Chemical evolution models

The special case of neutron capture elements

in the Early Galaxy

Text

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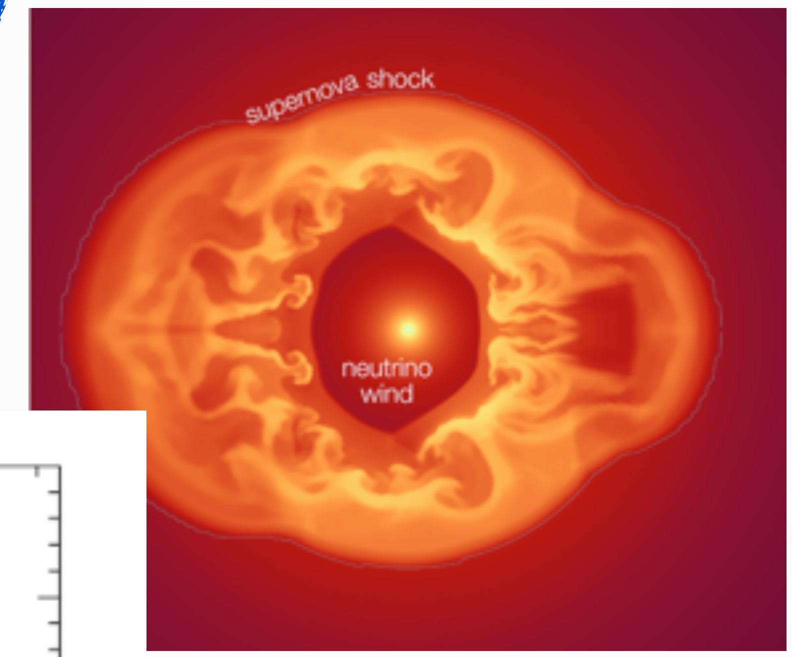
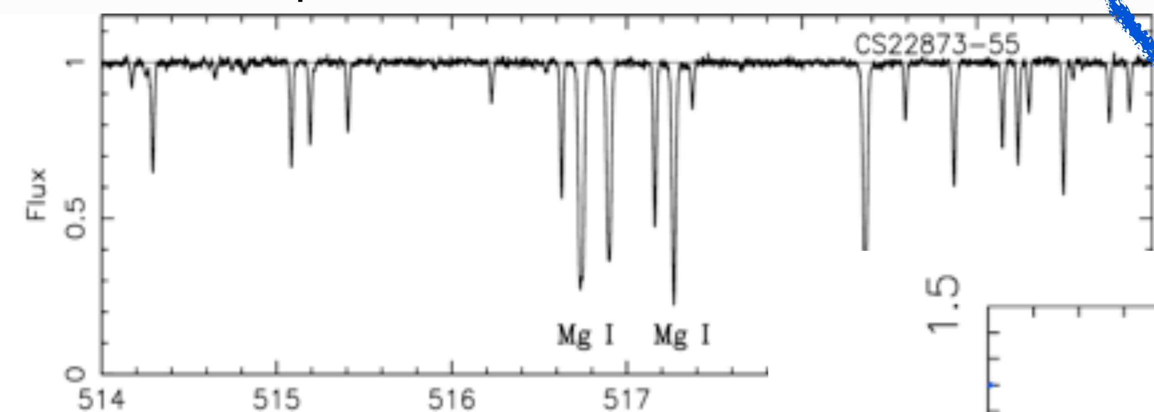
Seattle, 30th July 2014
INT workshop on the r-process

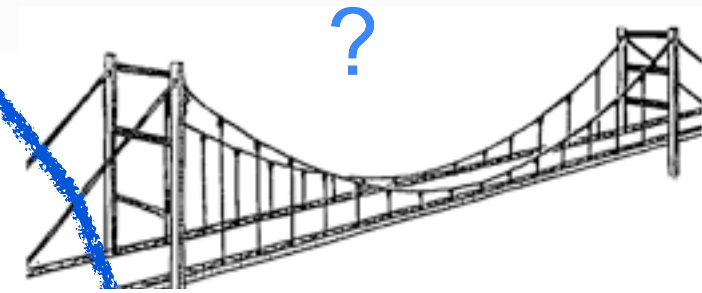
Chemical evolution models?

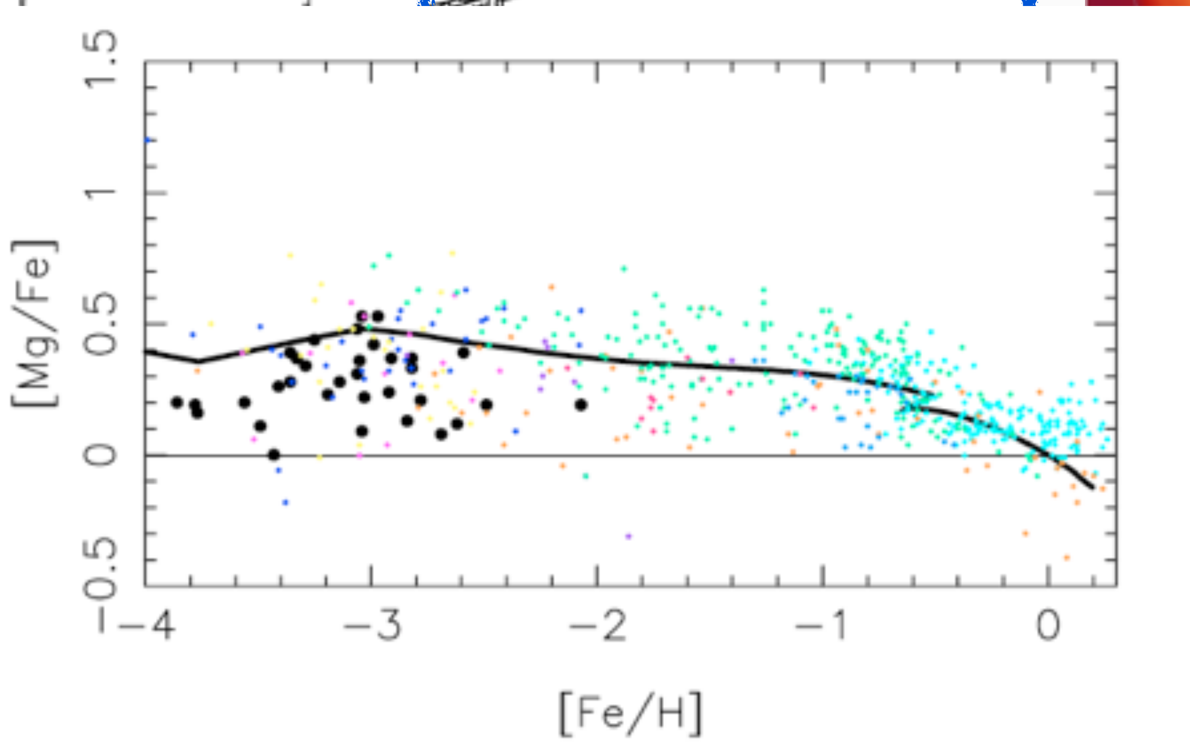
Stellar evolution



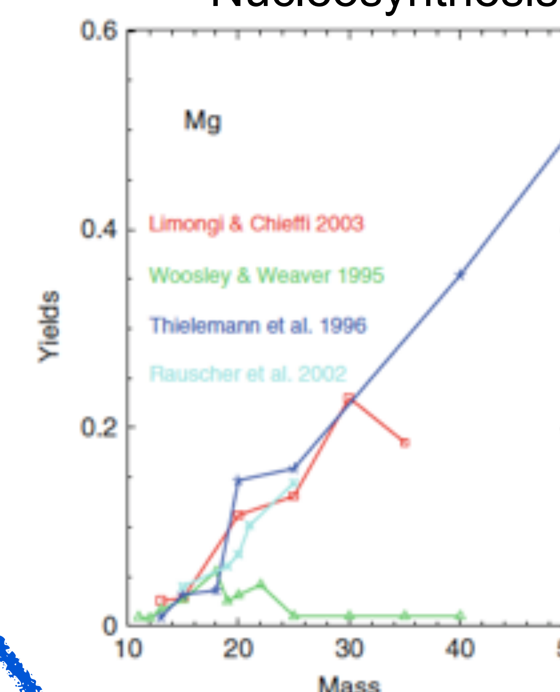
Stellar spectra



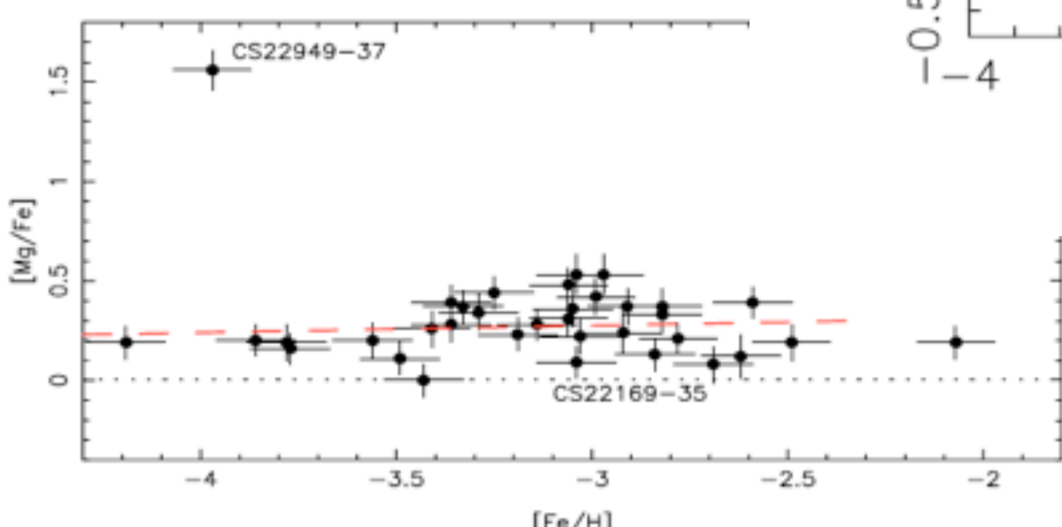




Nucleosynthesis



Stellar chemical abundances

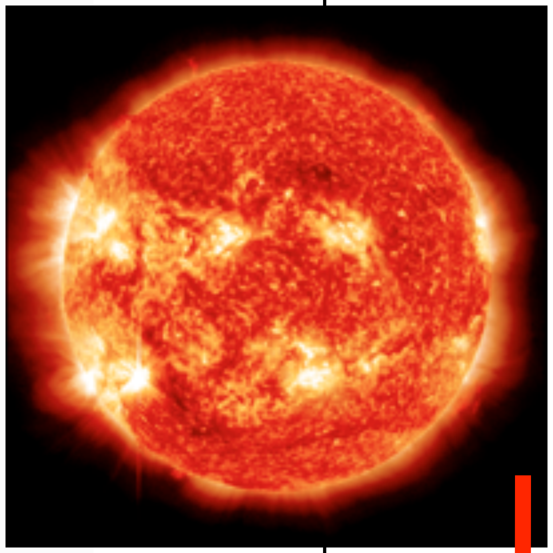


The CE model for the Galactic halo

The oldest fossil stars are present in this component of the MW. Here the first polluters of the Universe have left their imprints in the low mass (and long living) stars that we observe nowadays

