Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

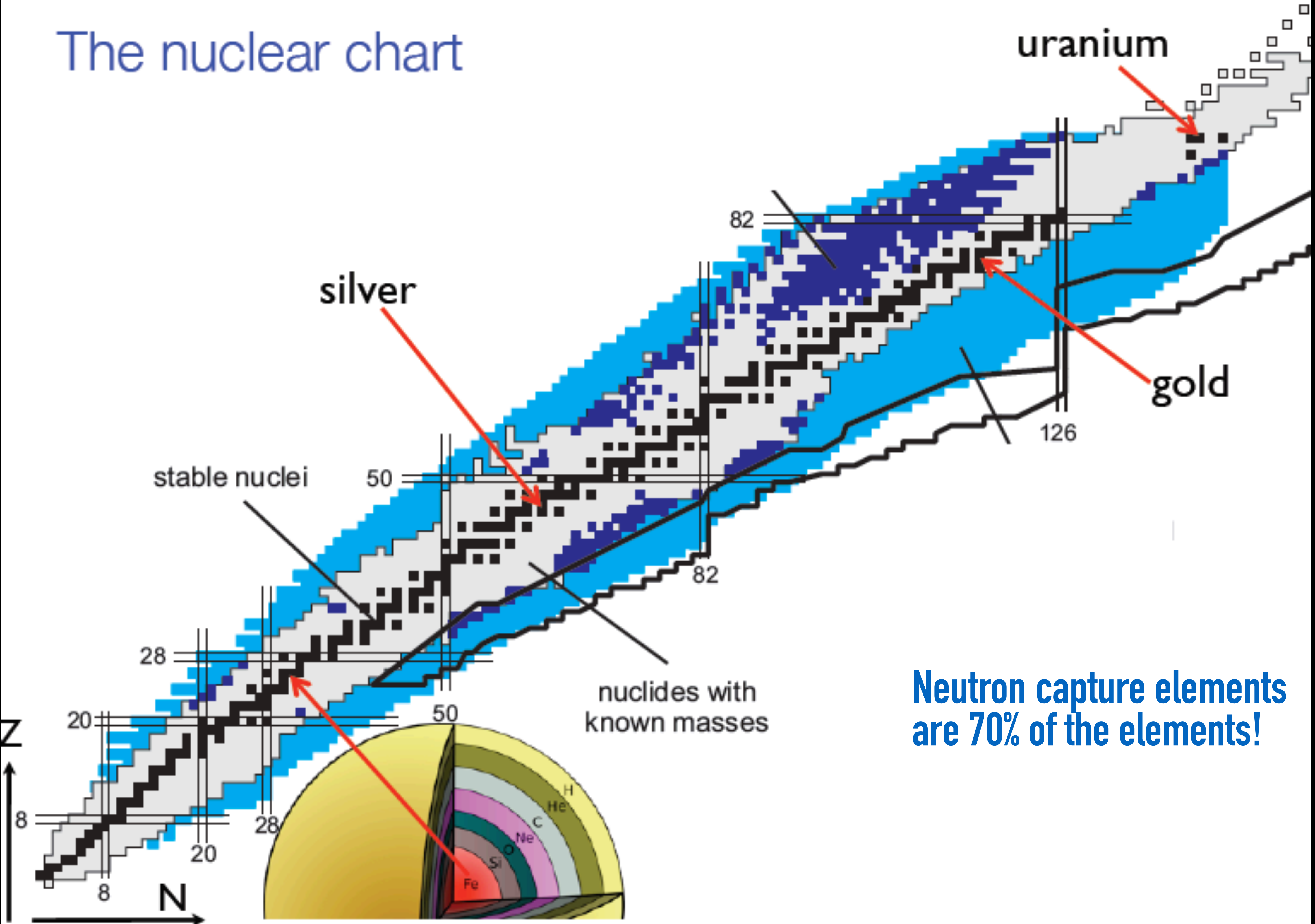
Neutron-Capture elements with HRMOS

Gabriele Cescutti
in collaboration with
Mariagrazia Franchini & Federico Rizzuti

Arcetri Observatory, 19th October 2021

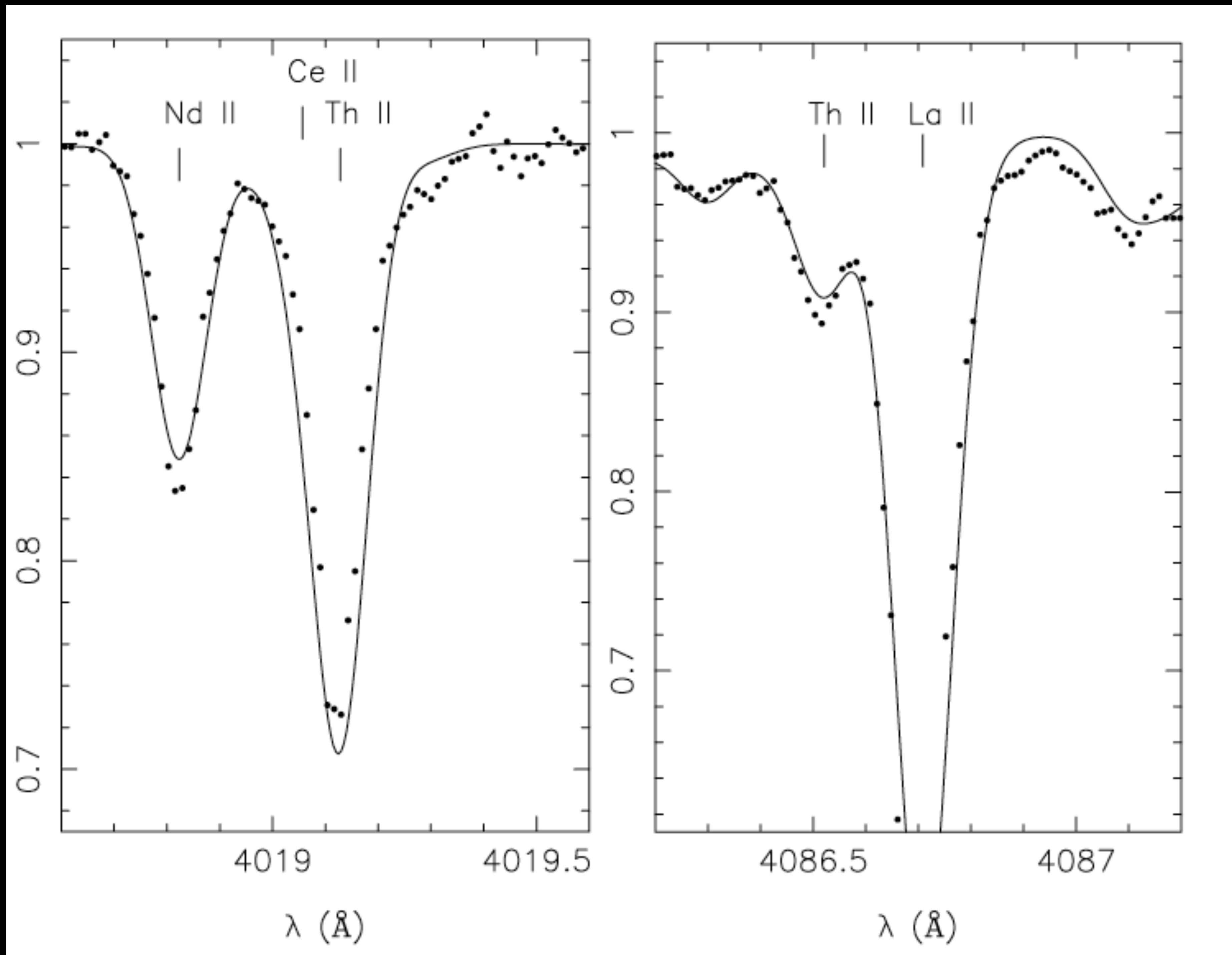
Why neutron capture elements?

The nuclear chart



Neutron capture elements are 70% of the elements!

Most of nc elements, not easy to be measured



Hill+01

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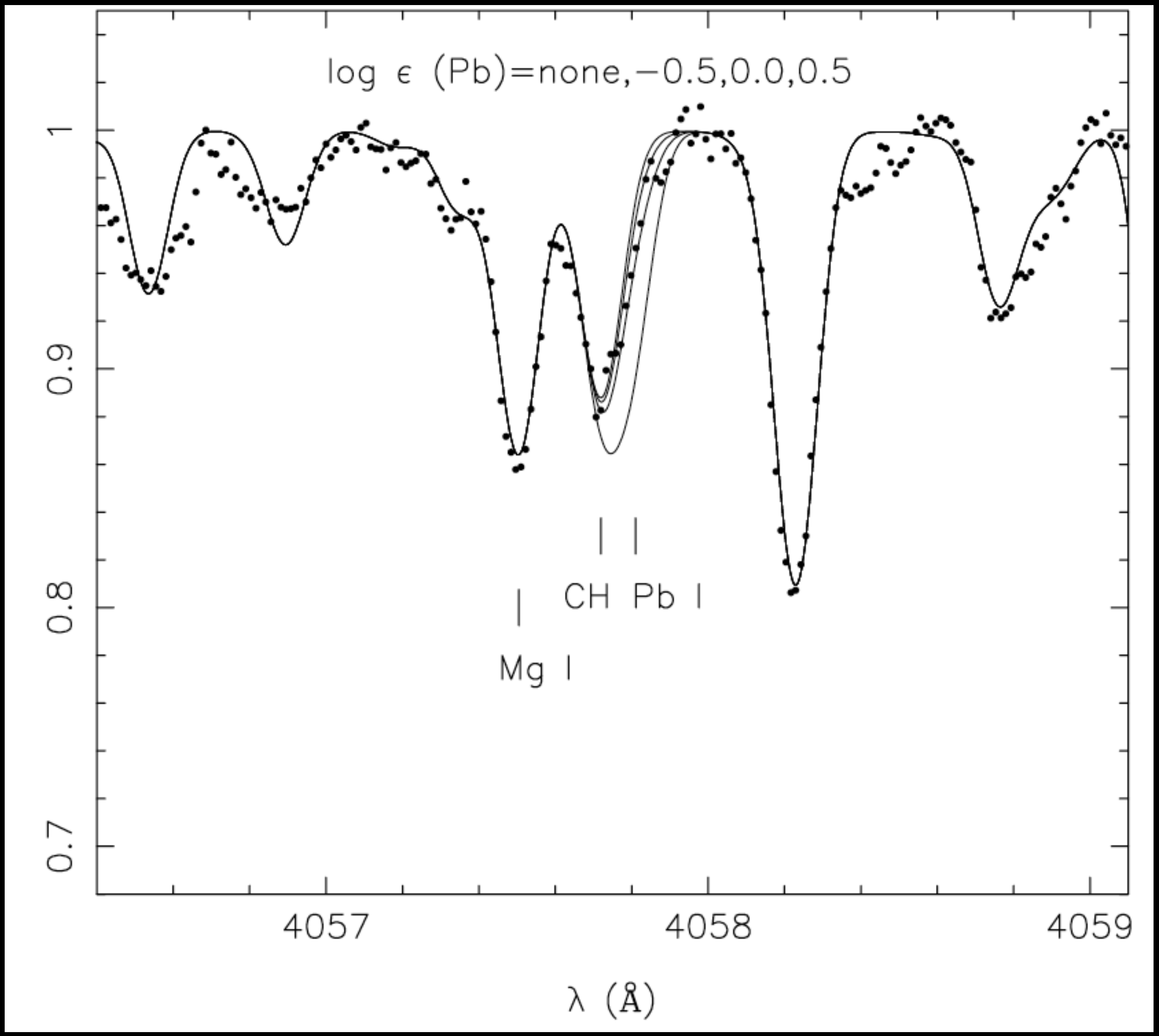
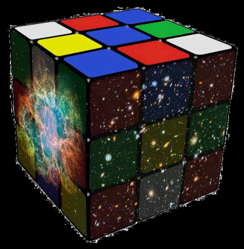
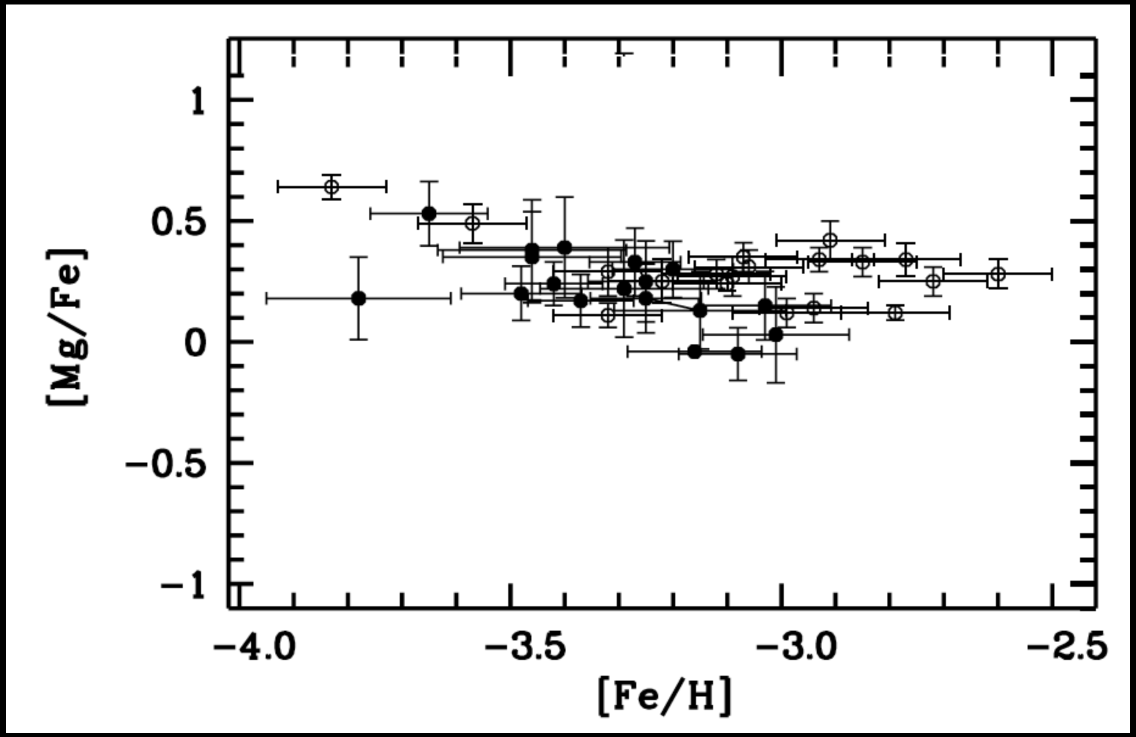


And if you want to measure bismuth… wait for CUBES

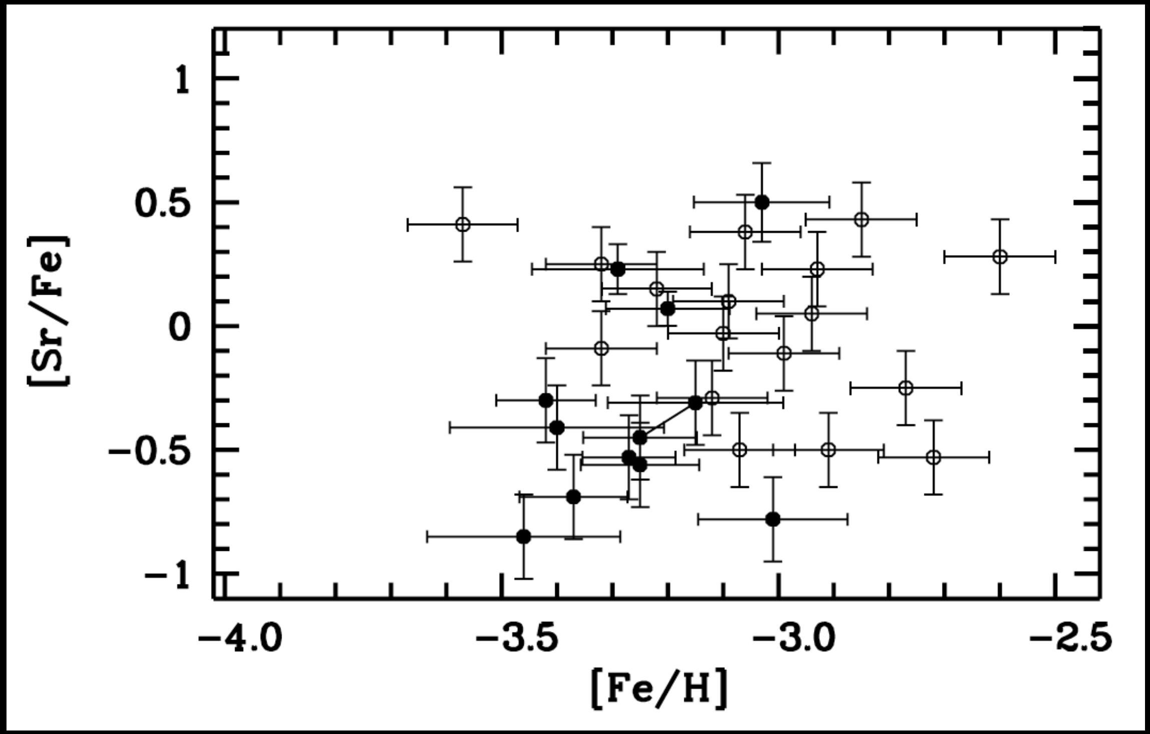


Why neutron capture elements?

