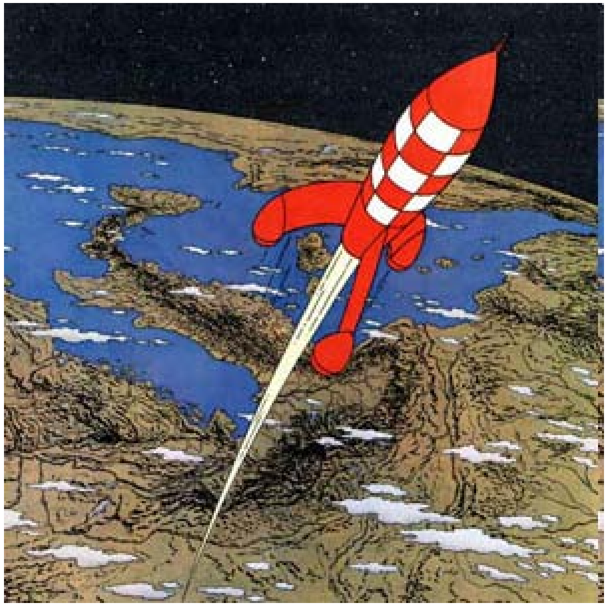
Hubble Space Telescope Orion Treasury Project Team

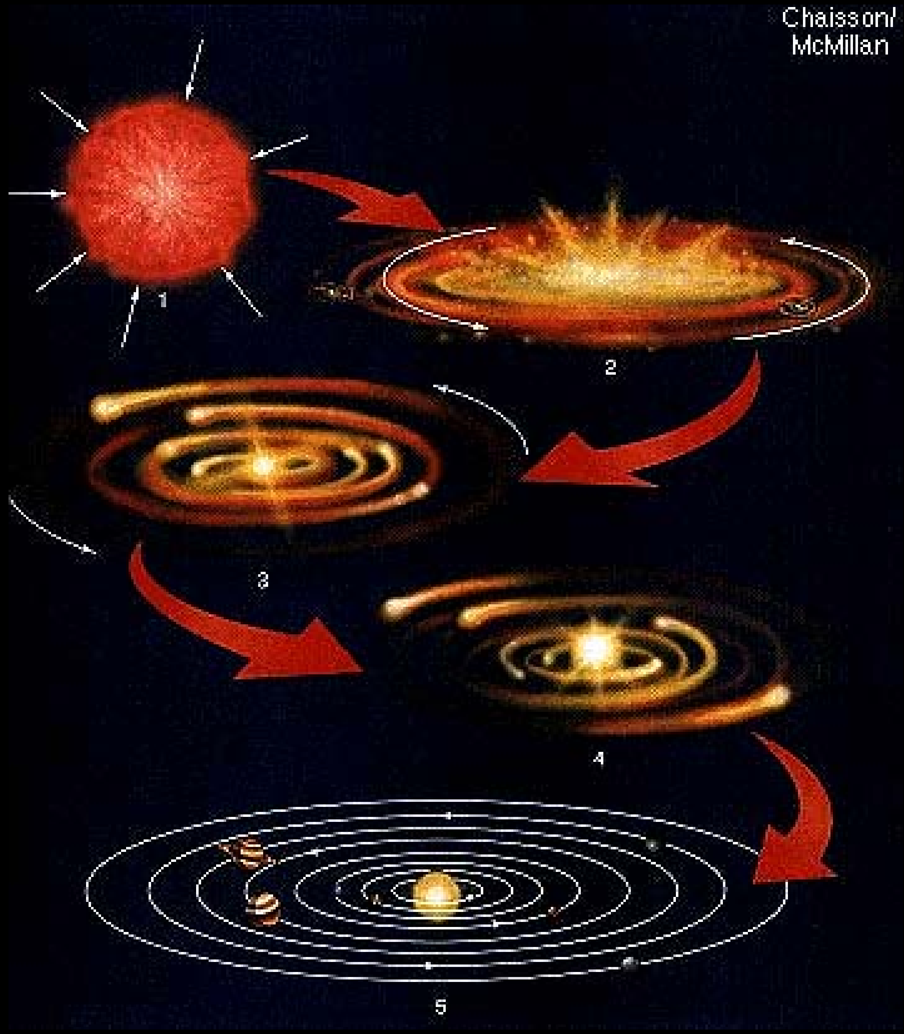
CRPG
Centre de Recherches Pétrographiques et Géochimiques



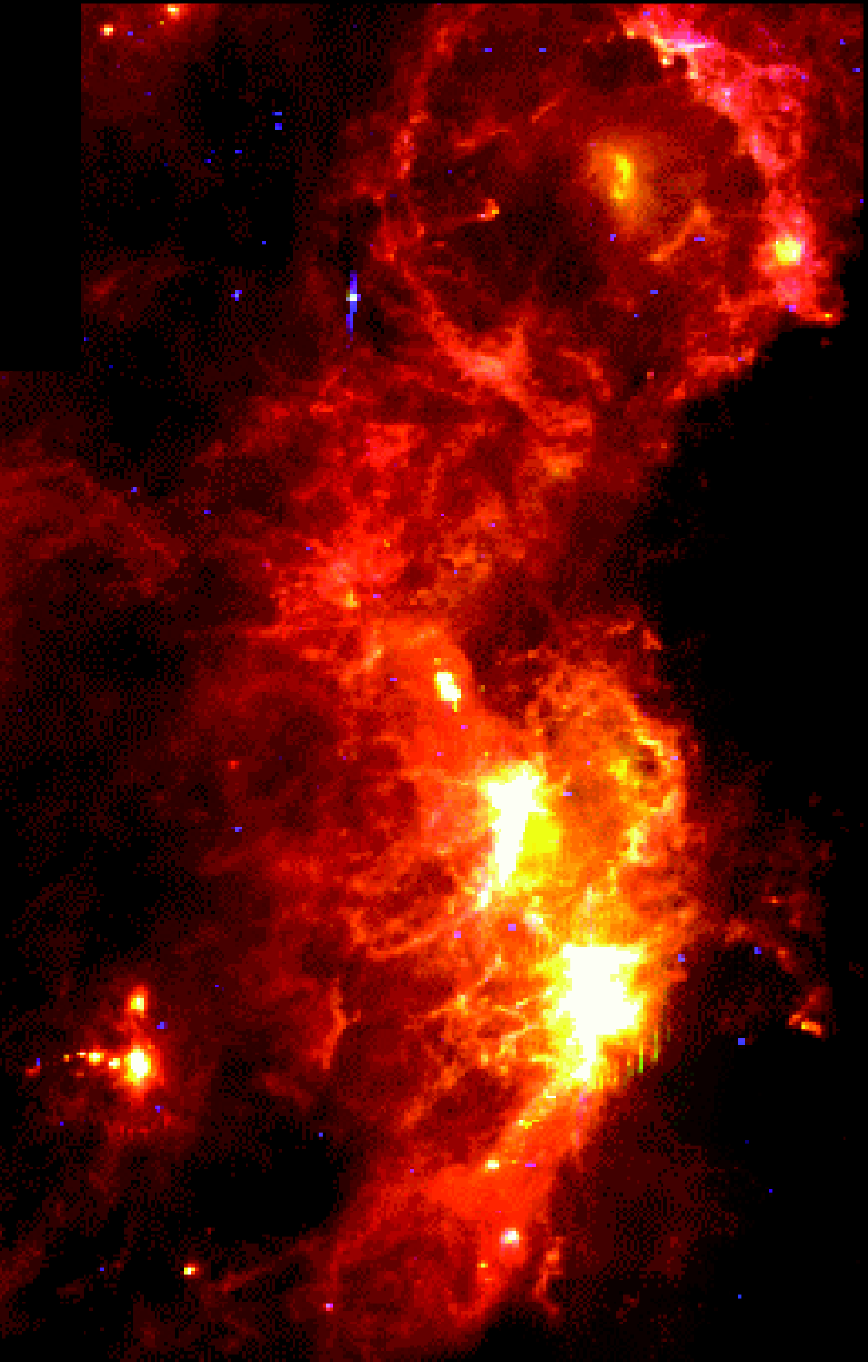
30 ans de missions spatiales de retours d'échantillons

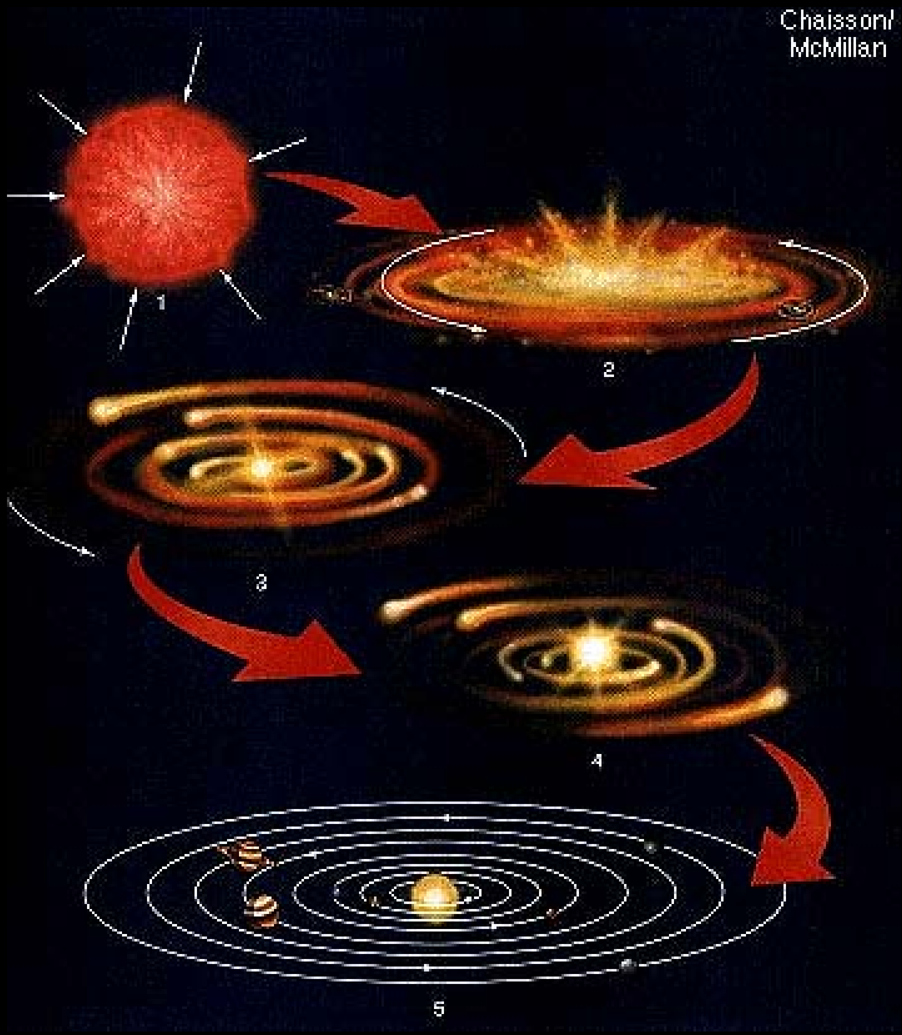
Bernard Marty
bmarty@crpg.cnrs-nancy.fr

Hubble Space Telescope Orion Treasury Project Team

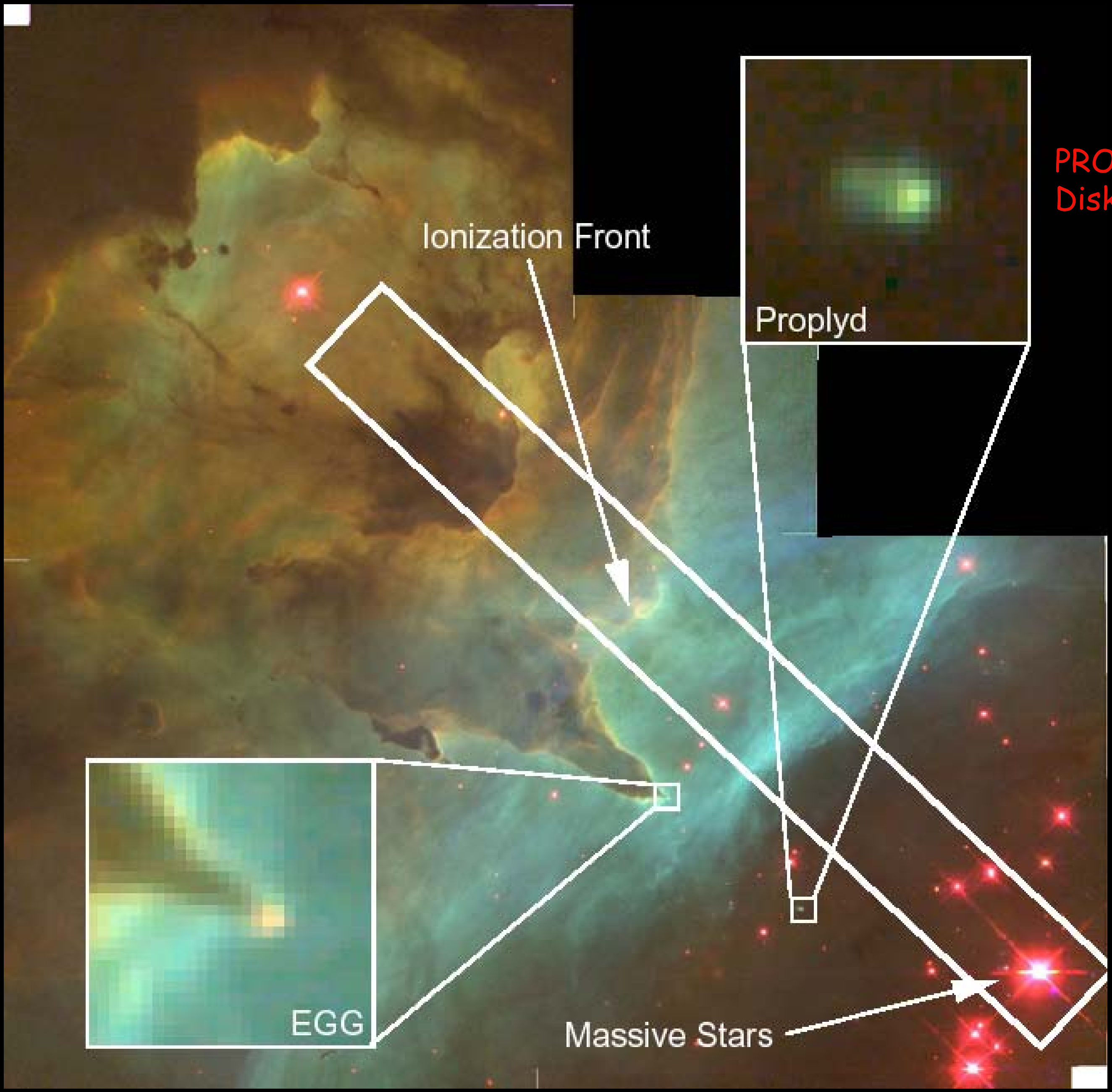


Chaisson/
McMillan





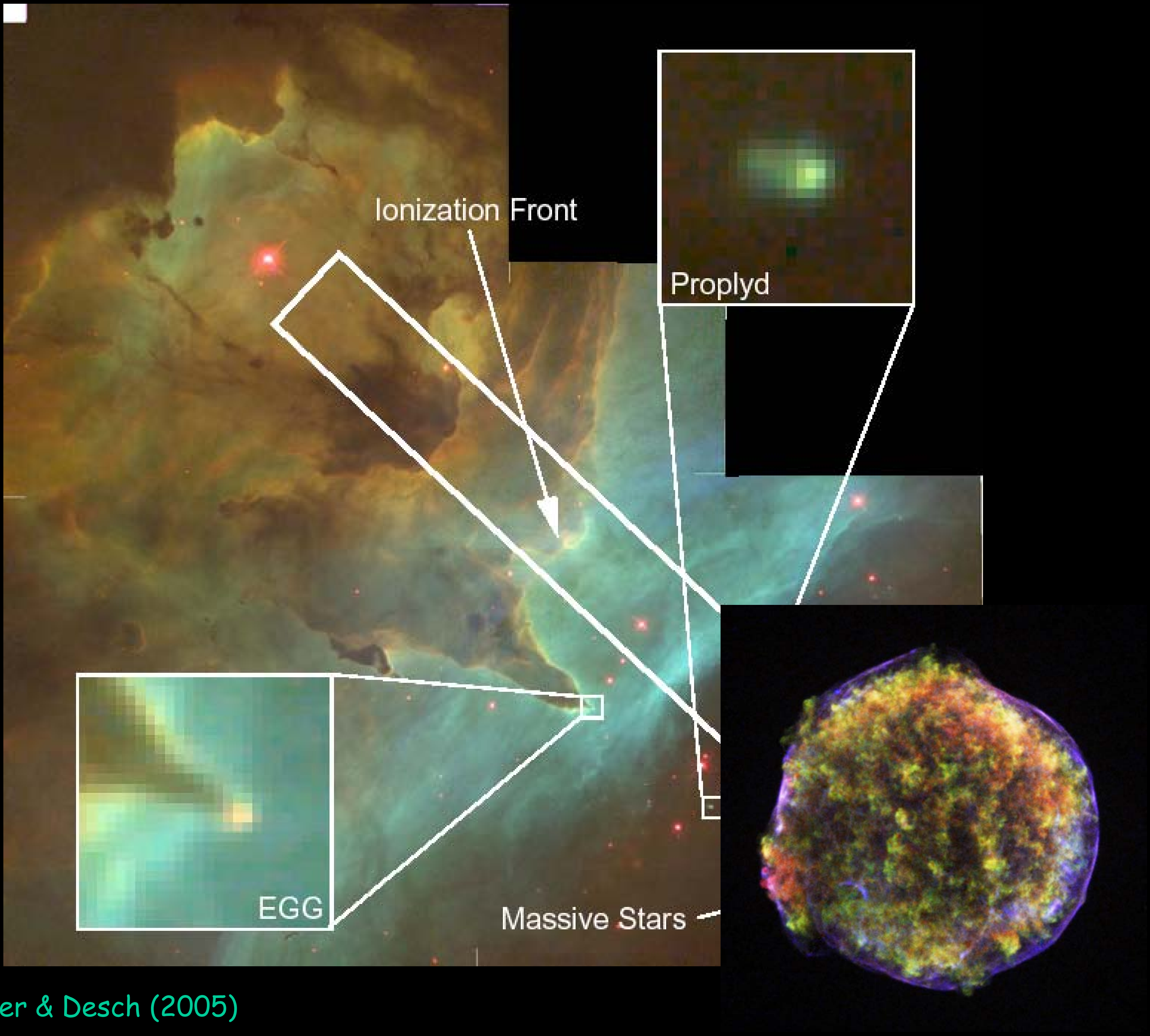
Orion



PROtoPLanetarY
Disk

Evaporative Gaseous Globule

NGC 6357, Hester & Desch (2005



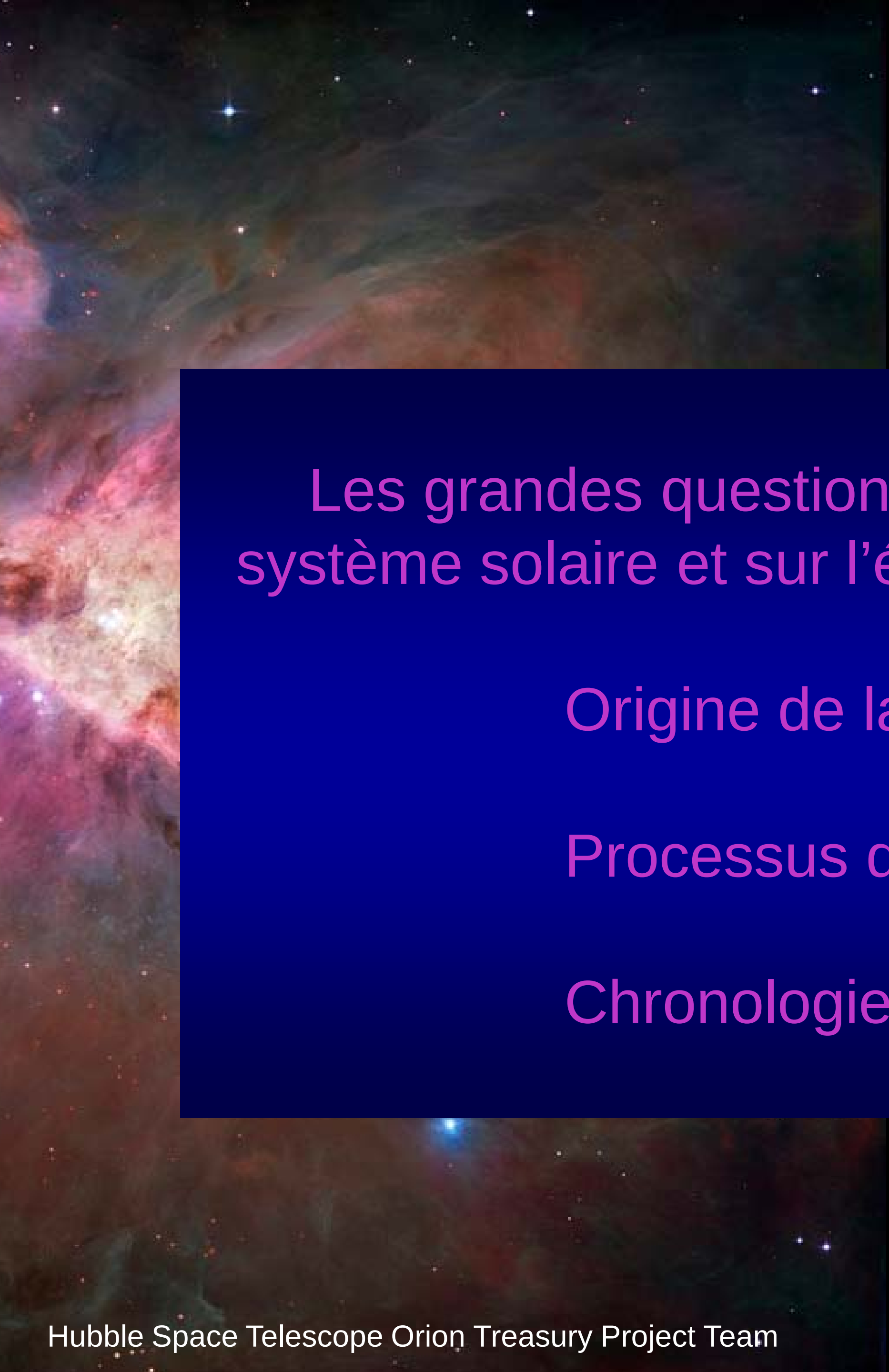
NGC 6357, Hester & Desch (2005)

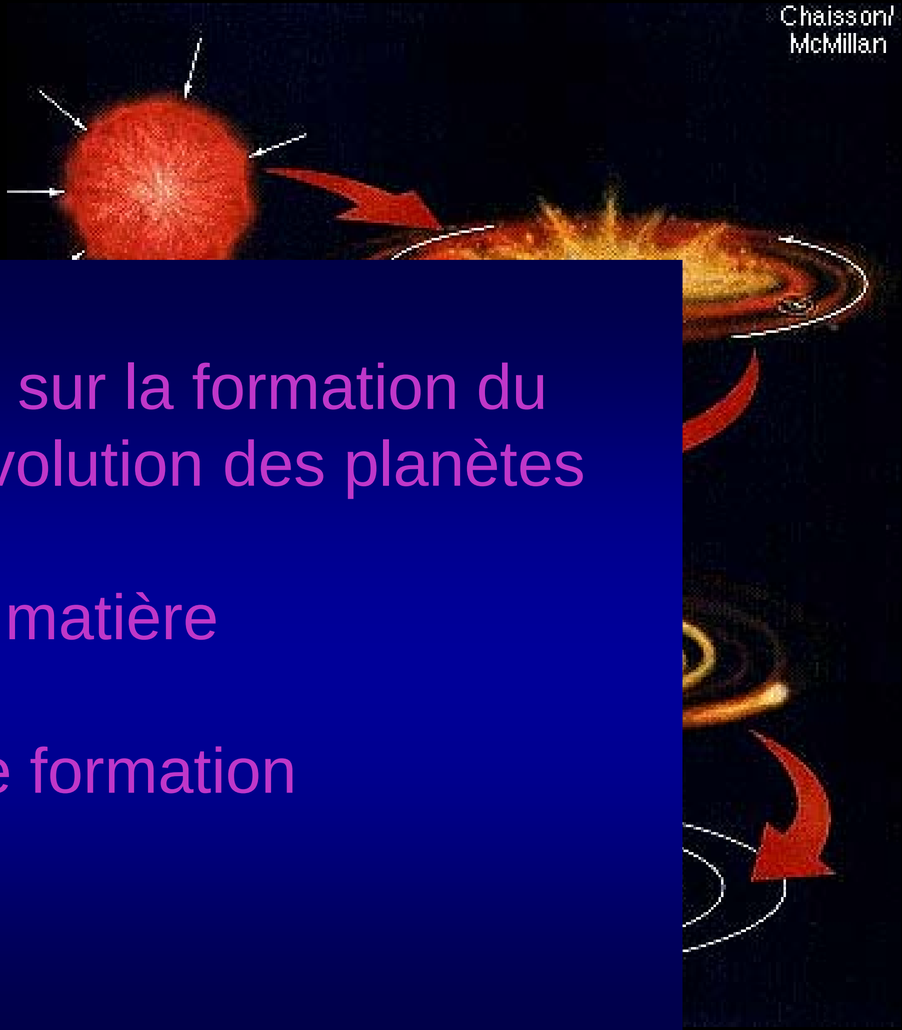
Les grandes questions sur la formation du système solaire et sur l’évolution des planètes

