AIP Leibniz-Institut für Astrophysik Potsdam

very heavy elements in the early Universe

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Possible way to constrain Nature of the First Stellar Generations:

The oldest stars in our Galaxy formed from the gas ejected by the First Stars

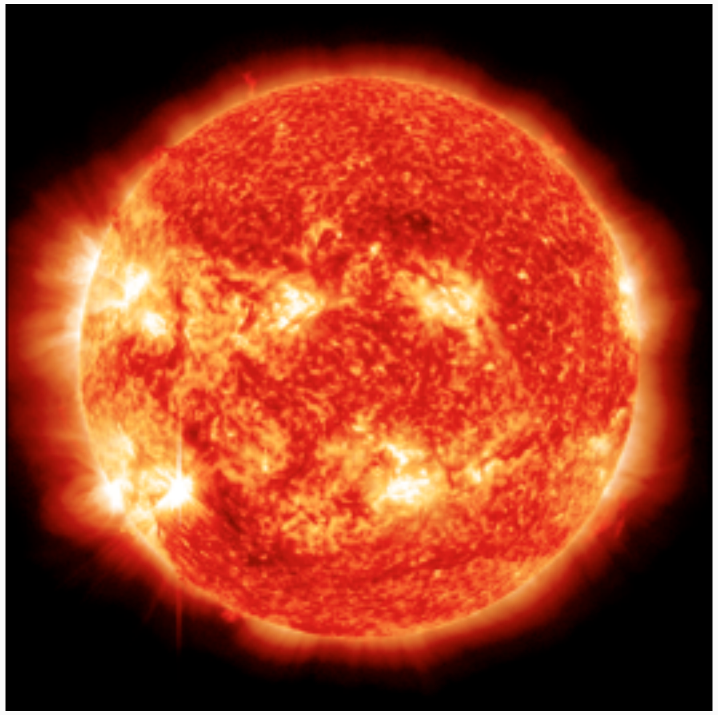
Massive Stars – short lifetimes

Core collapse Supernova

First polluters in the Universe

→

Low mass stars – long lifetimes

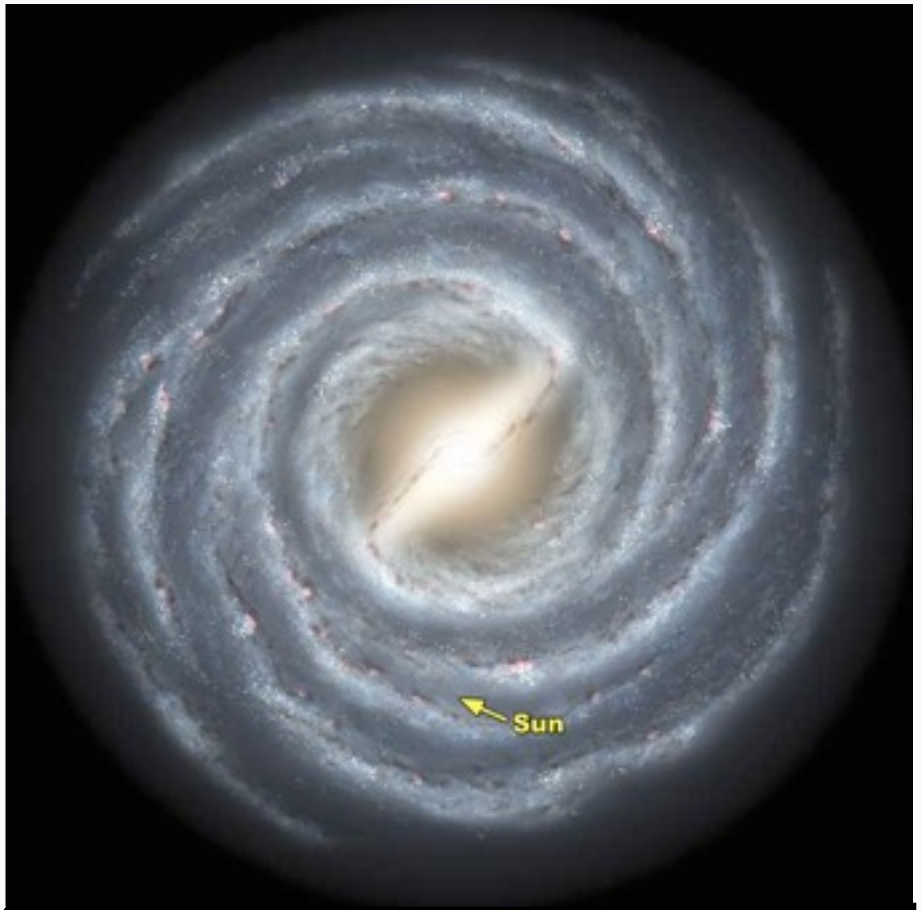


The Sun

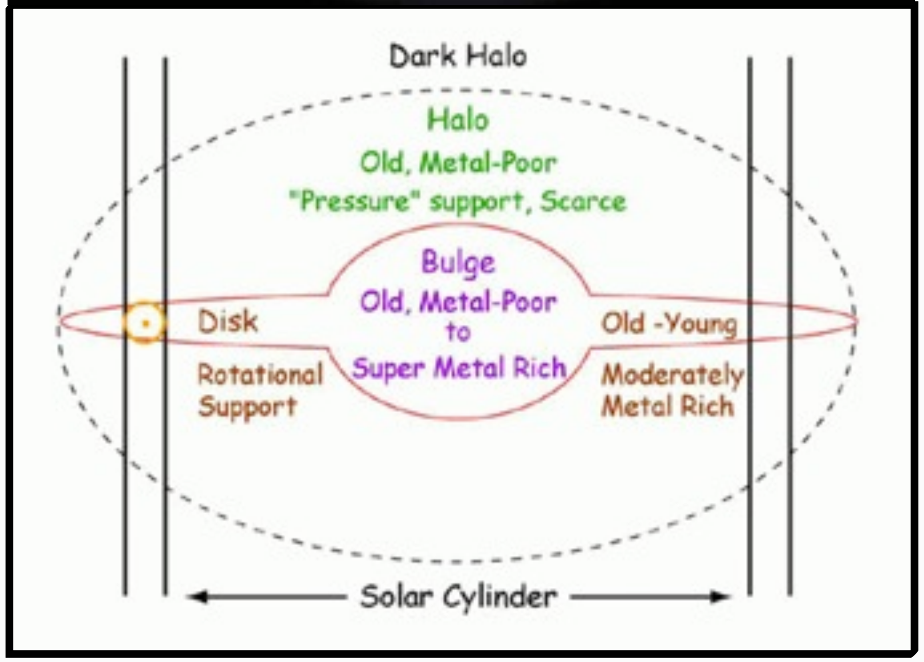
Imprints of the First stars

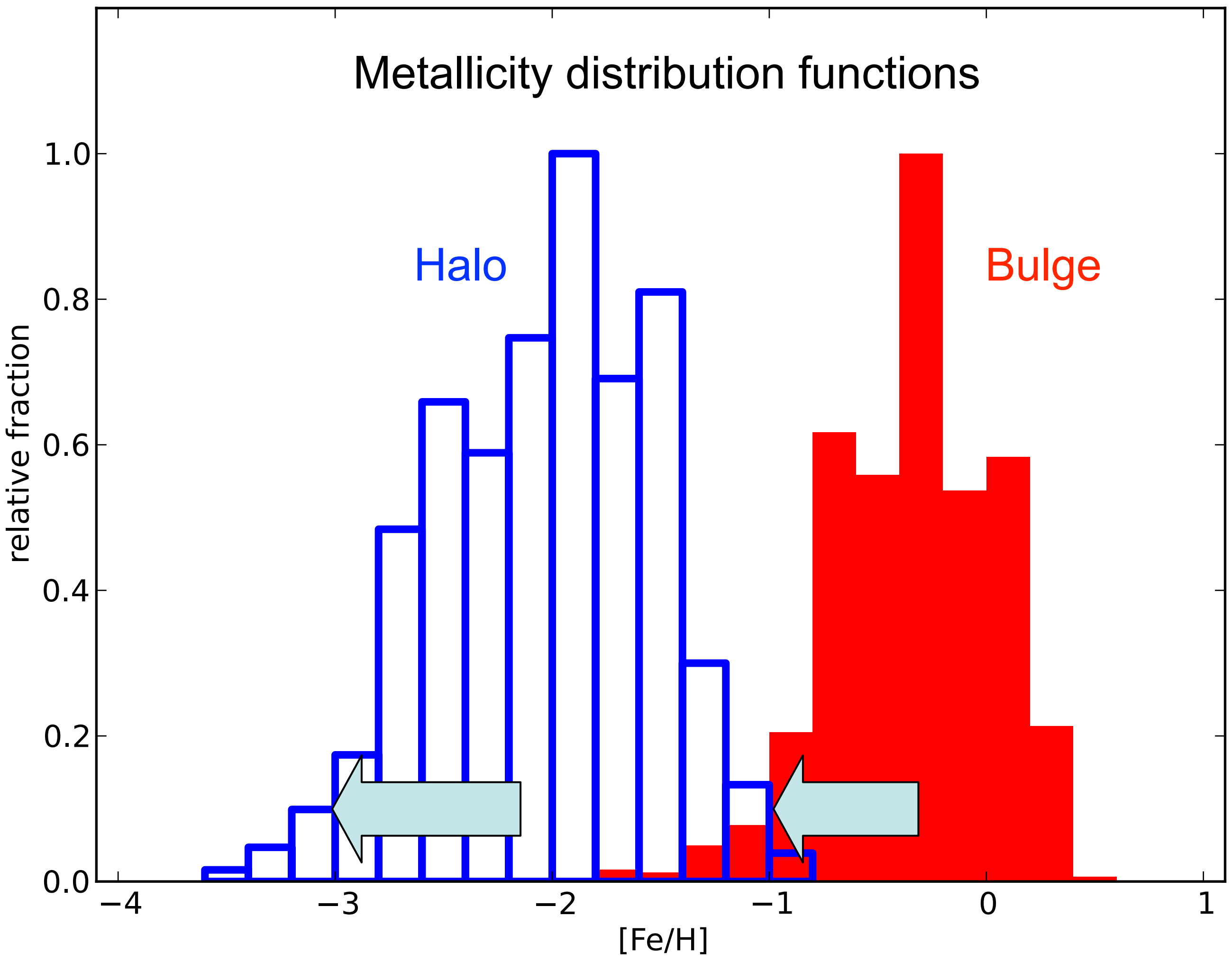
Where are the oldest fossil stars in the MW?