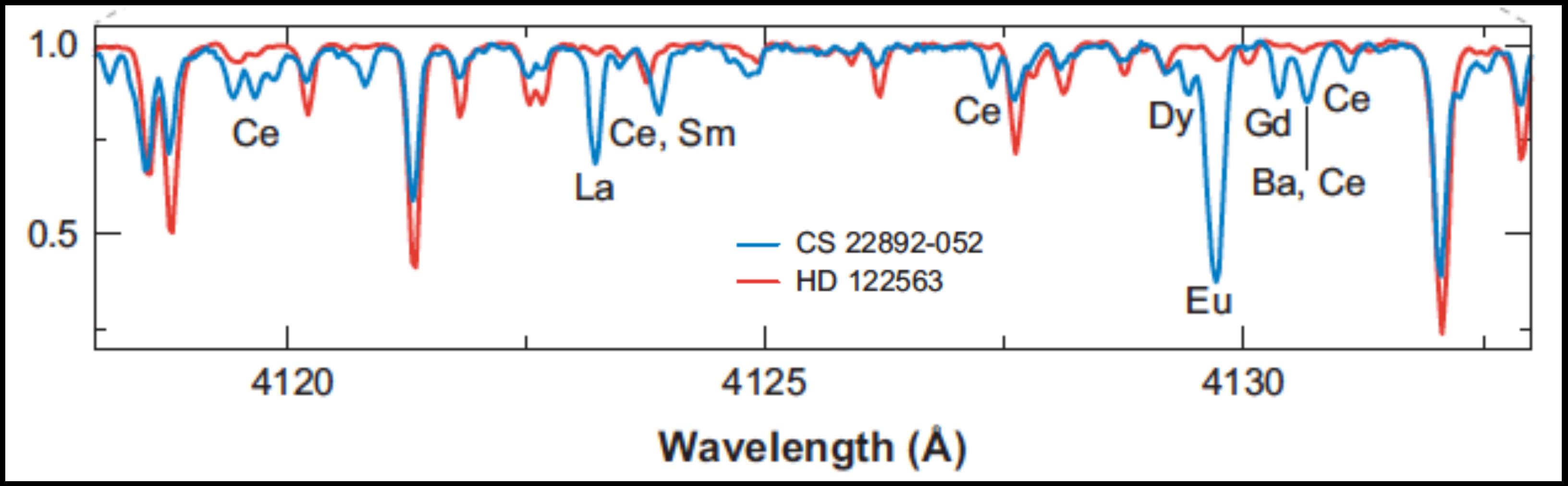
Mg: alpha-element



Sr: neutron capture element



Bonifacio+12



Sneden+08

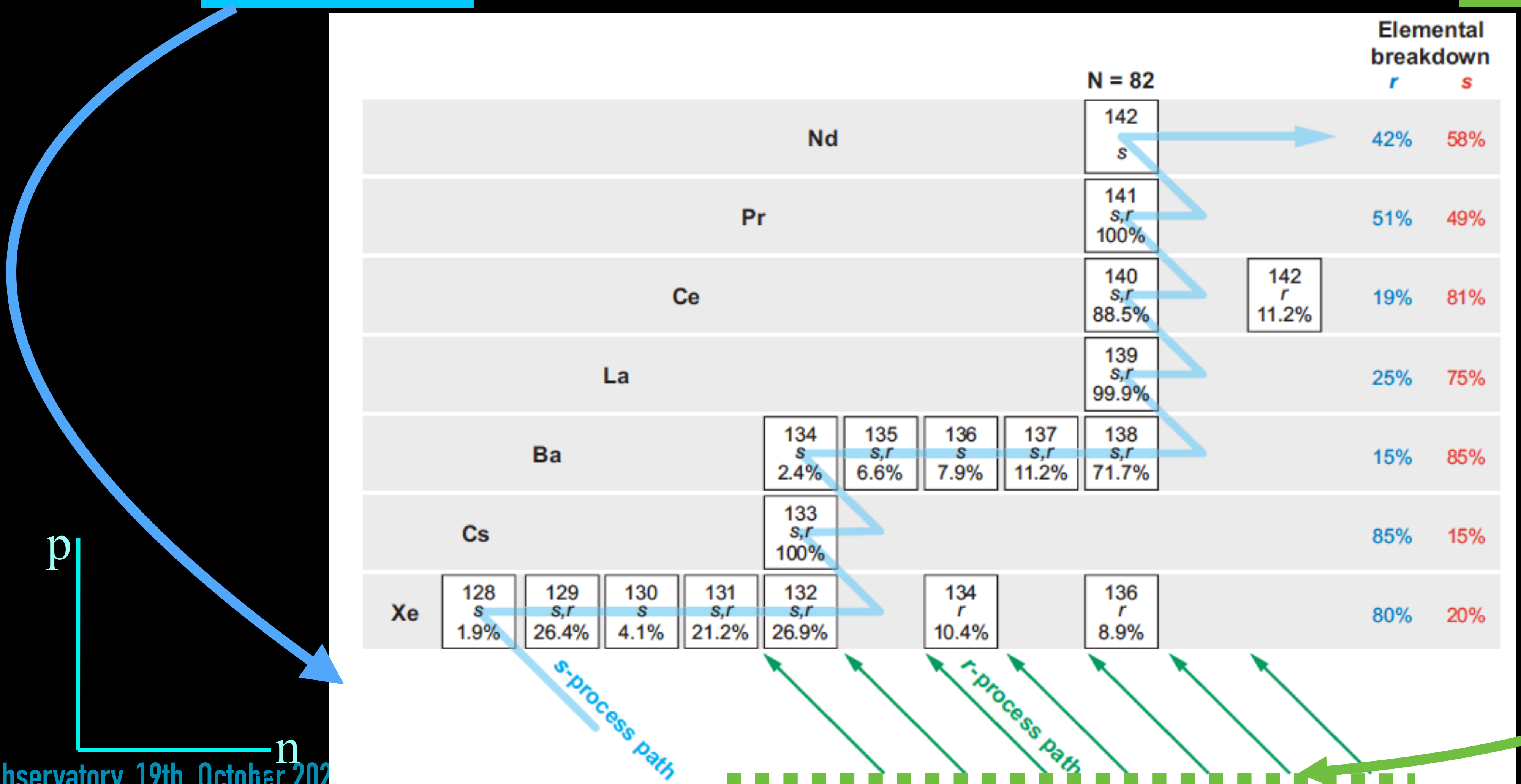
Neutron capture elements: r-s process

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

Two cases:

s-process | Different Timescale of the neutron capture | r-process

$\tau_\beta << \tau_c$ | Different process path | $\tau_\beta >> \tau_c$



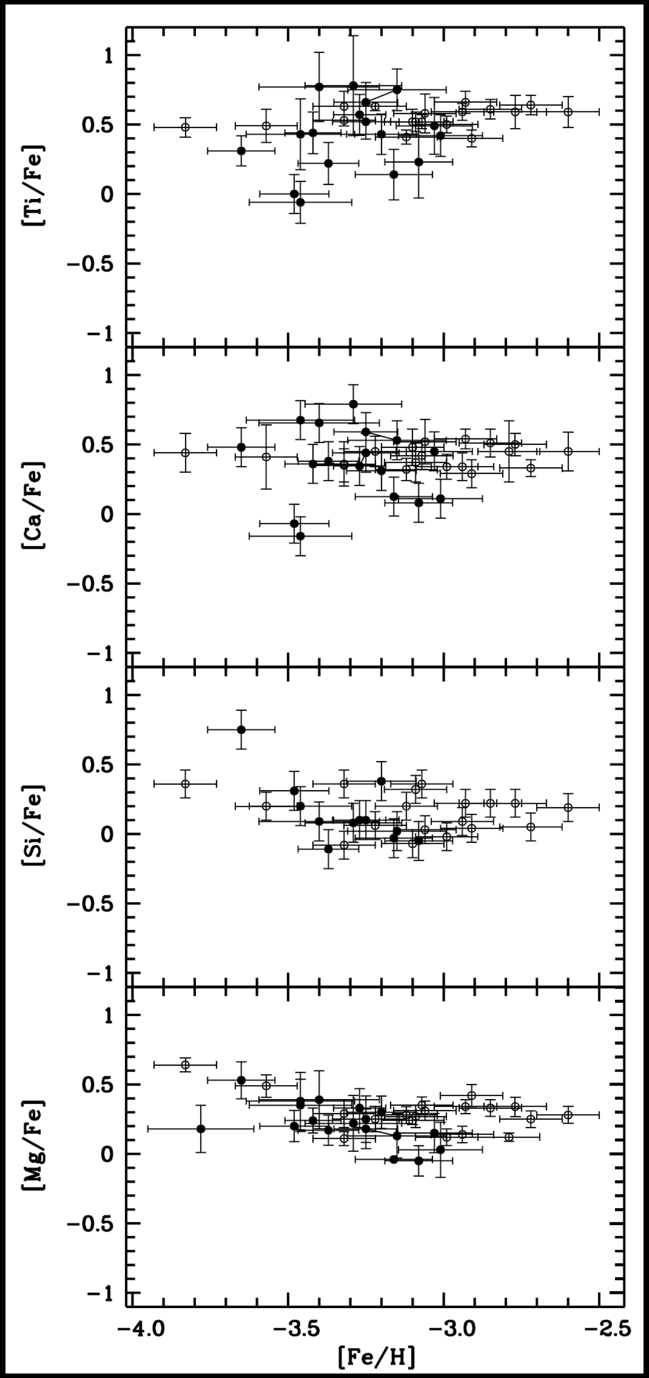
Neutron capture elements

from Truran 1981 to ~8 years ago

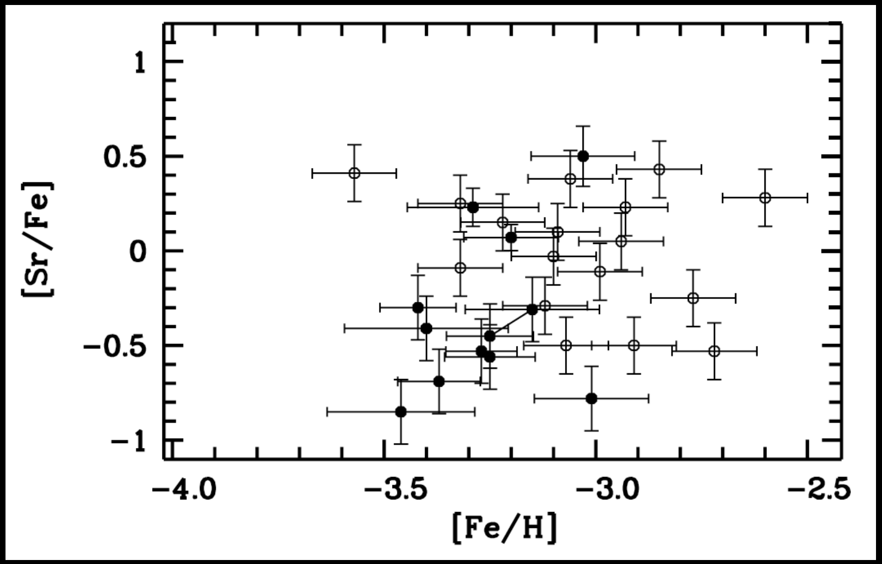
	s-process	Early Galaxy	r-process
site	Low-(intermediate) mass stars		NS mergers (& Massive stars?)
time scale	>300Myr		< 30Myr (excluding NS mergers)
yields	Cristallo+11		....
	Karakas+12		

Stochastic chemical evolution models

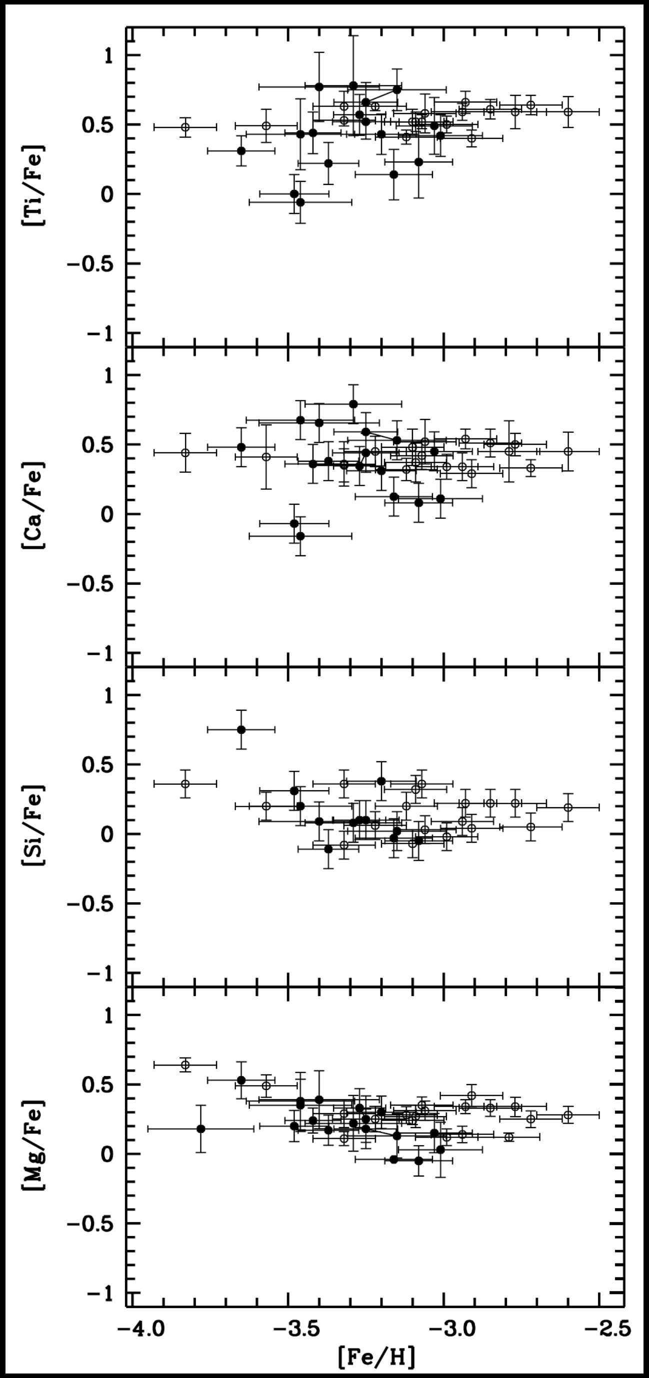
Problem:
Neutron capture elements present
a spread alpha elements do not



Bonifacio+12



Stochastic chemical evolution models



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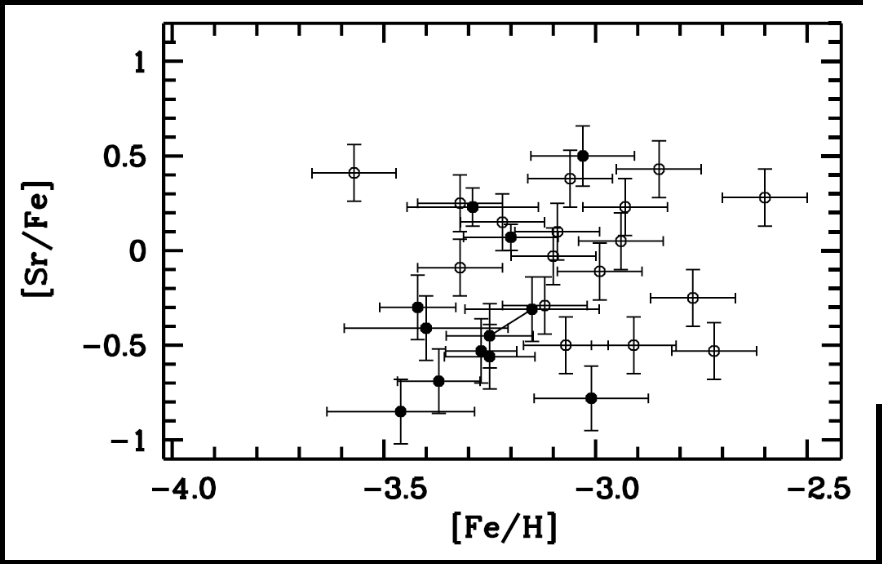

Solution:
The volumes in which the ISM is well mixed are discrete. Assuming a SNe bubble as typical volume with a low regime of star formation the IMF is not fully sampled.
This promotes spread among different volumes if nucleosynthesis of the element is is different among different SNe,