Origine de la matière

Processus de formation

Chronologie


Hubble Space Telescope Orion Treasury Project Team

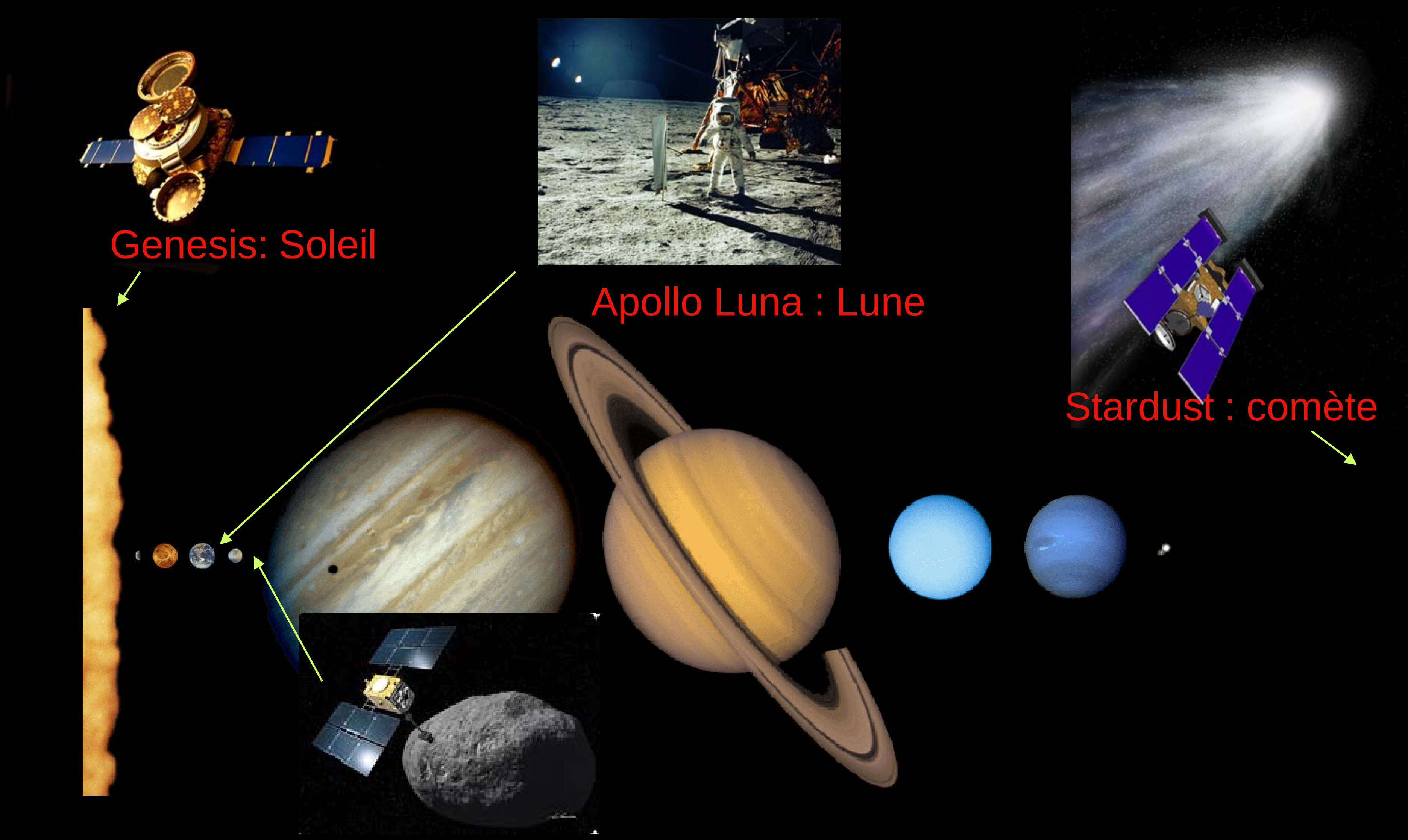

Chaisson/ McMillan

Sonde ionique

ICP-MS

TIMS

Mars Science Laboratory, un robot qui analyse la surface de Mars



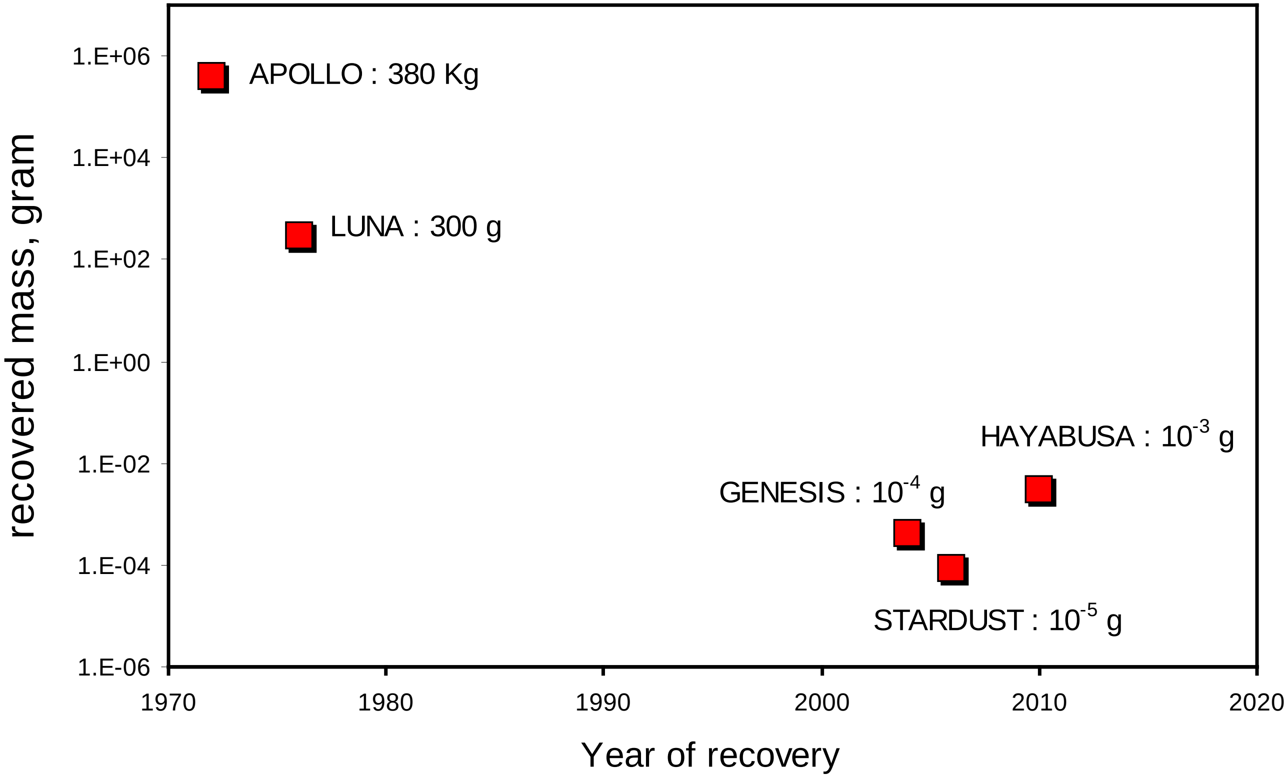
Genesis: Soleil

Apollo Luna : Lune

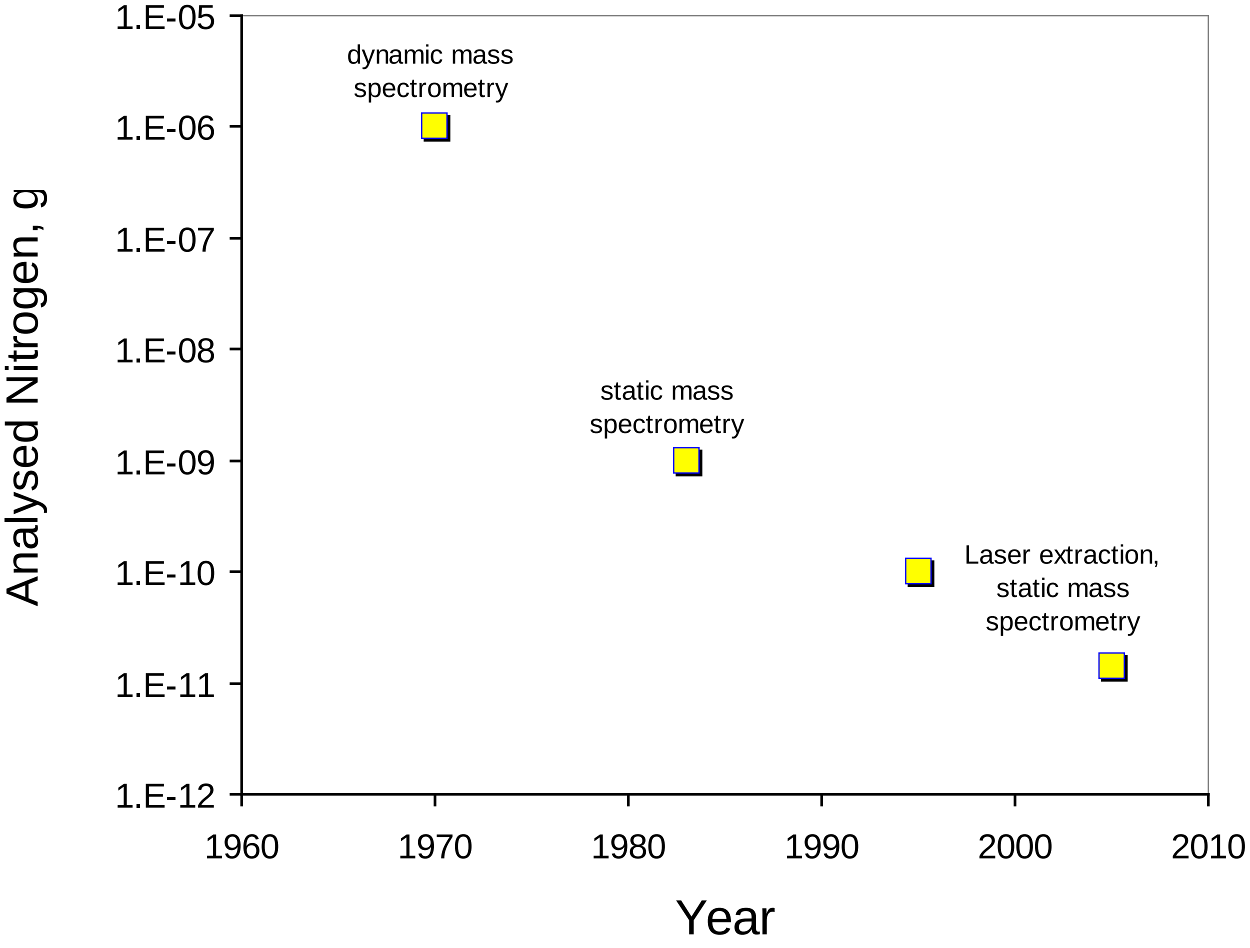
Stardust : comète

Hayabusa : astéroïde

Quantité d'échantillons ET ramenées par les missions spatiales



Quantité d'azote nécessaire pour effectuer une analyse isotopique au niveau du pour mille



Composition du système solaire lointain : Stardust

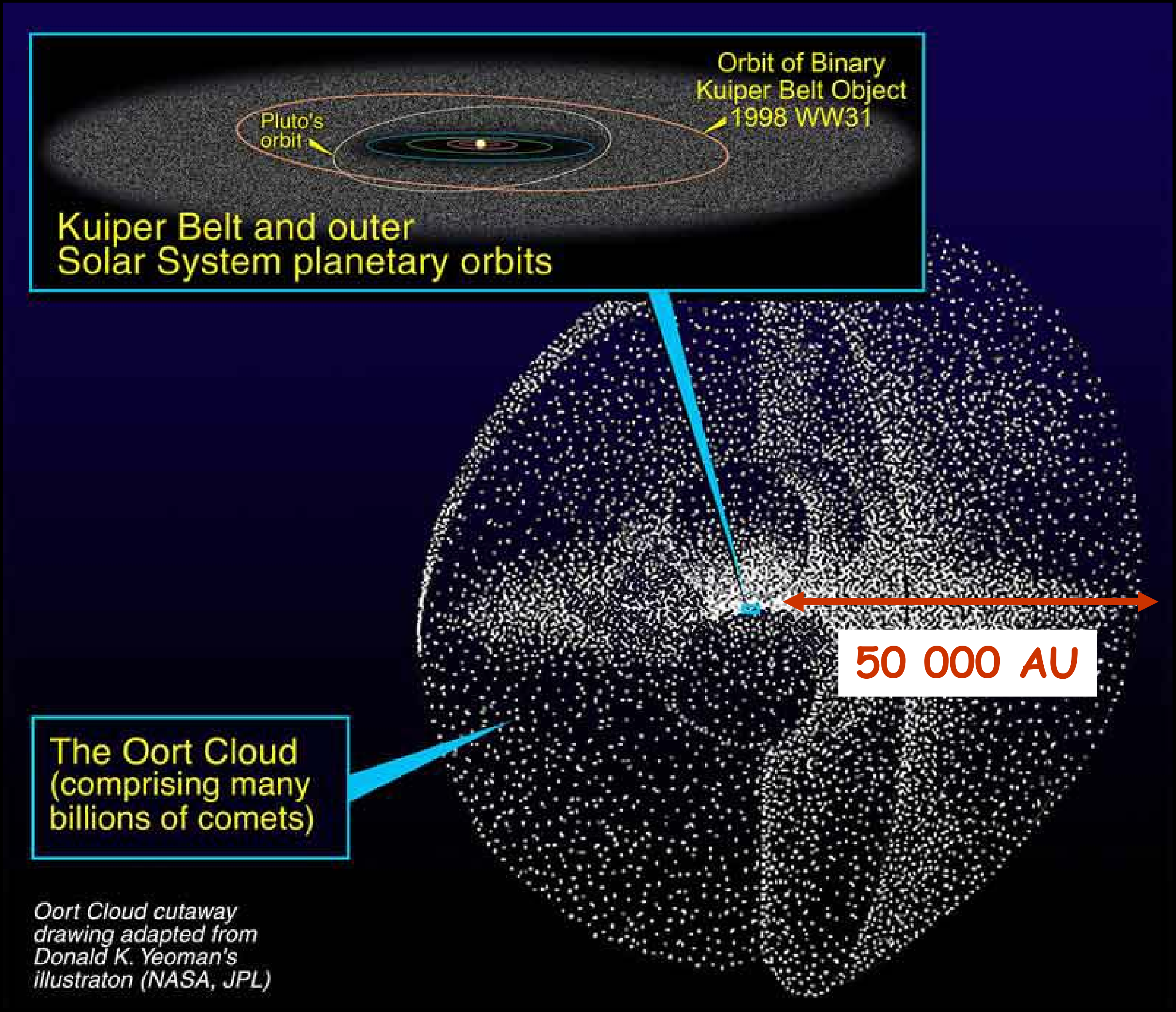
NASA Program *Discovery*
PI : Don Brownlee

Questions

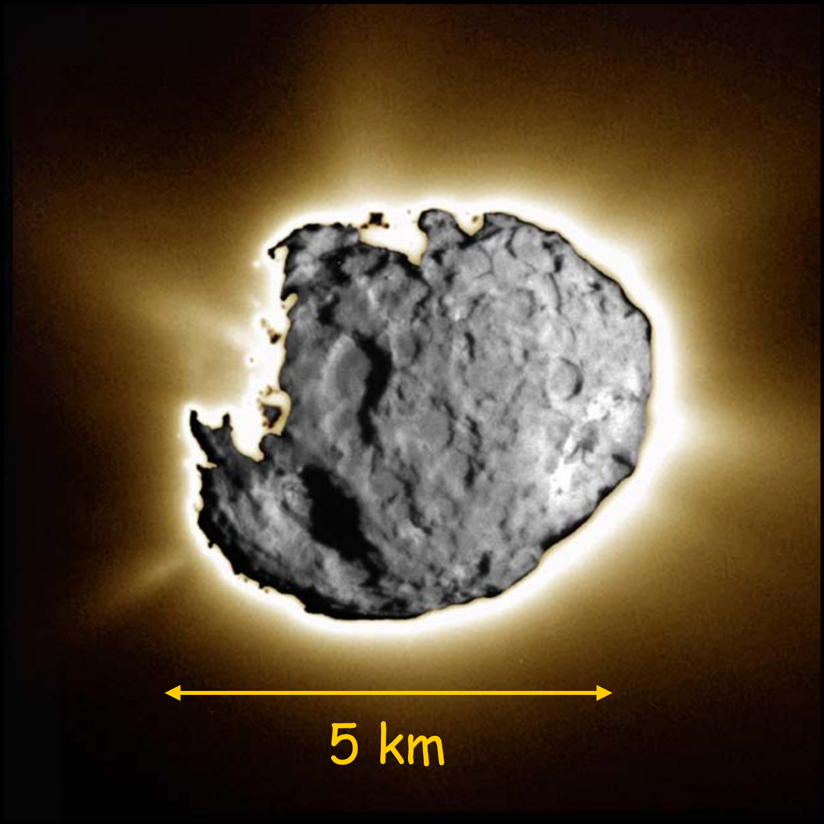
Matière cométaire solaire ou interstellaire ?

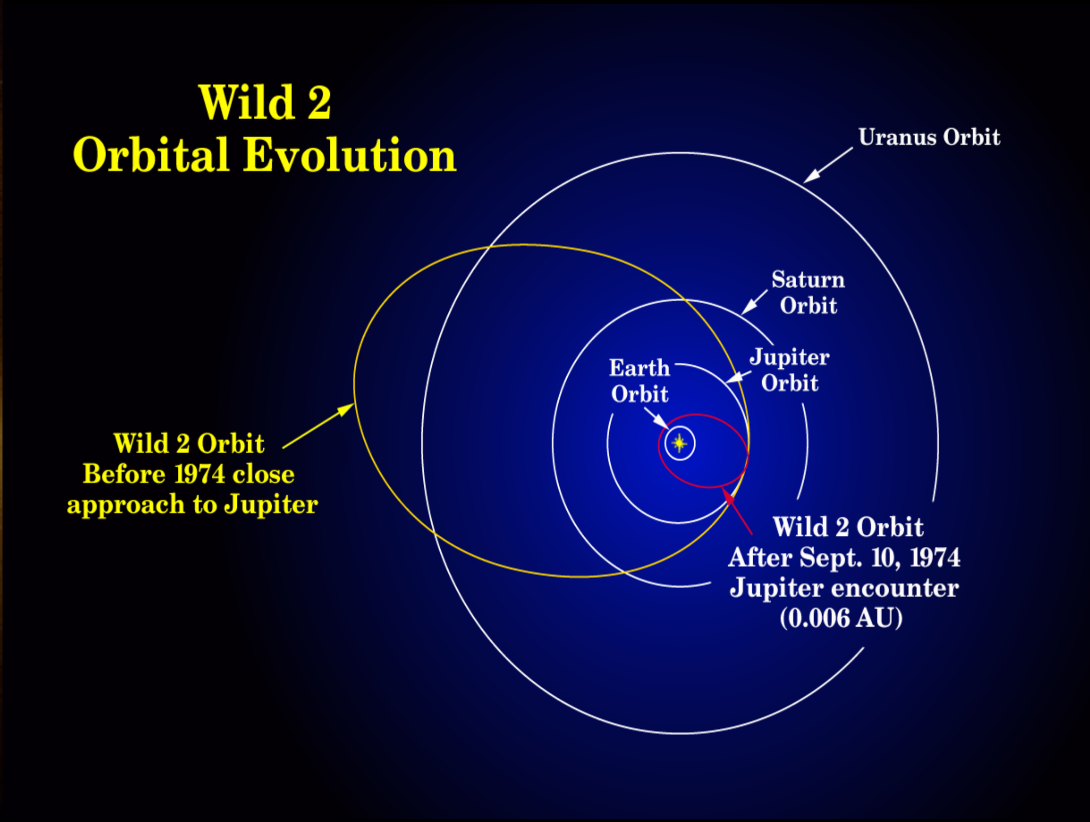
Avons nous déjà des échantillons de comète sur Terre (ex : Interplanetary Dust particles -IDPs) ?

Relation entre comètes et atmosphères ?



Oort Cloud cutaway drawing adapted from Donald K. Yeoman's illustraton (NASA, JPL)



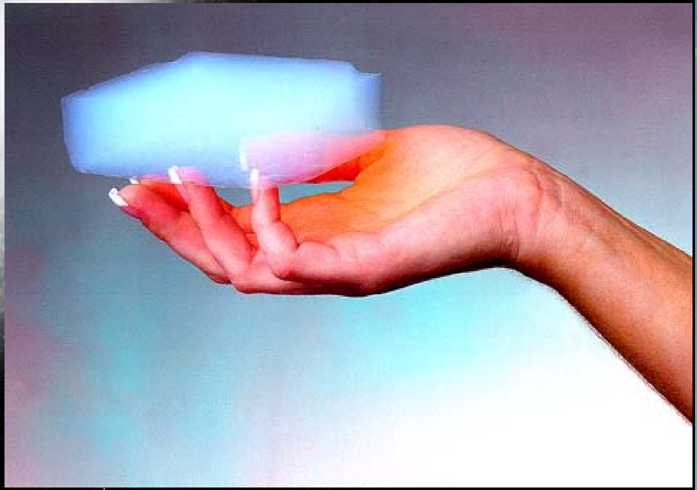


Comète « fraîche » dans son orbite actuelle depuis seulement 30 ans

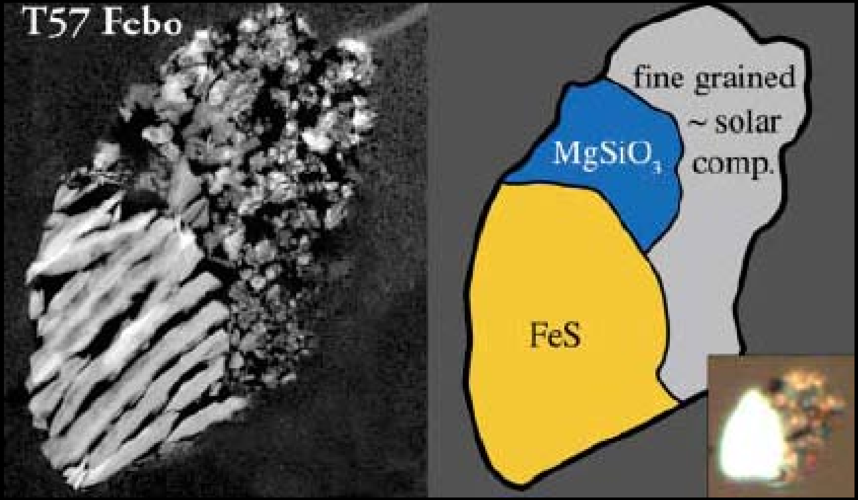
Proche de la Terre

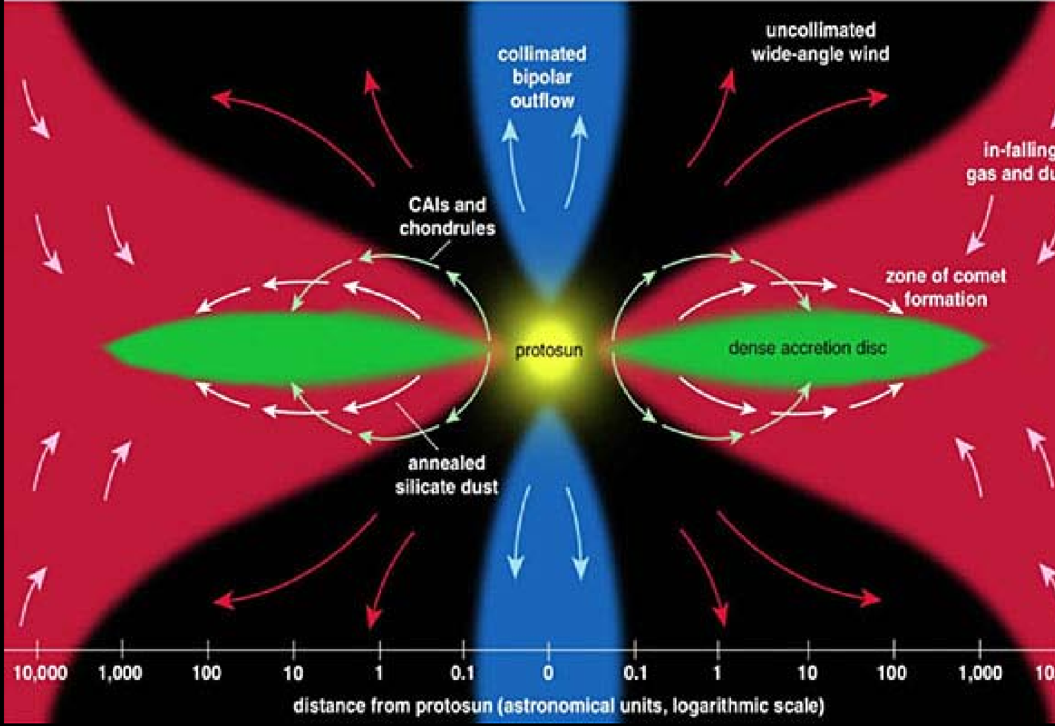
Stardust : Echantillonnage et retour sur Terre le 15 Janvier 2006

Les grains de la coma ont été piégés dans de l’aérogel à une vitesse de 6.1 km/s



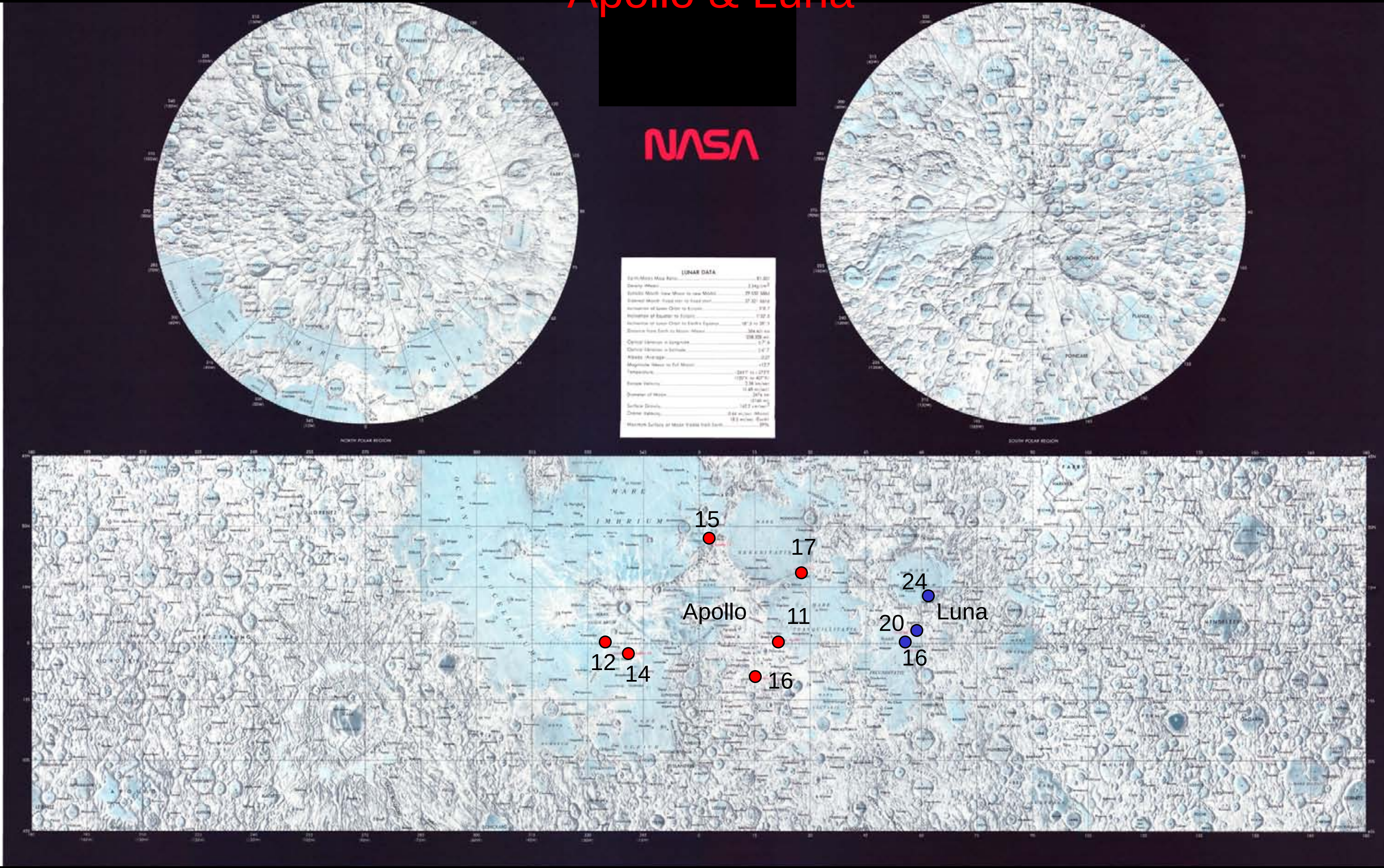
La composition des grains de Stardust ressemble fortement à celle typique des météorites primitives – présence de phases réfractaires dont CAI, compositions isotopiques dans la même gamme : conforte les modèles de mélange de la matière à très grande échelle dans le système solaire naissant





Mélange de phases haute température et de glaces

Apollo & Luna



Apollo

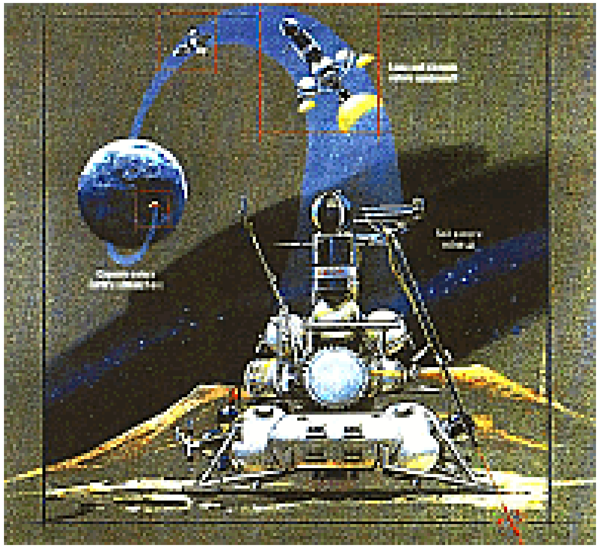
A one-kilogram (2.2 lb) Apollo 16 breccia rock formed from meteorite impact. Shiny, black, impact-generated glass was splashed on the side.

