METEORITES, ISOTOPIC DATATION

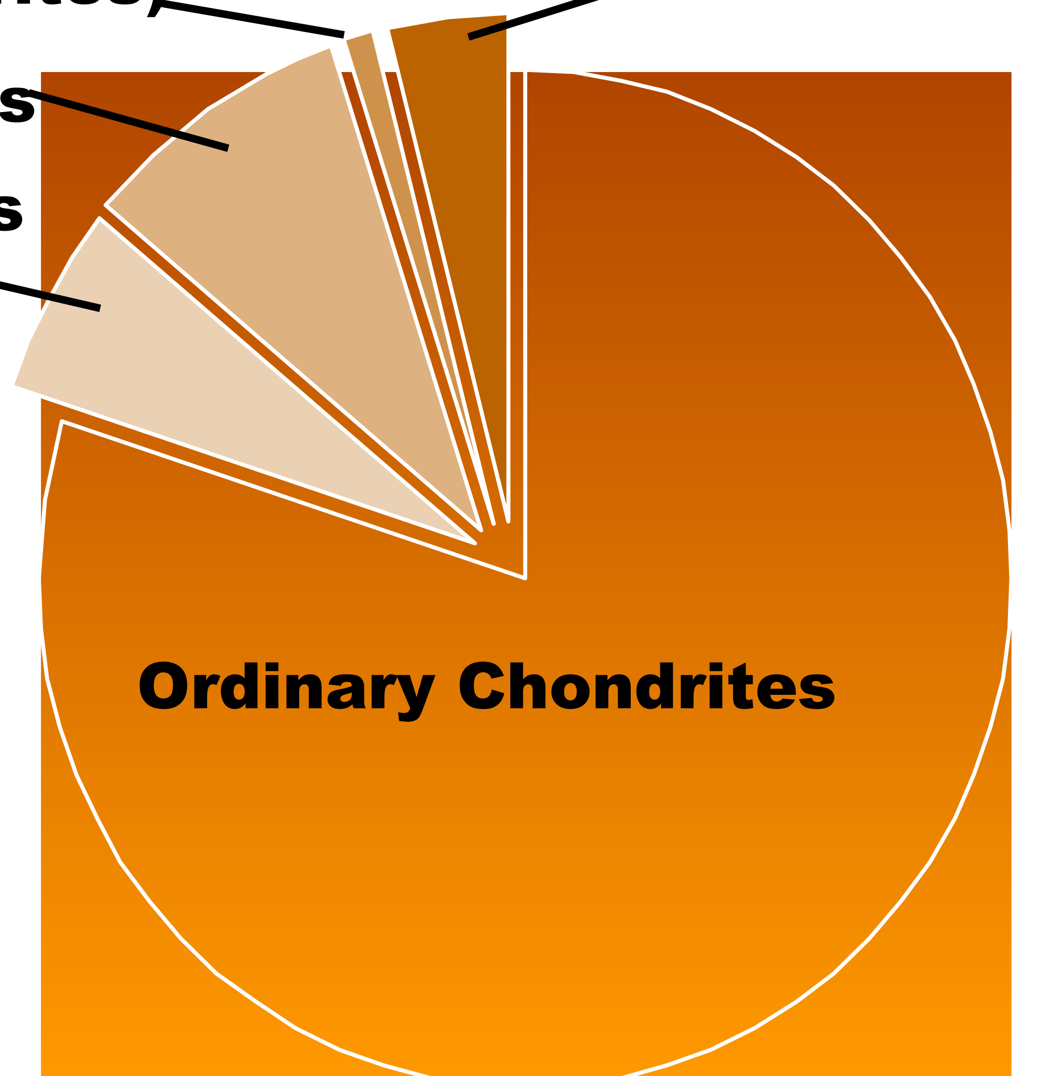
MASTER I.M.A.G.2.E — Physique & Terre Environnement Espace — Université Nice Sophia-Antipolis — Départements

Université Nice SOPHIA ANTIPOLIS

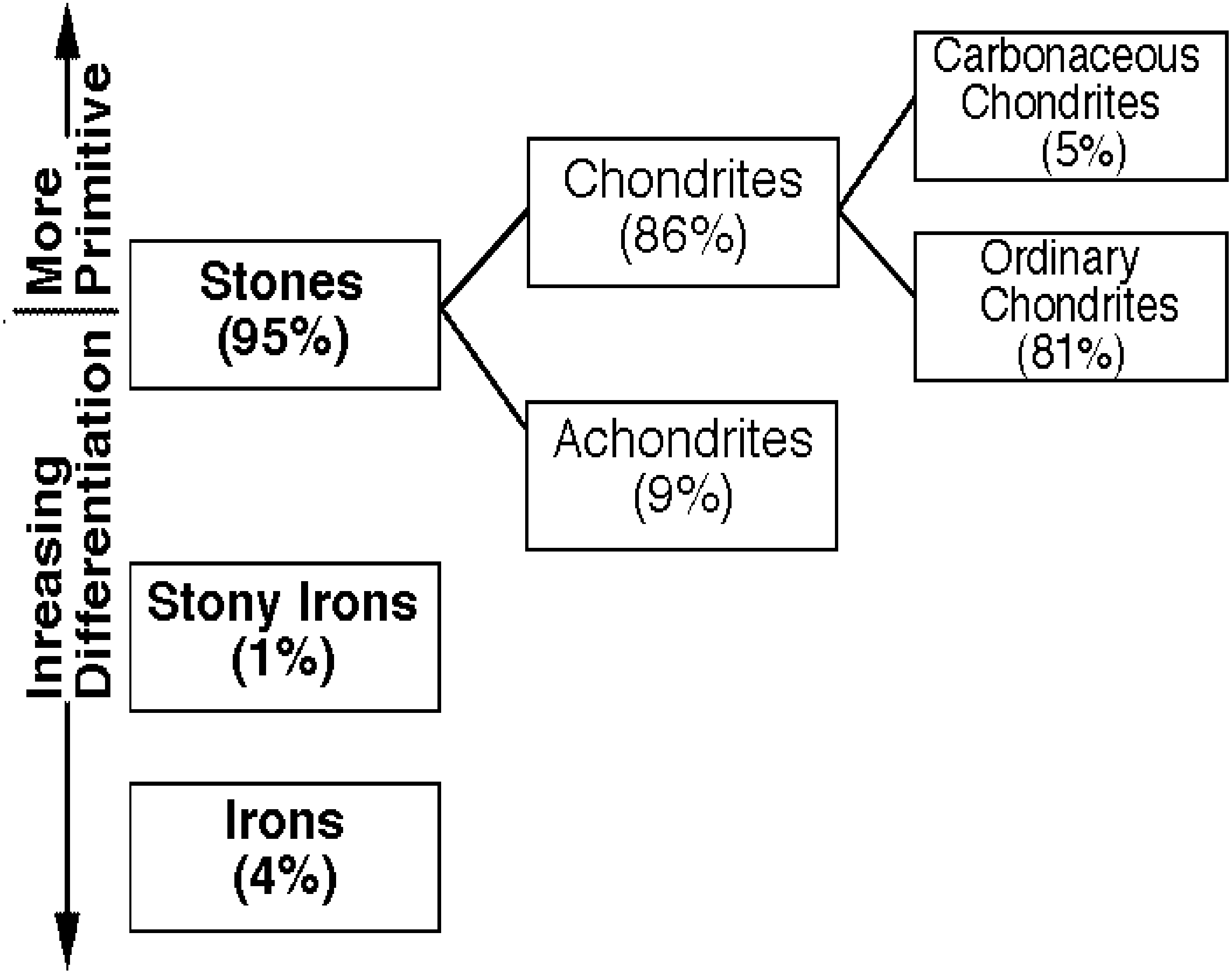
Aurélien CRIDA

MÉTÉORITES

Falls :



MÉTÉORITES : CLASSIFICATION

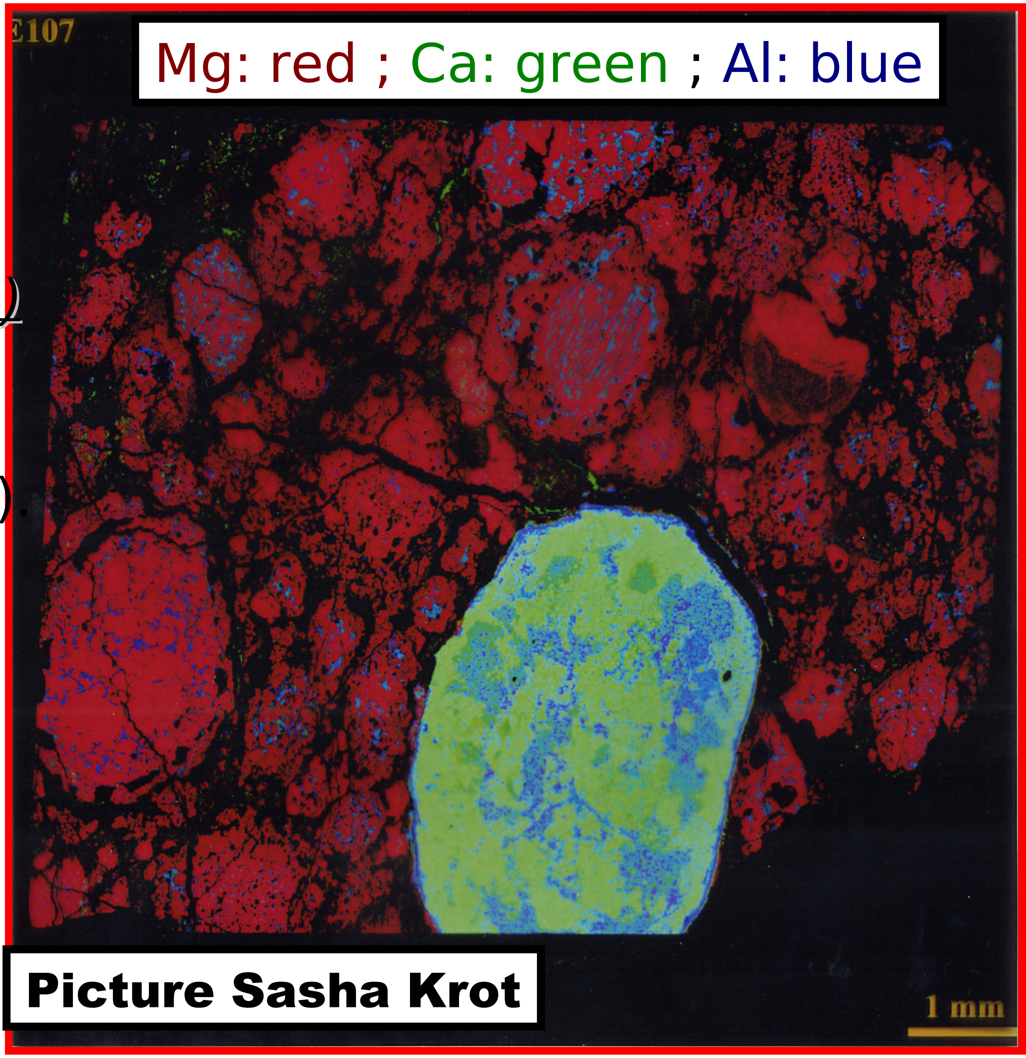


COMPOSITION of CHONDRITES

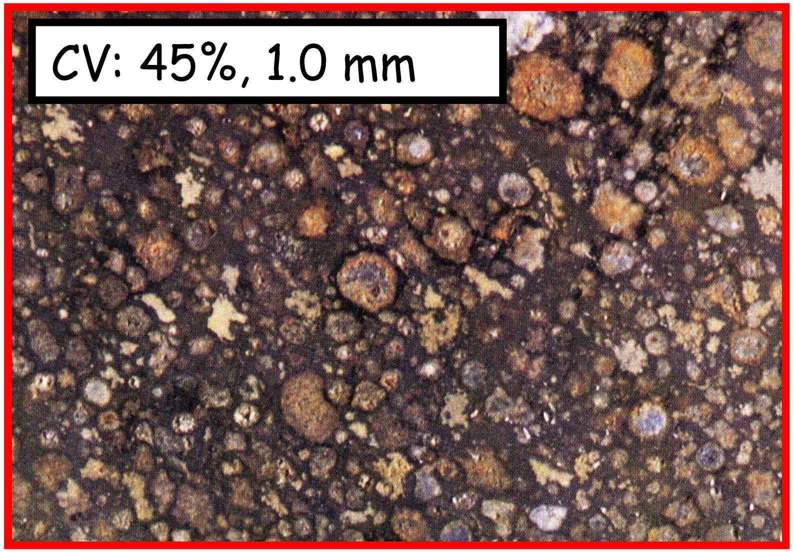
☆ *Chondrules* (fr: *chondres*)
Silicate/metal beads.
Varying sizes (10 µm- few mm).

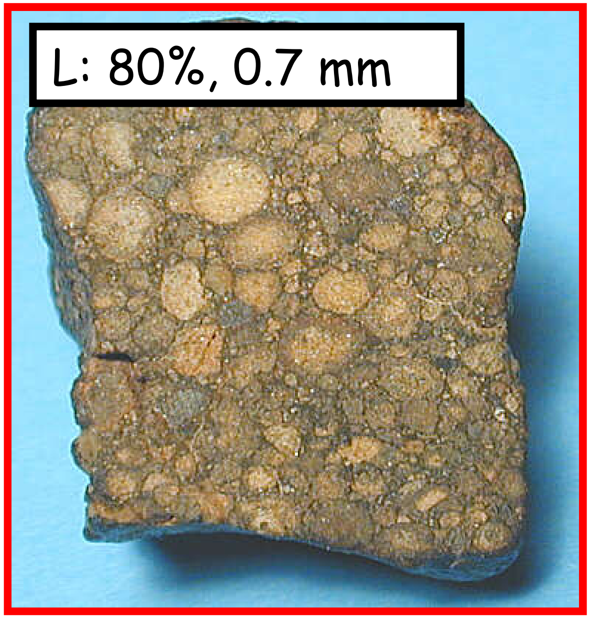
☆ *Refractory inclusions = CAI (Calcium-Aluminum rich Inclusions)*
Contain Ca- and Al-rich minerals.
Varying sizes (10 µm- few cm).

☆ *Matrix* (fr: *matrice*)
Silicates, oxides, amorphous.
Fine-grained (< µm).

