La mission Stardust:
Une comète au laboratoire

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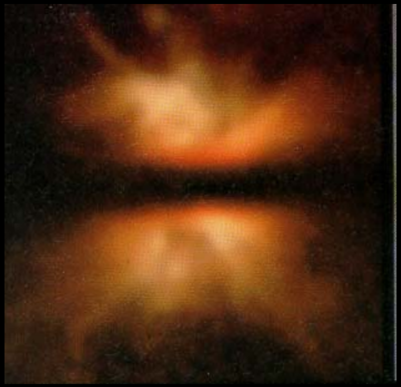
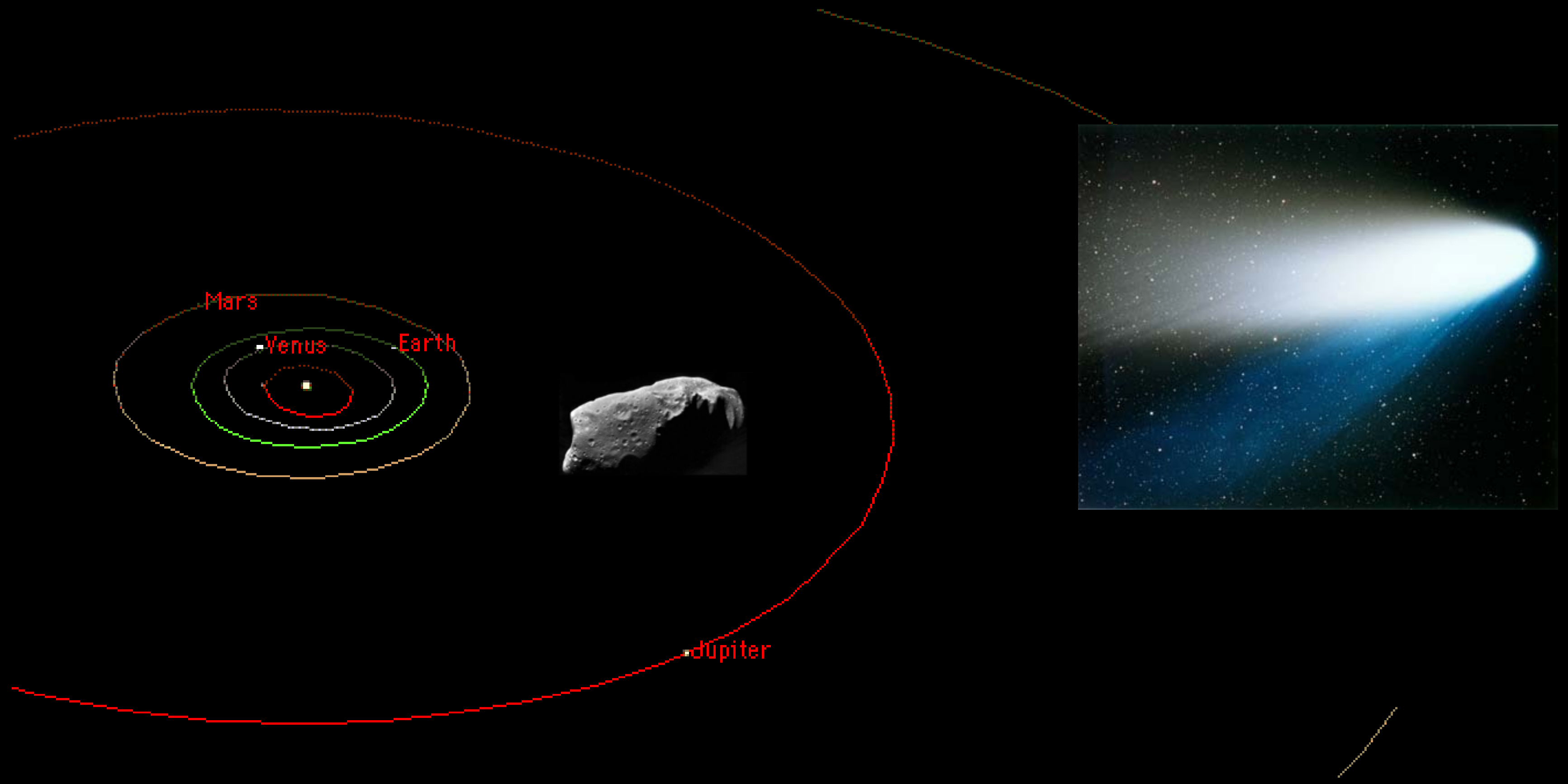
1. Remarques liminaires

Small bodies are *primitive*



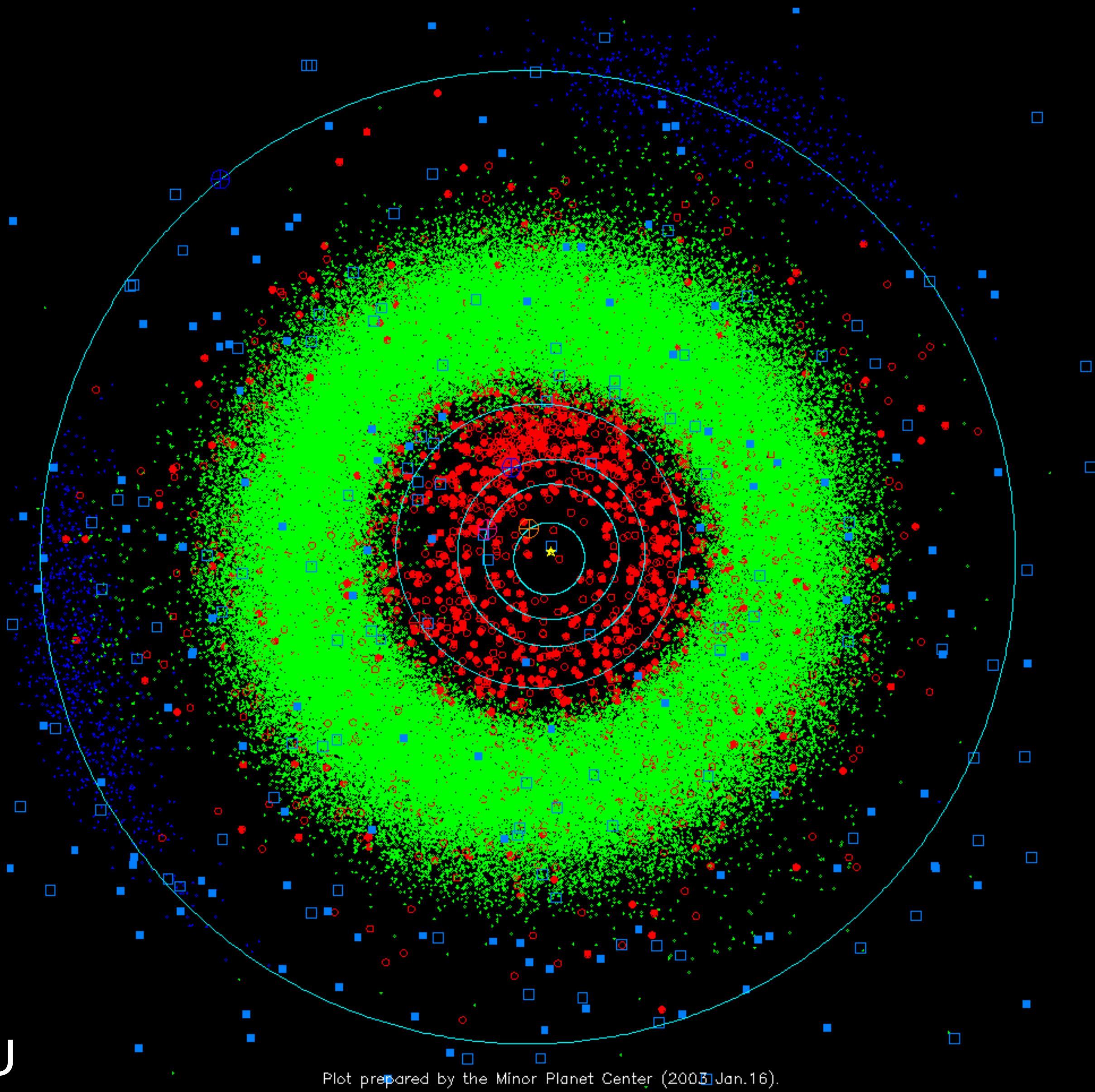



The inner and outer Solar System



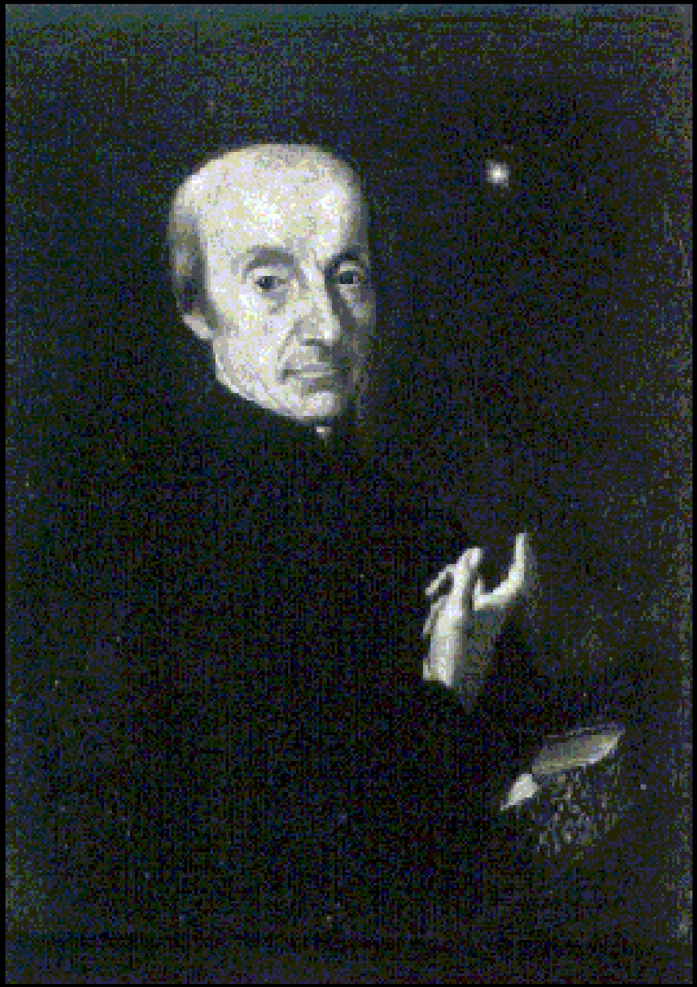
2. Asteroids

Asteroids: Where?



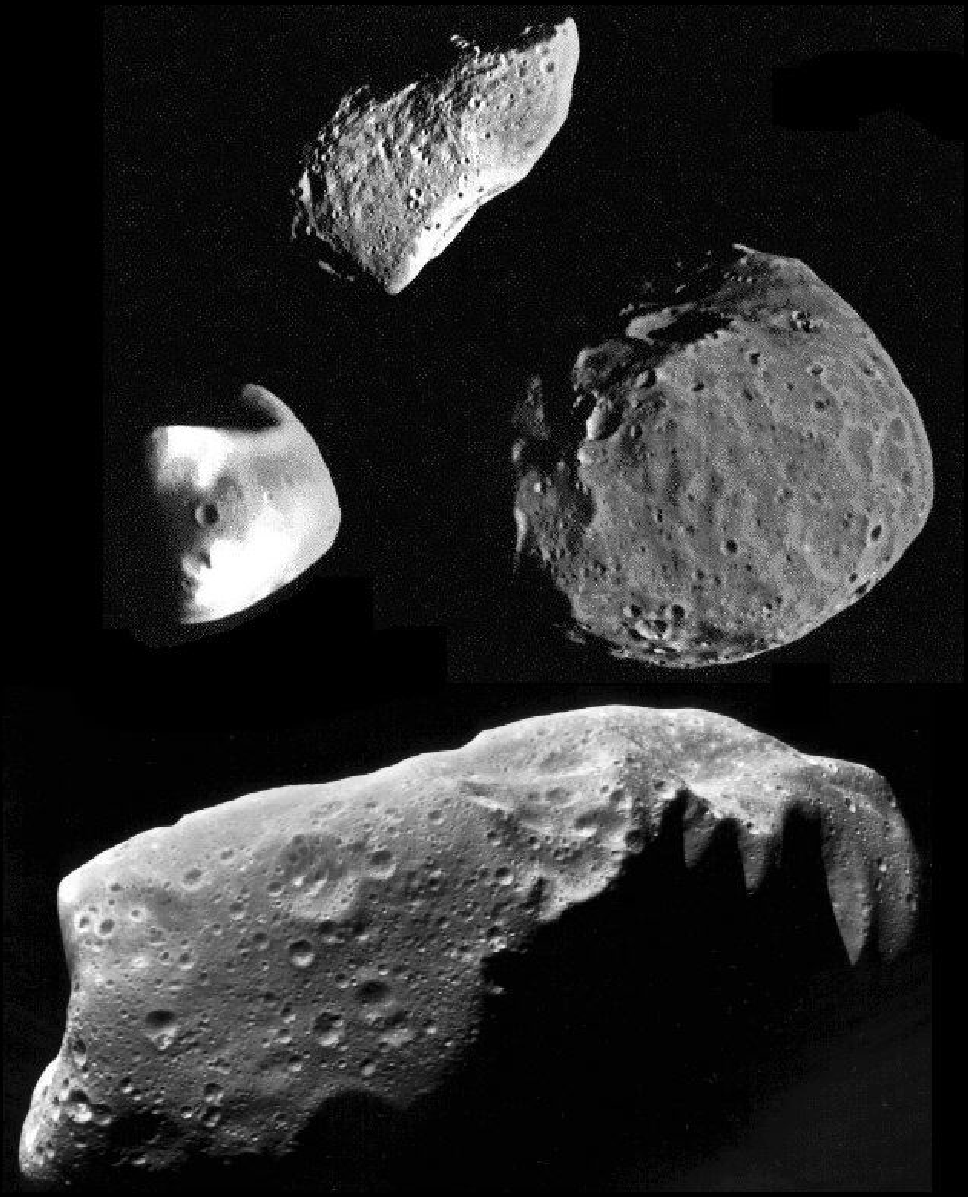
In red: q < 1.3 AU

Asteroids: General



- First discovered is Ceres 1801 (948 km)
- Soon followed by
  - Pallas 1802 (532 km)
  - Juno 1805
  - Vesta 1807 (529 km)
- Next discoveries: 1854
- Total mass ~ 4 % of the Moon
- Tens of thousands of asteroids known
- 1 to 2 million asteroids with diameter > 1 km

Asteroids: What?



- Corps rocheux
- Faible densité: 0.96 g.cm^{-3} (Eunomia) à Eros (2.12 g.cm^{-3})
- Certains contiennent de la glace

3. Les comètes

Comets

They are rich in water

➔ They have an extended coma

(up to 100 x 10^6 km)

They have eccentrical and inclined orbits

➔ They come back

They come from the outer solar system

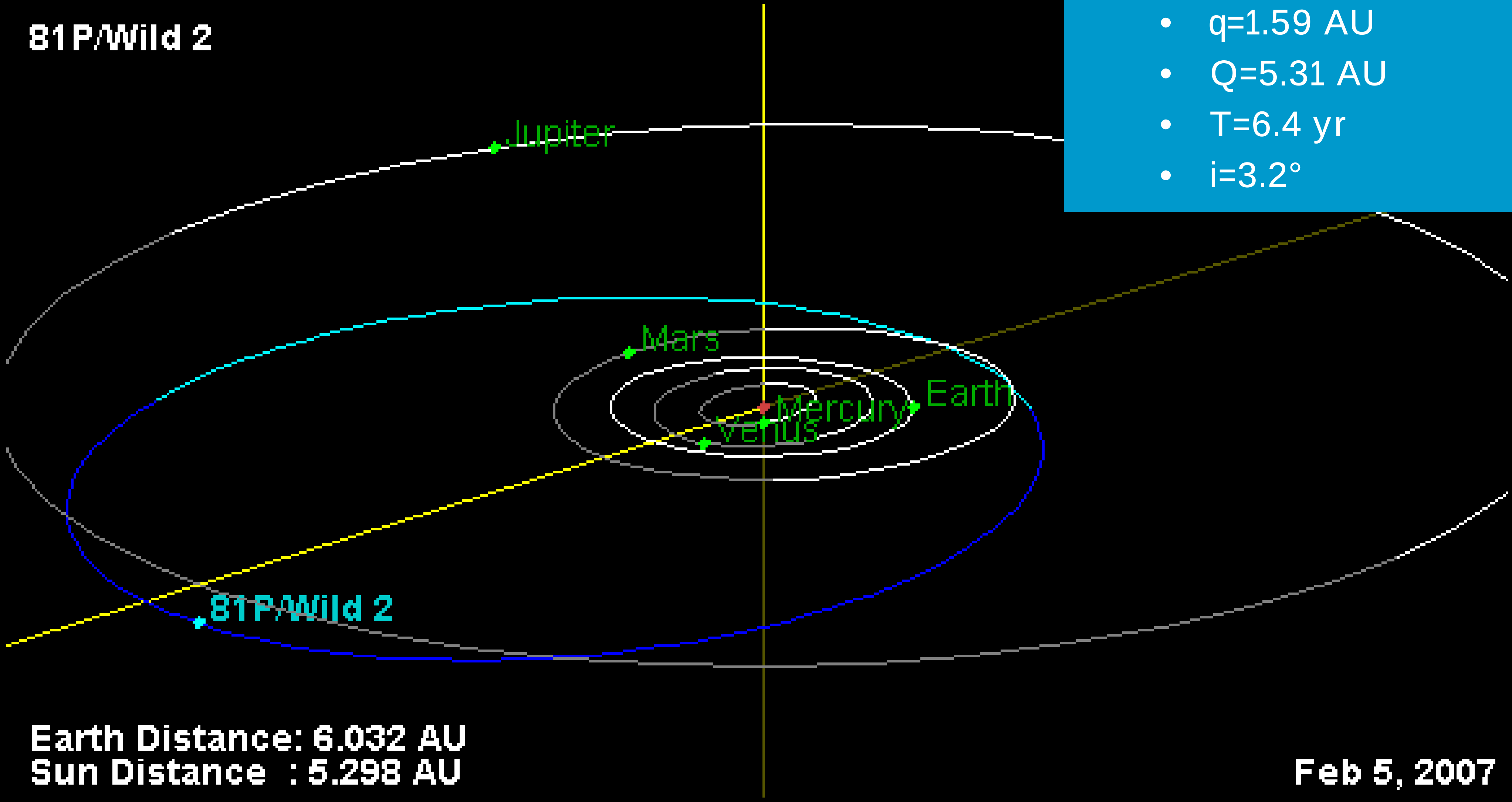
1997 comète Hale Bopp

Two types of comets

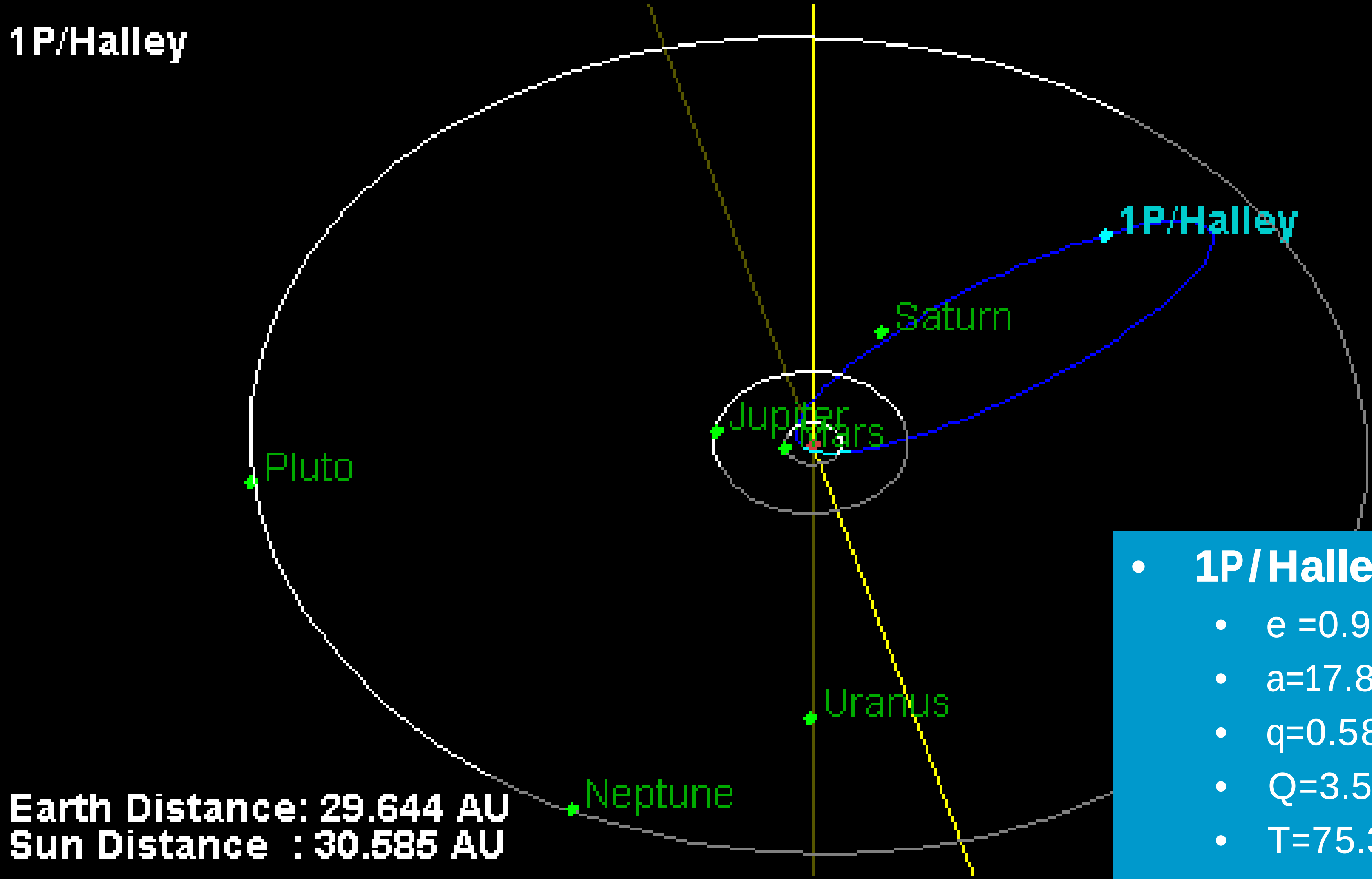
- **Short period comets (T<200 yr)**
  - T<20 yr Jupiter type
  - T>20 yr Halley type
- **Long period comets (T>200 yr)**
  - Oort cloud comets

Jupiter family comets

- **Wild 2**
  - e =0.538
  - a=3.45 AU
  - q=1.59 AU
  - Q=5.31 AU
  - T=6.4 yr
  - i=3.2°



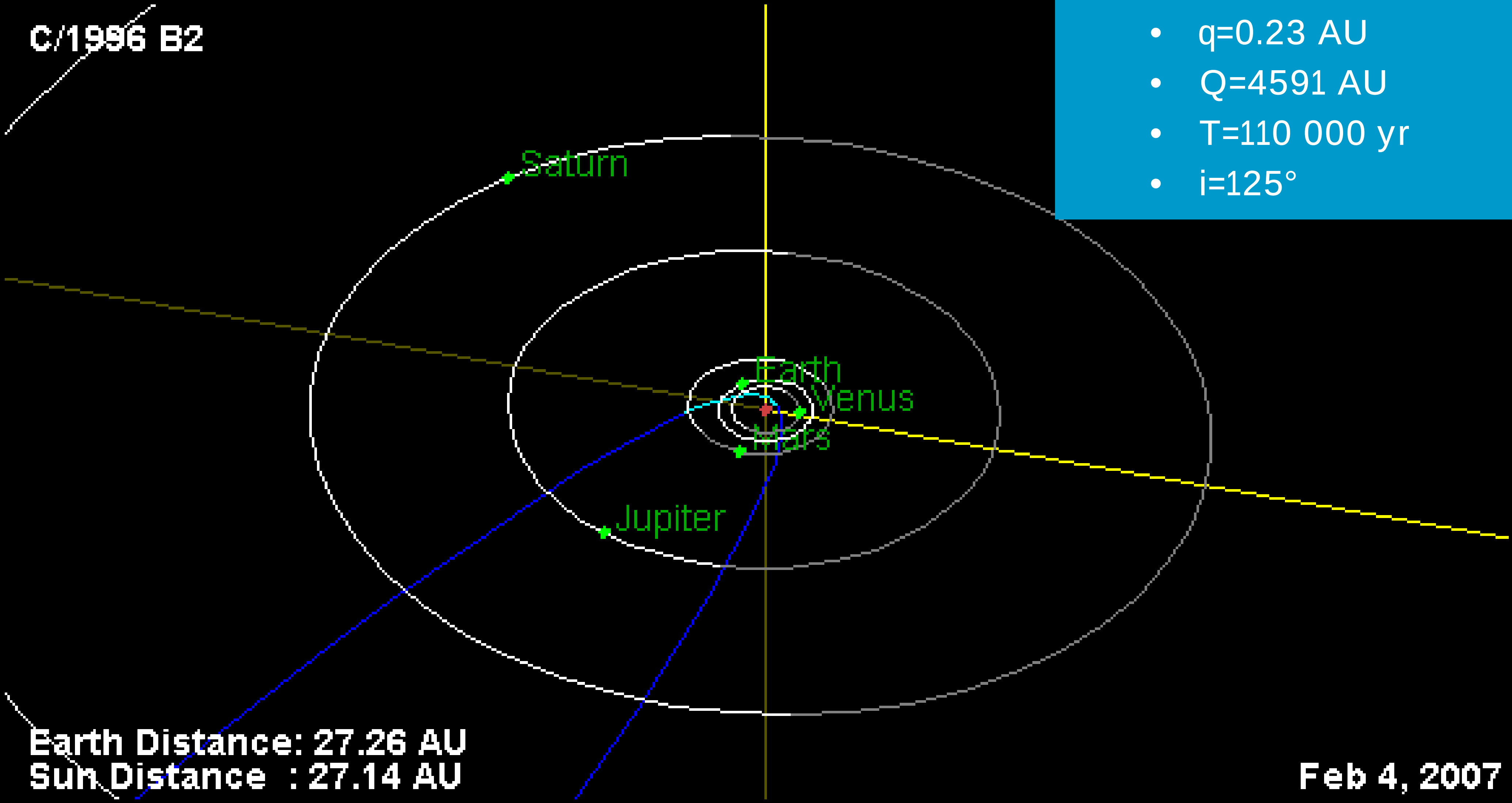
Halley type comets



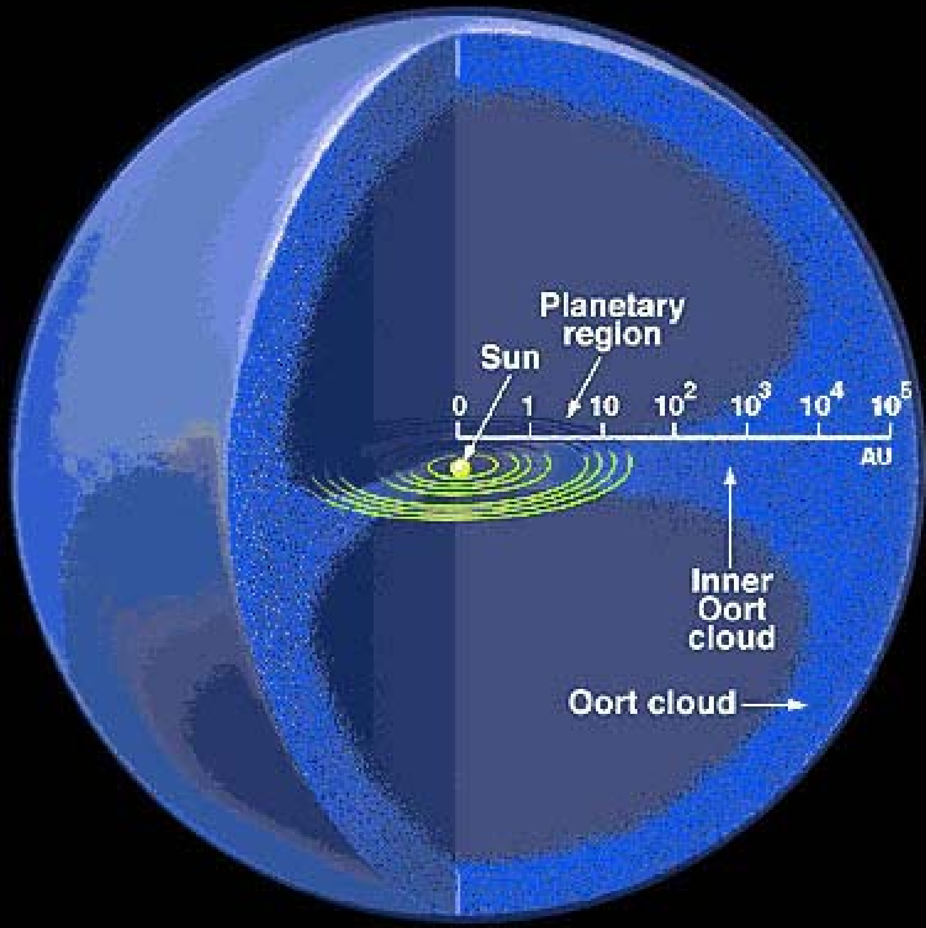
- **1P/Halley**
  - e =0.967
  - a=17.83 AU
  - q=0.586 AU
  - Q=3.5.08 AU
  - T=75.3 yr
  - i=162°

