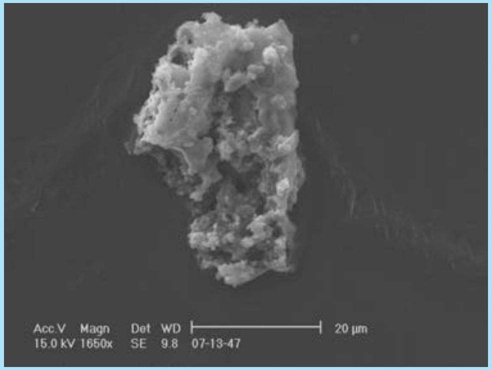
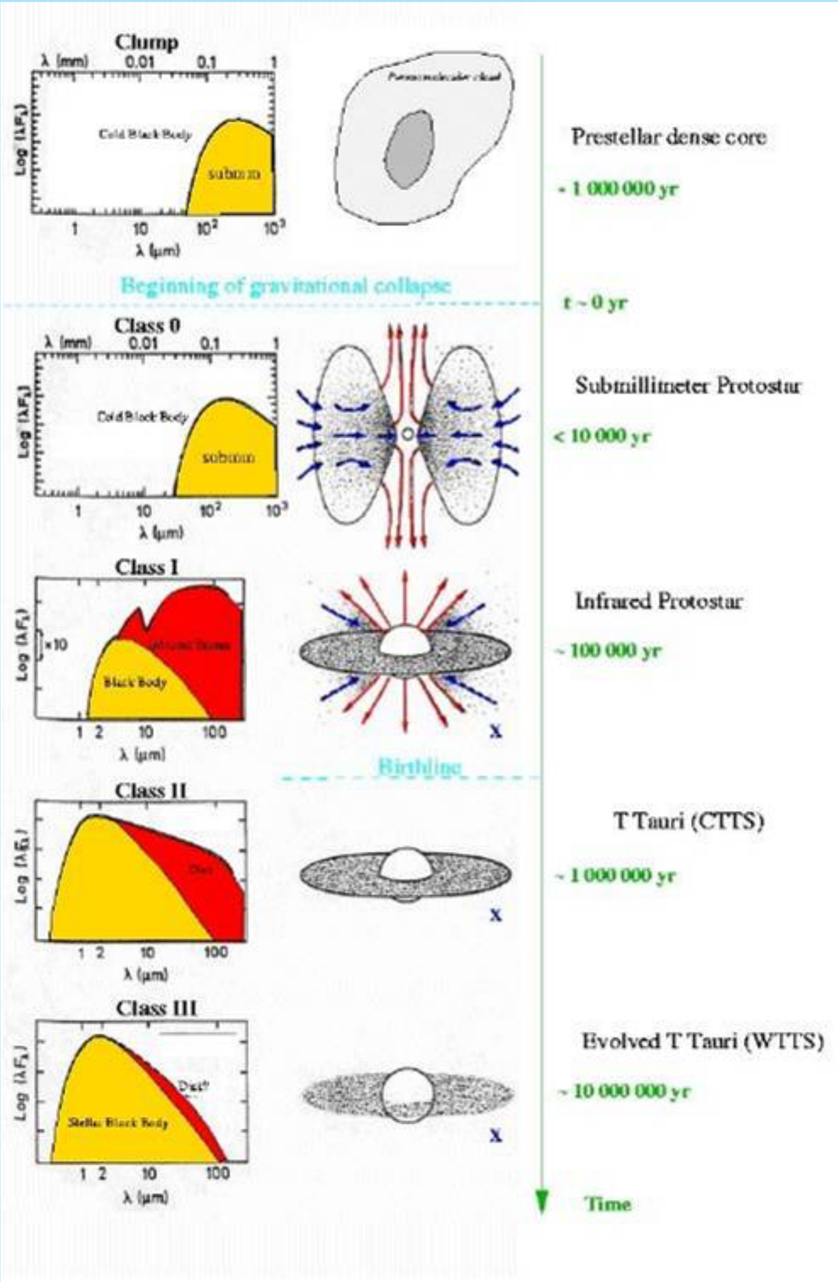
Analyses isotopiques de poussières interplanétaires,

qu'apprenons-nous sur la frontière du système solaire?



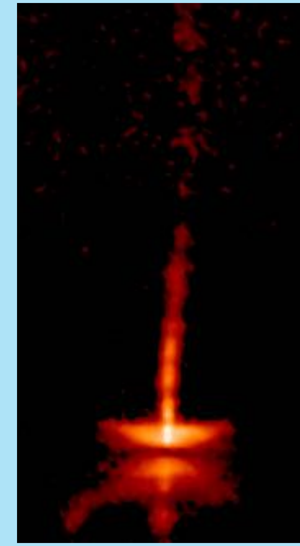
Jean Duprat
CSNSM-CNRS Univ. Paris Sud

Before the main sequence



Different time scales

- Class 0 & I :
  - The proto-star is embedded
  - High accretion rate
  - T ~ 10^4-10^5 years
  - $M_{star} = 0.5 - 0.8\ M_{\odot}$
- Class II & III :
  - Disk of gas and debris
  - Lower accretion rate
  - T ~ 10^5-10^6 years
  - $M_{star} = 0.8 - 1\ M_{\odot}$

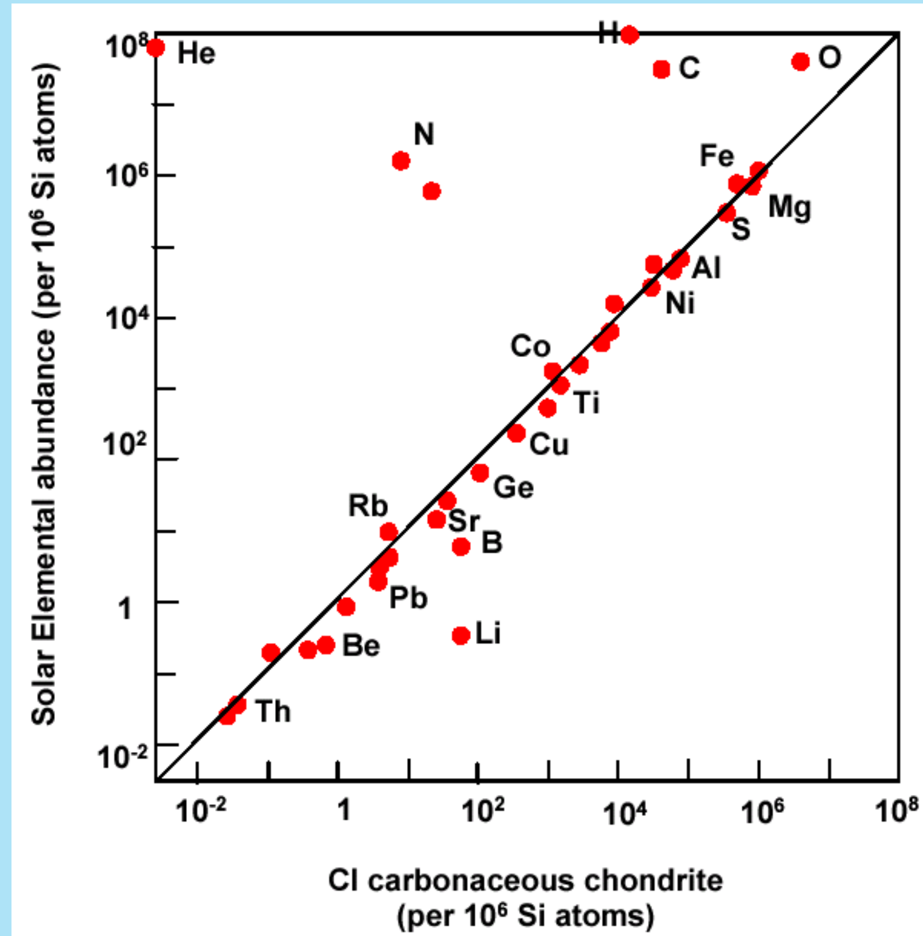


HH 30
Télescope Hubble

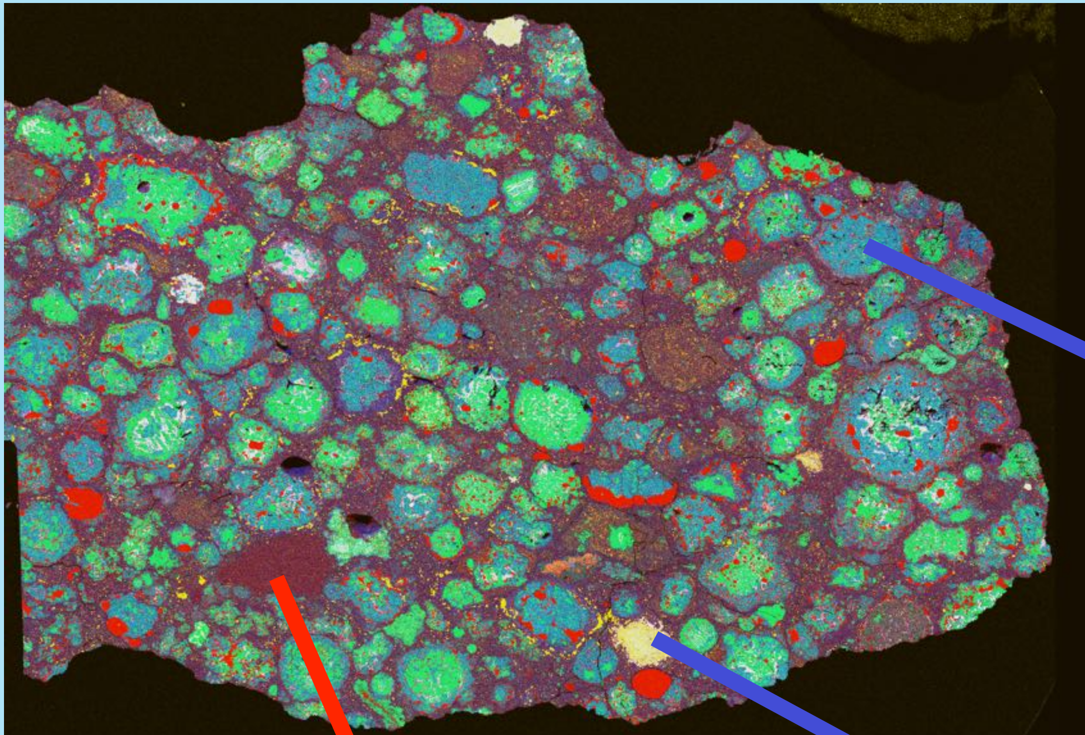
Meteorites & Antarctica

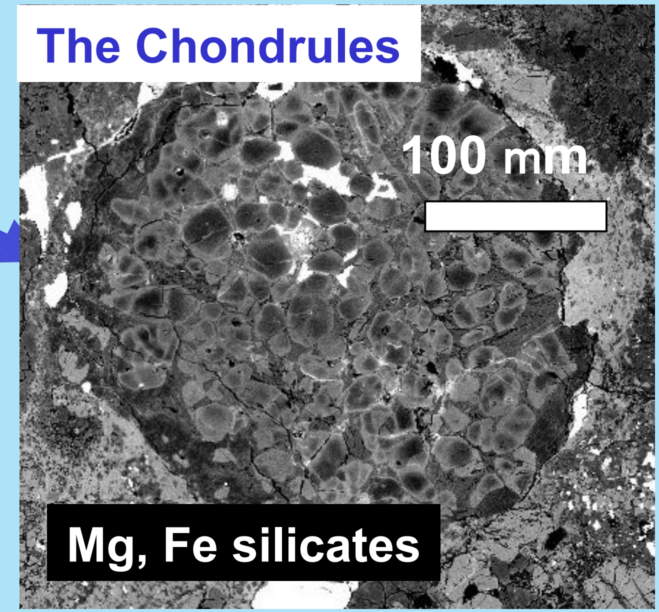
Antarctic Meteorite Research

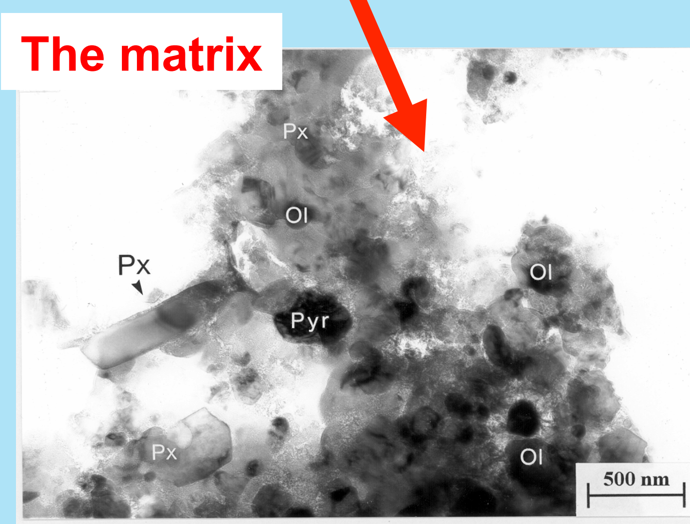
PI : R. Harvey, US



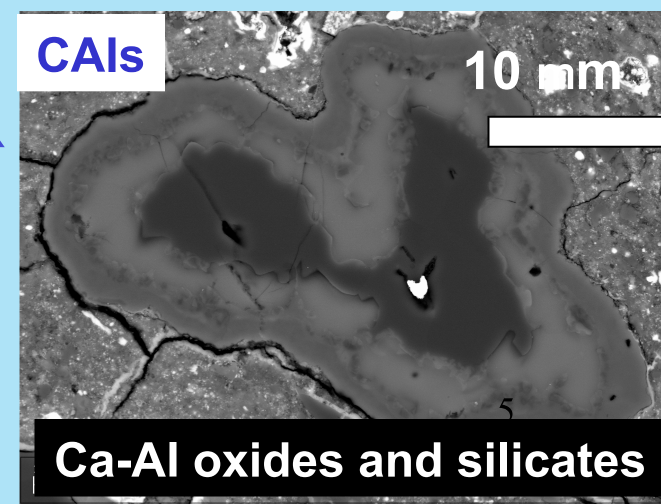
The main components in Chondrites : matrix & refractory phases