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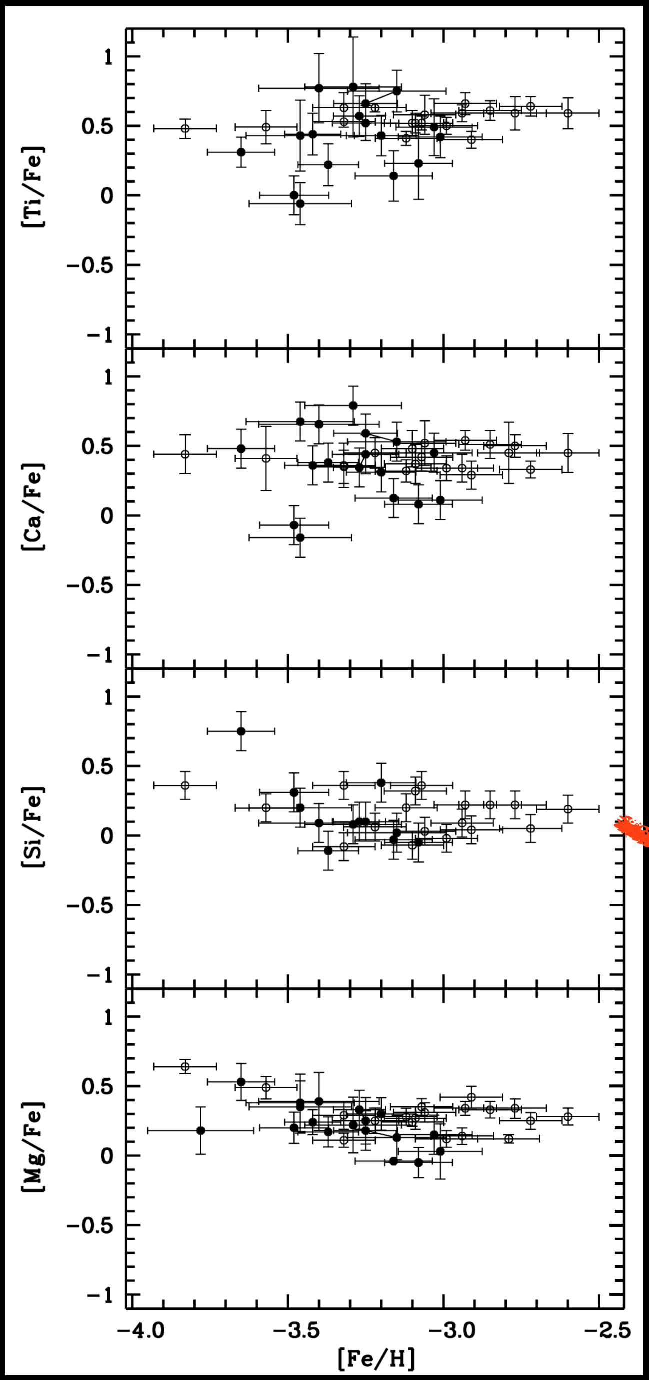

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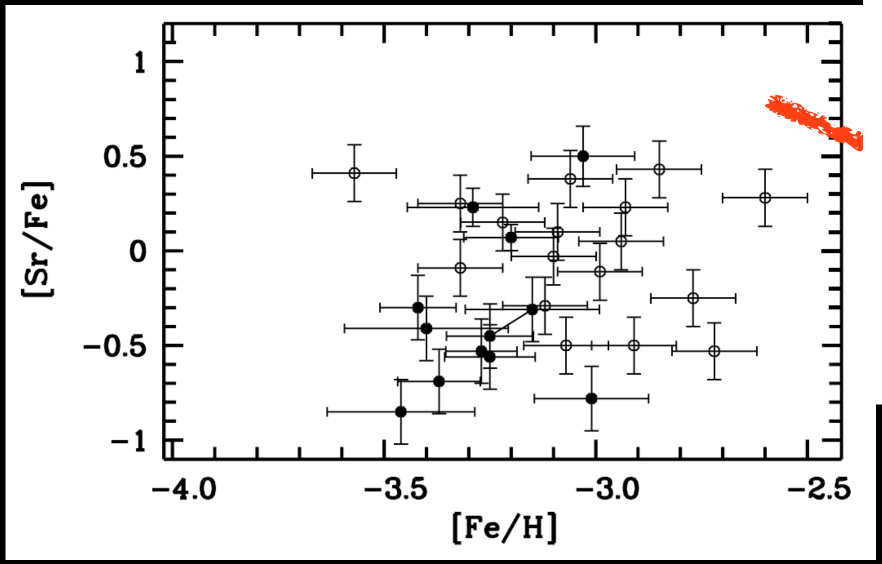

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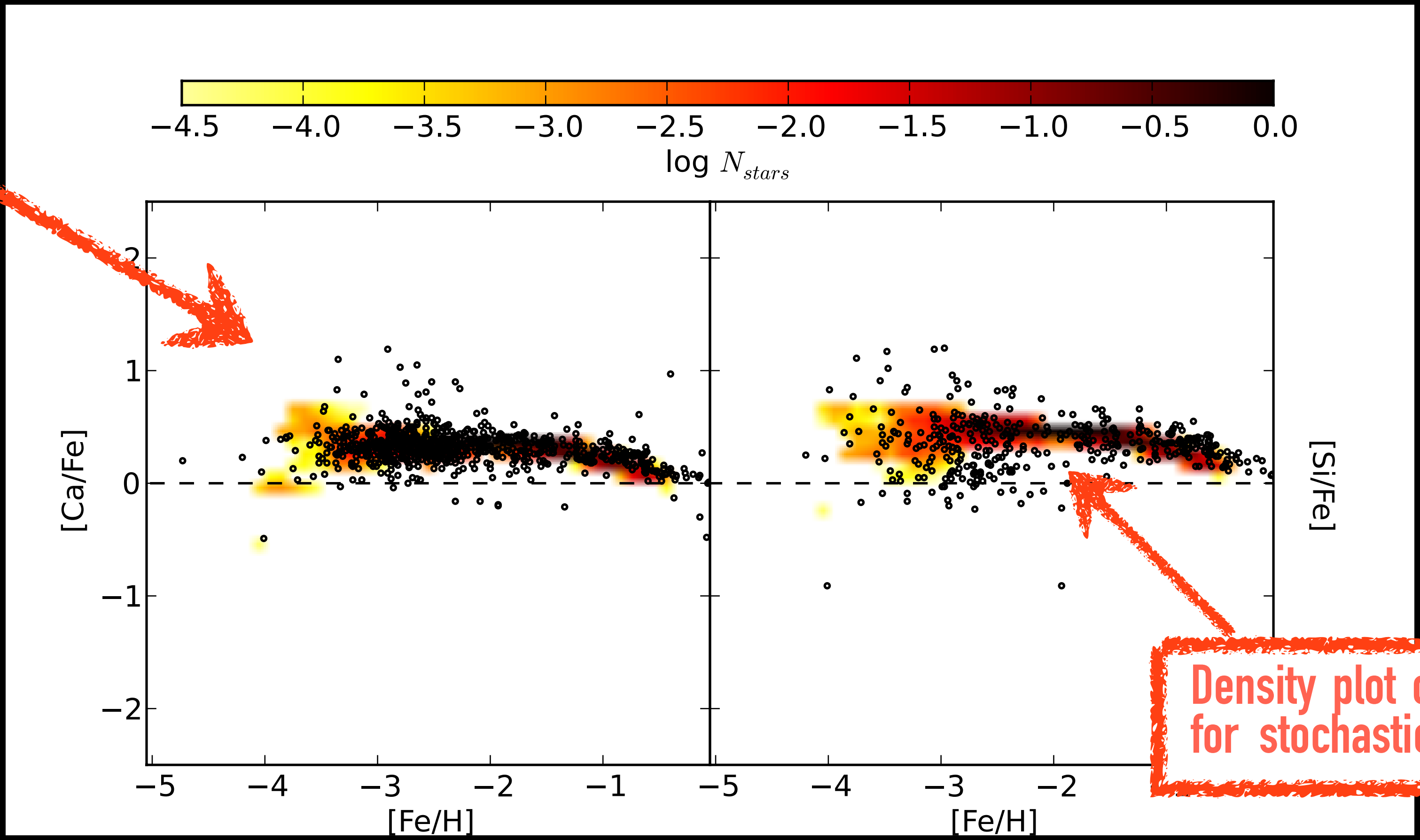

Density plot of long living stars
for stochastic model

Cescutti 2008
Cescutti et al. 2013

data collected in
Frebel 2010

Stochastic model for Ba in the Galactic halo

We run the stochastic model (based on Cescutti '08) with these yields for the Ba production:

10% of all the massive stars produce $8\ 10^{-6}$ Msun of Ba

data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16

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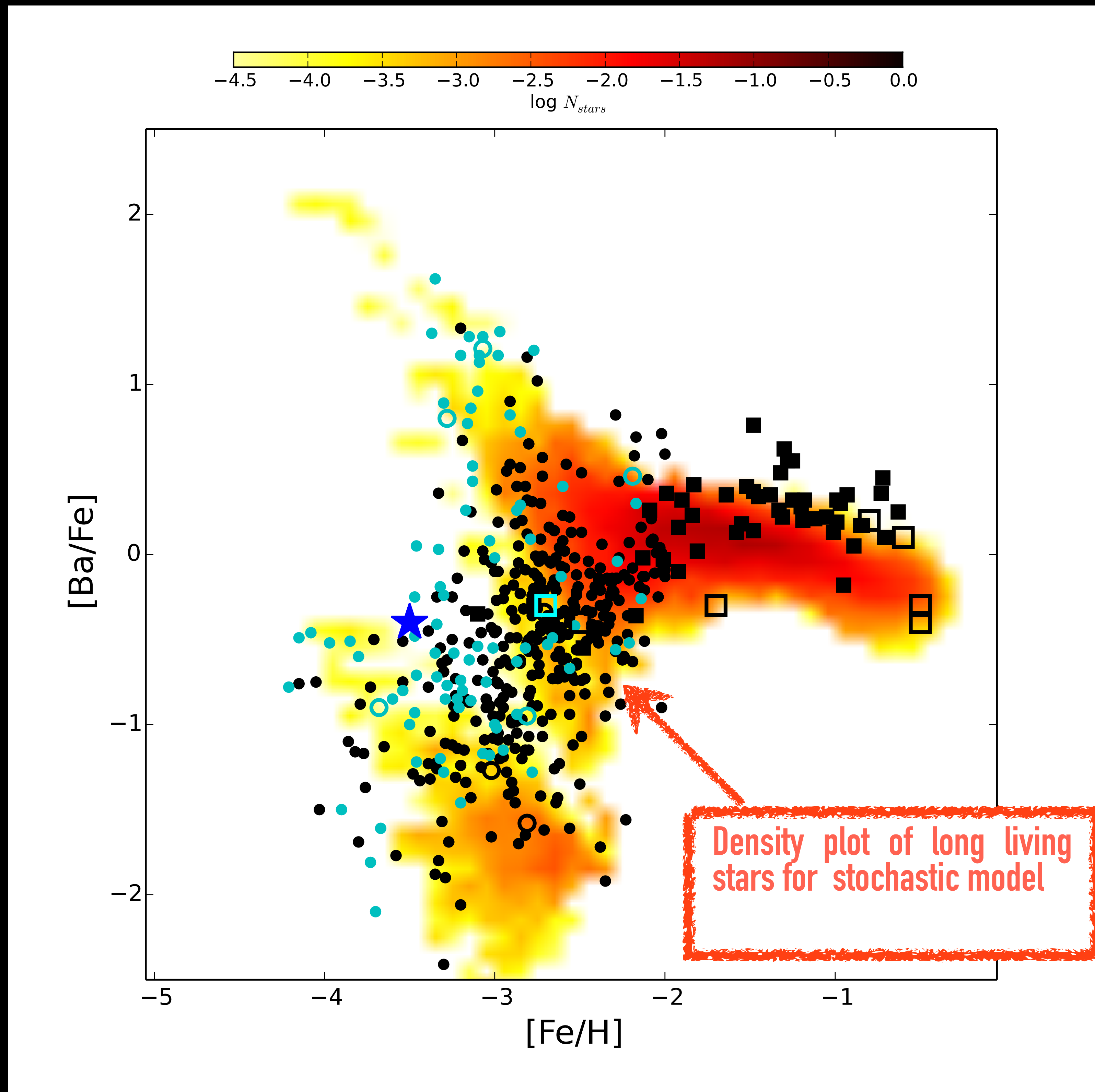

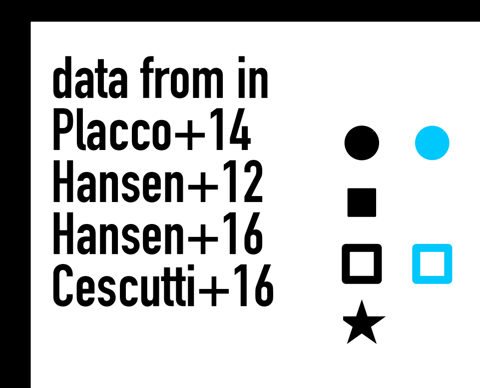

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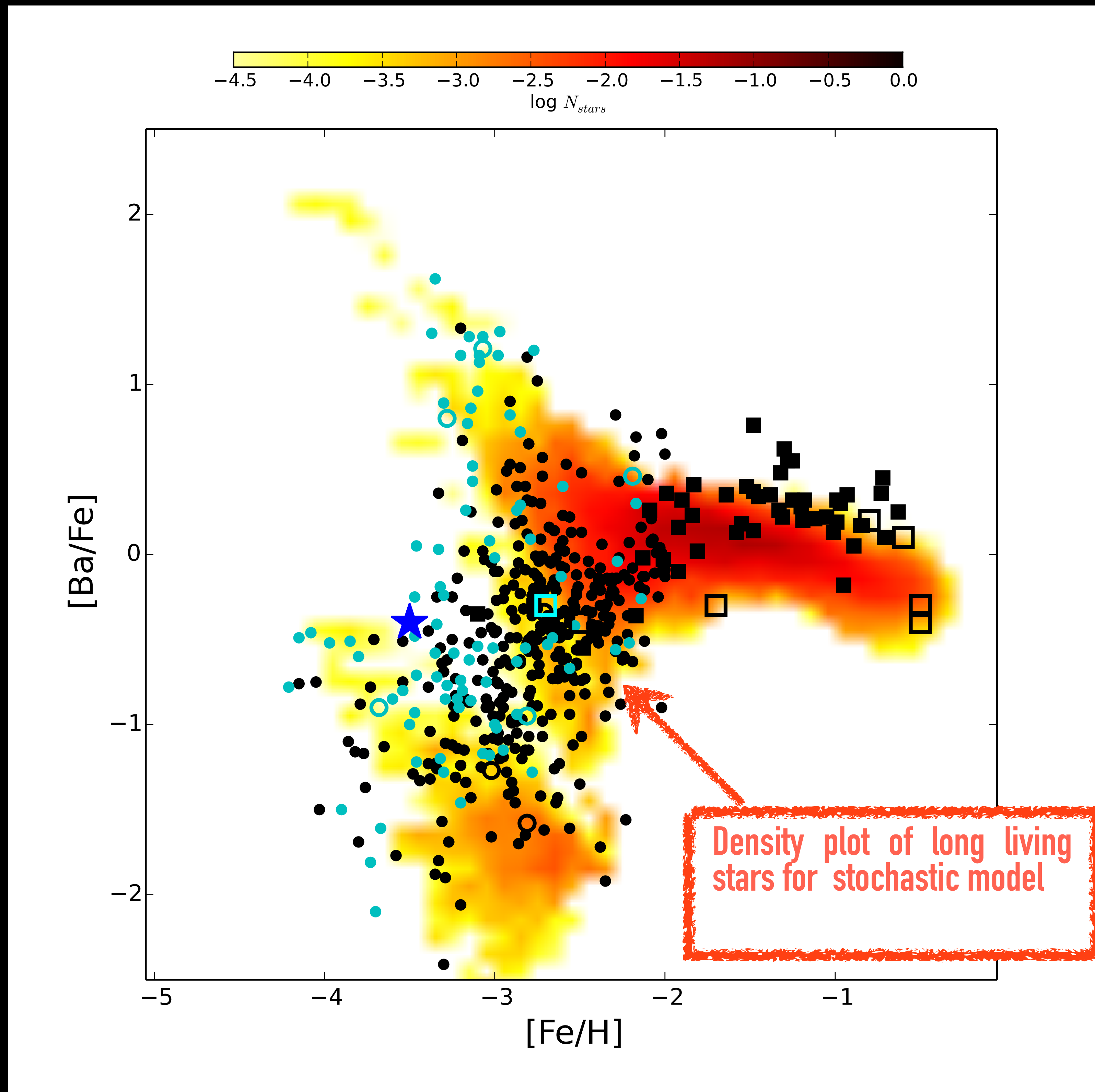
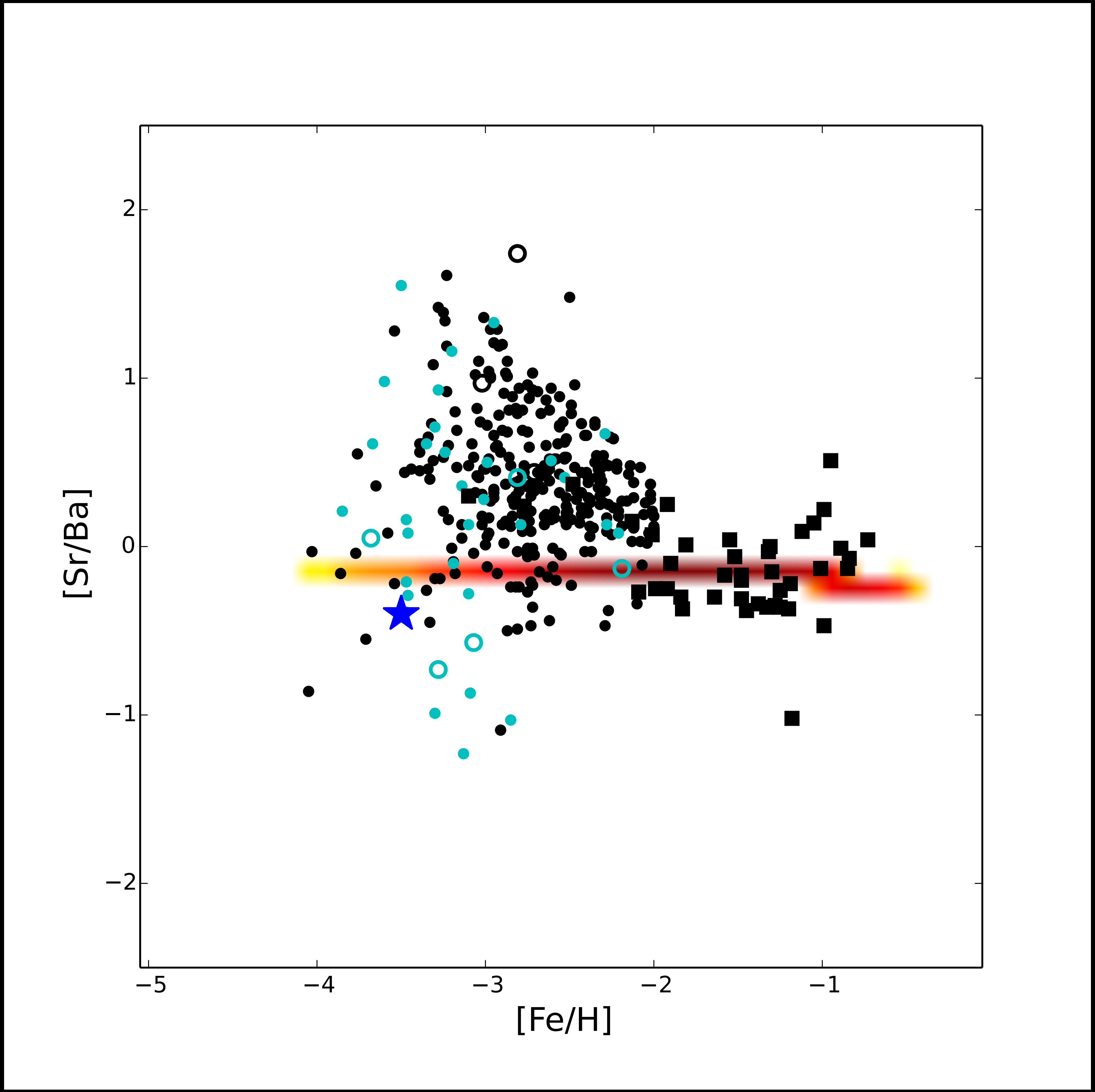


