
CDR (KDP-D)	Apr 1-9, 2014
Start of ATLO	March 23, 2015
PER	Oct 14-16, 2015
PSR	May 10-11, 2016
Ship to KSC	May 20, 2016
FOR / ORR	Jun 21-24, 2016
SMSR	Aug 9, 2016
MRB / KDP-E	Aug 18, 2016
FRR	Sep 1, 2016
LRR	Sep 6, 2016
Launch	Sep 8, 2016

Another Review @ LM

High Bay @ LM

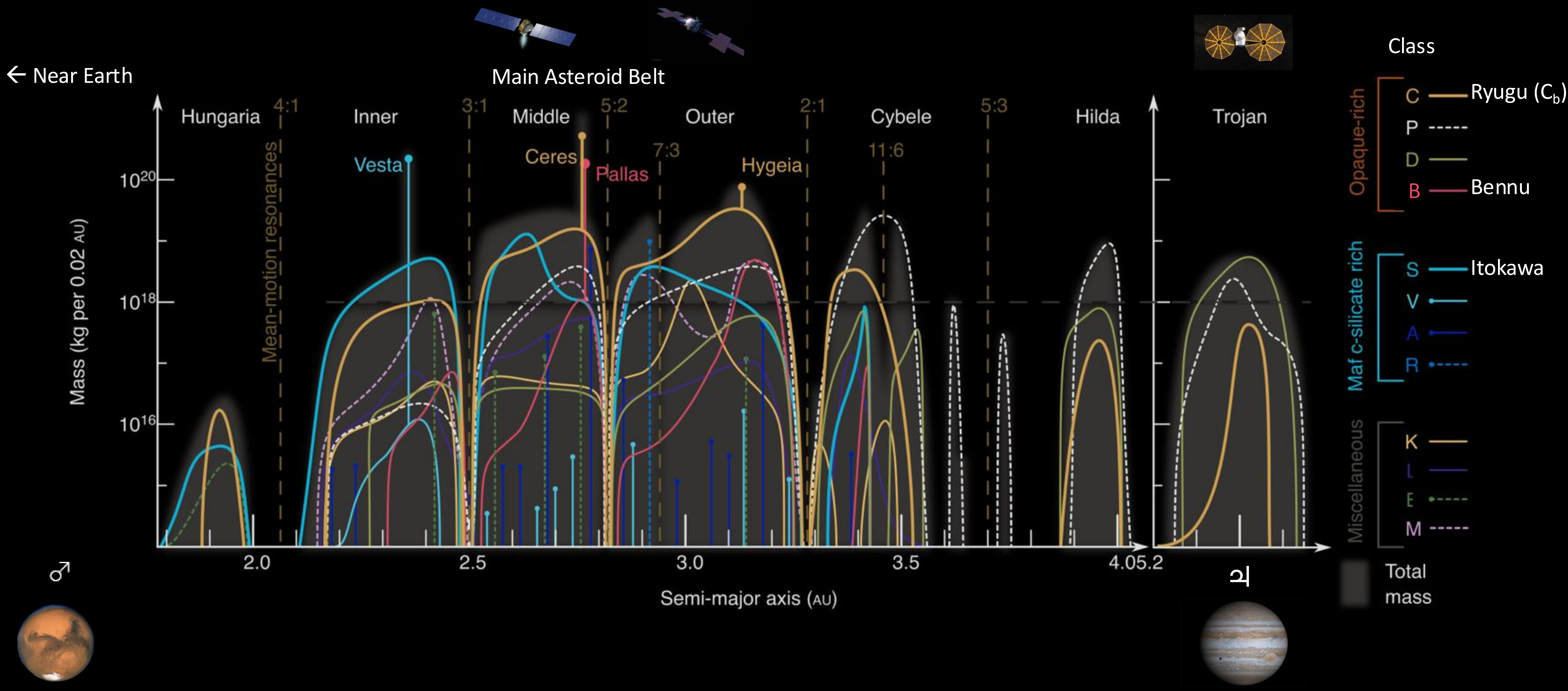
PHSF @ KSC



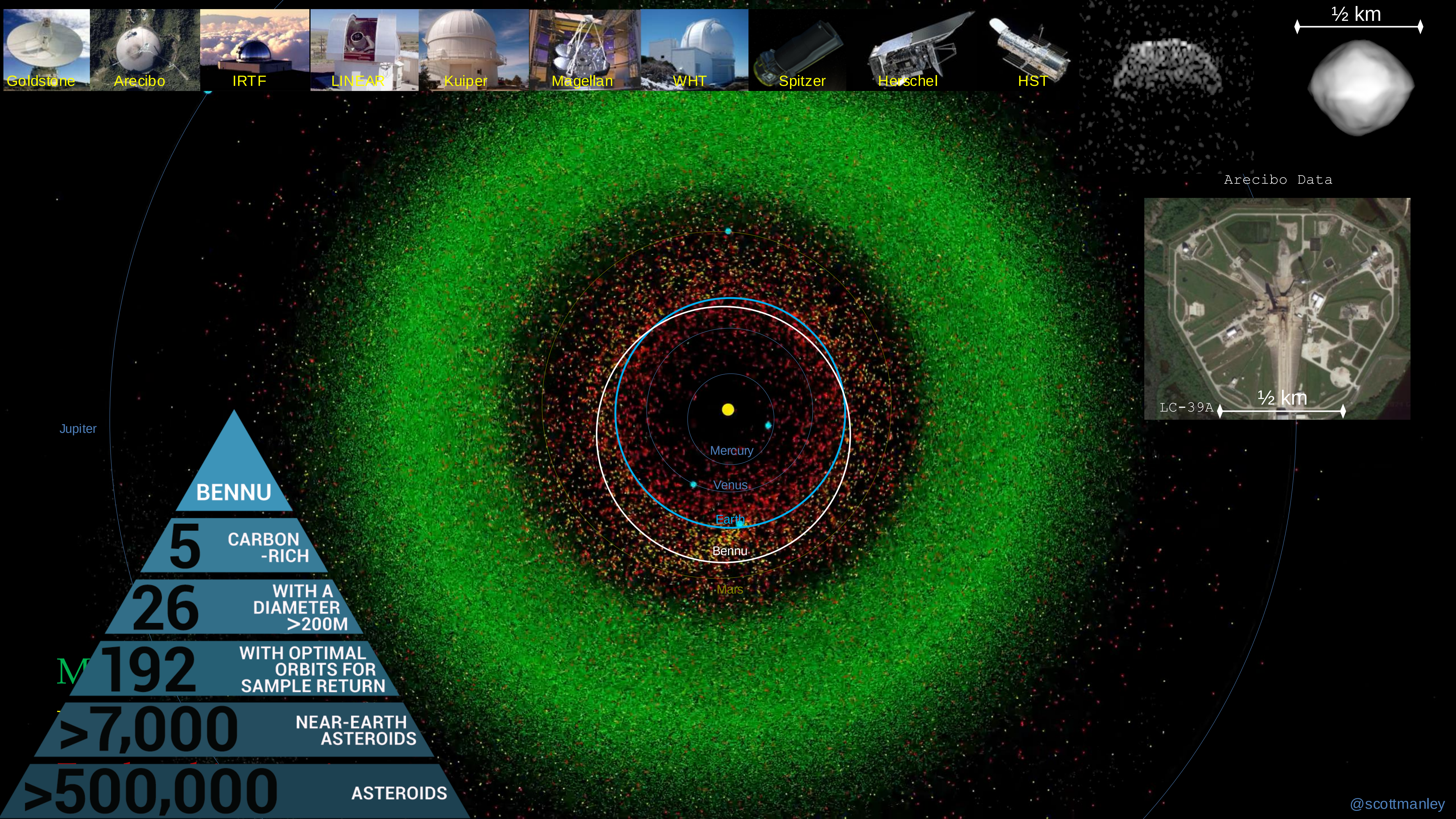
Atlas V 411
C_3 = 29.3 km^2/s^2

s/c wet mass = 2104.2 kg
s/c dry mass = 900.5 kg
fuel load 1199.9 kg N_2H_4
3.8 kg He pressurant

Different Sources of Asteroids



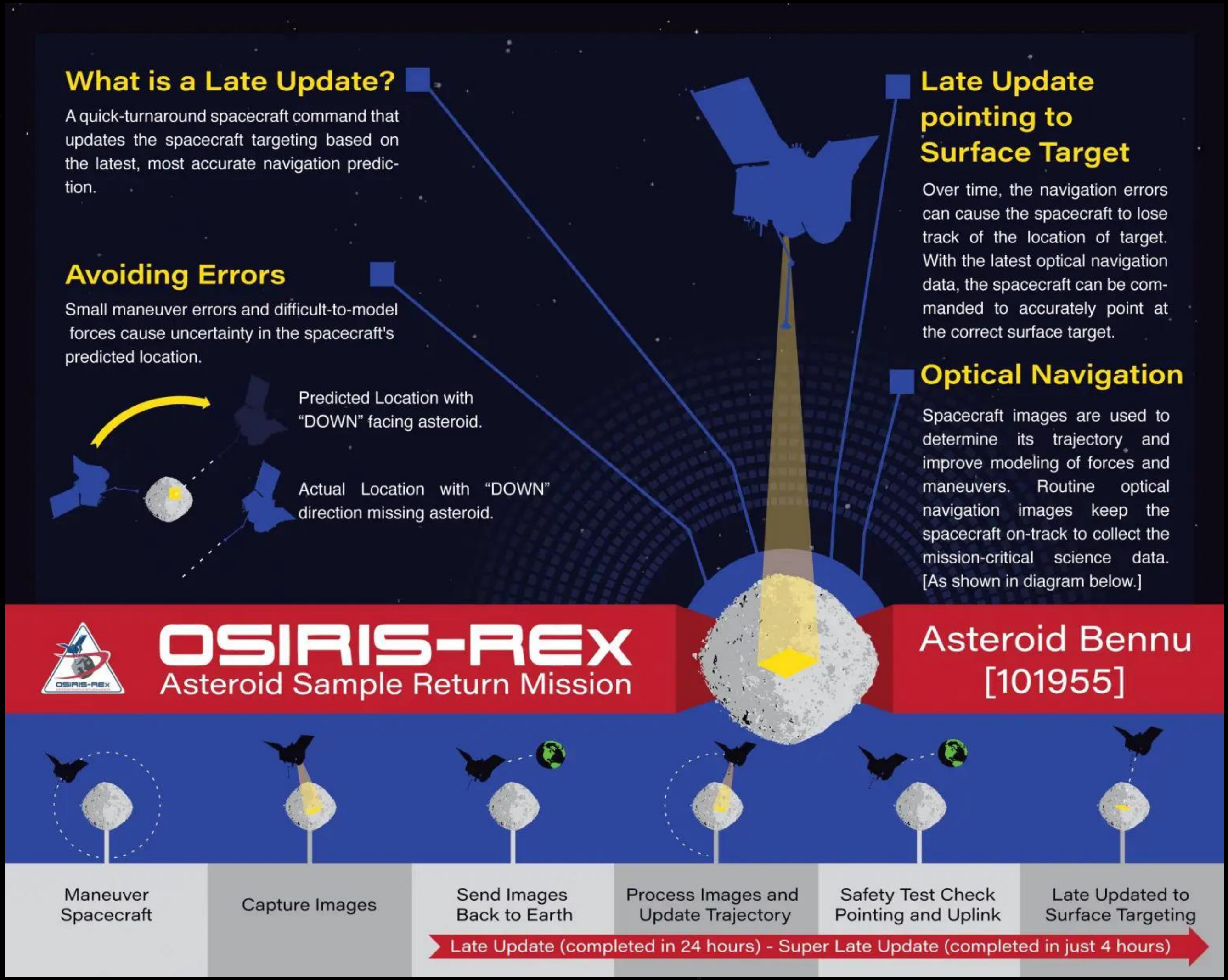
DeMeo and Carry *Nature* (2014) 505, 629-634.