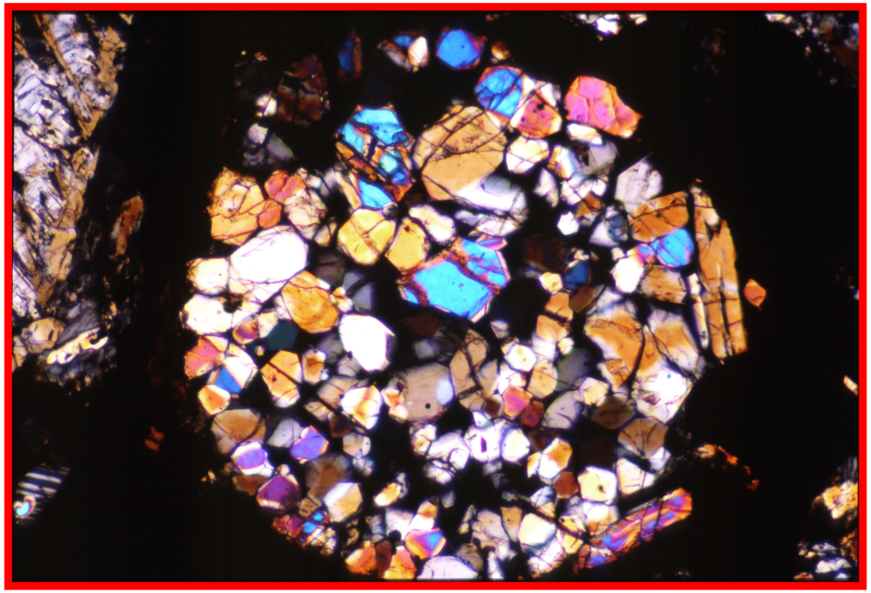


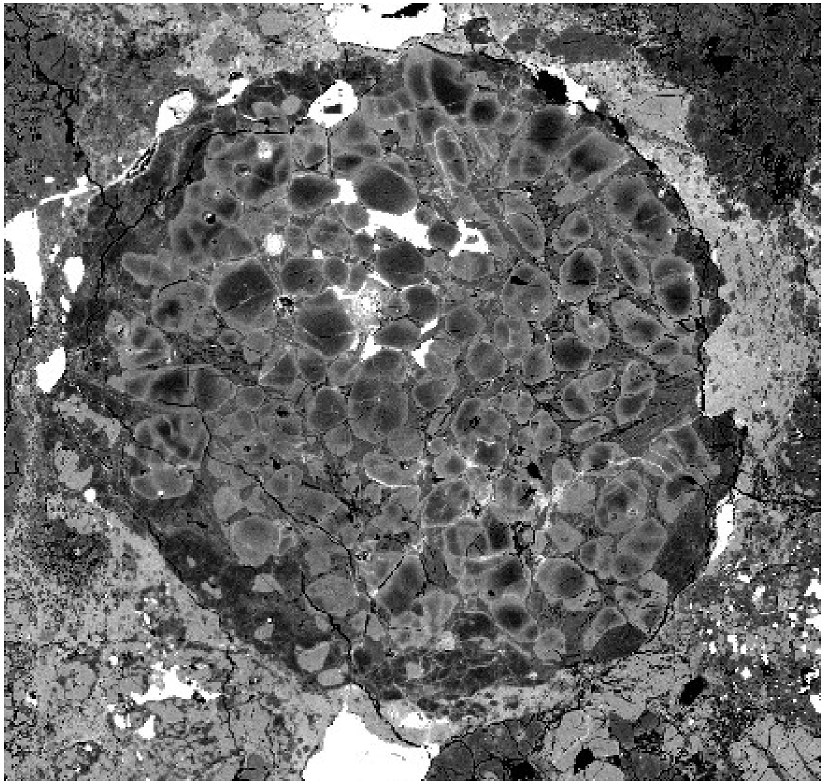
CHONDRULES : Proportion and Size





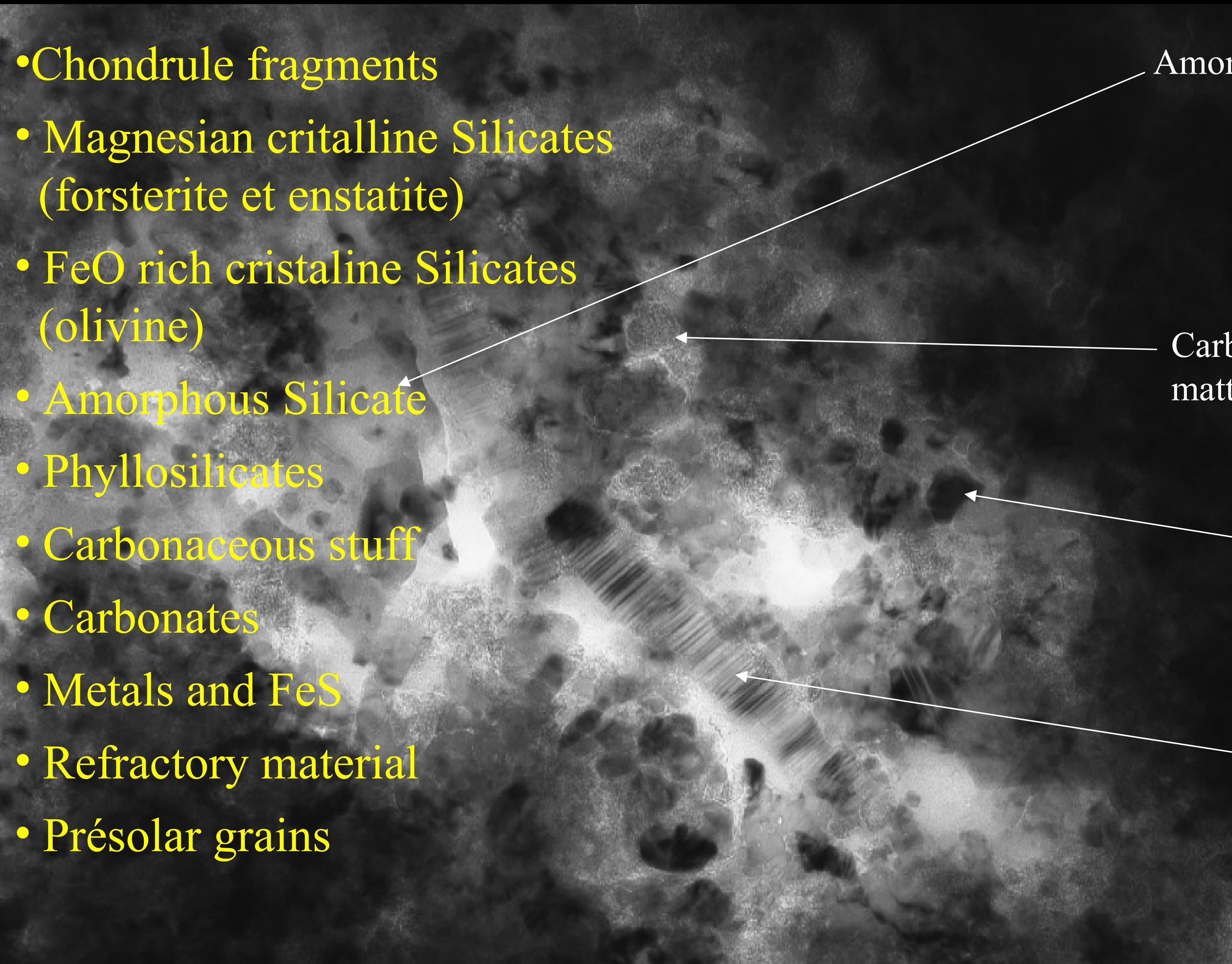
Ex: PORPHYRITIC CHONDRULE





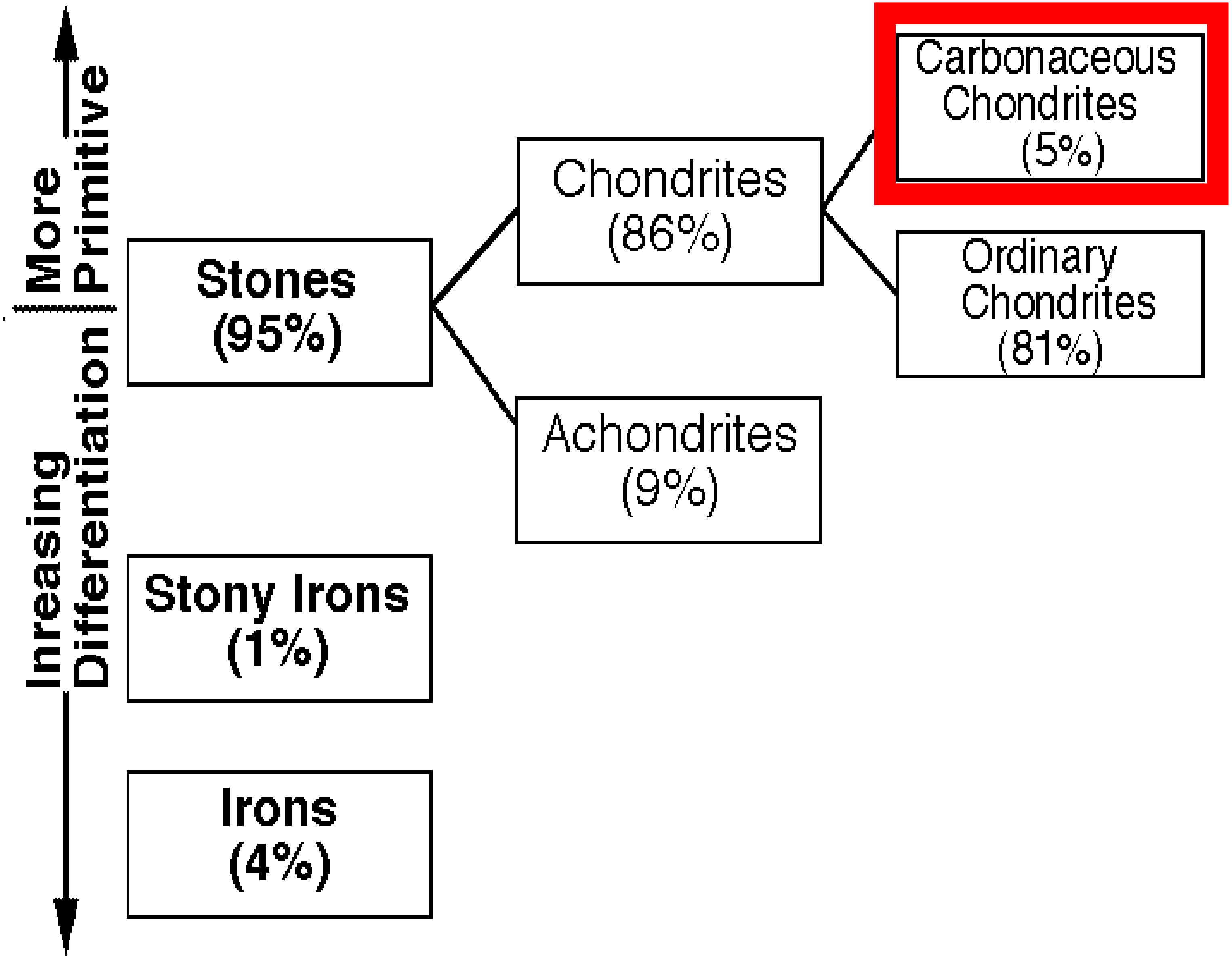
- Olivine [$(Mg,Fe)_2SiO_4$] and pyroxene [$(Mg,Fe)SiO_3$] *phenocrysts* set in a glassy matrix

MATRIX of the CHONDRITES

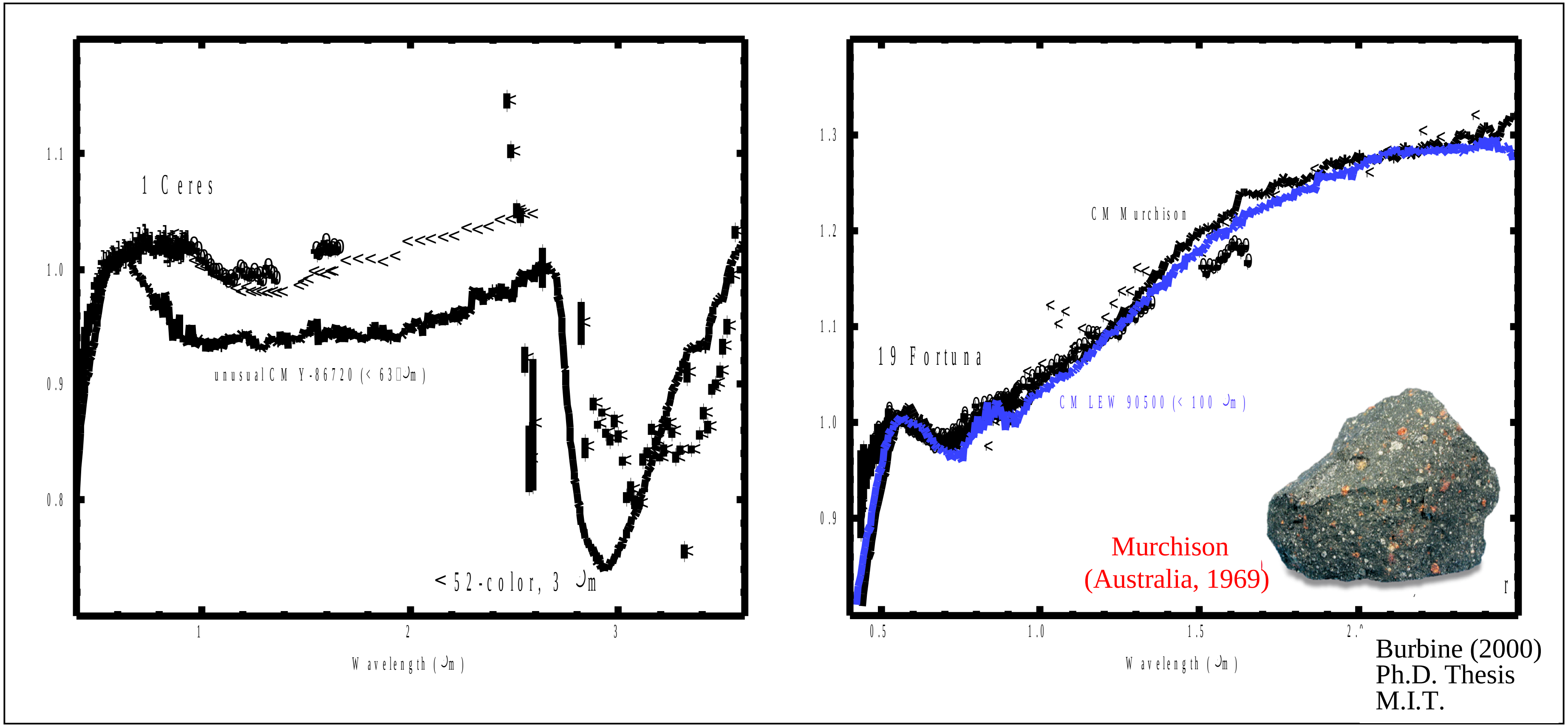


- Chondrule fragments
- Magnesian critalline Silicates (forsterite et enstatite)
- FeO rich cristaline Silicates (olivine)
- Amorphous Silicate
- Phyllosilicates
- Carbonaceous stuff
- Carbonates
- Metals and FeS
- Refractory material
- Présolar grains

CONNECTIONS ASTÉROÏDES-MÉTÉORITES

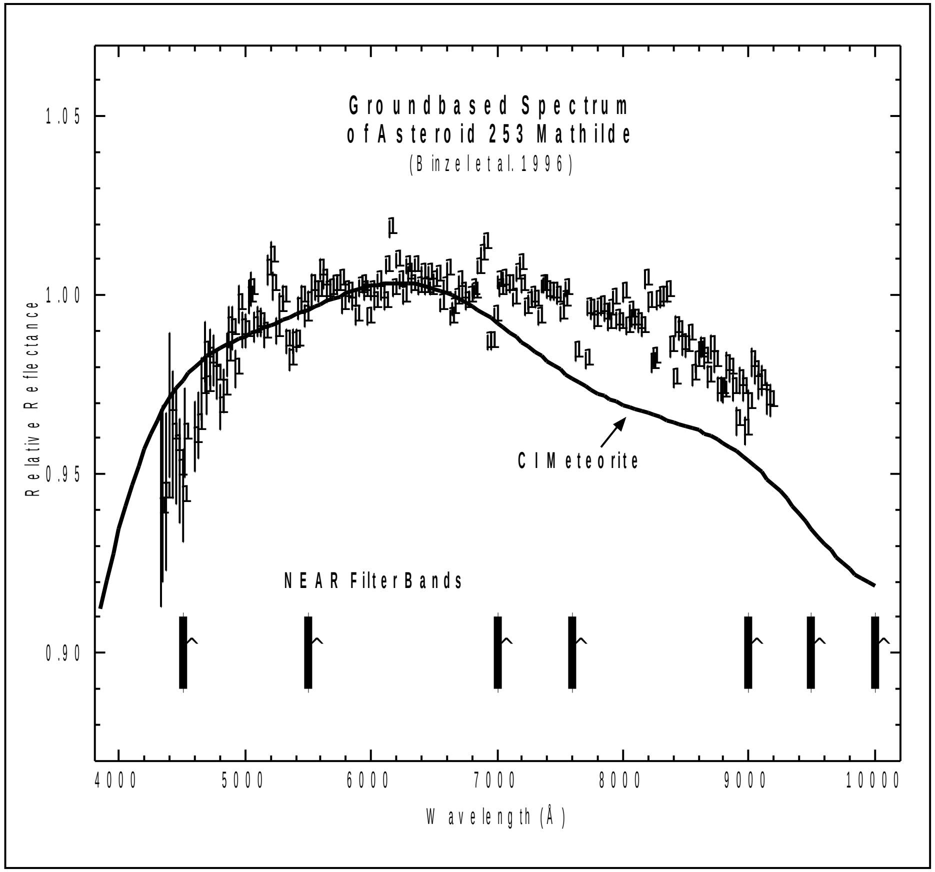


CONNECTIONS ASTÉROÏDES-MÉTÉORITES

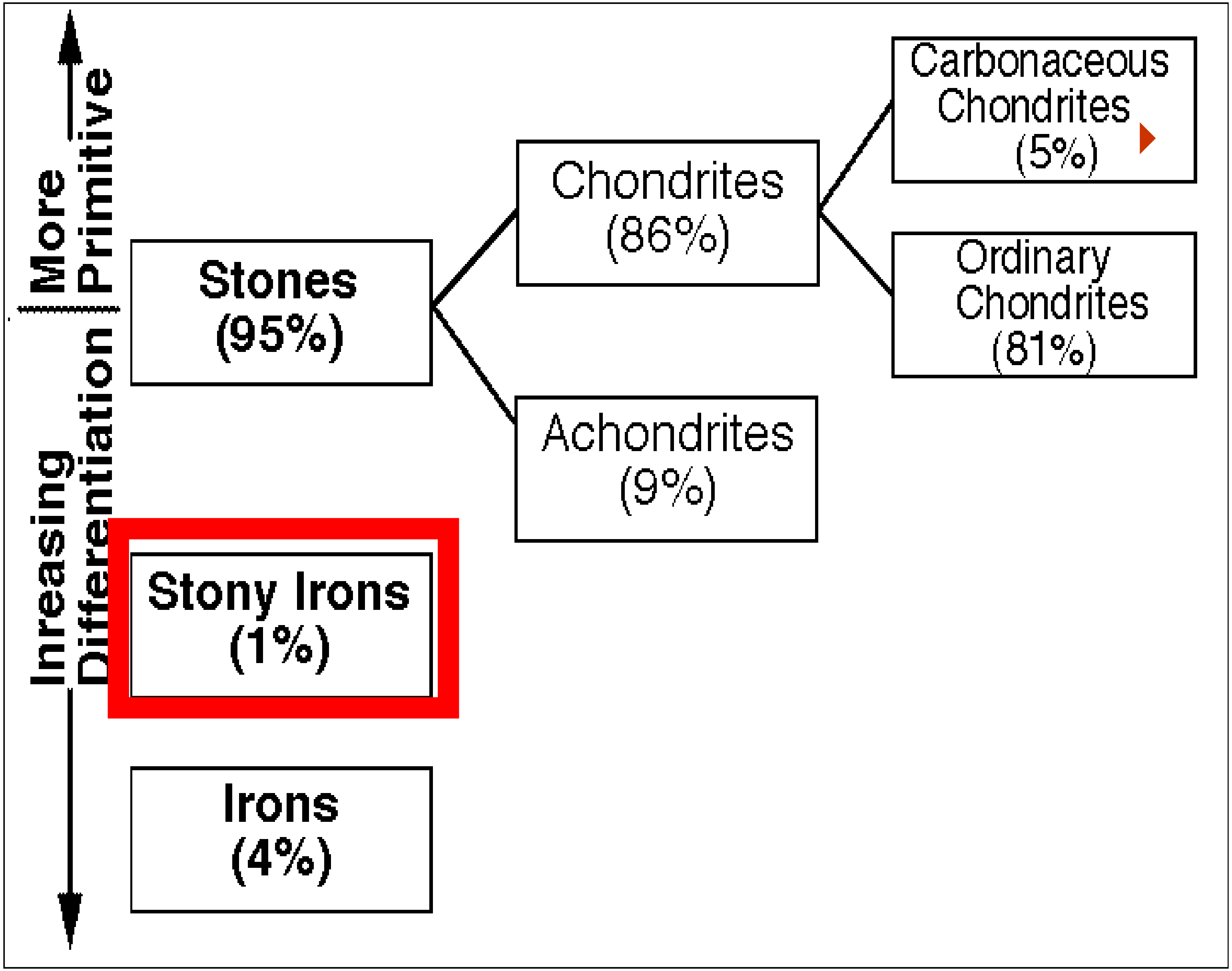


Good agreement between asteroids of spectral type C and Carbonaceous Chondrites.

