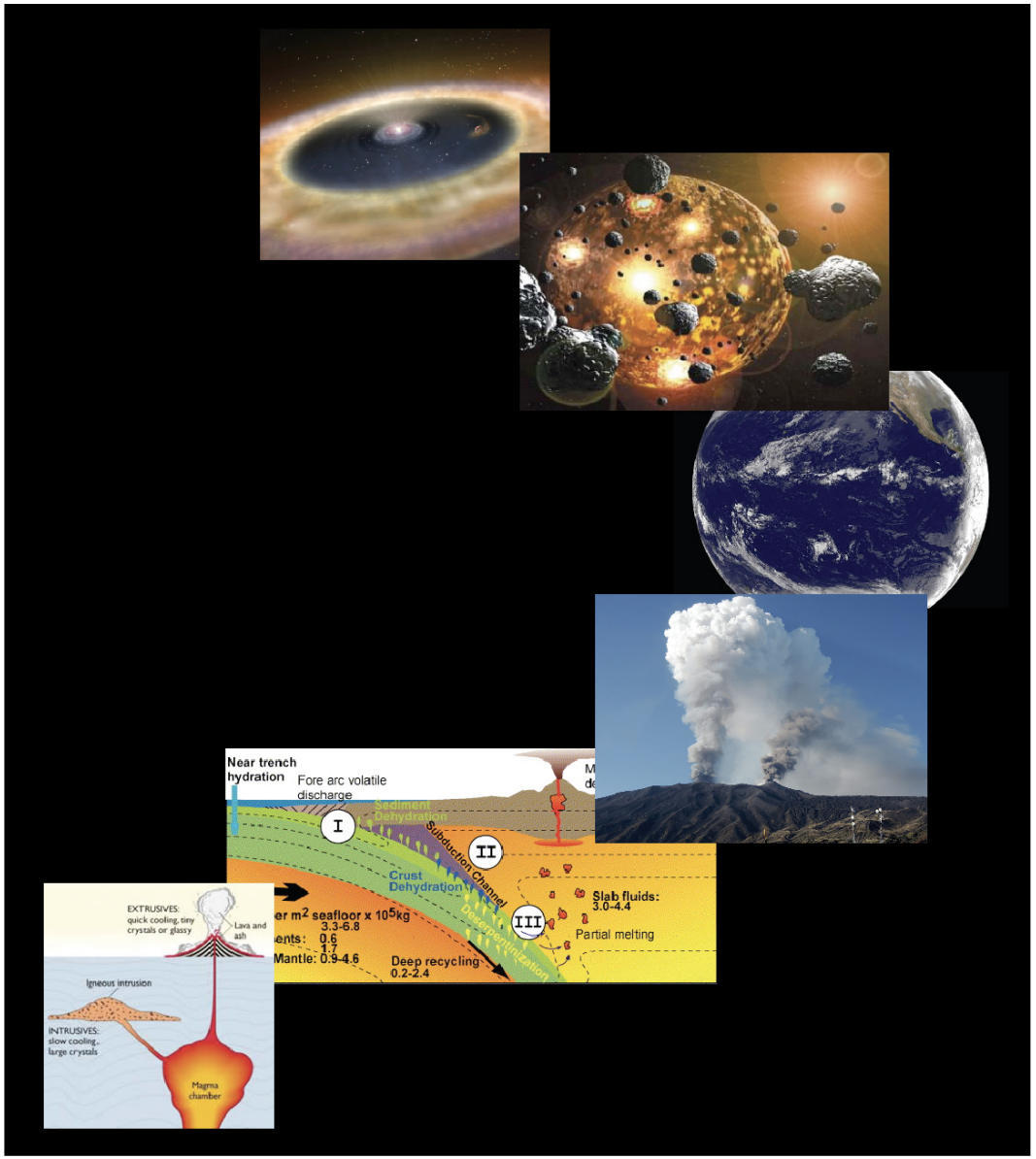
# Magmas et Eléments Volatils
# MEV 1:
# Origine des éléments volatils sur Terre

Manuel Moreira

# Plan

- Introduction
- La formation de la Terre
  - Le système solaire
  - Les corps parents de la Terre
  - Eléments de géochimie
- Atmosphères
  - Atmosphère ?
  - Compositions
  - Origines possibles
  - Origine de l'eau sur Terre

# Introduction



# Interventions

- M. Moreira le 5 octobre
- F. Gaillard: 12 octobre
- M. Moreira le 15 octobre
- C. Martel, G. Prouteau, B. Scaillet, L. Arbaret, M. Pichavant

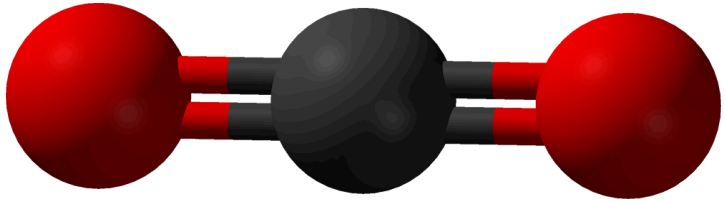
# Eléments volatils

- Définition « cosmochimique »: température de condensation (ou ébullition/sublimation) basse
- Par extension: gaz dans les atmosphères planétaires
- Mais pas seulement !! Ex potassium est considéré comme volatil en cosmochimie
- Dans la suite du cours: ca sera souvent les éléments ou molécules très volatils qui seront considérés (eau, $CO_2$, gaz rares, halogènes, soufre)

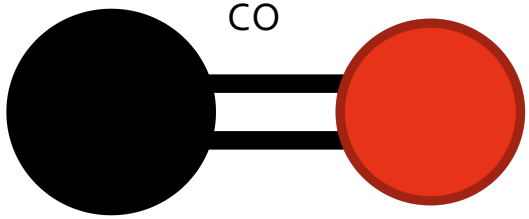
# Ex du Carbone

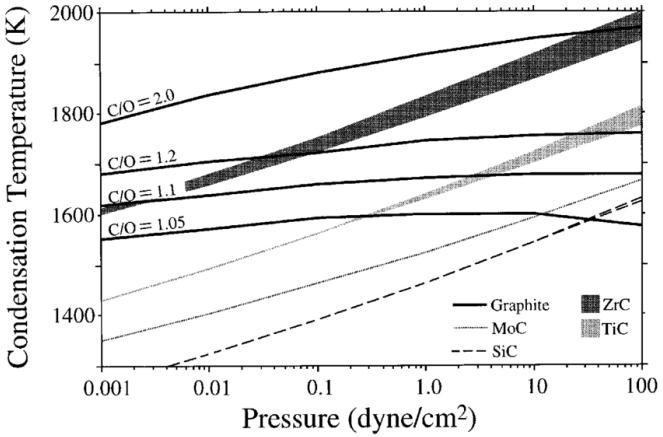
diamant

$CO_2$

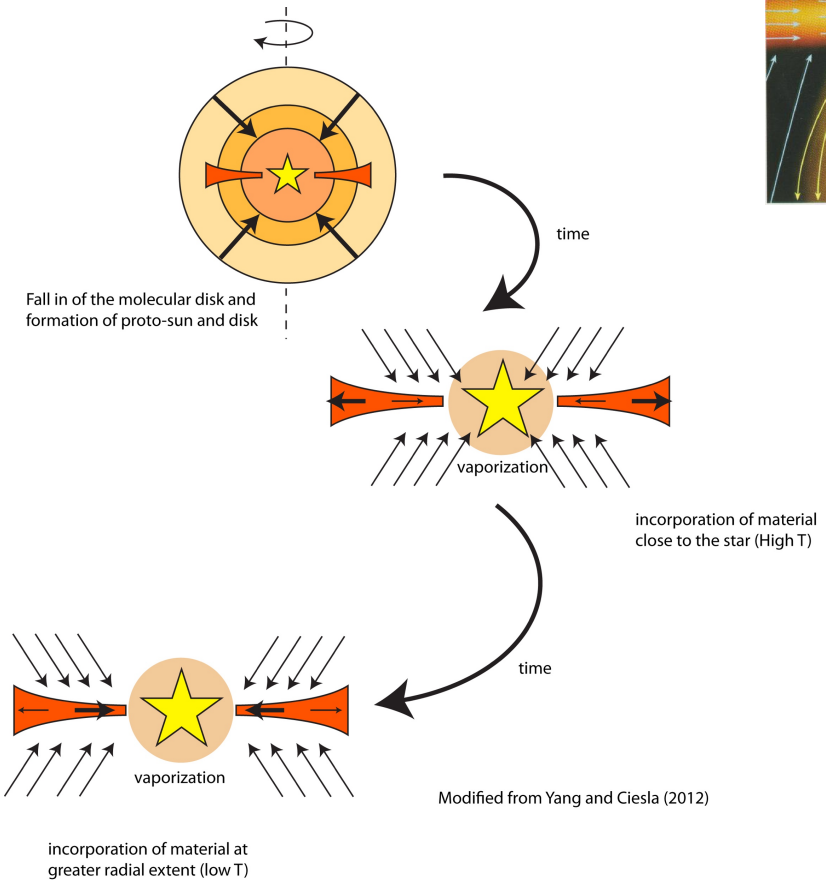


CO

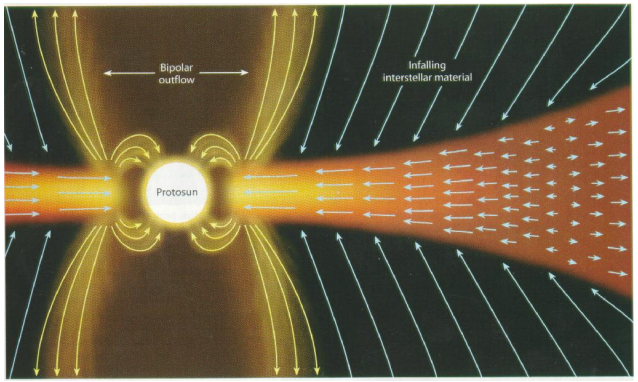




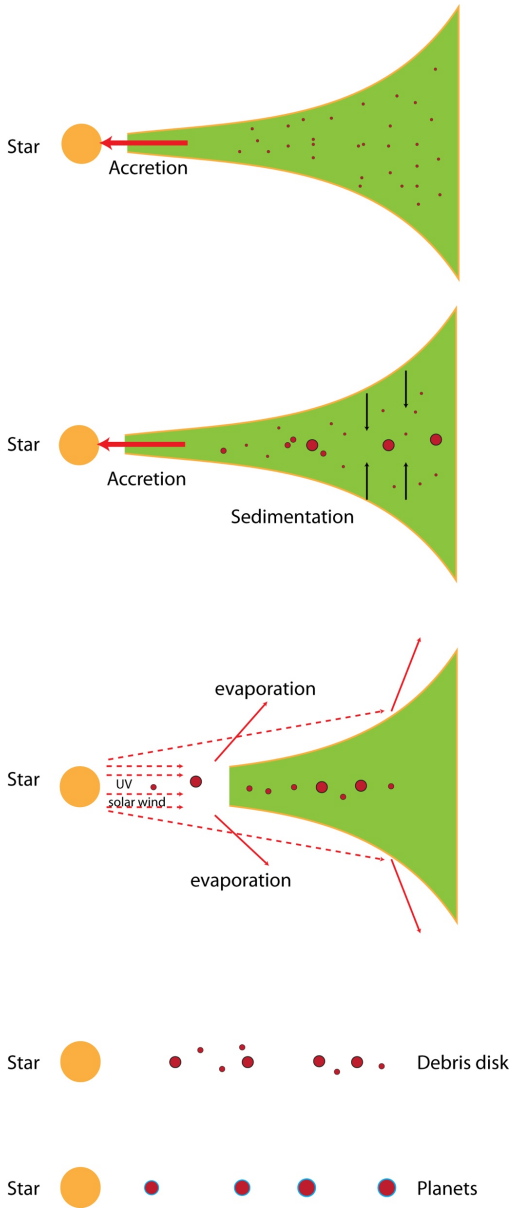
# Formation du système solaire



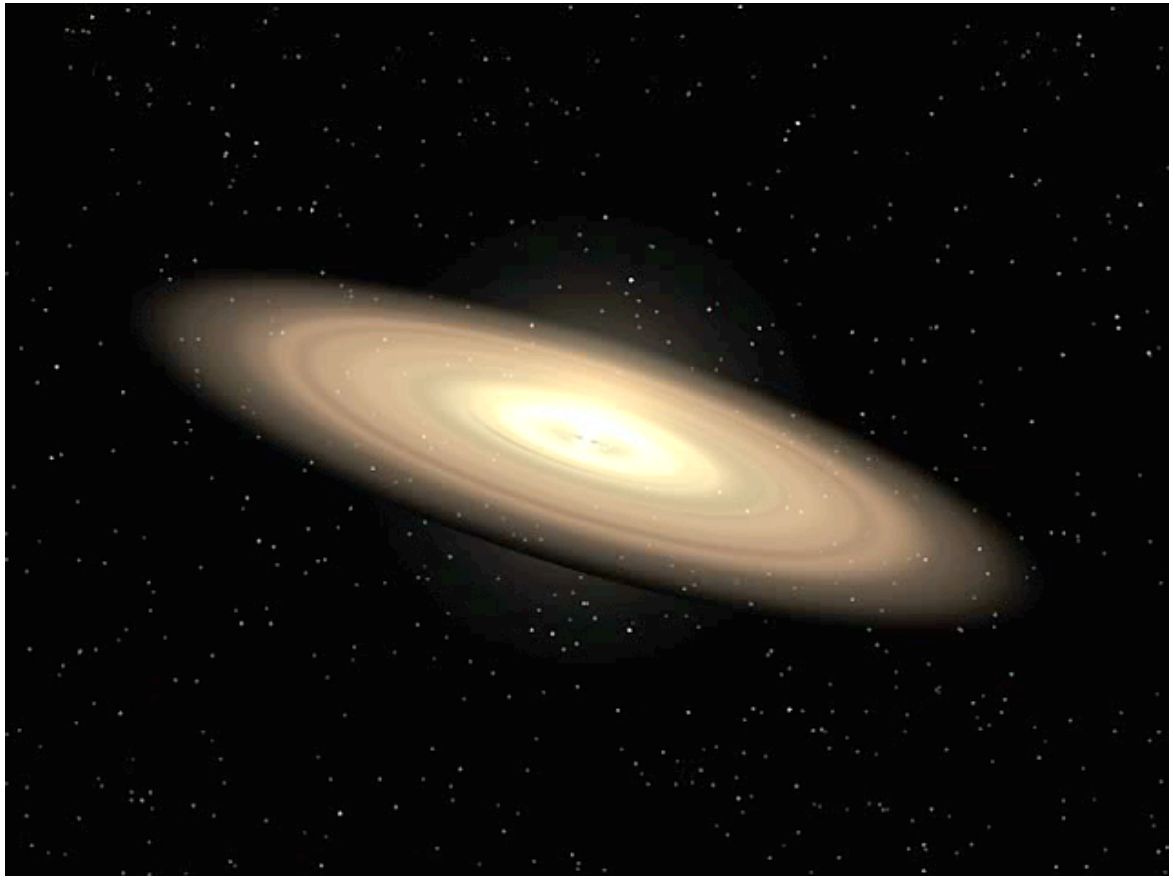

Modified from Yang and Ciesla (2012)



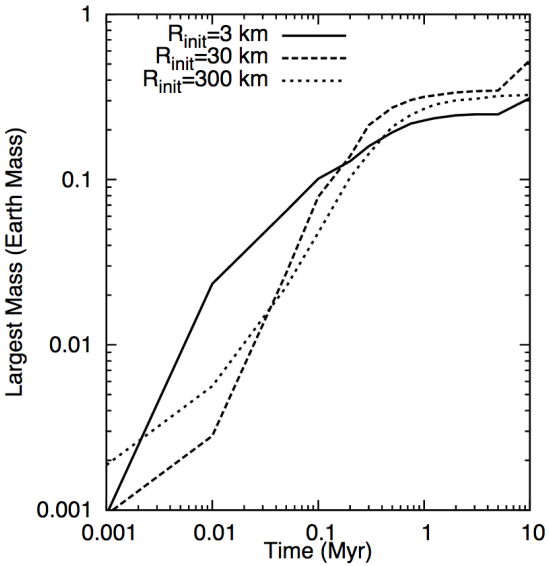
# Etapes clés de la formation du système solaire



# Formation de la Terre

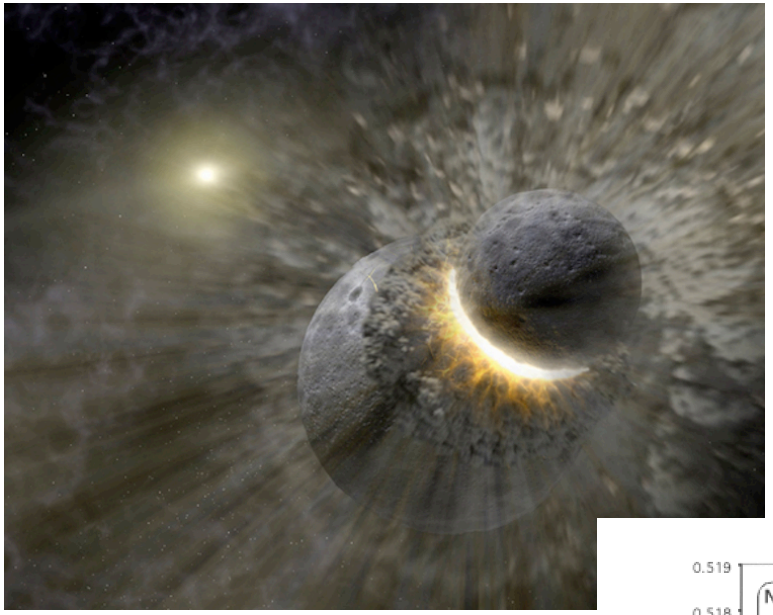


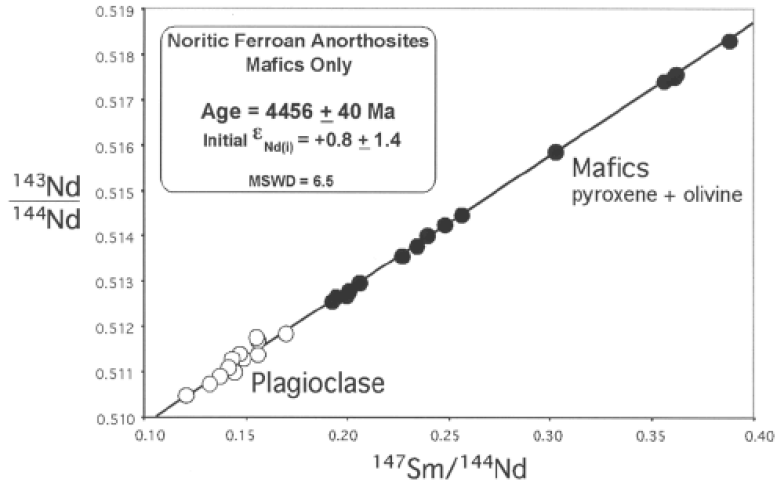
# Accrétion de la Terre



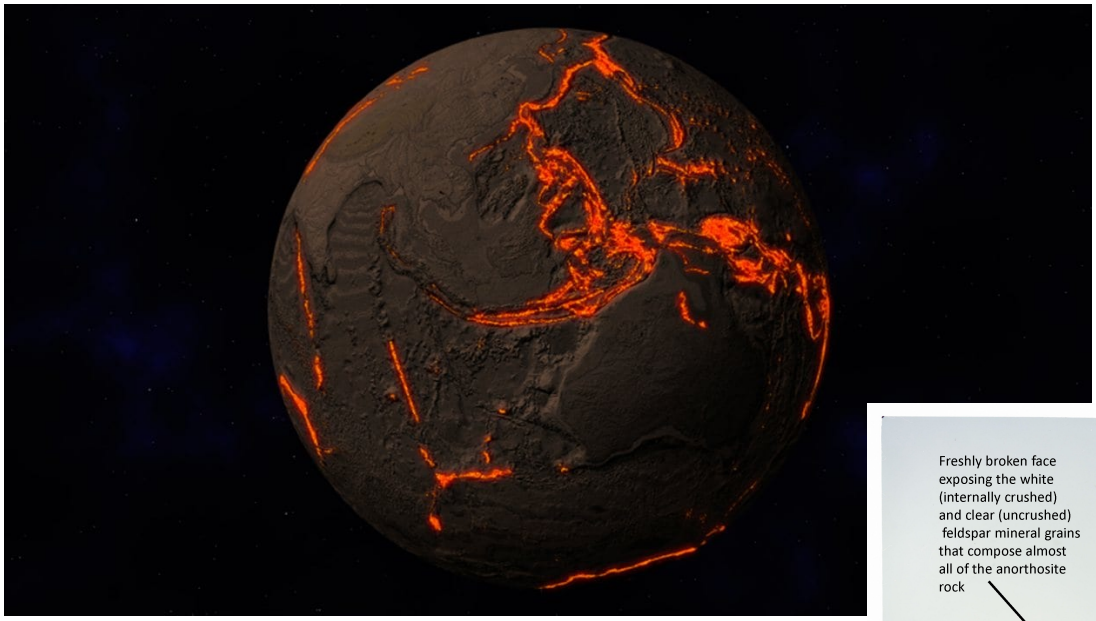
# Une accrétion lente

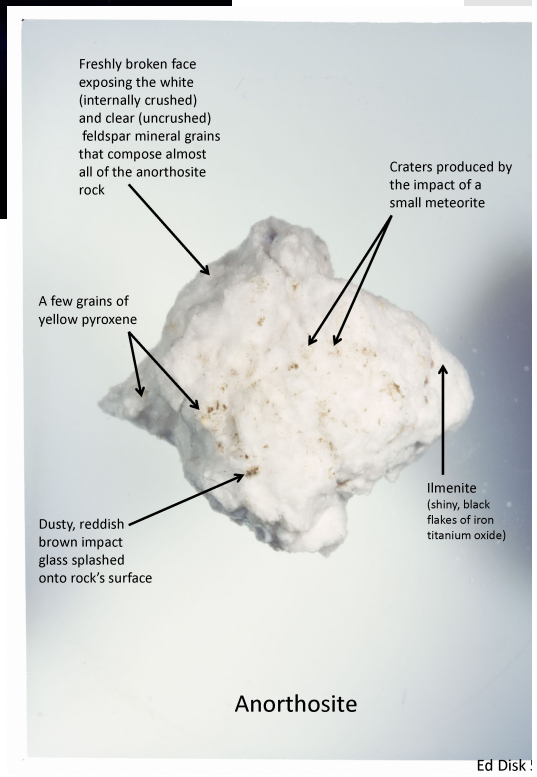
# La formation de la Lune: la fin d'une accrétion violente