Goldstone
Arecibo
IRTF
LINEAR
Kuiper
Magellan
WHT
Spitzer
Herschel
HST
½ km
Arecibo Data
LC-39A
½ km
Jupiter
Mercury
Venus
Earth
Bennu
Mars
BENNU
5 CARBON -RICH
26 WITH A DIAMETER >200M
192 WITH OPTIMAL ORBITS FOR SAMPLE RETURN
>7,000 NEAR-EARTH ASTEROIDS
>500,000 ASTEROIDS
@scottmanley

Complex flight dynamics at a small body

- Smallest maneuver 0.1 mm/s; largest 431 m/s
- 10 orbit insertions; 127 deep space maneuvers
- First frozen orbit at a small body
- 37k optical navigation images
- Lowest orbit (832 m semimajor axis) around smallest object (490 m ave.)
- One safe mode in 7 years (human error outbound cruise)



Madrid DSN Outage 10/11/19

Derived from Flight Data

https://svs.gsfc.nasa.gov/4905

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Derived from Flight Data

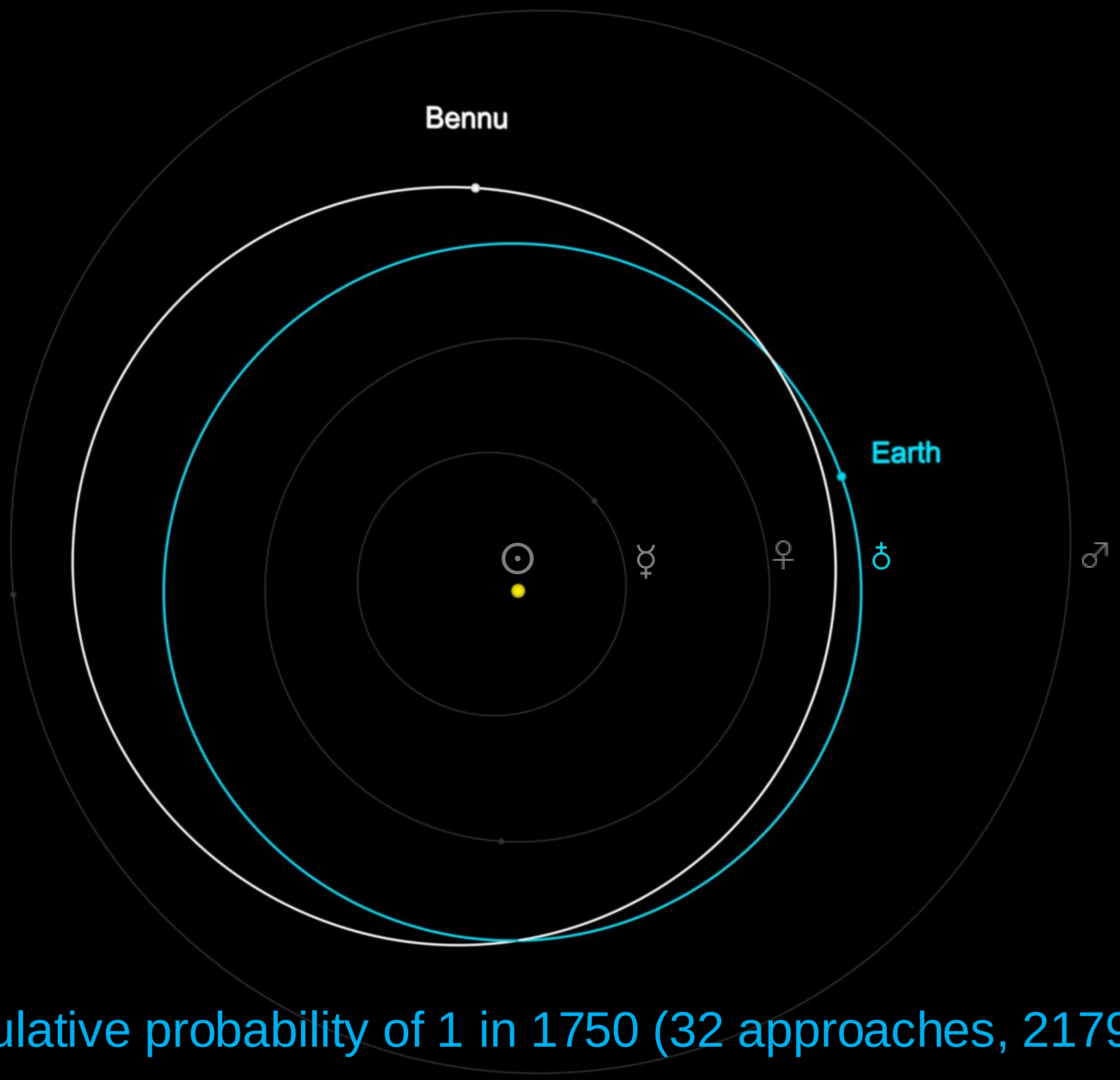
https://svs.gsfc.nasa.gov/4905

Particle ejections

Physical properties: interior voids, 8µg, 1.19 g/mL density

Derived from Flight Data

Refined Bennu impact probability

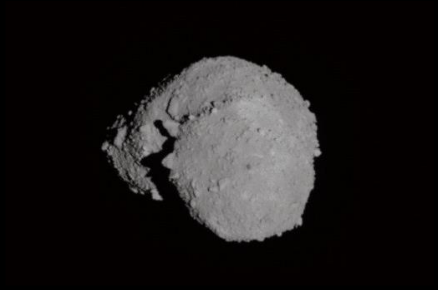


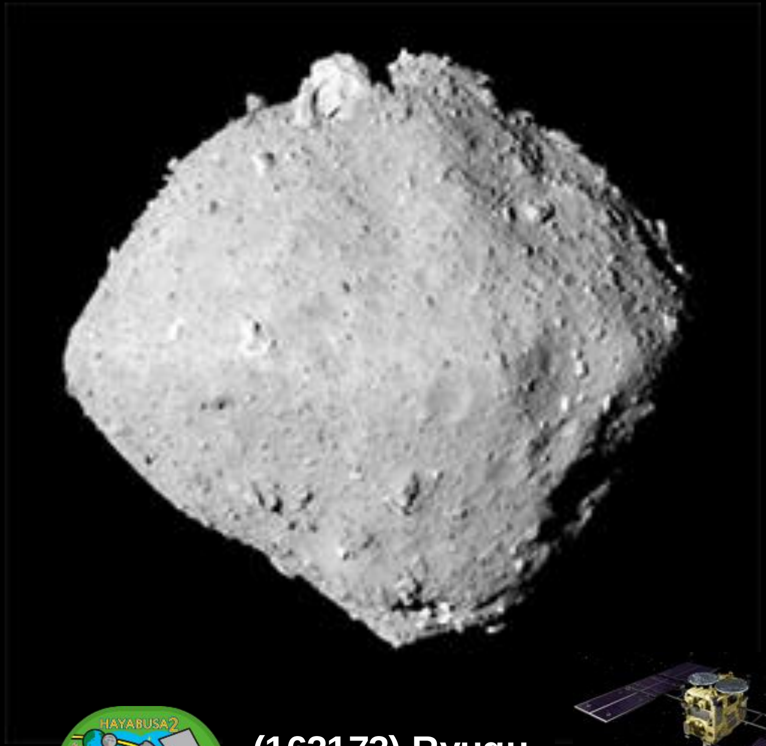
Jan 2135

Cumulative probability of 1 in 1750 (32 approaches, 2179-2300)

