Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

With materials from V. Hill, M. Spite and M. Pignatari

Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

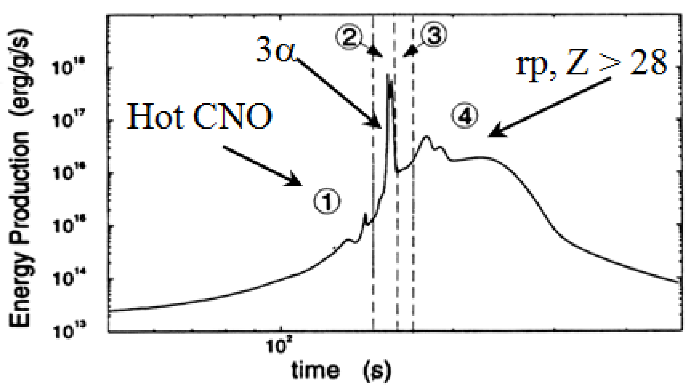
Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

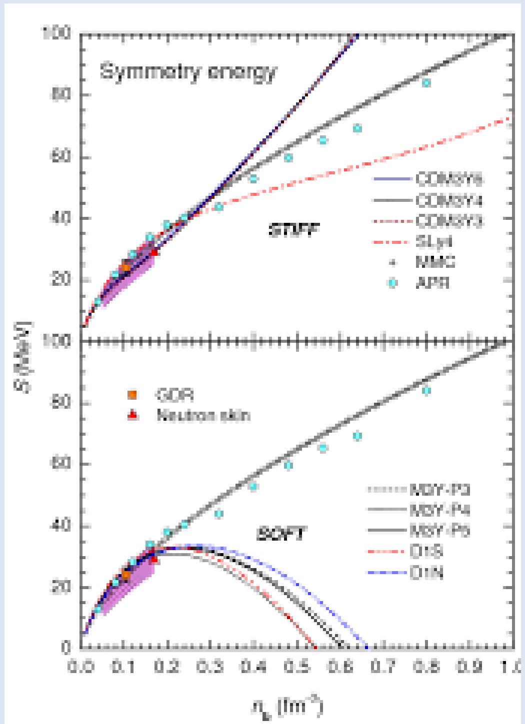
With materials from V. Hill, M. Spite and M. Pignatari

Nuclear astrophysics

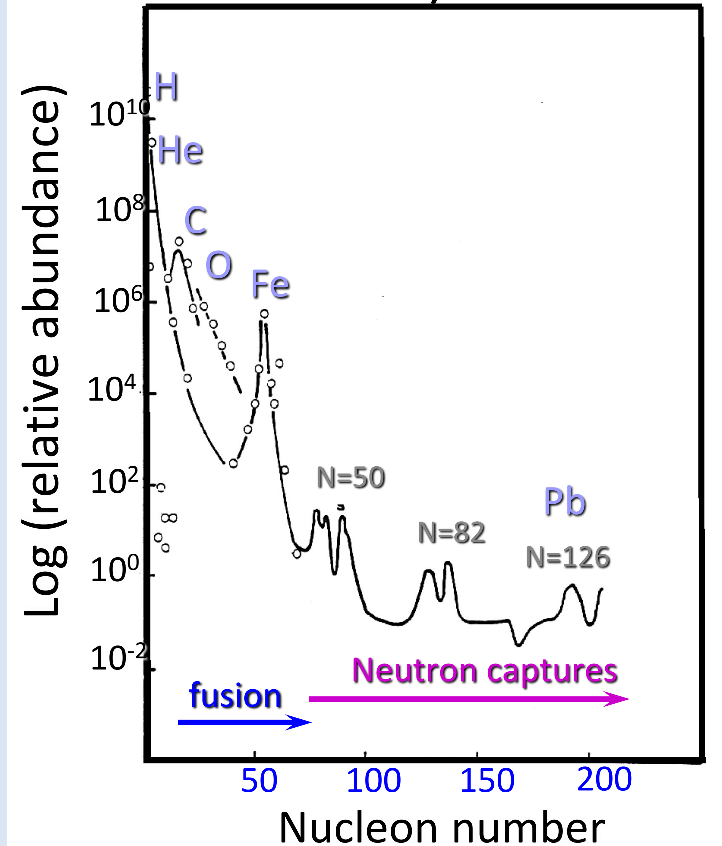
Nuclear reactions in stars



EOS of nuclear matter



Nucleosynthesis



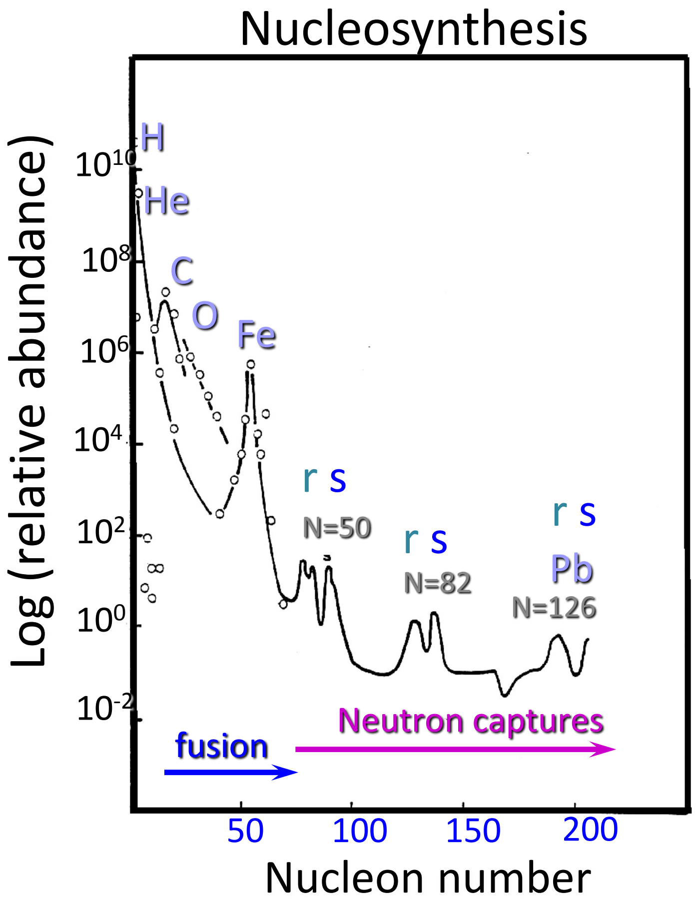
Strong connexions with:

Stellar hydrodymanics

Astronomy, geocosmochemistry

Galactic chemical evolution

Abundance curve of the elements in solar sytem



Decreasing trend / reduced fusion cross section

Fe peak -> stronger binding energy per nucleon

Flat component afterwards -> neutron captures

Double peaks -> (at least) 2 classes of processes connected to closed shells

Decomposition of the 2 processes (r,s)

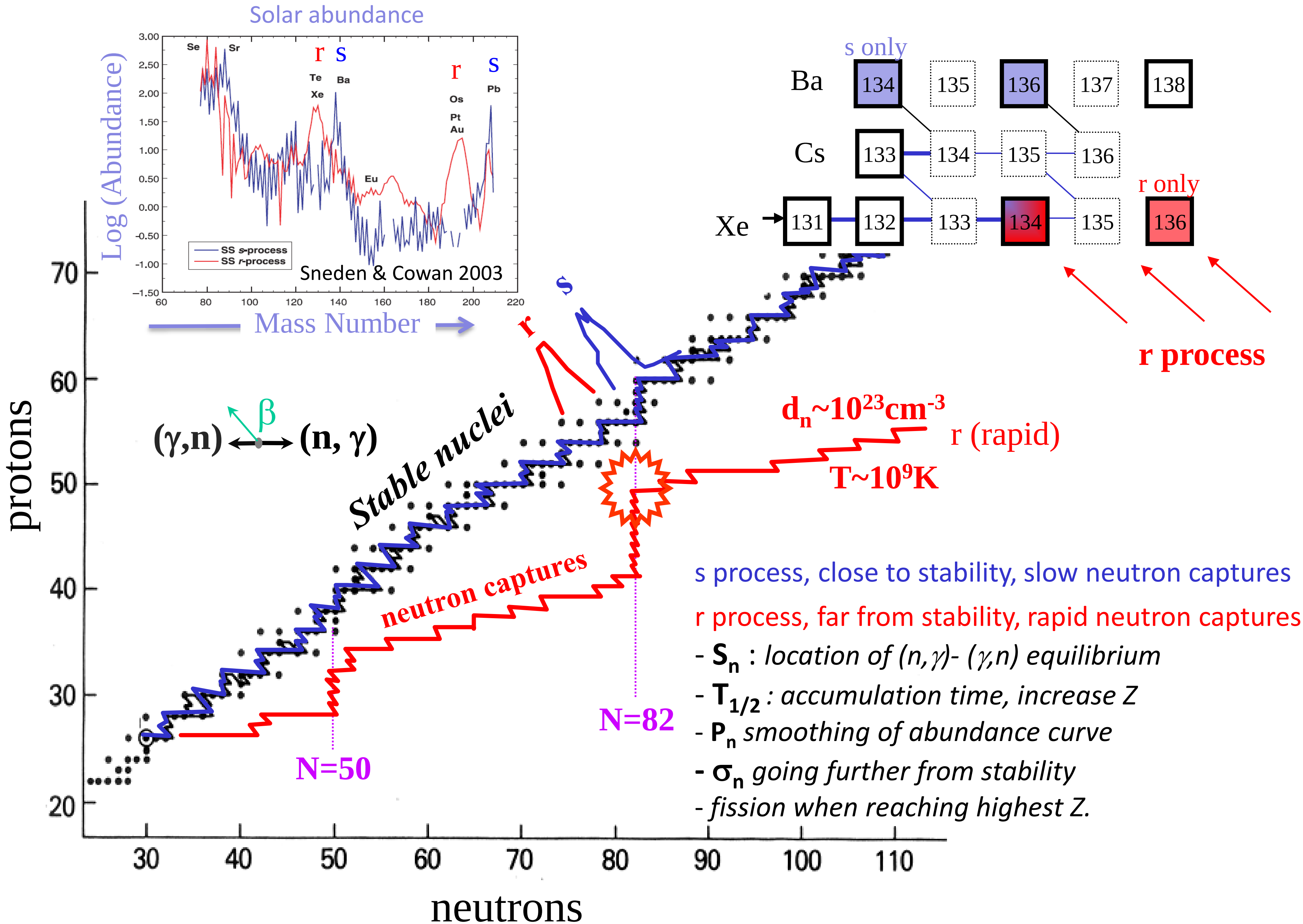
Abundance in SS may come from many successive enrichments of different elemental patterns

Search for ‘young’ stars:
-> less mixing
-> Hopefully disentangle between s and r processes

Do young stars still exist ?

Where / how to find them ? Which composition ?

Neutron capture processes: classical picture



s process, close to stability, slow neutron captures

r process, far from stability, rapid neutron captures

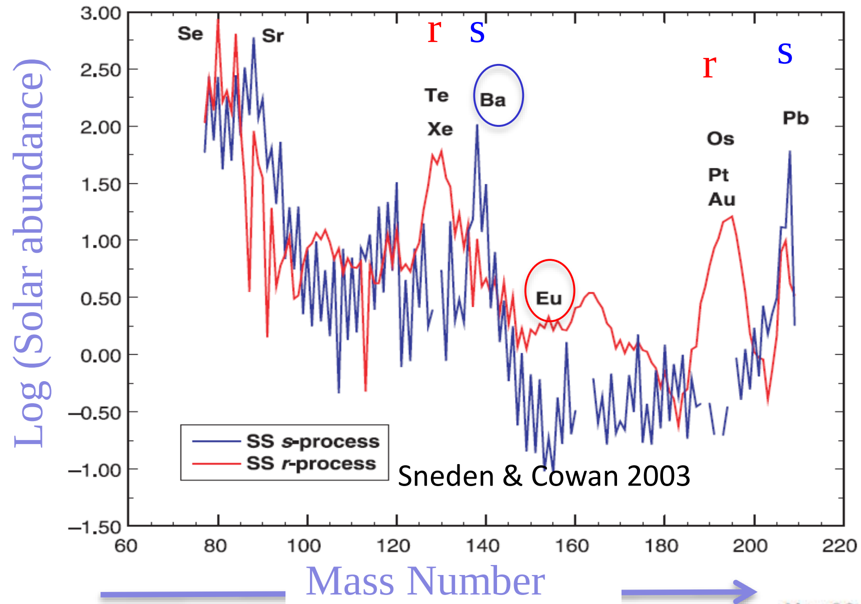
- **S_n** : *location of (n,γ)- (γ,n) equilibrium*
- **$T_{1/2}$** *: accumulation time, increase Z*
- **P_n** *smoothing of abundance curve*
- **σ_n** *going further from stability*
- *fission when reaching highest Z.*

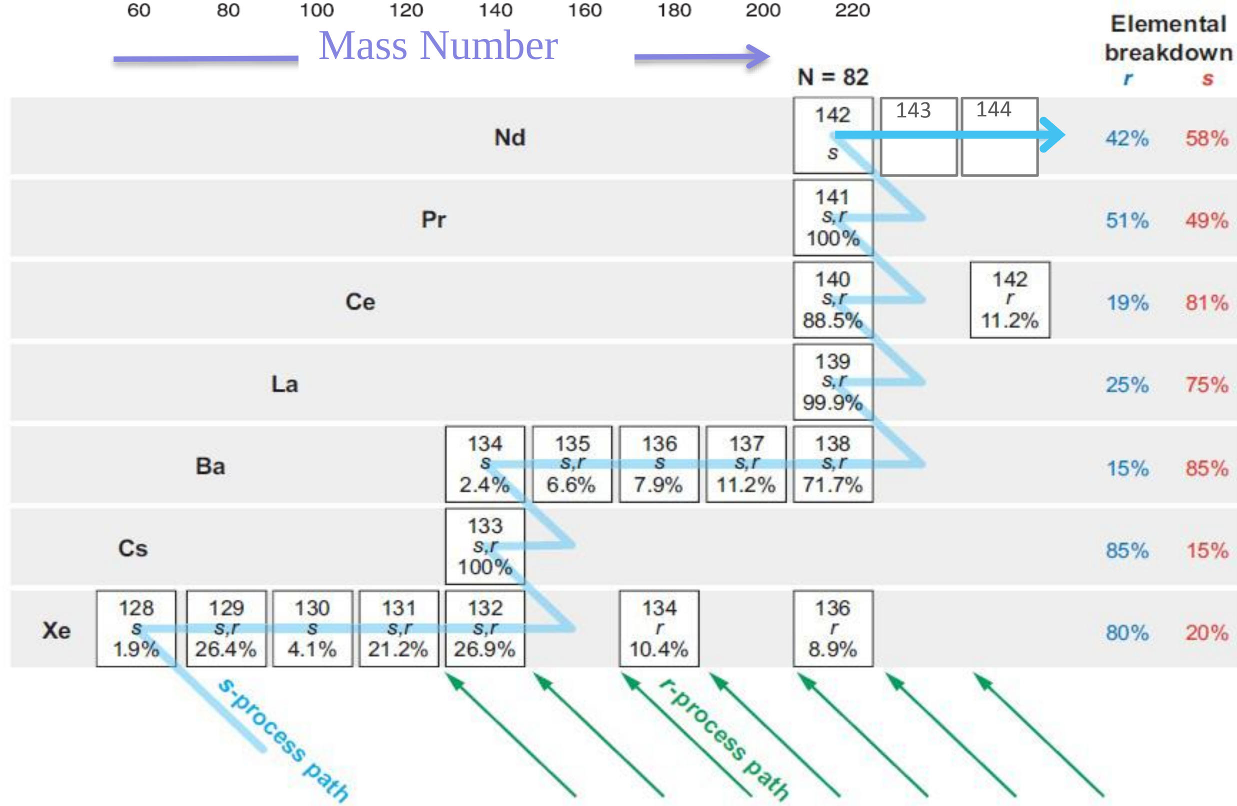
Elemental breakdown in r and s components

In the solar system:

