STARS WITHOUT BORDERS

A GALAXY IN CRISIS

LJUBLJANA, SLOVENIA

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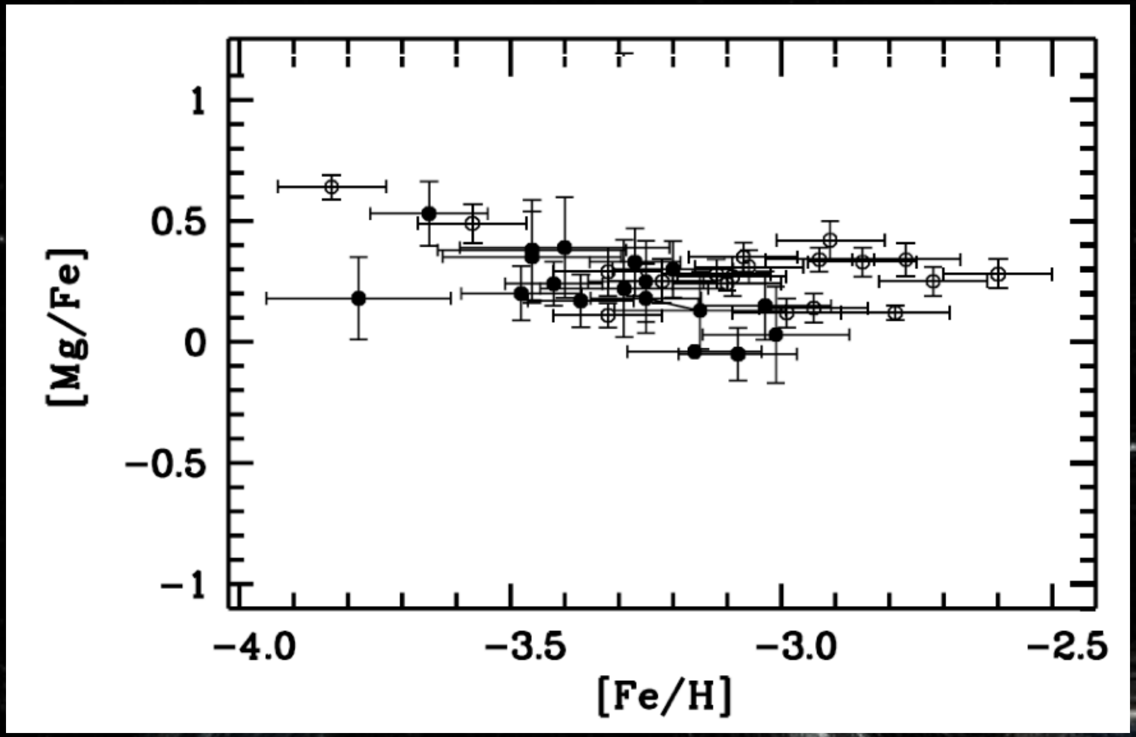
Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

Neutron capture elements across the Galaxy

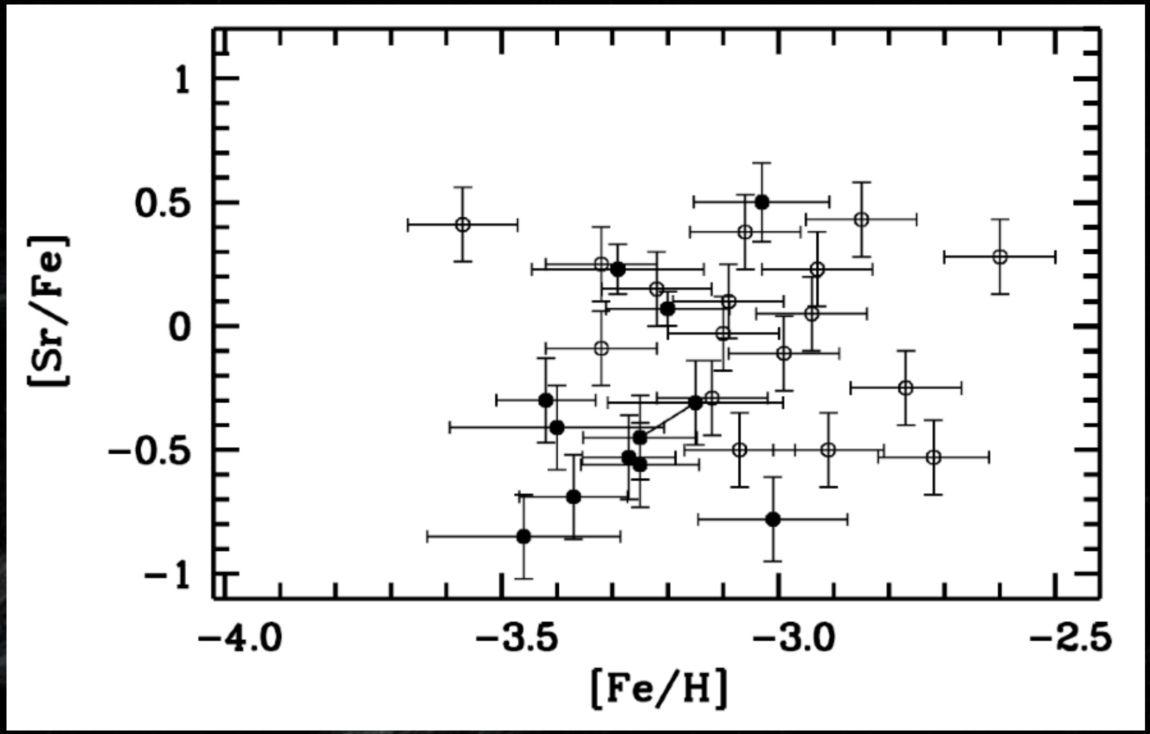
Gabriele Cescutti

Why neutron capture elements?

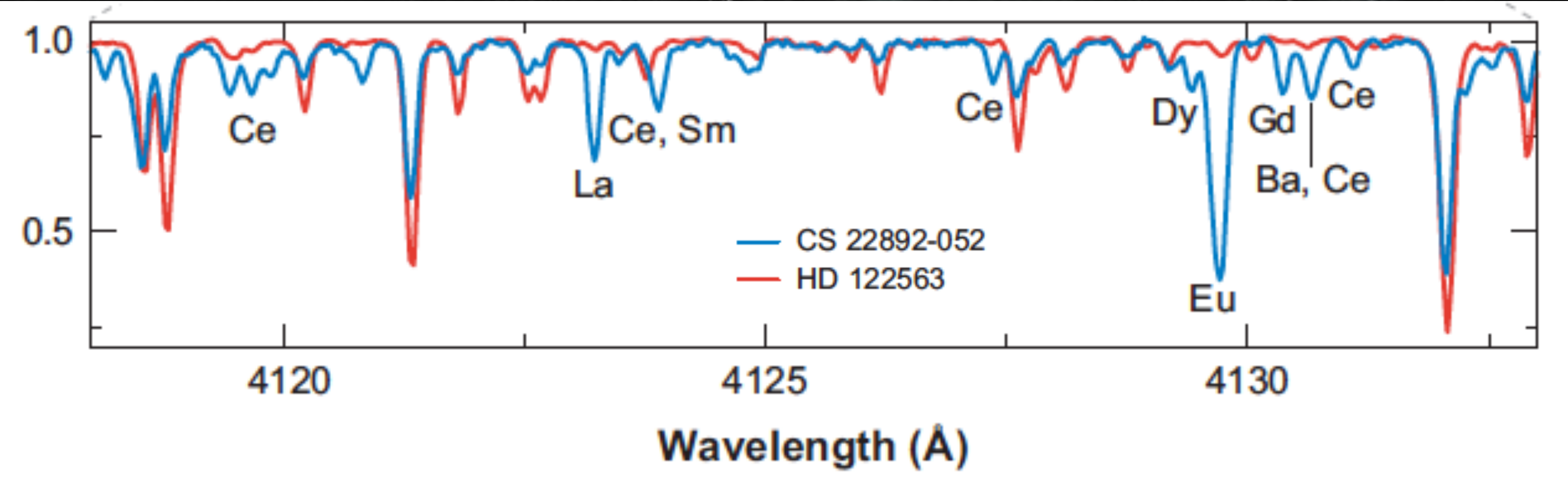
Mg: alpha-element



Sr: neutron capture element

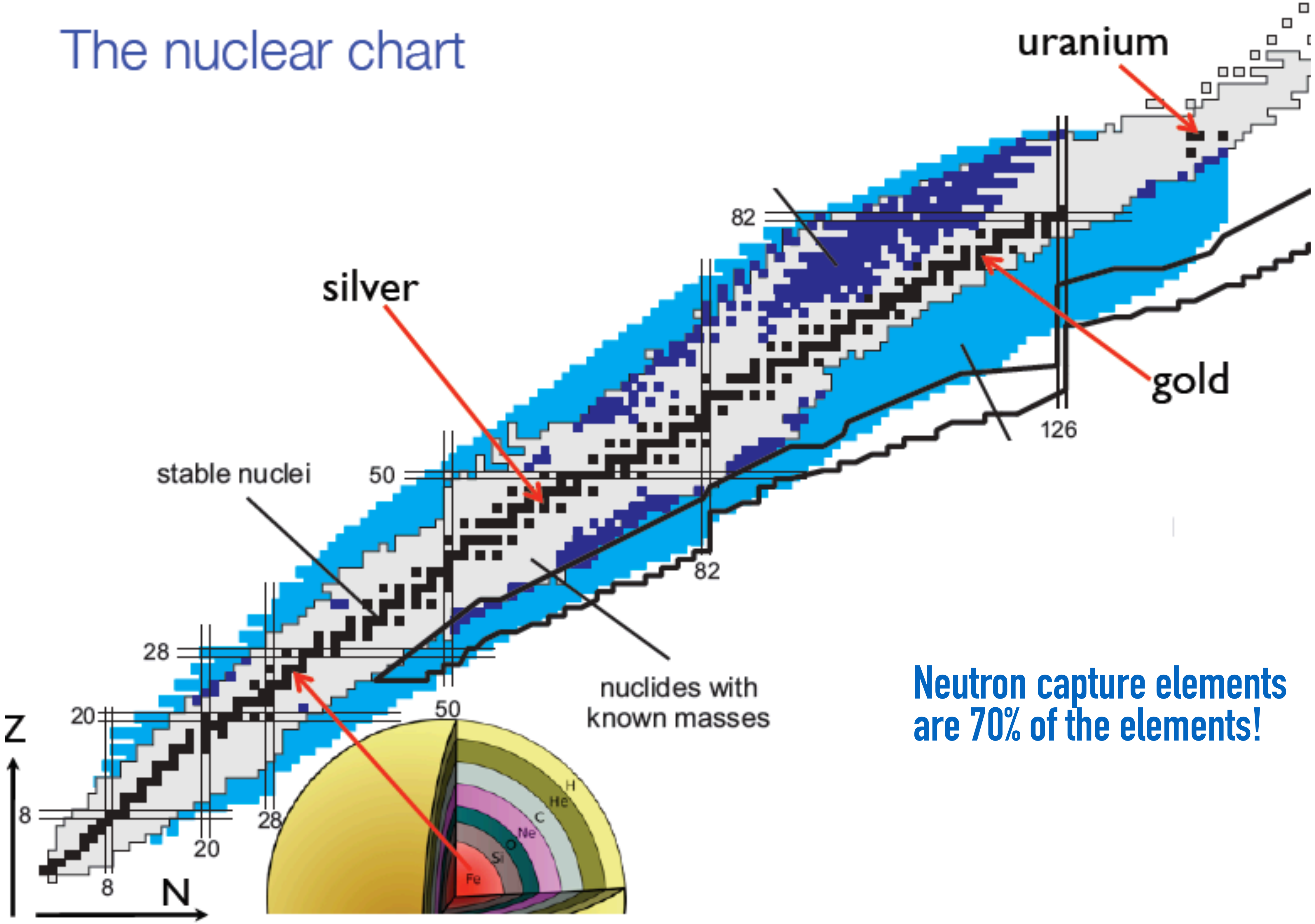


Bonifacio+12



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).

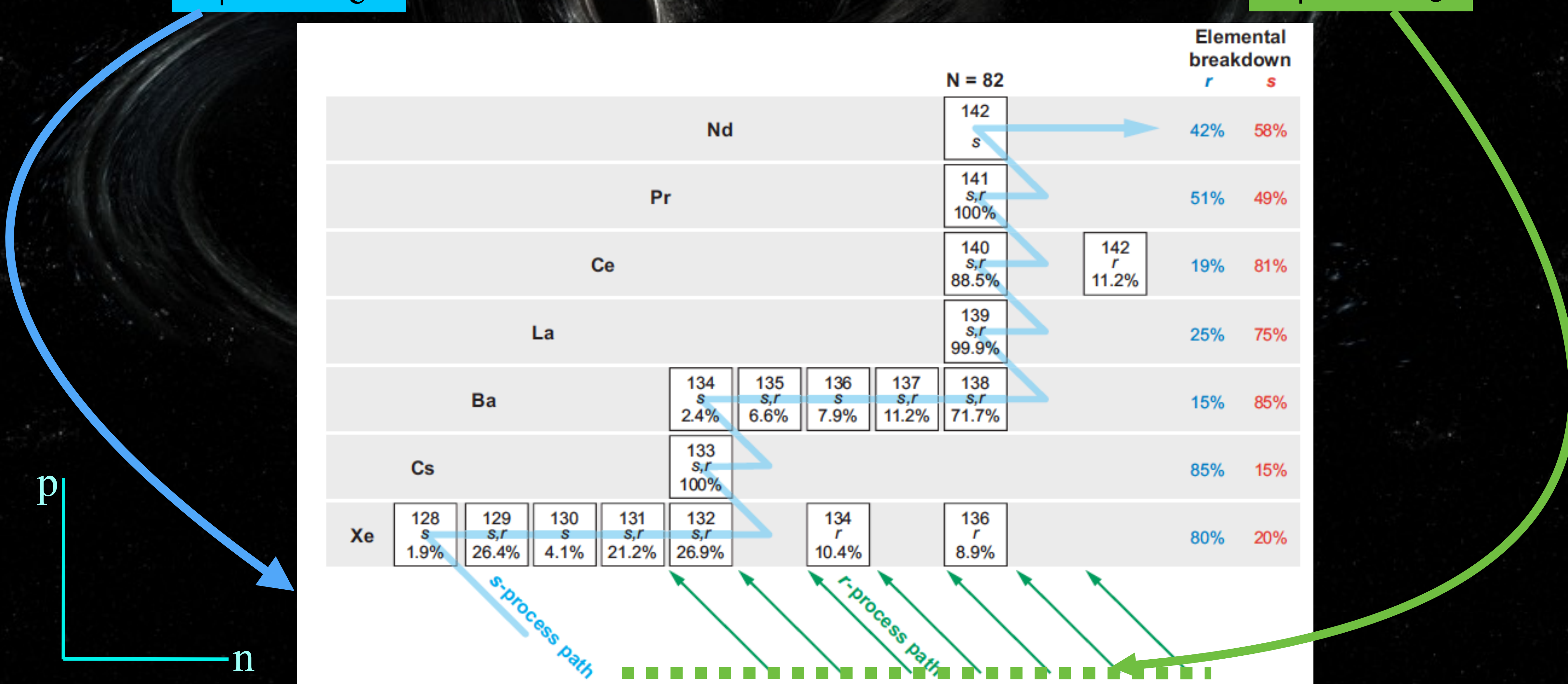
Two cases:

s-process | **r-process**

Different Timescale of the neutron capture

$\tau_\beta << \tau_c$ | $\tau_\beta >> \tau_c$

Different process path



Neutron capture elements

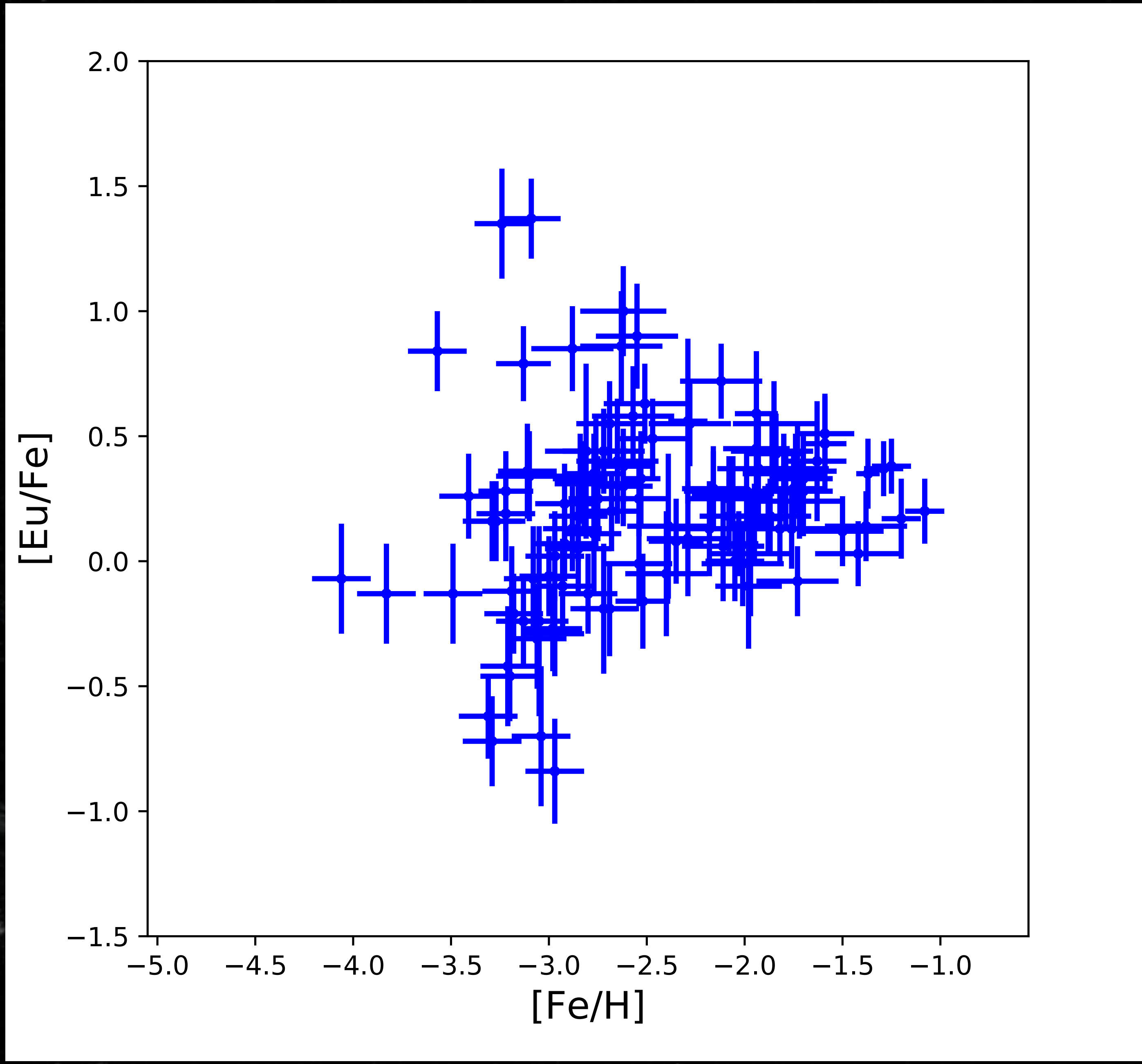
from Truran 1981 to ~8 years ago

Early Galaxy

	s-process	r-process
site	Low-(intermediate) mass stars	NS mergers (& Massive stars?)
time scale	>300Myr	< 30Myr (excluding NS mergers)
yields	Cristallo+11 Karakas+12	predictions available, but not yet comparable to real data

Eu/Fe in the Galactic halo

Since McWilliam98 idea of rare events



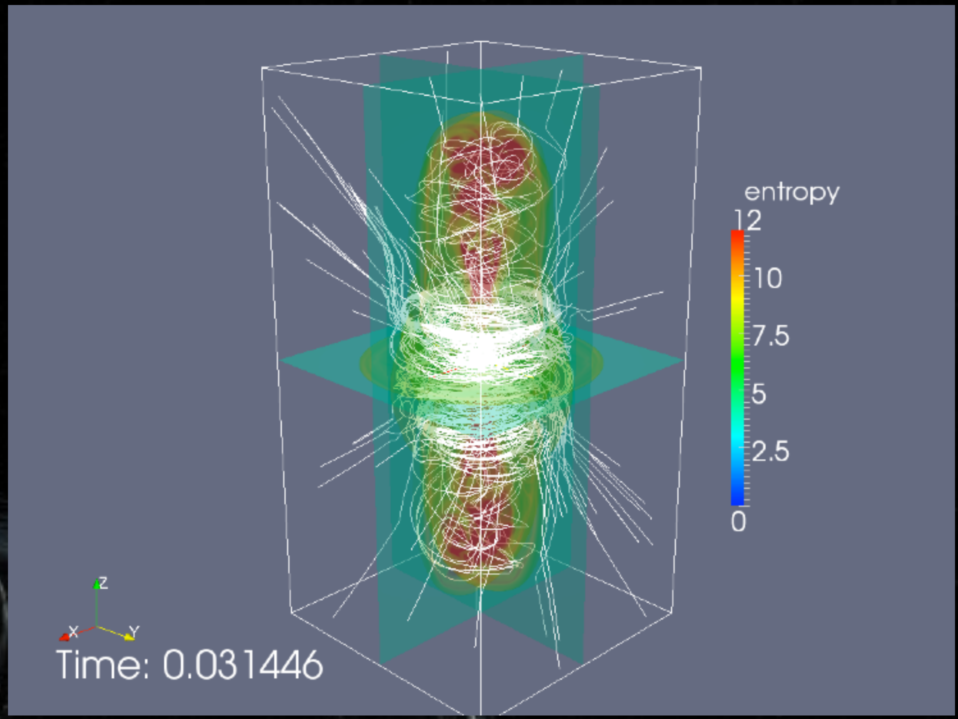
JINA collections

Site(s) of the r-process?

Electron Capture SNe (Wanajo+11)

Cescutti+13

Magnetorotat. driven SNe (Winteler+12)



Cescutti+14

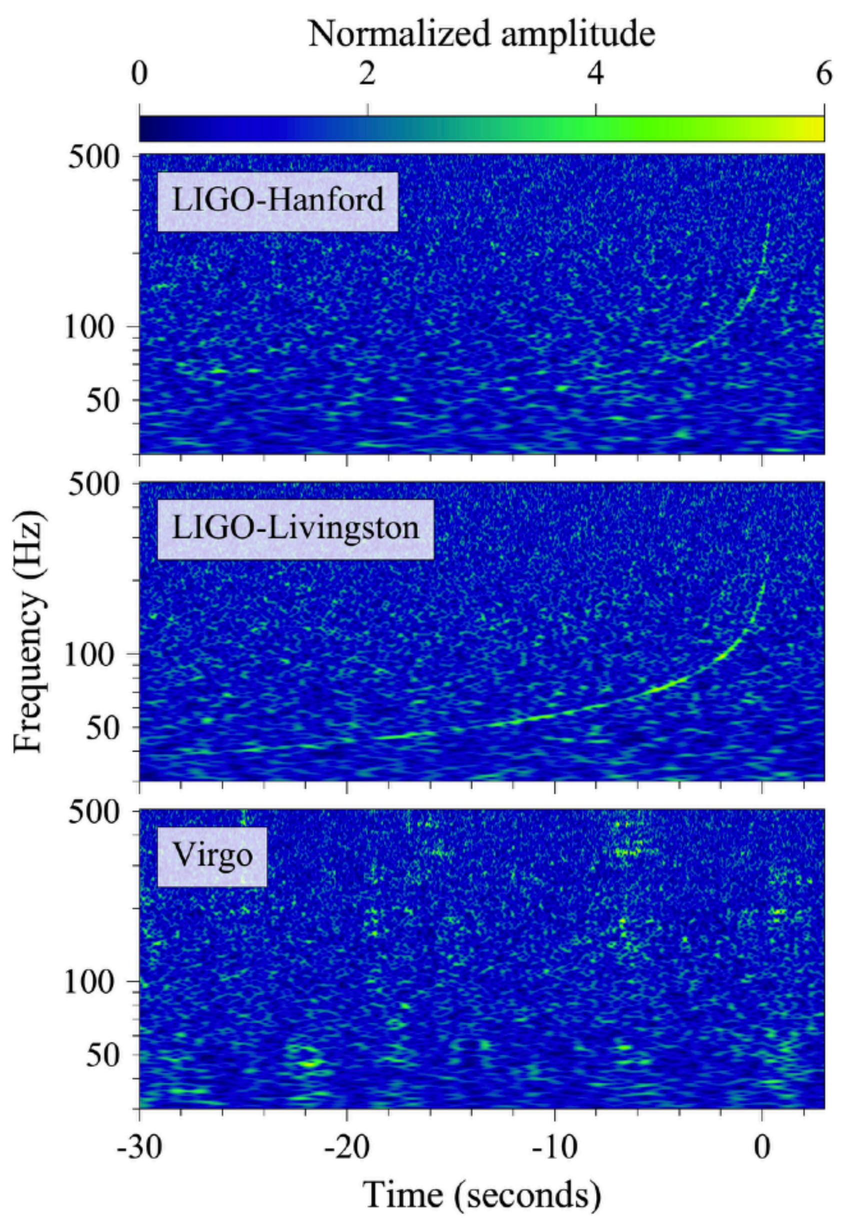
Neutron star mergers (Rosswog+13)

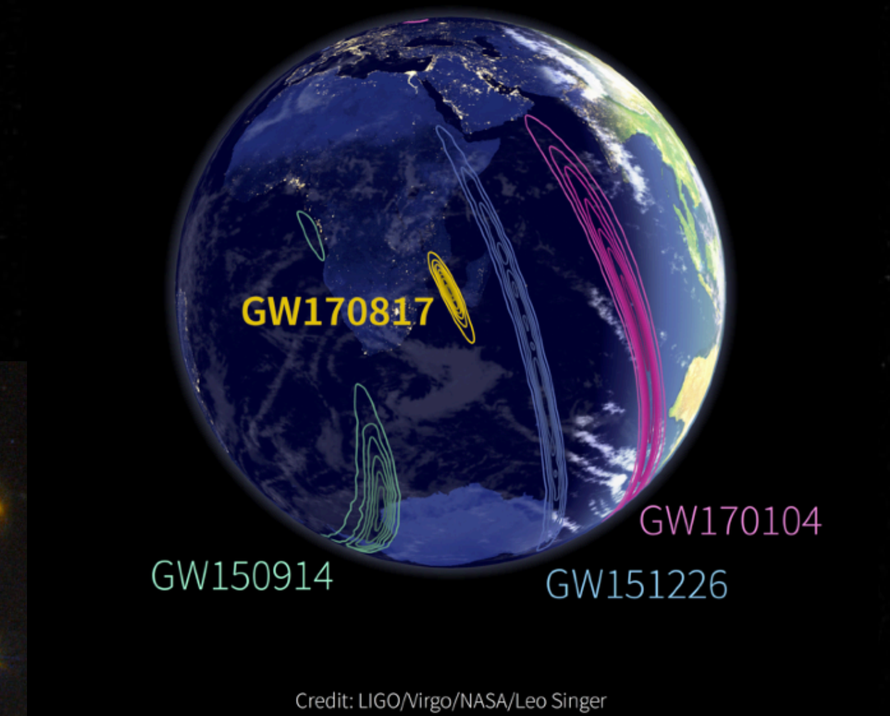
(Cescutti+15, Matteucci+14,…)