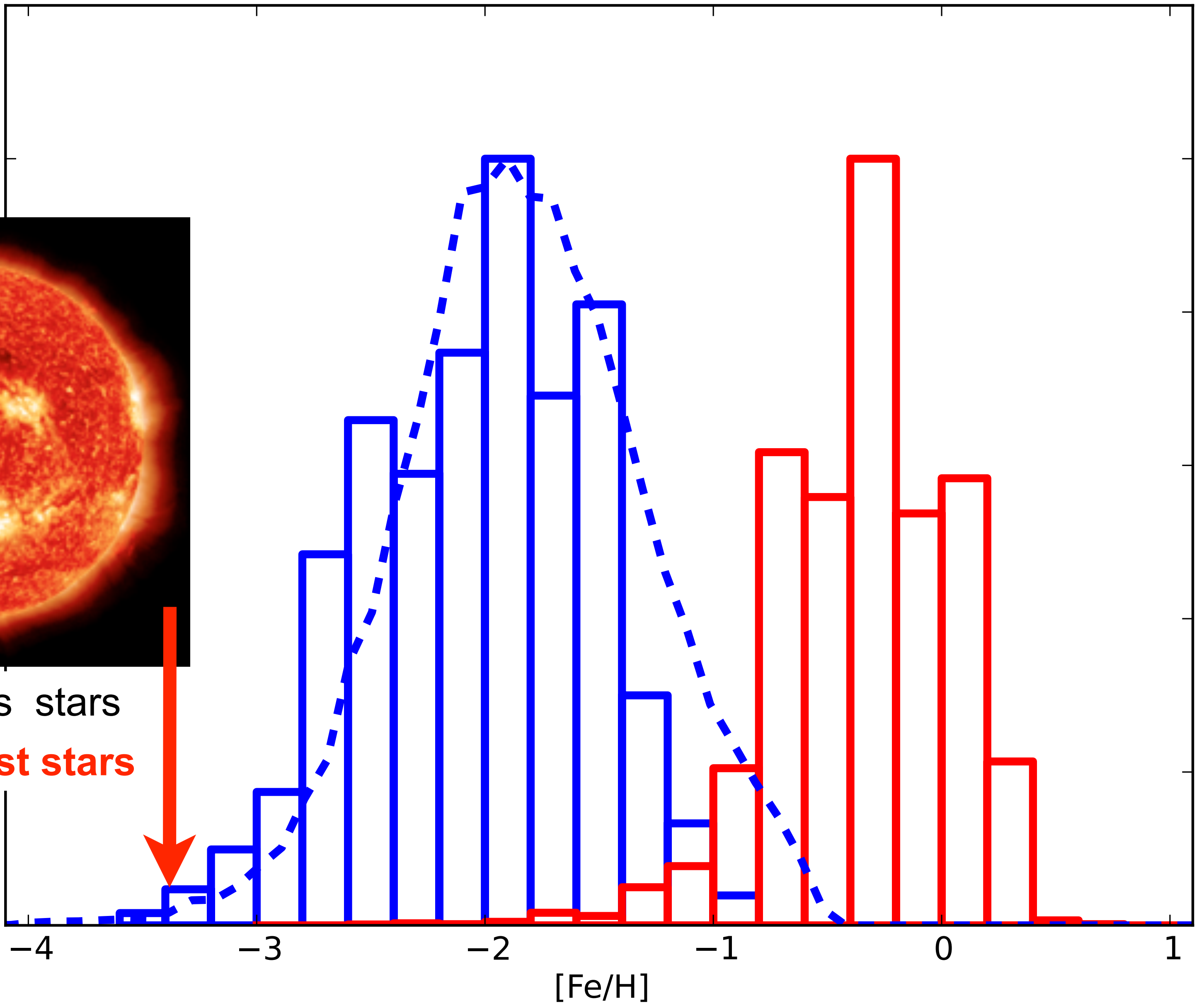
Core collapse Supernova

First polluters in the Universe



Low mass stars

Imprints of the first stars



Comparison between the metallicity distribution function of our halo model and the observed MDF by Li+ (2010) main-sequence turnoff stars in the HESS (Hamburg ESO survey)

Why the neutron capture elements are a special case?

Their nucleosynthesis is really complex.
At least (*! and only in the early Galaxy!*) **two progenitors are needed.**

The observed abundances (see previous talk by Ian) present spread of more than 2 dex for [nc/Fe]. This spread is peculiar of these elements and the simplest idea to solve this problem is that at least one of the progenitors is rare.
Implications by means of a stochastic chemical evolution model

It is not clear at this moment which is the event which produces the largest amount of neutron capture elements, few astrophysical sites present the proper conditions, but still no clear solution is available.
Model results to test different scenarios
Electron **C**apture SNe - **M**agneto**R**otational**D**riven SN - **N**eutron **S**tar mergers

In this context, **(stochastic) chemical evolution models** are able to provide important **constraints on the rate** (/ amount of r-process material produced) and on the **timescale** that the r-process events should have to match the observed abundance in halo stars *(and possibly we can extend the comparison to the dwarf galaxies and the bulge of the Milky Way).*

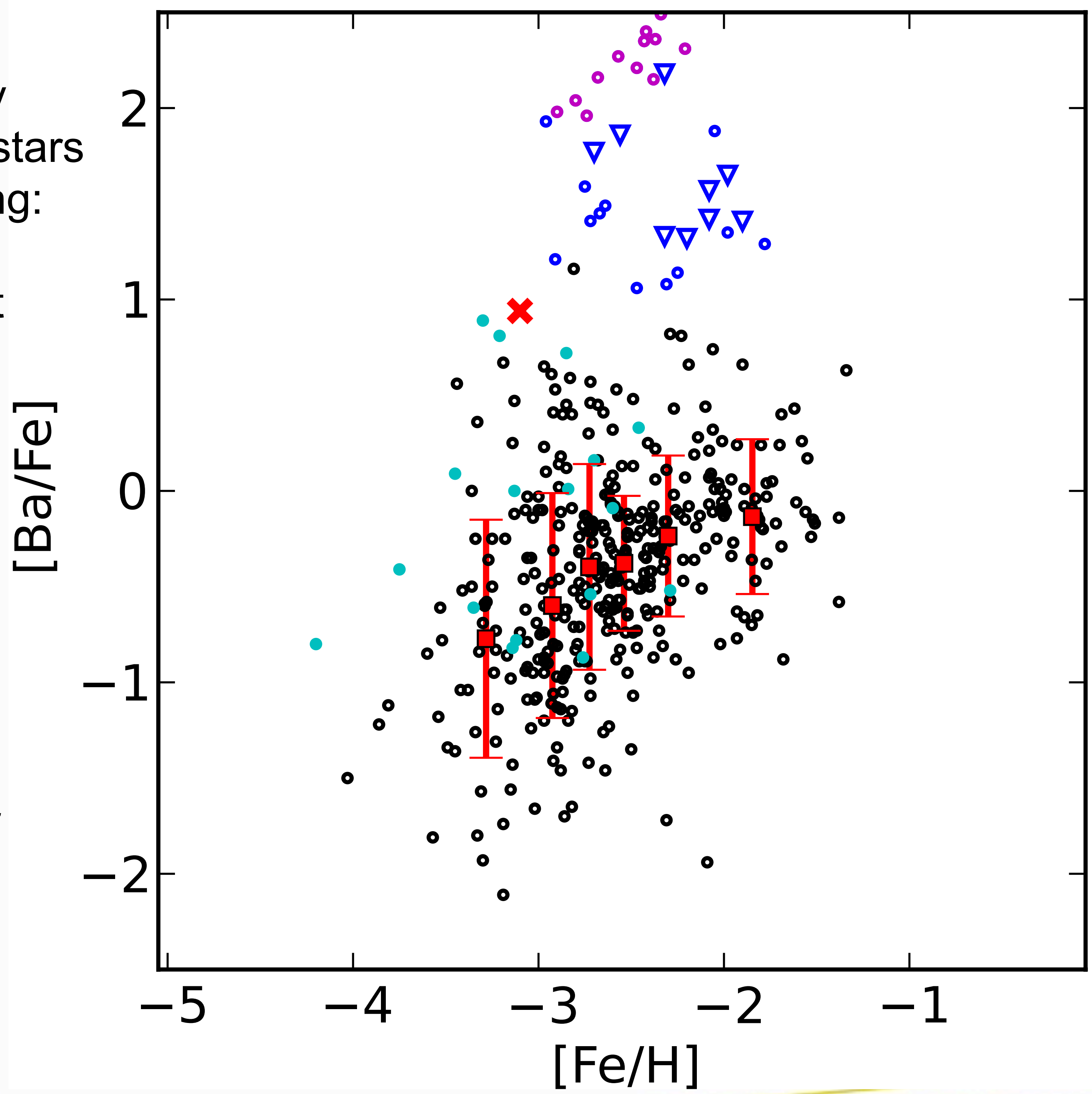
Production of the (main) r-process: an empirical constraint

For Ba the contribution by other process in massive stars is expected to be not strong:

weak r-process should not produce Ba.

s-process enrichment by low mass stars, negligible in the halo (at least for [Fe/H]<-2.5)

We will present how the production in fast rotating massive stars is important but it does not affect this approximation.



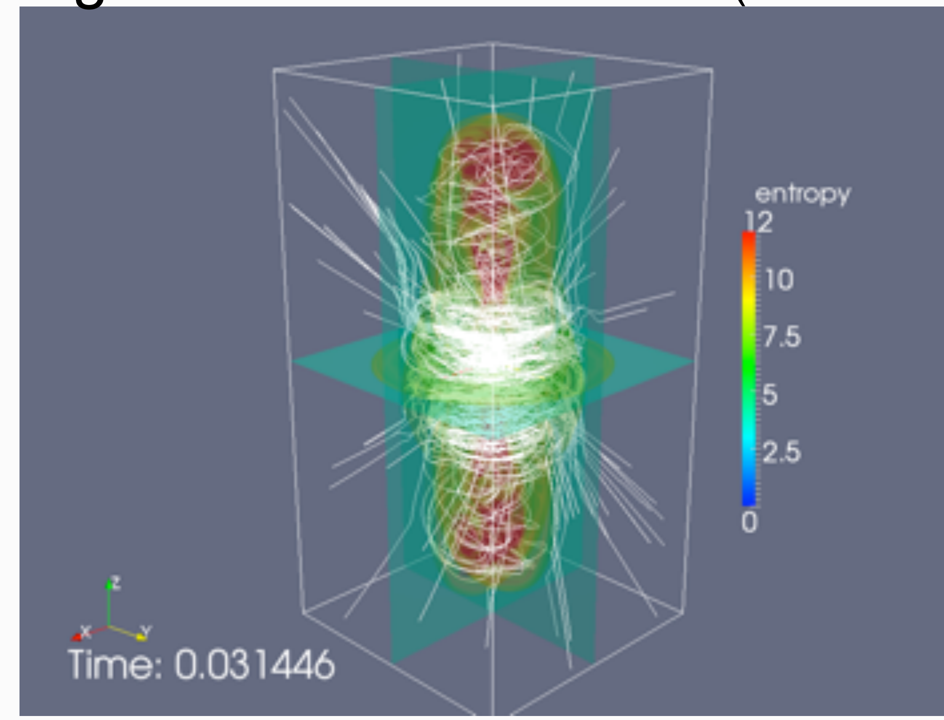
CEMP-s likely formed through binary process not taken in to account here

data collected by Frebel '10

halo stars:
normal
cemp-s
cemp-no

Electron Capture SNe (Wanajo+11)

Magnetorotat. driven SNe (Winteler+12)

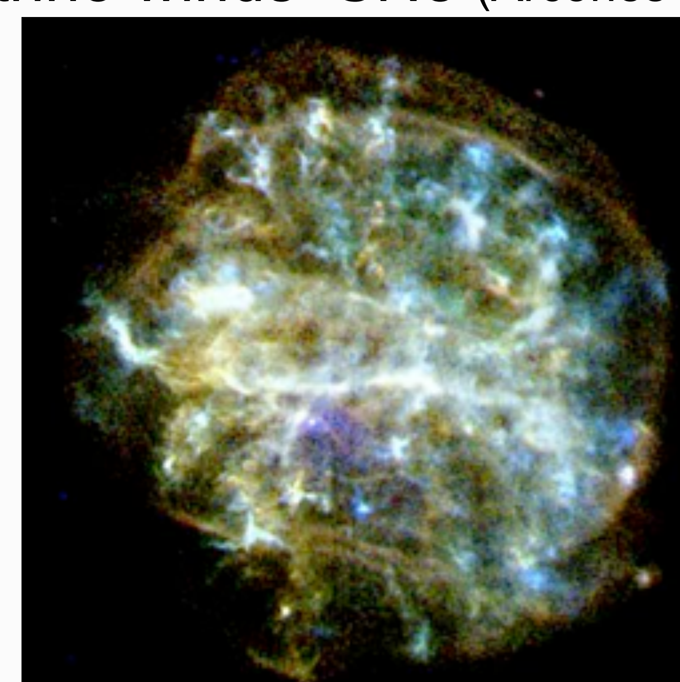


Site(s) of the r-process?