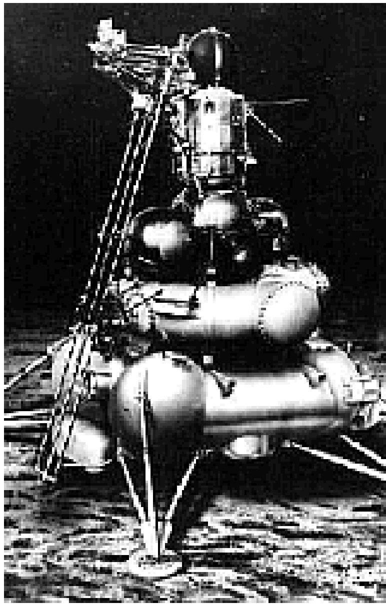
- Entre 1969 et 1972, six missions Apollo ont ramené sur Terre 382 Kg de roches, carottages, sables et poussières de la surface lunaire

- 2200 échantillons sont conservés dans un bâtiment spécial du Johnson Space Center

Luna

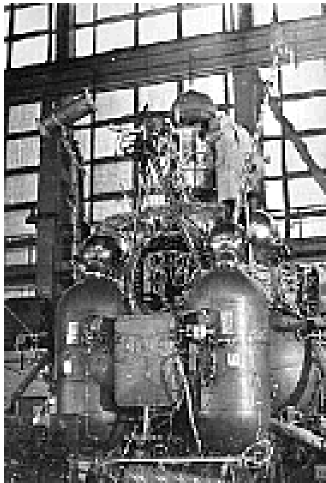
1970-1976

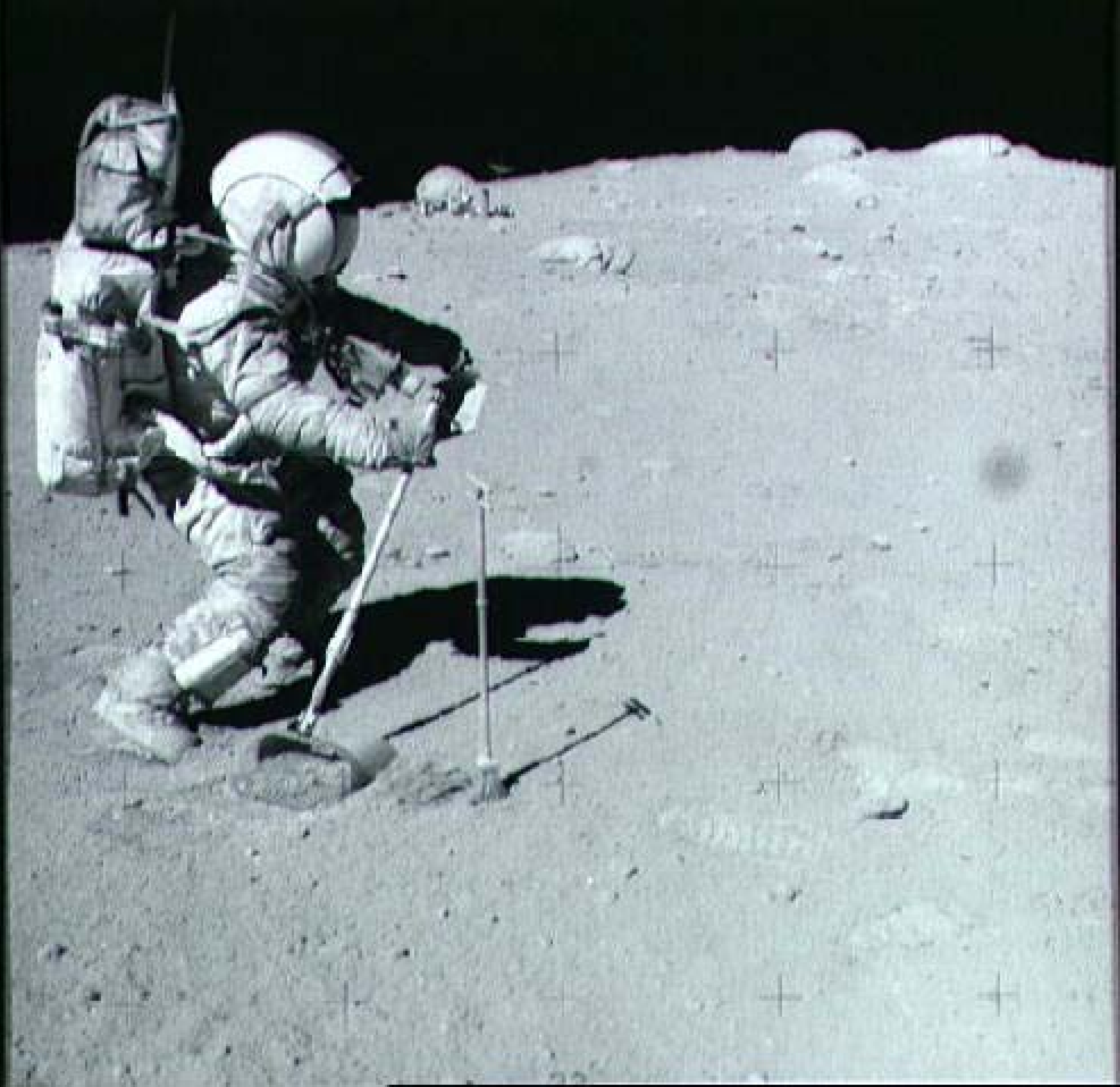




- 3 missions automatiques (Luna 16, 20 and 24) ont ramené 300 g de sols et brêches lunaires, notamment lors de carottages

- Les échantillons sont conservés à l’Institut Verdnasky à Moscou





Top Ten Scientific Discoveries Made During Apollo-Luna Exploration of the Moon

1. The Moon is not a primordial object; it is an evolved terrestrial planet with internal zoning

2. The Moon is ancient and still preserves an early history (the first billion years) that must be common to all terrestrial planets.

3. The youngest Moon rocks are virtually as old as the oldest Earth rocks.

4. The Moon and Earth are genetically related and formed from different proportions of a common reservoir of materials - Oxygen isotopes

5. The Moon is lifeless; it contains no living organisms, fossils, or native organic compounds.

6. All Moon rocks originated through high-temperature processes with little or no involvement with water. Three types: basalts, anorthosites, and breccias.

7. Early in its history, the Moon was melted to great depths to form a "magma ocean." The lunar highlands contain the remnants of early, low density rocks that floated to the surface of the magma ocean.

8. The lunar magma ocean was followed by a series of huge asteroid impacts that created basins which were later filled by lava flows.

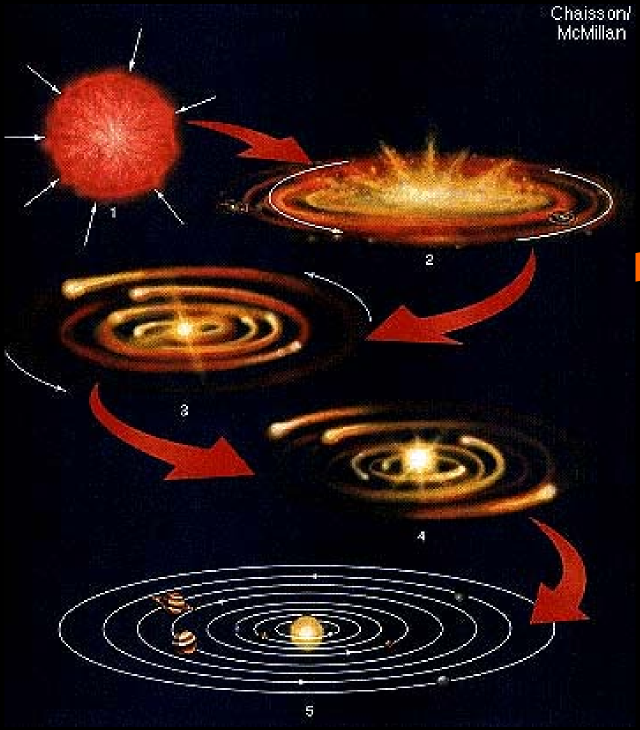
9. The Moon is asymmetrical, possibly as a consequence of its evolution under Earth's gravitational influence. Its crust is thicker on the far side, while most volcanic basins -- and unusual mass concentrations -- occur on the near side.

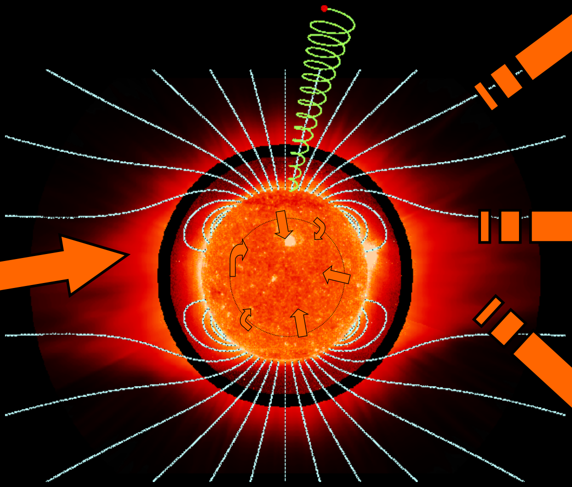
10. The surface of the Moon is covered by a rubble pile of rock fragments and dust, called the lunar regolith, that contains a unique radiation history of the Sun

GENESIS
SEARCH FOR ORIGINS

Priorités de la mission :

1- oxygène isotopique
2- azote isotopique
3 – Gaz rares

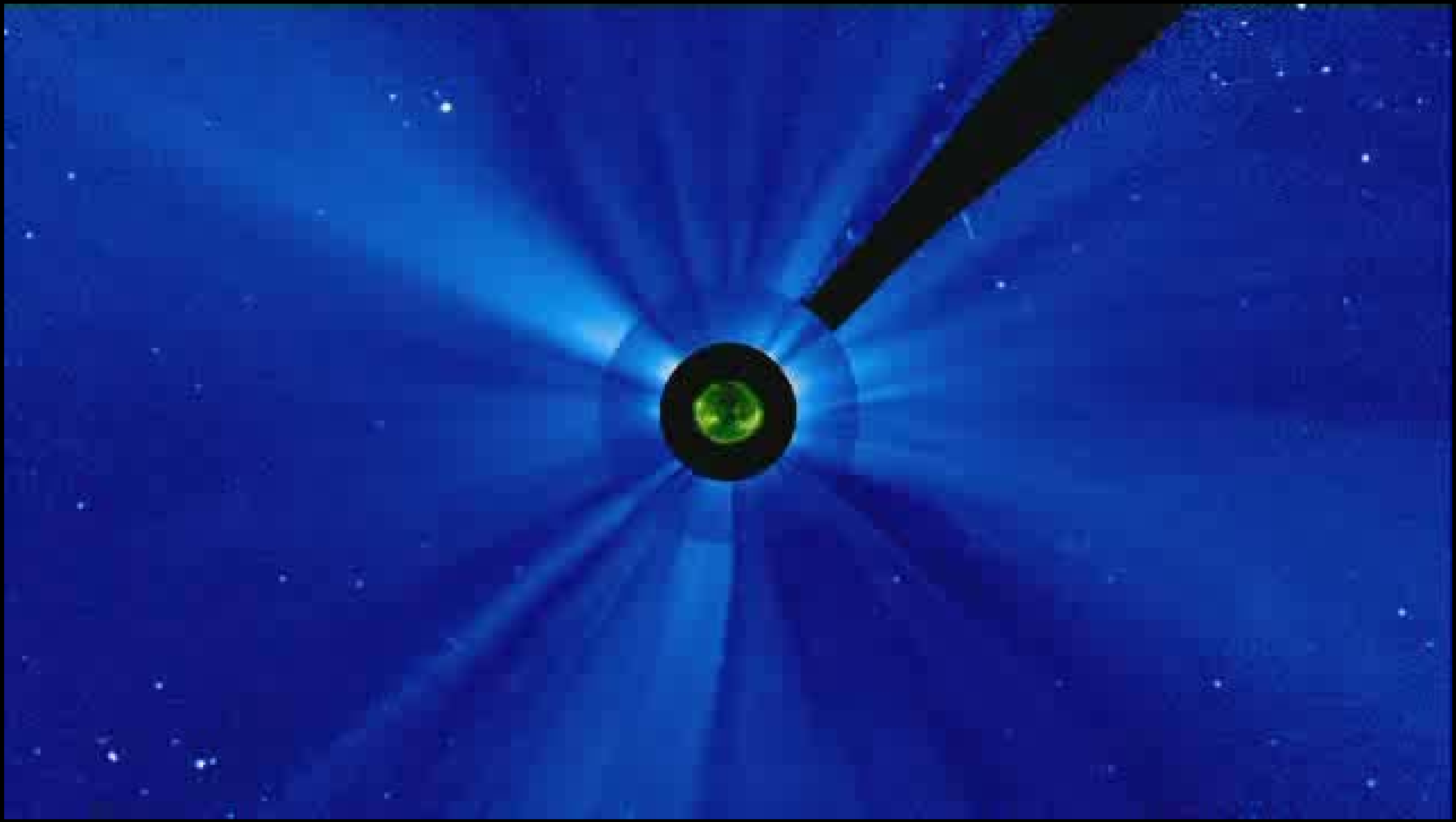




Soleil

Vent solaire

Vent solaire
&
flares solaires

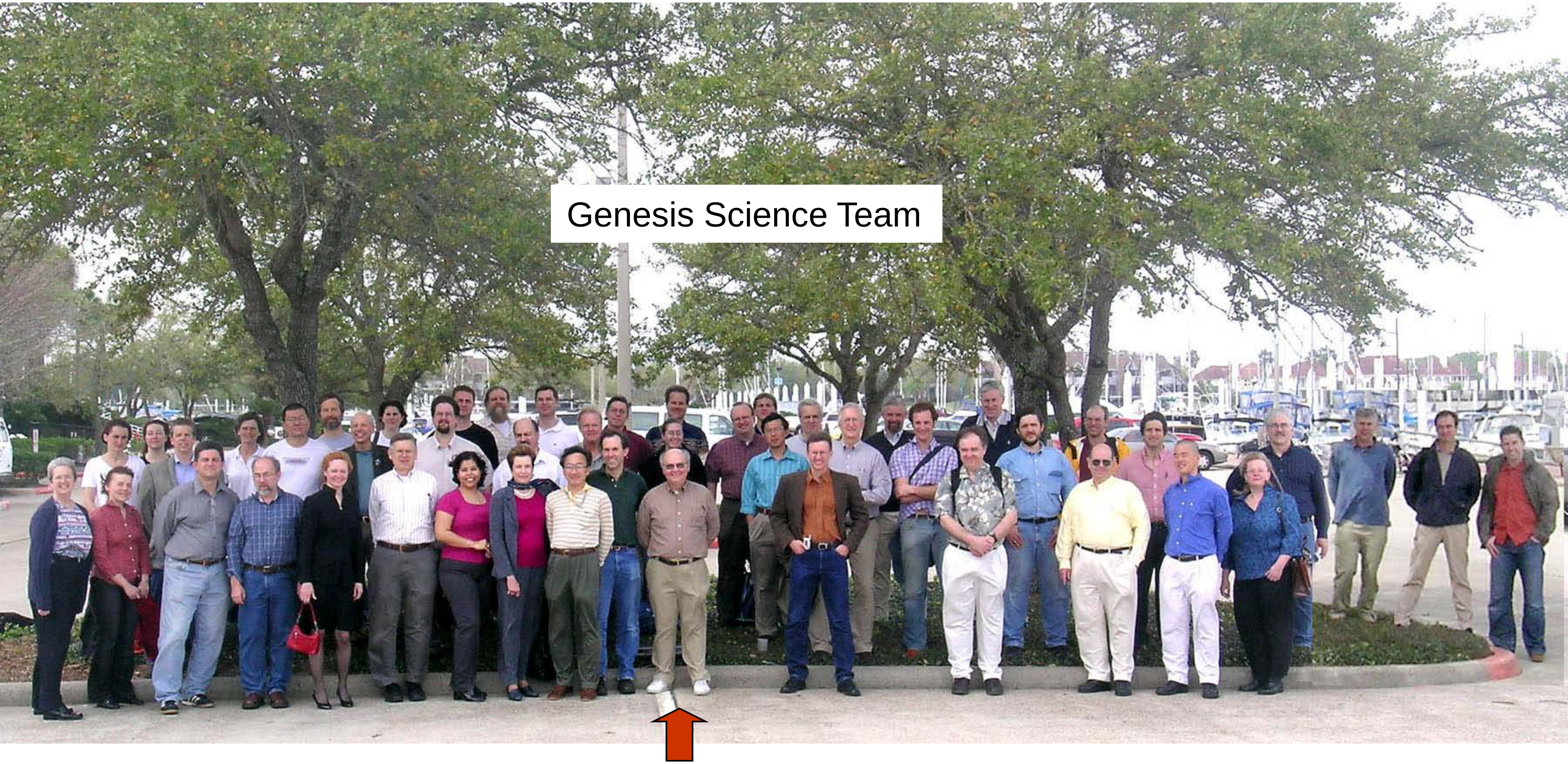


GENESIS
SEARCH FOR ORIGINS

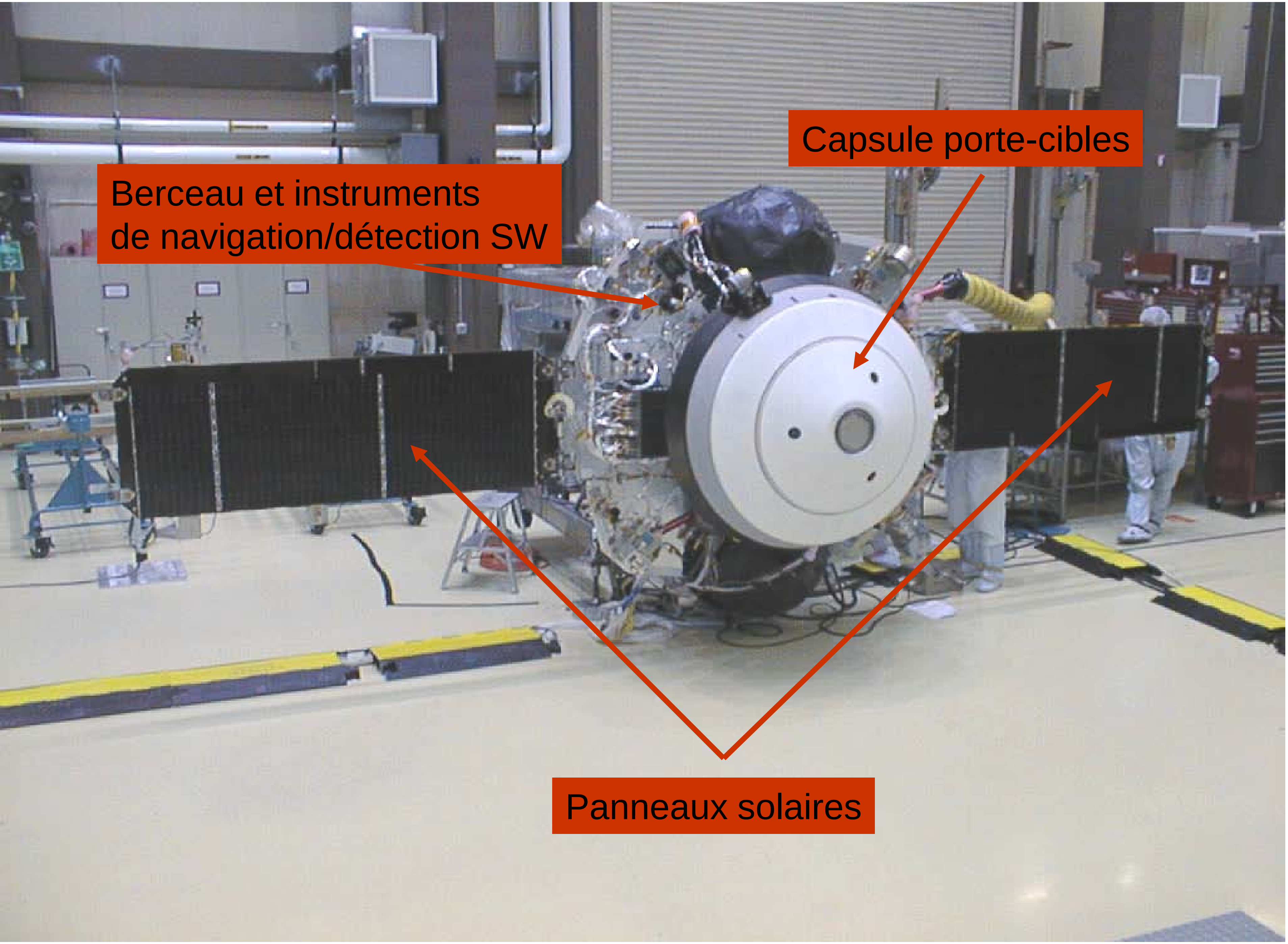
- Genesis a échantillonné pendant 3 ans 10^{20} ions du vent solaire (=0.4 milligrammes) à 1.5 millions de km de la Terre

- Premiers échantillons ET ramenés depuis 3 décades

NASA discovery program
260 millions $
1 gramme de matière solaire : 650 milliards de dollars


