Cryogenic Comet Sample Return

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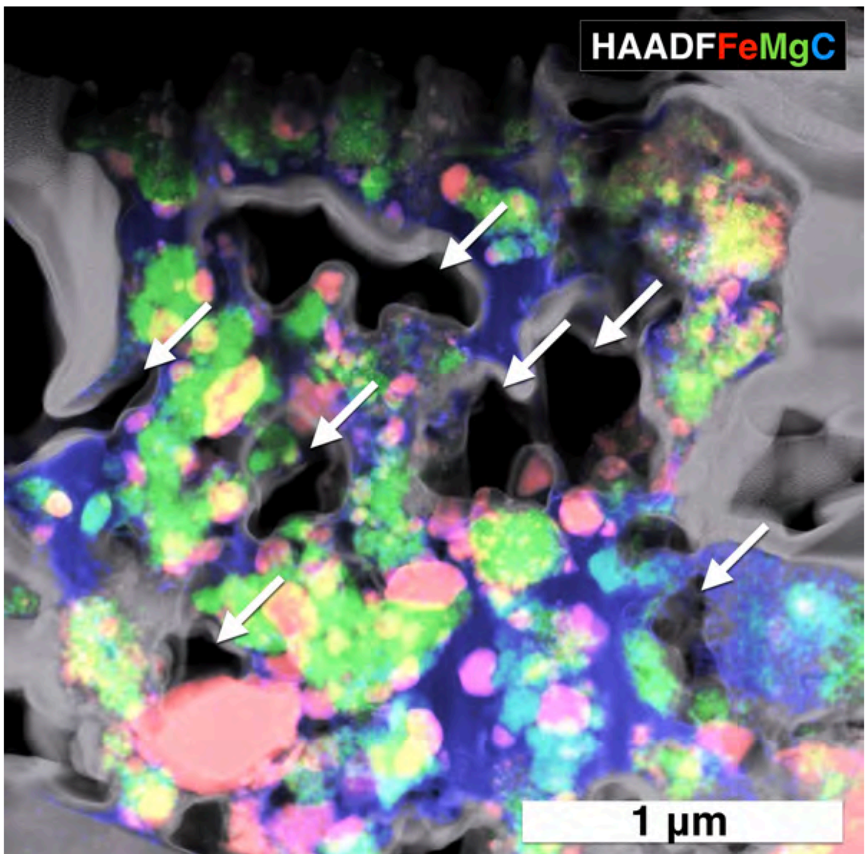

Science

What has changed since 2013

New studies needed

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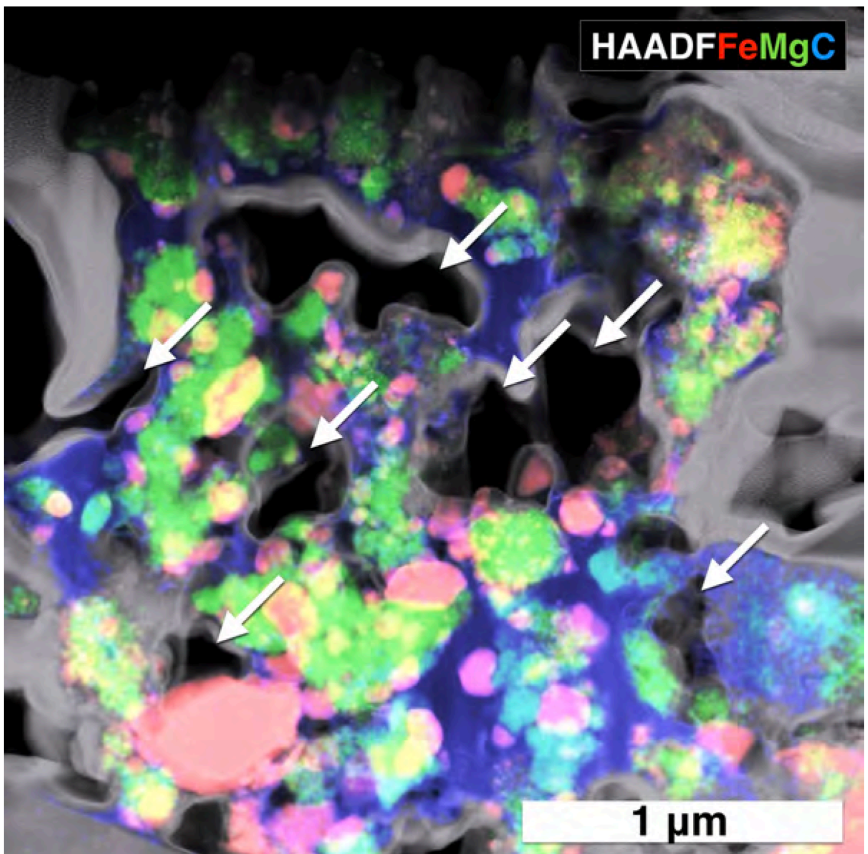


Science

What has changed since 2013

New studies needed


Spitzer Science Center

>99% of small bodies in the solar system are Kuiper Belt Objects

… but are underrepresented in our collections by >10^{13} by mass

… the icy component is not represented at all

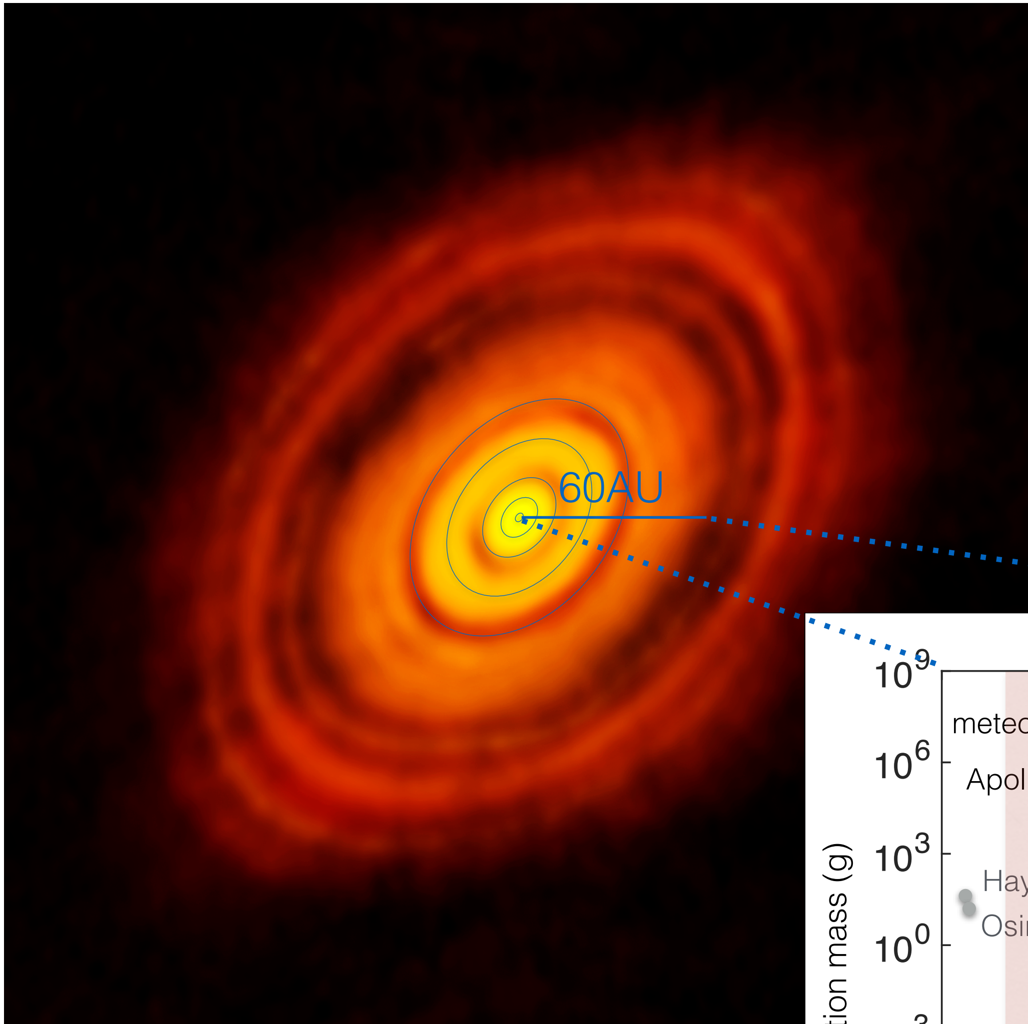
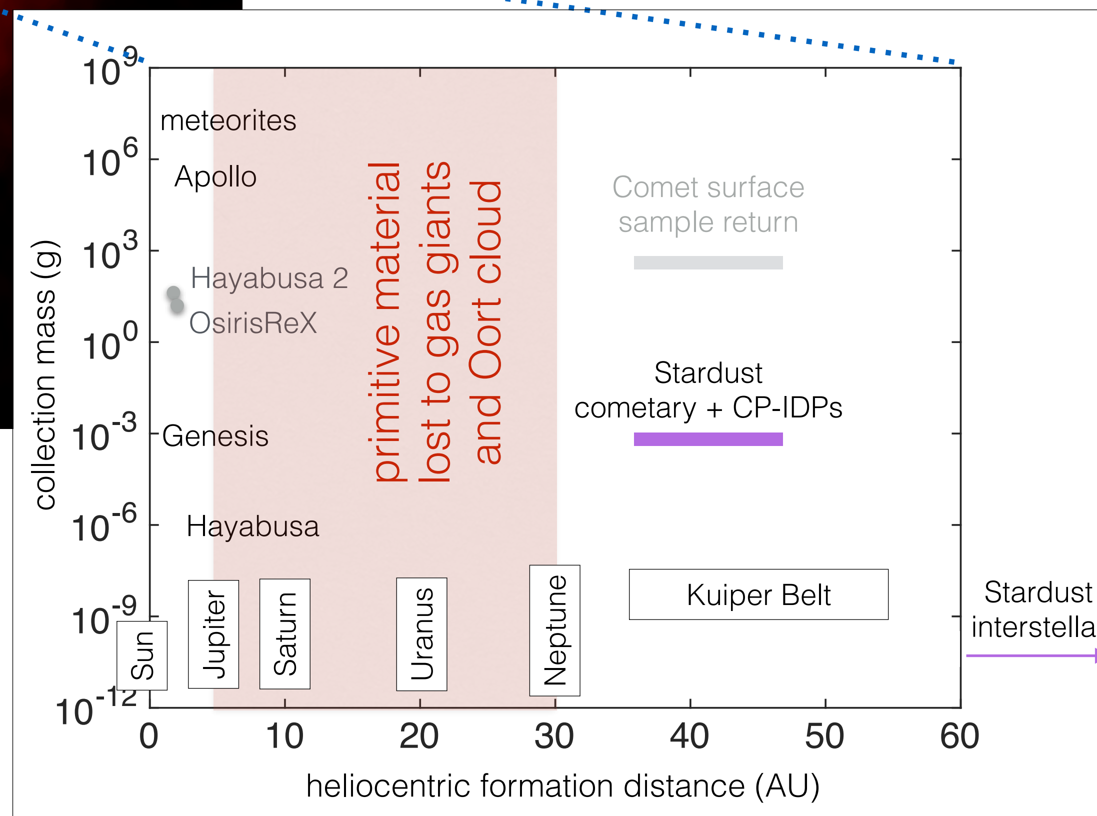
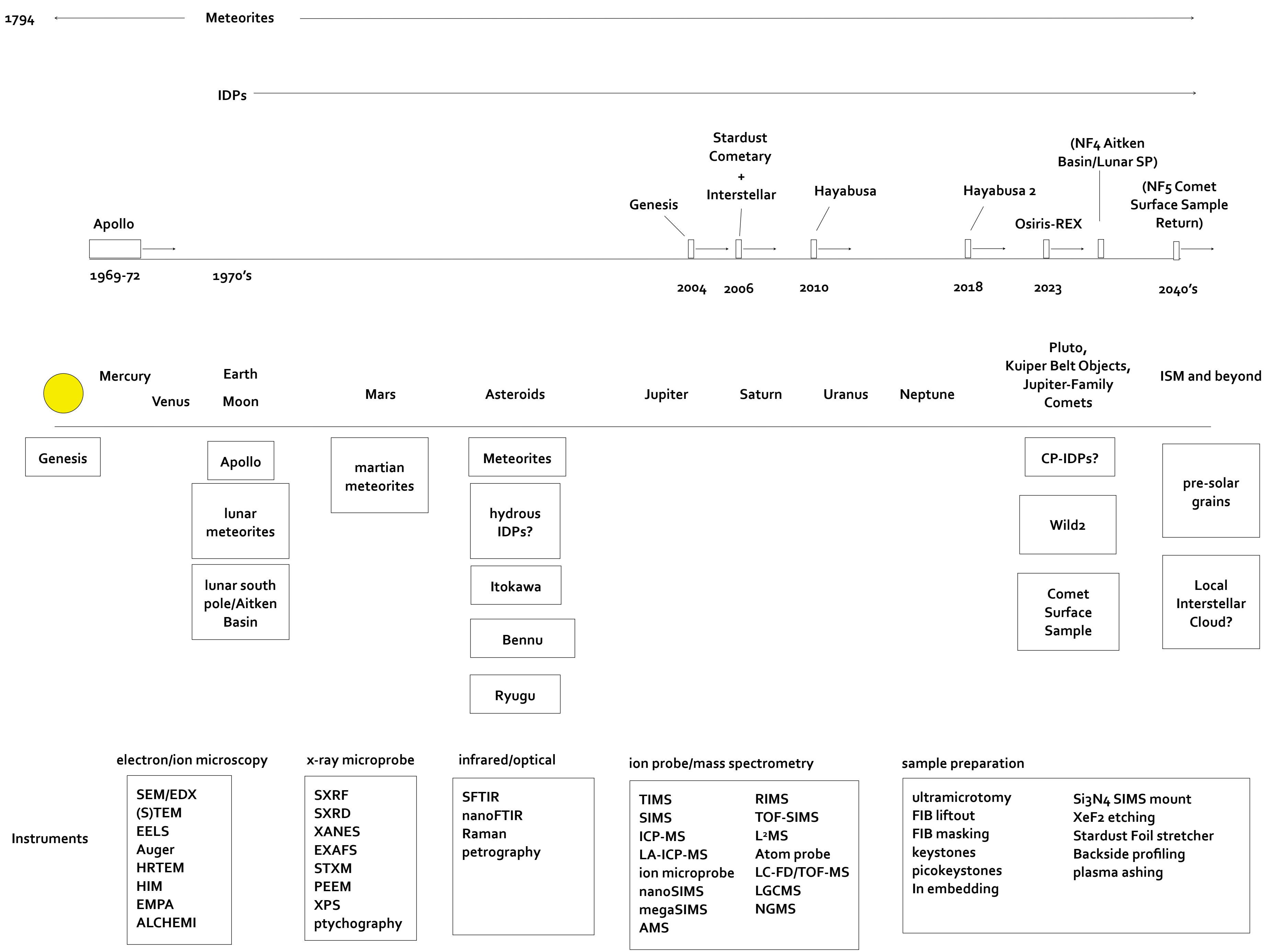


