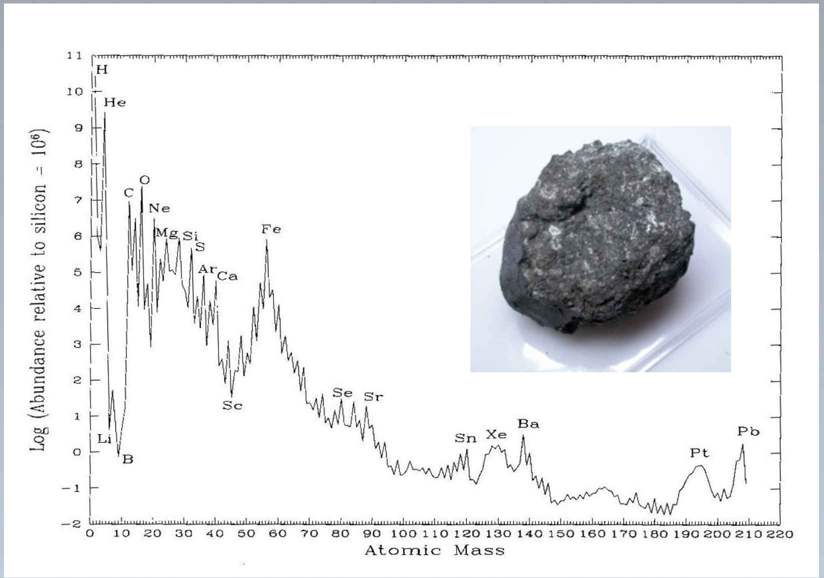
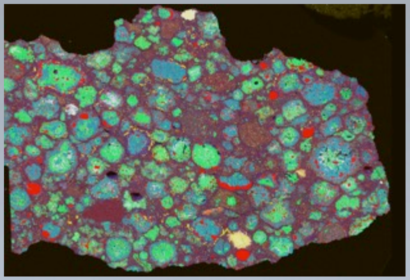
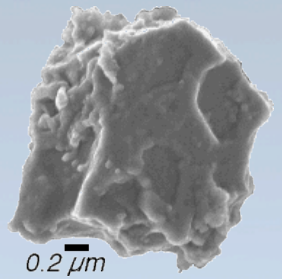
The abundance of elements, *what do we learn from extraterrestrial samples ?*



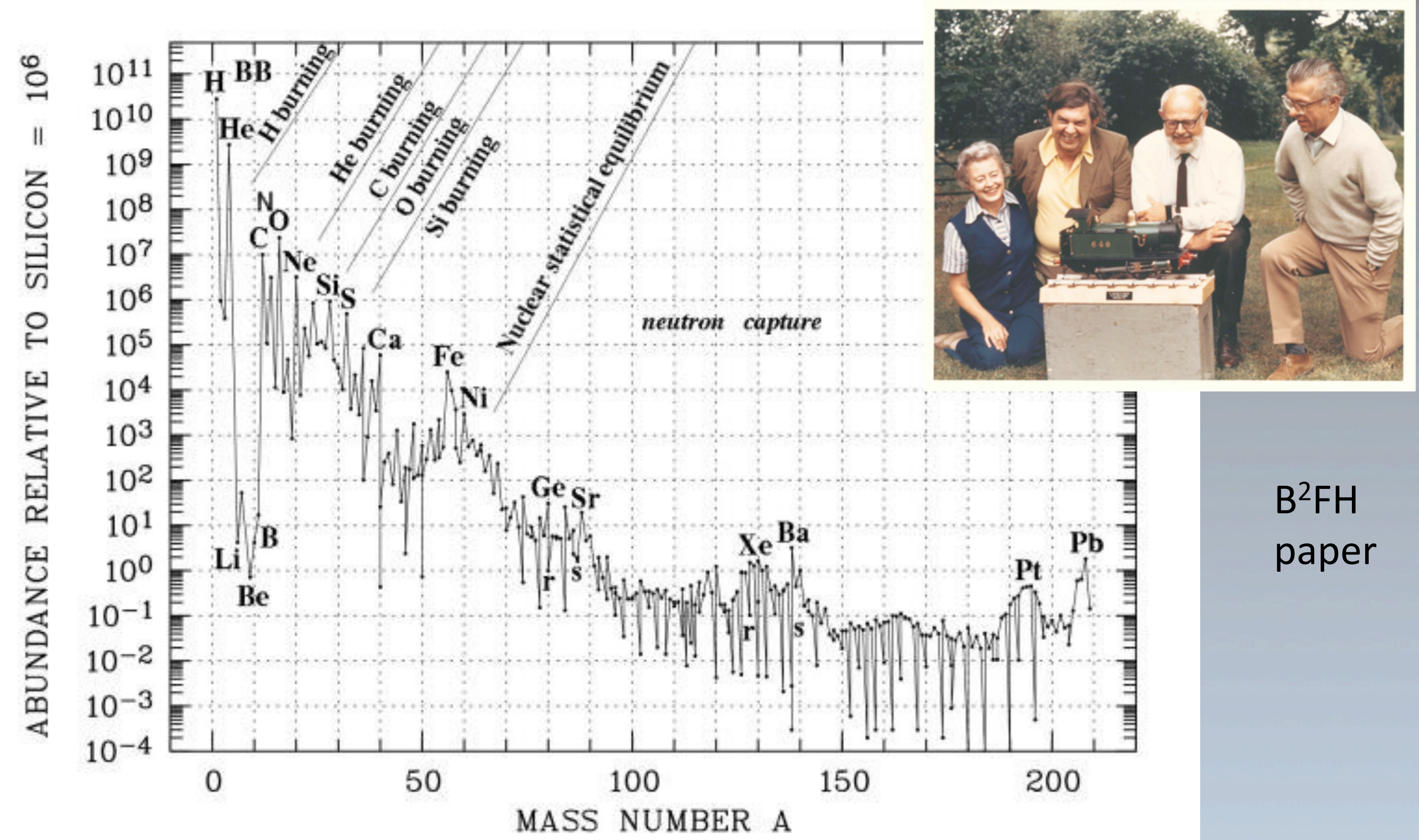




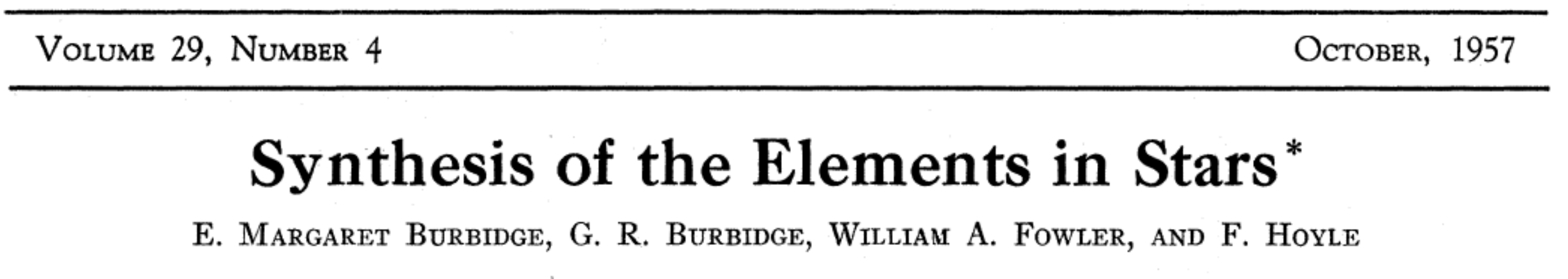
EJC 2016 "Origin of Nuclei in the Universe »
25-30 september 2016

J. Duprat
Centre de Sciences Nucléaires et Sciences de la Matière in Orsay
CSNSM-IN2P3-CNRS / Univ. Paris-Sud / Univ. Paris-Saclay.

The elements abundance pattern



B^{2}FH paper



Volume 29, Number 4 October, 1957

Synthesis of the Elements in Stars*

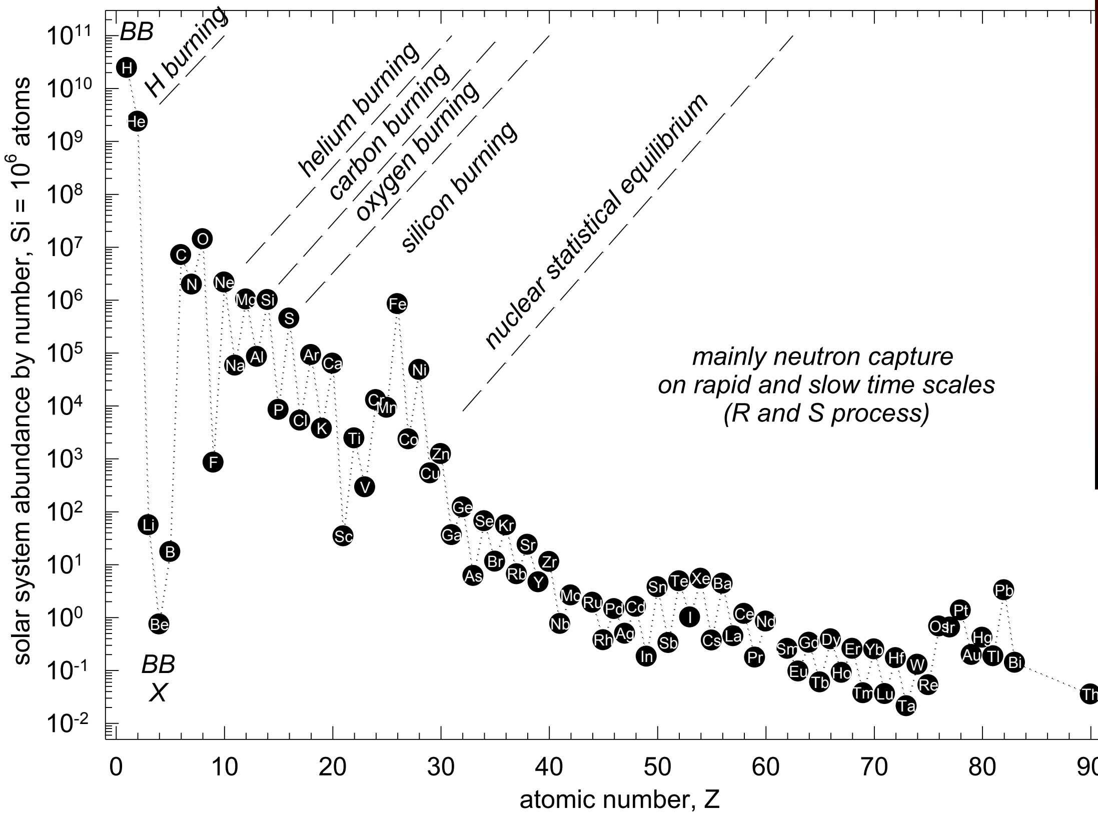
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

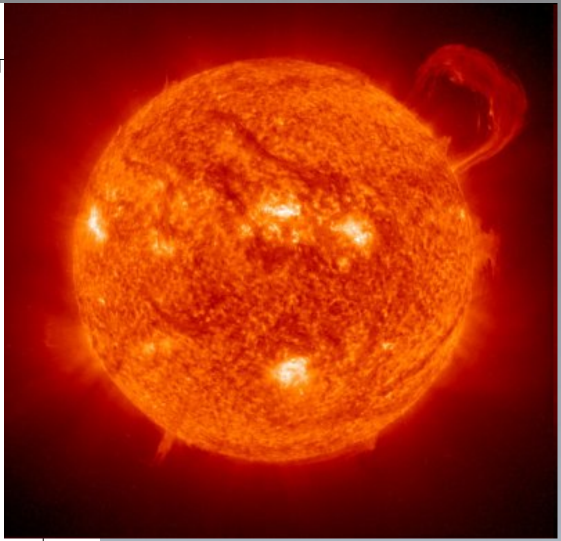
Outline

- **The element abundance pattern itself**
  - What is the element abundance pattern and where is it measured ?
  - The importance of meteorite data, what is a primitive sample ?
  - Asteroids and comets
  - The main features observed on the abundance pattern

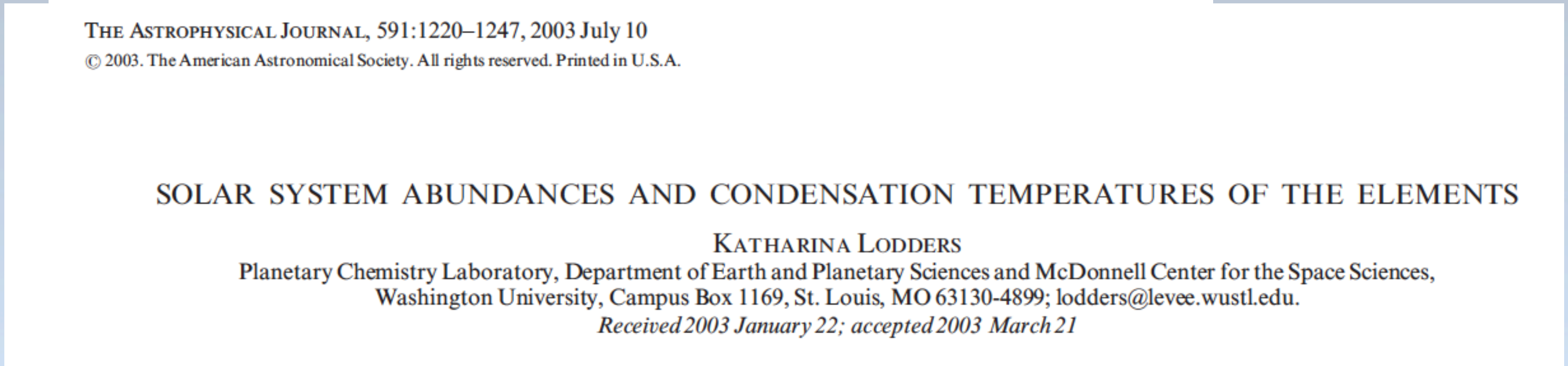
- **Beyond the average element abundance pattern**
  - ***Pre-solar grains***. How do we find them ? What do they look like ?
  - The origin of pre-solar grains ? Open issues
  - ***Short-lived radio-nuclei*** and the context of the solar system birth
  - The amount of short-lived *radio-nuclei* in the protoplanetary disk
  - Why is it such a problem ? Is the solar system generic ?
  - Their importance for planetary science

The elements abundance in the Sun





99.9 % of the mass



The Astrophysical Journal, 591:1220–1247, 2003 July 10

SOLAR SYSTEM ABUNDANCES AND CONDENSATION TEMPERATURES OF THE ELEMENTS

Katharina Lodders
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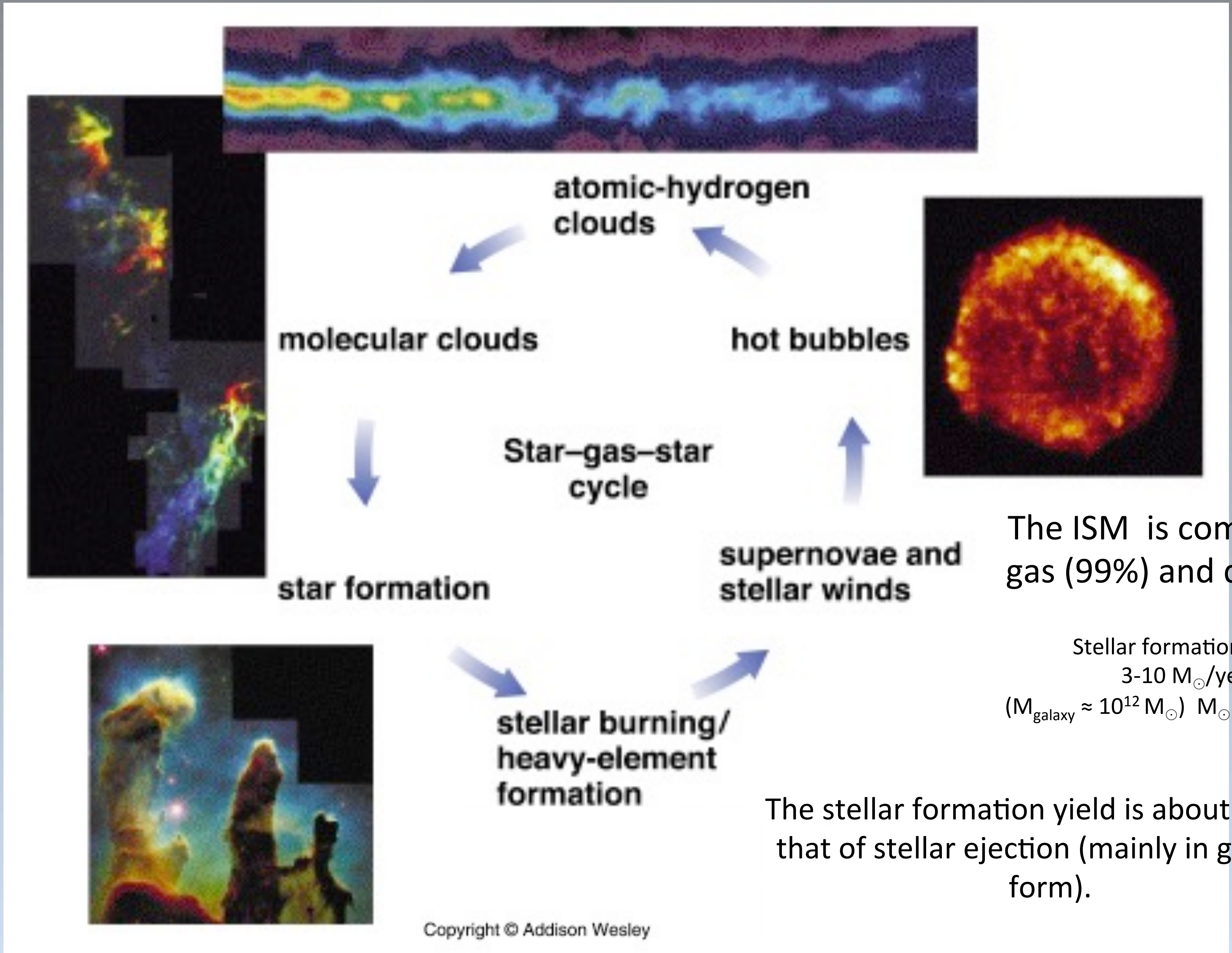
Received 2003 January 22; accepted 2003 March 21

The cycle of matter in the Inter-Stellar Medium (ISM)

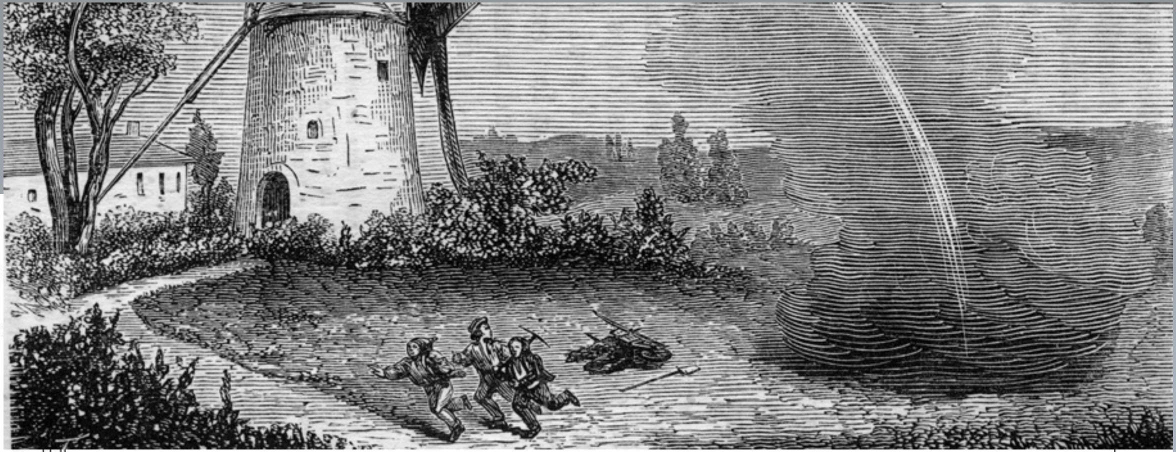


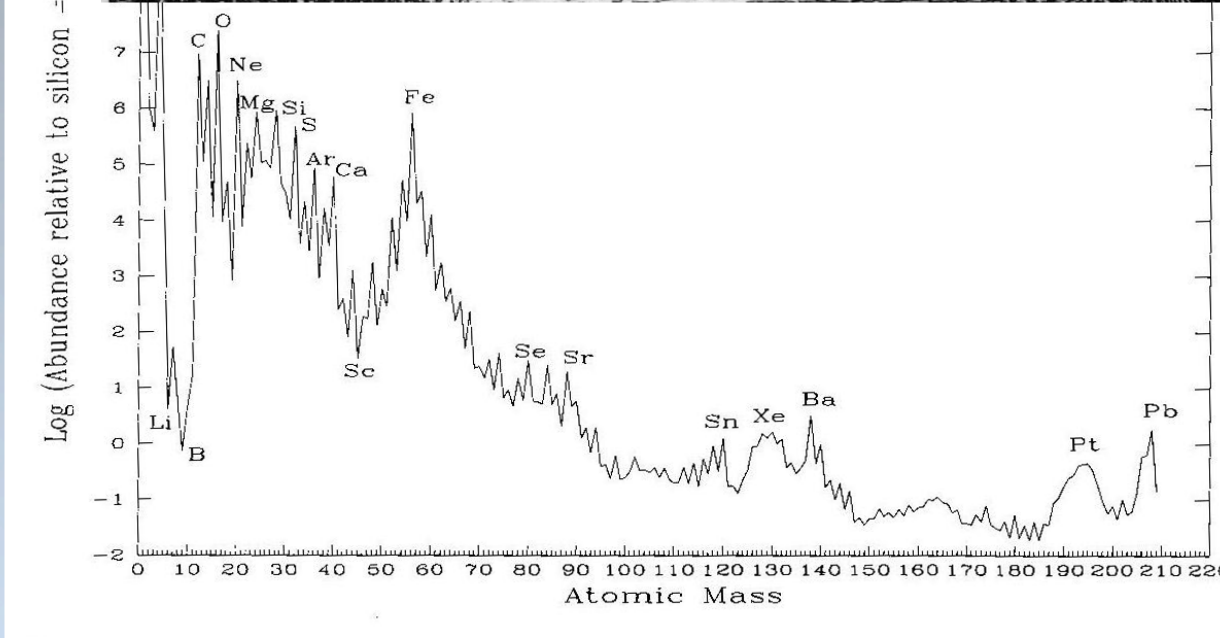
The ISM is composed of gas (99%) and dust (1%).

Stellar formation yield :
3-10 $M_\odot$/year
($M_{galaxy} \approx 10^{12} M_\odot$) $M_\odot$= Solar mass

The stellar formation yield is about 5 times that of stellar ejection (mainly in gaseous form).

Where do we measure this abundance pattern? the chondrite connexion

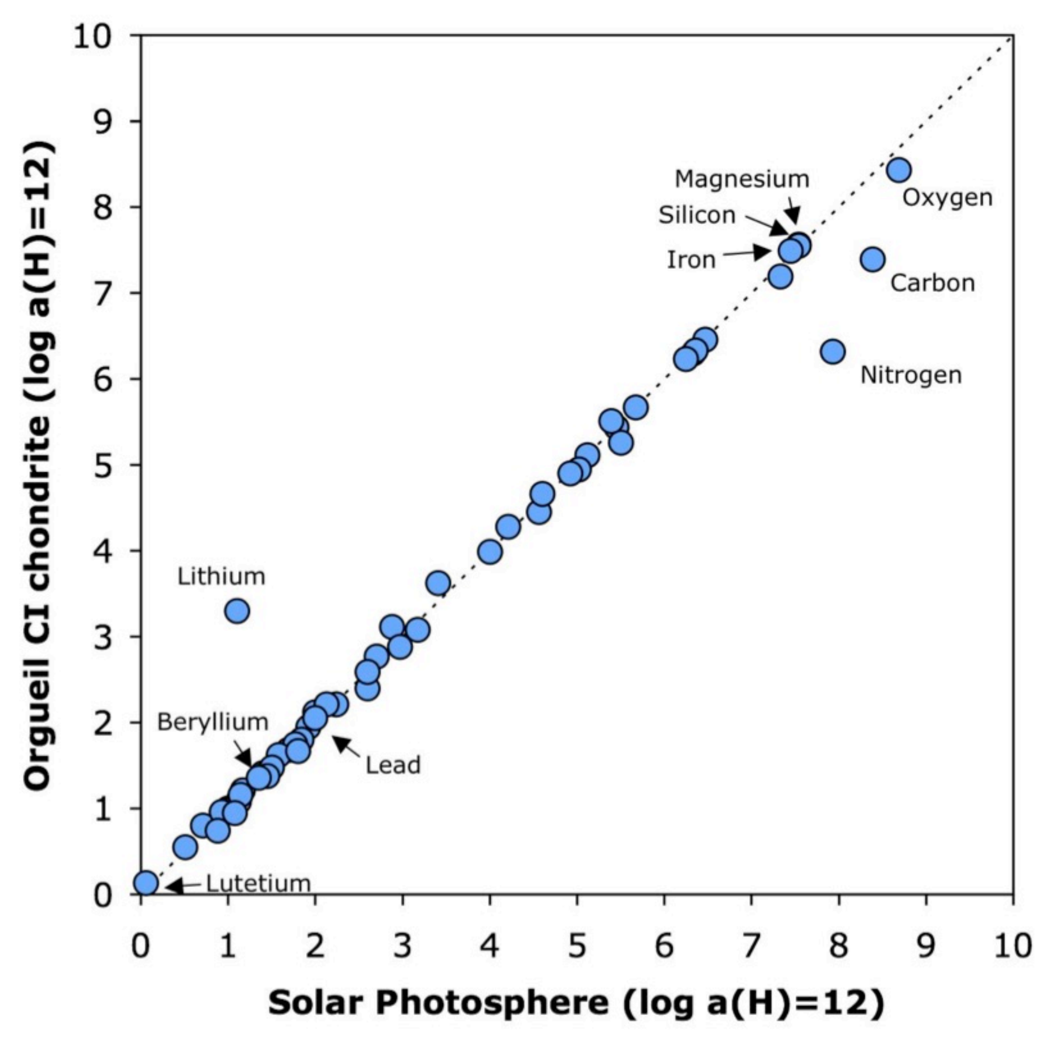


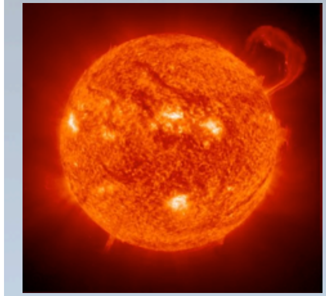


Orgueil meteorite
a CI chondrite

The abundance of most elements in Orgueil (CI) meteorite is that of the Sun, over almost 9 orders of magnitudes

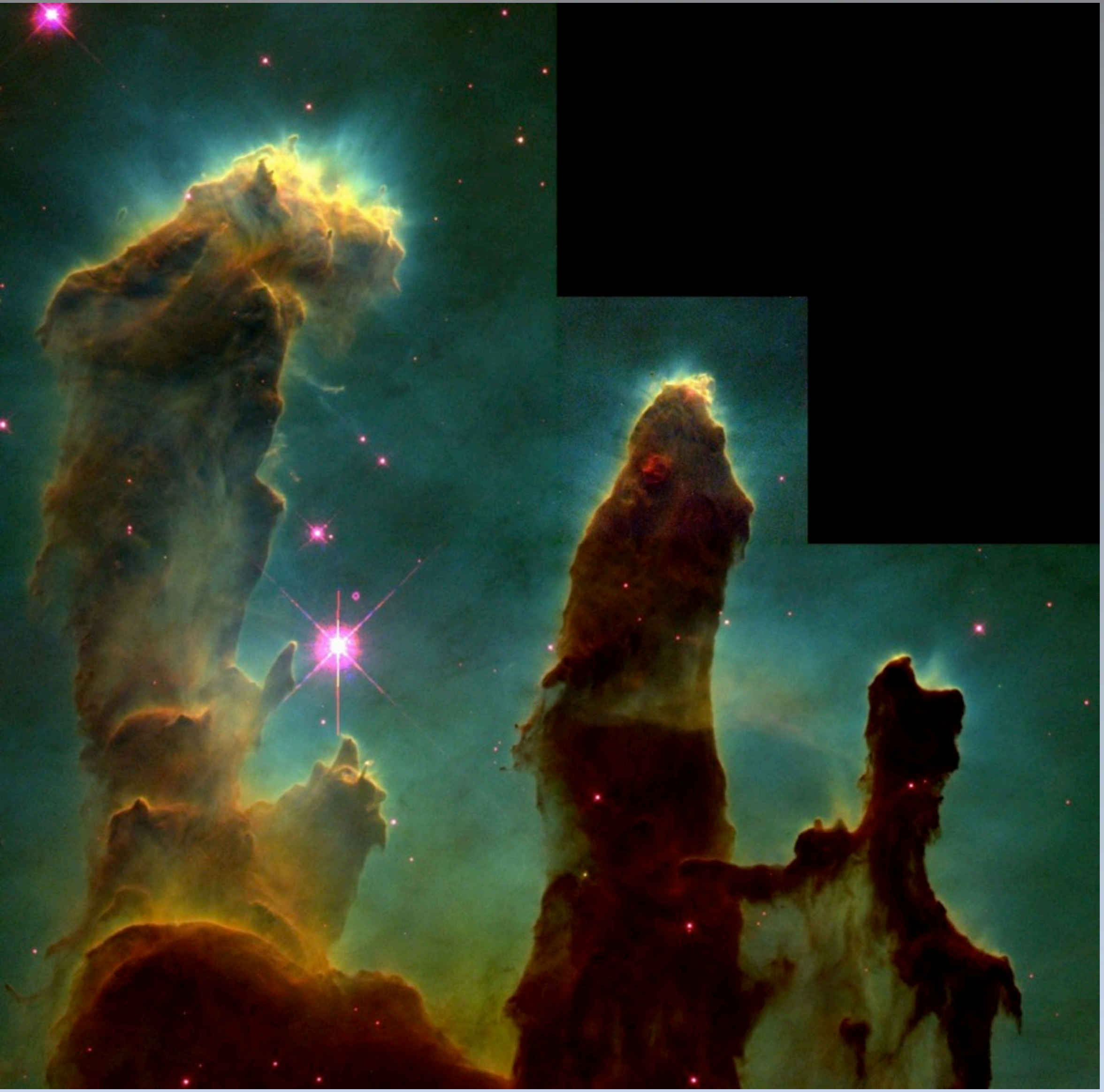
Orgueil (CI)