Eu is a pure r element

Ba is mainly an s element





Lectures in nuclear astrophysics : Parts I

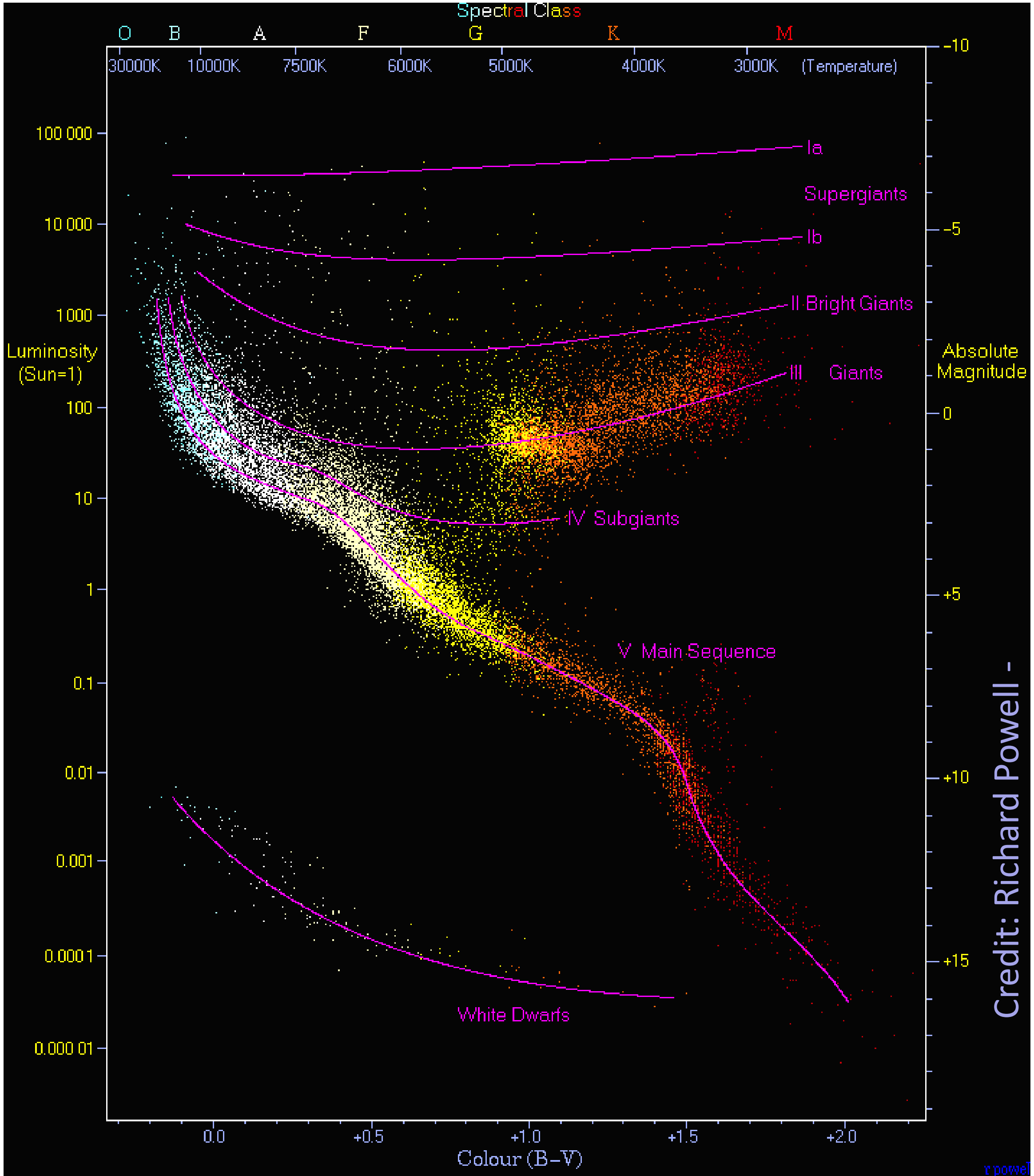
O. Sorlin (GANIL, France)

Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

With materials from V. Hill, M. Spite and M. Pignatari

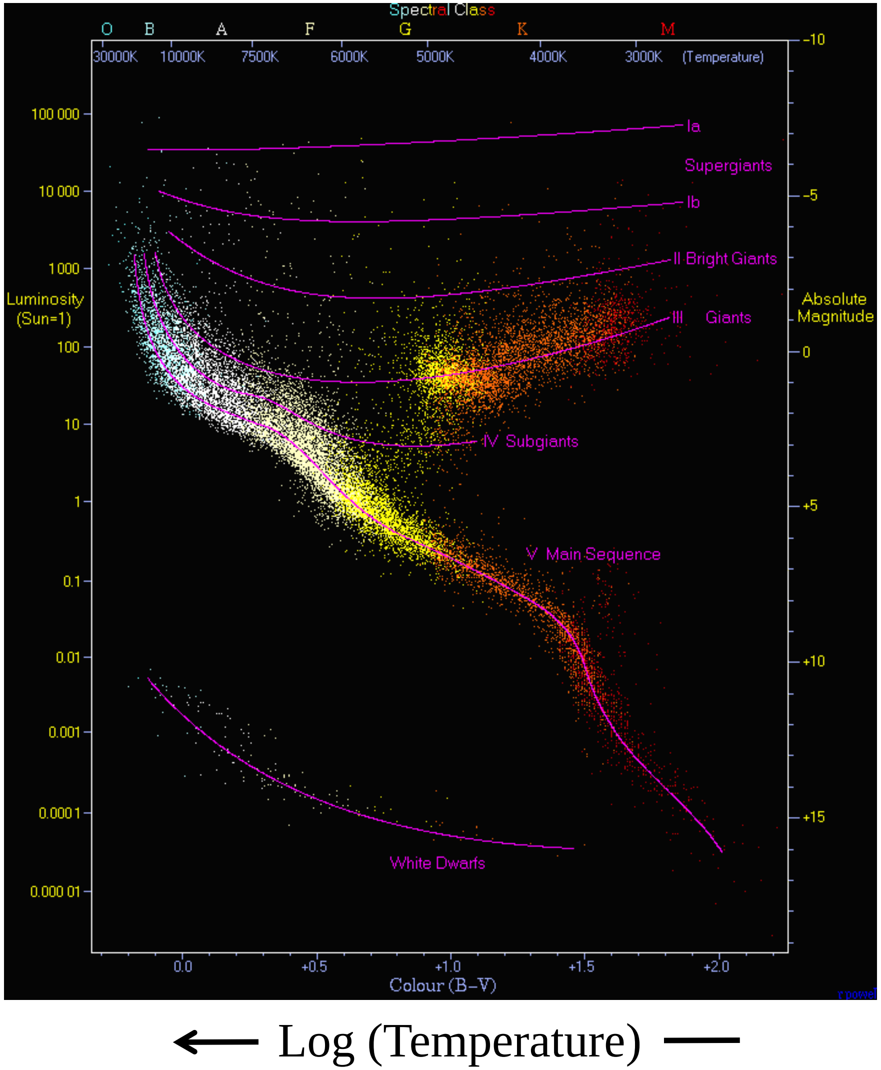
The Hertzprung – Russel diagram



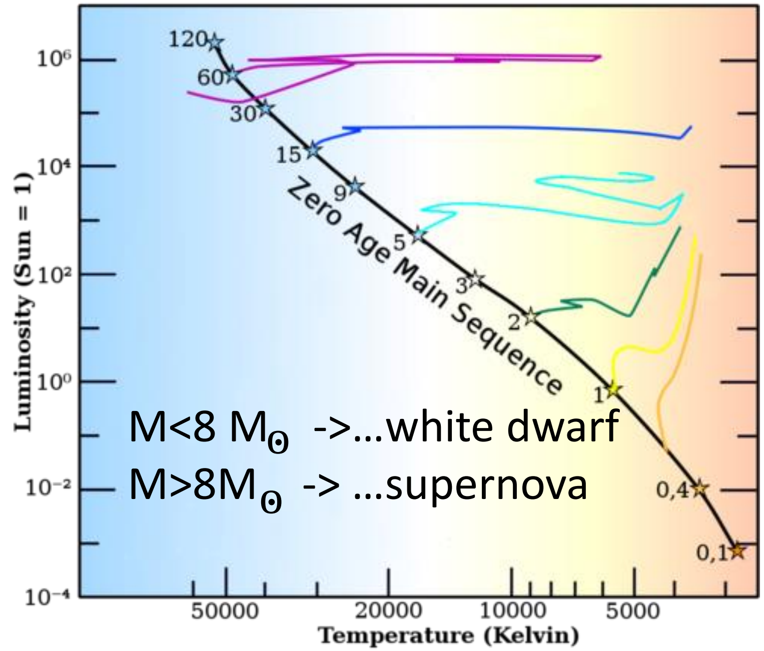
Credit: Richard Powell -

A simplistic history of stellar evolution

The Hertzprung – Russel diagram



Credit: Richard Powell -



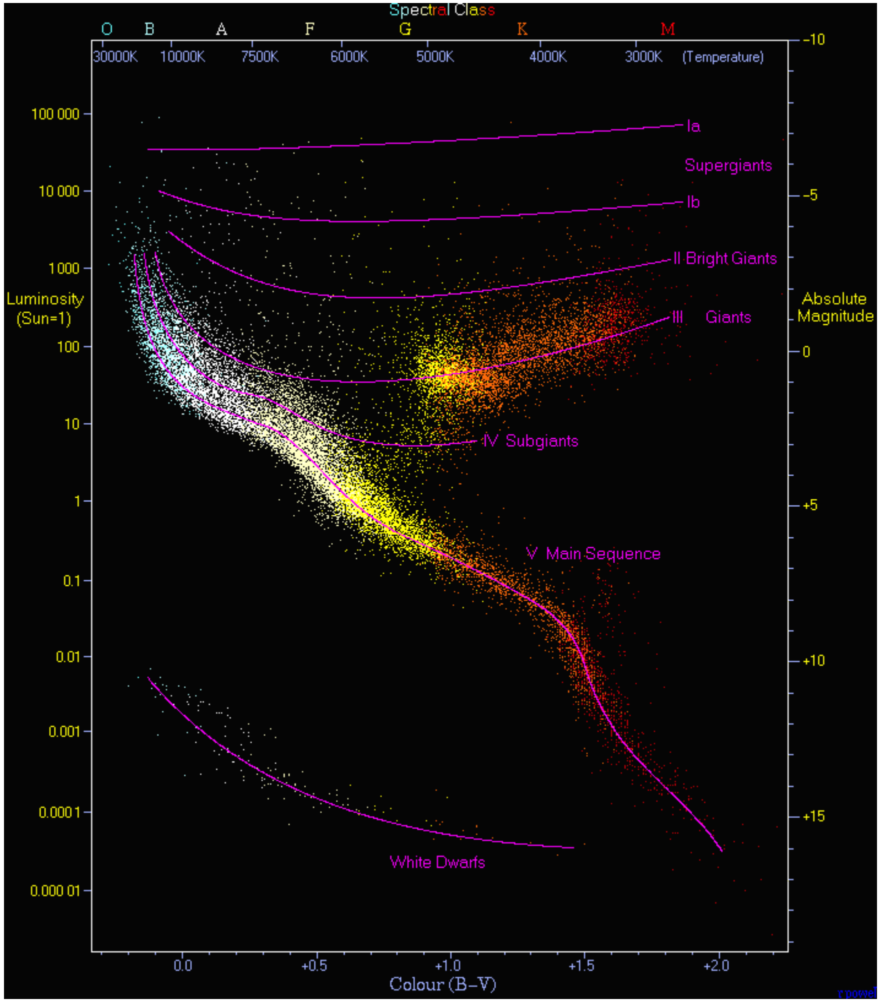
Stars leave the MS when a large fraction of H has fused. It contracts and initiate more H to fuse, thus becoming brighter. It increases its radius, making its surface cooler (more red).

When the star's mass is large enough, He start to burn and the star moves on the AGB phase. In this phase outer layer can mix with interior

At the end of their life stars that cannot ignite C burning end up in WD, otherwise in SN

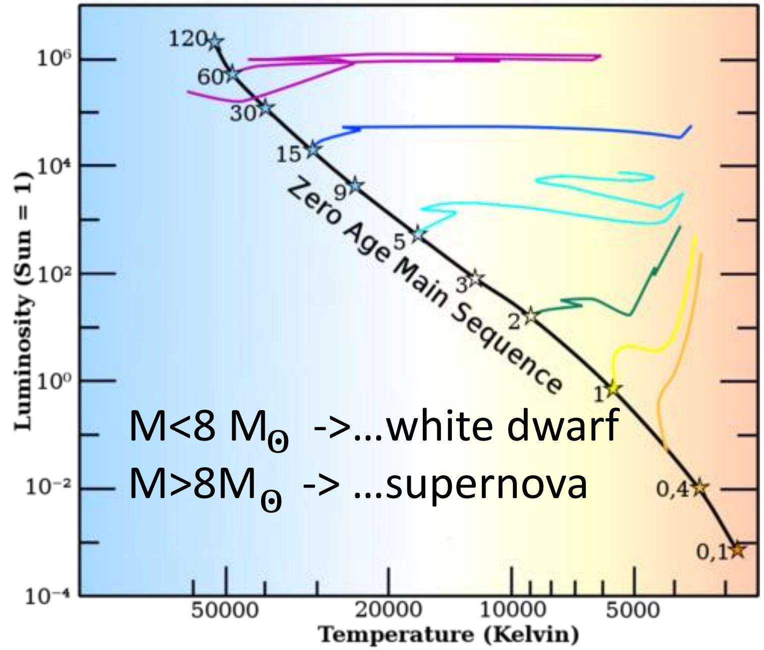
A simplistic history of stellar evolution

The Hertzprung – Russel diagram



Credit: Richard Powell -

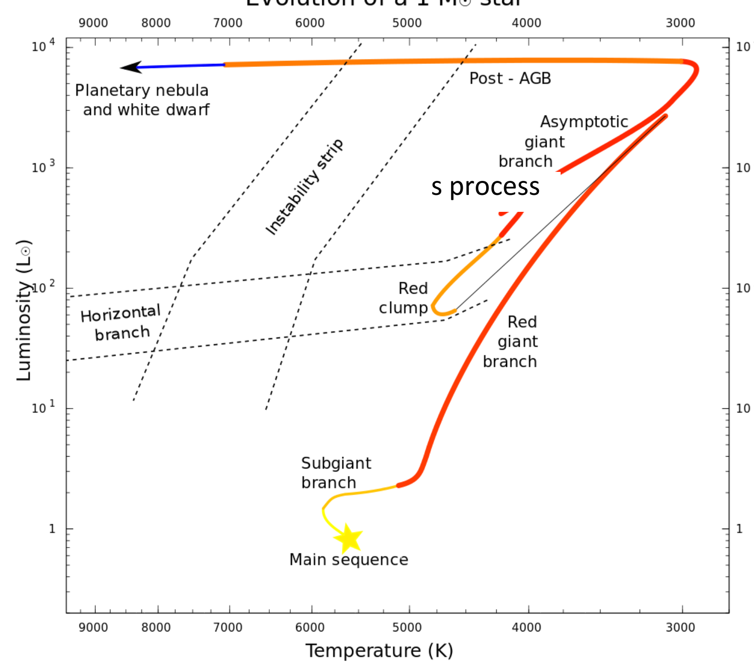
← Log (Temperature) —



M<8 $M_\odot$ ->…white dwarf

M>8$M_\odot$ -> …supernova

Evolution of a 1 $M_\odot$ star



s process

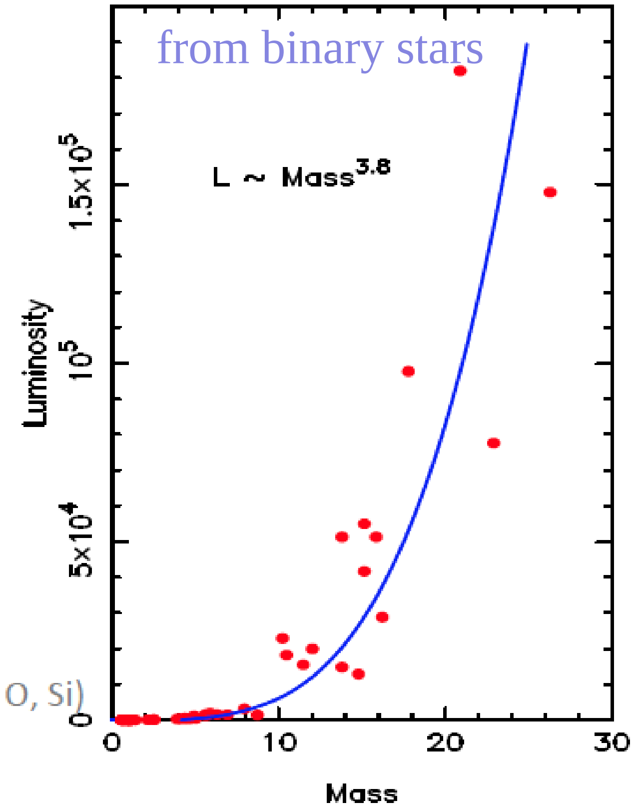
Planck : age of the Universe 13 800 x10^6 yr

lifetime of the stars

luminosity ~ $\propto \mathcal{M}^4$
quantity of fuel $\propto \mathcal{M}$

➔ **More a star is massive more its lifetime is short...**

	lifetime	
0.8 $\mathcal{M}_\odot$	15 000 x10^6 yr	$\mathcal{M} < 8\ \mathcal{M}_\odot$ core becomes degenerate after He burning phase ➞ white dwarfs
1 $\mathcal{M}_\odot$	10 000 x10^6 yr	
6 $\mathcal{M}_\odot$	113 x10^6 yr	
10 $\mathcal{M}_\odot$	31 x10^6 yr	$\mathcal{M} > 8\ \mathcal{M}_\odot$ succession of burnings (H, He, C, Ne, O, Si) an iron core is formed. The core collapse ➞ SNII
30 $\mathcal{M}_\odot$	2 x10^6 yr	
60 $\mathcal{M}_\odot$	0.4 x10^6 yr	