We can reproduce the [Ba/Fe] spread...

data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16

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 '08)

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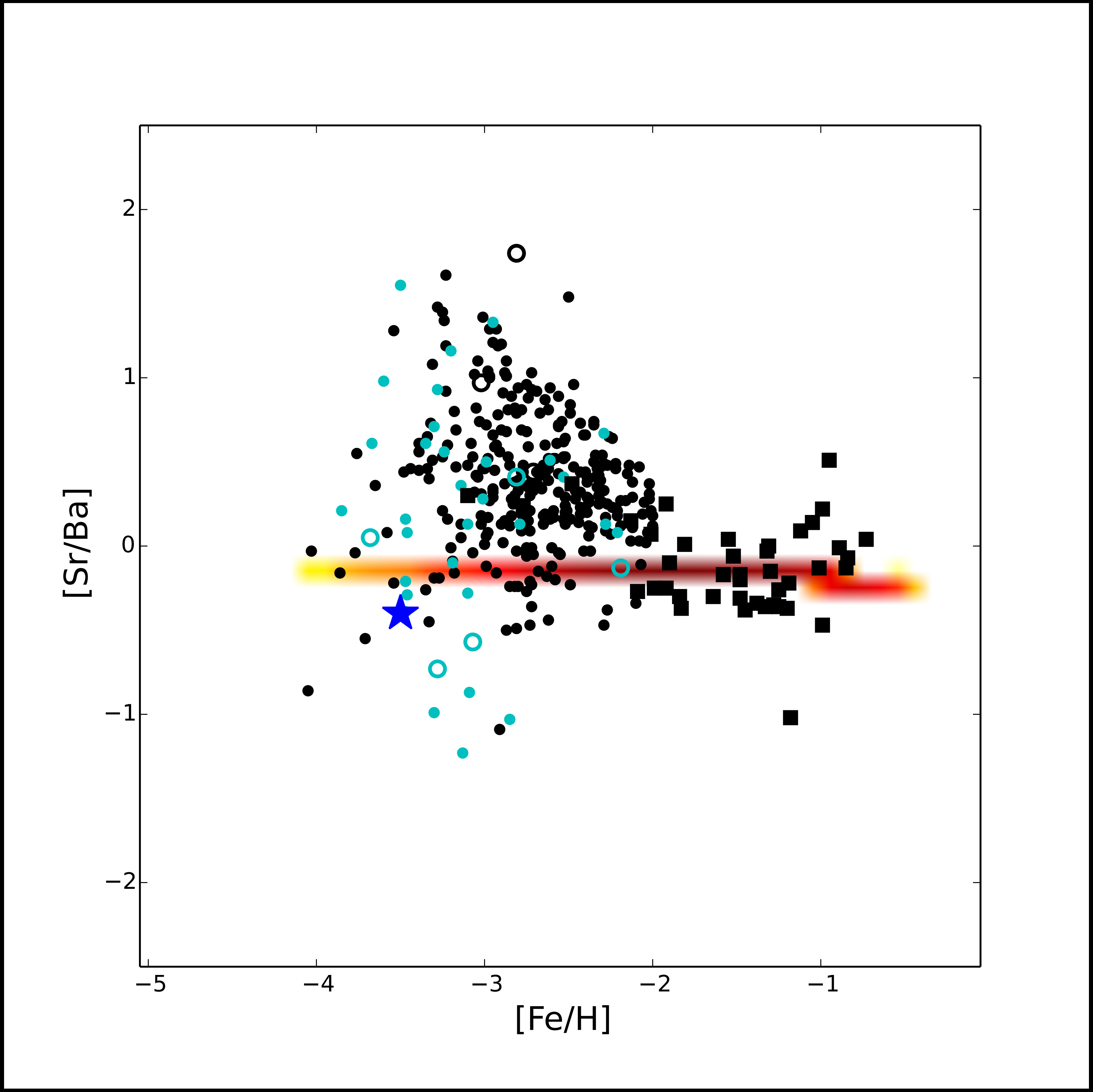

It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

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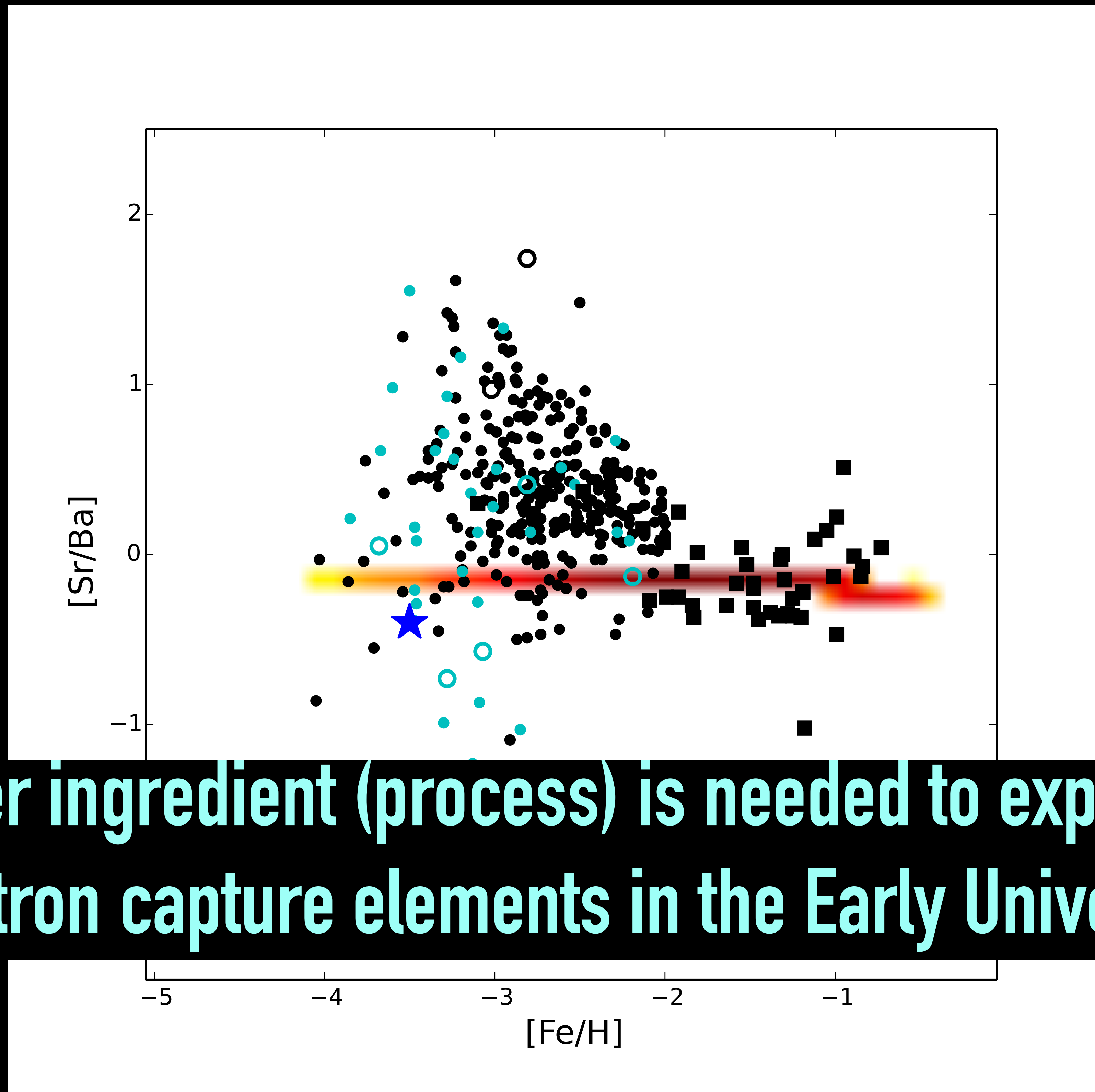

It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
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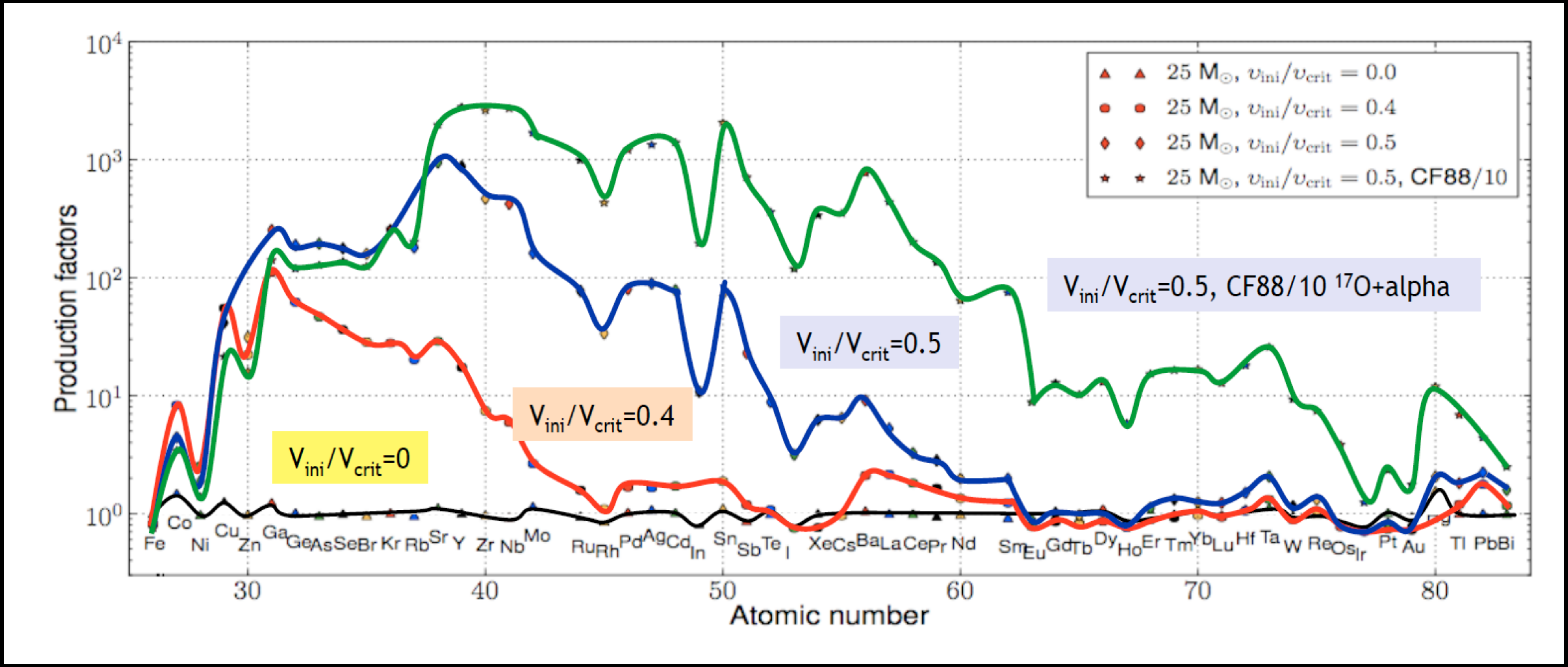
Another ingredient (process) is needed to explain the neutron capture elements in the Early Universe!

Low metallicity and rotating massive stars

Frischknecht et al. 2012 , 2016 (self-consistent models with reaction network including 613 isotopes up to Bi)



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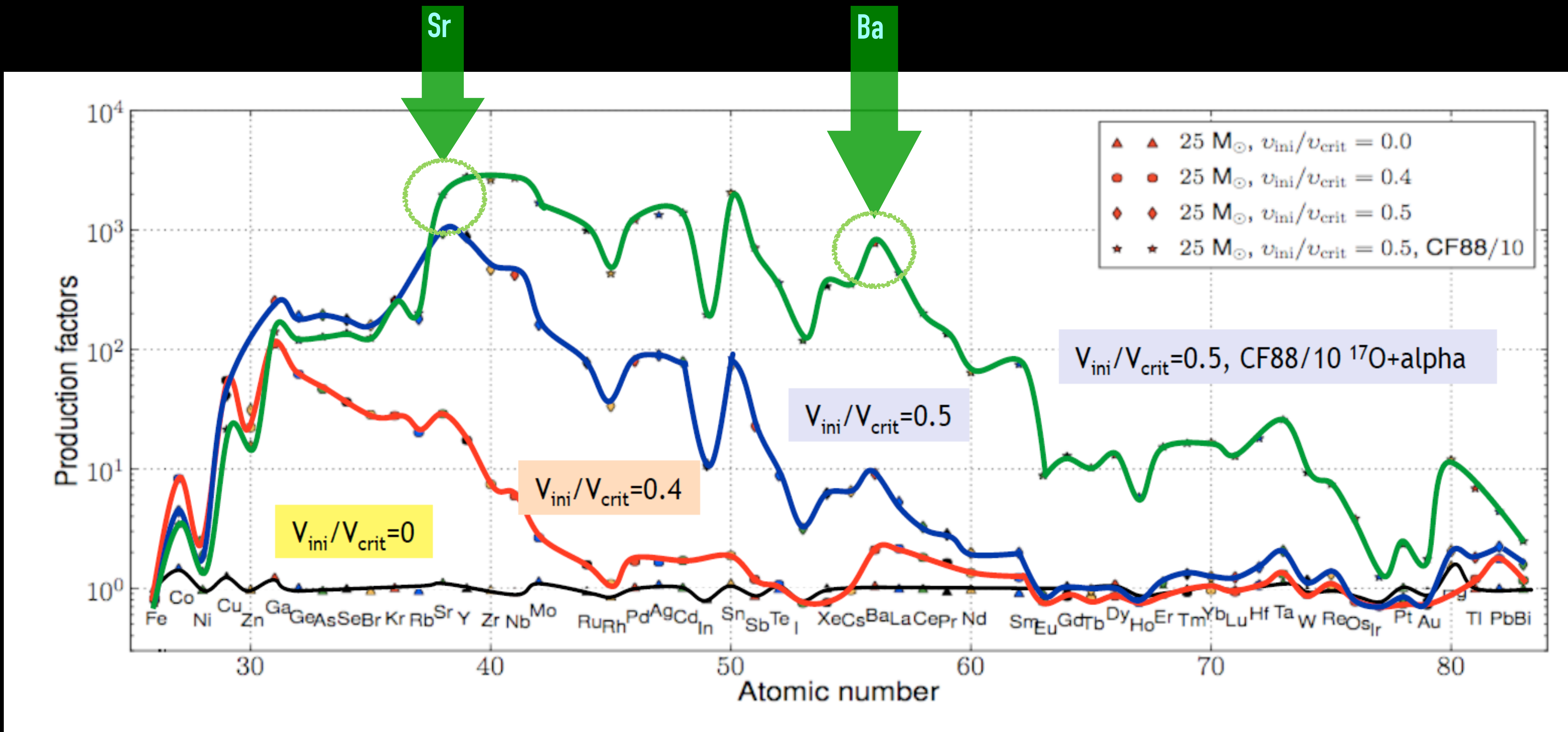
Rotating massive stars can contribute to s-process elements!