Neutron star mergers (Rosswog+13)

other possible sites?

Neutrino winds SNe (Arcones+07)



Electron Capture SNe

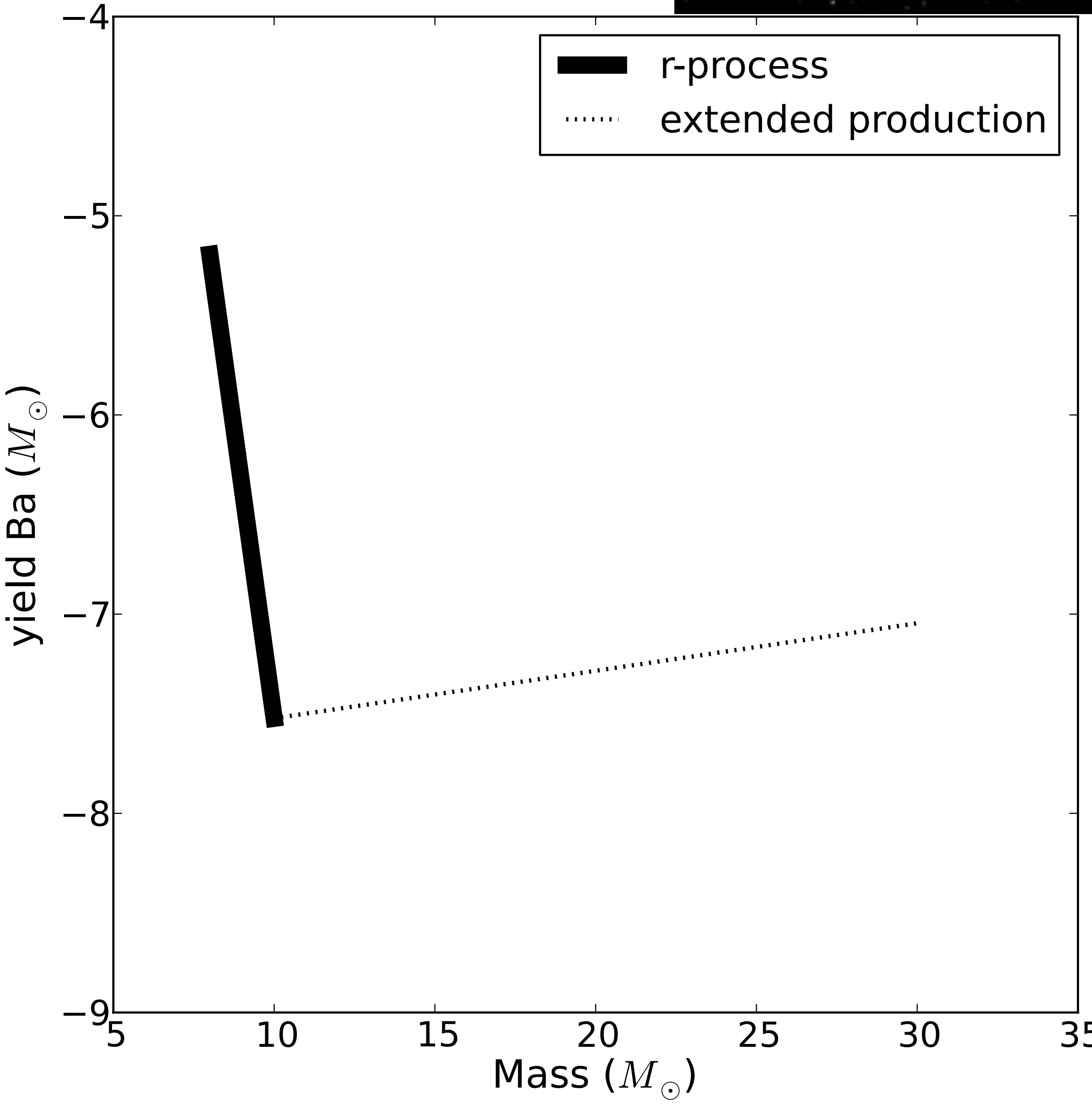
(Wanajo+11)

In this scenario, the rate is already set since they are produce only in a narrow range of masses from 8 to 10Msun. We just have to compute the yields necessary to fit the data.

Theoretical predictions do not confirm the production of Ba and Eu (Wanajo+ 2011).

Extended production needed to explain the [Ba/Fe] poor EMP stars

These values compatible to recent results by Li+2014



Cescutti, Chiappini, Hirschi, Meynet e Frischknecht 2013

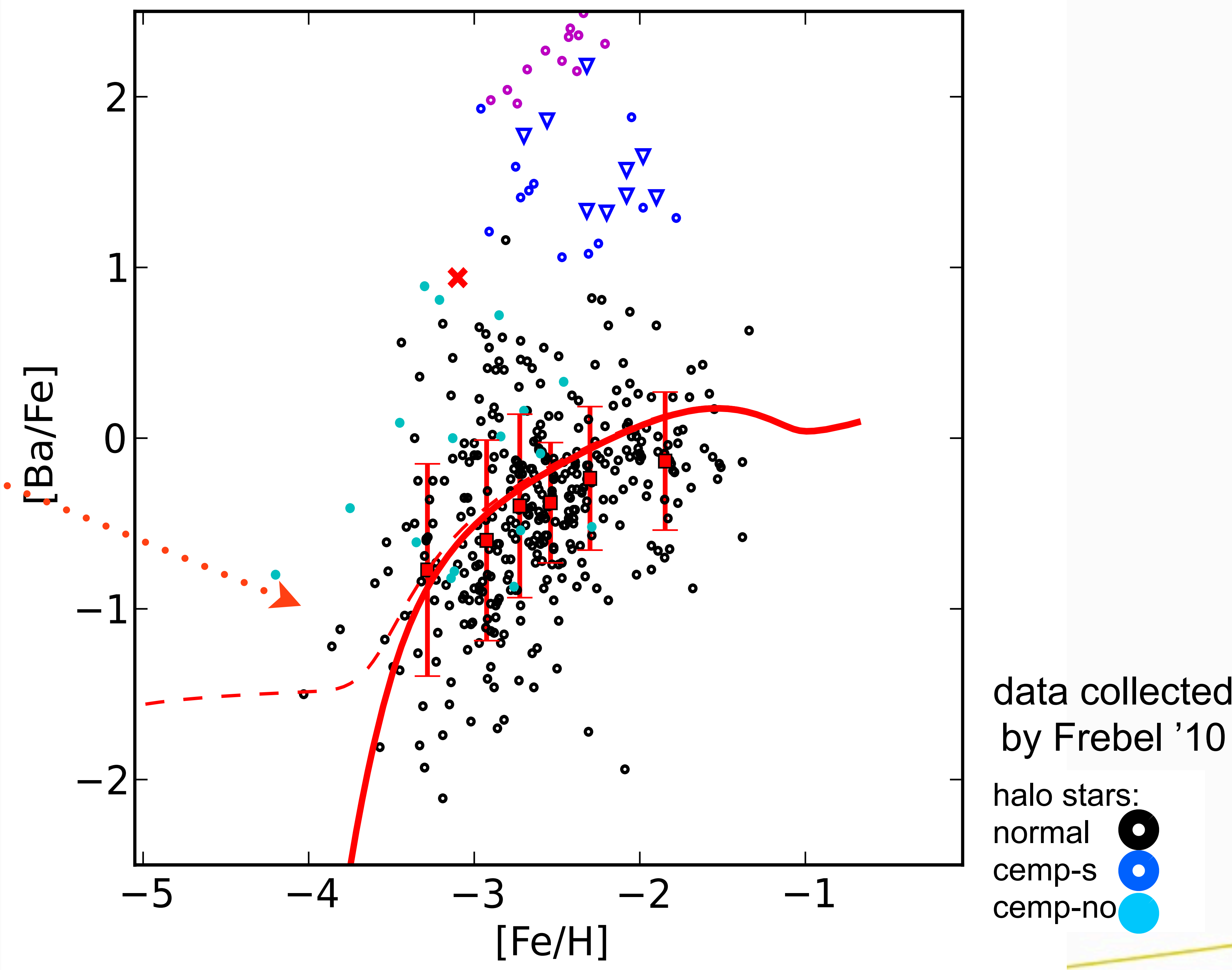
Results with an standard model

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

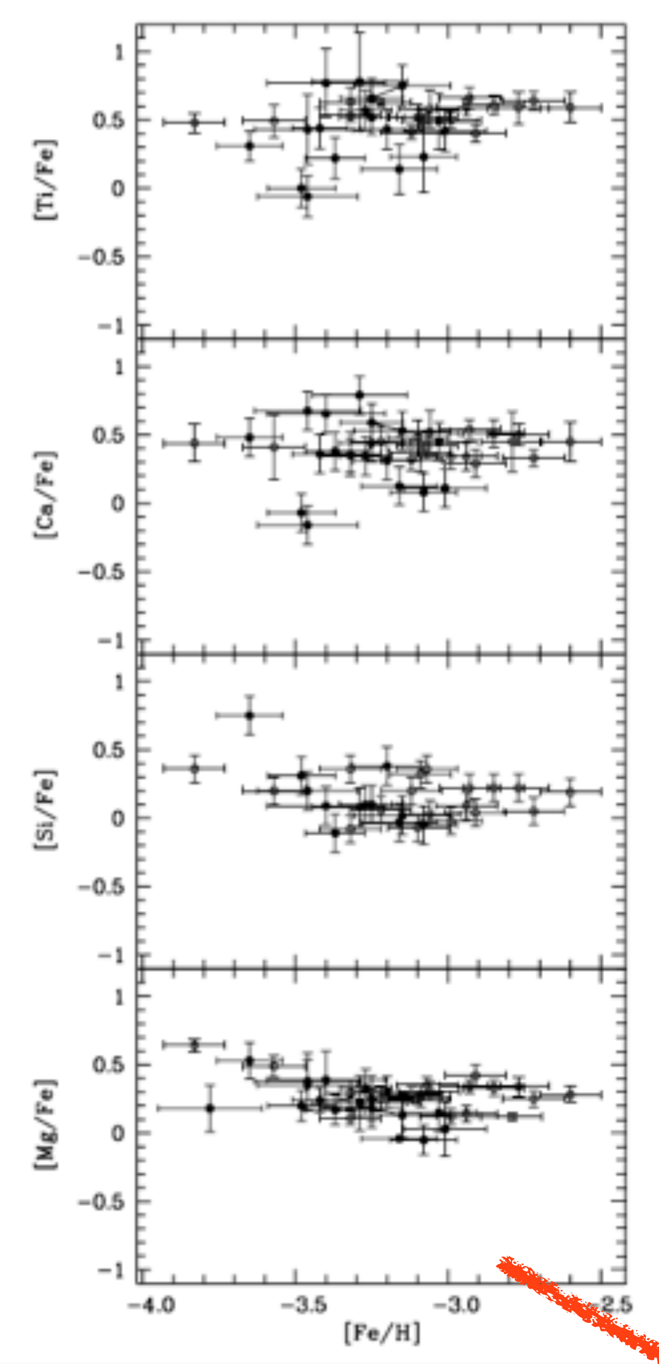
Note that the extended production may help here

BUT

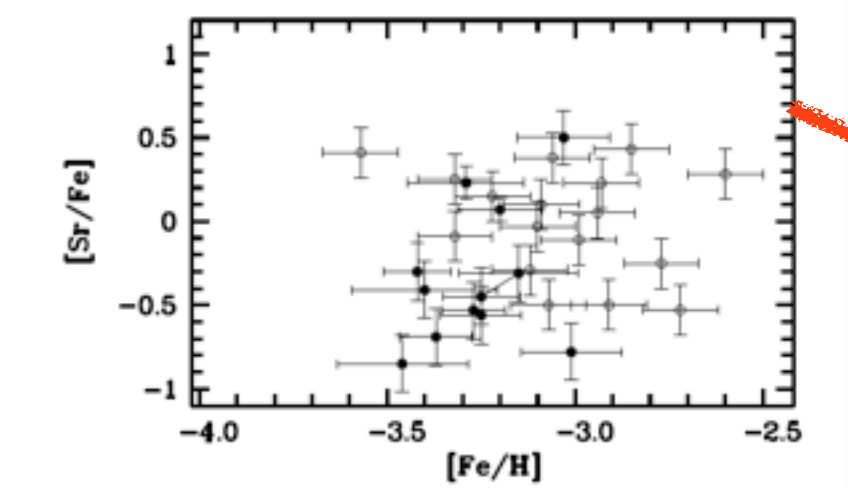
This homogenous model cannot be used to have an insight of the spread observed in the halo stars, only the trend is recovered.