Genesis Science Team

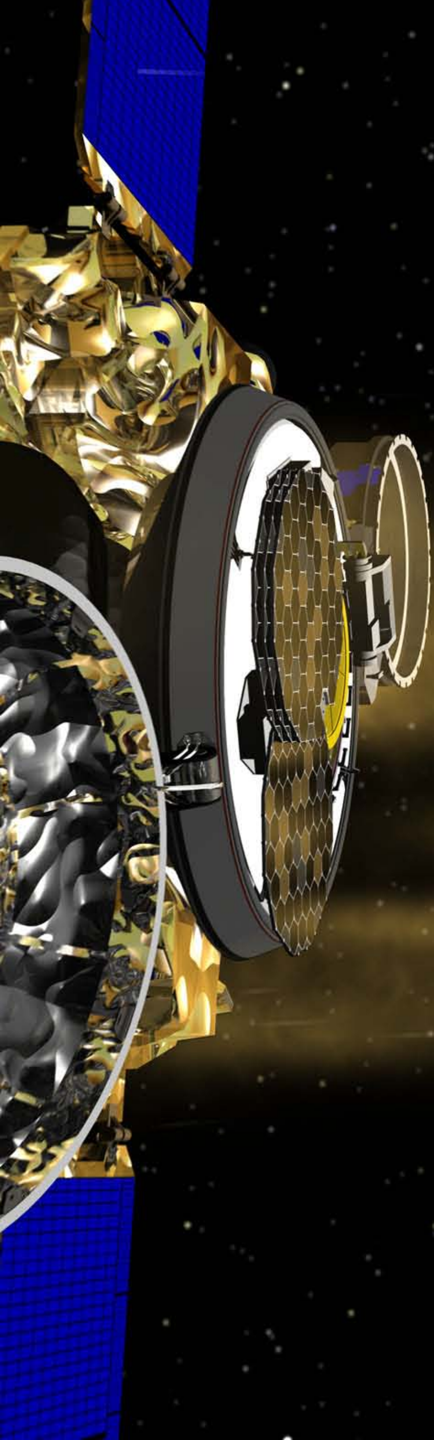
PI : Don Burnett, Caltech

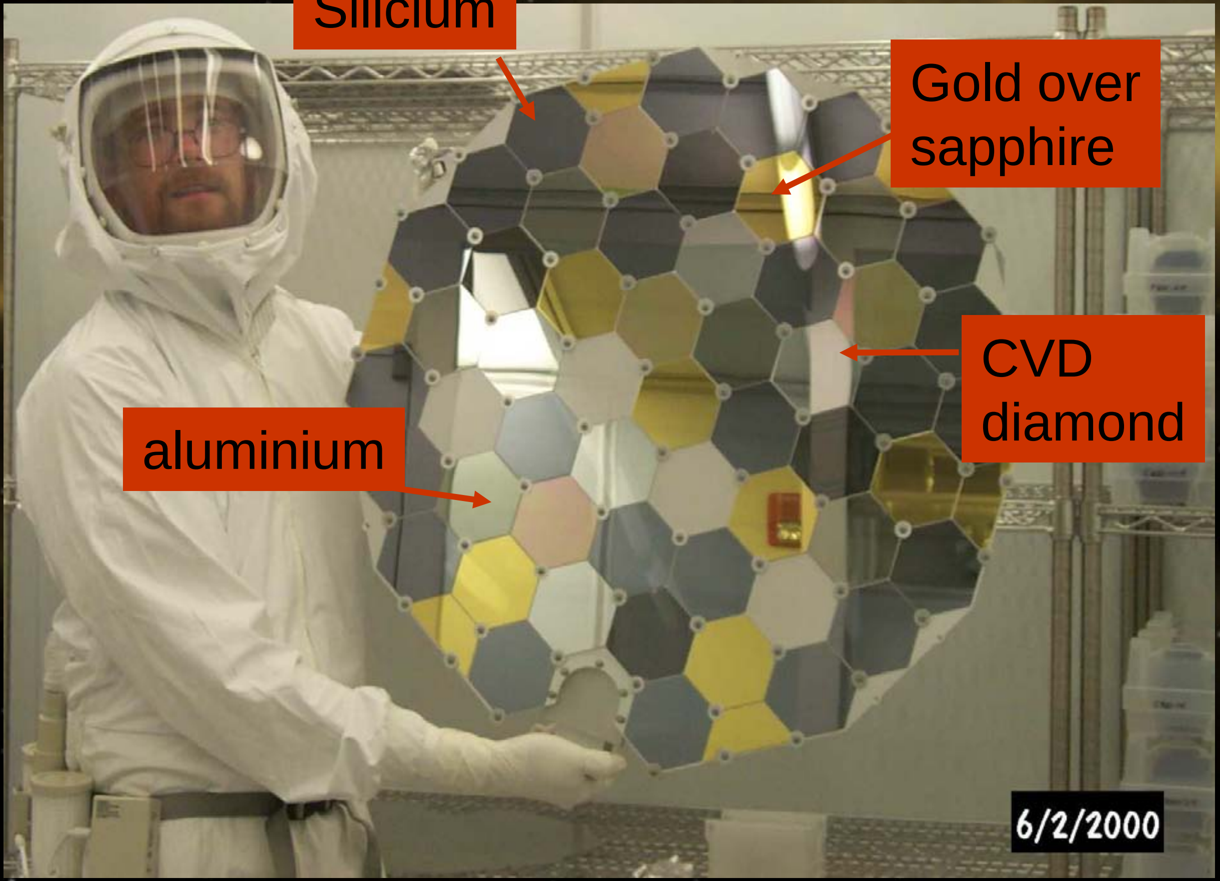


Capsule porte-cibles

Berceau et instruments de navigation/détection SW

Panneaux solaires





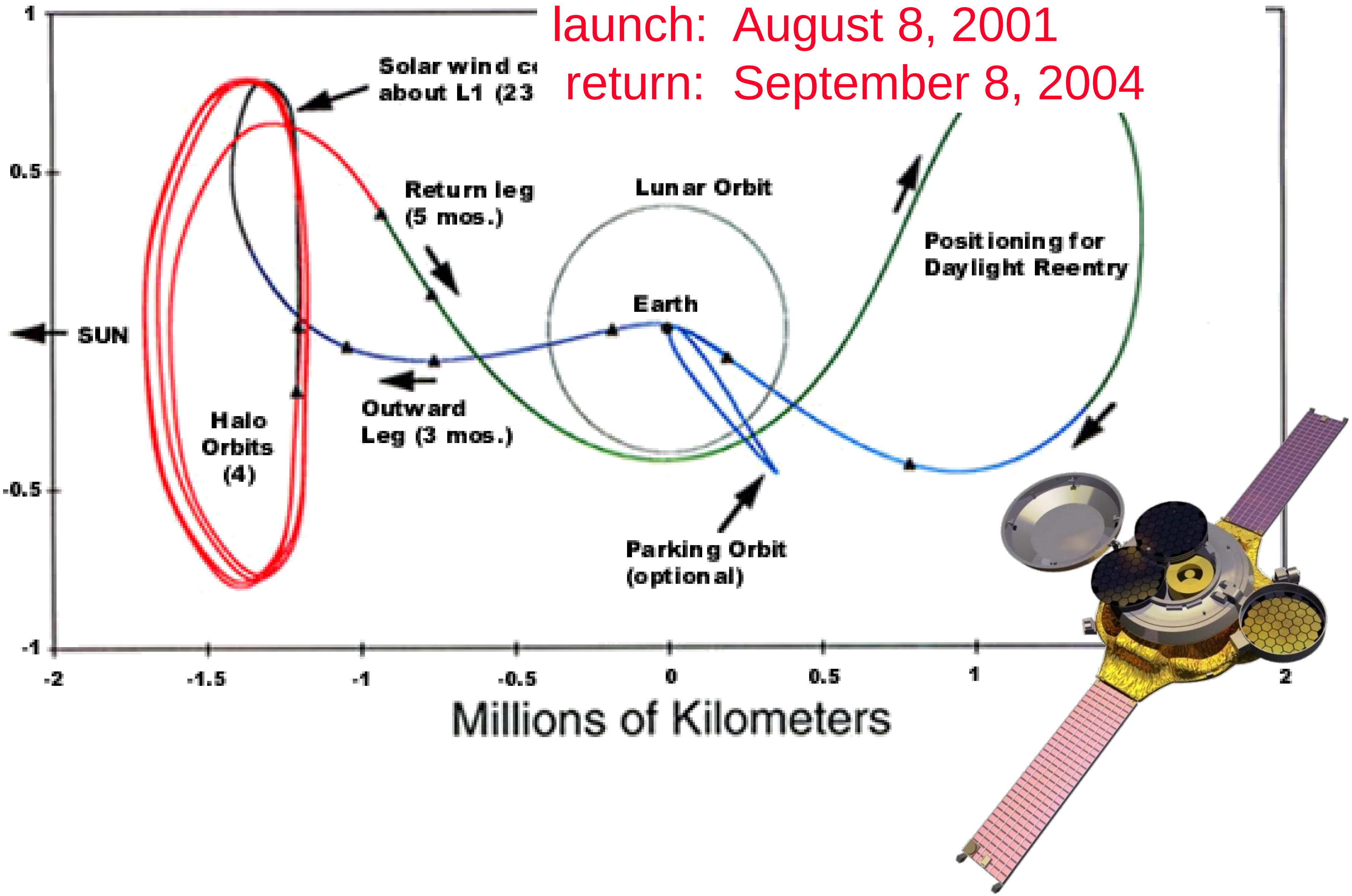
Silicium

Gold over sapphire

CVD diamond

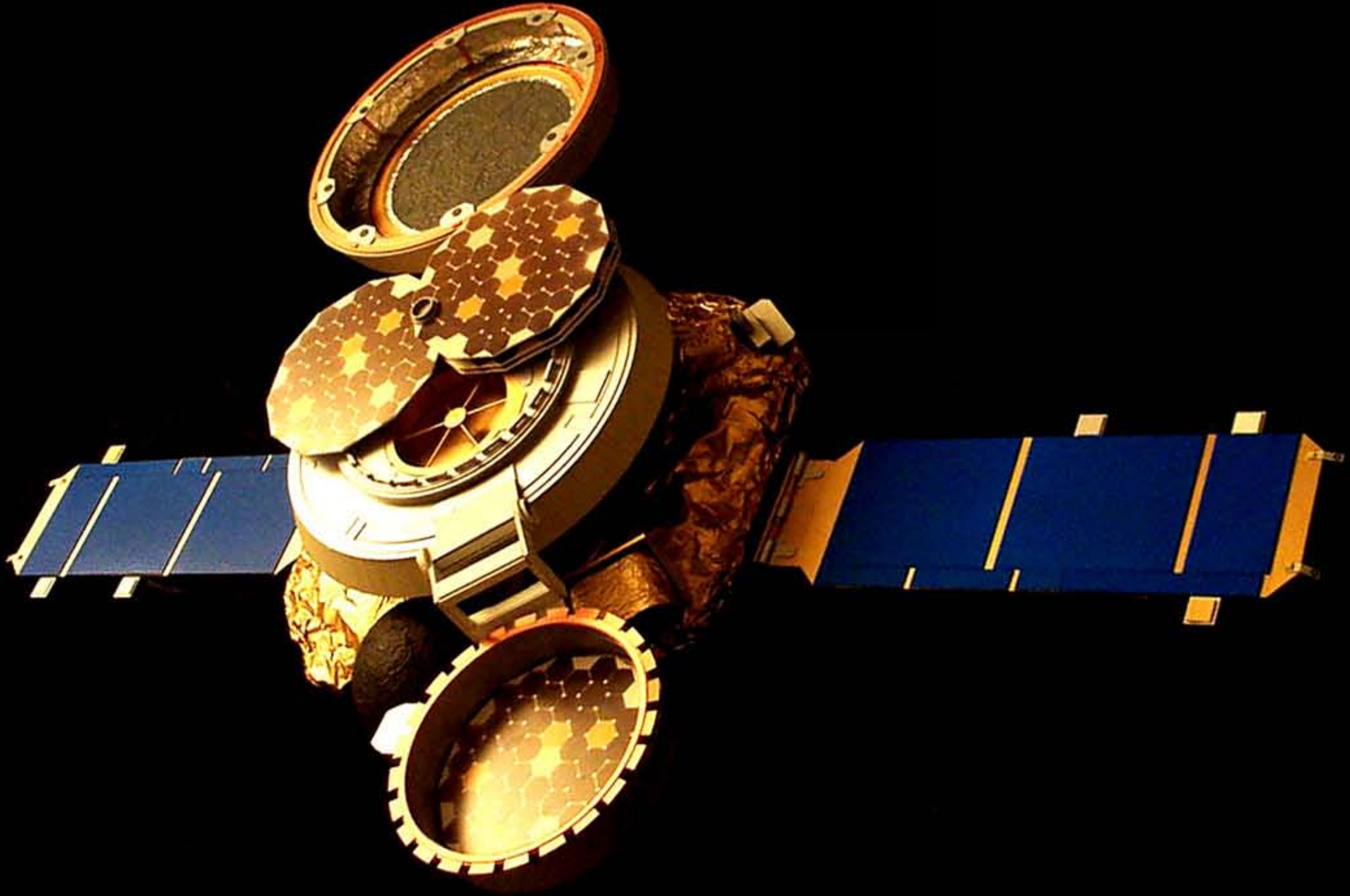
aluminium

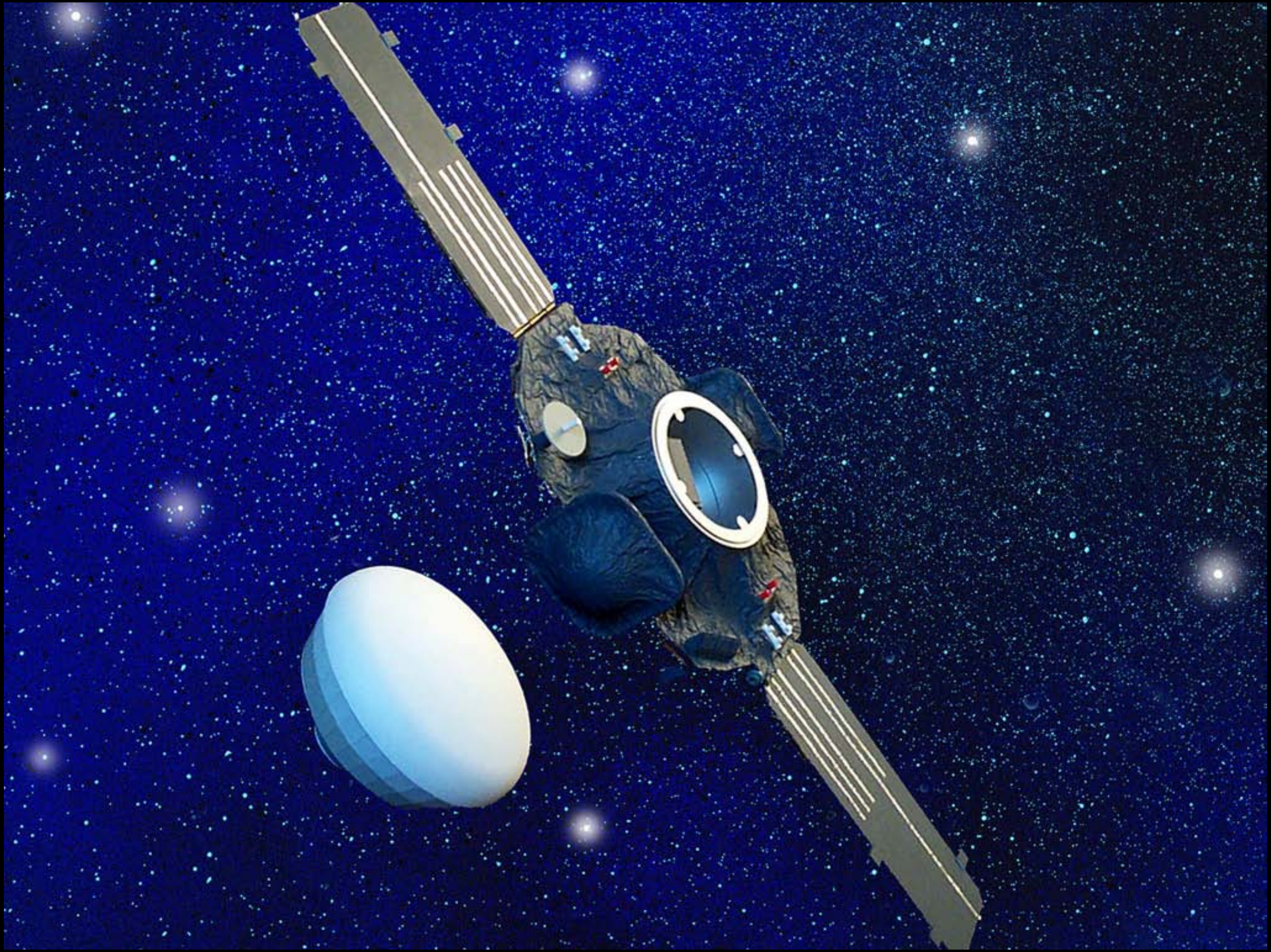
Genesis mission flight plan

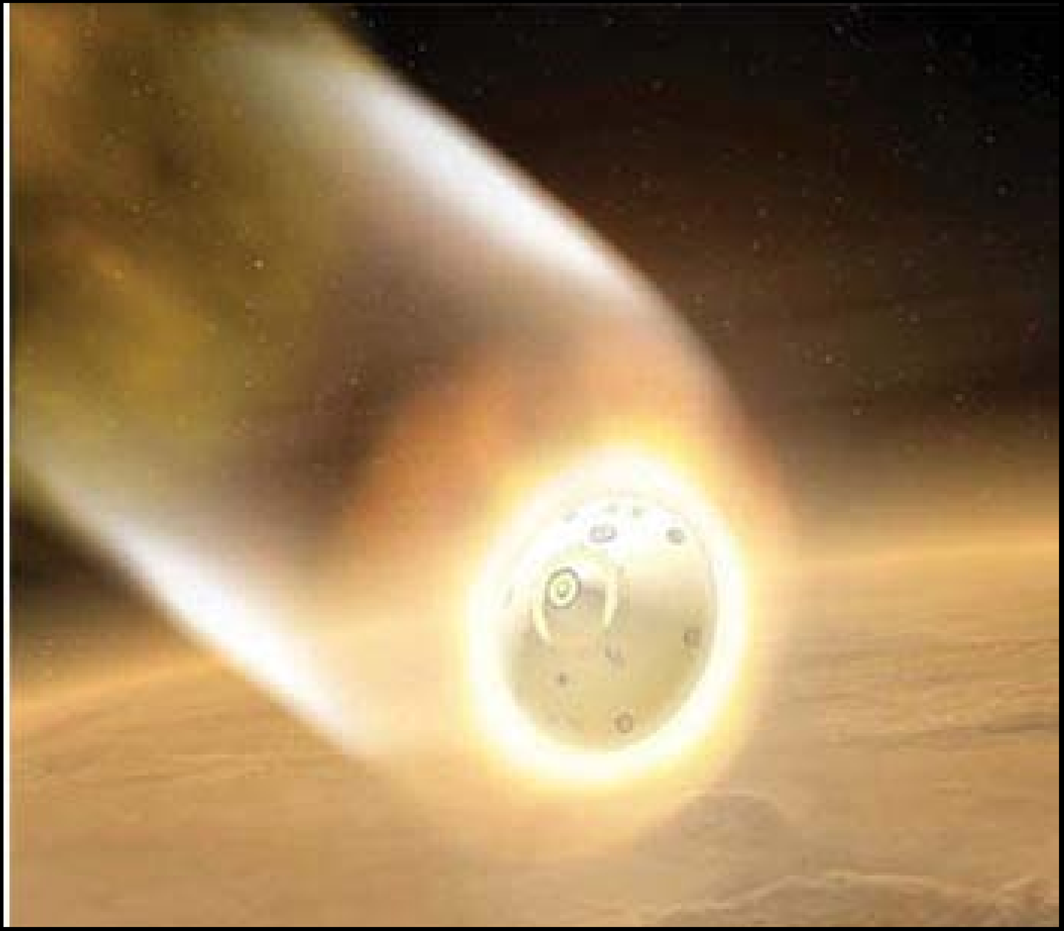


launch: August 8, 2001

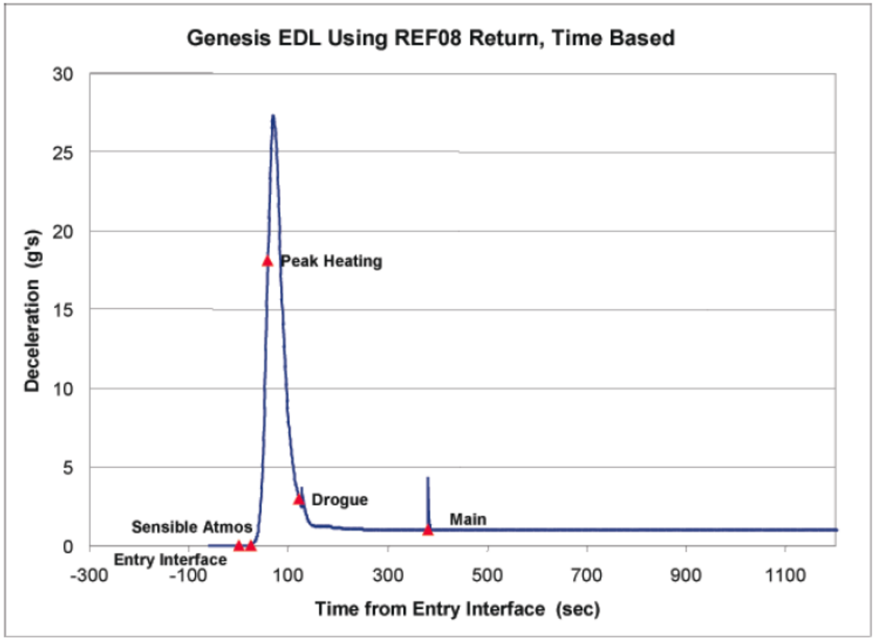
return: September 8, 2004

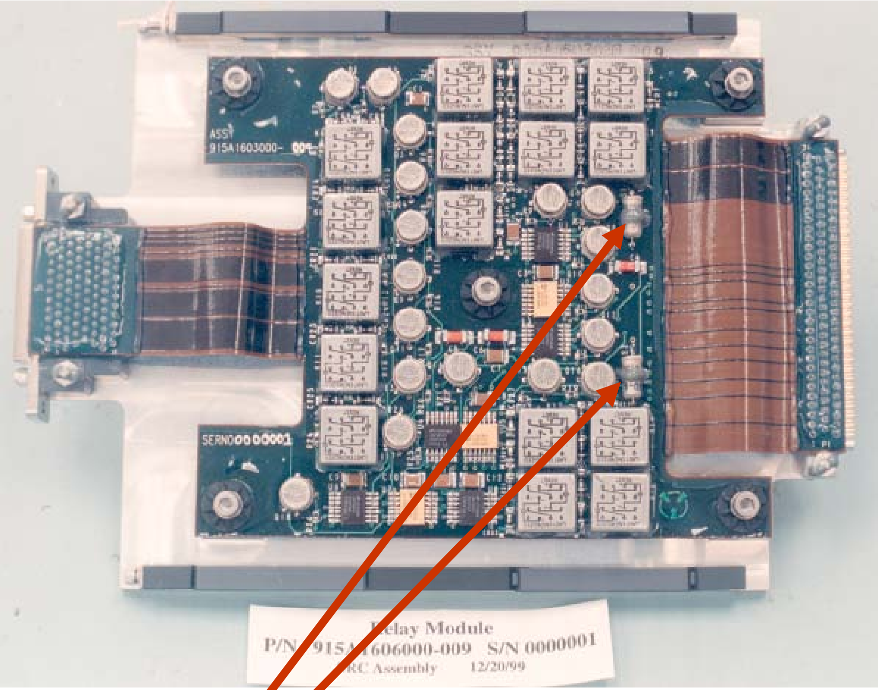


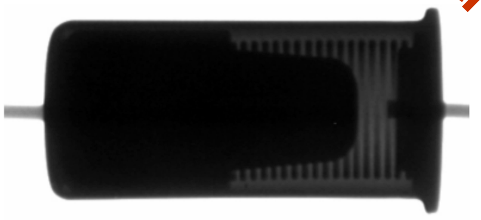


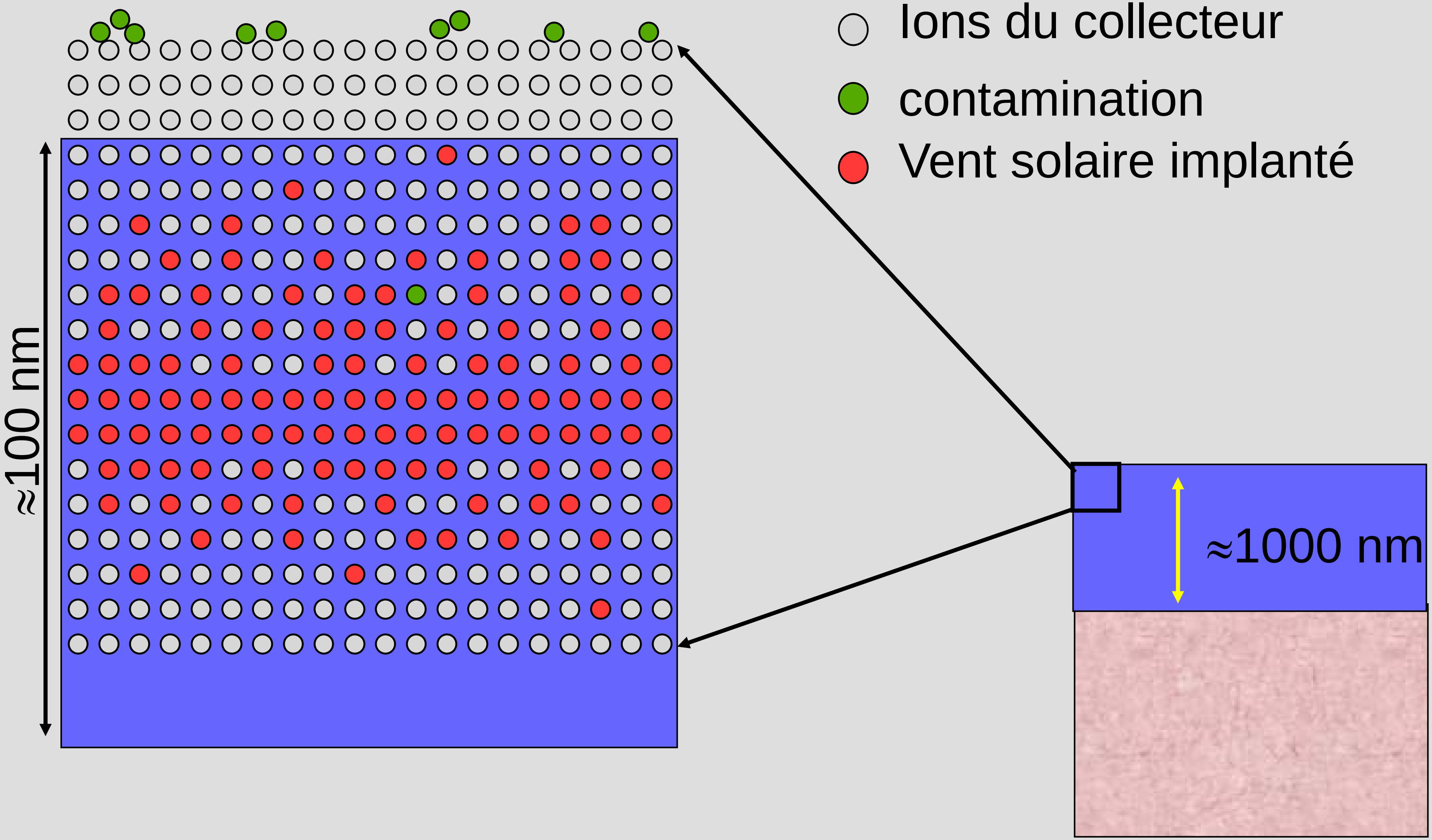


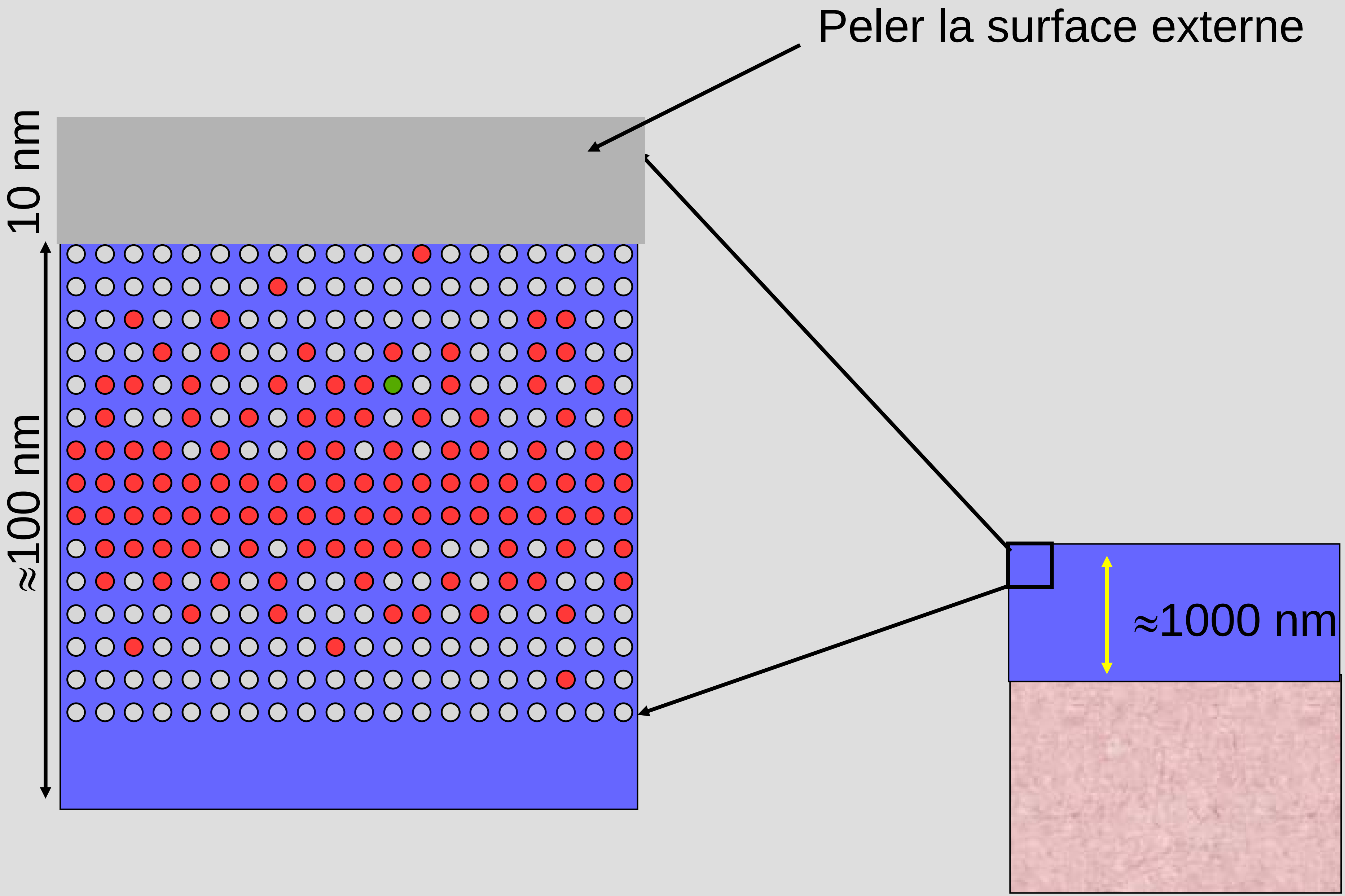
8 Septembre 2004

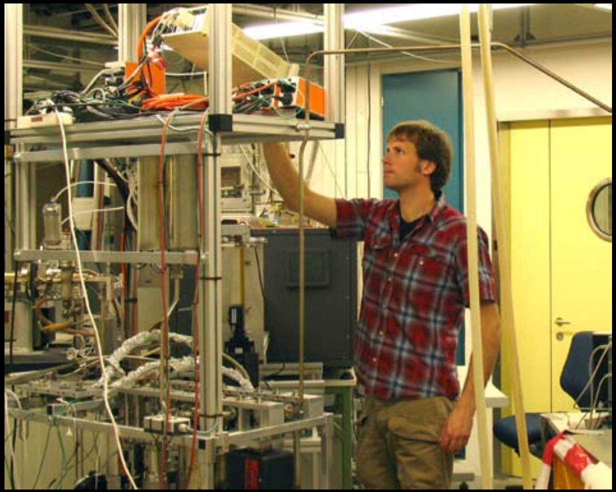

Genesis EDL Using REF08 Return, Time Based
Deceleration (g's)
30
25
20
15
10
5
0
-300
-100
100
300
500
700
900
1100
Time from Entry Interface (sec)
Peak Heating
Drogue
Main
Sensible Atmos
Entry Interface


ASSY
915A1603000-
SERNO0000001
Relay Module
P/N 915A1606000-009 S/N 0000001
RC Assembly 12/20/99

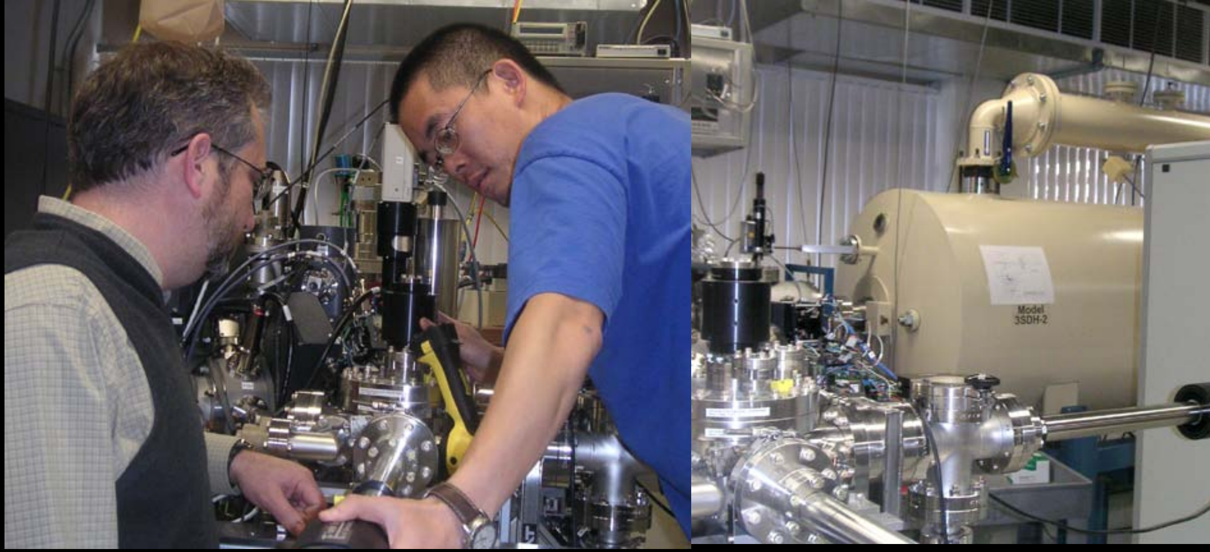



○ Ions du collecteur
● contamination
● Vent solaire implanté
≈100 nm
≈1000 nm

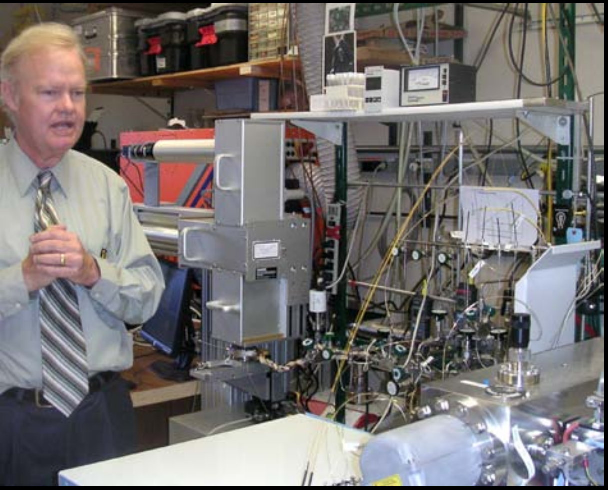

Peler la surface externe
10 nm
≈100 nm
≈1000 nm



Acid attack under vacuum
Laser ablation (St Louis, Zurich)

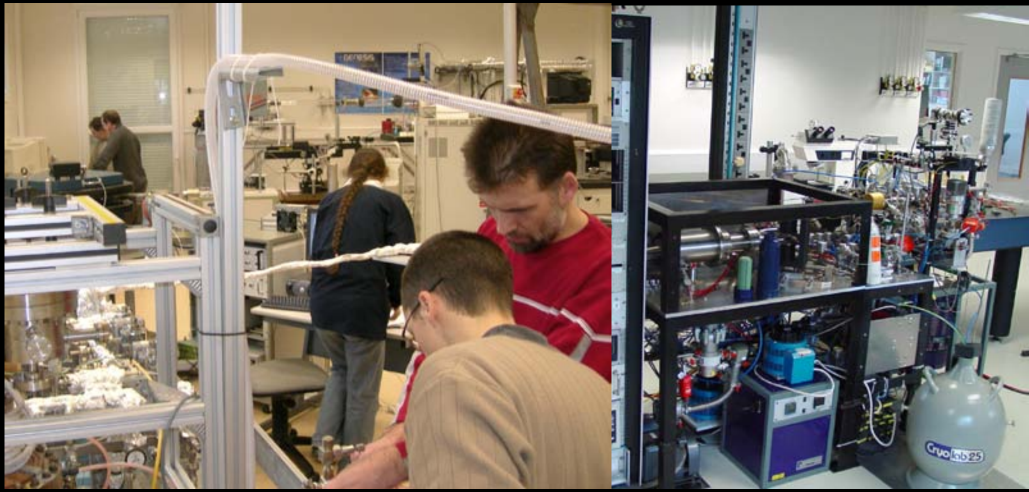


Megasisms (Los Angeles)



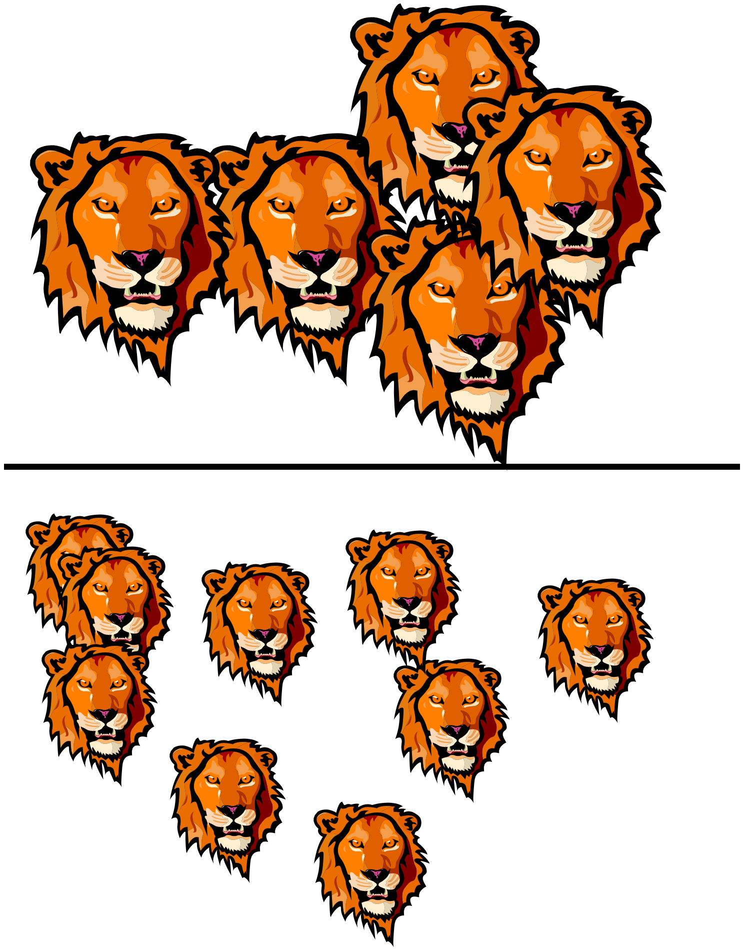
Fluorination
(San Diego)

