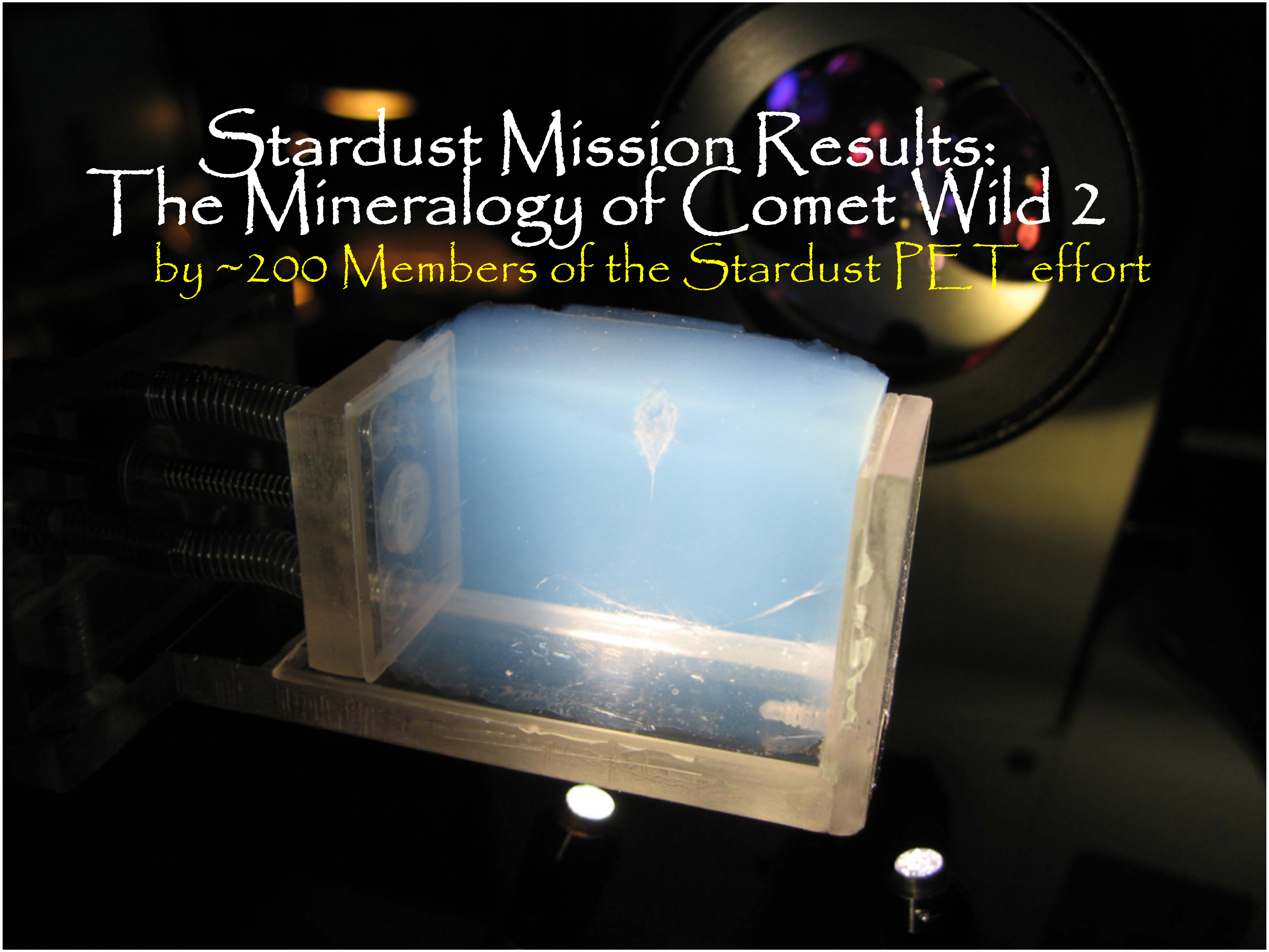
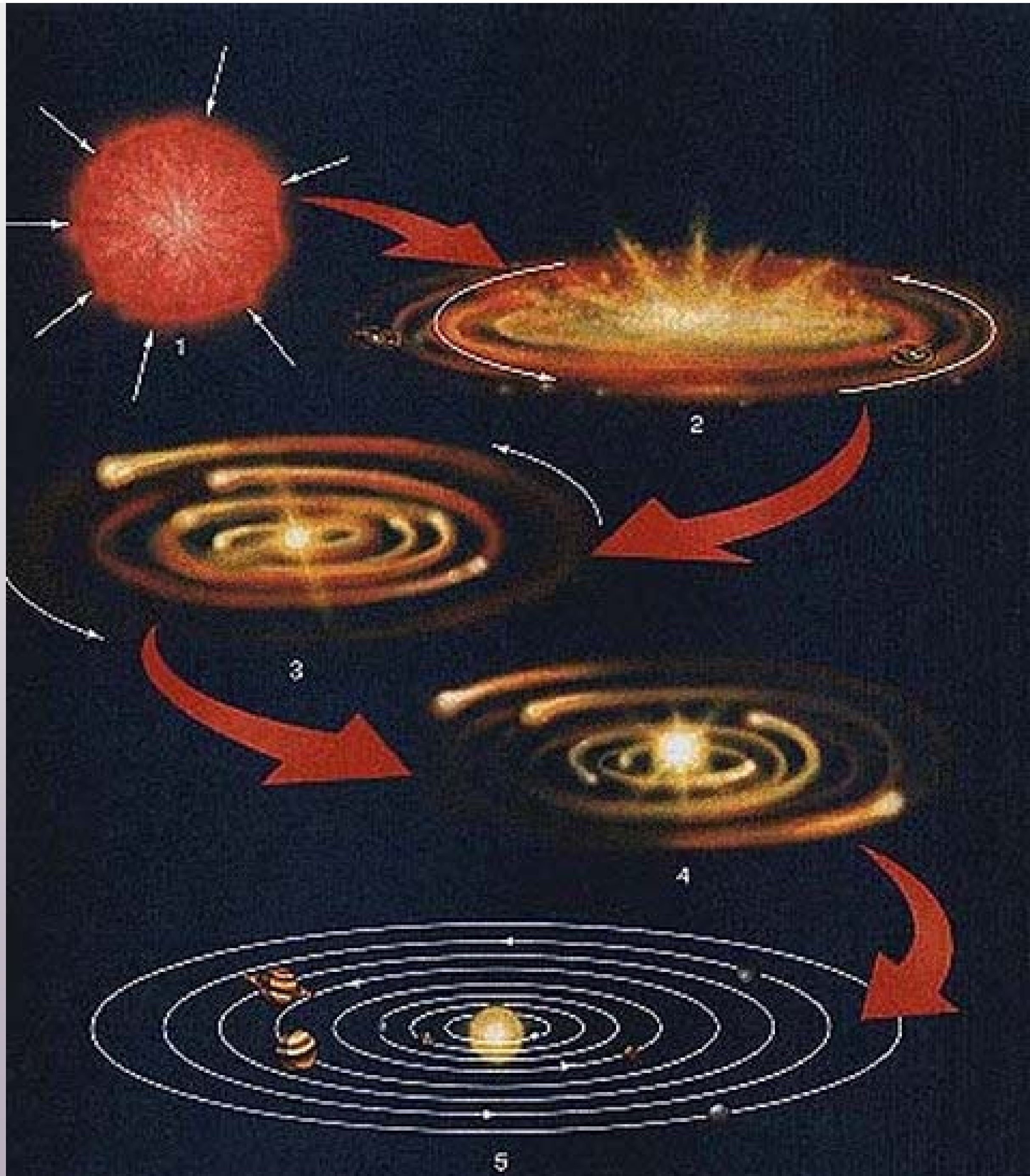
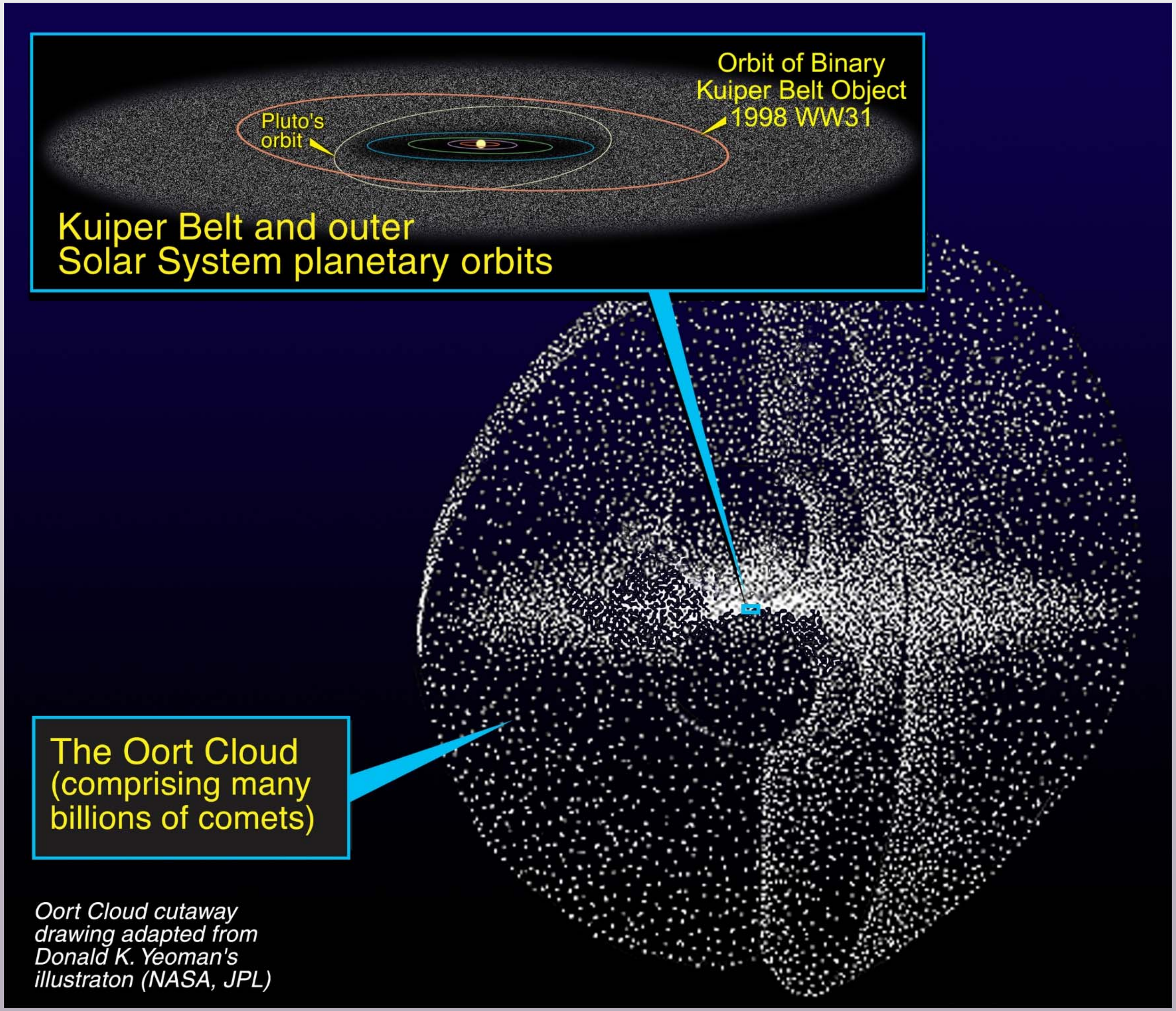
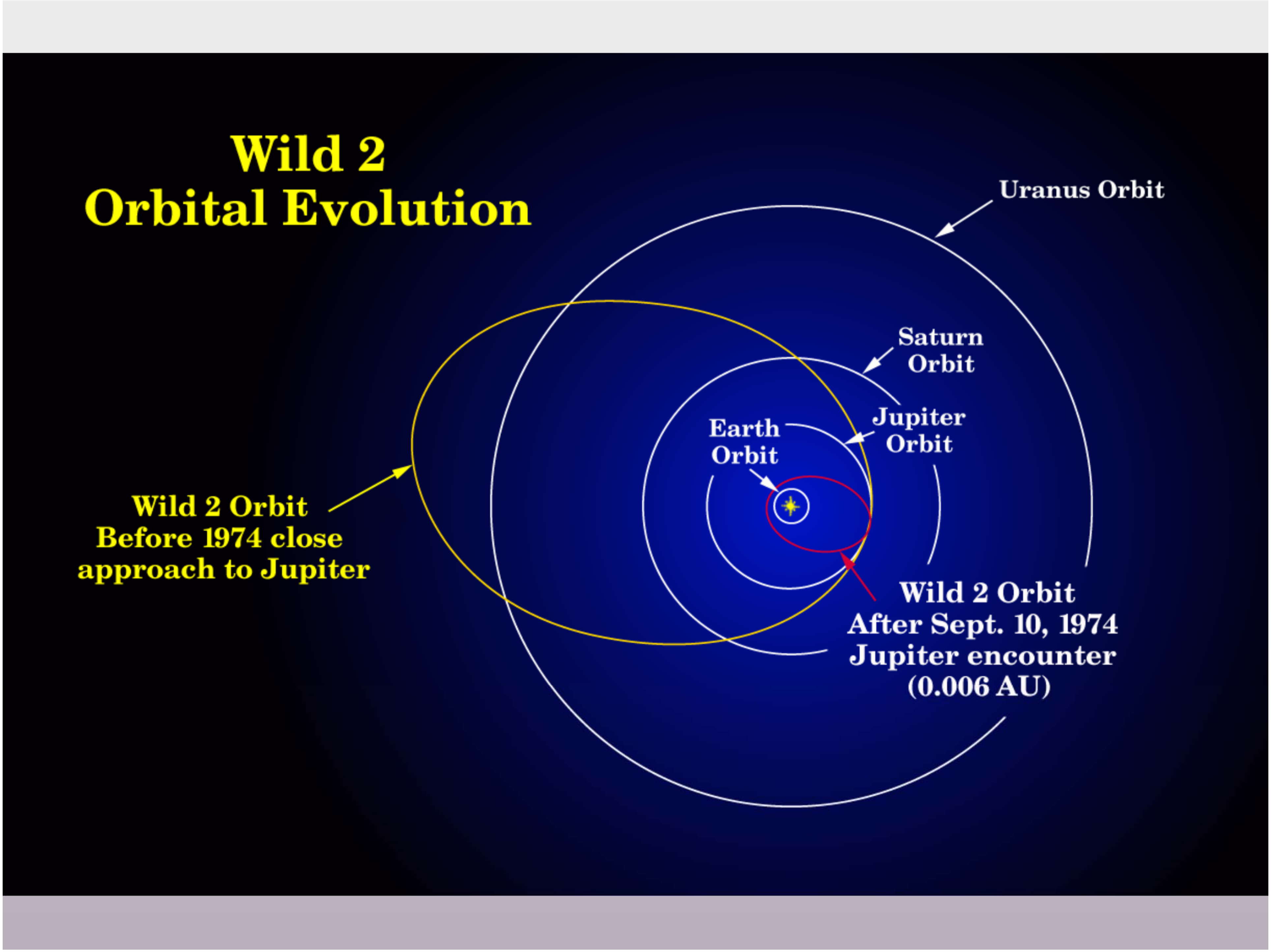
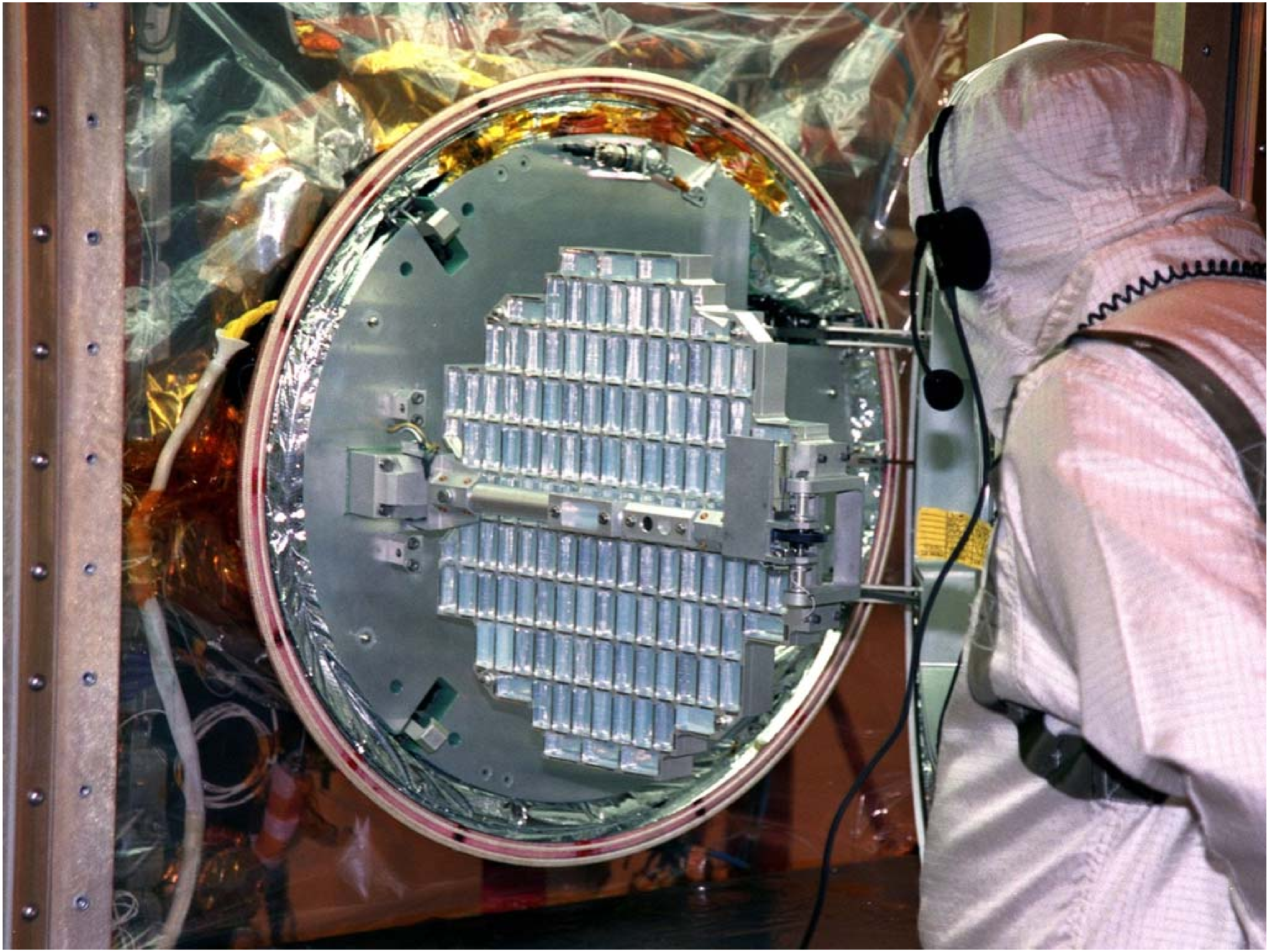

Stardust Mission Results:
The Mineralogy of Comet Wild 2
by ~200 Members of the Stardust PET effort


1
2
3
4
5

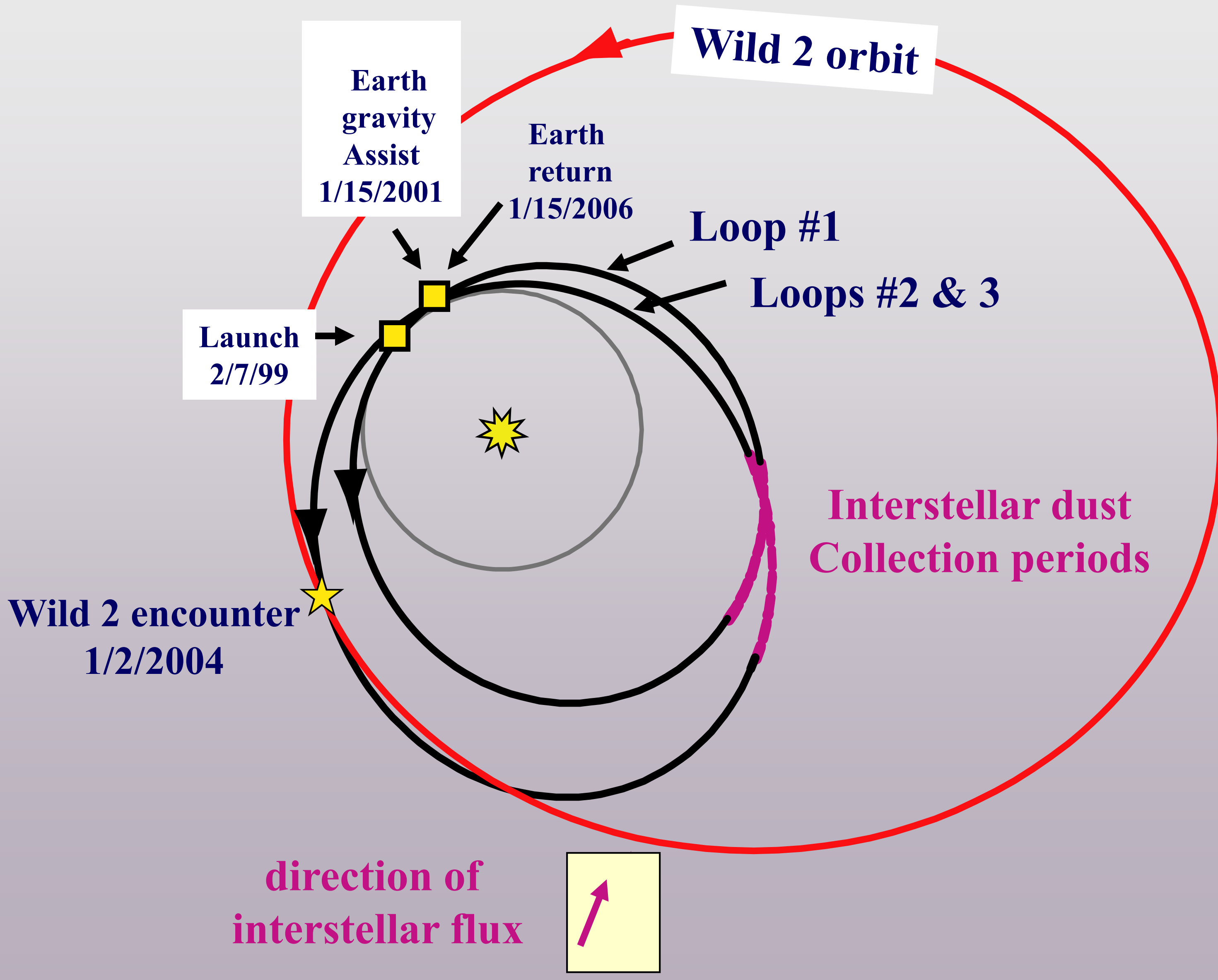

Orbit of Binary
Kuiper Belt Object
1998 WW31
Pluto's
orbit
Kuiper Belt and outer
Solar System planetary orbits
The Oort Cloud
(comprising many
billions of comets)
Oort Cloud cutaway
drawing adapted from
Donald K. Yeoman's
illustraton (NASA, JPL)

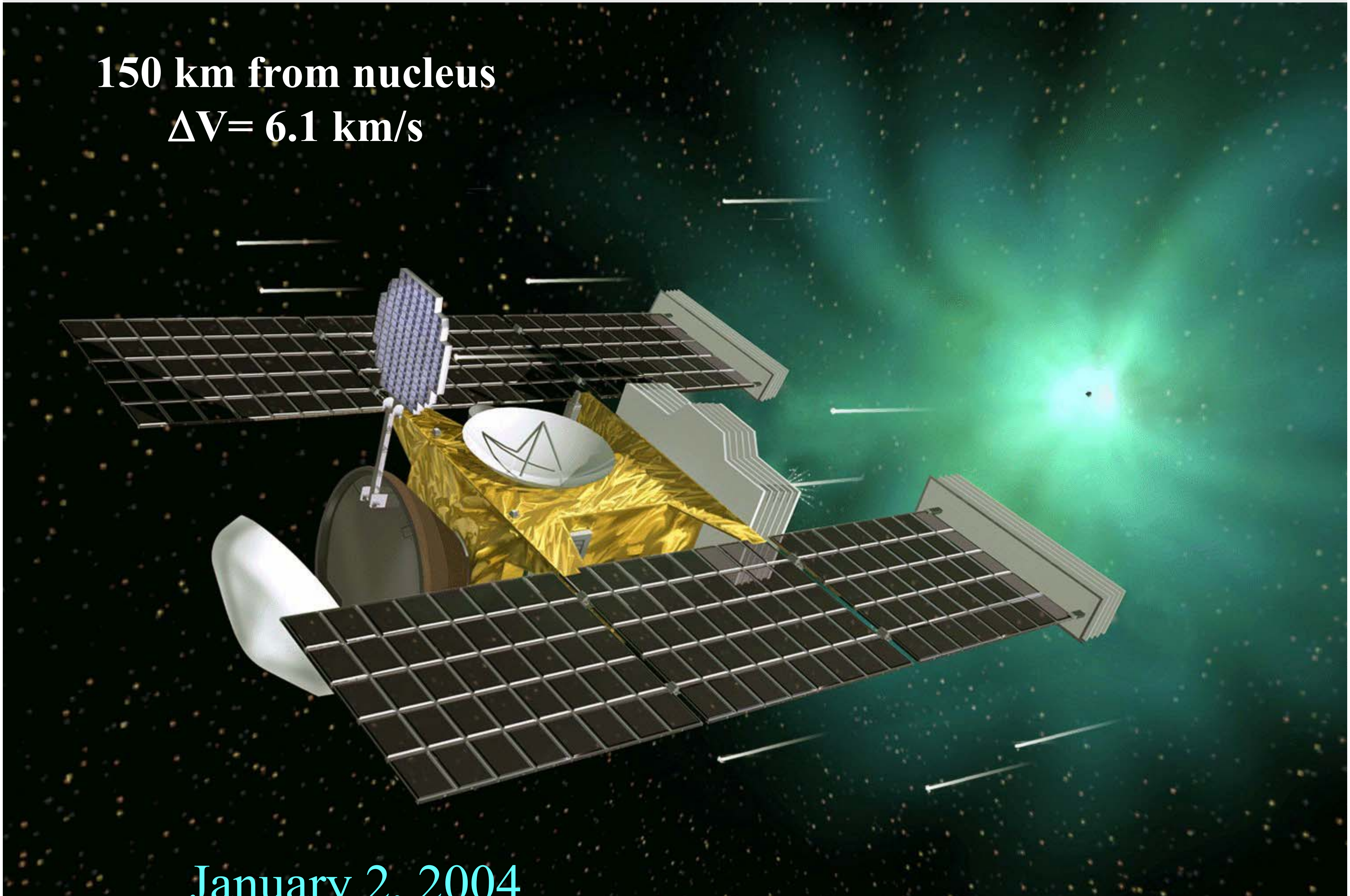

Wild 2
Orbital Evolution
Uranus Orbit
Saturn
Orbit
Jupiter
Orbit
Earth
Orbit
Wild 2 Orbit
Before 1974 close
approach to Jupiter
Wild 2 Orbit
After Sept. 10, 1974
Jupiter encounter
(0.006 AU)

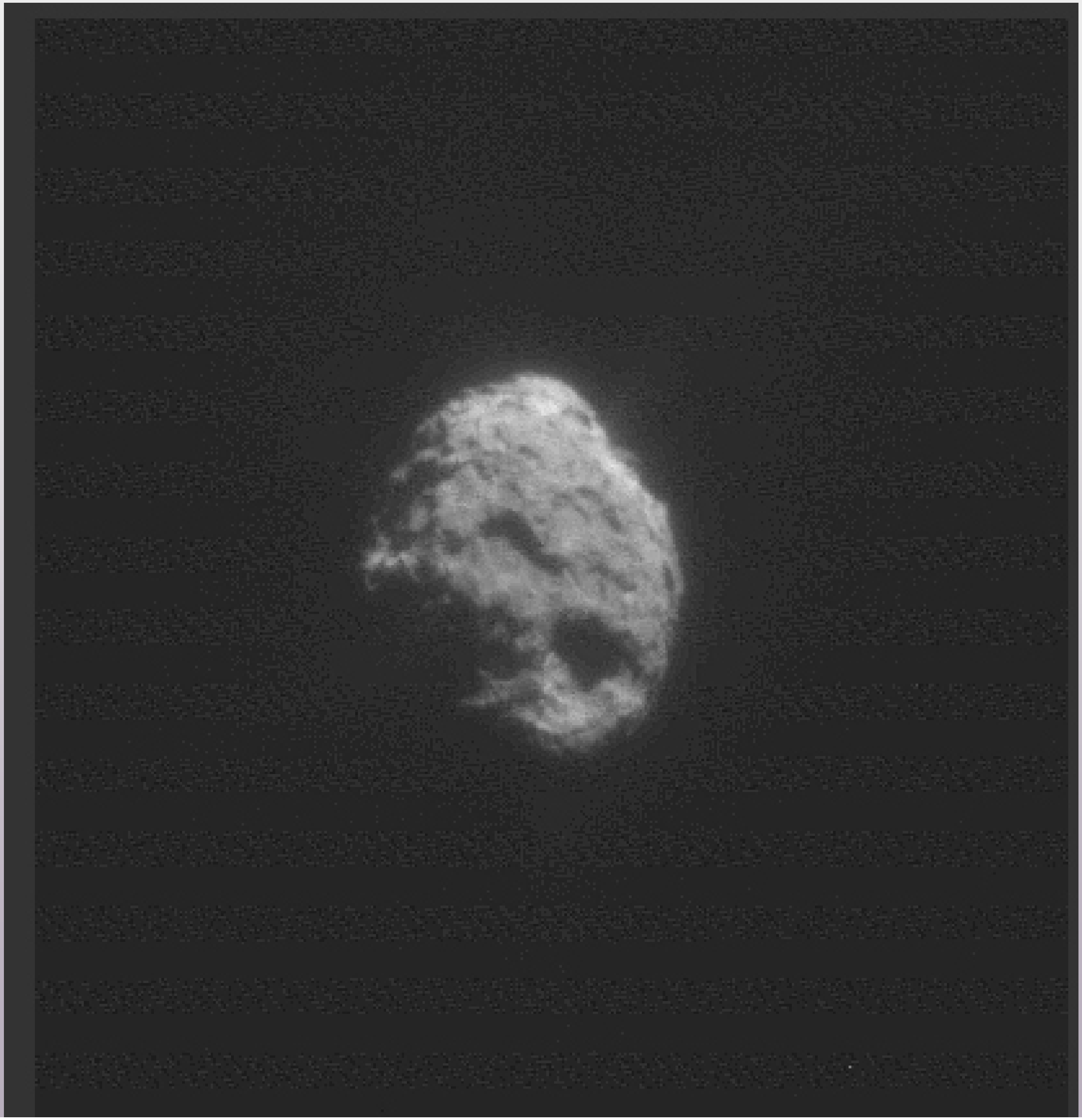


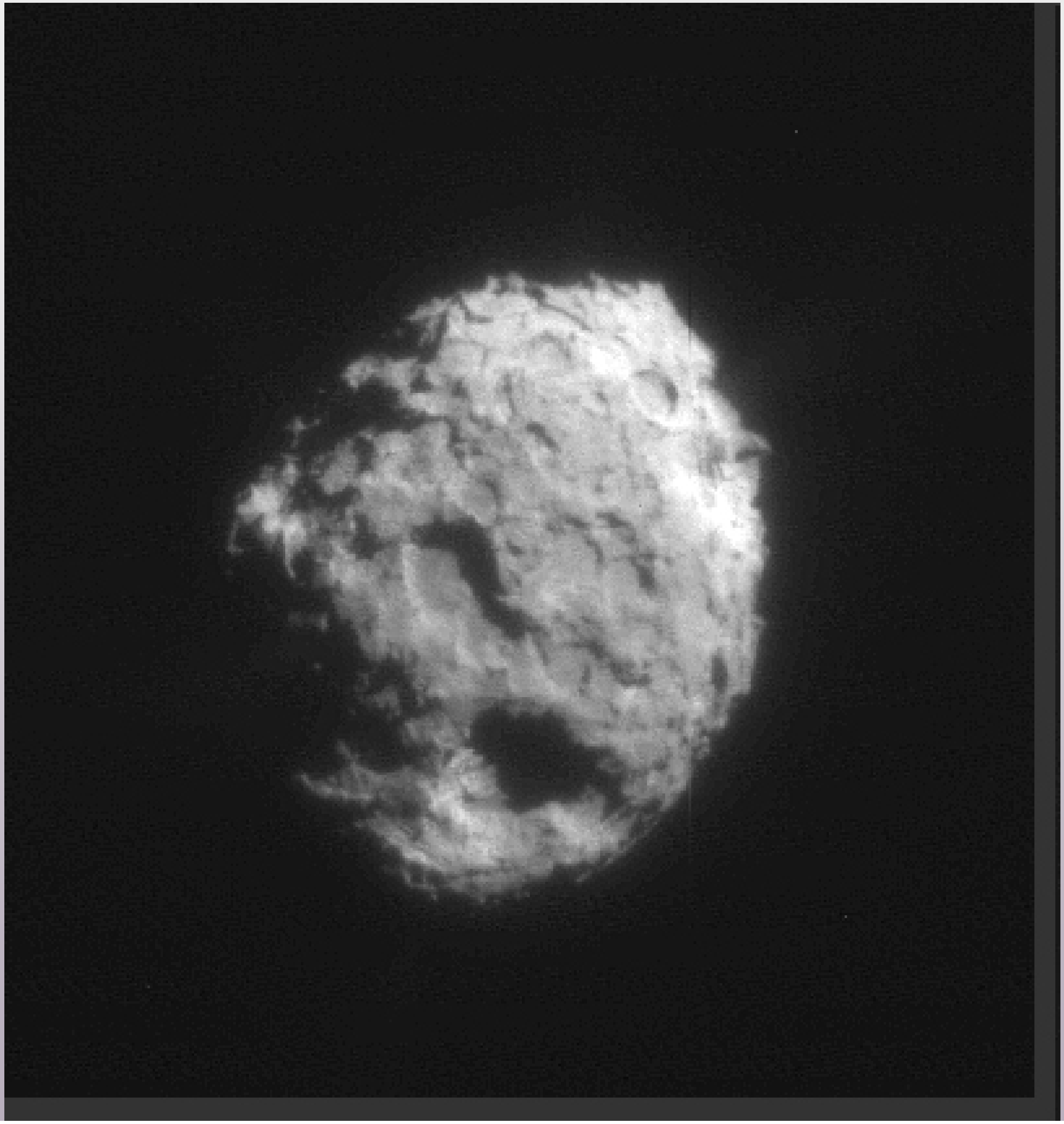
Launch Feb 7, 1999

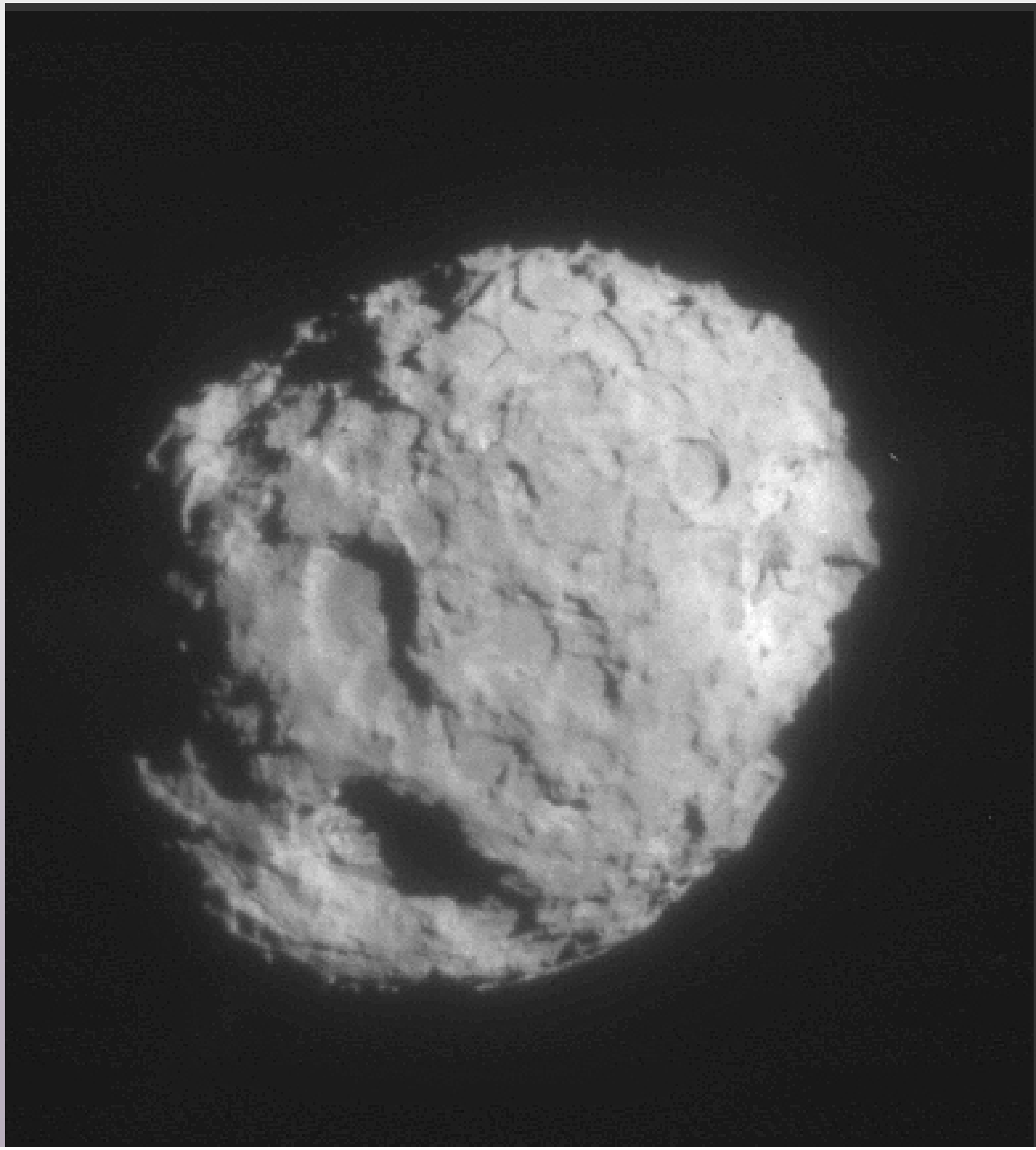
Stardust's Ride - 3 loops around the Sun

