Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

Astro Fit 2 Astronomy Fellowships in Italy

Neutron capture elements

in the

Early Universe

Gabriele Cescutti

ifpU

ChETEC Action

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

4MOST

MEANE

How can we check the

Nucleosynthesis (& nucleosynthetic sites)?

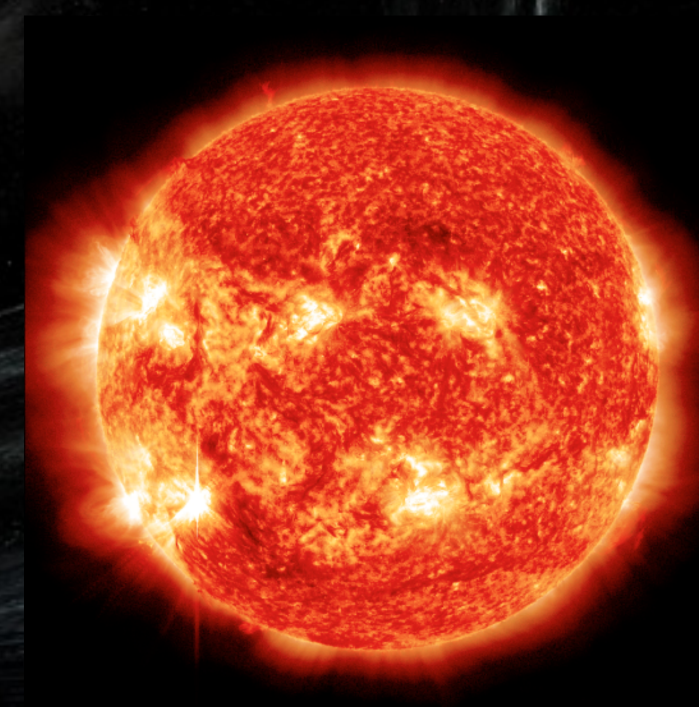
The oldest stars in our Galaxy formed from the gas ejected by few stellar generations:

Massive Stars – short lifetimes

Core collapse Supernova (and NSM?)

First polluters in the Universe

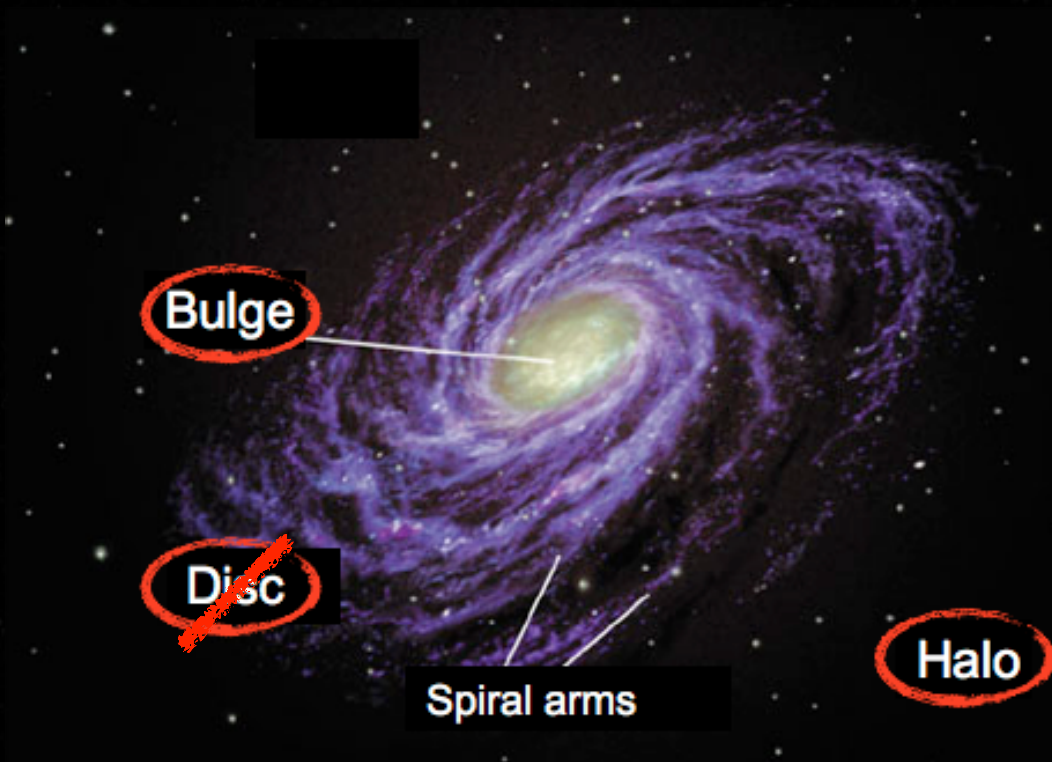
Low mass stars – long lifetimes

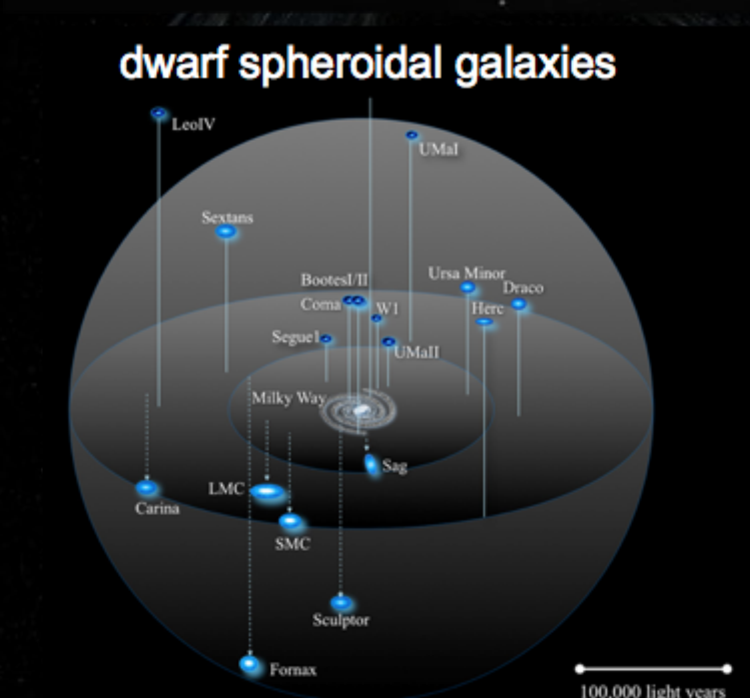


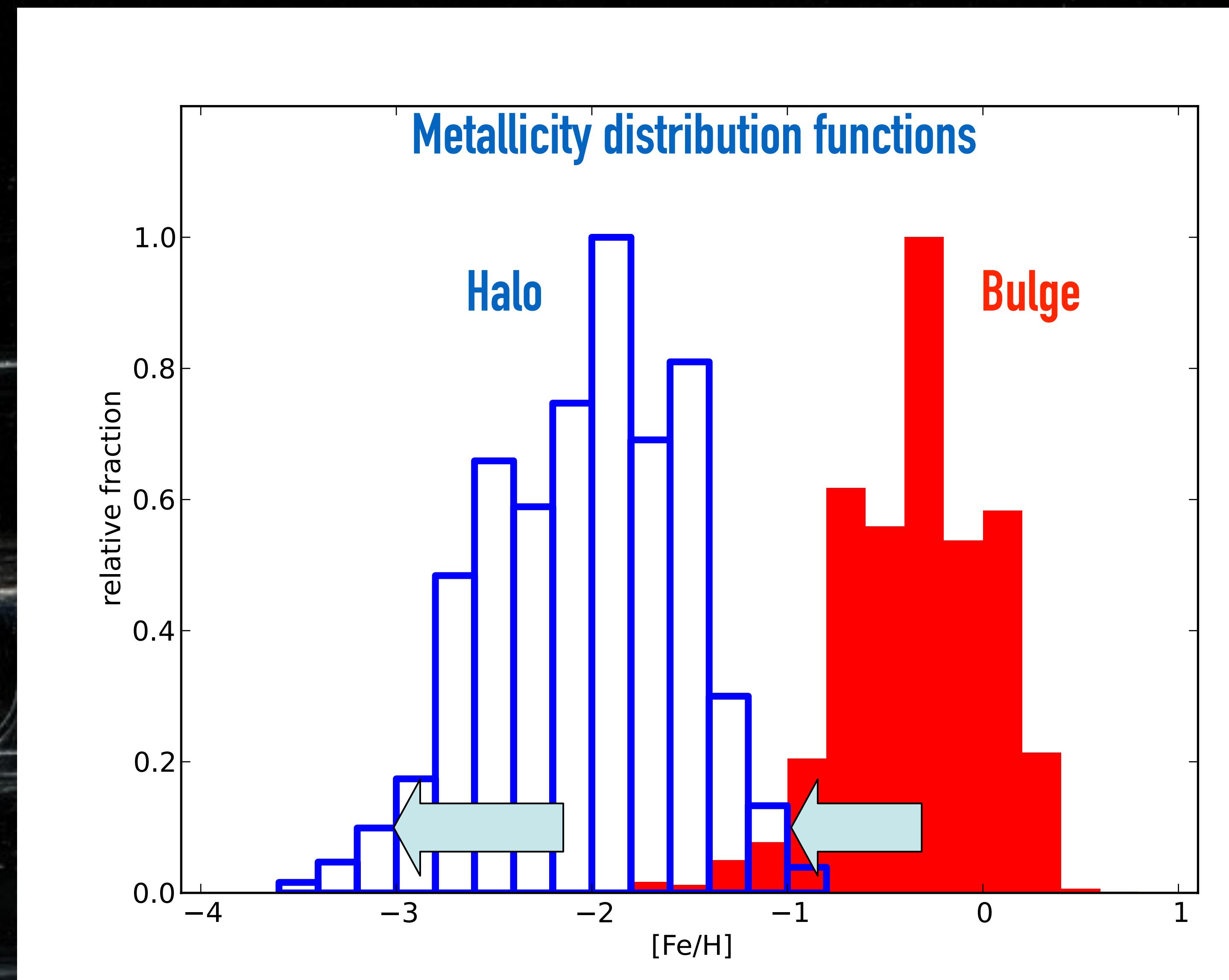
The Sun

Imprints of the first stars

Where are the oldest fossil stars in the MW?