Laser ablation, sims (Milton Keynes & Nancy)

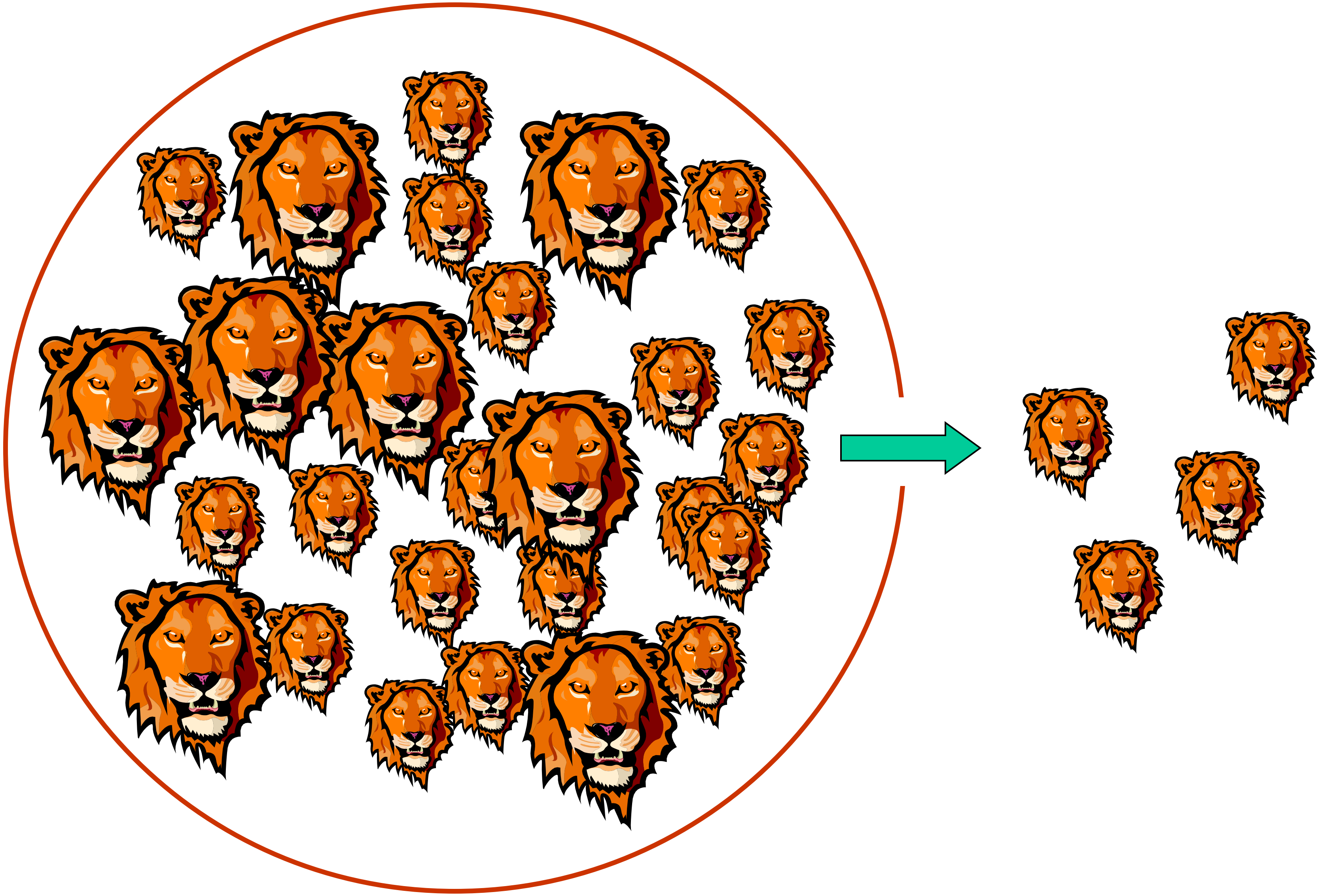


Les tribus d’isotopes

Rapport isotopique =



Caractérise l’histoire de l’élément



Variation isotopique ~ fractionnement

Fractionnement isotopique :

Variation des rapports isotopiques d'un élément
En fonction de la masse

➡ $\Delta M/M$

Oxygène : 3 isotopes ^{16}O, ^{17}O, ^{18}O

$$\Delta^{18}O/^{16}O \sim 2 \times \Delta^{17}O/^{16}O$$

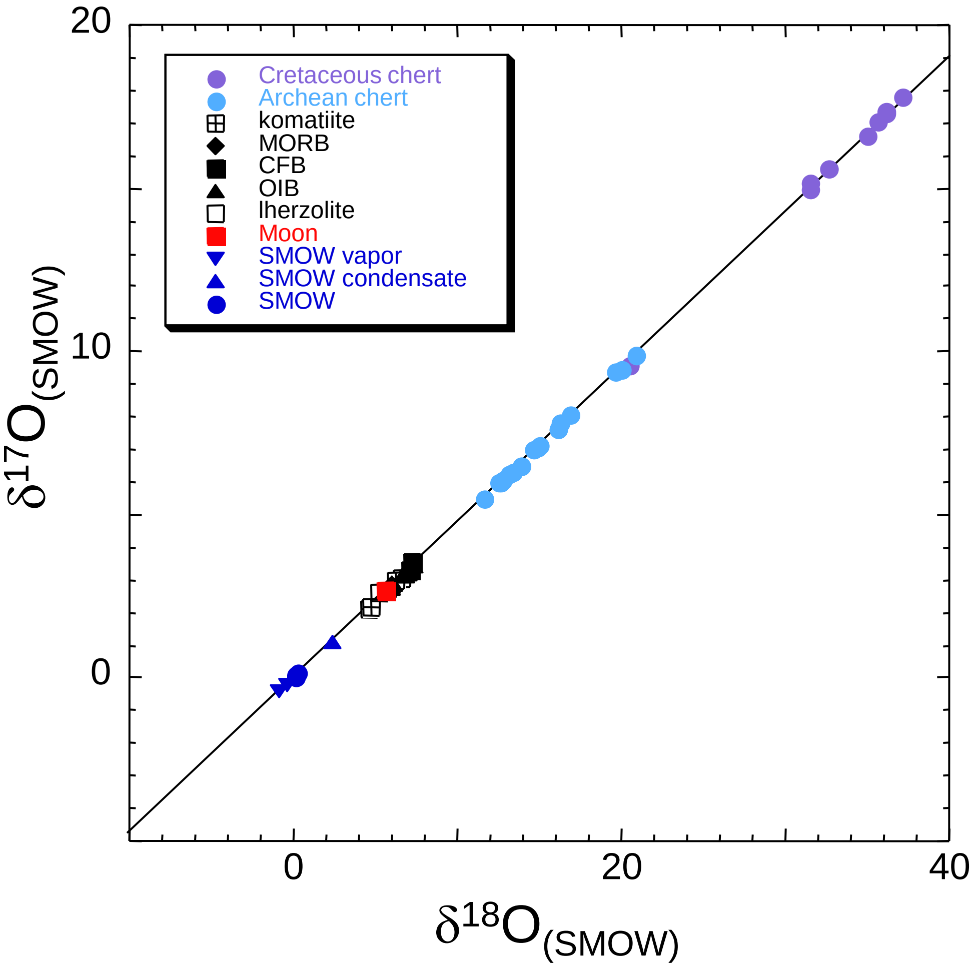
On définit :

$\delta^{18}O$ et $\delta^{17}O$ comme les écart un parties pour mille de $^{18}O/^{16}O$ et $^{17}O/^{16}O$ par rapport à une référence (l'oxygène terrestre)

Cosmochimie isotopique de l'oxygène

^{16}O, ^{17}O, ^{18}O

($^{18}O/^{16}O \approx 2 \times 10^{-3}$ & $^{17}O/^{16}O \approx 4 \times 10^{-4}$)

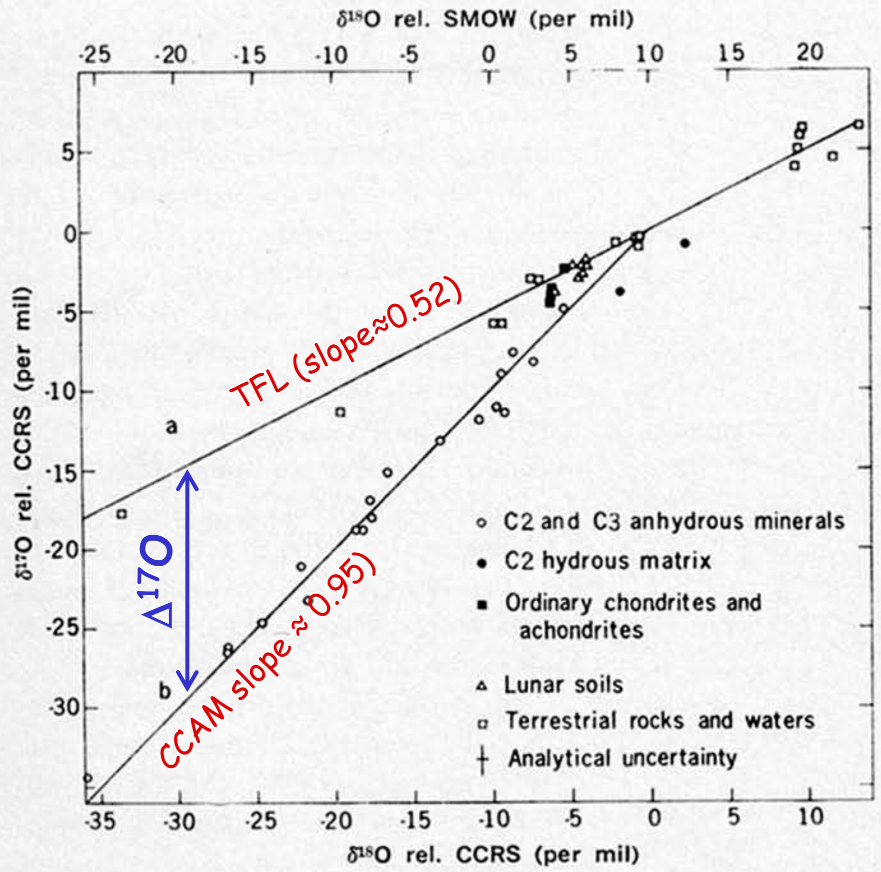


- Produits dans des étoiles différentes
- Élément le plus abondant dans les roches
- Également important (CO, H_2O) dans la nébuleuse proto-solaire
- Fractionnements dépendants, et indépendants, des masses

$$\delta^{18}O = \left(\frac{\left(^{18}O/^{16}O\right)}{\left(^{18}O/^{16}O\right)_{SMOW}} - 1 \right) \times 1000$$

$\delta^{17}O \approx 0.52 \times \delta^{18}O$

Robert, Rejou-Michel & Javoy (1992)



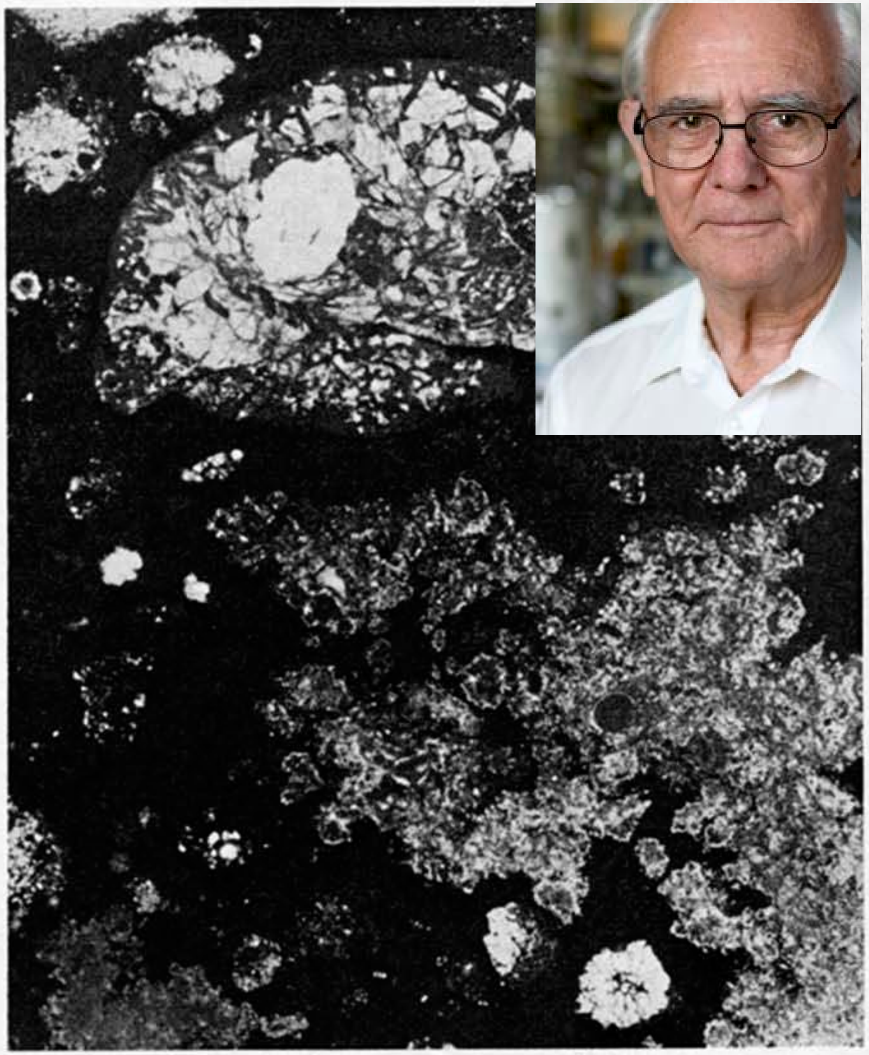
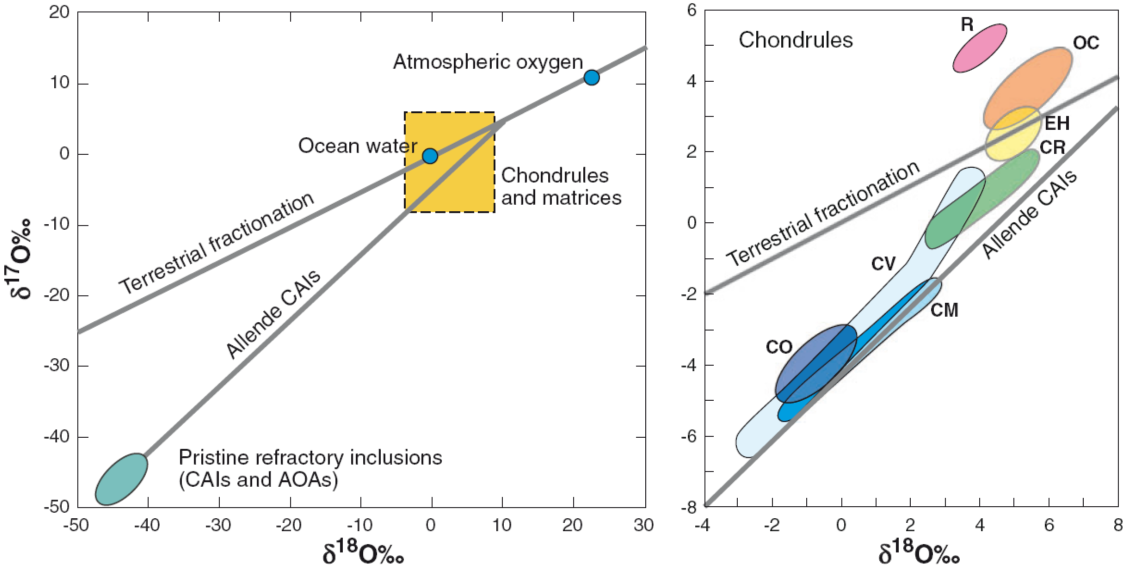


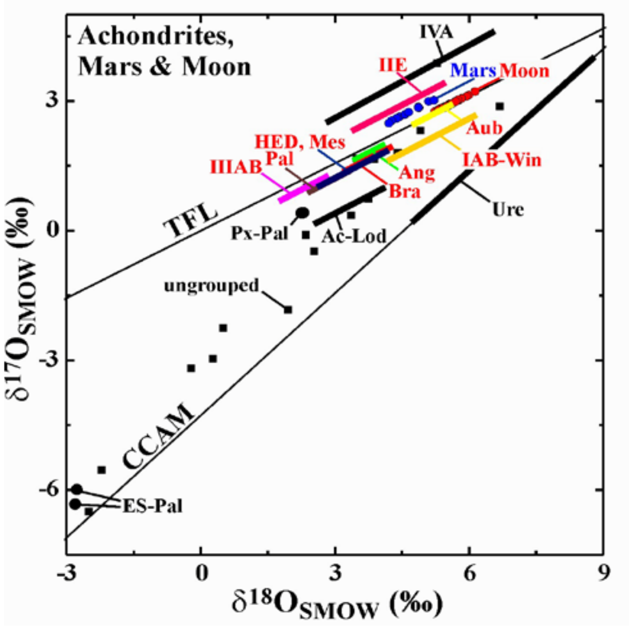
Fig. 1 (left). Relationship between ^{17}O/^{16}O variations and ^{18}O/^{16}O variations for terrestrial, lunar, and meteoritic samples. Points lying along line a, with a slope of +½, define the trend for chemical isotope effects; points lying along line b, with a slope of +1, define a mixing line between "normal" oxygen and an ^{16}O-rich component. The points on line b are all from phases in carbonaceous chondrites. The reference standards are SMOW [standard mean ocean water (*13*)] and CCRS [carbonaceous chondrite reference standard (see text)]. Fig. 2 (right). Photomicrograph of a section of the Allende meteorite, showing two large white inclusions (see text). Area of section, 8 by 10 mm. [Courtesy Richard J. Kjarval, Graphic Arts Facility, Physical Sciences Division, University of Chicago]

Clayton, Grossman & Mayeda (1973)

Cosmochimie isotopique de l’oxygène



Scott, 2007

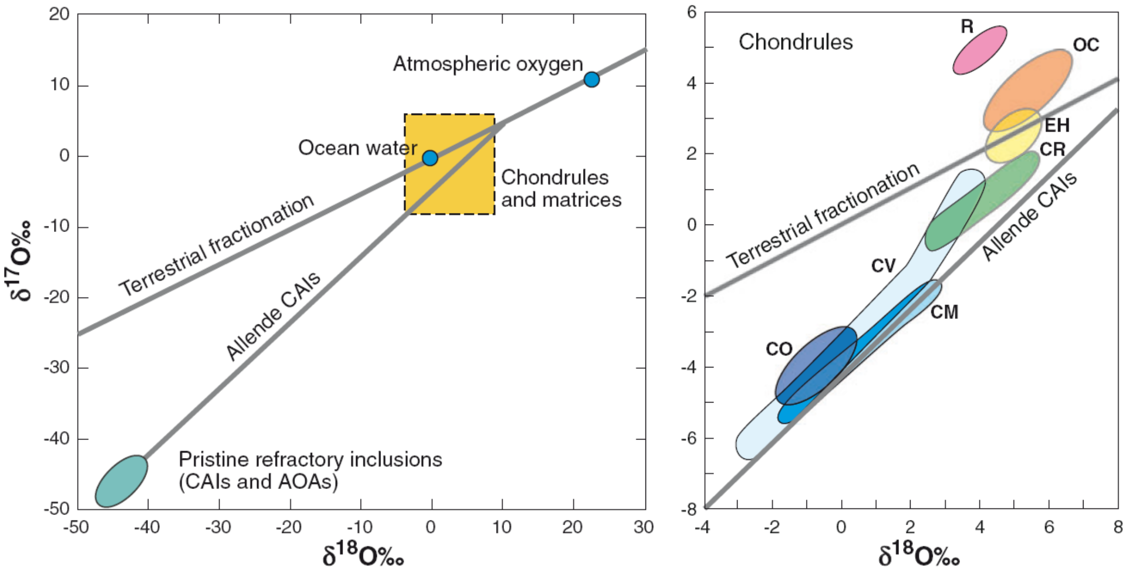


Krot, 2007

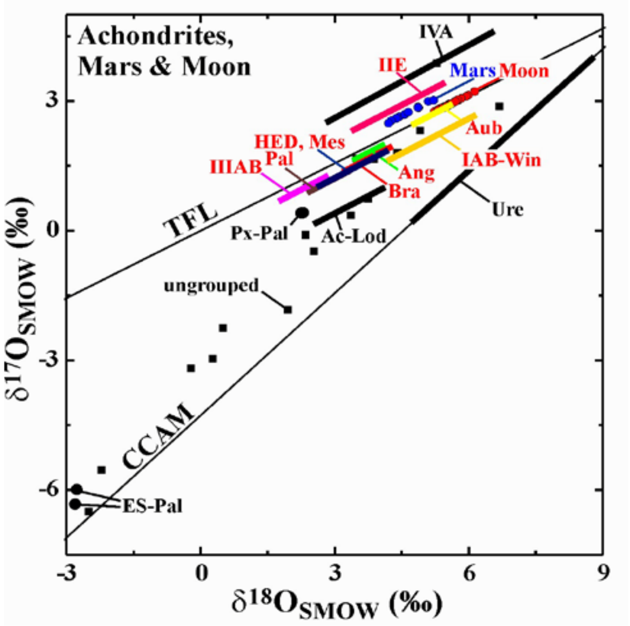
Définit plusieurs familles à l’échalle des corps planétaires

mais…

Cosmochimie isotopique de l'oxygène



Scott, 2007

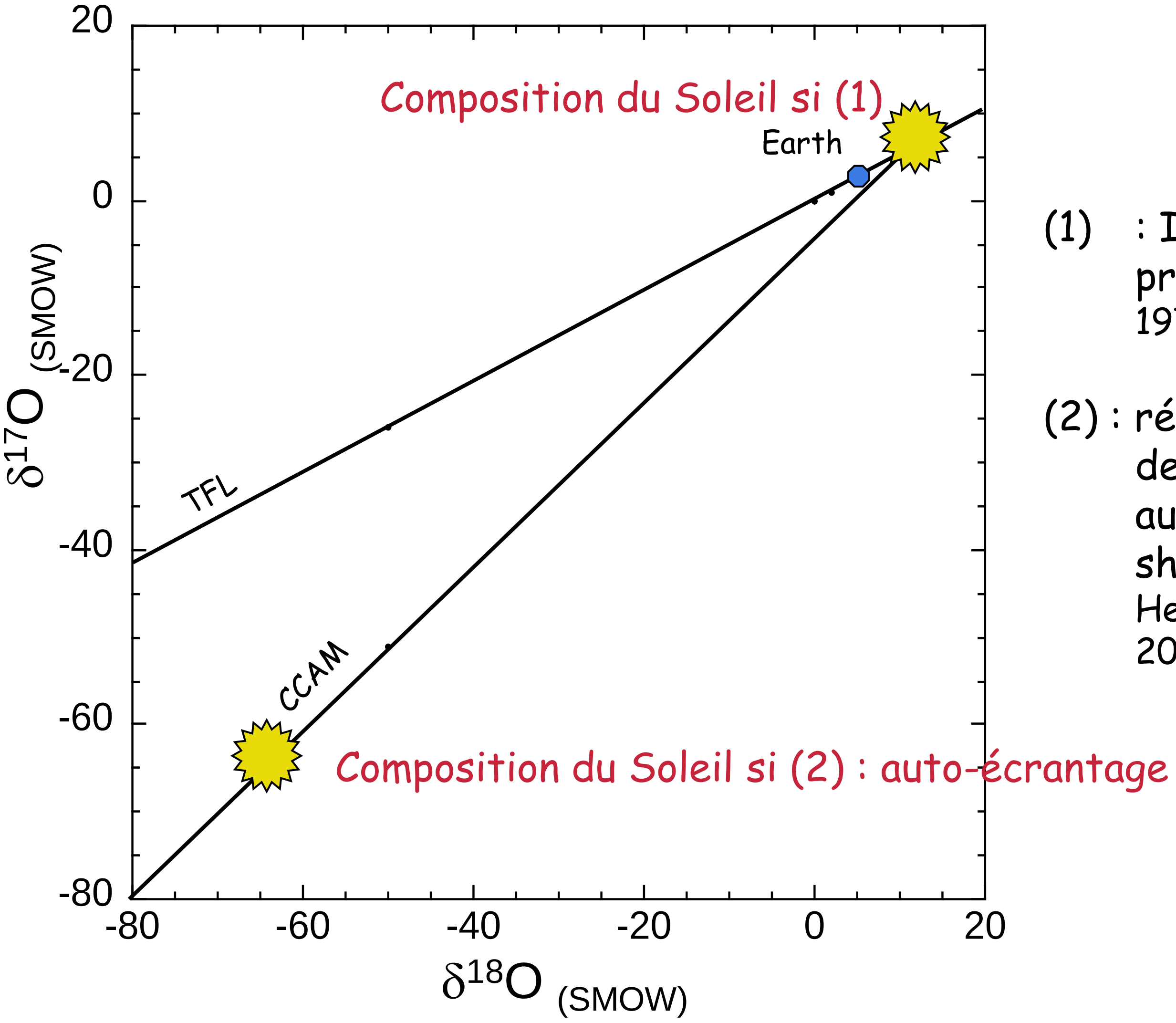


Krot, 2007

Ou se trouve le soleil ?

?

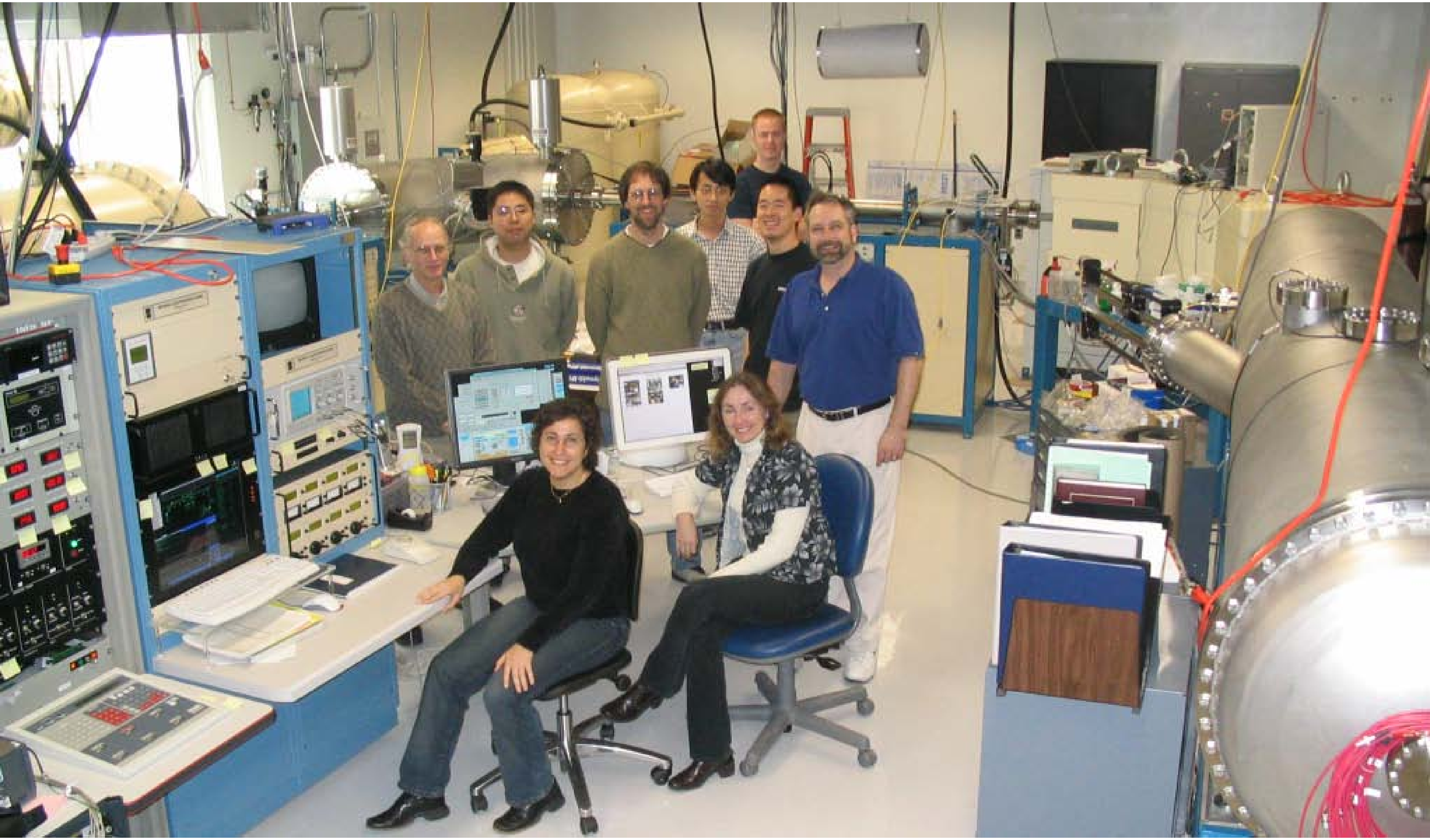
Origine des variations indépendantes de la masse ?