Oort cloud comets

- **Hyakutake**
  - e =0.99989
  - a=2295 AU
  - q=0.23 AU
  - Q=4591 AU
  - T=110 000 yr
  - i=125°

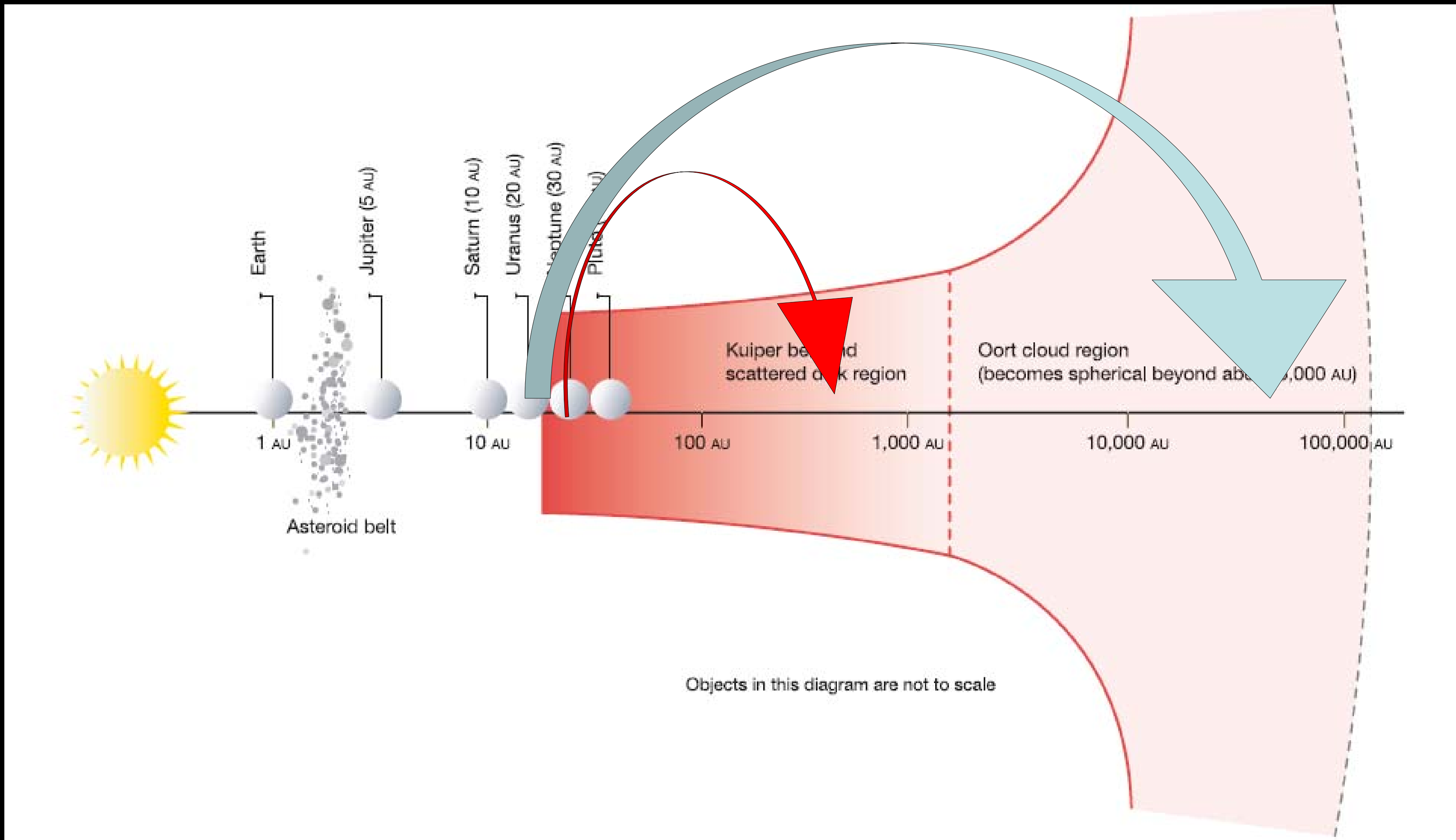


The Oort cloud



Expelled from the Oort cloud to the inner Solar System because of a passing star

“One” origin for comets



Les comètes: propriétés observables

- **Objet actif**
  - Différence d'avec les astéroïdes

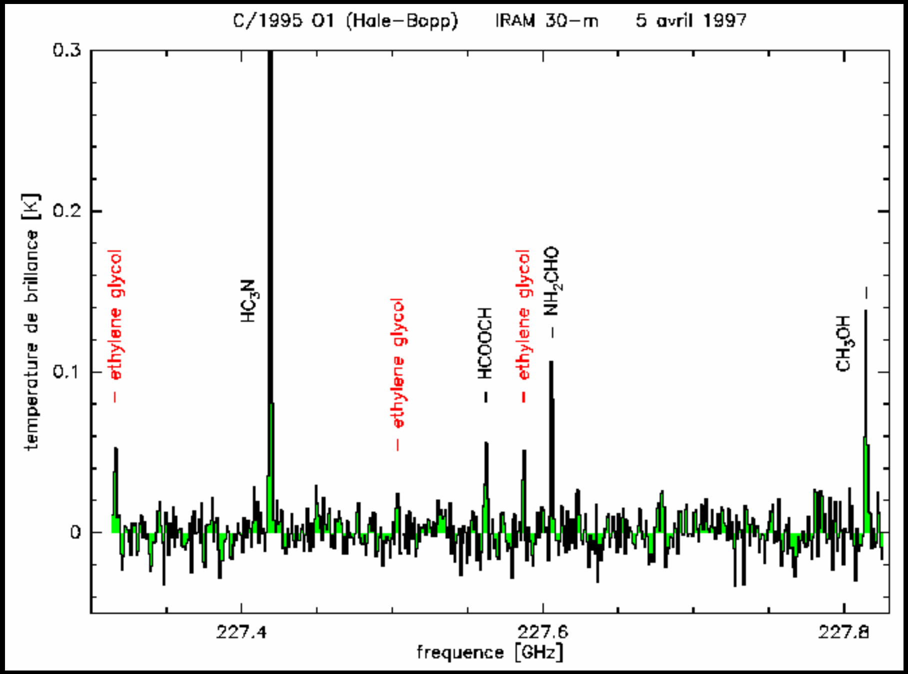
- **Noyau**
  - Difficile à observer depuis la Terre

- **Queues (coma)**
  - Ions (rectiligne, vent solaire)
  - Poussière (courbé)
  - Observations photométriques et spectroscopiques
  - Tonnes/seconde de gaz et poussières

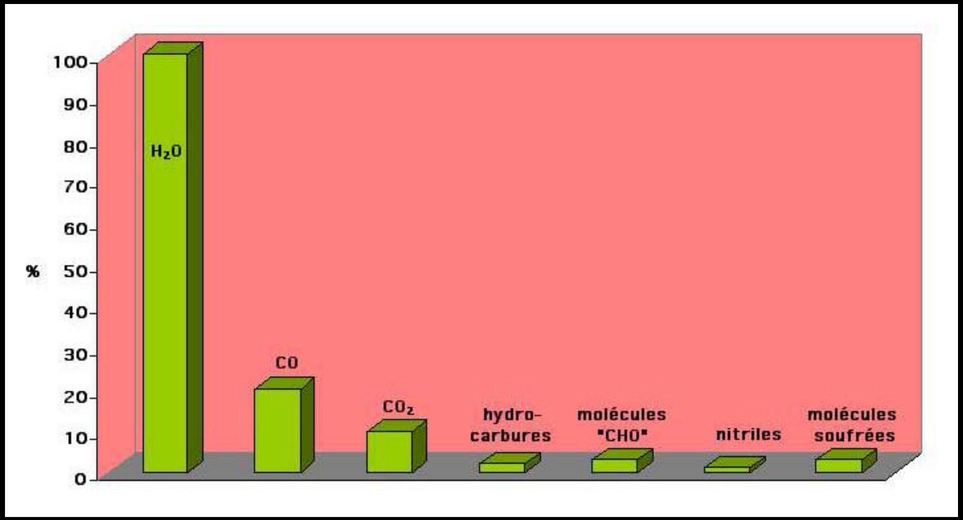
Comets: Radio observations

molécule		abondance relative	technique d'observation
eau	H2O	100	IR, radio
monoxyde de carbone	CO	23	radio, IR, UV
dioxyde de carbone	CO2	6	IR
méthane	CH4	0,6	IR
acétylène	C2H2	0,1	IR
éthane	C2H6	0,3	IR
méthanol	CH3OH	2,4	radio, IR
formaldéhyde	H2CO	1,1	radio
éthylène glycol	HOCH2CH2OH	0,25	radio
acide formique	HCOOH	0,09	radio
éthanal	CH3CHO	0,02	radio
formiate de méthyle	HCOOCH3	0,08	radio
ammoniac	NH3	0,7	radio, IR
cyanure d'hydrogène	HCN	0,25	radio, IR
isocyanure d'hydrogène	HNC	0,04	radio
cyanure de méthyle	CH3CN	0,02	radio
cyanoacétylène	HC3N	0,02	radio
acide isocyanique	HNCO	0,1	radio
formamide	NH2CHO	0,015	radio
sulfure d'hydrogène	H2S	1,5	radio
monoxyde de soufre	SO	0,3	radio
dioxyde de soufre	SO2	0,2	radio
oxysulfure de carbone	OCS	0,4	radio, IR
disulfure de carbone	CS2	0,2	UV, radio
thioformaldéhyde	H2CS	0,02	radio
disoufre	S2	0,005	UV

Les "abondances relatives" sont données ici en nombre de molécules par rapport à l'eau.



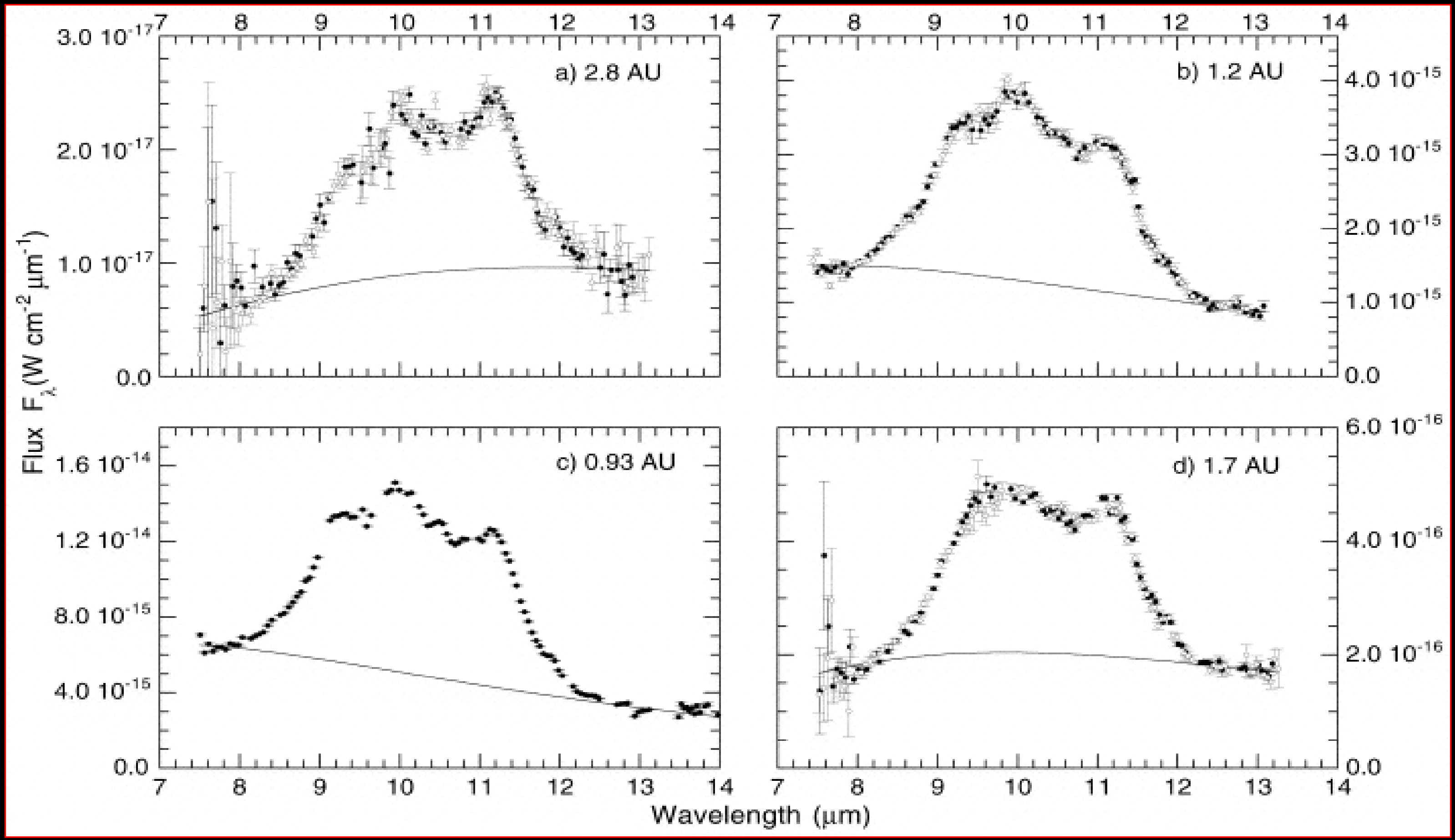
Radio observations provide the ice composition



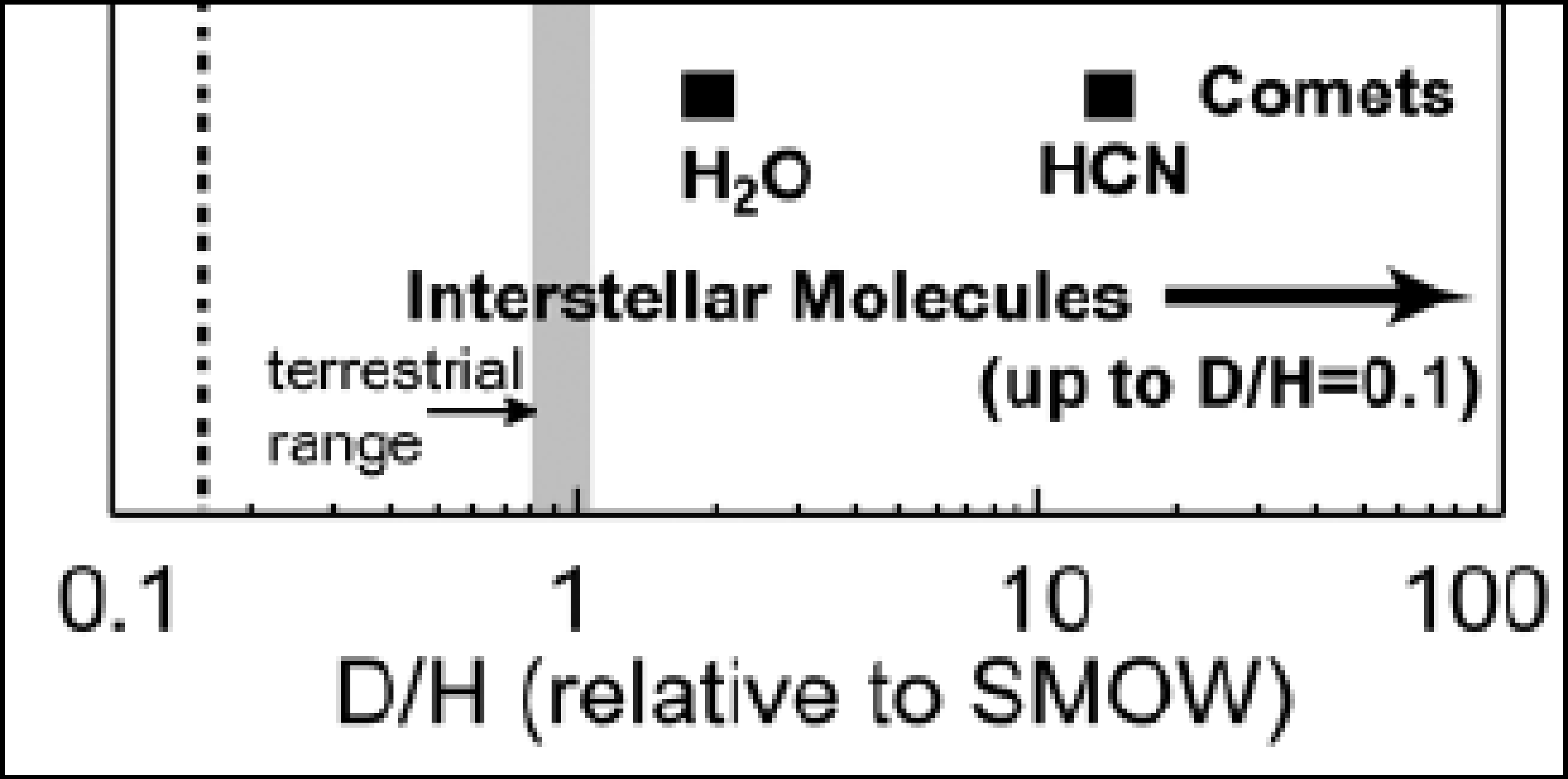
Crovisier (2006)

IR emission of dust grains from the coma

- Depends on temperature, size, crystallinity
- Detection of olivine and pyroxene

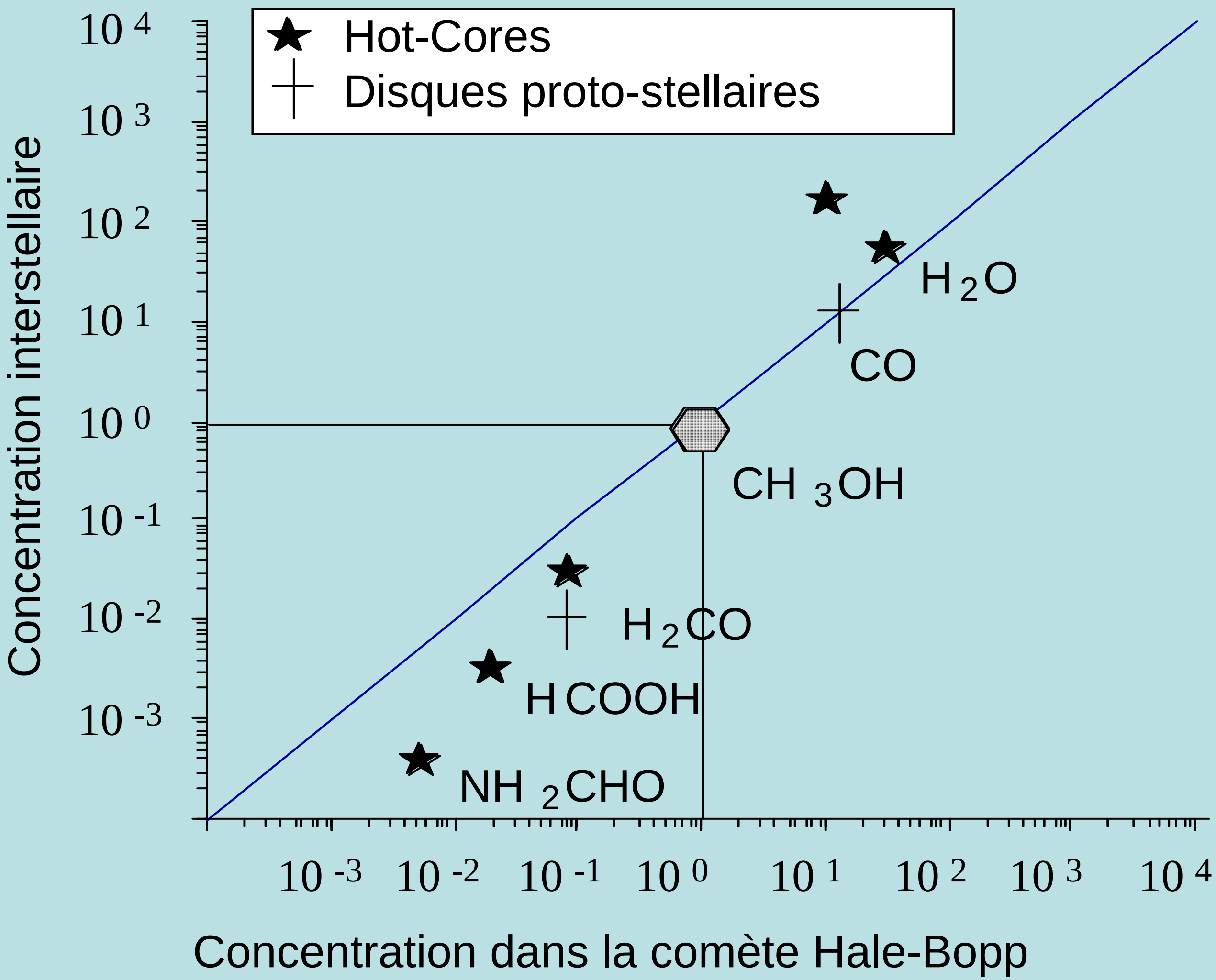


Comets and the interstellar medium



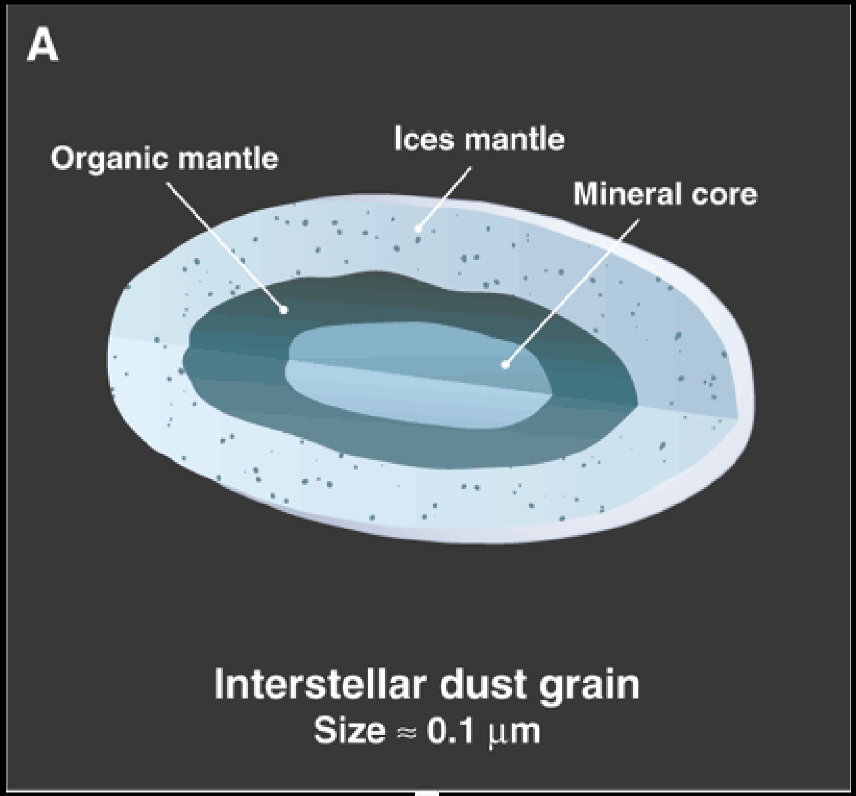
Deuterium enrichments made by ion molecule reactions

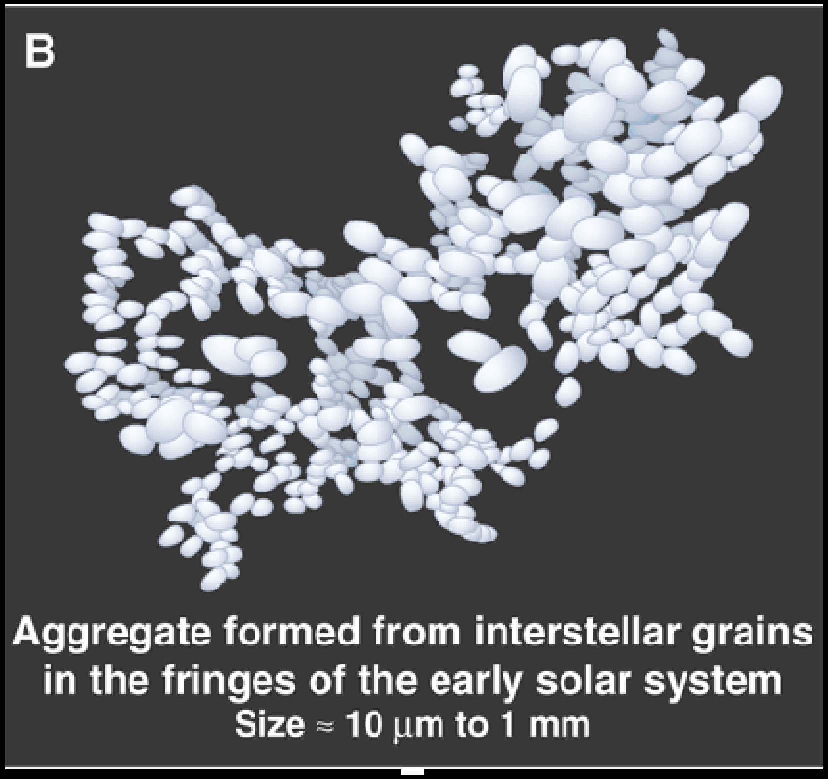
Comets and the interstellar medium



d'après Bockelée-Morvan et col.