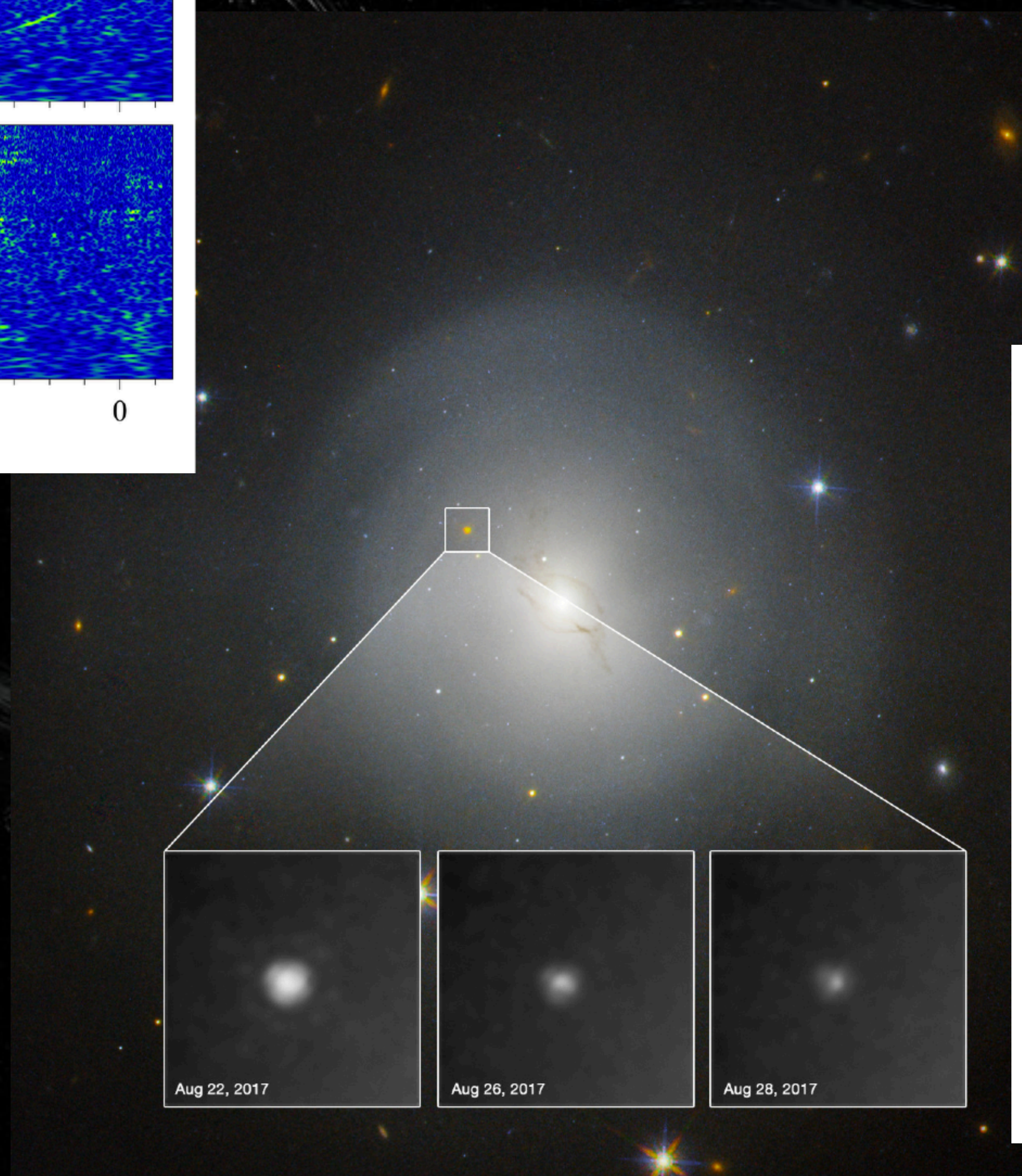
Neutrino winds SNe (Arcones+07,Wanajo 13)

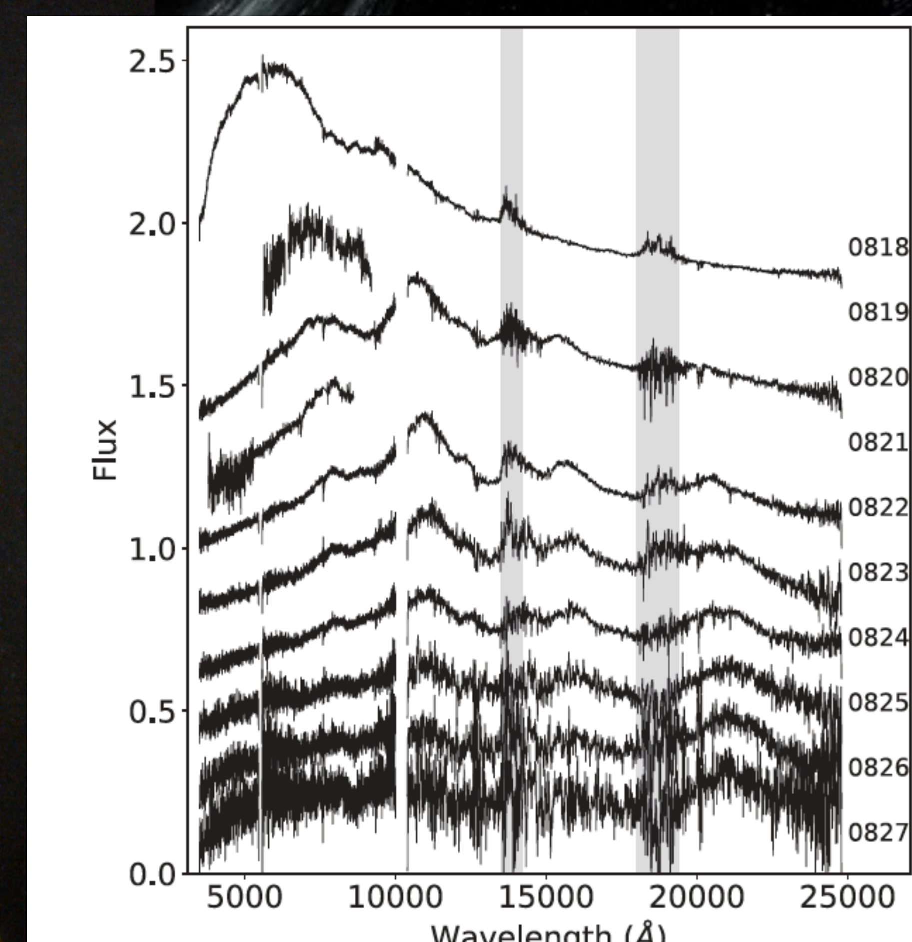
other possible sites?

After GW170817...

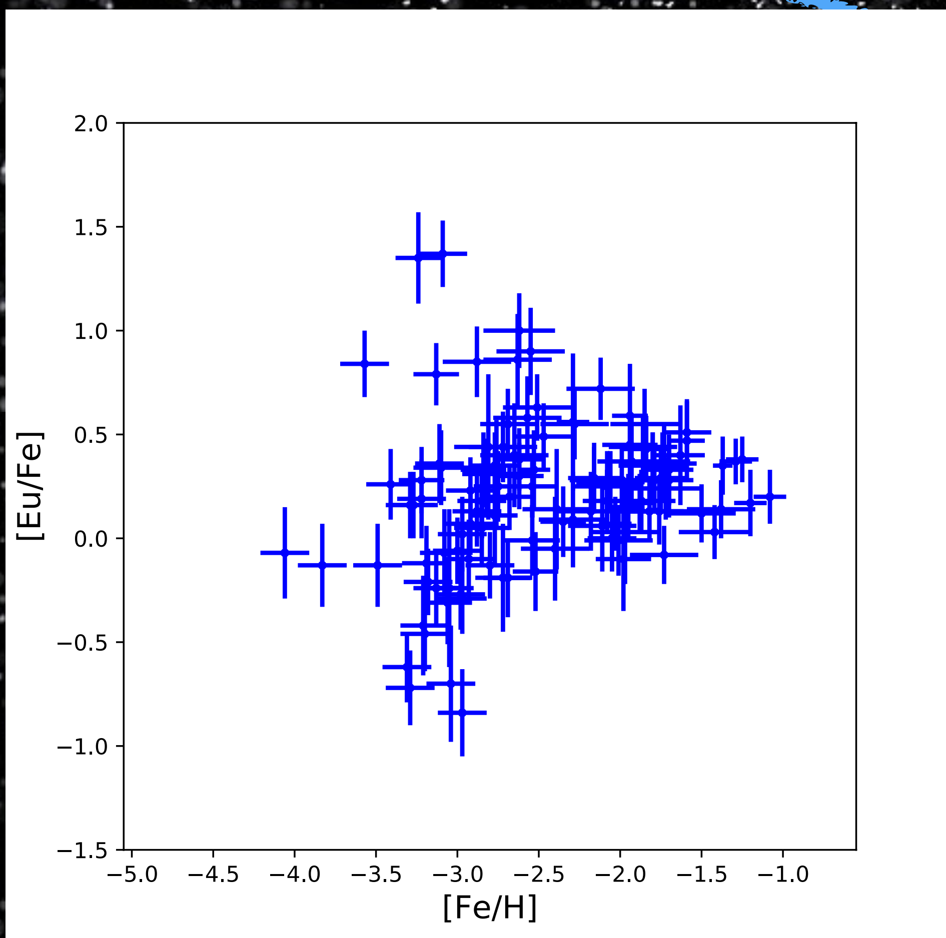


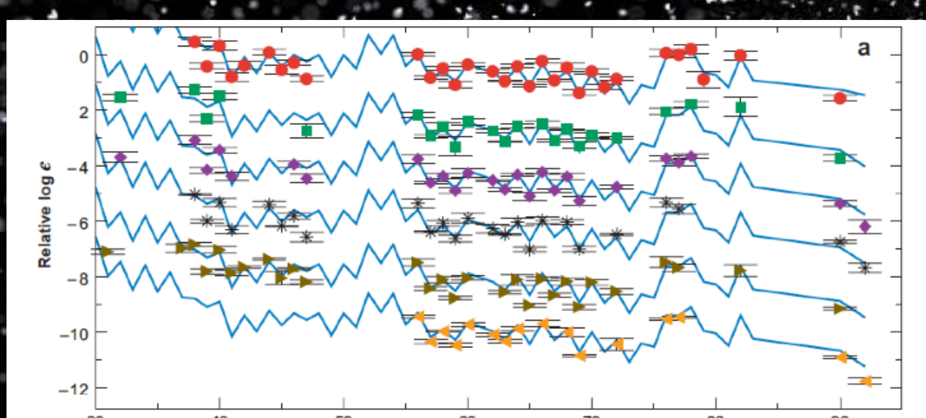


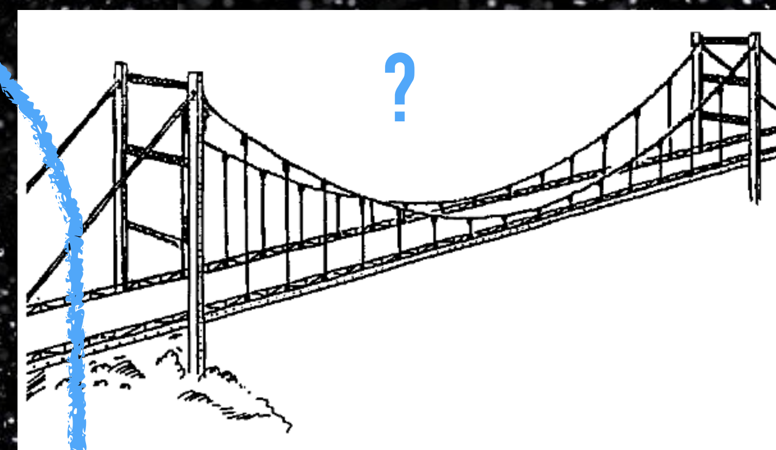




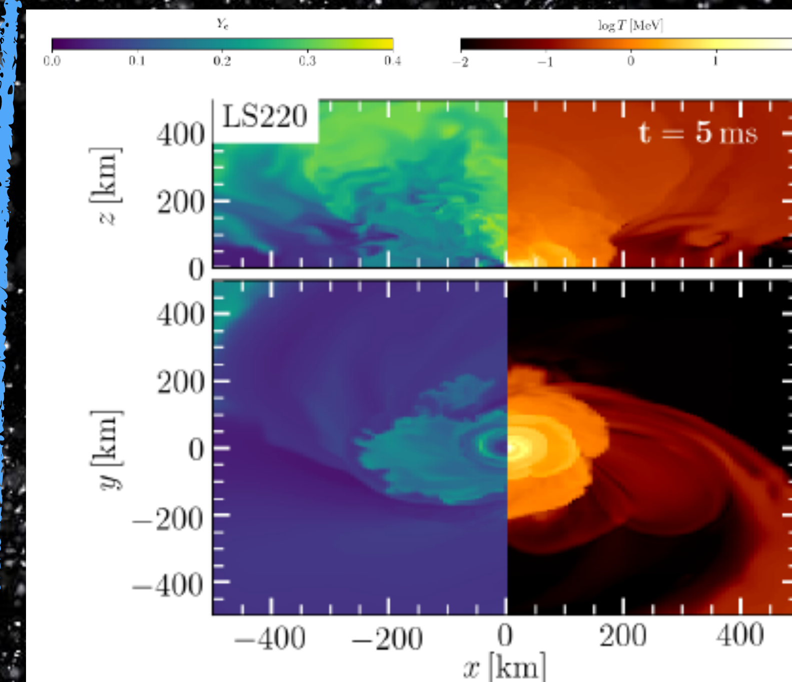
How to?