It is the starting composition in high Z elements of the Local Inter-Stellar Medium 4.5 Gyrs ago

Stars are forming in dense molecular clouds



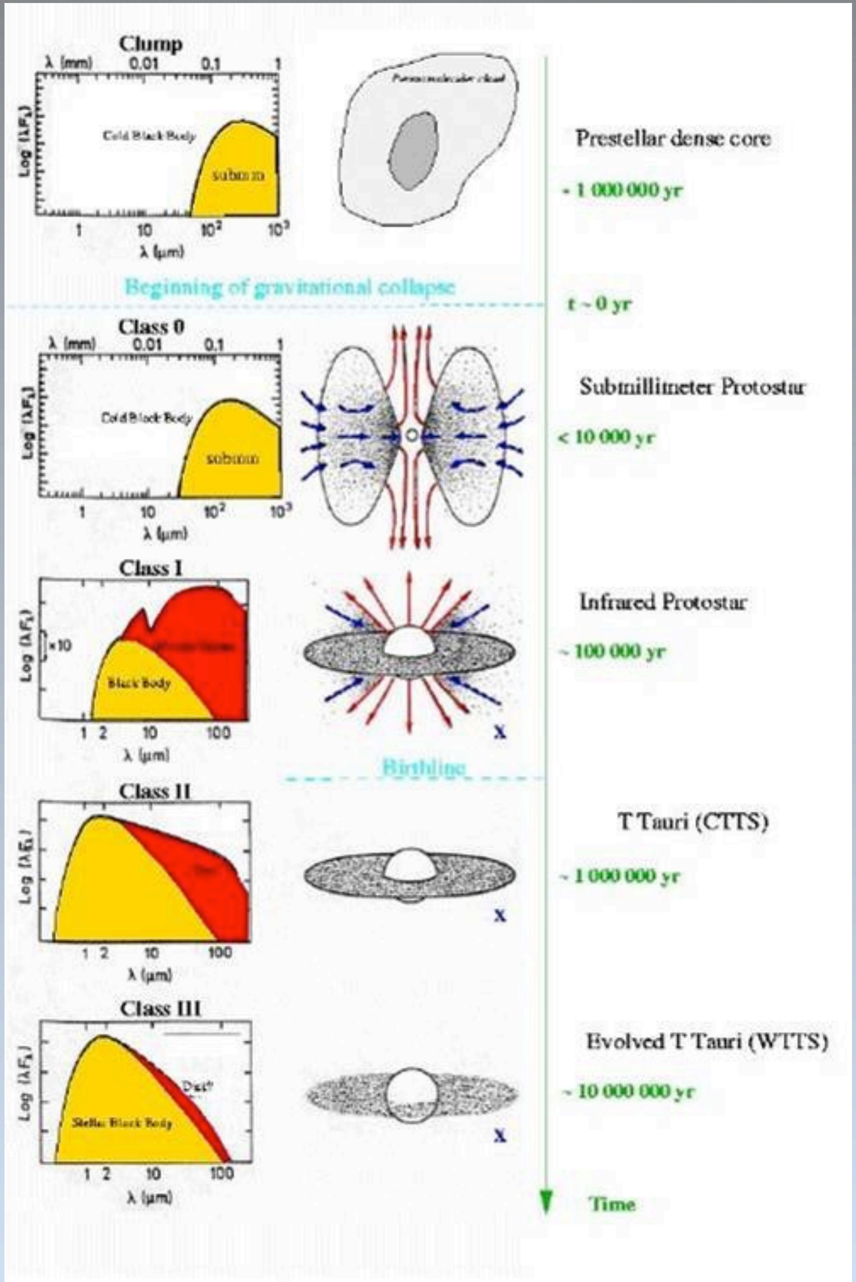
An emblematic example

The Eagle nebula

Distance 6500 LY (2 kpc)

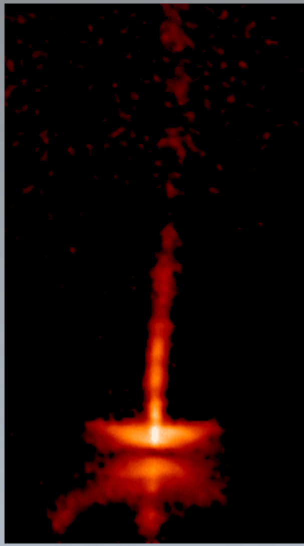
Size of the clouds :
1 LY, ~50 kAU, ~ 0.3 pc

Before the main sequence



Different time scales

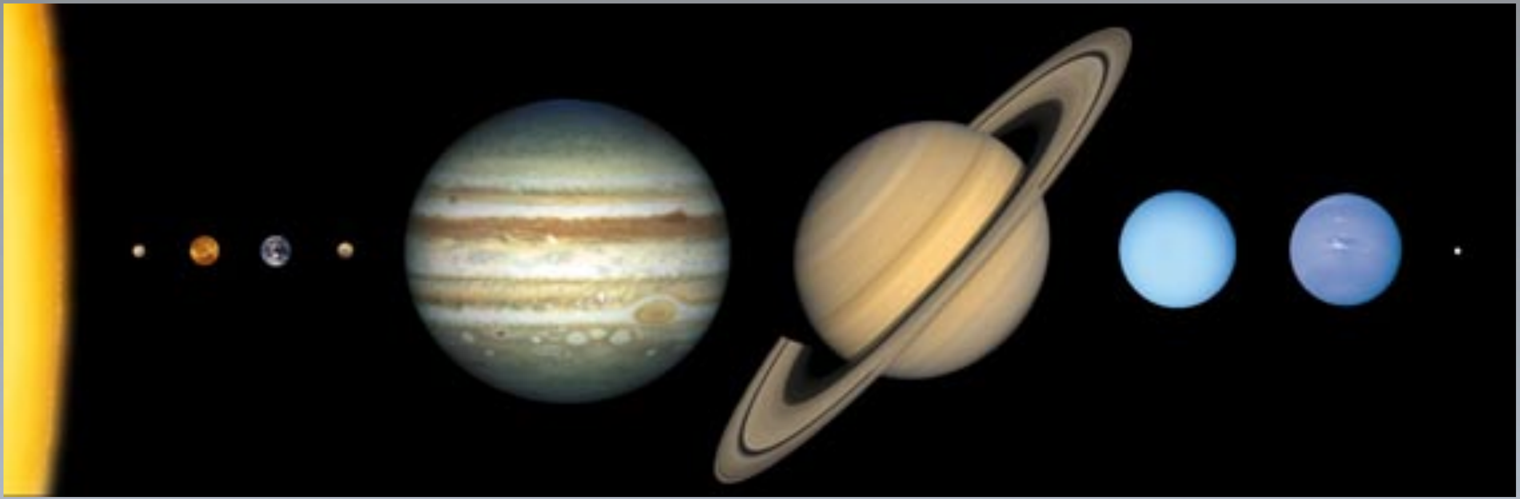
- Class 0 & I :
  - The proto-star is embedded
  - High accretion rate
  - T ~ 10^4-10^5 years
  - M_{star} = 0.5 → 0.8 $M_\odot$



HH 30
HST

- Class II & III :
  - Disc of gas and dust then debris
  - Lower accretion rate
  - T ~ 10^6-10^7 years
  - M_{star} = 0.8 → 1 $M_\odot$

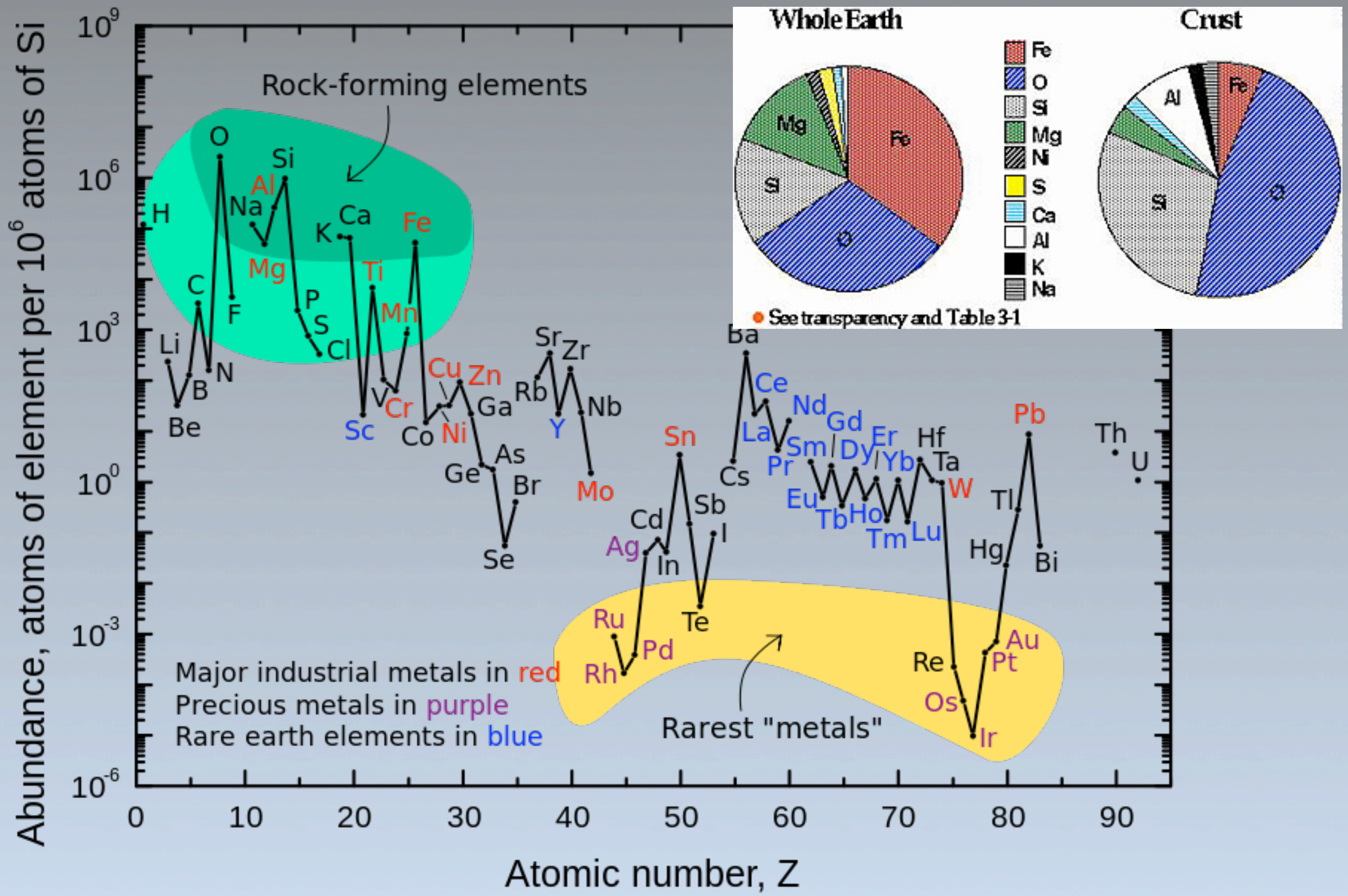
The final solar system architecture



- M Soleil ($M_\odot$) : $1.99\ 10^{30}$ kg
- M Terre ($M_\oplus$) : $5.97\ 10^{24}$ kg
- M Jupiter ($M_{♃}$) : $1.90\ 10^{27}$ kg (317 $M_\oplus$, 0.1% $M_\odot$)

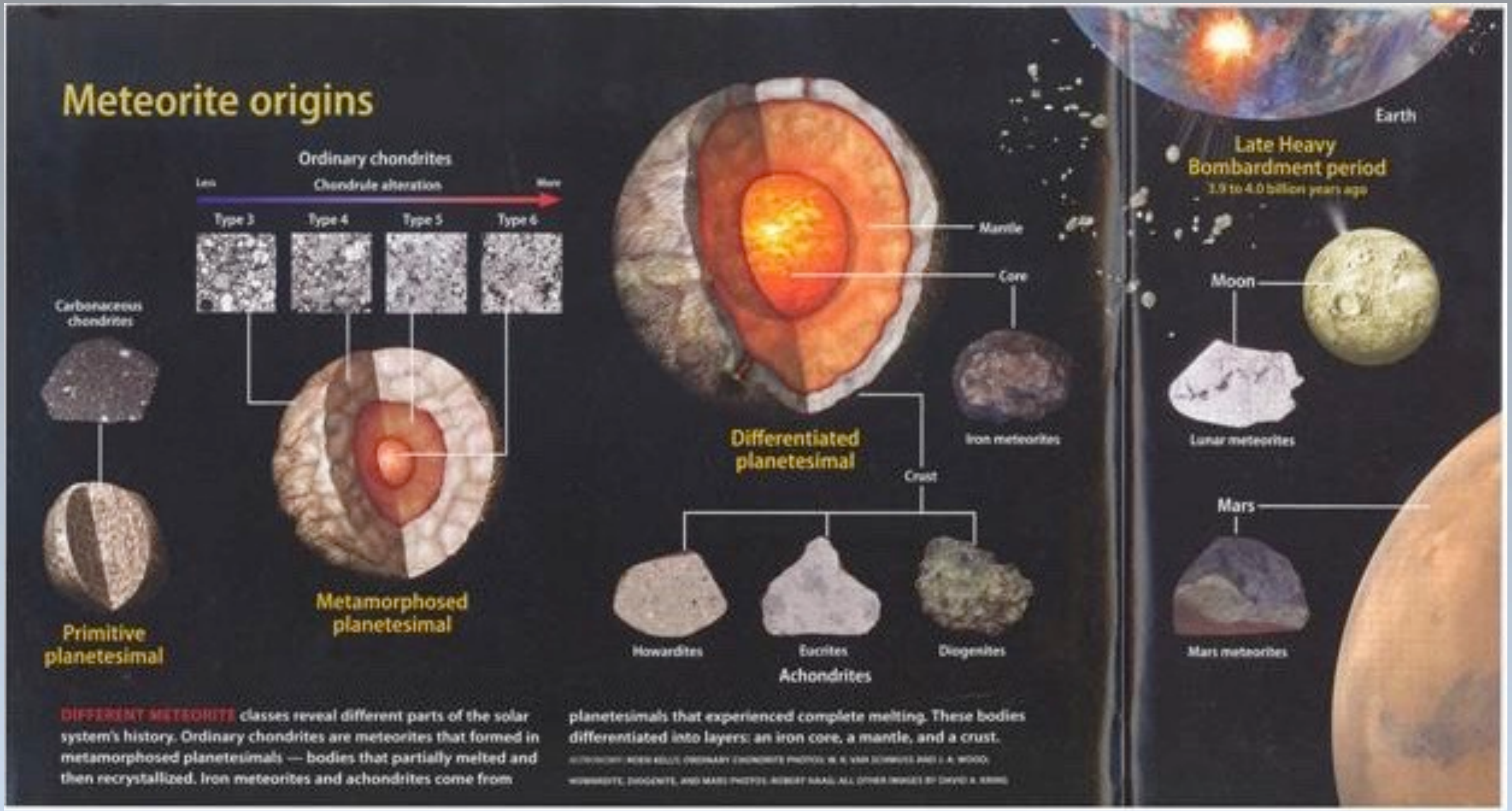
There a spectacular dichotomy between
the inner (rocky) and outer (gaseous/icy) solar system

Abundance of elements on Earth



What is a primitive sample ?

the key role of small-bodies



DIFFERENT METEORITE classes reveal different parts of the solar system's history. Ordinary chondrites are meteorites that formed in metamorphosed planetesimals — bodies that partially melted and then recrystallized. Iron meteorites and achondrites come from planetesimals that experienced complete melting. These bodies differentiated into layers: an iron core, a mantle, and a crust.

Kring, D. (2006), Astronomy

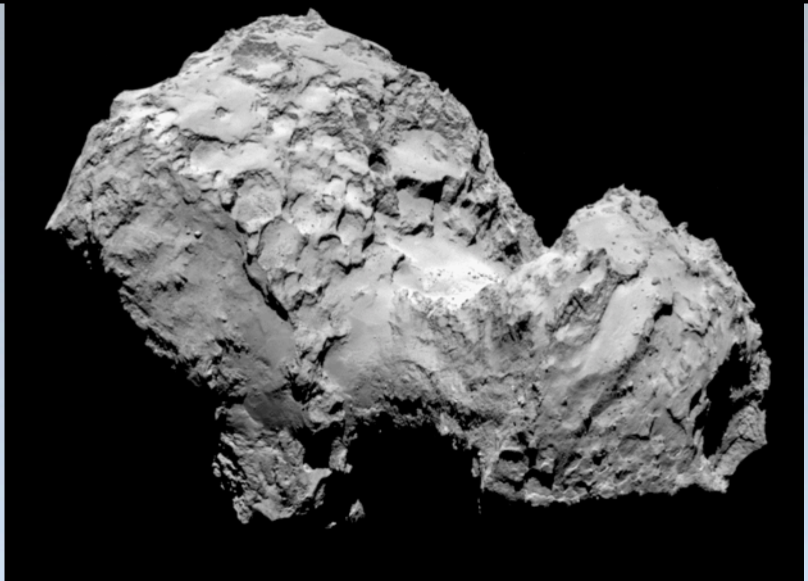
The solar system small bodies

- The asteroids
  - between Mars and Jupiter

- The Kuiper belt object (KBO)
  - between 30 et 50 AU

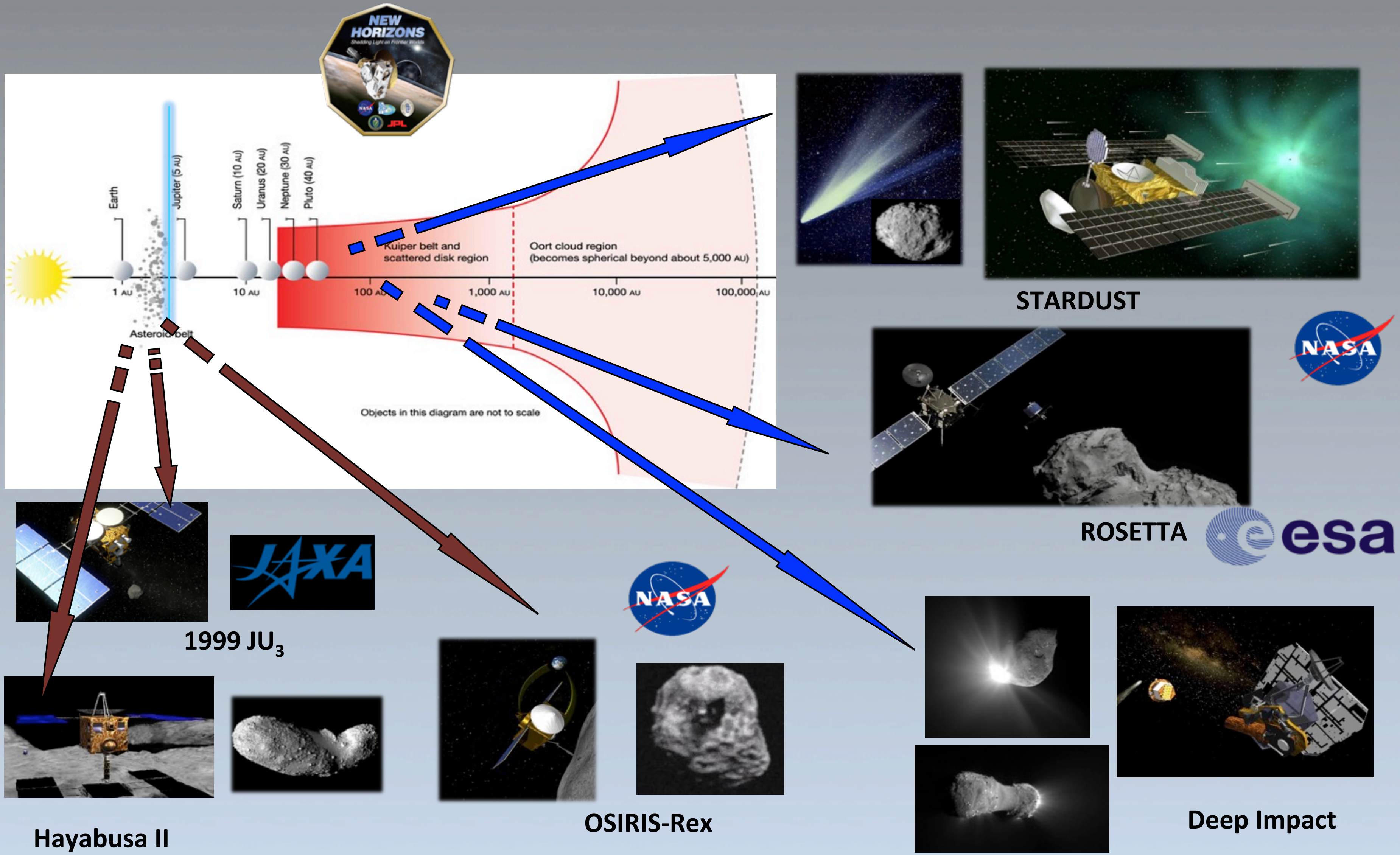
- The comets
  - Jupiter-type
  - Oort-cloud Comets (> 5 000 AU)

(25143) Itokawa Asteroid



67P/Churyumov–Gerasimenko
ESA Rosetta mission

A major goal for the futur space missions



STARDUST

ROSETTA

1999 JU$_3$

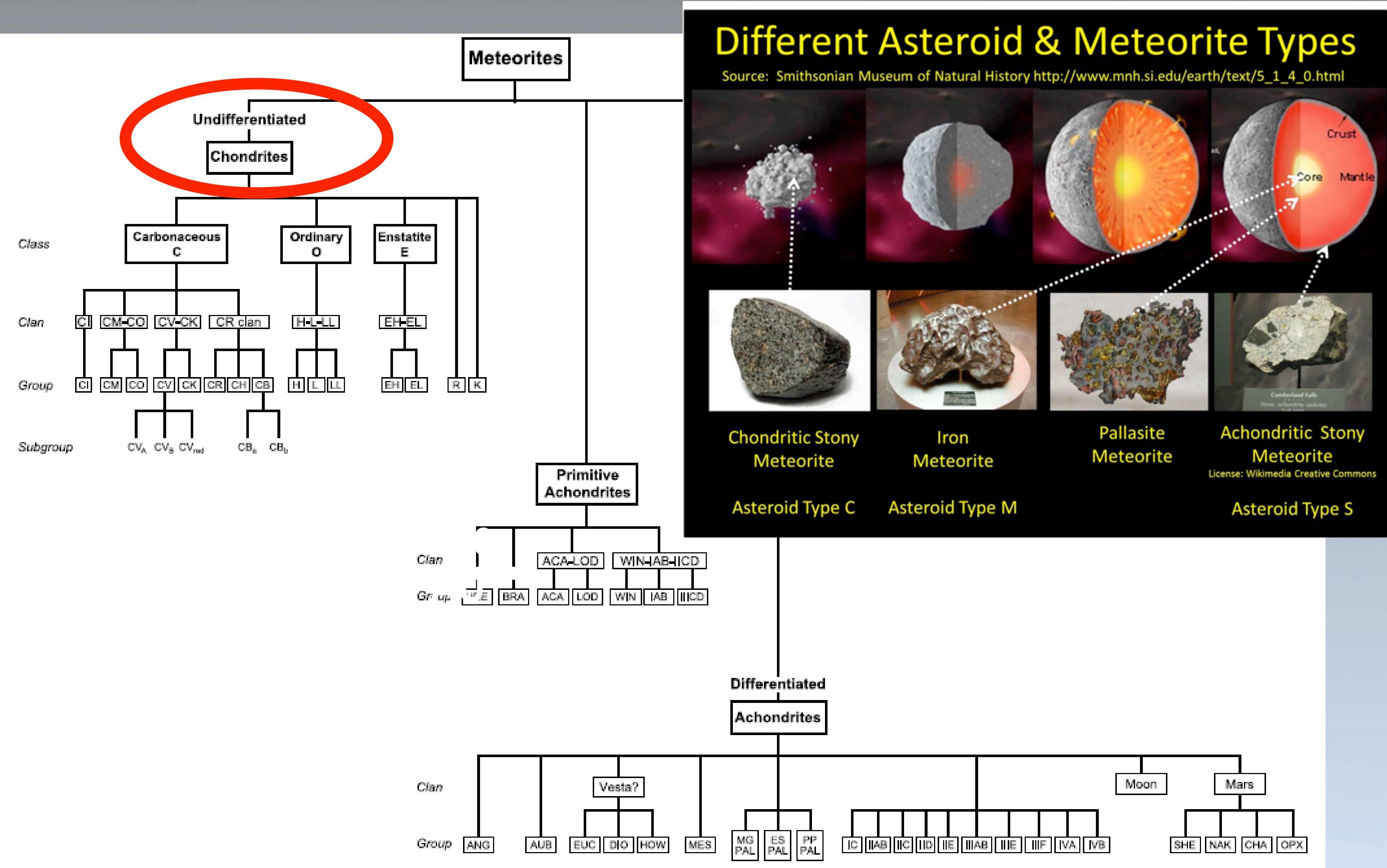
Hayabusa II

OSIRIS-Rex

Deep Impact

Analysing the solid component of small bodies provides unique information on the composition of the proto-solar nebulae and the context of the solar system birth

The different types of meteorites



Different Asteroid & Meteorite Types

Source: Smithsonian Museum of Natural History http://www.mnh.si.edu/earth/text/5_1_4_0.html