Comets and the interstellar medium





- **This is the dominant model for cometary dust**

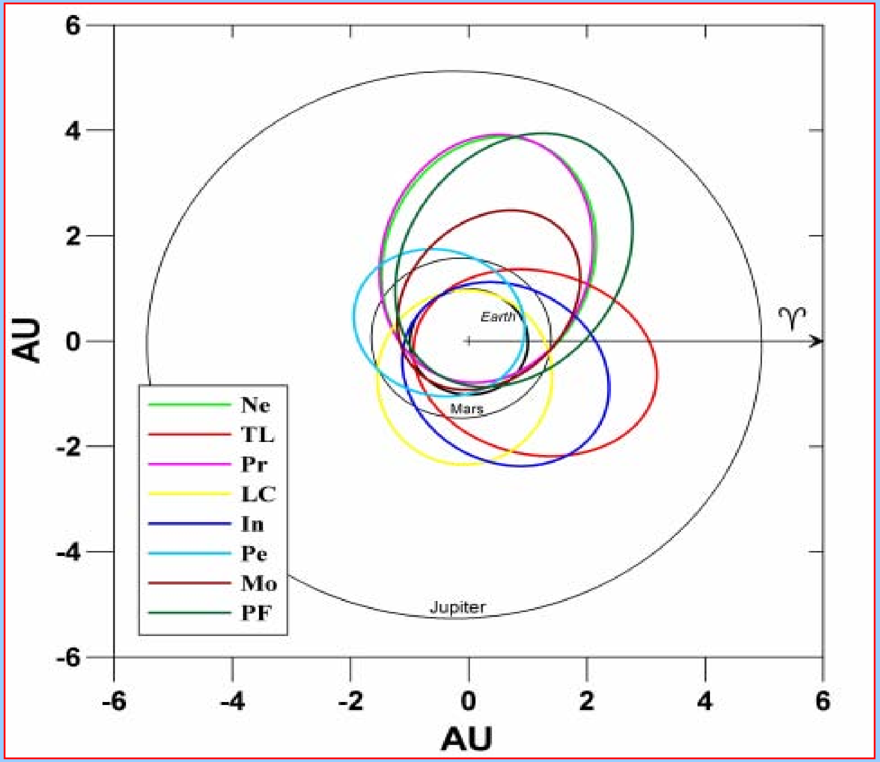
Comets : Summary

- **Formed further away than asteroids**
- **Comets are rich in ice**
- **They contain dust (what nature, how much?)**
- **They are supposed to be primitive (sampling the interstellar medium)**

4. La matière extraterrestre sur Terre

Meteorites come from asteroids

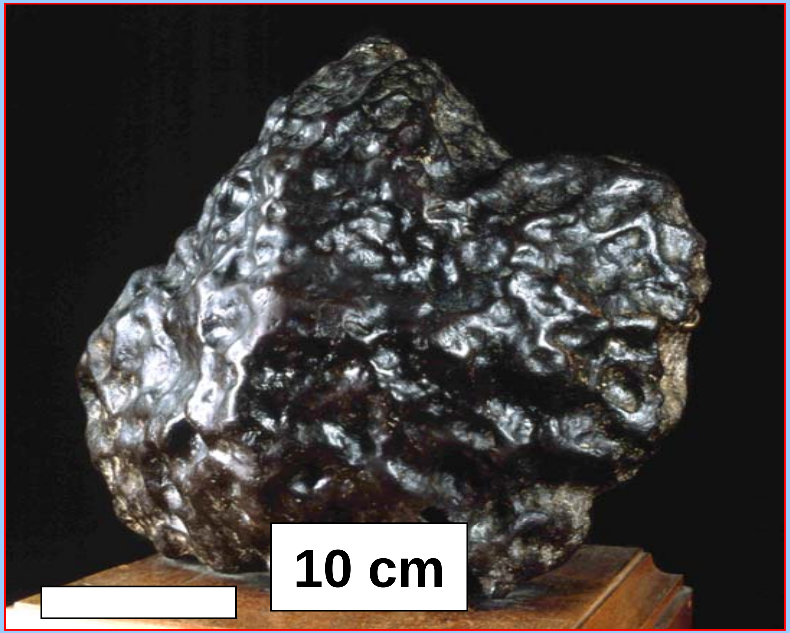
- ☆ The origin of meteorites has been disputed since their identification as extraterrestrial objects
  - ☆ First calculation from Biot (1803)

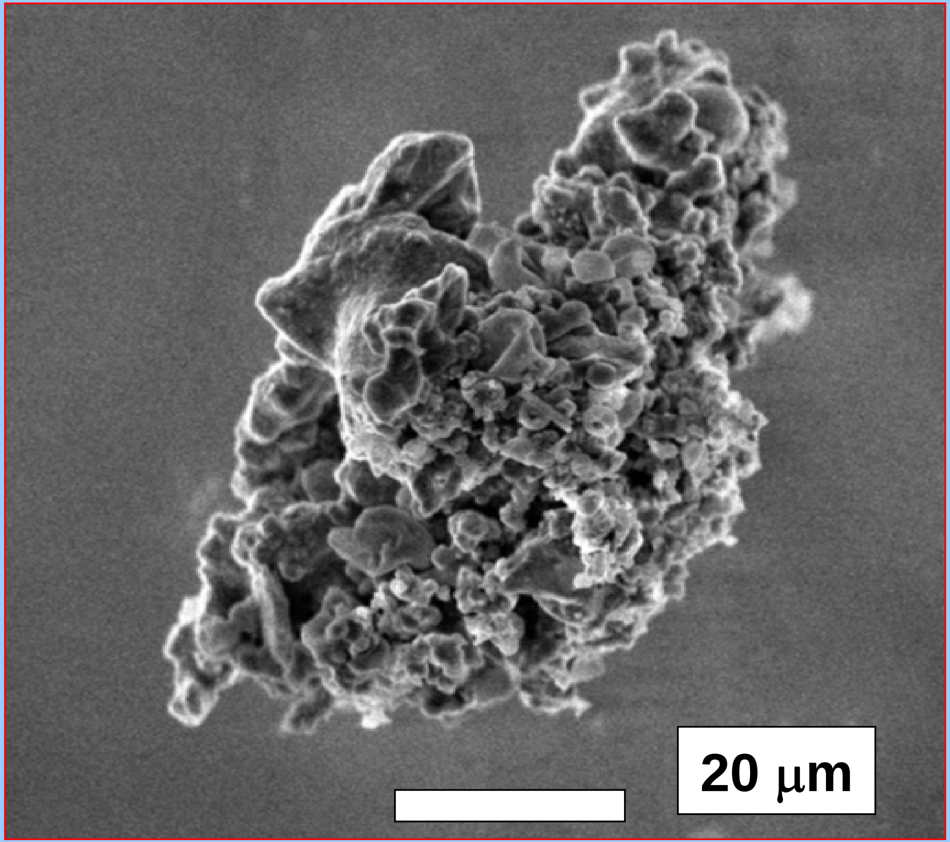


- ☆ Only the orbit of 8 meteorites is known
  - ☆ All come from the asteroid belt
- ☆ It is now widely accepted that
  - ☆ <u>Most meteorites come from asteroids</u>
  - ☆ 26 meteorites come from Mars
  - ☆ 32 meteorites come from the Moon

Meteorites: some definitions

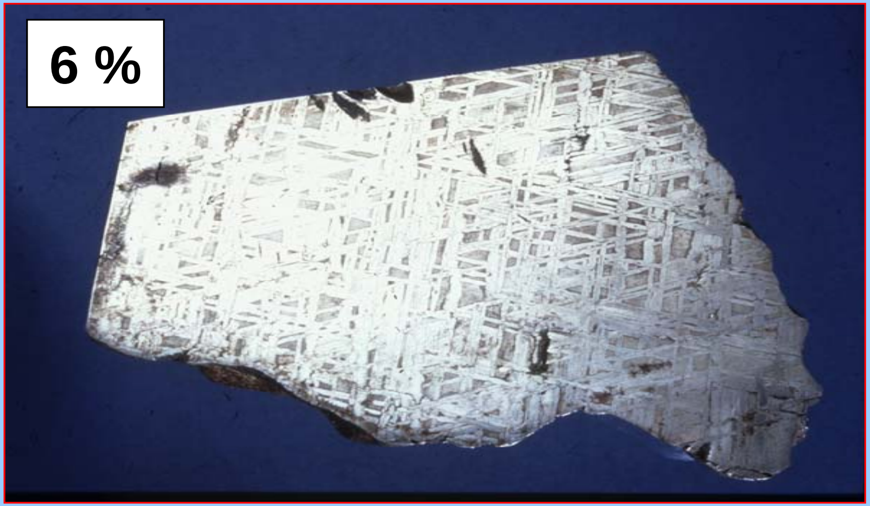
- Micrometeorites: size < cm
  - Antarctic micrometeorites
  - IDPs
- Meteorites: cm <size < 100 m (?)

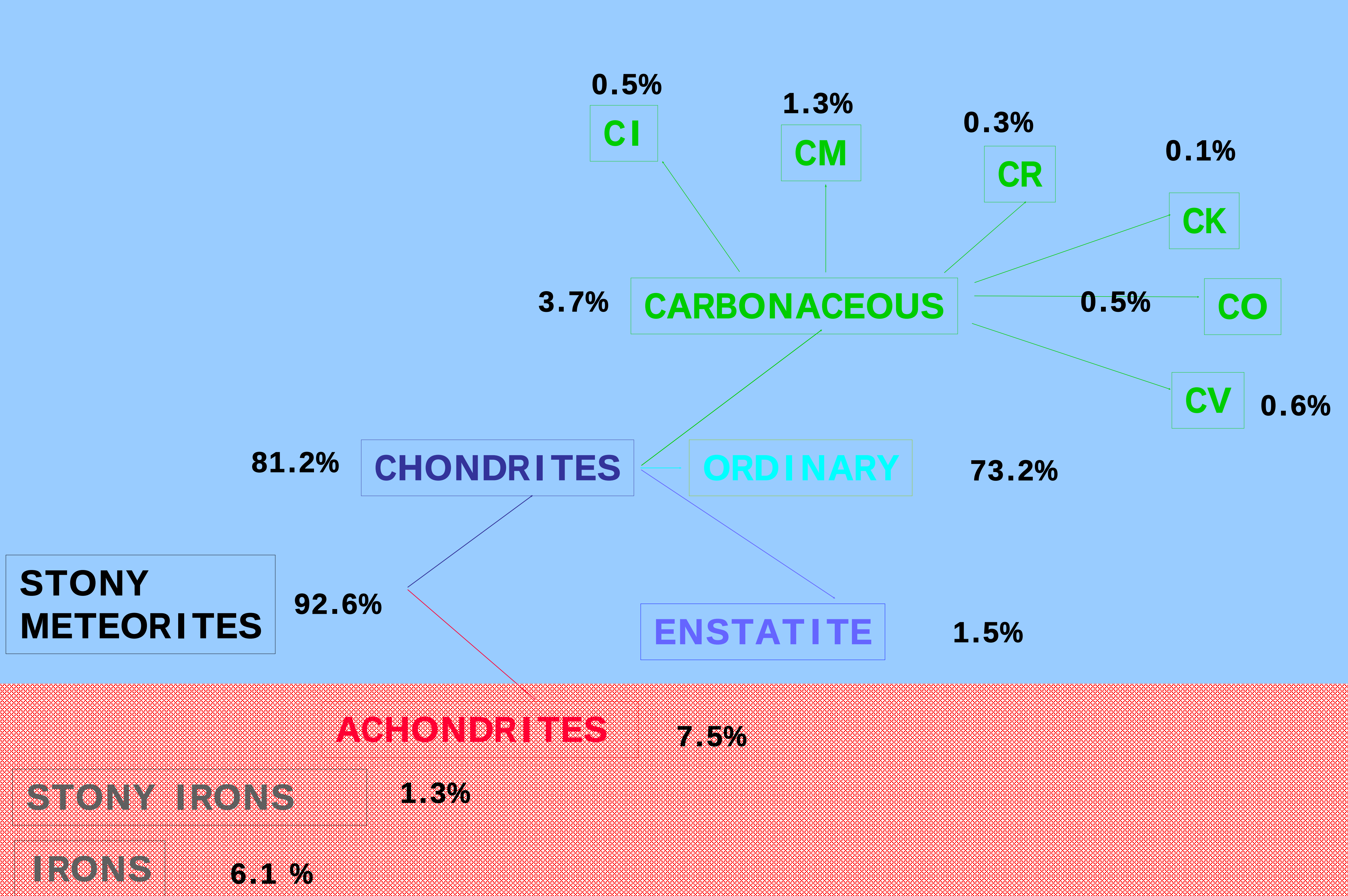




Meteorites

- ☆ There are 3 main types of meteorites
  - ☆ Stones [93 %]
  - ☆ Irons [6 %]
  - ☆ Stony-irons [1 %]



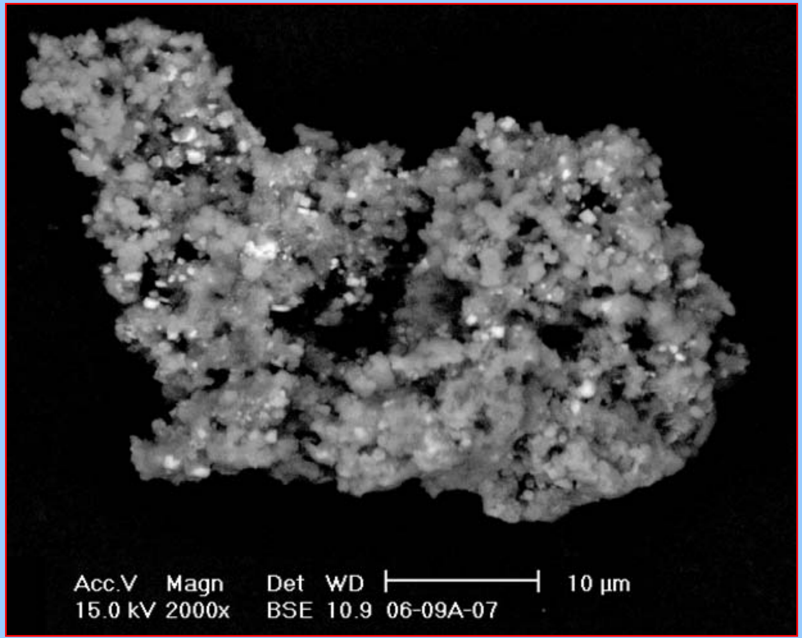

0.5%
CI
1.3%
CM
0.3%
CR
0.1%
CK
3.7%
CARBONACEOUS
0.5%
CO
CV
0.6%
81.2%
CHONDRITES
ORDINARY
73.2%
STONY METEORITES
92.6%
ENSTATITE
1.5%
ACHONDRITES
7.5%
STONY IRONS
1.3%
IRONS
6.1 %

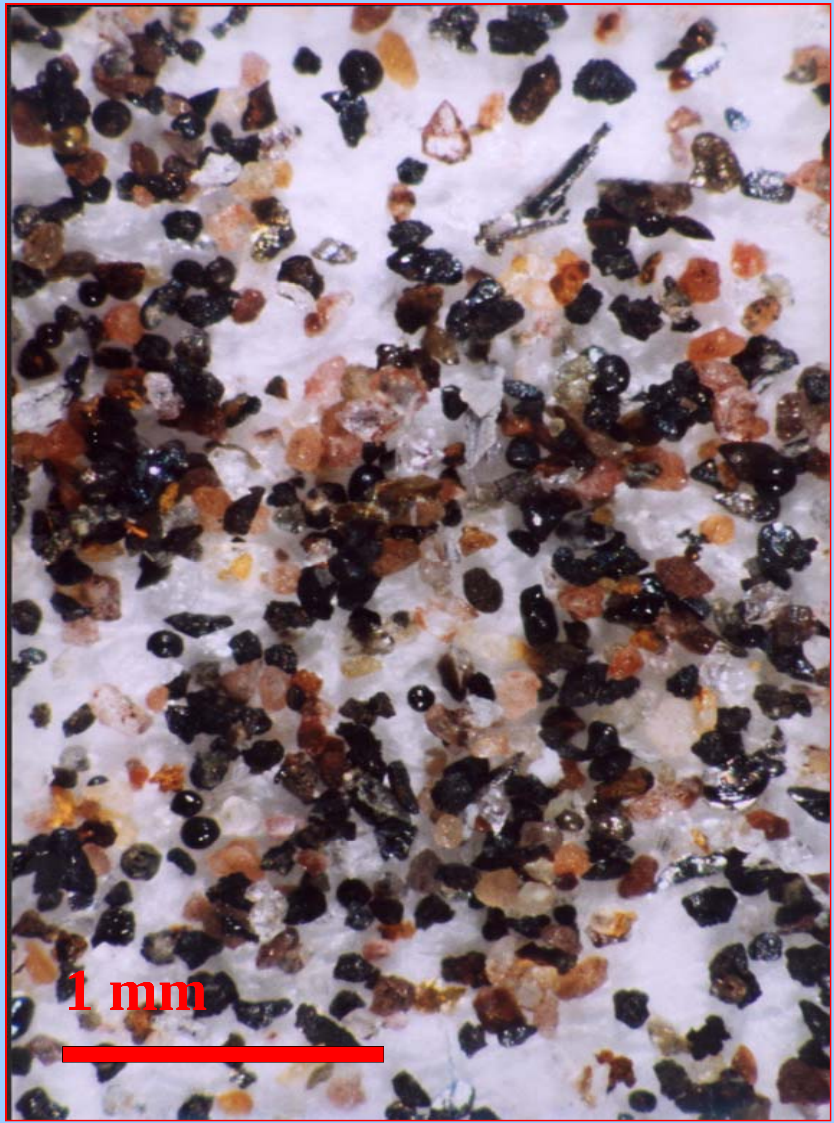
Les Micrométéorites Antarctiques

Collectes développées par le CSNSM (Orsay)

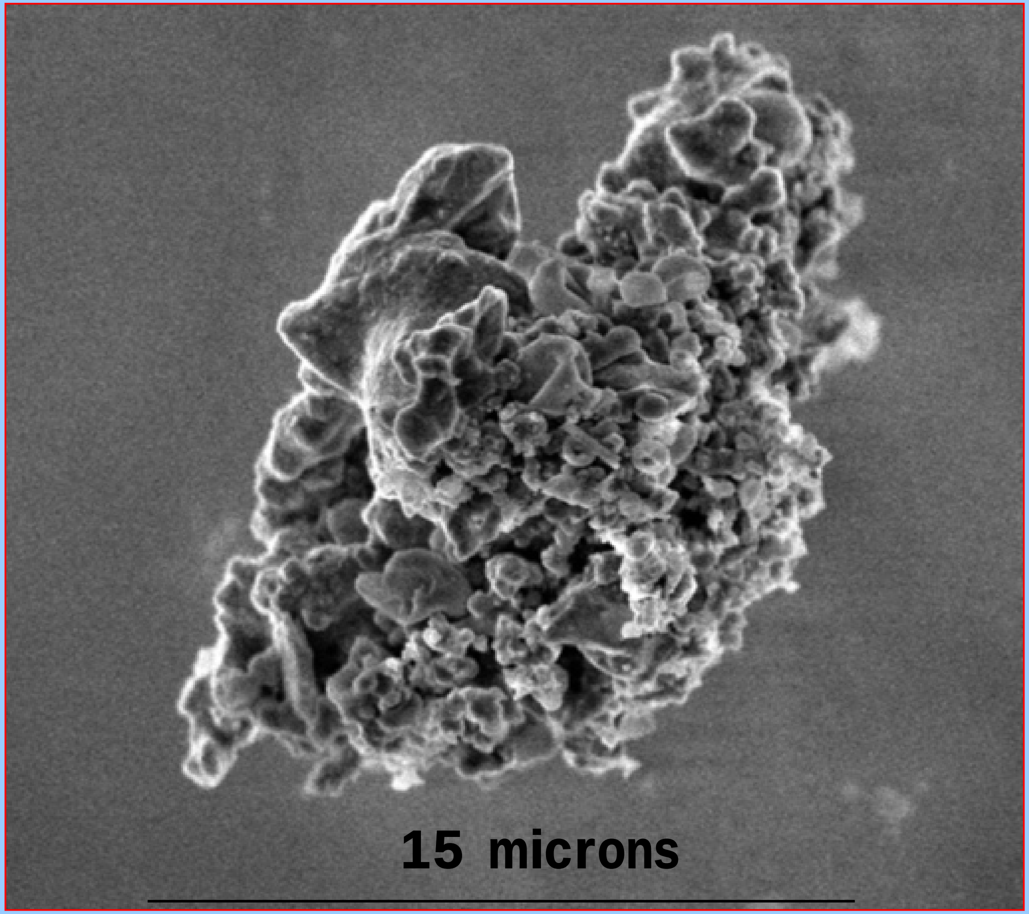
M. Maurette *et al.*, *Nature* (1991)

Duprat et al. ASR 2007





Interplanetary Dust Particles (IDPs)



Interplanetary Dust Particles are collected in the Earth's atmosphere by NASA ER-2's

Primitivity

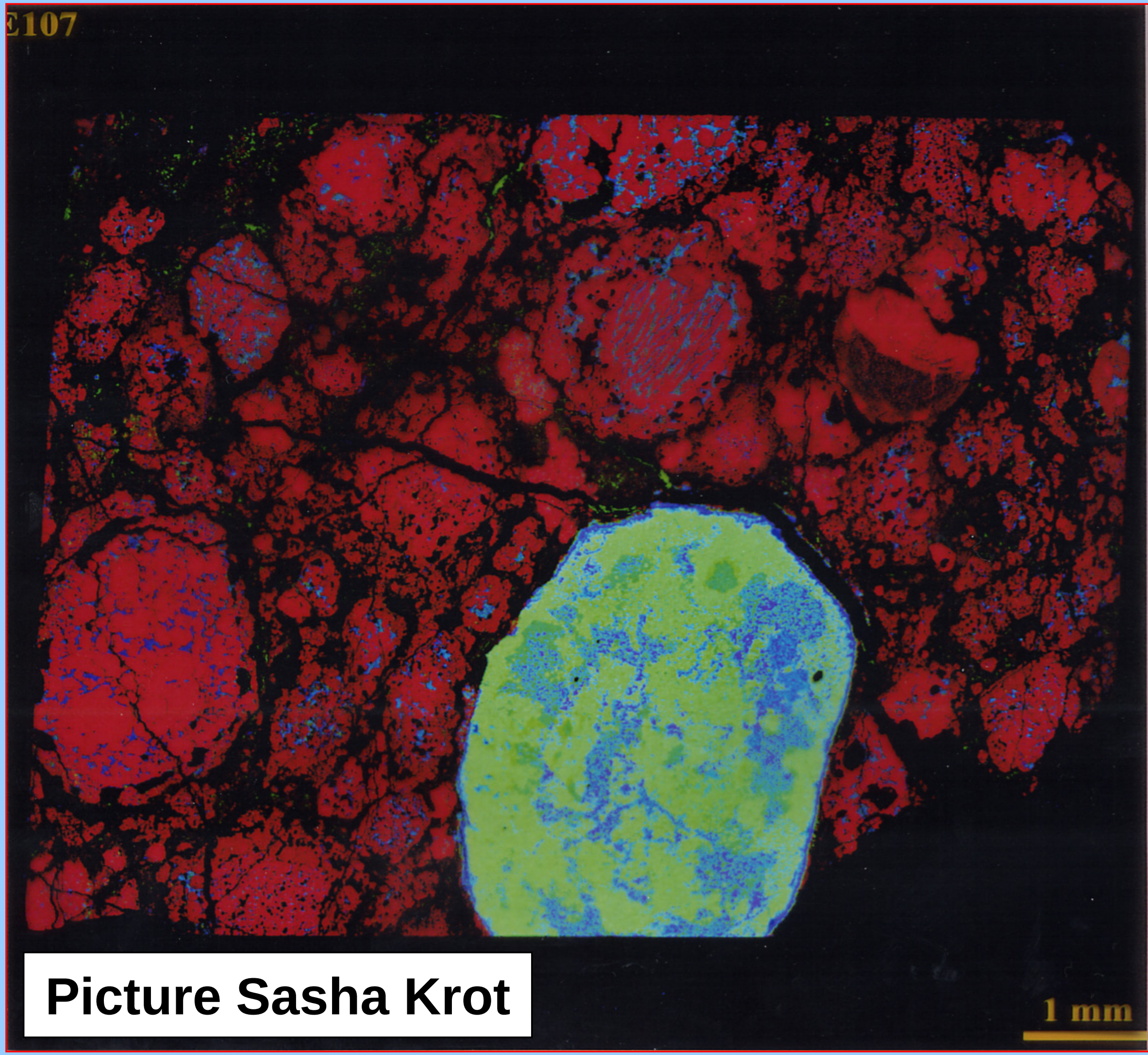
- Primitivity is an ambiguous word depending on what you are interested in

- Carbonaceous chondrites, IDPs and Antarctic micrometeorites are considered primitive
  - Chemical composition close to that of the Sun
  - Rich in presolar grains (interstellar dust)
  - Rich in isotopic anomalies (H, C, N – interstellar heritage)

  - Did not suffer secondary modifications such as hydrothermalism or metamorphism
  - Oldest objects

Components of chondrites

- ☆ ***Chondrules***
  - ☆ Silicate/metal beads
  - ☆ Varying sizes (10 μm- few mm)
- ☆ ***Refractory inclusions***
  - ☆ Contain Ca- and Al-rich minerals
  - ☆ Varying sizes (10 μm- few cm)
- ☆ ***Matrix***
  - ☆ Silicates, oxides, amorphous
  - ☆ Fine-grained (< μm)

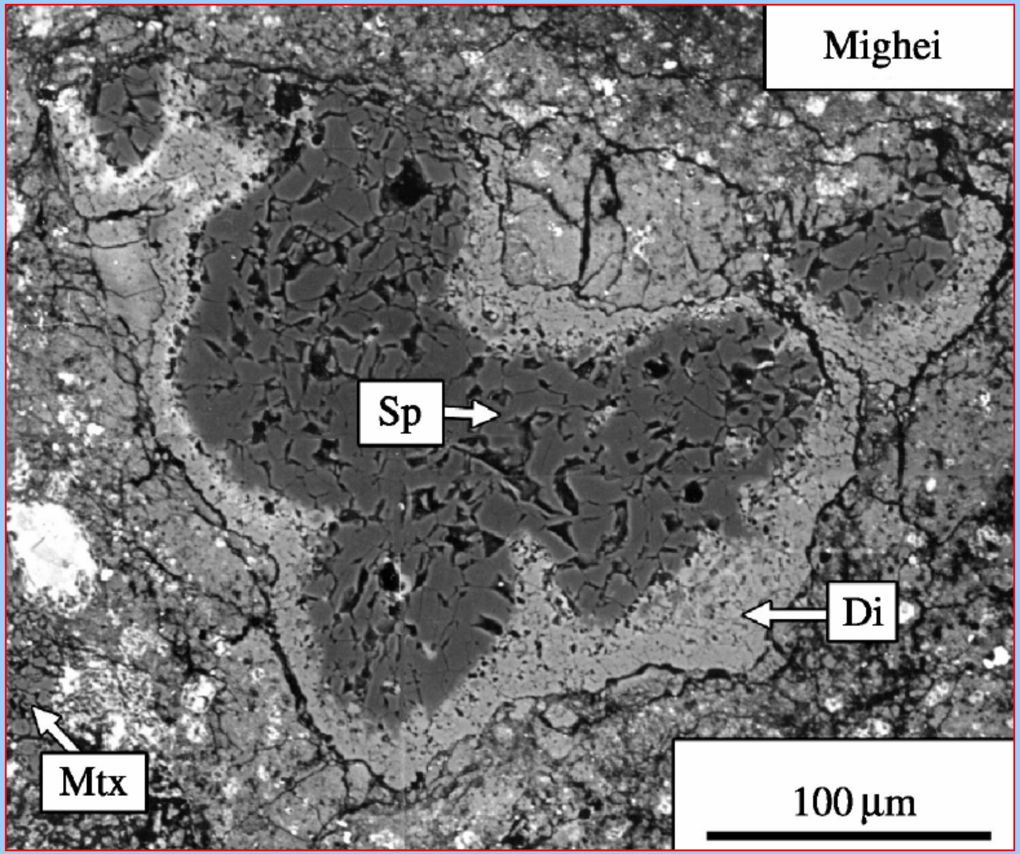


Picture Sasha Krot

Mg: red Ca: green Al: blue

The mineralogy of Calcium-, Aluminium-rich Inclusions

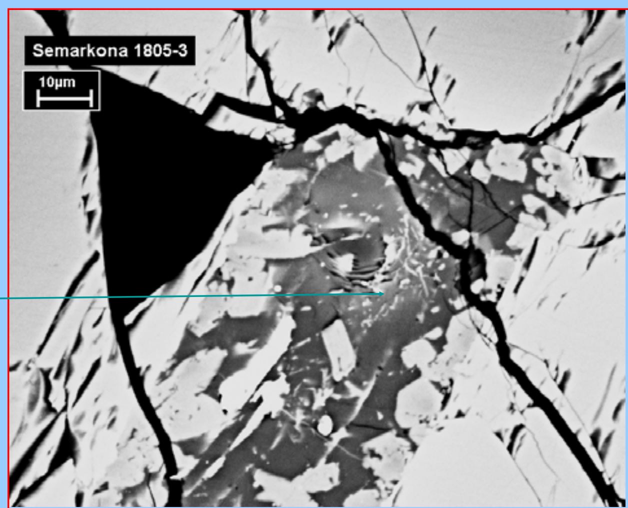
- Acronym is *CAIs*
- Also named white inclusions or *refractory inclusions*
- Discovered in 1967 by Madame Christophe in the *Vigarano* meteorite (CV3)
- CAIs are made of Ca- and Al-rich oxides and silicates
  - Melilite [$CaAl_{2x}Mg_{1-x}Si_{2-x}O_7$]
  - Spinel [Mg_2AlO_4]
  - Anorthite [$CaAl_2Si_2O_8$]
  - Perovskite [$CaTiO_3$]
  - Diopside [$CaMgSi_2O_6$]
- They are believed to be the first objects to have formed in the accretion disk

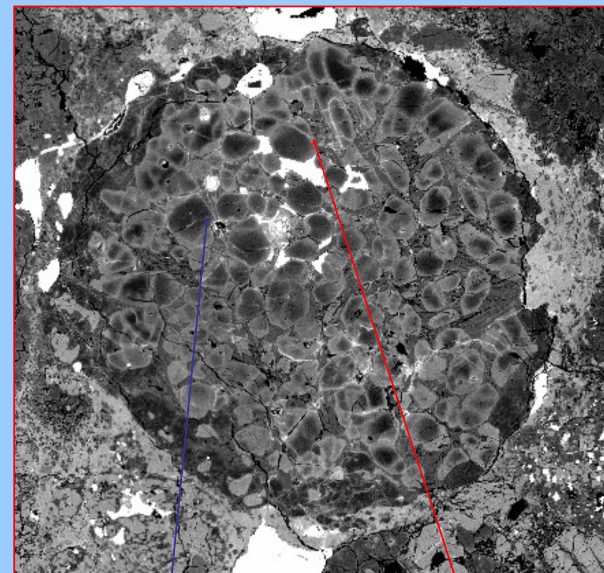


The mineralogy of chondrules

- ☆ Chondrules are made of
  - ☆ Olivine $(Mg,Fe)Si_2O_4$
  - ☆ Pyroxene $(Mg,Fe,Ca)SiO_3$
  - ☆ Metal (Fe,Ni)
  - ☆ Glass SiO_2- and alkali-rich [K, Na]
  - ☆ Iron sulfide FeS