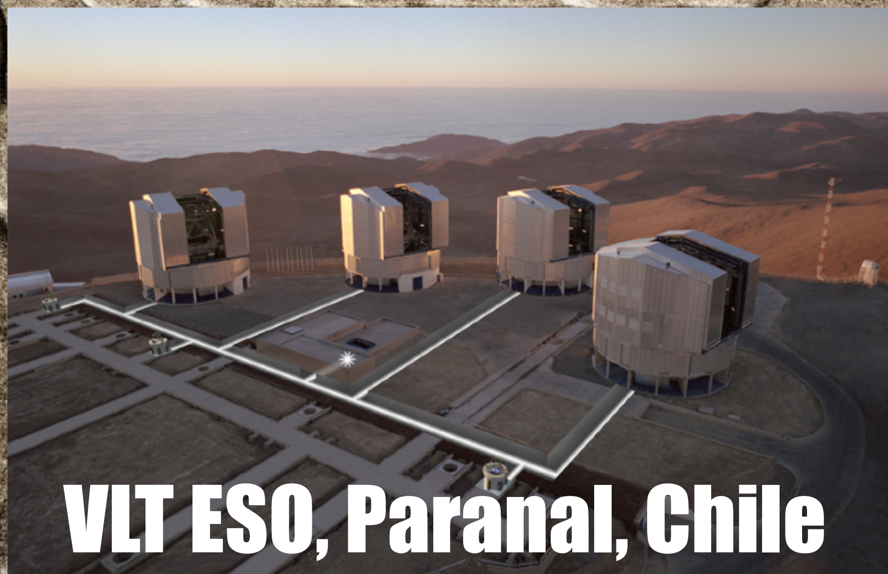


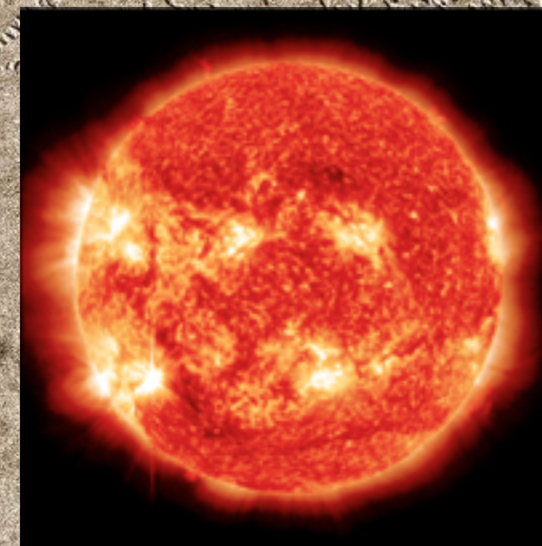


In the Halo
[Fe/H] < −3
data by Li et al. 2010

In the Bulge
[Fe/H] ~ −1
data by Ness et al. 2013

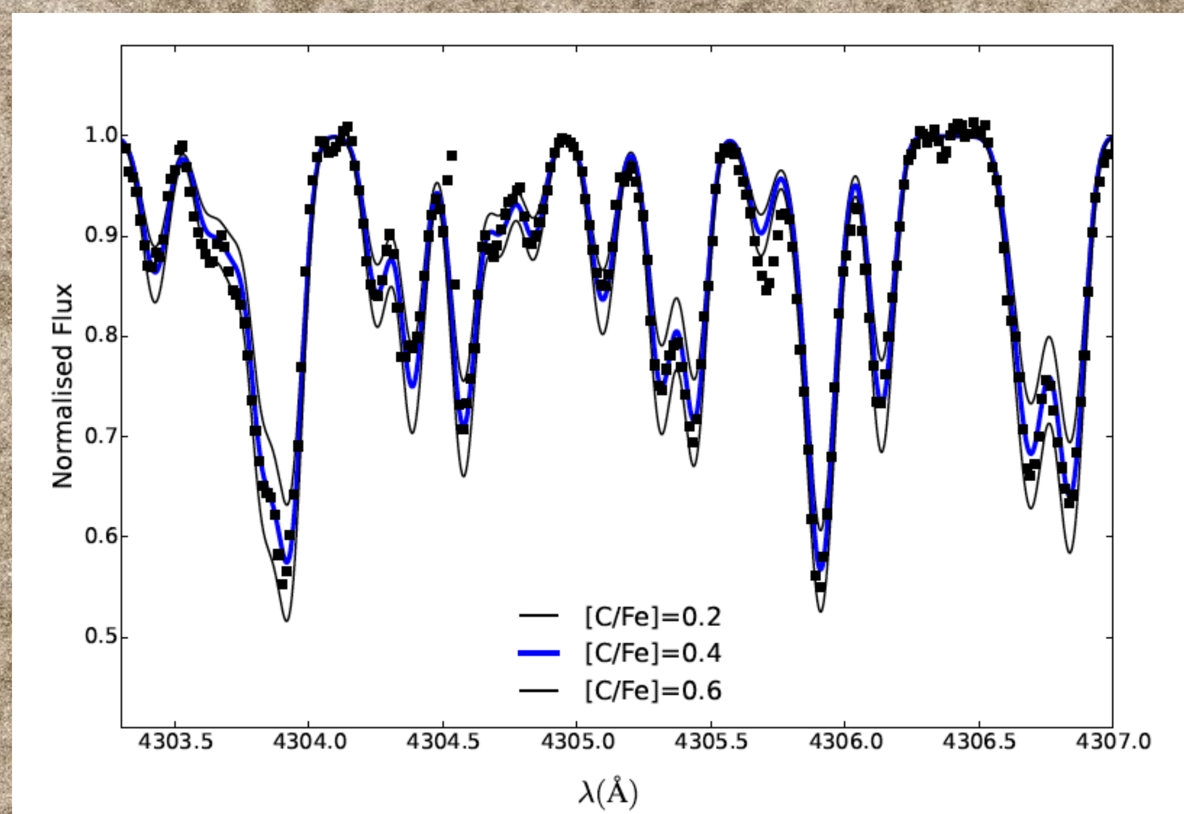
Chemical abundances in stars





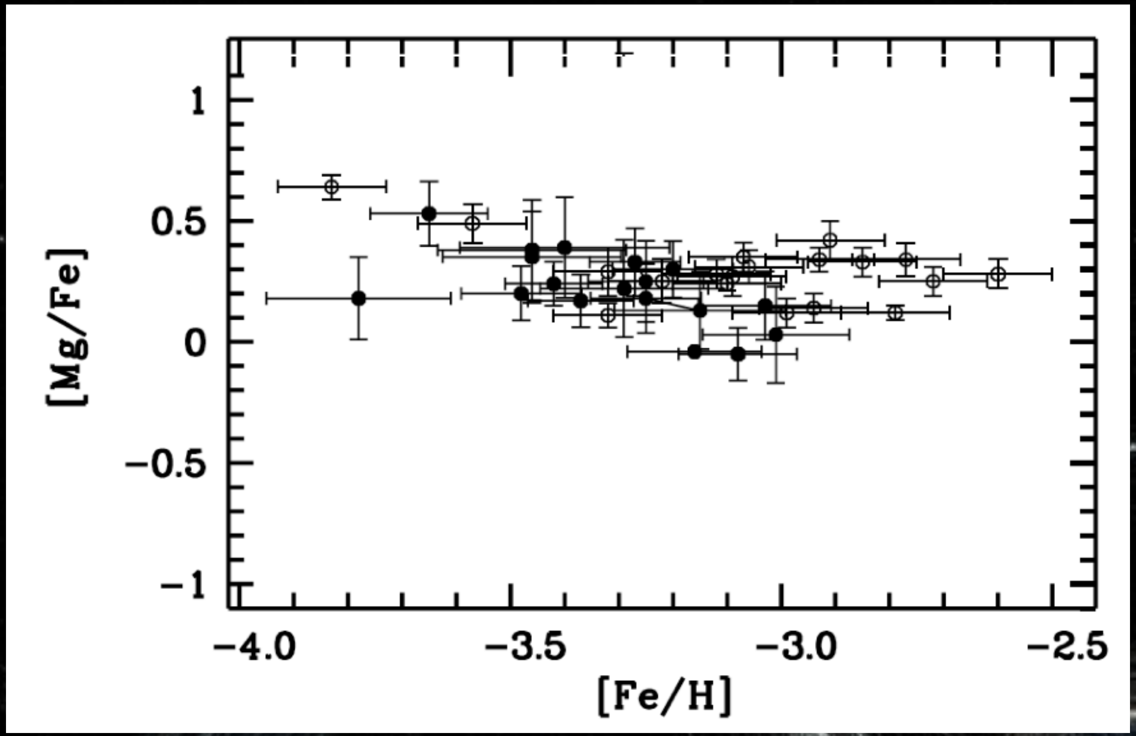
High resolution spectra of stars

Abundances of chemical elements

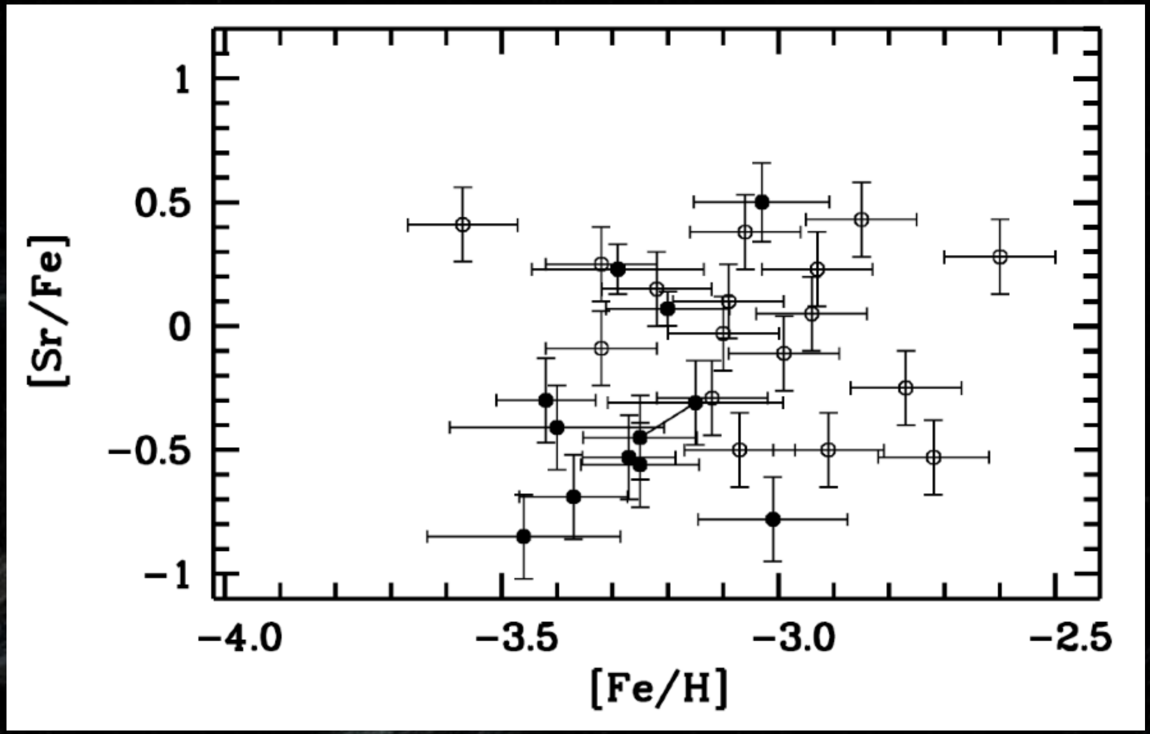


Chemical Abundances in stars

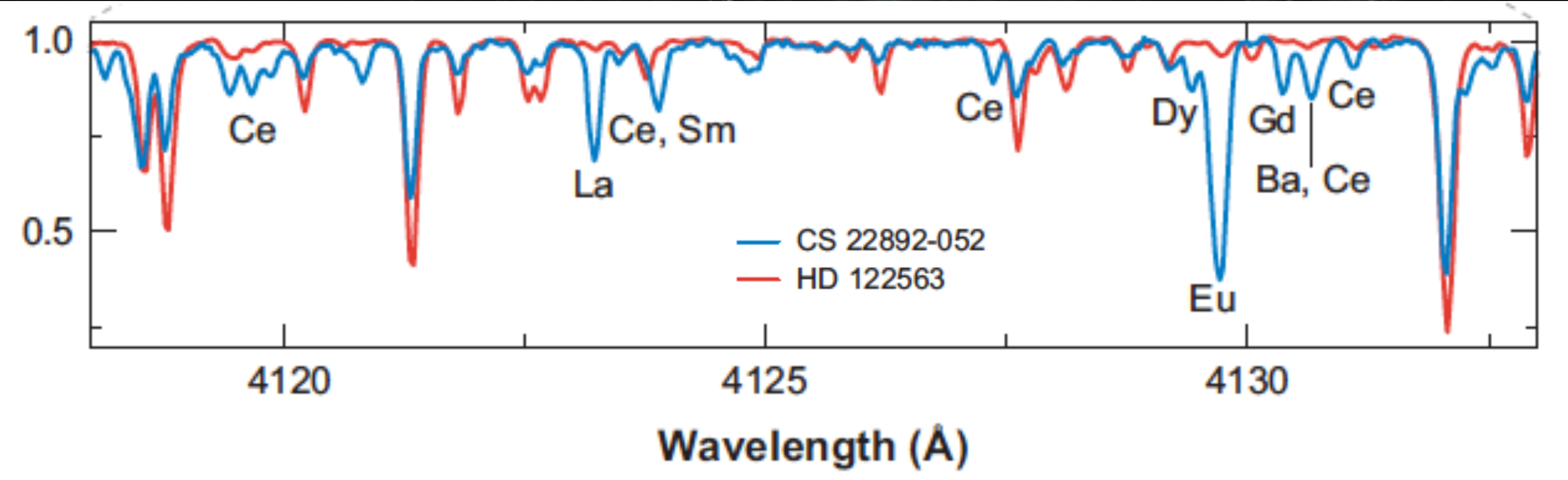
Mg: alpha-element



Sr: neutron capture element



Bonifacio+12



Sneden+08

Neutron capture elements

from Truran 1981 to ~8 years ago

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

Karakas+12

Early Galaxy

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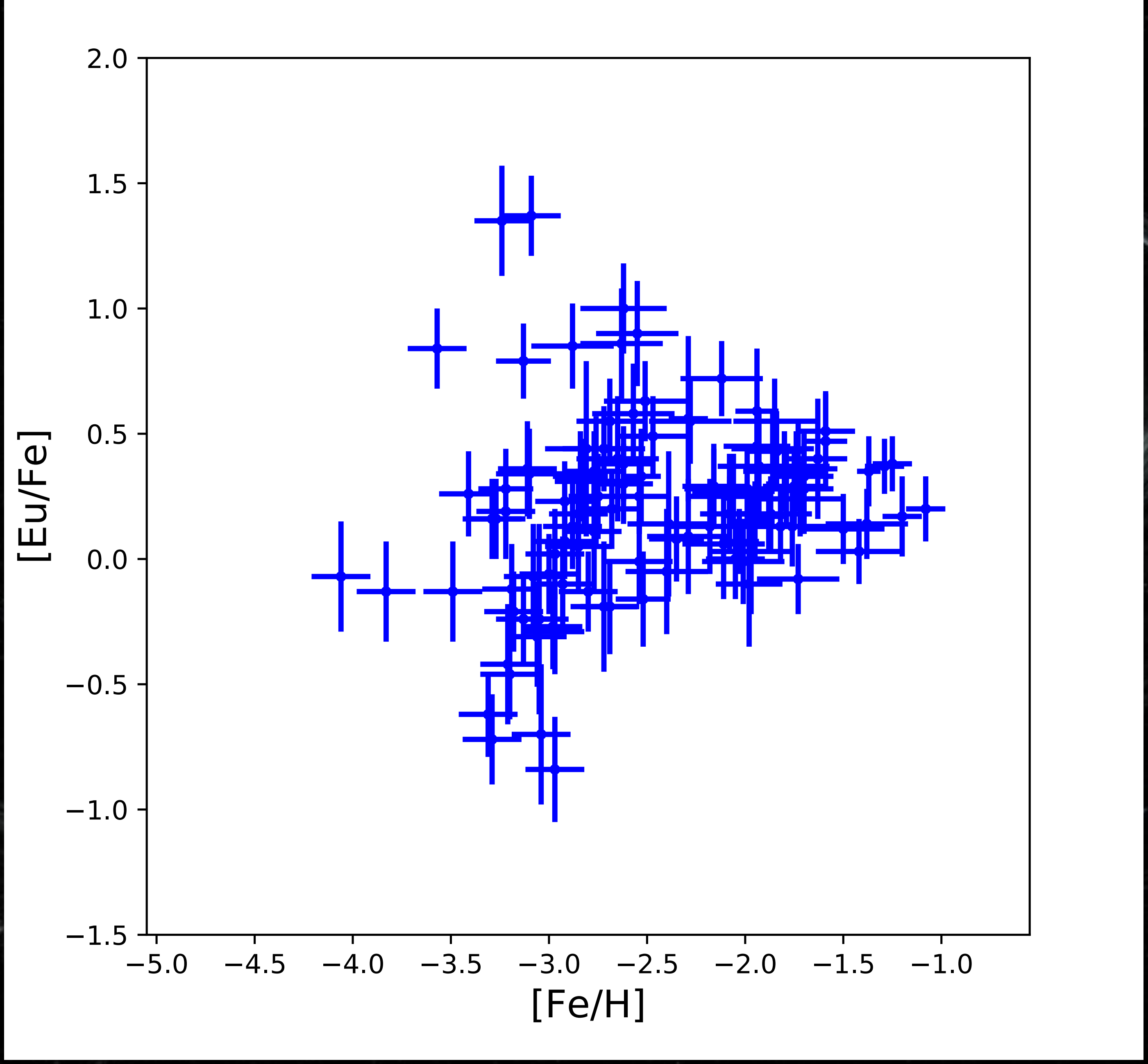
Eu/Fe in the Galactic halo

Since McWilliam98 idea of rare events

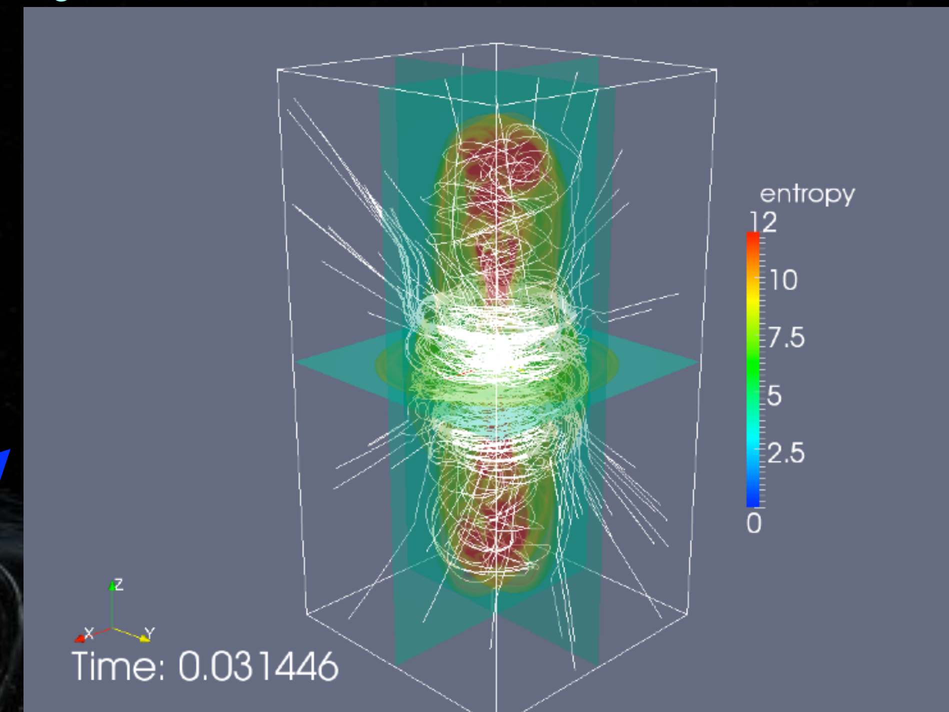


JINA collections

Electron Capture SNe (Wanajo+11)

Cescutti+13

Magnetorotat. driven SNe (Winteler+12)



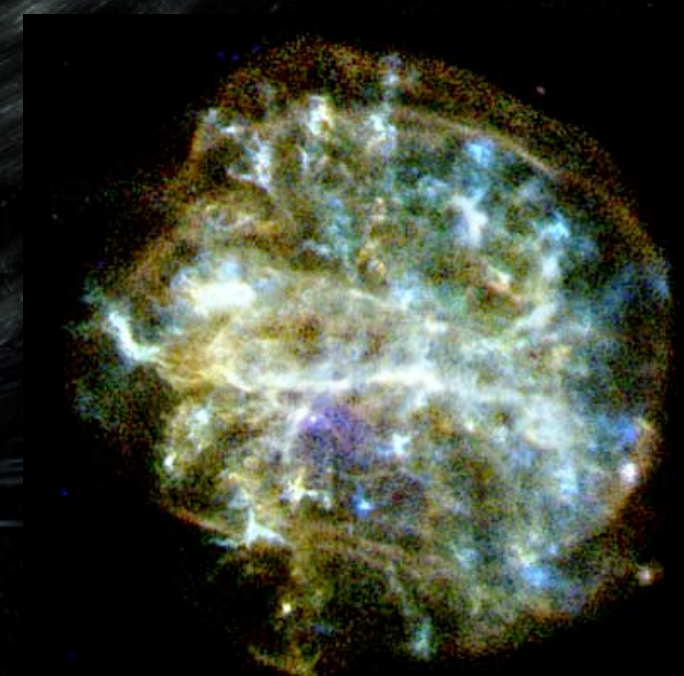
Cescutti+14

Site(s) of the r-process?

Neutron star mergers (Rosswog+13)

(Cescutti+15, Matteucci+14,…)

Neutrino winds SNe (Arcones+07,Wanajo 13)



other possible sites?

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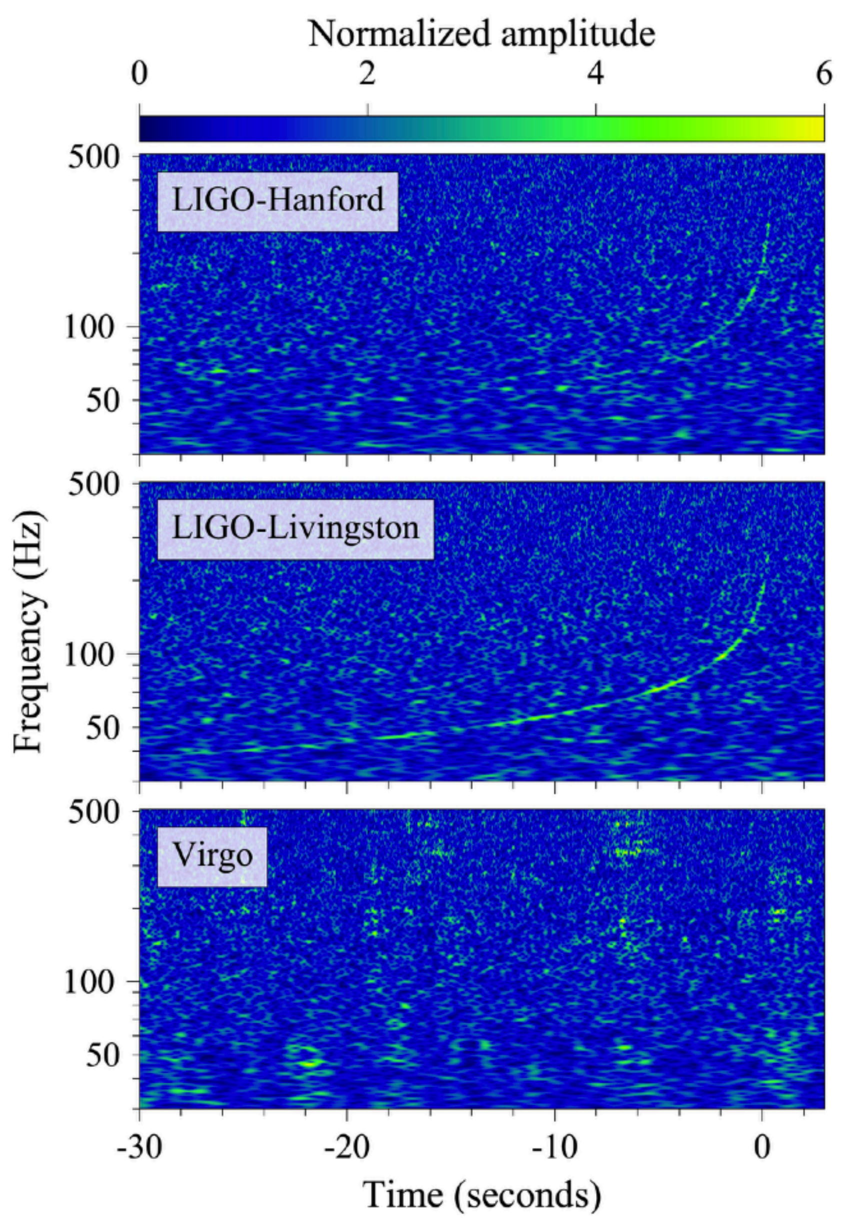
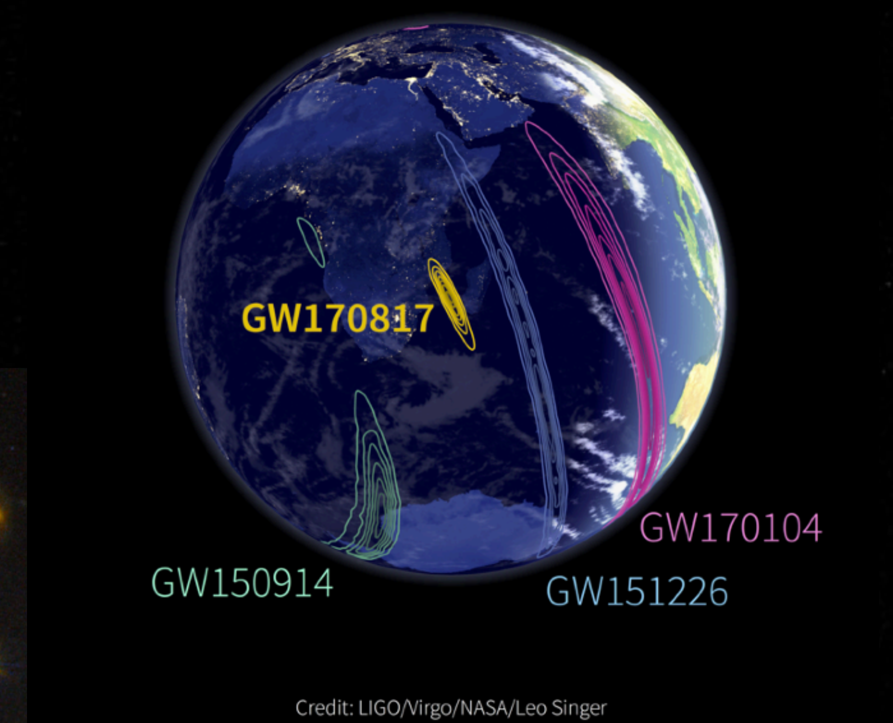
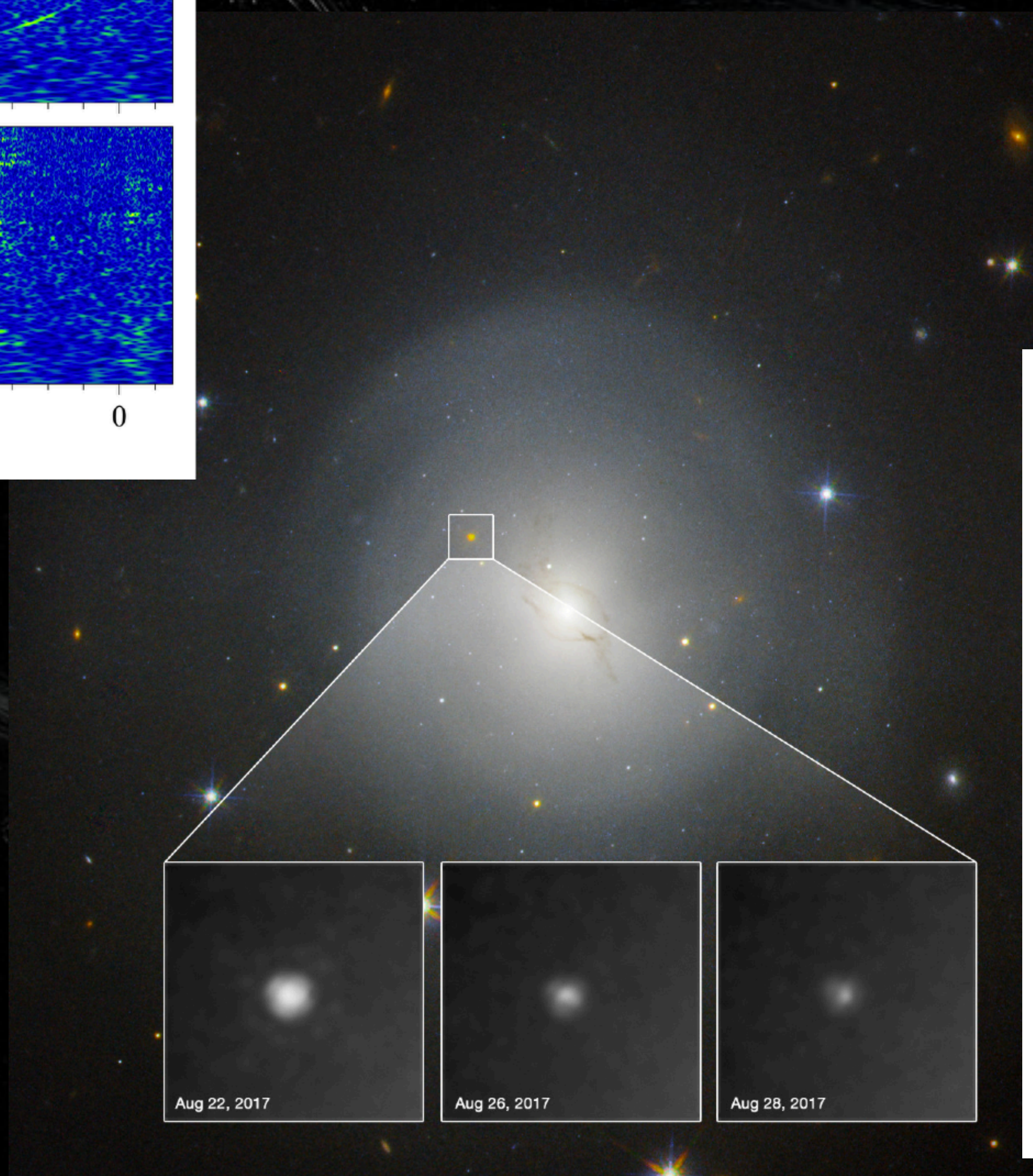
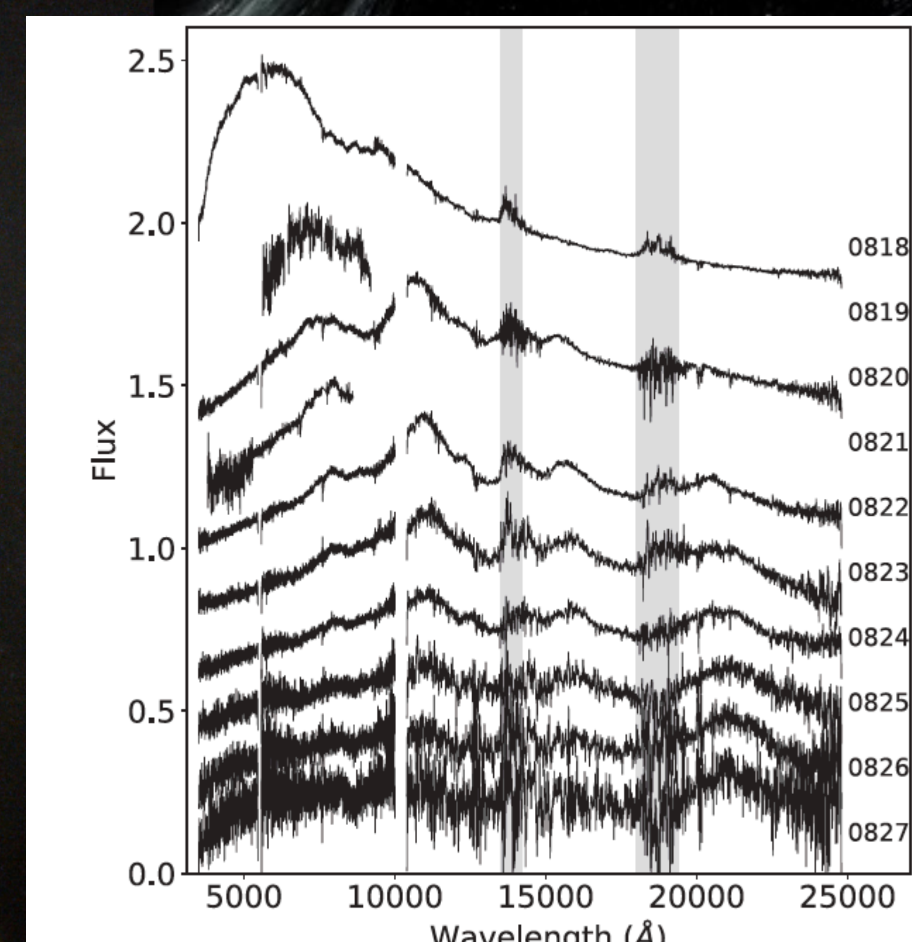
After GW170817 . . .