Face on



Edge on





In the Halo
[Fe/H] < -3
data by Li et al. 2010

In the Bulge
[Fe/H] ~ -1
data by Ness et al. 2013

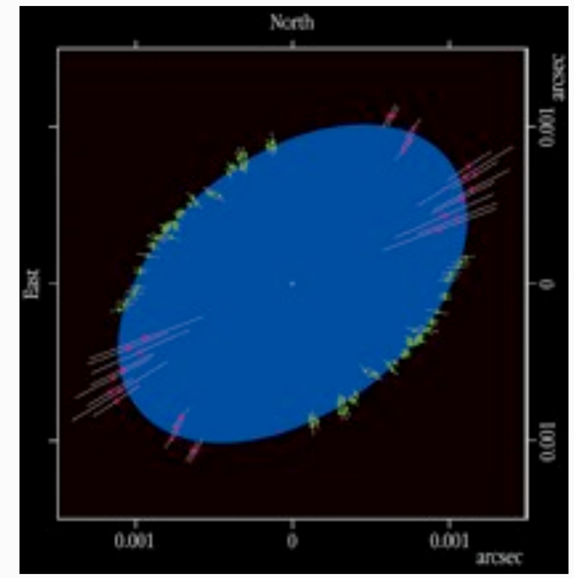
First Stars:
fast rotators?

In the Local Universe

Stellar Rotation:

Can explain observed stellar properties that models without rotation/mass-loss cannot
(e.g. departure from spherical form)

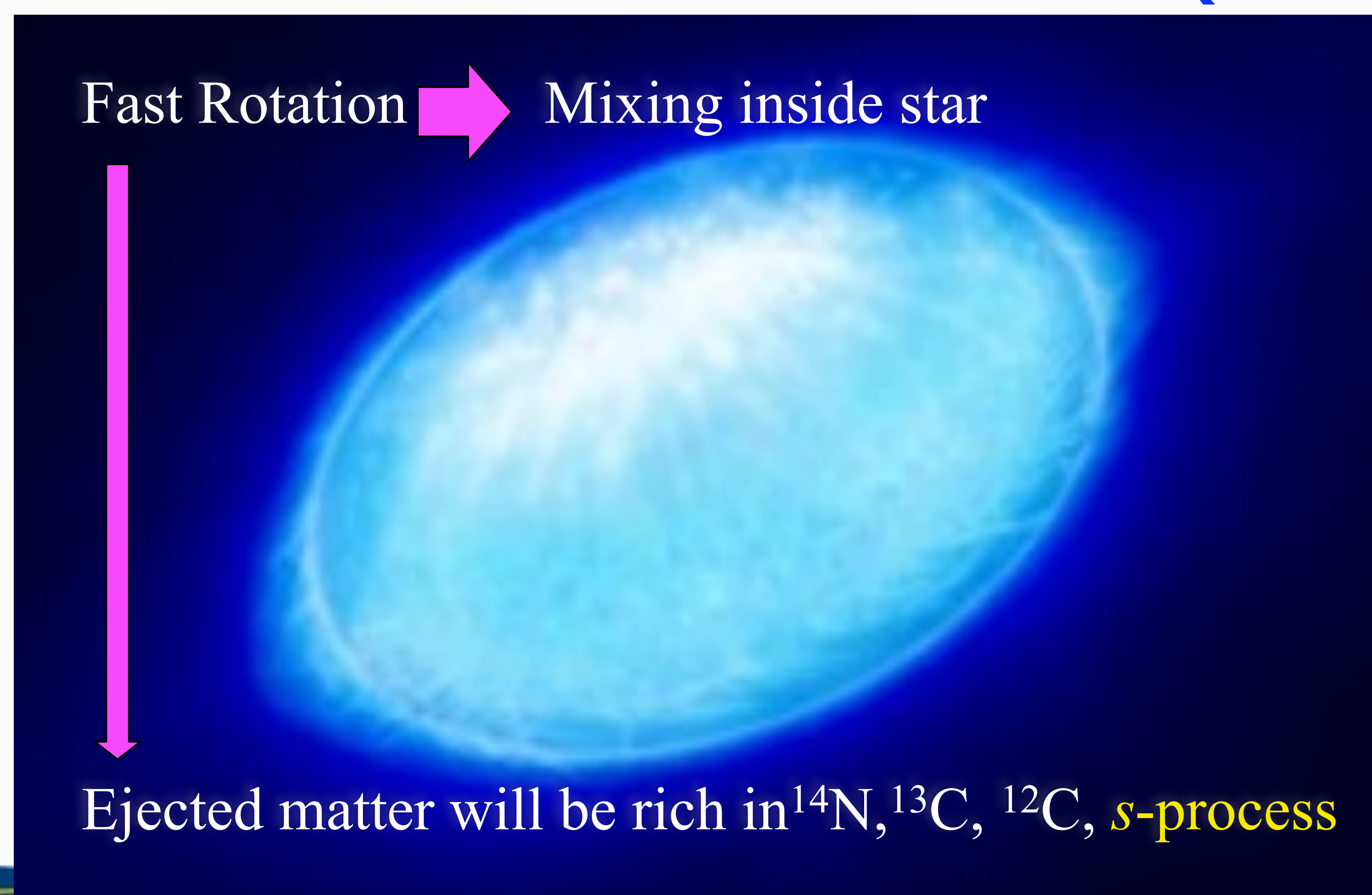
Achernar VLTI



R_e/R_p=1.5

In the Early Universe

Low metals: stars rotate faster (more compact)



Meynet
&
Maeder talks

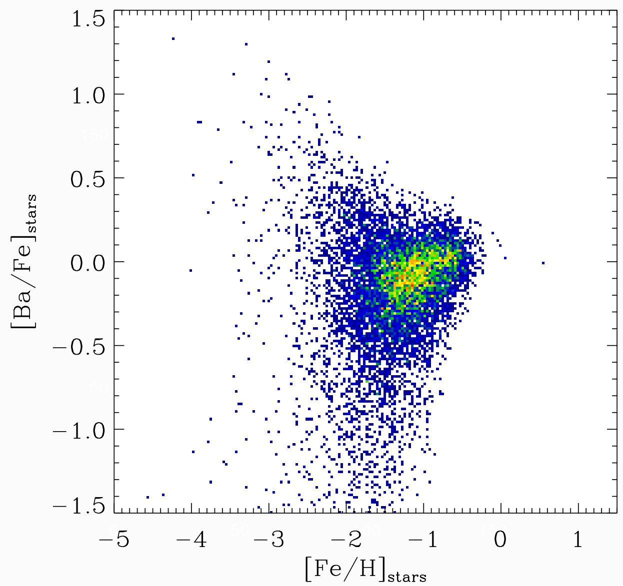
How to predict the chemical enrichment?

Chemical evolution models!

Models for the chemical evolution of galaxies are not self-consistent but they have a predictive power (and are extremely fast). They need to assume the infall of gas, the collapse of gas and metals into stars (*star formation*), the *synthesis of new elements* within these stars, and the subsequent release of metal-enriched gas as stars lose mass and die. An additional feature can be the outflow of gas from the system.

Cosmological simulations with a detailed chemical enrichment treatment are a promising way. Simulations are time demanding and they need anyway a faster tool to check our nucleosynthesis and

"Is it really a Milky Way-like galaxy? (cit. Matteucci)

