The first source(s) of neutron capture elements

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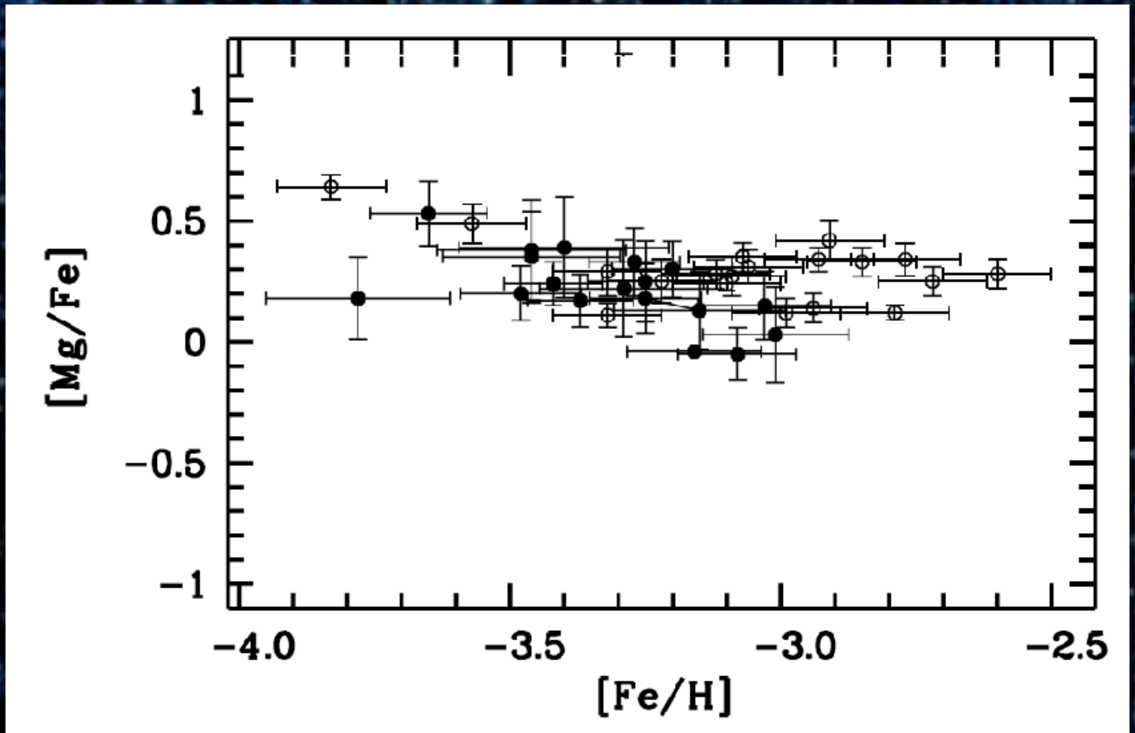
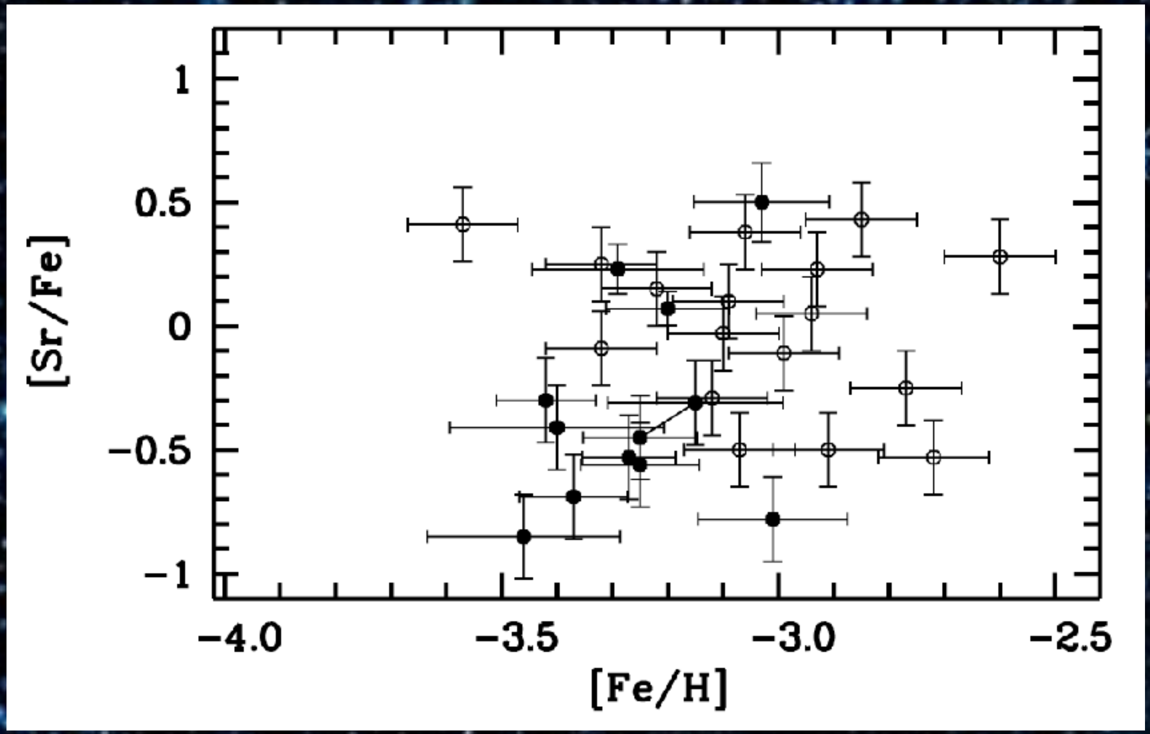
Why neutron capture elements?

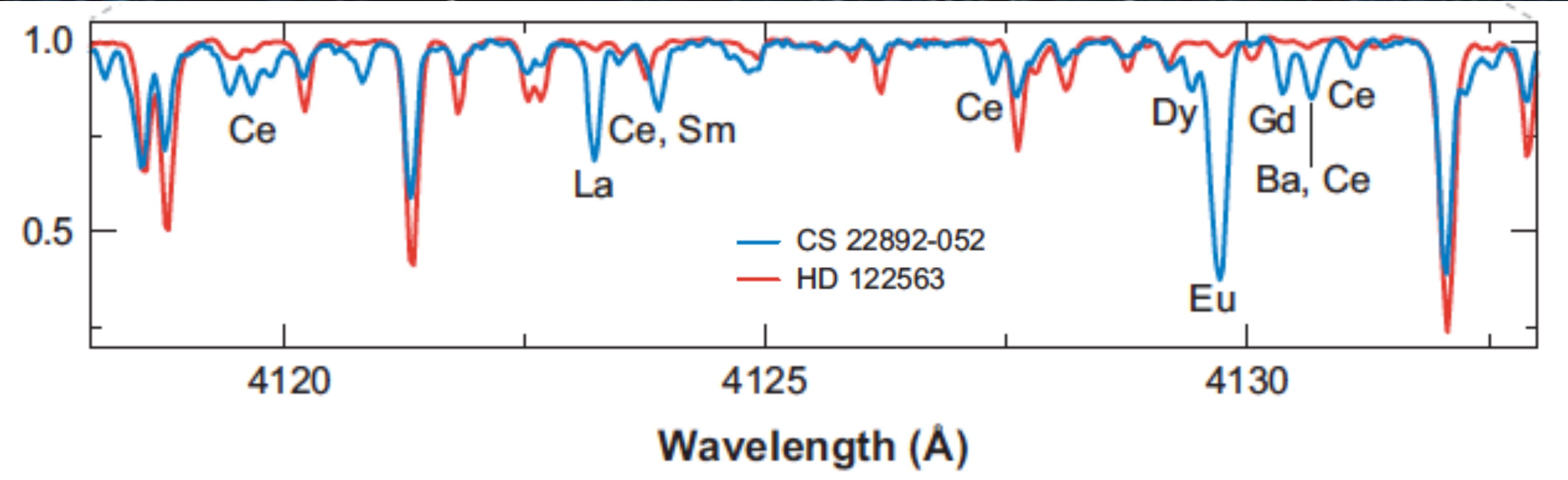
Mg: alpha-element



Sr: neutron capture element

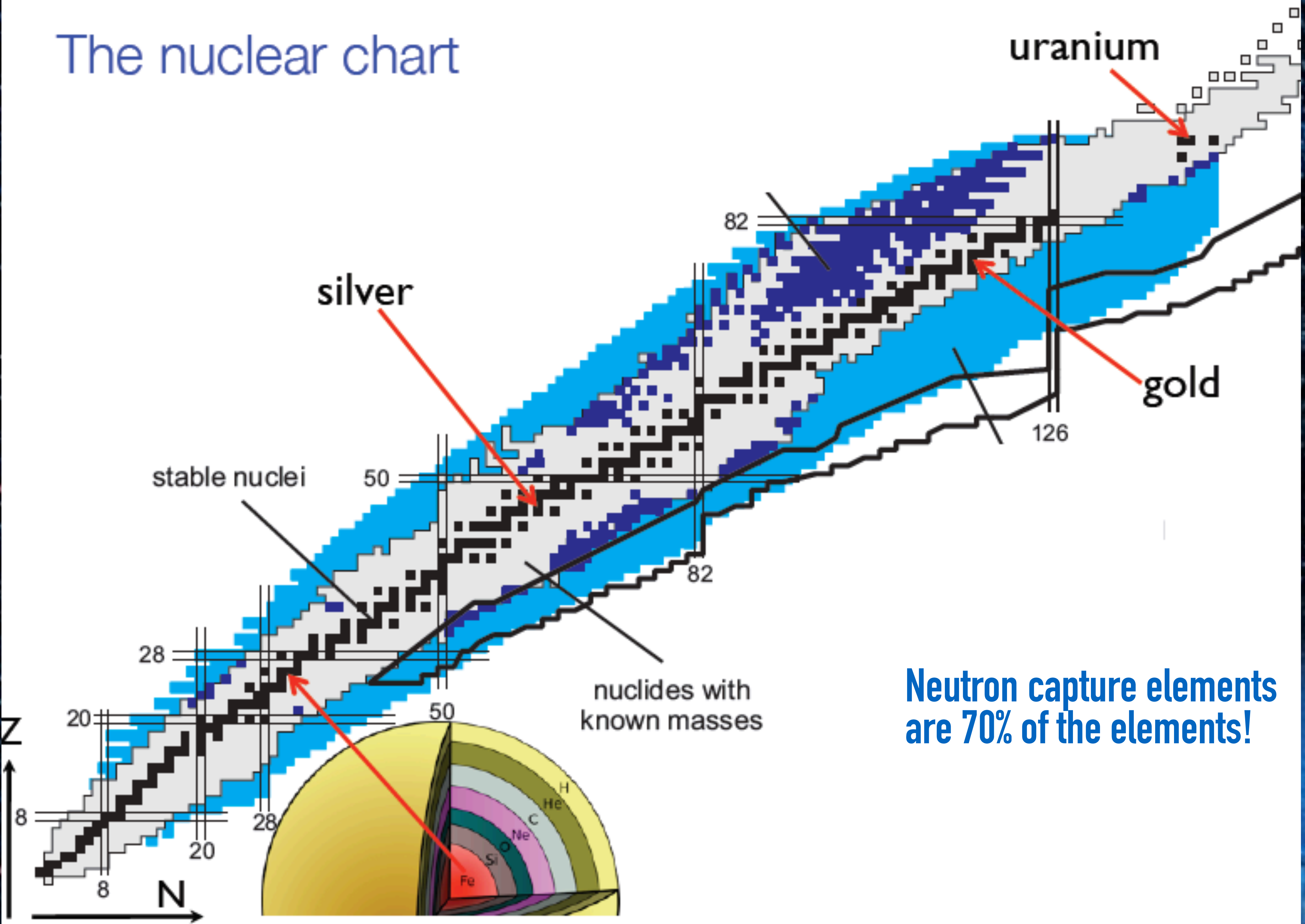


Bonifacio+12



Sneden+08

The nuclear chart



Neutron capture elements are 70% of the elements!

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).

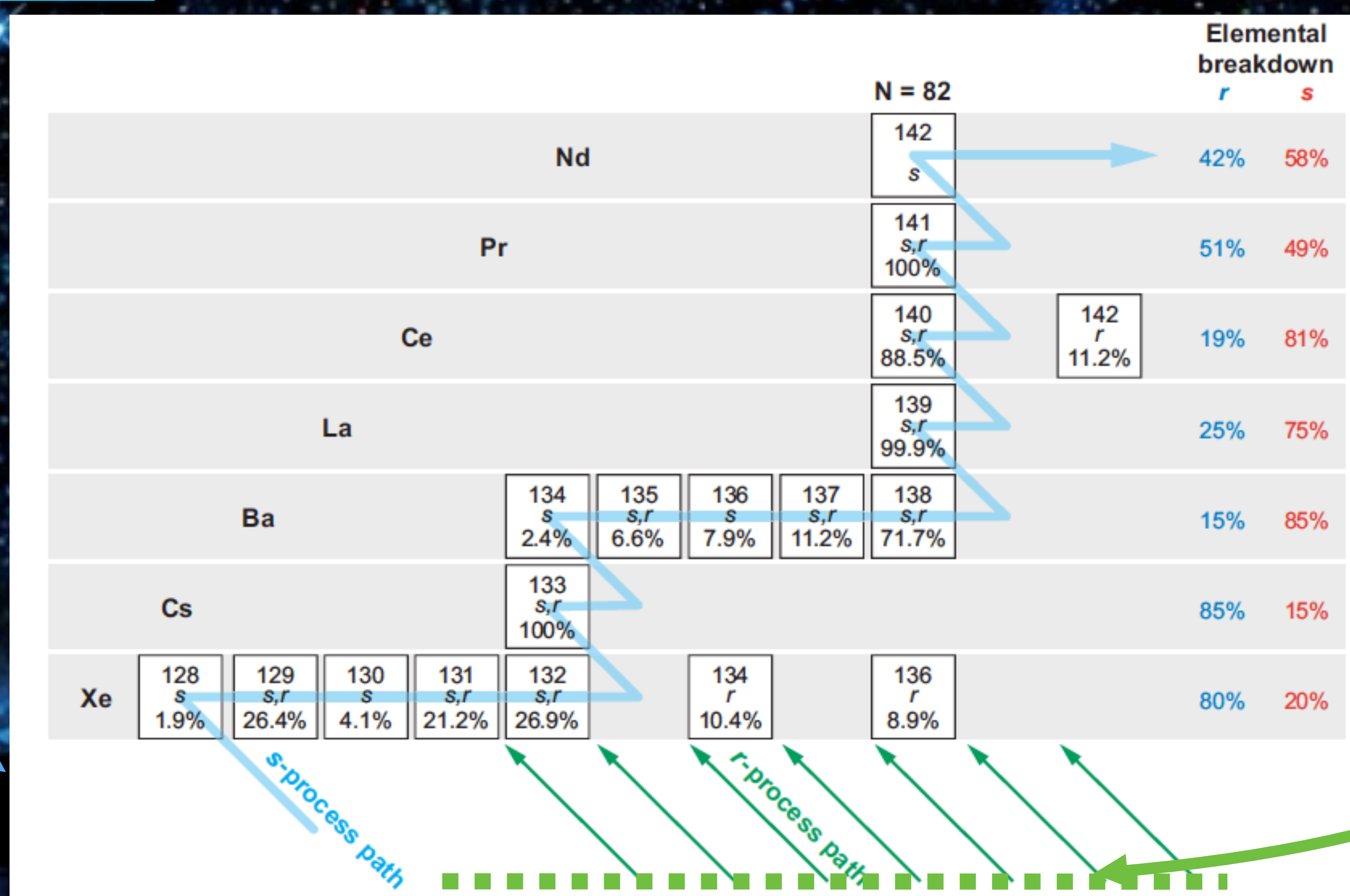
Two cases:

s-process — $\tau_\beta << \tau_c$

r-process — $\tau_\beta >> \tau_c$

Different Timescale of the neutron capture

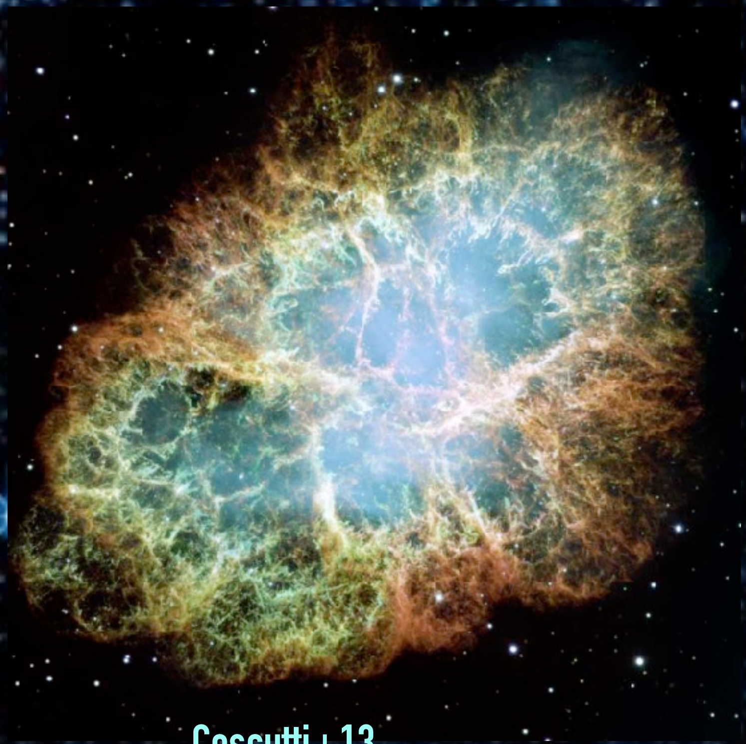
Different process path



p

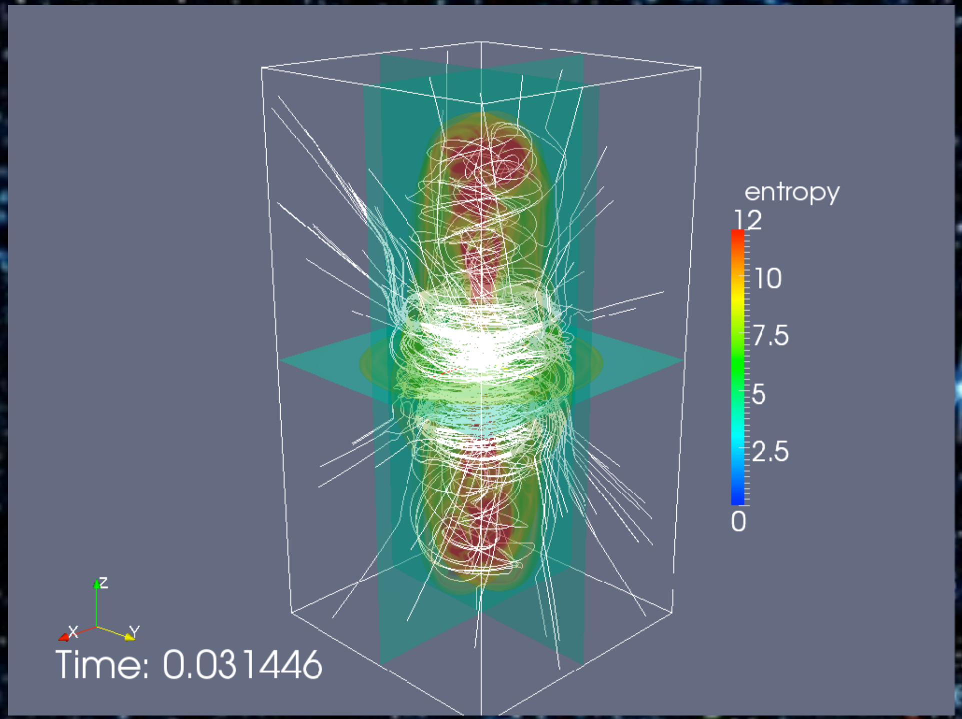
n

Electron Capture SNe (Wanajo+11)



Cescutti+13

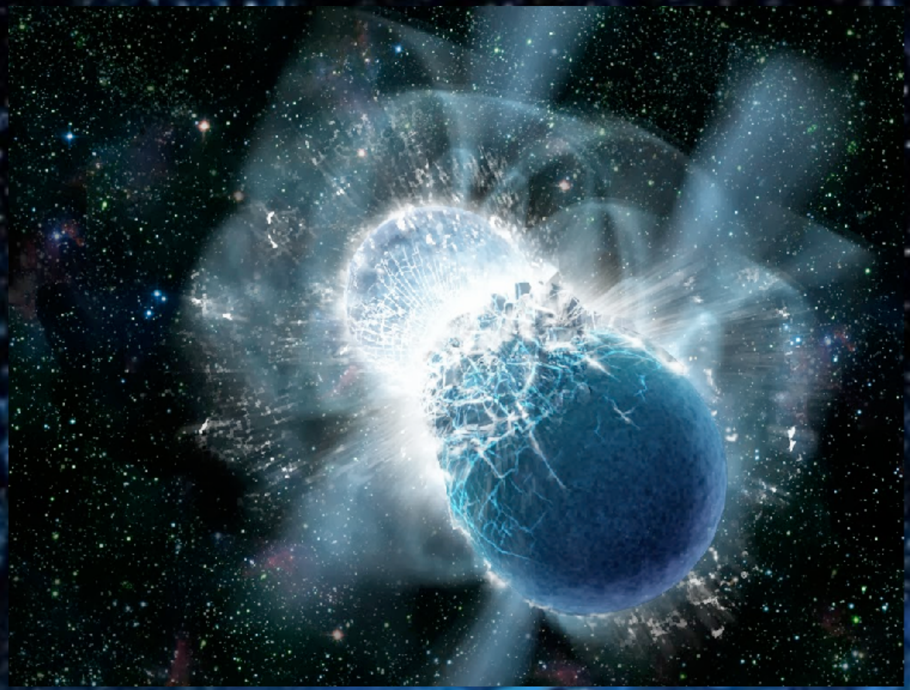
Magnetorotat. driven SNe (Winteler+12)



Cescutti+14

Europium (r-process)

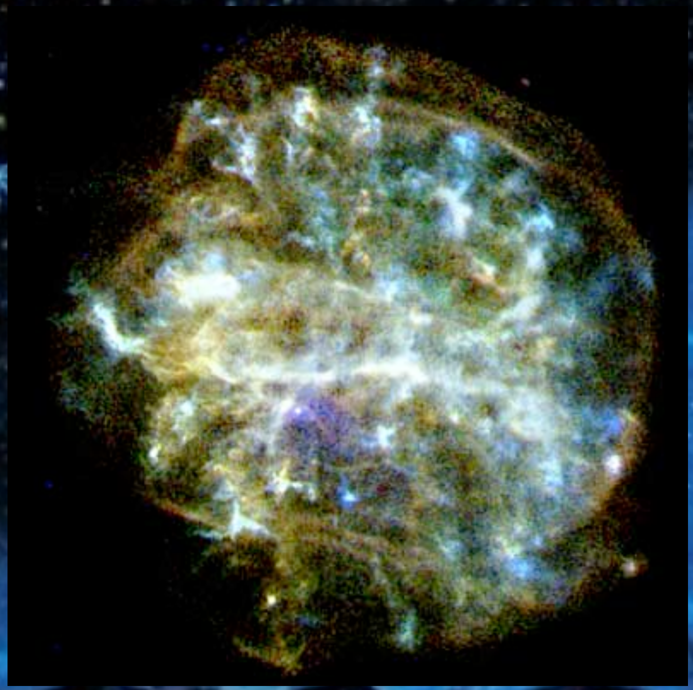
Neutron star mergers (Rosswog+13)



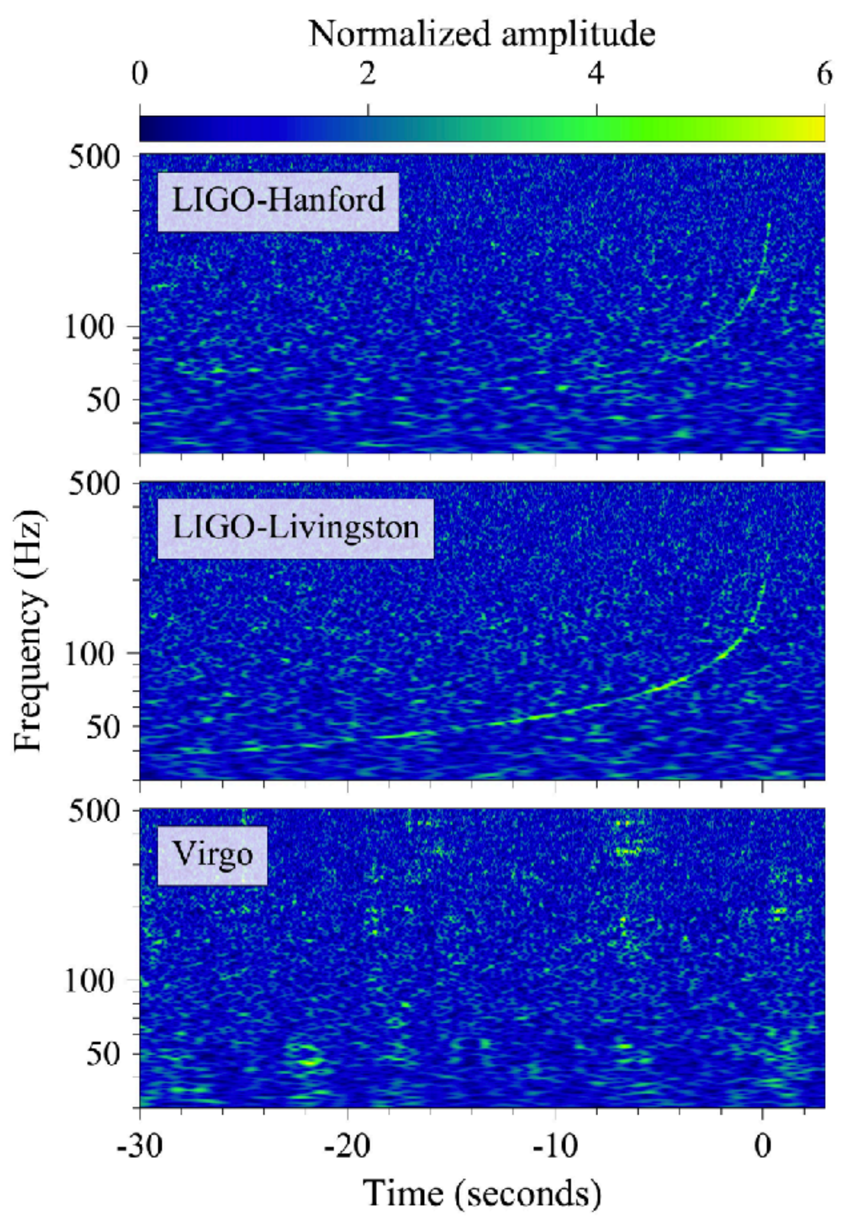
(Cescutti+15, Matteucci+14,. . .)

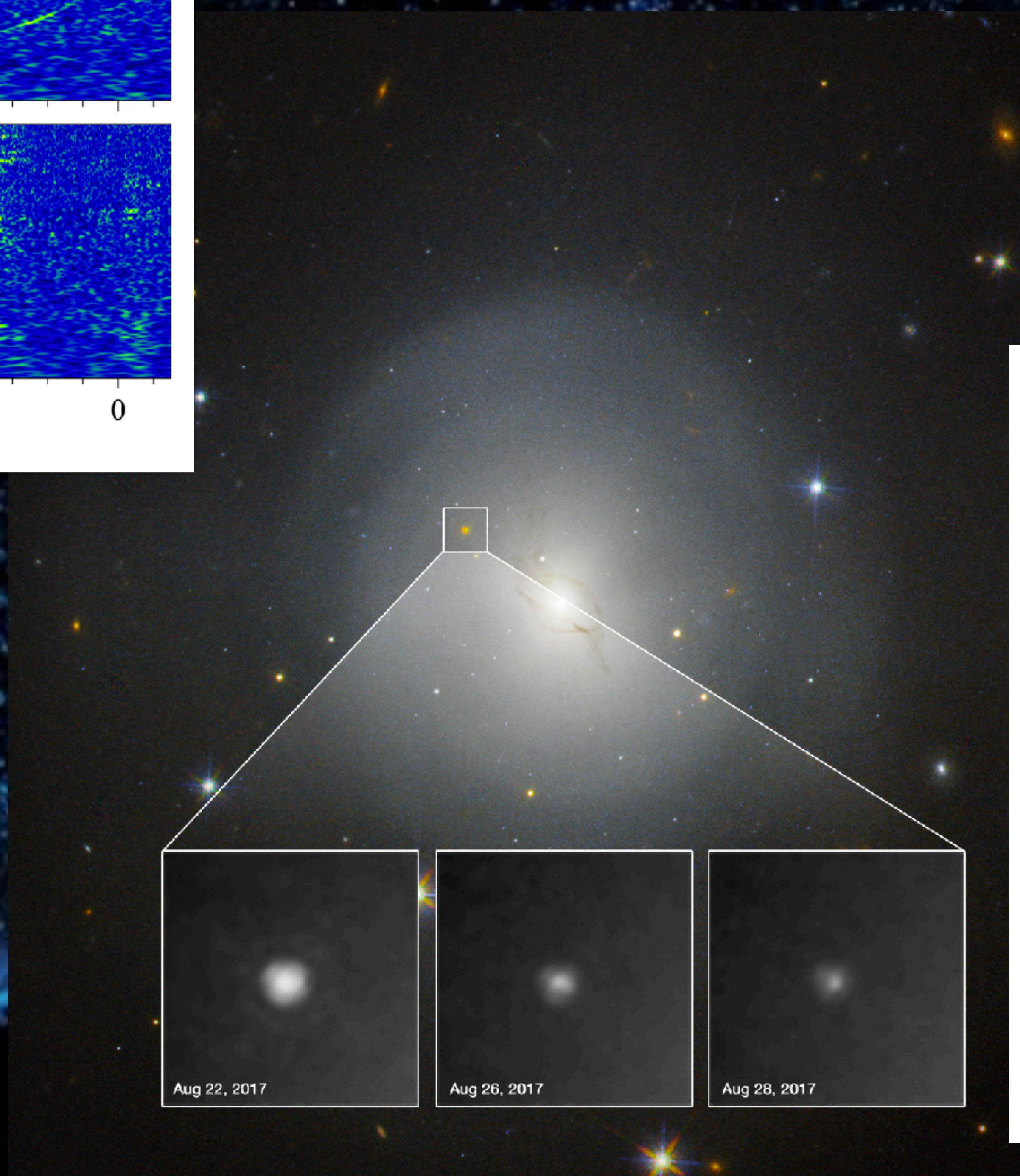
other possible sites?

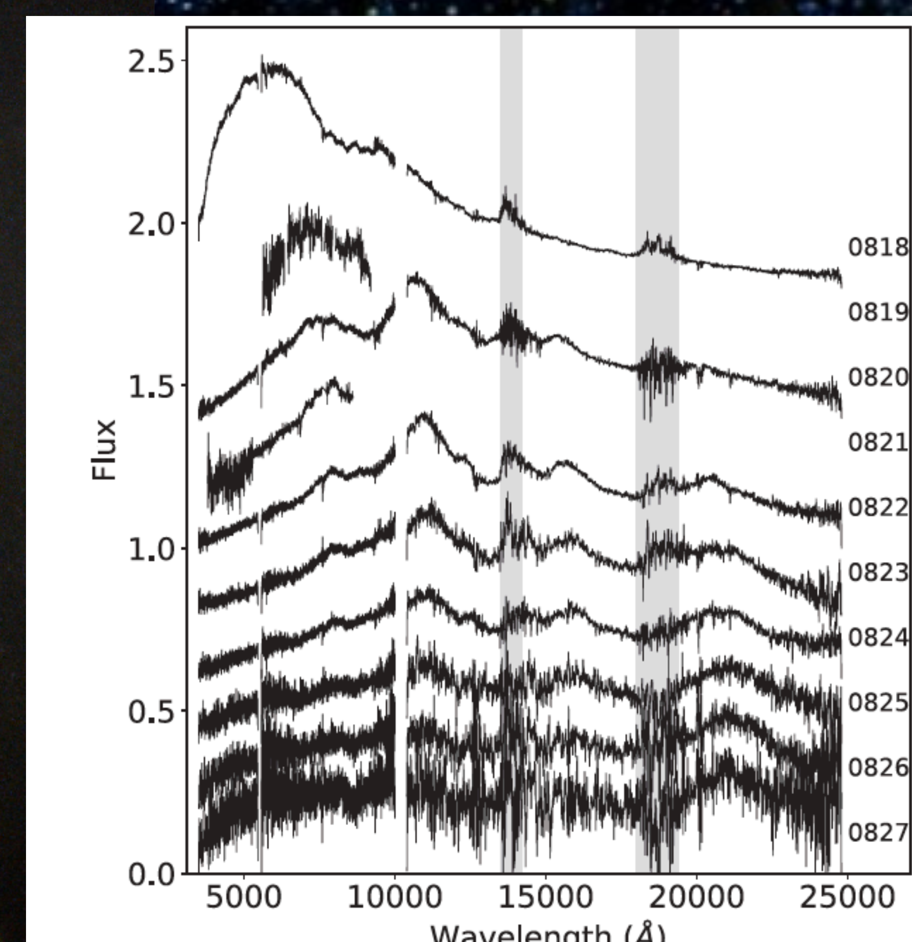
Neutrino winds SNe (Arcones+07,Wanajo 13)



After GW170817...