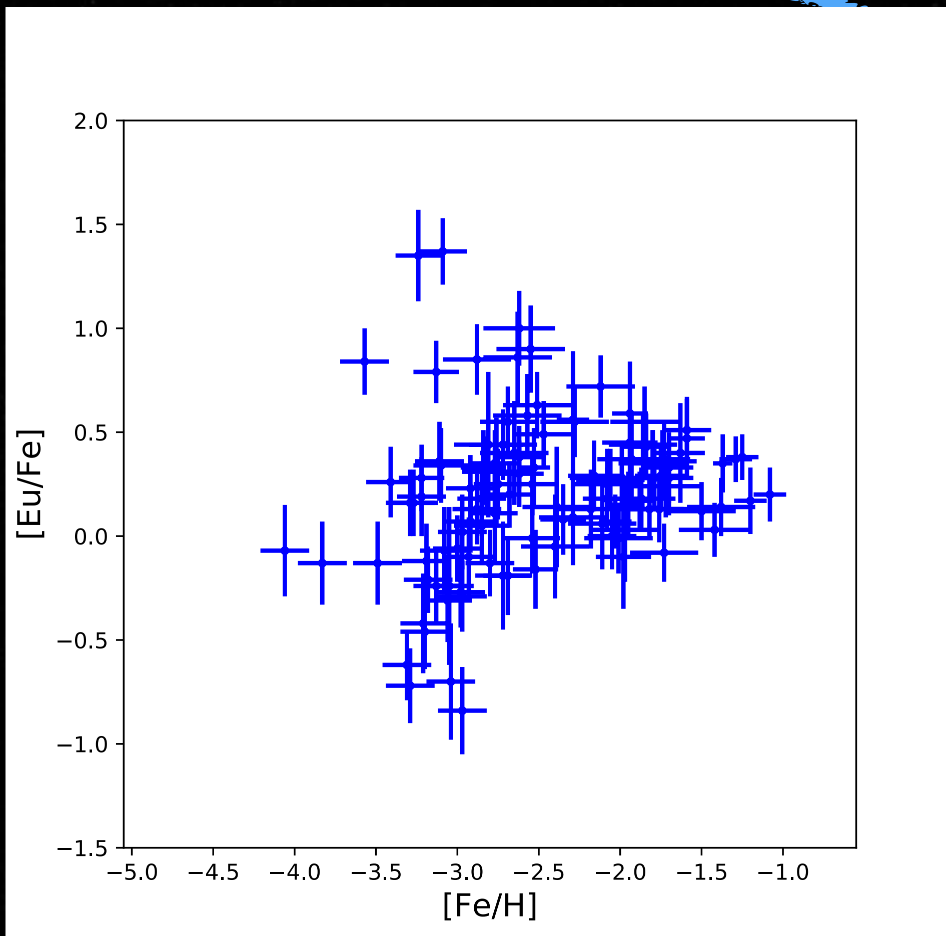


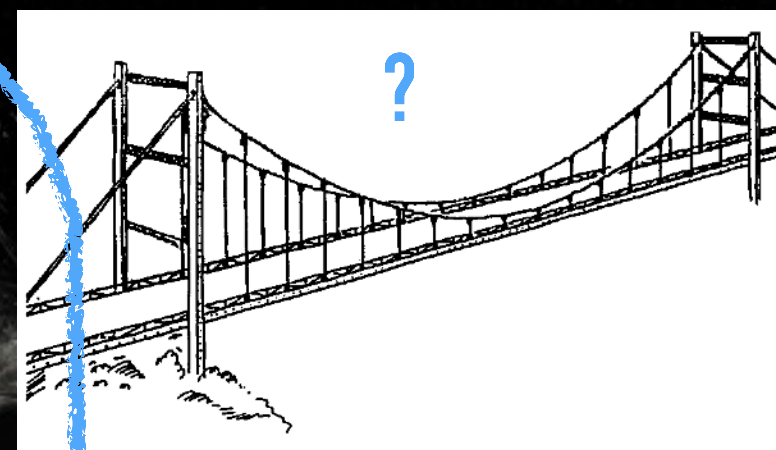


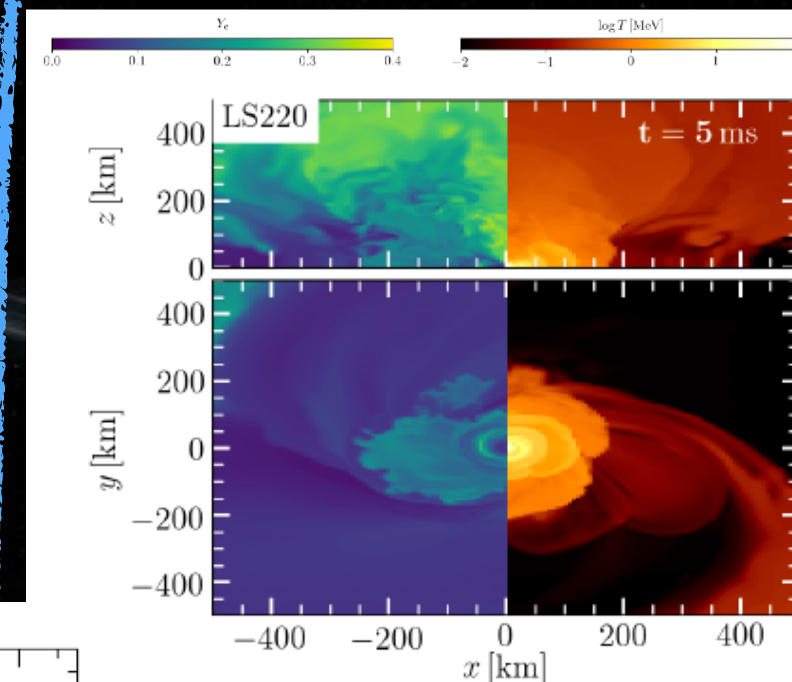


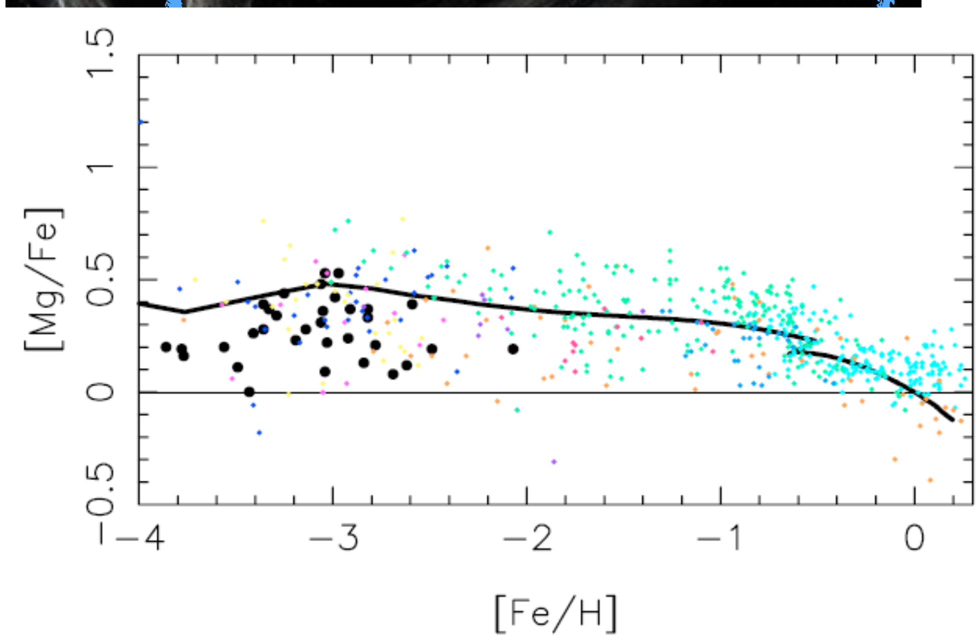
How to?

Neutron star mergers



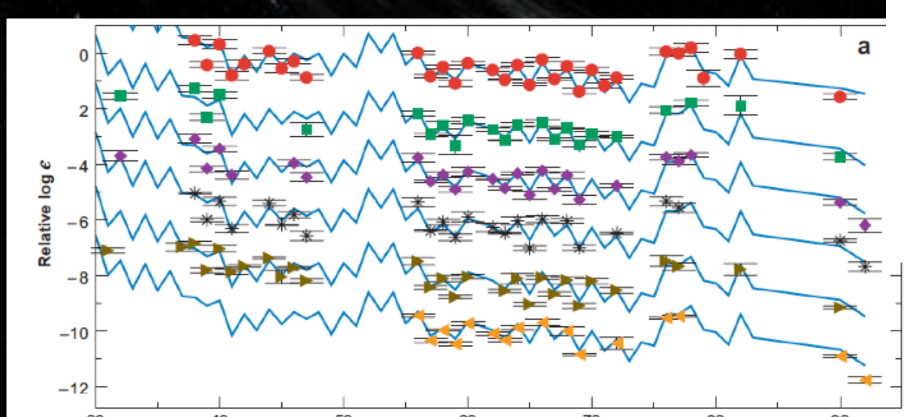


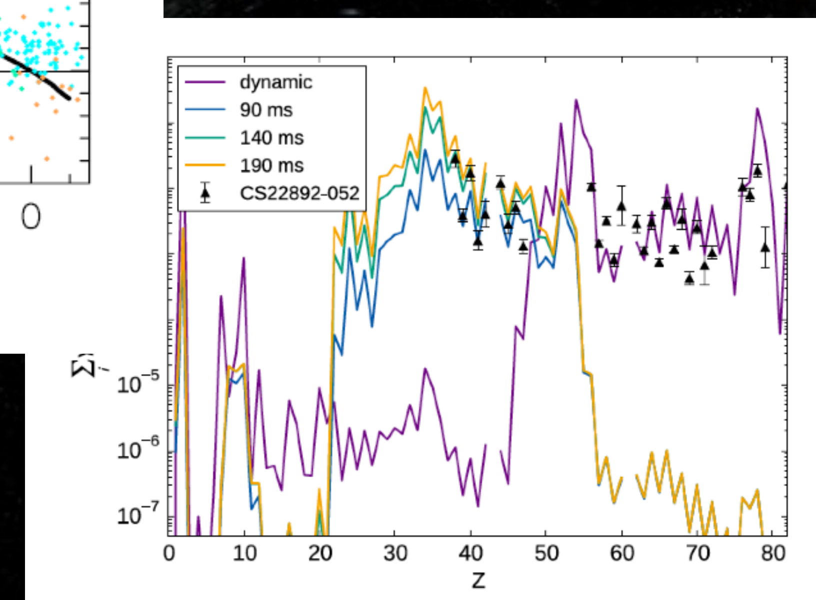




r-process

Francois+04





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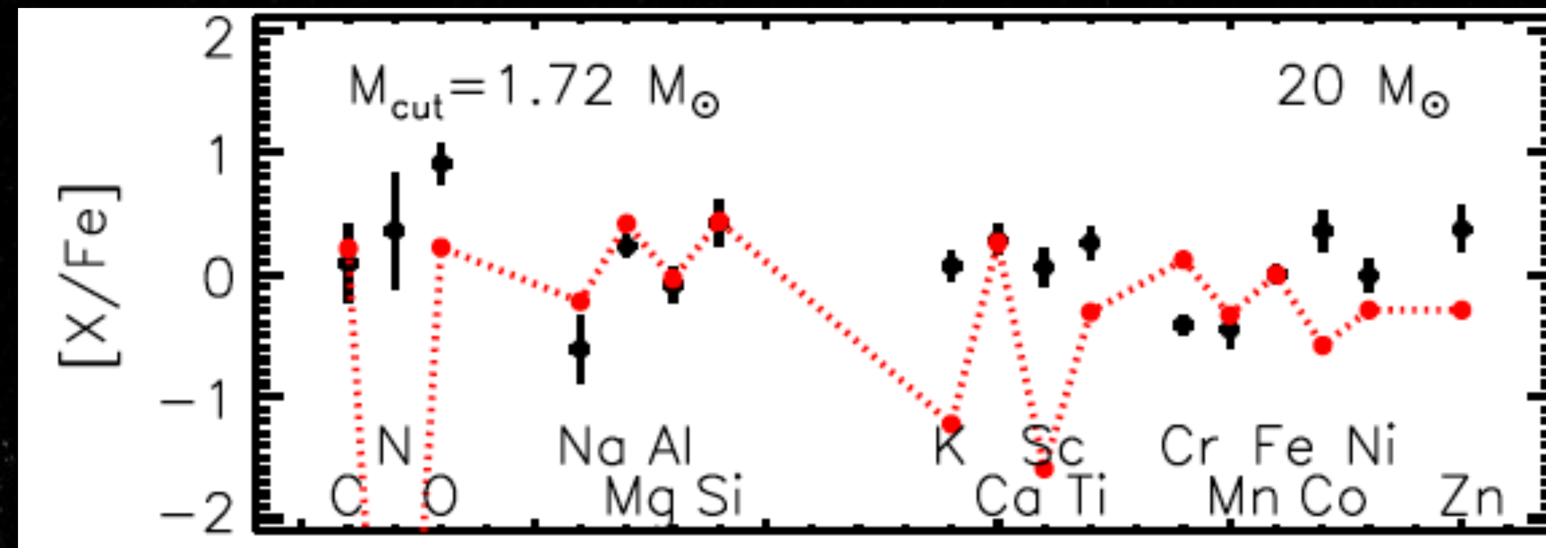
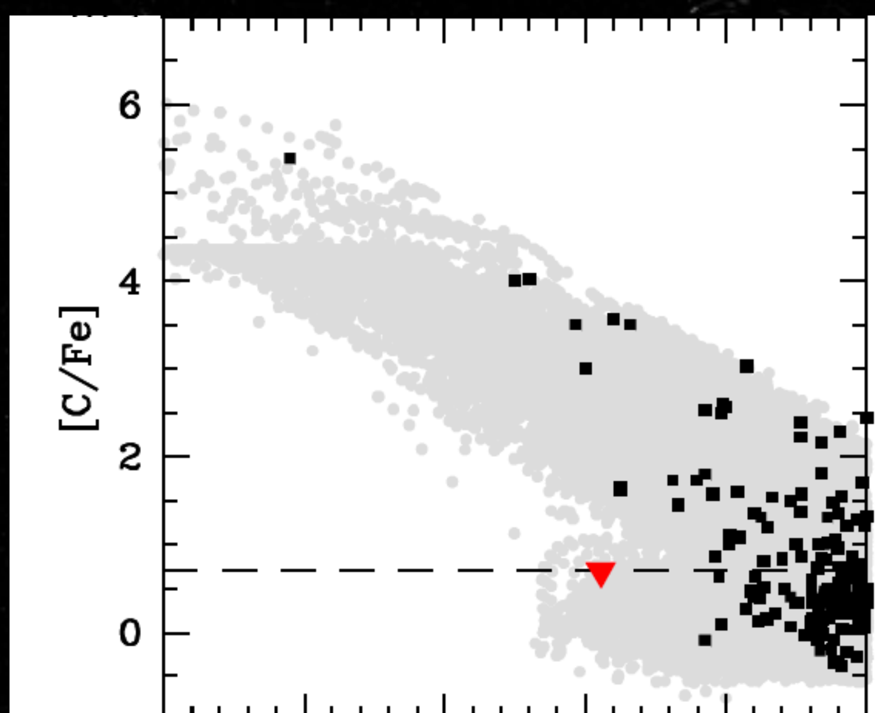
Possible solutions

