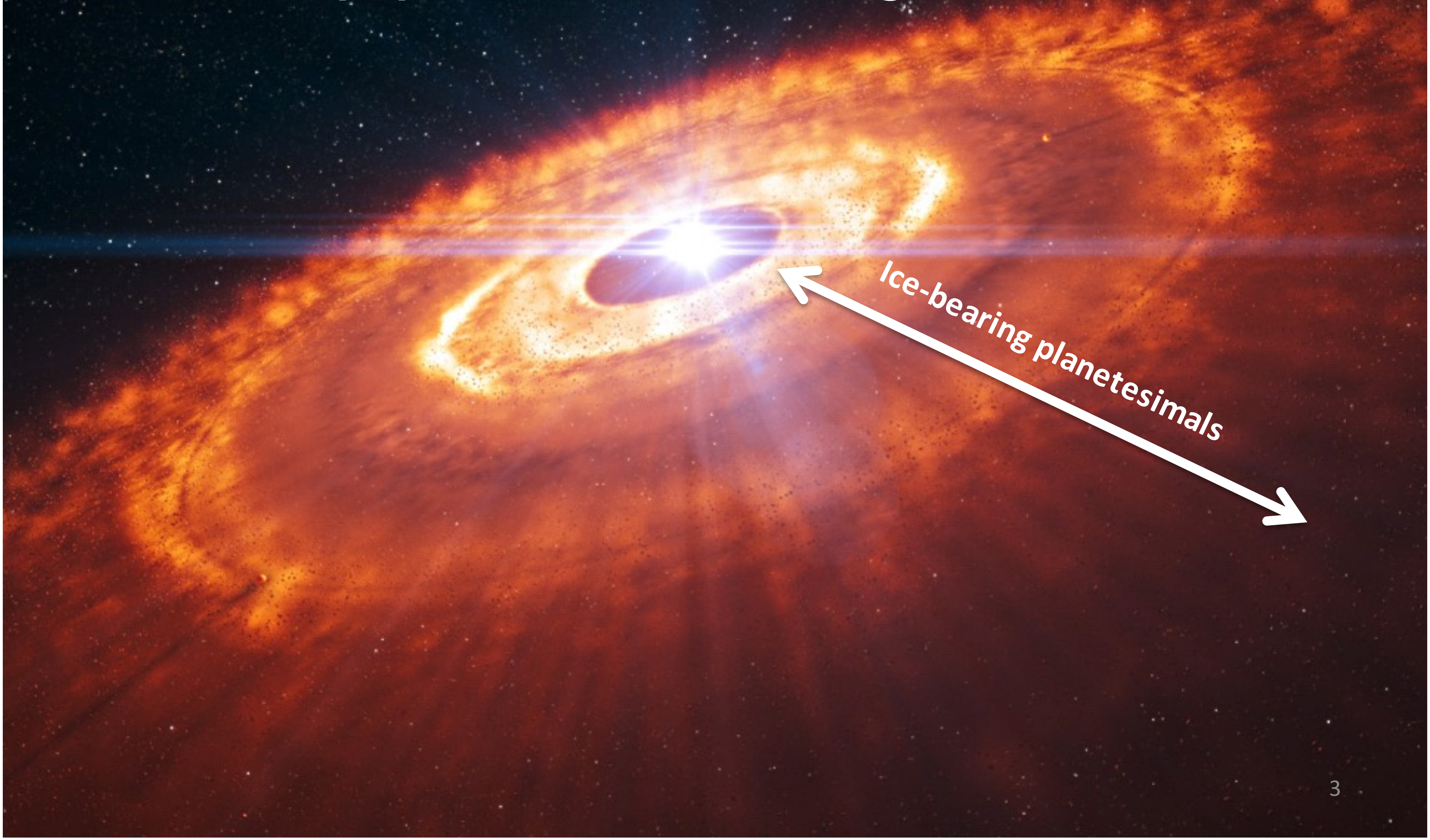
What samples of a comet tell us about the origin of the solar system

Don Brownlee
University of Washington
ASU Feb 22 2017

SS formed from disk of gas, dust & rocks
Gas & dust was short lived – only a few my
Rapid formation of km-sized bodies (planetesimals)
Radial P&T gradient

Most of the disk formed ice-bearing planetesimals
Comets – surviving members
of the vast population of ice-bearing bodies



Comparison of solids in the inner and outer disk regions
Important clues for disk processes
Most records are in small grains – requires sample analysis

Materials from inner disk regions

Meteorites – moderately strong rocks from asteroidal sources
Some are well preserved collections of nebular materials
Selection process – atmospheric entry & orbital delivery
All modified to some extent by "parent body processes"
Even the best - heated to ice melting temperature
Hydrated silicates – warm & wet in early SS (^{26}Al decay?)

Materials from outer disk regions

Need samples from ice-rich planetesimals

Samples from comets – stored beyond Neptune
Perhaps a few meteorites??
Interplanetary Dust samples (IDPs) – reach Earth & survive atm entry
Directly collected comet samples

COMETS - Distinctive property

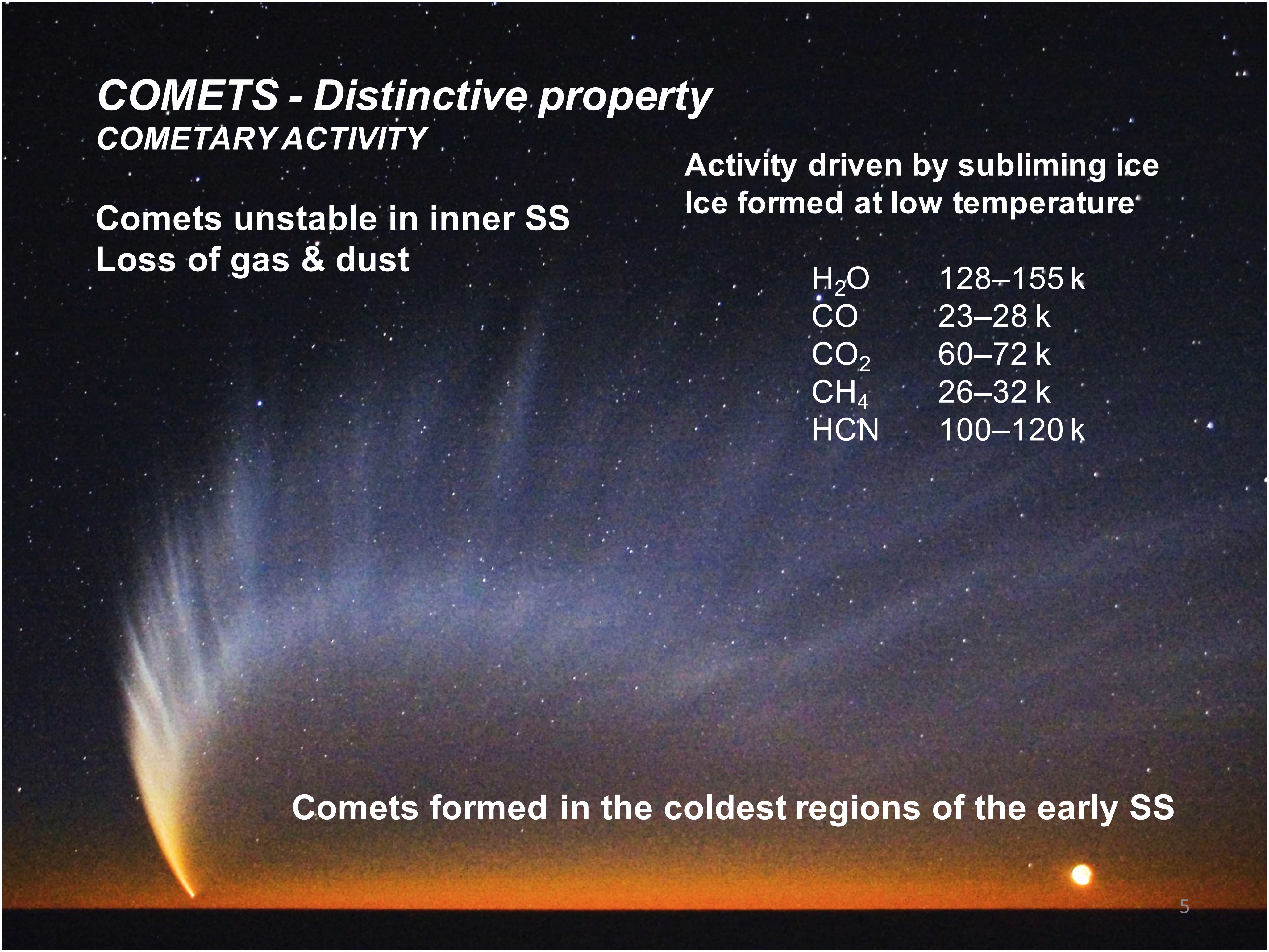
COMETARY ACTIVITY

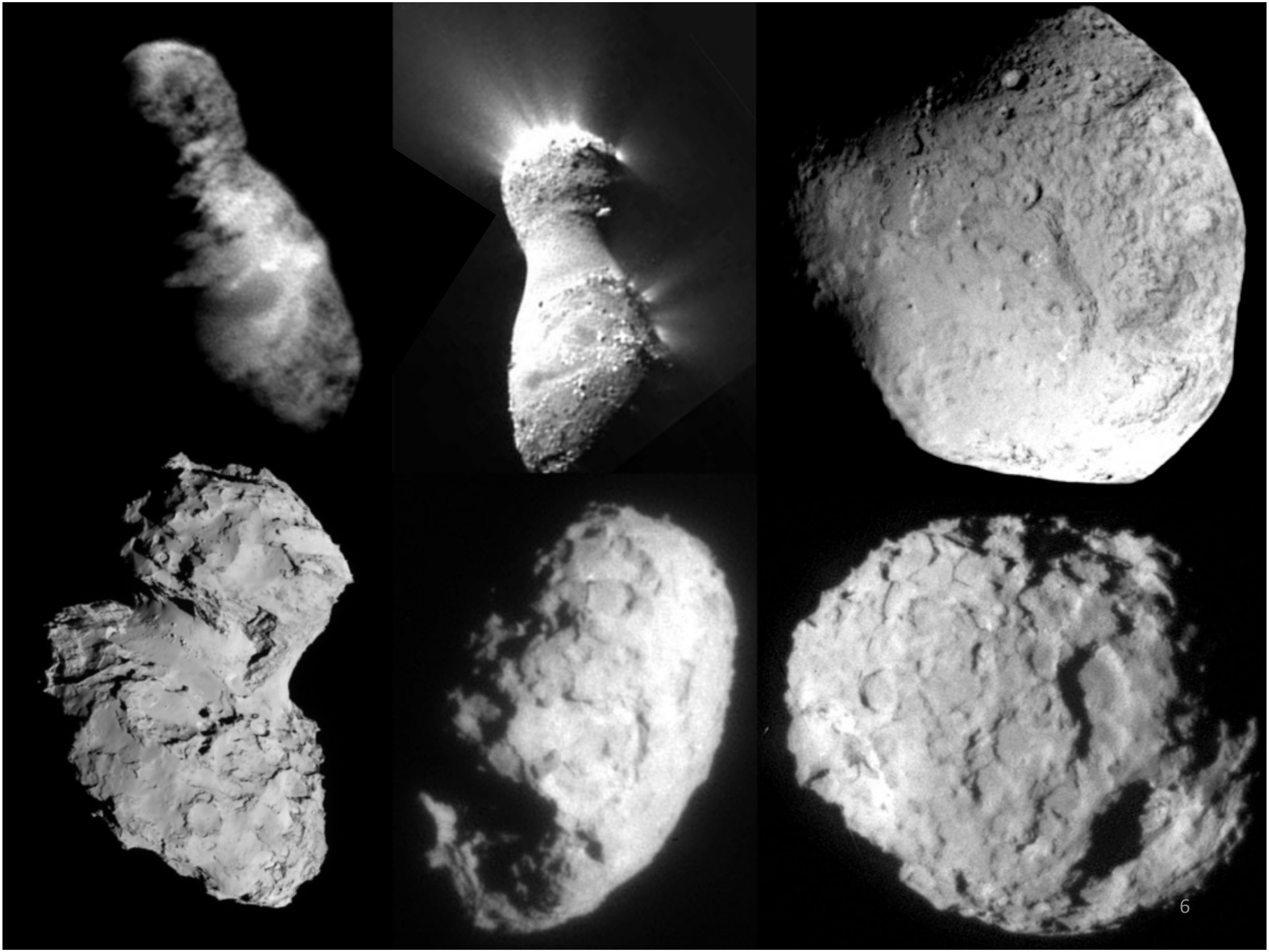
Comets unstable in inner SS
Loss of gas & dust

Activity driven by subliming ice
Ice formed at low temperature

H_2O	128–155 k
CO	23–28 k
CO_2	60–72 k
CH_4	26–32 k
HCN	100–120 k

Comets formed in the coldest regions of the early SS

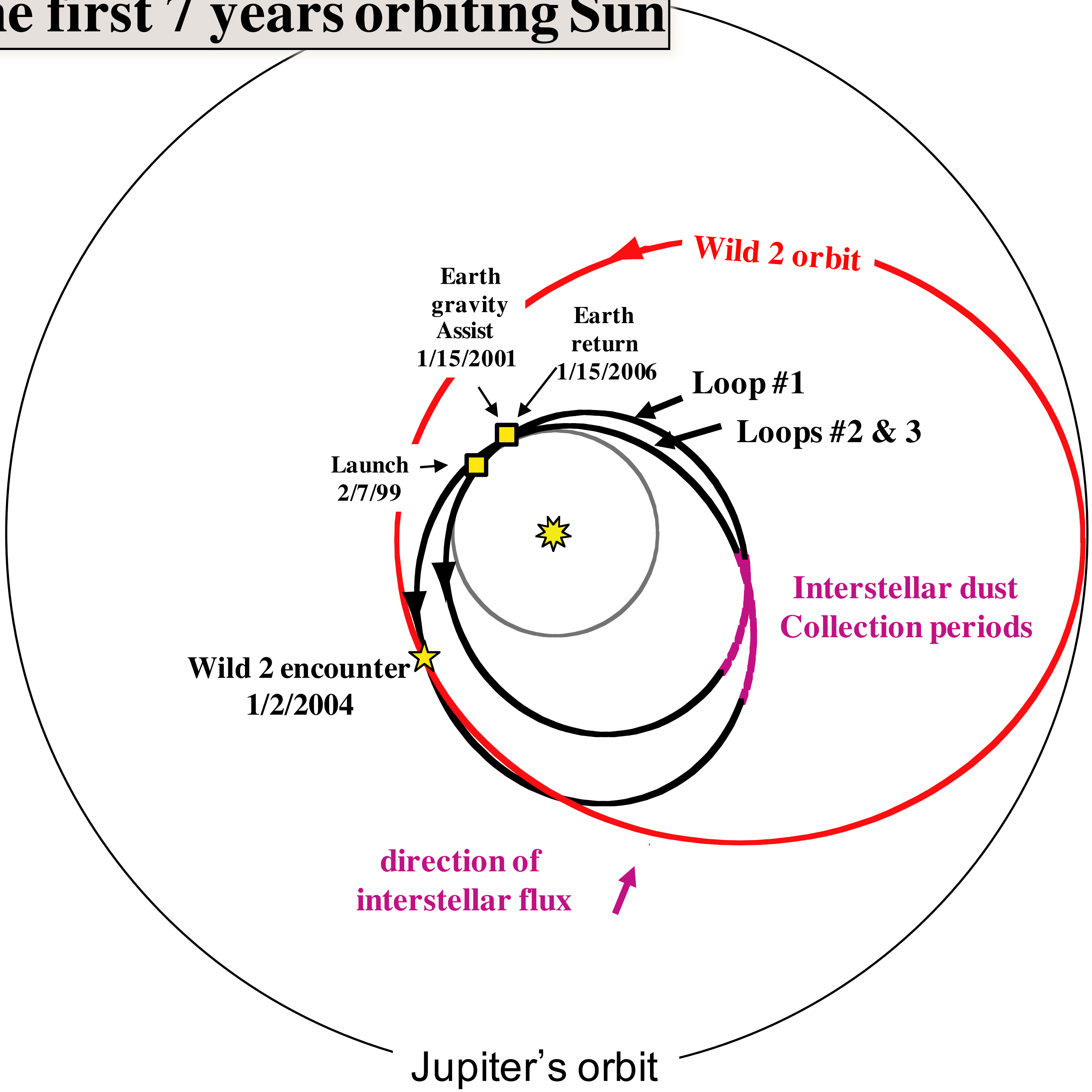




Collecting Comet Dust on a flyby mission (6.1 km/s)

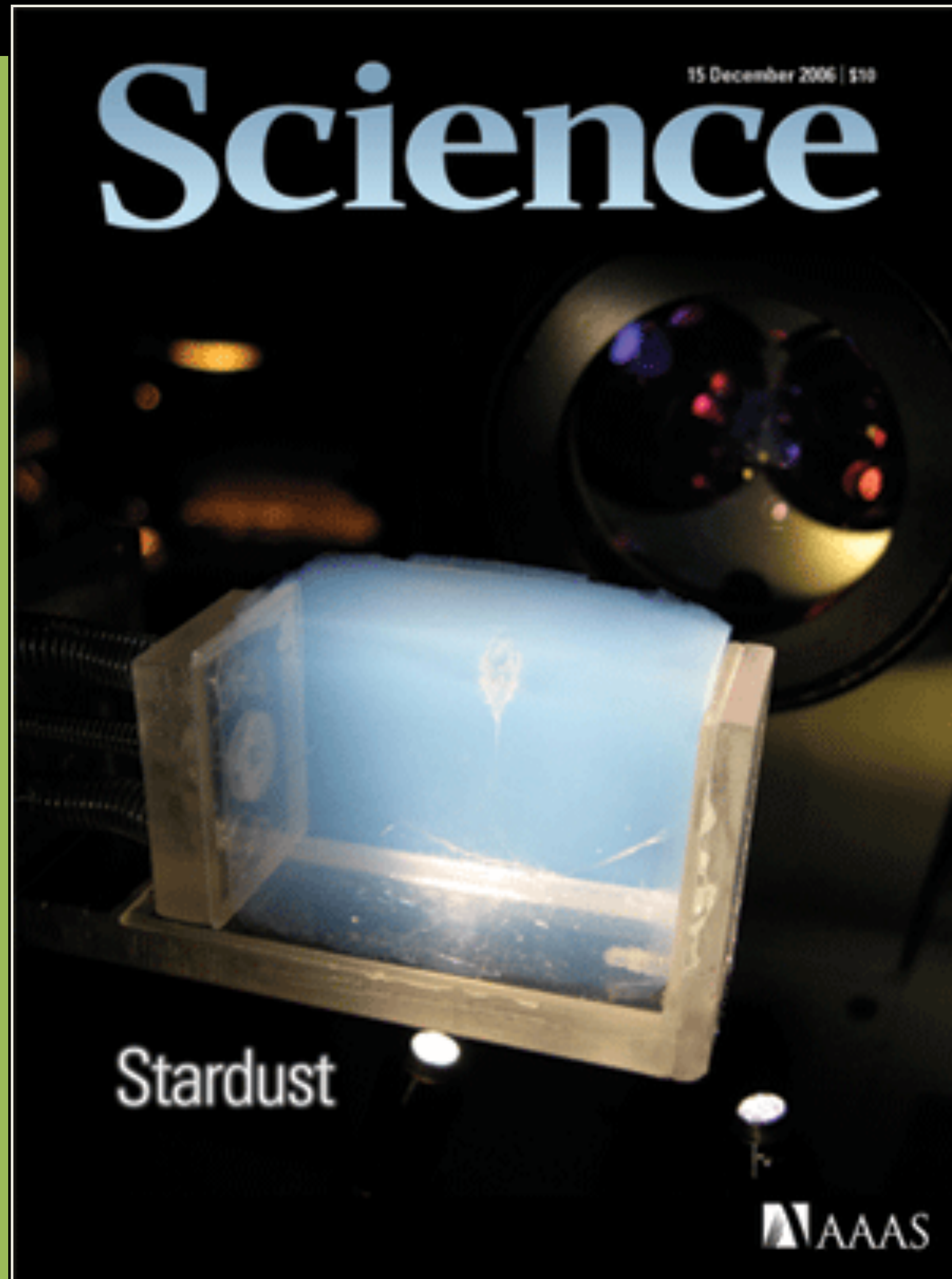
Comet Wild 2 A typical Jupiter Family Comet