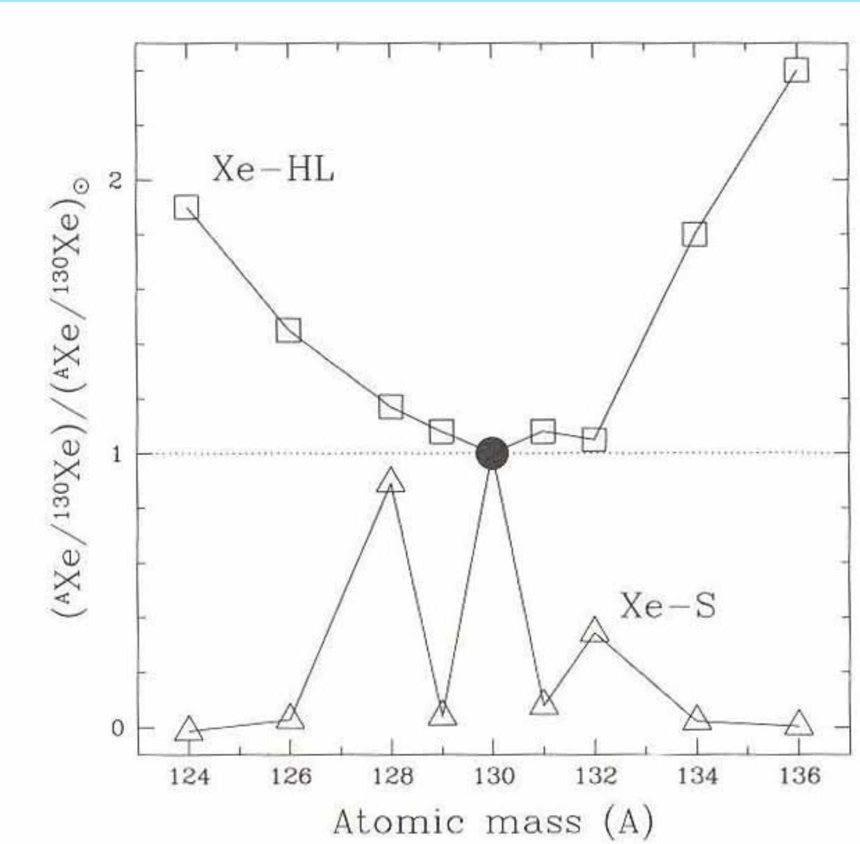




In the matrix on finds the presolar grains

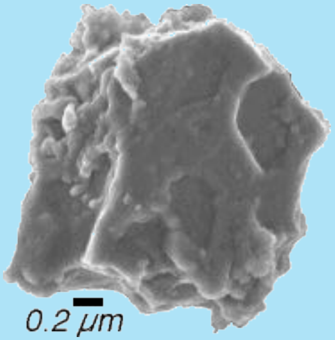


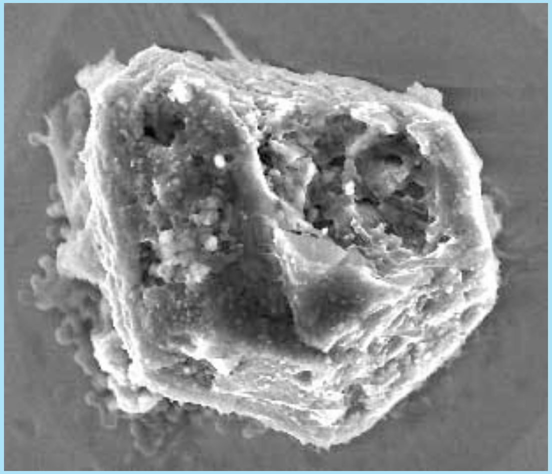
Xenology in chondrites

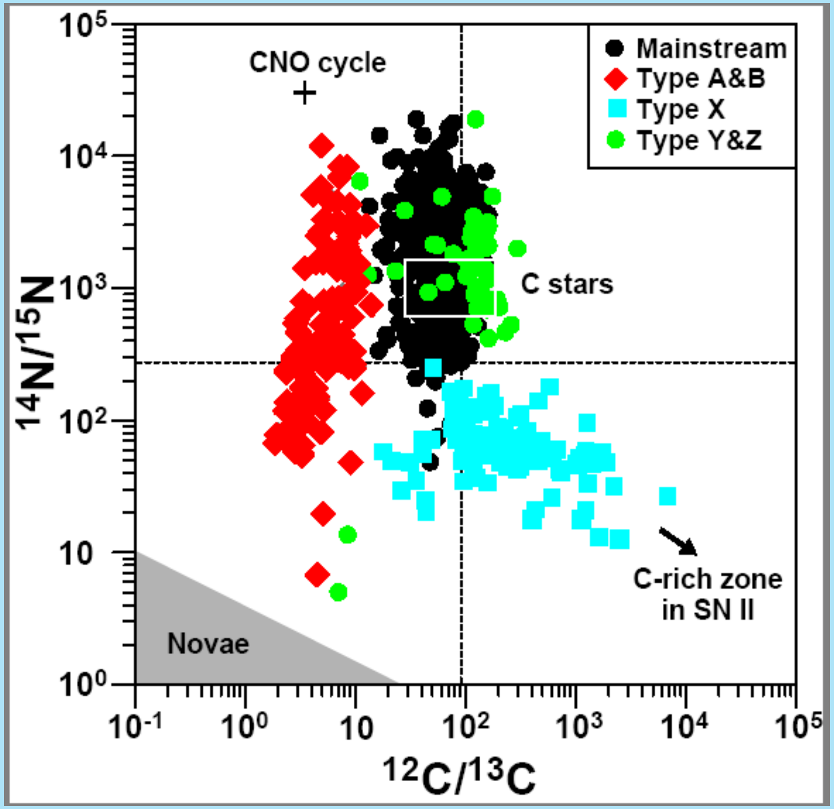


- The survival of presolar phases was first demonstrated by Renolds et al (1964) using the isotopic composition of noble gases in a carbonaceous chondrite (Renazzo)
- The Xe isotopic data show various components with relative ratios strongly different from the solar average values
- Two main component :
  - Xe-HL (Heavy-Light)
  - Xe-S

The pre-solar SiC grains

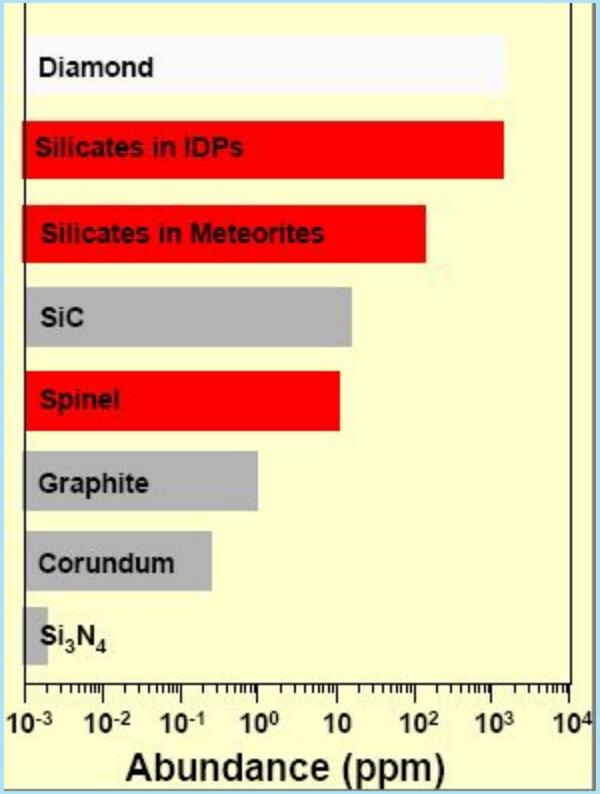






- It took 25 years to identify the carrier of these anomalies
- The size of these grains is 1-10 mm
- Thousands are analyzed so far

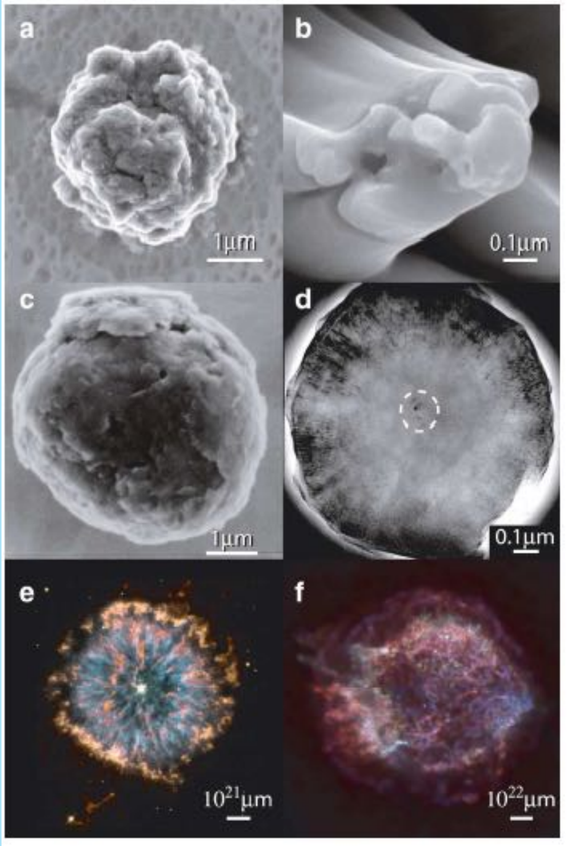
Presolar grains abondance in chondrites



SiC

Graphite

Planetary nebulae NGC 6751 HST



Spinel

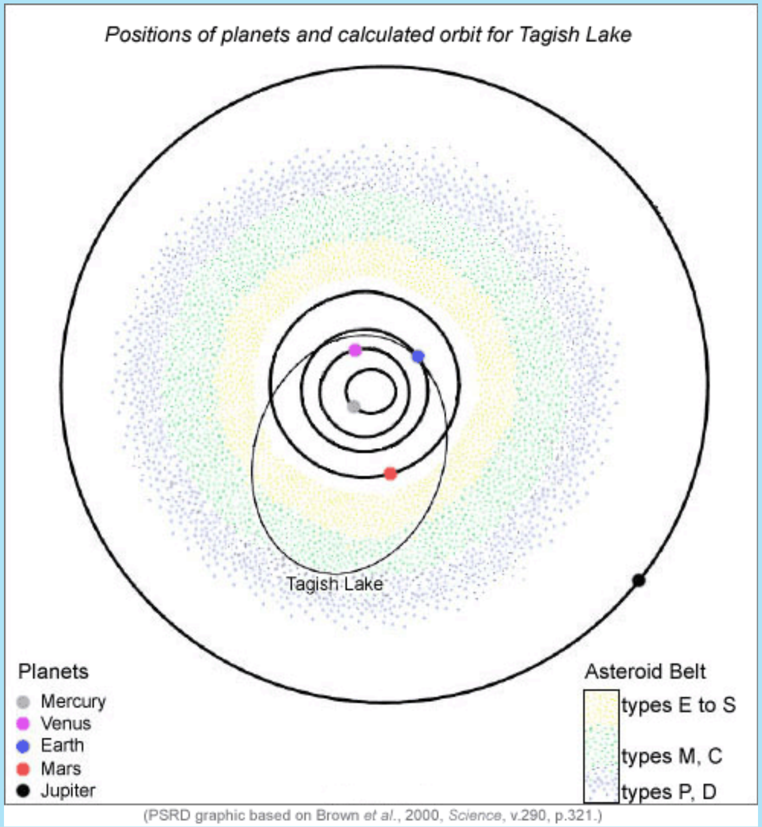
TEM thin section Graphite & TiC

Remanant of SN Cas A

Nittler EPSL 2003

- Presolar grains are vapor phase condensate in stellar envelopes
- Presolar grains are **refractory**
- The condensation sequence strongly on the composition of the stellar gas, mainly on the C/O ratio
  - if C/O < 1 all the carbon is in the gas phase locked in the CO molecule (very stable even at high T°) : condensation of oxides and silicates
  - If C/O >1, a large fraction of the carbon is available for solid phases and condensate in graphites and carbides

Most meteorites are coming from the asteroid belt between Mars and Jupiter

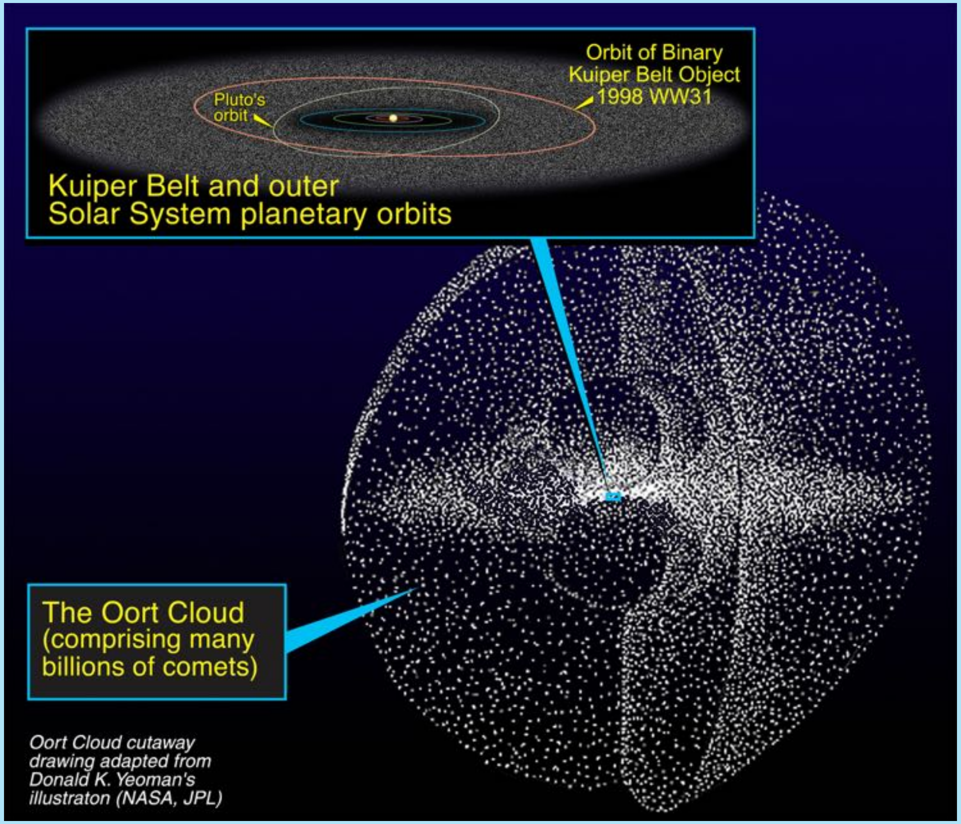


Brown et al. Science 2000

They are sampling a restricted part of **the inner solar system**

The comets

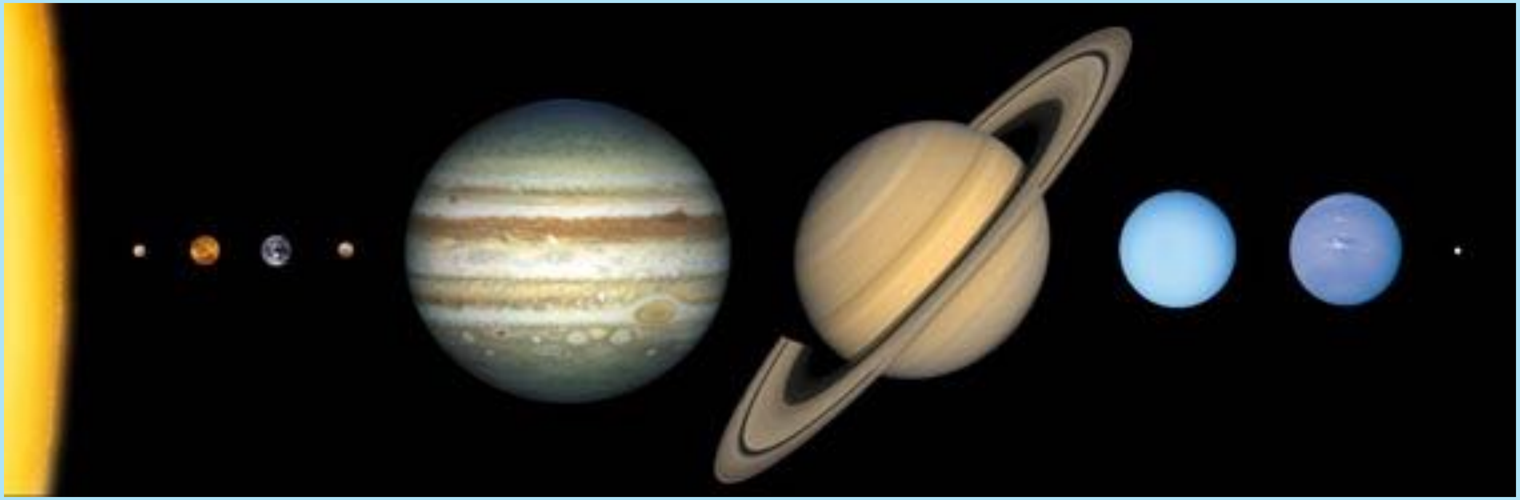
dust from the outer solar system



Sun-Earth : **1 AU** = 10^9 km

Kuiper belt : 70 AU
Oort Cloud : 50-100 10^3 AU

The snow line concept

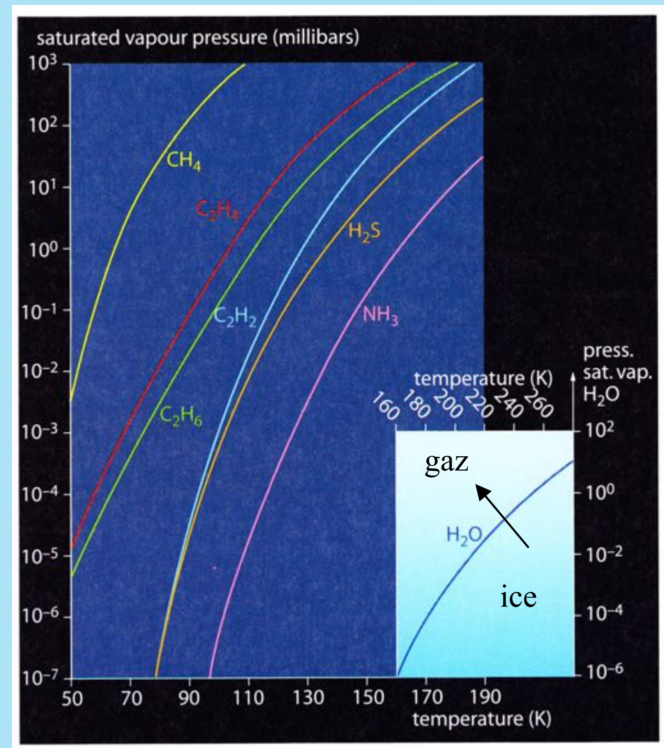


a strong dichotomy between
the inner and outer solar system

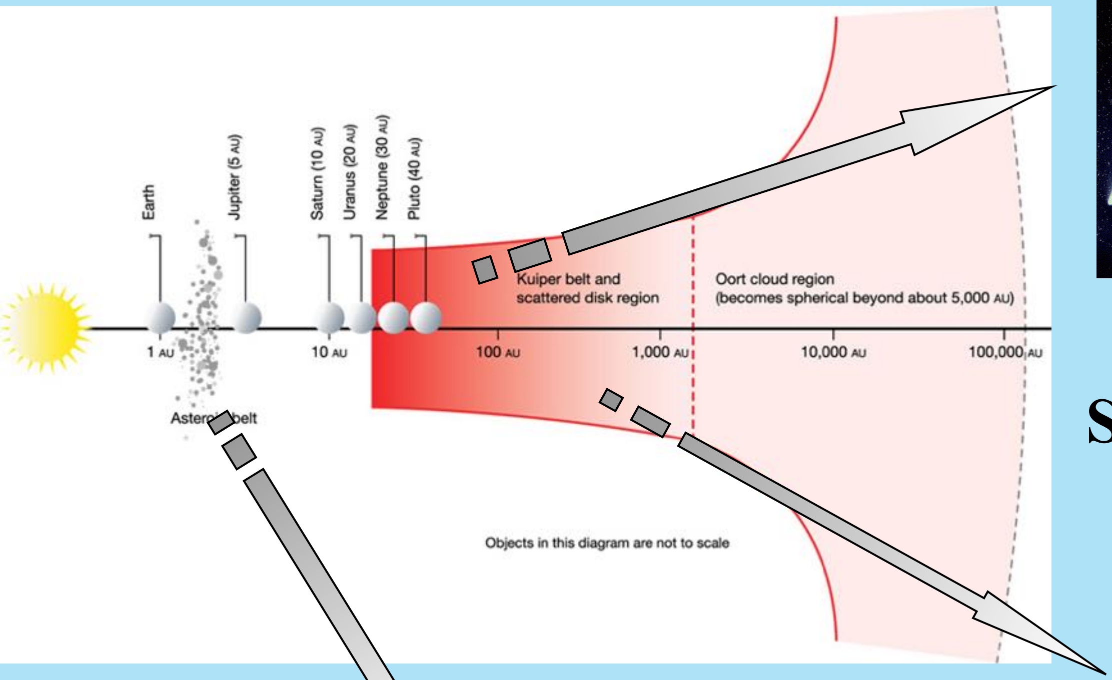
TABLE 1. Properties of Solar System Planets