Direct comparison of stellar abundances to nucleosynthesis results

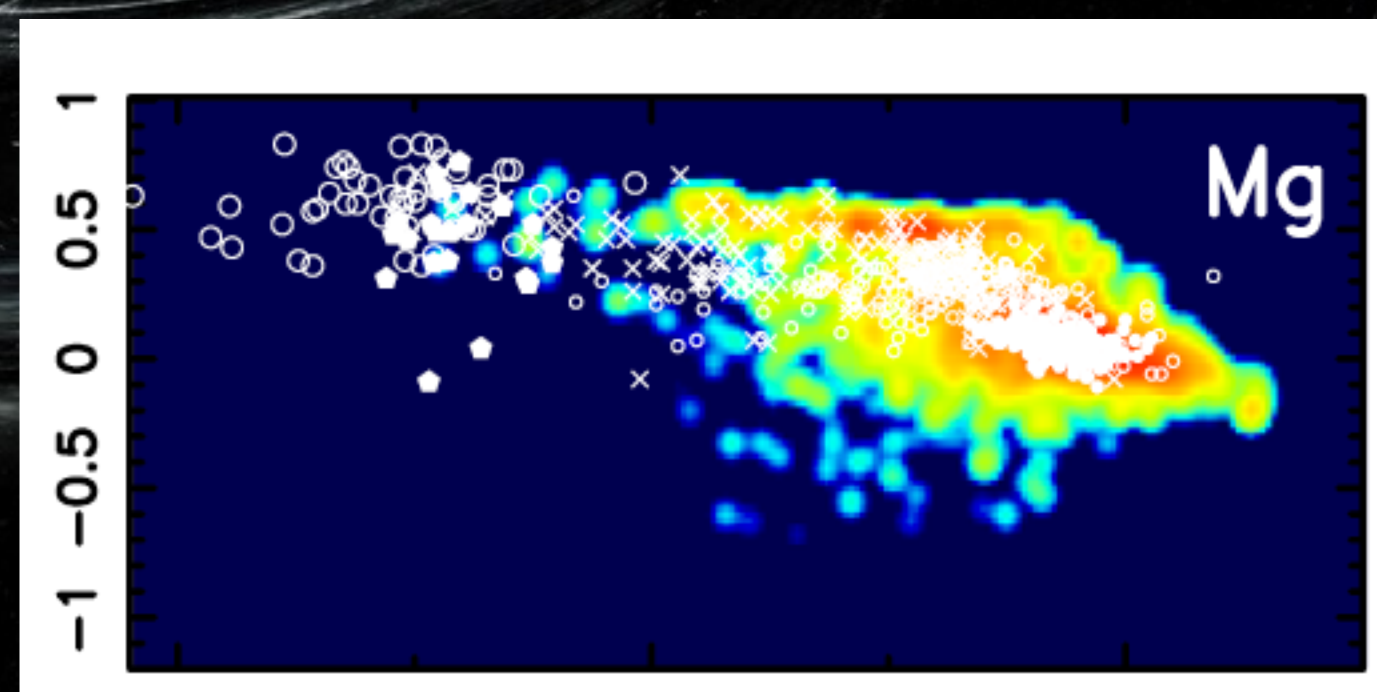
Limongi&Chieffi+12





semi analytic models in a cosmological context

DeBennassuti+17

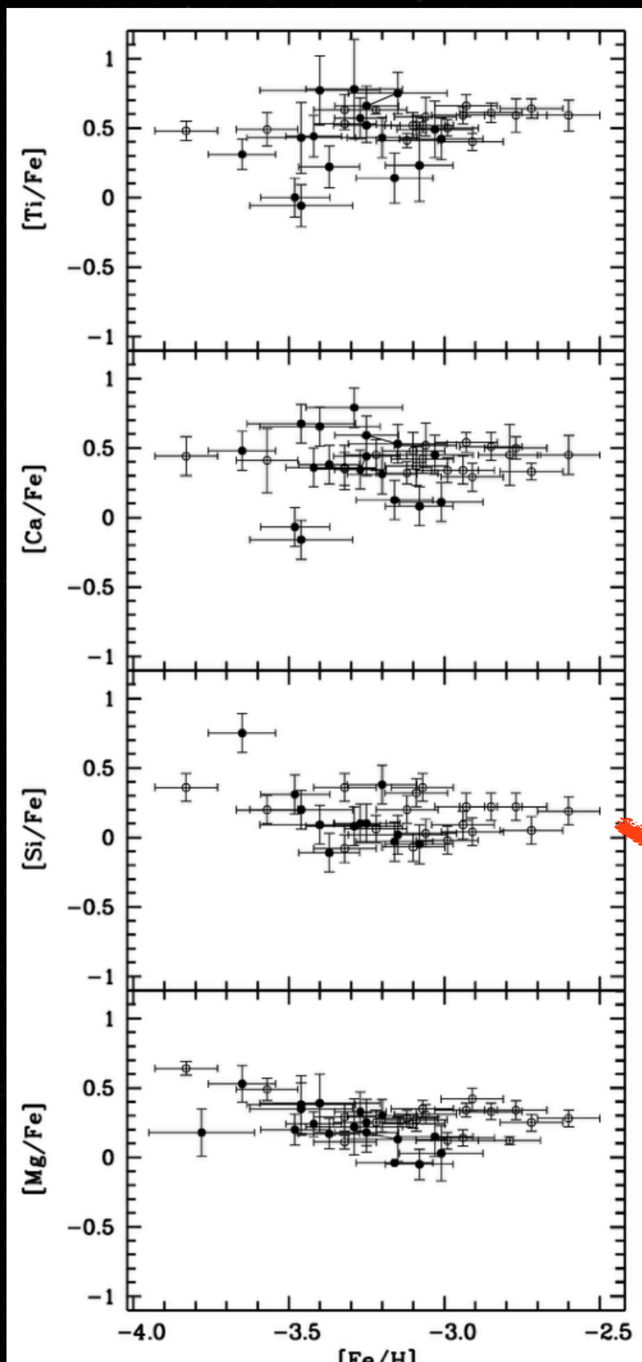


Simulation with gas in cosmological context

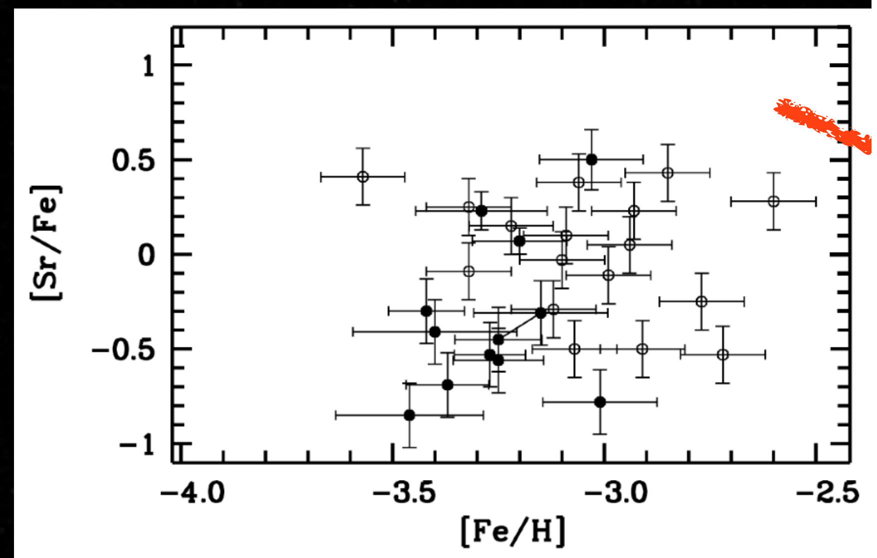
Kobayashi+11

Stochastic chemical evolution models

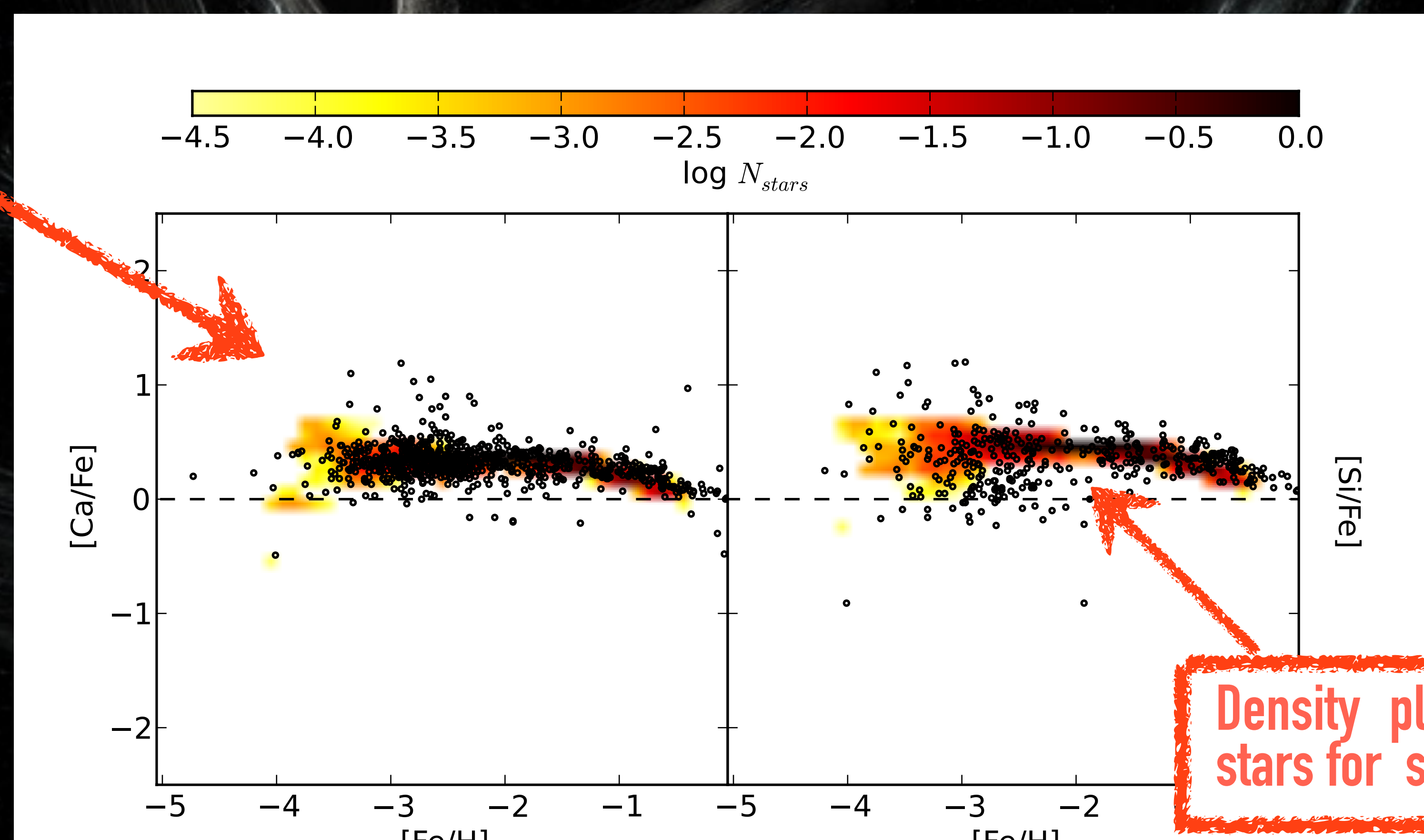
Problem:
Neutron capture elements present a spread alpha elements do not



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

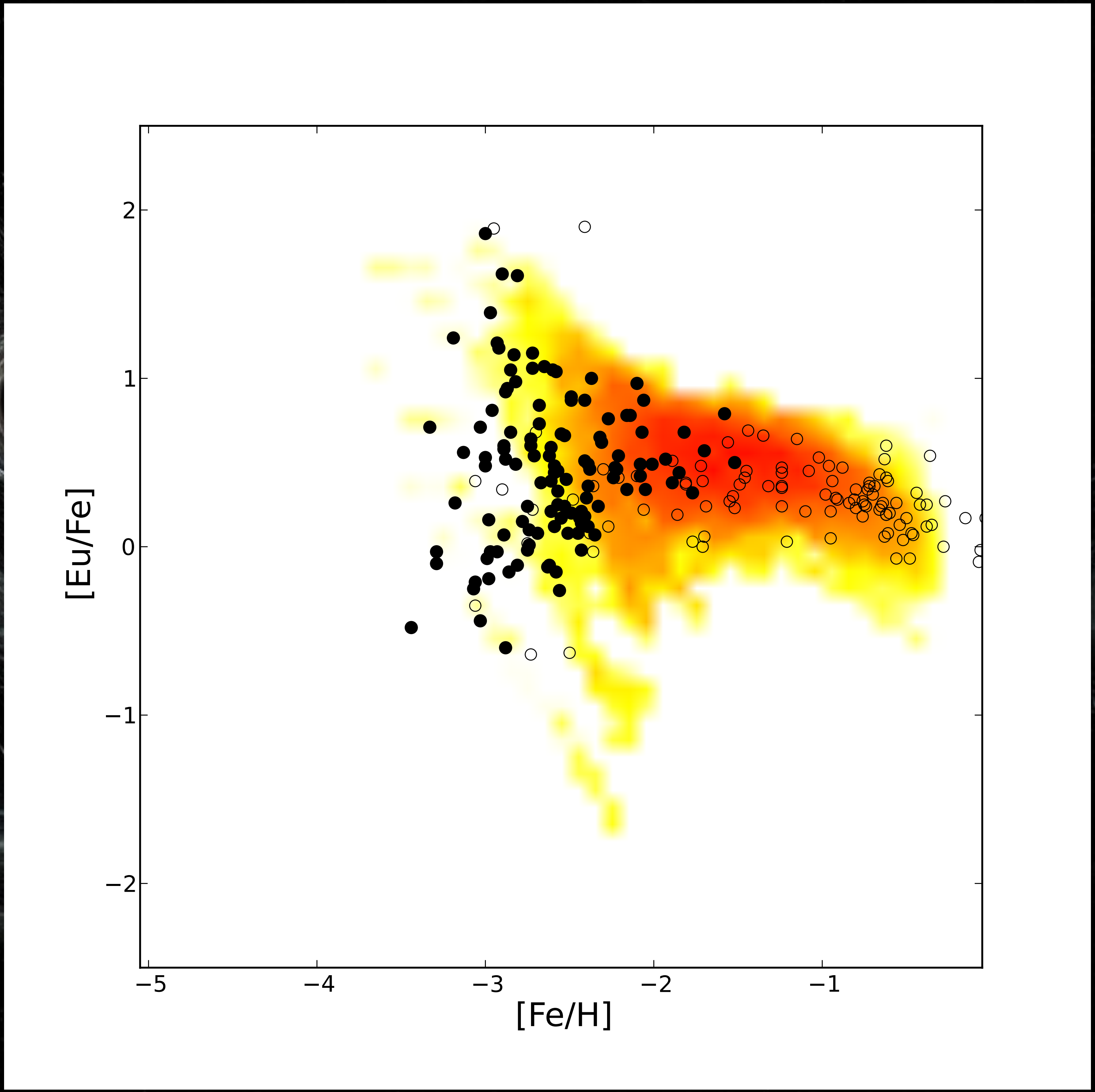
delay for the merging 1Myr

Cescutti, Romano, Matteucci, Chiappini and Hirschi 2015

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

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.



