Past Sample Return Missions and Major Achievements

Michael Zolensky, NASA JSC

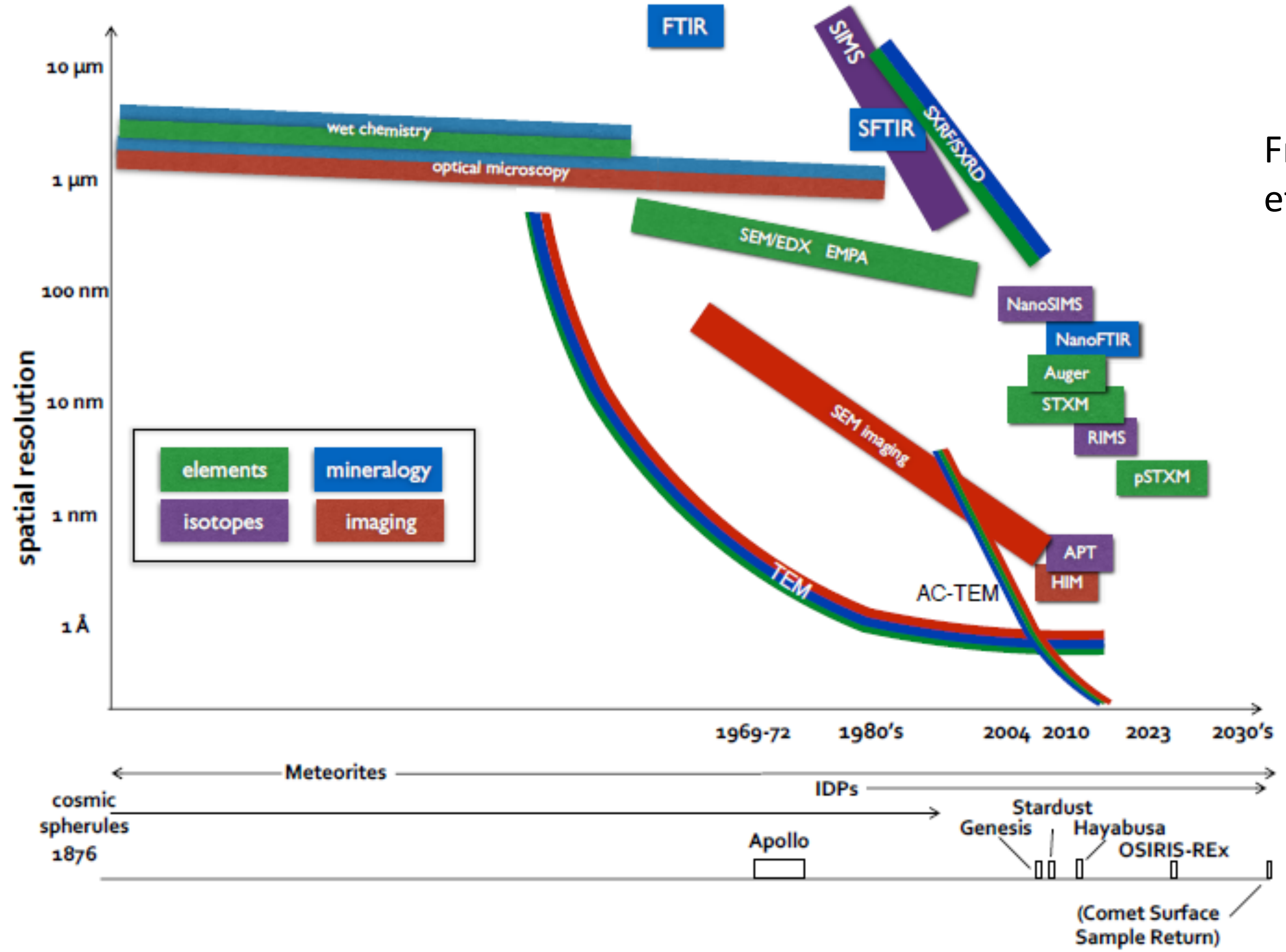
Advances in analytical capabilities since the 1960s

Summary of past sample return missions

Major unanswered science questions from these missions

Lessons learned from these missions (in my opinion)

