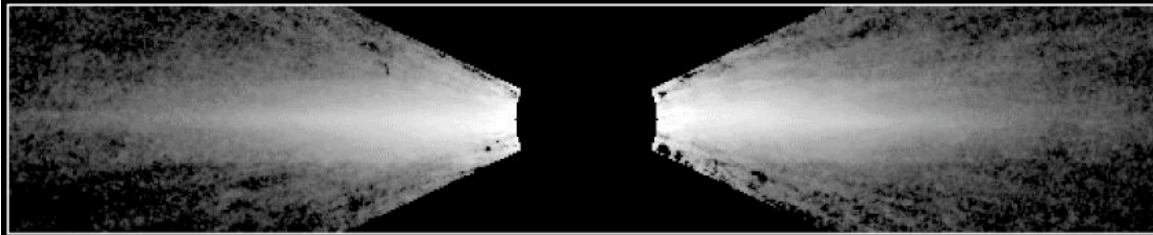
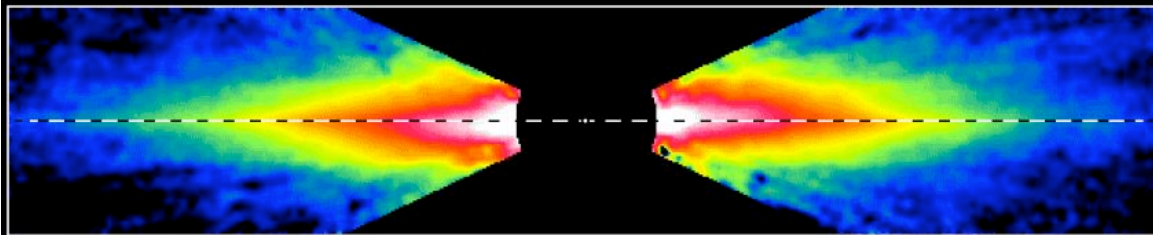


Du gaz aux grains et aux premières planètes: processus et chronologie



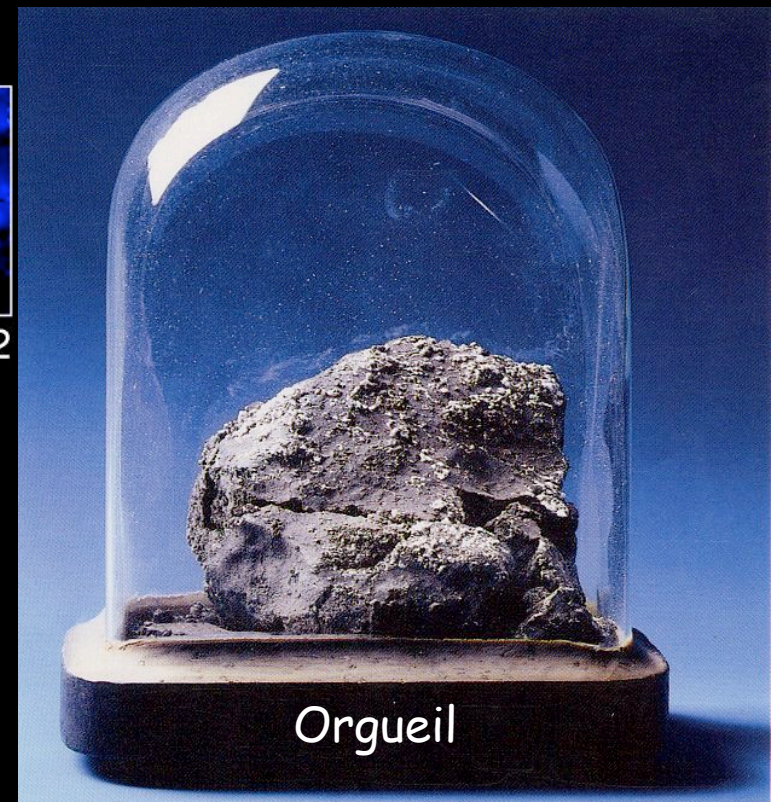
Size of Pluto's Orbit



Warped Disk · Beta Pictoris

HST · WFPC2

PRC96-02 · ST ScI OPO · January 17, 1995 · C. Burrows and J. Krist (ST ScI), WFPC2 IDT, NASA



Orgueil

Composition et formation des premiers solides du
Système Solaire

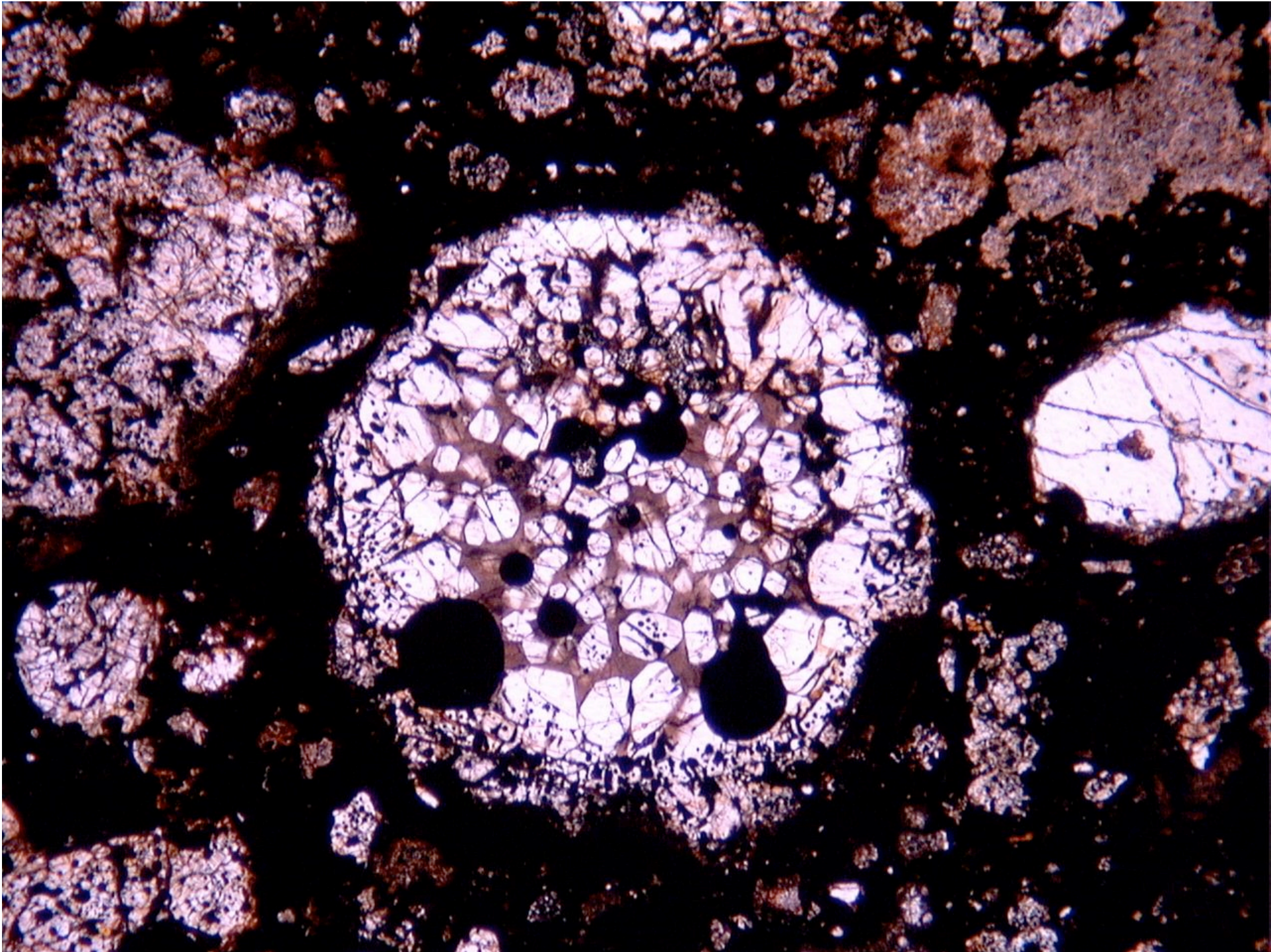
Compositions dans le Système Solaire

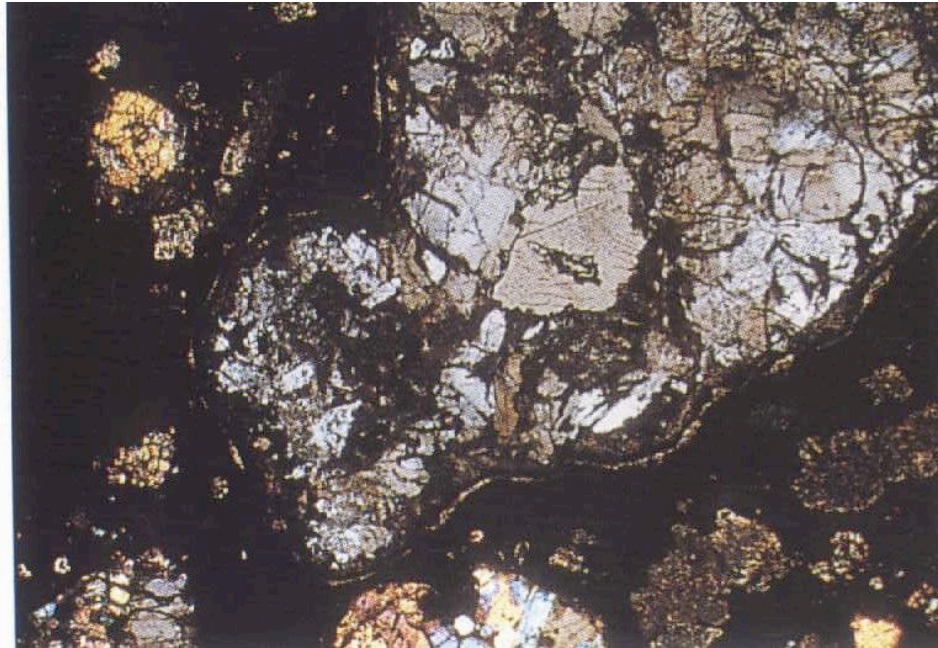
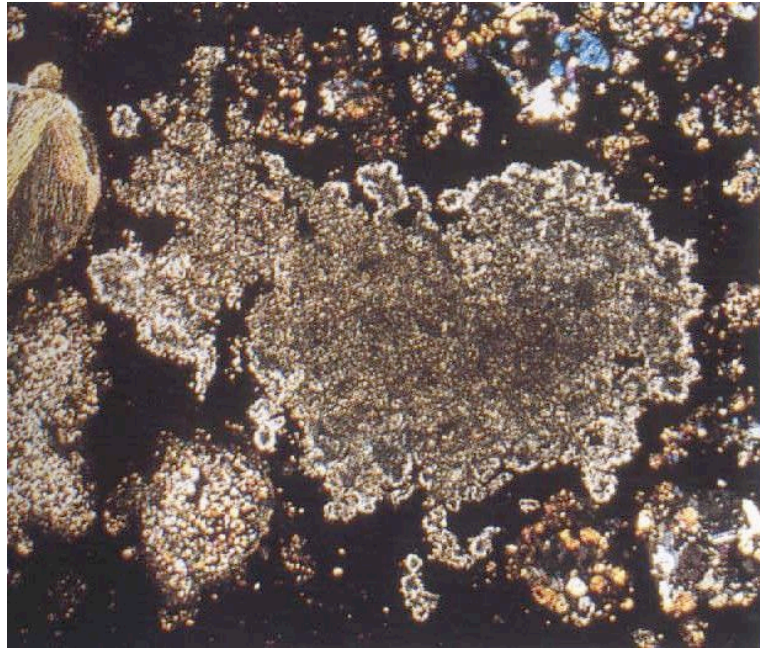
Les disques protoplanétaires: théorie

Les disques protoplanétaires: observations &
interprétations physiques



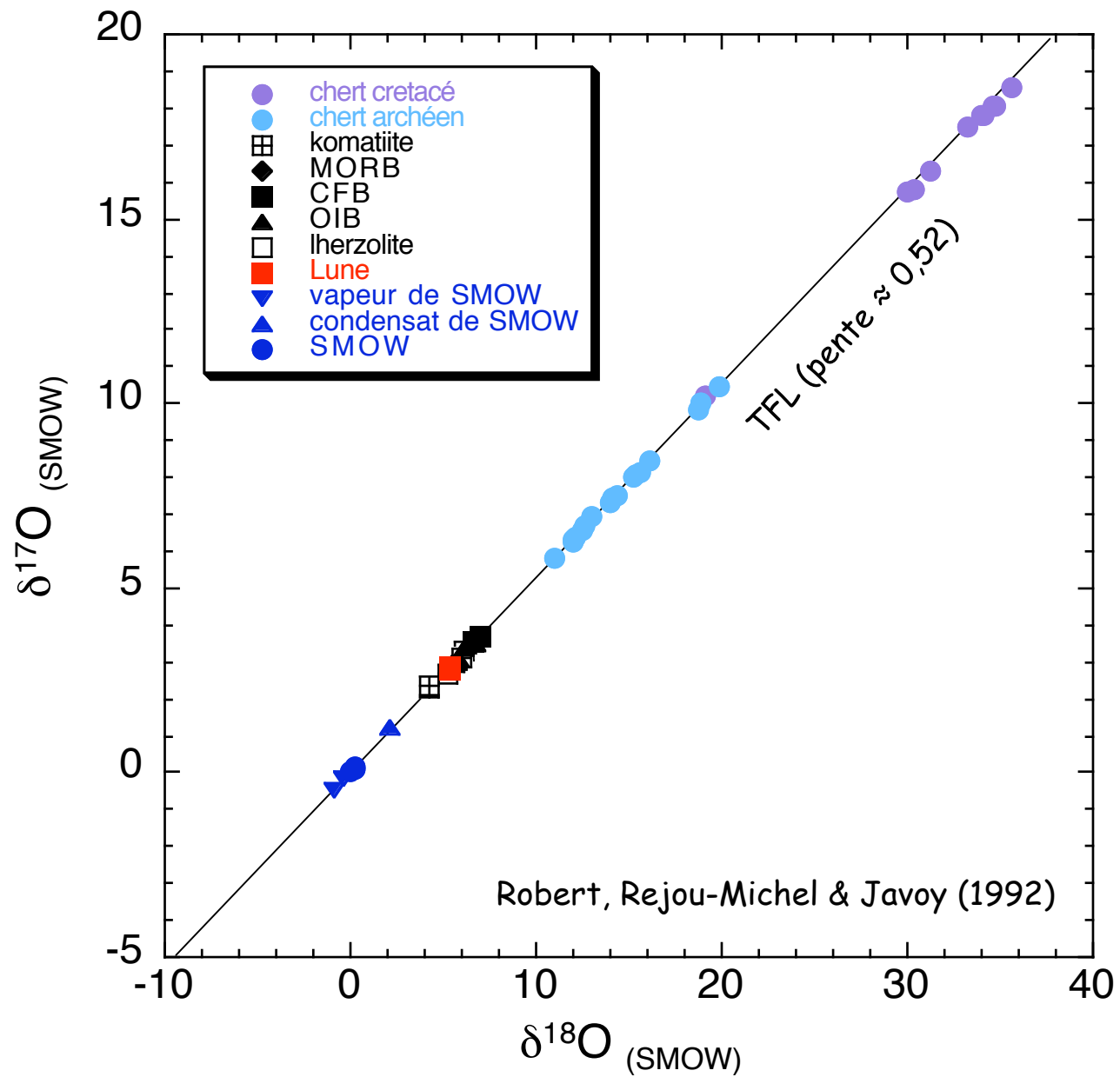
Chondrites = roches sédimentaires formées dans la nébuleuse solaire





Inclusions réfractaires
riches en Ca et en Al (CAIs)
= composants parmi les plus
primitifs à l'intérieur des
météorites primitives

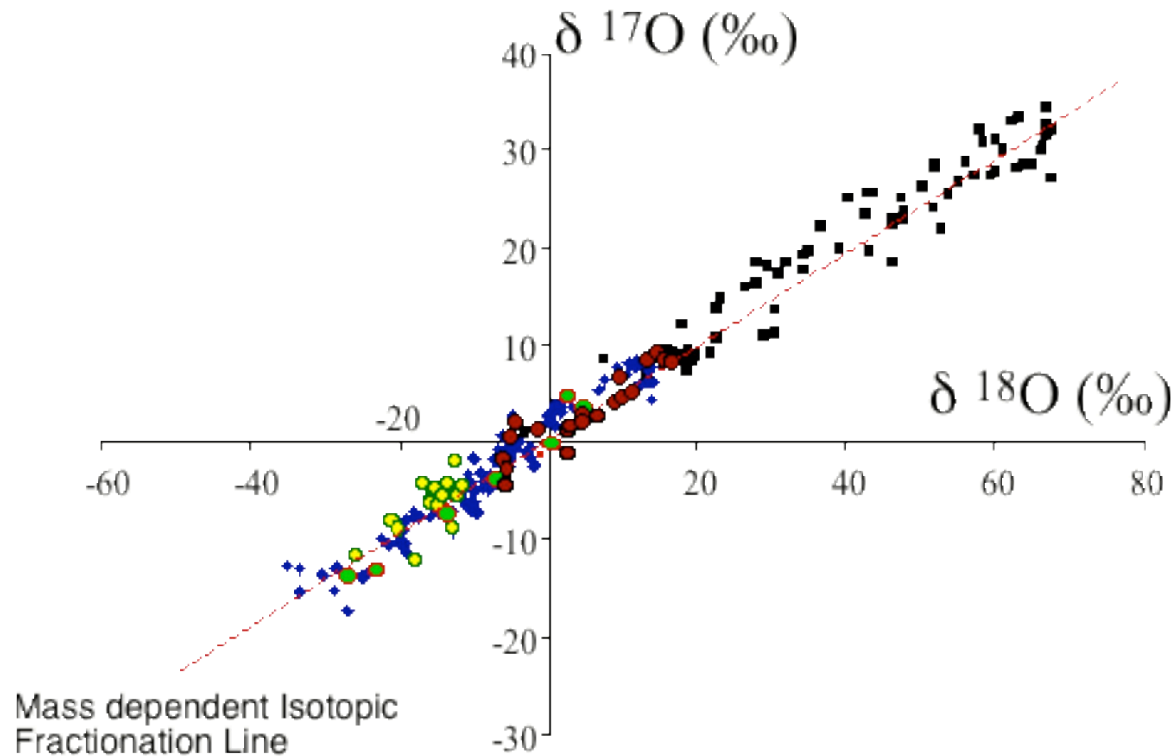
- composition solaire (pour la plupart des rapports isotopiques)
- composition réfractaire : formés à très haute température (près du Soleil ?)
- âges les plus anciens parmi tous les composants des météorites ($4567,2 \pm 0,6$ Ma)



Expériences d'évaporation et de condensation (avec réactions dans le gaz)

(Robert & Chaussidon, non publié)

Evaporated Solids	Gas	Pressure	T (condensation)
■ SiO ₂	CO ₂	5 × 10 ⁻³	1400 K
◆ SiO ₂	CO ₂	5 × 10 ⁻¹	1280 K
● SiO ₂	CO ₂	5 × 10 ⁻¹	1200 K
● SiO ₂ + Al	CO ₂	5 × 10 ⁻¹	1270 K
● SiO ₂ + Al	CO ₂	5 × 10 ⁻³	1160 K



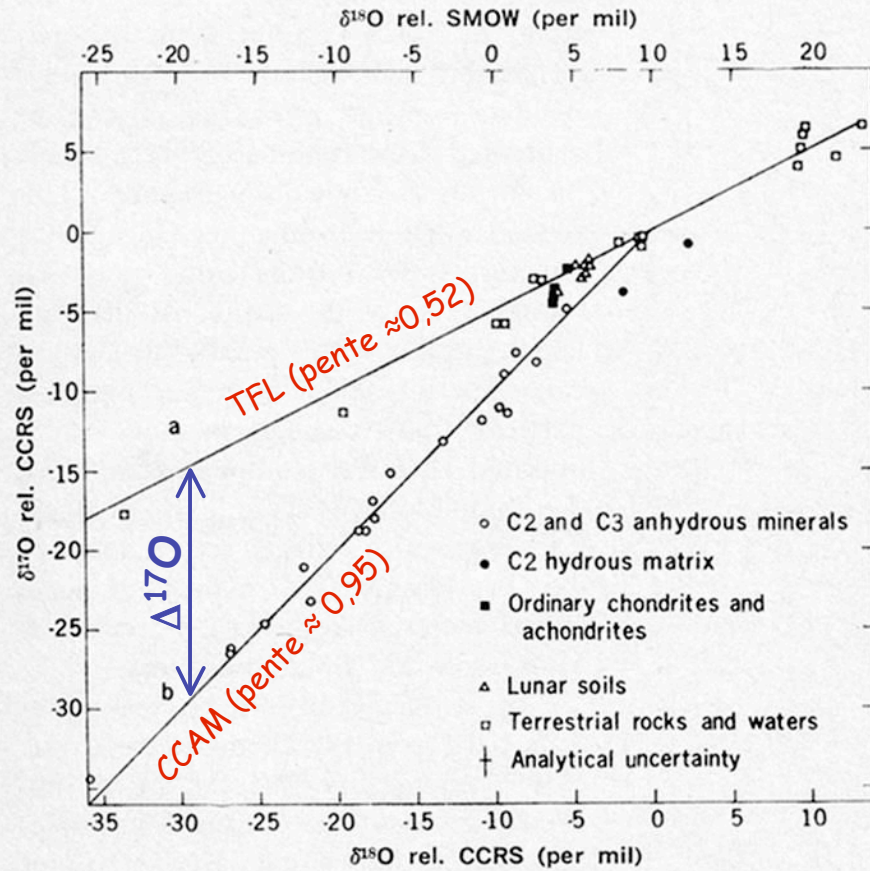


Fig. 1 (left). Relationship between $^{17}\text{O}/^{16}\text{O}$ variations and $^{18}\text{O}/^{16}\text{O}$ variations for terrestrial, lunar, and meteoritic samples. Points lying along line a, with a slope of $+1/2$, define the trend for chemical isotope effects; points lying along line b, with a slope of $+1$, define a mixing line between "normal" oxygen and an ^{18}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)].

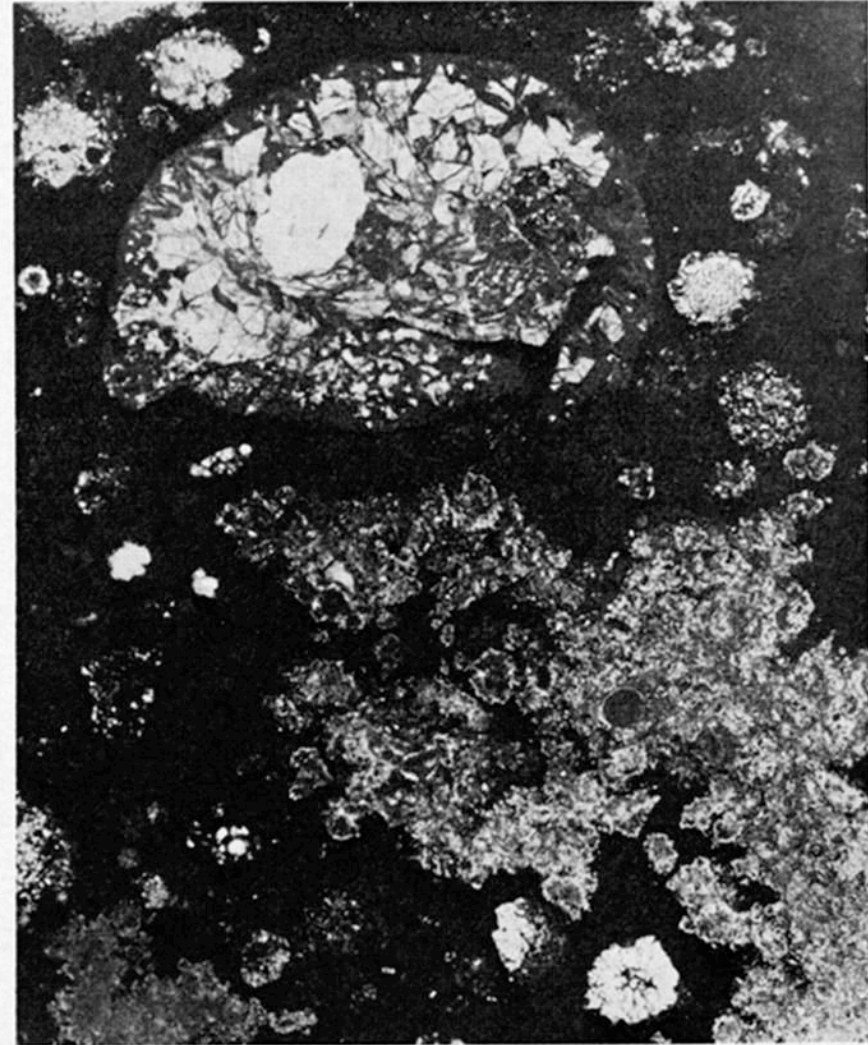
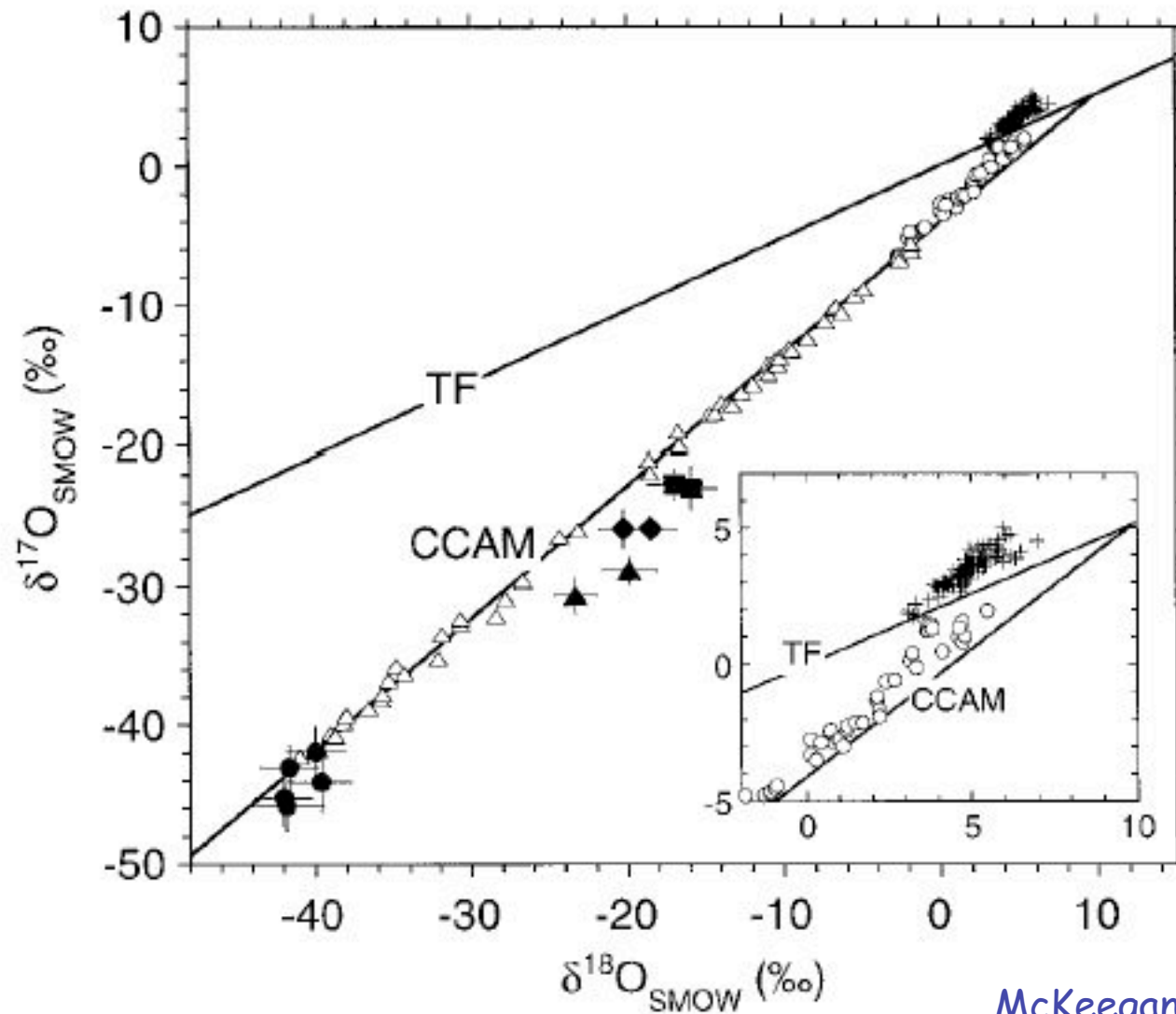


Fig. 2 (right). Photomicrograph of a section of the Allende meteorite, showing two large white inclusions (see text). Area of section, 8 by 10 mm. [Courtesy Richard J. Kjarval, Graphic Arts Facility, Physical Sciences Division, University of Chicago]

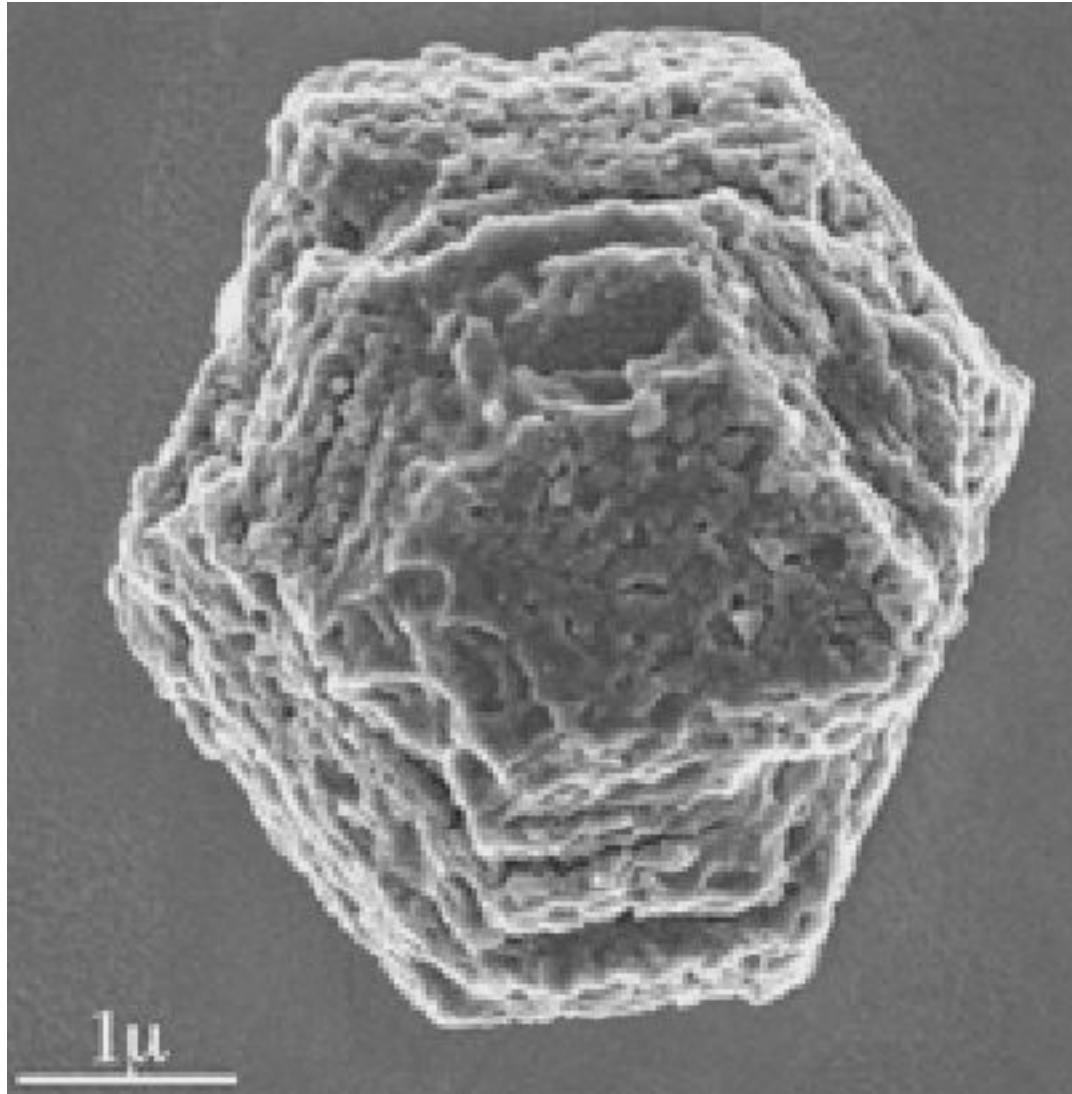
Clayton, Grossman & Mayeda (1973)

Excès de ^{16}O dans les CAIs et les chondres des chondrites carbonées et des chondrites ordinaires



