Heavy elements
Abundance pattern in Extremely Metal-poor stars

Formation of the elements in the early Galaxy

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I History Formation of the elements,
Chemical enrichment of the Galaxy

II The Extremely Metal-Poor stars (EMP)

III Abundance of the elements in EMP (CEMP) stars
- -The lithium problem
- -From C to Zn
- -The neutron capture elements

I History Formation of the elements,
Chemical enrichment of the Galaxy

The astronomical background in 1950

1929 Rutherford age of the earth (radioactive dating)

Age of the meteorites age of the Sun ∼5 Gyr

∼1941 Temperature of the stars (Barbier Chalonge 1941)

(distribution of the energy)

∼1940 measurements of L $\mathcal{R}$ and $\mathcal{M}$

(binary stars , eclipsing binaries)

➡ the Mass-luminosity relation dwarfs: $L \propto \mathcal{M}^4$)

(Parenago 1937, Kuiper 1938, Russell 1940...)

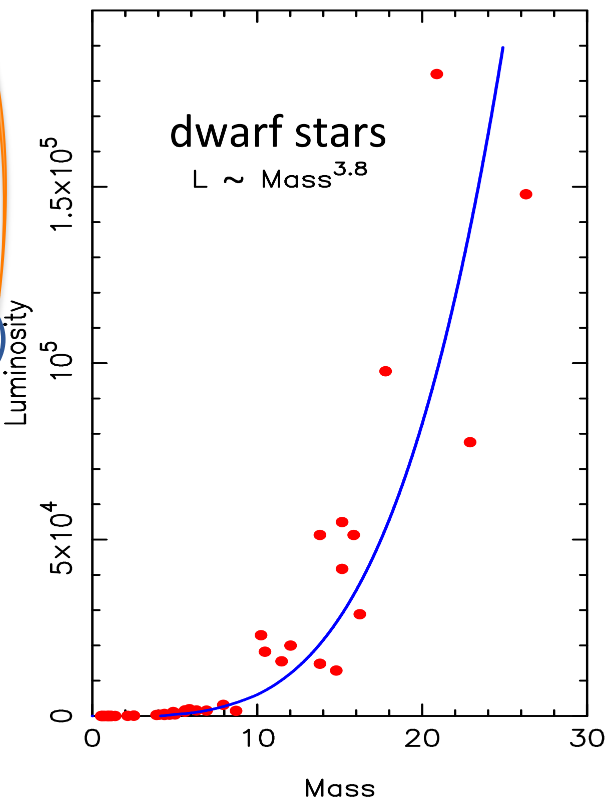
1939 "An Introduction to the study of stellar structure"

(Subrahmanyan Chandrasekhar 1939)

➡Physical conditions inside the stars

nuclear fusions = source of stellar energy

in the Sun H ➡He



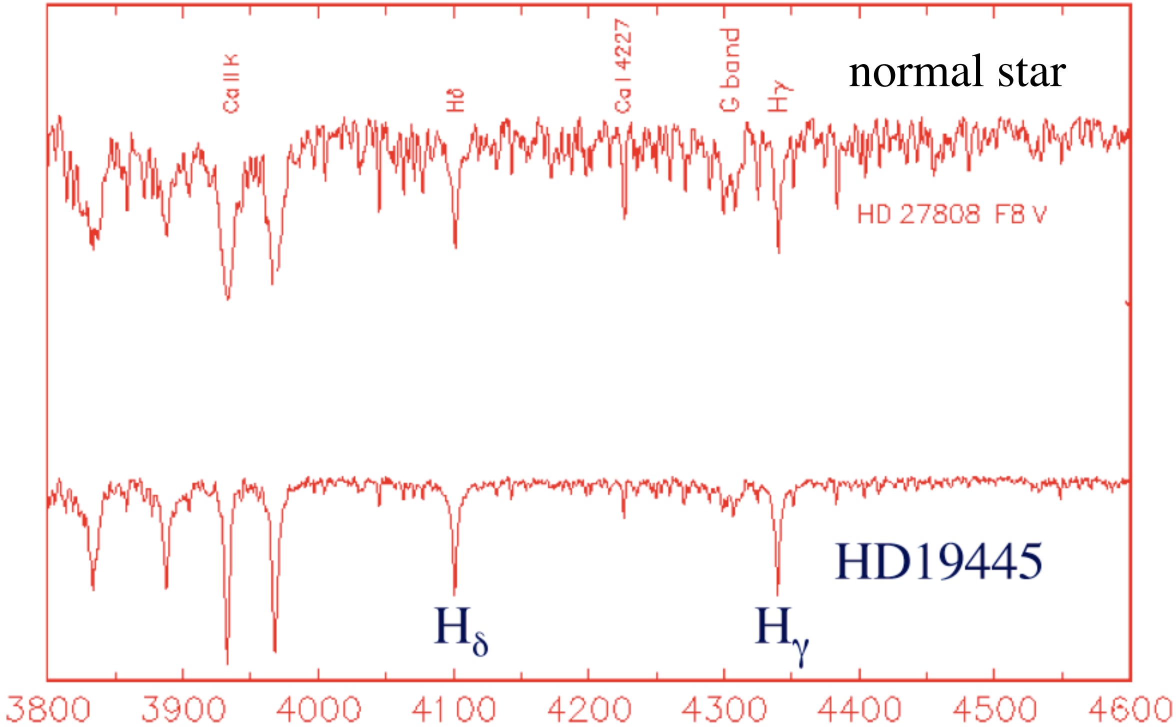
1946 Gamow and also **1950-Alpher et al. :**

elements are formed during the Big Bang

After 1950 ...

1951 Chamberlain & Aller HD19445 HD140283

very metal-poor stars in the Galactic Halo



The chemical composition of the stars is not always the same !

HD19445

Chamberlain et Aller found 10 times less metals than the Sun

In fact it is 100

in this star Vr is very different from the disk star, it crosses the glactic disk by chance, but belong to the Halo.

After 1950 ...

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

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

on earth

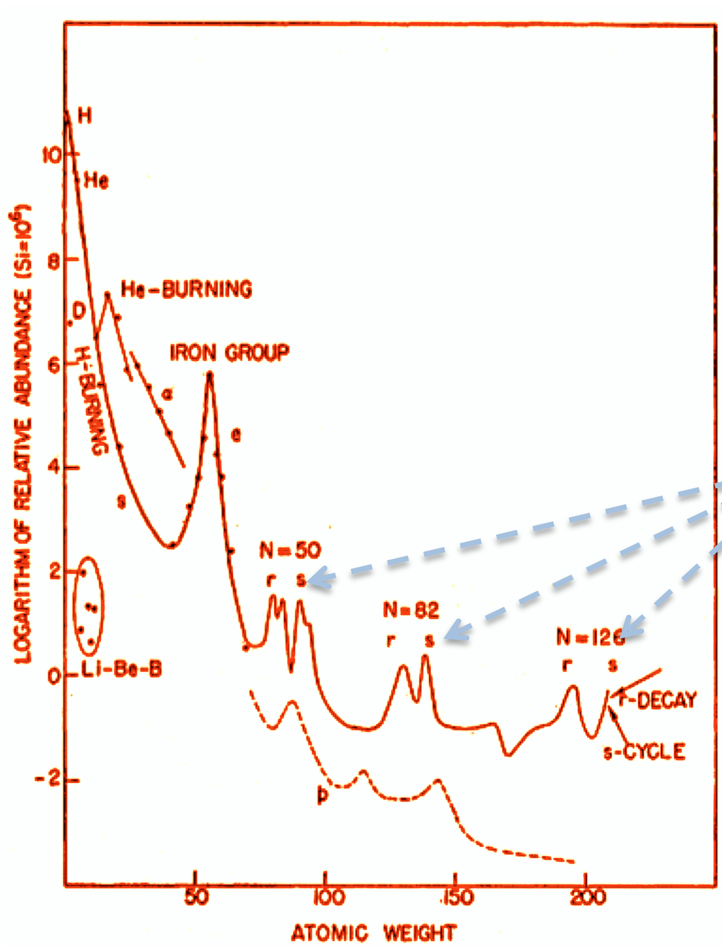
in the meteorites

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

After 1950 ...



1956 Suess & Urey
Pattern of element abundances in the Solar system

-association of magic neutron numbers with abundance peaks

-separation of peaks corresponding to both slow and rapid neutron addition (compared to the ß decay)

1957 ...

1957 Cameron, PASP 169, 201

"Nuclear reactions in stars and nucleogenesis"

1957 Burbidge Burbidge Fowler & Hoyle (B^2FH), Rev of Mod. Phys. 29, 547

"Synthesis of the elements in stars"

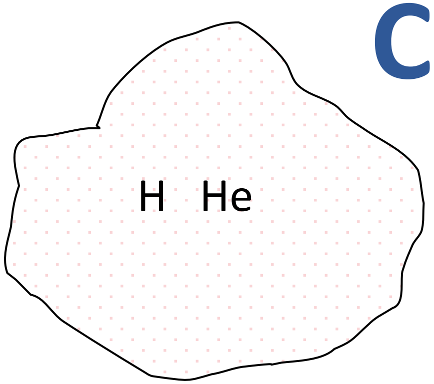
In order to produce all known nuclear species in stars B^2FH suggested 8 separate processes

1- Hydrogen burning
2- Helium burning
3- α process
4- e process
5- s process
6- r process
7- p process
8- "x" process (for D, Li, Be, B)

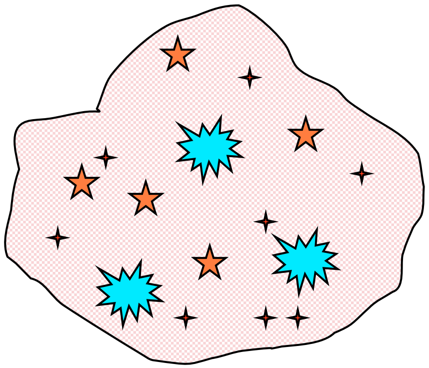
Now: Formation of the elements

- Big Bang → H, D, He, ^{7}Li
- Cosmic rays → ^{6}Li, ^{7}Li, Be, B
- Stars → other elements (metals)
  - supernovae
  - stellar winds

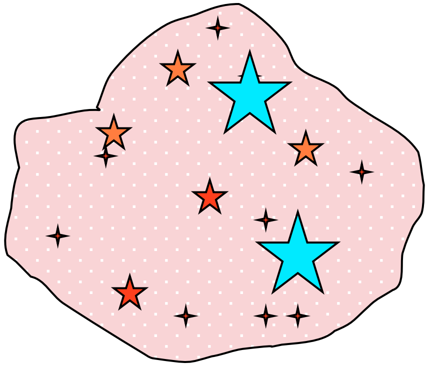
Chemical enrichment of the Galaxy



Formation of the Galaxy
(primordial material)



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



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

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

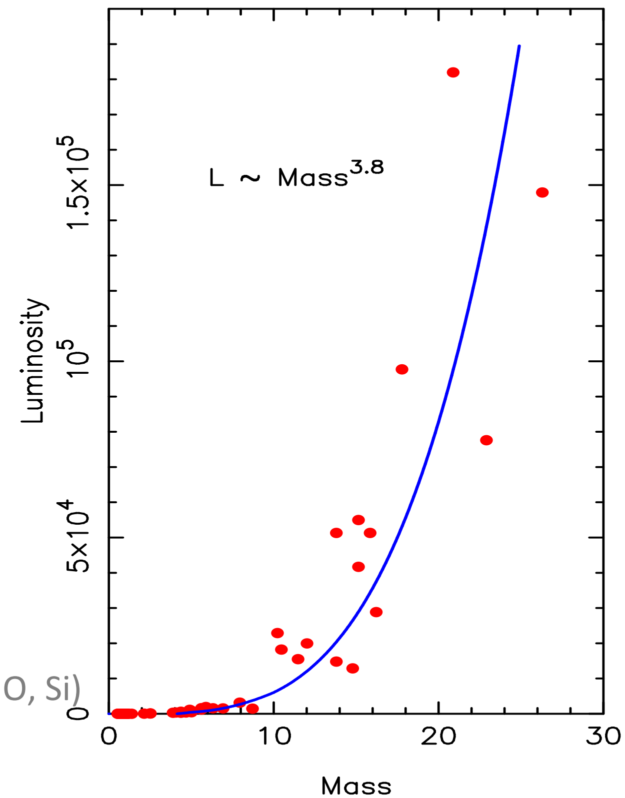
lifetime of the stars

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

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

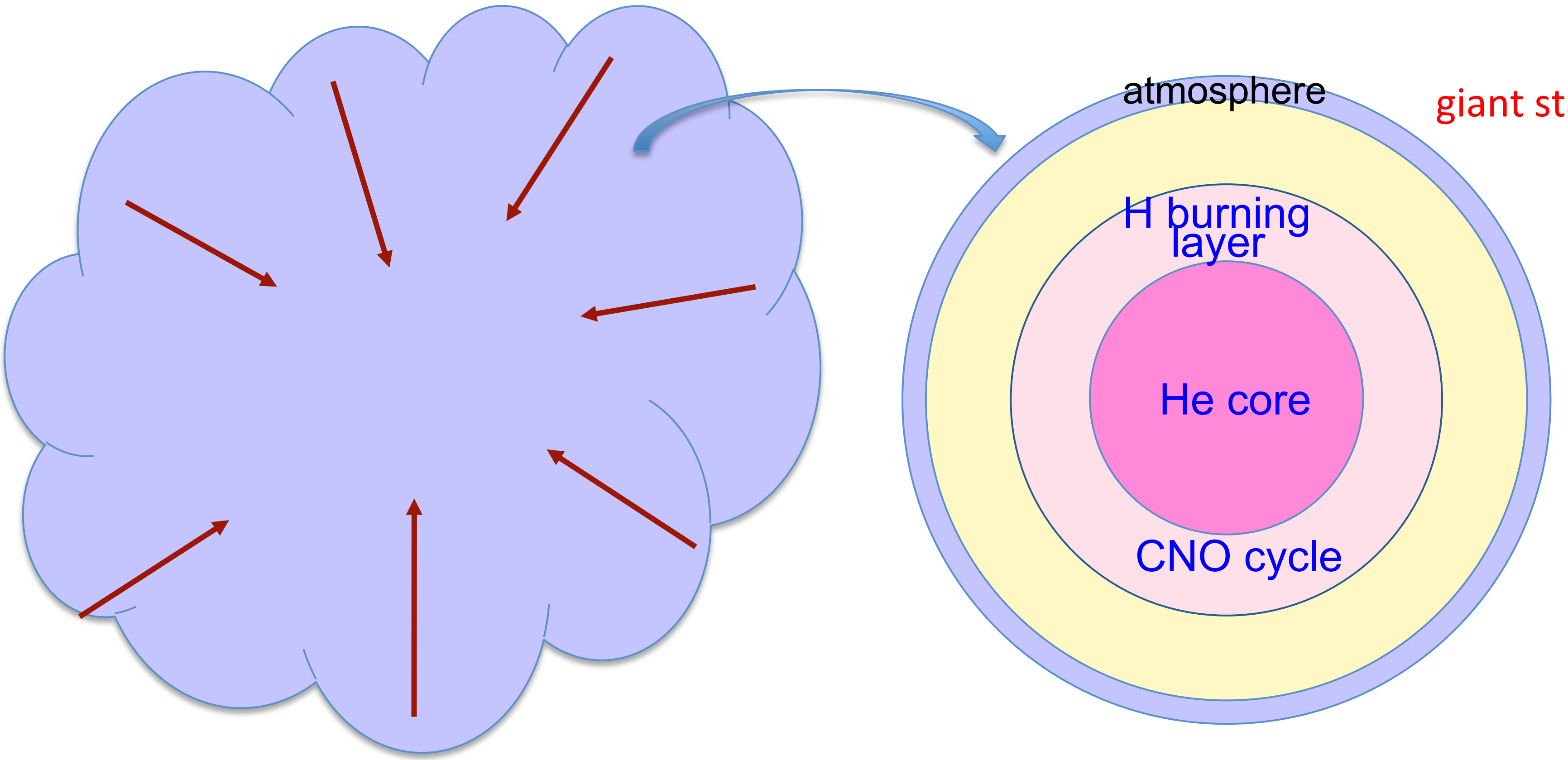
lifetime

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	



- **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**

A fundamental remark !