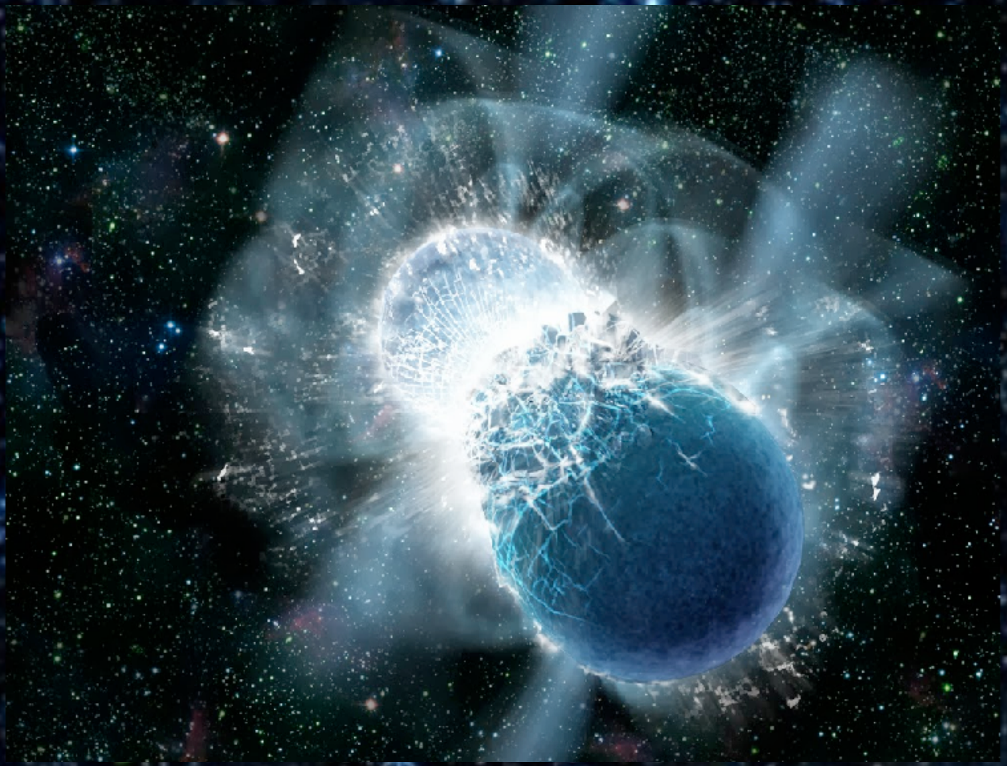
Neutron stars mergers

Progenitors are rare:
only few percent of the massive stars are formed in binary system which can produce a NS merger.

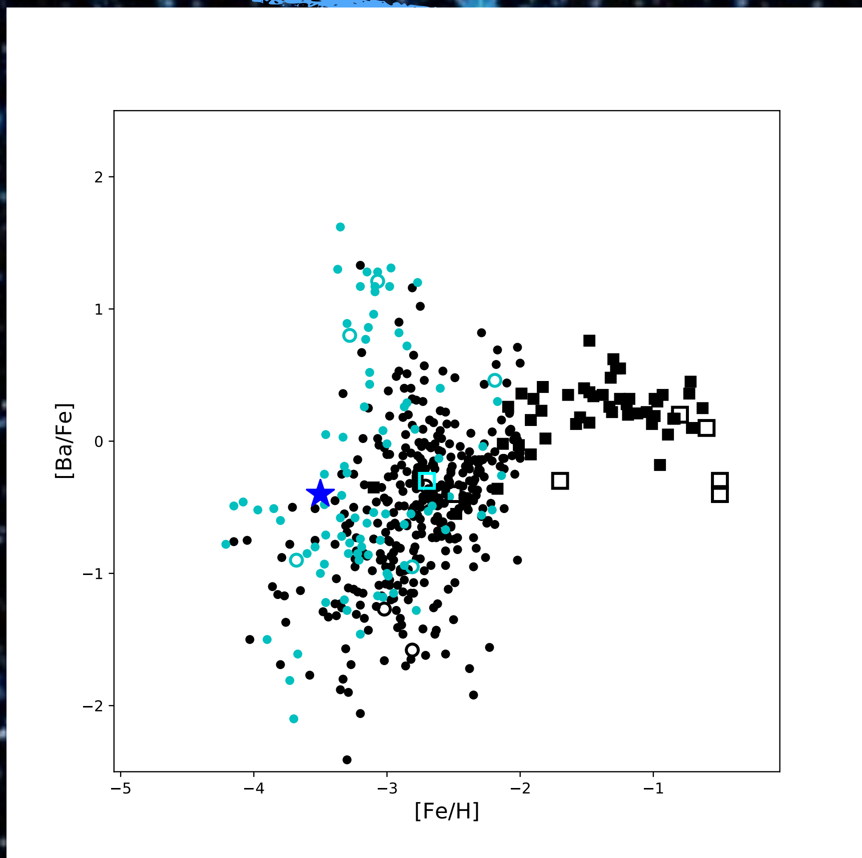
This percentage is not constrained at all the metallicities, the rate can be constrained only at the present time.

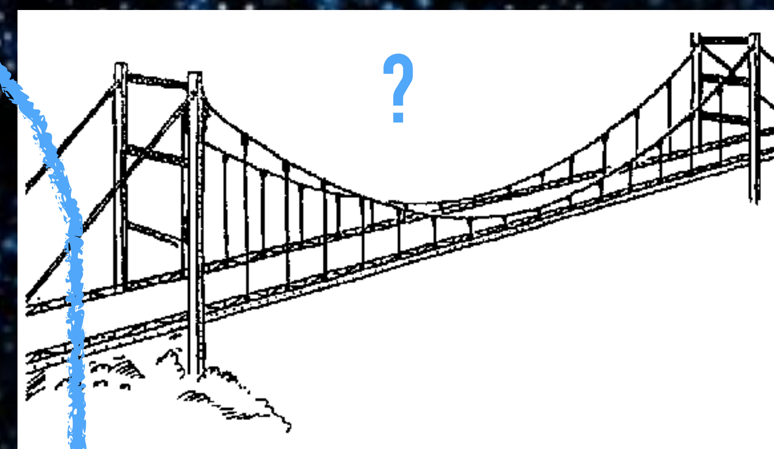
A key feature of NS merger is the delay between the formation of the binary system of neutron stars and the merging event.

Neutron star mergers (Rosswog+13)

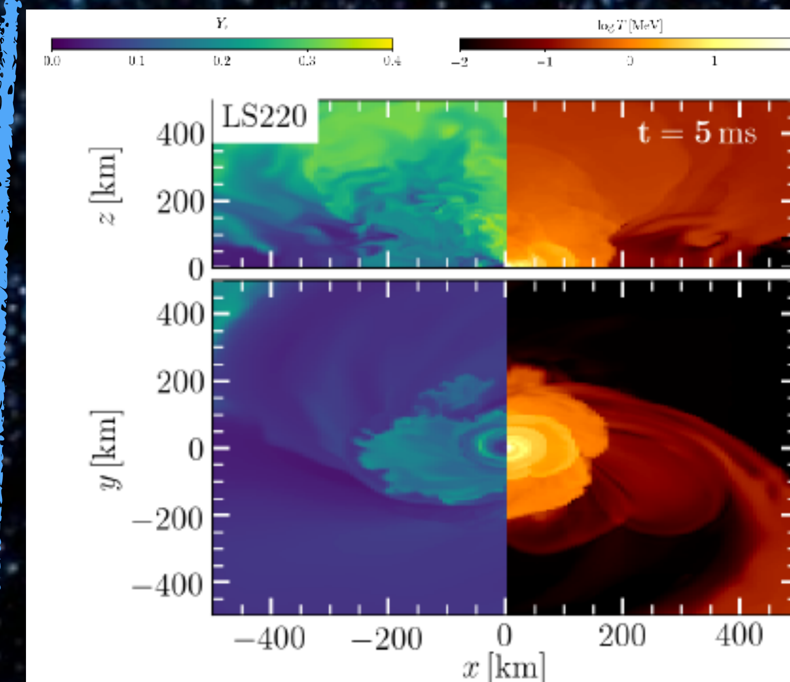


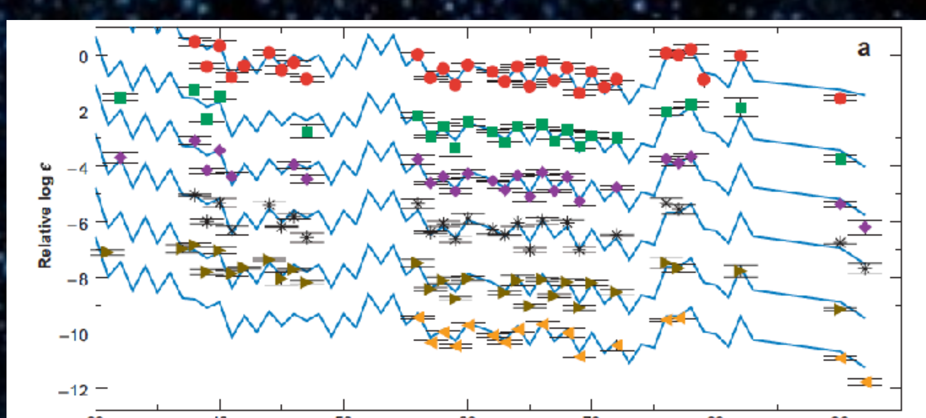
How to?