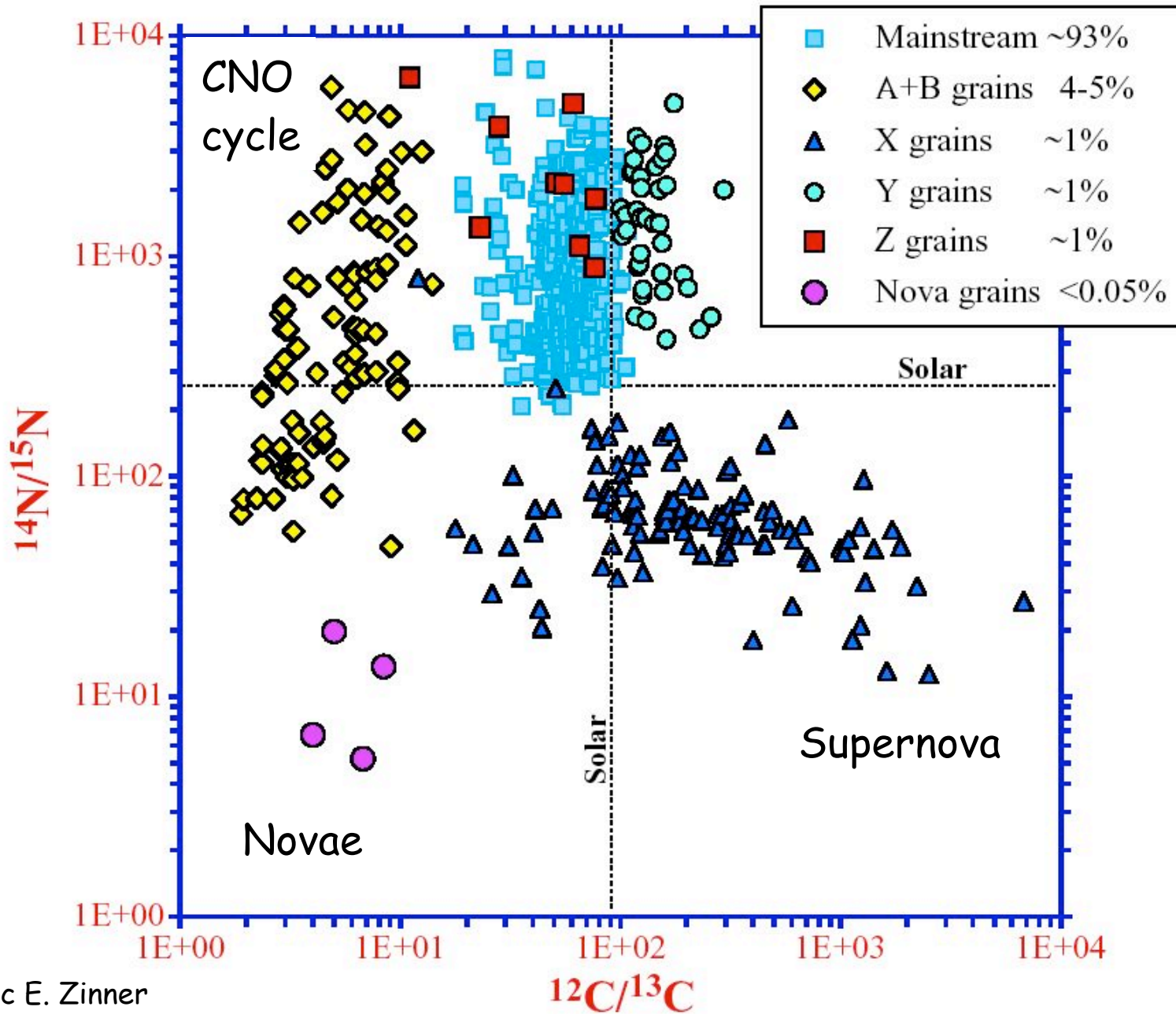
McKeegan et al., 1998

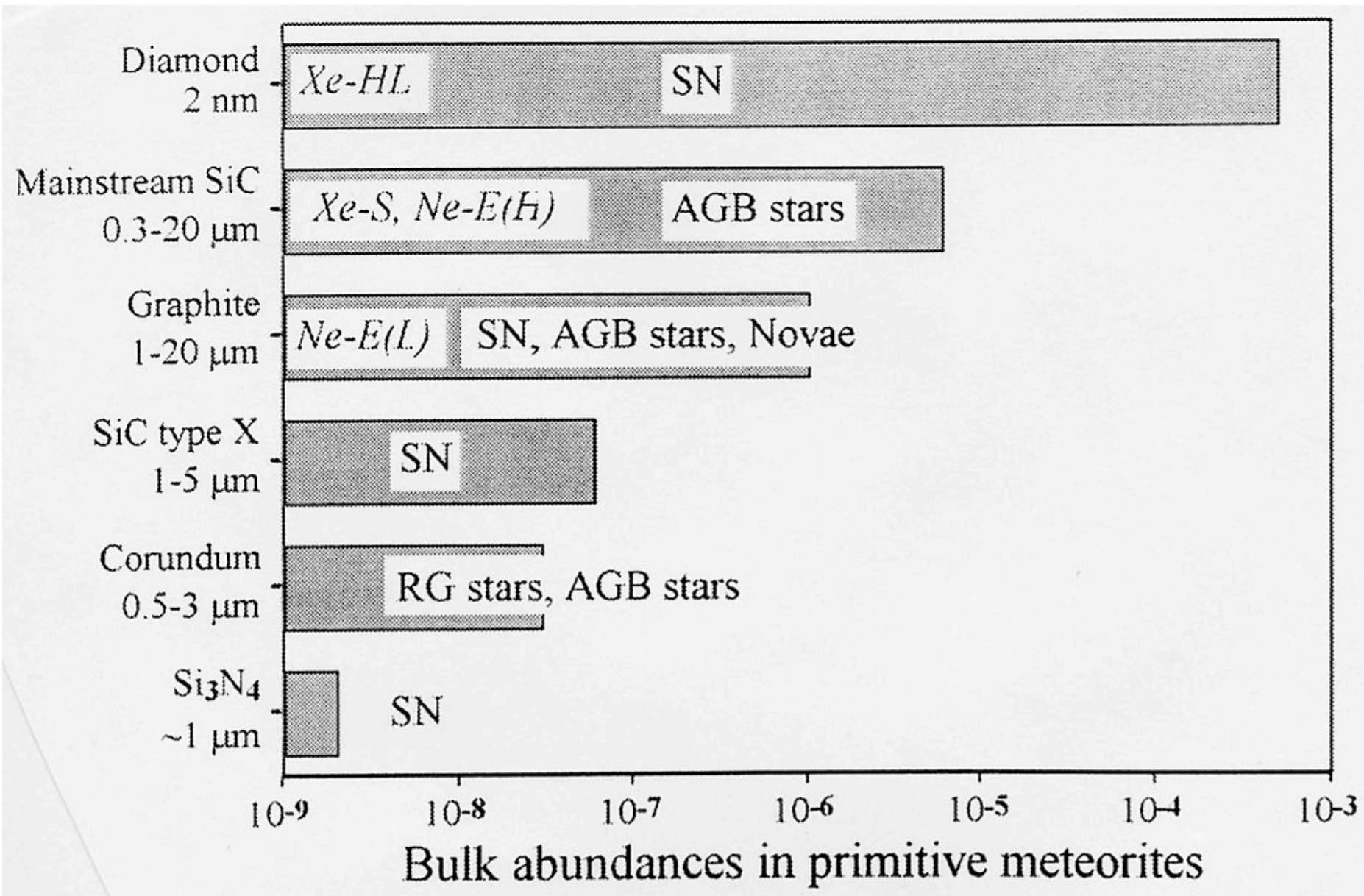
SiC présolaire (après attaque acide)



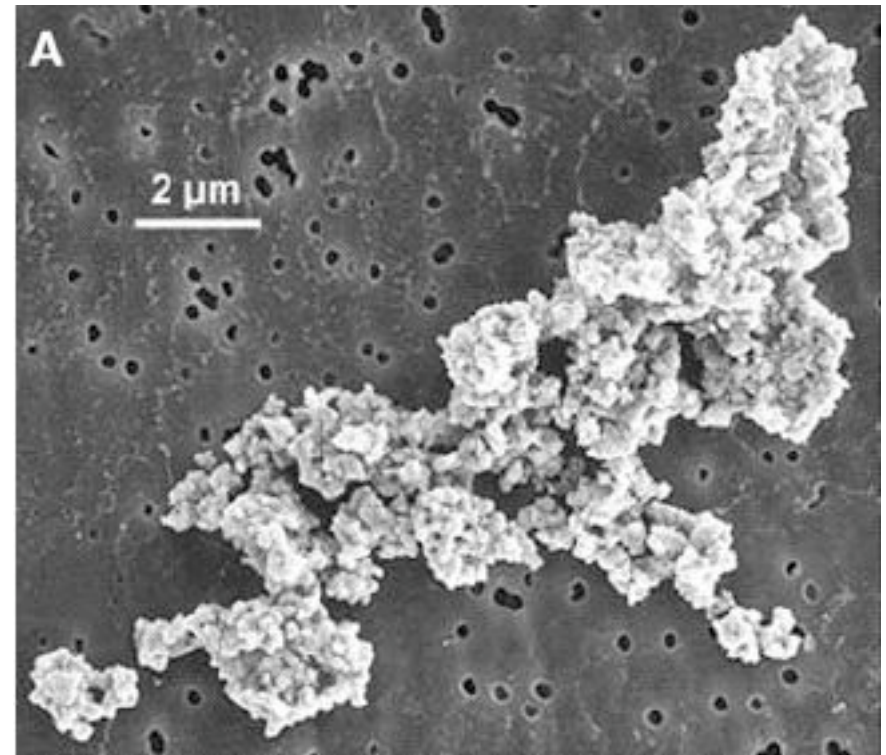
Bernatovicz et al. (2000)

Presolar SiC grains





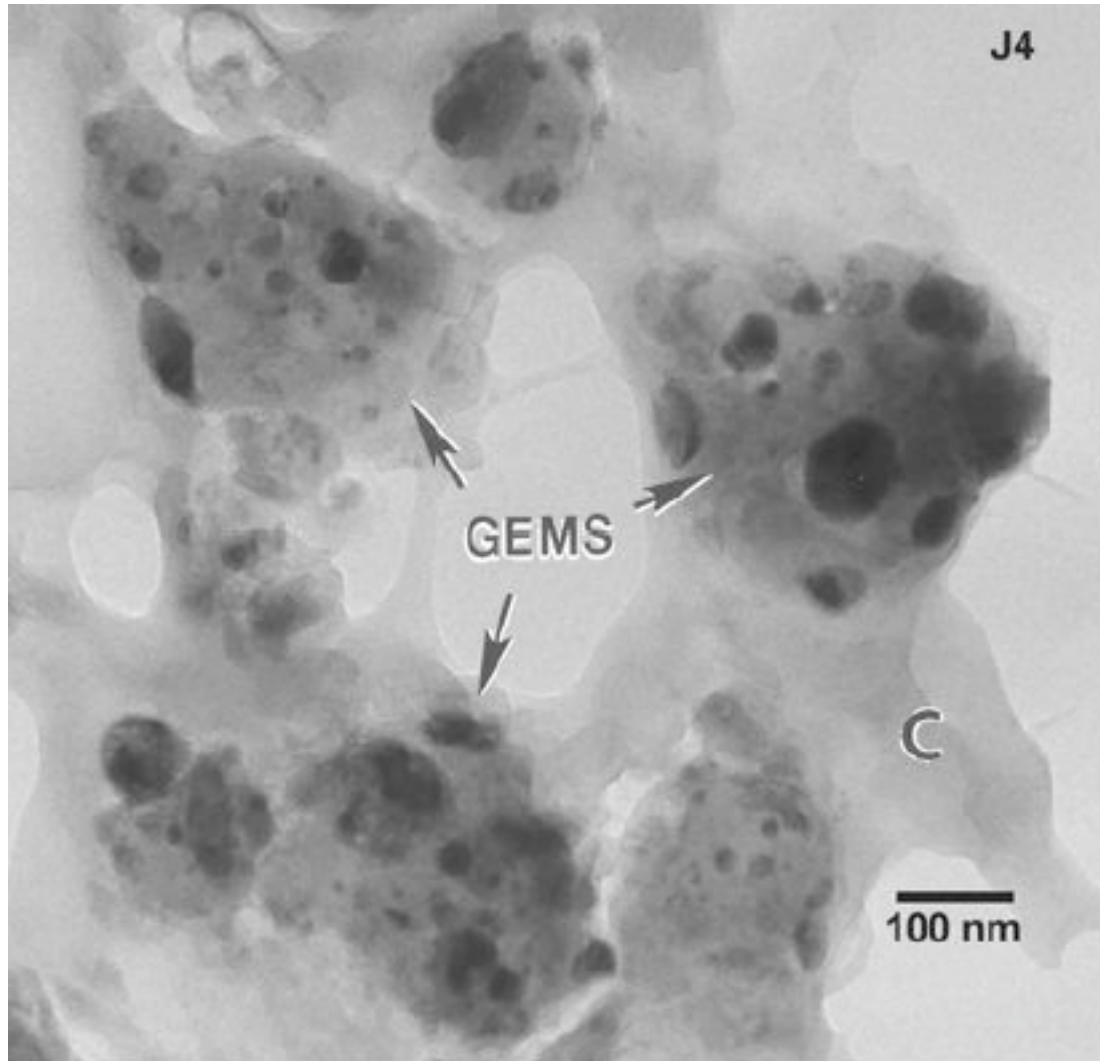
Les particules de poussière
interplanétaires
(IDPs)



Bradley et al. (2005)

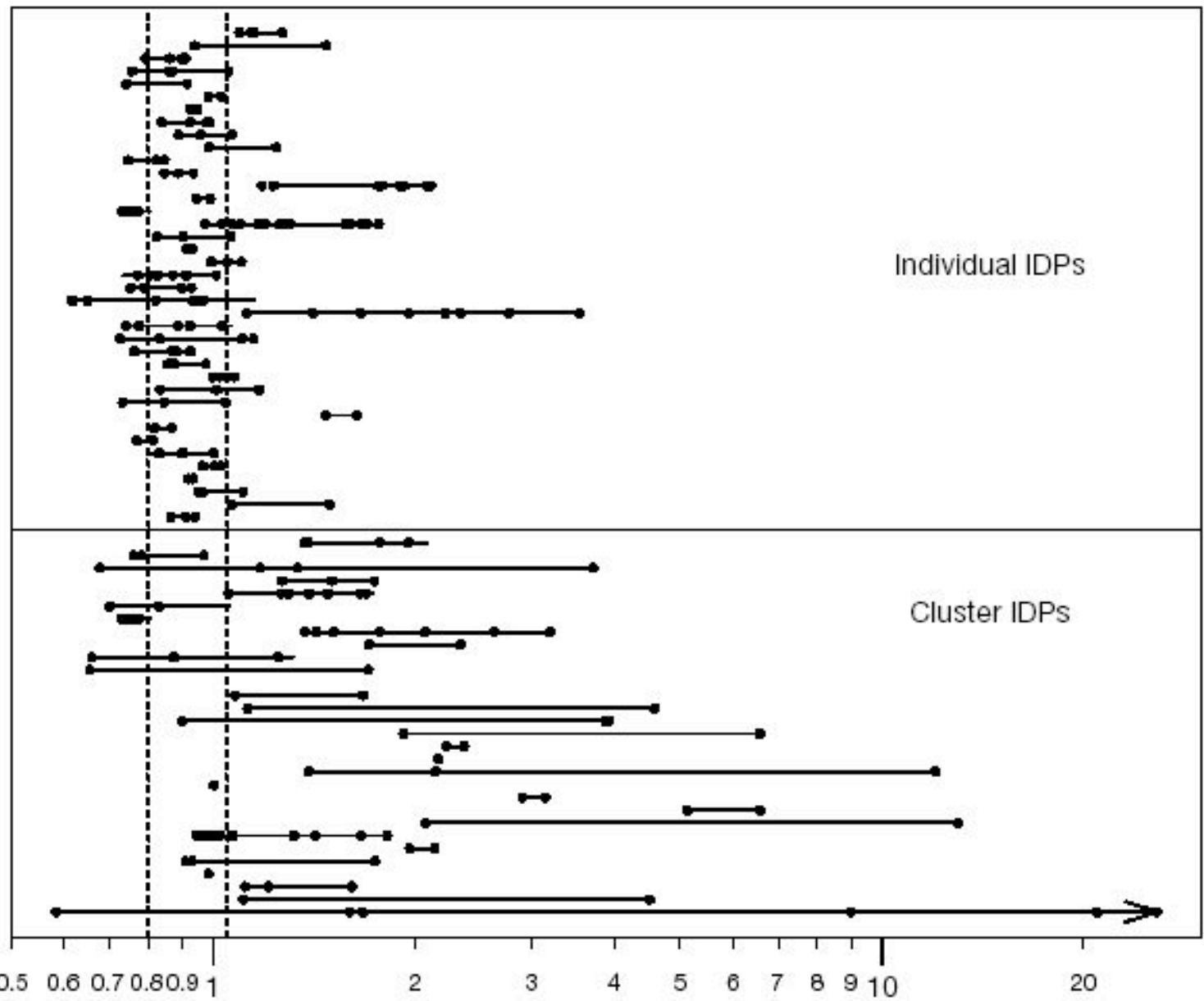
- CP IDPs (chondritiques et poreuses) : GEMS + px & ol pauvres en Fe + sulfure de Fe & Ni. (grain fin $\approx 0.1\mu\text{m}$, [C] & [S] > 4 % pds, chondritiques au nm !
fragments de comètes ?
- CS IDPs (chondritiques) : phyllosilicates + carbonates + silicates
fragments d'astéroïdes, chondrites CI ou CM

Les IDPs chondritiques poreuses vues de plus près



- = mélange dans une matrice carbonée riche en matière organique de :
- silicates cristallins à grain fin
 - GEMS (glass with embedded metal & sulfides)
 - sulfures de Fe et de Ni

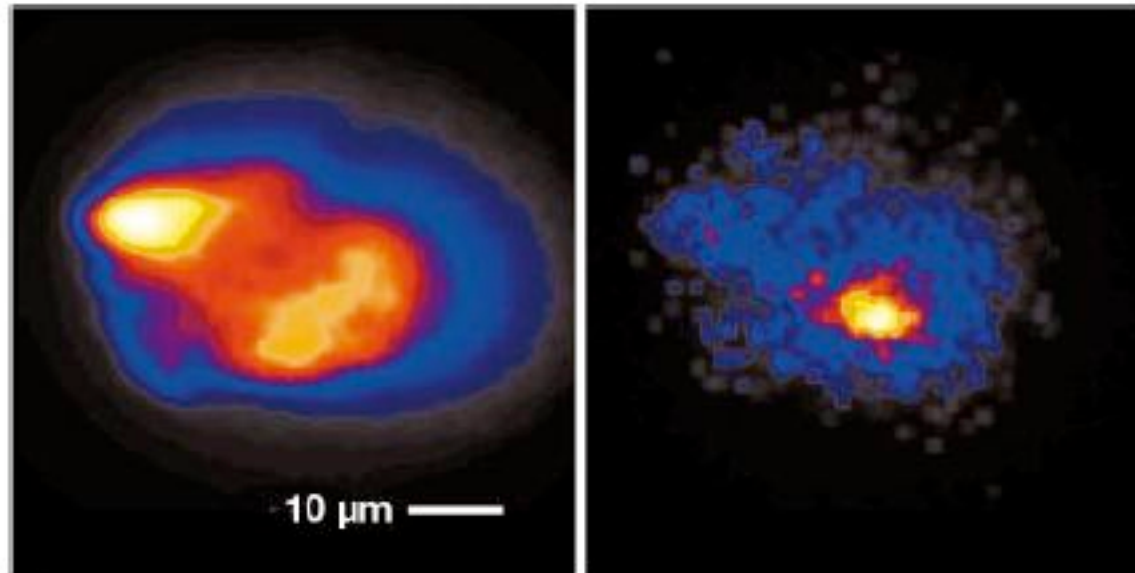
Keller & Messenger (2004)



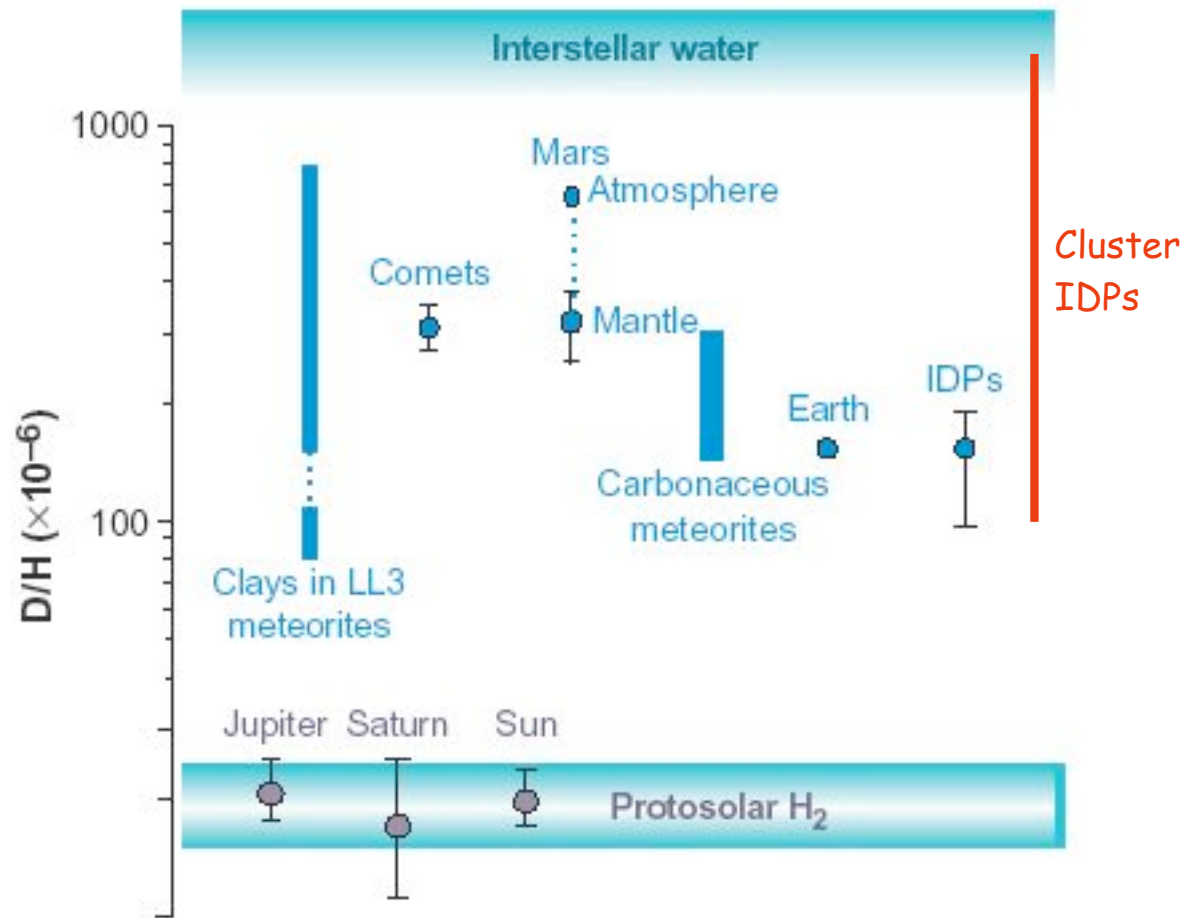
Messenger (2000)

$(D/H)_{IDP} / (D/H)_{SMOW}$

Hétérogénéités de D/H présentes à l'échelle du micron

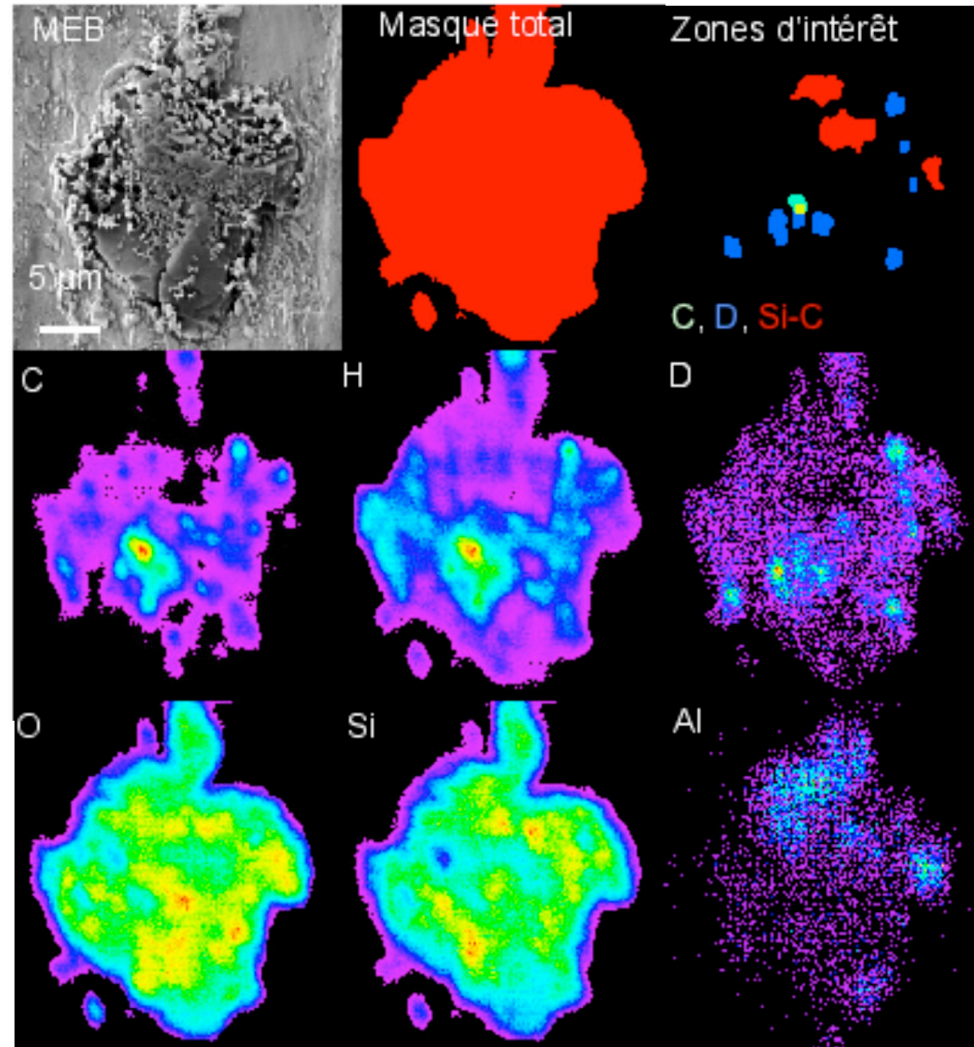


Messenger (2000)

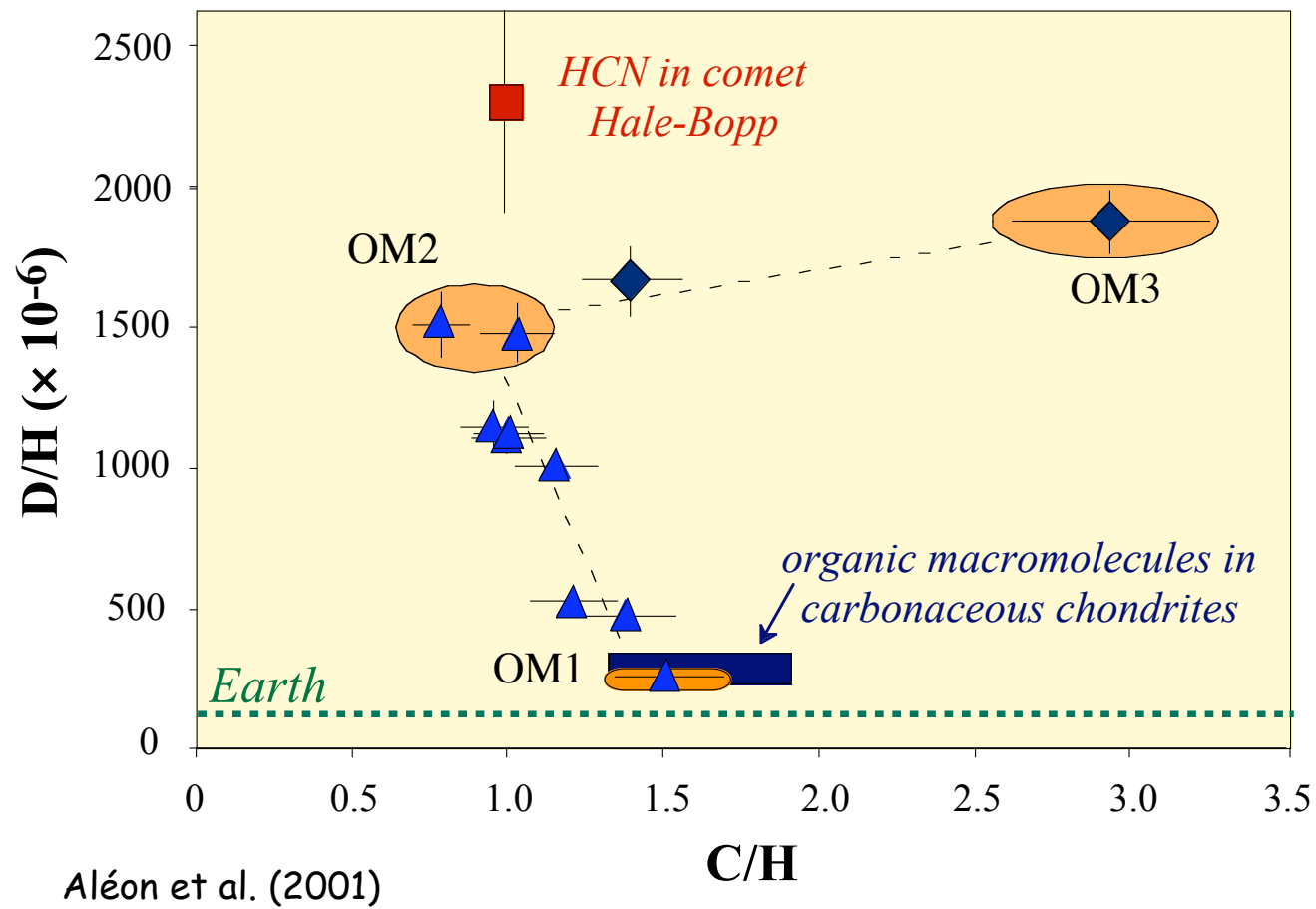


Robert (2001)

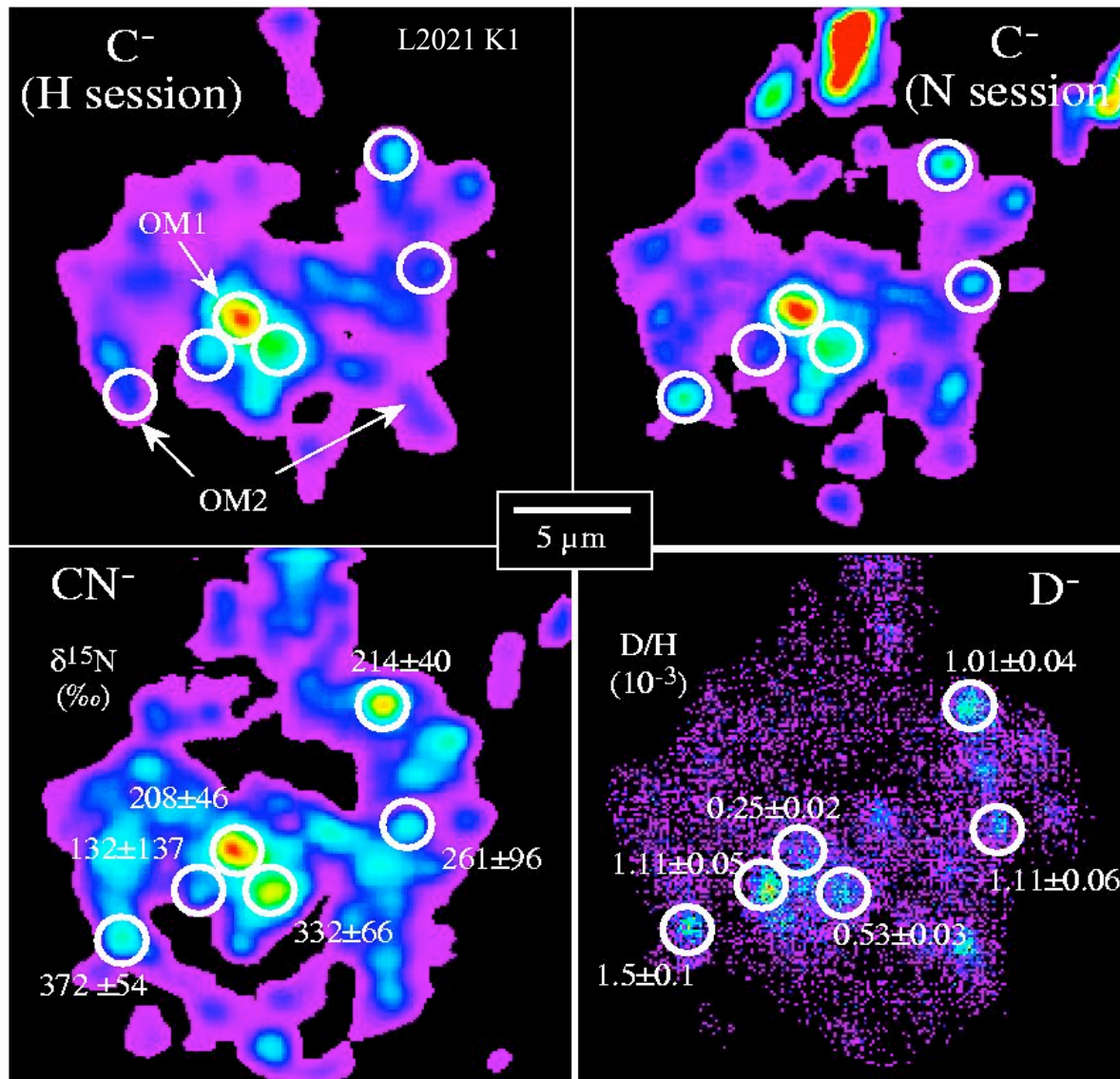
Les enrichissements en Deuterium sont portés par de la matière organique



Aléon et al. (2001)



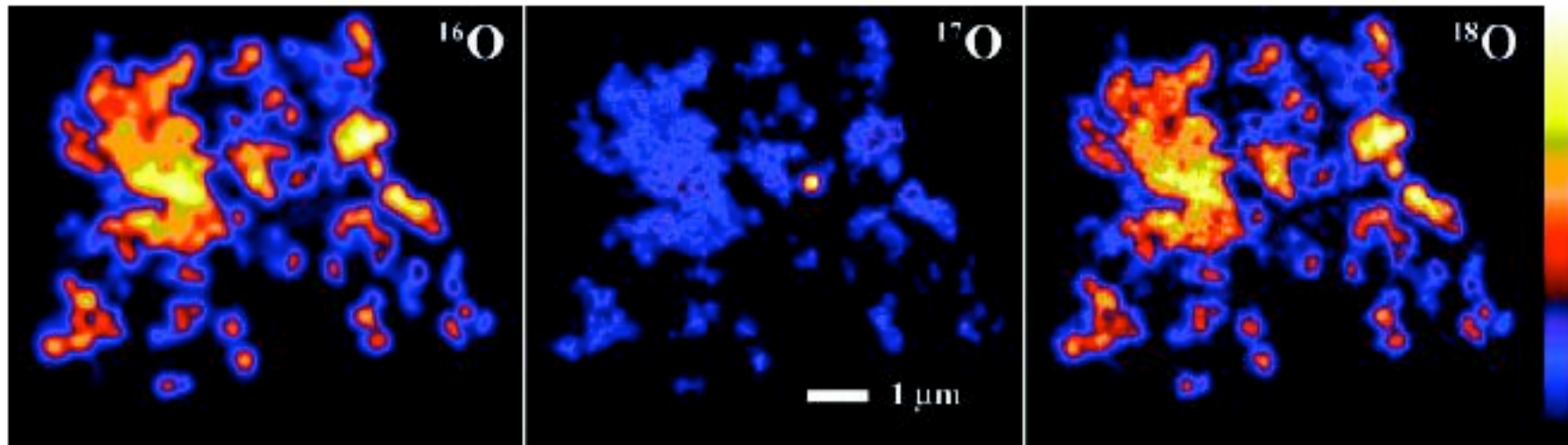
Les enrichissements en ^{15}N sont couplés aux enrichissements en D dans la matière organique



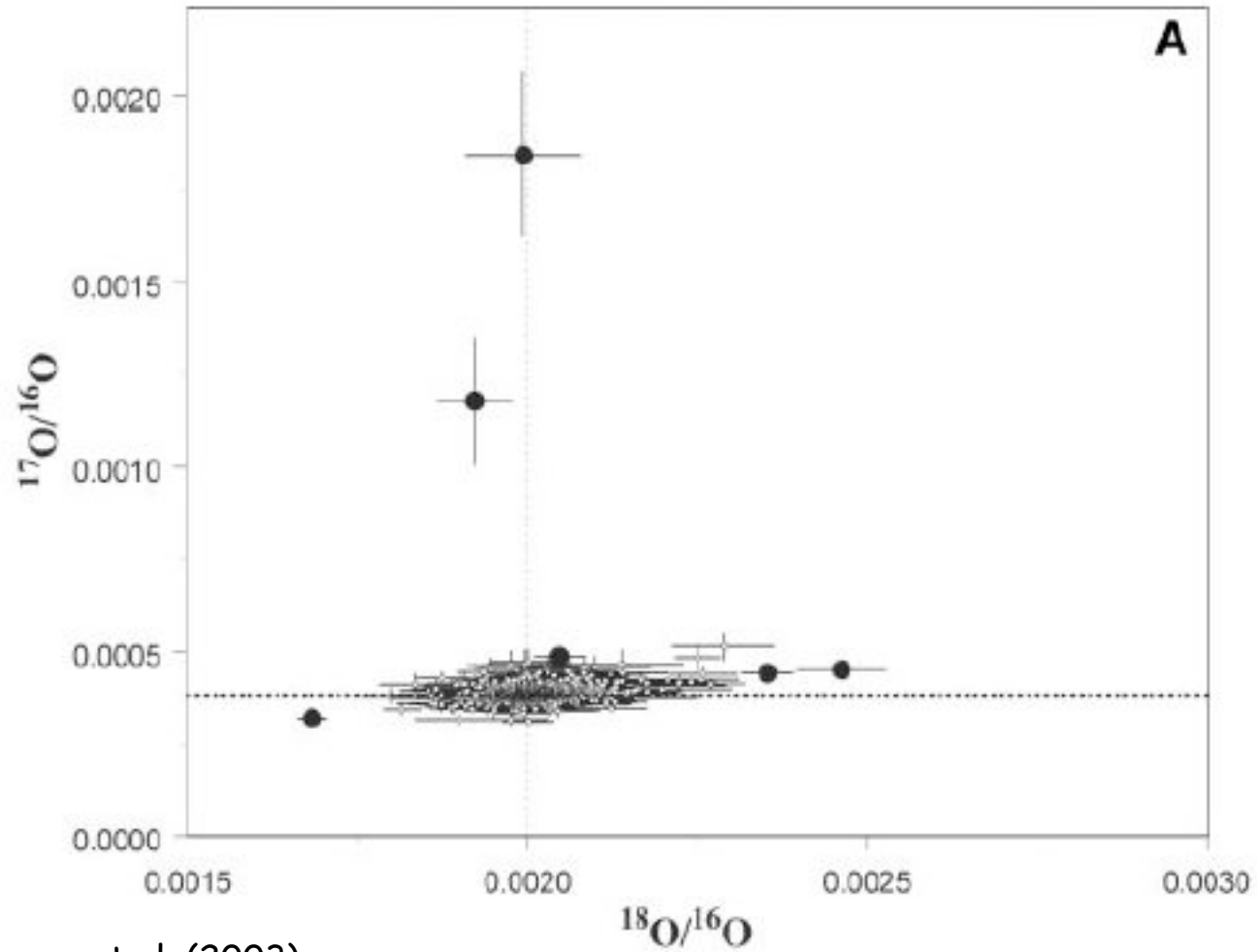
matière macromoléculaire
dont la composition
isotopique est héritée
de réactions chimiques
dans le milieu
interstellaire froid.