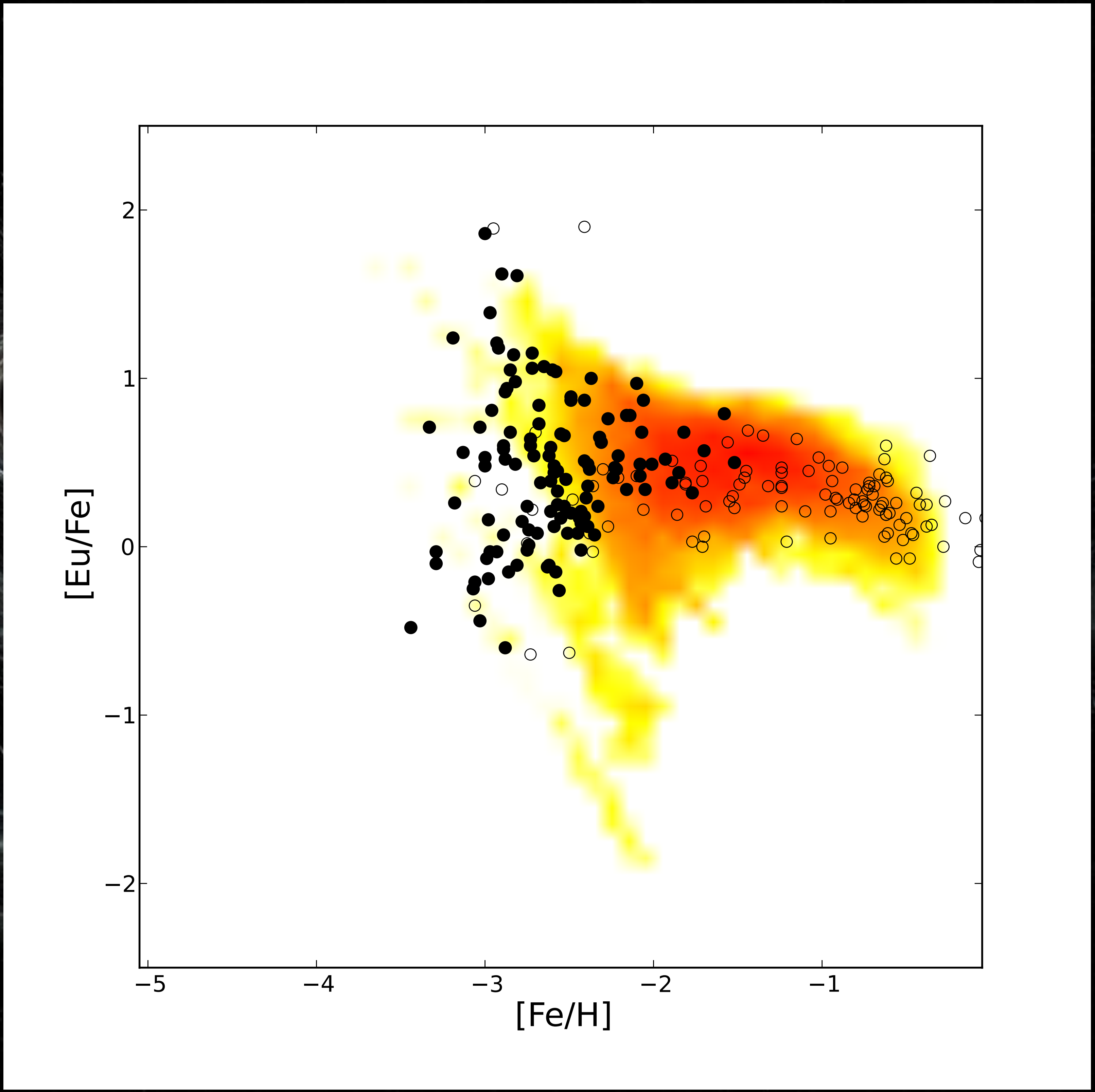
Neutron star mergers

delay for the merging 10 Myr

Cescutti+15

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

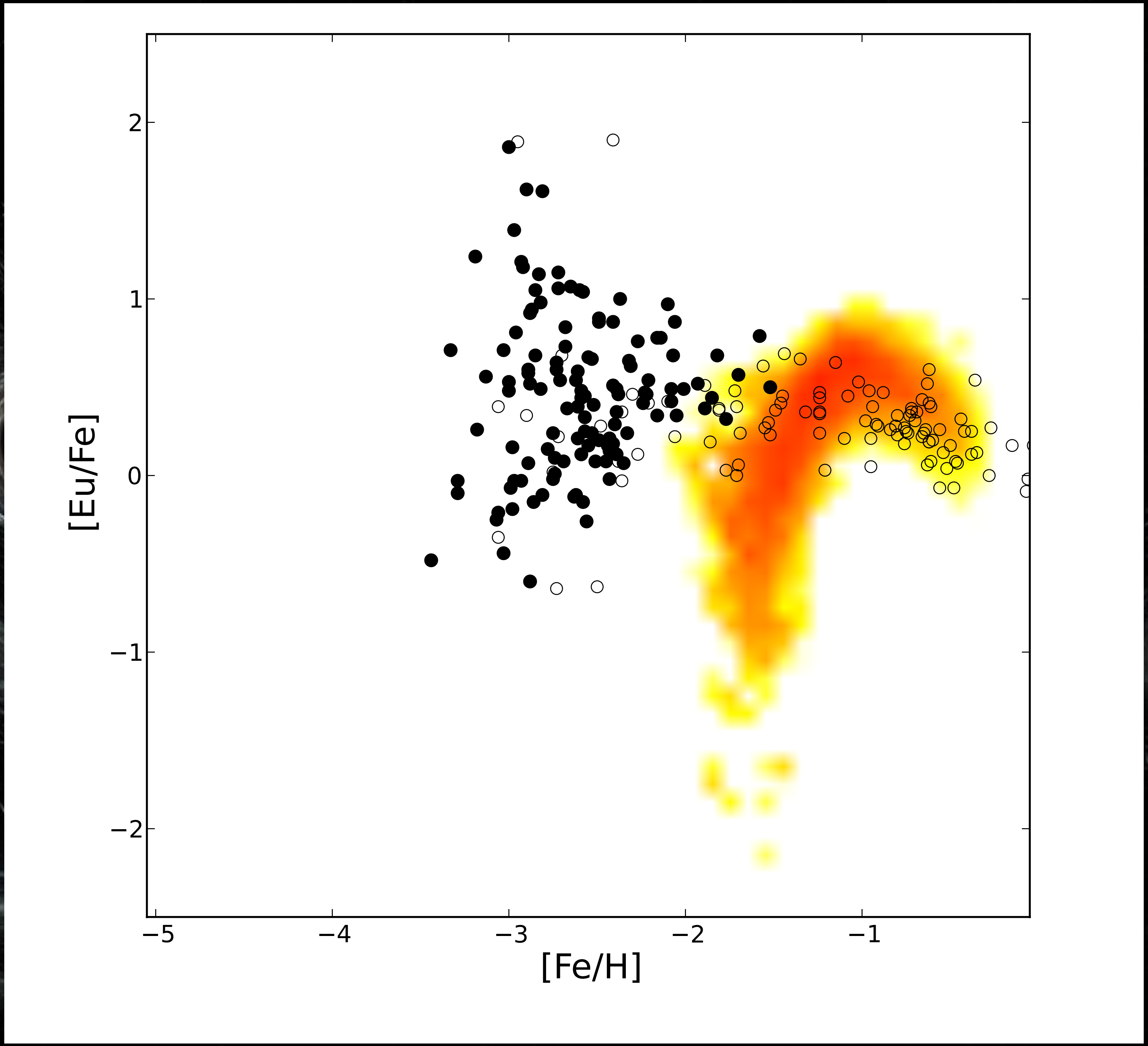
delay for the merging 100 Myr

Cescutti+15

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

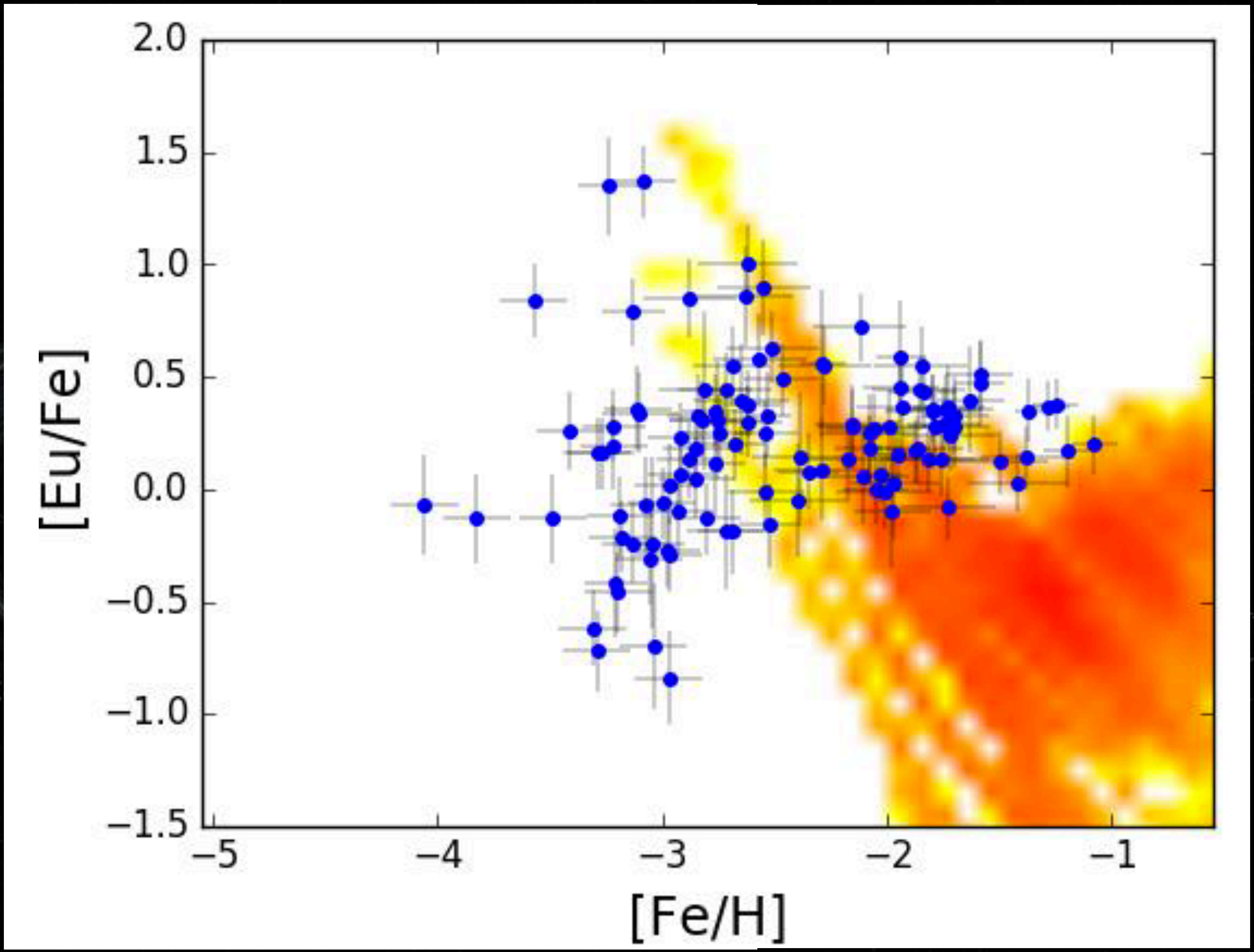
Therefore from the point of view of the chemical evolution of the Galactic halo, we can conclude that only if most of the NS mergers enriches in timescale <10Myr, the scenario can be supported.

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

Neutron star mergers
delay time distribution: t^{-1}



Bachelor thesis Lorenzo Cavallo 2018

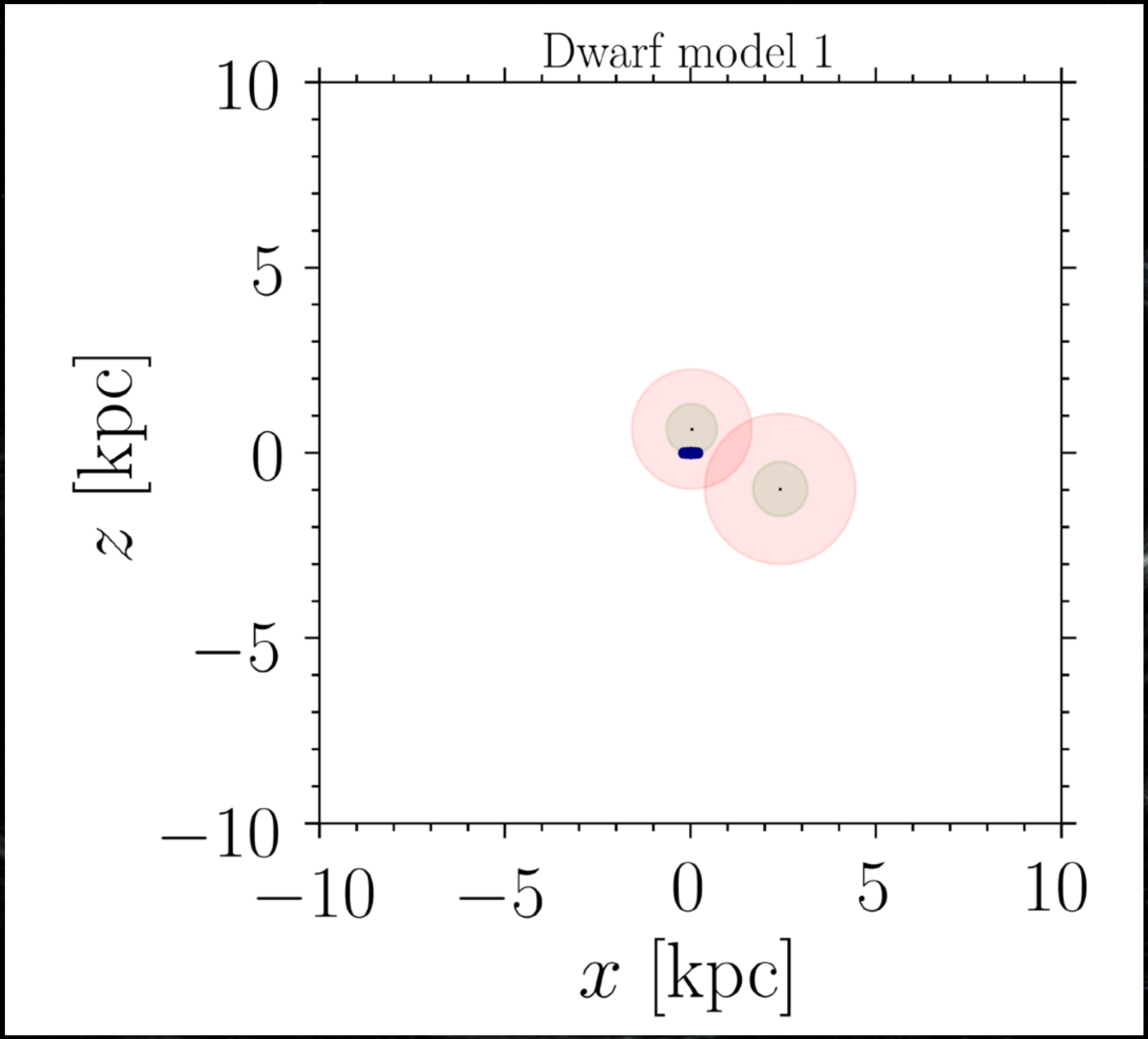
NSM: More detailed delay time distribution and other issues within a standard chemical evolution model:

next talk by Benoit!

(see also Simonetti+19)

Early r-process enrichment by neutron star mergers

dynamics of NSBs in the gravitational potentials of different types of host galaxies

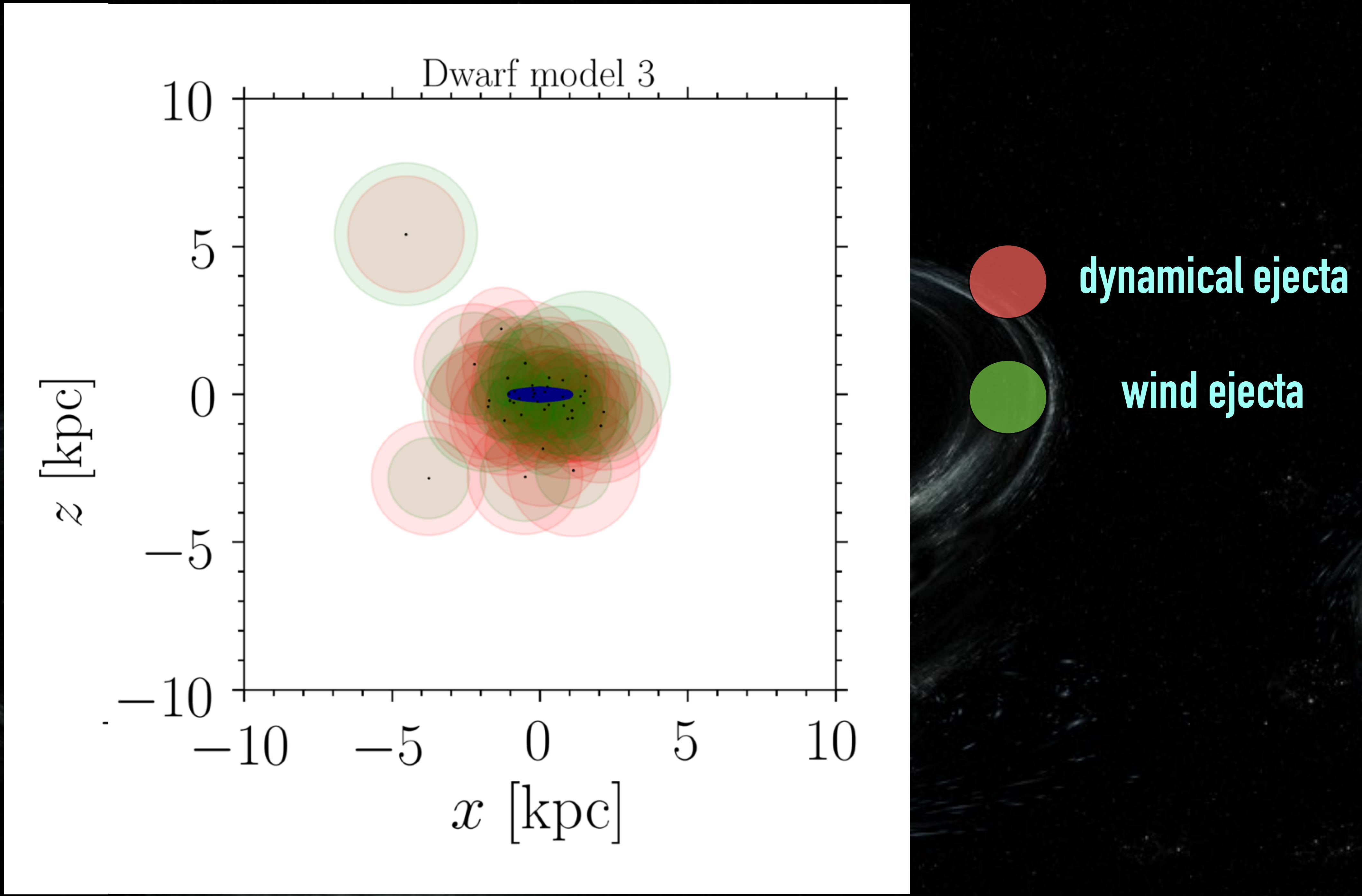


dynamical ejecta

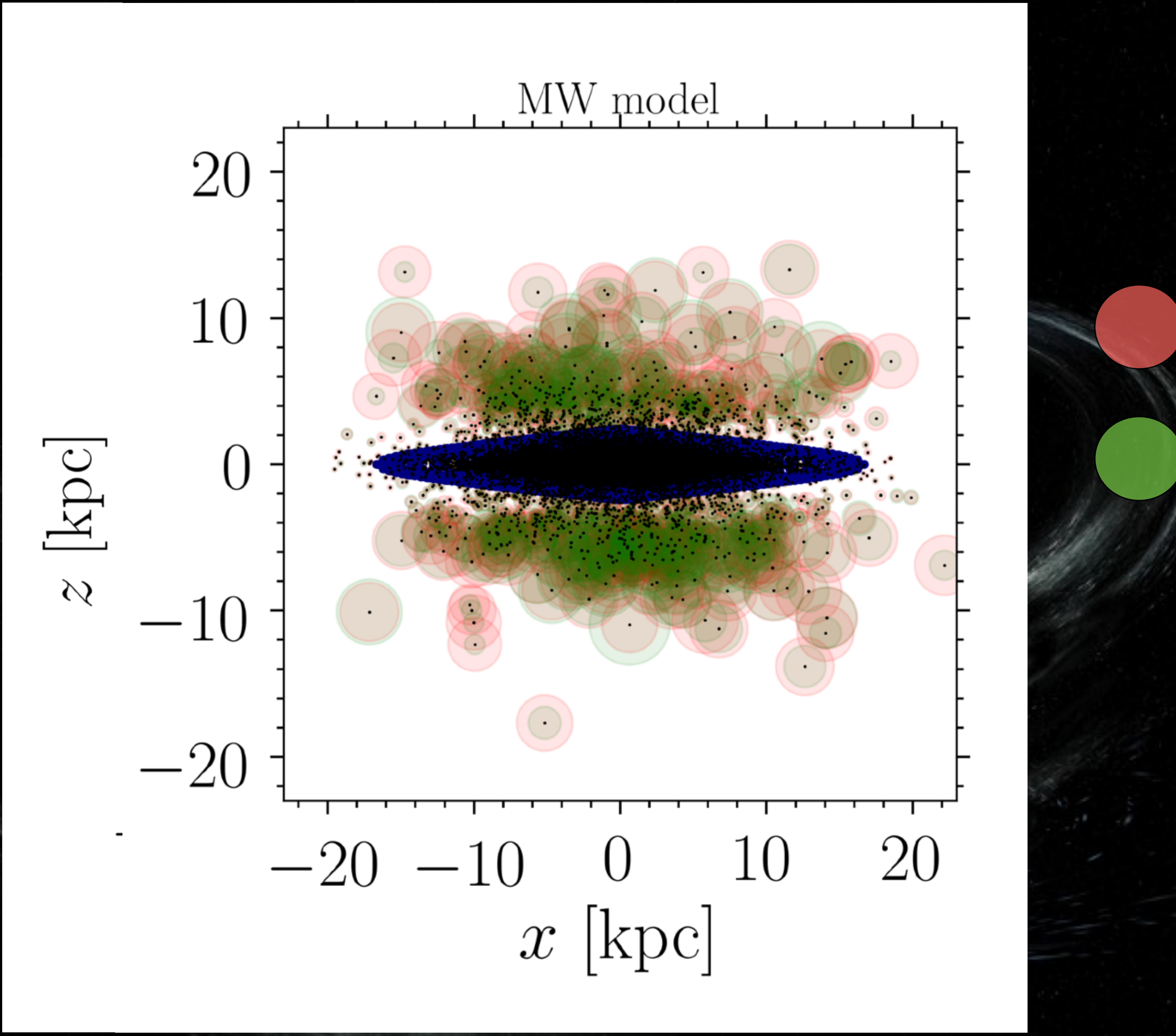
wind ejecta

Bonetti, Perego, Dotti and Cescutti (submitted)

10^5 Msun SF lasts 1Gyr about 50CCSNe

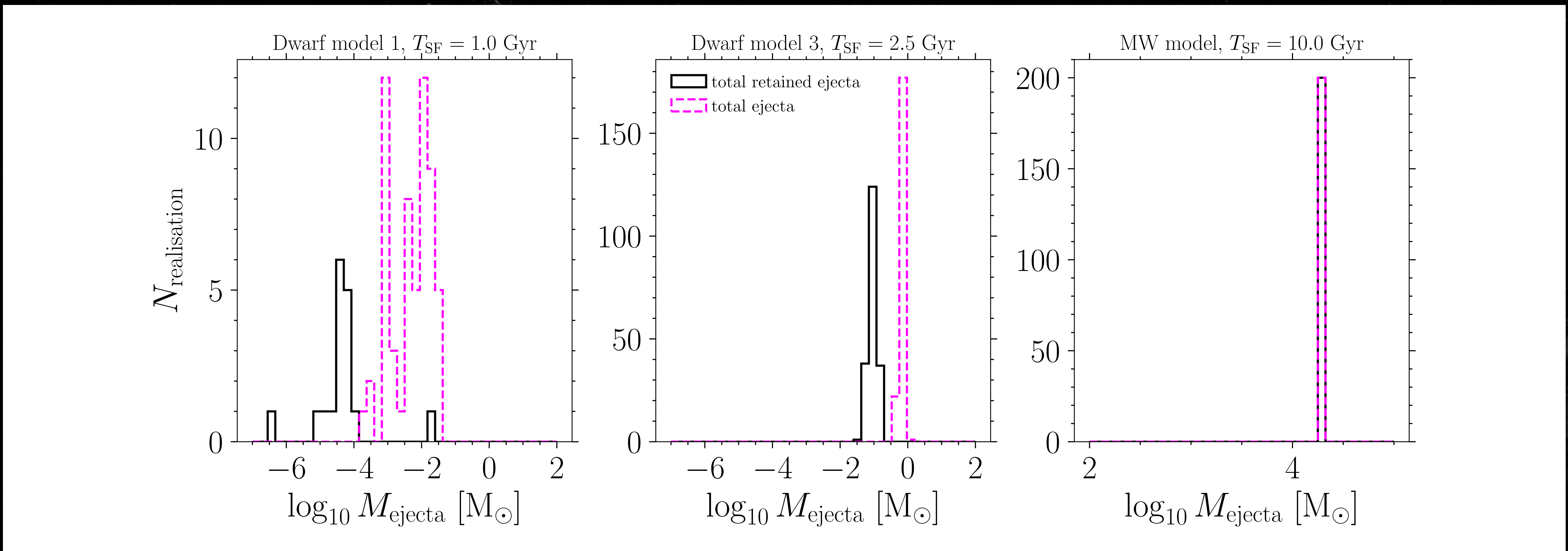


10^7 Msun SF lasts 2.5 Gyr about 14000 CCSNe

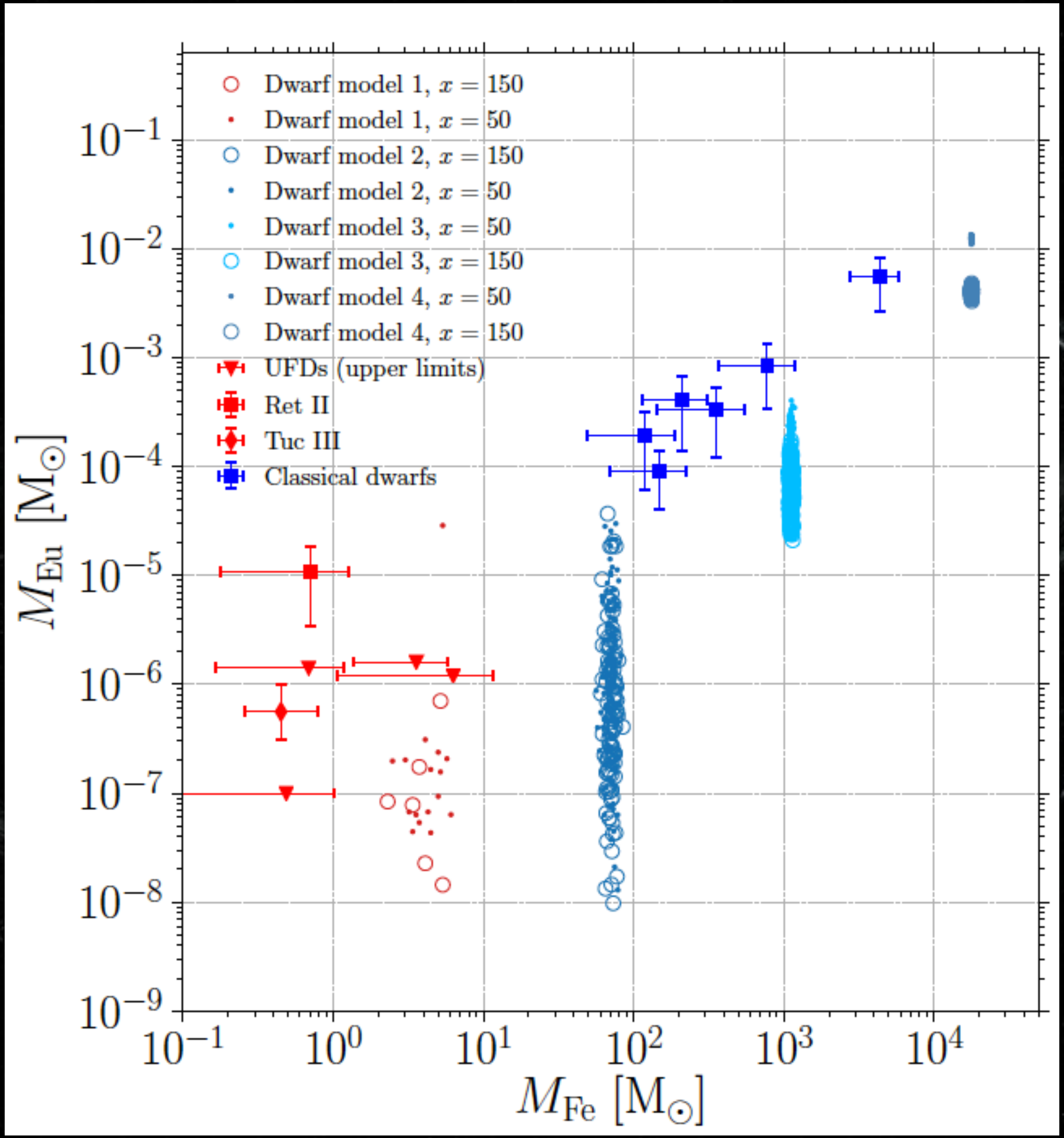


10^11 Msun SF lasts 14Gyr

200 realisations for each model



Comparison with averaged observations



Other solutions?