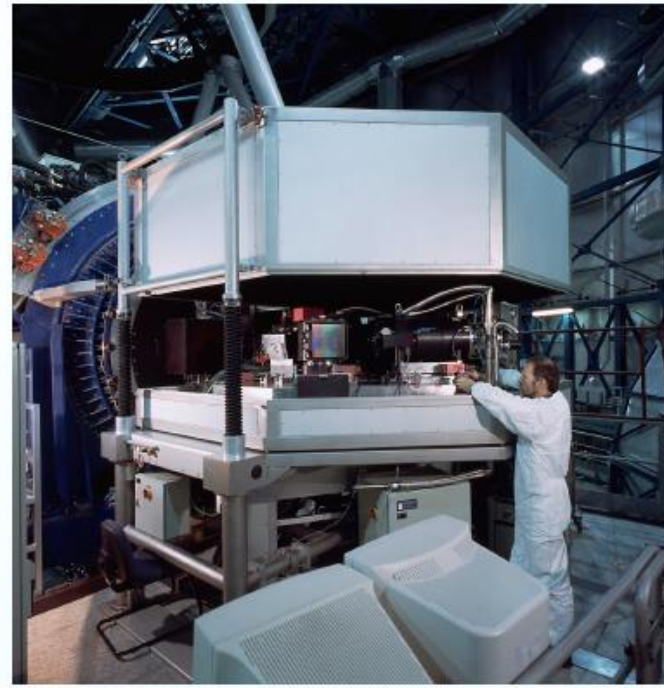


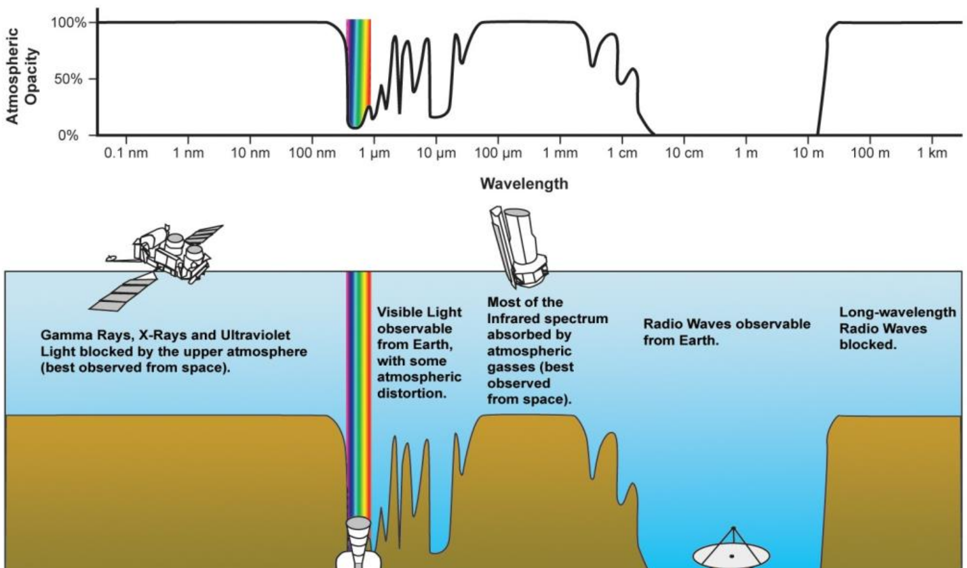
t_{MS} (yrs) ≈ $10^{10}\ (M/M_\odot)^{-2.8}$

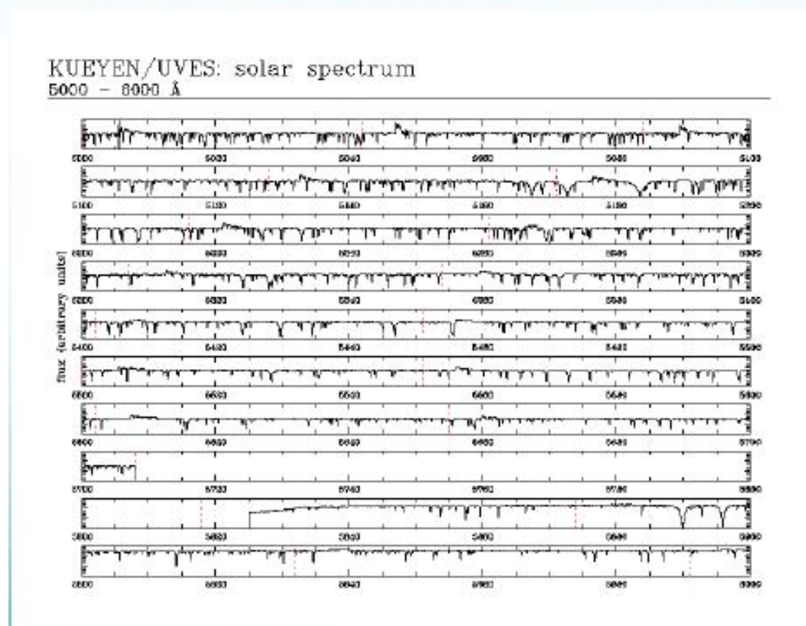
- **If in the first Gyr, stars were formed with $\mathcal{M} < 0.9\ \mathcal{M}_\odot$, they are still shining today** (main sequence stars or giants)

- **In this first Gyr only massive stars $\mathcal{M} > 5\ \mathcal{M}_\odot$ had time to enrich the matter**

How to measure elemental abundances in stars ?





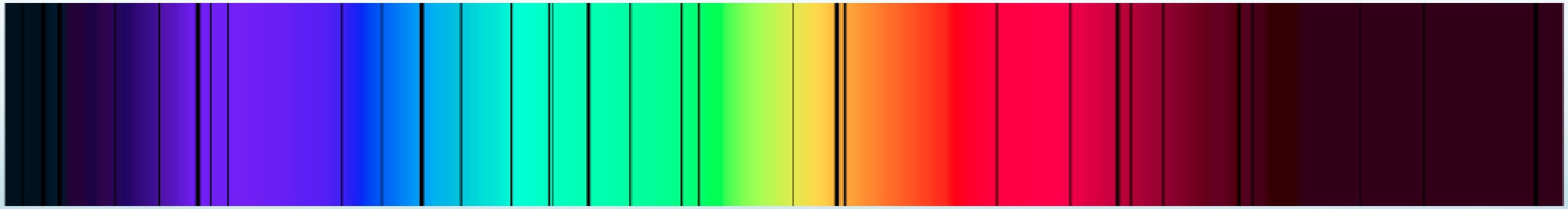


Absorption Spectra

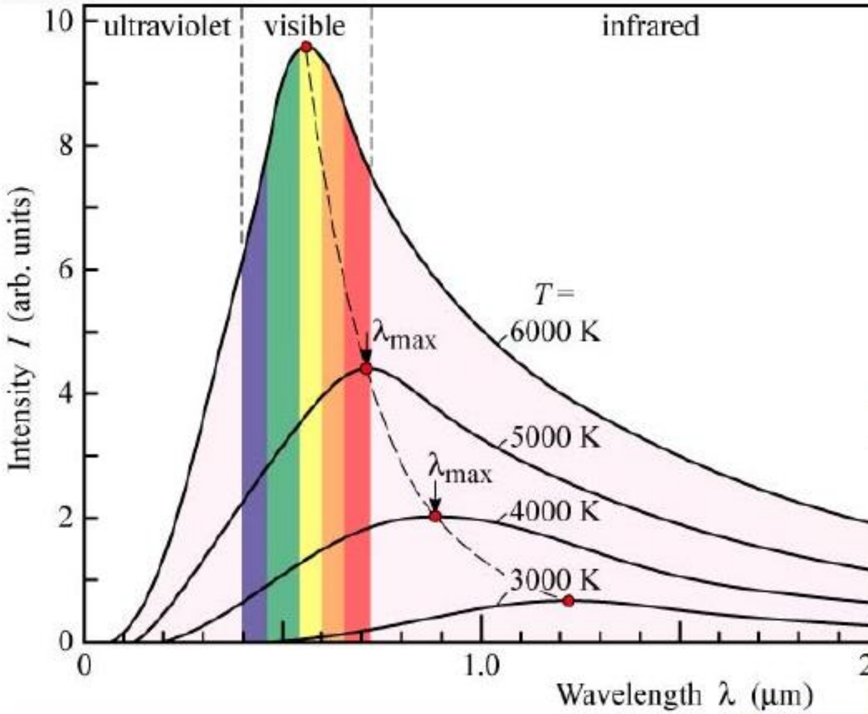
Absorption spectra occur when electromagnetic radiation from a background star passes through a relatively cold gas. Long lived stars ("fossils") mostly belong to this case, and have Teff up to ~6500K.

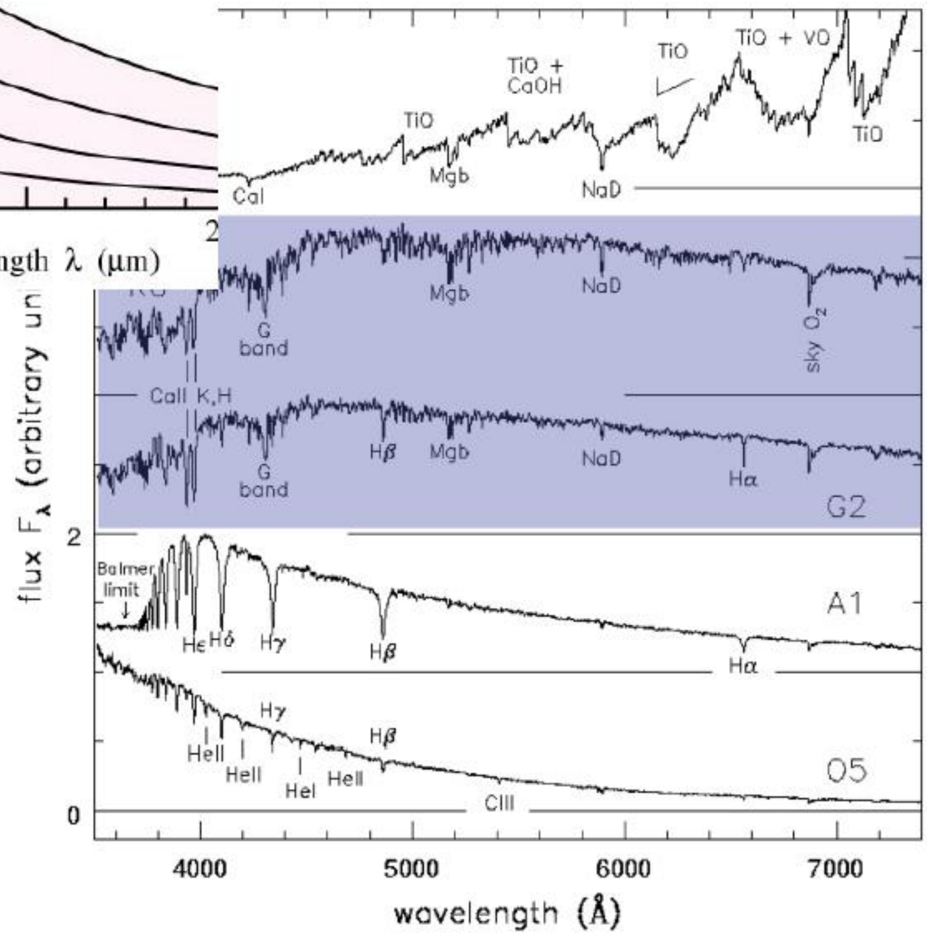
- Radiation at specific wavelengths from the star interacts with (is absorbed by) atoms in the cold gas, causing their electrons to gain energy and enter excited states.

- These electrons quickly de-excite and emit photons at the same wavelengths. However, the direction of the emitted light is random and this leads to the appearance of dark lines (or missing light) in the resulting spectra, corresponding to the wavelengths that were absorbed by the gas. These lines are known as absorption lines.



Temperature drives the spectra appearance





T ~ 4000K

Molecules!

Mainly neutral metal lines

T ~ 6000K

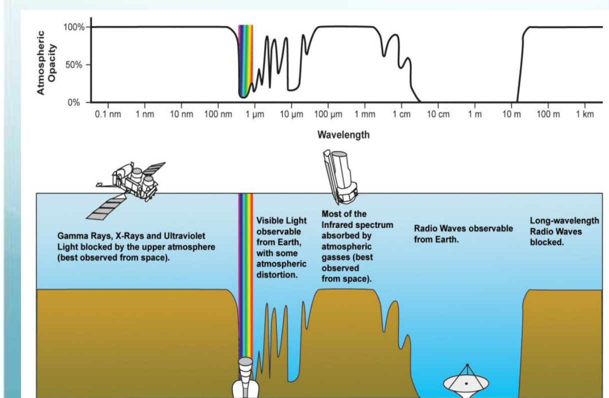
Ionised Metal lines

T < 11 000K

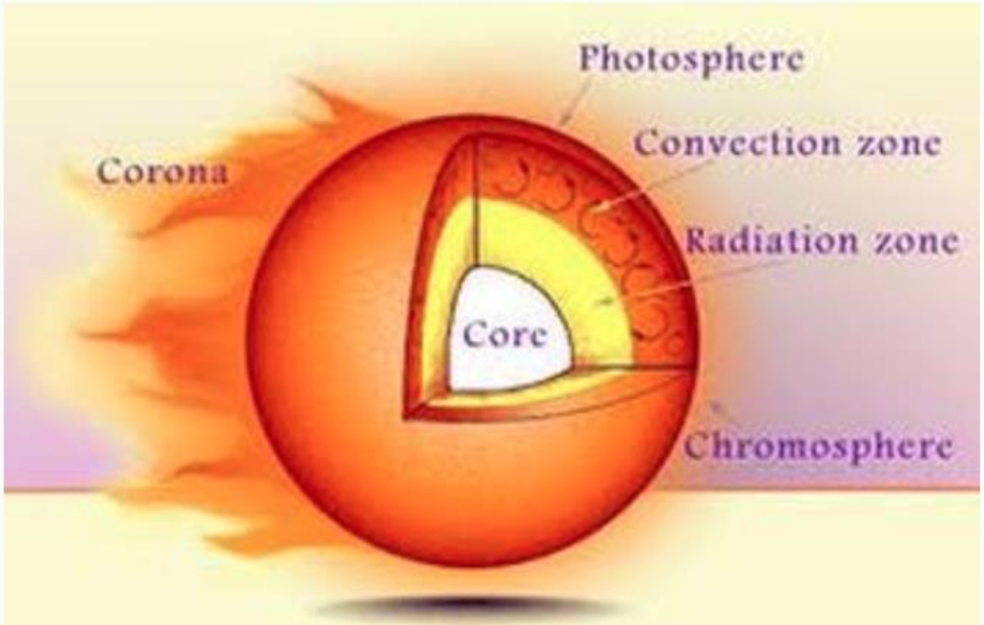
Dominated by neutral H

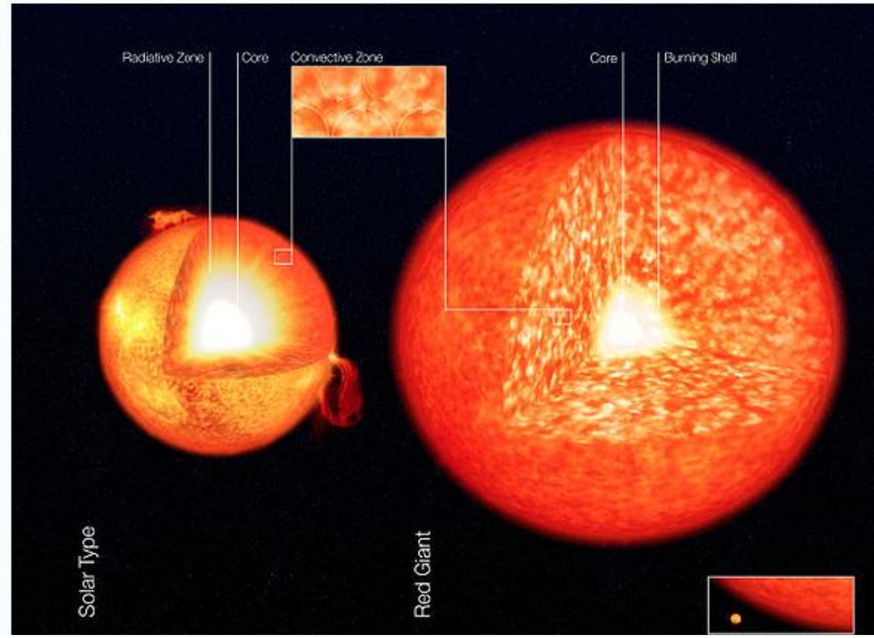
T ~ 30 000K

Highly ionised species



What part of the star do we "see"?