Aléon et al. (2003)

Les IDPs chondritiques poreuses contiennent des silicates présolaires



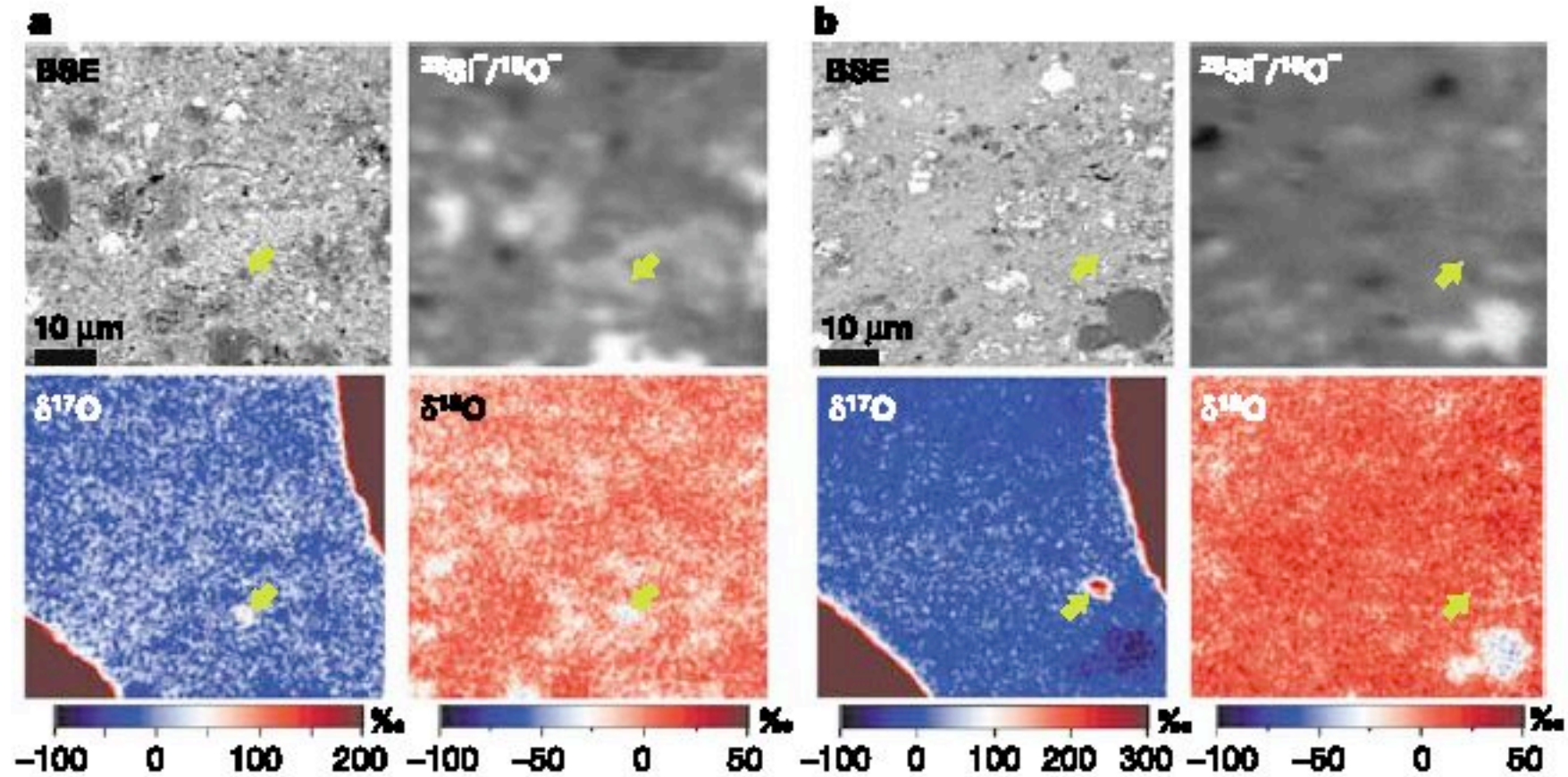
Messenger et al. (2003)



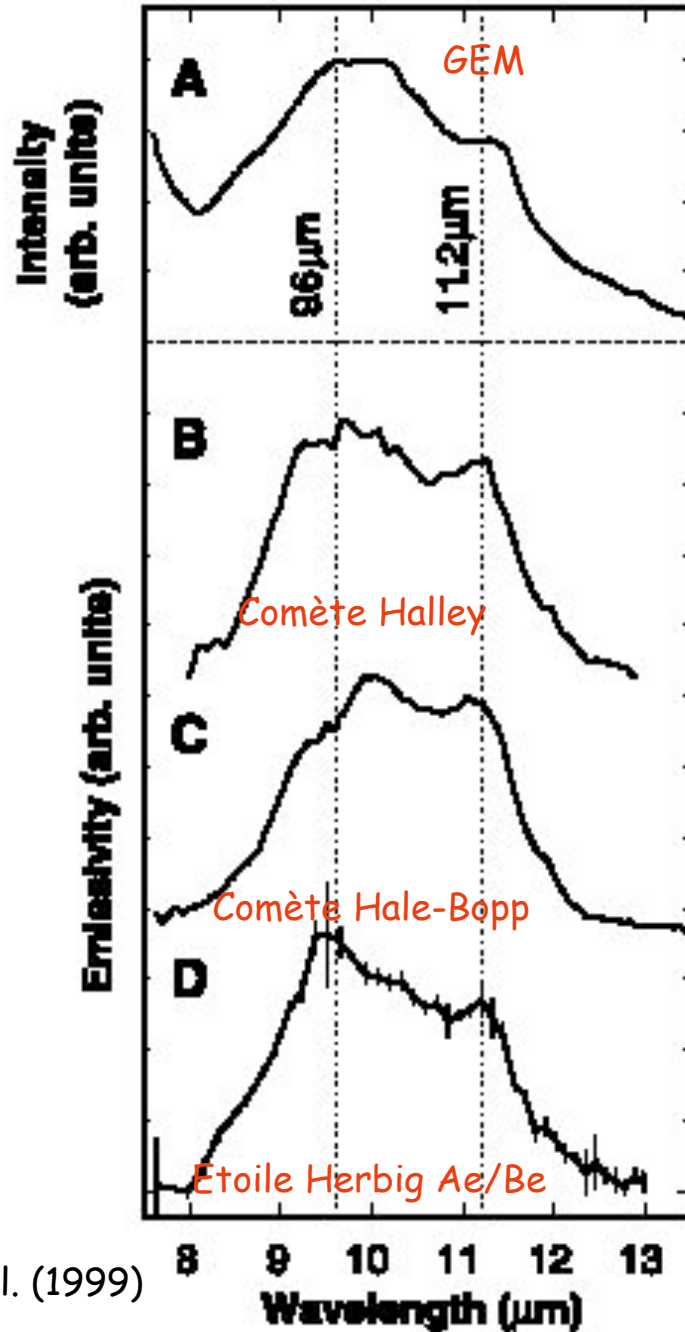
Messenger et al. (2003)

fraction de silicates présolaires ≈ 5500 ppm
 (à la fois silicates cristallins et amorphes - GEMS-)

Il existe aussi des silicates présolaires dans la matrice des chondrites, mais apparemment en moindre abondance ($\approx 3\text{-}30$ ppm)

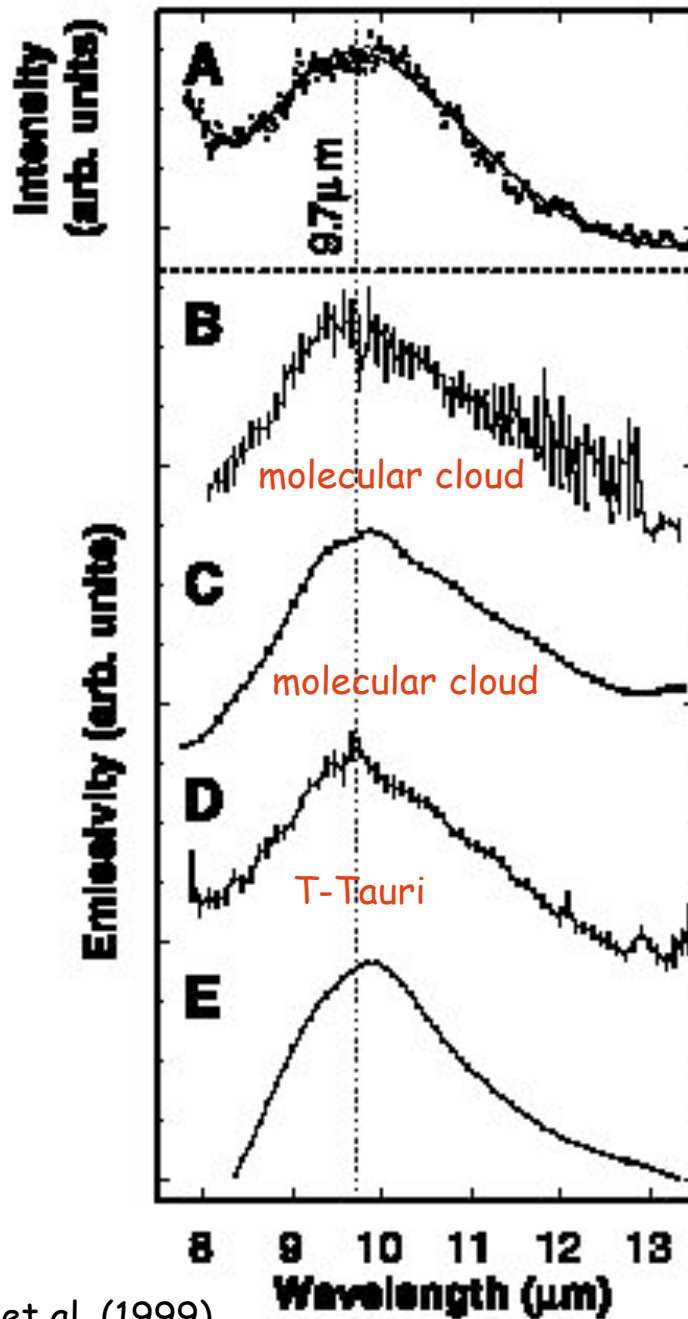


Nagashima et al. (2004)



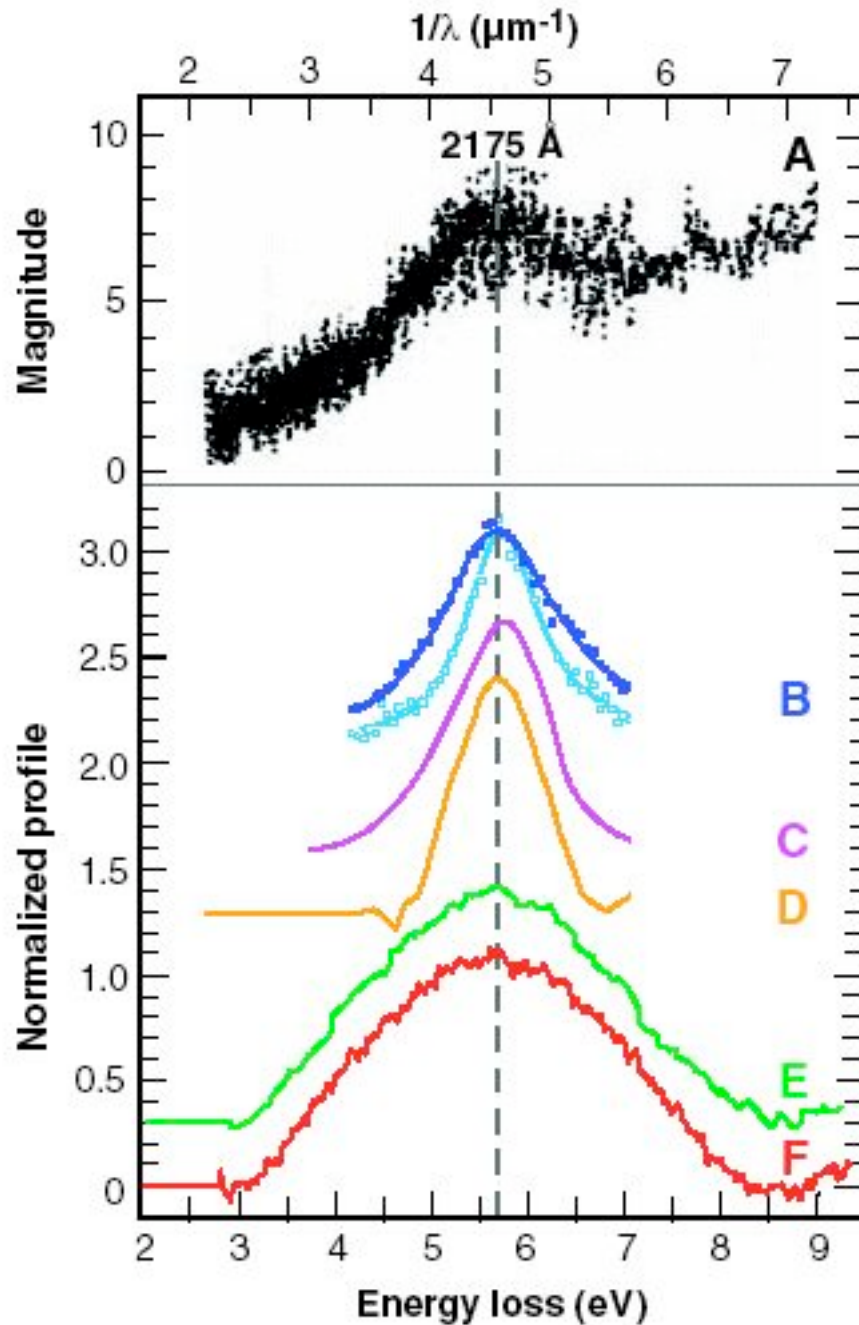
Les spectres dans l'IR des GEMS sont très semblables à ceux des comètes

Bradley et al. (1999)



Les spectres dans l'IR des GEMS sont très semblables à ceux des silicates amorphes du MIS

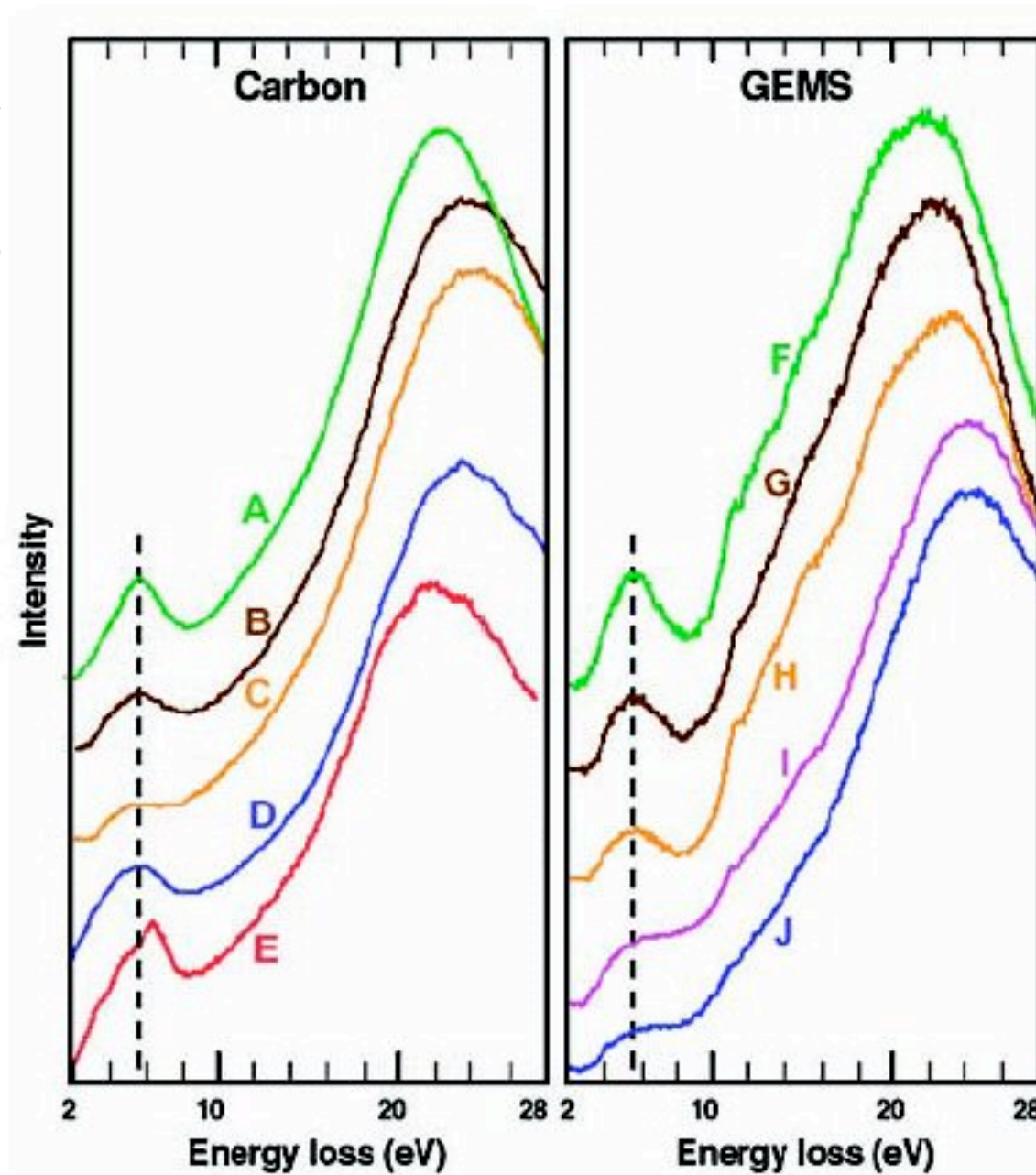
Bradley et al. (1999)



Comparaison entre les spectres d'extinction UV-visible du MIS et ceux des IDPs

Bradley et al. (2005)

Spectres
extinction UV
dans des sous
Grains d'IDPS

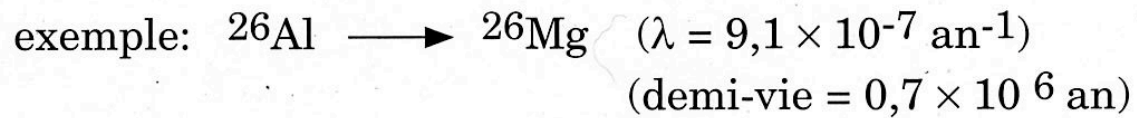


Quelques questions d'actualité

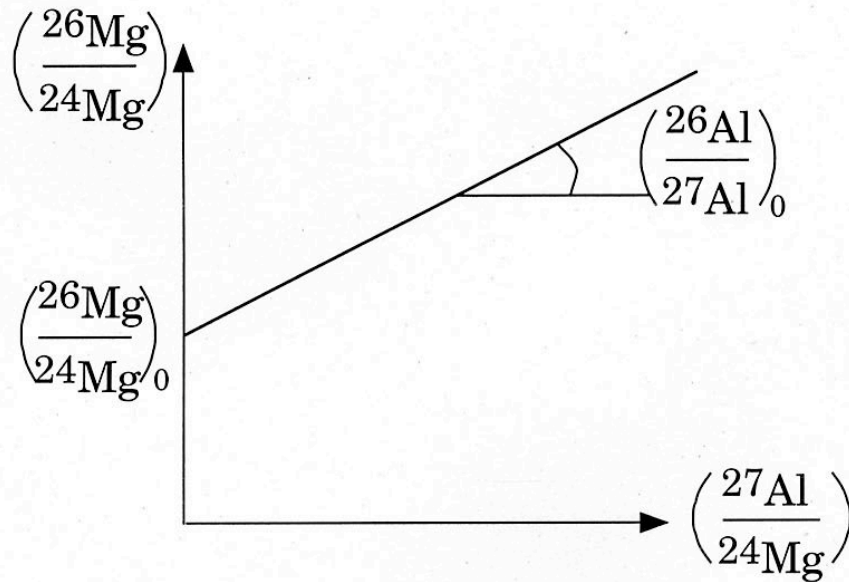
- contexte astrophysique de la naissance du système solaire
(origine des radioactivités éteintes)
- origine des premiers solides
(condensation, CAIs, chondres)
- durée des processus de haute température
(âge des CAIs et des chondres)
- vitesse à laquelle les premières planètes se différencient
(angrites, ...)
- différence de composition isotopique entre le gaz et les solides
(vent solaire)

- Mise en évidence des radioactivités éteintes grâce aux produits de désintégration stables

Radioactivité éteinte : $P_0 - \cancel{P} = F - F_0$



- Comment peut on la détecter dans une météorite ?



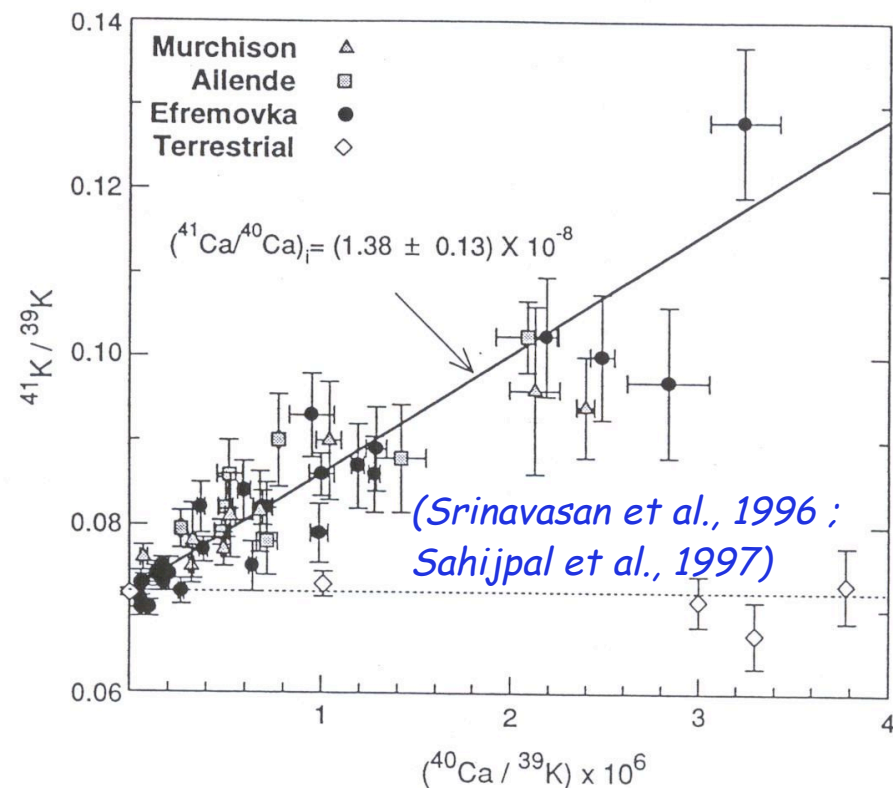
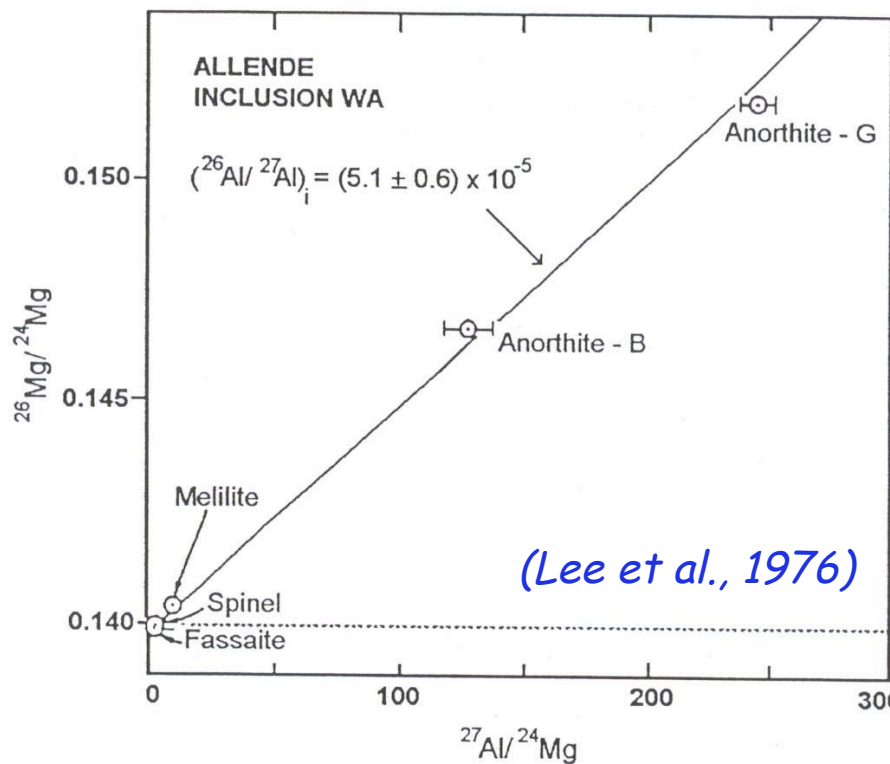
$$^{26}\text{Mg} = ^{26}\text{Mg}_0 + ^{26}\text{Al}_0$$

$$\left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right) = \left(\frac{^{26}\text{Mg}}{^{24}\text{Mg}}\right)_0 + \left(\frac{^{26}\text{Al}}{^{27}\text{Al}}\right)_0 \times \left(\frac{^{27}\text{Al}}{^{24}\text{Mg}}\right)$$

décroît avec le temps
en $e^{-(\lambda \times t)}$

Evidence for the presence of short-lived nuclides in the early solar system

- decay products spatially associated (at the micrometer scale) with stable isotope of radioactive parent nuclide \Rightarrow *isochron*



List of short-lived nuclides identified in meteorites

Radioactive Isotope	$T_{1/2}$ (Ma)	Daughter Isotope	Initial Abundance	Objects
^7Be	53 days	^7Li	$^7\text{Be}/^9\text{Be} \approx 6 \times 10^{-3}$	CAIs
^{41}Ca	0.1	^{41}K	$^{41}\text{Ca}/^{40}\text{Ca} \approx 1.5 \times 10^{-8}$	CAIs
^{36}Cl	0.3	^{36}Ar	$^{36}\text{Cl}/^{35}\text{Cl} \approx 0.5-1 \times 10^{-5}$	CAIs
^{26}Al	0.74	^{26}Mg	$^{26}\text{Al}/^{27}\text{Al} \approx 5 \times 10^{-5}$	CAIs, CHs, DIFF
^{10}Be	1.5	^{10}Be	$^{10}\text{Be}/^9\text{Be} \approx 1 \times 10^{-3}$	CAIs
^{60}Fe	1.5	^{60}Ni	$^{60}\text{Fe}/^{56}\text{Fe} \approx 0.5-1.2 \times 10^{-6}$	CAIs, DIFF
^{53}Mn	3.7	^{53}Cr	$^{53}\text{Mn}/^{55}\text{Mn} \approx 1.4-4 \times 10^{-5}$	CAIs, CHs, DIFF
^{107}Pd	6.5	^{107}Ag	$^{107}\text{Pd}/^{108}\text{Pd} \approx 2 \times 10^{-5}$	DIFF
^{182}Hf	9	^{182}W	$^{182}\text{Hf}/^{180}\text{Hf} \approx 1 \times 10^{-4}$	CHs, DIFF
^{129}I	16	^{129}Xe	$^{129}\text{I}/^{127}\text{I} \approx 10^{-4}$	CAIs, CHs, DIFF
^{92}Nb	36	^{92}Zr	$^{92}\text{Nb}/^{93}\text{Nb} \approx 2 \times 10^{-5}$	CHs, DIFF
^{244}Pu	82	Fission Products	$^{244}\text{Pu}/^{238}\text{U} \approx 7 \times 10^{-3}$	CAIs, DIFF
^{146}Nd	103	^{142}Nd	$^{146}\text{Nd}/^{144}\text{Nd} \approx 5 \times 10^{-3}$	DIFF

Possible origins of short-lived nuclides

- (1) continuous production/destruction in the galaxy (stellar sources) : **source for nuclides with long half-life** (Meyer & Clayton, 2000). But abundances of some nuclides don't match models of galactic chemical evolution (e. g.) :
 - $^{26}\text{Al}_{\text{ESS}} > \text{a factor of } \approx 10^4$
 - $^{129}\text{I}_{\text{ESS}} < \text{a factor of } \approx 10^2$
 - $^{53}\text{Mn}_{\text{ESS}} \approx \text{OK}$

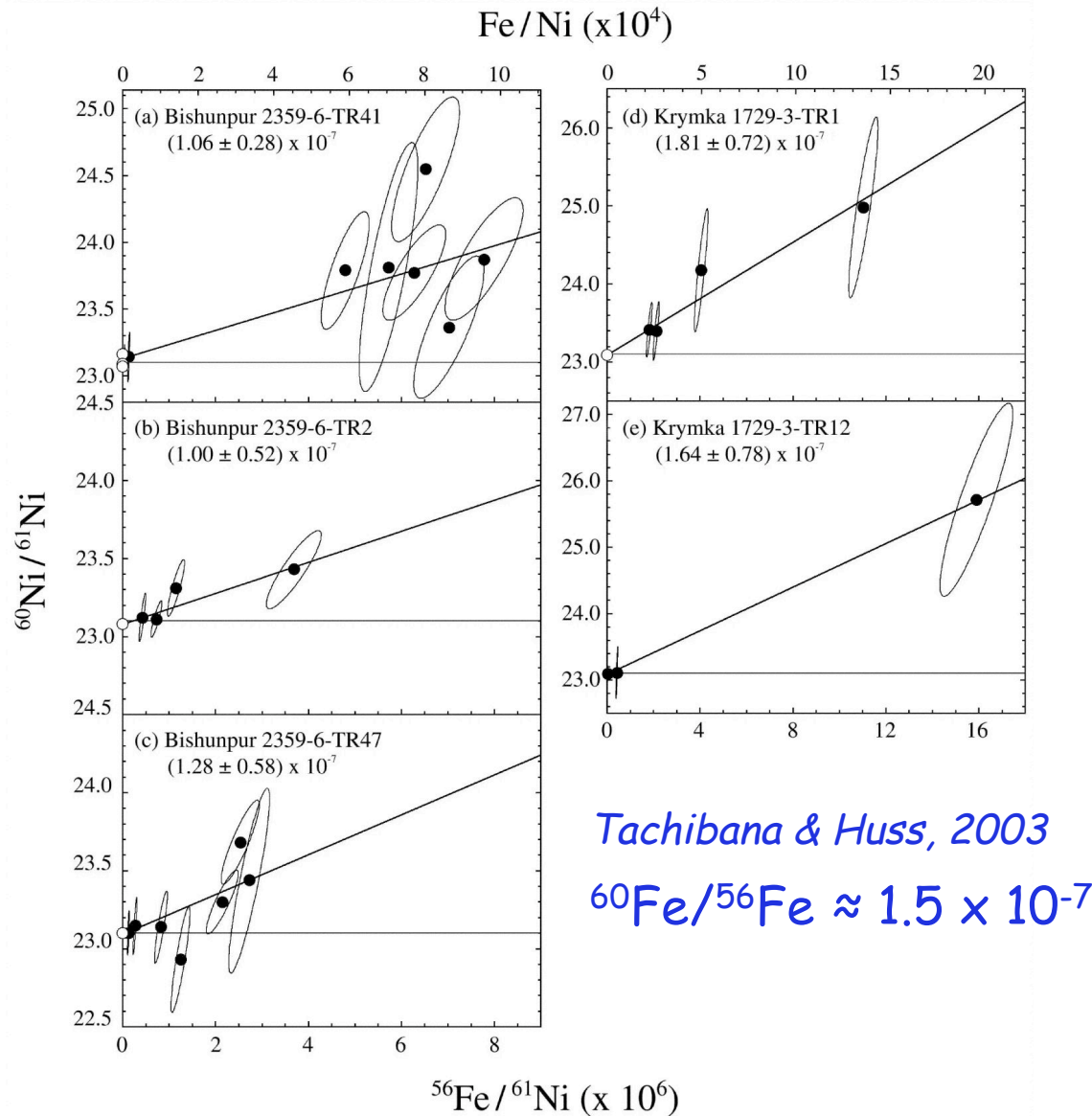
- (2) pollution of the nascent solar system by a nearby star : last minute injection of nuclides : **most often cited origin for nuclides with half-life $< 5\text{Ma}$ and is demonstrated by the presence of ^{60}Fe** (not made by irradiation, Lee et al., 1998)

- (3) in situ production by spallation reactions in the presolar cloud (GCRs) or in the protosolar cloud (solar cosmic rays emitted by the young T-Tauri Sun) : **demonstrated by ^{10}Be and ^7Be but is generally not considered as a significant source for other nuclides**

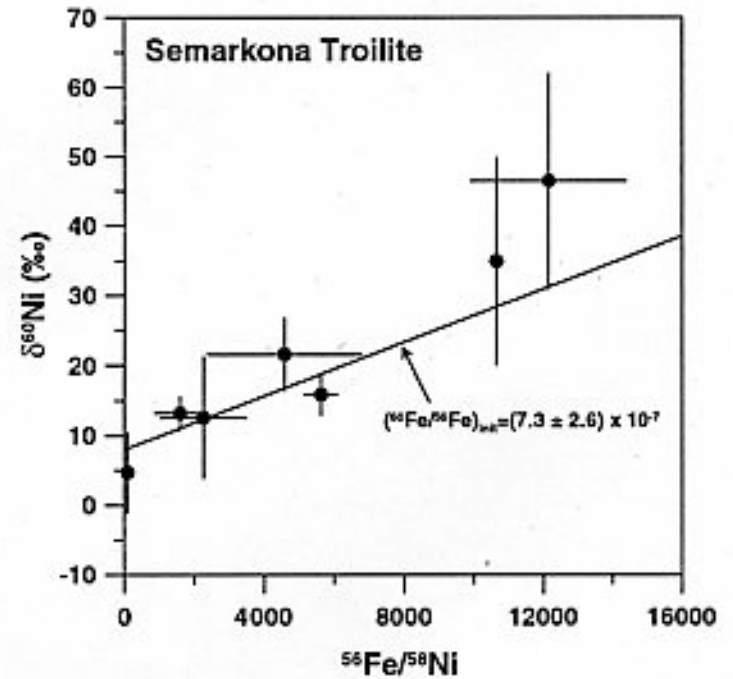
A presolar cloud origin for short-lived nuclides ?