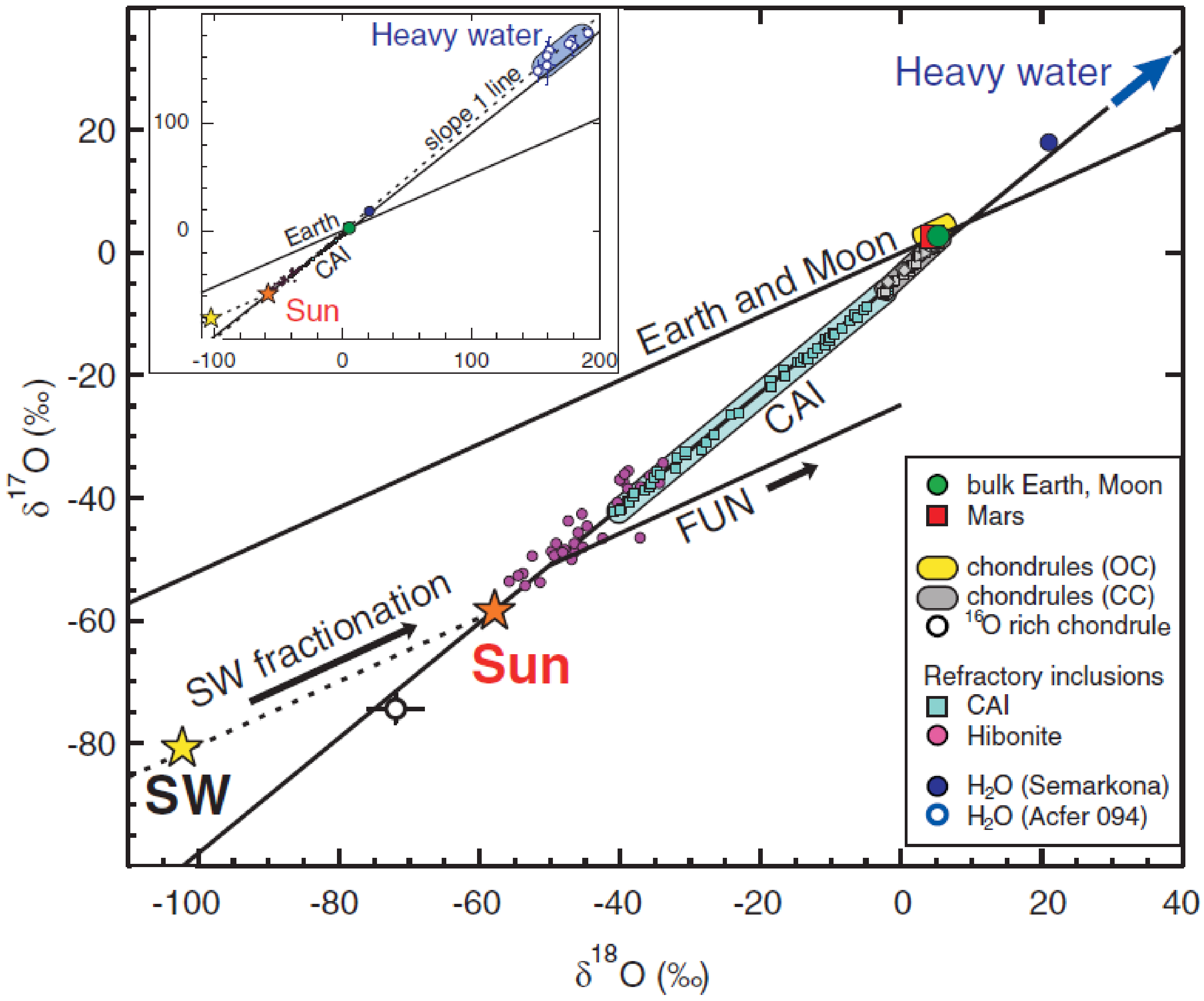


(1) : Injection d'une composante pré-solaire (Clayton et al., 1973)

(2) : réactions photo-chimiques de type ozone ou de type auto-écrantage (self shielding) (Thiemens & Heidenreich, 1983) (Clayton, 2002)

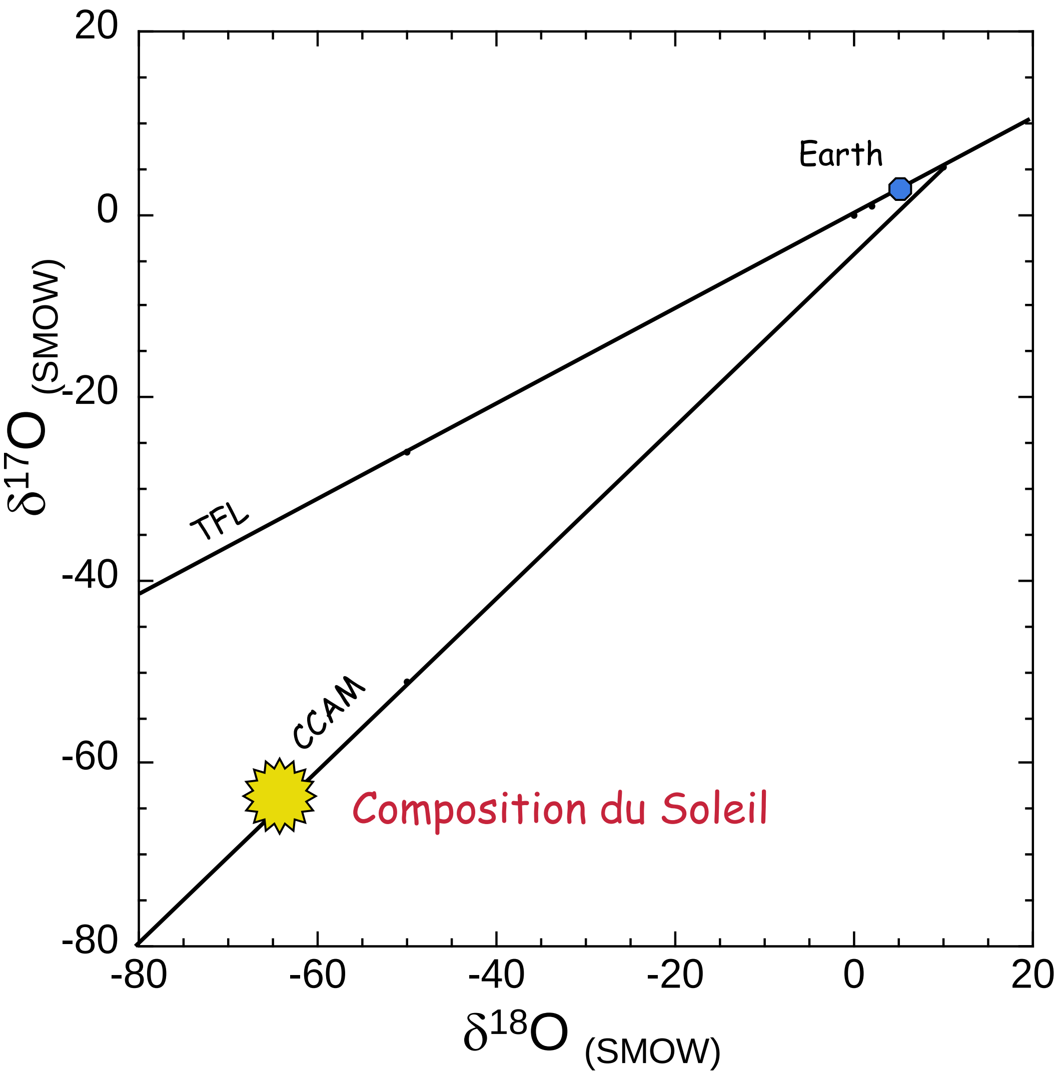
UCLA MegaSIMS laboratory





McKeegan et al., 2011

Origine des variations indépendantes de la masse ?

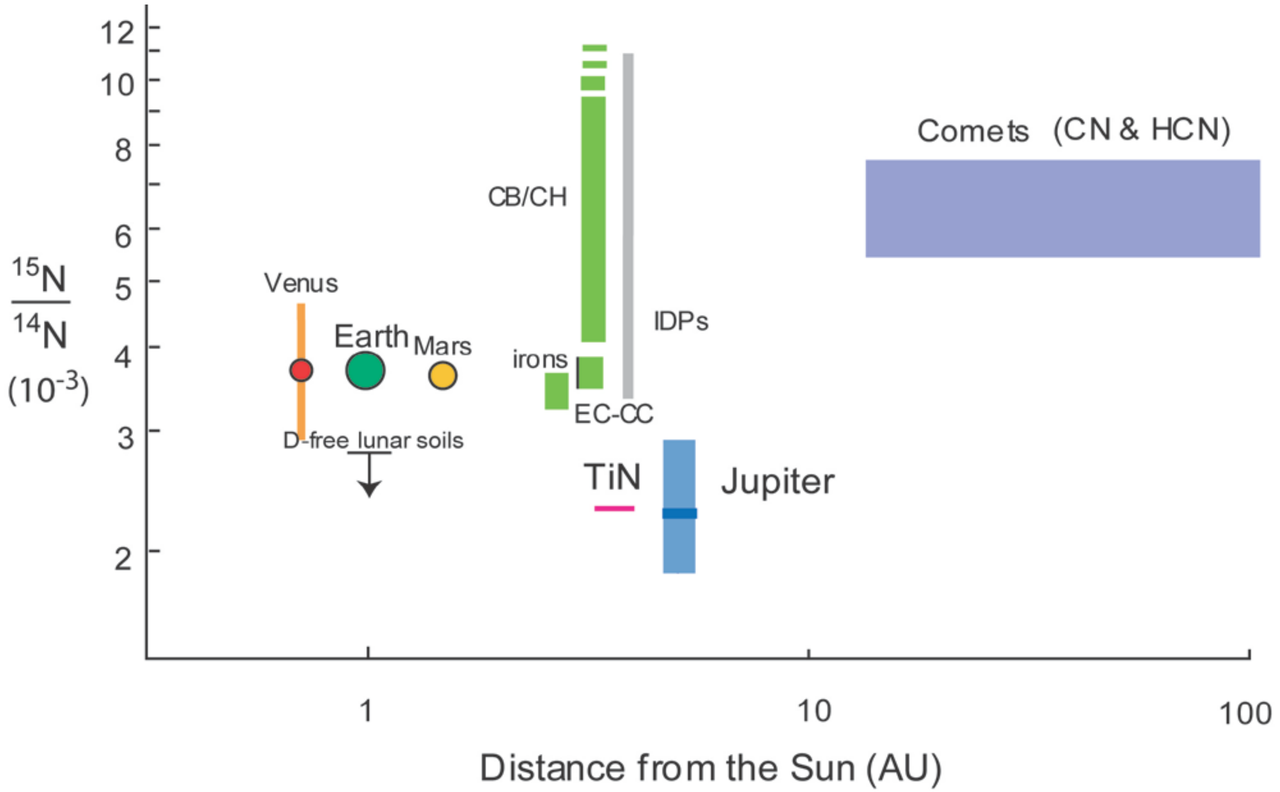


réactions photo-chimiques de type auto-écrantage (self shielding) (Thiemens & Heidenreich, 1983) (Clayton, 2002)

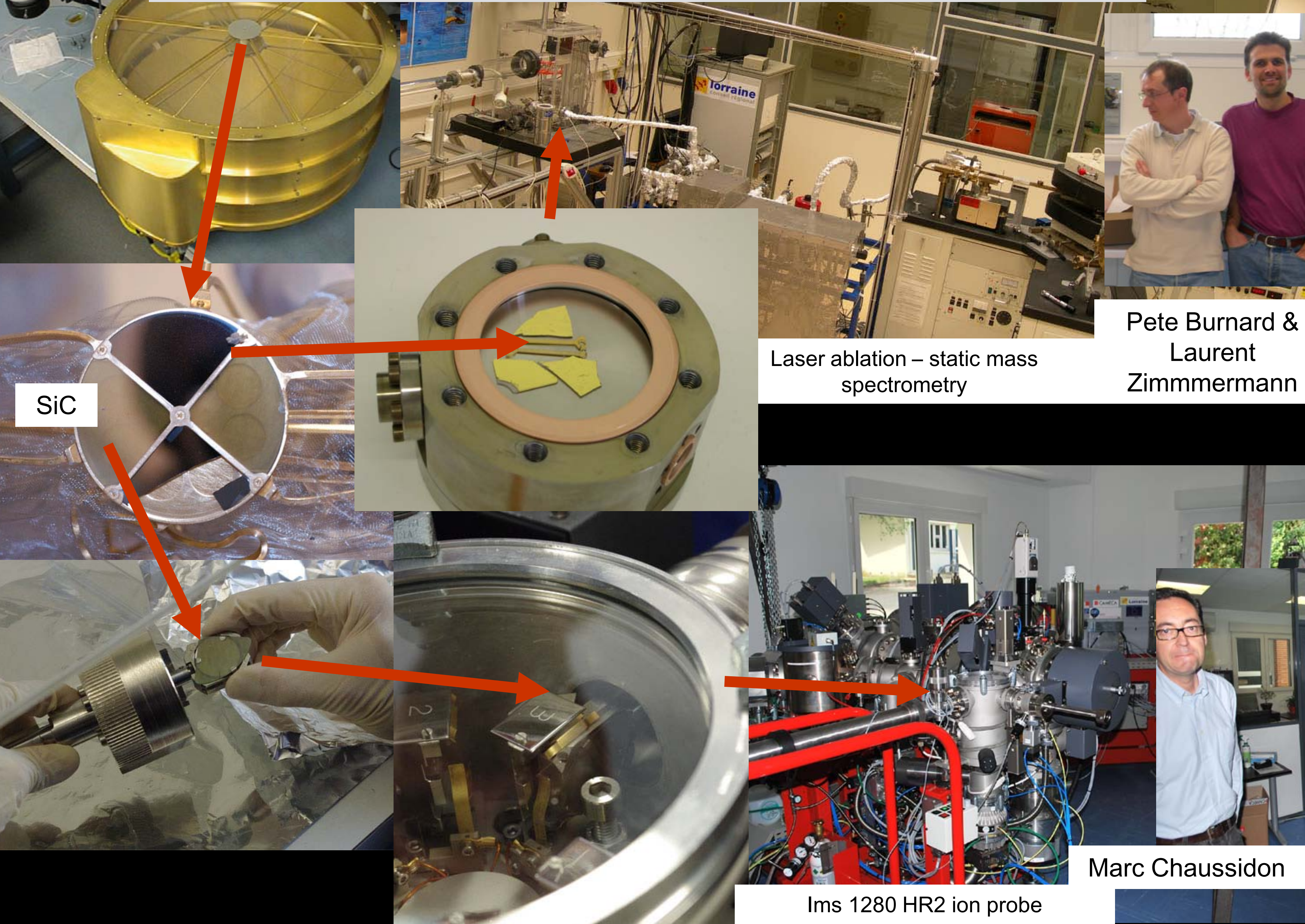
→ interactions entre le gaz et l'irradiation précoce t intense du Soleil jeune.

Cosmochimie isotopique de l’azote

- 2 isotopes :
  Atmosphère ^{14}N : 272, ^{15}N : 1
- Origines stellaires différentes
- Principalement dans la matière organique, les nitrures, et les atmosphères planétaires



Analyse isotopique de l’azote de Genesis au CRPG à Nancy



SiC

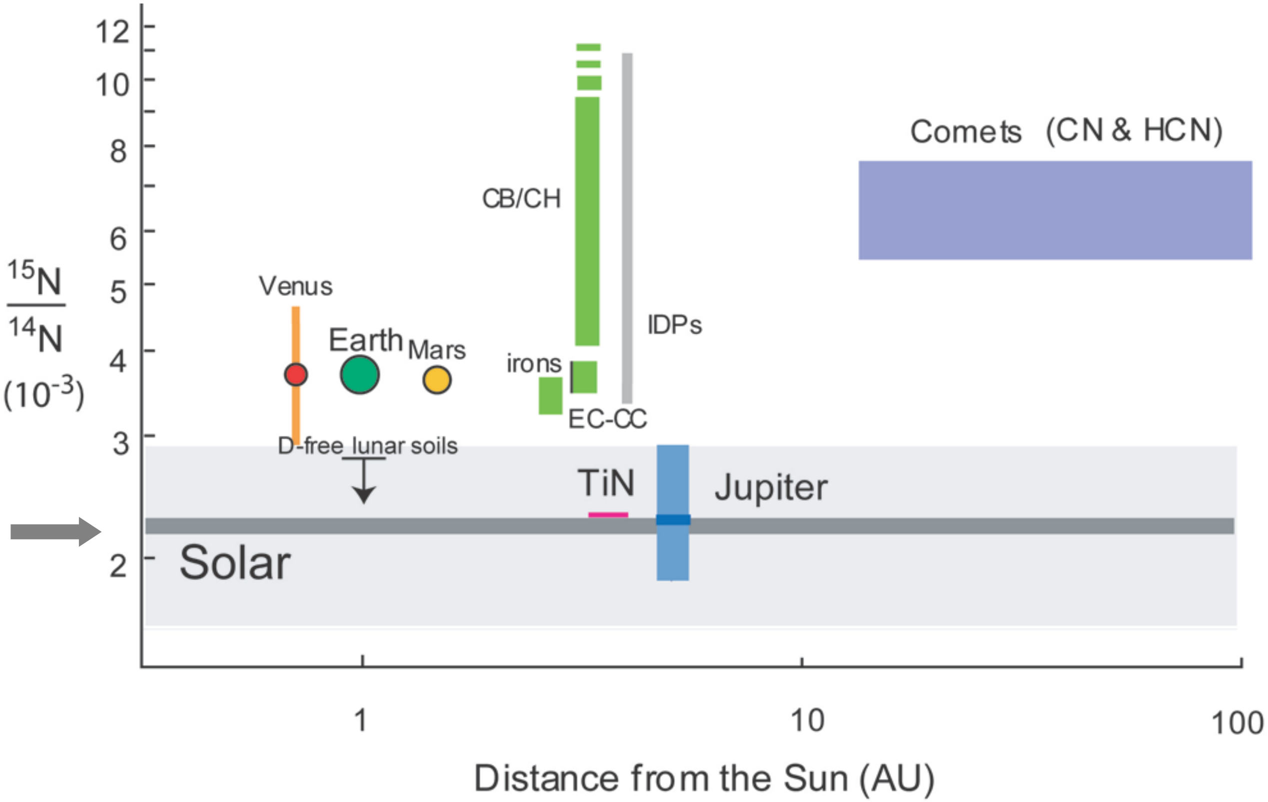
Laser ablation – static mass spectrometry

Pete Burnard & Laurent Zimmmermann

Ims 1280 HR2 ion probe

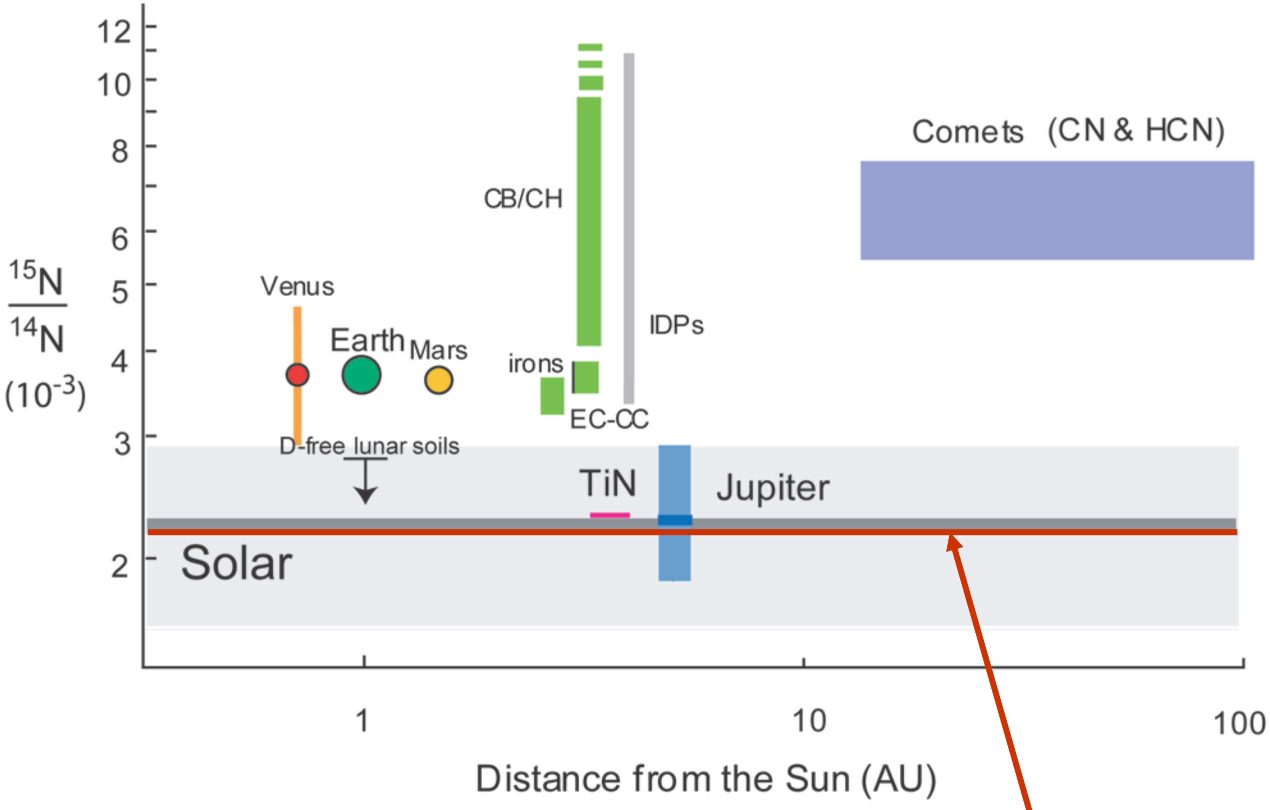
Marc Chaussidon

Cosmochimie isotopique de l’azote

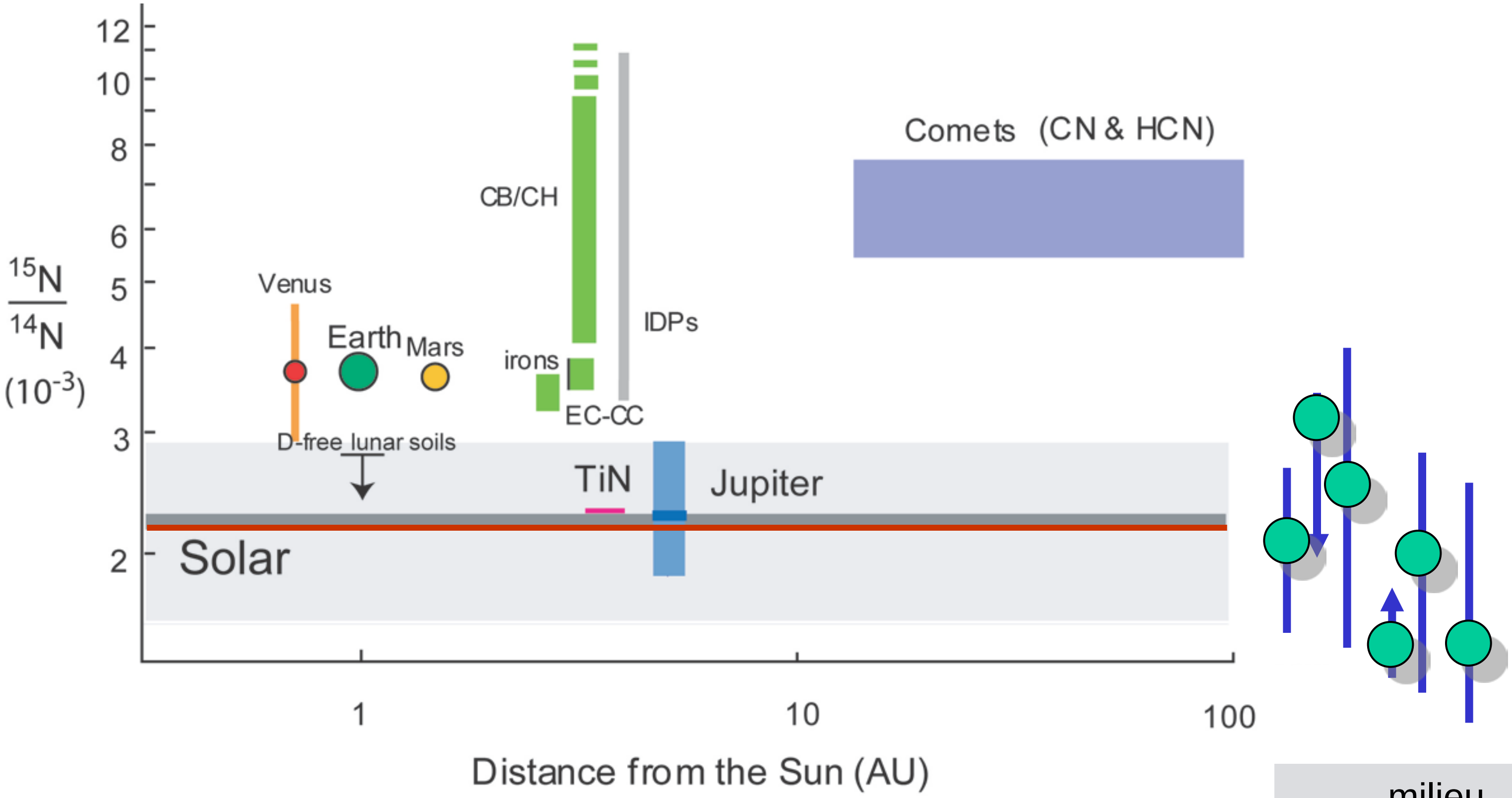


Laser ablation – static mass spectrometry CRPG

Cosmochimie isotopique de l'azote



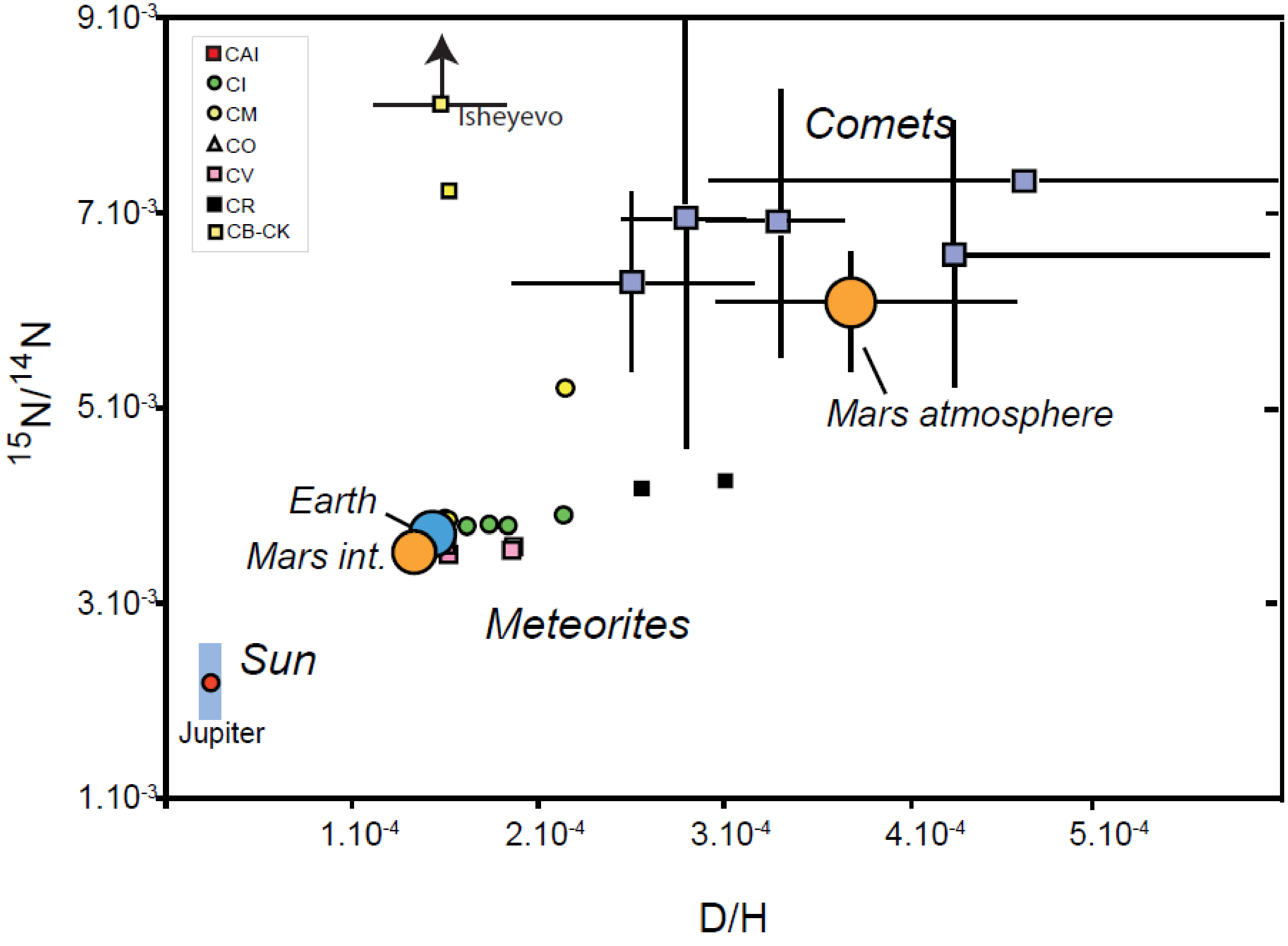
Sonde ionique Ims 1280 CRPG



milieu interstellaire
Gerin et al (2009)

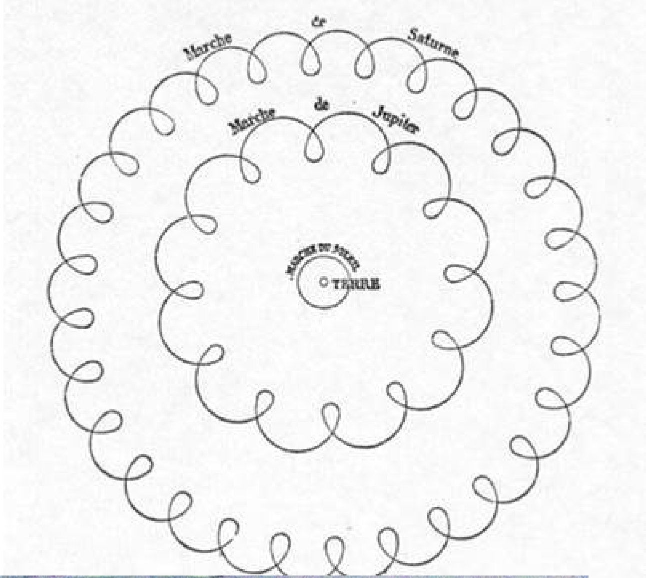
Les enrichissements en ^{15}N ont été produits dans le système solaire

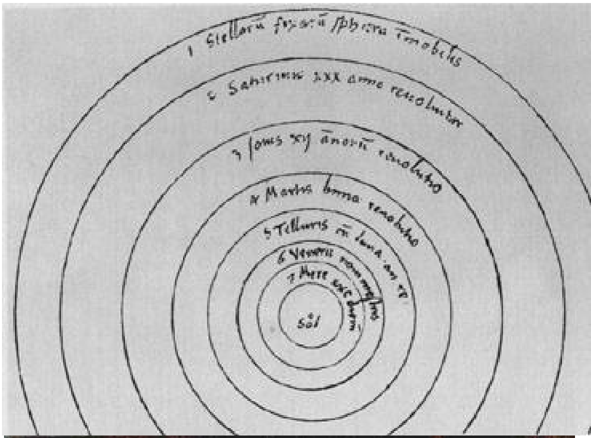
Origine des océans : source astéroïdale et non cométaire



- Tous les réservoirs cosmochimiques échantillonnés (à part Jupiter) sont anormaux
- Il faut maintenant comprendre la cause de ces variations isotopiques très importantes capables d’enrichir les solides en ^{17}O, ^{18}O, et ^{15}N, par rapport aux majeurs ^{16}O et ^{14}N

Intéractions matière-rayonnement aux confins du système solaire ?