# La notion d'océan de magma

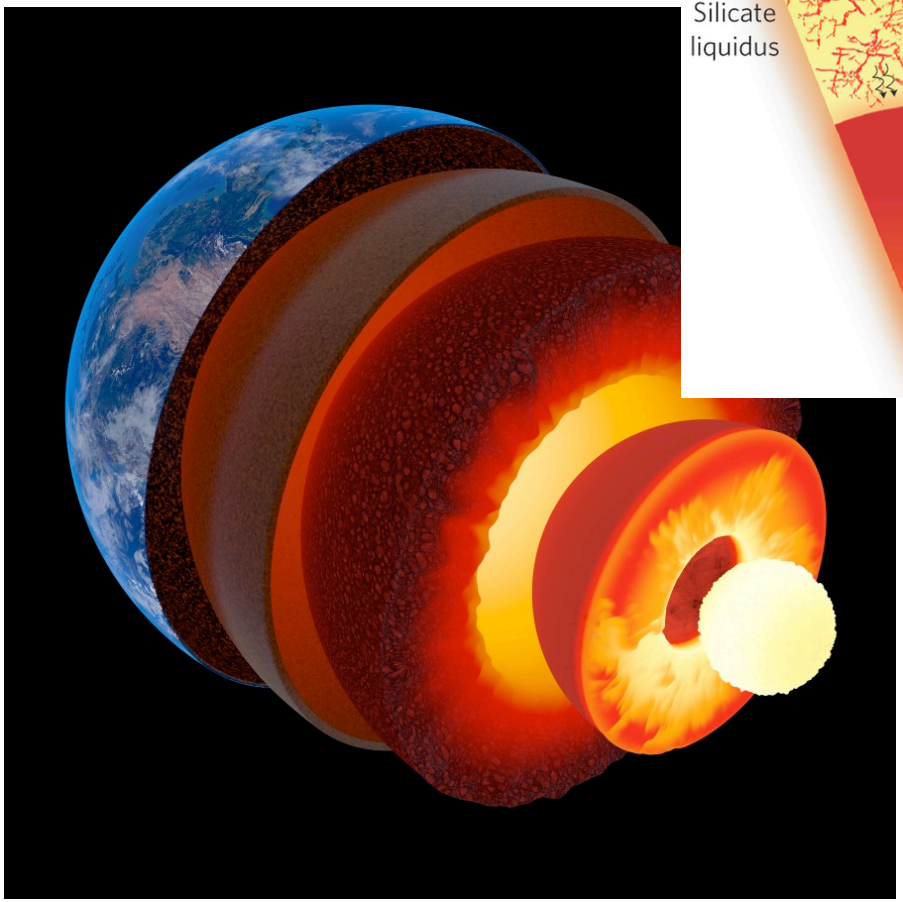


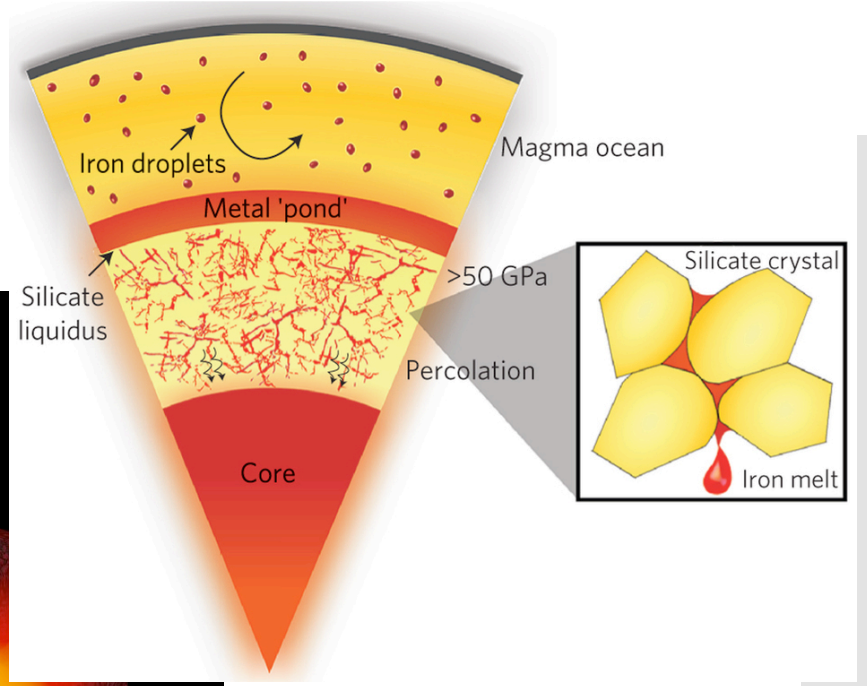



Ed Disk

- Vient de l'observation sur la lune des « continents » lunaires (anorthosites)
- Favorise la formation du noyau et de l'atmosphère
- Pas d'évidence directe de son existence

# Formation du noyau

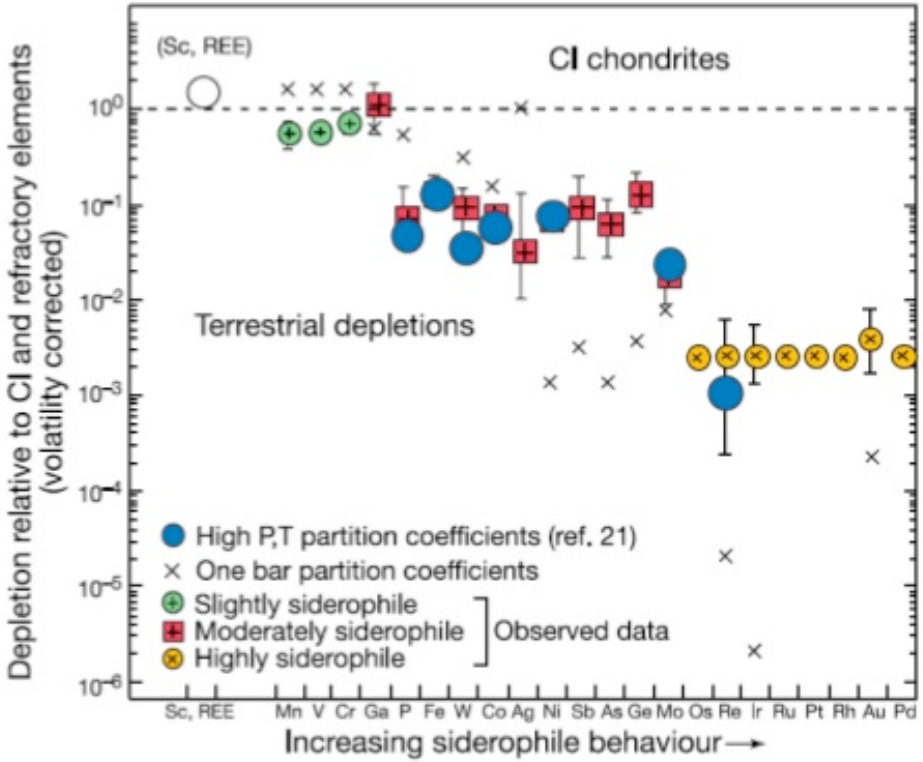




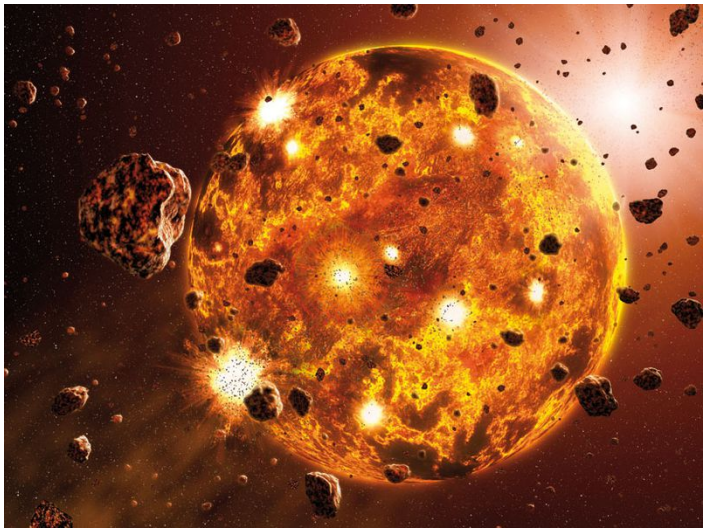
# Notion de verni tardif

Noyau + Manteau = Terre Totale

Eléments sidérophiles sont allés dans le noyau en fonction de leur caractère sidérophile

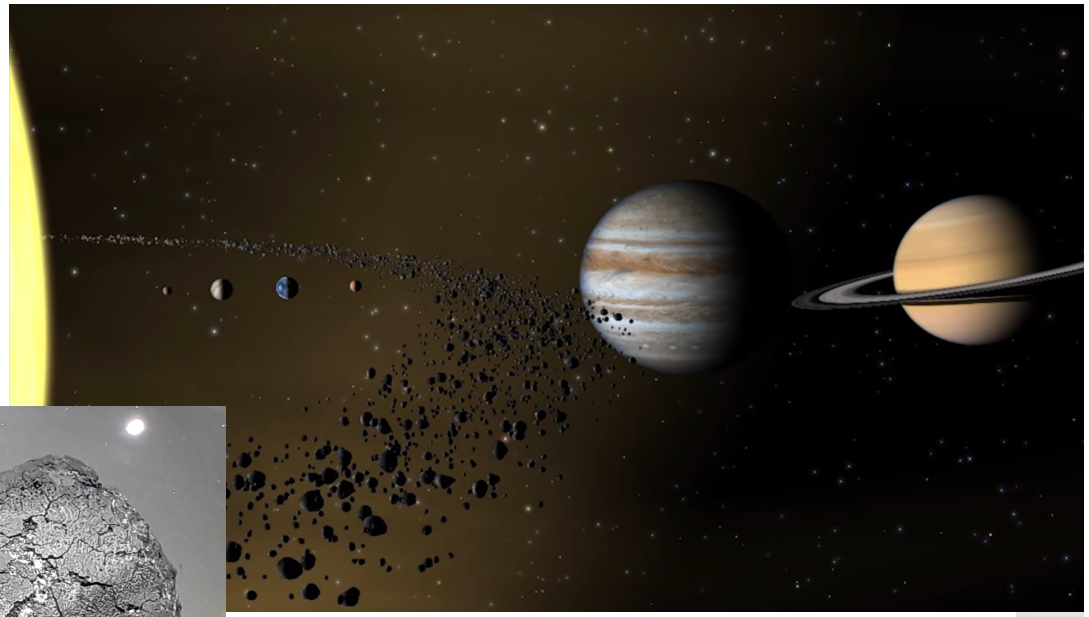


En fin d'accrétion quand le noyau est déjà quasi formé (4.45 Ga)

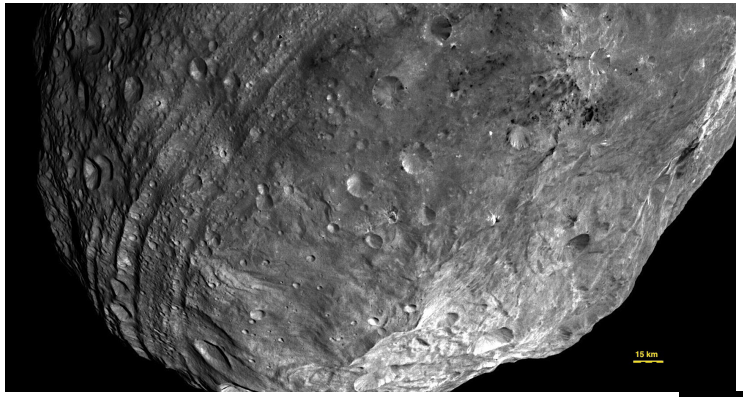


Le grand bombardement tardif (~4Ga)