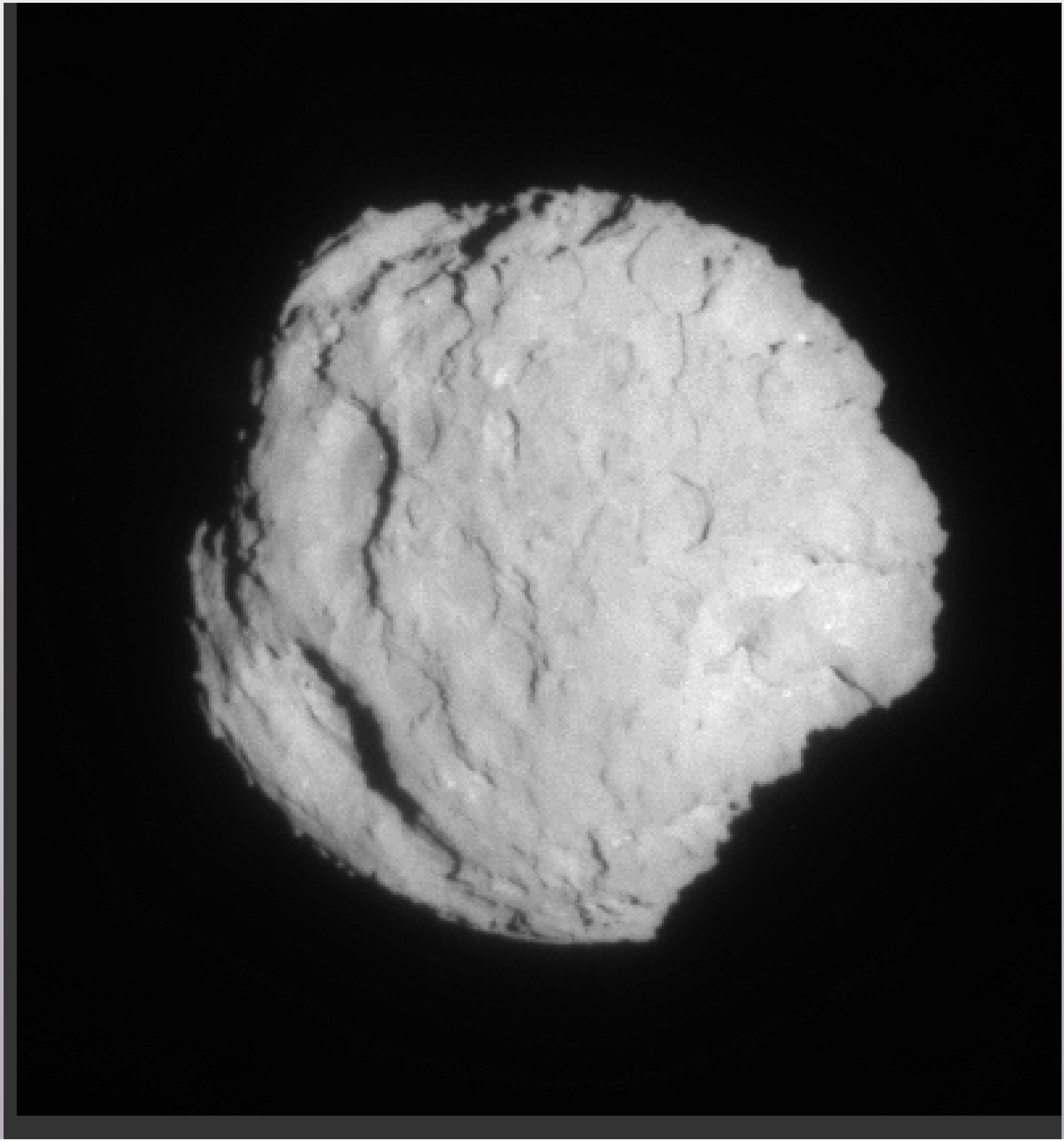


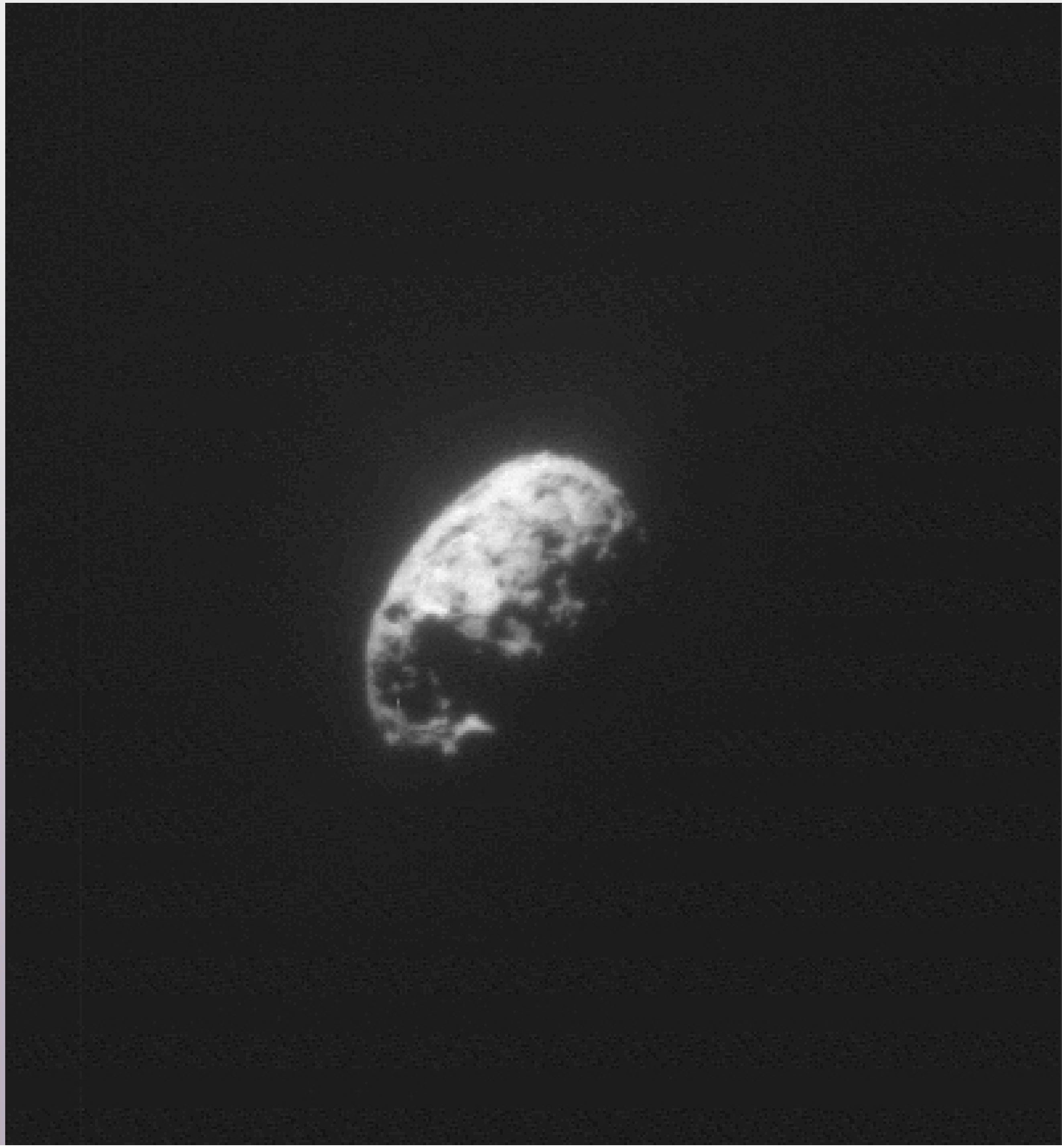

150 km from nucleus
ΔV= 6.1 km/s
January 2, 2004

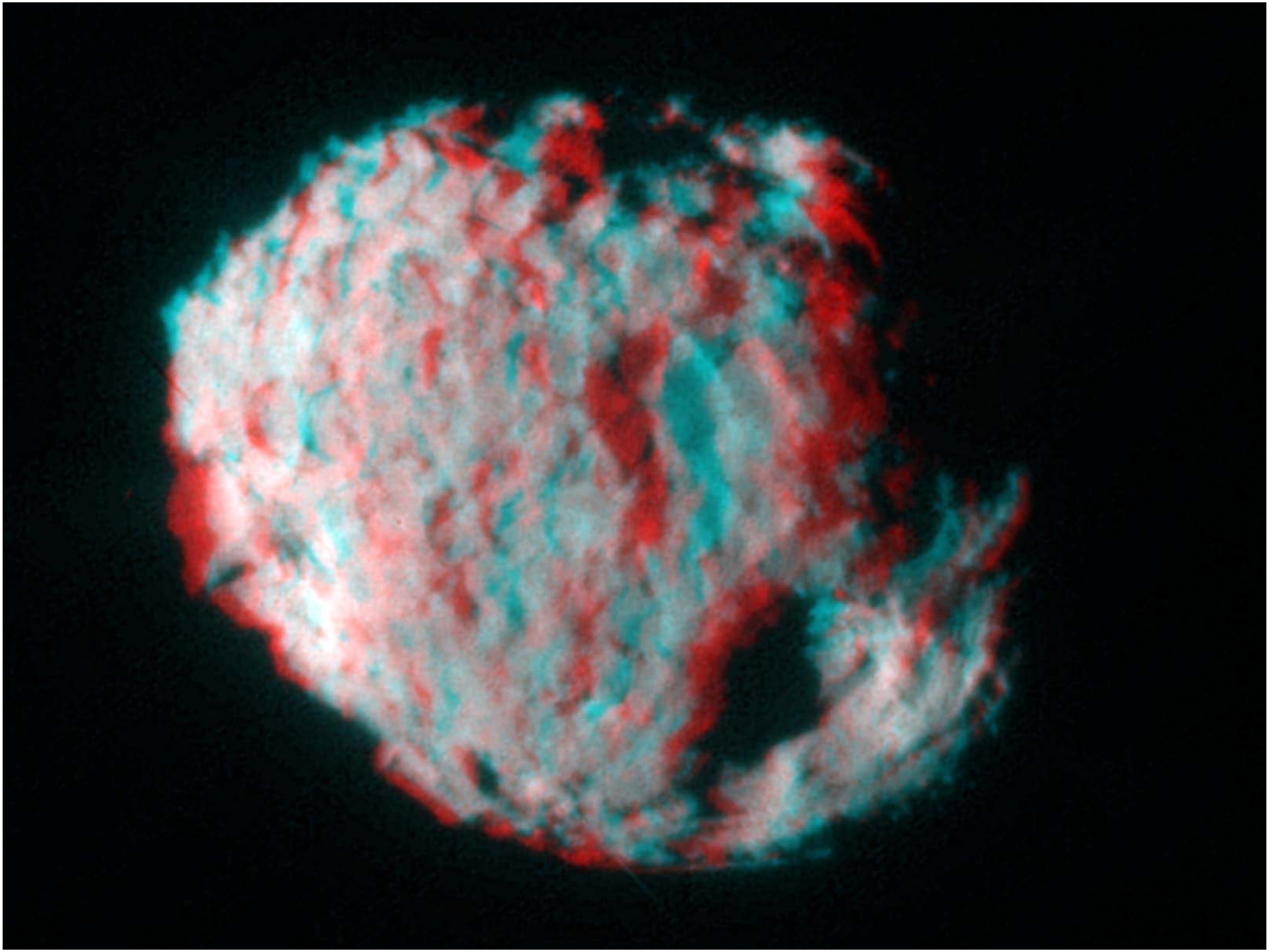


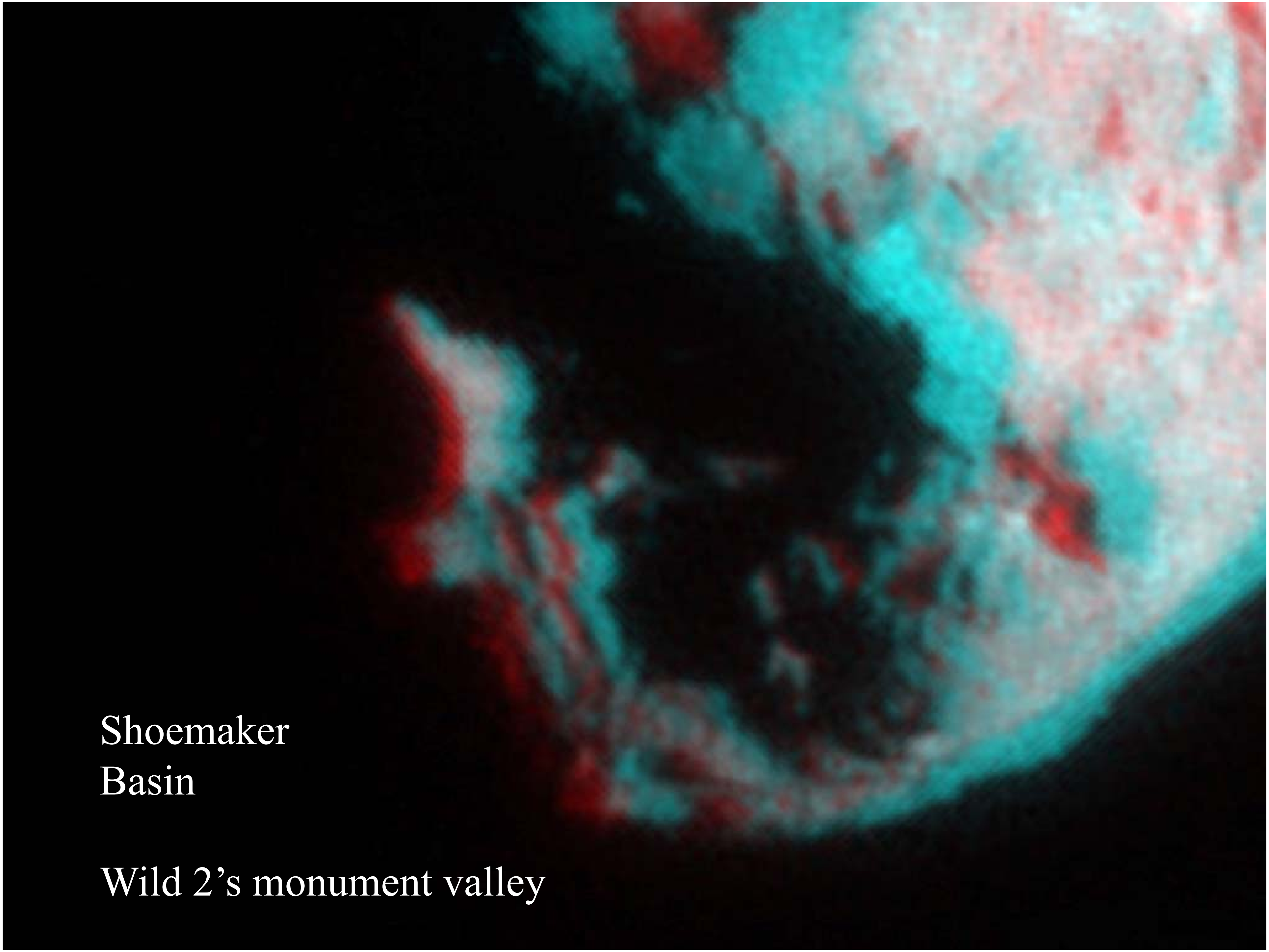


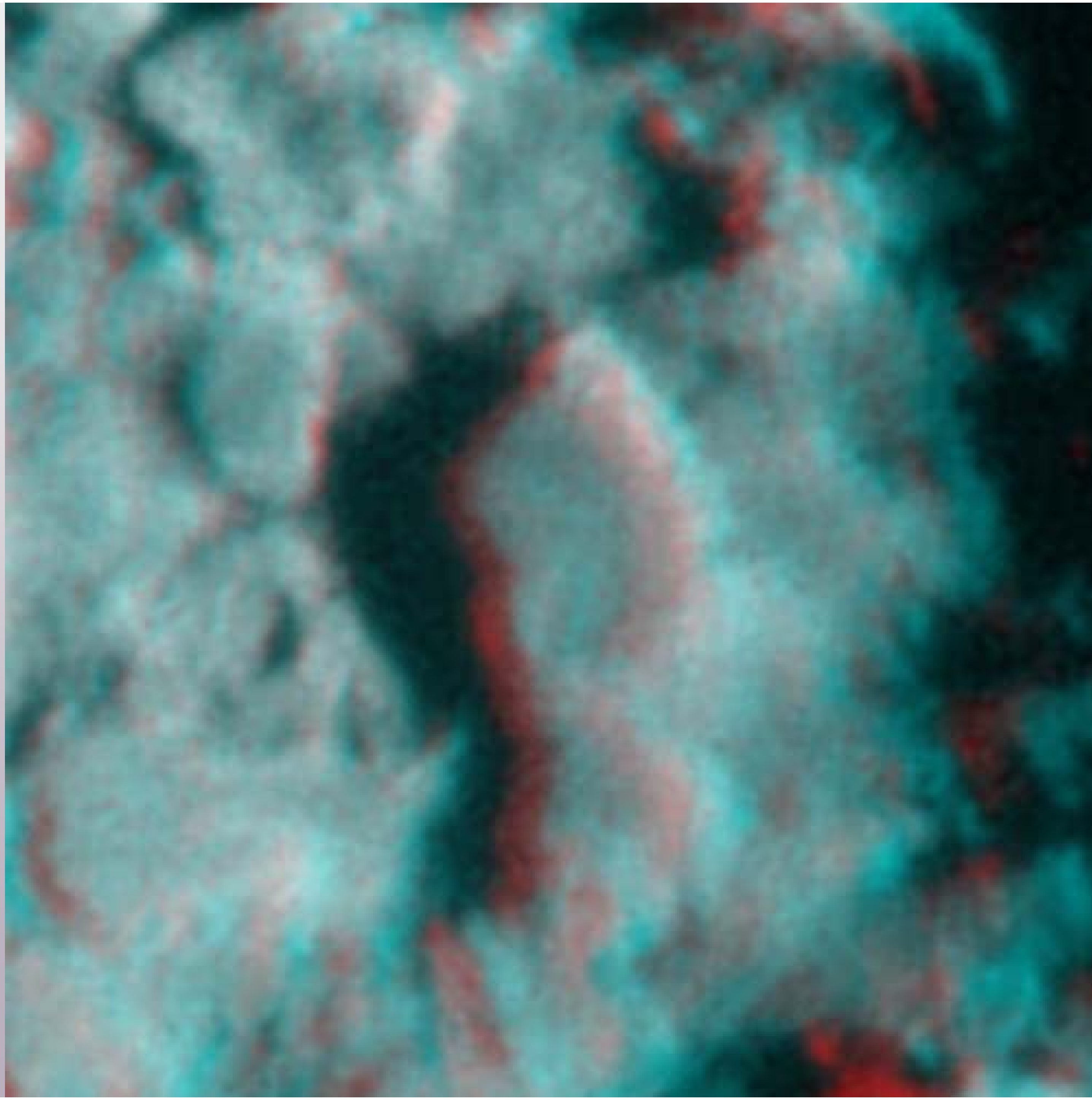




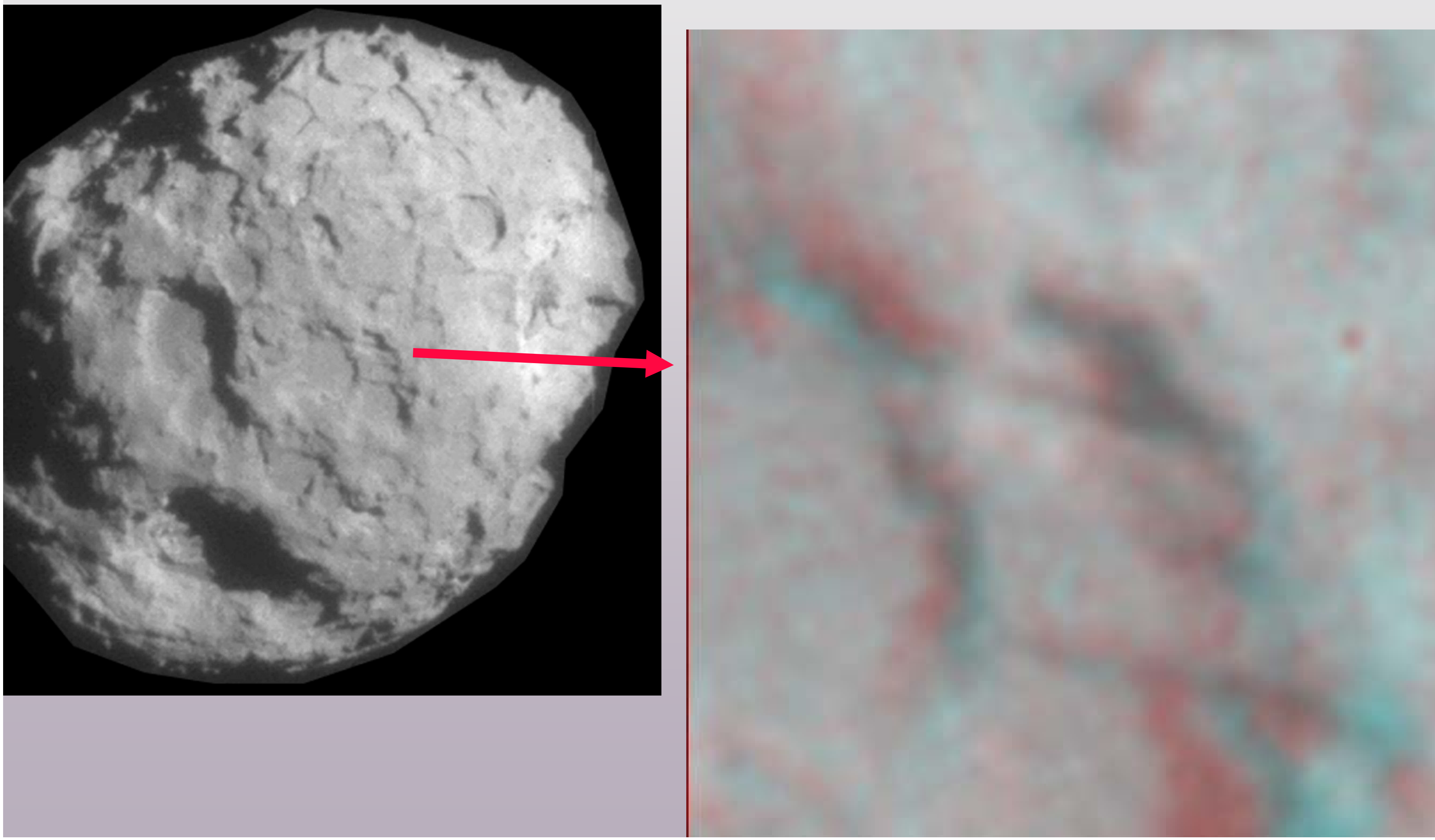




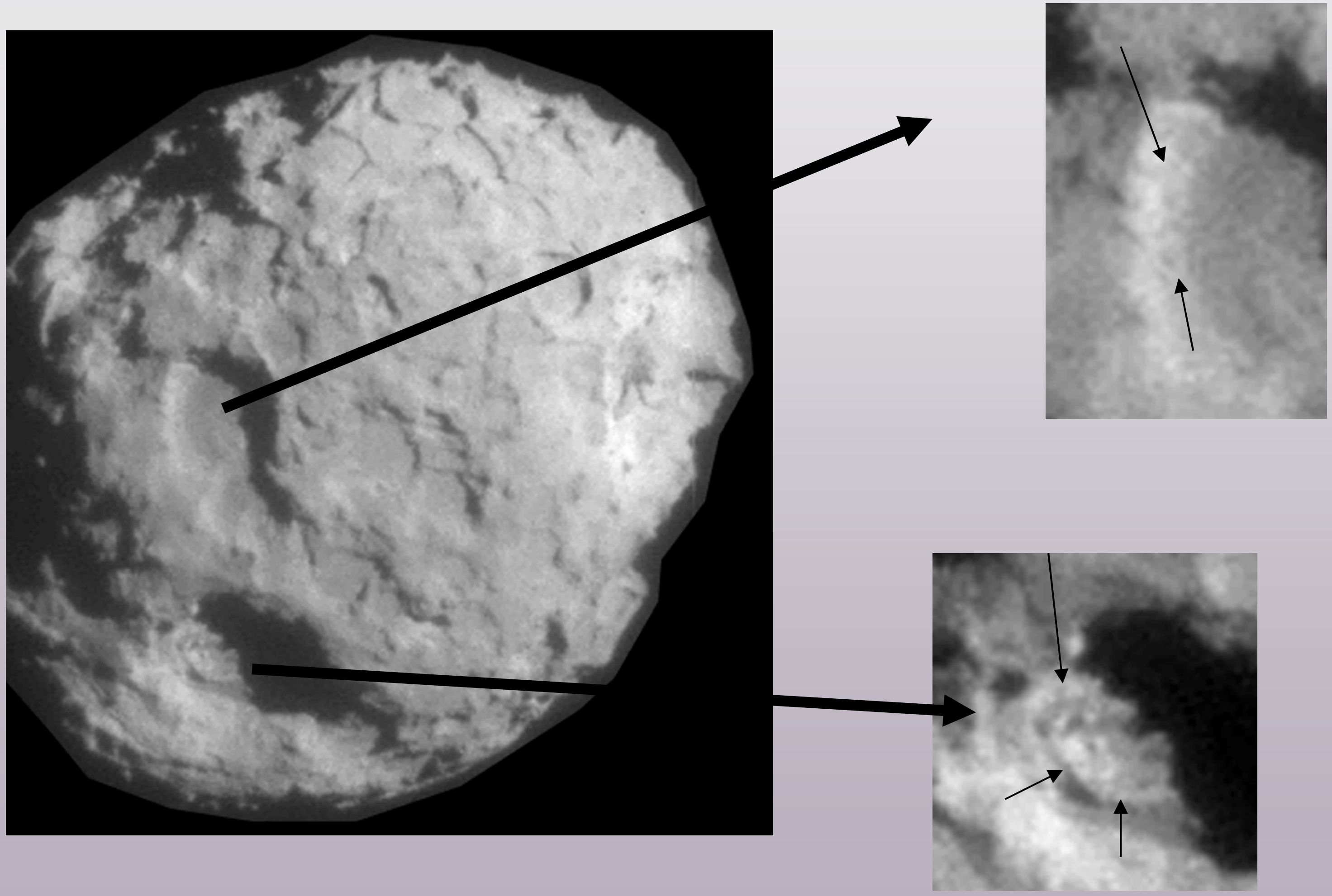

Shoemaker
Basin
Wild 2’s monument valley

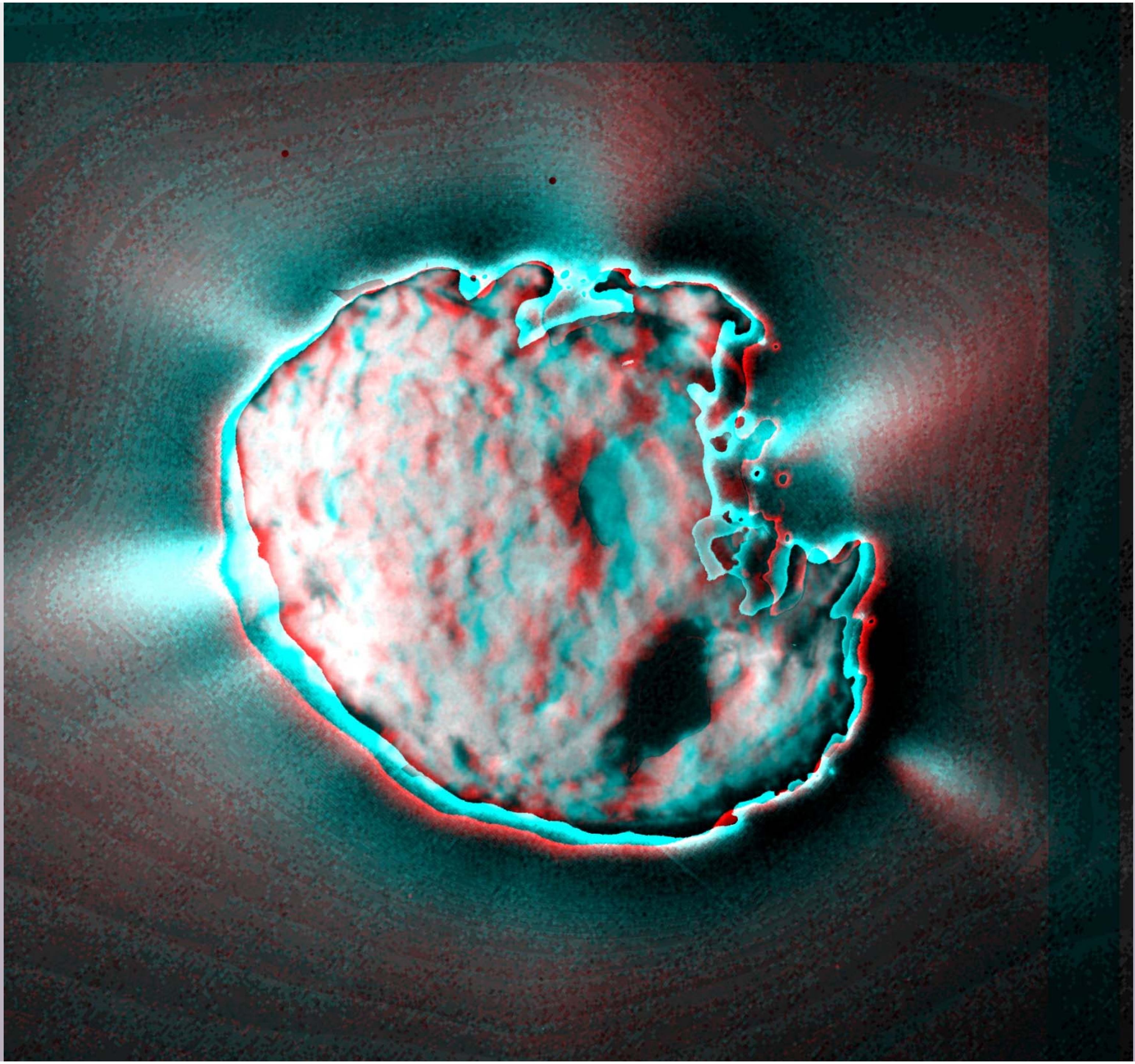


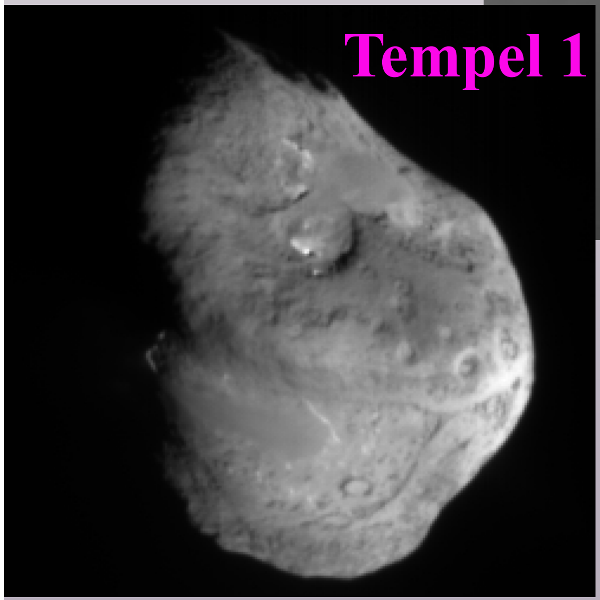
Faulting



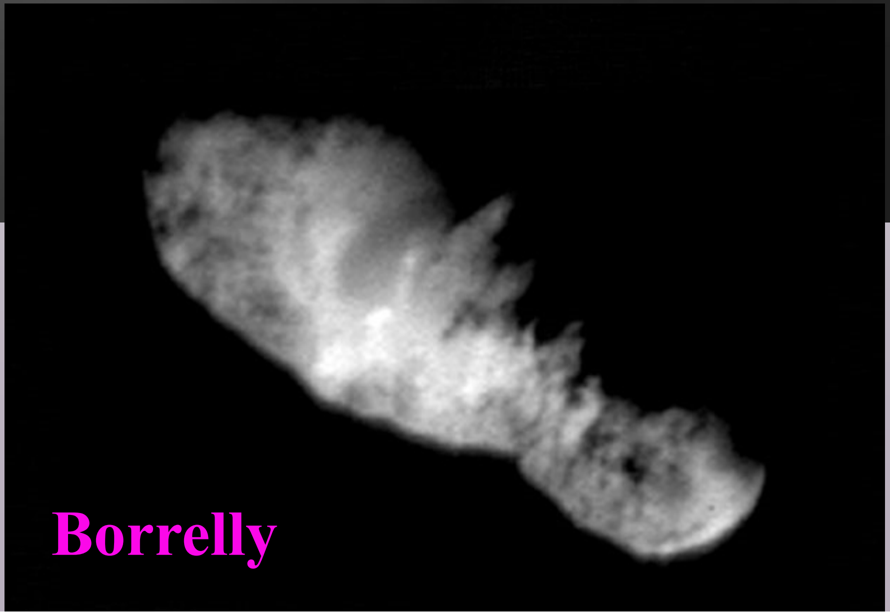
Mass Wasting - Landslides







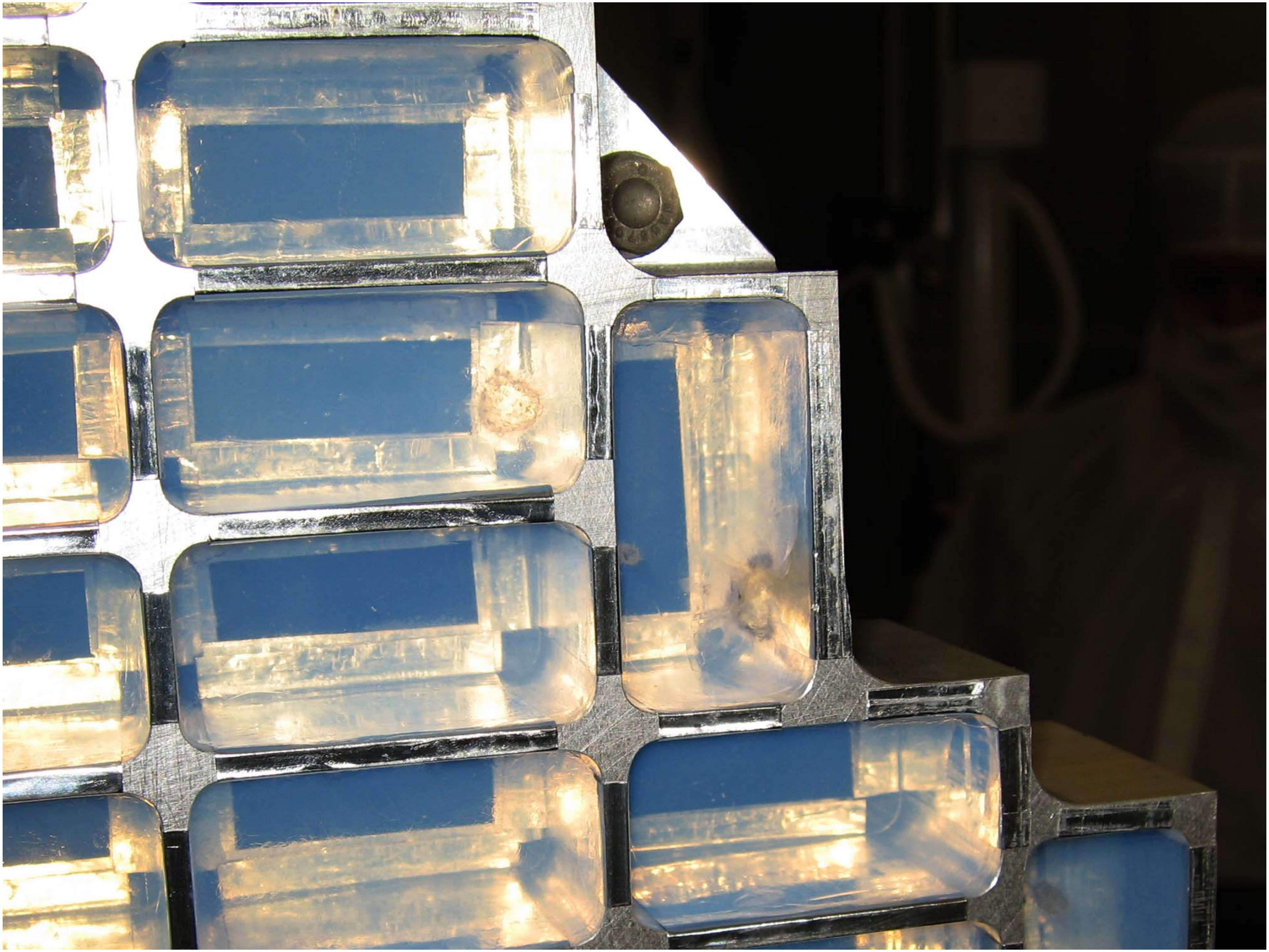
8x5

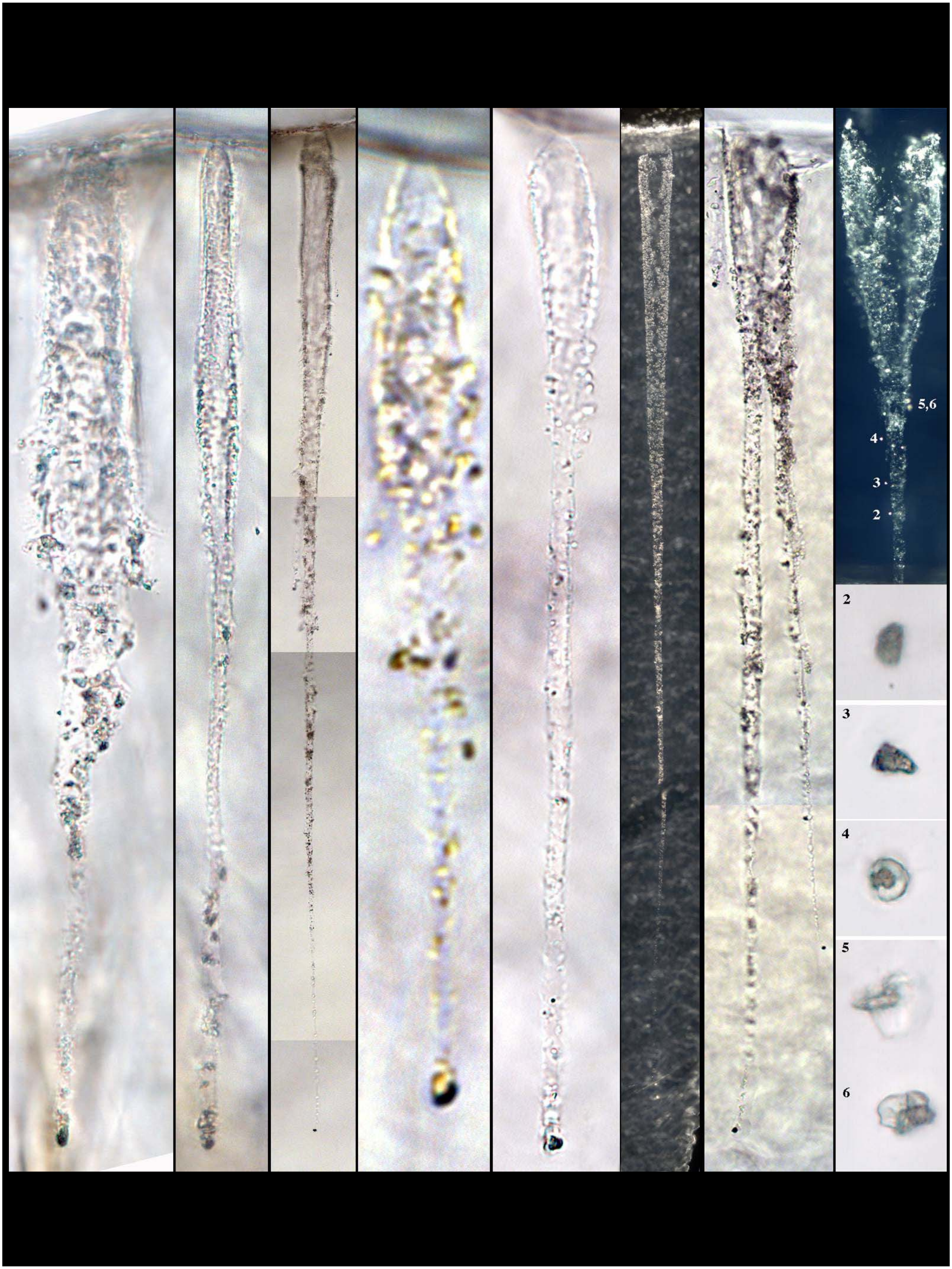


Primary Science Goal

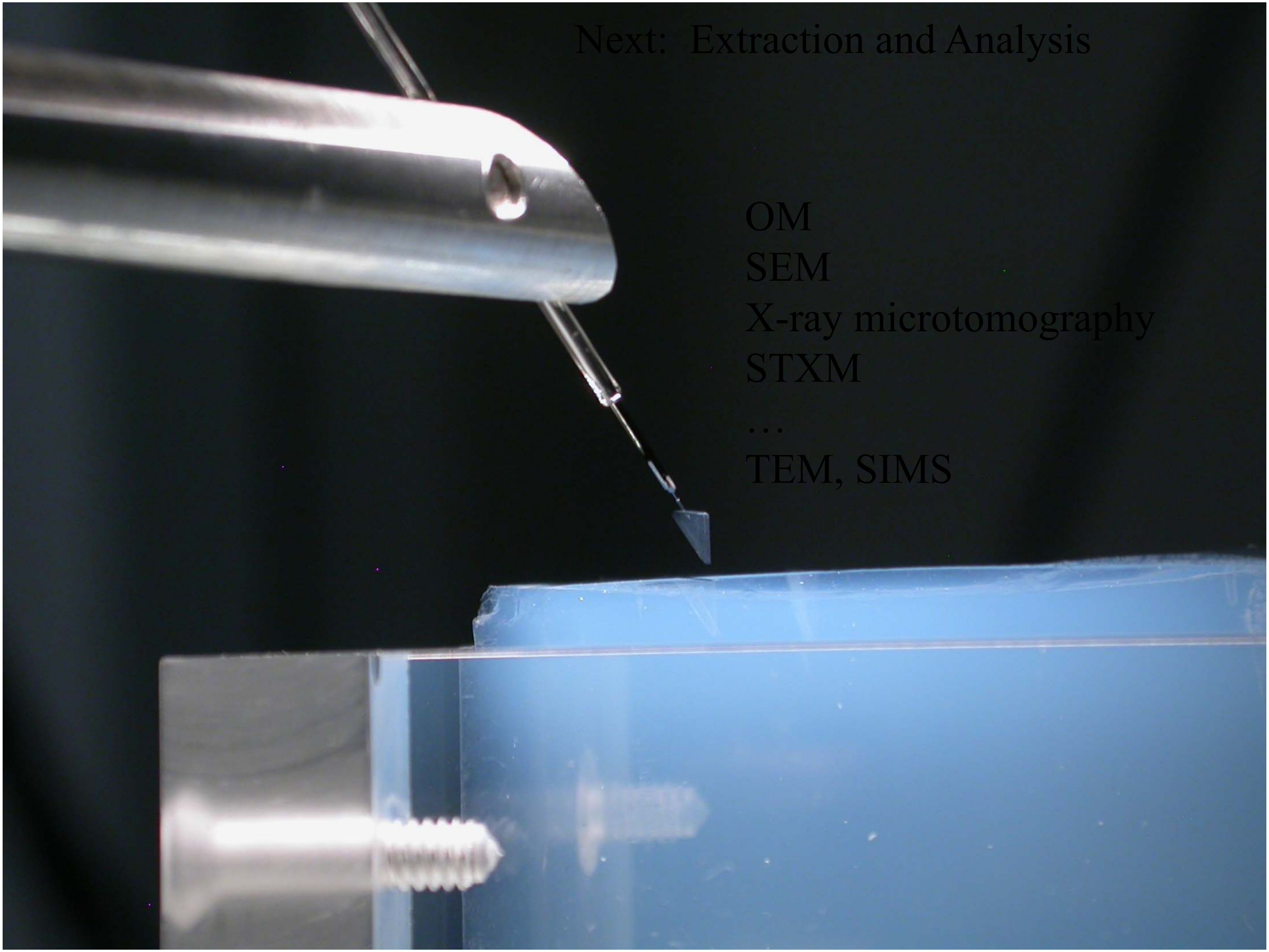
- **Collect solid samples from a comet that formed beyond Neptune**
- **Return the samples for laboratory analysis**

100% Success!





5,6
4
3
2
2
3
4
5
6


Next: Extraction and Analysis
OM
SEM
X-ray microtomography
STXM
…
TEM, SIMS

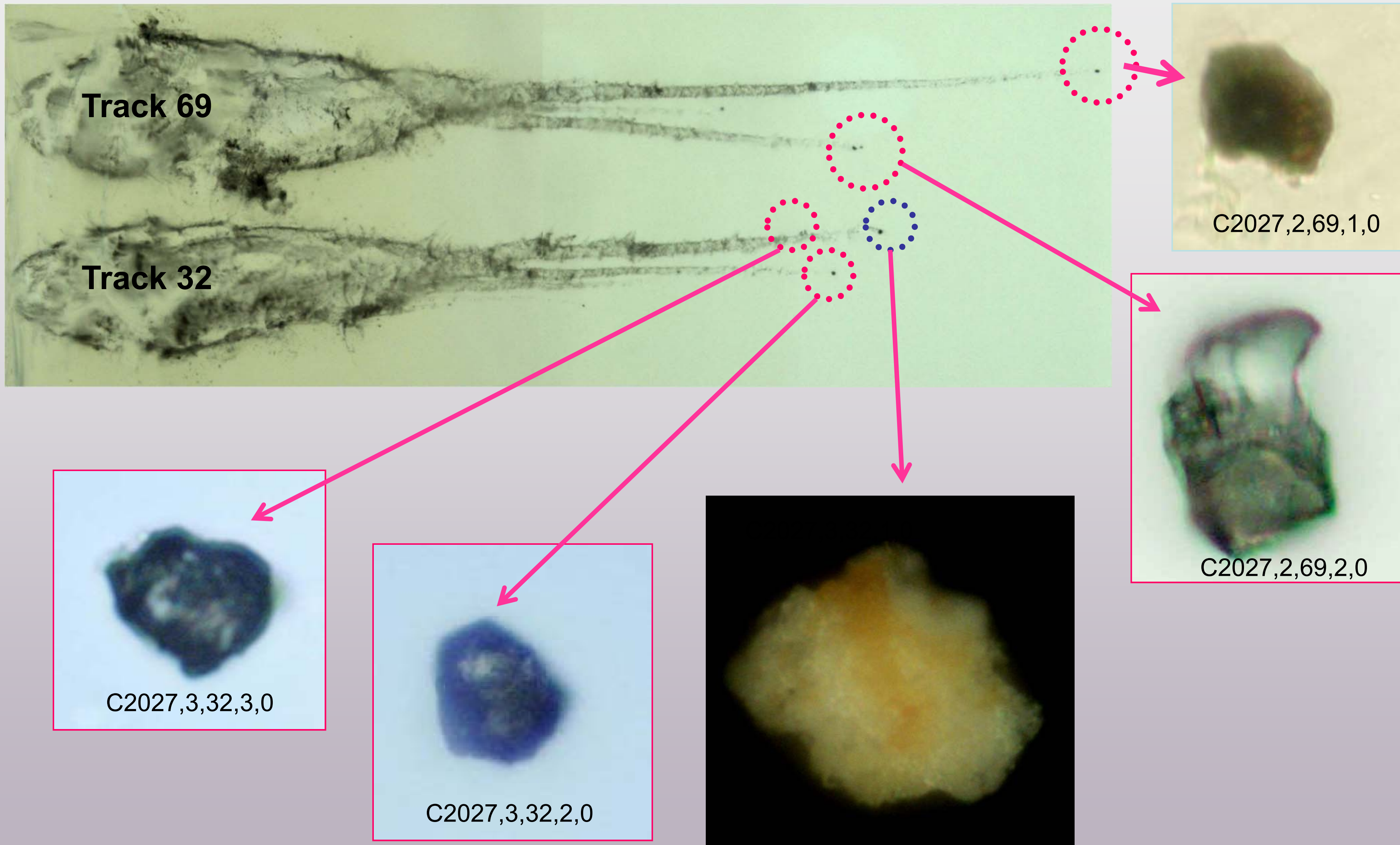
Preliminary analysis of the comet samples was done by an international team of 188 scientists