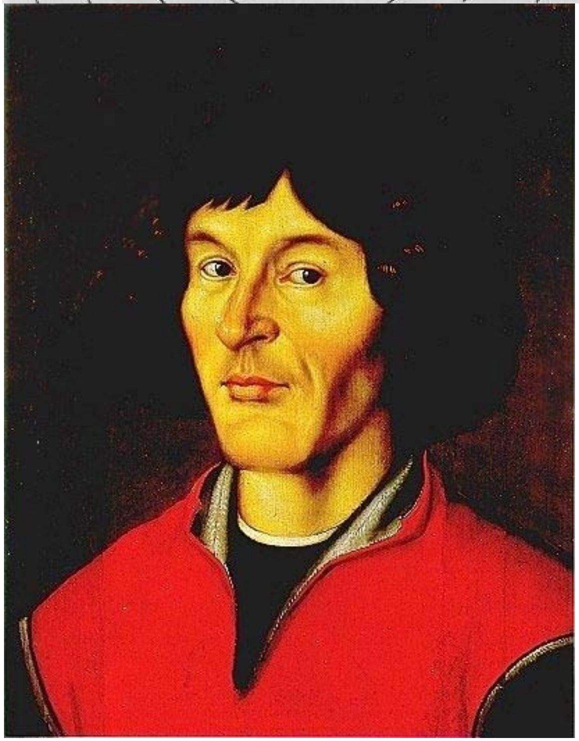




Il aura fallu 14 siècles pour passer d'une vision ptoléméenne d'un système centré sur la Terre à une vision copernicienne centrée sur le Soleil

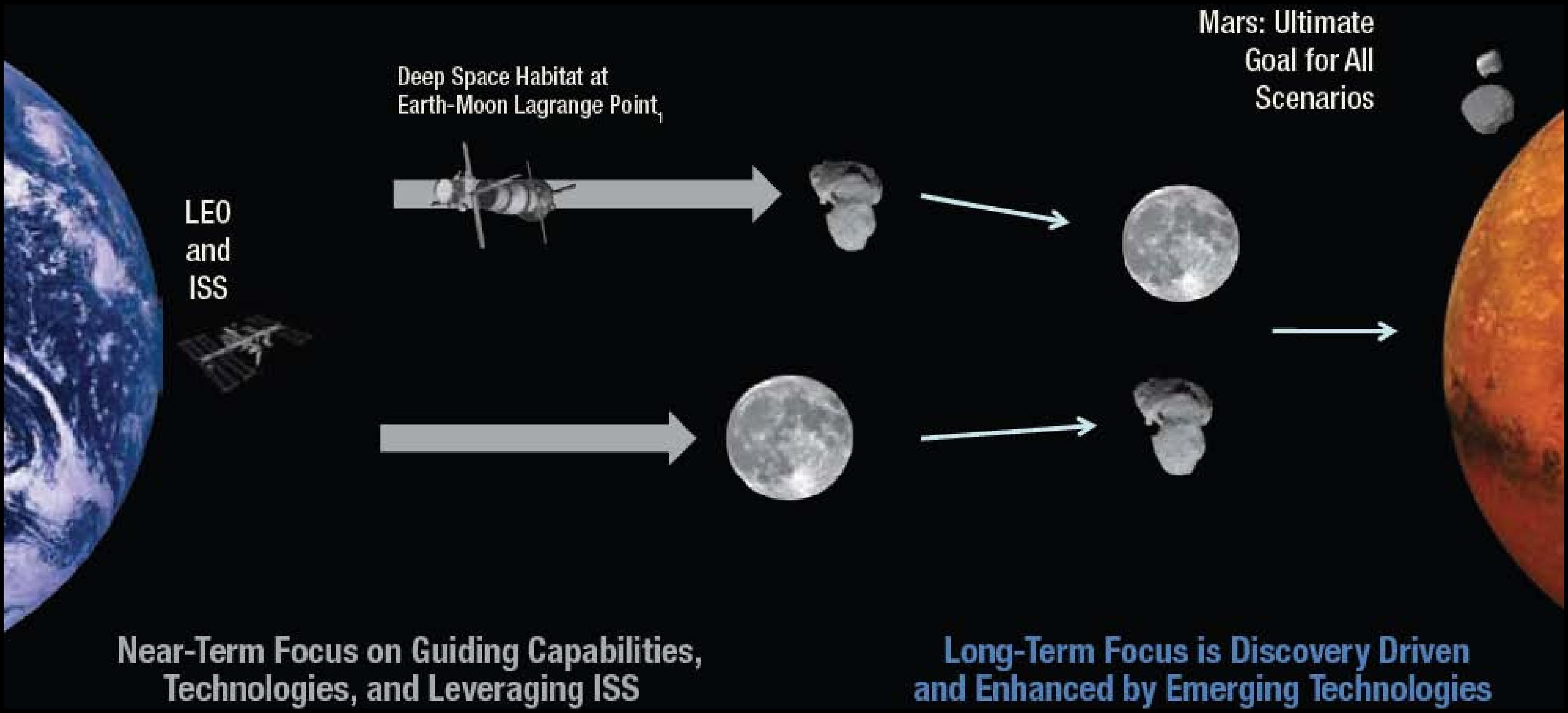
Et 3 décennies pour s'en convaincre dans le cas des isotopes !

Ptolémée 90-168.



Nicolas Copernic (1473-1543)

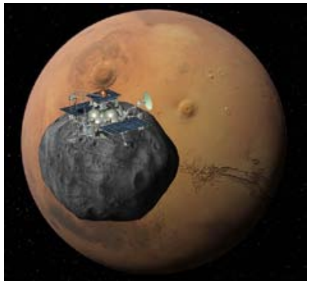
La route de l’exploration du système solaire



Prochaines missions de retours d'échantillons

Osiris-Rex : NASA, Retour d'échantillon d'un astéroïde primitif

Départ en 2016, retour en 2023



Phobos-Grunt : Agence spatiale russe, collab. CNES, retour d'échantillon de Phobos, l'une des deux lunes de Mars,

Départ en 2011

Marco-Polo-R : ESA, retour d'échantillon d'un astéroïde primitif, peut être un noyau cométaire,

Sélectionnée, en concurrence avec 3 autres missions, décision fin 2013, départ en 2021, retour en 2026

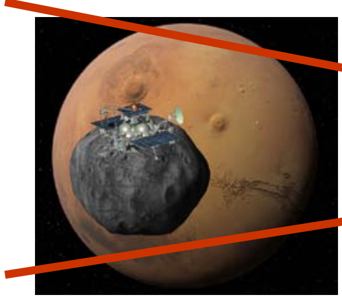
Hayabusa 2, JAXA, astéroïde primitif

Départ en 2014

Prochaines missions de retours d'échantillons

Osiris-Rex : NASA, Retour d'échantillon d'un astéroïde primitif

Départ en 2016, retour en 2023



~~**Phobos-Grunt** : Agence spatiale russe, collab. CNES, retour d'échantillon de Phobos, l'une des deux lunes de Mars,~~

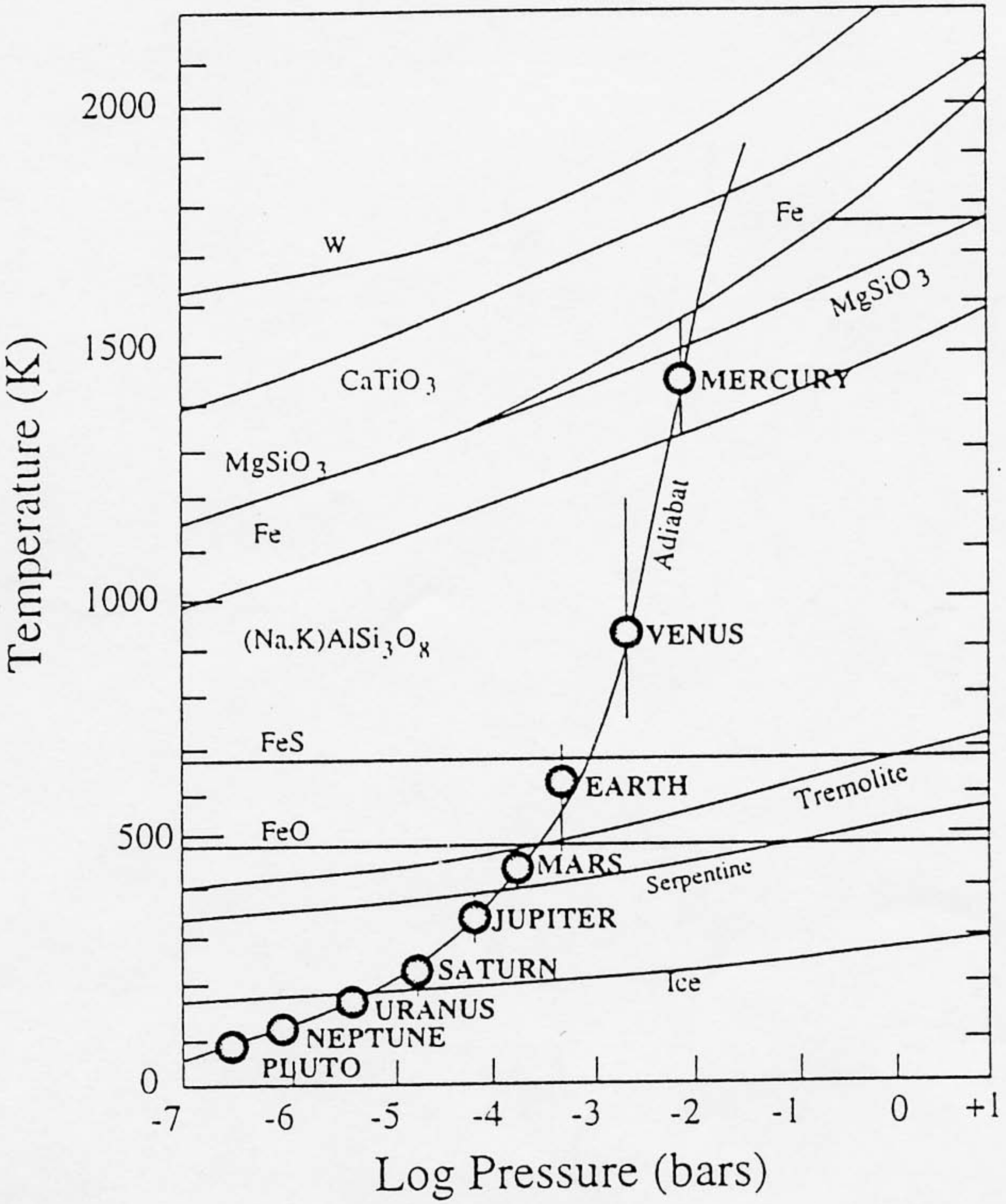
~~Départ en 2011~~

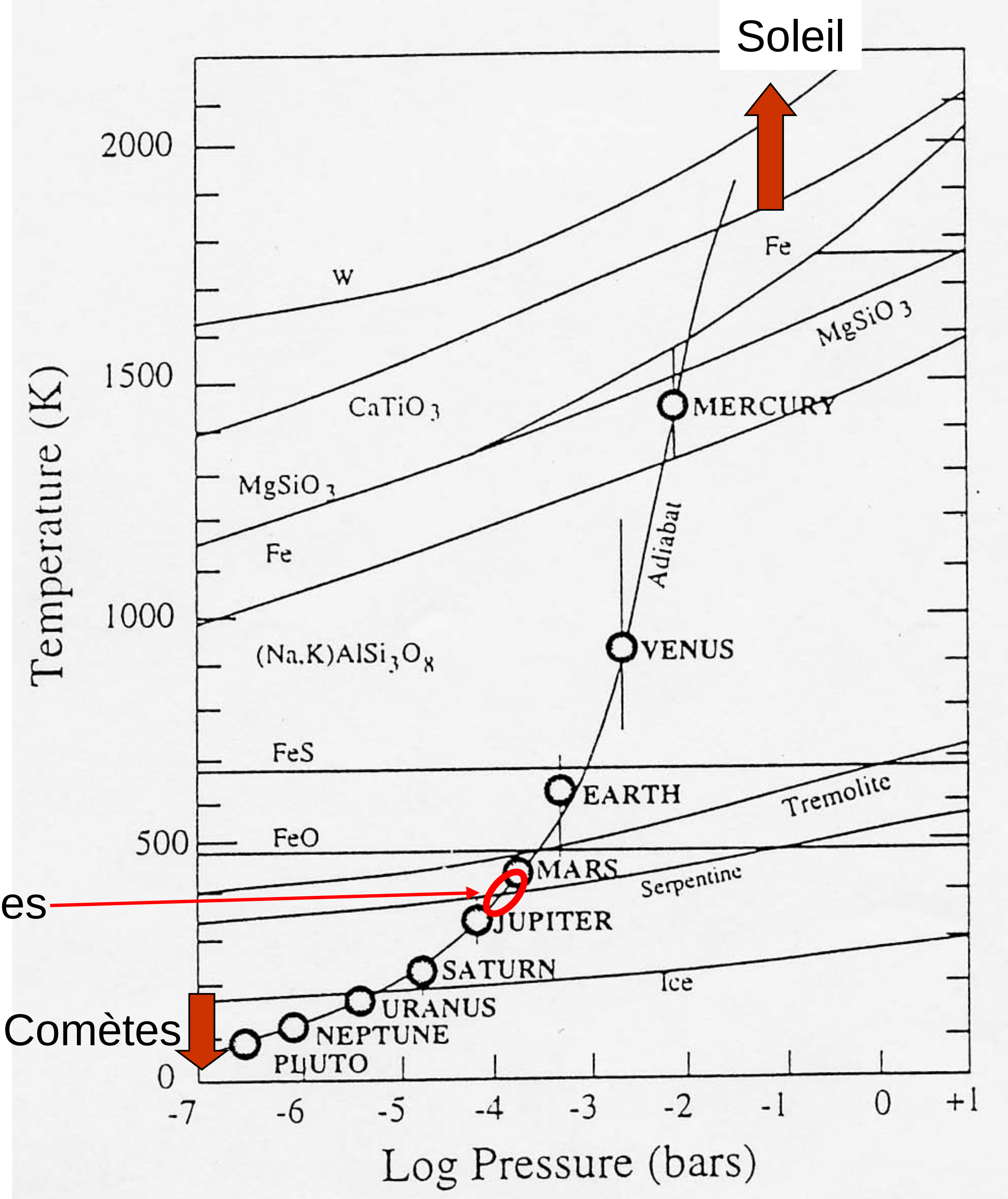
Marco-Polo-R : ESA, retour d'échantillon d'un astéroïde primitif, peut être un noyau cométaire,

Sélectionnée, en concurrence avec 3 autres missions, décision fin 2013, départ en 2021, retour en 2026

Hayabusa 2, JAXA, astéroïde primitif

Départ en 2014


Temperature (K)
2000
1500
1000
500
0
-7
-6
-5
-4
-3
-2
-1
0
+1
Log Pressure (bars)
W
CaTiO$_3$
MgSiO$_3$
Fe
(Na,K)AlSi$_3$O$_8$
FeS
FeO
Fe
MgSiO$_3$
Adiabat
MERCURY
VENUS
EARTH
Tremolite
MARS
Serpentine
JUPITER
SATURN
Ice
URANUS
NEPTUNE
PLUTO



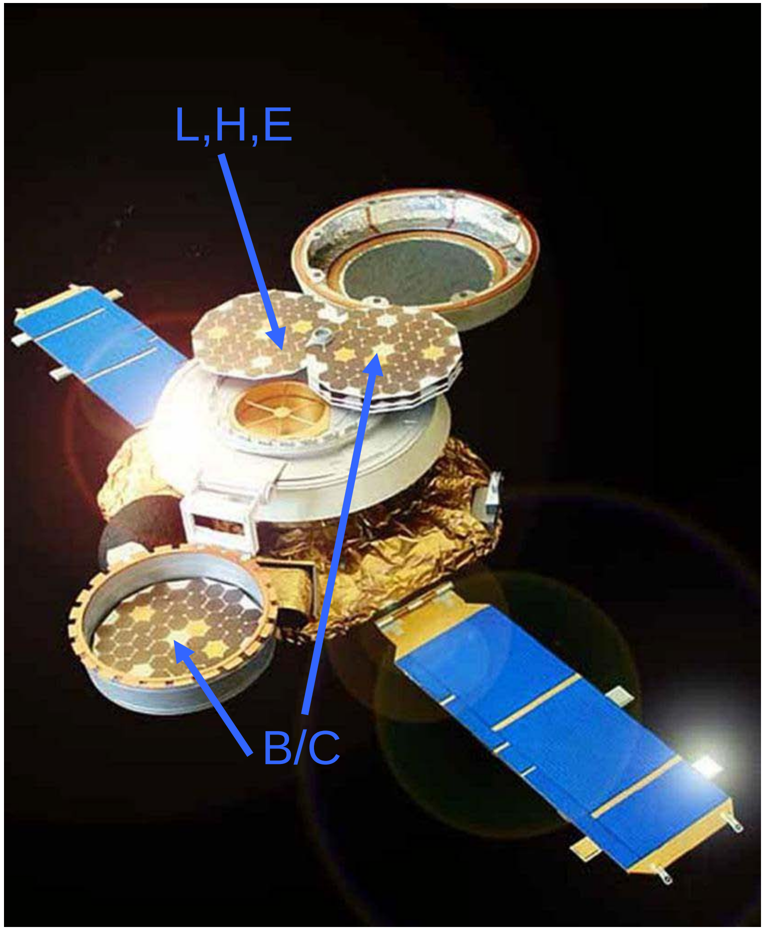
Soleil

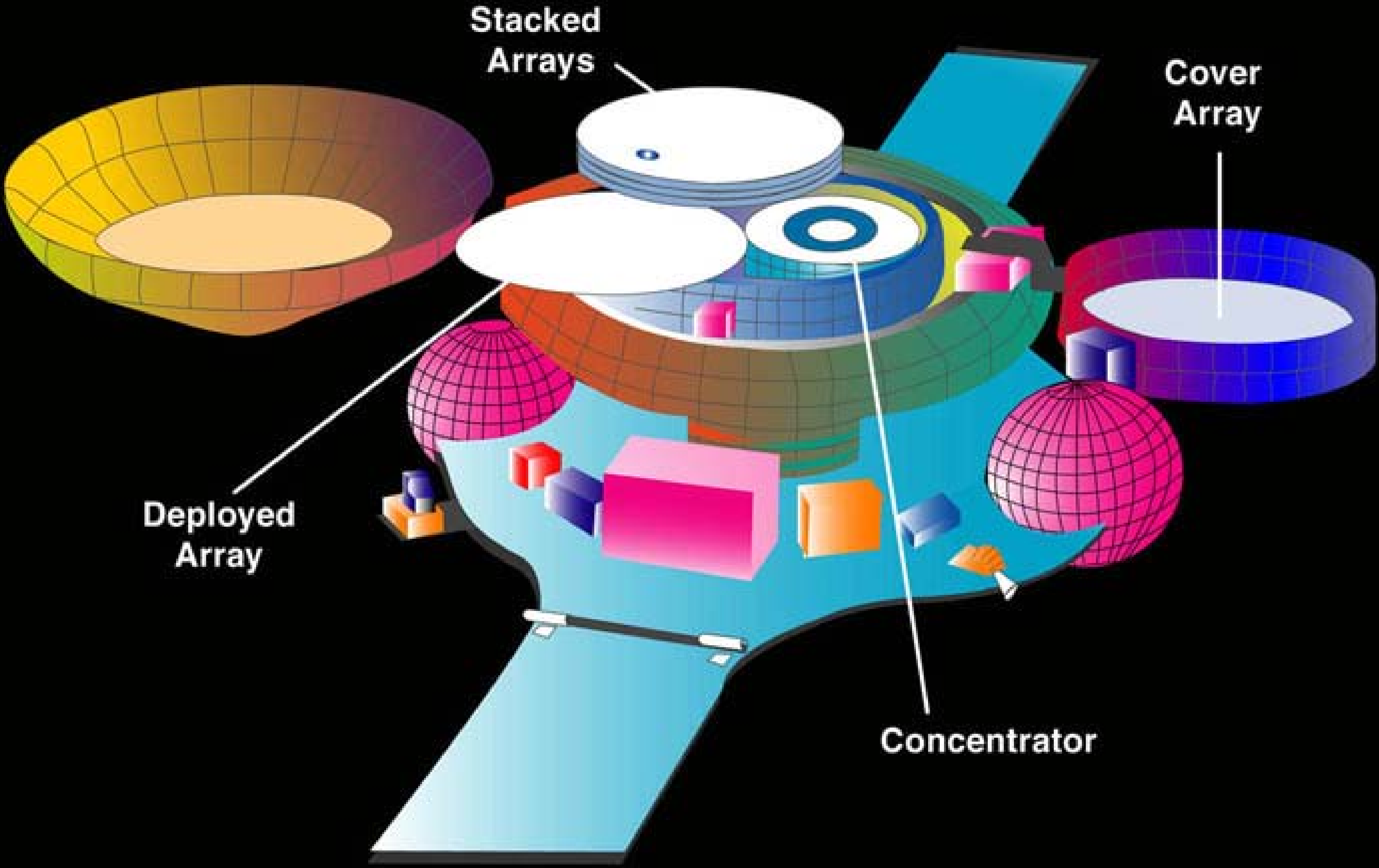
Météorites

Comètes

Vent solaire échantillonné spécifiquement à plusieurs énergies

Array	Description	Days exposed
B/C	bulk solar wind	852.83
H	high-speed (500-800 km/s)	313.01
L	low-speed (<500 km/s)	333.67
E	coronal mass ejection (CME)	193.25