Chemical composition of the atmosphere of a star **today**

=

Chemical composition of the matter which has formed the star

There are exceptions ...!

II The Extremely Metal-Poor stars (EMP)

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

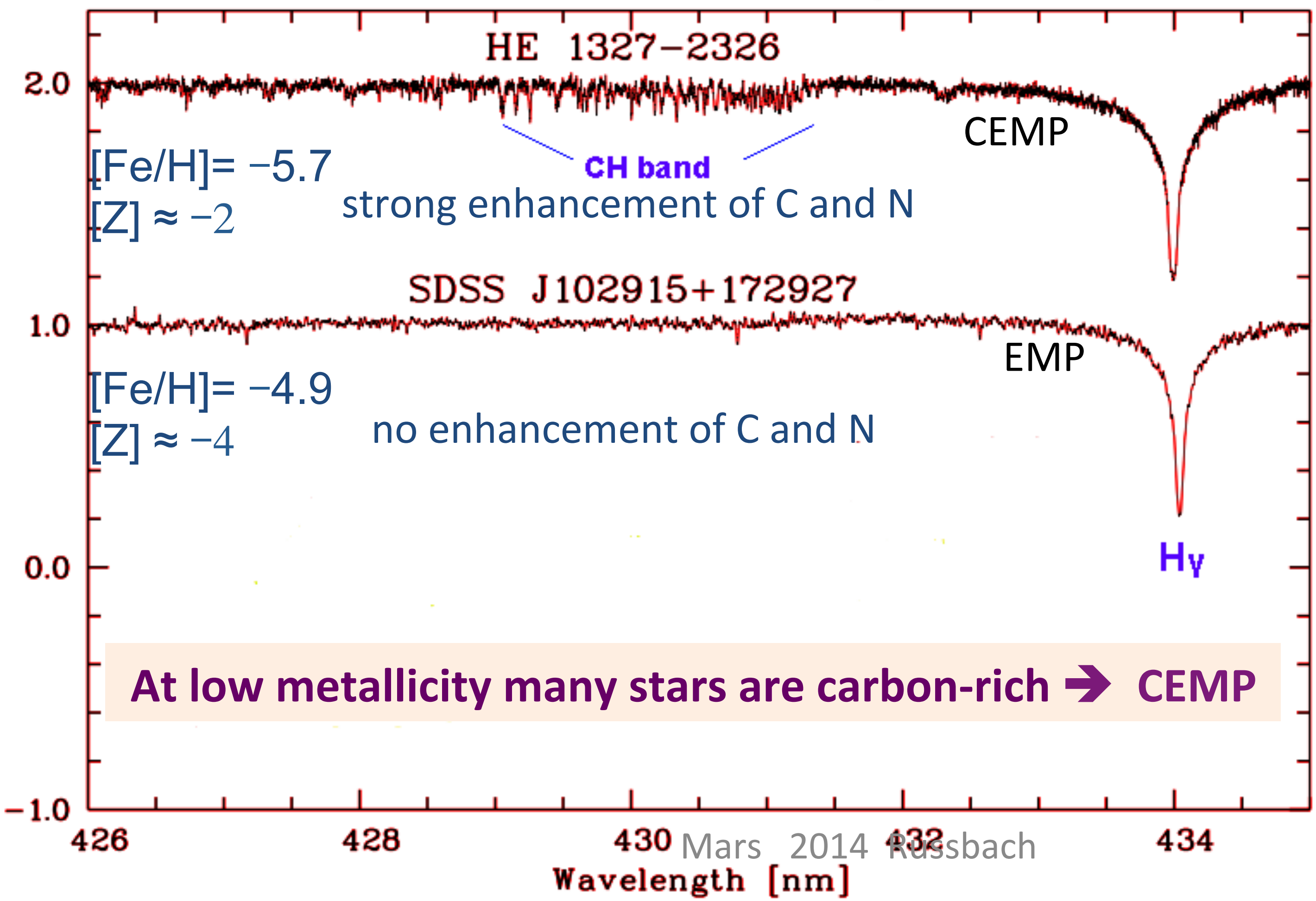
($[X/H] = \log (X/H)_{\star} - \log (X/H)_{\odot}$ ...)

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

EMP CEMP stars

Stars with zero metal ?

The most metal-poor stars known ~~today~~: a month ago ≈100 000 times less iron than the Sun



Frebel et al. (2005)

Caffau et al. (2012)

NEW !

EMP CEMP stars

The Keller et al. star [Fe/H]≤−7.1

Keller et al. 2014 ArXiv1402.1517

2014 Nature 506, 463 (Feb, 2014)

10 000 000 times less iron !

Carbon-rich ➔(CEMP)

Only the lines of Li, C, Ca, Mg are visible:

A(Li) = 0.7

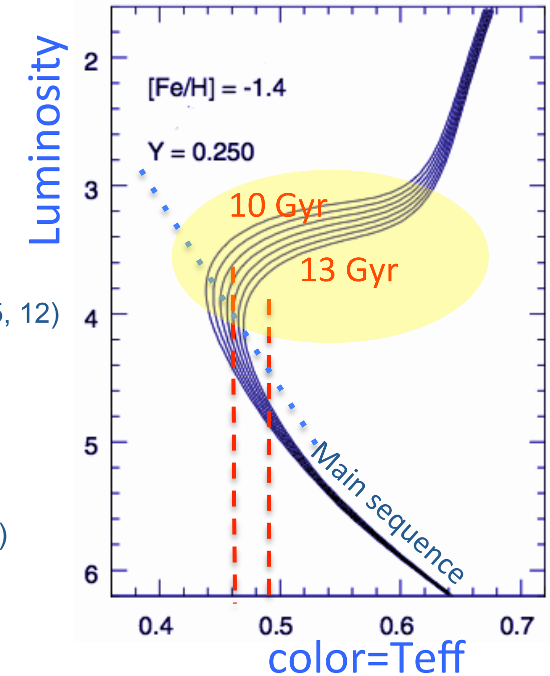
[C/H] =-2.6

[Ca/H] =-7.0

[Mg/H]=-3.8

Planck : age of the Universe 13.8 Gyr

Are the metal-poor stars really old?



Theory of stellar evolution

HD 140283 distance → luminosity well known

[Fe/H]= -2.4 → age = ~ **14.4**±1.1Gyr (Bond et al. 2013 ApJ 765, 12)

Globular clusters comparison observations to theory

[Fe/H] = -2.5 → age = ~ **13** Gyr±0.5Gyr (VandenBerg et al. 2013 ApJ 775, 134)

Radioactive dating U/Th (uncertainty due to production ratios)

CS31082-001 (Cayrel et al. 2001 Nature 409, 691) [Fe/H]=-3.0 U/Th ➔ **14** ± 1 Gyr

HE1523-091 (Frebel et al. 2007, ApJ 660, L117) [Fe/H]=-3.0 U/Th ➔ **13** ± 1 Gyr

+ systematic errors ! ?

III Abundance of the elements in EMP (CEMP) stars
-The lithium problem

^{7}Li is one of the elements formed
during the primordial nucleosynthesis
(H, D, ^{3}He, ^{4}He, ^{7}Li)

many teams working on the abundance determination of lithium:
good agreement.

^{7}Li abundance

1/Predictions: (**Coc et al. 2013,** DOI: 10.1103/PhysRevD.87.123530,
from Planck collaboration data)

quantity of ^{7}Li formed during the primordial nucleosynthesis (standard BBN)

$N_{^{7}Li} / N_H = 524 \times 10^{-12}$ **$A(^{7}Li) = 2.72$**

2/Measurements in EMP stars:

Abundance of Li in the matter shortly after the BB

In a perfect world these abundances would be the same...

^{7}Li abundance

But...

Lithium is a very fragile element

destroyed :

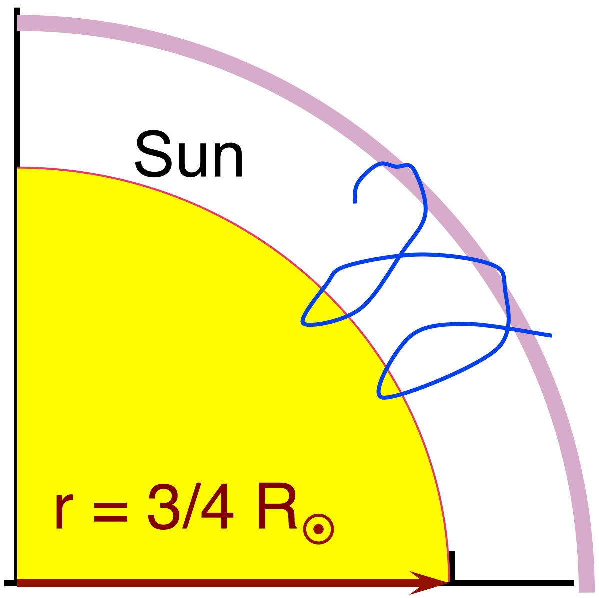
^{7}Li T>2.5 10^{6} K

$^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

if mixing between the atmosphere and these hot layers

⇒lithium is destroyed little by little in the atmosphere

$A(Li)_{\odot} \approx 1.0$

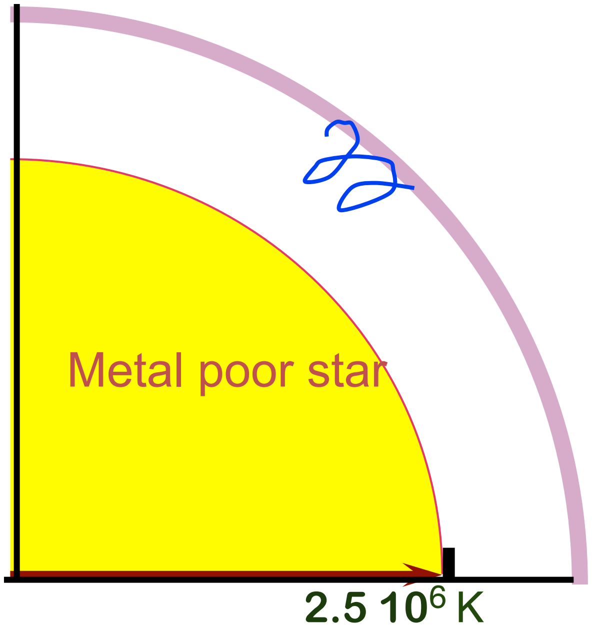


2 10^{6} K

^{7}Li abundance

In warm metal-poor stars
(turnoff stars: Teff > 5900K)
mixing is not as deep as in solar type stars

➟lithium is preserved.