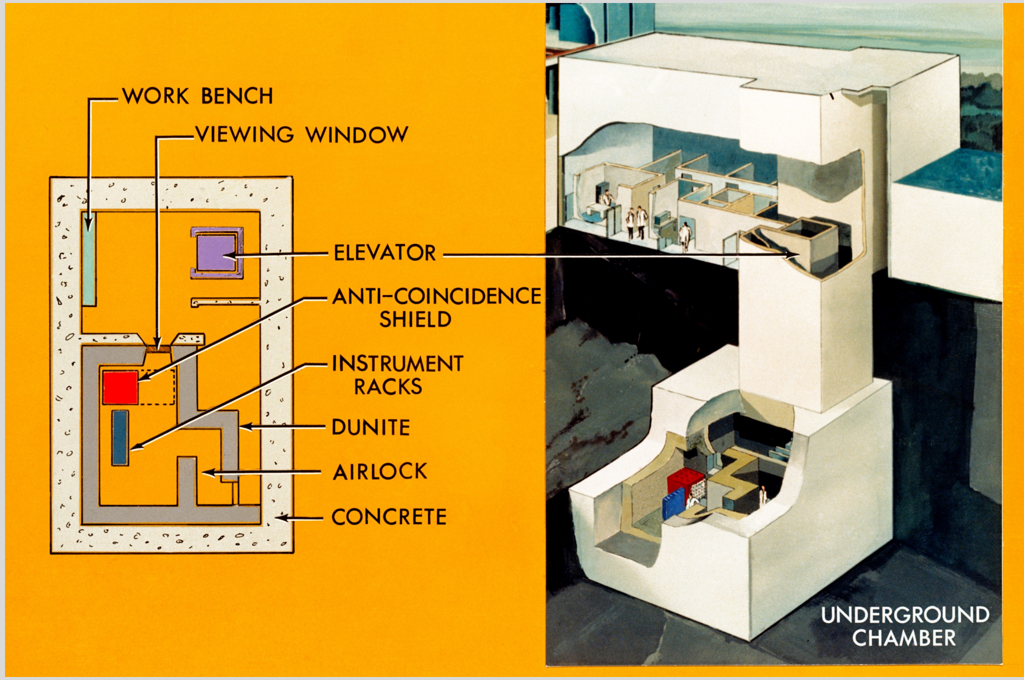
Advances in Laboratory Instrumentation

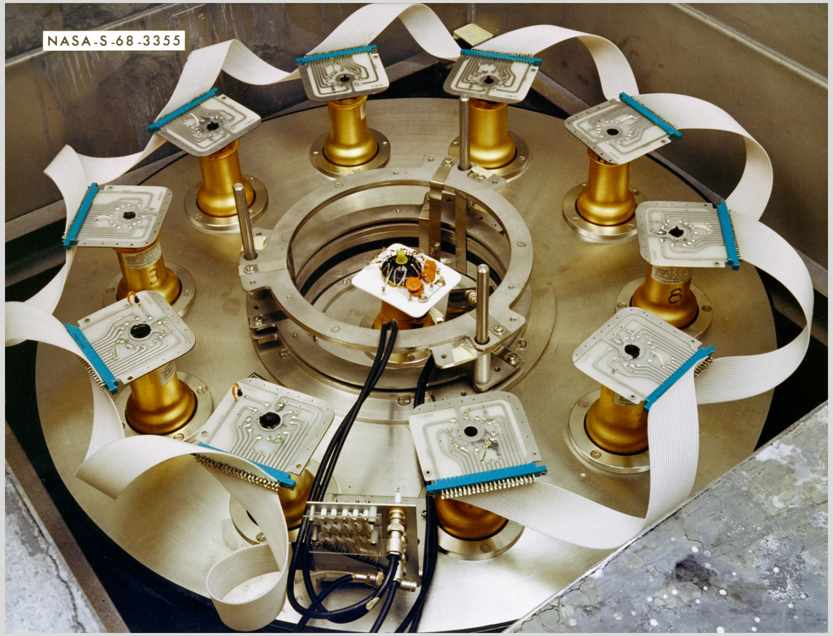


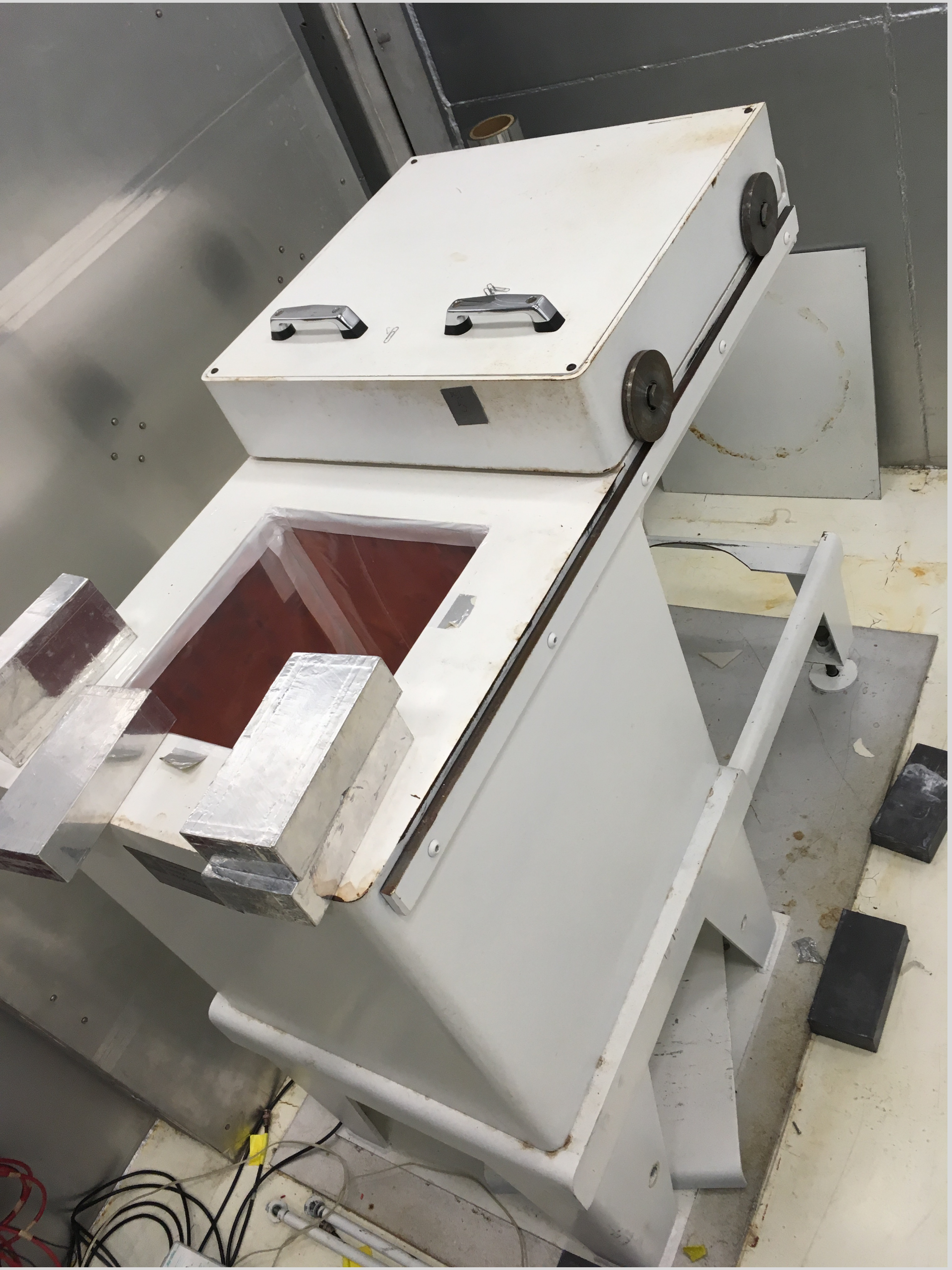
From Westphal et al., MAPS 2017

Bulk/Trace Element Measurements Circa 1969

Instrumental Neutron Activation Analysis

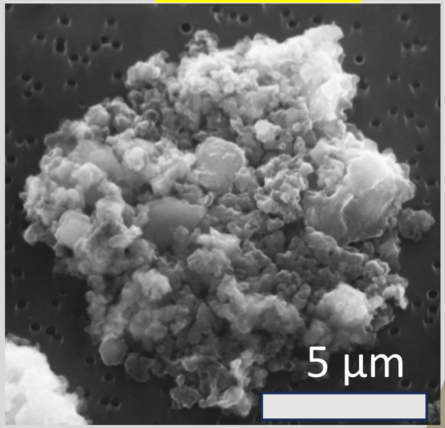






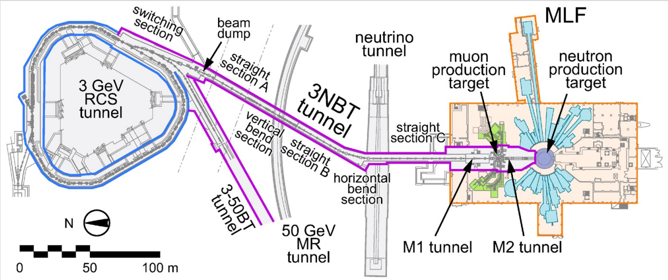
Trace Element Measurements Circa 1989

Instrumental Neutron Activation



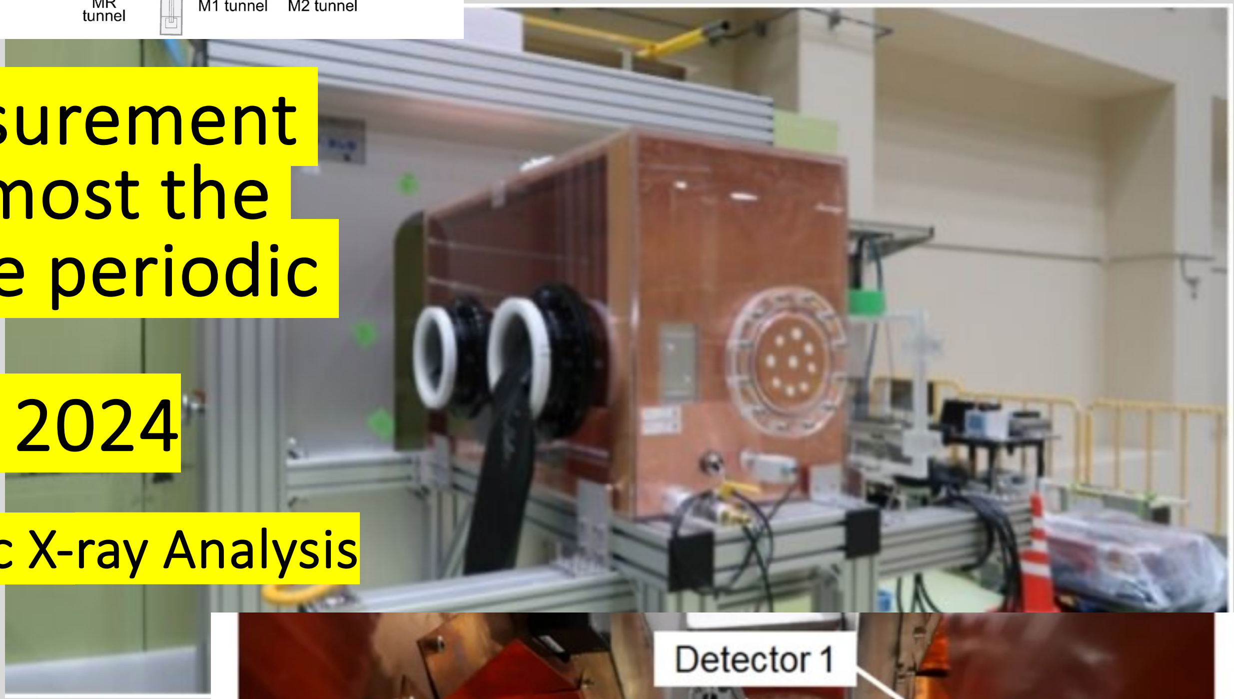
- Muon X-rays conducted at the Japan Proton Accelerator Research Complex (J-PARC) - the most intensely pulsed muon beam in the world

