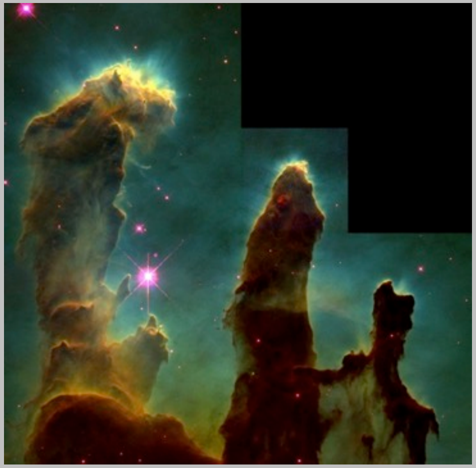
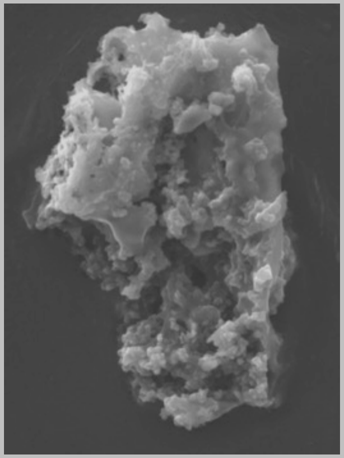
L'origine de la matière organique interplanétaire

ce que nous apprennent les analyses de poussières cométaires.

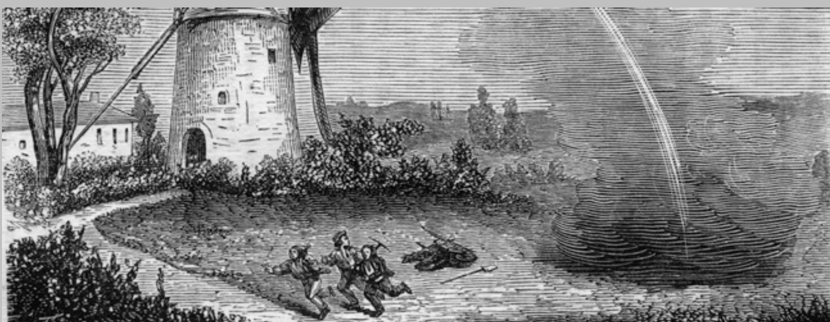


Séminaire LAL, 15 Novembre 2016

Jean Duprat
CSNSM-CNRS Univ. Paris Sud

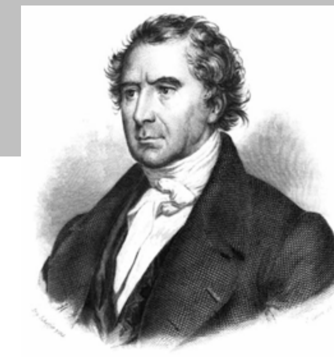


Organics in interplanetary dust is an ancient quest…



Chute de la météorite d'Orgueil
14 mai 1864 (©MNHN)

- Les poussières contiennent à peu près les mêmes substances que les chutes de pierres, et **certaines contiennent du carbone**
- Comparaison avec les météorites carbonnées (Alais, Orgueil…)



208 ASTRONOMIE POPULAIRE.

§ 6. — Chutes de poussières.

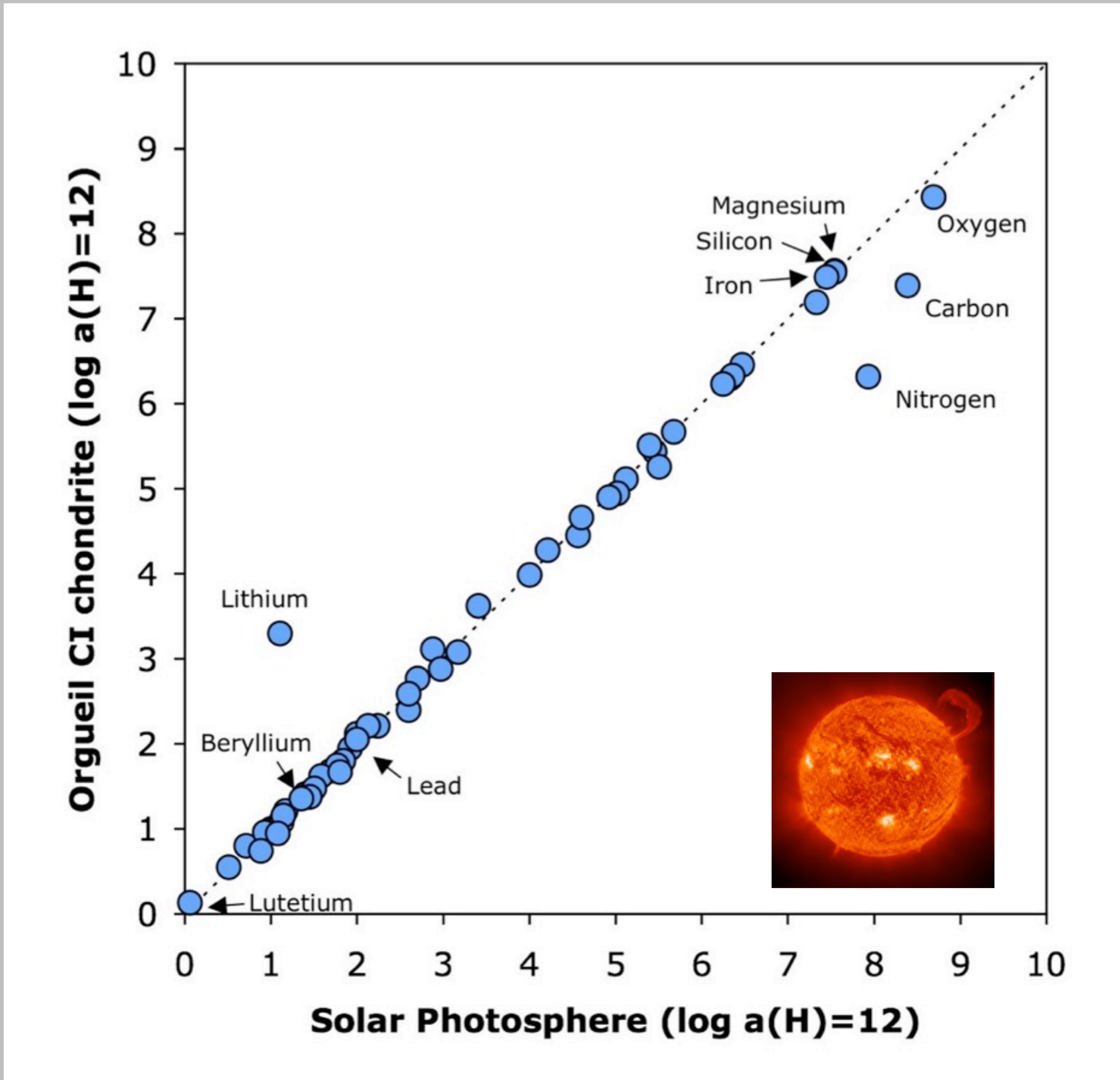
L'observation attentive des chutes de poussières fait présumer qu'elles ne diffèrent pas essentiellement des chutes d'aérolithes ordinaires. Quelquefois elles ont été accompagnées de chutes de pierres, comme aussi d'un météore de feu. Les poussières paraissent contenir à peu près les mêmes substances que les pierres météoriques. Il semble qu'il n'y a d'autre différence que dans la rapidité avec laquelle ces amas de matière chaotique dispersés dans l'univers, arrivent dans notre atmosphère. Probablement dans la poussière rouge et noire, l'oxyde de fer est la principale matière colorante. Dans la poussière noire, on trouve aussi du carbone. On doit regarder les pierres noires et très-friables tombées à Alais en 1806 (voir p. 196) comme formant en quelque sorte le passage de la poussière noire aux aérolithes ordinaires.

Arago et Barral 1854

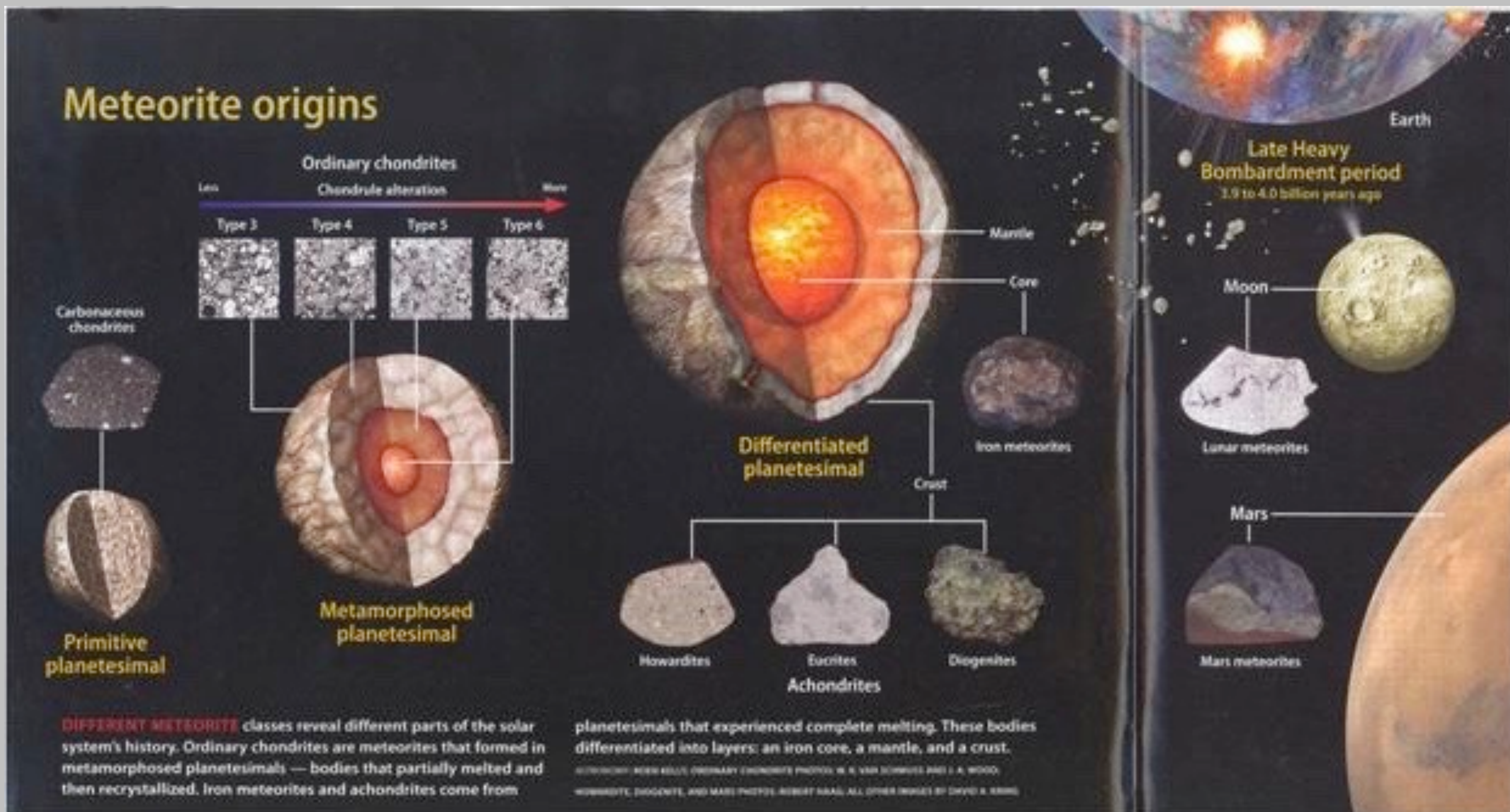
Comparaison Sun / Chondrites

Orgueil (CI)

The composition of Orgueil (CI) meteorite is that of the Sun photosphere, over almost 9 orders of magnitudes

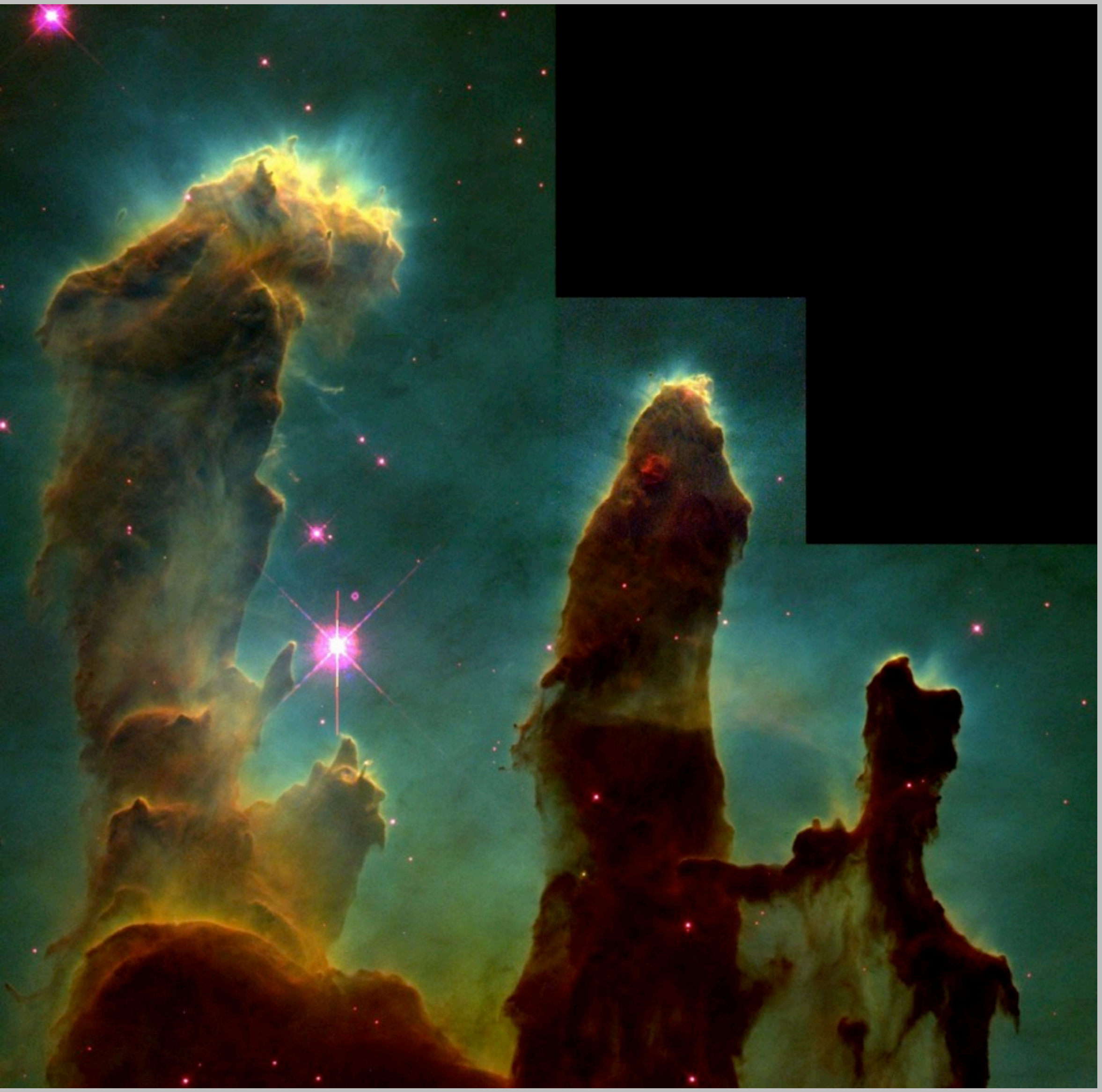


What is a primitive interplanetary sample ?
The key role of small-bodies



Kring, D. (2006), Astronomy

Dense molecular clouds, the stars forming regions

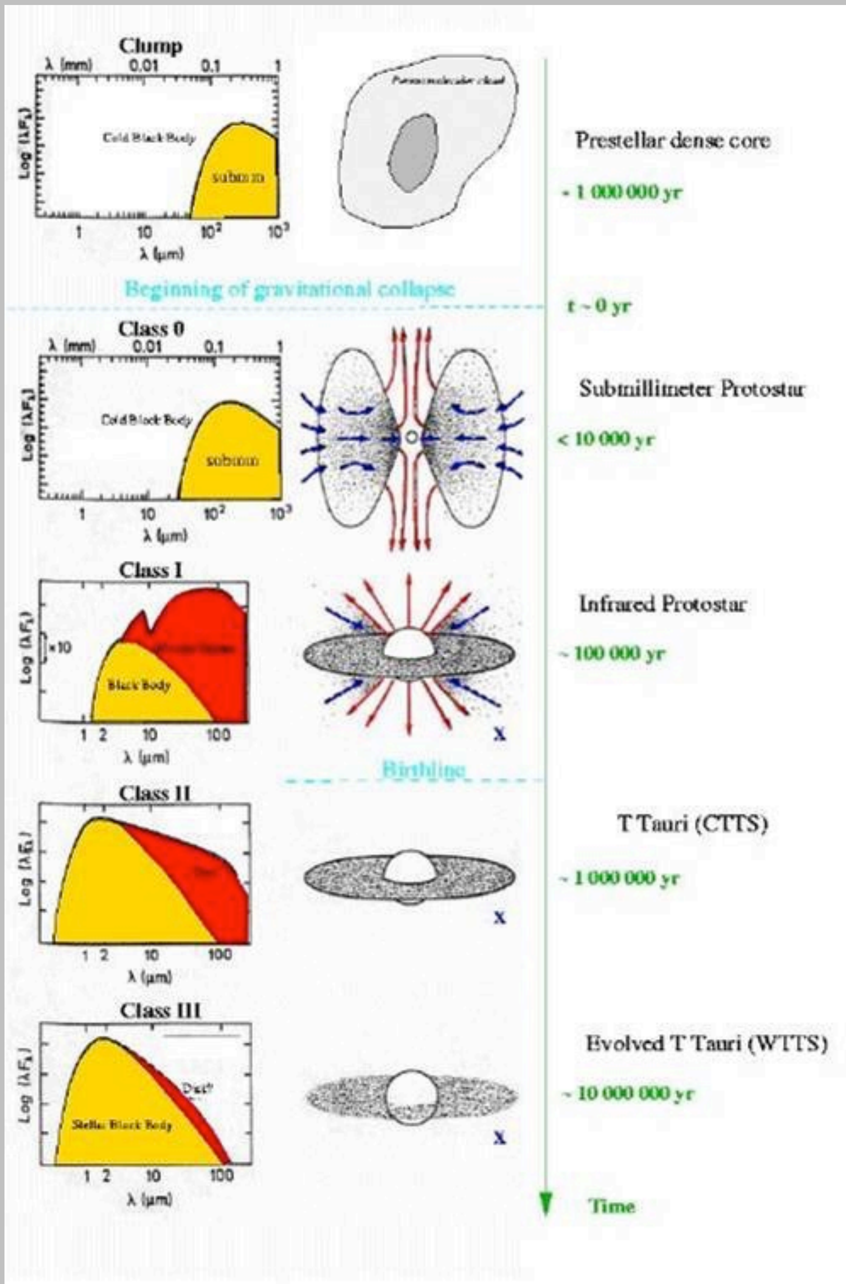


The Eagle nebula,
an emblematic example

Distance 6500 LY (2 kpc)

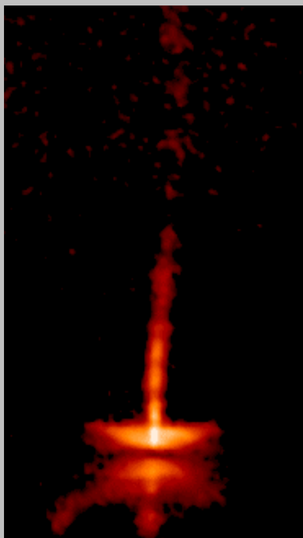
Size of the clouds :
1 LY, ~50 kAU, ~ 0.3 pc

Before the main sequence



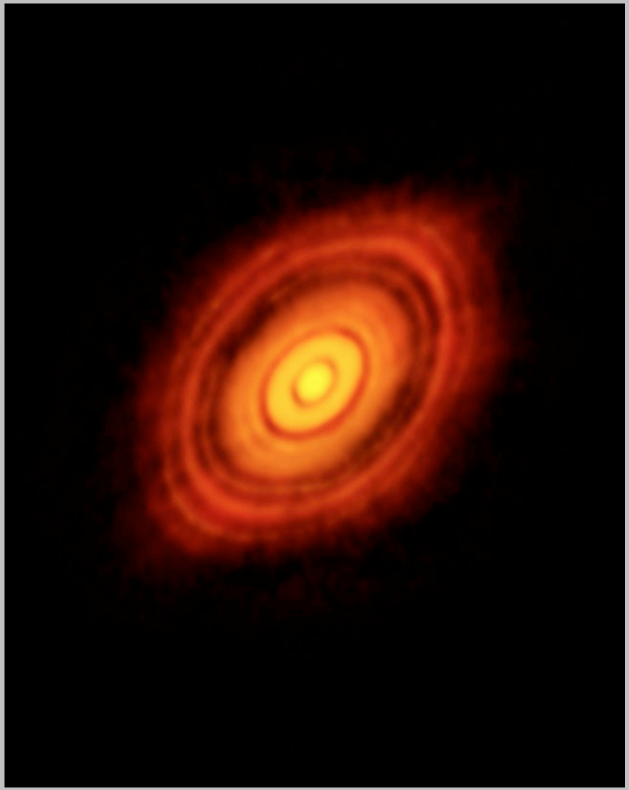
Different time scales

- Class 0 & I :
  - The proto-star is embedded
  - High accretion rate
  - T ~ 10^4-10^5 years
  - $M_{star} = 0.5 \rightarrow 0.8\ M_\odot$
- Class II & III :
  - Disc of gas and dust then debris
  - Lower accretion rate
  - T ~ 10^6-10^7 years
  - $M_{star} = 0.8 \rightarrow 1\ M_\odot$