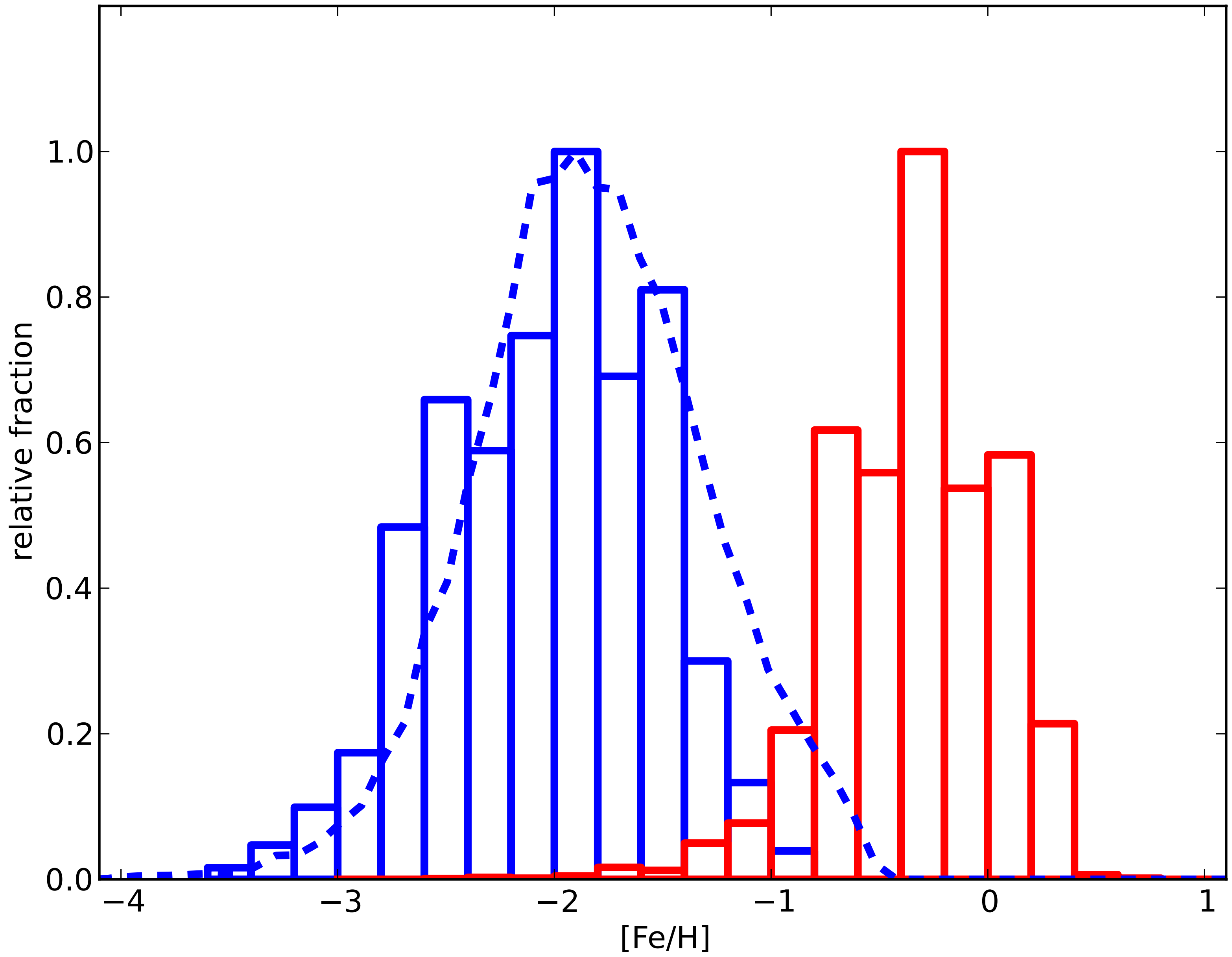


Preliminary results obtained at AIP with C. Scannapieco for a isolated DM halo

MDF of the Galactic halo

Comparison between our halo model (see Chiappini+ 2006)
Basic ingredients: Gaussian infall (tau=250Myr), outflow ~ SF, Scalo IMF

and the observed MDF by Li+ (2010)
main-sequence turnoff stars in the HESS (Hamburg ESO survey)



Neutron capture elements

from Truran 1981 to ~5 years ago

	s-process	r-process
site	Low-(intermediate) mass stars *Trippella talk*	Massive stars (& NS mergers) O-Ne-Mg core explosions? NS stars mergers?Magneto rot. driven SN? many scenarios...
time scale	>300Myr	< 30Myr (excluding NS mergers)
yields	Busso et al. 2001 *Cristallo+ 2011* *Karakas+ 2012)*	....

Early Galaxy

Neutron capture elements

The picture now

AIP

Early Galaxy

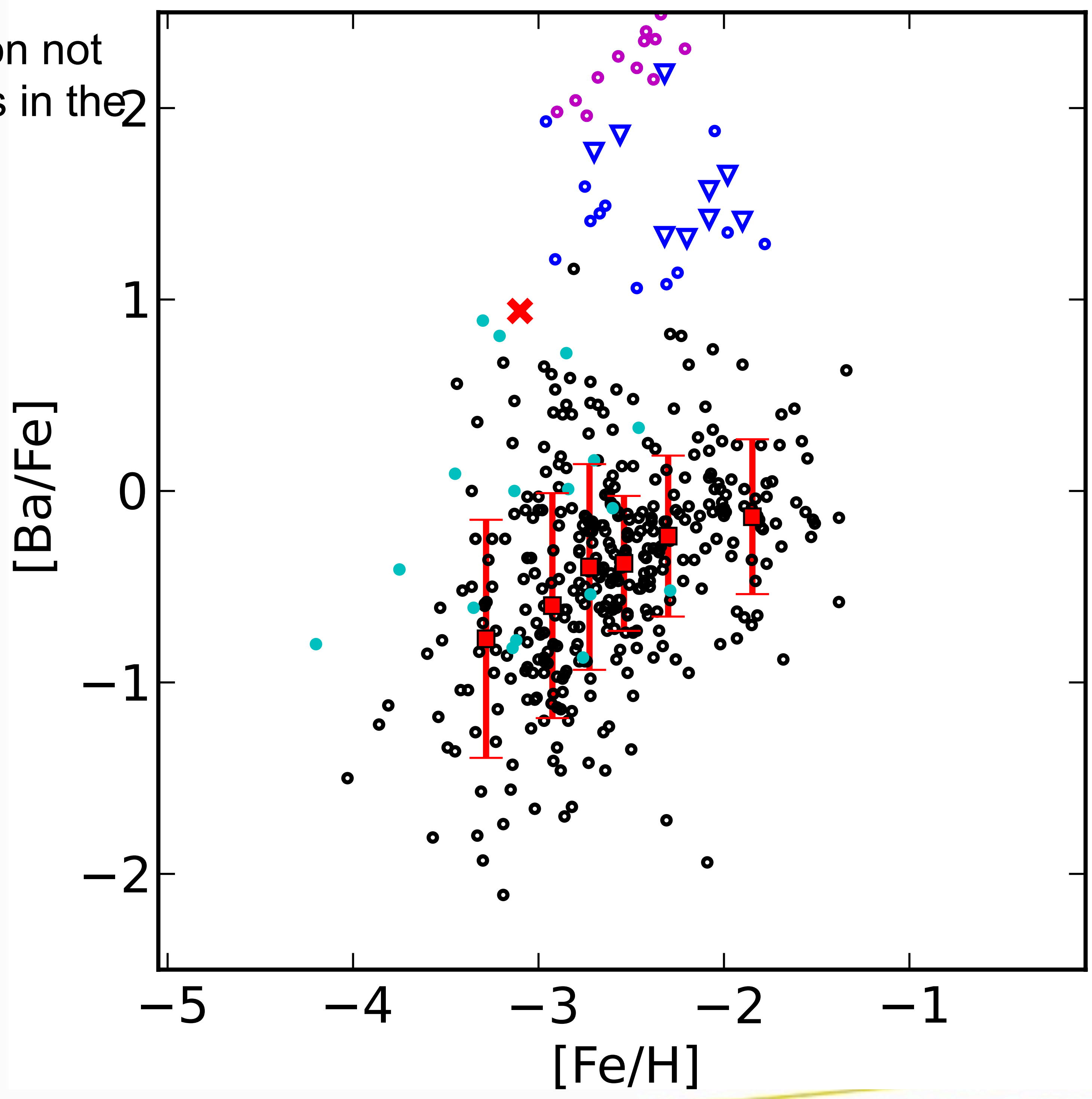
s-process		r-process
Low-(intermediate) mass stars	rotating Massive stars	Massive stars (& NS mergers)
		O-Ne-Mg core explosions? NS stars mergers?Magneto rot. driven SN? many scenarios...
>300Myr	< 30Myr	< 30Myr (excluding NS mergers)
Busso+ 2001	Frischknecht+ 2012	....
Cristallo+ 2011 Karakas+ 2012)	*Pignatari+ 2008, Limongi talk*	

Empirical yields for r-process

Why empirical?
r-process site of production not established, uncertainties in the predictions!

Meynet/Thielemann talk

s-process enrichment by low mass stars, negligible in the halo (short formation timescale).



CEMP-s likely formed through binary process not taken in to account here

data collected by Frebel ’10

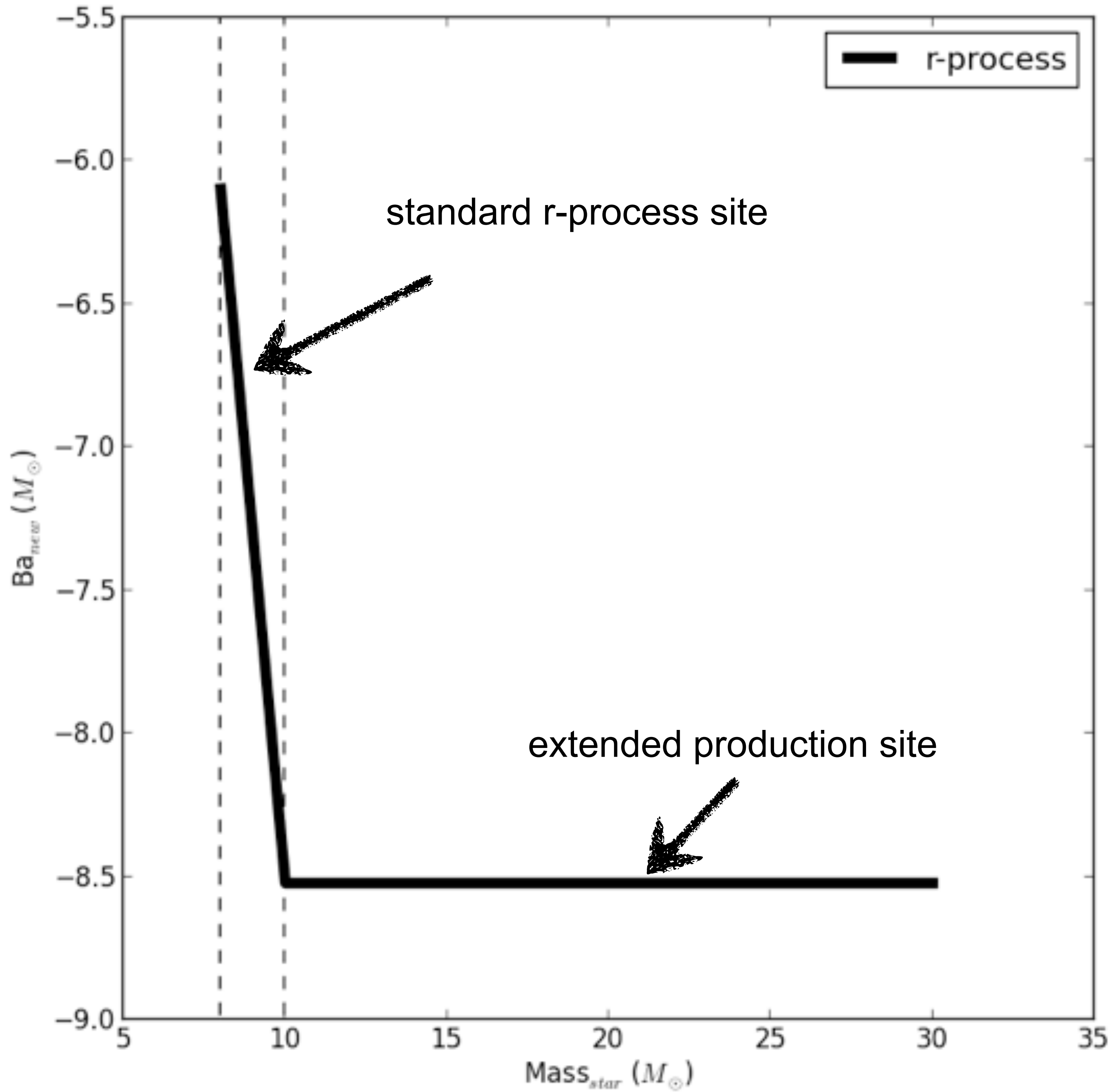
halo stars:
normal
cemp-s
cemp-no

Empirical yields for r-process

To fit the data,
2 regimes
of production:

1) High level of production
in the low tail of massive stars
(standard
r-process site)
RARE EVENTS

2) Low level of production
from an
extended range

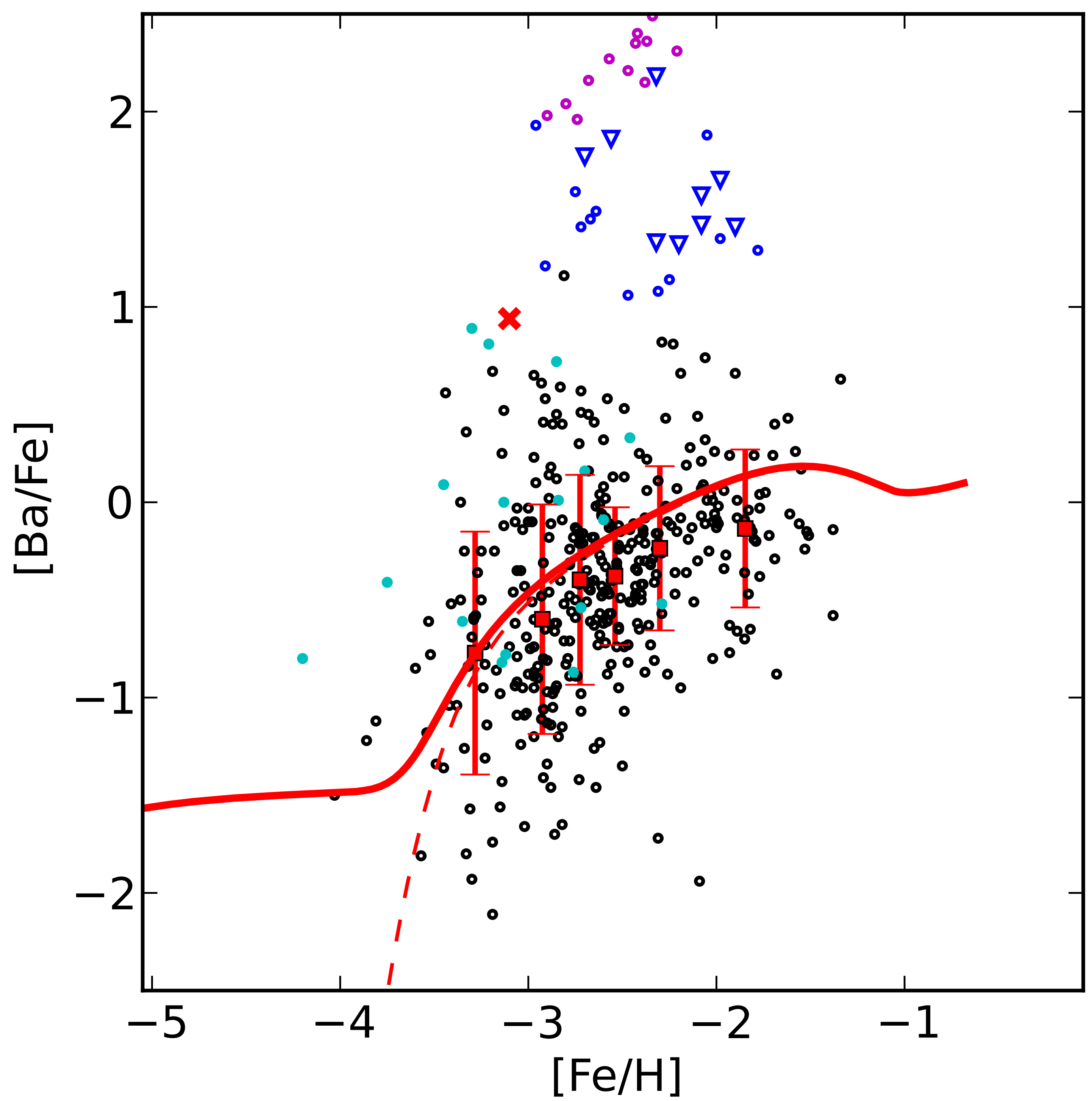


Results for Barium

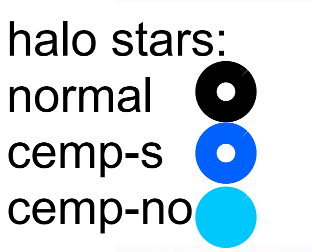
By construction of the yields themselves, it fits the data...

BUT

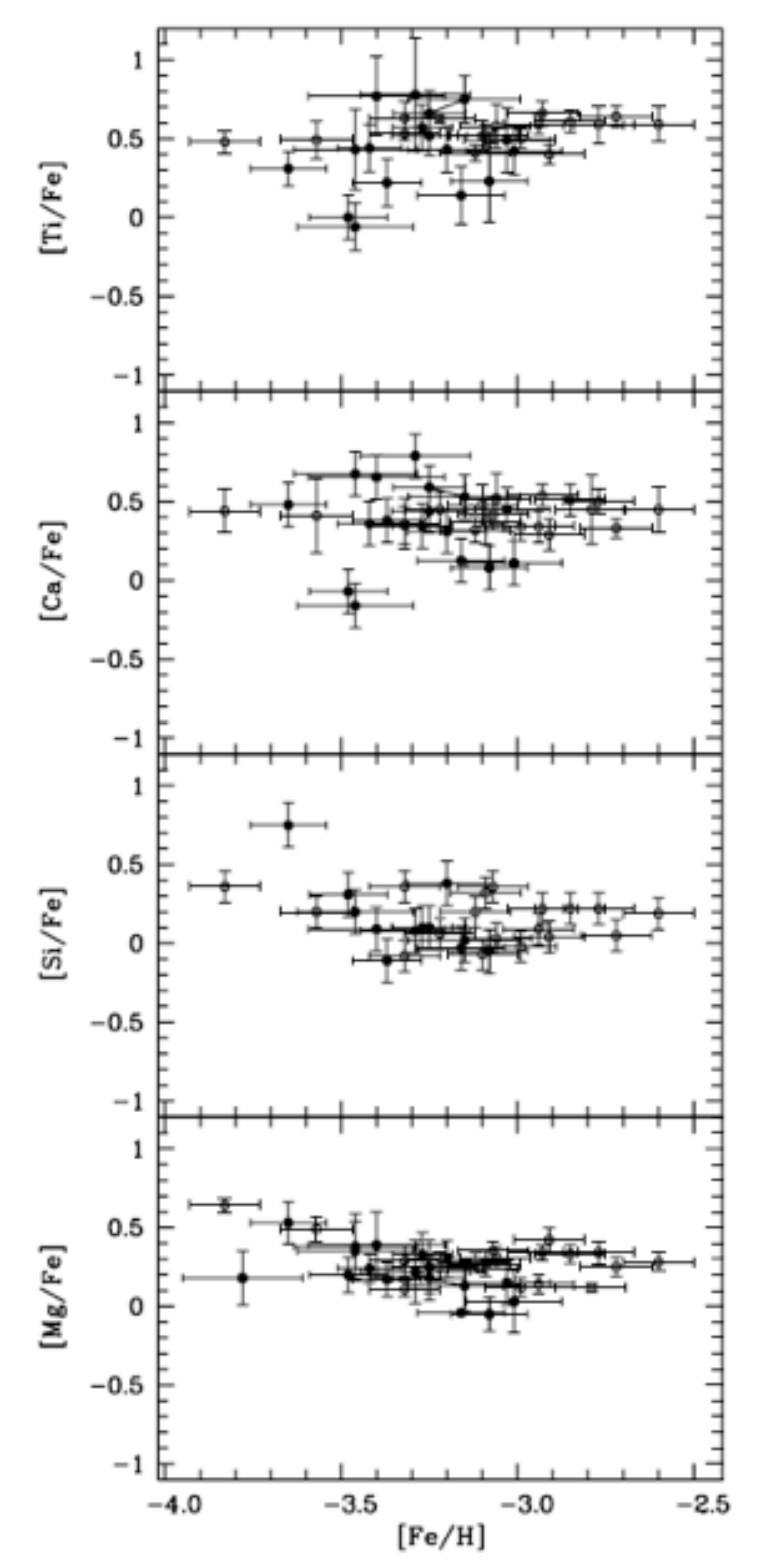
This homogenous model cannot be used to have an insight of the spread observed in the halo stars, only the trend is recovered.