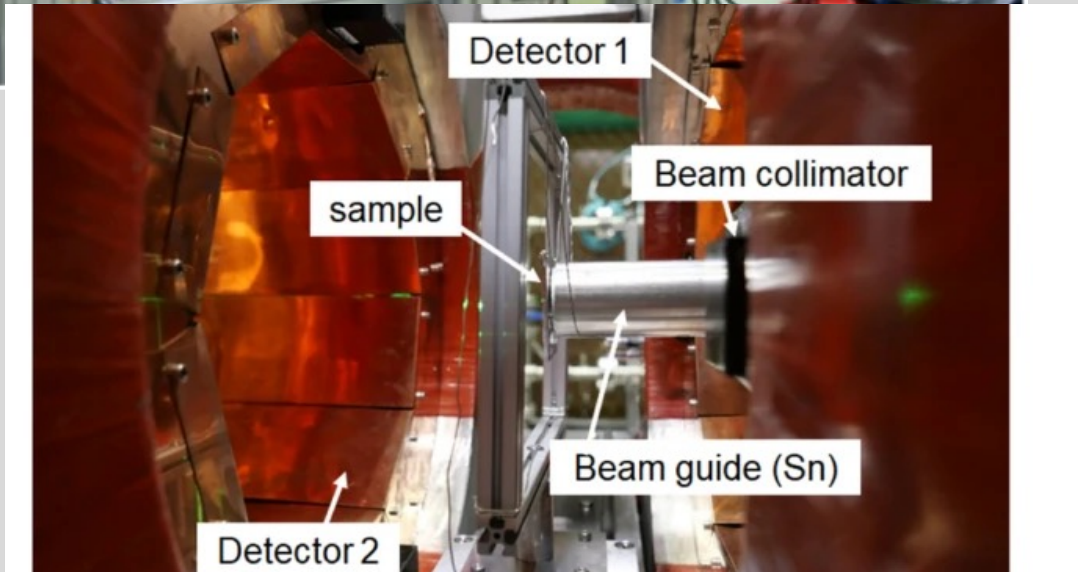
From Ninomiya et al., Nature, 2024

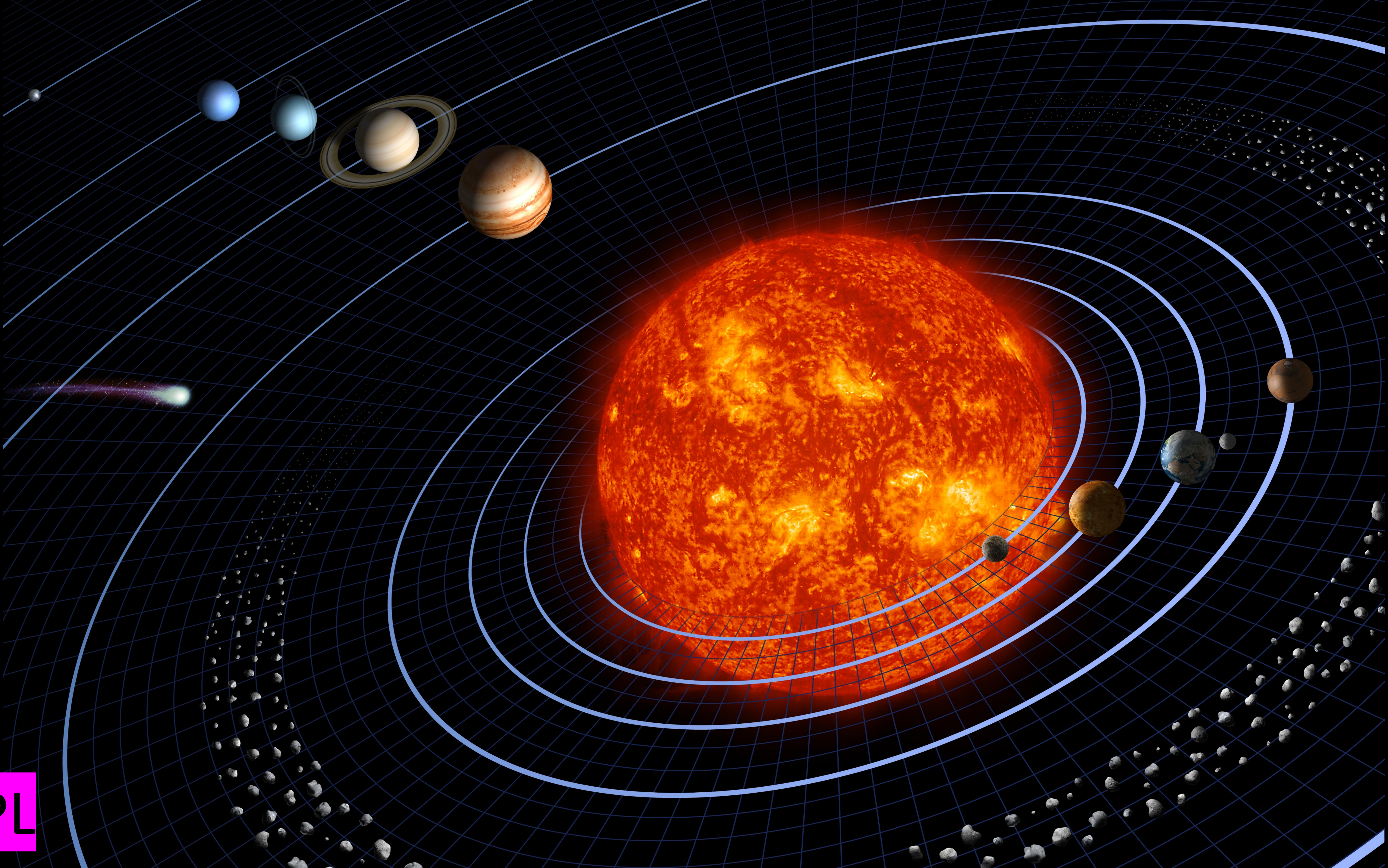


Measurement of almost the entire periodic table
Circa 2024

Muonic X-ray Analysis

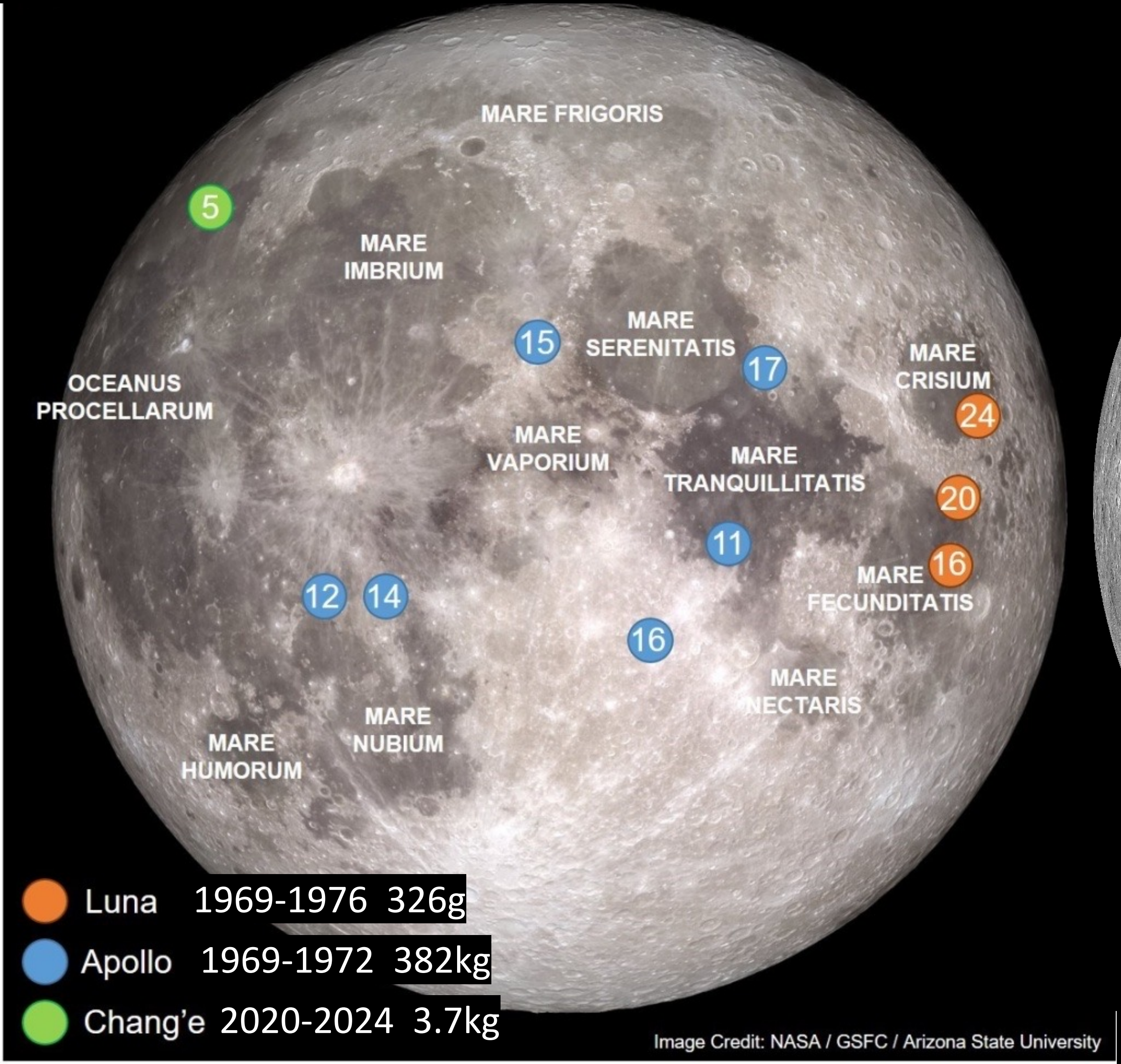




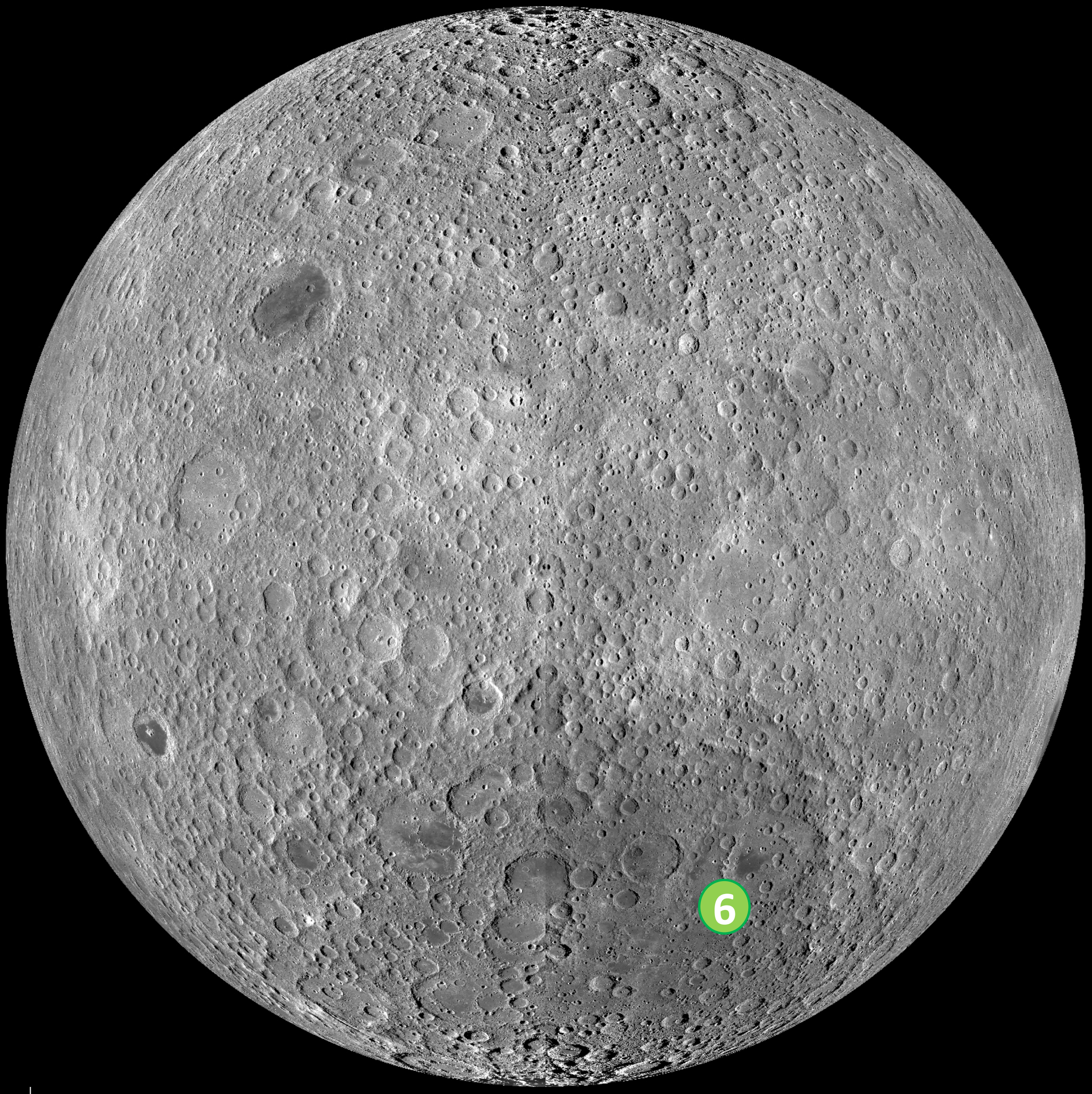


JPL

Lunar Near Side



Lunar Far Side



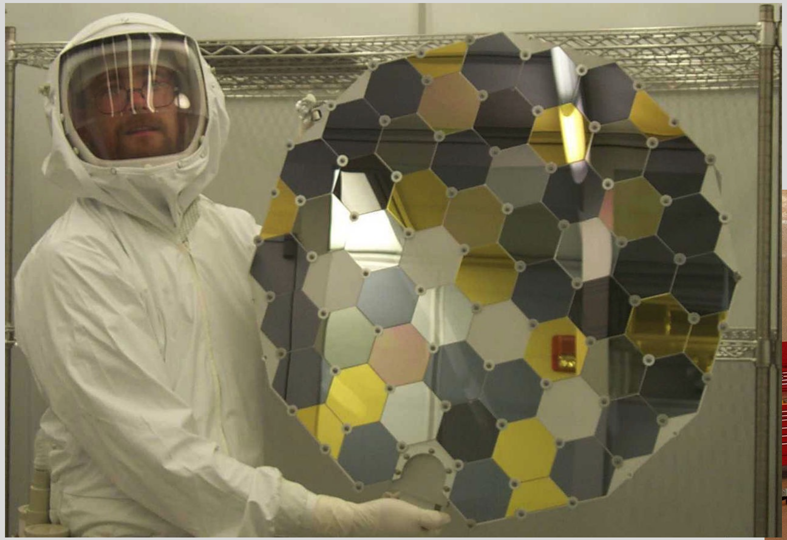
The Moon
Apollo, Luna, Chang'e, Lunar Meteorites

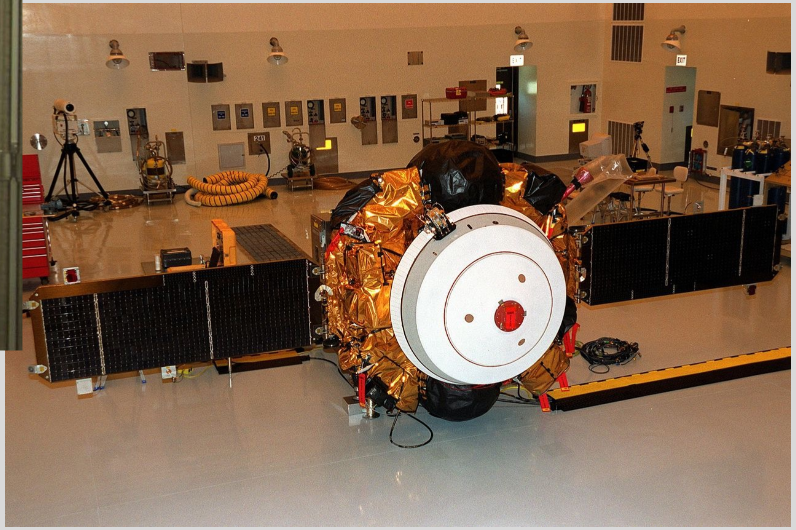
Major unanswered questions:

- What is the nature and amount of water at South Pole?
- Was there a global lunar magma ocean (and can we verify alternative hypotheses)?
- What does the lunar mantle look like?
- Details of the Bombardment history, including the age of South Pole Aitken basin, and possible involvement with early life emergence on Earth
- How did the solar system's climate (solar wind, cosmic rays) change throughout time?
- What was the detailed thermal history of the Moon (e.g. ages of oldest and youngest basalts)?

The Sun
The Genesis Mission 2001-2004

- Despite landing issues, the mission was very successful



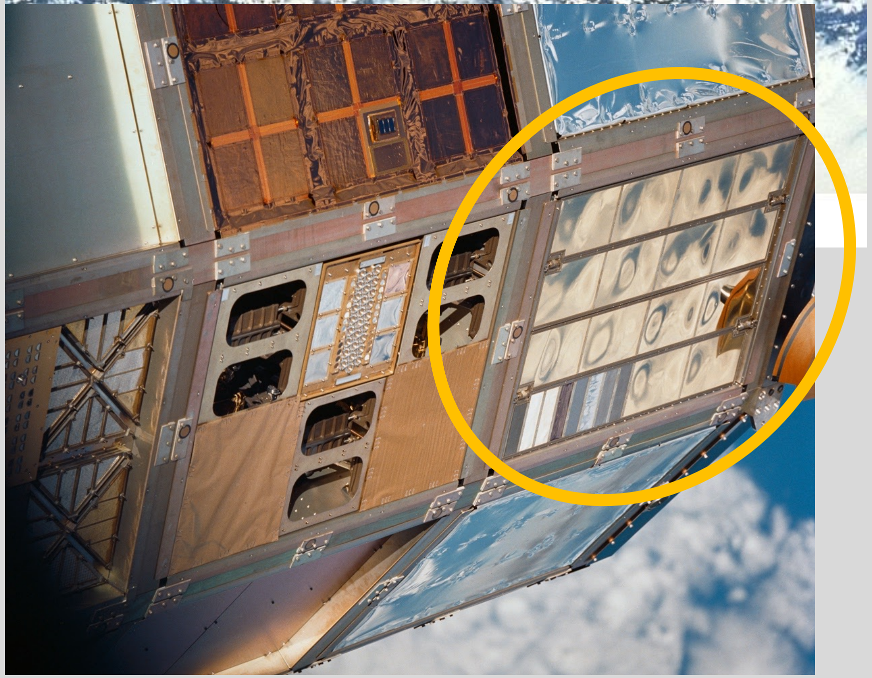


The Genesis Mission 2001-2004

- **Major result:** Measurement of O isotope abundances – Sun has a higher proportion of ^{16}O relative to the Earth, Moon, Mars, and bulk meteorites
  - This implies that an unknown process depleted ^{16}O by about 6% from the Sun's disk of protoplanetary material prior to the coalescence of dust grains into the inner planets and the asteroid belt
- **Major unanswered question**: What is the carbon bulk/isotope abundance of the solar photosphere?

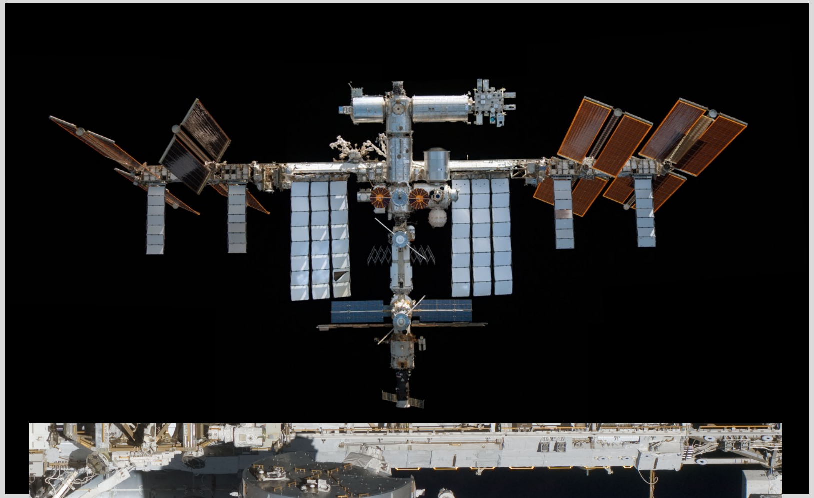
Interplanetary Dust – from Asteroids and Comets
Collected in Earth Orbit

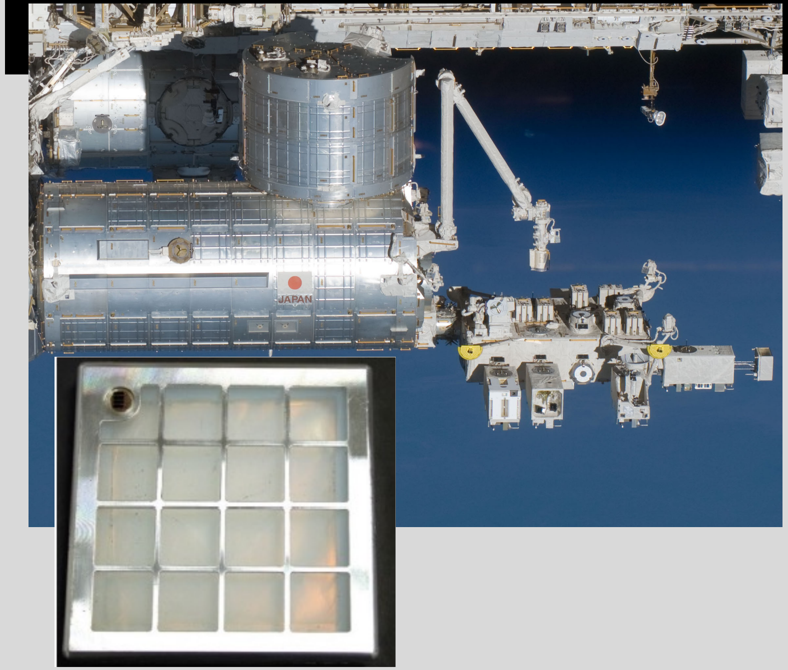
Long Duration Exposure Facility 1984-1990