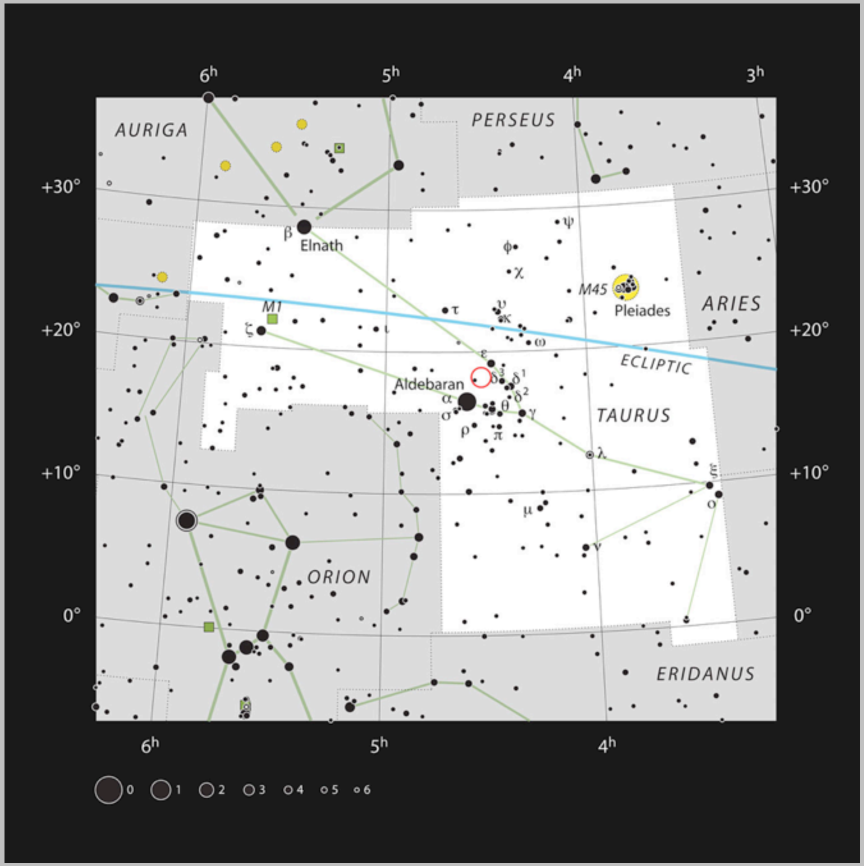


HH 30
Hubble

ALMA ESO observatory (mm and sub-mm)

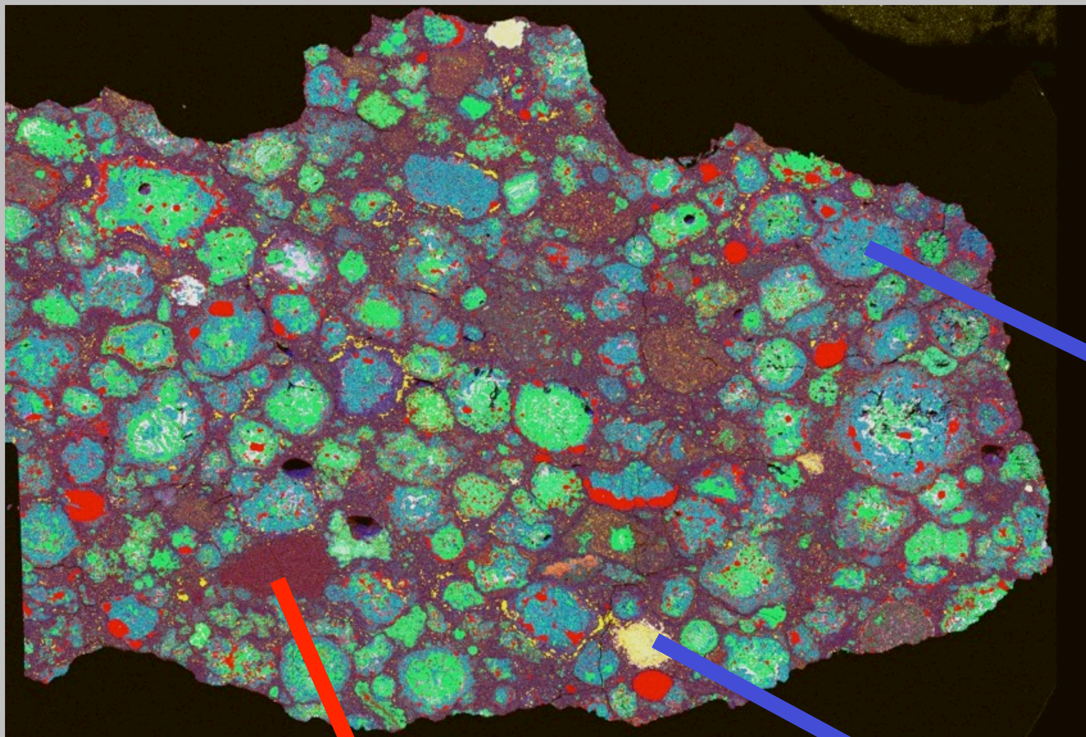


HL-Tauri (450 LY)
6 november 2014

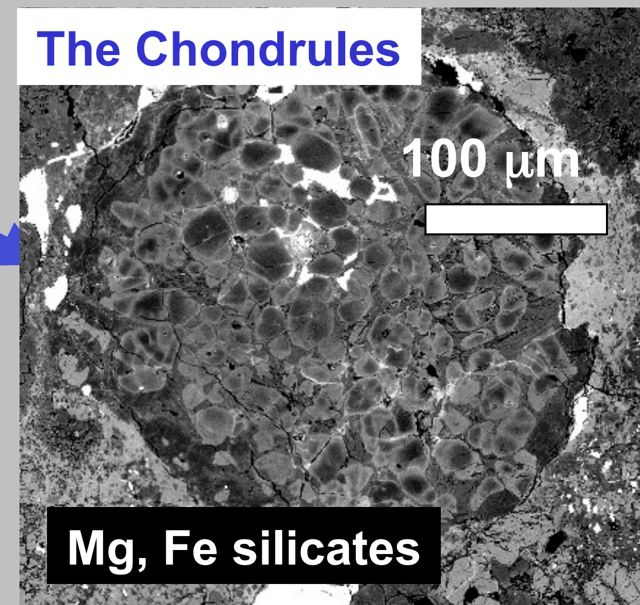


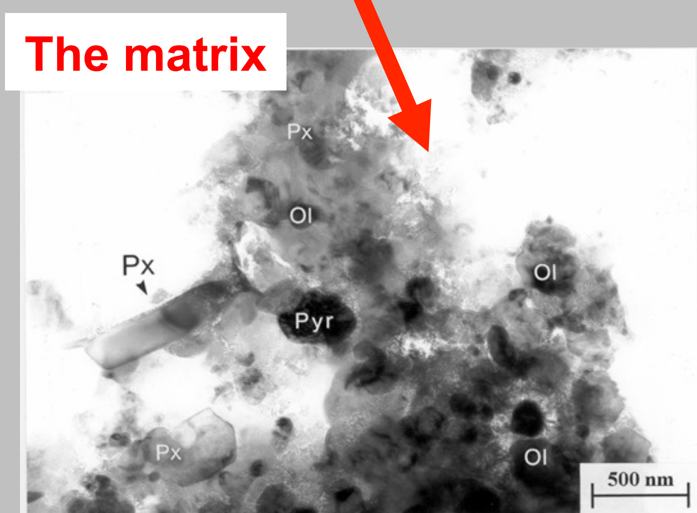
Proto-planetary disks will be a key target for JWST telescope

The main components in Chondrites : matrix & refractory phases

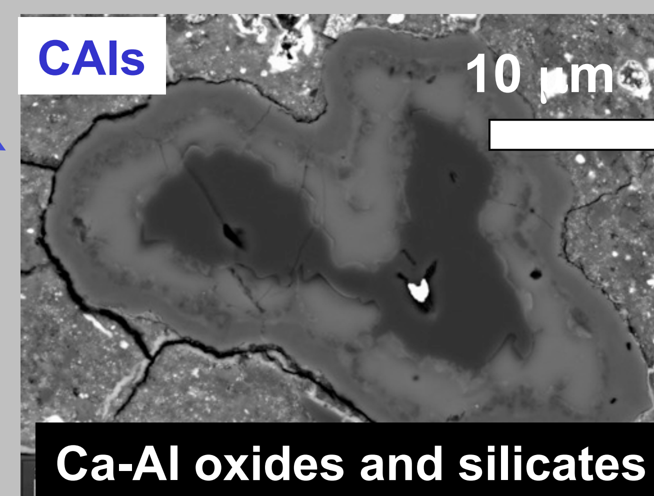


In refractory phase are the oldest solids of the solar system (extinct radioactivities)



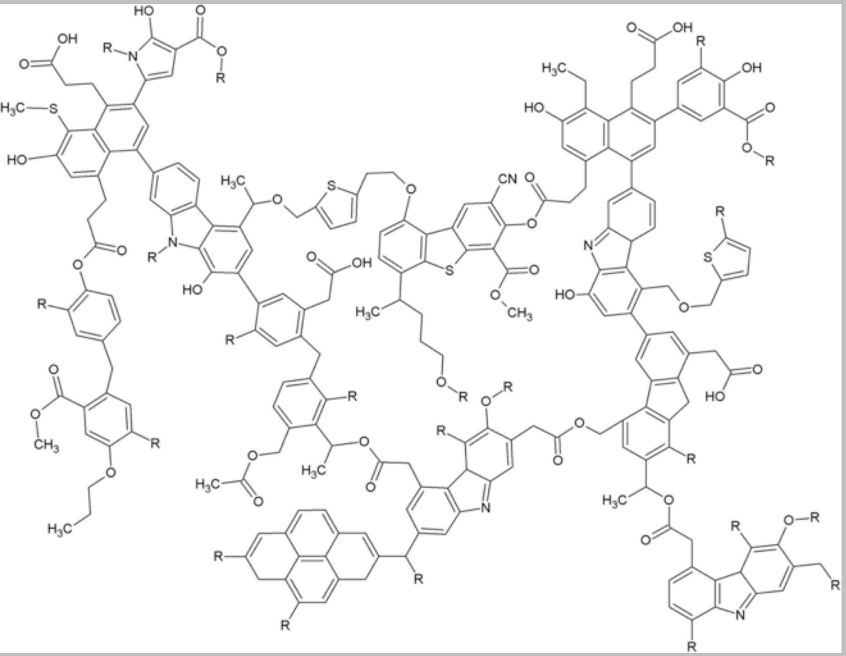


In the matrix we find the presolar grains and the organic matter



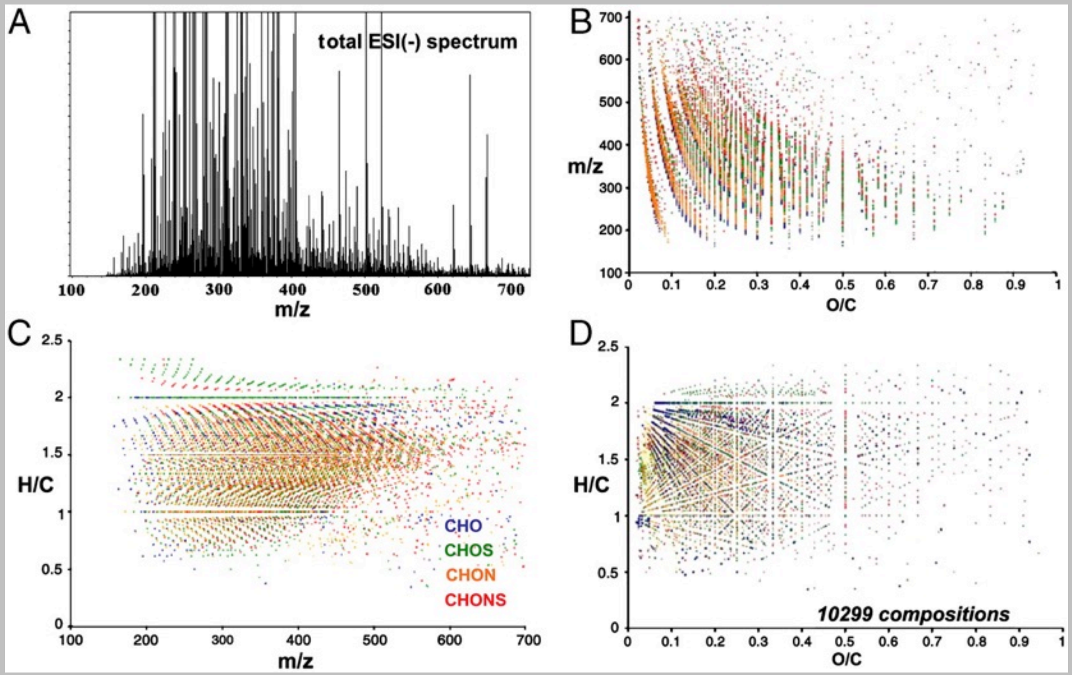
The primitive interplanetary organics

IOM
The Isoluble Organic Matter structure



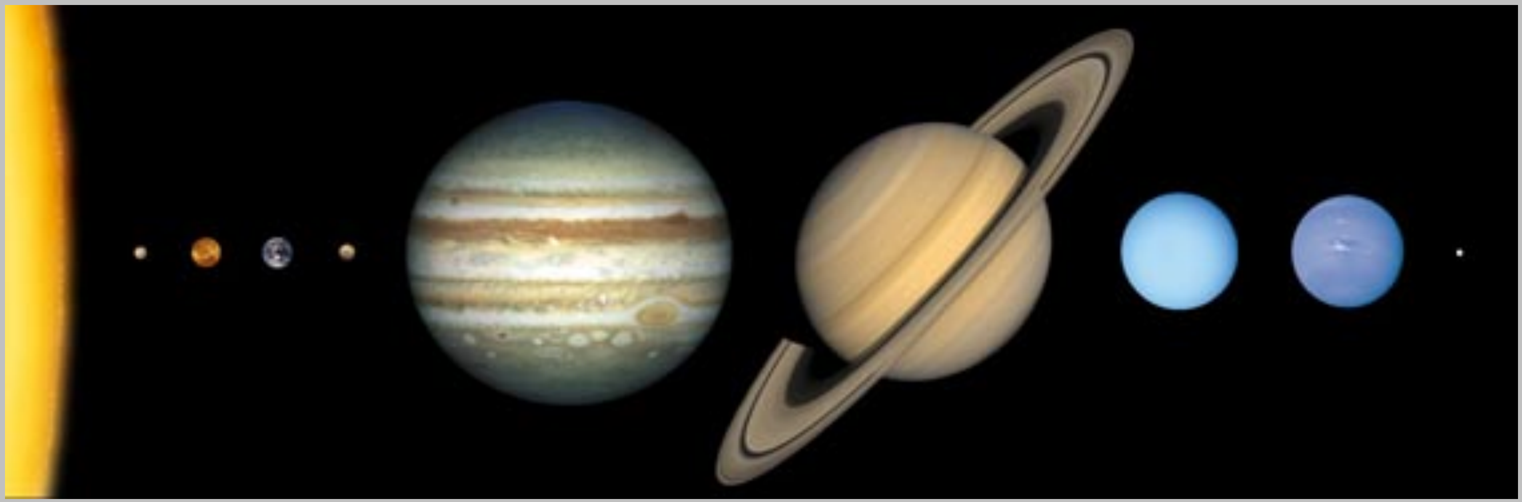
Derenne & Robert 2010

The soluble organic matter (SOM)
High molecular diversity of extraterrestrial organic matter in Murchison meteorite revealed 40 years after its fall
Philippe Schmitt-Kopplin et al. PNAS 2010;107:2763-2768



2 components : IOM and SOM

The solar system final architecture



The inner solar system :

- Terrestrial planets (rocks)
- Low masses (total 2 $M_\oplus$)
- High densities
- Secondary atmospheres

The outer solar system :

- Giant planets (gas & ice)
- High masses (317 $M_\oplus$, 95 $M_\oplus$)
- Low densities
- Primary atmospheres

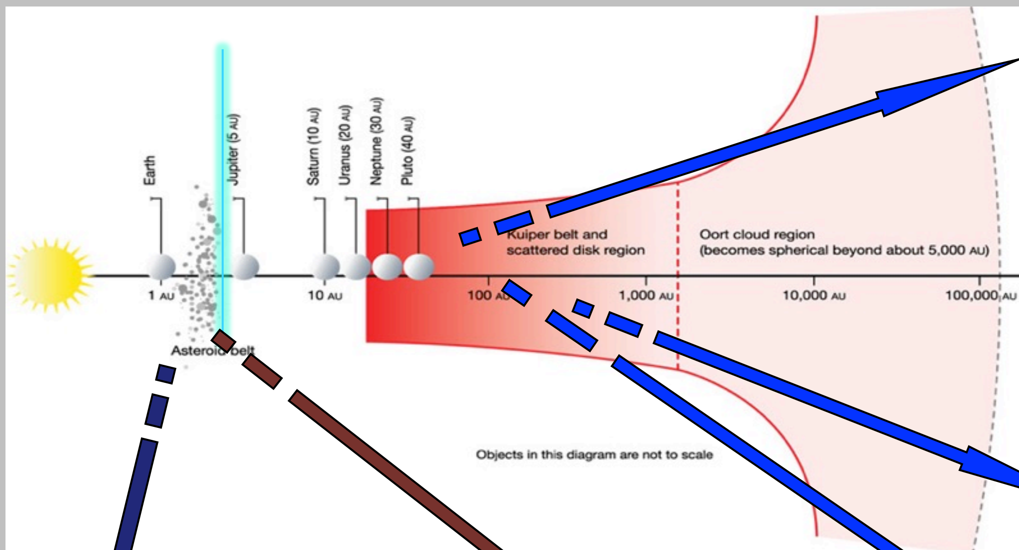
The snow line marks a striking

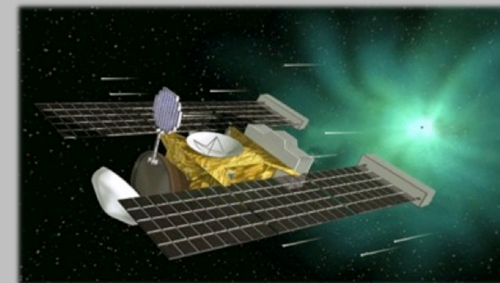
dichotomy between the inner and outer solar system

the growth of planets is governed by ***accretion of solids…***

Asteroids & comets

A major challenge for spatial missions



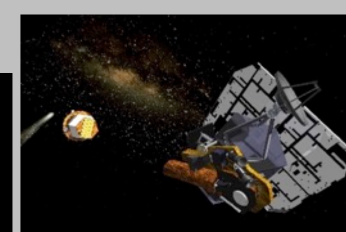



STARDUST

ROSETTA/PHILAE


Hayabusa I &II


OSIRIS-REx (2016)