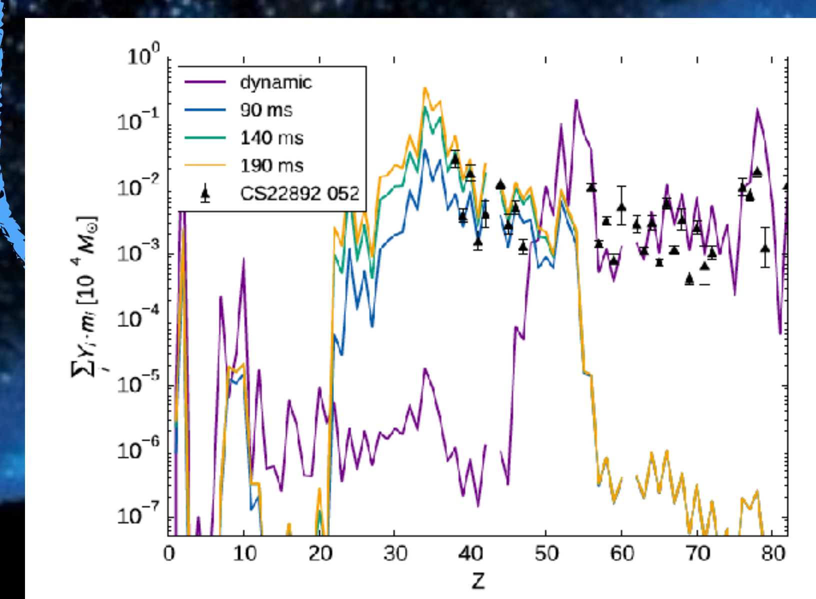


Neutron star mergers





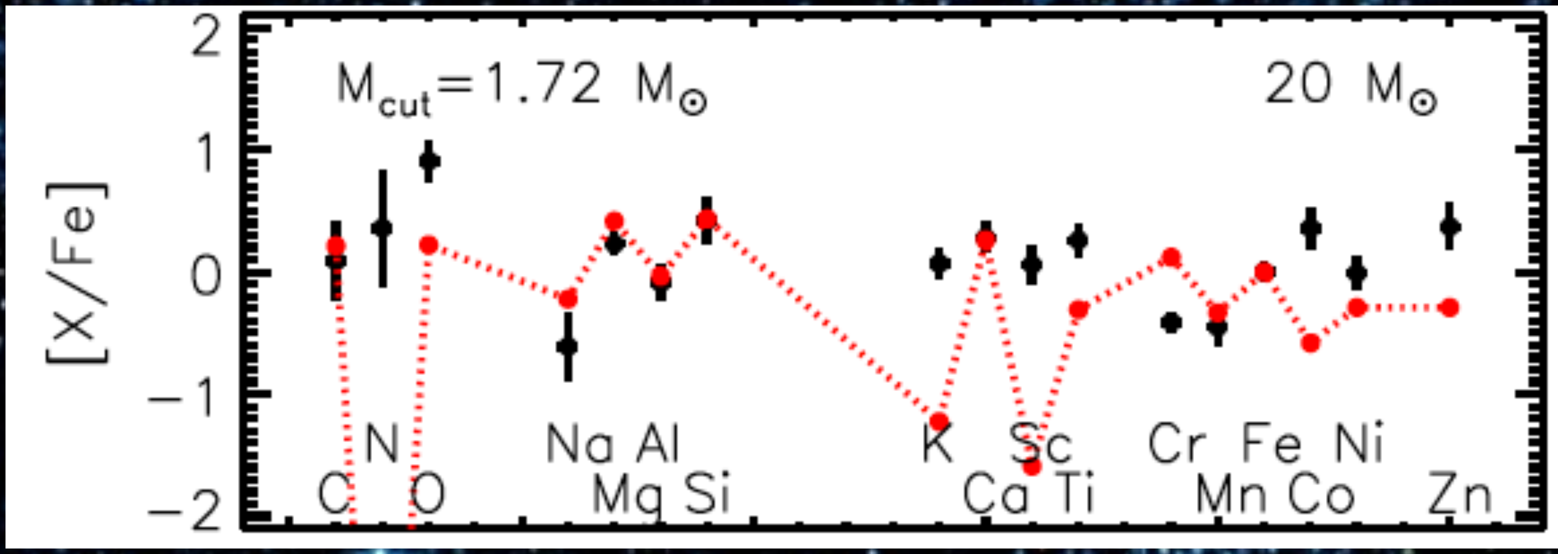
r-process

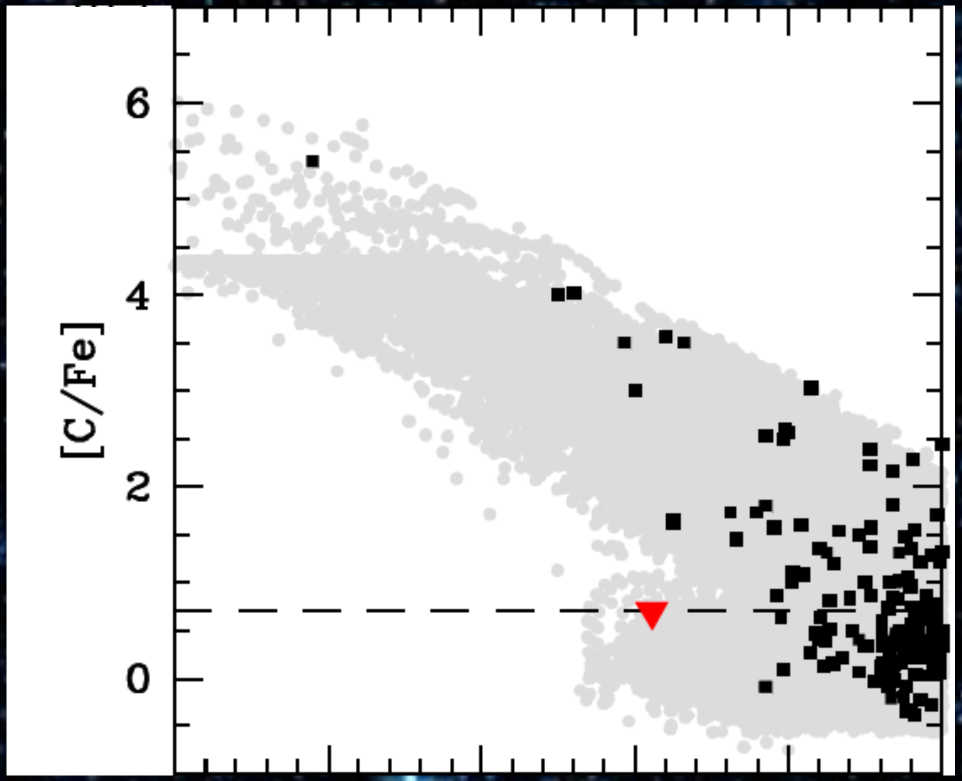


Possible solutions

Direct comparison of stellar abundances to nucleosynthesis results

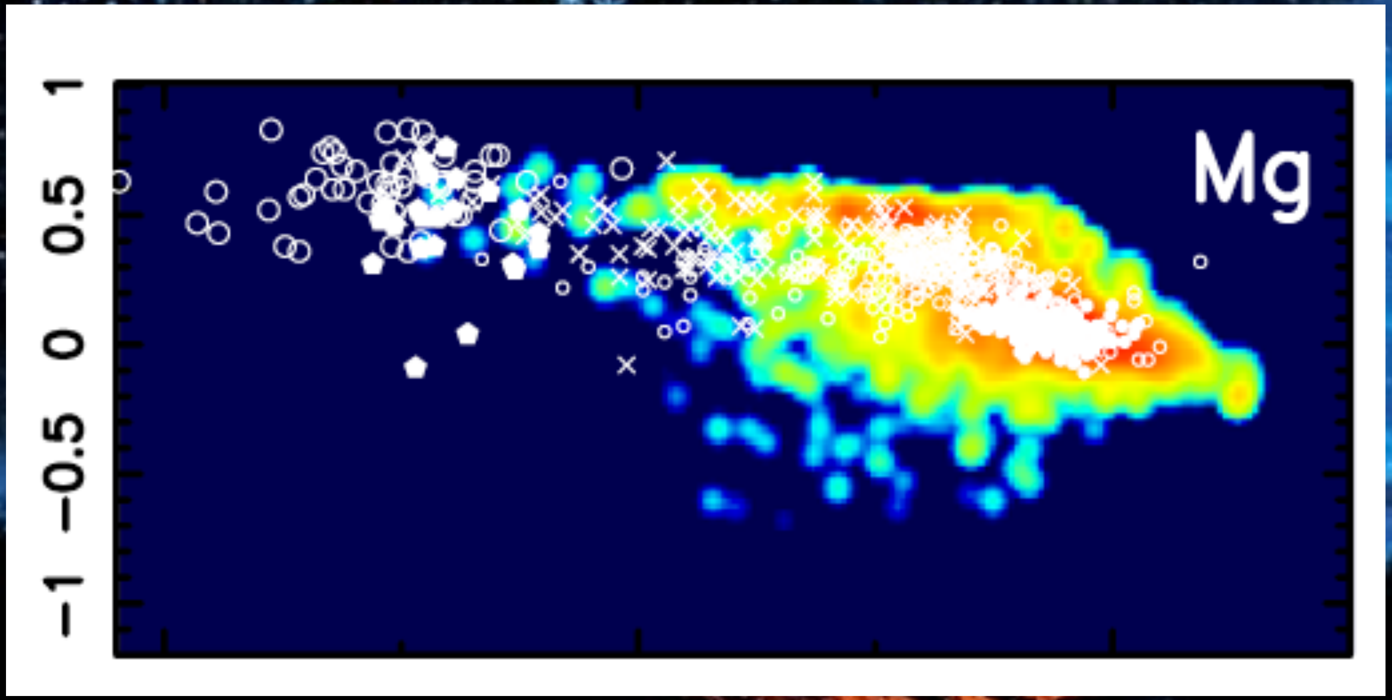
Limongi&Chieffi+12





semi analytic models in a cosmological context

DeBennassuti+17

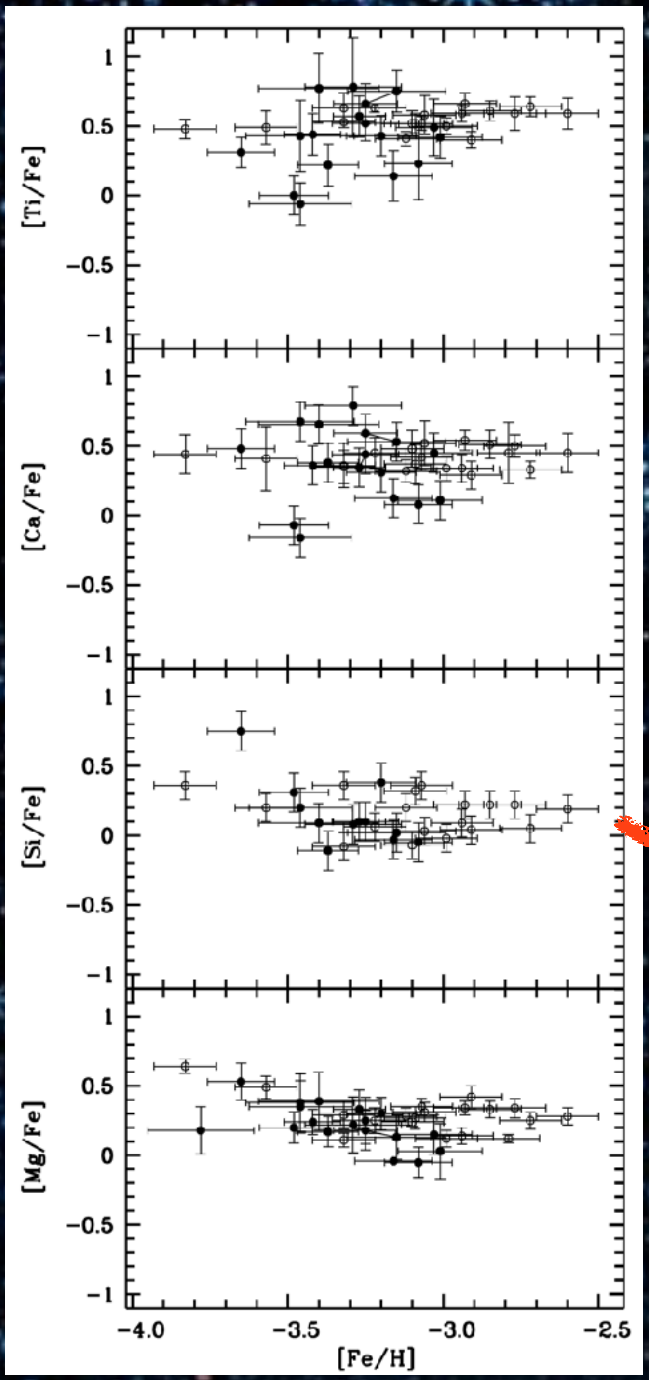


Simulation with gas
in cosmological context

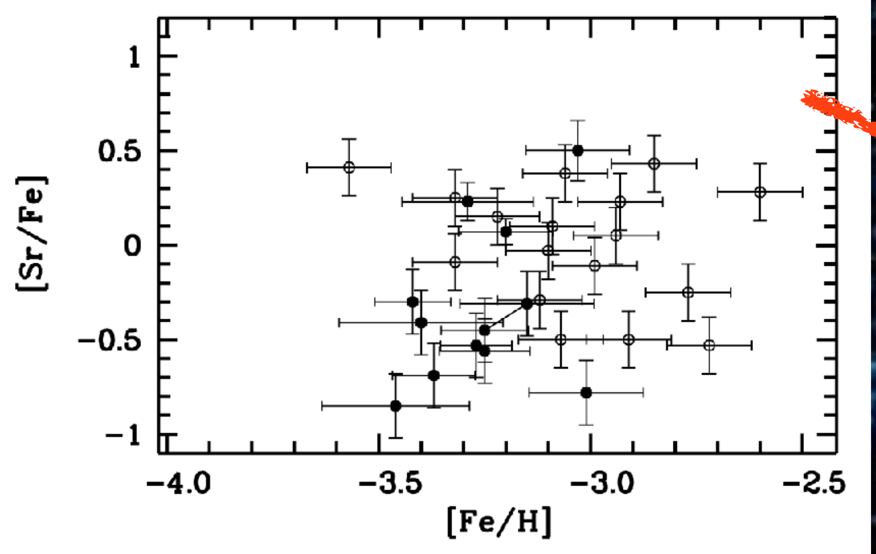
Kobayashi+11

Stochastic chemical evolution models

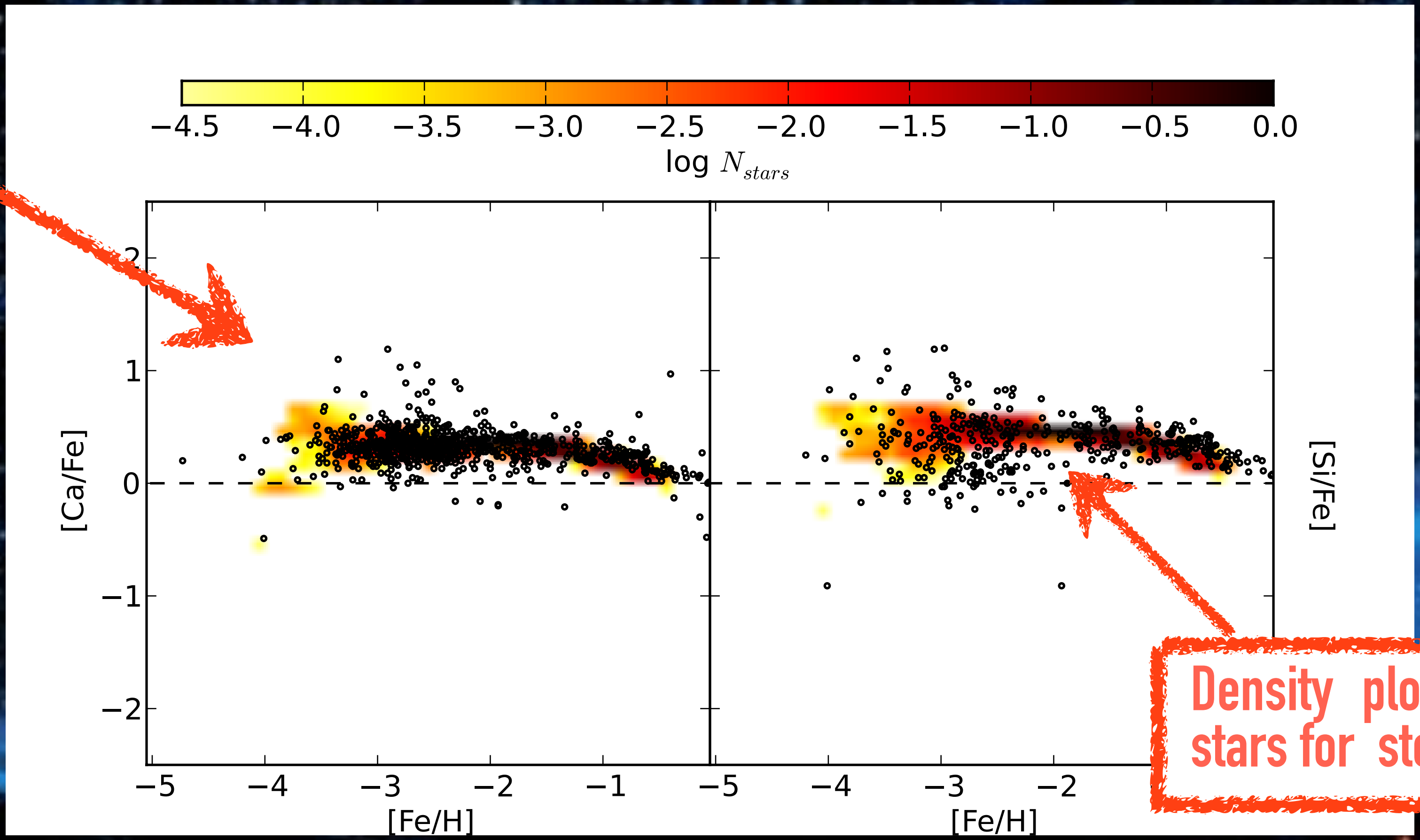
Problem:
Neutron capture elements present a spread alpha elements do not



Bonifacio+12



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.



Density plot of long living stars for stochastic model

Cescutti 2008
Cescutti et al. 2013

data collected in Frebel 2010

Neutron stars mergers

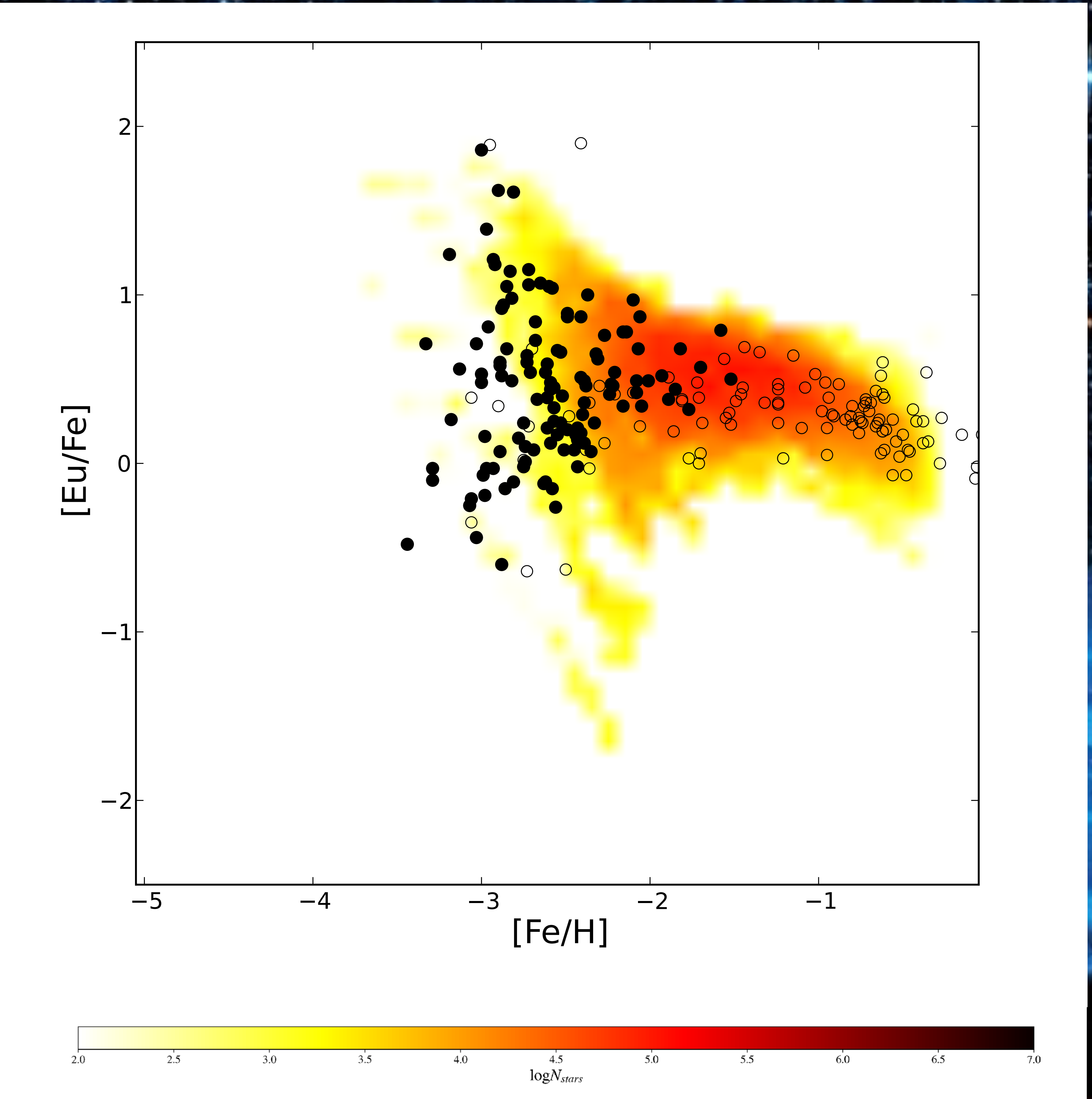
delay for the merging 1Myr

Cescutti, Romano, Matteucci, Chiappini and Hirschi 2015

Results with alpha=0.04 (NSM/SNe)

8 10^{-6} Msun of Eu

What about the impact of increasing the delay for the merging?