Micrometeoroid and Debris experiment on MIR 1996

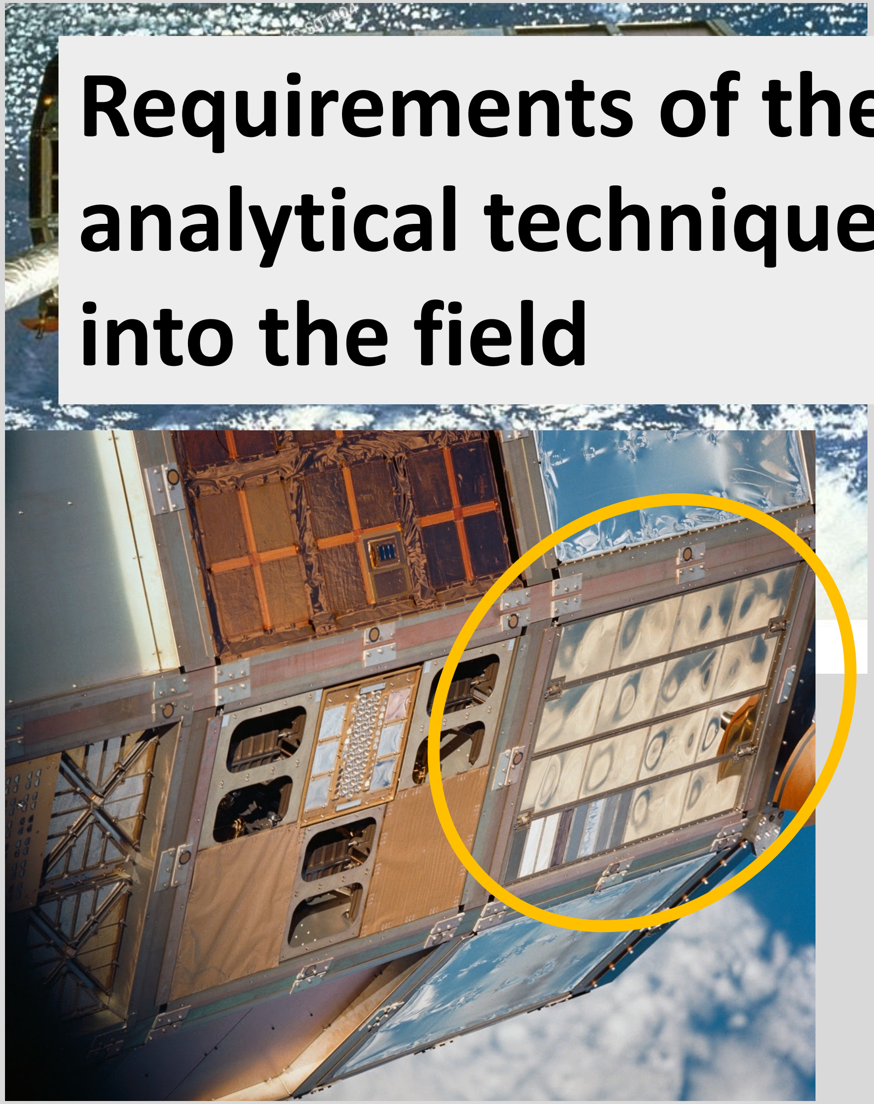
Tanpopo experiment on ISS 2015-2018



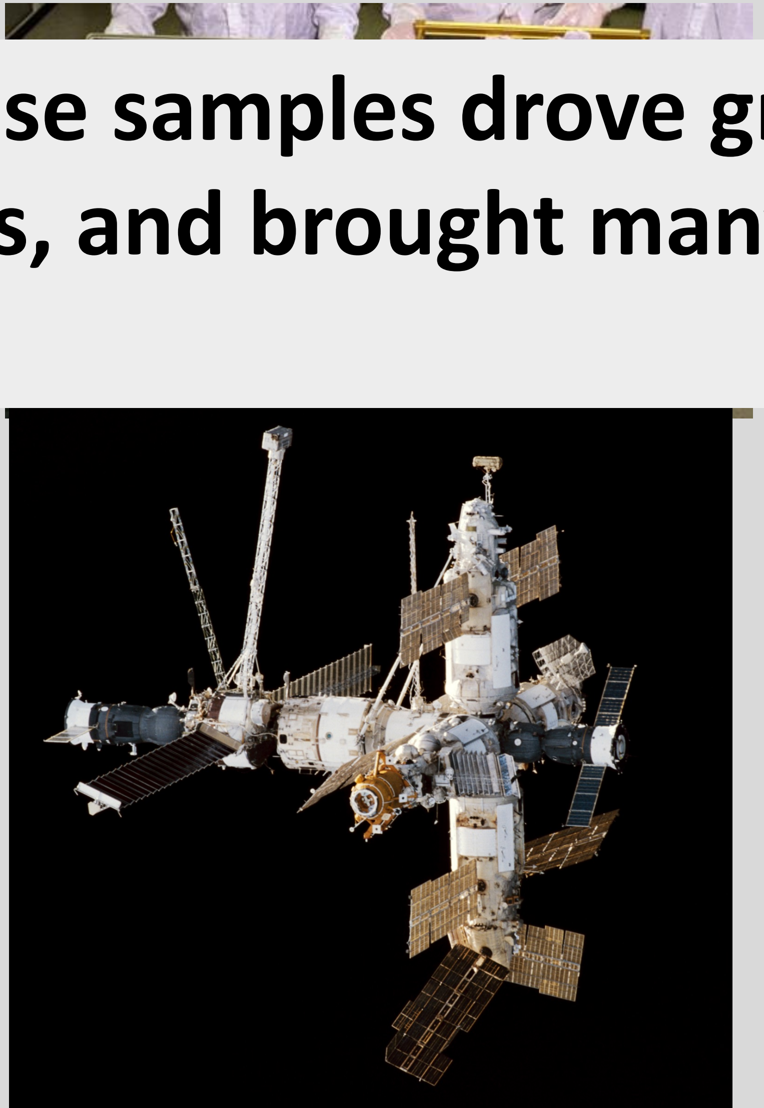


Interplanetary Dust – from Asteroids and Comets Collected in Earth Orbit

Long Duration Exposure Facility 1984-1990



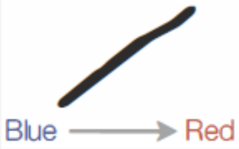
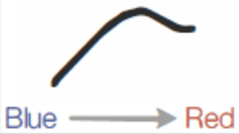
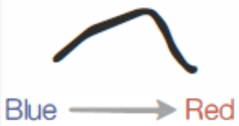
Micrometeoroid and Debris experiment on MIR 1996



Tanpopo experiment on ISS 2015-2018

Requirements of these samples drove great advances in analytical techniques, and brought many new scientists into the field

ASTEROID TAXONOMIC CLASSIFICATIONS

Major Taxonomic Types	Reflectance Spectrum (0.4-0.9 um)	Spectral Features	Visible Albedo	Suspected Composition
D (D,T)		Relatively featureless spectrum Steep red slope	0.02-0.06	Primitive carbonaceous Organic-rich compounds Hydrated minerals
C (C,B,F,G)		Slight bluish to slight reddish slope Shallow to deep absorption blueward of 0.5 µm Hydrated asteroids with absorption at 0.7 and 3.0 µm	0.03-0.10	Hydrated minerals Silicates Organics
X (E,M,P)		Slightly reddish spectrum E: absorption features at 0.5 and 0.6 µm	E: 0.18-0.40 M: 0.10-0.18 P: 0.03-0.10	E: Enstatite-rich M: metallic, Nickel-Iron P: Carbonaceous, Organics
S (S,Q,A,K,L)		Moderately steep red slope ($\lambda < 0.7$ µm) Shallow to deep absorption at 1.0 and 2.0 µm	0.10-0.22	Stony composition Magnesium Iron silicates
V		Moderate to steep red slope ($\lambda < 0.7$ µm) Very deep absorption at 1.0 µm	0.20-0.60	Volcanic basalts Plutonic rocks

From Bodnarik et al., 2011

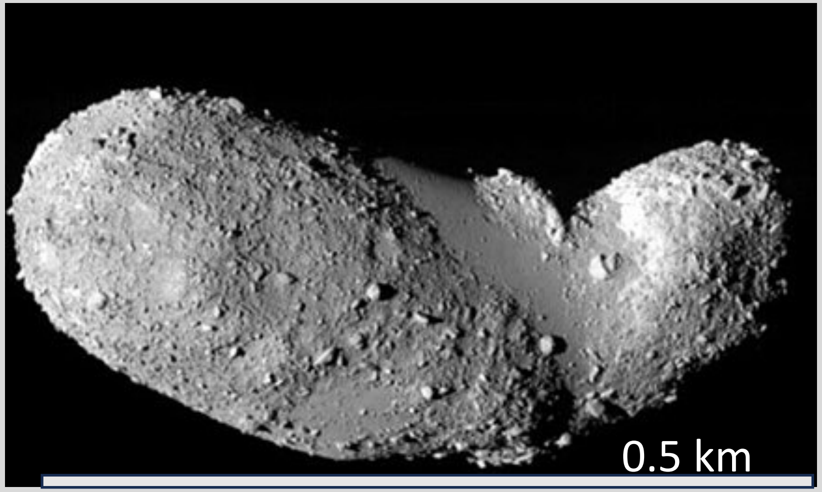
Asteroid Sample Return Missions

Hayabusa

2003-2010

S class

<1g recovered

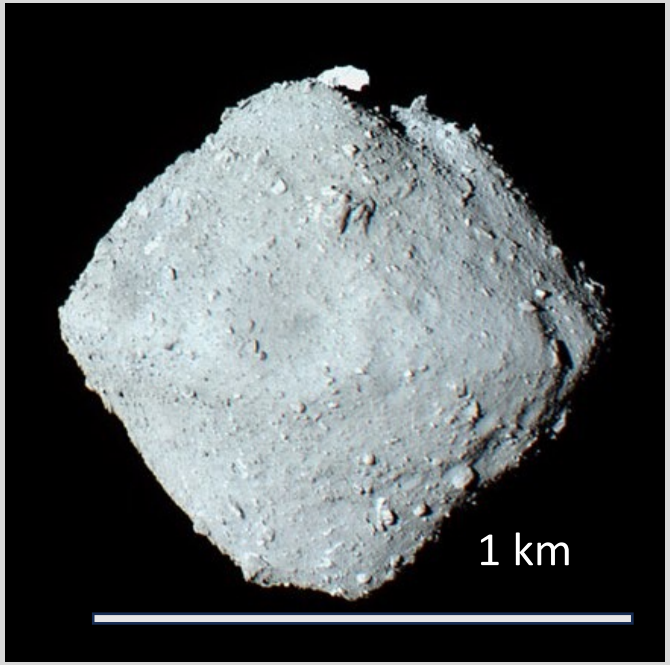


Hayabusa2

2014-2020

C class

5.4g

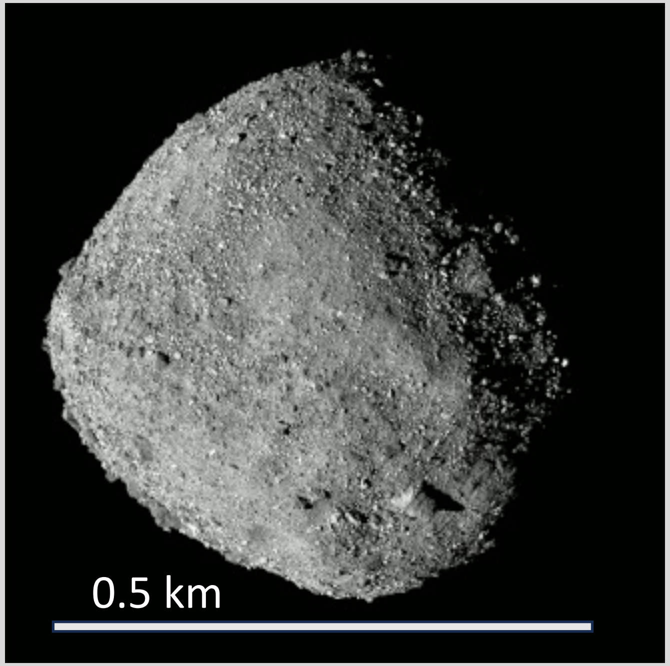


OSIRIS-REx

2016-2023

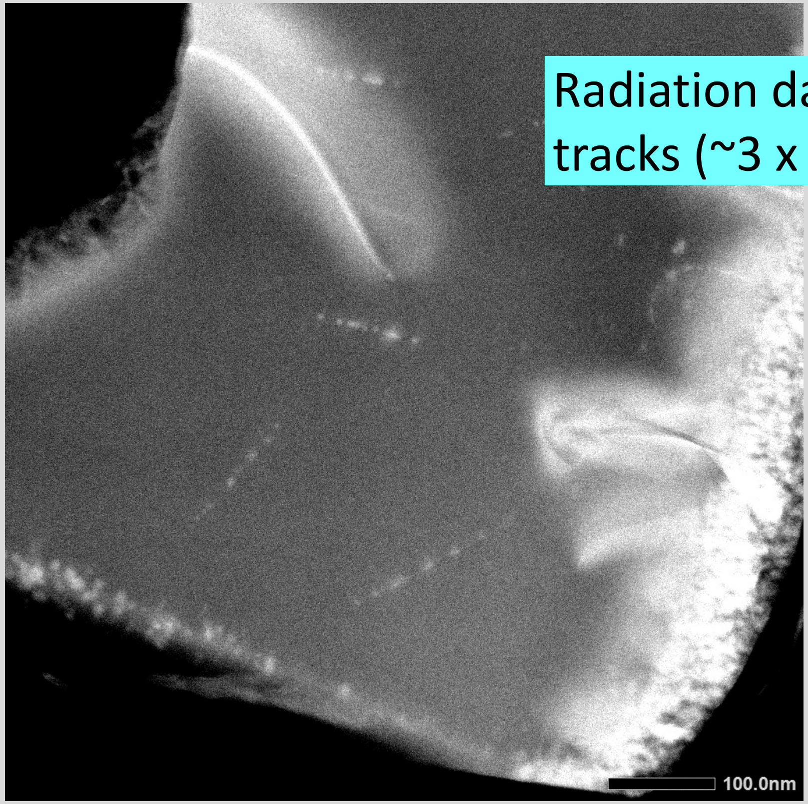
B class (subclass of C)

121g



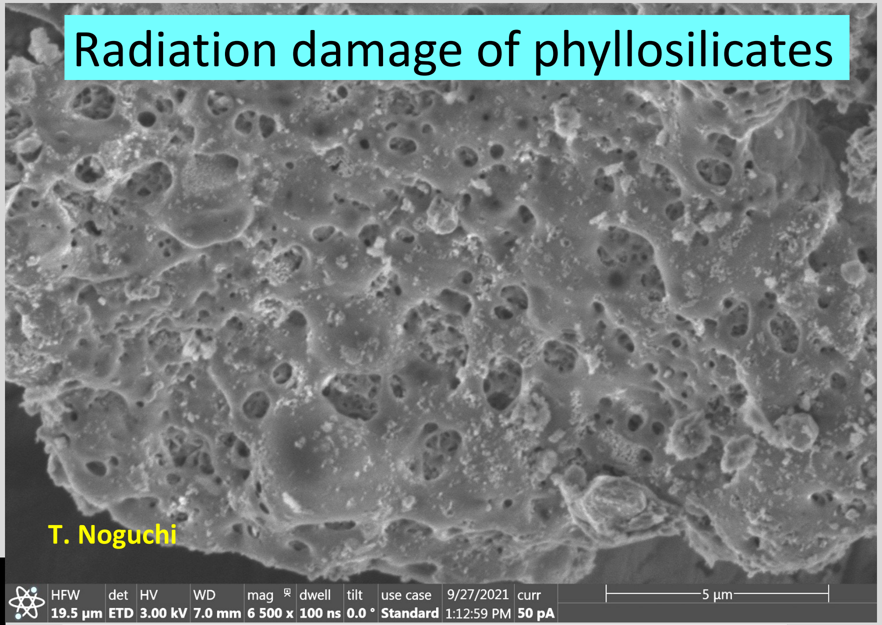
Severe textural modification of asteroid Ryugu phyllosilicates by Space Weathering

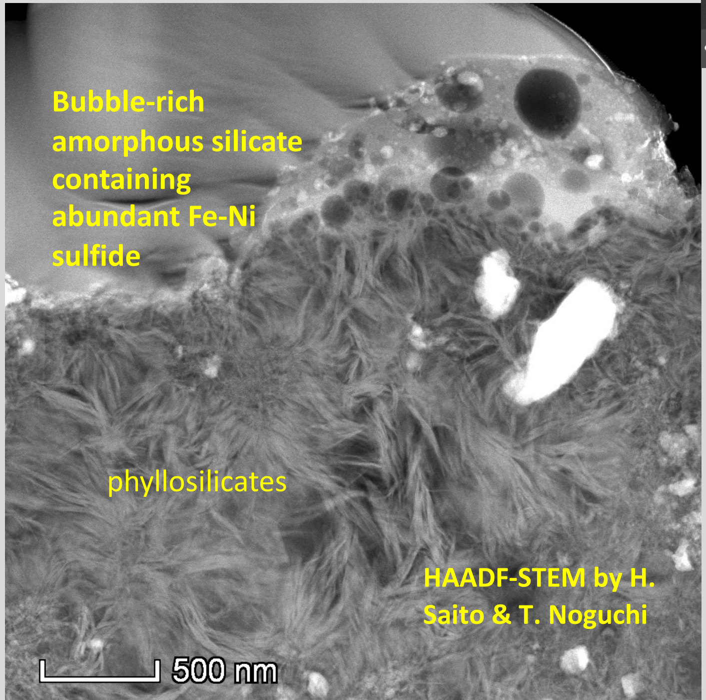
Radiation damage and solar flare tracks (~3 x 10^8 cm^{-2}) in olivine