image courtesy ALMA collaboration

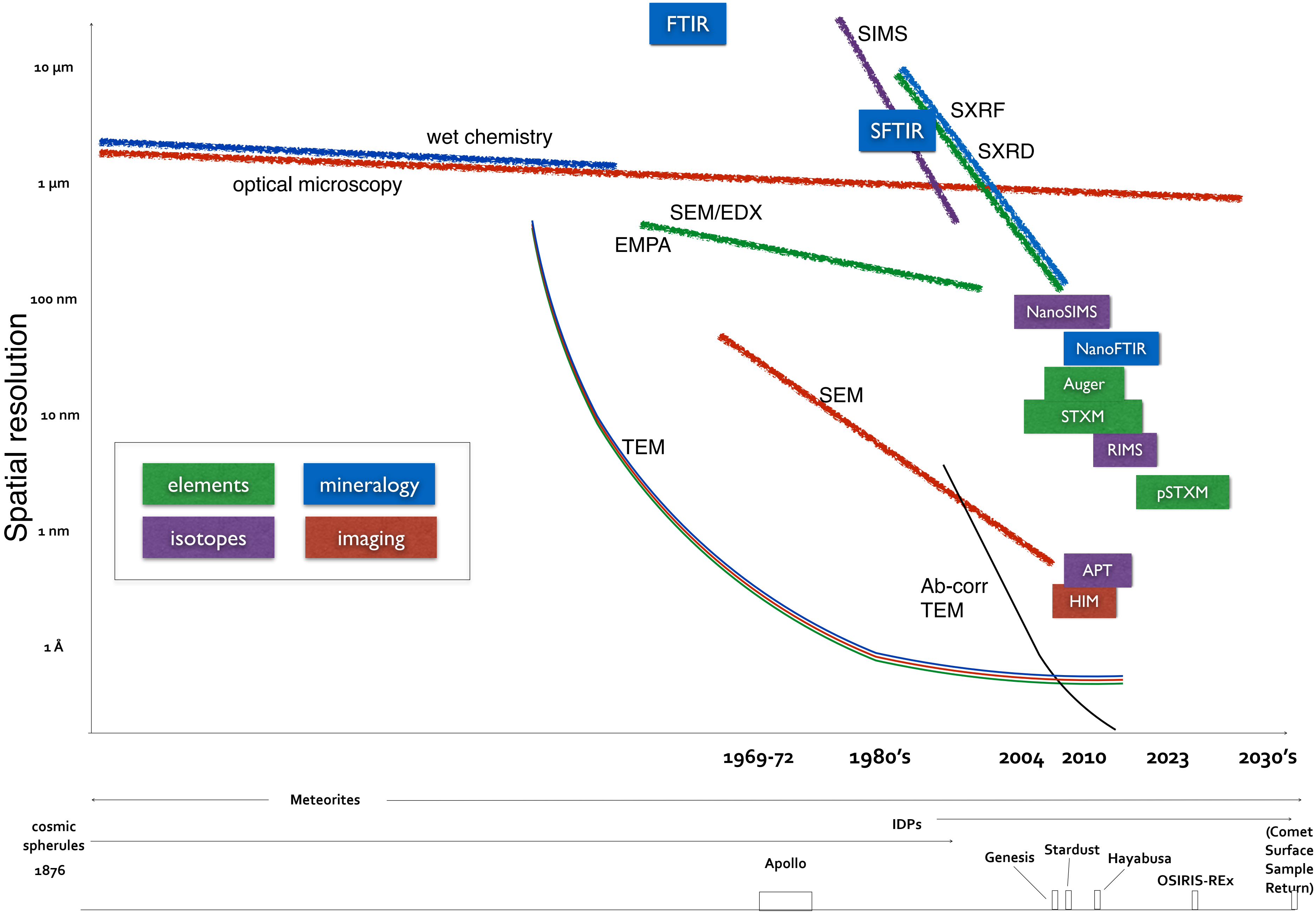



1794
Meteorites
IDPs
Apollo
1969-72
1970's
Genesis
2004
Stardust
Cometary
+
Interstellar
2006
Hayabusa
2010
Hayabusa 2
2018
Osiris-REX
2023
(NF_4 Aitken
Basin/Lunar SP)
(NF_5 Comet
Surface Sample
Return)
2040's
Mercury
Venus
Earth
Moon
Mars
Asteroids
Jupiter
Saturn
Uranus
Neptune
Pluto,
Kuiper Belt Objects,
Jupiter-Family
Comets
ISM and beyond
Genesis
Apollo
lunar meteorites
lunar south pole/Aitken Basin
martian meteorites
Meteorites
hydrous IDPs?
Itokawa
Bennu
Ryugu
CP-IDPs?
Wild2
Comet Surface Sample
pre-solar grains
Local Interstellar Cloud?
Instruments
electron/ion microscopy
SEM/EDX
(S)TEM
EELS
Auger
HRTEM
HIM
EMPA
ALCHEMI
x-ray microprobe
SXRF
SXRD
XANES
EXAFS
STXM
PEEM
XPS
ptychography
infrared/optical
SFTIR
nanoFTIR
Raman
petrography
ion probe/mass spectrometry
TIMS
SIMS
ICP-MS
LA-ICP-MS
ion microprobe
nanoSIMS
megaSIMS
AMS
RIMS
TOF-SIMS
L^2MS
Atom probe
LC-FD/TOF-MS
LGCMS
NGMS
sample preparation
ultramicrotomy
FIB liftout
FIB masking
keystones
picokeystones
In embedding
Si_3N_4 SIMS mount
XeF_2 etching
Stardust Foil stretcher
Backside profiling
plasma ashing