PROVIDED DIRECT INFORMATION ON COMETARY MATERIALS

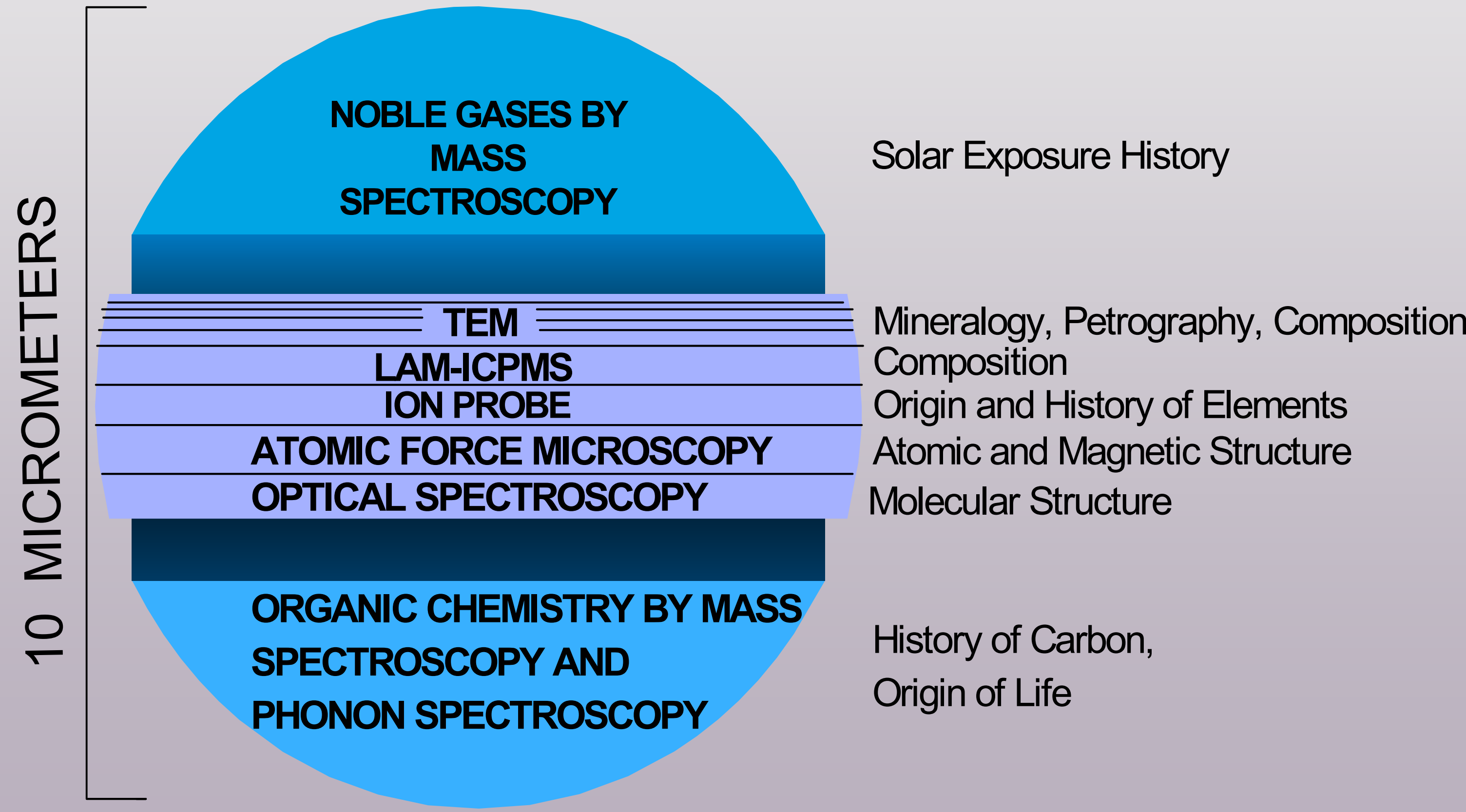
Fundamental insight into

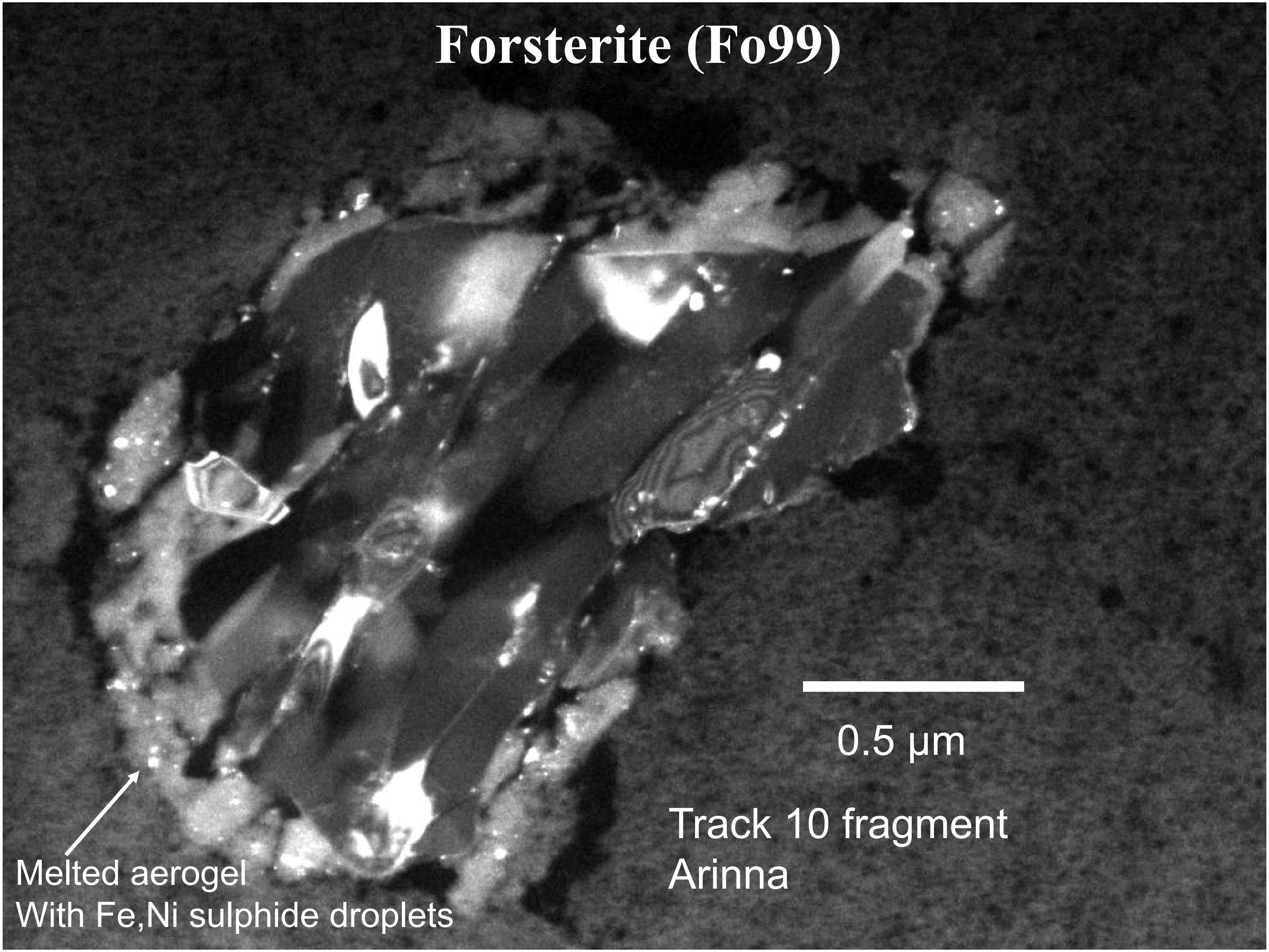
- **The nature of comets**
- **The origin of comets**
- **The origin of the solar system**

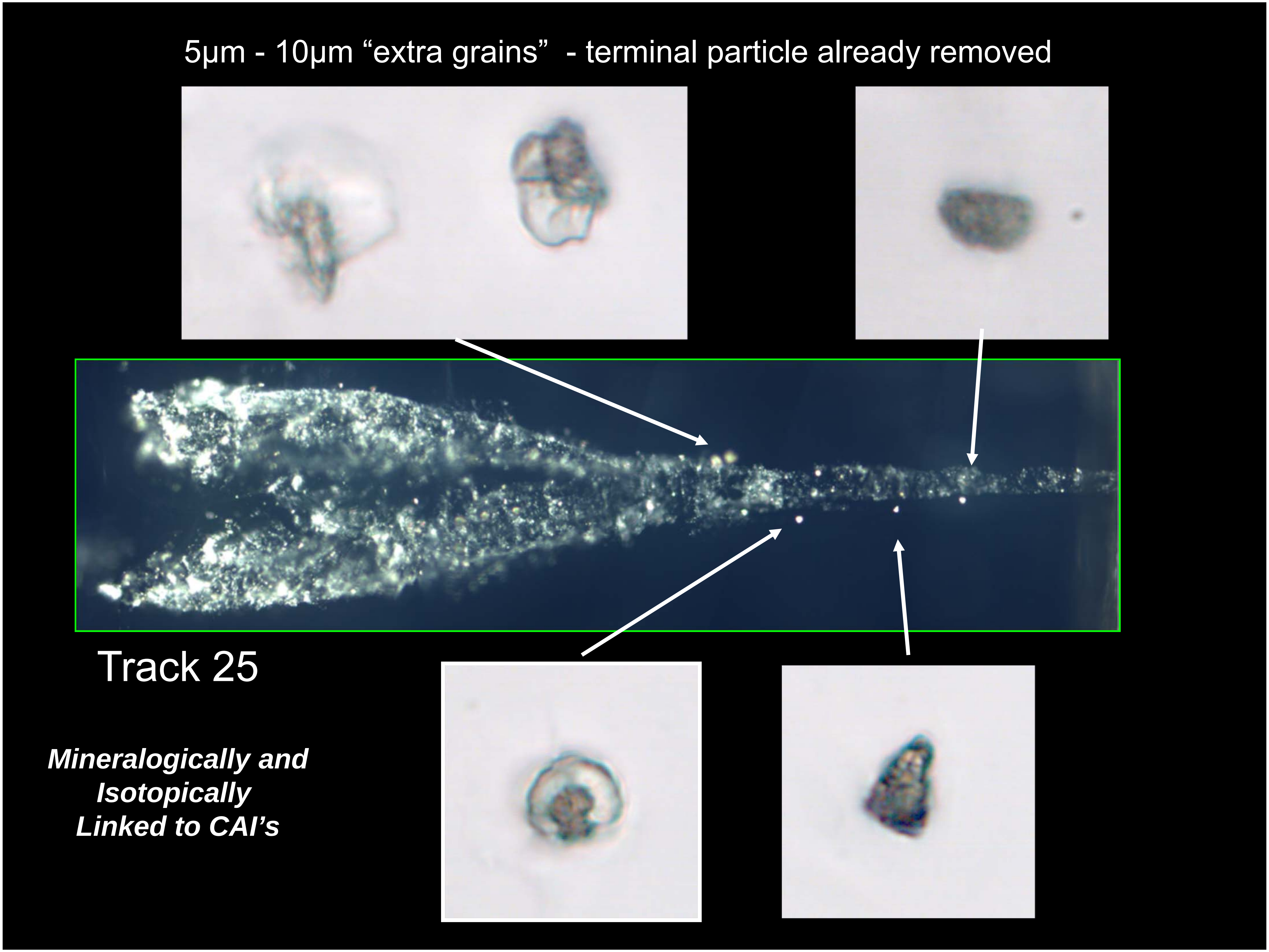
STARDUST Sample#



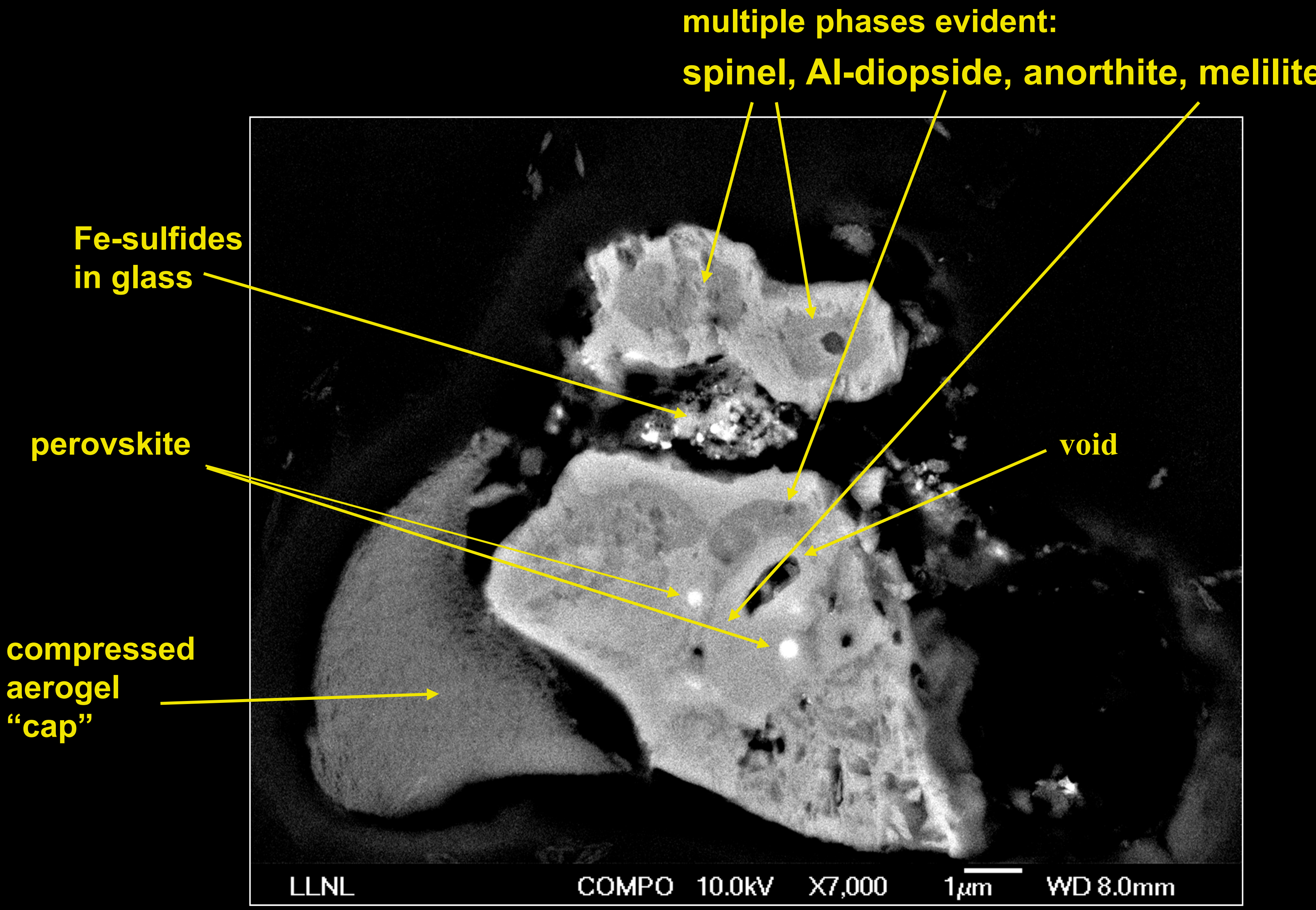
The range of analyses performed on Cosmic Dust has vastly increased over the past 2.5 decades




Forsterite (Fo99)
0.5 µm
Track 10 fragment
Arinna
Melted aerogel
With Fe,Ni sulphide droplets


5μm - 10μm “extra grains” - terminal particle already removed
Track 25
Mineralogically and
Isotopically
Linked to CAI’s

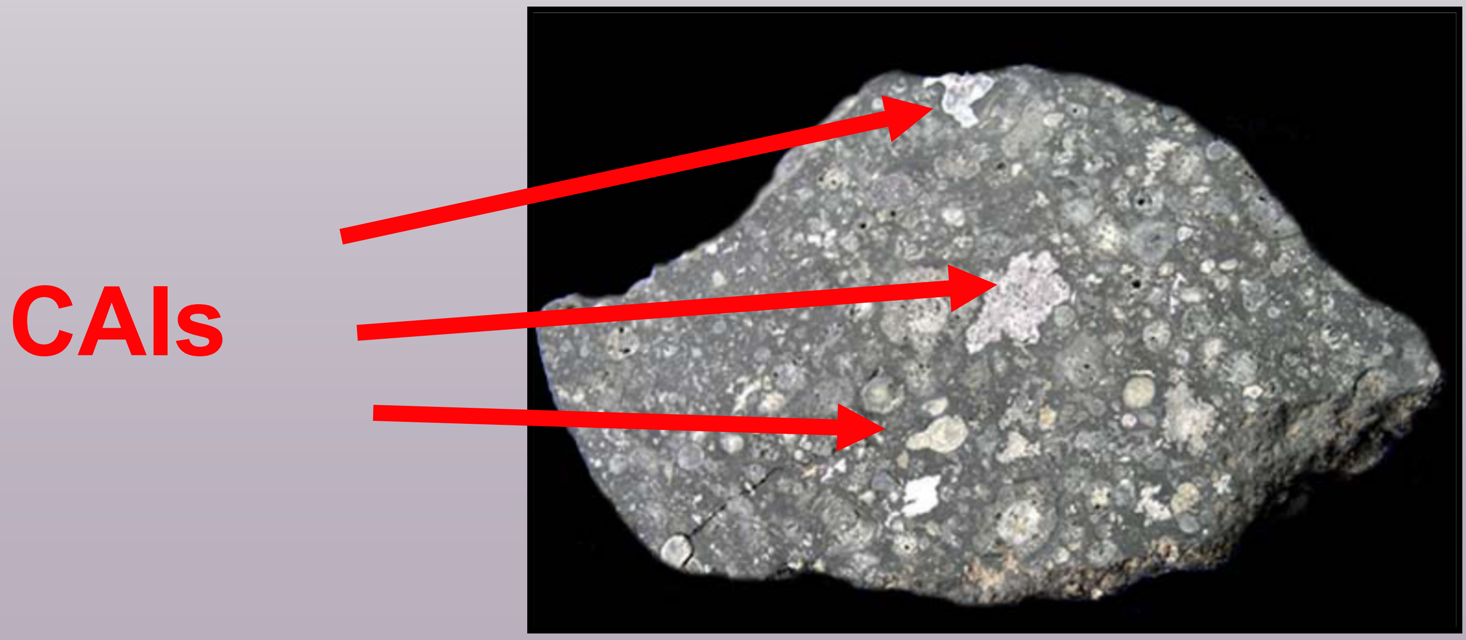
CAI particle

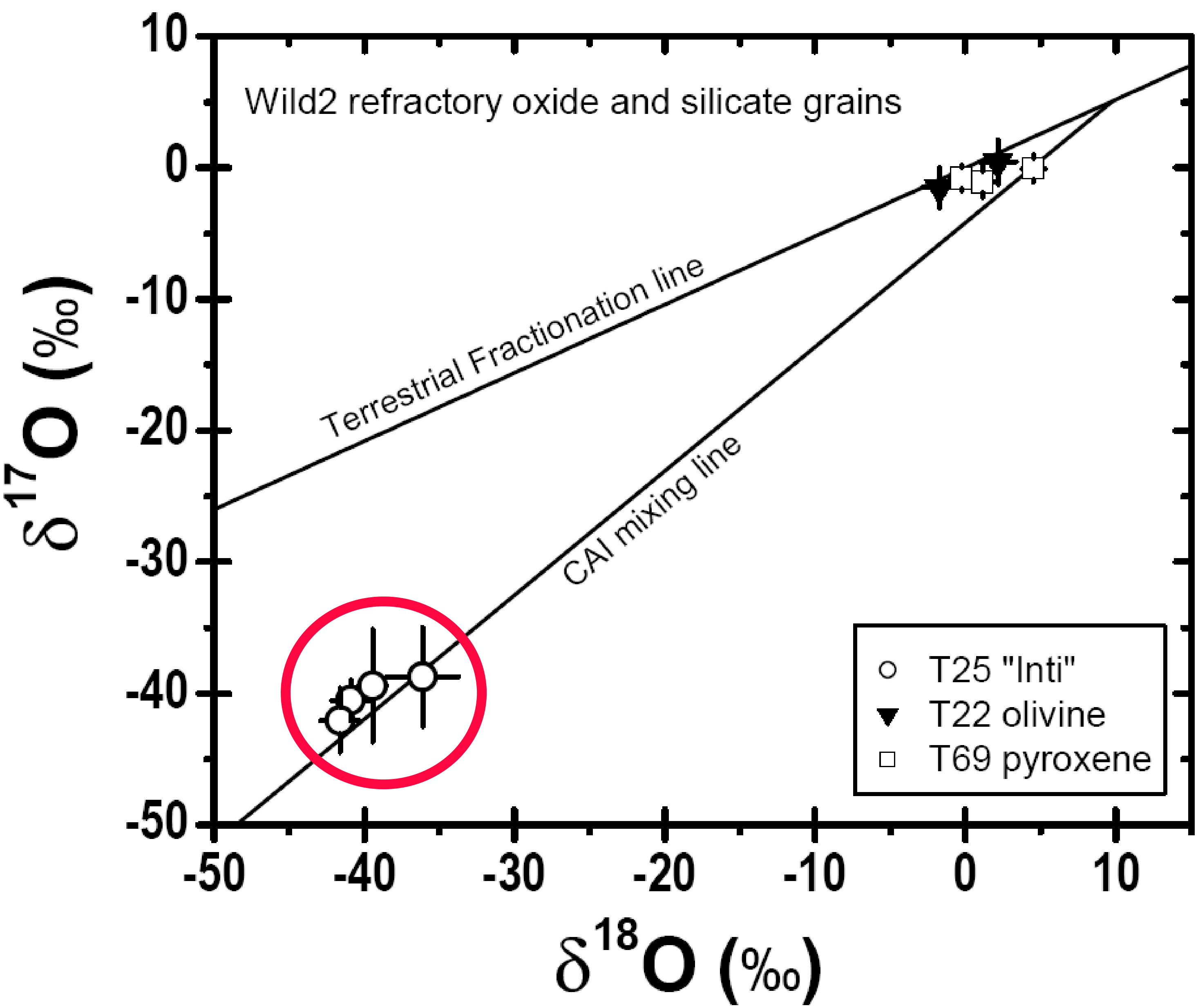


Calcium Aluminum Inclusions (CAI's)

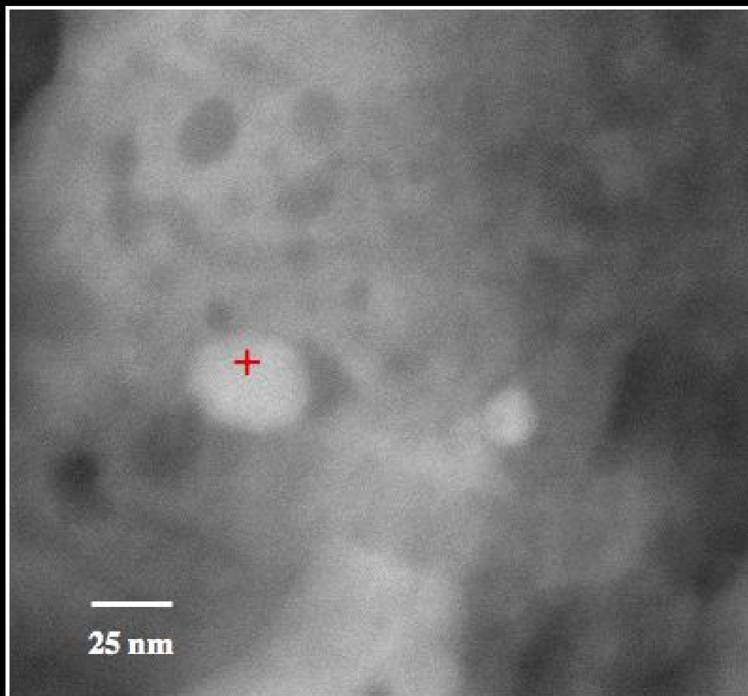
- The oldest materials that formed in the solar system
- ^{16}O enriched - possibly due to photochemical shielding effects near young Sun
- Contain exotic refractory minerals and rims that condense >1400K