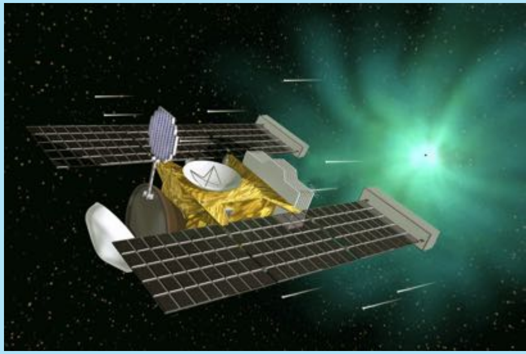
Planet	Orbital Semimajor Axis (AU)	Mass ($M_\oplus$)	Mean Density (g/cm^3)	Eccentricity
Mercury	0.39	0.055	5.4	0.20
Venus	0.72	0.82	5.2	0.007
Earth ($M_\oplus$)	1.0	1.0	5.5	0.02
Mars	1.5	0.11	4.0	0.09
Jupiter	5.2	318	1.3	0.05
Saturn	9.6	95.1	0.70	0.06
Uranus	19	14.5	1.6	0.05
Neptune	30	17.2	1.6	0.009

Notes: Pluto is not included because it is more typical of outer Solar System Kuiper belt objects. $1M_\oplus = 6 \times 10^{27}$g $= 3 \times 10^{-6} M_\odot$



The solar system small bodies
Asteroids & Comets





STARDUST mission (2006)

ROSETTA mission (2014)

Itokawa

Mission Hayabusa

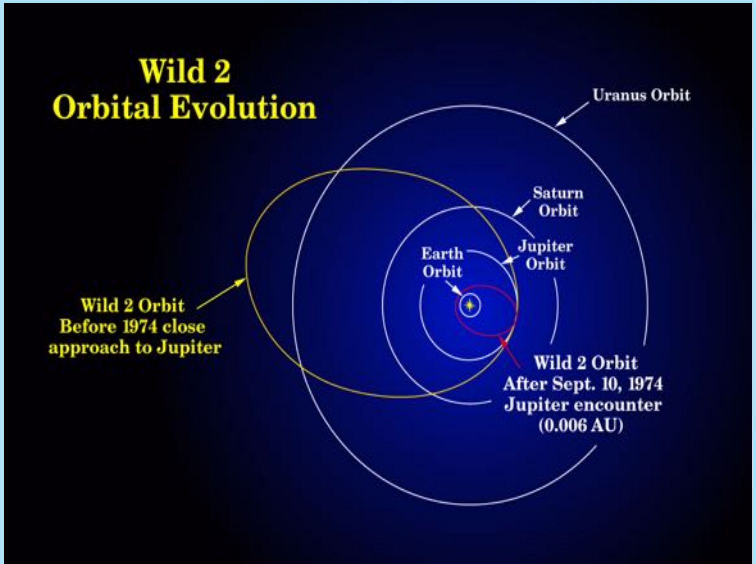
(2010)

The STARDUST mission (NASA)

- **Program *Discovery***
- 168.4 US M$ (not including launch)
- **PI: Don Brownlee (University of Washington)**
- **First sample return mission from a solar system primitive body**

- Jupiter Family Comet
- Discovered 1978 (Mr Wild)
- Period T = 6.39 yr (before 10-9-1975, 43 ans)
- Sizes: 5.5 × 4 × 3.3 km

- First sample return since Apollo missions (70's)
- Information on the chemical and isotopic composition of the LISM 4.5 Gyrs ago.
- The solid component of comets : solar or interstellar ?



Stardust, the return, January 15th 2006

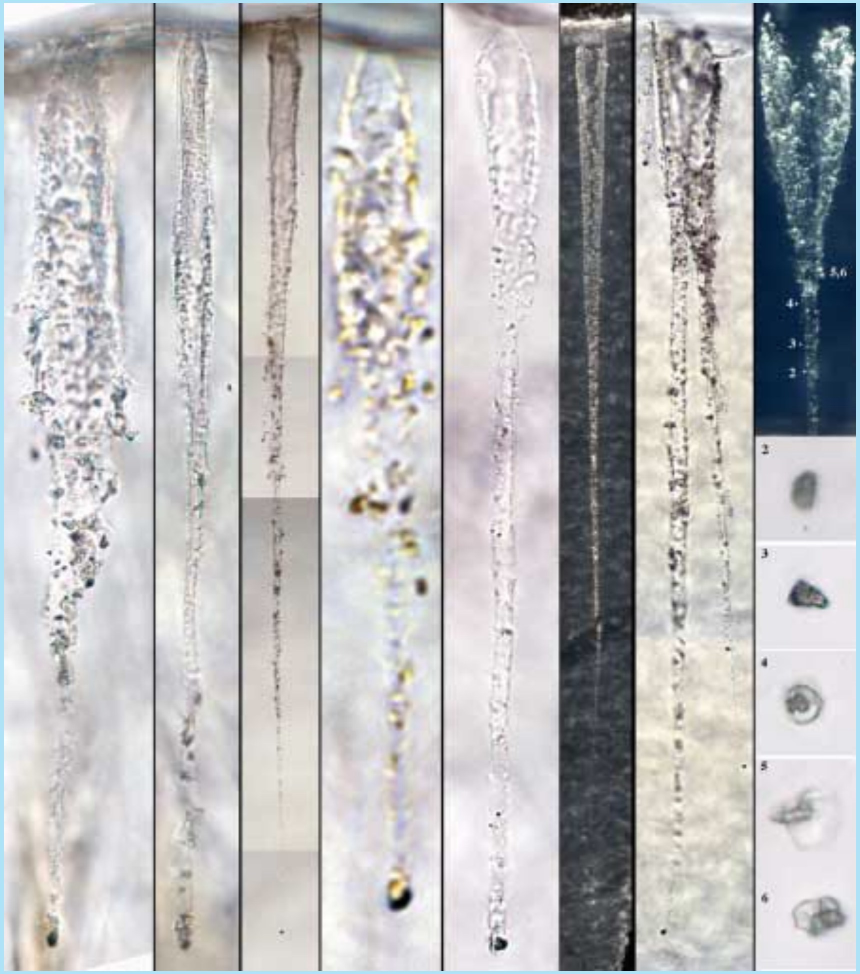
Velocity entry ~ 46 400 km/h

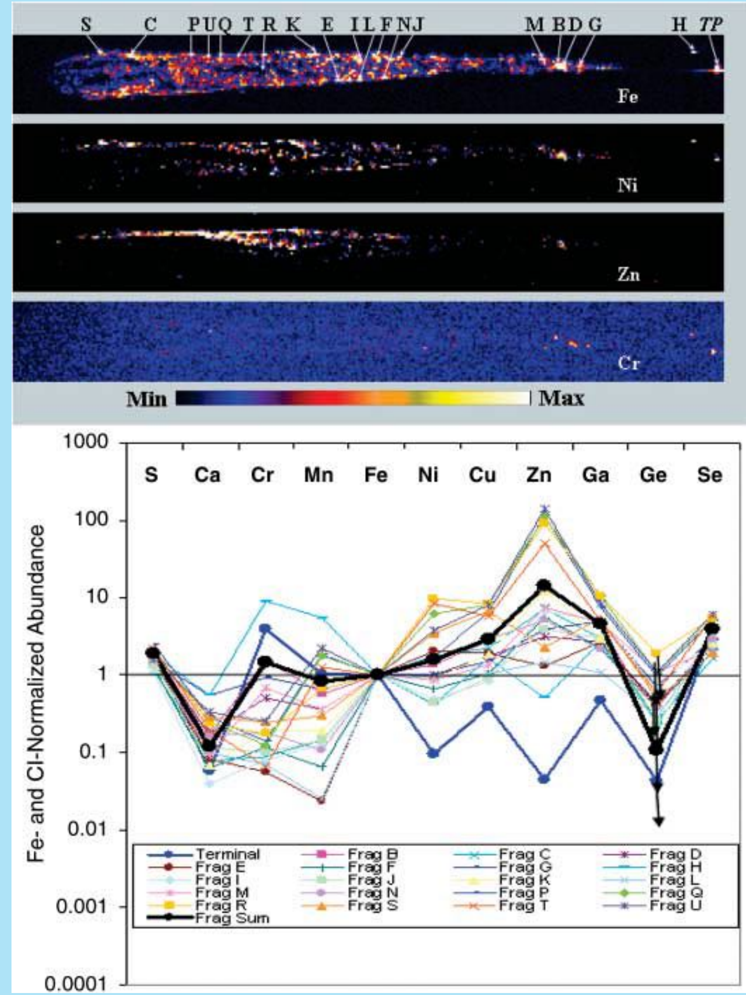
T_{max}: 2700 C

3 days later @ Johnson Space Center

~ 1000 grains with sizes > 5 mm
~ 100 mg of cometary dust

The main results

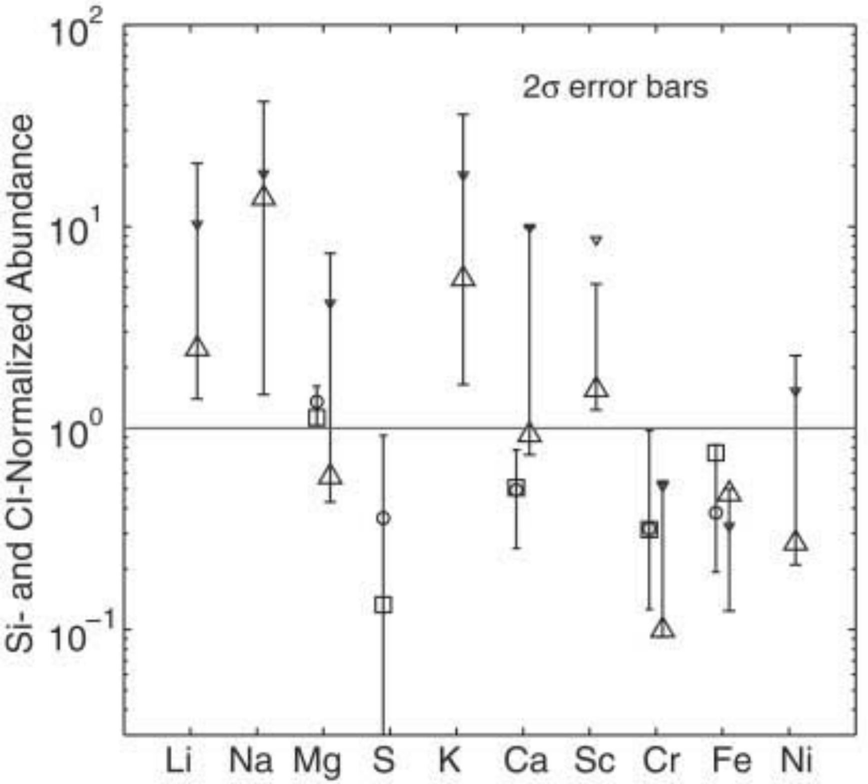


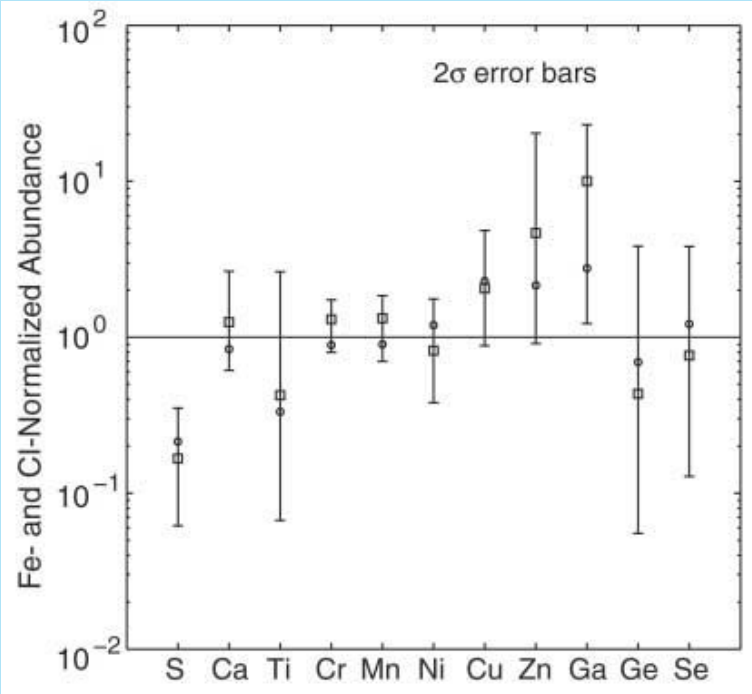


Brownlee et al. Science 2006

The bulk composition is
identical within a facteur 2 to that of CI chondrites Flynn et al. 2006