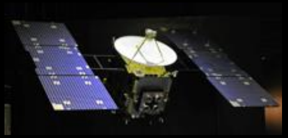
Simulation

Comparing Asteroids



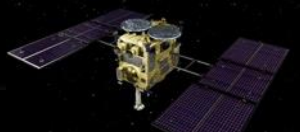


(25143) Itokawa
0.5 x 0.3 x 0.2 km
Hayabusa 2005



Bus: 1.5x1.5x1m
Wet mass: 530 kg

(162173) Ryugu
1 km
Hayabusa2 2018



Bus: 1.6x1.4x1m
Wet mass: 600 kg

(101955) Bennu
0.5 km
OSIRIS-REx 2018

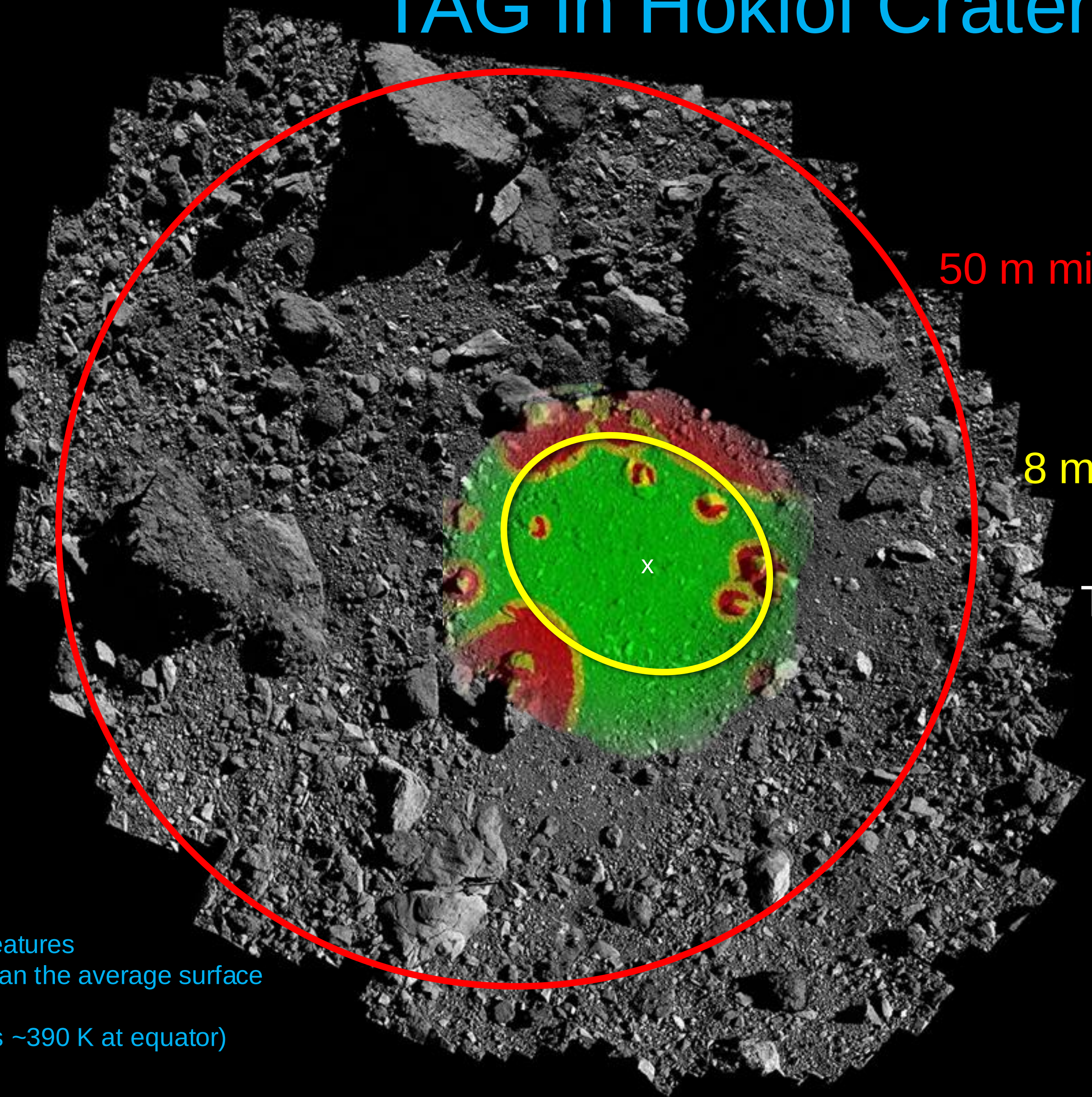
Bus: 3.1x3.1x2.7m
Wet mass: 1529 kg

½x¼x¼ km Rubble Pile, Bilobar, 2 Spin Axes	X	1 km Rubble Pile, Spinning Top, Retrograde	✓	½ km Rubble Pile, Spinning Top, Retrograde
Earth-Crossing, 1.32 AU Semimajor Axis	X	Earth-Crossing, 1.19 AU Semimajor Axis	✓	Earth-Crossing, 1.13 AU Semimajor Axis
Flora Dynamical Family	X	Eulalia or Polana Dynamical Family	✓	Eulalia or Nysa-Polana Dynamical Family
1.9 g/mL	X	1.19 g/mL	✓	1.19 g/mL
23% Albedo, Class S	X	4.4% Albedo, Class C_b	✓	4.6% Albedo, Class B
Dehydrated pyroxenes	X	Dehydrated phyllosilicates, carbonate	~	Hydrated phyllosilicates, carbonate, pyroxene xenoliths

After Oba, et al. (2023) *Nature Communications*, 14**:** 3107


OSIRIS-REx
MAVEN
MAVEN
Guidance, Navigation and Control
DELL

TAG in Hokioi Crater



50 m mission design TAG ellipse

8 m TAG ellipse at Nightingale site

TAG 73 cm from center

Among the youngest impact features
Spectrally redder in VISNIR than the average surface
Mid-latitude (56˚,43˚) location
Limited peak T ~360 K (versus ~390 K at equator)

Flight Imagery

TAG Crater

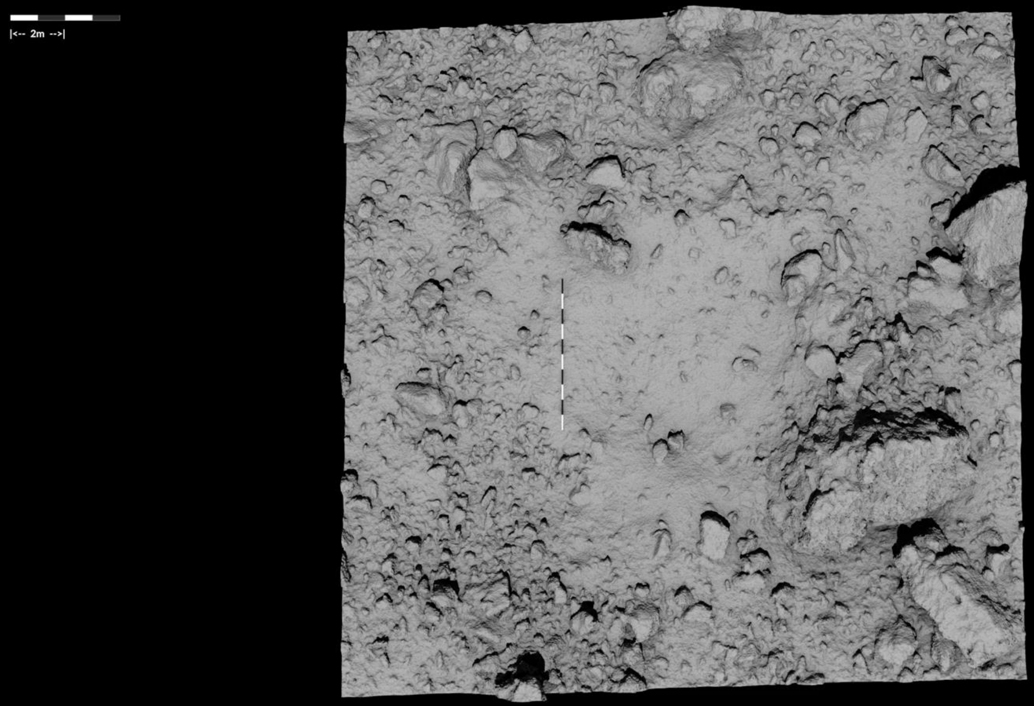
- Applied stereophotoclinometry to construct a 5-cm terrain model

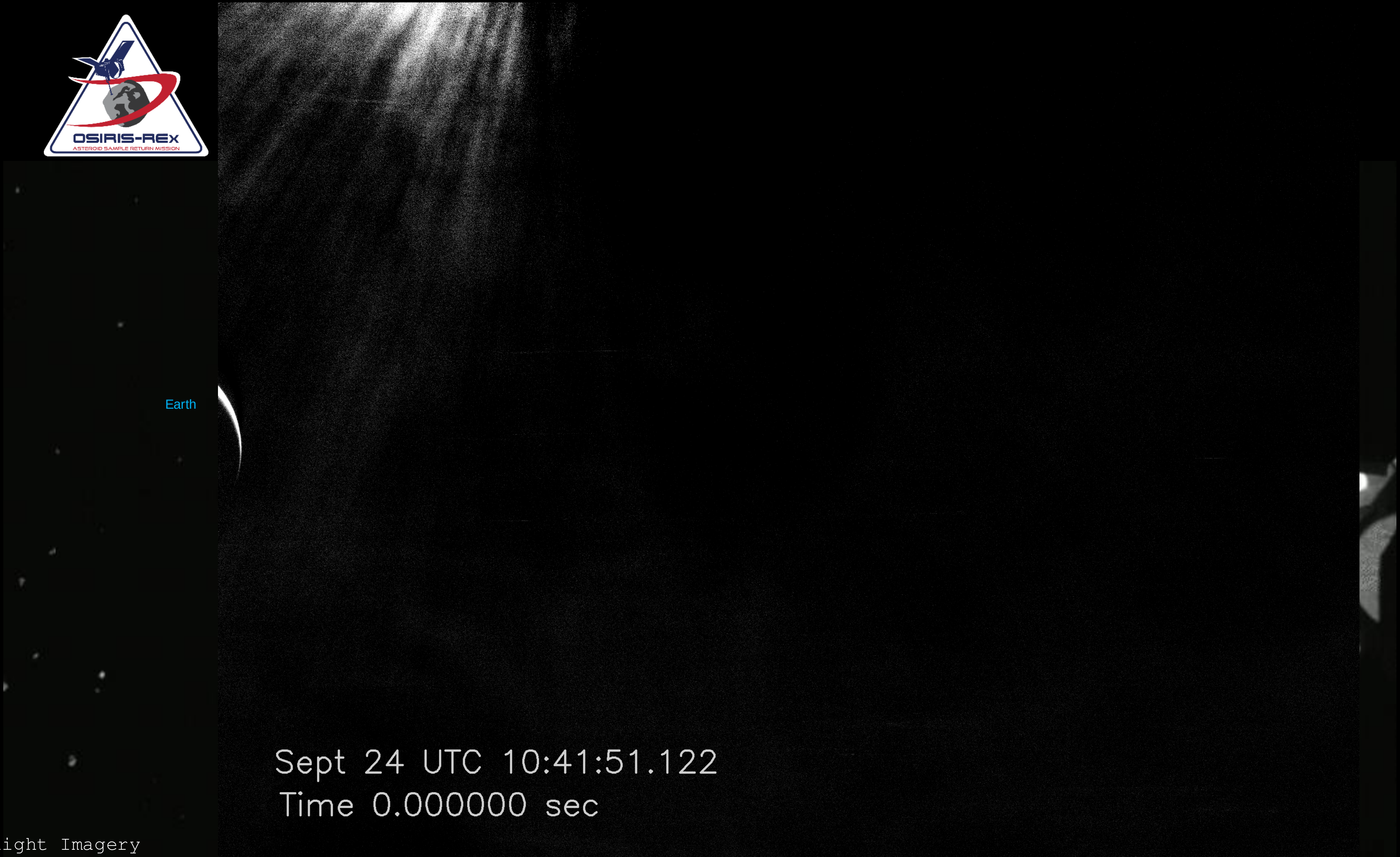
- Crater: 9.0 × 6.5 m
  0.68 ± 0.1 m deep