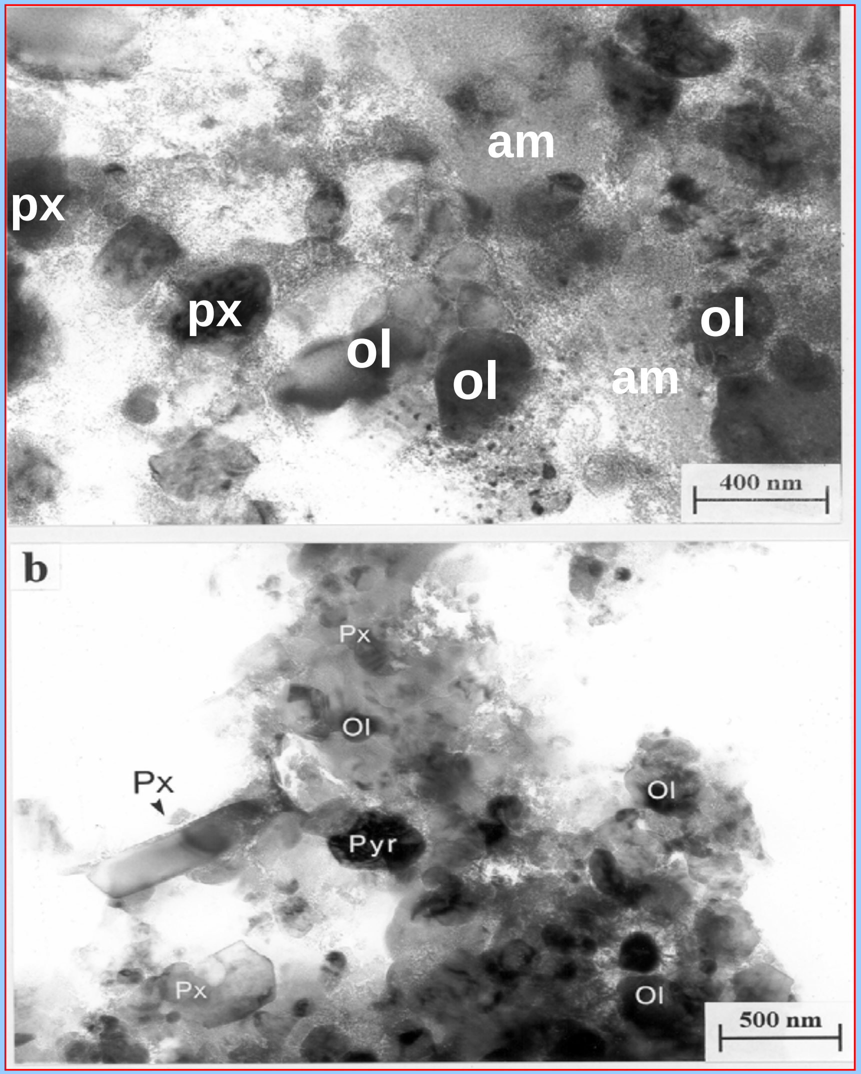
- ☆ The glass phase is interstitial
  - ☆ Mesostasis

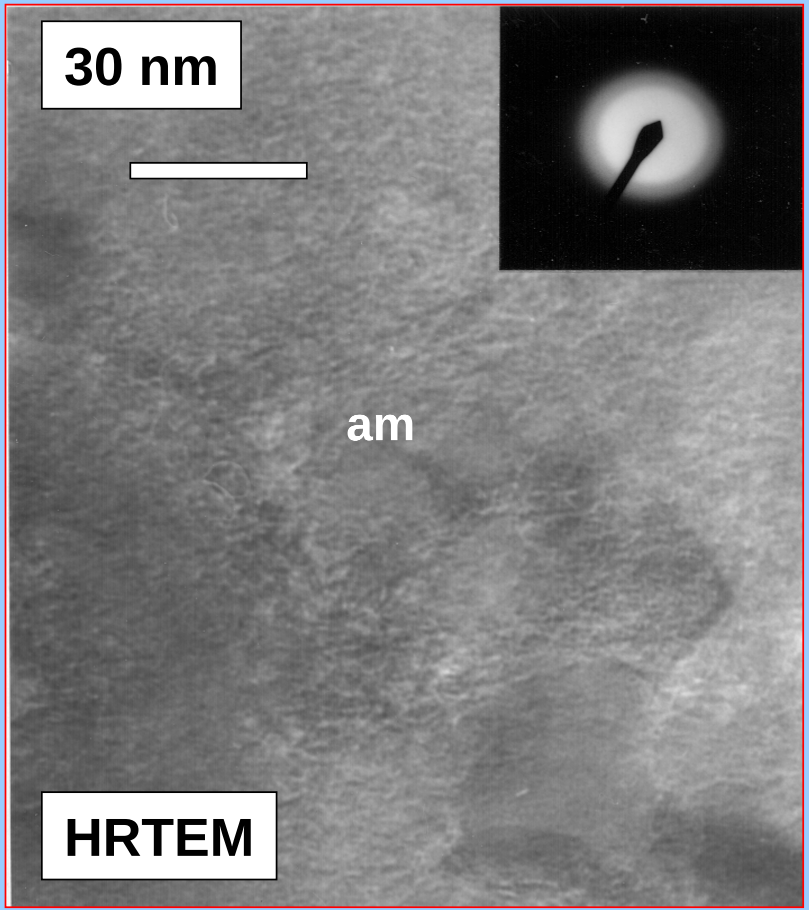




The matrix of Acfer 094

- The matrix consists of small olivines (ol), pyroxenes (px) and sulfides (pyr) embedded in an amorphous groundmass (am)

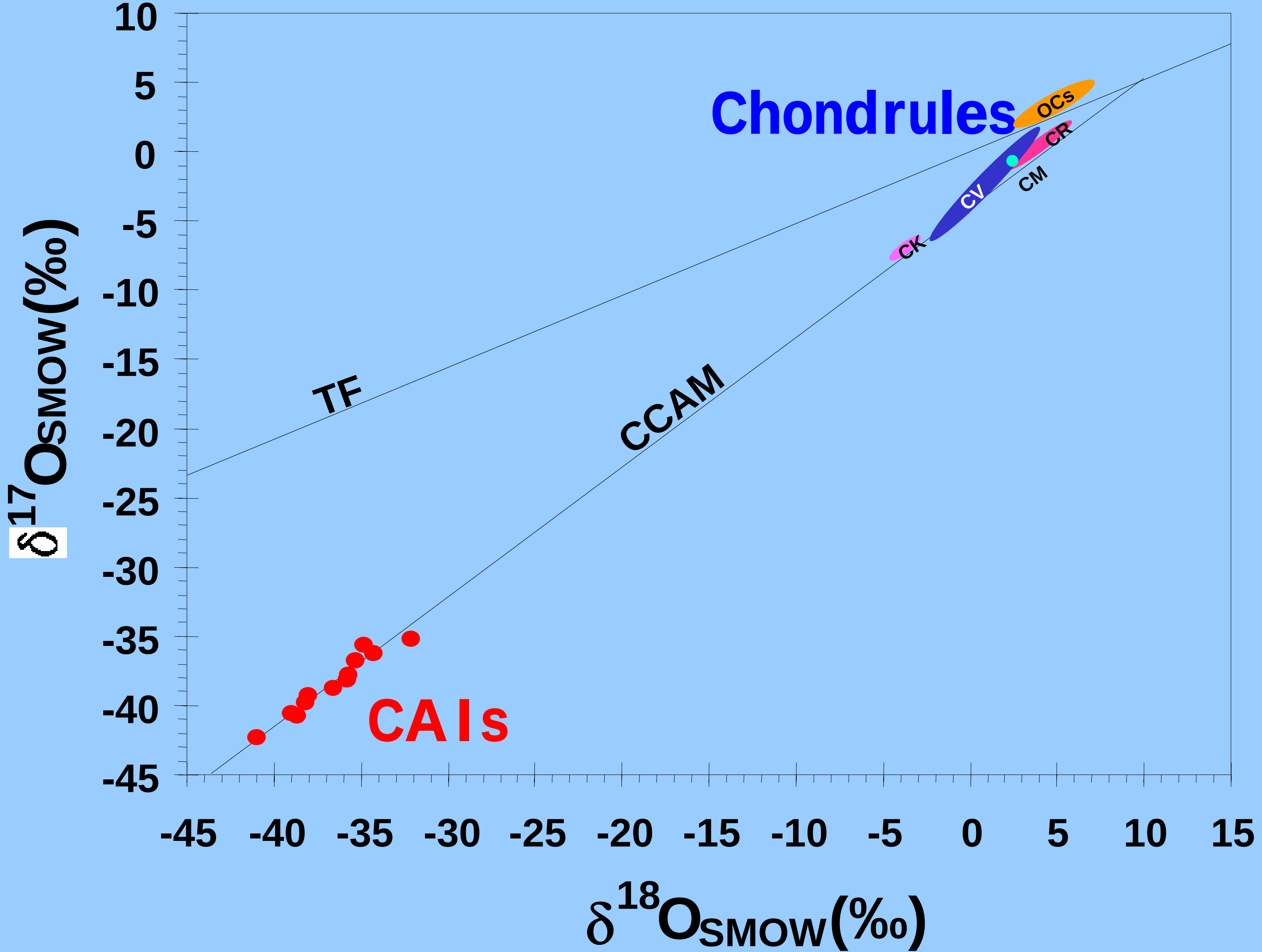




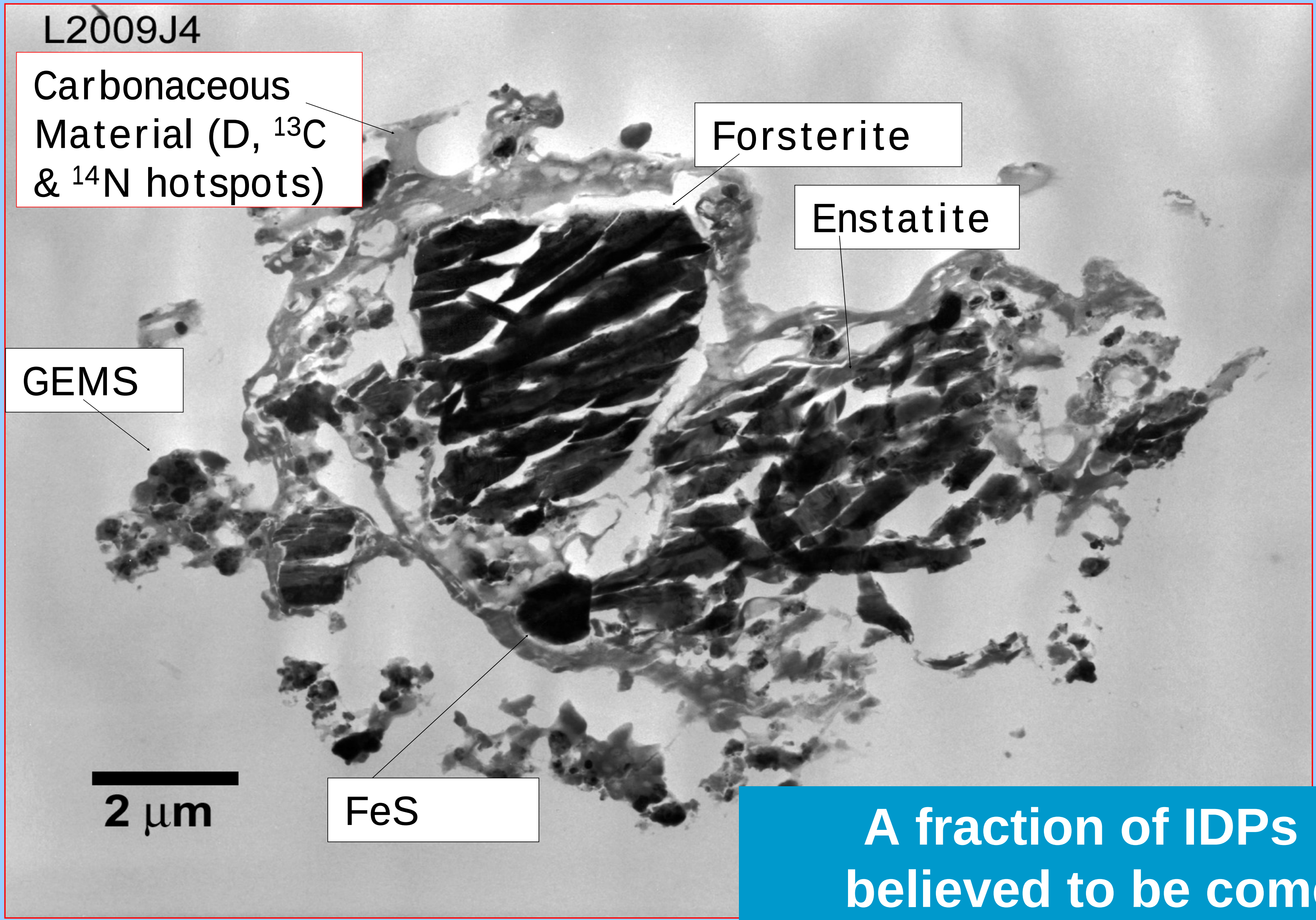
Greshake, GCA 1997

Chondrules and CAIs in meteorites

☆ CAIs have ^{16}O-rich oxygen isotopic composition



TEM view of an interplanetary dust particle



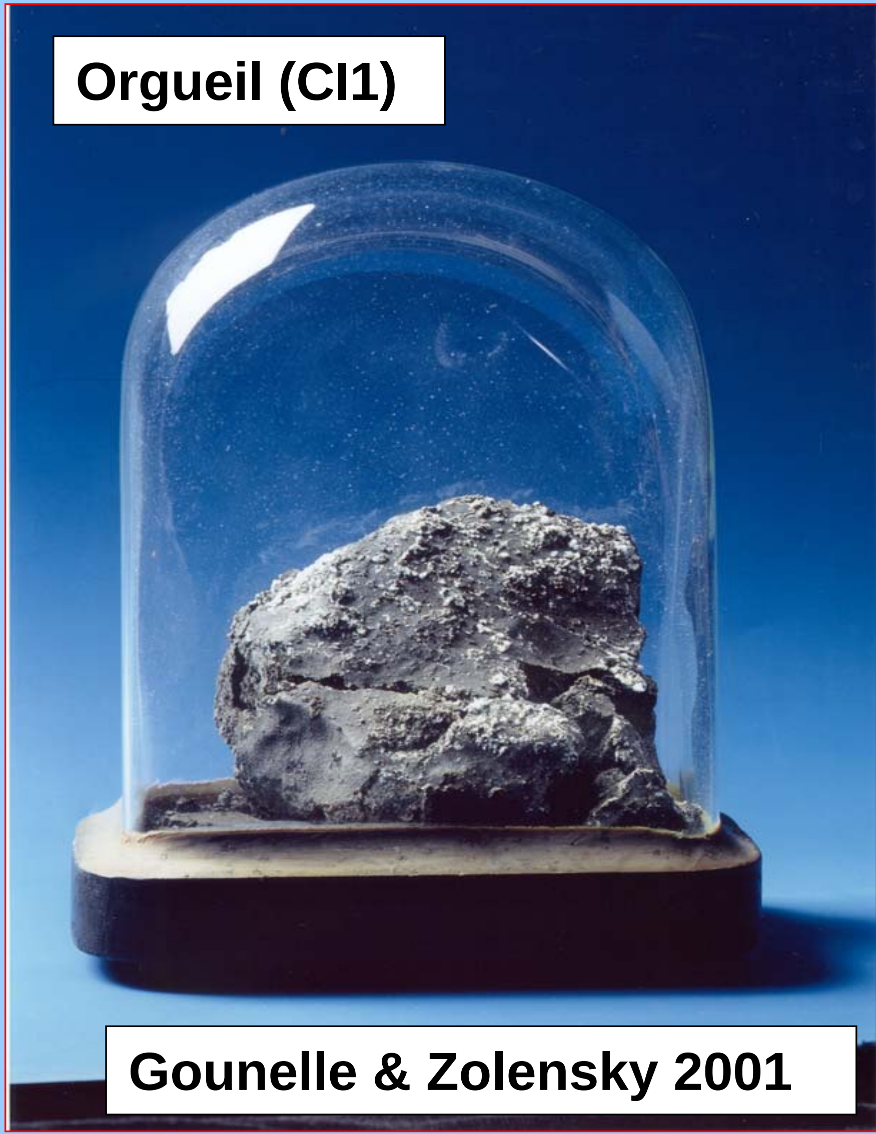
A fraction of IDPs is believed to be cometary

5. Do we have cometary meteorites in our collections?

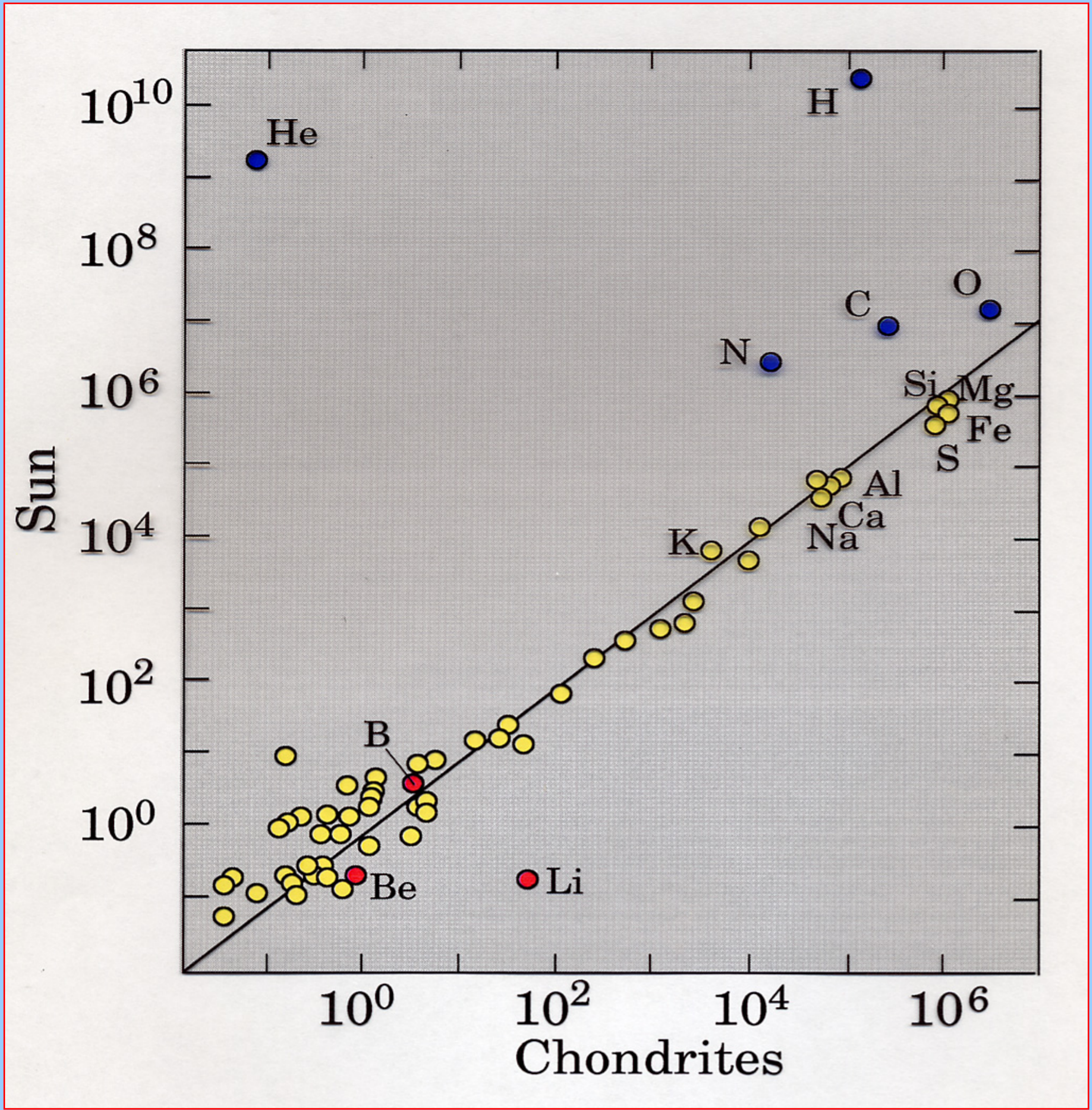
Gounelle, Spurný & Bland (2006) *Meteoritics & Planetary Sciences*, 41, 135-150

The special nature of CI1 chondrites

- Rare rocks (**Orgueil**, Alais, Ivuna, Tonk, Revelstoke)
  - CI1 chondrites represent 0.5 % of the meteorites falls
- Extremely porous rocks (up to 35 %)
- Very dark rocks (low albedos)
- CI1 chondrites strongly interact with the atmosphere (formation of sulfate veins)

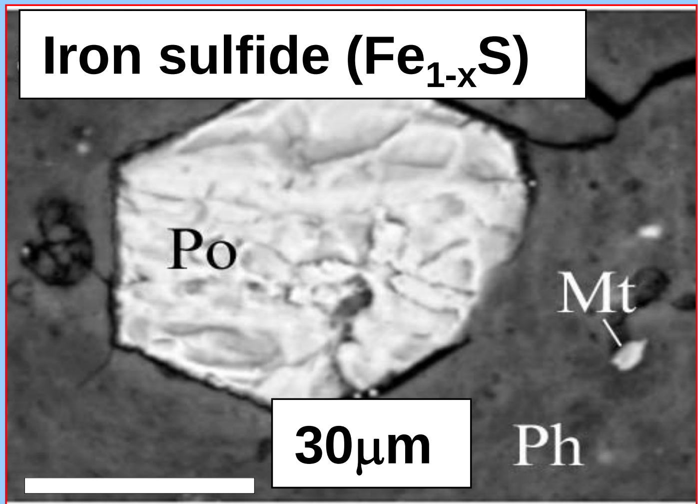


The chemical composition of CI1 chondrites

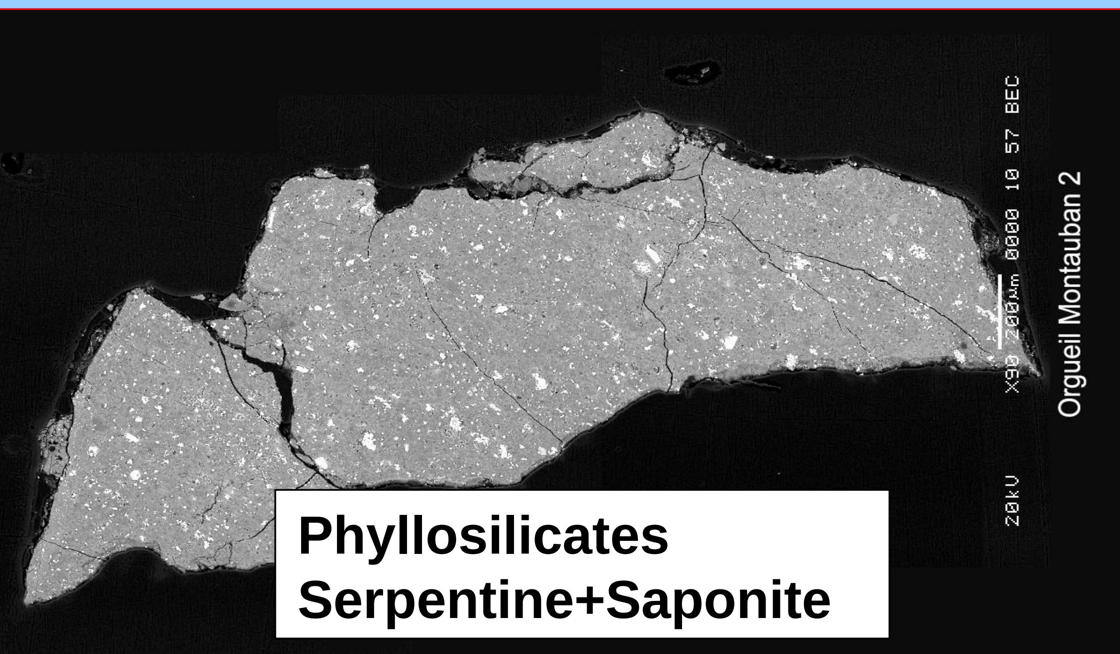


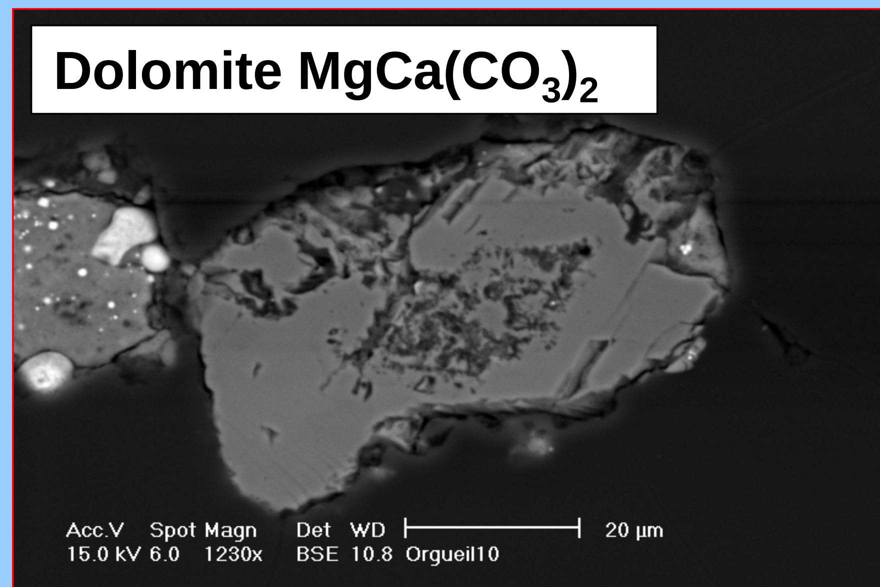
☆ Best chemical match with the solar photoshere of all chondrites

Secondary minerals in CI1 chondrites



☆Although chemically pristine, CI1 chondrites are the most <u>hydrothermally altered</u> chondrites (serpentine, saponite, sulfides, Ca-Mg carbonates, magnetite)





The fall of the Orgueil meteorite

- Orgueil meteorite fell May 18th 1864 in southern France

- Fireball seen from north of France to north of Spain

- **10 pages** of visual observations published by Daubrée in the main scientific journal of the time
  - Compte Rendus de l'Académie des Sciences de Paris

The Orgueil fireball observations

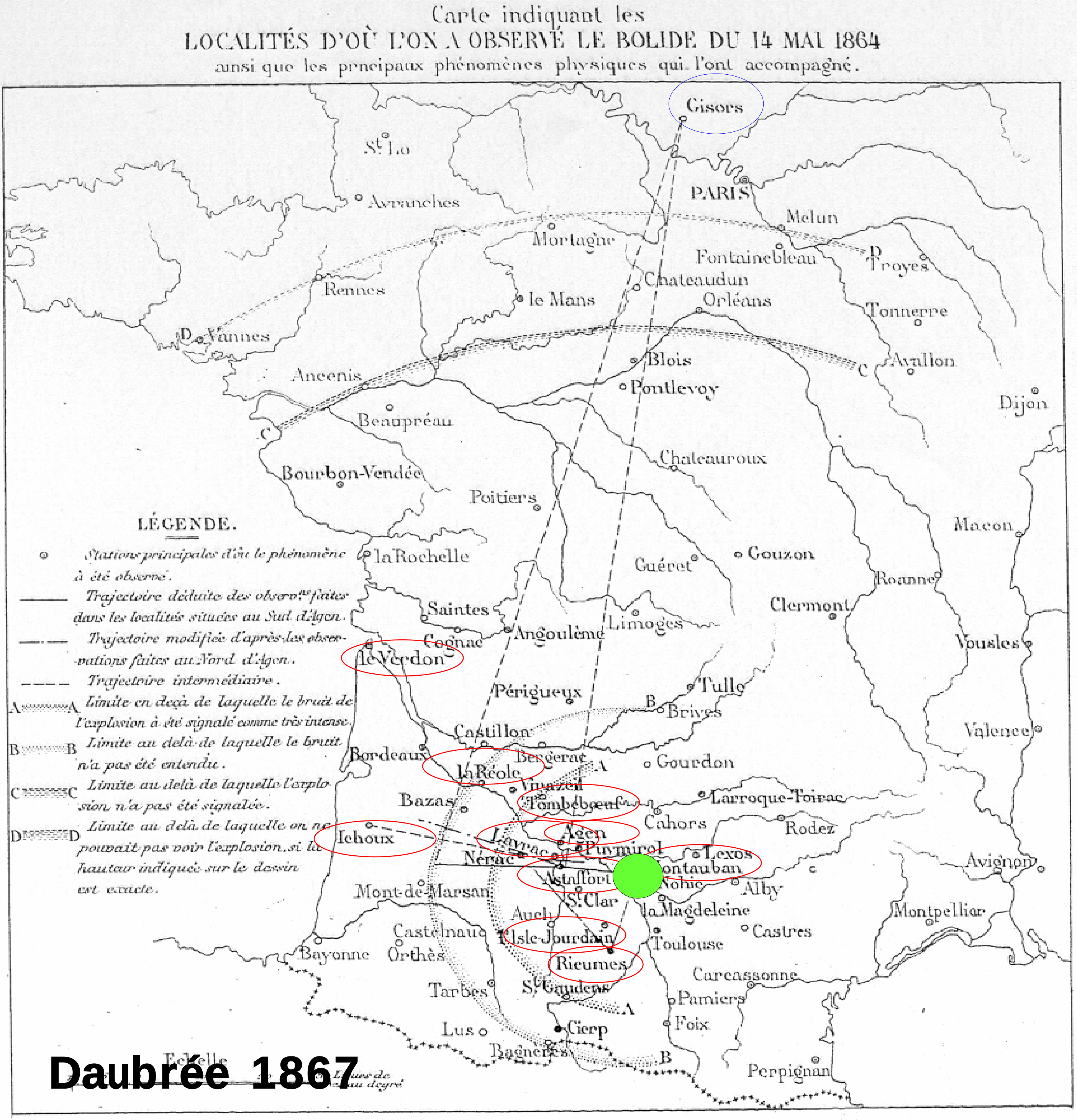
Letter of M. d'Esparbès à M. Le Verrier

A 8 heures 13 minutes du soir, un effet de lumière prodigieux est venu inonder la ville. Chacun a cru se trouver au milieu des flammes. Cet effet a duré quelques secondes; il a été produit par quelque chose de la grosseur de la Lune au plein, qui s'est dirigé comme une étoile filante, laissant à sa suite une traînée de feu légèrement bleuâtre. Cette traînée a disparu aussi peu à peu, et le ciel est redevenu serein; cependant, dix minutes après, ça produisait encore l'effet d'un long nuage fixe.