Composition moyenne de la comète Wild 2



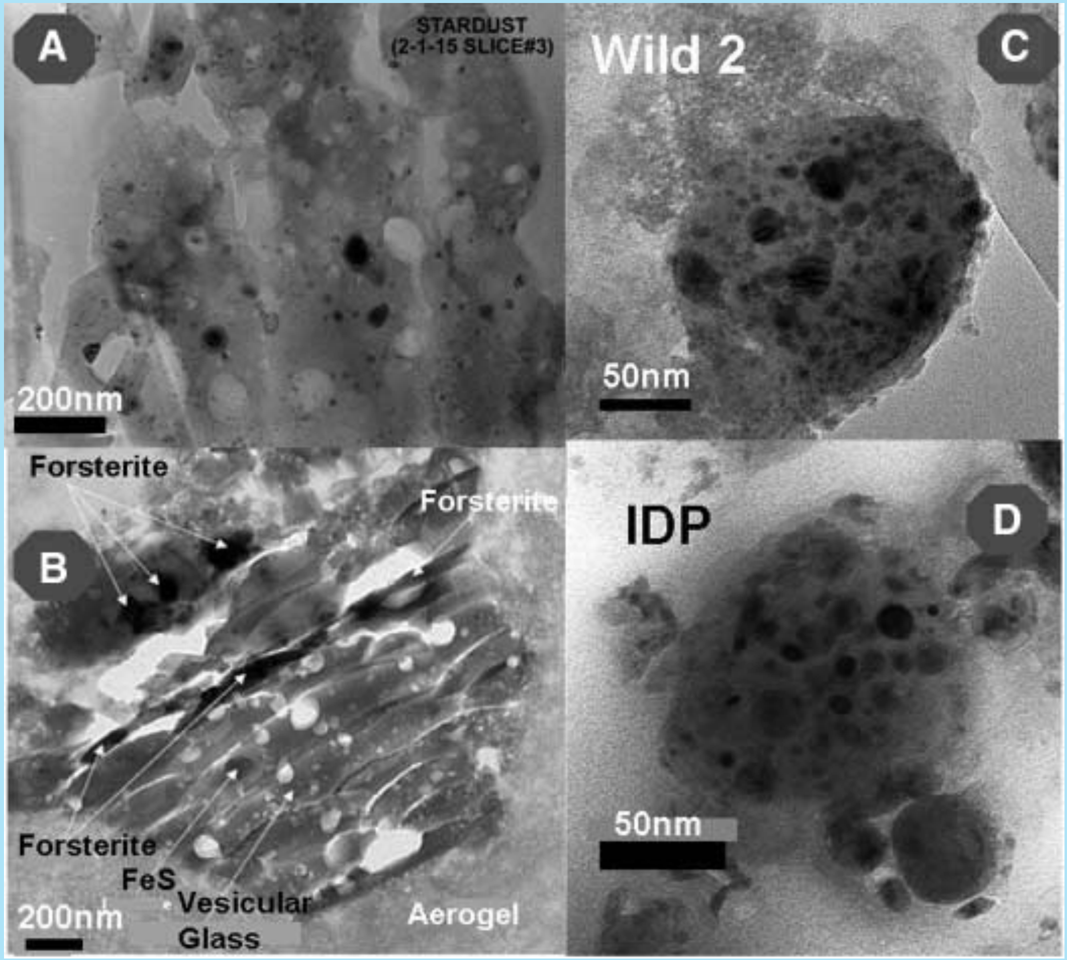


Flynn et al. Science 2006

La même que celle des chondrites carbonées CI

An homogeneous protoplanetary disk

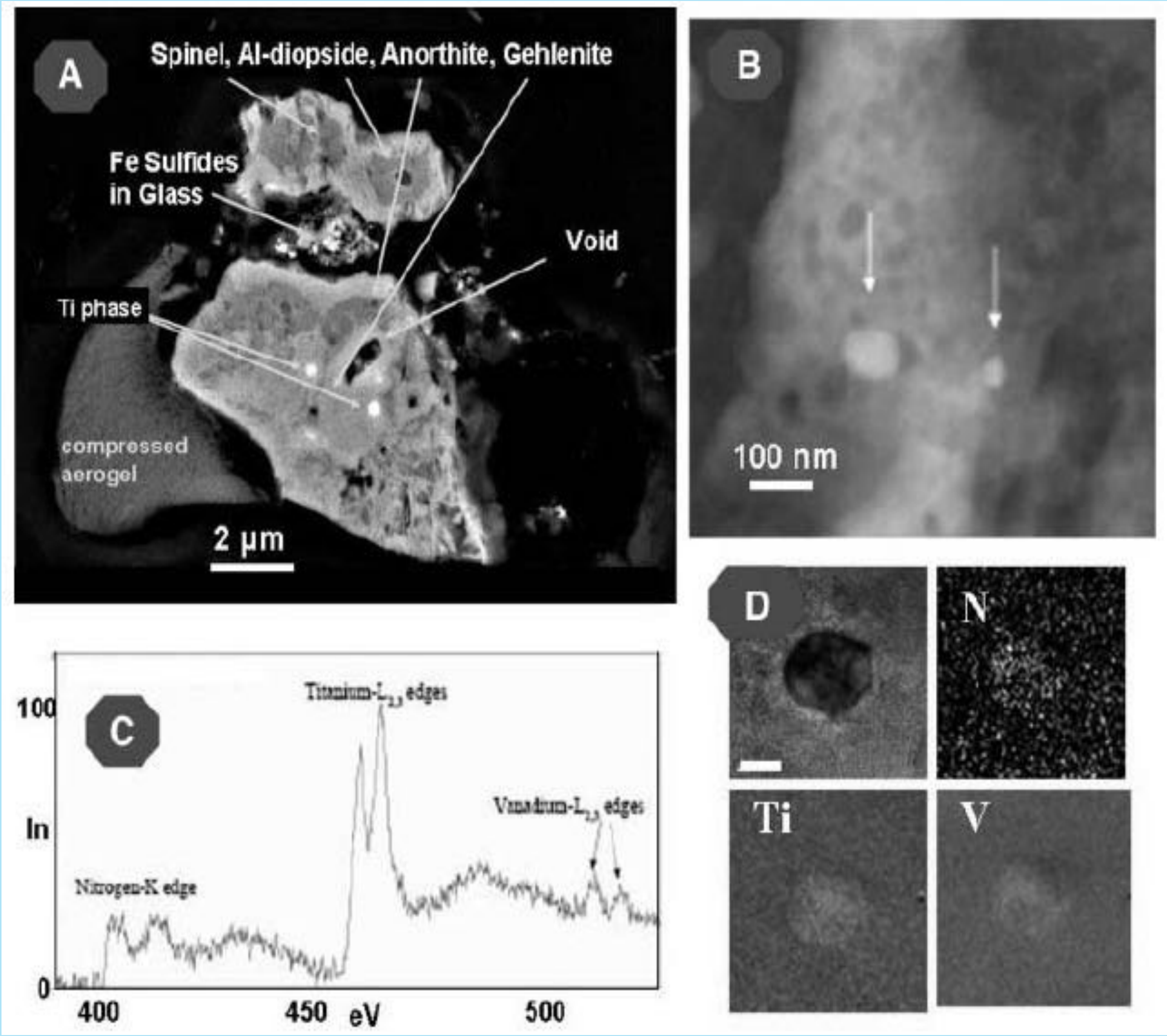
Les minéraux de Wild2



Zolensky et al. Science 2006

- Des phases cristallines et amorphes

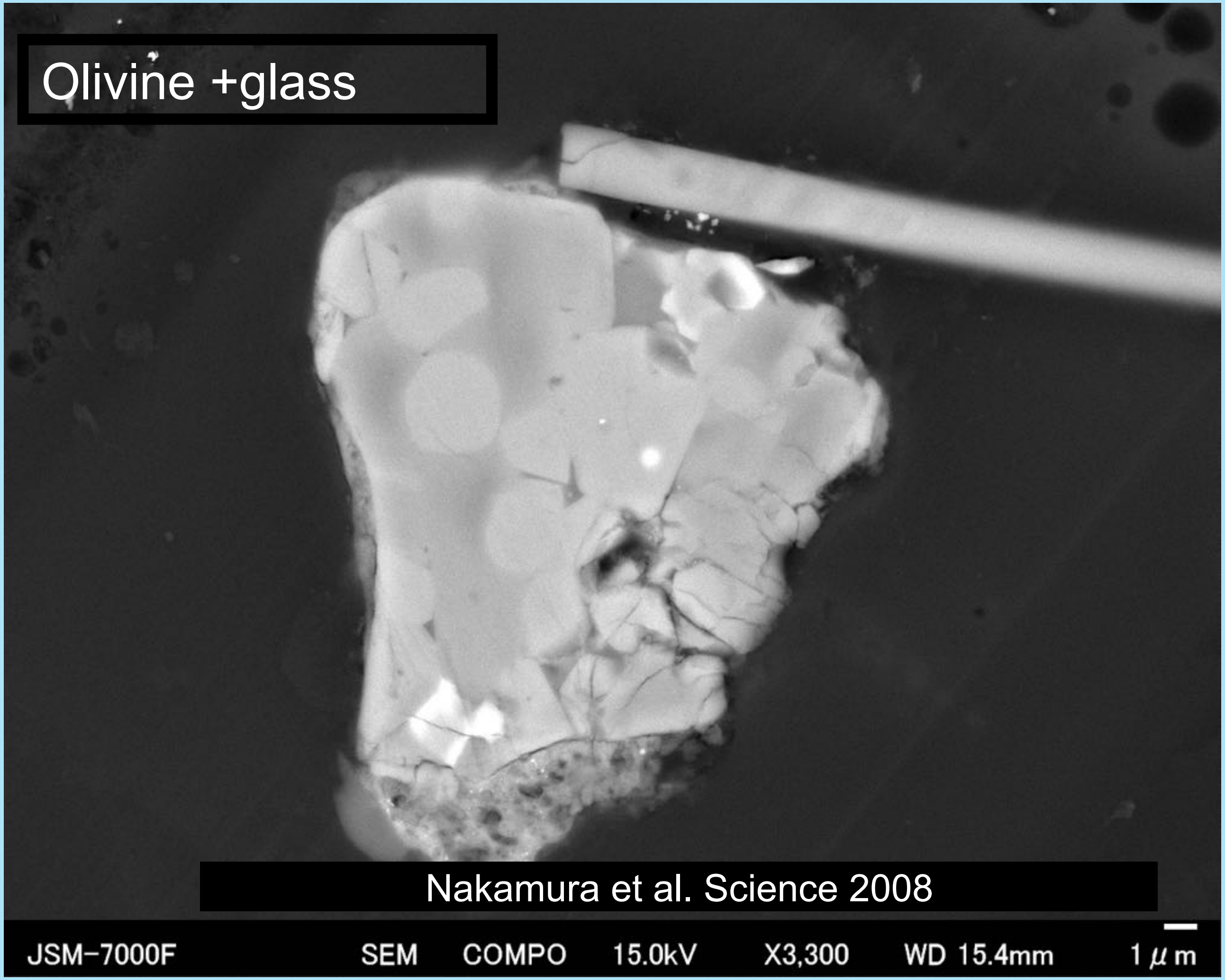
Calcium-Aluminium-rich objects in comets



Zolensky et al. Science 2006

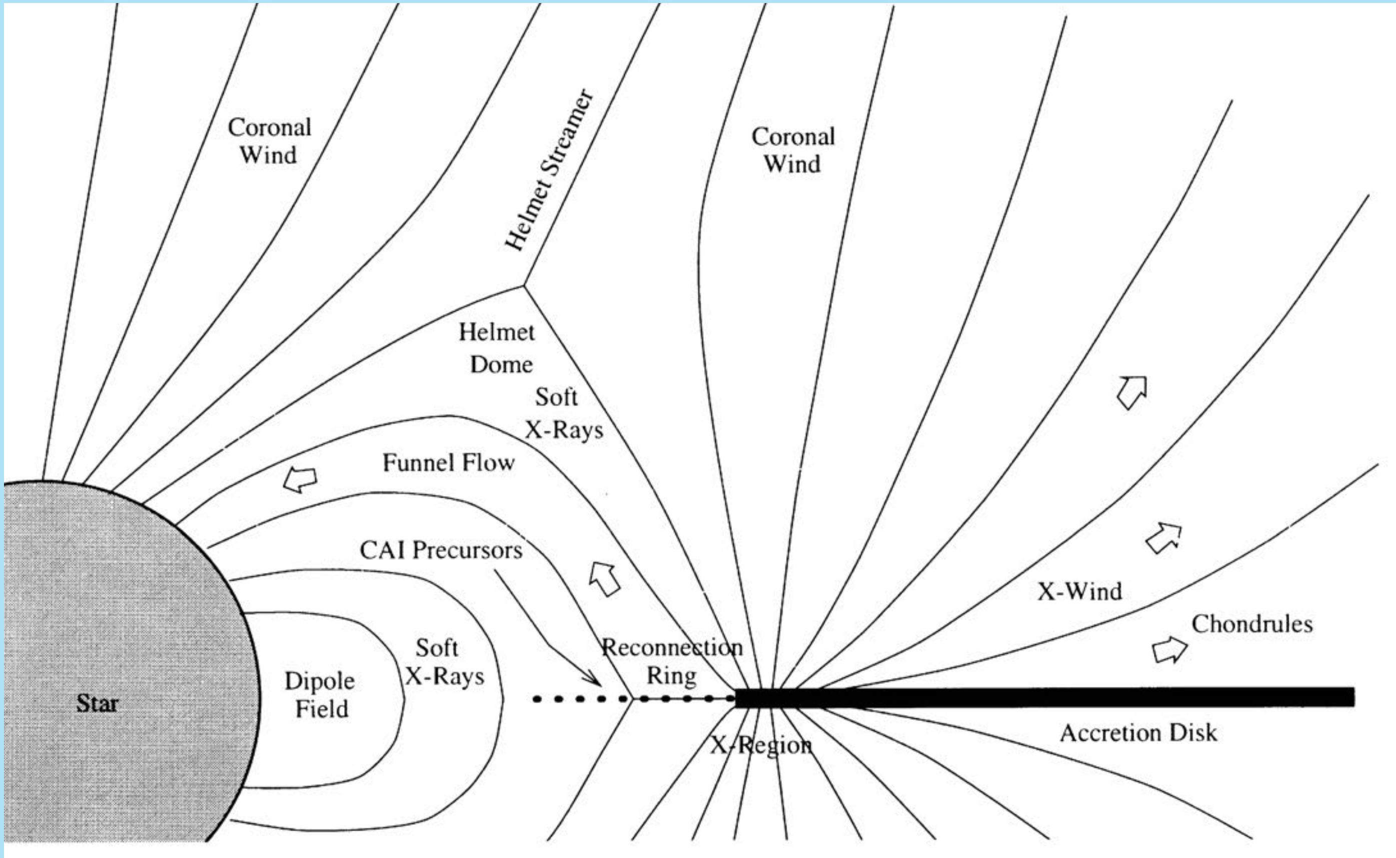
"Remarcably enough, we have found fire and ice," **D. Browlee mars 2006.**

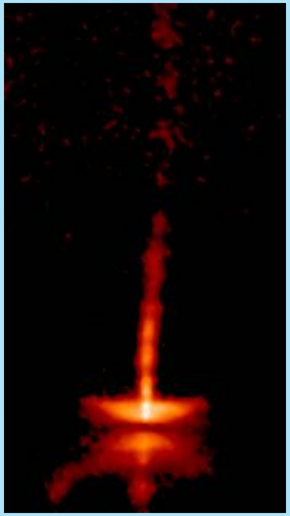
A cometary chondrule



High T phase - important radial mixing in the Solar System

Radial transport in the protoplanetary disk



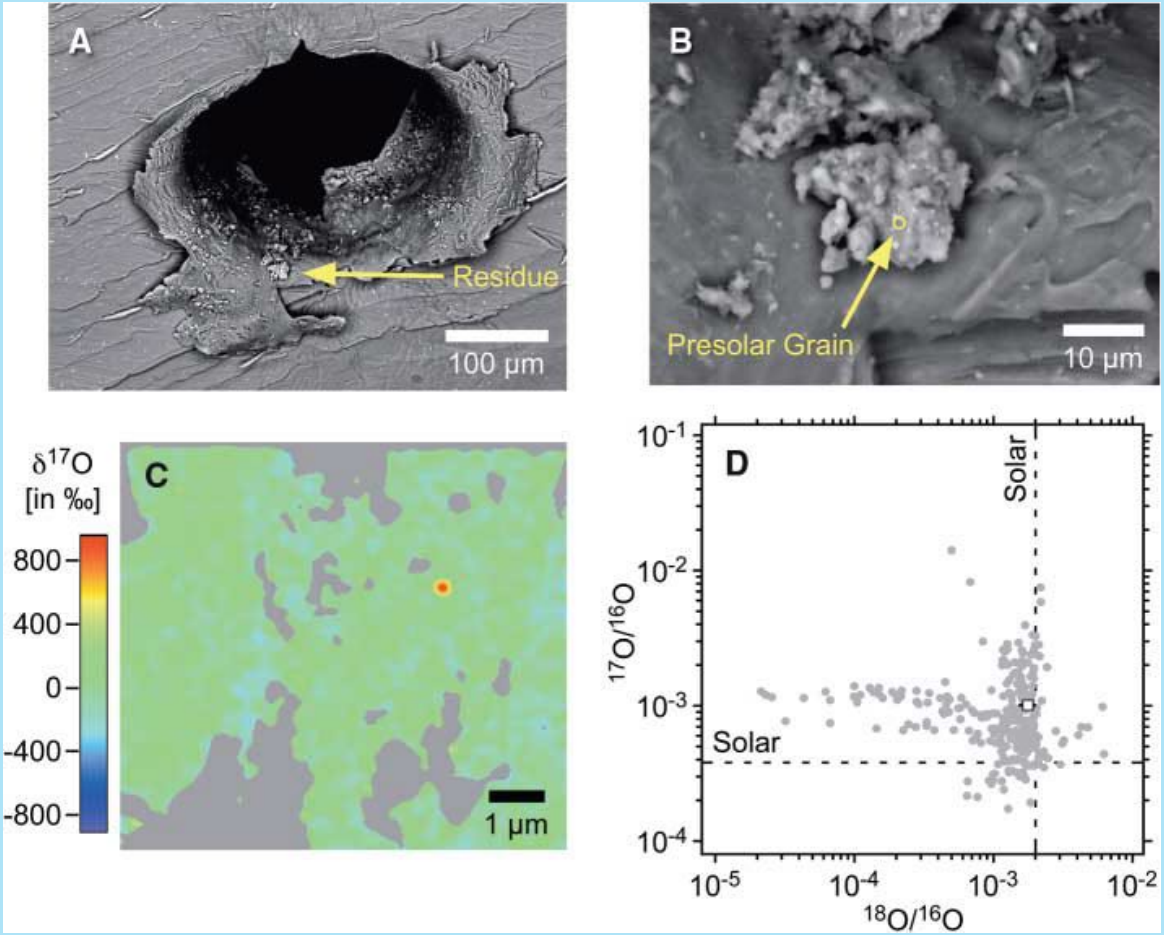


HH 30, Hubble image

Shu et al. Science 1996, Shu et al ApJ 2001, Lee et al ApJ 1998

"CAI and Chondrules are formed at close distance from the star (the reconnection ring : R=0.06 AU) then transported at several AU over the disk by the x-wind…"

Recherche de grains pré-solaires



- Analyses sur 20 slides (5700 micron^2) 12 particules analysées, pas de grains présolaires identifiés
- La particules de Wild2 ne contiennent pas de grains pur 12C (Halley)
- Un grain présolaire identifié dans un cratère (feuille d'aluminium) sur 37 cratères analysés
- **Les particules de WILD2 ne contiennent pas plus de grains présolaires que la matière astéroïdale primitive…**