data collected by Frebel '10

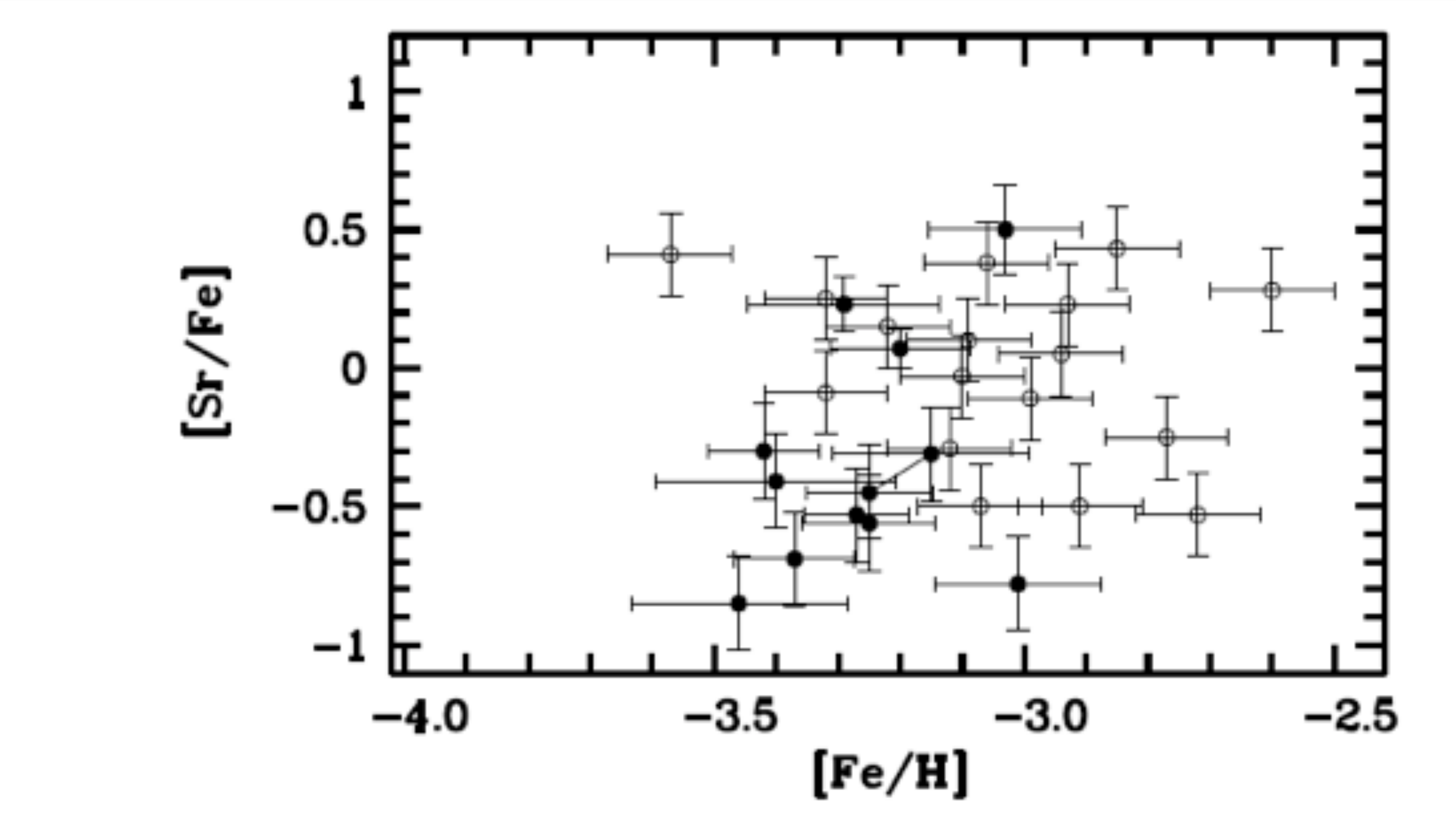


The problem of the spread



α-elements do not show scatter whereas the neutron capture elements do show a lareg spread...

In this case, it is shown the results for sample of halo stars, measured homogeneously by the same authors.



Bonifacio et al. (2012)

Inhomogeneous chemical evolution model for the halo of the Milky Way

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Problem to solve:
The neutron capture elements at low metallicities show spread whereas α-elements (O, Ca, Si, Mg) do not
Main assumptions:

A random formation of new stars subjects to the condition that the cumulative mass distribution follows a given initial mass function;

α-elements and neutron capture elements are produced with different dependence to the stellar mass:
- shallow dependence to the mass for α-elements
- peaked and strong mass dependent for neutron capture elements

Inhomogeneous chemical evolution model for the halo of the Milky Way

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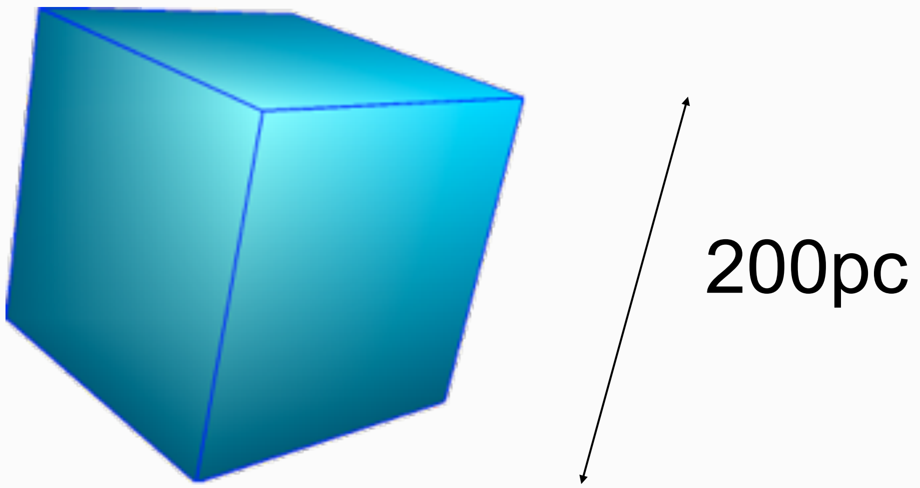
We divide the halo in boxes each one of the typical size of 200 pc and we treat each box as isolate from the other boxes.



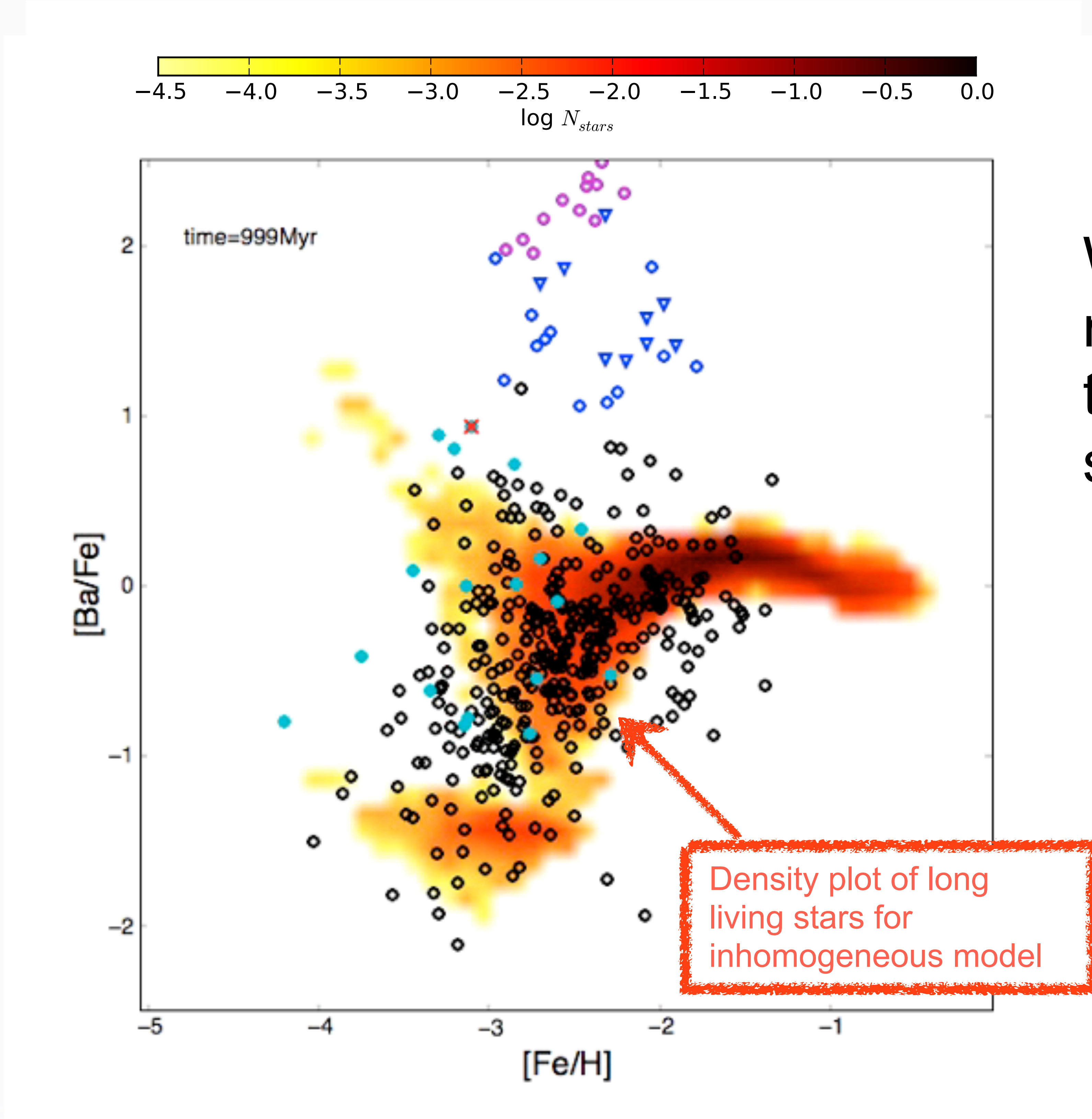
Inside each box, we simulate for 1 Gyr the chemical enrichment.

The main parameters are the same as those of the homogeneous model but in each box the masses of the formed stars are different and this fact produces different enrichments.

Inhomogenous model for Ba

The homogeneous model with the empirical yields fits the data but cannot explain the spread...