Deux minutes environ après ce résultat de lumière électrique produit, une détonation comparable au bruit d'une pièce de canon, se prolongeant de quatre-vingts à cent secondes, s'est fait entendre.

Il faisait une délicieuse soirée du mois de mai. Le temps était superbe.

Published by Daubrée, Compte-rendus de l'Académie des Sciences de Paris, vol 58 (1864)



Observations used for trajectory and orbit determination

More northern observation

Meteorites fall

Orbit calculations made by P. Spurný

The Orgueil fireball observations

No.	Place of observation (Observer)	Geographic coordinates	Original values	Corrected values (used in computations)	Comments
1.	Rieumes (Lajous)	λ=1.118° E φ=43.414° N	1. point A=156°, Z=68° 2. point A=205°, Z=73.5° (flare)	1. point A=156°, Z=68° 2. point A=205°, Z=73.5° (flare)	On the northern sky, from W to E Duration between both points 3s!! After 3 minutes loud sound
2.	Nerac (Lespiault)	λ=0.336° E φ=44.138° N	1. A=87.7°, Z=52.6° (5° S from Pollux) 2. several degrees N from zenith 3. A=283°, Z=39.5° (¼ distance between ε and α Boo from ε) 4. A=300°, Z=65° (flare 15° N from Jupiter)	1. not used – too close to radiant 2. A=180°, Z=1° - rather almost zenith, slightly to N 3. A=287°, Z=39.5° 4. A=288°, Z=65°	Sound exactly 3 minutes after flare
3.	Montauban (Pauliet)	λ=1.353° E φ=44.019° N	1. SW 2. Constellation Leo ≈ A=0°, Z=30° 3. A=324°, Z=56° (left from Saturn and α Vir) 4. A=307°, Z=82° (slightly below Jup.)	1. not used 2. A=0°, Z=38° 3. and 4. not used because these are beyond the impact area	Sound after 1-2 minutes
4.	Agen (Bourrieres)	λ=0.625° E φ=44.198° N	1. over the town, somewhat to the S	1. A=0°, Z=18°	
5.	Layrac (Daubree paper)	λ=0.661° E φ=44.133° N	1. close to the zenith, literally "flew over heads".	1. A=0°, Z=10°	
6.	Astaffort (Lafitte)	λ=0.650° E φ=44.061° N	from NW to SE, very high – in zenith, terminated about 30° above SE horizon	1. A=110°, Z=20° 2. A=0°, Z=0° 3. A=290°, Z=45°	observed at 8 hours and several minutes in the evening sound after 4 minutes
7.	L'Isle Jourdain (Jacquot)	λ=1.080° E φ=43.613° N	almost horizontal flight above northern horizon from west to east	1. A=130°, Z=62° 2. A=205°, Z=61°	sound after 3-4 minutes exploded and fragmented into many pieces; persistent train 15min
8.	Ichoux (newspaper)	λ=0.968° W φ=44.328° N	almost perpendicularly to the horizon, direction from west to east	1. A=277°, Z=45° 2. A=284°, Z=83°	around 8 hours in the evening, duration several seconds, 3 detonations
9.	Verdon (Laussedat)	λ=0.628° E φ=44.814° N	1. A=29.5°, Z=43.6° - across the Moon	1. A=29.5°, Z=54°	

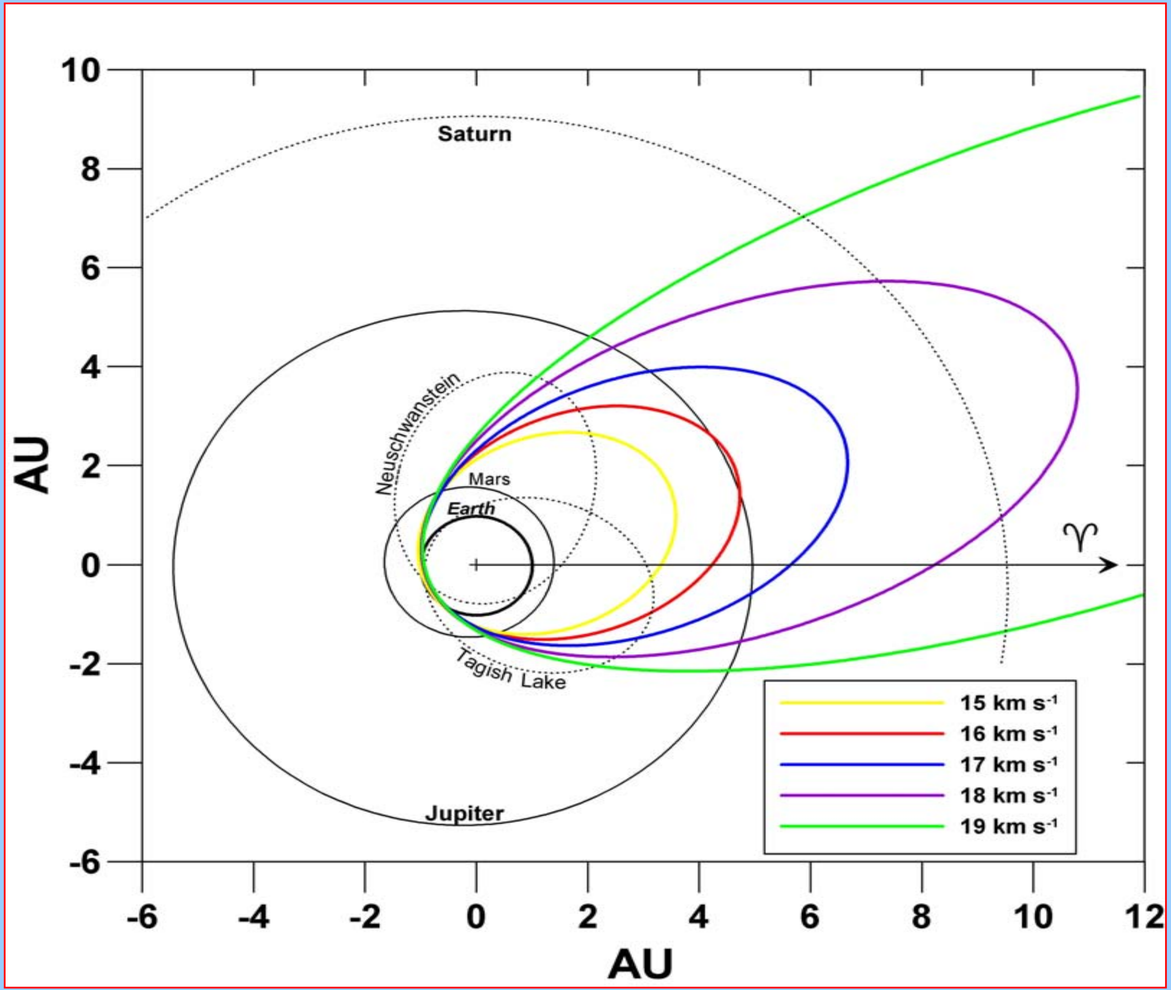
The Orgueil fireball observations

10.	La Reole (Laussedat)	λ=0.036° W φ=44.588° N	1. A=29.6°, Z=44.4° (Moon position) above or across the Moon	1. A=30°, Z=30° shifted about 14° above the Moon – in agreement with observation	
11.	Bezu-Saint-Eloi (Brongniart)	λ=1.695° E φ=49.296° N	On southern horizon, somewhat to the west, near horizon (~10-15°), slope to the horizon about 20-25°	1. A=15°, Z=86° 2. A=9°, Z=88° must be much closer to horizon	between 7:50 and 8:00 in the evening
12.	Tombeboeuf (Cruzel)	λ=0.455° E φ=44.508° N	WNW→above Leo→left from Saturn and α Vir 1. point A=49°, Z=20° (above Leo) 2. point A=330°, Z=55° (flare, between Saturn and α Vir) 3. point A=307°, Z=82° (end near to Jupiter)	1. point A=49°, Z=38° 2. point A=338°, Z=55° 3. point A=312°, Z=82°	sound 2.5 minutes after
13.	Orgueil (meteorite position)	λ=1.400° E φ=43.875° N	1. A=0°, Z=0° (in zenith)	1. A=110°, Z=1° (in zenith)	impact place

- ☆ From all these observations reported by Daubrée in the Compte-rendus, we (Pavel Spurný)
  - ☆ Calculated the atmospheric trajectory of the Orgueil meteor
  - ☆ Calculated the orbit of the Orgueil meteorid

The orbit of the Orgueil meteorite

Velocity likely > 18 km/s: **Orgueil a cometary meteorite?**



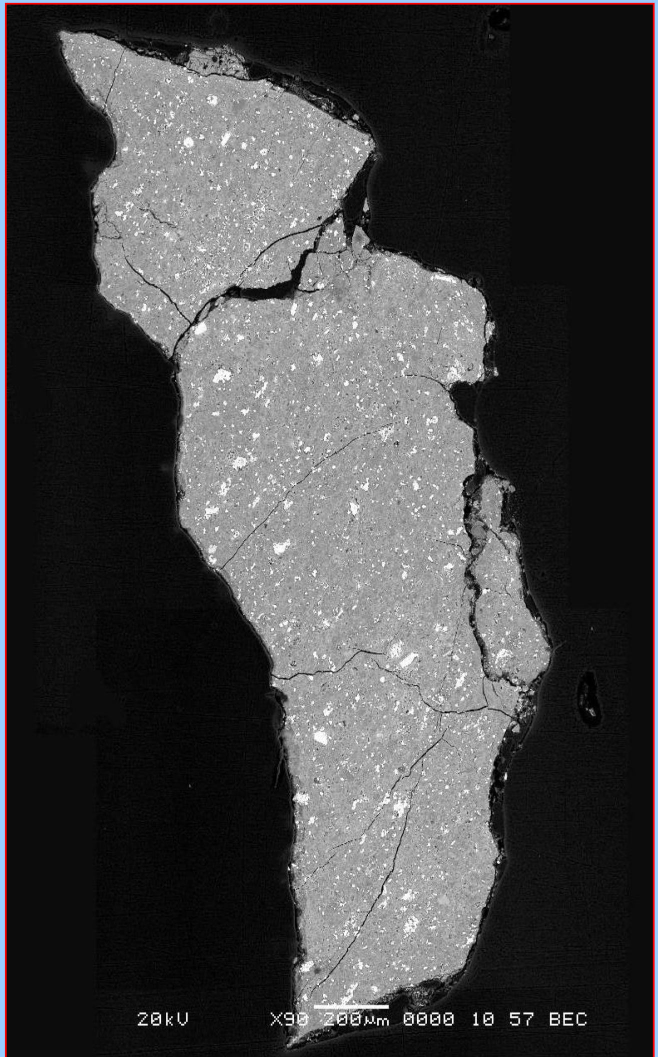
Implications of a cometary origin for CI1 chondrites

Comets are not primitive but processed

Comets suffered hydrothermal alteration

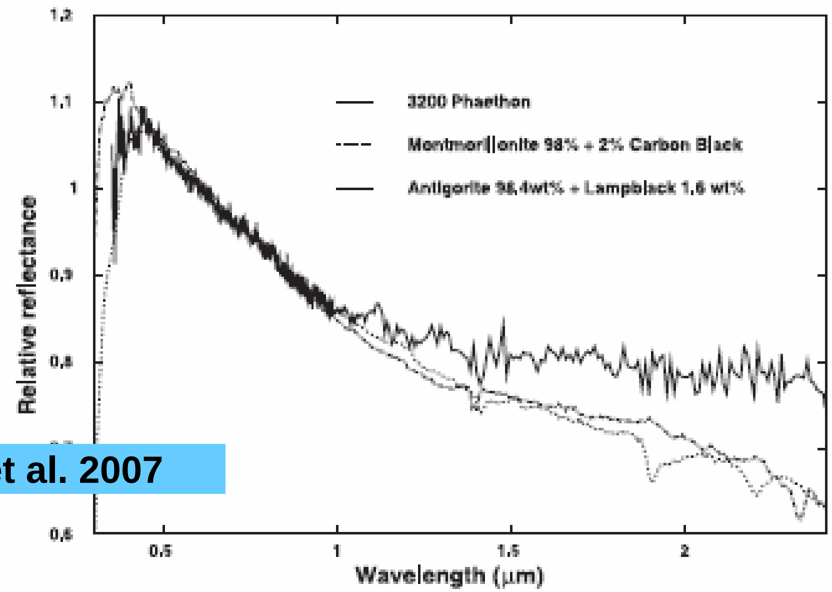
There is a **continuum** between comets and asteroids

(Image courtesy of Mike Zolensky, NASA JSC)

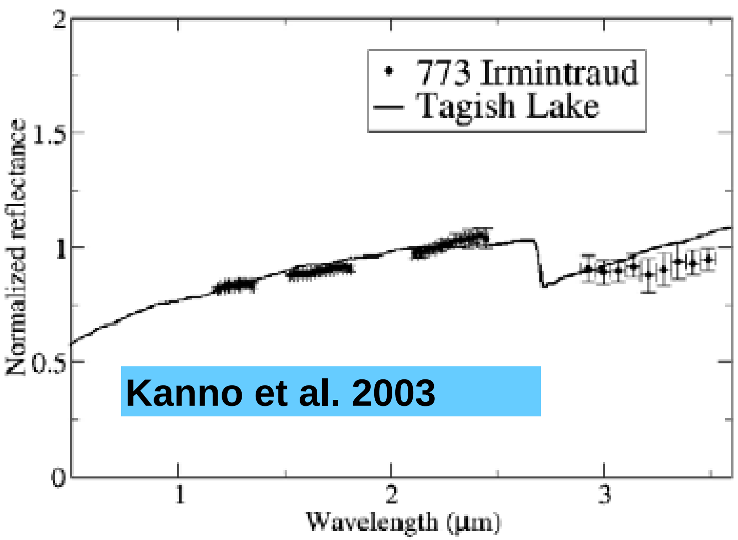


Orgueil Montauban 2

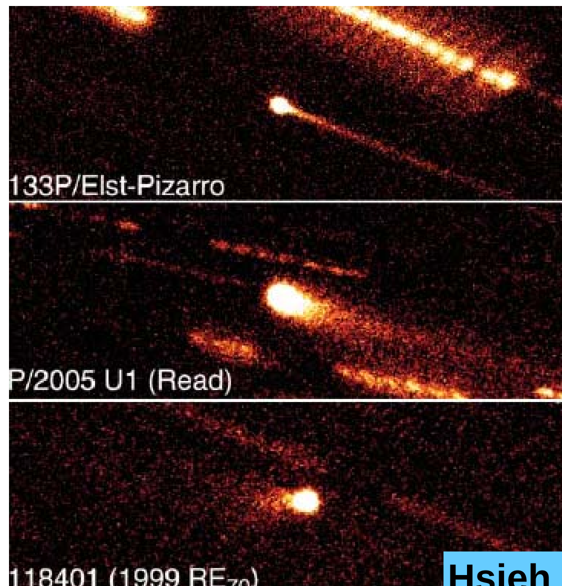
The continuum asteroid-comet



Licandro et al. 2007

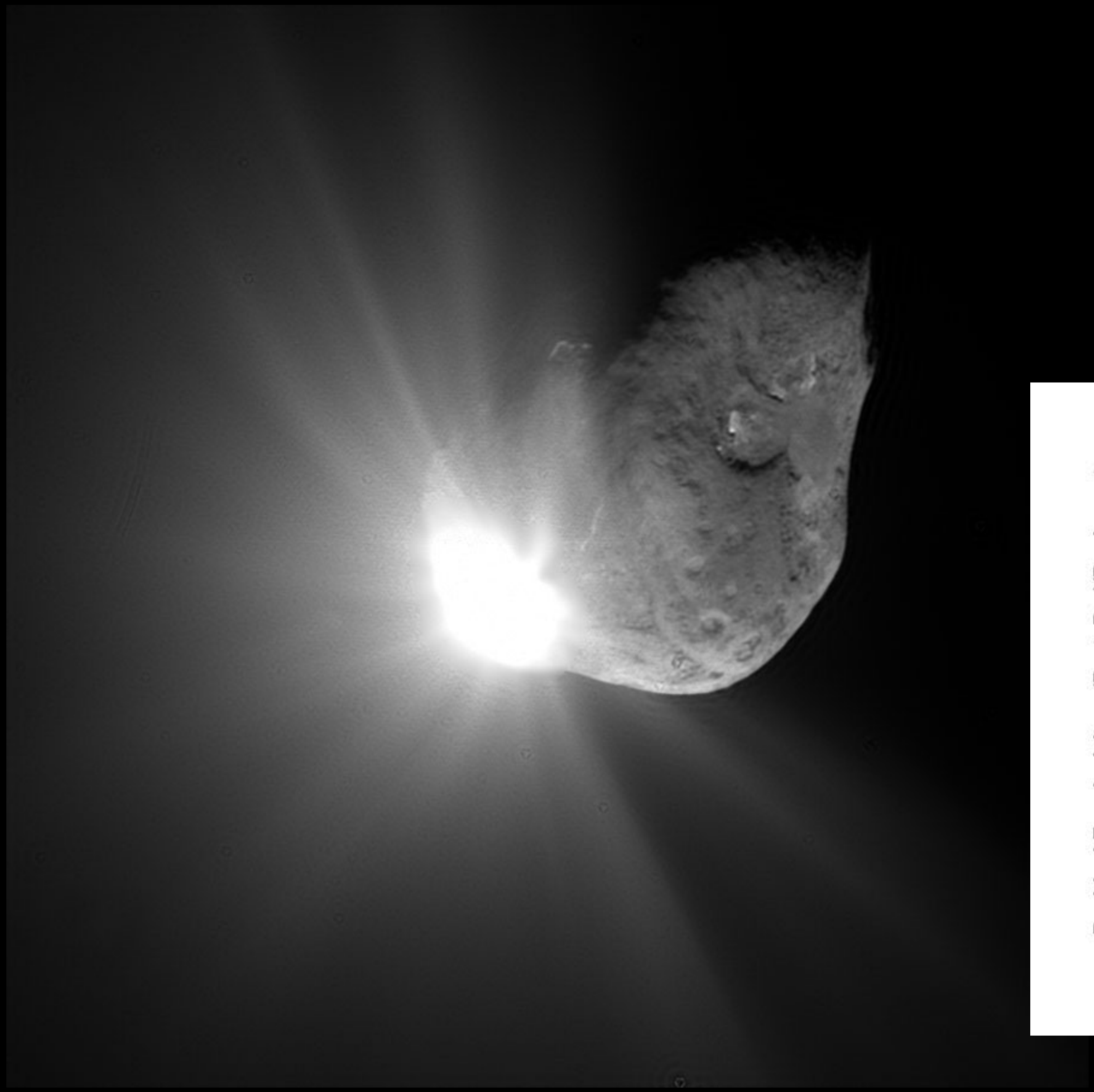


Kanno et al. 2003

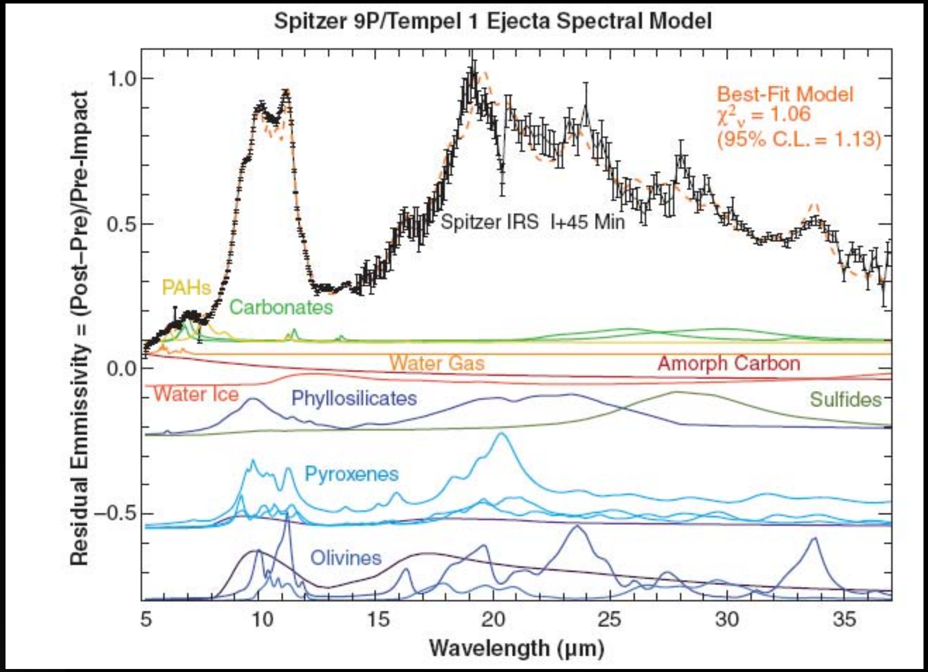


Hsieh & Luu 2006

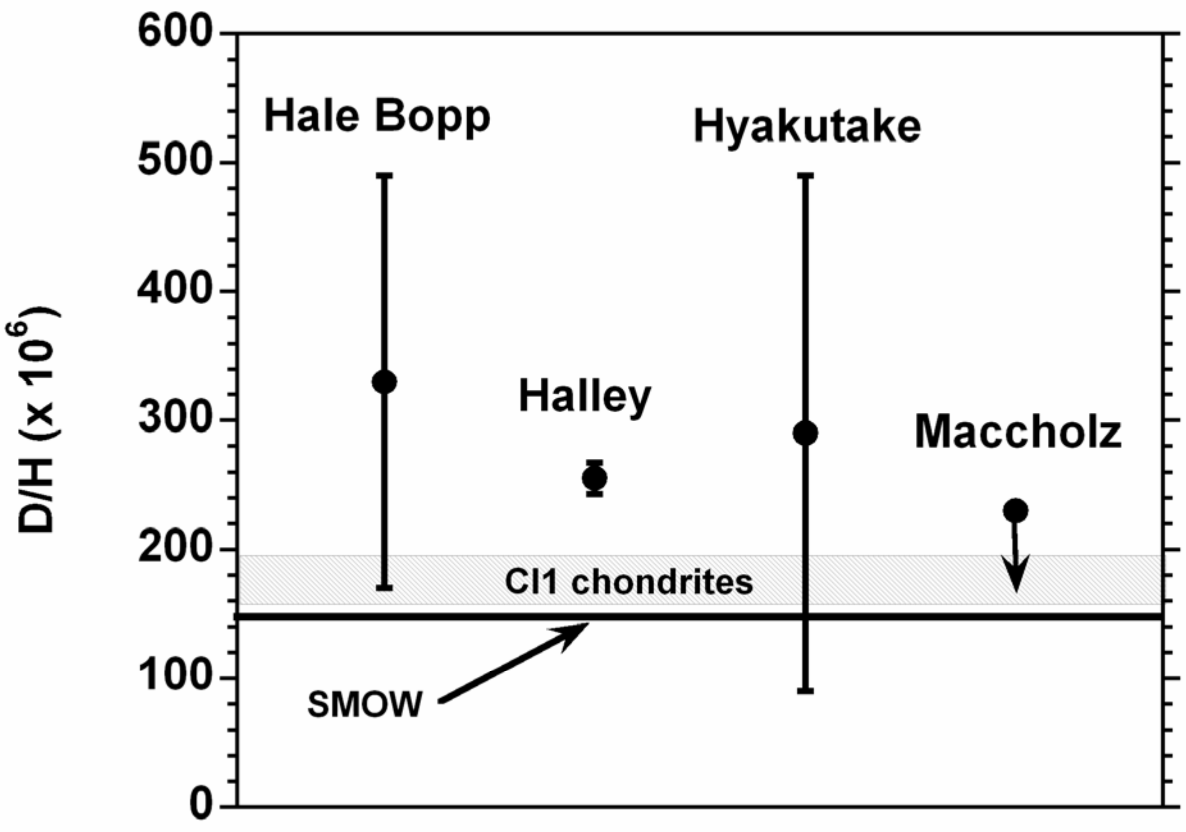
La mission Deep Impact



- 370 kg copper projectile
- Crater 200-300 m across

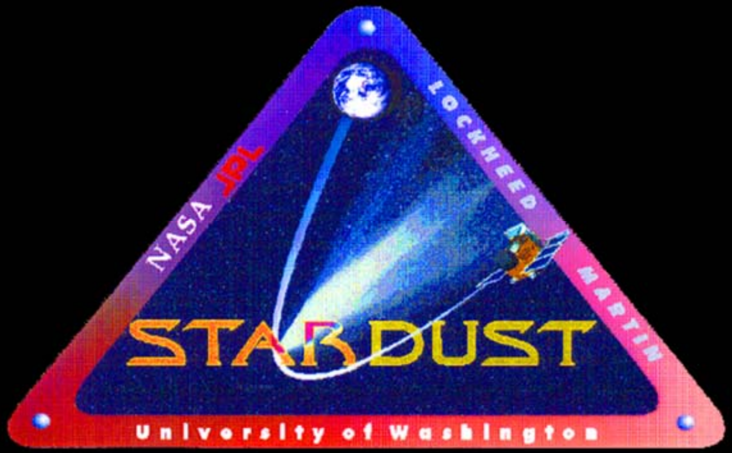


The D/H problem



6. The Stardust mission

Stardust: Mission de retour d'échantillons cométaires



- ☆ **Programme *Discovery*** : Des missions à forte composante scientifique et à faible coût

- ☆ 168.4 millions de dollars US hors lancement

- ☆ Responsable scientifique: Don Brownlee

- ☆ **Première mission de retour d'échantillons depuis Apollo**

Objectifs scientifiques de la mission

Objectif prioritaire

Retour de poussières cométaires

Objectifs secondaires

Retour de poussières interstellaires

Imagerie du noyau cométaire

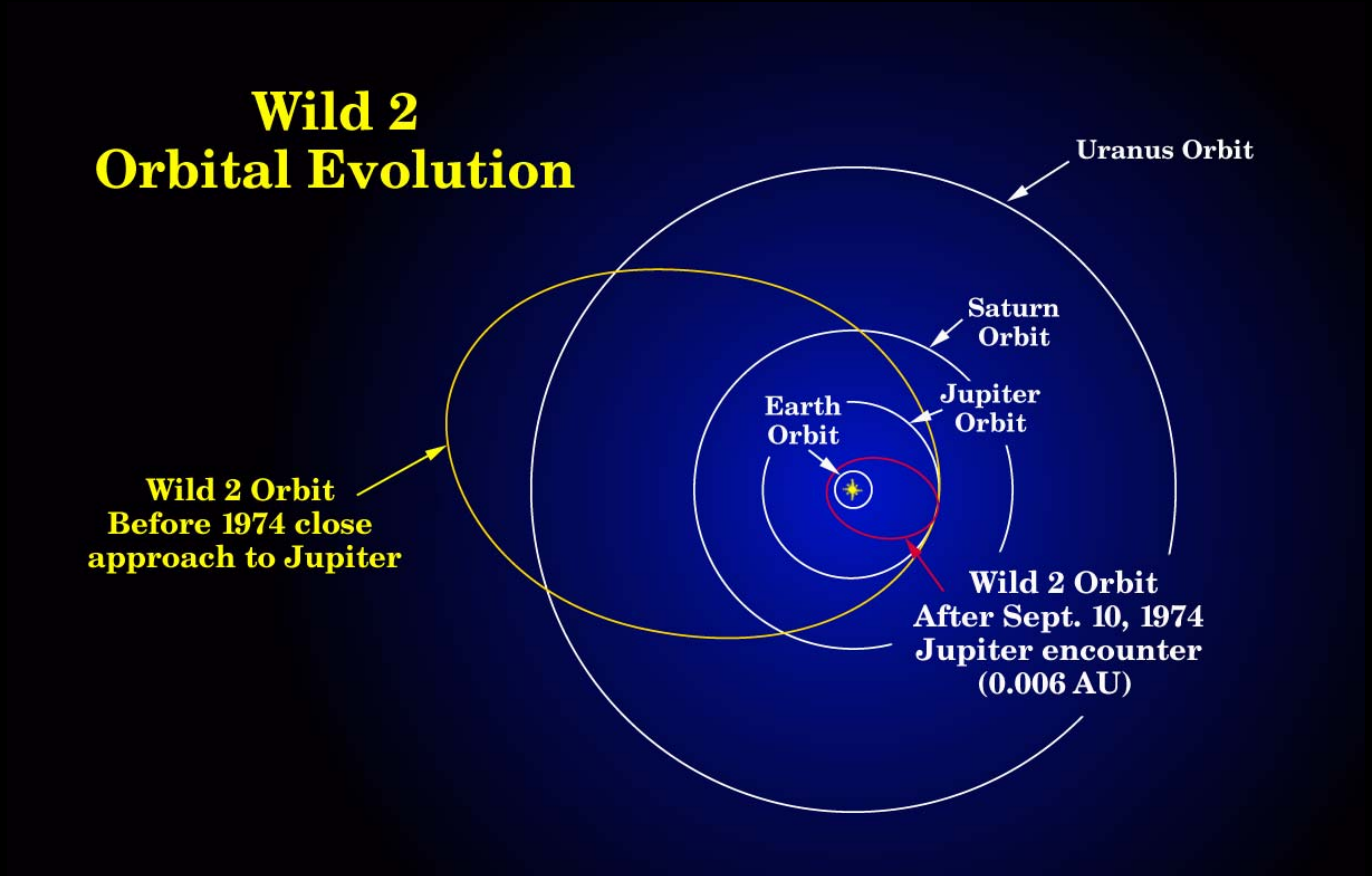
Questions scientifiques de la mission

Comparaison avec les astéroïdes

Matériau cométaire: solaire ou interstellaire?