Stellar light emitted at the solar photosphere radiates through the stellar atmosphere where absorption lines are formed. Hence, observation probe the composition at the surface of the star

In low-mass stars (about 1 solar mass) , the convective zone does not reach the very center of the star where nuclear reaction take place -> the surface contain the initial composition at the birth of the star or that of the initial gas in which it formed

In giant stars, mixing episodes can occur when the star leaves the main sequence. It implies that some internally products isotopes can be dredged up to the surface (^{13}C, ^{14}N), while some more fragile ones can be depleted at the surface (Li).

Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

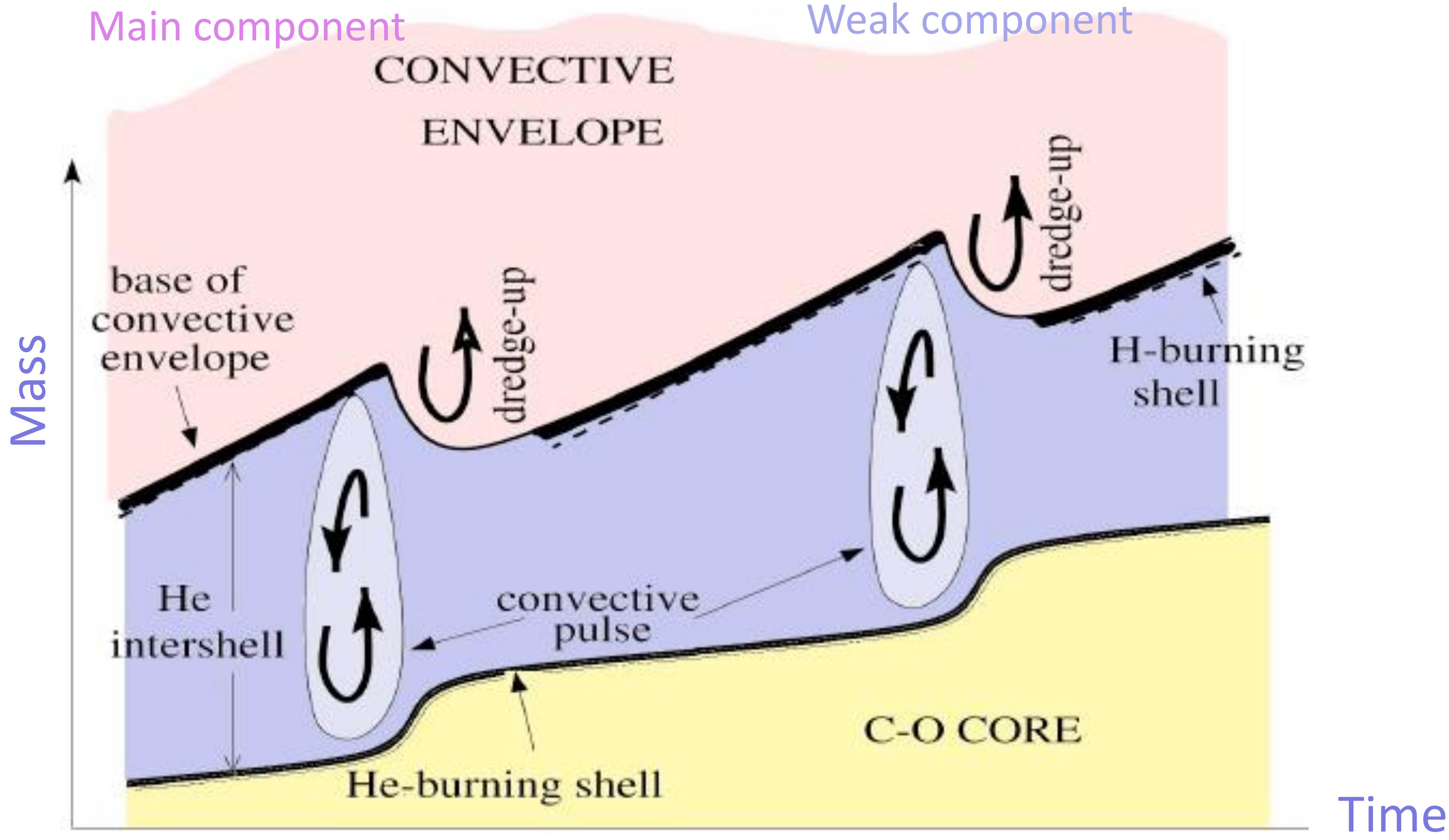
I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

With materials from V. Hill, M. Spite and M. Pignatari

Neutron sources in the s process

Low mass AGB stars < 3 $M_\odot$
Low temperature 10^8 K
$^{12}C(p,\gamma)^{13}N(\beta^-)^{13}C(\alpha,n)$
Flux 10^8 n cm^{-3}
Duration 10^5 y, A > 80
Main component

Intermediate mass AGB > 3 $M_\odot$
Higher temperature 3 10^8 K
$^{14}N(\alpha,\gamma)^{18}F(\beta^+)^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$
Flux 10^{13} n cm^{-3}
Duration 10 y, A ≈ 60-80
Weak component



s-process n-captures ongoing in stars

1952 Merrill find Tc lines in S stars (AGB stars)

Tc is a short period radioactive element **not observed**

on earth

in the meteorites

in the Sun

1955 Cameron shows that neutron captures on iron seeds are able to explain the presence of Tc in S stars

It was indicated previously that the neutron-capture processes should quickly bring Tc^{99} into local abundance equilibrium with its neighbors along the main neutron-capture path. The half-life of Tc^{99} of 210,000 years may be comparable to the time required for

-> s process nucleosynthesis

Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

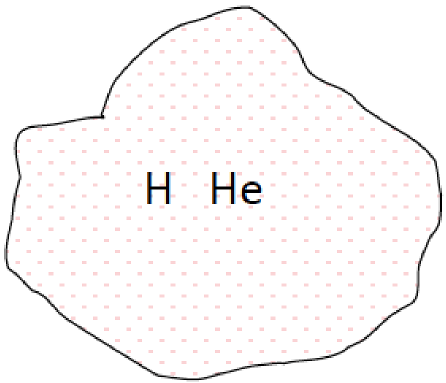
Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

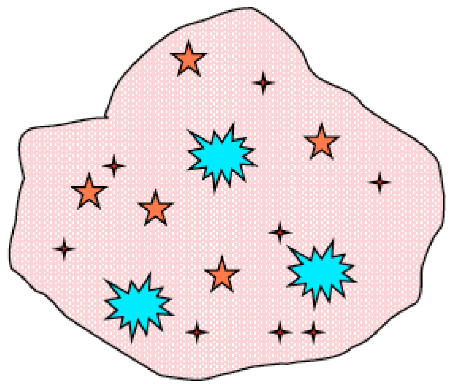
With materials from V. Hill, M. Spite and M. Pignatari

Enrichment in elements over time ?

> Galactic chemical evolution



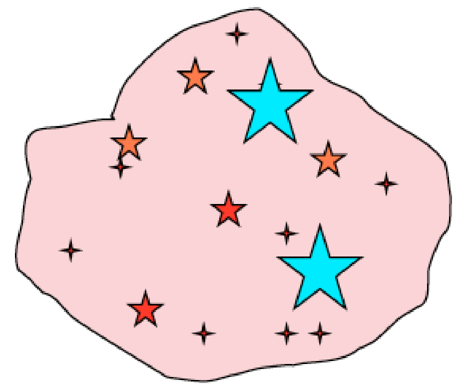
Formation of the Galaxy (primordial material)



stars are formed, they explode, and enrich the matter with their products (**stellar winds, supernovae**)

↓

A lot of Fe, possibly heavy elements as well



New stars are formed, explode, little by little the matter becomes richer in elements formed inside the stars...

Little by little, the Galactic matter is enriched in elements formed inside the stars

The Fe content is a good tracer of the enrichment of stars from earlier exploded ones

EMP stars

Extremely Metal Poor stars

The chemical composition of the atmosphere of the **old stars,** born at the very beginning of the Galaxy, is the witness of the chemical composition of the gas in the early matter.

How to find them ?

Since at their birth the matter was enriched by a very small number of supernovae, they are very metal-poor.

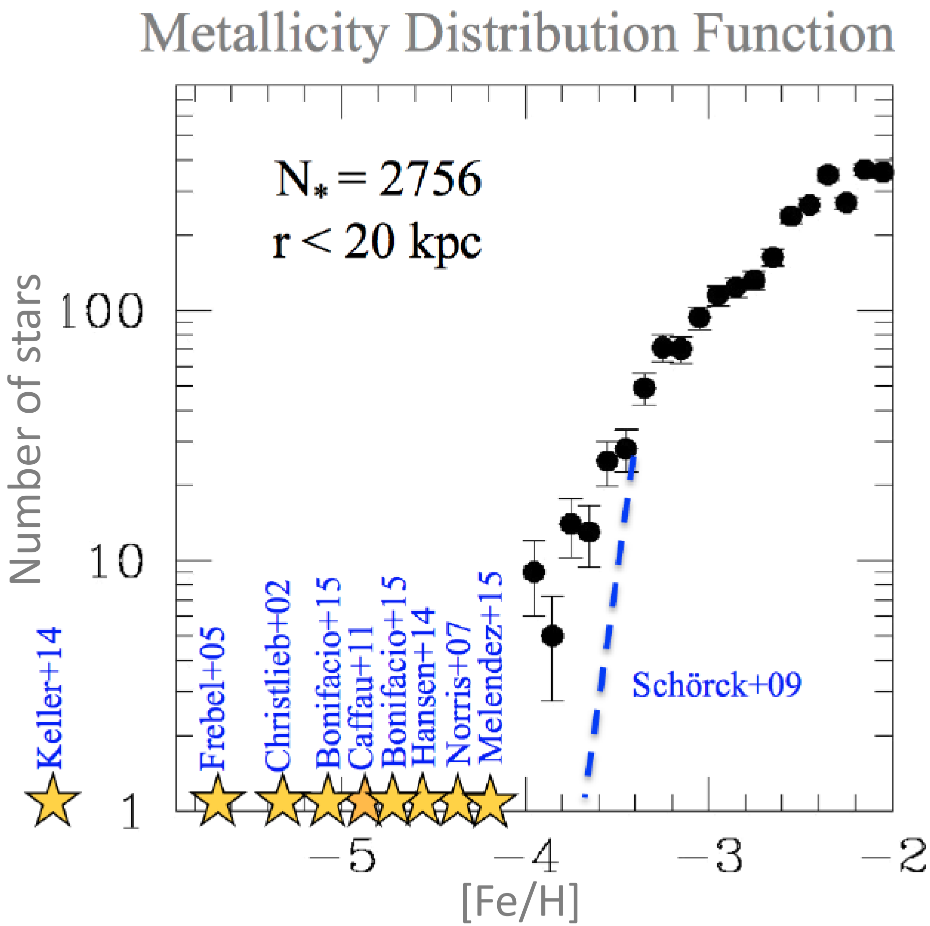
Metallicity is taken as a criterion of primevality

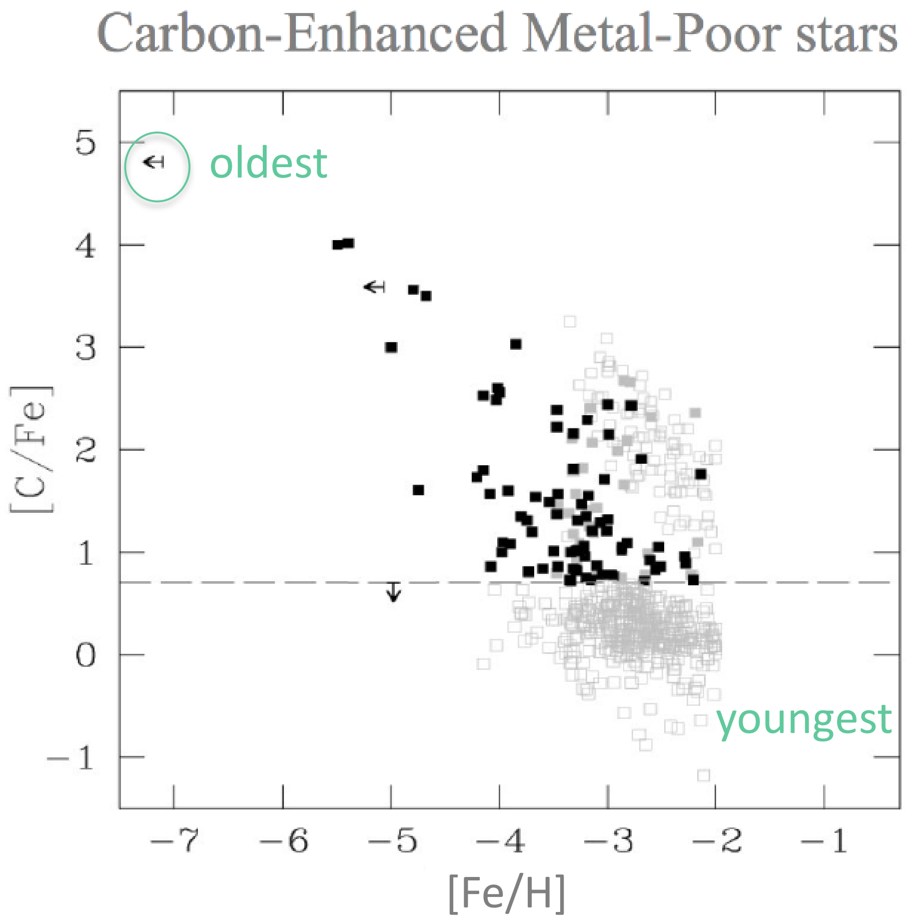
Definitions: $[Fe/H] = \log (Fe/H)_{\star} - \log (Fe/H)_{\odot}$