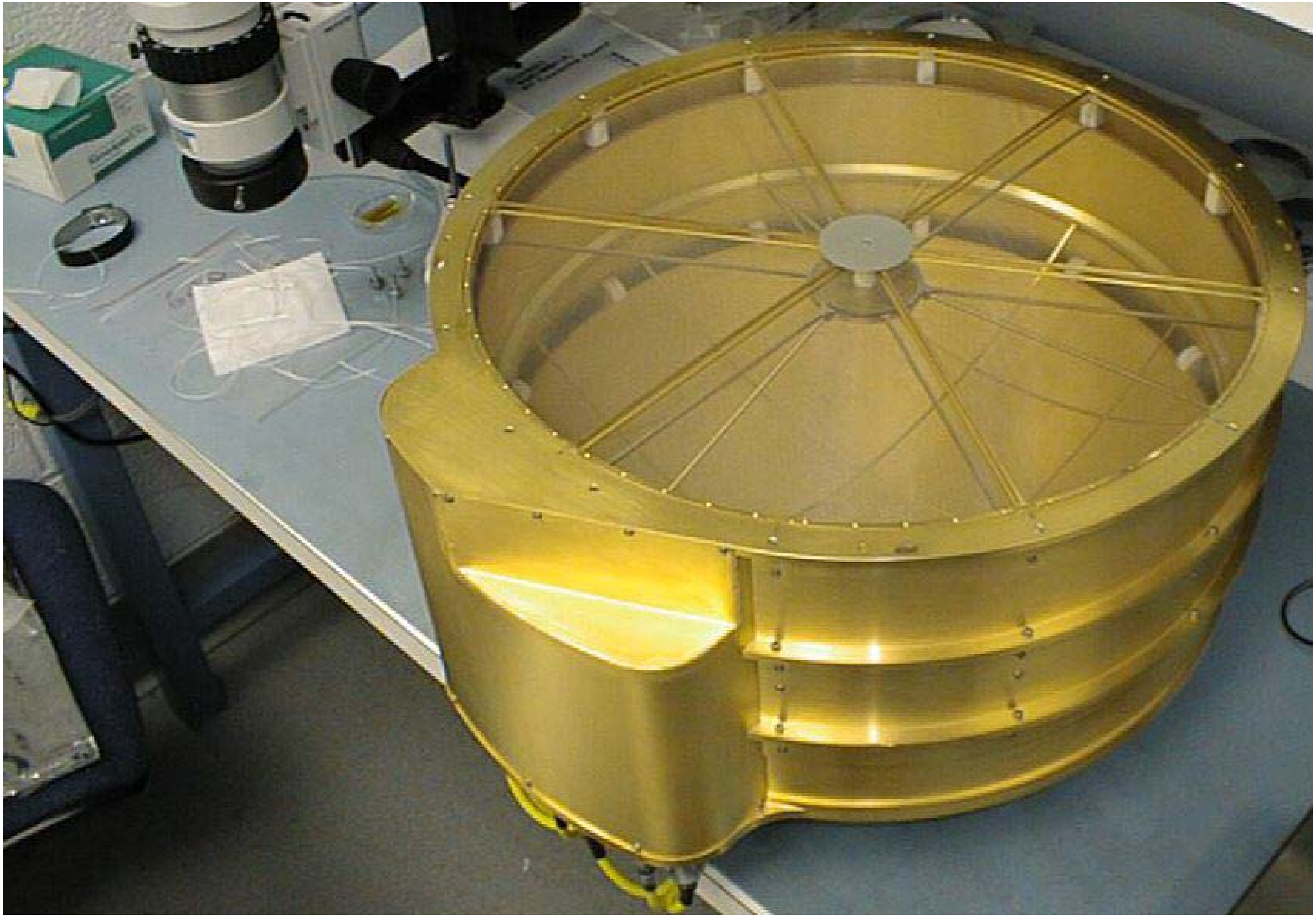
Stacked Arrays

Cover Array

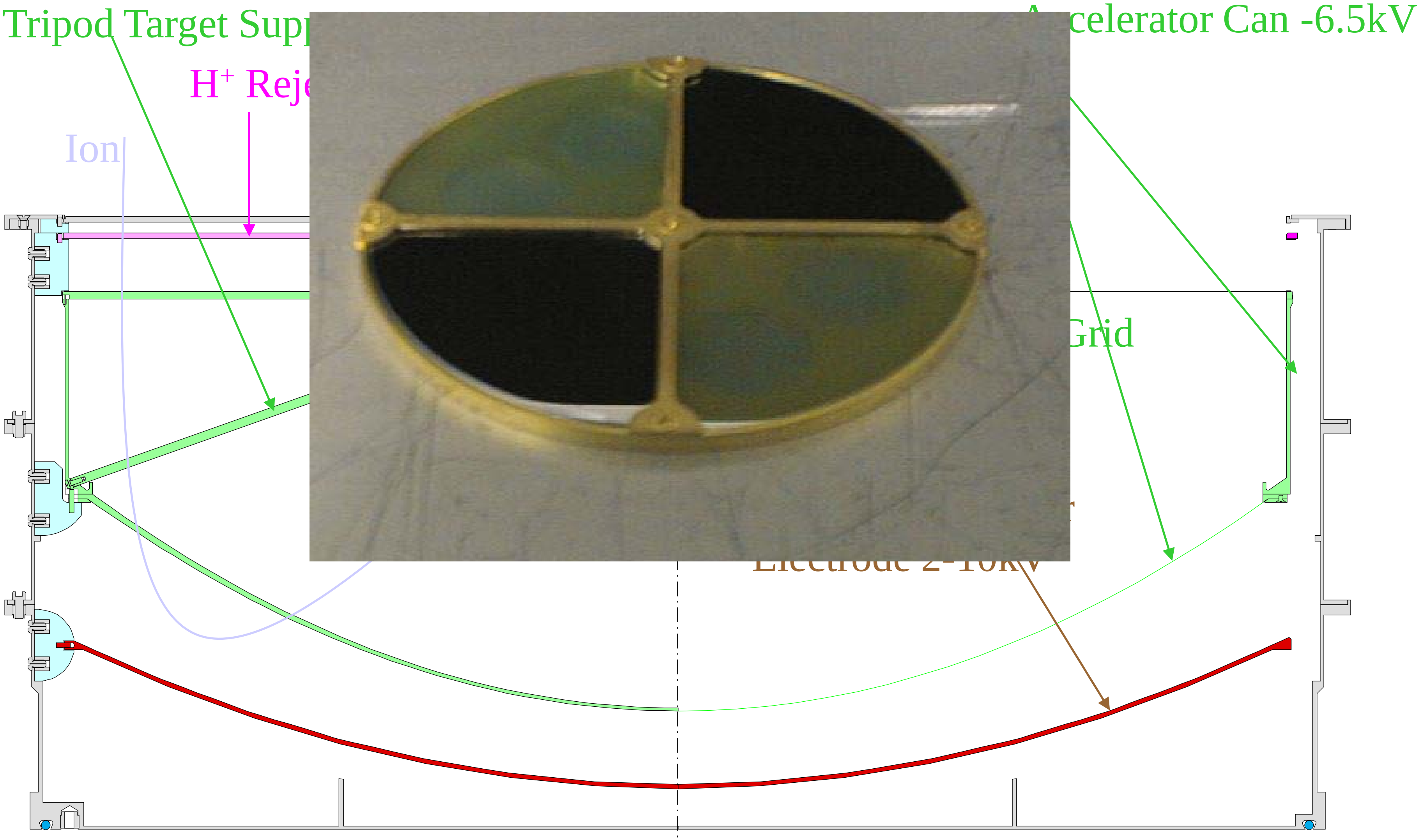
Deployed Array

Concentrator

1/2/1998

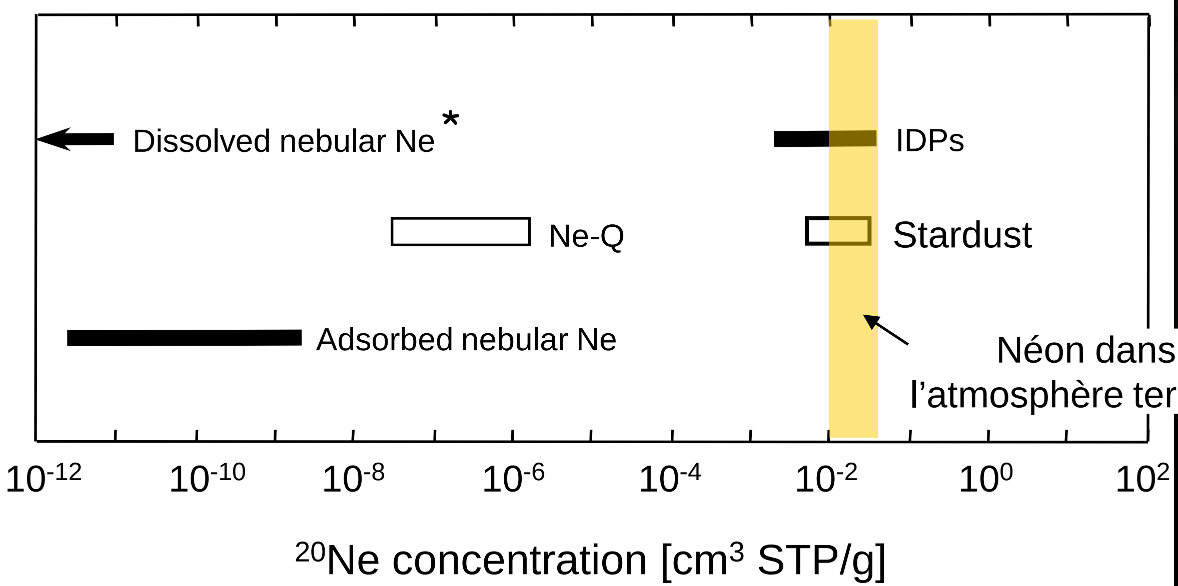


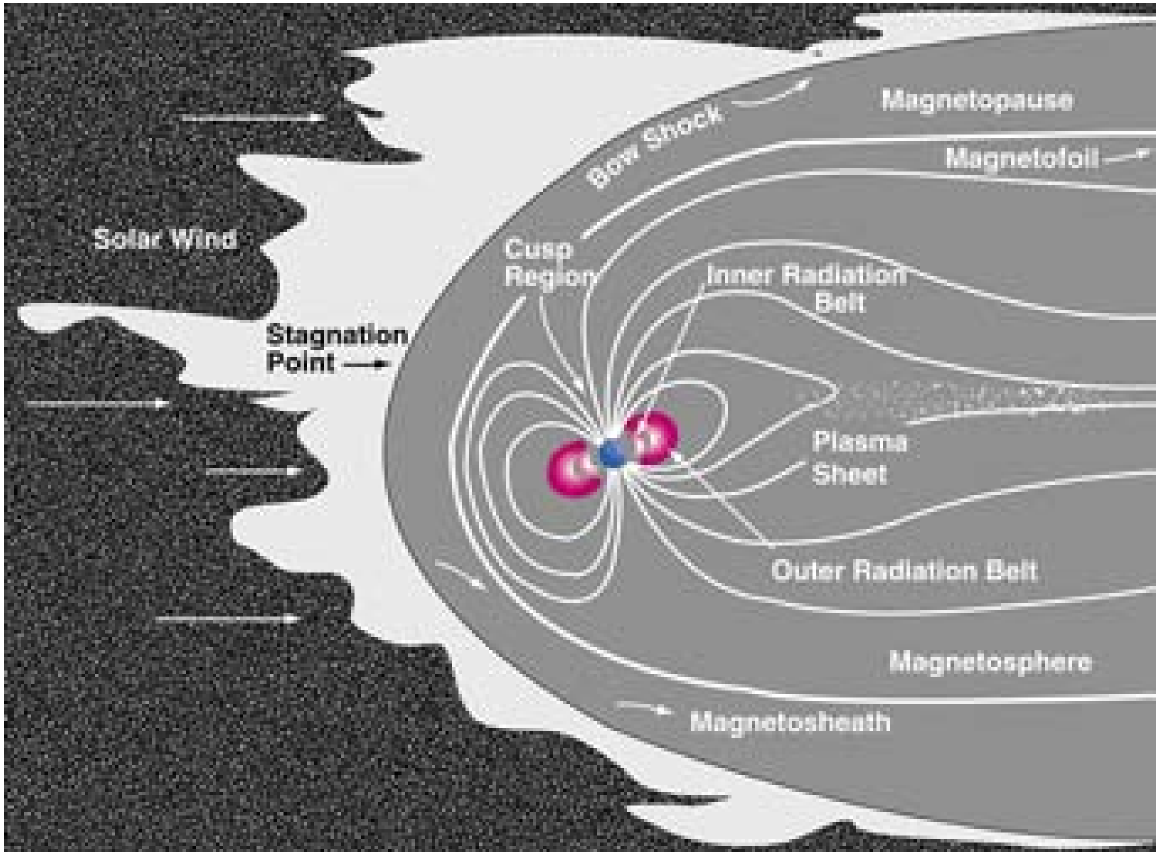
Concentrator Cross-section

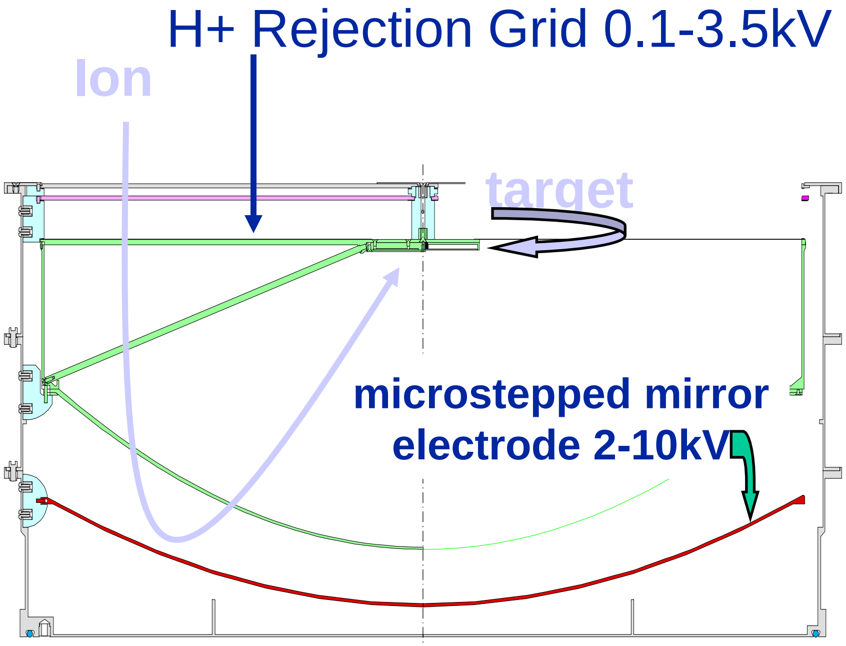


Stardust au CRPG : très riche en gaz rares
Contribution significative aux gaz rares des atmosphères planétaires

Apollo and Luna landing sites
Lick Observatory
Photograph




Magnetopause
Bow Shock
Magnetotail
Solar Wind
Cusp Region
Inner Radiation Belt
Stagnation Point
Plasma Sheet
Outer Radiation Belt
Magnetosphere
Magnetosheath



H+ Rejection Grid 0.1-3.5kV

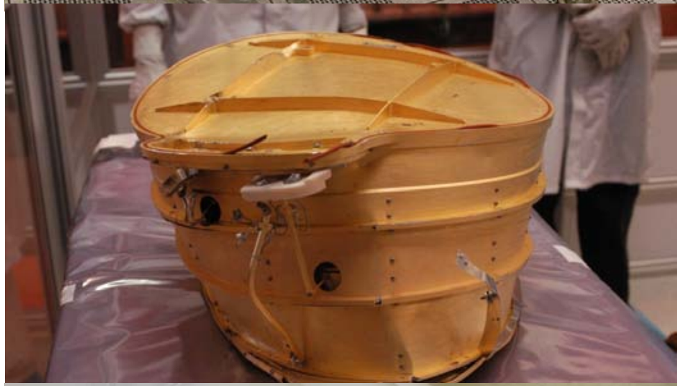
Ion

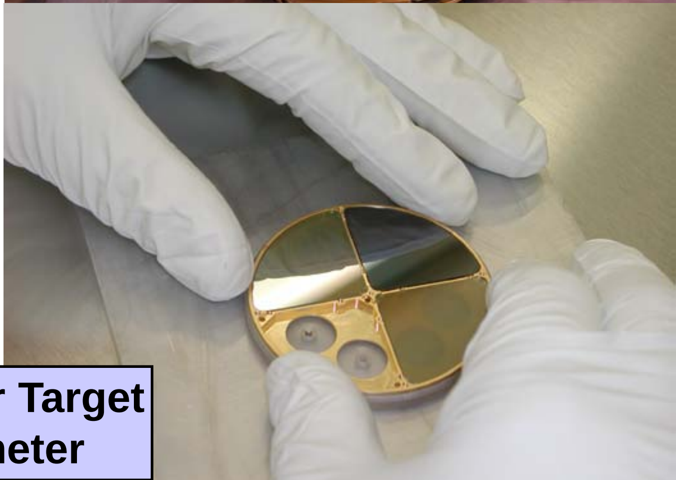
target

microstepped mirror electrode 2-10kV

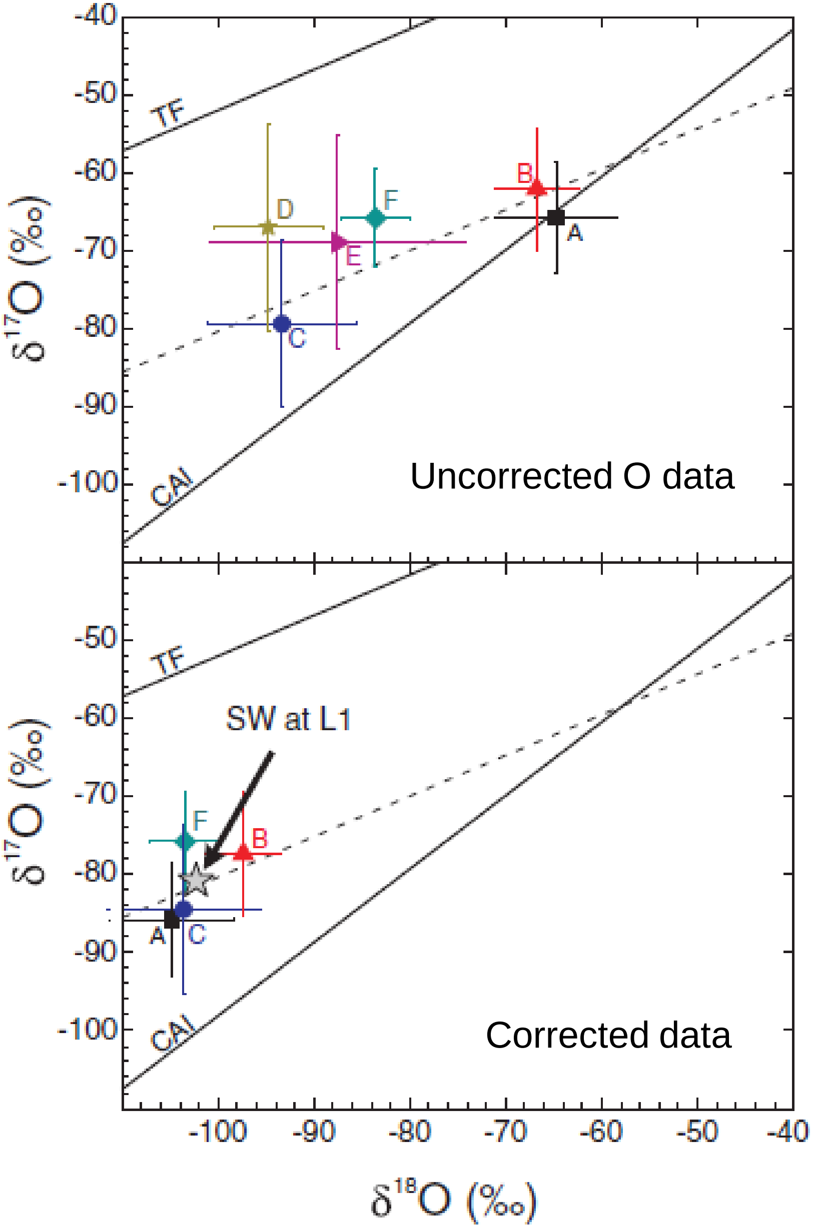
Target materials:

- Silicon Carbide
- diamond-like C film
- ^{13}C CVD Diamond





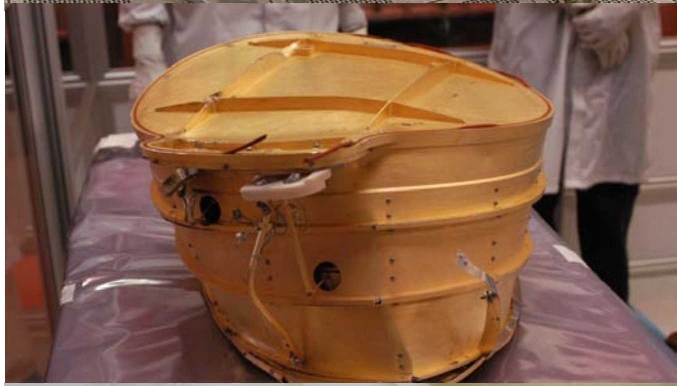
Concentrator Target
6 cm diameter

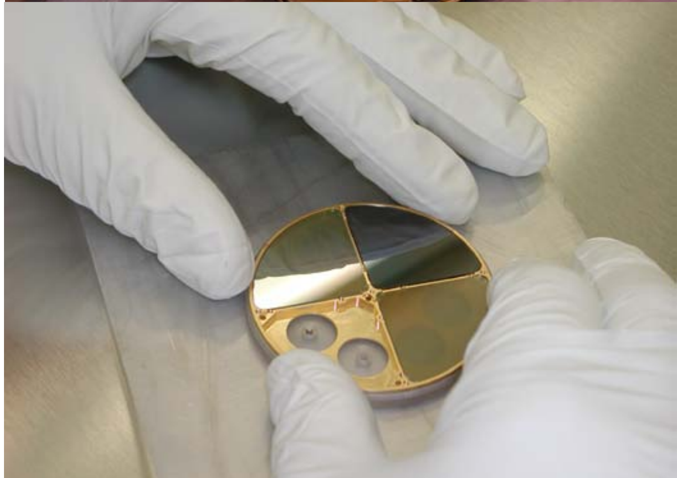

Uncorrected O data

Corrected data

SiC quadrant analyzed for O and N isotopes

O isotope data corrected for Concentrator's fractionation using Ne isotopes analyzed at ETH zurich along the same radius





Bochsler (2000) Coulomb Drag Model

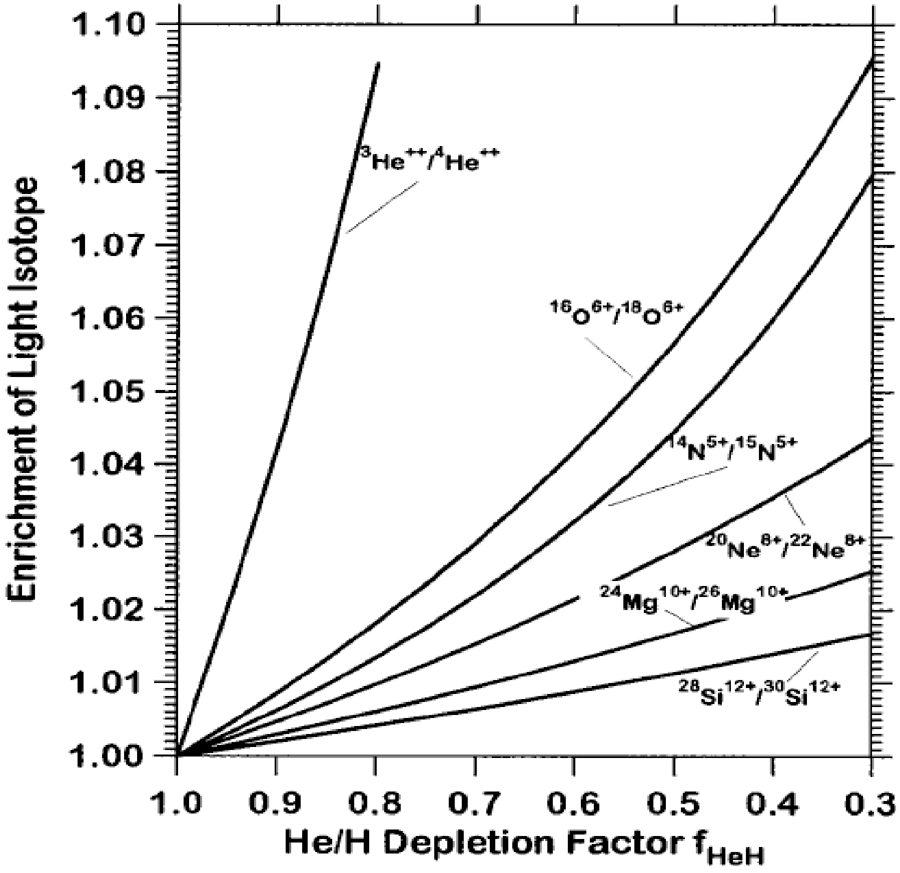
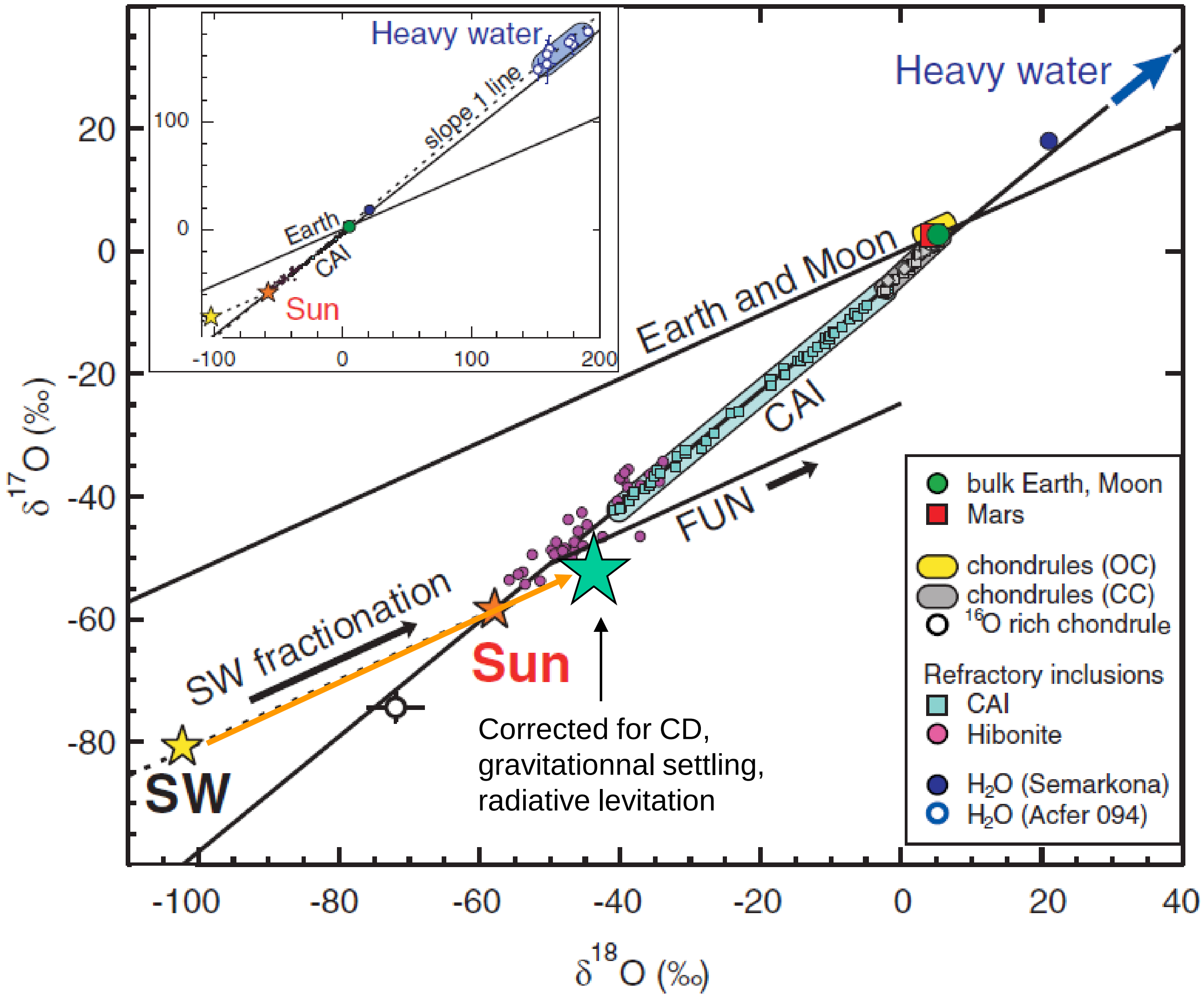


Figure 5. Expected isotope fractionation factors associated with He/H depletion factors. For instance, a depletion of He/H to 30% of its normal value in the equatorial streamer belt implies an enhancement of the $^{28}Si^{12+}/^{30}Si^{12+}$ ratio up to 1.7% over its normal coronal value.

All solar wind samples are depleted in He/H *elemental* relative to helioseismology solar ratio by about a factor of 2.5.

Model *assumes* that all He/H fractionation all due to Coulomb Drag.

With this assumption, fractionations for other isotope ratios can be calculated.



Corrected for CD, gravitationnal settling, radiative levitation

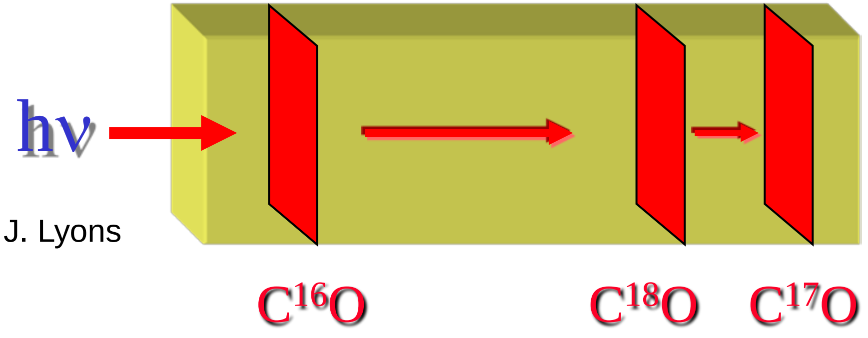
McKeegan et al., 2011

Origin of the oxygen isotope anomaly

- Requires process(es) able to increase ^{17}O and ^{18}O at equal rates
- Injection of nucleosynthetic ^{16}O unlikely (and no correlation with other isotope anomalies in cations (^{32}Si, ^{48}Ca, ^{50}Ti, ^{26}Al, etc.)
- Photodissociation of CO transfert of signal to H_2O

$$CO + h\nu(91-110) \rightarrow C + O \qquad \Delta^{17}O(O) > 0$$

$$O + H_2 \rightarrow H_2O \text{ (net)} \qquad \Delta^{17}O(H_2O) > 0$$



Courtesy of J. Lyons

Self shielding

- Could take place either at the disk surface through illumination by nearby stars (Lyons & Young, 2005), or in the collapsing cloud core (Yurimoto & Kuramoto, 2004)

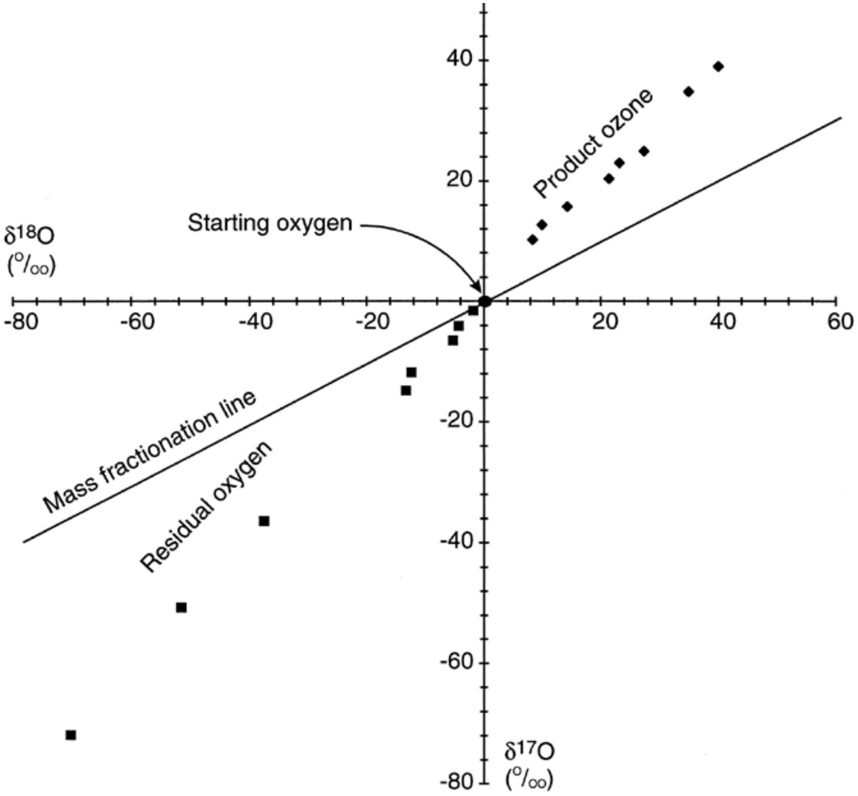
Origin of the oxygen isotope anomaly

- The issue of having $(^{17}O/^{16}O)/(^{18}O/^{16}O)$ equal exactly to 1 or not

- Absorption bands for predissociation of CO are, or are not, self-shielding

- requires more precise absorption cross sections in the bandwiths of interest

- “mass-independent” anomalies with a slope of 1 can be produced by some gas-phase chemical reactions (e.g., ozone production, Thiemens et al., 1999)



experimental data from Thiemens, 1999