Altération hydrothermale dans les comètes?

La comète Wild 2



4.5 km de diamètre

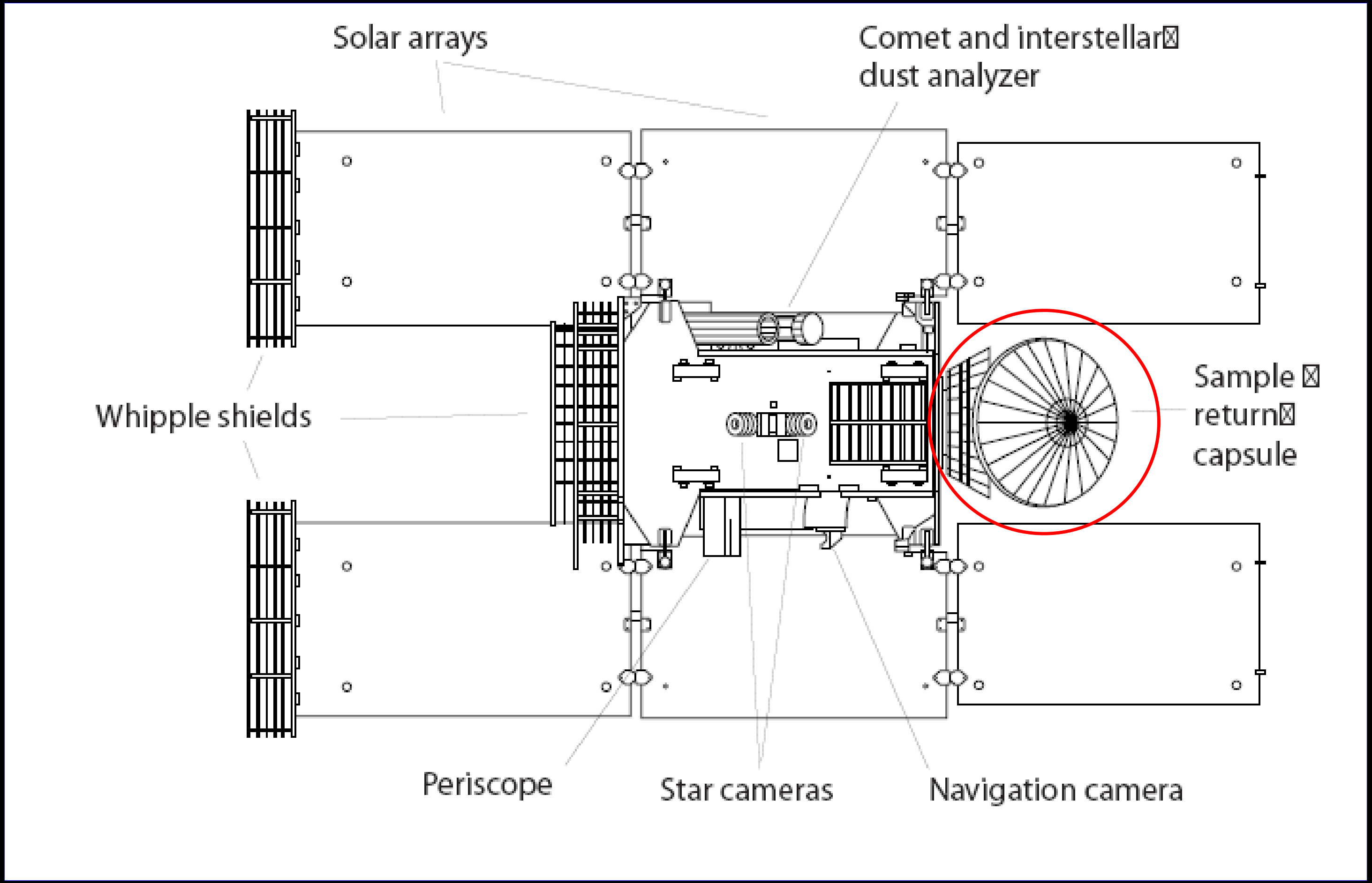
Découverte par Monsieur Wild en 1978

Depuis ~30 ans dans son orbite actuelle

Période de révolution 6.39 ans

Echelle de temps dynamique ~ 10 000 ans

Décollage de la sonde le 7 février 1999 à Cap Kennedy



Fusée Delta

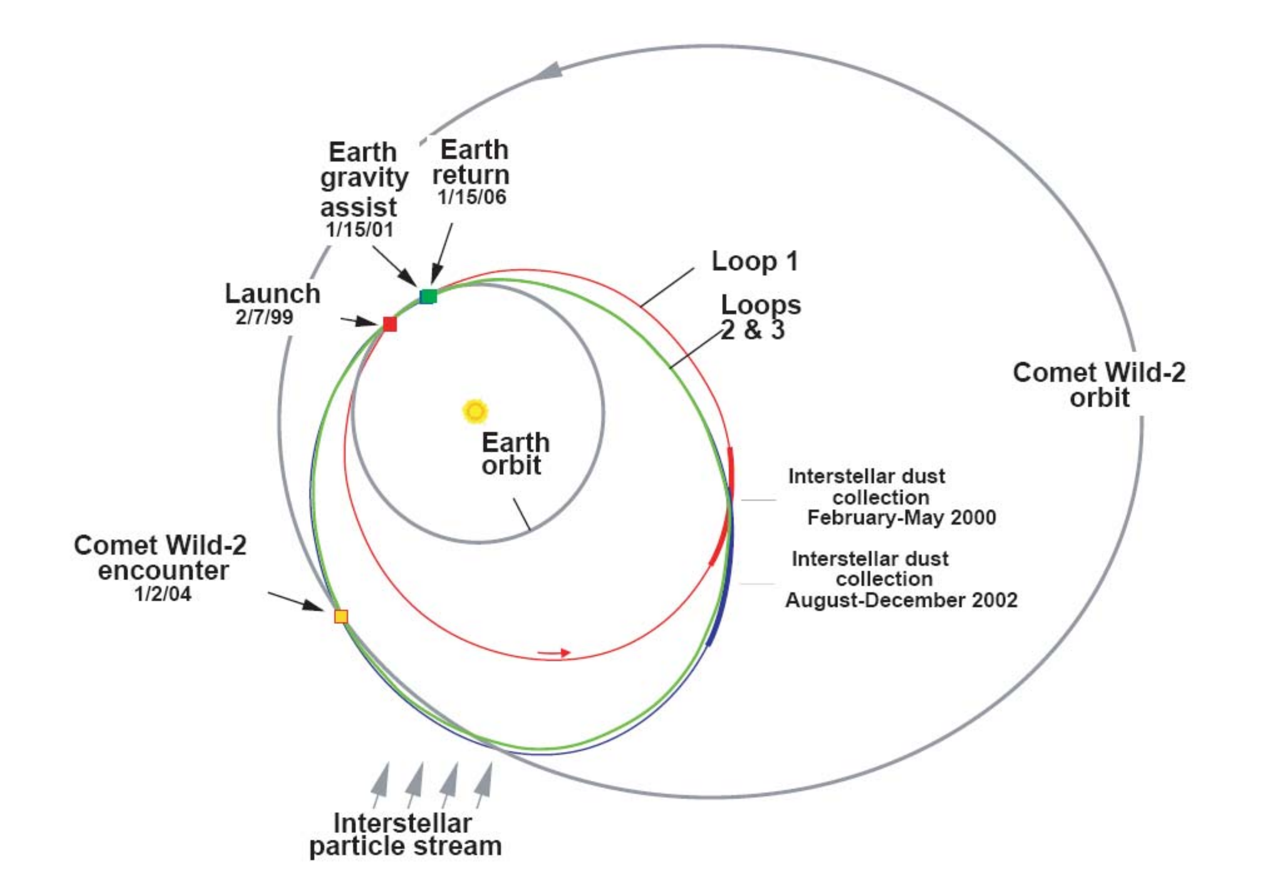
Poids total : 385 kg

Carburant 85 kg

Capsule 45.7 kg

1.7 m

Trajectoire de la sonde Stardust



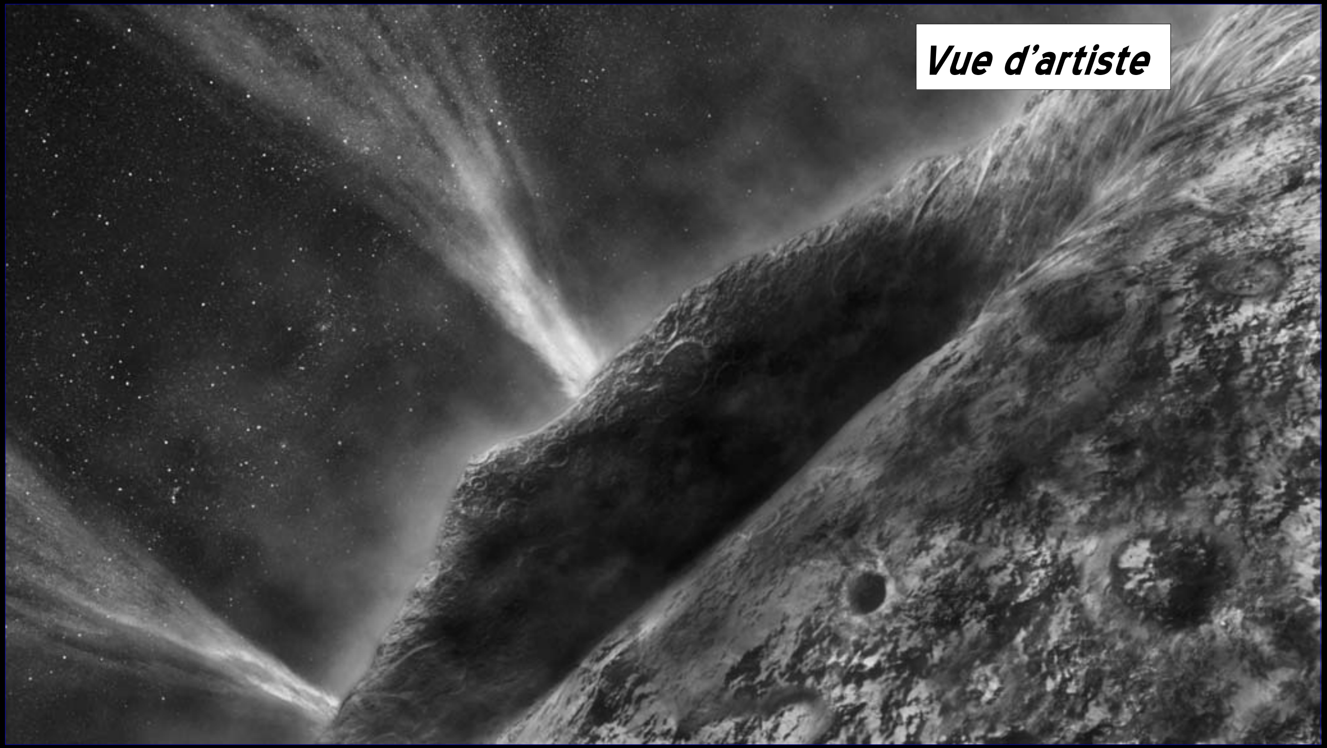
Mission trajectory

3 boucles autour de la Terre

Voyage aller: 4 ans et demi

Voyage retour: 2 ans

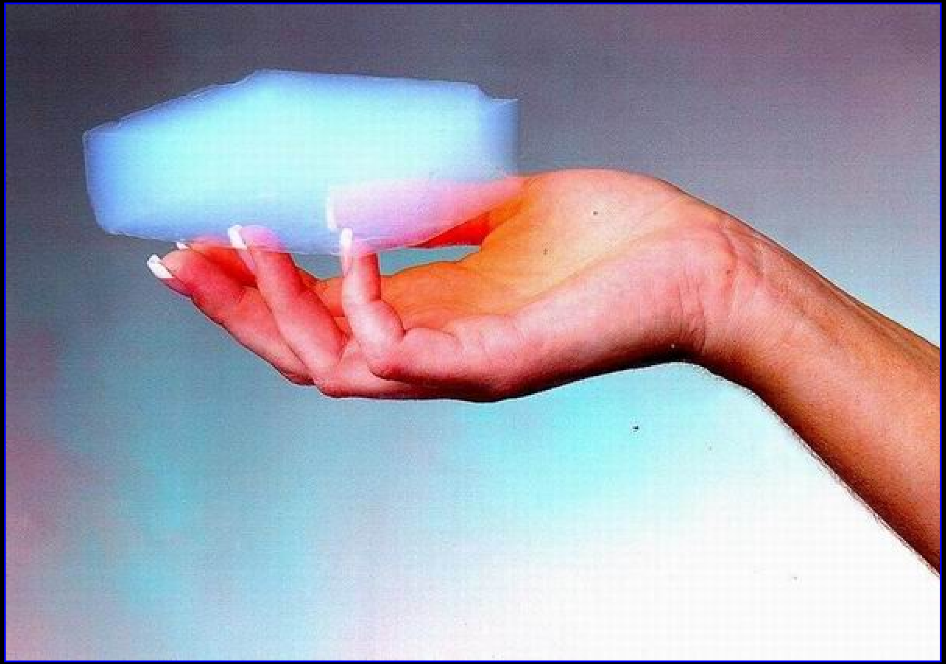
La rencontre: 2 janvier 2004 à 11.40 (PST)



Passage à 236 km de la comète

Vitesse relative des poussières cométaires et de la sonde = 6.1 km/s

Capture dans une raquette d'aérogel

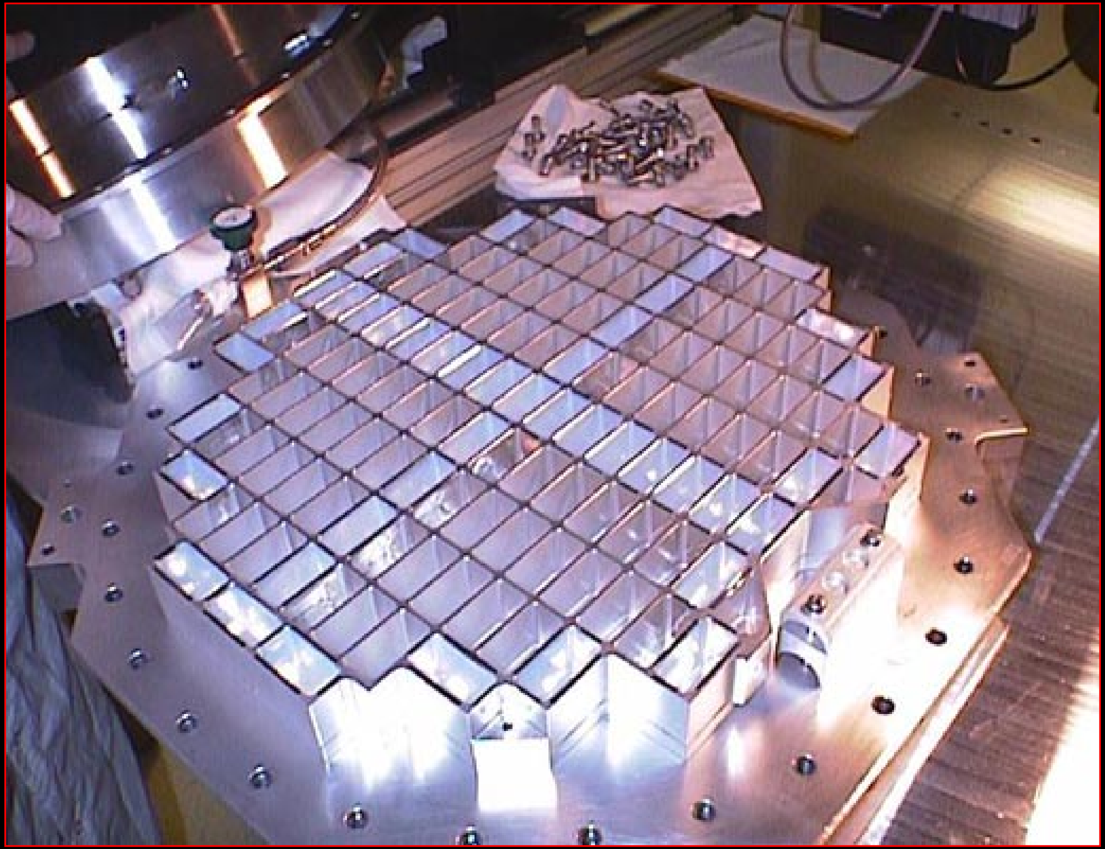


Gel de silice

Composé de vide a 99.8 %

1000 fois moins dense que le verre

Les montants en aluminium sont aussi des détecteurs



130 parallepipèdes d'aérogel 2 x 4 cm

Surface totale de collection: 1000 cm2

A side: poussières cométaires

B side: poussières interstellaires

Capture dans une raquette d’aérogel

Movie

Cometary flyby

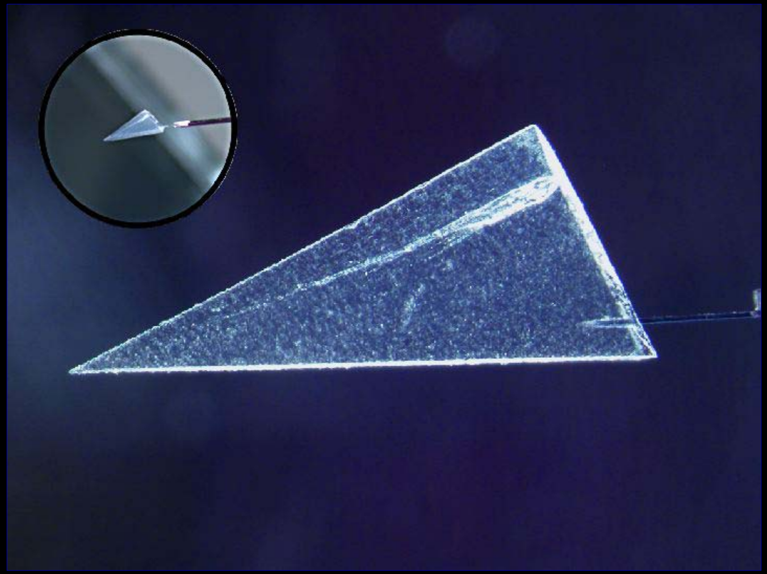
Movie

Retour sur Terre des échantillons le 15 janvier 2006

Entrée dans l'atmosphère terrestre à la vitesse de 46 400 km/h

Température maximale du bouclier thermique: 2700 C

Extraction des particules dans la salle blanche de la NASA



Environ un millier de grains de taille supérieure à 5 µm

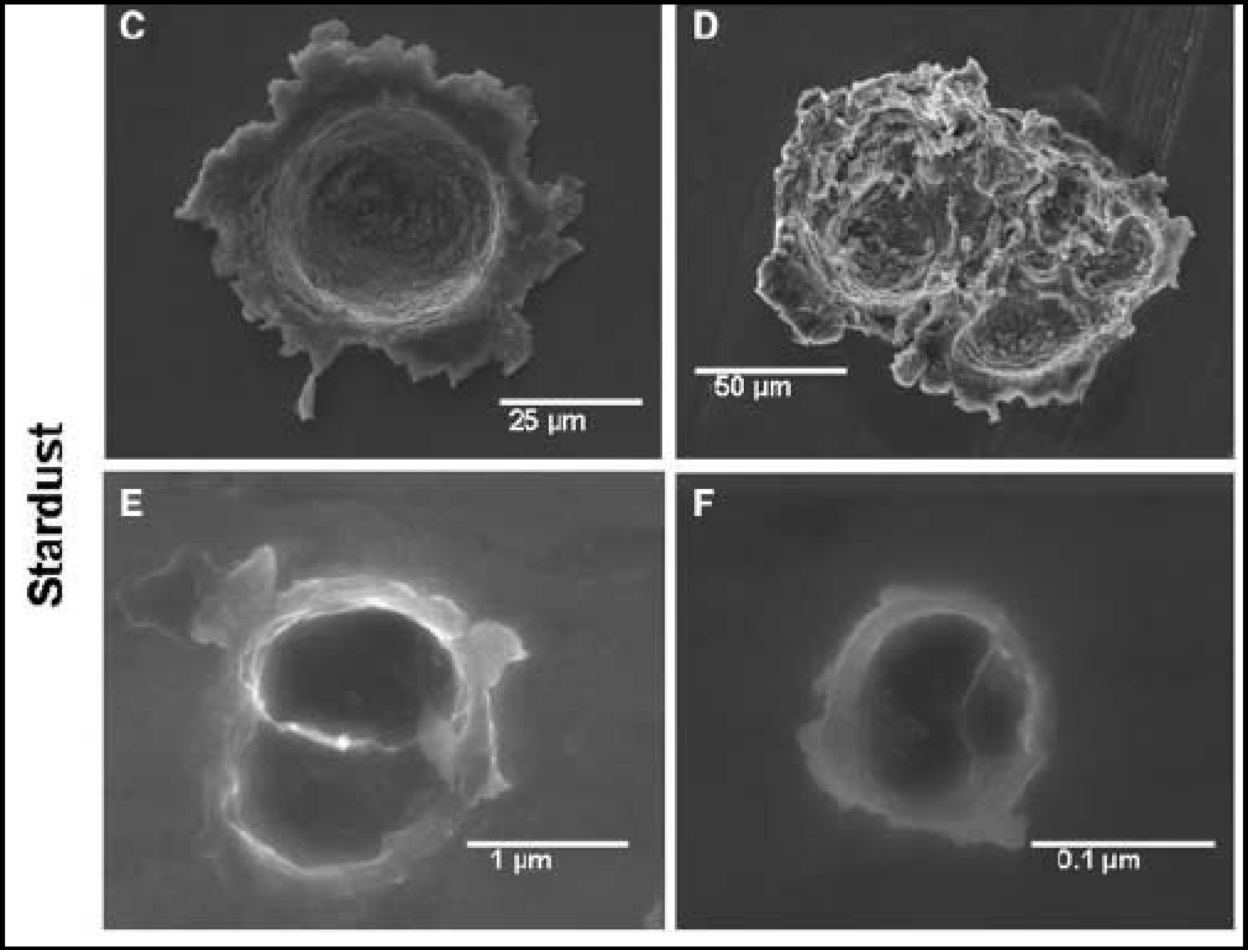
100 µg de matière

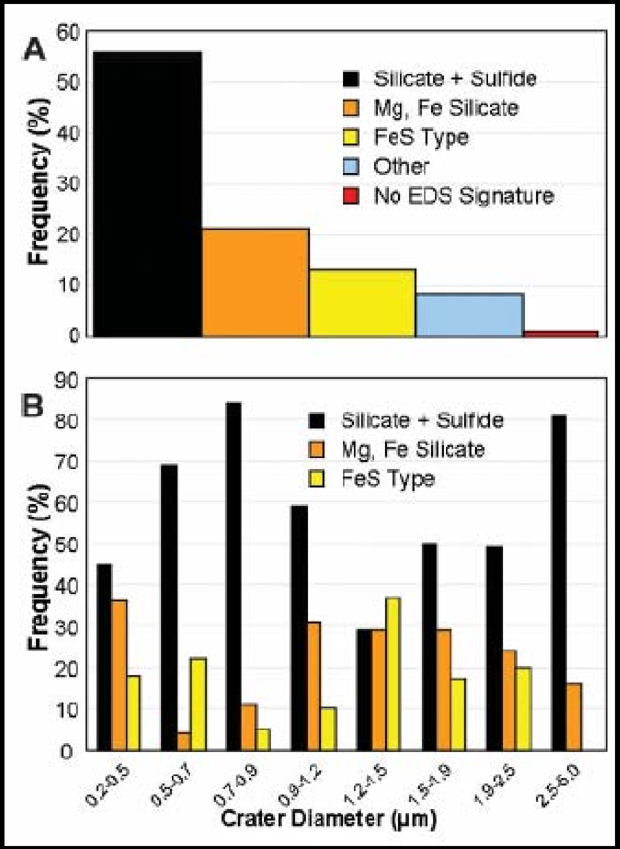
7. The Stardust mission: Results

Special issue of Science, 15 december 2006

Brownlee, Zolensky, McKeegan, Sandford, Horz...