We run the inhomogenous model (Cescutti ’08) with the new yields

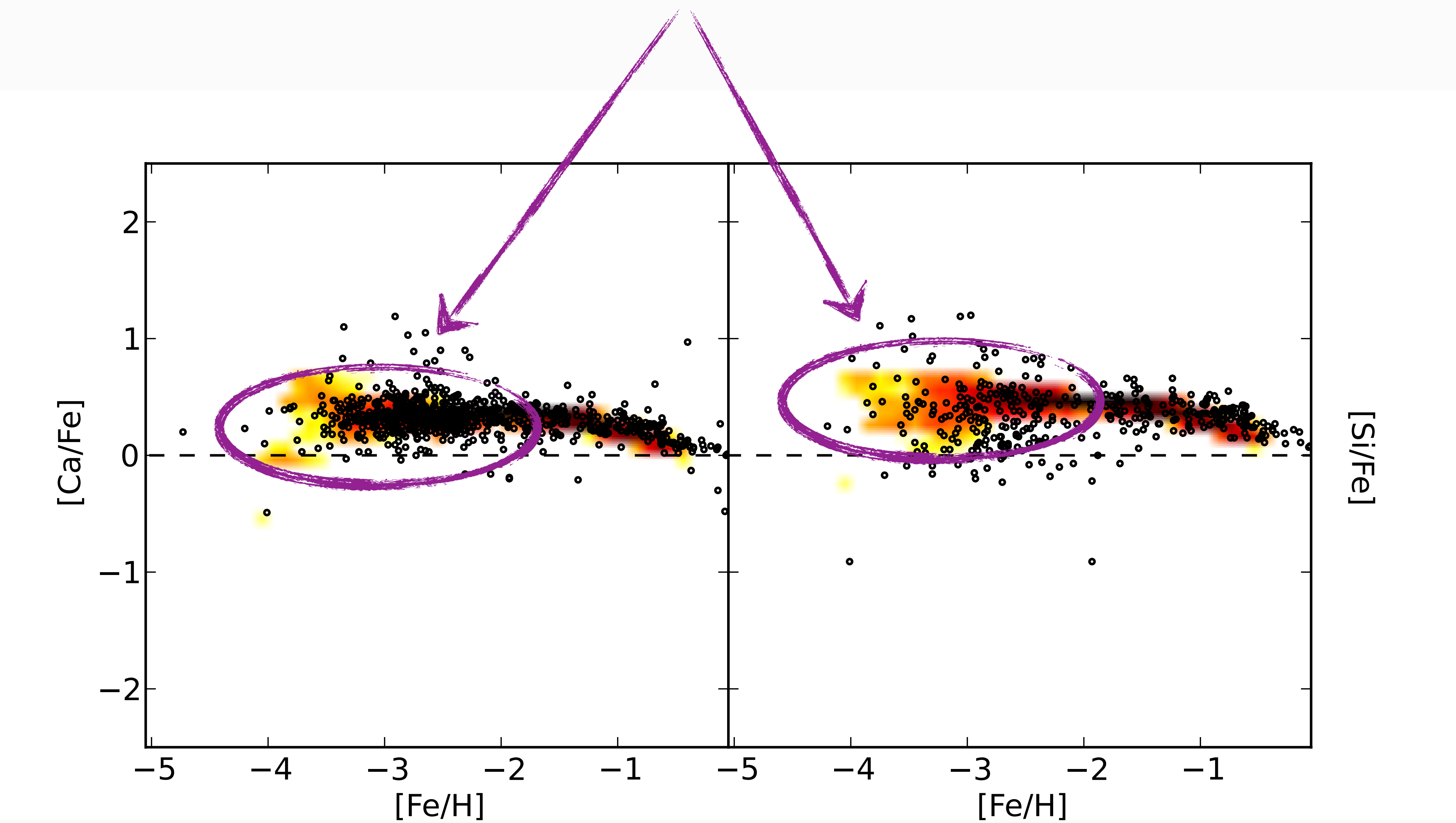


We can reproduce the [Ba/Fe] spread...

halo stars:
normal
cemp-s
cemp-no

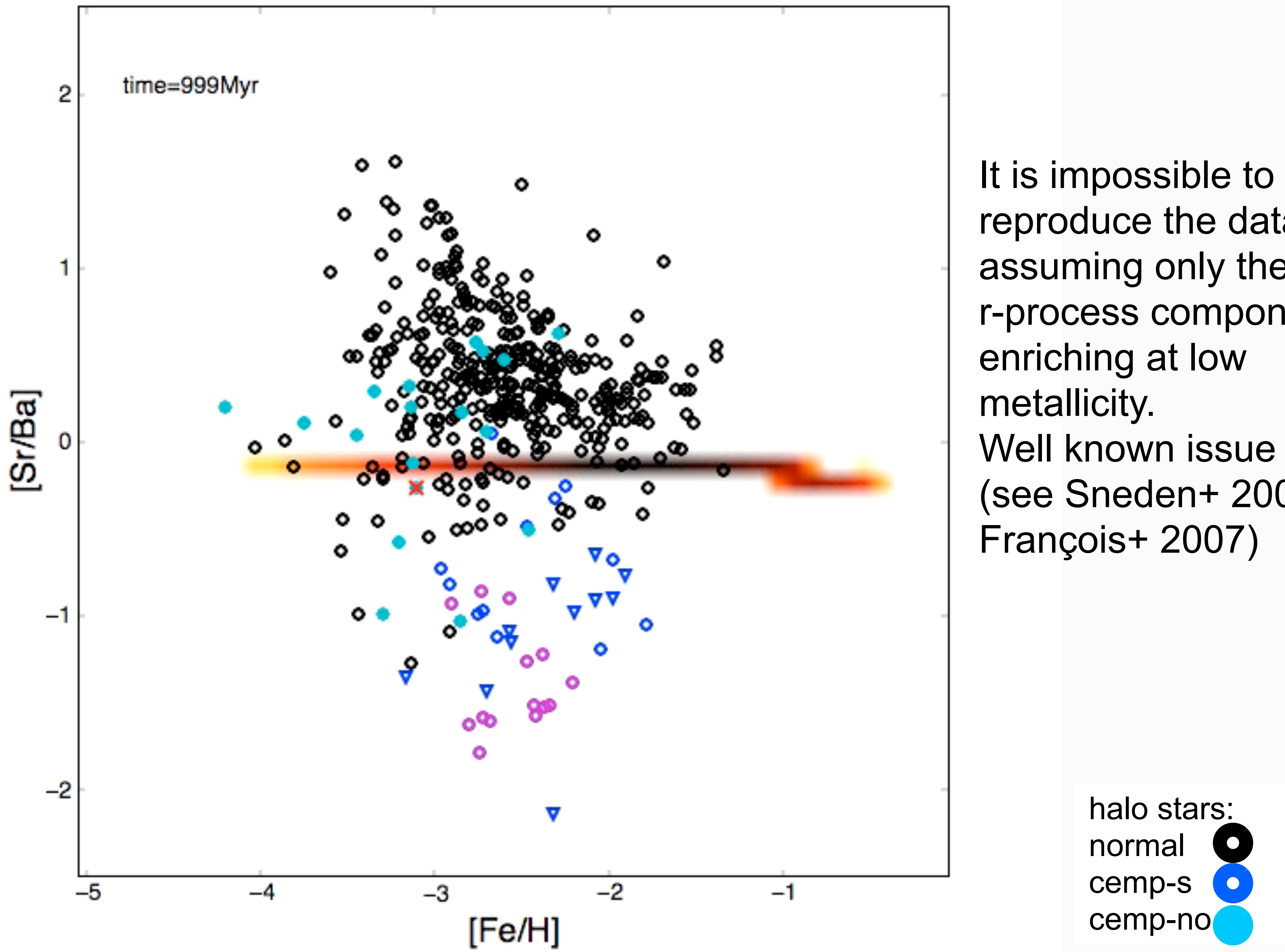
NO spread for alphas!!!

With standard yields for alpha the inhomogeneous model does not predict spread (less than the data!!!)



Puzzling result for the "heavy to light" n.c. element ratio

For Sr yields: scaled Ba yields according to the r-process signature of the solar system (Sneden+ 08)



It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
Well known issue (see Sneden+ 2003, François+ 2007)

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Signatures of Fast Rotators found in the Galactic Halo

(1) Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)

(2) Increase in the C/O ratio in the early Universe

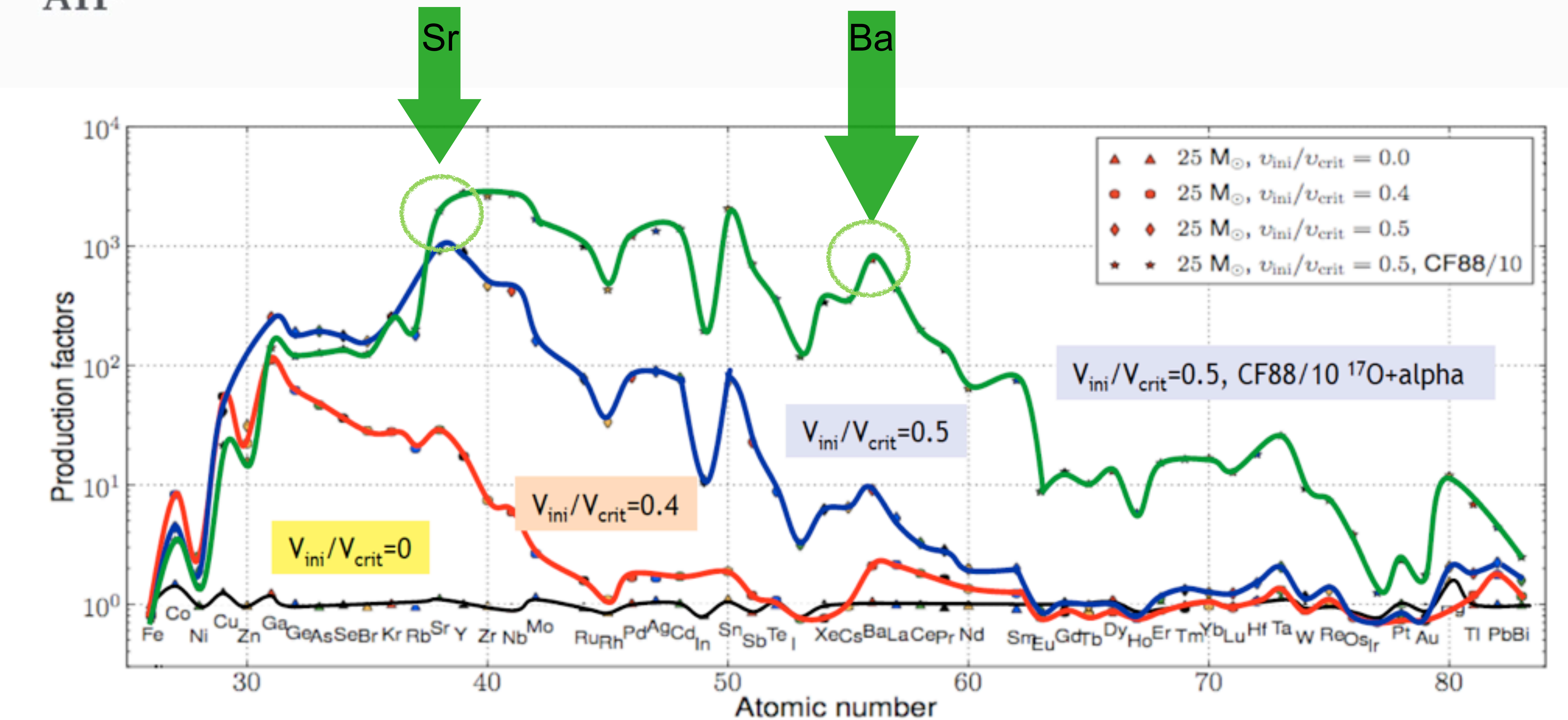
(3) Large amounts of ^{13}C in the early Universe (Chiappini et al. 2008 A&A Letters)

(4) Early production of Be and B by cosmic ray spallation (Prantzos 2012)

5 Early production of neutron capture elements through a boosted s-process (Sr,Ba,...)

5th signature: Fast rotators imprints in s-process elements?