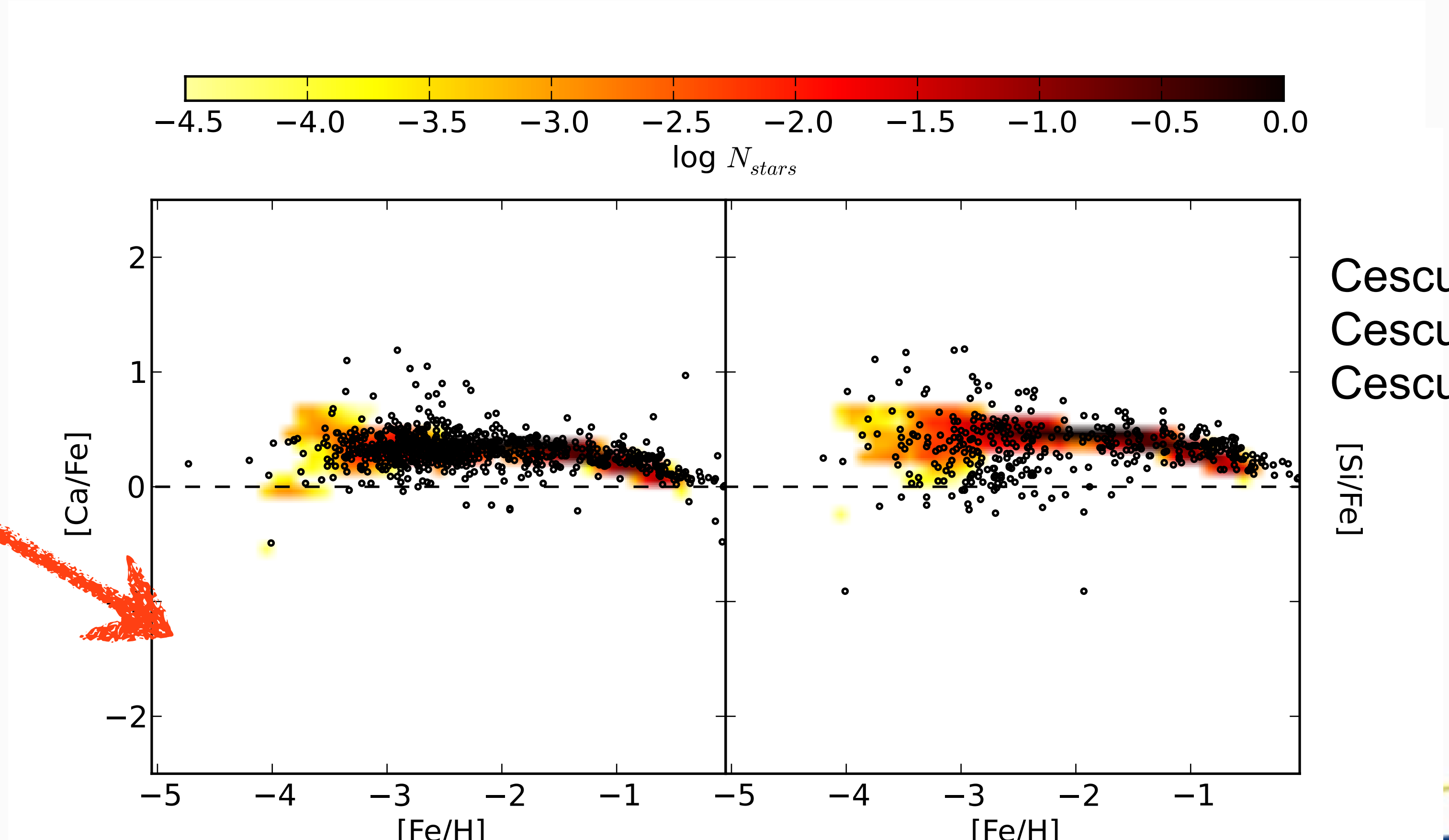
Stochastic chemical evolution models



Problem:
Neutron capture elements present a spread alpha elements do not



Solution:
The volumes in which the ISM is well mixed are discrete. In each volume at low regime of star formation the IMF is not fully sampled.
This can promote spread among different volumes if nucleosynthesis of the element is strongly dependent to the mass.



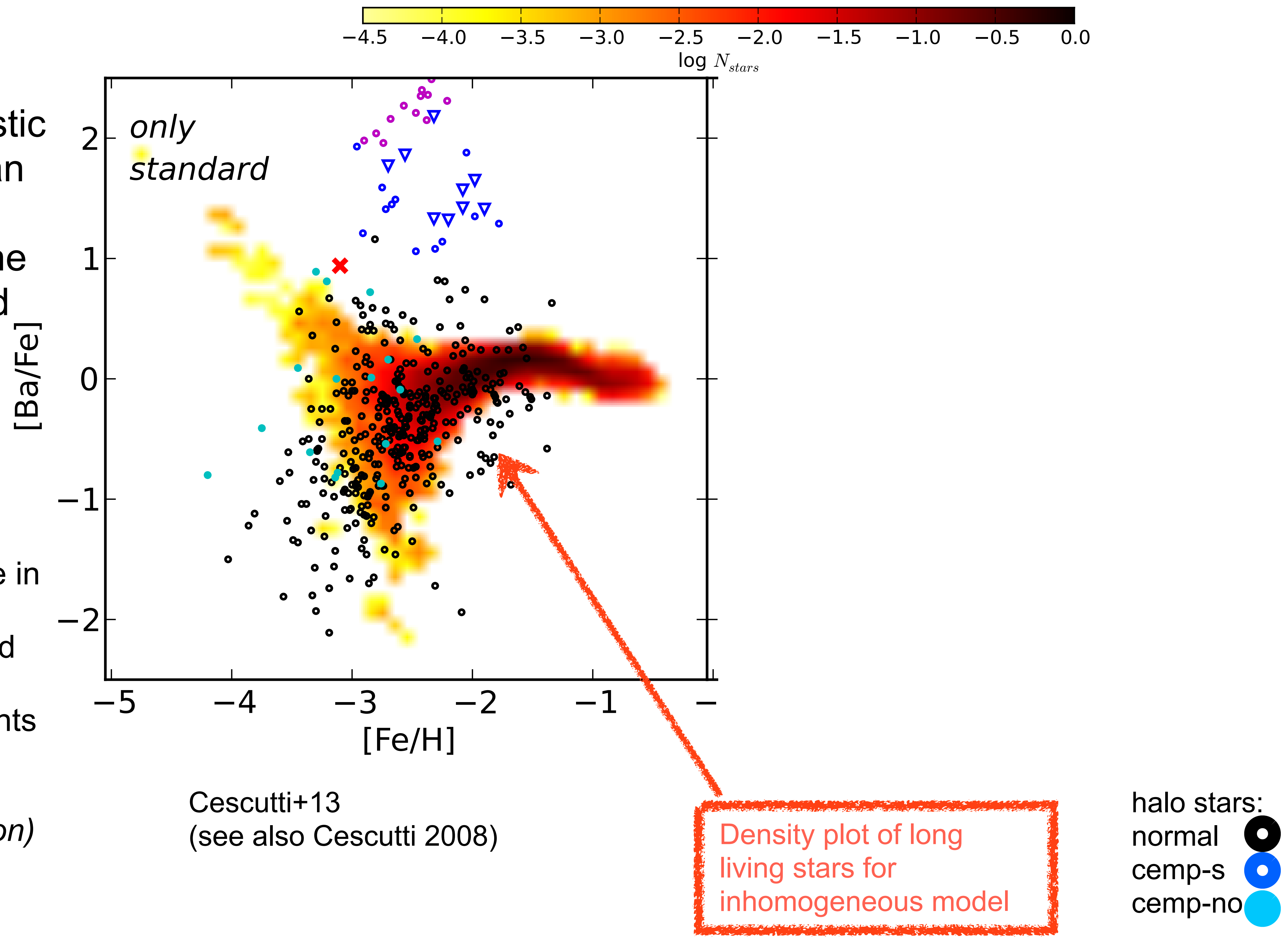
Cescutti & Chiappini 2014
Cescutti et al. 2013
Cescutti 2008

Stochastic model results

With the stochastic CE model we can have an explanation of the spread observed in Ba (and in nc elements).

There is a signature in Ba that there is the need of an extended and low productive source of nc elements

(and s-process in spinstars is an option)



Cescutti+13
(see also Cescutti 2008)

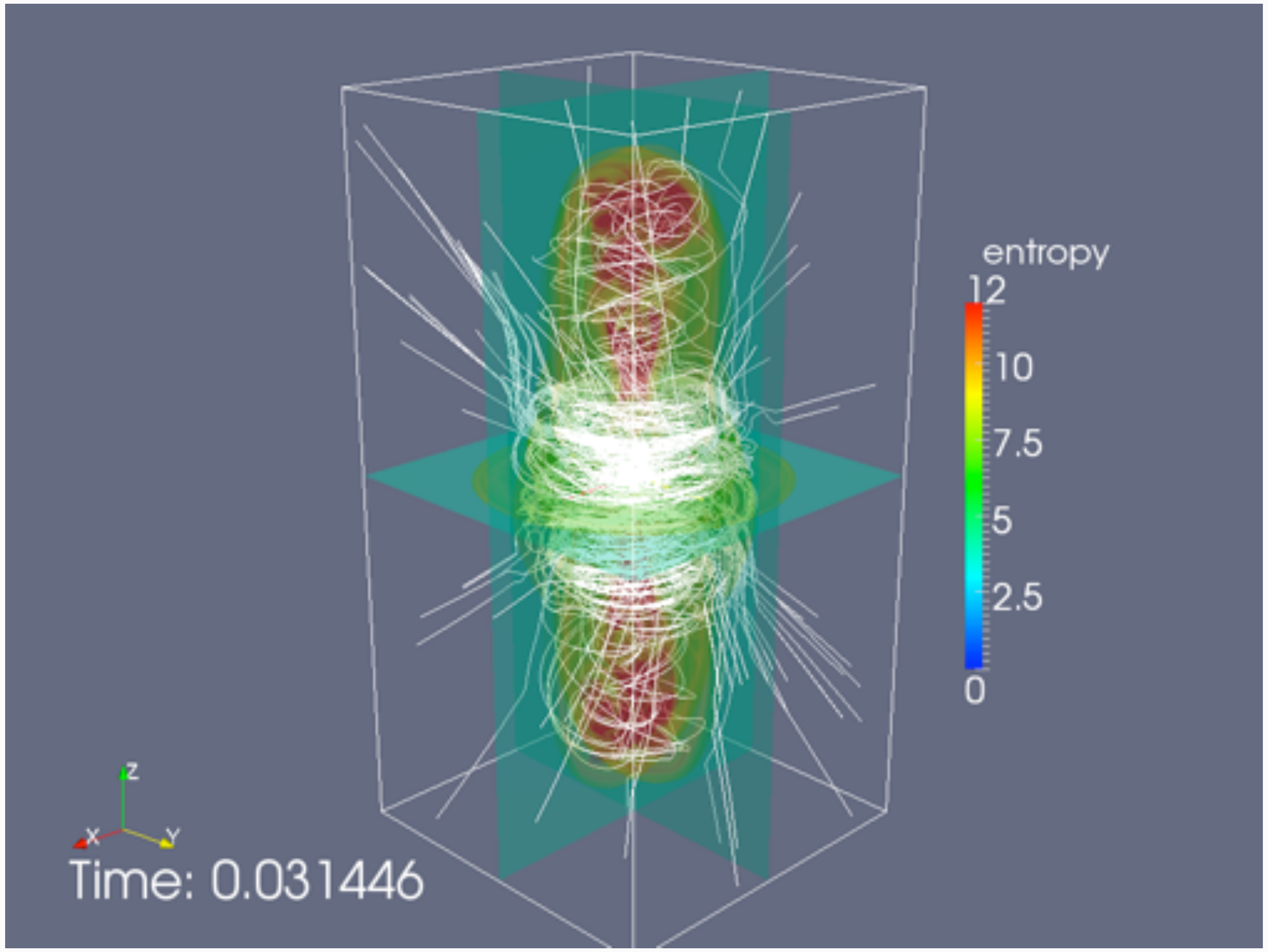
Magneto Rotationally Driven SN scenario (MRD)

(Winteler+12)

The progenitors of MRD SNe are believed to be rare: only a small percentage of the massive stars (~1-5%)

We have results for 5% and for an higher value (10%).