$([X/H] = \log (X/H)_{\star} - \log (X/H)_{\odot} \ \ldots)$

ex: $[Fe/H] = -2$ ➔ 100 times less iron than the Sun

Observations in the Galaxy

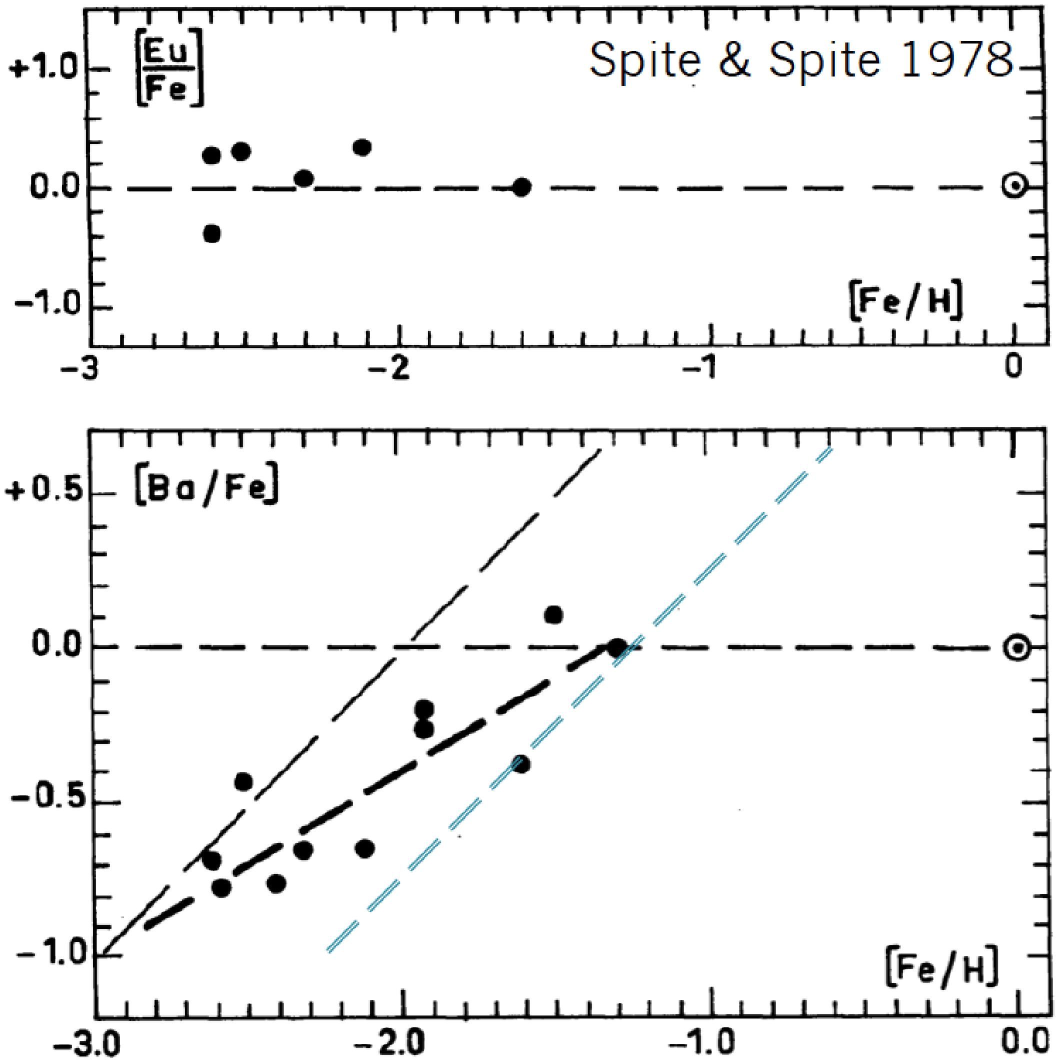




Metallicity distribution show a sharp decline and then a drop at [Fe/H]<-4

Most of the stars with [Fe/H]<-4 are C rich

Heavy n-captures in metal-poor stars



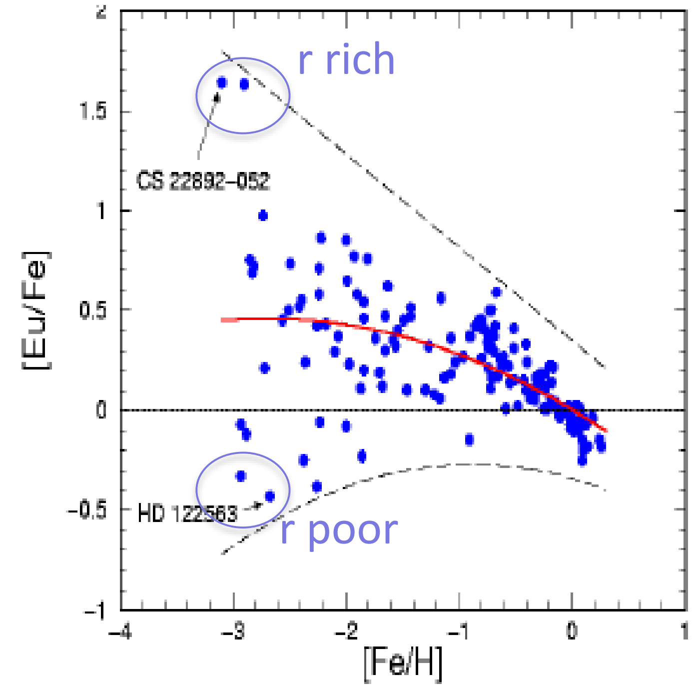
- Eu (almost pure r-process nuclei in the Sun), is slighlty enhanced in low metallicity stars unlike Ba, Y which decreases at low metallicities
- Ba and Y “s-process” nuclei have a different trend with [Fe/H] than a secondary process would allow.
- Truran (1981) was the first to propose a coherent picture of the s- and r-process elements in the galaxy, where the r- process occurs in a primary way in short-lived contributors.

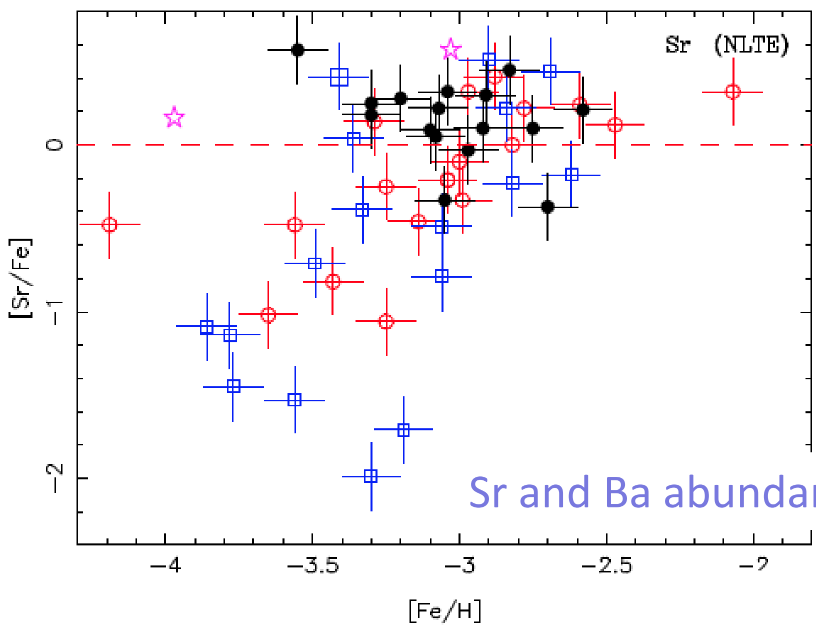
Heavy neutron capture elements in metal-poor stars

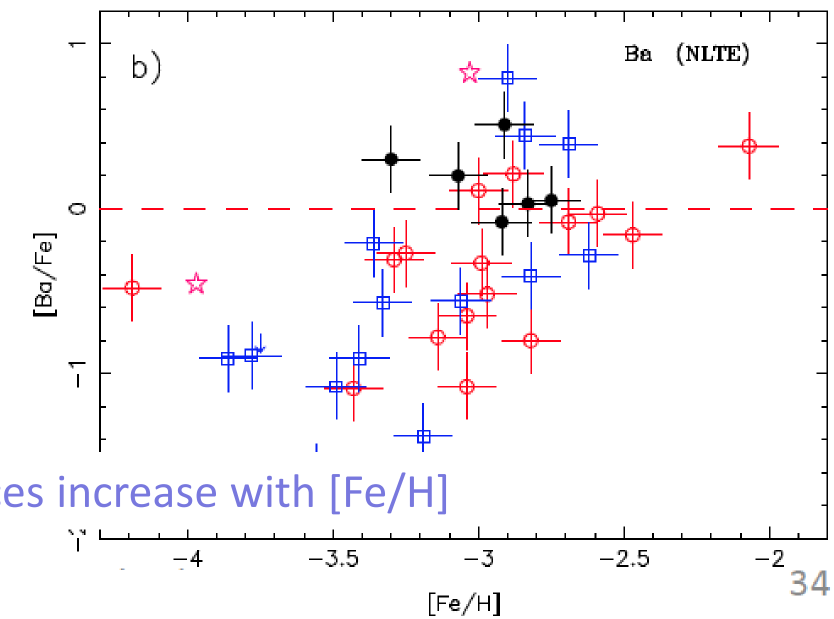
Adding more observations leads to a large scatter of [Eu/Fe] ratio: r rich and r poor.

This suggests that the r process can be very well produced in few first generation stars. It is however a rather process.

Ba is confirmed to be of secondary process as Sr as they both increase with [Fe/H].







Sr and Ba abundances increase with [Fe/H]

Lectures in nuclear astrophysics : Parts I

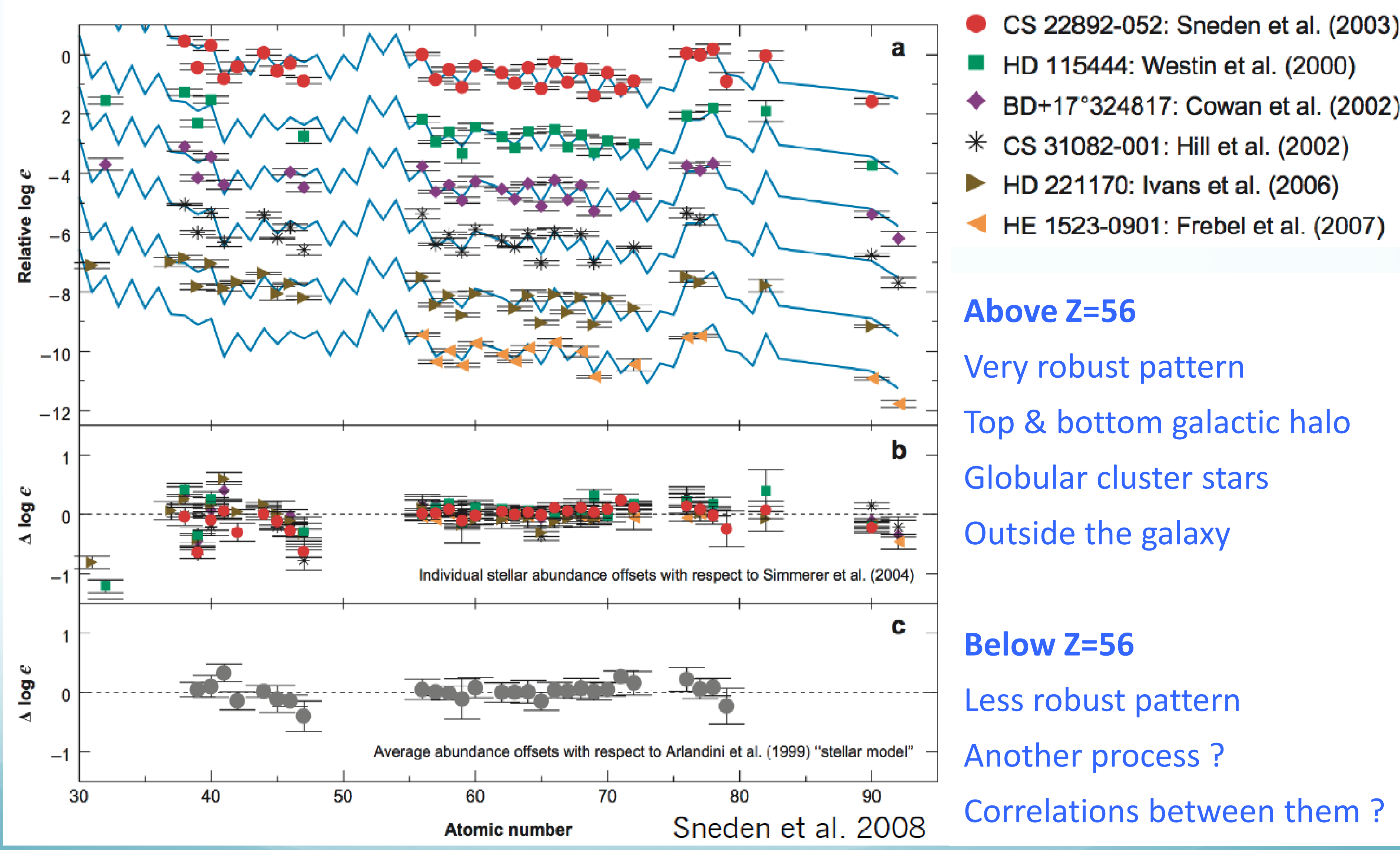
O. Sorlin (GANIL, France)

Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

With materials from V. Hill, M. Spite and M. Pignatari

A universal r-process?



Sneden et al. 2008

Above Z=56

Very robust pattern

Top & bottom galactic halo

Globular cluster stars

Outside the galaxy

Below Z=56

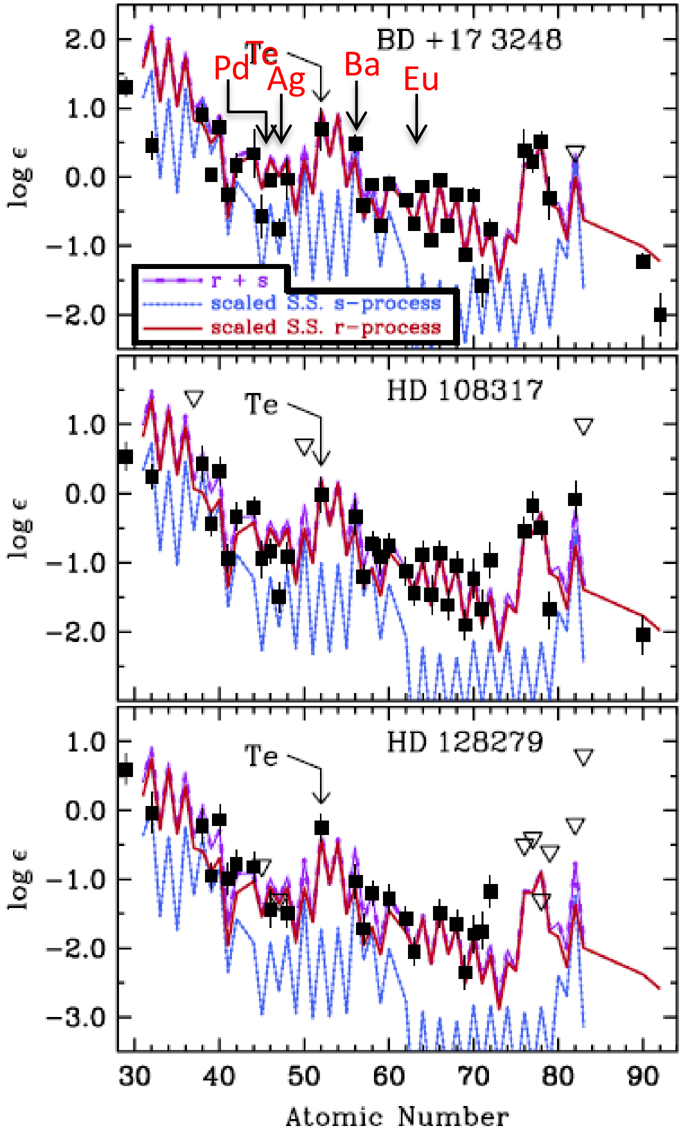
Less robust pattern

Another process ?