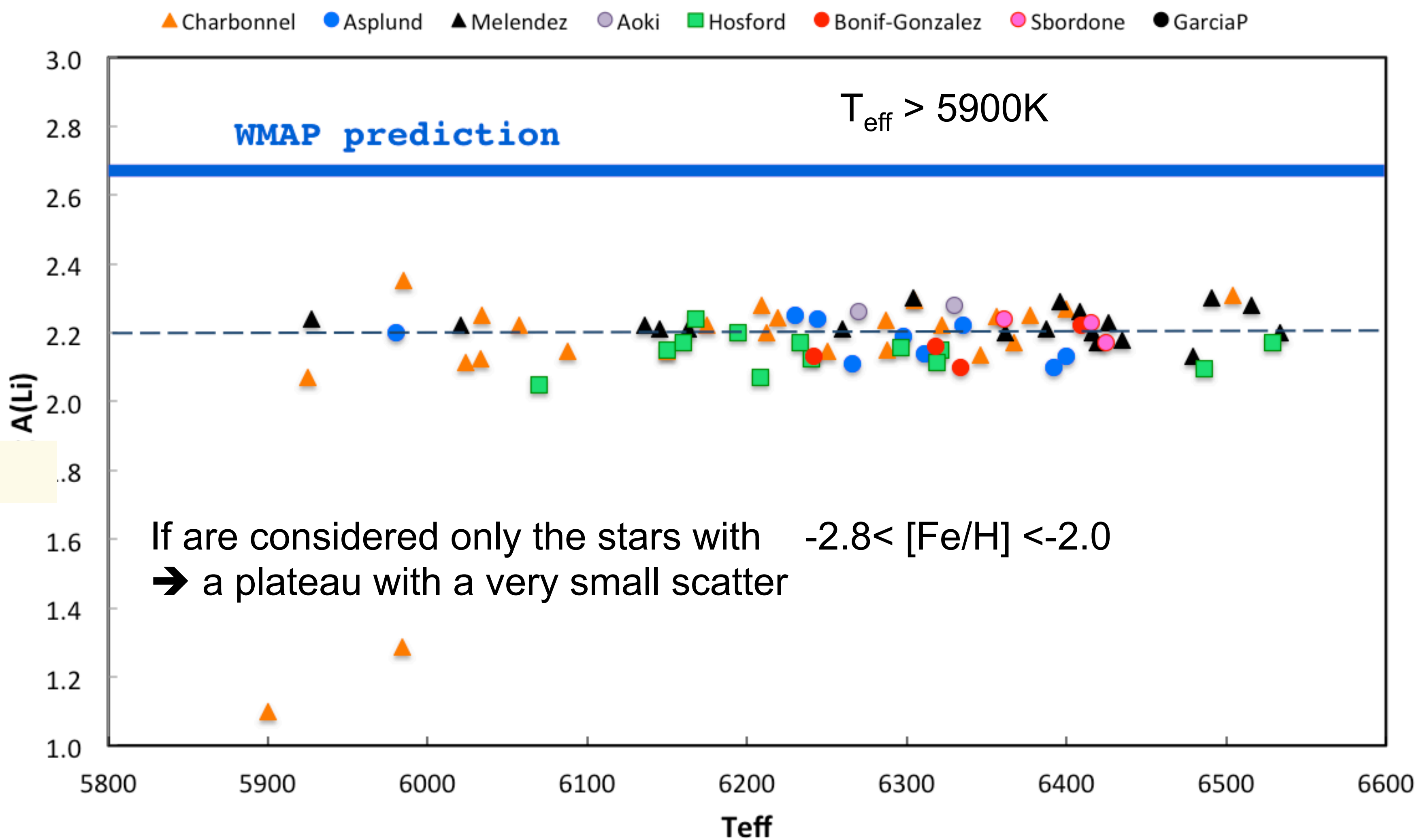
A priori :

Abundance of lithium in old metal-poor turnoff stars

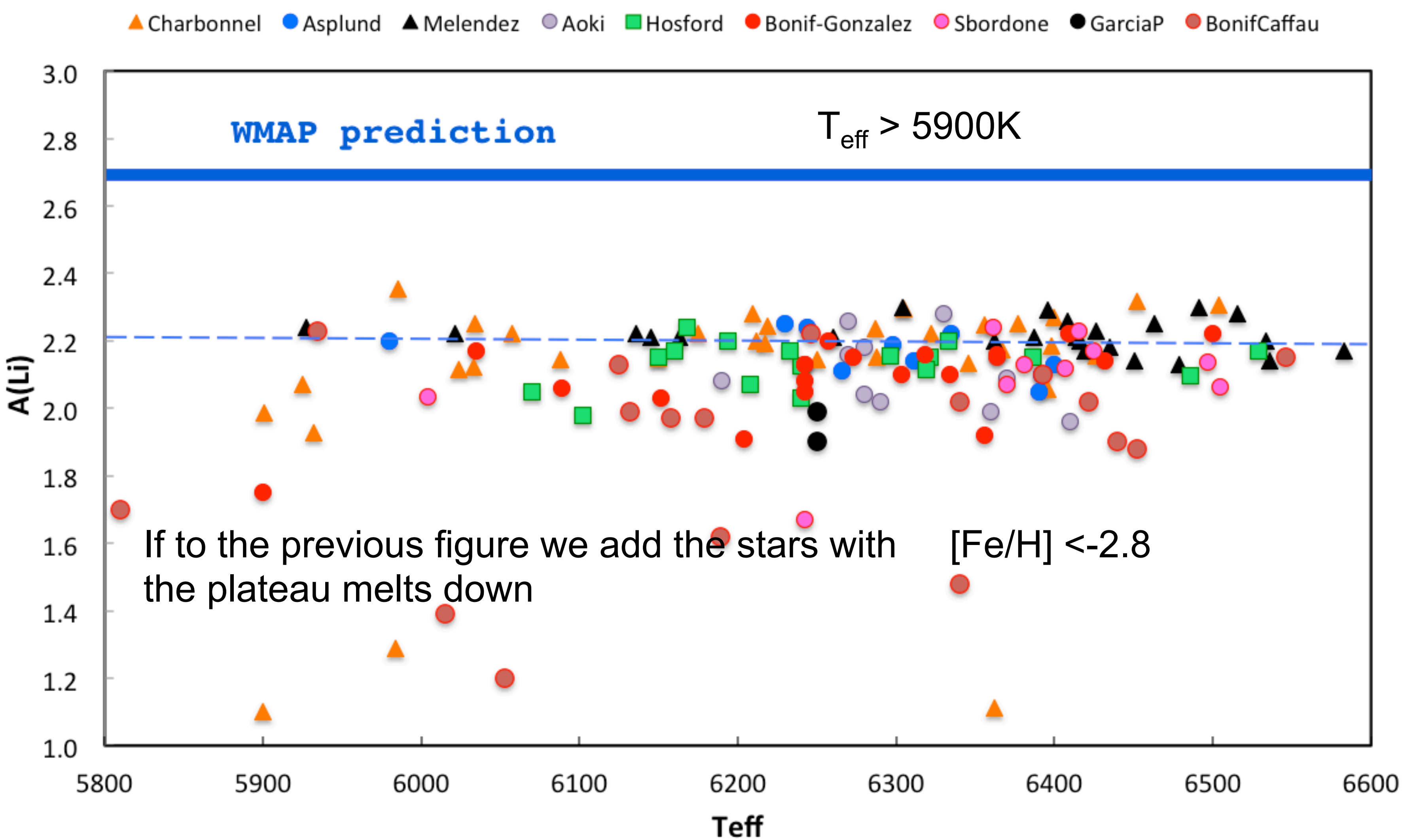
=

Abundance of lithium in the primitive galactic matter

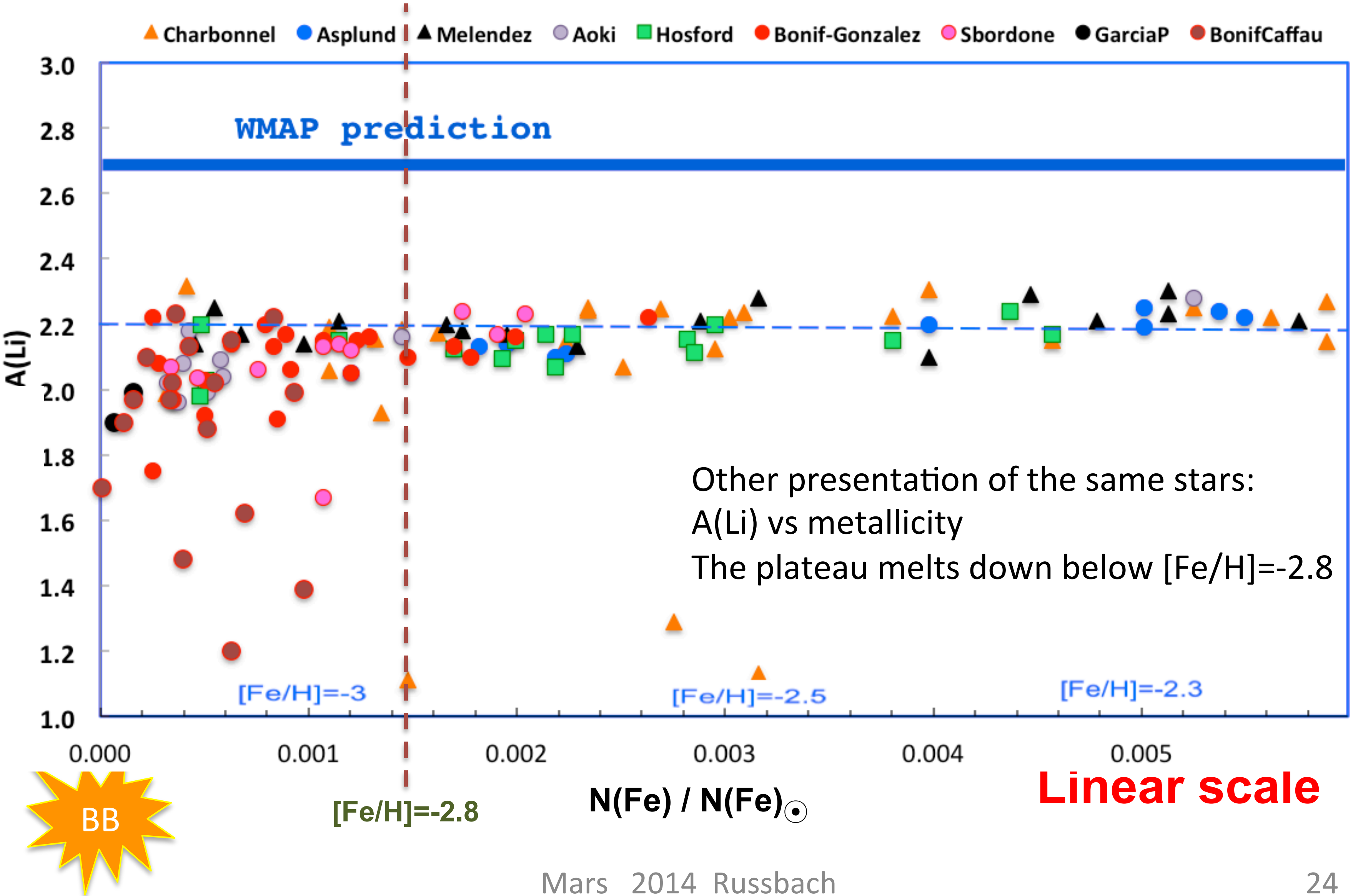
^{7}Li abundance in the EMP stars



^{7}Li abundance in the EMP stars



^{7}Li abundance in the EMP stars



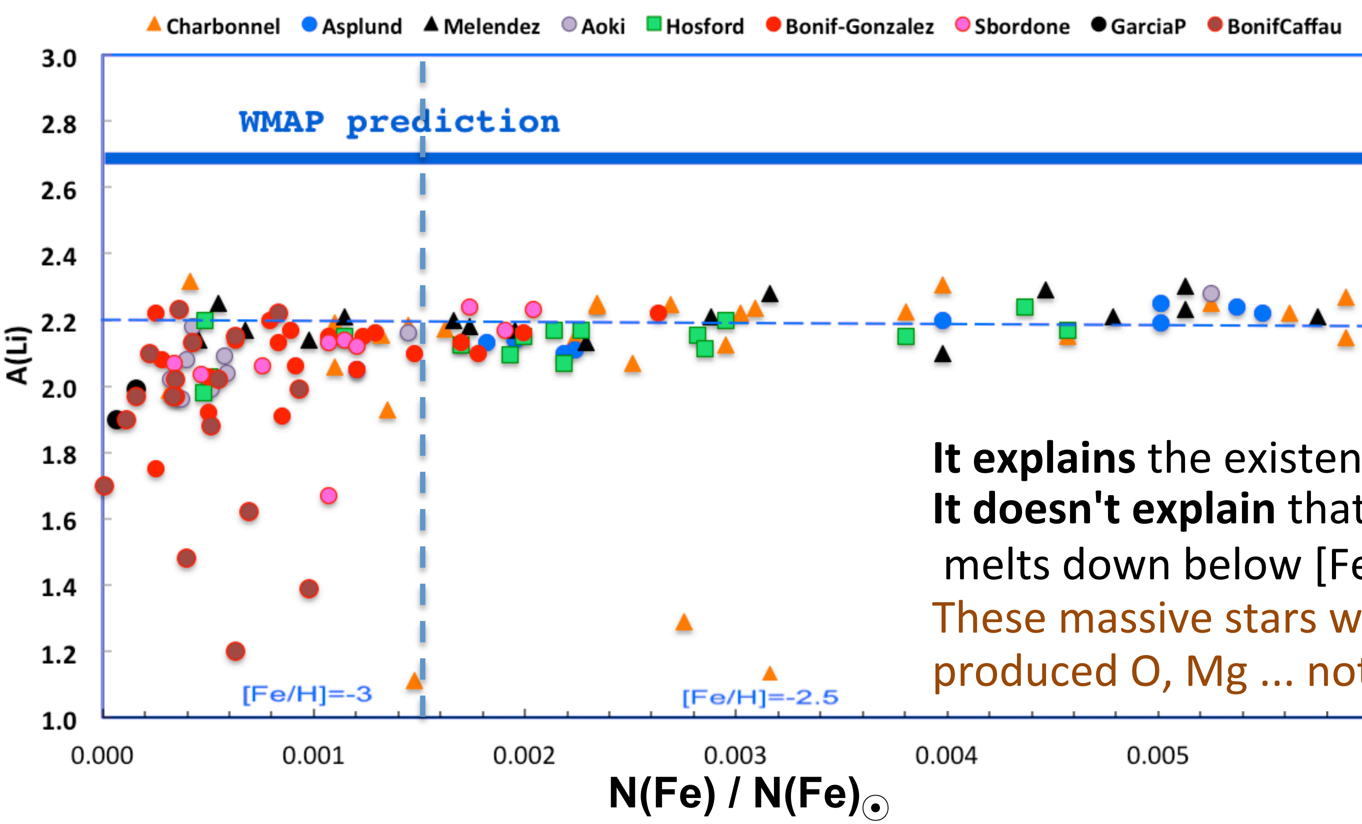
Other presentation of the same stars:
A(Li) vs metallicity
The plateau melts down below [Fe/H]=-2.8

Linear scale

^{7}Li problem - 1st interpretation in the frame of the SBB

Lithium has been destroyed in the galactic matter <u>before</u> the formation of the old metal-poor stars.