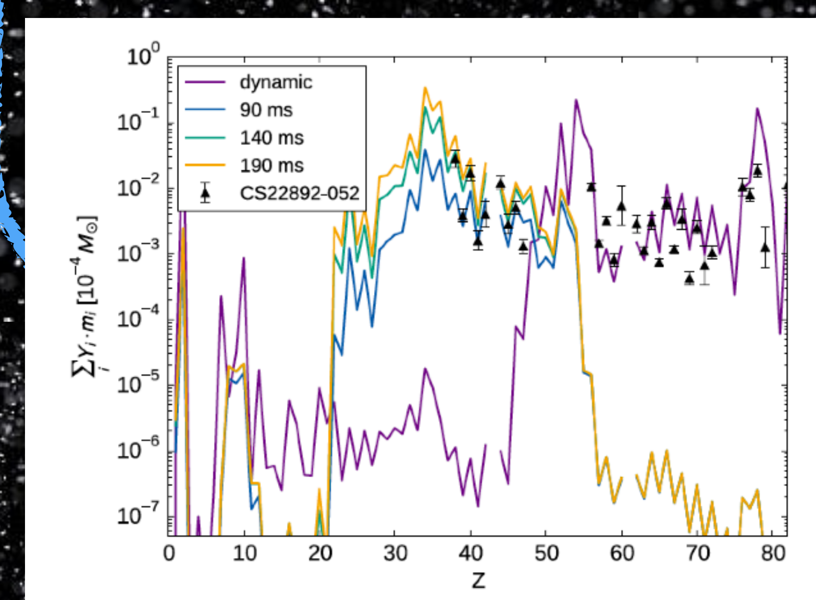




Neutron star mergers

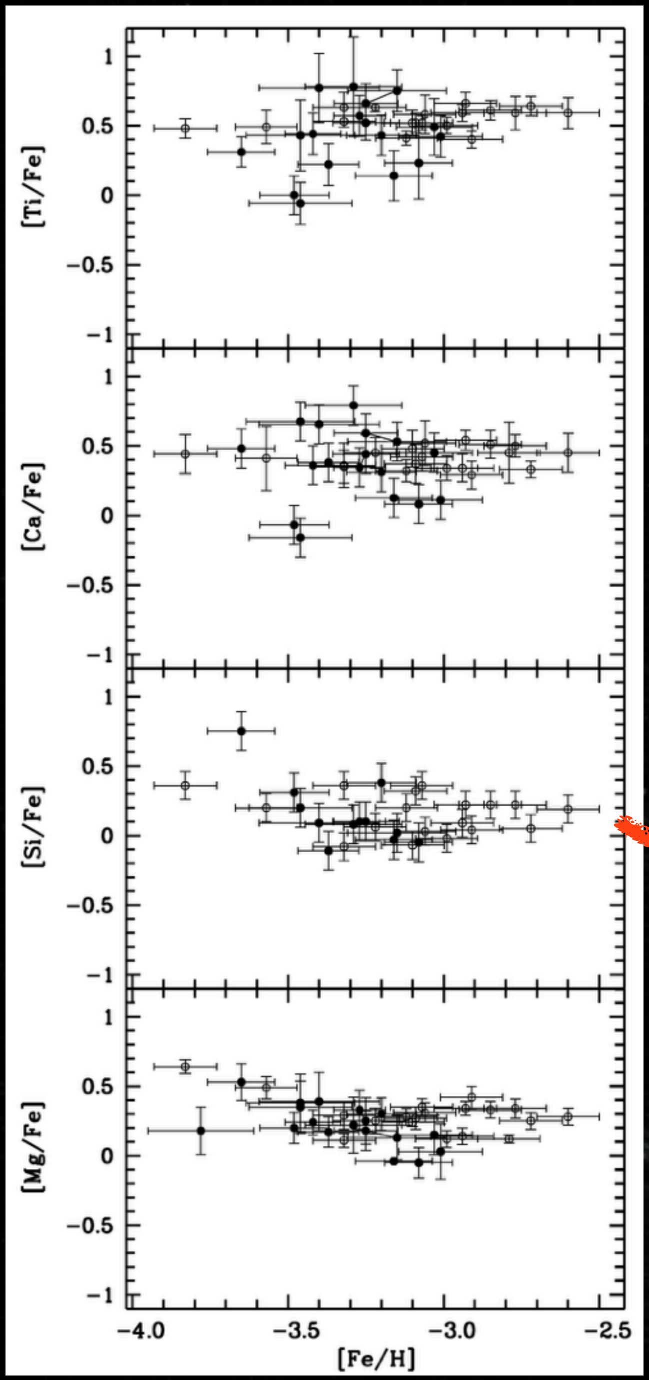


r-process

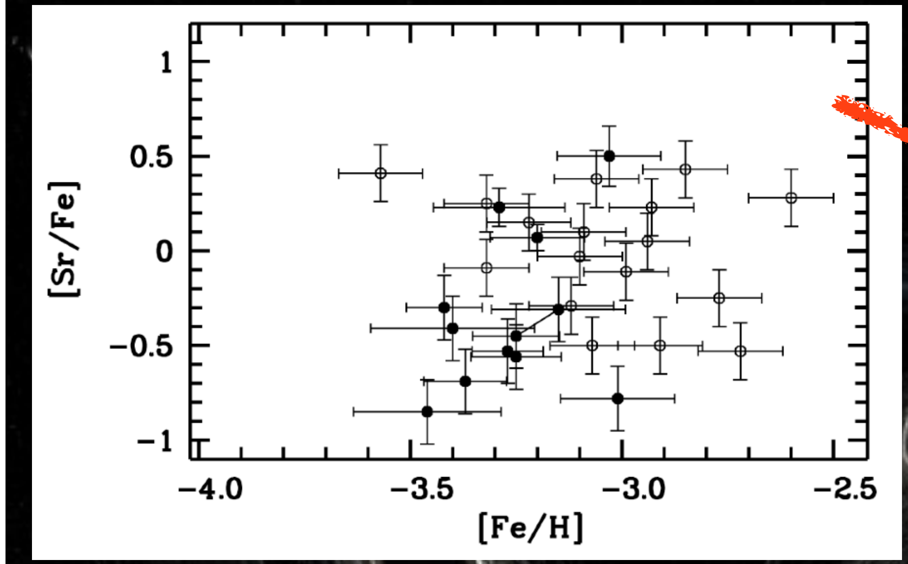


Stochastic chemical evolution models

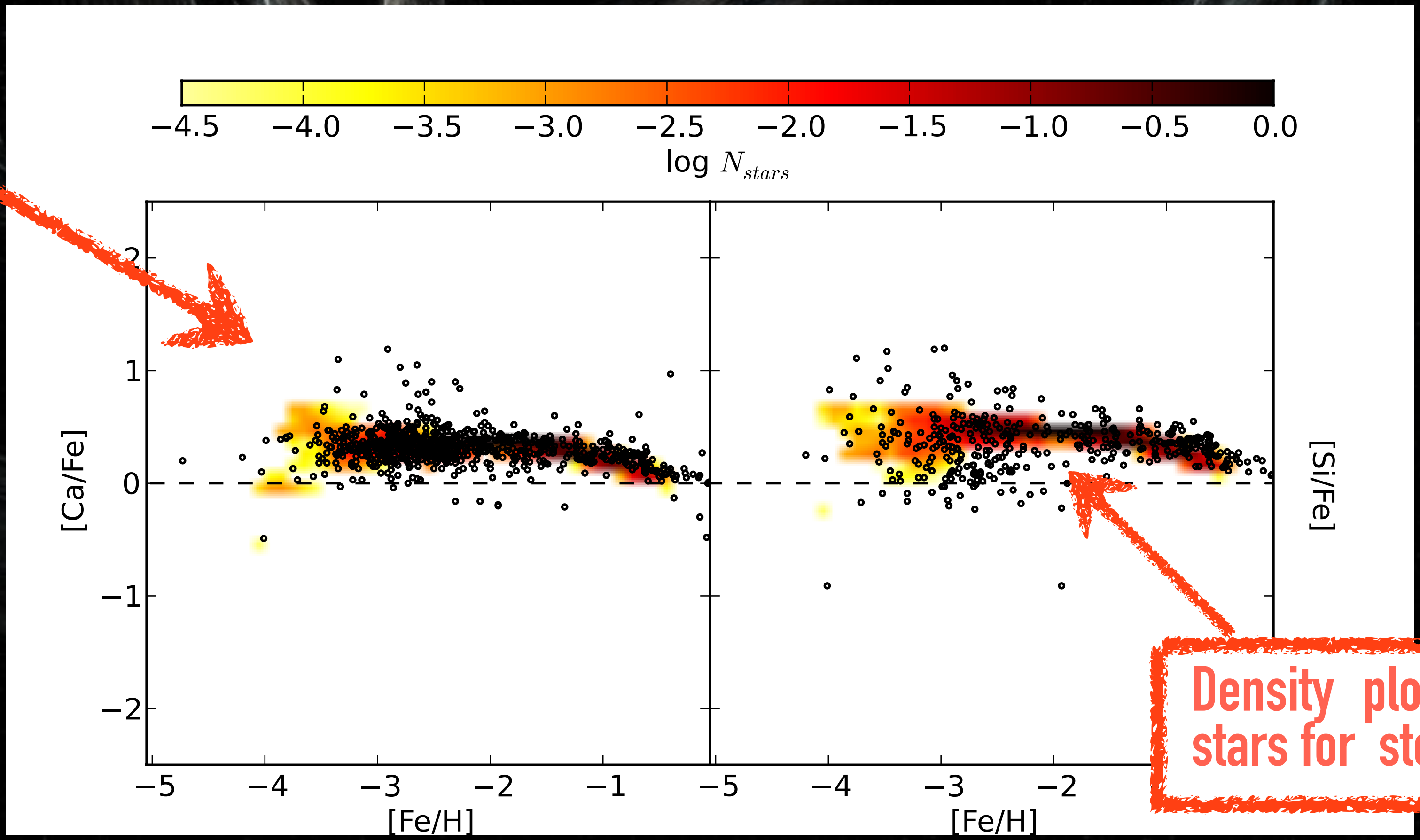
Problem:
Neutron capture elements present a spread alpha elements do not



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

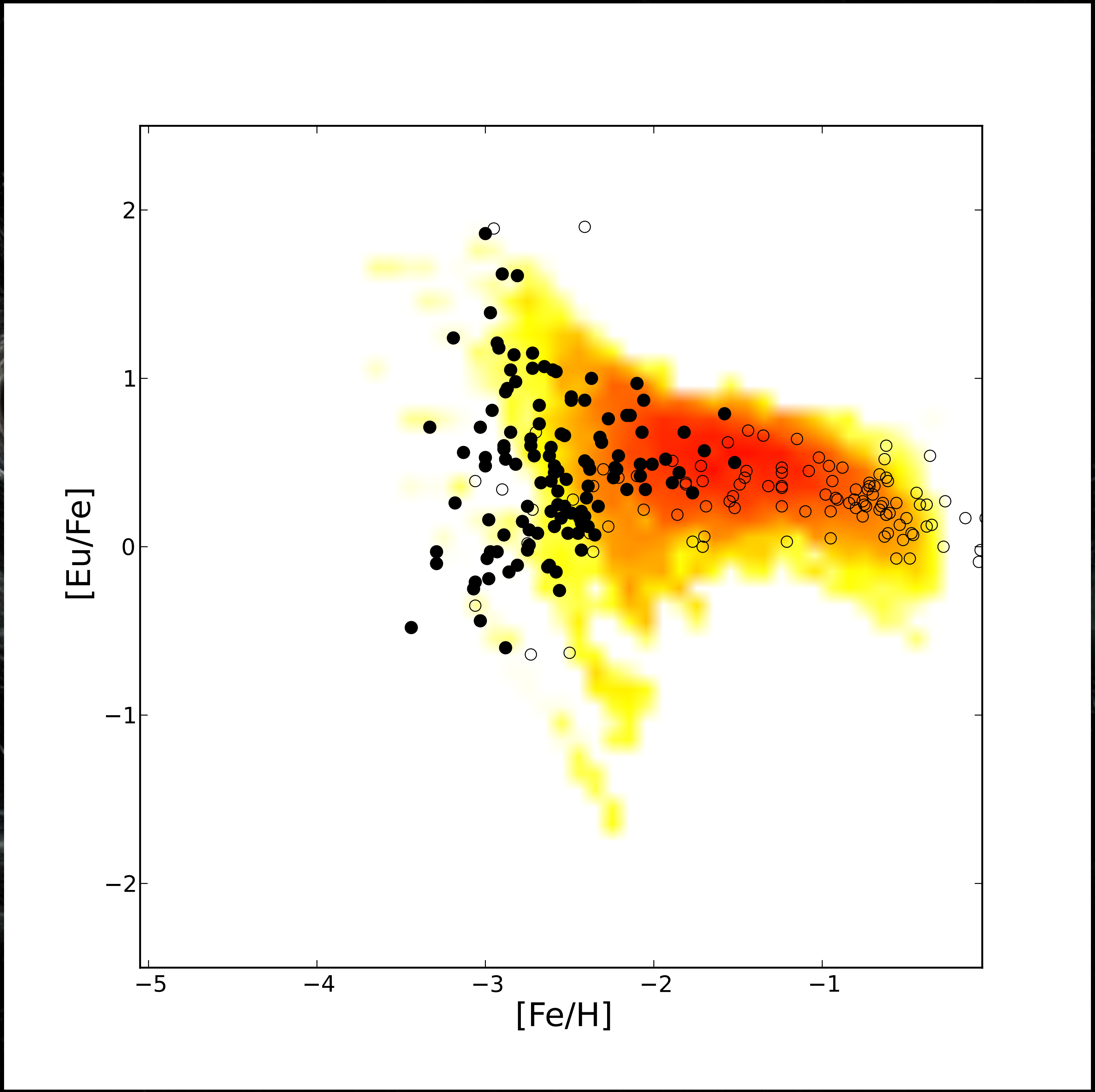
Neutron stars mergers

delay for the merging 1Myr

Cescutti,Romano,Matteucci,
Chiappini and Hirschi 2015

Results with alpha=0.04
(NSM/SNe)

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



Neutron star mergers

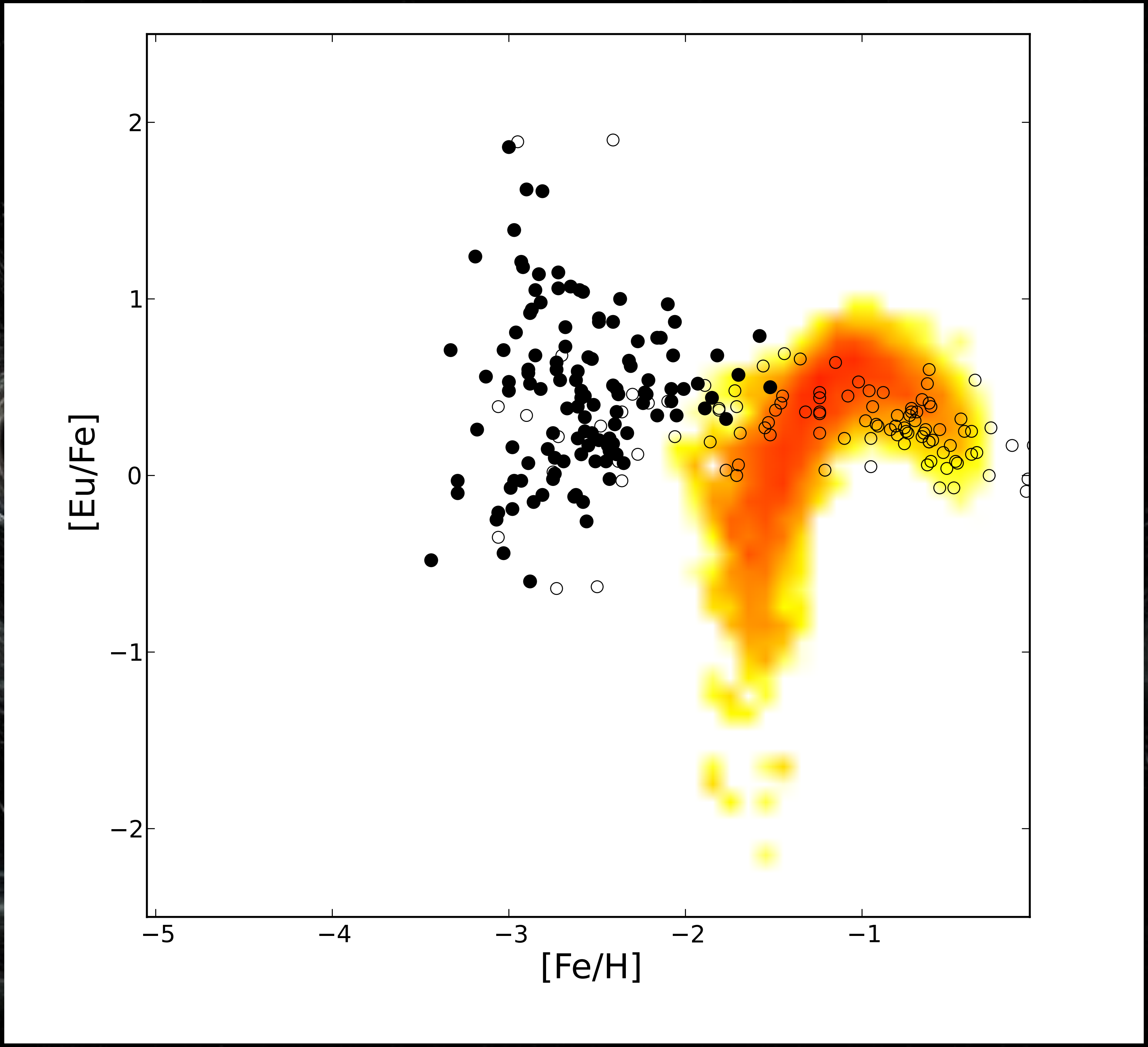
delay for the merging 100 Myr

Cescutti+15

For a delay of 100 Myr the model results are not 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.