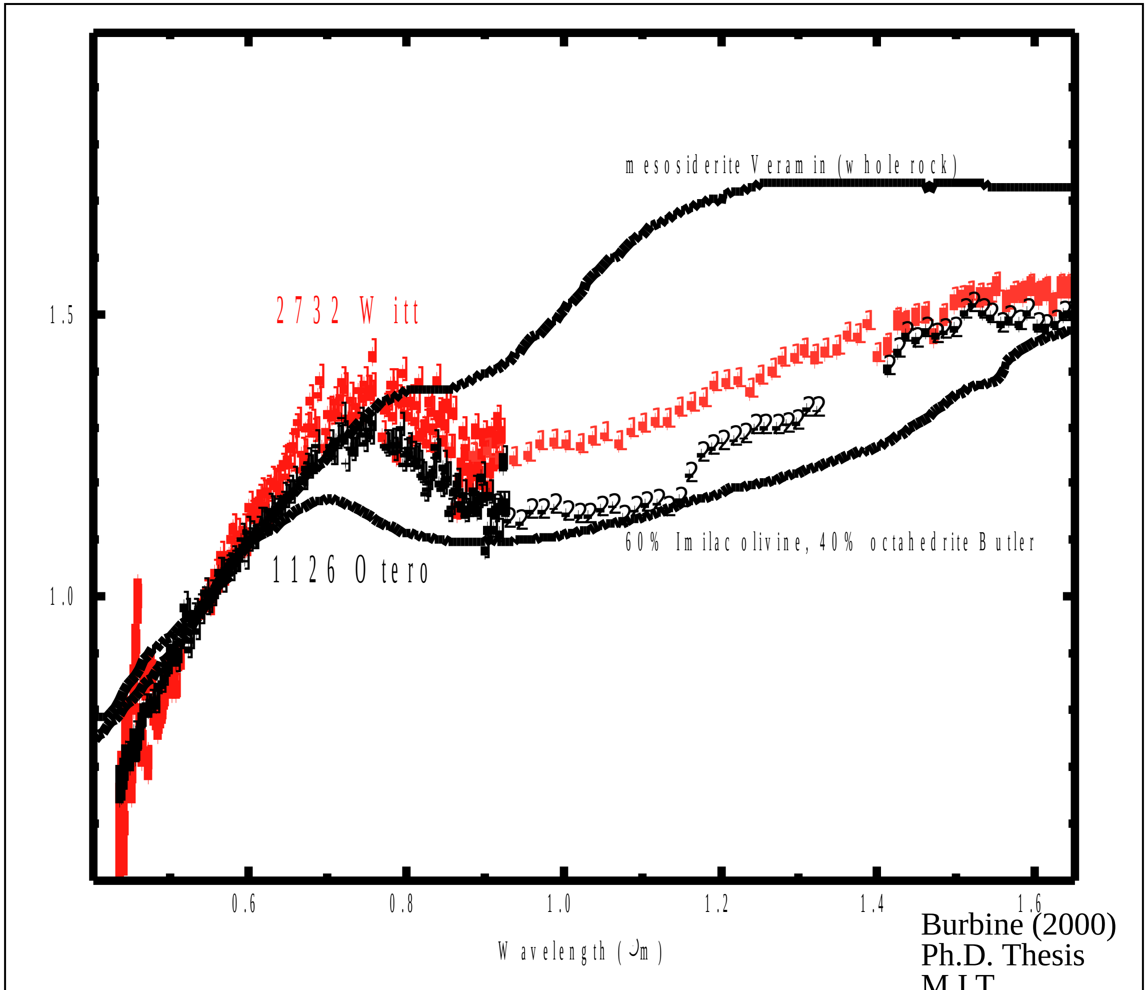
CONNECTIONS ASTÉROÏDES-MÉTÉORITES



CONNECTIONS ASTÉROÏDES-MÉTÉORITES



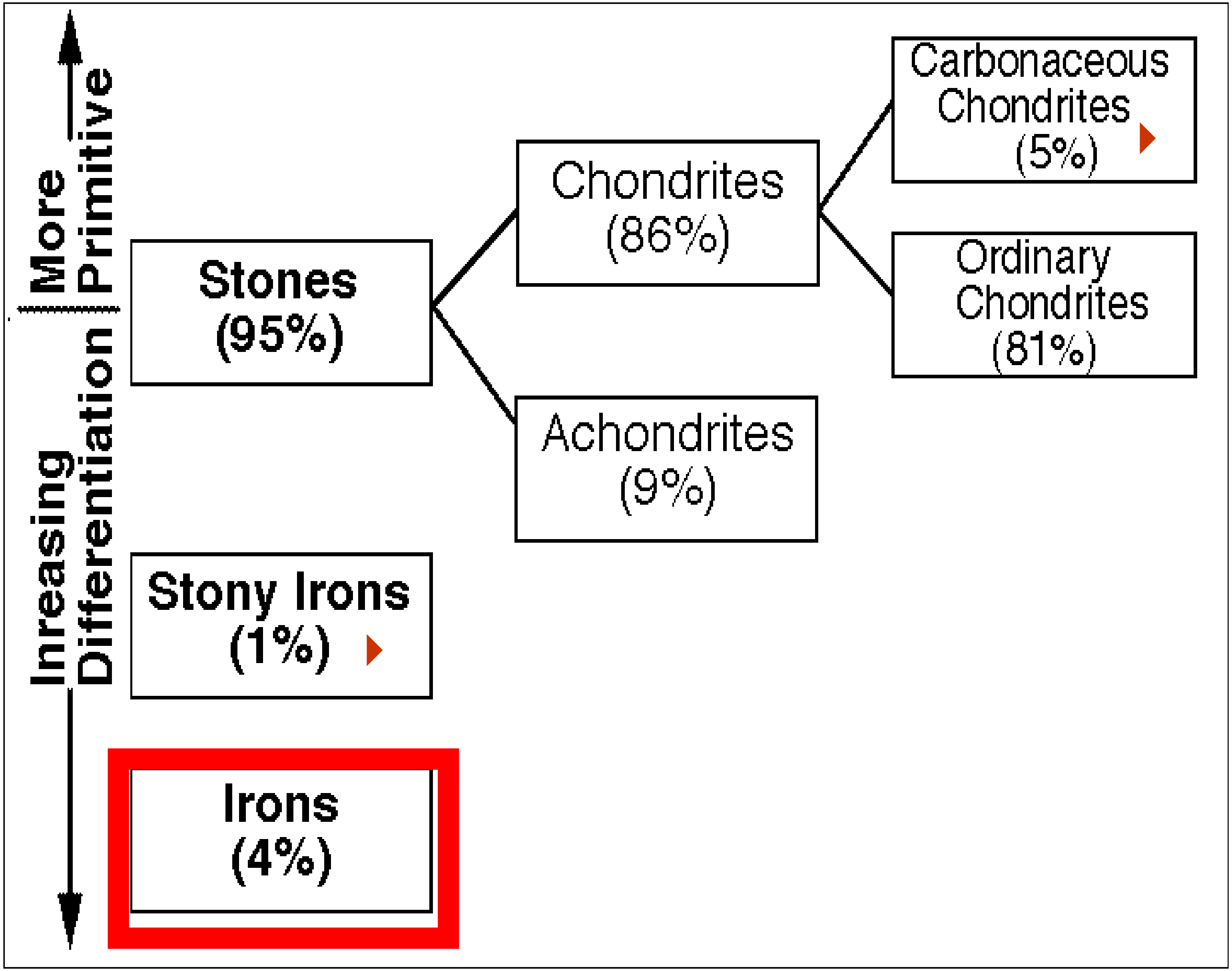
CONNECTIONS ASTÉROÏDES-MÉTÉORITES



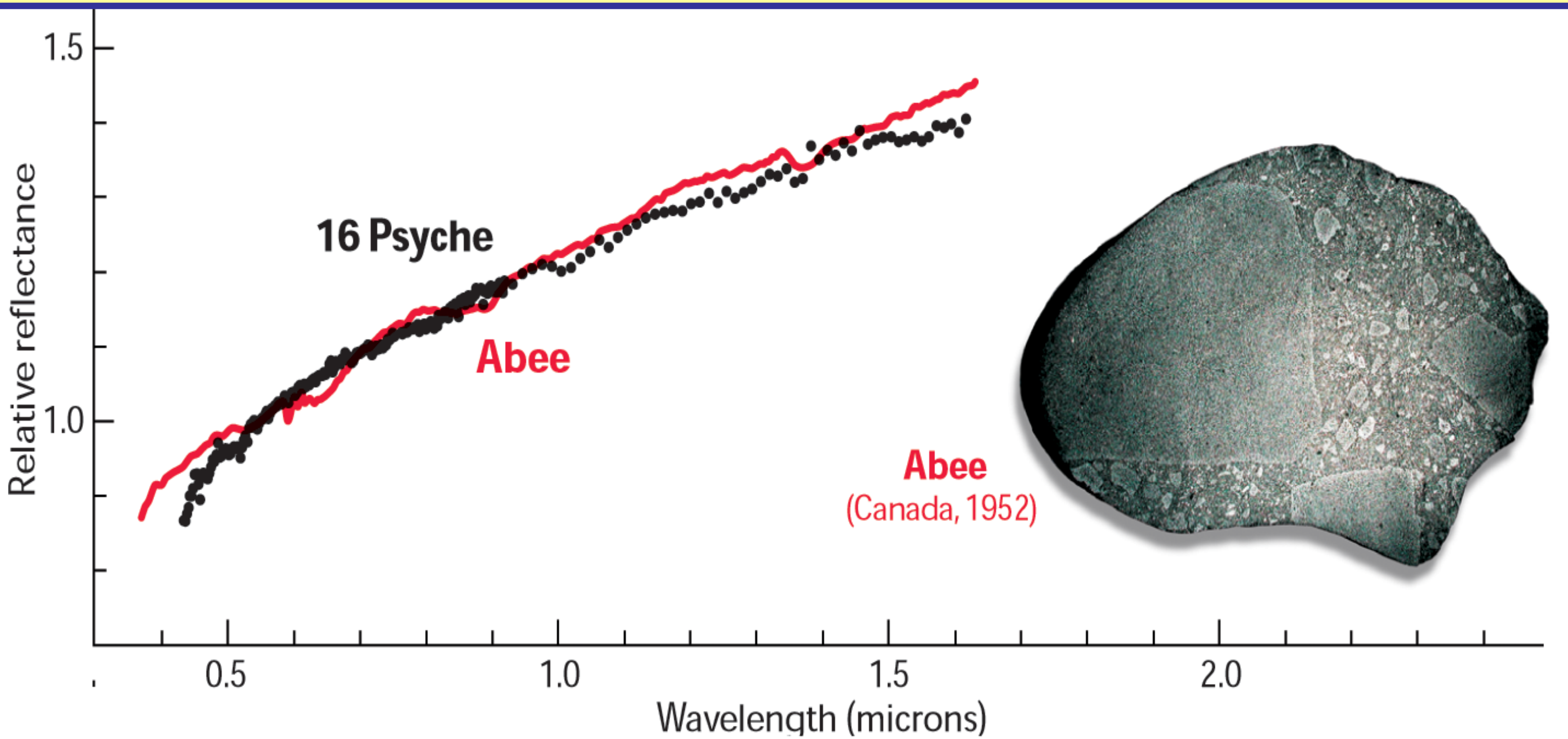
Burbine (2000)
Ph.D. Thesis
M.I.T.

Possible agreement between astéroides of type A and stony-iron meteorites.

CONNECTIONS ASTÉROÏDES-MÉTÉORITES

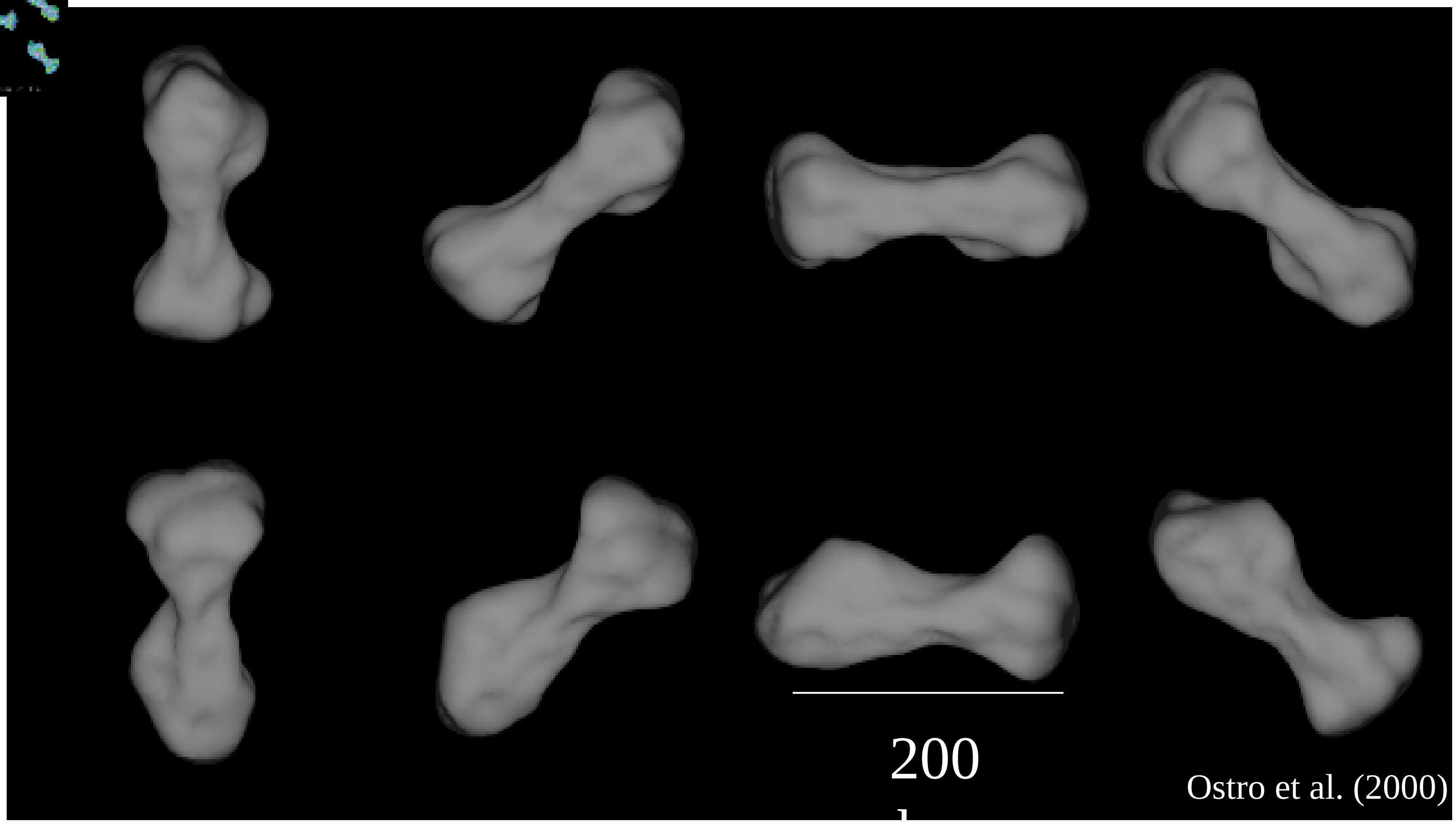


CONNECTIONS ASTÉROÏDES-MÉTÉORITES



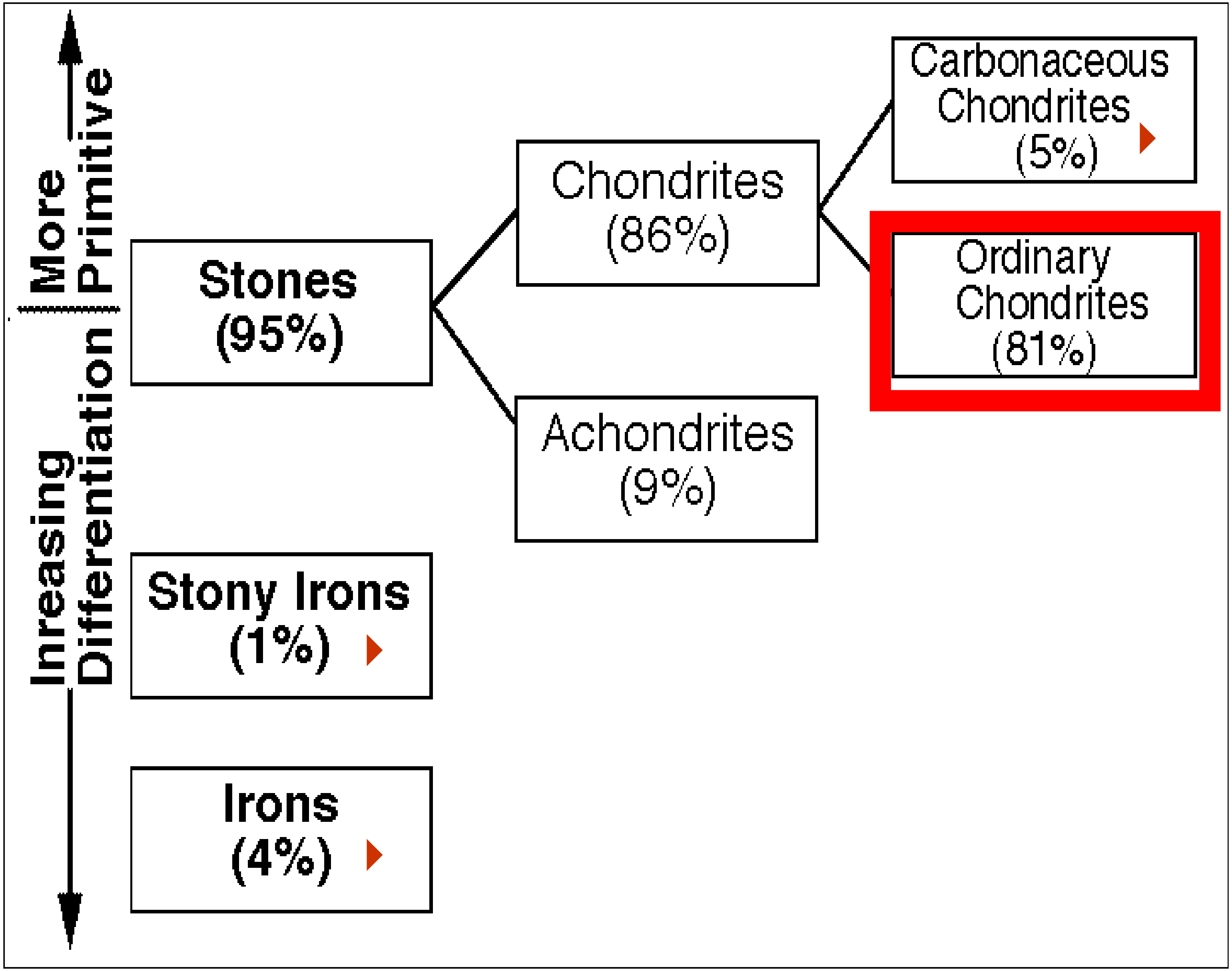
Iron has a smooth spectrum, inclined towards the red.
Quite similar to asteroids of type M.

CONNECTIONS ASTÉROÏDES-MÉTÉORITES

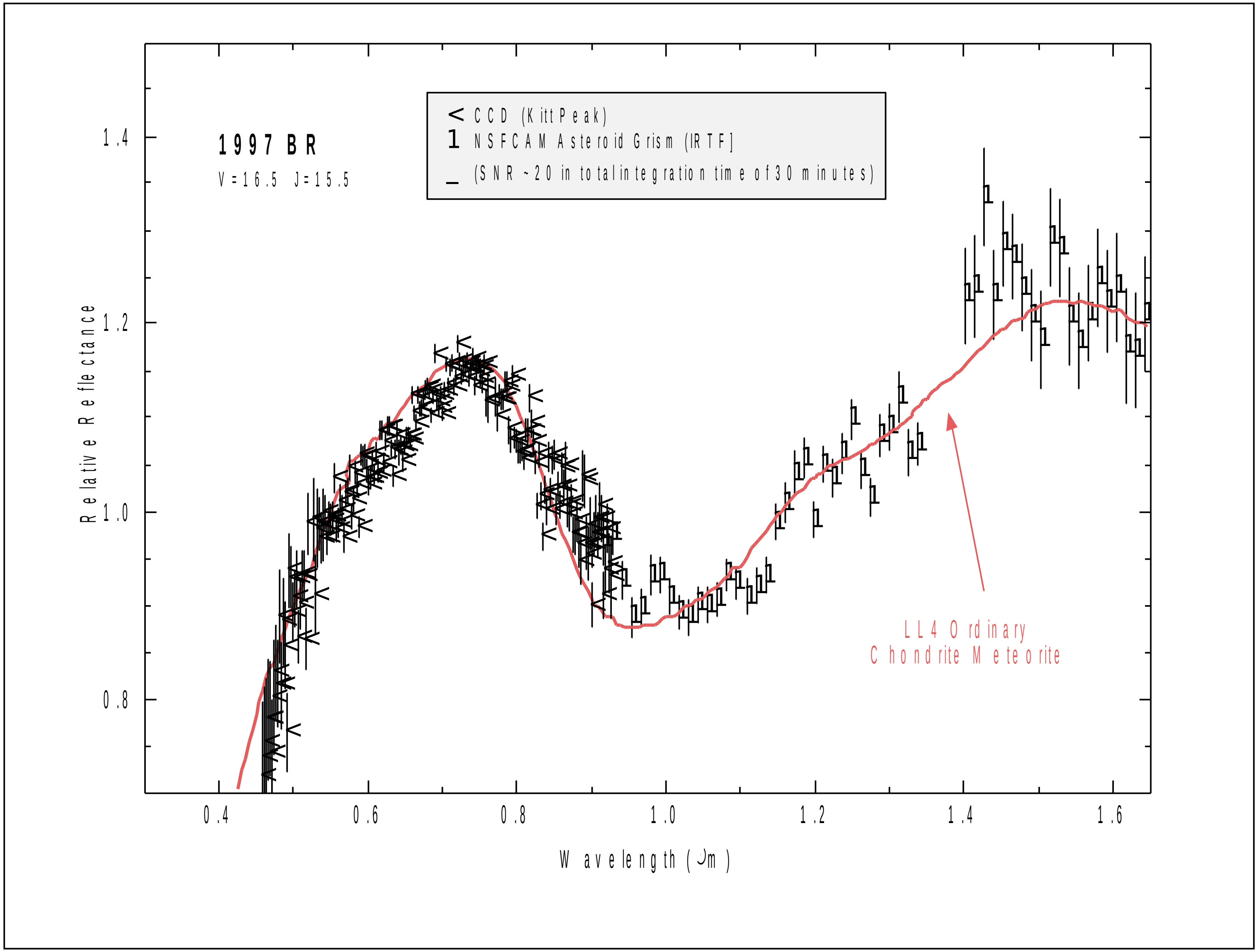


Radar measurements of M-type asteroids provide a strong link to iron meteorite compositions.