The Allende meteorite

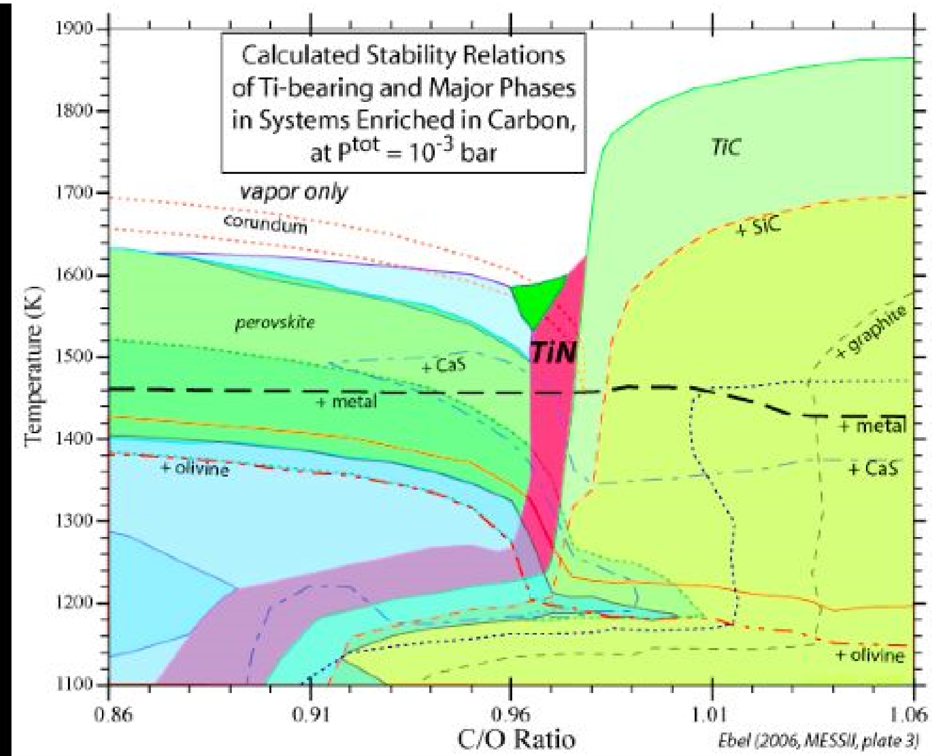


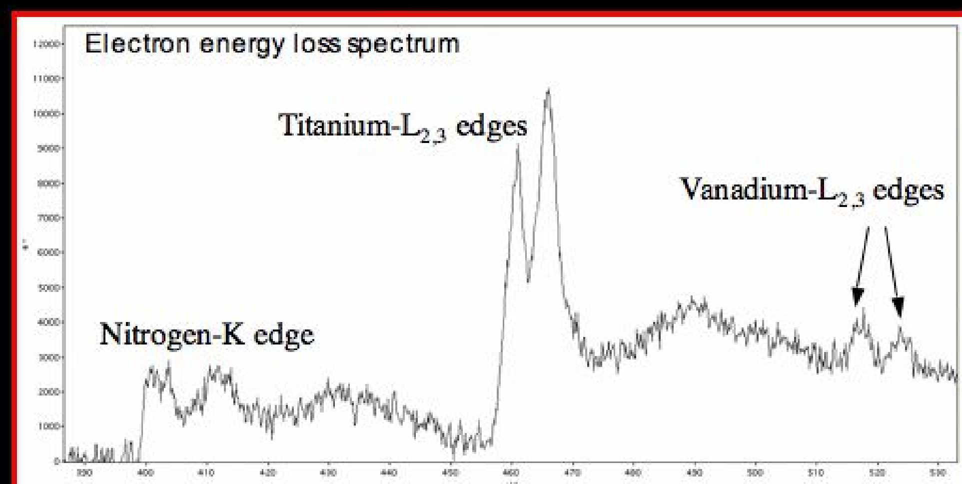

Wild2 refractory oxide and silicate grains
Terrestrial Fractionation line
CAI mixing line
T25 "Inti"
T22 olivine
T69 pyroxene
10
0
-10
-20
-30
-40
-50
-50
-40
-30
-20
-10
0
10
$\delta^{17}O$ (‰)
$\delta^{18}O$ (‰)

TiN (Osbornite) inclusions in Inti



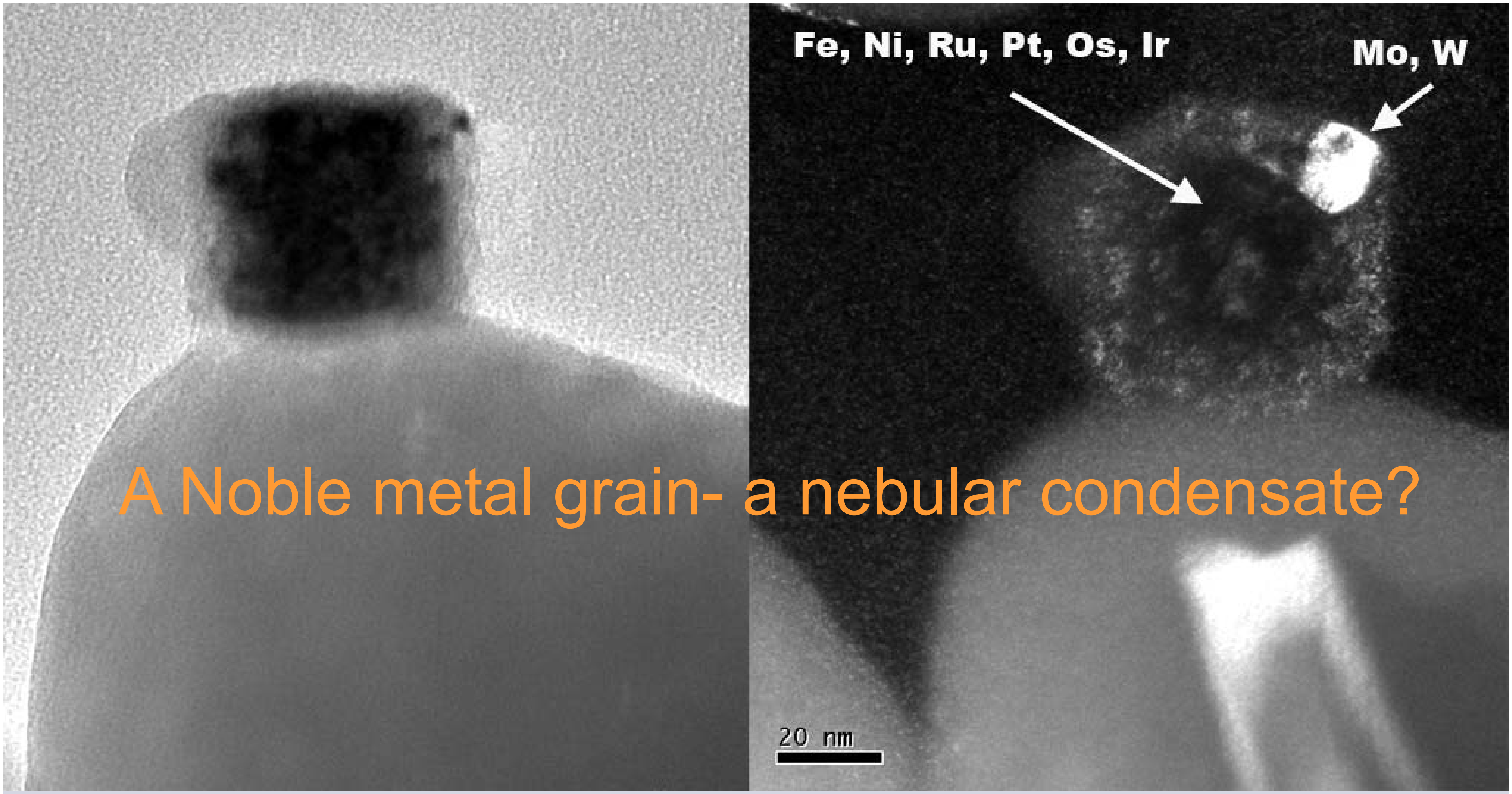
~2 Å diameter nanoprobe positioned on upper region of inclusion

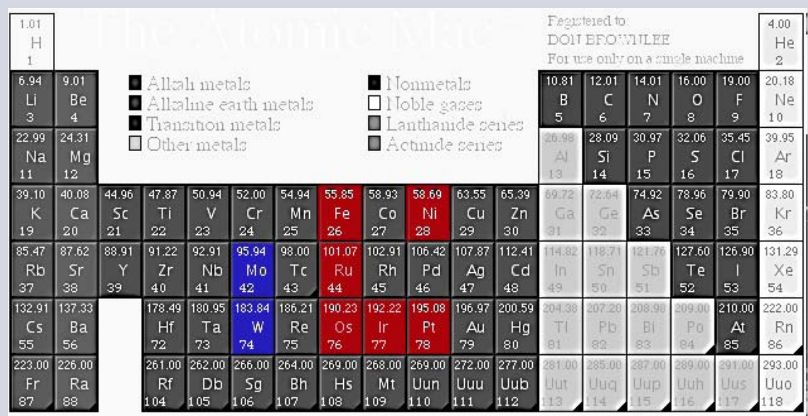


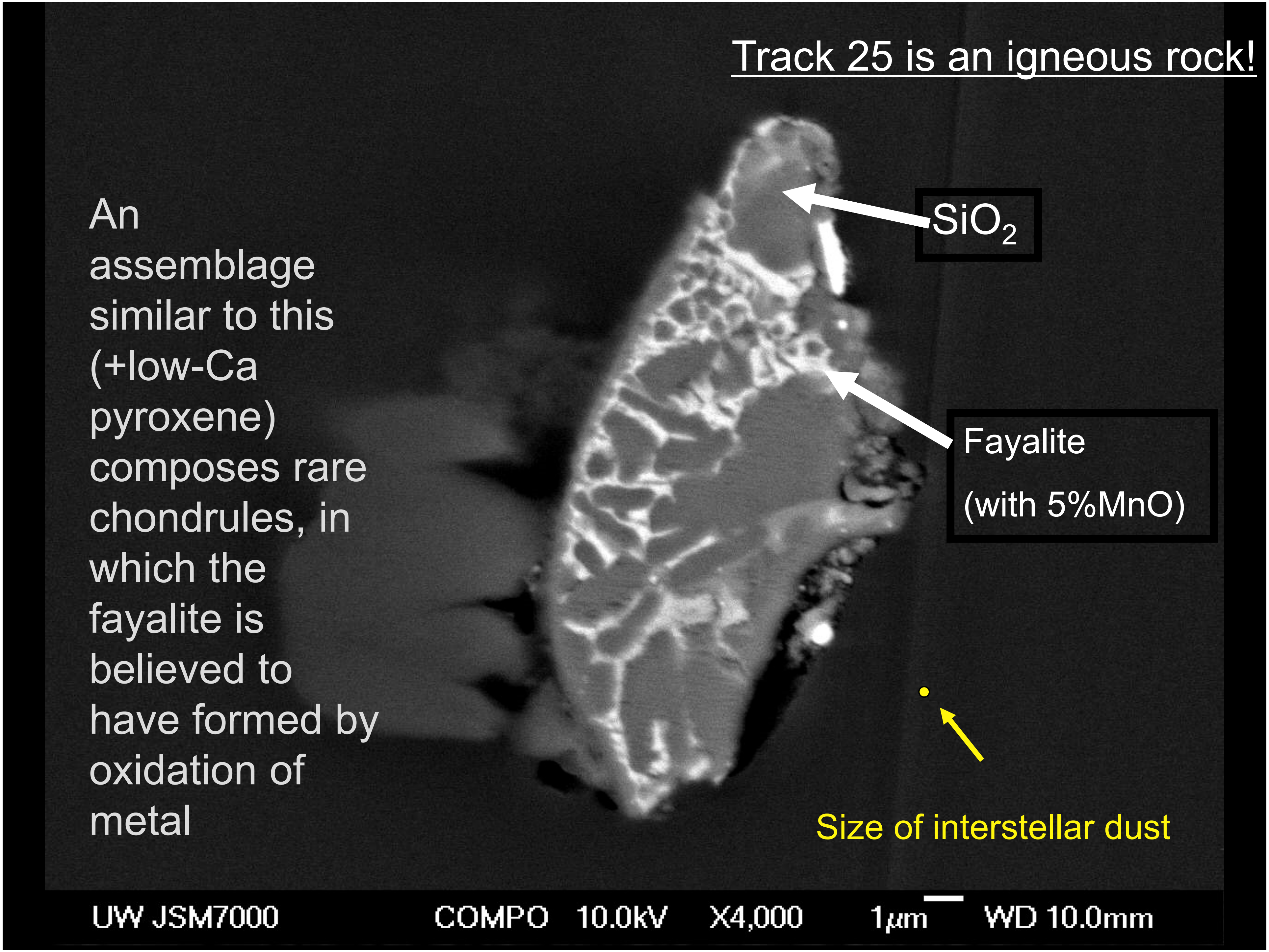


Dai, Bradley et al

A Noble metal grain- a nebular condensate?



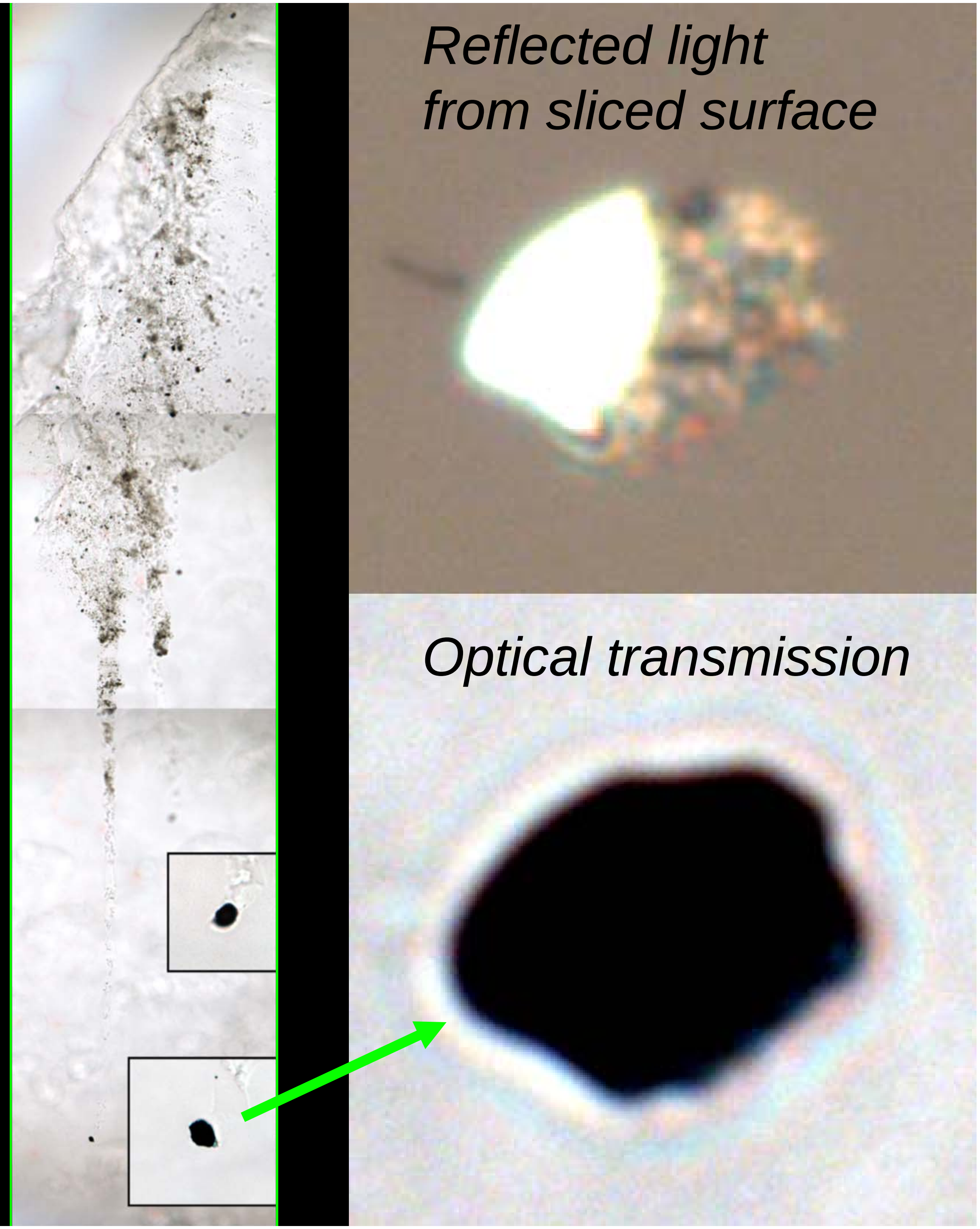


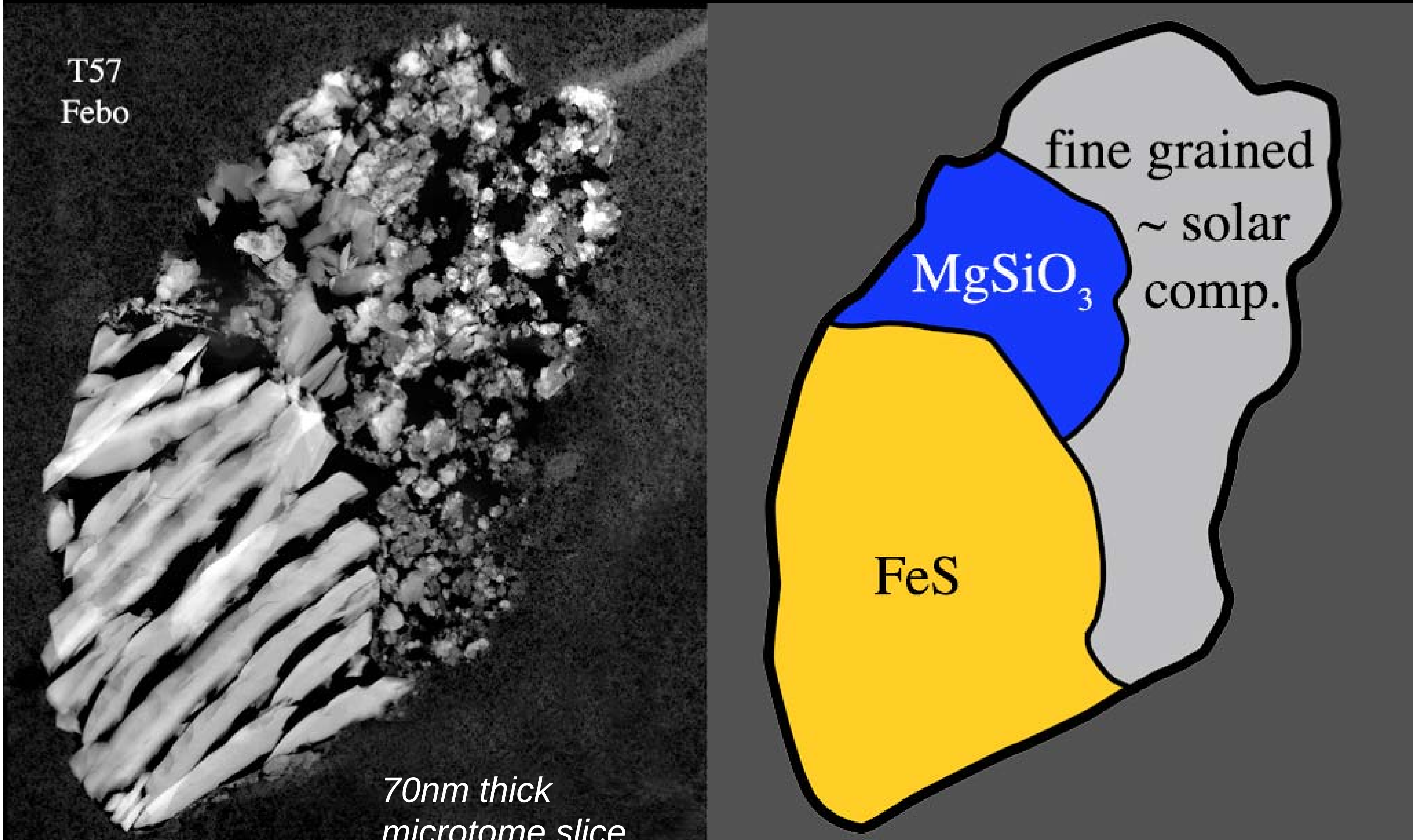

Track 25 is an igneous rock!
An assemblage similar to this (+low-Ca pyroxene) composes rare chondrules, in which the fayalite is believed to have formed by oxidation of metal
SiO_2
Fayalite
(with 5%MnO)
Size of interstellar dust
UW JSM7000
COMPO
10.0kV
X4,000
1μm
WD 10.0mm

Track 57
Fragment B

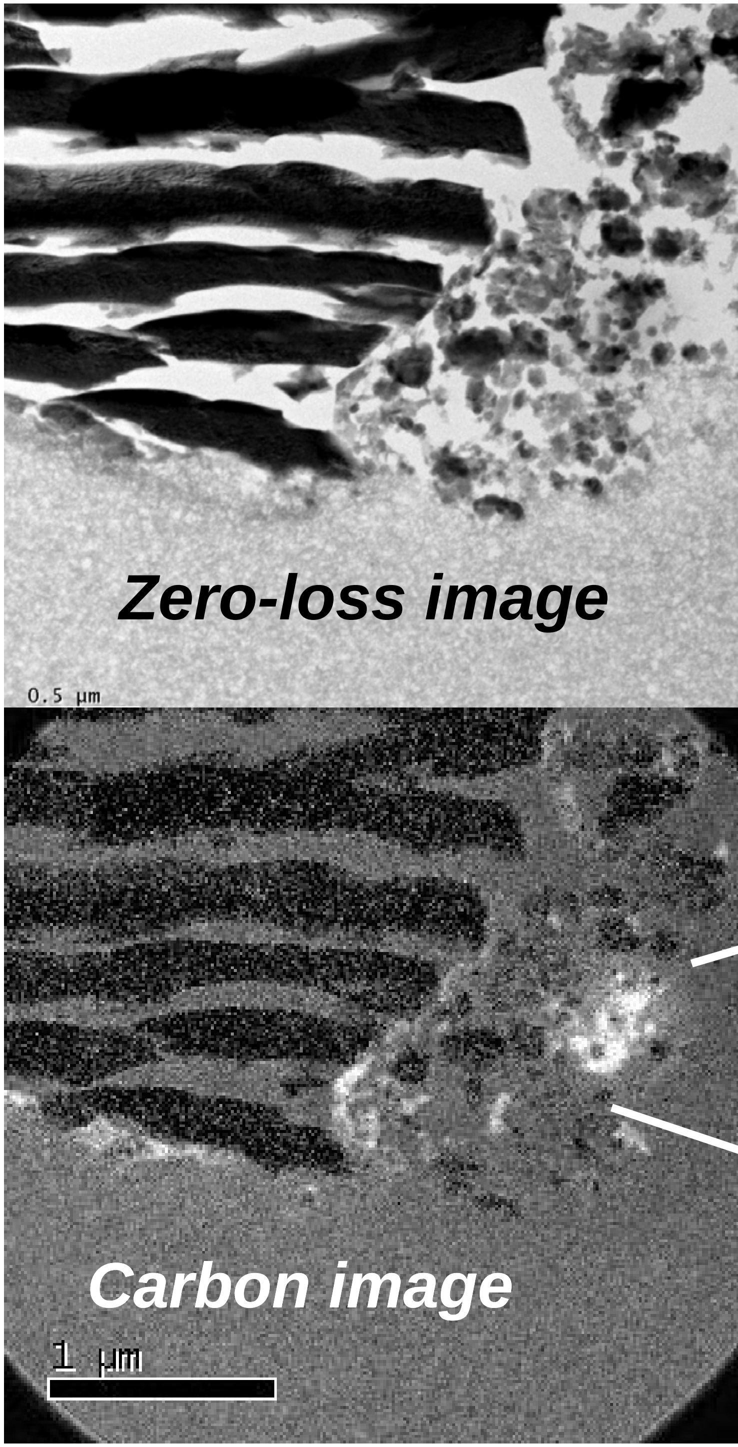
8µm rock
3 major components

Sulfide
Enstatite
Fine-grained solar comp. matl

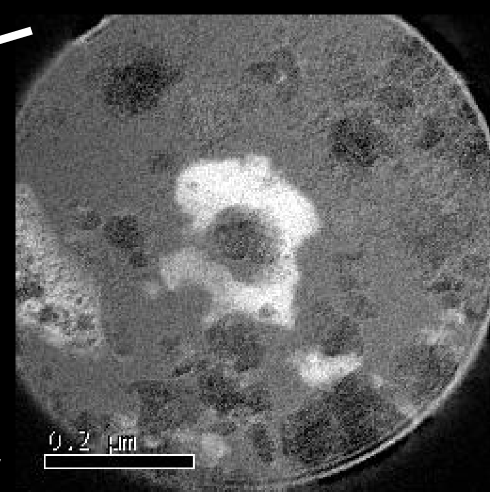


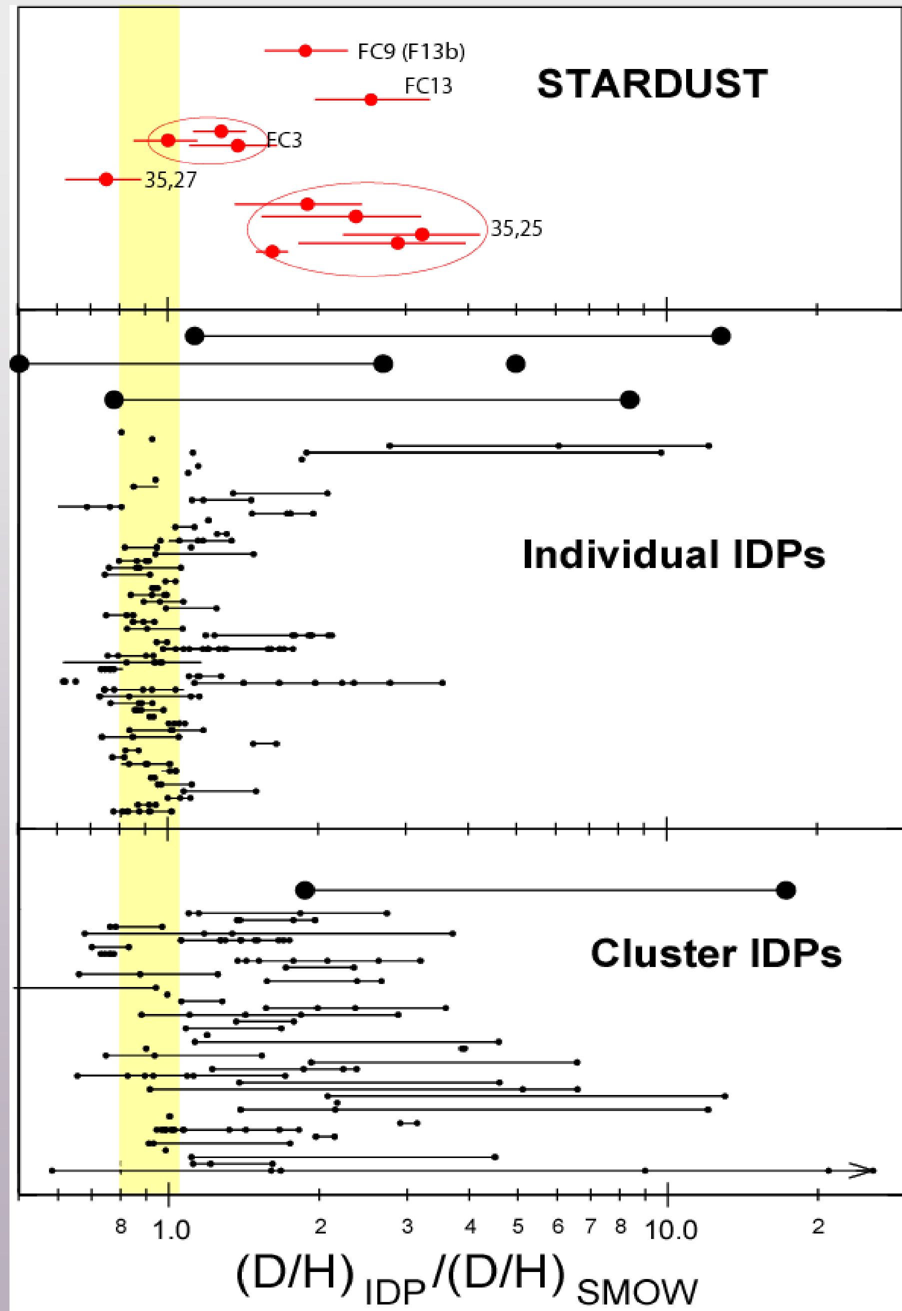

T57
Febo
70nm thick
microtome slice
fine grained
~ solar
comp.
MgSiO3
FeS

Energy filtered imaging of Track 57



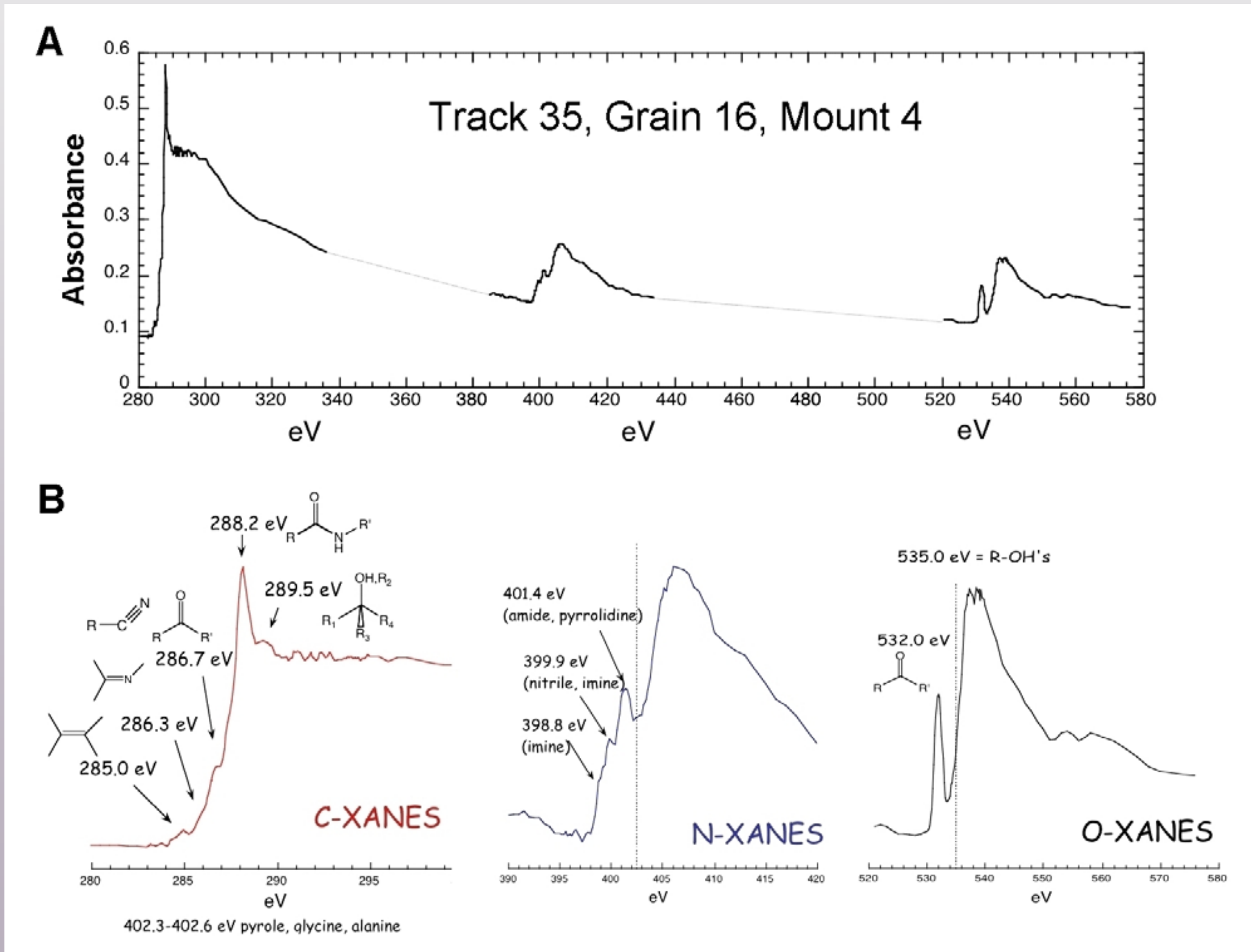
Organic carbon with ^{15}N excess





STARDUST
FC9 (F13b)
FC13
FC3
35,27
35,25
Individual IDPs
Cluster IDPs
8
1.0
2
3
4
5
6
7
8
10.0
2
(D/H) IDP/(D/H) SMOW

Cometary Organics were successfully collected X-ray Absorption Near Edge Spectroscopy (XANES)



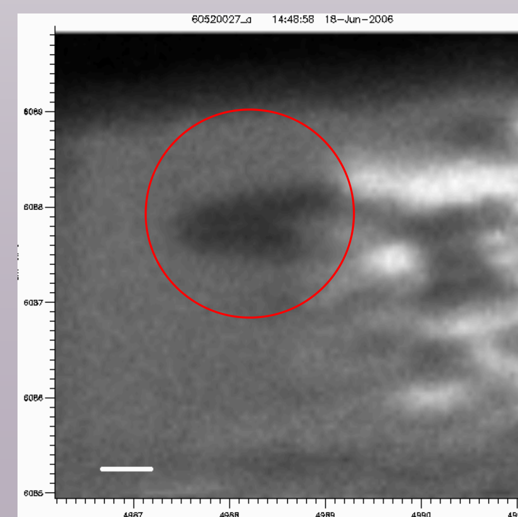
From C-, N-, and O-XANES one obtains:

(1) Information on chemical structures

(2) N/C and O/C values:

STARDUST : $C_{100}O_{39}N_8$

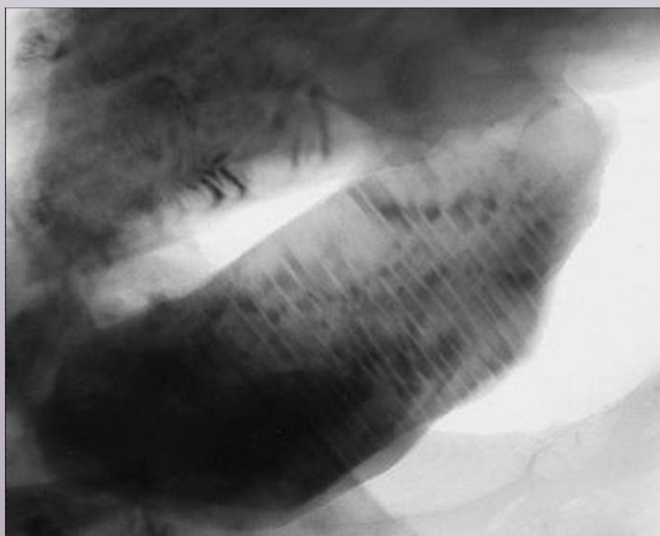
Murchison : $C_{100}O_{18.3}N_{3.8}$



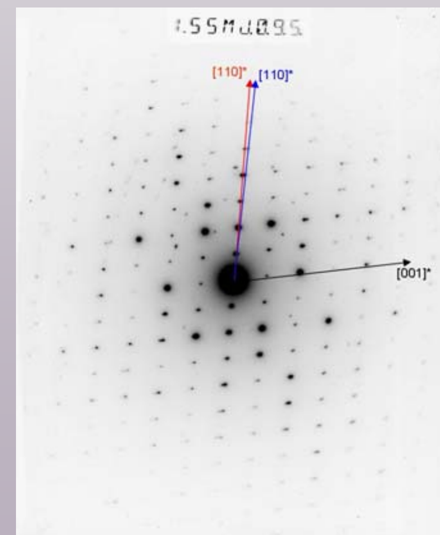
Cody et al.