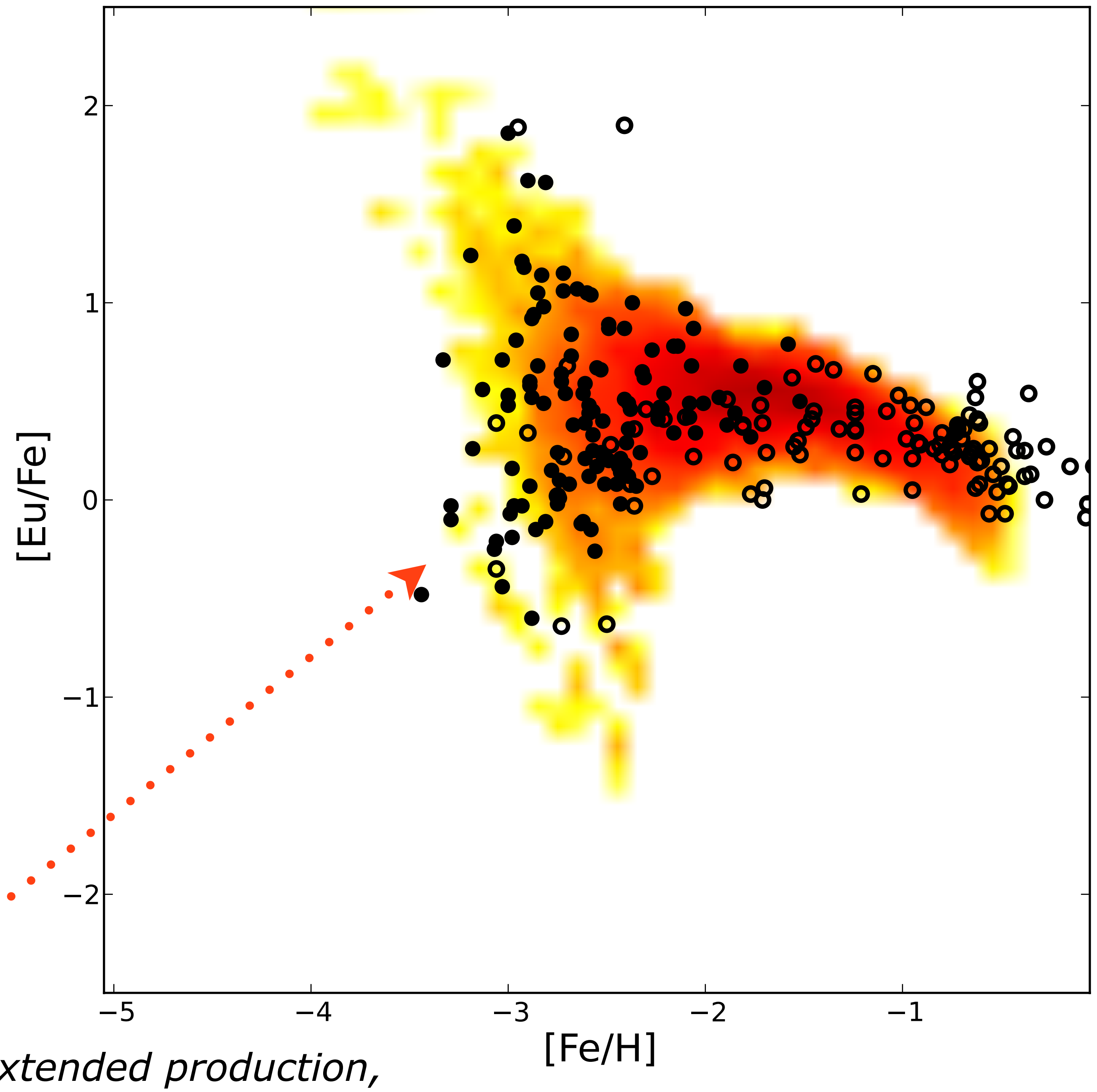
This percentage is not well constrained, in particular for the early Universe.



Magneto Rotationally Driven SN scenario (MRD) 10%

In the best model shown here the amount of r-process in each event is roughly the same as the max (8Msun) in the previous model
(scaled to Eu!)

The percentage of event in the massive stars is higher than expected (at least at the solar metallicity), but it is expected to increase toward the metal poor regime (Woosley and Heger 2006)



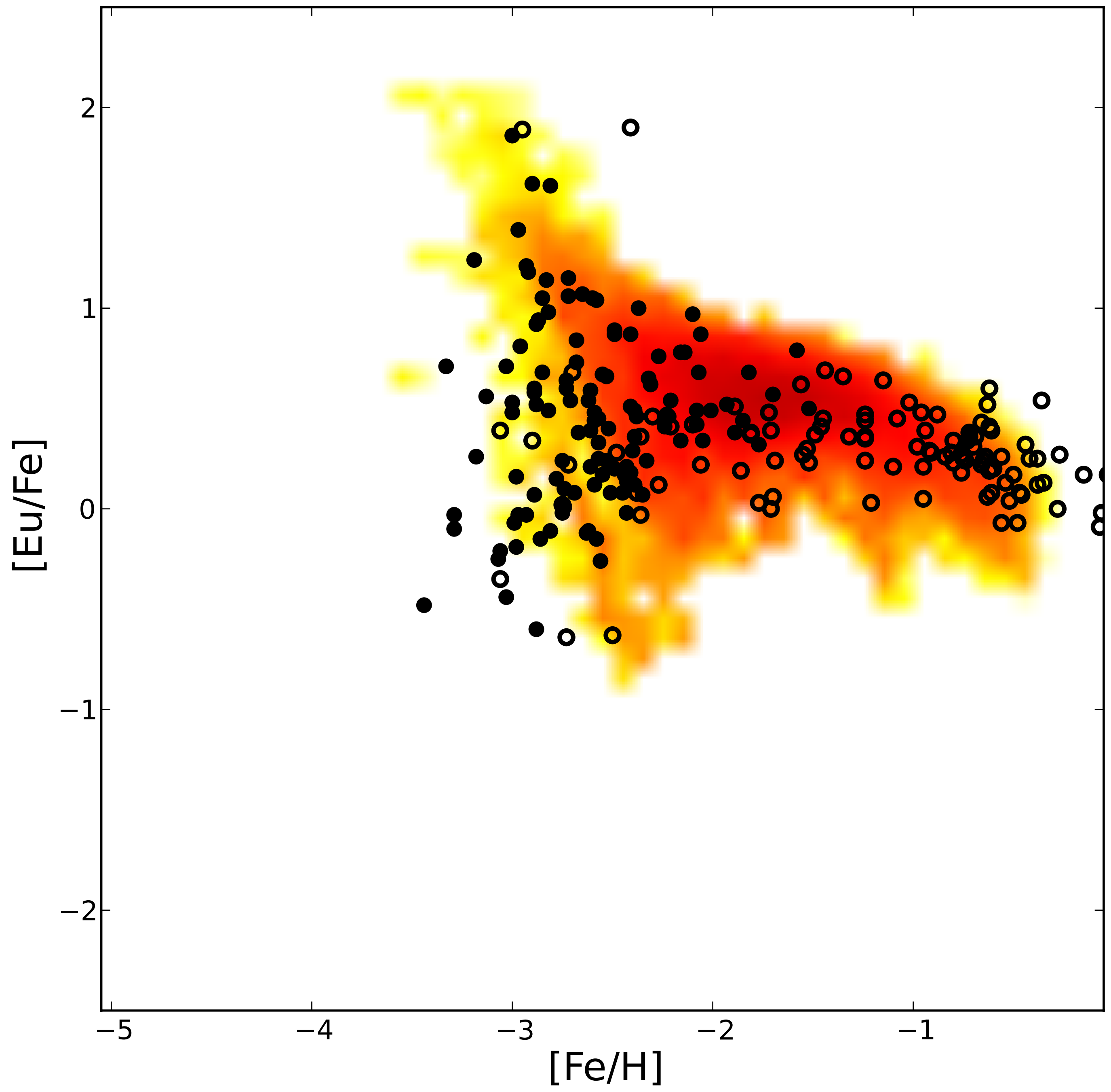
No need for Eu of an extended production, just upper limit-
really Eu low or just observational limits?

Magneto Rotationally Driven SN scenario (MRD) 5%

The amount of a single event is increased to match again the distribution.

The model is in reasonable agreement but already at this stage present a too high spread in the intermediate metallicity.

Other reason to discard this model are connected with the [Sr/Ba] distribution in halo stars.



Neutron stars mergers

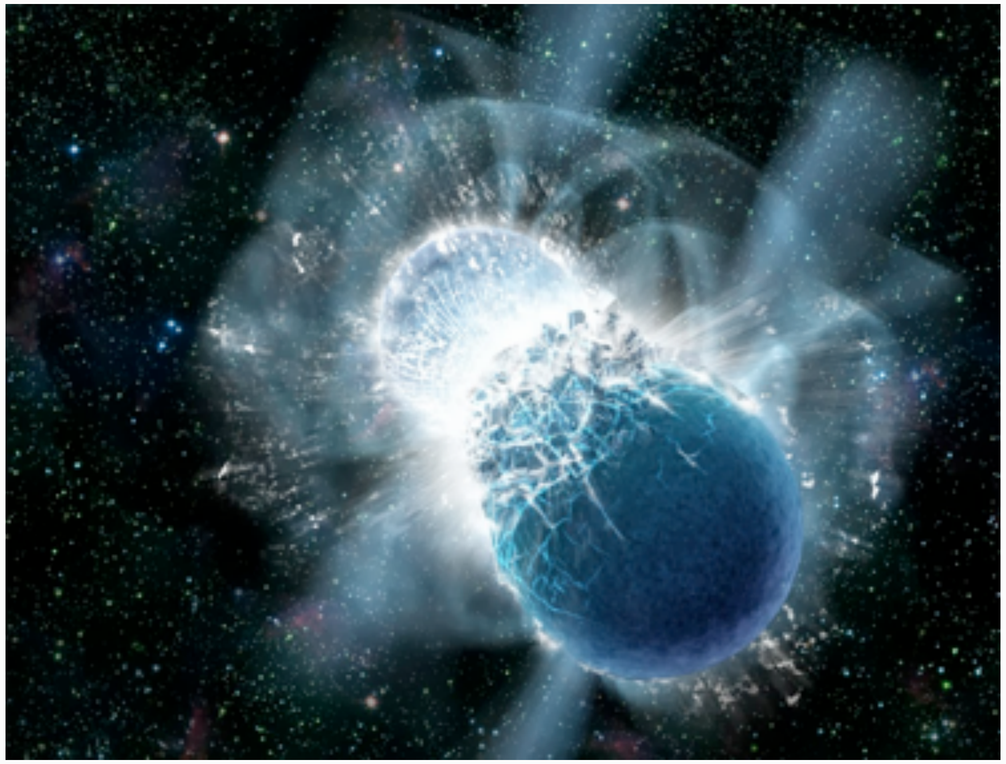
Also this progenitor are rare, probably the rarest: only few percent of the massive stars are formed in binary system which can produce a NS merger.

Again this percentage is not constrained at all the metallicities, the rate is constrained just at the present time.

The key difference between NS merger and MRD SN is the delay between the formation of the binary system of neutron stars and the merging event.

We investigate delay of 1, 10 and 100Myr.