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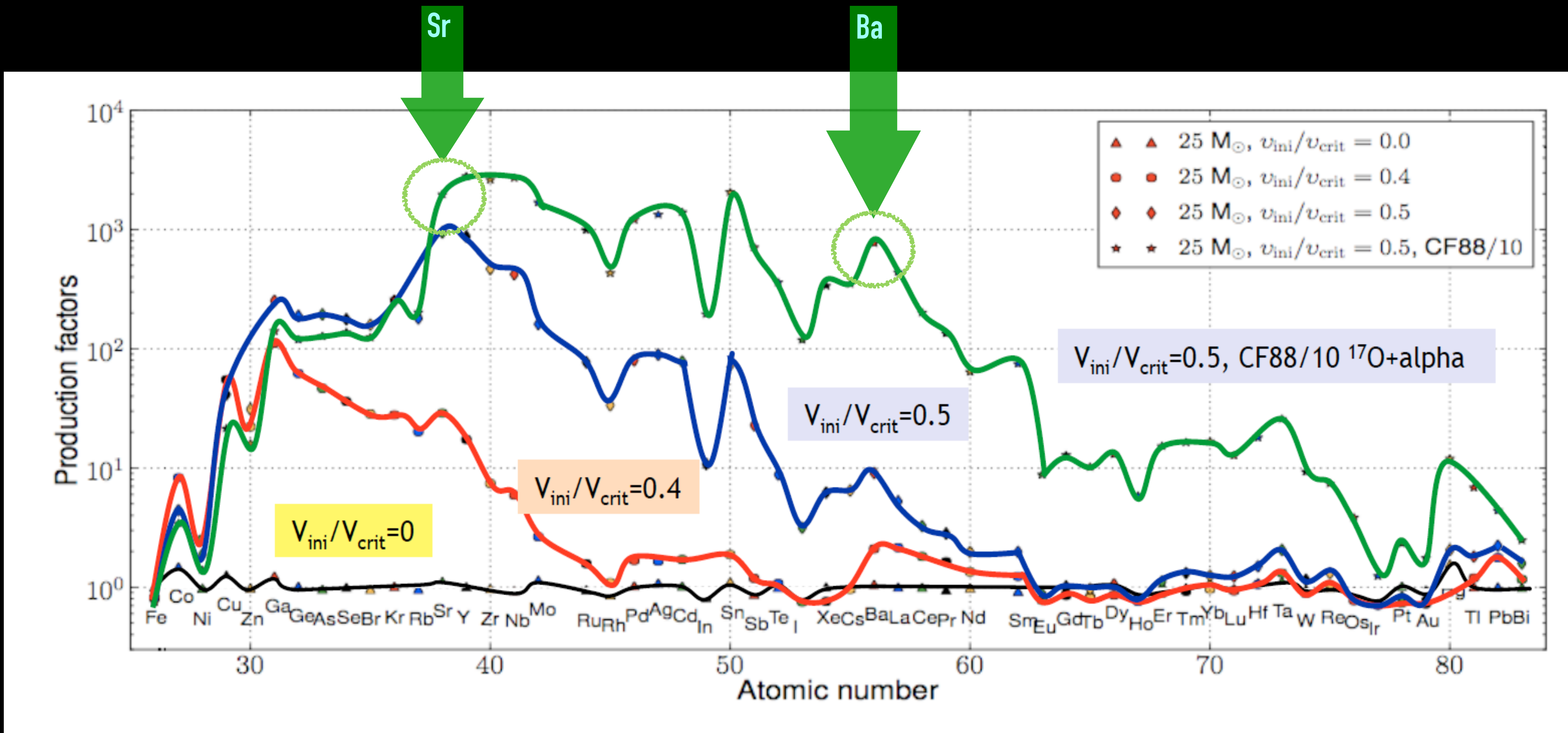

Can they explain the puzzles for Sr and Ba in halo?

Neutron capture elements

from Chiappini+11

Early Galaxy

	s-process		r-process
site	Low-(intermediate) mass stars	rotating Massive stars	NS mergers (& Massive stars?)
time scale	>300Myr	< 30Myr	< 30Myr (excluding NS mergers)
yields	Cristallo+ 2011	(Frischknecht+ 2012) Frischknecht+ 2016	....
	Karakas+ 2012	Limongi and Chieffi 2018	

s-process from rotating massive stars

+ an r-process site (the 2 productions are not coupled!)

Cescutti et al. (2013)
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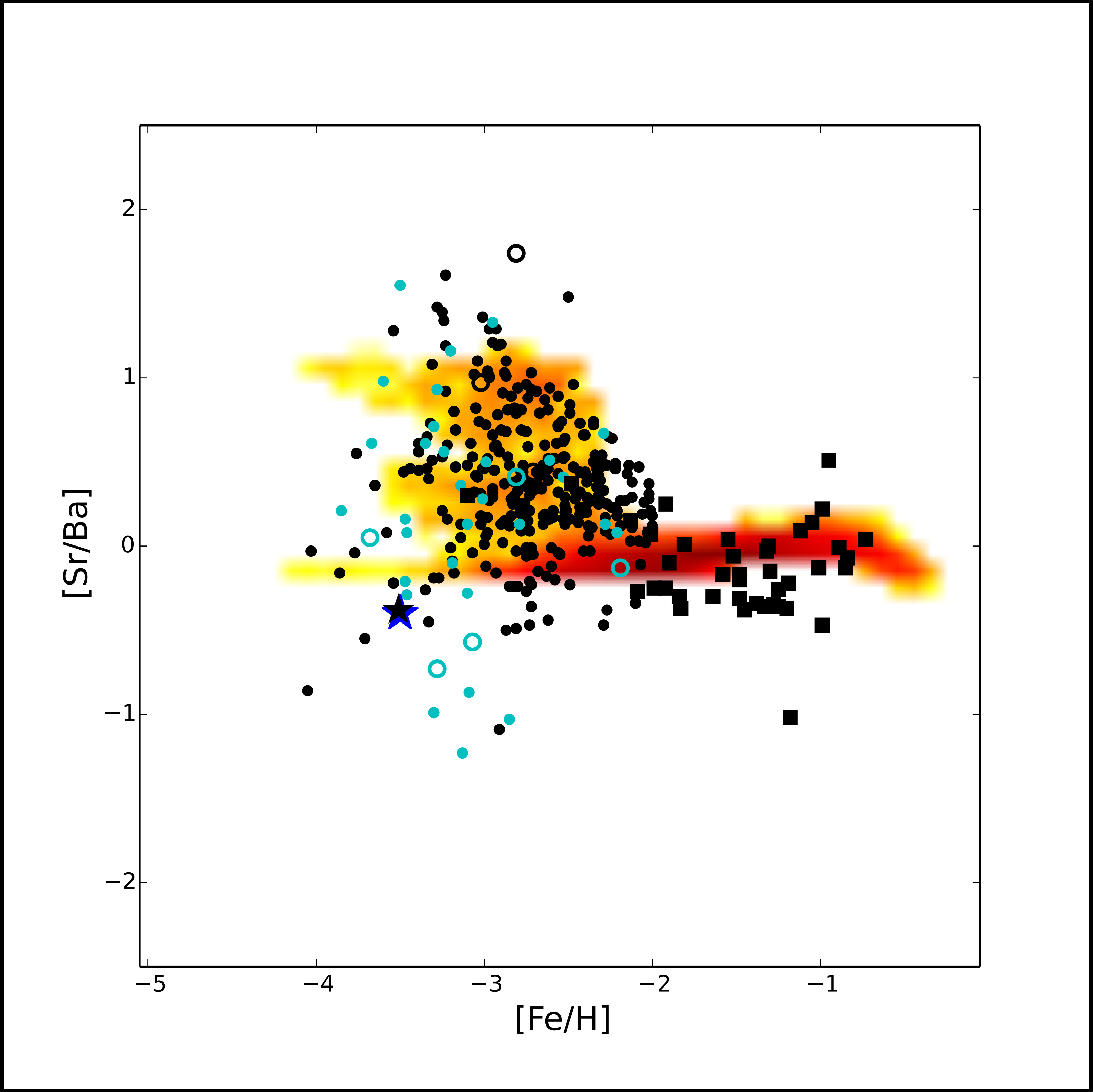

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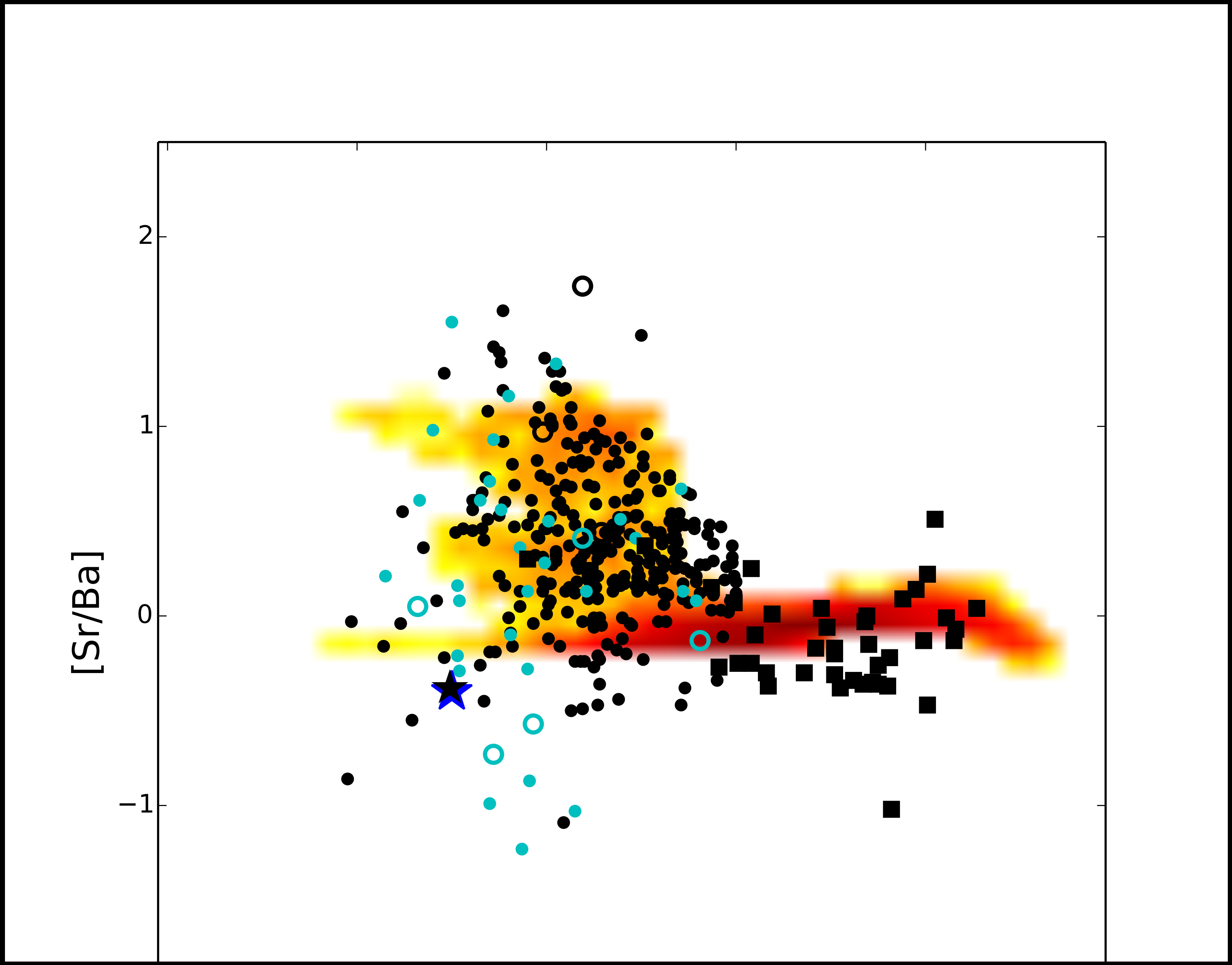
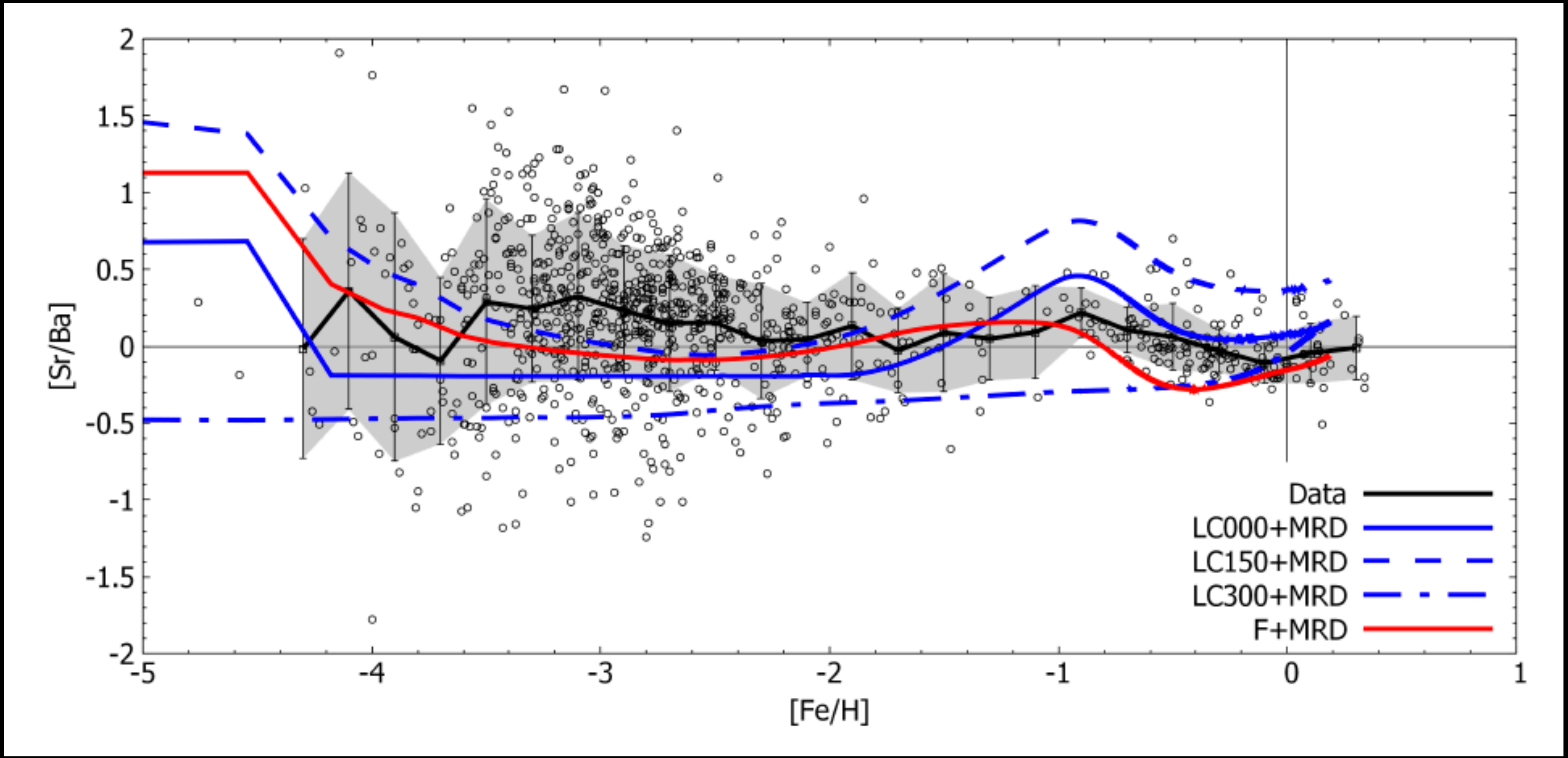