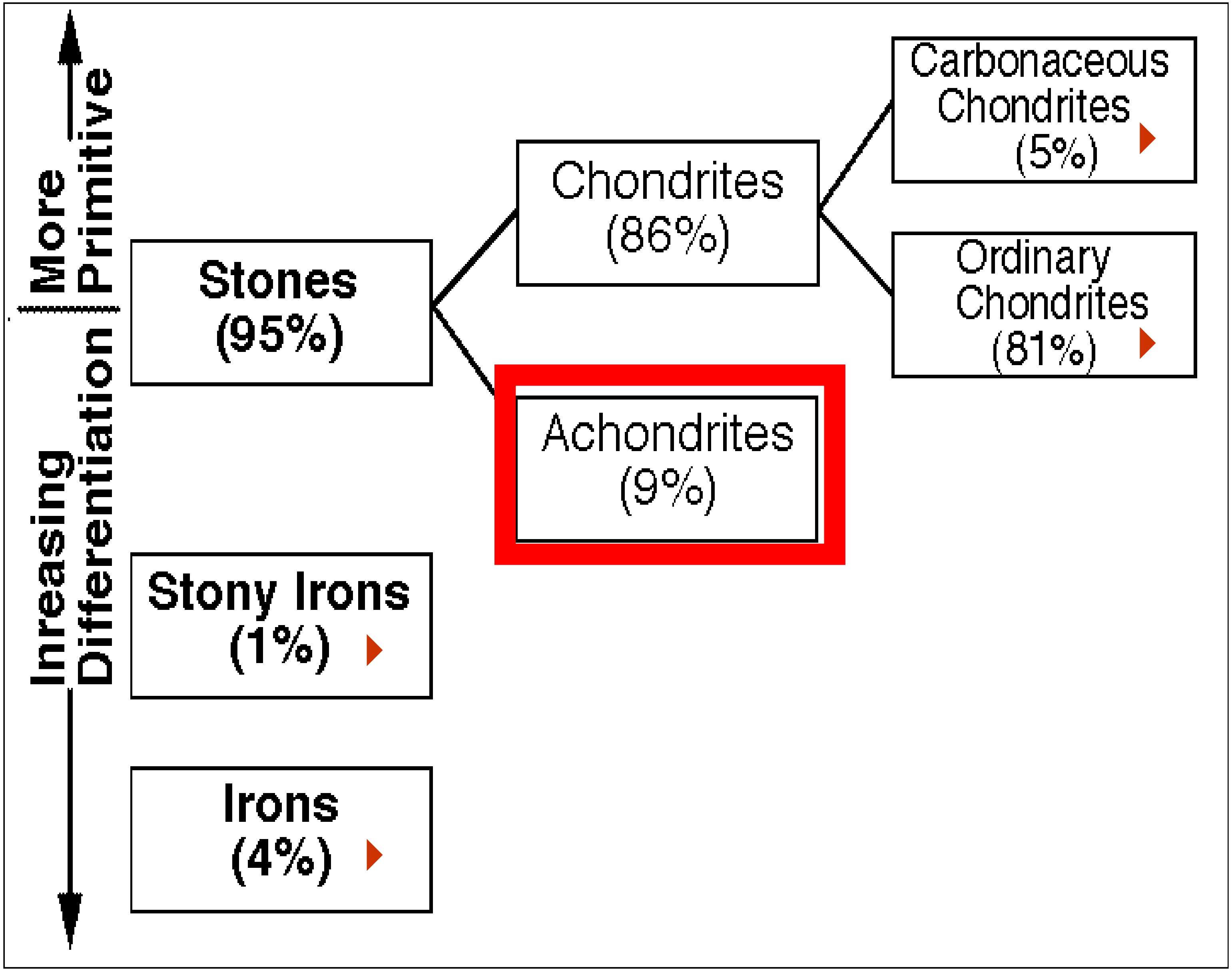
CONNECTIONS ASTÉROÏDES-MÉTÉORITES



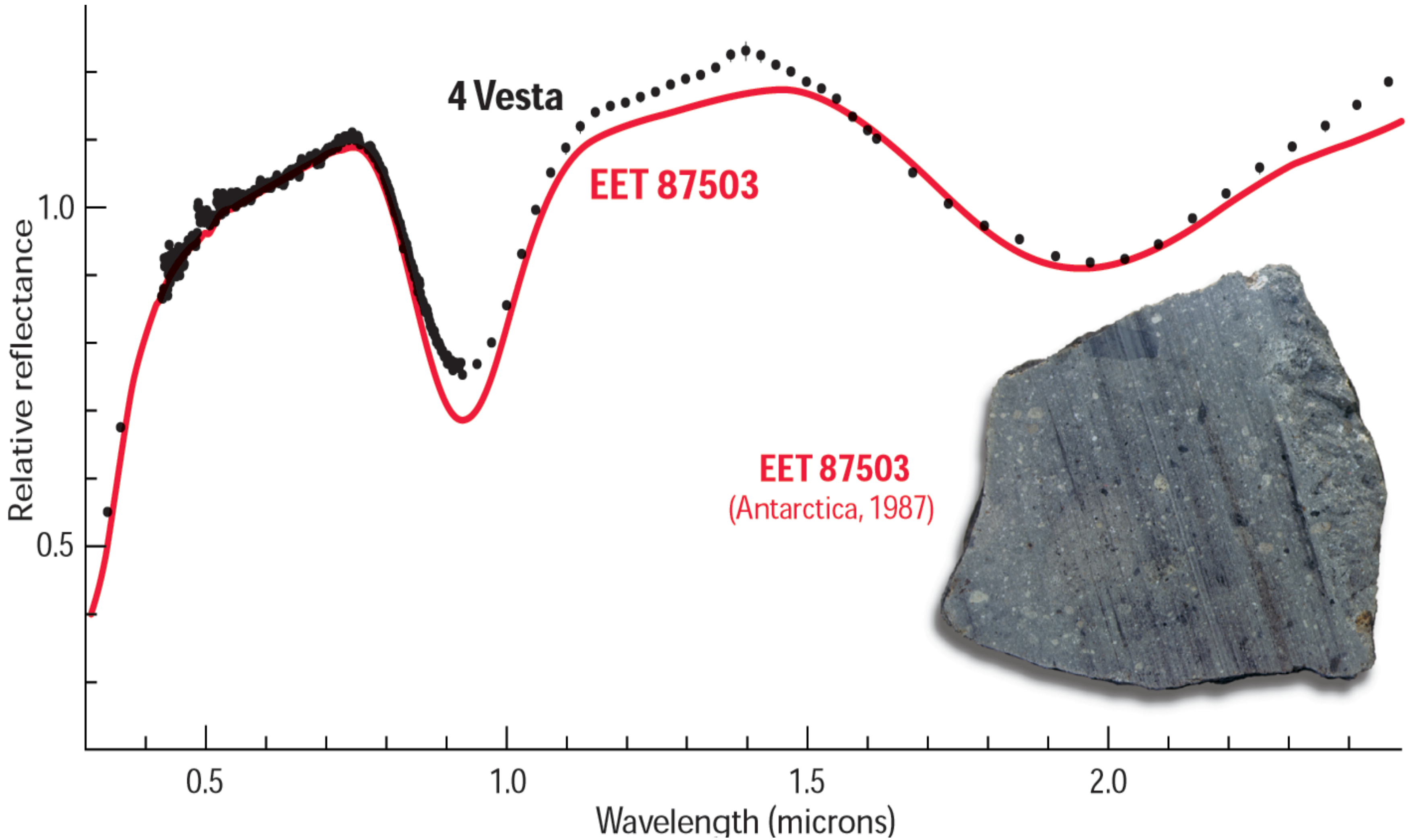
CONNECTIONS ASTÉROÏDES-MÉTÉORITES



CONNECTIONS ASTÉROÏDES-MÉTÉORITES

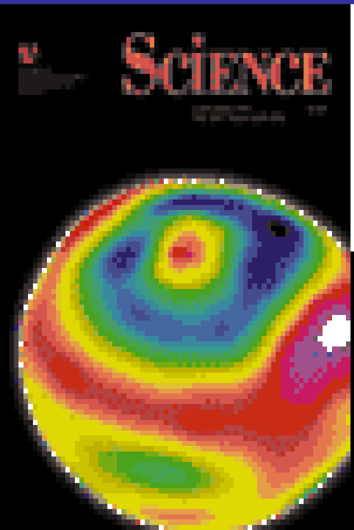


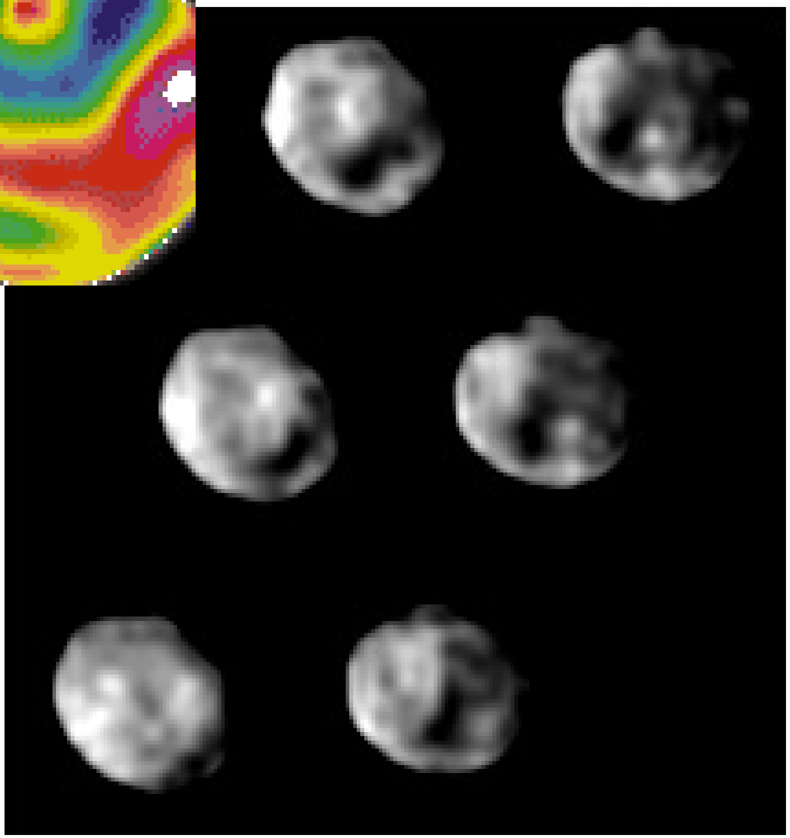
CONNECTIONS ASTÉROÏDES-MÉTÉORITES



Spectral match between Vesta and achondrite meteorites (HEDs) first found by McCord et al. (1970).

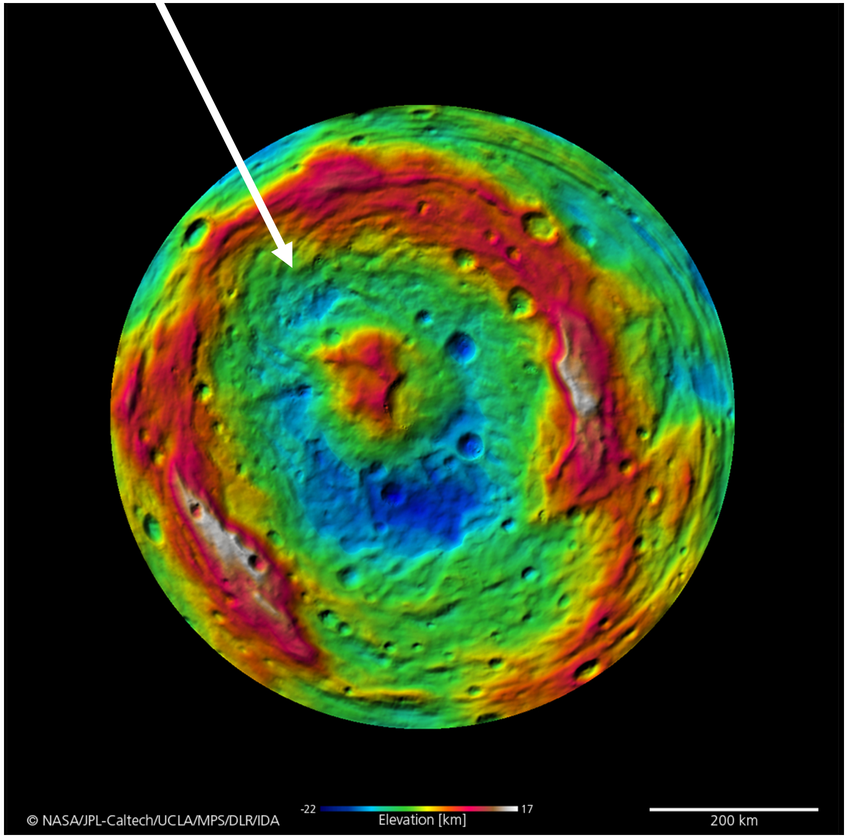
VESTA





Images HST

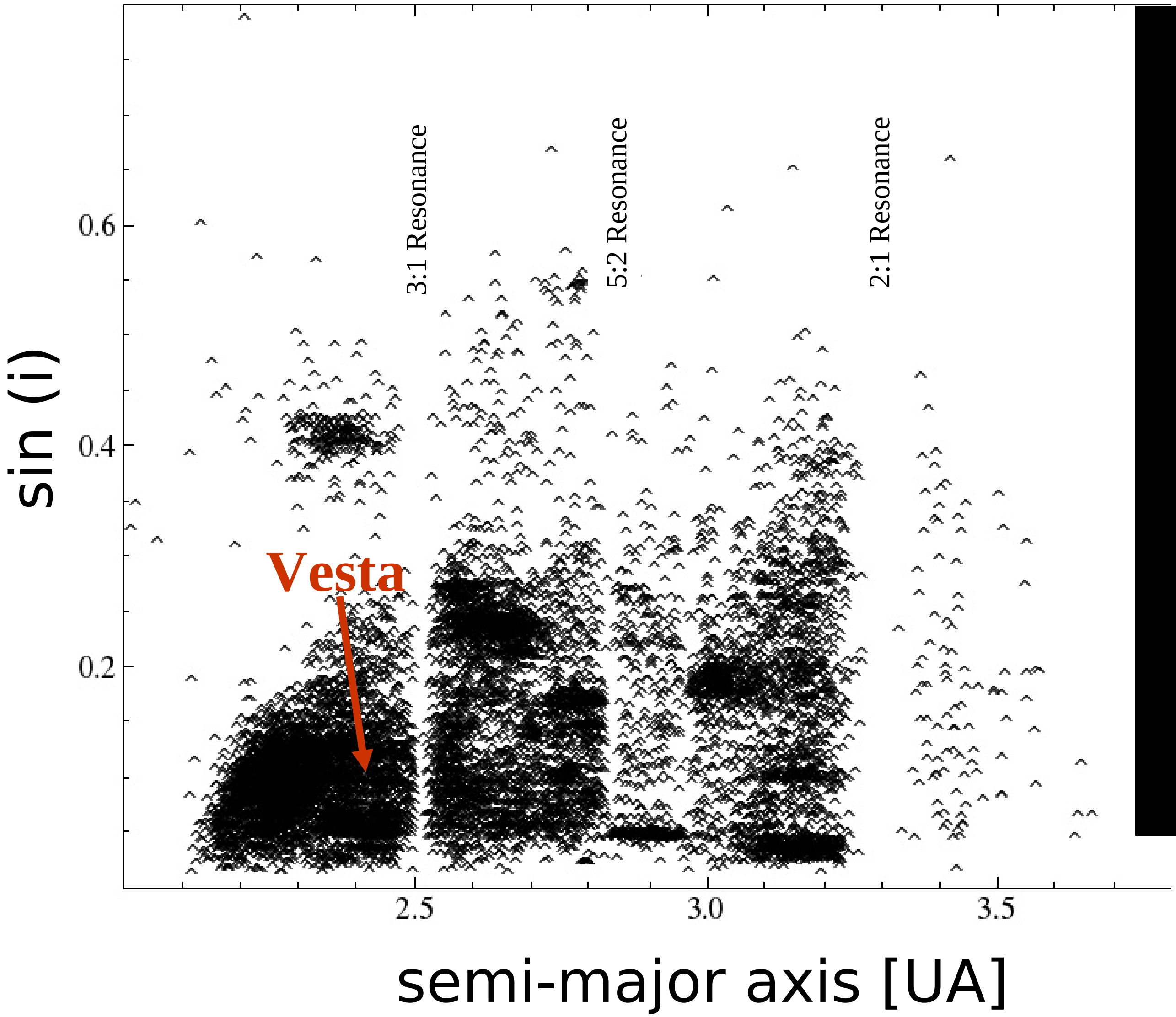
Impact basin of
460 km diametre



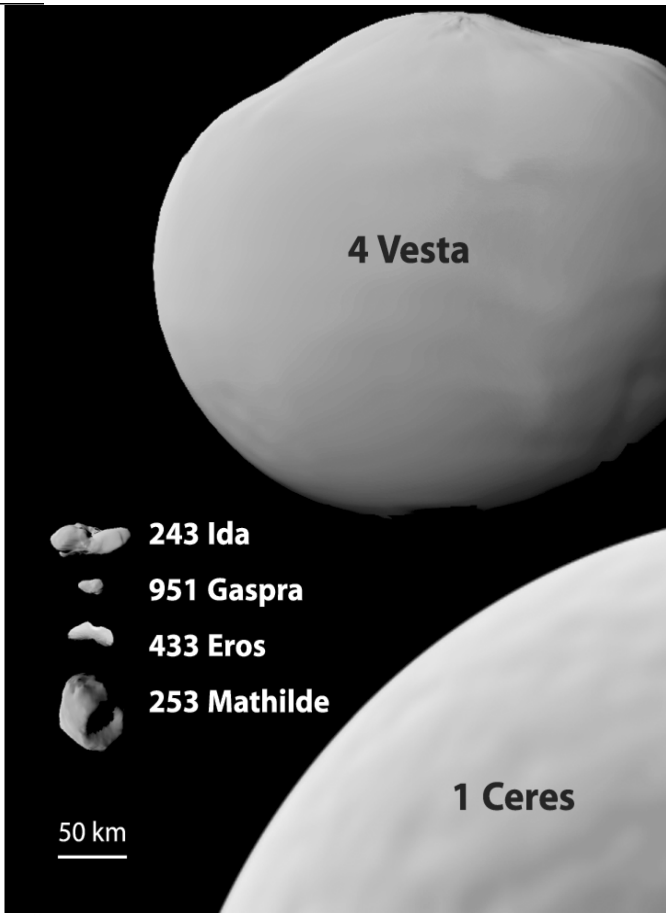
Reconstruction topographique

Thomas, Binzel et al. (1997)

