The composition of interplanetary and cometary dust

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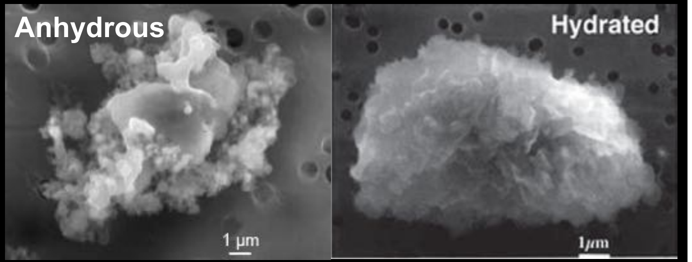
- UMET Lille: H. Leroux, C. Le Guillou
- IMPMC Paris: K. Benzerara, L. Remusat
- IPAG Grenoble: E. Quirico, L. Bonal, M. Battandier, F.R. Orthous-Daunay, V. Vuitton
- Univ. Tohoku (Japan): T. Nakamura
- Univ. New Mexico (USA): E. Dobrica
- Univ. Hawai'I (USA): J.P. Bradley, H. Ishii

Interplanetary dust collections

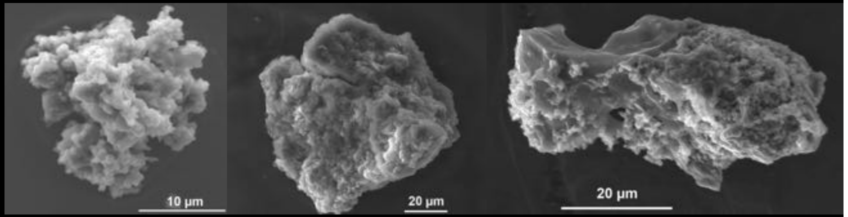
- Current cosmic Dust flux ~ **30 000 tons/year** (Mass max ~ 200 µm)
- Deep Sea collections (since 1875…)
  - Cosmic spherules : melted and weathered particles
- NASA stratospheric collections since the 70s : **IDPs** (5-50 µm)
- Polar collections since the 80s (Greenland then Antarctica): **Micrometeorites** (F, J, US, I)
  - From ice and snow: 20-500 µm
  - From sediments (Transantarctic Mountains) : 200 - 2000 µm (mostly melted)

HMS Challenger

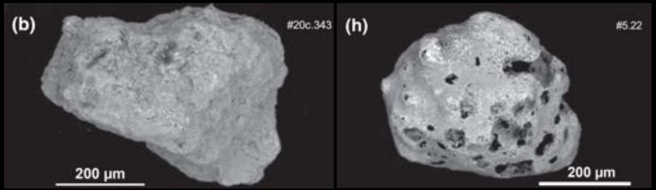
(Murray & Renard 1891)



(Taylor et al. 2016)



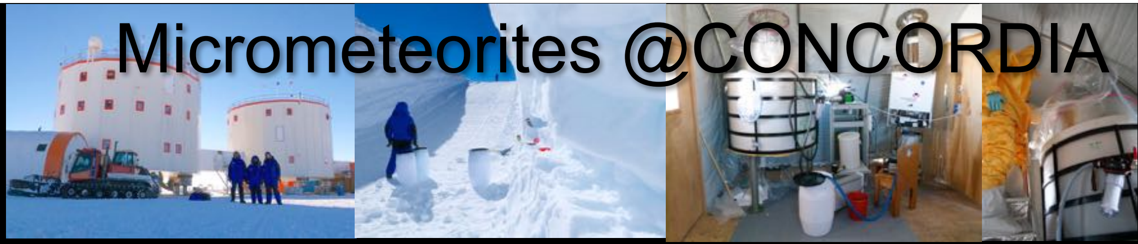
(Duprat et al. 2007, 2010)



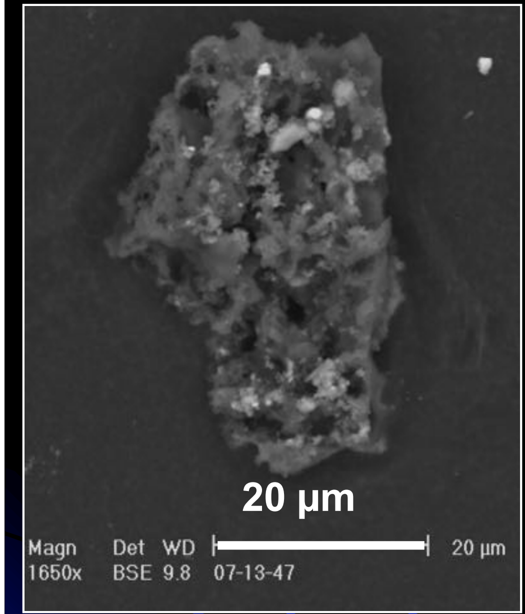
(Van Ginneken et al. 2012)

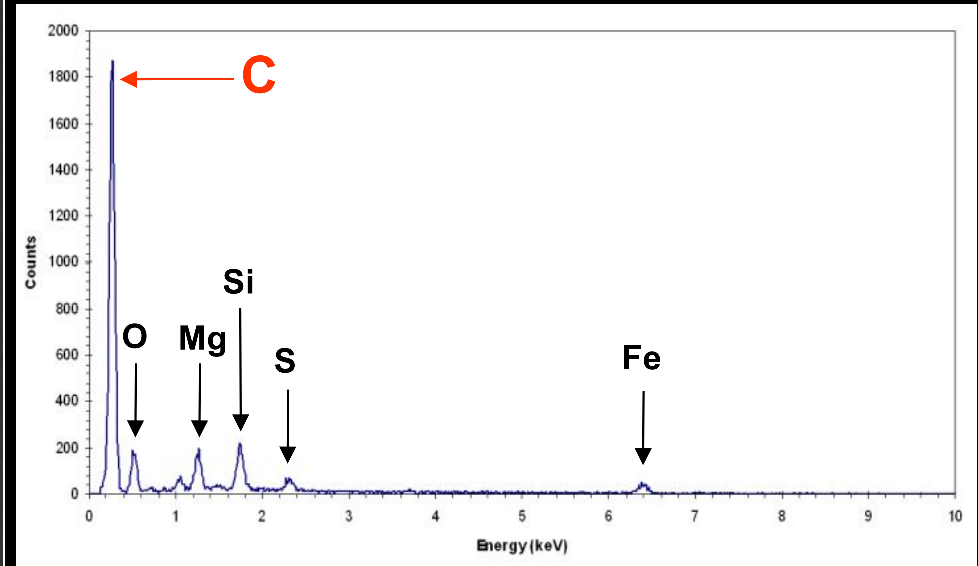
IDPs and MMs

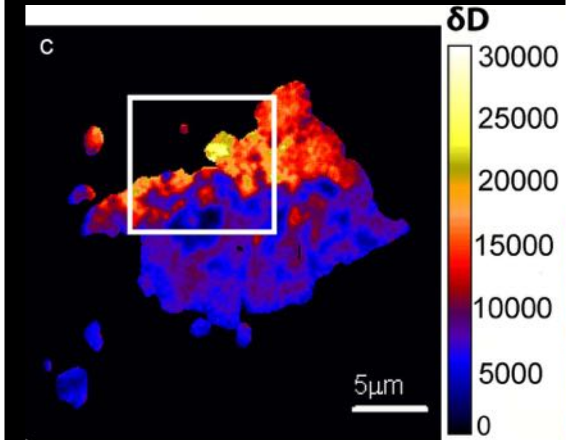
- Hydrous particles : composition, mineralogy, isotopes links to carbonaceous chondrites (CCs)
- But: miniaturized components (e.g. CAIs and chondrules compared to CCs
- For dust < 500 μm: rarely linked to thermally metamorphosed material like ordinary chondrites (80% of meteorites)
- Outliers (cometary origin?) – C-rich anhydrous particles
  - Chondritic porous anhydrous IDPs (CP-IDPs)
  - Ultracarbonaceous Antarctic Micrometeorites (UCAMMs)



Ultracarbonaceous Antarctic Micrometeorites (UCAMMs)







(Duprat *et al.* Science 2010, Dobrica *et al.* 2011, 2012)

- Found in J and F collections (and IDPs)
- Particles dominated by OM + minor mineral component
- Extreme D/H ratios (low T formation – outer regions)

IDPs and MMs

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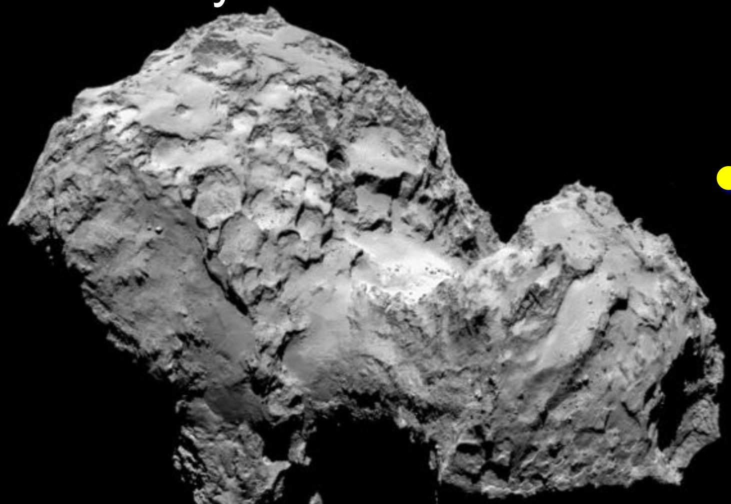
✶ Cometary dust best preserved the initial dust composition

⇒ Data from spatial missions (Giotto/Vega, Stardust, Deep Impact, Rosetta)