- nuclear reactions of low-energy heavy cosmic rays with ambient cloud core matter :
 - ^{26}Al (Clayton, 1994)
 - ^{41}Ca but not ^{26}Al (Ramaty et al., 1996)
- direct stopping of low-energy cosmic rays :
 - ^{26}Al (Clayton and Jin, 1995)
 - ^{10}Be (Desch et al., 2004)
- Original observations of enhanced cosmic ray flux in the Orion nebula (Bloemen et al., 1994) has been retracted (Bloemen et al., 1999), but ???
- These models predict an isotopic homogeneity for the short-lived nuclides in the early solar system : probably not verified for ^{10}Be

Evidence for ^{60}Fe ($T_{1/2} = 1.5 \text{ Ma}$) (sulfides from primitive and ordinary chondrites)

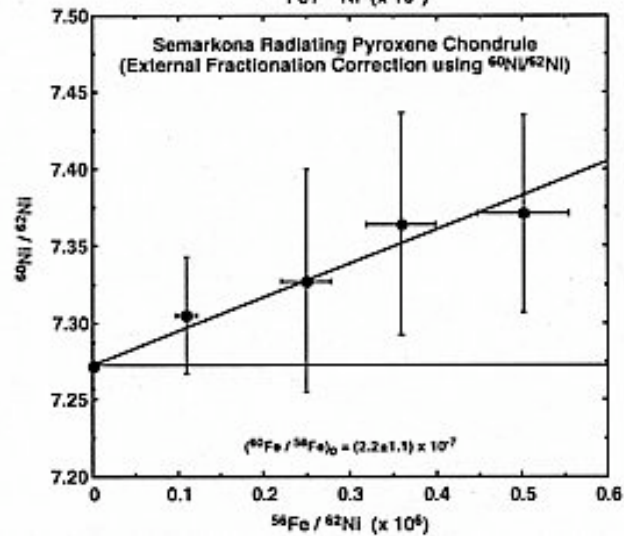
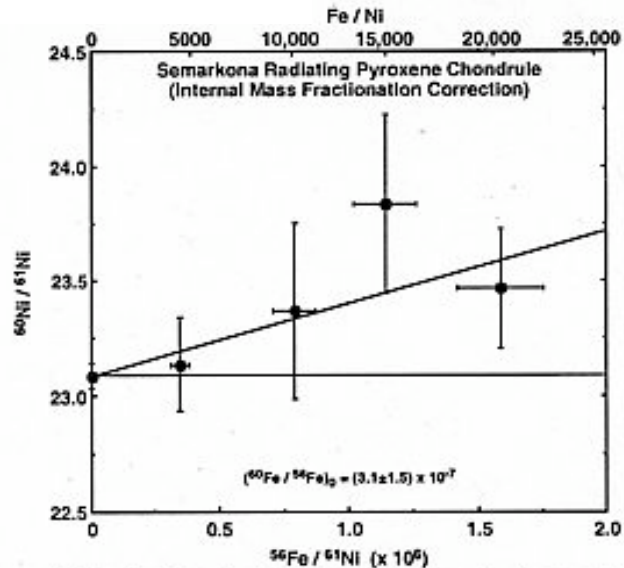


Tachibana & Huss, 2003
 $^{60}\text{Fe}/^{56}\text{Fe} \approx 1.5 \times 10^{-7}$

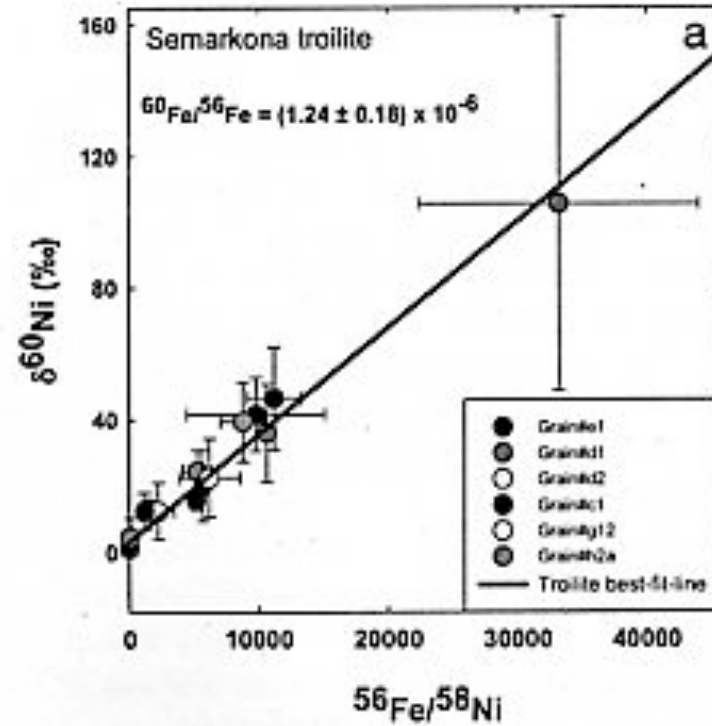


Mostefaoui et al., 2004a
 $^{60}\text{Fe}/^{56}\text{Fe} \approx 7 \times 10^{-7}$

Evidence for ^{60}Fe (2)



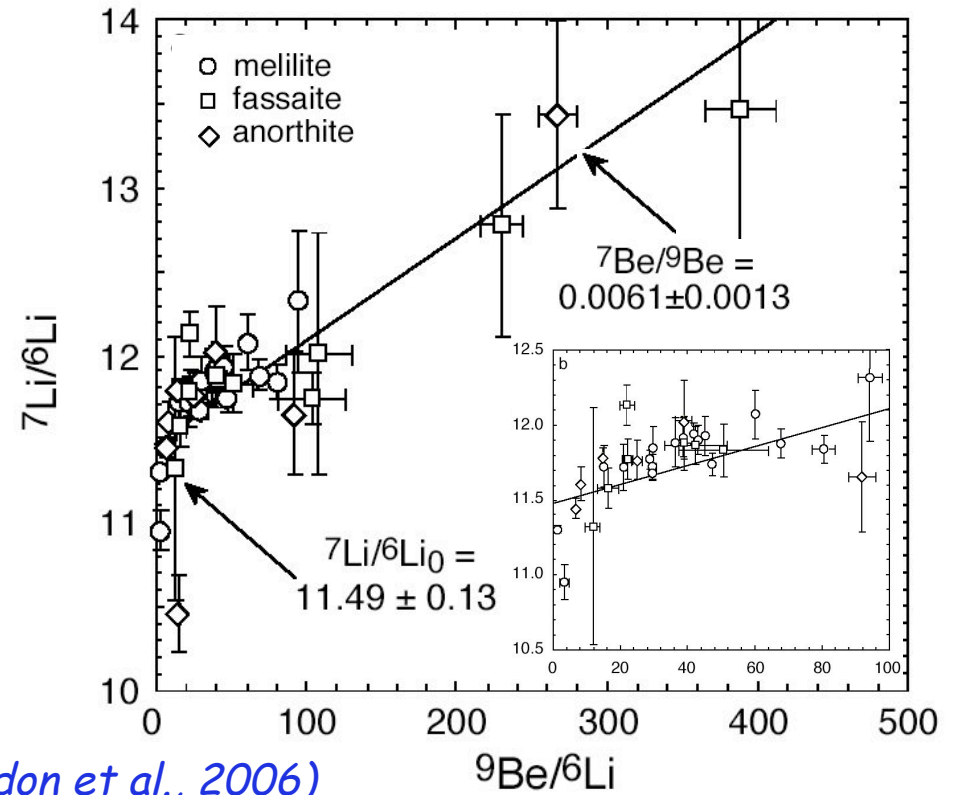
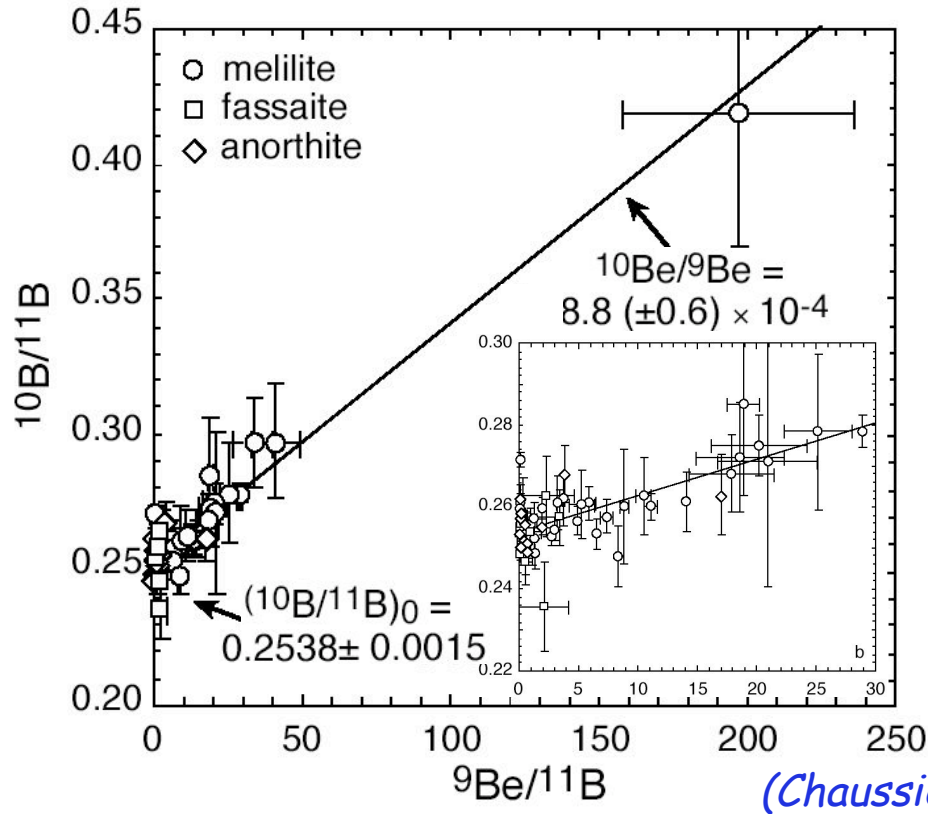
$^{60}\text{Fe}/^{56}\text{Fe} \approx 2 \times 10^{-7}$
Huss & Tachibana, 2004



Mostefaoui et al., 2004b
 $^{60}\text{Fe}/^{56}\text{Fe} \approx 1.2 \times 10^{-6}$

- in CAIs
 $^{60}\text{Fe}/^{56}\text{Fe} < 1.6 \times 10^{-6}$
(Birck & Lugmair, 1988)

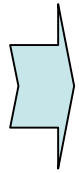
Evidence for ^{10}Be ($T_{1/2} = 1.5 \text{ Ma}$) and ^7Be ($T_{1/2} = 53 \text{ days}$)



$$^{10}\text{Be}/^9\text{Be} \approx 1 \times 10^{-3}$$

$$^7\text{Be}/^9\text{Be} \approx 6 \times 10^{-3}$$

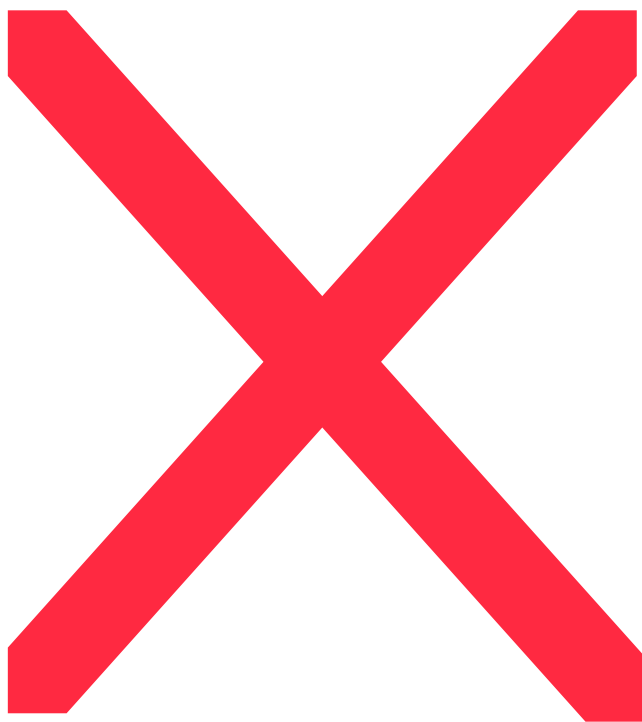
(McKeegan et al., 2000 ; Sugiura et al., 2001 ;
MacPherson et al., 2003 ; Chaussidon et al., 2004)



The various short-lived radionuclides observed seem hardly compatible with a unique nucleosynthetic source

If several sources, then :

- inventory of possible sources ?
- respective contributions of each source ?
- how, when and where these products were introduced in the solar system ?
- what are the implications in terms of chronology, source of heat for differentiation, ...
and of the astrophysical context for Solar system formation ?

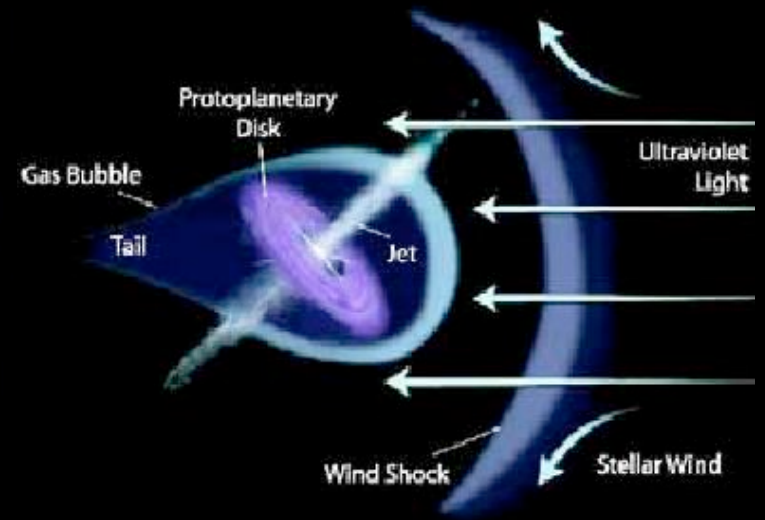
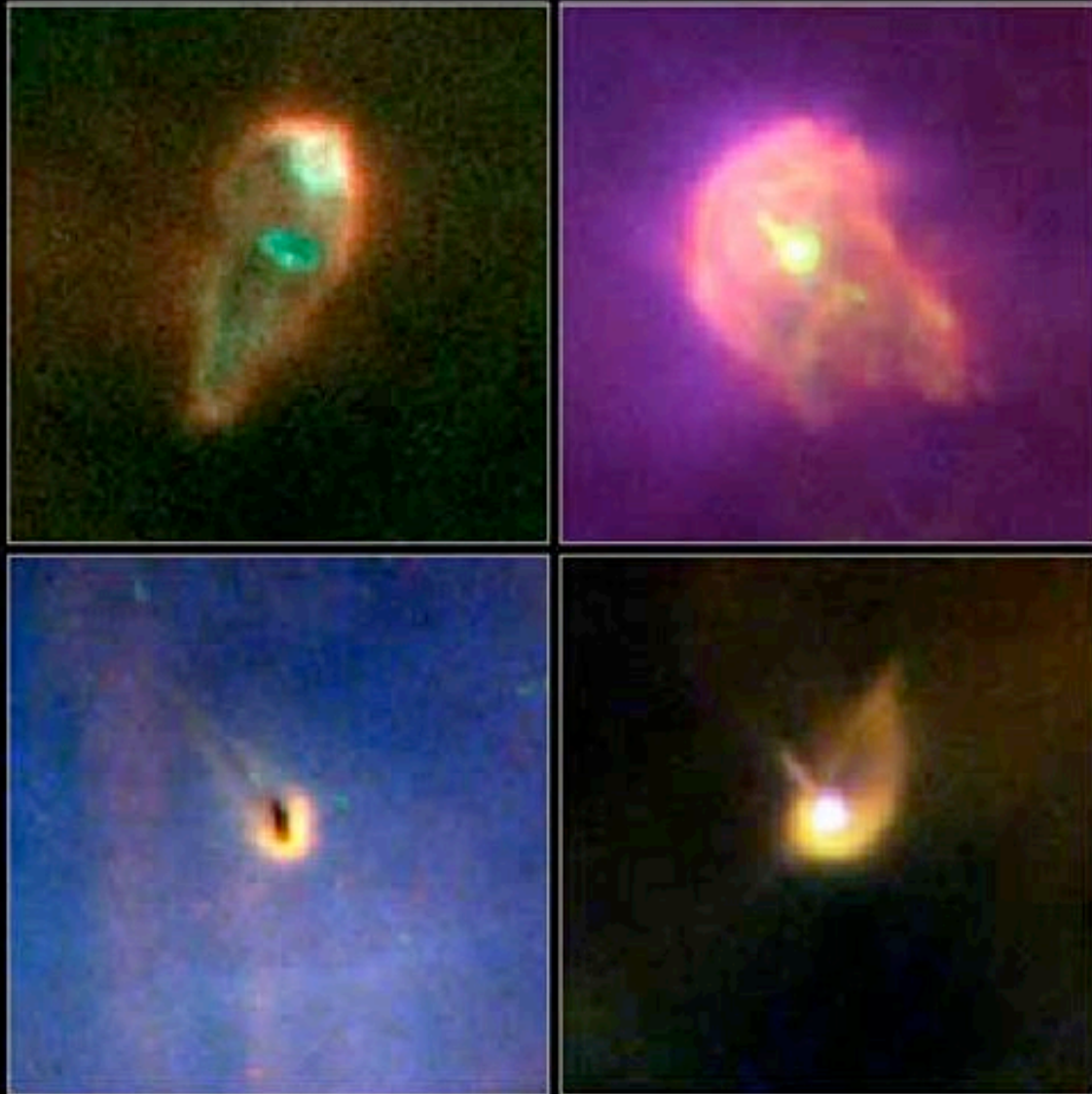




Chandra observation (7 days long, 50 X-rays images)
Courtesy Eric Feigelson (COUP/NASA)

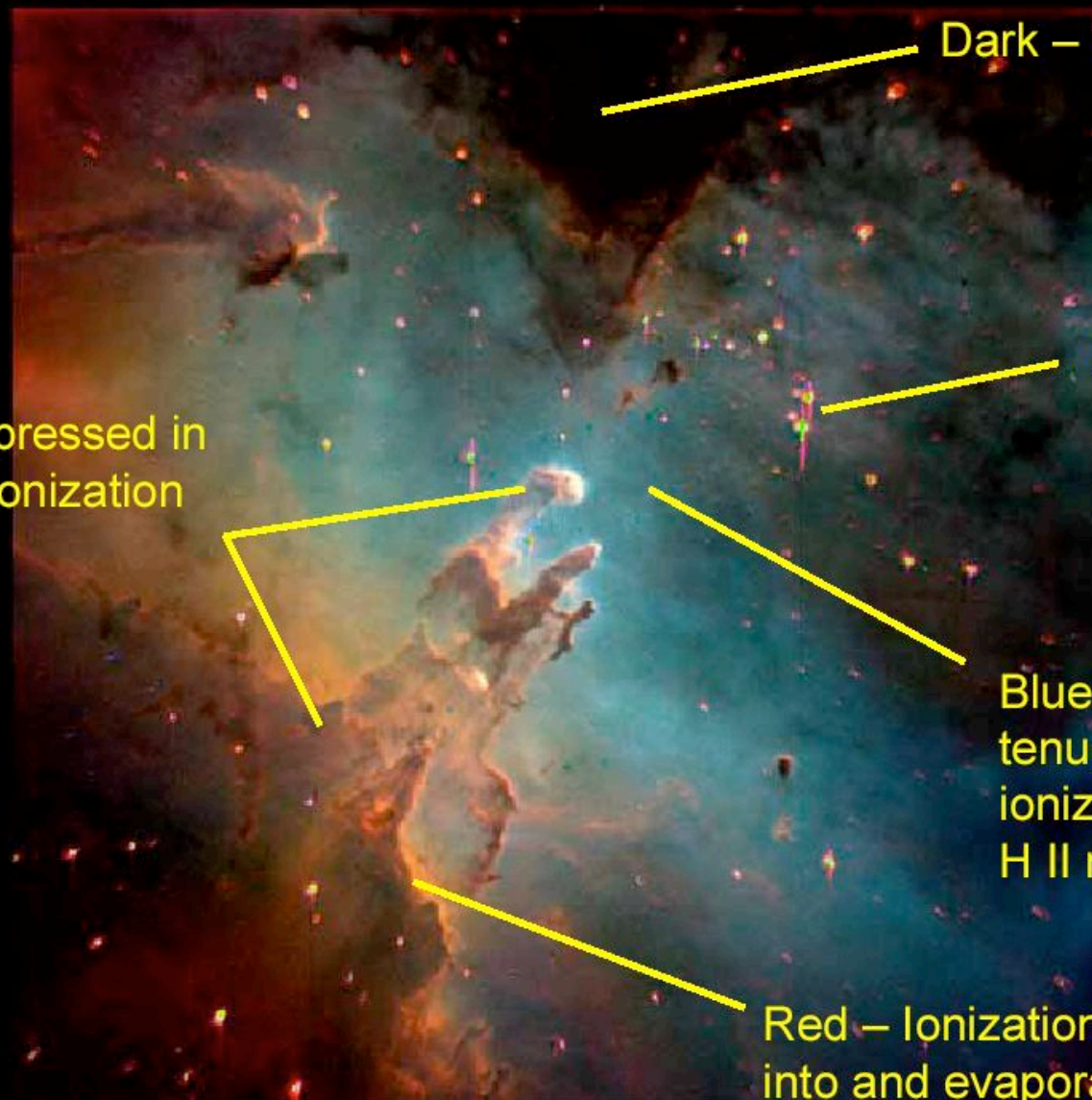


Courtesy Eric Feigelson (COUP/NASA)



Disks in Orion

HST images, Orion (Bally et al., 2000)



Dark – Molecular gas

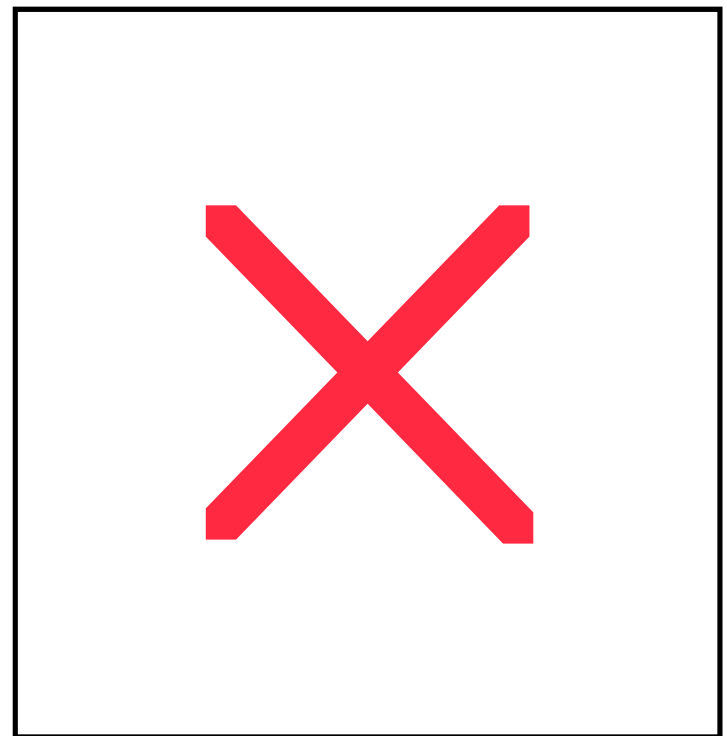
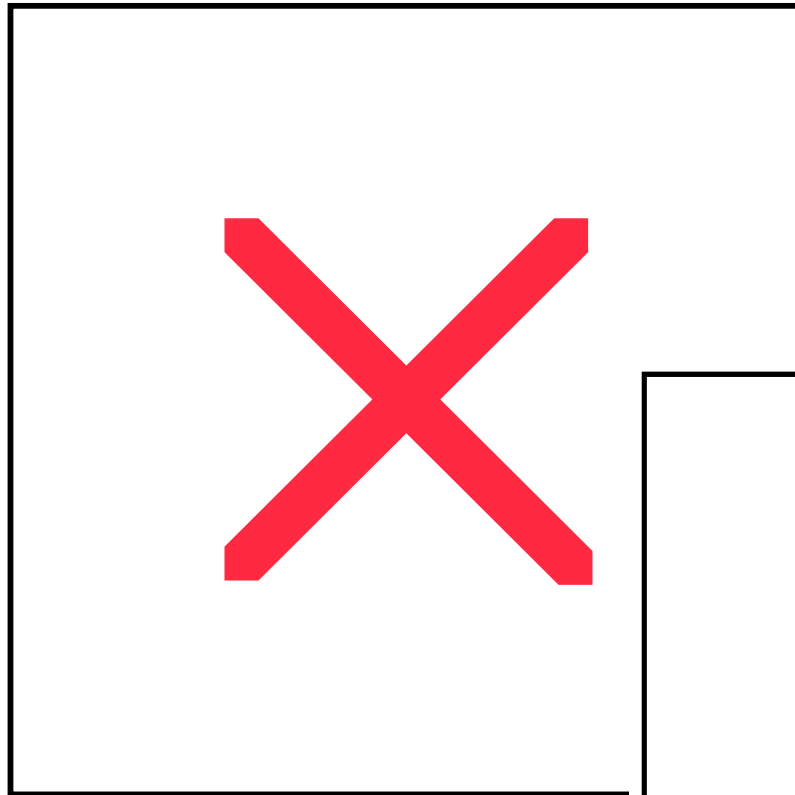
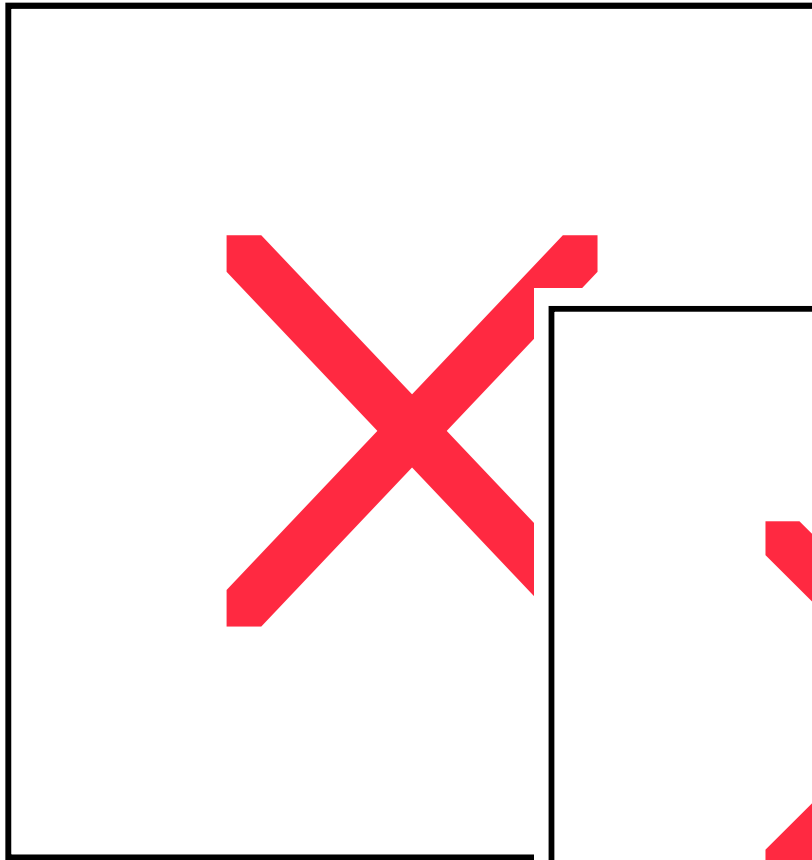
Massive stars

Dense gas compressed in advance of the ionization front

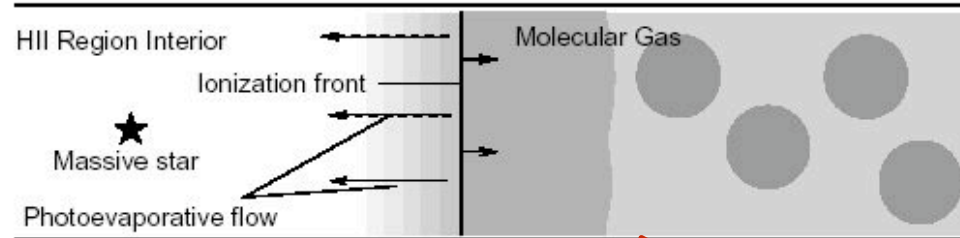
Blue – Hot ($\sim 10^4$ K), tenuous ($\sim 30 \text{ cm}^{-3}$), ionized cavity. The H II region interior.

Red – Ionization front pushing into and evaporating dense gas

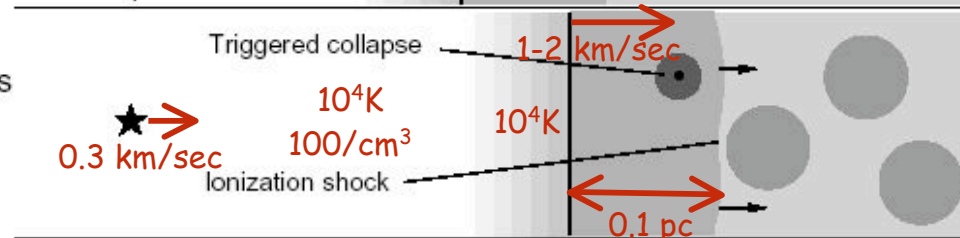
Eagle nebula M16, Hester & Desch (2005)



(1) Radiation from a massive star drives an ionization front into surrounding molecular gas.

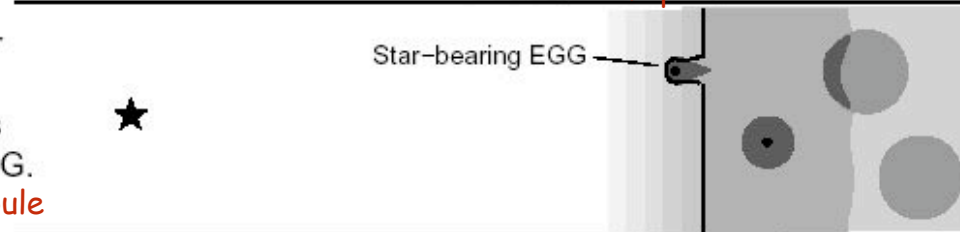


(2) The ionization front (plus winds and previous SNe) drive a shock, triggering collapse of molecular cores.



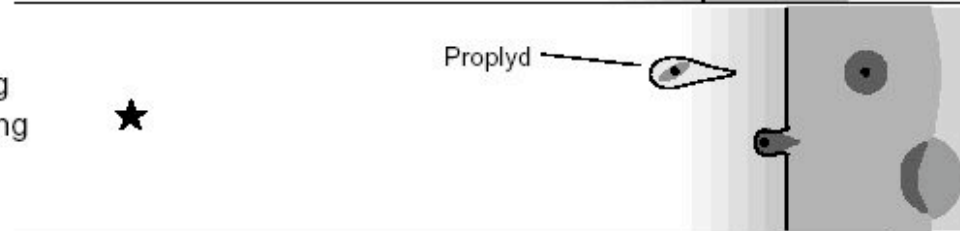
(3) ~100,000 years after triggered collapse, the ionization front overruns the core, forming an EGG.

Evaporative Gaseous Globule

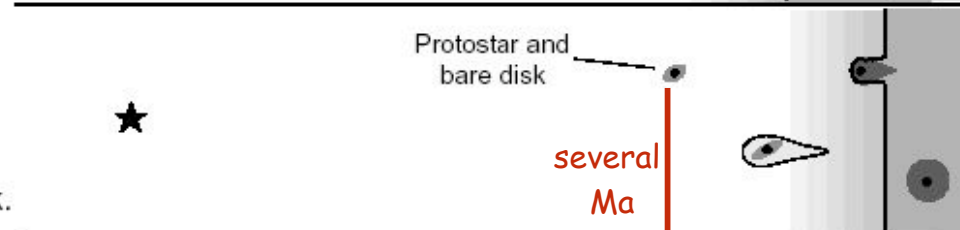


(4) EGGs evaporate in ~10,000 years, exposing the disk. The evaporating disk is a proplyd.