A s-process (from rotating massive stars)
and an r-process (from rare events)
can reproduce the neutron capture elements in the Early Universe

Confirmed in Rizzuti et al. (2019)

adopting Limongi&Chieffi18



see also Prantzos et al. 2018

Data+stochastic modelling

assuming Limongi&Chieffi18 yields with 3 rotational velocities (300km/s, 150km/s and 0 km/s) + interpolation

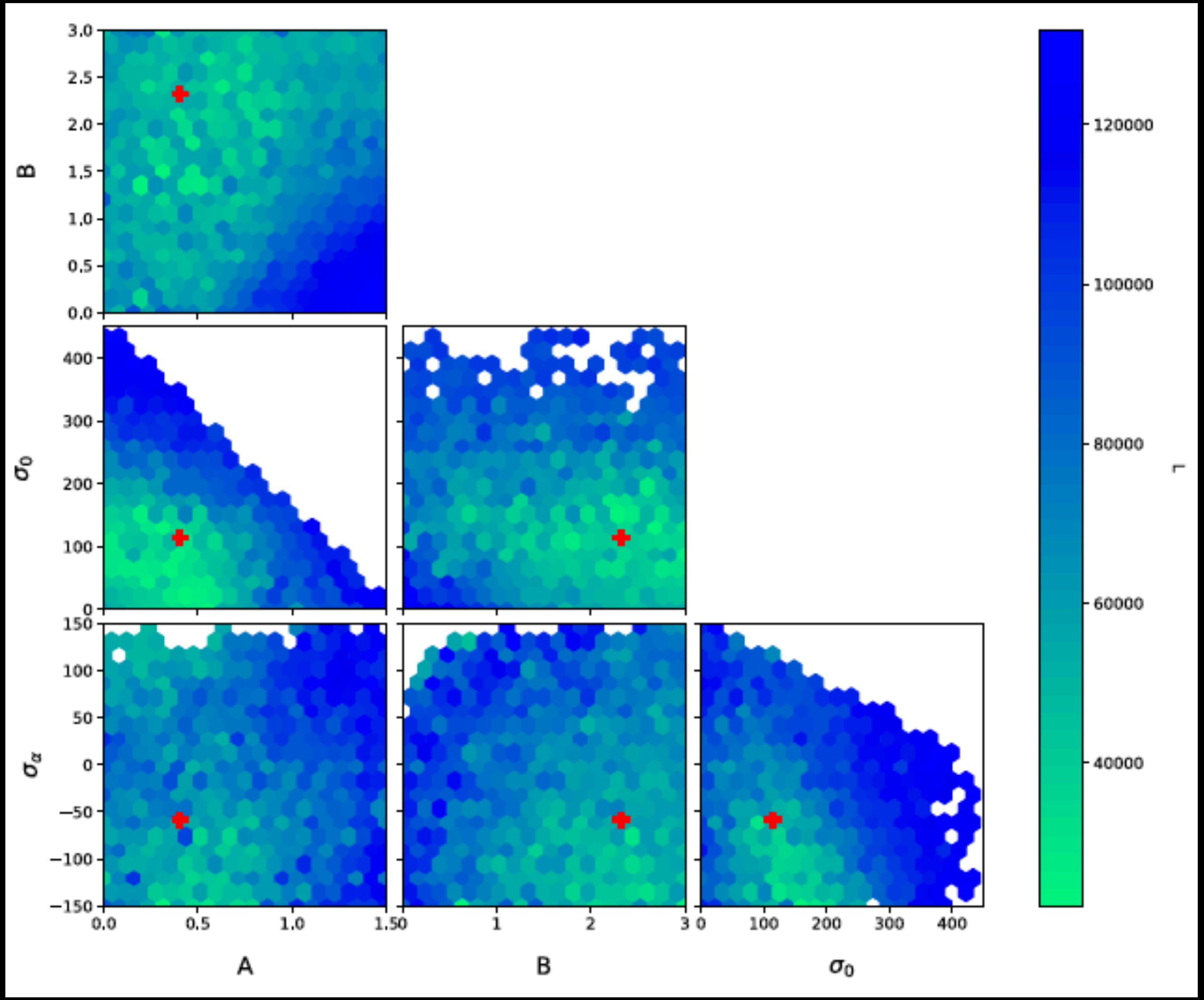
$$v_{rot}([Fe/H]) \propto e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

$$\mu = \begin{cases} 300 \cdot A \cdot \exp\{-B \cdot ([\mathrm{Fe/H}]+3)\}\ \mathrm{km\,s^{-1}} & \text{for [Fe/H]} \geq -3 \\ 300 \cdot A\ \ \mathrm{km\,s^{-1}} & \text{for [Fe/H]} < -3 \end{cases}, \quad (7)$$

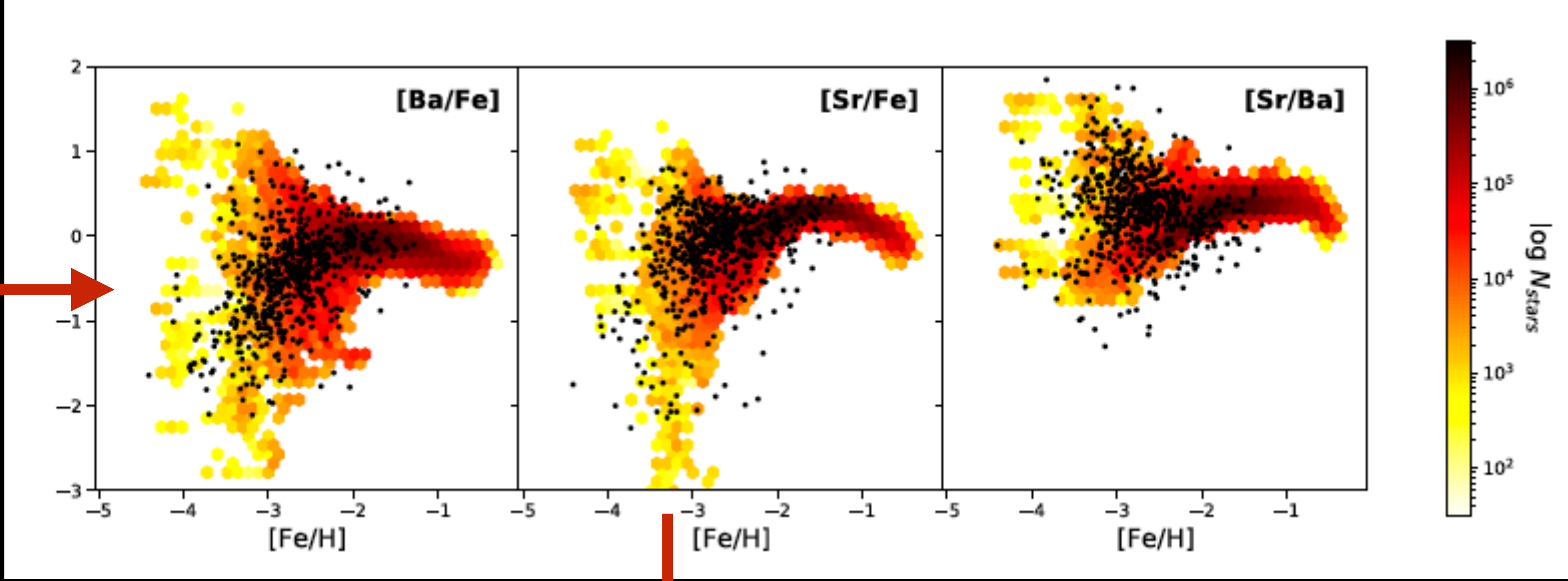
$$\sigma = \begin{cases} \sigma_0 + \sigma_\alpha \cdot ([\mathrm{Fe/H}]+3) & \text{for [Fe/H]} \geq -3 \\ \sigma_0 & \text{for [Fe/H]} < -3 \\ 0 & \text{for } \sigma_0 + \sigma_\alpha \cdot ([\mathrm{Fe/H}]+3) < 0 \end{cases}, \quad (8)$$

Rizzuti et al. 2021

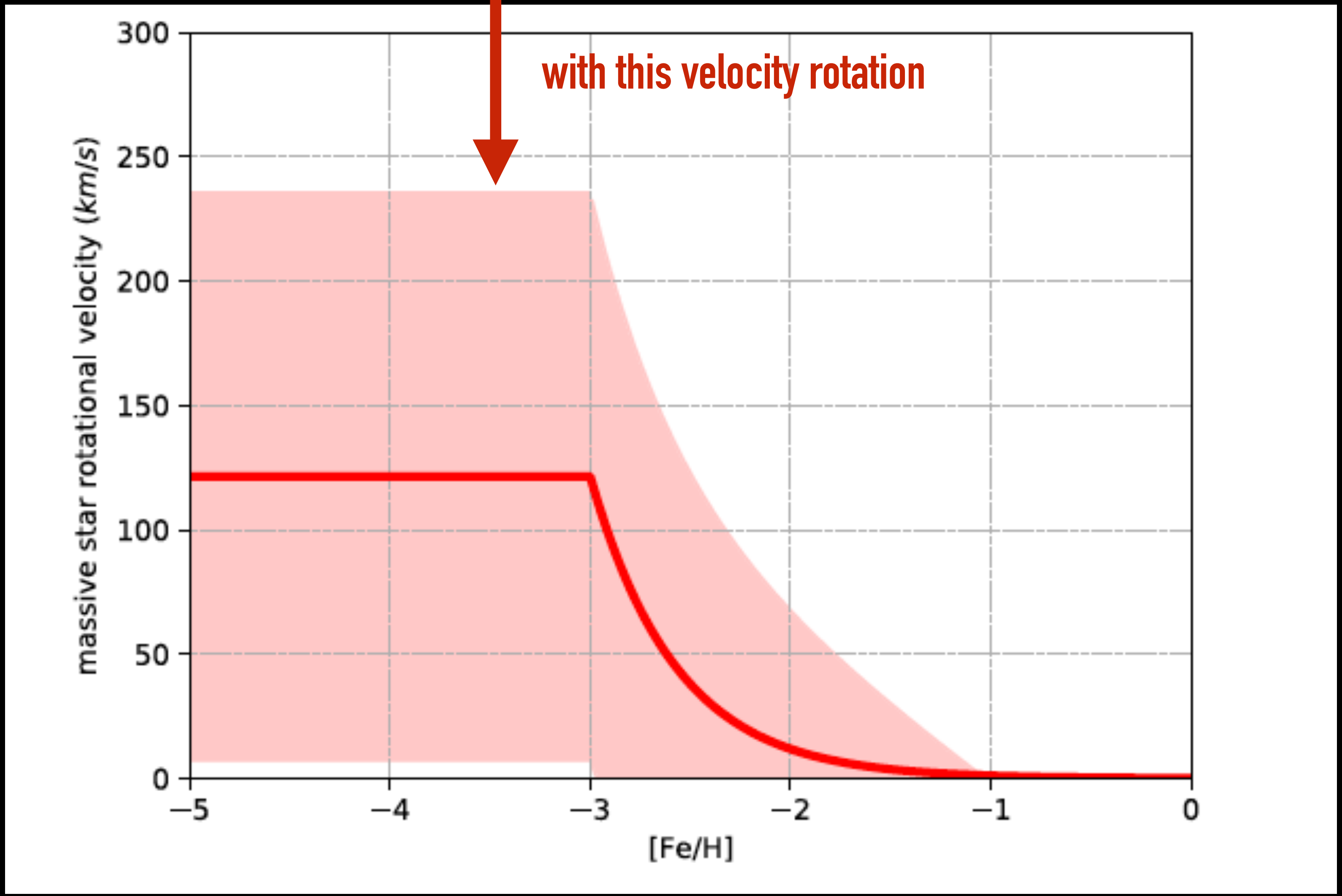
$$L = -\sum_{\mathrm{data}} \log(\mathrm{model}\,[\mathrm{data}])$$



BEST MODEL



with this velocity rotation



CAVEAT

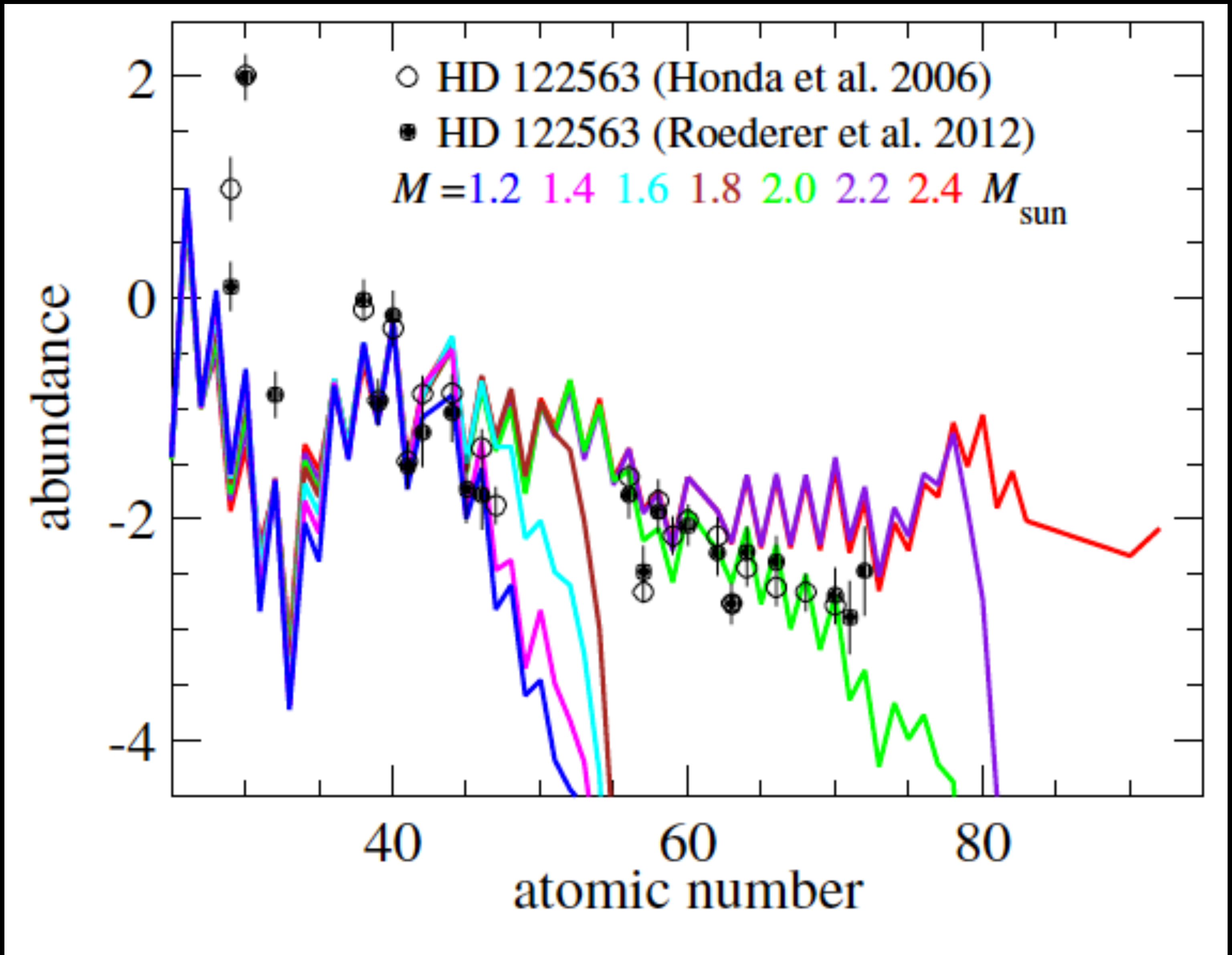
The only possible answer?