⇒ Data from CP-IDPs and UCAMMs

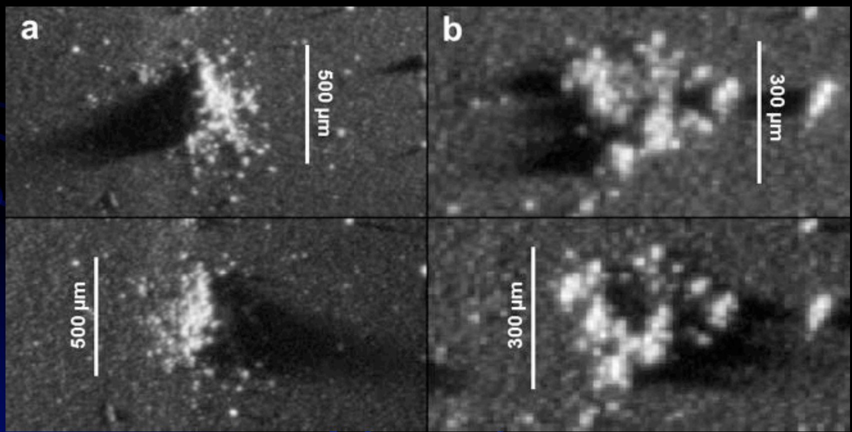
Structure of cometary dust

67P/Churyumov-Gerasimenko

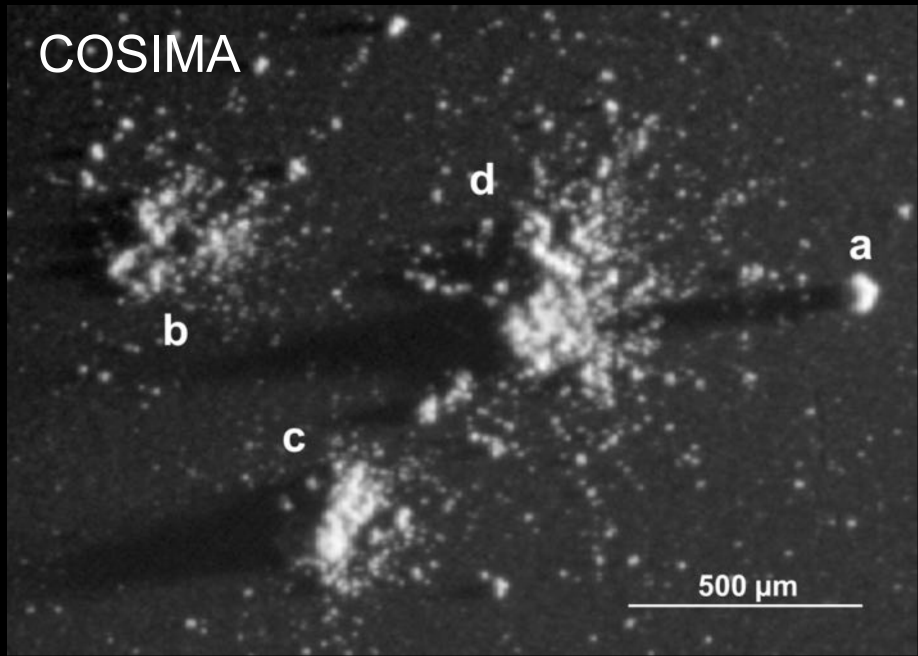


OSIRIS NAC Image Aug. 03, 2014

- 3 dust instruments : MIDAS, GIADA, COSIMA *(ROSINA)*

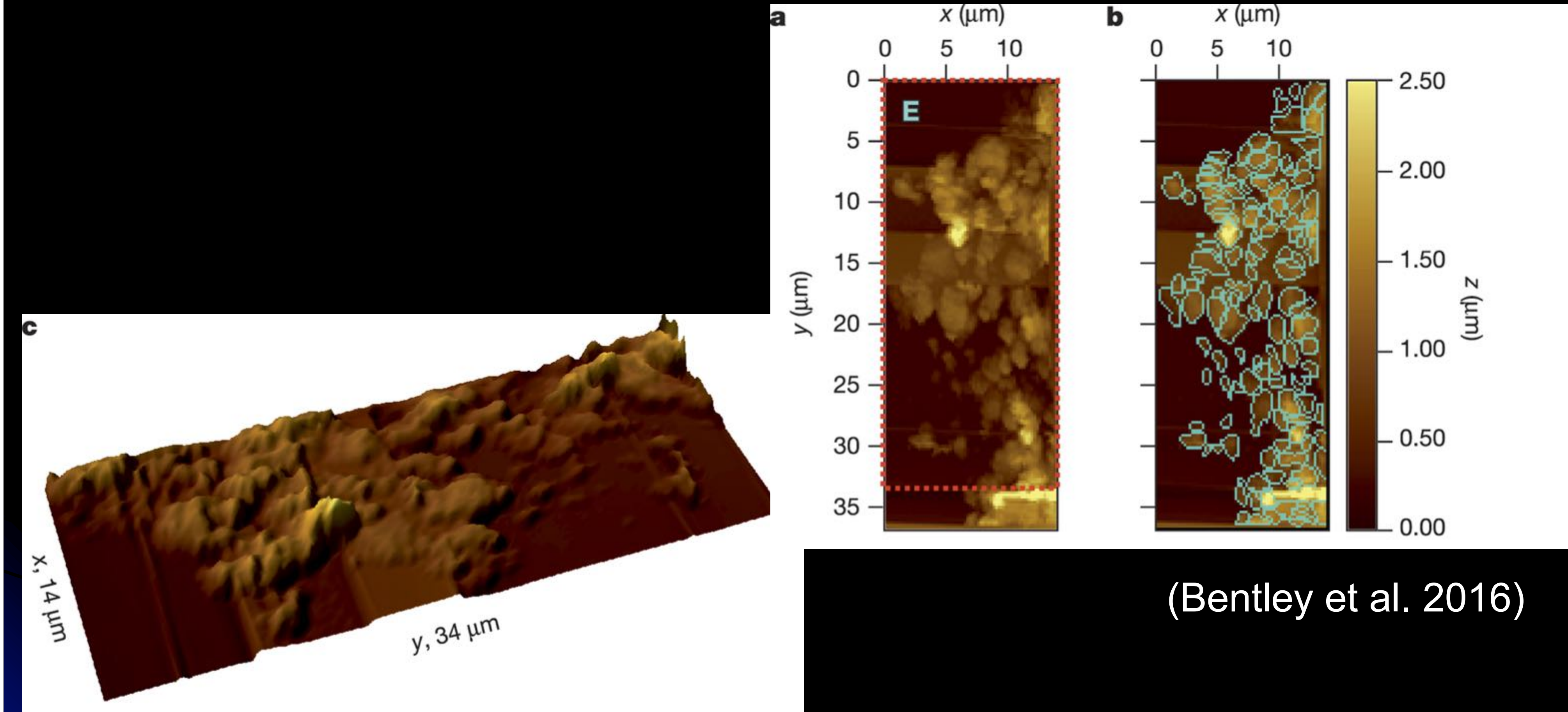


(Schulz et al. 2015)



(Langevin et al. 2016)

Sub-um image of comet dust (MIDAS)



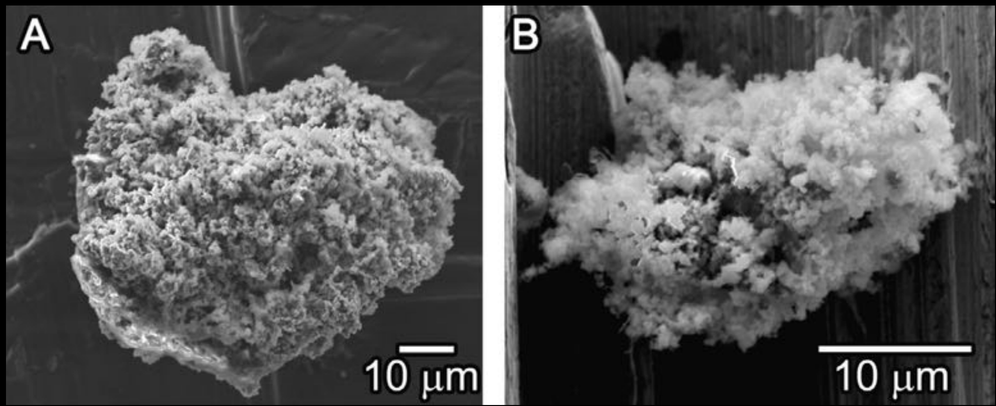
(Bentley et al. 2016)

- Atomic force microscope
- Very fluffy textures

CP-IDPs, CP-MMs and UCAMMs

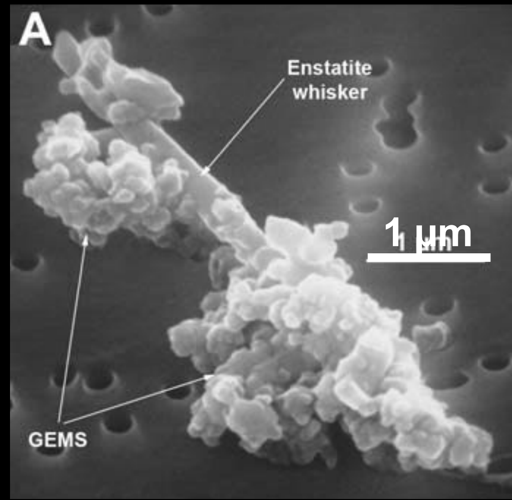
- Cometary samples (?) collected on Earth
- Fluffy textures

CP-MMs



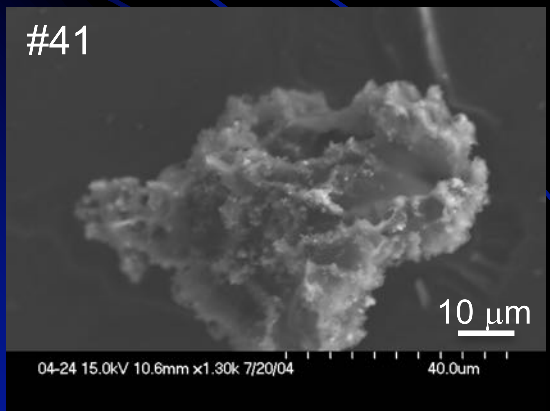
Noguchi+2015

CP IDP

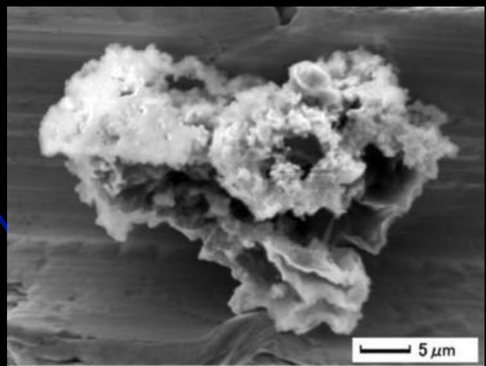


Ishii+2008

UCAMMs

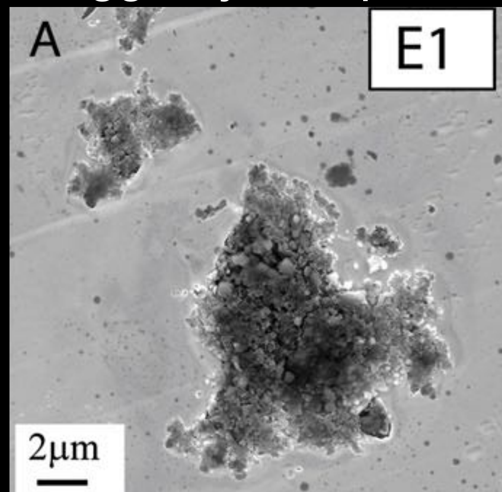


Duprat+2010



Yabuta+2017

Grigg-Skjellerup IDP



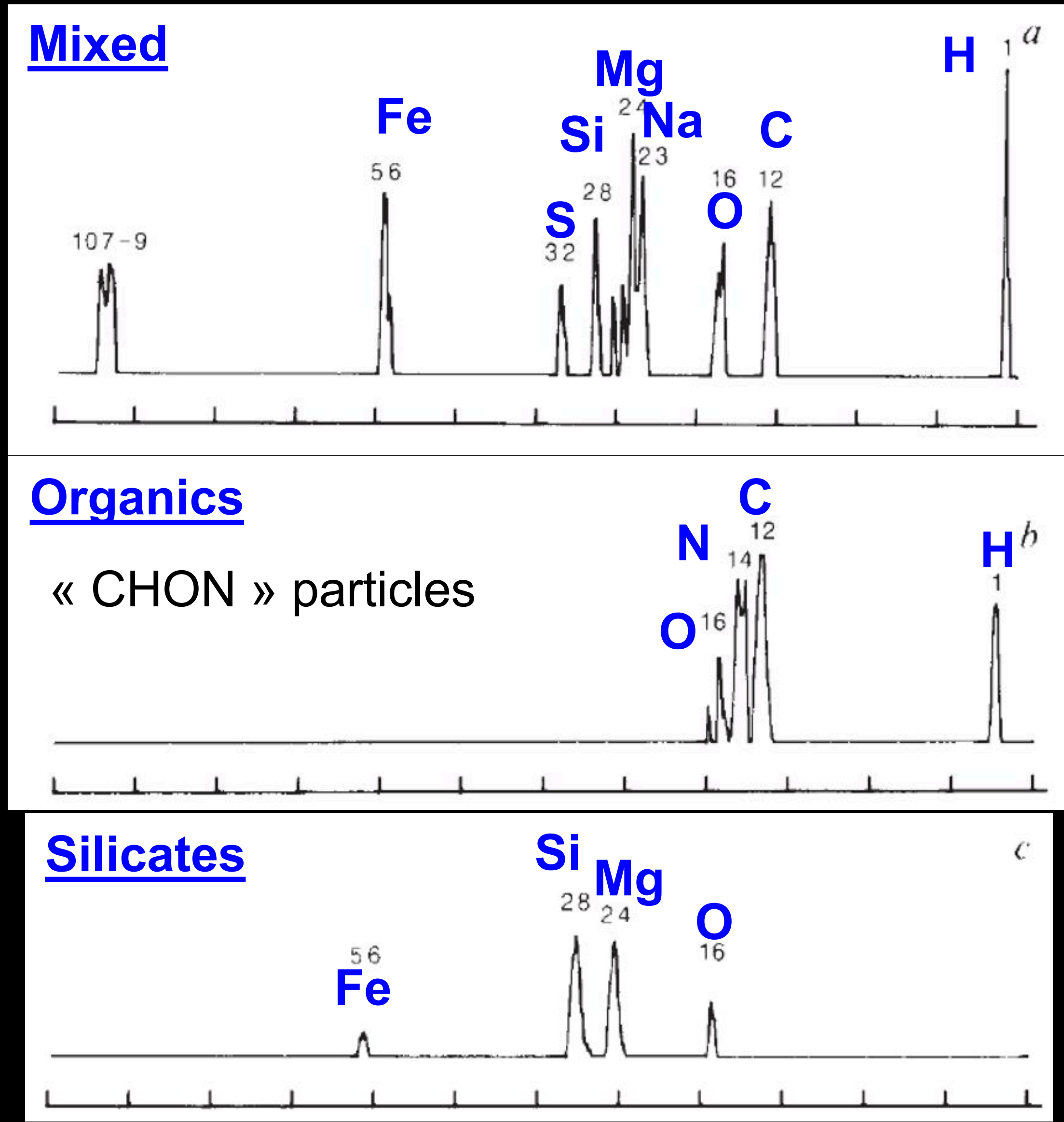
Busemann+2009

Bulk composition

First data : 1986!

Comet Halley

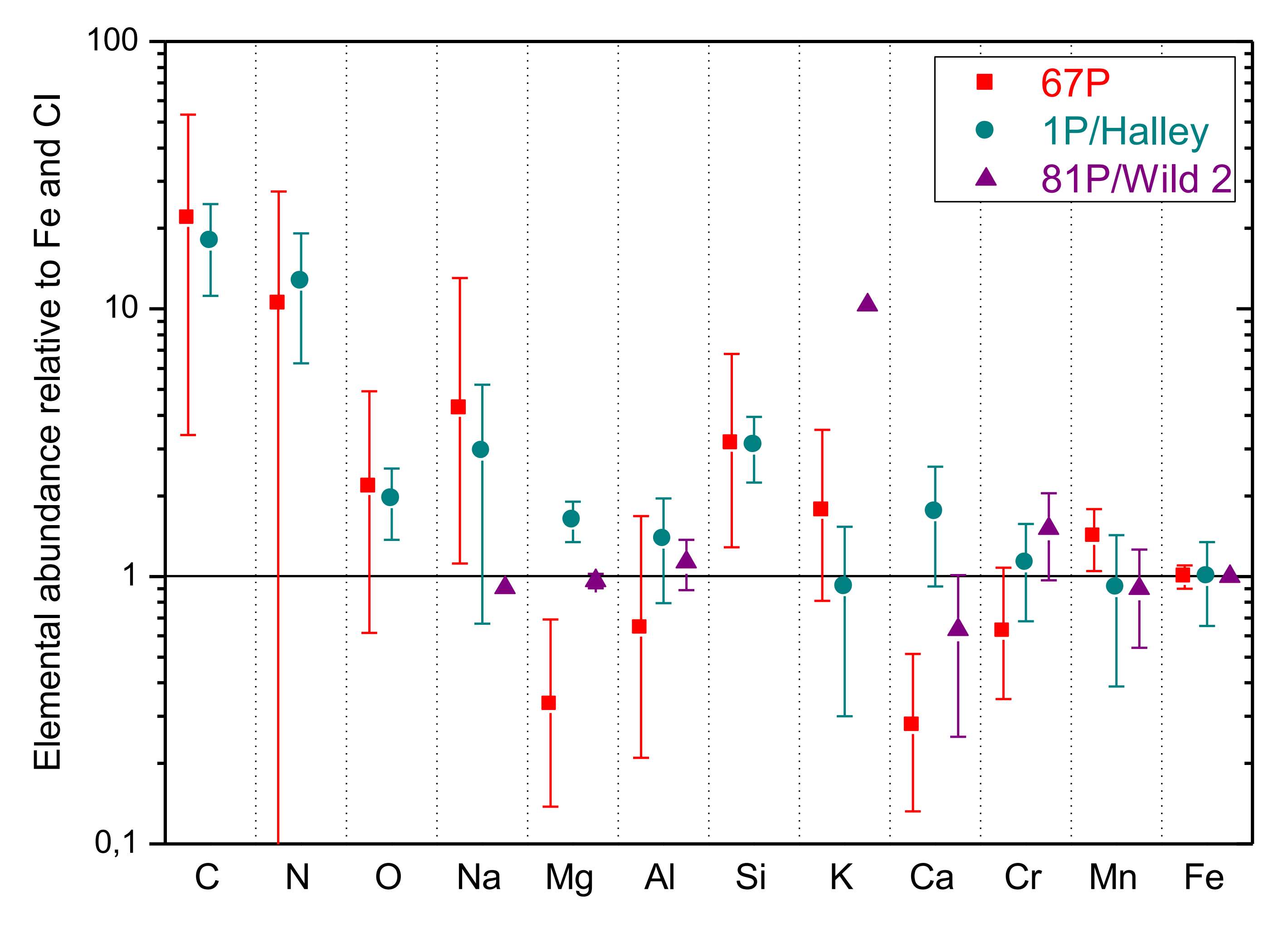
80% of the spectra



(PIA data)