Craters due to hypervelocity impacts

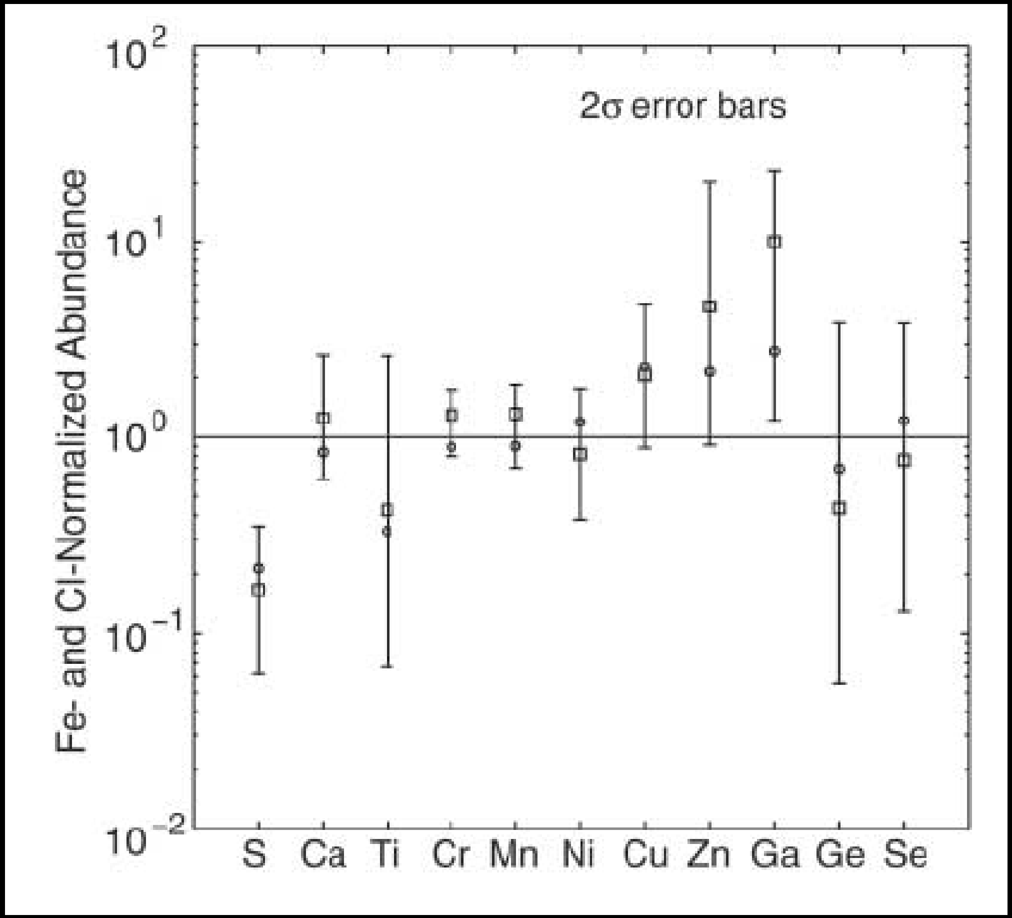




200 craters analyzed

15 % of the total collection area

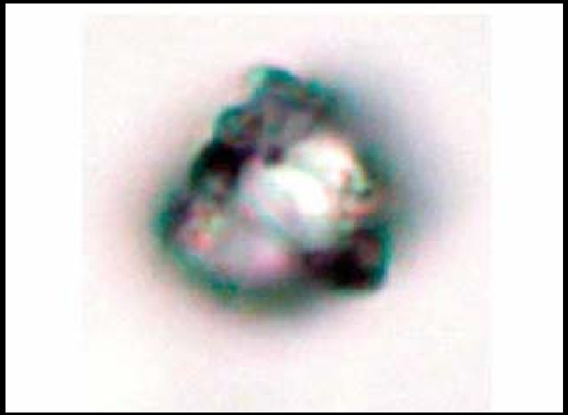
Chemical composition

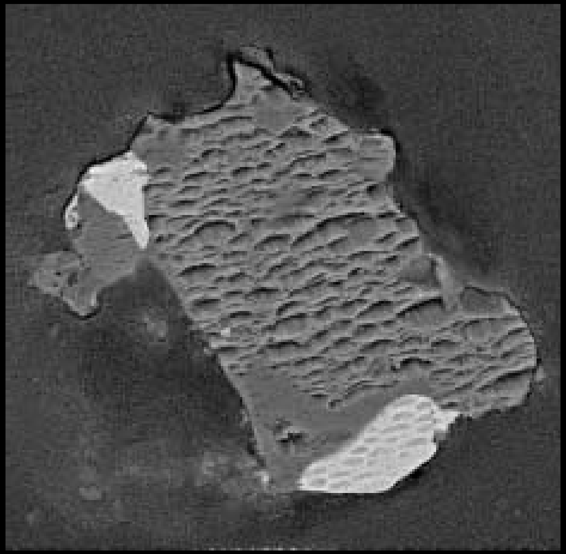


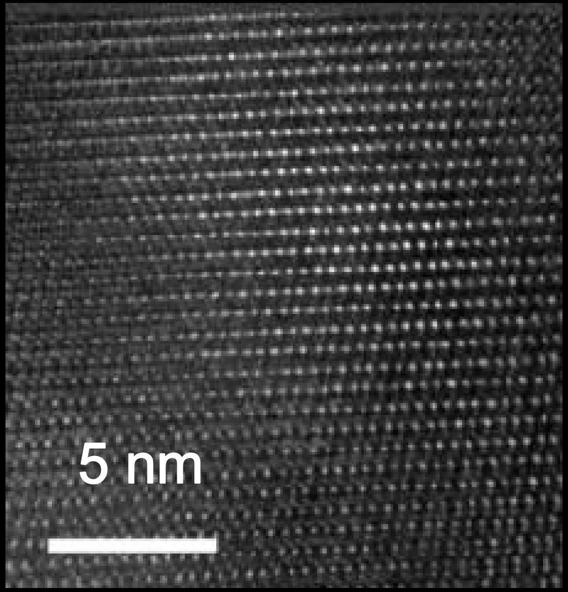
Difficult to obtain

Roughly solar (CI1)

Extracted dust





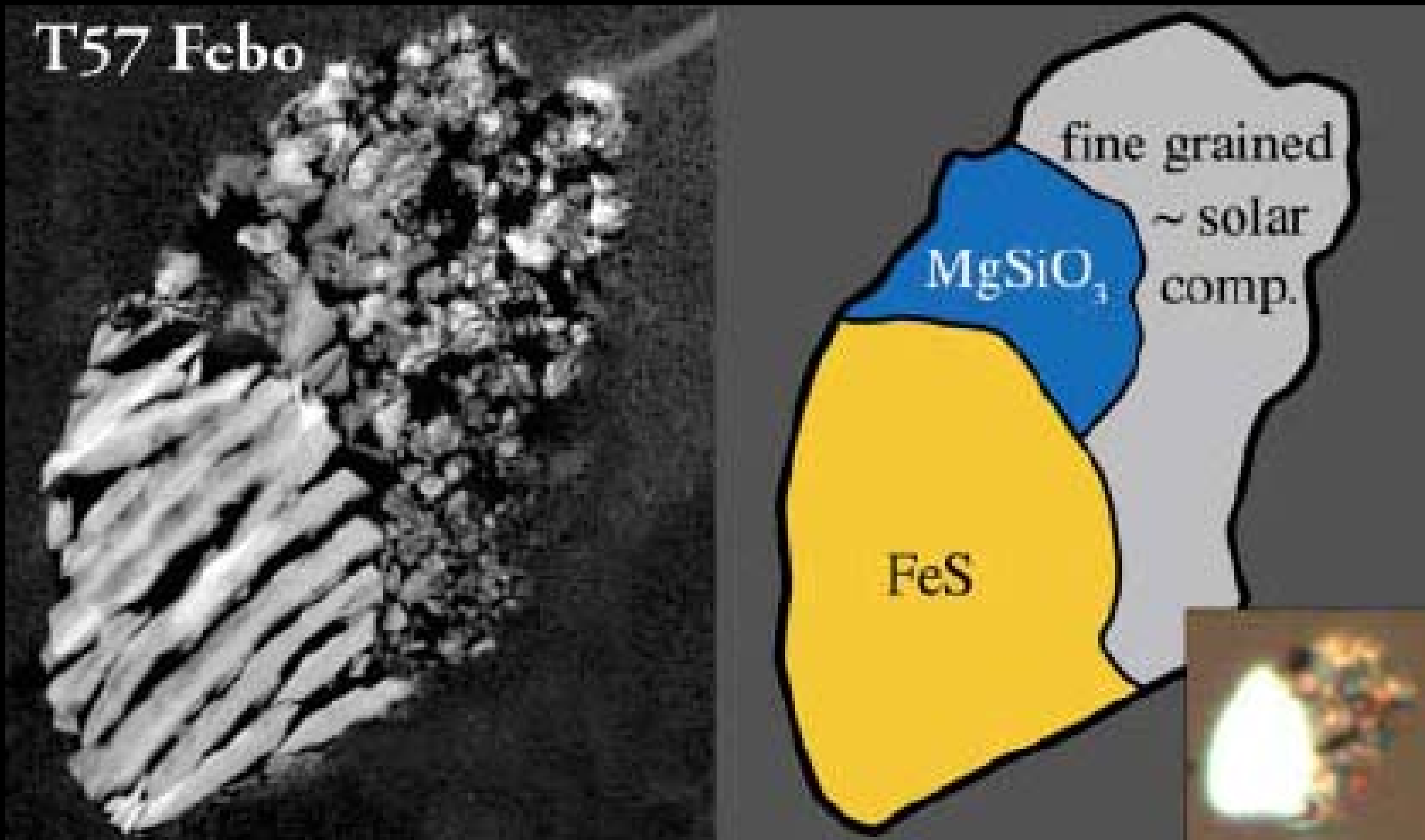


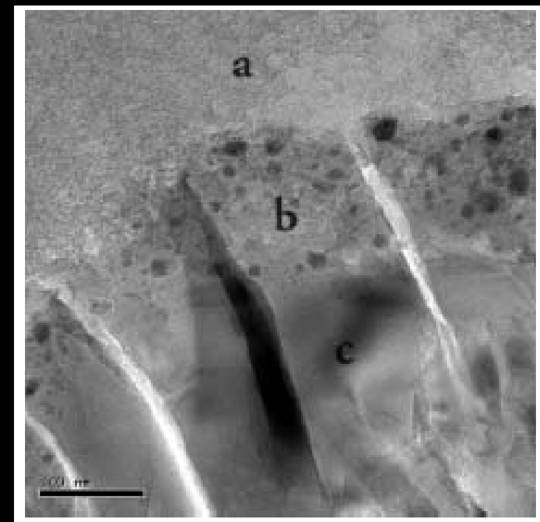
Track 27: Sitara (~ 2 mm)

Terminal particle is 8 μm

Not all tracks have a clear terminal particle

Basic mineralogy



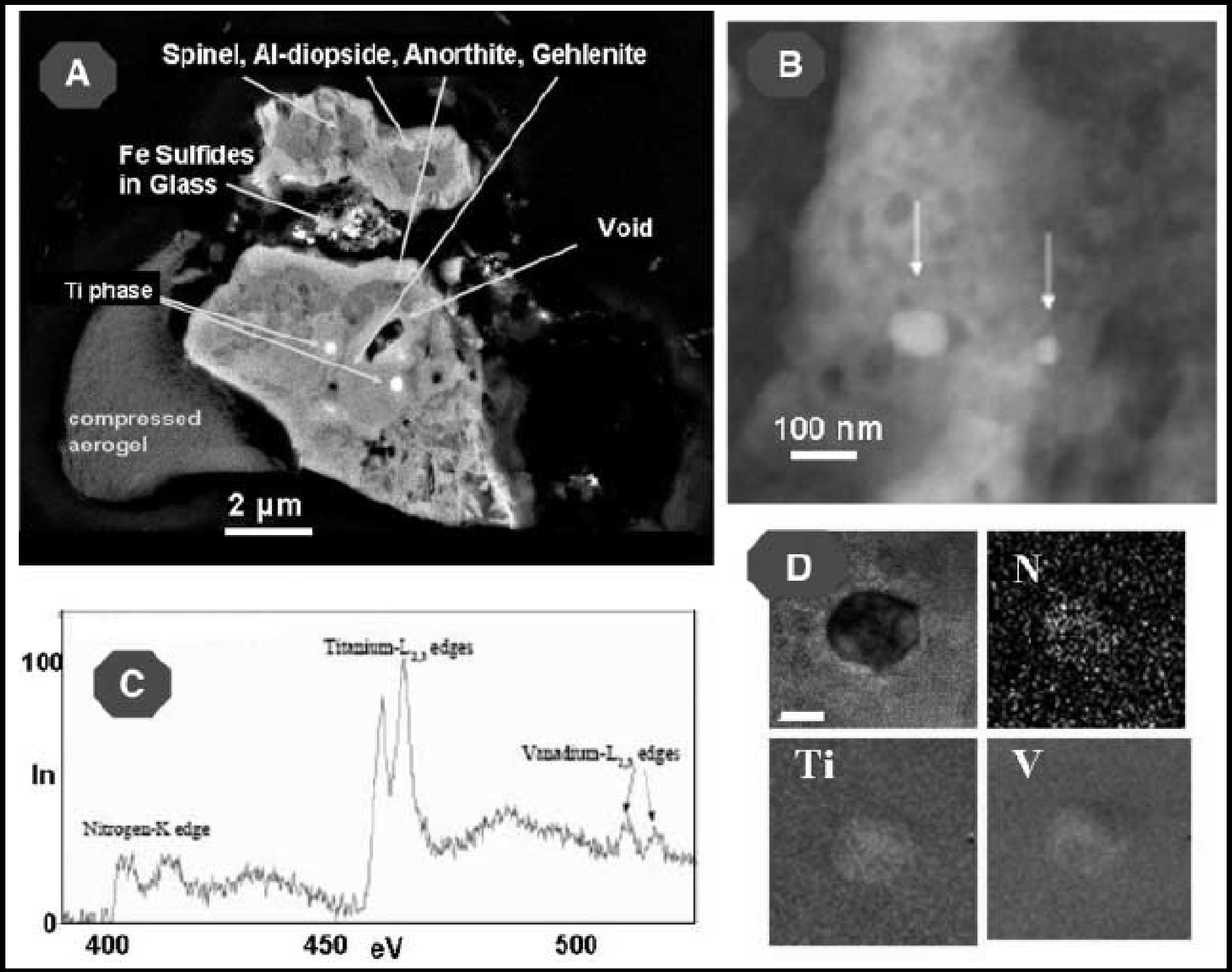


Olivine, pyroxene, sulfides, metal

Melted aerogel

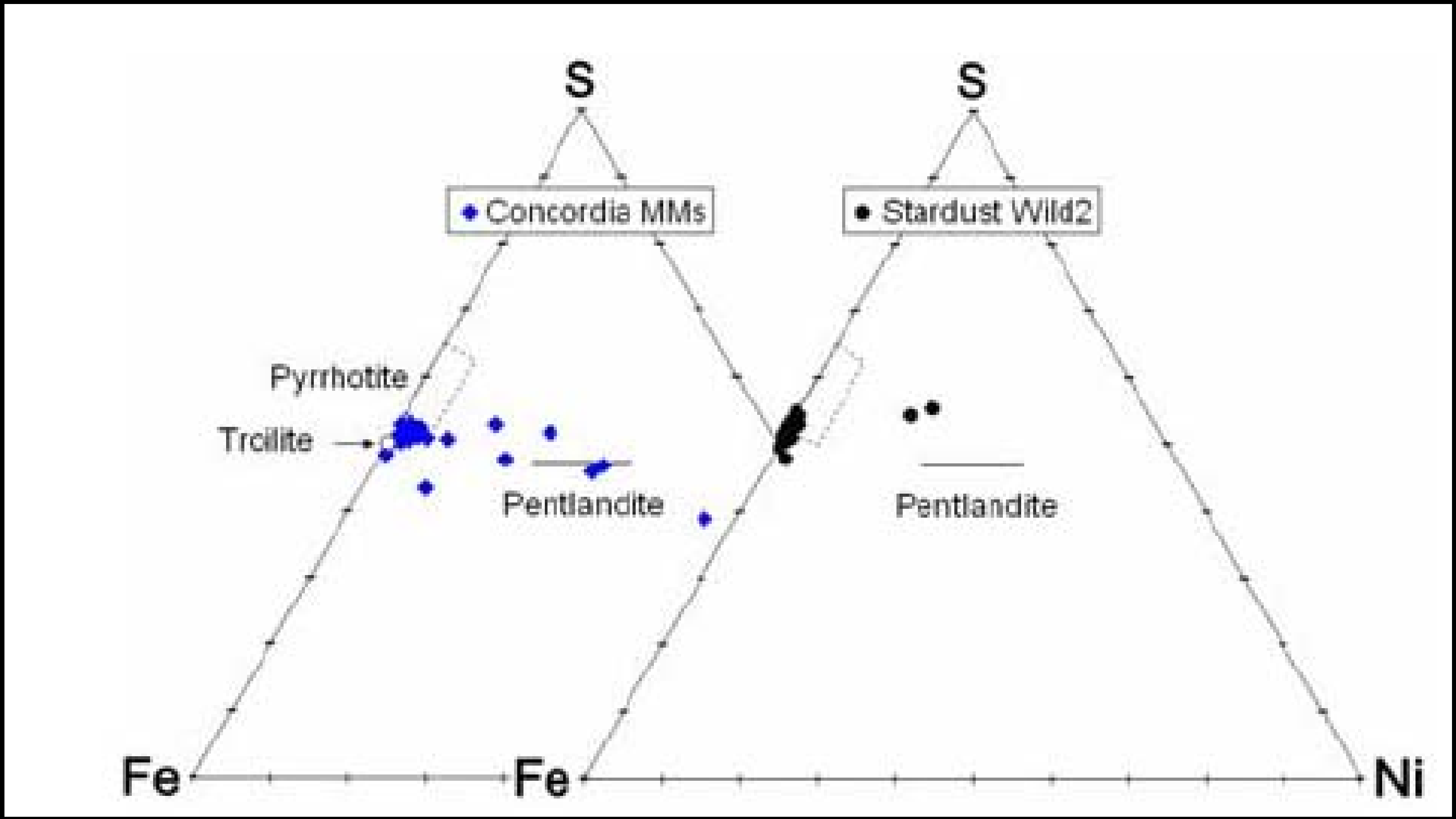
Similar to what is found in primitive meteorites

Calcium-Aluminium-rich objects in comets



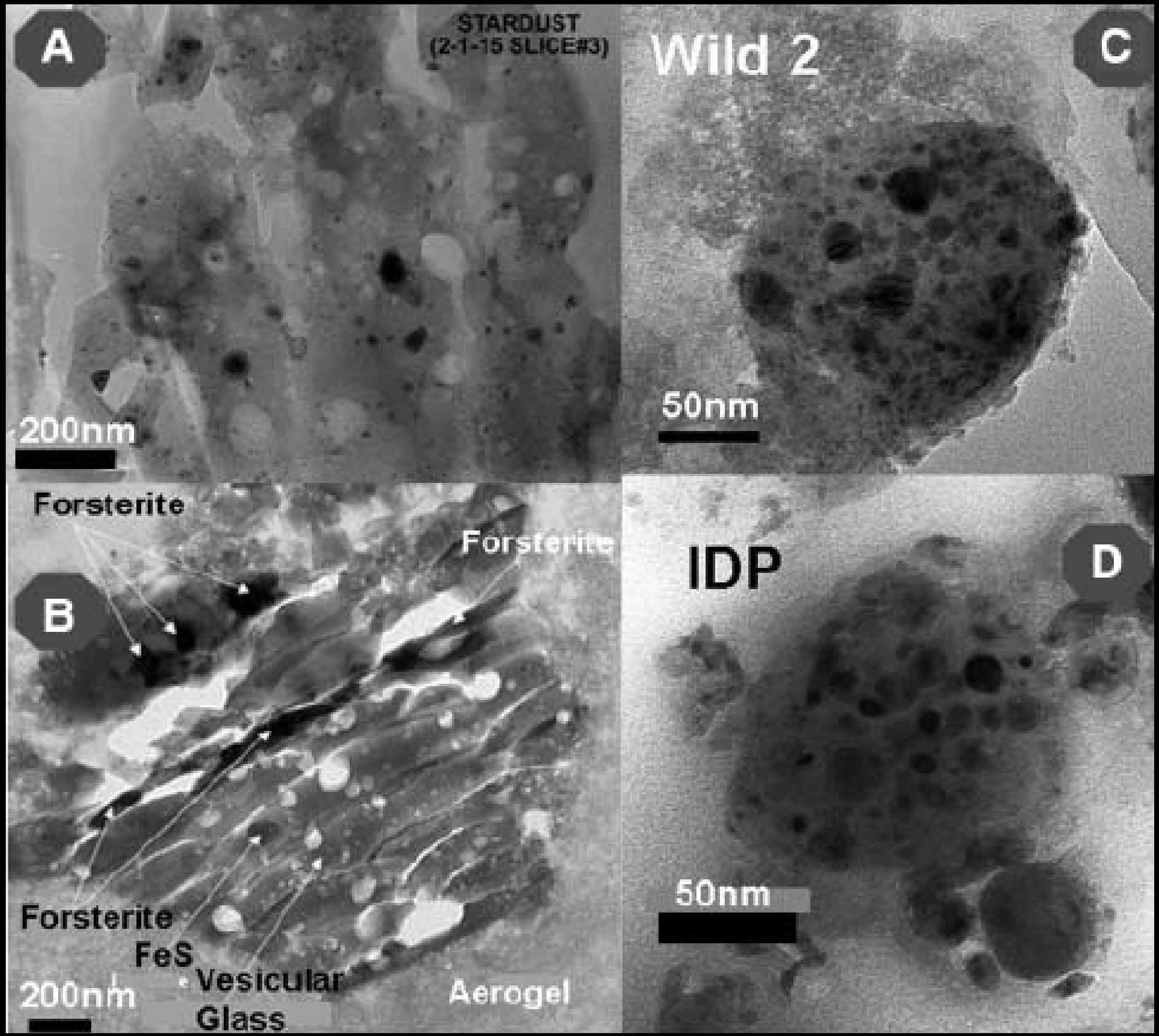
Important radial mixing in the Solar System

Some similarities with Antarctic micrometeorites



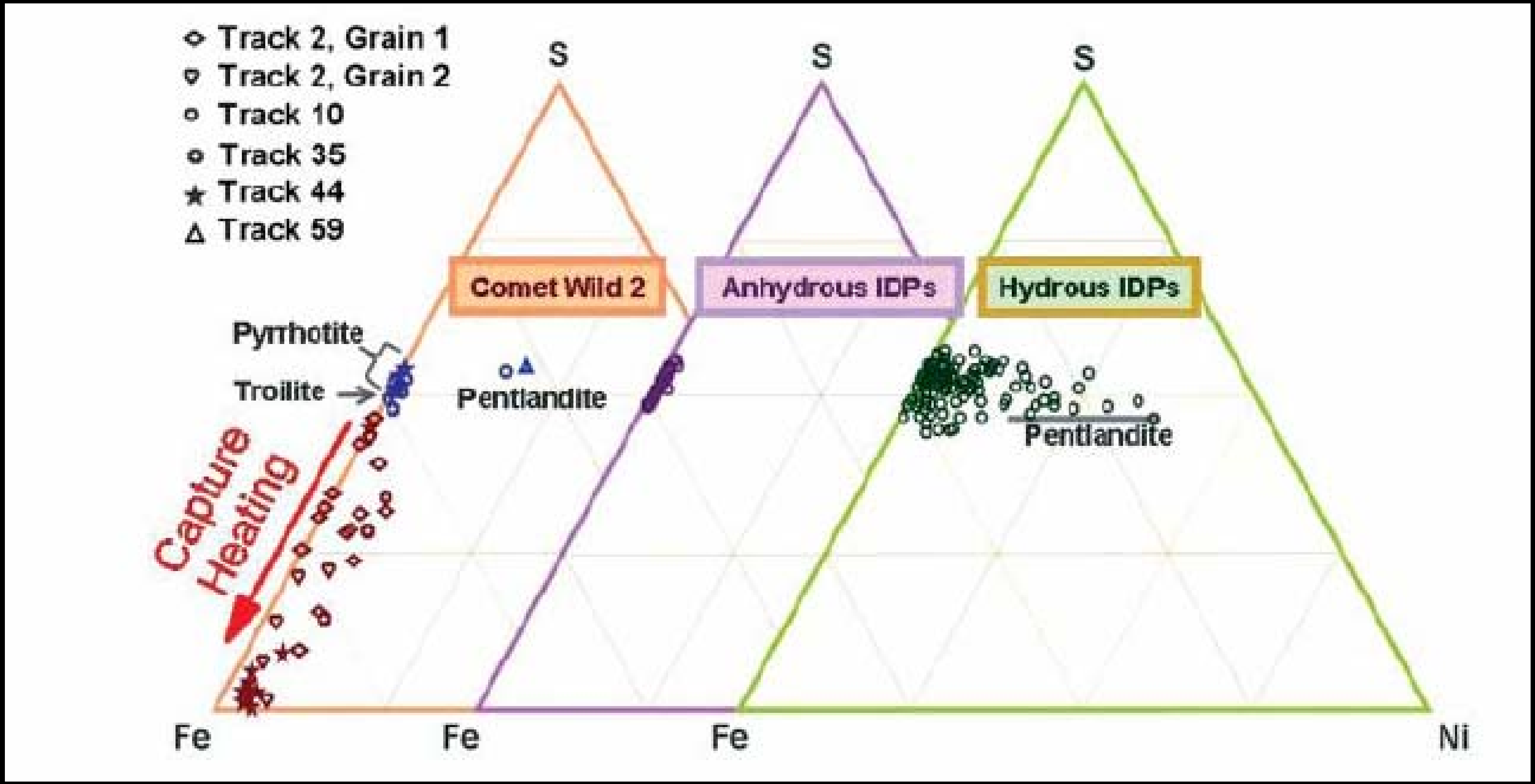
Engrand et al. 2007

Some similarities with IDPs

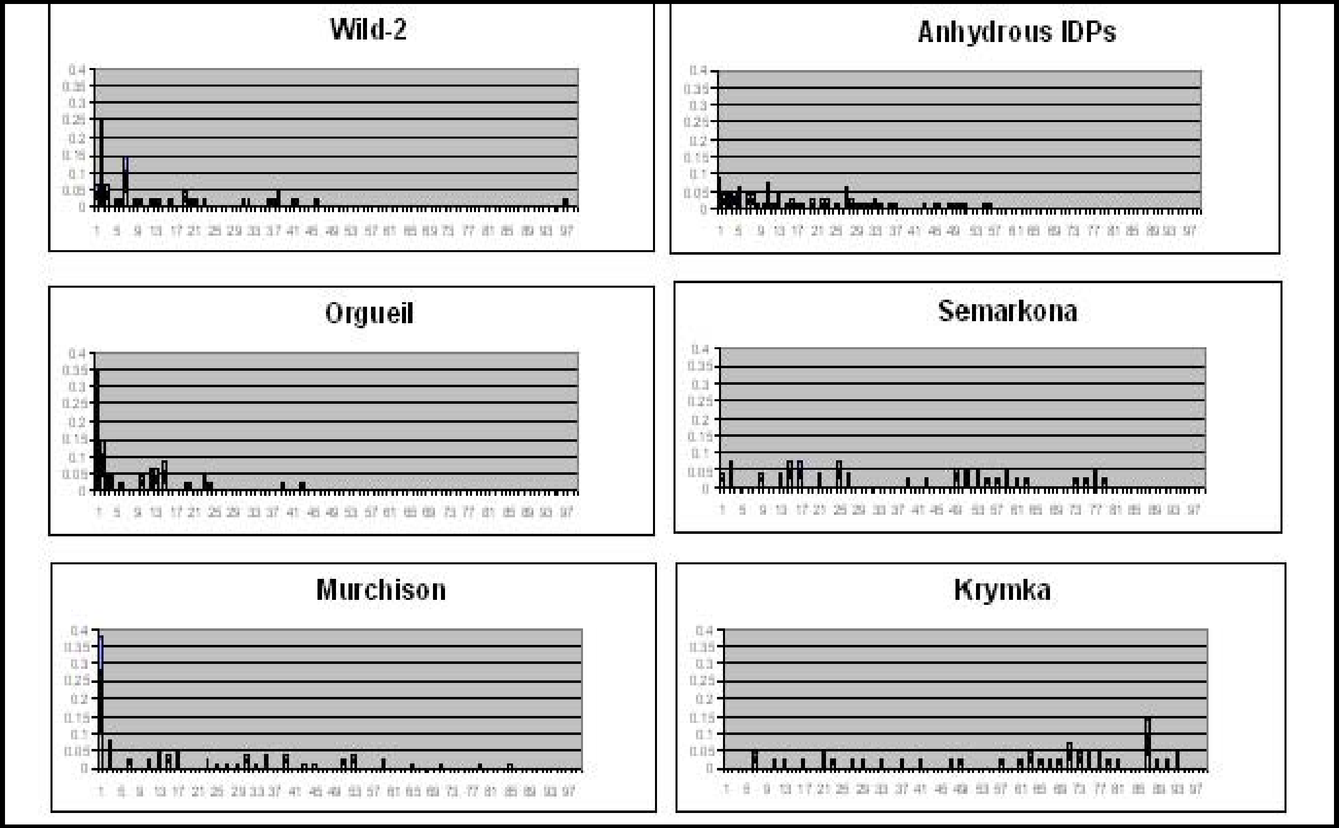


Presence of GEMs (Glass Embedded with Meal and Sulfide) or melted aerogel ?