What about a distribution of delays?

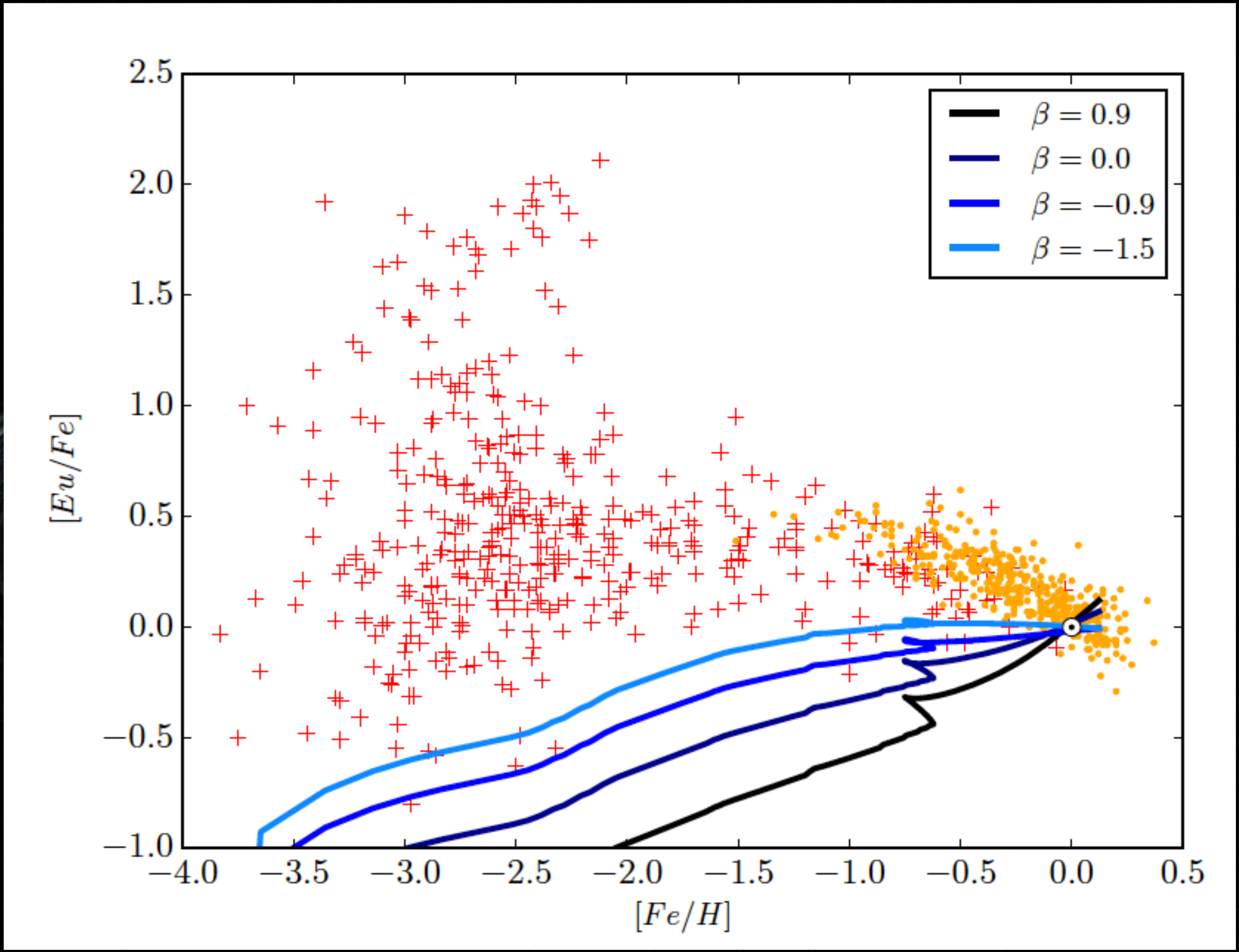


This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the astro-ph Shen+2014

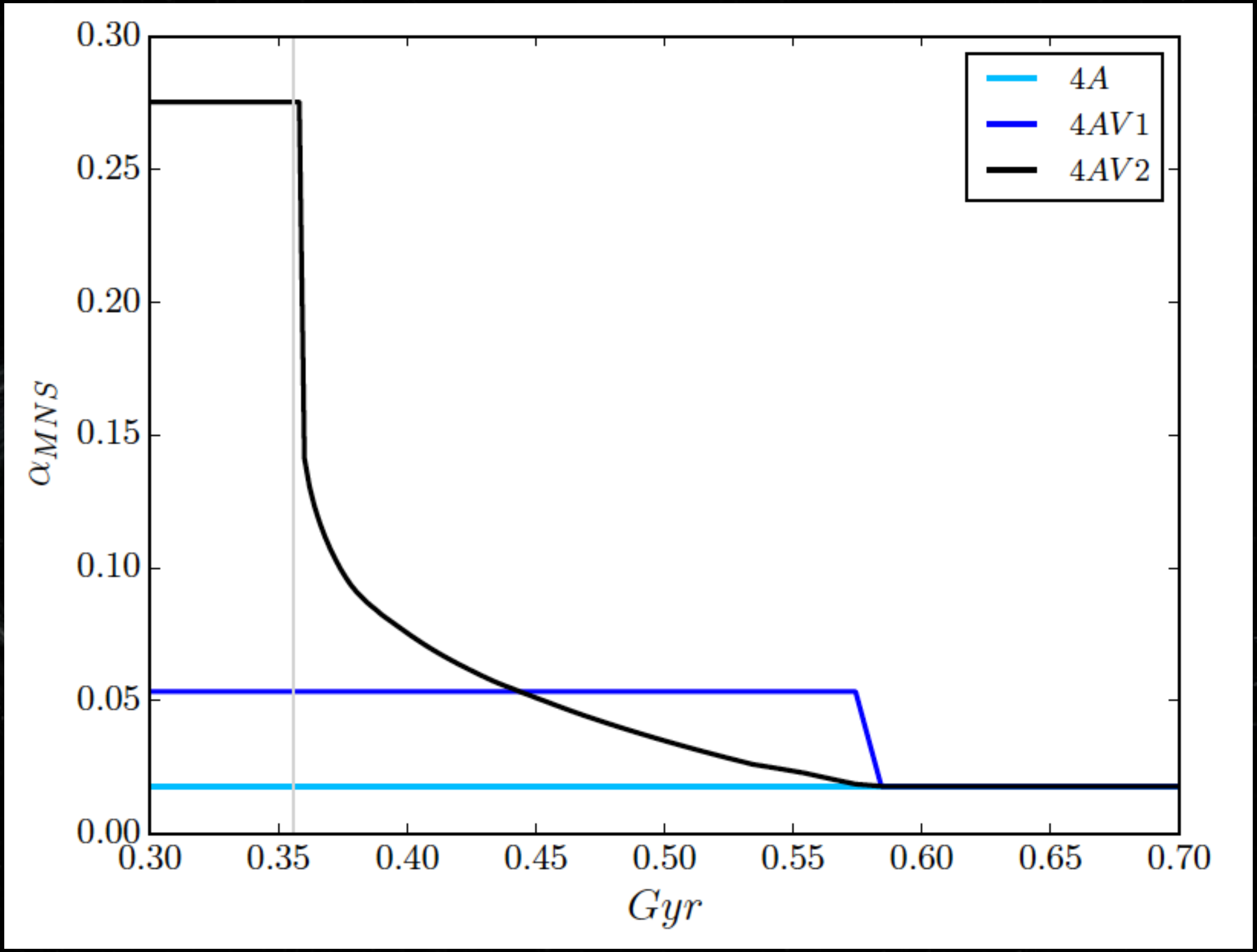
Detailed DTD for NSM

Simonetti+19

see also Cotè+19

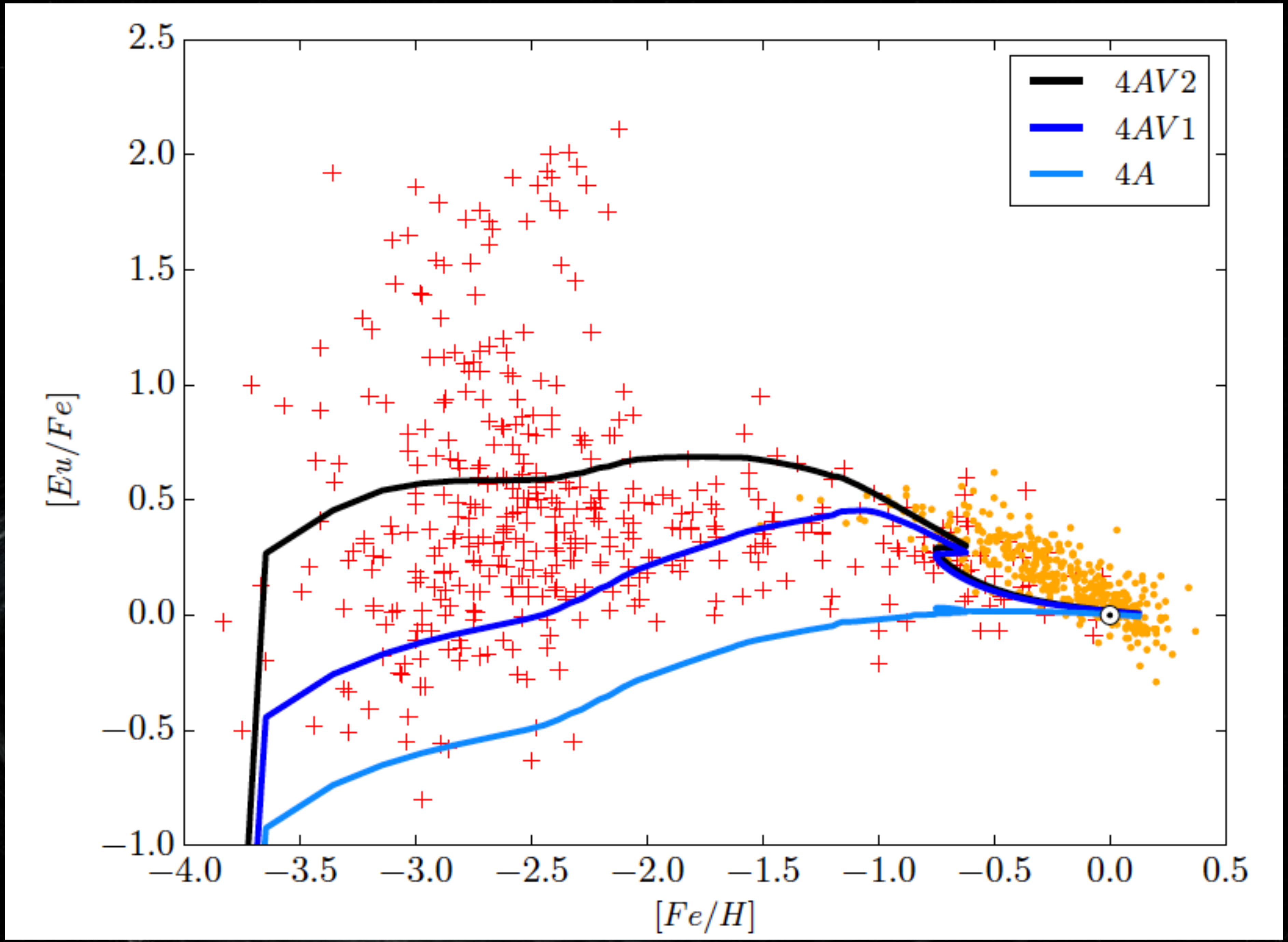


Models with detailed DTD for NSM variation of the alpha (fraction NSM/SNe)



Simonetti+19

Models with detailed DTD for NSM



variation of alpha, possible solution!

see also Schoenrich&Weinberg19

Simonetti+19


Other solutions?