- Displaced volume is 12.2 ± 0.9 m^3

- Bulk density of 500 to 700 kg/m^3

- Nearly cohesionless (<0.001 Pa) granular material





Flight Imagery

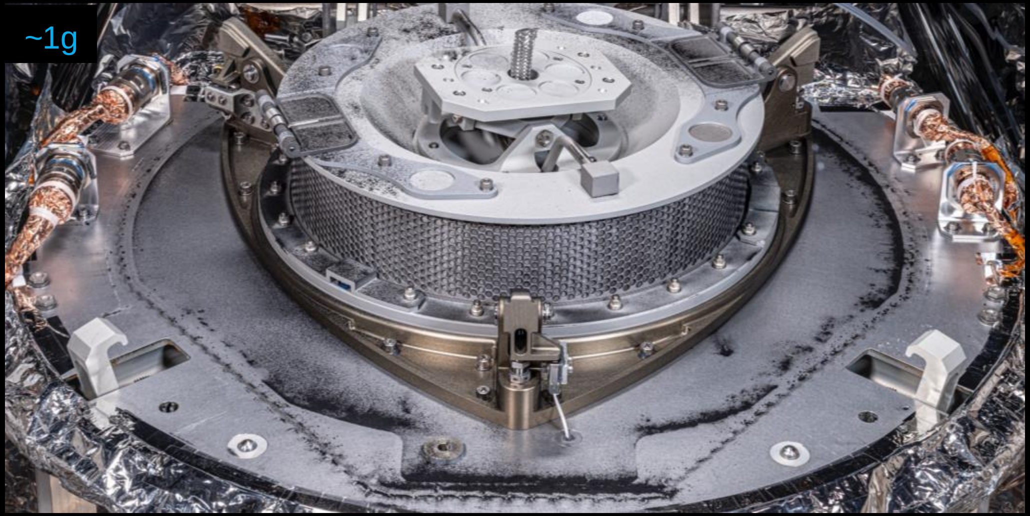

LANDING ELLIPSE
PROCESSING HANG
West Wendover
14 km
Currie
Ibapah
80
93

Bennu SRC landing site


Safe
Document
Bag
Secure
Helicopter
N249TH
Purge
Fly
Receive

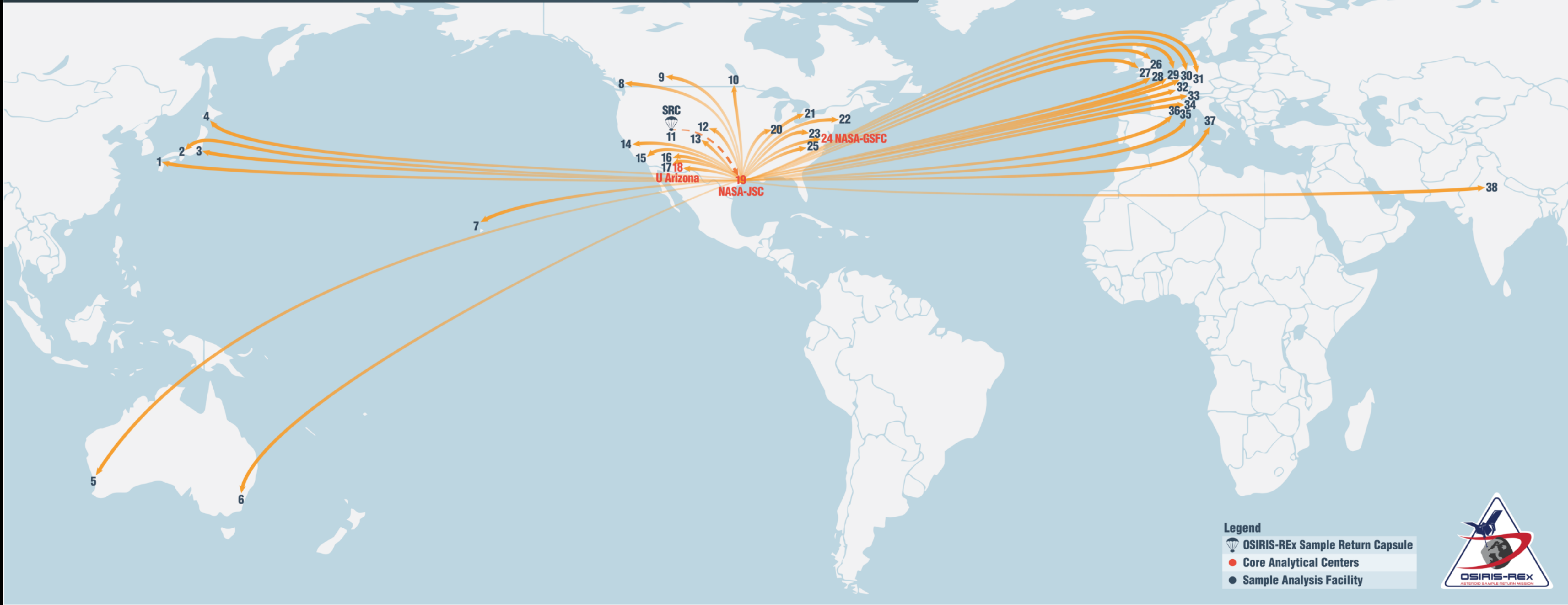
121.6g of sample

Requirement: Collect and return 60g from asteroid Bennu



Erika Blumenfeld – Joseph Aebersold JSC

Locations of Sample Analysis Facilities for the OSIRIS-REx Mission

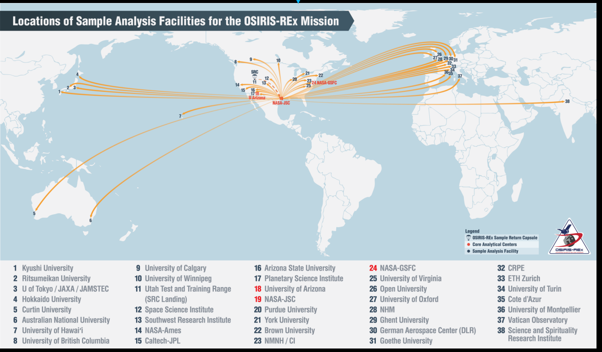


1 Kyushi University
2 Ritsumeikan University
3 U of Tokyo / JAXA / JAMSTEC
4 Hokkaido University
5 Curtin University
6 Australian National University
7 University of Hawai'i
8 University of British Columbia
9 University of Calgary
10 University of Winnipeg
11 Utah Test and Training Range (SRC Landing)
12 Space Science Institute
13 Southwest Research Institute
14 NASA-Ames
15 Caltech-JPL
16 Arizona State University
17 Planetary Science Institute
18 University of Arizona
19 NASA-JSC
20 Purdue University
21 York University
22 Brown University
23 NMNH / CI
24 NASA-GSFC
25 University of Virginia
26 Open University
27 University of Oxford
28 NHM
29 Ghent University
30 German Aerospace Center (DLR)
31 Goethe University
32 CRPE
33 ETH Zurich
34 University of Turin
35 Cote d'Azur
36 University of Montpellier
37 Vatican Observatory
38 Science and Spirituality Research Institute

Sample Distribution

121.6g &
24 contact pads

Up to 25%
(14% planned)



0.55% &
1 contact pad

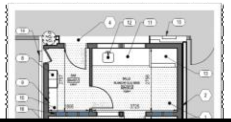
4% &
1 contact pad

54th Lunar and Planetary Science Conference 2023 (LPI Contrib. No. 2806) 1726.pdf

OVERVIEW OF THE CURATION FACILITY FOR THE CANADIAN PORTION OF BENNU SAMPLE FROM THE OSIRIS-REx MISSION. C.E. Moisset[1], P. Hill[1], T. Haltigin[1], Rémy Grenier[1], and S. Routhier[1], [1]Canadian Space Agency, 6767 Route de l'Aéroport, Saint-Hubert, QC, J3Y 8Y9, Canada (ConservationBennu-BennuCuration@asc-csa.gc.ca; caroline-emmanuelle.moisset@asc-csa.gc.ca, patrick.hill@asc-csa.gc.ca, timothy.haltigin@asc-csa.gc.ca, rémy.grenier@asc-csa.gc.ca, stephane.routhier@asc-csa.gc.ca).

Introduction: On October 20th, 2020, the OSIRIS-REx mission collected a sample from the asteroid Bennu [1], which will be delivered to Earth on September 24th, 2023. Studying the sample will allow scientists to address fundamental questions about the solar system formation and evolution, its early composition, potential water delivery to early Earth, and the source of its organic compounds, to name a few. In exchange for contributing the OSIRIS-REx Laser Altimeter (OLA) instrument, which collected ranging data to produce a 3D model of the asteroid (Figure 1) that helped identify the sampling site, Canada will receive a portion of the Bennu sample. The Canadian Space Agency is currently planning its Curation

The sample will be conserved under curation-grade nitrogen in sample cabinets. Samples that have never been on loan will be stored in separate cabinets from those that are returning from loan.



≥70%
(Remainder)

Sample	Type	Newsletter	Original Weight (grams)	Current Weight (grams)
OREX-800069-0	aggregate	6,1	0.001	0.001
OREX-800070-0	aggregate	6,1	0.074	0.074
OREX-800071-0	aggregate	6,1	0.092	0.092
OREX-800072-0	particle	6,1	0.034	0.034
OREX-800073-0	particle	6,1	0.068	0.068
OREX-800074-0	aggregate	6,1	0.012	0.012
OREX-800075-0	aggregate	6,1	0.401	0.401
OREX-800076-0	aggregate	6,1	0.517	0.517
OREX-800077-0	aggregate	6,1	1.056	1.056
OREX-800078-0	aggregate	6,1	0.000	0.000
OREX-800079-0	aggregate	6,1	0.141	0.141
OREX-800080-0	aggregate	6,1	0.122	0.122
OREX-800081-0	particle	6,1	0.372	0.372
OREX-800082-0	particle	6,1	0.075	0.075
OREX-800083-0	aggregate	6,1	1.358	1.358
OREX-800084-0	particle	6,1	0.113	0.113
OREX-800085-0	aggregate	6,1	1.896	1.896
OREX-800086-0	aggregate	6,1	0.000	0.000
OREX-800087-0	particle	6,1	0.372	0.372
OREX-800088-0	particle	6,1	0.329	0.329
OREX-800089-0	particle	6,1	0.313	0.313