Clinopyroxenes

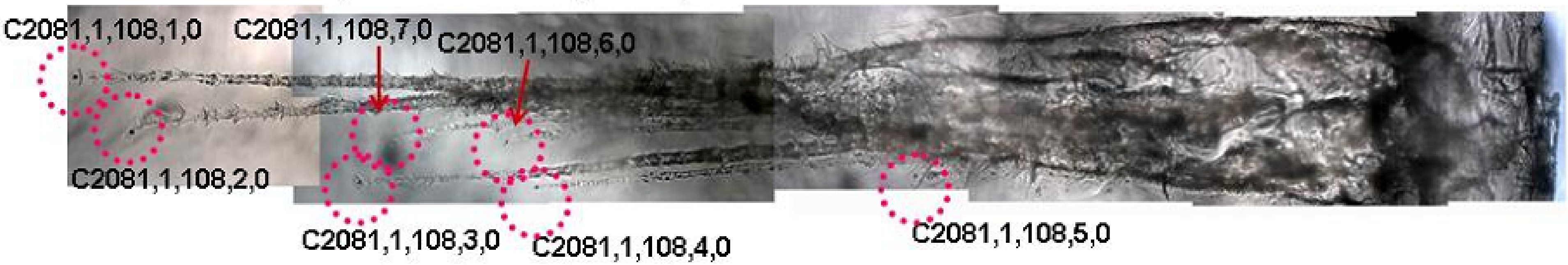
- Are widespread in the Wild 2 grains
- Reported to contain up to 5 wt% Na_2O and 13 wt% Cr_2O_3



Diopside exsolution lamellae within enstatite

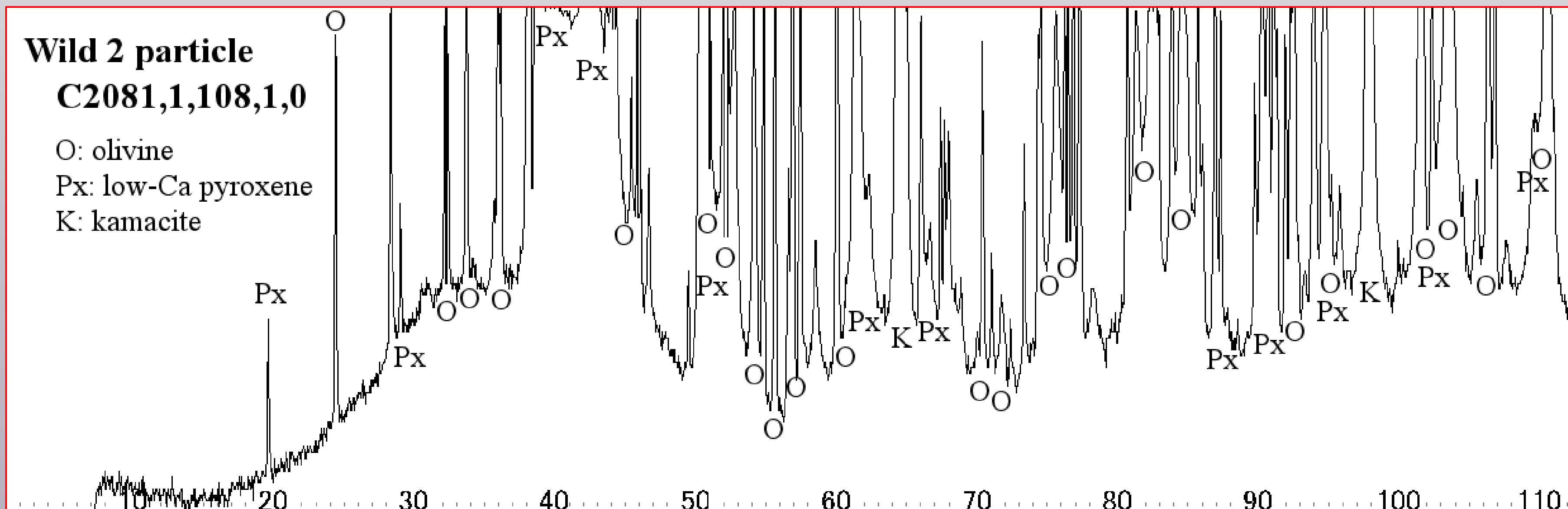


Extracted from C2081, track#04 13212 μm long track CO#14750



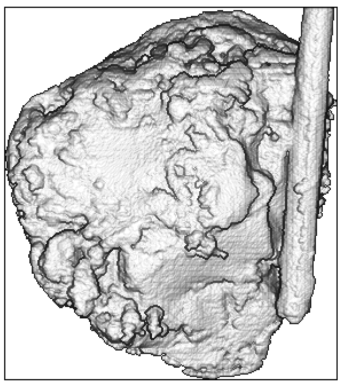
Gozen-sama: C2081,1,108,1,0

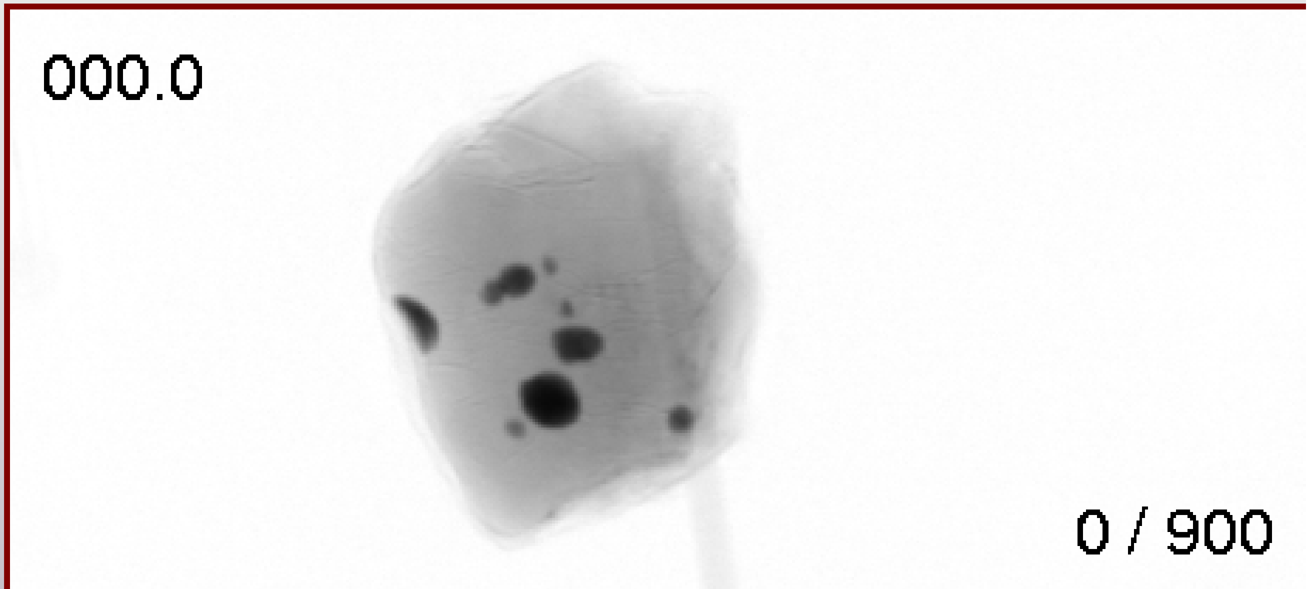
Crystalline type

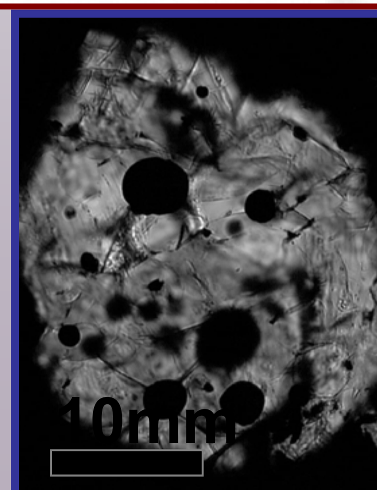


Tomoki Nakamura, Akira Tsuchiyama and many others

Three dimensional structure of **Gozen-sama**

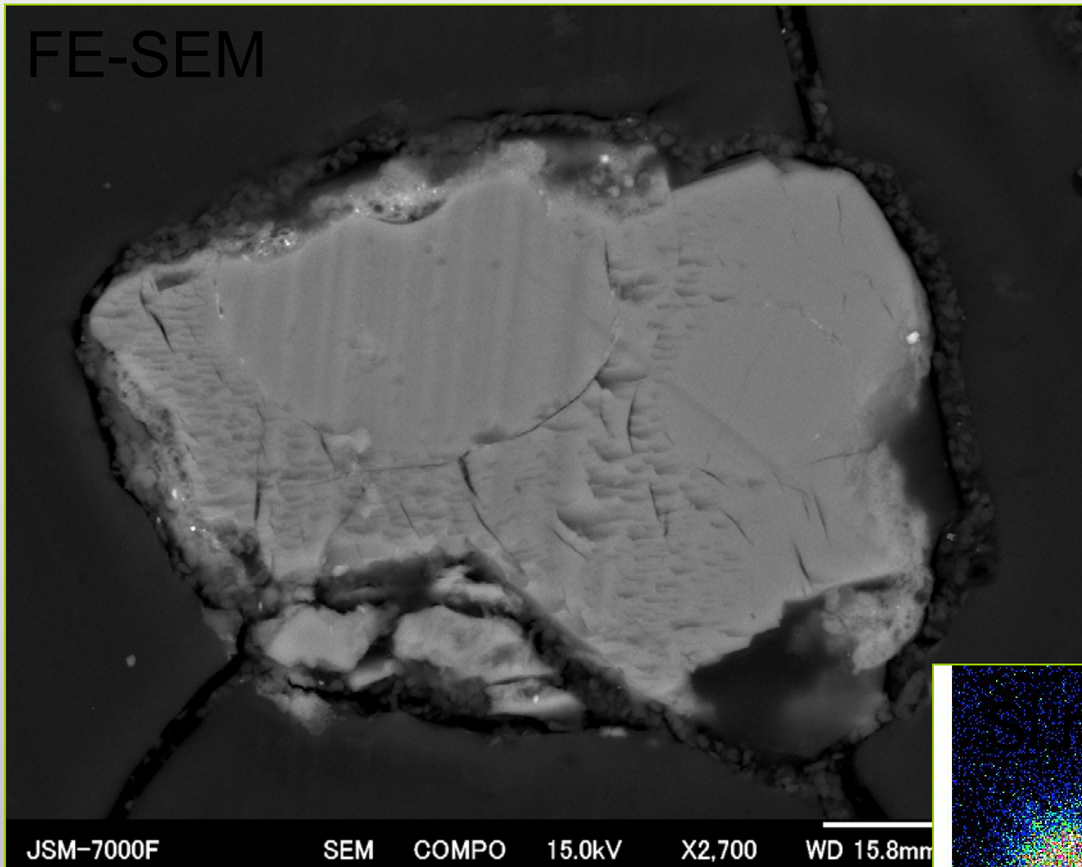


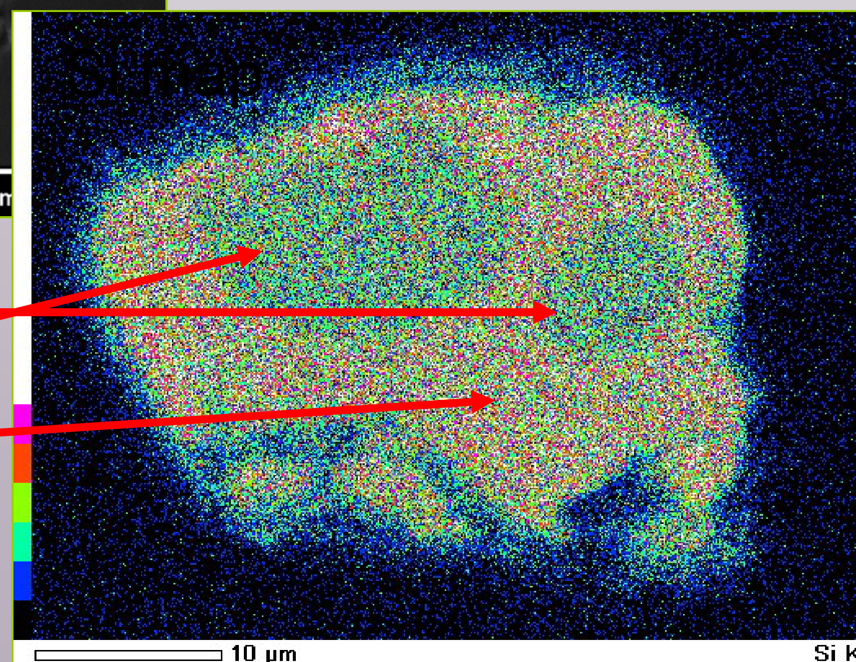




Chondrule in a CO3 chondrite

Gozen-sama

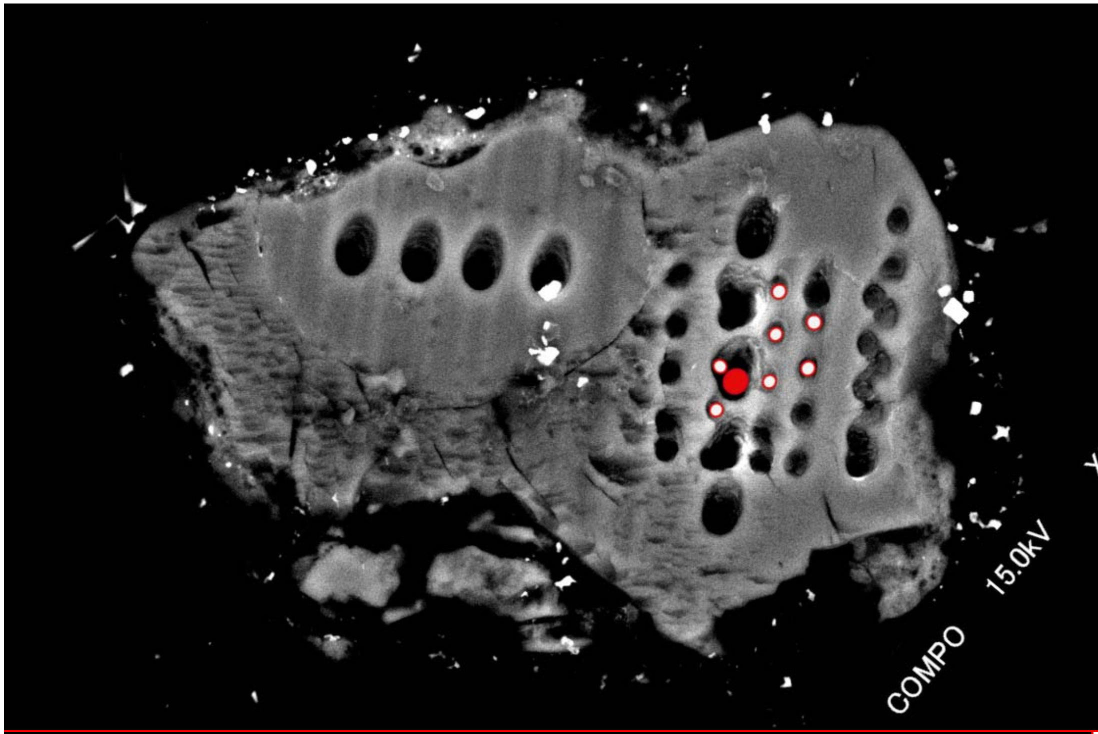




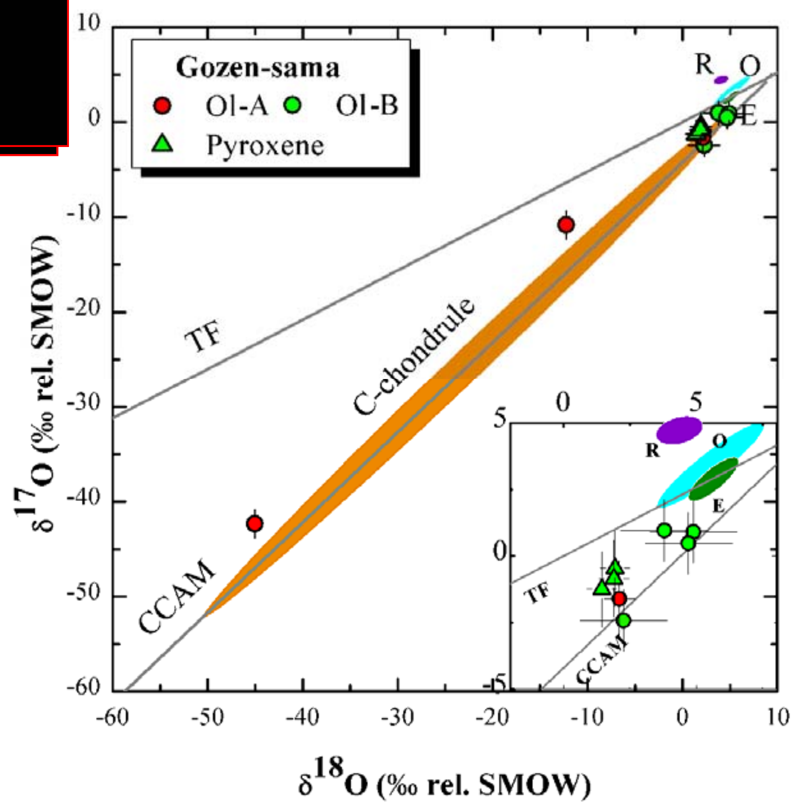
Ol-A **Fo_{95}**

Ol-B **Fo_{94}**

LPx **$En_{95}Wo_{1}$**

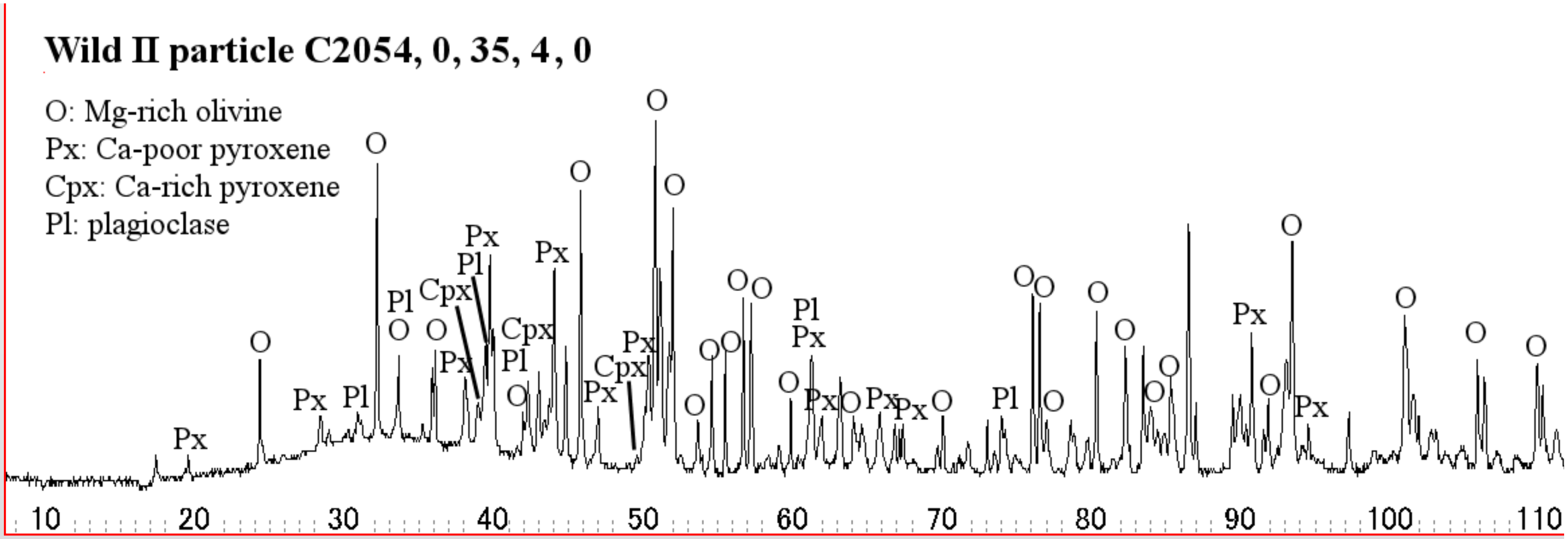


Gozen-sama
oxygen isotopes



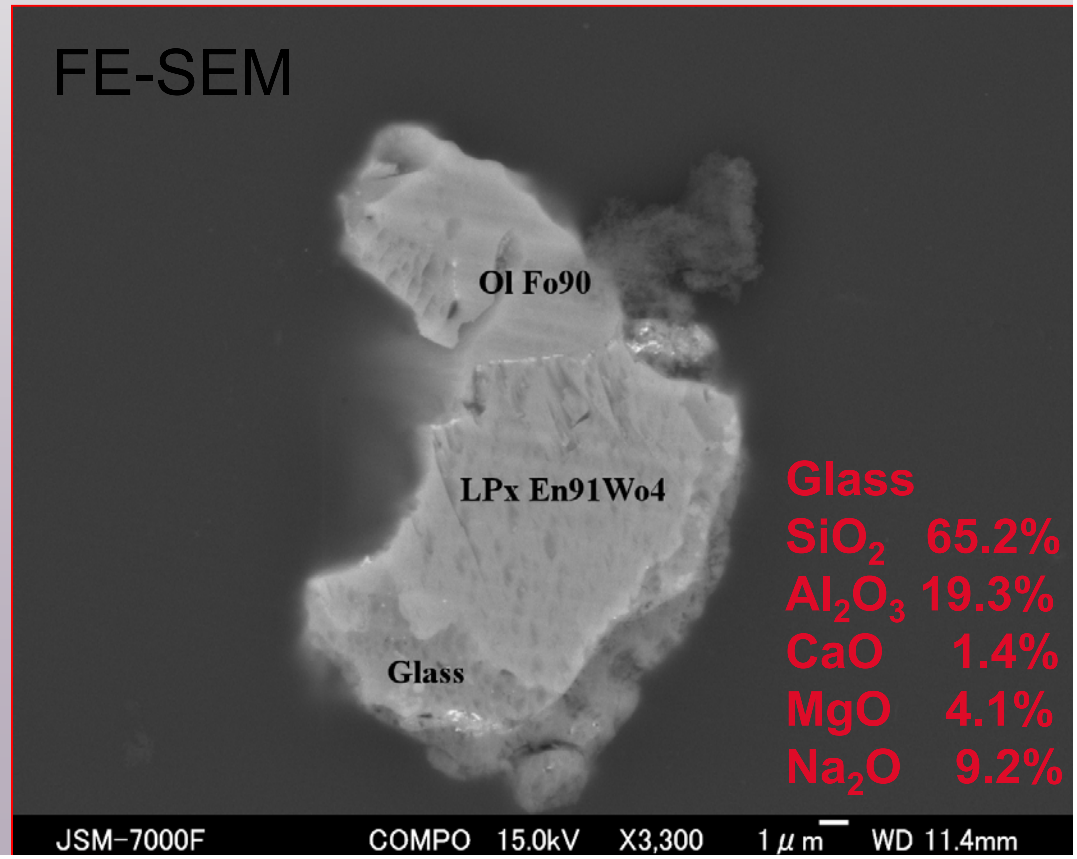
Ol-A ^{16}**O-rich**
Ol-B ^{16}**O-poor**
LPx **intermediate**

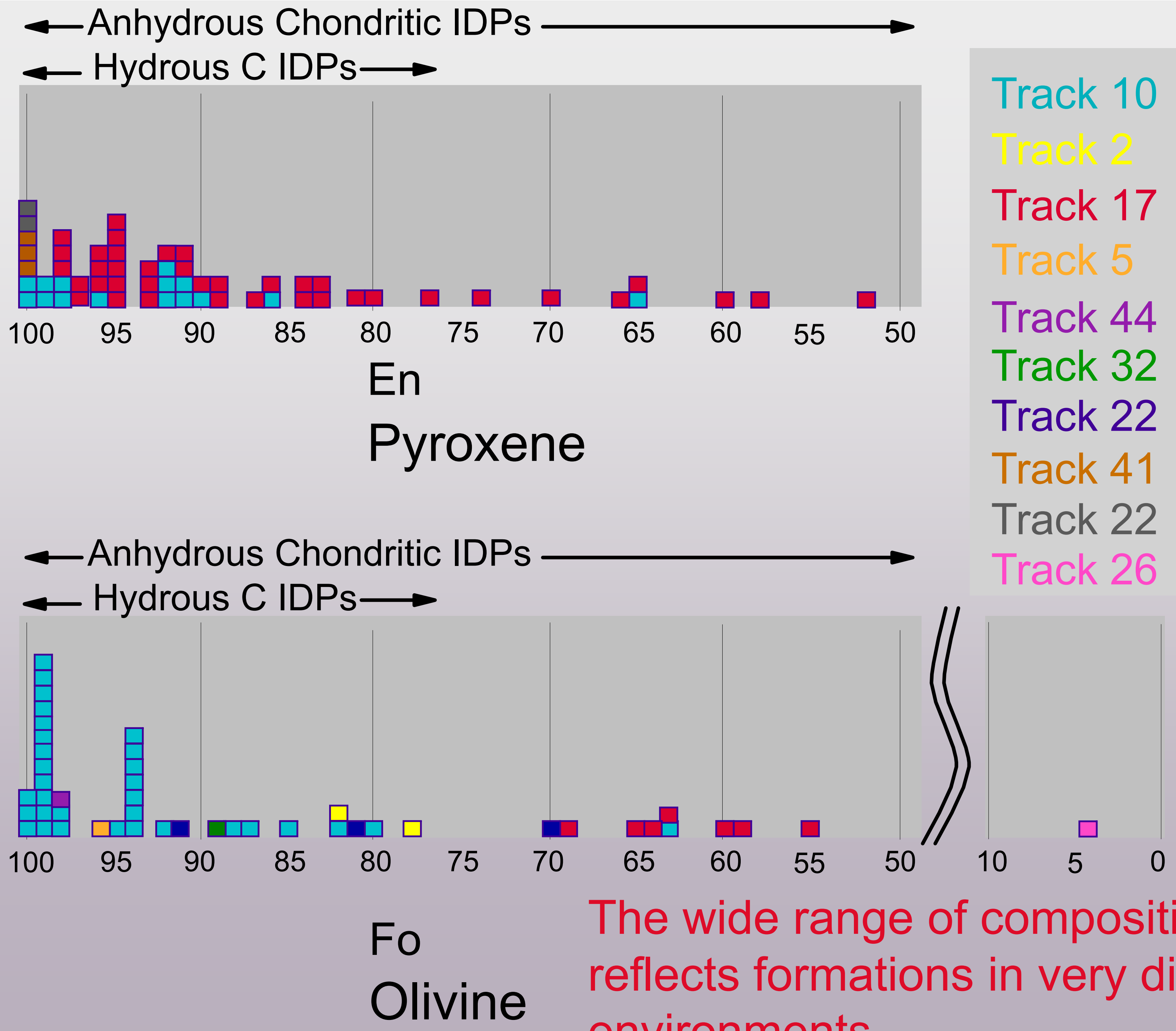
A product of incomplete melting of ^{16}O-rich and ^{16}O-poor precursors



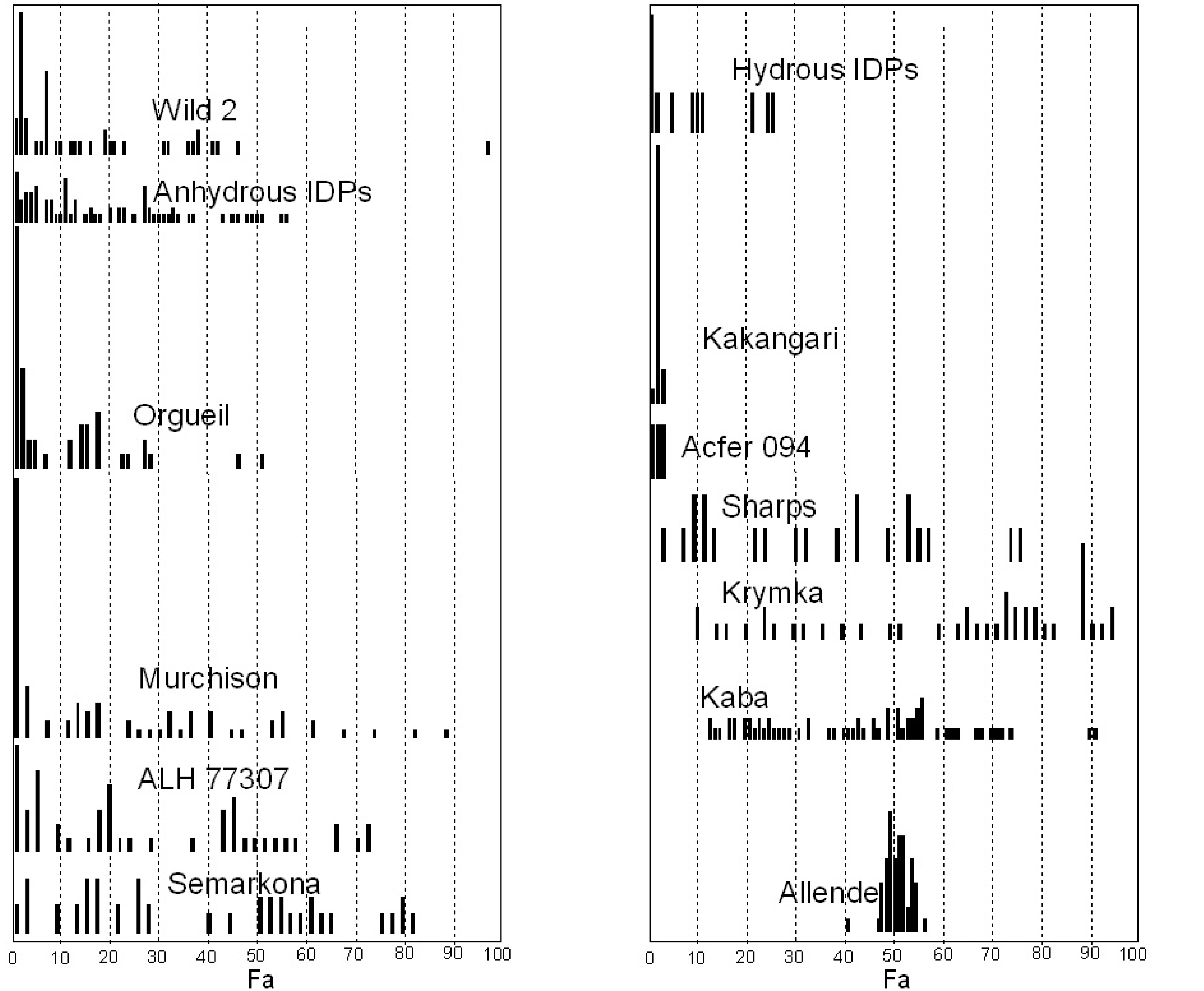
Lilly: C2054,0,35,4,0

Crystalline type

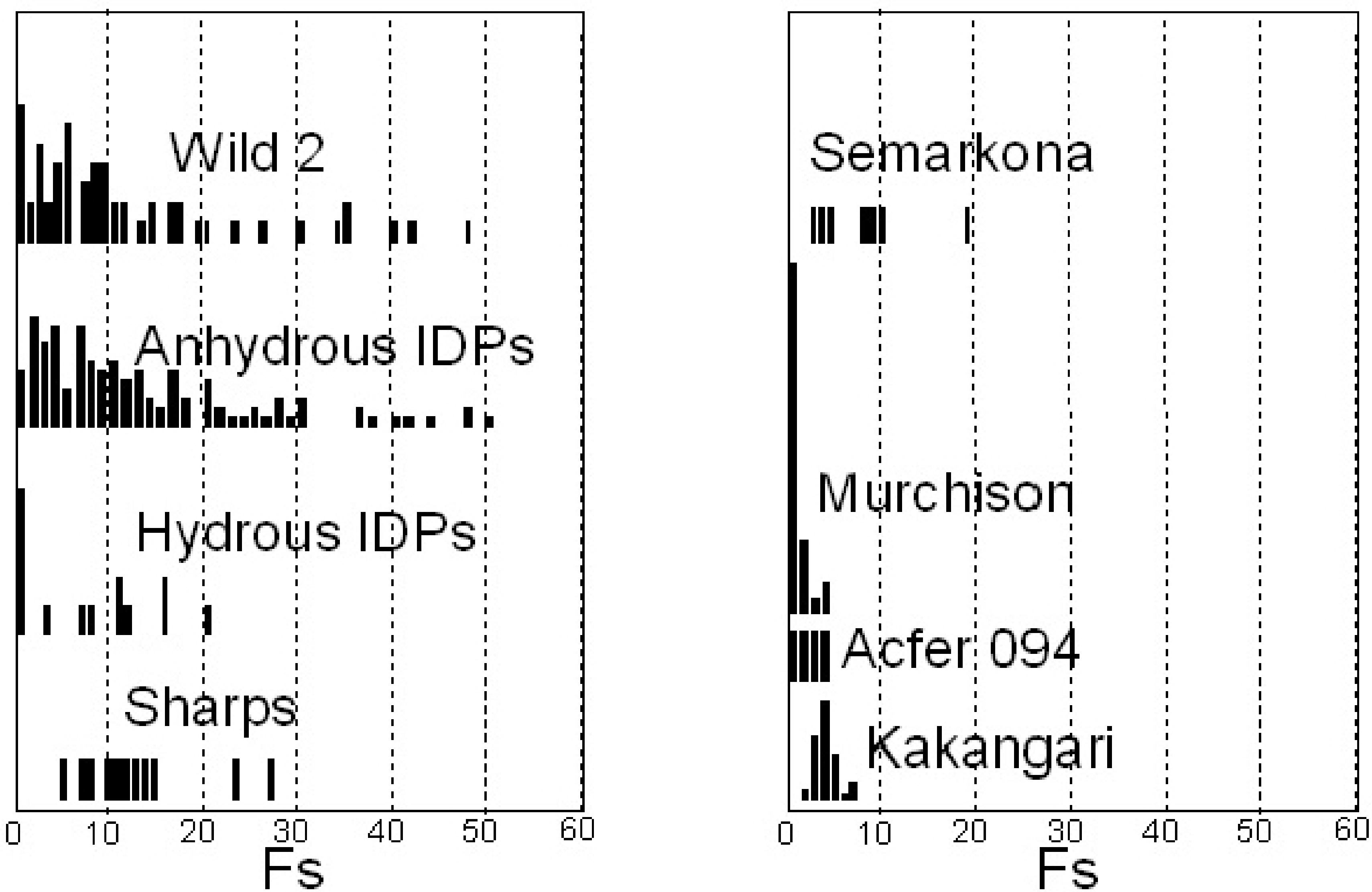




The wide range of compositions reflects formations in very different environments

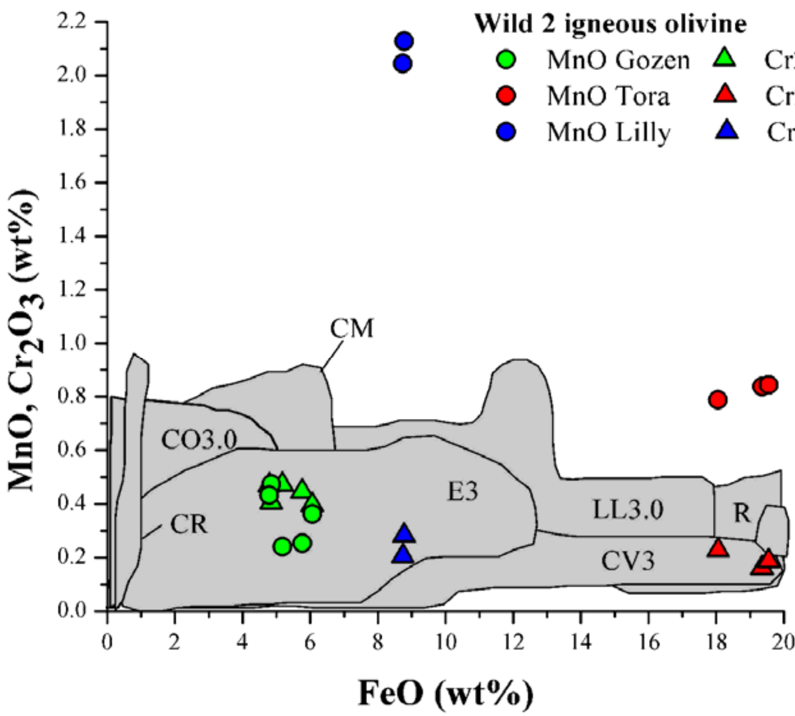


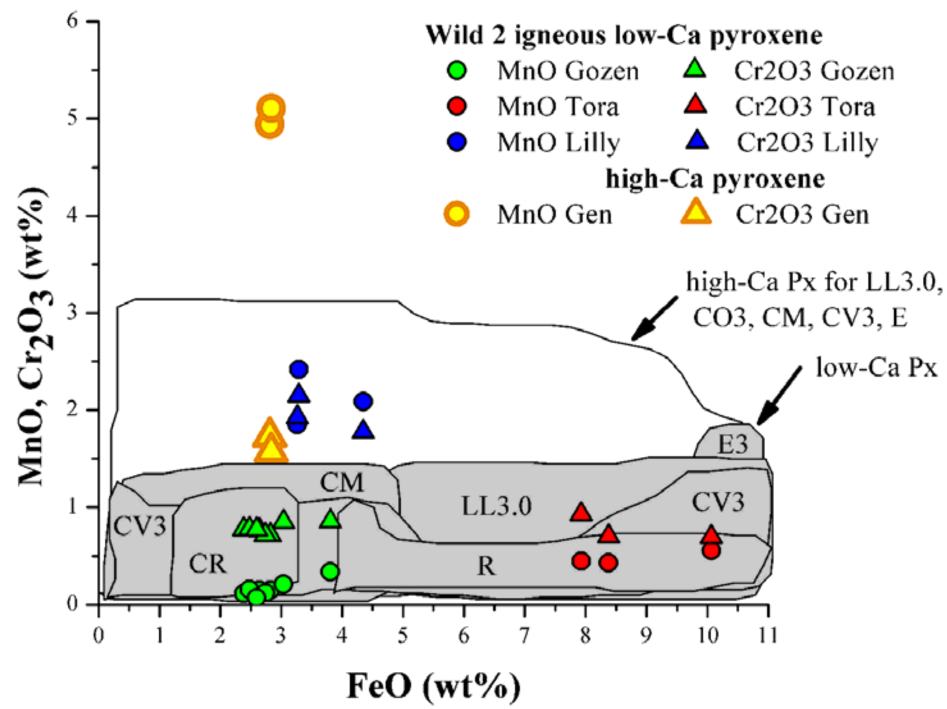
Wild 2
Anhydrous IDPs
Orgueil
Murchison
ALH 77307
Semarkona
0 10 20 30 40 50 60 70 80 90 100
Fa
Hydrous IDPs
Kakangari
Acfer 094
Sharps
Krymka
Kaba
Allende
0 10 20 30 40 50 60 70 80 90 100
Fa