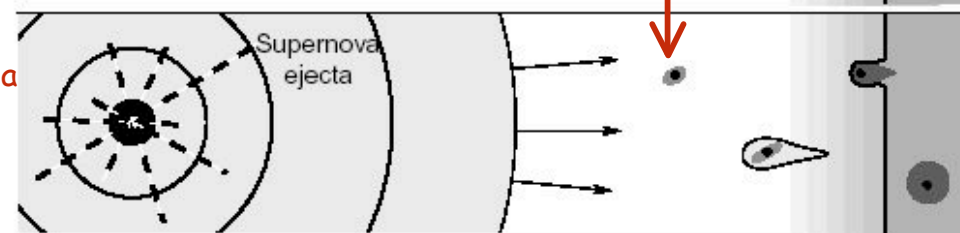
PROtoPLANetarYDisk



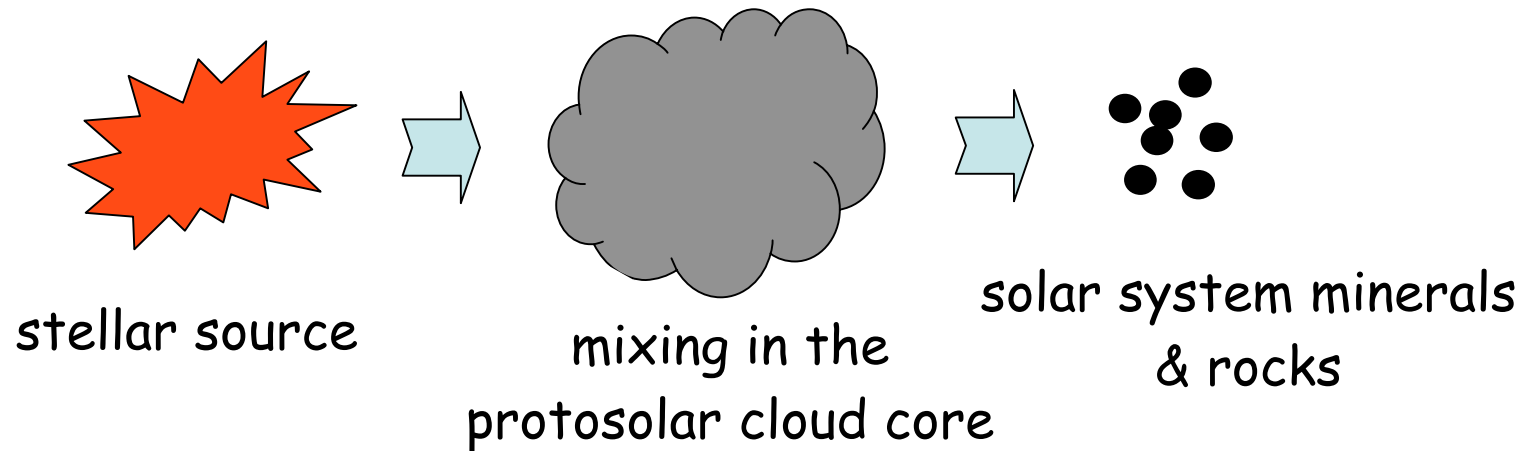
(5) In ~10,000 years, disks erode to ~50 AU. Disk evaporation ends, leaving a protostar and bare protoplanetary disk.



(6) The massive star goes supernova, 3-30 Ma injecting newly synthesized elements into surrounding disks.



Injections models (and their uncertainties)

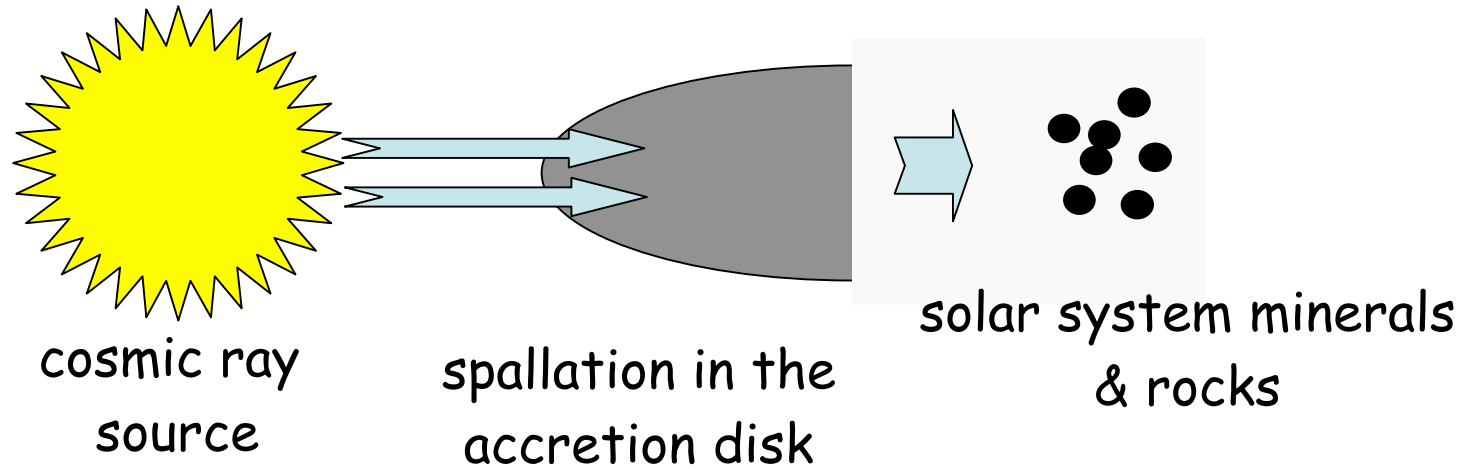


$$(N_R/N_S)_{\text{solar nebula}, \Delta_1} = \alpha_w \times (N_R/N_S)_w \times f_0 \times \exp(-\Delta_1/\tau)$$

(Wasserburg et al., 1998)

- ☆ α_w = enrichment factor (relative to ISM) of the stable isotope in the stellar wind ← nucleosynthetic models
- ☆ $(N_R/N_S)_w$ = abundance ratio (radioactive to stable) in the wind ←
- ☆ f_0 = mixing ratio between the wind and the progenitor ISM ← adjusted parameters
- ☆ Δ_1 = time between the injection and the crystallization ←
- ☆ τ = mean life of the ESR ← (within realistic limits)

Irradiation models (and their uncertainties)



$$\frac{N_R}{N_S} = F_0 \Delta t \sum_i y^{i_{CR}} \sum_j \frac{x^T_j}{x_S} \int \sigma(E) N(E) dE$$

- ☆ F_0 is the proton flux (in $\text{cm}^{-2} \cdot \text{s}^{-1}$)
 - ☆ Δt is the irradiation time
 - ☆ $N(E)dE$ is the differential number of accelerated protons
 - ☆ y_{CR}^i is the abundance relative to proton of the CR i (^4He , ^3He)
 - ☆ x_j is the abundance of the target
 - ☆ x^T_s is the abundance of the reference stable isotope
 - ☆ σ is the nuclear cross section
- irradiation models
- adjusted parameters
(within realistic limits)

Similarities and differences between the injection and irradiation models

$$(N_R/N_S)_{\text{solar nebula}, \Delta_1} = \alpha_w \times (N_R/N_S)_w \times f_0 \times \exp(-\Delta_1/\tau)$$

astrophysical setting of the nucleosynthesis

chemistry

astrophysical setting of the irradiation

$$\frac{N_R}{N_S} = F_0 \Delta t \sum_i y^i_{CR} \sum_j \left(\frac{x^T_j}{x_S} \right) \int \sigma(E) N(E) dE \times \exp(-\Delta_1/\tau)$$

chemistry of the target

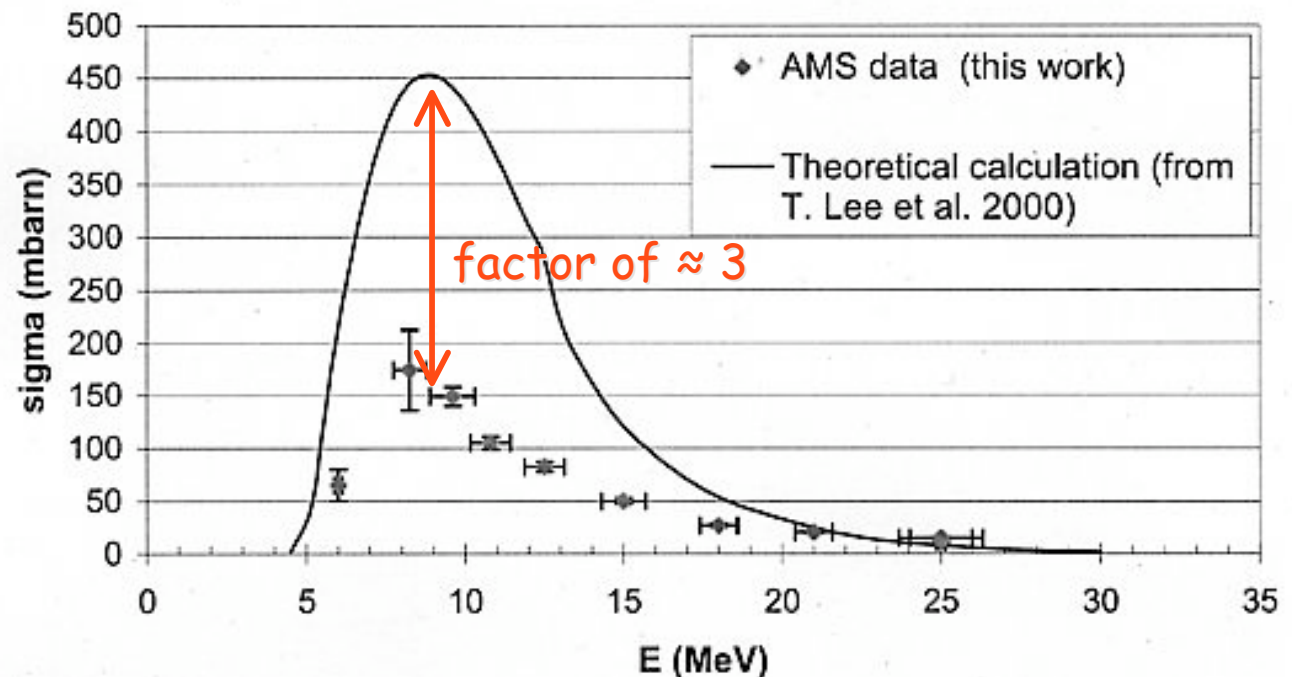
All models critically depend on the various cross-sections used :
uncertainties of at least a factor of ≈ 2

- (Busso et al. 2003) : "the major uncertainty in the ^{60}Fe production in AGB lies in the neutron capture cross sections of both ^{59}Fe and ^{60}Fe which are based on theoretical estimates only"

$$\sigma(30\text{KeV})(^{59}\text{Fe}) = 12.3 \text{ mbarn (Woosley et al., 1978)}$$

$$\sigma(30\text{KeV})(^{59}\text{Fe}) = 22.5 \text{ mbarn (Rauscher & Thielemann, 2000)}$$

- recent experimental determination of $^{24}\text{Mg}(^3\text{He},p)^{26}\text{Al}$ by Fitoussi et al. (2004)



Predictions of the injections models
of the irradiation models
(that can be tested in meteorites)

- values for the isotopic ratios : *initial* or *maximum* (e. g. $^{26}\text{Al}/^{27}\text{Al}$)
- coupling (*no a priori coupling*) between the abundances in meteoritic components of short-lived nuclides having the same source
- homogeneity (*no a priori homogeneity*) of the distribution in the solar system of short-lived nuclides
(e.g. in injection models $^{26}\text{Al}/^{27}\text{Al}_{\text{CAIs}} = ^{26}\text{Al}/^{27}\text{Al}_{\text{solar system}}$)
- *presence* or absence of other very short-lived nuclides

Isotopic ratios predicted by the injections models (1)

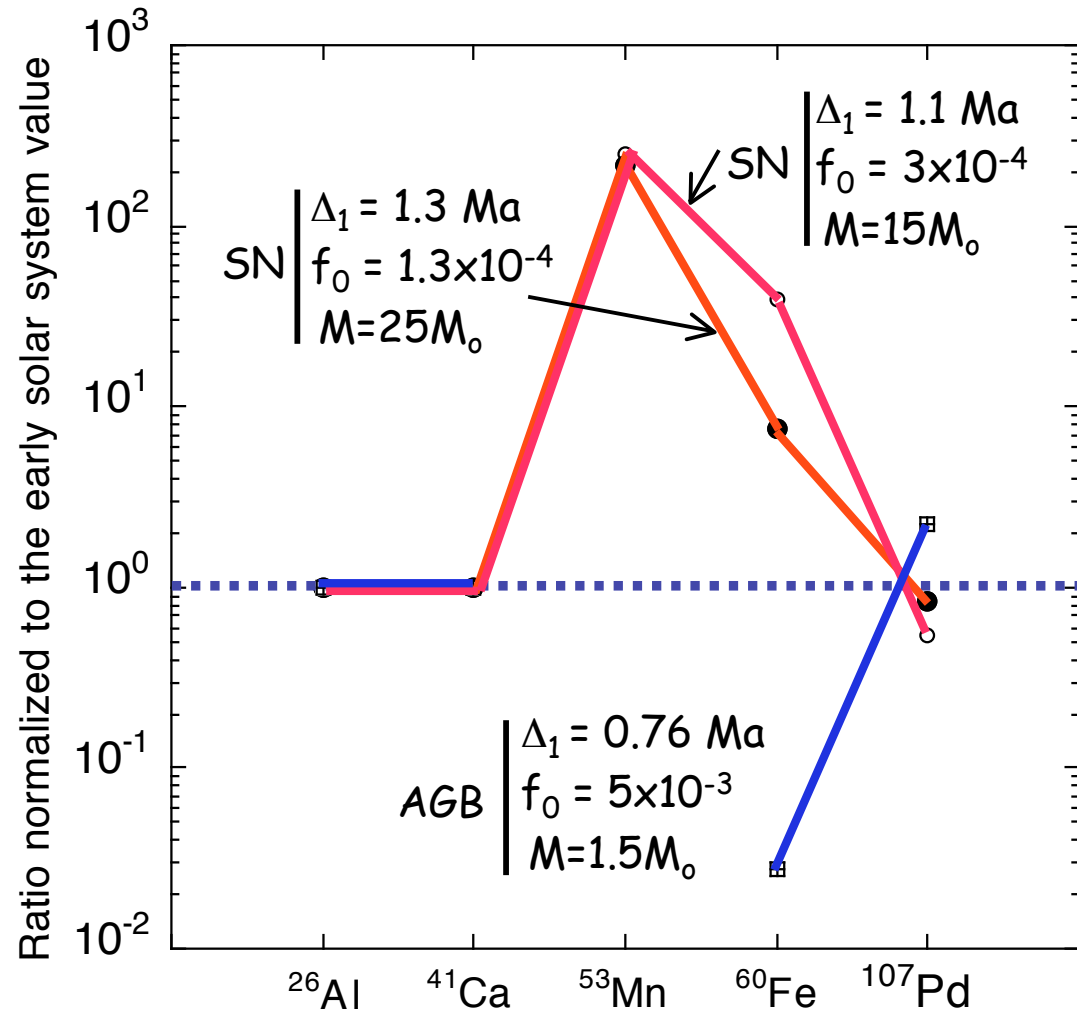
Can a single star deliver the contentious radionuclides ?

(~~^{10}Be~~ , ^{26}Al , ^{36}Cl , ^{41}Ca , ^{53}Mn , ^{60}Fe)

- Novae
 - Cannot produce ^{60}Fe (José, 2002)
 - Wolf-Rayet stars (Arnould et al., 1996)
 - They produce very little ^{60}Fe and no ^{53}Mn (unless SN explosion)
 - Supernovae
 - AGB
- good candidates

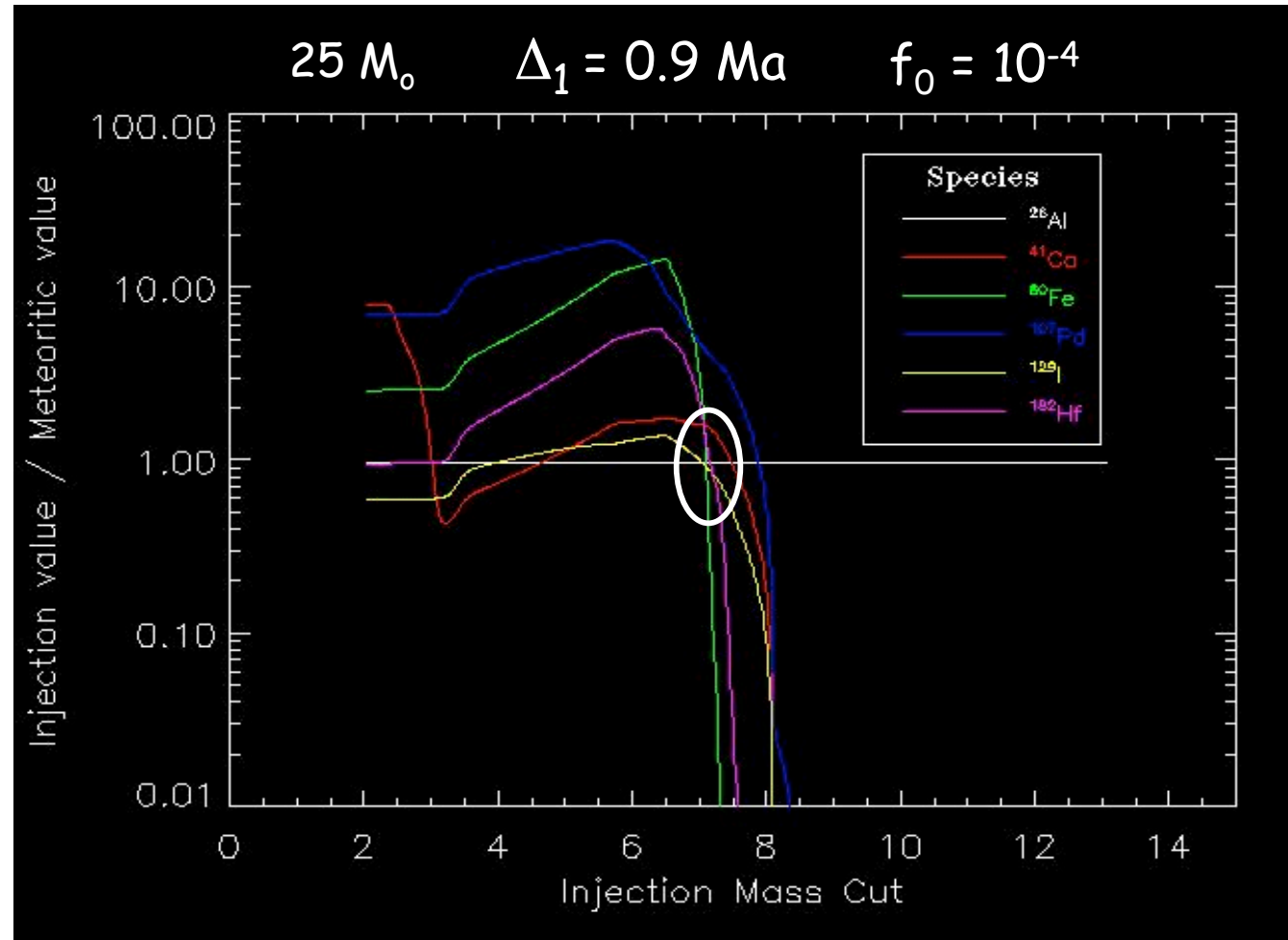
Isotopic ratios predicted by the injections models (2)

- SN II : overproduce ^{53}Mn by ≈ 100 and ^{60}Fe by ≈ 10 (Rauscher et al., 2002 ; Busso et al., 2003)
- AGB : no production of ^{53}Mn , underproduce ^{60}Fe by ≈ 10 (relative to new ESS abundances) and large uncertainty on ^{26}Al (more than a factor of 3 due to models of cool bottom processing \approx OK within uncertainties (Busso et al., 2003).



Isotopic ratios predicted by the injections models (3)

- mass cut in ejected supernova material (Meyer et al., 2003 ; Meyer & Clayton 2004)



Isotopic ratios predicted by the spallation models (1)

(Chaussidon & Gounelle, 2005)

Can a single irradiation process deliver the contentious radionuclides ?

(${}^7\text{Be}$, ${}^{10}\text{Be}$, ${}^{26}\text{Al}$, ${}^{36}\text{Cl}$, ${}^{41}\text{Ca}$, ${}^{53}\text{Mn}$, ~~${}^{60}\text{Fe}$~~)

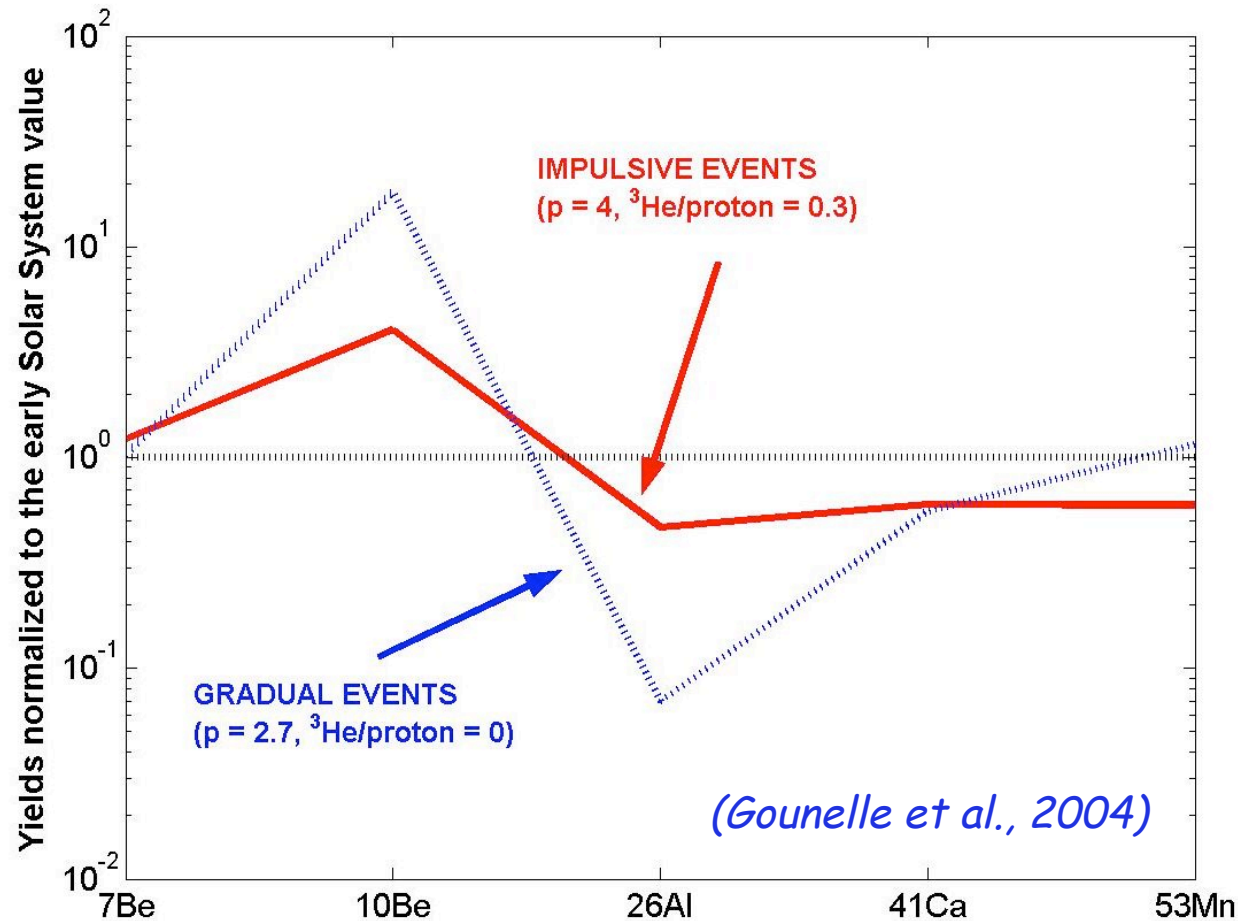
Differences between the models :

- Astrophysical context for the irradiation (distance to the Sun)
- Physical nature of the target (solids or gas)
- Chemistry of the targets
- Source of the cosmic rays

Two examples :

- irradiation at asteroidal distances of solid grains (CI chemistry) by solar cosmic rays (Goswami et al., 2001 ; Marhas et al., 2002)
- irradiation in the context of the X-wind (Shu et al., 1996) of gas and/or grains (CI and/or CAI chemistry, normal or layered structure) (Lee et al., 1998 ; Gounelle et al., 2001, 2004 ; Leya et al., 2003, 2004)

Isotopic ratios predicted by the spallation models (3)



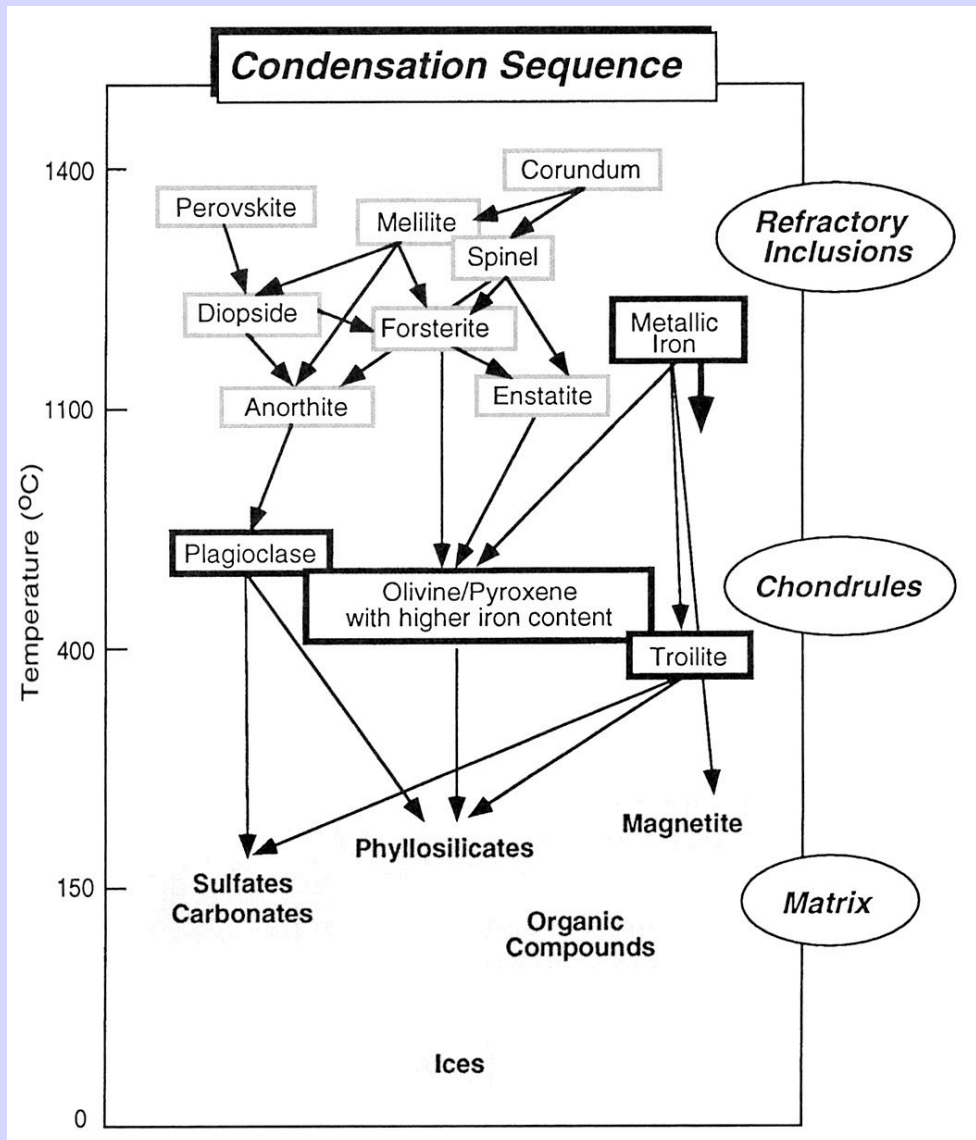
- irradiation close to the Sun
- target of specific composition
- core-mantle structure of proto CAIs
- ${}^3\text{He}$ -rich impulsive &
 ${}^3\text{He}$ -poor gradual flares
- proton luminosity deduced from
X luminosity ($L_x \sim 5 \times 10^{30} \text{ erg.s}^{-1}$)

Produce within
uncertainties the
short-lived nuclides
at their observed
abundances

Quelques questions d'actualité

- contexte astrophysique de la naissance du système solaire
(origine des radioactivités éteintes)
- origine des premiers solides
(condensation, CAIs, chondres)
- durée des processus de haute température
(âge des CAIs et des chondres)
- vitesse à laquelle les premières planètes se différencient
(angrites, ...)
- différence de composition isotopique entre le gaz et les solides
(vent solaire)

La séquence de condensation



McSween (2000)

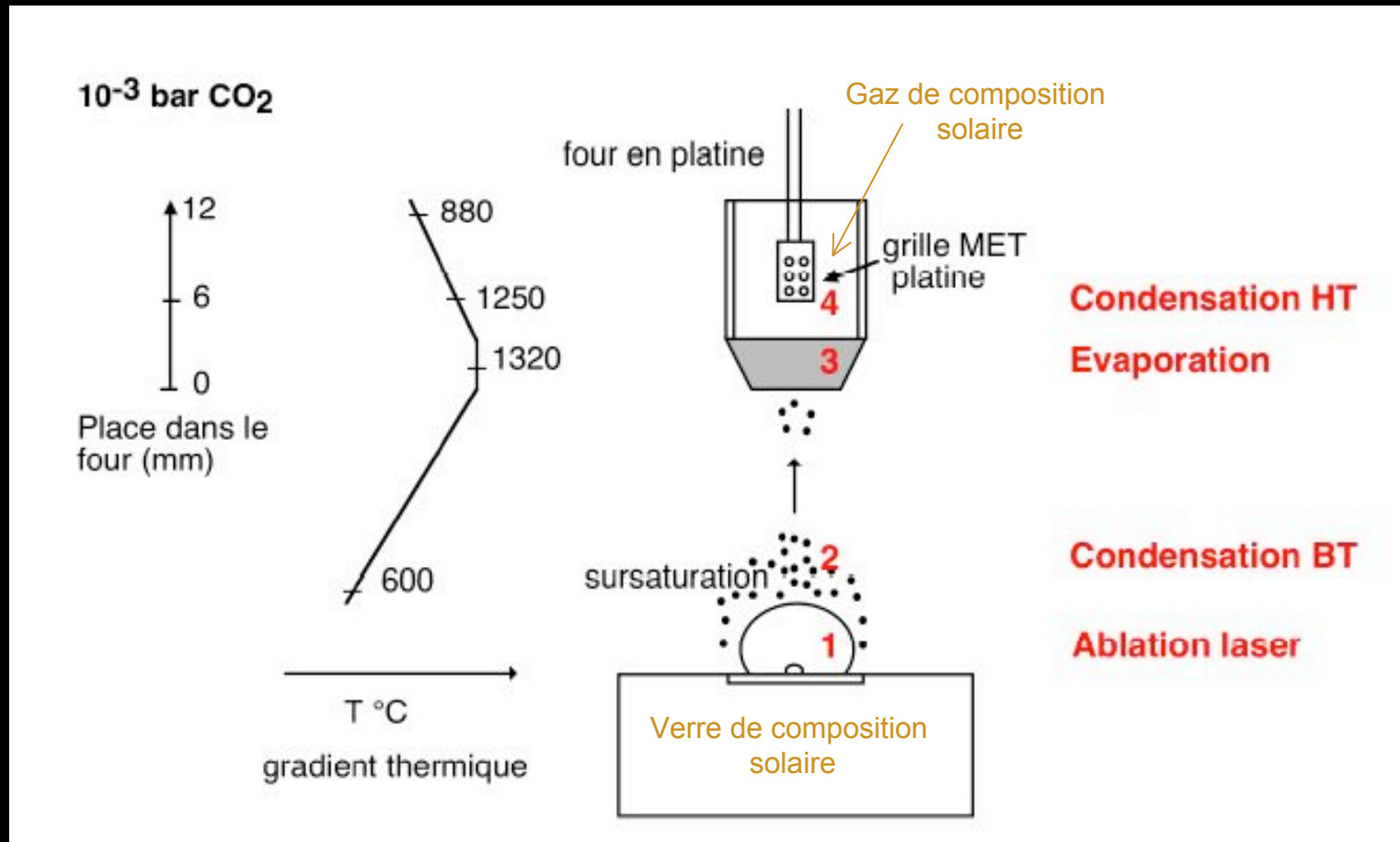
TABLE 1-10

Approximate Sequence of Condensation of Phases and Elements from a Gas of Solar Composition at 10^{-3} atm Total Pressure

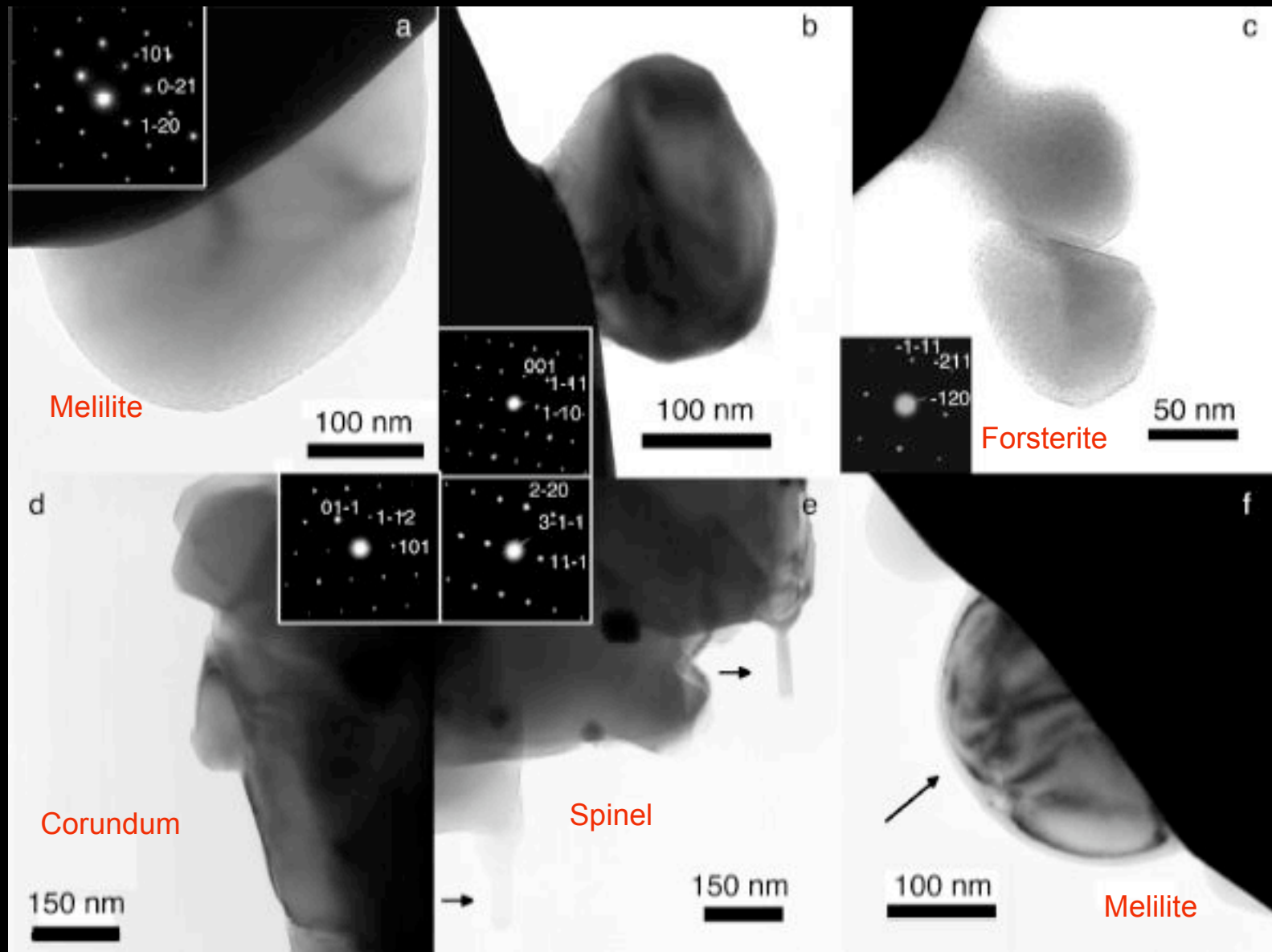
Phase	Formula	Temperature
Hibonite	$\text{CaAl}_{12}\text{O}_{19}$	1770 K
Corundum	Al_2O_3	1758 K
Platinum metals	Pt, W, Mo, Ta Zr, REE, U, Th Sc, Ir	
Perovskite	CaTiO_3	1647 K
Melilite	$\text{Ca}_2\text{Al}_2\text{SiO}_7$ $\text{Ca}_2\text{Mg}_2\text{Si}_2\text{O}_7$	1625 K
Spinel	MgAl_2O_4 Al_2SiO_5	1513 K
Metallic iron	Fe, Ni	1473 K
Diopside	$\text{CaMgSi}_2\text{O}_6$	1450 K
Forsterite	Mg_2SiO_4	1444 K
Anorthite	$\text{CaAl}_2\text{Si}_2\text{O}_8$ Ca_2SiO_4 CaSiO_3	1362 K
Enstatite	MgSiO_3 Cr_2O_3 P, Au, Li MnSiO_3 MnS, Ag As, Cu, Ge	1349 K
Feldspar	$(\text{Na,K})\text{AlSi}_3\text{O}_8$ Ag, Sb, F, Ge Sn, Zn, Se, Te, Cd	
Reaction products	$(\text{Mg,Fe})_2\text{SiO}_4$ $(\text{Mg,Fe})\text{SiO}_3$	1000 K
Troilite, pentlandite	FeS, (Fe, Ni)S Pb, Bi, In, Tl	700 K
Magnetite	Fe_3O_4	405 K
Hydrous minerals	$\text{Mg}_3\text{Si}_2\text{O}_7 \cdot 2\text{H}_2\text{O}$, etc.	
Calcite	CaCO_3	<400 K
Ices	H_2O , NH_3 , CH_4	<200 K

Anders (1968), Grossman (1972), Fuchs and others (1973), Grossman and Larimer (1974).