Chondritic Stony Meteorite

Asteroid Type C

Iron Meteorite

Asteroid Type M

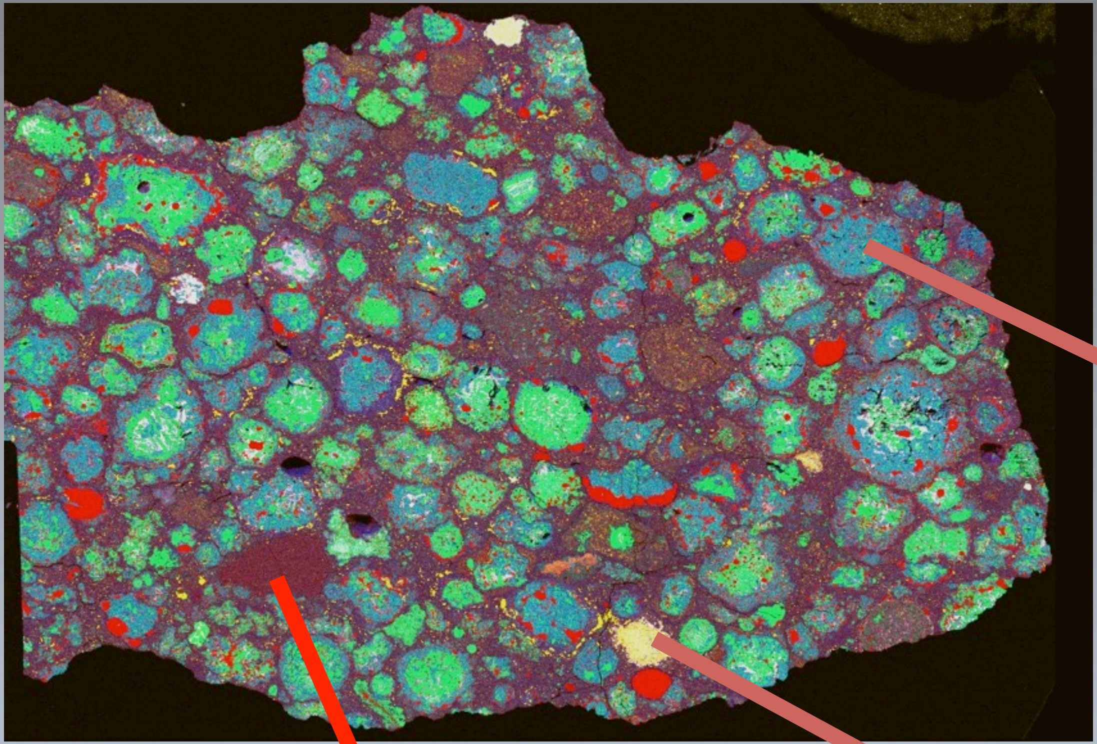
Pallasite Meteorite

Achondritic Stony Meteorite

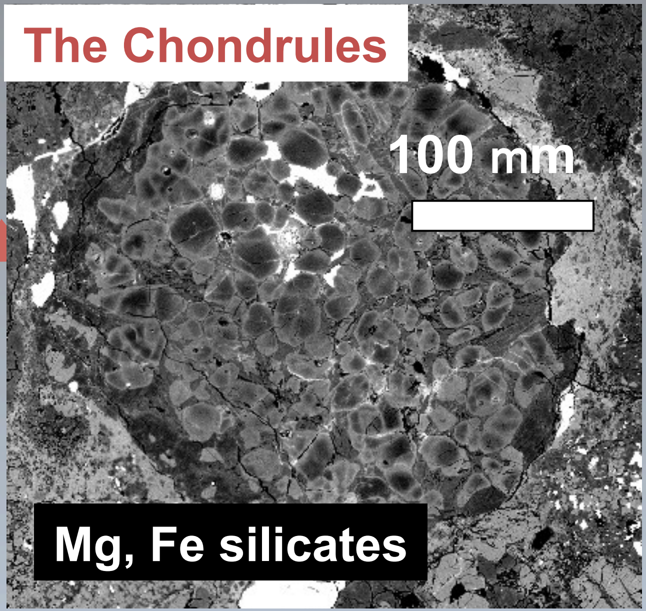
License: Wikimedia Creative Commons

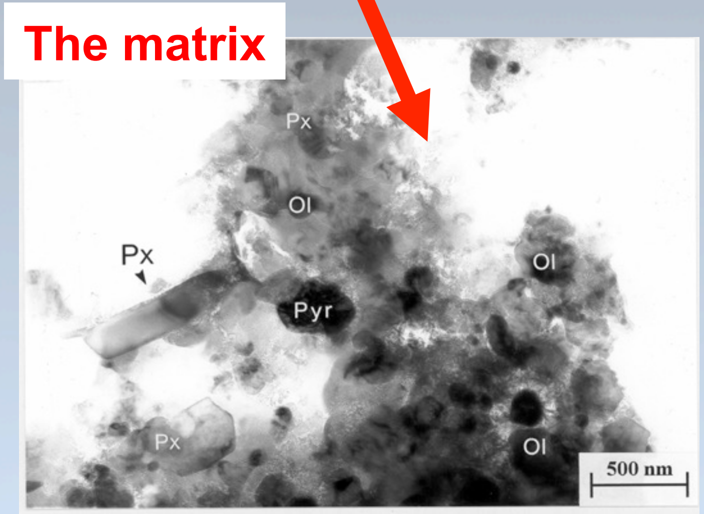
Asteroid Type S

Within a Chondrite : chondrules, CAIs, and the matrix

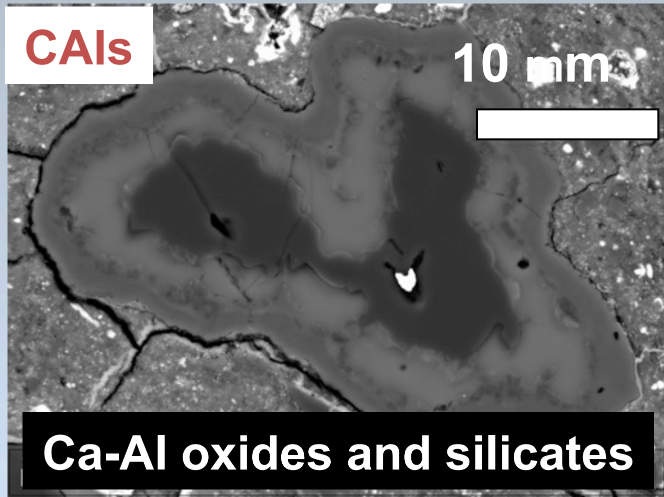


In refractory phase we found extinct radioactivities

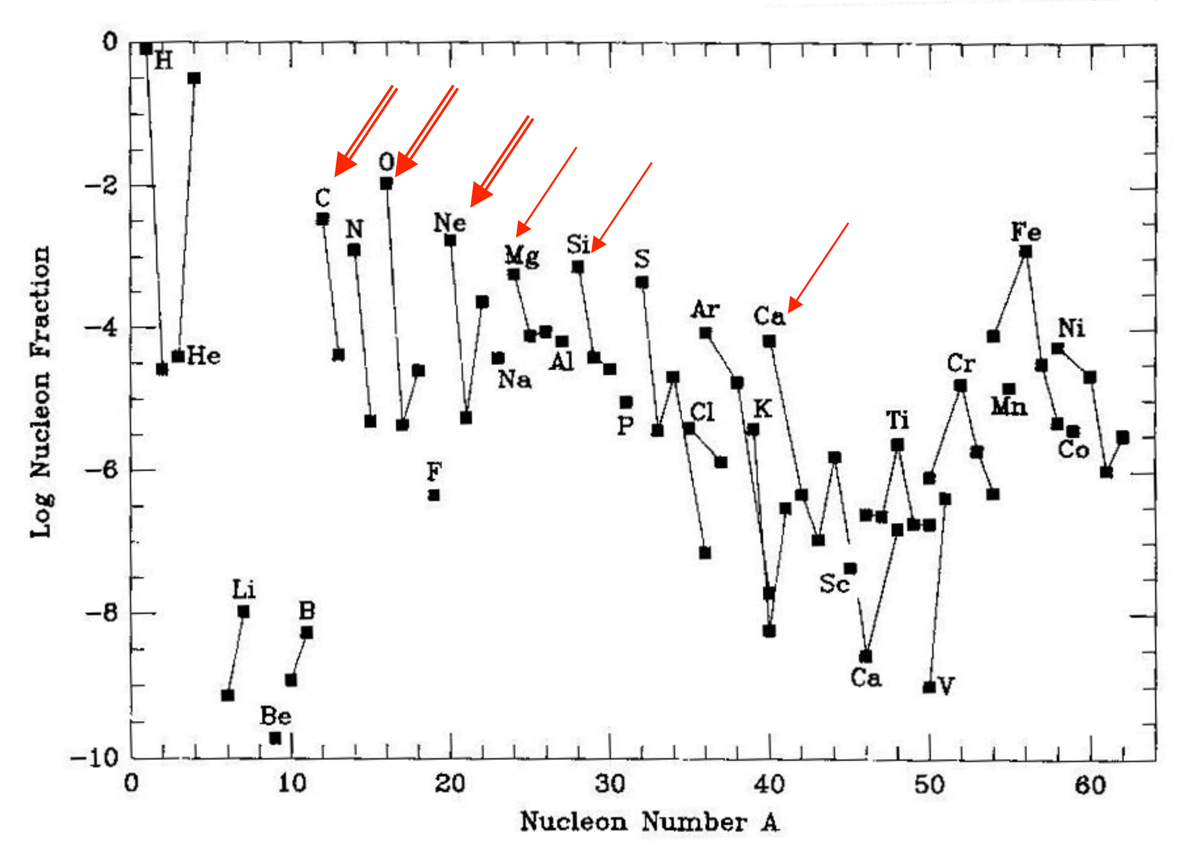




Presolar grains are in the matrix



For 6 < Z < 20



α nuclei

^{12}C, ^{16}O (He burning)

^{12}C+^{12}C → **^{20}Ne + α** (C burning)

^{20}Ne(γ,α)^{16}O

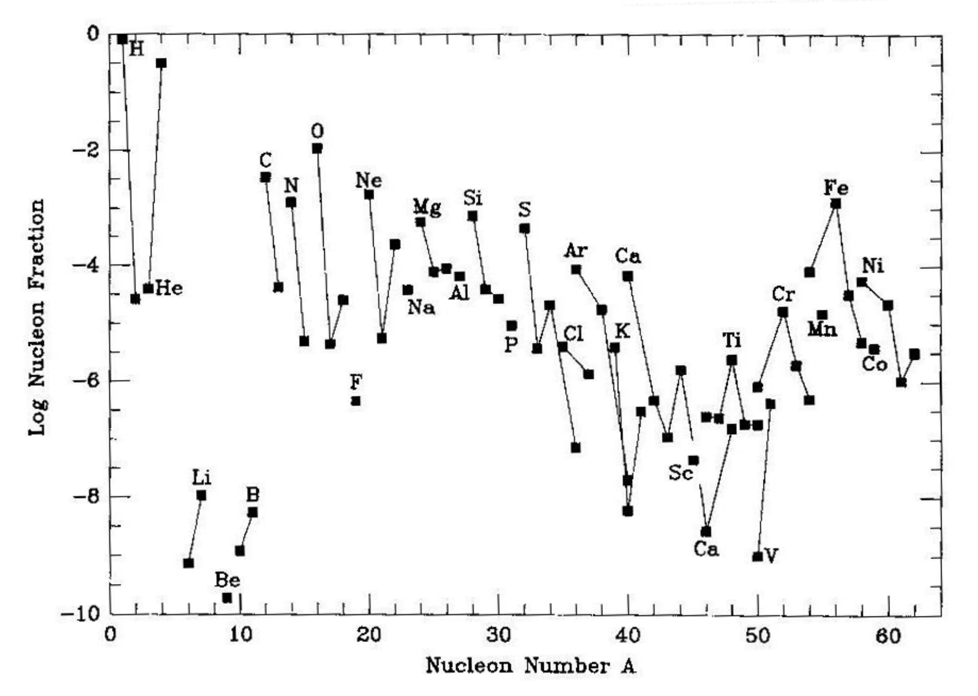
^{20}Ne(α, γ)**^{24}Mg**

^{16}O+^{16}O → **^{28}Si+α** (O burning)

N=Z nuclei are more abundant

^{24}Mg(12,12) >> ^{26}Mg(12,14)
^{28}Si(14,14) >> ^{30}Si(14,16)
^{40}Ca (20,20) >> ^{42}Ca

The odd-even staggering



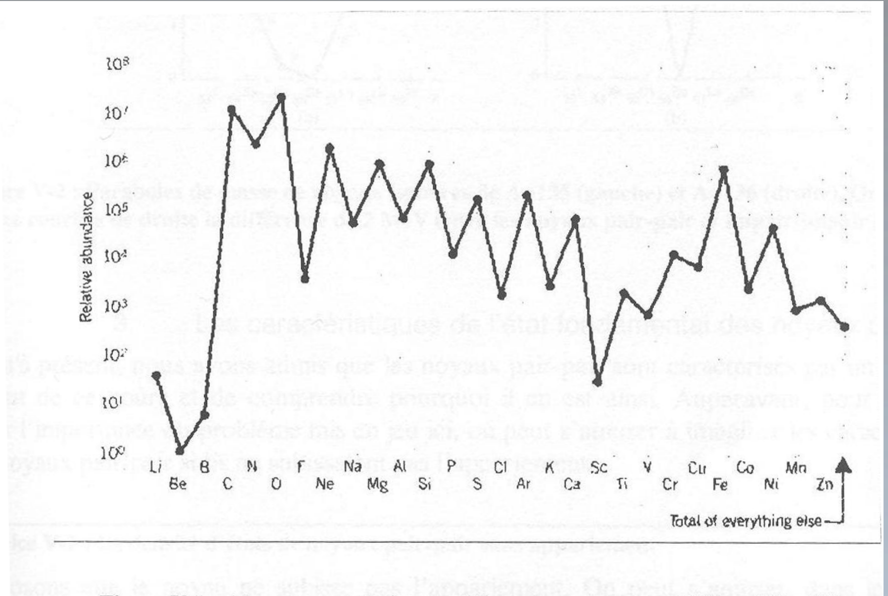
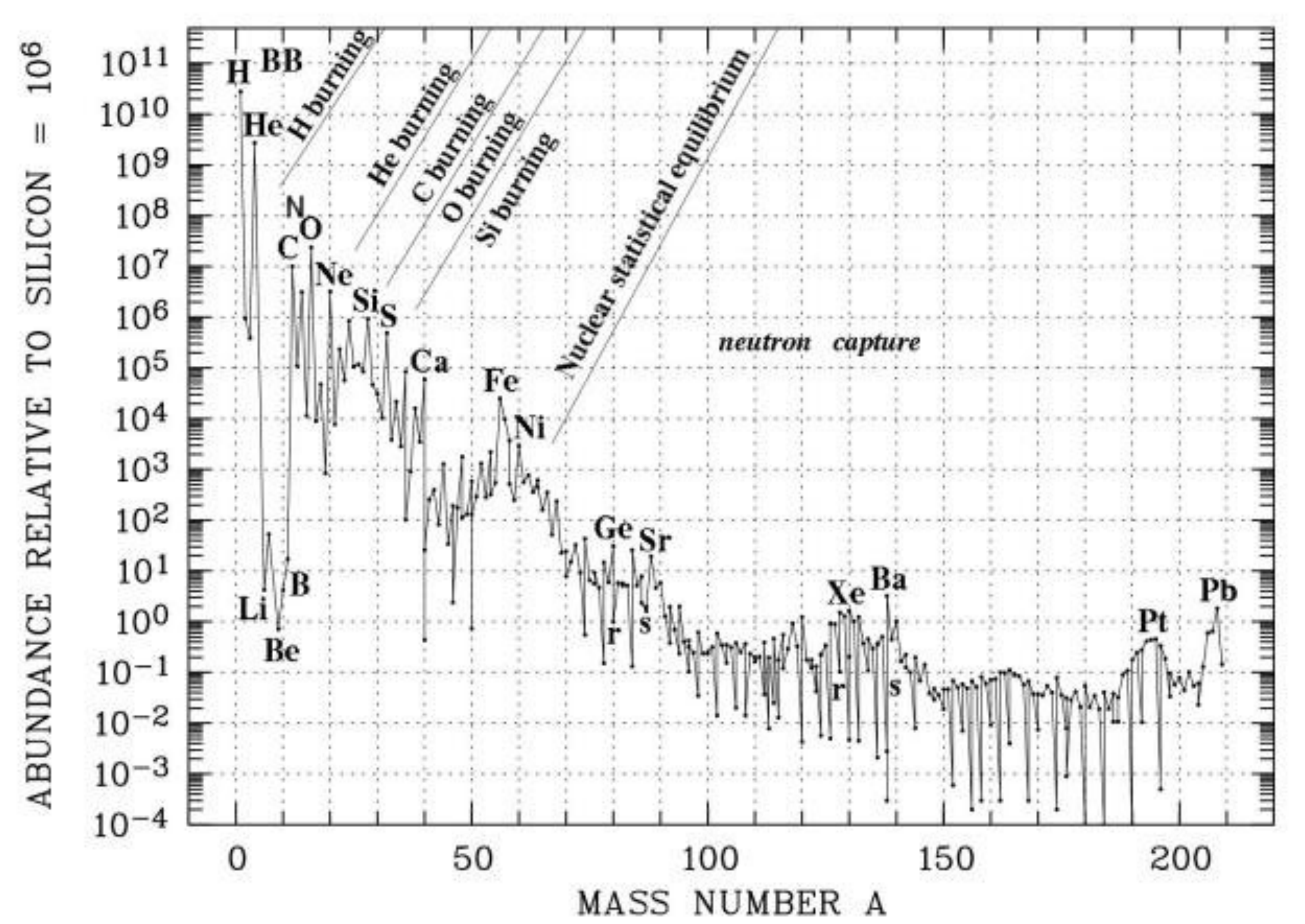


Figure V-1 : Abondance relative des éléments au-delà de l'Hélium [Kra88]

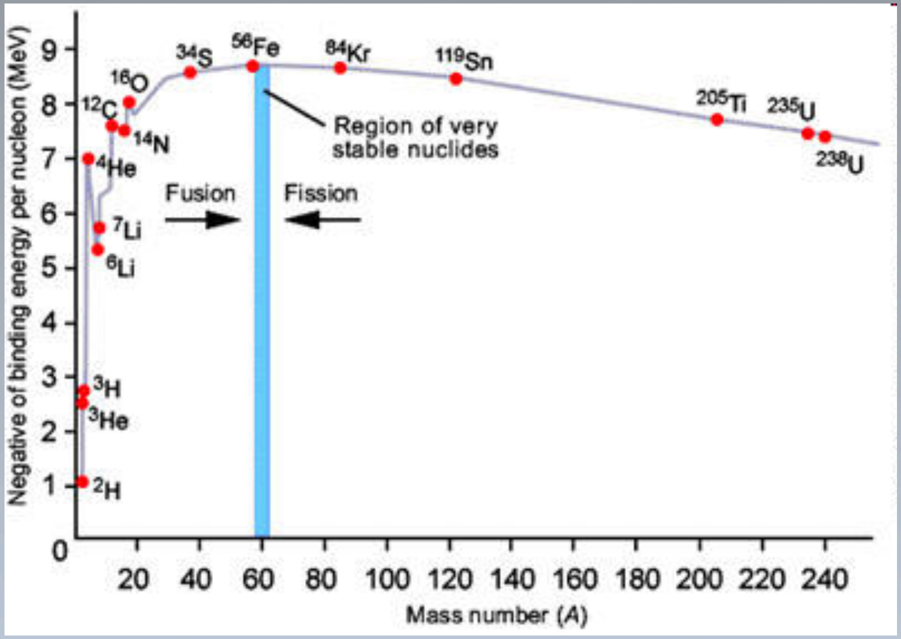
- Stable odd-odd nuclei are rare : D, ^{6}Li, ^{10}Be et ^{14}N
- The masses of even-even nuclei and odd-odd nuclei are separated by 2 MeV
- The ground state spin and parity of all even-even nuclei is always $J^p = 0^+$
- The energy of the first excited state in an even-even nucleus is always higher than that of the odd-even.

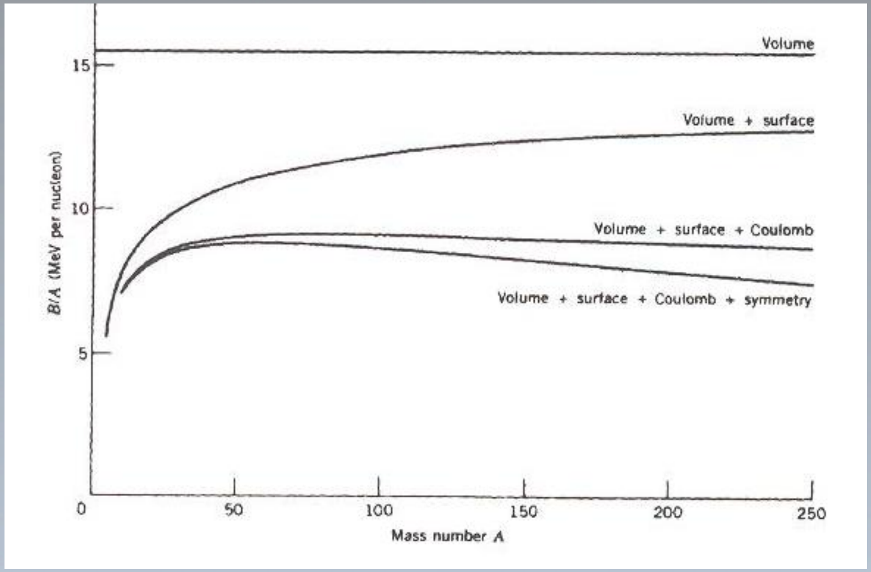
All these features are due to **the paring energy**

The iron peak



Reminder on nuclear physics B(A)





- The strong interaction has a short range : B(A) ≈ cst + corrections (see liquid drop model)

- The B(A) general behavior results from the combined effects of coulomb repulsion, surface and symmetry energy. It produces a maximum at A ~ 60.

Above the iron peak

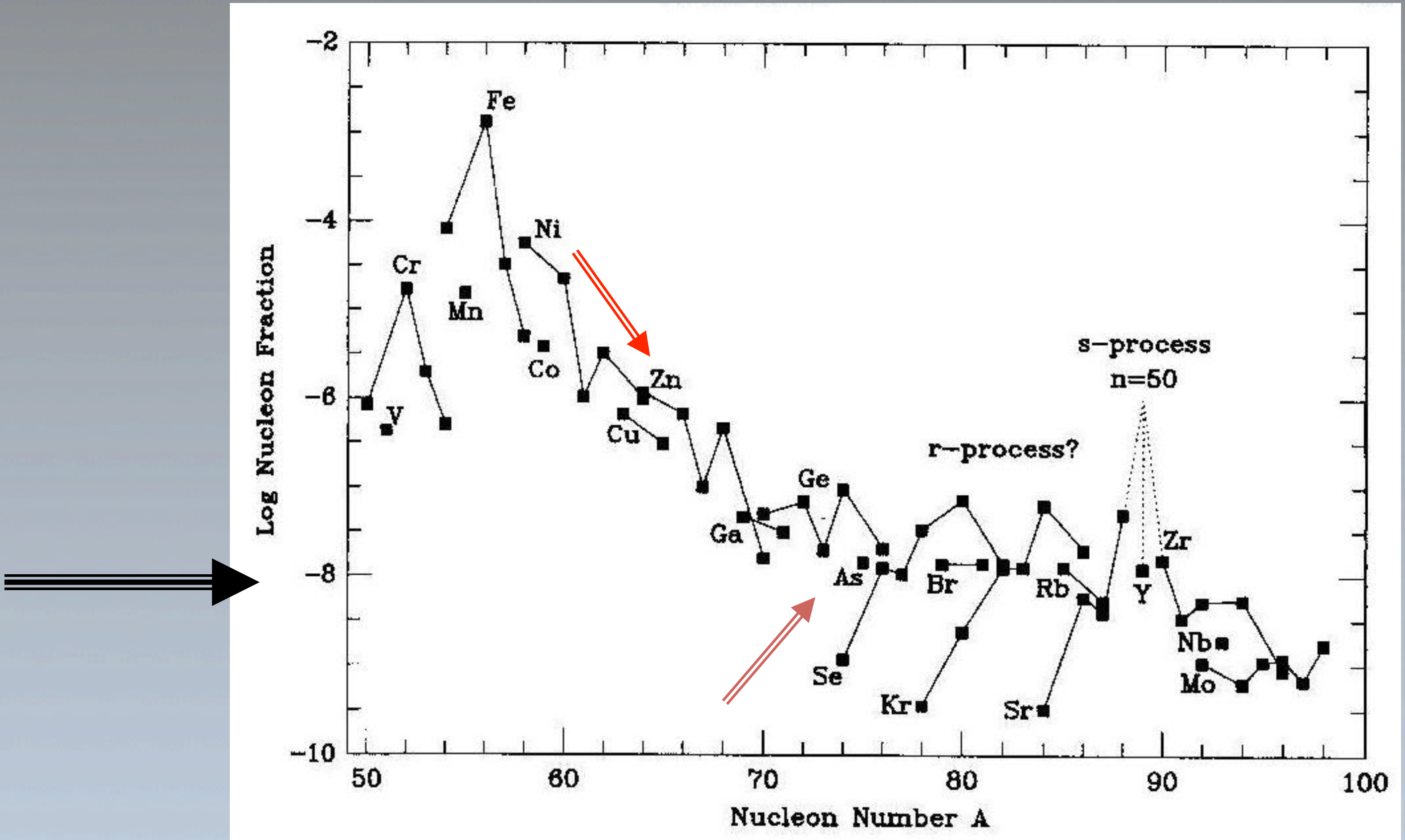


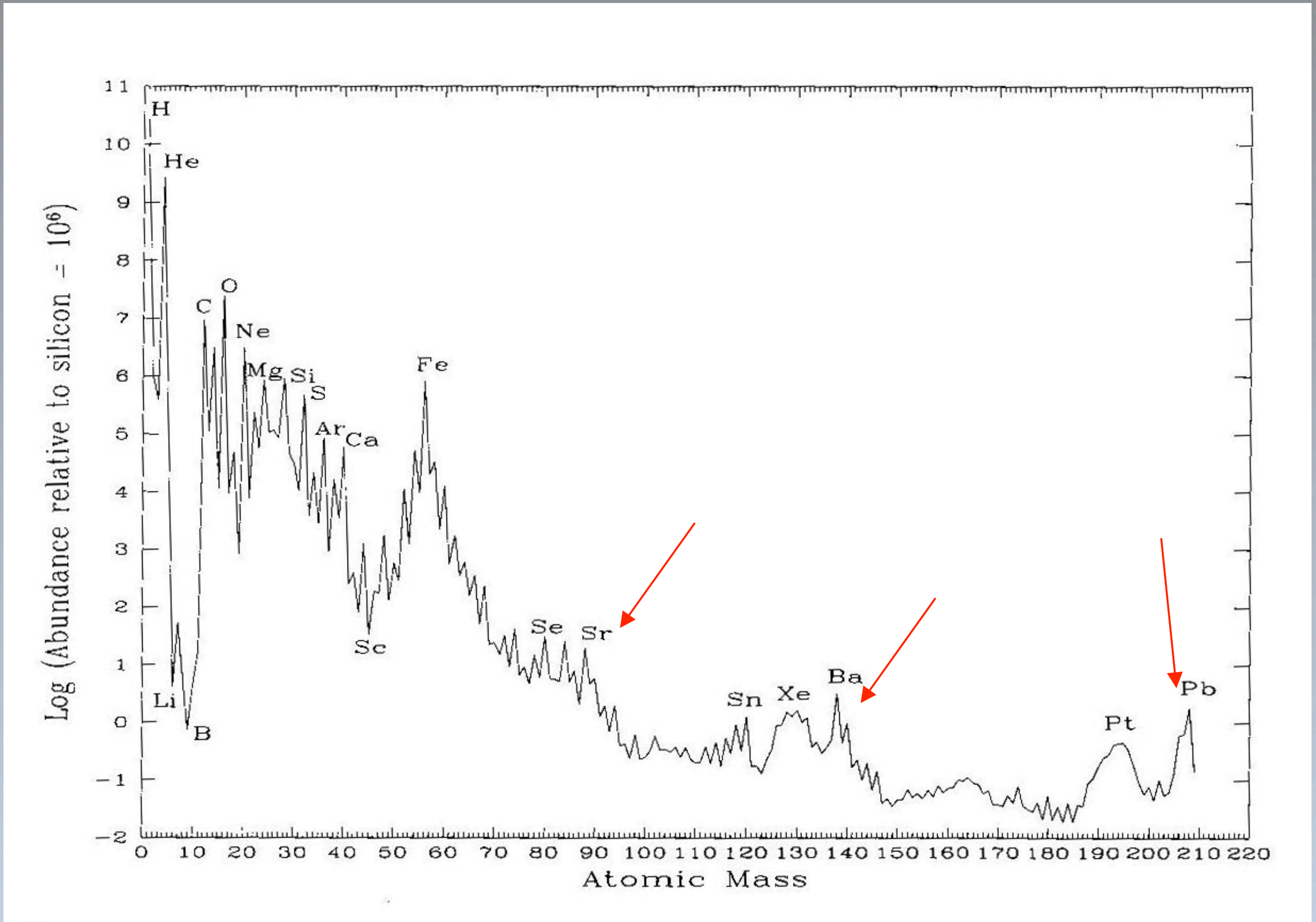
Fig. 2.3. Abundance ($A = 50, 100$)

Before Ge : neutron poor isotopes are more abundant

After Ge : neutron rich nuclei are more abundant

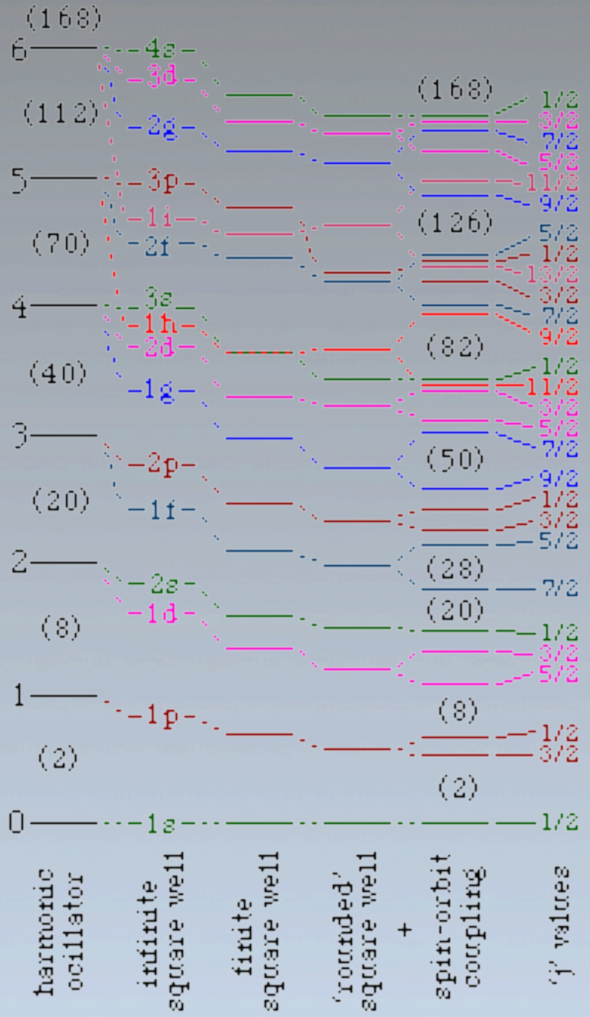
The coulomb barrier gets high, the neutron capture takes over