Neutron star mergers (Rosswog+13)



Neutron star mergers

delay for the merging 1Myr

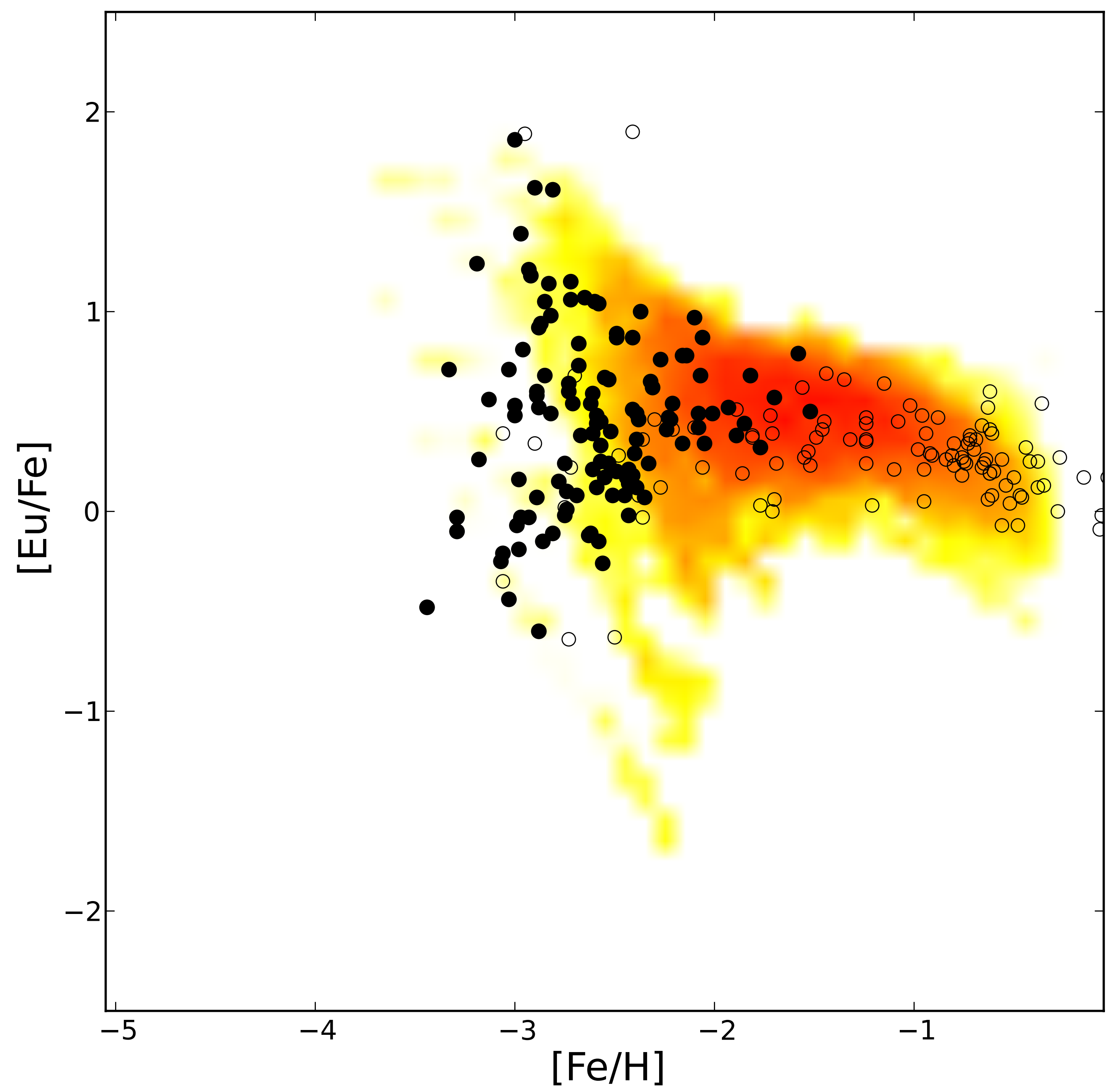
PRELIMINARY RESULTS

For these results, 4% of the massive stars are progenitors NS merger which produce r-process material.

The amount of a single event is basically the same as for the MRD scenario with 5%.

Technically the model is really similar and indeed produces a similar spread.

Probably more interesting is the impact of increasing the delay for the merging.



Neutron star mergers

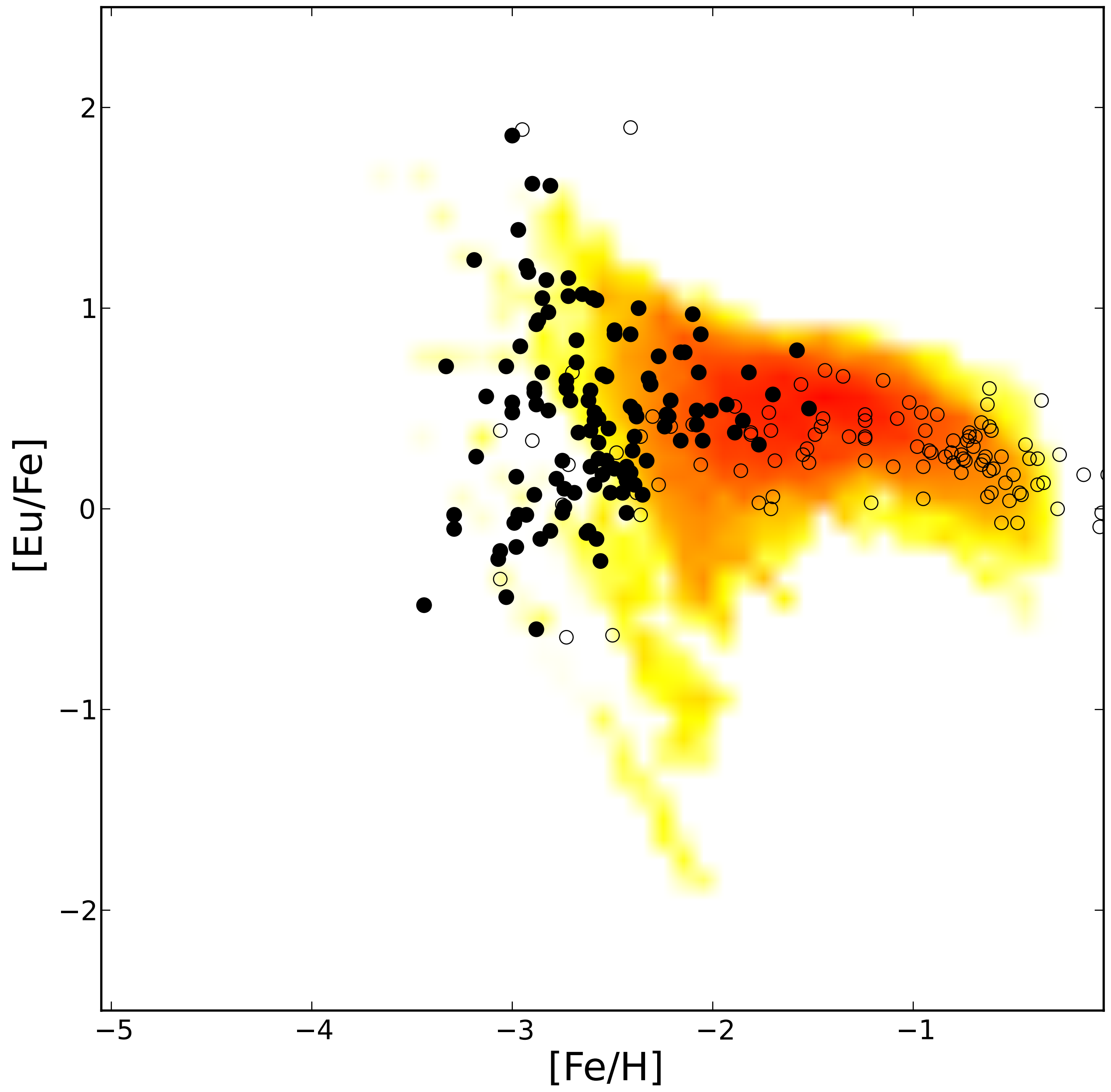
delay for the merging 10 Myr

PRELIMINARY RESULTS

AIP

If we increase the delay up to 10 Myr no strong impact is visible.

The progenitors enrich in a timescale which is still compatible to the a normal SNII timescale.



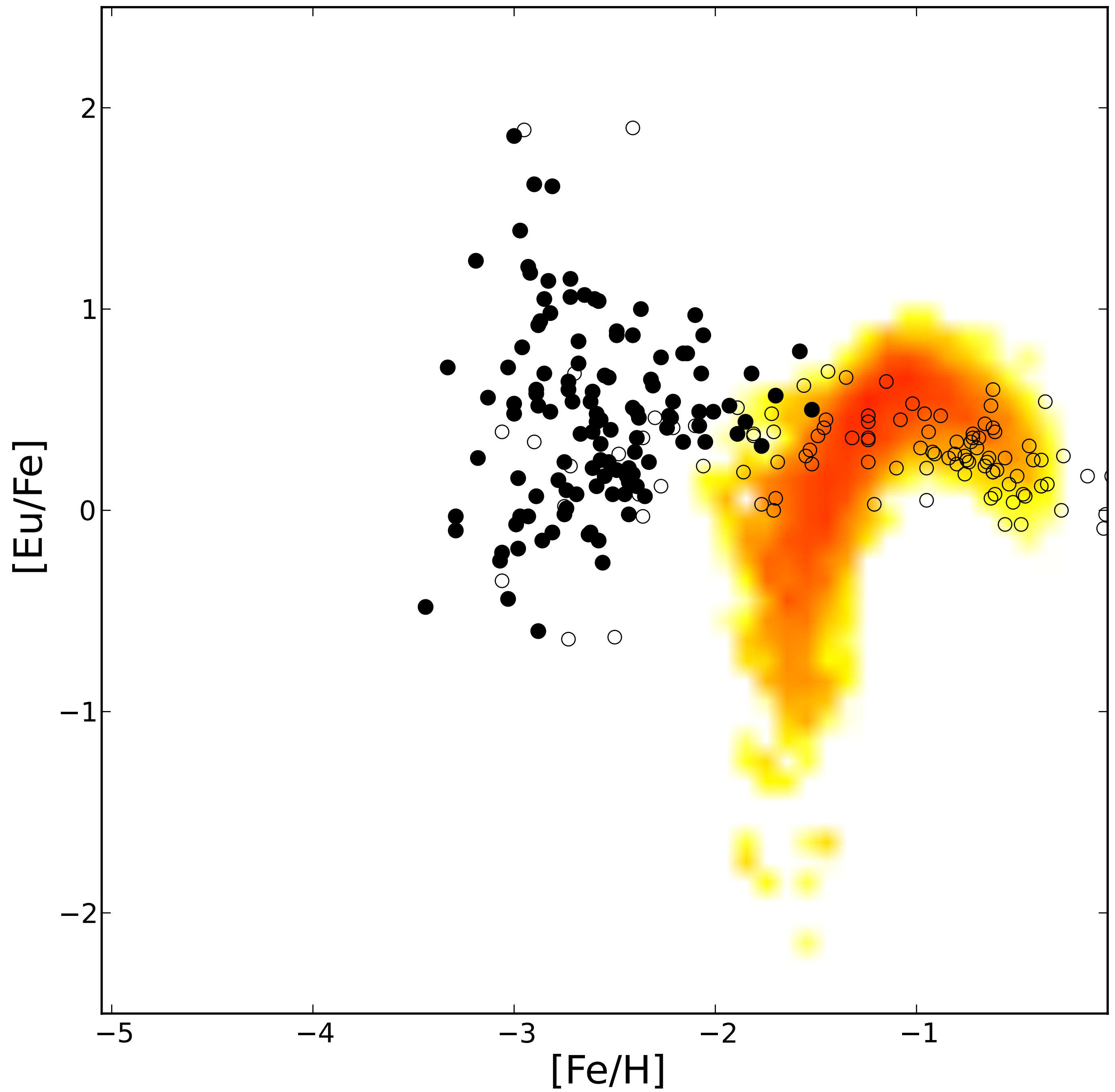
Neutron star mergers

delay for the merging 100Myr
PRELIMINARY RESULTS

For a delay of 100 Myr the model results are not anymore compatible to the observational data.