Wild 2
Anhydrous IDPs
Hydrous IDPs
Sharps
0 10 20 30 40 50 60
Fs
Semarkona
Murchison
Acfer 094
Kakangari
0 10 20 30 40 50 60
Fs

Minor elements in olivine





Minor elements in pyroxene

STARDUST Sample# C2067,1,111,1,0 on special Mike's mount for SXRD

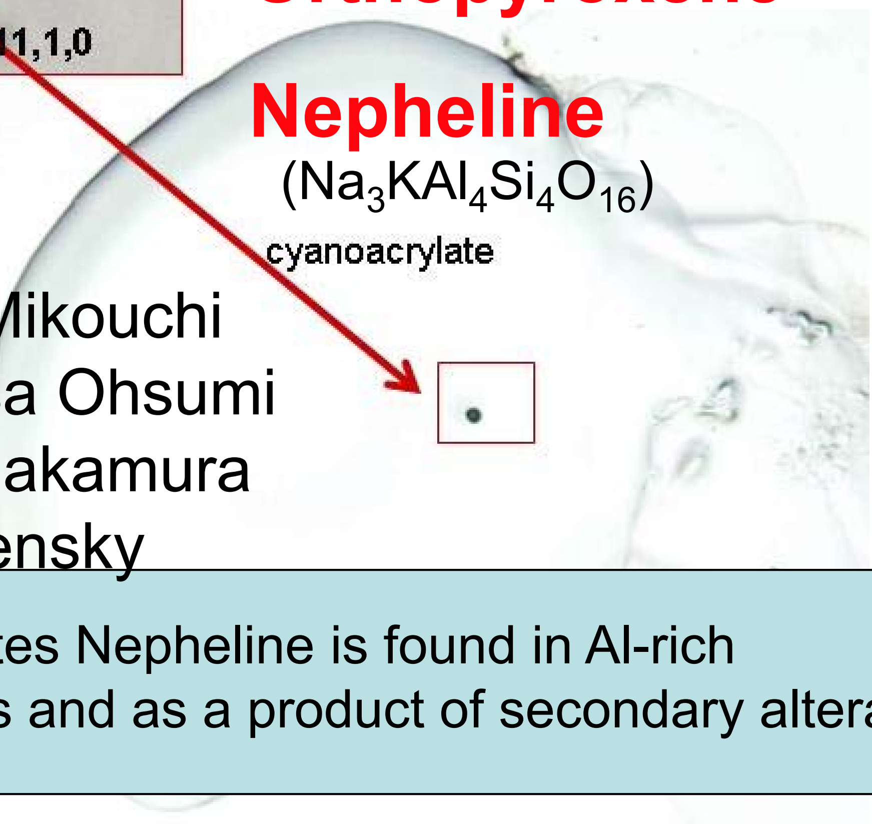
Extracted from C2067 Quickstone 10741μm long bulb track CO#14737

Olivine

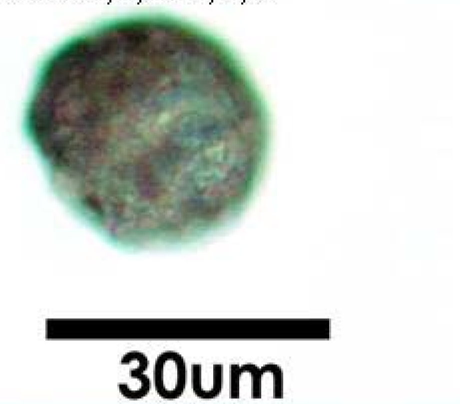
Orthopyroxene

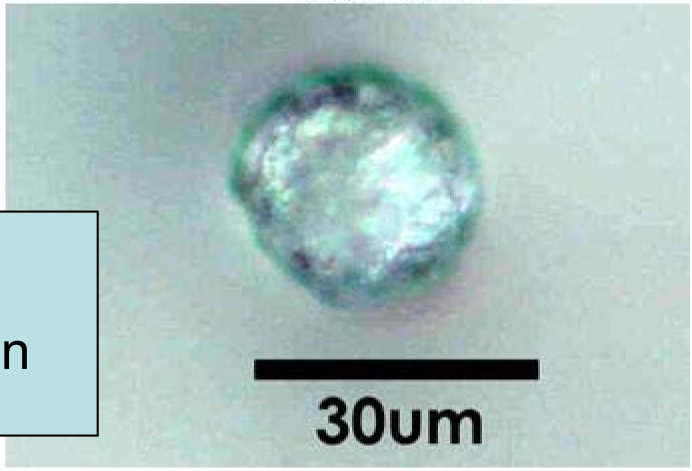
Nepheline

($Na_3KAl_4Si_4O_{16}$)



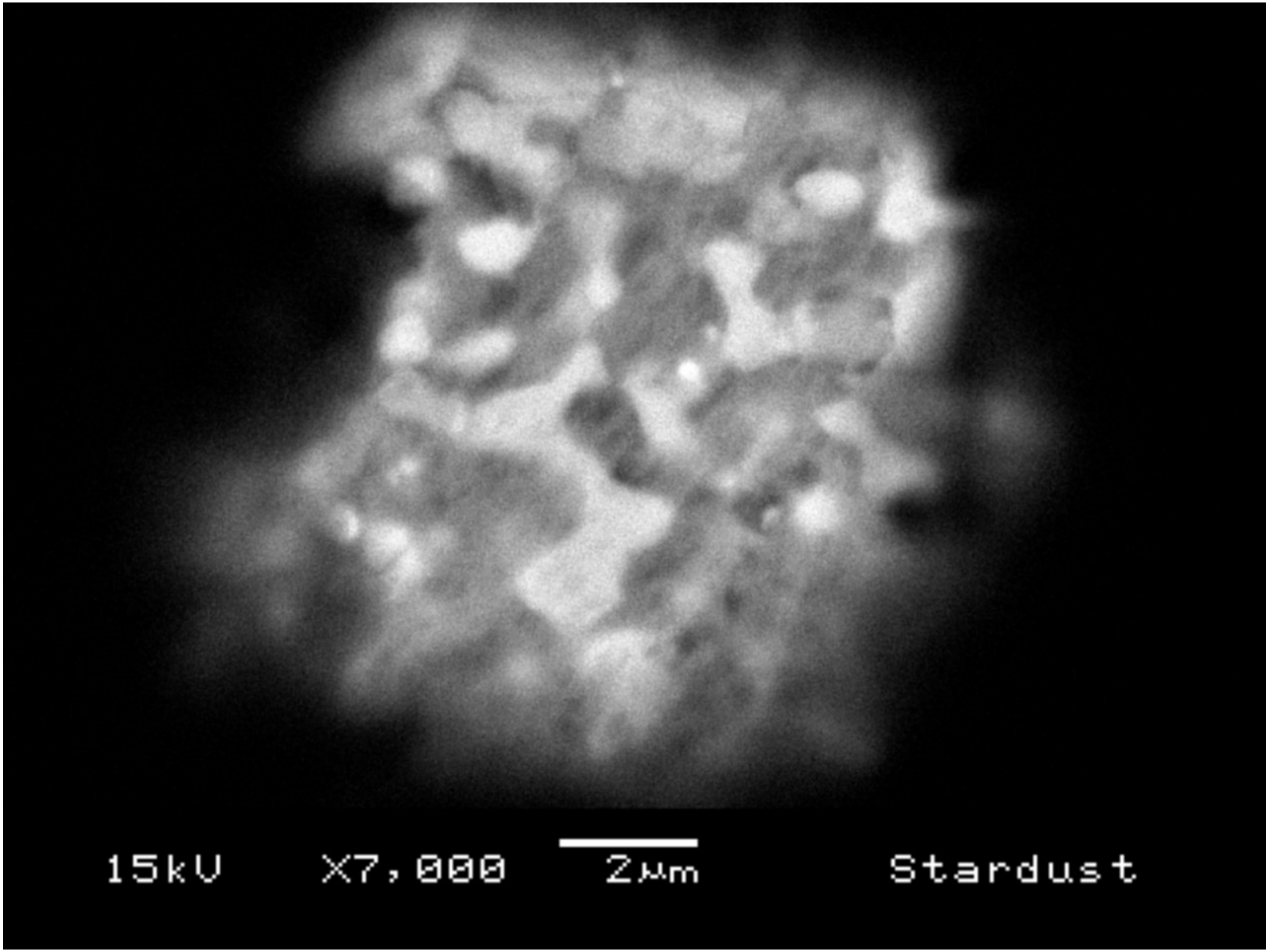
C2067,1,111,1,0



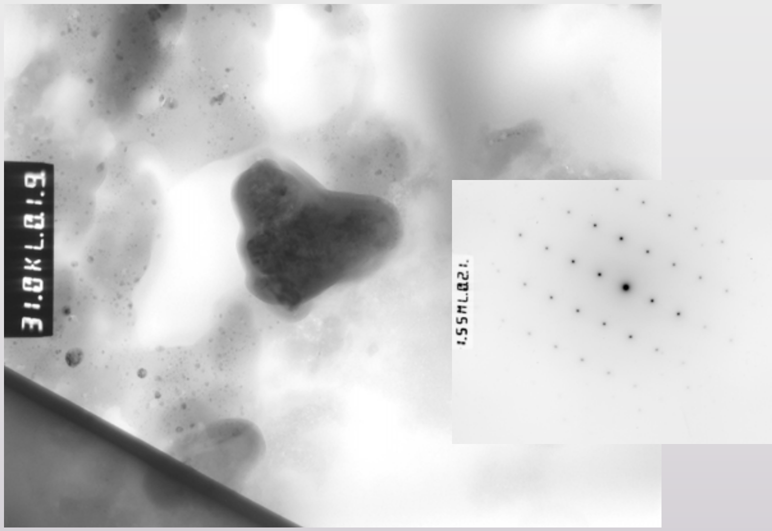


Takashi Mikouchi
Kazumasa Ohsumi
Tomoki Nakamura
Mike Zolensky

In meteorites Nepheline is found in Al-rich chondrules and as a product of secondary alteration


15kV
X7,000
2μm
Stardust

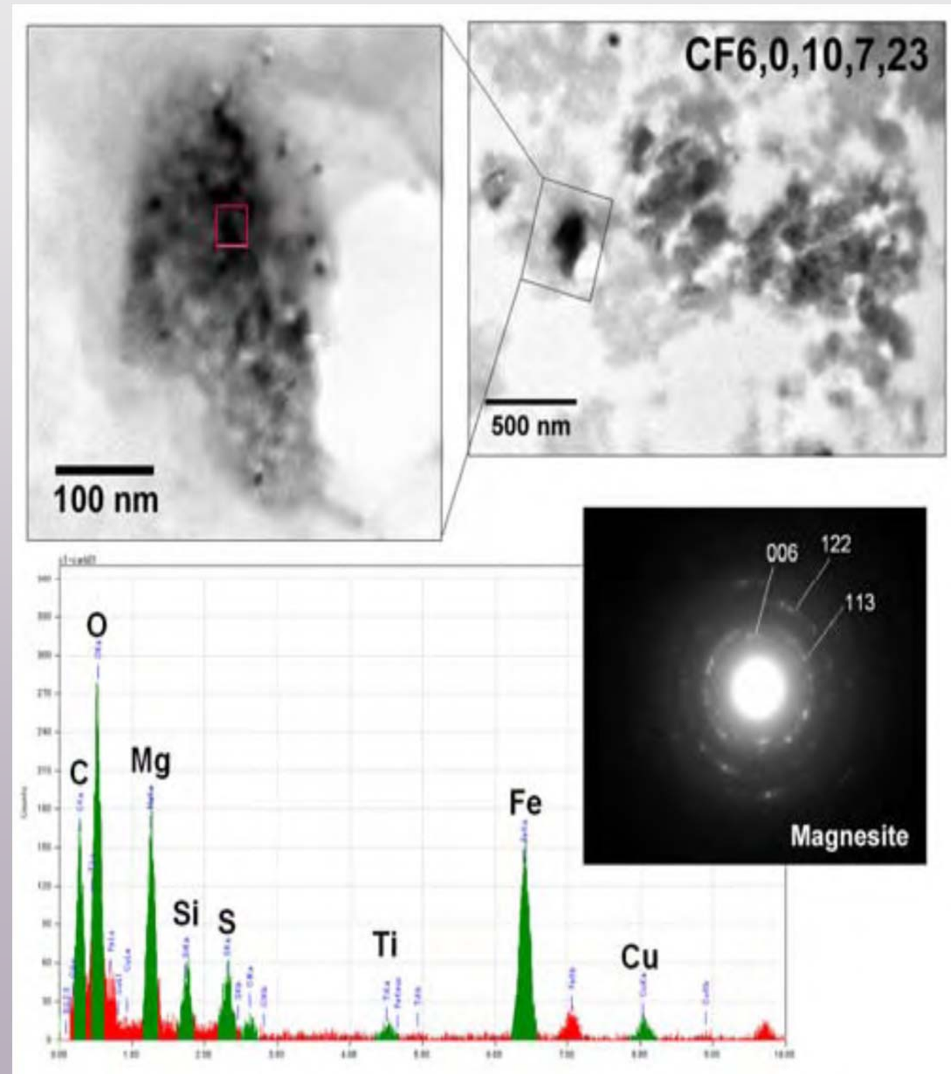
Ca-Fe-Mg carbonates - Some of which are Cometary



Calcite crystal

Field of view is 3 μm wide

Mg-Fe Carbonate Grains



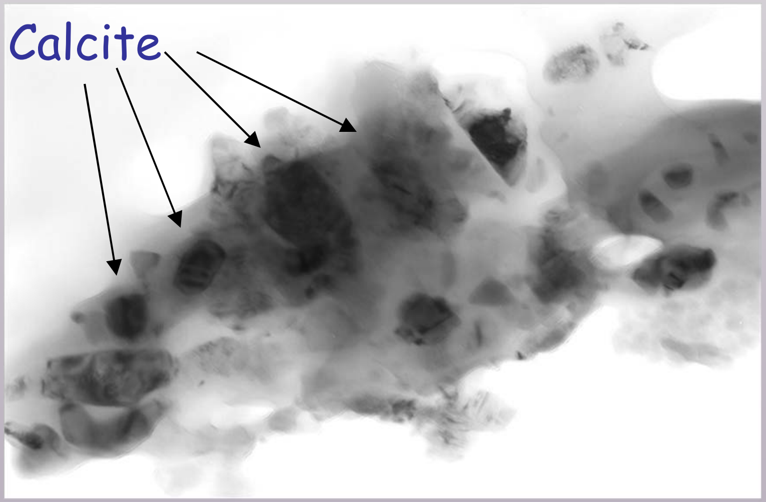
Hugues Leroux

Sue Wirick

Takashi Mikouchi

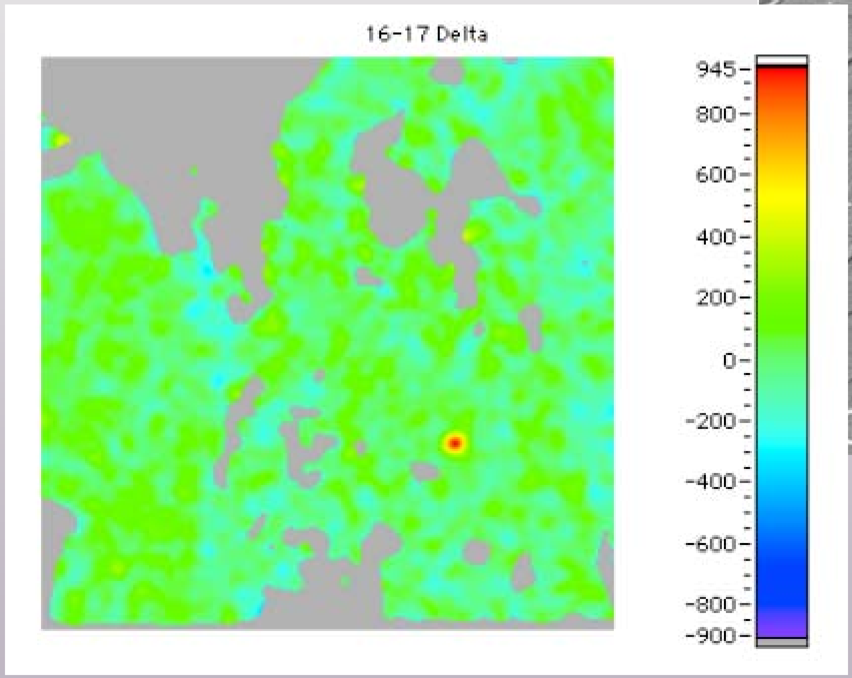
Aqueous Alteration?

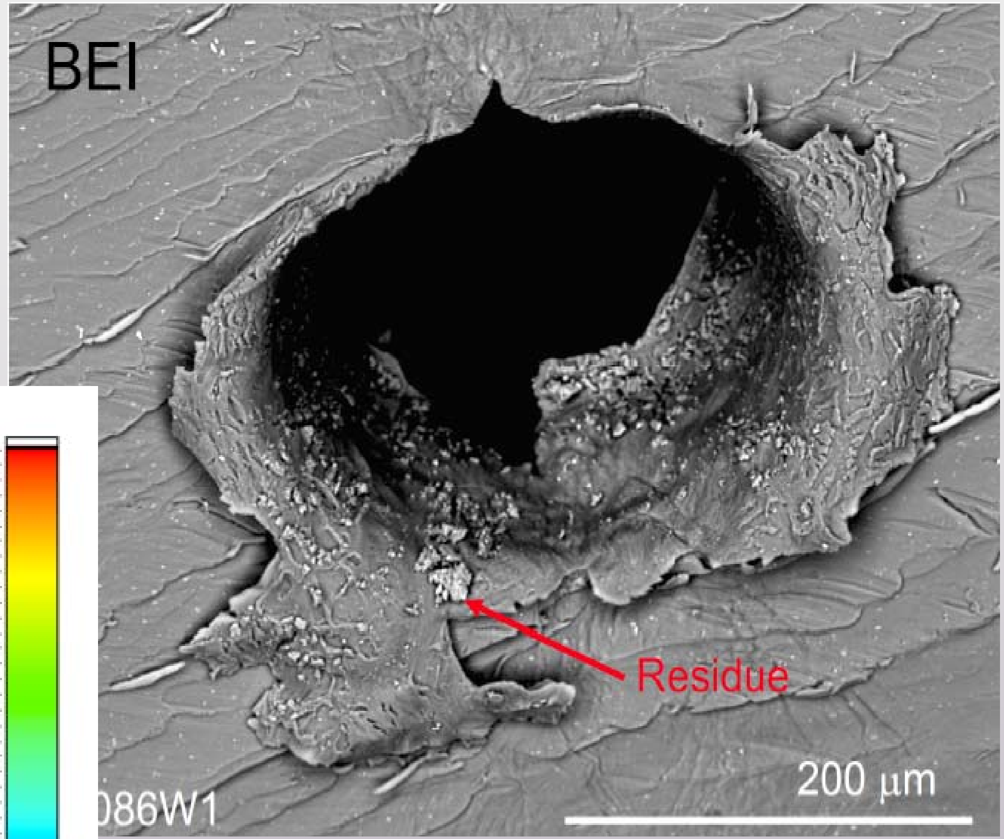
- No definitive evidence
  - no hydrous phases

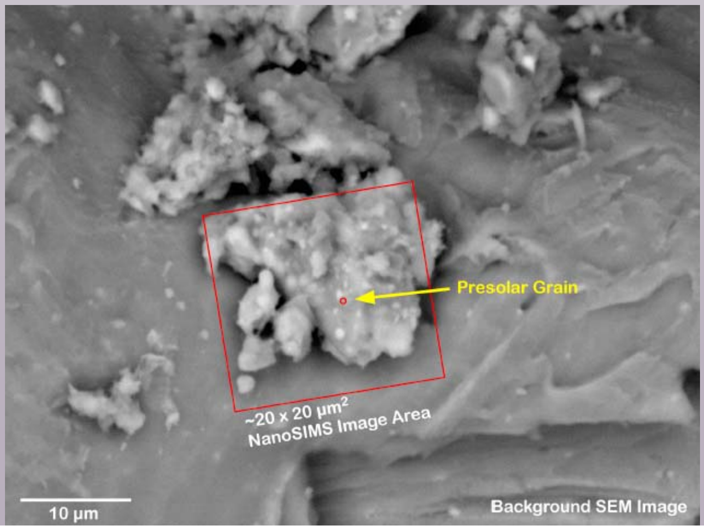


large crater that perforated foil:

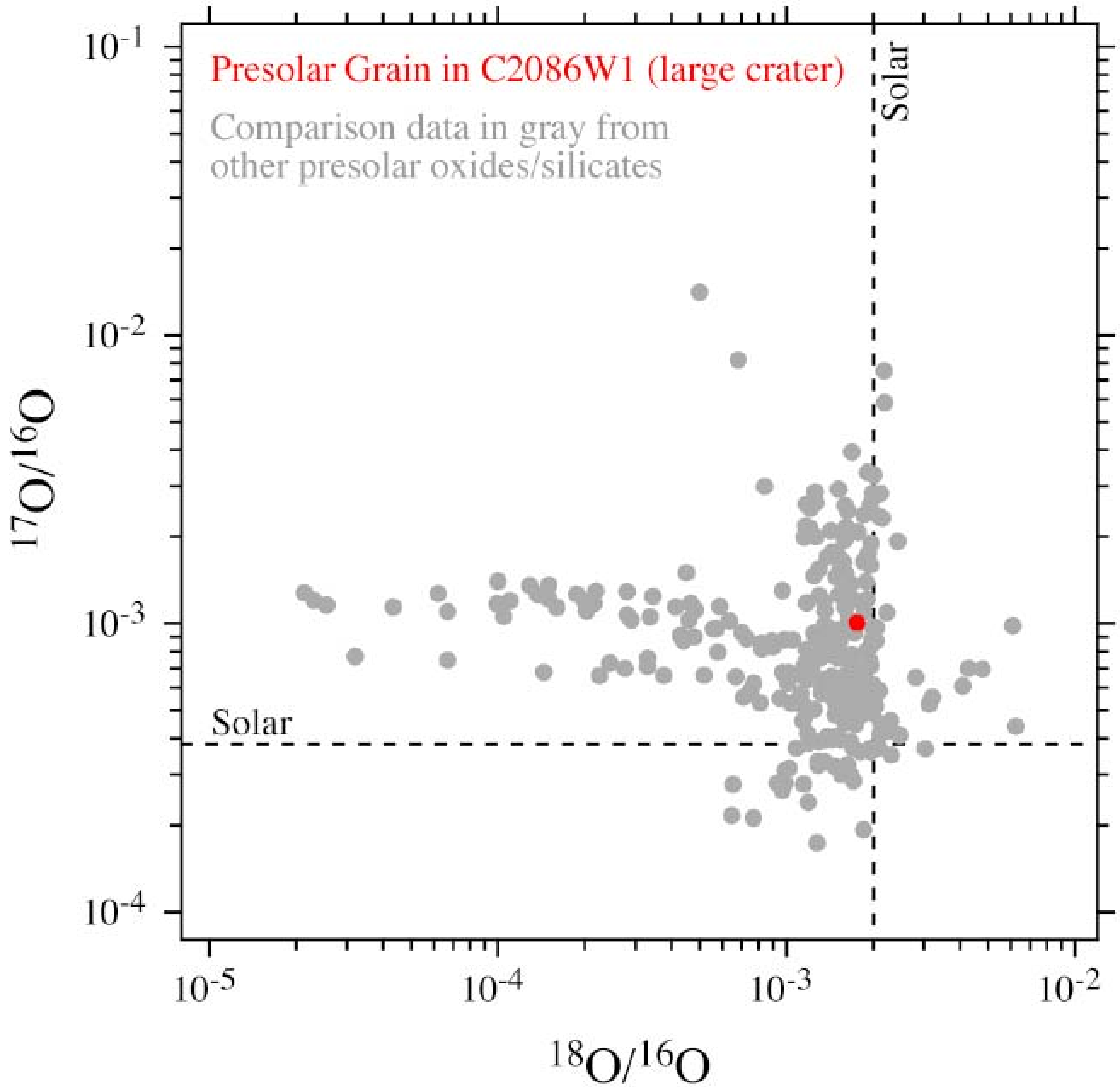
Three presolar grains found!







Frank Stadermann



Huge ^{17}O-enrichment:

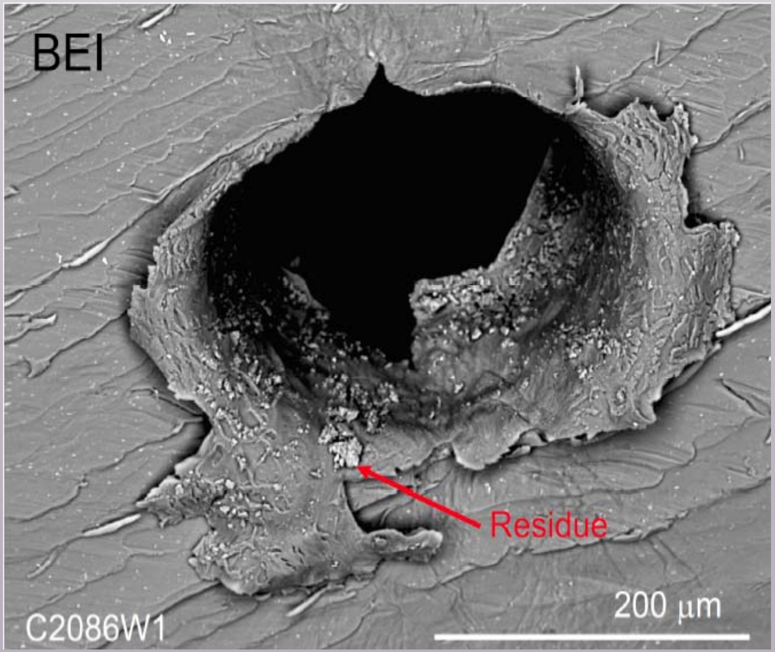
$^{17}O/^{16}O$ = $(1.01 \pm 0.10) \times 10^{-3}$

$^{18}O/^{16}O$ = $(1.77 \pm 0.12) \times 10^{-3}$

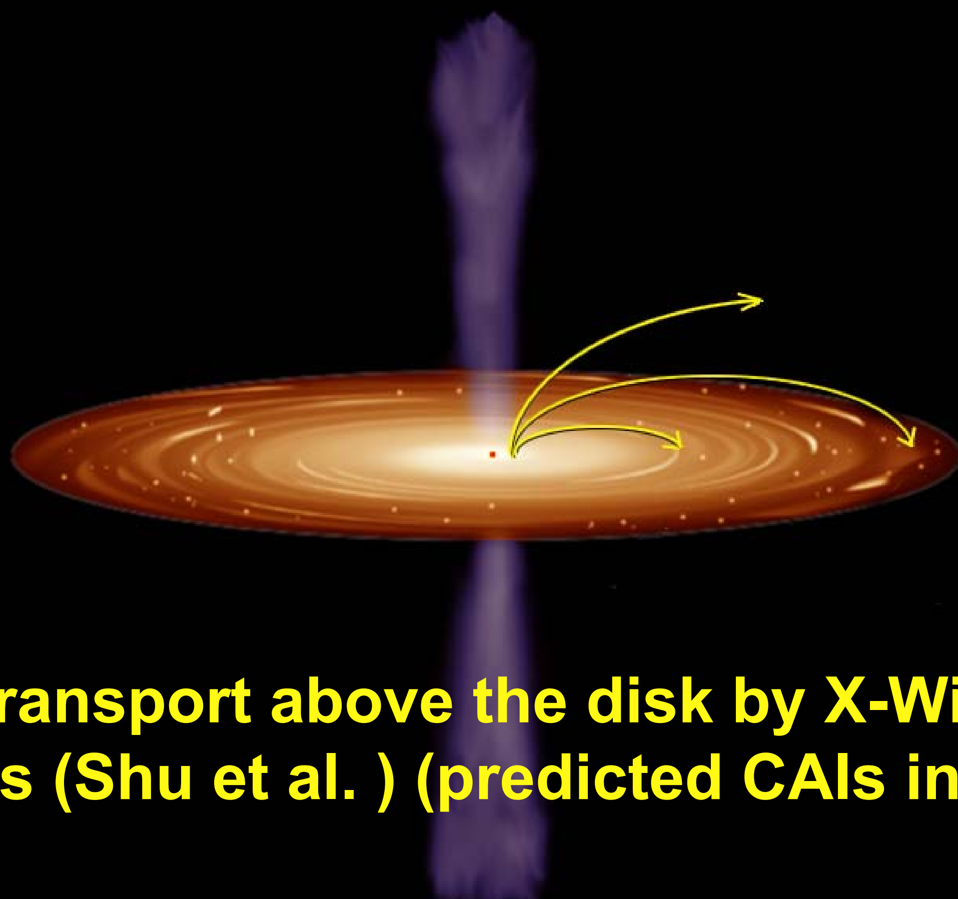
origin in Red Giant or AGB star

Concentration of Presolar Grains in Wild 2 samples

- No higher than in primitive chondrites and IDPs, and possibly significantly lower concentrations



Inner Solar system origin - with large radial transport



Ballistic transport above the disk by X-Wind or other disk winds (Shu et al.) (predicted CAIs in comets)

Or perhaps through the disk by a viscous transport mechanism

THE PRIMARY RESULTS

The rocky components of the comet (most of its total mass) formed in the inner solar system at white-hot temperatures

Inner solar nebula materials were abundantly transported to beyond the orbit of Neptune

The comet is not dominated by interstellar dust.

Crystalline grains in disks around stars are probably not produced by gentle annealing processes.

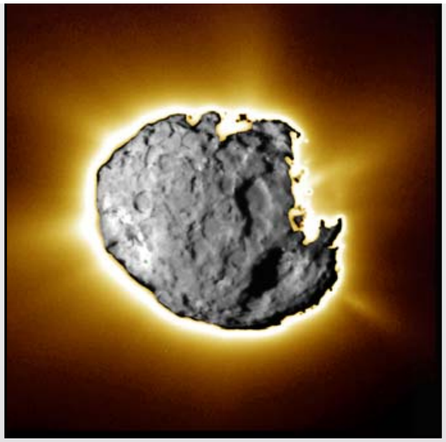
Comets are an odd mix of low- and high-temperature components

Some of the ices formed ~30K

^{15}N rich organics collected by Stardust probably also formed ~30K

Most of the rocky components (the dominant component) formed >1500K!

Mineralogy of Wild 2



- Dominated by olivine, orthopyroxene and clinopyroxene of amazingly diverse compositions; Fe-Ni sulfides, and other phases commonly found in chondrite meteorites
- Refractory grains (CAI) and possible chondrules
- Volatile components present but not dominant

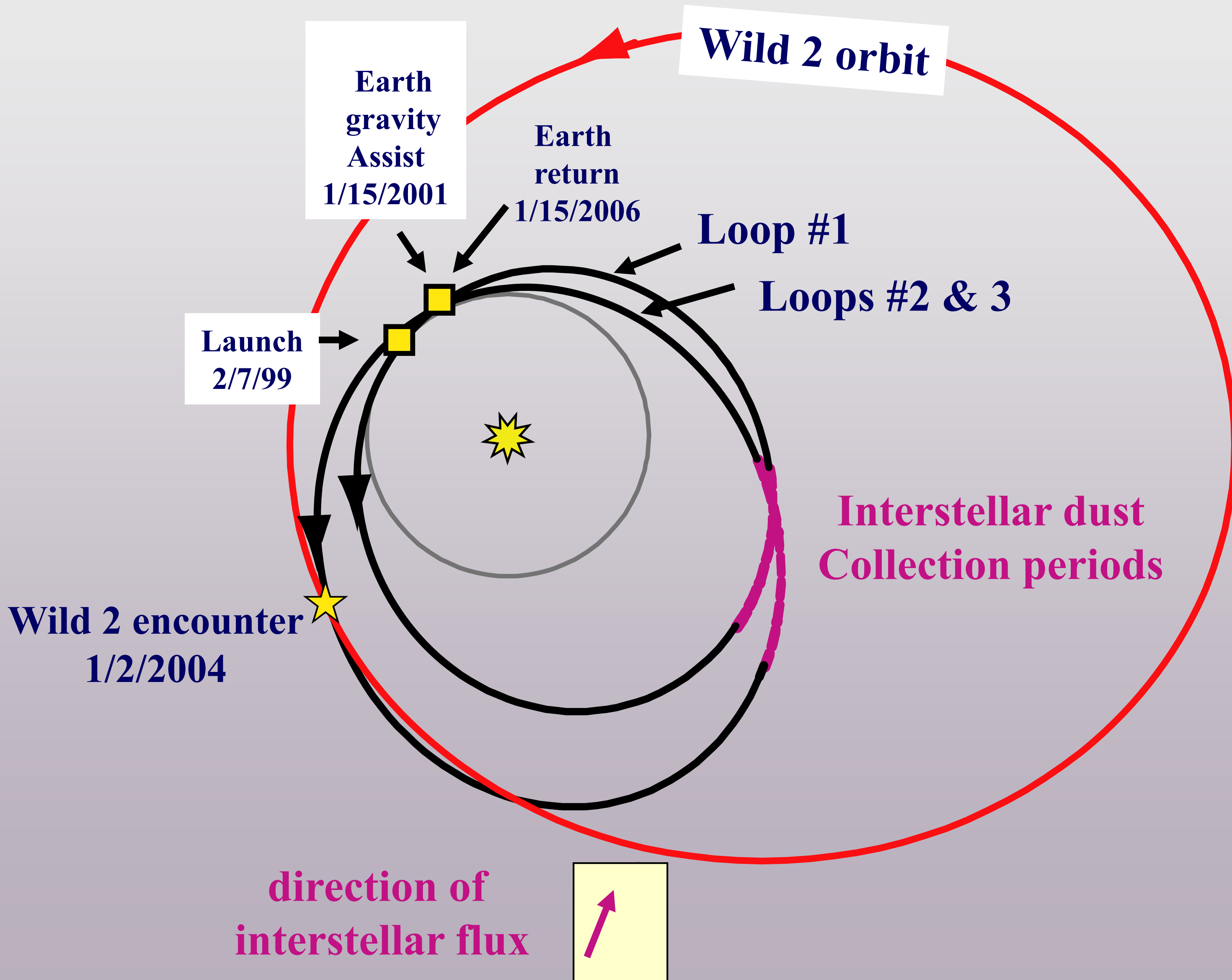
Mineralogy of Wild 2

- Presolar grains are present, but scarce
- No definitive evidence for cometary aqueous alteration - yet
- Cometary organics survived the collection process – please ask George Cody
- Bottom Line – This comet was assembled from materials formed across the entire nebular disk – an assemblage both of low- and high-temperature components
- Comets are not as simple we imagined them to be

Progress in viewing comets

Increase in imaging resolution of 18 orders of magnitude!