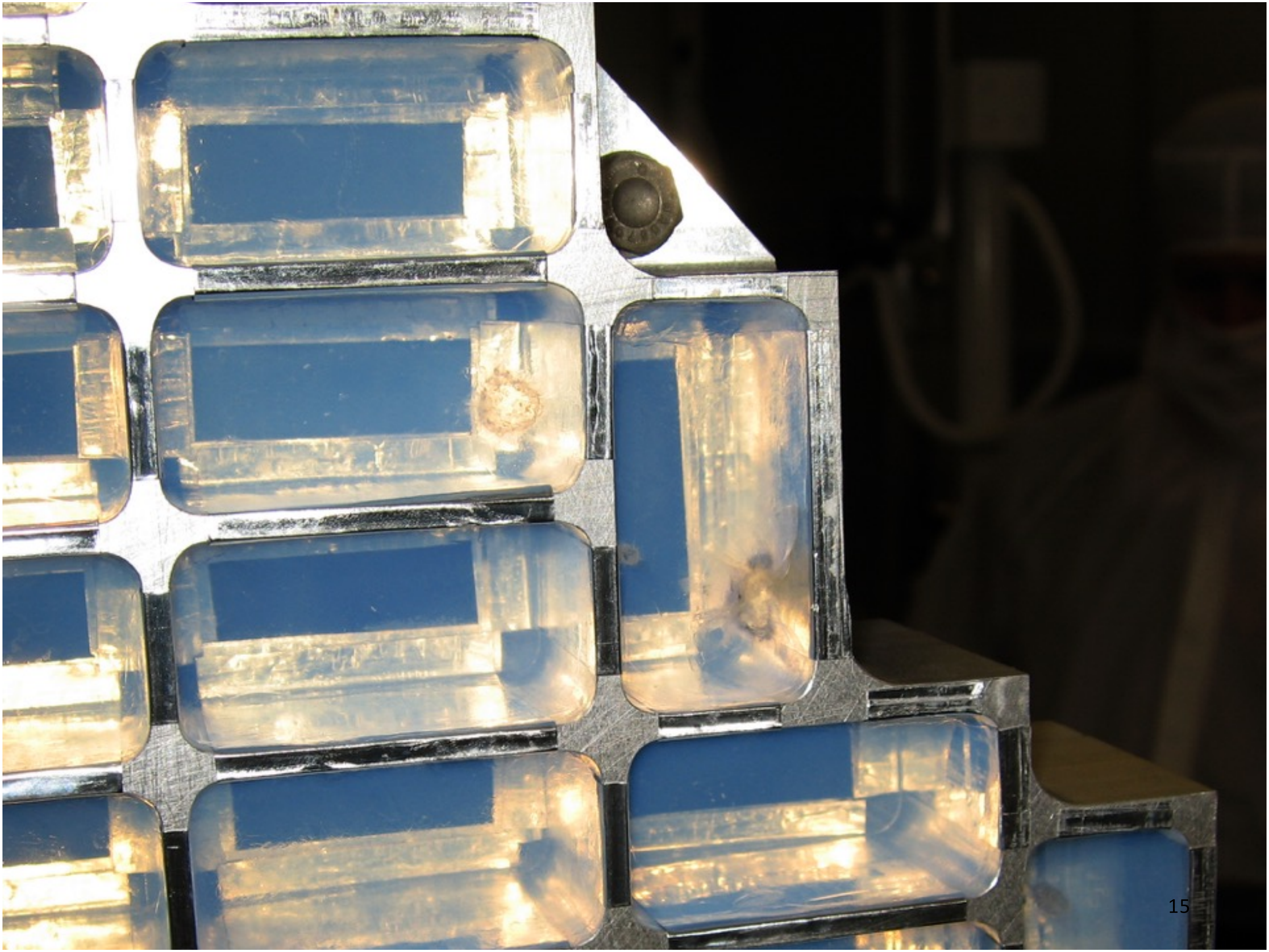
The first 7 years orbiting Sun



Before 1974 Wild 2 was on an orbit from Jupiter to past Uranus

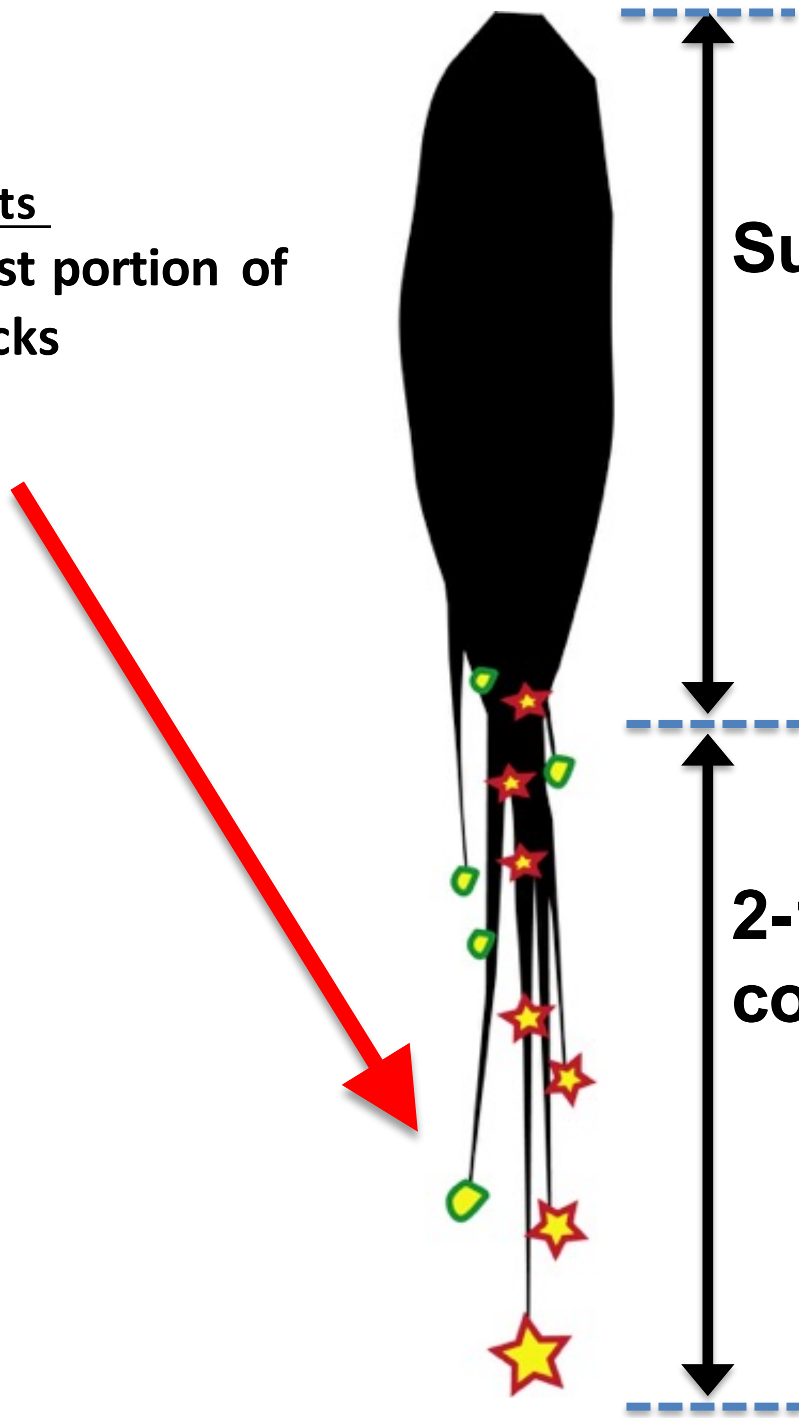
Stardust Silica Aerogel (0.01 – 0.05 g/cc)





Large solid components

Found in the deepest portion of aerogel capture tracks

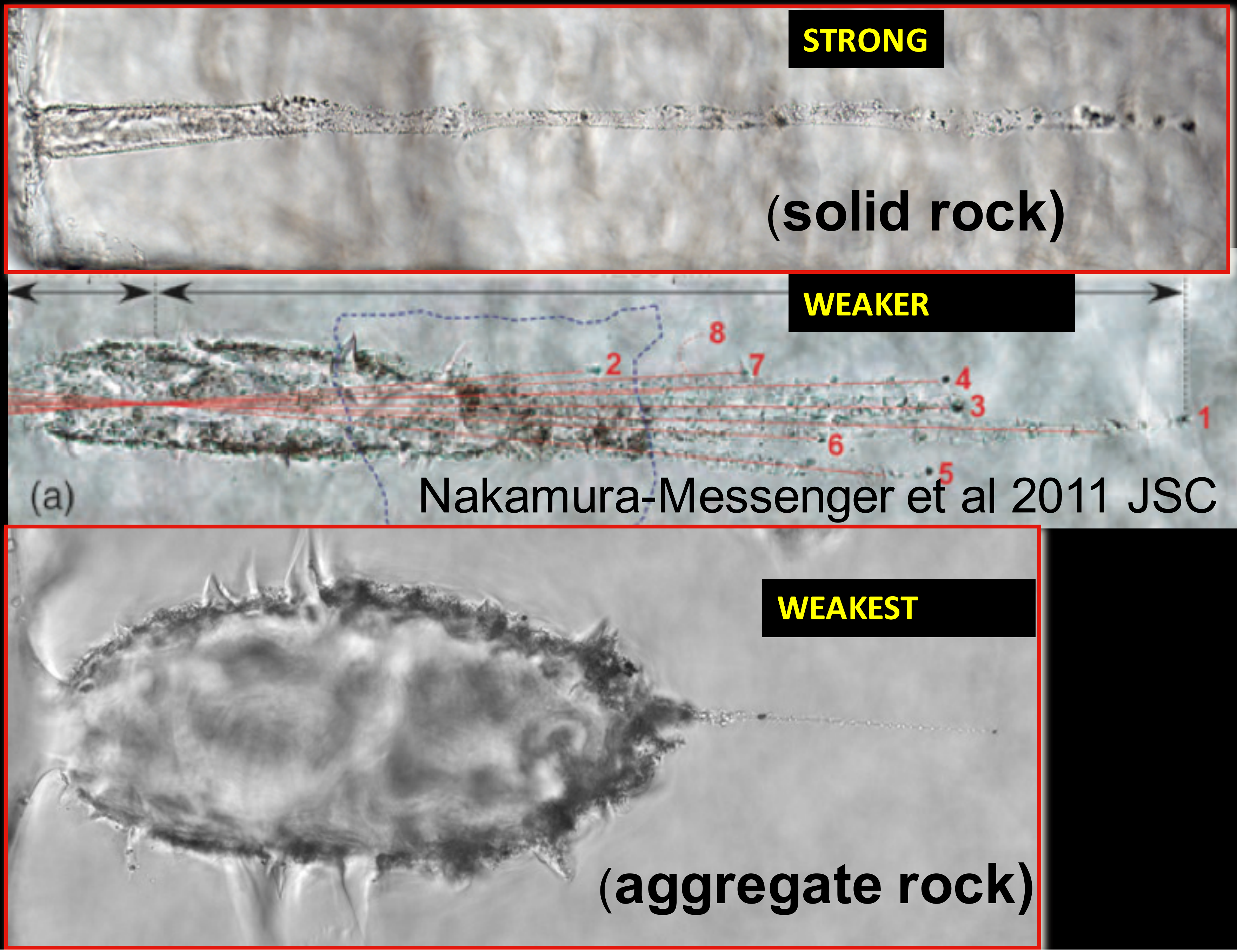


Submicron components

2-100µm solid components

Very well preserved!

6 Km/S Comet Particles Captured In Silica Aerogel



What is in the tracks? Brief summary

1) Unequilibrated mix of submicron – 100μm solid components

1) Most components >2μm are phases and phase assemblages found in primitive meteorites – high temperature materials

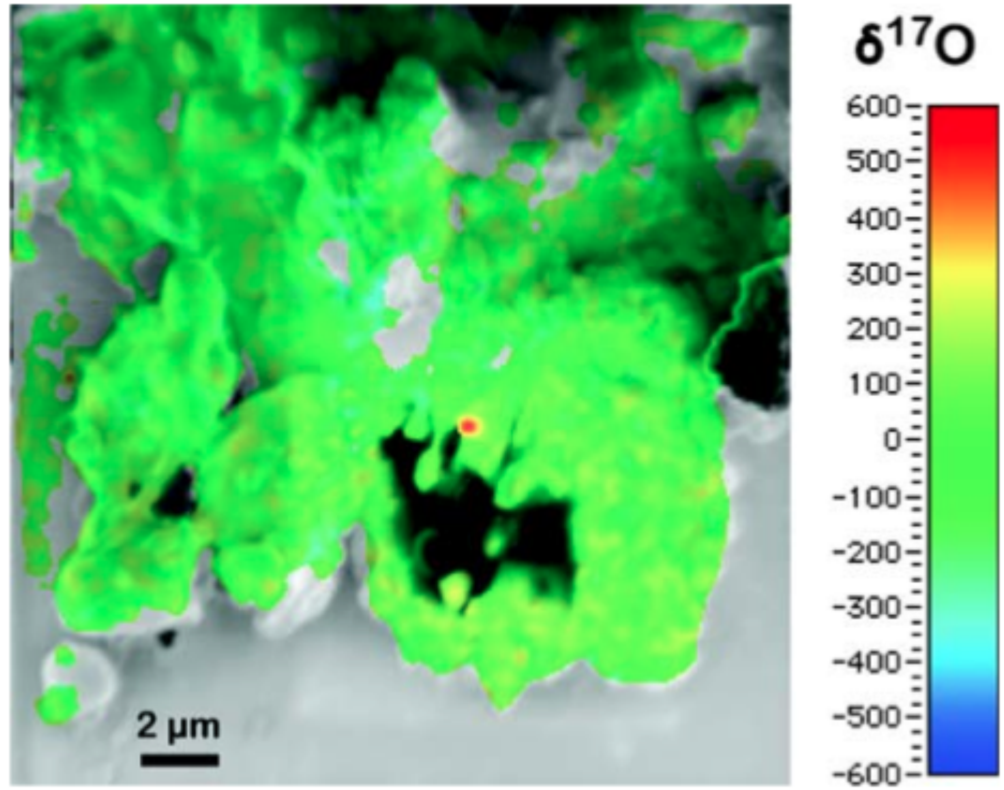
3) Isotopically anomalous pre-solar grains are rare

