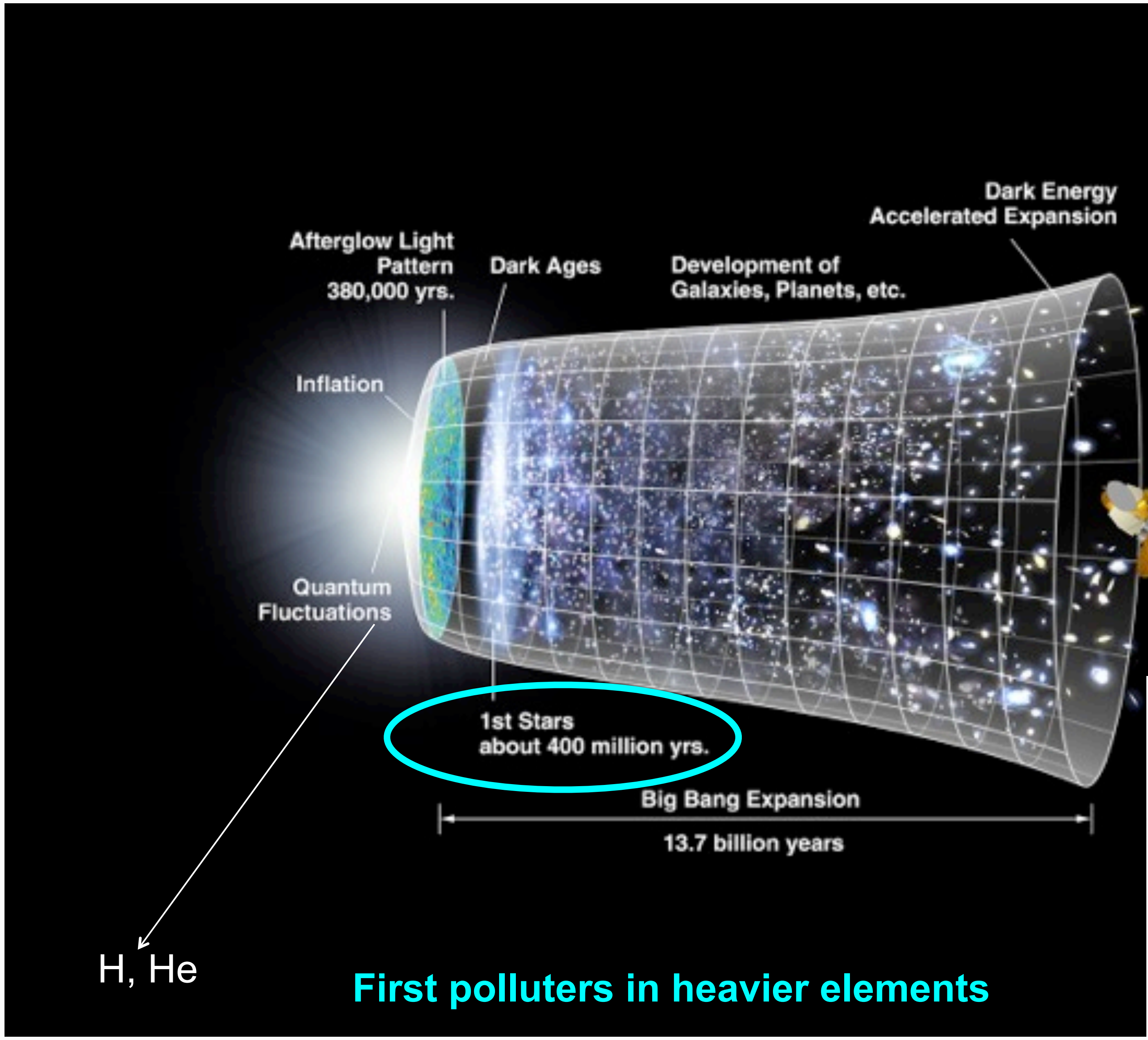
Spinstars in the Early Universe: an s-process signature in the oldest Galactic stars?

Gabriele Cescutti, Cristina Chiappini

Urs Frischknecht, Raphael Hirschi and Georges Meynet

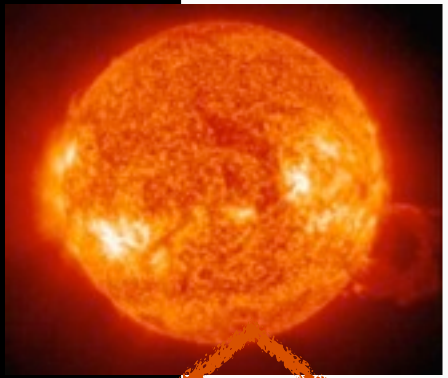
The Nature of the First Stars

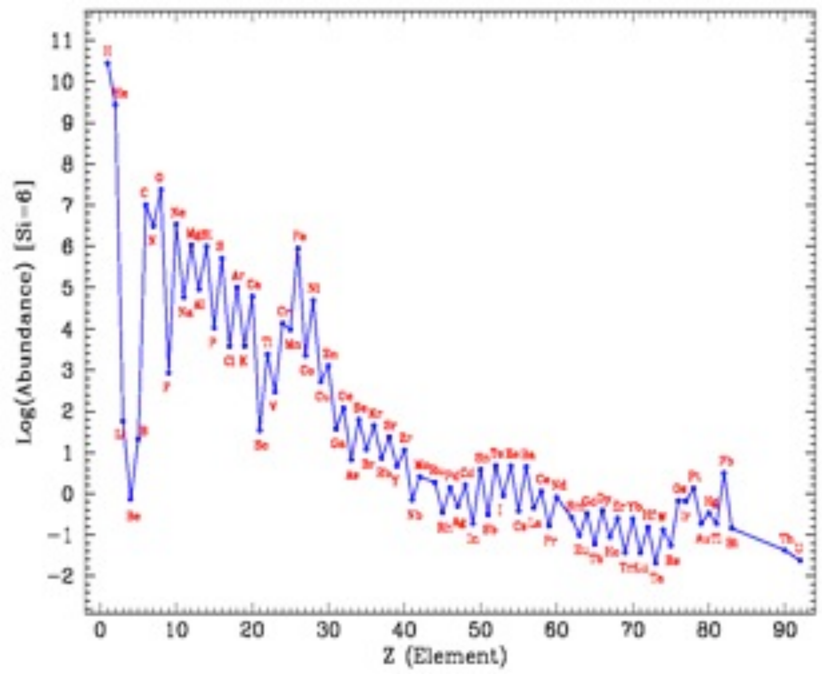
Chemical enrichment of the Early Universe



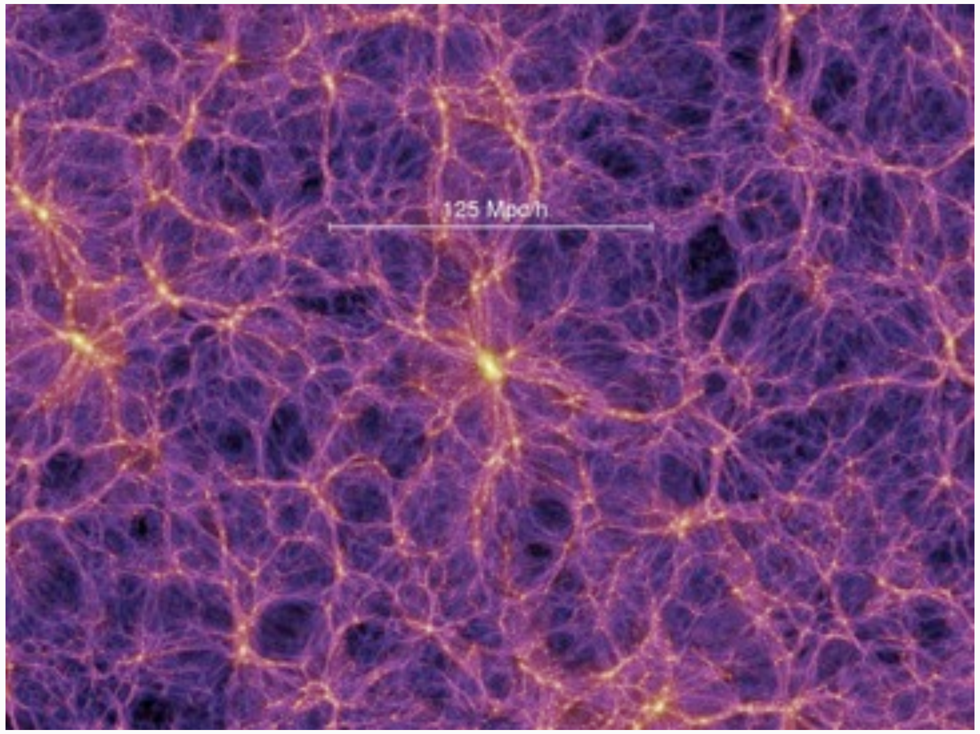
H, He

First polluters in heavier elements



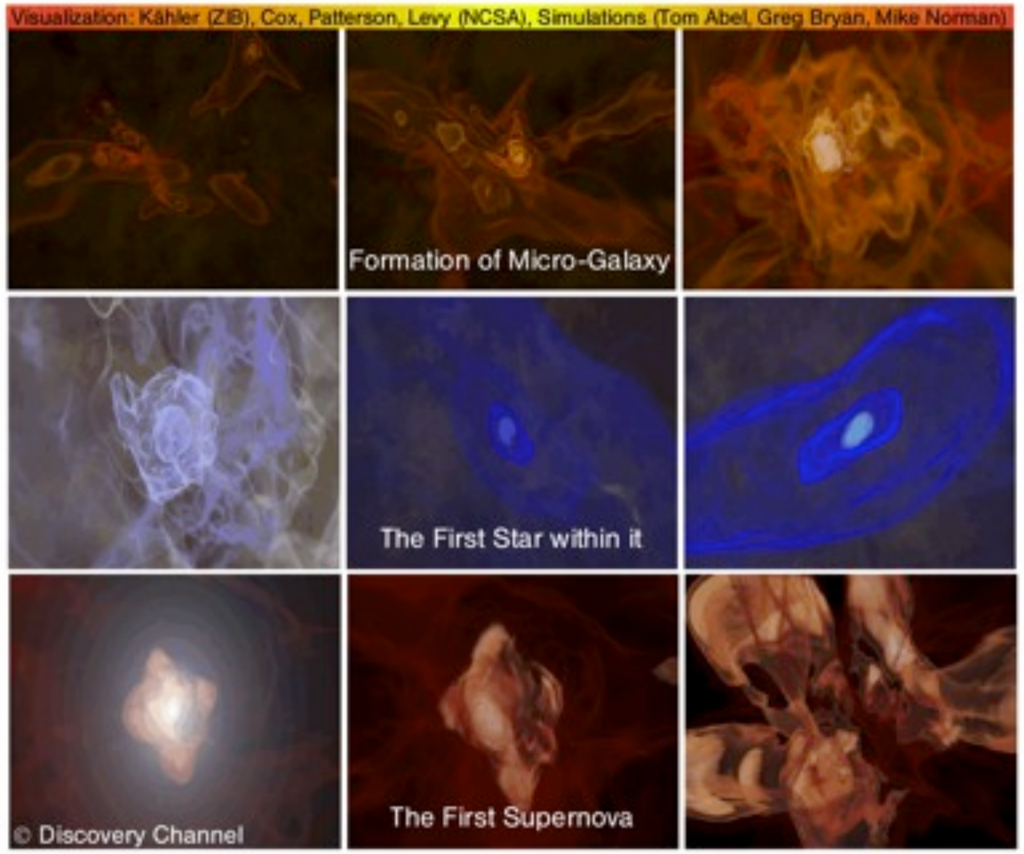


Simulation of the First Stars



Start with a stadium and then focus on a single atom within that stadium!

The theoretical challenge:
Total dynamical range 10^{12} !


Visualization: Kähler (ZIB), Cox, Patterson, Levy (NCSA), Simulations (Tom Abel, Greg Bryan, Mike Norman)

Alternative way to constrain Nature of the First Stellar Generations:

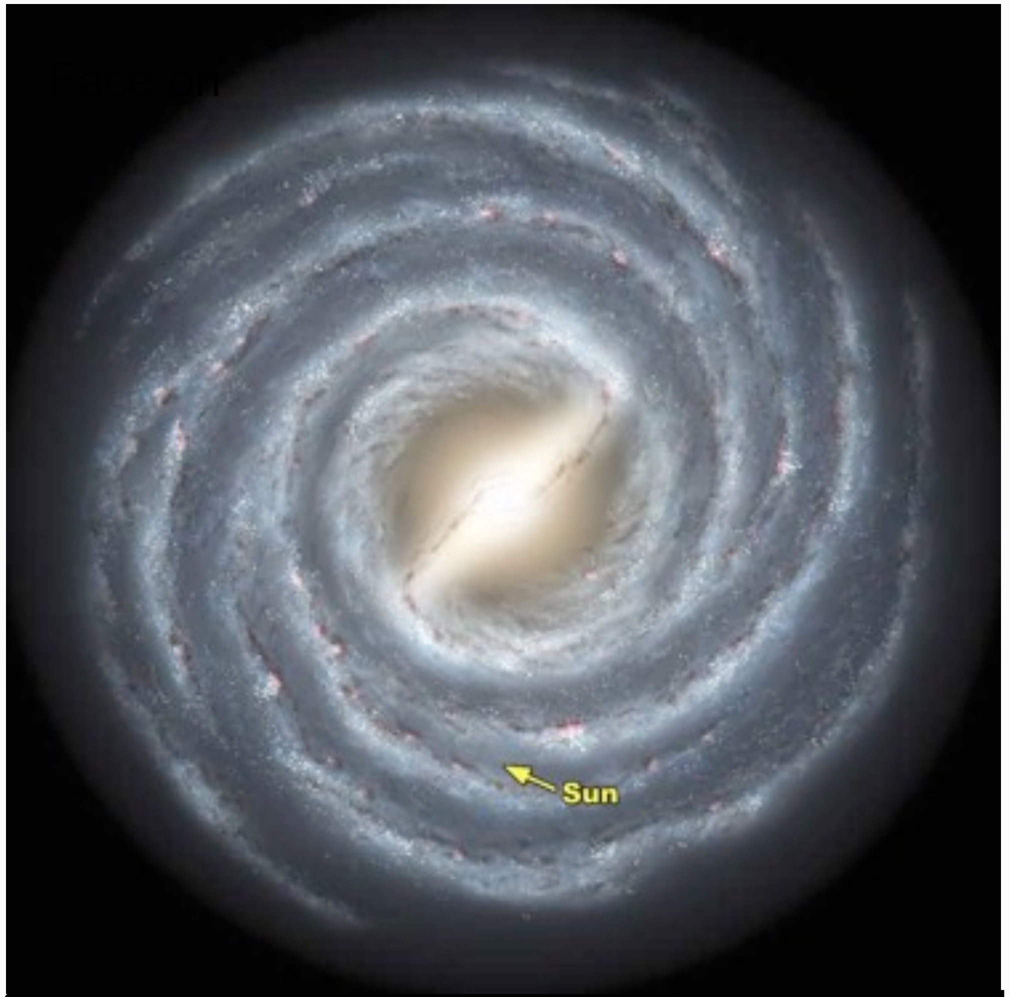
Oldest stars in our Galaxy formed from the gas ejected by the first stars!