McKeegan et al. Science 2006

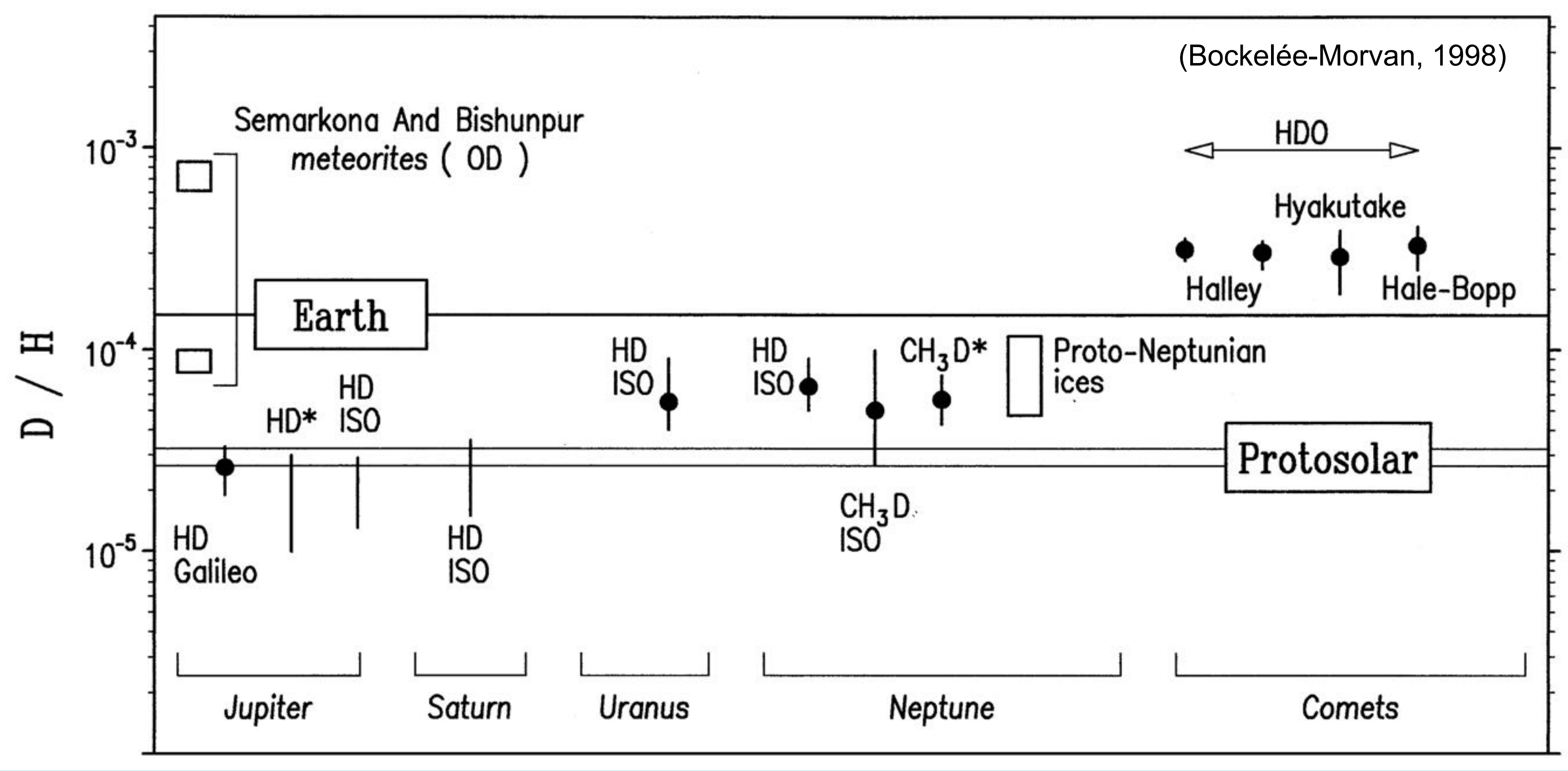
D/H ratios in the solar system

- Protosolar H_2 : D/H ~ 3×10^{-5}
- SMOW H_2O : D/H ~ 15×10^{-5}
- Cometary H_2O : D/H ~ 30×10^{-5}

The origin of the Deuterium excesses

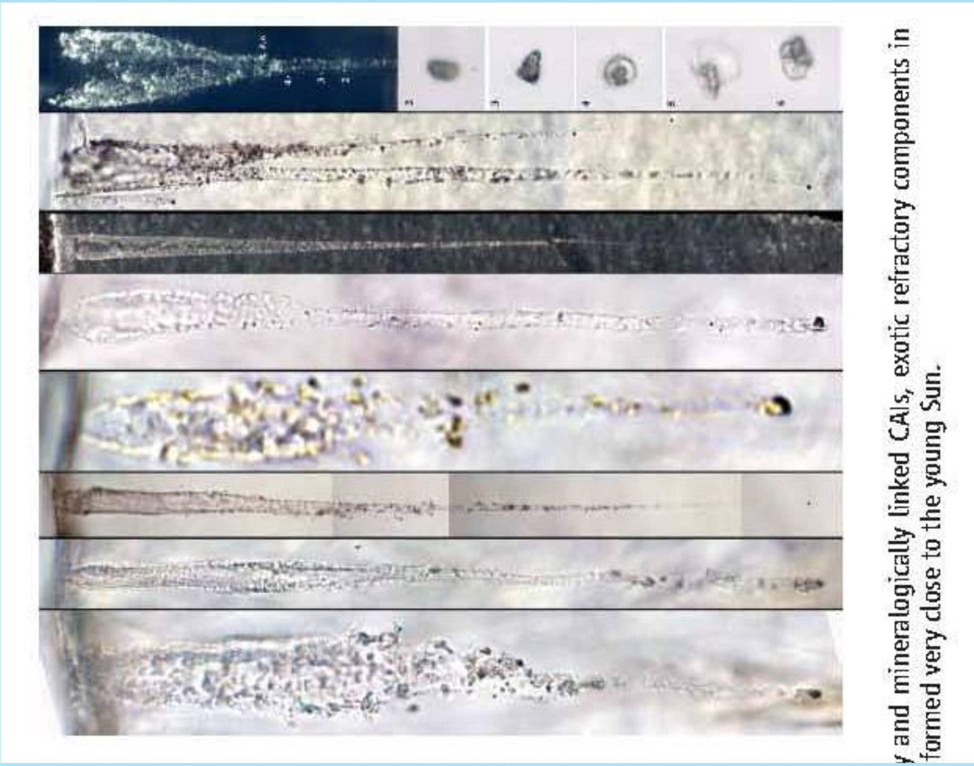
Ion-molecules reactions at low temperature

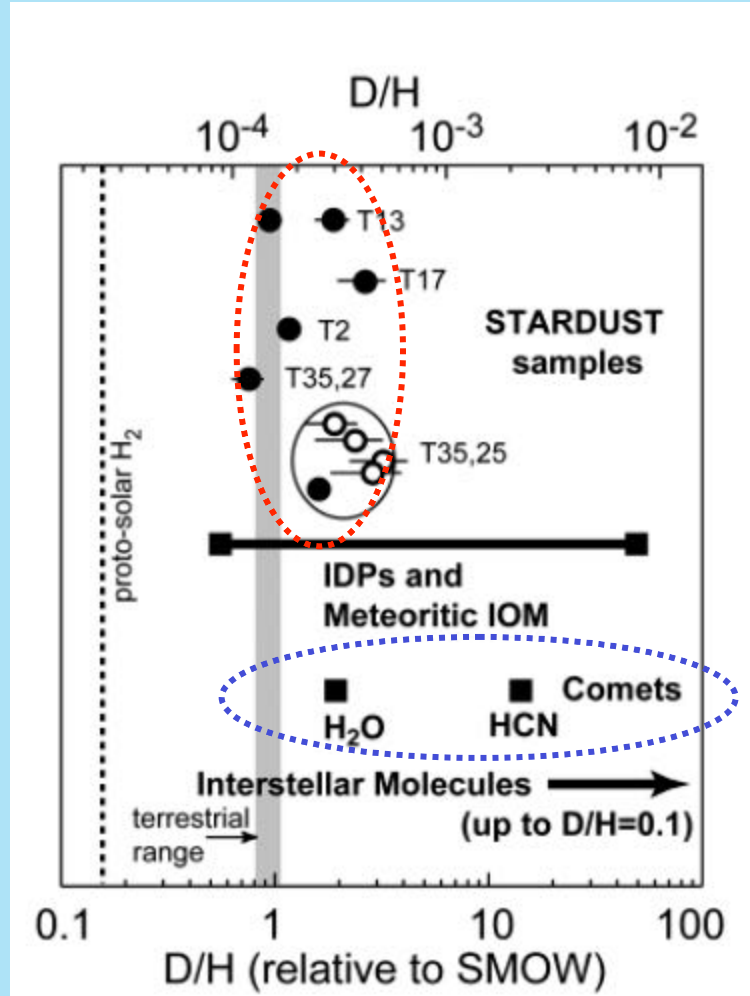
$$H_3^+ + \mathbf{HD} \rightleftarrows \mathbf{H_2D^+} + H_2$$



The quest for pristine early solar system material…

D/H of 81P/Wild2 particles (STARDUST data)

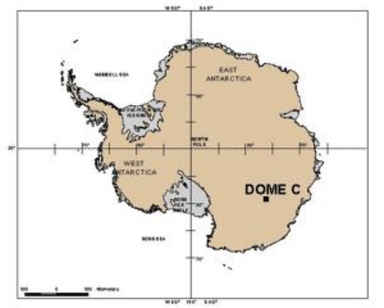




McKeegan et al Science 2006

$D/H < 3 \times D/H_{smow}$

- Heterogeneity of the cometary reservoir ?
- Alteration of the particles :
  - heating
  - mixing with aerogel



The **unique advantages** of Central Antarctica Regions for Extraterrestrial Dust research

* Dome C is **extremely preserved from terrestrial dust contamination** within the MMs size range [d > 50mm] :
  - 1100 kms from the coasts of Adélie Land, 3200 m in altitude
  - The dominant wind blowing from centre to coast
  - The surface snow is separated from the bedrock by more 3,5 km of ice

-> a **high ET/T ratio** is expected, search for **new objects**

* Dome C **snow stays at low temperature** thought the year **(-70° < T<-20°)**

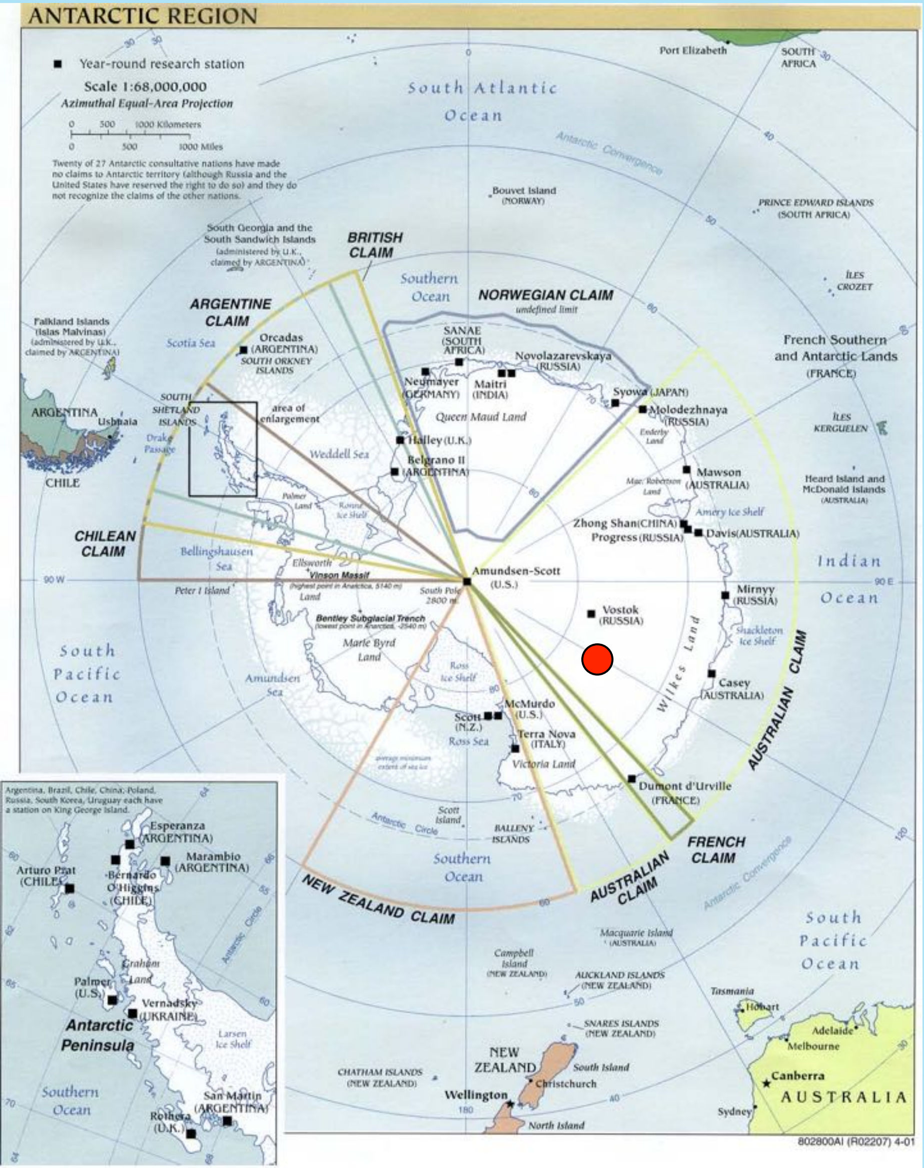
-> **unique condition of preservation from terrestrial weathering** are expected

- Dome C has **very low and regular precipitation rate :**

-> recover micrometeorites from **reasonable volume of snow** (few m^3)
-> measure a **FLUX of ET particles/m^2/year**
-> search for **variations in intensity/composition of the flux** in the last century

Duprat et al. *EAS series 2005*.

The polar Instituts (IPEV / PNRA)



Le Programme
« Micrométéorites @ Dôme C »

Dôme C, Janvier 2000

Neige de surface

(0-80 cm) @ 3 km du camp

Dôme C, Janvier 2002

Tranchée 3-4 mètres

V = 11 m^3

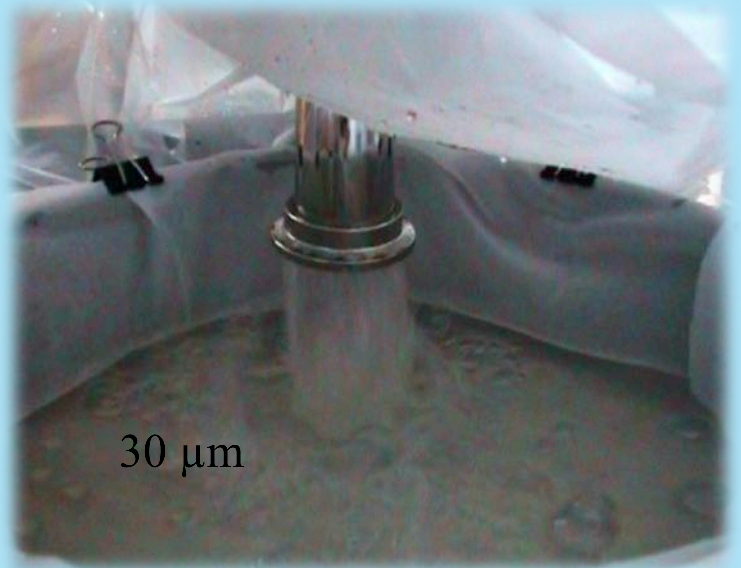
Dôme C, Janvier 2006-2014

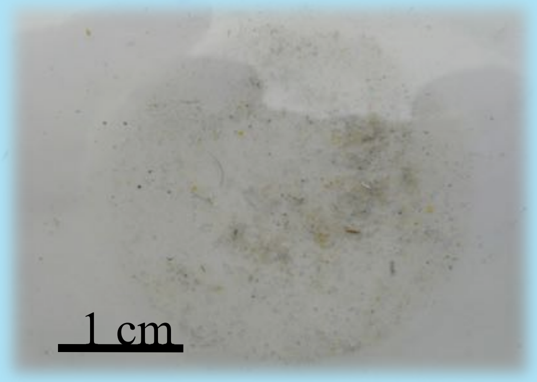
Tranchée 4-5 mètres

V = 25 m^3

The melting/sieving procedure

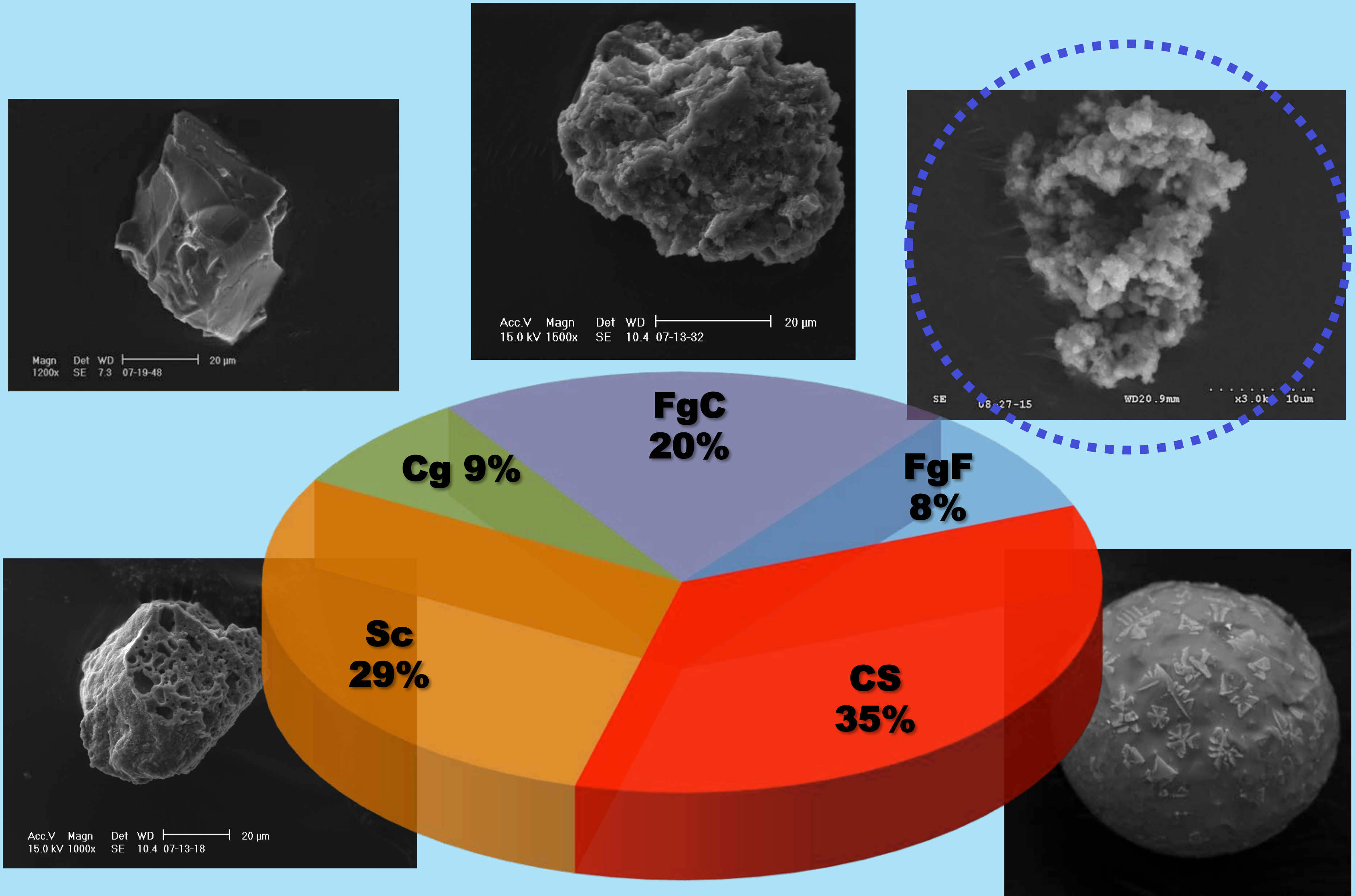
High efficiency double tank stainless steel smelter / 35kW propane boiler