Advantages of sample return

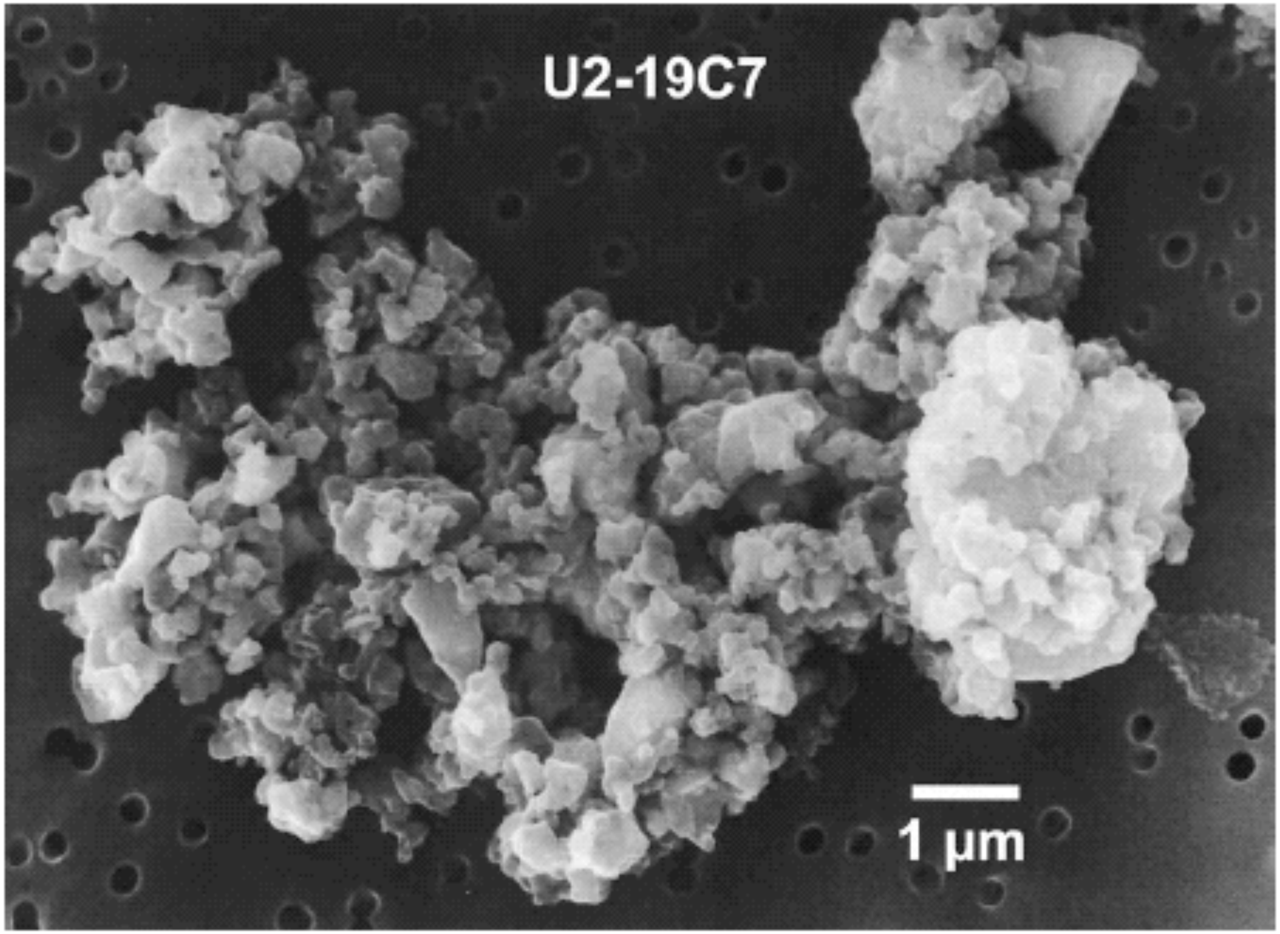
Advanced Light Source, Lawrence Berkeley Lab

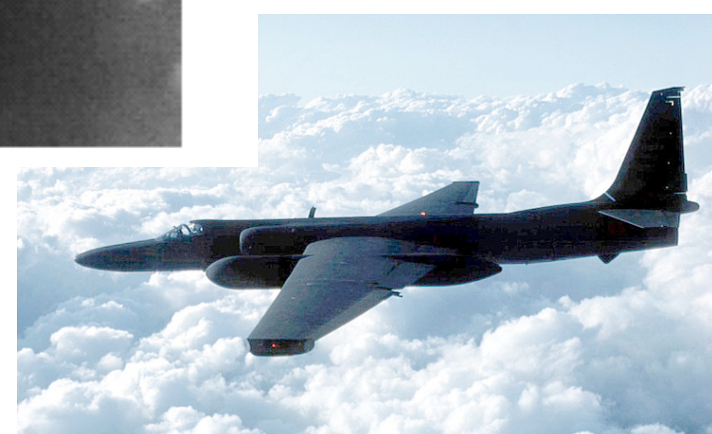
- Use instruments that cannot be flown in space
- Take advantage of advances in analytical capabilities
- Study samples for decades
- Carefully coordinated analyses using a variety of instruments



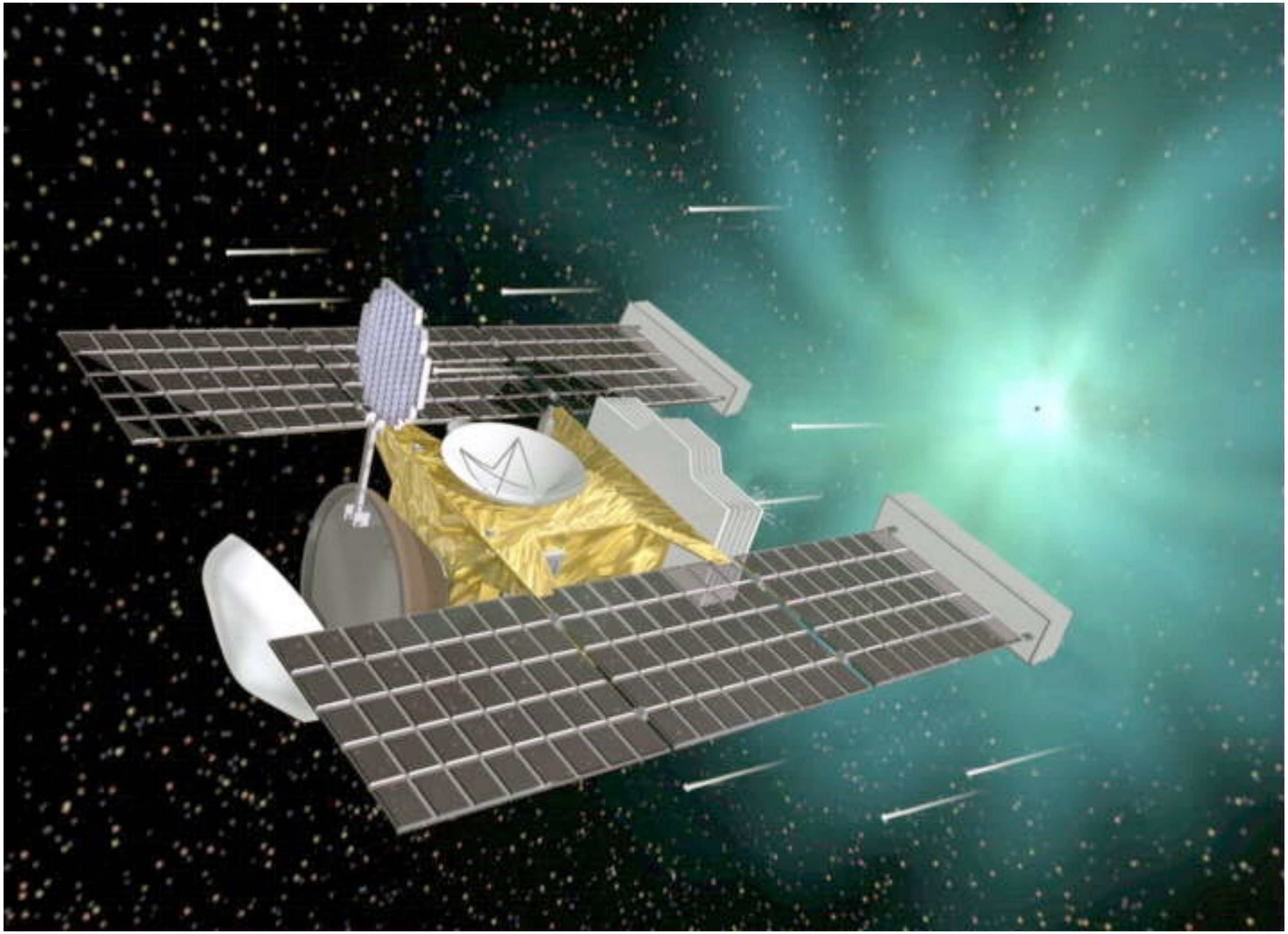
FTIR
SIMS
SXRF
SFTIR
SXRD
wet chemistry
optical microscopy
10 µm
1 µm
100 nm
10 nm
1 nm
1 Å
Spatial resolution
SEM/EDX
EMPA
NanoSIMS
NanoFTIR
Auger
STXM
RIMS
pSTXM
SEM
TEM
Ab-corr
TEM
APT
HIM
elements
mineralogy
isotopes
imaging
1969-72
1980's
2004
2010
2023
2030's
Meteorites
cosmic
spherules
1876
IDPs
Apollo
Genesis
Stardust
Hayabusa
OSIRIS-REx
(Comet
Surface
Sample
Return)