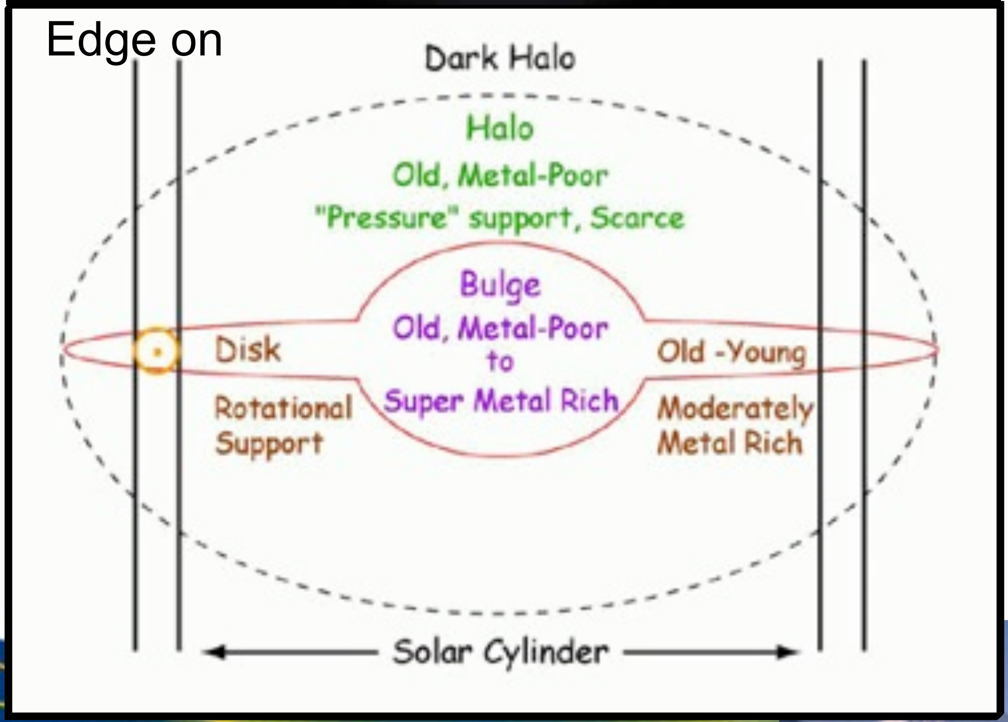
Core collapse Supernova

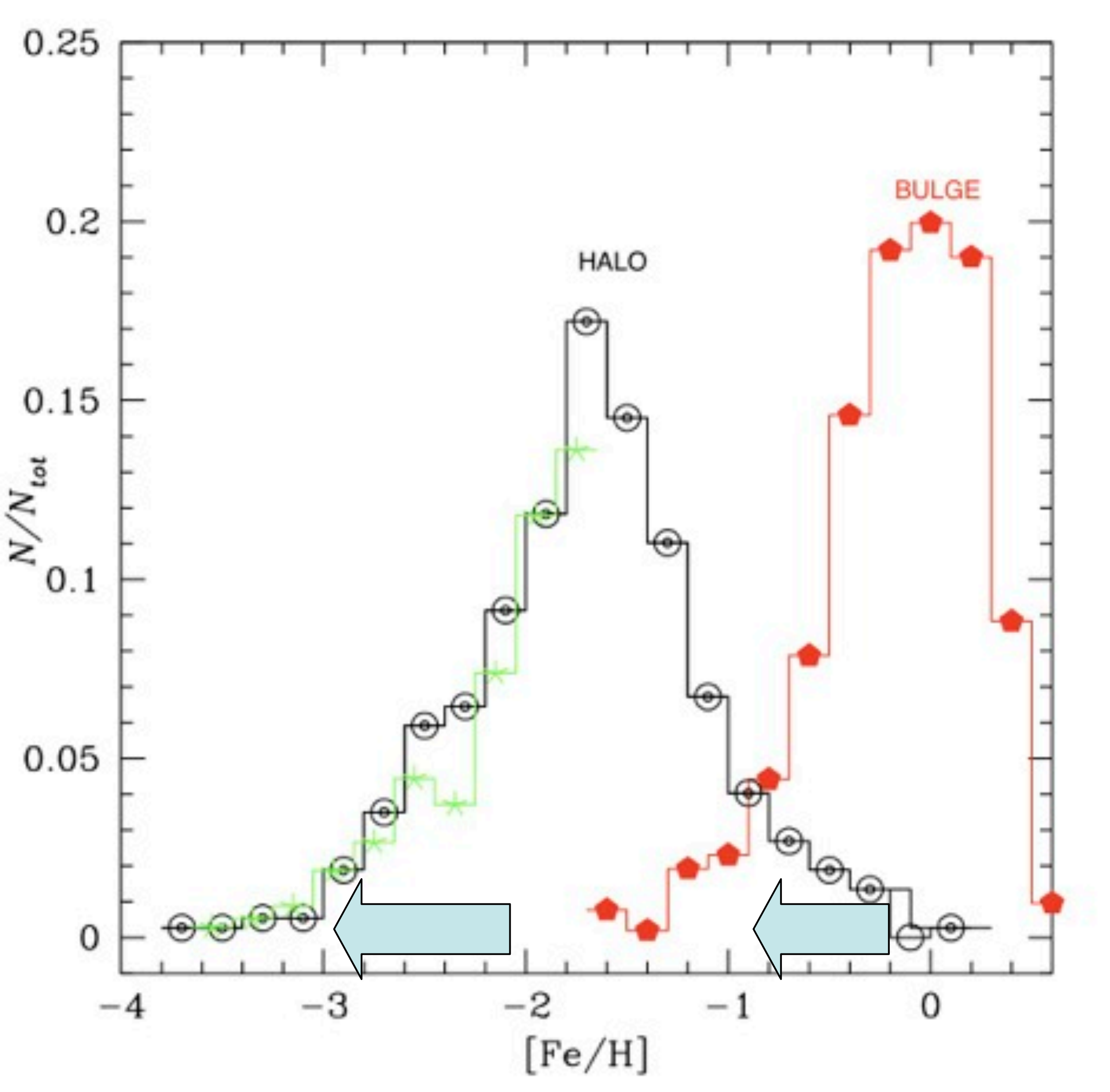
Massive Stars – short lifetimes

Polluters in the Early Universe!

Where are the oldest fossil records in the MW?







In the Halo
[Fe/H] < -3

In the Bulge
[Fe/H] ~ -1

Galactic chemical evolution

Stars and interstellar gas in galaxies exhibit diverse chemical element abundance patterns that are shaped by their environment and formation histories.

The aim of Galactic Chemical Evolution is to use the observed abundances in stars and the interstellar medium to reconstruct the chemical history and unlock earlier epochs in the Universe, probe the mechanisms of galaxy formation, and gain insight into the stellar evolution, constraining the stellar yields.

Models for the chemical evolution of galaxies need to account for 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 is the ongoing accretion of gas from outside the system.

Galactic chemical evolution

An homogeneous model follows the time evolution of the gas fraction of element A with this equation:

$$\dot{G}_A(R,t) =$$

$\Psi\ (R, t) = v(R,t)\ G(R,t)^k$

$$-X_A(R,t)\ \Psi\ (R, t) + \dot{G}_{A,\mathrm{infall}}\ (R,t) \quad - X_A(R,t)\ \dot{W}_A\ (R, t)$$

1) Locked in stars **2) Infalling in the system** **3)Flowing from the system**

$$+ \int_M \Psi\ (R, t - \tau(\acute{m}))\ \varphi\ (\acute{m})\ Q(\acute{m}, z(t - \tau(\acute{m})))_A\ d\acute{m}$$

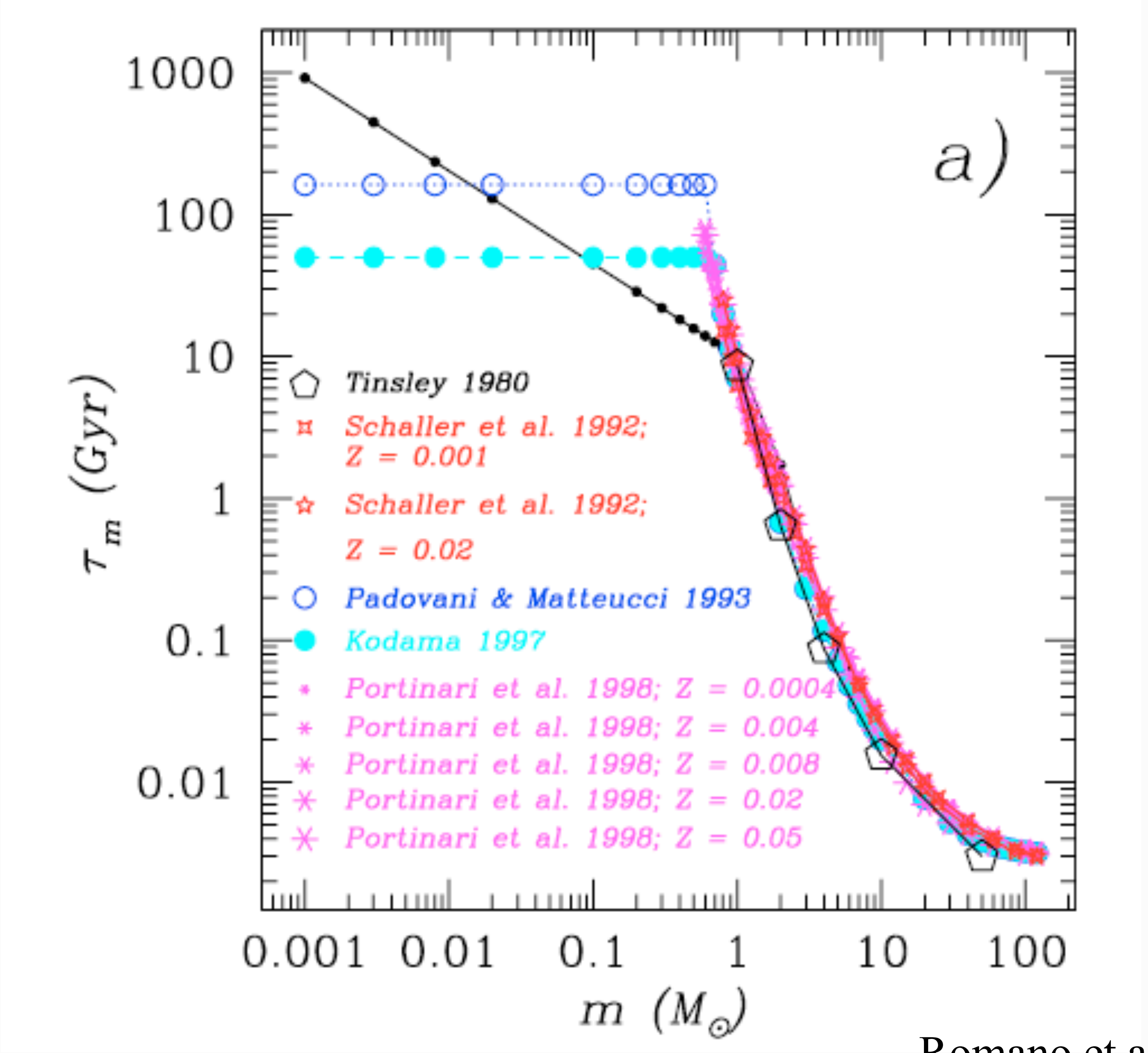
4) Produced by stars

Stellar nucleosynthesis (nuclear reaction rate!)

Stellar lifetimes

Compilation of stellar lifetimes from different authors:
Note the short lifetime for massive stars.

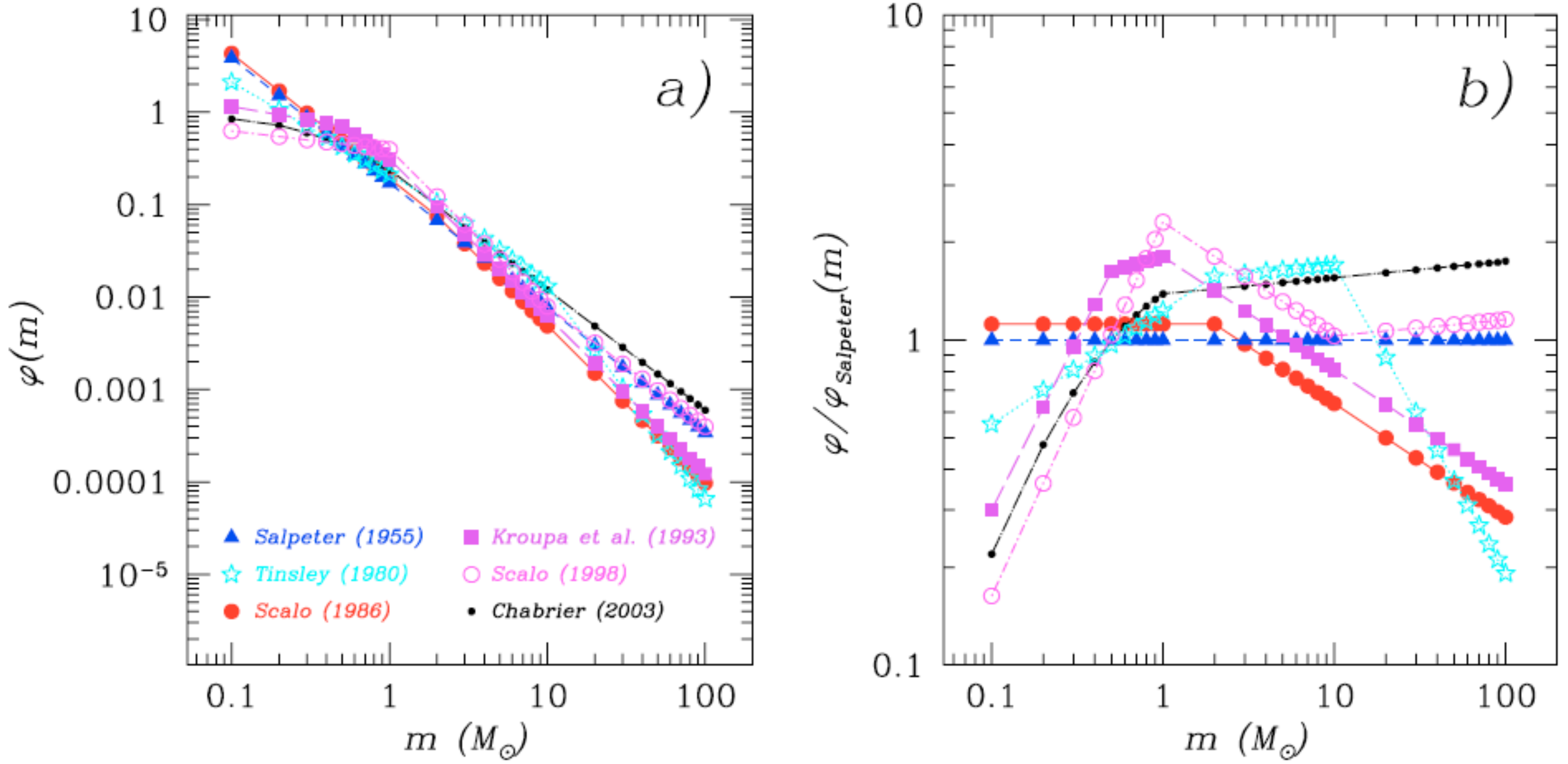
So they almost contribute instantaneously, more complex is the treatment of low intermediate mass stars (important for elements as s-process elements, CNO), their timescales are much longer.