Neutron star mergers

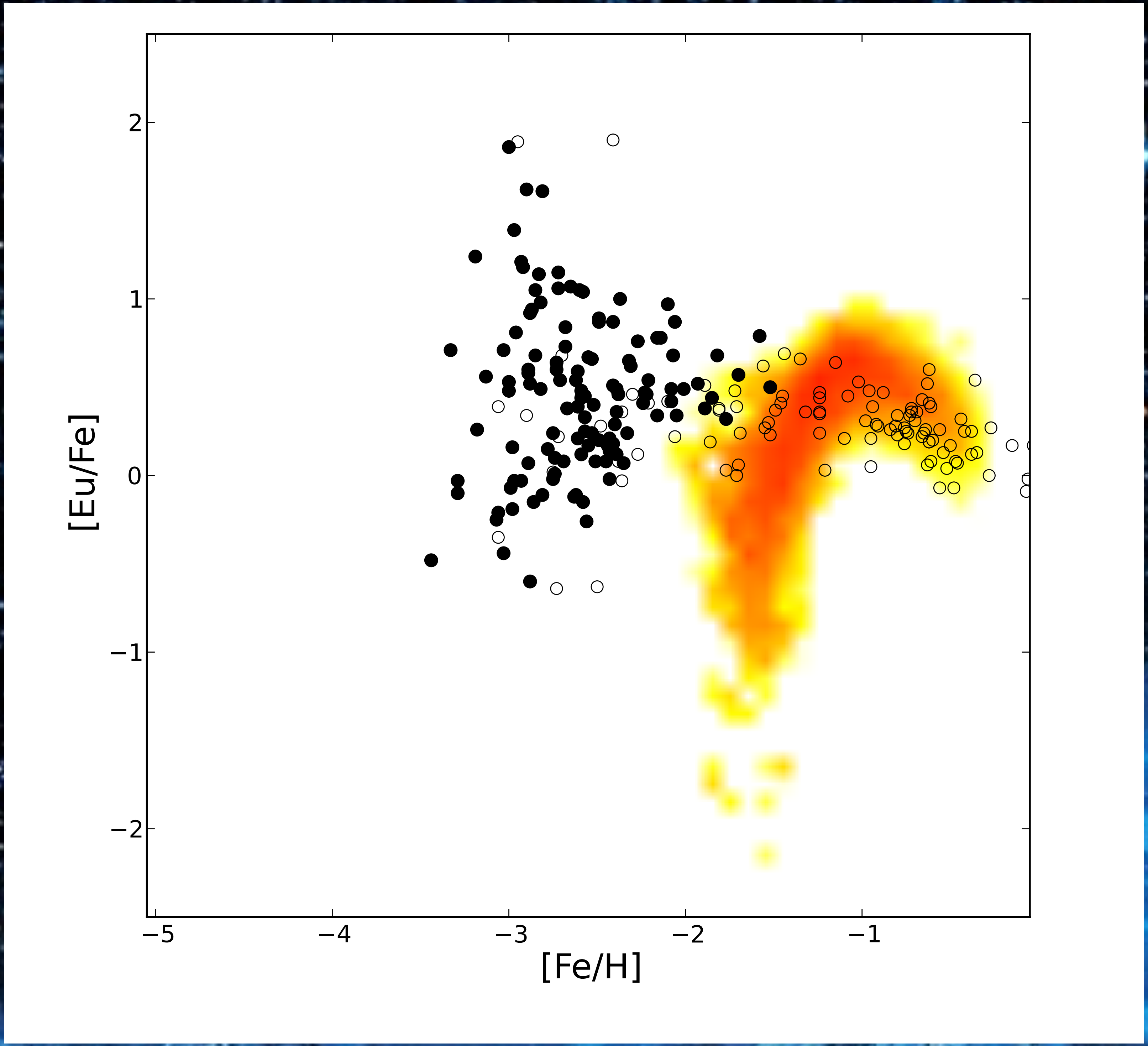
delay for the merging 100 Myr

Cescutti+15

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

Therefore, only if most of the NS mergers enriches in timescale <10Myr, the scenario can be supported.

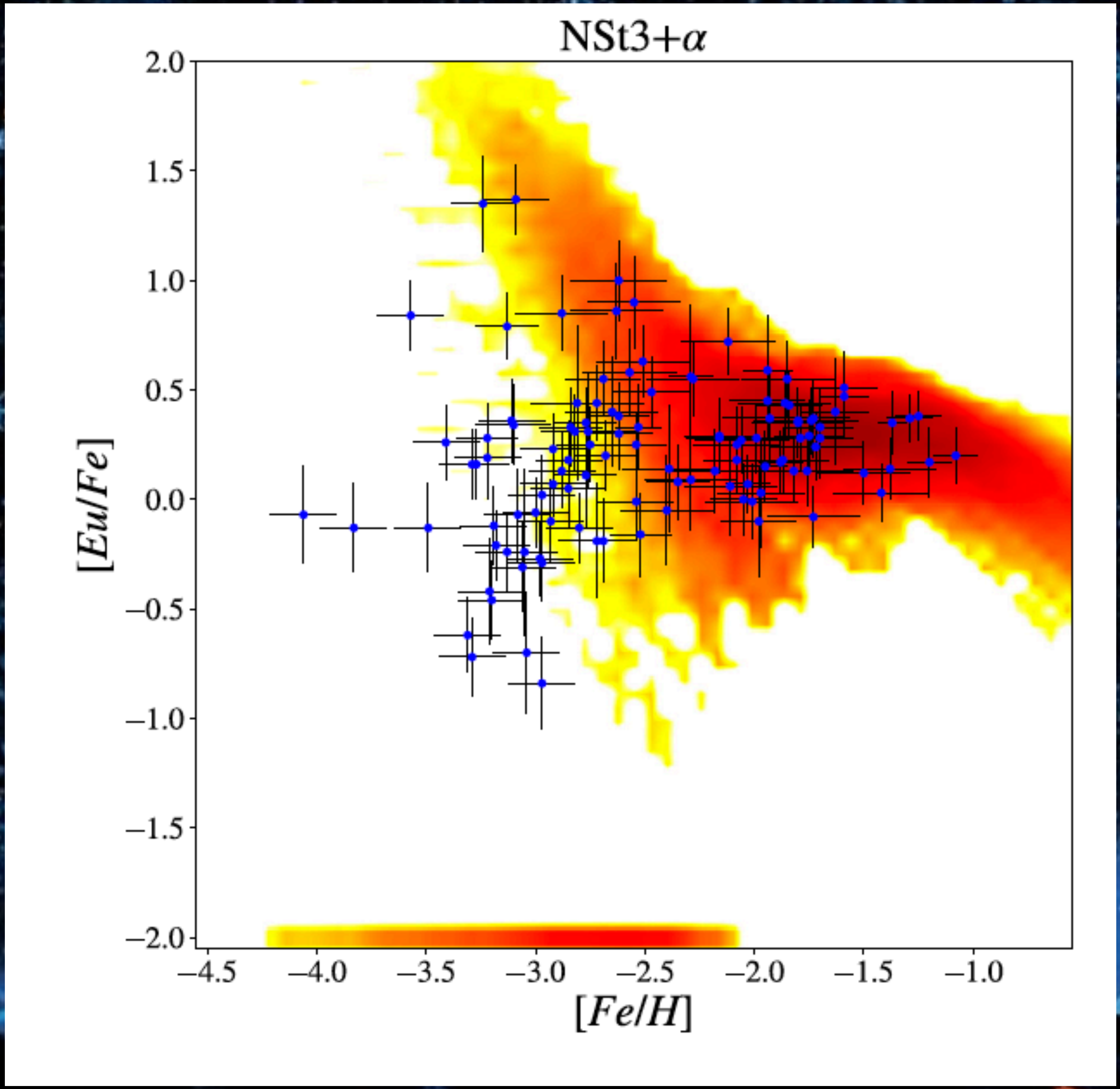
What about a distribution of delays?



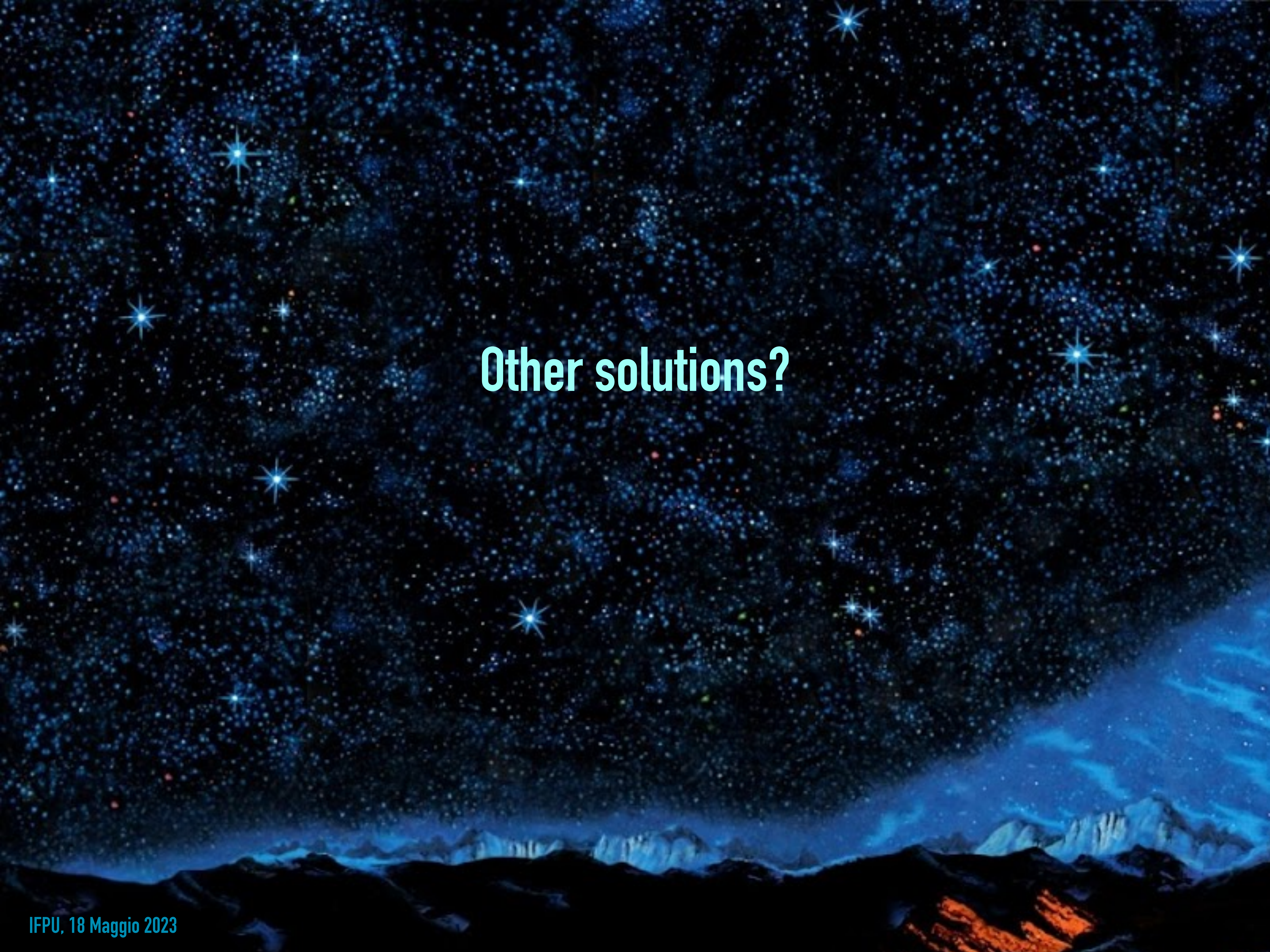
This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the astro-ph Shen+2014

Stochastic model

with a delay time distribution $t^{-1.5}$
(and varying alpha)



Cavallo+21



Other solutions?

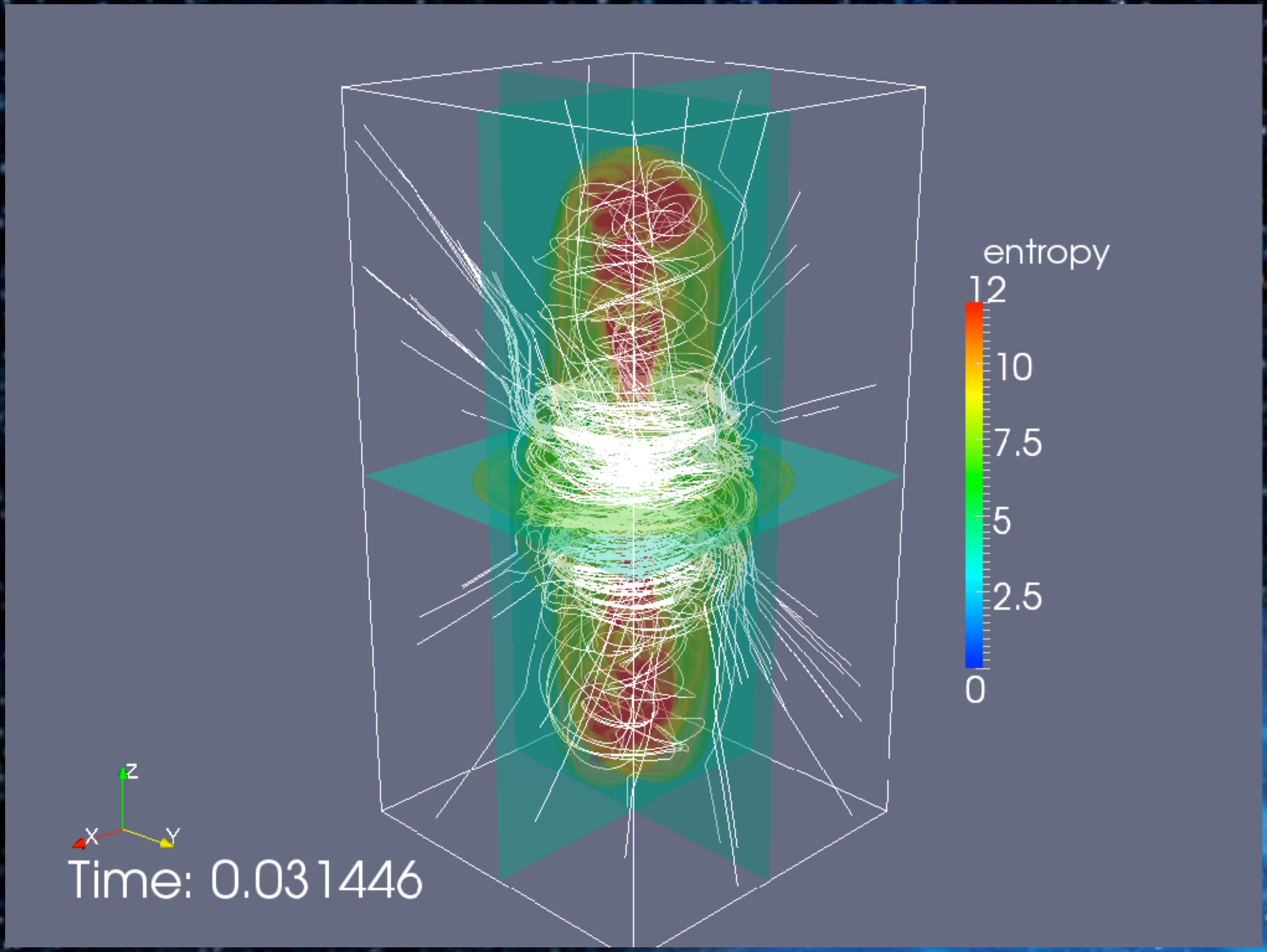
Magneto Rotationally Driven SN scenario (MRD)

(Winteler+12, Nishimura+15)

The progenitors of MRD SNe are believed to be rare and possibly connected to long GRBs.
Only a small percentage of the massive stars (~1-5%)

Our results use an higher value (10%), but this percentage is not well constrained, in particular for the early Universe.

Therefore in the stochastic model not all the massive stars produce neutron capture elements.