Can they explain the puzzles for Sr and Ba in halo?



Fast rotators could contribute to s-process elements!

Limongi talk

Frischknecht et al. 2012

(self-consistent *spinstar* models with reaction network including 613 isotopes up to Bi)

s-Process from fast rotators

+ standard r-process site (the 2 productions are decoupled!)

Cescutti et al. (2013)

Boosted models:

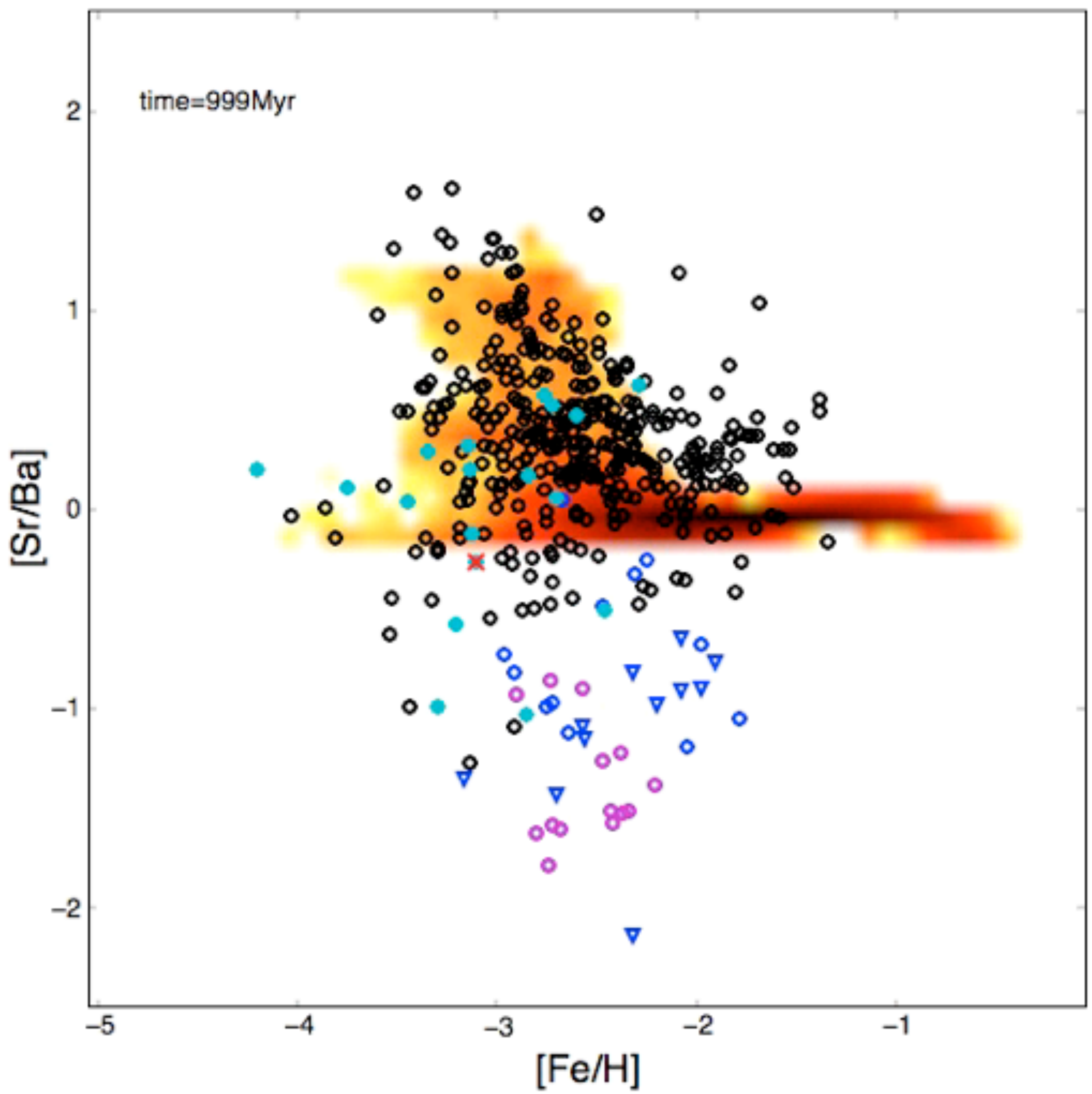
V_{ini}/V_{crit}=0.5

&

0.1

of the reaction rate by Caughlan & Fowler '88 for $^{17}O\ (\alpha, \gamma)$

Boosted s-process from fast rotators assumed only for [Fe/H]<-3



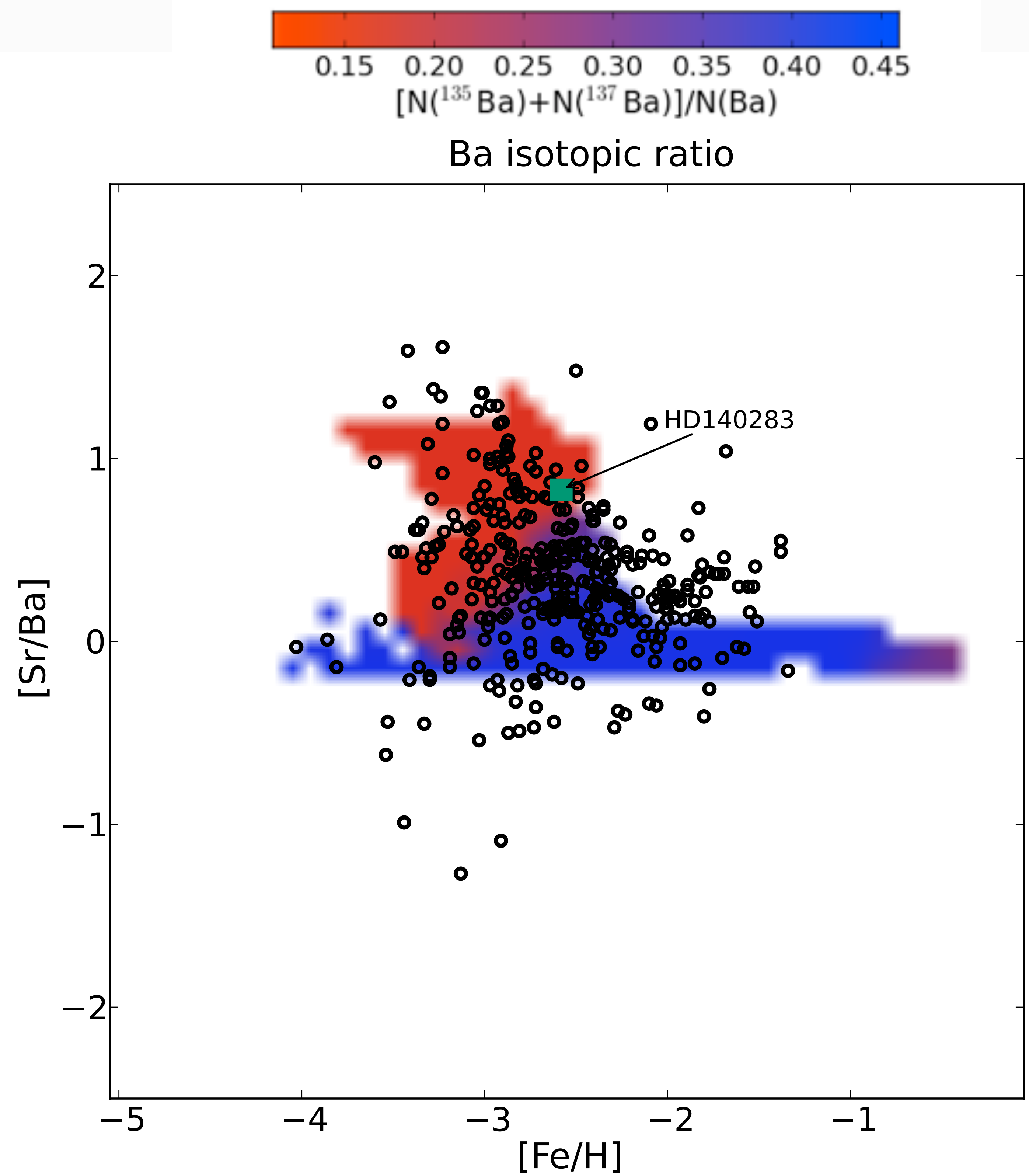
s-process from spinstars provide a solution!

halo stars:
normal
cemp-s
cemp-no

s-Process from fast rotators

+ standard r-process site (the 2 productions are decoupled!)

The spinstars scenario naturally produces also a prediction on the Ba isotopic ratio in halo star.