ASTÉROIDES



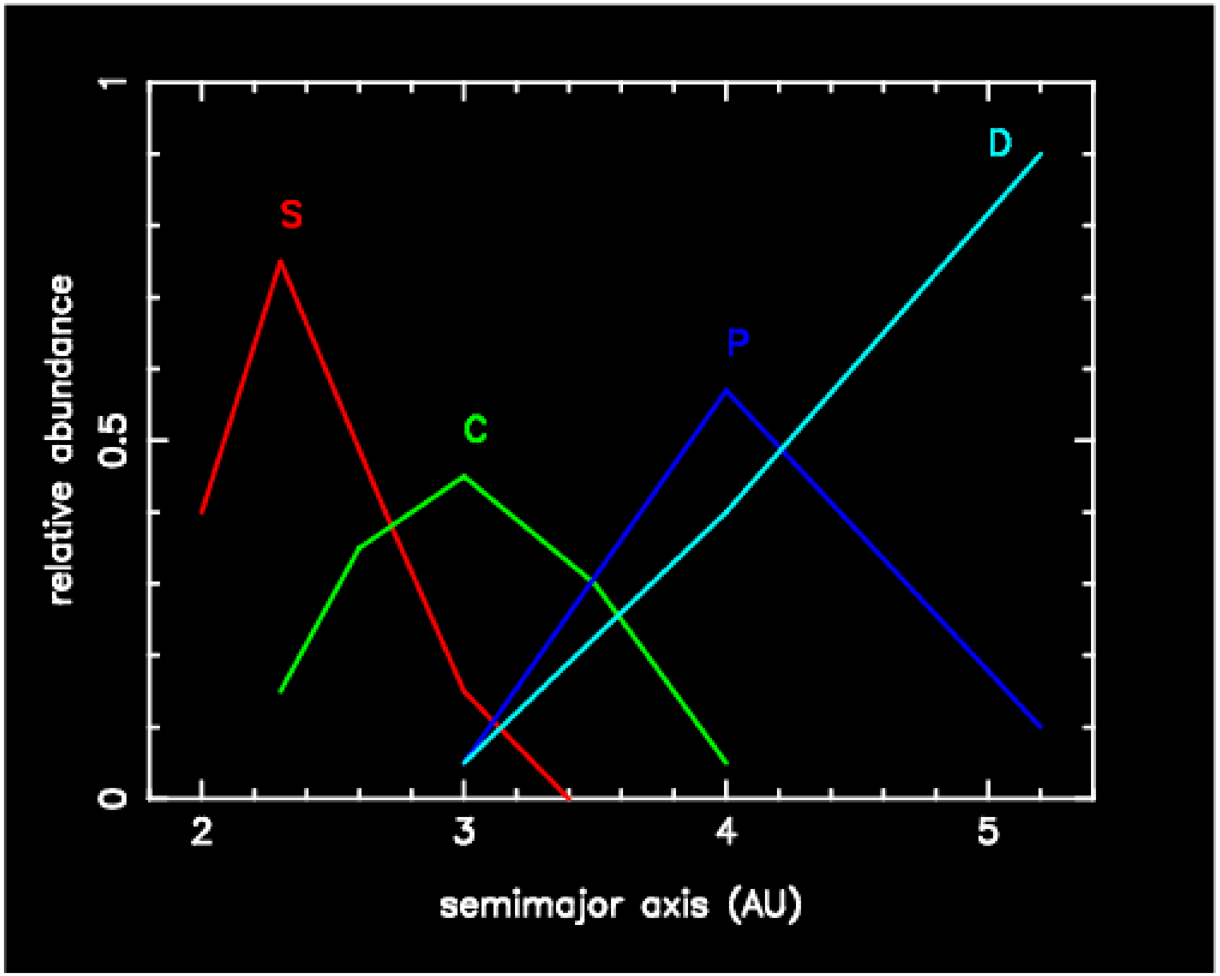
sin (i)
0.6
0.4
0.2
3:1 Resonance
5:2 Resonance
2:1 Resonance
Vesta
2.5
3.0
3.5
semi-major axis [UA]



4 Vesta
243 Ida
951 Gaspra
433 Eros
253 Mathilde
1 Ceres
50 km

ASTÉROIDES

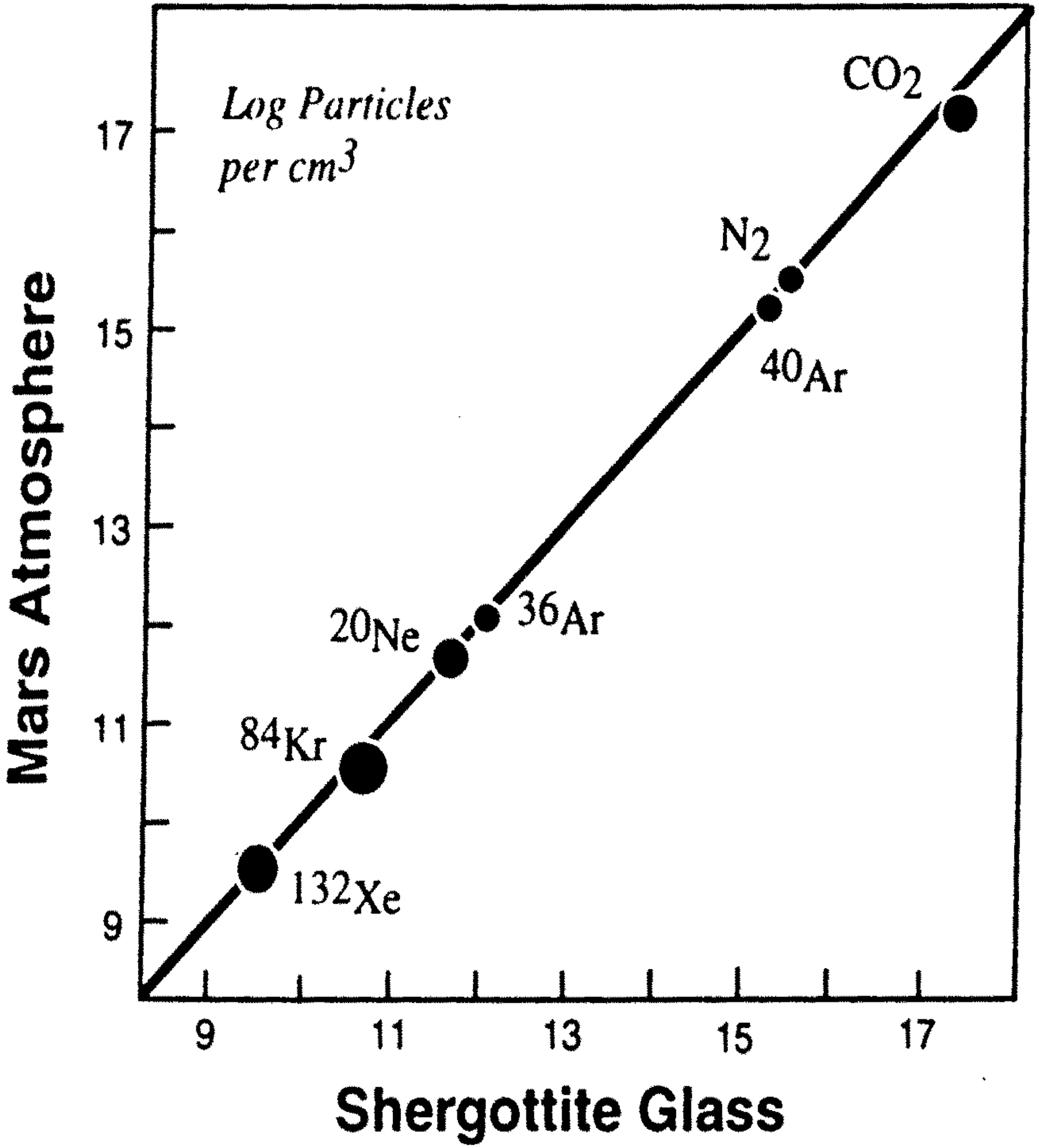
Repartition of taxonomic types :

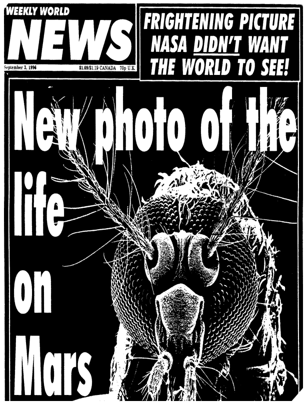


From Gradie and Tedesco (1982)

MARTIAN METEORITES

Shergottite, Nakhlite, Chassignite (SNC) Meteorites:





Abundances

ABUNDANCES

- The abundance of an element El in the photosphere of the Sun is measured via emission lines.
- In the solar spectroscopic community:

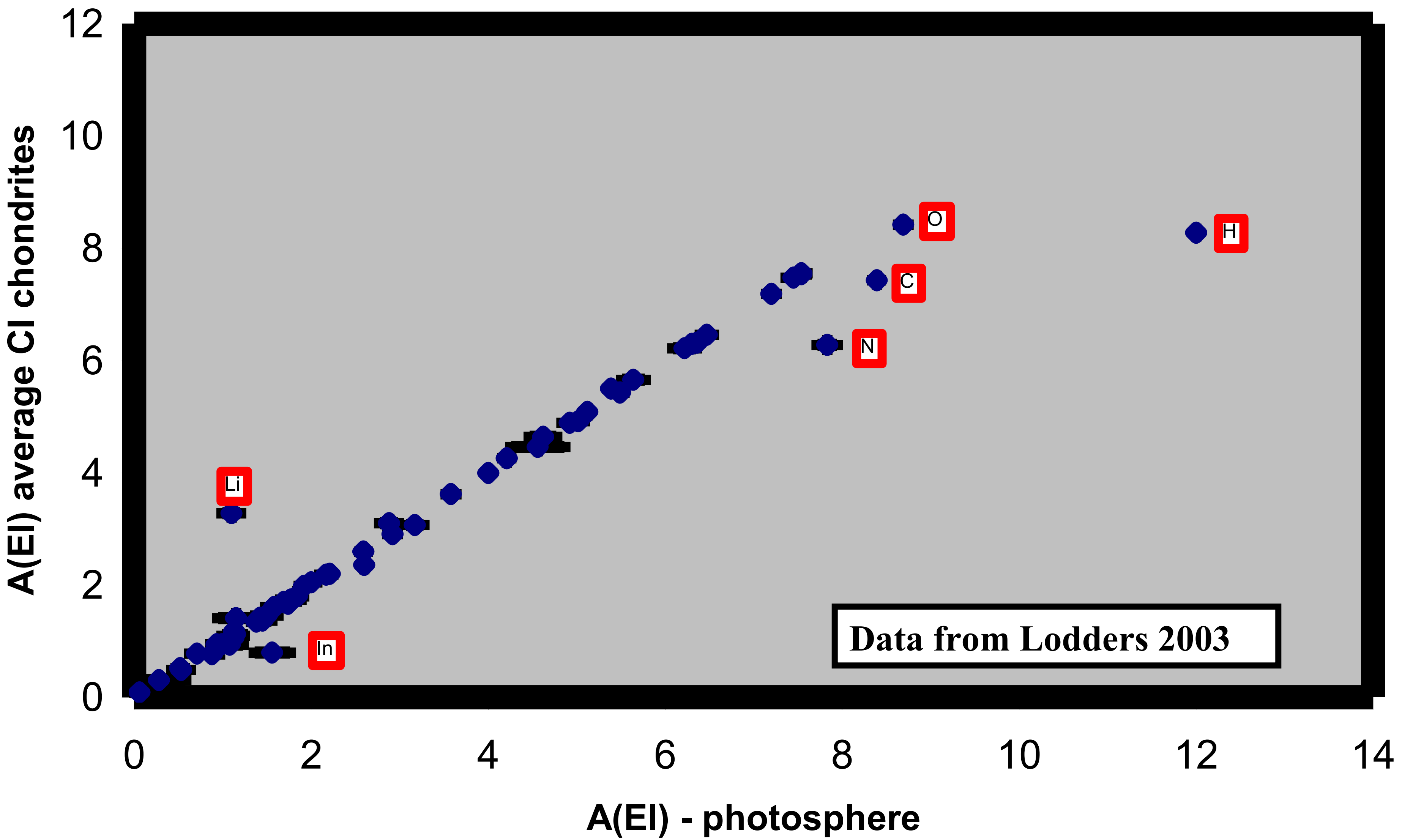
$$A(El) = \log[n(El)/n(H)] + 12$$

- In this scale, A(H) = 12.

- Meteorites abundances are measured in the laboratory [more precise]
- Meteorites abundances are rescaled so that

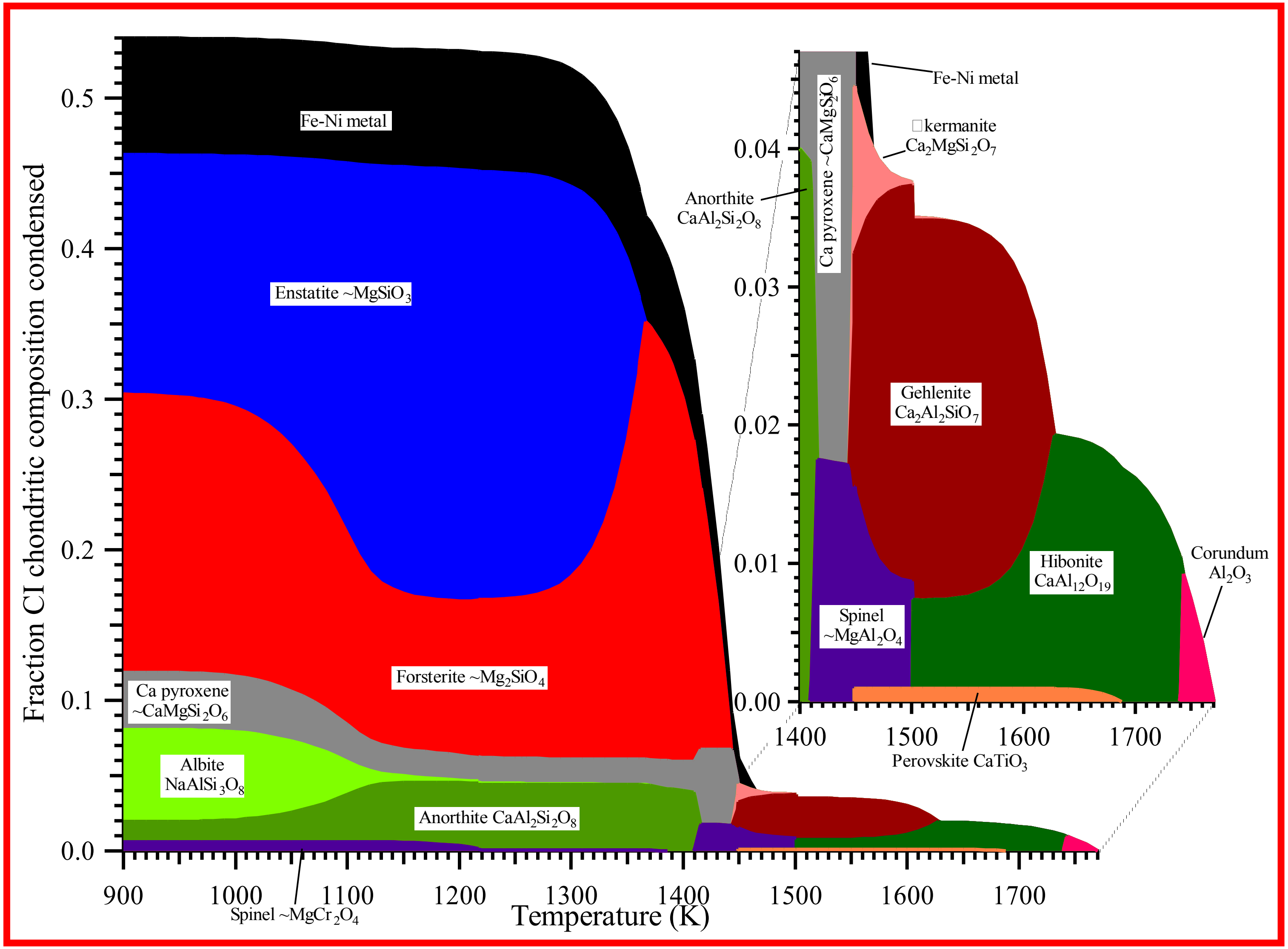
$$A(Si)_{meteorites} = A(Si)_{photosphere}$$

ABNUDANCES



12
10
8
6
4
2
0
0
2
4
6
8
10
12
14
A(El) average CI chondrites
A(El) - photosphere
O
H
C
N
Li
In
Data from Lodders 2003

CONDENSATION SEQUENCE



Davis and Richter, TOG 2003

Age of Chondrites

RADIOACTIVE DECLINE

- Radioactivity discovered by Becquerel in 1896
- Radioactivity α: $^{A}_{Z}P \rightarrow {}^{A-4}_{Z-2}F + {}^{4}He$
- Radioactivity β^-: $^{A}_{Z}P \rightarrow {}^{A}_{Z+1}F + e^- + \underline{\nu_e}$ $(n \rightarrow p + e^- + \underline{\nu_e})$
- Radioactivity β^+: $^{A}_{Z}P \rightarrow {}^{A}_{Z-1}F + e^+ + \nu_e \bar{x}$ $(n \rightarrow p + e^- + \nu_e)$

$$\mathbf{N(t) = N(0) \times \exp(-\lambda t)}$$

or: $$\mathbf{N(t) = N(0) \times (1/2)^{-t/T}}$$

- Radioactive decay characterized by:
  - The decay constant (λ)
  - The half-life ($T_{1/2}$)