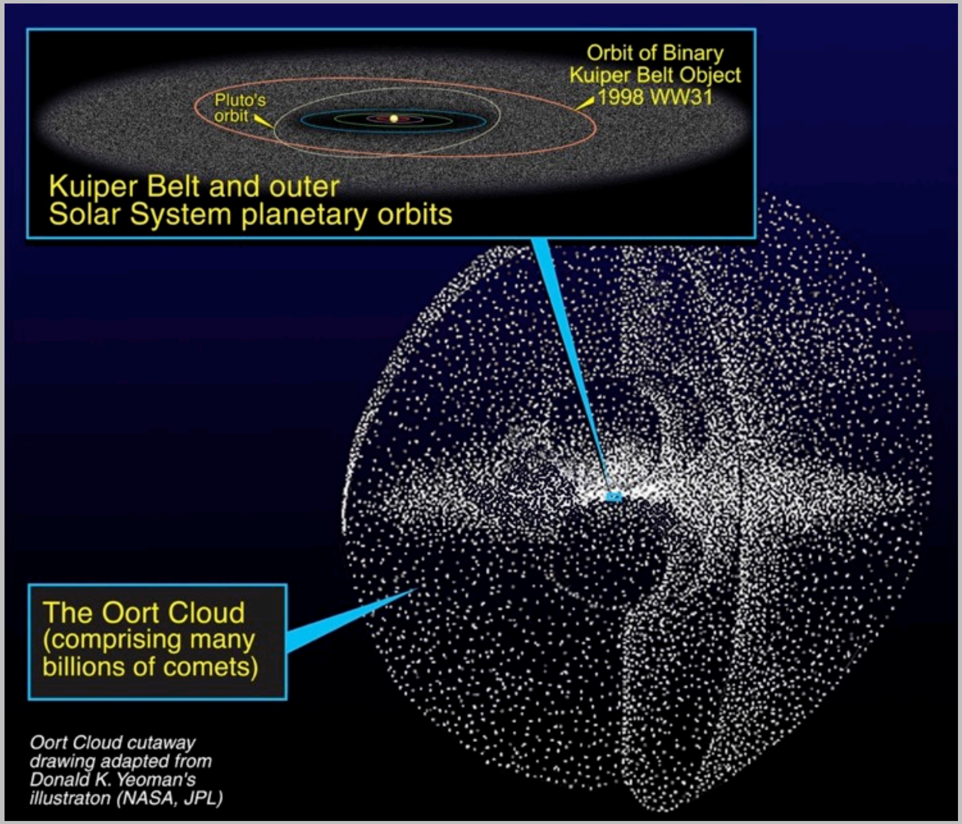



Deep Impact

Probing the composition of the proto-planetary disk

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

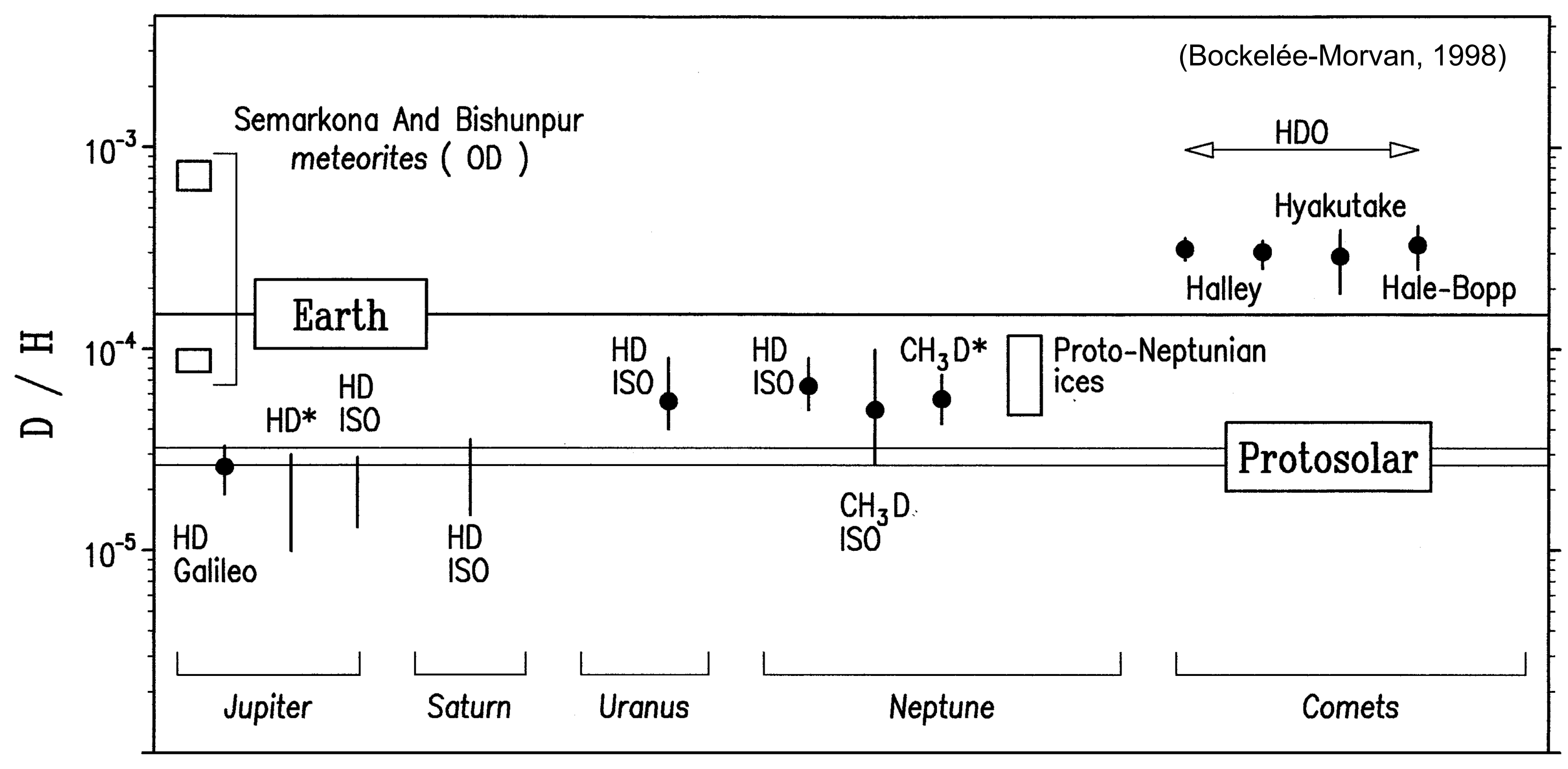
D/H ratios in the solar system

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

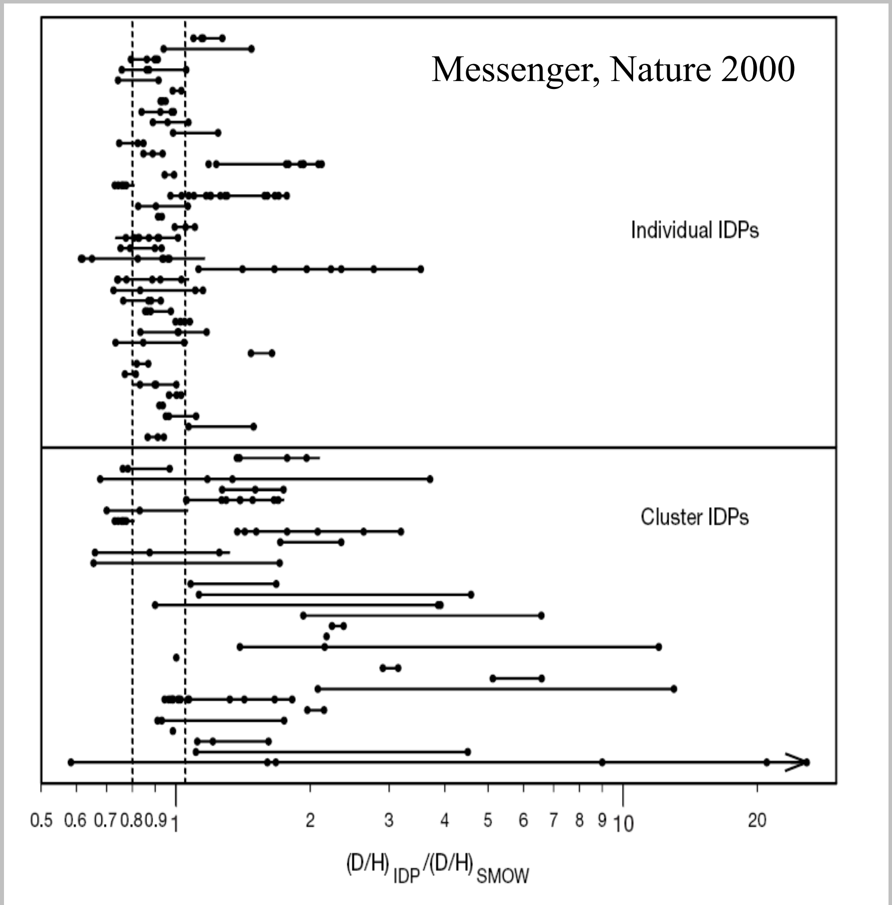
The origin of the Deuterium excesses

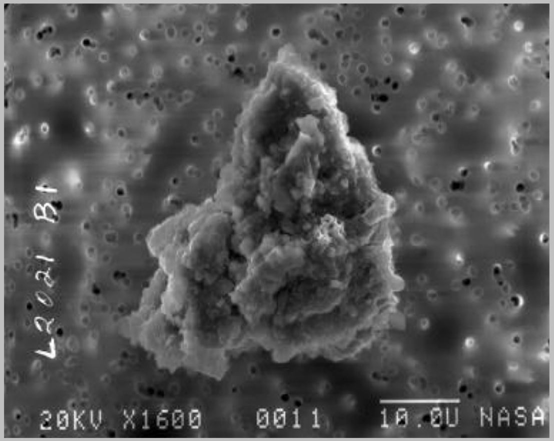
Ion-molecules reactions at low temperature

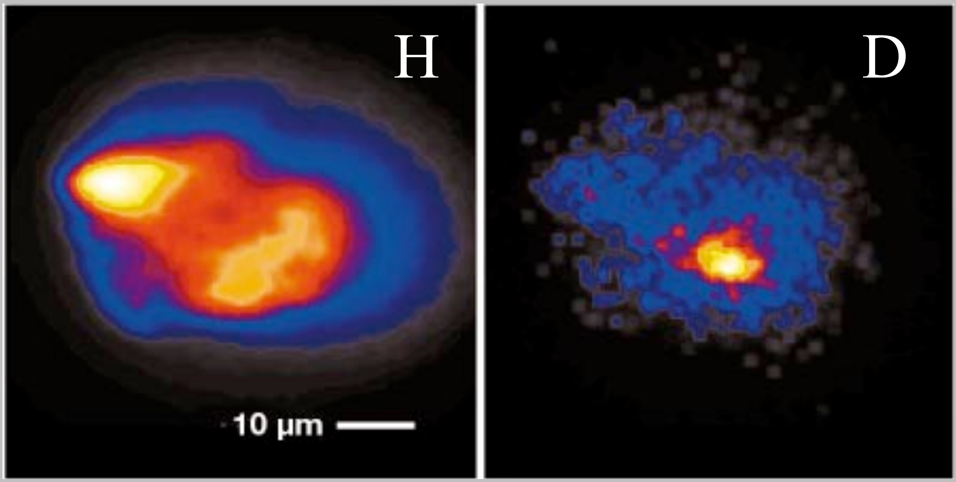
$$H_3^+ + \mathbf{HD} \rightleftharpoons \mathbf{H_2D^+} + H_2$$



D/H in Stratospheric Interplanetary Dust Particles







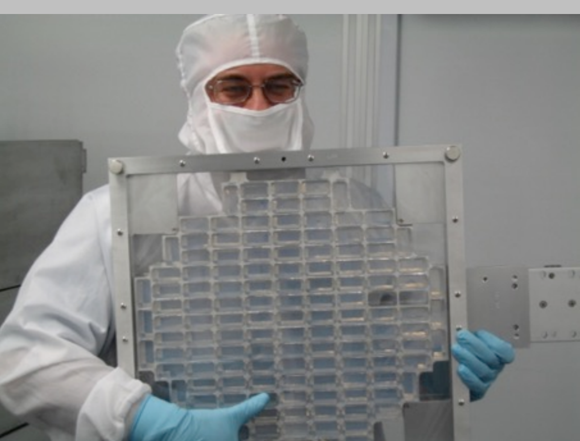
D enrichments points toward a cometary origin

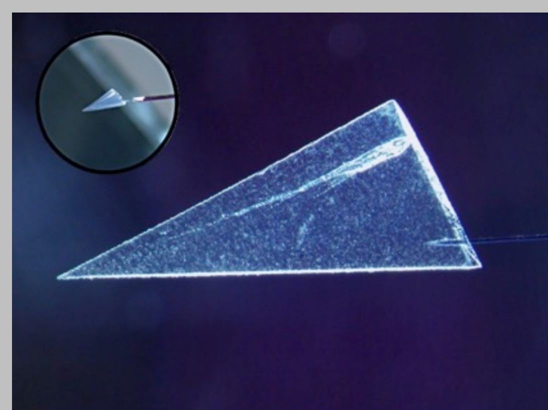
STARDUST mission, dust particles from comet 81P/Wild2

February 1999

January 2004
Comet 81P/Wild 2

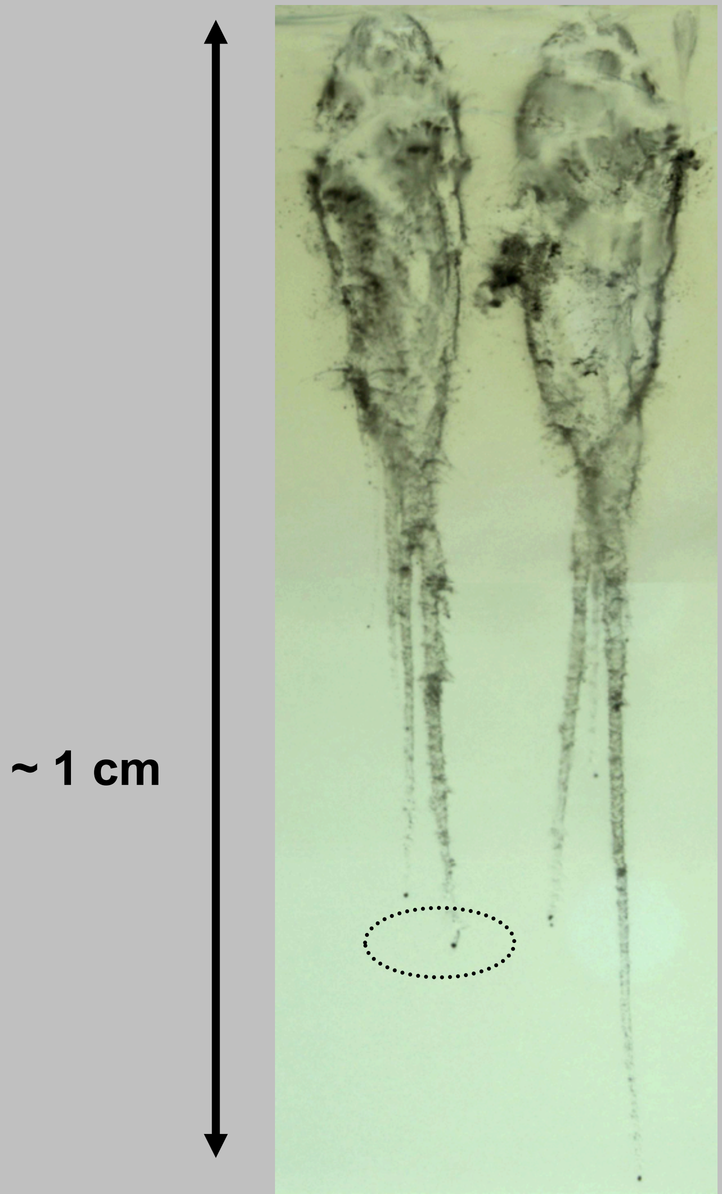
January 2006

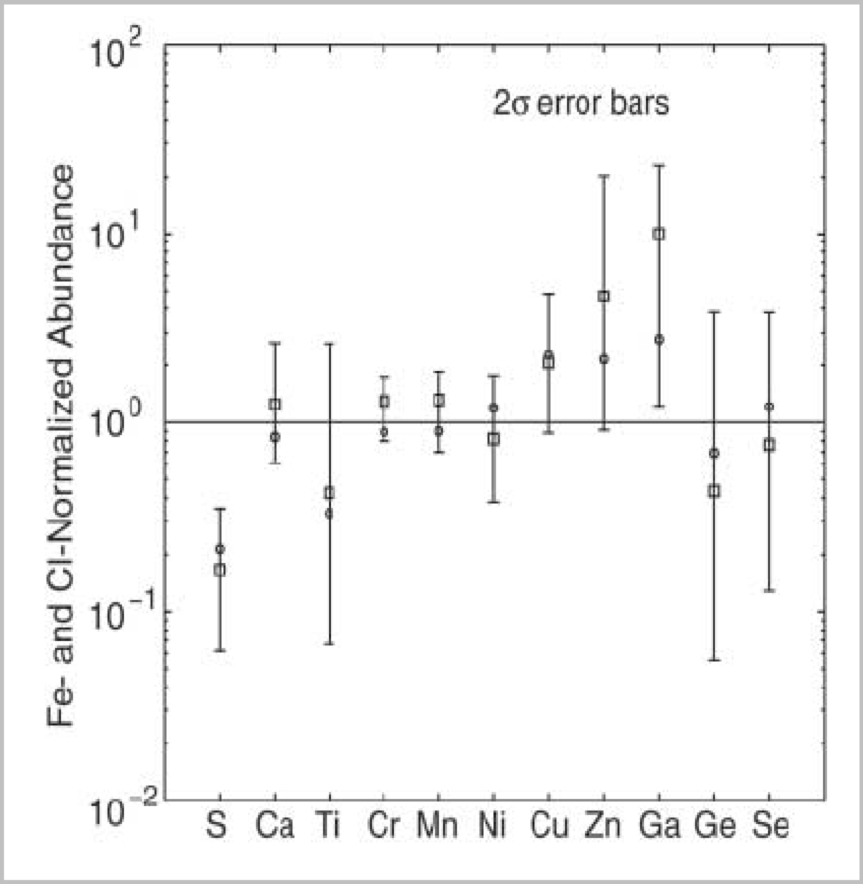




December 2006, the first results…

The bulk composition of 81P/Wild2

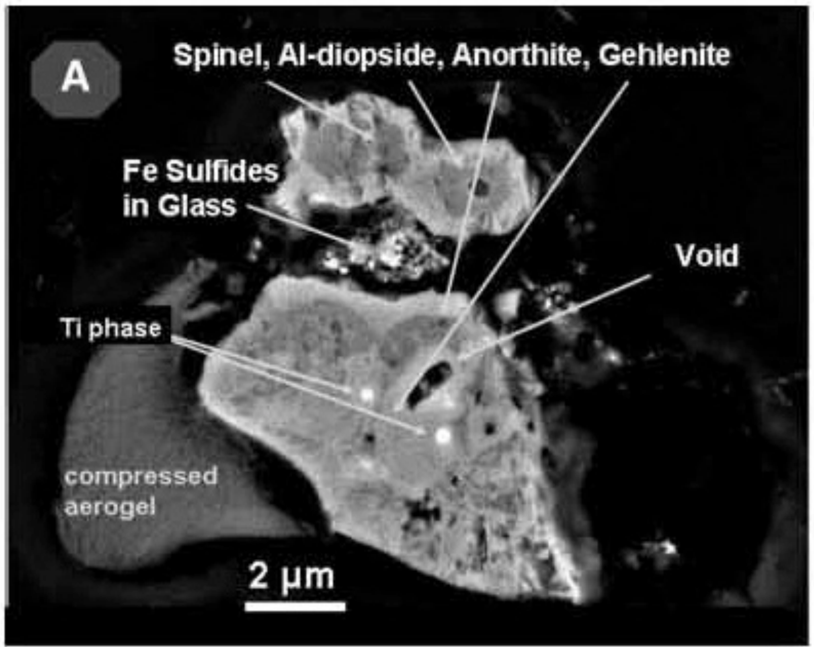




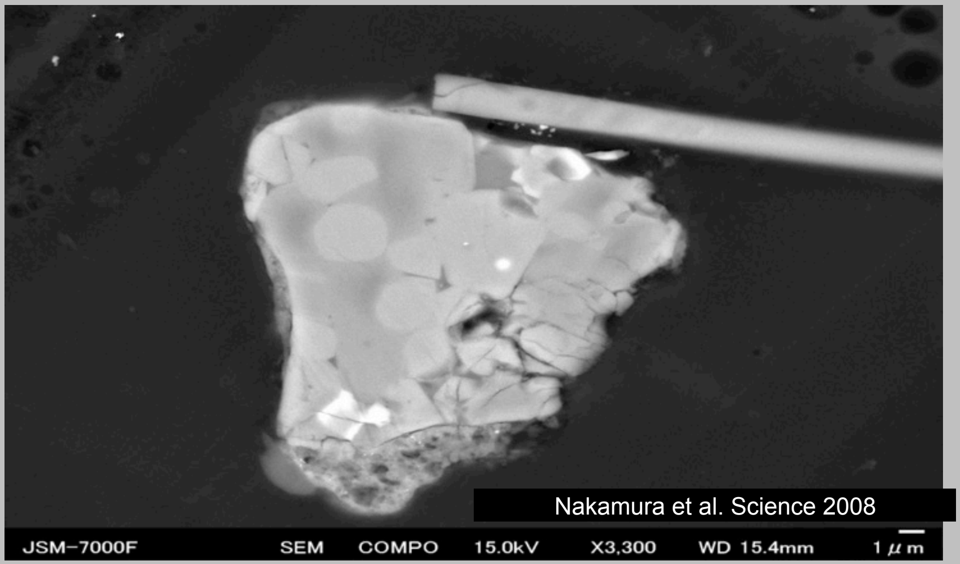
The bulk composition is similar to that of CI chondrites