# Les météorites

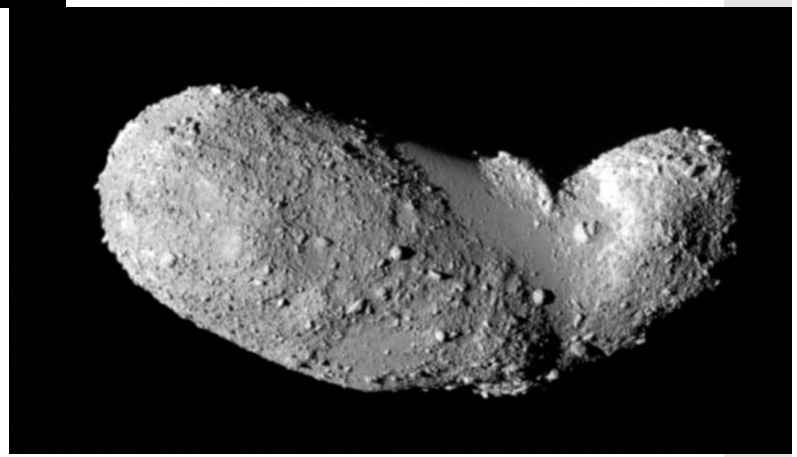


# Observations des astéroides



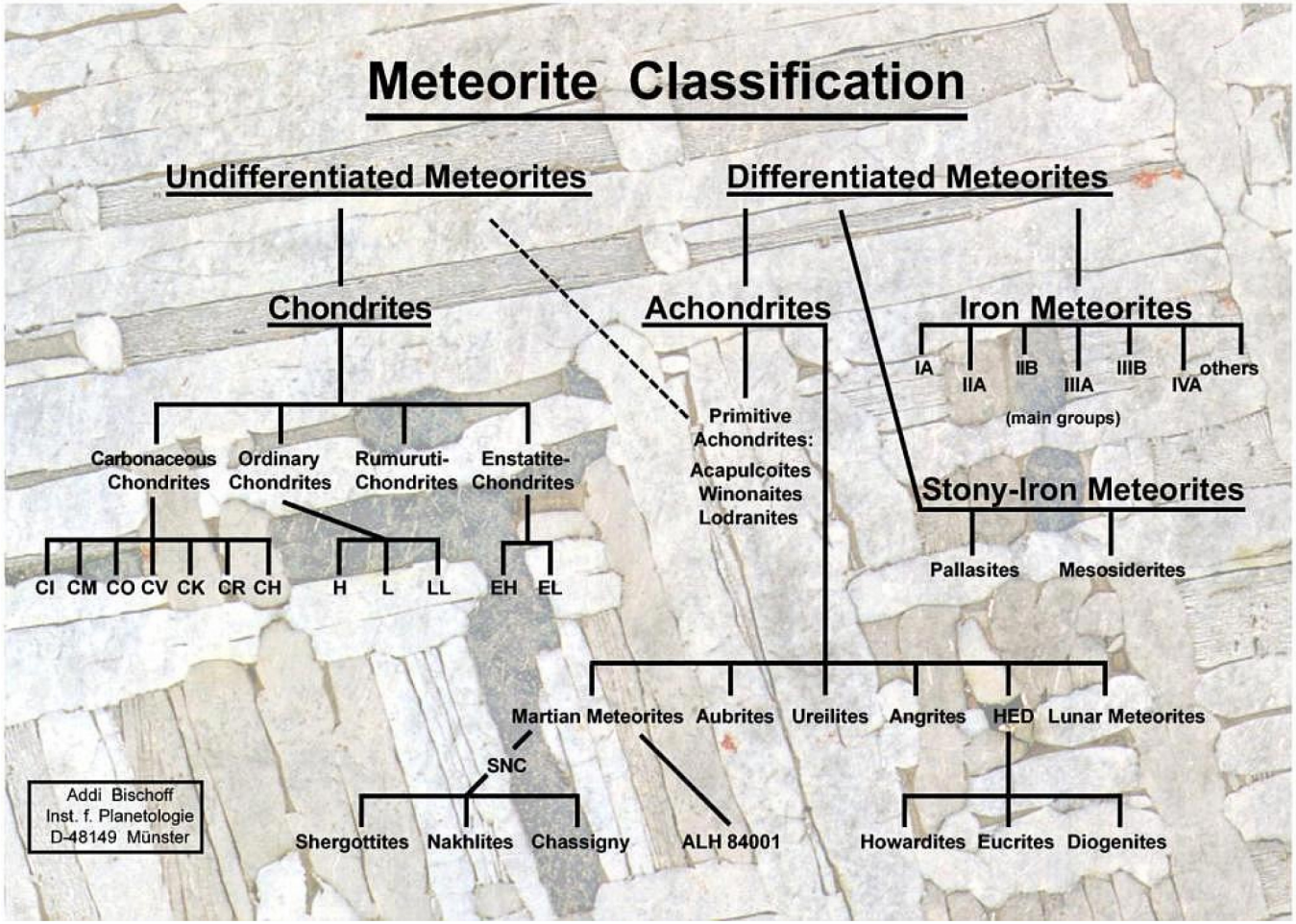

Vesta

Itokawa

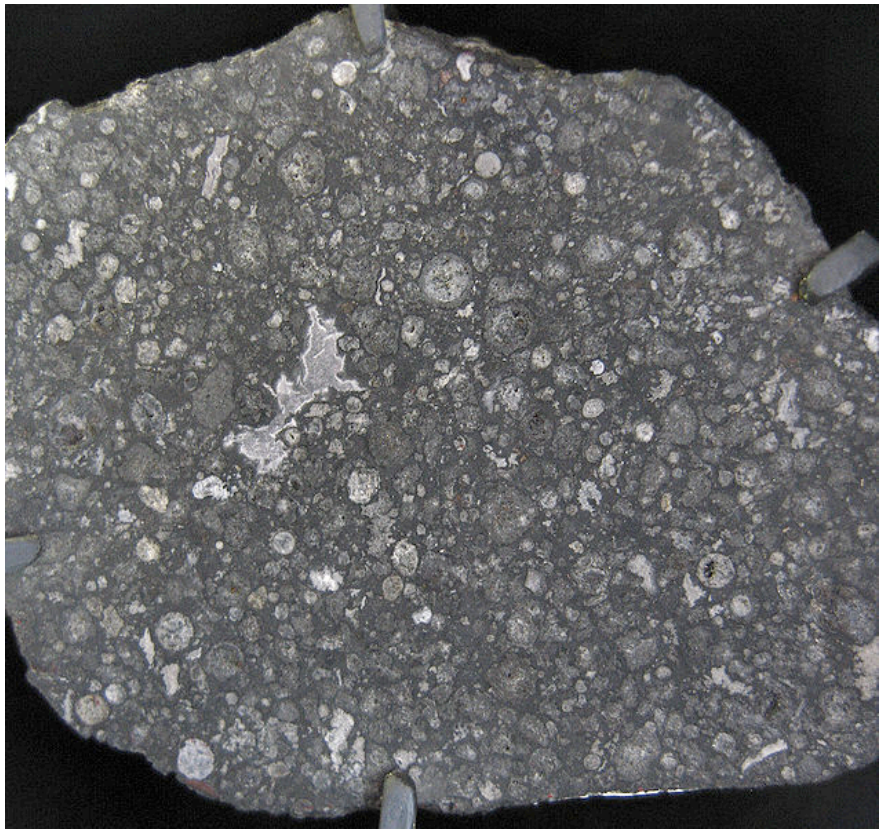


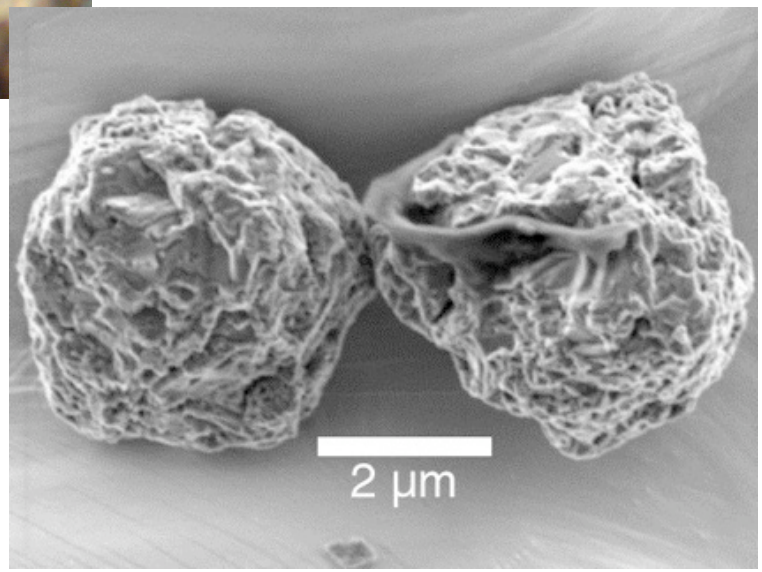
Ryugu

# Classes de météorites



# Les chondrites




2 µm

# La matière organique soluble et insoluble des chondrites

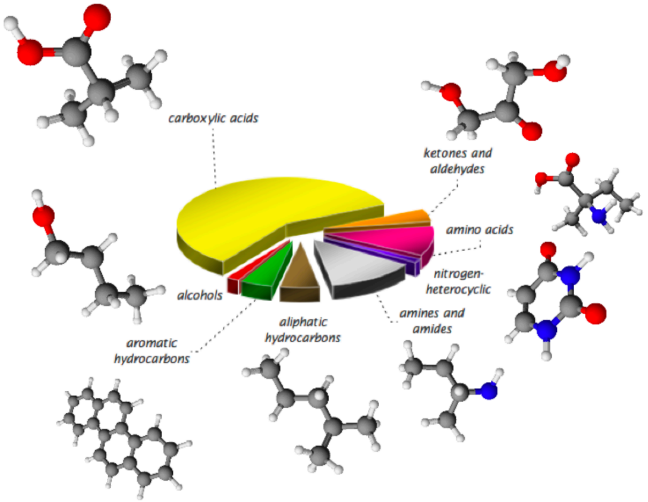



**Fig. 1.** Distribution and molecular models of soluble molecules in the Murchison meteorite.

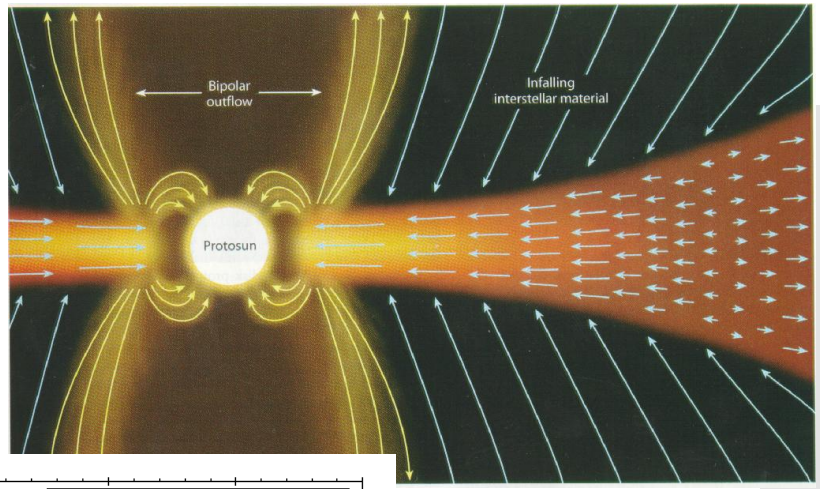
**Table 1**
The abundances of insoluble (IOM) and soluble (SOM) organic components in the least metamorphosed carbonaceous chondrites, including the ungrouped C2 Tagish Lake. For the CMs, all data are from the Murchison CM2 meteorite (updated from Botta and Bada, 2002), unless otherwise noted. The abundances are in μg/g (ppm), except where indicated.

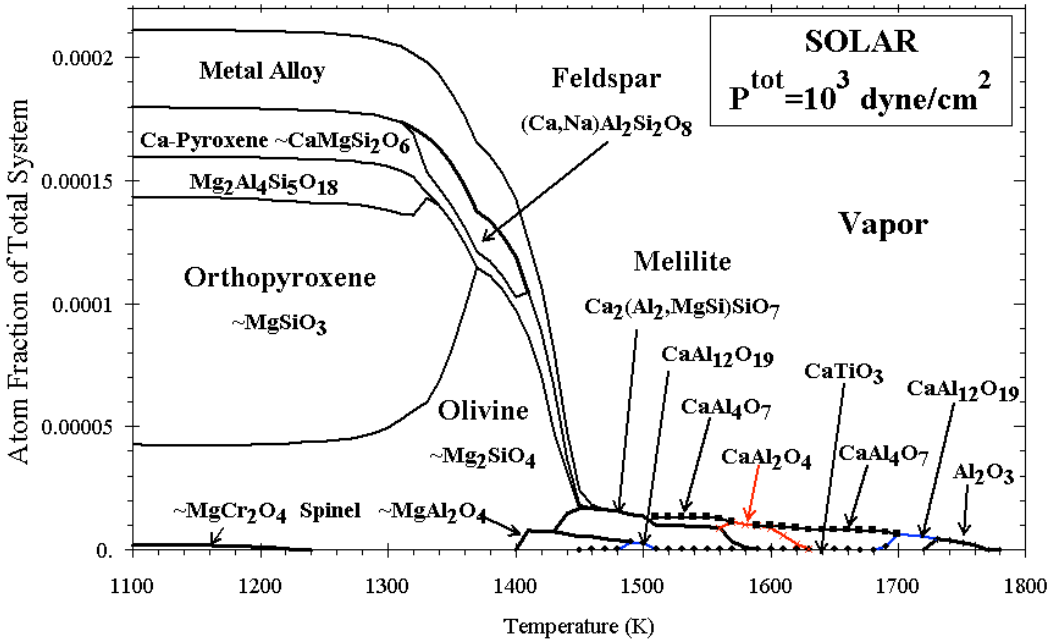
| | CI | CM | CR | Tag. Lake |
|---|---|---|---|---|
| Matrix (vol.%) | 100 | ~50 | ~30 | ~80 |
| Bulk C (wt.%)[a] | 3.7 | 2.0 | 1.2 | 4.1 |
| C in IOM (wt.%)[b] | 2.1 | 0.96 | 0.48 | 1.8 |
| Amino acids | ~5[c] | 14–71[f] | ~1–250[d] | 1.9–4.9[e] |
| Aromatic hydrocarbons | | 3[f] | 16[g] | |
| Aliphatic hydrocarbons | | >35 | | |
| Monocarboxylic acids | | >300 | 96[g] | 359–656[e] |
| Hydroxy- and dicarboxylic acids | | 14–15 | 212[g] | |
| Purines and pyrimidines | | 1.3 | | |
| Basic N-heterocycles | | 7 | | |
| Amines | 14[i] | 5–7[i] | 103[g] | |
| Alcohols | | 11 | | |
| Aldehydes and ketones | | 27 | | |
| Sulphonic acids | | 68 | | |
| Phosphonic acids | | 2 | | |
| Polyols | | >8[h] | | |

[a] Averages from Alexander et al. (2012)

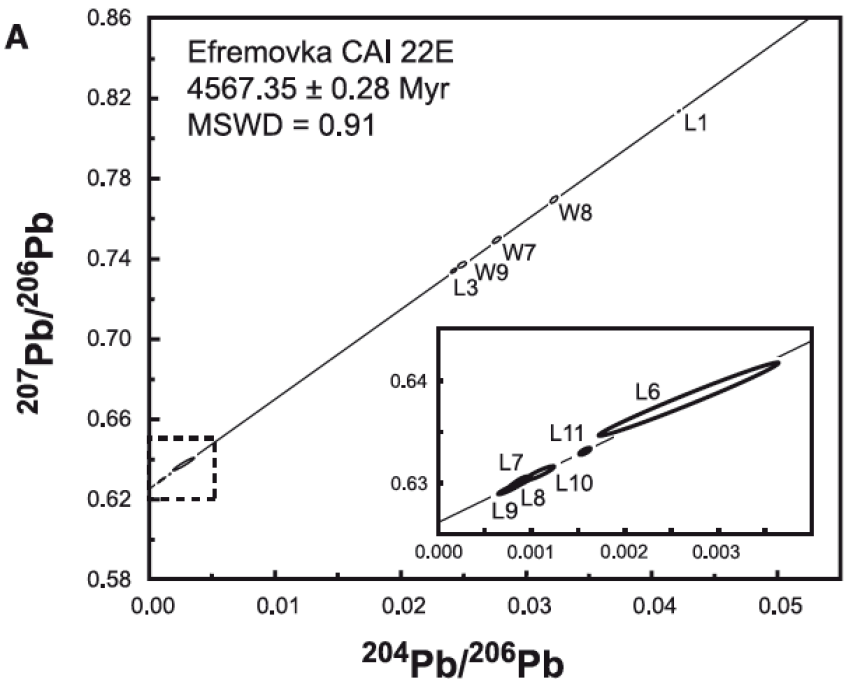
Présolaire ou Solaire ?

# Formation des CAI

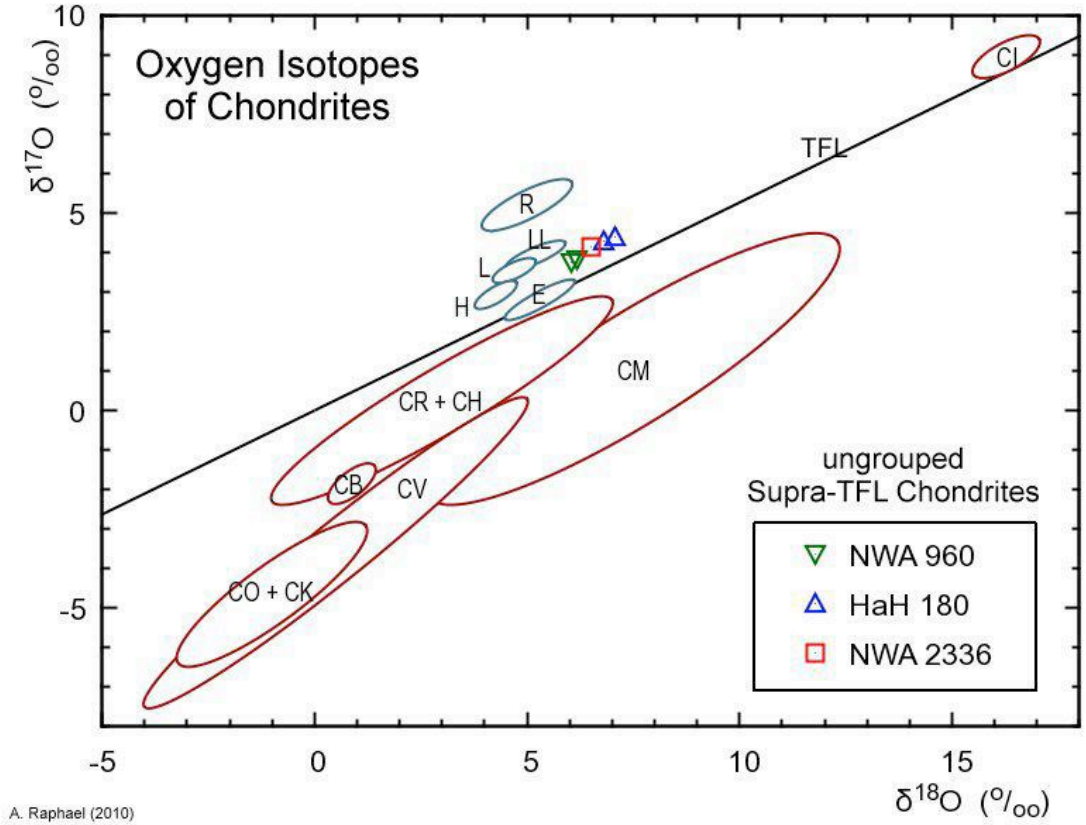


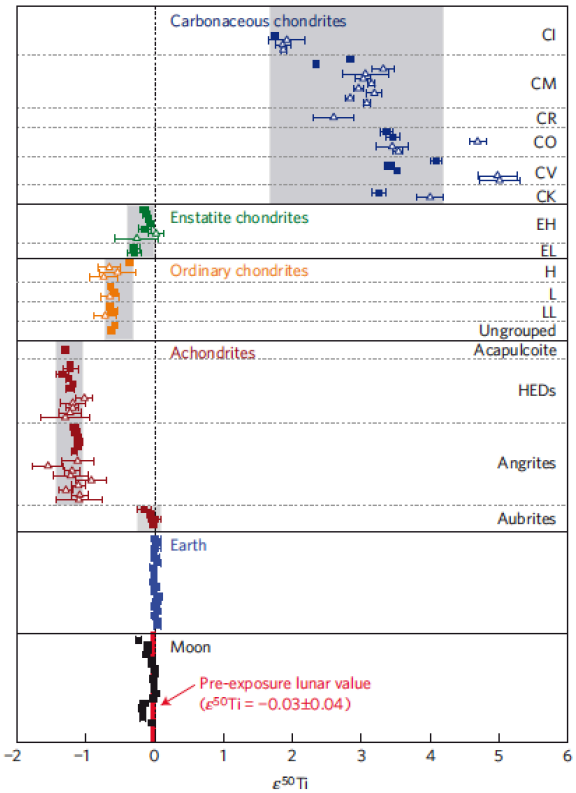
# Âge du système solaire

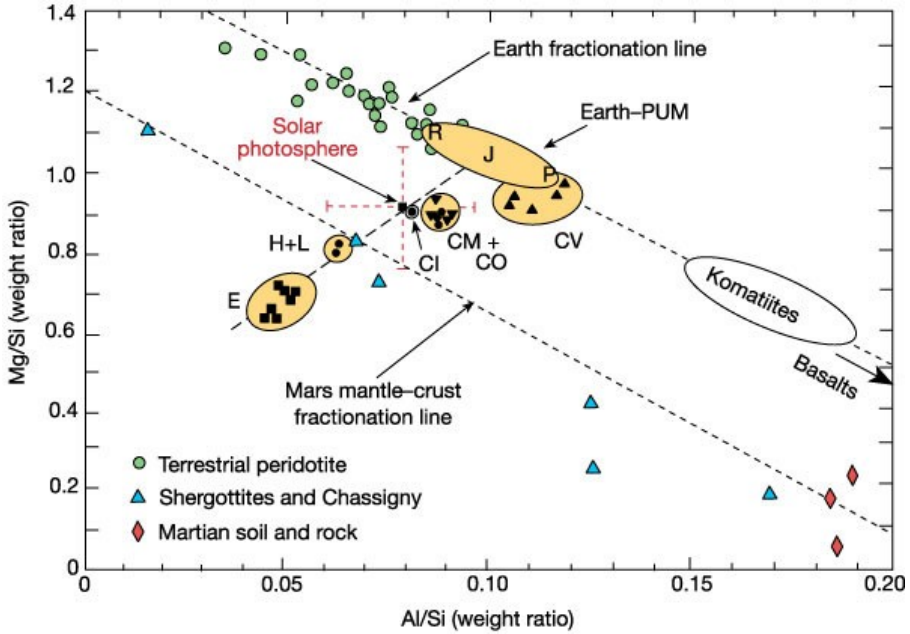


# Les corps parents de la Terre



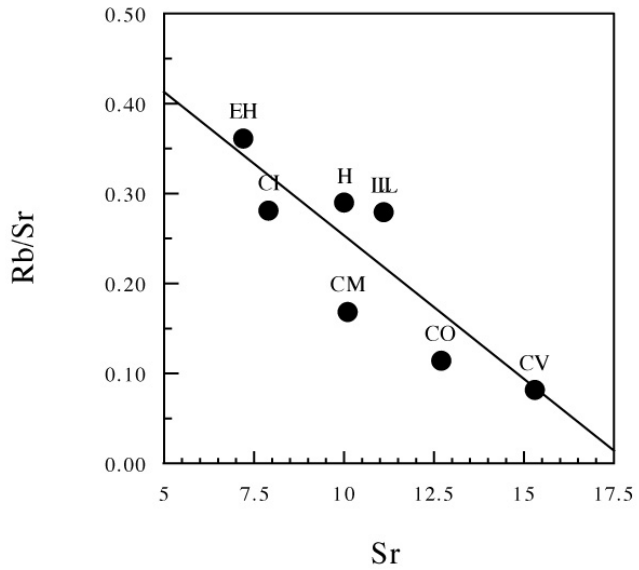
# Le débat sur l'exacte nature des corps parents