CP-IDPs: cometary origin

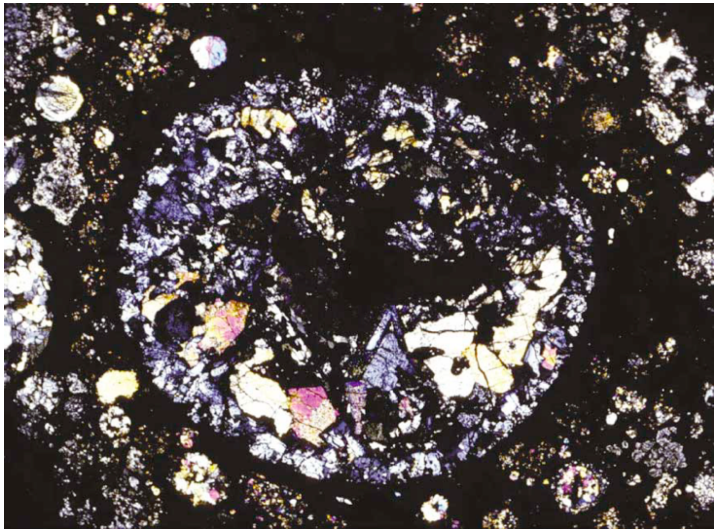




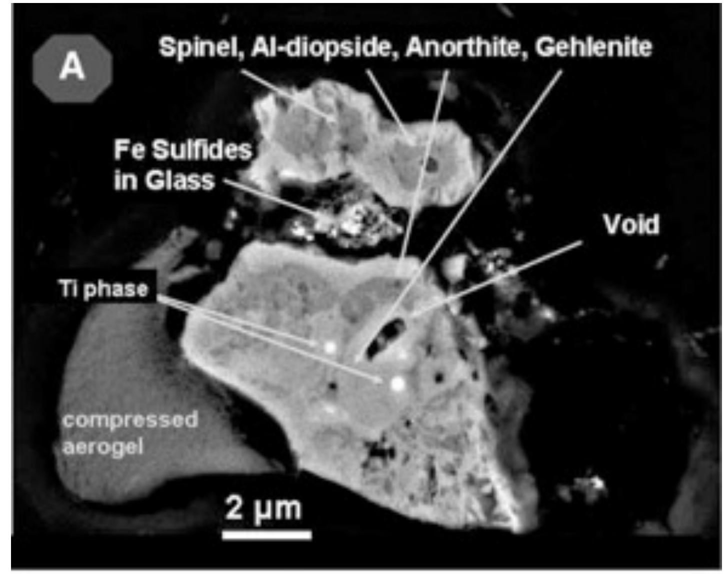
Stardust



NASA Discovery mission

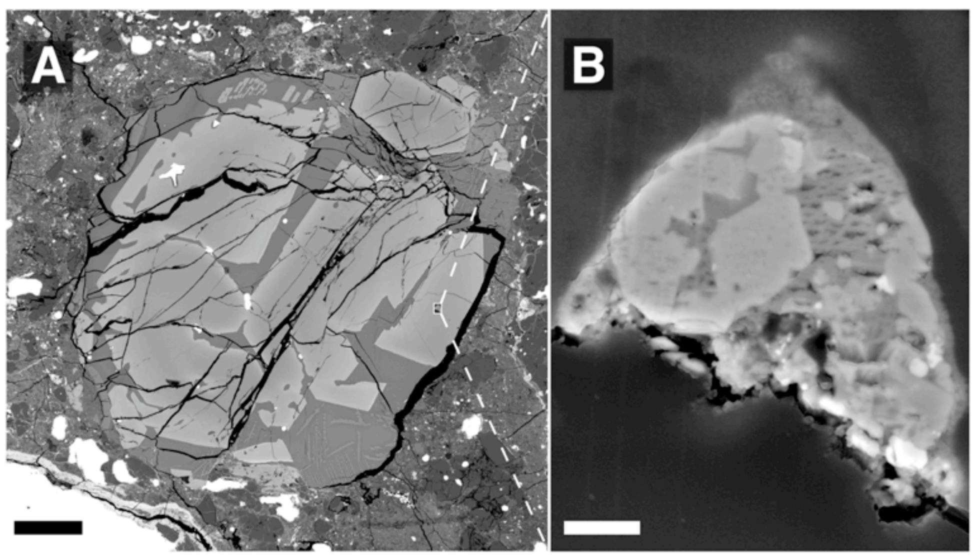


CAI



μCAI

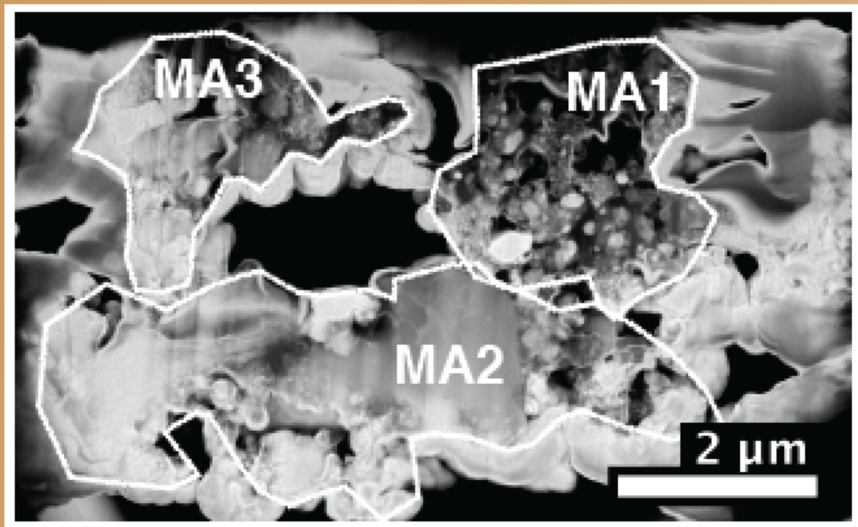
chondrule

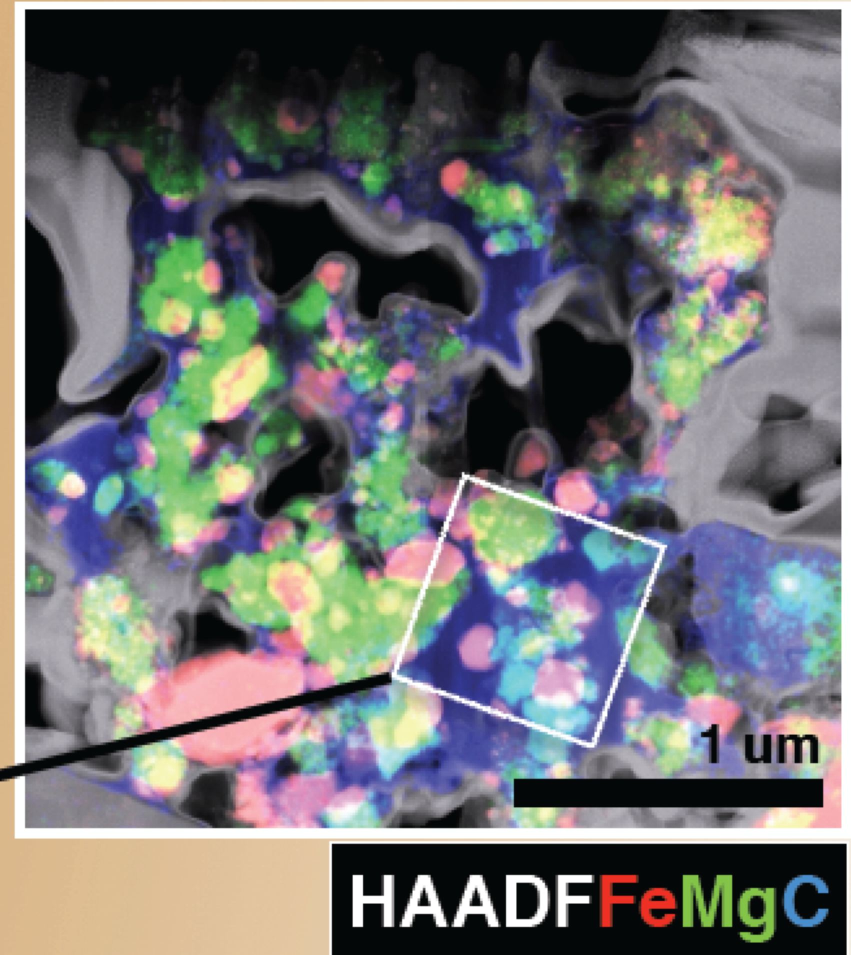


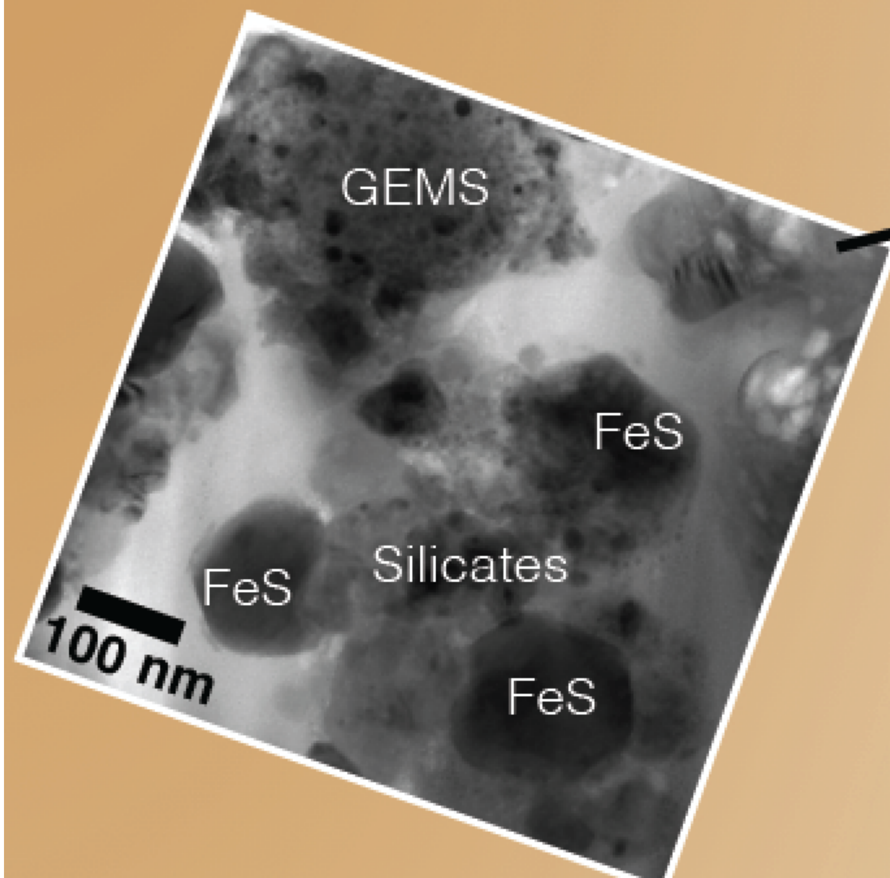
100μm

2μm

μchondrule







In the image above, the FIB-process carbon has been subtracted off using the Ga and Pt maps. The remaining carbon in the map is cometary and is shown in blue.