Flynn et al. Science 2006

Refractory phases in a cometary dust



Brownlee et al. Science 2006

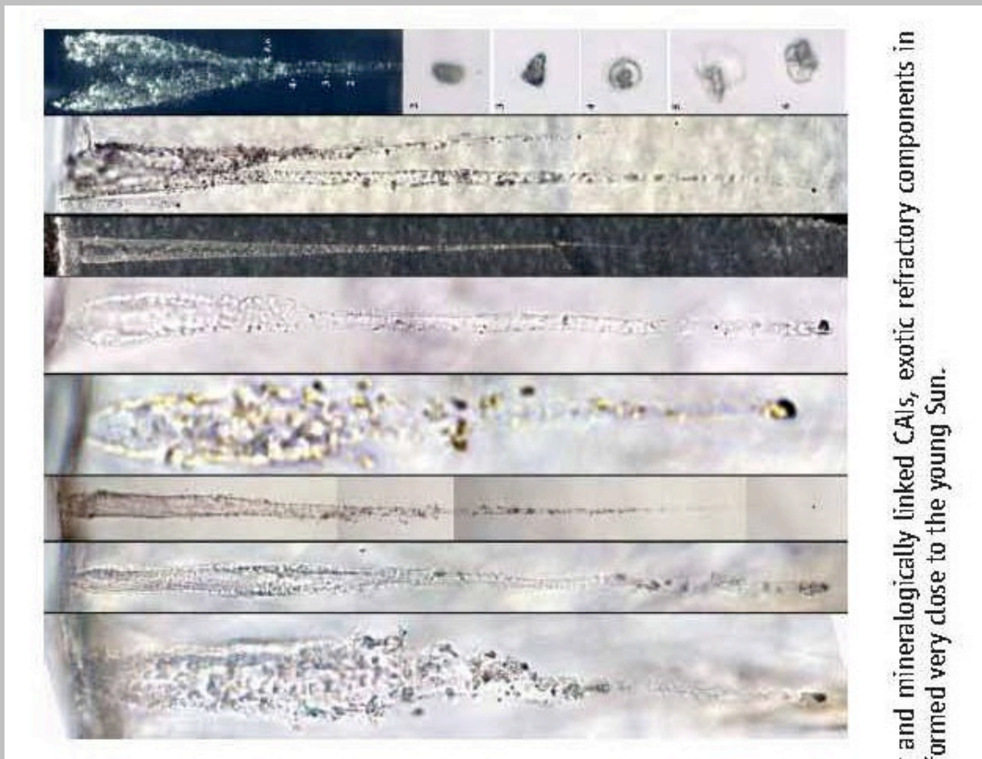


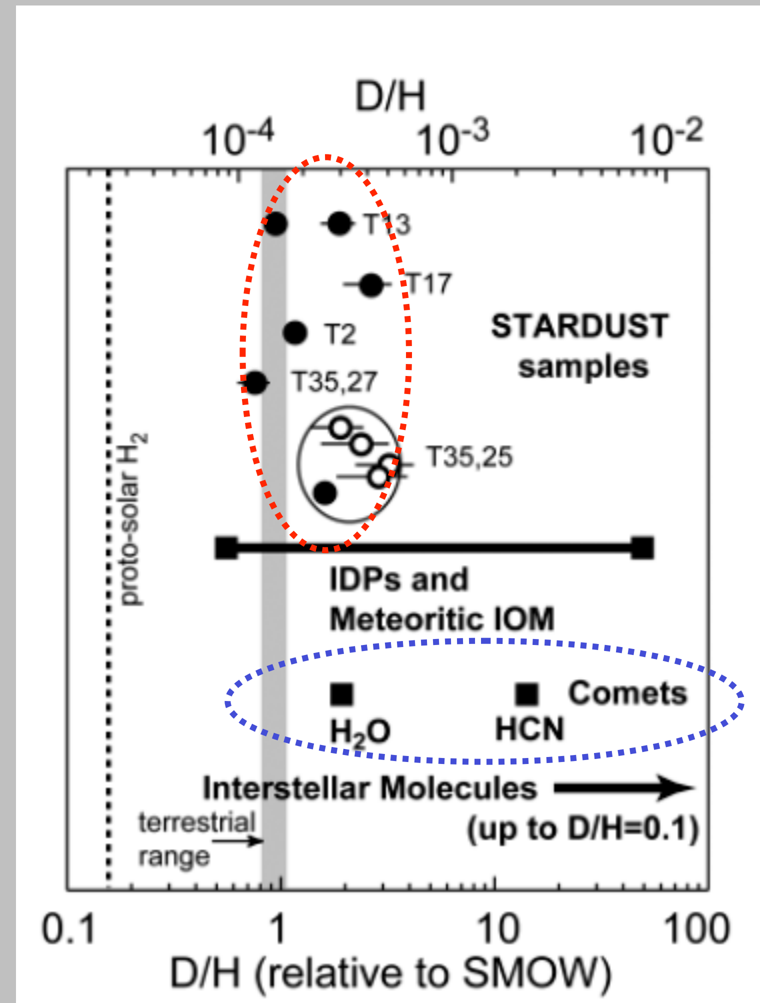
"Remarkably enough, we have found fire and ice"

- Evidence for high temperature temperature phases in cometary material.
- Ca, Al rich Inclusions **(CAI) and chondrules condensed close to the protosun then were transported to the comet forming region**

«…Their presence in a comet proves that the formation of the solar system included **mixing on the grandest scales**…» Brownlee et al. Science 2006

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

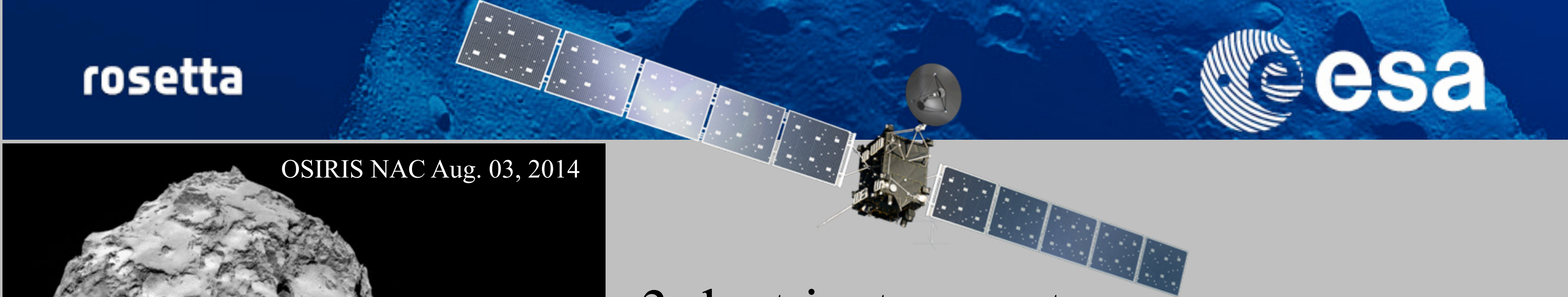


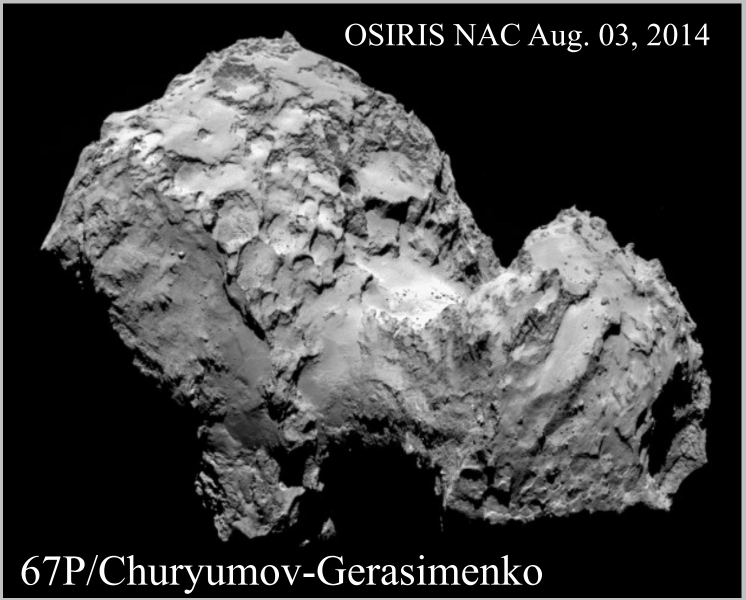


McKeegan et al Science 2006

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

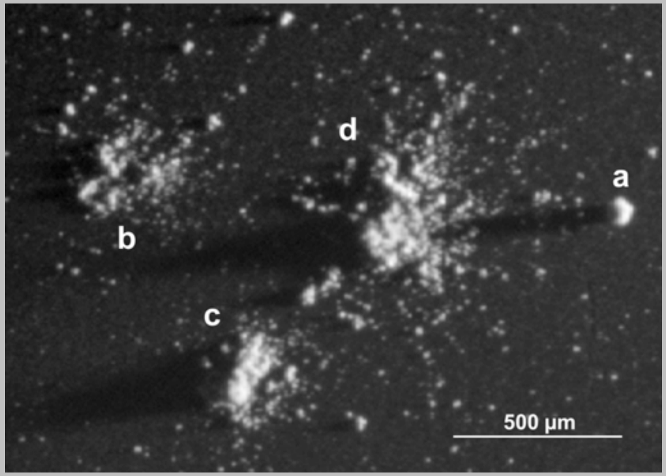
- Heterogeneity of the cometary reservoir ?
- Alteration of the particles :
  - heating
  - mixing with aerogel



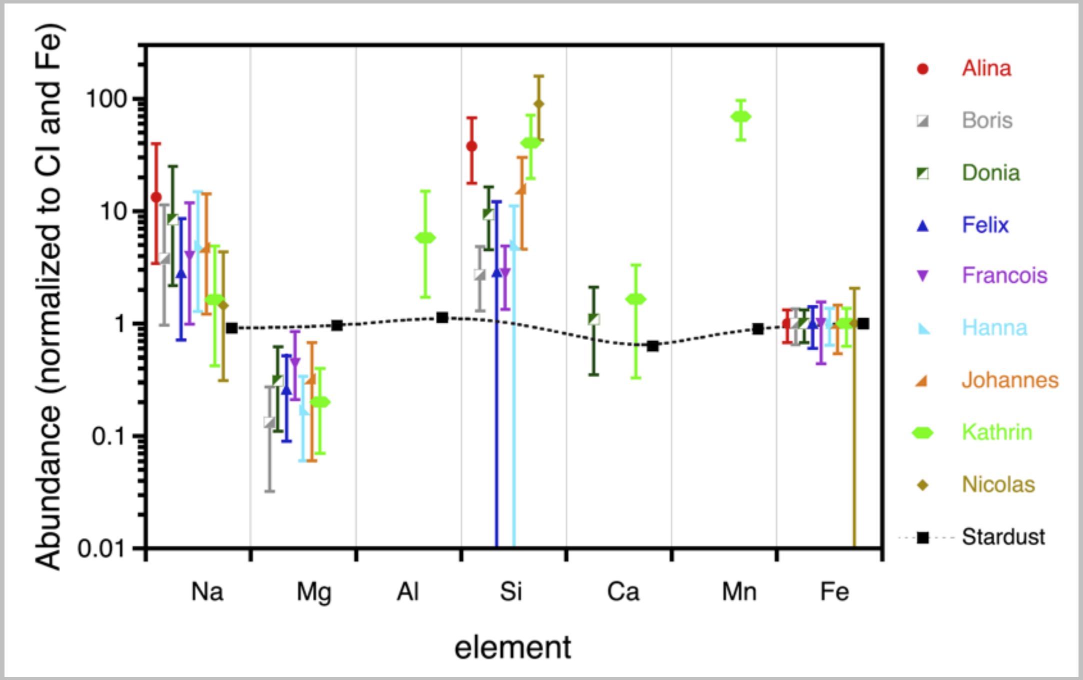


3 dust instruments

Composition : COSIMA *(ROSINA)*



(Langevin et al. 2016)



(Hilchenbach et al. 2016)

ROSETTA Mission

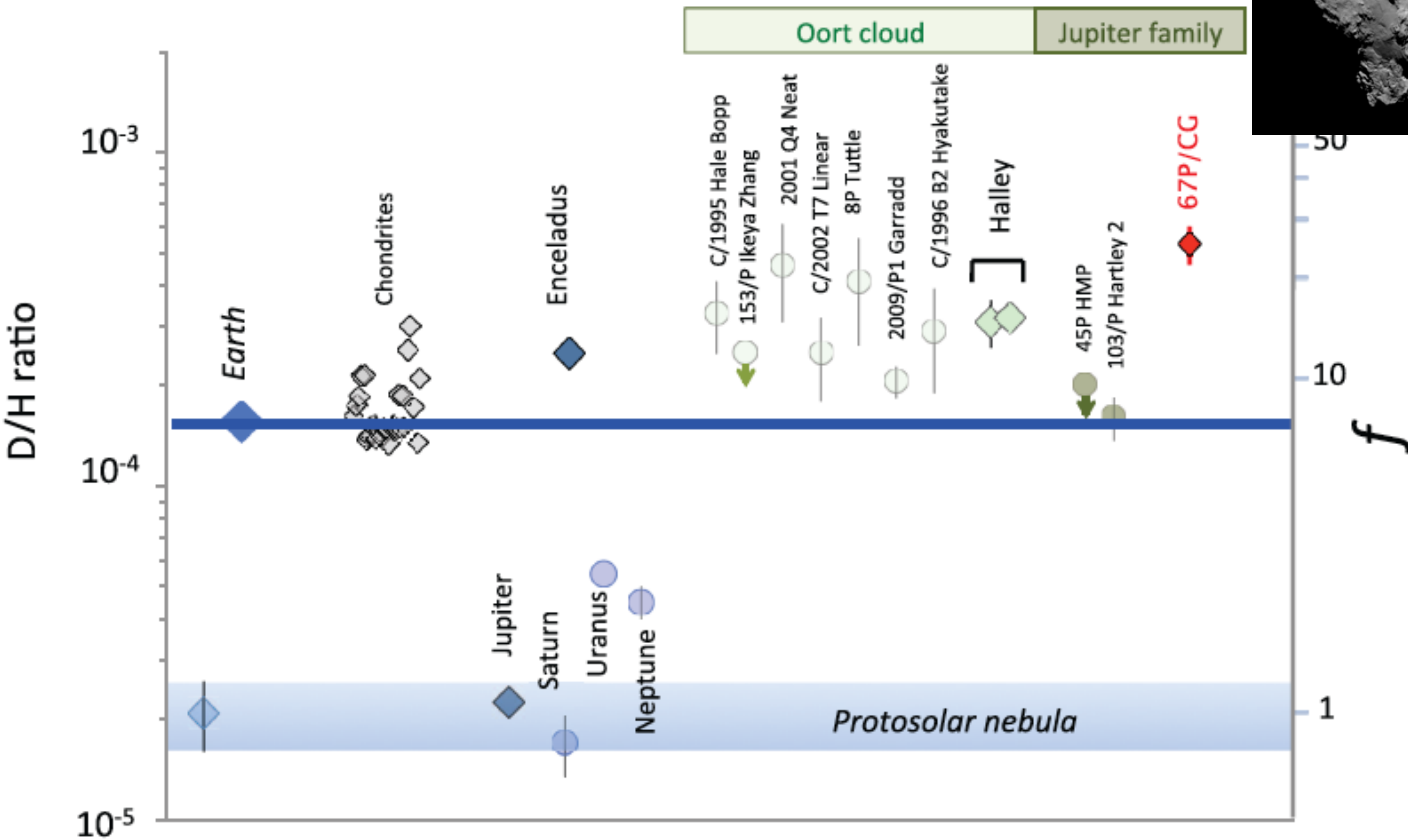
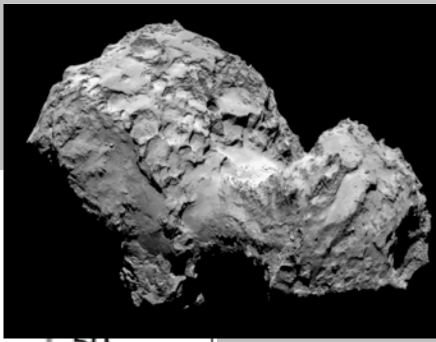
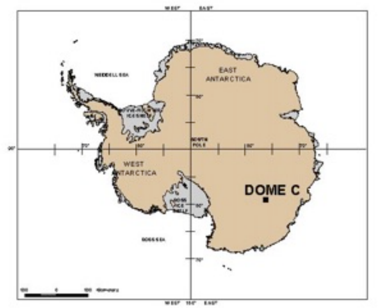


Fig. 3. D/H ratios in different objects of the solar system. Data are from (1, 2, 5–7, 26–28) and references therein. Diamonds represent data obtained by means of in situ mass spectrometry measurements, and circles refer to data obtained with astronomical methods.



K. Altwegg et al. Science 2015



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 > 50µm] :

- 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**

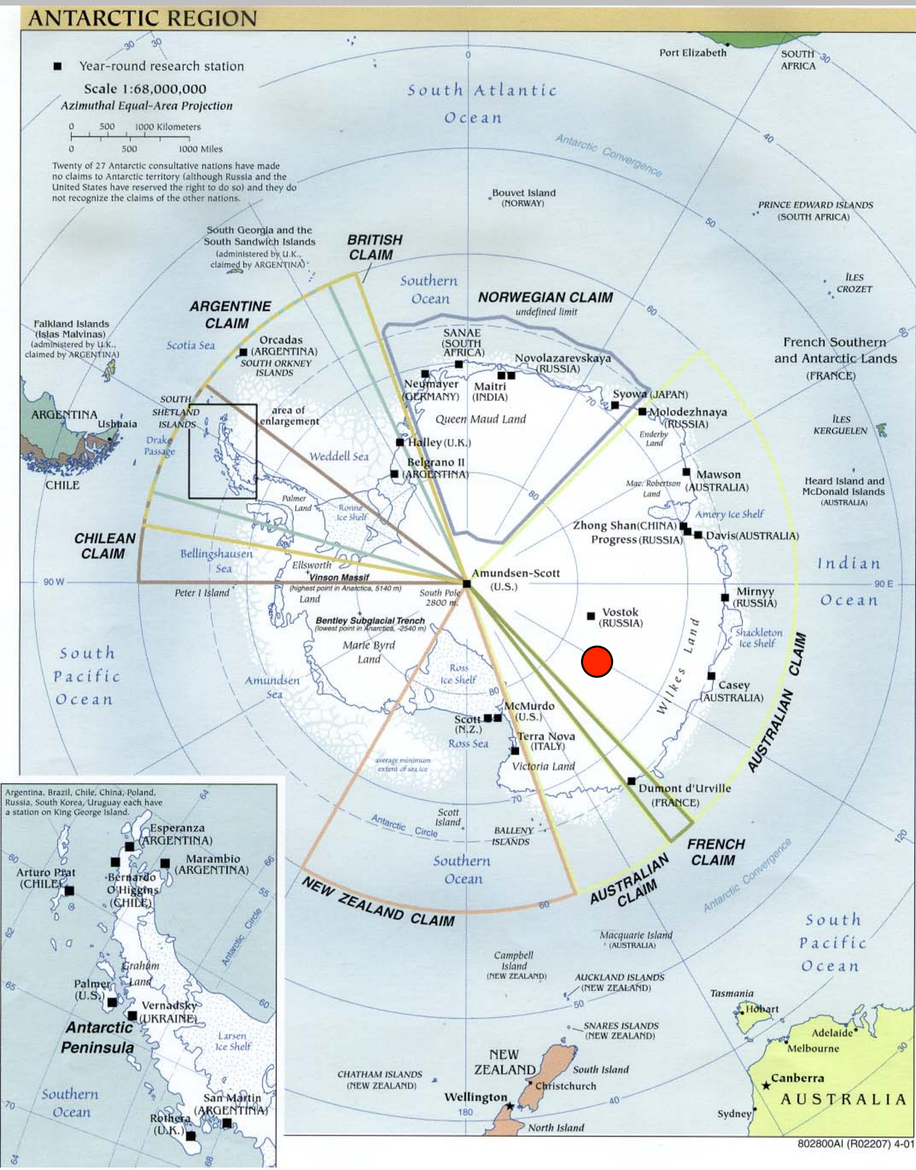
* Dome C **snow stays at low temperature** thought the year **(-70° < T<-20°)**

-> **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

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

2006-2014-2016

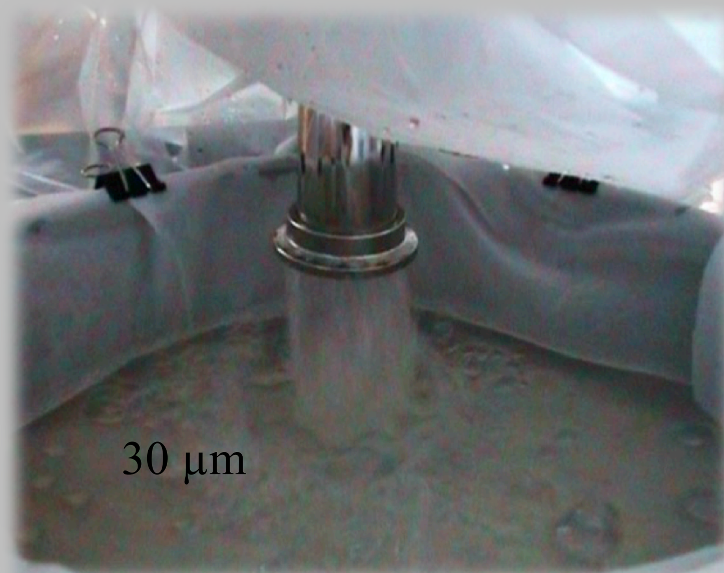
Tranchée 4-5 mètres

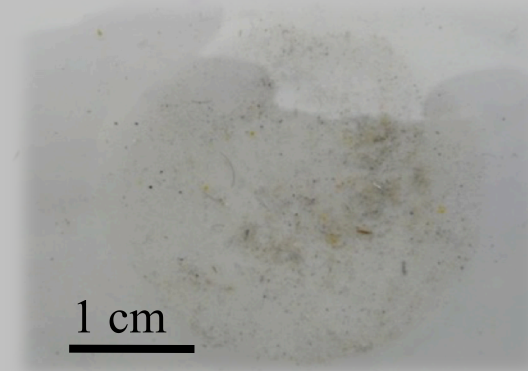
V = 25 m^3

Duprat et al. *EAS series 2005*.