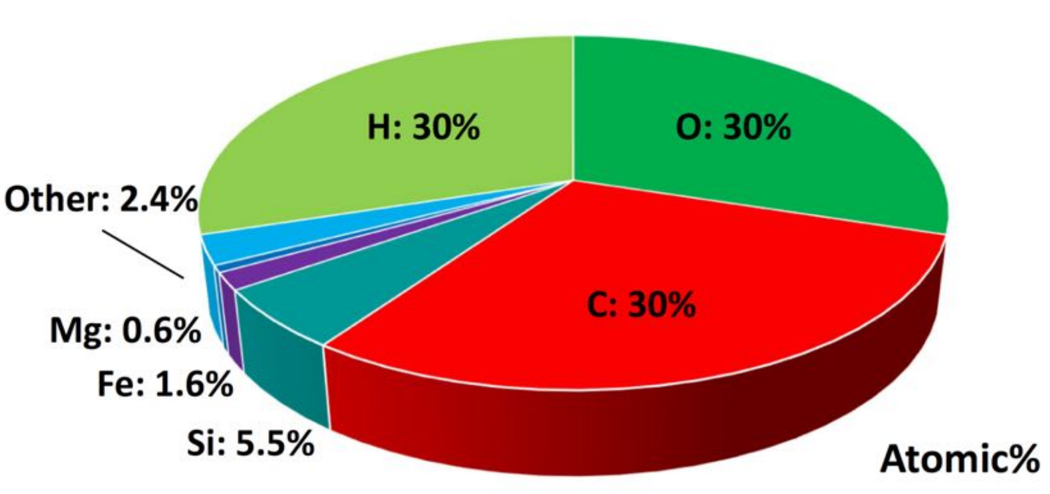
(Kissel et al. 1986)

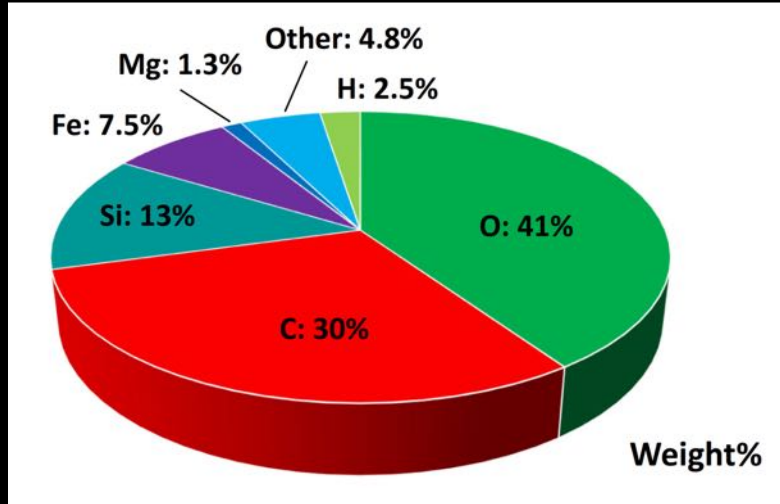
Composition of cometary dust (1P/Halley, 81P/Wild2, 67P/C-G)



(Bardyn et al, MNRAS 2017)

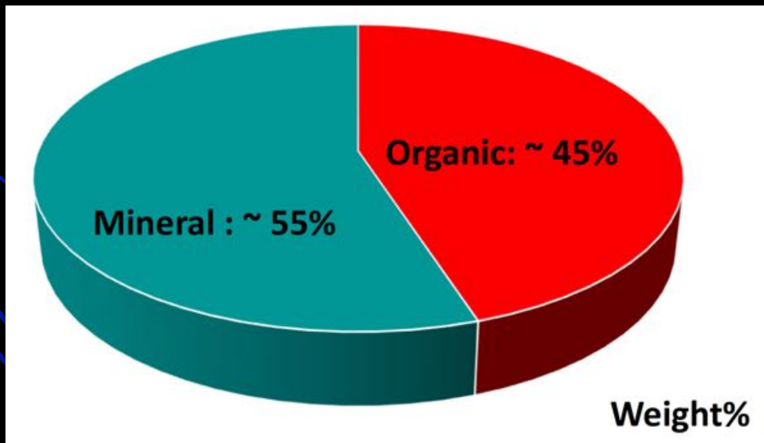
Composition of 67P dust (COSIMA)





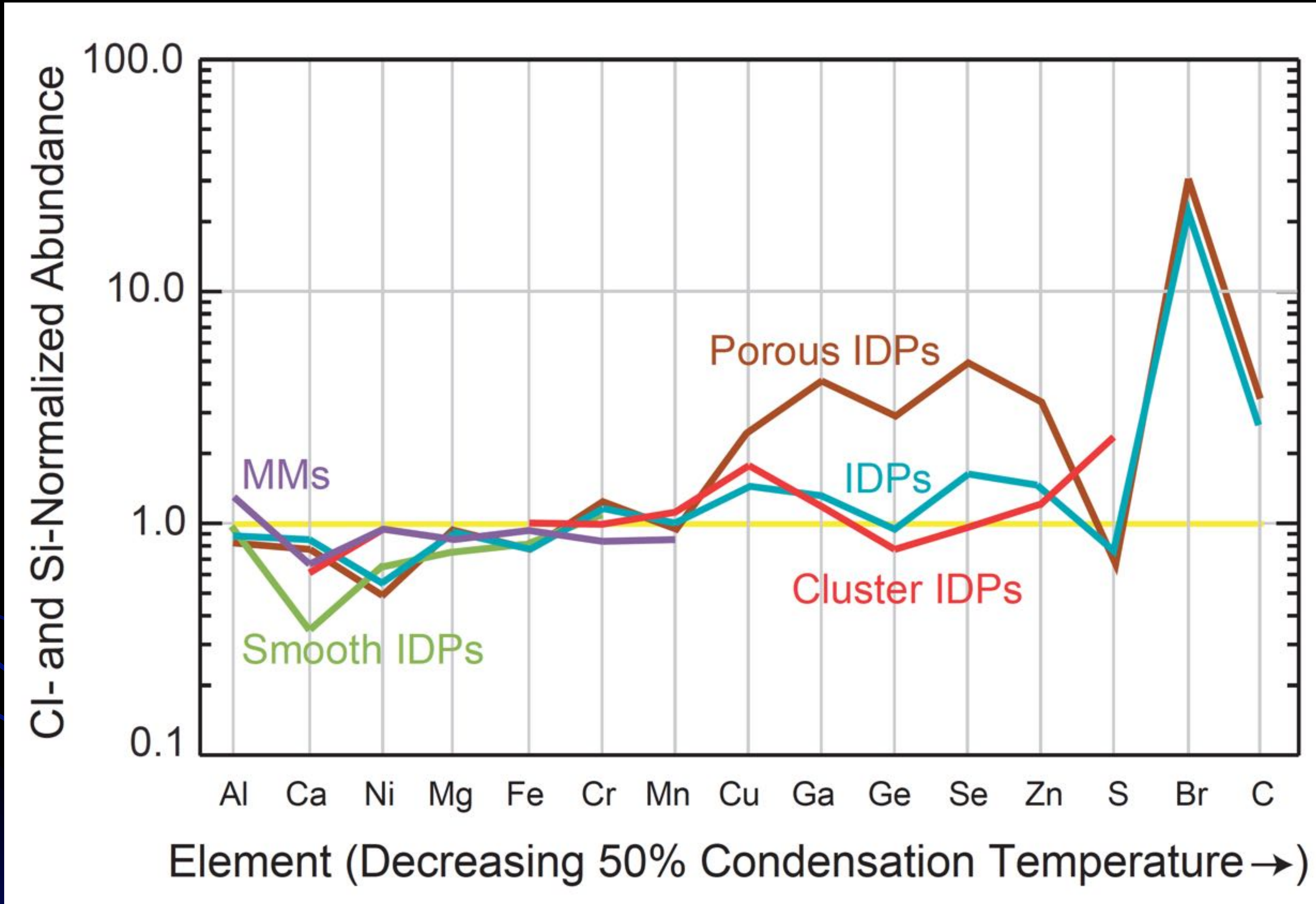
Assuming H/C = 1
S, Ni, … = Solar

(Bardyn et al. MNRAS 2017)



O Mineral as SiO_4
Rest of O in organics

Composition of IDPs and MMs

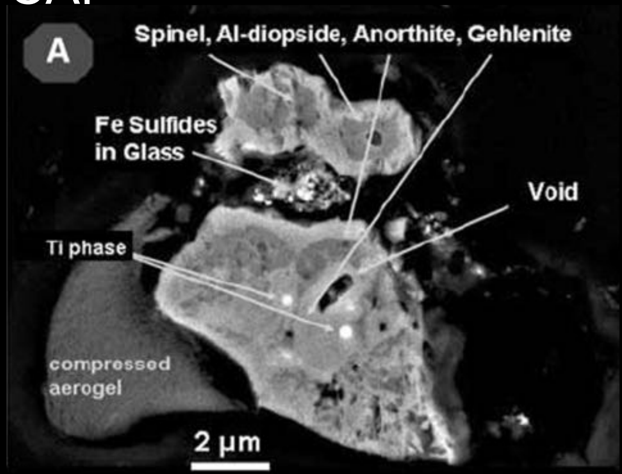


Flynn+2016

Composition: Mineralogy (crystalline and glassy phases)