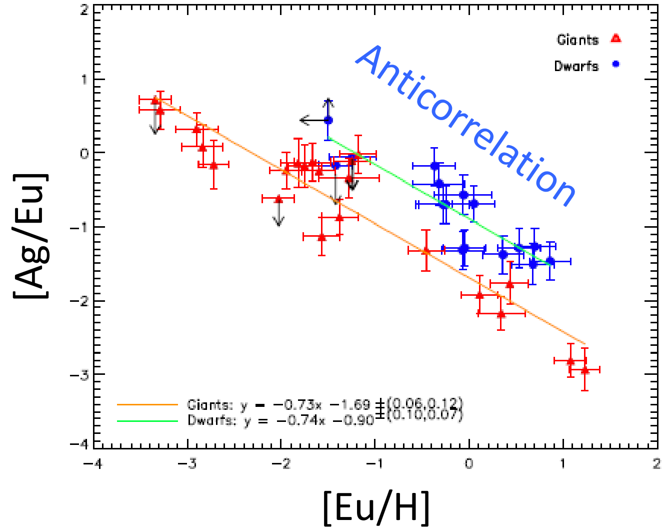
Correlations between them ?

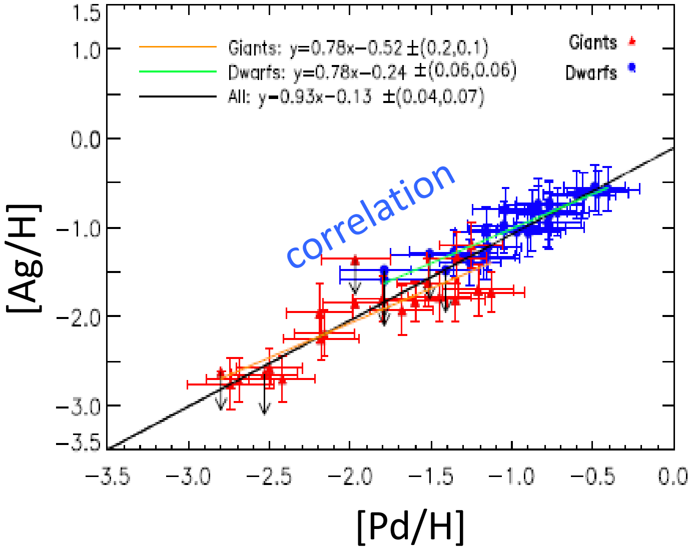
Correlations betwen light and heavy elements ?

Roederer 2012 Hubble



(PhD-thesis C.J. Hansen 2011)





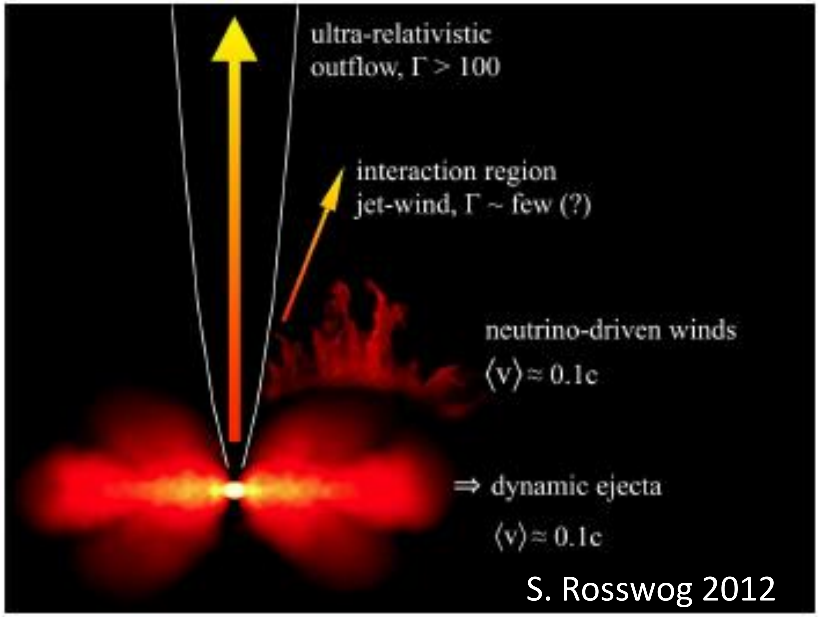
Two categories of r process elements: light and heavy elements

The frontier at Z=56 corresponds to the A=130 peak

r-process in stars: where ?

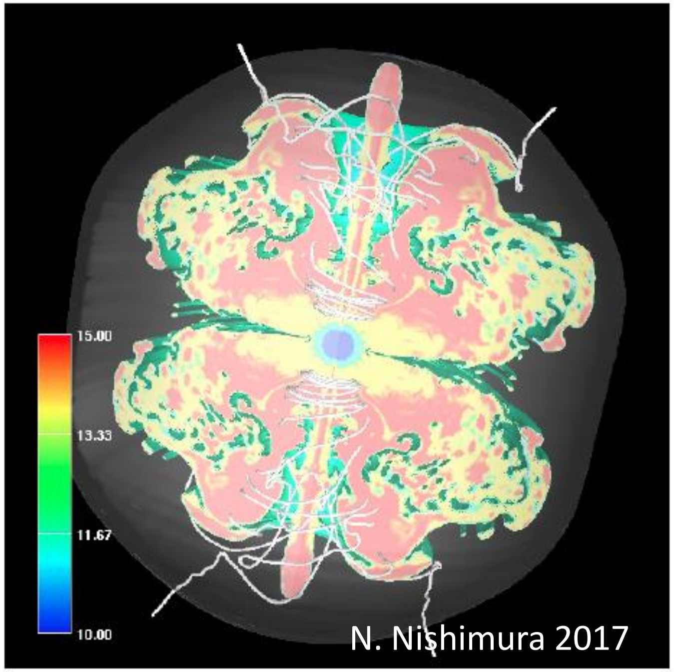
One of the biggest remaining question …

Binary neutron stars:
Matter ejection and r-process nucleosynthesis from dynamic ejecta and eutron driven wind



Expected to produce and eject a lot of r elements. They are however rather rare events.

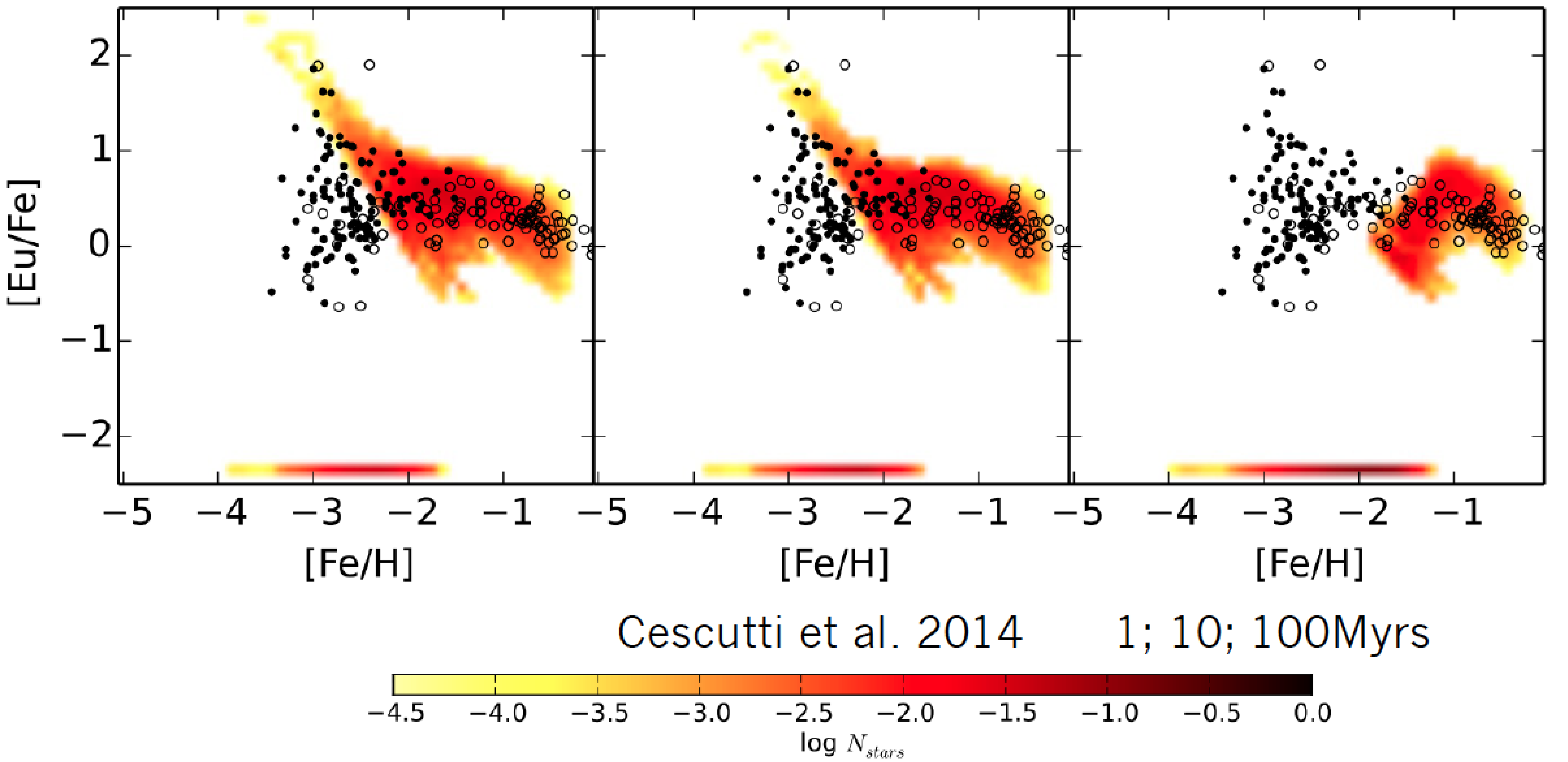
Highly-magnetized core-collapse supernovae



Only highly magnetized CCSNe may have suitable conditions to develop r process nucleosynthesis

Deduce the stellar site(s) of the r-process from observations of poorly-mixed stars

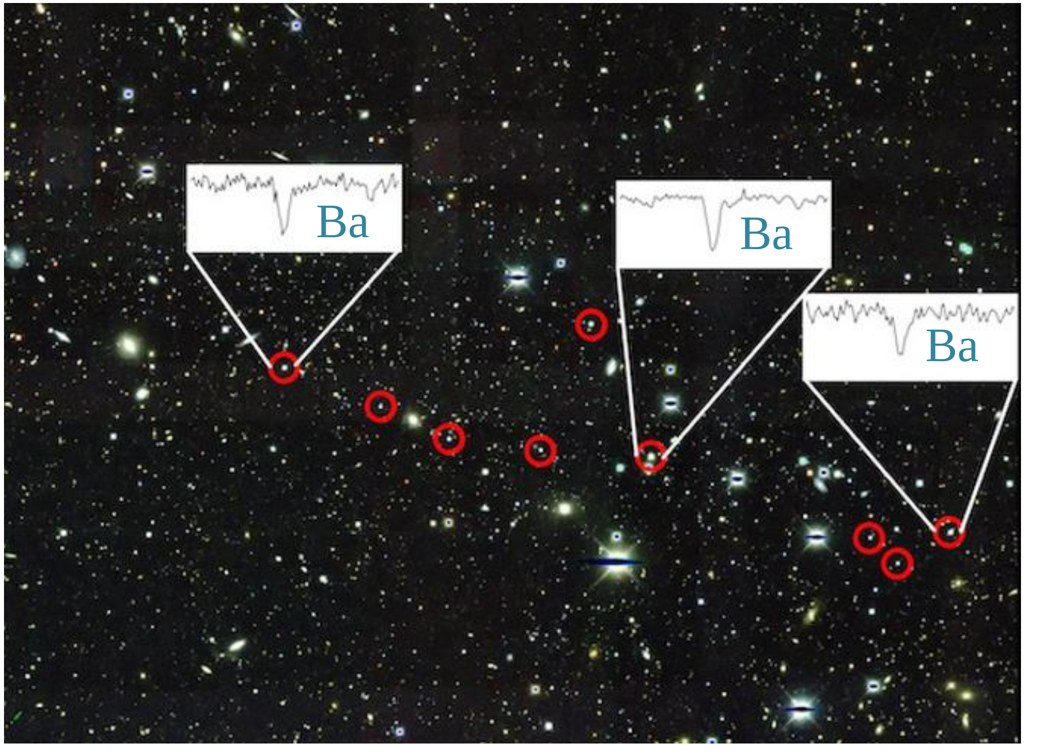
R process in NS-NS: timescale problem

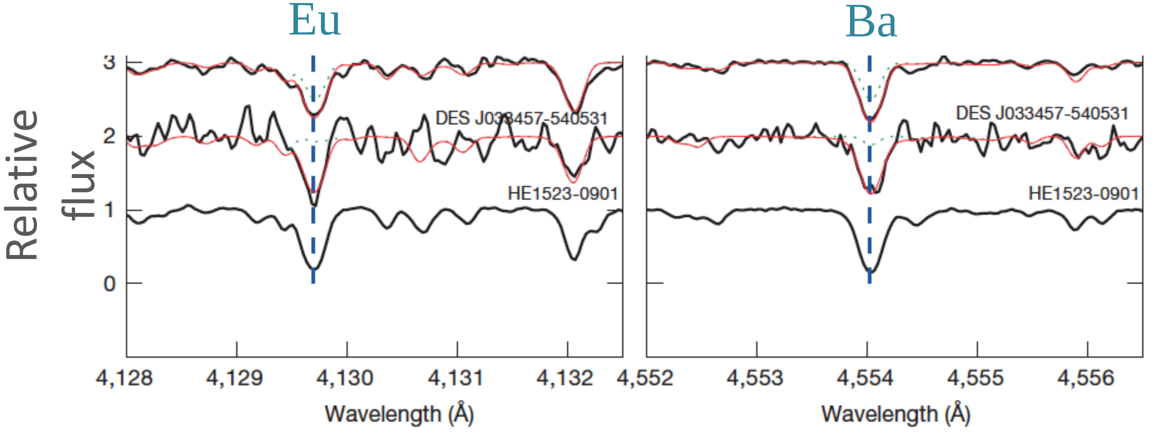


To make binary star mergers (BNS, NS-NS) as a contributor to the early galactic evolution, one needs to assume their very fast occurrence (much faster than commonly thought) and add some CCSNe contribution on top as BNS cannot produce modest enhancements in Eu.

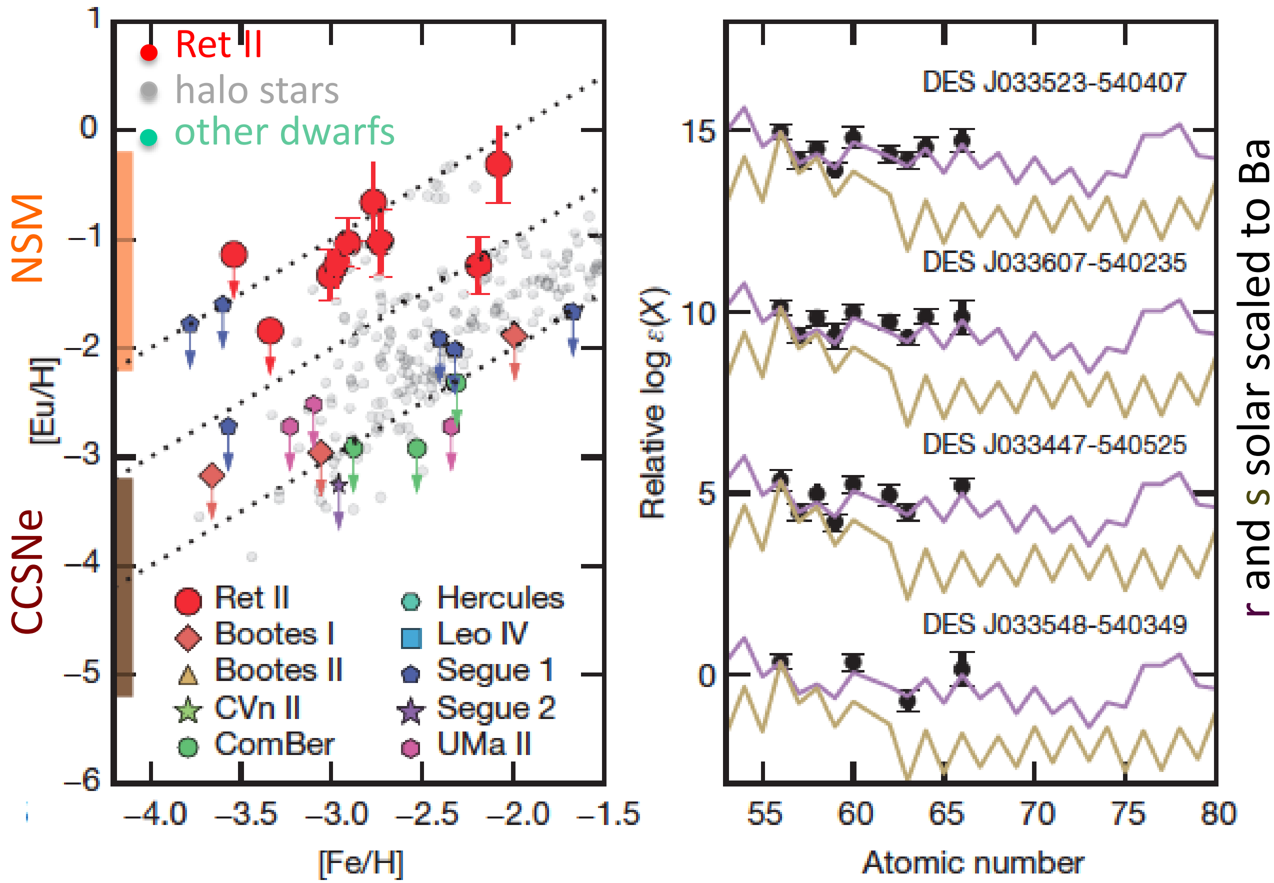
Clues from outside the galaxy

Dark energy Survey / Fermilab, ret II dwarf galaxy : Ji, Frebel et al.