Showing 201 to 221 of 221 entries — First Previous 1 … 5 6 7 8 9 Next Last

1 Apr 2024

OSIRIS-REX ASTEROID SAMPLE RETURN MISSION

JAXA

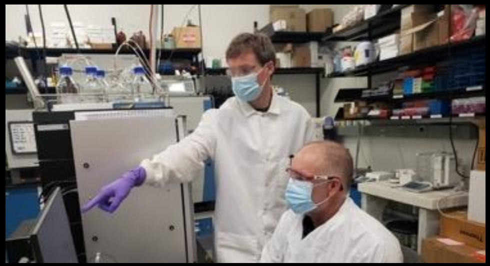
CSA ASC

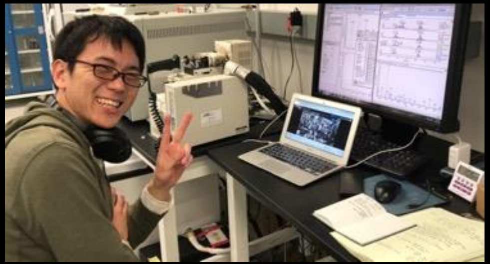
NASA

Sample Science


Fourier Transform Infrared Microscopy


2D Gas Chromatography High Resolution Mass Spectrometry


Liquid Chromatography Fourier Transform Mass Spectrometry


Gas Chromatography Mass Spectrometry

Compound Specific Isotopic Ratio Mass Spectrometry


Transmission Electron Microscopy


Electron Microprobe Analysis


Inductively Coupled Plasma Mass Spectrometry


Nanoscale Secondary Ion Mass Spectrometry


Visible Light Microscopy


Scanning-Electron Microscopy Energy-Dispersive X-ray Spectroscopy

X-ray Absorption Near-Edge Structure Spectroscopy


Accelerator Mass Spectrometry


70% for the Future

Sample Analysis Plan (Organics Only)

Key

Action
- Interfaces
- Solid
- Solvent
- Gas
- Result
- Tier 1 Publication
- EMS Publication
- FY24 Publication
- FY25 Publication

Institution
- NASA ARC
- NASA GSFC
- NASA JSC
- JPL
- U. Arizona
- Brown U.
- CIW
- Penn State
- CSUSM
- Field Mus/UChicago
- Helmholtz Munich
- Hokkiado U.
- JAMSTEC
- Kyushu U.

Flow
- Solid under N_2
- Solid
- Thin section
- Gas
- Liquid
- Residue
- Demineralized IOM
- Information

Notes

EMS = Early Mission Science
IOM = Insoluble Organic Material
PAH = Polycyclic Aromatic Hydrocarbon
SOM = Soluble Organic Material
Participating Scientist sample allocation
Undefined/TBD
Avionics sample has been allocated and mass accounted, parent OREX-500002-0 (22 mg)
Avionics sample has been allocated and mass accounted, parent OREX-500002-0 (6 mg)
Aggregate sample has been allocated and mass accounted, parent OREX-800031-0 (55 mg)
Aggregate sample has been allocated from MAPWG, parent OREX-800044-101 (18 mg)
Aggregate sample has been allocated and mass accounted, parent OREX-800107-0 (6425 mg)
Aggregate samples have been allocated and mass accounted, parents OREX-8000007-0 (326 mg)
Angular SOI OREX-800055-3 (49 mg)
Hummocky SOI OREX-800088-3 (38 mg)
Future mottled SOI OREX-800023-0 (~60 mg)
Some analyses overlap with Elements and Isotopes Analysis Plan

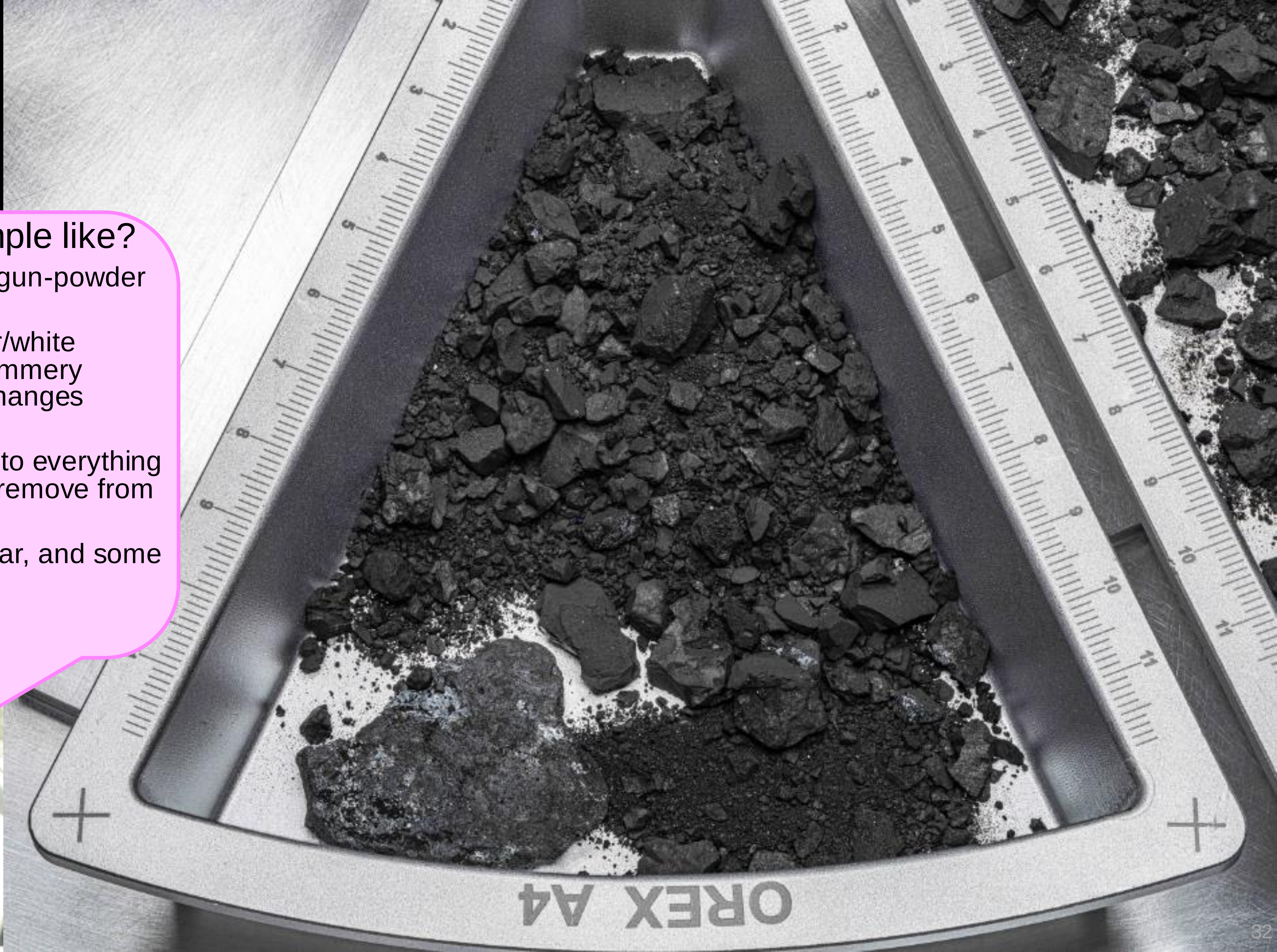
Total mass counted against SOAWG:
6425-(0.0488+.06944+.01086+.09081)+22+6+55+49+38+121+205 = 6920.78 mg of 7784 = 88.9%

Techniques

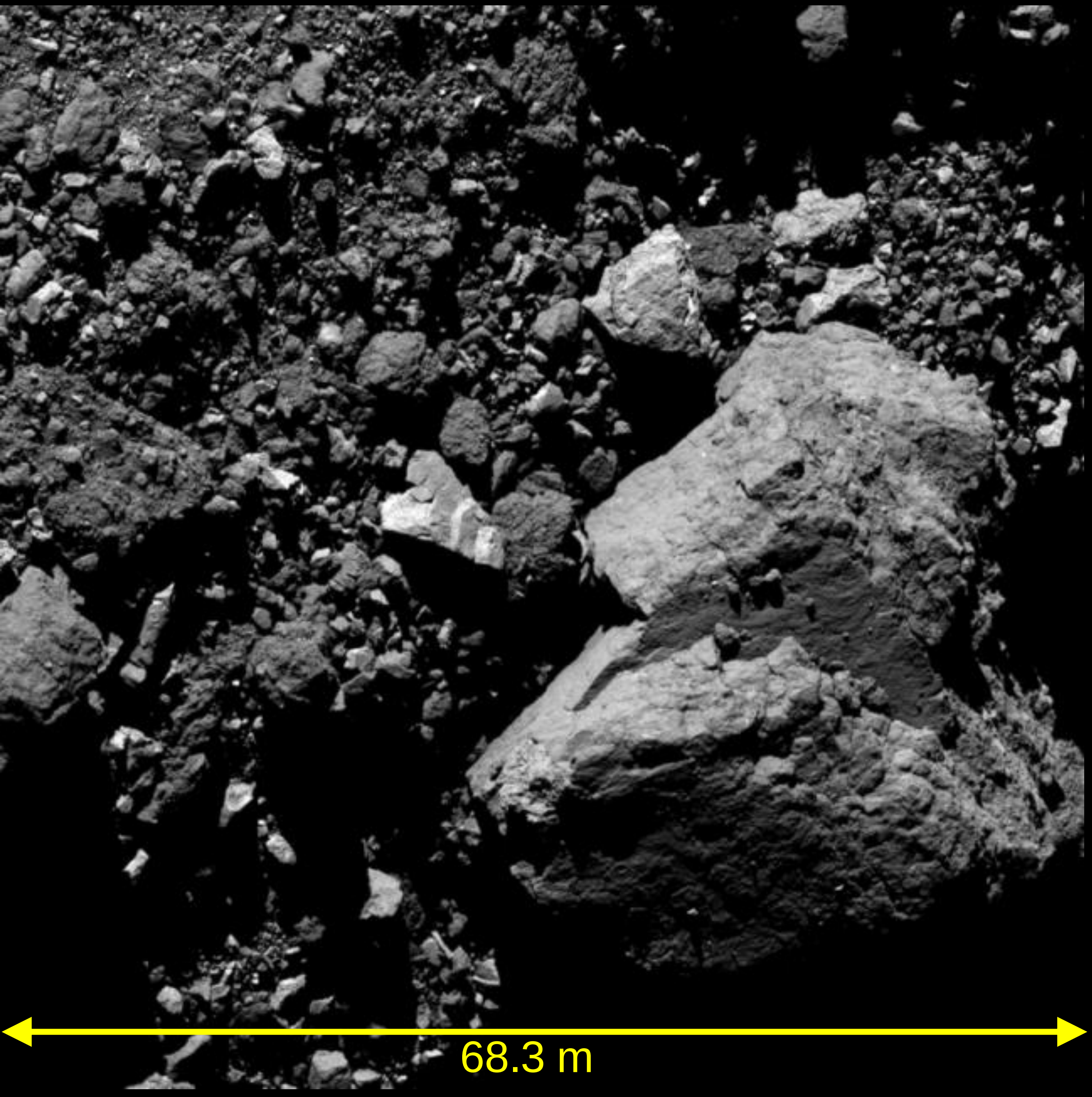
Capillary Electrophoresis-Mass Spectrometry (CE-MS)
Desorption Electrospray Ionization-Mass spectrometry (DESI-MS)
Elemental Analysis-Isotopic Ratio Mass Spectrometry (EA-IRMS)
Fourier Transform Ion Cyclotron Resonance Mass Spectrometry (FTICR-MS)
Gas Chromatography-Mass Spectrometry (GC-MS)
Gas Chromatography–Fourier Transform-Isotopic Ratio Mass Spectrometry (GC-FTMS)
Gas Chromatography–Combustion-Isotopic Ratio Mass Spectrometry (GC-IRMS)
Ion Chromatography (IC)
Ion Chromatography-Mass Spectrometry (IC-MS)
Keyence digital stereo microscopy
Liquid Chromatography-Mass Spectrometry (LC-MS)
Microprobe Two Step Laser Mass Spectrometry (μL^2MS)
Microscale Fourier Transform Infrared Spectroscopy (µ-FTIR)
Nanoscale Fourier Transform Infrared Spectroscopy (nano-FTIR)
Nanoscale secondary ion mass spectrometry (nanoSIMS)
Nuclear Magnetic Resonance Spectroscopy (NMR)
Pyrolysis-Gas Chromatography-Mass Spectrometry (pyGC-MS)
Raman Vibrational Spectroscopy
Scanning Electron Microscopy/Energy-Dispersive X-ray Spectroscopy (SEM/EDS)
Solid-State Nuclear Magnetic Resonance Spectroscopy (SS-NMR)
Thermal Desorption/Pyrolysis-Gas Chromatography-Mass Spectrometry (TD/pyGC-MS)
Two-dimensional Gas Chromatography-Mass Spectrometry (GC×GC-MS)
X-ray Absorption Near-Edge Structure Spectroscopy (XANES)