Terra Incognita: cryogenic extraterrestrial materials

No cryogenic (<150K) natural material *of any kind* has ever been studied in the laboratory

Science questions

- What are the principal molecular components of the ices? What structures can be recognized, and what are their sizes? Are the ices homogeneous or heterogeneous?
- How are the volatile components (CO, CO_2, HCN, CH_4, noble gases, etc.) distributed on small scales within cometary materials? Are they trapped in more "refractory" ices, or do they exist as distinct phases?
- What ice phases are present, and how are they distributed? Are the ices amorphous or crystalline? If amorphous, is the ice in the low-density or high-density form? If crystalline, is the ice in a cubic or hexagonal structure or in the form of a clathrate? If clathrates are present, what form are they in? Are Type II methanol-containing clathrates present?
- How are the various volatile ices and organics distributed? What is their spatial relationship with each other and with minerals, etc.?
- Do the D/H, $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, and $^{13}C/^{12}C$ isotopic ratios in the ices and volatile organics vary with molecular carrier and on what size scales?
- Are there icy analogs of presolar grains, that is, presolar condensates with enormous isotopic anomalies?
- How do the composition and physical structure of the ices drive and influence cometary activity and long-term evolution of the comet parent body?

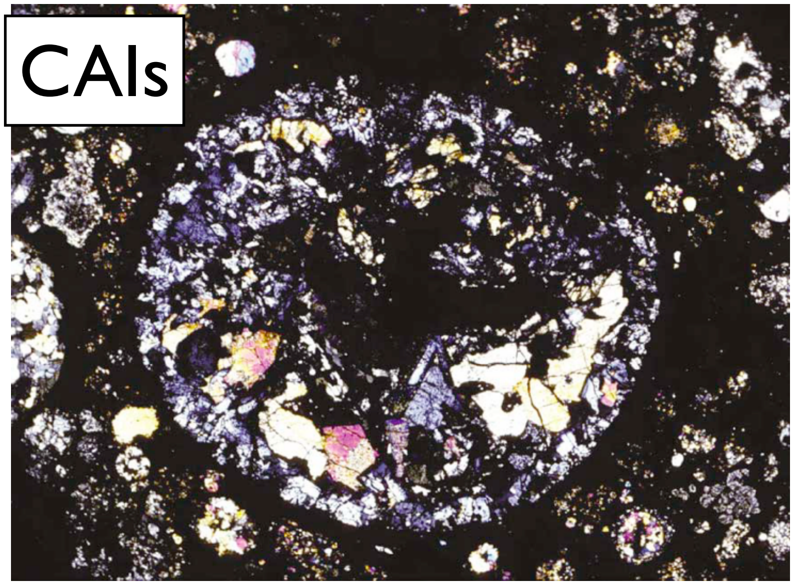
Previous work: Veverka et al. study (2008)

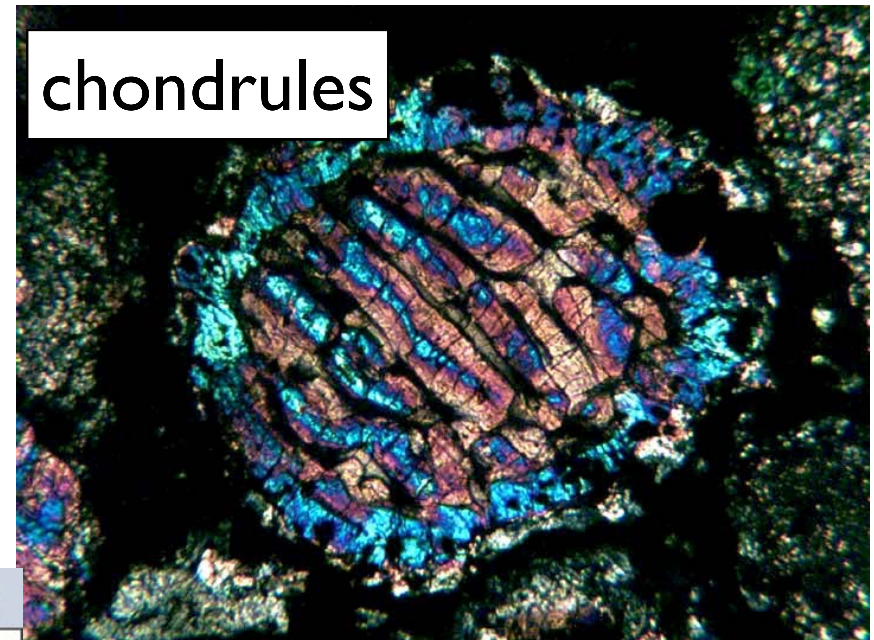
- Obtaining a single, stratified, subsurface core
- Obtaining samples from multiple locations
- Verification of acceptable ice content
- Provisions for resampling in case of an unacceptable core
- Encapsulation and cryogenic return

implicit or explicit assumptions

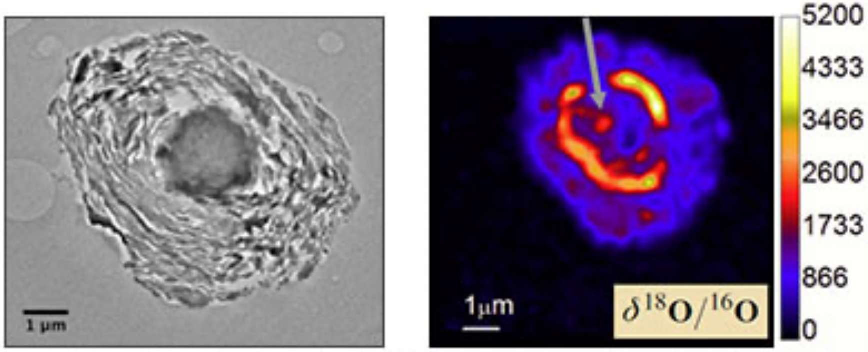
- The lowest practical storage temperature is 90 K
- Retention of sublimed volatiles has significant science value
- The only practical Earth return mode is high-speed atmospheric entry with a sample return capsule, similar to Genesis or Stardust

If we only had vaporized meteorites, we would miss….





Presolar Graphite Grain from Orgueil Meteorite



(From Groopman *et al.*, 2014, *The Astrophysical Journal*, 790:9, doi:10.1088/0004-637X/790/1/9.)

… and so much more

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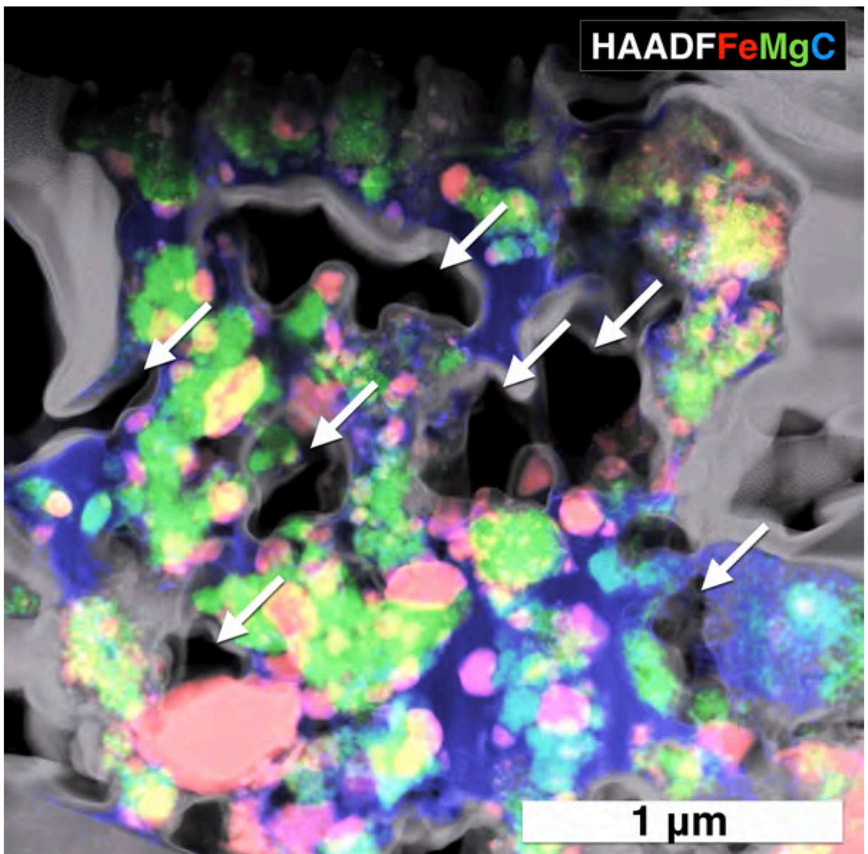

Science

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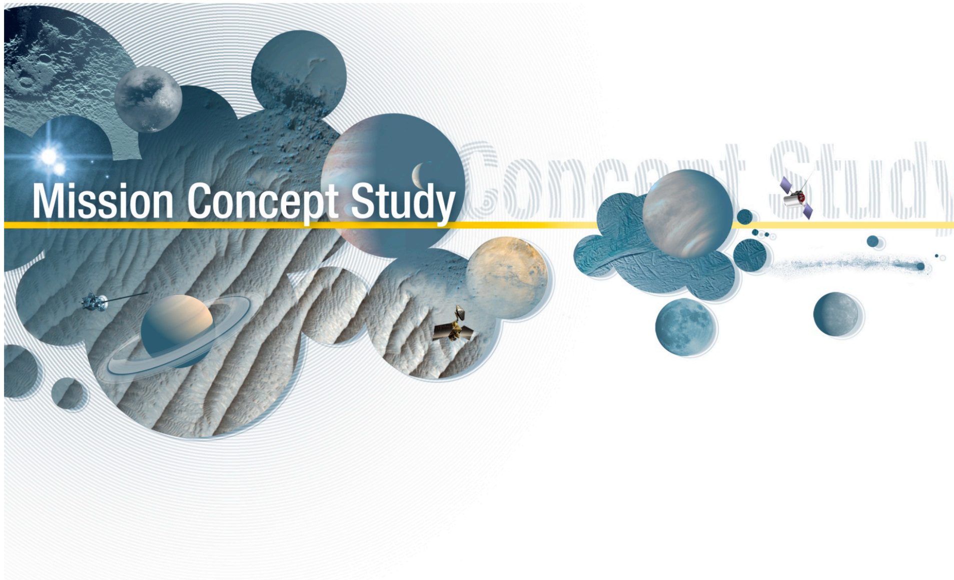