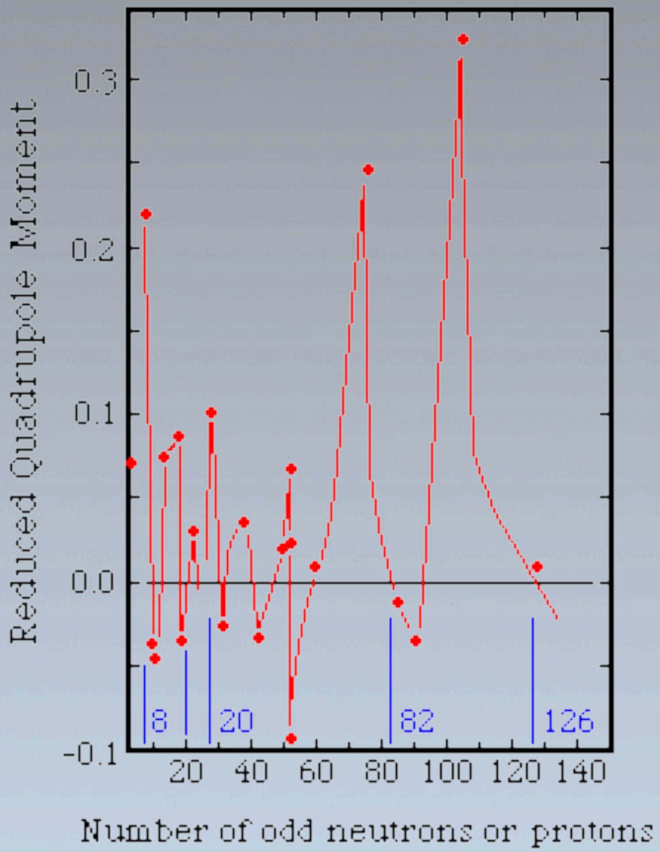
The *s process* peaks



^{88}Sr (Z=38, **N=50**), ^{138}Ba(Z=56, **N=82**), **^{208}Pb(Z=82,N=126)**

Reminders on nuclear structure, the independent-particle model

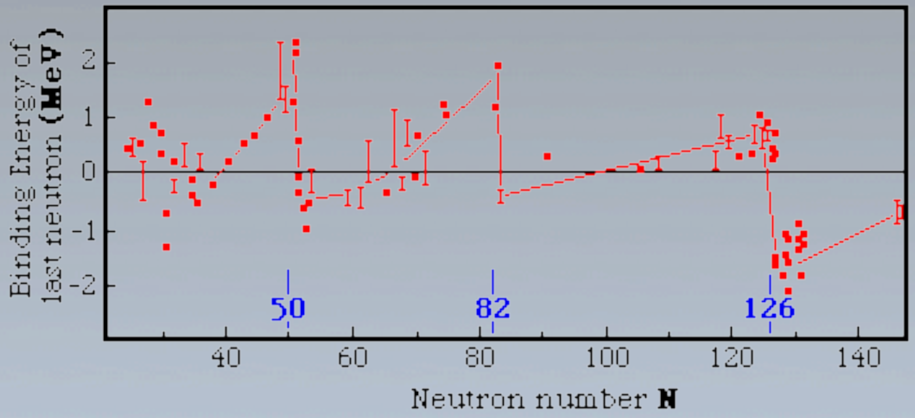


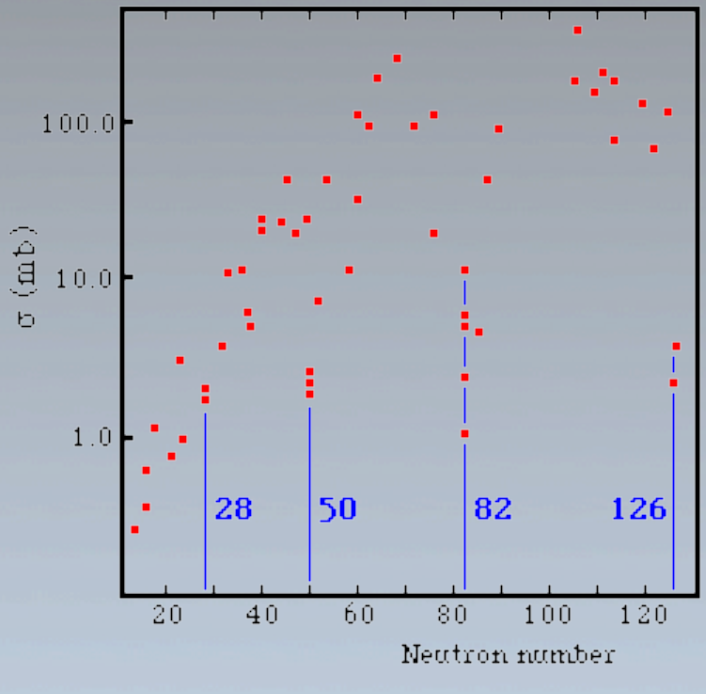


The spherical shell model magic numbers

2, 8, 20, 28, 50, 82, 126, 168

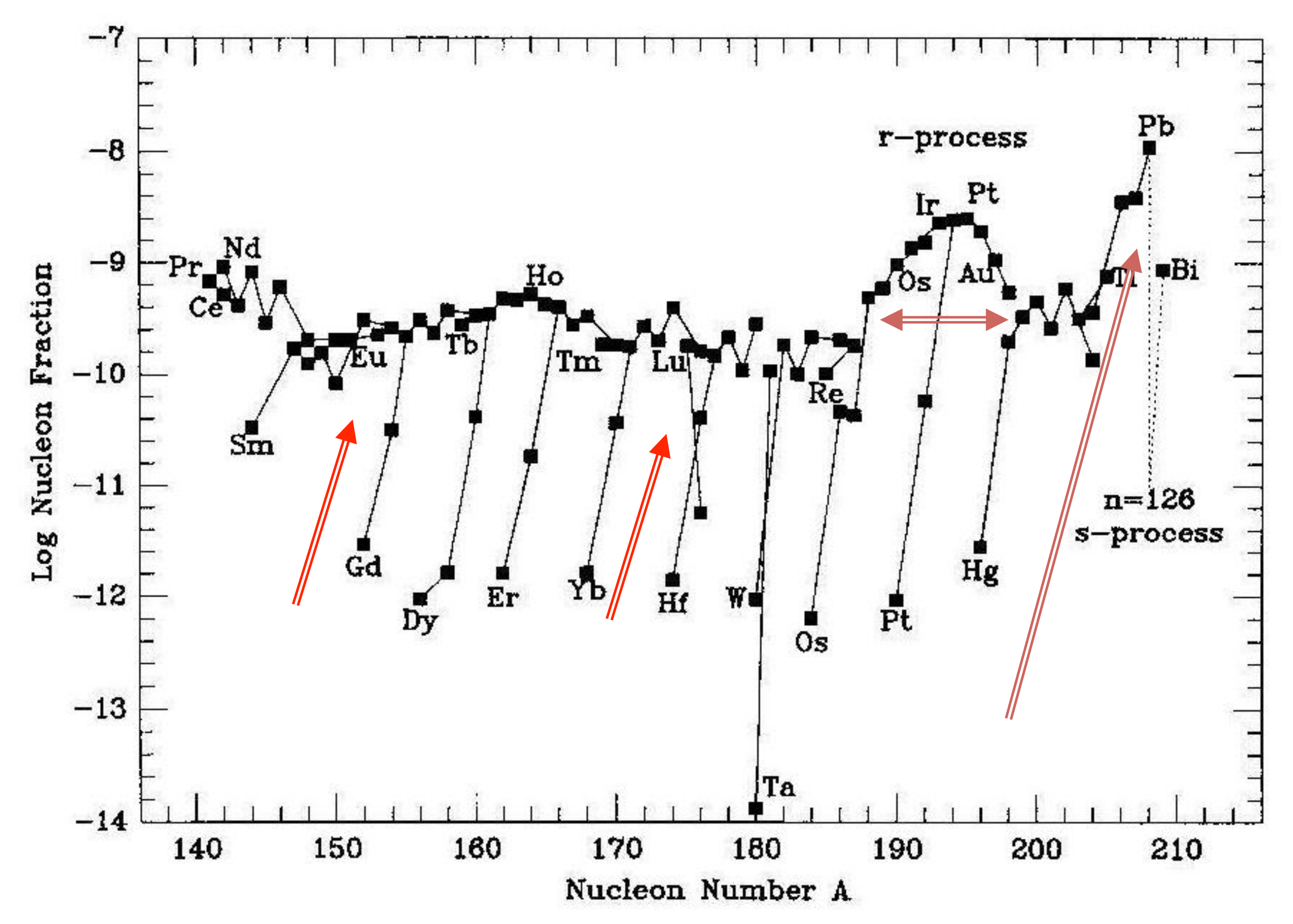
Neutron capture cross sections





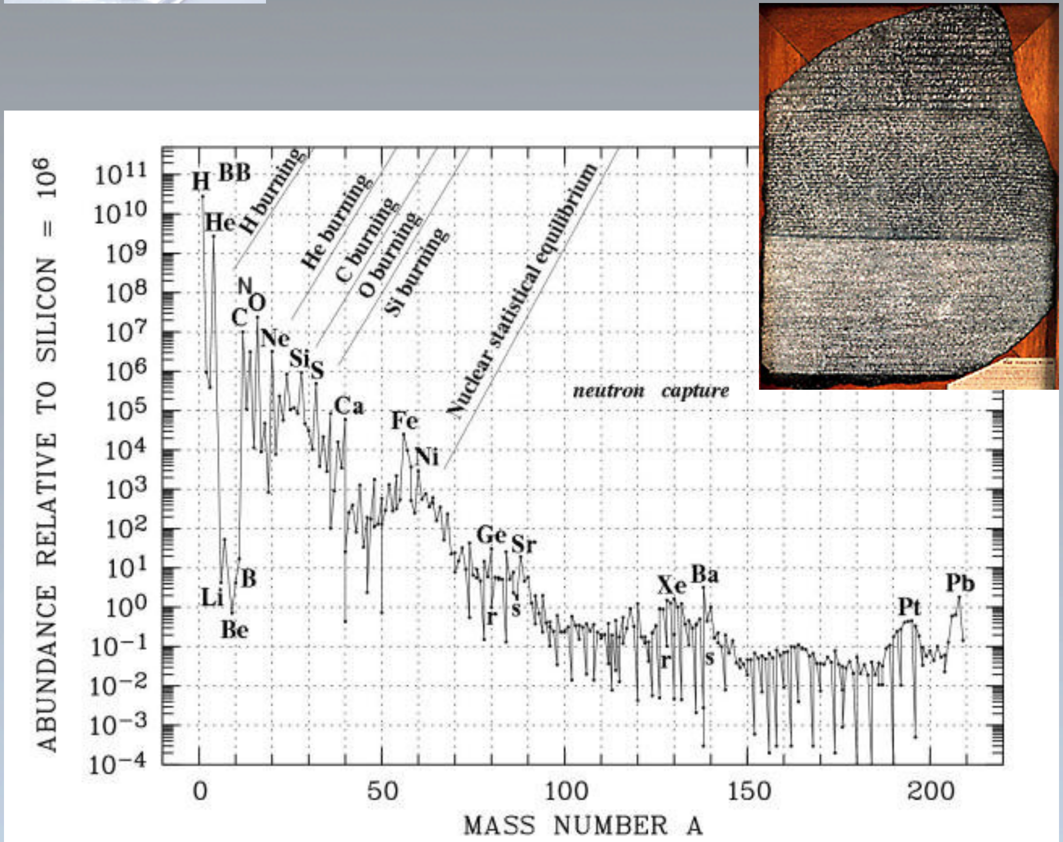
The neutron binding energy is maximal

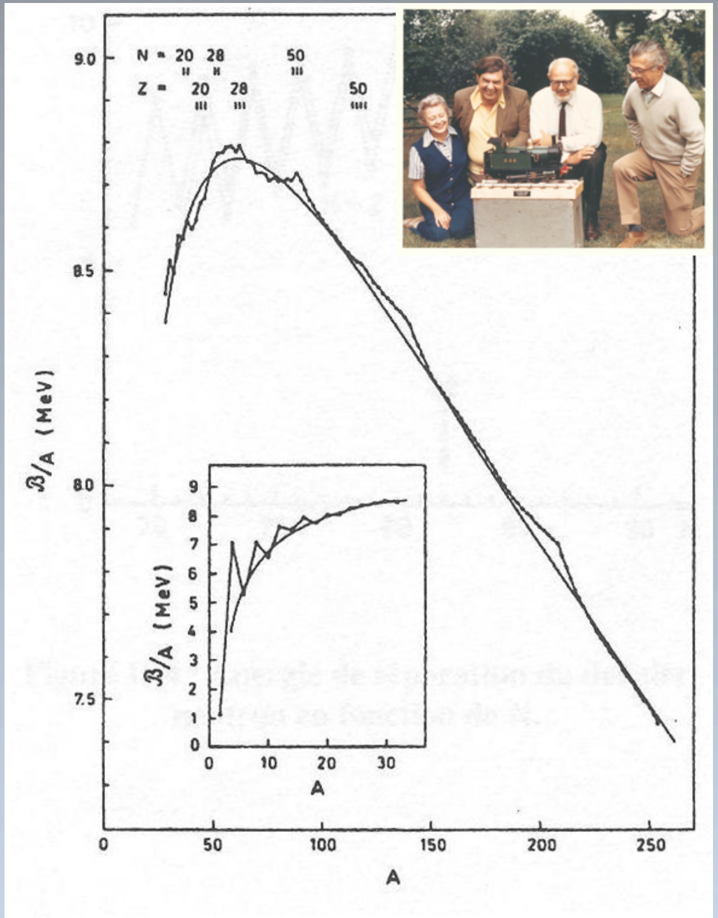
At even higher mass A=140-210



Again, a large structure around **A=195** and a thin one around **A=208**.

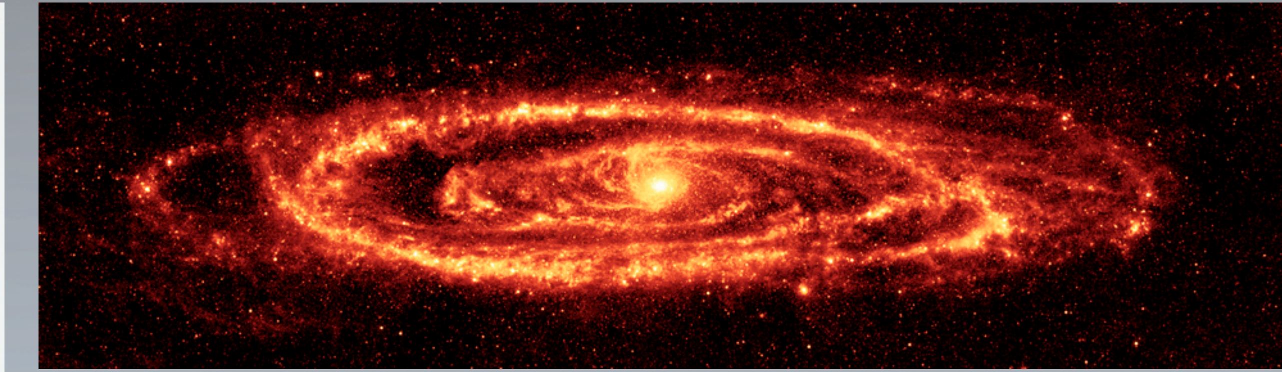
To summarize



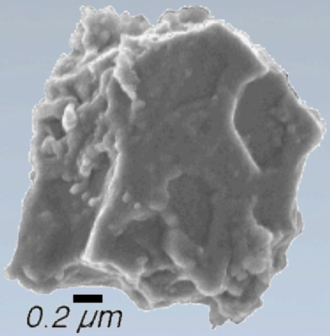


- The ***rapid (r)*** and ***slow (s)*** peaks are due to nuclear structure shells effects

Beyong the average abundance pattern, *the quest for star dust*

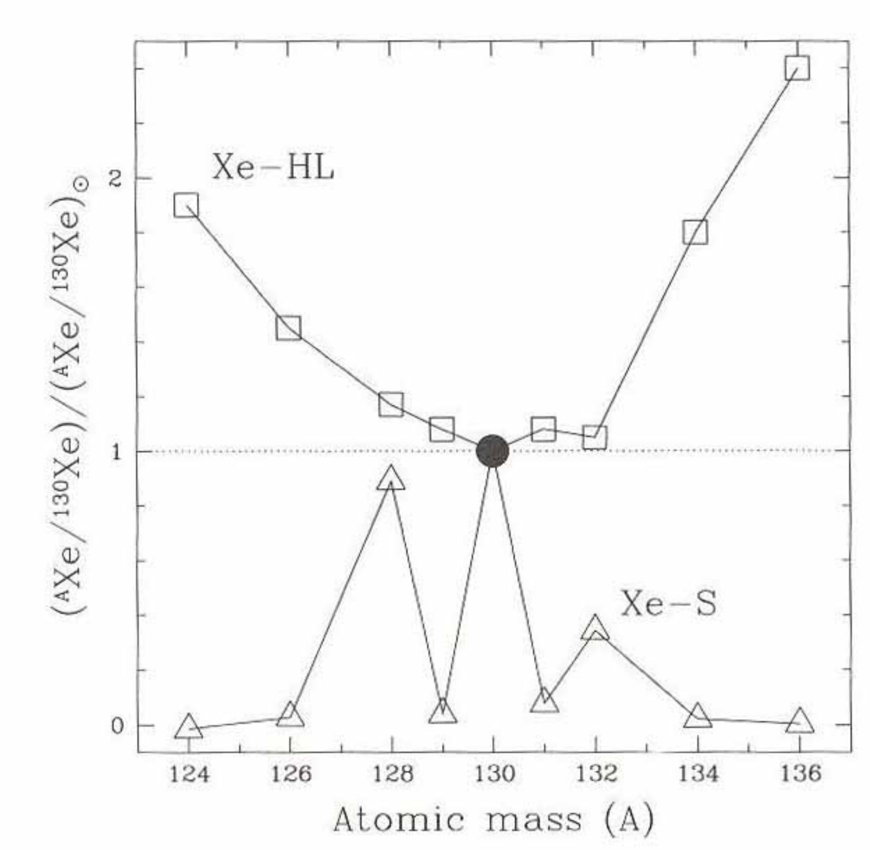


Infrared image of Andromeda Galaxy (dust)
24.0 µm Spitzer MIPS

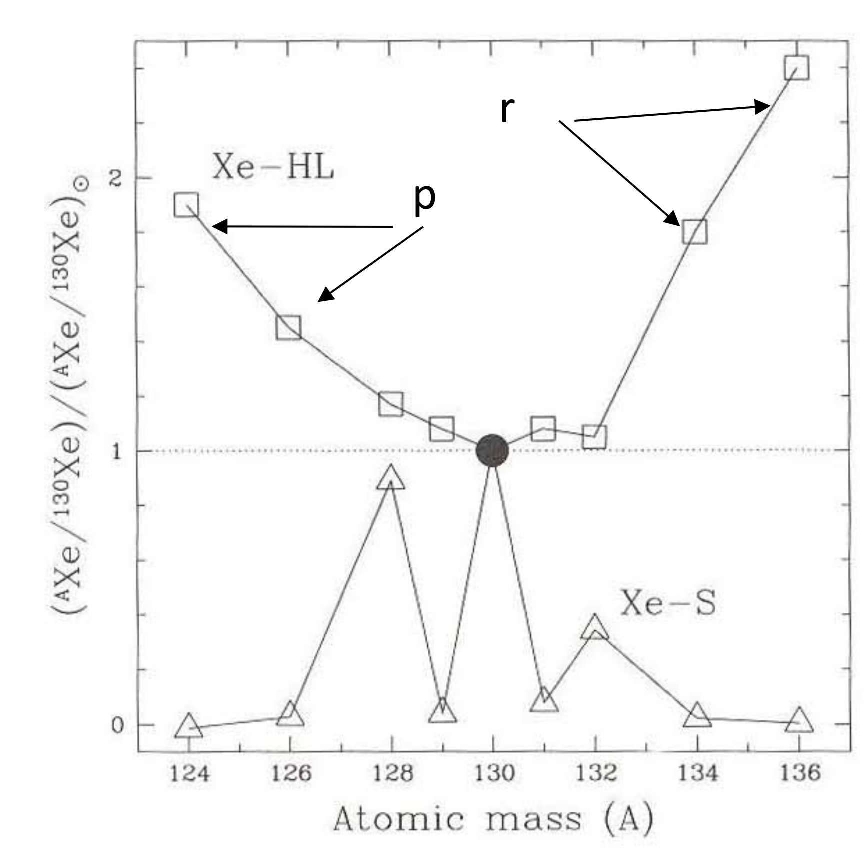


A part of elements produced in stars are locked in solids and travel trough ISM as interstellar dust… where are they gone ?

"Xenology" in chondrites



- The survival of presolar phases was first demonstrated by Renolds et al (1964) using the isotopic composition of noble gases in a carbonaceous chondrite (Renazzo)
- The Xe isotopic data show various components with relative ratios strongly different from the solar average values
- Two main component :
  - Xe-HL (Heavy-Light)
  - Xe-S



The Xe-HL component

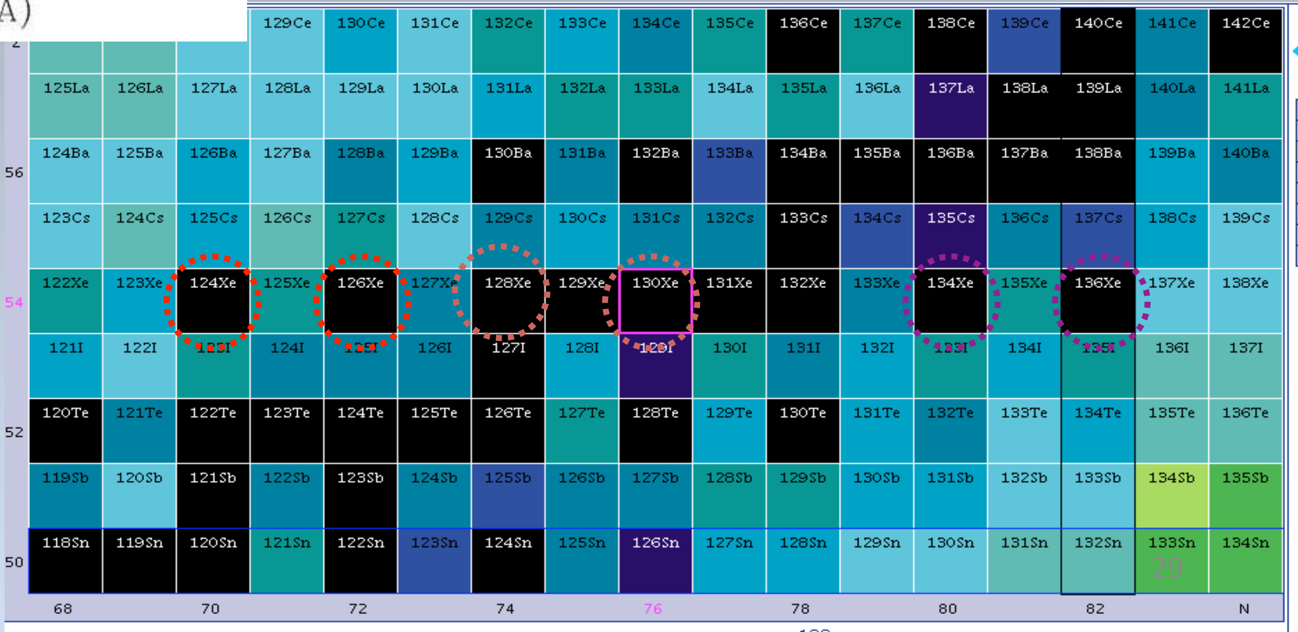
Xe-HL (Heavy-Light) holds the signature of :

- *p-process* (^{124}Xe, ^{126}Xe)
- *r-process* (^{134}Xe, ^{136}Xe)

^{124,126}Xe : p nuclei

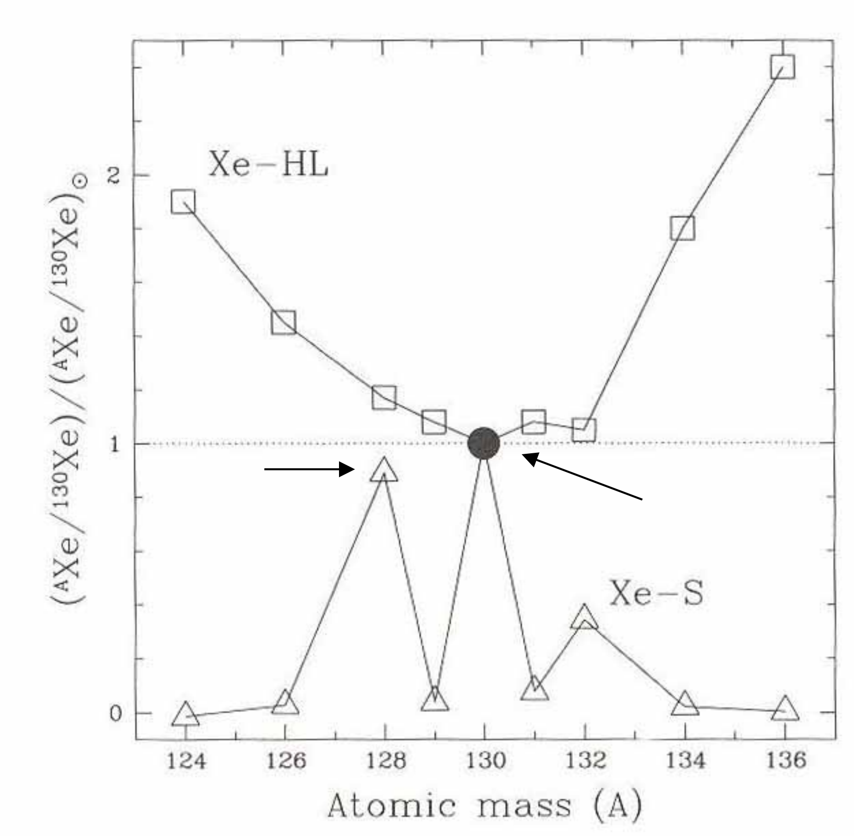
^{128,130}Xe : pure s nuclei

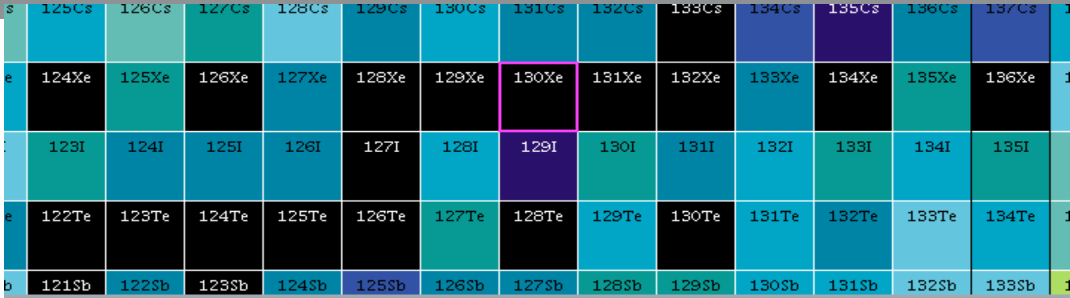
^{134,136}Xe : r nuclei



				129Ce	130Ce	131Ce	132Ce	133Ce	134Ce	135Ce	136Ce	137Ce	138Ce	139Ce	140Ce	141Ce	142Ce
	125La	126La	127La	128La	129La	130La	131La	132La	133La	134La	135La	136La	137La	138La	139La	140La	141La
56	124Ba	125Ba	126Ba	127Ba	128Ba	129Ba	130Ba	131Ba	132Ba	133Ba	134Ba	135Ba	136Ba	137Ba	138Ba	139Ba	140Ba
	123Cs	124Cs	125Cs	126Cs	127Cs	128Cs	129Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs
54	122Xe	123Xe	124Xe	125Xe	126Xe	127X	128Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe
	121I	122I	123I	124I	125I	126I	127I	128I	129I	130I	131I	132I	133I	134I	135I	136I	137I
52	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te	128Te	129Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te
	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb	127Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb
50	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn	126Sn	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn
	68		70		72		74		76		78		80		82		N

Xe-S bulk component





125Cs	126Cs	127Cs	128Cs	129Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs
124Xe	125Xe	126Xe	127Xe	128Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe
123I	124I	125I	126I	127I	128I	129I	130I	131I	132I	133I	134I	135I
122Te	123Te	124Te	125Te	126Te	127Te	128Te	129Te	130Te	131Te	132Te	133Te	134Te
121Sb	122Sb	123Sb	124Sb	125Sb	126Sb	127Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb

Relative overabundance of 2 pure *s-nuclei*

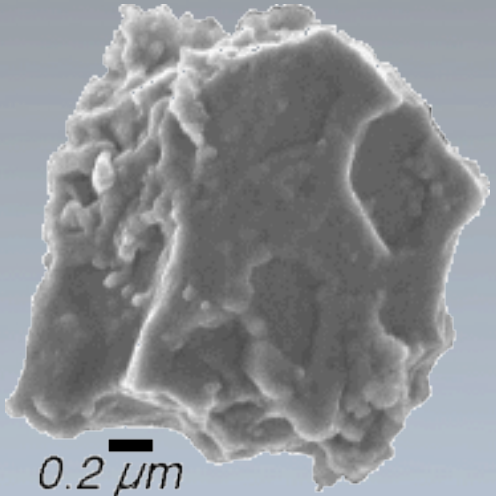
^{128}Xe and ^{130}Xe

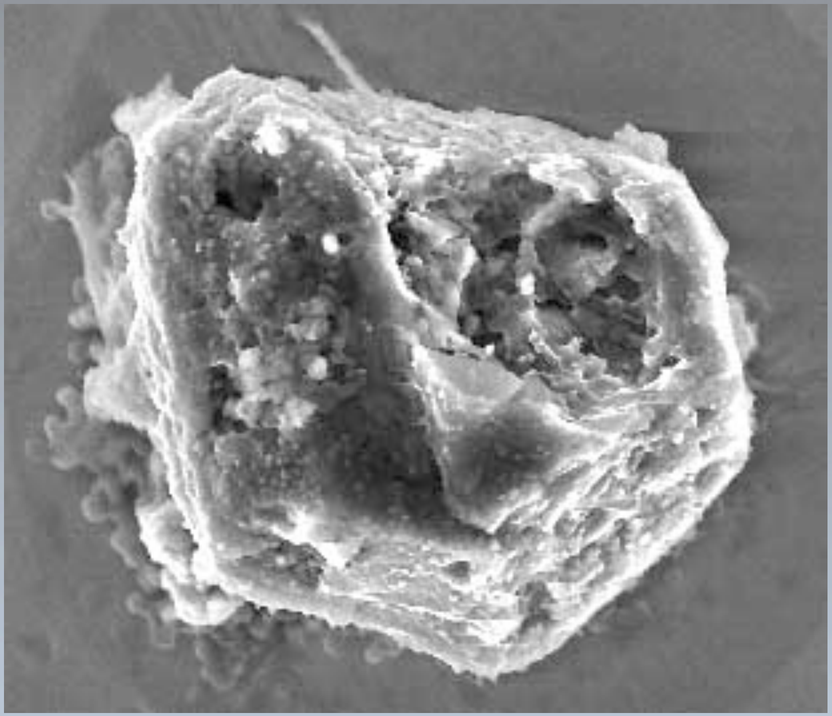
Xe-S holds the

s-*process* signature

Is it possible to identify
the carriers of these isotopic anomalies ?