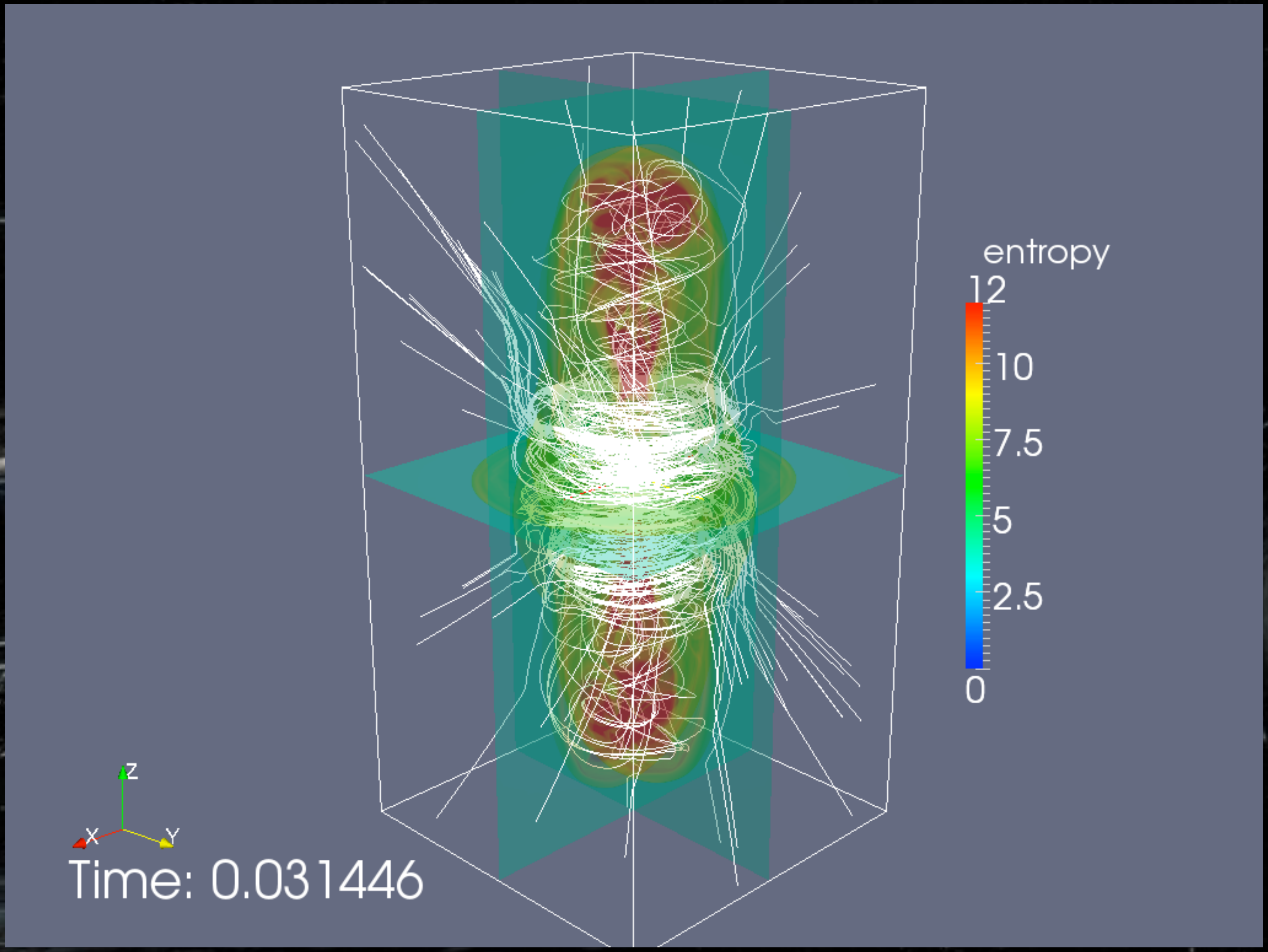
Magneto Rotationally Driven SN scenario (MRD)

(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.

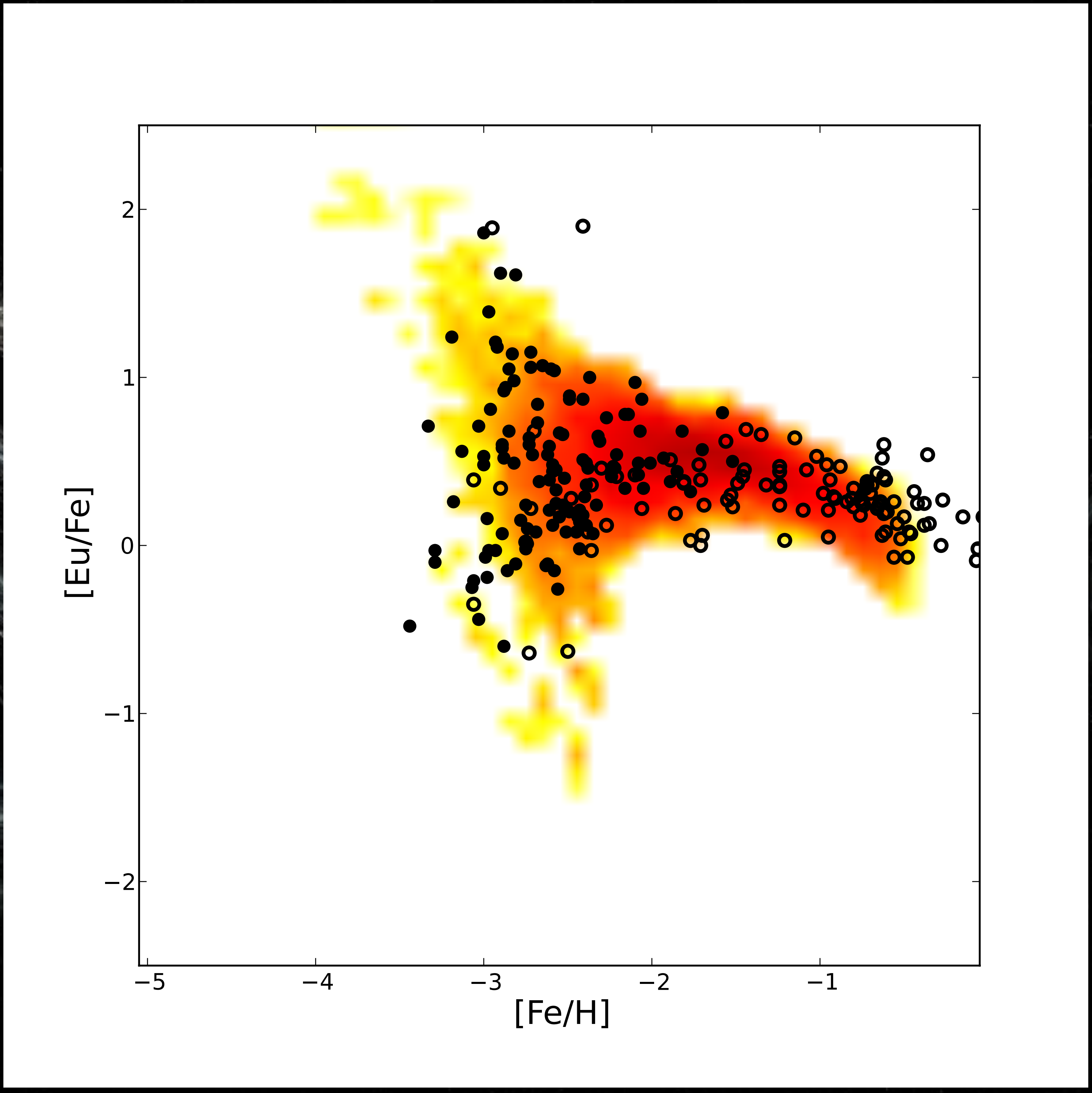


Magneto Rotationally Driven SN scenario (MRD) 10%

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)



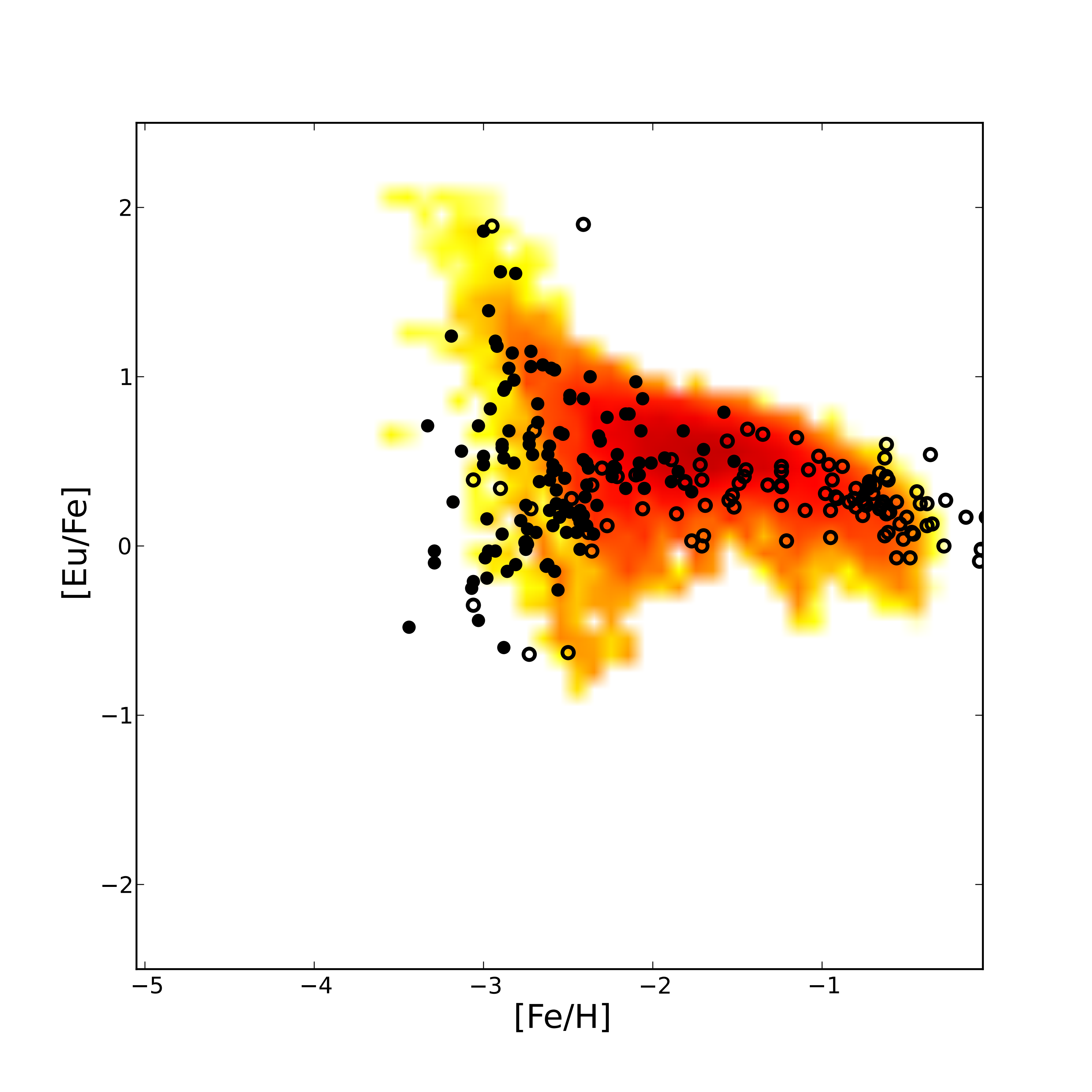
Magneto Rotationally Driven SN scenario (MRD) 5%

Cescutti+14

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

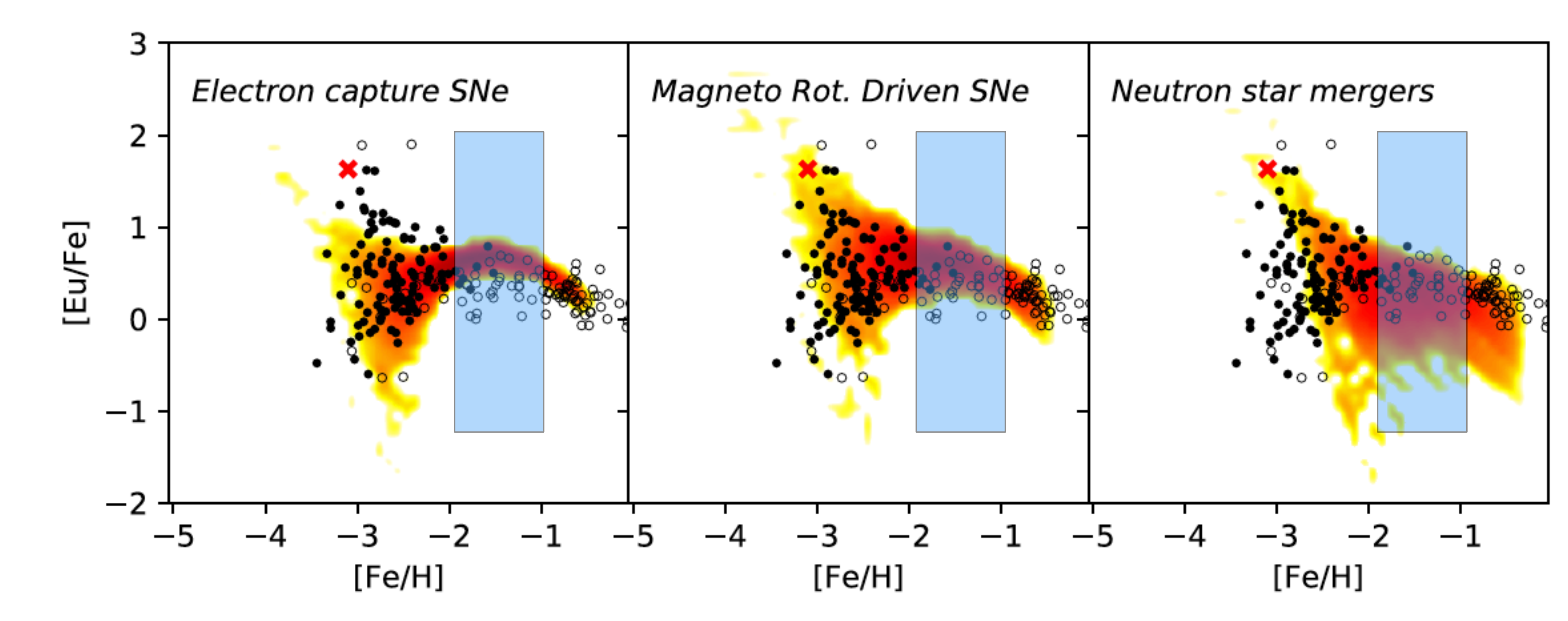
The amount of a single event is similar to the one for the NSM scenario with short delay.

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



MINCE

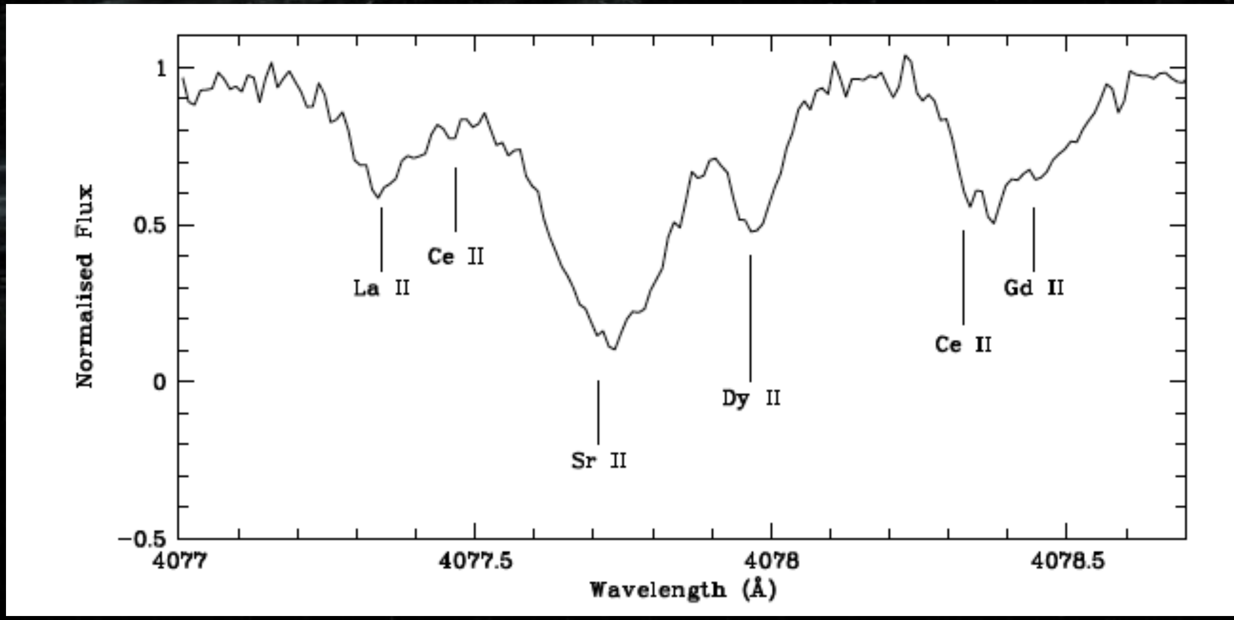
measuring neutron capture elements at intermediate metallicity
Main investigators Bonifacio & Cescutti



Observational proposals at several facilities from (TNG,CFHT,3.6m,2.2m,Magellan,OHP,NOT)

2/3 accepted up to now, 3 no outcome yet

Open collaboration with colleagues all over Europe and Chile to fill this gap!