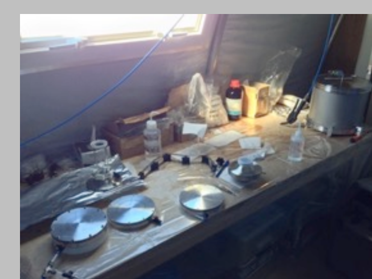
The melting/sieving procedure

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

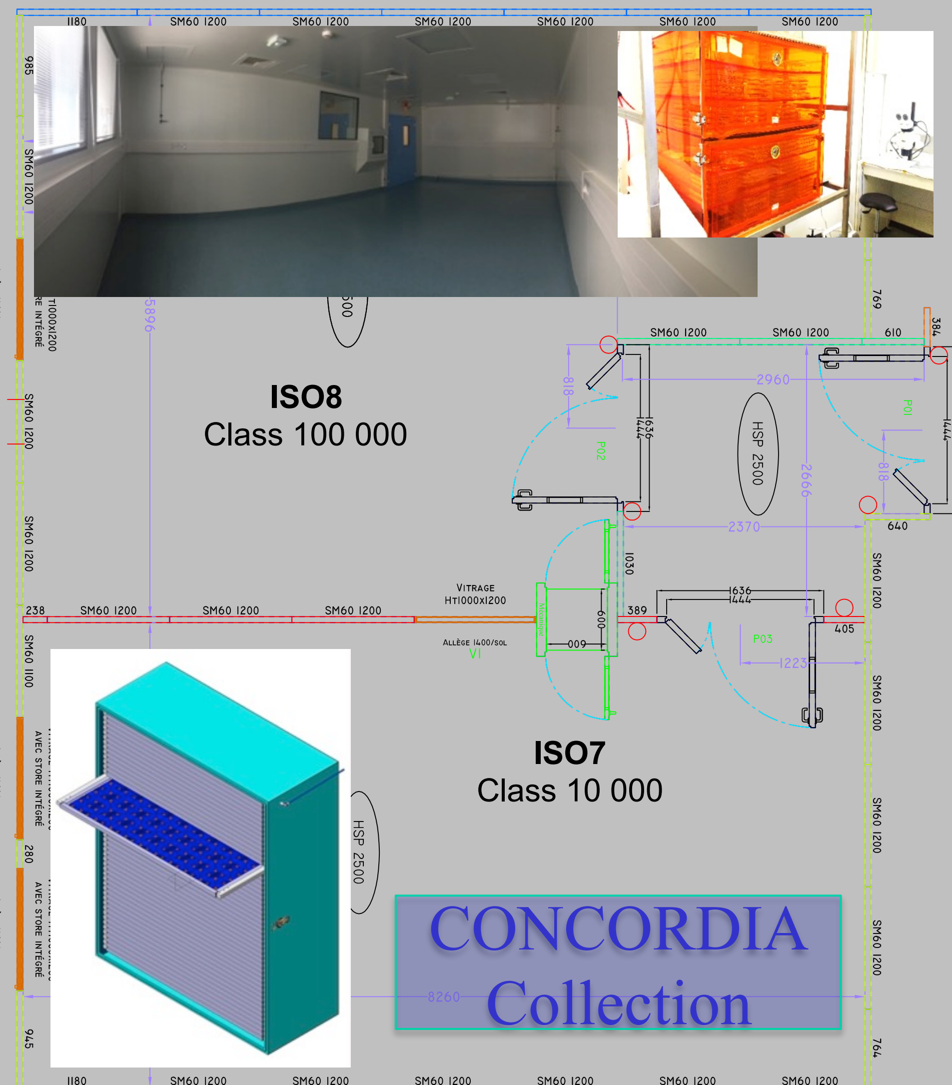


CSNSM-IAS campaign January 2016

The **MYRTHO facility**

Micrometeorites, ea**R**ly solar s**Y**stem, **Th**ematic consortium **O**rsay

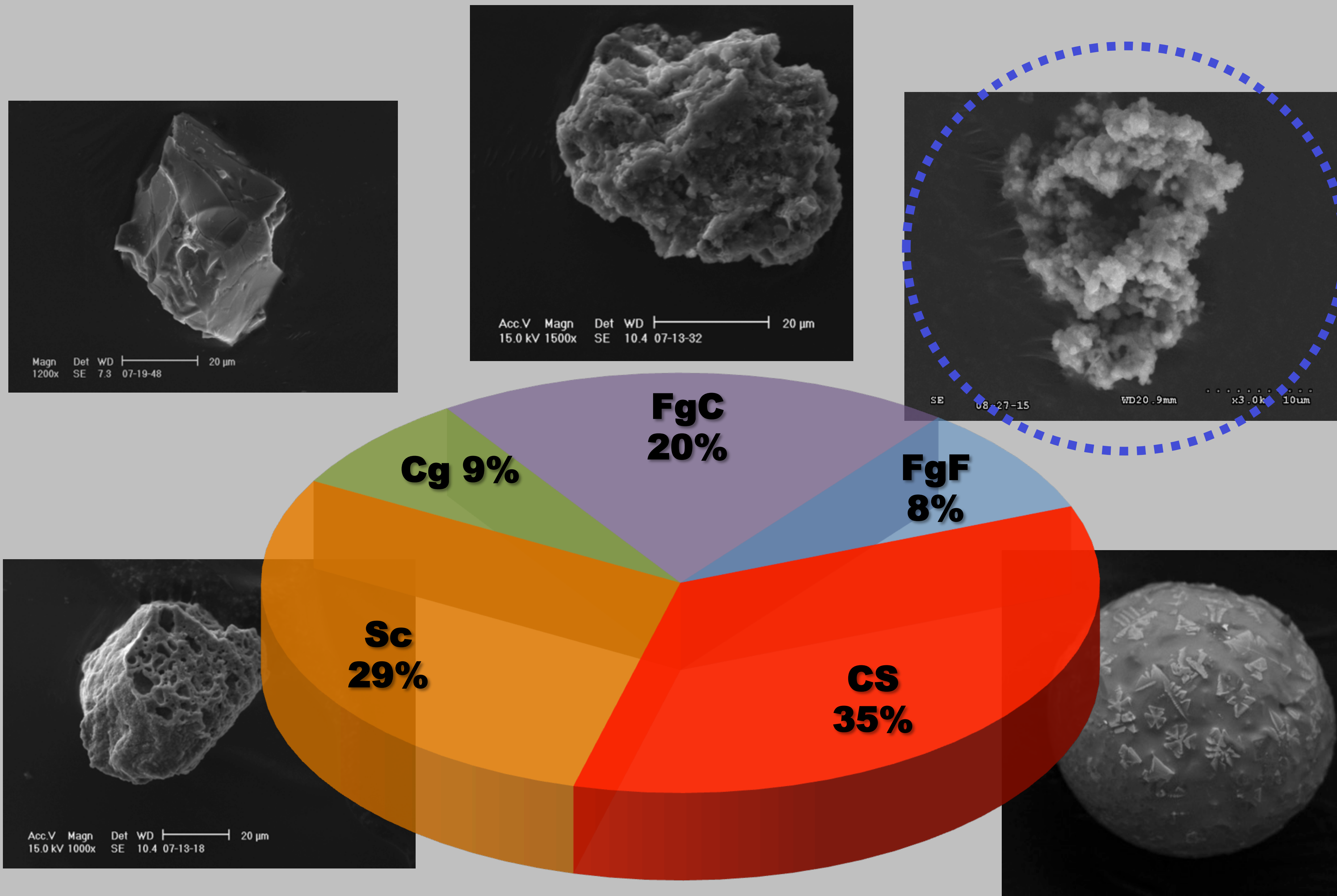
- A 100 m^2 clean room
- CONCORDIA micrometeorite curation / analyses / gamma detectors development
- µ- balance, µ- press, ultra-µ-tome,…
- SEM + µ-IR (2017)



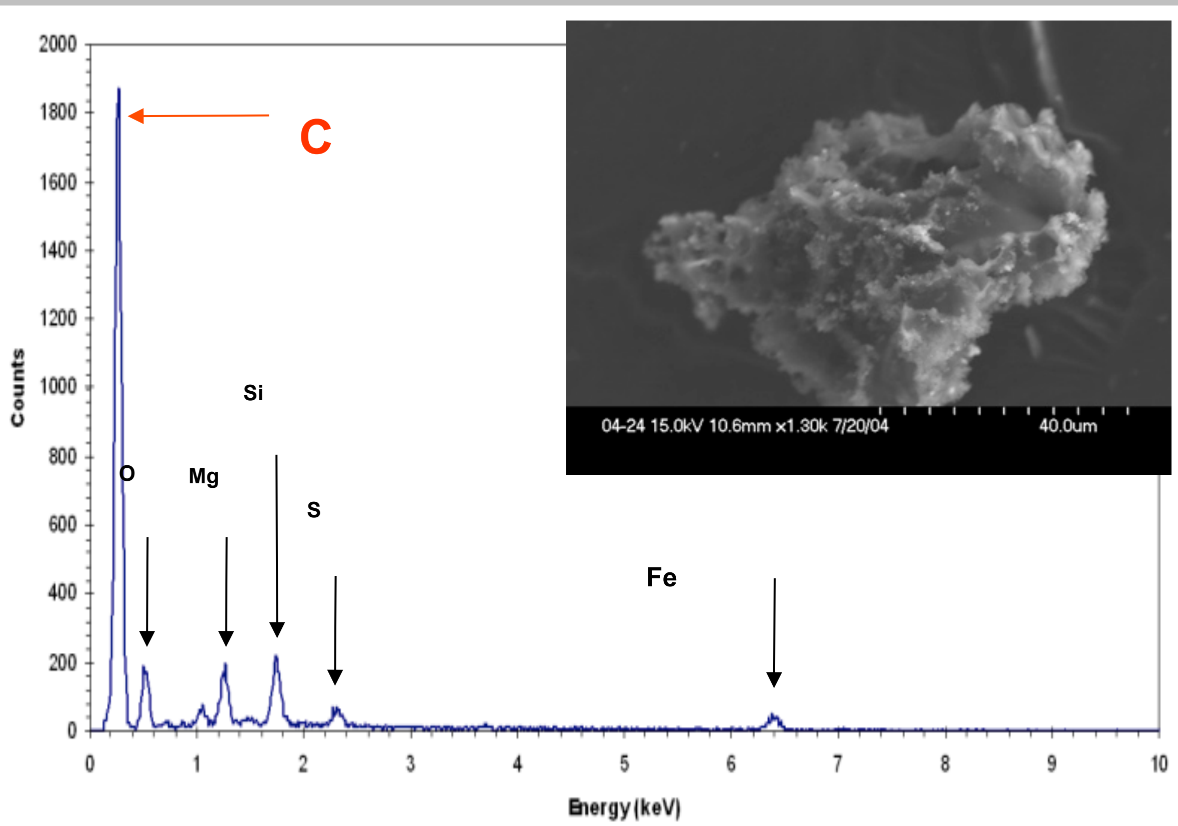
ThermoScientific Nicolet iN10

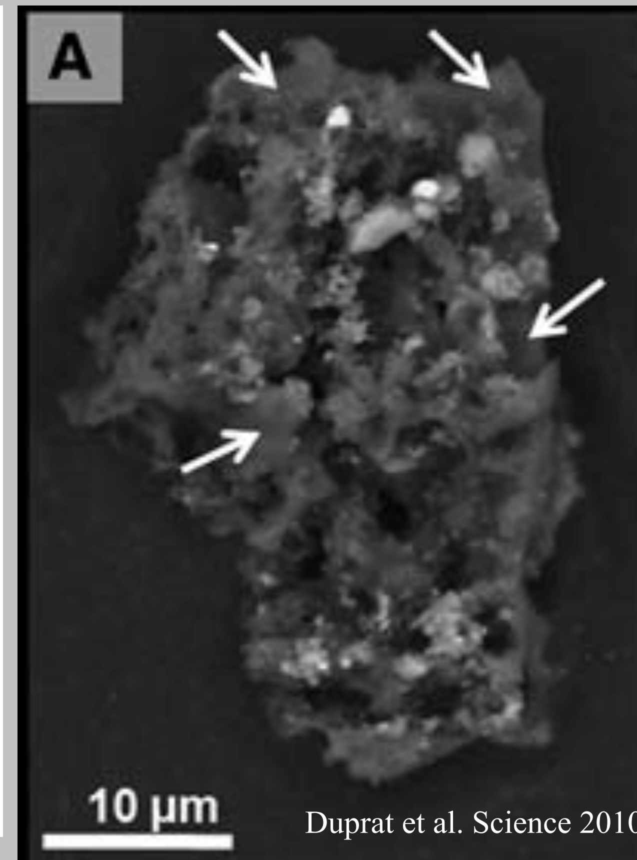
October 2016

The CONCORDIA Collection, different types of micrometeorites



The discovery of 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%

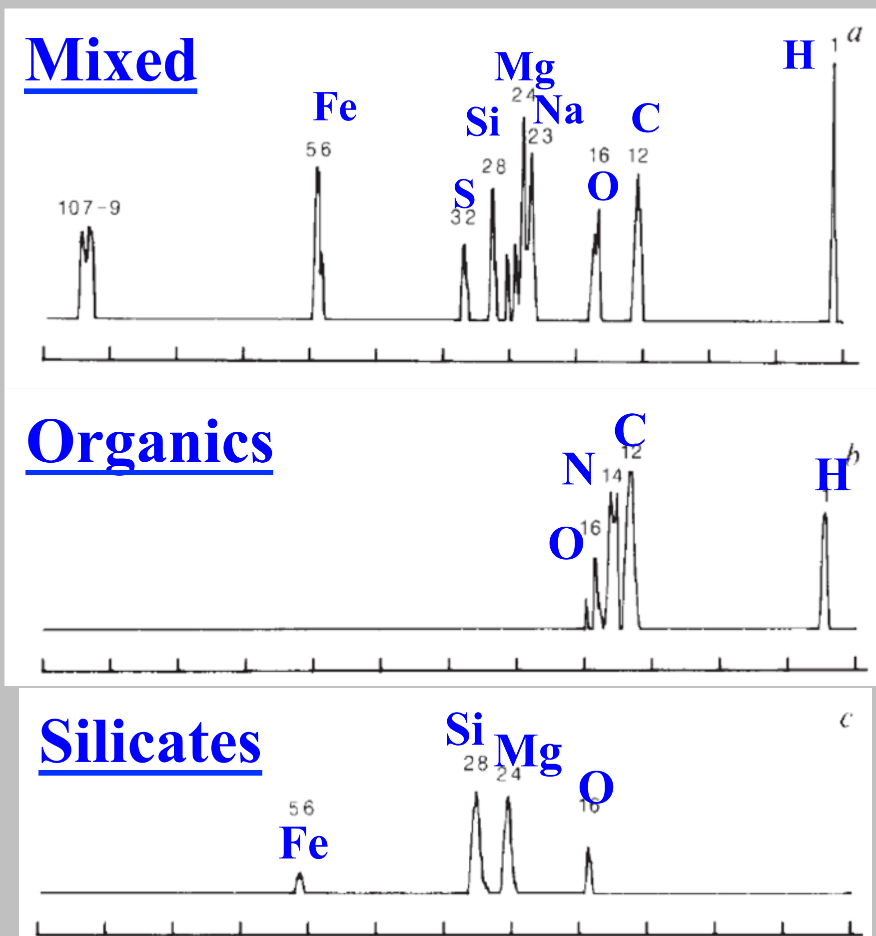
A new type of extraterrestrial material

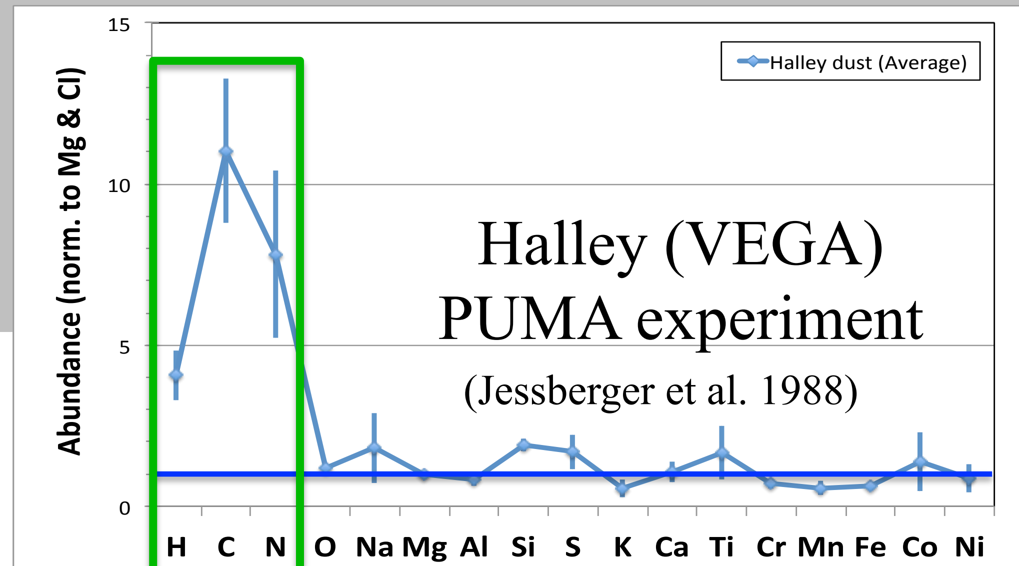
CHON particles and C-rich IDPs

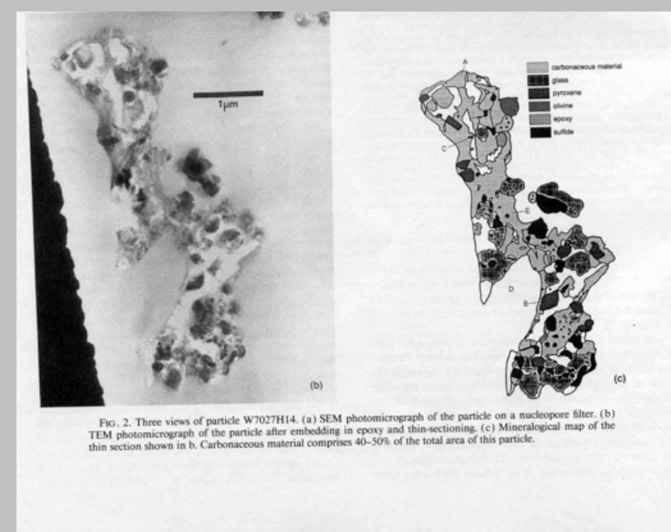
1P/Halley comet

CHON particles, Giotto
(Kissel et al. Nature 1986)

(PIA data)

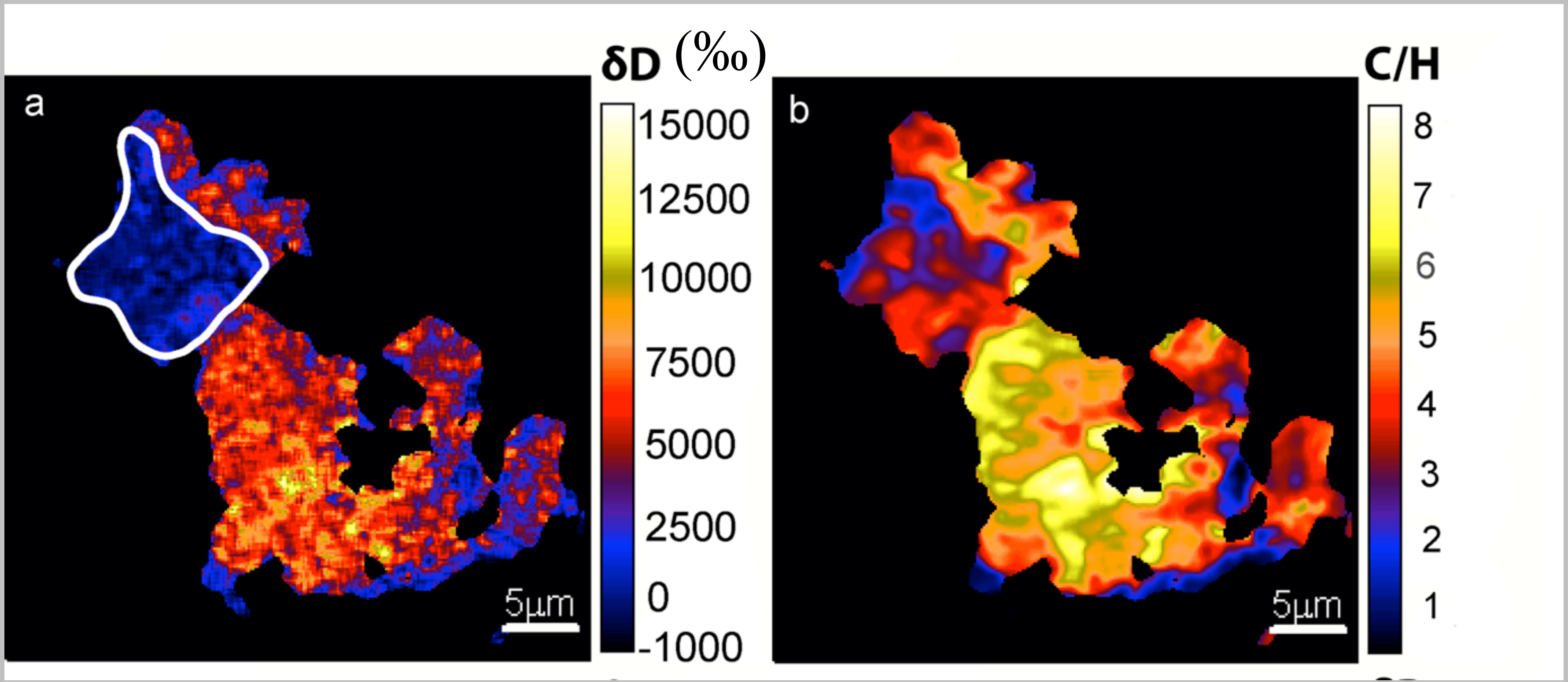






C-rich IDPs (Thomas et al GCA 1998)