Condensation d'un gaz de composition solaire

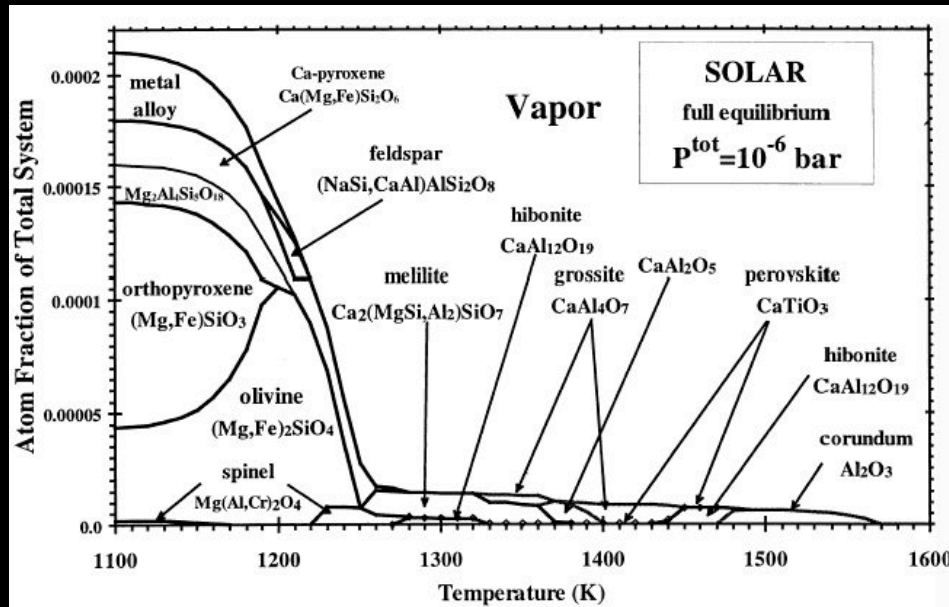


Condensation Haute température d'un gaz de composition solaire



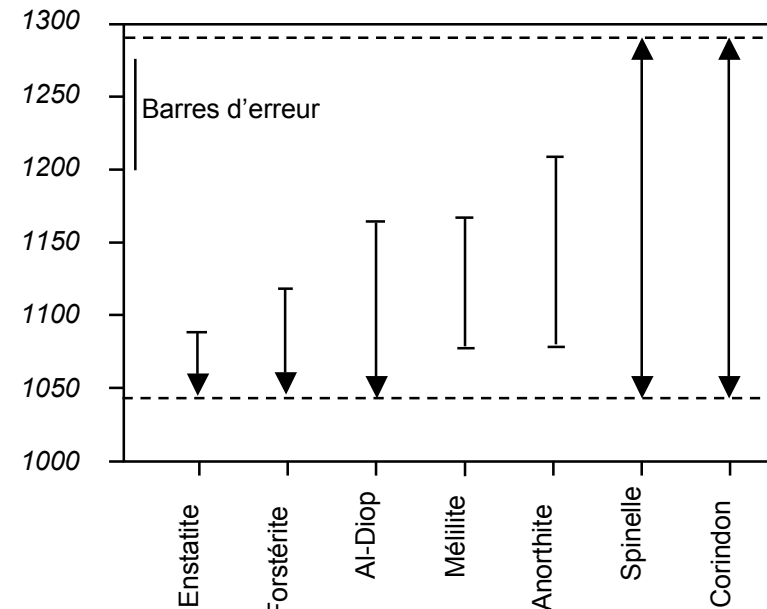
Condensation Haute température d'un gaz de composition solaire

Séquence théorique

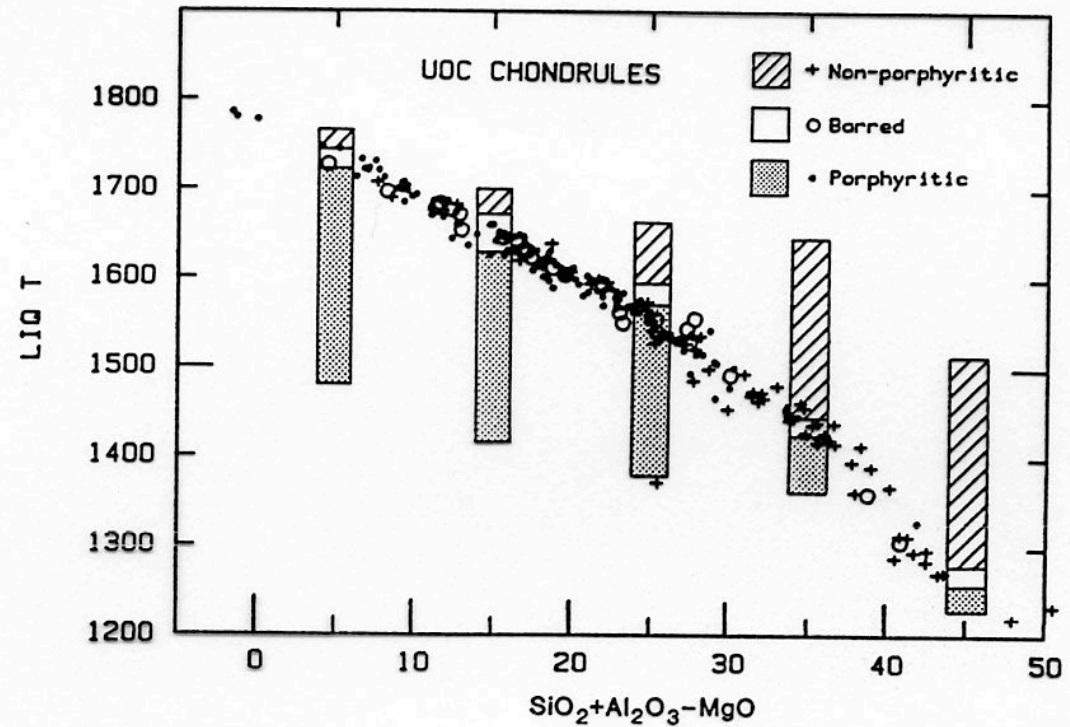
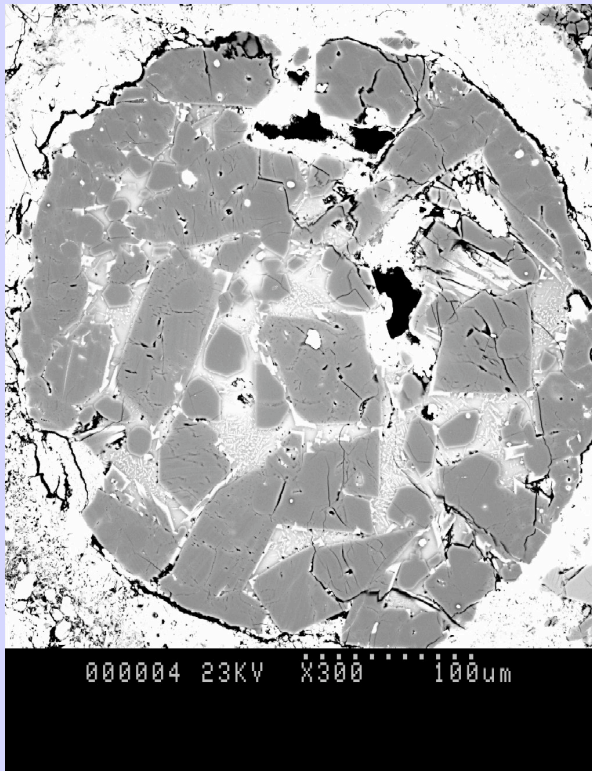
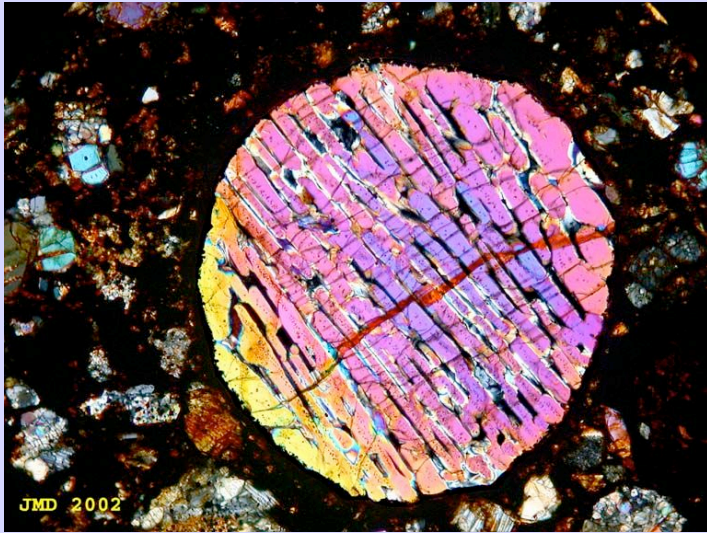


- condensation sous forme cristallisée
- influence de la cinétique
- formation des CAI par condensation directe d'un gaz chaud

Séquence expérimentale



Les chondres

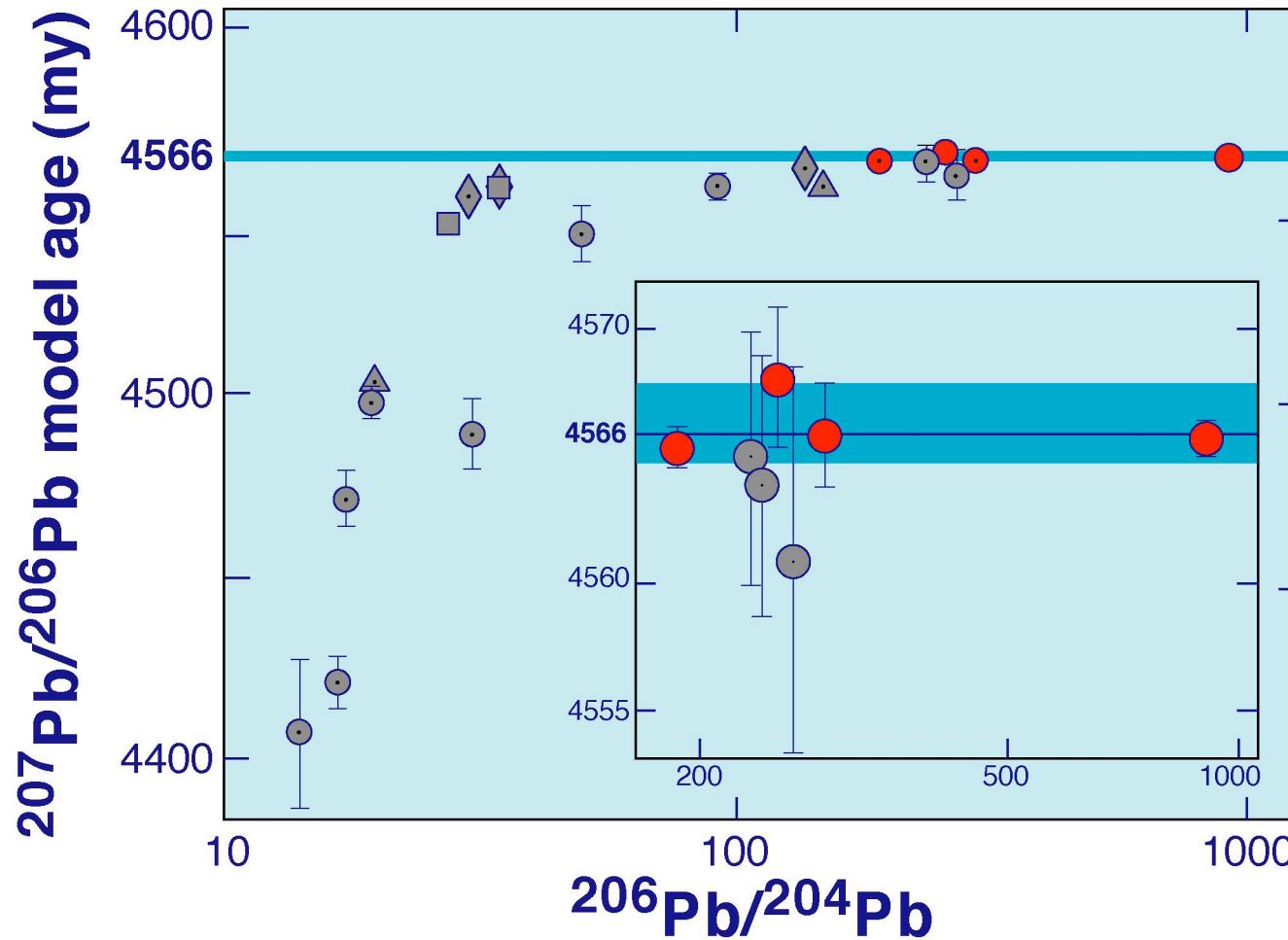


Radomsky & Hewins (1990)

Quelques questions d'actualité

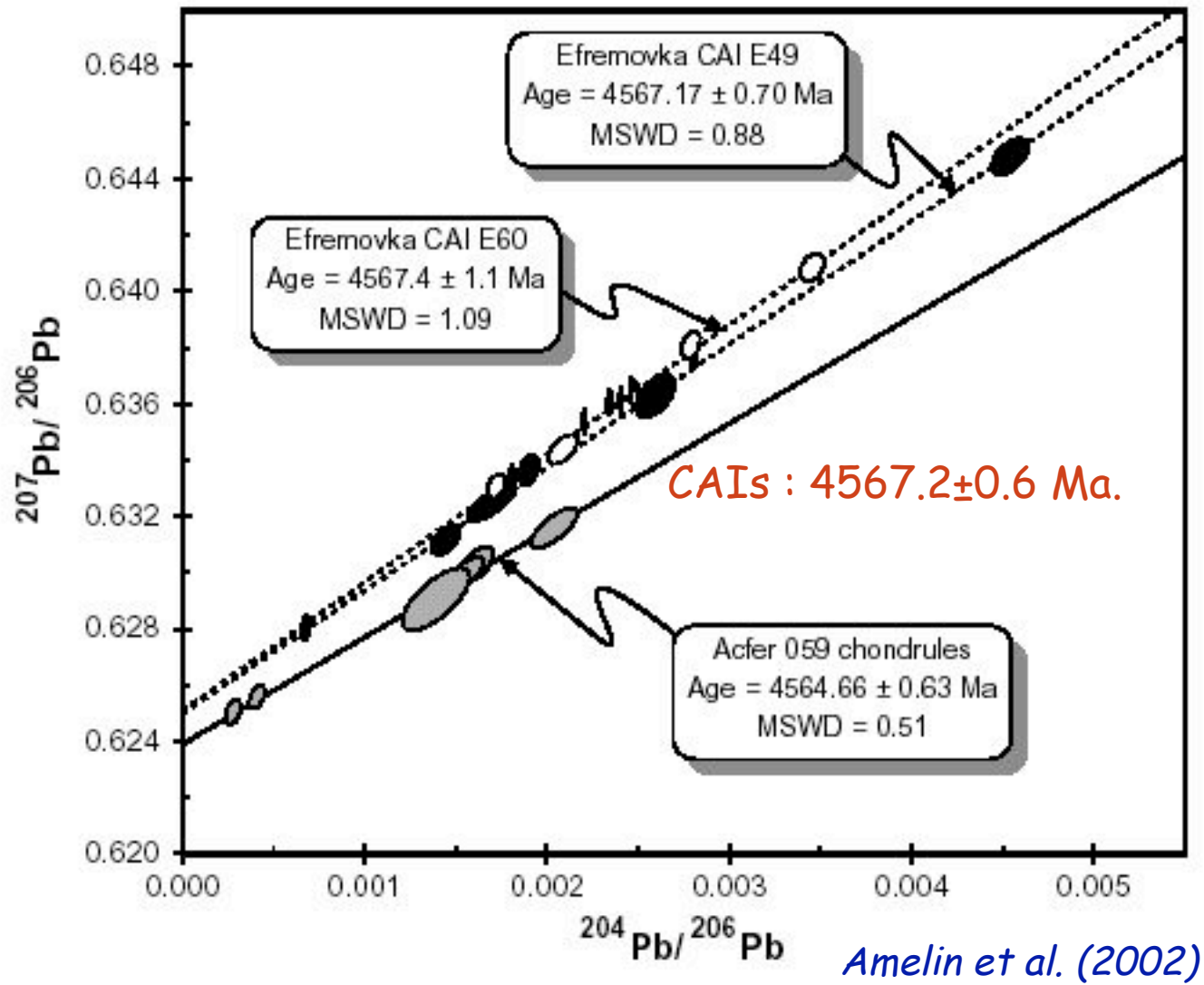
- contexte astrophysique de la naissance du système solaire
(origine des radioactivités éteintes)
- origine des premiers solides
(condensation, CAIs, chondres)
- durée des processus de haute température
(âge des CAIs et des chondres)
- vitesse à laquelle les premières planètes se différencient
(angrites, ...)
- différence de composition isotopique entre le gaz et les solides
(vent solaire)

âge Pb-Pb des CAIs = $4.566^{+0.002}_{-0.001}$

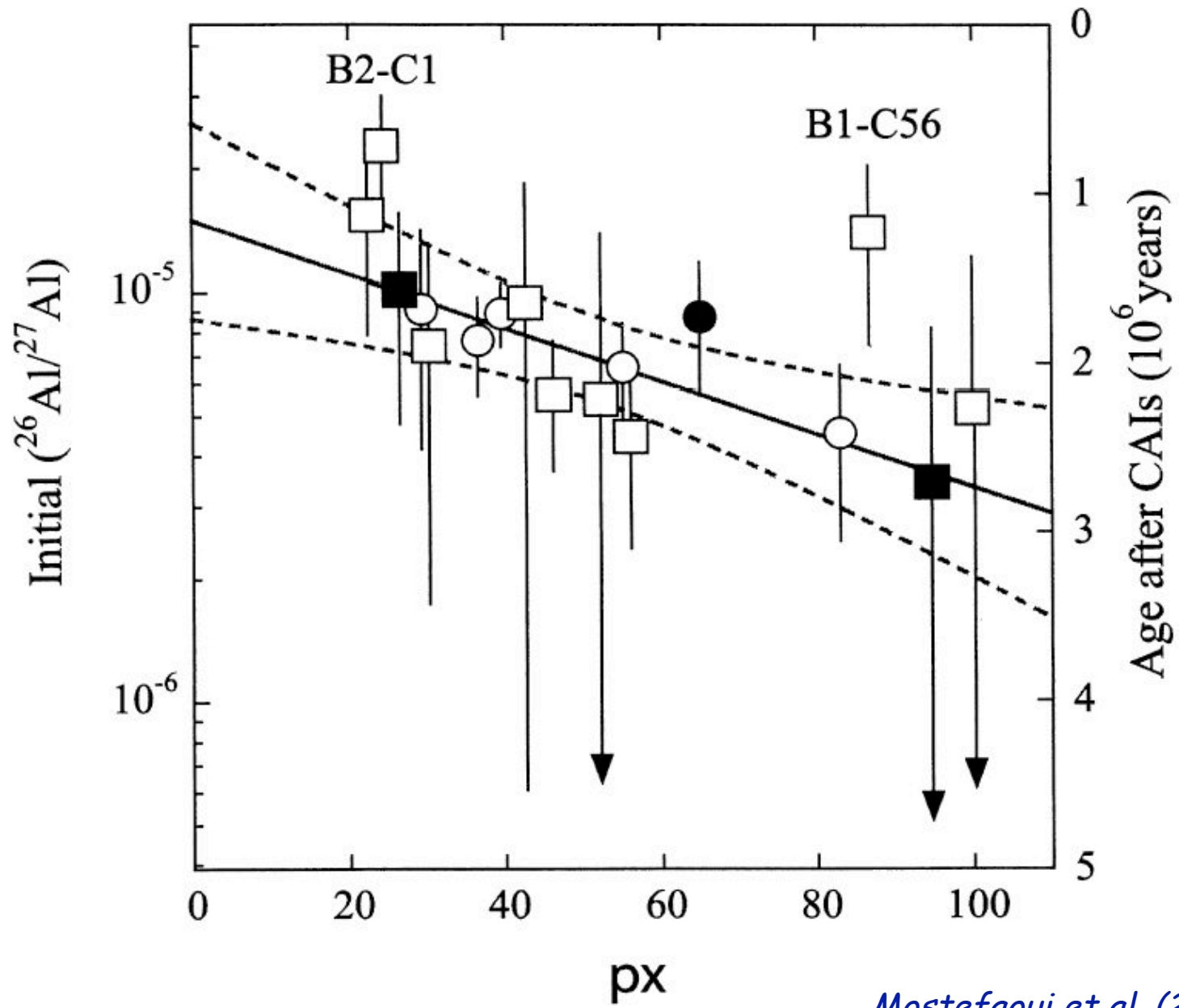


Göpel, Manhès & Allègre (1993)

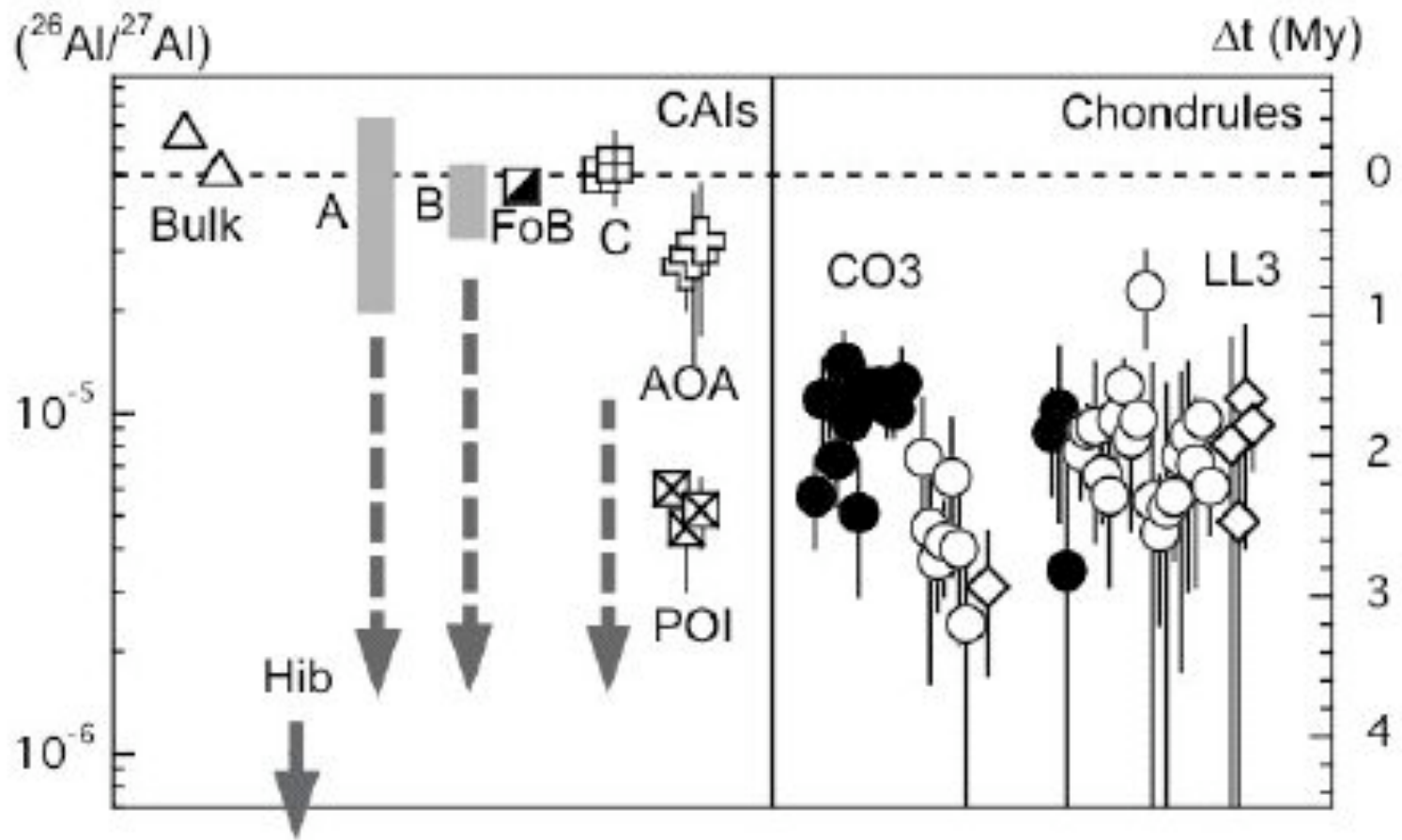
Allègre, Manhès & Göpel (1995)



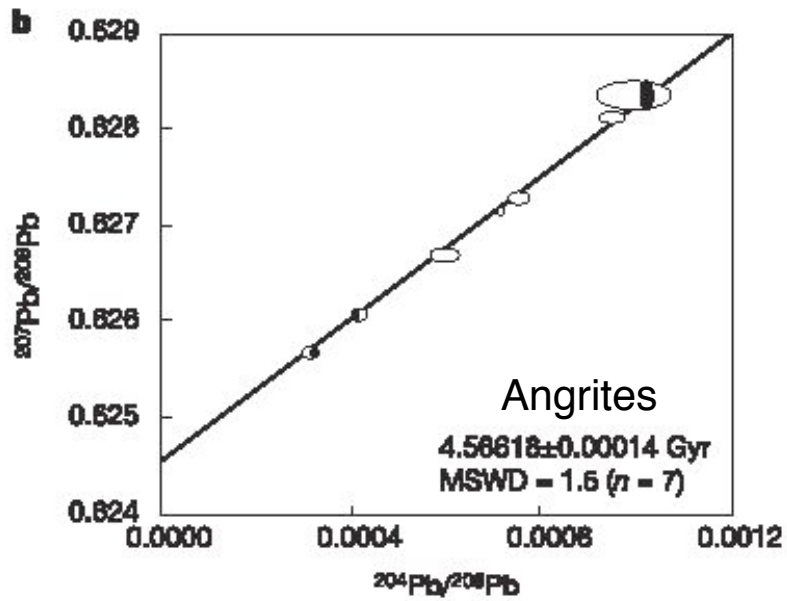
Bouvier et al. (soumis) : âge Pb-Pb CAIs = 4568.3 ± 0.4 Ma.



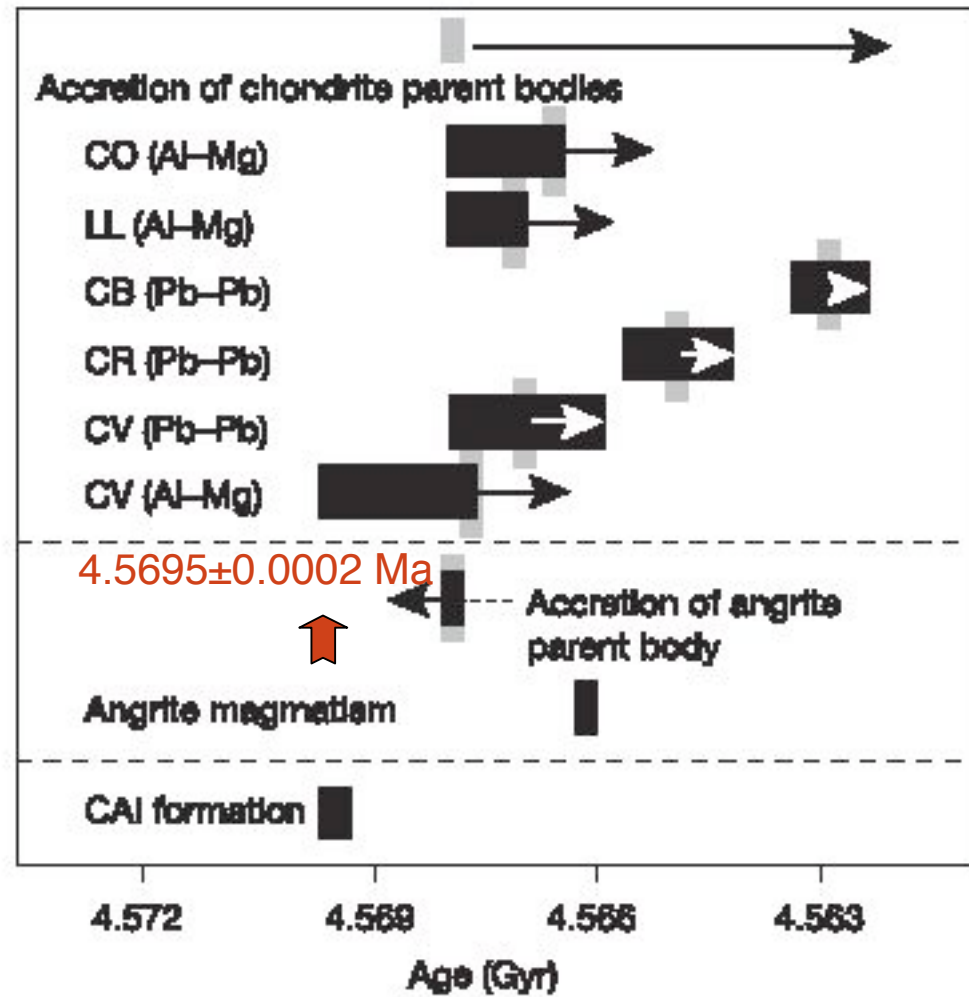
Mostefaoui et al. (2002)

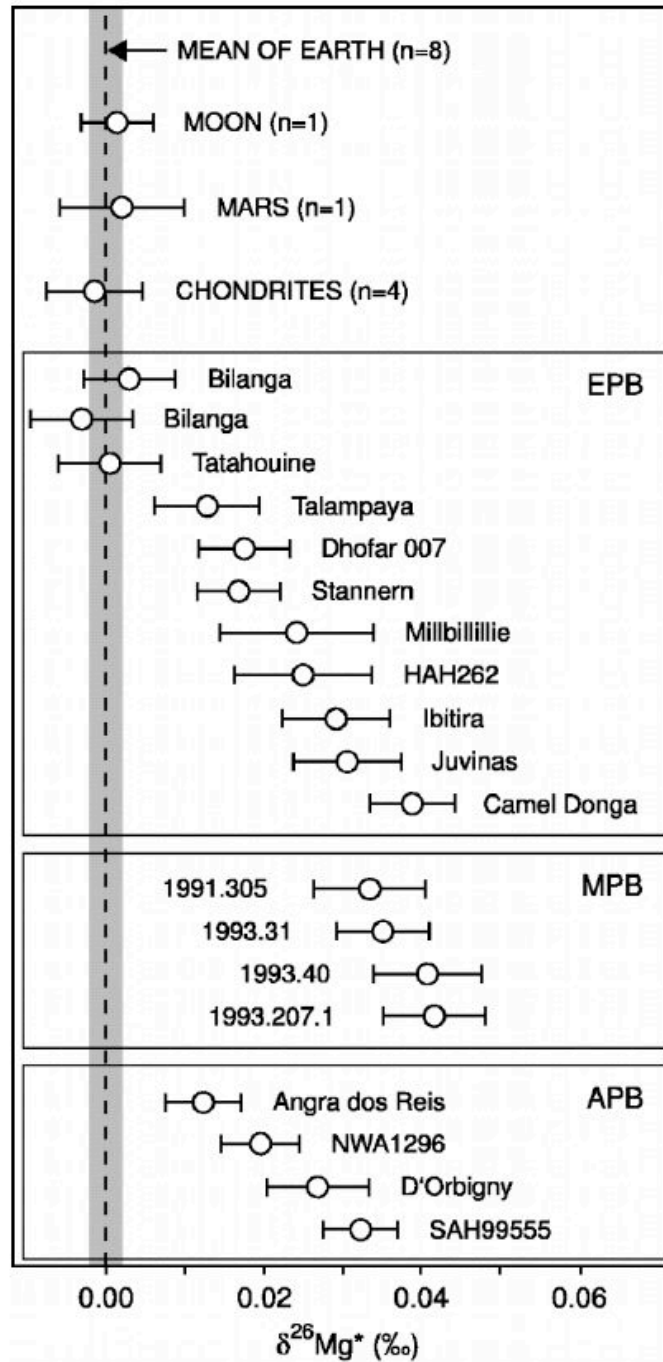


Kita et al. (2005)