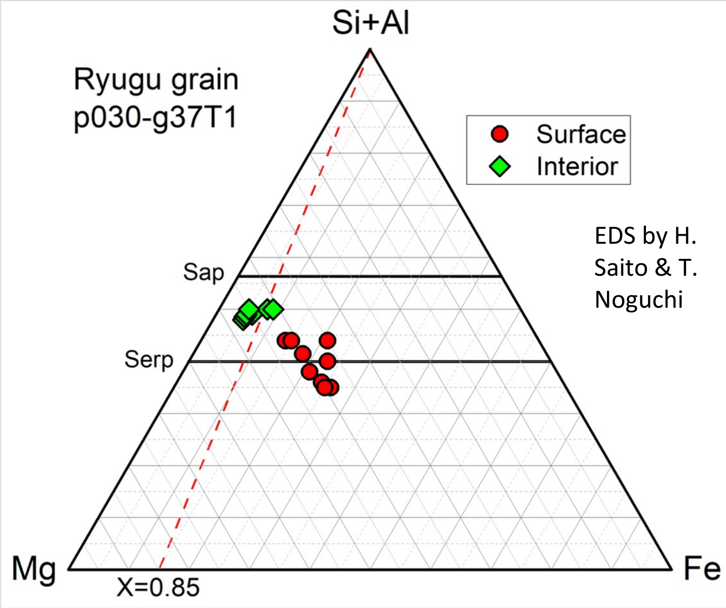


LAADF-STEM by Y. Igami & T. Matsumoto

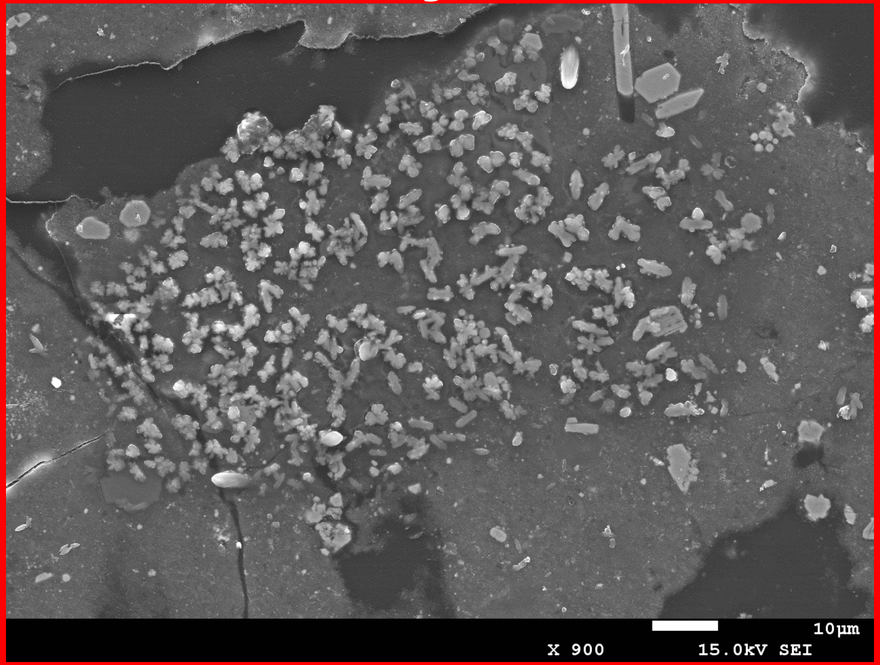
Radiation damage of phyllosilicates







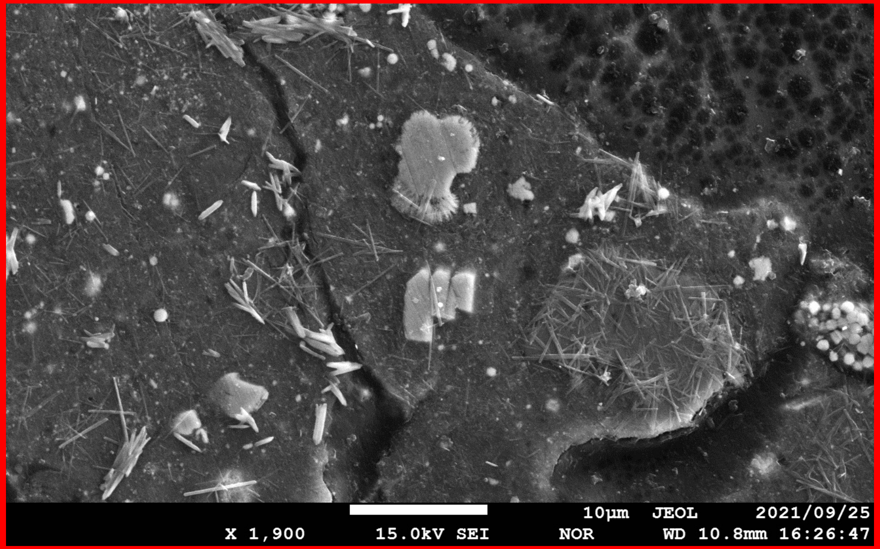
Sulfate growth on Ryugu grain surface – from terrestrial hydration/oxidation/hydrolysis

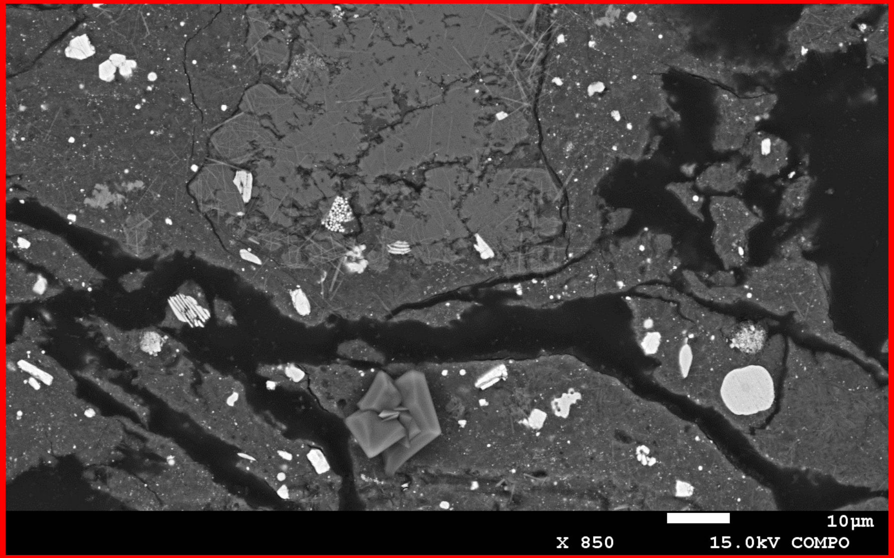


Despite the sample being maintained in N_2 or a near vacuum

Analogous changes were observed

in the asteroid Itokawa samples





Asteroid Sample Return Missions
Top Level Results

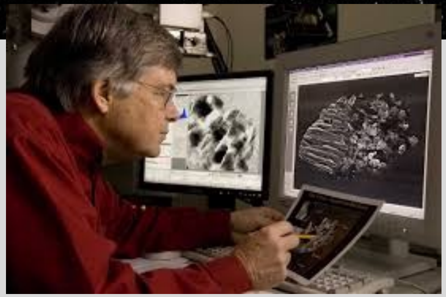
- S-class asteroids: Verified to be source of Ordinary Chondrite meteorites
- C-class asteroids: Verified to be the source of at least some carbonaceous chondrite meteorites – perhaps also dead comets?
- C-class asteroids: verified to be very volatile (including water and CO_2) and organic rich
- Both Ryugu and Bennu are essentially identical to CI chondrite meteorites
  - CIs are a very rare meteorite type, but are very friable and so long suspected to be significantly more common than indicated by meteorite recovery statistics
- Space Weathering was demonstrated to significantly affect asteroid reflectance spectra
  - Includes effects of solar wind implantation, micrometeoroid impacts, vacuum and thermal processing
- Returned materials were phenomenally reactive with Earth's atmosphere
  - Oxidation and hydrolysis begin immediately

Asteroid Sample Return Missions
Major unanswered Questions

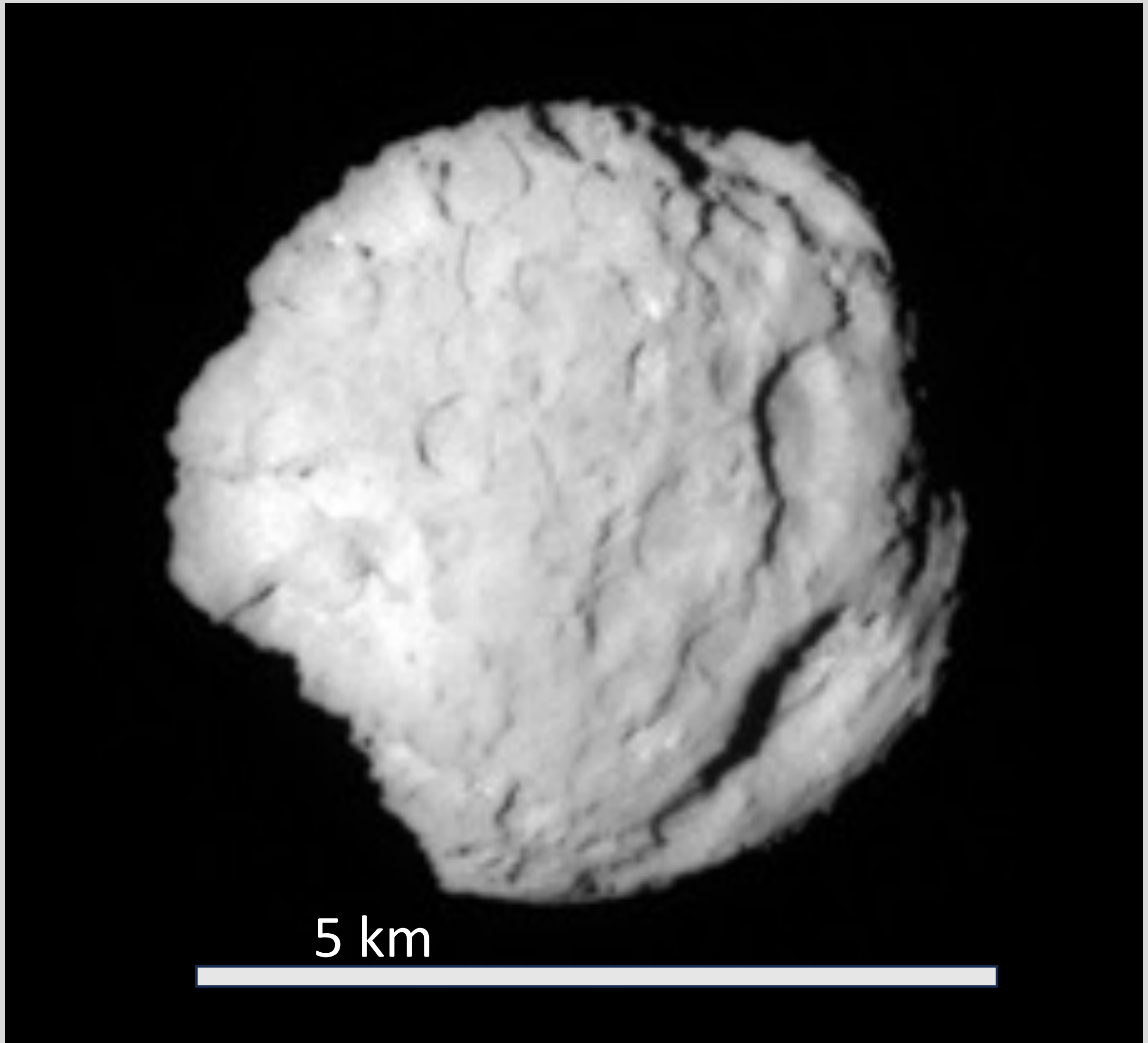
- Absolute chronology of many geological processes still poorly understood
- Residual difficulties interpreting reflectance spectra of asteroids
  - Bennu was presumed to be a CM chondrite, but ultimately proved to be CI1/2
- Majority of asteroids still poorly understood

Comet Sample Return Mission
Coma grain return from Jupiter family Comet 81P/Wild2