No stars with 2.2<A(Li)<2.7 ➔ 2/3 of the quantity of ^{7}Li has been destroyed

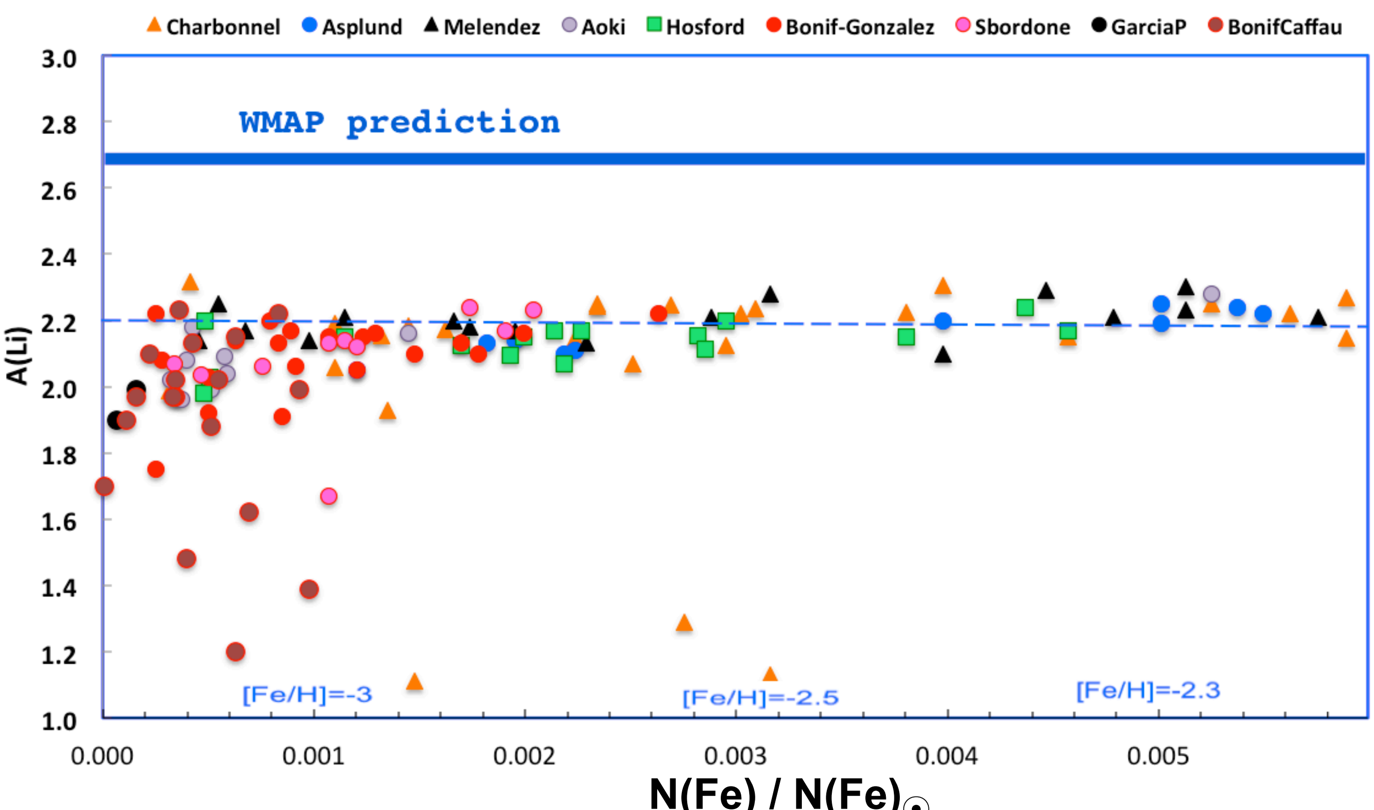


astration in a **first generation of (only) massive Pop III stars (Piau 2006)**

It explains the existence of a plateau
It doesn't explain that the plateau melts down below [Fe/H]=-2.8]
These massive stars would have produced O, Mg ... not observed (Prantzos 2007)

^{7}Li problem – 2nd interpretation in the frame of the SBB

The EMP stars formed from a Li-rich matter (A(Li=2.7) but ^{7}Li has been depleted in the atmosphere of the old metal-poor stars (uniform depletion for Teff>5900K and -2.8 <[Fe/H]< -2.0)



proposed mechanism:

gravitational settling partially compensated by turbulence

(Michaud et al. 1984, Richard et al., 2005, Korn et al., 2006)...

depletion in the pre-main sequence phase

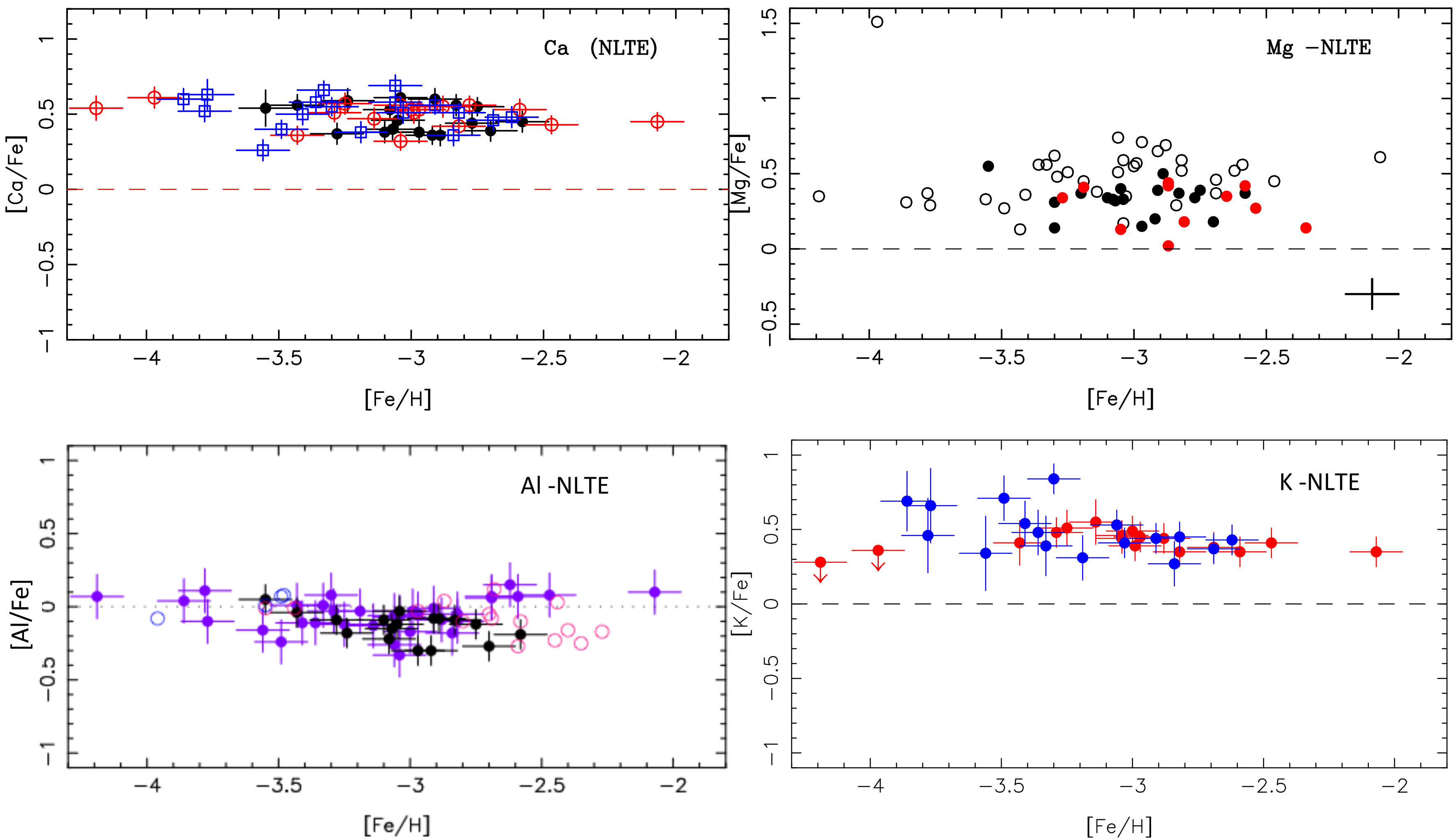
There was a problem with ^{6}Li which is not built by the BB and seemed relatively abundant in metal-poor stars (Asplund et al. 2006-2008).
This was the result of a misinterpretation of the profile of the lithium feature. (Lind, K. 2013, A&A 554, 96L)

No more problem of ^{6}Li !

III Abundance of the elements in EMP stars -C to Zn

Many teams working on the abundance of C-Zn in metal-poor Galactic stars
-Japan (Aoki, Honda....)
-USA (Cohen, McWilliam, Johnson, Frebel ...)
-Australia (Bessell, Norris, Keller, Asplund...)
-Europe (Heidelberg-group, Paris-group, Italian groups......)

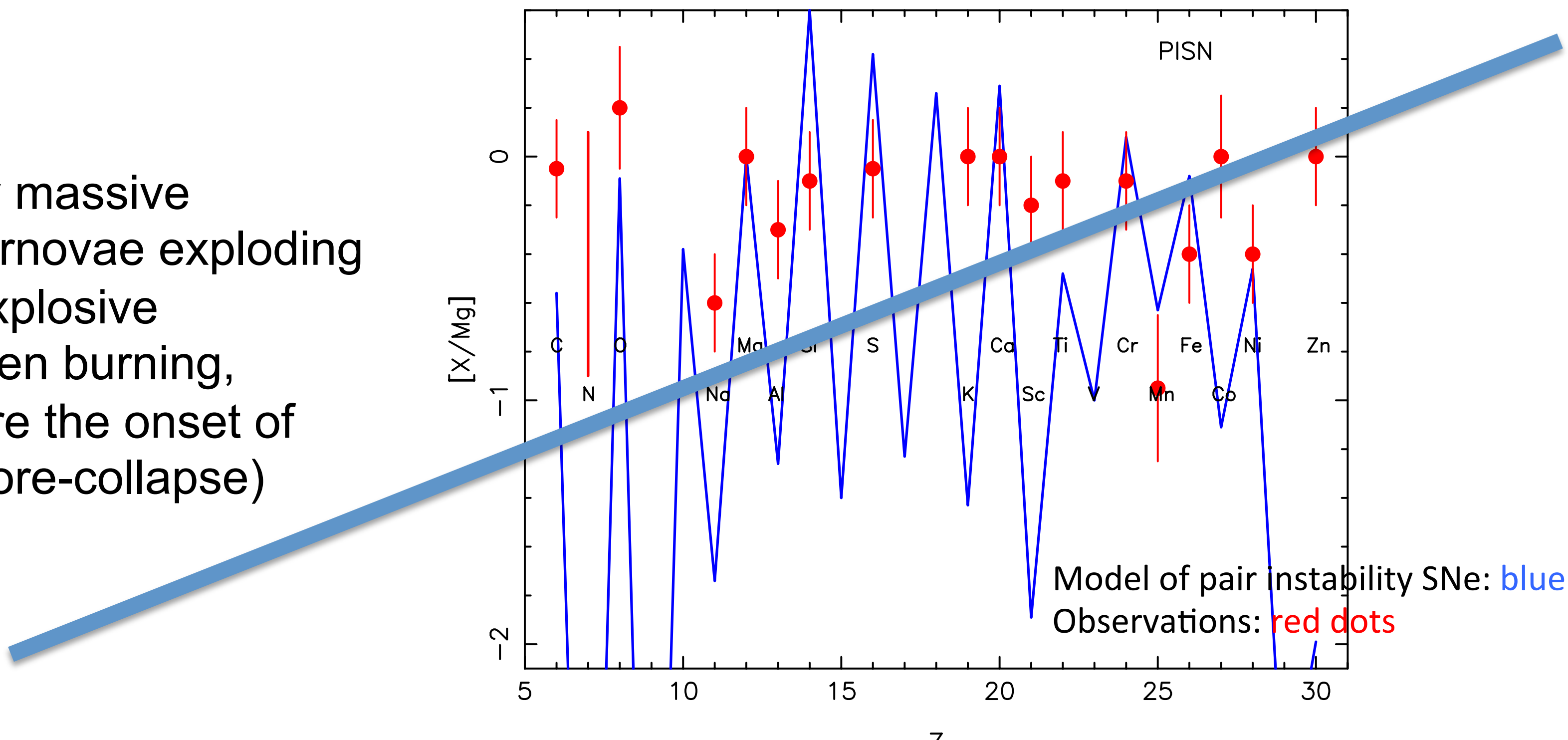
Abundance in EMP stars from C to Zn



Abundance in EMP stars from C to Zn

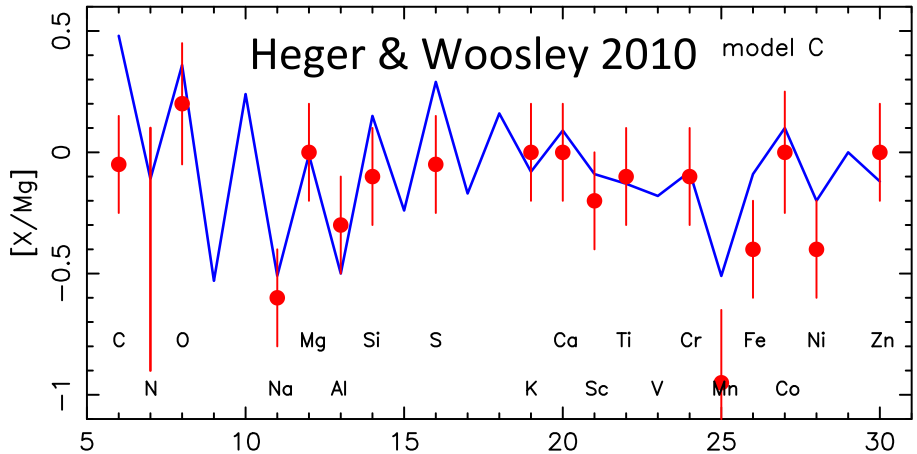
Pair instability supernovae yields (Heger & Woosley 2003) metal-free stars: too large odd-even scatter predicted...