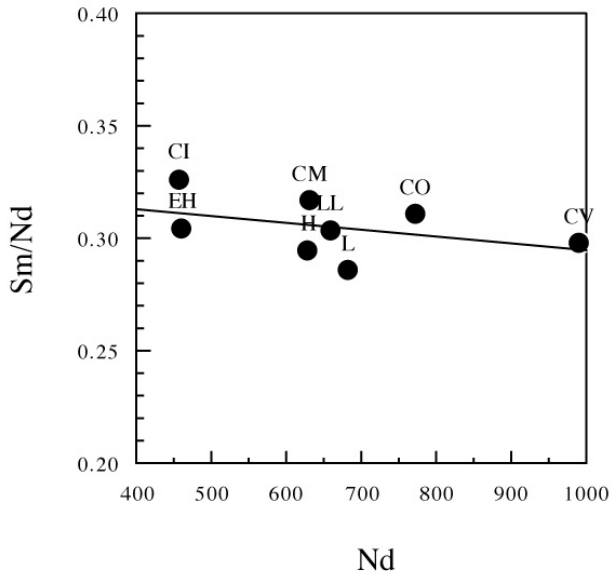


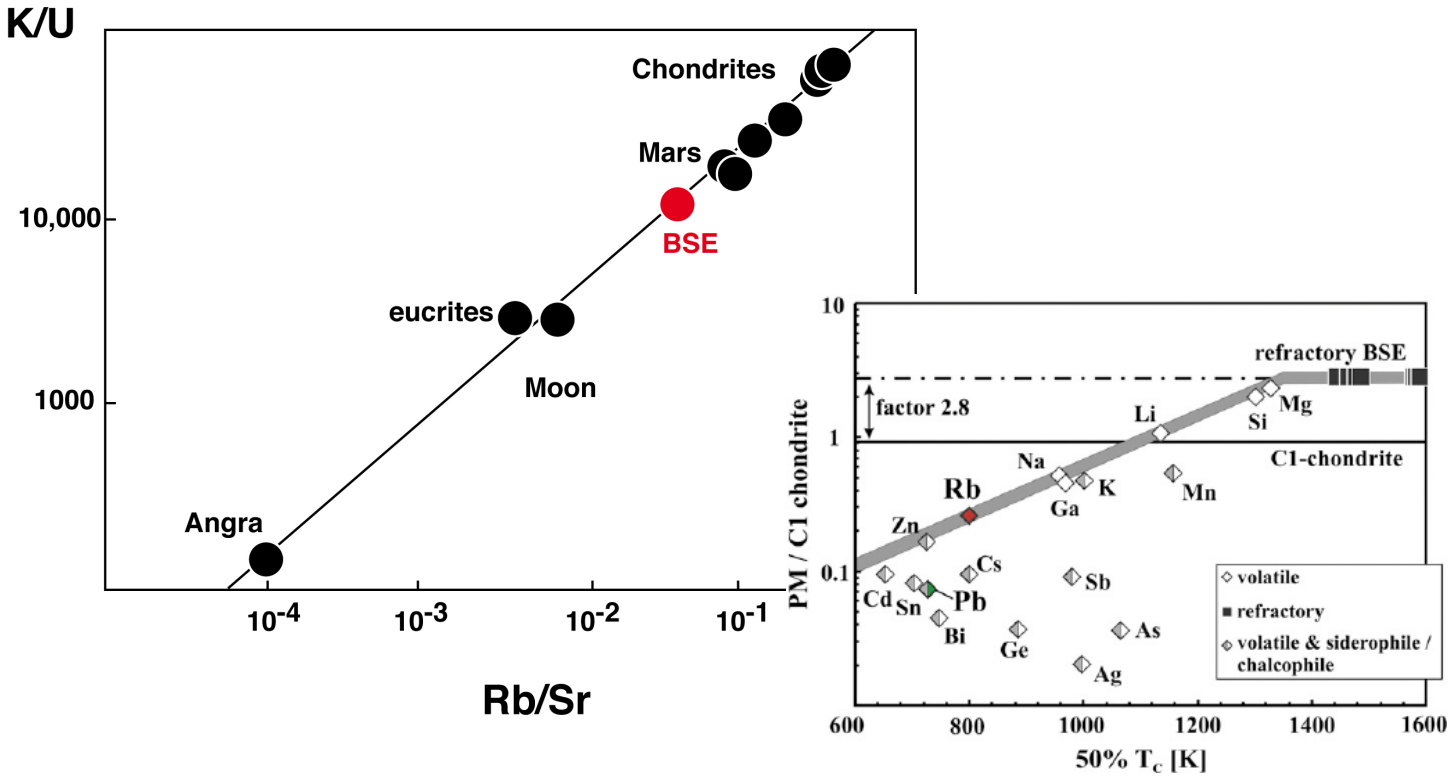




Résoudre ce problème permet de comprendre les conditions de formation des corps parents de la Terre, et notamment de leur teneur en éléments volatils.

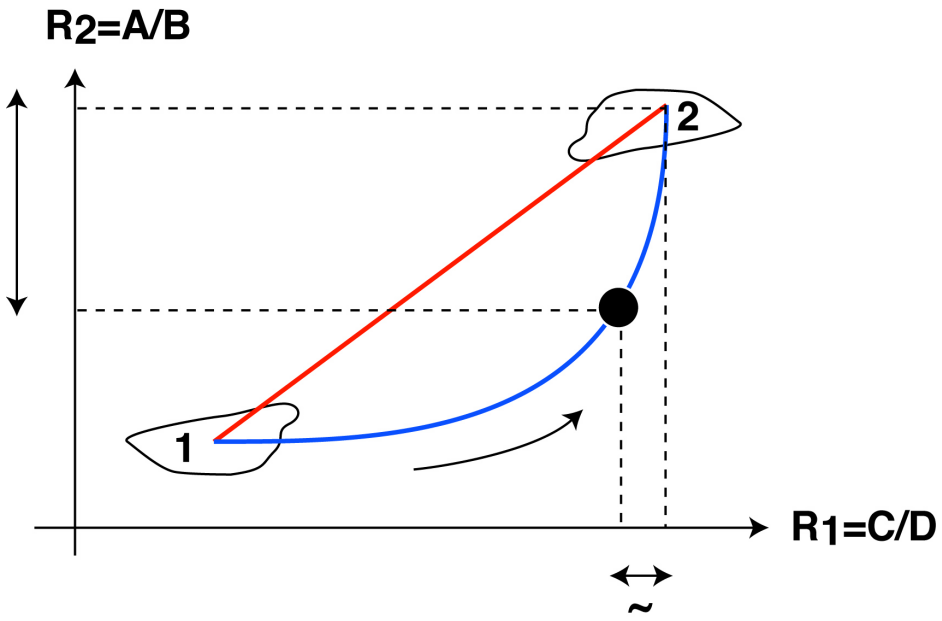
# Eléments volatils dans les corps parents



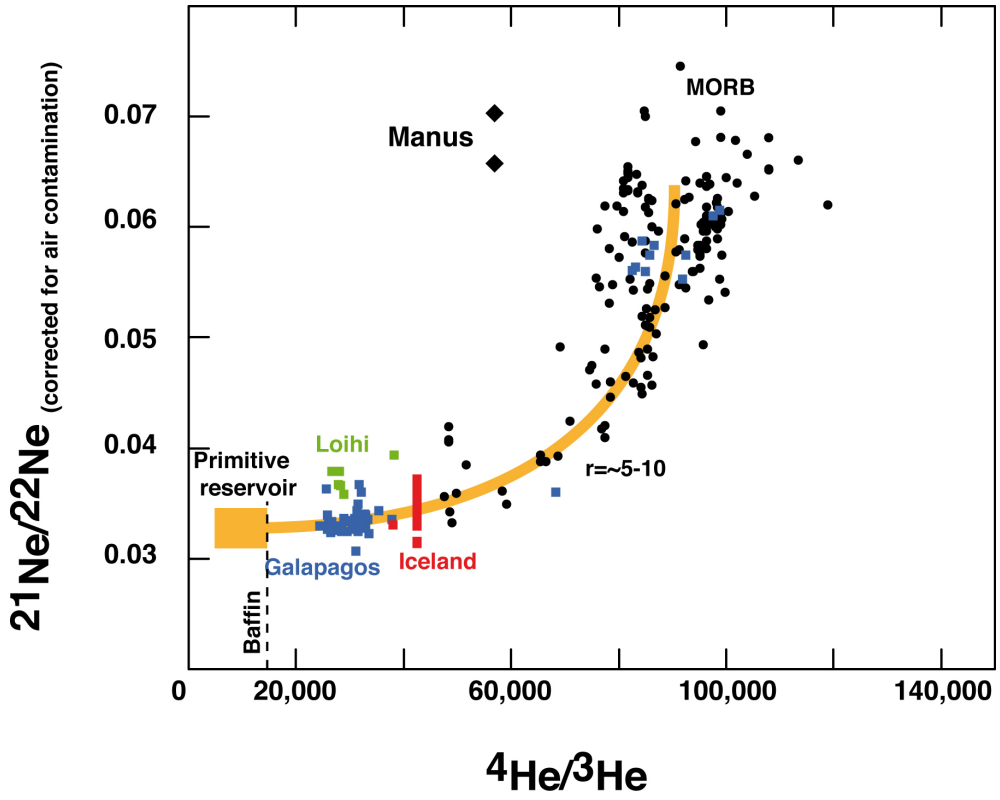

K/U
Chondrites
Mars
BSE
eucrites
Moon
Angra
10,000
1000
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
Rb/Sr
refractory BSE
factor 2.8
C1-chondrite
PM / C1 chondrite
10
1
0.1
Mg
Si
Li
Na
Rb
Ga
K
Mn
Zn
Cs
Cd
Sn
Pb
Bi
Ge
Sb
As
Ag
volatile
refractory
volatile & siderophile / chalcophile
600
800
1000
1200
1400
1600
50% $T_c$ [K]

# Les outils géochimiques: 1) le mélange




$$\left[\frac{A}{B}\right]_m = \alpha\left[\frac{A}{B}\right]_1 + (1-\alpha)\left[\frac{A}{B}\right]_2$$

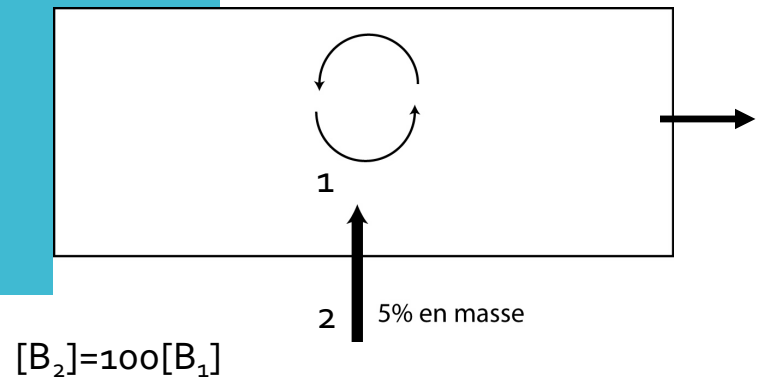
# Exemple sur Terre



# % masse ≠ proportion de mélange

$$\left[\frac{A}{B}\right]_m = \alpha\left[\frac{A}{B}\right]_1 + (1-\alpha)\left[\frac{A}{B}\right]_2$$

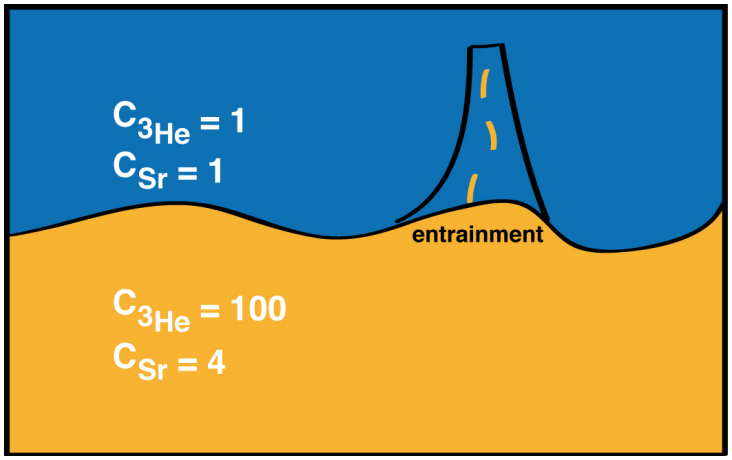
$$\alpha = \frac{B_1}{B_1 + B_2} = \frac{[B_1]M_1}{[B_1]M_1 + [B_2]M_2} = \frac{1}{1 + \frac{[B_2]M_2}{[B_1]M_1}}$$

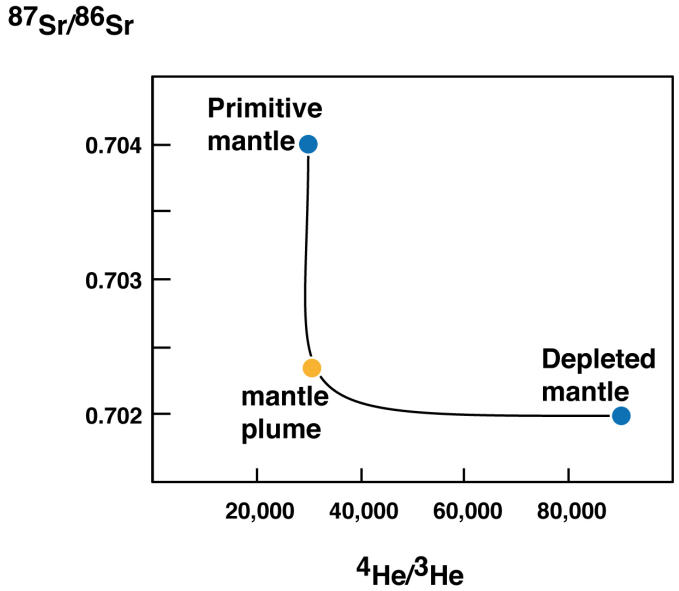



$[B_2]=100[B_1]$

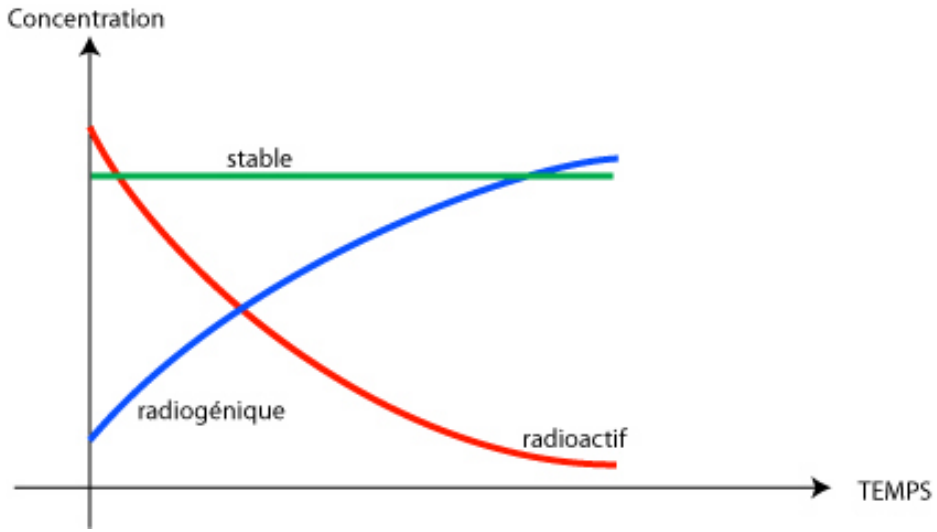
$$1-\alpha = 1 - \frac{1}{1+100\cdot 0.053} = 84\%$$

# Exemple sur les panaches du manteau



# 2) La radioactivité

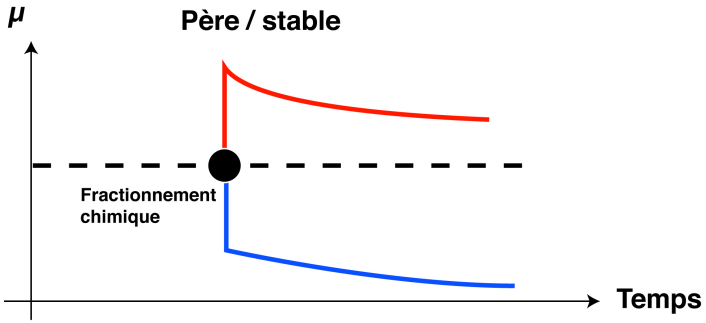


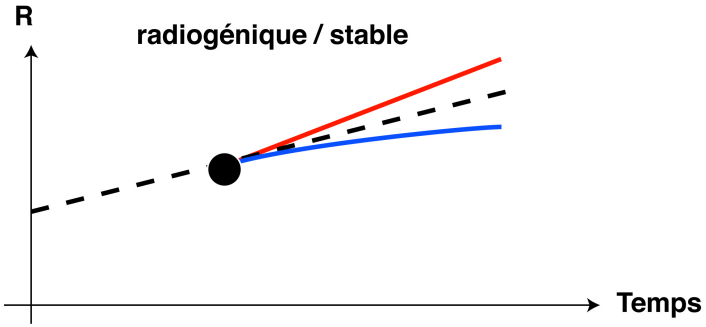

Père, fils, isotope stable, isotope radiogénique, radioactif

# La radioactivité

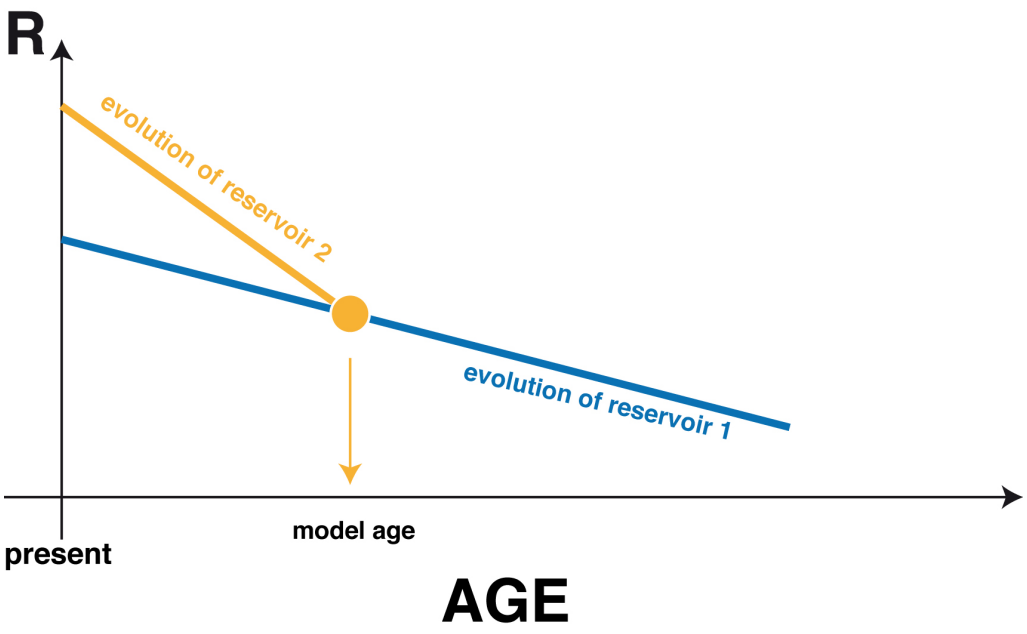
$$R(t) = \frac{F}{S} = R_0 + \frac{P(t)}{S}\left[\exp(\lambda t) - 1\right] = R_0 + \mu(t)\left[\exp(\lambda t) - 1\right]$$