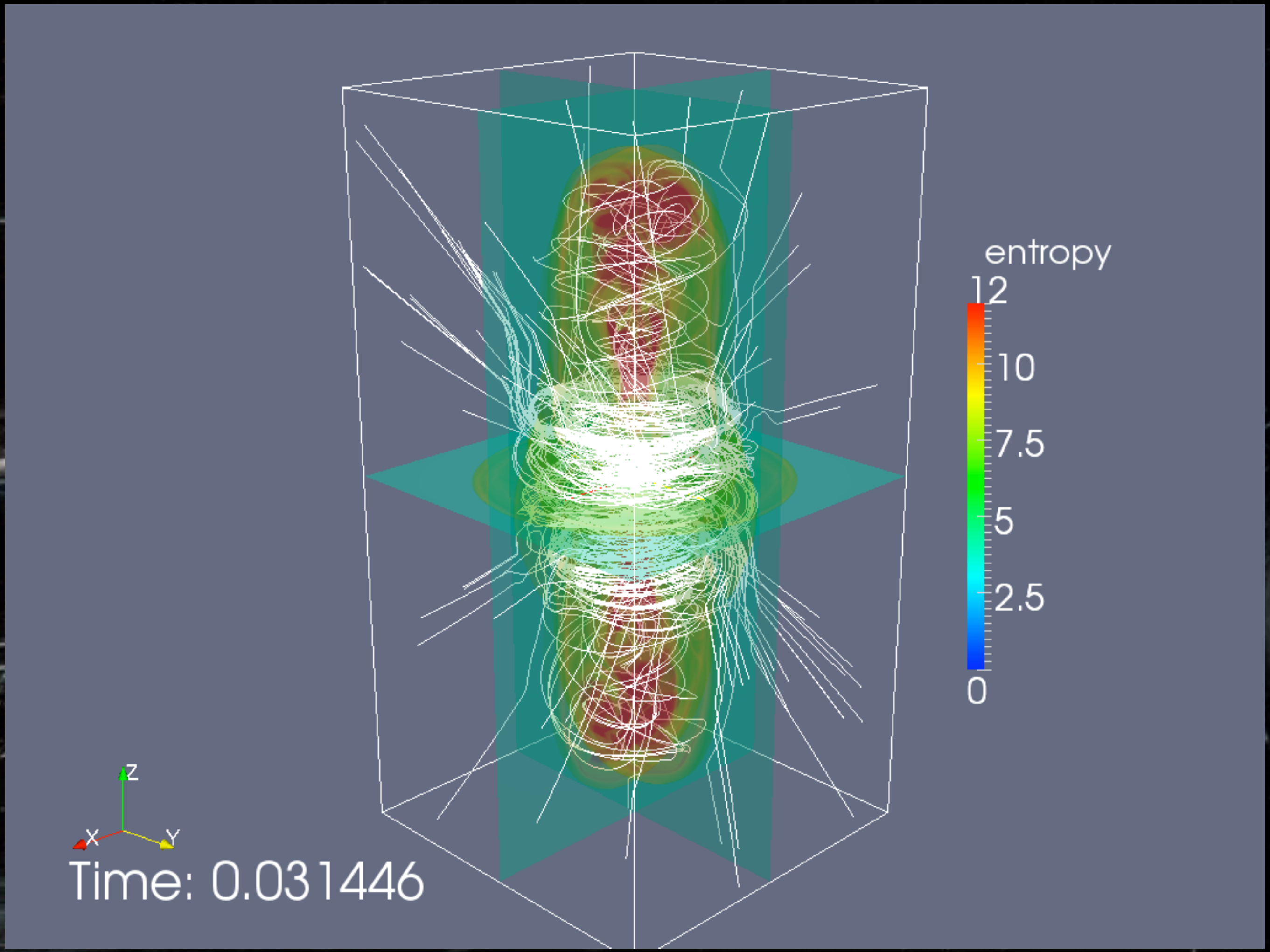
Magneto Rotationally Driven SN scenario (MRD)

(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.

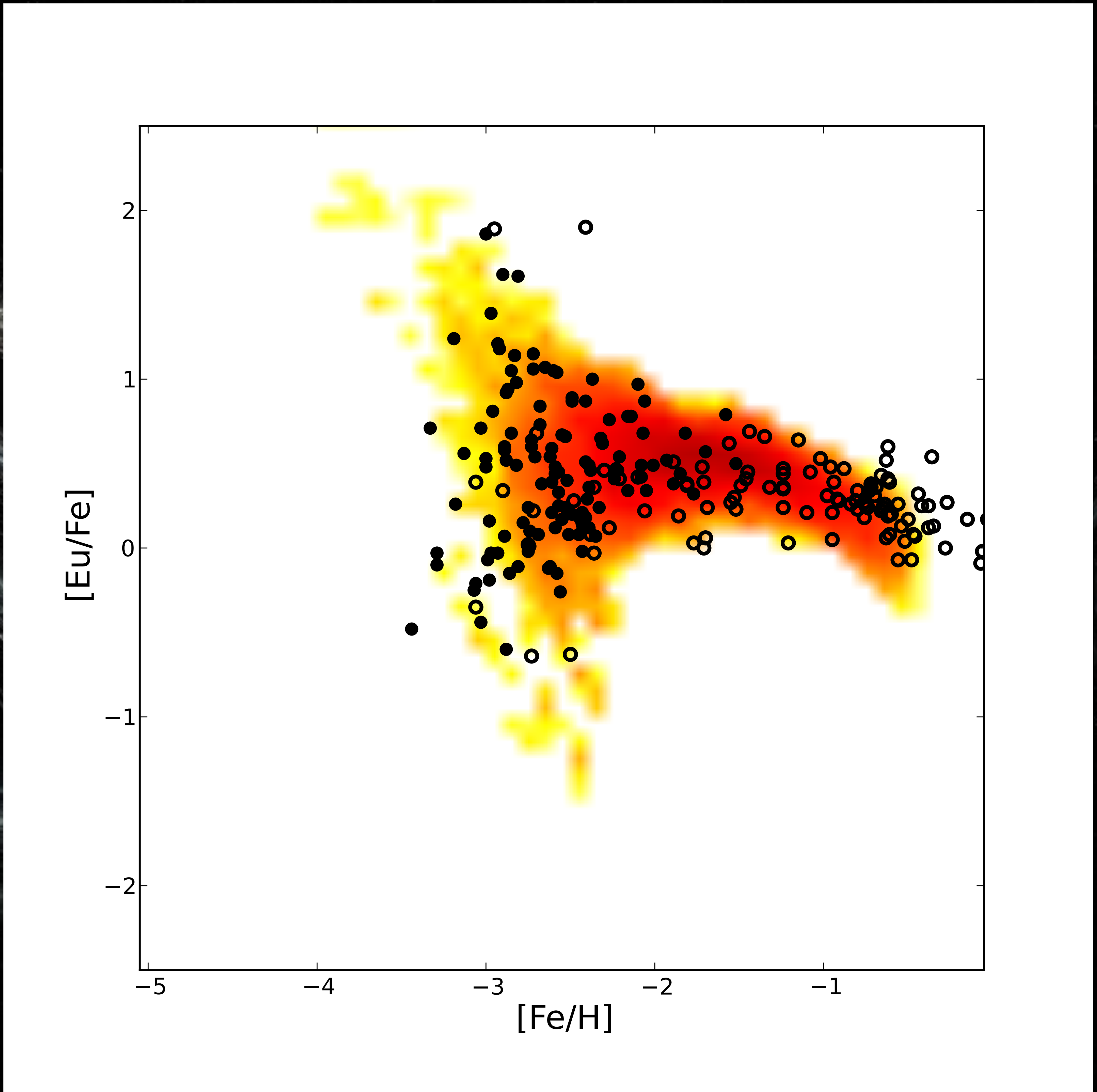


Magneto Rotationally Driven SN scenario (MRD) 10%

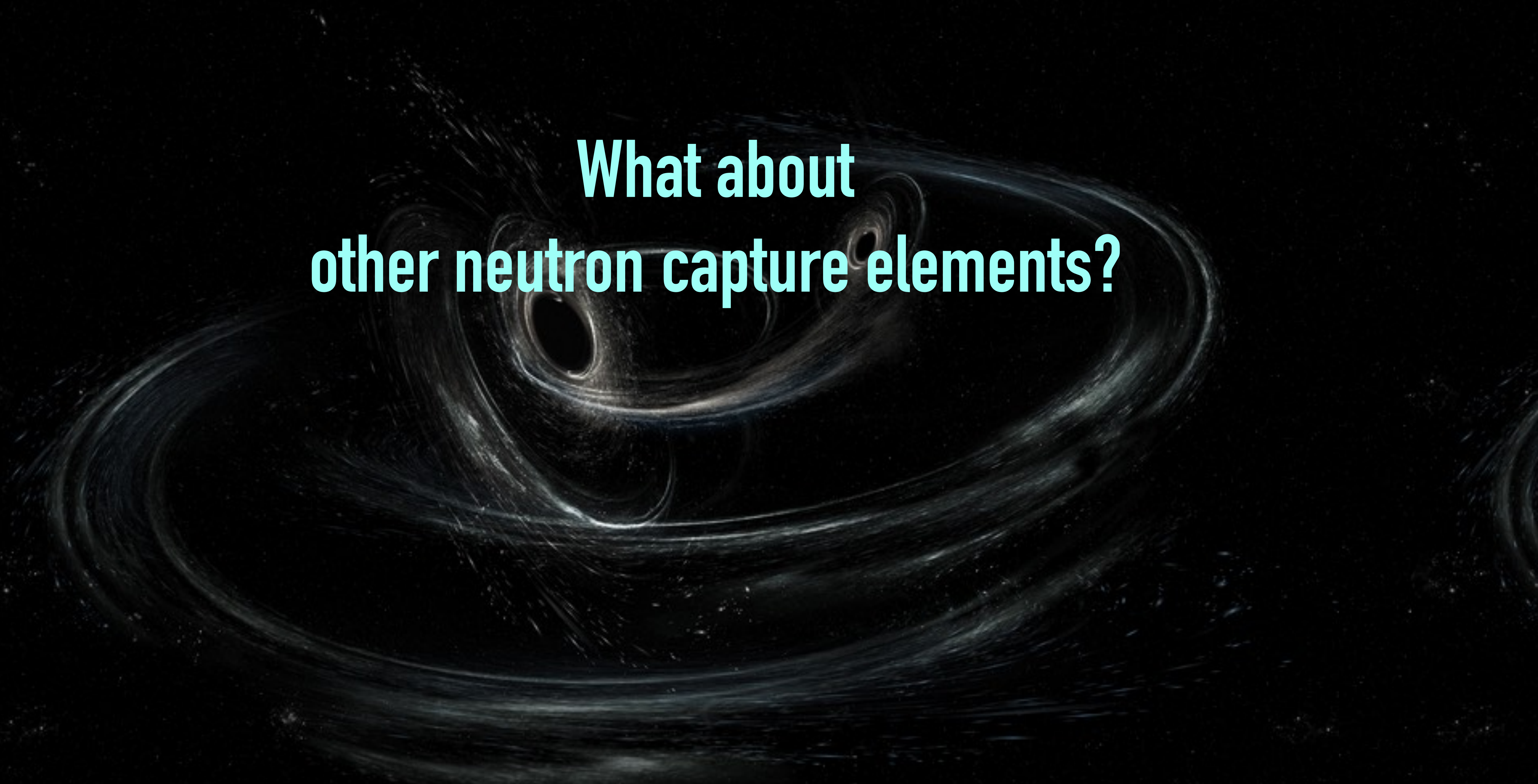
Cescutti+14

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)

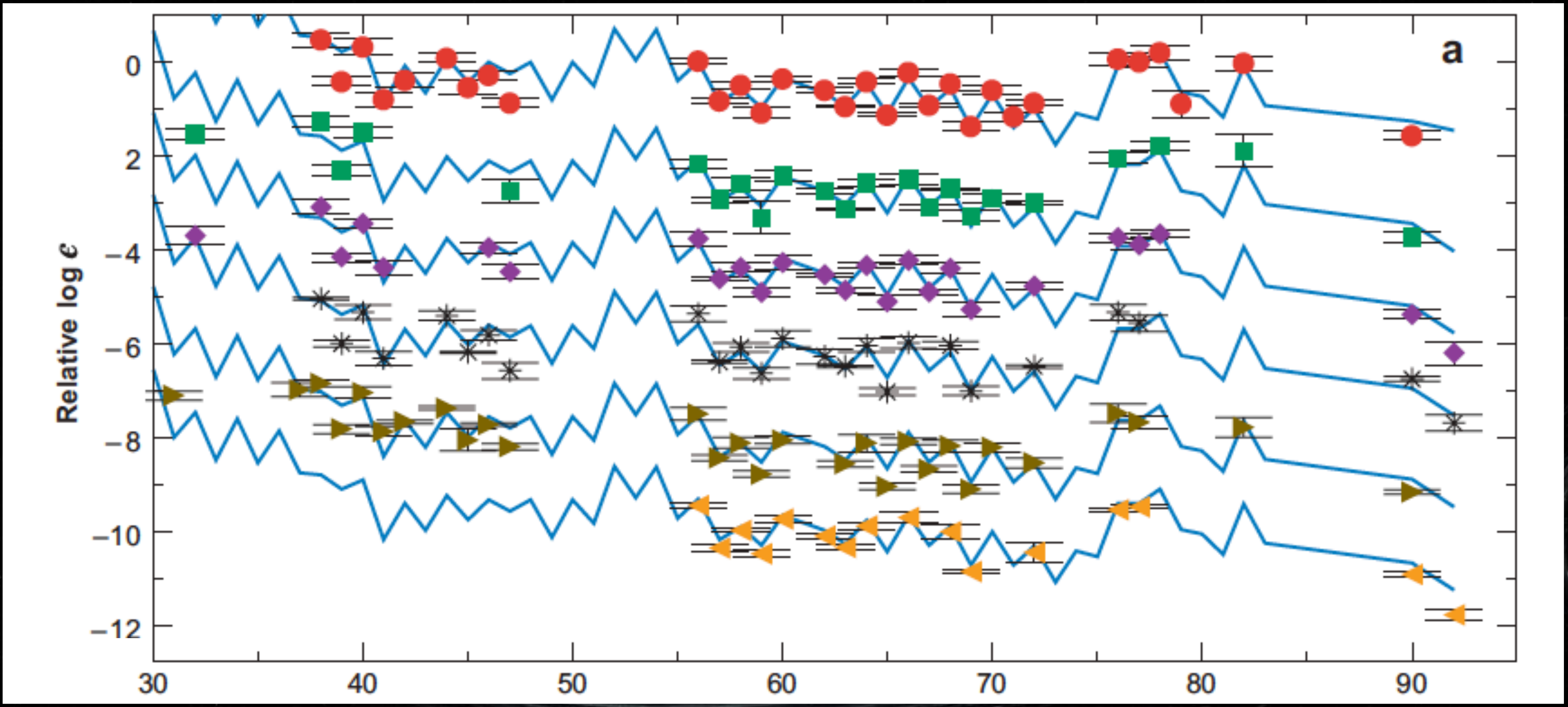


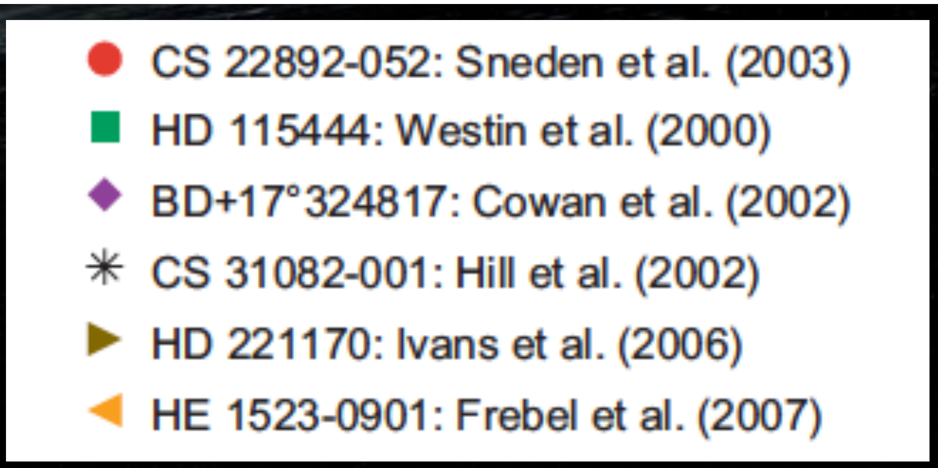
What about
other neutron capture elements?