Therefore from the point of view of the chemical evolution of the Galactic halo, we can conclude that only if most of the NS mergers enriches in timescale <10Myr, the scenario can be supported.

If a distribution of delays is available we can simulate the results.

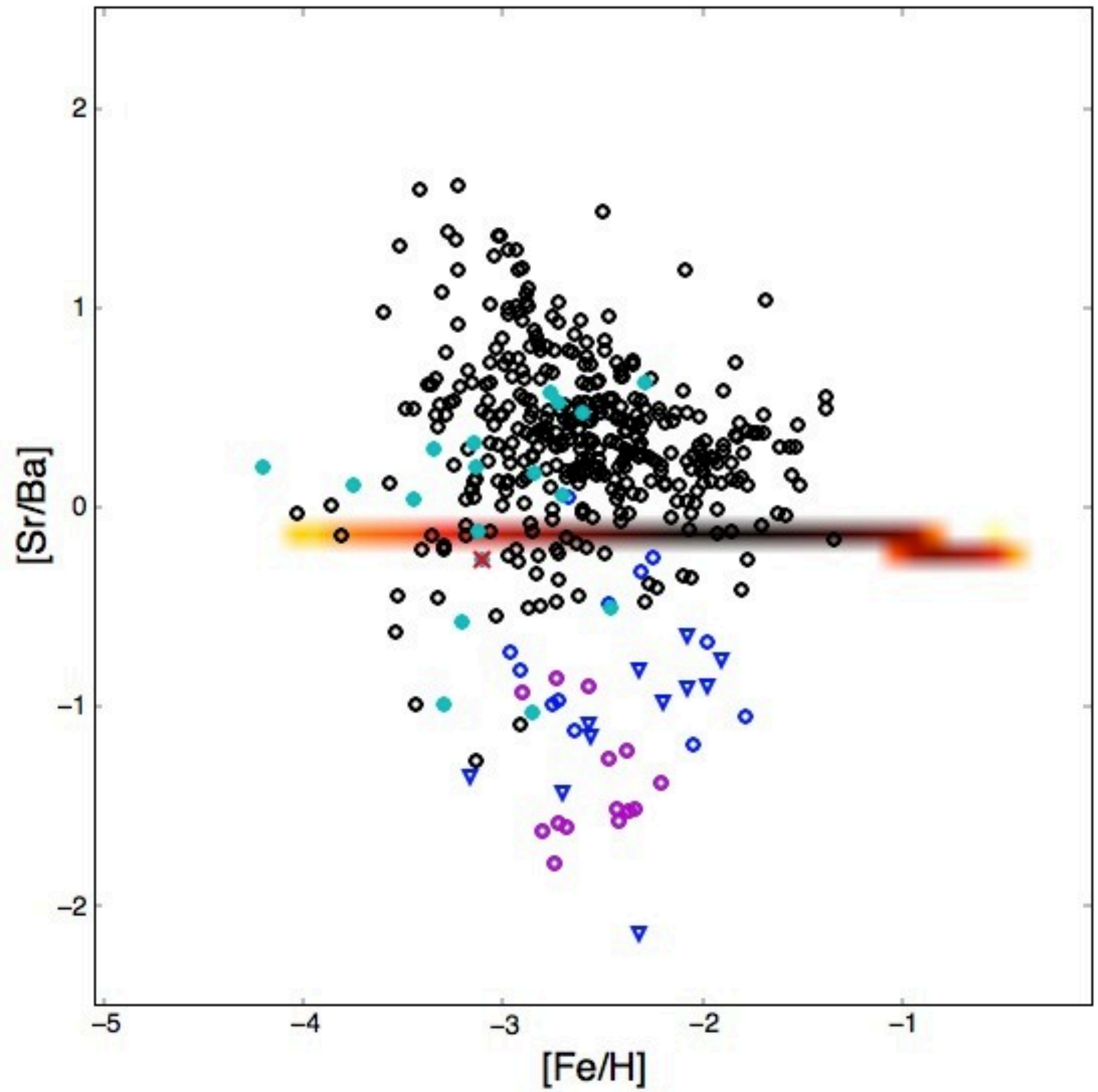


This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the recent astro-ph Shen+2014?

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

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

EC scenario is shown but no differences in th results for the other scenarios, simply the ratio fixed.



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

halo stars:
normal
cemp-s
cemp-no

Neutron capture elements

from Truran 1981 to ~3 years ago

Early Galaxy

	s-process	r-process
site	Low-(intermediate) mass stars	Massive stars (& NS mergers)
time scale	>300Myr	< 30Myr (excluding NS mergers)
yields	Busso et al. 2001 (*Cristallo+ 2011 Karakas+ 2012)*)	....

AIP

Neutron capture elements

The picture since Chiappini+2011 (Nature)

	s-process	Early Galaxy	r-process
site	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...
time scale	>300Myr	< 30Myr	< 30Myr (excluding NS mergers)
yields	Busso+ 2001	Frischknecht+ 2012	....
	Cristallo+ 2011 *Karakas+ 2012*	*Pignatari+ 2008,* *Limongi yields still unpublished*	

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

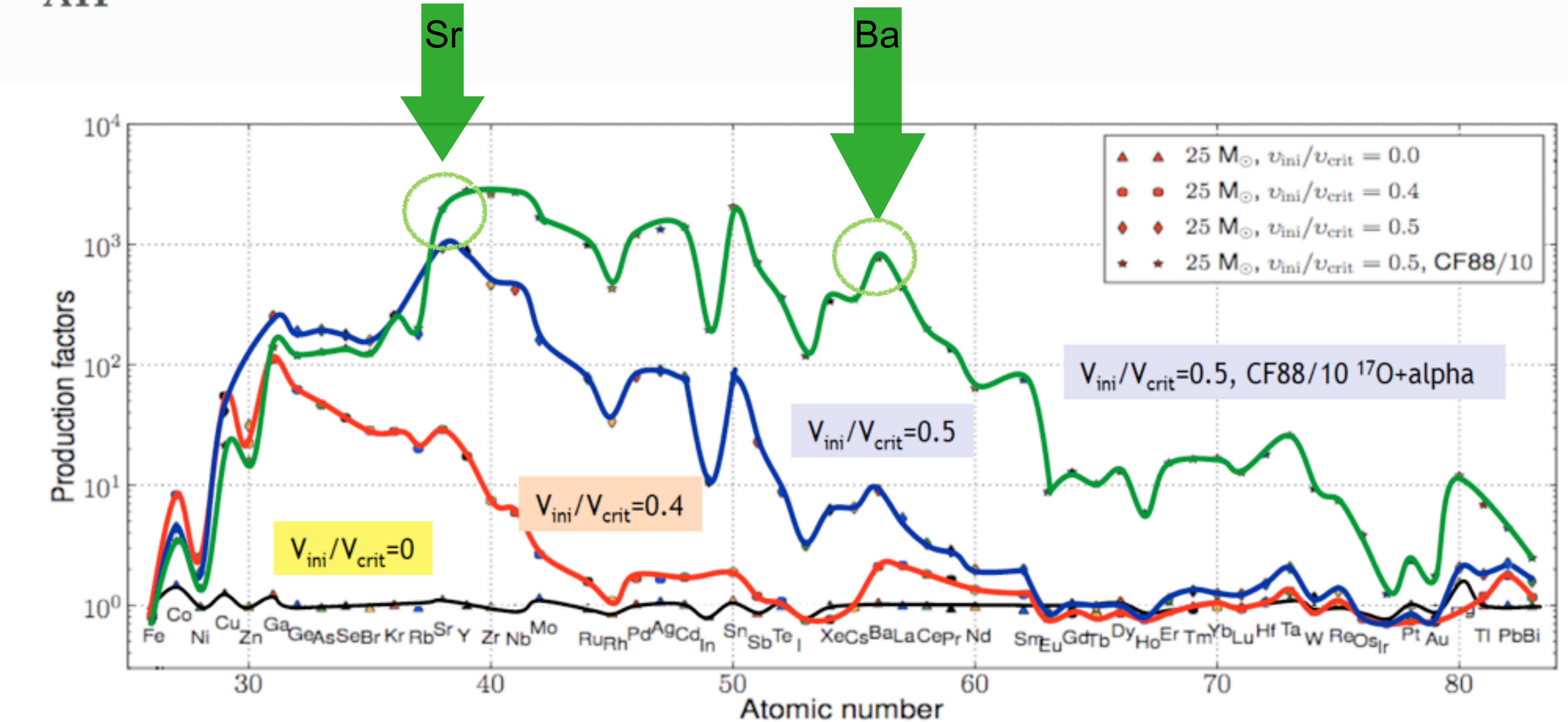
(3) Large amounts of ^{13}C in the early Universe (Chiappini et al. 2008 A&A Letters)