The Xe-S component is carried by SiC

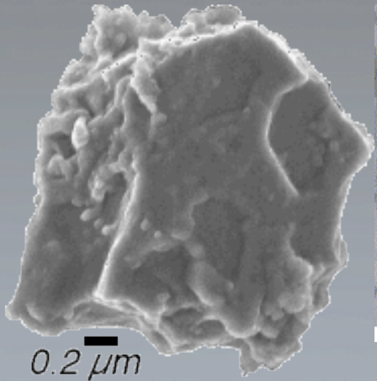


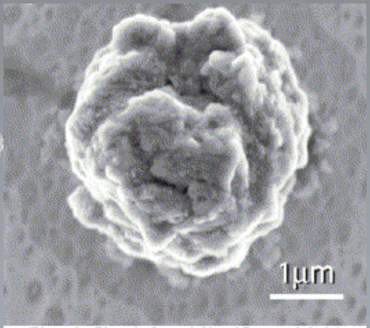


- It took 25 years to identify the carrier of these anomalies
- The size of these grains is 1-10 mm
- Thousands are analyzed so far

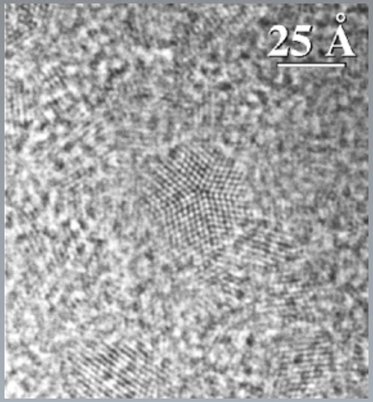
Presolar grains are extracted from the matrix of carbonaceous chondrites

Météorite d'Allende

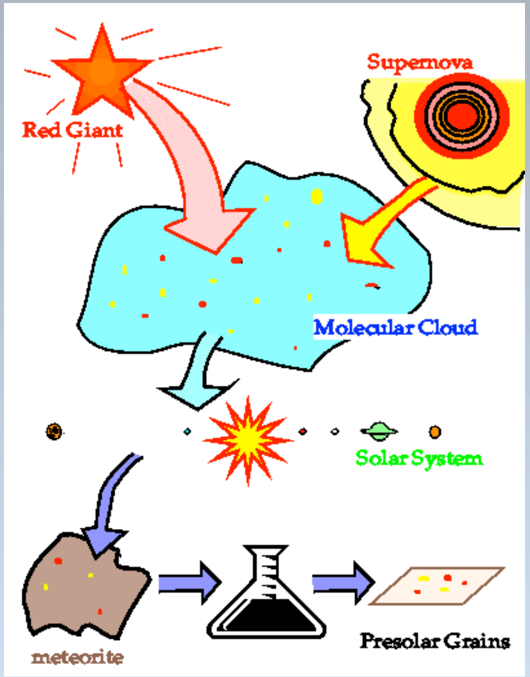




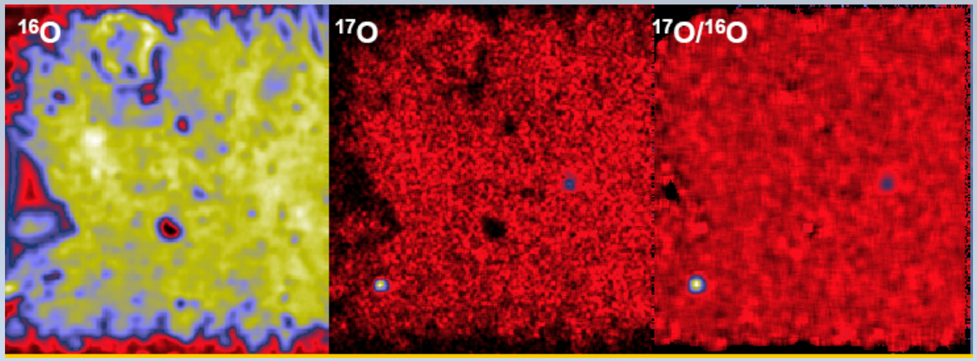
(Photo by Rhonda Stroud, Naval Research Lab.)



The matrix of chondrites contains small mineral phases (SiC, Graphites, nano-diamants … < 10 µm) directly inherited from stellar envelopes of generations prior the Sun.

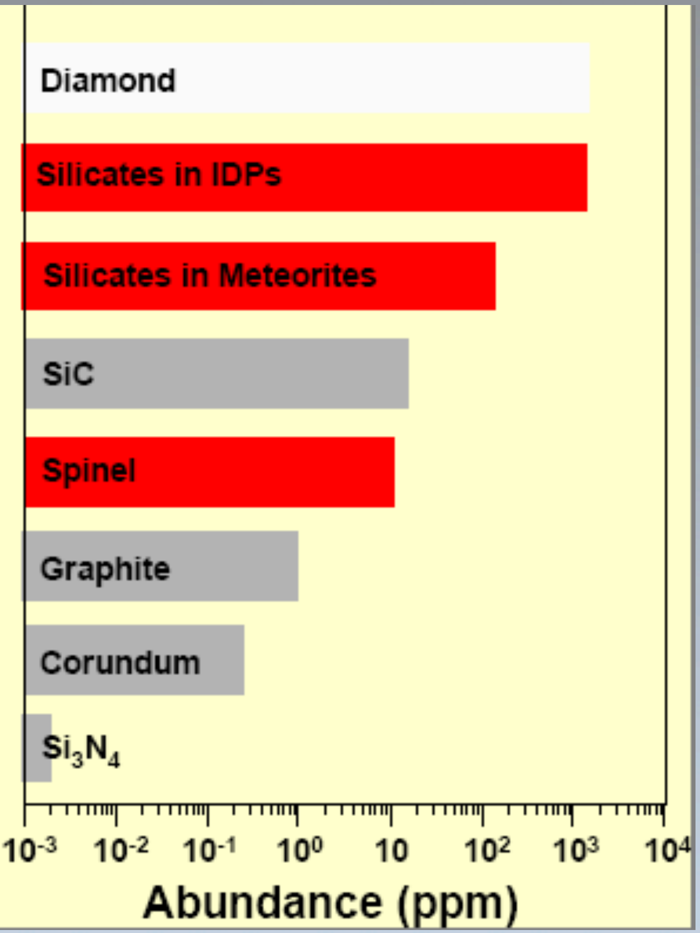


Larry Nittler,
Carnegie Institution of Washington



In-situ secondary ion mass image (P. Hoppe et al)

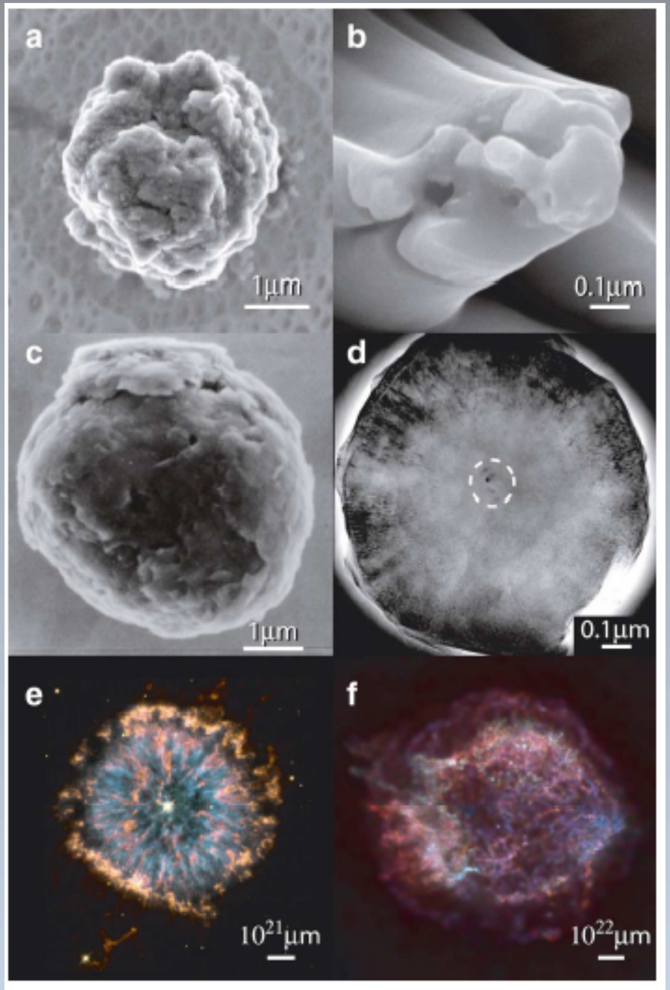
Presolar grains abondance in chondrites



SiC

Graphite

Planetary
nebulae
NGC 6751
HST



Spinel

TEM thin section
Graphite &
TiC

Remnant of
SN Cas A

Nittler EPSL 2003

Is it possible to identify the nucleosynthetic sites of these grains ?

Clues on the astrophysical sites of presolar grains

- Pre-solar grains are vapor phase condensate in stellar envelopes
- Presolar grains are **refractory**, Tcond = 1300-300 K°
- Their condensation sequence strongly on the composition of the stellar gas, mainly on the C/O ratio :
  - if **C/O < 1** all the carbon is locked in the **CO molecule** in the gas phase (stable even at high T°)

  ➔ condensation of oxides and silicates

  - If **C/O >1**, a large fraction of the carbon is available for solid phases

  ➔ condensation of graphites and carbides

Identification of the astrophysical site of SiC

- The average solar C/O is <1, $(C/O)_{sun} = 0.4$
  - in meteorites most of SiC are presolar

- SiC condense in a C rich environement: **C/O>1**
- Massive stars are not good candidates (they produce more O than C, C/O <1)

- SiC contain s-process nuclei (Xe-s carriers)

SiC condense in C-rich stars

that are rich in s-process nuclei

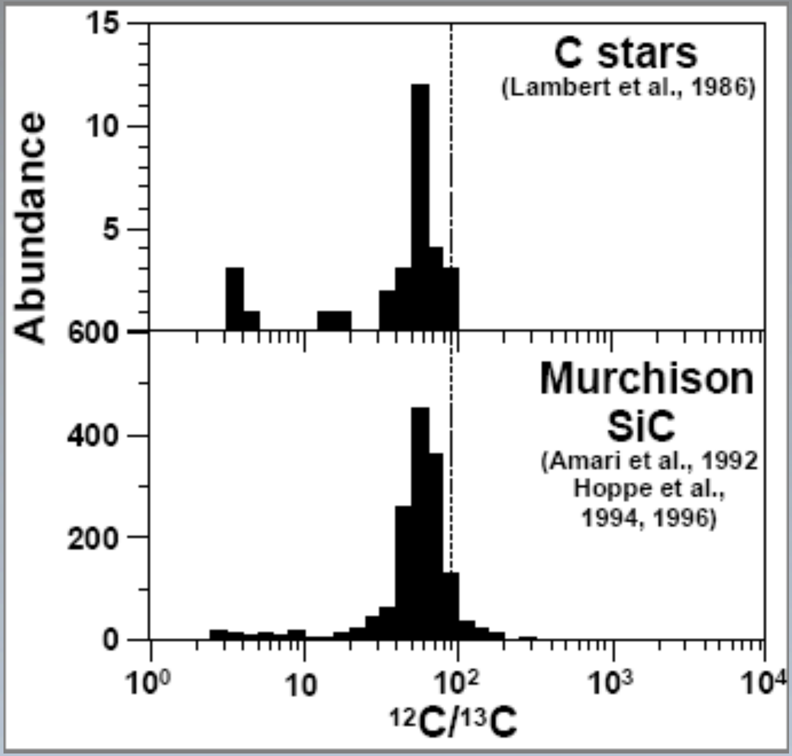
→ AGBs

Mainstream SiC are coming from AGB

Arguments :

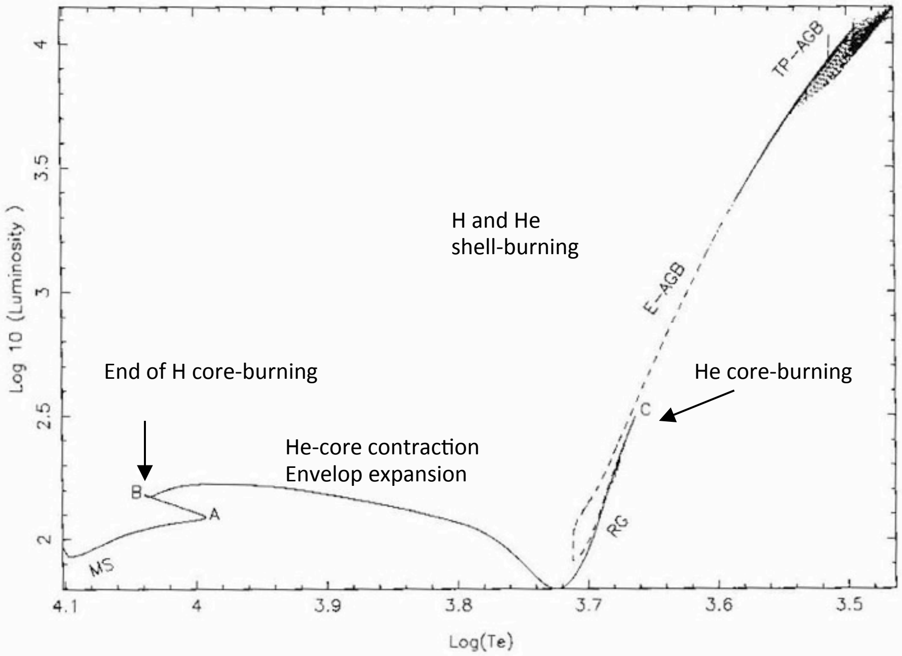
- The $^{12}C/^{13}C$ ratio distribution is similar to that observed in C-stars
- AGB are the main producers of *C-rich dust*
- SiC are seen in AGBs envelopes (*emission line @ 11.2 mm, Speck et al 1997*)

- SiC contain s-process elements
- The isotopic signatures in C & N are that expected from AGB



C isotopic ratios in C_2 bands in C-stars and in SiC

The stellar evolution in AGBs



H and He shell-burning

End of H core-burning

He core-burning

He-core contraction Envelop expansion

Fig. 4.3 Hertzsprung-Russell diagram, in which the stellar luminosity (on a Log_{10} scale) is plotted as a function of the effective (i.e. surface) temperature (also on a Log_{10} scale, and decreasing to the right), showing the theoretical evolution of a star of $Z = 0.02$ and mass 3 $M_{\odot}$. The label MS is for main sequence, RG for red giant, E-AGB for early Asymptotic Giant Branch and TP-AGB for thermally pulsing Asymptotic Giant Branch (see text for details and explanation of points labelled A, B and C).

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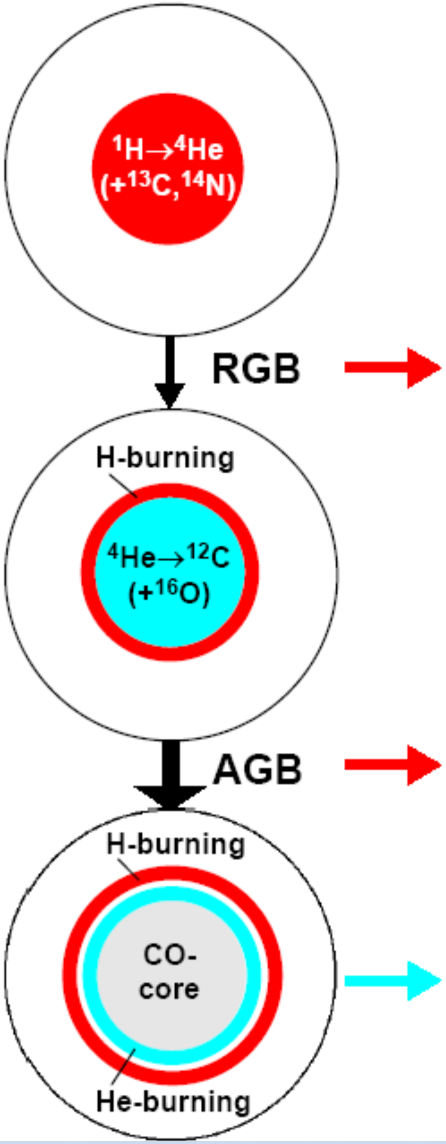
The internal structure of a 3 M AGB



$^{1}\text{H} \rightarrow {}^{4}\text{He}$ (+^{13}C, ^{14}N)

Main Sequence

RGB

"1. Dredge-up"
(^{4}He, ^{13}C, ^{14}N)

H-burning

$^{4}\text{He} \rightarrow {}^{12}\text{C}$ (+^{16}O)

AGB

M > 4 $M_{\odot}$:
"2. Dredge-up"
(^{4}He, ^{13}C, ^{14}N)

H-burning

CO-core

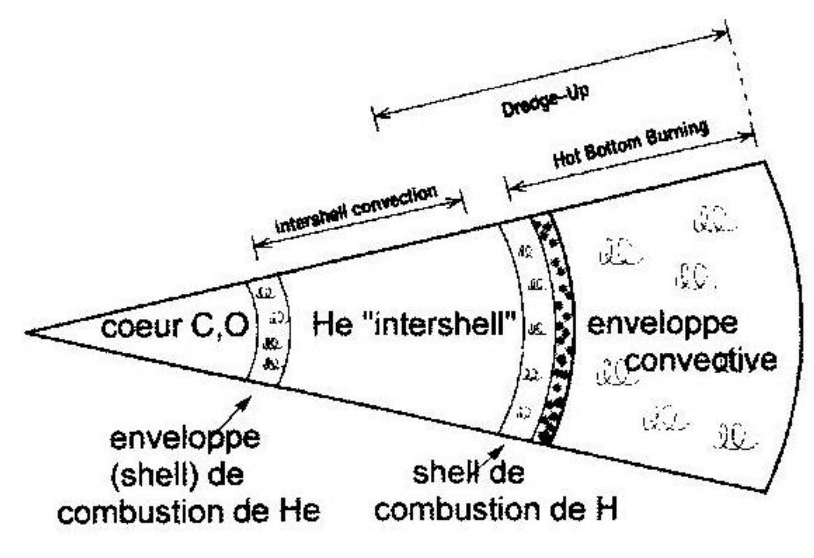
He-burning

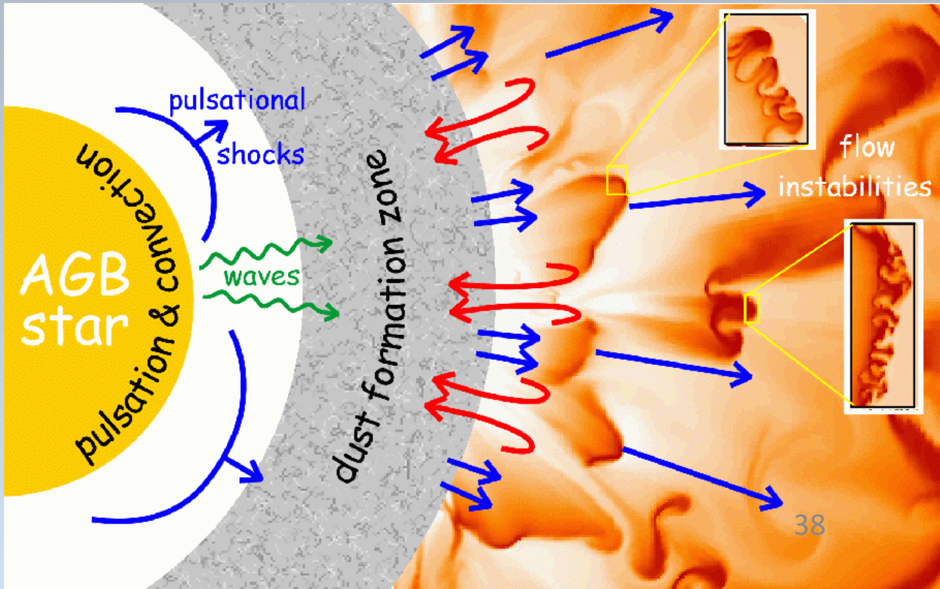
"3. Dredge-up"
(^{12}C, s-process El.

→ Carbon star
(C/O > 1)

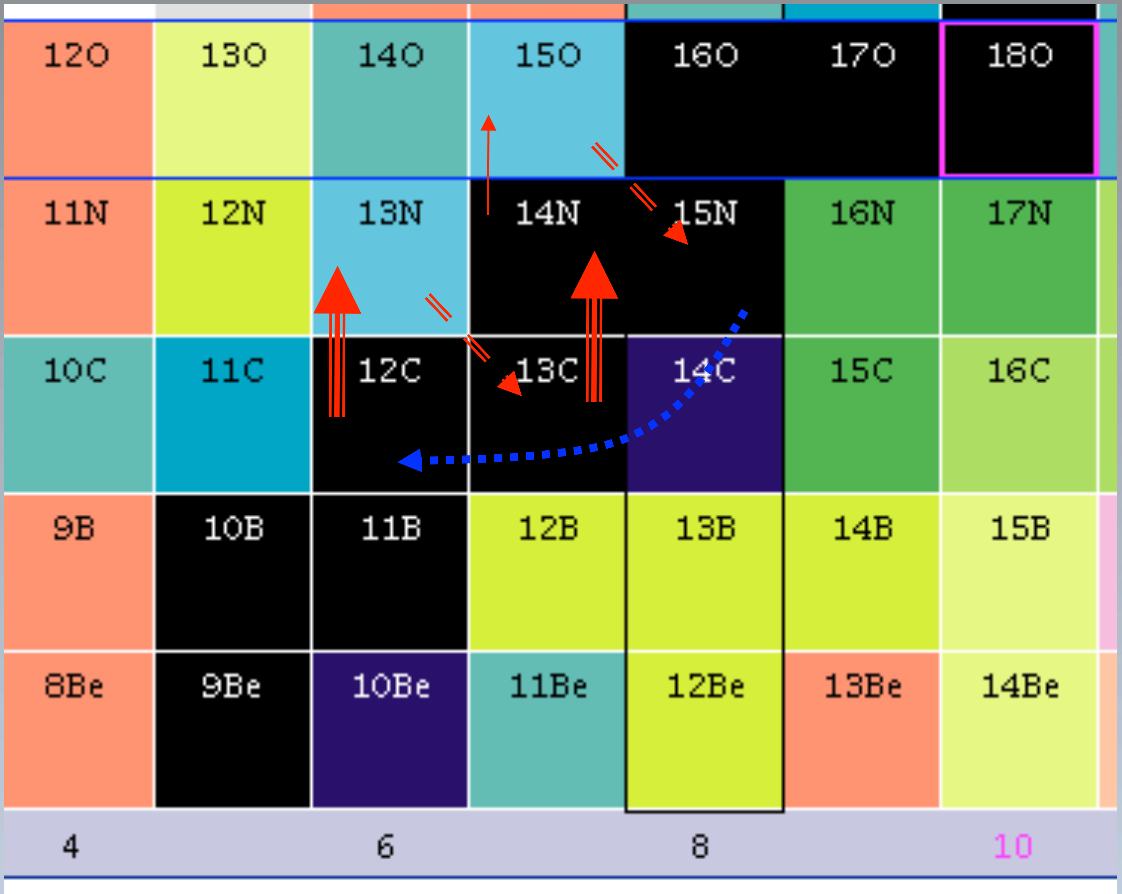
AGB stars, a carbonaceous dust factory

- He-shell burning produces C
- H & He shell burning
  - He burning on the aches of the CNO cycle (^{14}N)
  - $^{14}N(\alpha,\gamma)^{18}O(\alpha,\gamma)^{22}Ne$
  - Stars rich in ^{22}Ne





Reminders on the CNO cycle



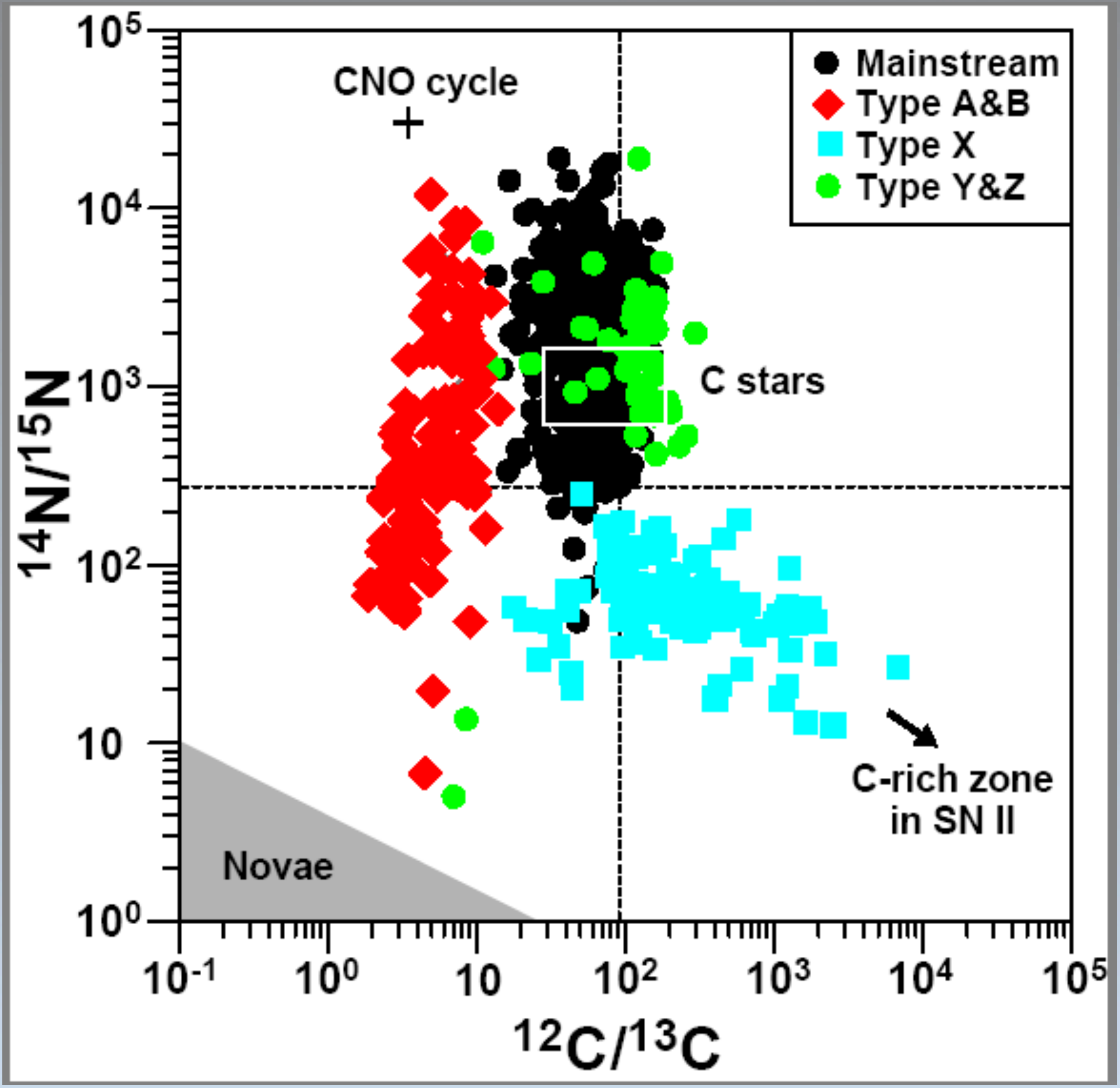
C/N = 3 → 0.01

$^{12}C/\mathbf{^{13}C}$= 89 → 3

$^{14}N/\mathbf{^{15}N}$ = 272 → >>10 000

- $\mathbf{^{12}C}(p,\gamma)^{13}N\ (\beta^+)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O\ (\beta^+)\ ^{15}N\mathbf{(p,\alpha)}\mathbf{^{12}C}$
- $^{14}N(p,\gamma)$ is week
- The CN cycle favors ^{13}C and ^{14}N

SiC compared to the CNO end-member

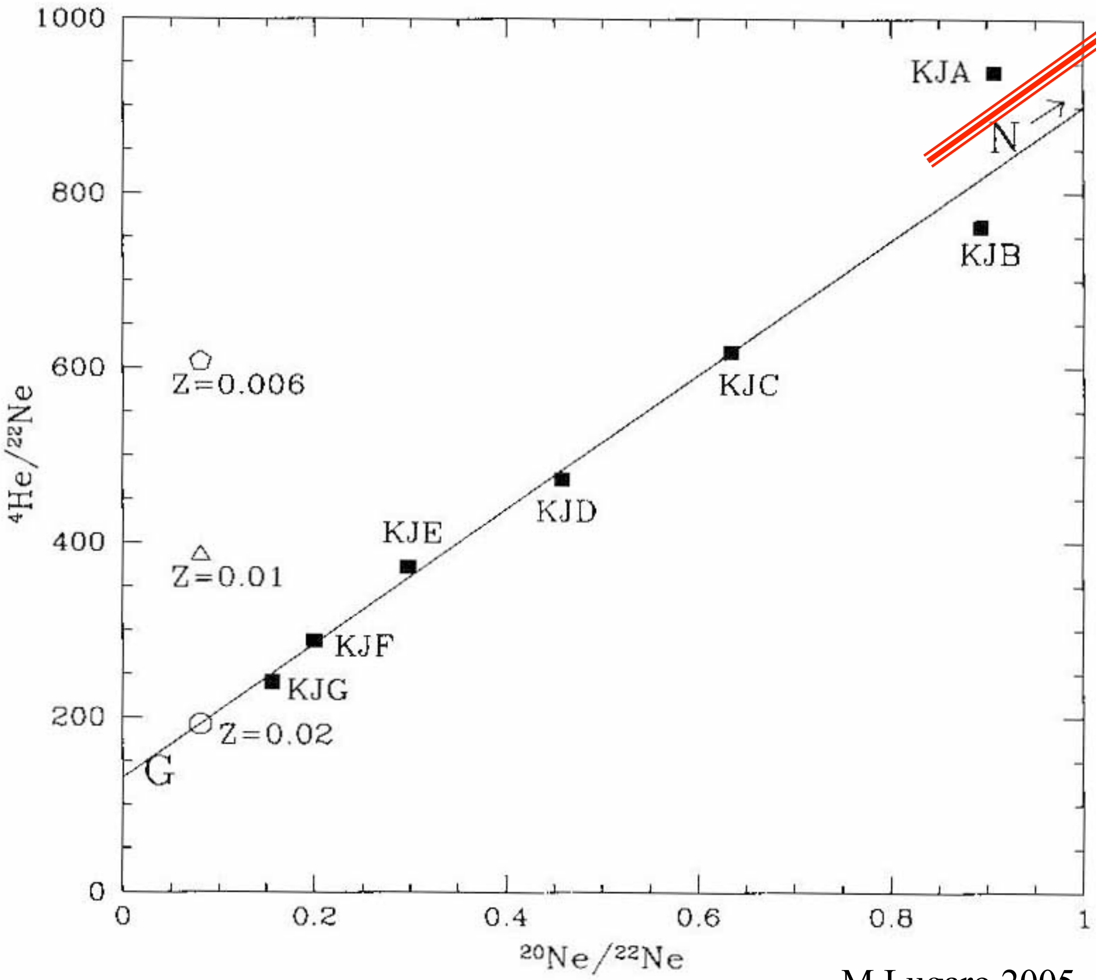


Ne-H in SiC

The solar end-member :

$^{4}He/^{22}Ne=2114$

$^{20}Ne/^{22}Ne=12.4$



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- The Ne concentration must be compared to other gases (here He) because it is included by implantation and not condensation.