Romano et al. (2003)

Initial mass function

Salpeter's IMF: $\varphi(m) \sim m^{-1.35}$

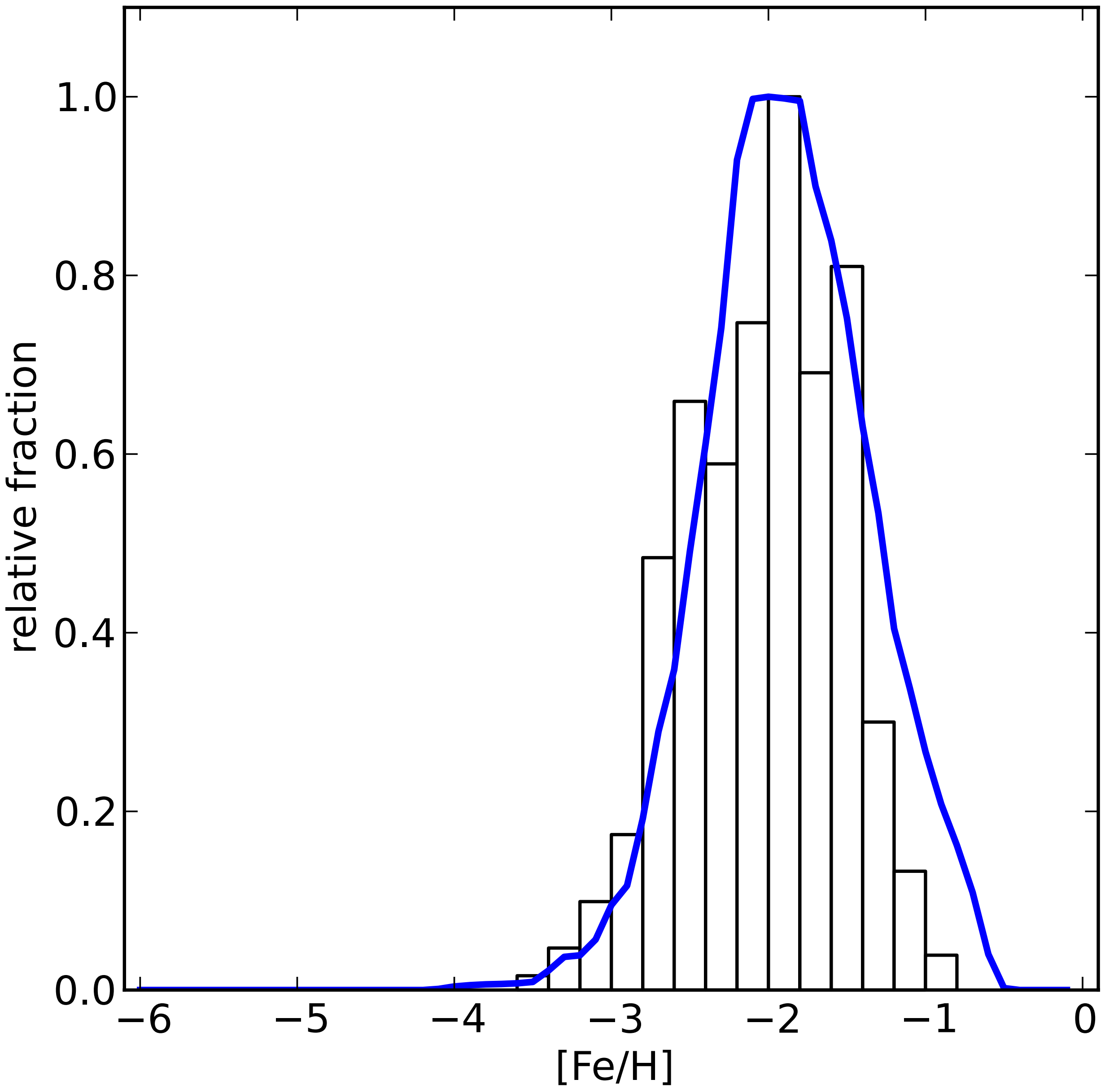


Romano et al. (2003)

Describe the probability to create a star with a certain mass.
to give an idea a star of 100Msun every ~50000 stars of 1Msun

Halo model

Comparison between the metallicity distribution function of the model (blue)
and the observed MDF
by Li et al. (2010): main-sequence turnoff stars in the HESS (Hamburg ESO survey)



Neutron capture elements: r-s process

The elements beyond the iron peak (A>60) are formed through neutron capture on seed nuclei (iron and silicon).
Two cases:

s-process

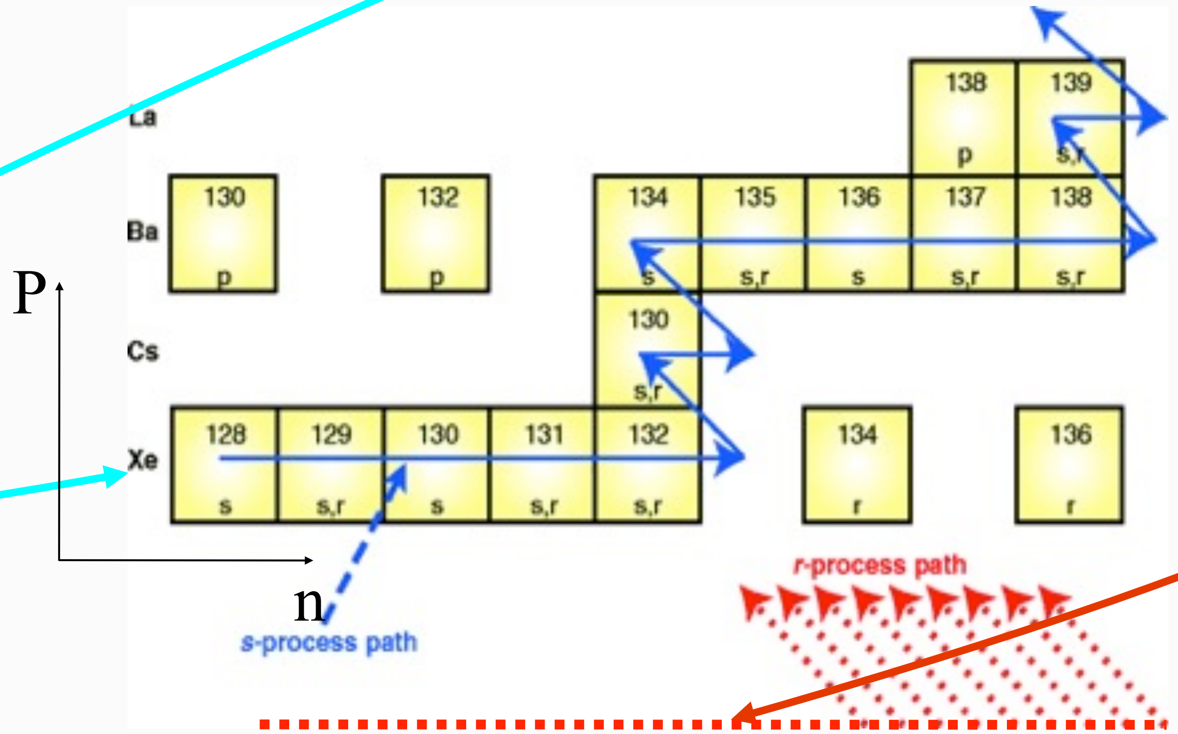
r-process

Different Timescale of the neutron capture

$\tau_\beta << \tau_c$

$\tau_\beta >> \tau_c$

Different process path



Neutron capture elements: r-s process

s-process		r-process
Low-(intermediate) mass stars	Where?	**Massive stars**
? also in massive stars ? *(Pignatari et al. 2008, Frischknecht et al. 2012)*		O-Ne-Mg core explosions? Neutron stars mergers? Magnetorotationally driven SN? many scenarios...
> 300Myr **(for low mass stars)**	When?	**< 30Myr** **(excluding NS mergers)**
Busso et al. 2001	Yields?	**....**
see also Cristallo et al (2011) *and Karakas et al. (2012)*		

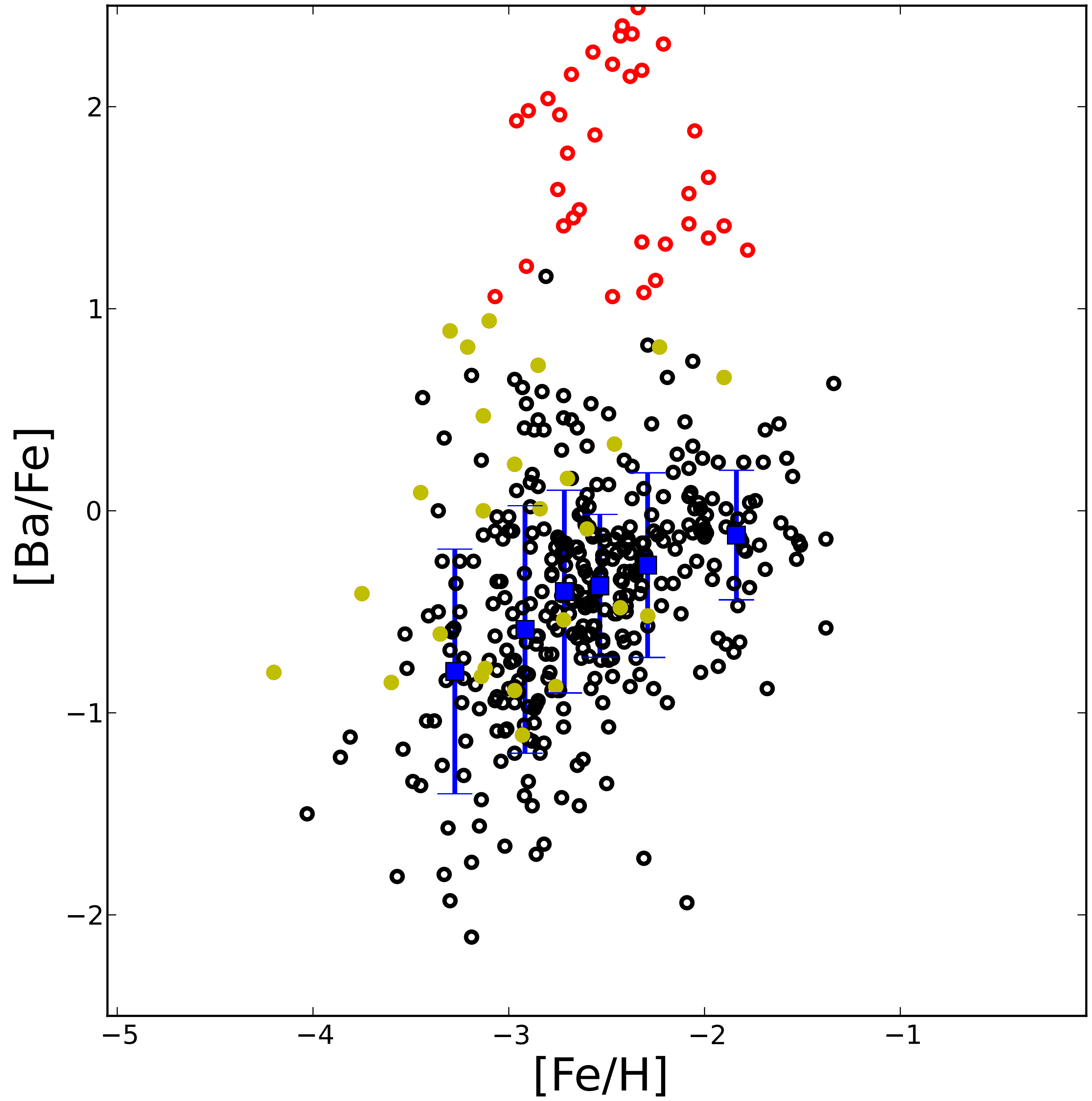
Empirical yields for r-process in the Galactic Halo

Why empirical?
r-process site of production not established, uncertainties in the predictions.
s-Process enrichment by low intermediate, negligible in the Halo (very fast formation)
Similar to
Cescutti et al. ’06