Stardust's Ride - 3 loops around the Sun

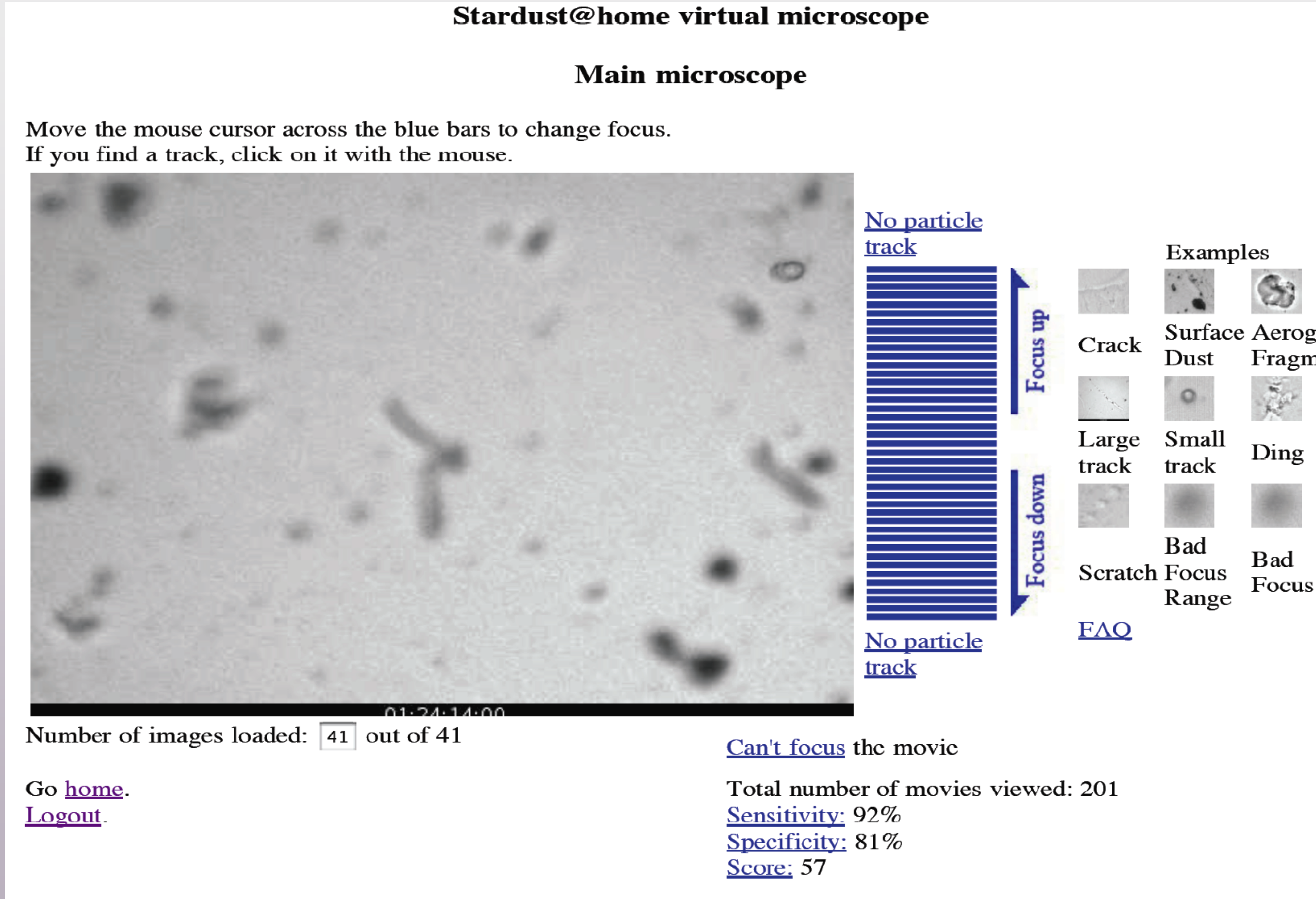


Scanning of the Stardust Interstellar Tray

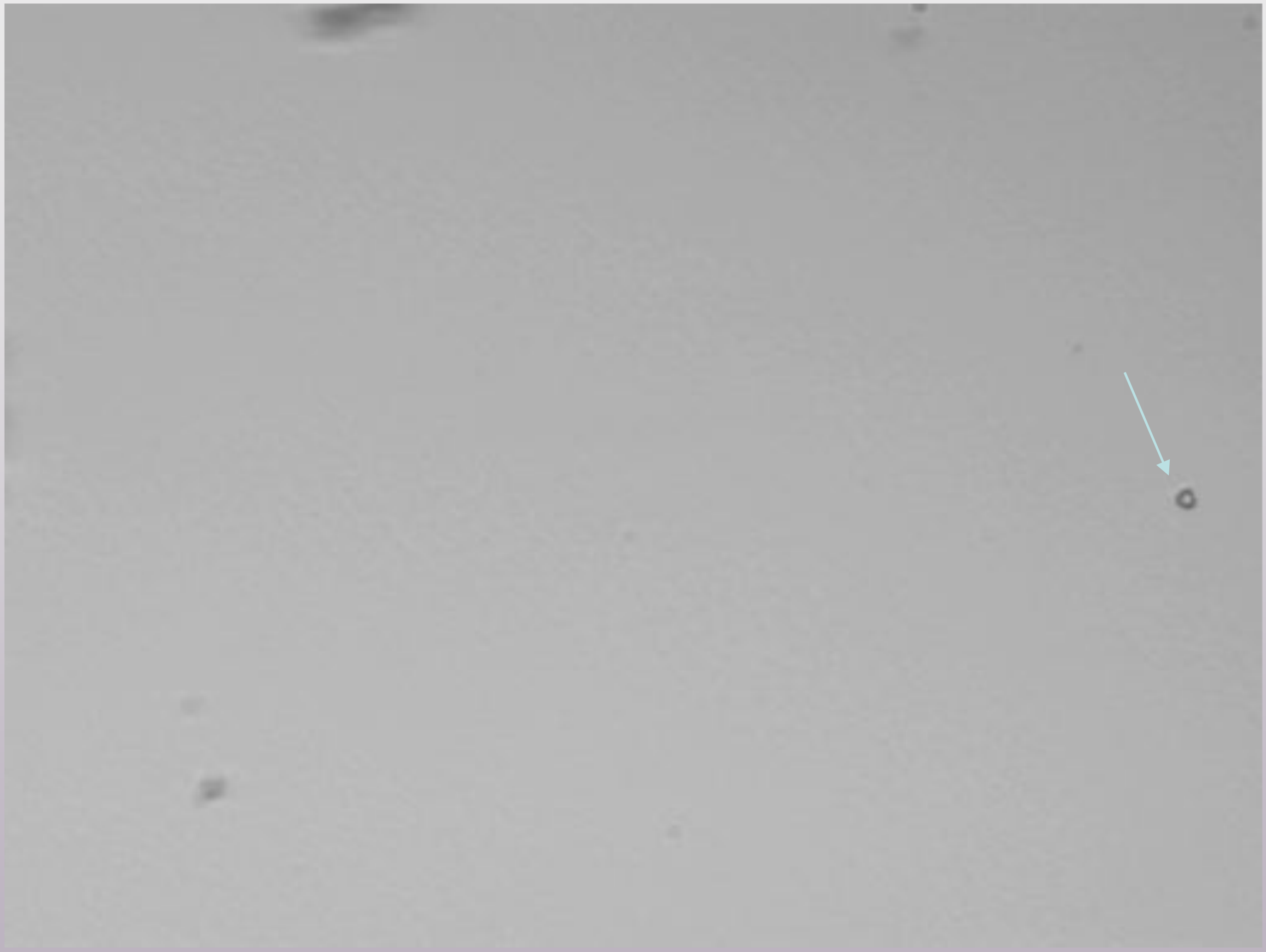
-Focus movies are posted on line, and 23,000 volunteers (worldwide) are searching for tracks

-to date about 50 candidates have been located

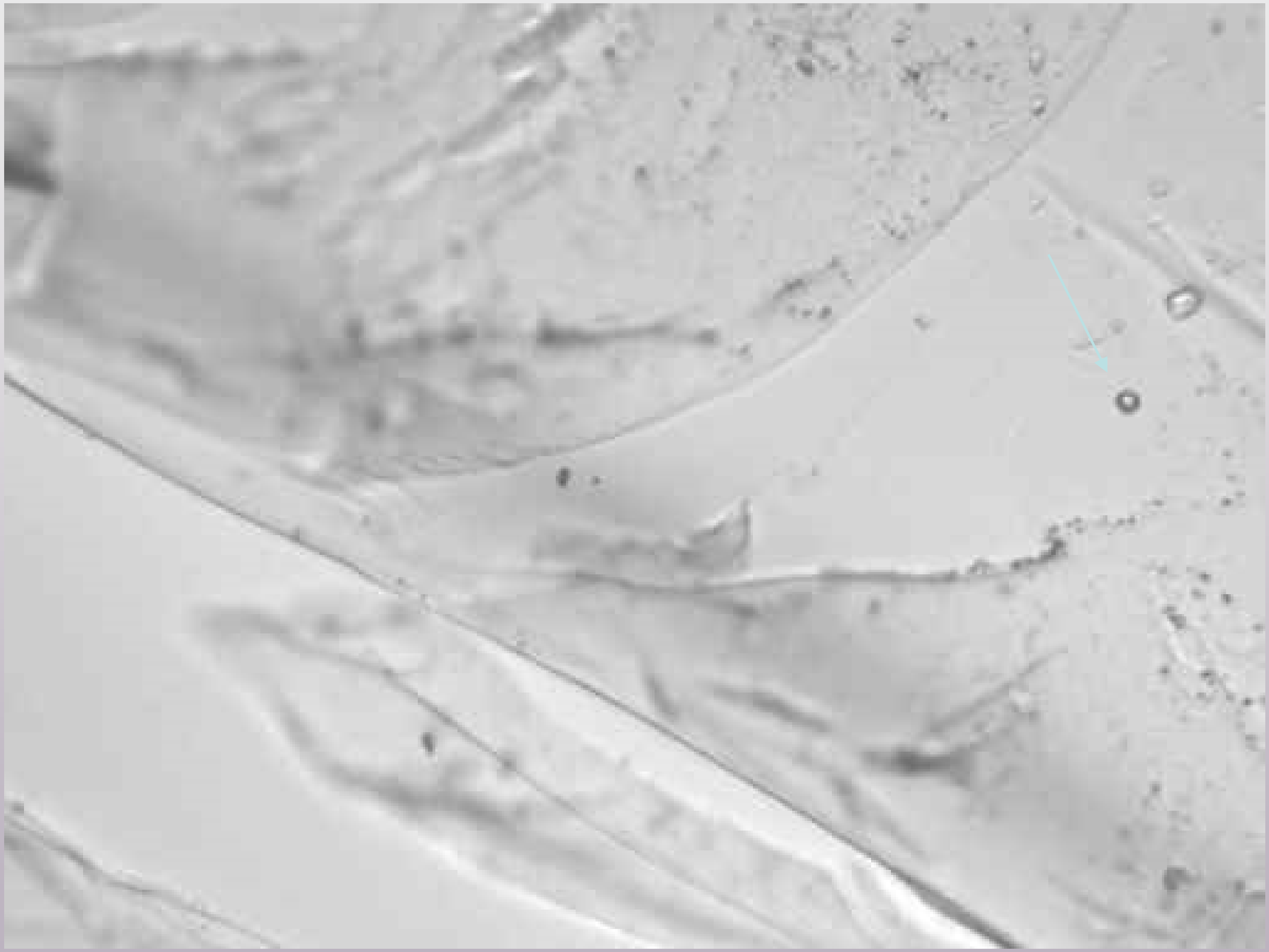
Stardust@home



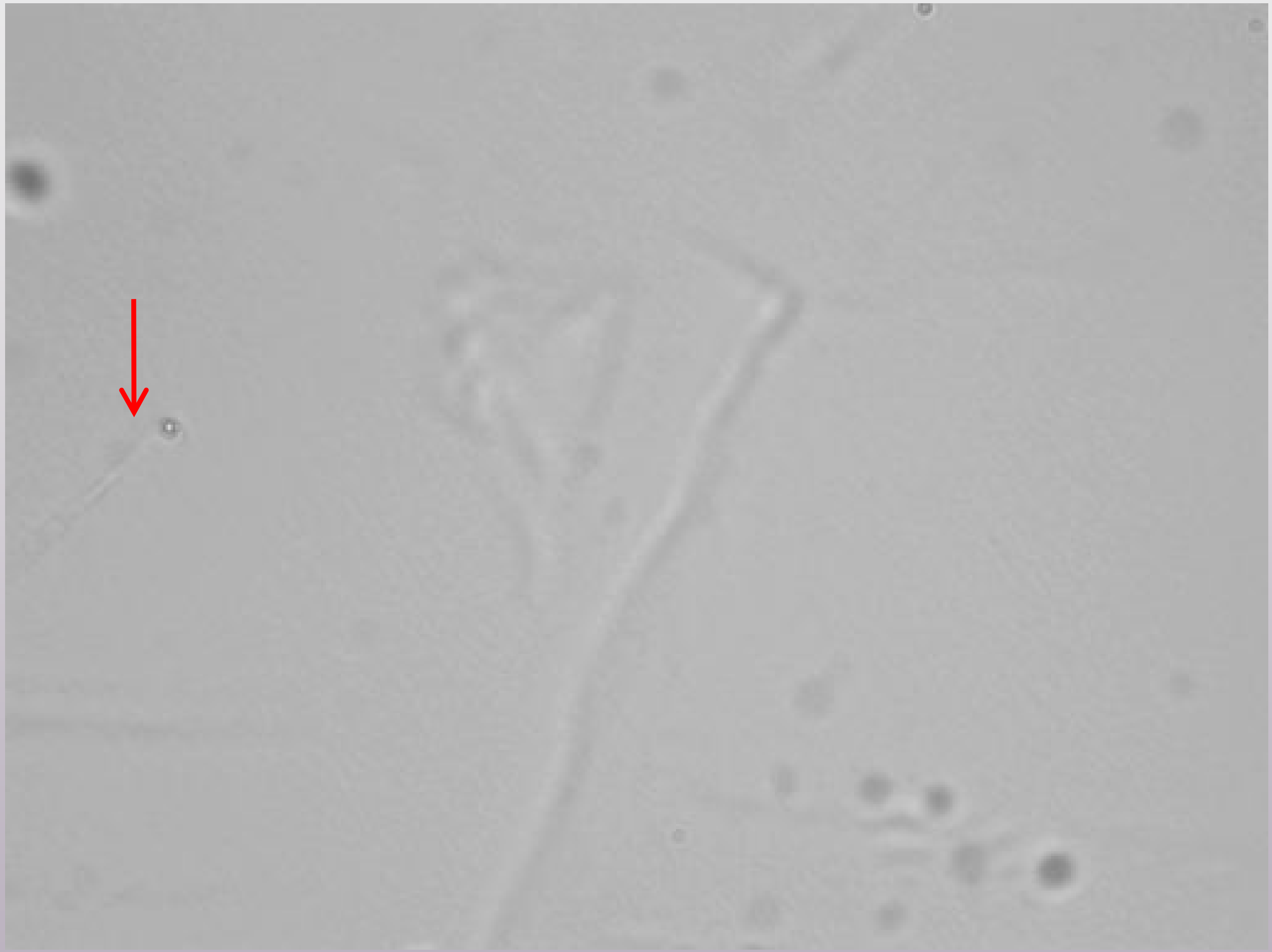
IS candidate

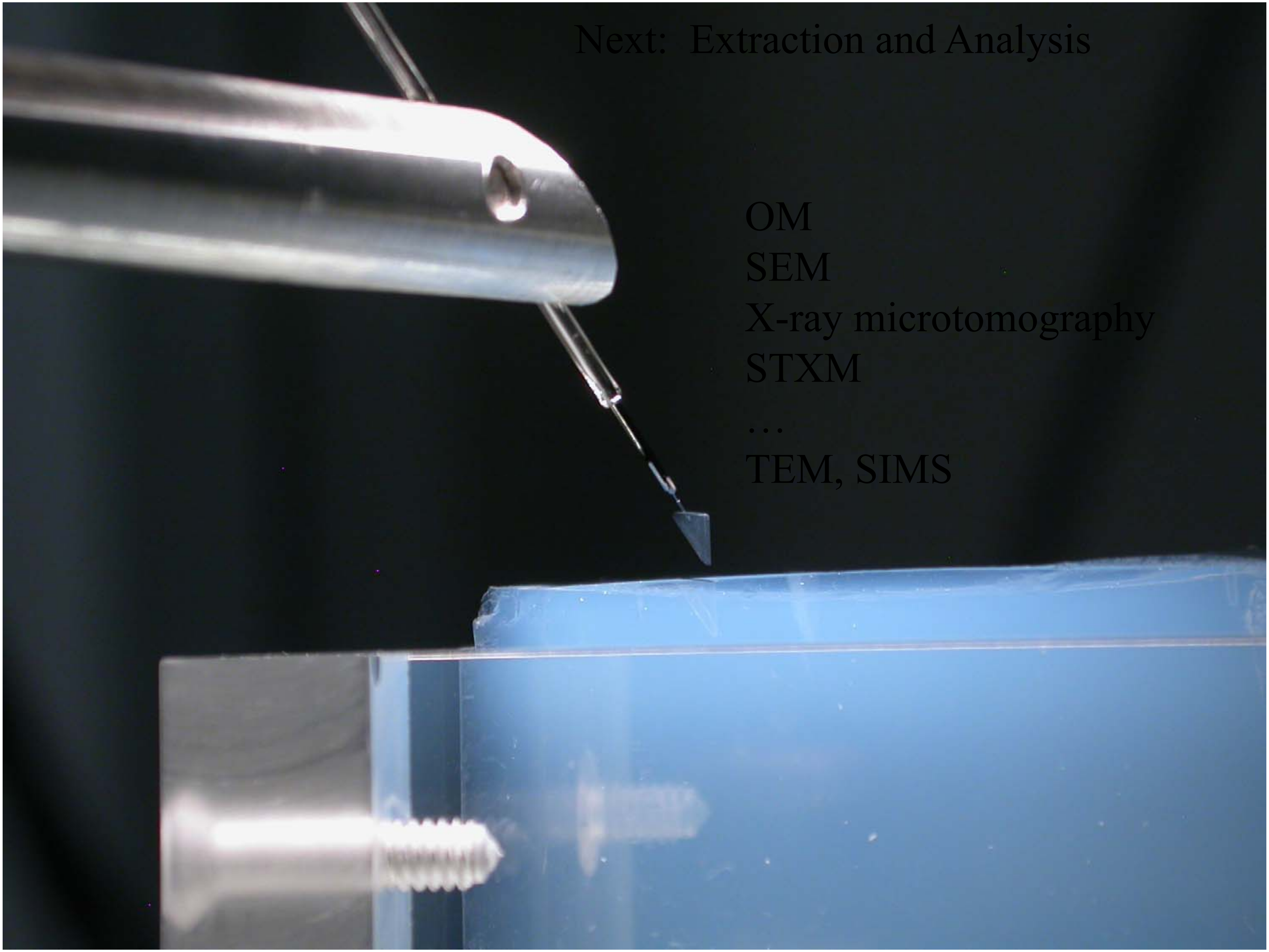


IS candidate



15 high-angle tracks




Next: Extraction and Analysis
OM
SEM
X-ray microtomography
STXM
…
TEM, SIMS

Stacked “picokeystones” for analysis of picogram residues

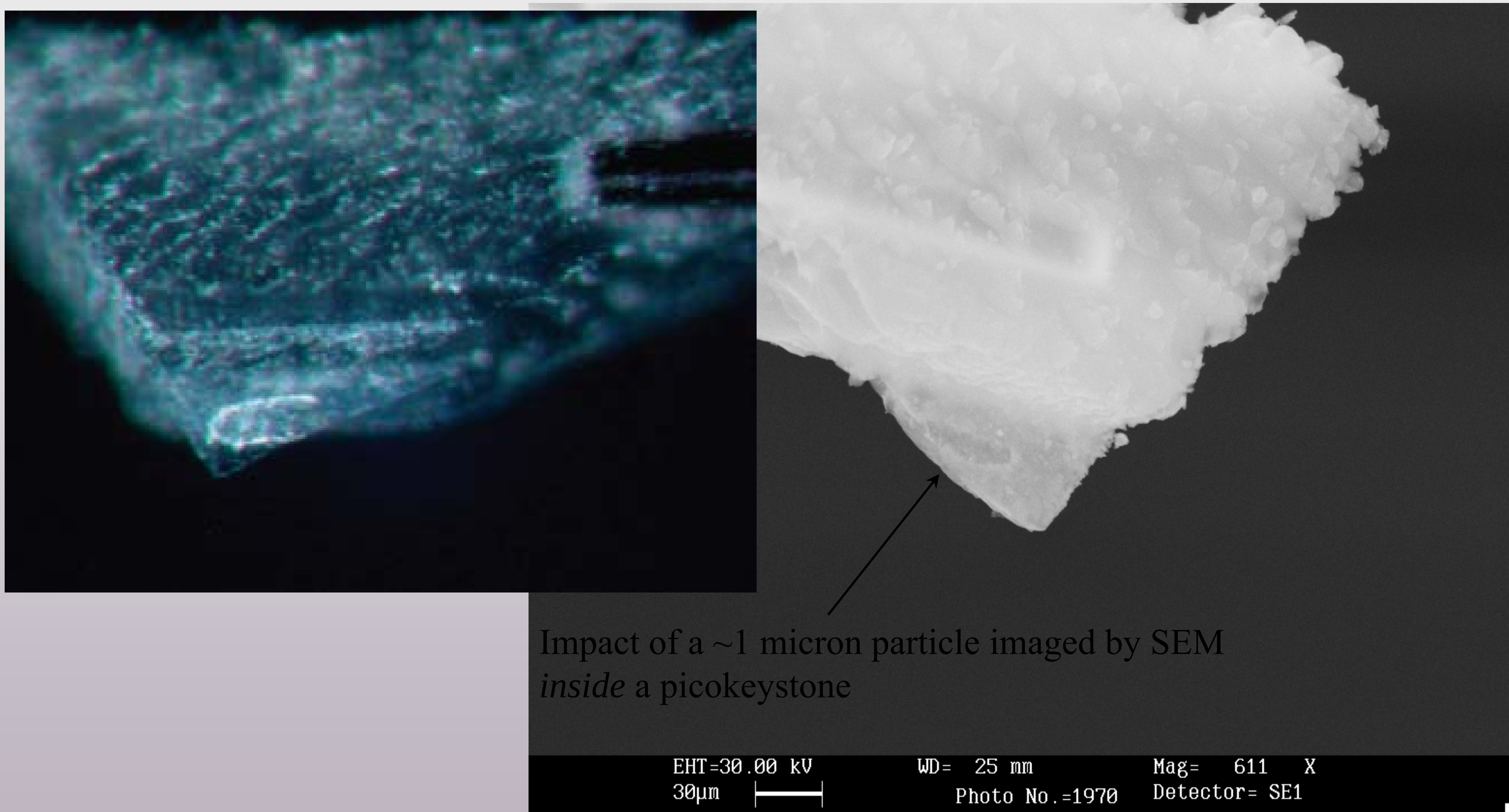


Image courtesy Giles Graham, LLNL

The Future of Stardust
(low cost but still going!)

Interstellar grains

- During cruise- the backside of the collector was used to collect Milky Way dust entering the solar system
- With the help of >30,000 volunteers, impact tracks have been found and their analysis is just beginning
- In the coming year we will begin analysis of some of these possible IS grains

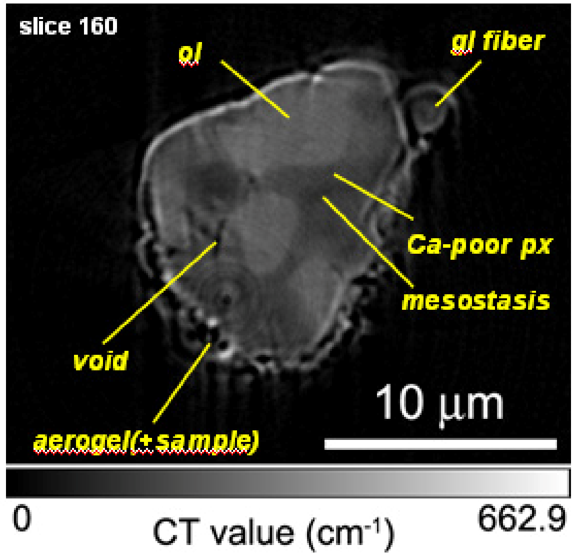
Stardust Next - Joe Ververka PI

- After its third Earth flyby, Stardust will encounter comet Tempel 1 and provide stereo imaging of its surface including the crater made by Deep Impact

Lessons for Sample Return

- Take contamination control very seriously from the start
  - Organics, carbonates
- Fly redundant witness coupons
- Use a sealed SRC
- Reconsider using UTTR as a landing site
- Don’t rush reentry and recovery planning
  - Luck played a role in the Stardust recovery success
- Having the Receiving and Curation Lab ready 1 year before SRC recovery is barely sufficient
- Run an Inclusive PET

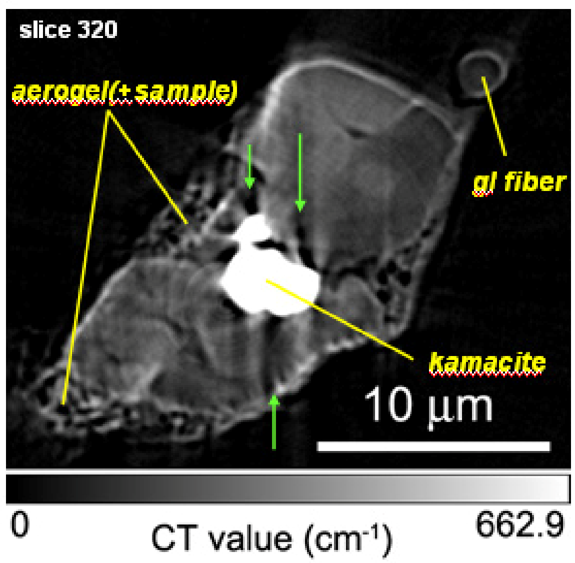
C2054,0,35,6,0



(Micro-)porhyritic textue
ol phenocrysts (bright)
dark Ca-poor px
mesostasis (darker)
voids in mesostasis

Bright surface
artifact due to refraction
of X-ray beams

Grain covered with
aerogel (+samples)



Kamacite crystals

Dark shadows (green arrows)
artifacts due to insufficient
X-ray transimission by
kamacite

Bright surface
artifact due to refraction
of X-ray beams

Grain covered with
aerogel (+samples)

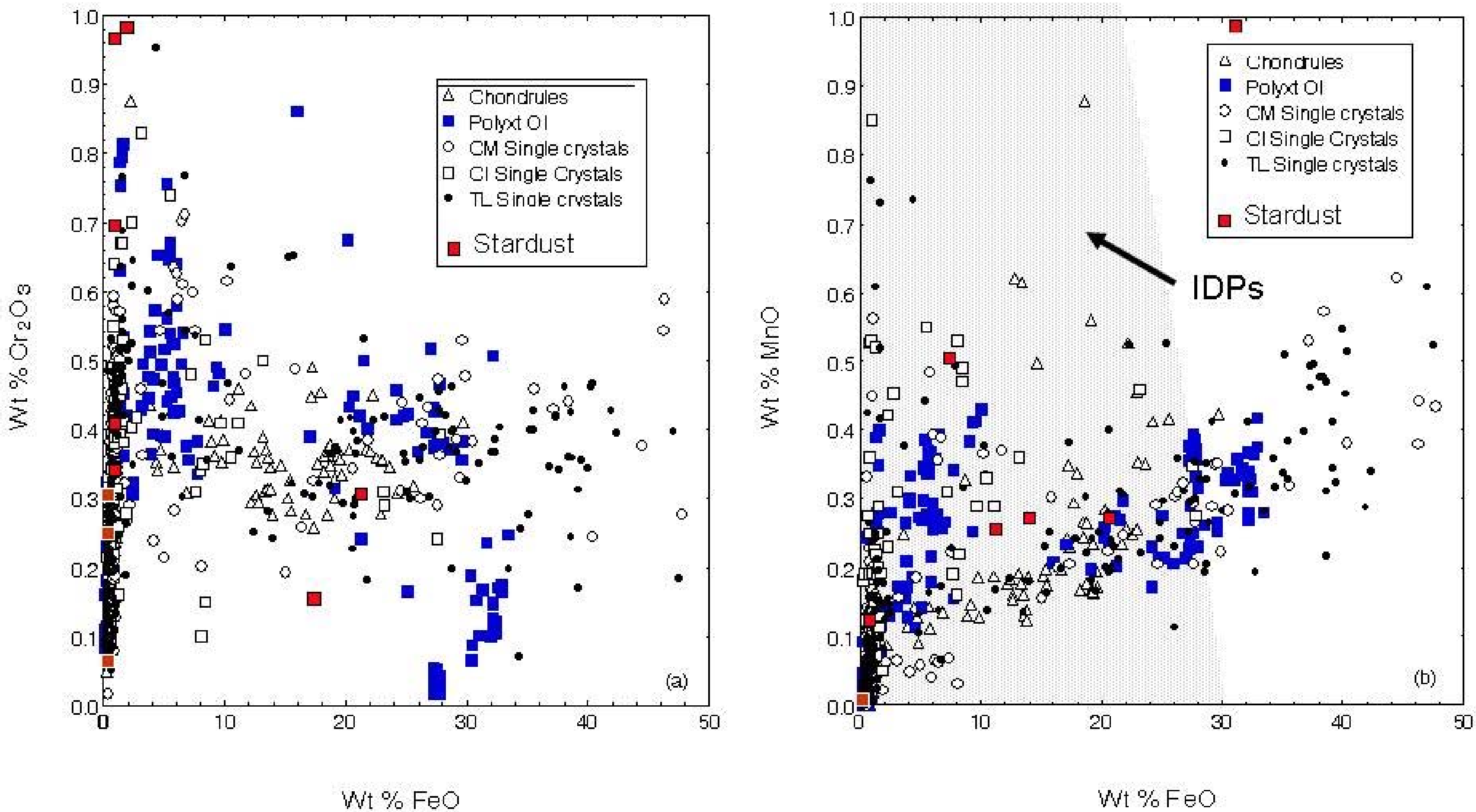
Akira Tsuchiyama, Tomoki Nakamura

Wild 2 (Kuiper Belt) olivine compositions

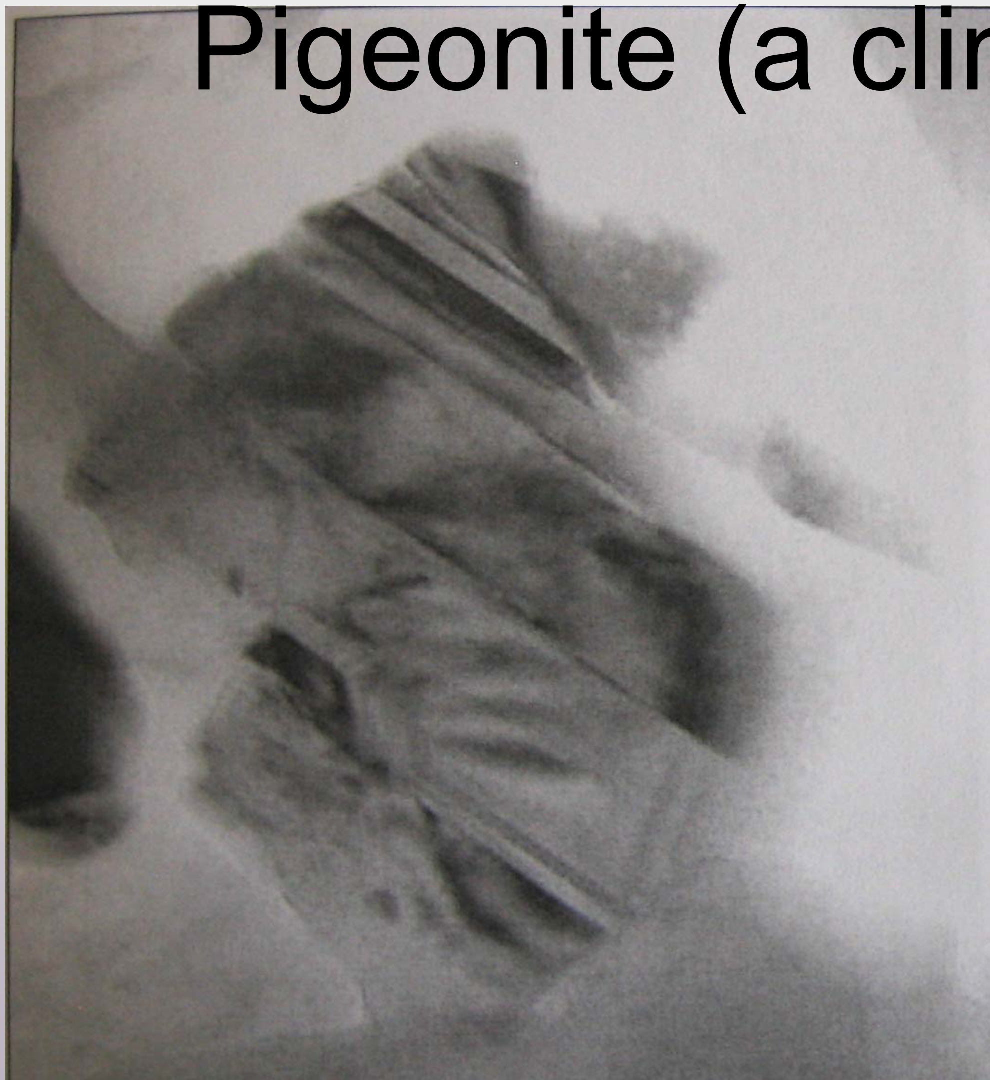
Al, Ca, Cr and Mn "tracers" imply similarity to inner nebula olivines

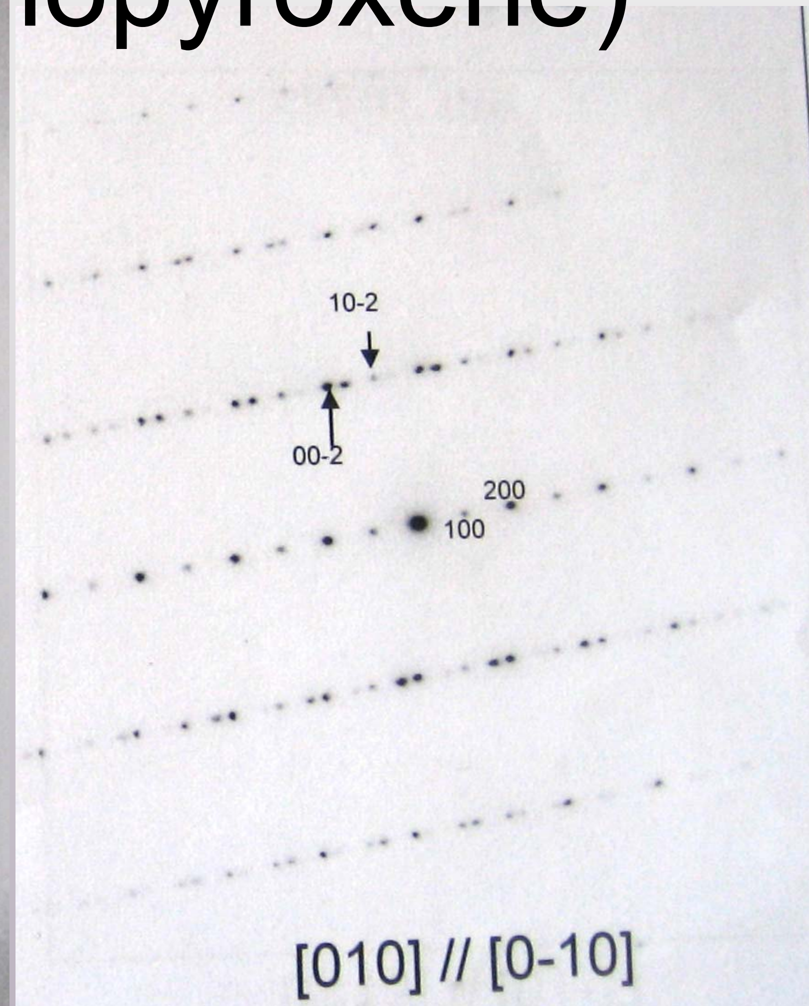
-

- the range of Fe/Mg clearly shows that Wild 2 is unequilibrated -

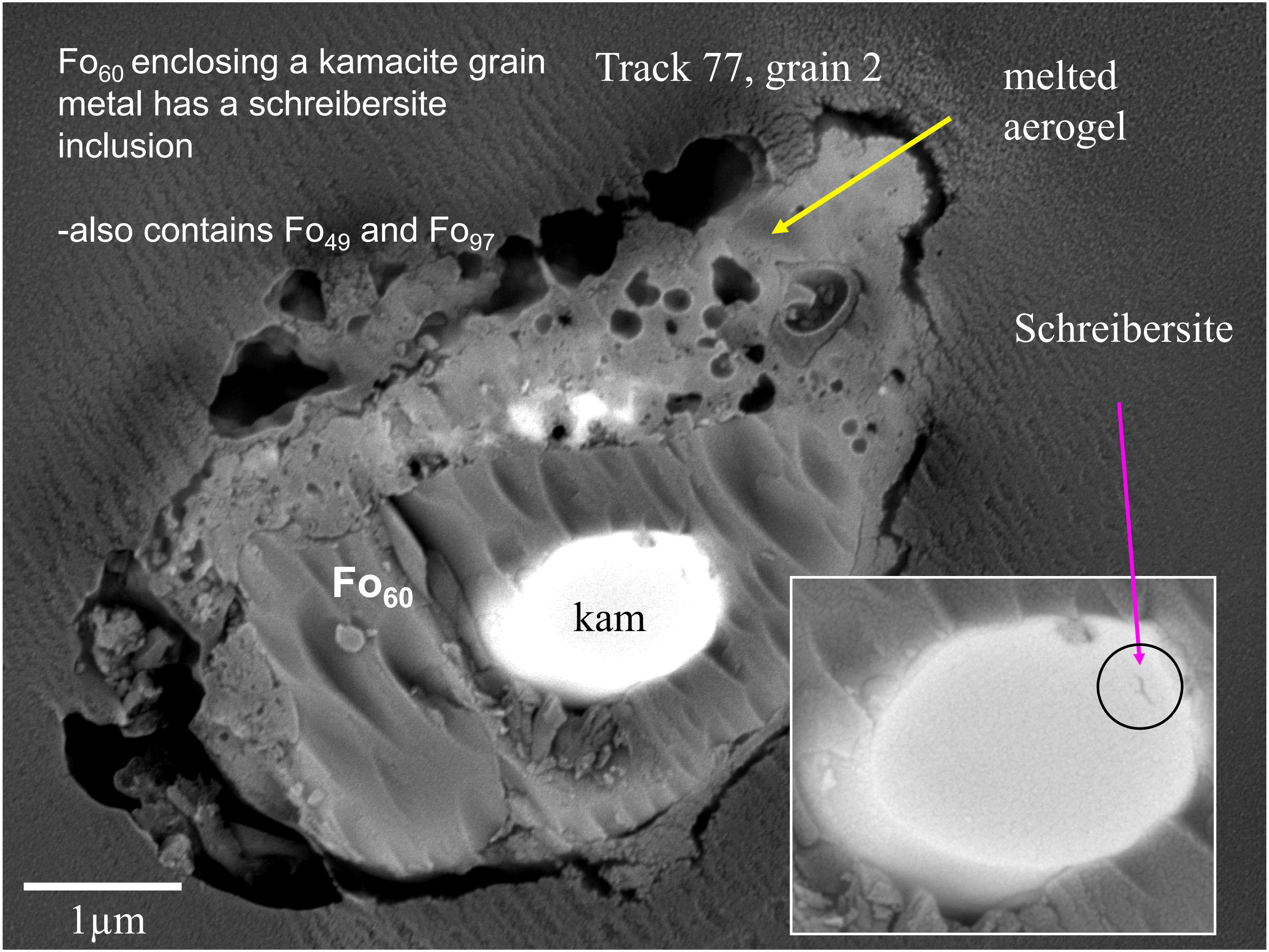


Pigeonite (a clinopyroxene)