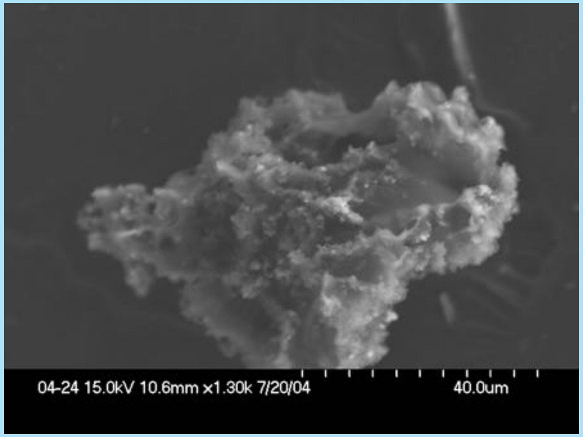


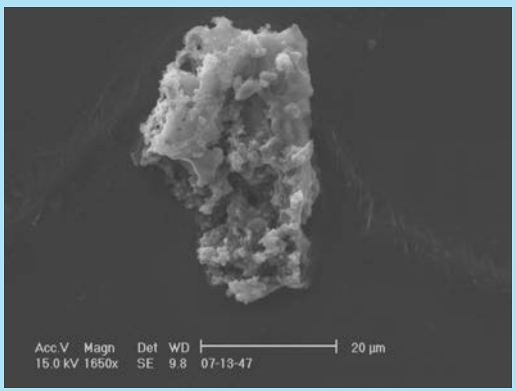
The 30 µm filters are pre-analyzed in a mini-lab to control terrestrial contamination

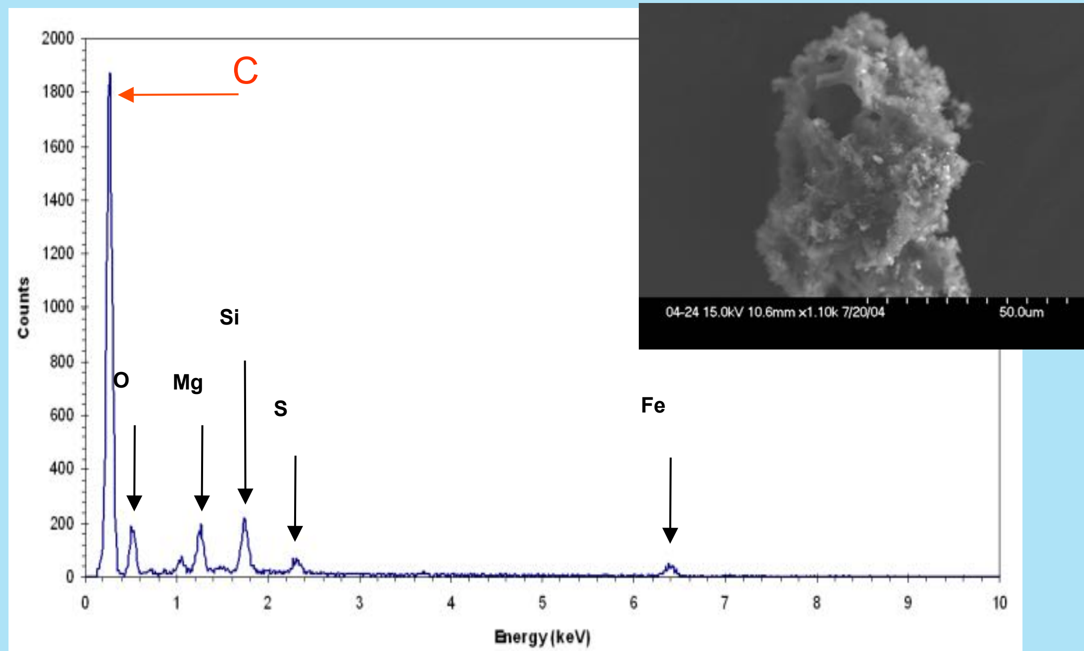
The CONCORDIA Collection, different types of micrometeorites



UltraCarbonaceous Antarctic MicroMeteorites (UCAMMs)







Dobrica, Engrand et al. LPSC 2008

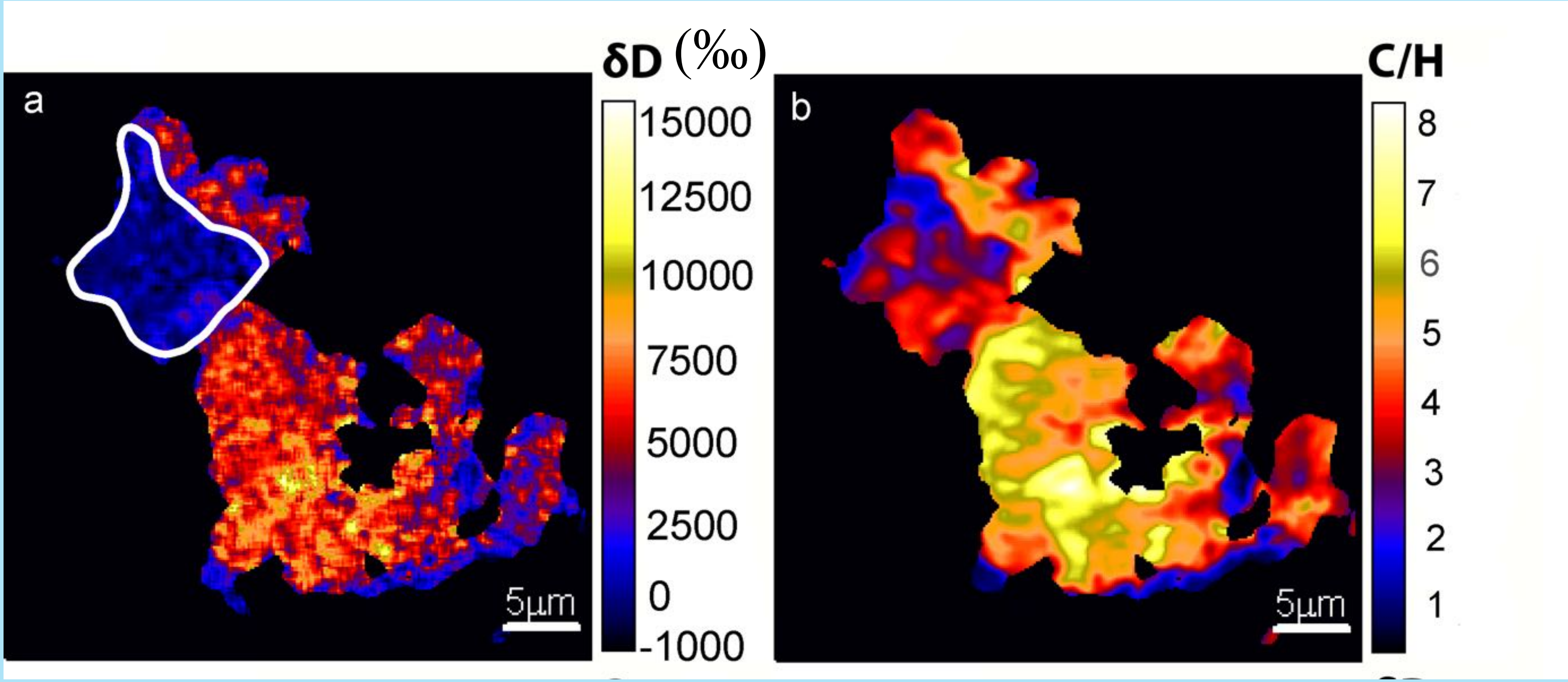
Among the fine grained particles, some exhibit extremely high carbon content, the UCAMMs.
In UCAMMs, the organic matter represent more than 50 vol%

A new type of extraterrestrial material similar to:

- *CHON* particles (Halley comet) (Kissel et al 1987)
- Rare C-rich IDP (stratospheric collections) (Thomas et al. 1993)

D/H ratios in ultracarbonaceous micrometeorites

Data Nanosims Muséum National Histoire Naturelle

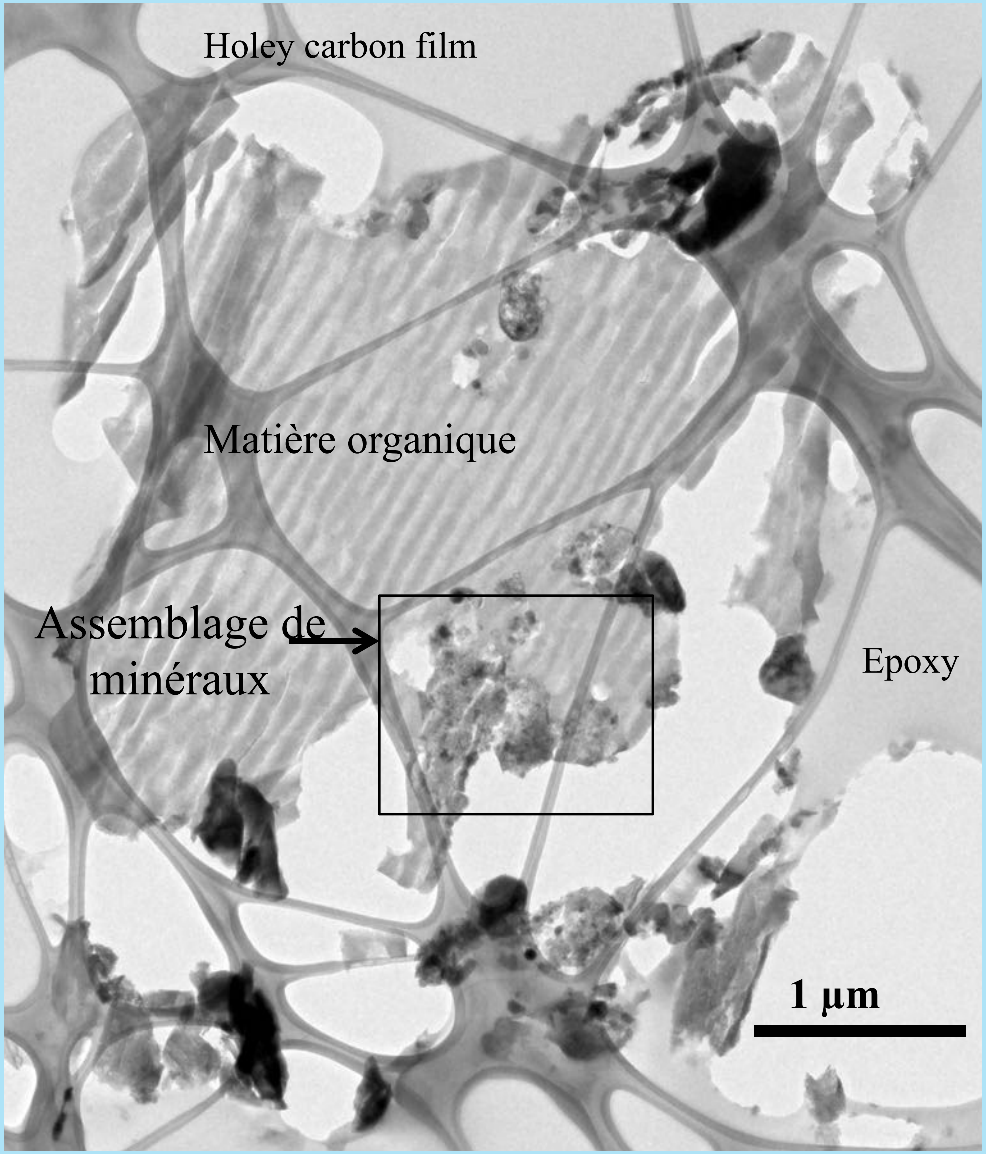


Duprat et al. Science 2010

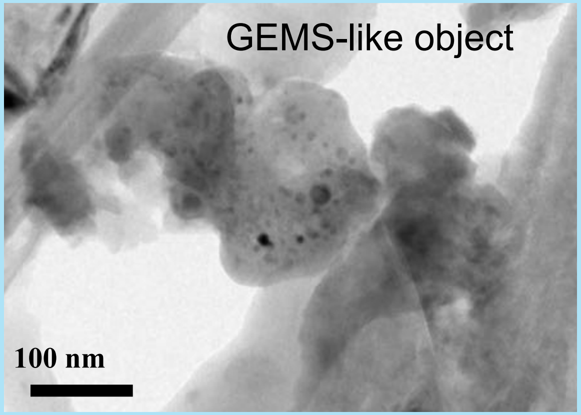
D/H in a UCAMM fragment (DC06-08-19)

- D/H ~ 10 x D/H_{smow}
- the D excesses are carried by the organic phase

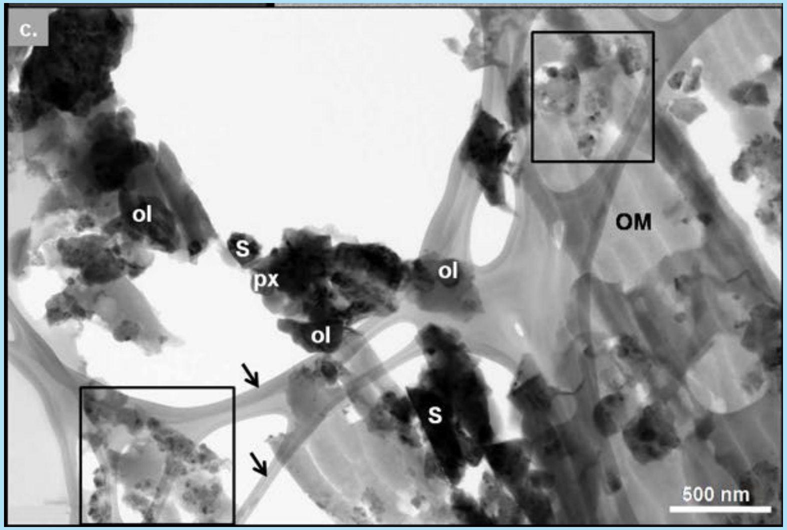
UCAMMs allow to study the intimate association between high (minerals) and low (organics) temperature phases.



Data TEM Univ. Lille (E. Dobrica, C. Engrand, H Leroux)



Amorphous phases



Crystalline phases 50-100 nm

Crystalline phases are typical of protoplanetary disk and similar to that reported in STARDUST samples

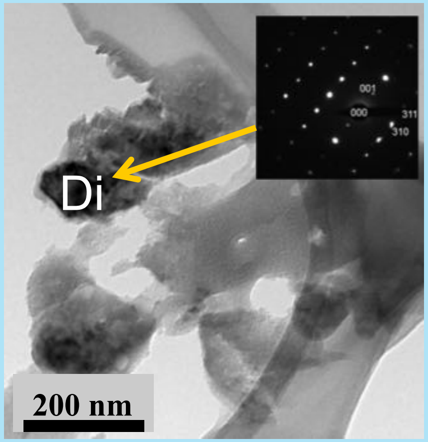
In the ISM

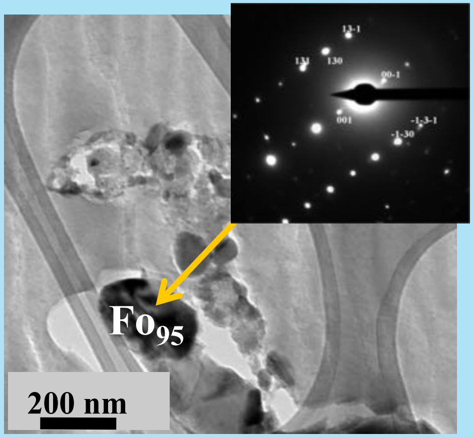
Xtal/Amorphous

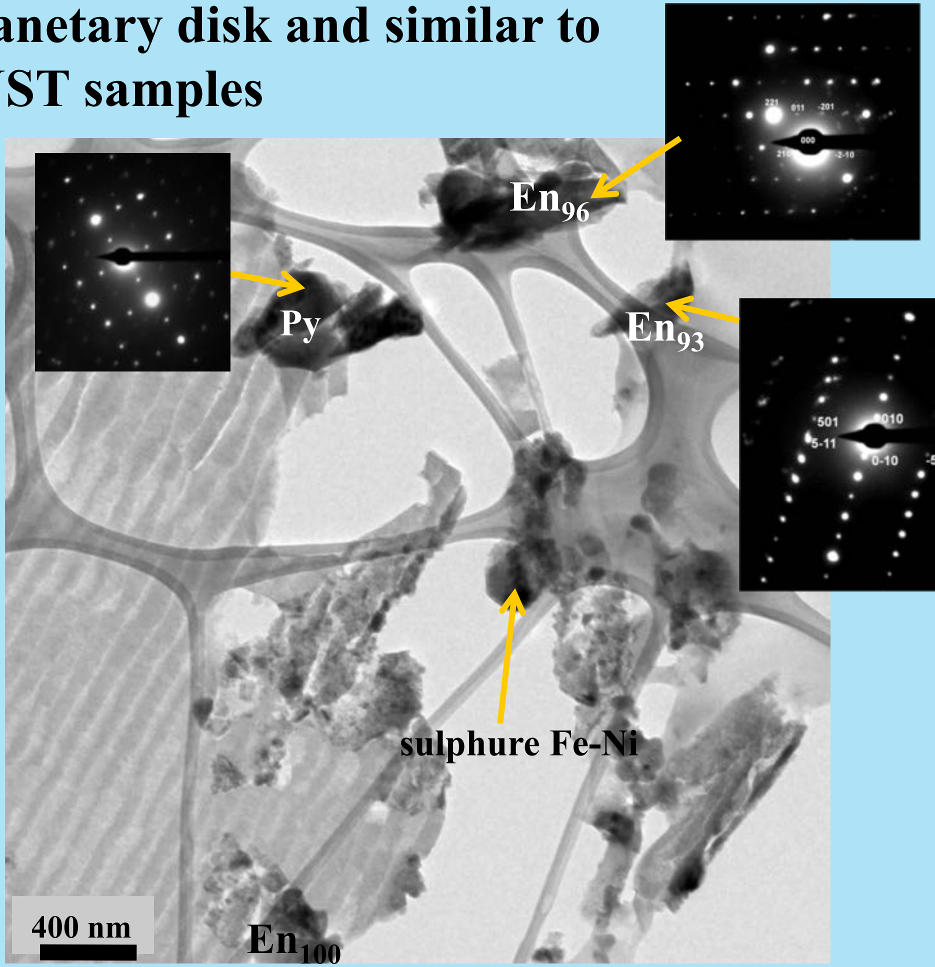
< 2.2 wt%

(Kemper et al. ApJ 2004)

Not at all what is observed in UCAMMs!