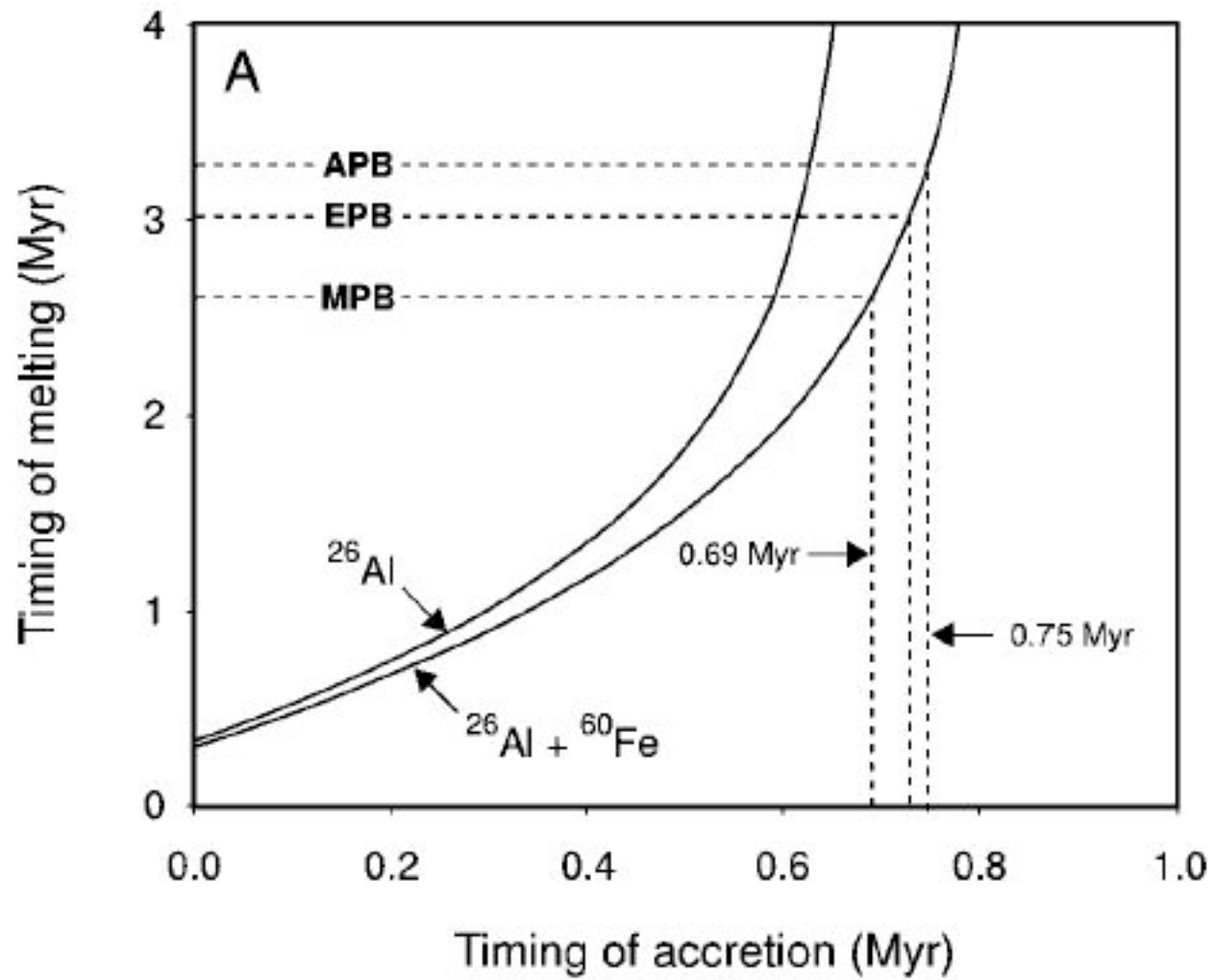
Baker et al. (2005)



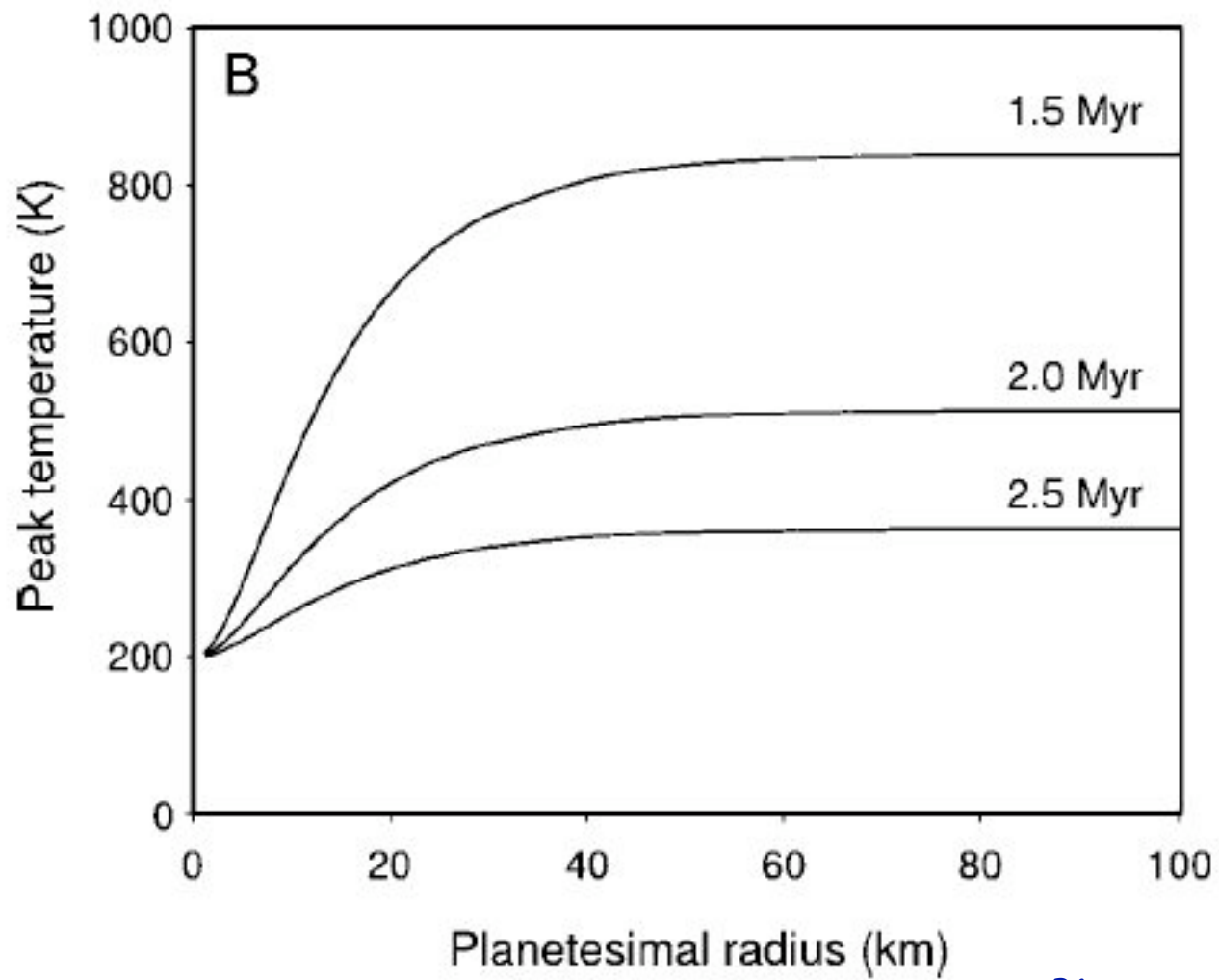


$$^{26}\text{Al}/^{27}\text{Al} = 1.3 \text{ à } 5 \times 10^{-6}$$

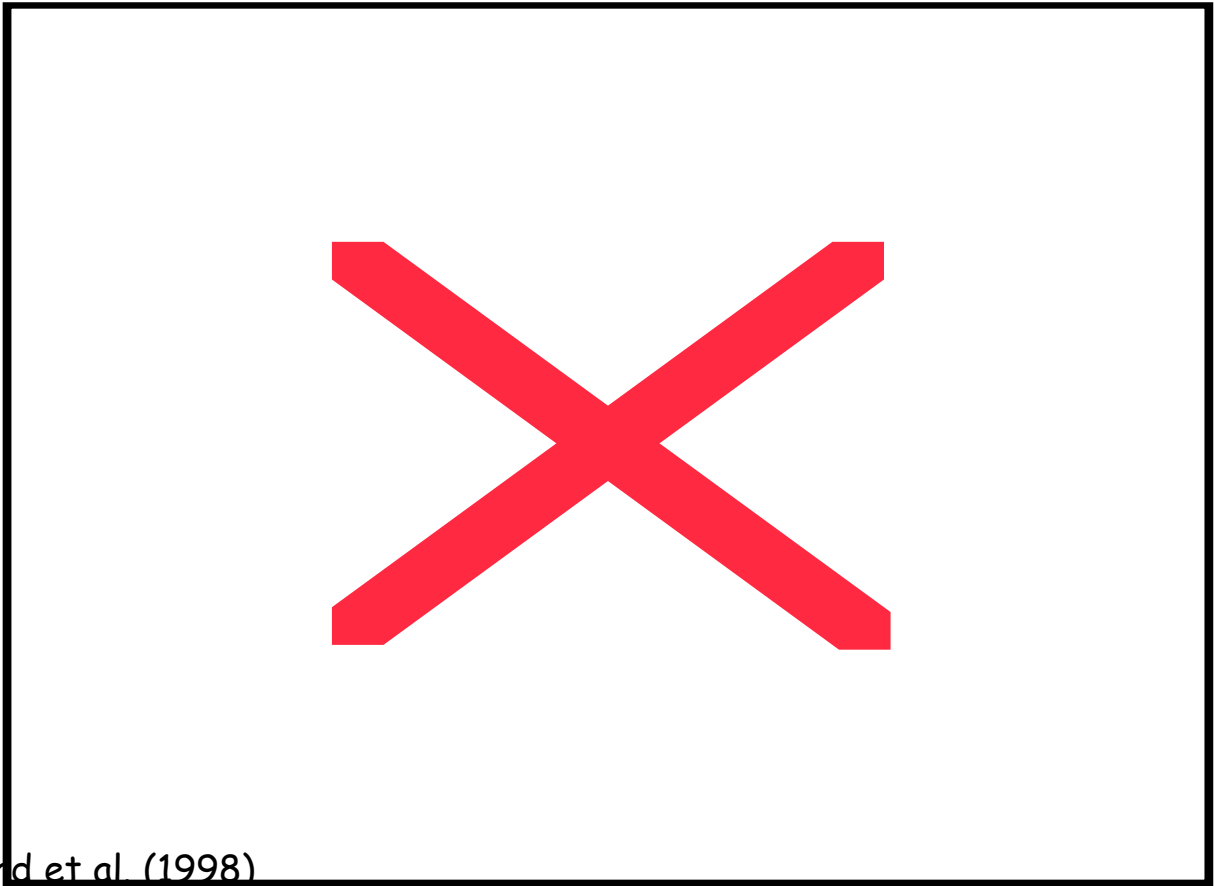
Bizzarro et al. (2005)



Bizzarro et al. (2005)



Bizzarro et al. (2005)

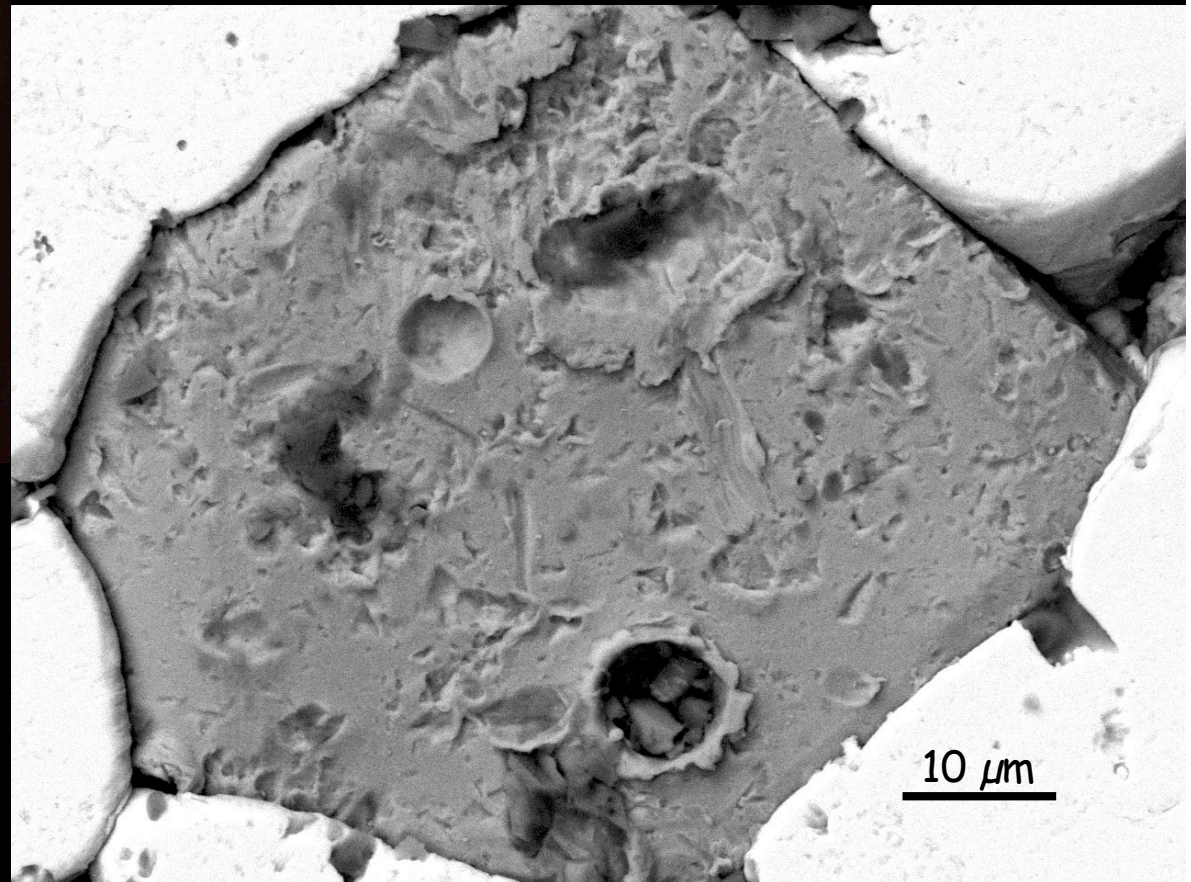
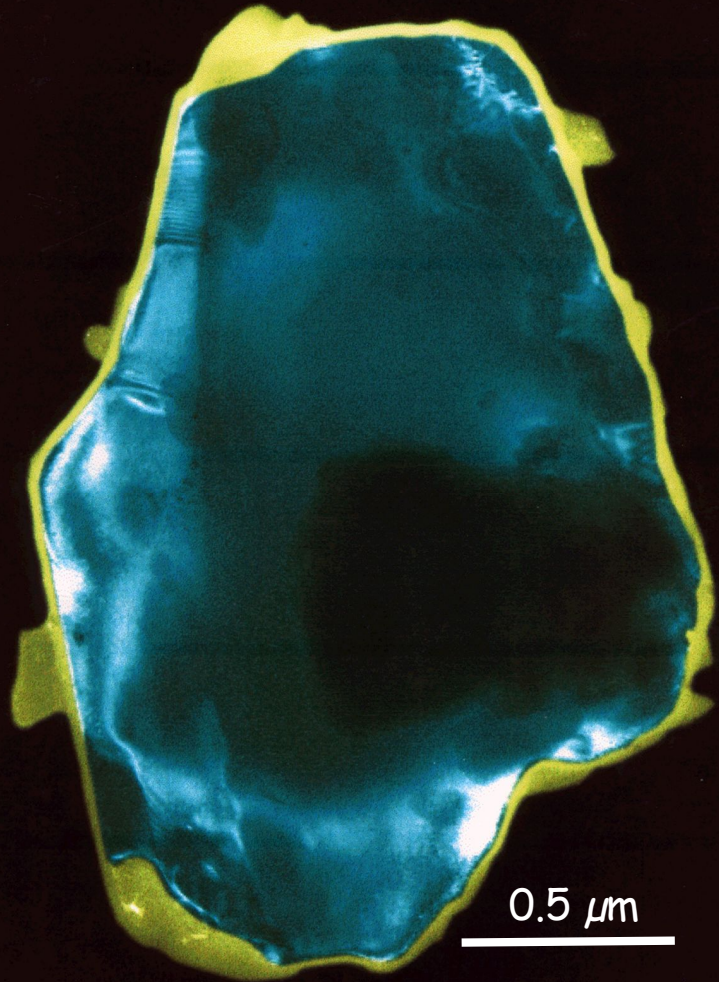


Holland et al. (1998)

Quelques questions d'actualité

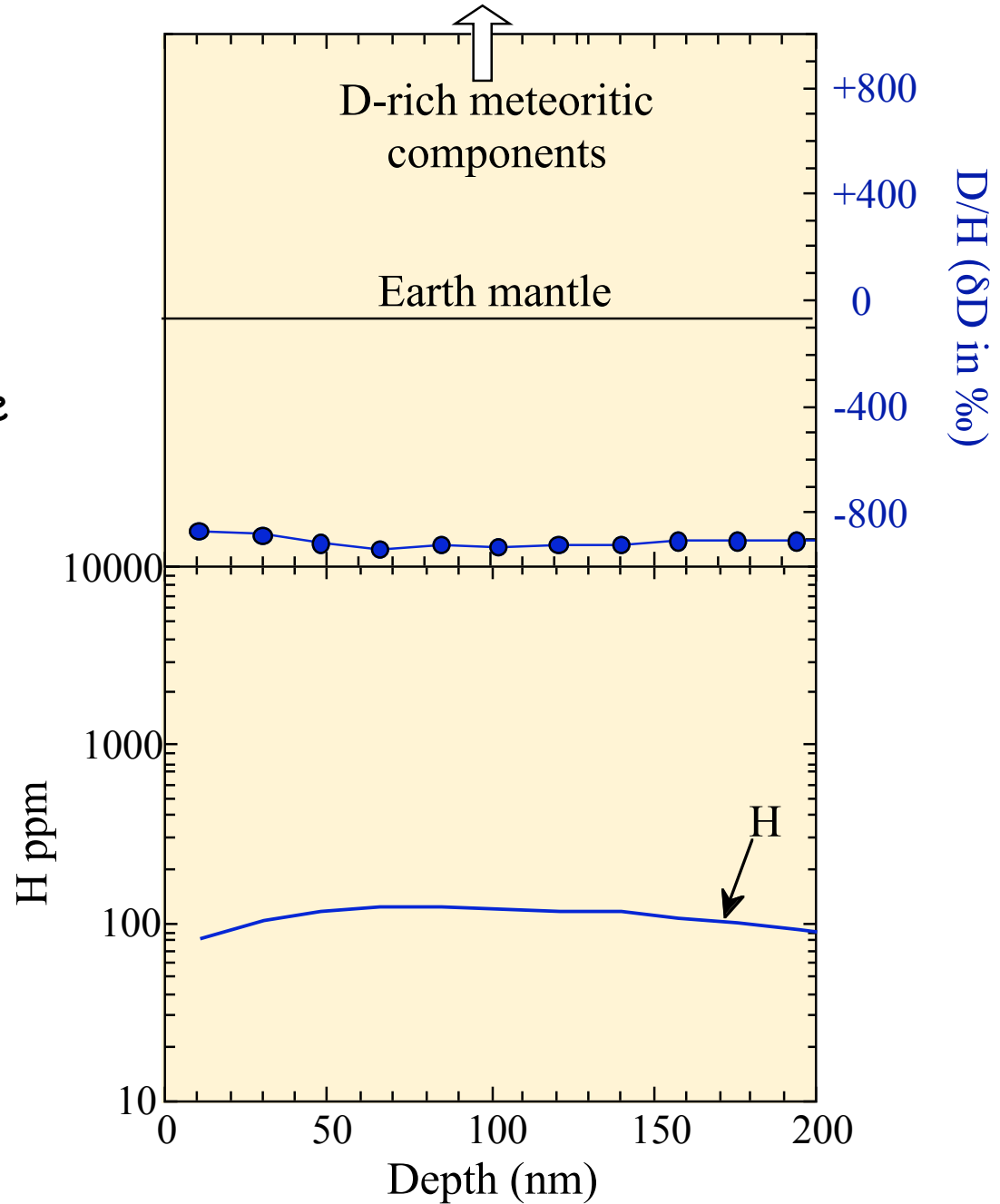
- contexte astrophysique de la naissance du système solaire
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- vitesse à laquelle les premières planètes se différencient
(angrites, ...)
- différence de composition isotopique entre le gaz et les solides
(vent solaire)

La composition isotopique
(H, Li, B, C, N, O)
du vent solaire implanté
dans les
sols lunaires



Sol lunaire 79035
Apollo 17
(silicate)
exposé il y a 1 à 2 Ga

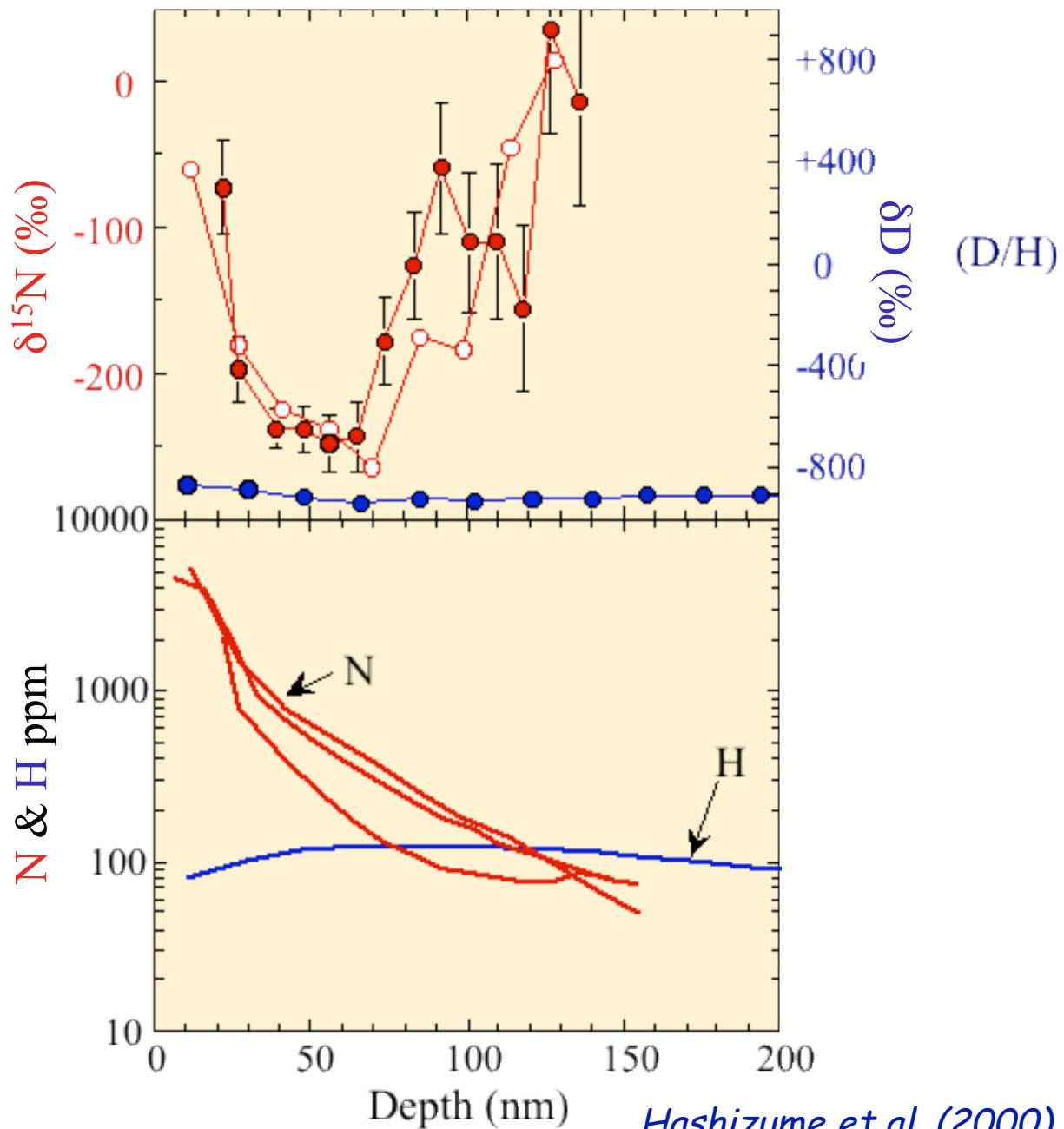
La composition isotopique
de l'H (pas de D!) est la
preuve de la présence
de vent solaire dans
l'échantillon



Il y a vers 50 à 100 nm
de profondeur de l'N
très pauvre en ^{15}N



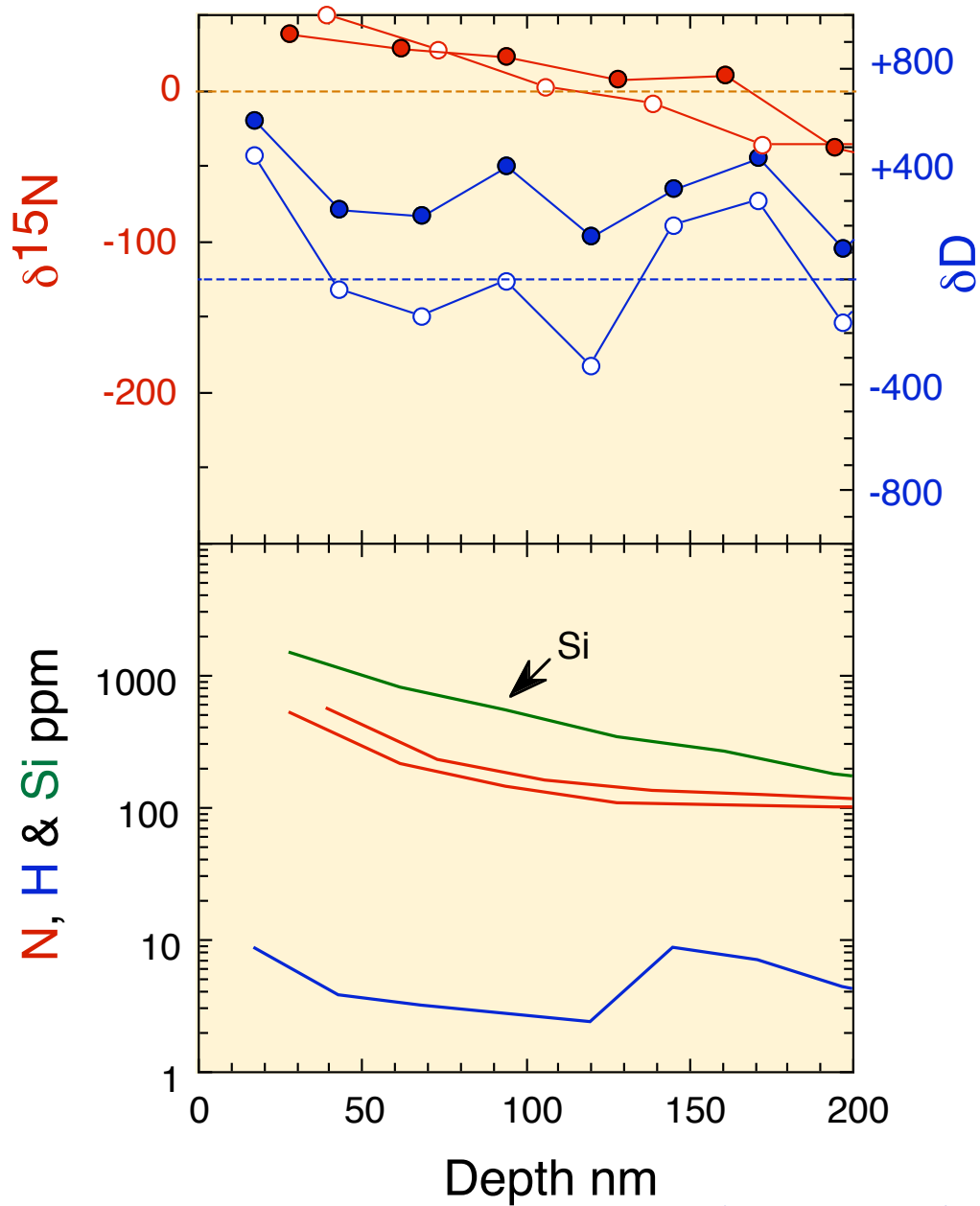
N du vent solaire



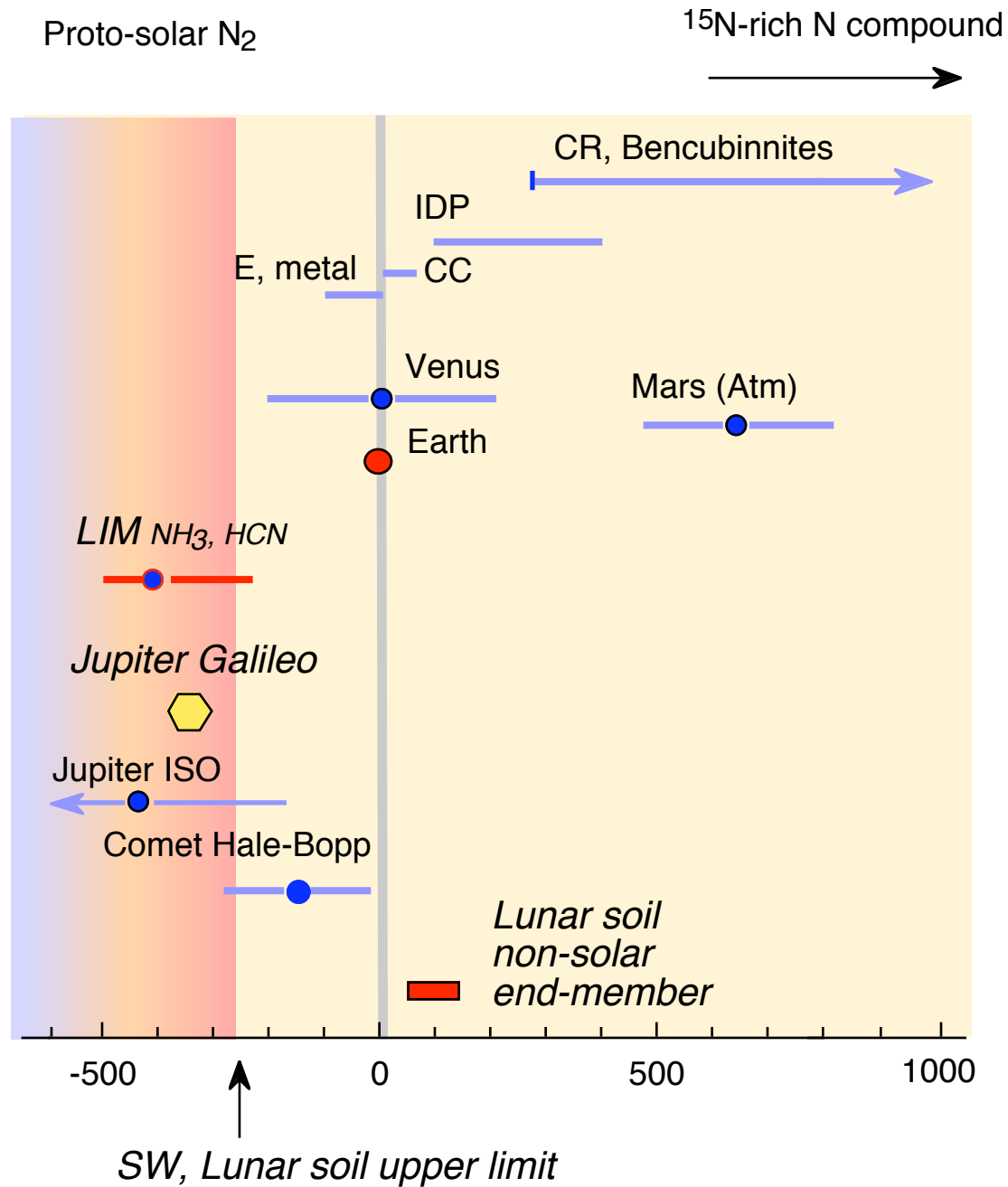
Sol lunaire 71501
Apollo 17
(ilménite)
exposé récemment