r-process

pattern in r-process rich stars

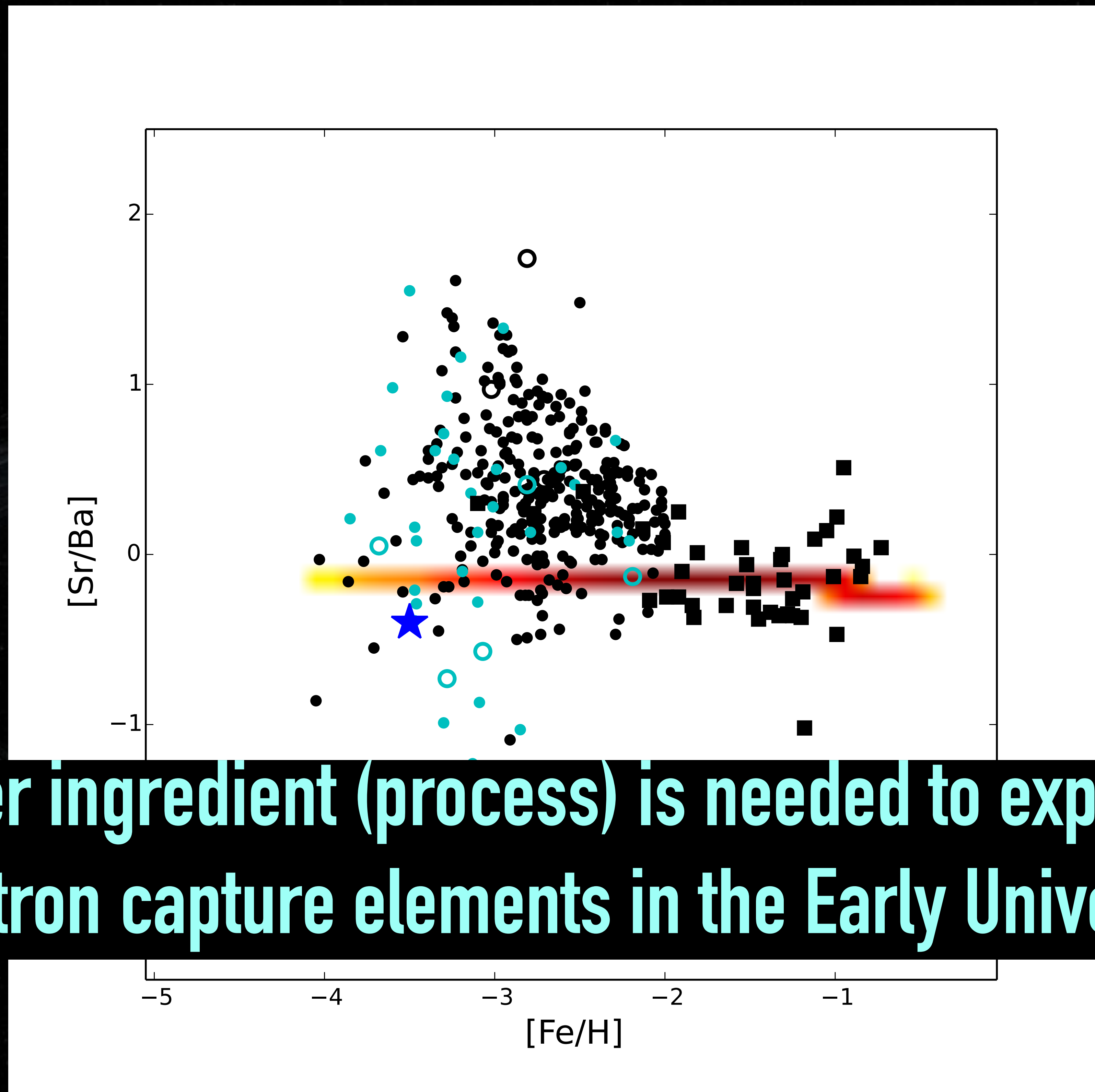




Sneden+08

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)



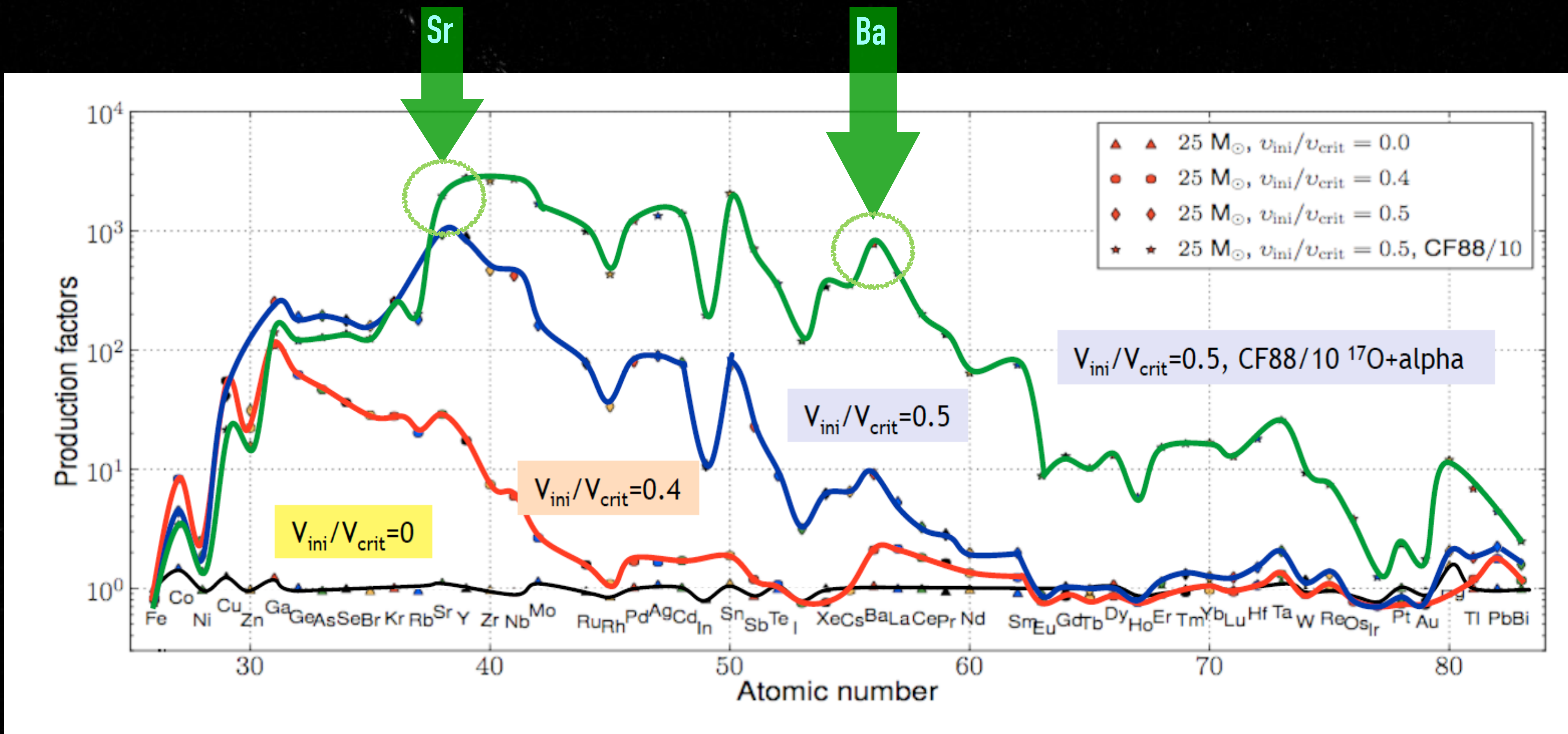
It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

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

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

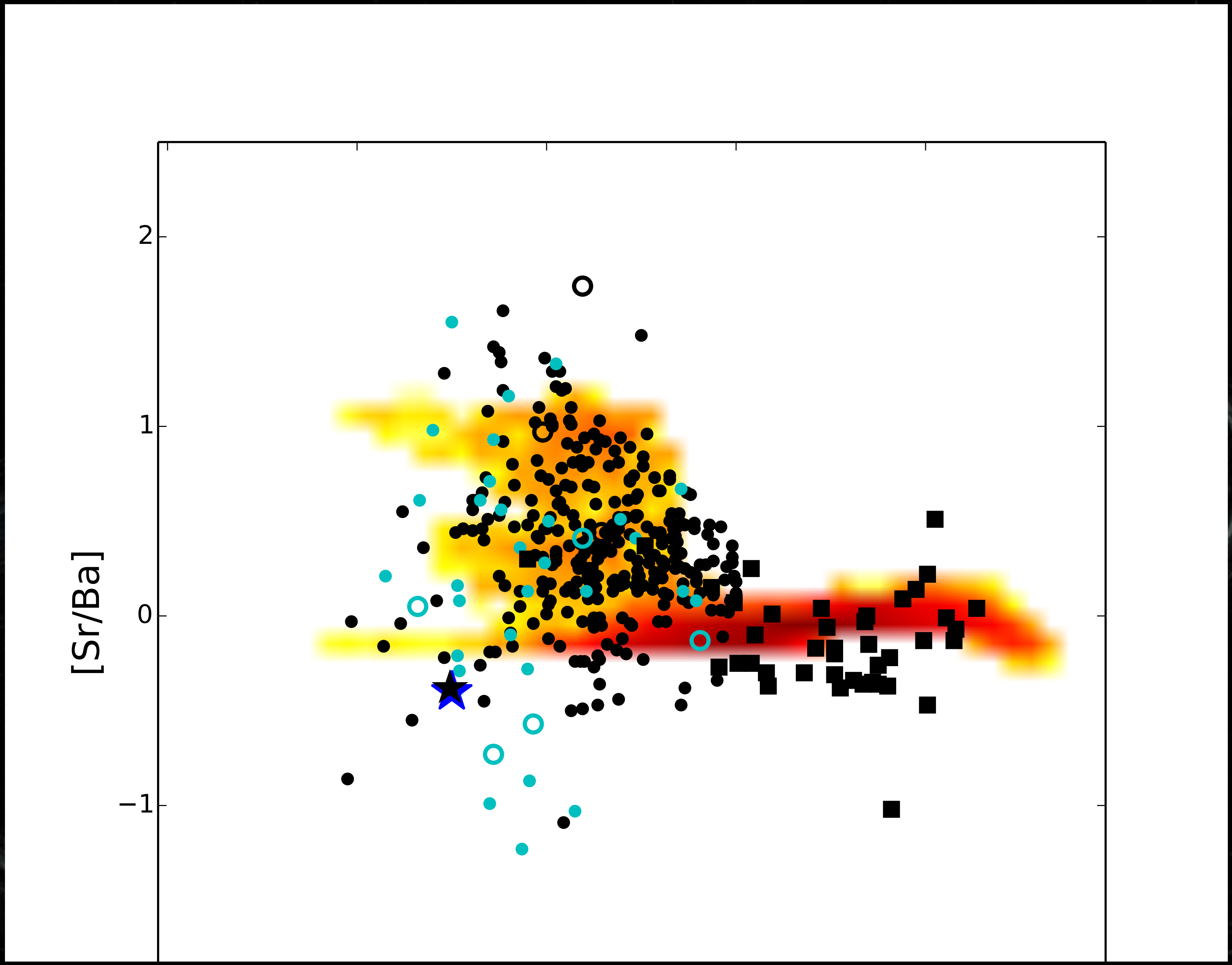
from Chiappini+11 (see also Pignatari08)