Data TEM, Dobrica, Leroux, Engrand

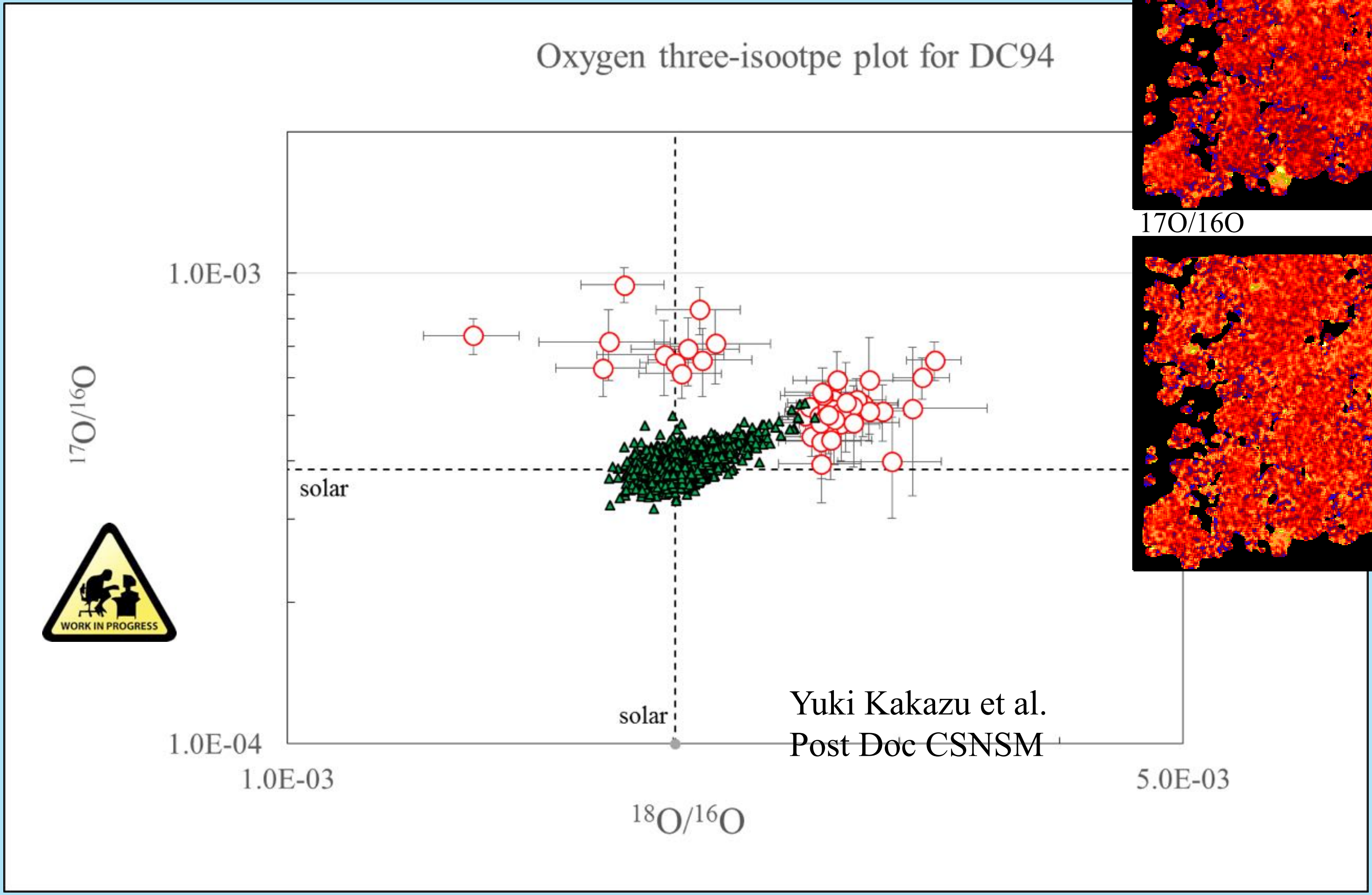
A mixing between high and low temperature materials

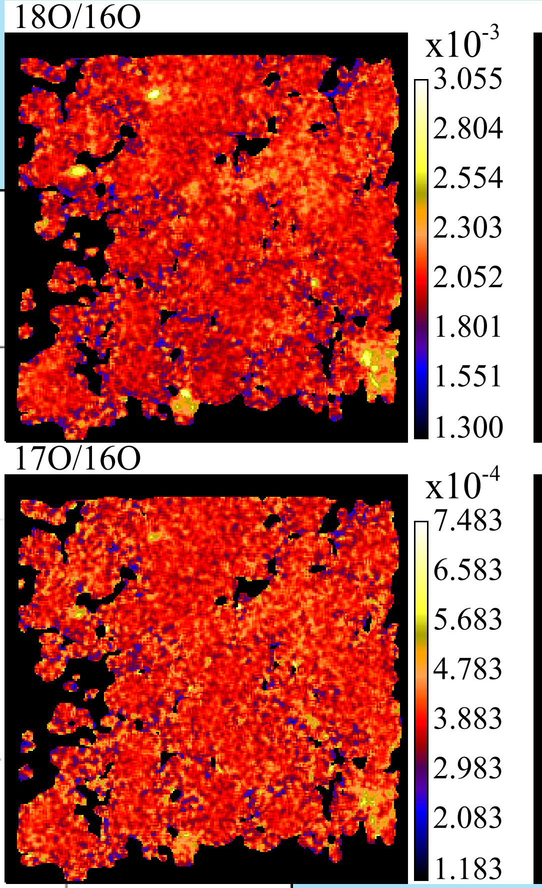
⟶ confirmation of the radial mixing from inner zones to the comet forming region

No sign of abnormal interstellar heritage

→ a local origin of the Deuterium excesses in the primitive organic matter, i.e. within the proto-planetary disk itself ?

Presolar Grains in an Ultra-Carbonaceous micrometeorite

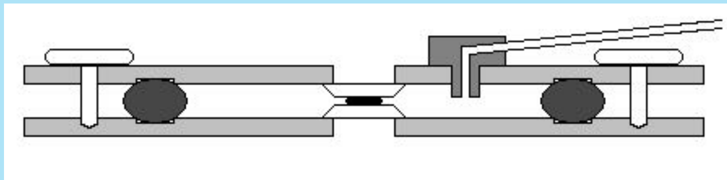


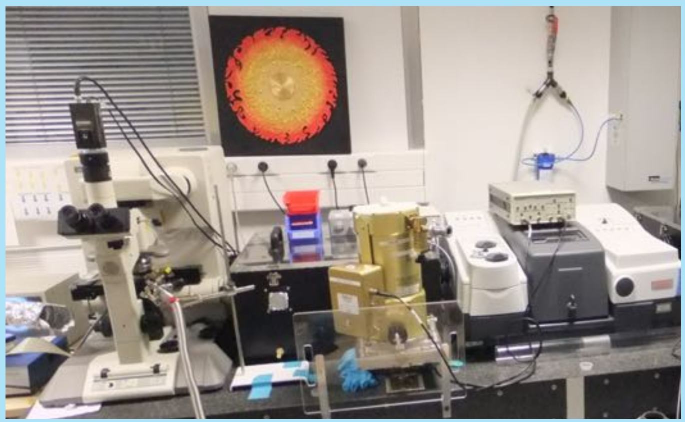


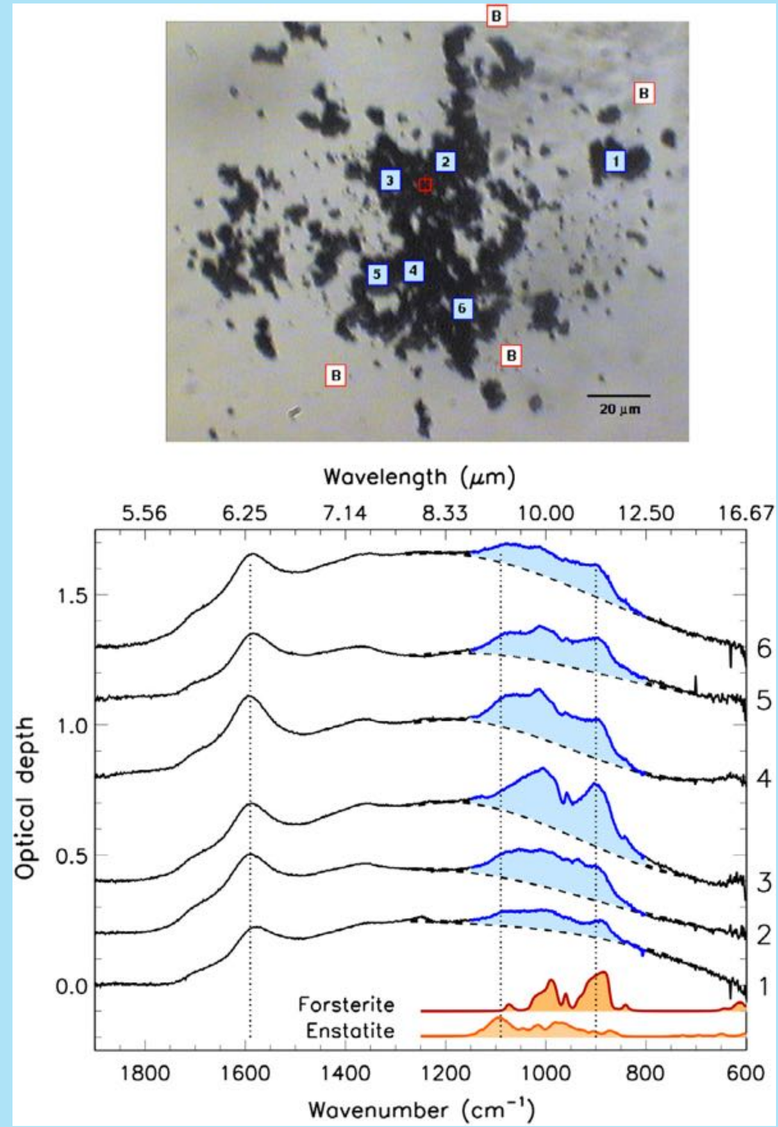
Yuki Kakazu et al.
Post Doc CSNSM

Coupled studies on the same sample

- ✓ Infra-Red transmission microanalyses @ synchrotron SOLEIL
- ✓ Elemental composition : SEM and electronic microprobe



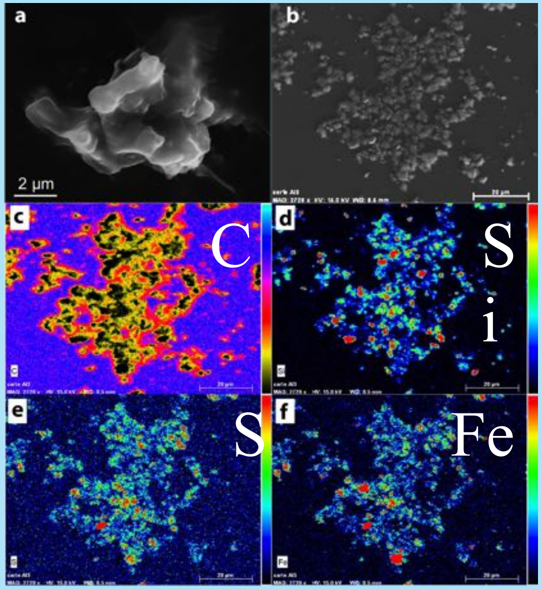




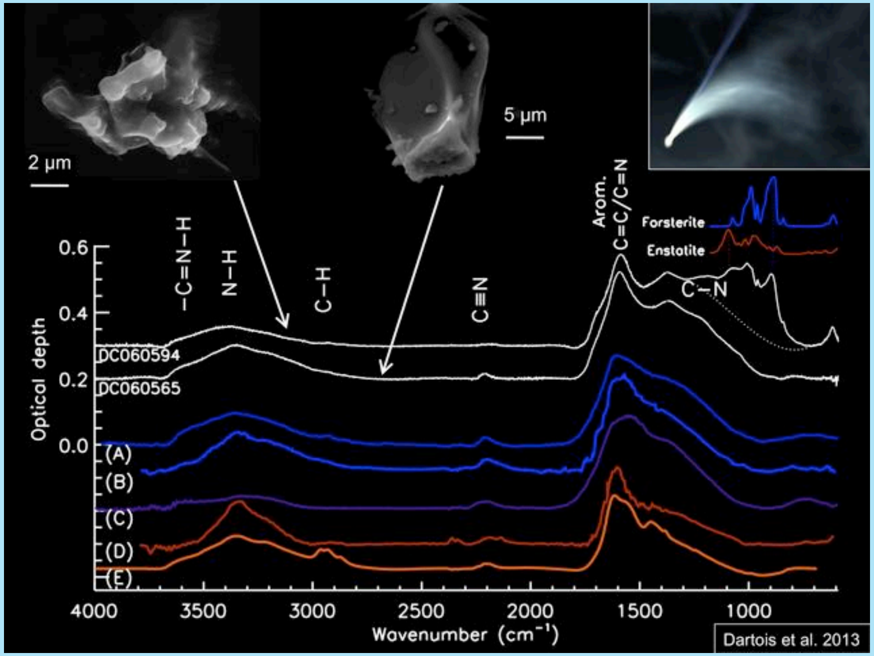
Dartois, Engrand et al. Icarus 2013

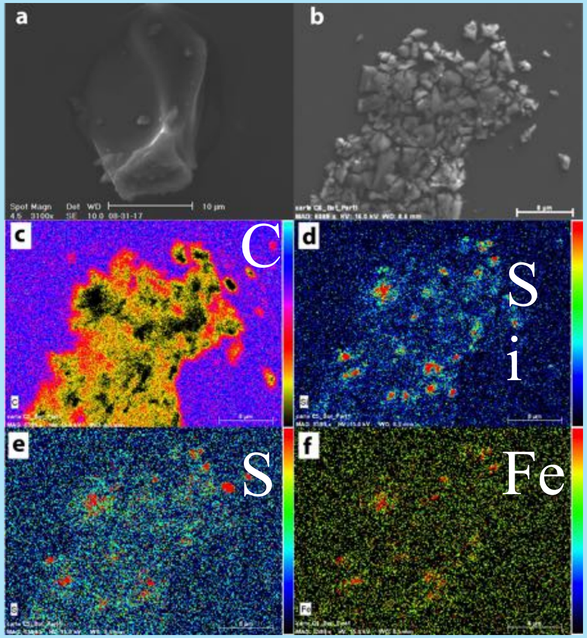
- ✓ Isotopic studies at the Nanosims
  (MNHN, Institut Curie Orsay)