D/H ratios in ultracarbonaceous micrometeorites



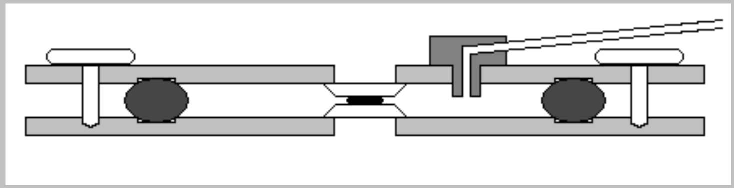
Duprat et al. Science 2010

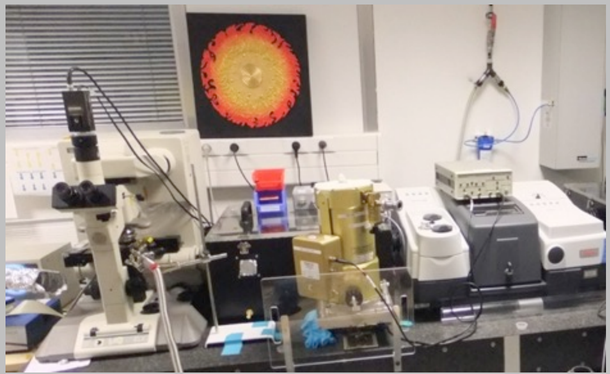
D/H in a UCAMM fragment (DC06-08-19)

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

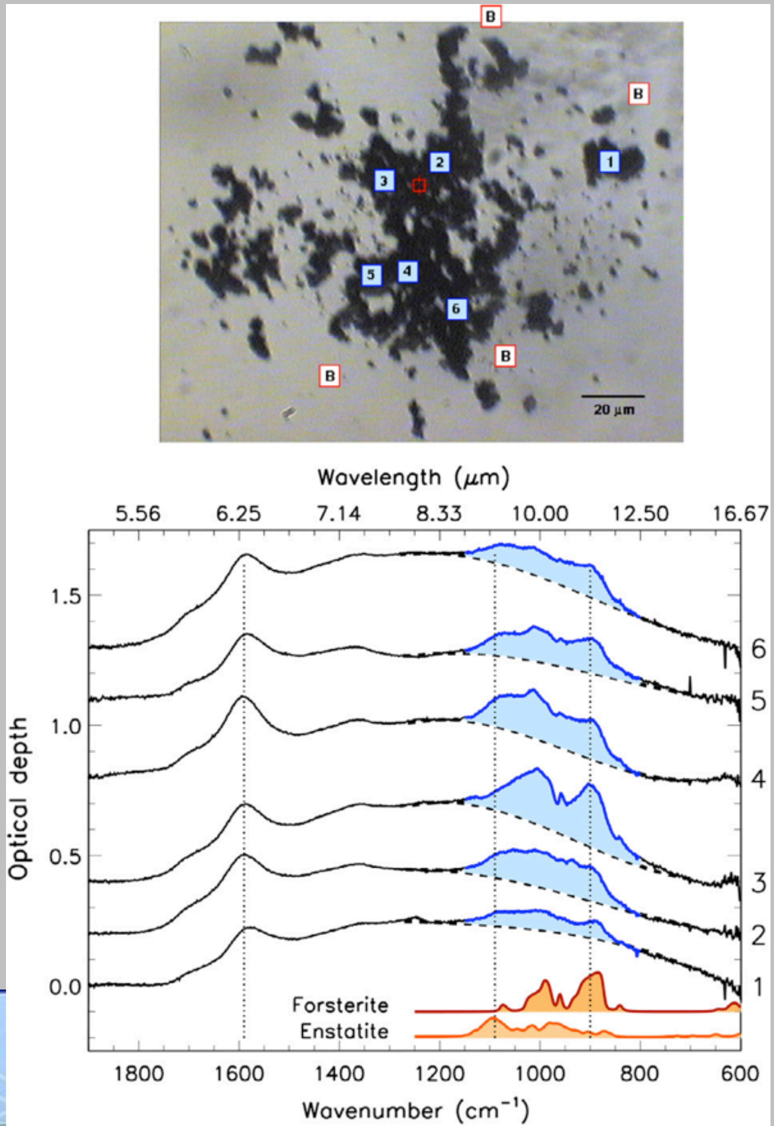
Giant cometary grains, a new window on extraterrestrial organics

Coupled studies on UCAMMs by the IAS-CSNSM- Institut Curie collaboration





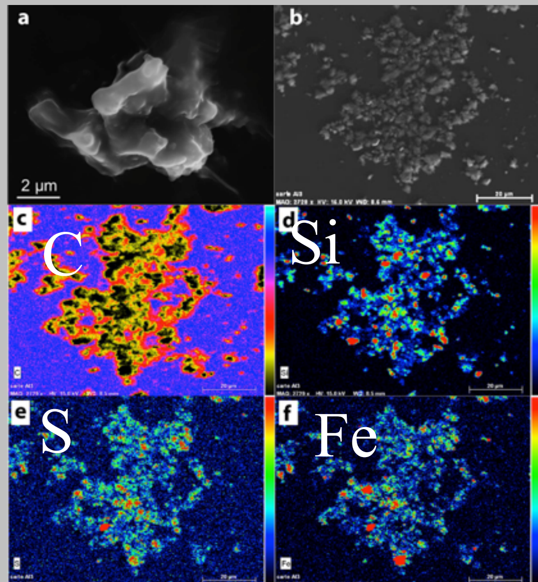
- ✓ Infra-Red transmission microanalyses
  @ synchrotron SOLEIL
- ✓ Elemental composition :
  SEM and electronic microprobe
- ✓ Isotopic studies at the Nanosims
  MNHN, Institut Curie Orsay



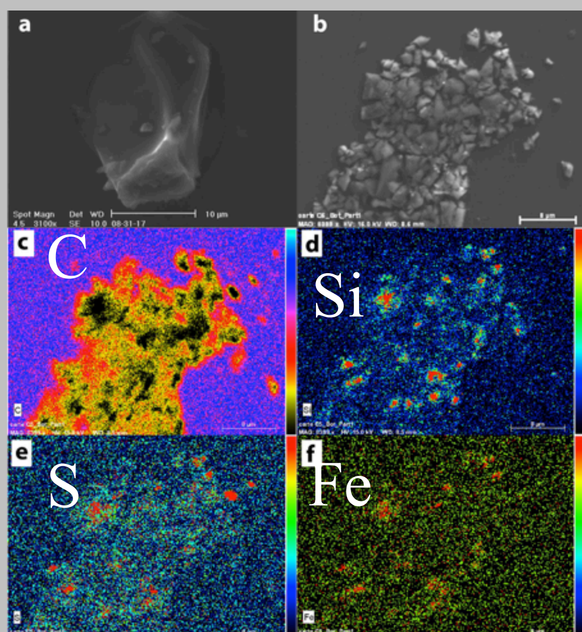
Dartois, Engrand et al. Icarus 2013

IAS Orsay · CSNSM · institut Curie · SOLEIL SYNCHROTRON

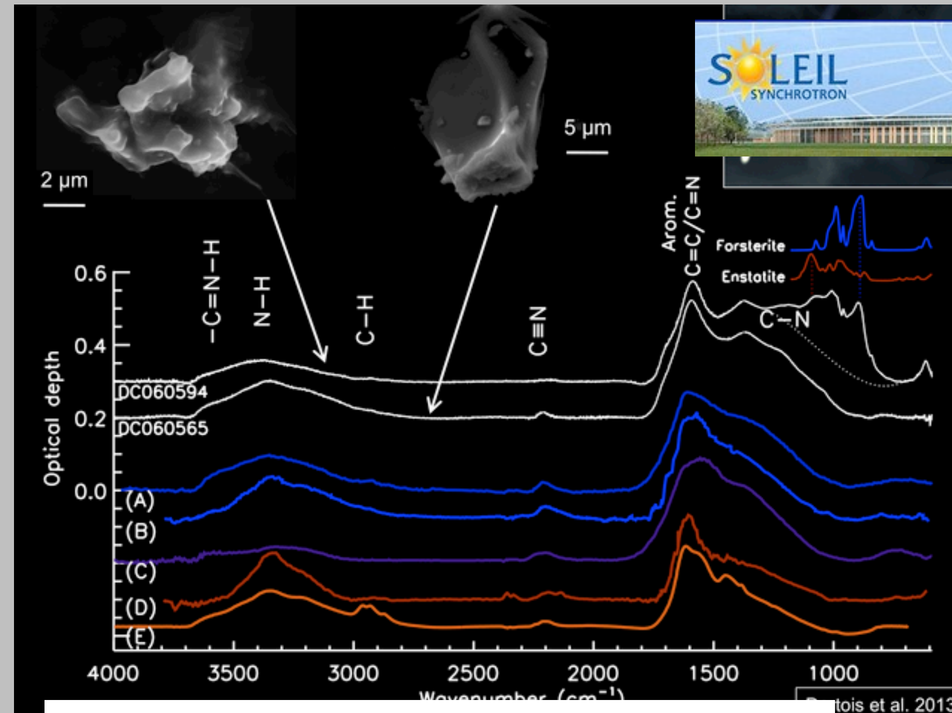
The UCAMM organic matter is nitrogen rich

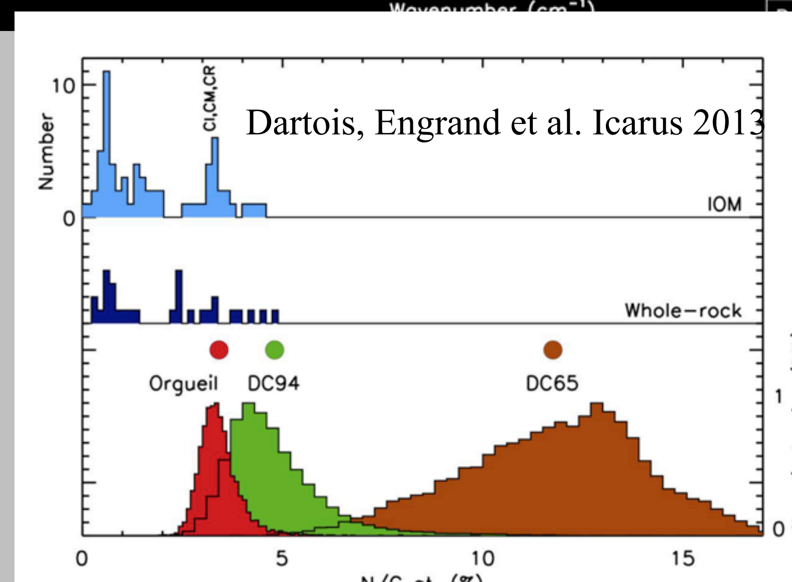


DC06-05-94, mineral rich

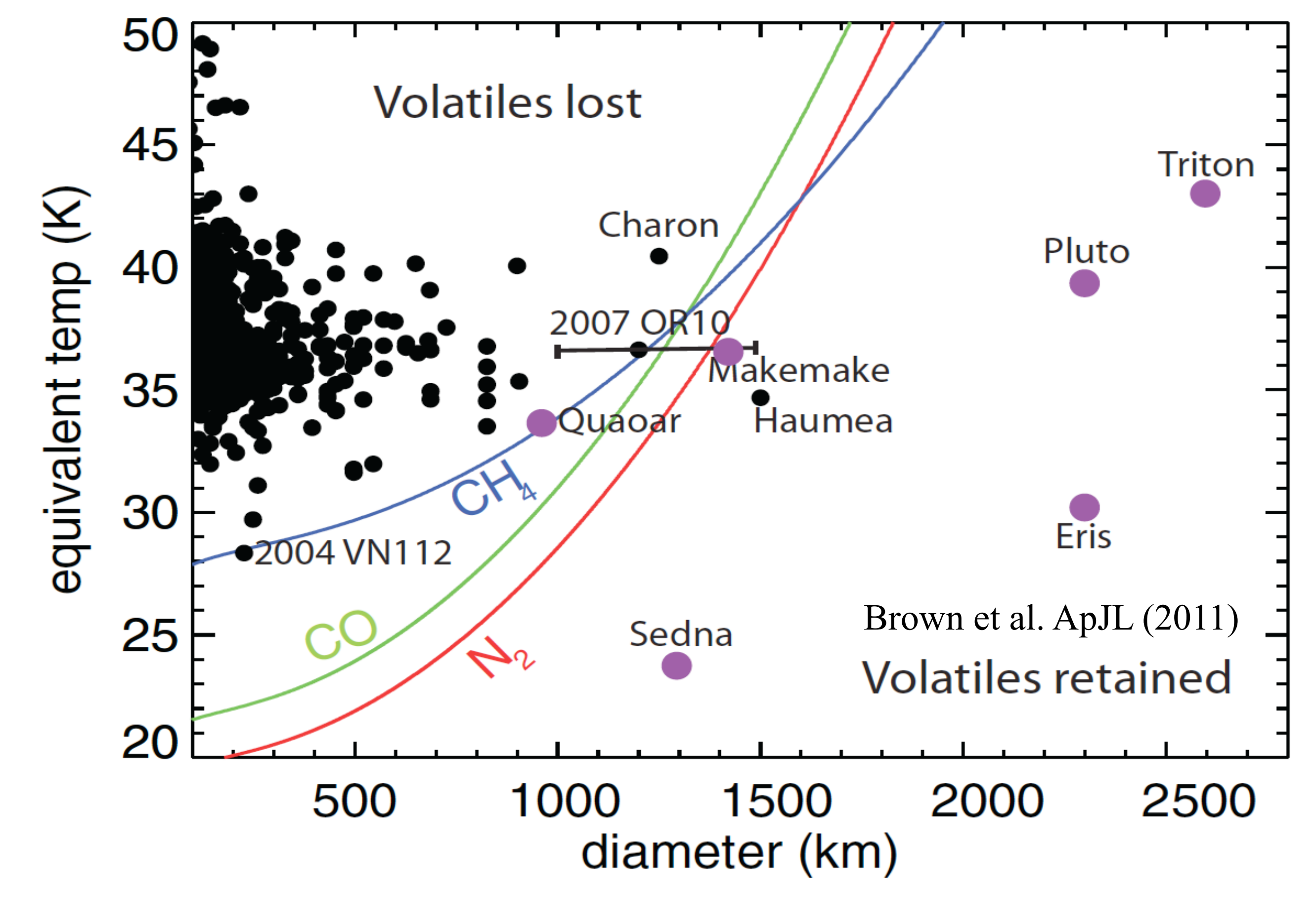


DC06-05-65, mineral poor

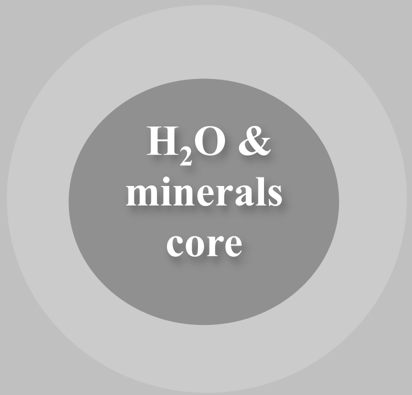




Samples from beyond the Nitrogen snowline ?



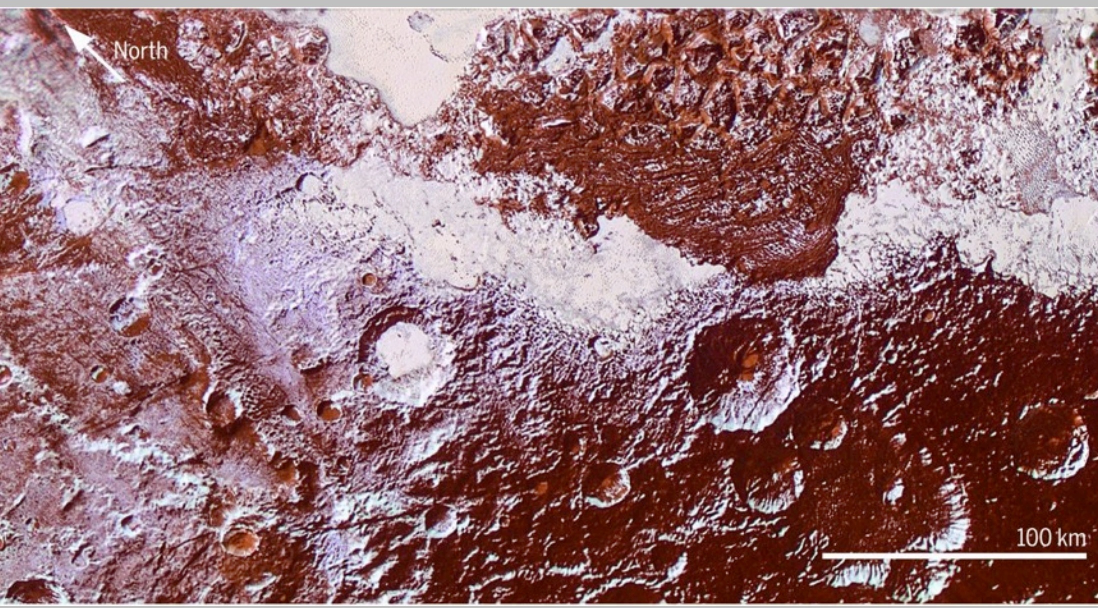
N2, NH3, CH4
icy mantle



N2-CH4 ices at the surface of icy bodies

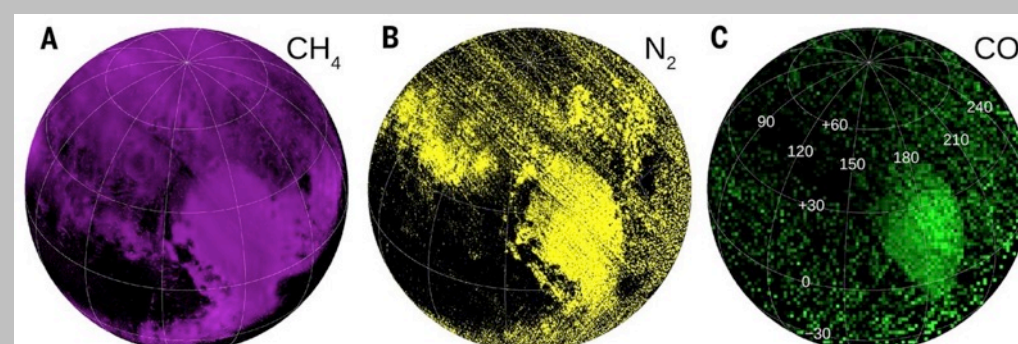
2016, Confirmation by new data from New Horizon space probe

Enhanced color view of Pluto's surface diversity
18 march 2016, NEW HORIZONS



Grundy et al. Science 18 march 2016

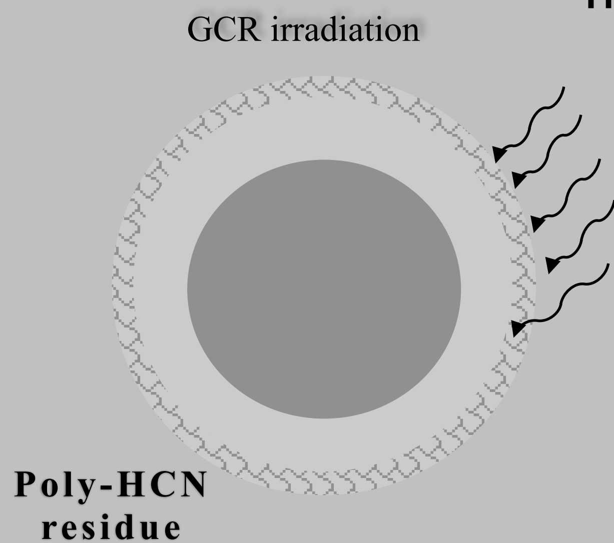
Maps of Pluto's ices
CH4, N2, and CO.