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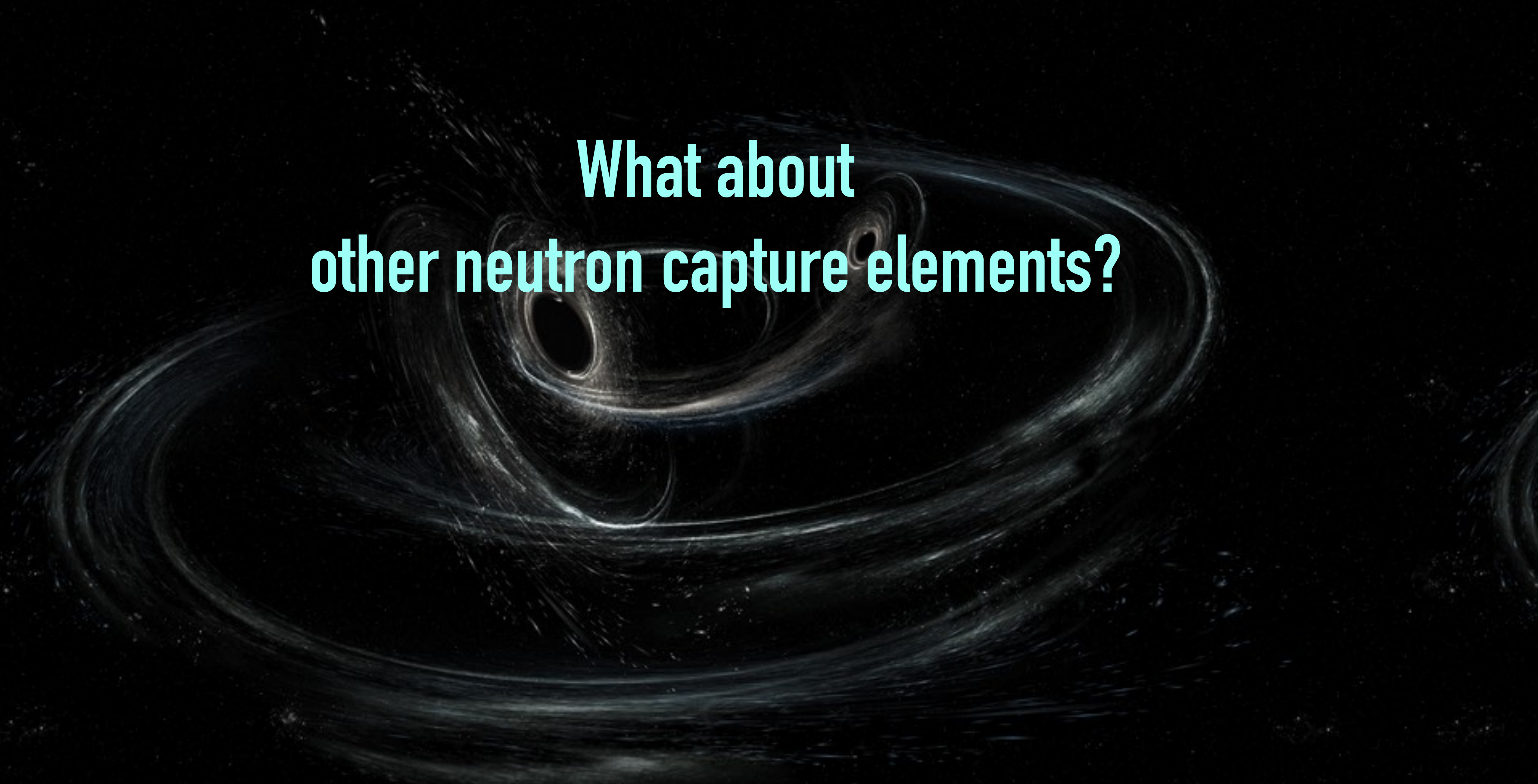
What about
other neutron capture elements?



Neutron capture elements

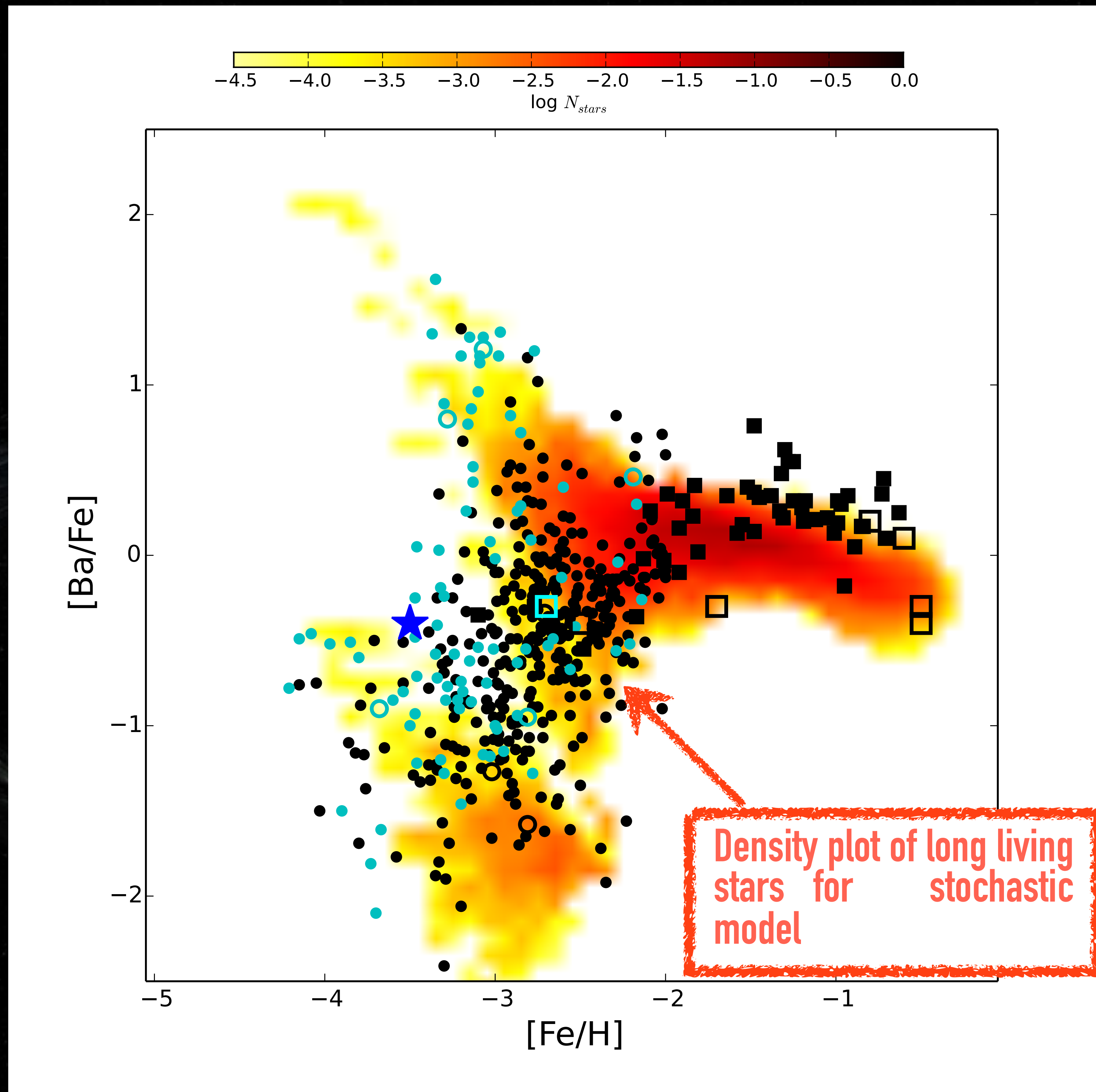
from Truran 1981 to ~6 years ago

	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 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

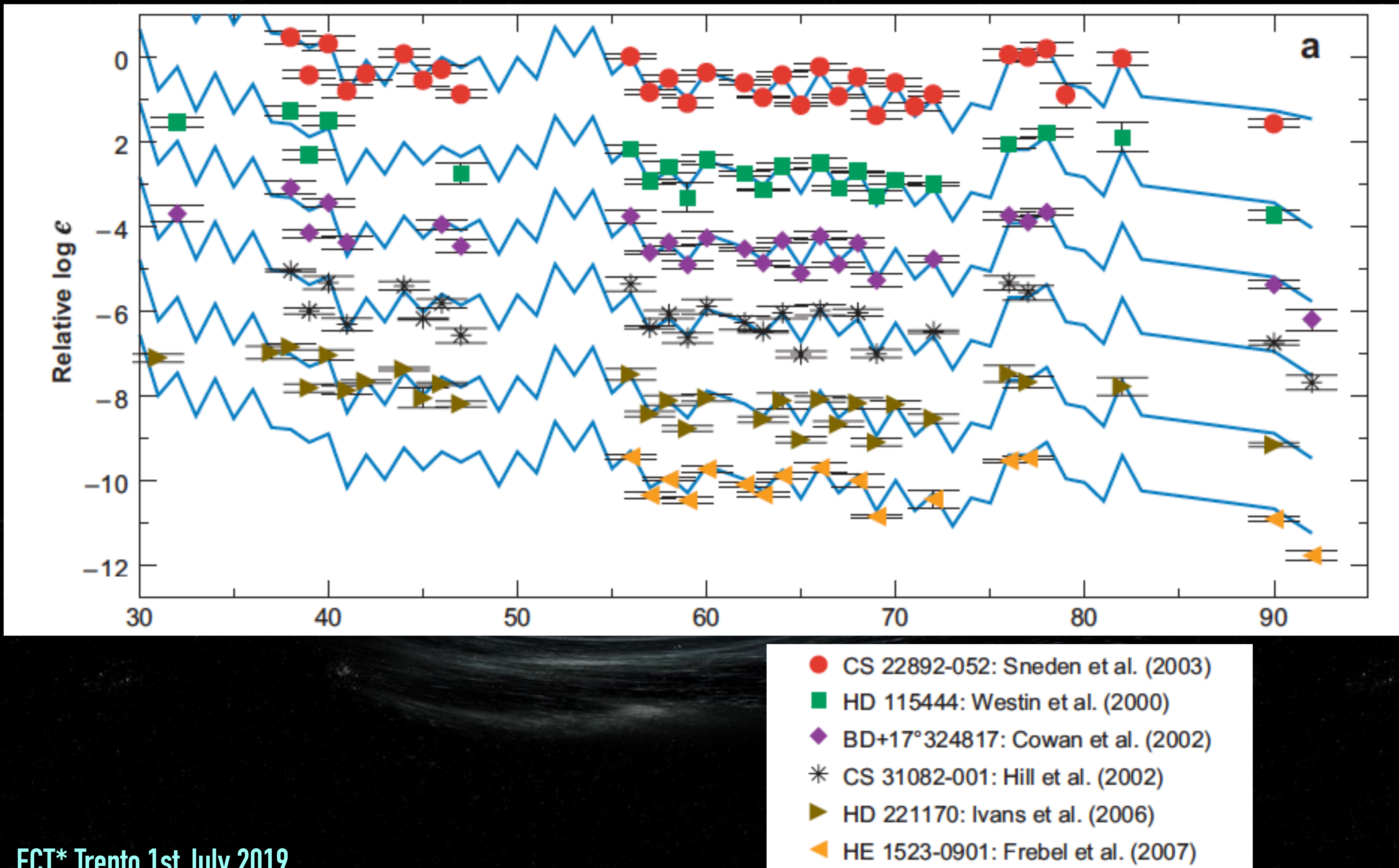


We can reproduce the [Ba/Fe] spread…

data from in
Placco+14 ● ●
Hansen+12 ■
Hansen+16 □ □
Cescutti+16 ★

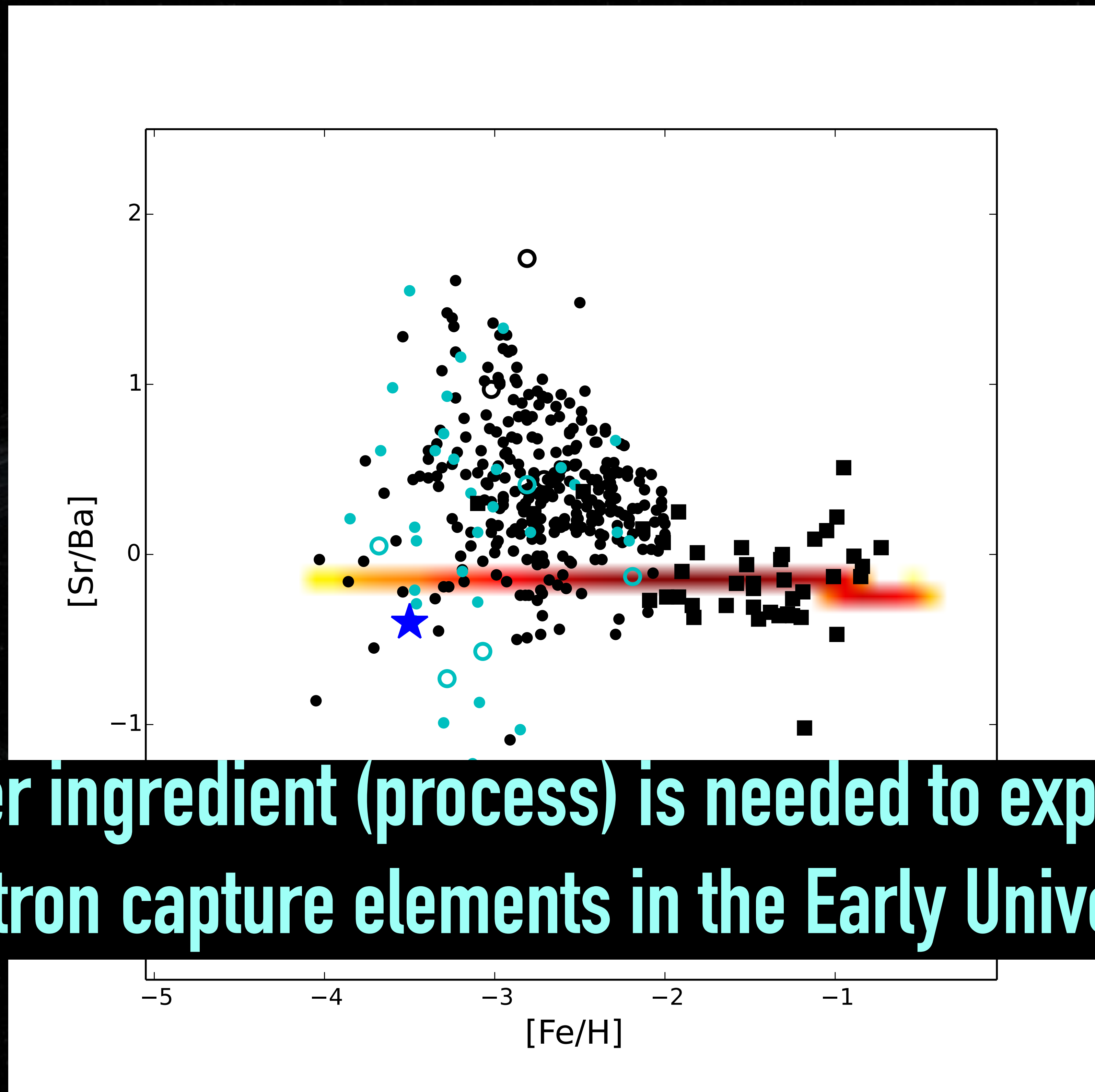
r-process

pattern in r-process rich stars



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)



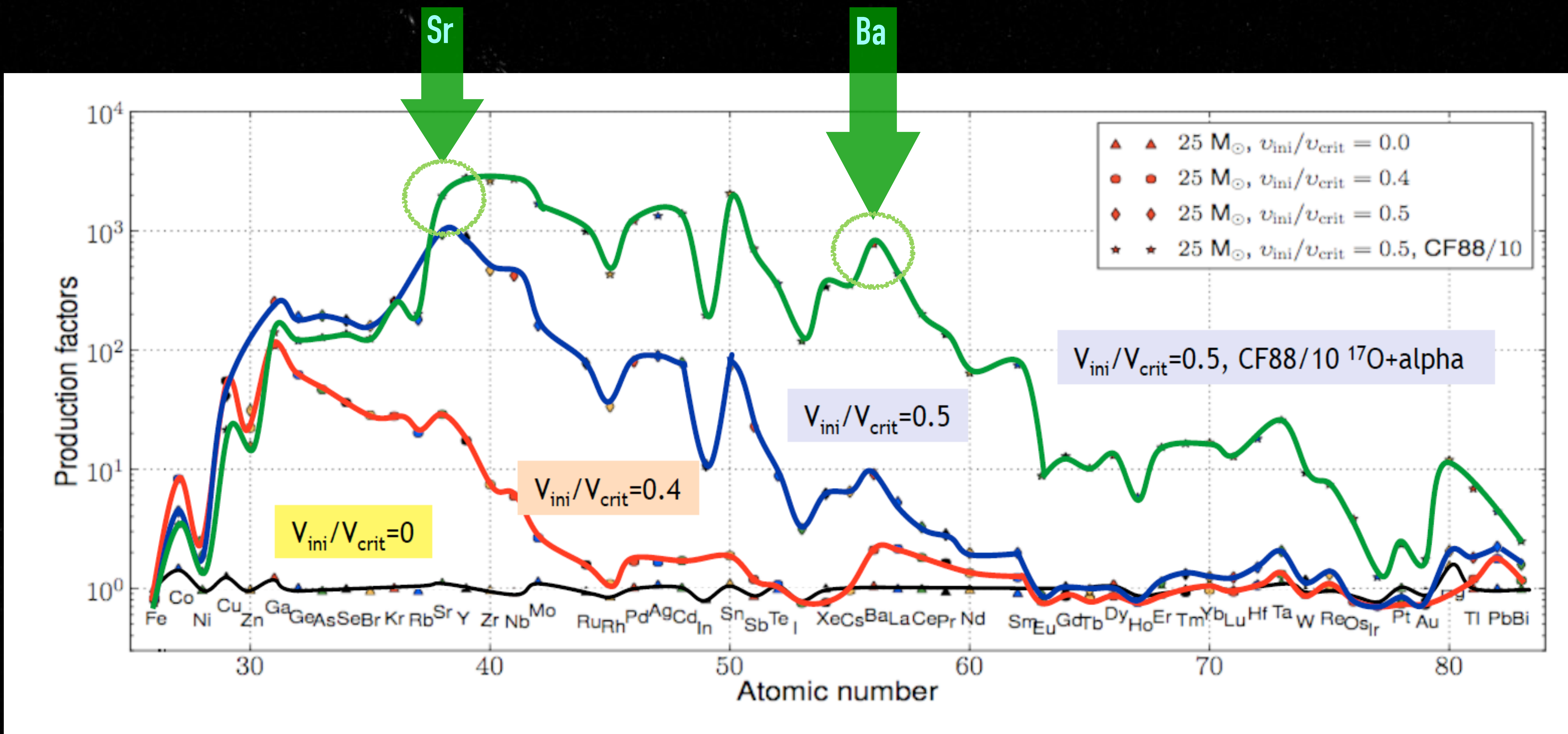
It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

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 Frischknecht+12 (see also Pignatari 2008)