BUT

New model
for the halo
Cescutti & Chiappini ’10
&

New data
collected by Frebel ’10



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

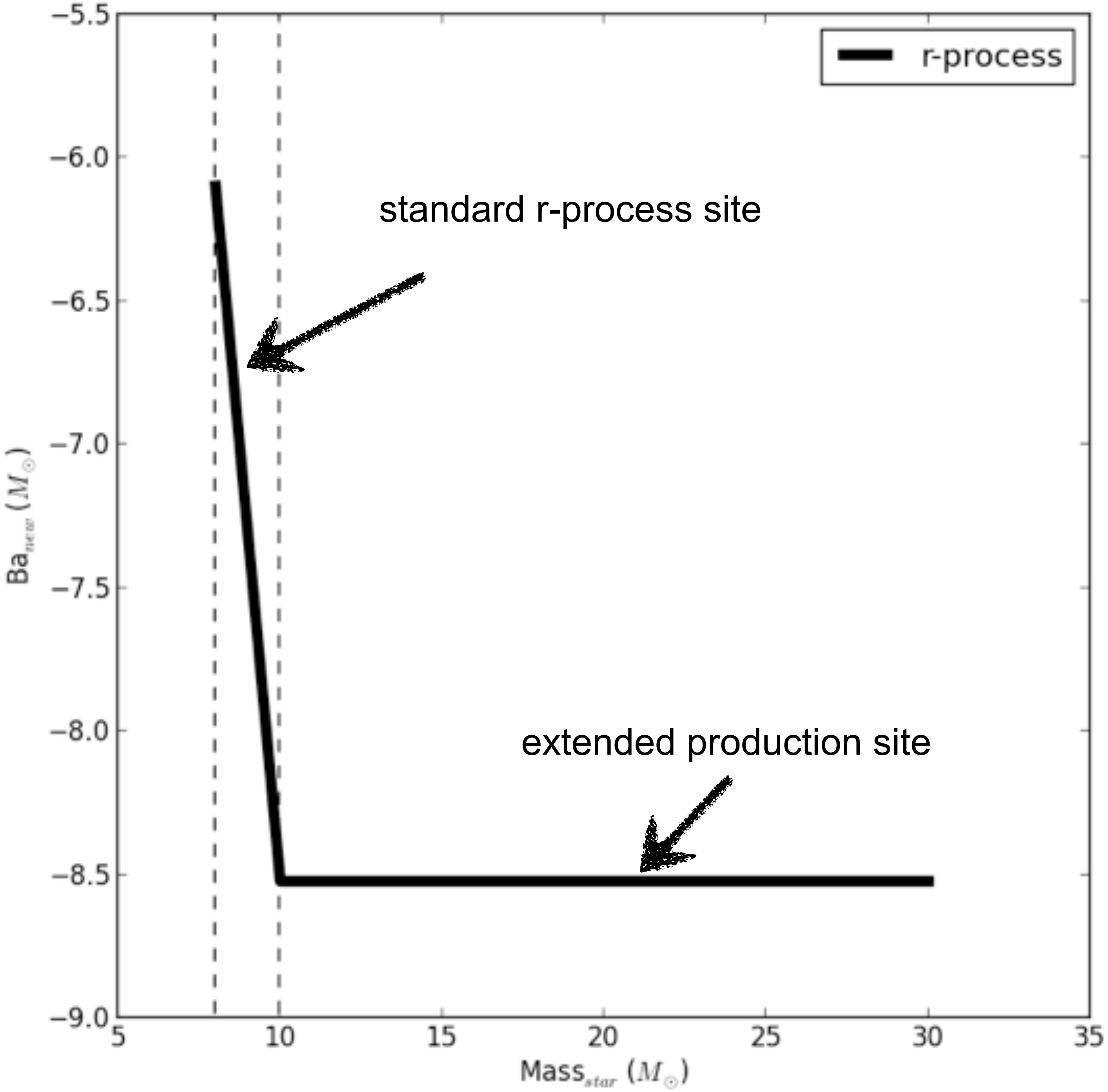
halo stars:
normal ●
CEMP-s ●
CEMP-no ●

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



standard r-process site

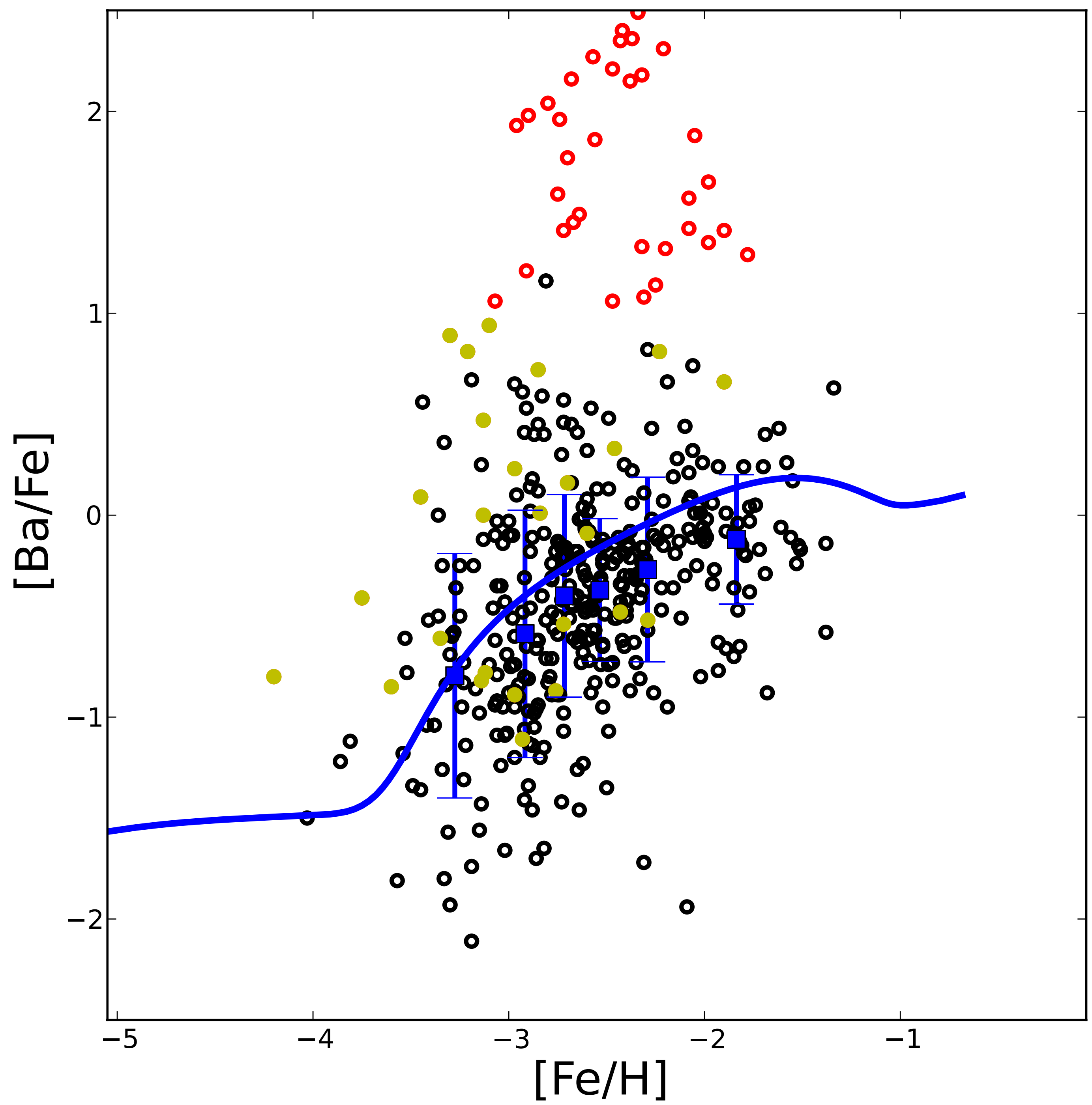
extended production site

Results for Barium

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

BUT

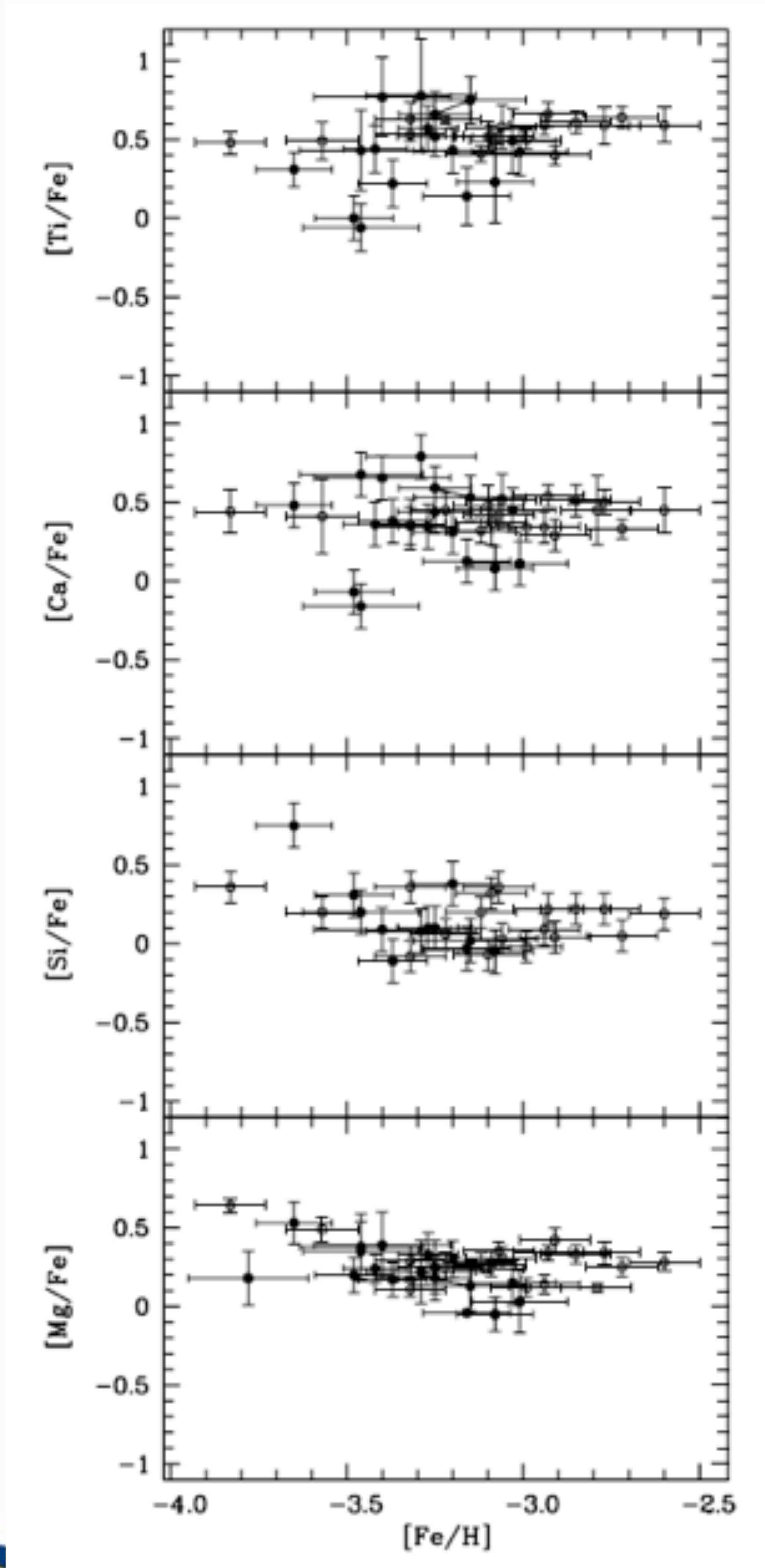
This homogenous model cannot be used to have an insight of the spread observed in the halo stars, only the trend is recovered.



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

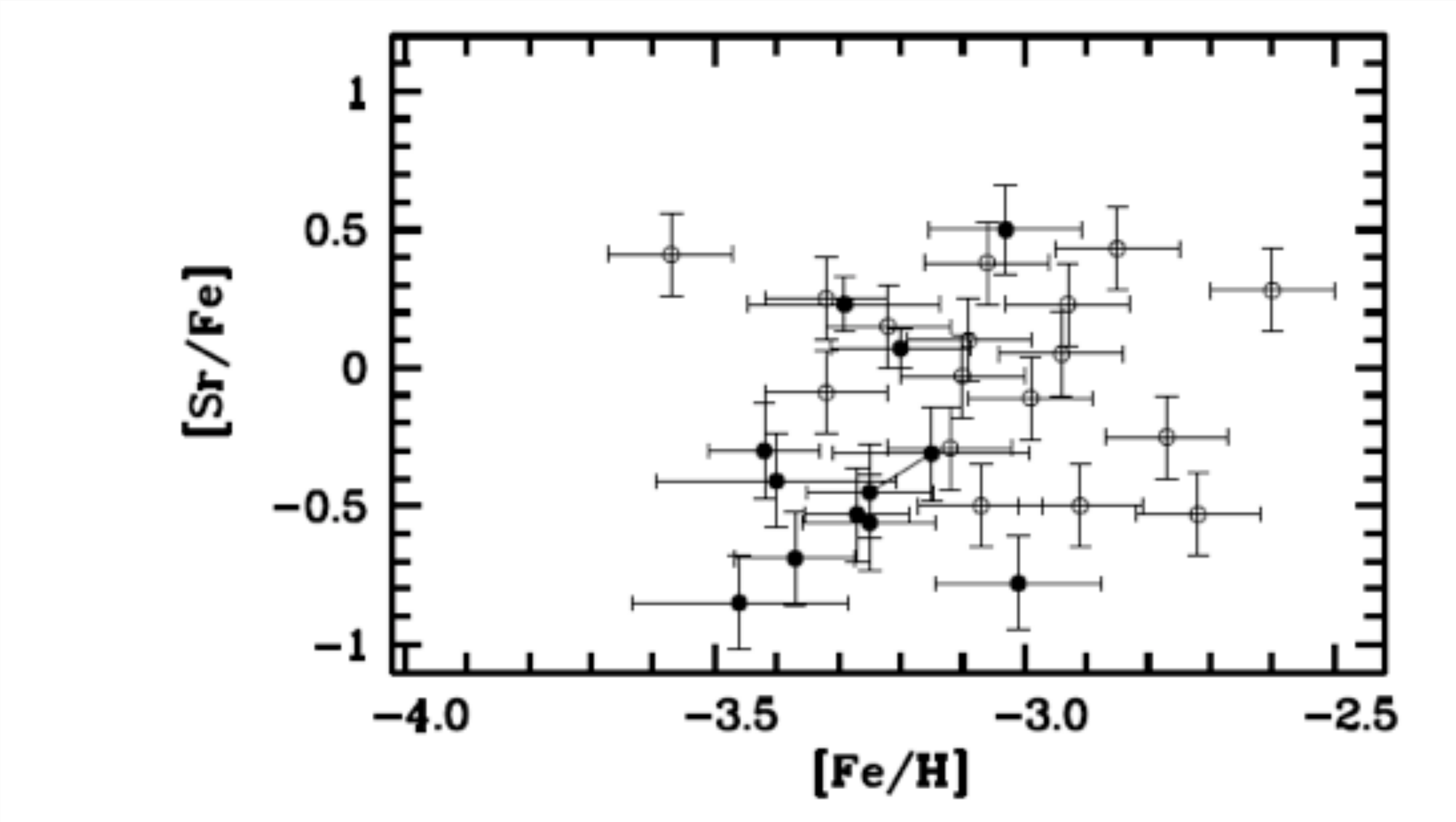
halo stars:
normal ●
CEMP-s ●
CEMP-no ●

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

Problem to solve:

The neutron capture elements at low metallicities show spread whereas α-elements (O, Ca, Si, Mg) do not

Main assumptions:

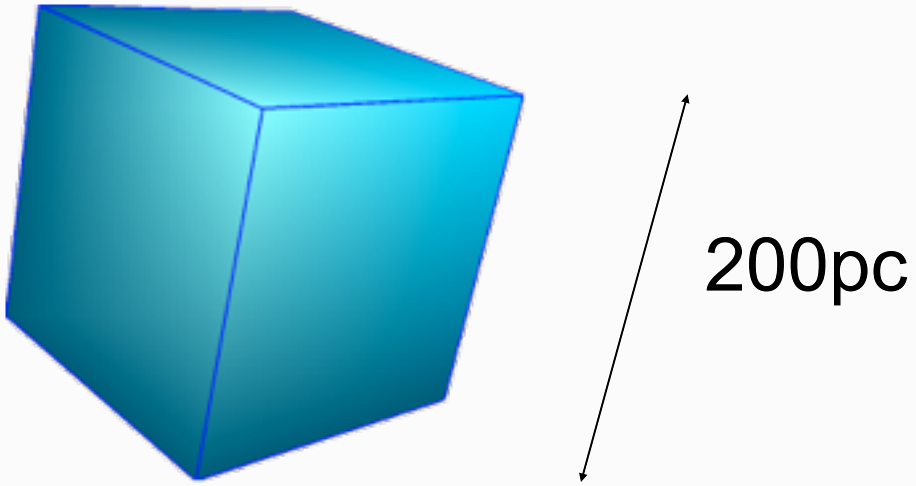
A random formation of new stars subjects to the condition that the cumulative mass distribution follows a given initial mass function;

α-elements and neutron capture elements are produced in different mass ranges:

- All the massive stars for α-elements
- 8-30 $M_\odot$ for neutron capture elements

Inhomogeneous chemical evolution model for the halo of the Milky Way

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.