AGES and ISOTOPIC COSMOCHEMISTRY

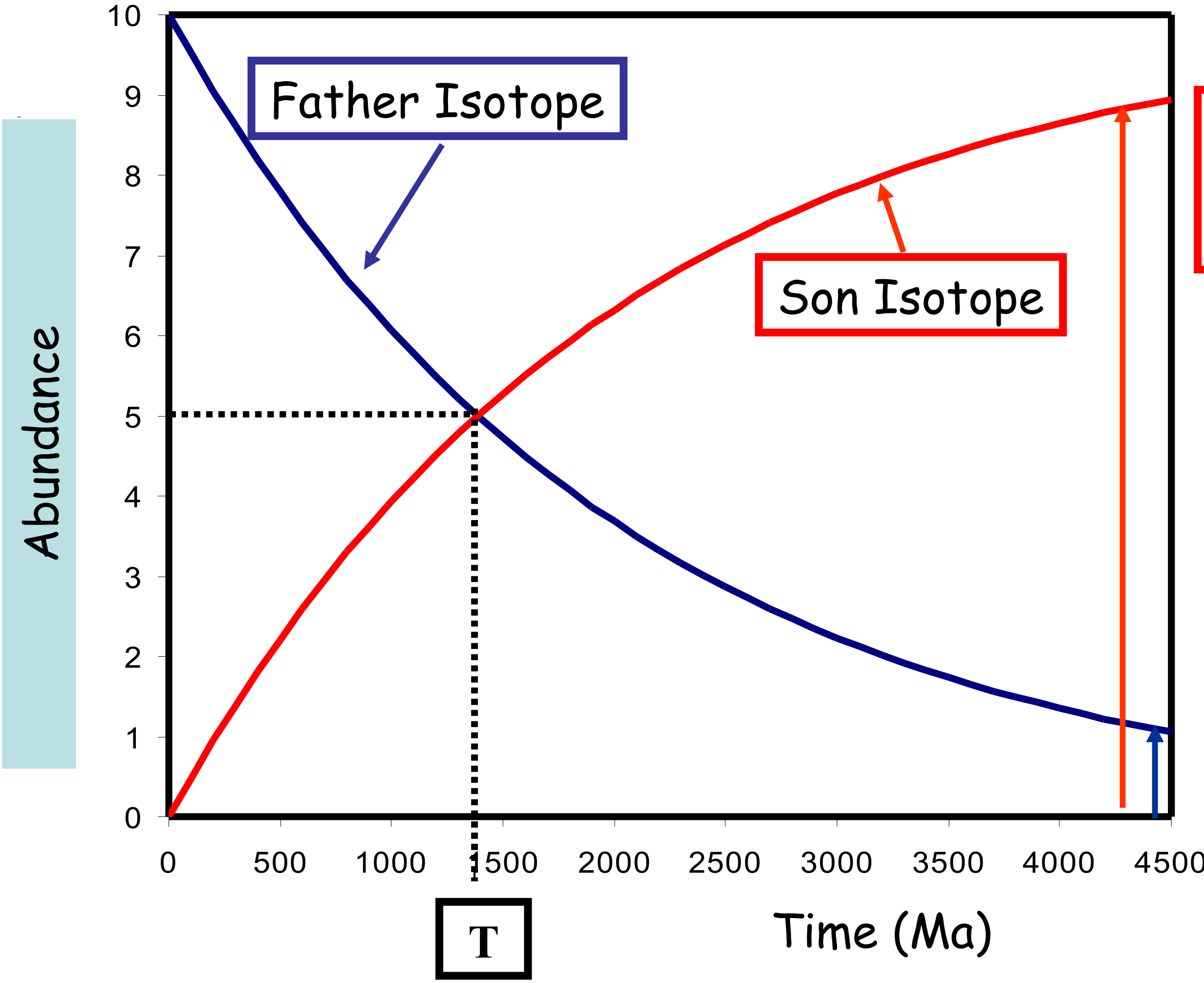
One of the most important successes of isotopic cosmochemistry is
the ability to date rocks, events…

- Radioactive chronometers are used to date events and processes

- chronometers
  - Long-lived chronometers are still alive ($T_{1/2}$ > 200 Ma)
  - Short-lived chronometers are extinct (Al-Mg; Hf-W;…)

- Main long-lived chronometers are
  - ^{238}U decaying into ^{206}Pb ($T_{1/2}$ = 4.5 x 10^9 yr) fission
  - ^{235}U decaying into ^{207}Pb ($T_{1/2}$ = 7.03 x 10^8 yr) fission
  - ^{87}Rb decaying into ^{87}Sr ($T_{1/2}$ = 4.8 x 10^{10} yr) β^-

PRINCIPLES of DATATION



$$S = F_0 (1 - e^{-\lambda t}) = F (e^{\lambda t} - 1)$$

$$F = F_0 e^{-\lambda t}$$

If F_0 is known, and S=0 at t=0, one just needs to measure F or S to deduce t. But in general, neither F_0 nor S(t=0) are known...

ABSOLUTE DATATION: long period isotopes

The system Pb-Pb :

$$^{206}Pb = ^{206}Pb_0 + ^{238}U(e^{\lambda_{238}t} - 1)$$

avec λ_{238} = **1,55125 10^{-10} an^{-1}** *(demi-vie = 4,47 Ga)*

$$^{207}Pb = ^{207}Pb_0 + ^{235}U(e^{\lambda_{235}t} - 1)$$

avec λ_{235} = **9,8485 10^{-10} an^{-1}** *(demi-vie = 0,704 Ga)*

$$\frac{^{206}Pb}{^{204}Pb} = \frac{^{206}Pb_0}{^{204}Pb} + \frac{^{238}U}{^{204}Pb}(e^{\lambda_{238}t} - 1)$$

$$\frac{^{207}Pb}{^{204}Pb} = \frac{^{207}Pb_0}{^{204}Pb} + \frac{^{235}U}{^{204}Pb}(e^{\lambda_{235}t} - 1)$$

ABSOLUTE DATATION: long period isotopes

The system Pb-Pb : (Hyp : $^{238}U/^{235}U = C^{te} = 137{,}88$)

$$\frac{\left(\frac{^{207}Pb}{^{204}Pb}\right) - \left(\frac{^{207}Pb}{^{204}Pb}\right)_0}{\left(\frac{^{206}Pb}{^{204}Pb}\right) - \left(\frac{^{206}Pb}{^{204}Pb}\right)_0} = \frac{1}{137{,}88}\,\frac{e^{\lambda_{235} t} - 1}{e^{\lambda_{238} t} - 1}$$

or: $(y - y_0)/(x - x_0) = a(t)$

Equation defining a straight line of slope depending on time : the slope gives the age ! This straight line is an **isochrone**.

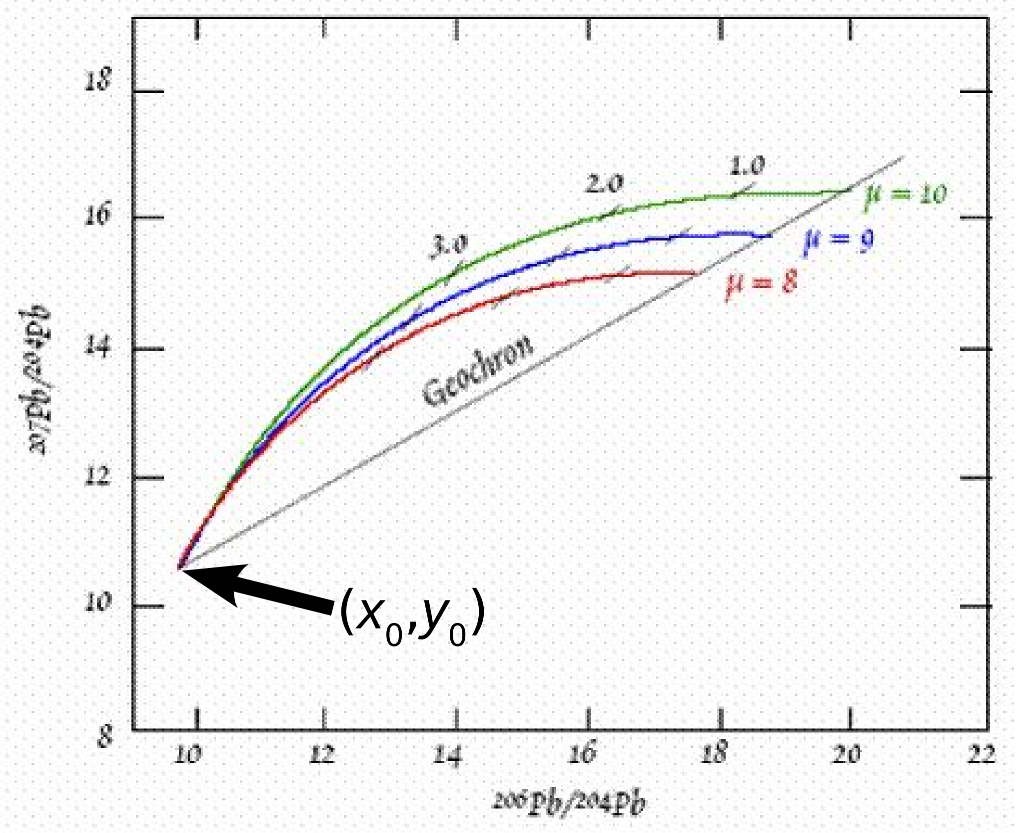
For an isochrone, at least 2 points are needed, from 2 minerals of a same object, having different initial U/Pb.

ABSOLUTE DATATION: long period isotopes

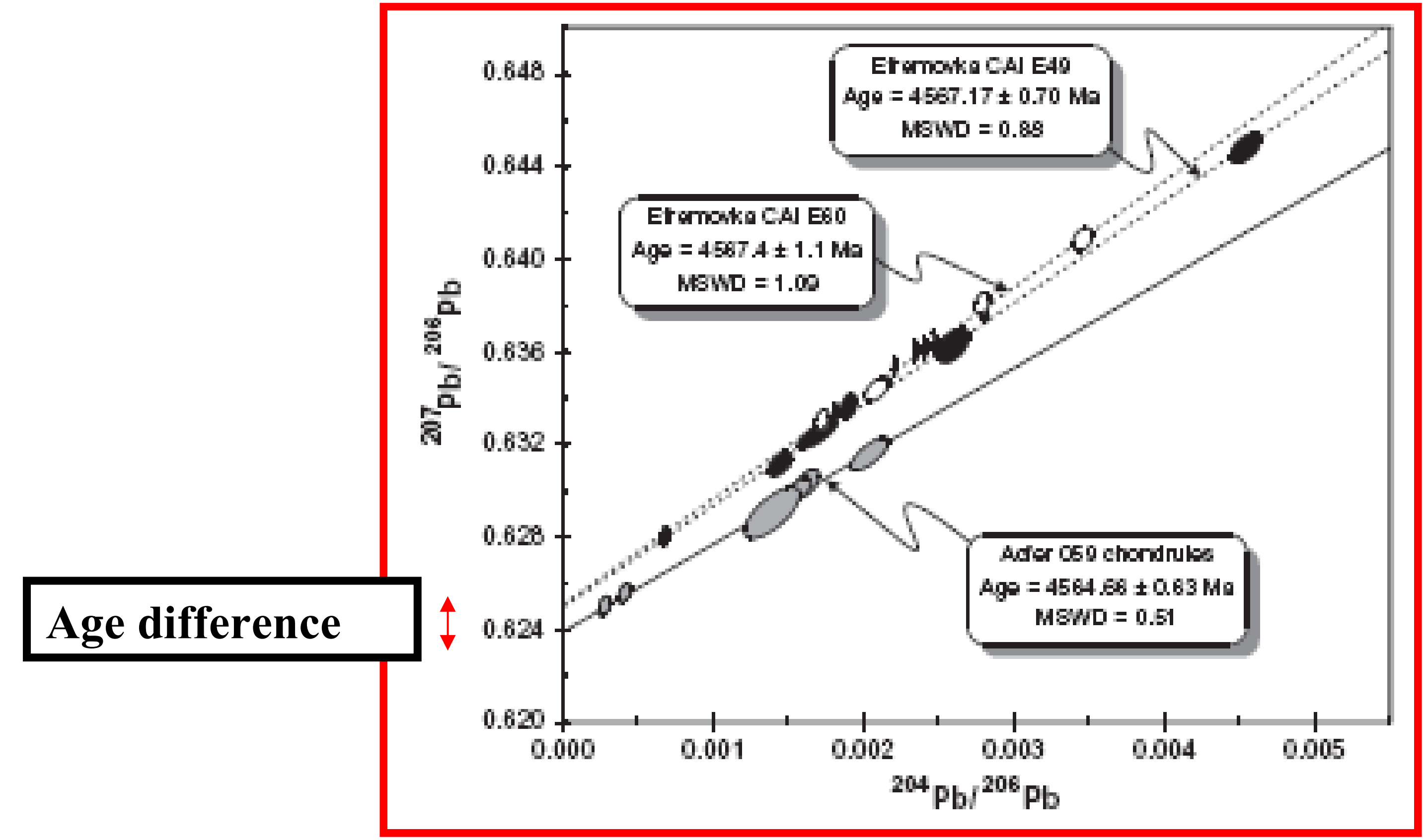
<u>The system Pb-Pb :</u>

Consider the formation of an asteroid. N kinds of minerals are created, with various μ=U/Pb (chemistry).
Then, the system doesn't evolve chemically anymore, but U → Pb inside the minerals.

In the Pb-Pb diagramm, the N points are aligned on a line of slope *a* (age of the asteroid).



ABSOLUTE DATATION: CAI & CHONDRULES



- ☆ The oldest dated CAI has **4567**.17 ± 0.70 Ma
  - ☆ Compatible with 4566 ± 2 Ma (Manhès et al. 1988)
- ☆ Does that dates the origin of Solar System?

Amelin et al., Science 2002

RELATIVE DATATION: short period isotopes

If extinct radioactivity, F=0, $S=S_0+F_0$.

<u>Ex: The system Hf-W</u> ($t_{1/2}$~ 9 Myr) :

Hafnium 182 decomposes into Tungsten 182.

$$^{182}W = {}^{182}W_{init} + {}^{182}Hf_{init}$$

$$\underbrace{\left(\frac{^{182}W}{^{184}W}\right)}_{y} = \underbrace{\left(\frac{^{182}W}{^{184}W}\right)_{init}}_{b} + \underbrace{\left(\frac{^{182}Hf}{^{180}Hf}\right)_{init}}_{a} * \underbrace{\left(\frac{^{180}Hf}{^{184}W}\right)}_{x}$$

The higher the rate $^{182}Hf/^{180}Hf$ was, the more the proportion of ^{182}W inside the tungsten increases with the general Hf/W ratio.

RELATIVE DATATION: short period isotopes

<u>The system Al-Mg</u> ($t_{1/2}$~0.71 Ma) : extinct radioactivity.

$$\left(\frac{^{26}Mg}{^{24}Mg}\right) = \left(\frac{^{26}Mg}{^{24}Mg}\right)_{t=t_f} + \left(\frac{^{26}Al}{^{24}Mg}\right)_{t=t_f}$$

(t_f = formation time)

$$\left(\frac{^{26}Al}{^{24}Mg}\right)_{t=t_f} = \left(\frac{^{26}Al}{^{27}Al}\right)_{t=t_f} \left(\frac{^{27}Al}{^{24}Mg}\right)$$

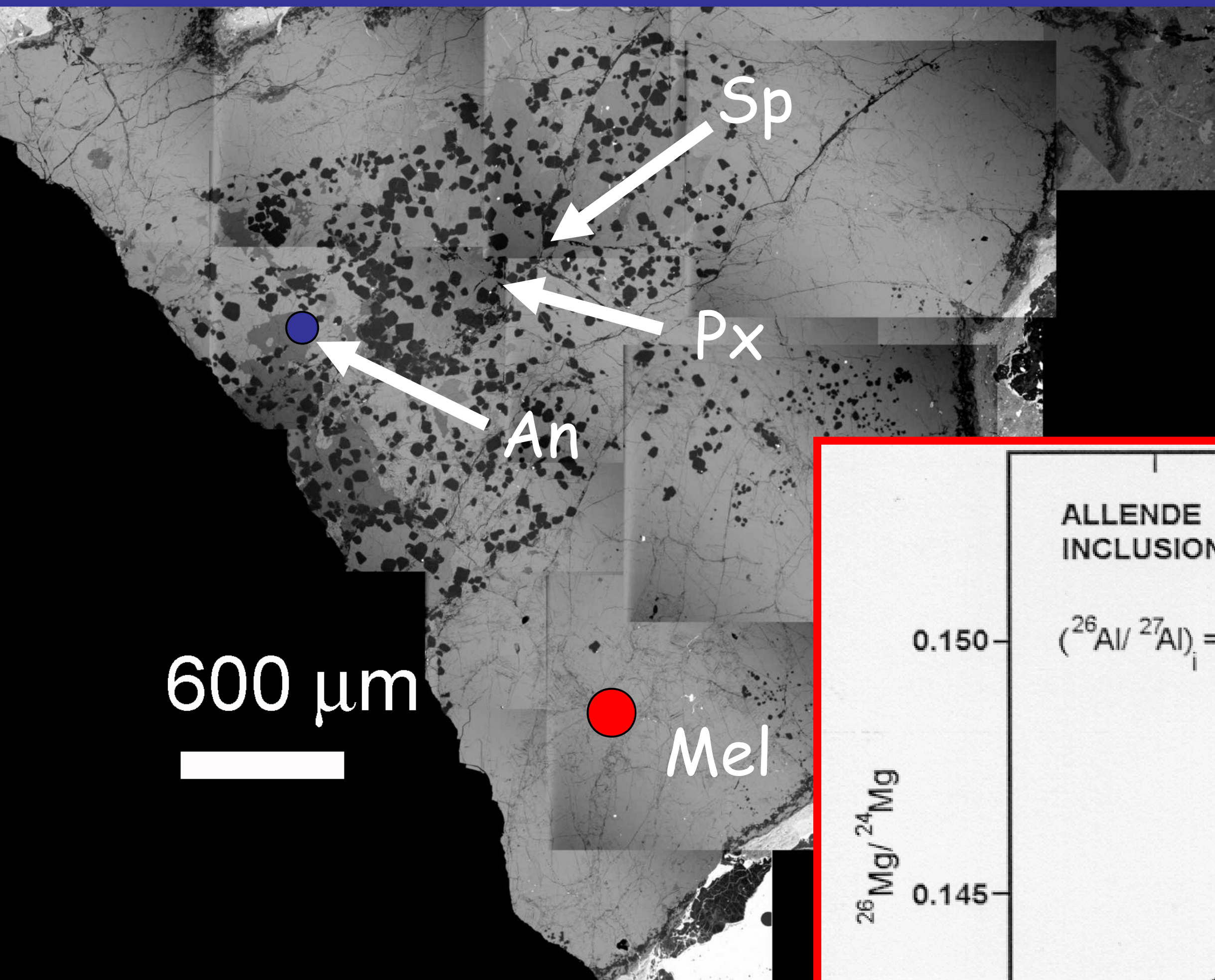
$$\left(\frac{^{26}Al}{^{27}Al}\right)_{t=t_f} = \left(\frac{^{26}Al}{^{27}Al}\right)_{t=t_0} e^{-\lambda(t_f - t_0)}$$

$$\underbrace{\left(\frac{^{26}Mg}{^{24}Mg}\right)}_{y} = \underbrace{\left(\frac{^{26}Mg}{^{24}Mg}\right)_{t=t_f}}_{b} + \underbrace{\left(\frac{^{26}Al}{^{27}Al}\right)_{t=t_0} e^{-\lambda(t_f - t_0)}}_{a} * \underbrace{\left(\frac{^{27}Al}{^{24}Mg}\right)}_{x}$$

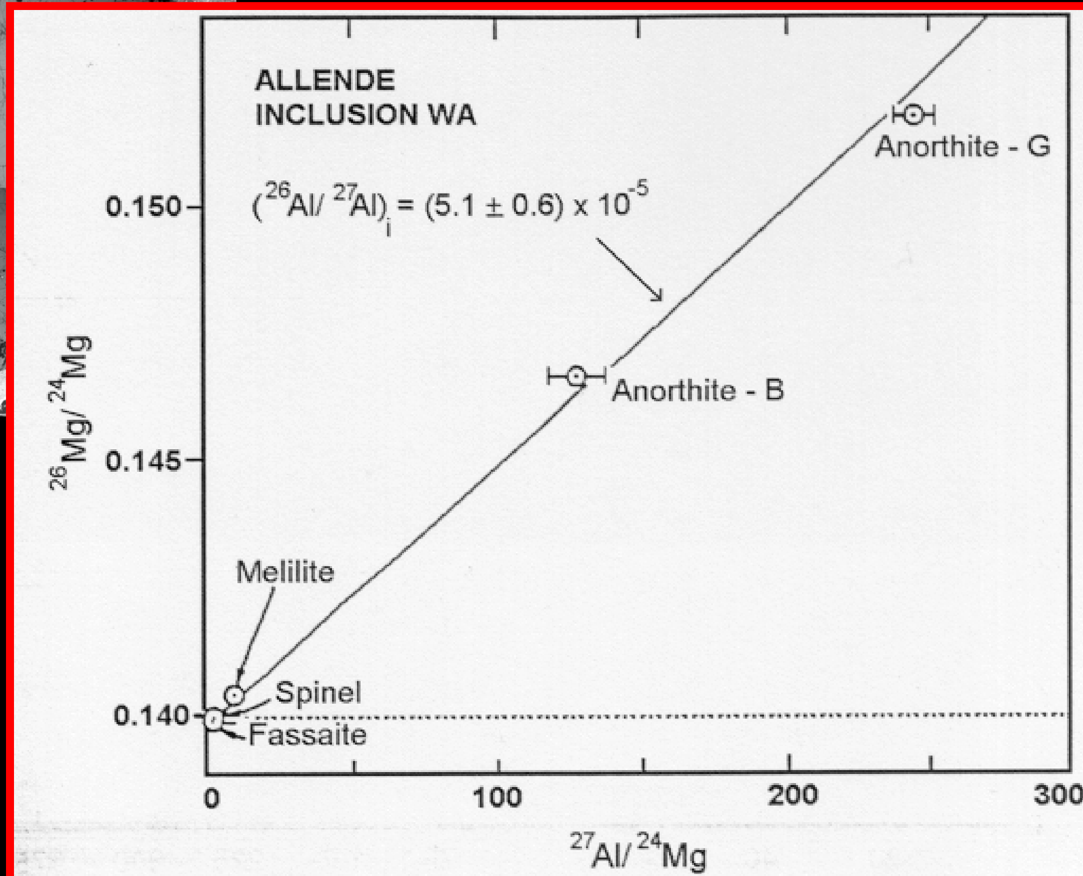
If one measures *x* and *y* of several minerals of a same object, the points align on a straight line of slope *a* : an **isochrone**.