# Rapport chimique/rapport isotopique

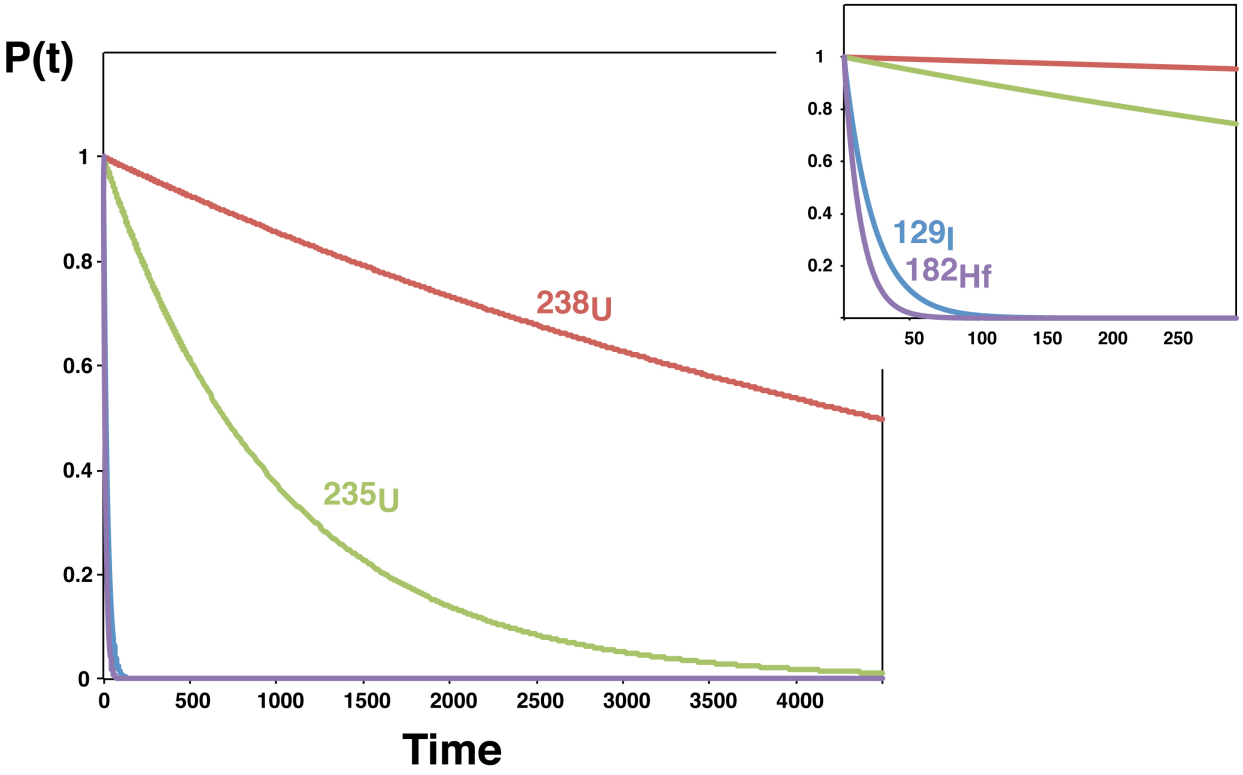


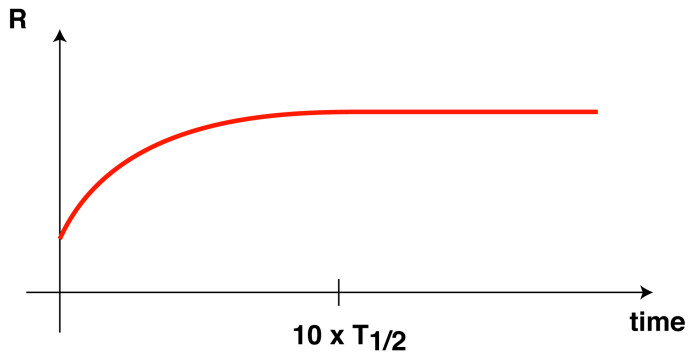
# Âge modèle en géochimie

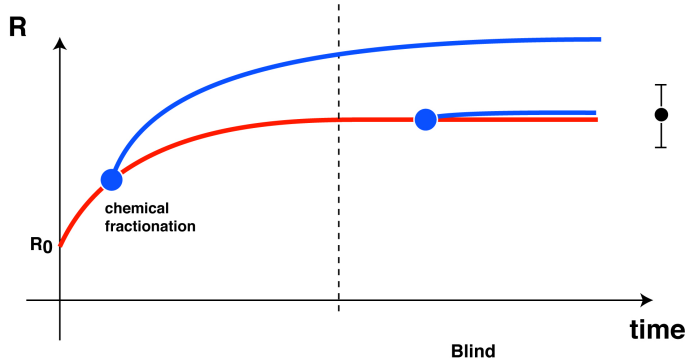


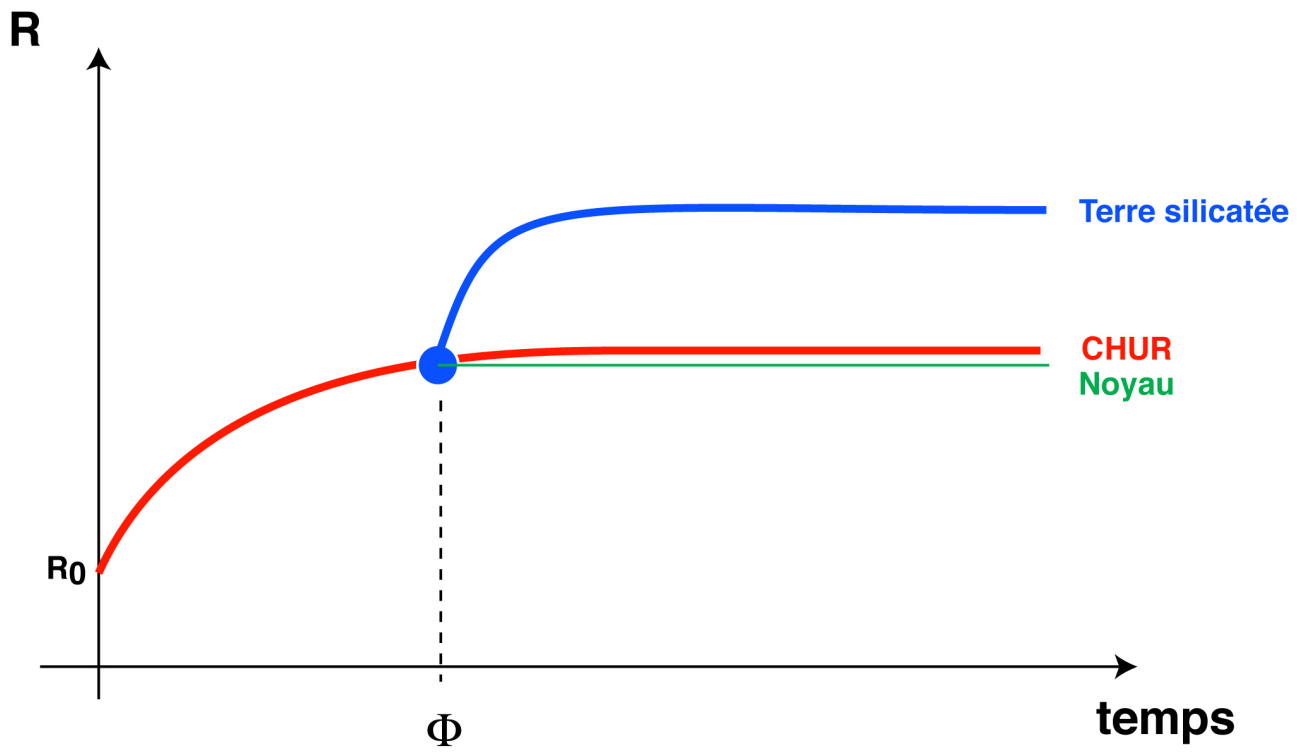
# Radioactivités de courte et longue période



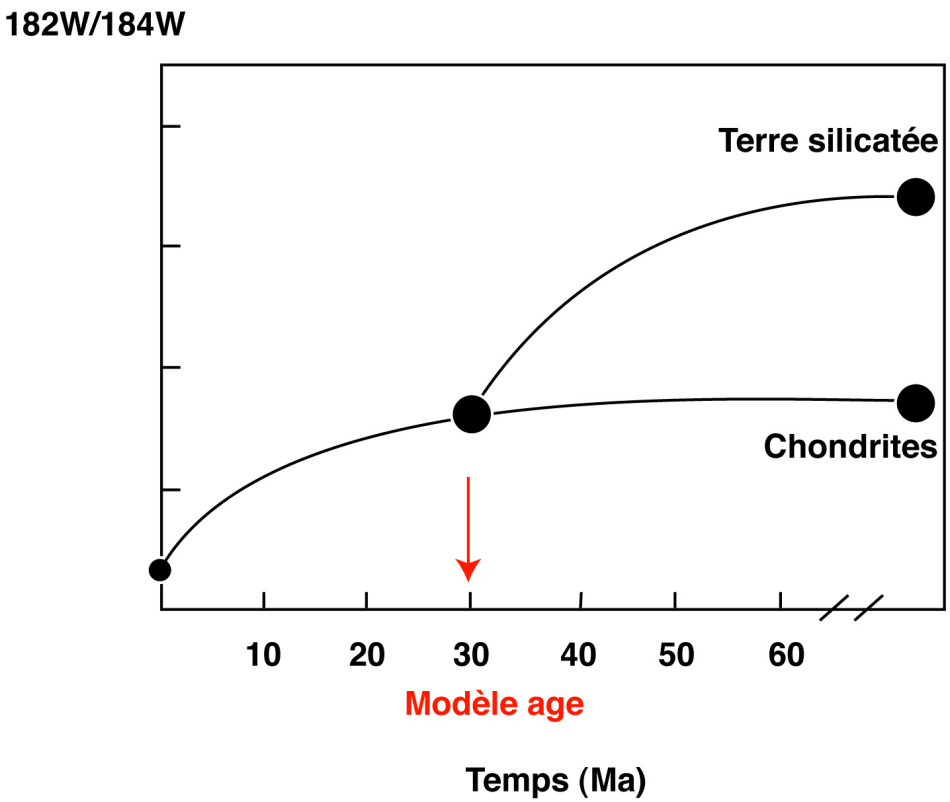
# Radioactivité « éteinte »



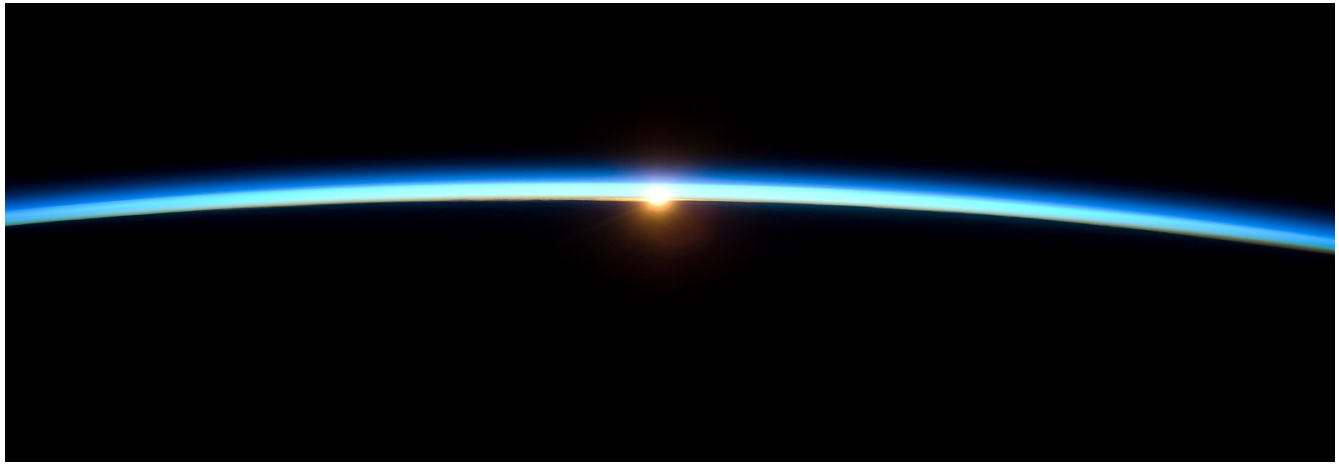

R
Terre silicatée
CHUR
Noyau
R0
Φ
temps

$^{182}Hf \Rightarrow {}^{182}W$ ($T_{1/2}$=9 Ma) (via $^{182}Ta$, $T_{1/2}$=114,43j)
2 éléments réfractaires :
H/W Bulk Earth= chondrite
Hf lithophile, W sidérophile



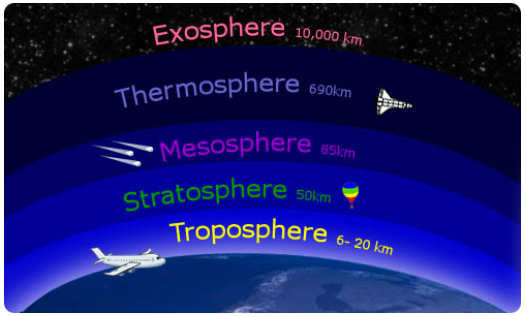
# 3) Origine des atmosphères

# Atmosphère

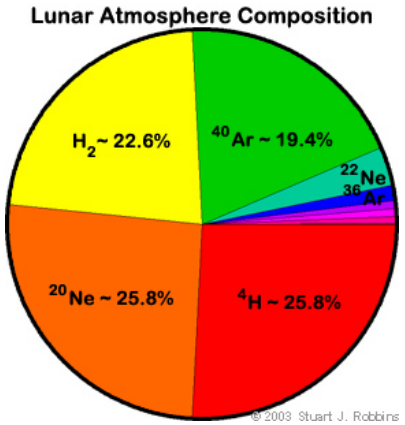


# Atmosphère ?

Couche de gaz entourant un objet céleste

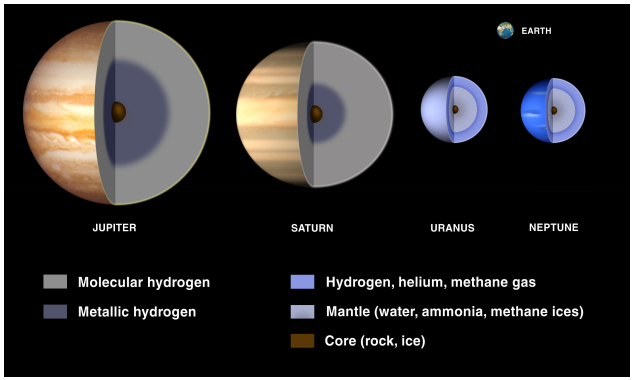


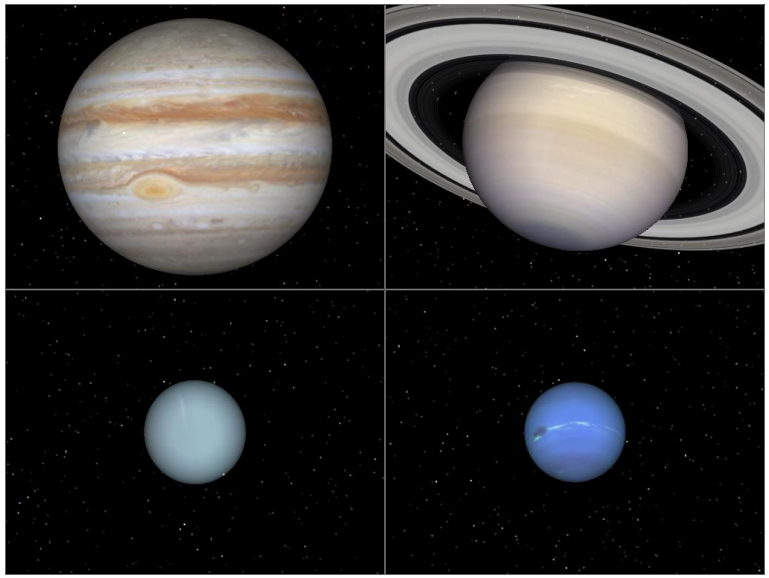

Parfois des structures complexes



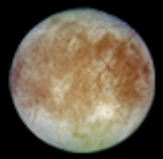
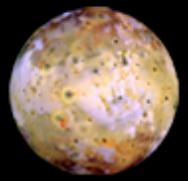
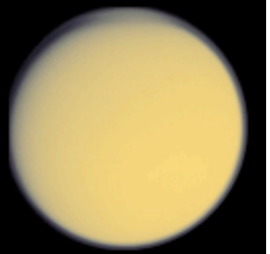

Ou plus simple

# Planètes géantes (Gaz et glace)



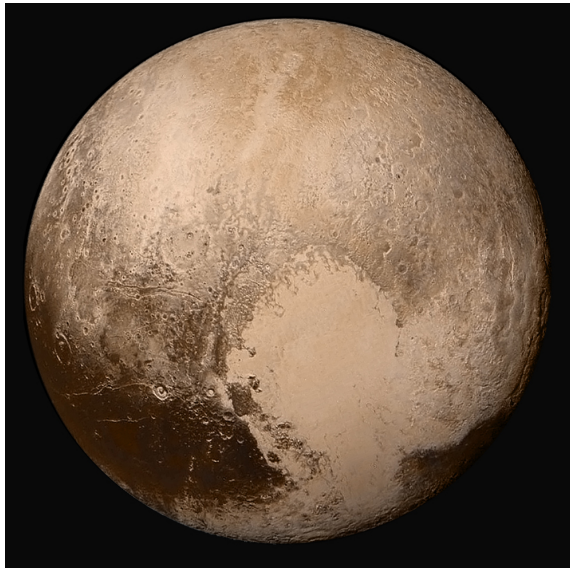



# Which moons in the Solar System have atmospheres?

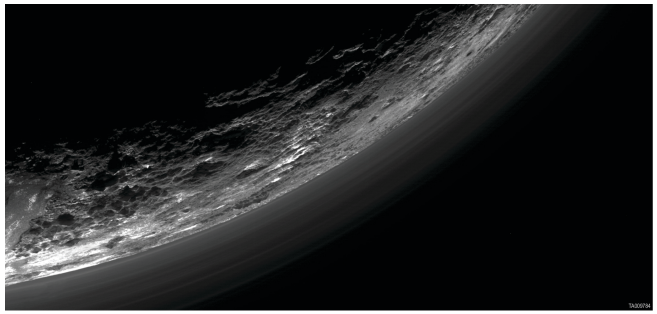
| Europa | Ganymede | Callisto | Io | Enceladus | Triton | Titan |
|---|---|---|---|---|---|---|
|  | | |  |  | |  |
| Diameter: 3160km | Diameter: 5262km | Diameter: 4800km | Diameter: 3630km | Diameter: 500km | Diameter: 2700km | Diameter: 5150km |
| Planet: Jupiter | Planet: Jupiter | Planet: Jupiter | Planet: Jupiter | Planet: Saturn | Planet: Neptune | Planet: Saturn |
| Pressure: $10^{-11}$ bar | Pressure: $< 10^{-10}$ bar | Pressure: $< 10^{-10}$ bar | Pressure: $10^{-9}$ bar | Pressure: Unknown | Pressure: $10^{-5}$ bar | Pressure: 1.5 bar |
| Composition: Water, oxygen | Composition: Oxygen, ozone | Composition: Carbon dioxide | Composition: Sulphur dioxide | Composition: Water vapour | Composition: Nitrogen, methane | Composition: Nitrogen, argon, methane, other organics |

*Atmospheric pressure at the Earth's surface is about 1 bar

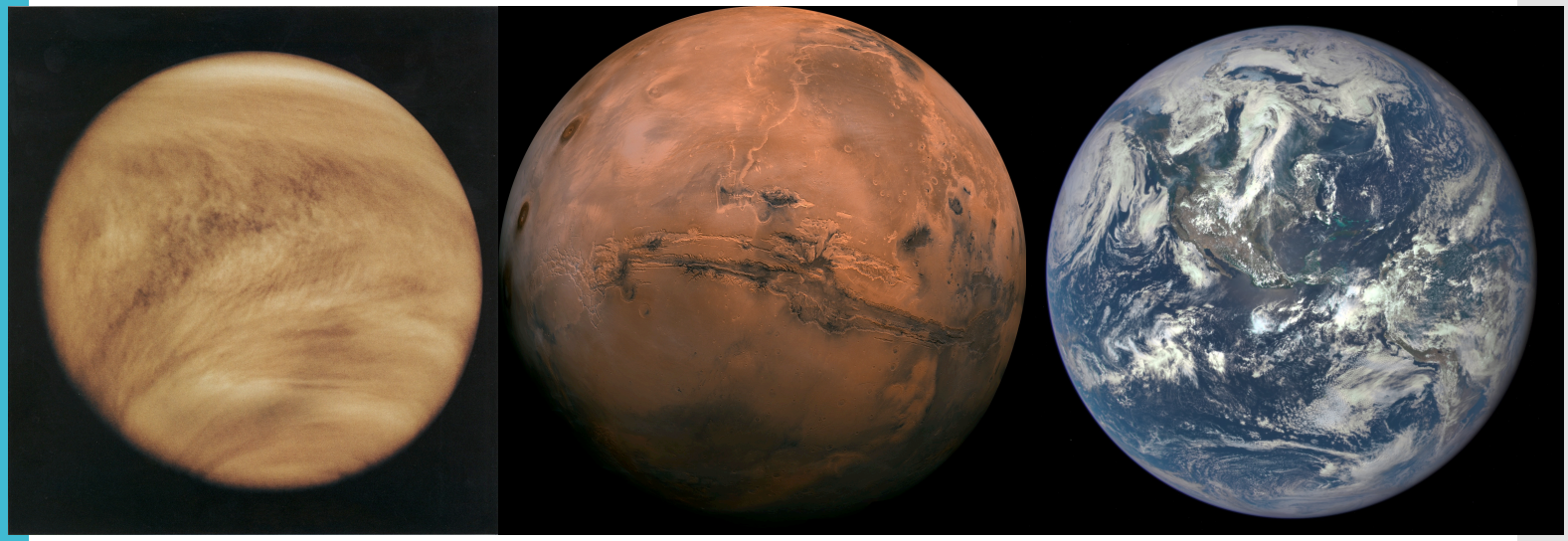
# Pluton a une atmosphère (15 microbars)