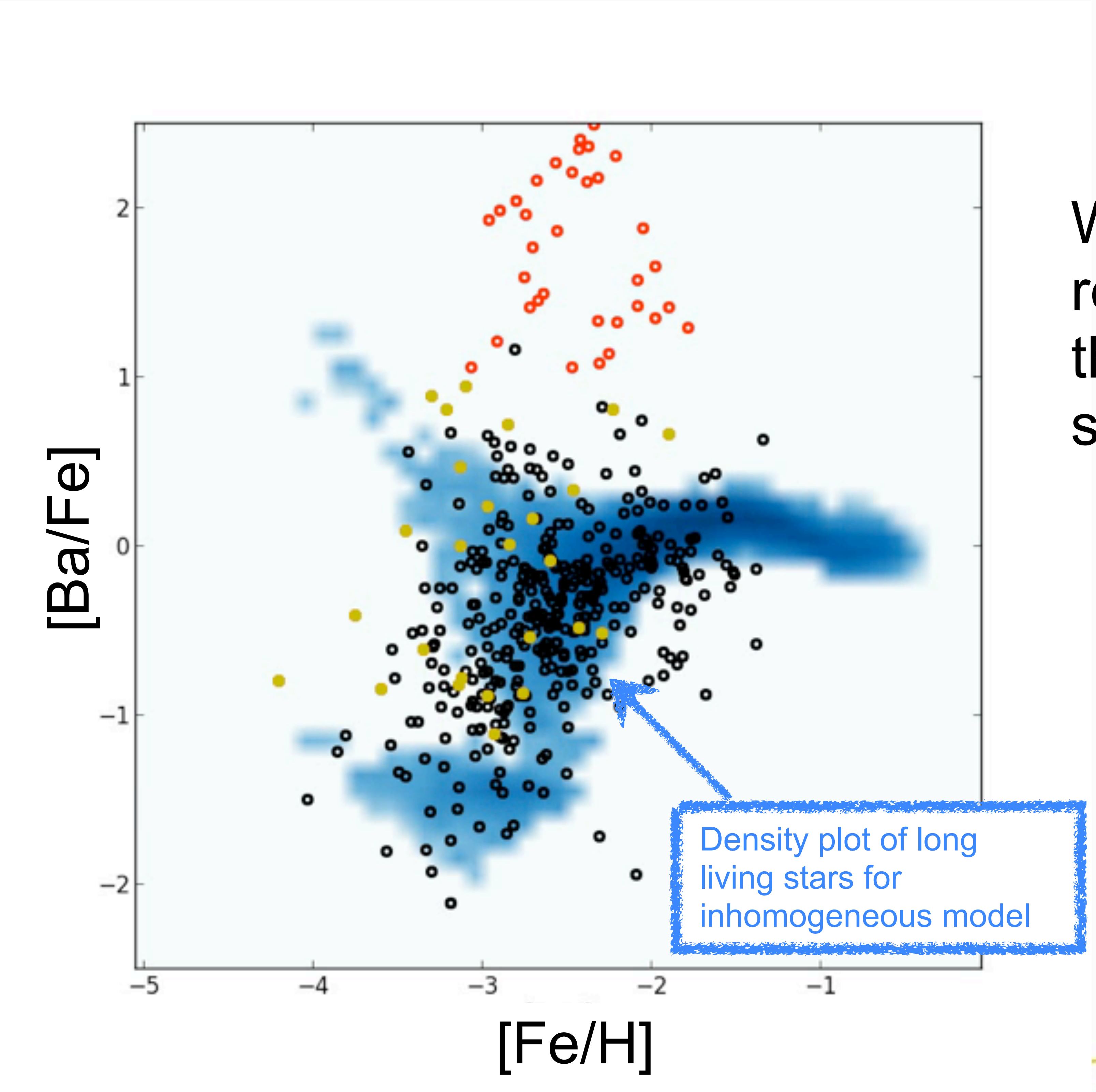
Inside each box, we simulate for 1 Gyr the chemical enrichment.

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

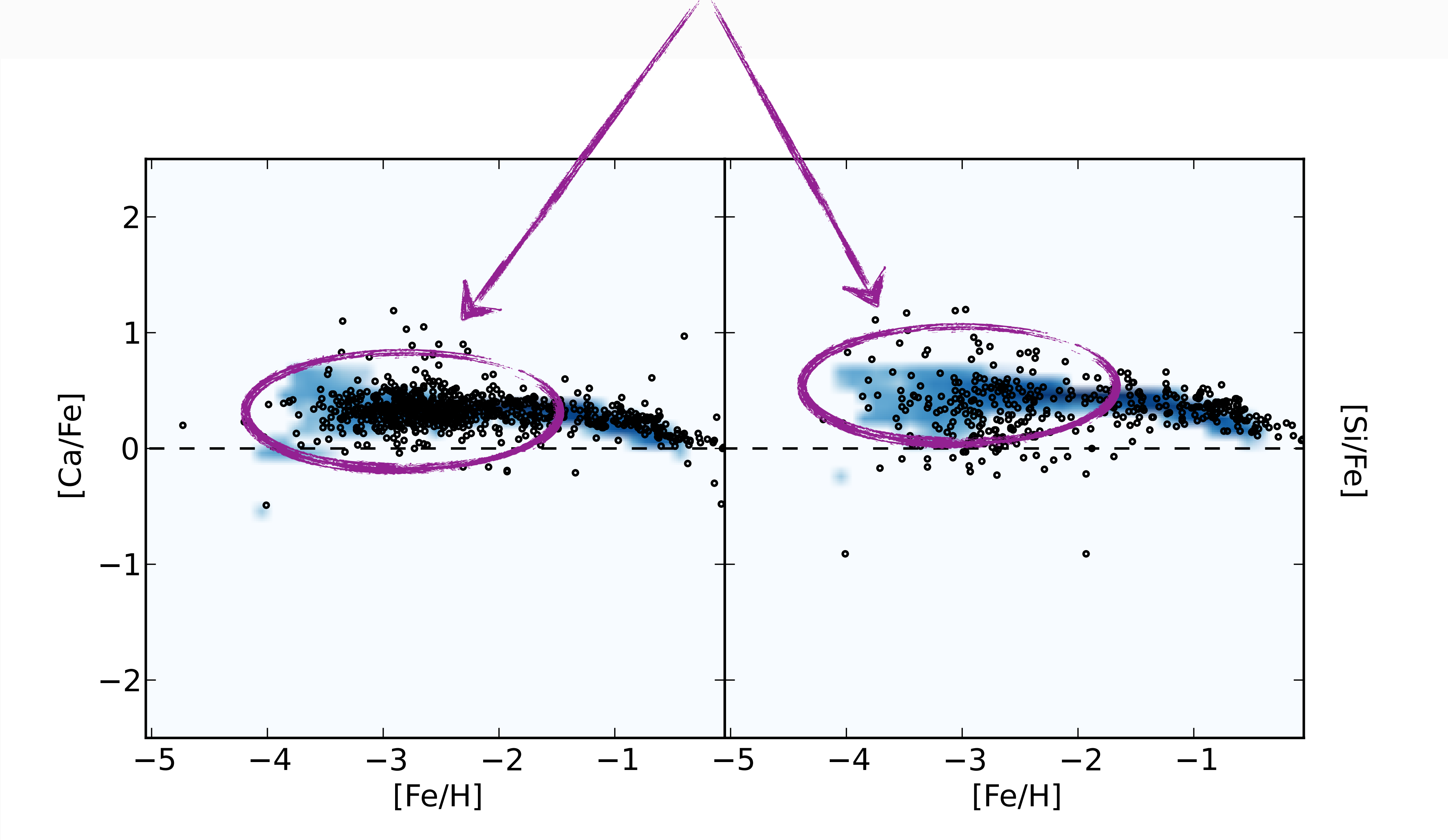


Density plot of long living stars for inhomogeneous model

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

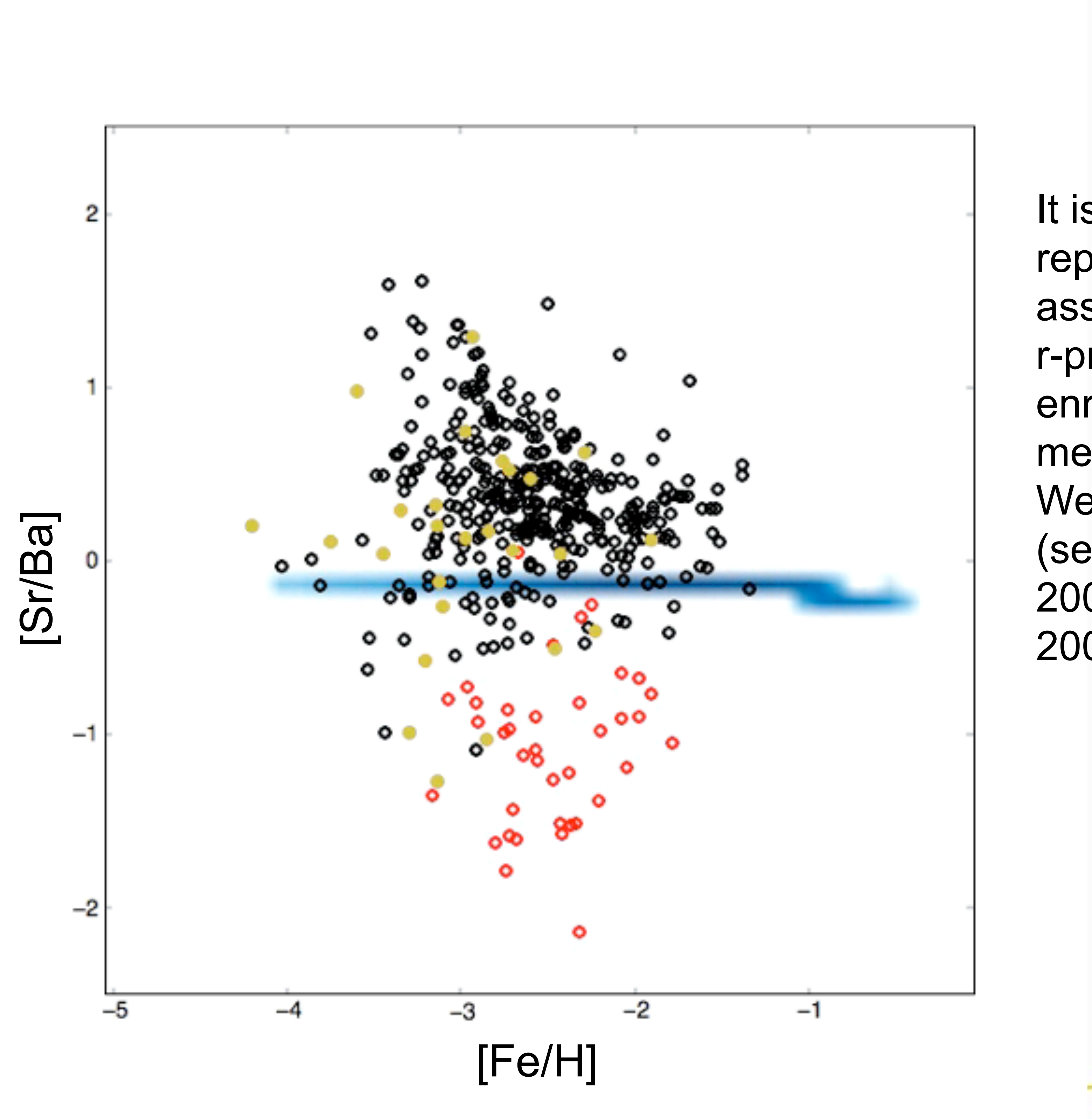
NO spread for alphas!!!

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 et al. 2008)



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

halo stars:
normal ●
cemp-s ●
cemp-no ●

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)

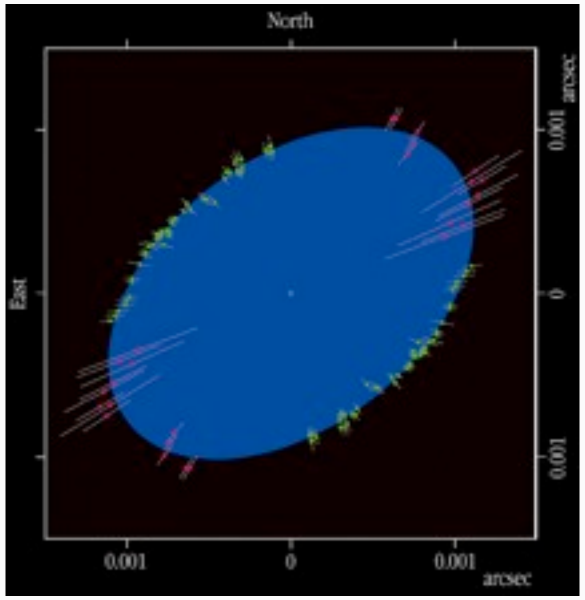
5 Early production of neutron capture elements through a boosted s-process (Sr,Ba,...)