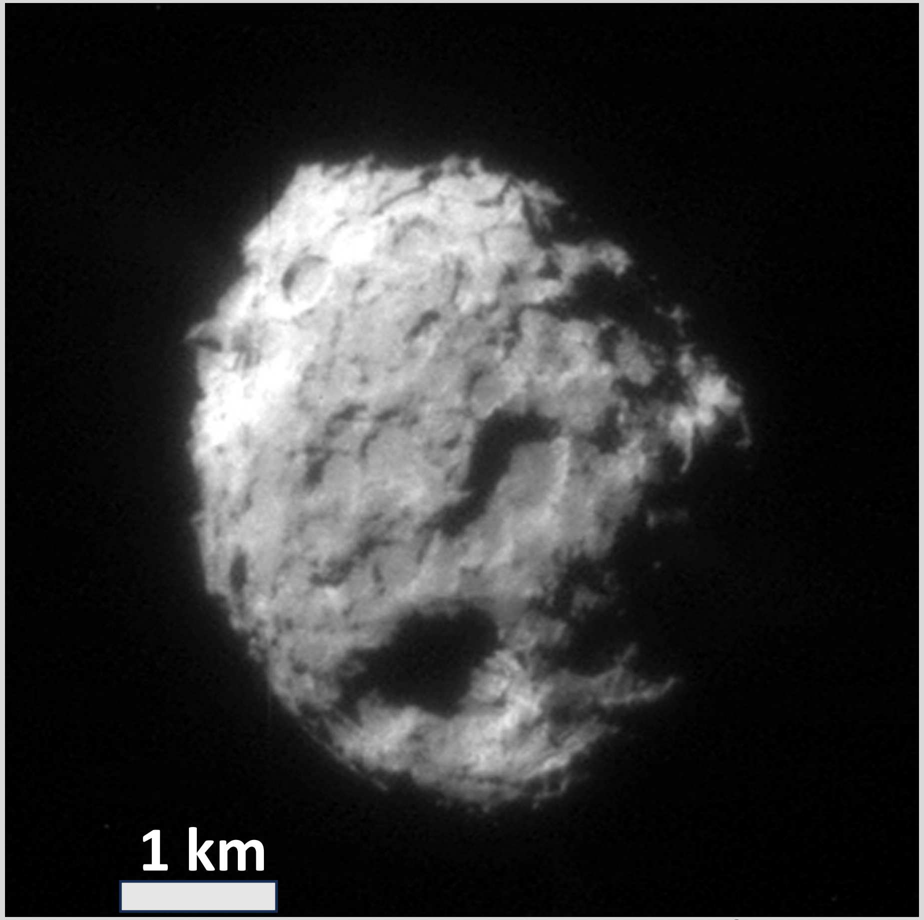
1999-2006

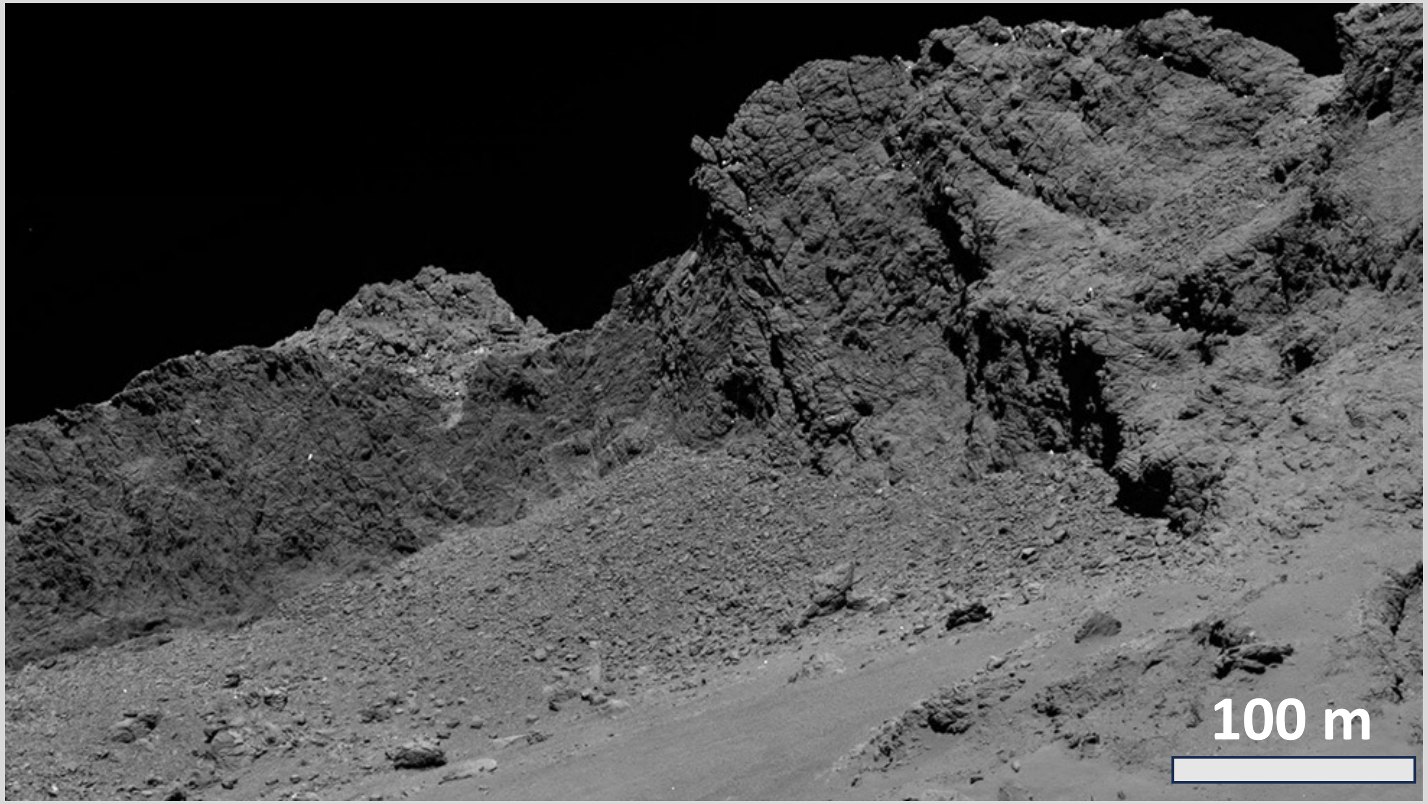


Don Brownlee



Imaging of 81P/Wild 2 compared to that for comet 67P/Churyamov-Gerasimenko

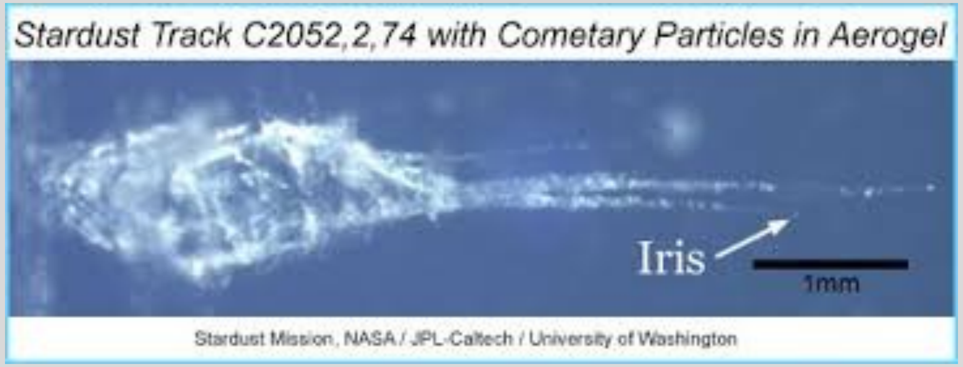




Lesson: Don’t make your camera optics the coldest part of the spacecraft

Limitations to Wild 2 Sample Knowledge

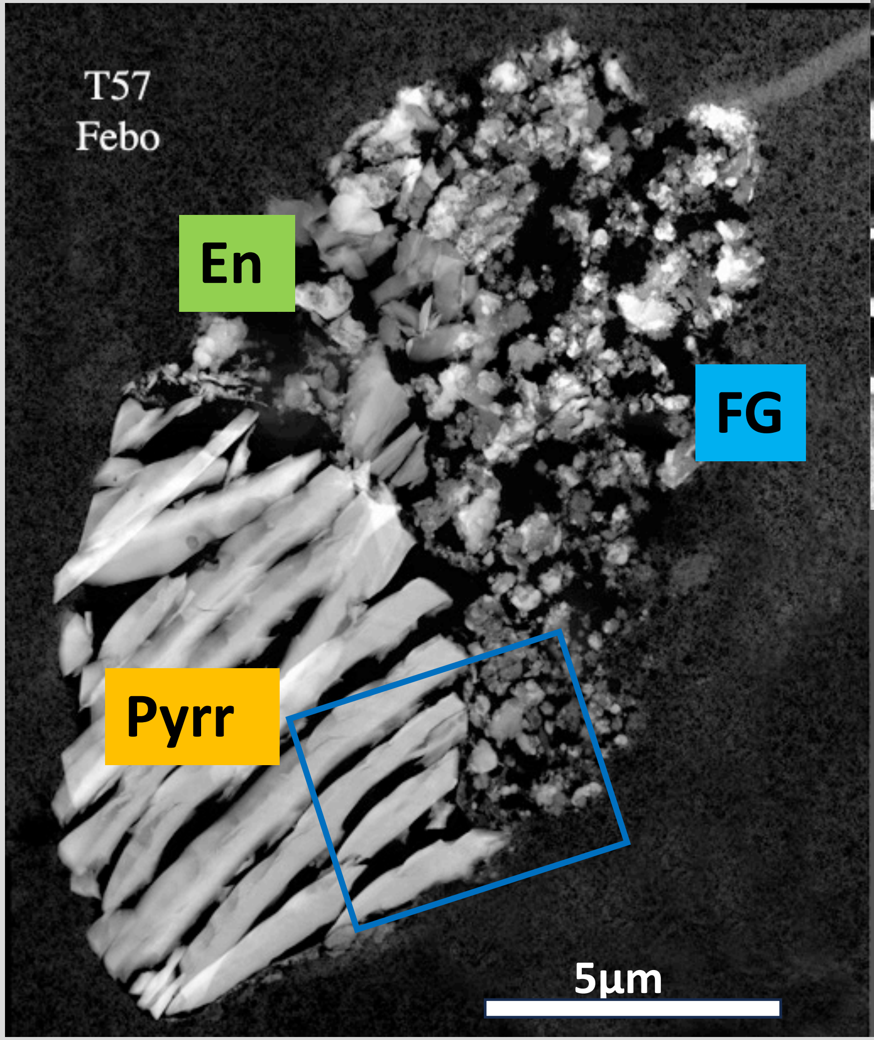
- Samples were collected at 6.2km/sec, resulting in the melting and vaporization of ~90% of the mass of each cometary grain

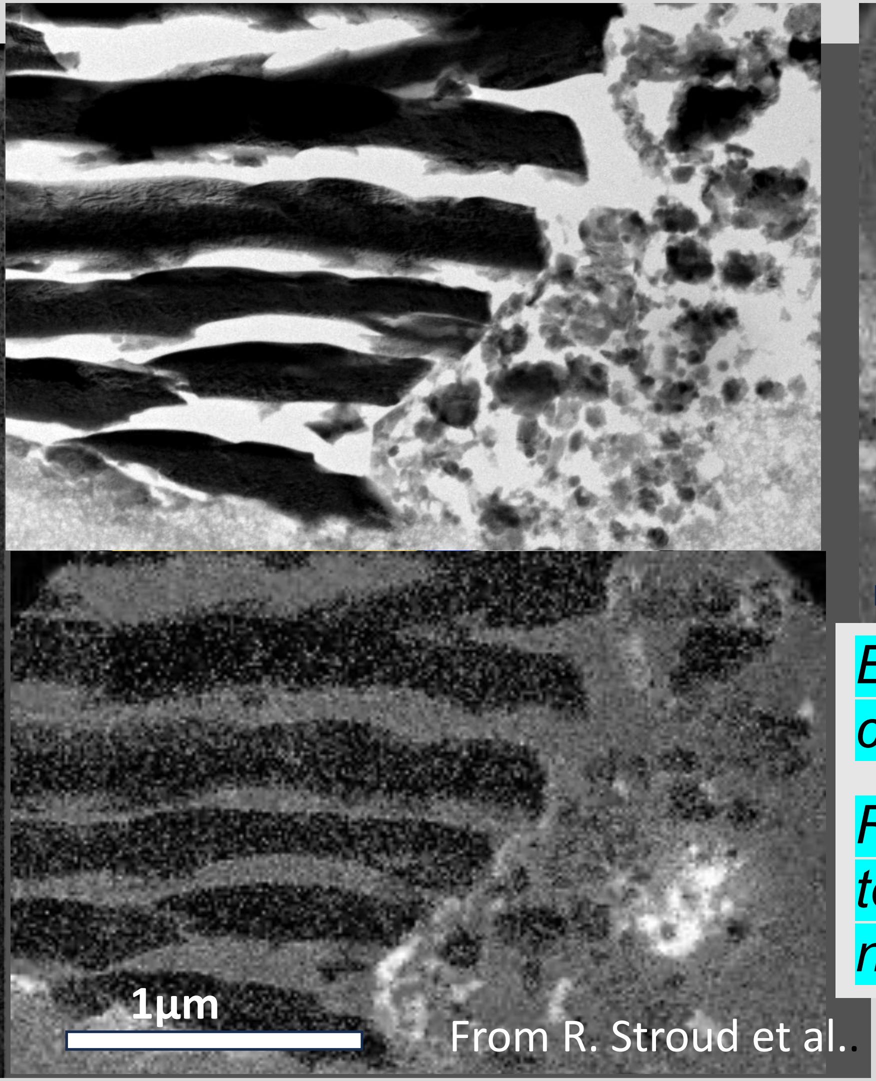


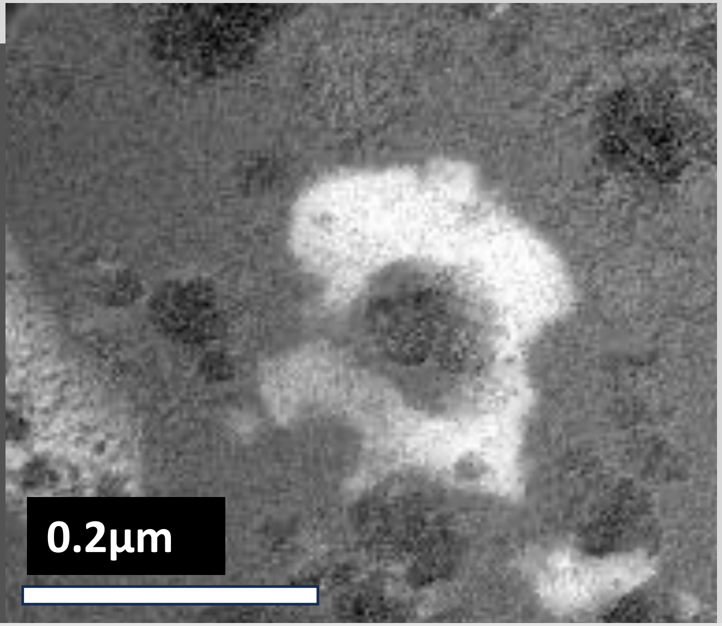
- This 90% was intimately mixed with silica aerogel
- In general, this most affected the finest-grained portion of the samples, as expected, but there are exceptions..