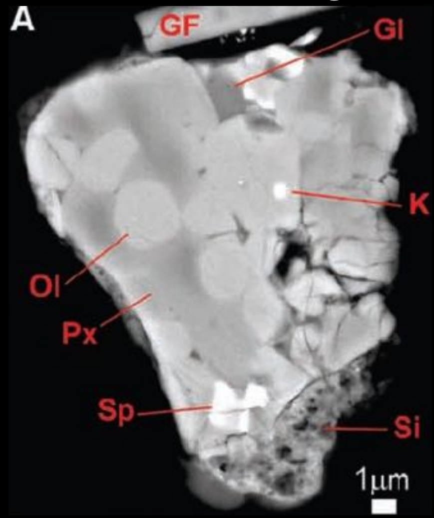
CAIs and chondrules in Comet Wild 2

CAI



Zolensky+2006

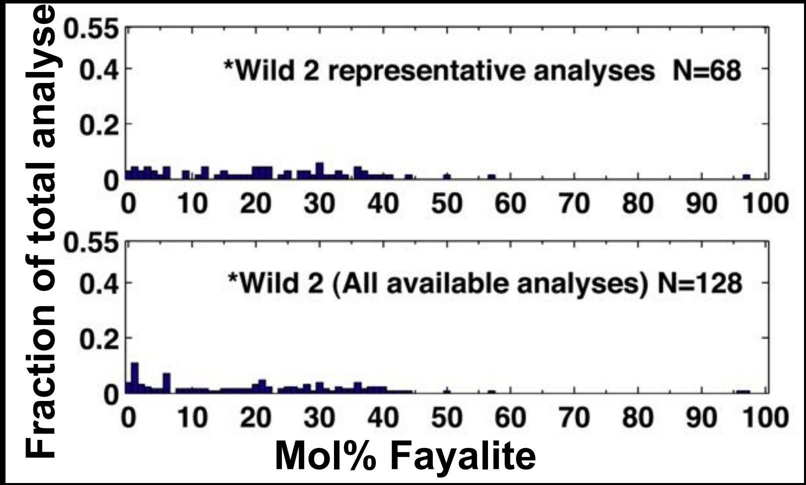
Chondrule fragment

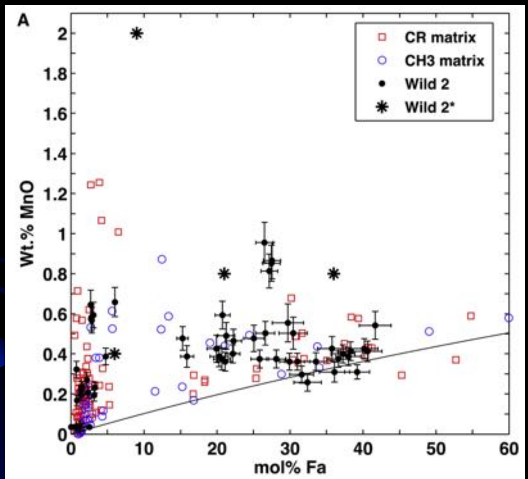


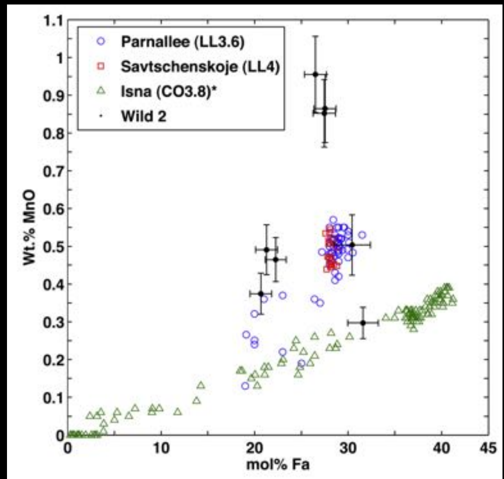
Nakamura+2008

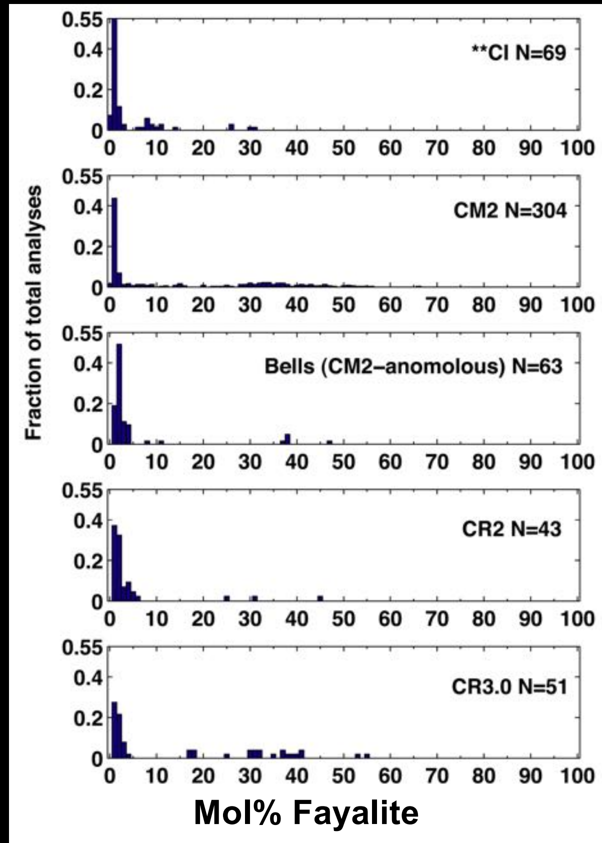
- CAIs (Ca-Al-rich inclusions): first mineral component in the solar nebula (abundance ~ 1% in CCs)
- Chondrules (formed ~ 2 Myr after CAIs): major component of all chondritic meteorites
- Crystalline minerals formed close to Sun
- Isotopic compositions close to that of meteorites
- Smaller sizes than in meteorites

Olivines in Wild 2







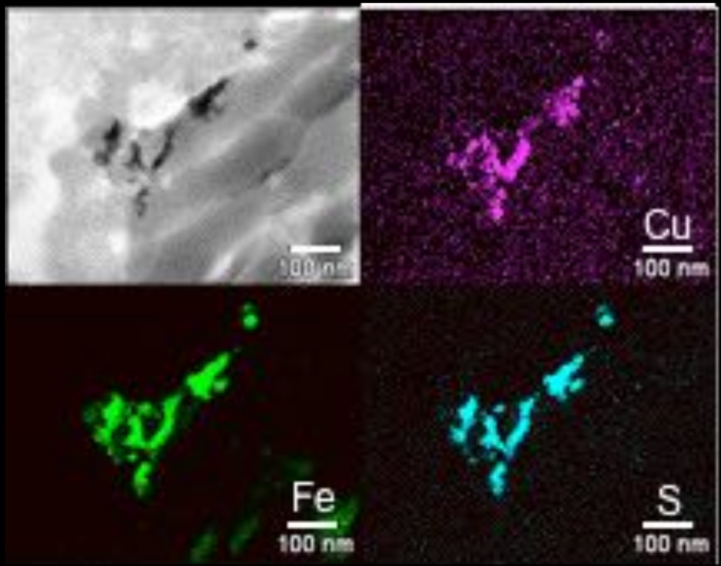


(Frank et al. 2014)

- Extraordinary diverse sampling (but not all chondrites are represented)
- Wide range of formation times/locations in the PPDisk : « mishmash of solar system nebular dust, dispersed asteroid components and products unique to the Kuiper belt processing »
- Late accretion? (also lack of ^{26}Al)

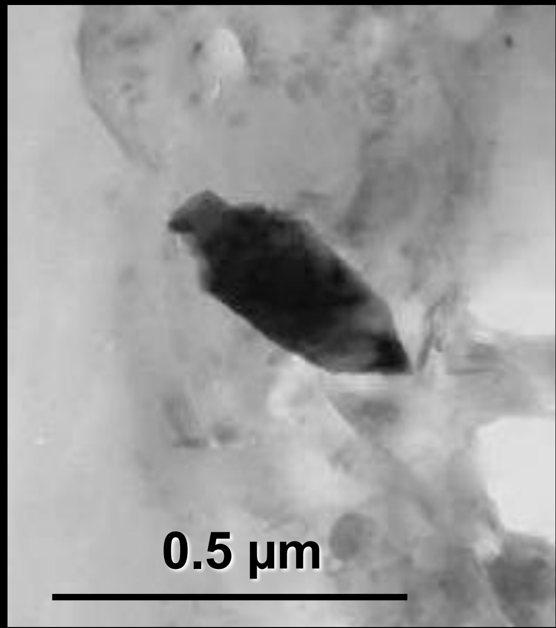
Wild 2: Aqueous alteration?

Cubanite ($CuFe_2S_3$)



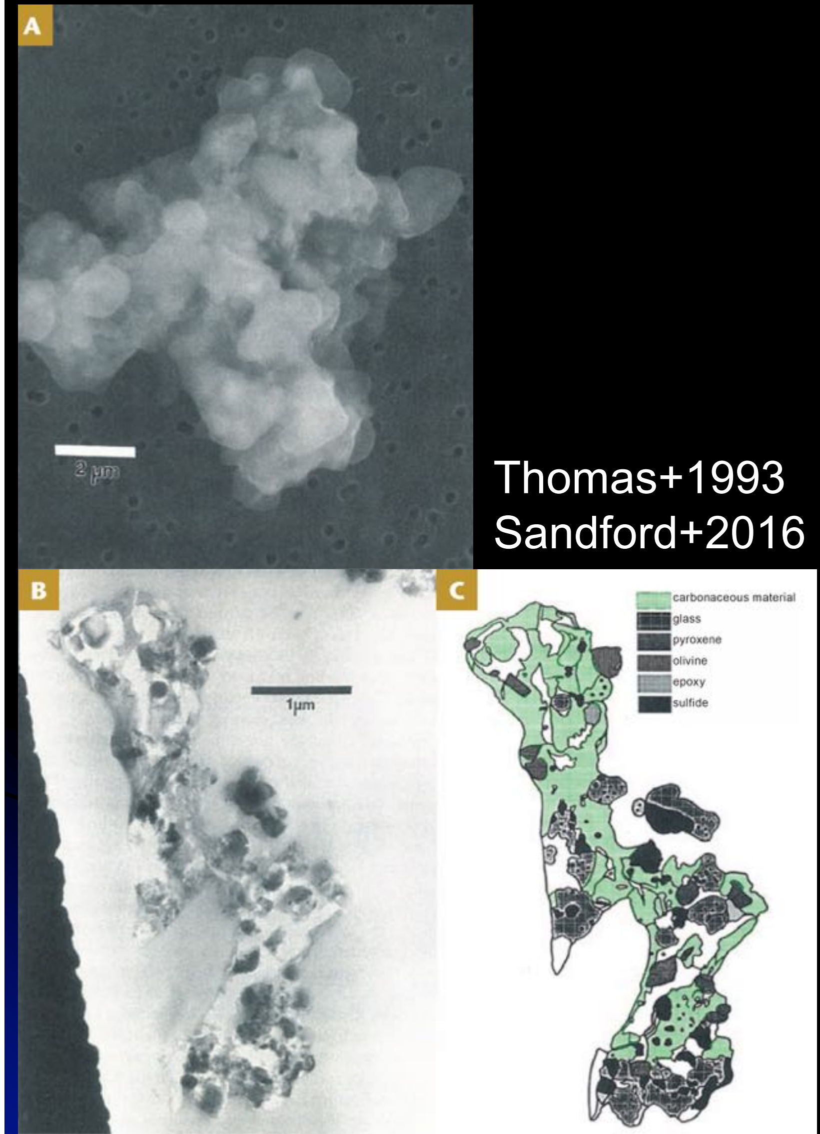
Berger+2011

Calcite (CaCO3)

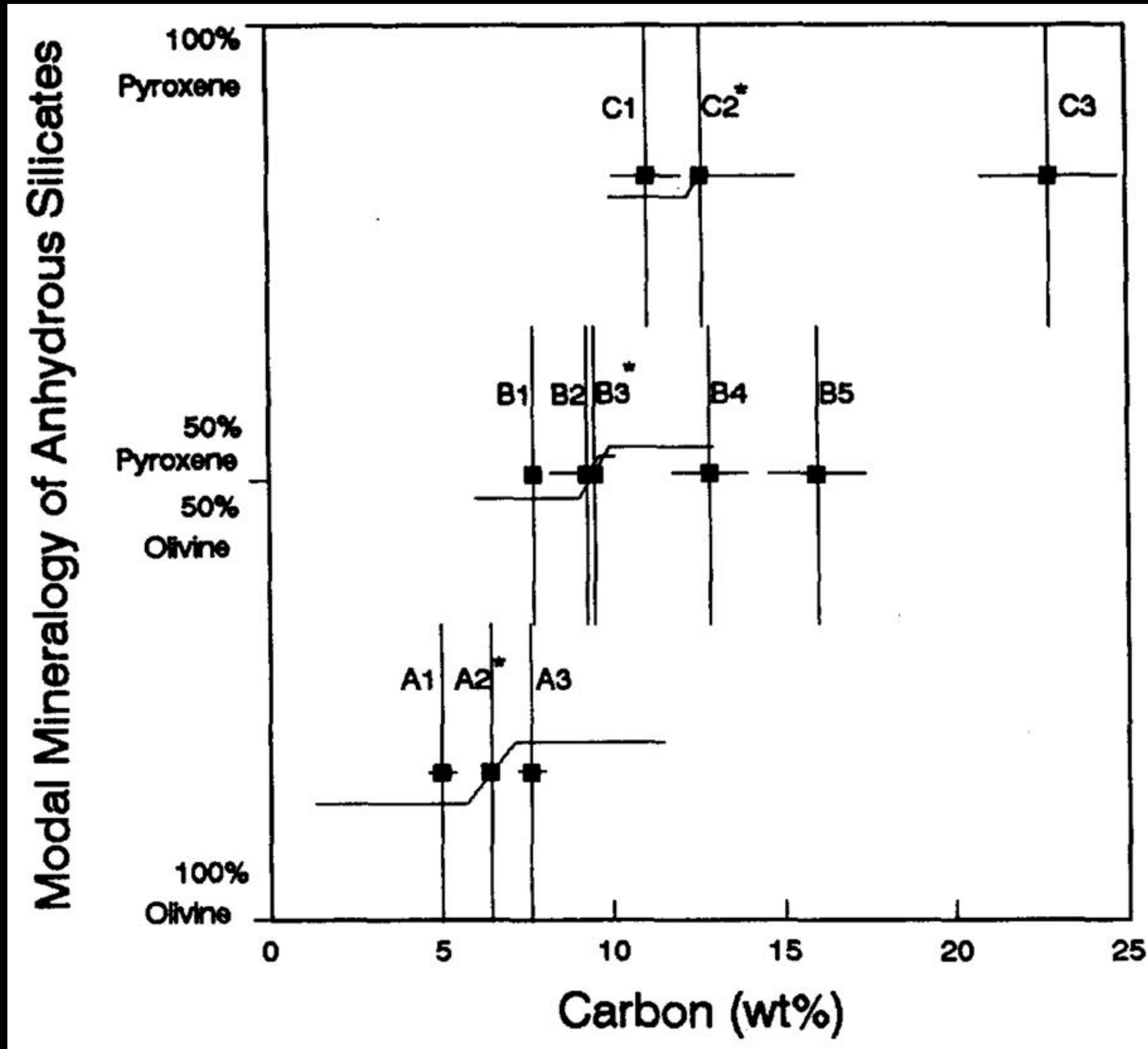


- Several occurences of carbonates (Mikouchi+2007, Wirick+2007)
- Detection of indigenous phyllosilicates is tentative
- also Deep Impact – Comet Tempel 1 ~ 10% Phyllosilicates, 4% carbonates?…(debated...) (Lisse + 2006)