In the
Local
Universe

Stellar Rotation:

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

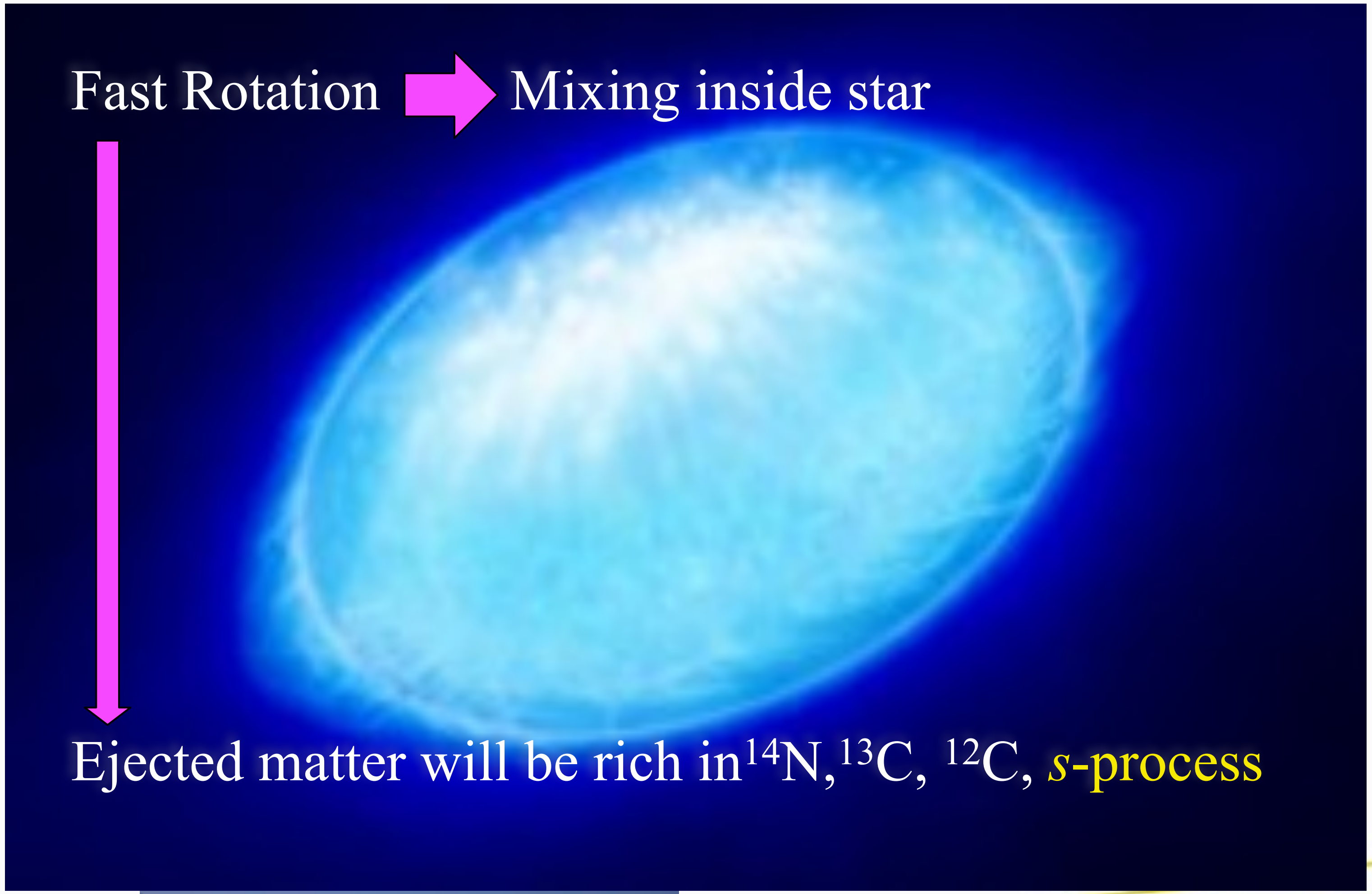
Achernar VLTI



R_e/R_p=1.5

In the
Early
Universe

Low metals: stars rotate faster (more compact)

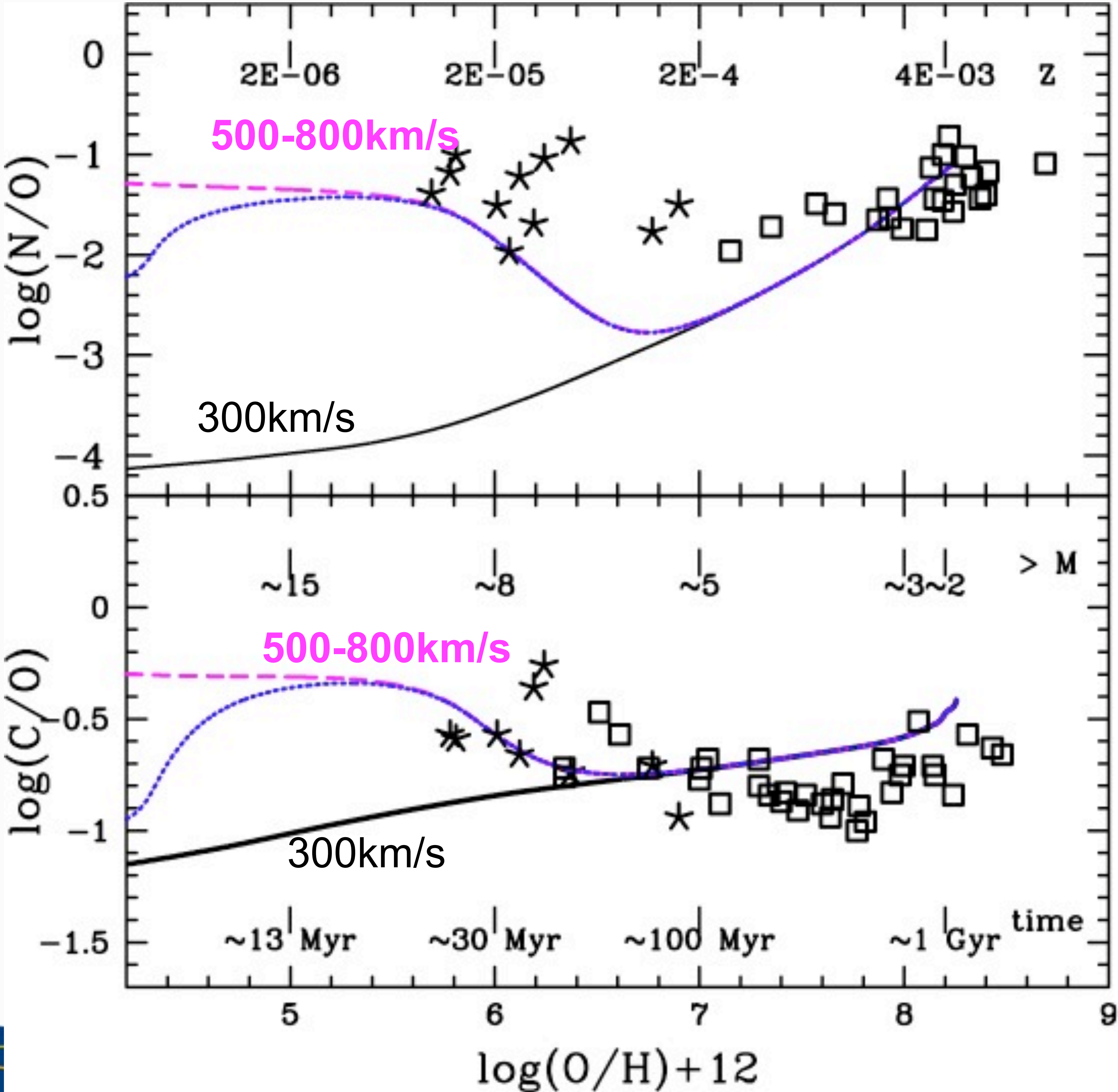


Fast Rotation → Mixing inside star

Ejected matter will be rich in ^{14}N, ^{13}C, ^{12}C, *s*-process

Chiappini, Hirschi, Meynet, Ekstroem, Maeder, Matteucci (2006a,b)

First & Second Signatures of Fast Rotators in the Early Universe

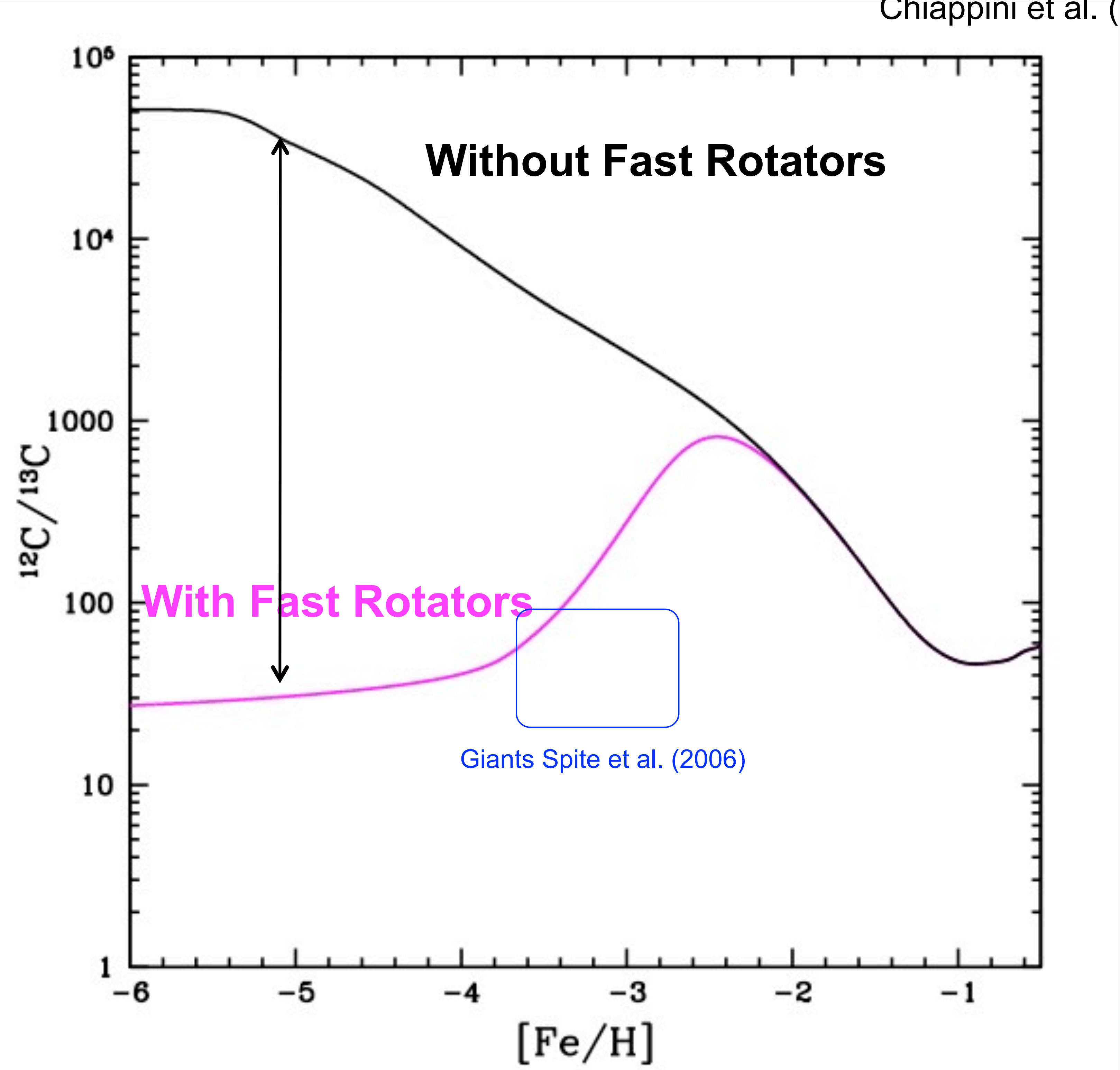


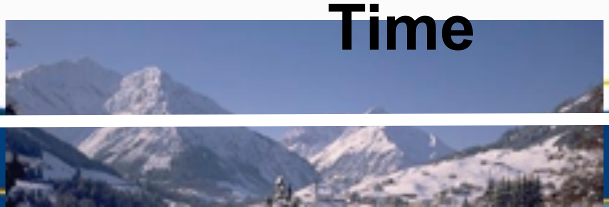
Early Universe shows large N/O and C/O ratios

Third Signature of Fast Rotators in the Early Universe

Chiappini et al. (2008, A&A Letter)

The expected $^{12}C/^{13}C$ ratio at [Fe/H]=-5 drops by 4 orders of mag upon the inclusion of fast rotators!