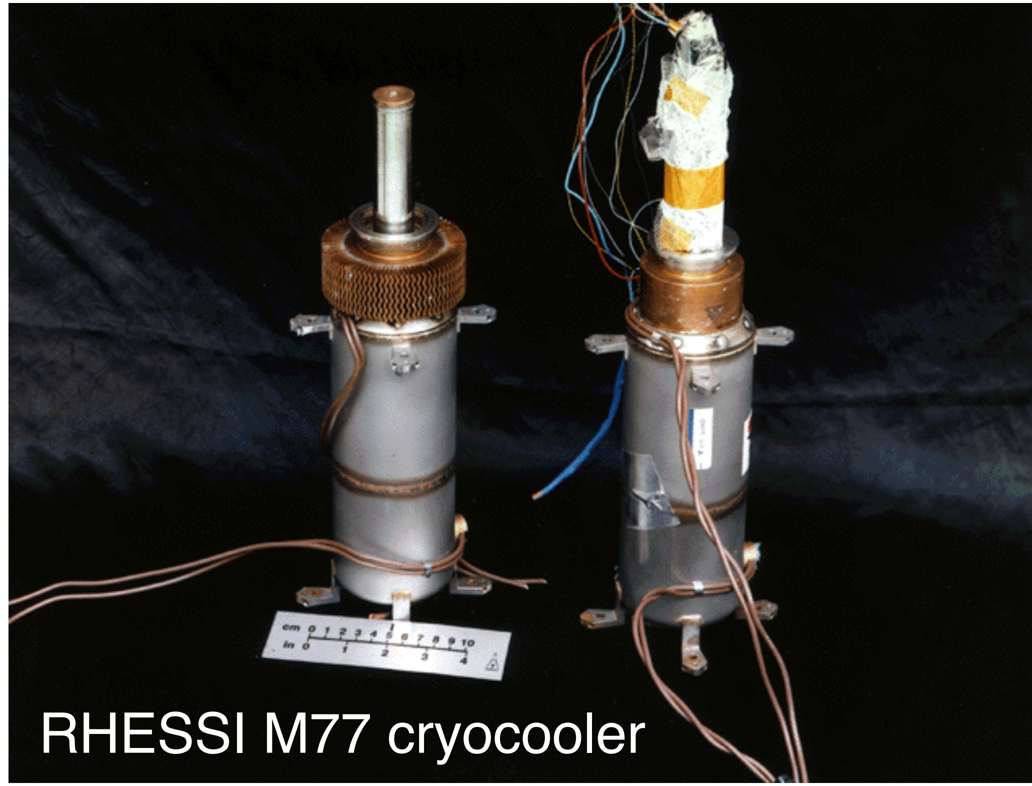
Cryogenic Comet Nucleus Sample Return (CNSR) Mission Technology Study

Joe Veverka

What has changed since the last Planetary Decadal:

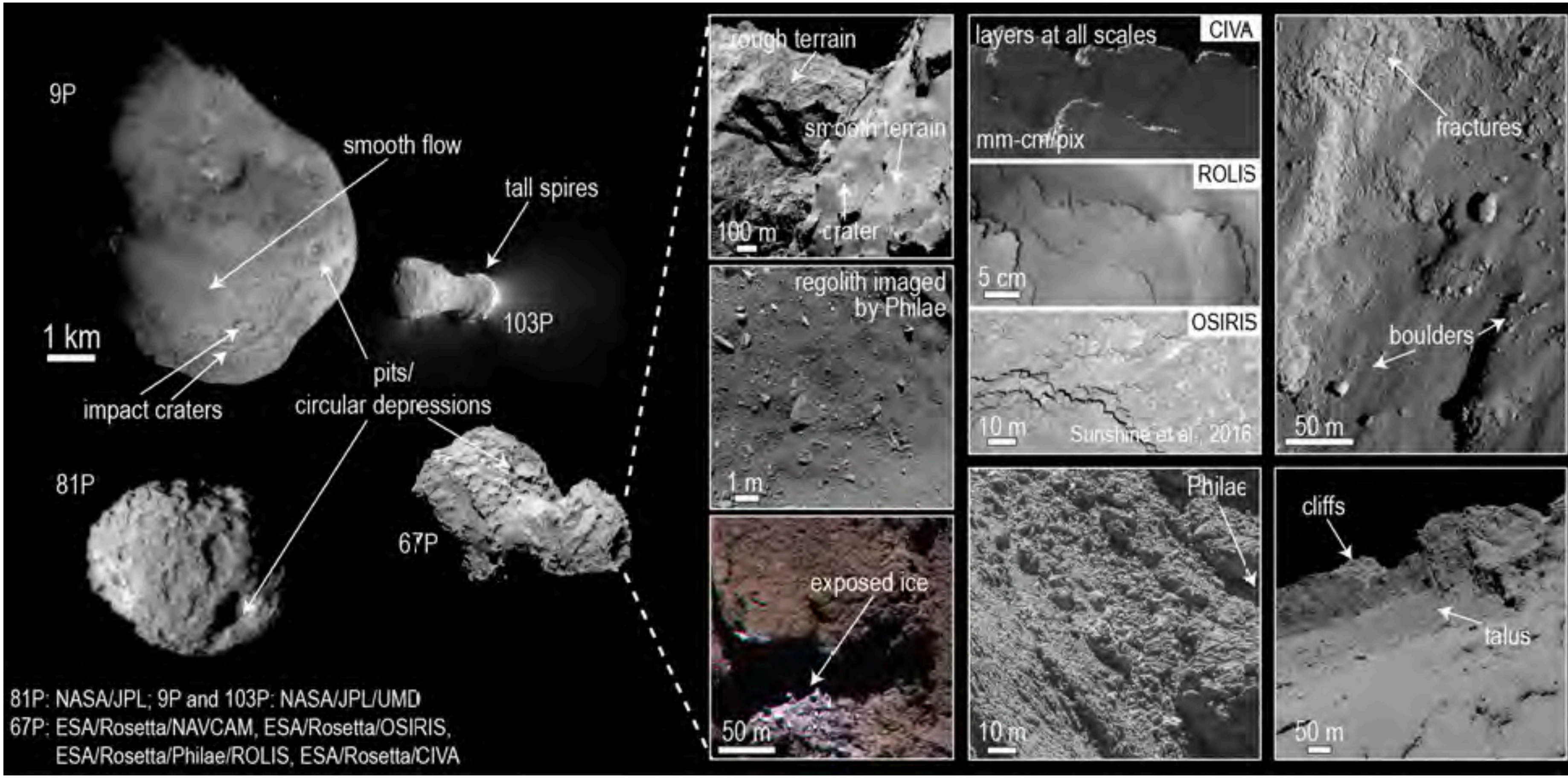
- High-heritage cryocooler technology
- Rosetta
- DOE investments and advancements in cryomicroscopy

Cryocoolers at TRL 9

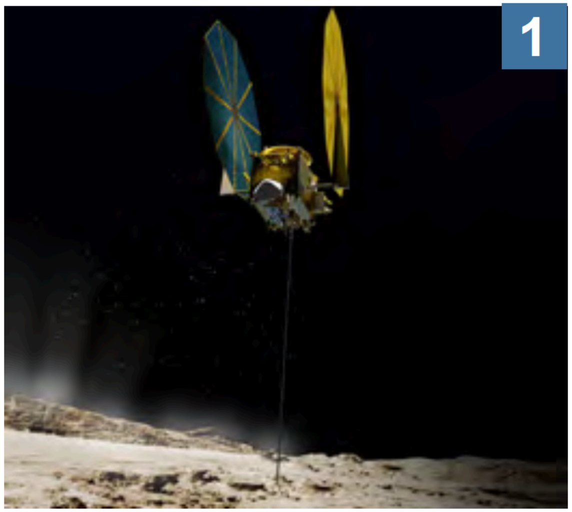

RHESSI M77 cryocooler

Long-duration, robust cryocooler technology now has extensive heritage on spacecraft. This is a game-changer for cryogenic sample return. An 80K Stirling cycle cryocooler was first deployed for spacecraft use in 1991 on the UARS ISAMS mission. Since this initial flight, cryocoolers have been flown on more than sixteen other spacecraft and several high altitude balloon missions such as COSI and GRIPS. The RHESSI cryocooler operated for more than 15 years. This experience base is primarily in the 50K to 150K temperature range. Current missions near launch and in development are setting the groundwork for 5K to 20K operational temperatures. This mission experience makes cryocoolers a key technology component for consideration in the cryogenic system.

We know much more about comets!

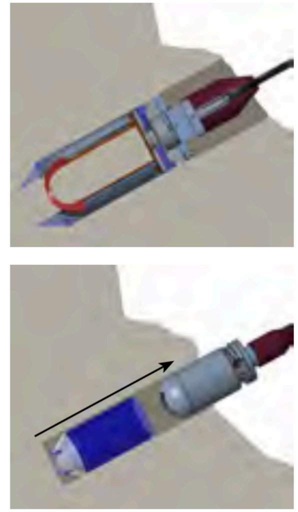


Sampling technology development



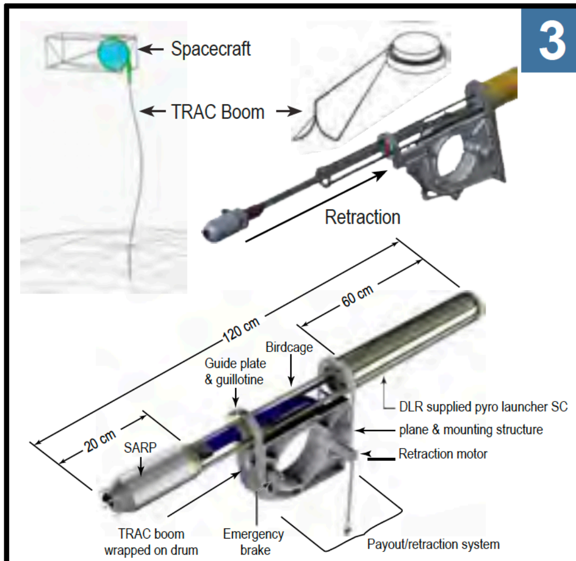
1

Stage 1 –Harpoon launch and sample collection (T=0; launch). *The launcher accelerates the harpoon at 10m altitude to penetrate >10 cm into the surface. Under-dense material is compressed to fill up the cartridge. The harpoon comes to rest through comet resistance and retraction system braking.*