Fine-grained material including organics shielded by large sturdy crystals

Brownlee et al.







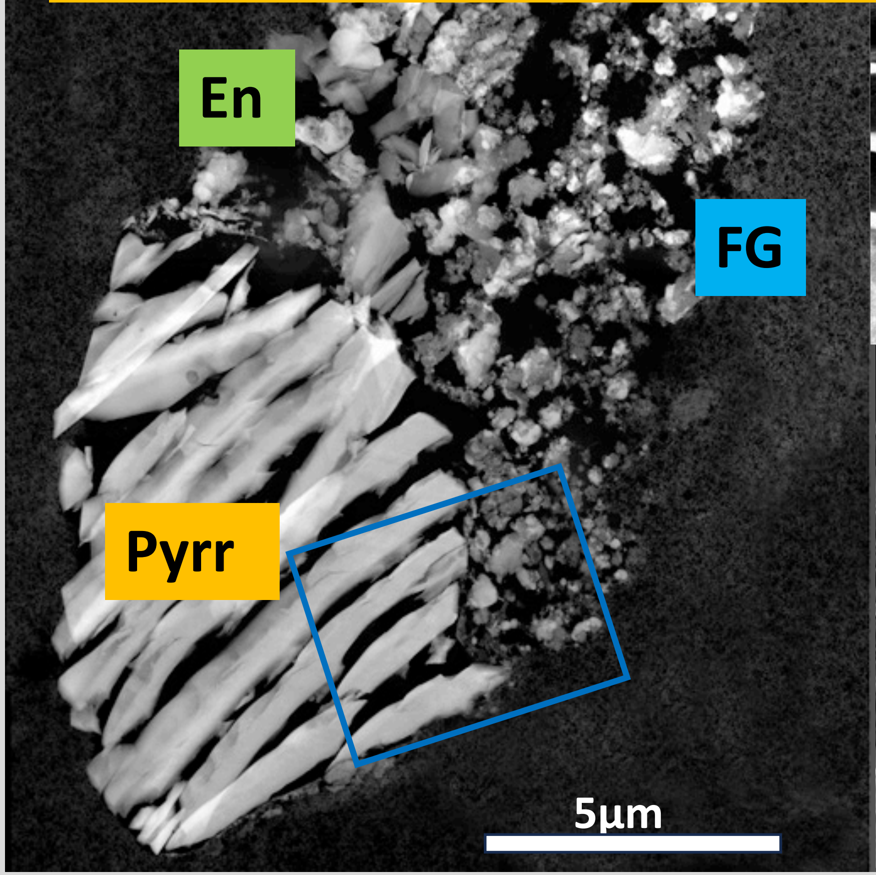
Energy-filtered image of organic carbon with ^{15}N excess

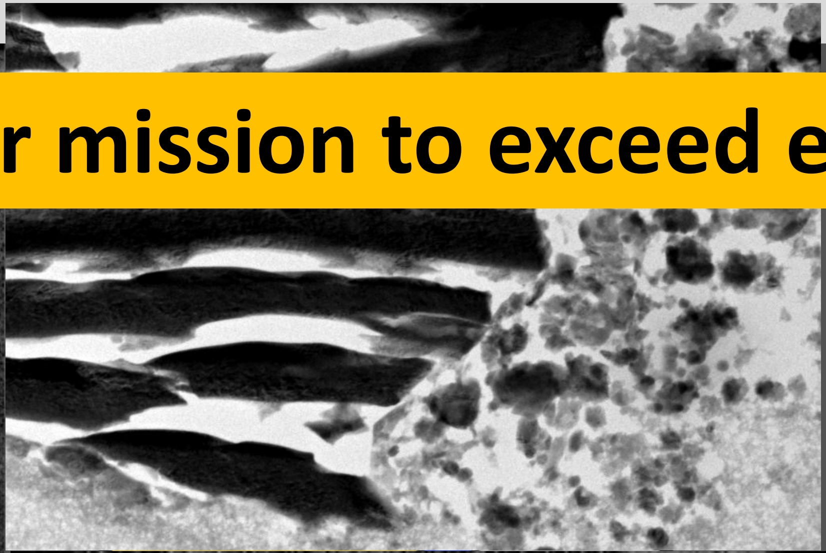
Requires very cold formation temperature – at the edge of the nebular disk or beyond

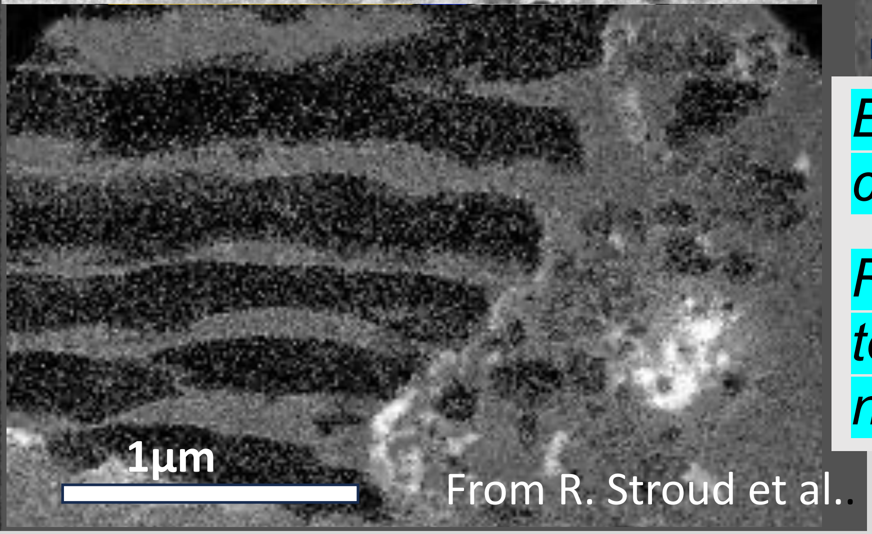
Fine-grained material including organics shielded by large sturdy crystals

Brownlee et al.

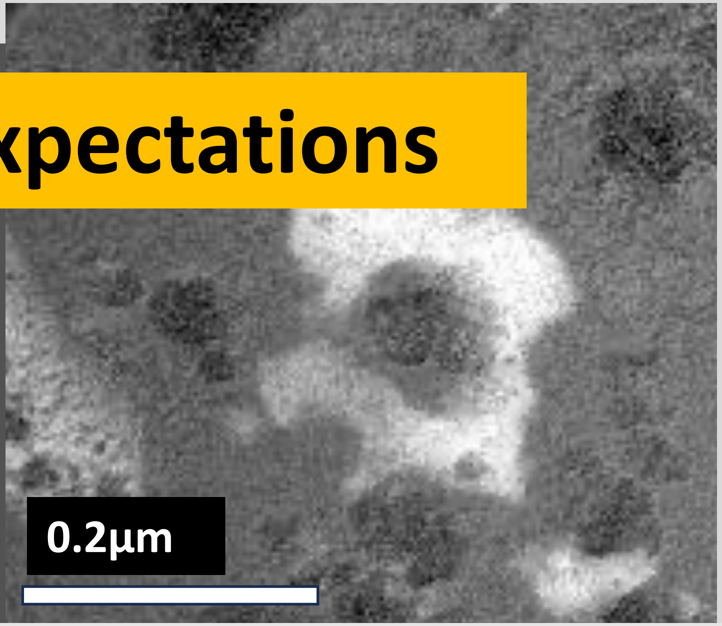
Be prepared for your mission to exceed expectations







From R. Stroud et al..



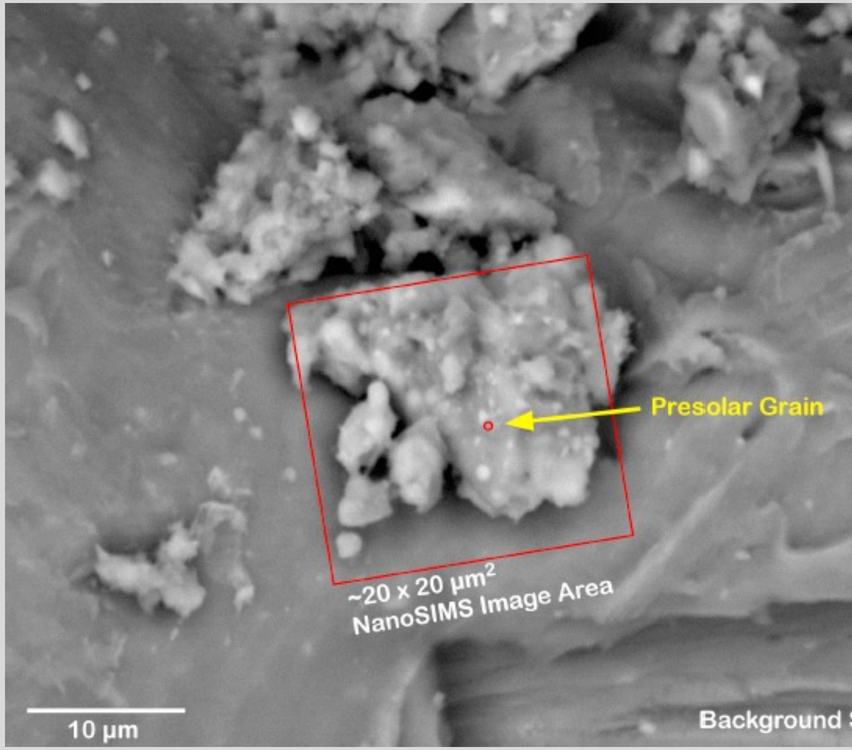
Energy-filtered image of organic carbon with ^{15}N excess

Requires very cold formation temperature – at the edge of the nebular disk or beyond

Presolar Grains in Wild 2

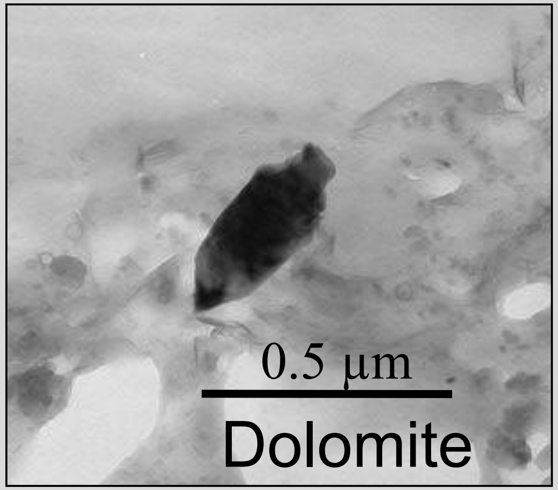
- The presolar grain abundance in Wild 2 is ~1000 ppm
- This is in the same range observed in anhydrous chondritic Iinterplanetary Dust Particles and higher than in chondrites
- Perhaps their abundance was higher in the destroyed fine-grained material
- In any case, Wild 2 was not dominated by presolar material

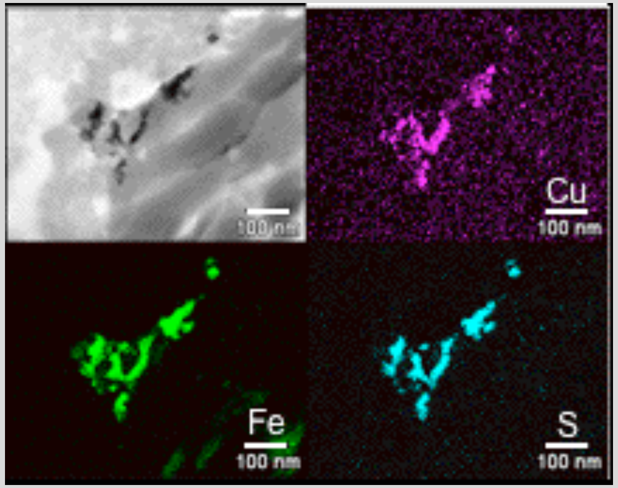
Floss et al. 2013, Larry Nittler



Was Liquid water present in Comet Wild 2?