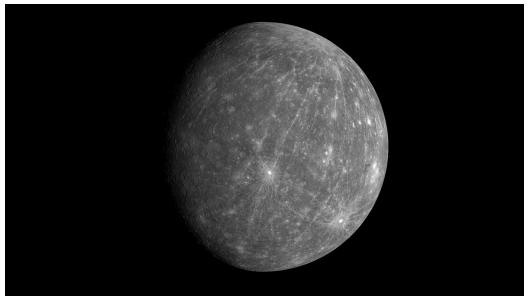


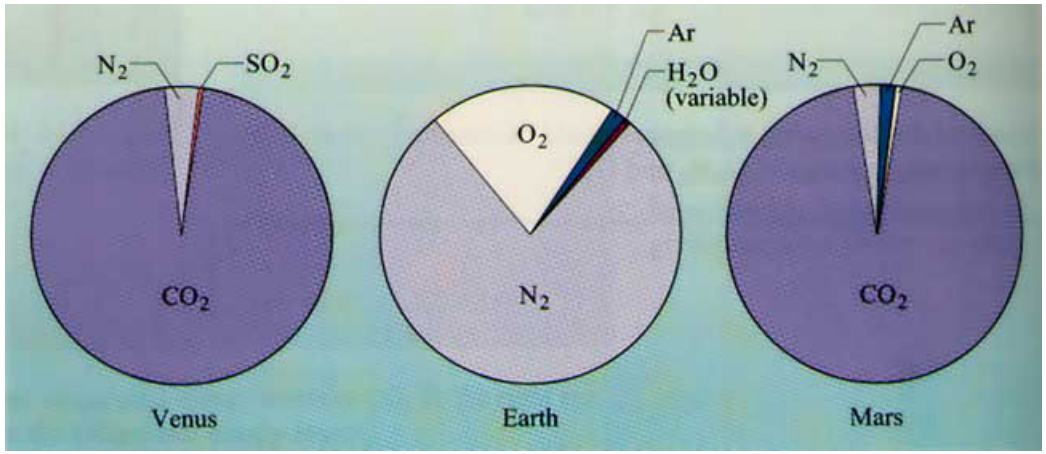
Sonde New Horizons



# Planètes telluriques

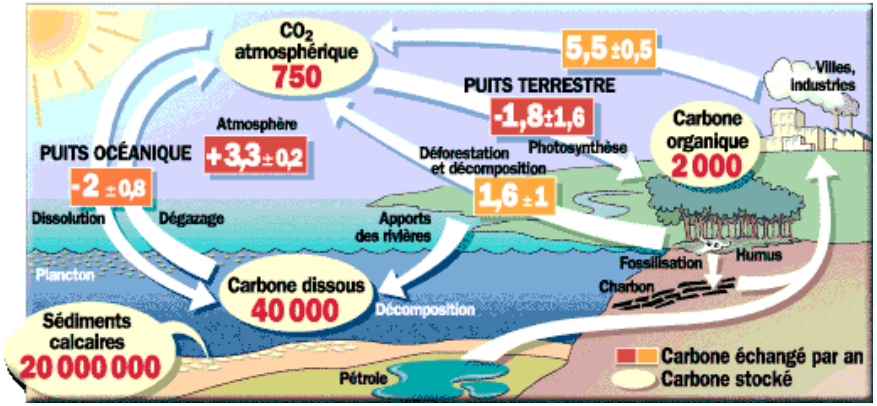




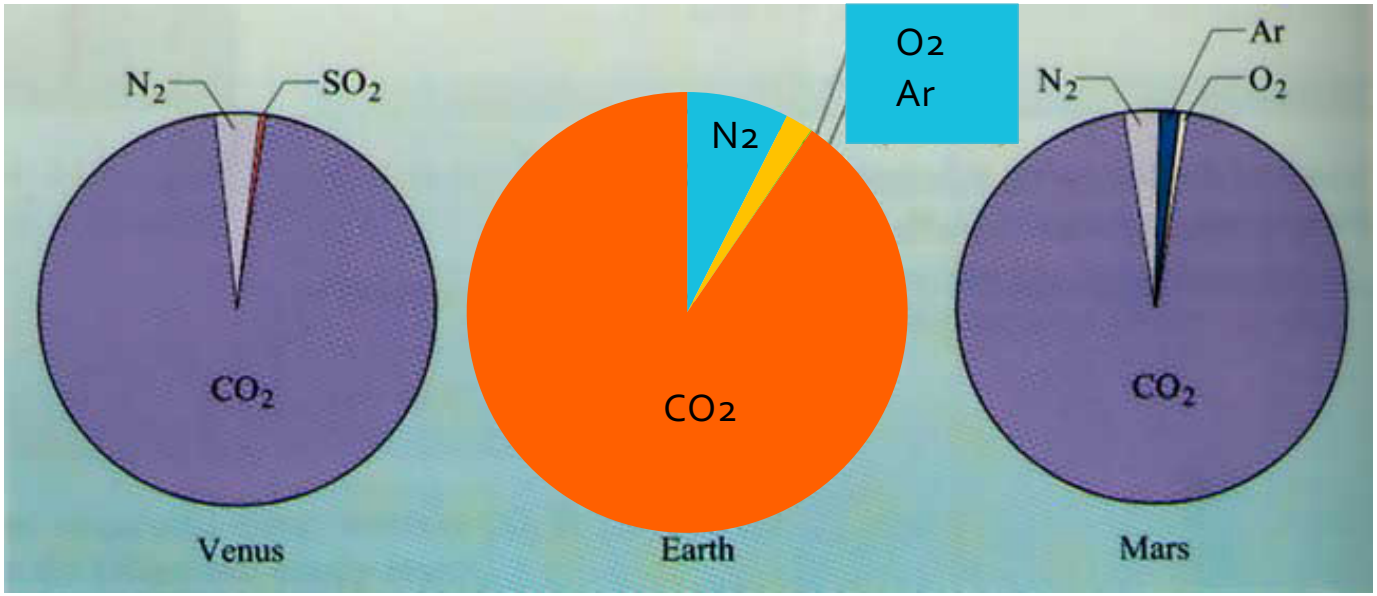



Il faut rajouter la matière organique et les carbonates

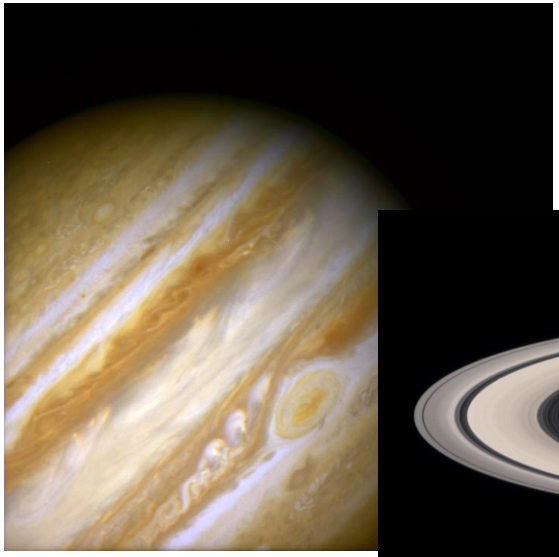
| | mixing ratio | total cm³STP | "real" atm | mixing ratio |
|---|---|---|---|---|
| dry air | 100,00% | 3,96E+24 | 4,14E+25 | 100,00% |
| $N_2$ | 78,10% | 3,09E+24 | 3,09E+24 | 7,48% |
| $O_2$ | 20,90% | 8,28E+23 | 8,28E+23 | 2,00% |
| Ar | 0,93% | 3,70E+22 | 3,70E+22 | 0,09% |
| $CO_2$ | 0,04% | 1,47E+21 | 3,74E+25 | 90,43% |

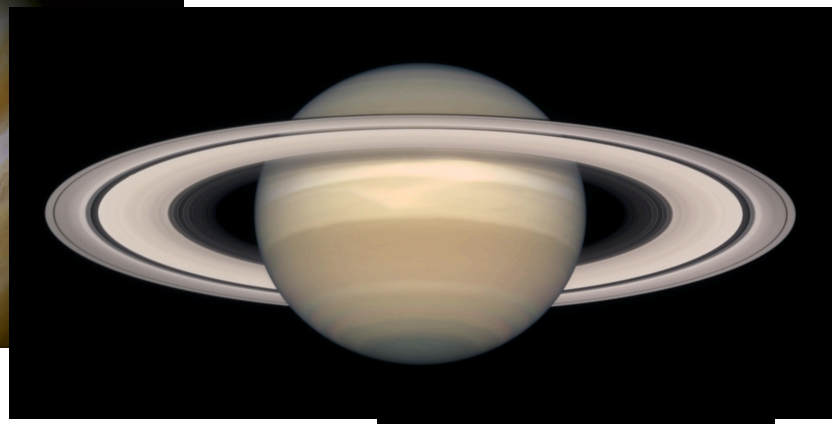


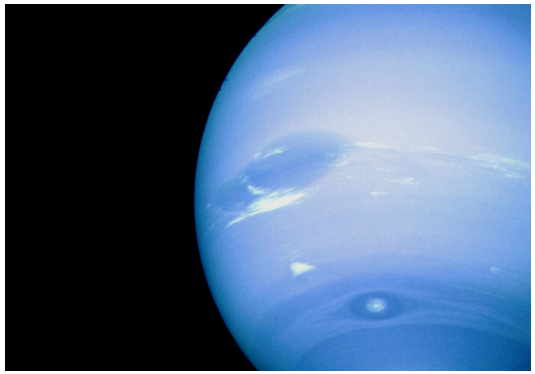
# La comparaison correcte



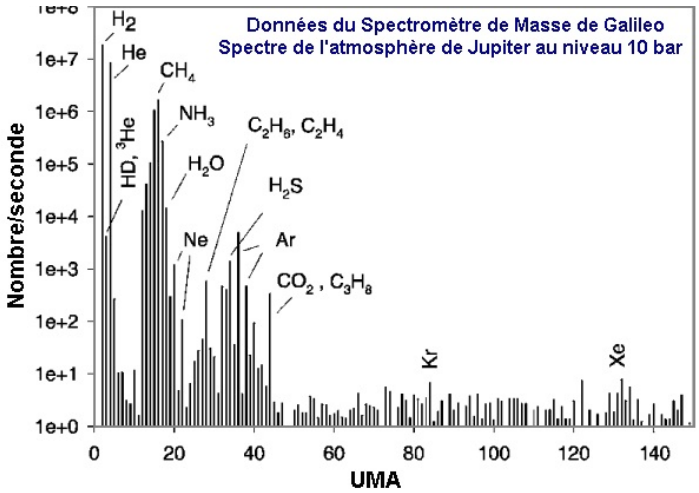
# Une différence de composition notable avec les planètes géantes

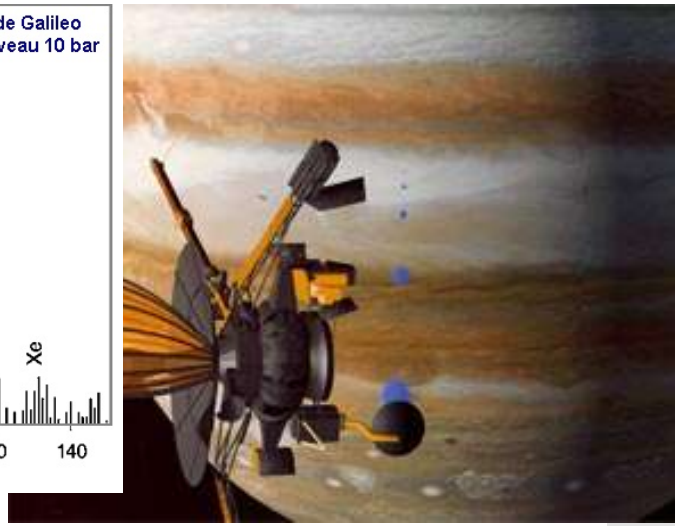




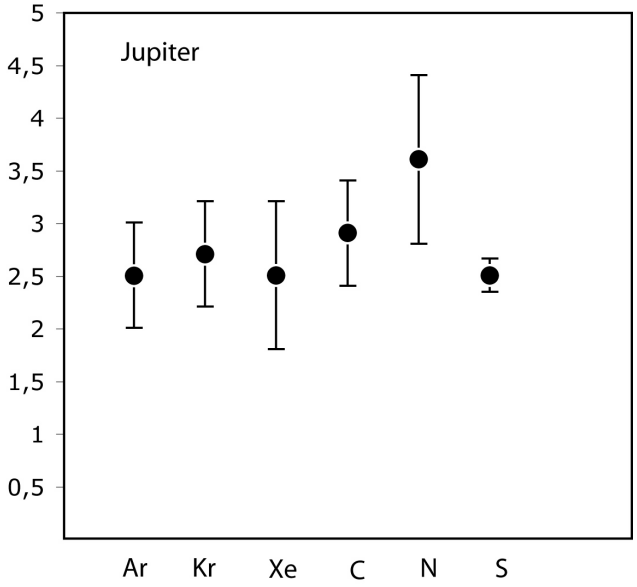


# Atmosphères riches en H et He



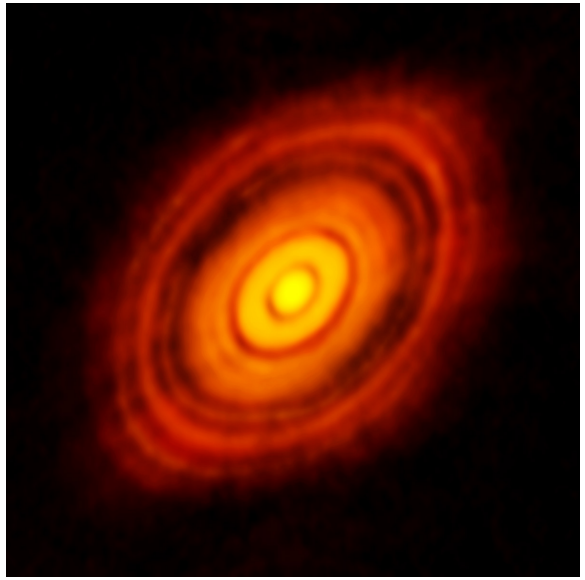
Abondance/Abondance nébuleuse



# Origines des atmosphères

- Planètes géantes : capture du gaz du disque d'accrétion (loin du soleil et environnement froid = contraction rapide)
- Planètes telluriques: gaz en « compétition » avec le soleil et environnement chaud= echappement
- Planètes telluriques: composition actuelle différente du gaz du disque mais y a t-il eu une atmosphère primitive solaire ?

# 1) Capture



Atacama Large Millimeter Array image of HL Tauri

- Jeune disque (1Ma)

- « gap » du a la formation d'au moins une planète?