The UCAMM organic matter is nitrogen rich

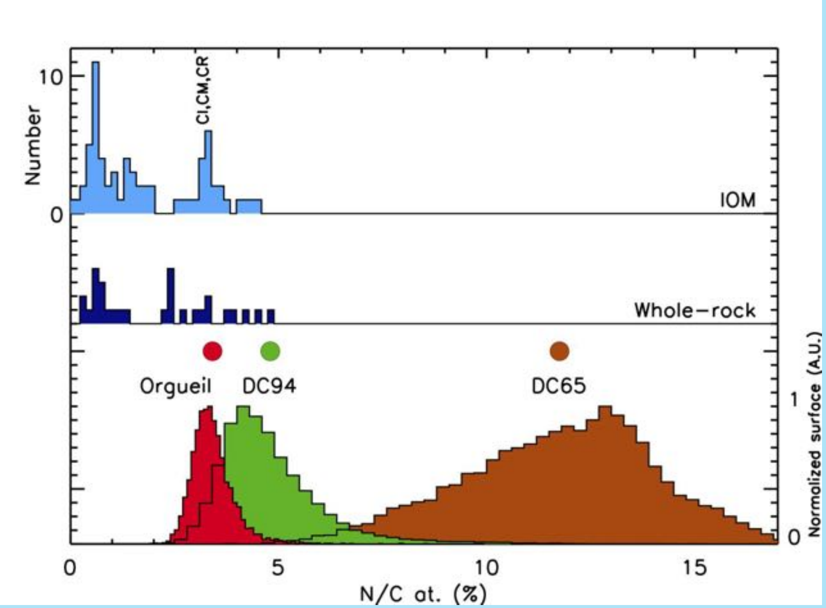


DC06-05-94, mineral rich



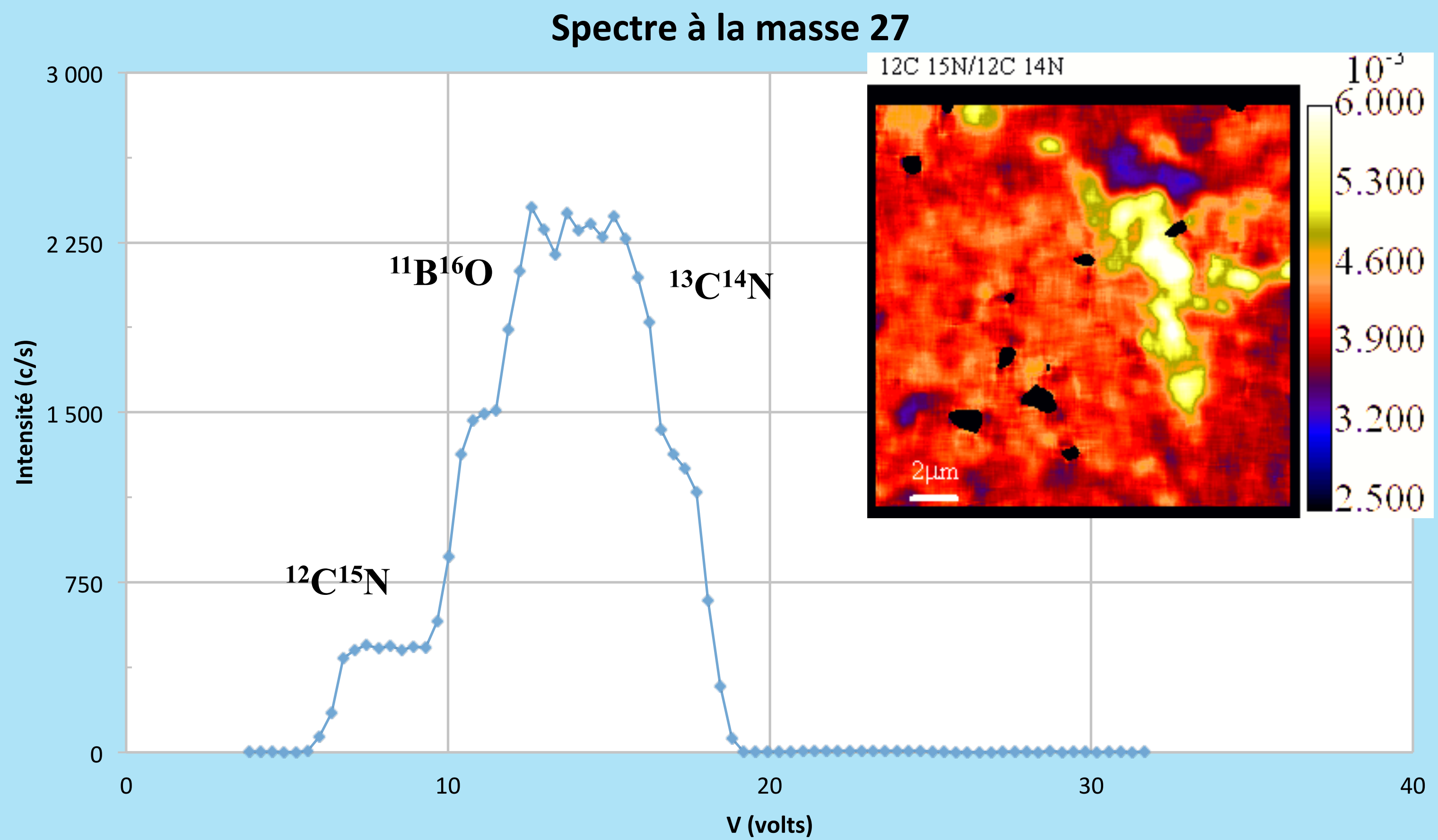


DC06-05-65, mineral poor



Dartois, Engrand et al. Icarus 2013

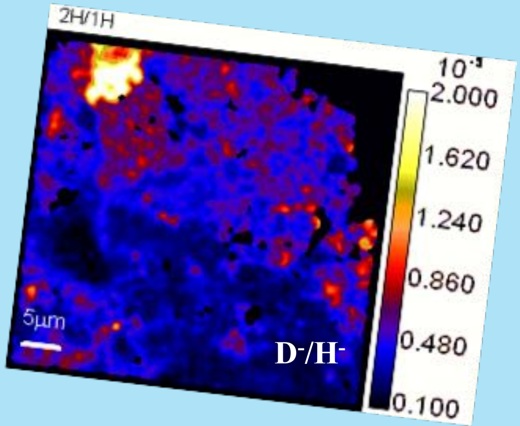
La composition isotopique de l'azote mesurée via la molécule CN



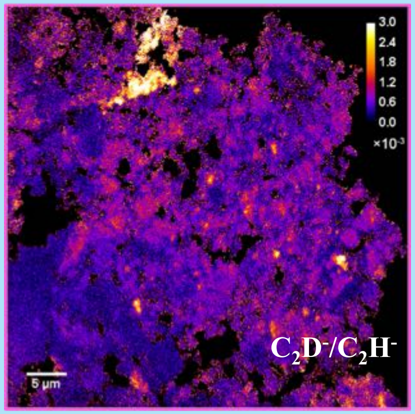
DATA NanoSIMS MNHN, ANR OGRESSE, 2012-2016

difficulté de mesurer $^{12}C^{15}N$ (interférence avec $^{11}B^{16}O$)

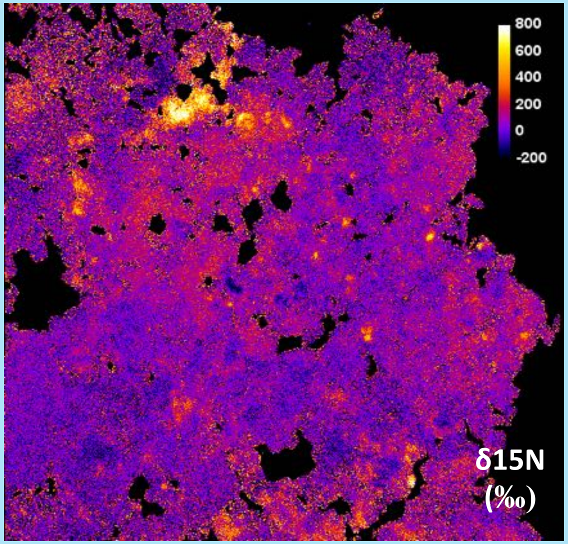
Hydrogen and Nitrogen isotopic measurements on UCAMMs



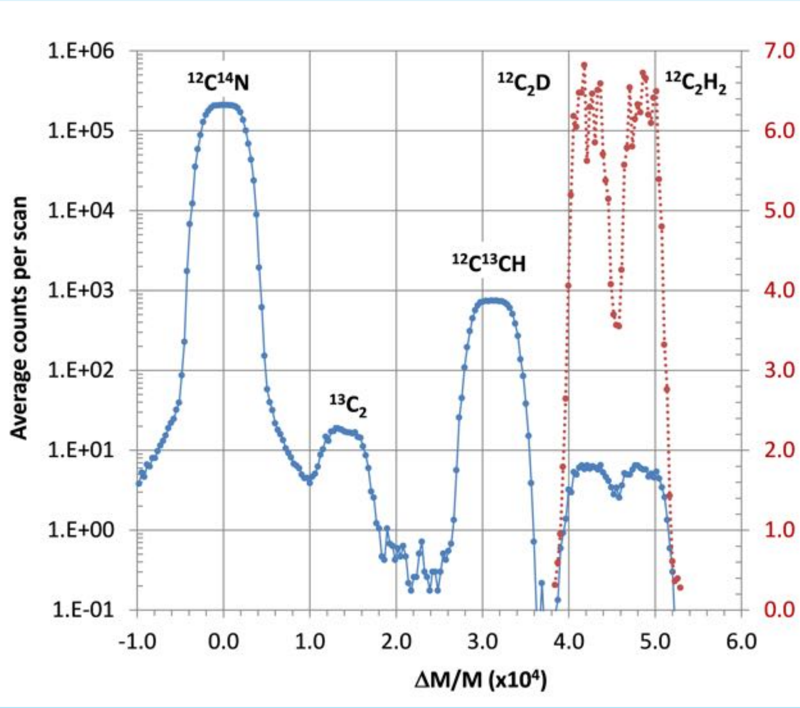
Fcp=22pA,
Low Res, 50x50 µm, (256x256)



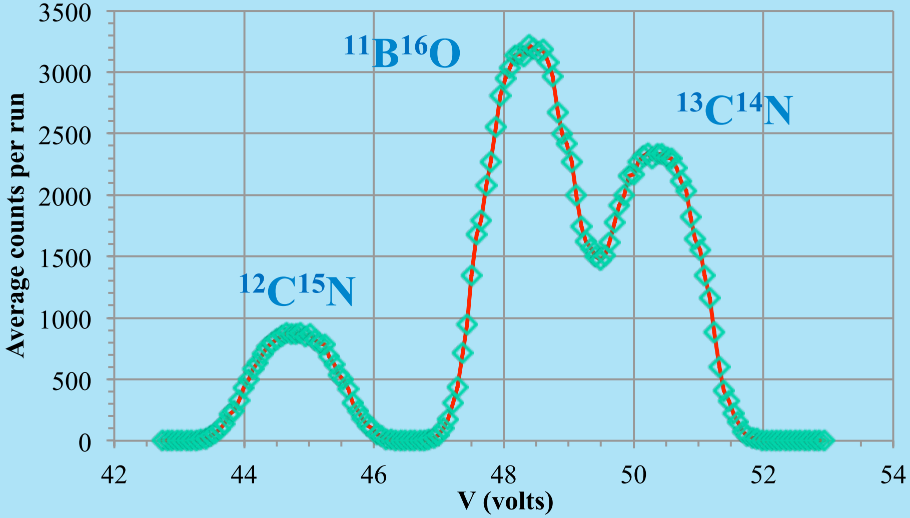
Fcp=11 pA,
High Res, , 50x50 µm (512x512)



Fcp=9.9 pA
High Res, , 50x50 µm (512x512)

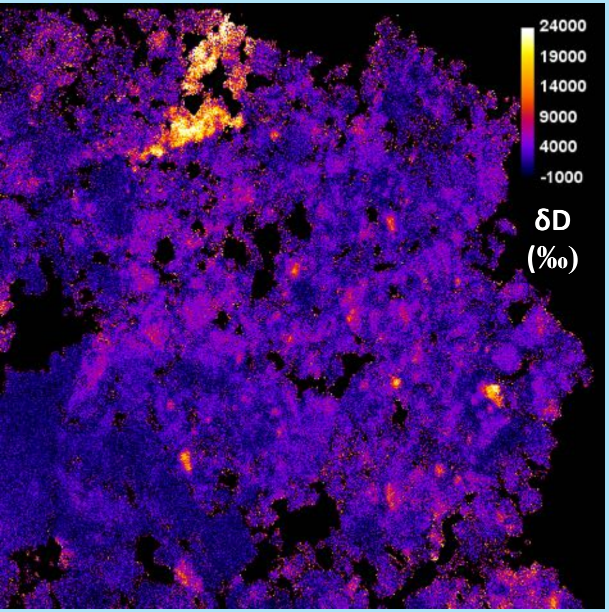


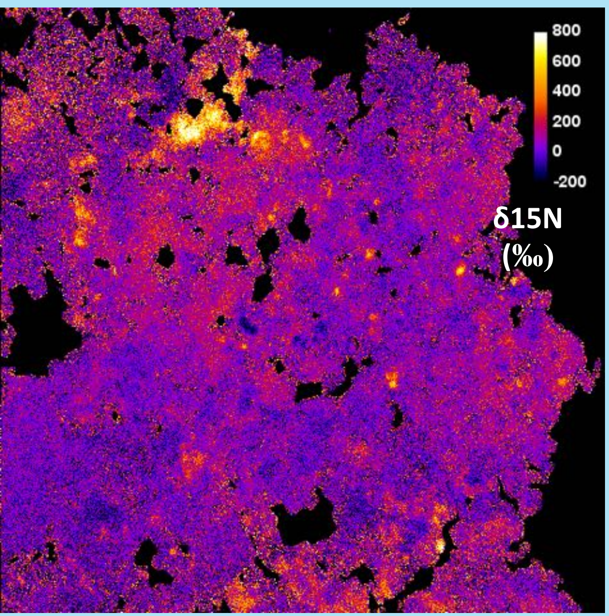
Scan (N=20) at mass A=26 on a Polyacrylonitril (150nm) film,
$^{12}C^{14}N$-$^{12}C^{13}CH$ use as reference, (C_2D-C_2H_2 1/16800)

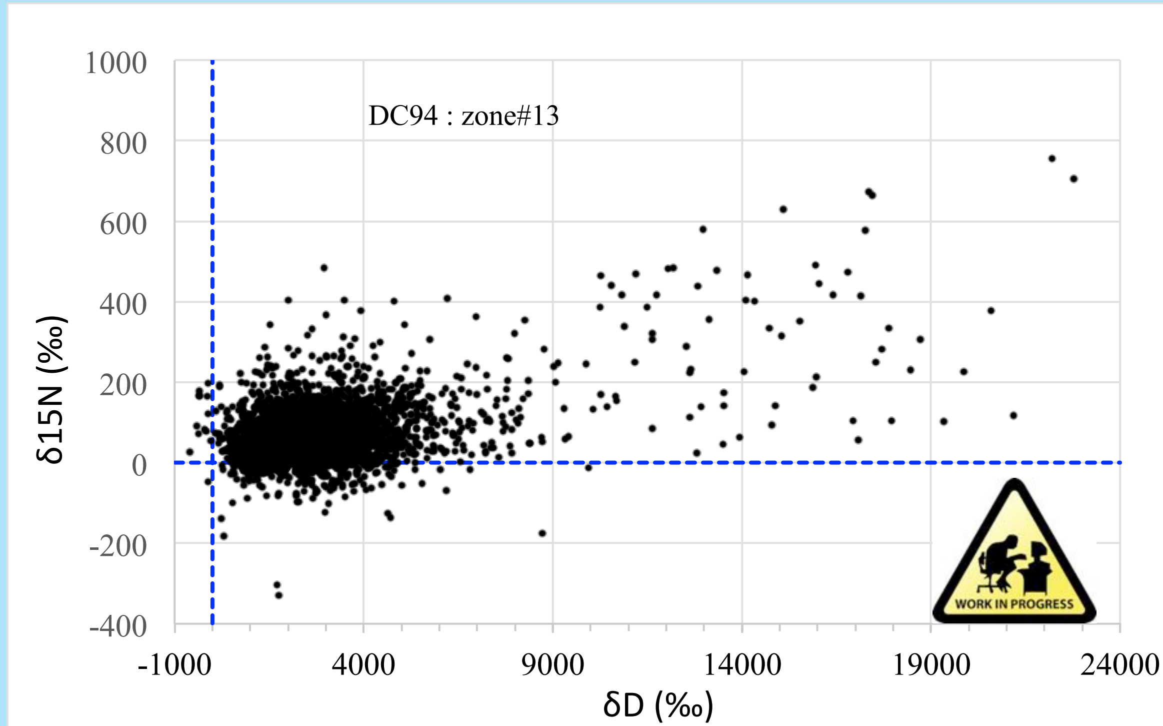


Scan (N=10) at mass A=27 on UCAMM 94
(the built-in instrument voltage were divided by 2)

Spatial correlations between D-rich and ^{15}N-rich phases







Noémie Bardin PhD

UCAMM DC06-05-94 zone # 13
Images size : 50 × 50 µm² (un-smoothed 512 × 512 px).
C_2D/C_2H, Fcp=11 pA, $C^{15}N/C^{14}N$ 30 frames , Fcp=9.9 pA Correlation plot, ROI size : 0.78*0.78 µm² (8*8 px)

Some areas exhibit a correlation between D and ^{15}N excesses but not all.
Still a work in progress…

Conclusion

- ✓ The central regions of the Antarctic continent provide the opportunity to recover **rare and fragile micrometeorites**
- ✓ Ultracarbonaceous Antarctic MicroMeteorites from CONCORDIA collection are most probably **giant cometary grains**
- ✓ **High mass resolution** with the Nanosims allows the use of polyatomic ions (e.g. OD/OH, CD/CH, C_2D/C_2H) for isotopic studies
- ✓ The organic matter from UCAMMS is **N-rich and D-rich** and **is** most probably sampling **material from beyond the nitrogen snow-line**