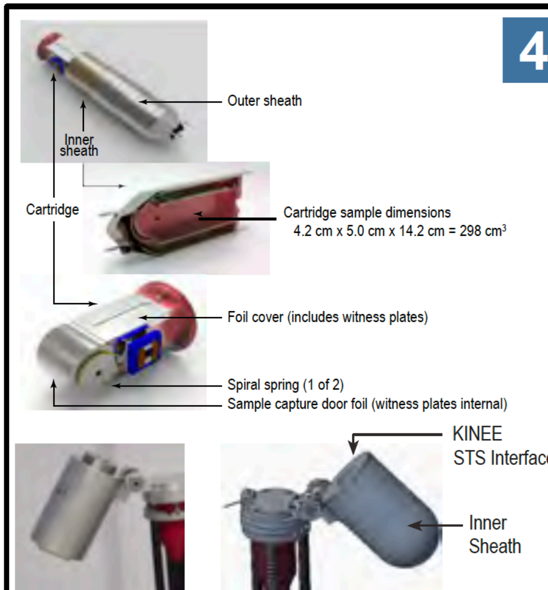
2

Stage 2 – Acquisition: harpoon door close and decouple (T=1–2 s). *A timer closes the cartridge door, cutting through material and fully encapsulating the sample. Another timer separates the outer sheath from the inner sheath, providing a well-understood friction force for removal.*



3

Stage 3 – Retraction: harpoon return (T=2–11 s). *The Boom Retraction and Deployment (BRAD) controls the harpoon return to the end of the launcher to avoid buckling. The harpoon is mechanically grounded at the end of the launcher.*



4

Stage 4 – Preparation: harpoon rotation (T=21 s). *A final timer actuates the flip hinge, rotating the cartridge and inner sheath away from the boom decoupler plate and exposing the sample storage system interface.*

Cryogenic sample curation, handling, sample prep, and analysis

- The advent of cryomicroscopy of biological samples has led to a profusion of commercially available tools for focused ion beam (FIB) microsampling, cryotransfer, and cryoelectron microscopy at 10s of K.
- The viability of isotopic measurements of meteoritical samples held at cryogenic temperatures has been demonstrated (Yurimoto et al., 2014).
- Cryogenic (77 K) stages are currently available at several synchrotron x-ray beamlines.
- The Department of Energy recently identified the development of electron microscopes and samples stages that enable work at 5K with <0.1 nm resolution for non-biological samples as a priority for addressing multiple agency Grand Challenges (DOE report, 2014). **These methods and instruments are already on the path to widespread adoption across the microanalysis research sector, and should be integrated into the Decadal Survey as part of the NASA technology roadmap for sample return.**

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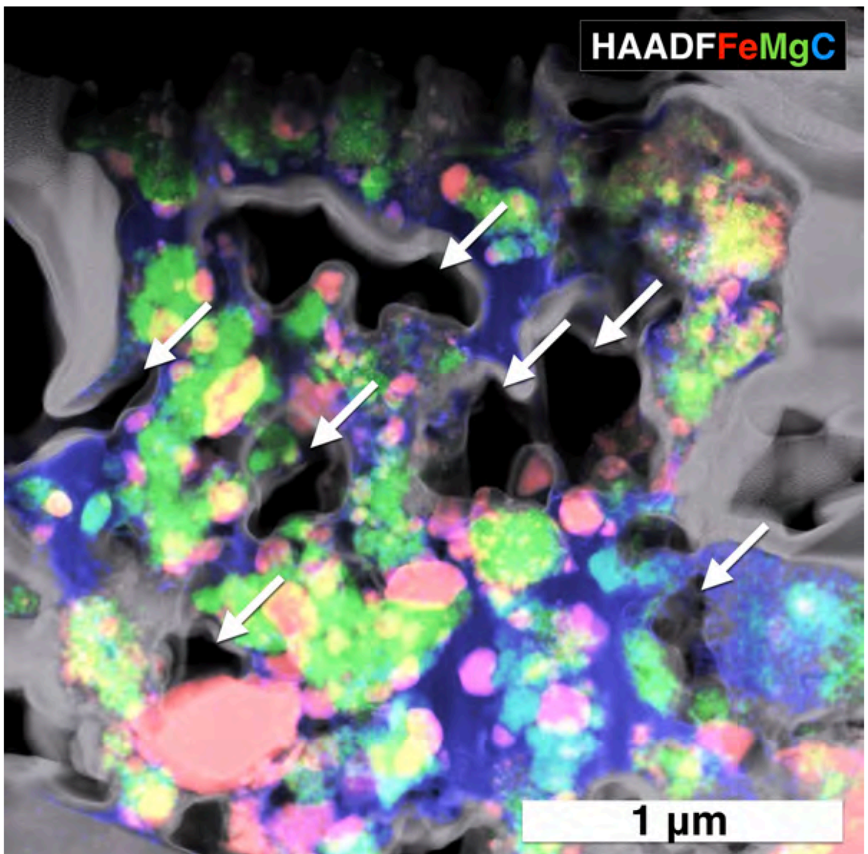

Science

What has changed since 2013

New studies needed

A cryogenic comet return mission would require:

- Further studies of thermal requirements necessary for preservation of petrological contexts
- A trade study of mass and power requirements for cryogenic systems
- Development of sampling technology that maximizes the return of primitive ices
- A trade study on mission architecture for two possible return modes
- Continued investment in cryogenic sample curation
- Continued investment in cryogenic sample handling and analysis techniques

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Based on the sublimation models of Veverka et al. (2008) (their Fig. 6-1), retention of many volatile species *within their microscopic context* would require maximum storage, transport and curation temperatures of order 60K. At higher temperatures, these species might be retained within the sample, but, depending on their structure, could have been sufficiently mobile that their original petrological context would have been lost. For example, amorphous H_2O ices undergo an amorphous-amorphous phase transition at $\sim$80 K that allows locate rearrangement of the ice matrix and allows some volatile species trapped in the ice to escape (Sandford & Allamandola, 1988). Highly volatile species (e.g., CO, O_2, noble gases, etc.) would be lost from the ice phase if not trapped in more abundant H_2O-rich ices. *Long-duration, reliable storage 60K is practically achievable with current technology (section 7.2).* **Here, we will extend the sublimation curves of Veverka et al. (2008) down to at least 60K, to better define thermal requirements from sample acquisition to laboratory analysis.**

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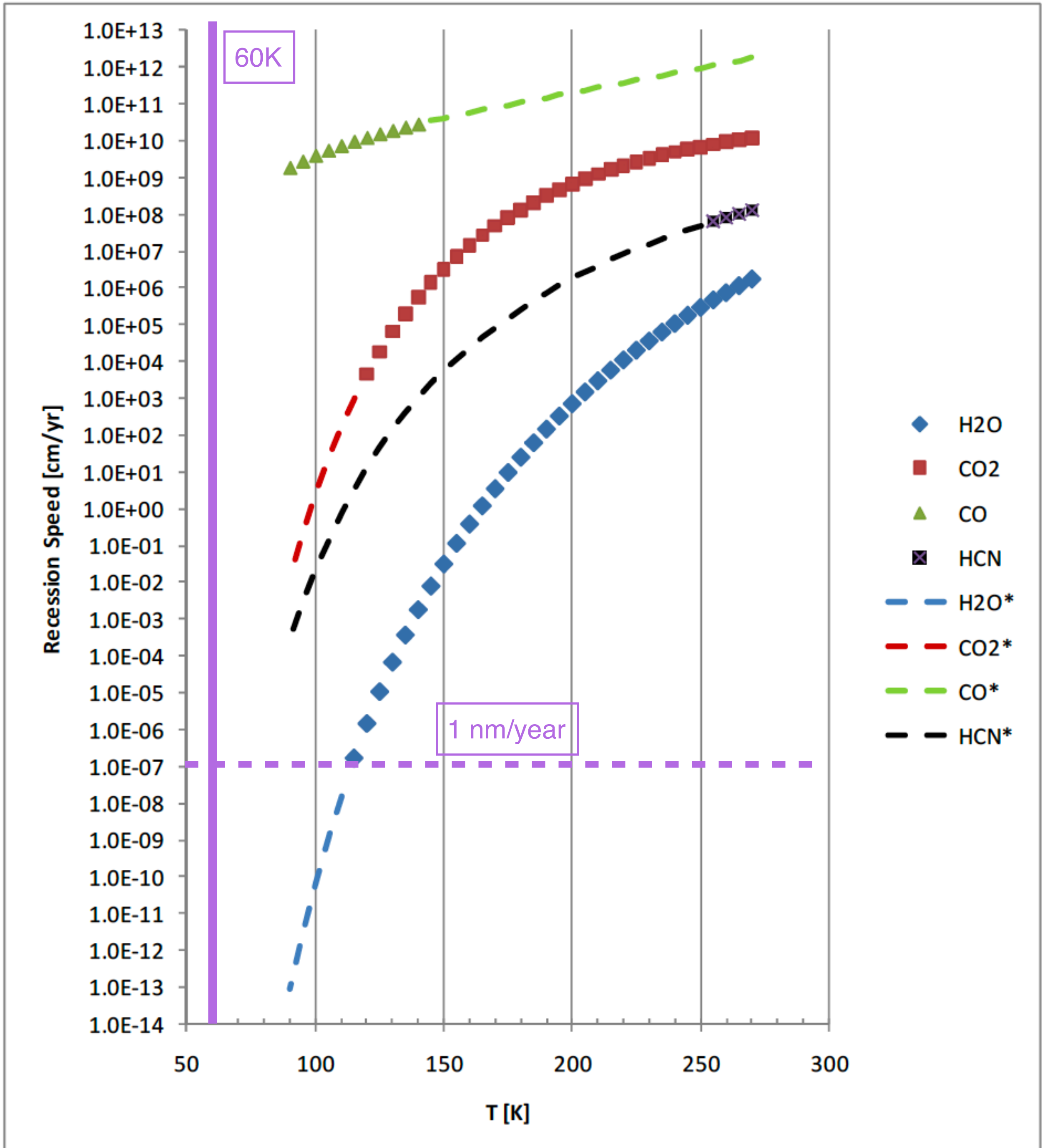
In the light of Rosetta observations of 67P:

- investigate remote sensing payloads and the time needed for selection of a site that will maximize the probability of collecting sample(s) that meet science requirements
- develop sampling options that can work over a range of surface strengths and terrains that are likely to contain primitive icy material
- develop ideas for ensuring return of more primitive materials below the outer processed and sintered layers of a comet.