What is the Bennu sample like?

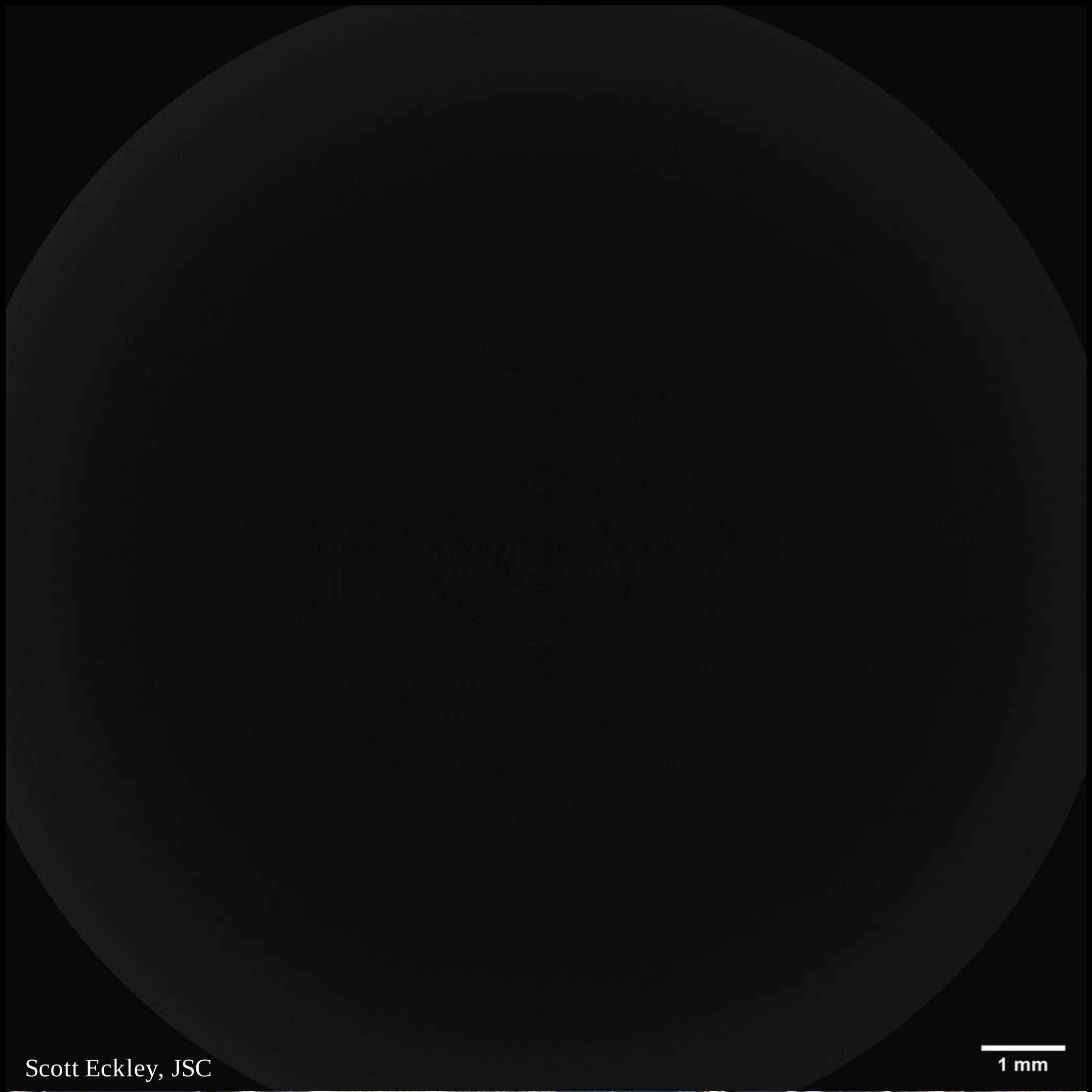
- Smell is very strong (sulfur, gun-powder and burned marshmallows)
- Dark black with some lighter/white particles throughout and shimmery particles (different lighting changes appearance)
- Very fine powders that stick to everything and are very challenging to remove from surfaces
- Some pieces are very angular, and some are very hummocky
- Density varies



Rachel Funk, JSC

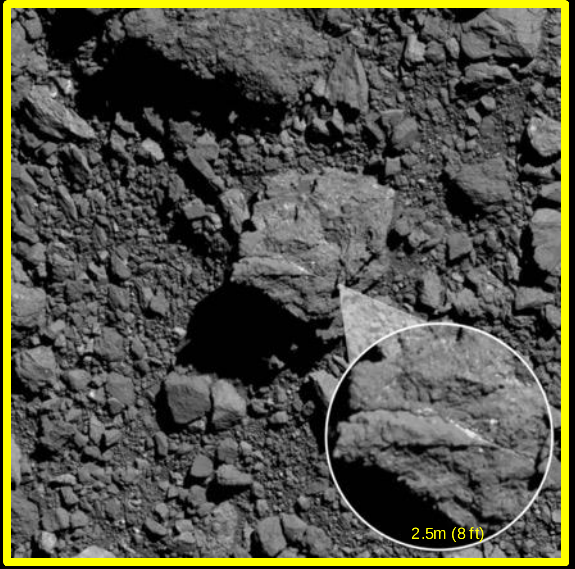


Flight Imagery



Smithsonian National Museum of Natural History

Sample Science



Flight Imagery

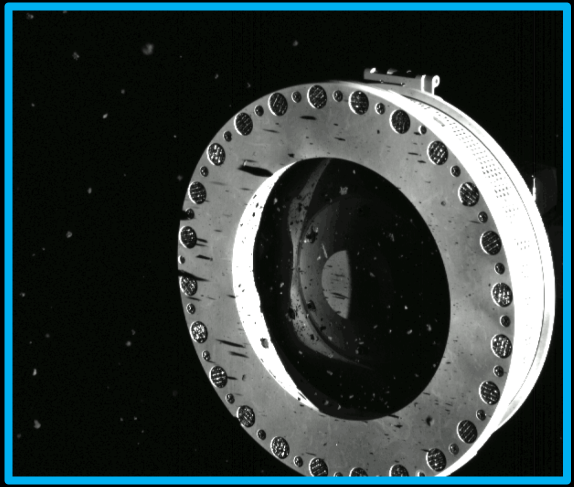
1. How does the sample compare with observations from the spacecraft at Bennu?
2. Does the sample contain organic compounds that could have influenced the origin of life?

3-11. What does the sample tell us about the history of the solar system?

12. How has the sample changed since collection?

JWST Imagery

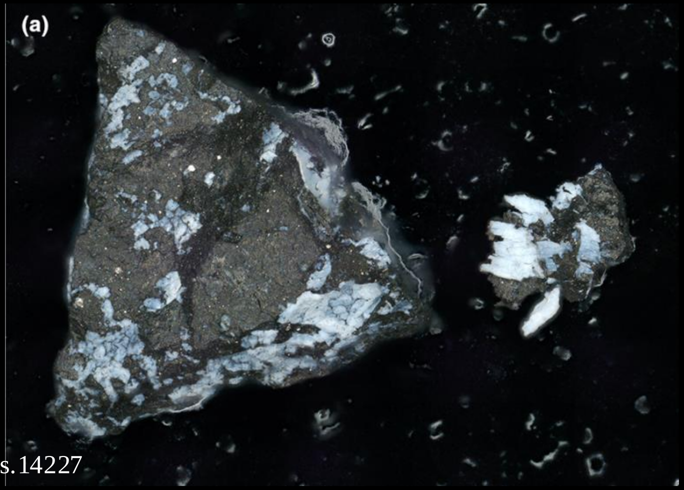

Fumarole, Yellowstone NP


Flight Imagery

1. How does the sample compare with observations from the spacecraft at Bennu?

Observed at Bennu:

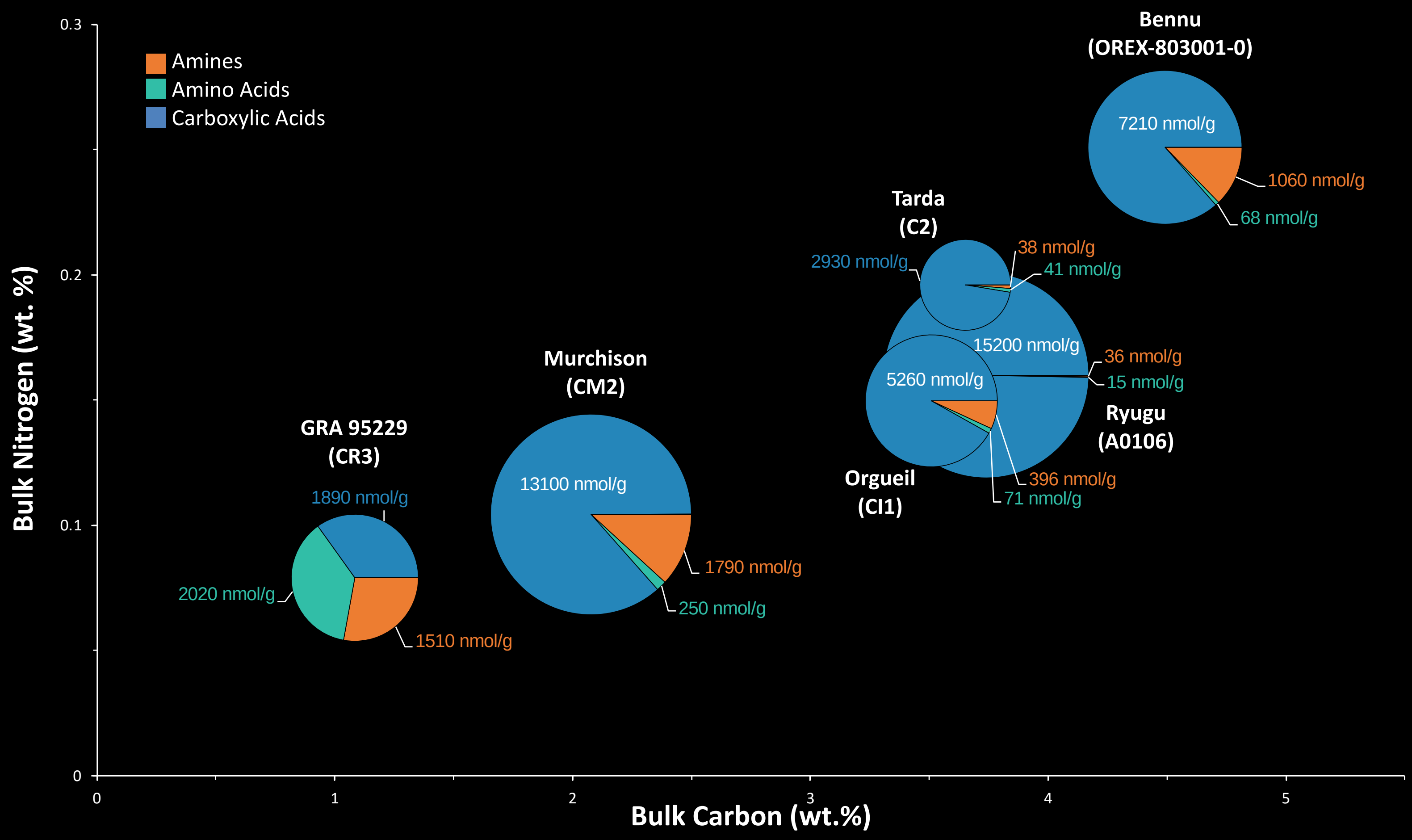
- Phyllosilicates
- Iron sulfides
- Magnetite
- Carbonates
- Hydrated, >1% C
- Xenoliths
- Phosphates



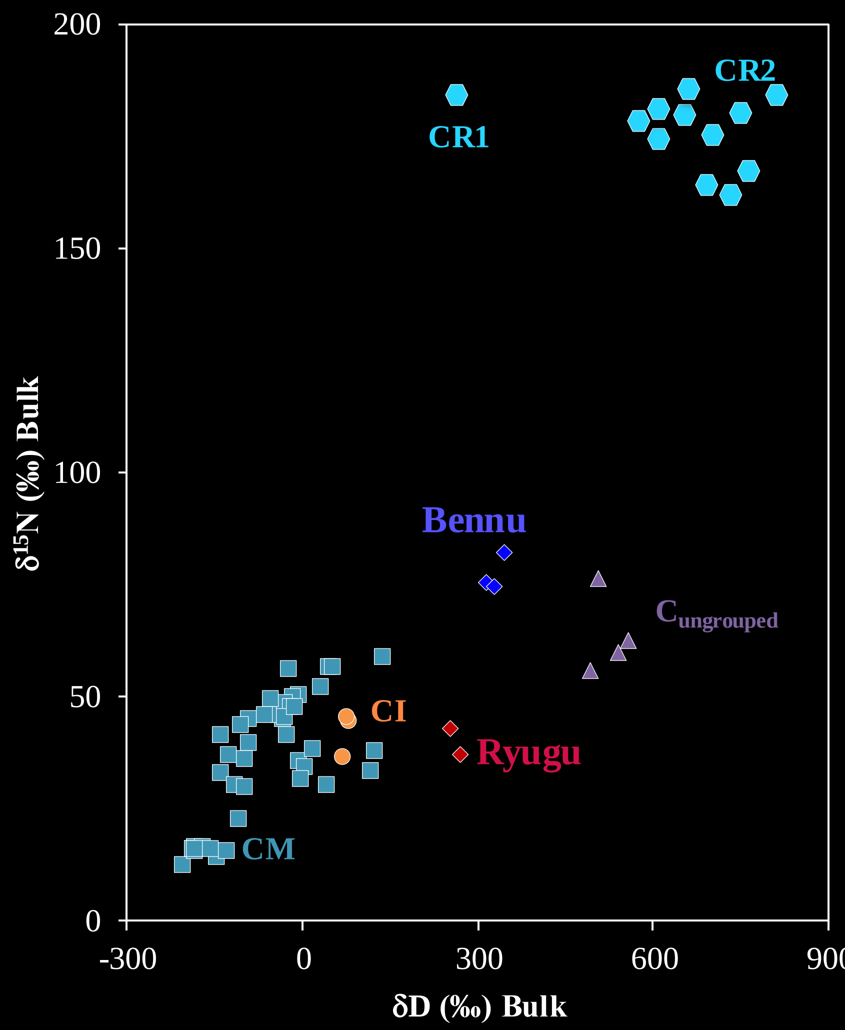
0.8-0.9%	H	
4.5-4.7%	C	by EA-IRMS
0.25%	N	

Lauretta, et al. (2024) *Met Planet Sci* 10.1111/maps.14227

2. Does the sample contain organic compounds that could have influenced the origin of life?



Dworkin et al. AbSciCon 2024

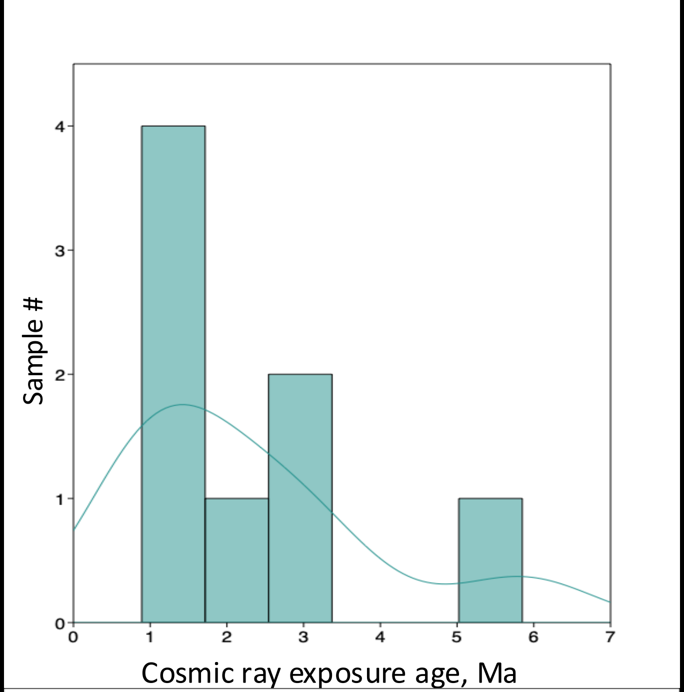


Lauretta, et al. (2024) *Met Planet Sci* 10.1111/maps.14227

3-11. What does the sample tell us about the history of the solar system? Recent History

Sample on Bennu’s surface for 1-6 Ma

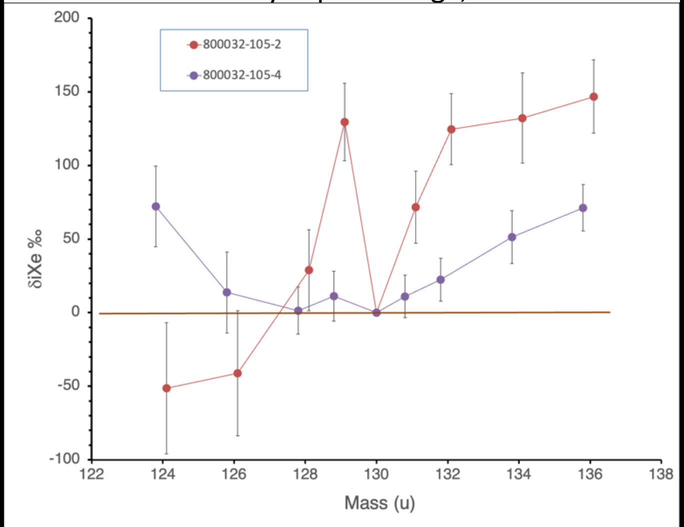
The ^{21}Ne cosmic ray exposure age is 1-6 Ma, consistent with Bennu dynamically decoupled from the main asteroid belt for 1.75 ± 0.75 million years