# Evaporation du gaz dans le disque

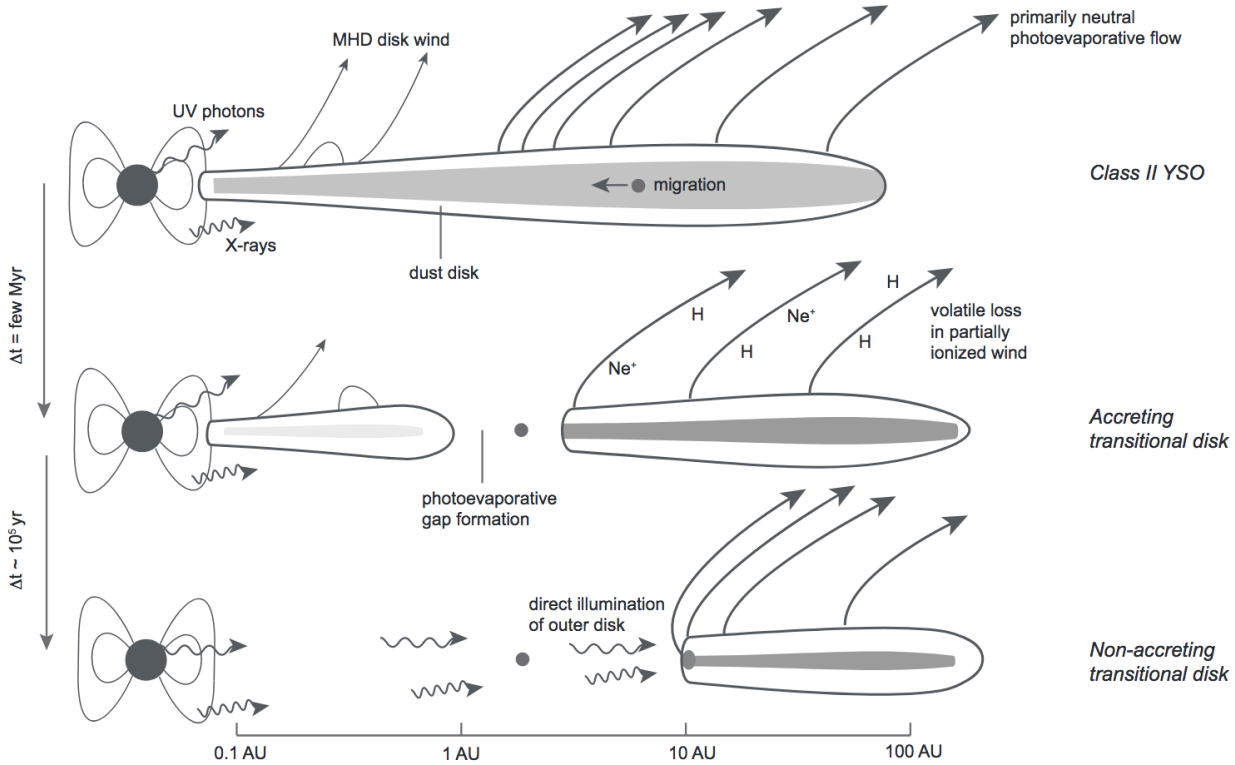
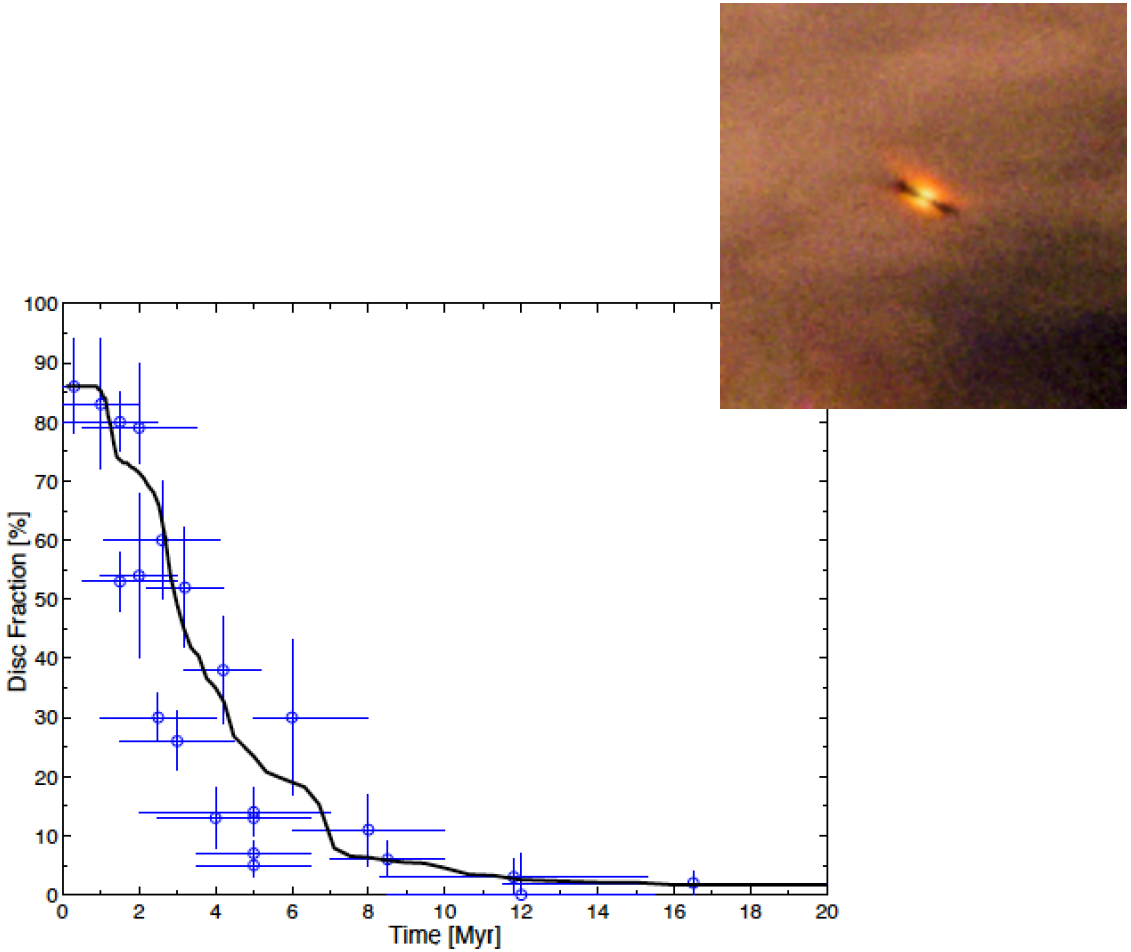
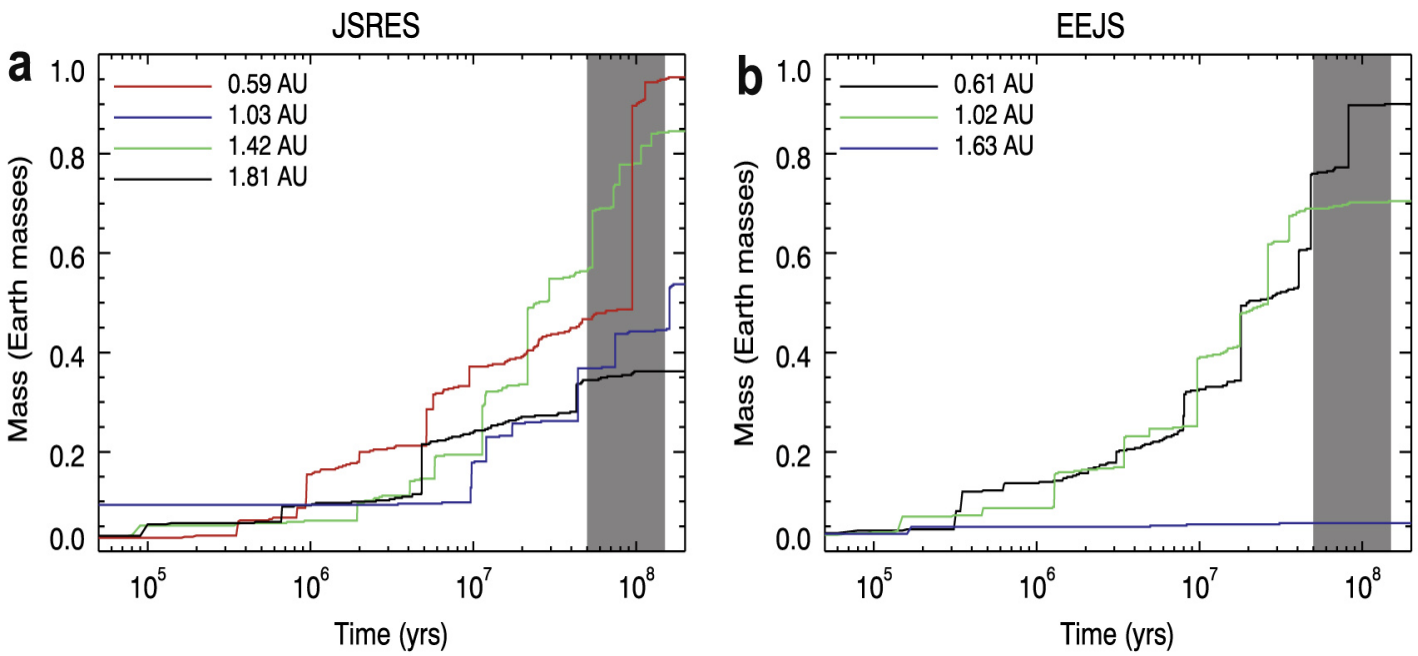



Fig. 6.— Schematic representation of the disk evolution and dispersal sequence outlined in Section 4.3. At early times accretion dominates the evolution, while mass-loss is dominated by some combination of X-ray and/or FUV photoevaporation and magnetic fields. At later times the photoevaporative flow is at least partially ionized, driven by EUV and/or X-ray irradiation, and once this wind overcomes the accretion flow the disk is rapidly cleared from the inside-out.

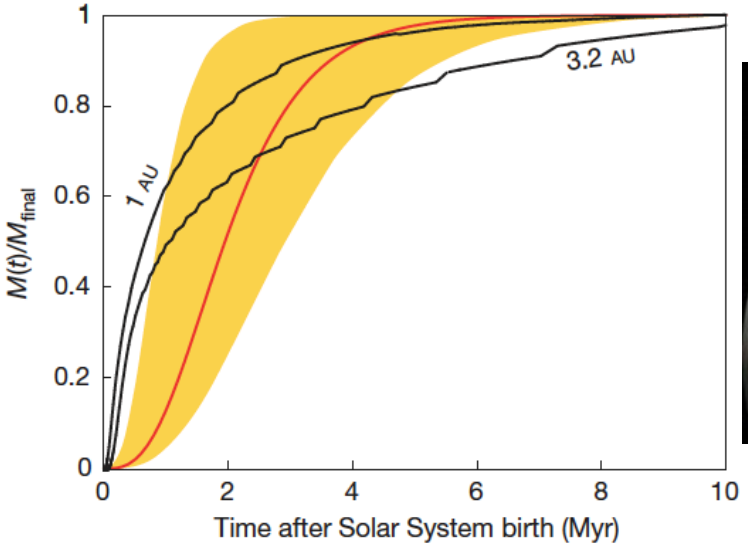
# Un processus rapide (<10Ma)



Une capture de gaz de la nébuleuse, sinon impossible, très difficile à faire



# Une capture de gaz de la nébuleuse, sinon impossible, très difficile à faire



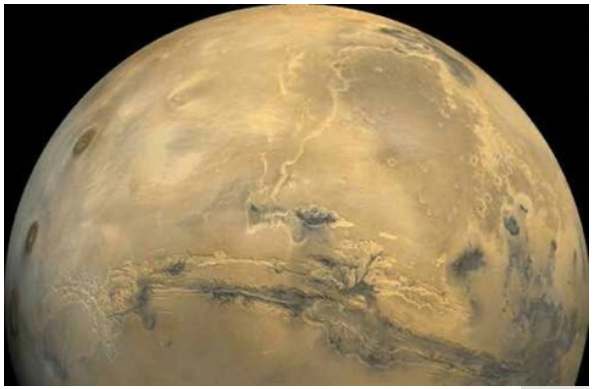



**Figure 2 | Accretion timescale of Mars inferred from $^{182}$Hf–$^{182}$W systematics.** The red curve is calculated from $M(t)/M_{final} = \tanh^3(t/\tau)$ with $\tau = 1.8^{+0.9}_{-1.0}$ Myr (see text for details). The yellow band corresponds to the 95% confidence interval on the accretion curve of Mars obtained by propagating all uncertainties on model parameters using a Monte Carlo simulation. The two black curves are model simulations of embryo growth at 1 and 3.2 AU (ref. 26) for comparison.

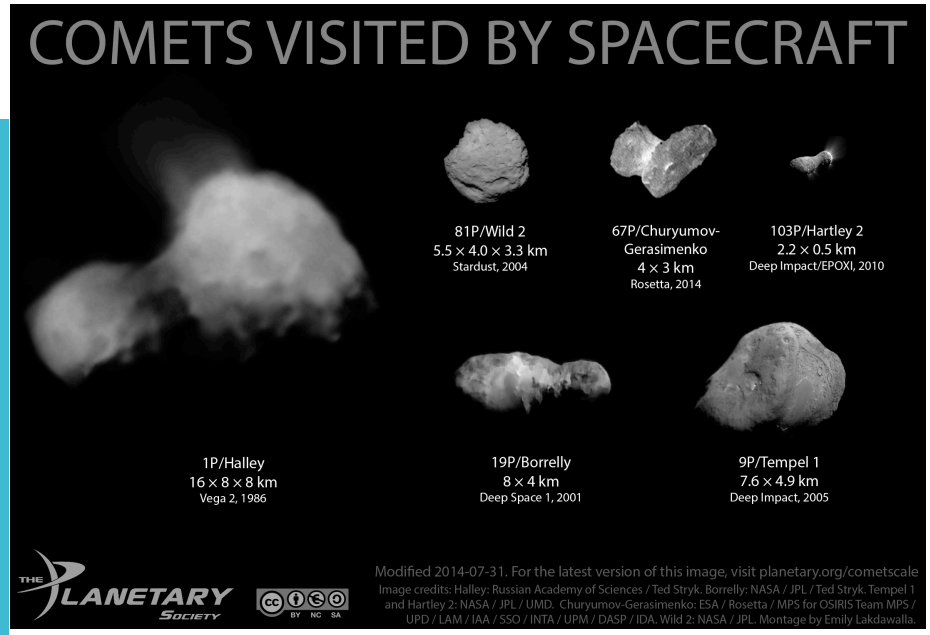
Mais faible masse => faible pression atmosphérique

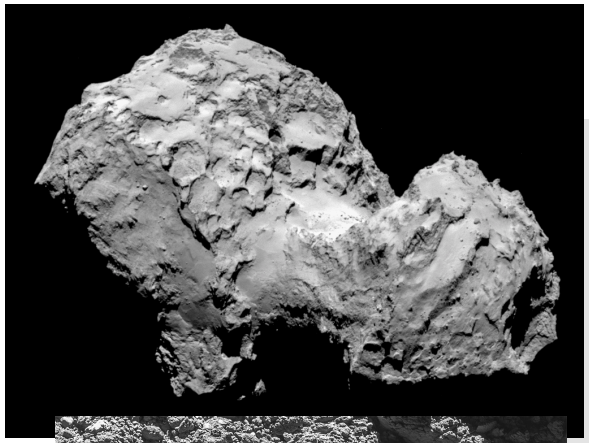
# Atmosphère primitive solaire encore débattue

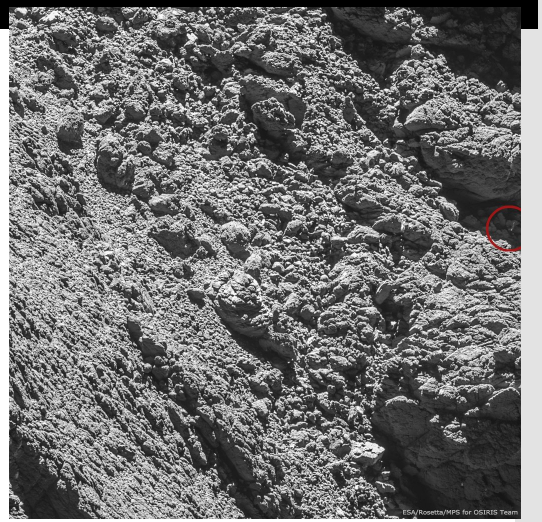
- Quelques traces dans le manteau (Helium, Néon), mais besoin d'études supplémentaires
- Important pour l'origine d'une partie de l'hydrogène sur Terre
- Pour la suite, on se placera dans un contexte ou les éléments volatils sont pendant l'accrétion ou après celle-ci.

# Origine de l'eau sur Terre

- Un vieux débat
- Trois hypothèses:
  - Comètes
  - Chondrites pendant l'accrétion
  - Chondrites après l'accrétion

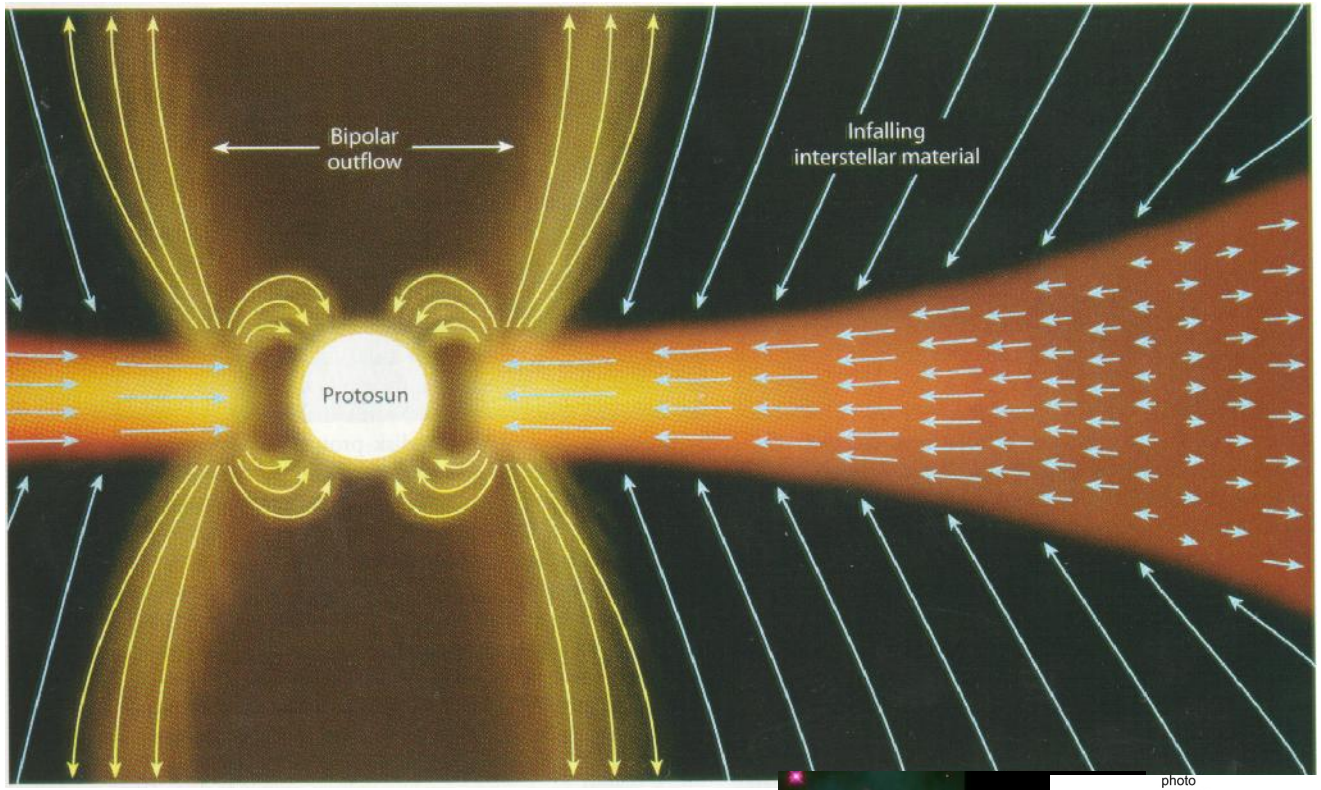

COMETS VISITED BY SPACECRAFT
81P/Wild 2
5.5 × 4.0 × 3.3 km
Stardust, 2004
67P/Churyumov-Gerasimenko
4 × 3 km
Rosetta, 2014
103P/Hartley 2
2.2 × 0.5 km
Deep Impact/EPOXI, 2010
1P/Halley
16 × 8 × 8 km
Vega 2, 1986
19P/Borrelly
8 × 4 km
Deep Space 1, 2001
9P/Tempel 1
7.6 × 4.9 km
Deep Impact, 2005
THE PLANETARY SOCIETY
BY NC SA
Modified 2014-07-31. For the latest version of this image, visit planetary.org/cometscale
Image credits: Halley: Russian Academy of Sciences / Ted Stryk. Borrelly: NASA / JPL / Ted Stryk. Tempel 1 and Hartley 2: NASA / JPL / UMD. Churyumov-Gerasimenko: ESA / Rosetta / MPS for OSIRIS Team MPS / UPD / LAM / IAA / SSO / INTA / UPM / DASP / IDA. Wild 2: NASA / JPL. Montage by Emily Lakdawalla.