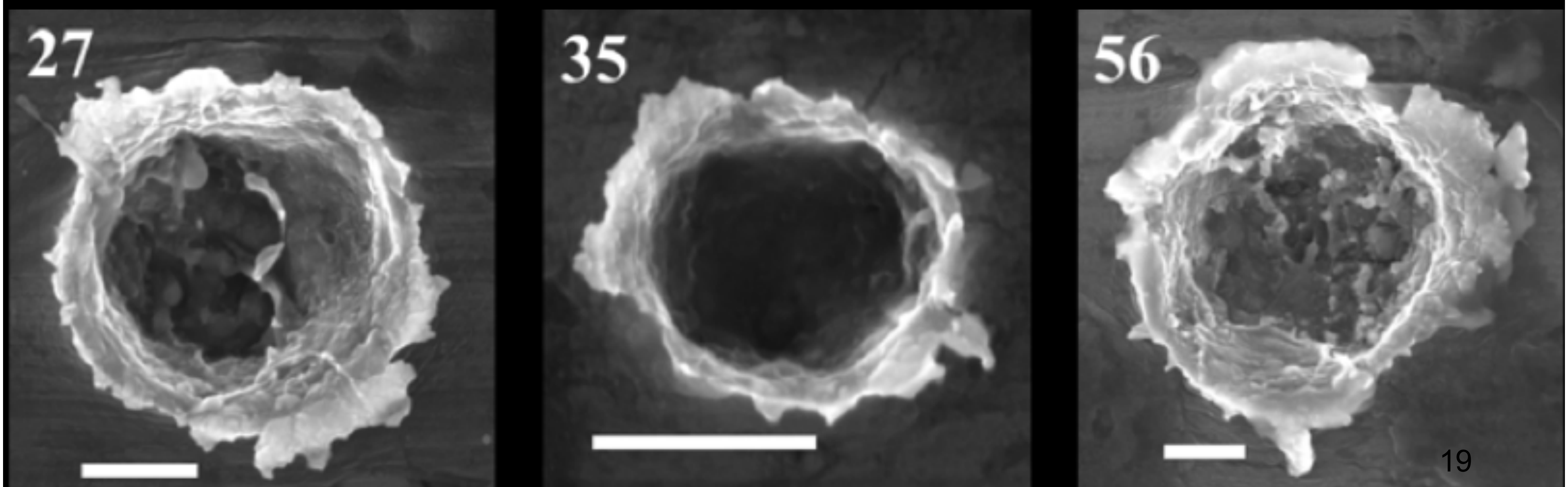
4) Hydrated silicates not found

5) Organics include hi D/H and $^{15}N/^{14}N$ materials & glycine

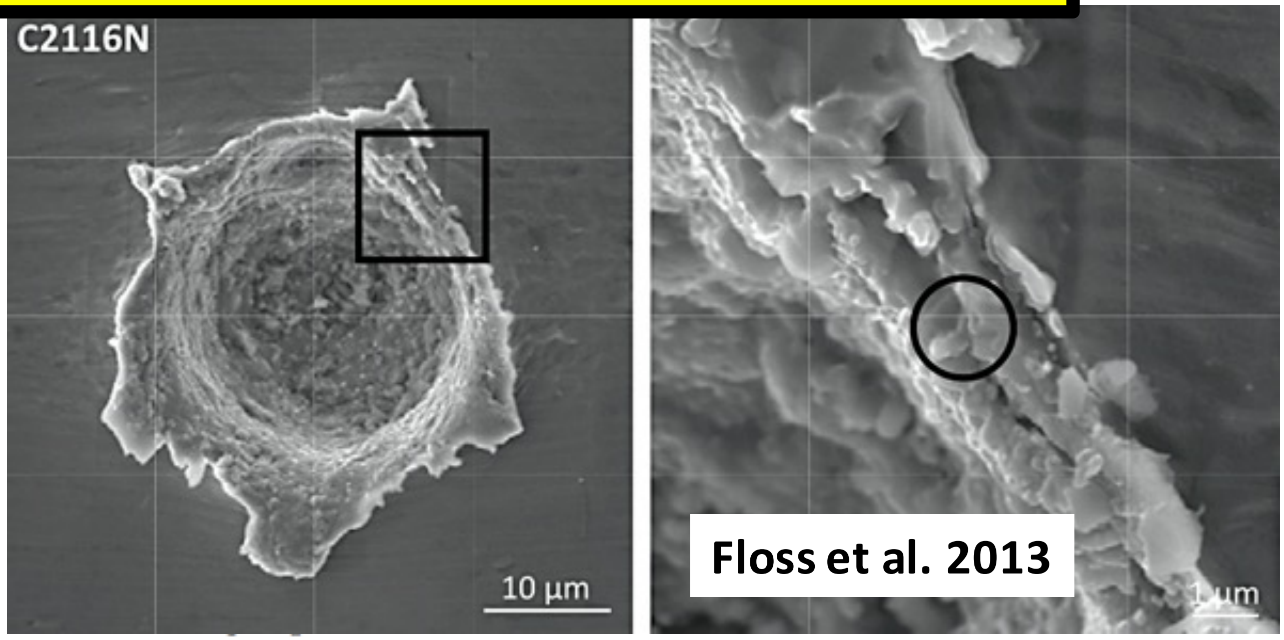
presolar grains in Wild 2

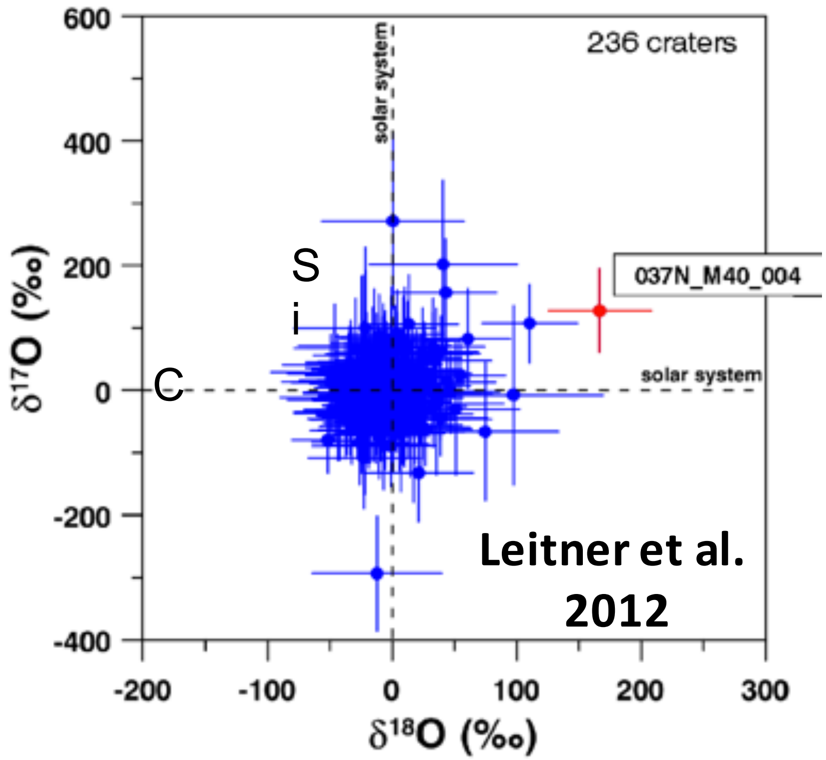
Stardermann et al. 2008



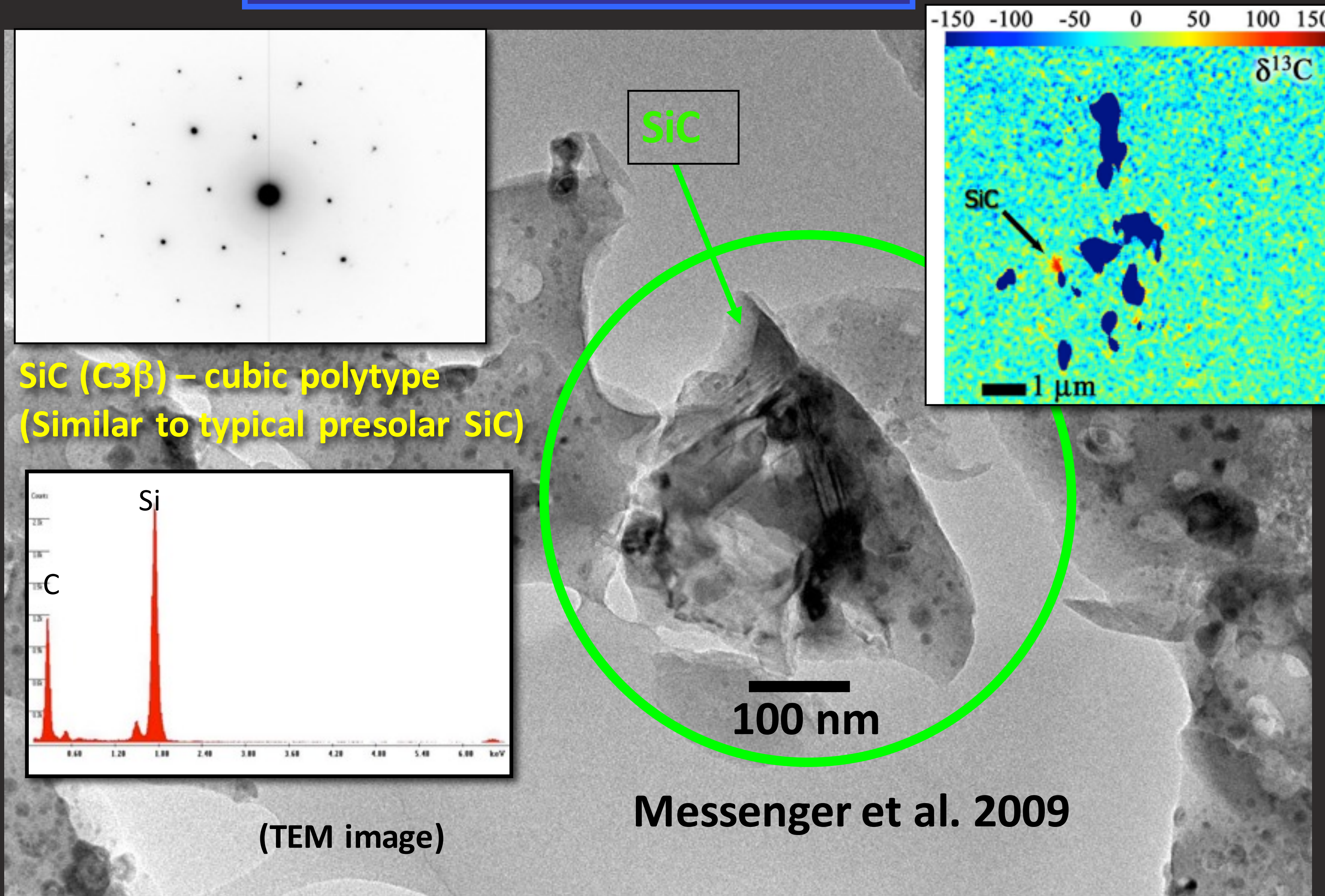


Finding presolar grains in a comet



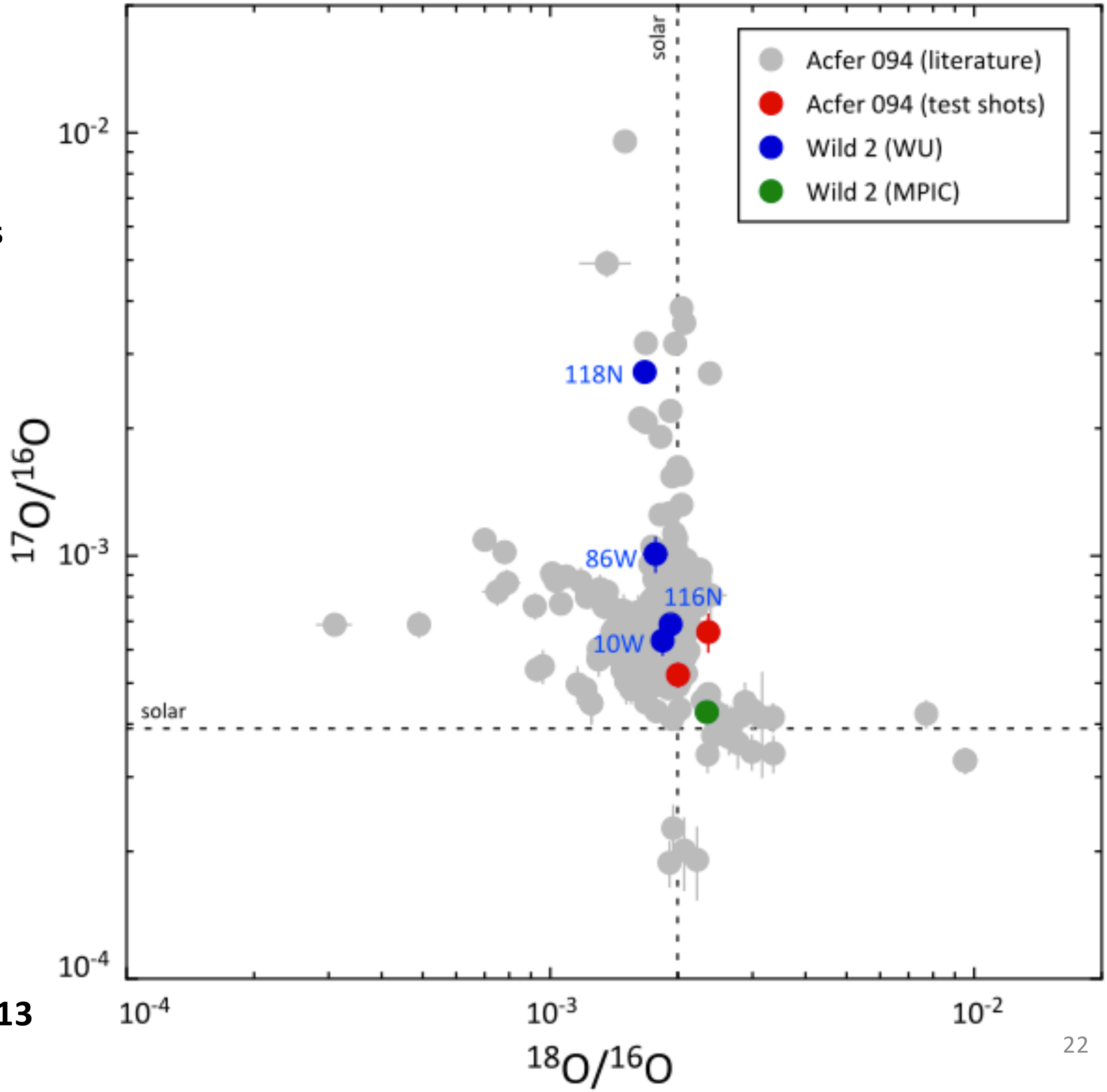


Presolar silicon carbide



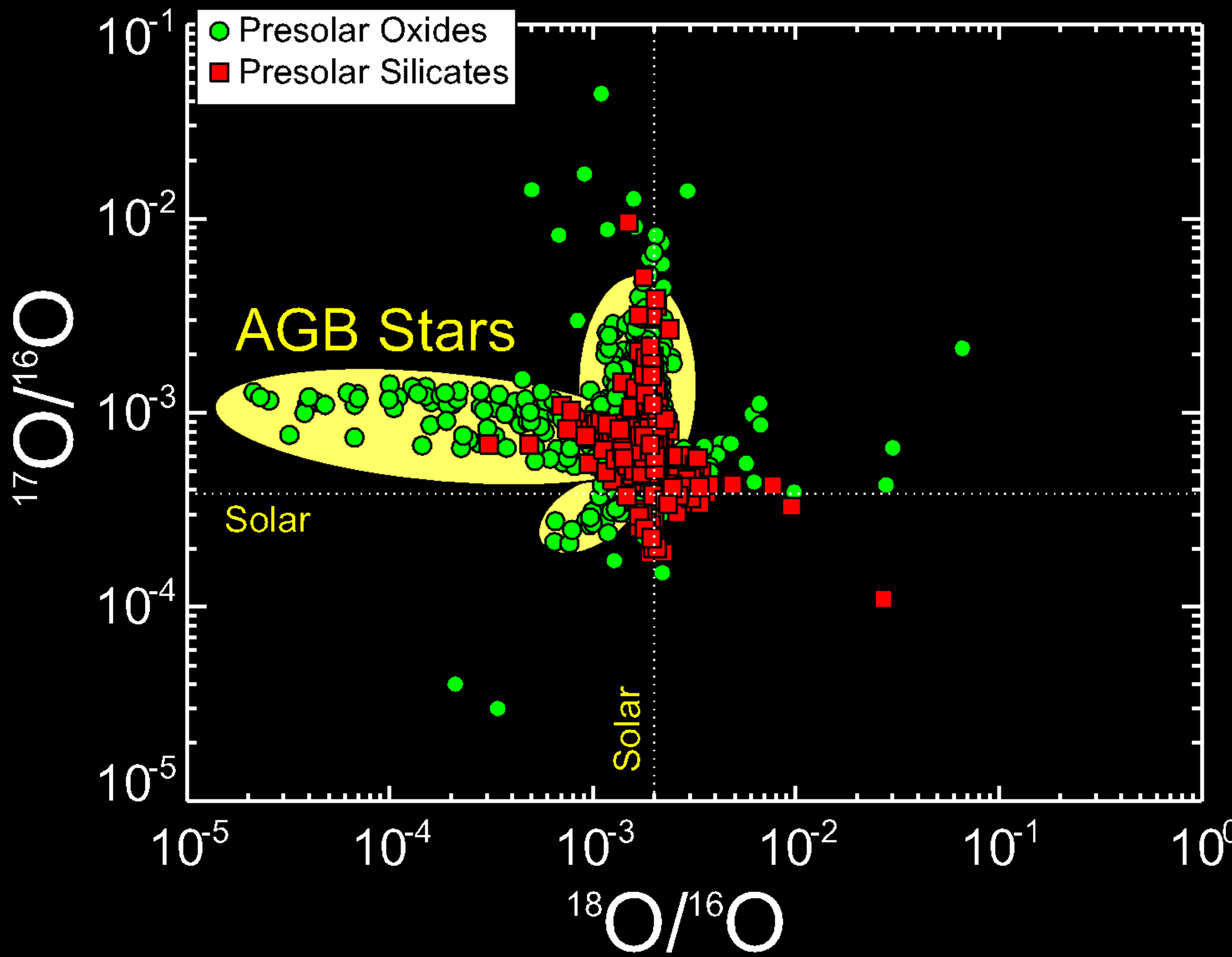
6 isotopically anomalous presolar grains

5 in craters
1 in aerogel



Floss et al. 2013

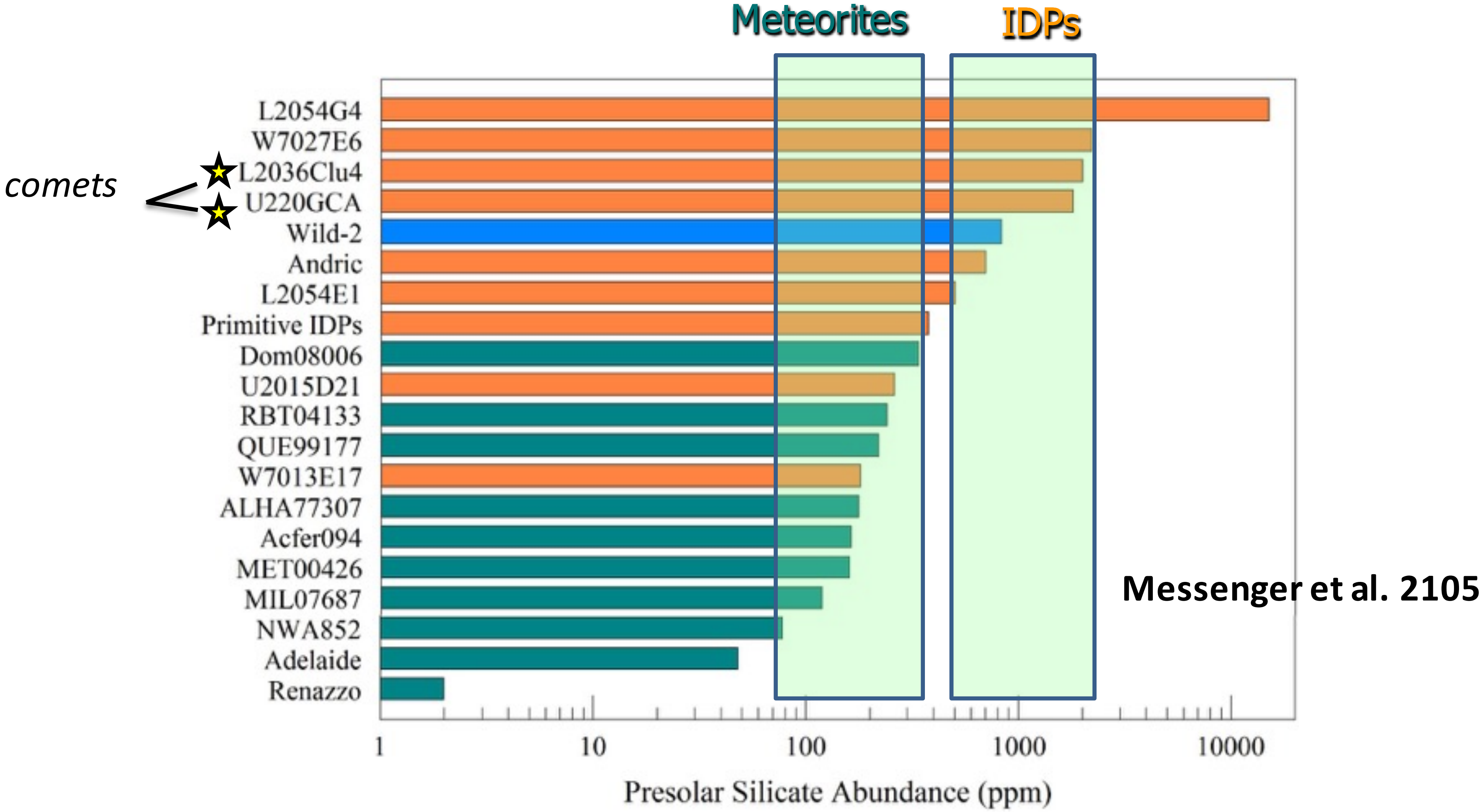
O-rich AGB stardust in meteorites



L. Nittler

~90% of presolar silicates/oxides

Presolar Silicate Abundances



Wild 2 isotopically anomalous presolar grains are rare

<<< than expected!!!