- SiC are enriched by a factor of 100 in ^{22}Ne compared to solar composition.
- In He shell burning, large amount of ^{22}Ne is produced by : **$^{14}N(\alpha,\gamma)^{18}O(\alpha,\gamma)^{22}Ne$**

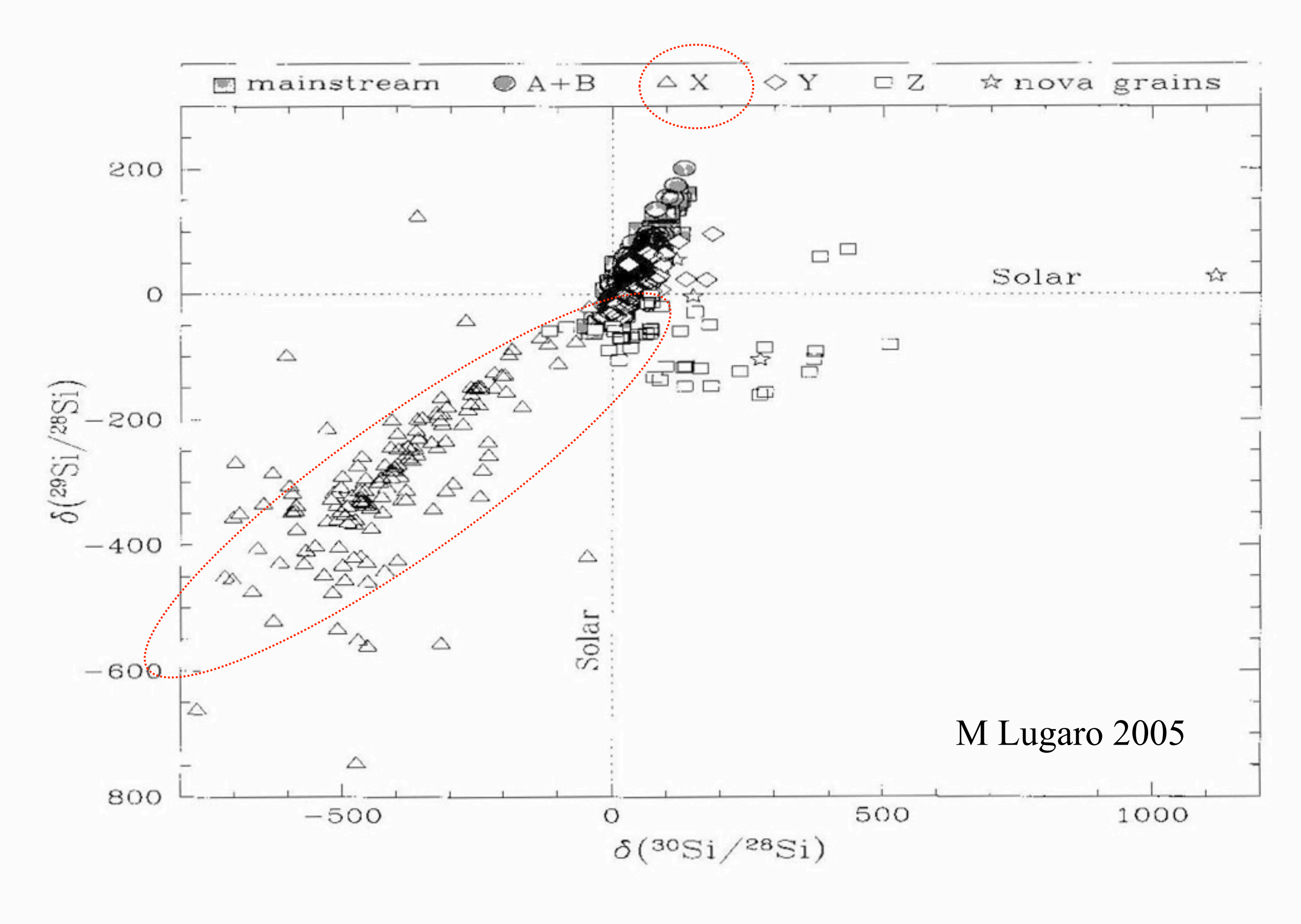
- The linear correlation comes from a mixing between :
  - The solar end-member
  - The ^{22}Ne AGB end-member.

Si isotopic composition of SiC

Different populations :

- Mainstream SiC grains do not exhibit large differences compared to solar values

- **SiC X grains are highly enriched in ^{28}Si, they originate from massive stars**



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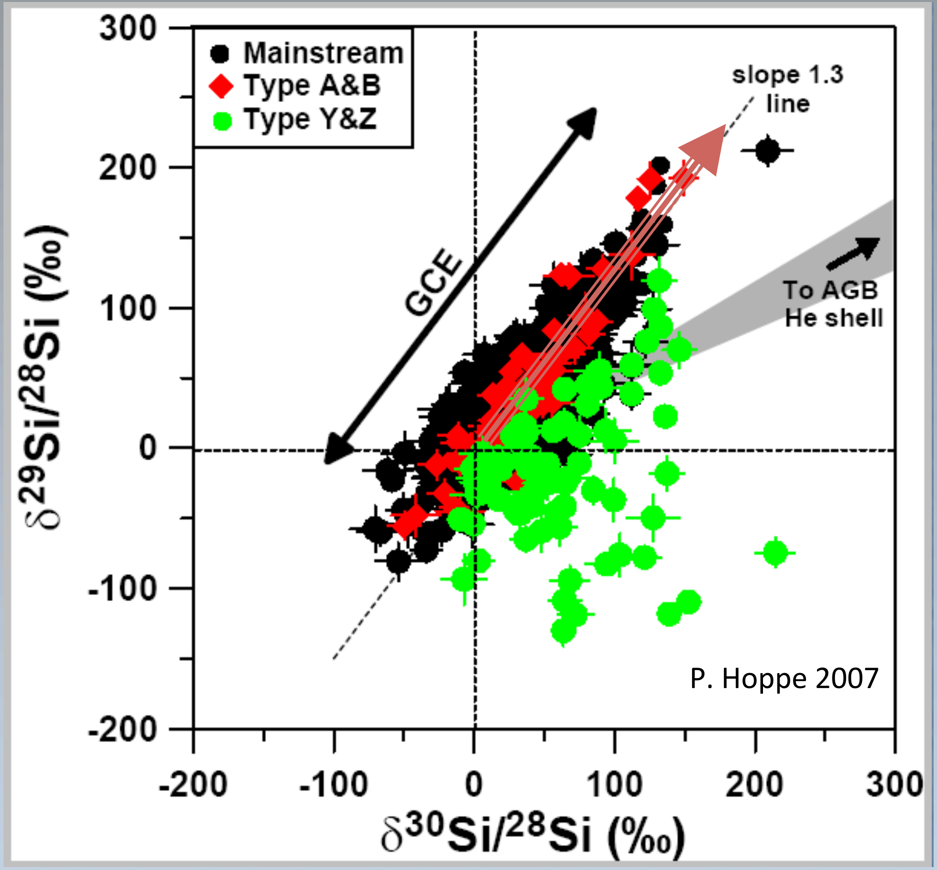
$$\delta\left(\frac{^{29}Si}{^{30}Si}\right)=\left(\left(\frac{^{29}Si}{^{30}Si}\right)_{sample}\Big/\left(\frac{^{29}Si}{^{30}Si}\right)_{\oplus}-1\right)\times 1000$$

The chemical evolution of the galaxy

- **^{28}Si is a primary nucleus (produced directly from initial H and He)**
- **$^{29,30}Si$ are secondary nuclei, their production depends on the star metallicity**
- **The chemical evolution of the galaxy (CEG) gradually enriches the galaxy in heavy isotopes ($^{29,30}Si$)**
- **However a question is still pending, why do the grains appears to be younger than the solar system itself ?!**

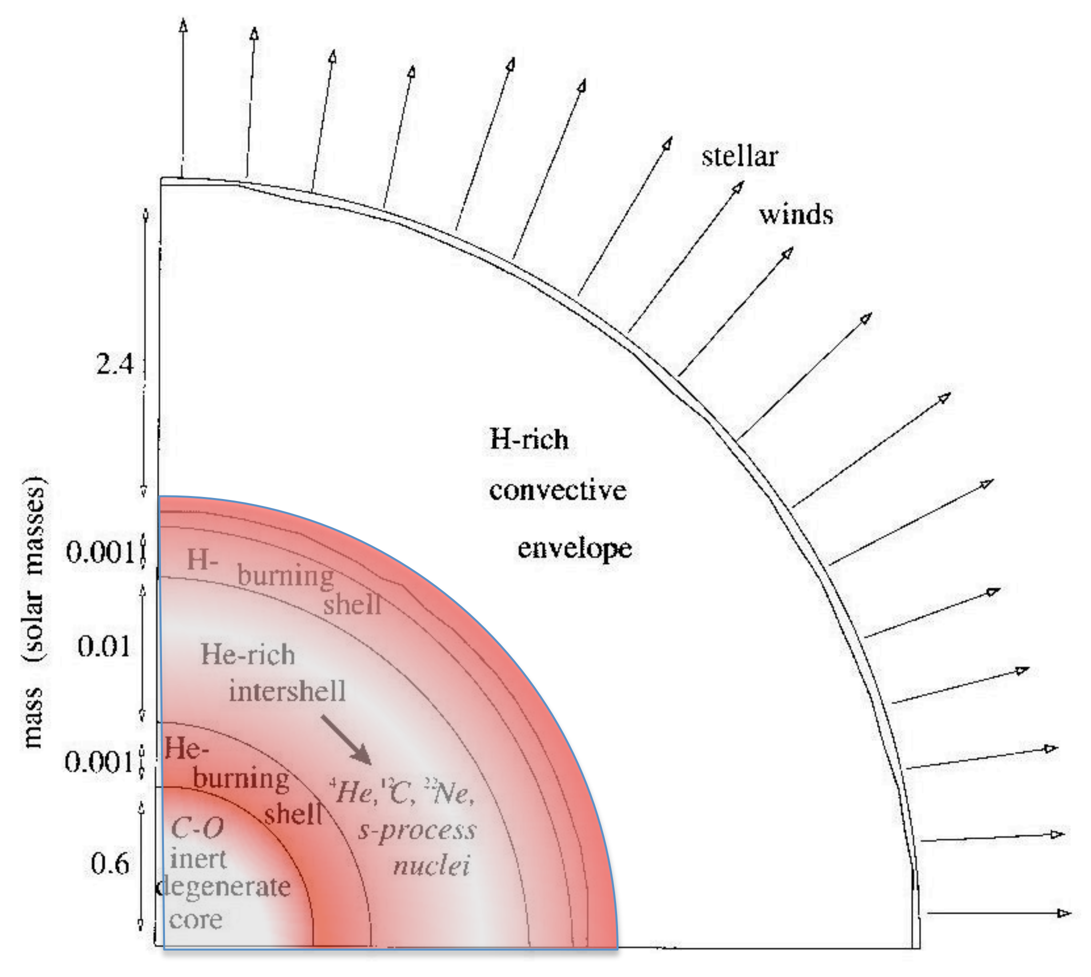


P. Hoppe 2007

Heavy elements in SiC

- Z > 26 elements are rare (traces, ~100 ppm)
- S-process elements are overabundant in MS SiC
  - Zr, Ba : 30 times more abundant than solar
- They exhibit isotopic signatures of the s-process
- The precision on the isotopic ratios (better than a few %) provides unique constraints on stellar nucleosynthesis models
- Large diversity of isotopic compositions:
  - different stellar conditions
  - the incorporation mechanism varies depending on the volatility of the element (vapor phase condensation, implantation …)

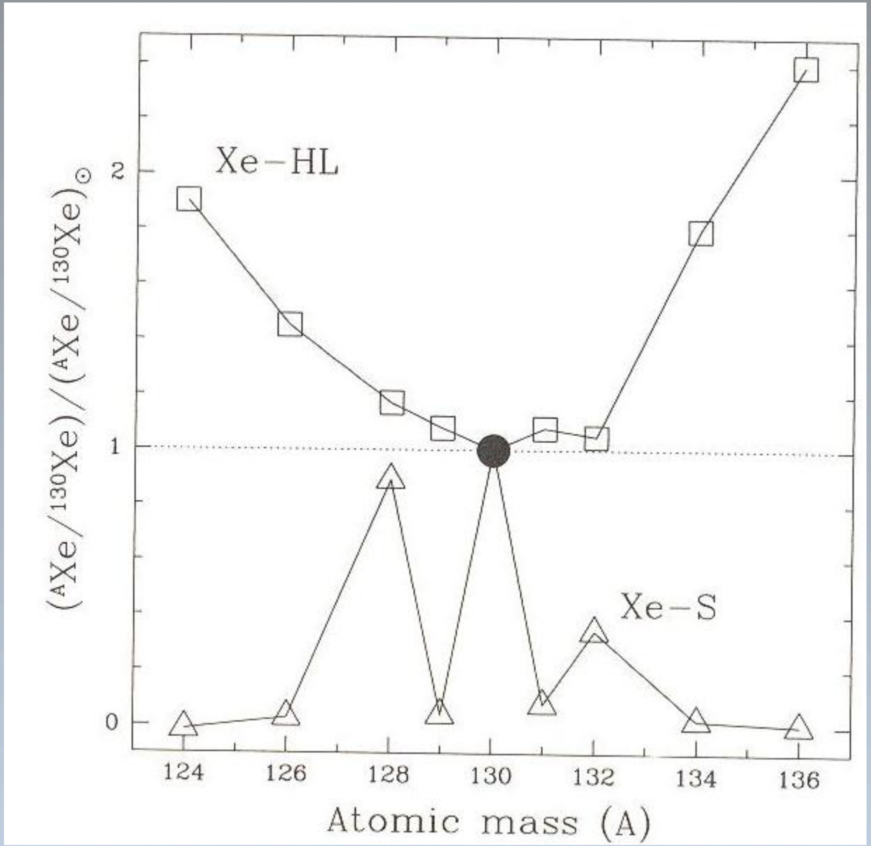
Neutrons sources in AGBs

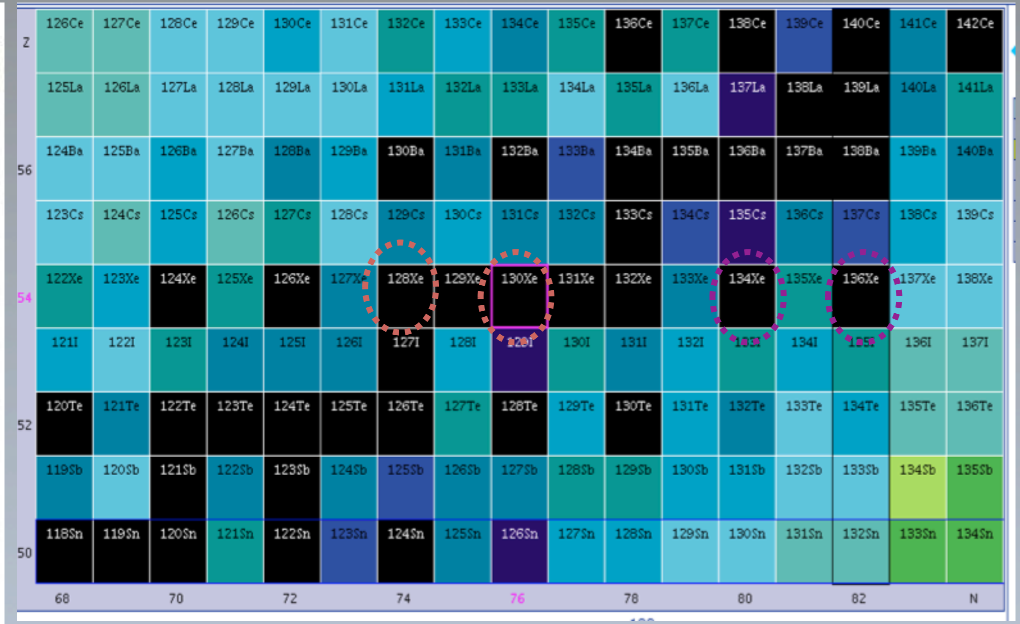


In the HeIS, the medium is dominated by a resulting from the H-shell (a=70 at%)

- Two neutron sources:
  - **$^{13}C(\alpha,n)^{16}O$** is energetically favored, active first when T > 0.9 10^8 K
  - $^{22}Ne(\alpha,n)^{25}Mg$ (a lot of ^{22}Ne) active for T > 3 10^8 K
- The s-process takes place in the **He-rich inter-shell (HeIS)** between the H-burning shell and the He-burning shell

S-process signature



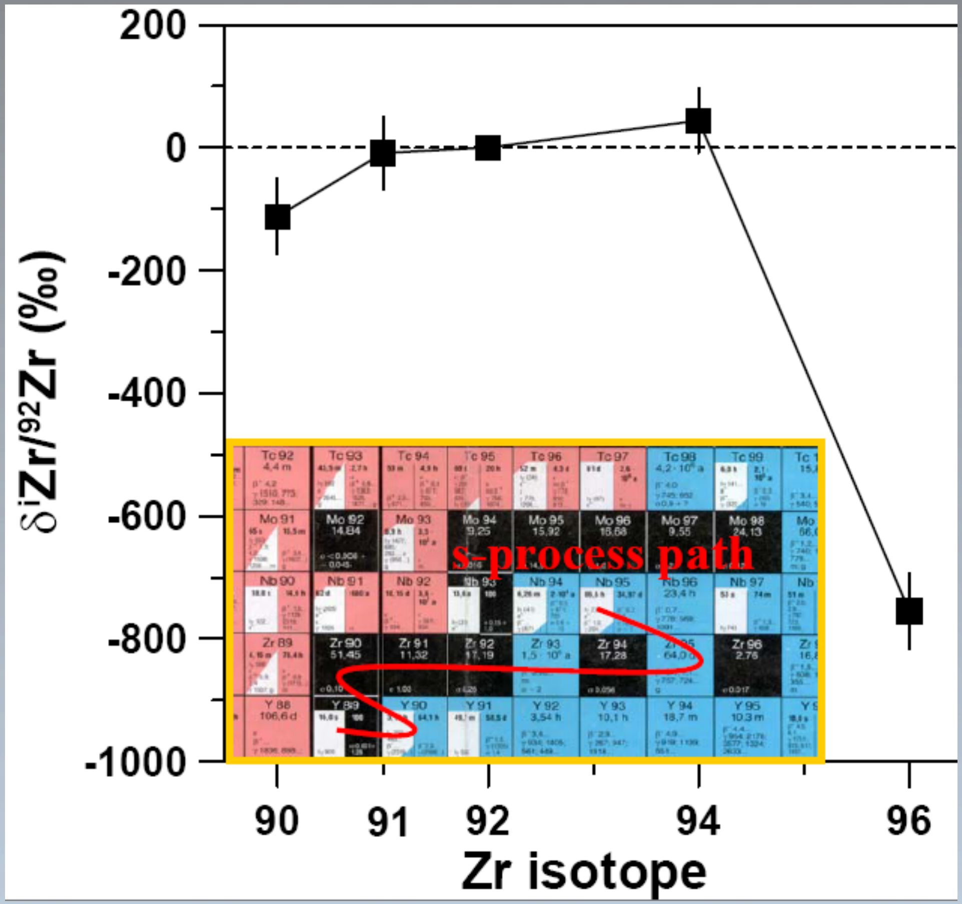


Z	126Ce	127Ce	128Ce	129Ce	130Ce	131Ce	132Ce	133Ce	134Ce	135Ce	136Ce	137Ce	138Ce	139Ce	140Ce	141Ce	142Ce
	125La	126La	127La	128La	129La	130La	131La	132La	133La	134La	135La	136La	137La	138La	139La	140La	141La
56	124Ba	125Ba	126Ba	127Ba	128Ba	129Ba	130Ba	131Ba	132Ba	133Ba	134Ba	135Ba	136Ba	137Ba	138Ba	139Ba	140Ba
	123Cs	124Cs	125Cs	126Cs	127Cs	128Cs	129Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs
54	122Xe	123Xe	124Xe	125Xe	126Xe	127Xe	128Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe
	121I	122I	123I	124I	125I	126I	127I	128I	129I	130I	131I	132I	133I	134I	135I	136I	137I
52	120Te	121Te	122Te	123Te	124Te	125Te	126Te	127Te	128Te	129Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te
	119Sb	120Sb	121Sb	122Sb	123Sb	124Sb	125Sb	126Sb	127Sb	128Sb	129Sb	130Sb	131Sb	132Sb	133Sb	134Sb	135Sb
50	118Sn	119Sn	120Sn	121Sn	122Sn	123Sn	124Sn	125Sn	126Sn	127Sn	128Sn	129Sn	130Sn	131Sn	132Sn	133Sn	134Sn
	68		70		72		74		76		78		80		82		N

^{128}Xe et ^{130}Xe are s-only nuclei

The SiC are the carriers of the Xe-S component that exhibit excess of ^{128}Xe et ^{130}Xe

Zr isotopes in SiC



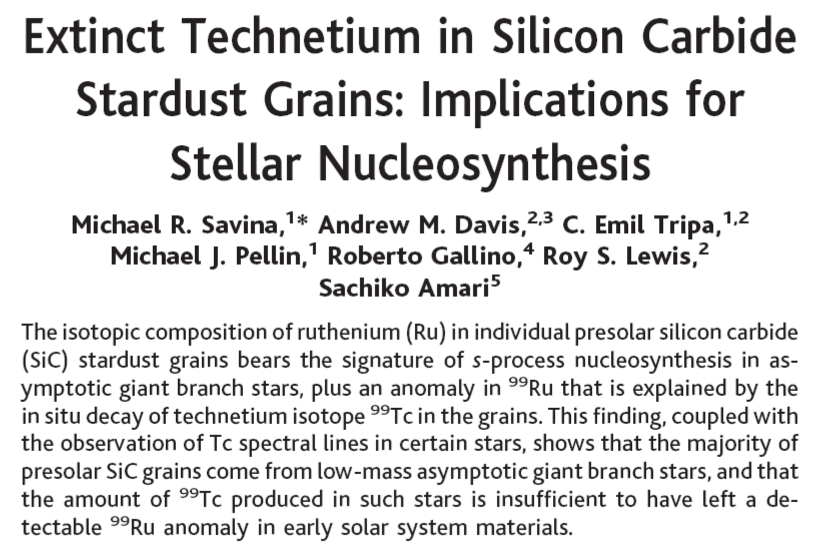
Nicolussi et al 1997

$$\delta\, {}^{i}Zr/{}^{96}Zr = \left[\frac{\left({}^{i}Zr/{}^{96}Zr\right)_{sample}}{\left({}^{i}Zr/{}^{96}Zr\right)_{solaire}} - 1\right]\times 1000$$

d units represent per mil deviations from the “solar” composition (‰)

^{91,92,94}Zr nuclei are relatively more abundant than ^{96}Zr

Ru isotopes in SiC

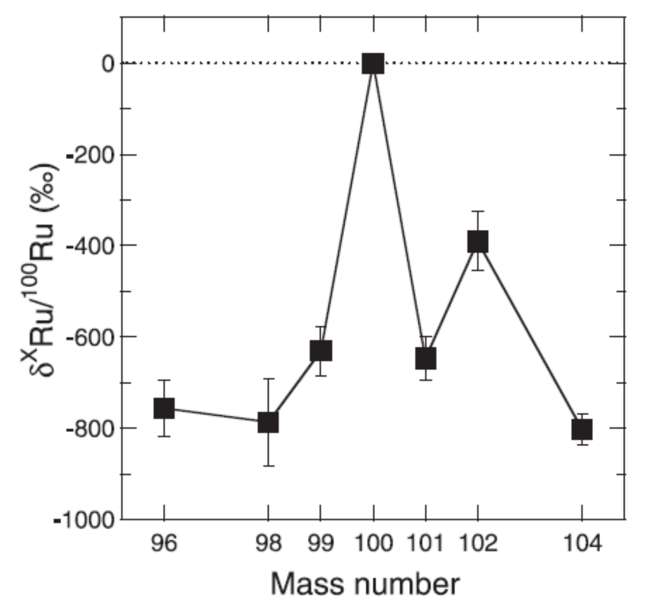


Extinct Technetium in Silicon Carbide Stardust Grains: Implications for Stellar Nucleosynthesis

Michael R. Savina,[1]* Andrew M. Davis,[2,3] C. Emil Tripa,[1,2]
Michael J. Pellin,[1] Roberto Gallino,[4] Roy S. Lewis,[2]
Sachiko Amari[5]

The isotopic composition of ruthenium (Ru) in individual presolar silicon carbide (SiC) stardust grains bears the signature of *s*-process nucleosynthesis in asymptotic giant branch stars, plus an anomaly in ^{99}Ru that is explained by the in situ decay of technetium isotope ^{99}Tc in the grains. This finding, coupled with the observation of Tc spectral lines in certain stars, shows that the majority of presolar SiC grains come from low-mass asymptotic giant branch stars, and that the amount of ^{99}Tc produced in such stars is insufficient to have left a detectable ^{99}Ru anomaly in early solar system materials.

Savina et al. Science 2004



REPORTS

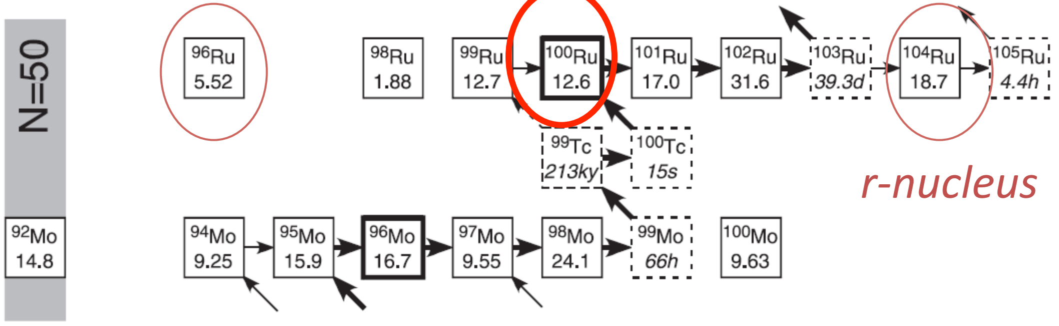
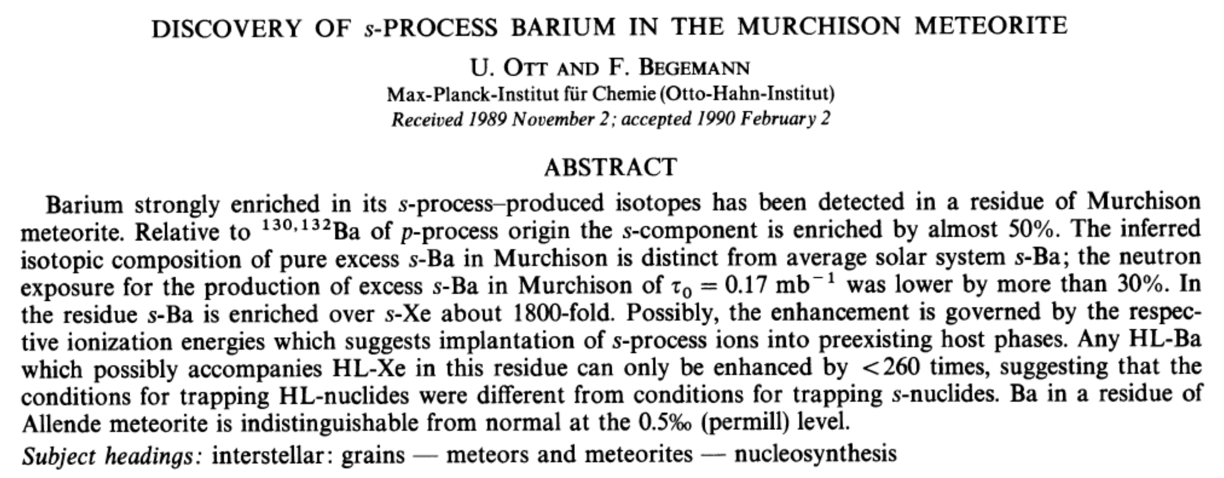


Fig. 1. Chart of the nuclides in the Ru region. Percent abundances (nonitalic) are shown for each stable isotope; laboratory half-lives (italic) are shown for each unstable isotope. The main *s*-process path is shown as bold arrows, and branches along the *s*-path are shown as finer arrows; ^{99}Tc decay that occurs in the envelope after TDU is shown as a dashed arrowtail. Unstable nuclei are outlined in dashed lines; *s*-process–only isotopes are outlined in bold. ^{96}Ru and ^{98}Ru are *p*-process isotopes; ^{100}Ru is an *s*-process–only isotope (it is shielded from the *r*-process by stable ^{100}Mo); ^{104}Ru is an *r*-process isotope; and ^{99}Ru, ^{101}Ru, and ^{102}Ru are produced by both the *r*- and *s*-processes.

Excess in ^{100}Ru (*s-only nucleus*)

Ba isotopes in SiC



DISCOVERY OF *s*-PROCESS BARIUM IN THE MURCHISON METEORITE

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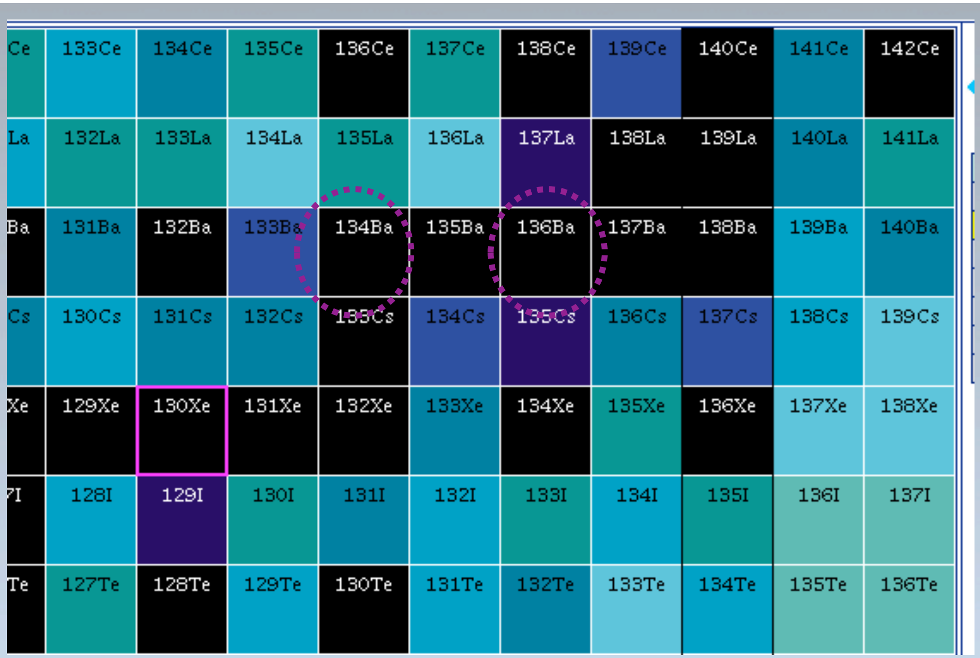
Received 1989 November 2; accepted 1990 February 2

ABSTRACT

Barium strongly enriched in its *s*-process–produced isotopes has been detected in a residue of Murchison meteorite. Relative to ^{130,132}Ba of *p*-process origin the *s*-component is enriched by almost 50%. The inferred isotopic composition of pure excess *s*-Ba in Murchison is distinct from average solar system *s*-Ba; the neutron exposure for the production of excess *s*-Ba in Murchison of $\tau_0 = 0.17$ mb^{-1} was lower by more than 30%. In the residue *s*-Ba is enriched over *s*-Xe about 1800-fold. Possibly, the enhancement is governed by the respective ionization energies which suggests implantation of *s*-process ions into preexisting host phases. Any HL-Ba which possibly accompanies HL-Xe in this residue can only be enhanced by <260 times, suggesting that the conditions for trapping HL-nuclides were different from conditions for trapping *s*-nuclides. Ba in a residue of Allende meteorite is indistinguishable from normal at the 0.5‰ (permill) level.