CP-IDPs are C-rich & Px-dominated



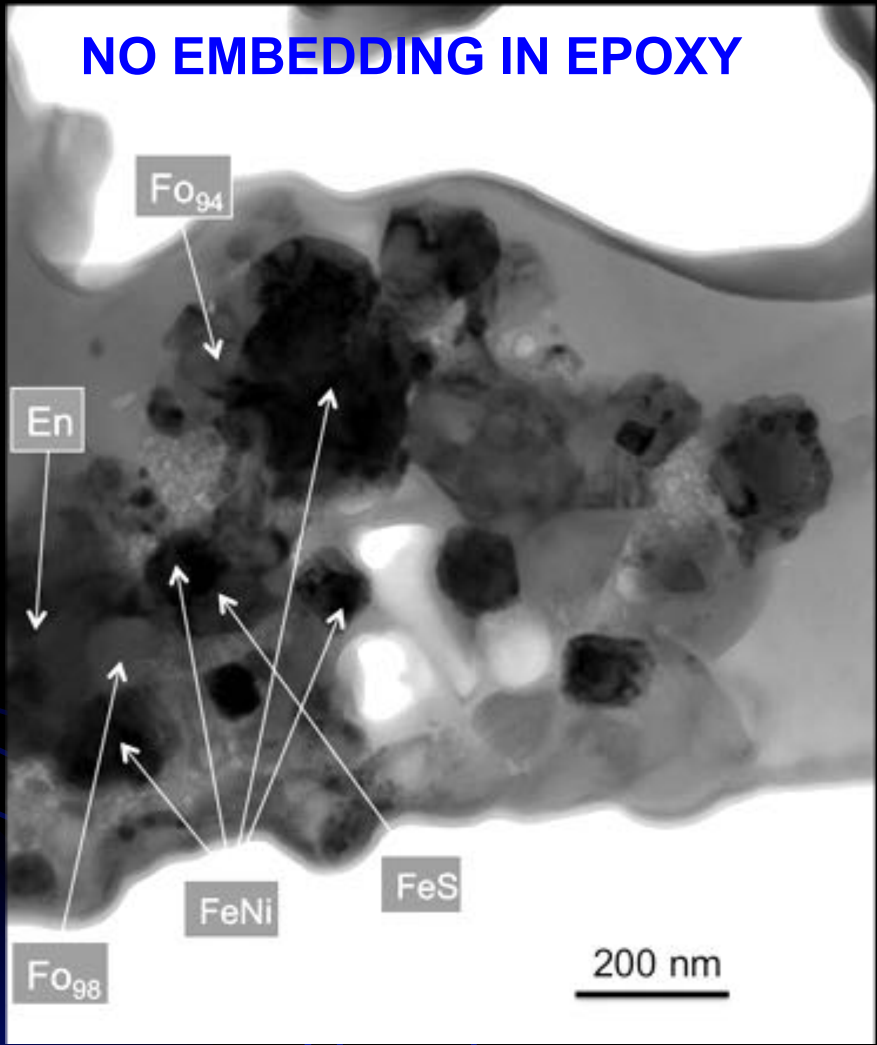
Thomas+1993
Sandford+2016

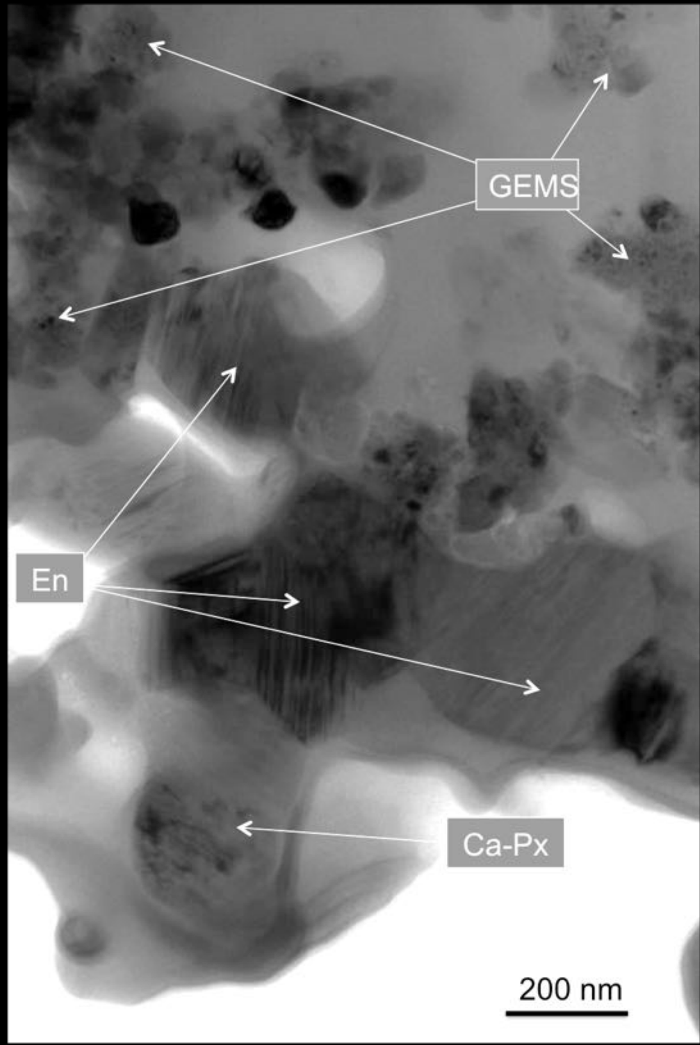


Thomas+1993

- More Px wrto Ol in CP-IDPs compared to CCs
- Correlation with C content

UCAMM Mineralogy

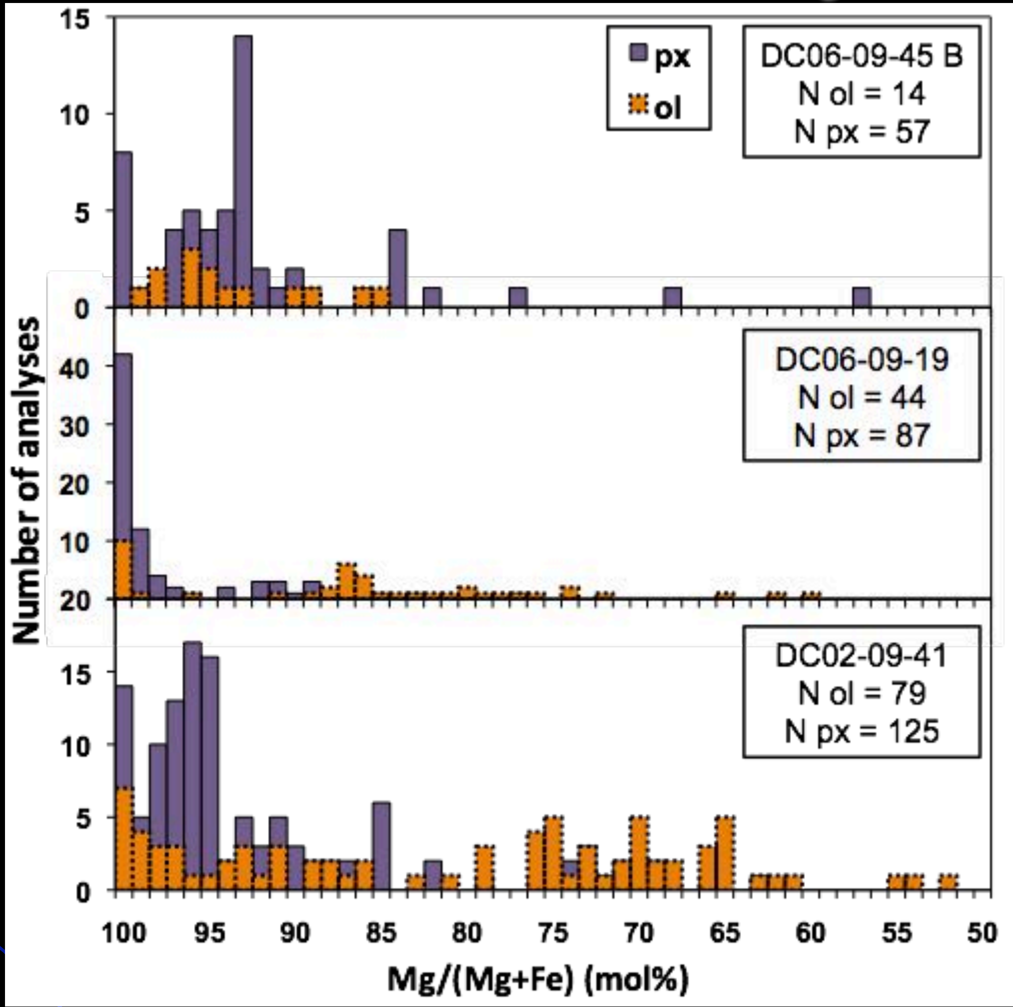




Dobrica+2012, Engrand+2015, Charon+2018

- Major minerals : cyrstalline Mg-rich Px and Ol, Fe-Ni sulfides, glassy phases (GEMS)

UCAMM Olivines & Pyroxenes

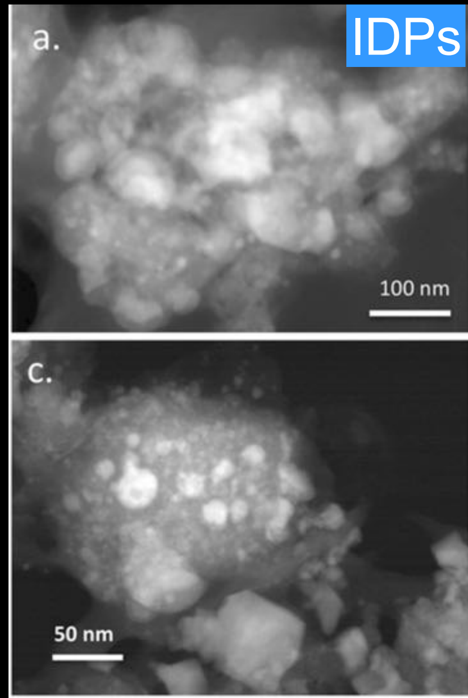


Dobrică+2012

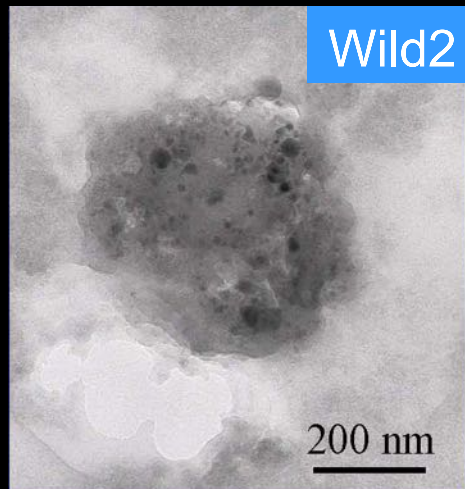
- High abundance of Px (Px/Ol from 2 to 5)
- Mostly Mg-rich composition but also Fe-rich
- Unequilibrated compositions

Glassy phases

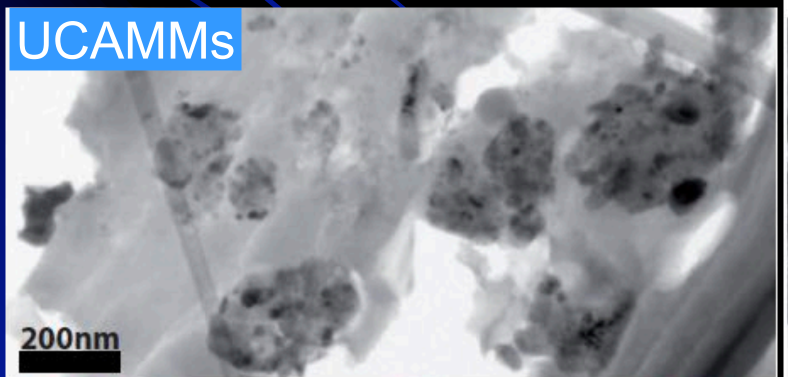
- Glassy silicates in ISM…
- GEMS: Glass with Embedded Metals and Sulfides (Bradley+1994)
- GEMS-like objects abundant in Stardust (indigeneous or impact?)
- GEMS in IDPs
- GEMS in UCAMMs
- Presolar origin of GEMS? - debated