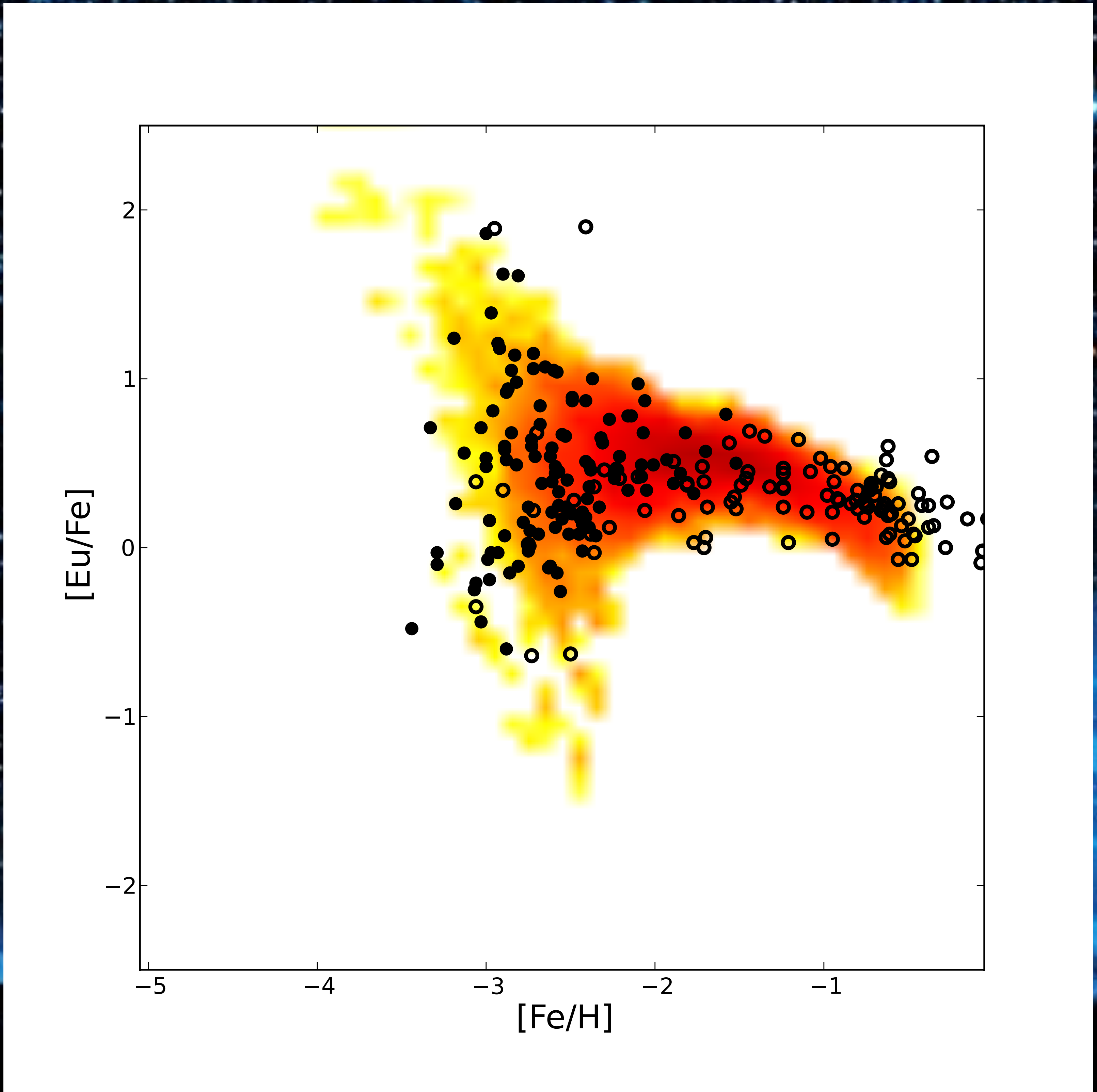


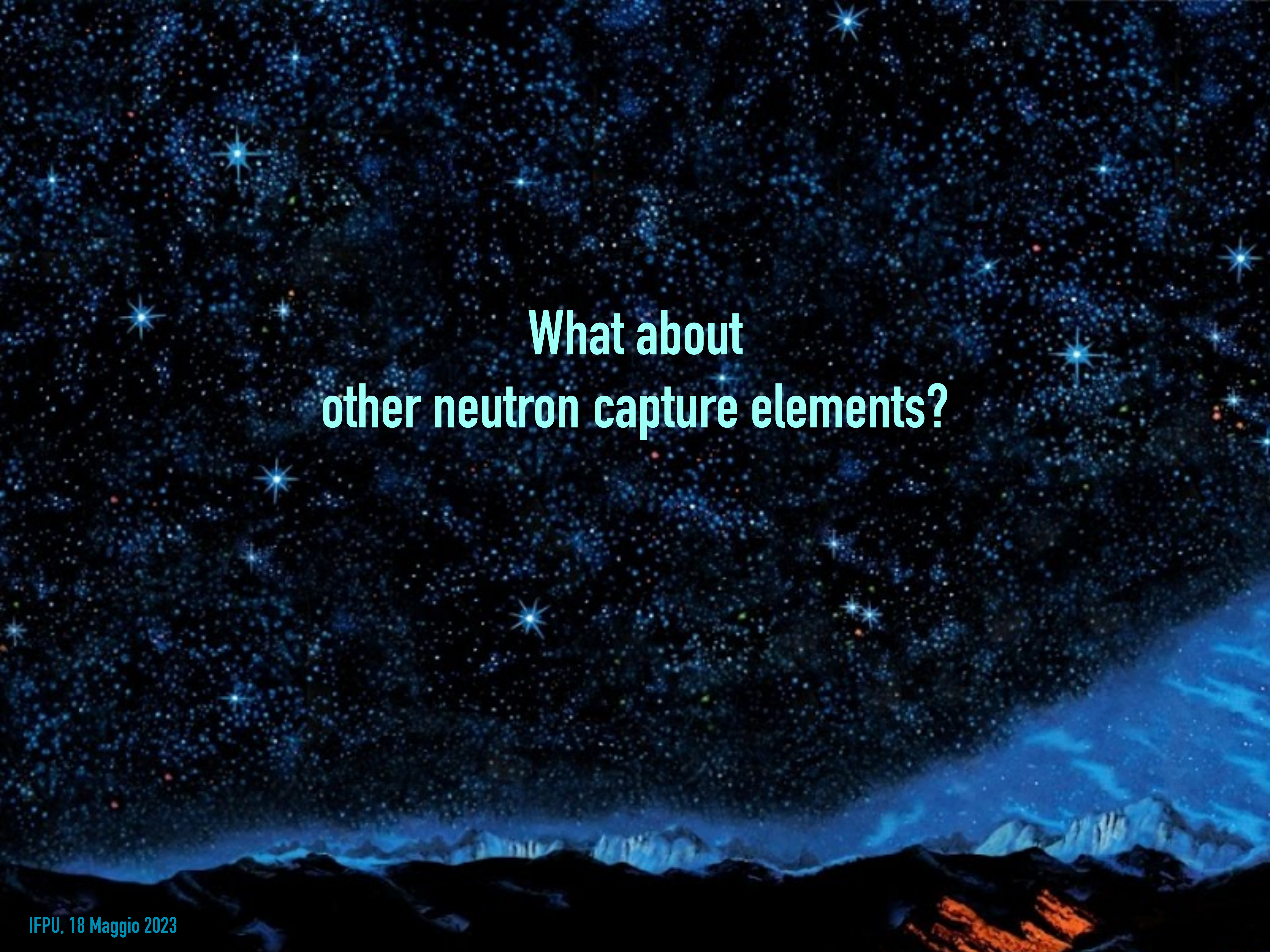
Magneto Rotationally Driven SN scenario (MRD) 10%

Cescutti+14

In the best model shown here the amount of r-process in each event is about 2 times the one assumed in NSM scenario

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





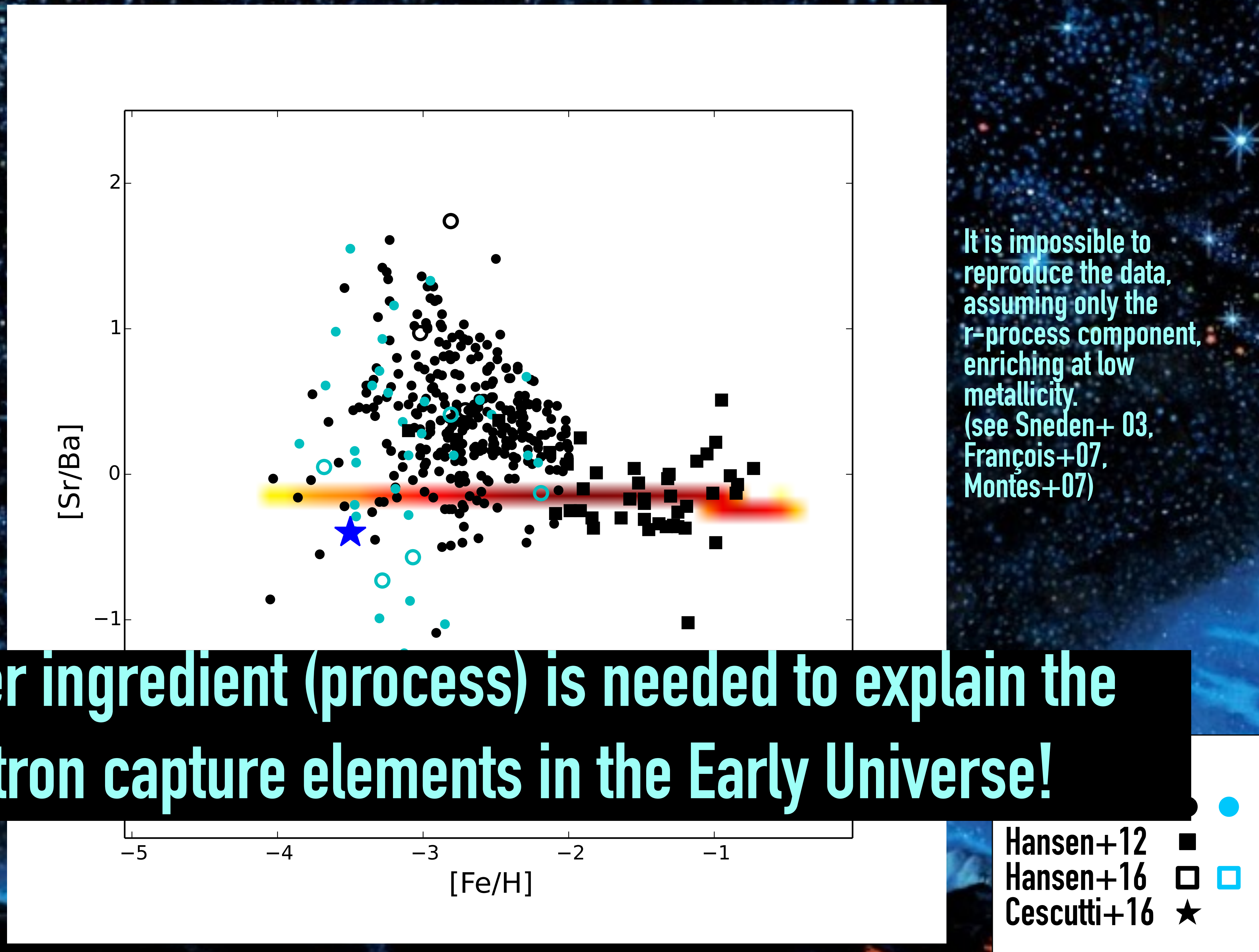
What about
other neutron capture elements?

Neutron capture elements

	s-process	Early Galaxy	r-process
site	Low-(intermediate) mass stars		NS mergers (& Massive stars?)
time scale	>300Myr		DTD NSM or/and < 30Myr for MRD SNe
yields	Cristallo+11		nucleosynthesis available (but . . .)
	Karakas+12		

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)

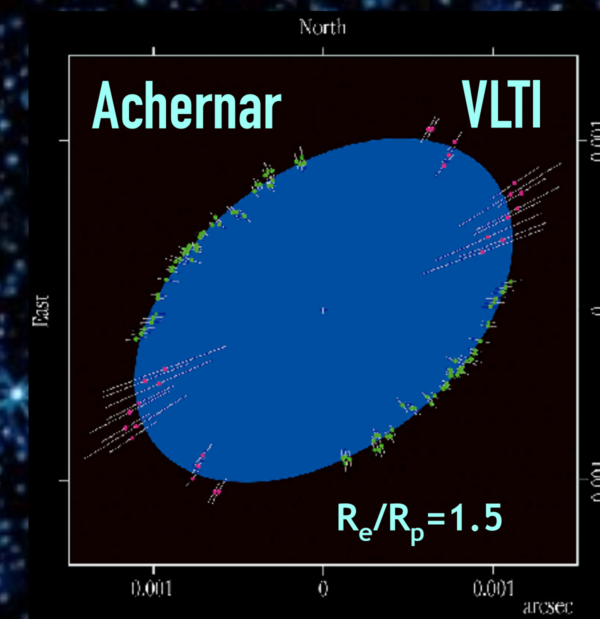


It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

Another ingredient (process) is needed to explain the neutron capture elements in the Early Universe!

Rotating massive stars in the early Universe

Massive stars rotate in the
Local Universe



In the Early Universe

Low metals: stars rotate faster (more compact)

Rotation ➡ Mixing inside star

Ejected matter will be rich in14N,13C, 12C, & s-process

Signatures:

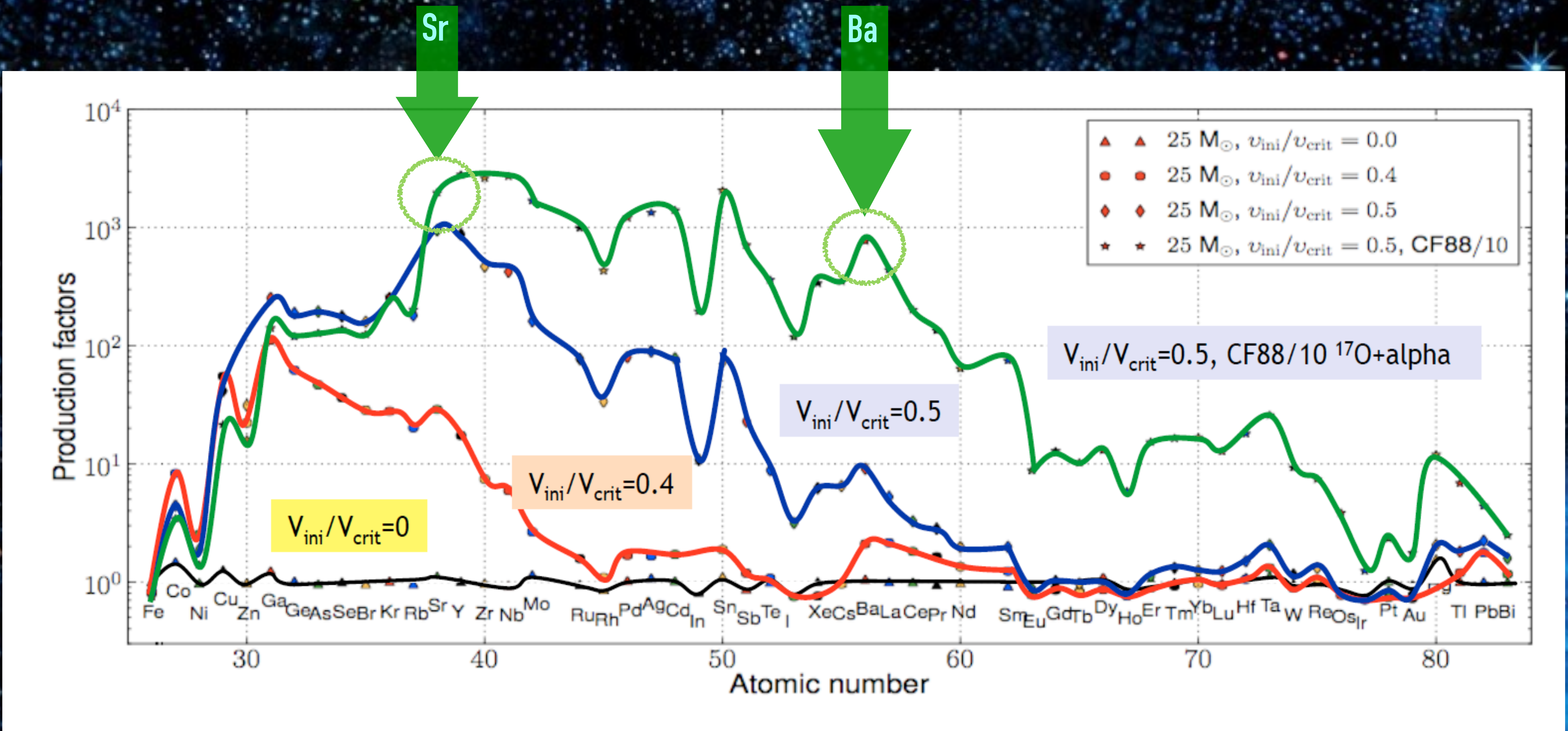
(1) Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)
(2) Increase in the C/O ratio in the early Universe
(3) Large amounts of 13C in the early Universe (Chiappini et al. 2008 A&A Letters)
(4) Early production of Be and B by cosmic ray spallation (Prantzos 2012)

Test the production of neutron capture elements from this s-process (Sr,Ba,…)!

Low metallicity and rotating massive stars

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

Rotating massive stars can contribute to s-process elements!