Subject headings: interstellar: grains — meteors and meteorites — nucleosynthesis



Ce	133Ce	134Ce	135Ce	136Ce	137Ce	138Ce	139Ce	140Ce	141Ce	142Ce
La	132La	133La	134La	135La	136La	137La	138La	139La	140La	141La
Ba	131Ba	132Ba	133Ba	134Ba	135Ba	136Ba	137Ba	138Ba	139Ba	140Ba
Cs	130Cs	131Cs	132Cs	133Cs	134Cs	135Cs	136Cs	137Cs	138Cs	139Cs
Xe	129Xe	130Xe	131Xe	132Xe	133Xe	134Xe	135Xe	136Xe	137Xe	138Xe
7I	128I	129I	130I	131I	132I	133I	134I	135I	136I	137I
Te	127Te	128Te	129Te	130Te	131Te	132Te	133Te	134Te	135Te	136Te

Enrichments in ^{134}Ba and ^{136}Ba (s-only nuclei)

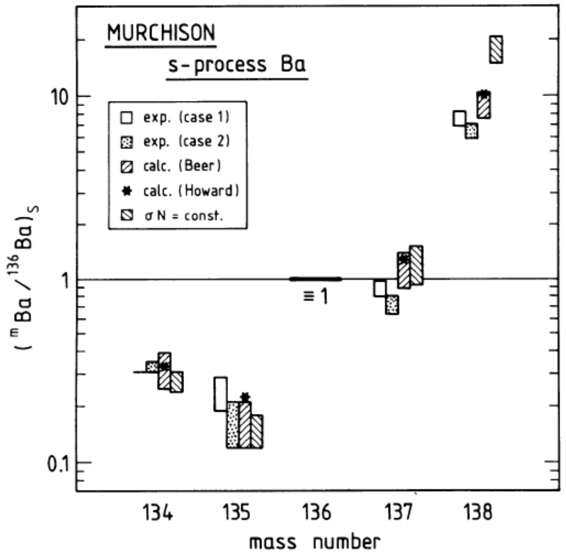


Fig. 2.—Isotopic composition of *s*-process Ba deduced from the mass fractionation corrected data (case 1) and uncorrected data (case 2) for Murchison R1CPF. The experimental data are compared to calculated values of Howard *et al.* (1986) and H. Beer (1989, personal communication) and to the local approximation (σN = const).

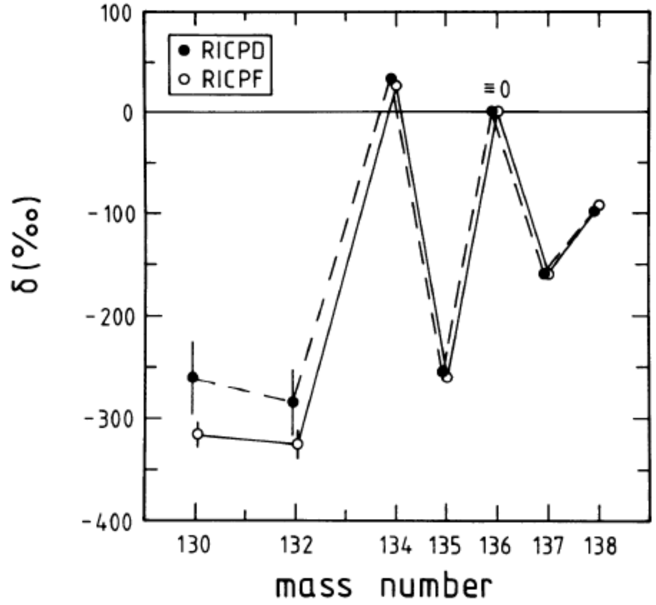
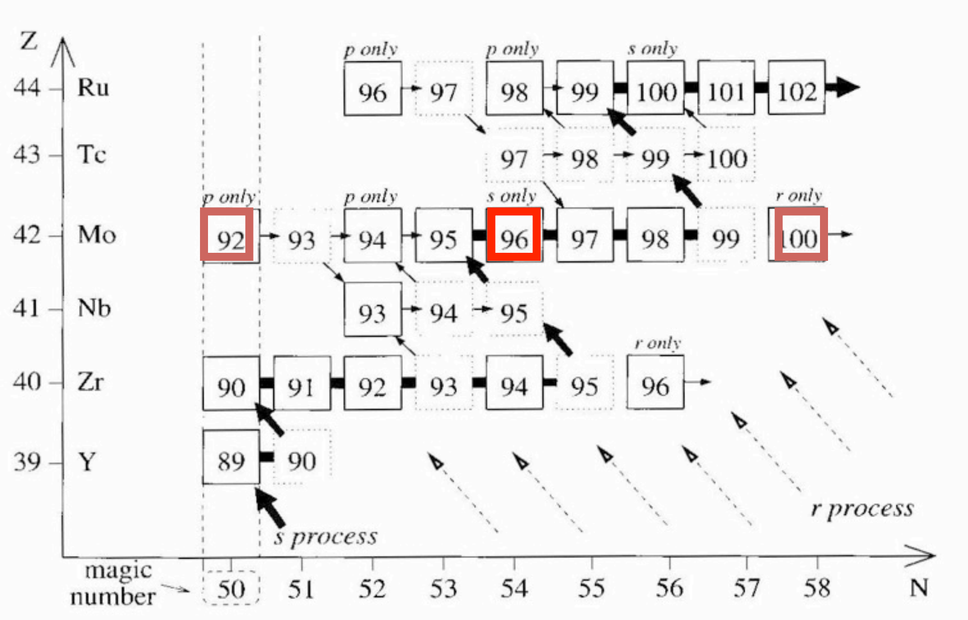
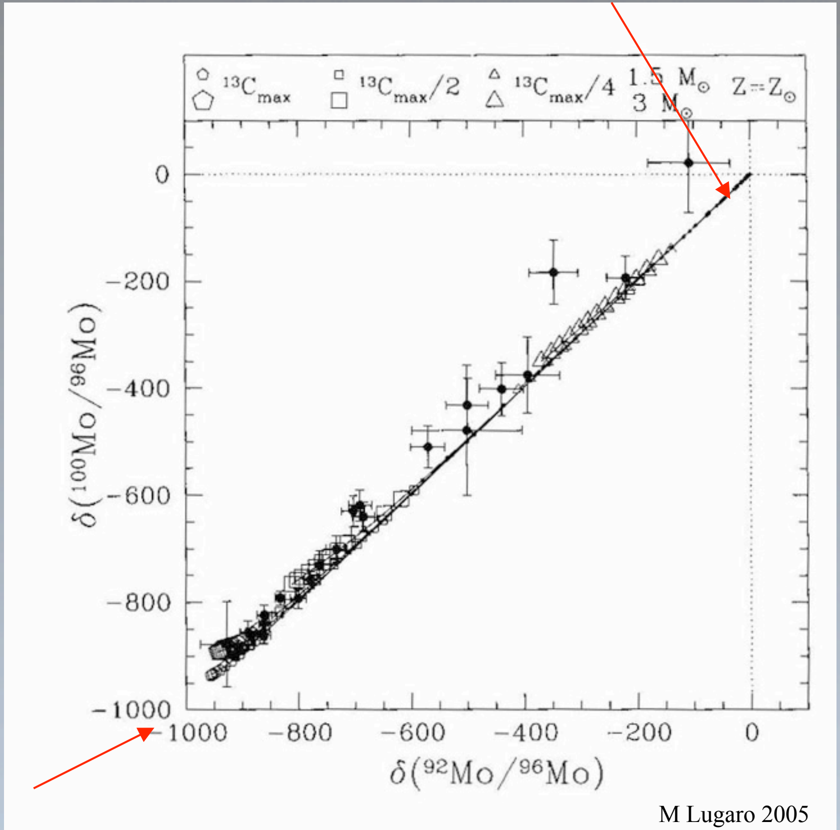


Fig. 1.—Isotopic composition of Ba in Murchison R1CPD (*filled circles*) and R1CPF (*open circles*). Shown is the deviation from normal in permill with ^{136}Ba as index isotope.

s-only nuclei vs. *p-only* (or *r-only)* nuclei



Solar composition (i.e. starting composition)



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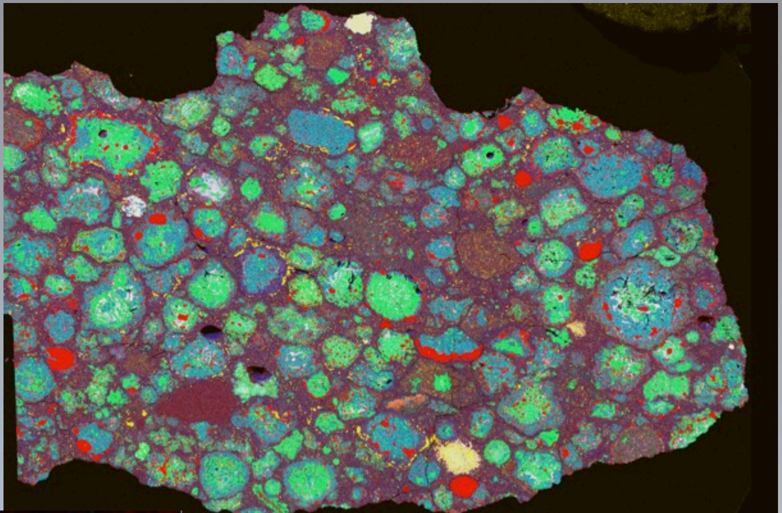
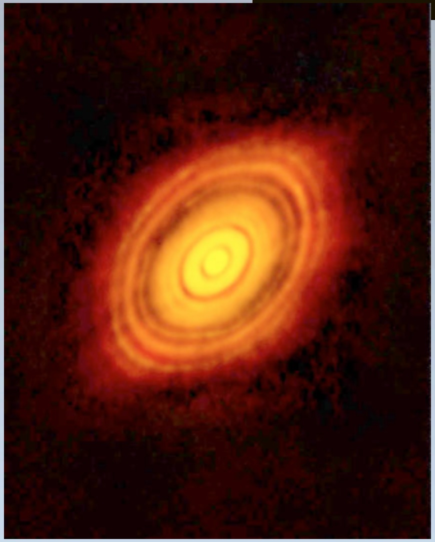
Mo isotopic composition in SiC

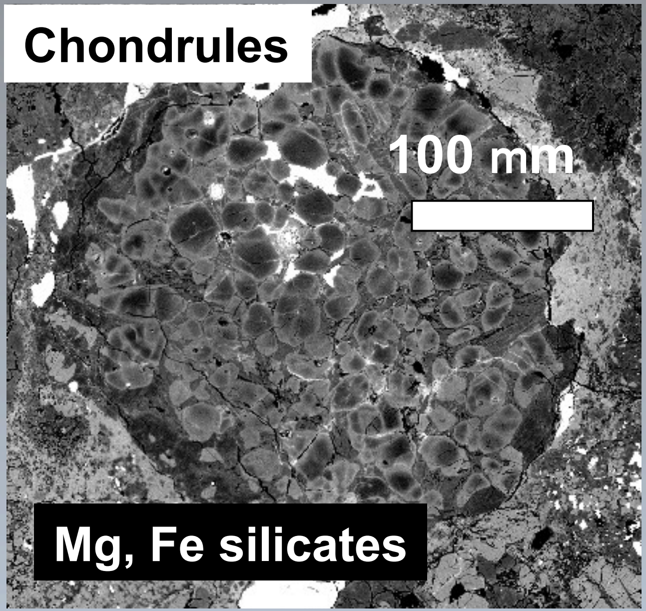
s process pure ^{96}Mo

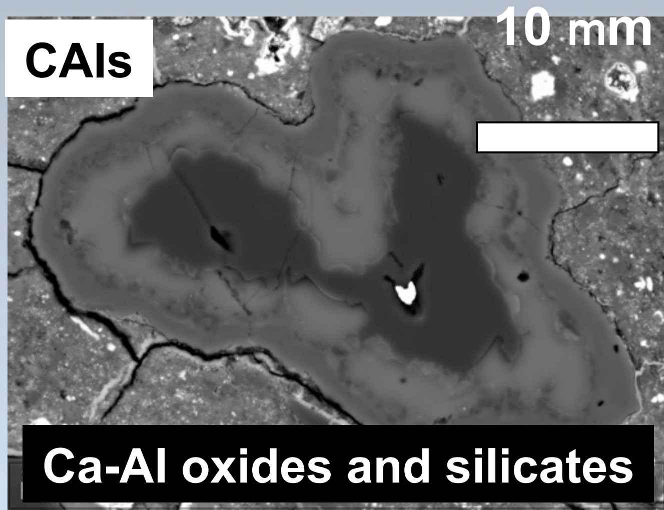
- Mixing between a solar end-member (i.e. the star's envelope) and a pure s-process end-member
- **^{96}Mo is produced in the SiC producing stars (AGB) but not ^{100}Mo nor ^{92}Mo**
- **The grains are very enriched in ^{96}Mo (s-only)** compared to solar
- Models taking into accounts various neutron fluxes (^{13}C pocket) for two stellar masses (1.5 and 3 M$_\odot$) can account for the data. The large symbols show when the condensation is possible (C/O>1)

Short-lived radionuclei, something is wrong in the abundance of radioactive nuclei in solar system protoplanetary disk





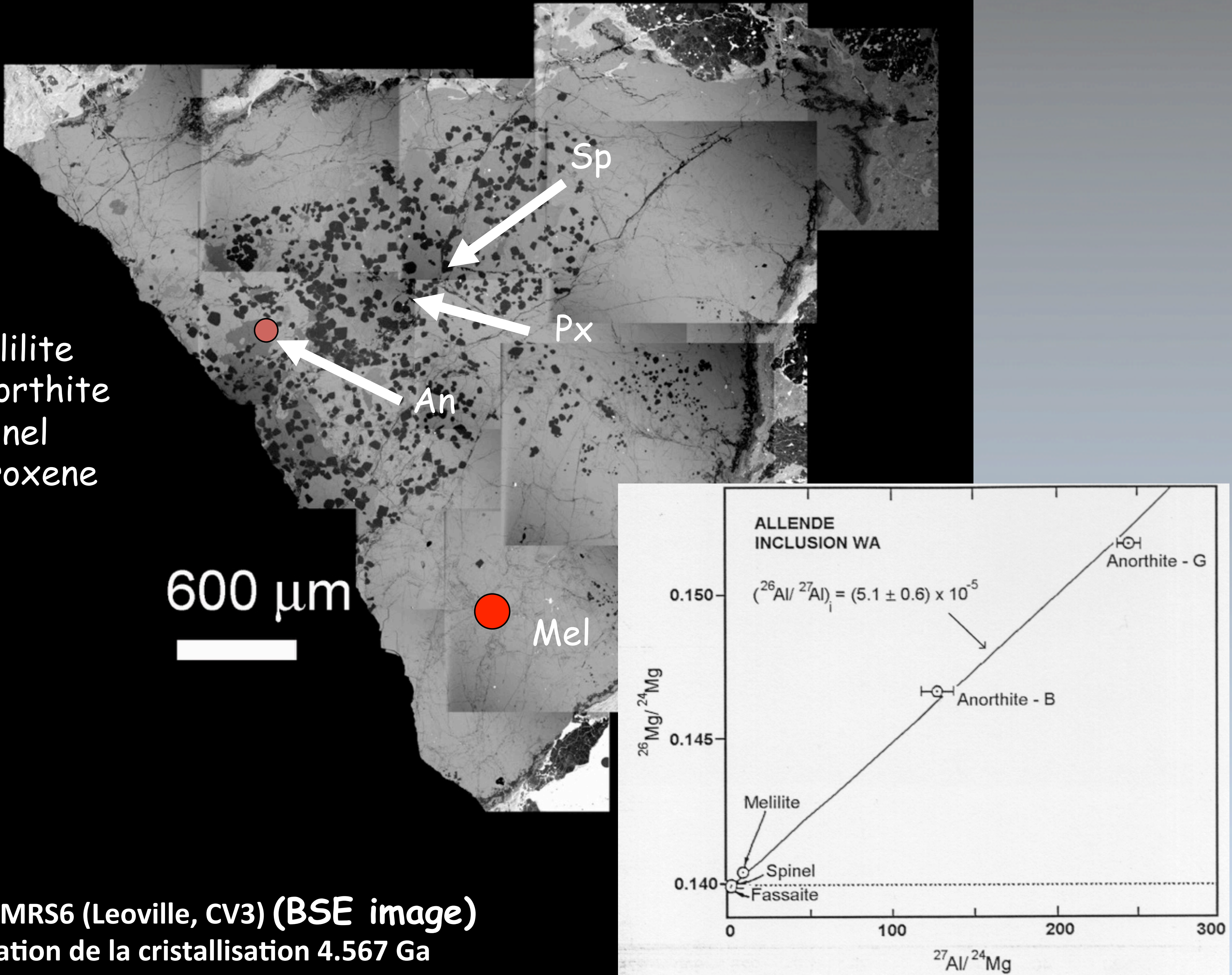




Refractory phase where extinct radioactivities are observed

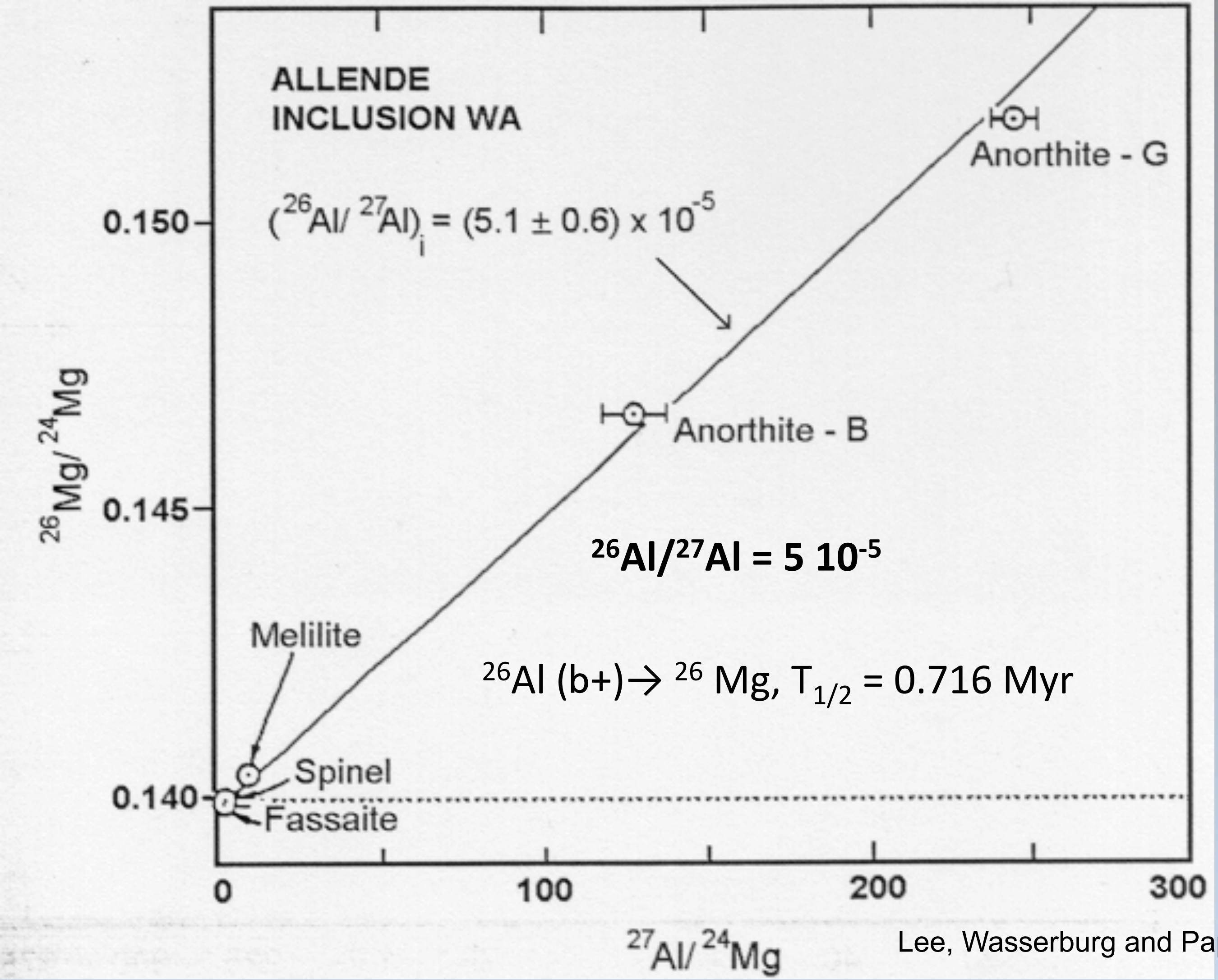
Short-lived radio-nuclei and the solar system birth

Melilite
Anorthite
Spinel
Pyroxene



CAI MRS6 (Leoville, CV3) (BSE image)
Datation de la cristallisation 4.567 Ga

^{26}Mg is linearly correlated to Al



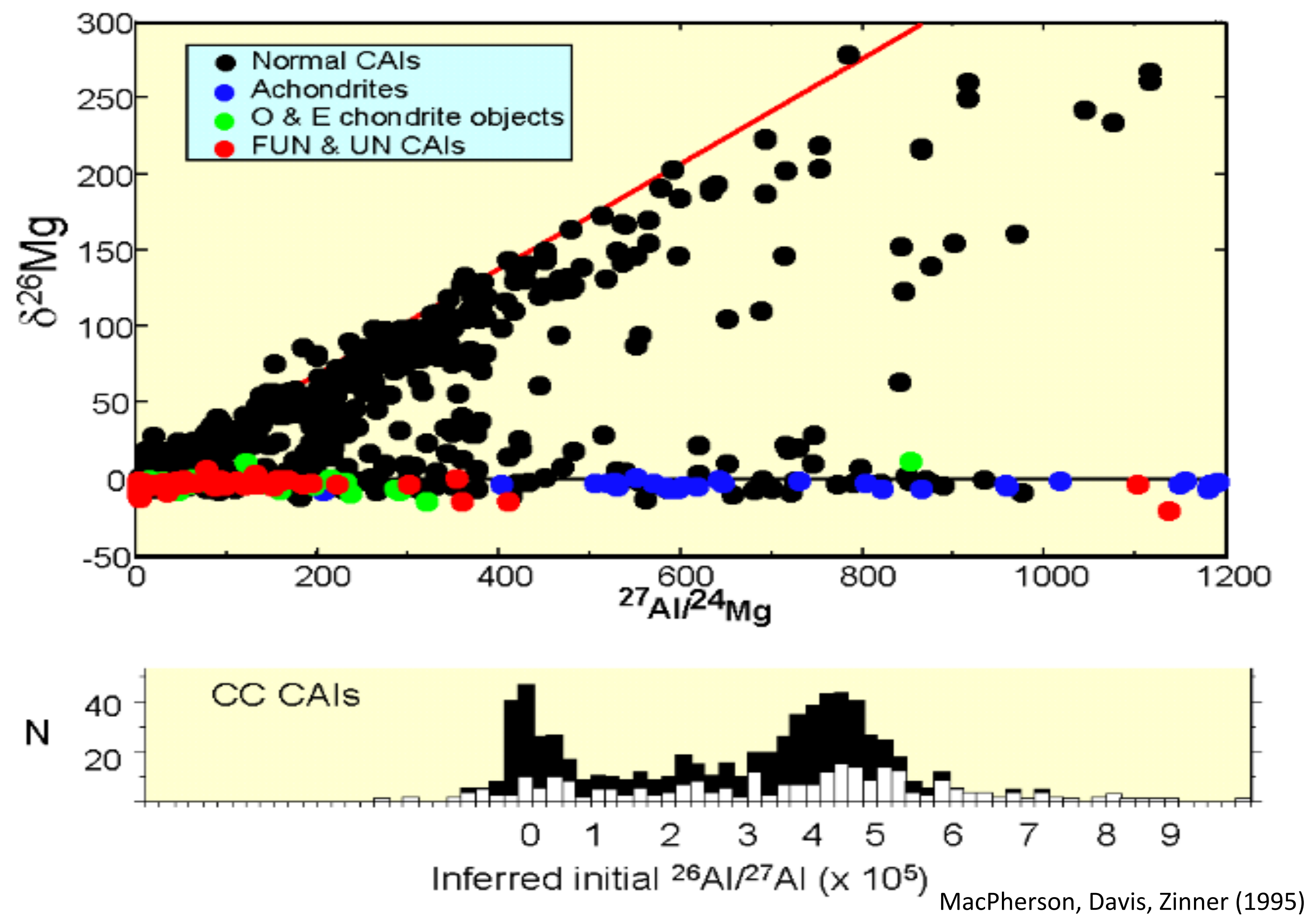
$^{26}Al/^{27}Al = 5\ 10^{-5}$

$^{26}Al\ (b+) \rightarrow {}^{26}Mg,\ T_{1/2} = 0.716$ Myr

Lee, Wasserburg and Papanastassiou (1976)

alive ^{26}Al was present in the early solar system

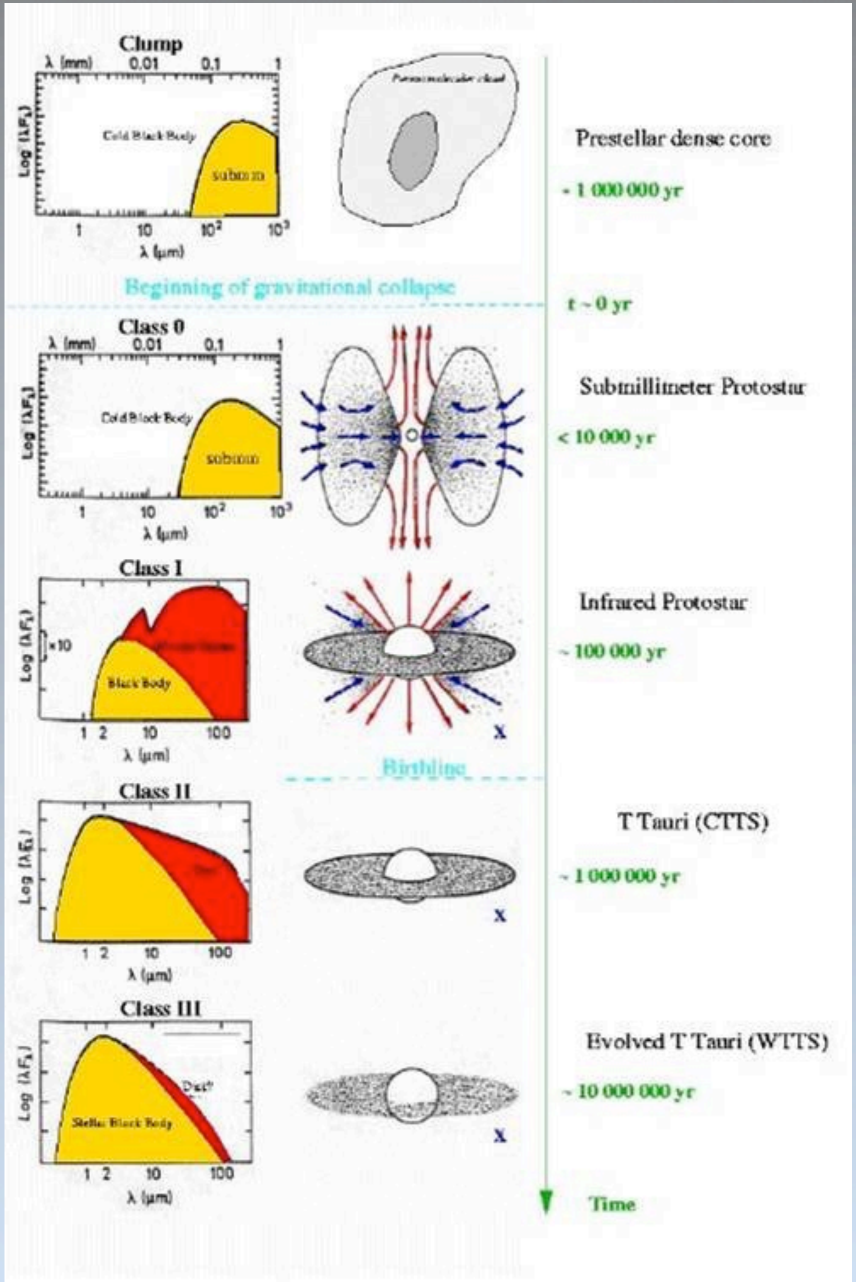
A bi-modal distribution



MacPherson, Davis, Zinner (1995)

The canonical value ^{26}Al/^{27}Al (t=0) = 5 10^{-5}

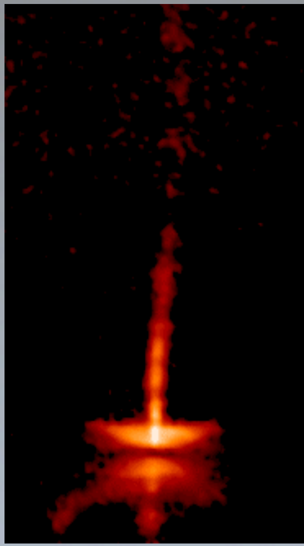
Before the main sequence



Different time scales

- Class 0 & I :
  - The proto-star is embedded
  - High accretion rate
  - T ~ 10^4-10^5 years
  - $M_{star} = 0.5 \rightarrow 0.8\ M_{\odot}$

- Class II & III :
  - Disc of gas and dust then debris
  - Lower accretion rate
  - T ~ 10^6-10^7 years
  - $M_{star} = 0.8 \rightarrow 1\ M_{\odot}$



HH 30
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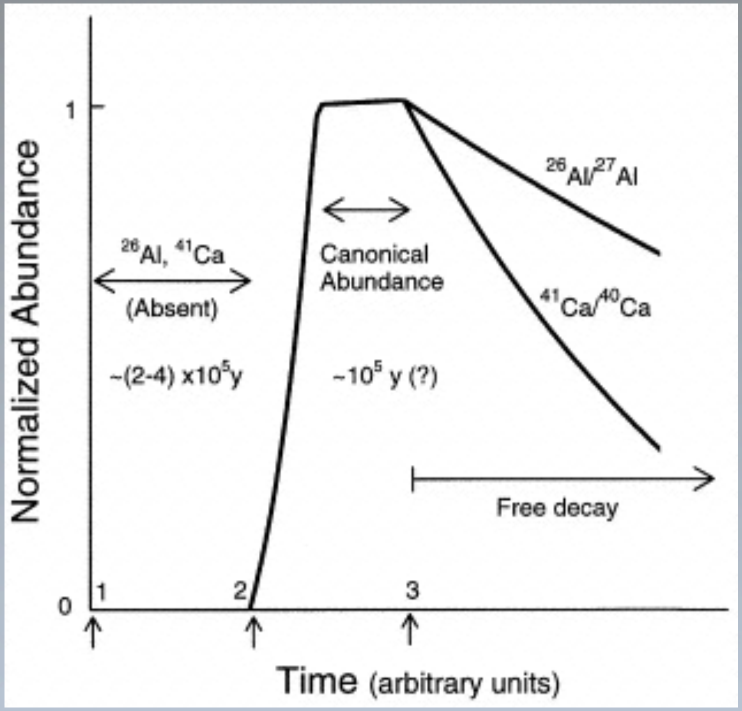
Some CAIs have $^{26}Al/^{27}Al \sim 0$

- **An metamorphic** episode
  - Reset et redistribute the Mg isotopes a few Myrs after crystallization
  - Difficult since some CAIs have no ^{26}Al but other isotopic anomalies that should also be reset (^{50}Ti…)
- **A chronological interpretation**
  - Some refractory phases formed when ^{26}Al was not present



Goswami & Sahjipal, ApJ 1998

Still an open question

What was the total amount of short lived nuclei in the proto-planetary disk?