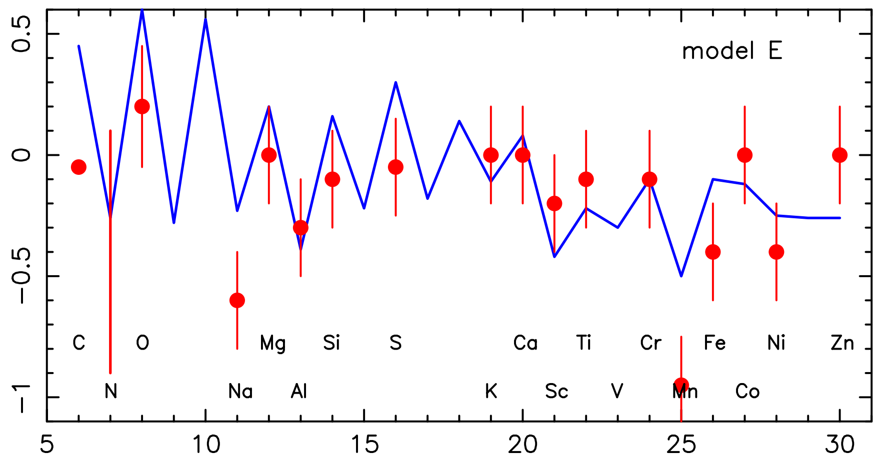
(very massive supernovae exploding by explosive oxygen burning, before the onset of Fe core-collapse)



Fits to Cayrel et al. 2014 (update of 2004) taken as representative sample for low metallicity sars.

Abundance in EMP stars from C to Zn





Core collapse supernovae

model C (blue solid line):
IMF integration yields from M=11 to 15$M_\odot$
Explosion energy E=0.9B

1 Bethe= 1B= 10^{51} ergs

model E (blue solid line):
"standard" IMF integration yields from M=10 to 100$M_\odot$
Explosion energy E=1.2B

Fits to Cayrel et al. 2014 (update of 2004) taken as representative sample for low metallicity sars.

III Abundance of the elements in EMP (and CEMP) stars -The neutron capture elements

From Sr to Pt in the EMP and the CEMP stars

Honda et al. (**2004**, ApJ 607, 474; **2006** ApJ 643, 1180; **2007** ApJ 666, 1189)
François et al. (**2007**) A&A 476, 937
Qian & Wasseburg (**2008**) ApJ 687 272
Roederer et al. (**2010**, ApJ 724, 975; **2011**, ApJ 732 L17; ApJ 742, 37 (Glob. clusters);
2014 ArXiv1402.4144)
Mashonkina et al. (**2010**) A&A 516, 146
Andrievsky et al. (**2011**) A&A 530, 105
Hansen et al. (**2012**) A&A 545, A31
Siqueira Mello et al. (**2013**) A&A 550, A122; +in prep
Peterson **(2011)** ApJ 742, 21; (**2013**) ApJ 768, L13
Cescutti Chiappini et al. (**2013**) A&A 553, A51
Aoki et al. **(2013)** ApJ 766, L13
etc...

Neutron capture el. in EMP stars

process	conditions	timescale	site
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, n_n~$10^{7\text{-}8}$/cm^3	10^2 yr and $10^{5\text{-}6}$ yrs	Massive stars (weak) ~~Low mass AGB stars~~ (main)
r-process (n-capture, ...)	T~1-2 GK τ_n~ µs, n_n~10^{24} /cm^3	< 1s	Type II Supernovae ? Neutron Star Mergers ?

In the very metal-poor stars formed in the first Gyr of the Galaxy
Matter enriched only by the ejecta of massive stars (with a lifetime <1 Gyr)

-the r process (processes)

-the weak-s process

➔ **key objects to study the site of the r-process**

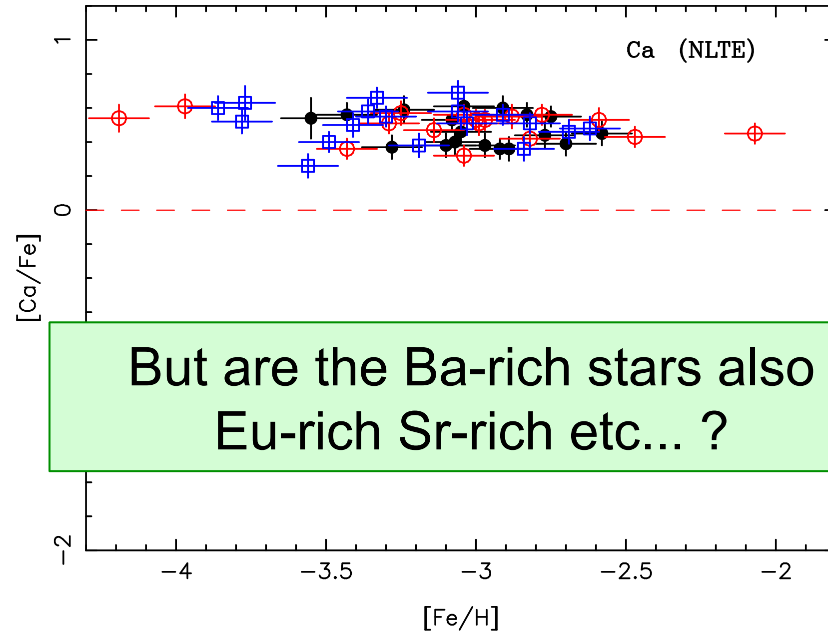
[On the contrary in the young stars (**Sun**) the low mass AGB stars had time to enrich the matter in the products of the main "s" process.]

What is observed ?

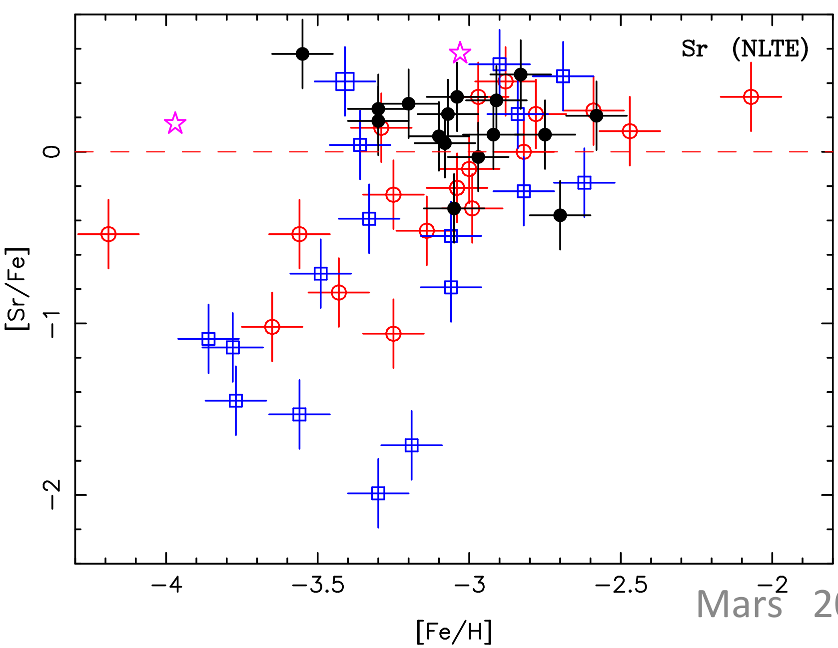
In the frame of the LP-ESO program "First Stars" **33** giants **17** turnoff stars observed field stars without carbon enrichment [Fe/H]<-2.5

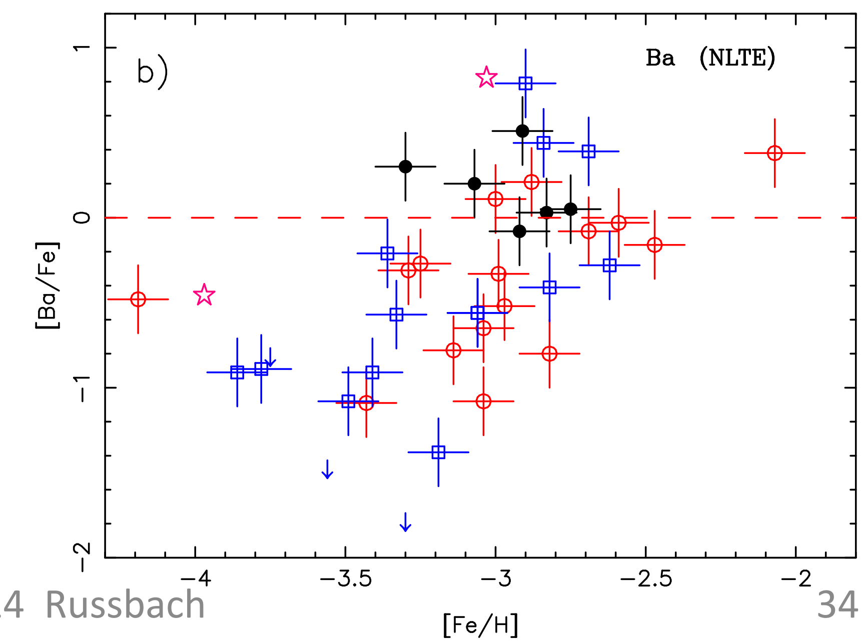
(Francois et al. AA 476, 935; Bonifacio et al. 501, 519; Andrievsky et al. 2011, AA 530, 105)

large **scatter** of the relations [X/Fe] vs [Fe/H] (where X is an heavy element)



But are the Ba-rich stars also Eu-rich Sr-rich etc... ?



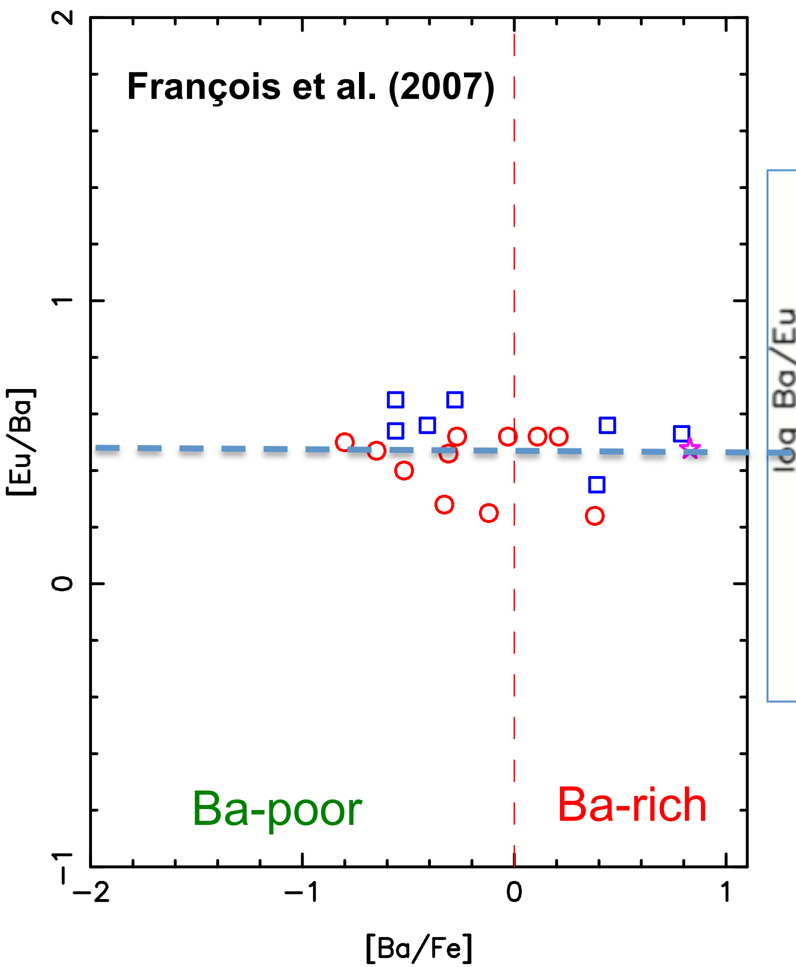


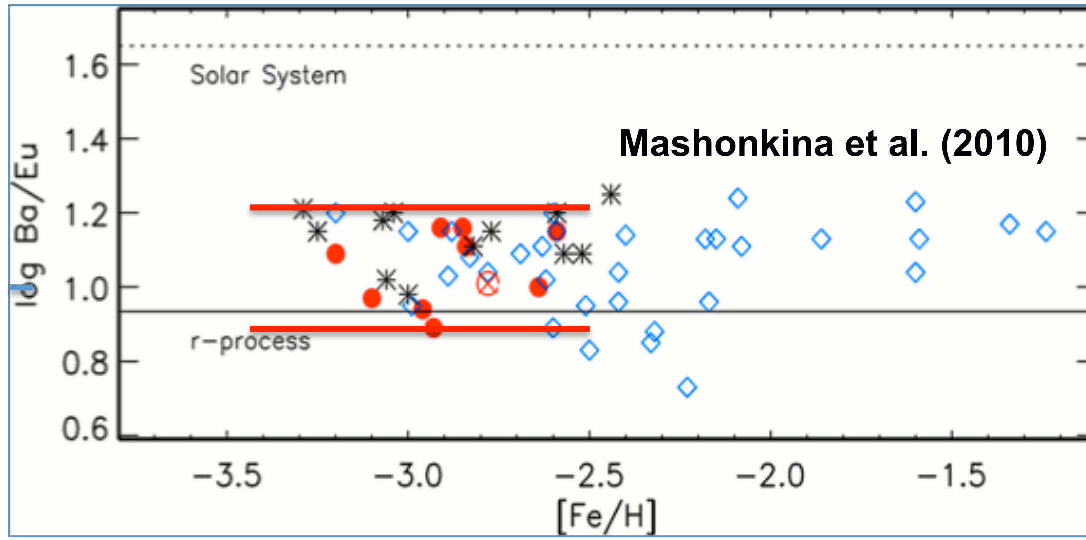
What is observed ?