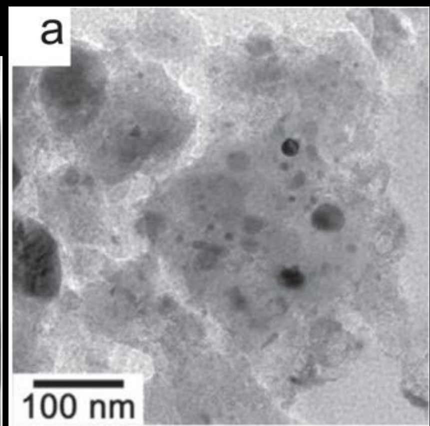
Bradley+1994 to Ishii+2018



Leroux+2008



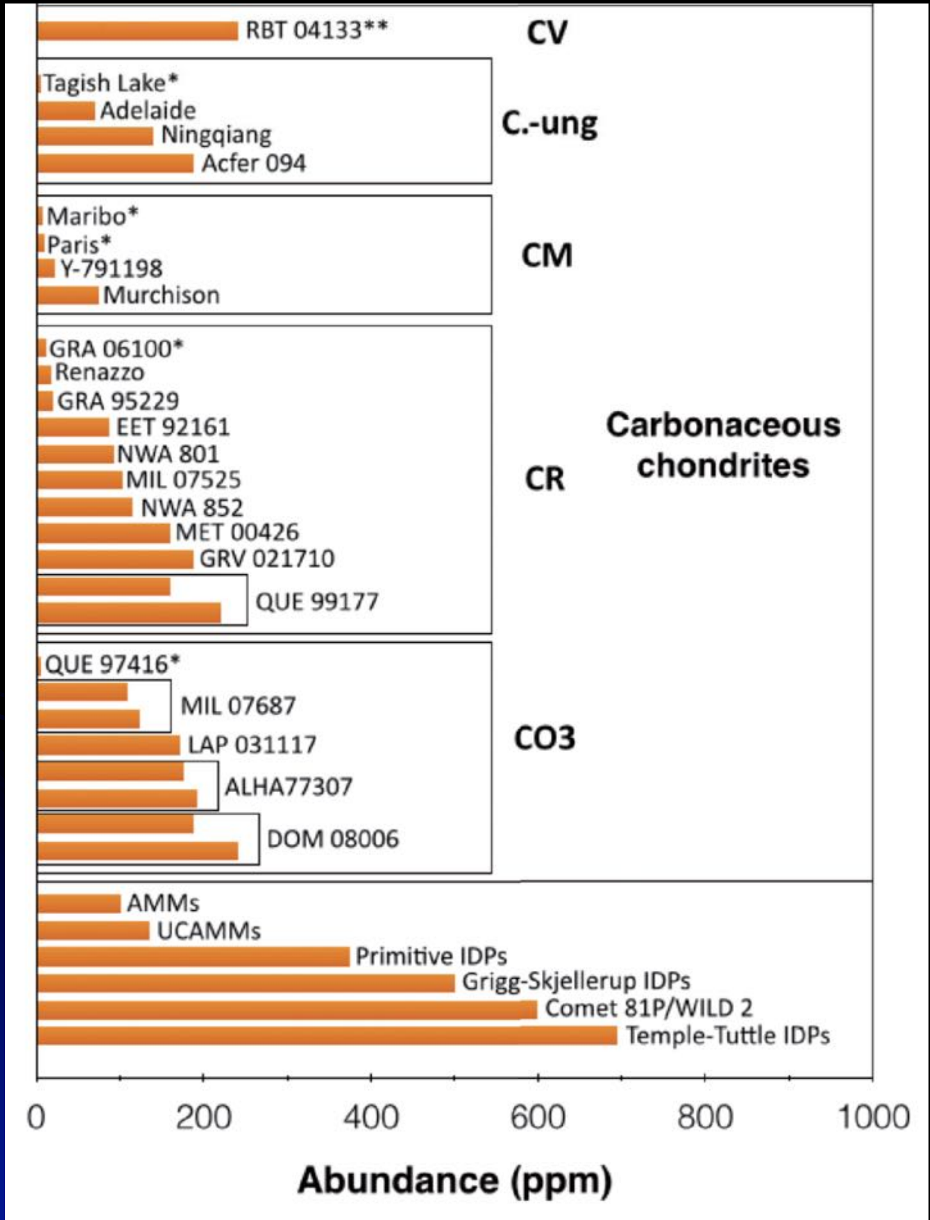
Dobrica+2012

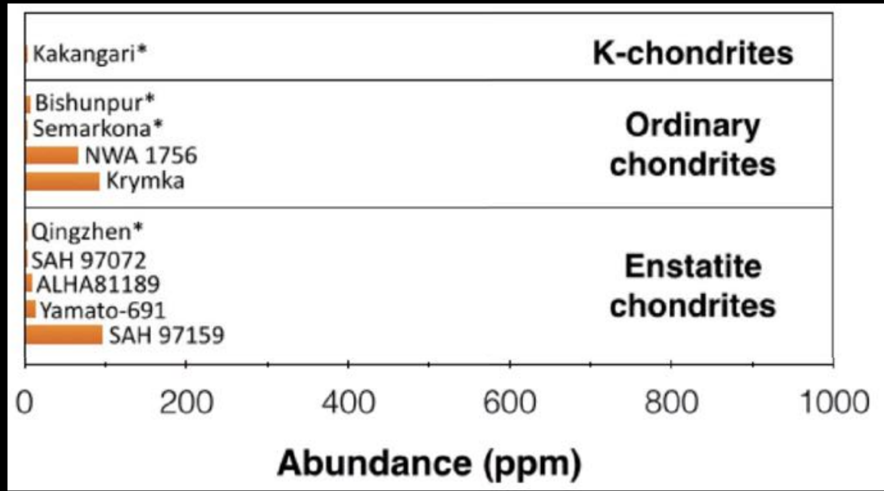


Yabuta+2012

Presolar grains

Presolar grains in extraterrestrial matter



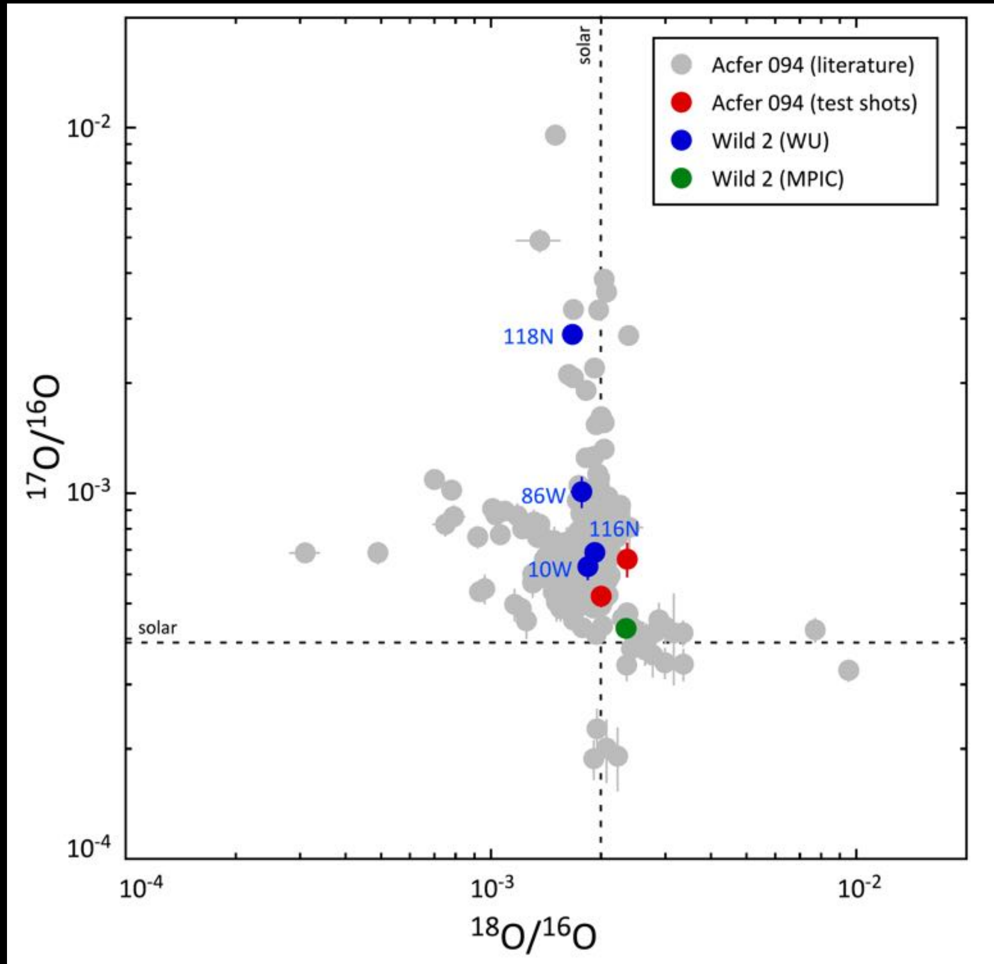


- Silicates are the most abundant presolar grains
- Abundance < 1%

Floss+ GJ 2013)

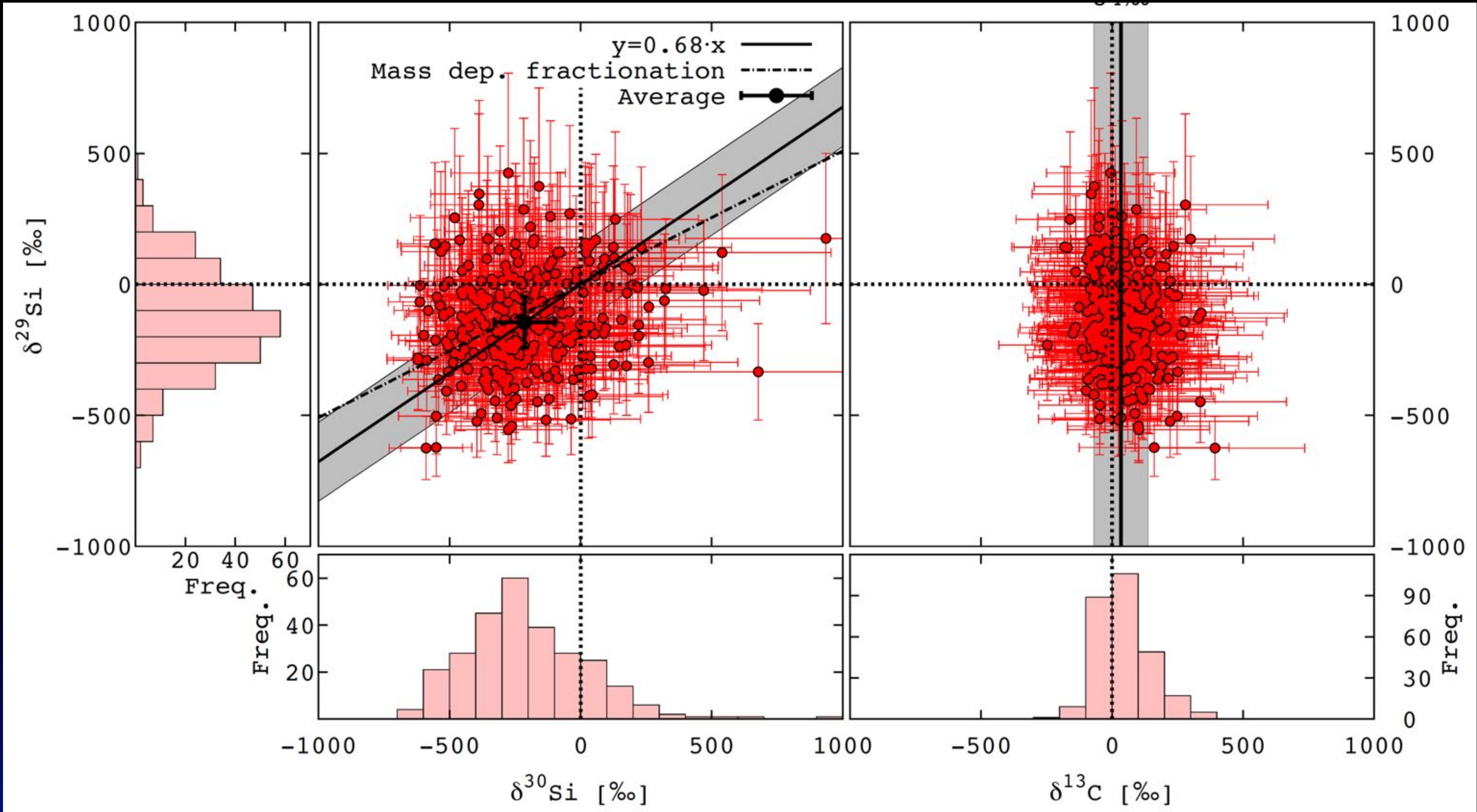
Stardust Presolar grains

- Stardust mission (81P/Wild2)
- anomalous silicates or oxides
  - corrected abundance (destruction impact) = 600-830 ppm
- SiC : 45 ppm



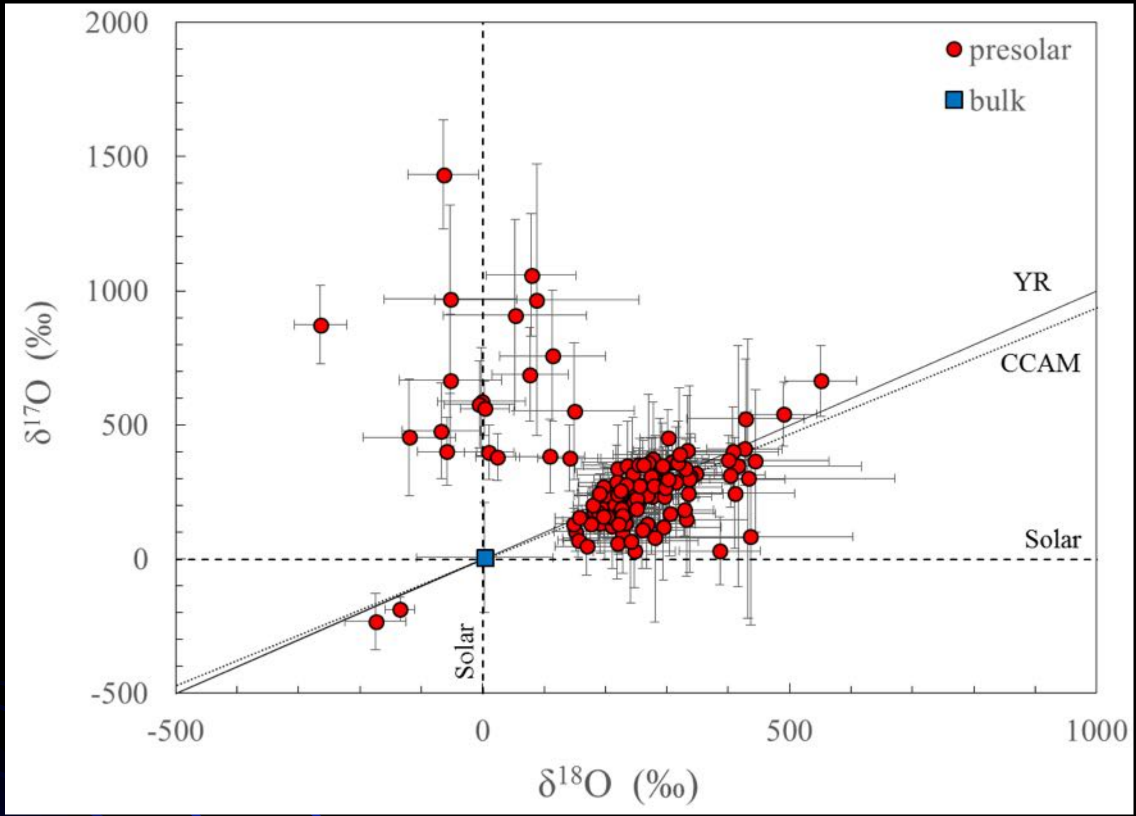
(Floss et al. ApJ 2013)

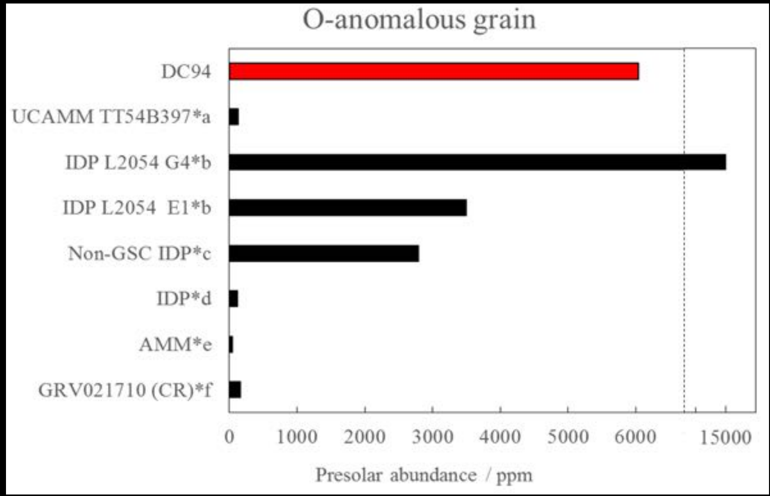
Presolar grains in 67P?