Same slope *a* <=> same age t_f (under the assumption that $(^{26}Al/^{27}Al)_{t0}$ is the same in all the Solar System). **EXO**

RELATIVE DATATION: short period iso<topes



Melilite
Anorthite
Spinel
Pyroxene

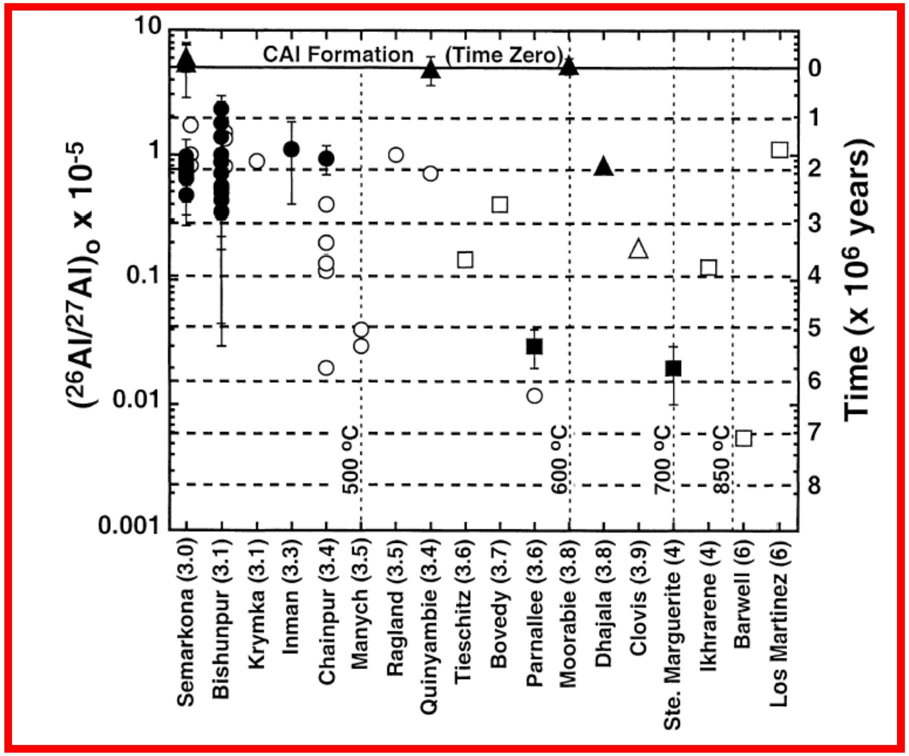


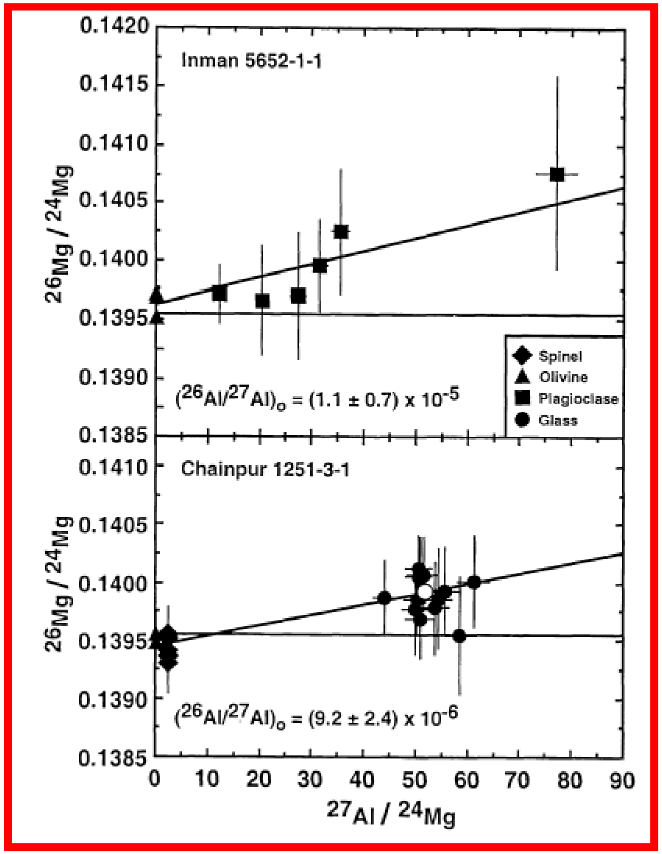
CAI MRS6 (Leoville, CV3)
Crystallized 4.567 Ga
(BSE image)

^{26}Al inside CHONDRULES

Maximum for *a* $=(^{26}Al/^{27}Al)_{t0}\, e^{-\lambda(t-t0)}$ inside chondrules : ~10^{-5}.

Inside CAI : ~ 4,5 x 10^{-5}.





Huss et al., MAPS 2001

^{26}Al inside CHONDRULES

Maximum for $a = ({}^{26}Al/{}^{27}Al)_{t0}\, e^{-\lambda(t-t0)}$ inside chondrules : ~10^{-5}.

Inside CAI : ~ $4,5 \times 10^{-5}$.

Thus $\exp(-\lambda(t_{CAI}-t_0)) / \exp(-\lambda(t_{chondres}-t_0)) = 4,5$

so $\exp(-\lambda t_{CAI}) = 4,5*\exp(-\lambda t_{chondres})$

so $t_{CAI} = t_{chondres} - \ln(4,5)/\lambda$

<u>Conclusion:</u> chondrules formed 2 Myrs after the CAIs.

We set $t_{CAI} = t_0 = 0$, birth of the Solar System.

PRINCIPLES of DATATION

Fundamental assumptions :

• The isotopic distribution of the chemical elements was the same at t=0 everywhere in the Solar System.

• Chemical fractionation doesn't induce any isotopic fractionation.

Attention :

• The ages obtained are "closure ages" (i.e. the time for which the system hasn't exchanged elements with the outer world).

• In fact, datation is made from isochrones (so from the analysis of several chemical components of the sample), thus one date the age of ***chemical fractionation*** of the system.

THE **Hf – W** SYSTEM : DIFFERENTIATION

The system Hf-W ($t_{1/2}$~ 9 Ma) :

Hafnium 182 declines into Tungstène 182.

Similarly as for the Al-Mg, system, one finds :

$$\underbrace{\left(\frac{^{182}W}{^{184}W}\right)}_{y} = \underbrace{\left(\frac{^{182}W}{^{184}W}\right)_{CAI}}_{b} + \underbrace{\left(\frac{^{182}Hf}{^{180}Hf}\right)_{CAI} e^{-\lambda(t-t_{CAI})}}_{a} * \underbrace{\left(\frac{^{180}Hf}{^{184}W}\right)}_{x}$$

But Hafnium is lithophile (goes into the mantle)
while the Tungsten is siderophile (goes into the core) :
chemical fractionation.

One date the closure of the system “mantle” or “core”, that is the ***differenciation*** of a planet !

THE **Hf – W** SYSTEM : DIFFERENTIATION

<u>The system Hf-W</u> ($t_{1/2}$~ 9 Ma) :

Late differenciation: all the ^{182}Hf has declined, all the W in the core.

Fast différentiation : ^{182}Hf in the mantle, produces there some ^{182}W.

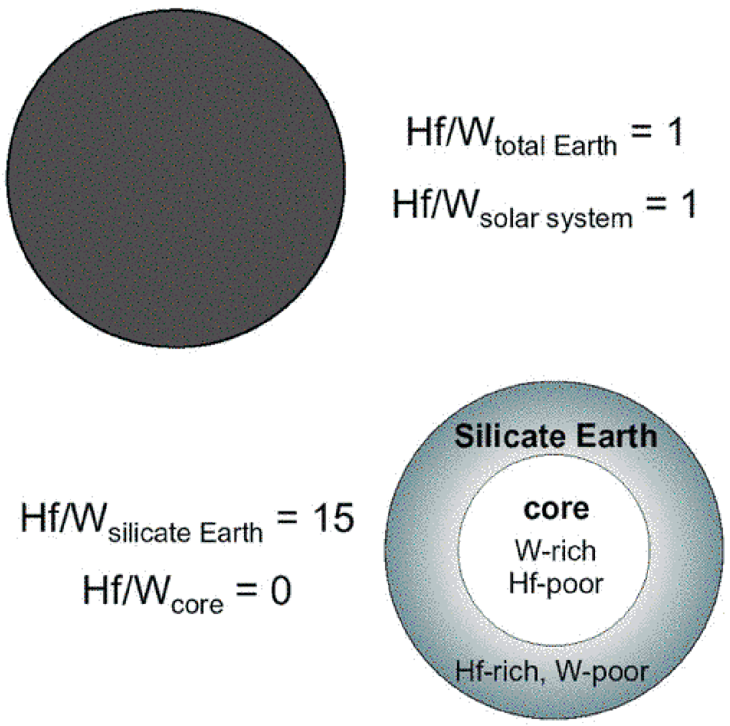
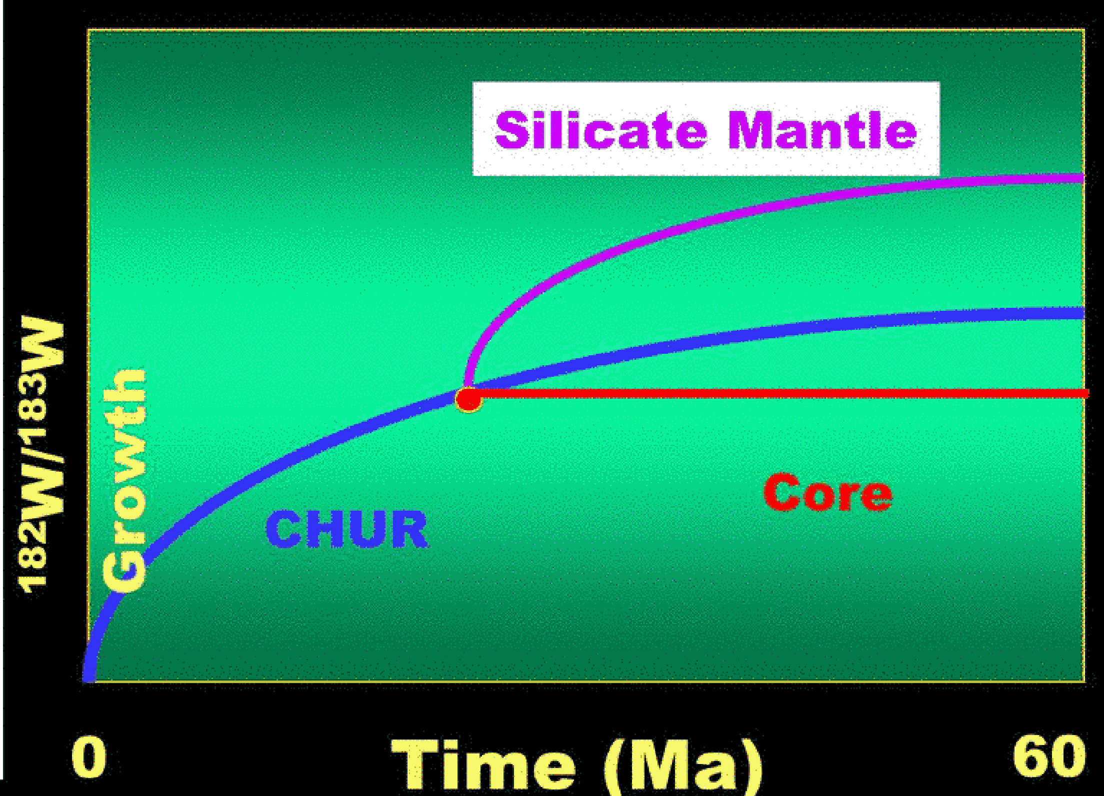


Fig. 2. Schematic showing the fractionation of Hf from W in the early solar system.

After Halliday et al. (2000)



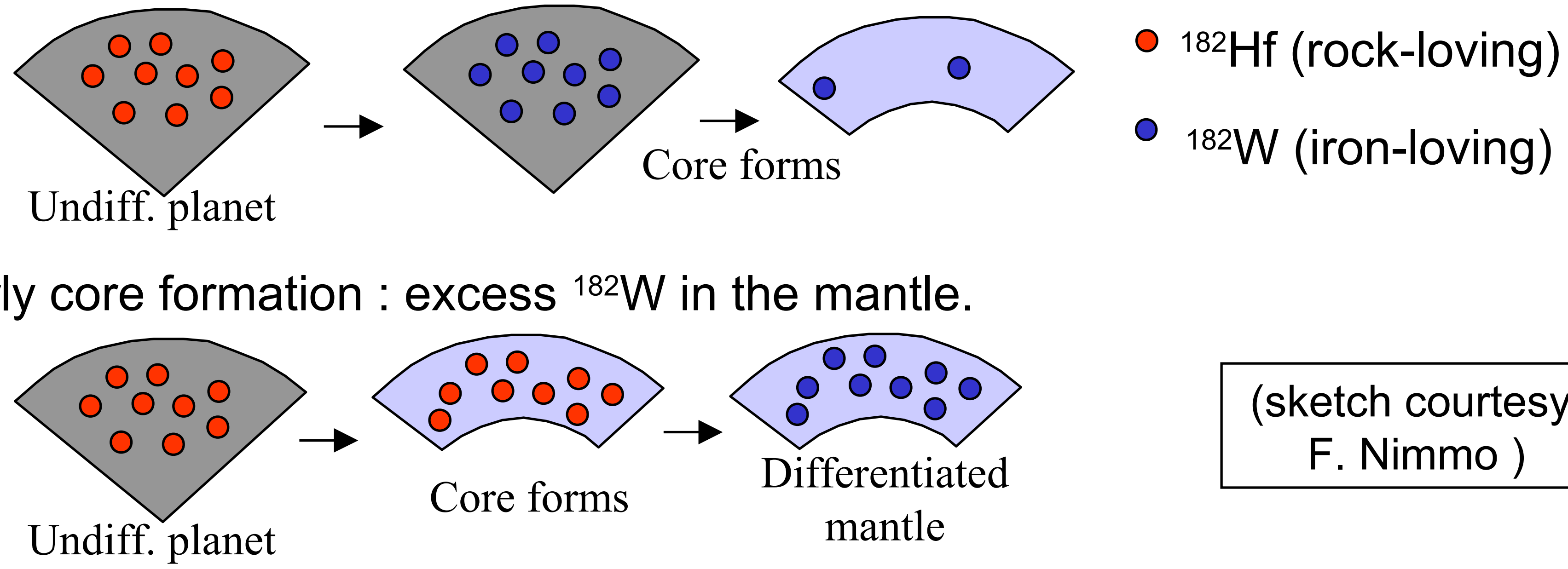
THE **Hf – W** SYSTEM : DIFFERENTIATION

<u>Age of the Moon, through</u> ^{182}Hf / ^{182}W <u>chronometer :</u>

$^{182}Hf \rightarrow {}^{182}W$, half life $\tau = 9.10^6$ years.

Late core formation : no excess ^{182}W in the mantle.

Early core formation : excess ^{182}W in the mantle.



(sketch courtesy: F. Nimmo)

Excess ^{182}W in lunar rocks → Moon solidified within 60 Myrs (Kleine et al. 2005, Lee et al. 1997, 2002)

THE **Hf – W** SYSTEM : DIFFERENTIATION

<u>Definition :</u>

$$\epsilon_{^{182}W} = \left[\frac{\left(\frac{^{182}W}{^{184}W}\right)_{objet}}{\left(\frac{^{182}W}{^{184}W}\right)_{reference}} - 1 \right] * 10^4$$

Analyse of 3 kinds of lunar rocks (Kleine et al, 2007, Science):

	KREEP	Low W basalt	High W basalt
$\varepsilon^{182}W$:	0,06 +/- 0,20	1,18 +/- 0,20	2,14 +/- 0,57
$^{180}Hf/^{184}W$:	10 +/- 10	26,5 +/- 6,5	> 45

<u>EXERCICE:</u> Deduce the age of solidification of the Moon.
One gives $(^{182}W/^{184}W)_{ref}=1$, $(^{182}Hf/^{180}Hf)_{CAI}=10^{-4}$.

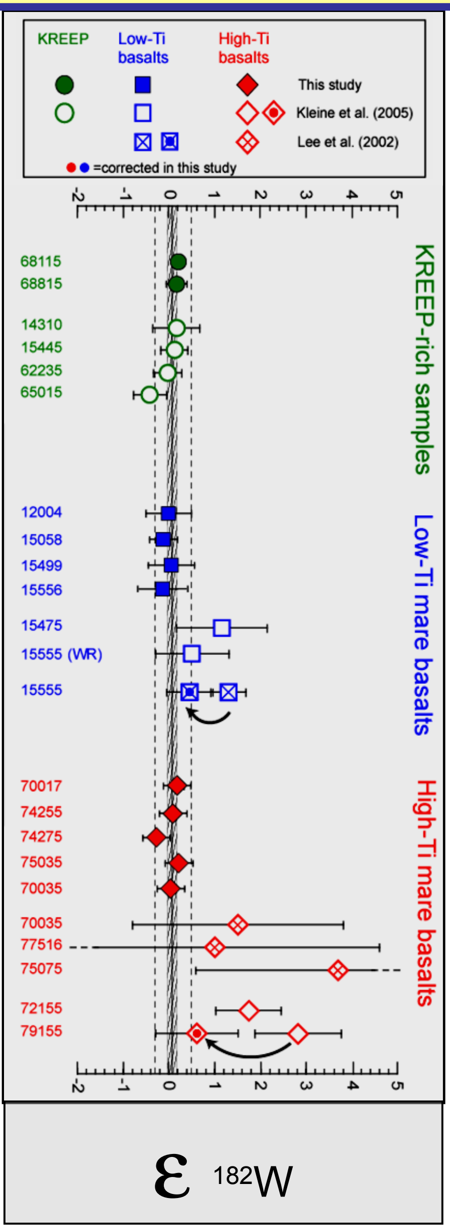
THE **Hf – W** SYSTEM : DIFFERENTIATION

Unluckily, ^{182}W is also coming from ^{181}Ta capturing a neutron (cosmic rays).