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

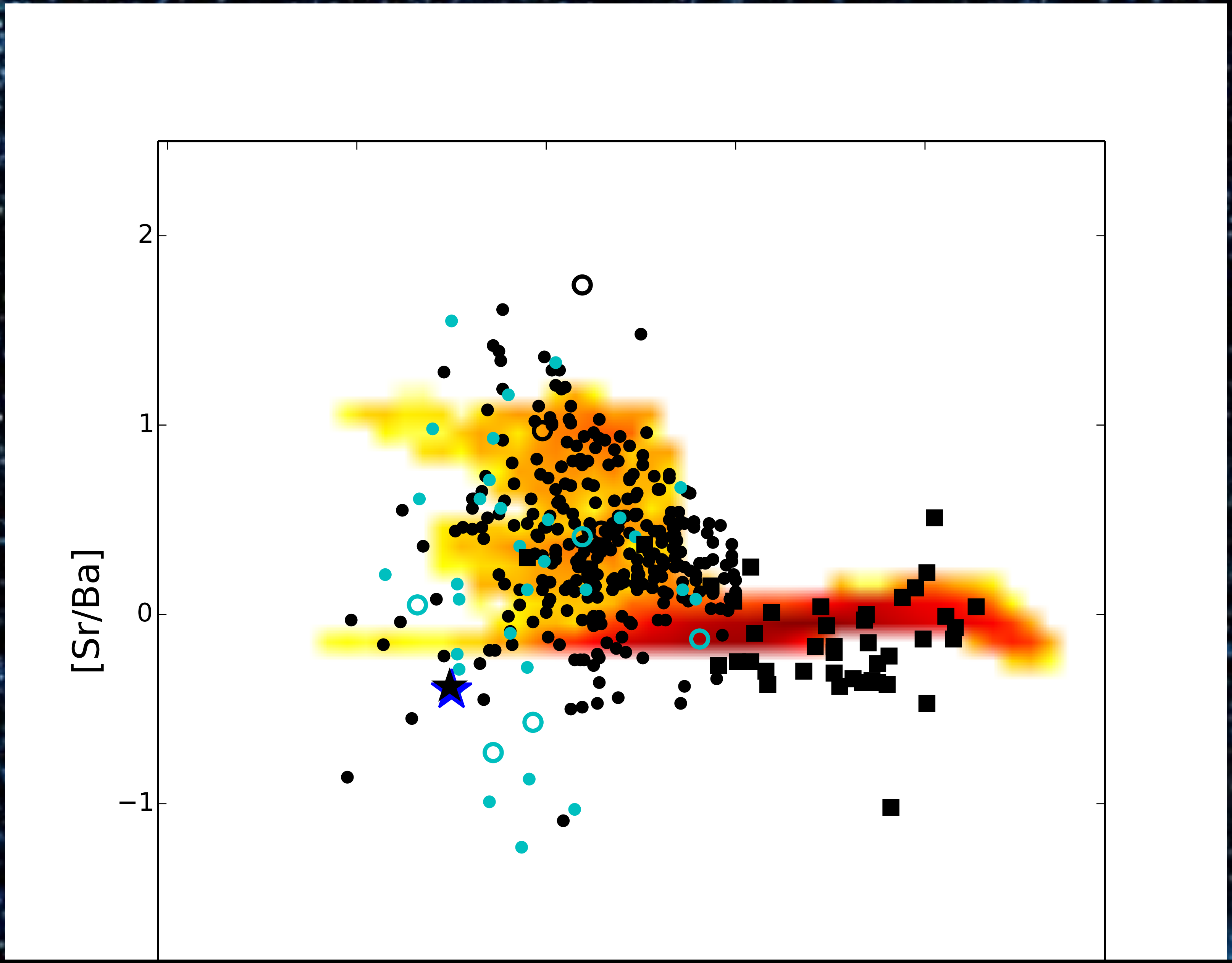
Neutron capture elements

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

s-process from rotating massive stars

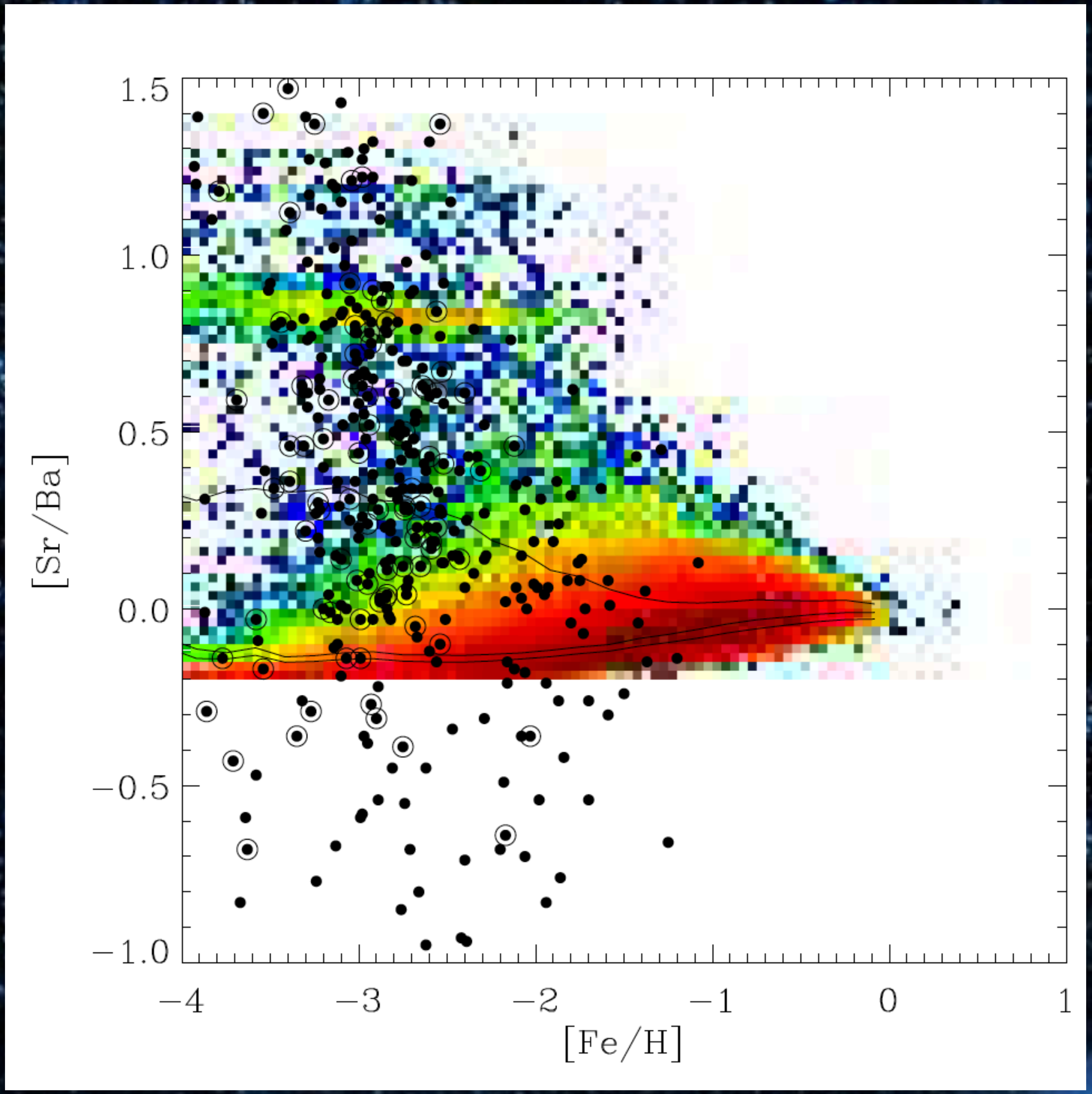
+ an r-process site (the 2 productions are not coupled!)

Cescutti et al. (2013)
Cescutti & Chiappini (2014)



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

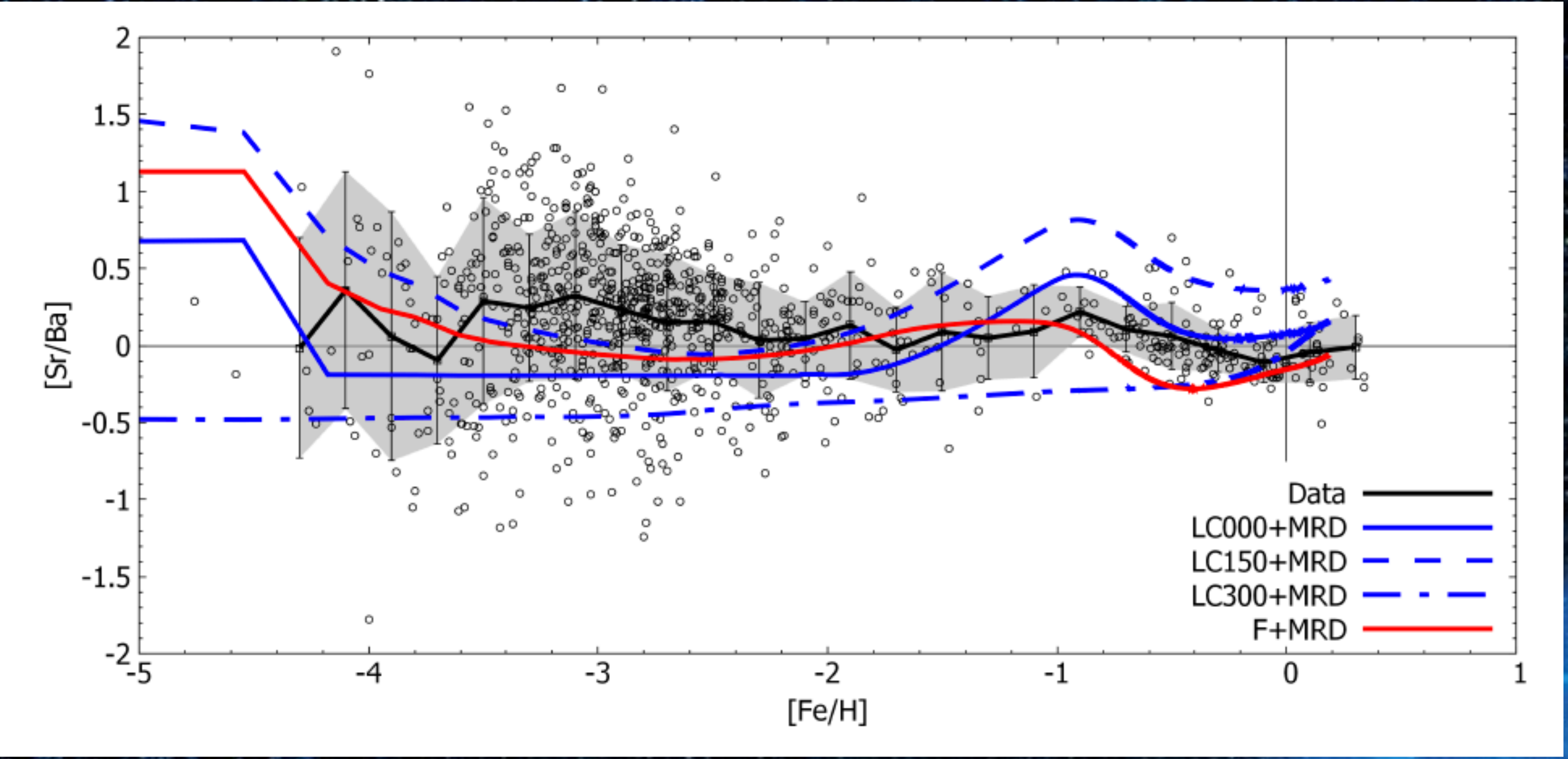
Results with an Sph simulation of the Galactic halo



Scannapieco, Cescutti & Chiappini (2022)

Confirmed in Rizzuti et al. (2019)