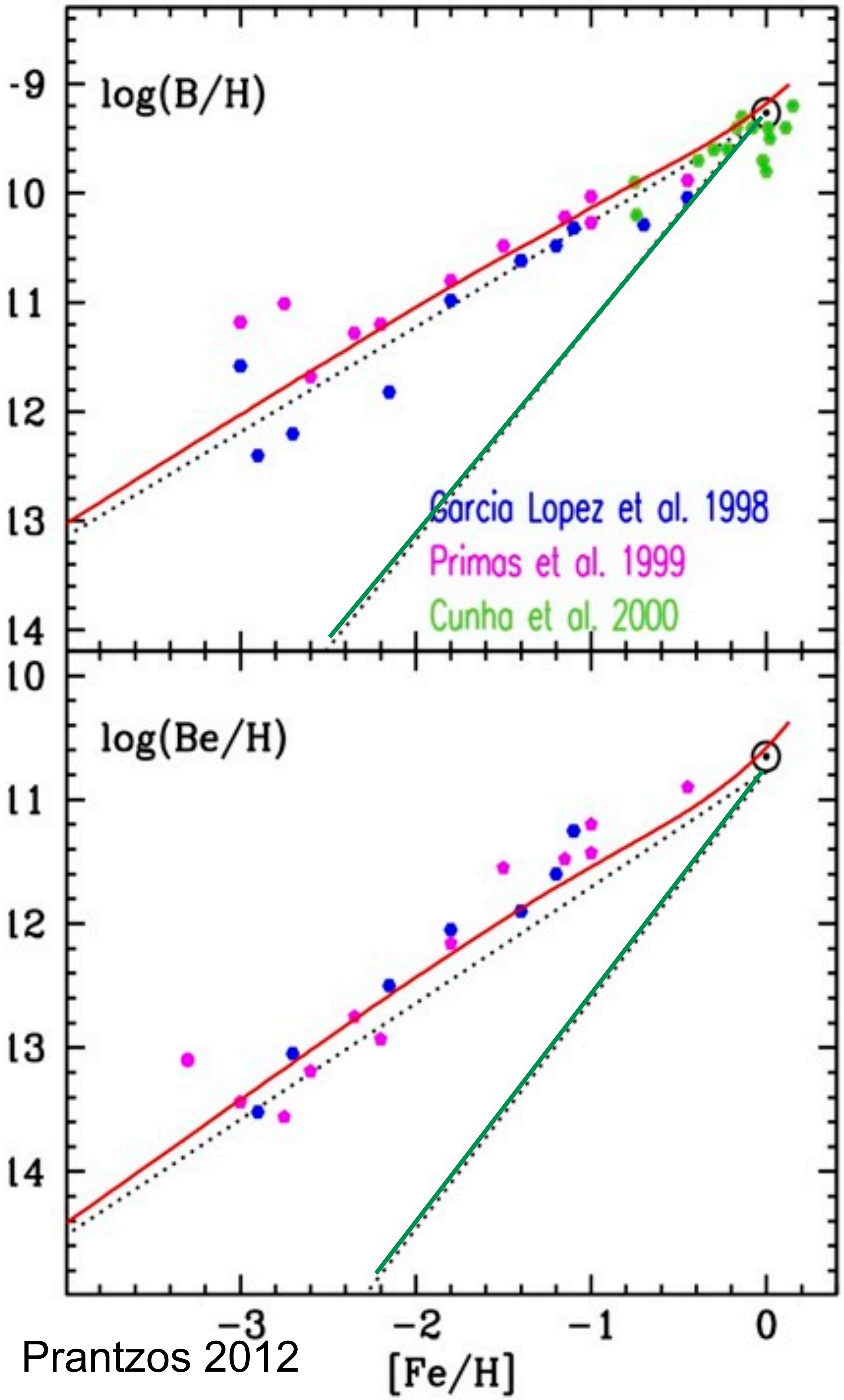
Time

Fourth Signature of Fast Rotators in the Early Universe?

Be and B – cosmic ray spallation on CNO nuclei.

Expected – secondary (green).
Observed – primary (red)

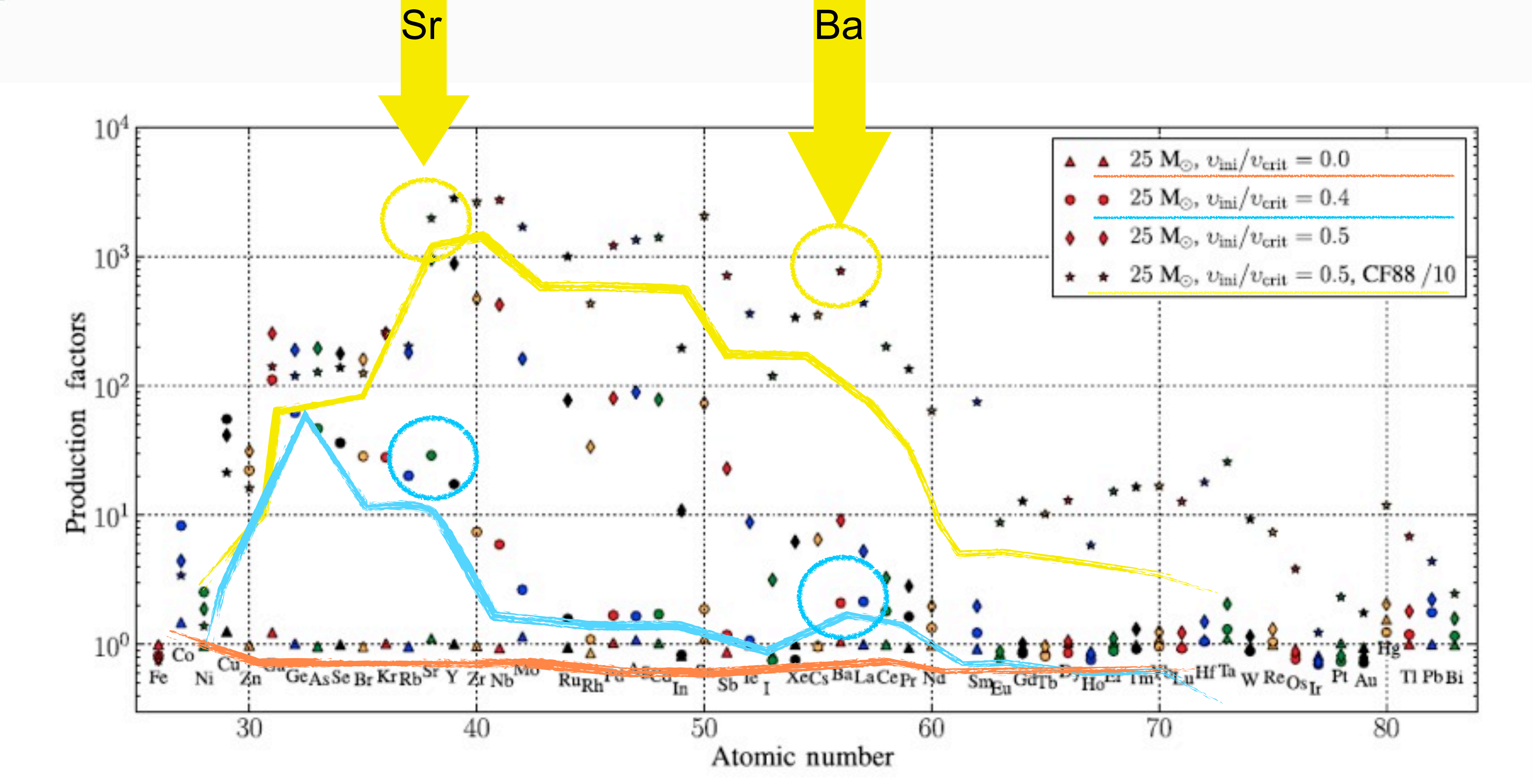
Better agreement if Universe enriched in CNO early on, and forward GCRs are accelerated when the forward shocks of SN propagate into the previously ejected envelope of fast rotators



Prantzos 2012

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

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

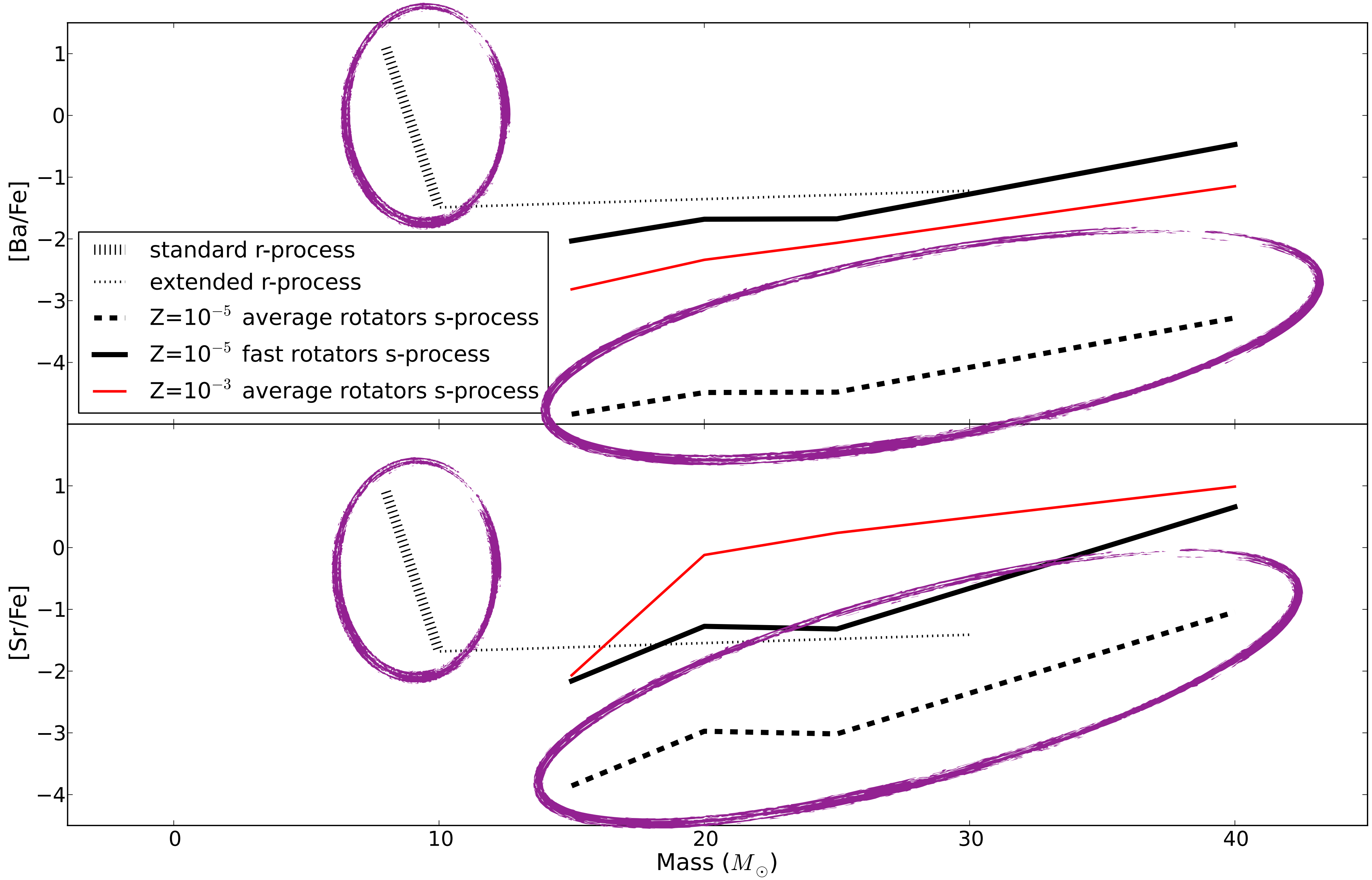


Fast rotators could contribute to s-process elements!

Frischknecht et al. 2012

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

Yields of s-Process from rotators with CF'88 rate for ^{17}O (α, γ)

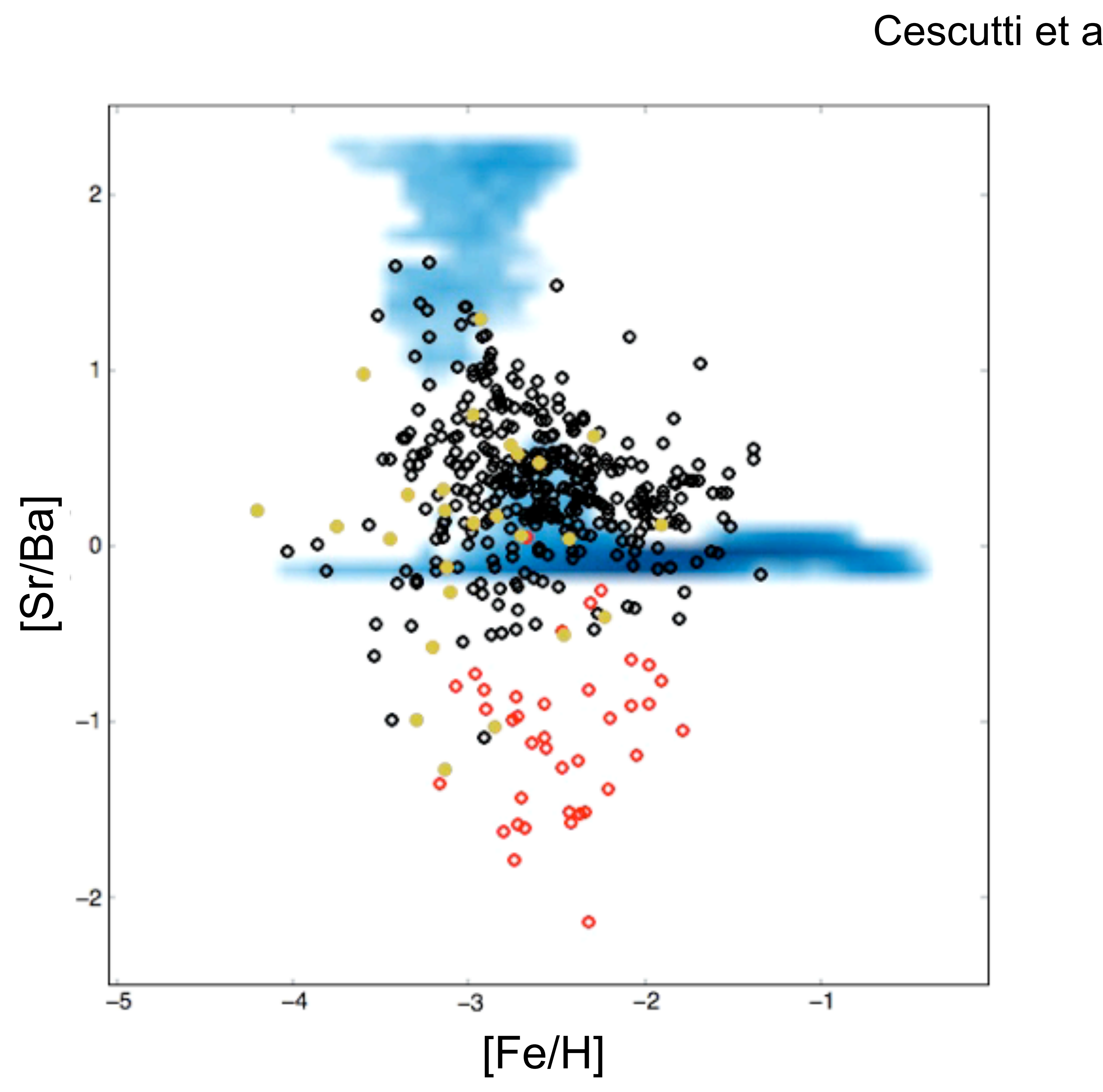


s-Process from average rotators

+ standard r-process site

Cescutti et al. (A&A submitted)