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

5 Early production of neutron capture elements through a 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!

Frischknecht et al. 2012

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

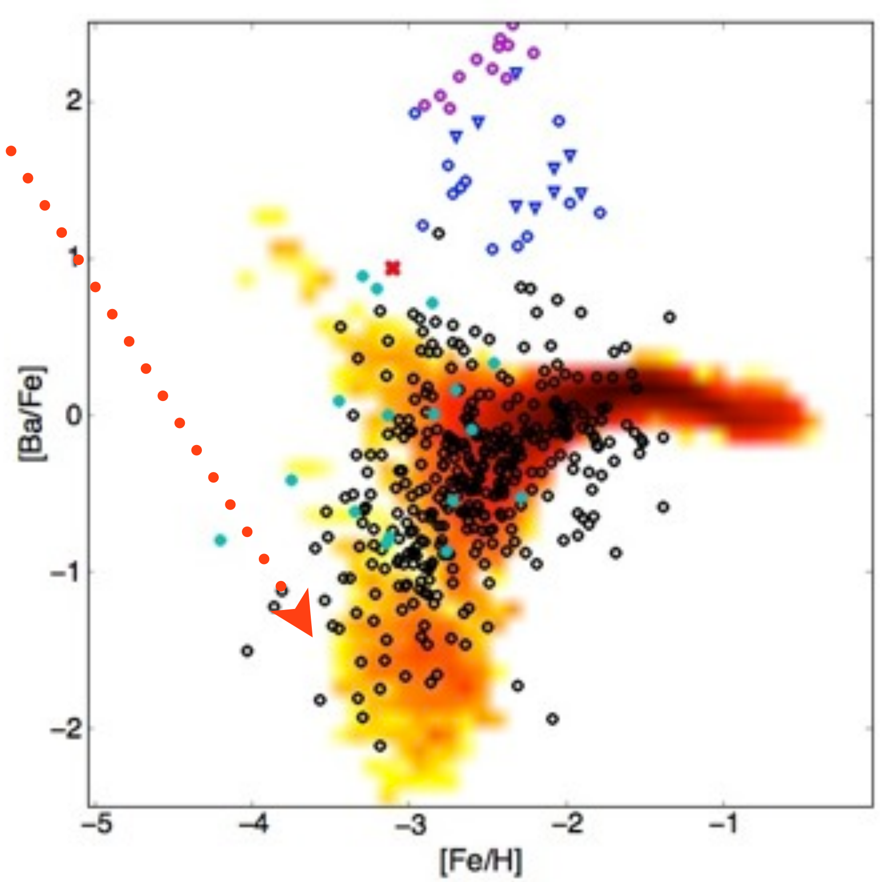
s-process from fast rotators

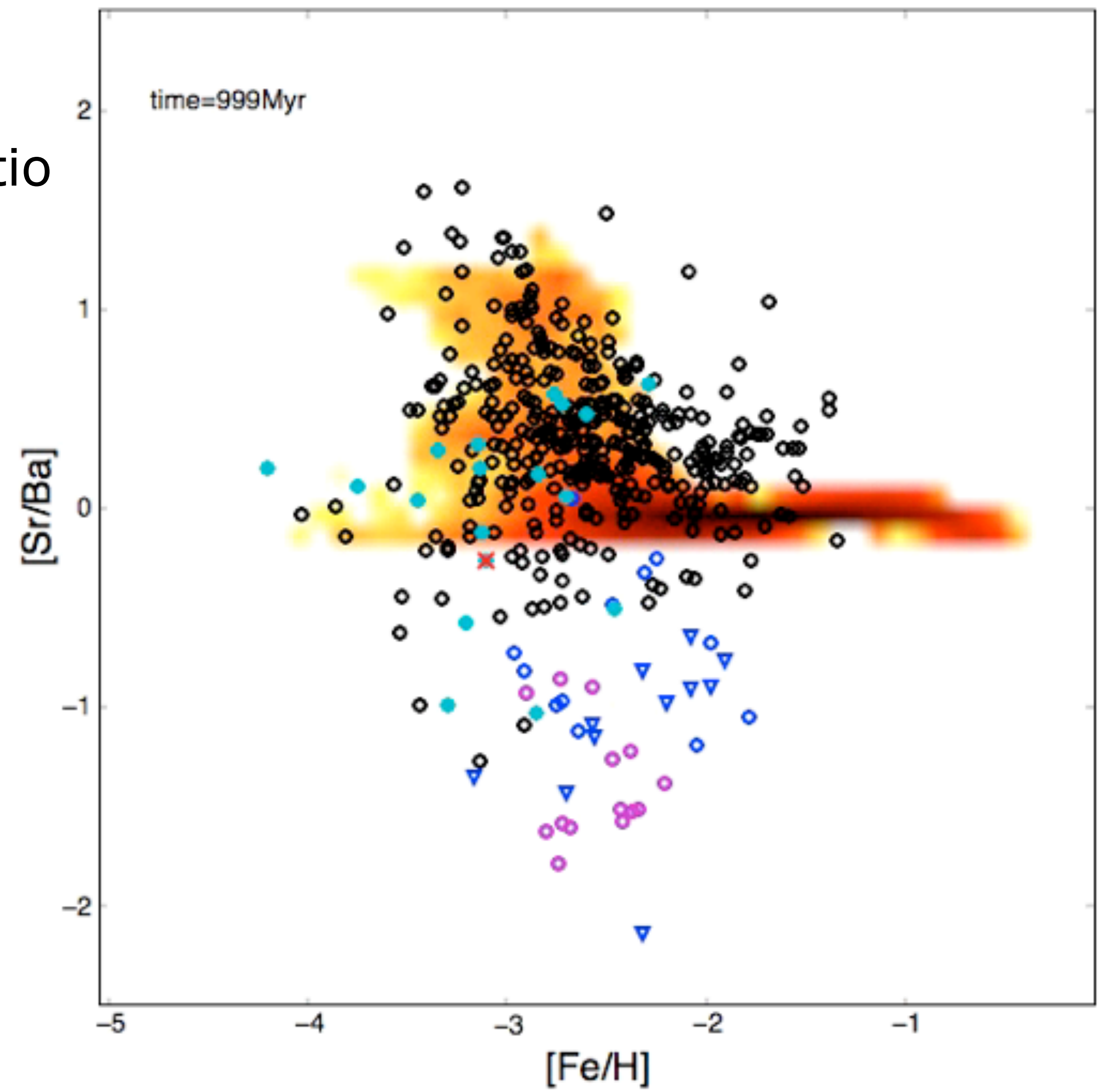
+ r-process site (the 2 productions are decoupled!)

The s-process from fast rotators can provide a solution for the [Sr/Ba] ratio

Here for the EC scenario, but the results is similar for MRD (Cescutti&Chiappini 2014) and NS merger (for a short delay).

It also naturally provides the extended production needed for [Ba/Fe].



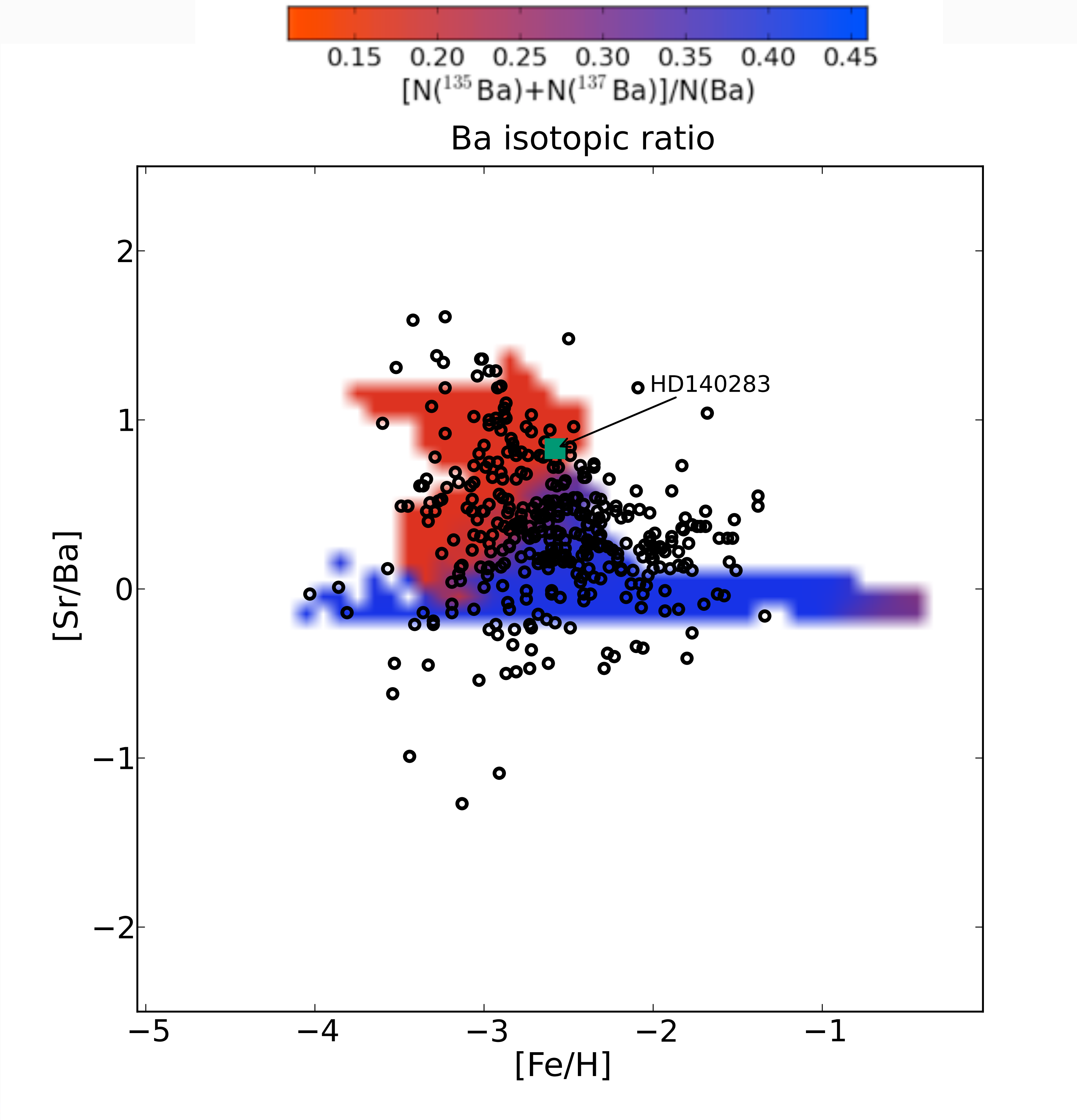


Cescutti, Chiappini, Hirschi, Meynet and Frischknecht (2013)

Isotopic ratio for Ba in halo stars

The spinstars scenario naturally predicts different Ba isotopic ratios in halo star.

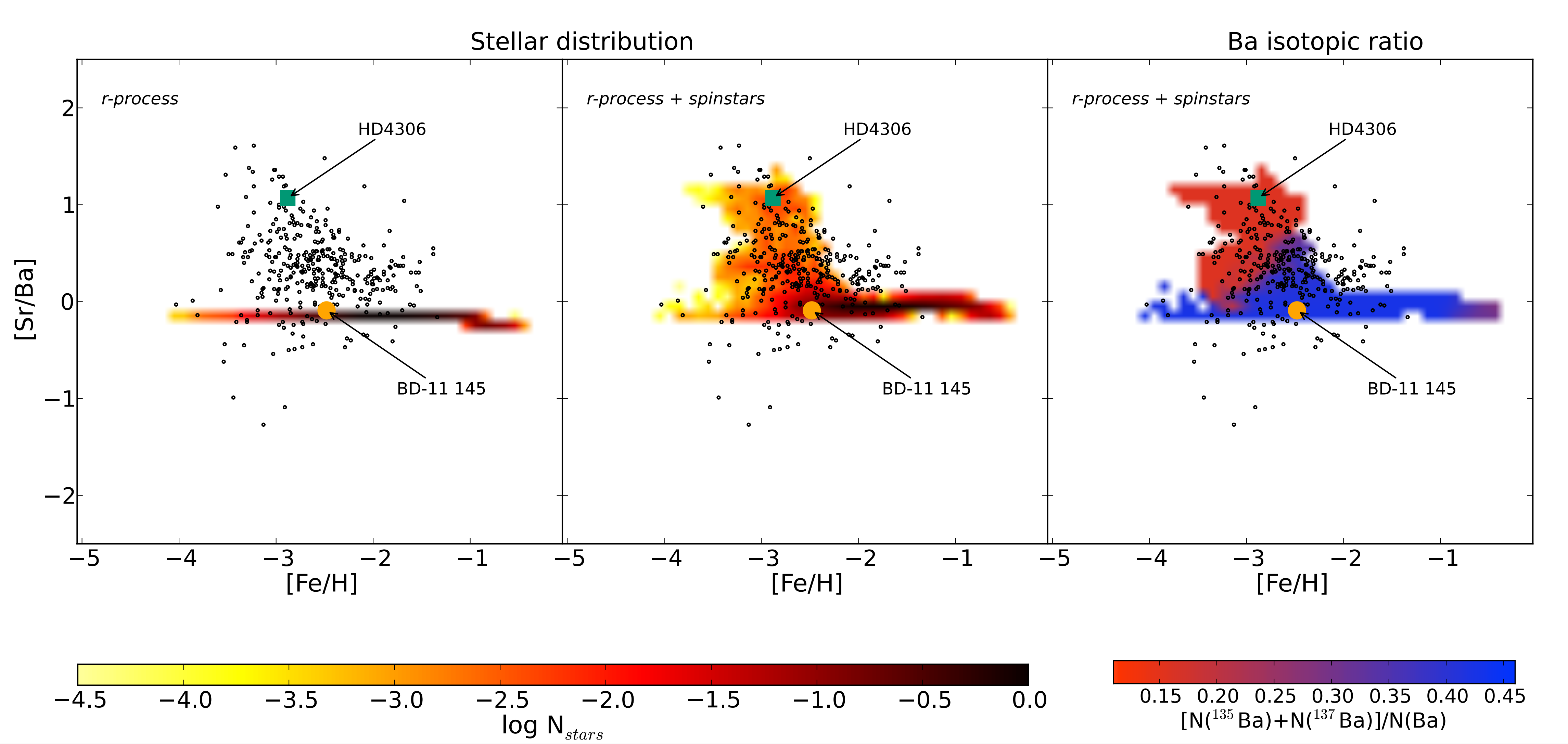
This prediction can be used to test our scenario.



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

Isotopic ratio for Ba in halo stars

We have a proposal which has been recently accepted by ESO to identify this tiny variation of the Ba line due to the different isotopic ratio.
We plan to measure this in two stars with a R>100000 and with a S/N~900 with UVES at VLT. The run is scheduled for the next October.



Conclusions

Chemical evolution models can add important pieces of information in the search for the progenitor of the neutron capture elements in the early Universe.
It is possible to constrain the rates and the timescales (this cannot be done just by direct comparison to the observational data).

At the present time, scenarios with a short timescale and rare (~<10% of SNII rate) are the most promising. The amount for each event is about 0.1-1 10^{-5} Msun in Eu (~10 times for Ba). MRD SN can be an option, NS mergers too if a short timescale (<10-30 Myr) is assumed.

(Fast) rotation in massive stars in the Early Galaxy promotes an s-process production. The impact of this production should be considered: it is a possible explanation for the [Sr/Ba] (and in general [ls/hs]) spread.
This theoretical scenario can be tested by measuring the hyperfine splitting of Ba line at 455nm (and we hope to have this measurement soon).