Below [Fe/H]=-2.5

in ***normal*** metal-poor stars (not C-rich)

Good correlation between Ba and Eu





Ba-rich = Eu-rich

r-rich star: [Eu/Fe]>0.3 (Barklem 2005)

r-II [Eu/Fe]>1.0 r-I 0.3<[Eu/Fe]<1.0

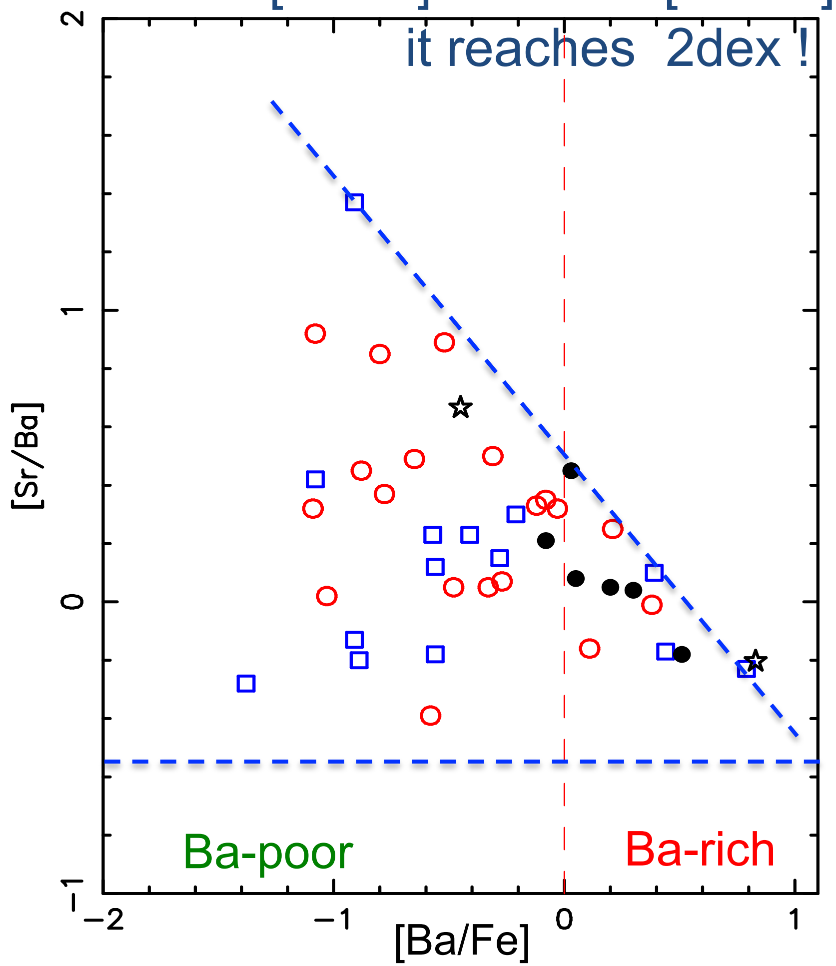
r-poor star: [Eu/Fe]<0.0

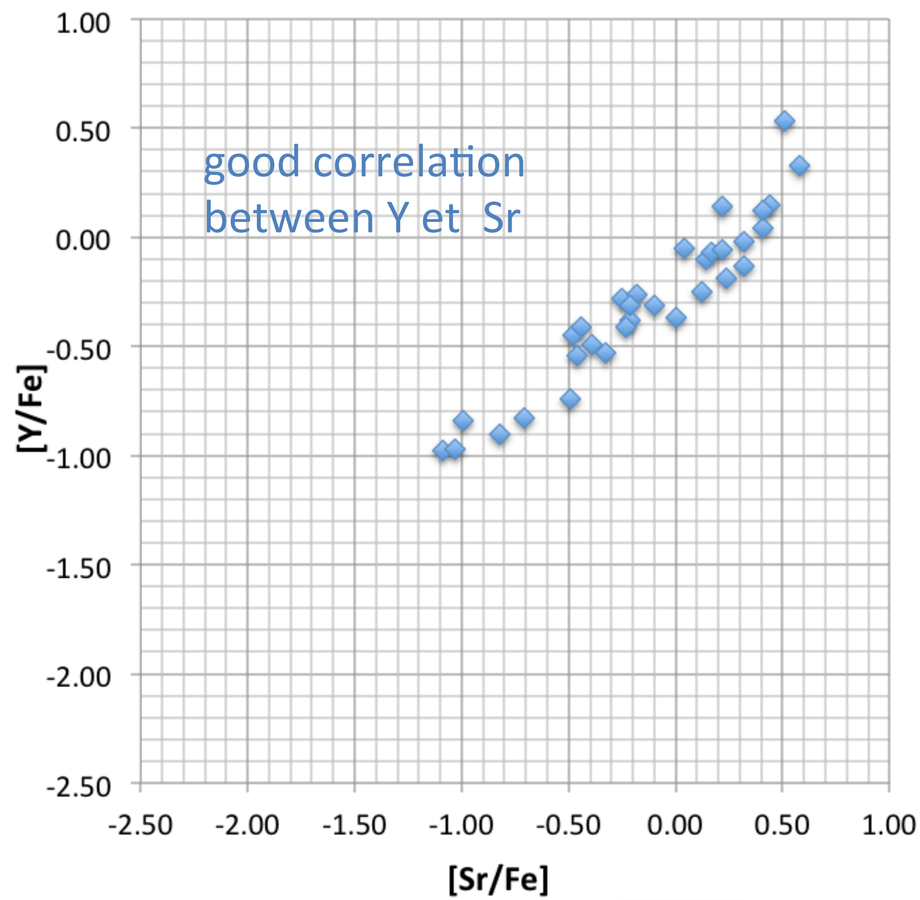
What is observed ?

Below [Fe/H]=-2.5

scatter of [Sr/Ba] ↗ when [Ba/Fe] ↘

EMP stars





What is observed ?

Comparison to the abundance pattern of the r-elements **in the Sun.** In the Sun the matter contains also heavy elements produced in low mass AGB stars (s process elements)

- the **isotopic abundances** are known (meteorites)

- Some isotopes can be formed only through the "s" process ex:

  ^{86}Sr ^{134}Ba ^{136}Ba ^{154}Gd

- s-process occurs in AGB stars during helium burning

  $^{22}Ne + {}^{4}He \rightarrow {}^{25}Mg + \mathbf{n}$

  $^{13}C + {}^{4}He \rightarrow {}^{16}O + \mathbf{n}$

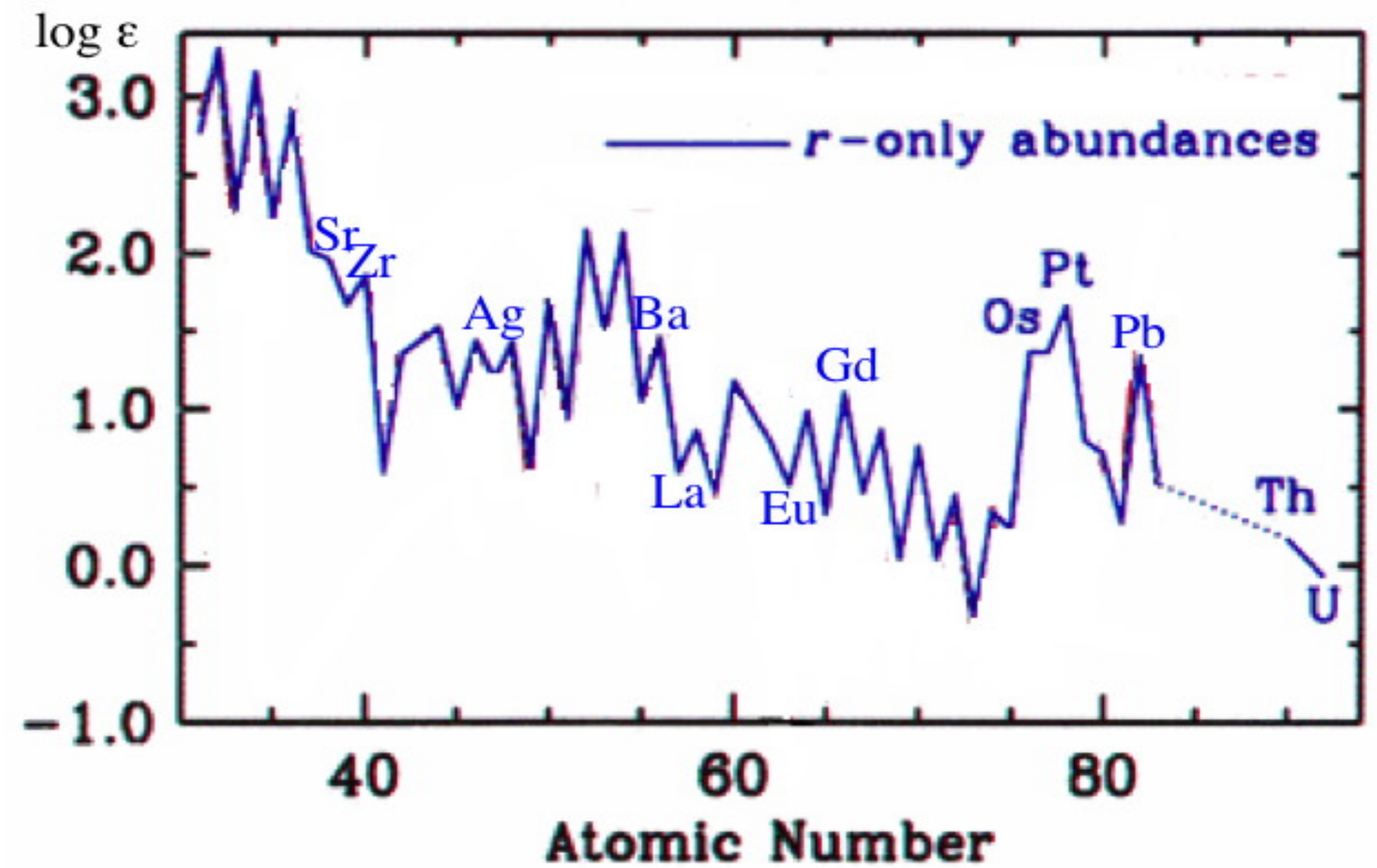
  ⇒physical conditions are known

  It is possible compute the s-process production

➠ in the Sun, fraction of the elements built by the r-process

What is observed ?

r-process abundance pattern in the Sun

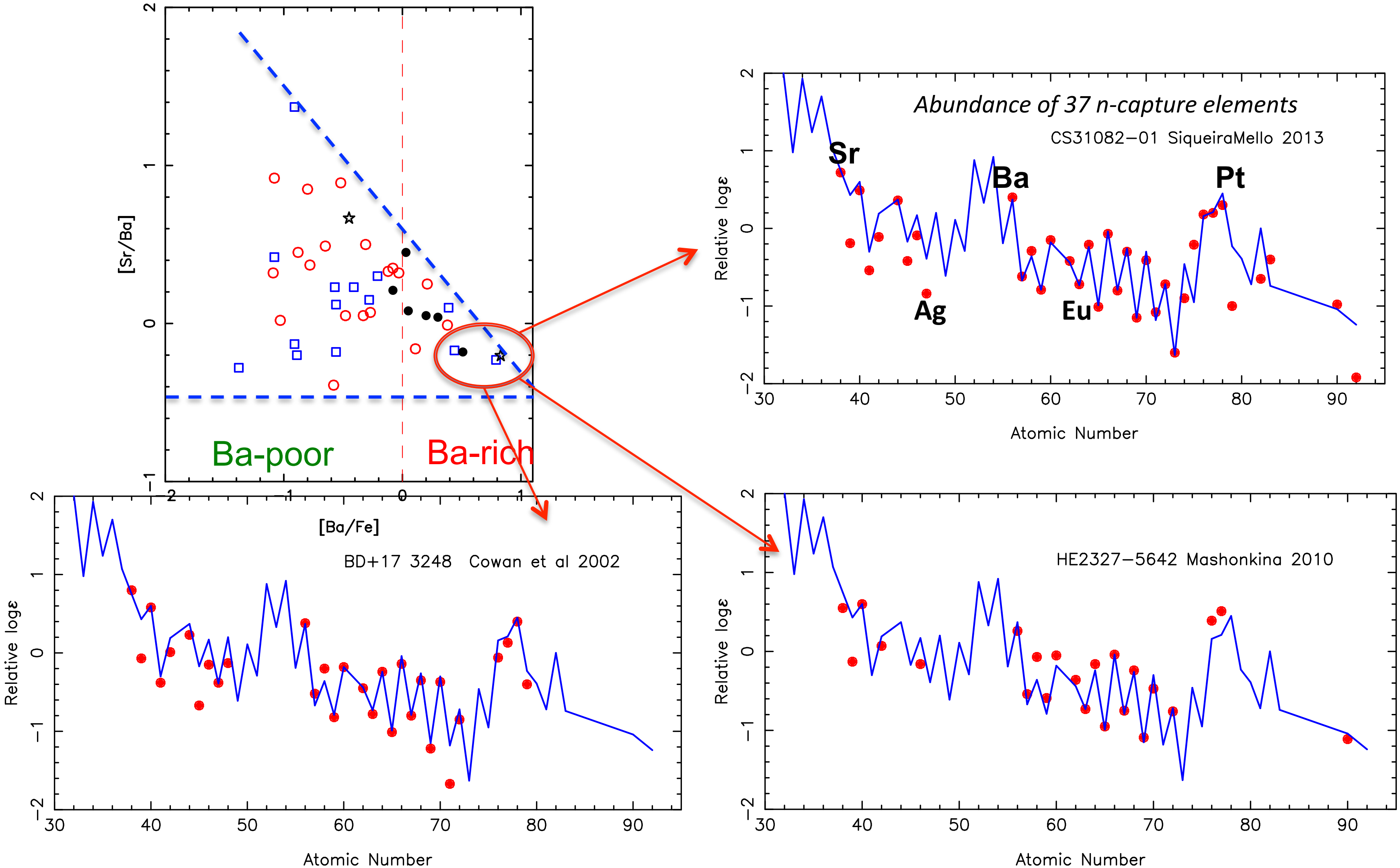


(Arlandini et al. 1999, Burris et al. 2000, Simmerer et al. 2004)

What is observed ?