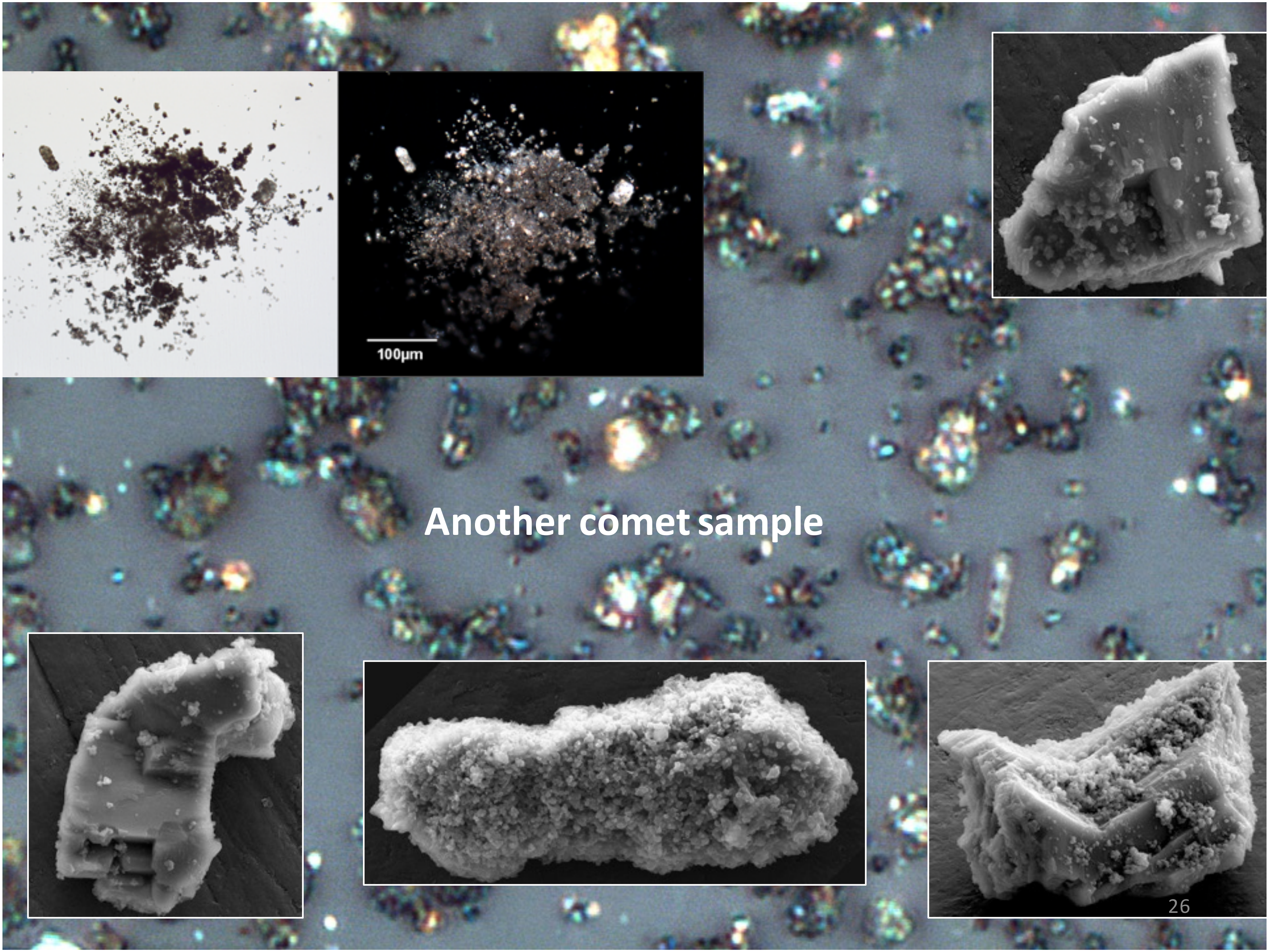
but apparently more abundant than in chondrites - similar to IDPs ~1000 ppm

Is Wild 2 an unusual comet -
Not dominated by presolar grains?

NO

No meteorites or cometary Interplanetary Dust contain abundant pre-solar grains

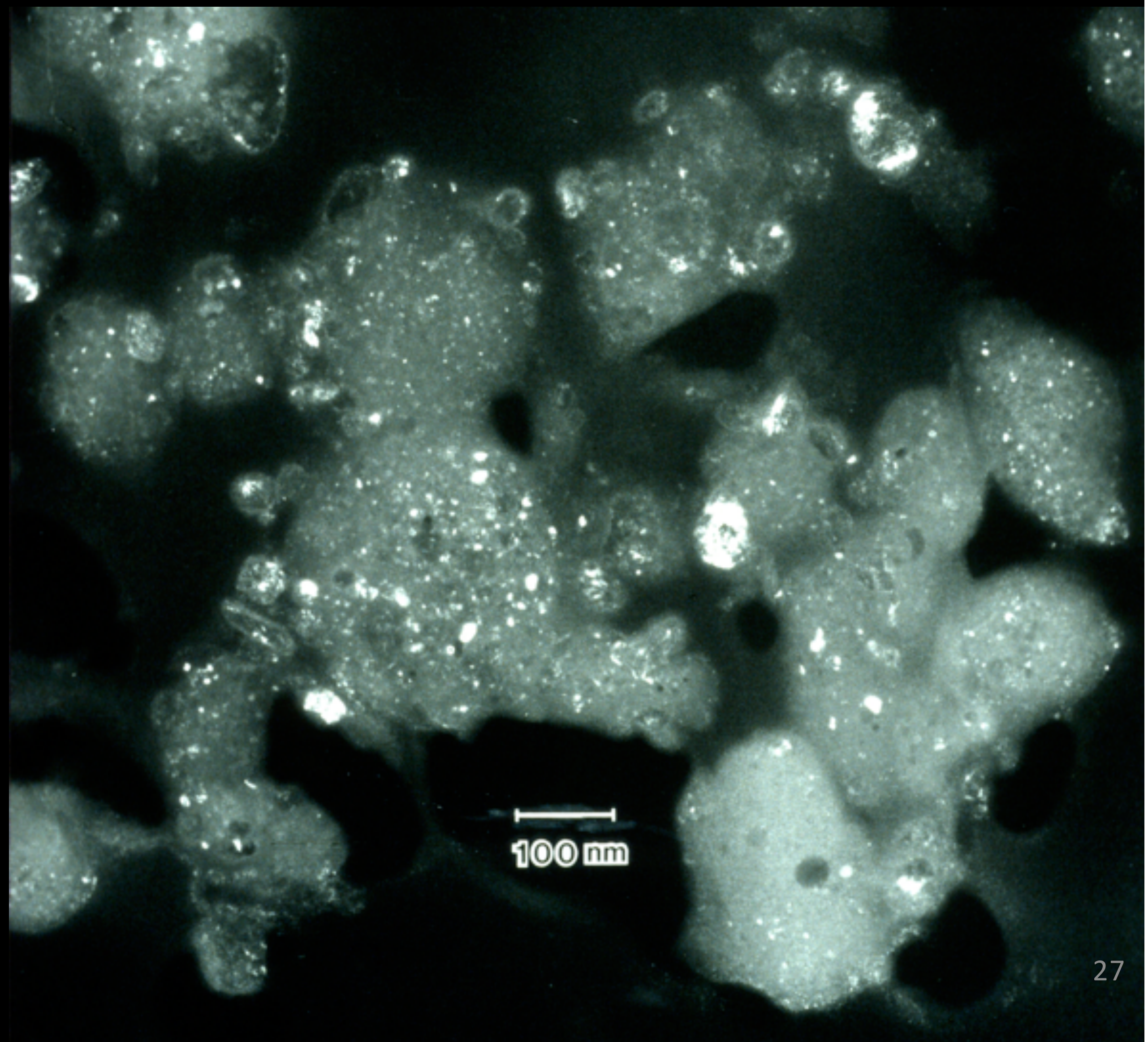
Isotopically anomalous presolar grains apparently did not survive well in the early solar system – anywhere!


100µm
Another comet sample

Are we missing something?

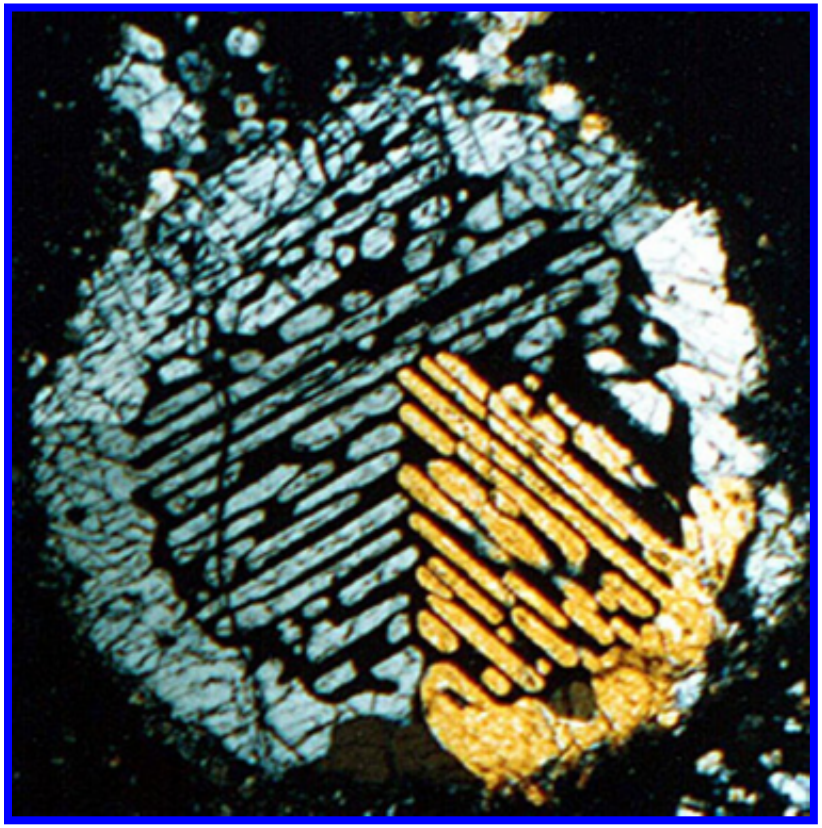
Does the comet contain
Isotopically normal GEMS?
Destroyed during capture?

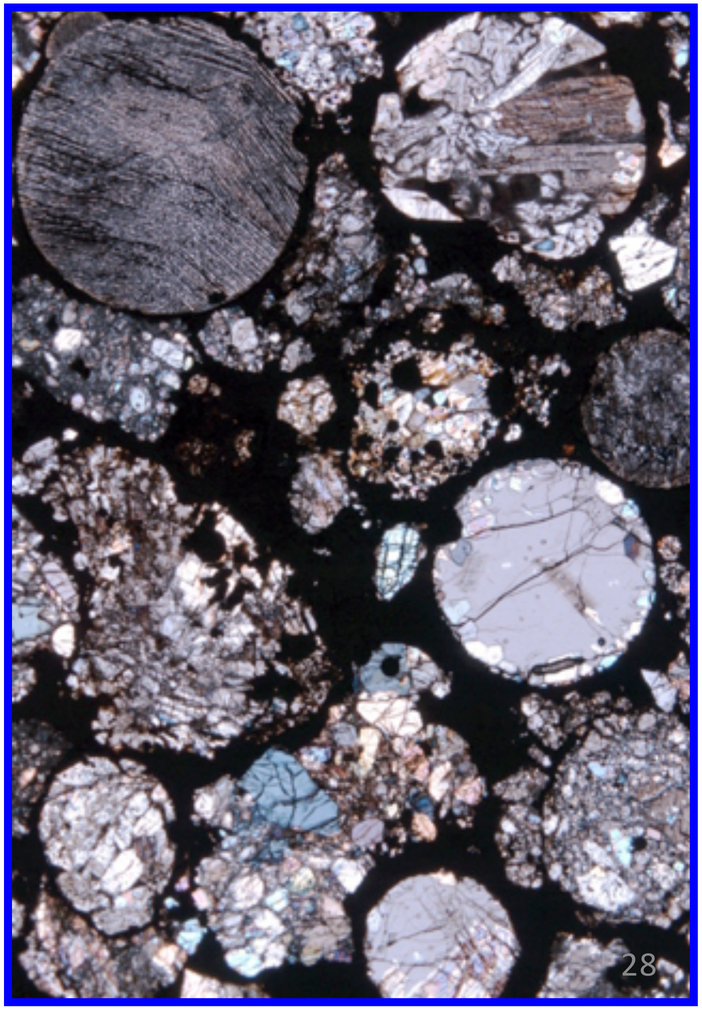
GEMS
Glass + Embedded Metal & Sulfide



Chondrules – rounded small bodies in meteorites

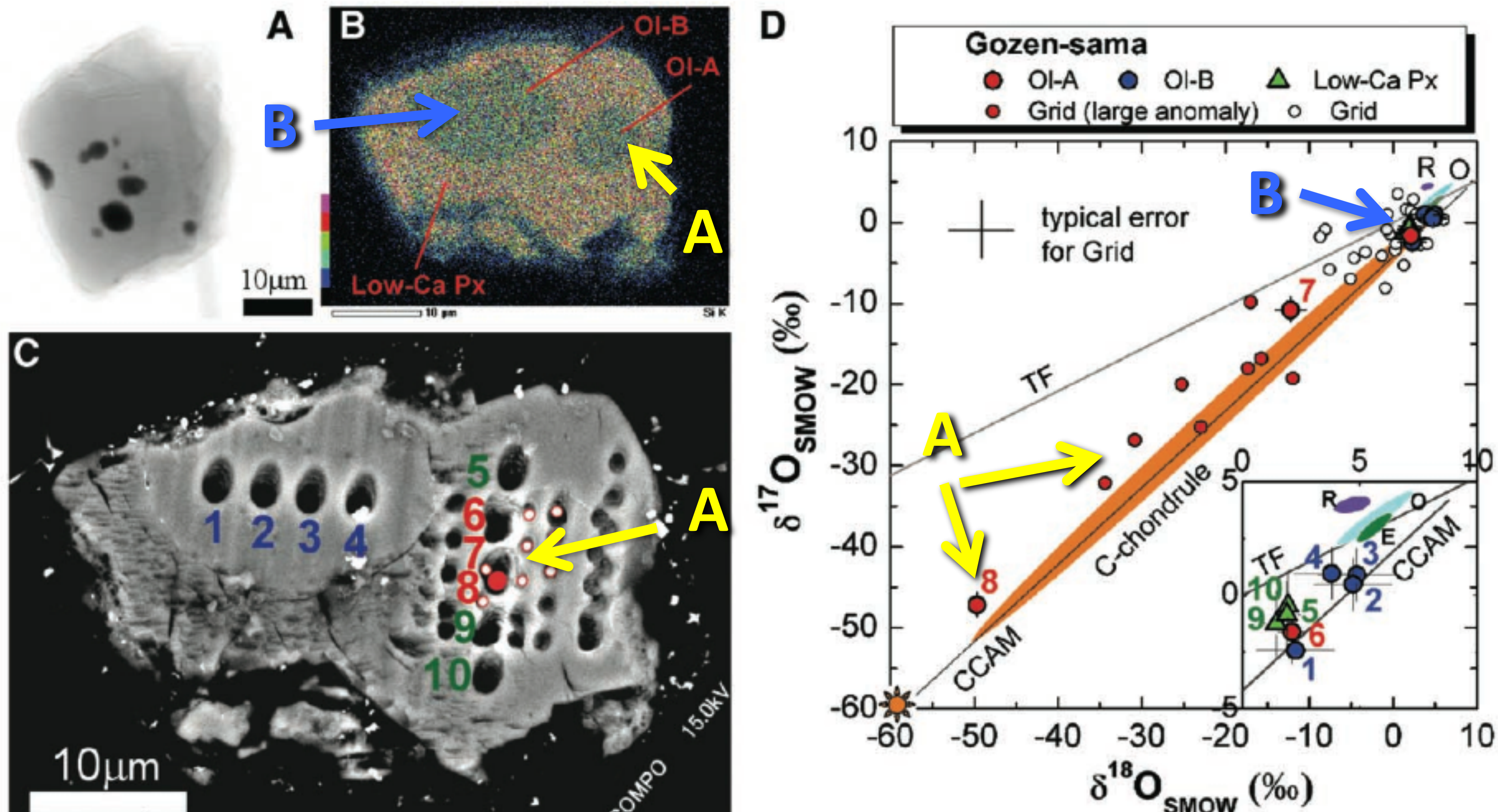
- Molten silicate droplets in the solar nebula
- Formed at 1550ºC to 2000ºC!
- <u>The dominant solids</u> where some asteroids formed



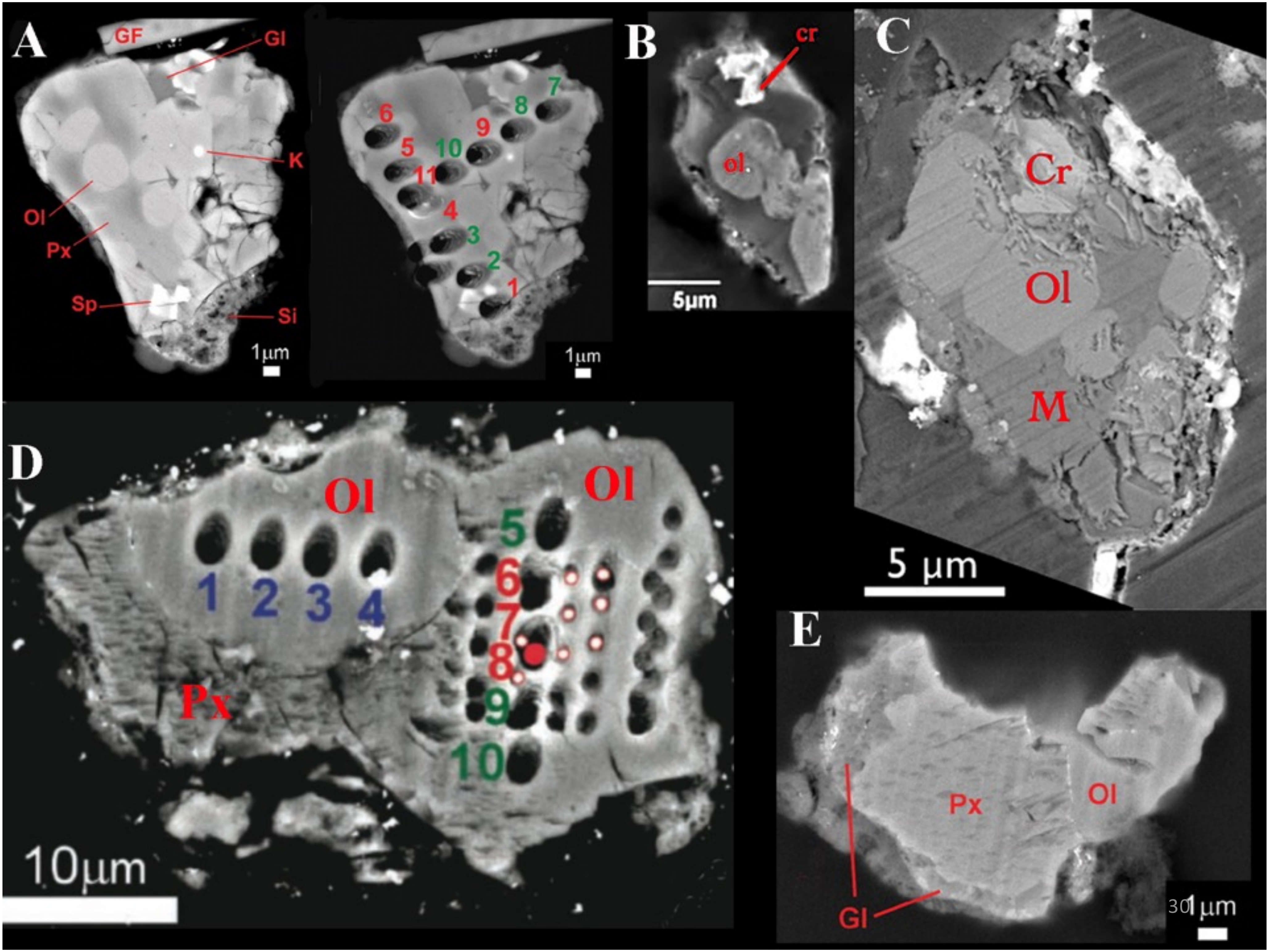


Relict ^{16}O-rich olivine in 40µm Gozen-sama chondrule

Complex multi-stage history - important analog to meteorite chondrules
Could not plausibly have formed by annealing of >10^6 amorphous interstellar grains!