Clues from outside the galaxy



Ji et al. Nature 2016

Given the amplitude and constancy in r-process enrichment, a single event is the most likely. This implies a single large-mass r process, likely to originate from NS-NS binary (CCSNe gives much smaller mass rate).

Lectures in nuclear astrophysics : Parts I

O. Sorlin (GANIL, France)

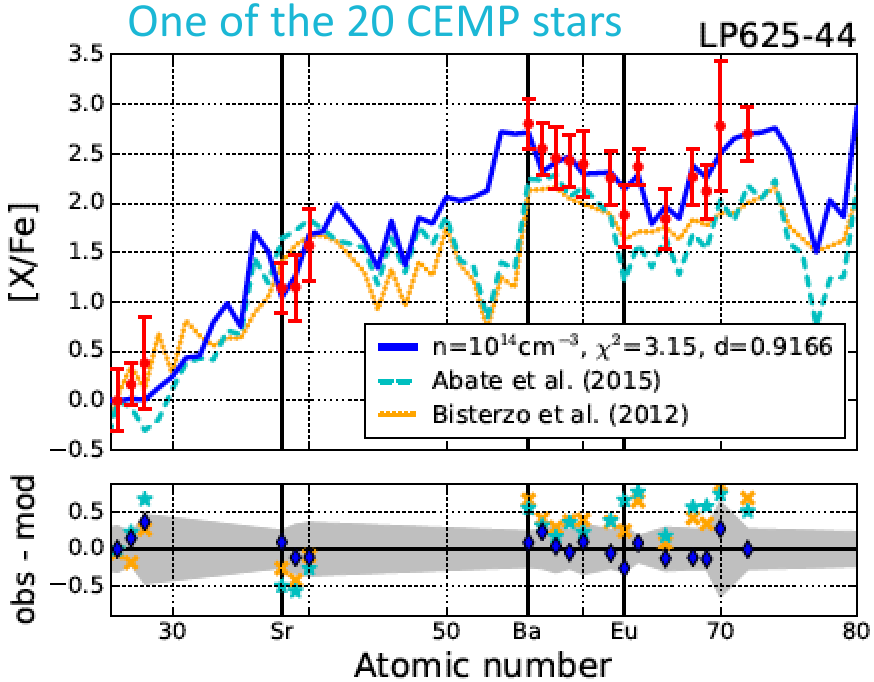
Extremely metal-poor (EMP) stars as probes of earliest heavy elements nucleosynthesis

I. Abundance curve in solar system & neutron capture processes
II. Few words about stellar evolution
III. The making of s process elements
IV. Galactic chemical evolution
V. Universal r-process abundances in EMP stars?
VI. Evidences of weak r-process from stars and meteorites

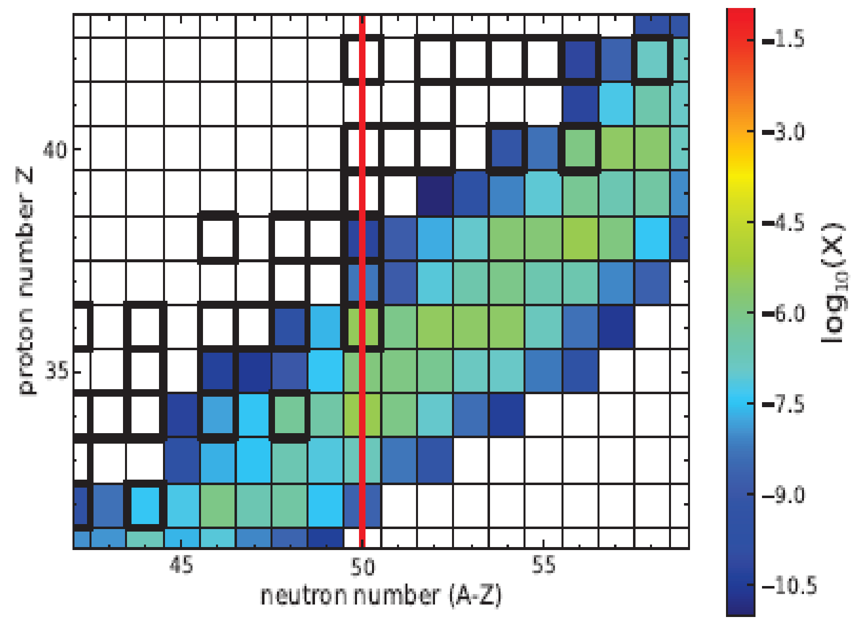
With materials from V. Hill, M. Spite and M. Pignatari

Carbon-enhanced metal-poor stars: an intermediate i-process

One of the 20 CEMP stars



i-process progenitors



Several CEMP stars of the galactic halo dispaly enrichments associated with both s and r process (e.g. Ba and Eu, resp). This is puzzling as s and r process differ by 10 orders of magnitude in neutron densities and occur in very different sites. (e.g. Roederer et al. ApJ. 2016, Denissenkov et al. Ap.J. L 2017 Mishenina et al. MNRAS 2015).

It is been proposed that an intermediate process (10^{15} cm^{-3}), found in explosive He shells, could account for these observations. (e.g. Hampel 2017, Pignatari 2016).

Neutron capture rates on unstable nuclei relatively close to stability are needed.

Information from stardusts collected on earth

Ejected material from a precusor star
Travel throughout the galaxy, embedded in host material
Incorporated into the solar system
Collected on earth
Expected to keep fingerprints of of their formation site

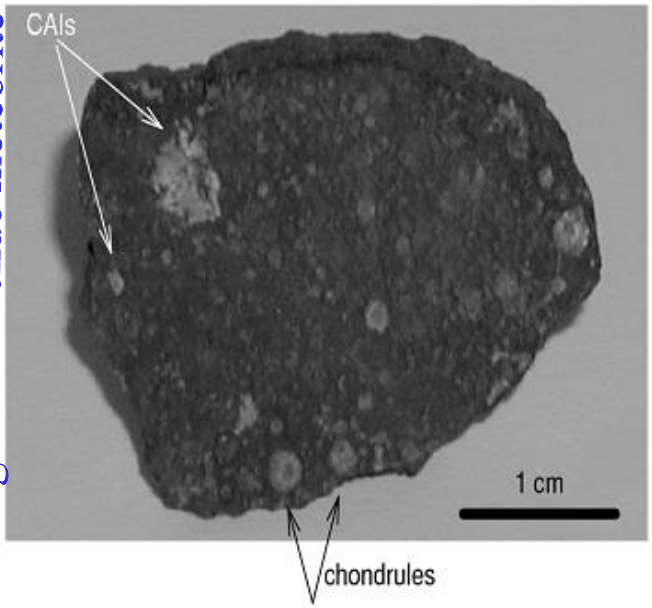
CaAl-rich inclusions:

High T condensates
First solids formed into solar system
Moderate isotopic anomalies/solar
Embedded in a host solid rock

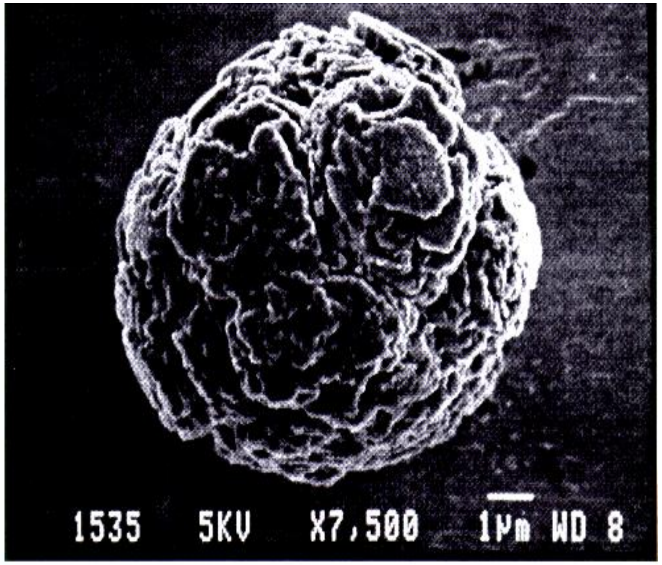
Si-C grains presolar grains:

Formed prior to the solar nebular
Huge isotopic anomalies/solar
Formed in supernovae (extinct ^{26}Al, ^{44}Ti)

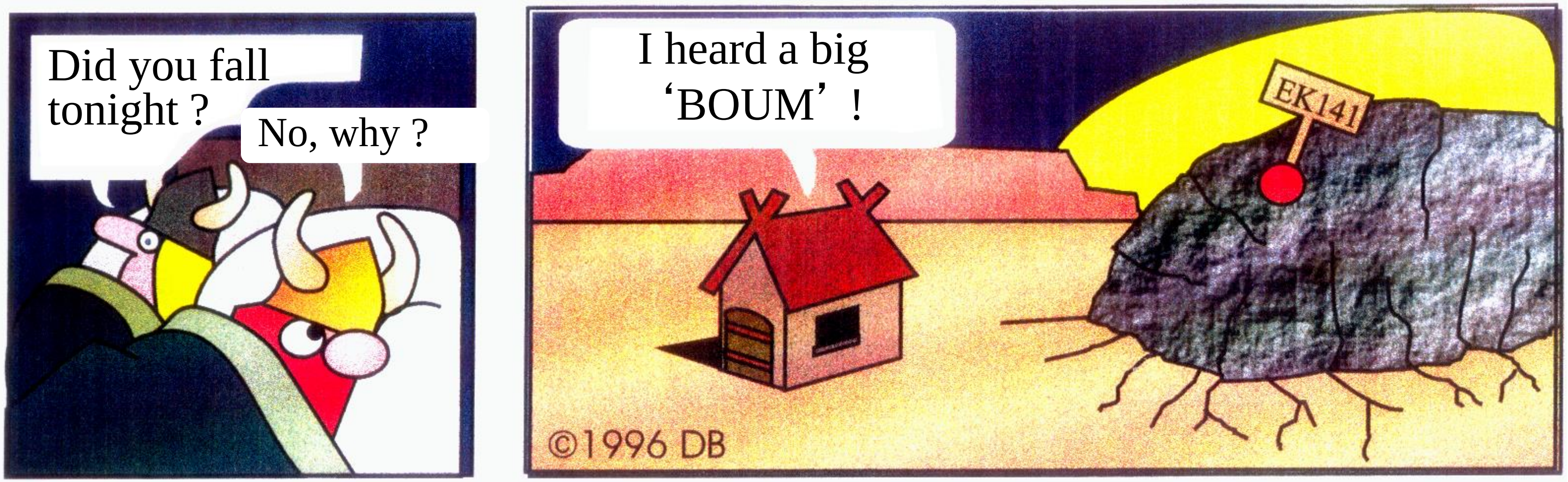
Fragment Allende meteorite



SiC- type X



^{48}Ca overabundance in EK 1-4-1 inclusion of meteorite



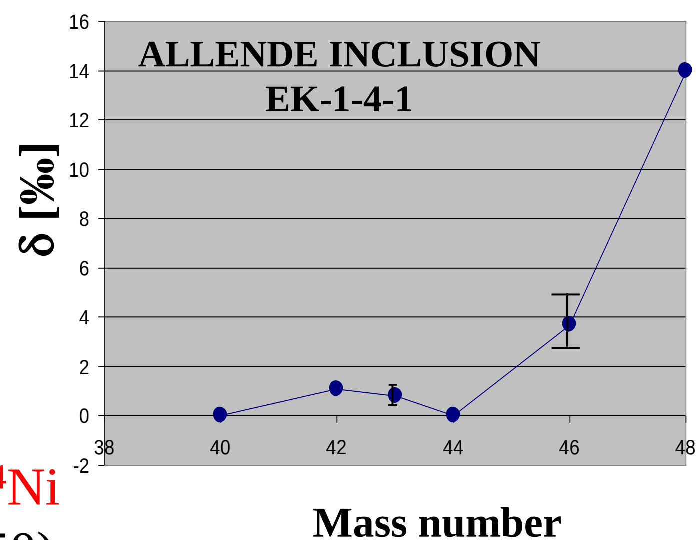
^{48}Ca/^{46}Ca ≈ 250 (solar =53)

Allende meteorite:

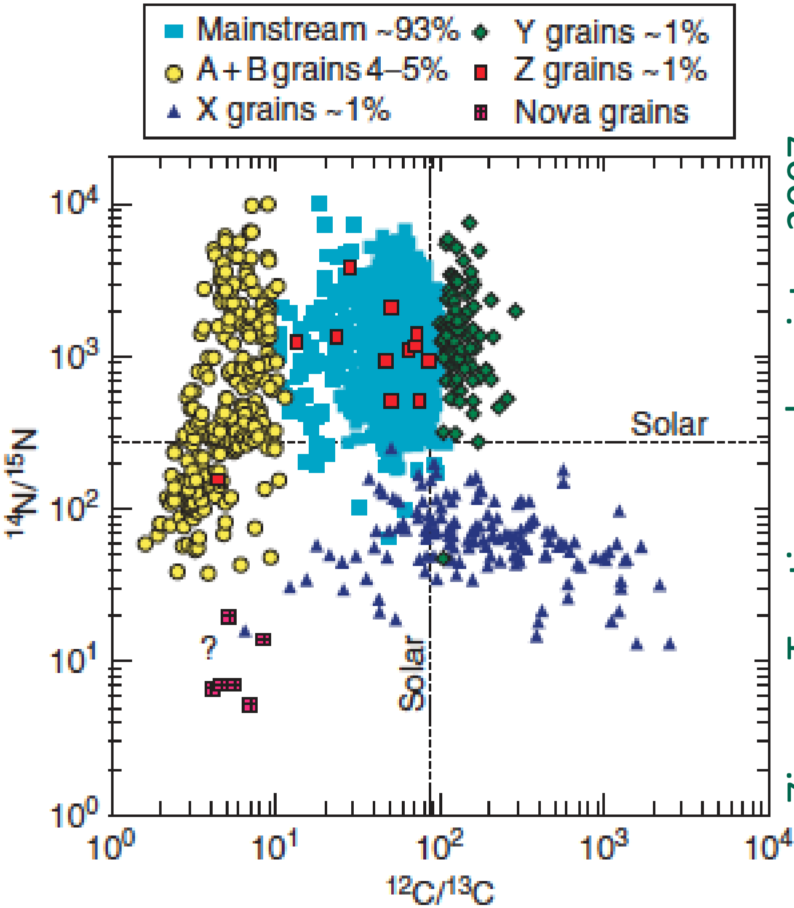
fell in 1969
weight 2t
chondraneous carbide
several CaAl-rich inclusions