Challenging to check these predictions.
See results by Magain (1995) & Gallagher+(2012)

Conclusions

Fast rotating massive stars

Solution for 4 signatures in the early Universe

(1) Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)

(2) Increase in the C/O ratio in the early Universe

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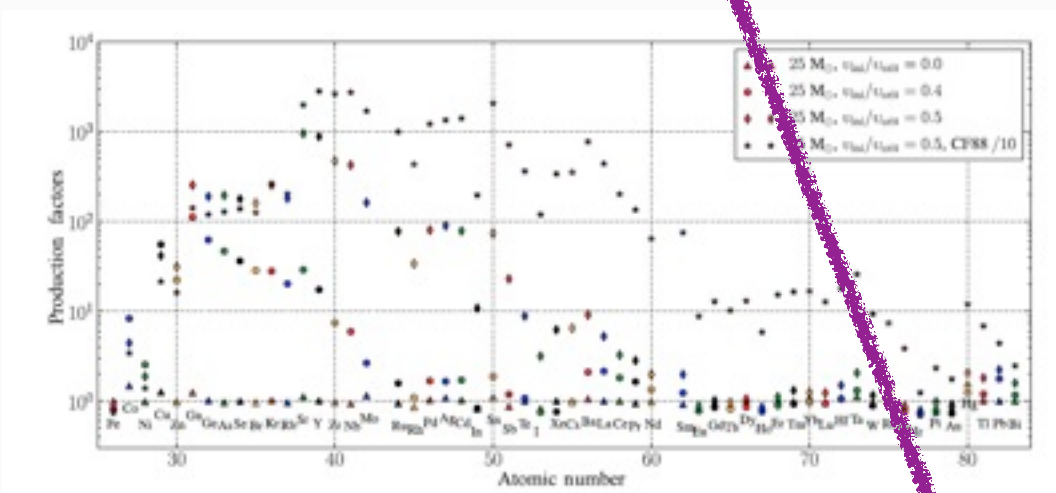


Models predict a boosted s-process

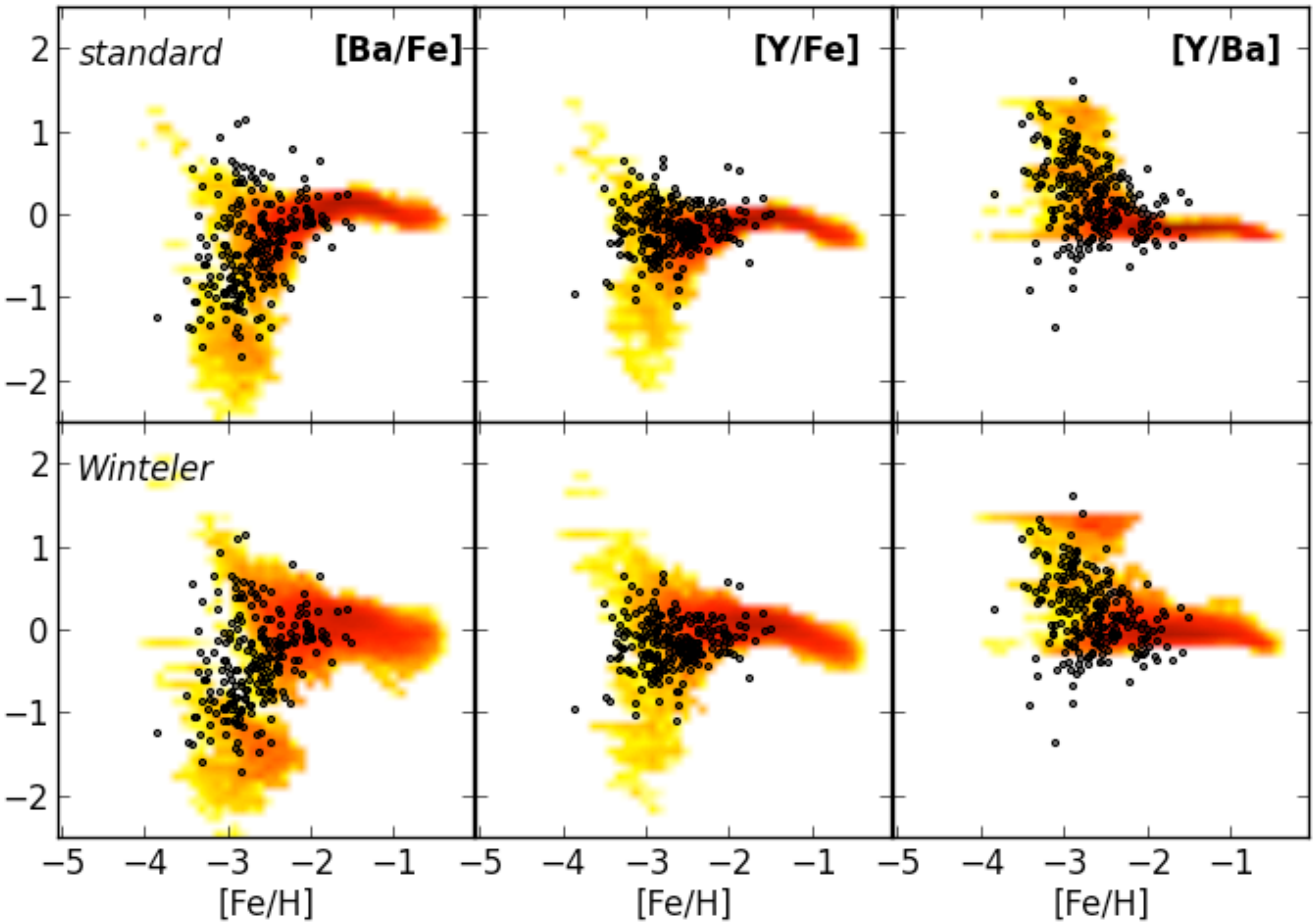
<u>5th signature</u>: The boosted s-process can solve the puzzle of Sr/Ba

In the Early Universe the stars were fast rotators!(?)

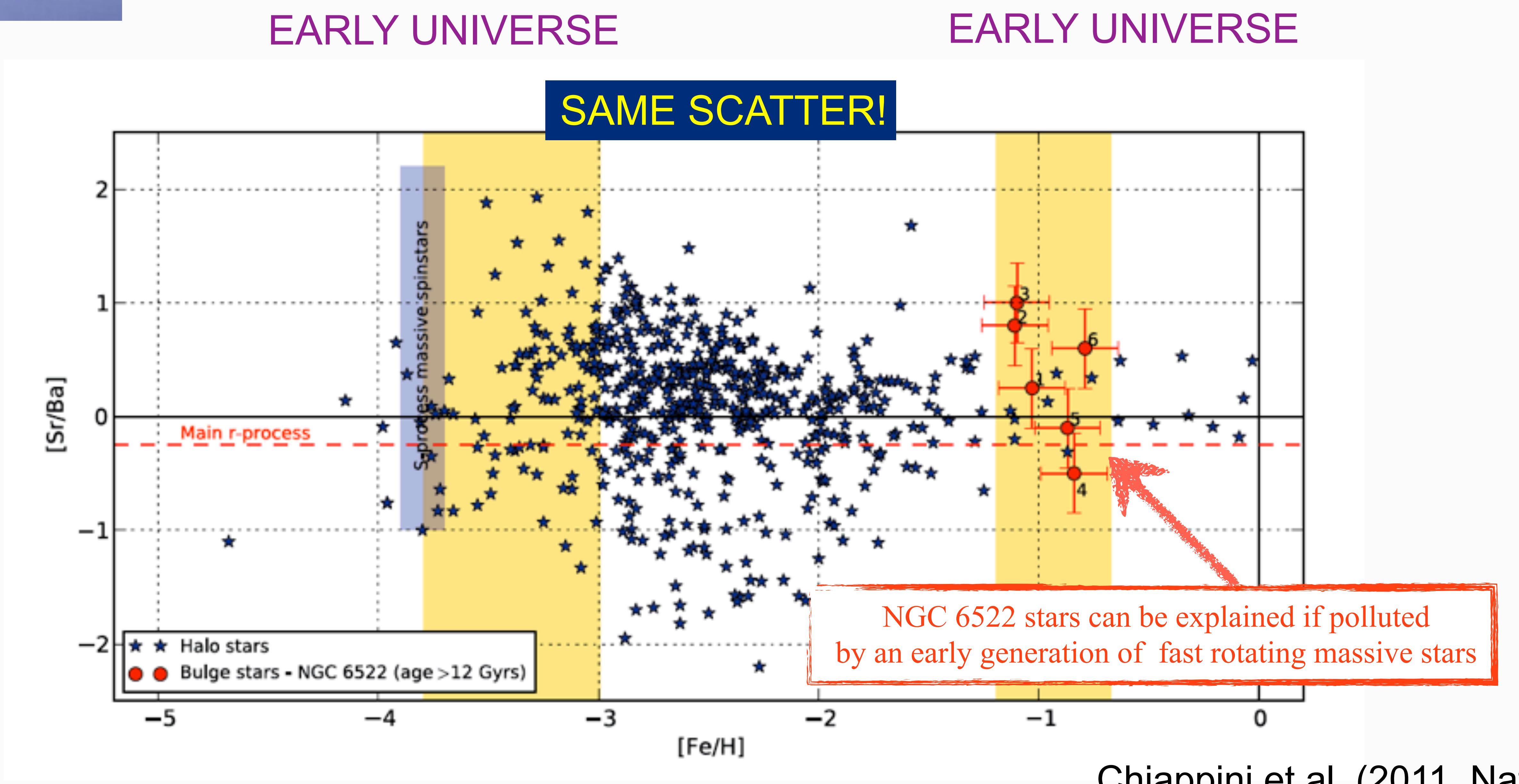
The true r-process site?

Standard model based on the electron capture SN.
rare because they are produce only in a narrow range of masses
Theoretical predictions do not confirm the production of Ba and Eu (Wanajo+ 2011)

Magnetorotationally driven SN scenario (***Winteler***+ 2012):
rare because only a small percentage of the massive stars (~1-5%)
However this percentage is not well constrained, in particular in the early Universe.



What's going on in the other fossil early Universe - the Bulge?



Chiappini et al. (2011, Nature)

Inhomogeneous model for the Bulge -
Soon first preliminary results, stay tuned