Nakamura et al. 2008



A
GF
Gl
K
Ol
Px
Sp
Si
1µm
6
5
11
4
3
2
1
10
9
8
7
1µm
B
cr
ol
5µm
C
Cr
Ol
M
5 µm
D
Ol
Ol
1
2
3
4
5
6
7
8
9
10
Px
10µm
E
Px
Ol
Gl
1 µm

Chondrules in Wild 2
the most common large grains?

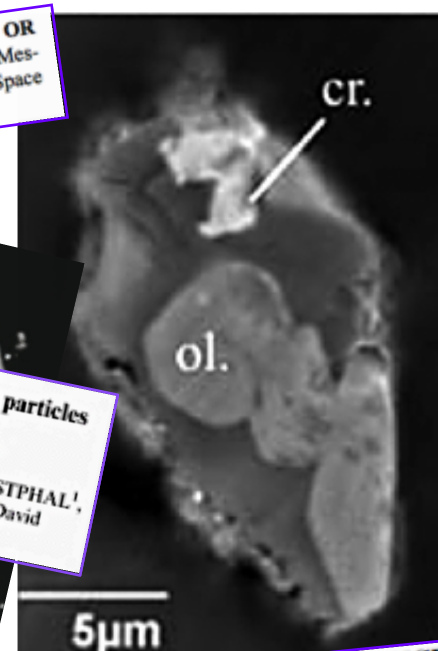
The dominant solids where OC's accreted

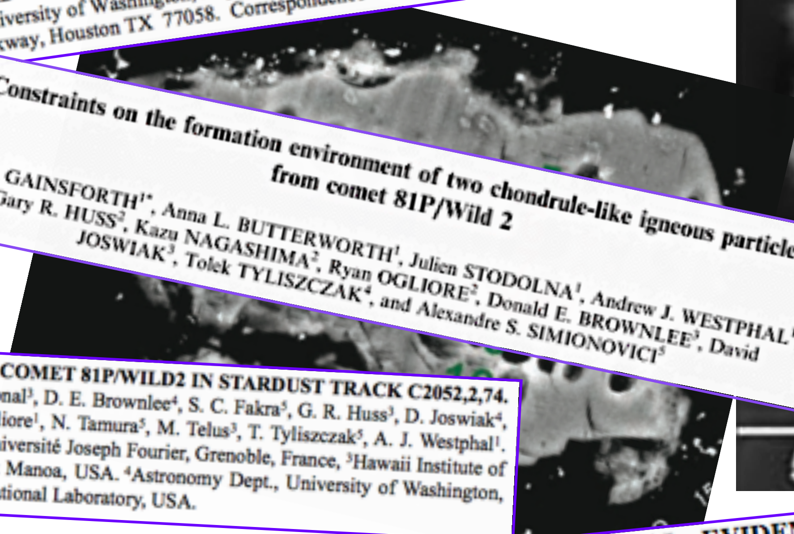
Pyroxenes microstructure in comet 81P/Wild 2 terminal Stardust particles

Damien JACOB[1*], Julien STODOLNA[1], Hugues LEROUX[1], Falko LANGENHORST[2], and F. HOUDELLIER[3]

CHONDRULE FRAGMENTS IN STARDUST ... AND 154
J. C. Bridges[1] and H. G. Changela[1]. [1]Space Research Centre, Dept. of Physics & Astronomy, University of Leicester, UK, LE1 7RH. j.bridges@le.ac.uk.

STARDUST TRACK 130 TERMINAL PARTICLE: POSSIBLE AL-RICH CHONDRULE FRAGMENT OR ALTERED AMOEBOID OLIVINE AGGREGATE.
D. J. Joswiak[1], D. E. Brownlee[1], G. Matrajt[1], S. M. Messenger[2] and M. Ito[2], [1]University of Washington, Dept. of Astronomy, 351580, Seattle WA 98195, [2]Johnson Space Center 2101 NASA Parkway, Houston TX 77058. Correspondence e-mail: joswiak@astro.washington.edu.



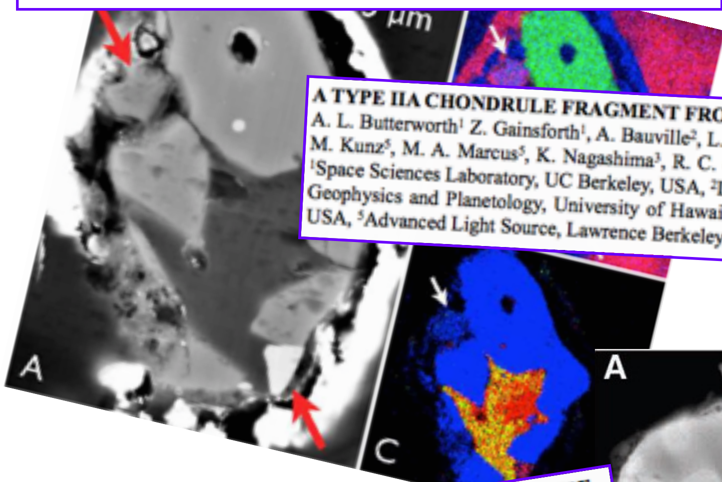


Chondrulelike Objects in Short-Period Comet 81P/Wild 2

Tomoki Nakamura,[1*] Takaaki Noguchi,[2] Akira Tsuchiyama,[3] Takayuki Ushikubo,[4] Noriko T. Kita,[4] John W. Valley,[4] Michael E. Zolensky,[5] Yuki Kakazu,[1] Kanako Sakamo... Etsuko Mashio,[3] Kentaro Uesugi,[6] Tsukasa Nakano[7]

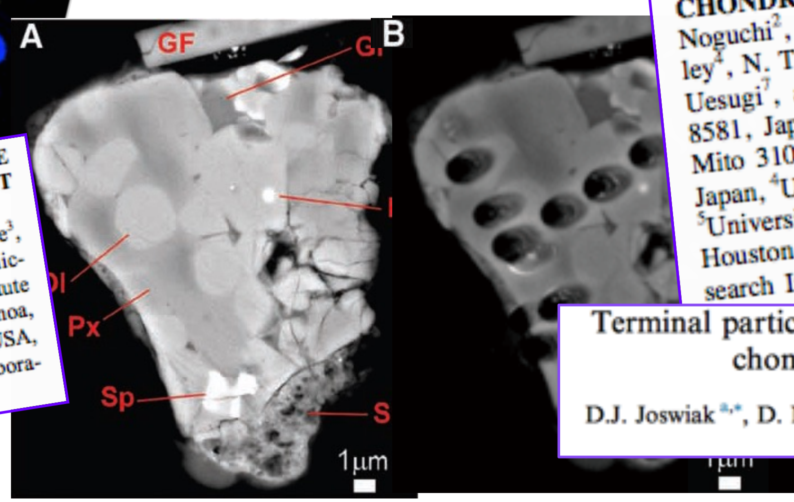
Constraints on the formation environment of two chondrule-like igneous particles from comet 81P/Wild 2

Zack GAINSFORTH[1*], Anna L. BUTTERWORTH[1], Julien STODOLNA[1], Andrew J. WESTPHAL[1], Gary R. HUSS[2], Kazu NAGASHIMA[2], Ryan OGLIORE[2], Donald E. BROWNLEE[3], David JOSWIAK[3], Tolek TYLISZCZAK[4], and Alexandre S. SIMIONOVICI[5]



A TYPE IIA CHONDRULE FRAGMENT FROM COMET 81P/WILD2 IN STARDUST TRACK C2052,2,74.
A. L. Butterworth[1] Z. Gainsforth[1], A. Bauville[2], L. Bonal[3], D. E. Brownlee[4], S. C. Fakra[5], G. R. Huss[3], D. Joswiak[4], M. Kunz[5], M. A. Marcus[5], K. Nagashima[3], R. C. Ogliore[1], N. Tamura[5], M. Telus[3], T. Tyliszczak[5], A. J. Westphal[1]. [1]Space Sciences Laboratory, UC Berkeley, USA, [2]L'université Joseph Fourier, Grenoble, France, [3]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, USA. [4]Astronomy Dept., University of Washington, USA, [5]Advanced Light Source, Lawrence Berkeley National Laboratory, USA.

ADDITIONAL EVIDENCE FOR THE PRESENCE OF CHONDRULES IN COMET 81P/WILD 2.
T. Nakamura[1], T. Noguchi[2], A. Tsuchiyama[3], T. Ushikubo[4], N. T. Kita[4], J. W. Valley[4], N. Takahata[5], Y. Sano[5], M. E. Zolensky[6], Y. Kakazu[1], K. Uesugi[7], and T. Nakano[8]. [1]Kyushu University, Fukuoka 812-8581, Japan (tomoki@geo.kyushu-u.ac.jp), [2]Ibaraki University, Mito 310-8512, Japan, [3]Osaka University, Toyonaka 560-0043, Japan, [4]University of Wisconsin-Madison, WI 53706-1692, USA, [5]University of Tokyo, Tokyo 164-8639, Japan, [6] NASA/JSC Houston, TX 77058, USA, [7]Japan Synchrotron Radiation Research Institute, SPring-8, Hyogo 679-5198, Japan, [8]Geological ... Tsukuba 305-8567, Japan.

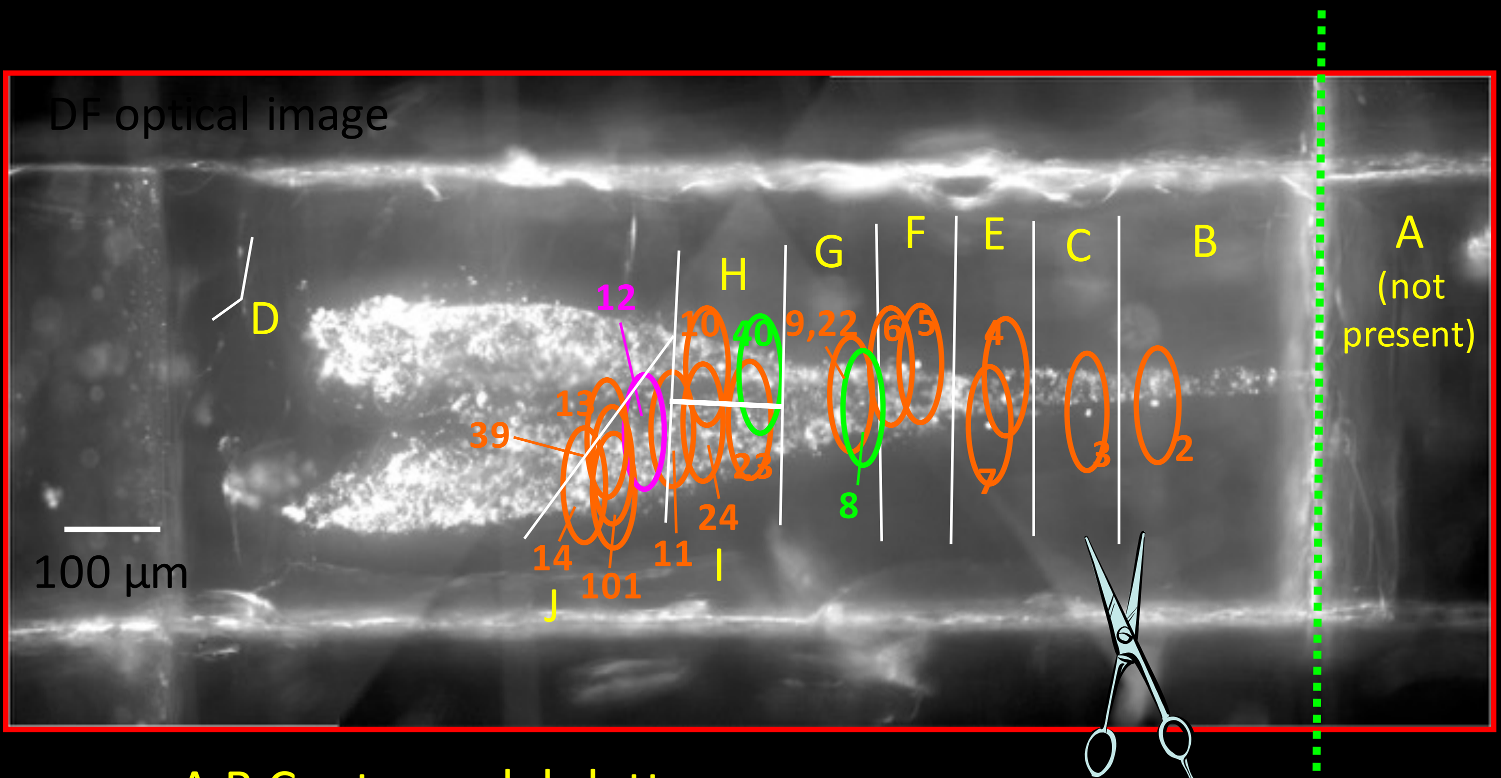


COORDINATED TEM/STXM/IMS ANALYSIS OF A TYPE IIA CHONDRULE FRAGMENT FROM COMET 81P/WILD2 STARDUST TRACK C2052,2,74
Z. Gainsforth[1], A. L. Butterworth[1], L. Bonal[2], D. E. Brownlee[3], G. R. Huss[2], D. Joswiak[3], R. C. Ogliore[1], M. Telus[2], T. Tyliszczak[4], A. J. Westphal[1], [1]U. C. Berkeley, USA, [2]Hawaii Institute of Geophysics and Planetology, University of Hawaii at Manoa, USA. [3]Astronomy Dept., University of Washington, USA, [4]Advanced Light Source, Lawrence Berkeley National Laboratory, USA

Terminal particle from Stardust track 130: Probable Al-rich chondrule fragment from comet Wild 2

D.J. Joswiak[a,*], D. Nakashima[b], D.E. Brownlee[a], G. Matrajt[a], T. Ushikubo[b], N.T. Kita[b], S. Messenger[c], M. Ito[d]