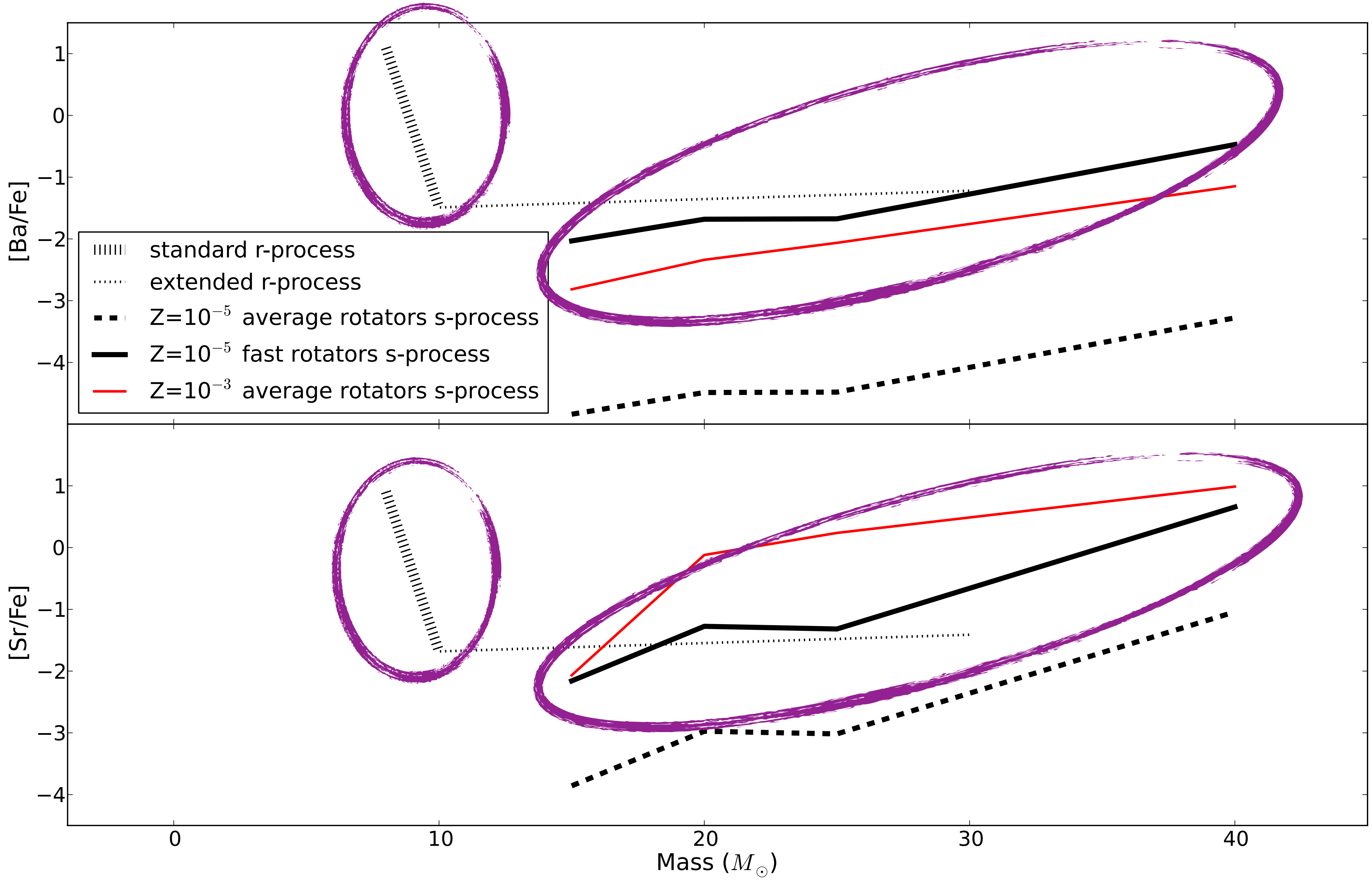
Average rotators
$V_{ini}/V_{crit}=0.4$
&
standard reaction rate by Caughlan & Fowler '88 for $^{17}O\ (\alpha, \gamma)$



halo stars:
normal ●
cemp-s ●
cemp-no ●

Yields of s-Process from fast rotators

with 1/10 of the CF’88 rate for ^{17}O (α, γ)

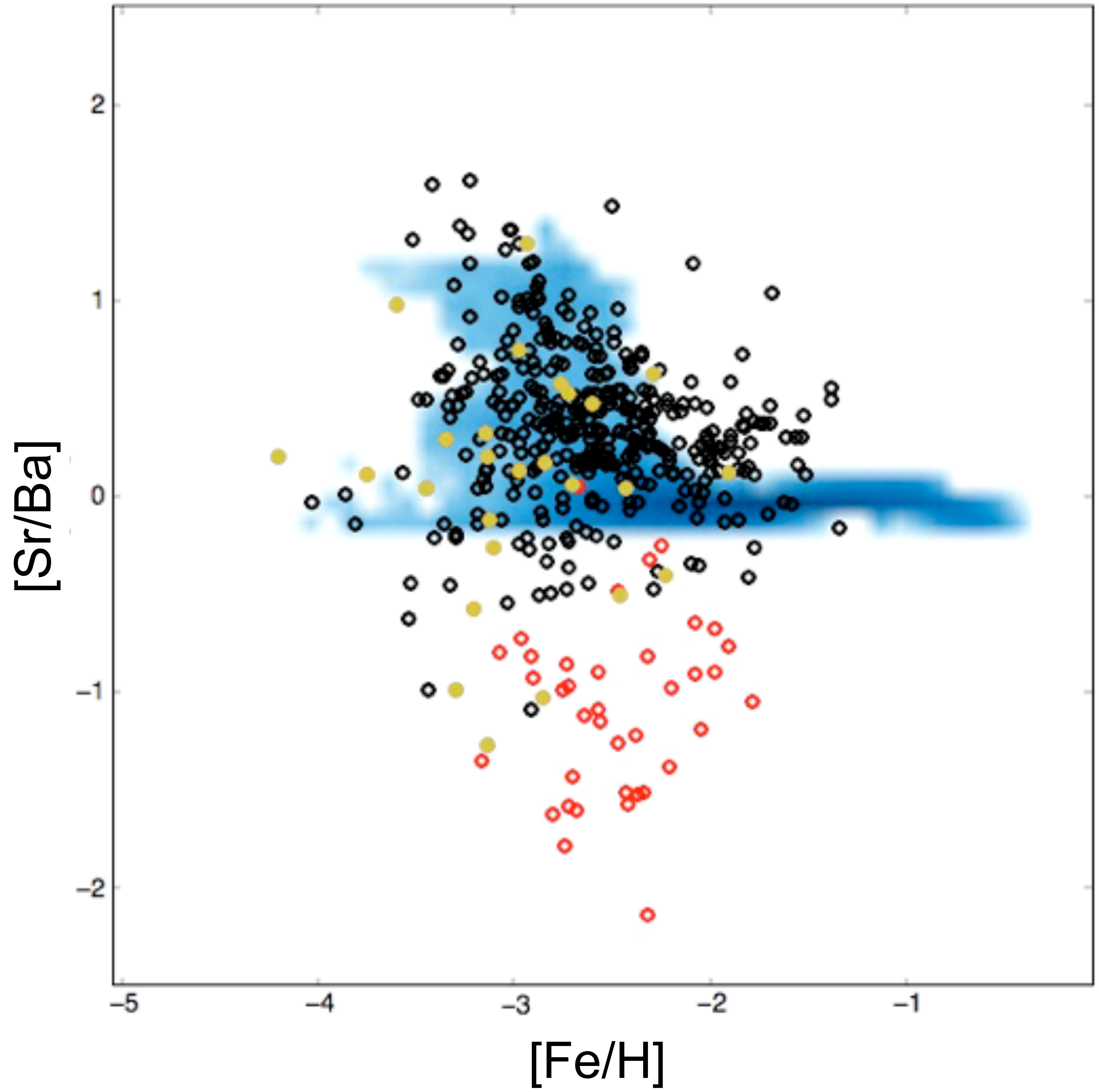


s-Process from fast rotators

+ standard r-process site

Cescutti et al. (A&A submitted)

Boosted models:
V_{ini}/V_{crit}=0.5
&
0.1
of the reaction rate by Caughlan & Fowler '88 for $^{17}O(\alpha,\gamma)$



s-process from spinstars provide a solution.

halo stars:
normal ●
cemp-s ●
cemp-no ●

Conclusions I

- By means of the comparison between the models and the new data at low metallicity we have obtained empirical yields for Ba that reproduced the observations.

- We have developed a model which is able to reproduce the spread of neutron capture elements and, at the same time, the small star to star scatter of the alpha elements.

- The Sr/Ba ratios in halo stars can not be explained by a single nucleosynthesis process but...

Conclusions II

Fast rotating massive stars

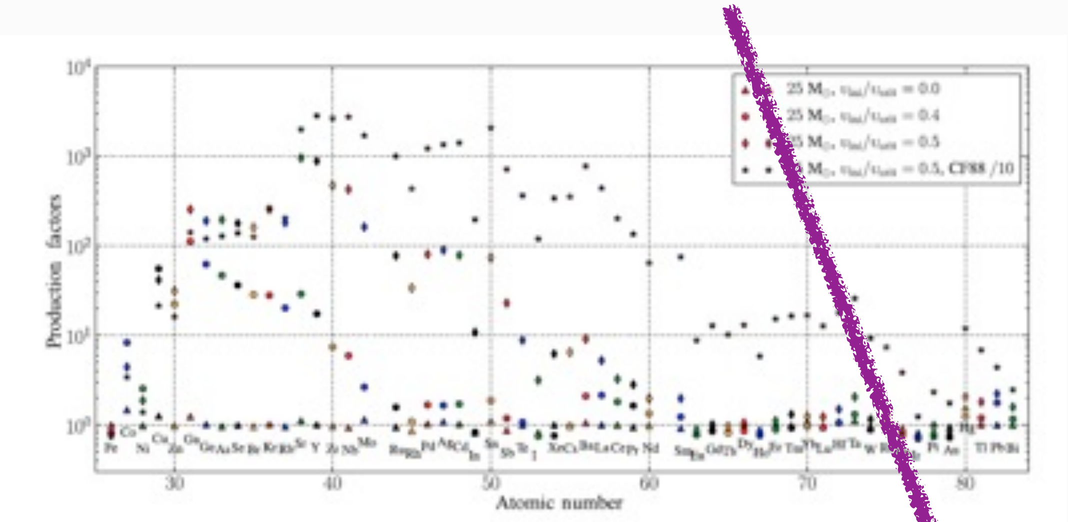
Solution for 4 signatures in the early Universe

(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

(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 2010)



Spinstar models predict a robust s-process

assuming a decreased value for the reaction rate $^{17}O\ (\alpha, \gamma)$

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

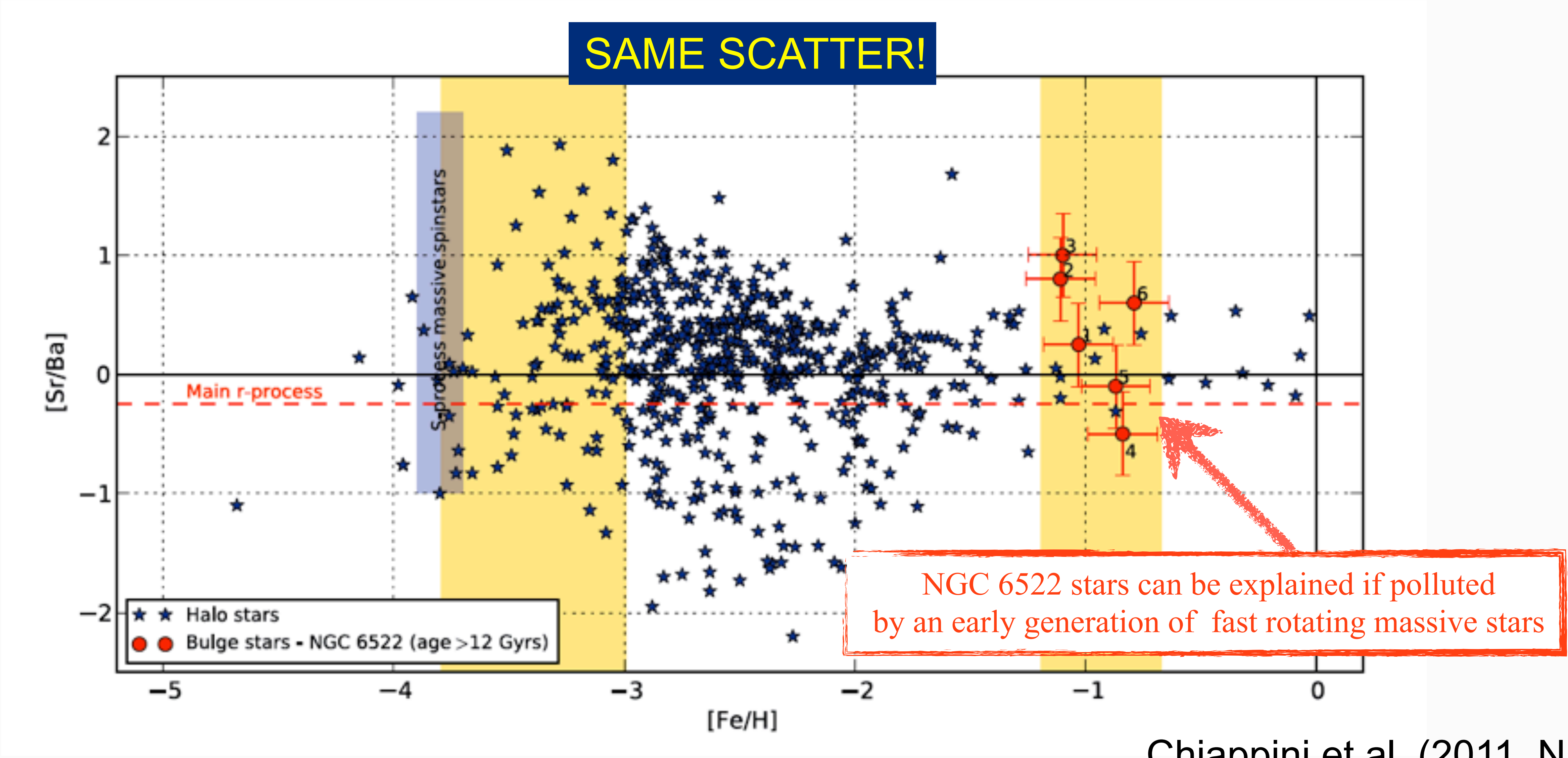
In the Early Universe the stars were fast rotators

and the reaction rate is really lower (see results by Fulton and collaborators!)

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

EARLY UNIVERSE

EARLY UNIVERSE



SAME SCATTER!

NGC 6522 stars can be explained if polluted by an early generation of fast rotating massive stars

Chiappini et al. (2011, Nature)

Inhomogenous model for the Bulge - Future project!