EMP r-rich stars

comparison to the solar r-process pattern



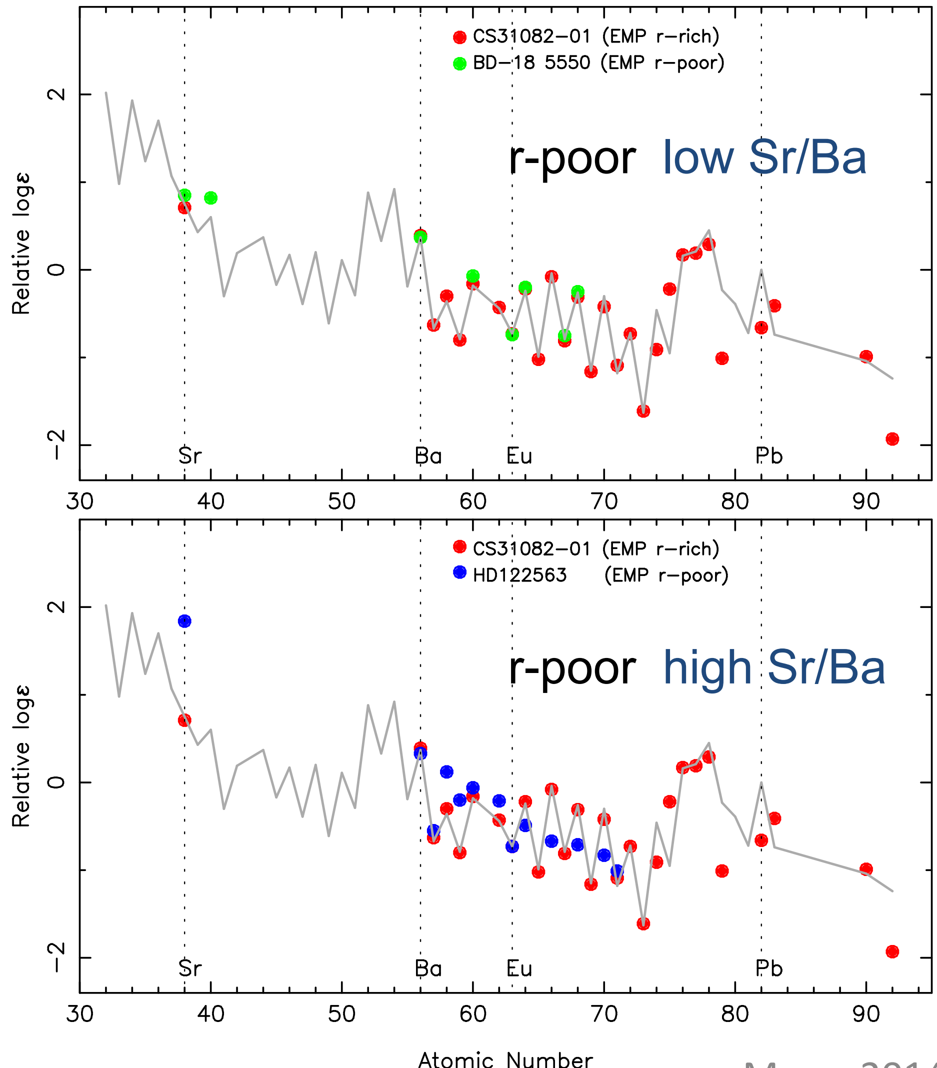
Between Ba and Pt very good agreement with the Solar r process pattern

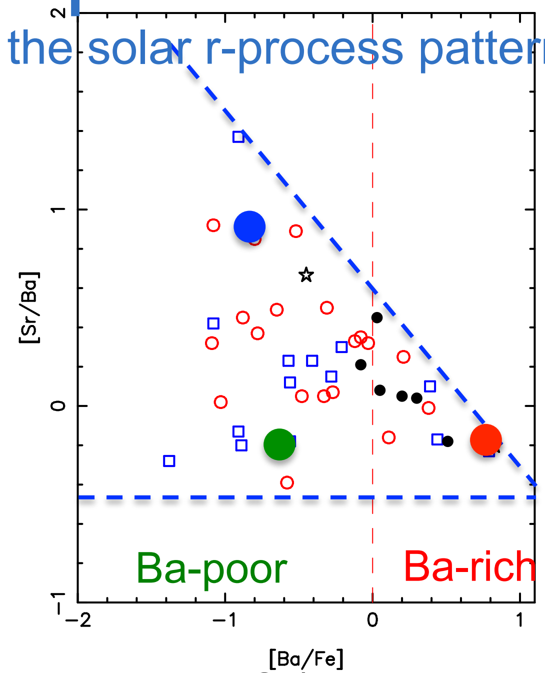
Is the r-process universal ?

EMP r-poor stars

comparison to the solar r-process pattern

What is observed ?





The position in the Sr/Ba diagram induces different heavy elements patterns (2nd peak)

- r-rich low Sr/Ba } = pattern
- r-poor low Sr/Ba
- r-poor high Sr/Ba ≠ pattern

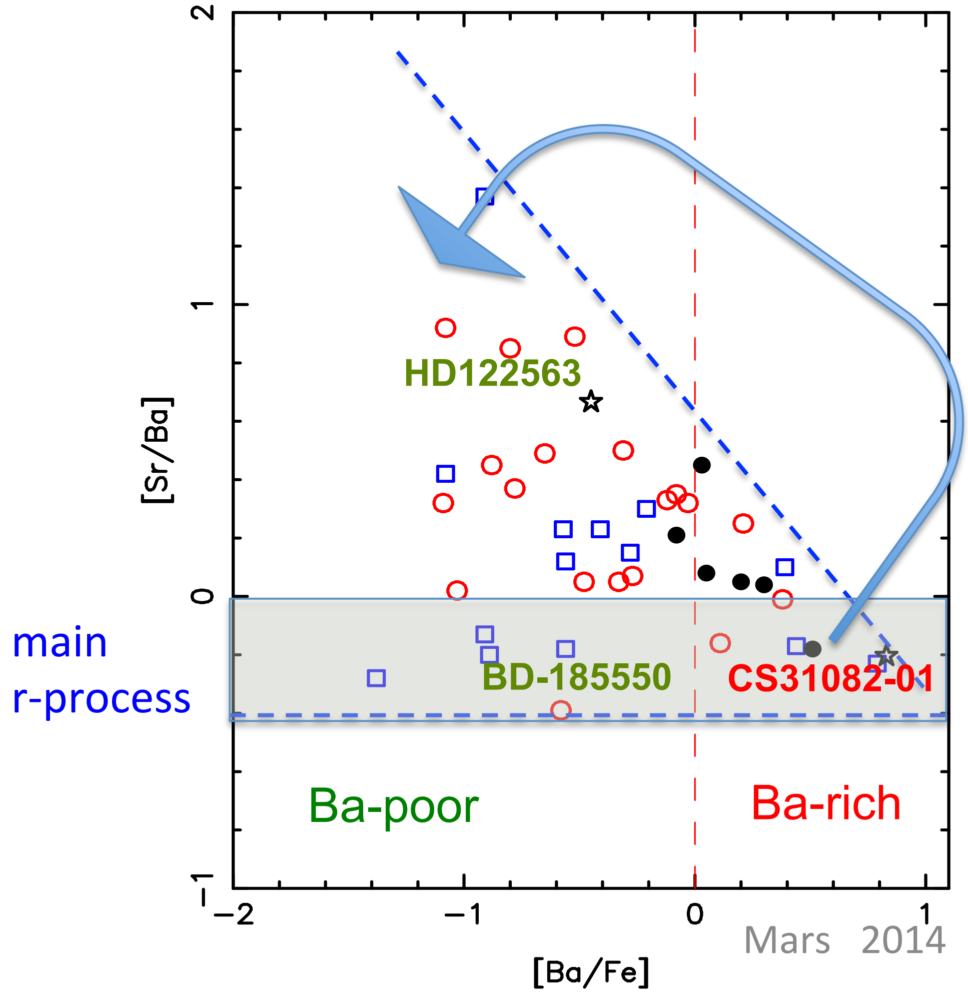
all the stars are scaled to Eu

CS 31082-01 Siqueira-Mello et al.(2013 AA 550 122)
HD 122563 Honda et al. (2006 ApJ 643, 1180)
BD -18 5550 Francois et al. (2007 AA 476, 935)

Empirical Interpretation ??

EMP stars [Fe/H]≈ −3.0

How to explain the increase of the scatter of [Sr/Ba] more a star is Ba-poor + the different **patterns** of the heavy elements (odd even effect less pronounced in Sr-rich stars)



A first (major) process would enrich the matter in neutron capture elements leading to the abundance pattern of the r-rich stars and the r-poor stars with [Sr/Ba] <0.0 like CS31082-01 and BD-18 5550.

Then a second process would add **Sr Y Zr**... (and maybe some heavier elements since the second peak looks different in HD122563 and CS31082-01)
This second process would not influence significantly the abundance pattern of the r-rich stars but would dramatically changes the pattern of the r-poor stars

Site of r-process ??

long standing mystery... (Thielemann 2013) Some possible sites (Review : Thielemann 2011)

ABLE TO BUILD HEAVIER r-elements good representation of stars with [Sr/Ba]<0.1
r-rich stars and r-poor stars with low Sr/Ba

Core collapse supernovae (Wanajo 2007, Farouqi 2009, Thielemann...)
neutrinos interact with matter of the outermost neutron-star layers ➔ moderately neutron-rich ejecta. If the outflow become supersonic T drops ➔ cold r process in neutrino driven winds

Coalescence of neutron star binary (Wanajo & Janka 2012)
nucleosynthesis in the neutrino-driven wind from the accretion disc around a black hole, formed as a remnant of binary NS merger

r-poor high Sr/Ba

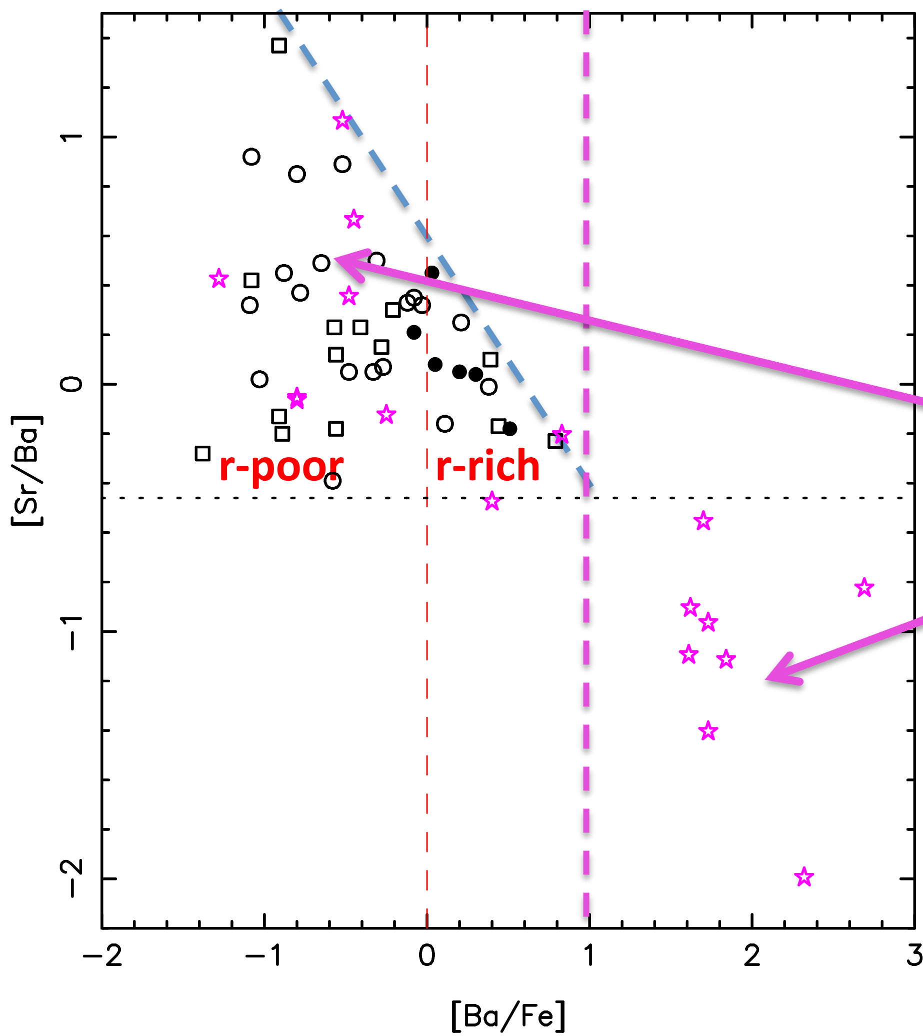
HEAVIER r-elements not synthesised

Neutrino driven winds from proto-neutron stars (Wanajo 2013) $\mathcal{M}>20\mathcal{M}_\odot$

Electron capture supernovae $\mathcal{M}\approx 9\ \mathcal{M}_\odot$ explode after C burning (core:O Ne Mg)
(Wanajo Janka & Müller 2012)