Early Galaxy

	s-process	s-process	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	Cristallo+ 2011	(Frischknecht+ 2012) Frischknecht+ 2016	....
	Karakas+ 2012	Limongi and Chieffi 2018	

s-process from rotating massive stars

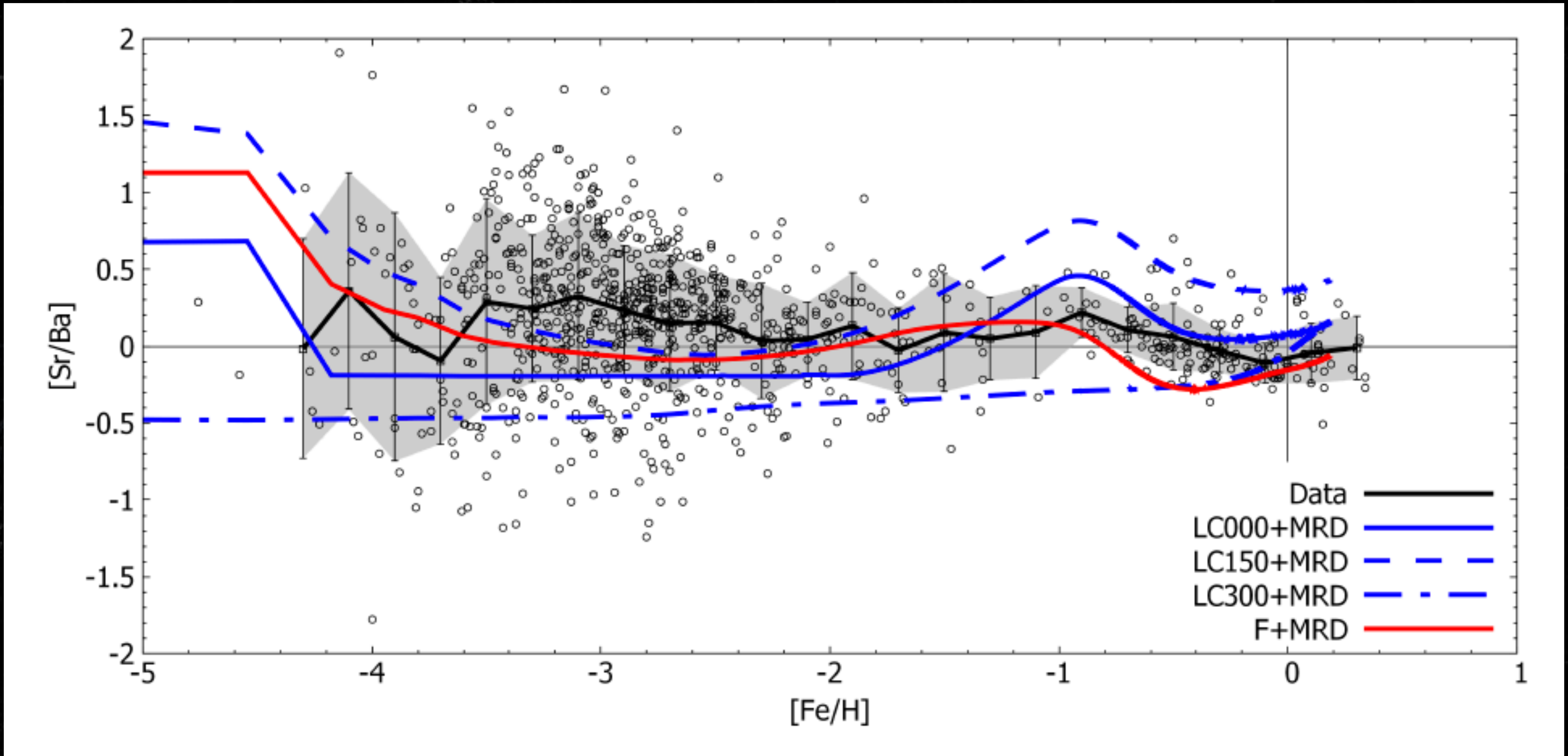
+ an r-process site (the 2 productions are not coupled!)



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 Limongi&Chieffi18



Rizzuti et al. (submitted)

see also Prantzos et al. 2018

CAVEAT

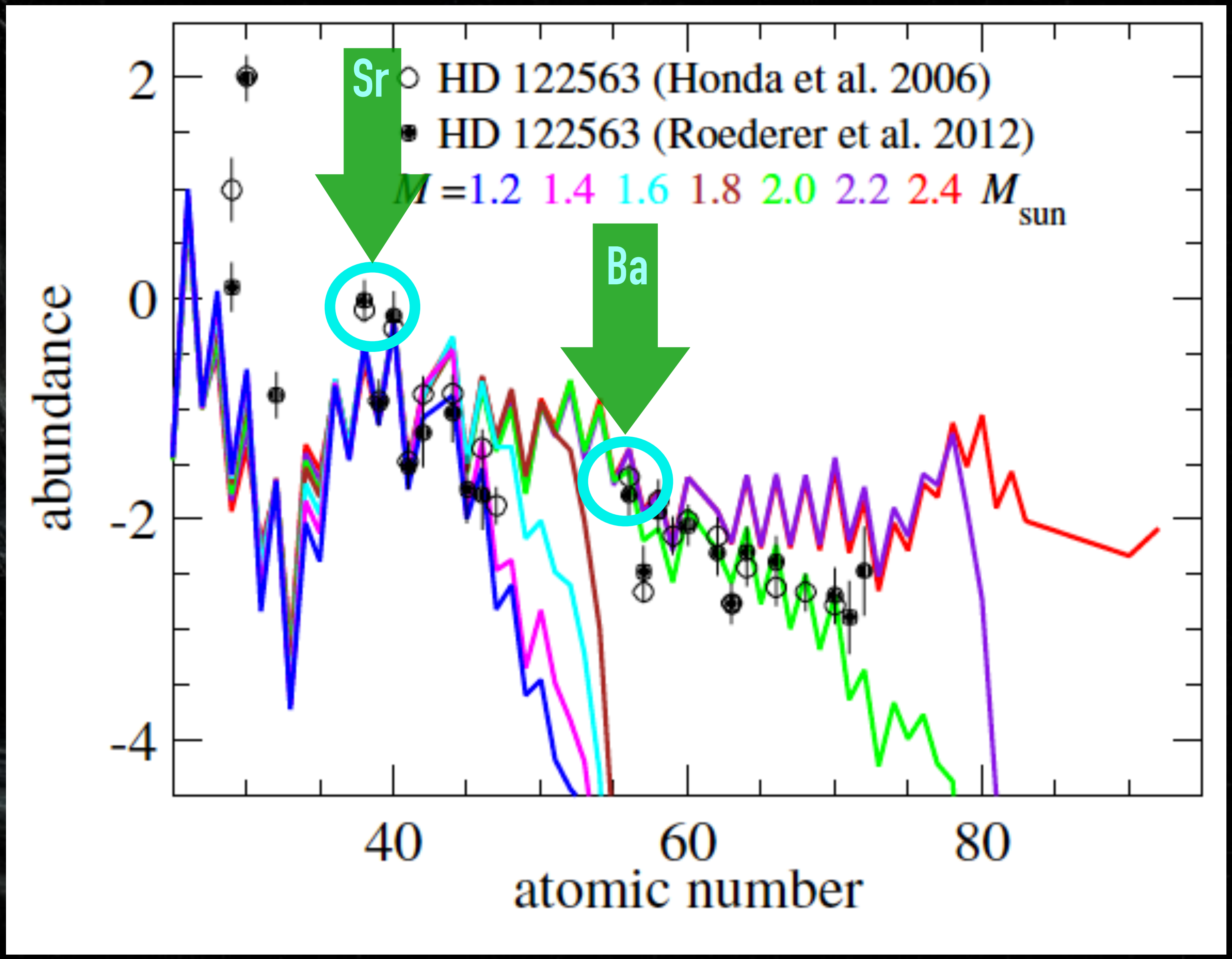
The only possible answer?

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

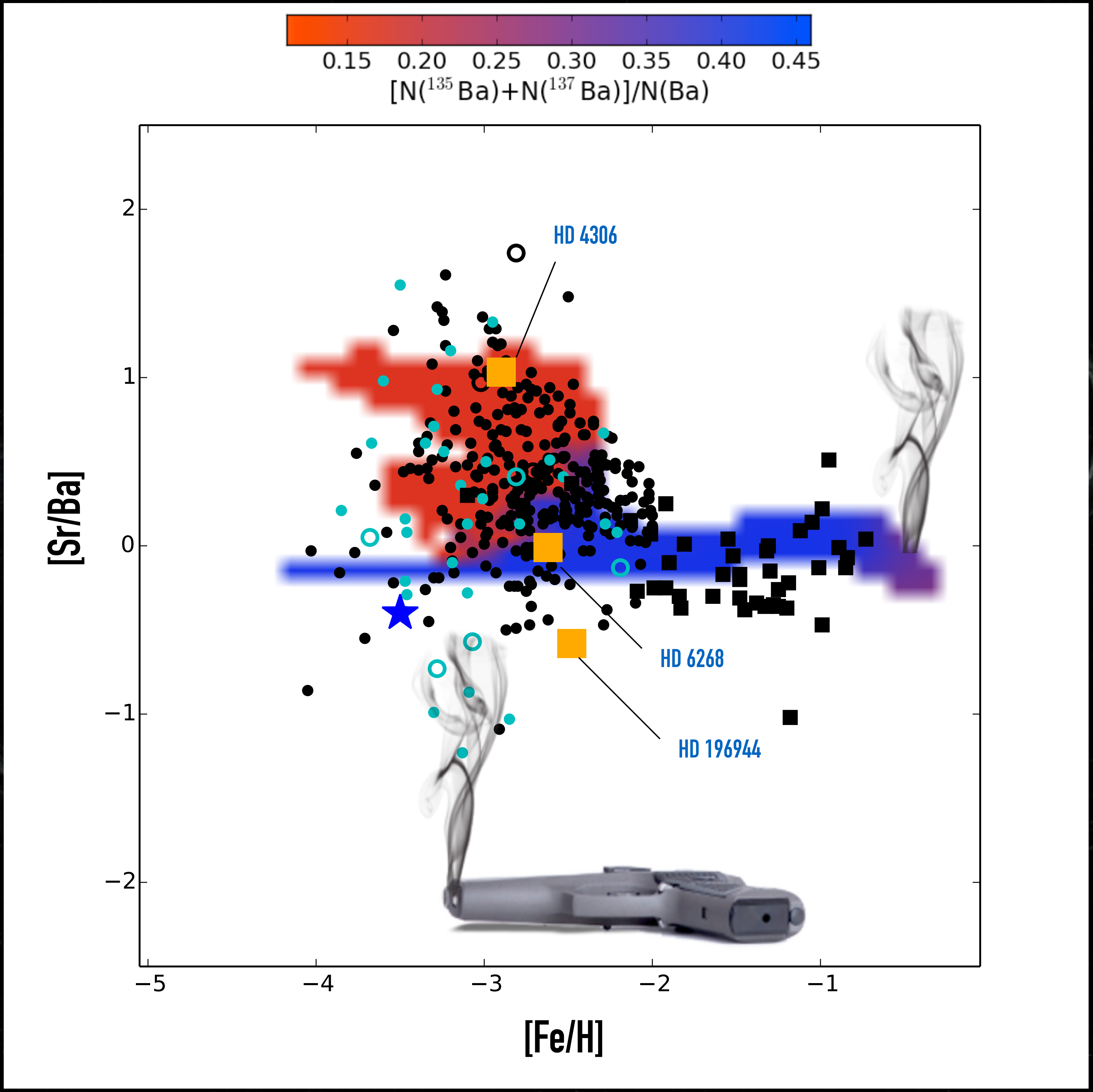
Isotopic ratio for Ba

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)



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

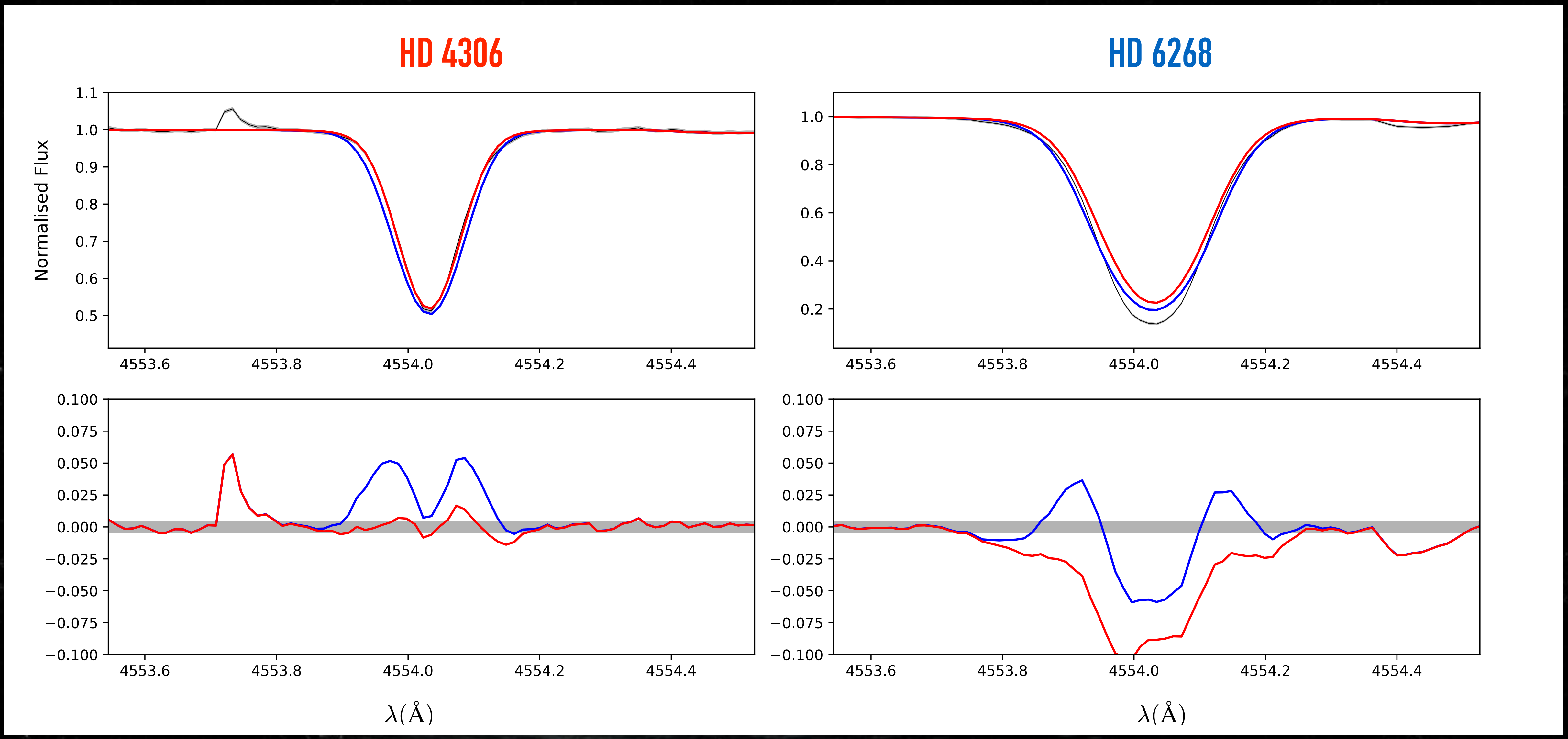
Cescutti and Chiappini (2014)

Preview of spectral analysis results ratio for Ba

s-process

r-process

Cescutti, Morossi + in prep.



It can be done, but R>50'000 & S/N>200,
see also Jablonka+15, Gallagher+15

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.

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.