Another possible solution is the production of

+ a weak r-process

(not able to produce all the elements up to thorium)

+ a main r-process



Wanajo 2013, r-process production in proto neutron star wind

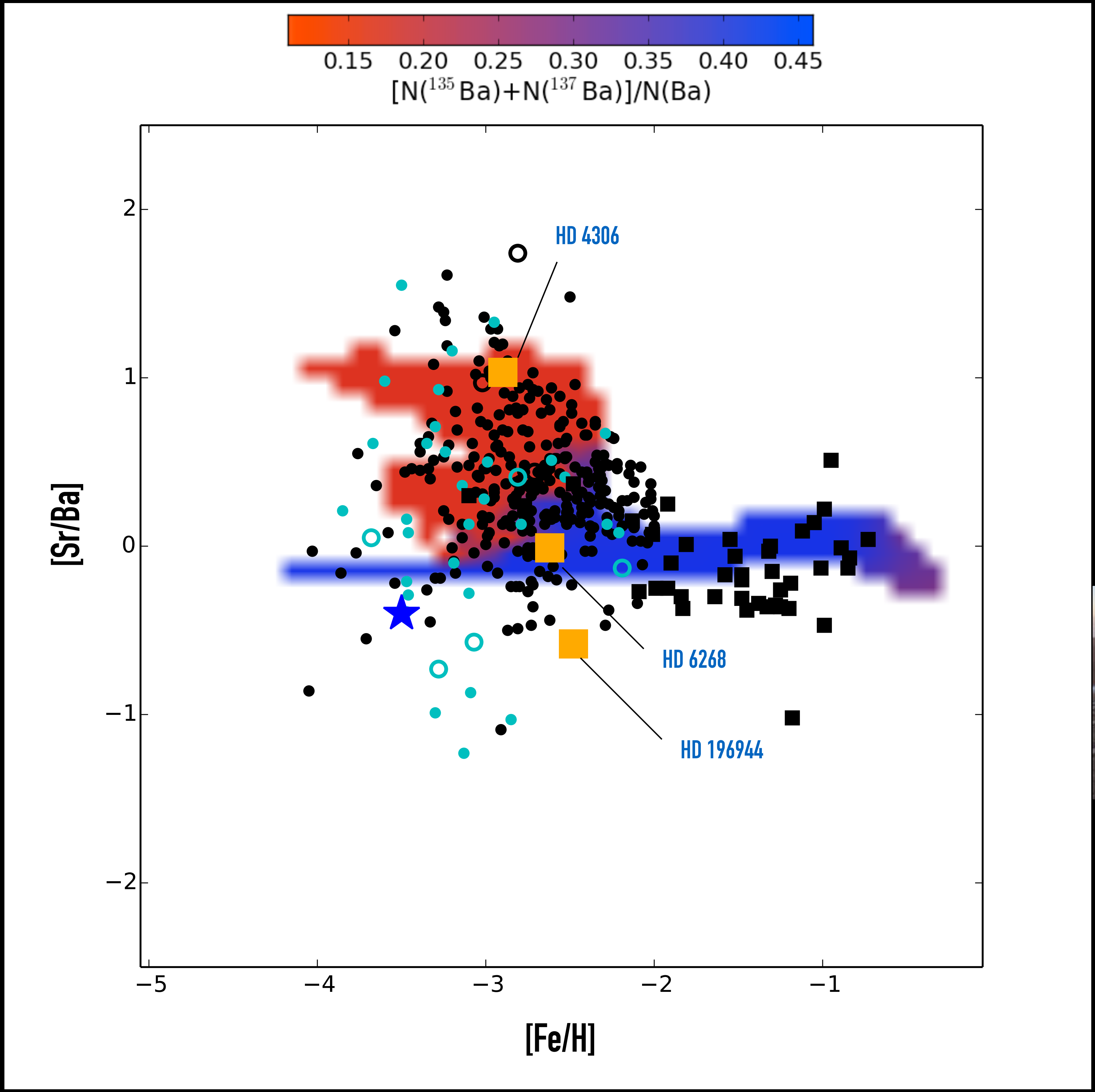
Isotopic ratio for Ba

The rotating massive stars scenario naturally predicts different Ba isotopic ratios in halo stars.

This prediction can be used to test our scenario.

Challenging to check these predictions

See results on HD 140283 from Magain (1995) to Gallagher+(2015)



Cescutti and Chiappini (2014)

3 stars with a R~100'000 & S/N~900 with UVES at VLT

"normal" value high R ~ 30'000 high S/N ~ 80-100

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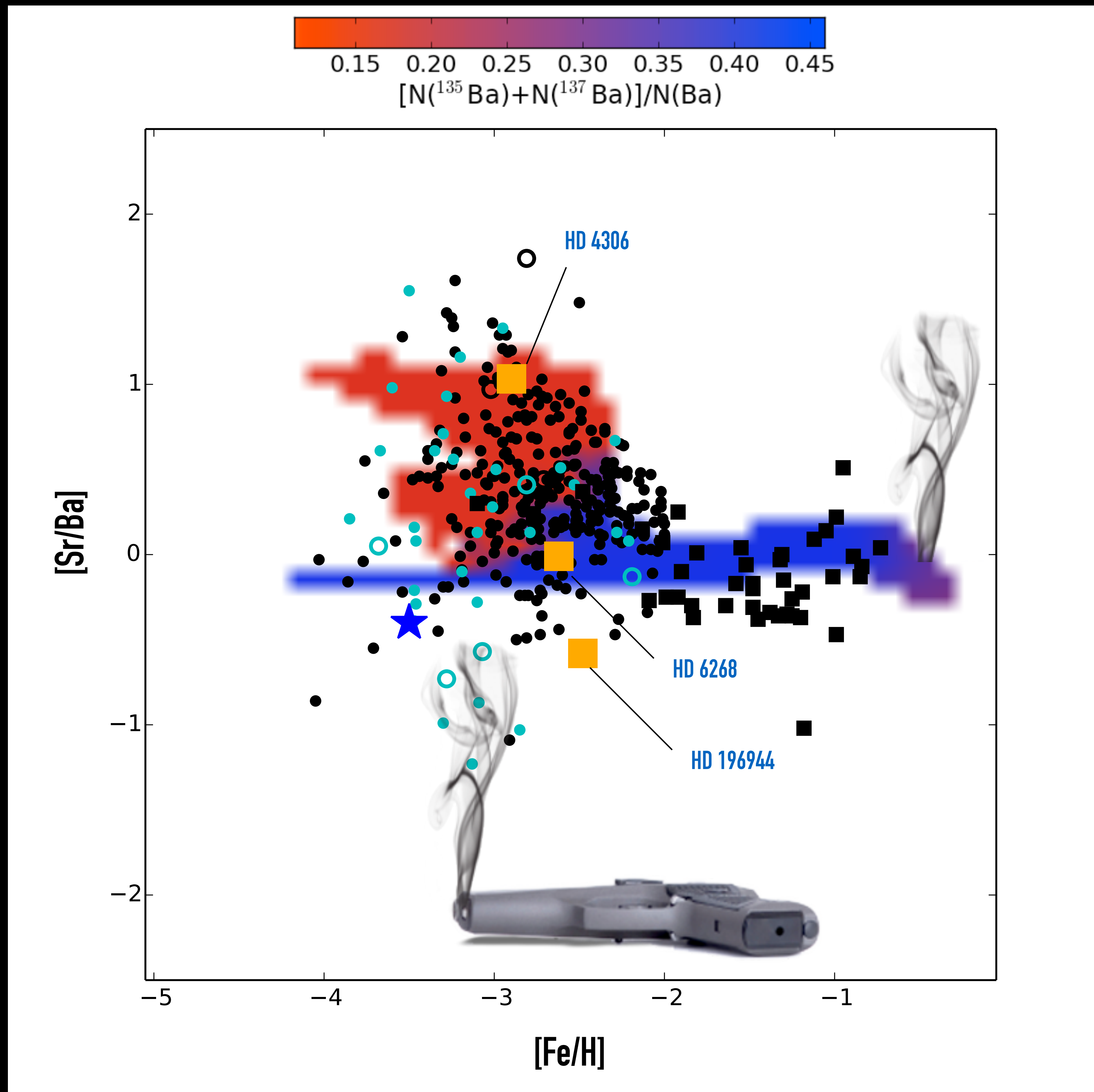

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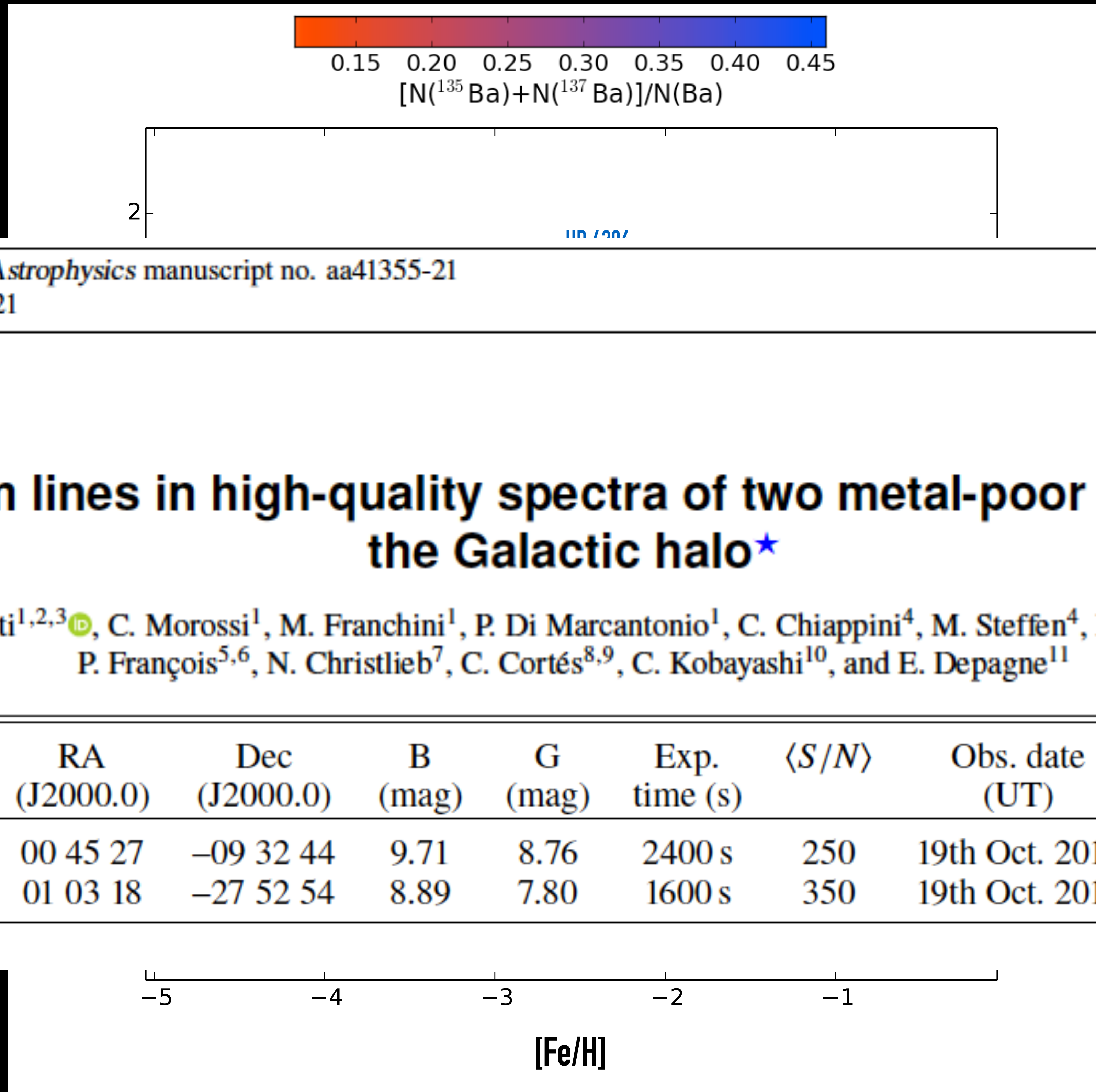
See results on HD 1402 from Maga to Gallaghe



Astronomy & Astrophysics manuscript no. aa41355-21 ©ESO 2021
October 13, 2021

Barium lines in high-quality spectra of two metal-poor giants in the Galactic halo*

G. Cescutti[1,2,3], C. Morossi[1], M. Franchini[1], P. Di Marcantonio[1], C. Chiappini[4], M. Steffen[4], M. Valentini[4], P. François[5,6], N. Christlieb[7], C. Cortés[8,9], C. Kobayashi[10], and E. Depagne[11]

Object	RA (J2000.0)	Dec (J2000.0)	B (mag)	G (mag)	Exp. time (s)	⟨S/N⟩	Obs. date (UT)	No. of exps.
HD 4306	00 45 27	–09 32 44	9.71	8.76	2400 s	250	19th Oct. 2016	3
HD 6268	01 03 18	–27 52 54	8.89	7.80	1600 s	350	19th Oct. 2016	2