Comparison EMP / CEMP

CEMP stars



Black symbols:
Normal EMP stars [Fe/H]<-2.7

pink stars symbols:
CEMP stars with [Fe/H]<-2.7

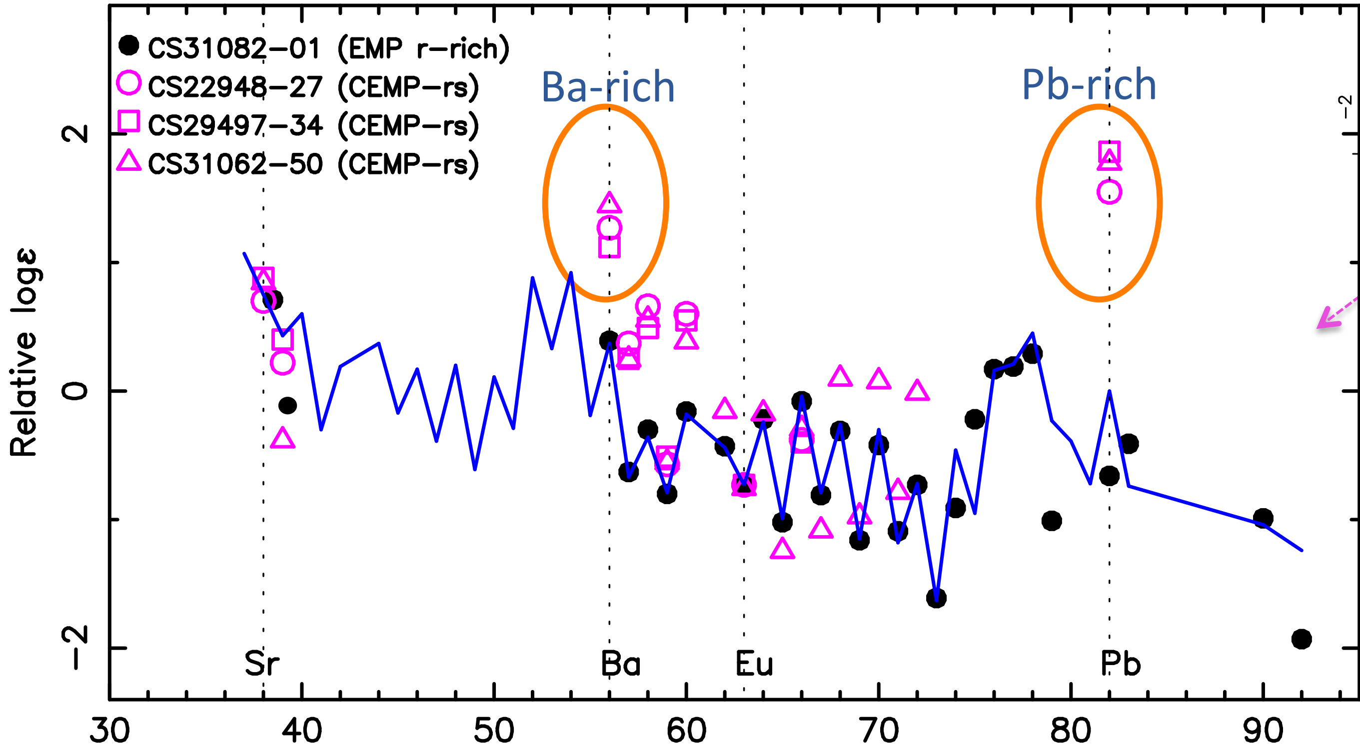
CEMP-no [Ba/Fe] < 1.0

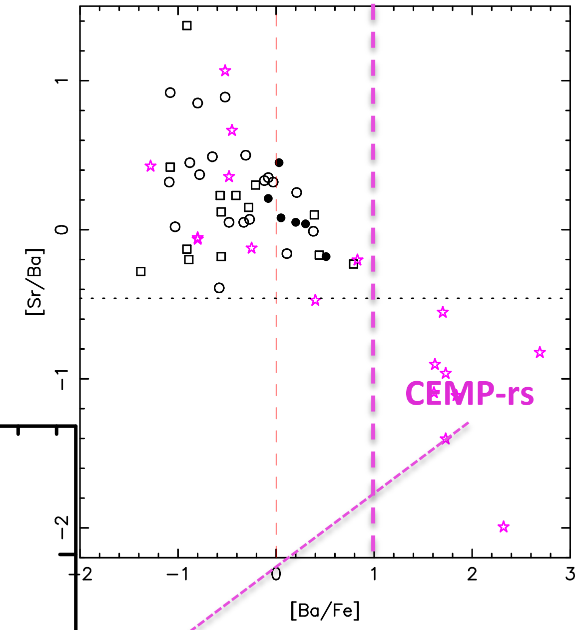
CEMP-rs
[Ba/Fe] > 1.0 and [Eu/Fe]>1.0

Comparison EMP / CEMP

CEMP-rs

● **EMP r-rich** **CEMP-rs : [Ba/Fe] > 1.0 [Eu/Fe] > 1.0**





(CEMP pink
normal EMP black)

all the stars are scaled to Eu

CS 31082-01 Siqueira-Mello et al.(2013)

CS22948-27 CS29497-34 Barbuy et al. (2005) CS31062-50 Johnson&Bolte (2004)

Comparison EMP / CEMP

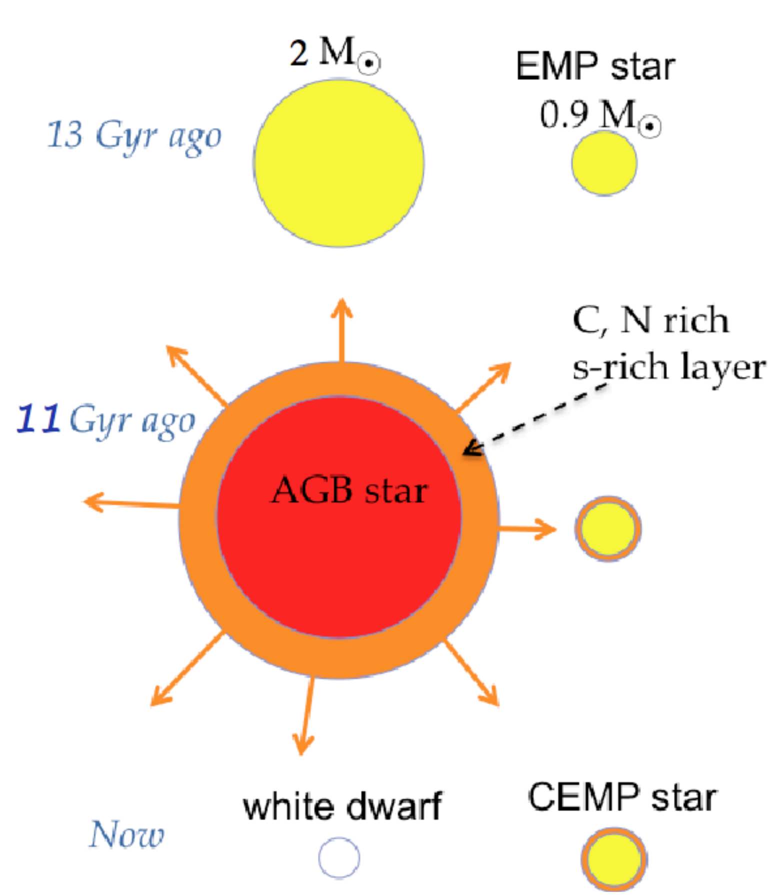
CEMP-rs

CEMP-rs stars are **binaries**
Ba La Ce Nd -rich and **Pb-rich**

odd even effect more pronounced than in the EMP r-rich stars

➔ **transfer of matter** from a companion in its AGB phase

1/ enrichment of C, N
2/ enrichment of **s** elements



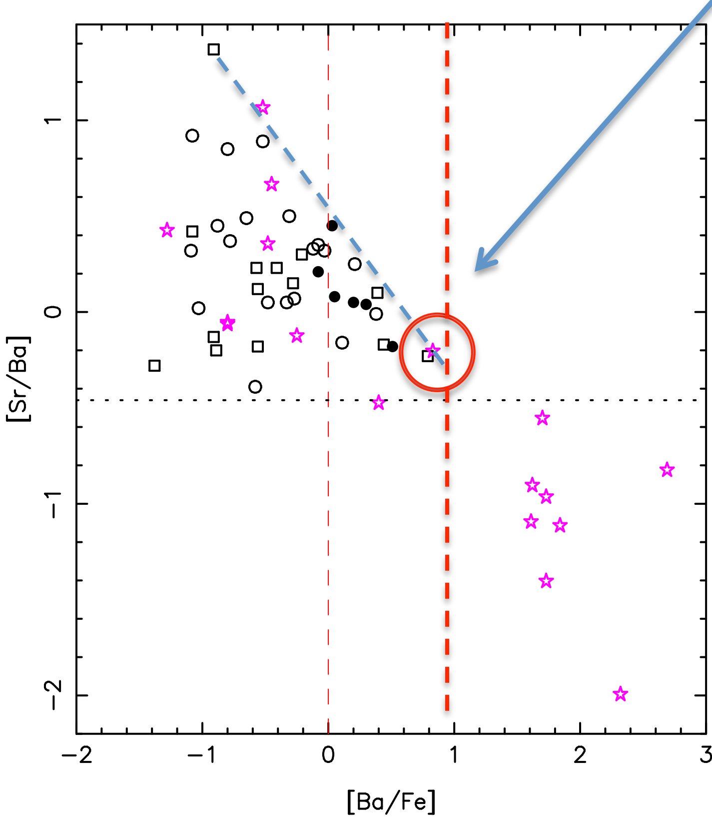
Comparison EMP / CEMP

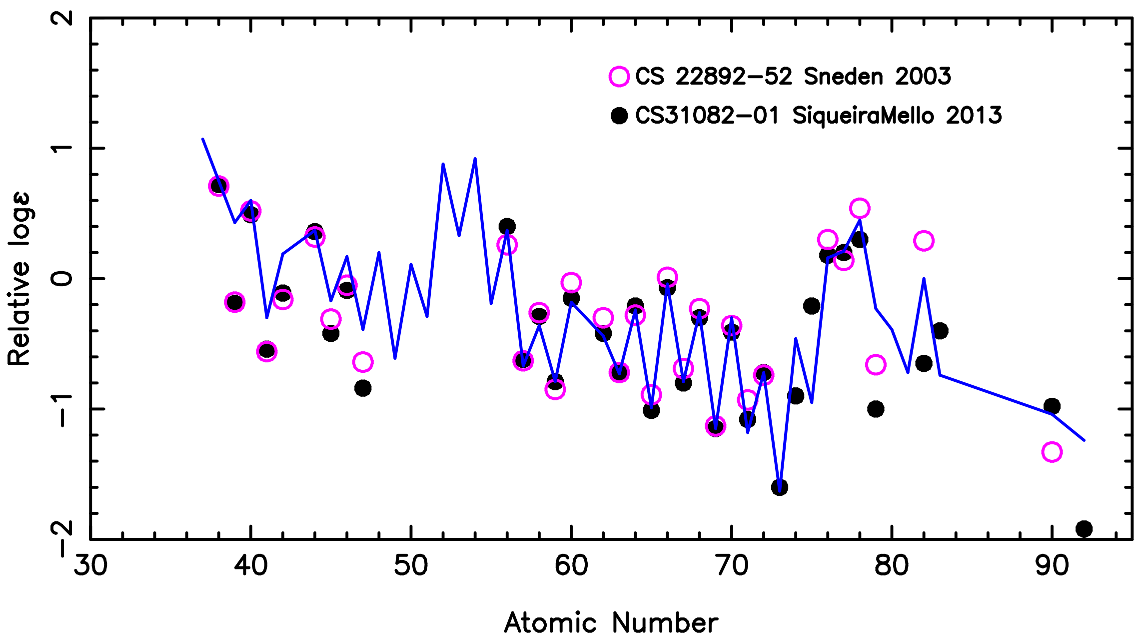
CEMP-no

region r-rich

same distribution in the [Sr/Ba] diagram as the "normal" EMP stars

Same abundance pattern ?

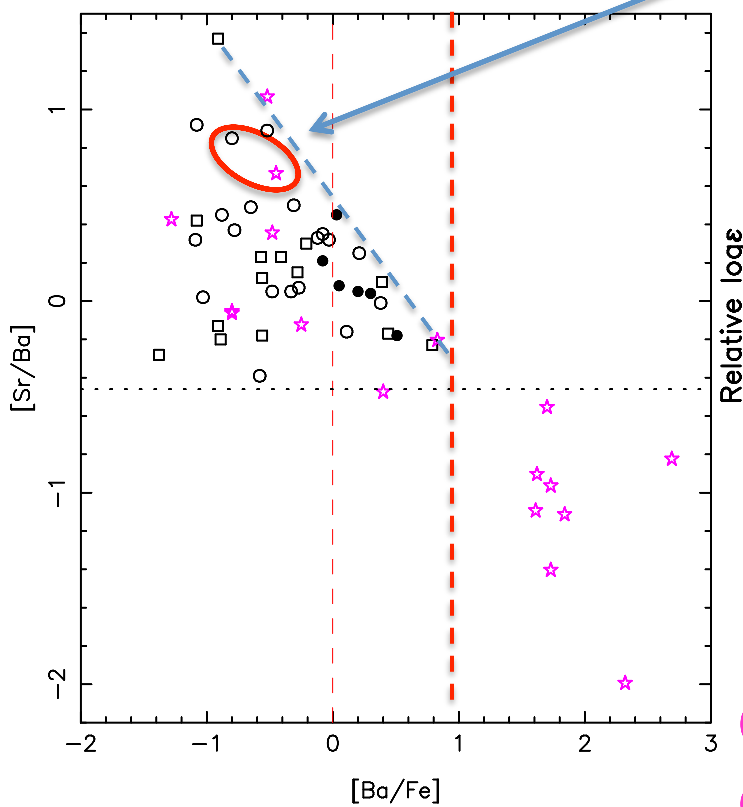




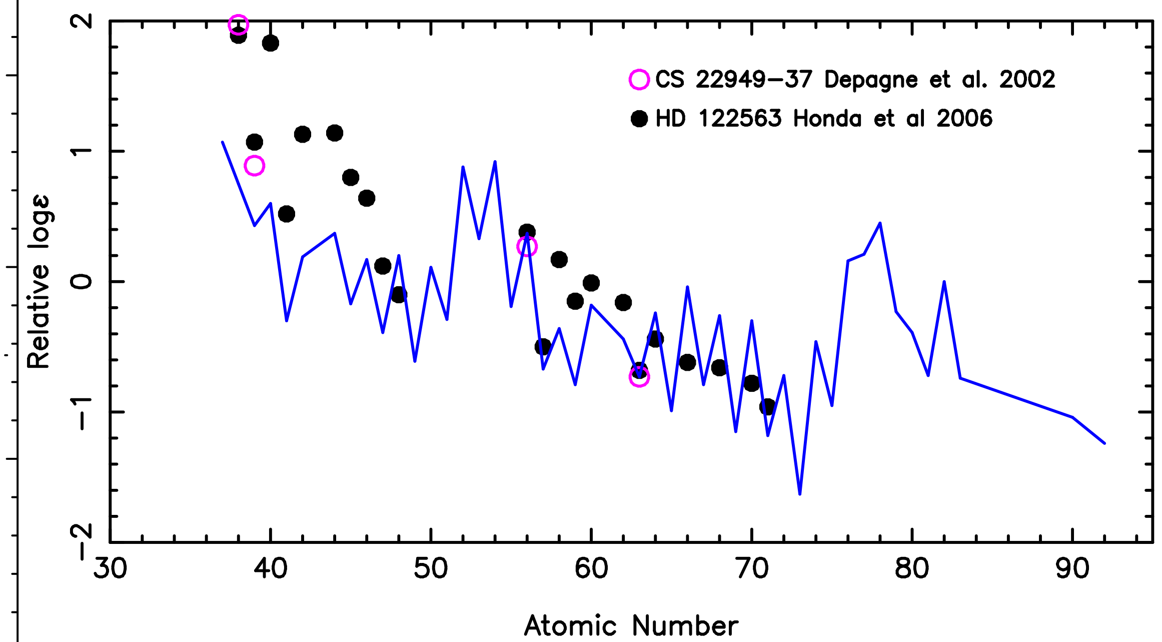
(CEMP pink normal EMP black)

Comparison EMP / CEMP

CEMP-no



high Sr/Ba



CEMP (pink) and EMP (black) are equally different from the solar r-process pattern **but more elements would be useful!**

Comparison EMP / CEMP

pattern of CEMP-no

=

pattern of EMP

CEMP = EMP stars born from a C rich matter ?

The end…

Thank you !