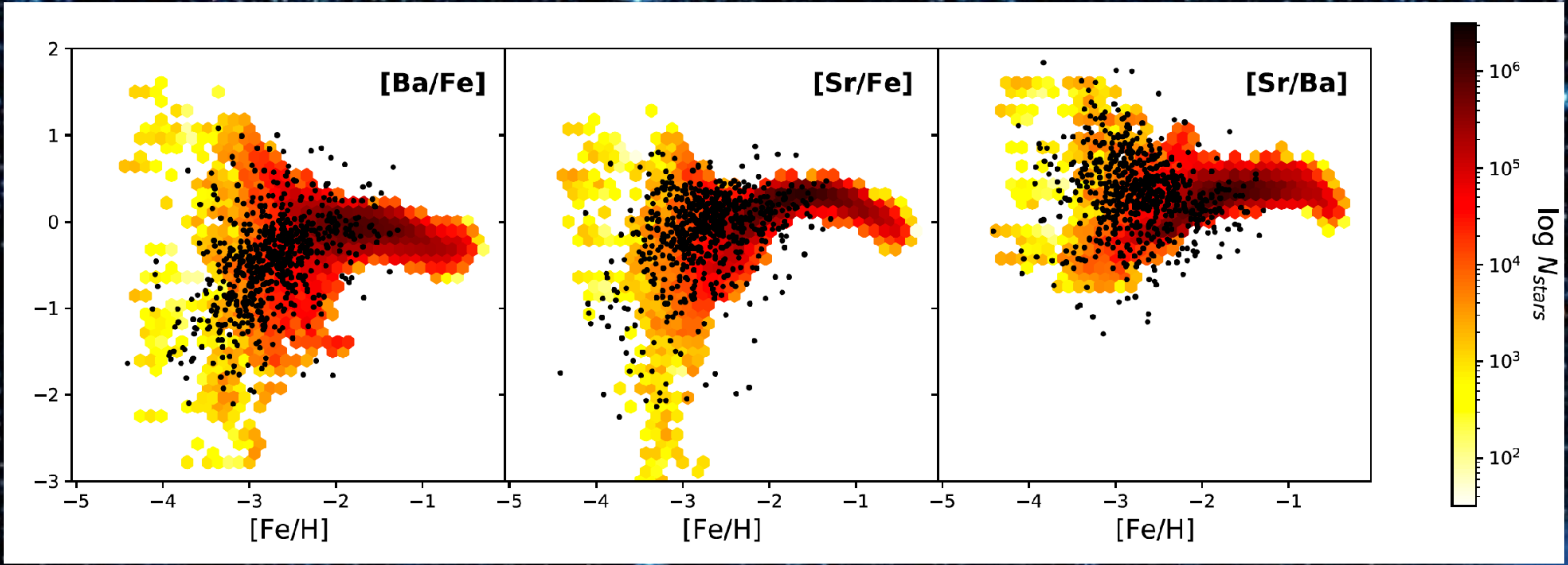
adopting Limongi&Chieffi18



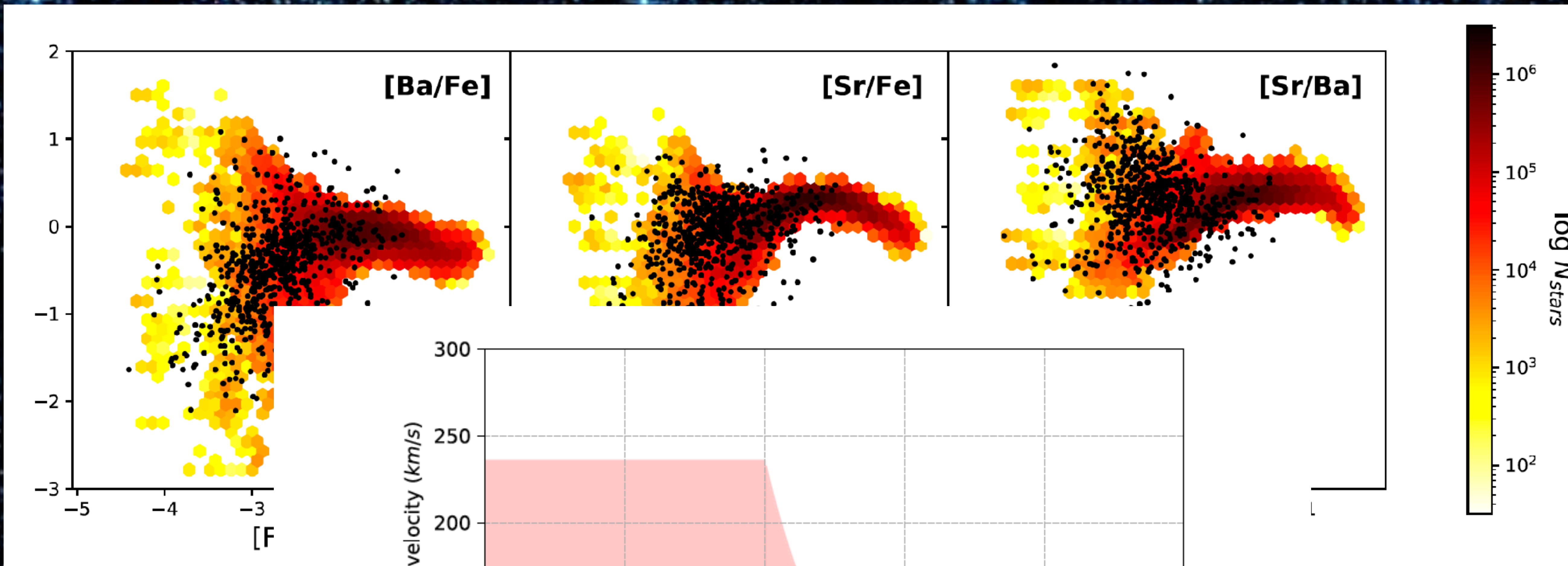
see also Prantzos et al. 2018

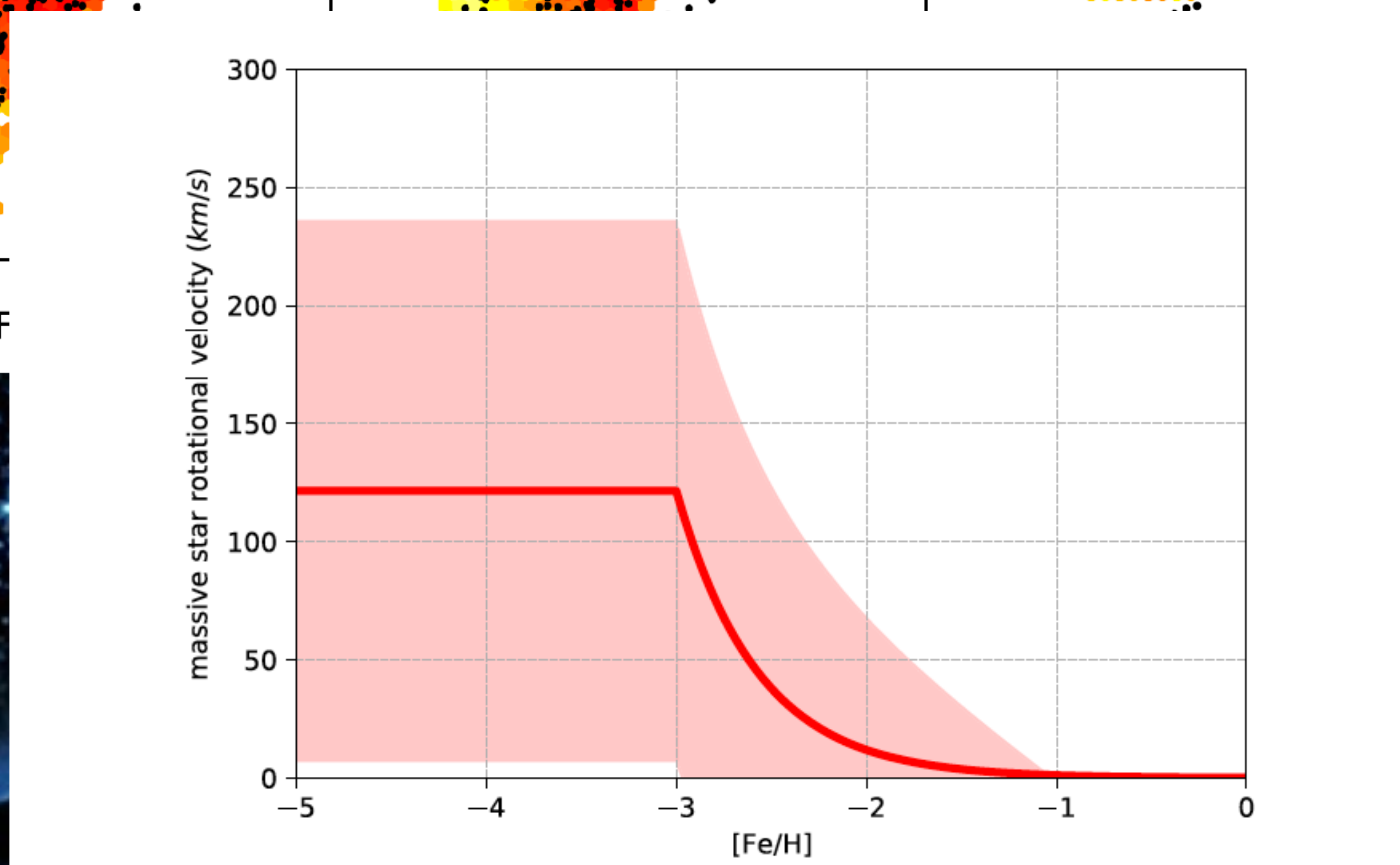
Rizzuti et al. (2021)

adopting Limongi&Chieffi18



Rizzuti et al. (2021)
adopting Limongi&Chieffi18





Conclusions

The neutron capture elements in the Galactic halo have been produced by (at least) 2 different processes:

A (main) r-process, rare and able to produce all the elements up to Th with a pattern as the one observed in r-process rich stars.

NSM are certainly the best candidate to play this role if they have a very short time scale, or if their frequency was higher at extremely low metallicity. Other sources like MRD SNe can also play this role.

Another process more frequent and that can produce both Sr and Ba (and [Sr/Ba]>0) with a production that is compatible with the s-process by rotating massive stars. We can use this to constrain the velocity distribution of the massive stars.

CAVEAT

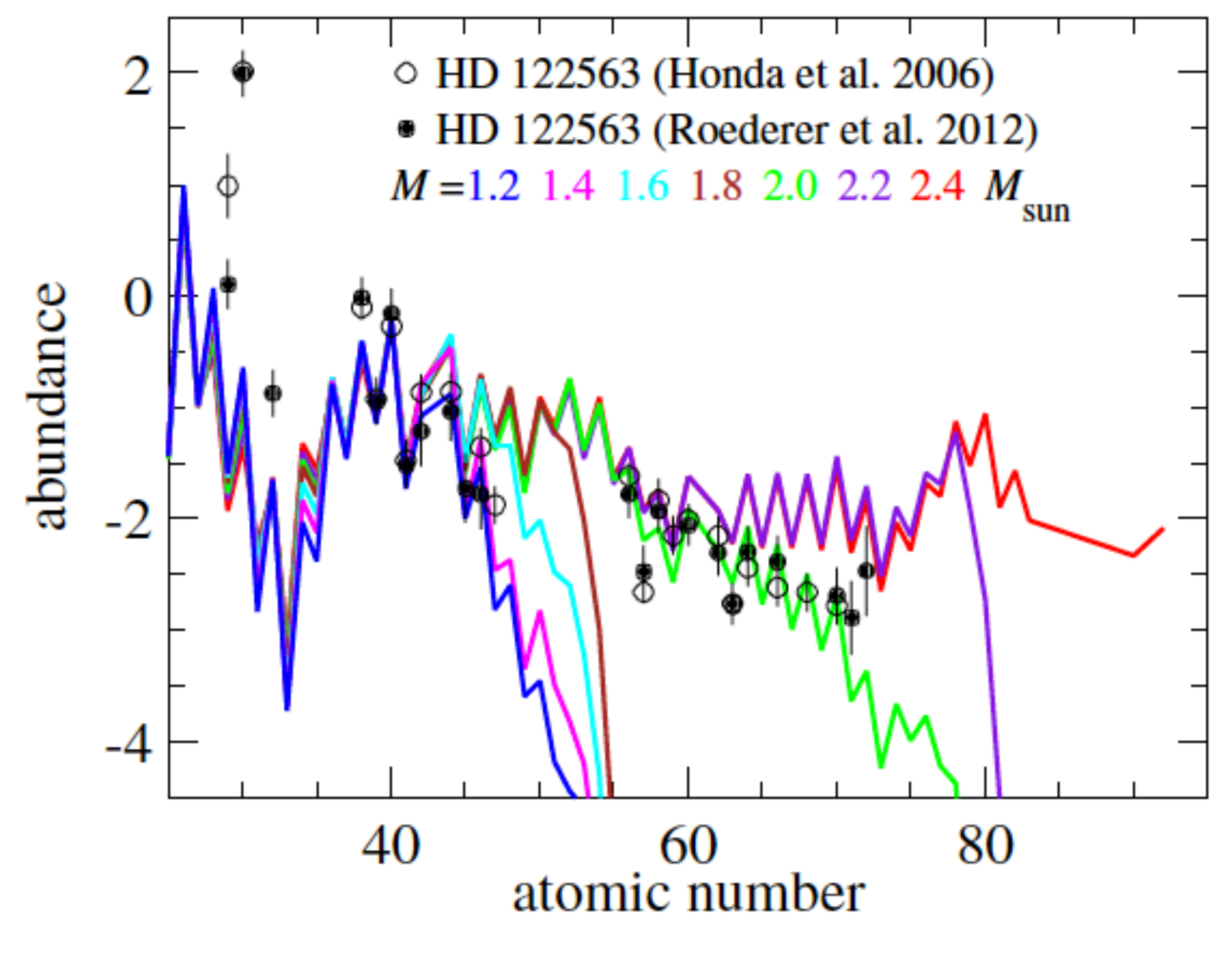
The only possible answer?

Another possible solution is the production of

\+ a weak r-process

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

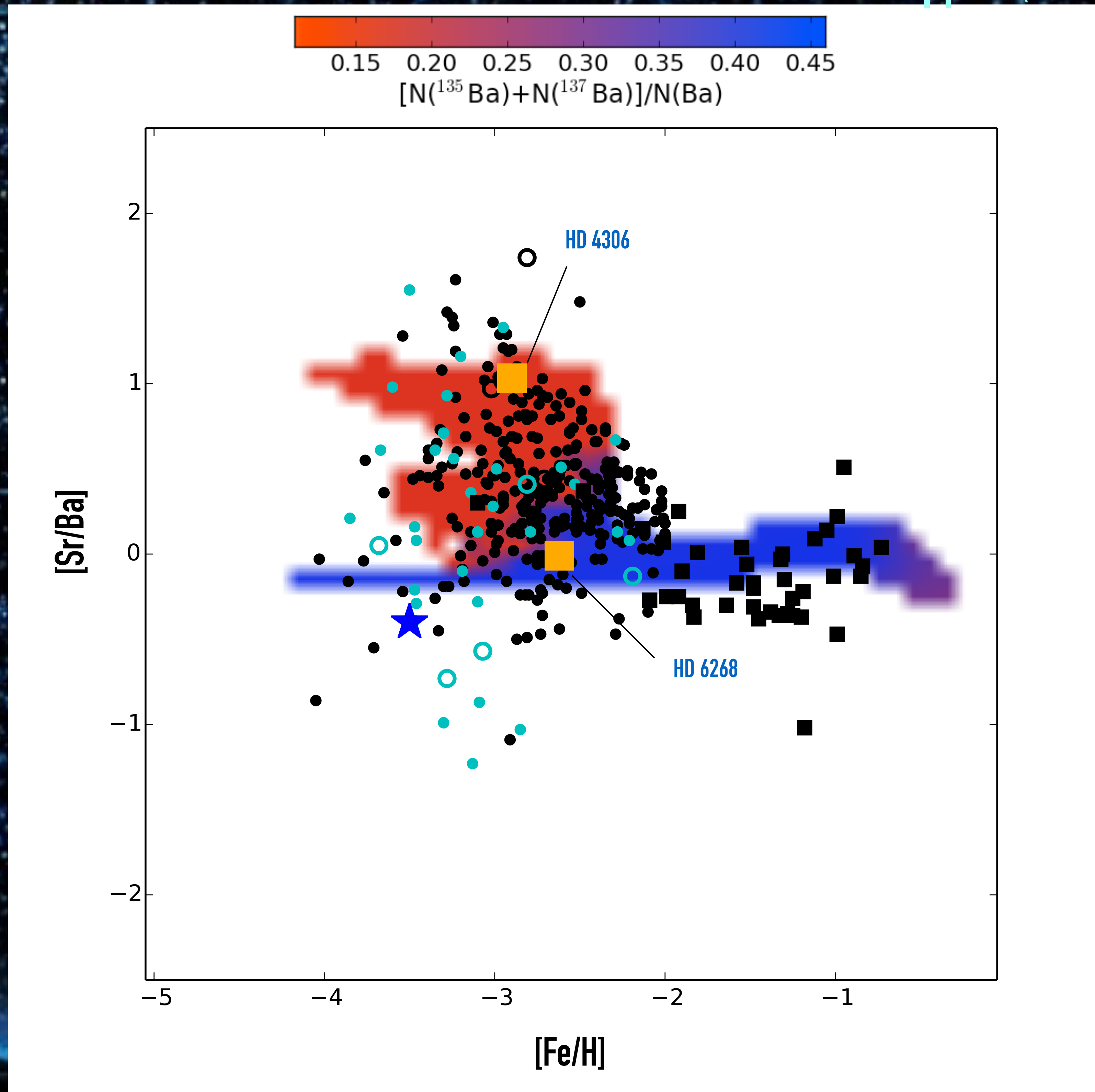
\+ a main r-process



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

Isotopic ratio for Ba

Cescutti and Chiappini (2014)



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

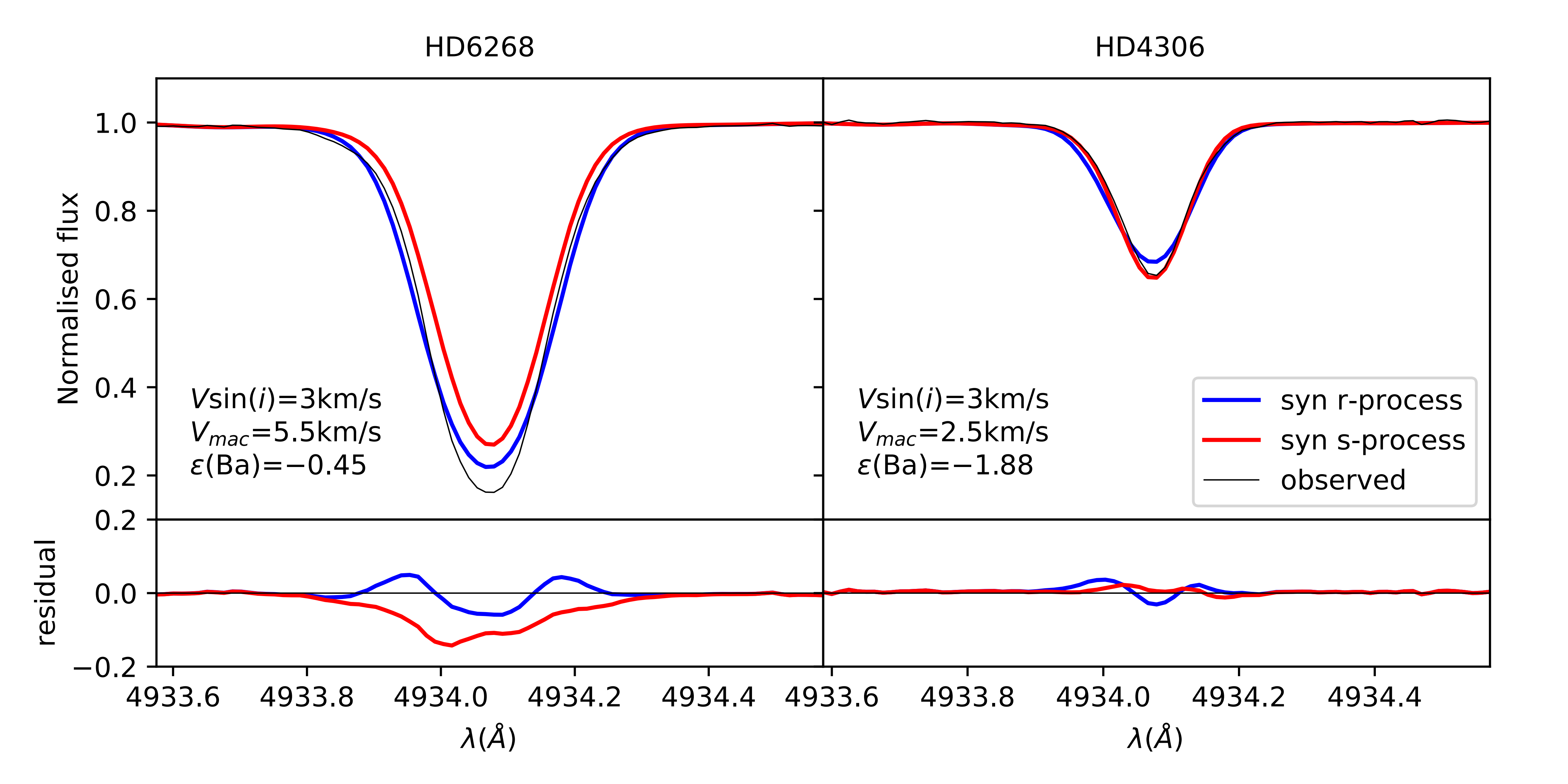
See results
on HD 140283
from Magain (1995)
to Gallagher+(2015)

2 stars
with a R~100'000 &
S/N~500
with UVES at VLT

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

Synthesis of barium lines

with hyperfine splitting effects



Cescutti +21

Conclusions

Our inspection of the barium lines has found that the profiles of the lines (suffering hfs) are different in the 2 stars.

The most likely explanation is that:

HD 6268 has been polluted by an r-process source
&
HD 4306 by and s-process source,

validating Cescutti&Chiappini14 results

HR and high S/N still provide fundamental information to Galactic Archaeology, fully complementary to the amazing results coming from present and future Multiobjects spectrographs.