- Very few observational constraints
- Importance for planetary evolution: ^{26}Al et ^{60}Fe are efficient heat sources for planetary differentiation
- Consequences on :
  - The origin of theses isotopes
  - The possibility to built an isotopic chronology

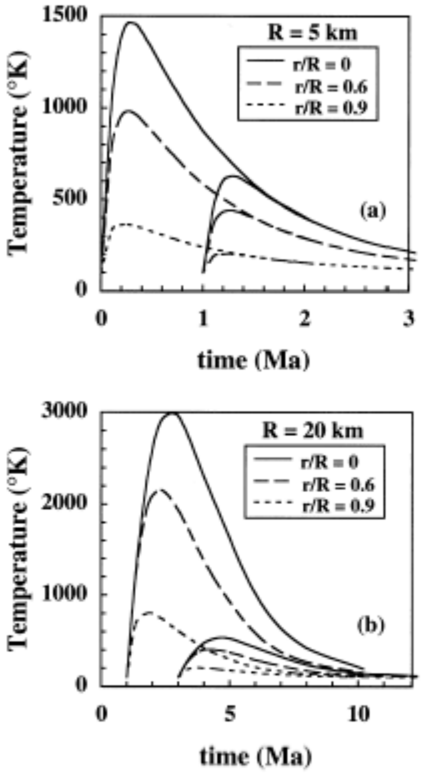


Fig. 7. Time–temperature profiles for planetesimals heated by the radioactive decay of ^{26}Al as described by Eq. 4. Curves are shown for the core ($r/R = 0$), the middle ($r/R = 0.6$), and the outer rim ($r/R = 0.9$) of planetesimals with radii of 5 km formed at $t = 0$ and 1 Ma (a) and 20 km formed at 1 and 3 Ma (b). Calculated using thermal properties of mafic igneous rock ($\kappa = 7.6 \times 10^{-7}$ m^2/s [31]), and a constant surface temperature of 100 K.

Latourette et al 1998

SLR are crucial to built an isotopic chronology

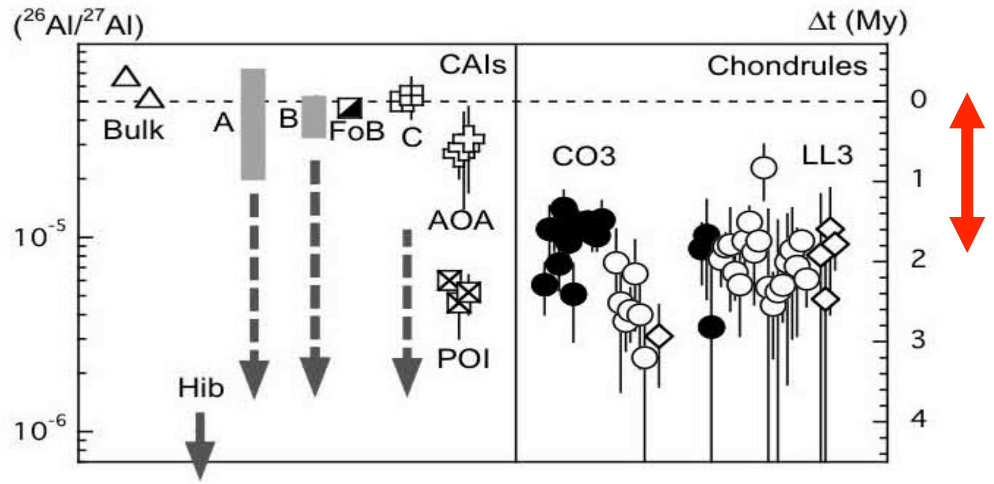
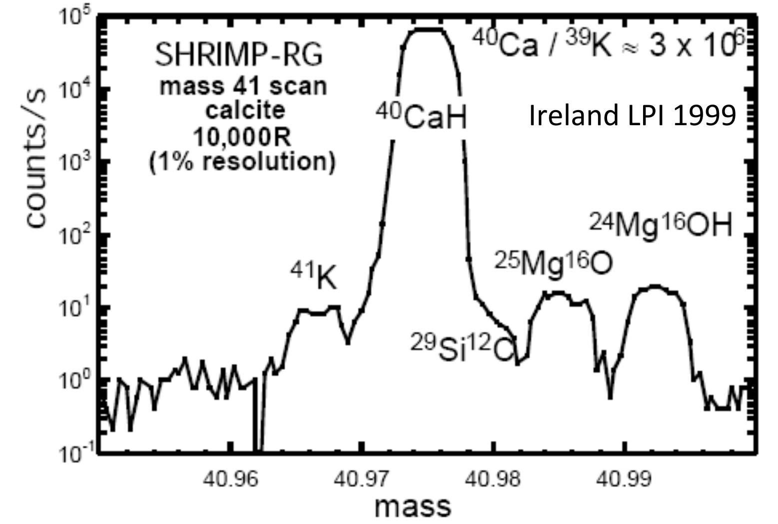


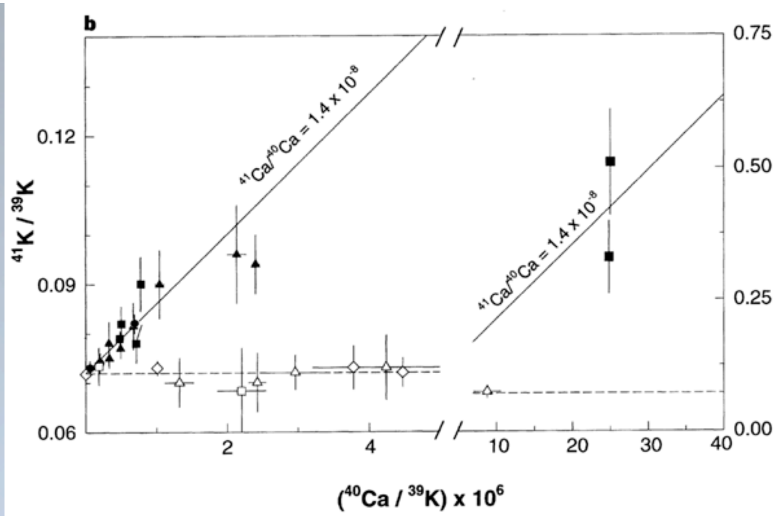
Figure 4. Initial ^{26}Al/^{27}Al ratios of CAIs and chondrules. Bulk CAIs: Galy et al. (2000); Bizzarro et al. (2004); CAIs: MacPherson et al. (1995); Imai & Yurimoto (2000); Itoh et al. (2002); Amelin et al. (2002); Hsu et al. (2003); Kita et al. (2004); Chondrules: Hutcheon & Hutchison (1989); Russell et al. (1996); Kita et al. (2000); McKeegan et al. (2000b); Huss et al. (2001); Yurimoto & Wasson (2003); Kunihiro et al. (2004); Kurahashi et al. (2004); Kita et al. (2005).

Kita et al 2005, Connelly et al. ApJ 2008

- The ^{26}Al/^{27}Al rations in chondrules are systematically lower than in CAIs
- Chronological interpretation : DT = 1-3 Myrs between the CAIs and chondrules formation.

^{41}Ca, a challenging case

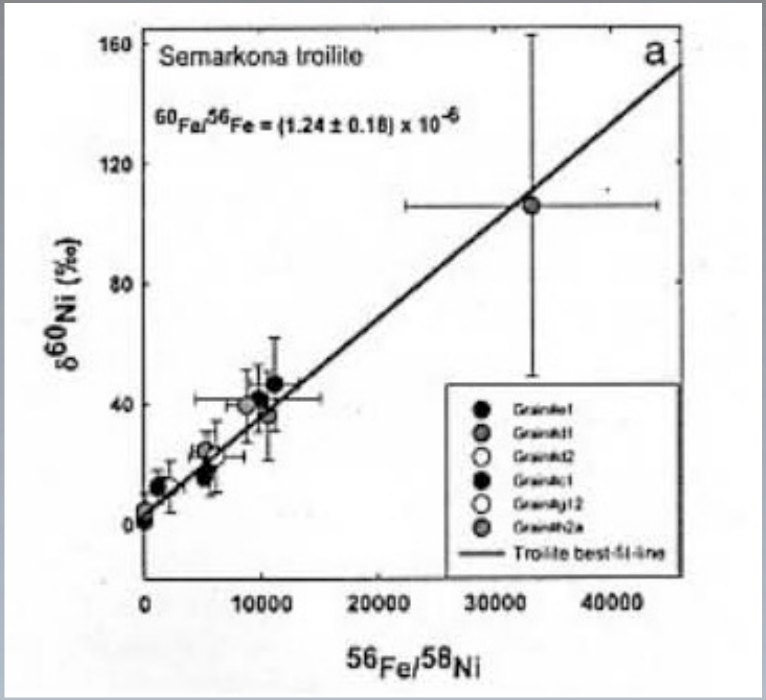




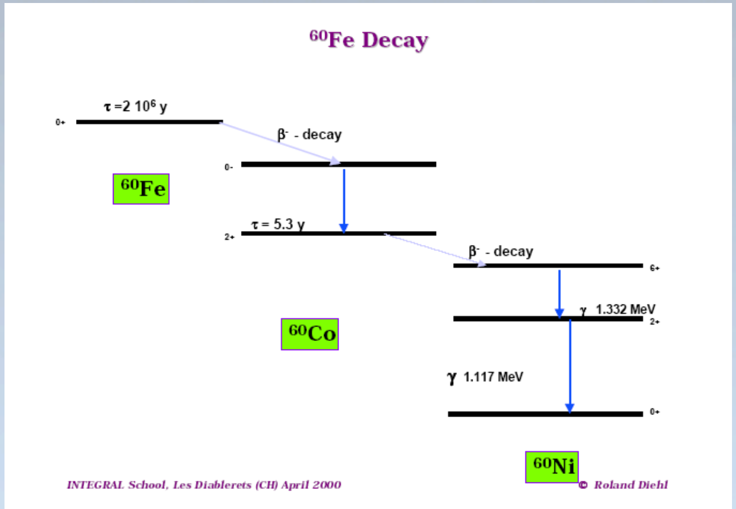
^{41}Ca → ^{41}K, $T_{1/2}$ = 0.1 Myr

^{41}K signal: 1-10 c/s Background ^{40}Ca (10^8 c/s), ^{40}CaH (10^{5}c/s), **(^{40}Ca-^{42}Ca)$^{++}$**

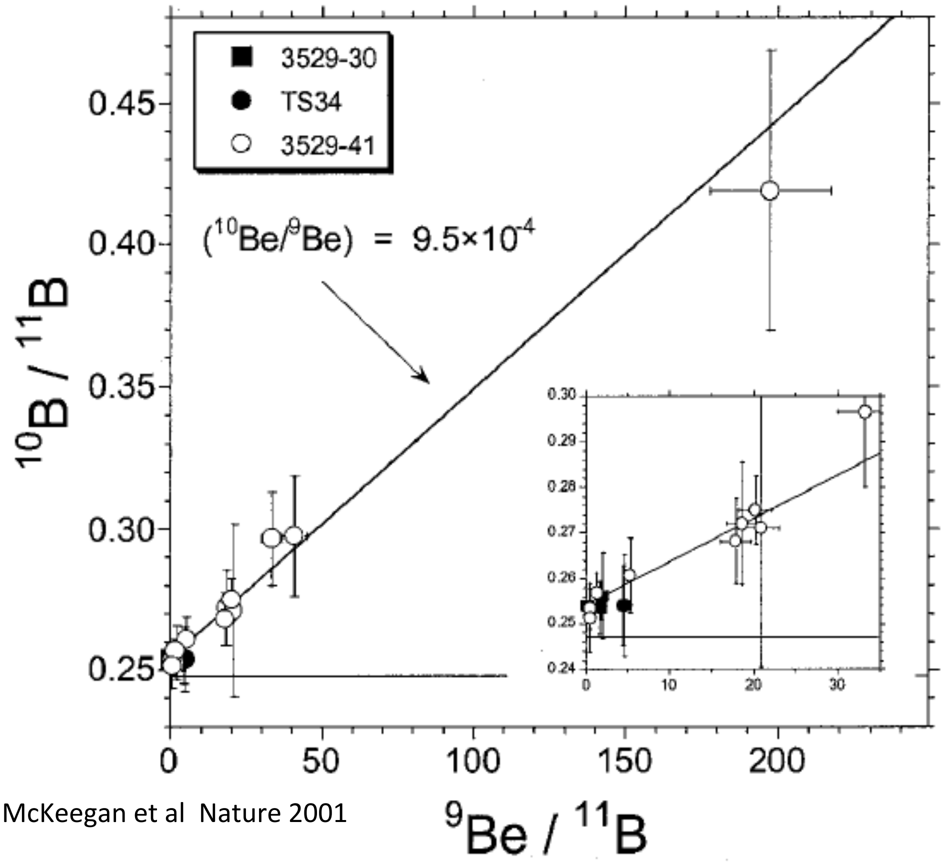
^{60}Fe, *the smoking gun*



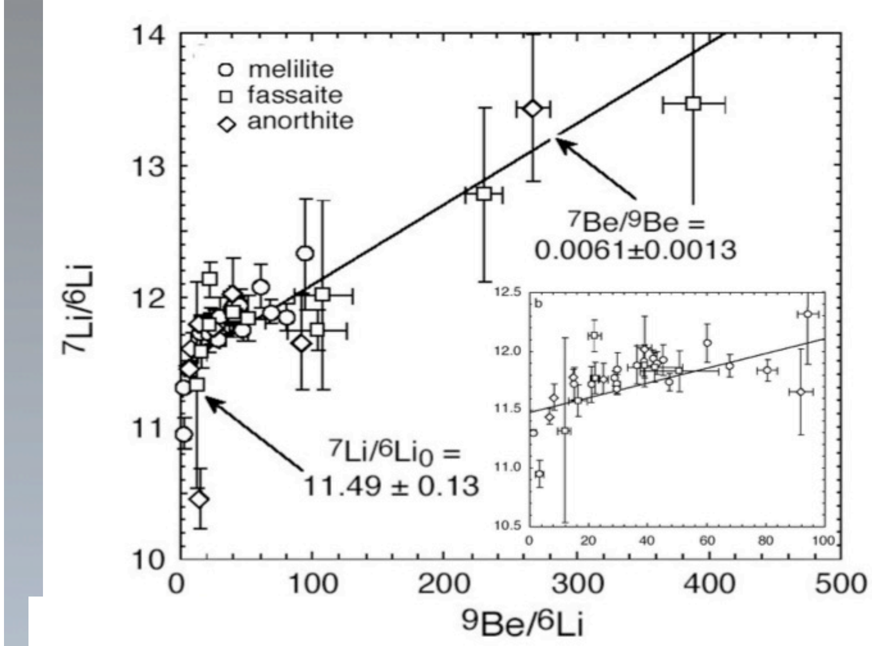
Mostefaoui et al 2004, Tang & Dauphas 2012, …



Non-thermal nucleosynthesys



McKeegan et al Nature 2001



Still uncertain :

^{7}Be ($T_{1/2}$ = 53 days) → ^{7}Li, ^{7}Be/^{9}Be = 6 10^{-3} ?

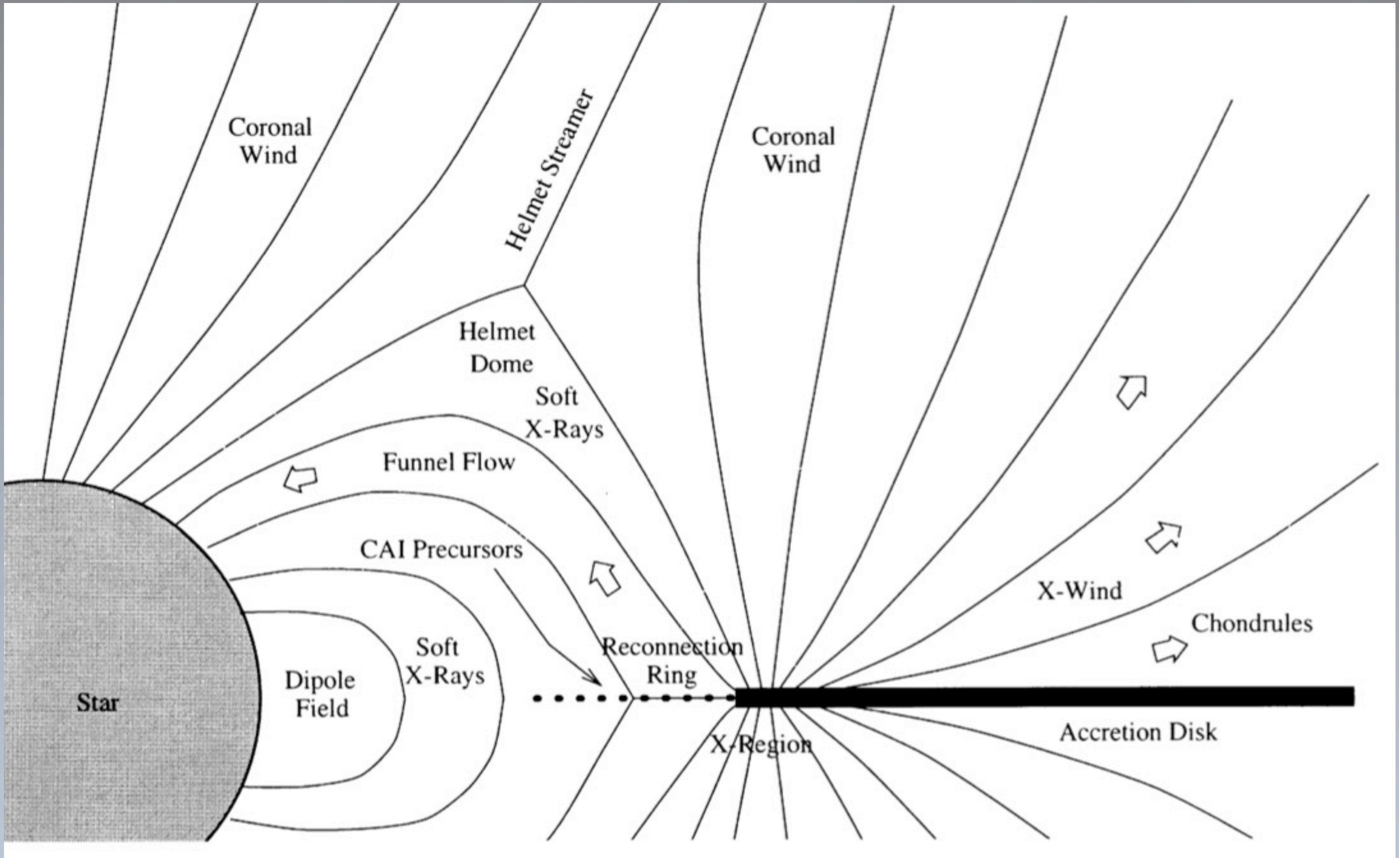
^{10}Be (β^{-}) → ^{10}B, $T_{1/2}$ = 1.4 Myr

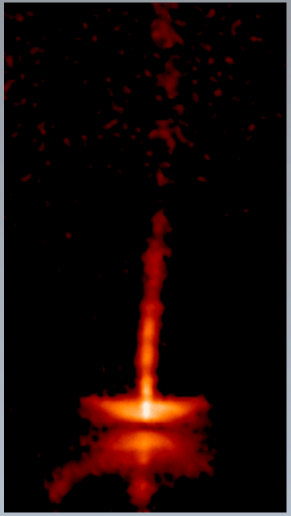
M. Chaussidon et al 2006

^{10}Be is produced by spallation reactions on CNO,

Irradiation induced by light particles accelerated by the young Sun ?

Irradiation in the early solar system ?





HH 30, Hubble image

Shu et al. Science 1996, Shu et al ApJ 2001, Lee et al ApJ 1998

"CAI and Chondrules are formed at close distance from the star (the reconnection ring : R=0.06 AU) then transported at several AU over the disk by the x-wind…"

The abundance of many short-lived nuclei are not compatible with the chemical evolution of the Galaxy.

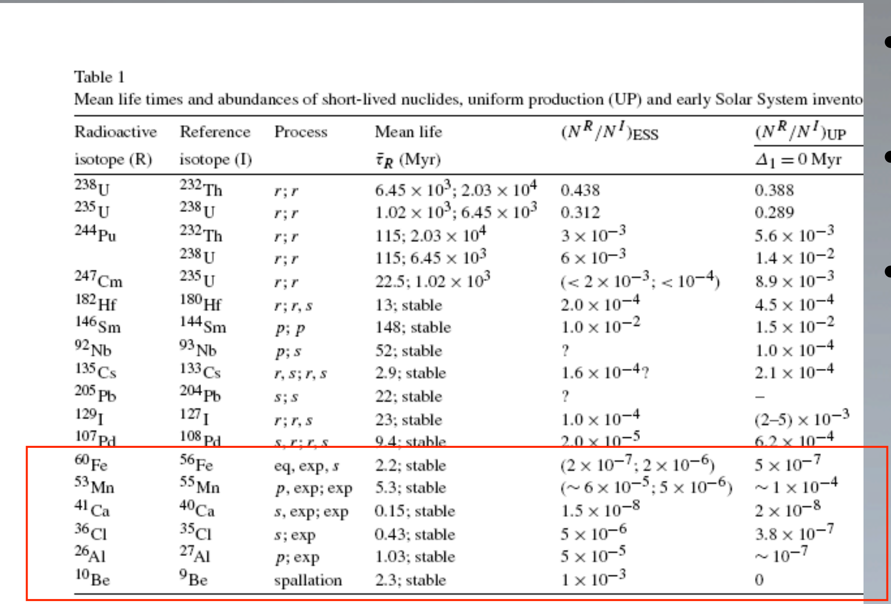


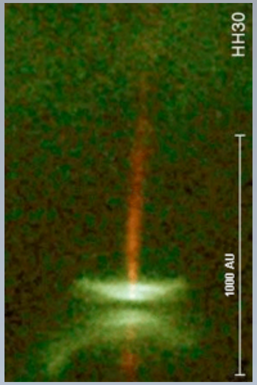
Table 1

Mean life times and abundances of short-lived nuclides, uniform production (UP) and early Solar System invento

Radioactive isotope (R)	Reference isotope (I)	Process	Mean life $\bar{\tau}_R$ (Myr)	$(N^R/N^I)_{\mathrm{ESS}}$	$(N^R/N^I)_{\mathrm{UP}}$ $\Delta_1 = 0$ Myr
^{238}U	^{232}Th	$r; r$	6.45×10^3; 2.03×10^4	0.438	0.388
^{235}U	^{238}U	$r; r$	1.02×10^3; 6.45×10^3	0.312	0.289
^{244}Pu	^{232}Th	$r; r$	115; 2.03×10^4	3×10^{-3}	5.6×10^{-3}
	^{238}U	$r; r$	115; 6.45×10^3	6×10^{-3}	1.4×10^{-2}
^{247}Cm	^{235}U	$r; r$	22.5; 1.02×10^3	$(< 2 \times 10^{-3}; < 10^{-4})$	8.9×10^{-3}
^{182}Hf	^{180}Hf	$r; r, s$	13; stable	2.0×10^{-4}	4.5×10^{-4}
^{146}Sm	^{144}Sm	$p; p$	148; stable	1.0×10^{-2}	1.5×10^{-2}
^{92}Nb	^{93}Nb	$p; s$	52; stable	?	1.0×10^{-4}
^{135}Cs	^{133}Cs	$r, s; r, s$	2.9; stable	1.6×10^{-4}?	2.1×10^{-4}
^{205}Pb	^{204}Pb	$s; s$	22; stable	?	–
^{129}I	^{127}I	$r; r, s$	23; stable	1.0×10^{-4}	$(2–5) \times 10^{-3}$
^{107}Pd	^{108}Pd	$s, r; r, s$	9.4; stable	2.0×10^{-5}	6.2×10^{-4}
^{60}Fe	^{56}Fe	eq, exp, s	2.2; stable	$(2 \times 10^{-7}; 2 \times 10^{-6})$	5×10^{-7}
^{53}Mn	^{55}Mn	p, exp; exp	5.3; stable	$(\sim 6 \times 10^{-5}; 5 \times 10^{-6})$	$\sim 1 \times 10^{-4}$
^{41}Ca	^{40}Ca	s, exp; exp	0.15; stable	1.5×10^{-8}	2×10^{-8}
^{36}Cl	^{35}Cl	s; exp	0.43; stable	5×10^{-6}	3.8×10^{-7}
^{26}Al	^{27}Al	p; exp	1.03; stable	5×10^{-5}	$\sim 10^{-7}$
^{10}Be	^{9}Be	spallation	2.3; stable	1×10^{-3}	0

Wasserburg et al Nucl. Phys; A 2006

- Is the astrophysical context of the Sun birth peculiar ? (see Gounelle & Meynet 2012, Young 2014…)
- Was the solar system nebulae polluted by the aches of a massive star ?
- What was the magnitude of irradiation-induced (i.e non-thermal) nucleosynthesis.



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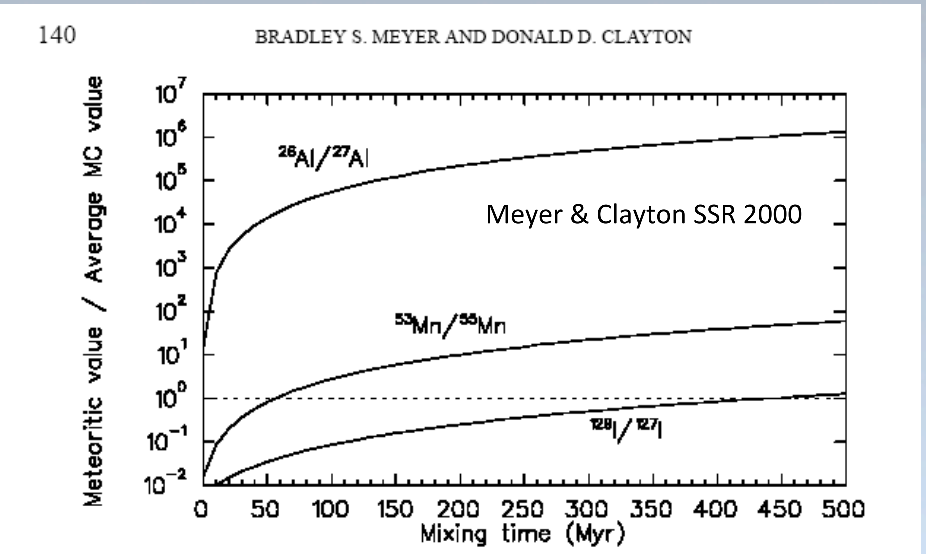
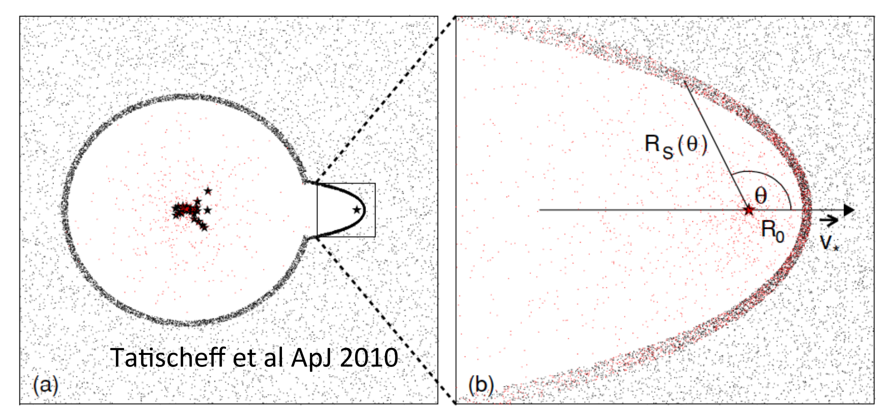


Meyer & Clayton SSR 2000



Tatischeff et al ApJ 2010