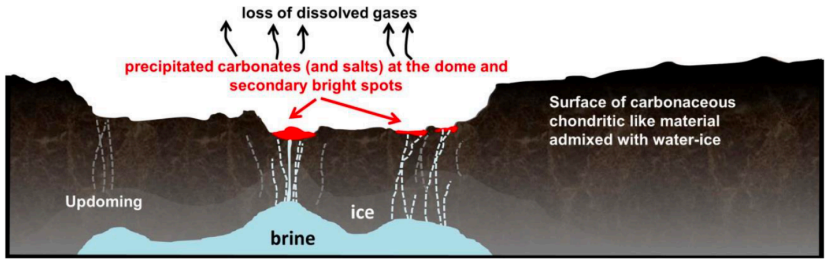


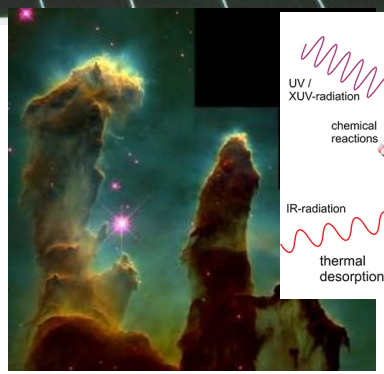

ESA/Rosetta/MPS for OSIRIS Team

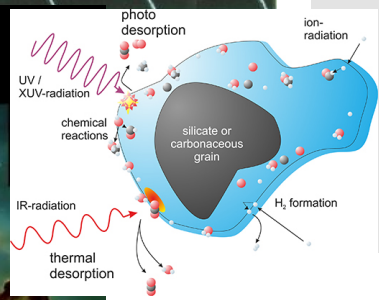
D/H ratio
$10^{-3}$
$10^{-4}$
$10^{-5}$
Earth
Asteroids
Enceladus
C/1995 O1 Hale-Bopp
153P/Ikeya-Zhang
C/2001 Q4 (NEAT)
C/2002 T7 (LINEAR)
8P/Tuttle
C/2009 P1 Garrard
C/1995 B2 Hyakutake
1P/Halley
45P/H-M-P
103P/Hartley 2
67P/C-G
Oort cloud
Jupiter family
Uranus
Neptune
Jupiter
Saturn
Protosolar nebula

# Plusieurs réservoirs d'eau dans le système solaire

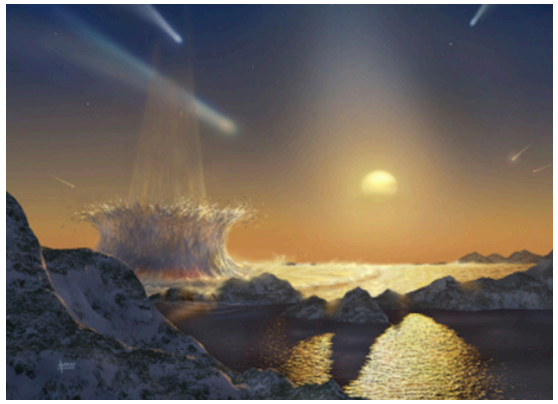


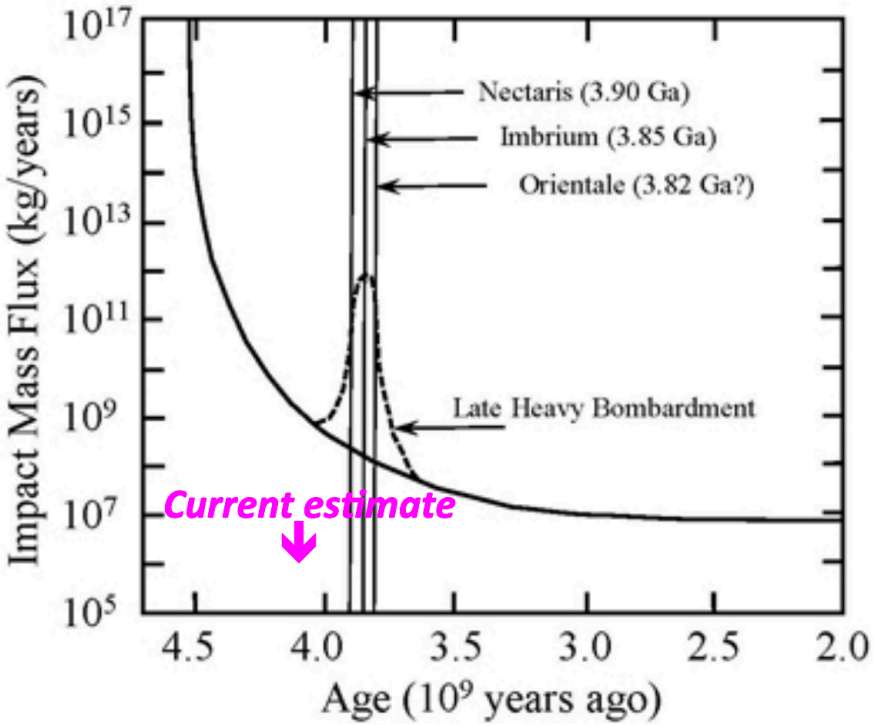



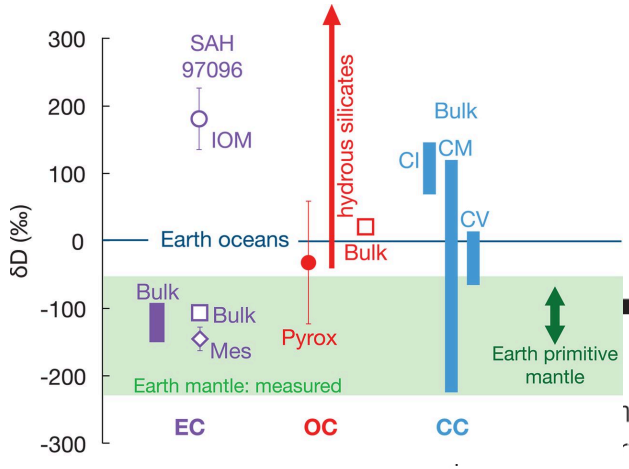


# Le bombardement tardif



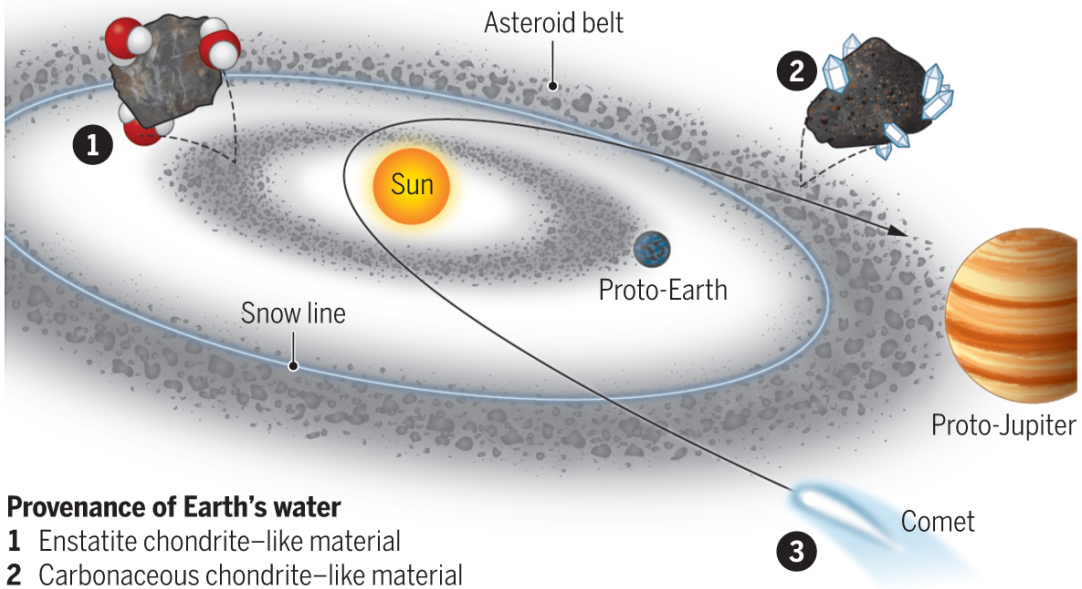


# L'eau des chondrites et sur Terre




## Earth's water

nts of enstatite chondrites indicate that water could have been primarily
rth's building blocks. Additional water was delivered to Earth's early
oceans and atmosphere by water-rich material from comets and the outer asteroid belt.




**Provenance of Earth's water**

**1** Enstatite chondrite–like material
**2** Carbonaceous chondrite–like material
**3** Comets contributing to the atmosphere's composition

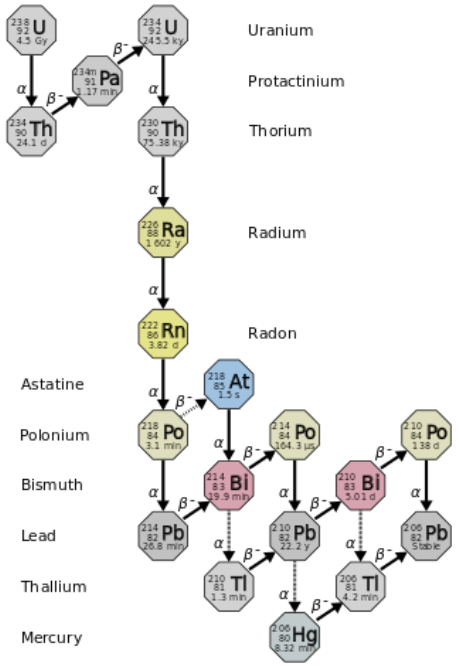
# Après la formation de la Terre …

# 4) Le dégazage du manteau (de la Terre)

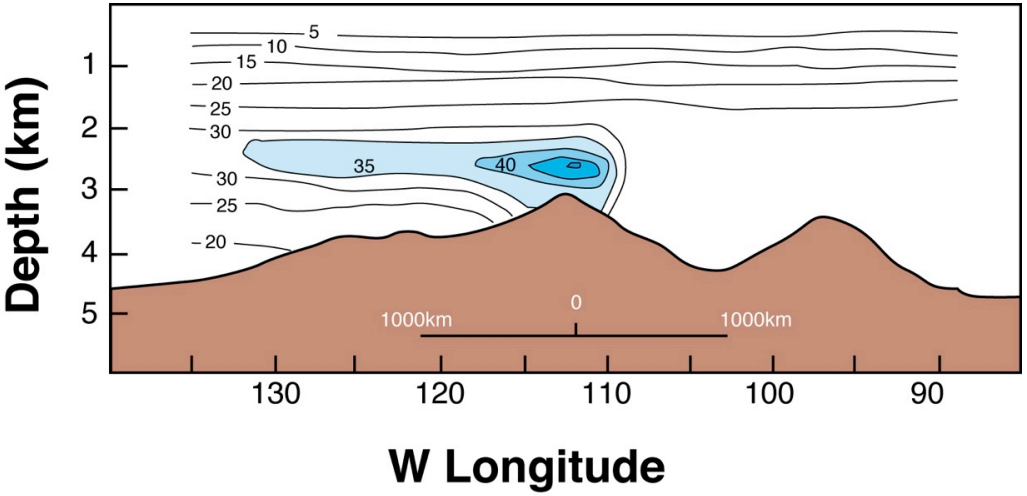
# L'hélium: l'évidence du dégazage actuel d'un gaz « ancien »

## Isotopes de l'Hélium

- Deux isotopes : $^{3}He$ and $^{4}He$
- 5ppm dans l'air
- 4He/3He dans l'air = 722 500
- S'échappent de l'atmosphère de la Terre



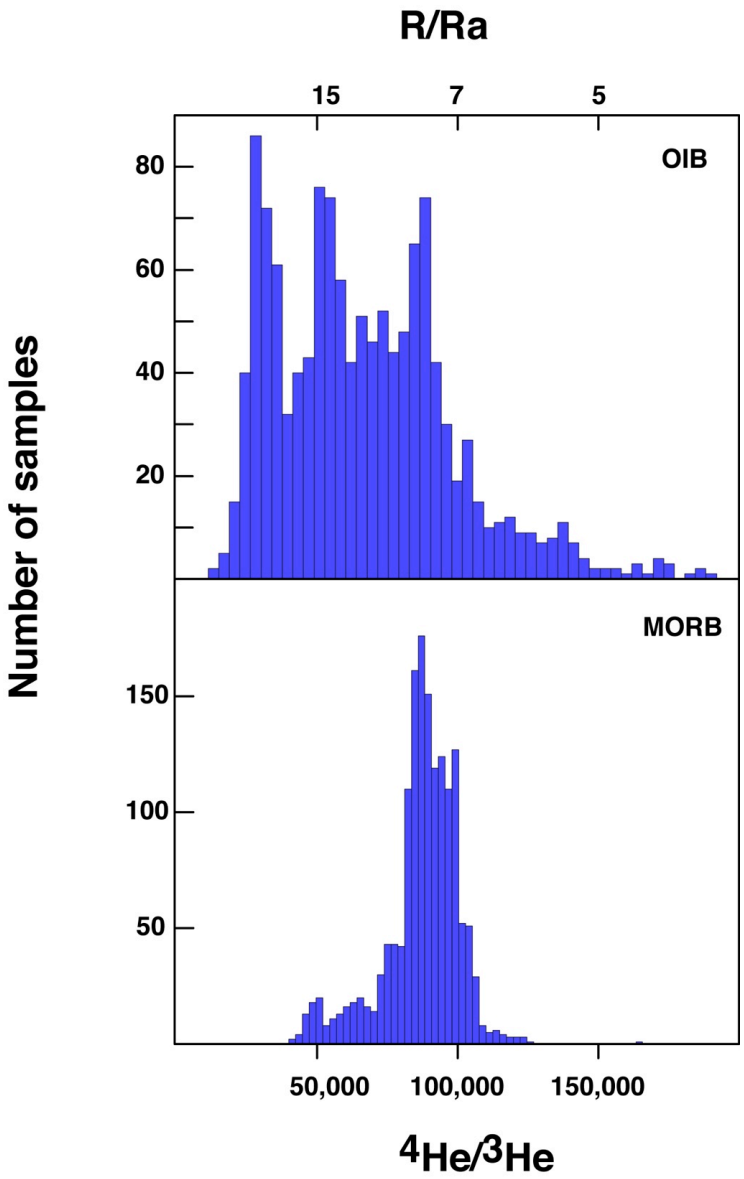
# Le dégazage actuel



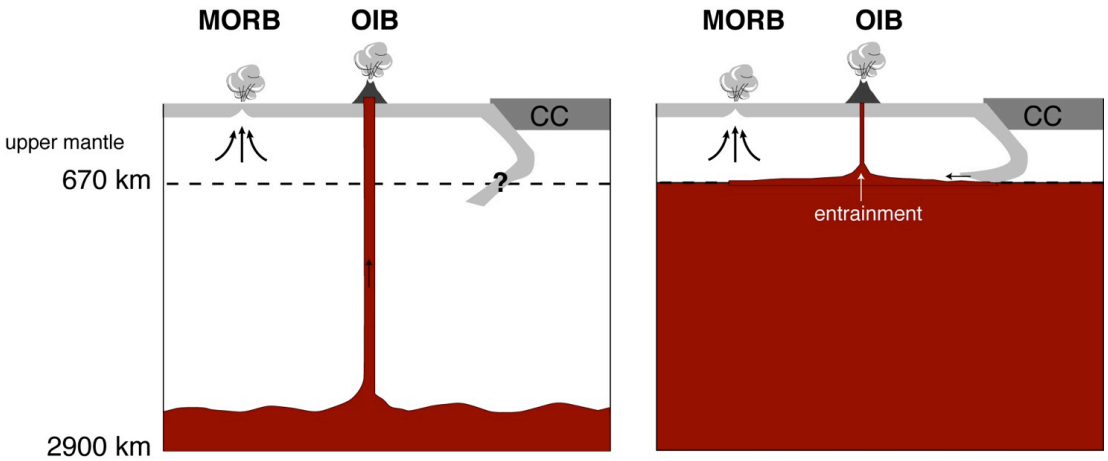

~1000 moles/ an de $^{3}He$

# Les échantillons du manteau montrent également des gaz rares primordiaux dans la Terre profonde

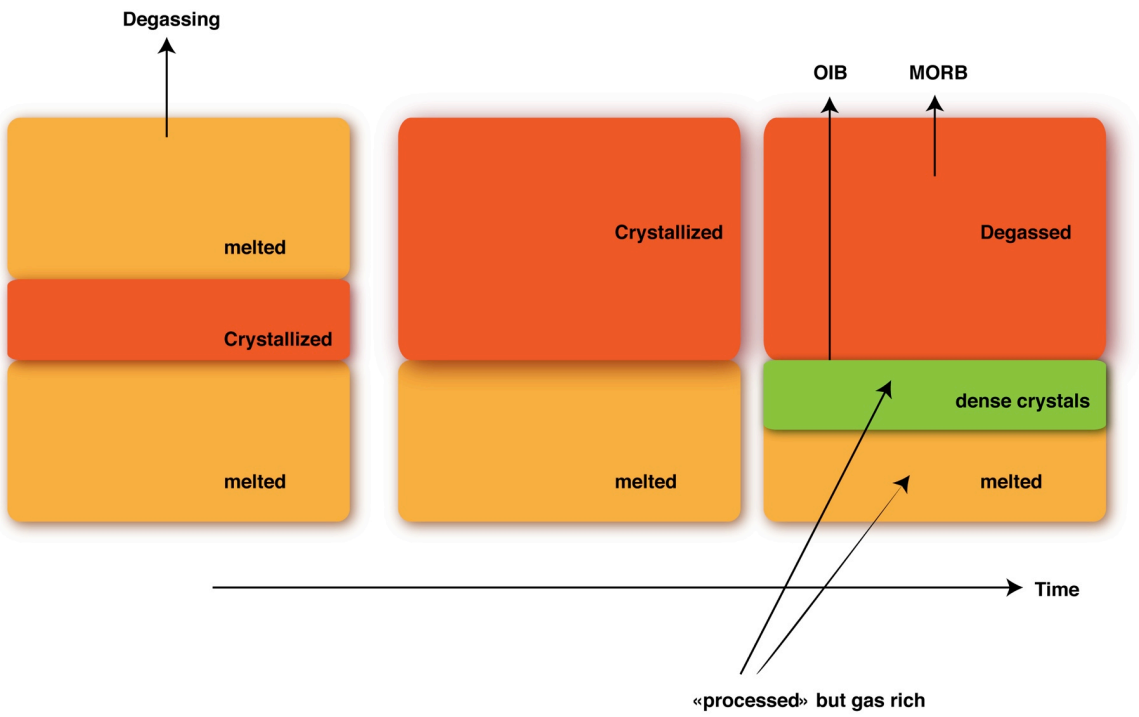
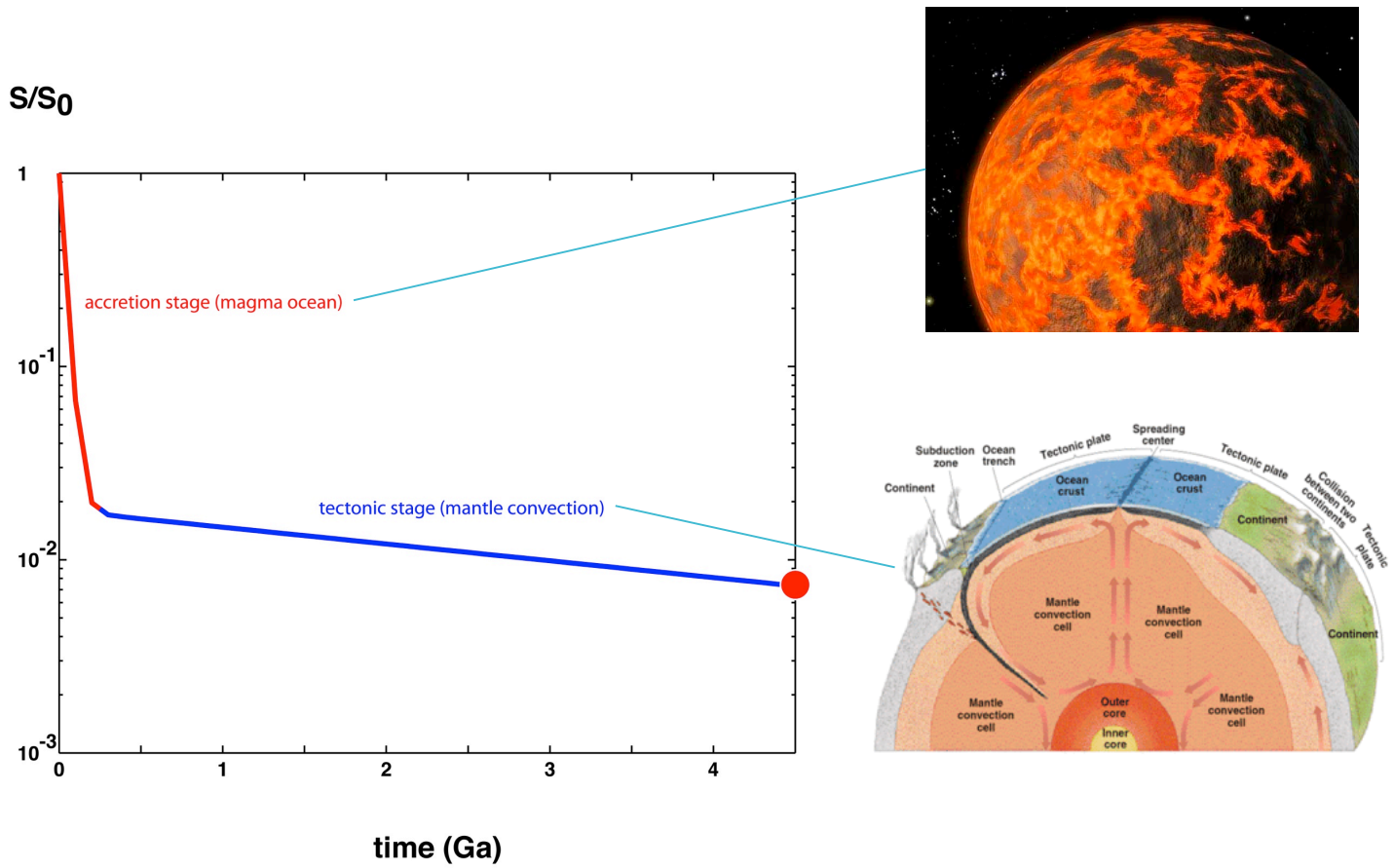
# Le rapport isotopique de l'hélium dans les basaltes océaniques



# Réservoirs profonds « riches » en gaz primordiaux



# Un gaz hérité des premiers millions d'années de l'histoire de la Terre



# Modèle au premier ordre du dégazage du manteau