60K
1 nm/year
Recession Speed [cm/yr]
T [K]
1.0E+13
1.0E+12
1.0E+11
1.0E+10
1.0E+09
1.0E+08
1.0E+07
1.0E+06
1.0E+05
1.0E+04
1.0E+03
1.0E+02
1.0E+01
1.0E+00
1.0E-01
1.0E-02
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
1.0E-08
1.0E-09
1.0E-10
1.0E-11
1.0E-12
1.0E-13
1.0E-14
50
100
150
200
250
300
H2O
CO2
CO
HCN
H2O*
CO2*
CO*
HCN*

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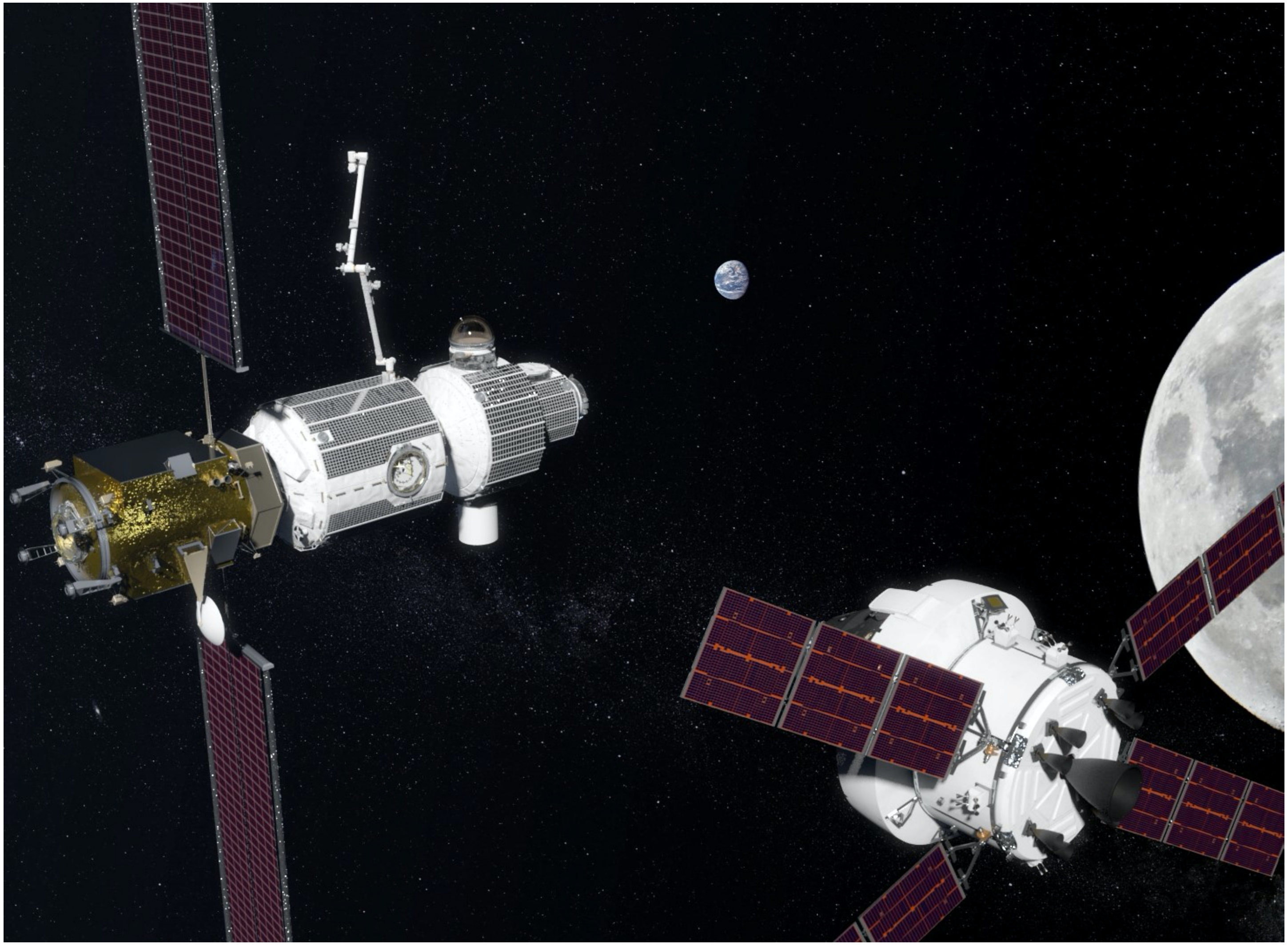
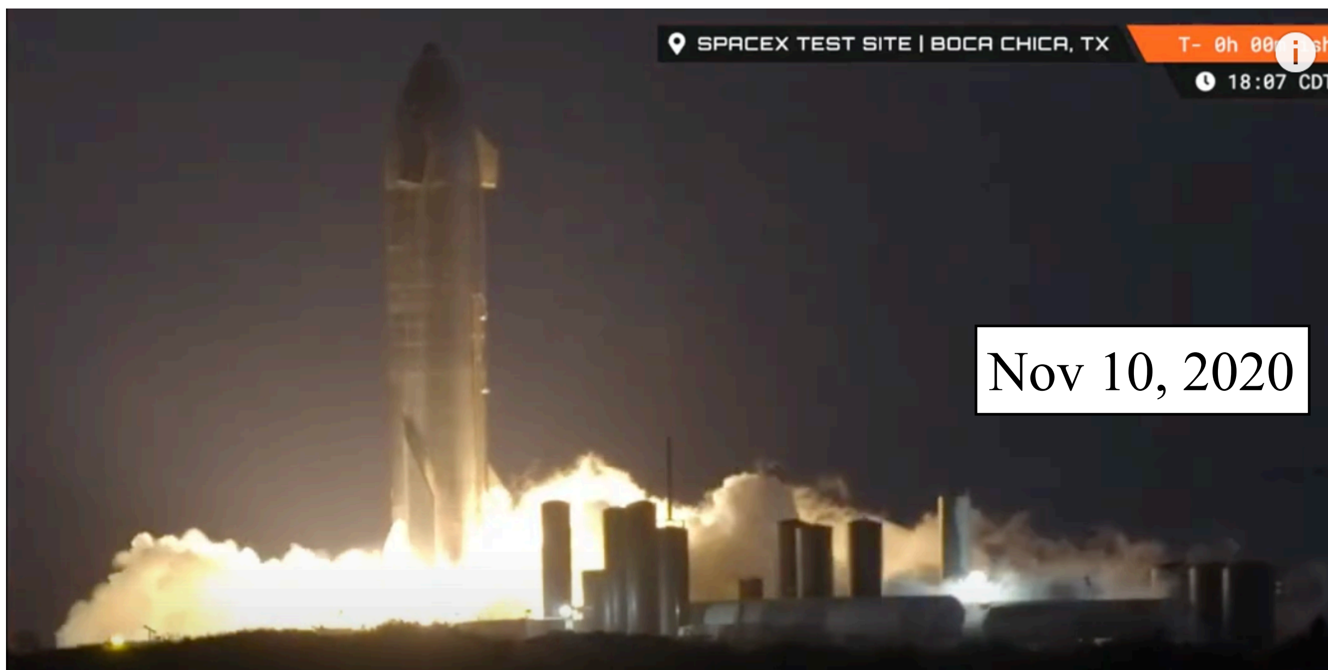
really three…


Stardust SRC
return

Deep Space Gateway



SpaceX Starship



Nov 10, 2020

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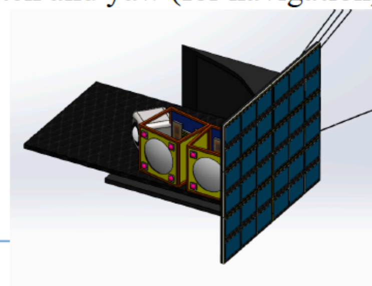
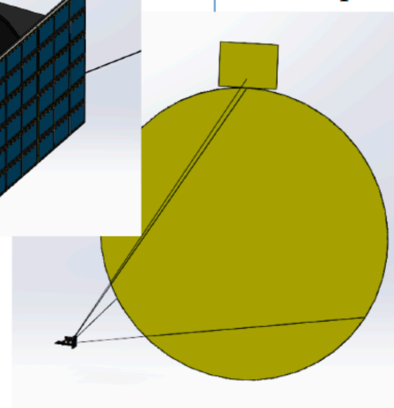
A Planetary Mission Concept Study proposal describes such studies in more detail

Swarms of Low-Cost Interplanetary Solar Sails
Collecting Data on 1,000s of Near Earth Objects

Innovation

* We propose to build a fleet of thousands of 10 gram interplanetary spacecraft to capture cometary dust samples from dozens of Jupiter-family comets, and to rendezvous with and image thousands of Near Earth Objects (NEO).
* Spacecraft consist of a 1m^2 solar sail, cell-phone camera, Linux computer, solar cells, battery, radiator fin, laser communication system, and MEMS motors to control sail orientation.
* Key innovation is MEMS motors on three sail shroud lines to control roll (for temperature), and pitch and yaw (for navigation).
* Spacecraft will be deployed and retrieved in GEO, and be able to navigate the inner solar system.
* Full systems could be launched in 3 years





Technical Approach

- Mission analysis and simulation
  - Mission profile for sample return from 100 comets
  - Navigation using camera localization
  - Thermal and trajectory control with three MEMS motors on mission to representative comet, and return
- Spacecraft model in CAD
  - Mechanical, electrical, thermal
- Bring MEMS sail control motors from TRL 2 to TRL 5 by testing through thousands of cycles in thermal vac chamber
- Development of miniature fields instruments

Potential & Benefits

- Current Planetary Decadal called out pristine cometary sample return as a high priority
- Recent New Frontiers 4 finalist was a cometary sample return mission (CAESAR)
- Earliest cometary sample return under NF in ~2045
- BLISS would carry out rapid (~5 years) cometary sample return from dozens of comets
- Reconnaissance and high-resolution imaging of >1,000 NEOs
- 1 Mbps interplanetary optical mesh communication network
- High-resolution synoptic observations of Earth’s magnetosphere with thousands of spacecraft

Evaluation Notes

Glass with Embedded Metals and Sulfides (GEMS)