Some similarities with IDPs

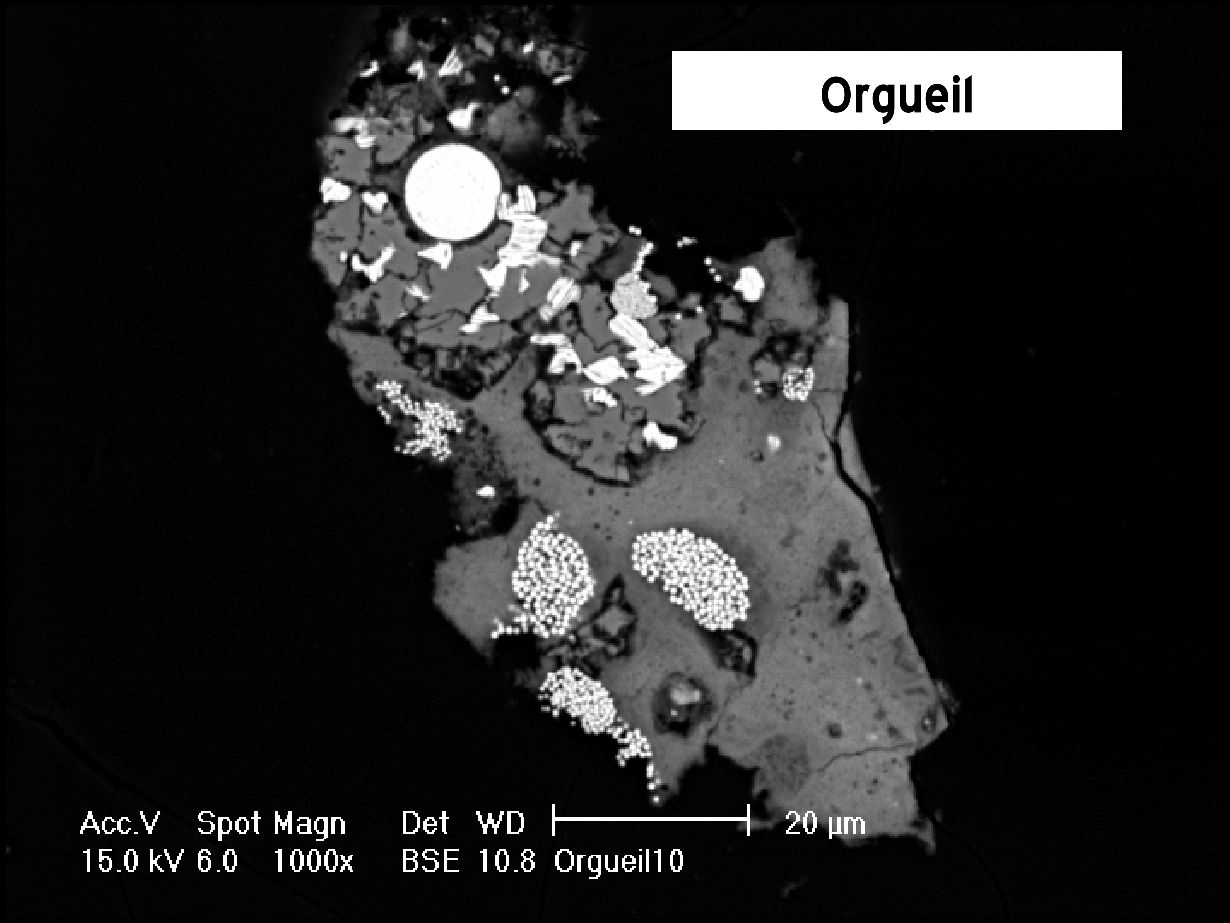


Some similarities with carbonaceous chondrites



Olivine compositions similar to those of Orgueil (CI1)

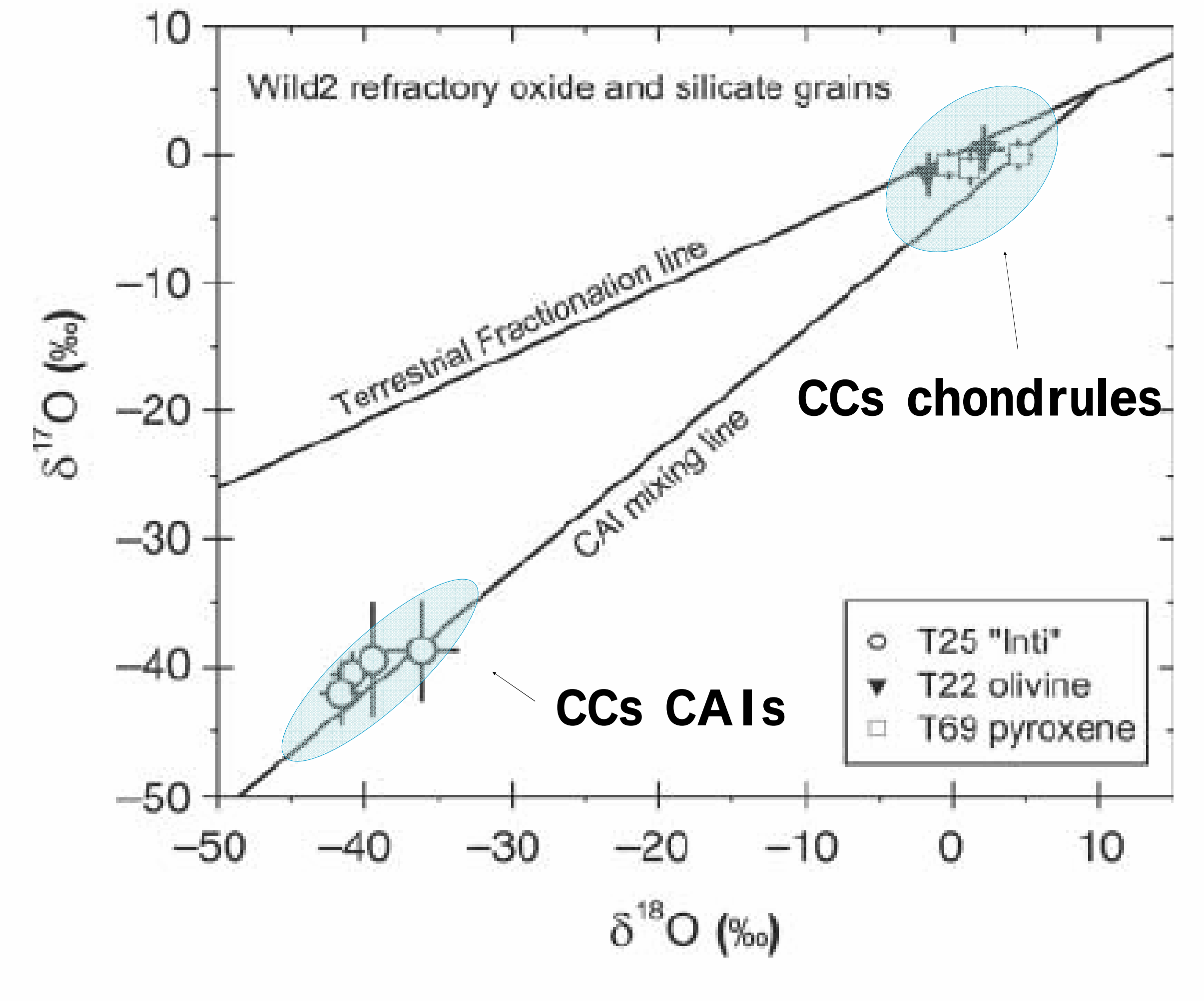
What was not found...



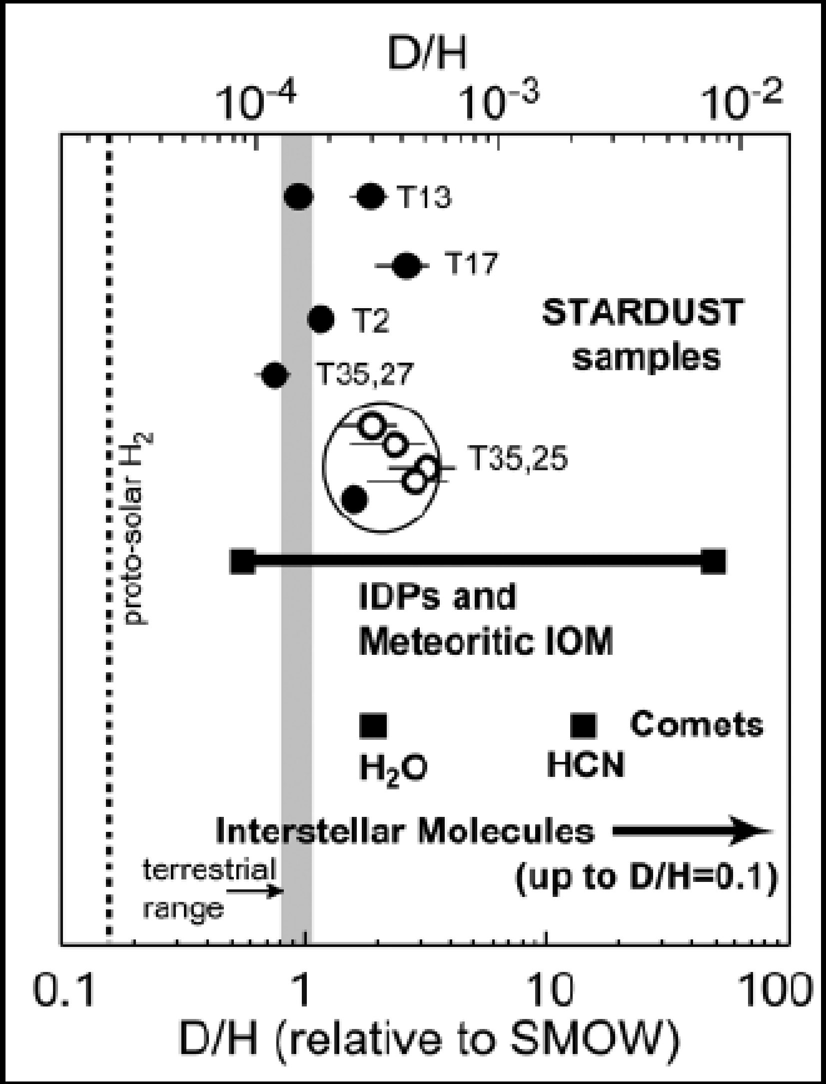
Phyllosilicates not found yet

But carbonates recently identified

Some similarities with carbonaceous chondrites



Not such a strong link to the interstellar medium

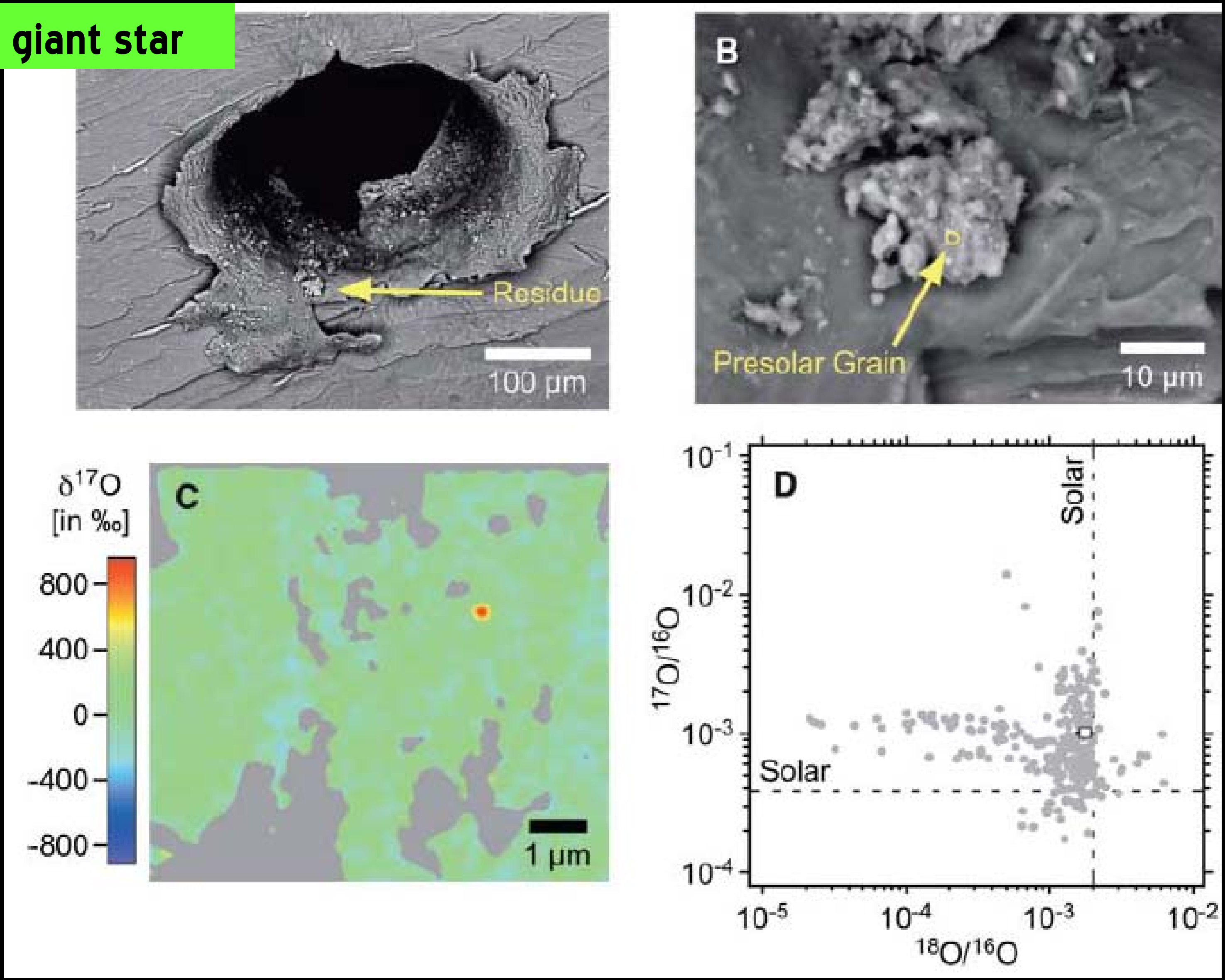


Movie

Note all particles enriched in deuterium

Discovery of *one* presolar grain

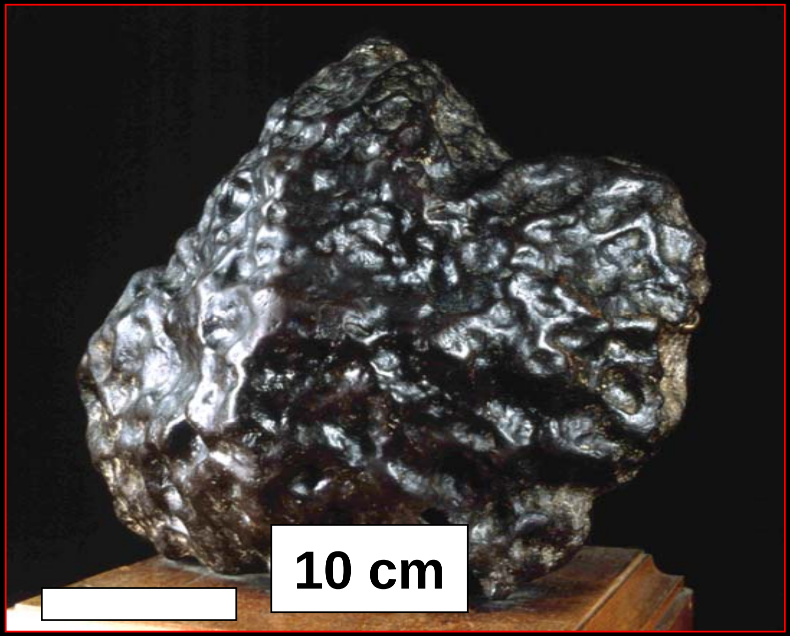
From a red giant star

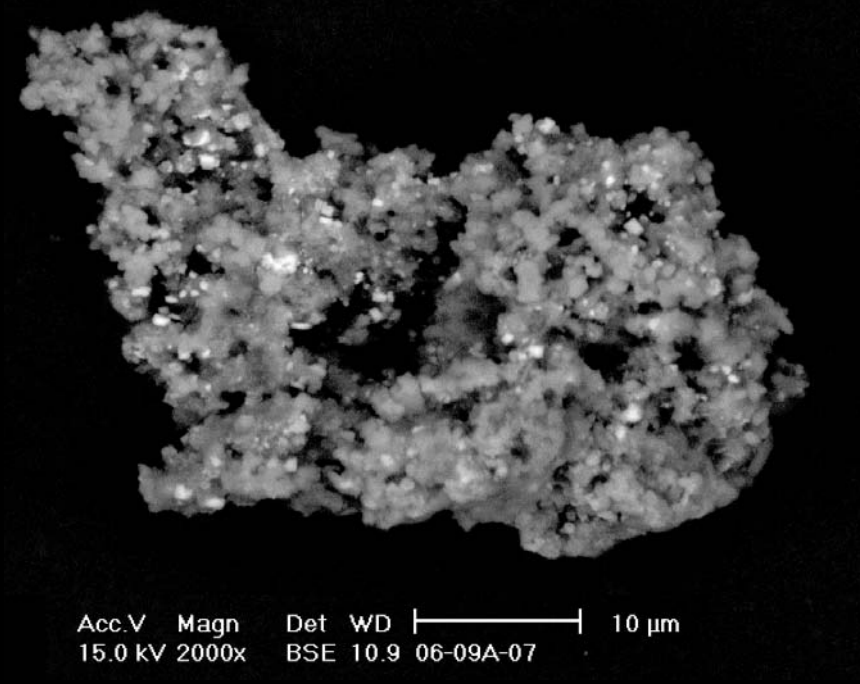


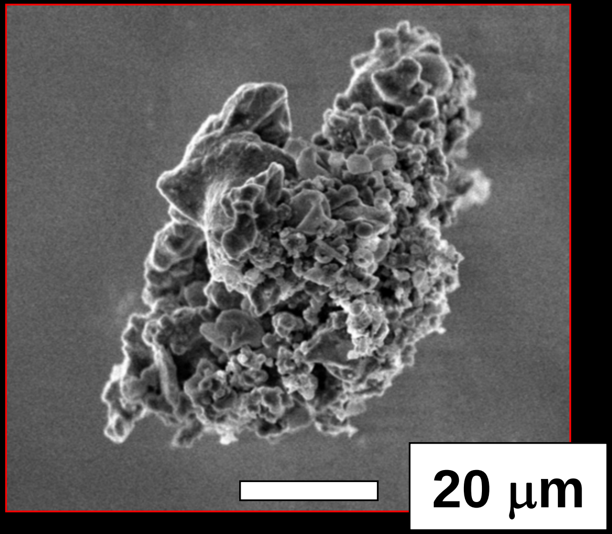
Abundance of presolar grains similar to that of meteorites

8. (Personal) conclusions

Conclusions 1

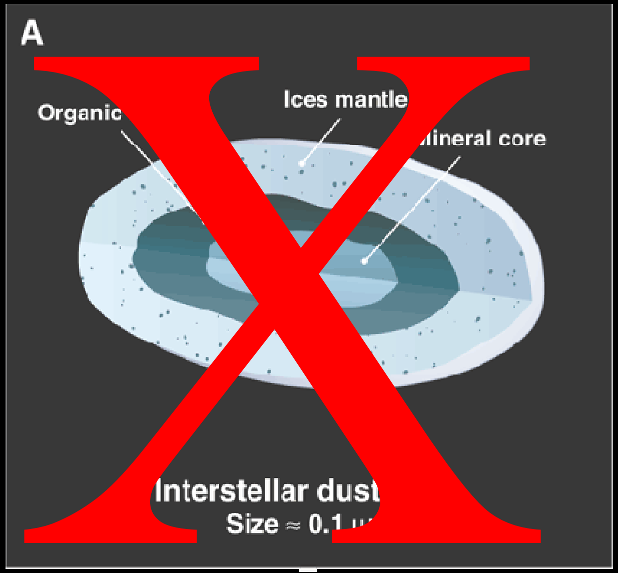






Similarities and differences with carbonaceous chondrites, Antarctic micrometeorites and IDPs

Conclusions 2



A solar system matter

-Chemistry

-Mineralogy

-Isotopic composition

Similar to inner Solar System matter

Weak interstellar heritage

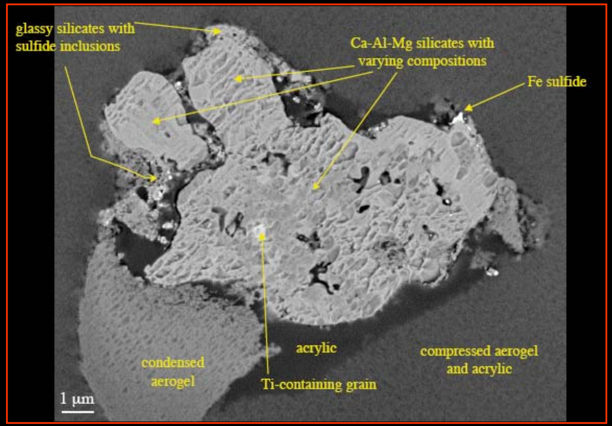
Conclusions 3

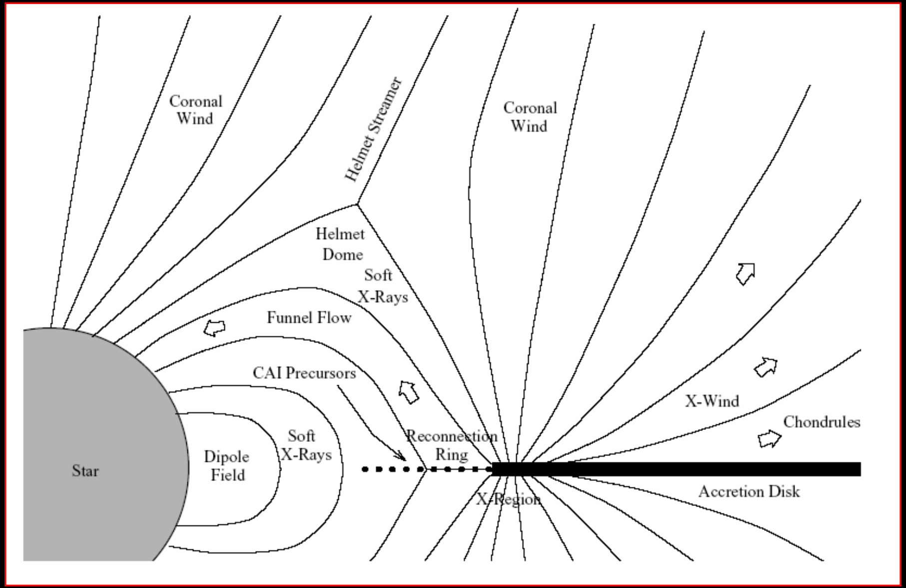
Toward an Astrophysical Theory of Chondrites

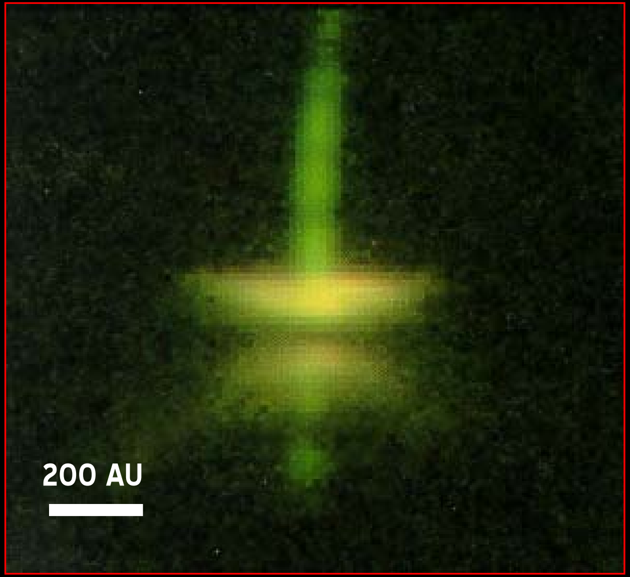
Frank H. Shu,* Hsien Shang, Typhoon Lee

at all distances from the sun. Thus, comets should also contain CAIs and chondrules.

SCIENCE • VOL. 271 • 15 MARCH 1996





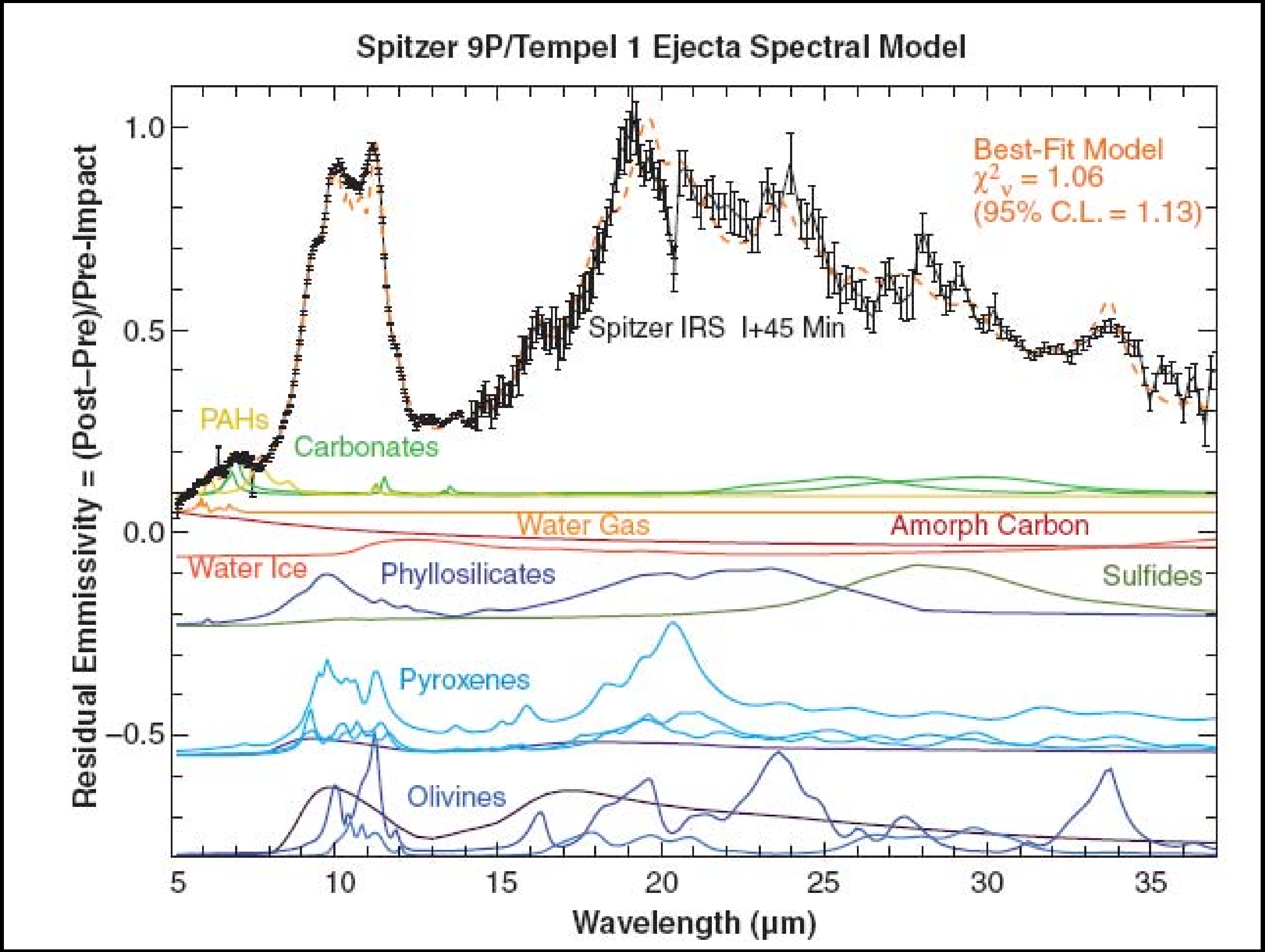


Mixing in the solar system

-Stellar outflows – x-wind

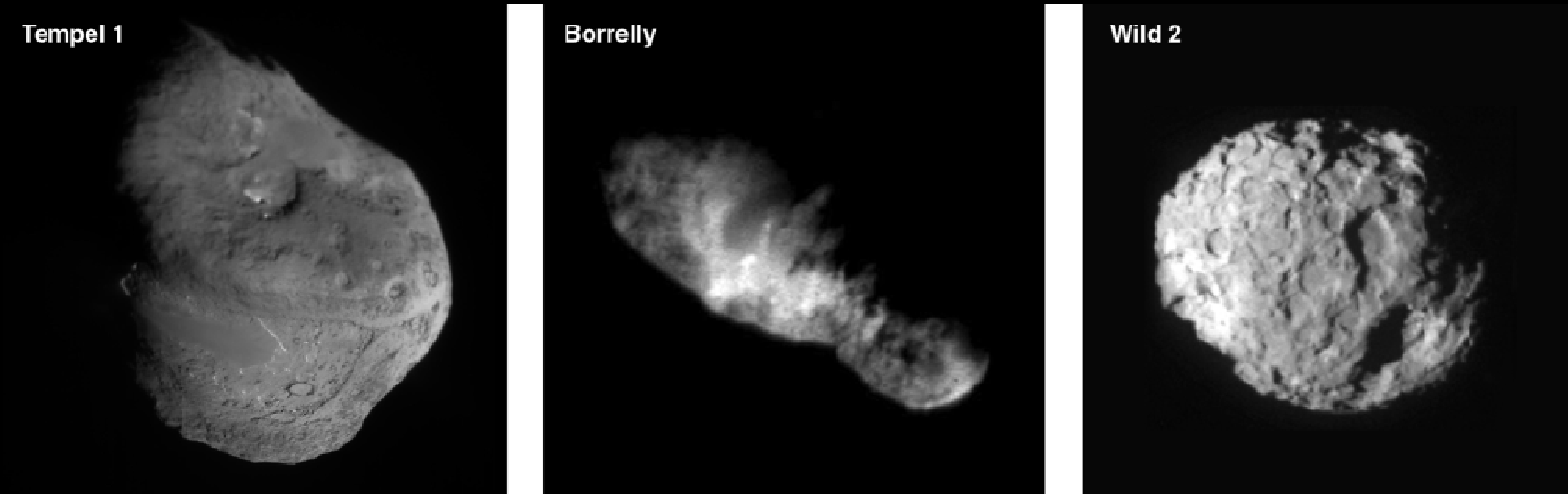
-Turbulence

Conclusions 4



No aqueous alteration in comets?

Conclusions 5



Not all comets are the same

Less than a *mg* of *dust* from the *surface* of *one* comet