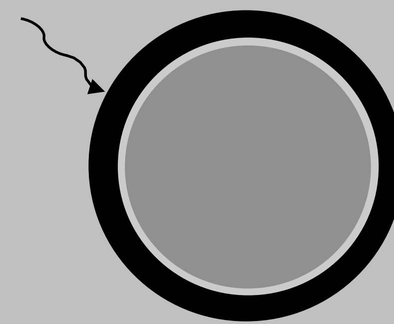
N_2-CH_4 ices at the surface of transneptunians objets

Hypotheses for the UCAMM formation

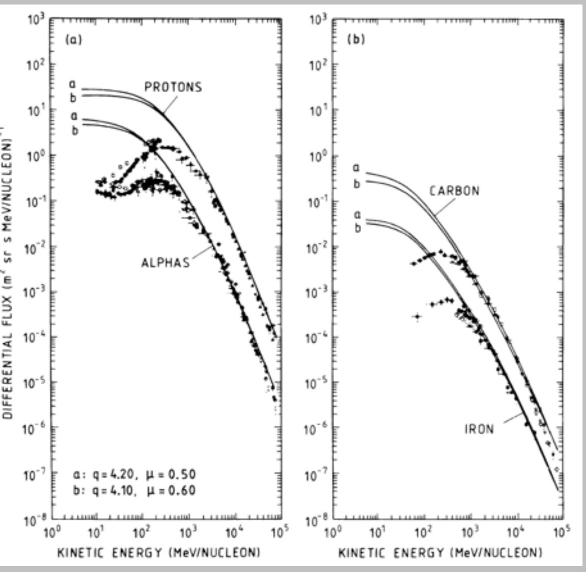
Step 1
accretion/condensation of
N-rich ices at the surface of a core (H2O ice + minerals)



Step 3
Sublimation of the N-rich ices and **concentration of the refractory poly-HCN precursor** at the surface of the parent body.

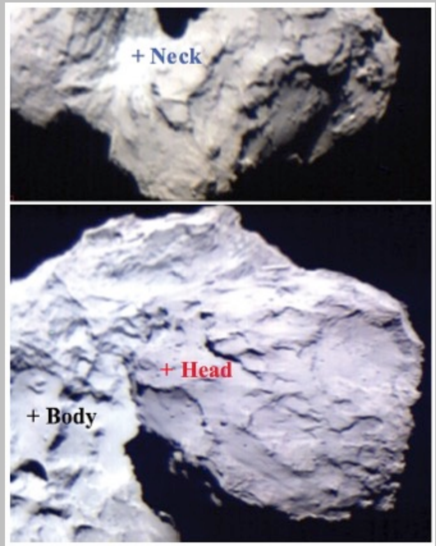


Refractory organic crust at the surface of 67P/C-G (VIRTIS DATA)



Step 2
Irradiation of the N-rich ice surface by GCR, **synthesis of a poly-HCN precursor**

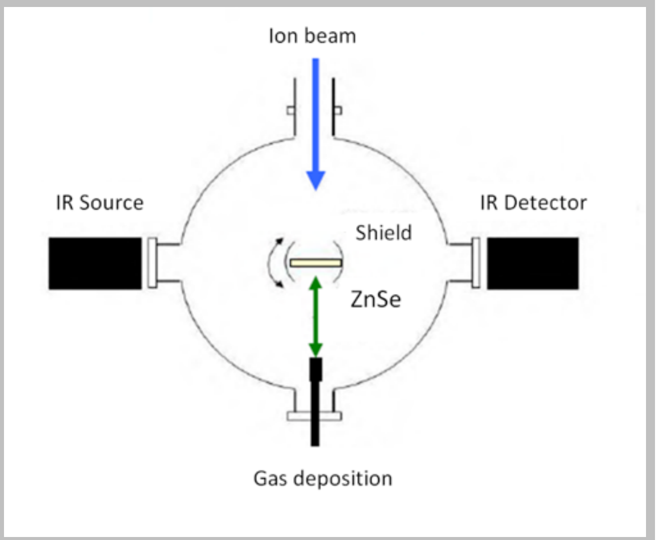
➔ Irradiation of N2-CH4 surface ices by GCR cosmic rays at large heliocentric distances (> 70 AU)



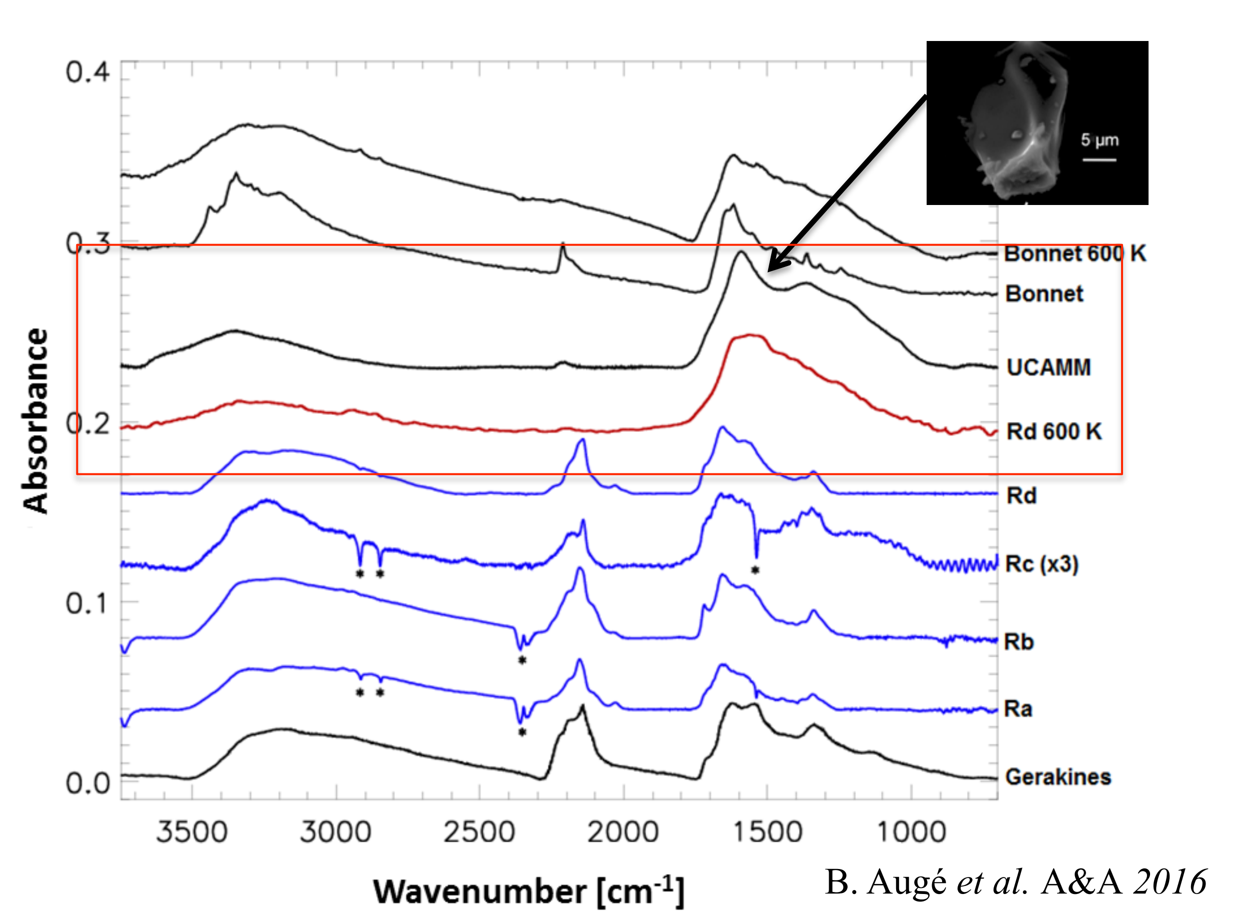
Capaccioni et al. Science 2015

Galactic Cosmic Ray interaction with N-rich ices

Ni^{11+} @44 MeV; 160 MeV
Ar^{15+}@160 MeV



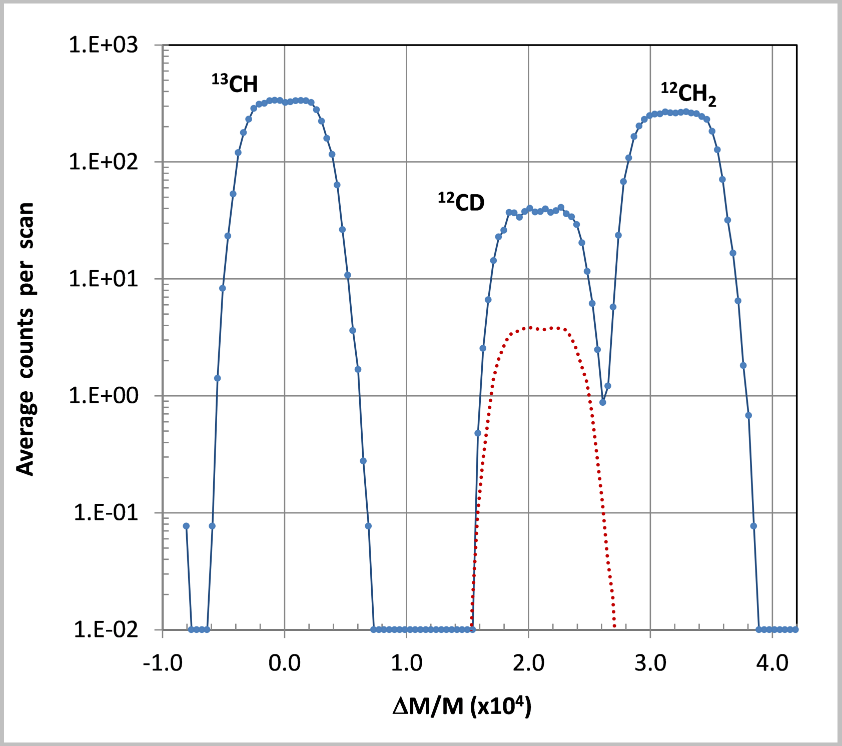
Target N2-CH4 ices
(90:10; 98:2)



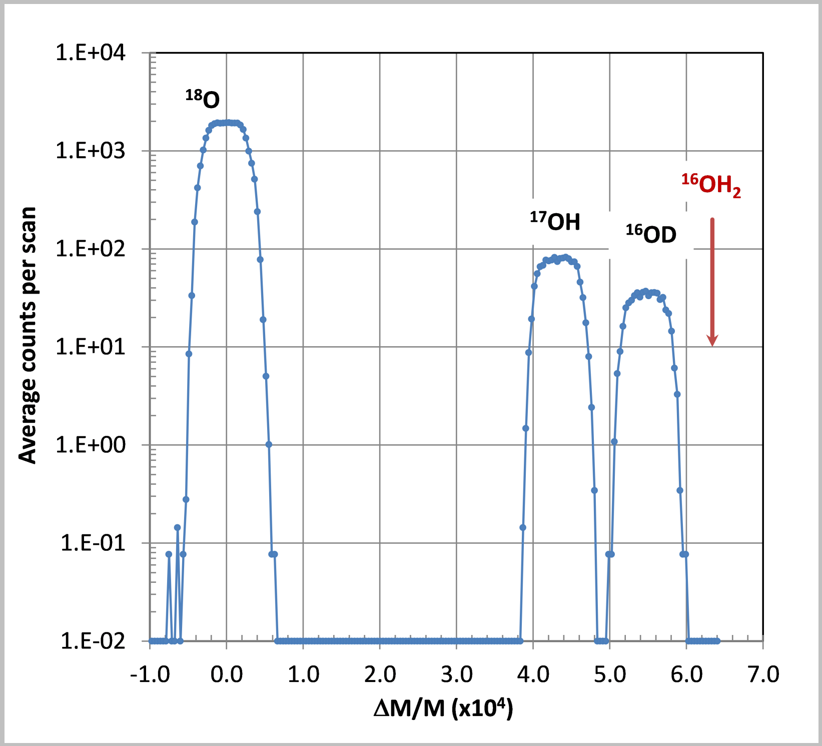
B. Augé *et al.* A&A *2016*

High energy ions irradiation of N2-CH4 ices
induce a refractory poly-HCN residue
that can be the precursor of the UCAMM OM.

Nanosims studies at high mass resolution



Mass spectrum at A=14, 15 scans, on D-rich Polystyrene (10xSMOW),
(^{13}C-^{12}CD is used as ΔM/M reference, ^{12}CH-$^{12}CH_2$ 1/8900)



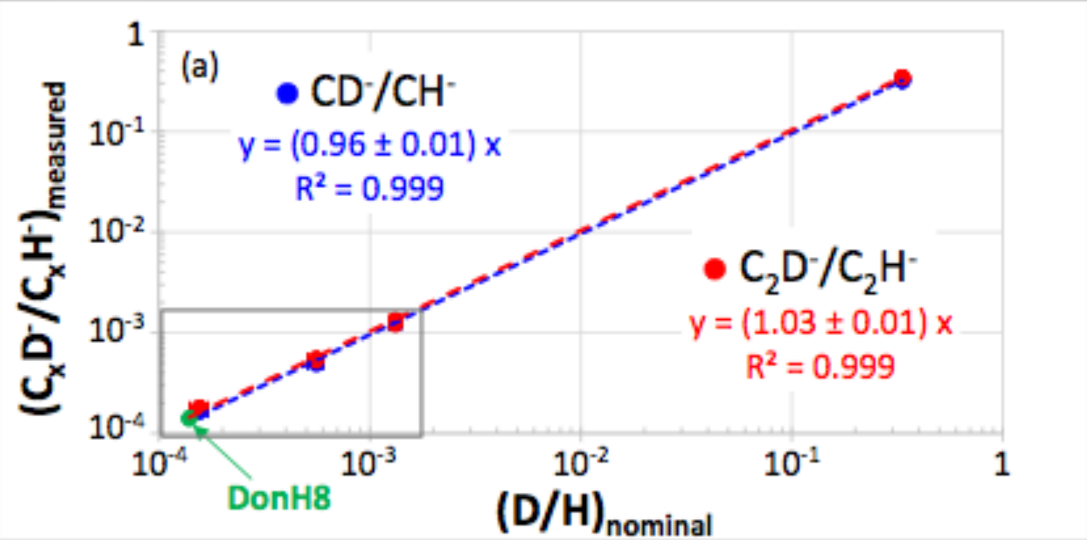
Mass spectrum at A=18, 15 scans, on Goethite,
(^{18}O-^{17}OH is used as ΔM/M reference, ^{17}OH-^{16}OD 1/8740)

Improvement performed in 2011-2014 by G. Slodzian on the Nanosims at Institut Curie
(Slodzian et al. *Microscopy & Microanalysis 2014* and *Nanosims workshop MNHN-Paris October 2014)*

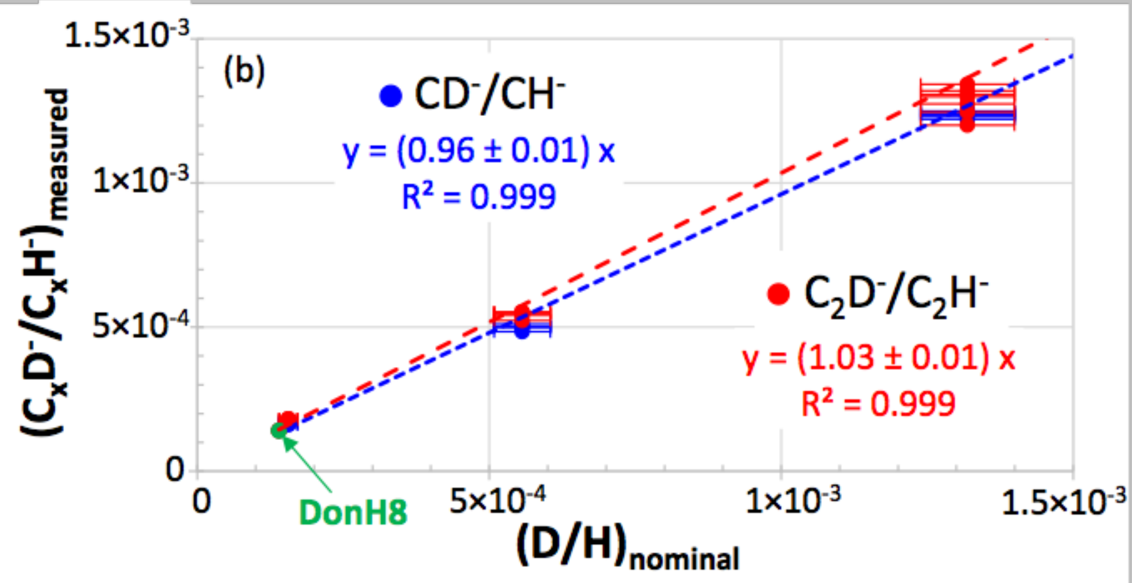
D/H ratios measurements using polyatomic secondary ions :

- Possibility to measure D/H and $^{15}N/^{14}N$ ratios with the same B field
- Sensitivity to the emitting phase
- Better IMF correction

Calibration of the Instrumental Mass Fractionation for D/H



Ultra-thin (≈ 200nm) sections of D-rich Polystrene (PS)



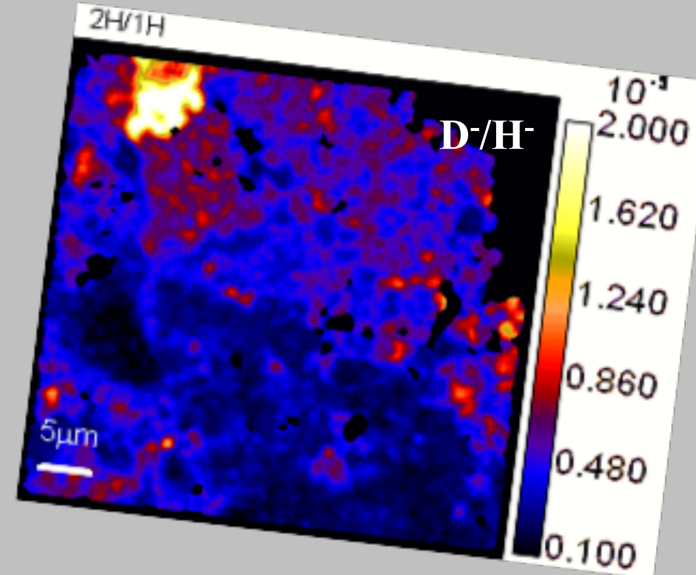
Echantillon	(D/H)	× $(D/H)_{smow}$
PS ND	1,56E-04	1
PS MD	5,56E-04	4
PS FD	1,32E-03	8
PS HD	3,33E-01	2000

The IMF slope is close to one

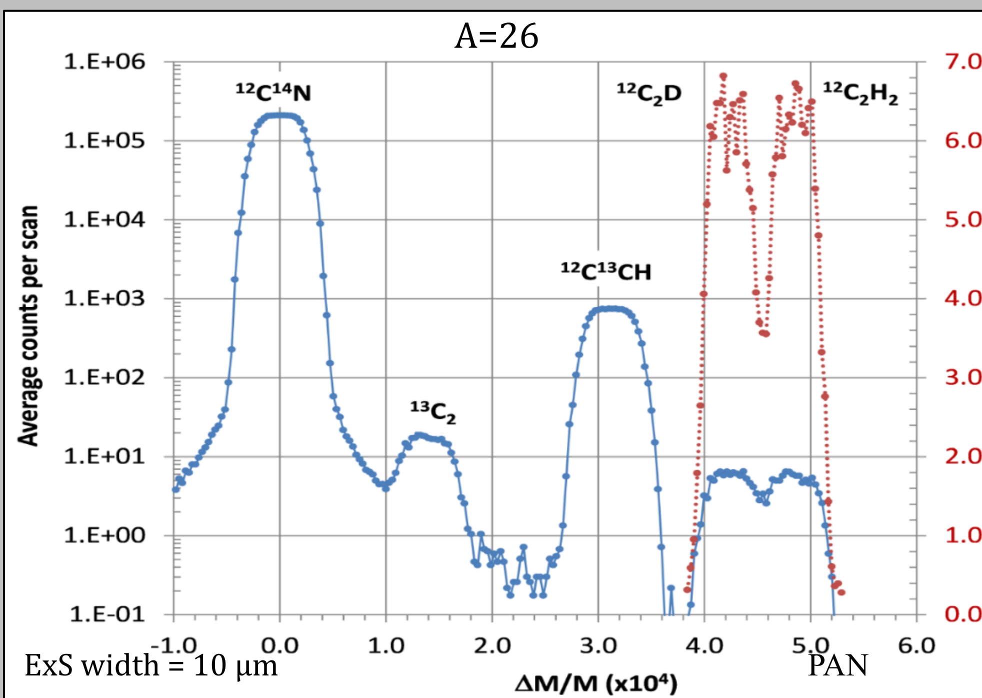
Ion	H^-	CH^-	OH^-	C_2H^-
EA (eV)	0.75	1.24	1.83	3

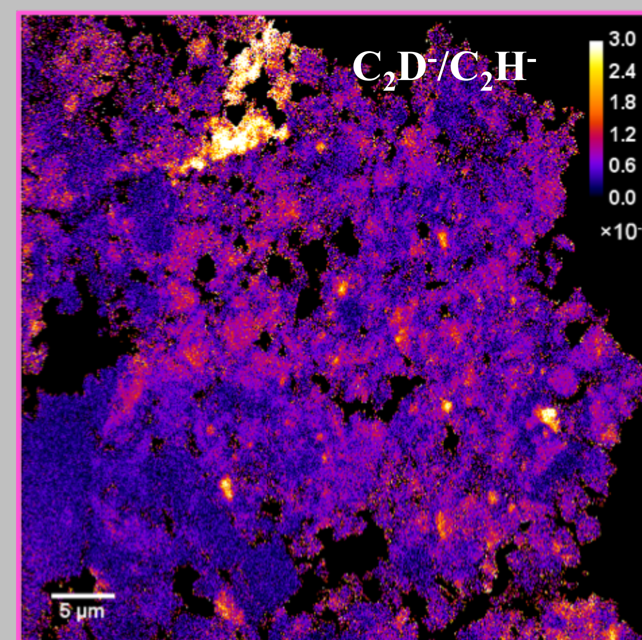
Bardin et al. LPSC 2014, Inter. Journ. Mass Spectro. 2015