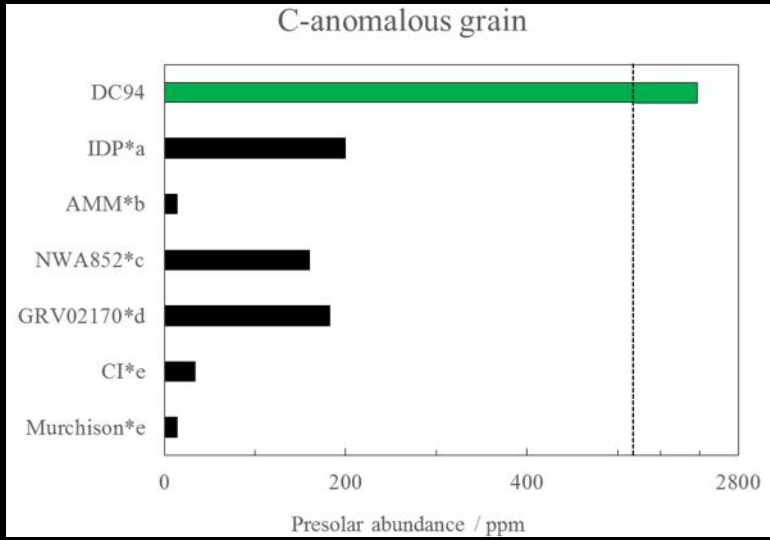


Rubin+2017

Presolar grains in UCAMMs







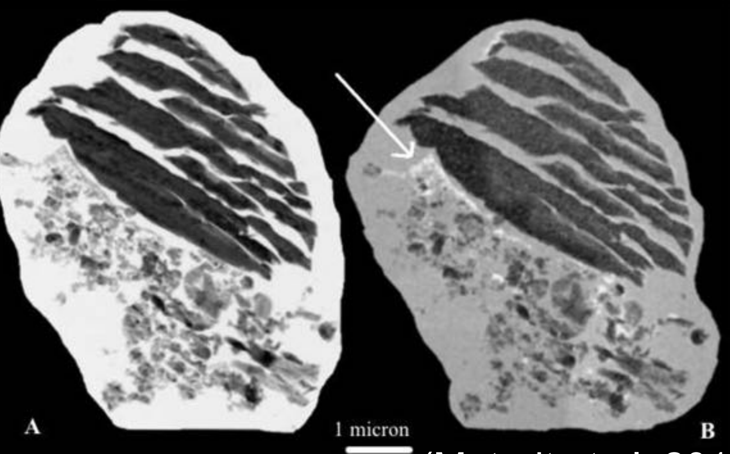
(Rojas+ in prep)

- « Large » abundance of presolar grains

Composition of cometary dust : organic fractions

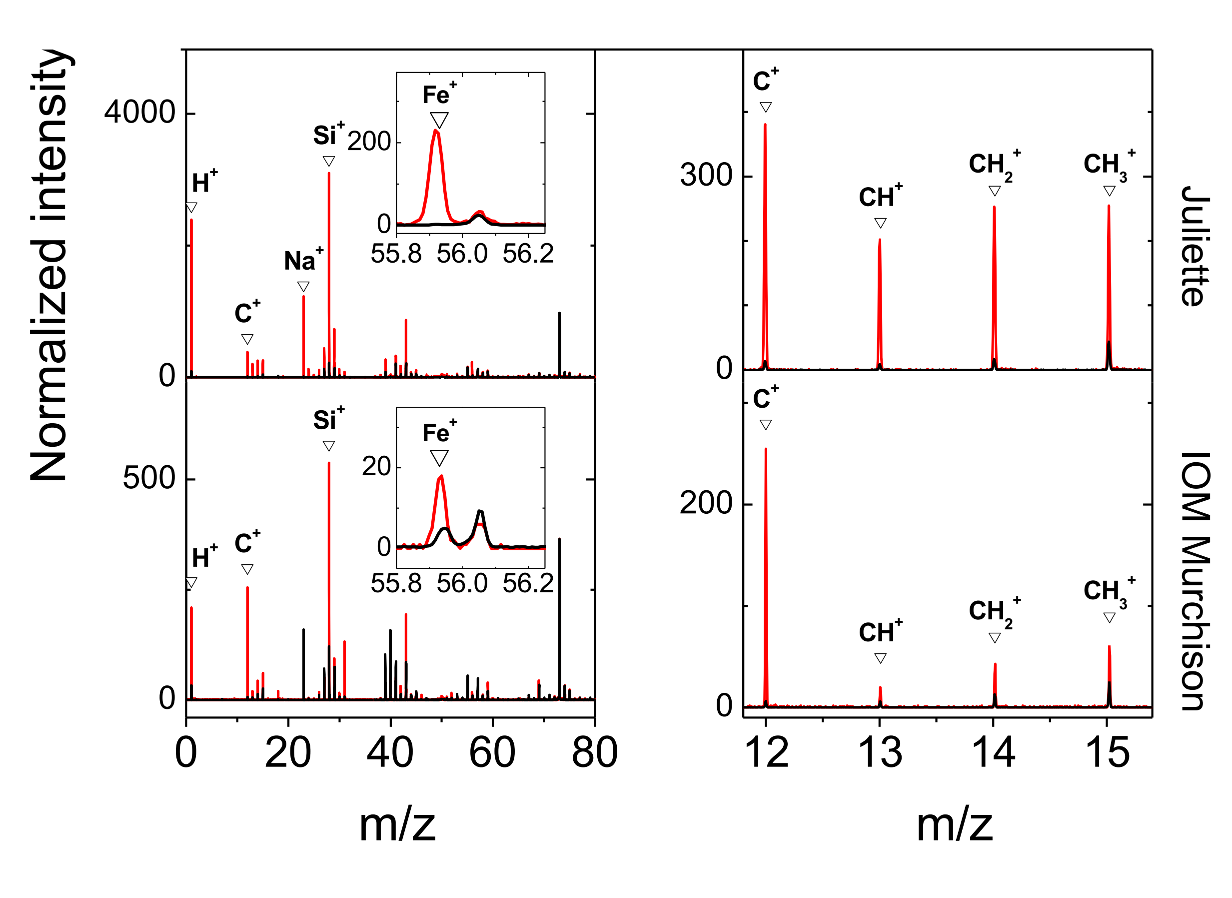
Carbonaceous phases in Wild 2

- Glycine (Elsila et al. 2009)
- Low amounts of labile and refractory OM (Cody et al. 2008, De Gregorio et al. 2010 & 2017, Matrajt et al. 2013)
  - polyaromatic C=O containing matter (similar to IOM in primitive meteorites and IDPs)
  - nanoglobules (also found in primitive meteorites and IDPs, with usually high ^{15}N enrichments).
  - nanoscale FeC inclusions coated with Poorly Graphitized Carbon in Cr-rich magnetite -> nebular oxidation of metal in a H_2O ice-rich and C-rich environment?
- Causes for this low C-content?
  - hypervelocity impact
  - collection of low C matter?



(Matrajt et al. 2013)

67P Cometary « Insoluble Organic Matter »

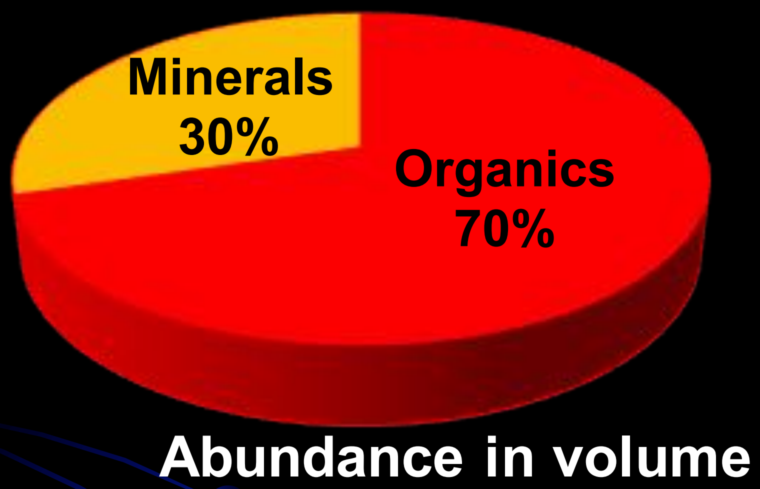


Fray+2016

- Best analogues:
  IOM extracted from CCs
  ⇒ high-molecular-weight organic matter in the particles of 67P
- CHx^+ / C^+ ratio higher in 67P than in IOM samples
  ⇒ H/C higher in 67P refractory organic matter than IOM?
- **C/Si ~ 5.5 ± 1.3**
  (Bardyn et al. 2017)
- **N/C ~ 0.035 ± 0.011**
  (Fray et al. 2017)

Solar photosphere: N/C= 0.3 ± 0.1
UCAMMs: N/C= 0.1-0.2

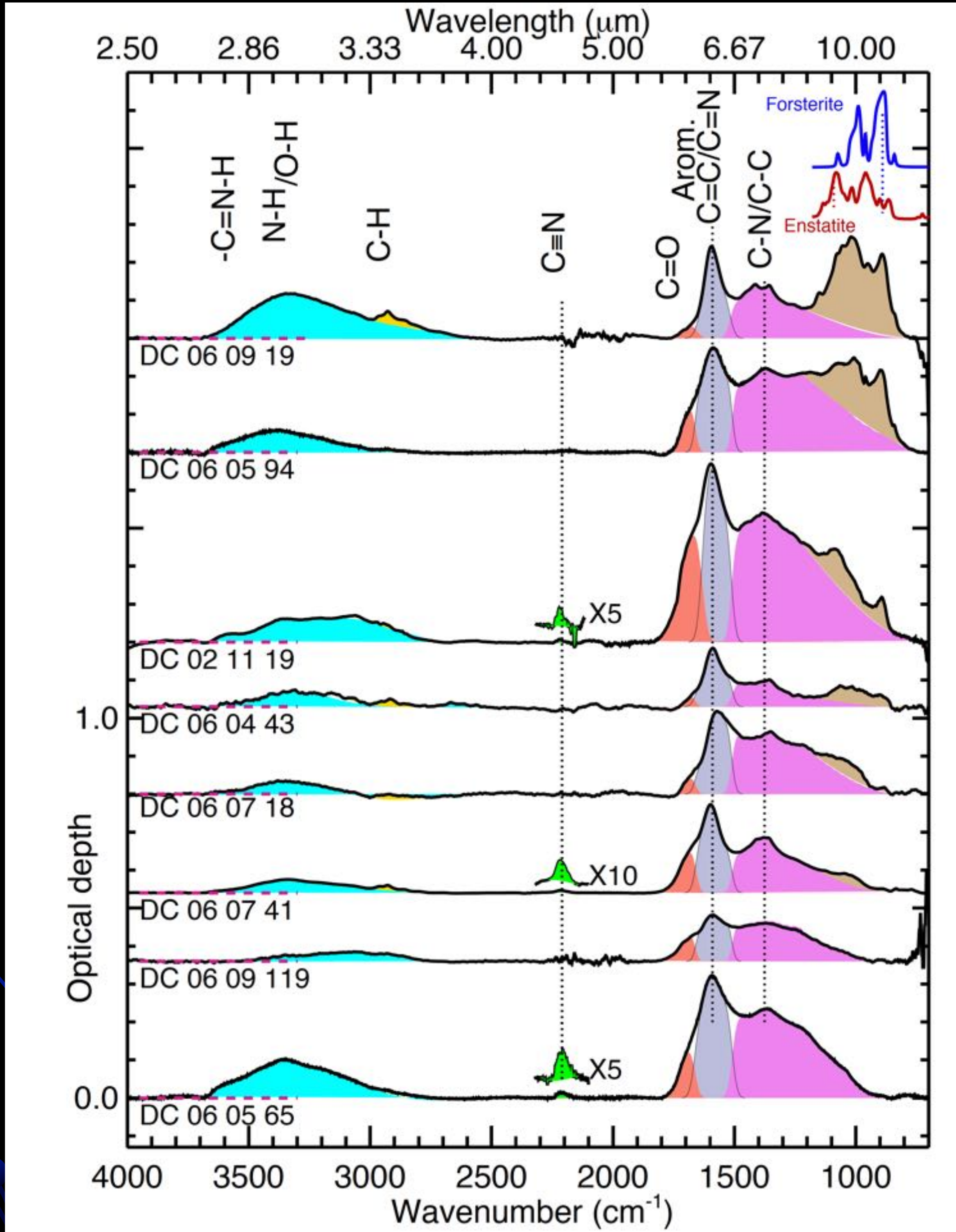
Modal composition of 67P dust (COSIMA)