EK1-4-1 inclusion :

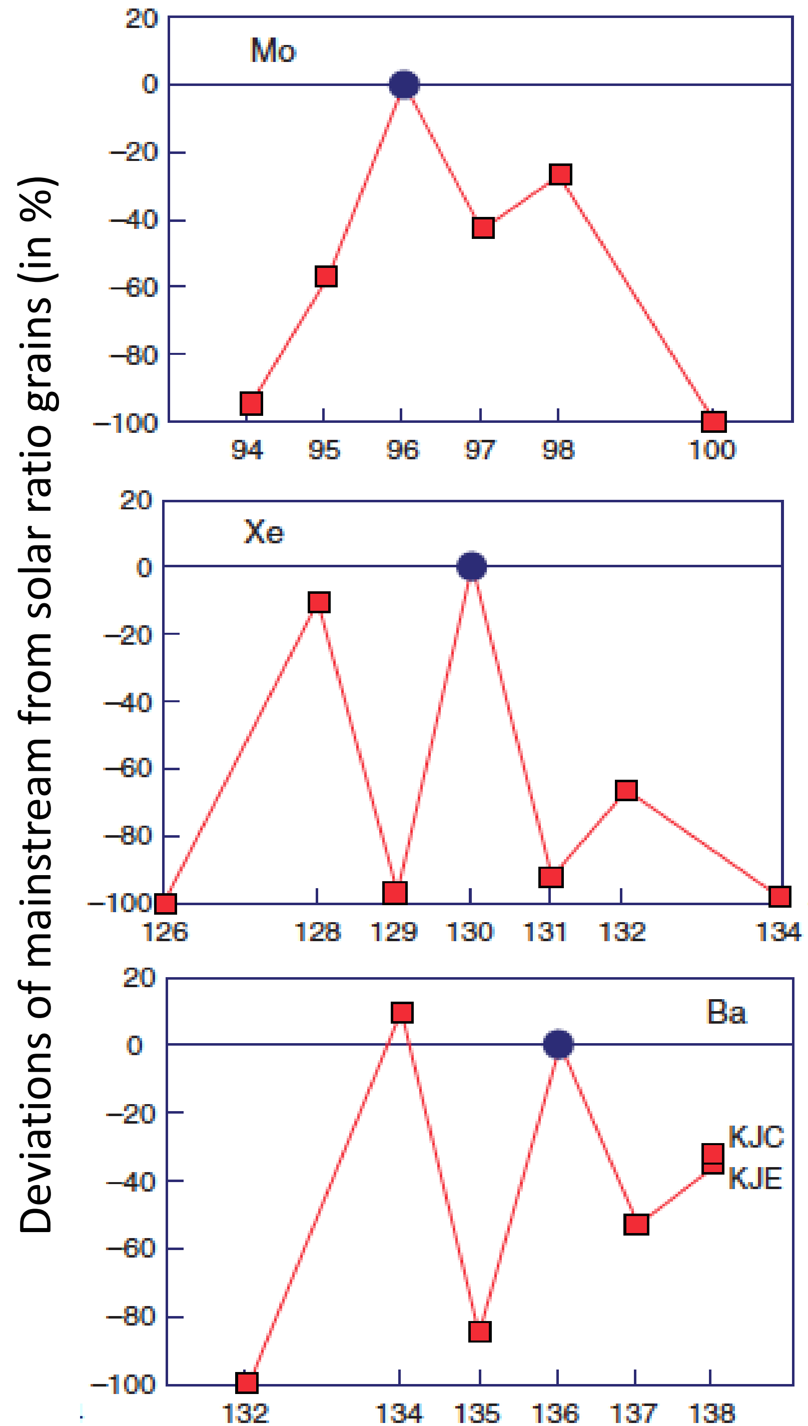
spherical shape, white colour
diametre 1cm
Fusion temperature 1500-1900K
Correlated over-abundances ^{48}Ca-^{50}Ti-^{54}Cr-^{58}Fe-^{64}Ni
Underabundance of ^{66}Zn, r process Nd, Sm (A~150)



Categories of Si-C grains



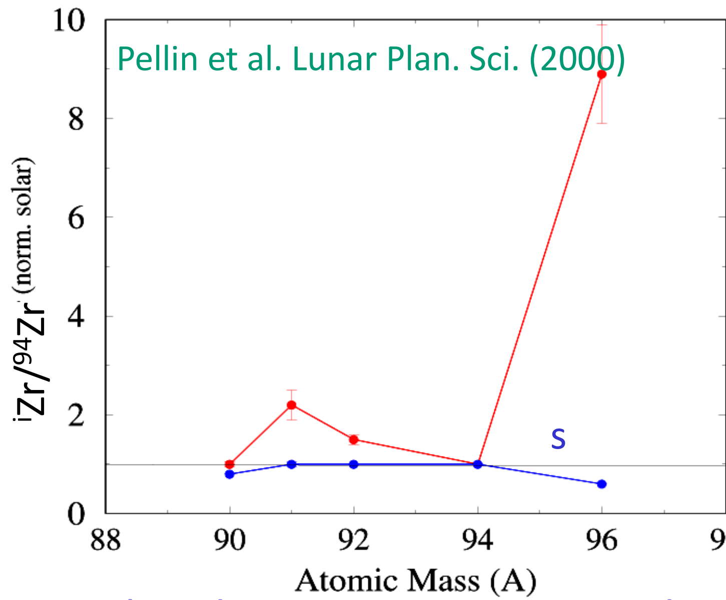
Zinner, Treatise on chemistry 2007

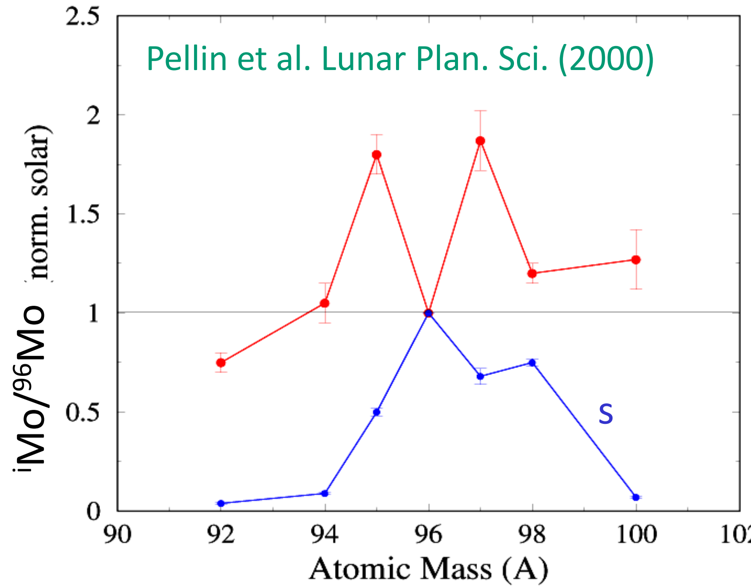


Isotopic compositions of mainstream grains differ significantly from solar ones (depleted in p and r) -> their origin is clearly extra solar. Their isotopic composition is typical of an s process.

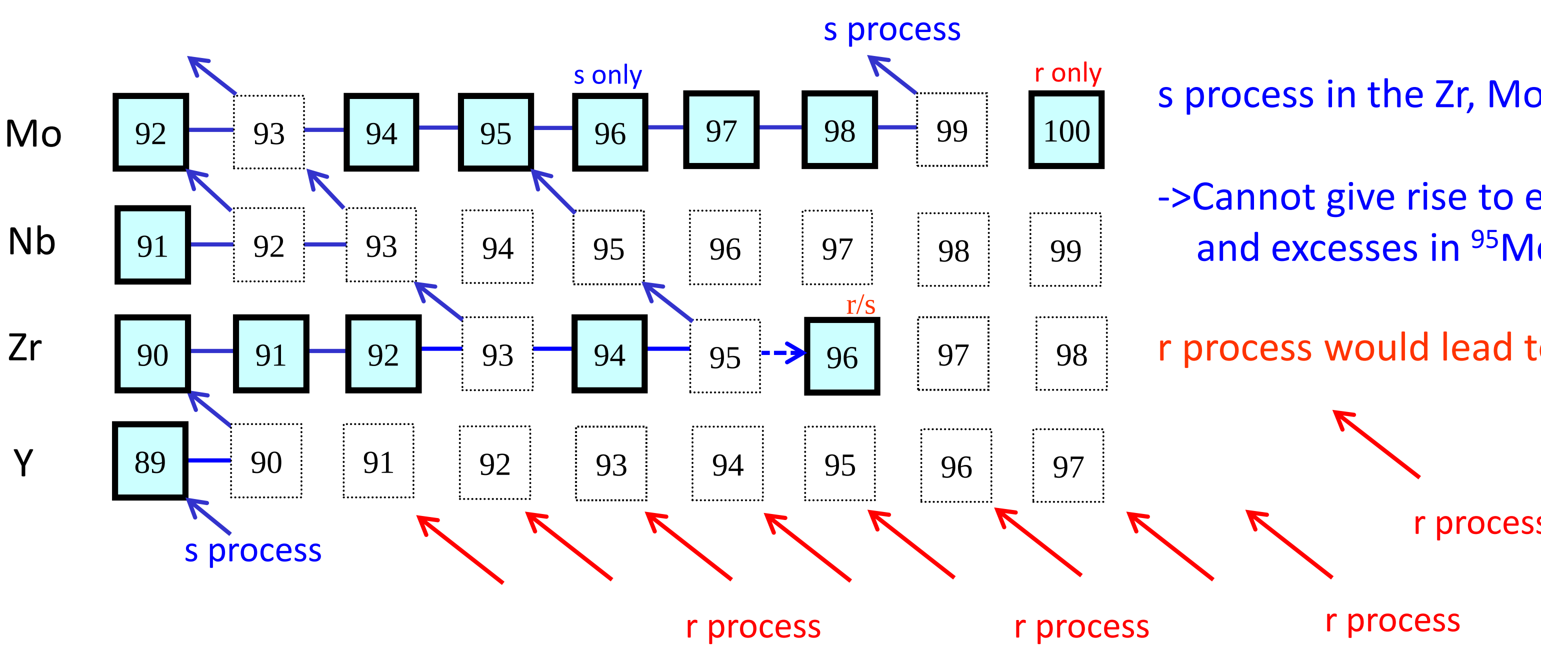
X grains likely come from supernovae explosions

Mo, Zr anomalies in Si-C presolar type x grains





Abundance patterns in Zr and Mo are intermediate between s and r

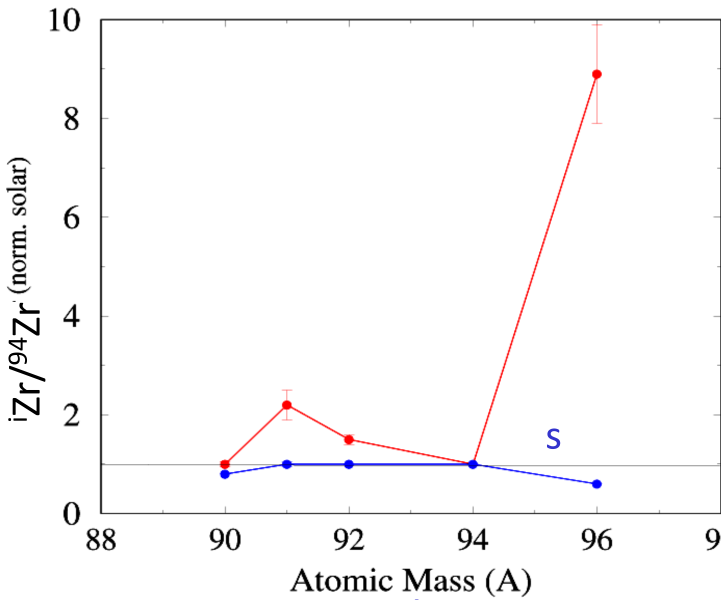


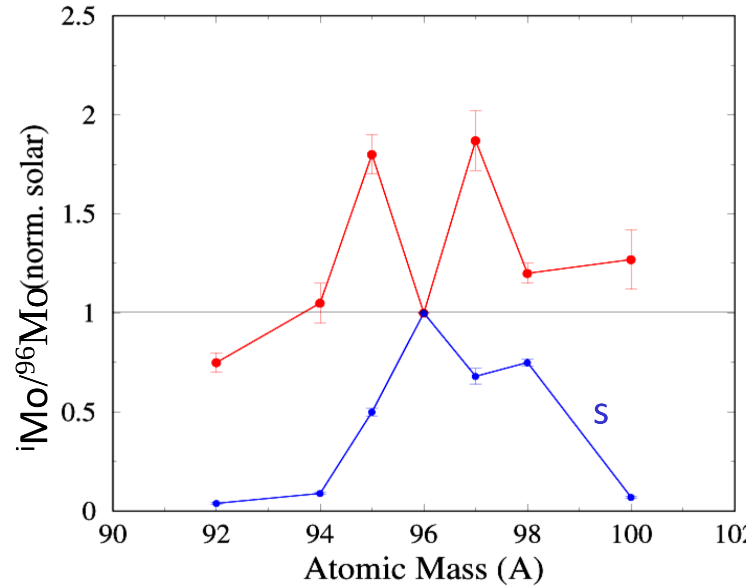
s process in the Zr, Mo region

->Cannot give rise to excess in ^{96}Zr
and excesses in ^{95}Mo and ^{97}Mo.

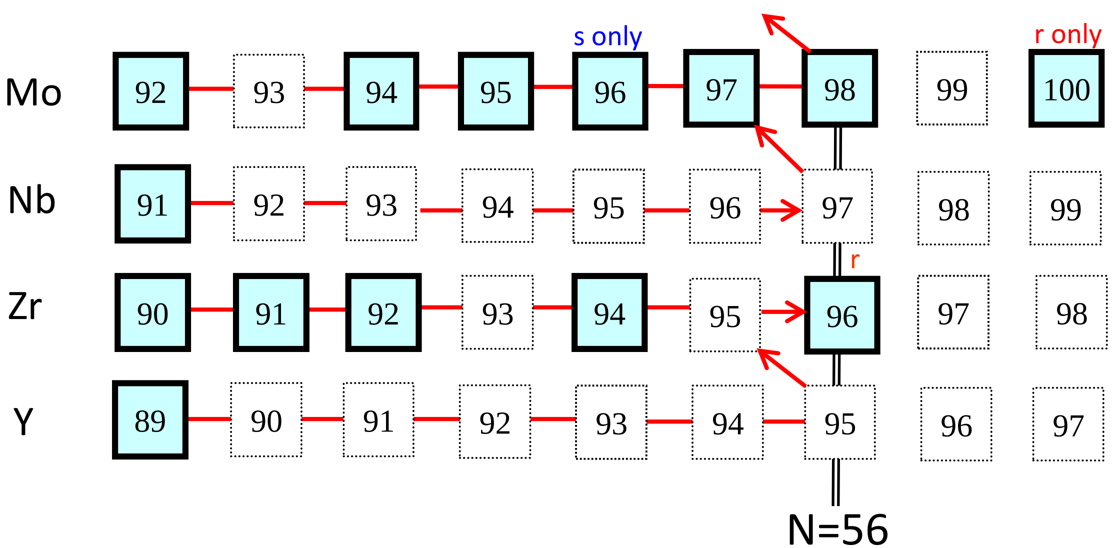
r process would lead to enhanced ^{100}Mo

Mo, Zr anomalies in Si-C presolar type x grains





Abundance patterns in Zr and Mo are intermediate between s and r: Pellin et al. Lunar Plan. Sci. (2000)



Neutron burst $10^{17} cm^{-3}$

B. Meyer et al. Ap.J. L 540 (2000)

-> i process ?

-> signature of N=56 subshell closure ?

Determine Nb, Y neutron captures

End of Lecture I.

Take away messages:

Elements heavier than Fe are produced by neutron capture processes

There exists two major categories of processes with low and high densities

s-process nucleosynthesis is observed and ongoing in AGB stars

r-process site(s) is so far unknown: supernova, neutron star mergers…

Observation in EMP display similar pattern above Z=56 -> robust r

Below Z=56, many more fluctutaions -> weak r process

Other signature of weak r process exist in CEMP-i stars and in meteorites