Instrumental developments in secondary ion mass spectrometry (SIMS)



Low Res, 50x50 µm, (256x256)



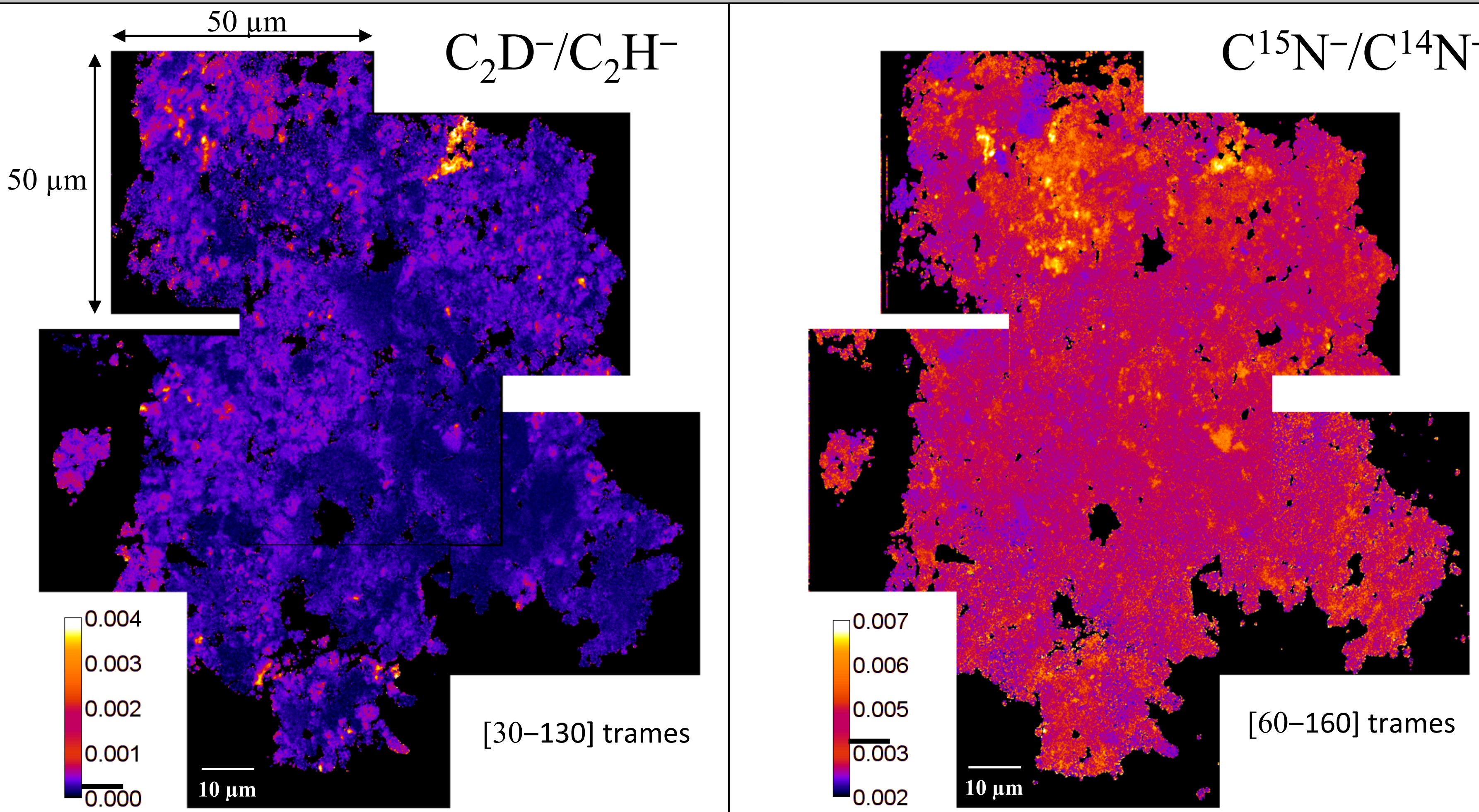


High Res, , 50x50 µm (512x512)
N. Bardin et al. 2015.

G. Slodzian et al., Microscopy & Microanalysis, 2014

C_2D^-/C_2H^- and $C^{15}N^-/C^{14}N^-$ isotopic images on the same UCAMM DC94 fragment

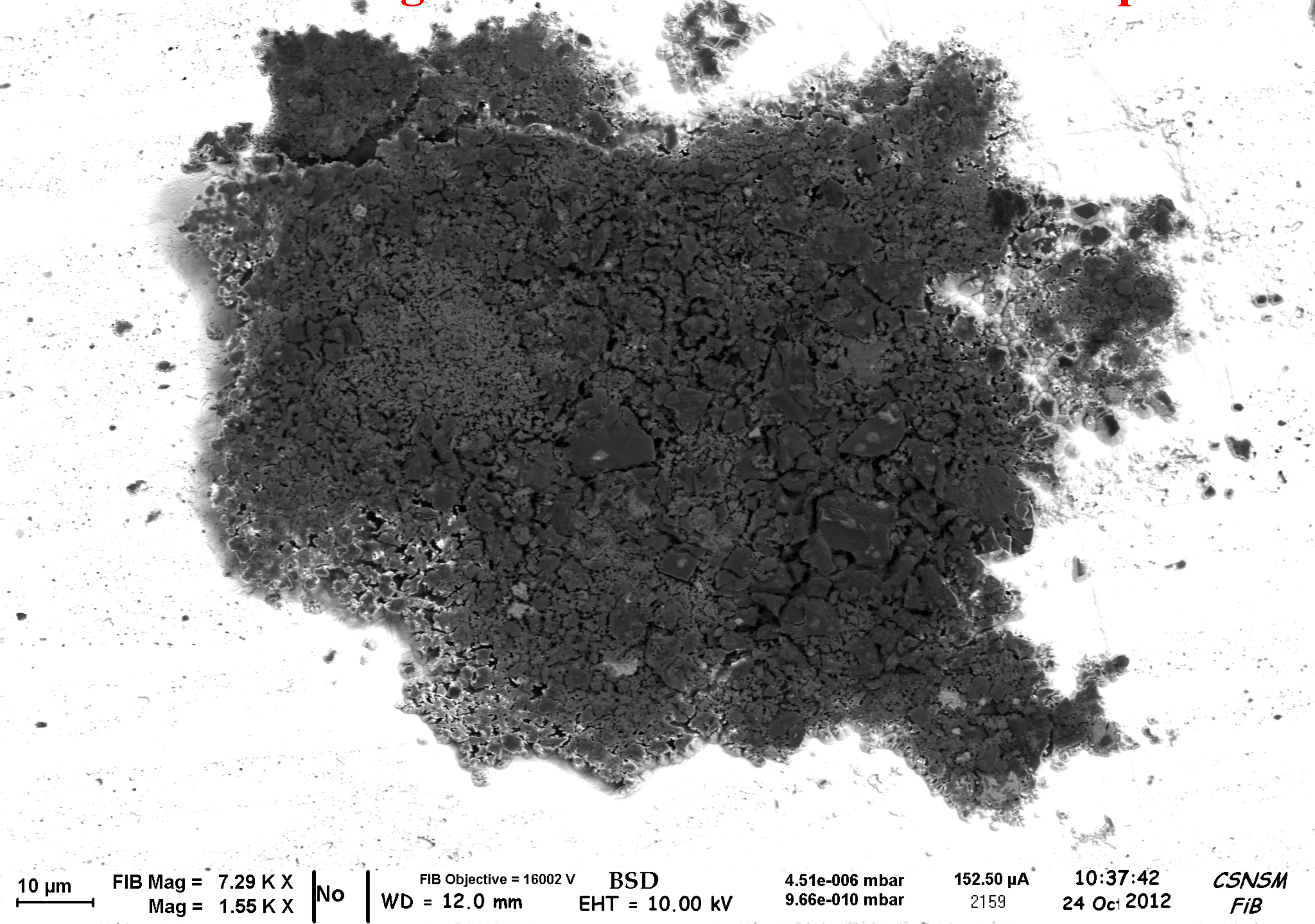
ImageJ



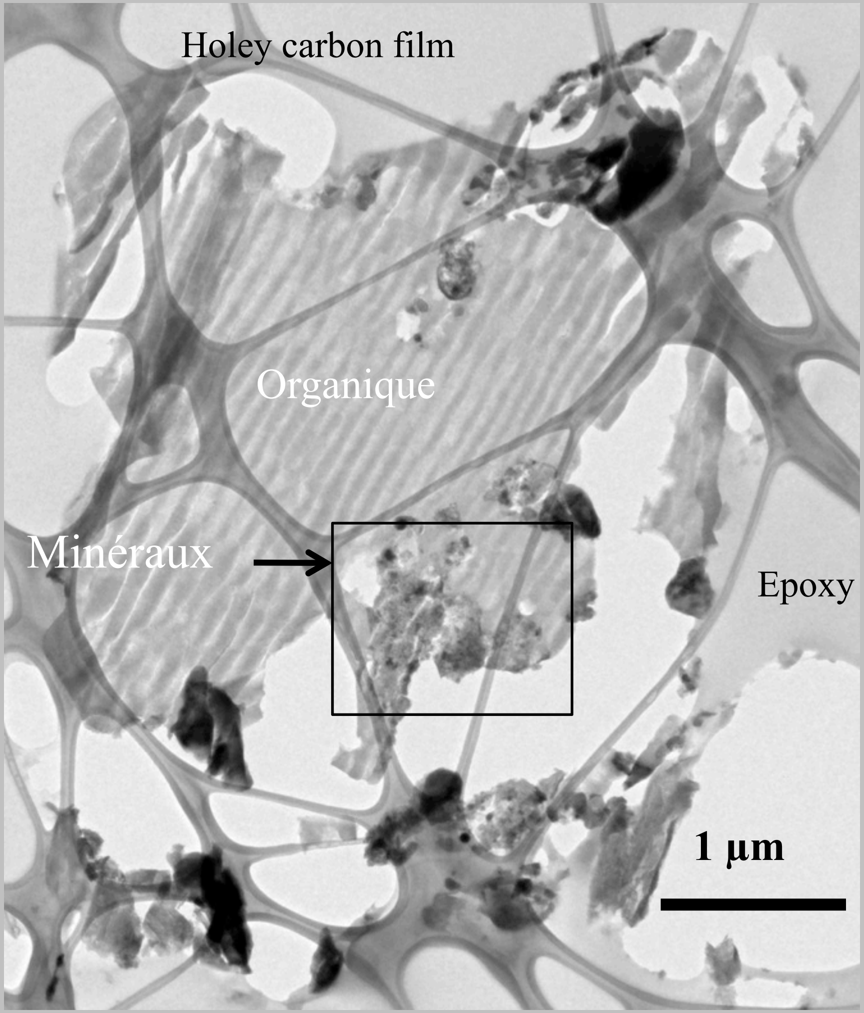
Bardin et al 2015

H & N isotopic SIMS images at the sub-micron scale (same B field)

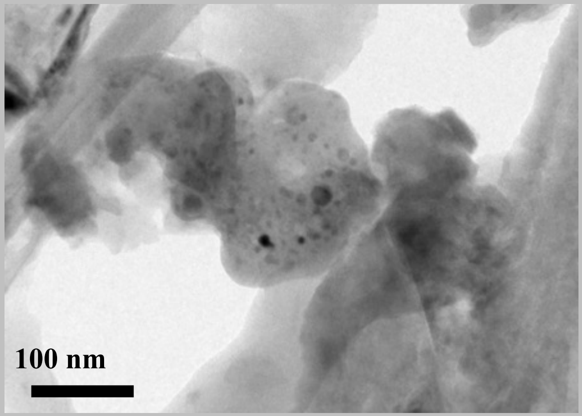
The UCAMMs organic matter exhibit various components



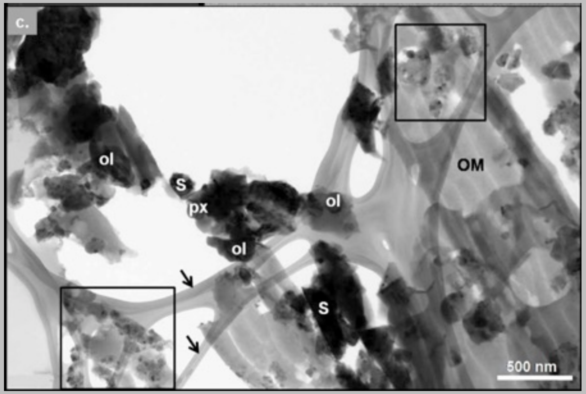
Association entre minéraux et matière organique primitive



Microscopie à transmission (E. Dobrica et al 2011)
Univ. Lille H. Leroux.



Des phases amorphes, similaires à celles observées dans le **milieu interstellaire**



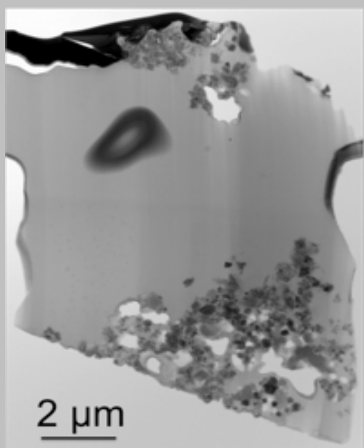
Des phases cristallines typiques des **disques protoplanétaires**

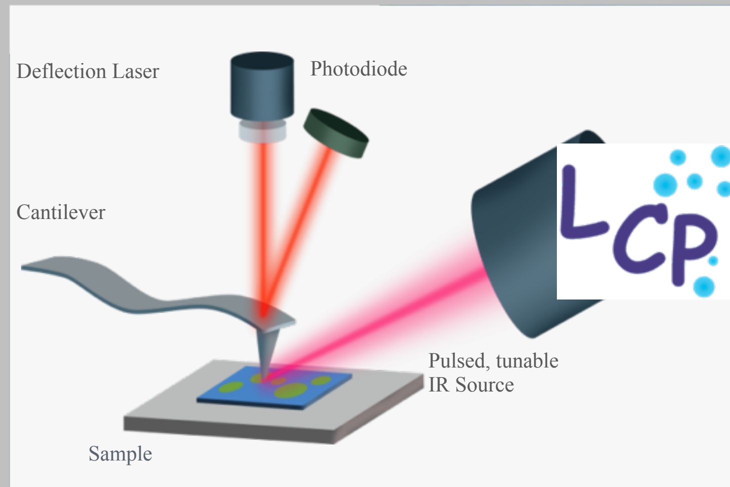
Une possibilité de distinguer l'héritage direct interstellaire issu du nuage moléculaire

UMET
Unité Matériaux Et Transformations

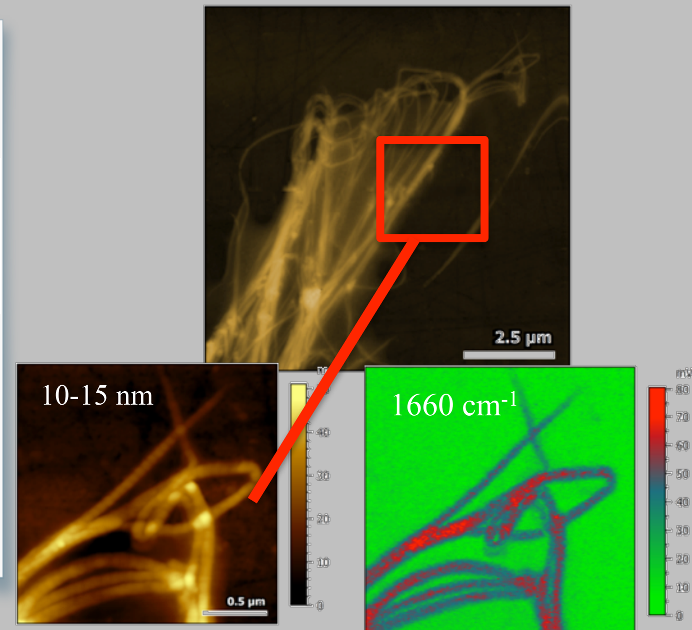
Analyses de grains cométaires par AFMIR et XANES

Coupe FIB 100 nm

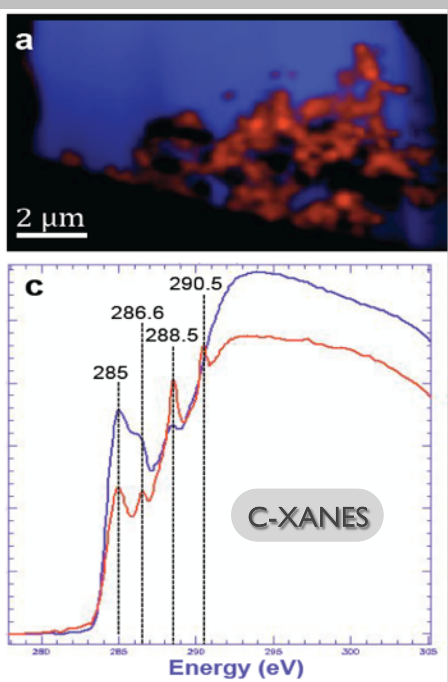




A Dazzi et al. Ultramicroscopy 2008



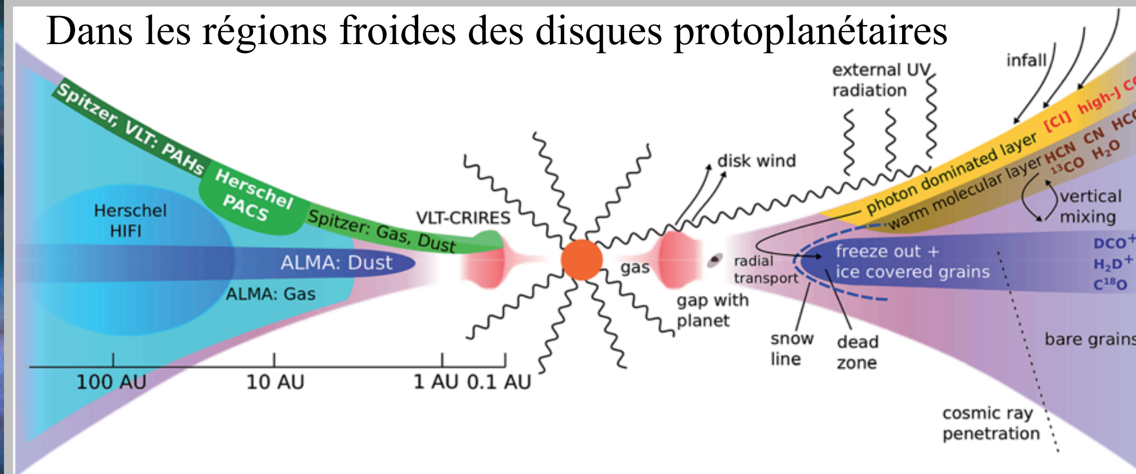
le défi expérimental du nanoIR

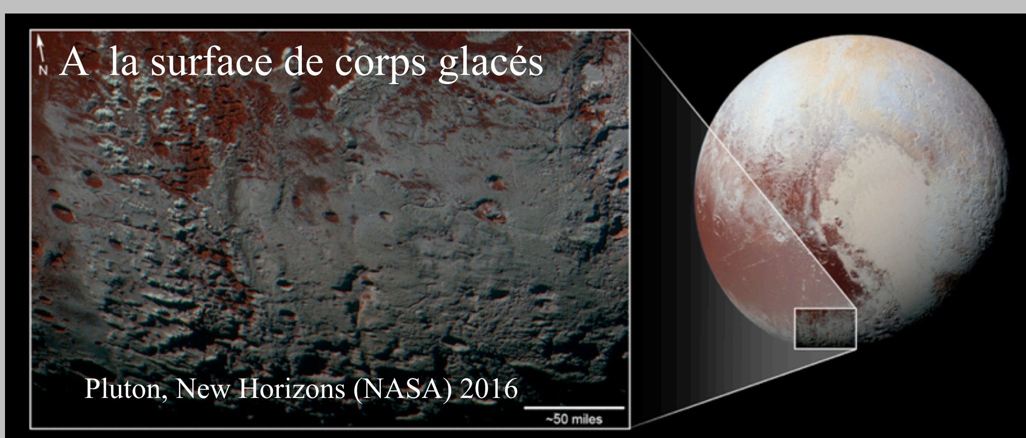


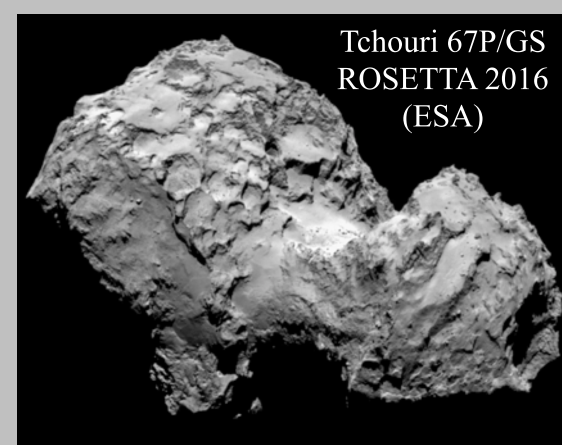
PANDA,
Paris-s**A**clay
interpla**N**etary **D**ust
Analysis

Engrand et al. 2015

Distinguer les origines de la matière organique primitive







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**
- ✓ At the frontier between **interstellar heritage and the cold regions of proto-planetary disks**