Touboul et al. (2007, Nature) : "*The dominant ^{182}W component in most lunar rocks reflects cosmogenic production*"

New data from unpolluted samples :

"*lunar and terrestrial mantles have identical $^{182}W/^{184}W$. This* [...] *constrains the age of the Moon and Earth to 62 Myrs (+90/-10)*".



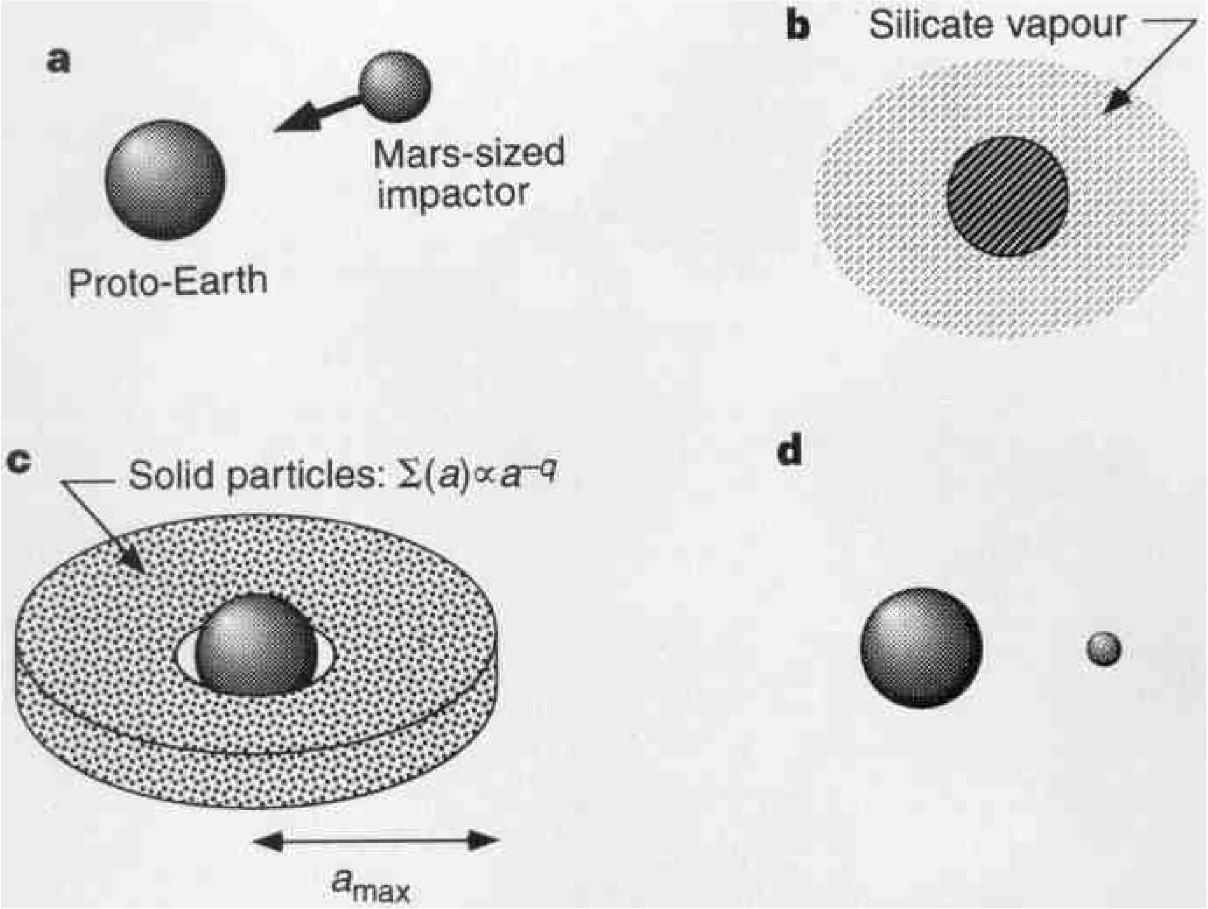
<u>Touboul et al. (2008) :</u>

- Same result for plagioclase separates from two ferroan anorthosites (i.e. crust).

- Measure of basalts cosmogenic pollution.

MOON FORMATION

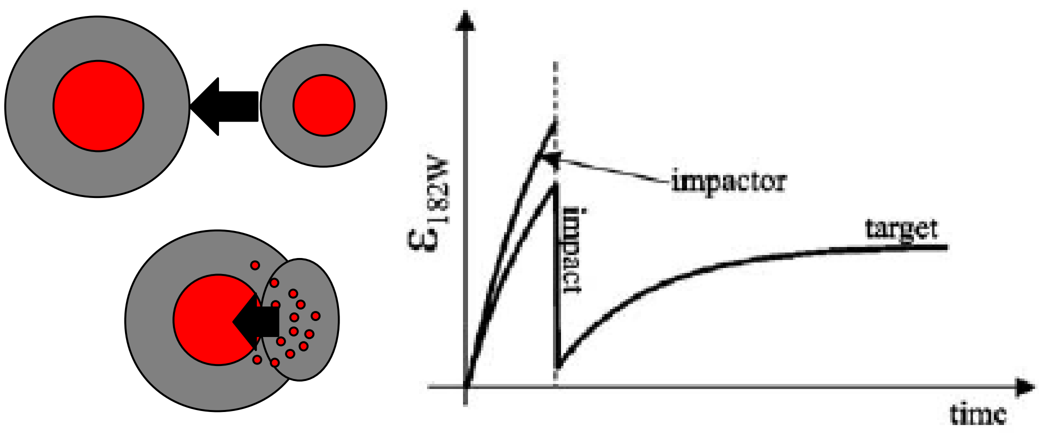
The Moon formed by a giant impact on the proto-Earth of a proto-planet of the size of Mars.



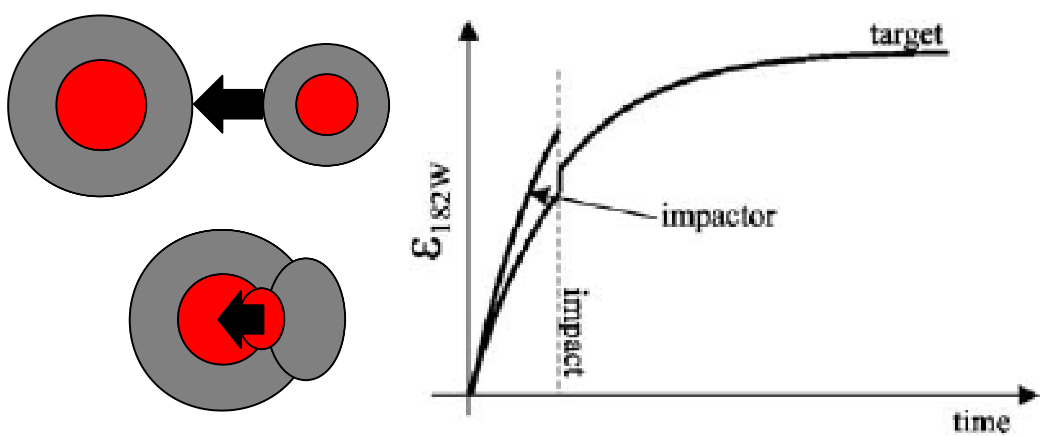
Do we date the differenciation of the proto-Earth ?
That of the impactor ? The collision ?

MOON FORMATION

Re-equilibration of the mantles :



Core merging :



(sketches courtesy: F. Nimmo)

It depends...
If reequilibration, the anomaly in ^{182}W is reduced (or reset) by the impact.

Total reequilibration -> one dates the impact.

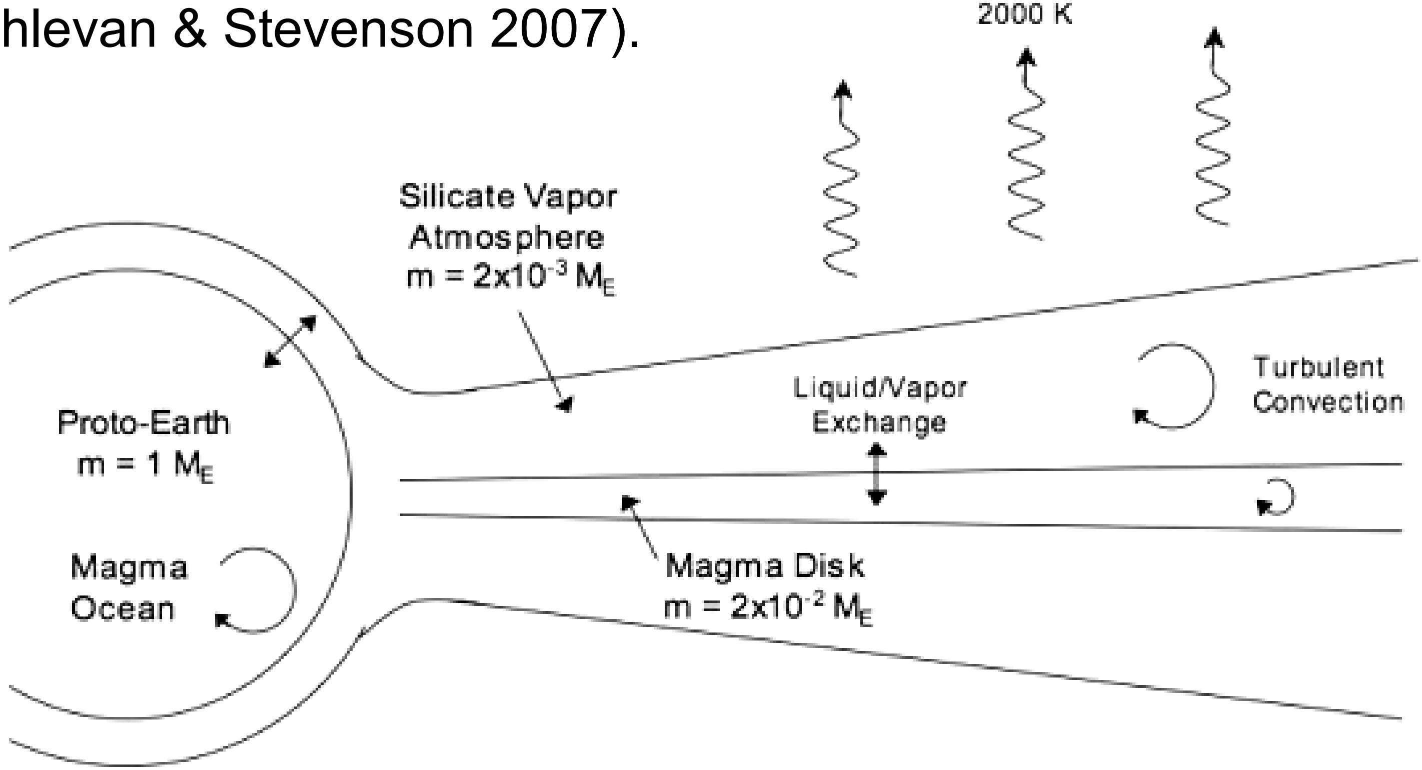
No reequilibration : we get the average $\varepsilon^{182}W$.

Oservations of terrestrial planets and asteroids suggest that there has been many giant impacts after 10 Ma, with requilibration (Nimmo & Agnor 2006).

MOON FORMATION

Isotopic equilibration just after the impact, between a magma ocean Earth, and a molten disc, via an atmosphere of silicates

(Pahlevan & Stevenson 2007).



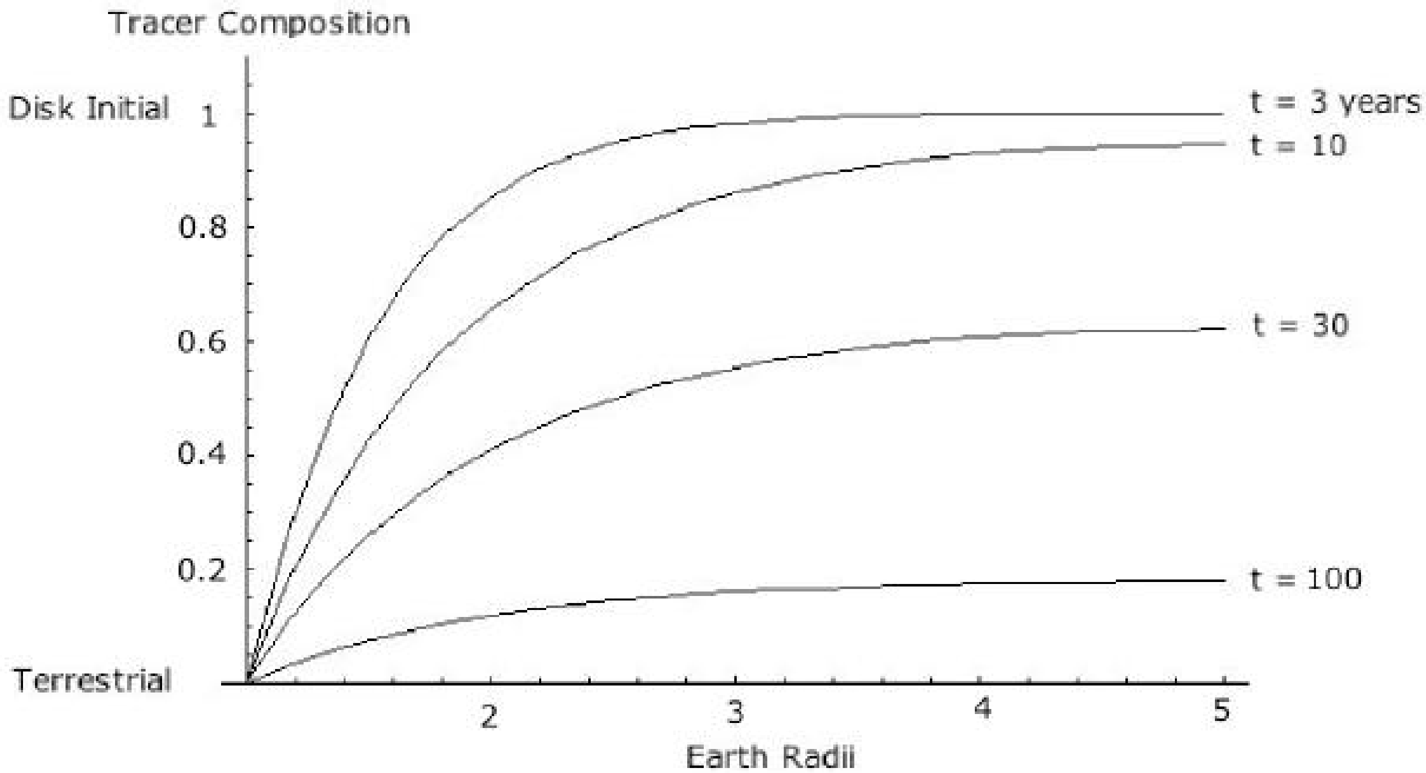
Disc during 100 to 1000 years, at 2500 K, 10 to 100 Bar.

Typical echange time between vapour and liquid : week.
Convection in the ocean : week. In the disc or the gas : day.

MOON FORMATION

Problem : radial mixing.

It needs more than 30 years to diffuse material to 4 terrestrial radii.

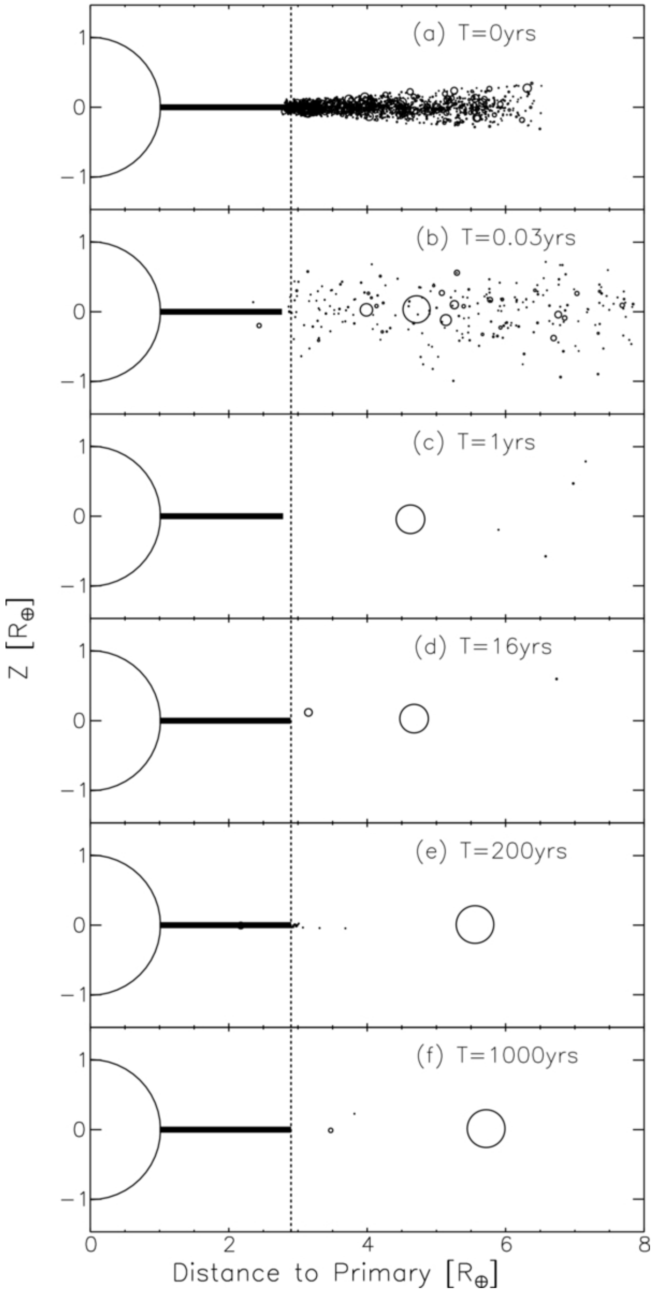


MOON FORMATION

Problem : radial mixing.

It needs more than 30 years to diffuse material to 4 terrestrial radii.

Salmon & Canup (2012) : Moon accretion stalls for ~100 years because the growing Moon repels the disc, and prevents its spreading.



MOON FORMATION

Conclusion :

The Moon formed after a giant impact on Earth.

This impact caused an Earth-Moon isotopic equilibration.

As the mantles of the Earth and the Moon still have the same $^{182}W/^{184}W$, ^{182}Hf was extinct at that time : the impact took place (at least) 60 Myrs after the CAI.

New result:

Jacobson, Morbidelli, et al, DPS meeting, oct. 2013, Denver

The amount of « late veneer » that the Moon accreted after it formed is correlated with the time of the last giant impact. For reasonable estimates of the late veneer, the impact must be late (~95+/-30 Myrs).