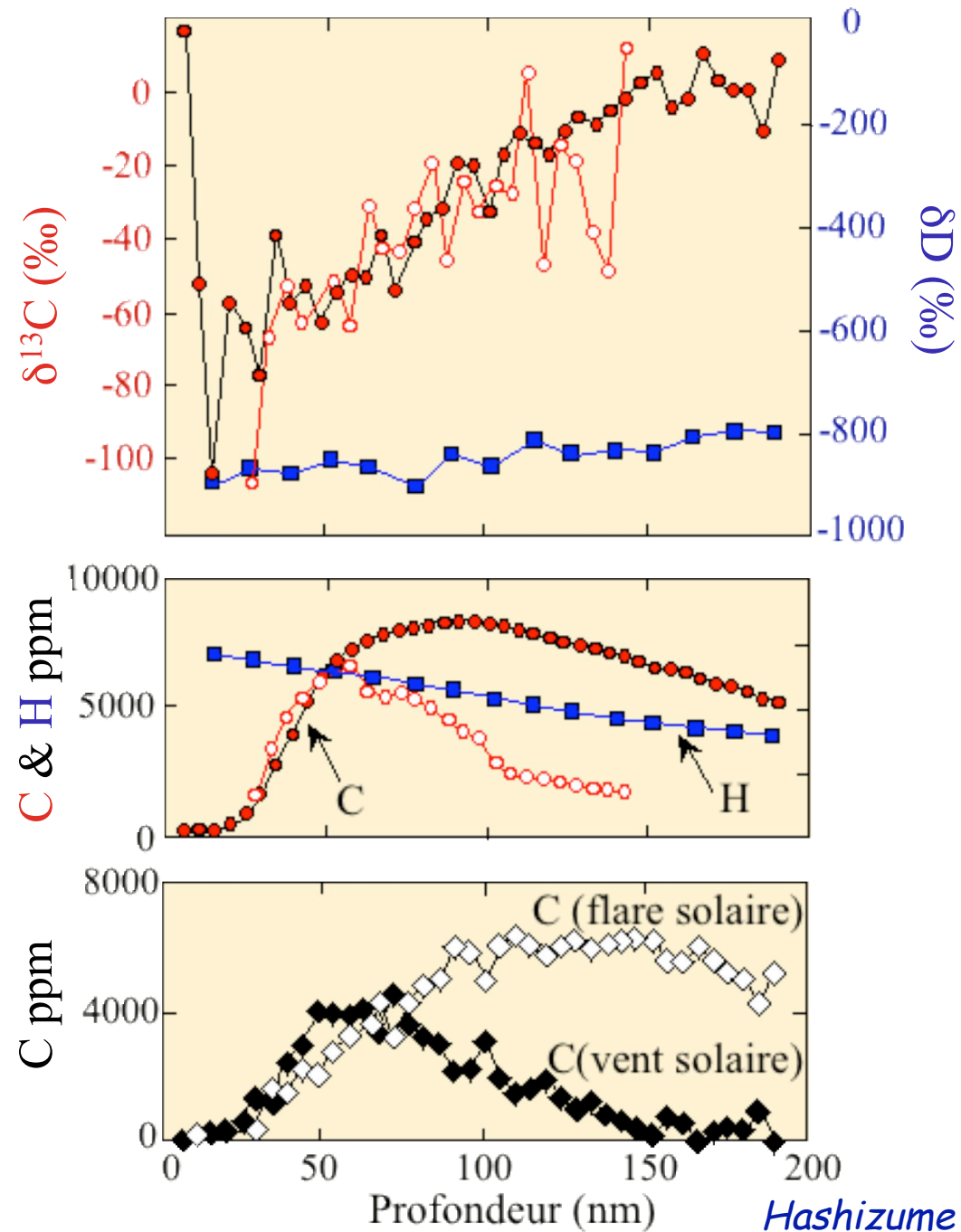
N planétaire



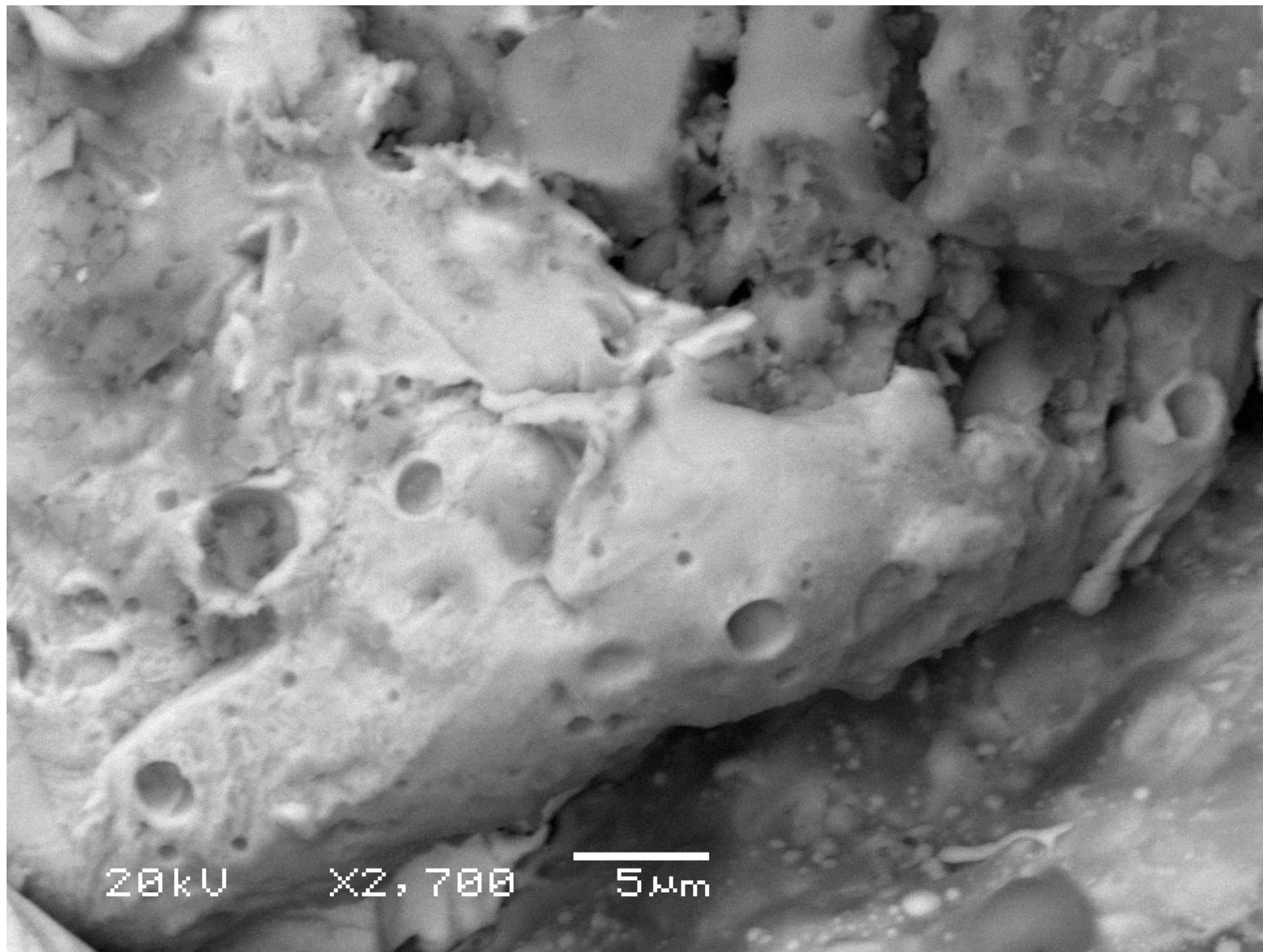
Hashizume et al. (2000)



Il y a vers 50 à 100 nm de profondeur du C très pauvre en ^{13}C



Hashizume et al. (2004)



20kV

X2,700

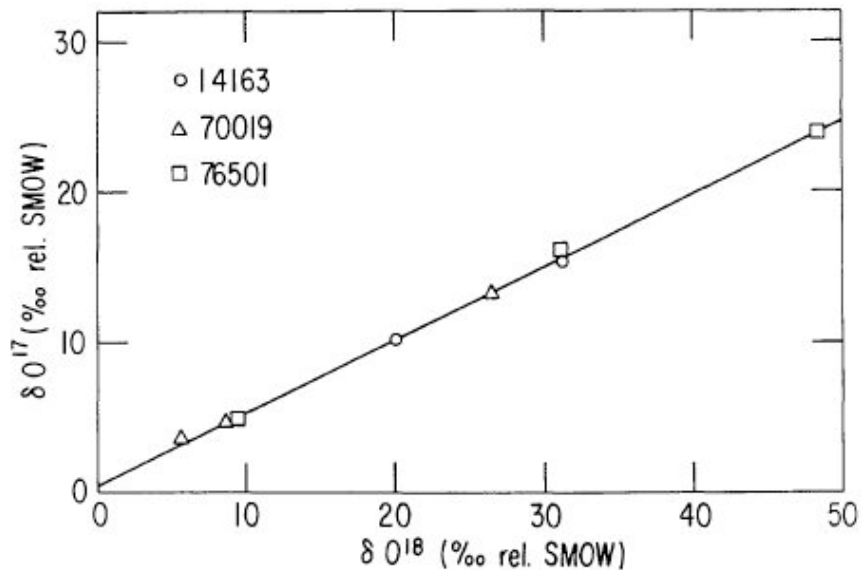
5 μm

Les trois composants contenant de l'oxygène déjà identifiés dans les sols lunaires

(1) les silicates lunaires

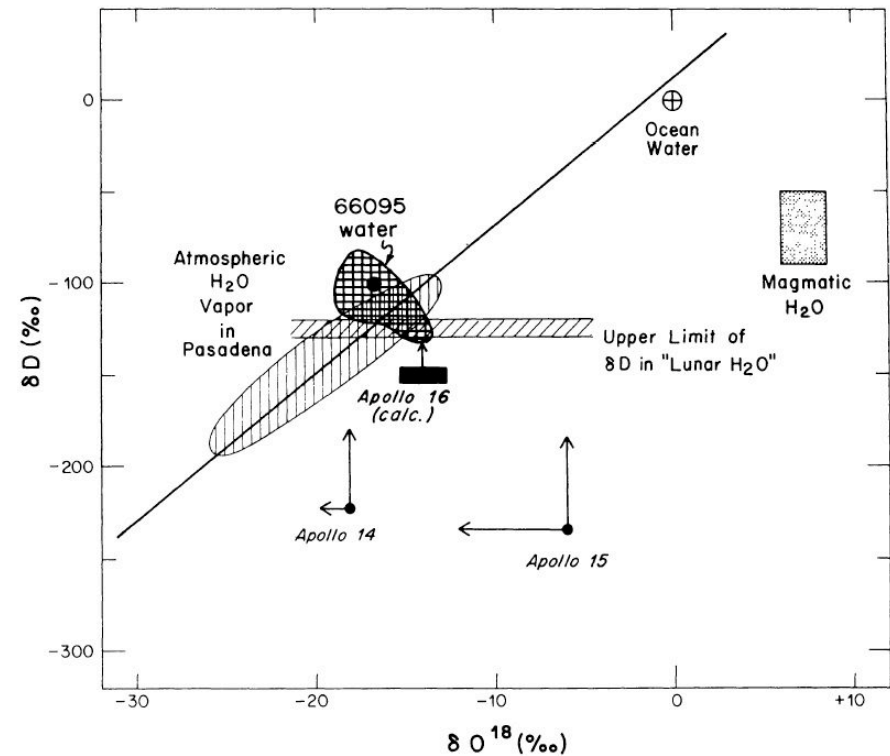
manteau lunaire, $\delta^{18}\text{O} = +5$ à $+7\text{‰}$,
 $\Delta^{17}\text{O} = 0.001 \pm 0.016\text{‰}$

(2) Le composant fractionné par évaporation/condensation

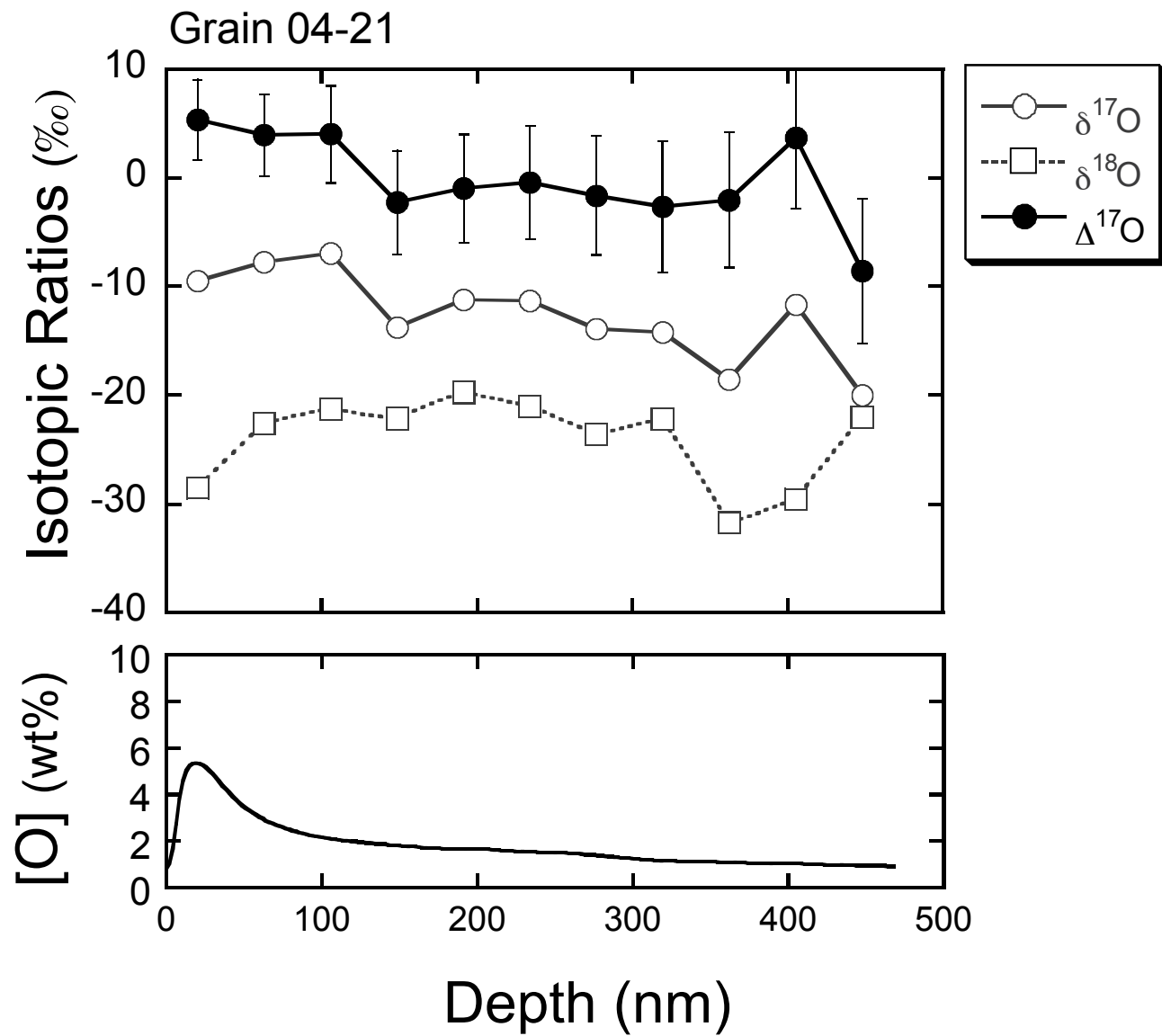


$\delta^{18}\text{O} = +40$ ou $+50\text{‰}$ et $\Delta^{17}\text{O} = 0 \text{‰}$
 (Clayton, et al., 1974)

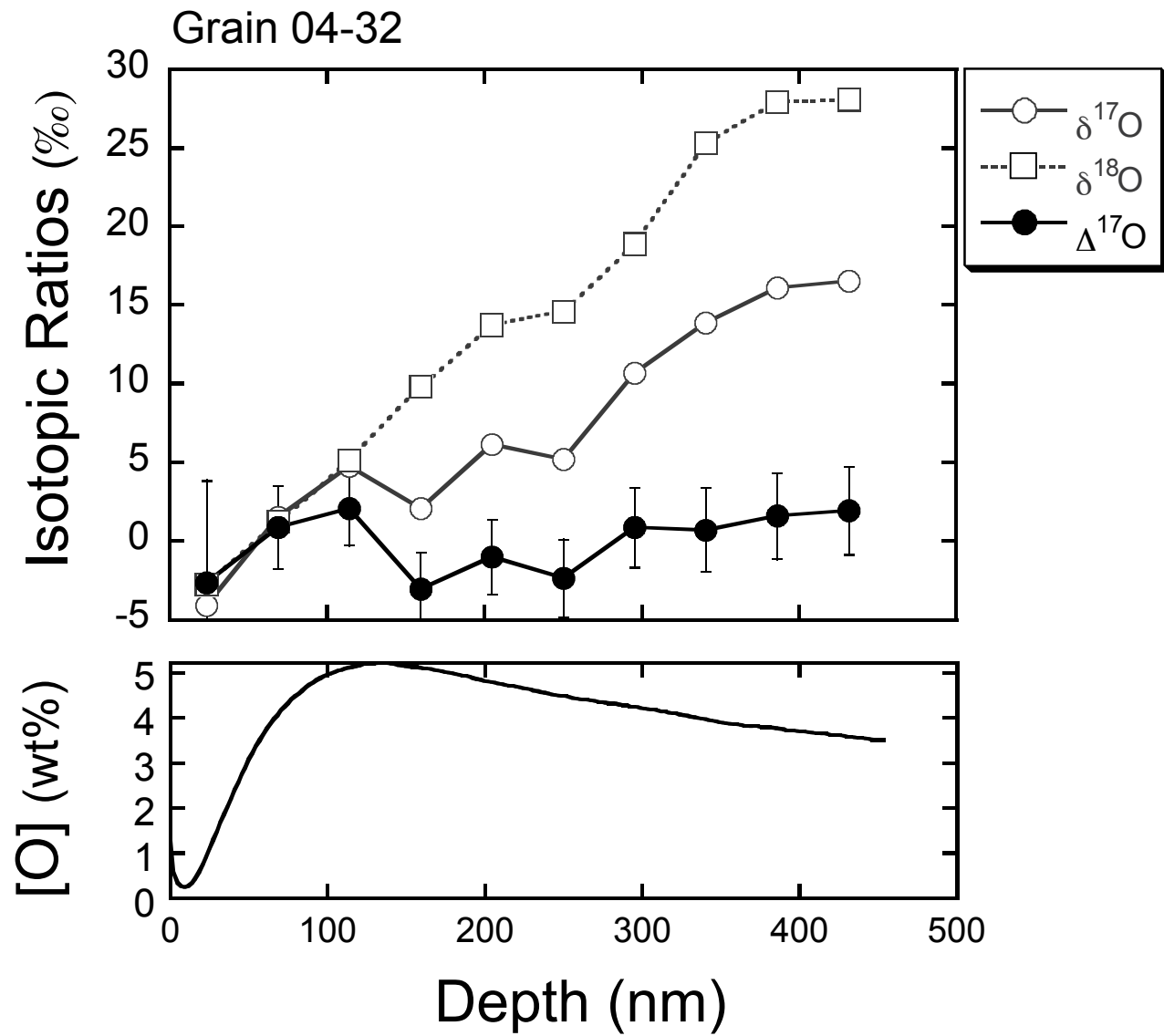
(3) La couche d'oxyde faite sur Terre



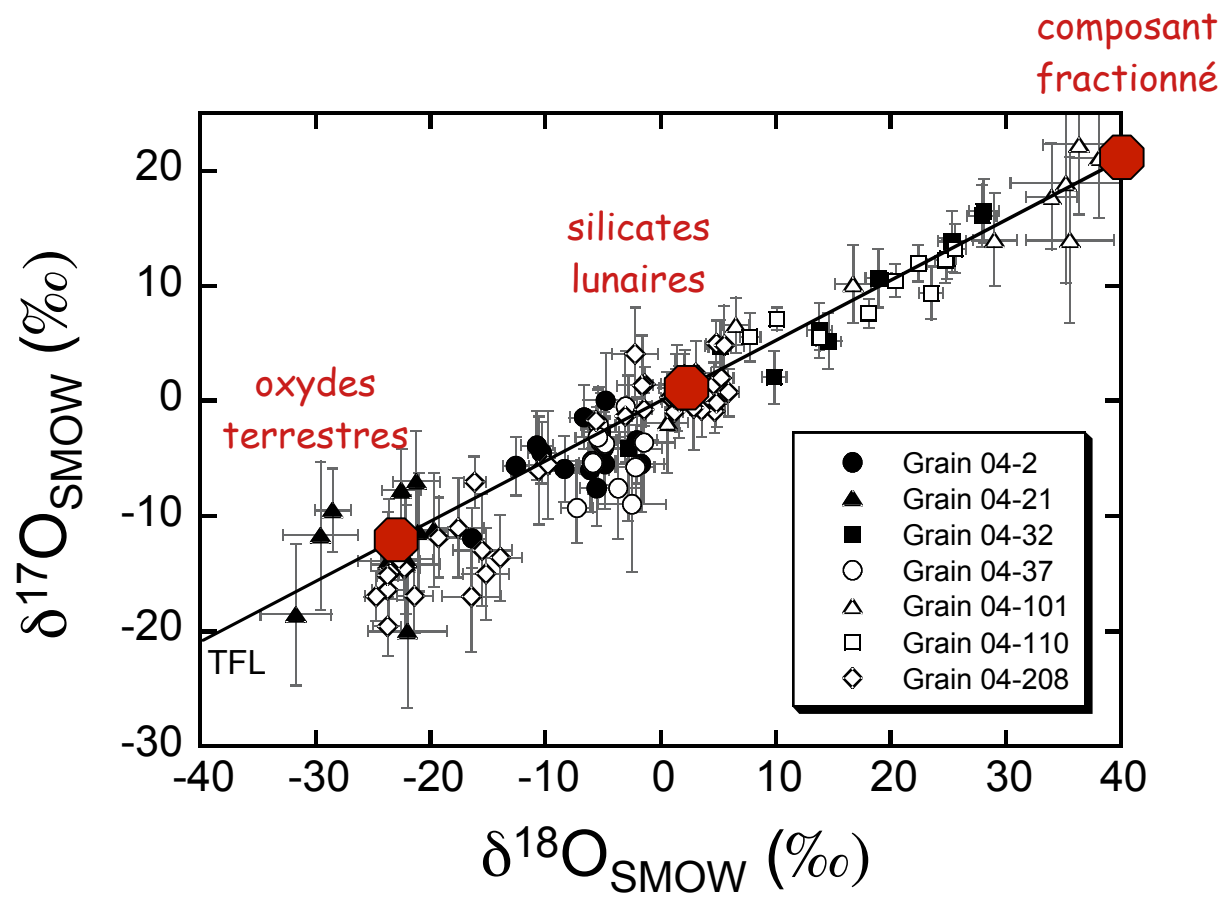
$\delta^{18}\text{O} \approx -20\text{‰}$ et $\Delta^{17}\text{O} = 0 \text{‰}$
 (Epstein & Taylor, 1974)

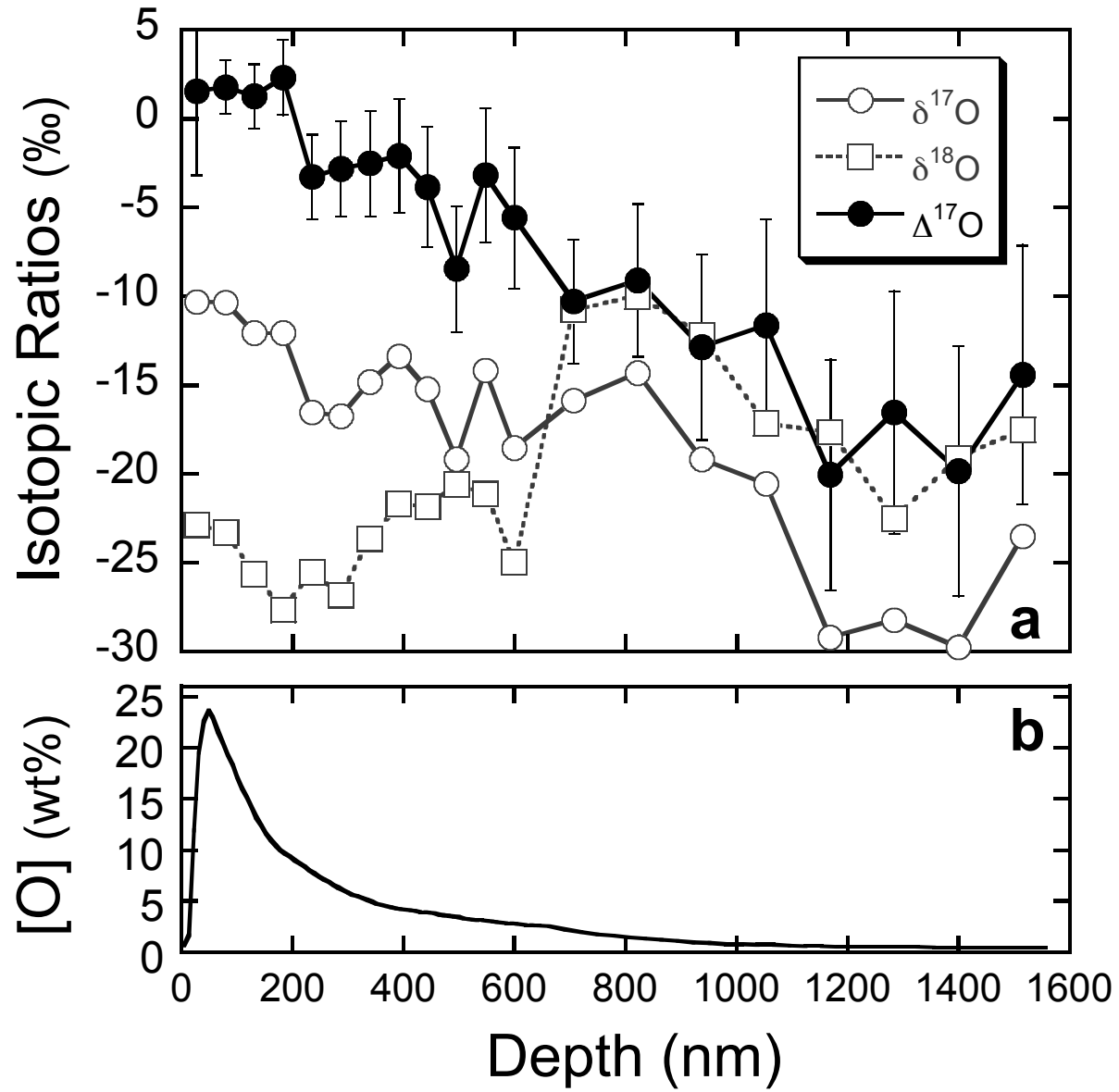


Hashizume et Chaussidon (2005)

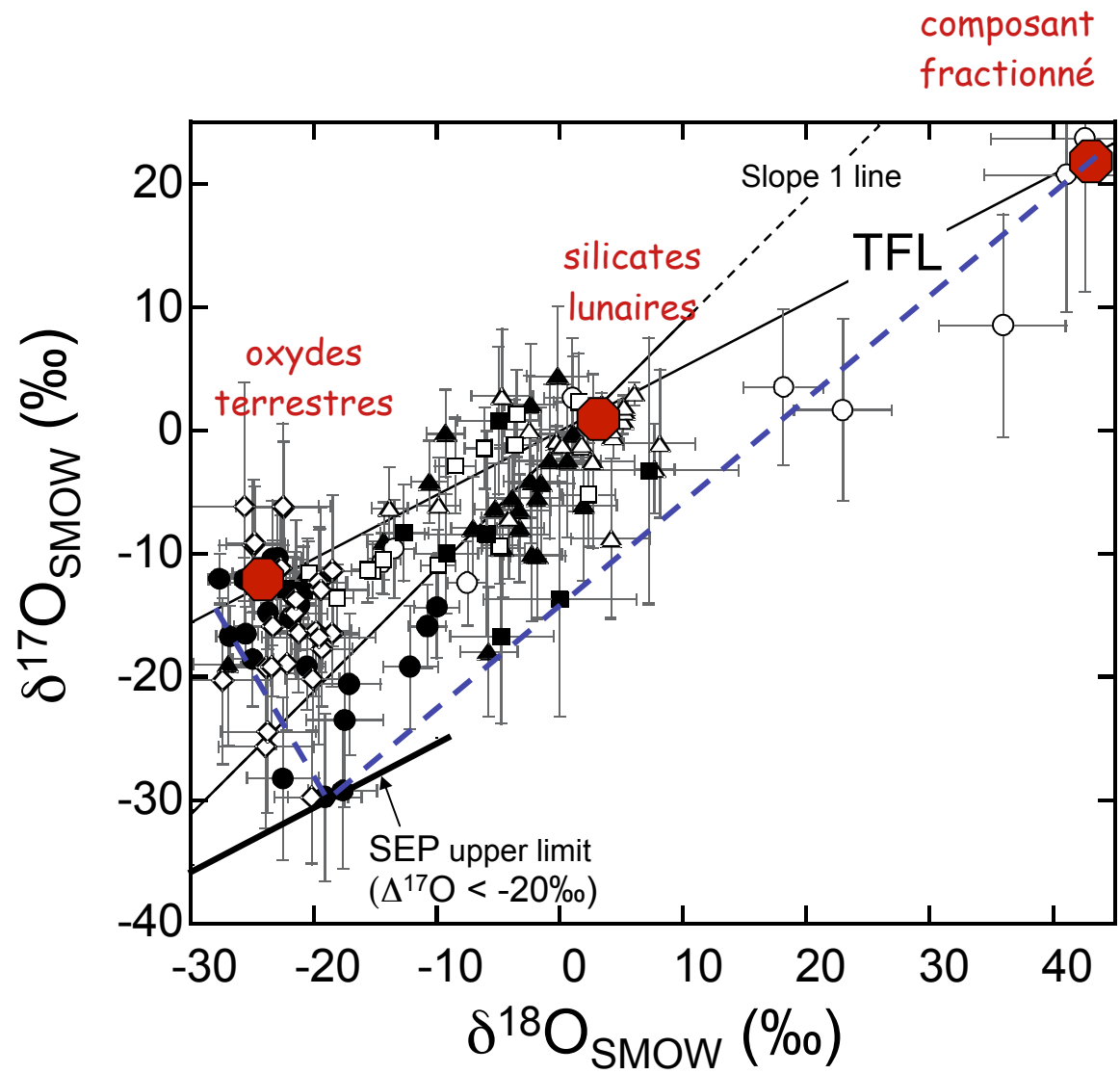


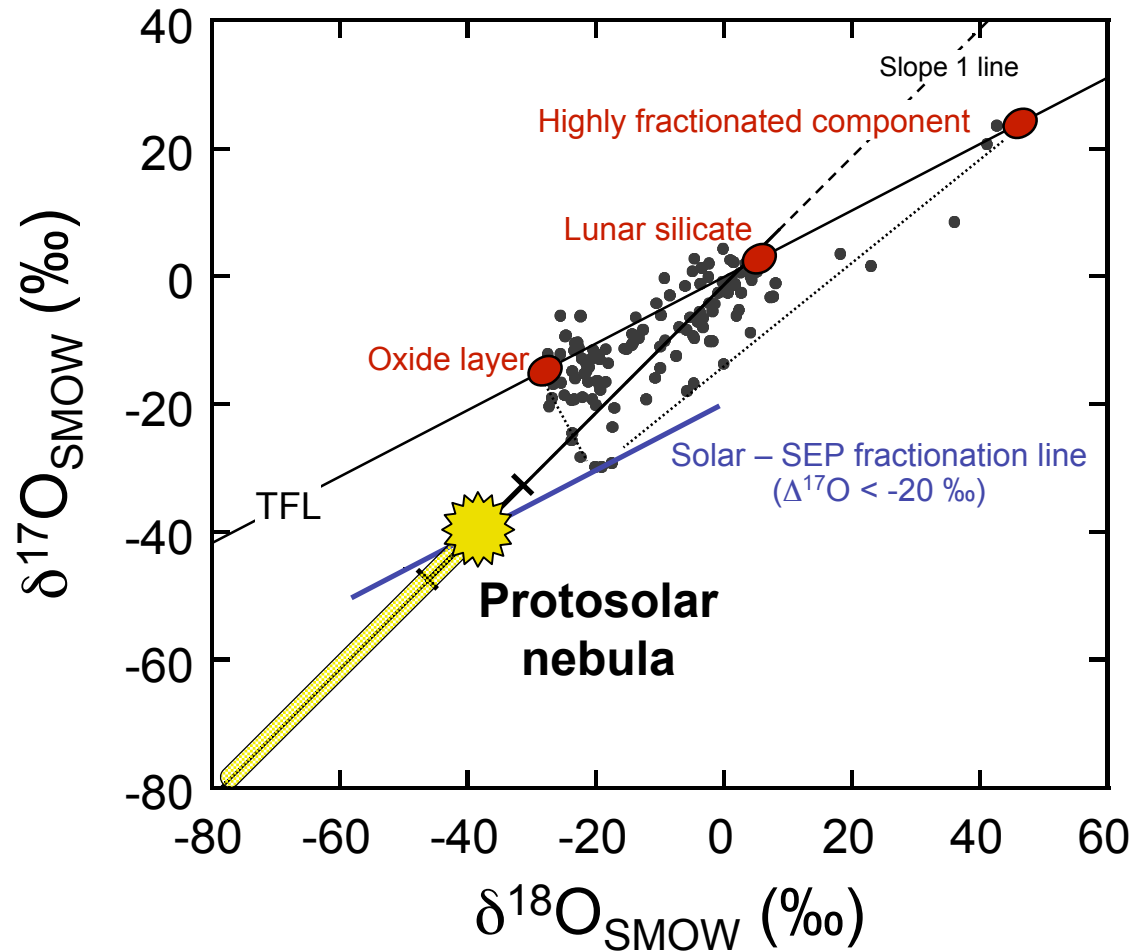
Hashizume et Chaussidon (2005)





Hashizume et Chaussidon (2005)



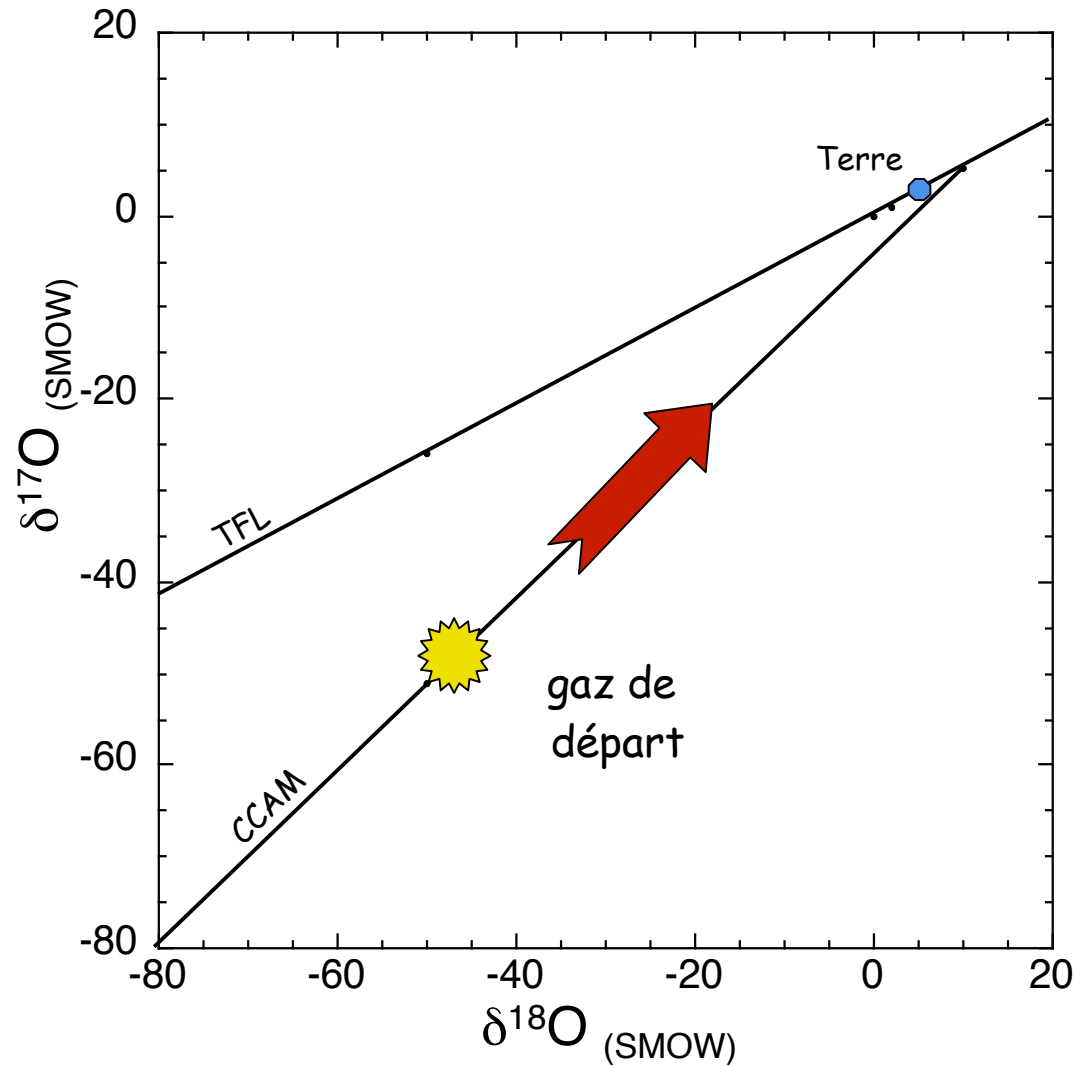


Le SEP est isotopiquement fractionné (de masse) par rapport au vent solaire (SW) et au Soleil (Wiens et al., 2004) avec pour les $\delta^{18}\text{O}$:

$$-50\text{‰} < \Delta_{\text{Soleil-SW}} < 0\text{‰}$$

$$0\text{‰} < \Delta_{\text{SEP-SW}} < +260\text{‰}$$

Seules les CAIs n'ont pas d'anomalie isotopique de l'oxygène !



Les silicates se sont formés à partir d'oxygène enrichi en ^{17}O et ^{18}O par :

- réactions non dépendantes de la masse ?
- self shielding des UV ?
- source des UV (interne, externe) ?

$\delta^{15}\text{N}$ vent solaire < -280‰

$\delta^{13}\text{C}$ vent solaire < -120‰

$\delta^{18}\text{O}$ vent solaire < -40‰

Composition solaire ?
Que représentent les chondrites ?