- No phyllosilicates reported
- Rare Ca-Mg-Fe carbonate and Cubanite ($CuFe_2S_3$) of possible aqueous origin
- So liquid water may have been present, but was at best very rare
- Were the hydrous phases destroyed during sample collection?
- Searches for these continue
- This obviously a critical issue if it can be shown that comets were ever warm enough to sustain a significant amount of liquid water





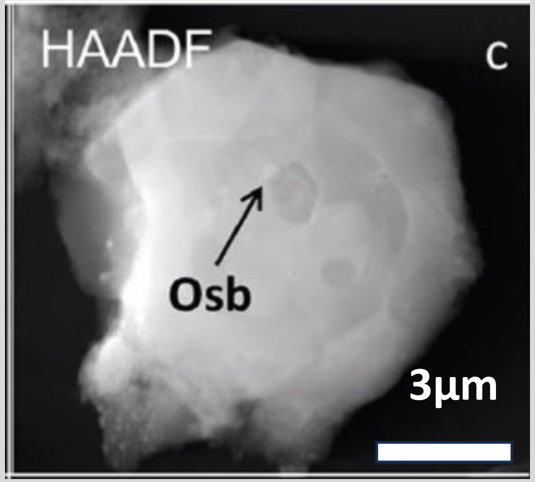
Cubanite

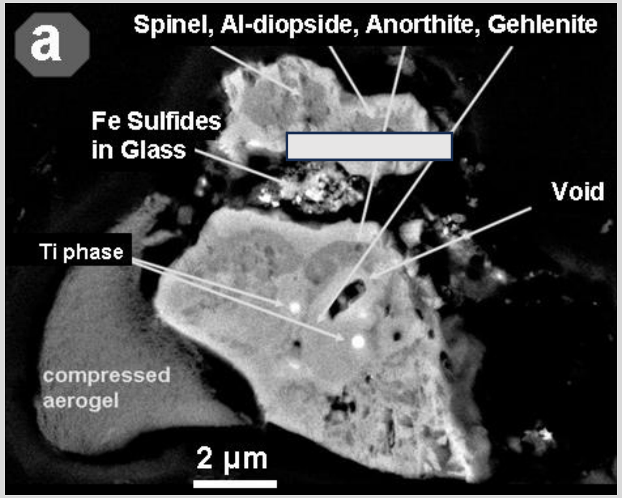
High Temperature Wild 2 Materials
Calcium Aluminum-rich Inclusions- CAI

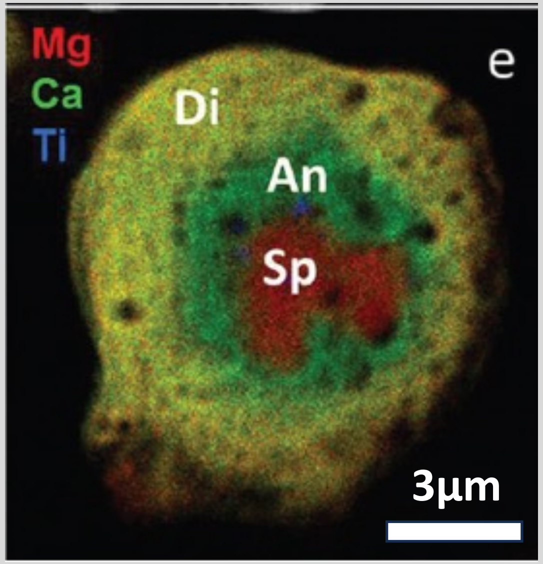
•Wild 2 CAI present in about the same abundance as in carbonaceous chondrites (~0.5 volume%)

•Wild 2 CAI appear to lack some of the most refractory CAI types (such as Type A, and hibonite-spinel varieties) – so were not heated as much as those in meteorites

•Are these differences real, or just apparent? Resolving this uncertainty is a high priority for future research

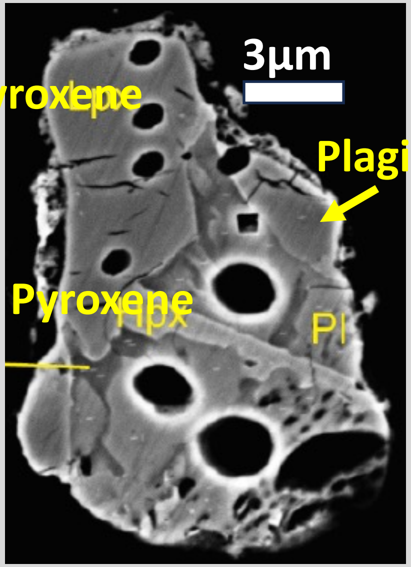


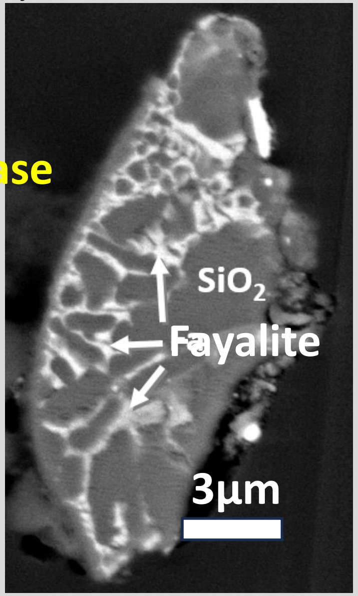


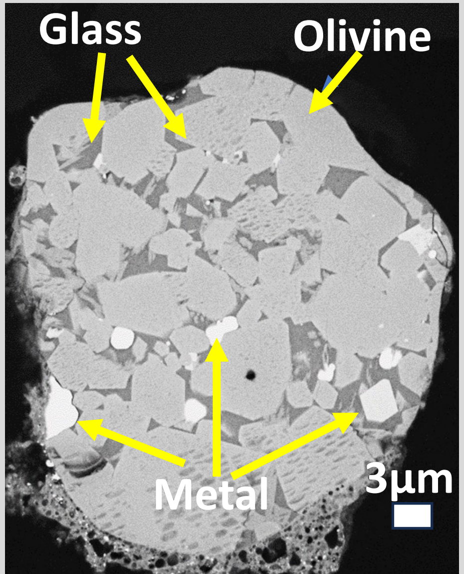


High Temperature Wild 2 Materials: Chondrules

- Wild 2 contains chondrules, which formed from melting of nebular dust and earlier generations of chondrules, and are of probable inner solar system origin
  - There are proposals for making these materials just outside the orbit of Jupiter
- There are also significant differences in the chemistry and mineralogy from meteoritic chondrules
  - the most common type of meteoritic chondrule is FeO- and volatile-poor chondrules, called Type I, whereas few Type 1 have been identified in Wild 2 (Joswiak *et al.*, MAPS 2012; LPSC 2024)
- Many more analyses, including oxygen isotope studies, are needed to assess the range of chondrule formation conditions

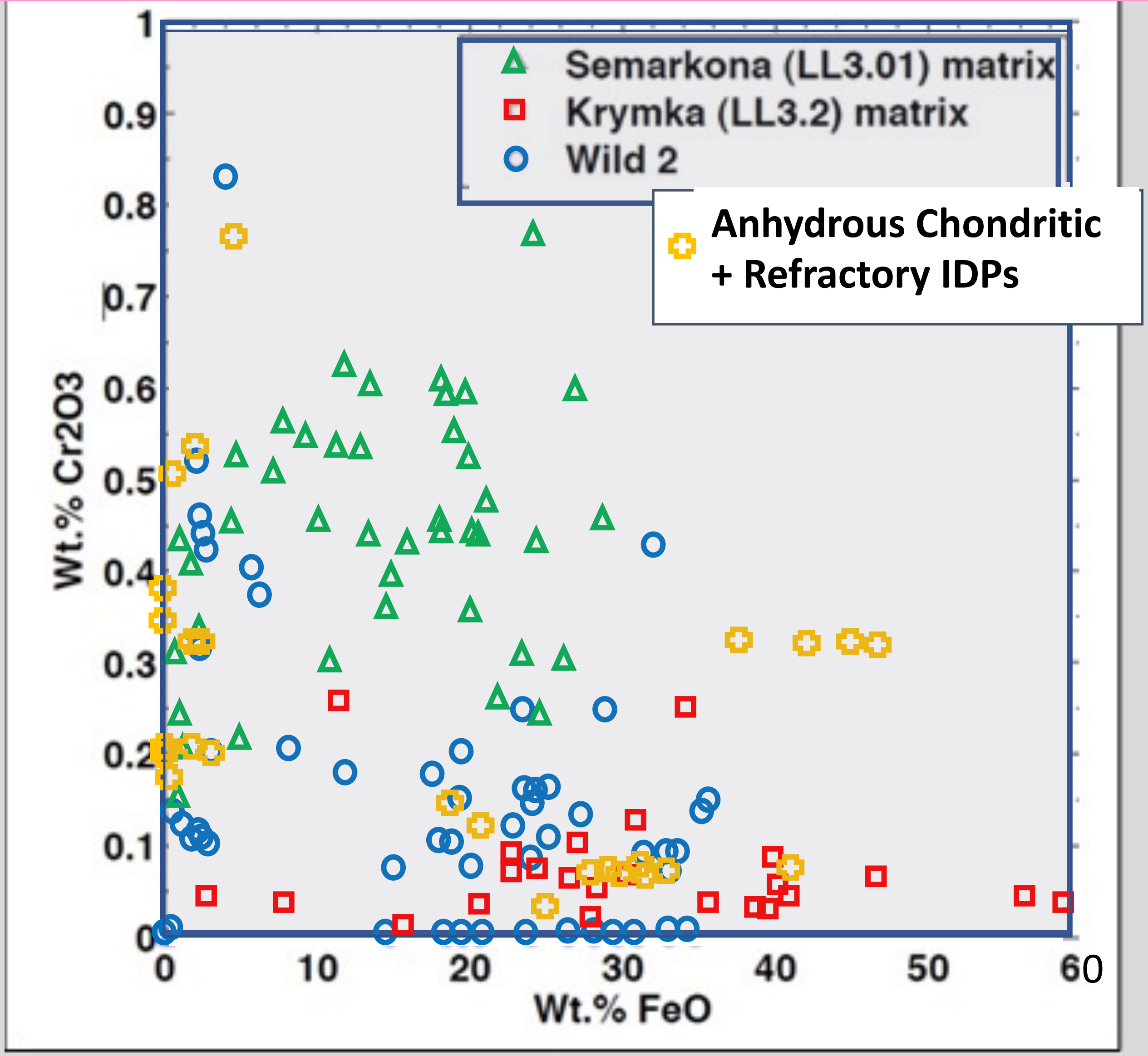






Nakamura et al., Science, 2008
Joswiak *et al.*, MAPS 2012; LPSC 2024

Were some comet components thermally metamorphosed?



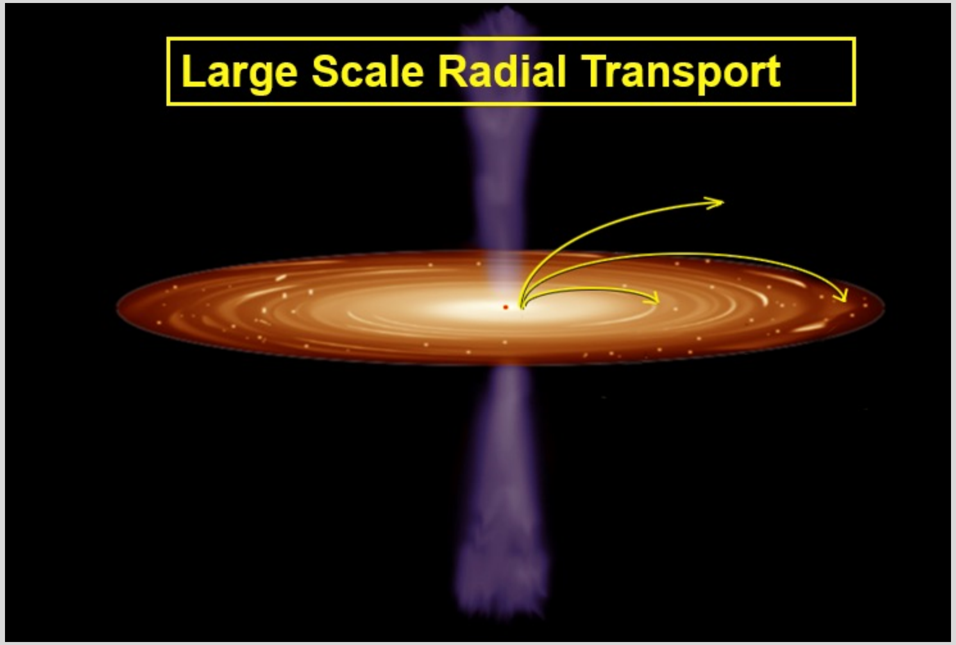
Wild 2 olivine similar to Krymka (3.2) chondrite, which has been metamorphosed to ~200°C

Were these comet components actually thermally metamorphosed?

Data from Christofferson and Buseck (1986), Klöck et al., (1989), Zolensky and Barrett (1994), Joswiak et al. (2009).

Presence of High temp materials in Wild 2 probably requires large scale radial transport of materials

- The mechanism of radial drift remains uncertain
- This is likely to remain a topic for much further study and modeling



But is Wild 2 truly representative of Jupiter-family comets?

Major unanswered Questions regarding Comets

How representative of Comet Wild 2 were the recovered coma dust samples?

We need to accurately characterize the nature and true relative abundance of this fine-grained material

- Determine bulk elemental and isotopic composition of fines for comparison with CI abundances
- Substantially improve statistics of oxygen-isotopic composition measurements of fines
- We need to accurately characterize the nature and true relative abundance of this fine-grained material

How much interstellar matter is preserved in comets? *Determine origin of fines*

Lessons learned from Previous Sample Return Missions - In my own opinion

- Sample intimate surfaces on spacecraft must be as clean as possible, with any contamination well documented and archived
- Samples must be returned to Earth in a completely airtight container
  - Returned samples are fantastically reaction to oxygen, water, organics, in fact any volatile material
  - We should not accept anything less
  - For the same reasons *meteorites cannot replace actual returned samples*
- The health and safety of the samples must be the primary mission priority
  - When astronauts (cosmonauts, taikonauts, etc.) are involved human health and safety is the priority → No astronaut involvement
- Prepare to be more successful than you imagined

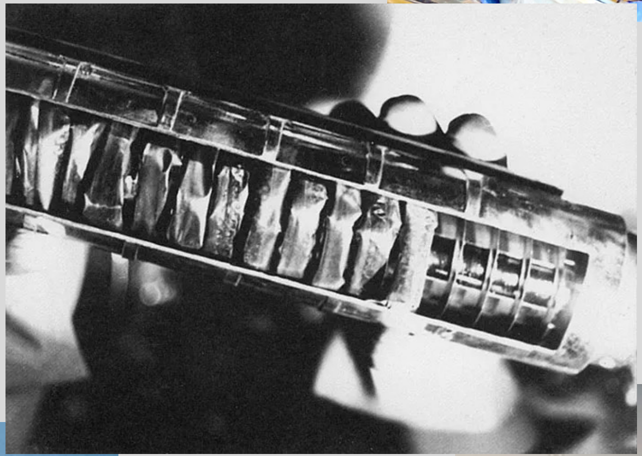
Lessons learned from Previous Sample Return Missions - In my own opinion

- Sample analysis techniques will continue to evolve, which means that during long missions the scope of planned preliminary analysis will change, so do not lock in sample preliminary examination plans too early and team membership should be very inclusive and flexible
- Returned samples will be extremely reactive to everything on Earth, despite our best efforts to prevent this – Sample preliminary examination much begin immediately upon recovery

Apollo 11 1969

Genesis 2004

Hayabusa 2010



Luna 24 1976

LDEF 1990

Stardust 2006

Chang’e 5 2020