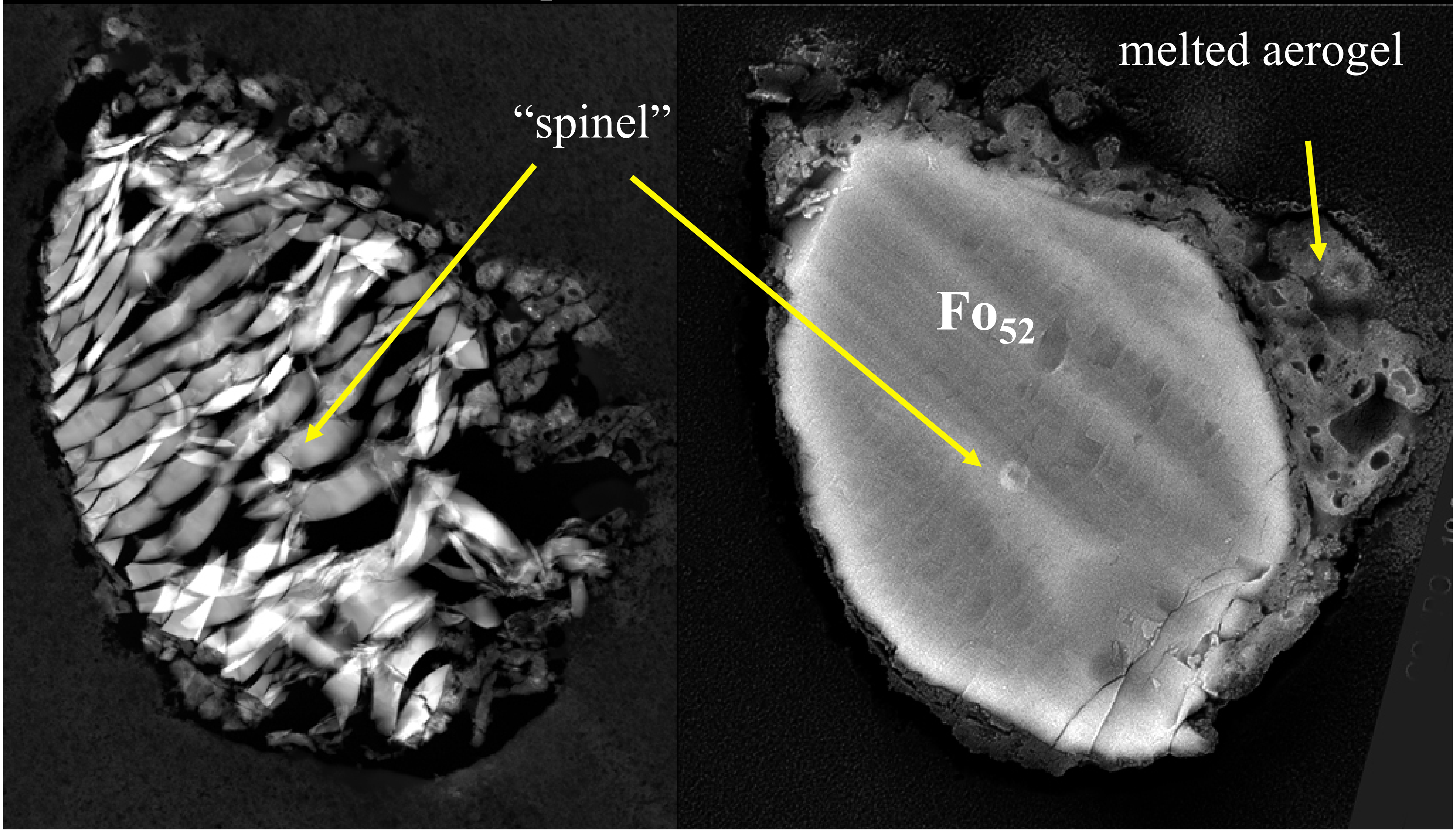


H. Leroux and group


Fo_{60} enclosing a kamacite grain metal has a schreibersite inclusion
-also contains Fo_{49} and Fo_{97}
Track 77, grain 2
melted aerogel
Schreibersite
Fo_{60}
kam
1 μm

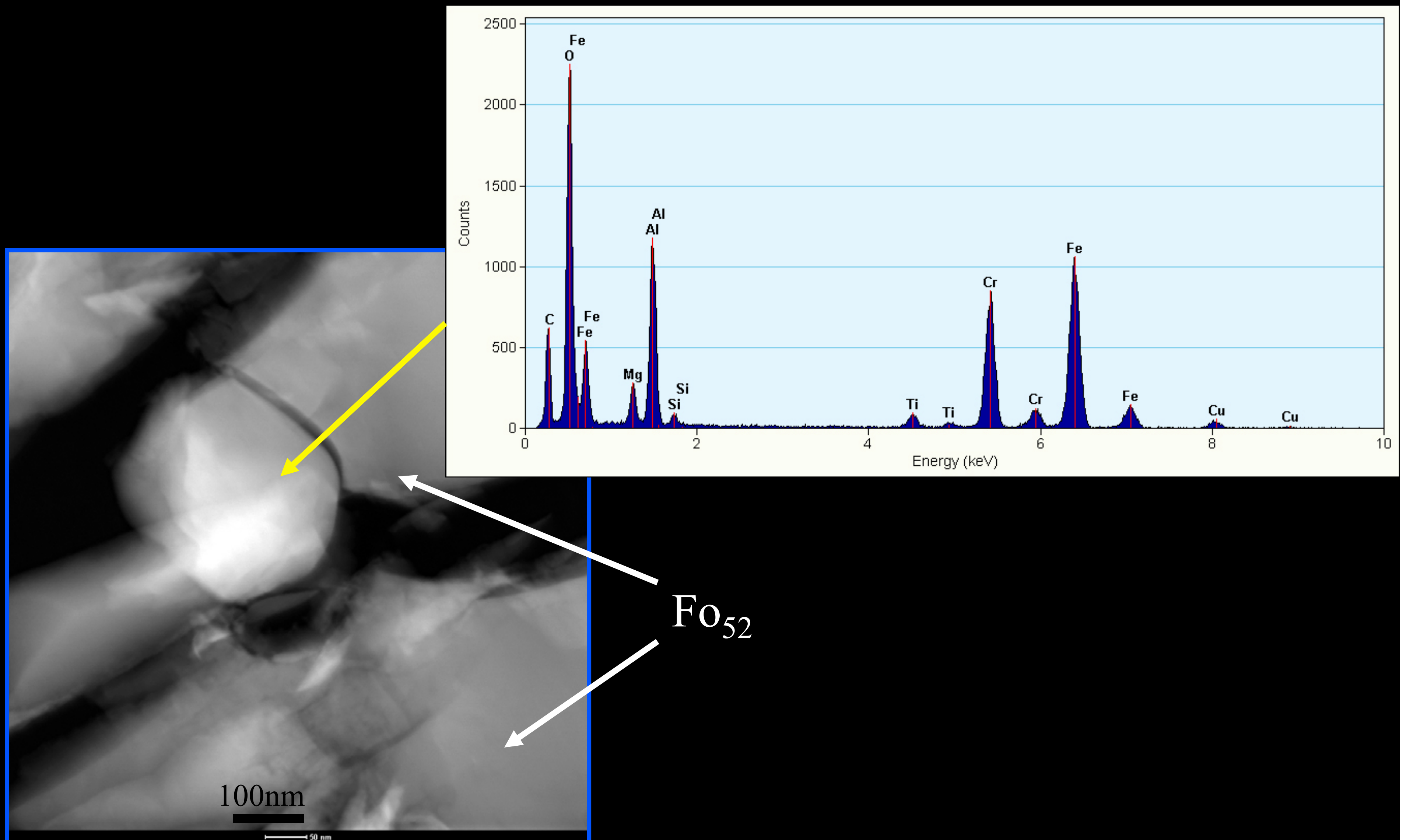
Track 77, grain 3

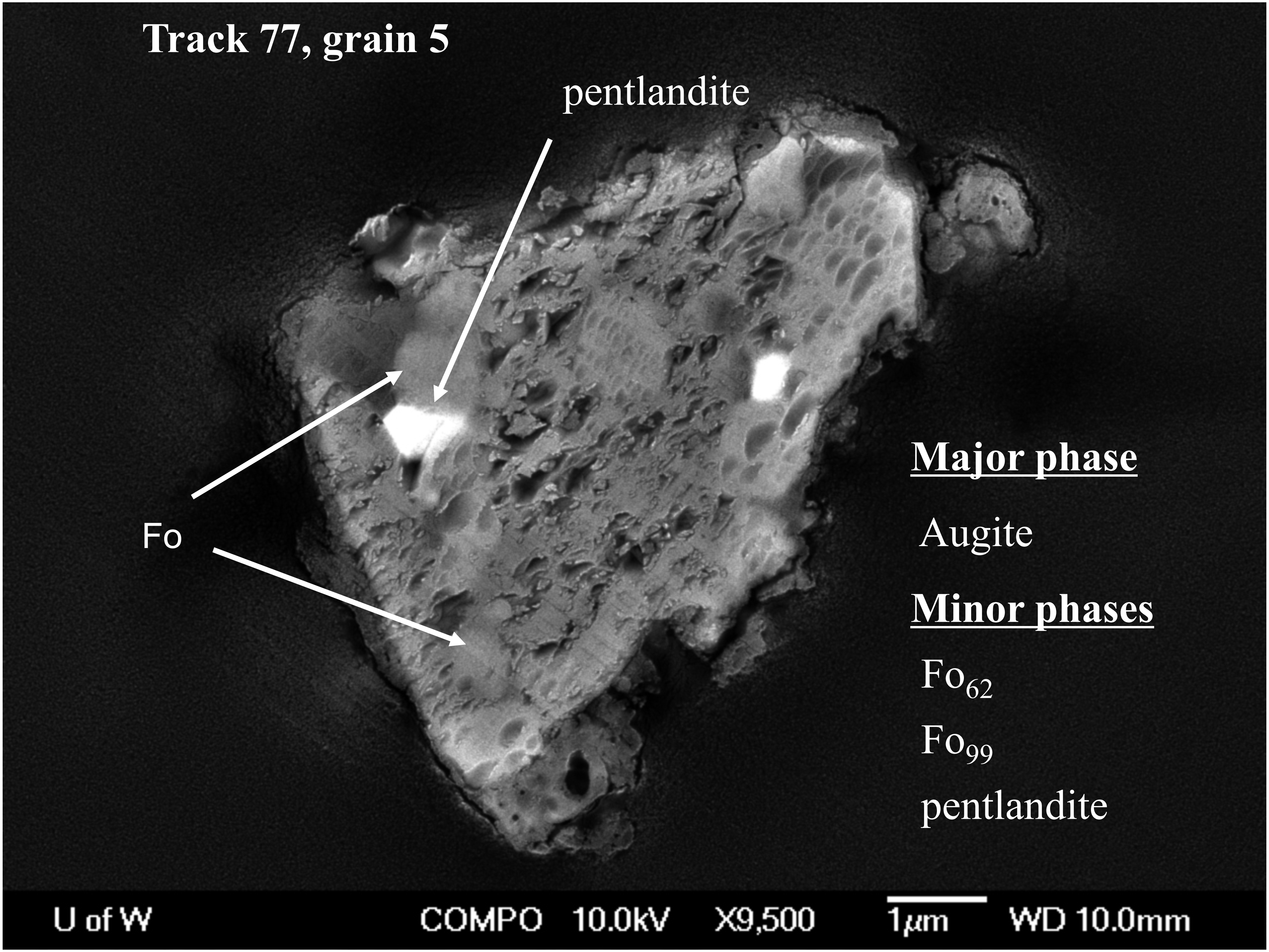
dominant phase Fo_{52}
trace spinel and schreibersite



Track grain 3

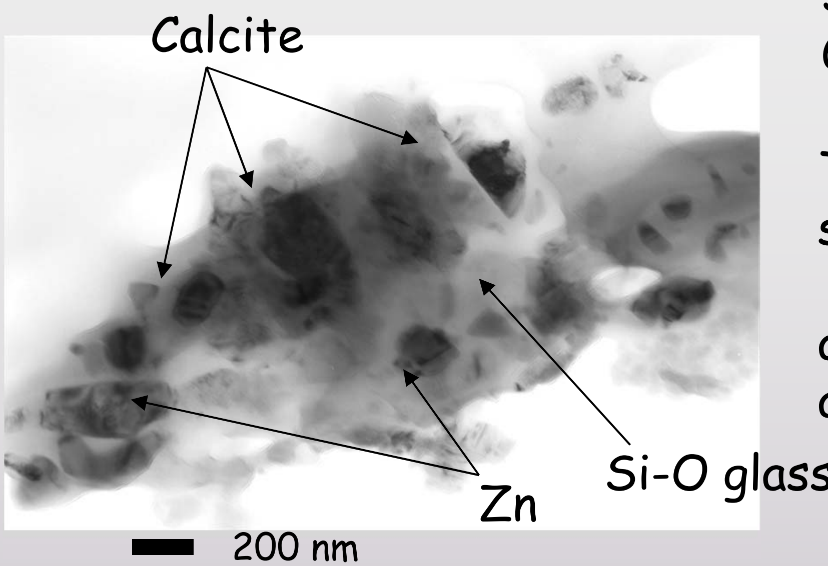
200nm “spinel“ (Mg-Al chromite) in Fo_{52} olivine



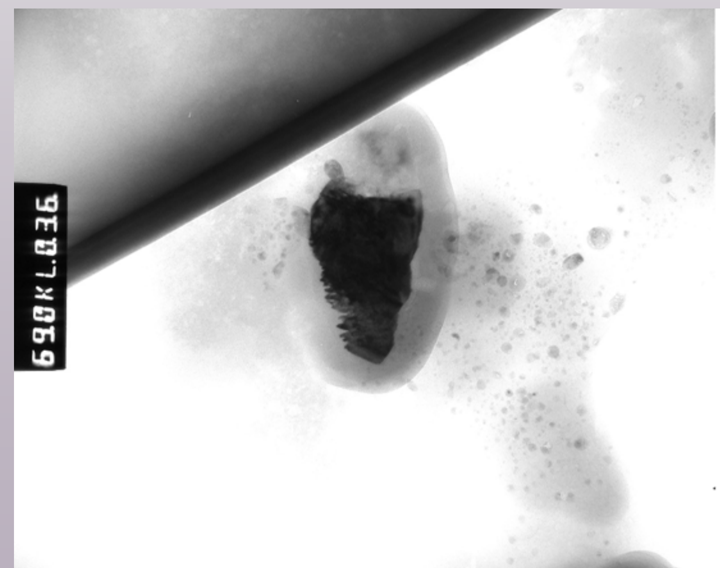

Track 77, grain 5
pentlandite
Fo
Major phase
Augite
Minor phases
Fo_{62}
Fo_{99}
pentlandite
U of W
COMPO 10.0kV X9,500 1μm WD 10.0mm

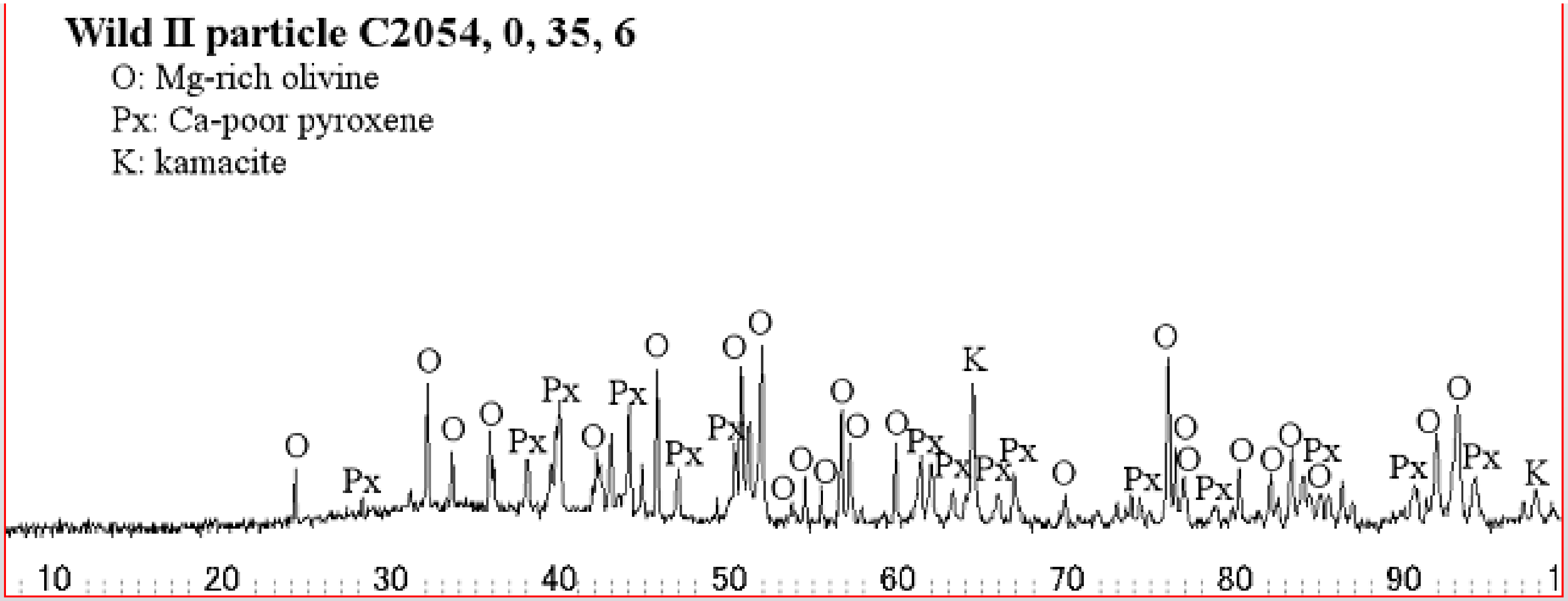
Stardust Sample C2027-2-69-1-4

TEM images showing several small calcite crystals, some in association with Zn-rich grains and Si-O glass – but always away from the main sample.



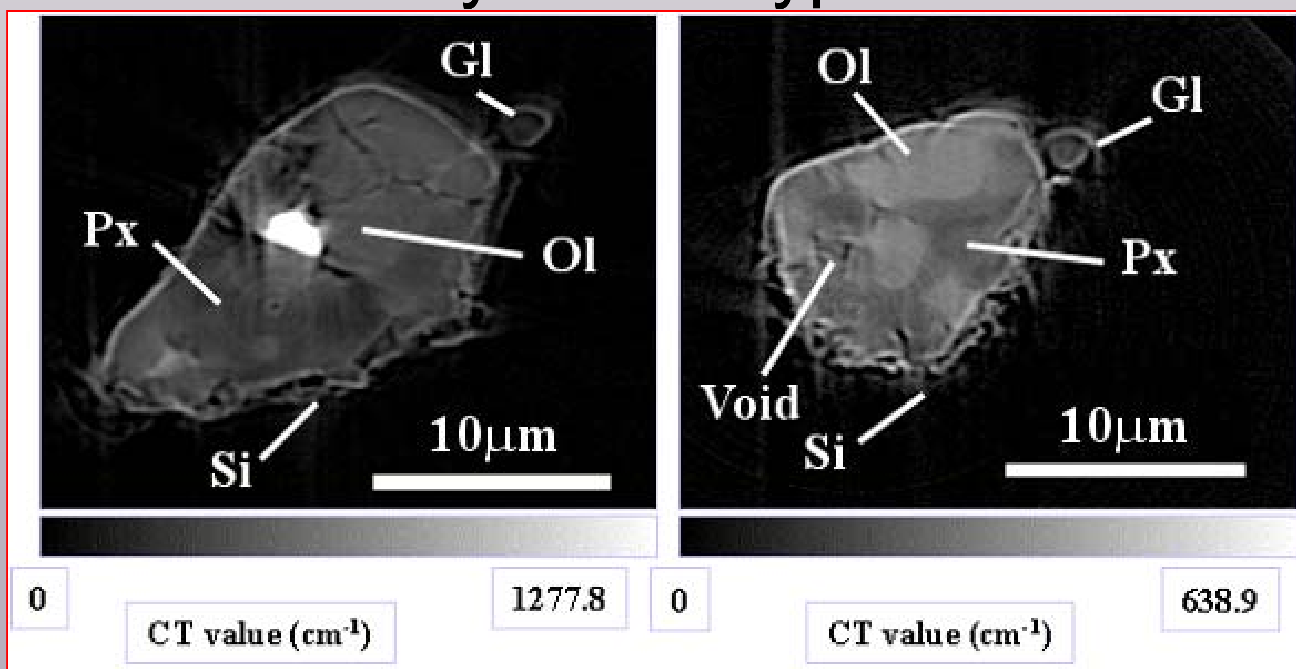
These could be contamination

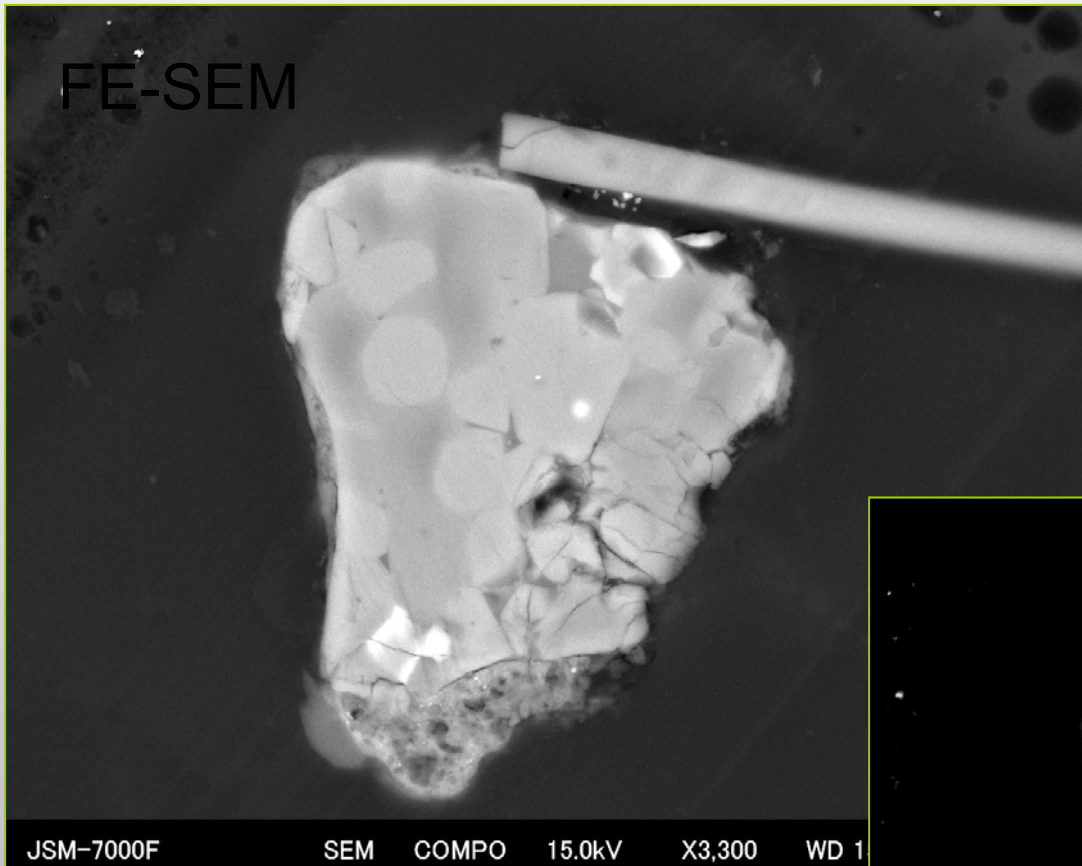




Torajiro: C2054, 0, 35, 6, 0

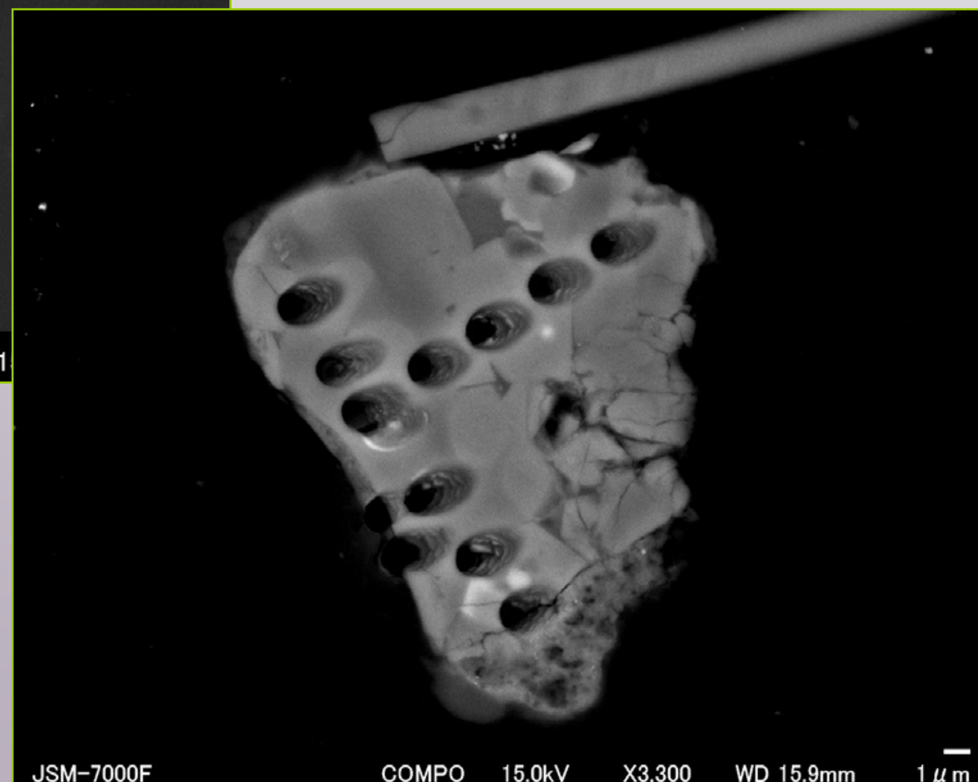
Crystalline type





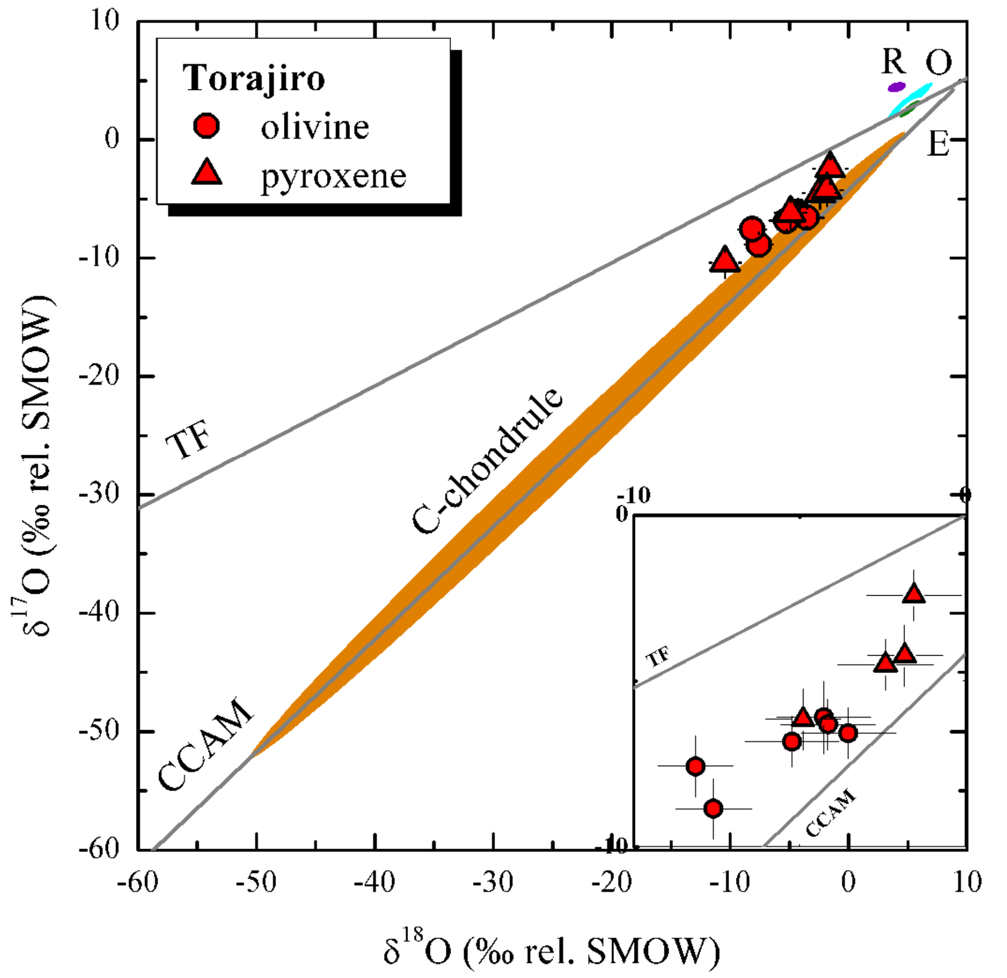
Torajiro

$Fo_{79\sim80}$
$En_{83}Wo_5 \sim En_{88}Wo_3$



The particle experienced partial melting at temperature higher than 1500 ^{o}C, prior to the formation of the comet.

Torajiro: oxygen isotope ratios



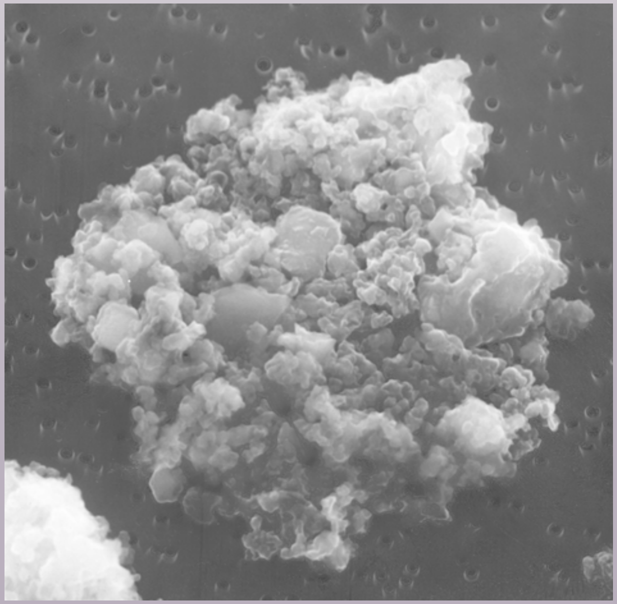
Conclusions

The four crystalline particles formed through melting at high temperature prior to formation of comet Wild 2. This is supported by the presence of poikilitic or porphyritic textures and the glass phases that are enclosed in, or directly in contact to, silicates.

Except for MnO enrichment in some of the particles, the four particles are similar in texture, mineral combination, major element abundance, and oxygen isotope ratios to chondrules in carbonaceous chondrites. Therefore, we suggest that the four crystalline particles are pieces of chondrules in the comet Wild 2.

Stratospheric Collection

- Since 1981 NASA has had a program to collect a representative record of the particle load of the lower stratosphere using impaction collectors flown on U-2, ER-2, and WB-57 aircraft
- The techniques for analysis of the Stardust Mission samples have grown directly out of this Program



Brief mission overview

- **4th Discovery mission**
- **Lockheed Martin, JPL, Univ of Washington**
- **200M$ cost cap**
- **7 year mission**
- **First solid sample return mission in >30 years**
- **MAJOR SCIENCE ACTIVITIES**

1) Jan 2, 2004 flyby of comet Wild 2
2) Jan 15, 2006 return to Earth & analysis

The Flyby

(6.1 km/s, 236 km miss distance, 4.5 km body)

- **Sample collection**
- **Particle impact counter (DFMI) & impact mass spectrometer (CIDA)**
- **72 images, 14 m/pixel max resolution, full phase angle coverage**

ALL FLYBY SCIENCE WAS BONUS SCIENCE

- **Wild 2 surface morphology is very rugged &**

  <u>unlike other small bodies-</u> including Halley (Giotto-Vega), Borrelly (Deep Space 1), Tempel 1 (Deep Impact)

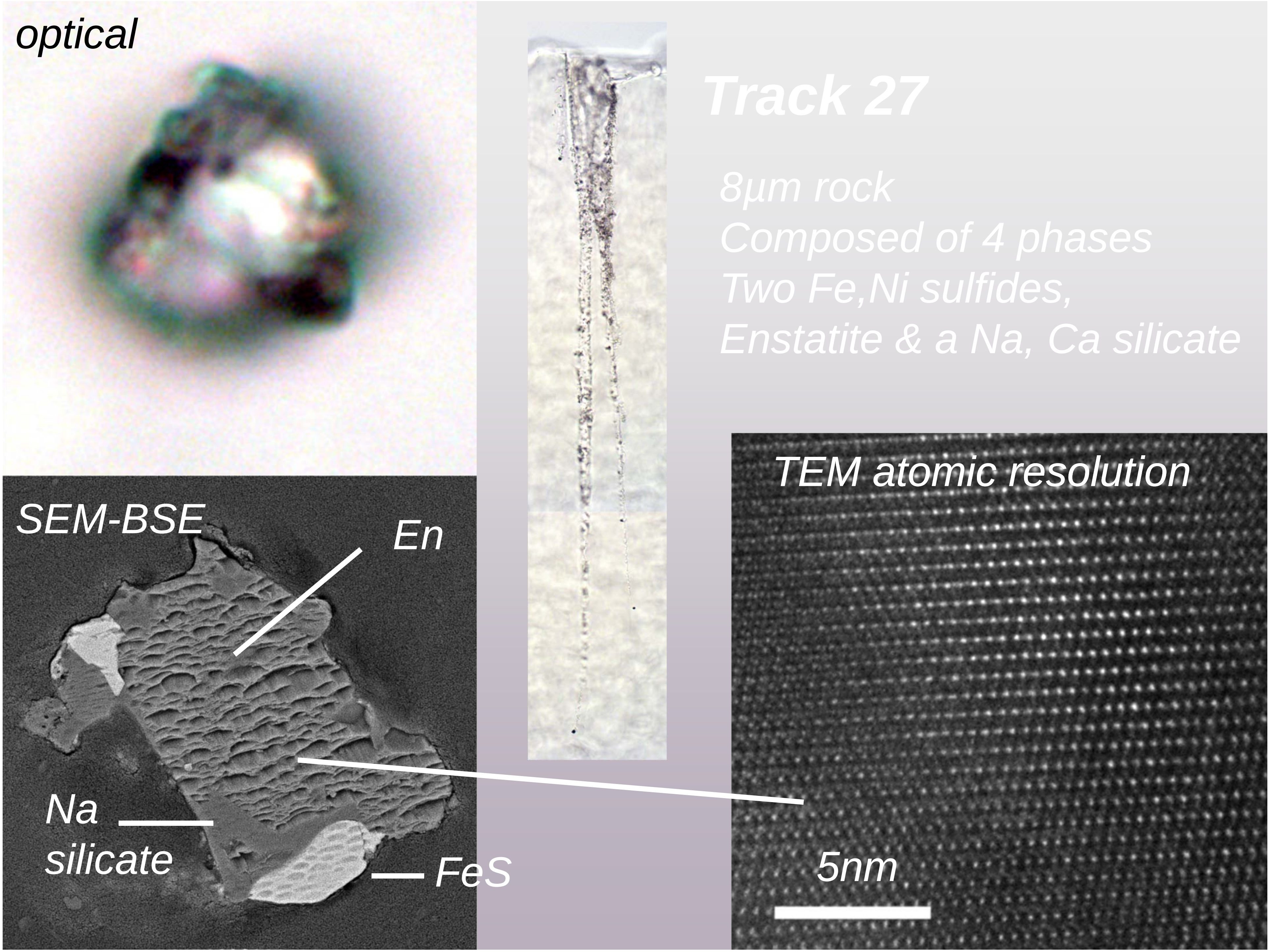
  … flat floor depressions bounded by cliffs, lack of obvious impact craters, erosional features like mesas and pinnacles

- **22 active jets, 2 on dark side, all surface regions active at some time?**

- **Dust size distribution similar to Halley- most mass in small rocks**

- **Fluxuations in dust flux consistent with jets <u>and</u> disruption of dust in coma**

- **Returned craters and in-situ dust data provide first test of in-situ dust impact data**


optical
Track 27
8µm rock
Composed of 4 phases
Two Fe,Ni sulfides,
Enstatite & a Na, Ca silicate
SEM-BSE
En
Na
silicate
FeS
TEM atomic resolution
5nm

O isotope ratios are within the range of carbonaceous-chondrite chondrules