Neon and Xenon originate from before the solar system formed

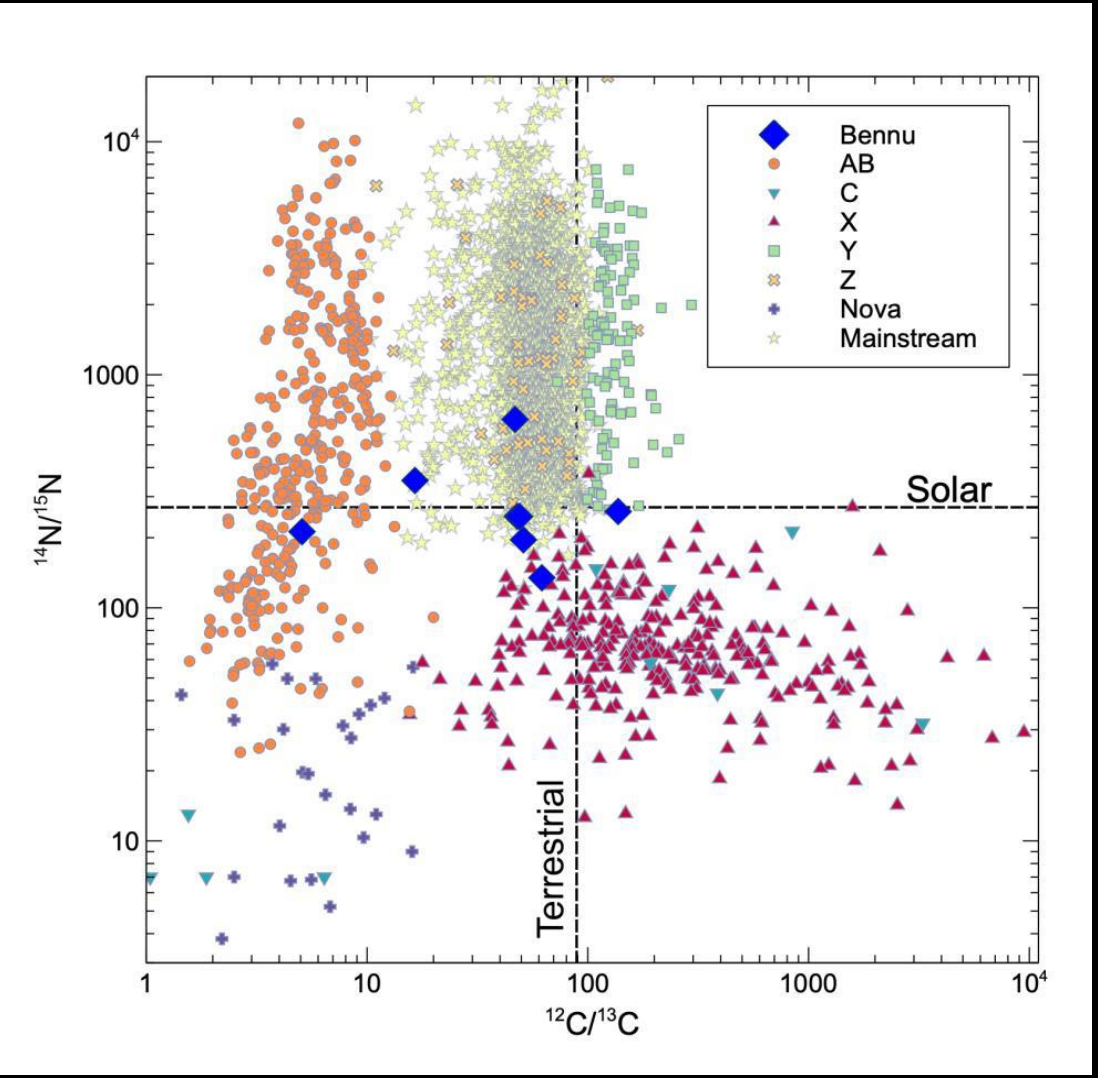
Neon is a mixture of Q-phase (seen in meteorites), solar wind, and presolar noble gases.

Xenon is enriched in presolar isotopes.



Marty et al. LPSC 2024

3-11. What does the sample tell us about the history of the solar system? Ancient History



Presolar SiC and graphite grains predate the solar system

Presolar grains derive from evolved stars and make up some of the building blocks of the solar system

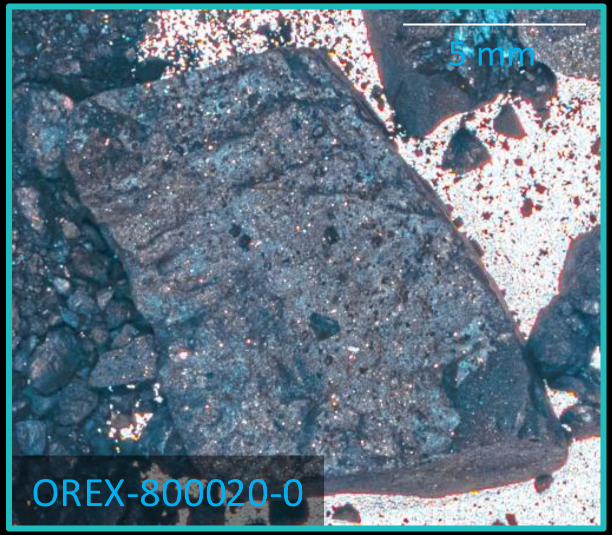
The isotopic compositions of the presolar SiC indicate diverse stellar sources, including supernova

The abundances of these grains are similar to those in unheated chondrite meteorites

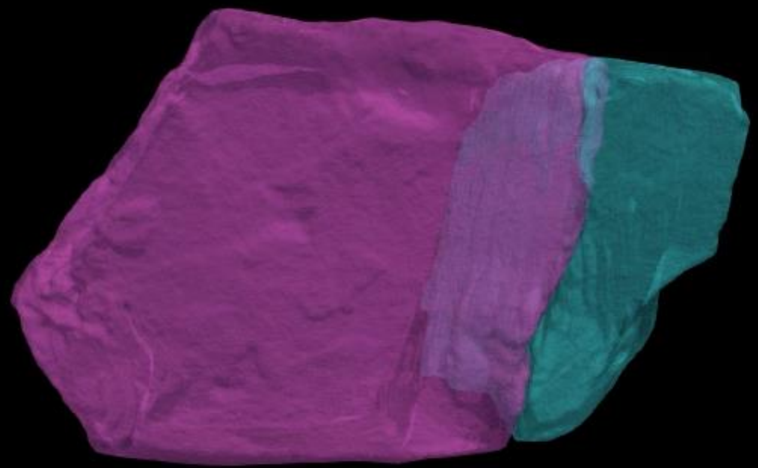
Lauretta, et al. (2024) *Met Planet Sci* 10.1111/maps.14227

12. How has the sample changed since collection?

Two of the larger stones in the sample fit together like puzzle pieces.



Shape models of OREX-800017-0 and OREX-800020-0 from Structured-Light Scanning



The face of OREX-800020-0 shown in the above AIVA image is the fracture plane (NASA/JSC/ARES).

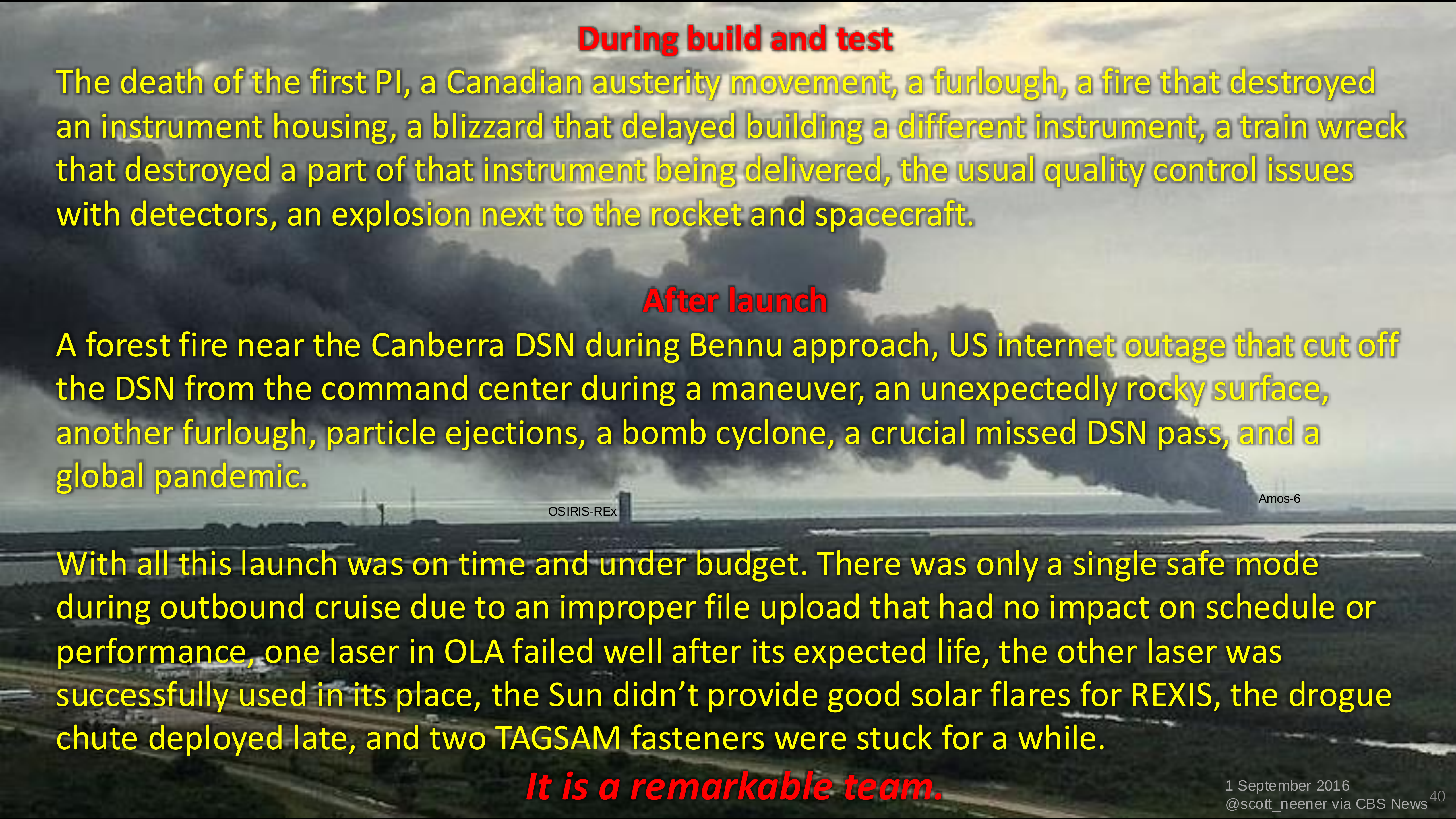
Ballouz et al. LPSC 2024

During build and test

The death of the first PI, a Canadian austerity movement, a furlough, a fire that destroyed an instrument housing, a blizzard that delayed building a different instrument, a train wreck that destroyed a part of that instrument being delivered, the usual quality control issues with detectors, an explosion next to the rocket and spacecraft.

After launch

A forest fire near the Canberra DSN during Bennu approach, US internet outage that cut off the DSN from the command center during a maneuver, an unexpectedly rocky surface, another furlough, particle ejections, a bomb cyclone, a crucial missed DSN pass, and a global pandemic.



With all this launch was on time and under budget. There was only a single safe mode during outbound cruise due to an improper file upload that had no impact on schedule or performance, one laser in OLA failed well after its expected life, the other laser was successfully used in its place, the Sun didn’t provide good solar flares for REXIS, the drogue chute deployed late, and two TAGSAM fasteners were stuck for a while.

It is a remarkable team.

1 September 2016
@scott_neener via CBS News

OSIRIS-REx
ASTEROID SAMPLE RETURN MISSION

NASA.gov/OSIRIS-REx

NASASolarSystem

AsteroidMission.org

NASASolarSystem

NASASolarSystem

Sample Catalogue

This material is based upon work supported by NASA under Award NNH09ZDA007O and Contract NNM10AA11C issued through the New Frontiers Program.

We are grateful to the entire OSIRIS-REx Team for making the return of samples from asteroid Bennu possible.