Assuming $d_{min}=3$ & $d_{org}=1$

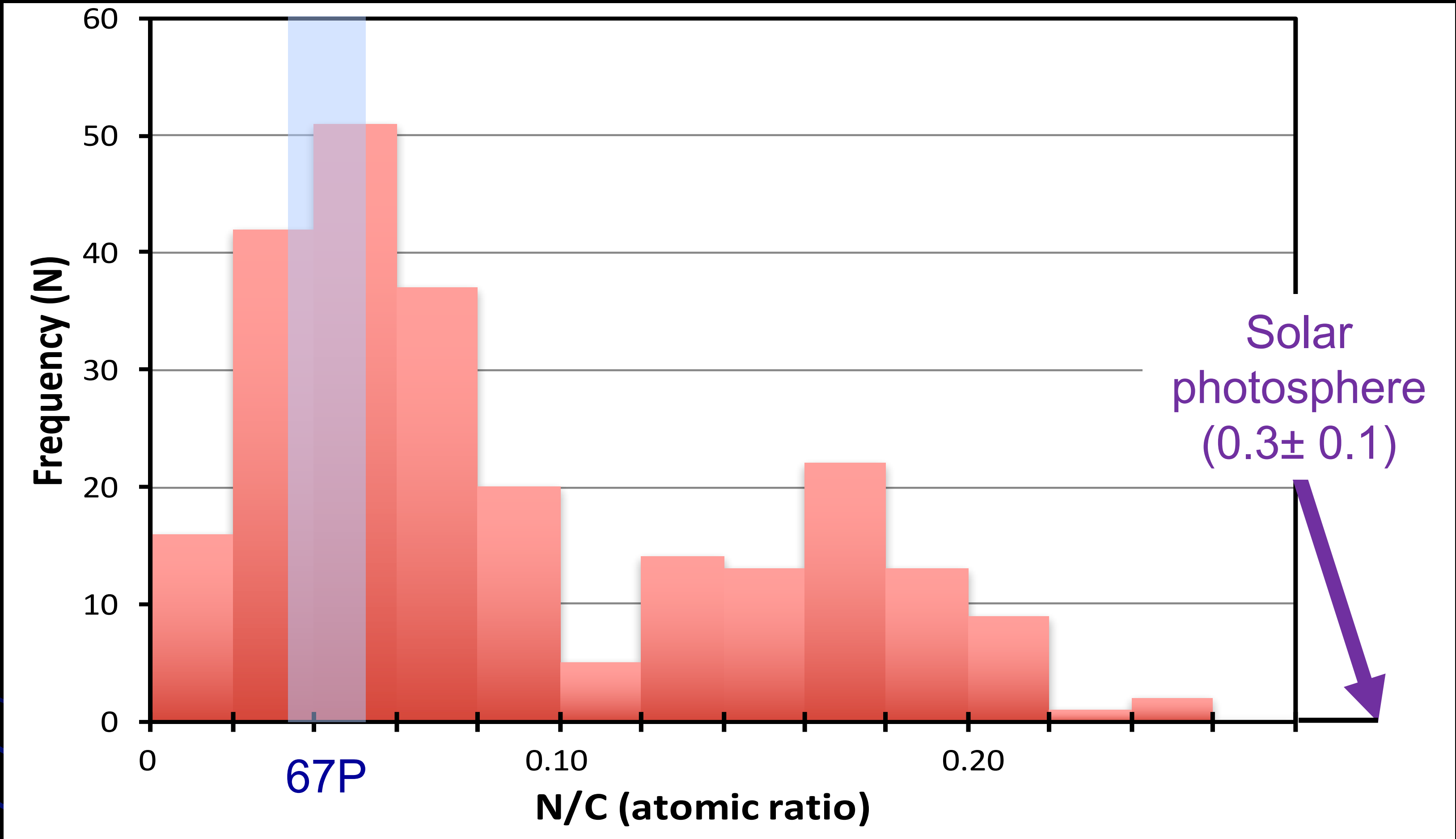
- GIADA: 52 % ± 8 % in volume of organic matter
  (Fulle et al. 2016)
- CONSERT: High carbon content of the nucleus
  (Herique et al. 2016)

N-rich OM in UCAMMs



Dartois+2018

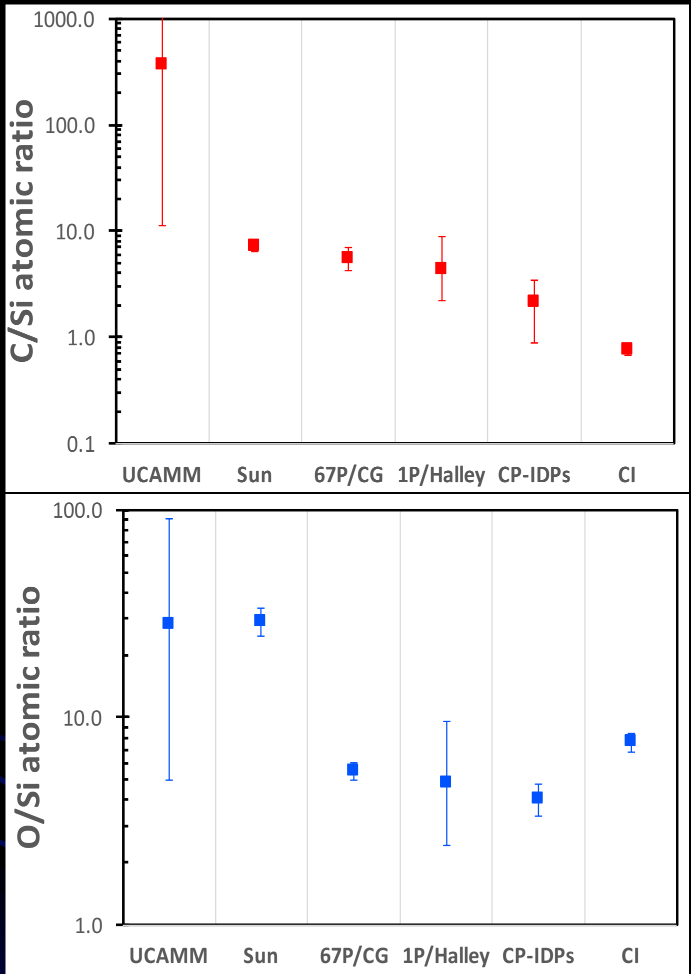
N/C atomic ratios in UCAMMs



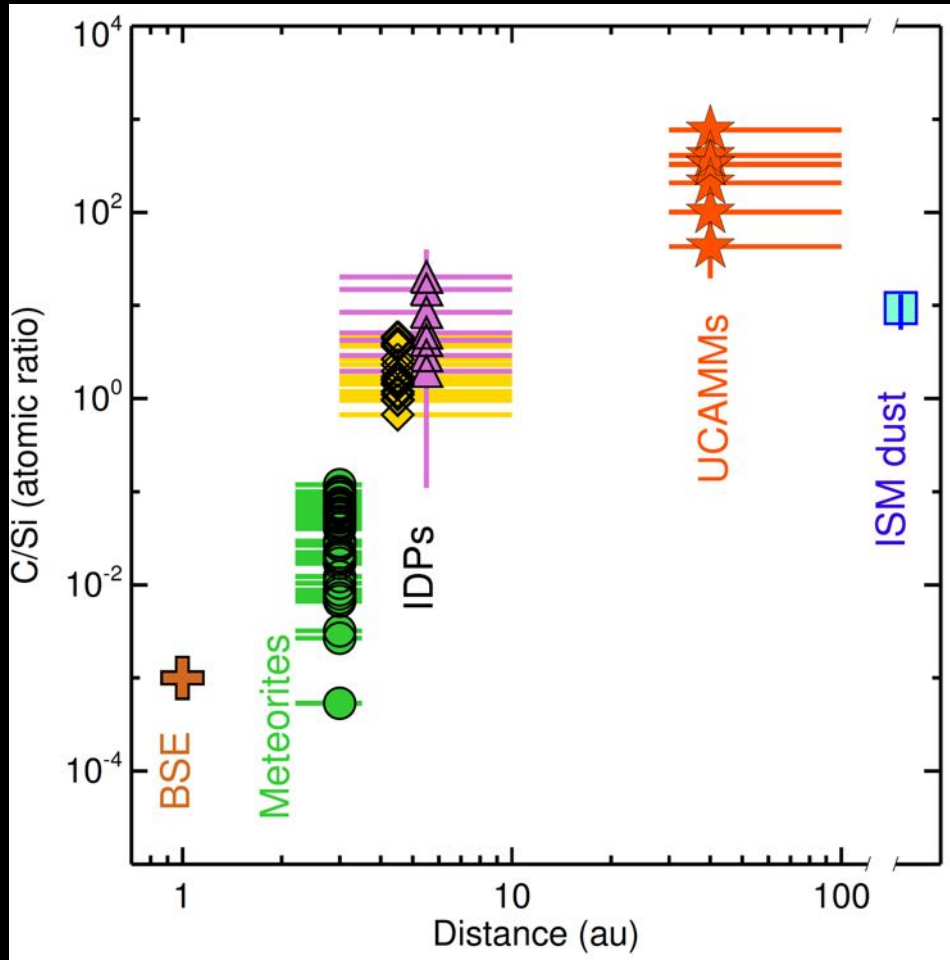
(Engrand et al. LPSC 2018)

- At least 2 organic phases, with different N contents

C/Si and O/Si of UCAMMs in context



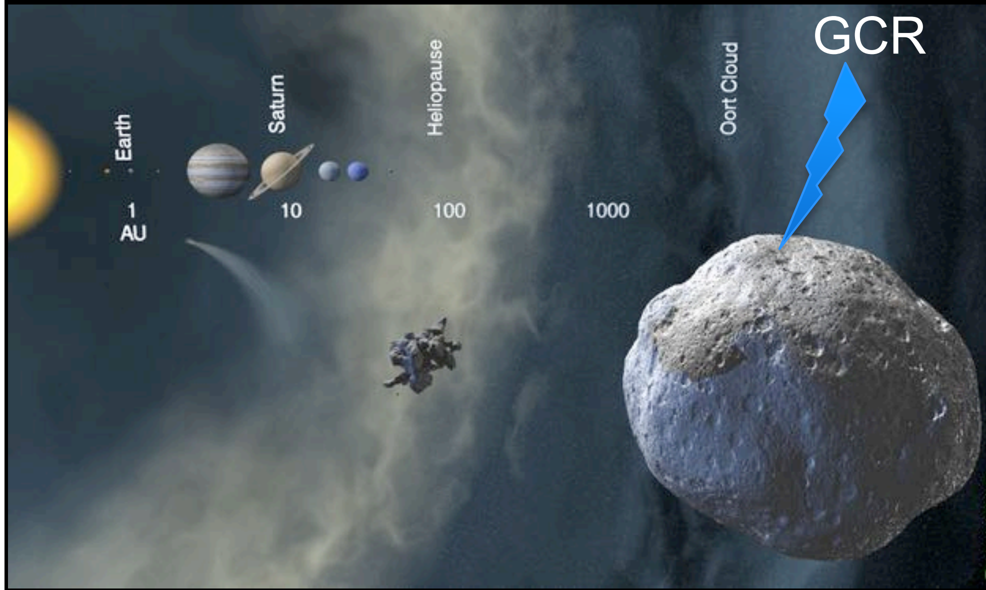
Engrand+2018 LPSC



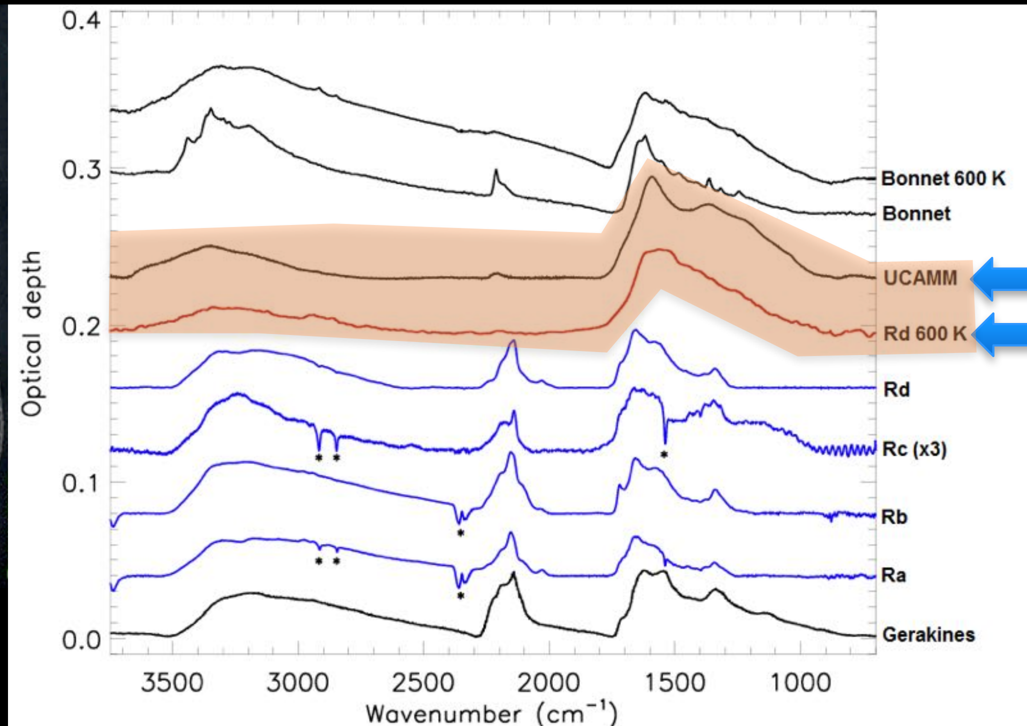
Dartois+2018

- C/Si > ISM value : not a presolar (« ISM ») heritage for the organic matter – local process
- ~ Solar O/Si (O mostly in minerals) -> from the solar system

Formation of N-rich OM by irradiation?



(Dartois, *et al.* 2013)



(Augé *et al.* A&A 2016)

- UCAMMs : material from **beyond the nitrogen snow-line**
- **Formation of N-rich OM** by **GCR irradiation** at surface of a Kuiper belt or Oort cloud icy objet ? (Dartois+2013, 2018)
- Or: formation by **UV photolysis** of ices with simulated interstellar/precometary compositions (Yabuta+2017)

Summary: Formation of cometary dust, connection to ISM ?

Minerals

- Wide variety of mineral phases from the inner solar system, transport to outer regions (Ol & Px IR spectroscopy, 81P, 67P, cosmic dust)
  - Incomplete mixing from the inside out. OK with models (Shu et al. 1997, Bockelée-Morvan et al. 2002, Ciesla 2007, Vinković 2009…).
  - Mineral sizes usually smaller – size sorting effect?
  - Mineralogical gradient in the PPdisk ? (Px/Ol)
- ^{26}Al dead at time of comet mineral formation (> a few Myrs)
- Presolar heritage in comet dust at most % level (81P, 67P Si isotopes, G-S IDPs, UCAMMs,…)

Summary: Formation of cometary dust, connection to ISM ?

Organic Matter : from the « inner » and outer regions?

- Low T formation (high D/H)
- N-poor OM (81P, 67P, CP-IDPs, UCAMMs): Formation in the inner regions (?) and brought the outer regions (present in meteorites – and in 67P)
- N-rich OM (and low C=O) in UCAMMs: in situ formation in the outer regions by GCR irradiation of N_2-CH_4 rich ices ?

Ices

- Some evidence for ISM connection (Martin's talk)

Future:

- Hayabusa 2 (soon!) sample return Ryugu 2020
- OSIRIS-REx Sample return Bennu 2023
- CAESAR (NF4) : 67P sample return? (2030s)