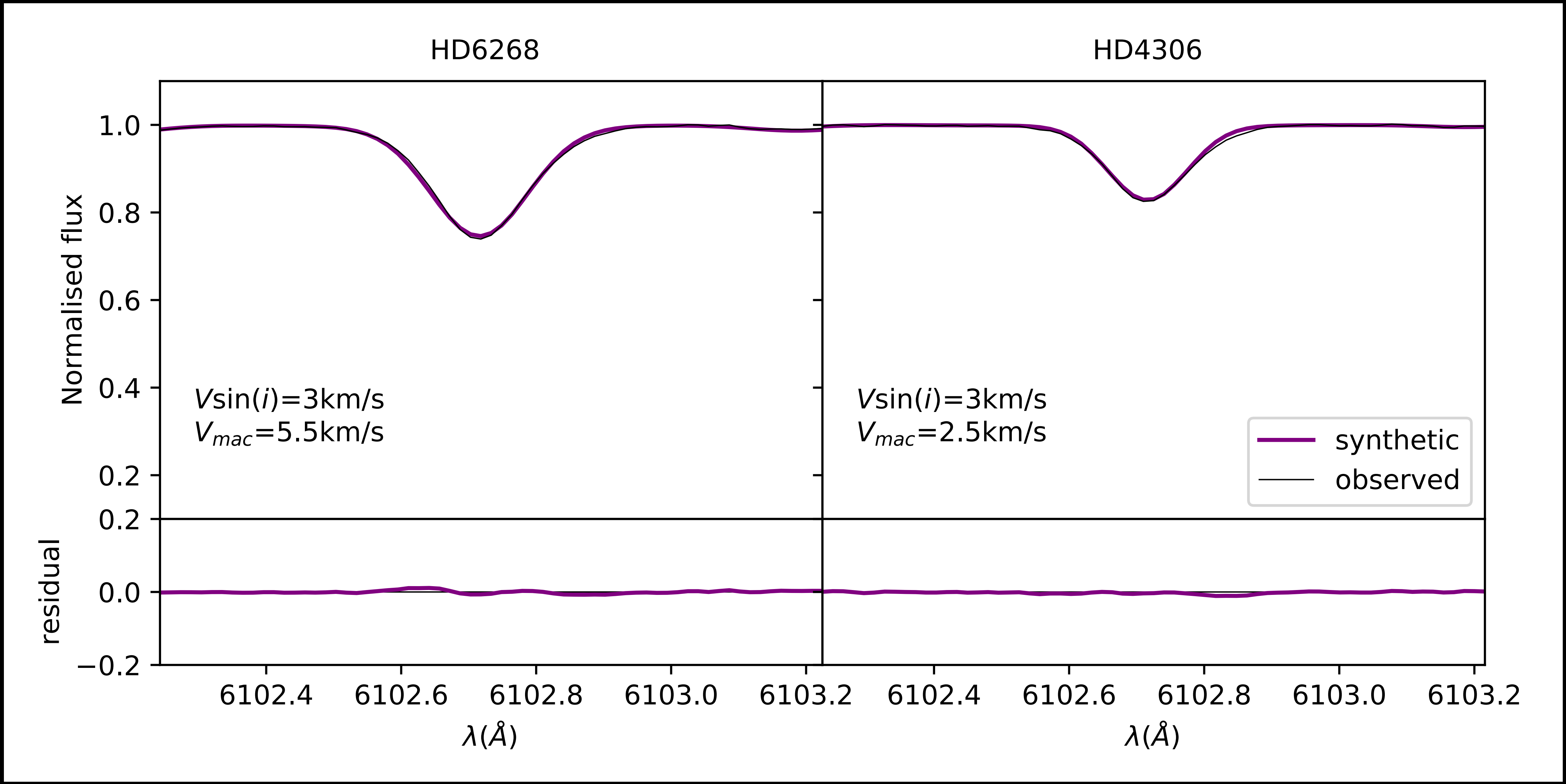
3 stars

0 &

high S/N ~ 80-100

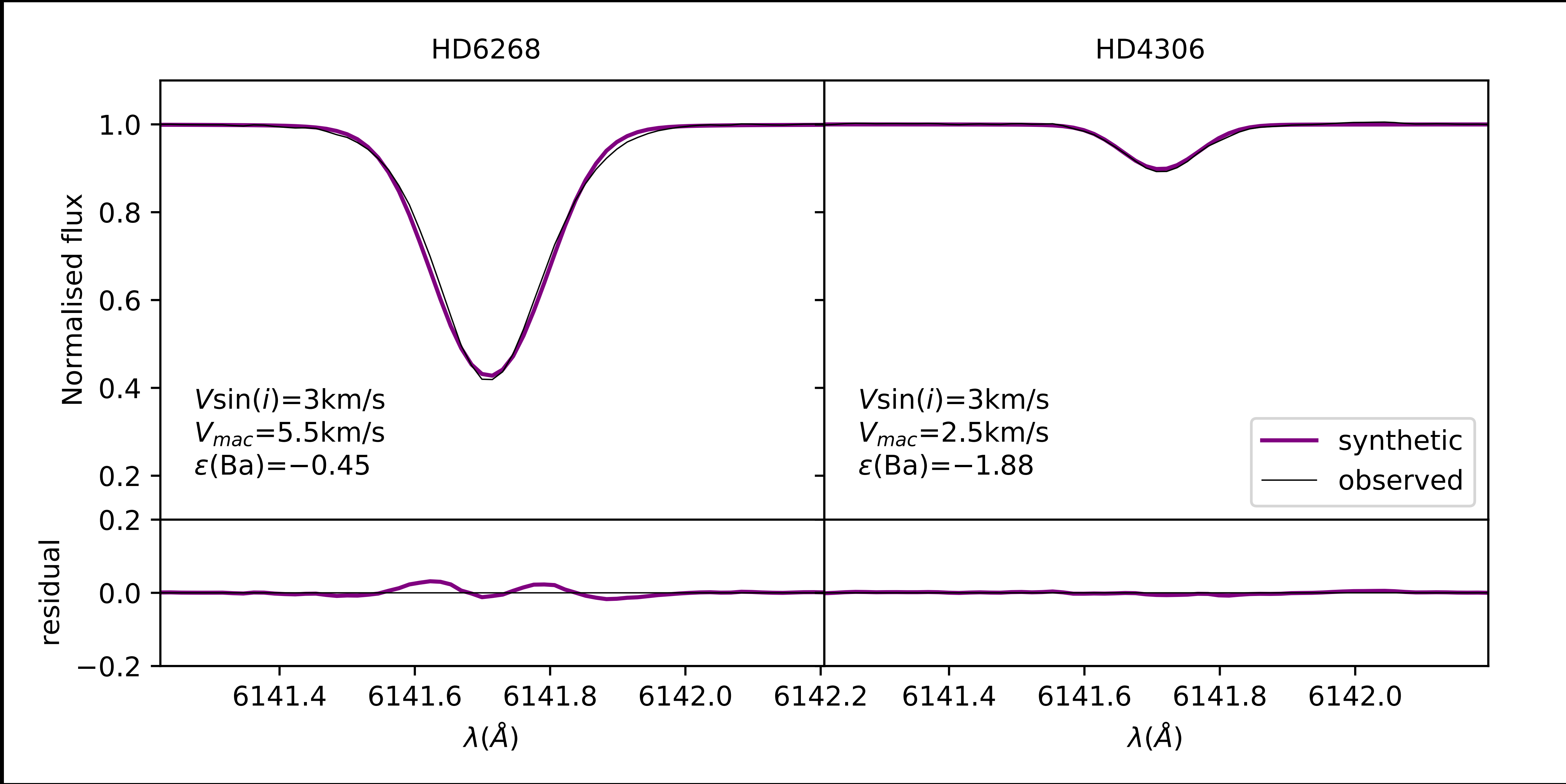
Cescutti and Chiappini (2014)

Synthesis of calcium lines



Synthesis of the barium line

with no hyperfine splitting effects



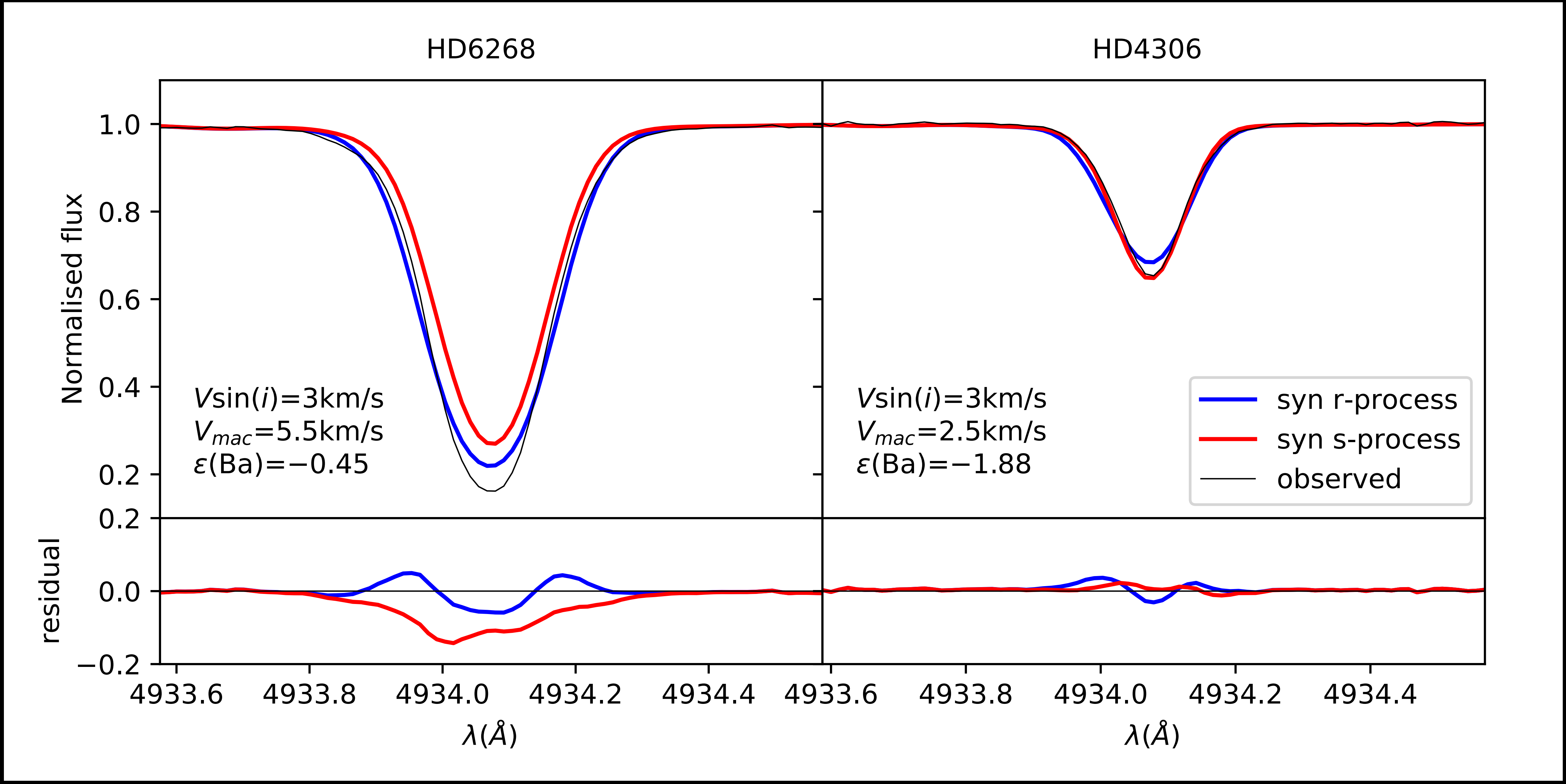
Synthesis of barium lines

with hyperfine splitting effects

Ba II	$E_{low} = 0.00$ eV log $gf = -0.15$ Wavelength (Å)	Strength	*s*-process fraction	*r*-process fraction
^{134}Ba			0.02	0.00
	4934.075	1.000		
^{135}Ba			0.03	0.40
	4934.034	0.3125		
	4934.045	0.0625		
	4934.093	0.3125		
	4934.104	0.3125		
^{136}Ba			0.10	0.00
	4934.075	1.000		
^{137}Ba			0.09	0.32
	4934.029	0.3125		
	4934.041	0.0625		
	4934.096	0.3125		
	4934.107	0.3125		
^{138}Ba			0.76	0.28
	4934.075	1.0		

Synthesis of barium lines

with hyperfine splitting effects



An empirical method

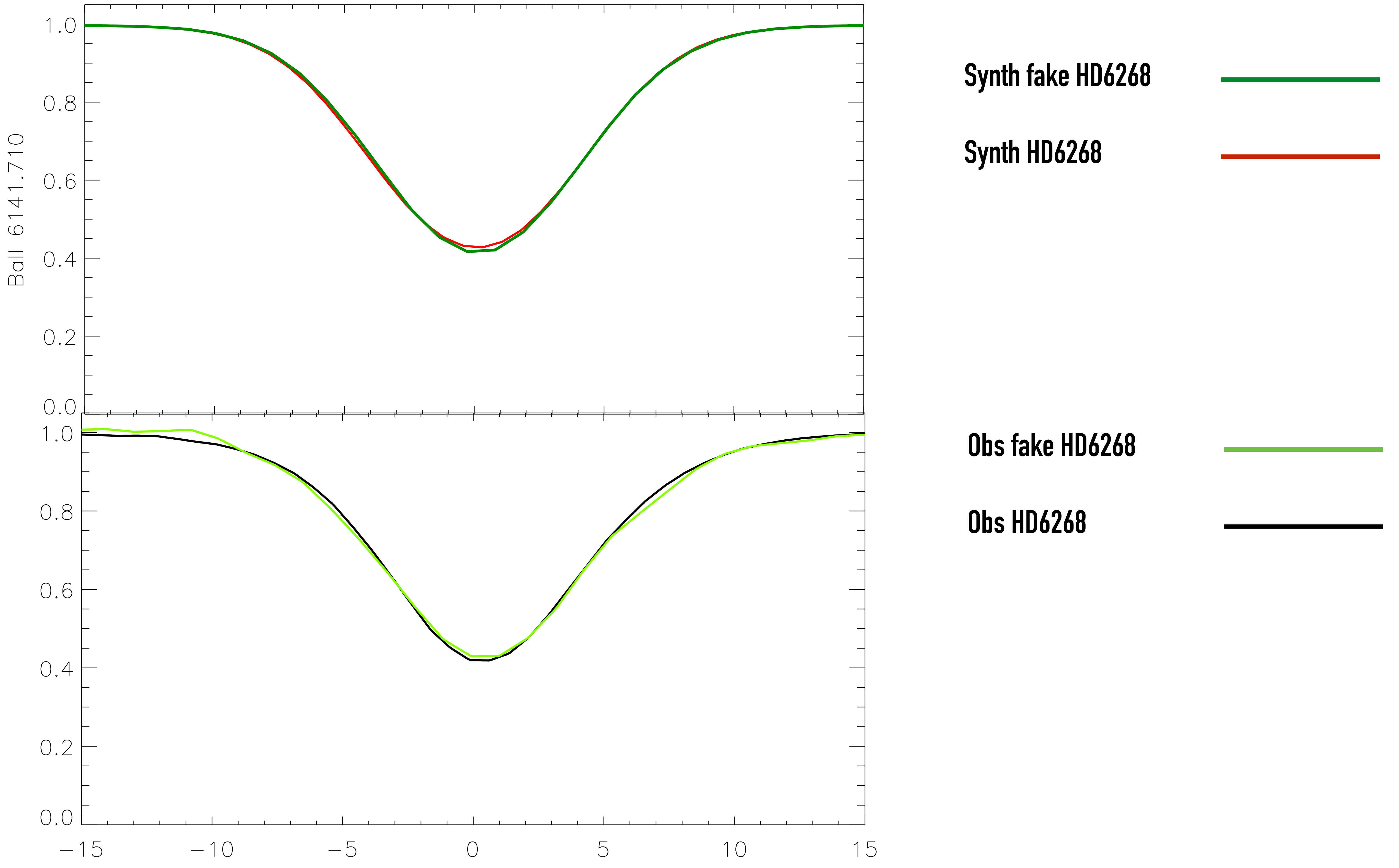
to transform the lines of HD 4306 in those of HD6268

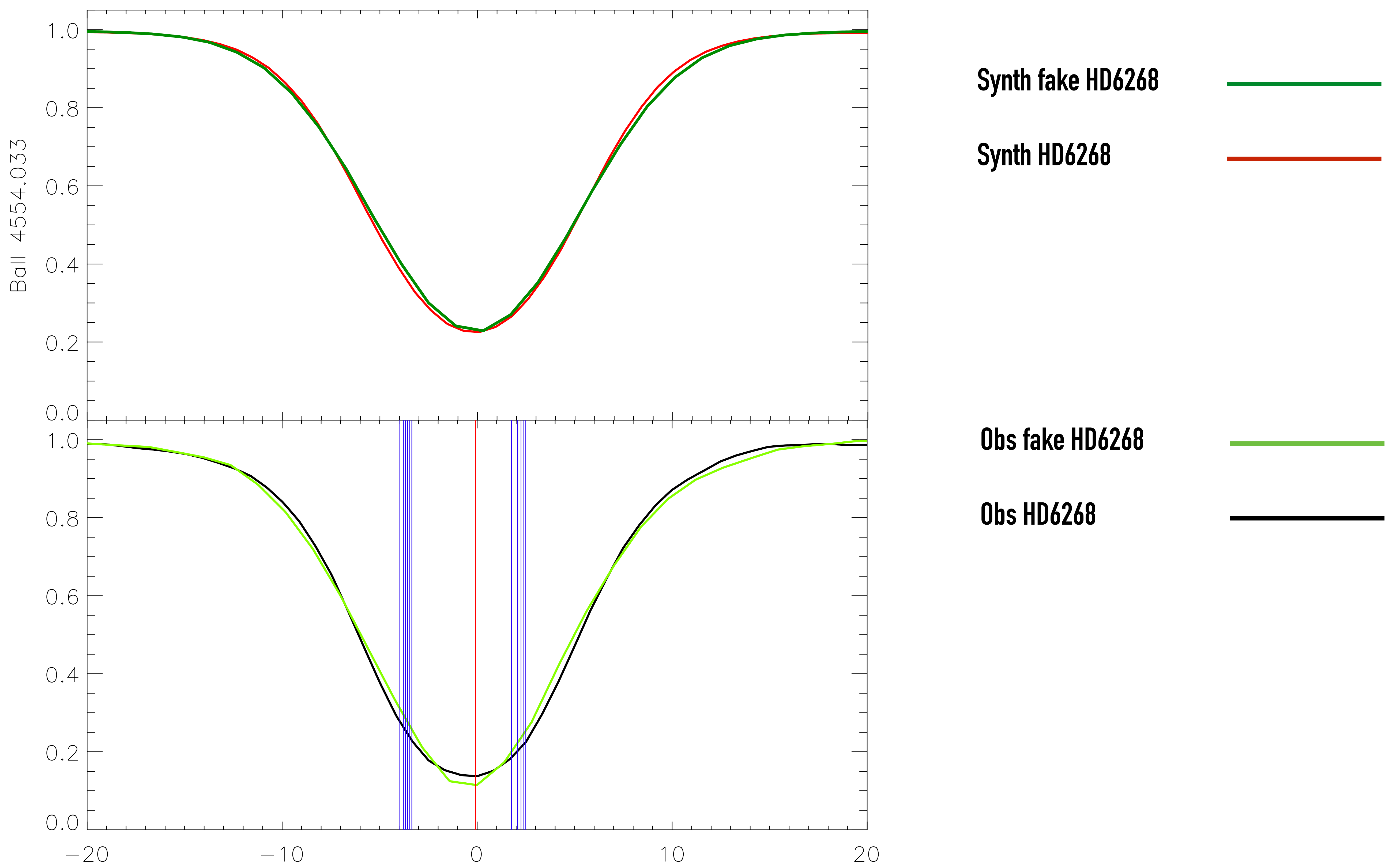
a scaling is applied in the velocity space

$$\Delta v = c \times \frac{(\lambda - \lambda_0)}{\lambda_0}$$

$$\Delta v^{\mathrm{fake-HD\,6268}} = b \cdot \Delta v^{\mathrm{HD\,4306}} \sqrt{\frac{T_{\mathrm{eff}}^{\mathrm{HD6268}}}{T_{\mathrm{eff}}^{\mathrm{HD4306}}} \frac{V_{\mathrm{mac}}^{\mathrm{HD6268}}}{V_{\mathrm{mac}}^{\mathrm{HD4306}}}}.$$

where b is determined using the synthetic spectra with an s-process composition to match the broadening


1.0
0.8
0.6
0.4
0.2
0.0
BaII 6141.710
1.0
0.8
0.6
0.4
0.2
0.0
−15
−10
−5
0
5
10
15
Synth fake HD6268
Synth HD6268
Obs fake HD6268
Obs HD6268



1.0
0.8
0.6
0.4
0.2
0.0
BaII 4554.033
1.0
0.8
0.6
0.4
0.2
0.0
−20
−10
0
10
20
Synth fake HD6268
Synth HD6268
Obs fake HD6268
Obs HD6268

Conclusions

Most of nc elements need HR
(always necessary for isotopic signatures)

The step forward is to apply statistical methods to
data +chemical evolution models

—> More Data with HR

Present and Future surveys are providing catalogues of
stars but the follow up of candidate stars will need a
HRMOS on a 8meter class telescope