Inti (Track 25) – fragments of a cometary CAI



1

Approx. TP location

Bottom of track cut off

A,B,C, etc. – slab letter

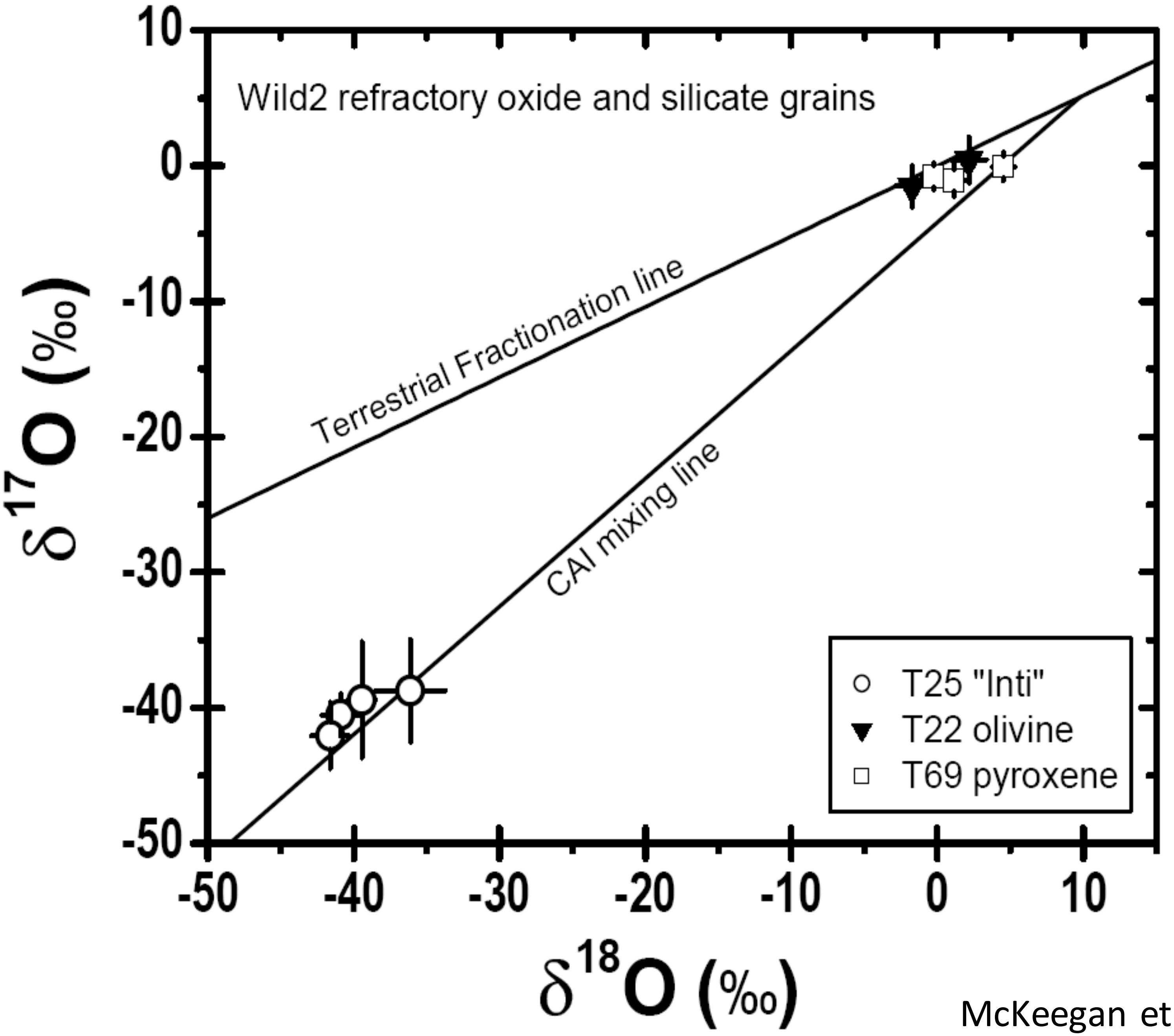
1,2,3,4,5, etc. – fragment number

= CAI fragment

= Non-CAI fragment

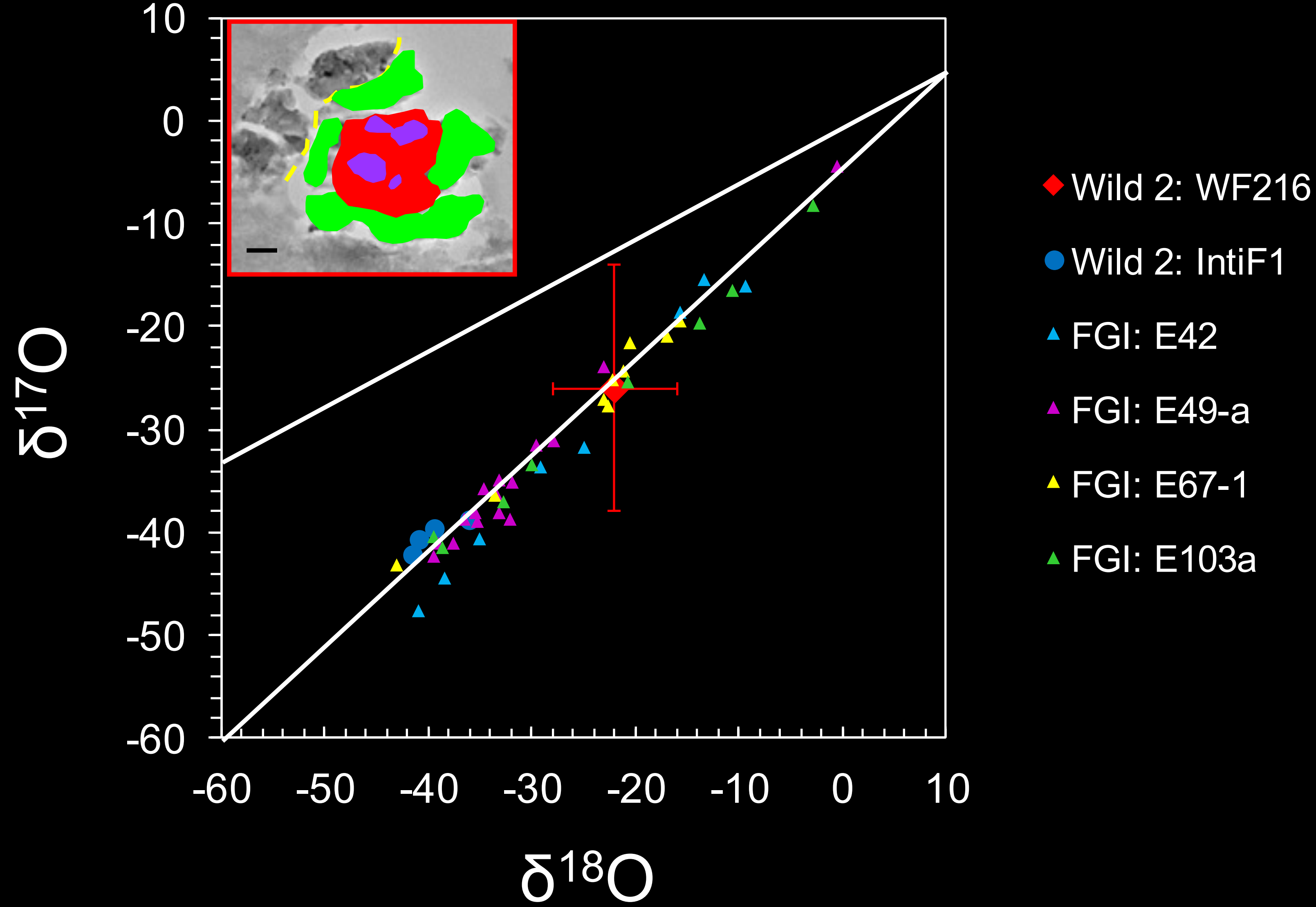
= Kool grain

Frag 12 = Kool grain

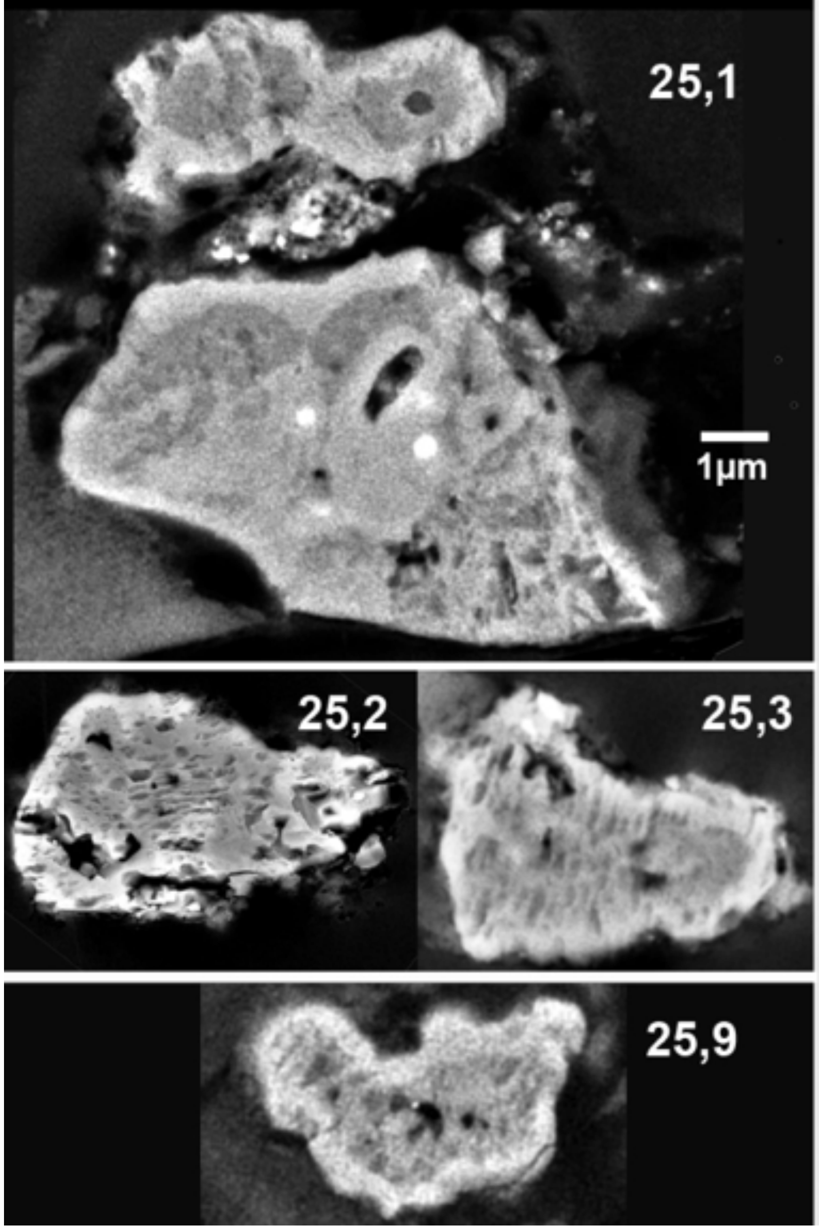


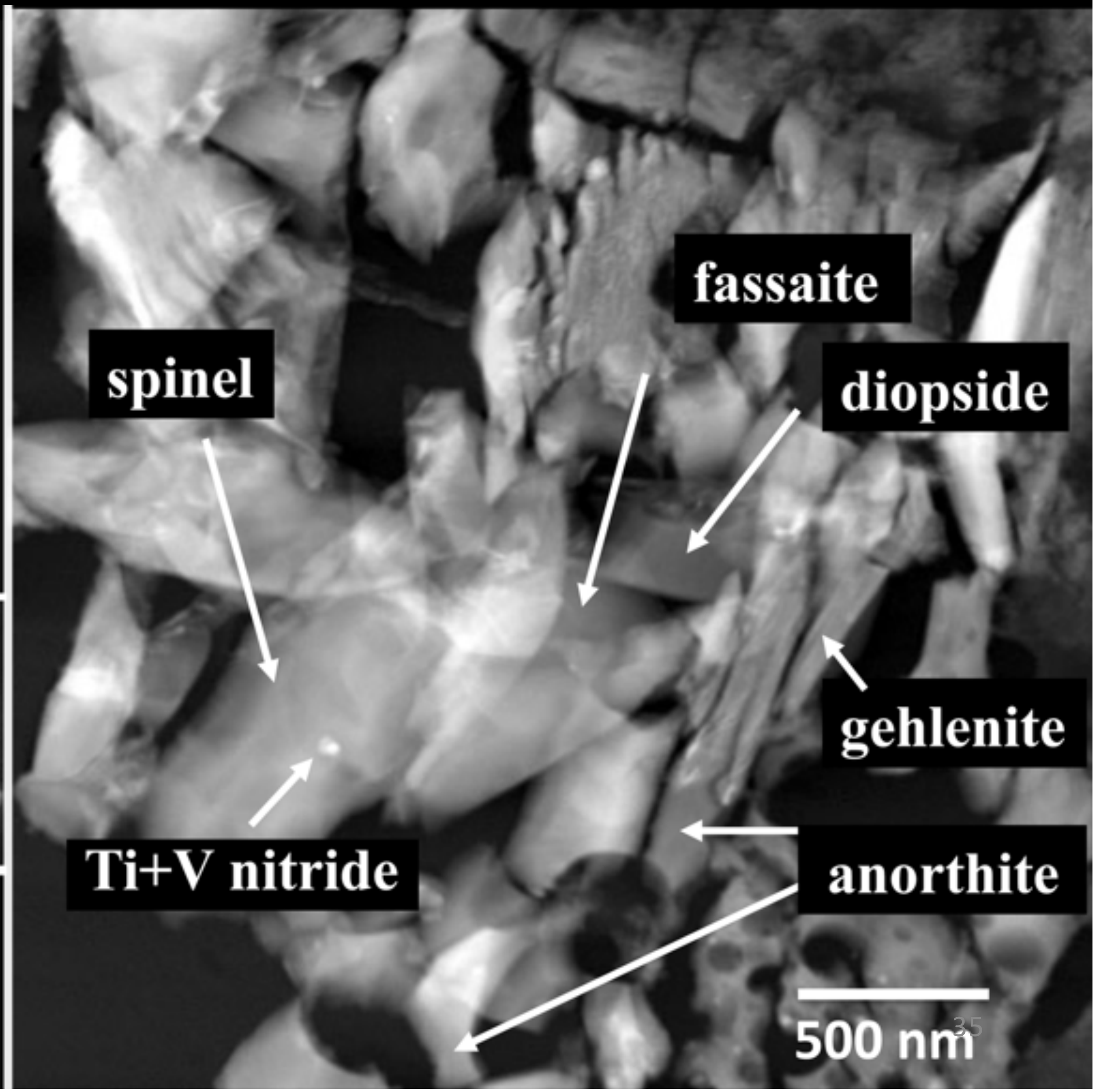
McKeegan et al.

Comet Wild 2 CAI: Oxygen Isotopes
Comparison to spinel-rich, fine-grained inclusions (FGIs)



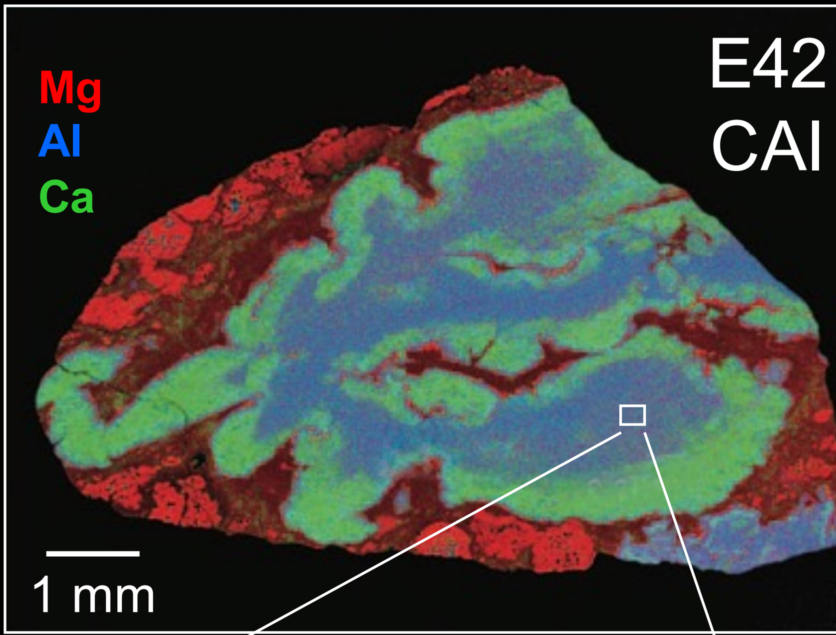
Common Wild 2 refractory nodular assemblies - Px rimming spinel & anorthite



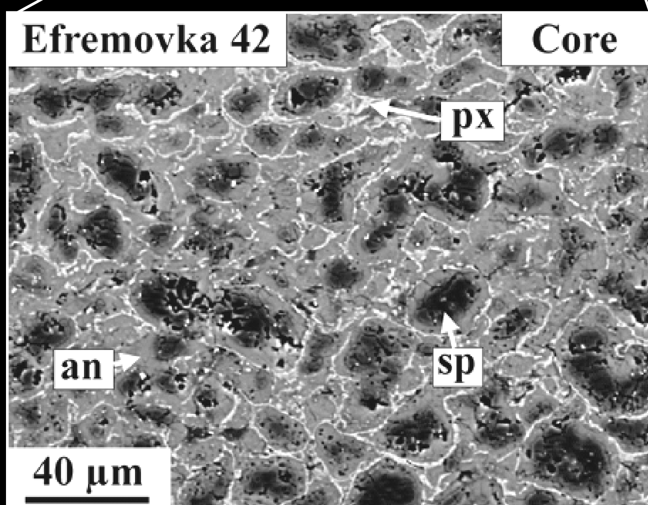


CAIs: FGIs in CV3 Chondrites and Comet Wild 2

Fine-grained, spinel-rich inclusion[1]



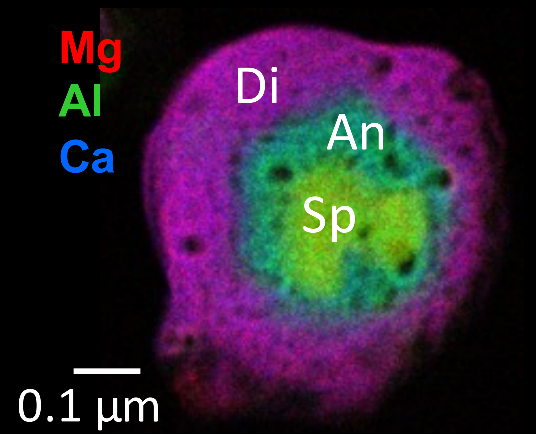
Nodules in FGIs[2]



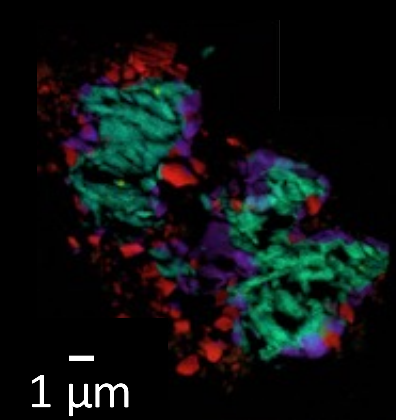
[1]Krot et al. (2004); [2]MacPherson et al. (2004)

Comet CAIs

Wild 2



Giant Cluster IDP

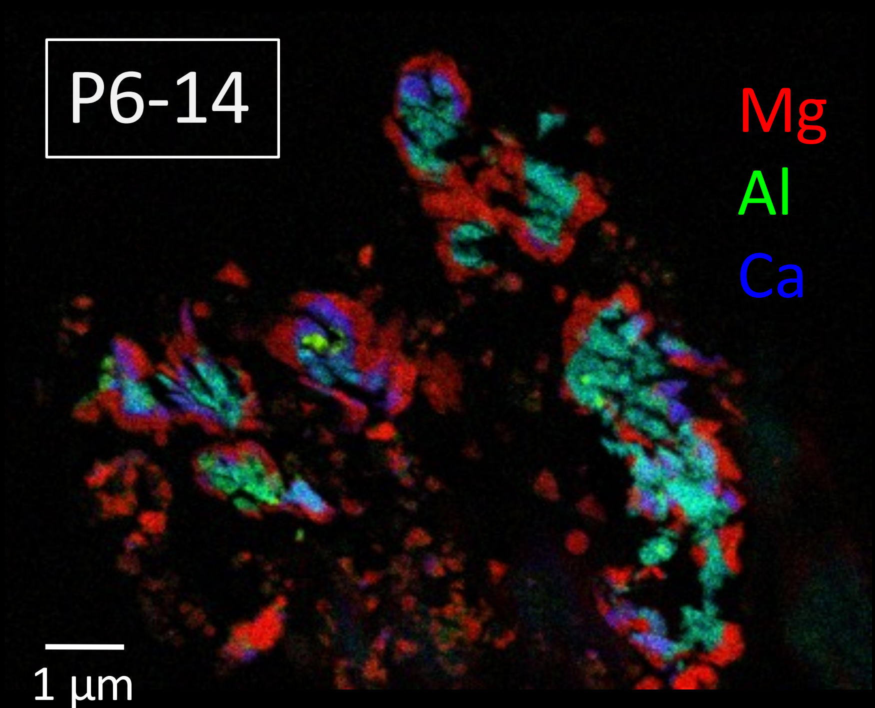


10^7 nodules in FGI

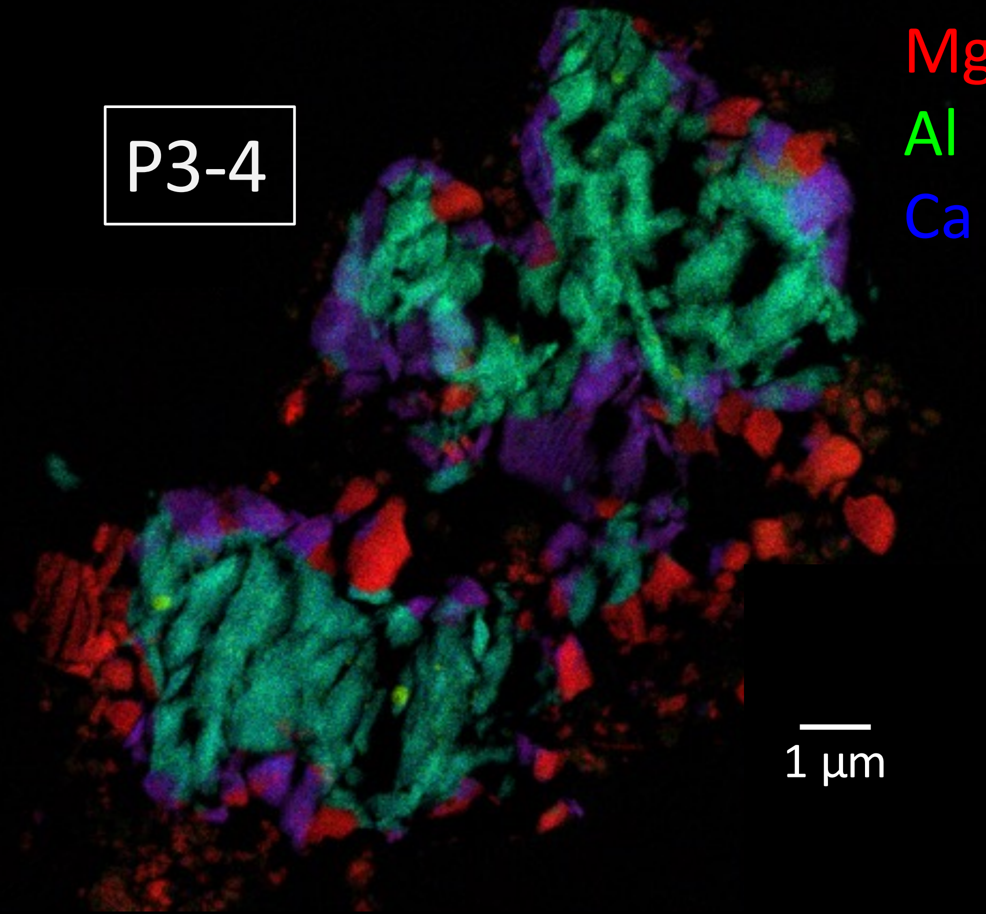
Properties of FGIs:

- ~5 - 50 µm in size
- nodular textures
- aggregates
- major minerals: Sp, An, Cpx+/-Mel
- little to no low T alteration minerals

CAIs in Giant Cluster IDP: Element Maps



- An$_{97\text{-}98}$
- Spinel (w/Cr)
- Diop/Fass
- En$_{99+}$ /Fo$_{99+}$

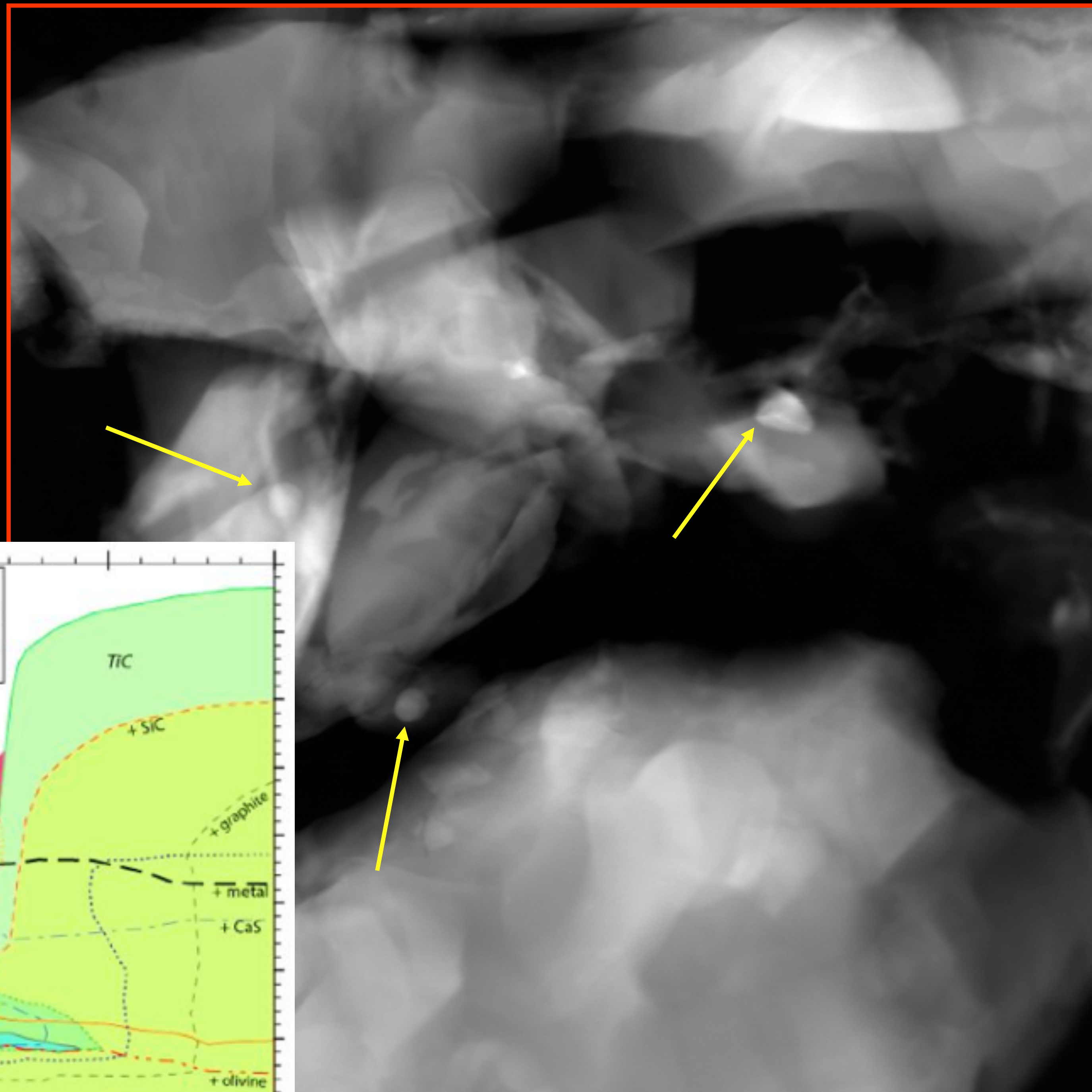


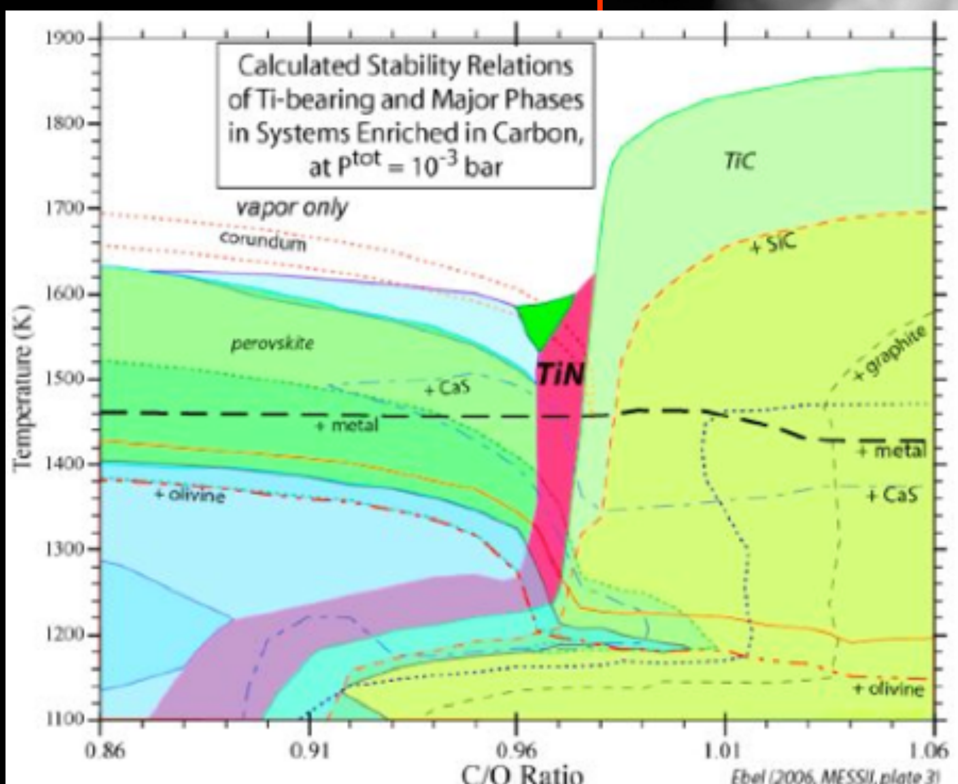
- An$_{94\text{-}96}$
- Spinel (w/Cr)
- Diop/Fass
- En$_{98}$

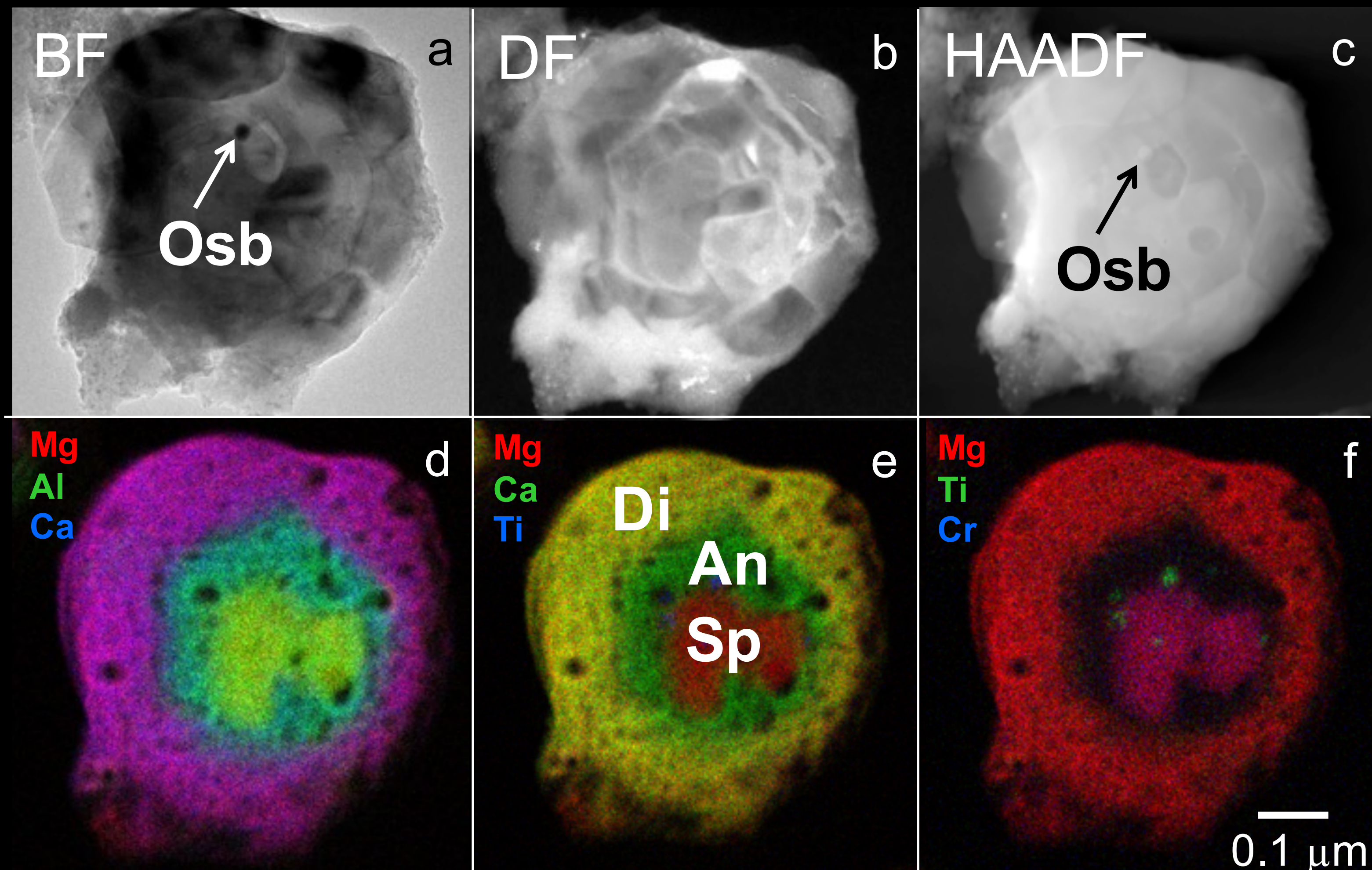
Orbornites

TiN

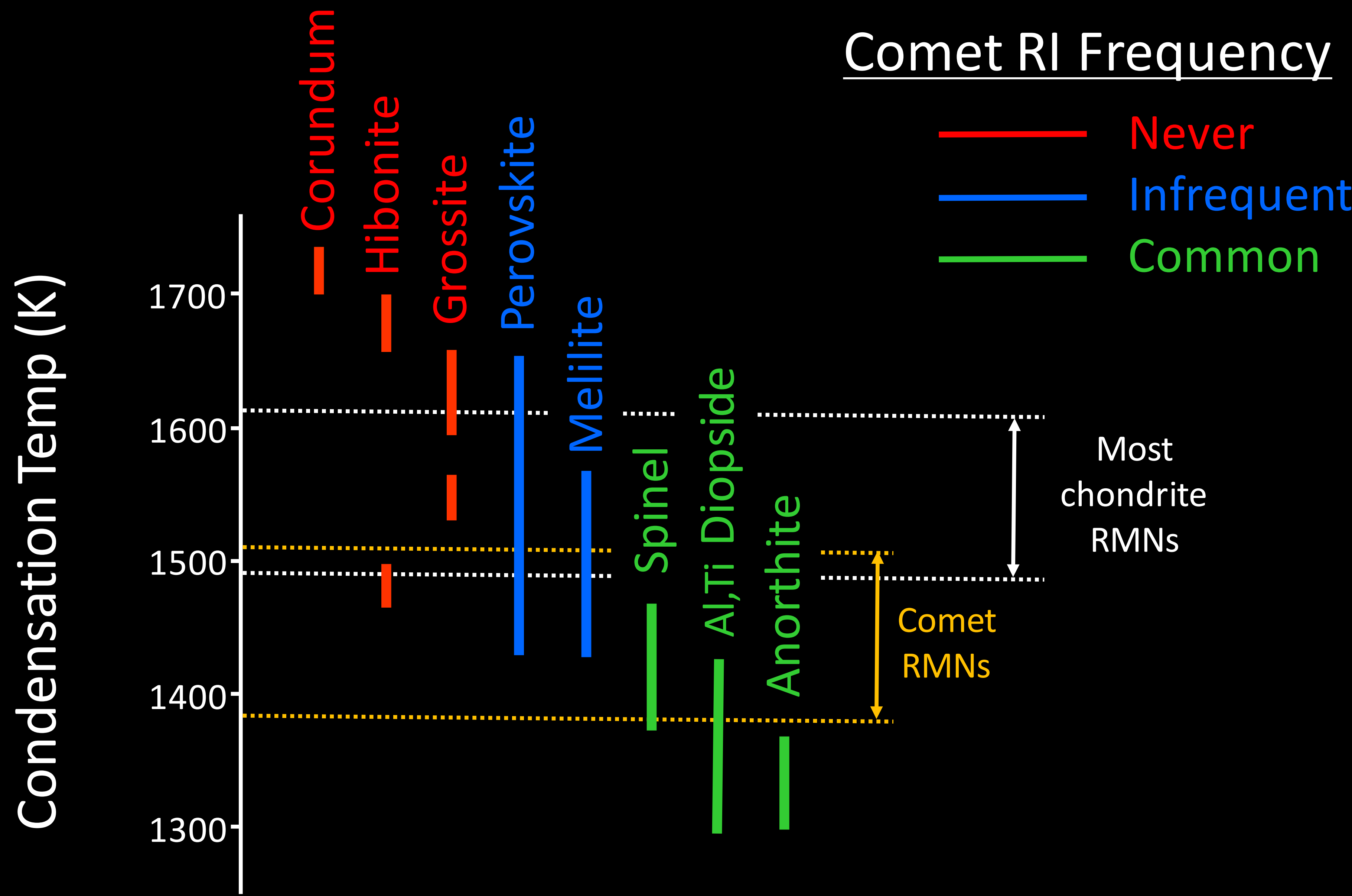
~30nm



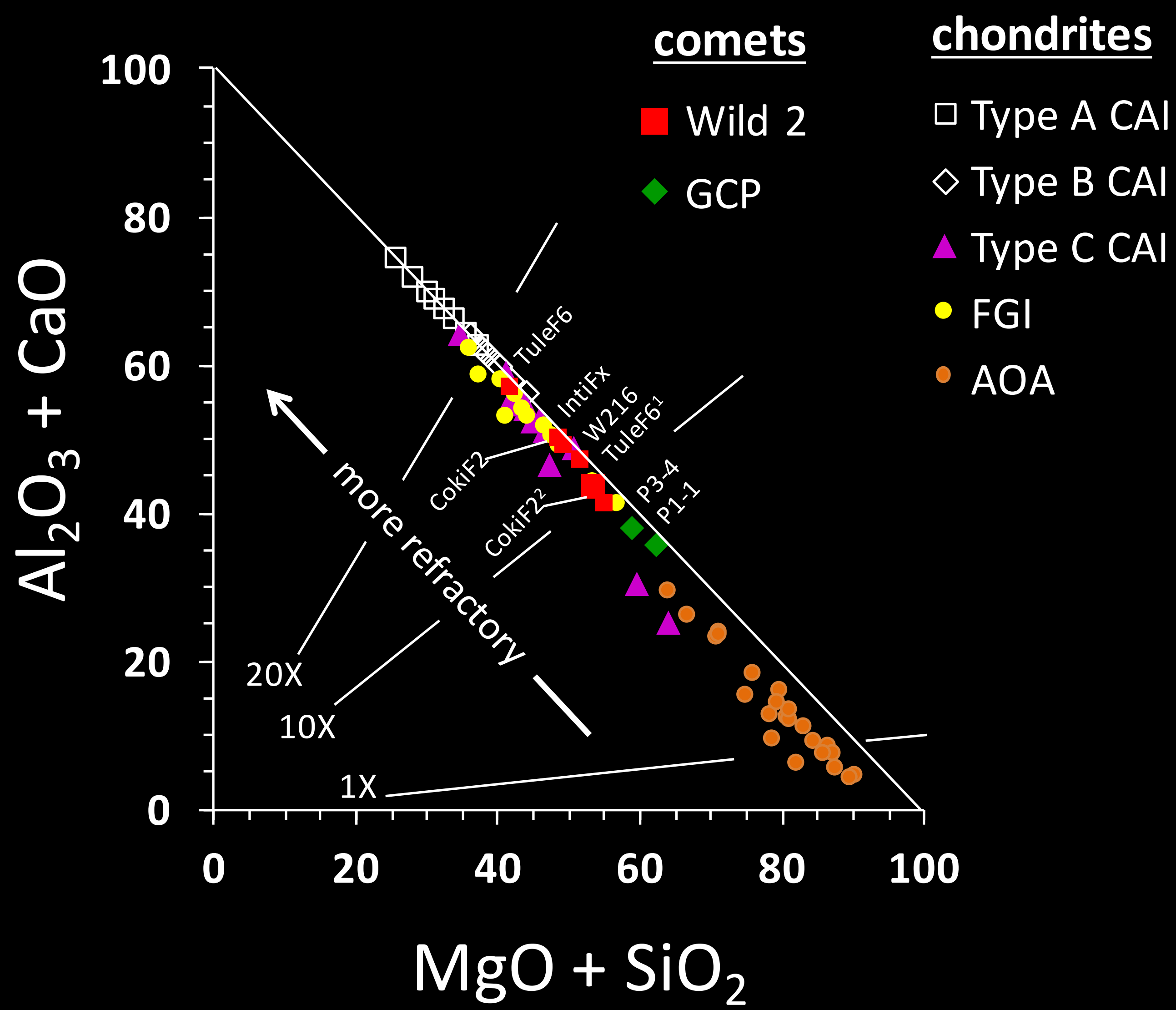



BF
a
Osb
DF
b
HAADF
c
Osb
Mg
Al
Ca
d
Mg
Ca
Ti
e
Di
An
Sp
Mg
Ti
Cr
f
0.1 μm

Cometary CAIs: Moderate Refractory Character



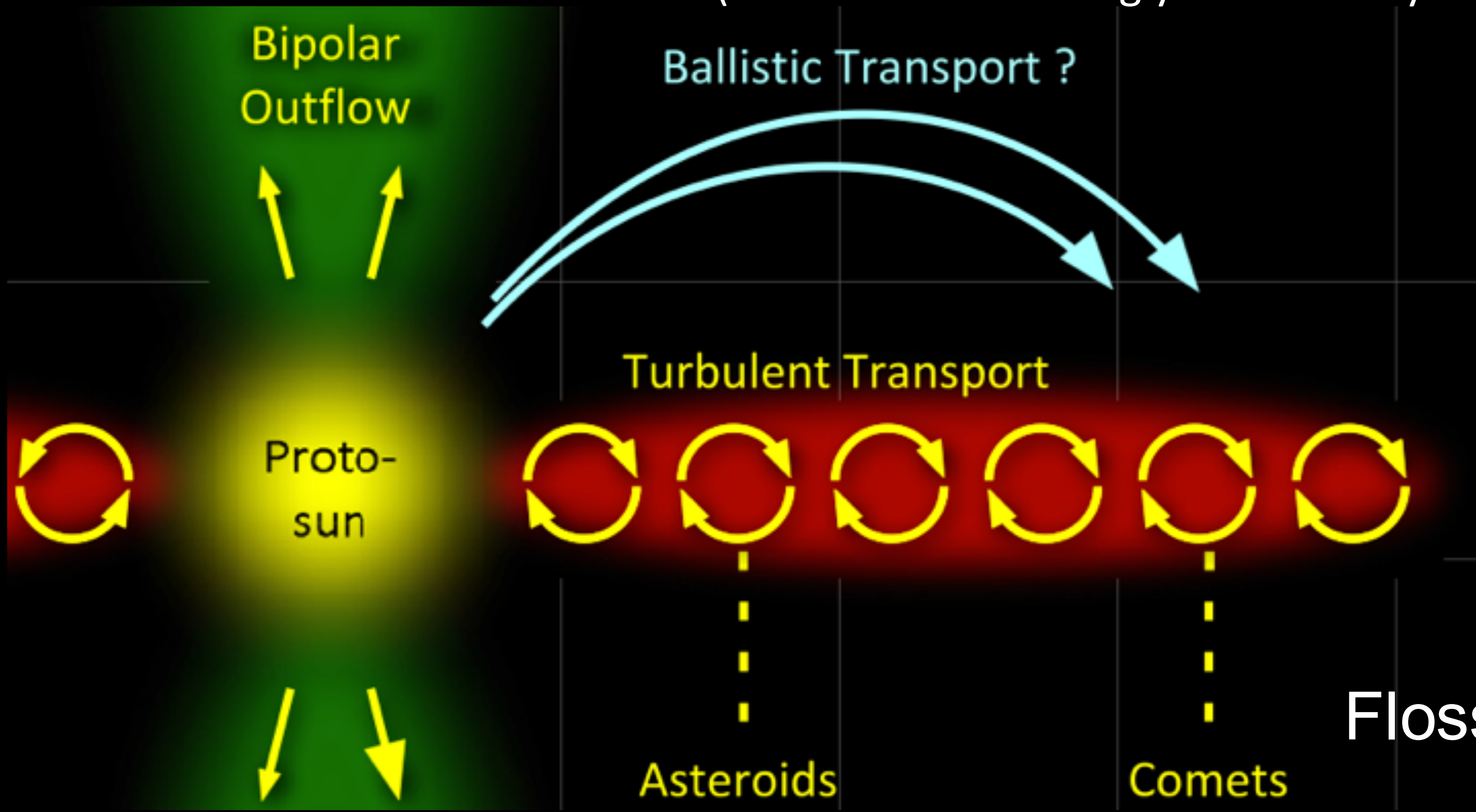
Cometary CAIs: Moderate Refractory Character



How did chondrite building materials reach the comet accretion region?

{Frank Shu predicted that CAIs & chondrules would be ejected by the X-Wind}

(X-wind model strongly criticized by Steve Desch)



Floss t al. 2013

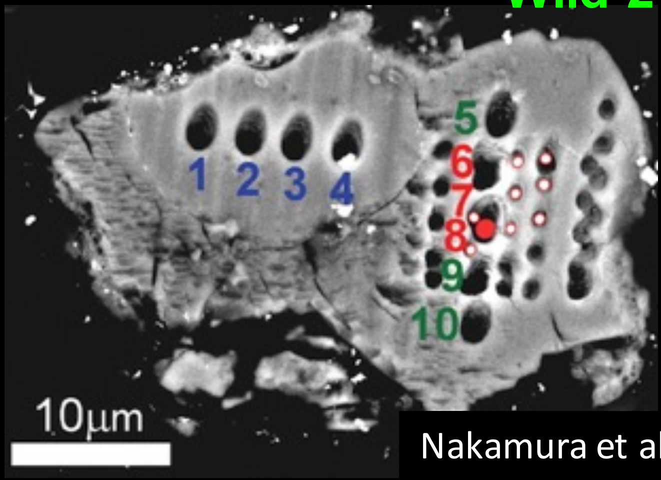
Disk or ballistic transport of submicron to 100µm solids??

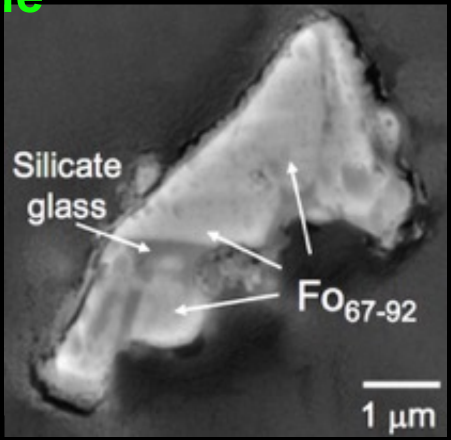
Did they form in-situ in the outer SS? Shocks or in giant planet embryos? Bridges et al. 2012

Using olivine $(Mg,Fe)_2SiO_4$ as a "tracer"

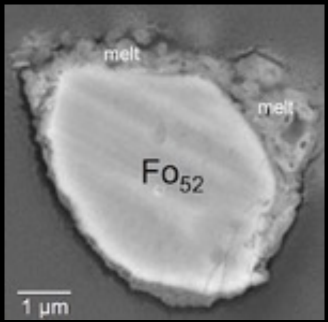
A major mineral in comets, meteorites & circumstellar disks

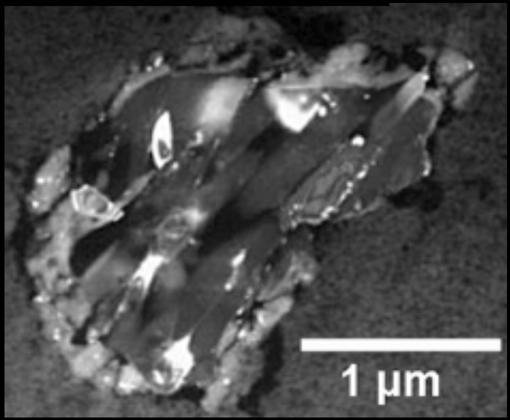
*** Wild 2 olivine ***

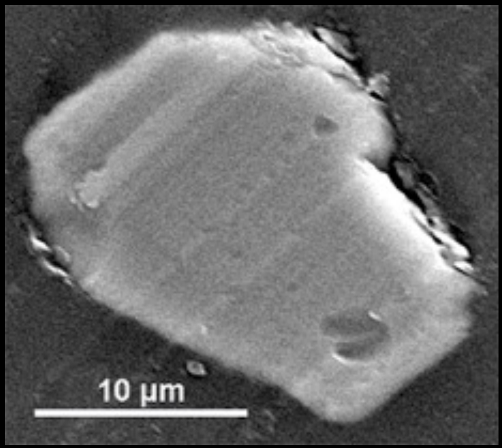


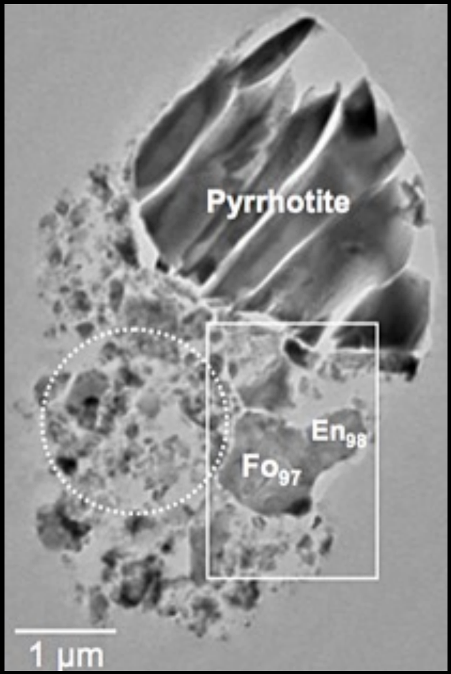


Nakamura et al. 2008









COMPARISON OF GRAIN POPULATIONS

A) accreted into comets

B) accreted into asteroids (primitive chondrites)

Using Mn abundances in olivine

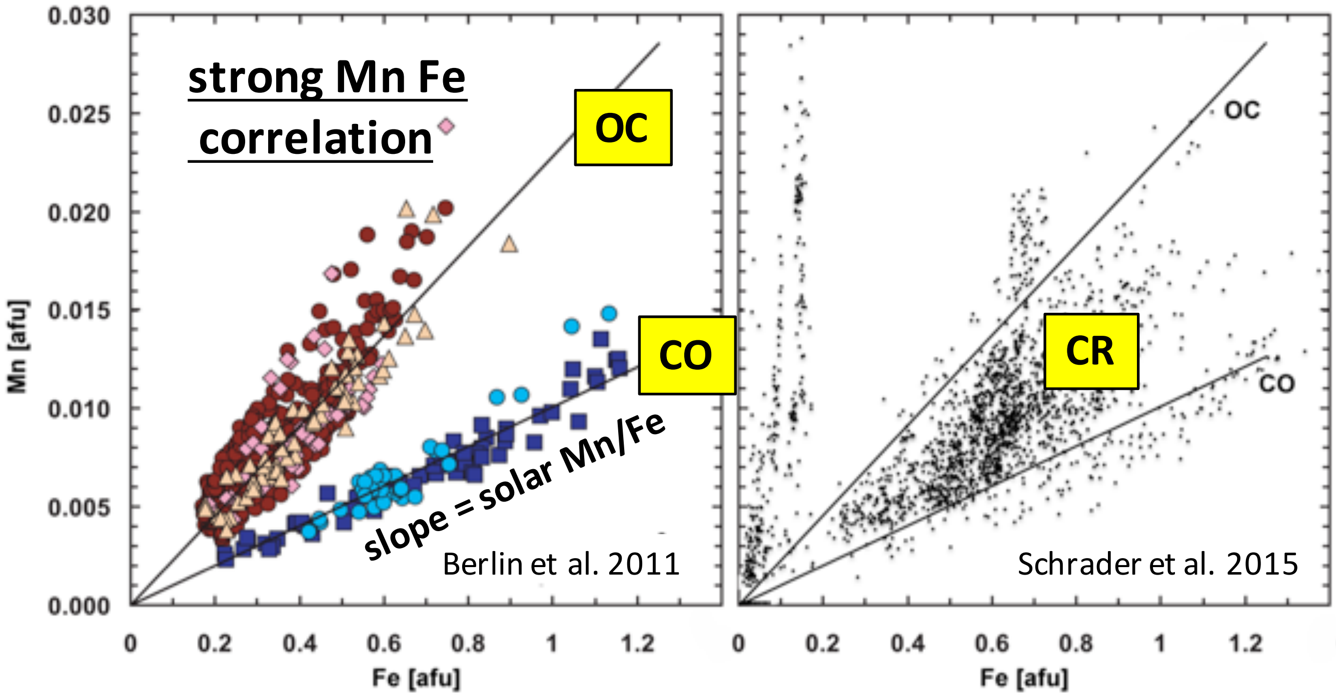
Mn is a minor element (<1%) that substitutes for Fe in olivine crystals (Fe++ and Mn++ have the same size and charge; solar Mn/Fe ~ 0.01)

Olivine Fe/Mn ratios influenced by nebular environments

Fe Mn volatility differences
Mn usually confined to silicates
Fe carried by silicates, metal & sulfides

Olivine in chondrules from different primitive chondrite groups distinctive Mn Fe compositions – related to nebular environments

OC (ordinary chondrites) 80% of meteorite falls
CO (type of carbonaceous chondrite) 0.6 % of meteorite falls
CR (type of carbonaceous chondrite) 0.2 % of meteorite falls



OC & CO olivines formed in two distinctive environments

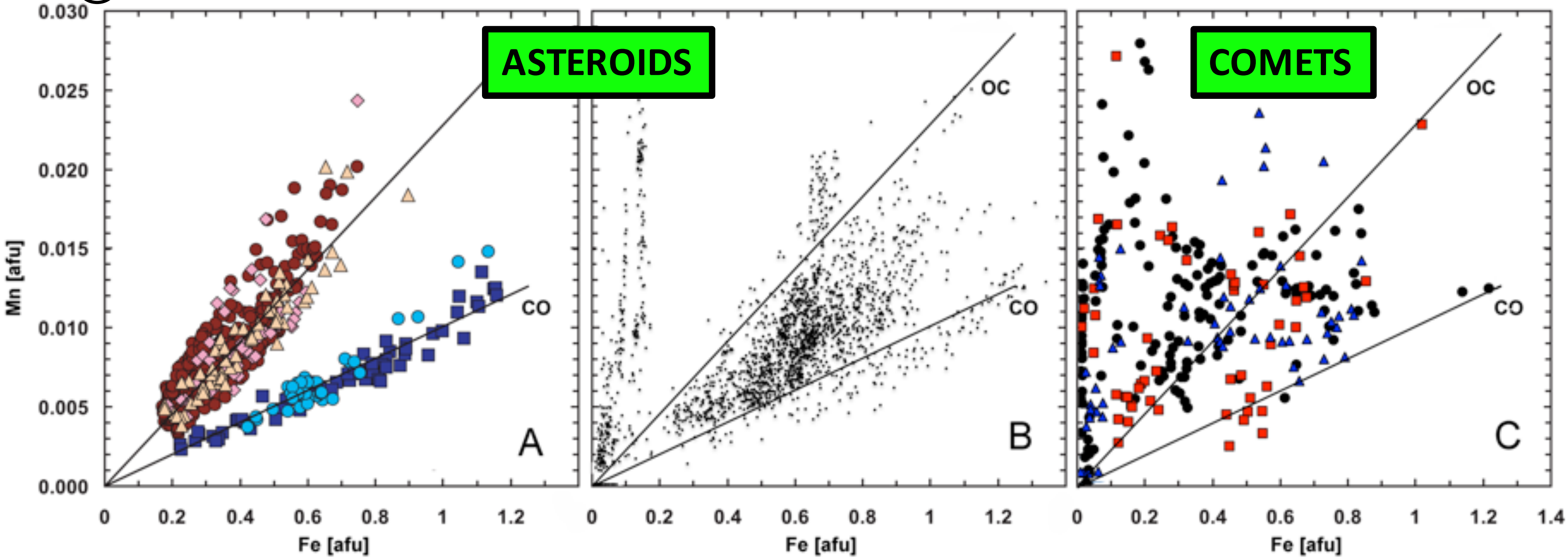
CR olivines formed in multiple environments

afu = atomic formula unit

Comet olivine

Wild 2 - black dots ● & blue triangles ▲
"Cometary" Interplanetary dust particle - red squares ■

① NO MN FE CORRELATION for Fe-rich olivine!
② NOT DOMINATED BY GRAINS FROM THE OC, CO OR CR FORMATION REGIONS!
③ SAMPLES A MORE DIVERSE SET OF ENVIROMENTS THAN ANY CHONDRITE GROUP!
④ TWO COMETS SHOW THE SAME DIVERSE PATTERN!



① **Wild 2 Mn Fe olivine distribution - unlike any chondrite group**

② **Matches olivine in a large "cometary" interplanetary dust particle**

③ **Wild 2 olivine cannot be derived from a single reservoir like common chondrites**

④ **Must have formed in numerous nebular environments**

HYPOTHESIS - HISTORY OF >1µm COMETARY ROCKY MATERIALS

Formed in many hot regions in the inner SS – over a few my

Transported & mixed >10AU

Pristine comets likely formed from similar complex mixtures of inner SS materials

Because of mixing – outer SS planetesimals are likely to have formed from similar mixes of nebular rocky materials – totally unlike asteroids in inner SS

Inner and Outer SS Planetesimals
Diversity of Initial Rocky Components

★ **Comets - mix of distantly made rocky materials**

LITTLE comet-to-comet DIVERSITY

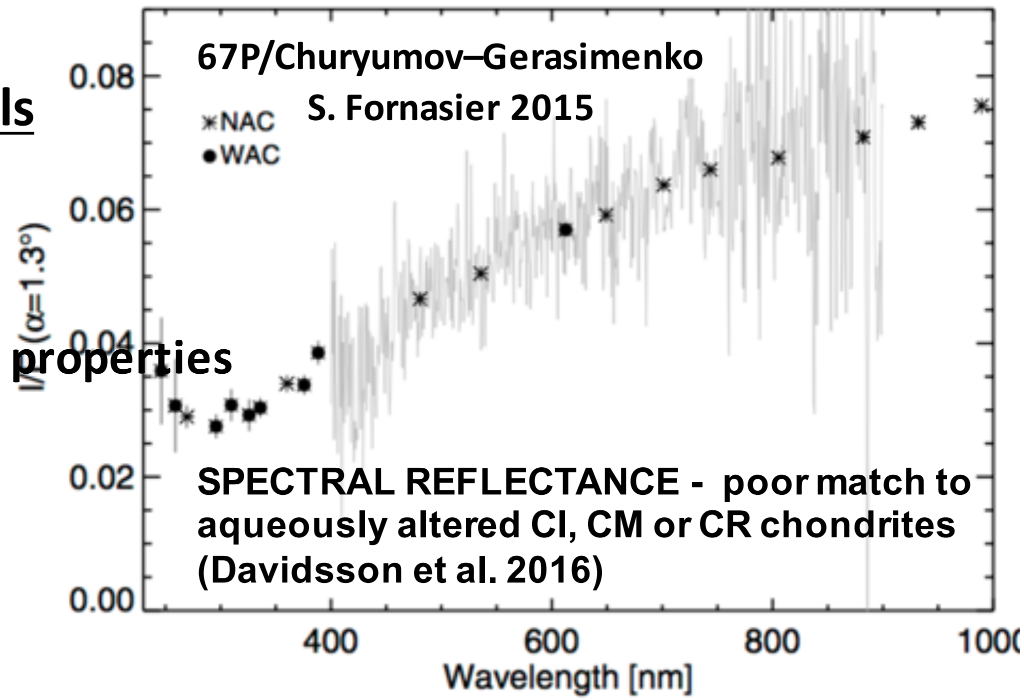
★ **Asteroids – dominated by local materials**

MUCH DIVERSITY

Regional variations give chondrite groups
distinctive elemental, mineralogical & isotopic properties

Inner SS planetesimals
Accretion timescales < mixing timescales

Comet solids ≠ meteorite types



SPECTRAL REFLECTANCE - poor match to aqueously altered CI, CM or CR chondrites (Davidsson et al. 2016)

Major Findings

- Wild 2 solids not dominated by isotopically anomalous pre-solar grains
  They were destroyed by solar system formation
- Wild 2 contains chondrule & CAI fragments
  (inner SS meteoritic materials formed at 1400-2100 K!)
- Most Wild 2 rocky solids were formed in the inner SS & transported beyond Neptune
- Formed by similar processes that formed high temperature chondrite components
- Rocky materials, organic & icy components – not formed in similar environments
- Comet siicates >1µm usually not formed by annealing of amorphous materials
- Wild 2 anhydrous silicates - comet not a fragment of a larger body

A major difference between comets & asteroids

Asteroids mainly accreted locally-made materials
(properties give chondrite groups distinctive properties)

Comets accreted solids transported 10's of AU
Sampled major portions of the entire disk