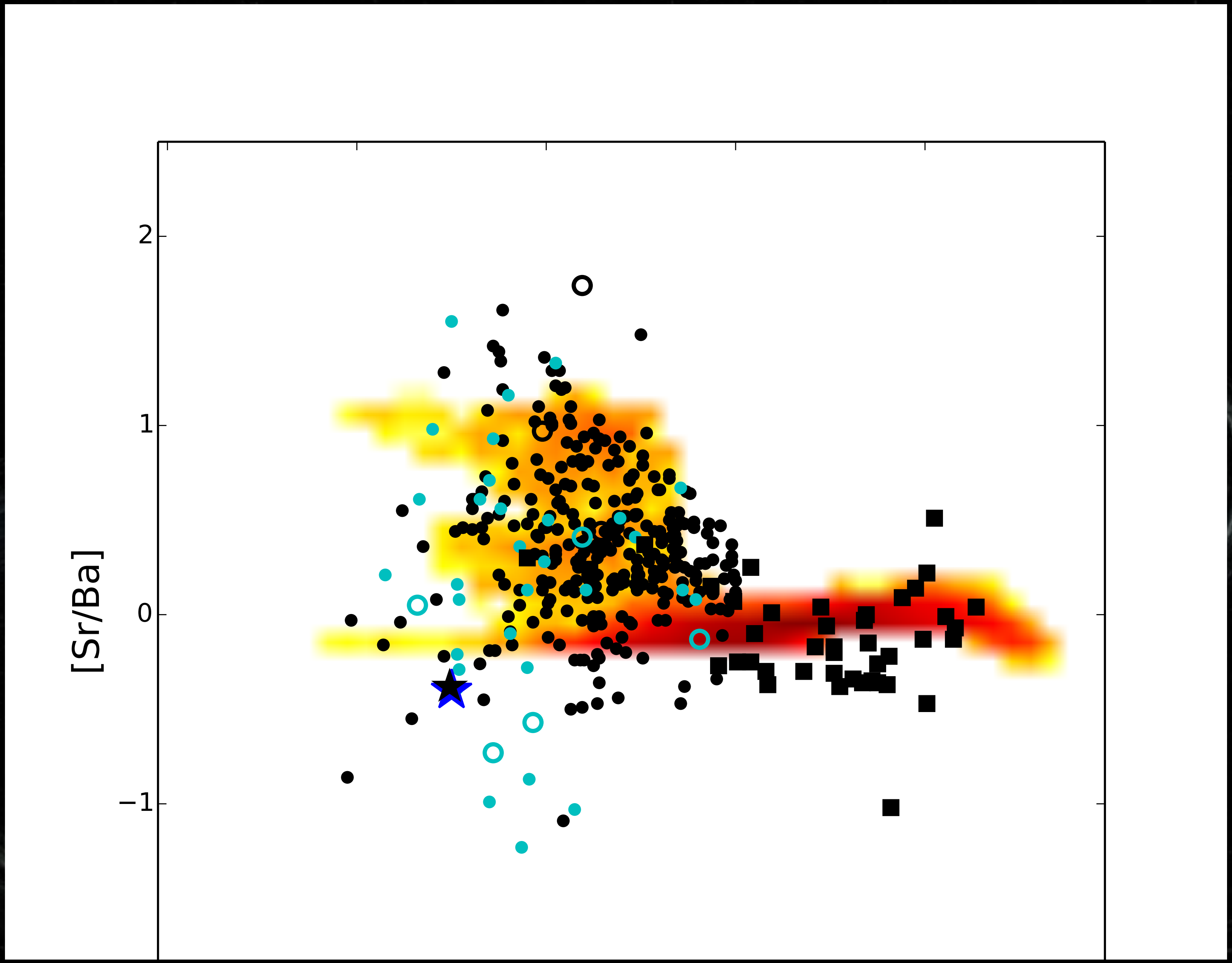
Early Galaxy

	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+ 2016	....
	Karakas+ 2012	Limongi and Chieffi 2018	

s-process from rotating massive stars

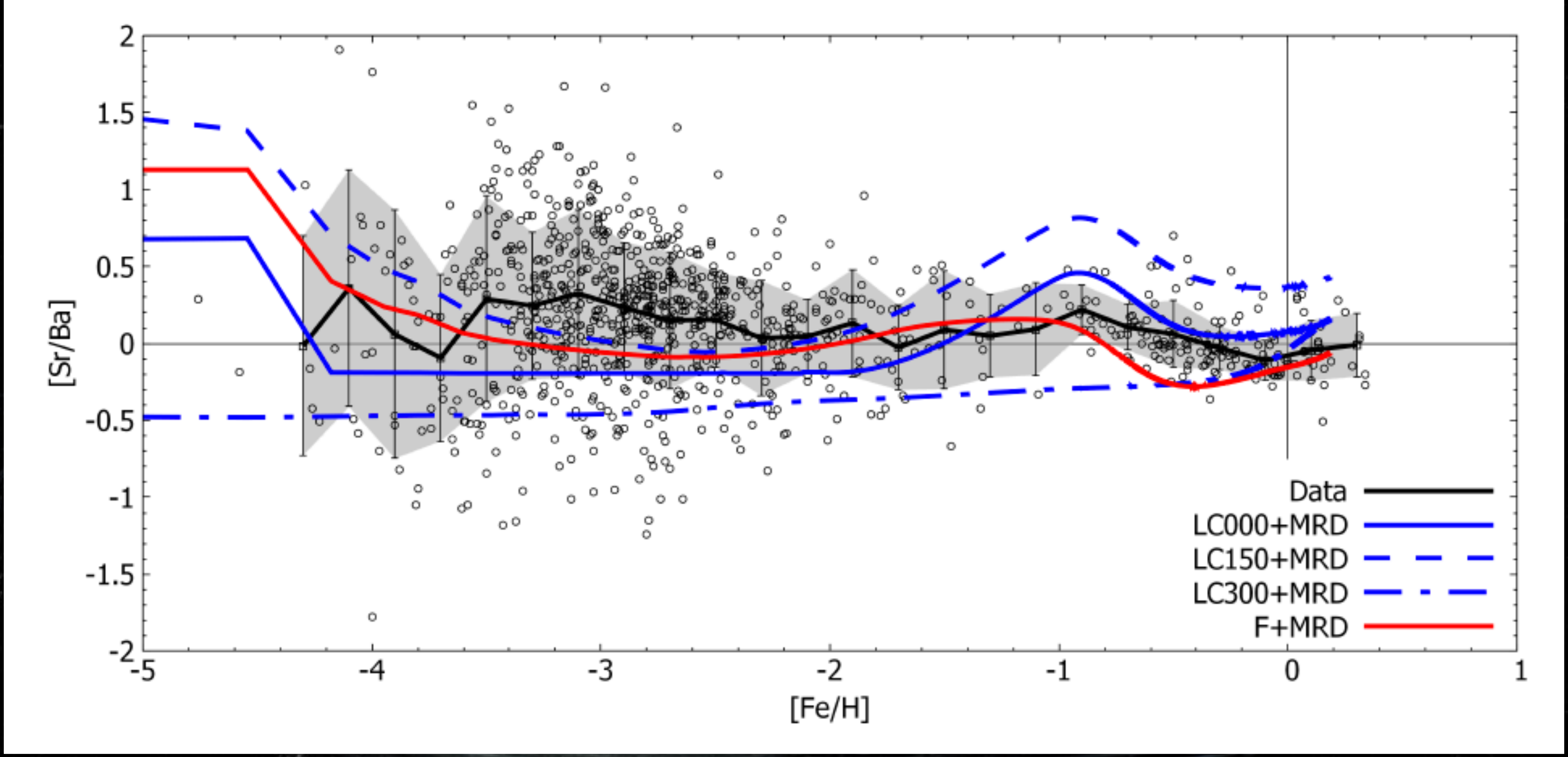
+ an r-process site (the 2 productions are not coupled!)

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

Not unique results
Same outcome adopting Limongi&Chieffi18



Rizzuti et al. (submitted)

see also Prantzos et al. 2018

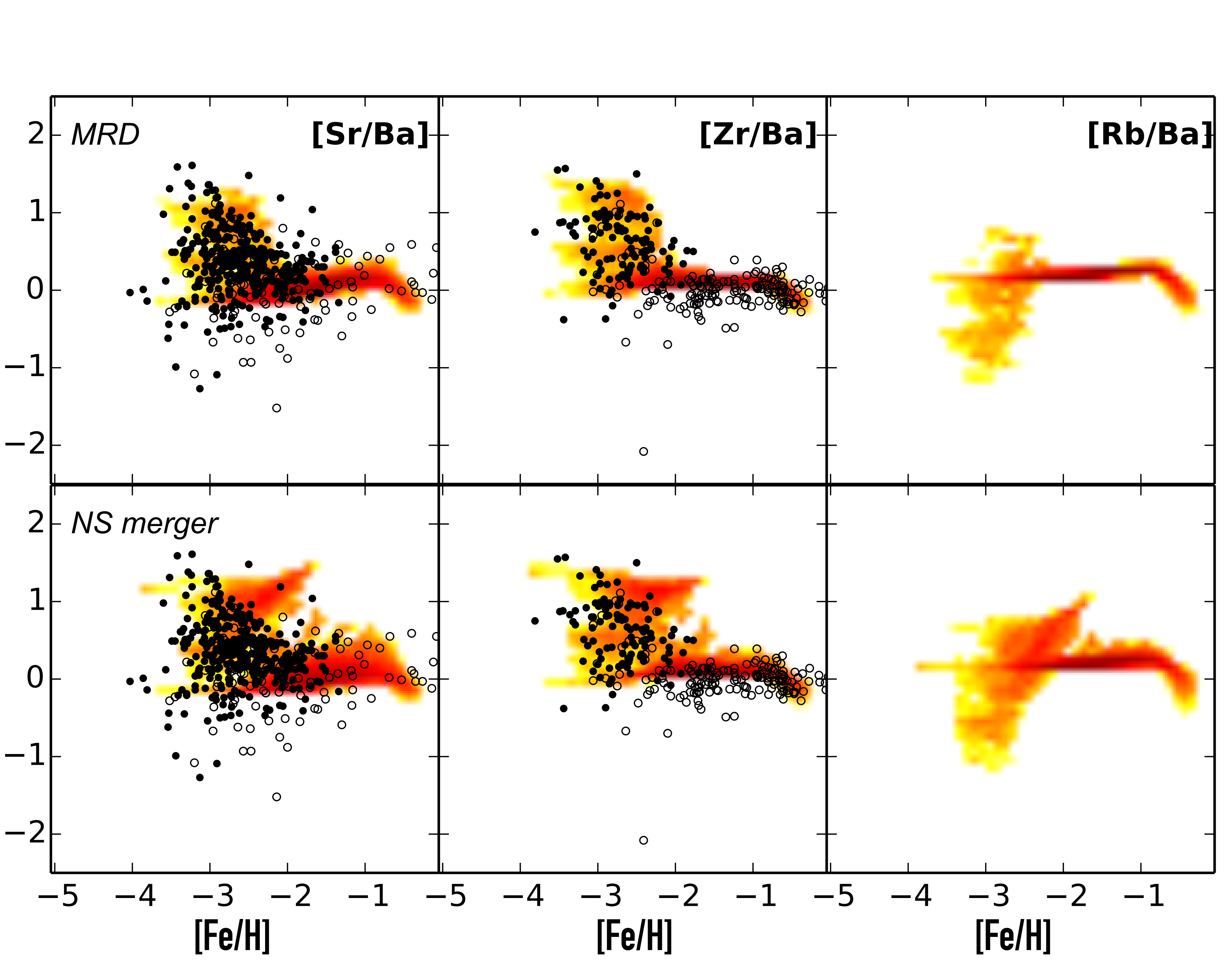
different r-processes + s-process from rotating massive stars

Cescutti+15

Different scenarios for r-process do not alter the results concerning rotating massive stars. They are still needed to explain the spread between heavy to light neutron capture elements.

A unbiased distribution of observed stars would be a key to disentangle between the different scenarios

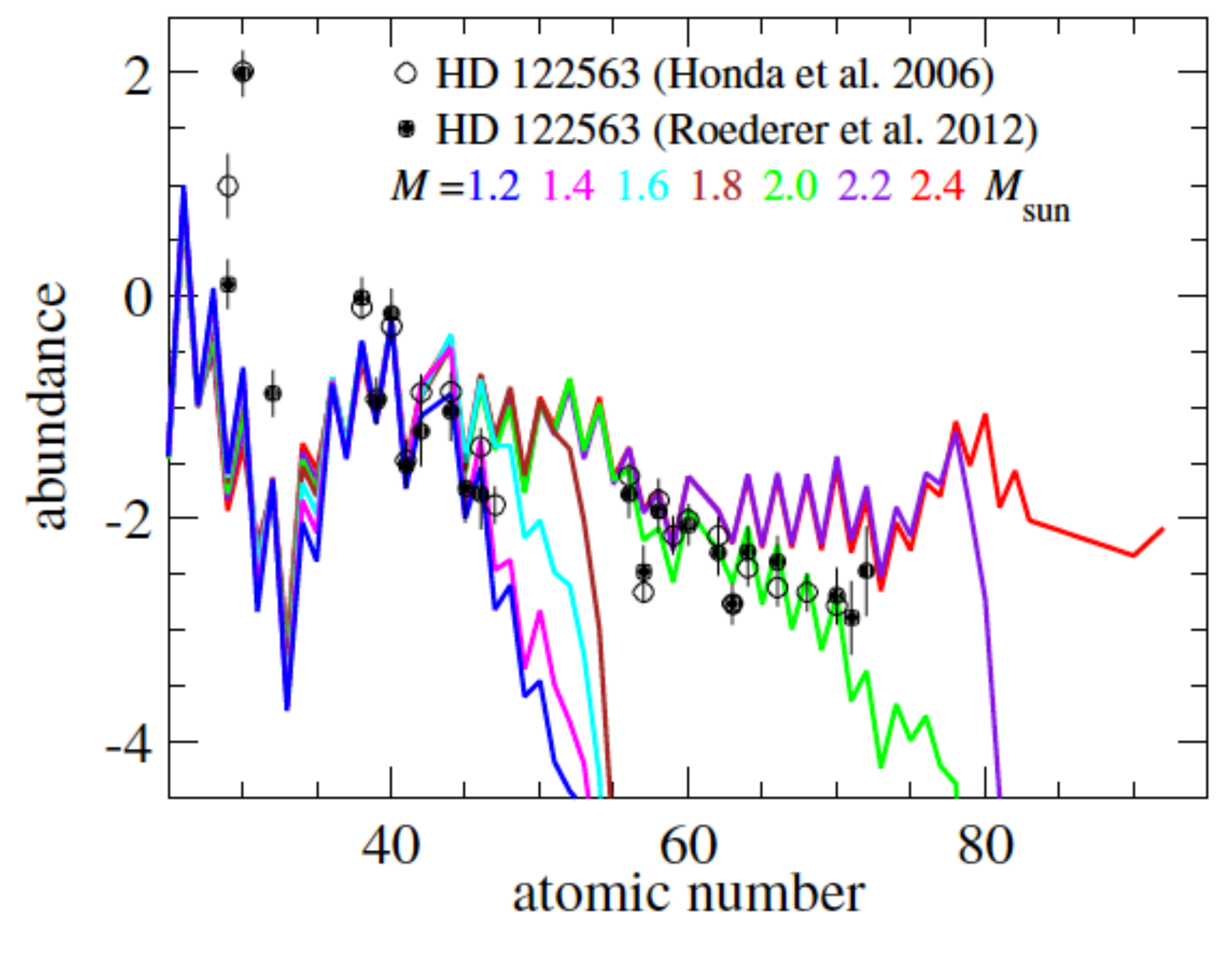
We present here also predictions for the distribution of Rb (few data available only for GCs)



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

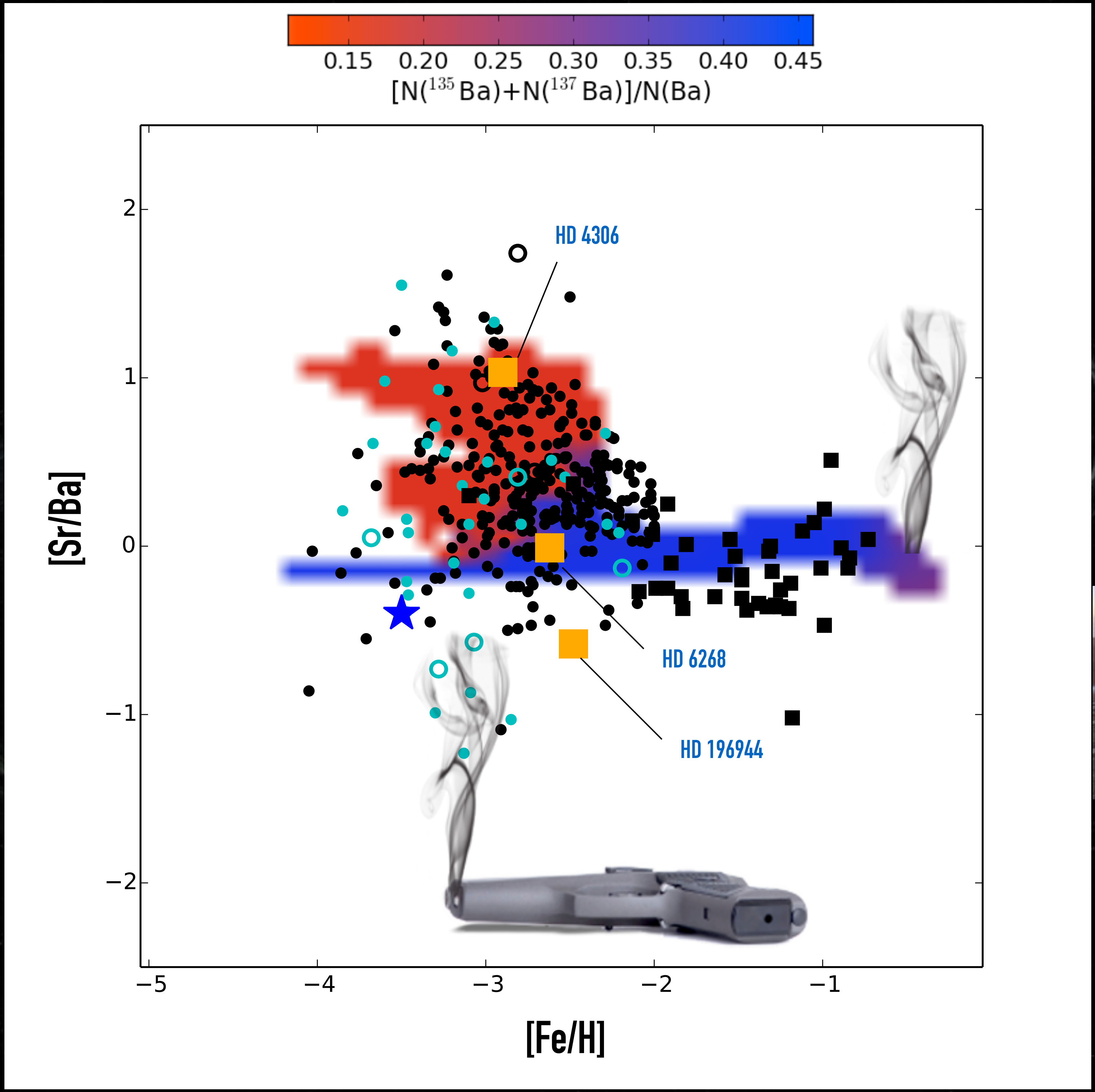
Isotopic ratio for Ba

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)

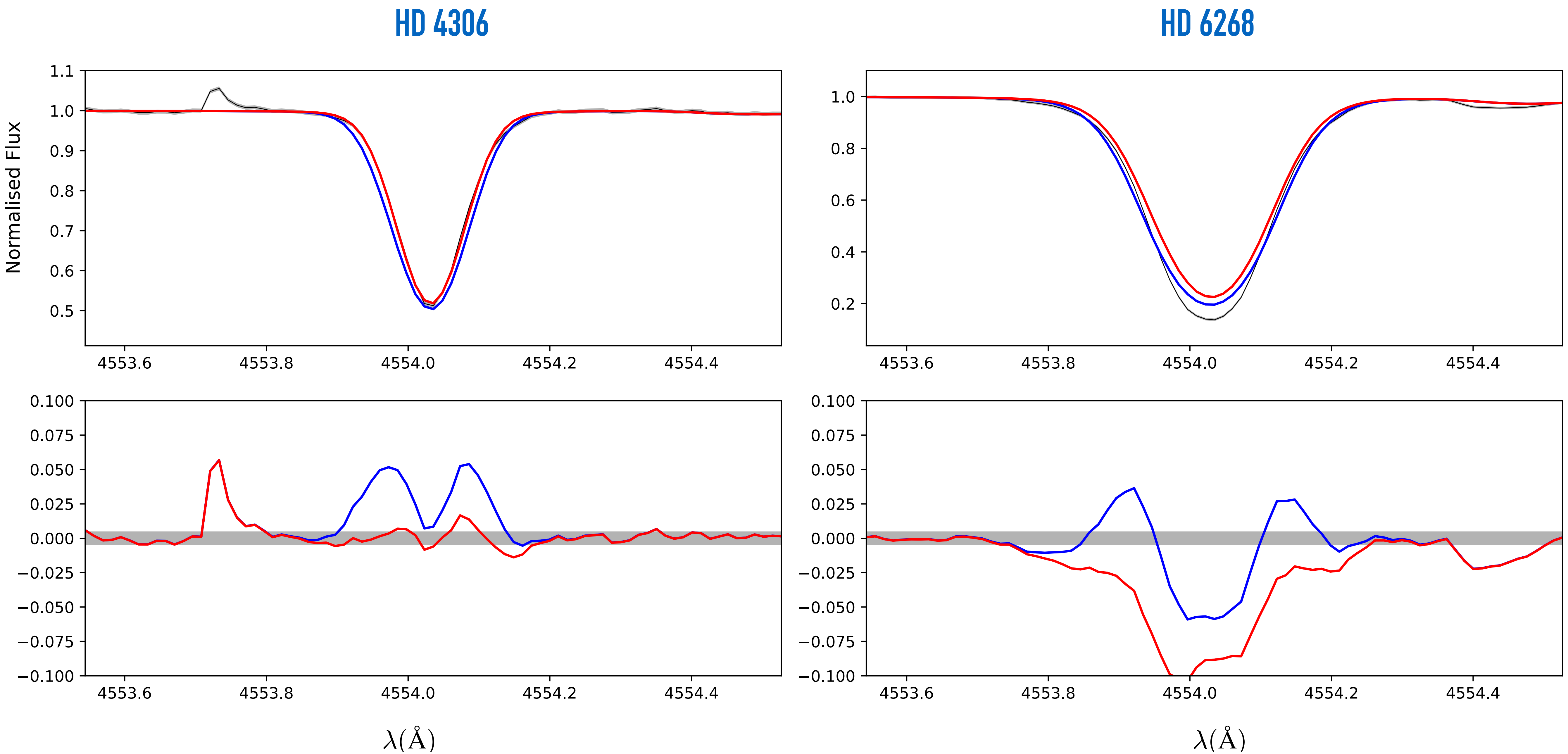


PI Cescutti
proposal at ESO to measure the Ba isotopic ratio in three stars with a R~100'000 & S/N~900
with UVES at VLT

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

Cescutti and Chiappini (2014)

Preview of spectral analysis results ratio for Ba



Cescutti, Morossi + in prep.

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 a large fraction explode within a very short time scale, (or if their frequency was higher at extremely low metallicity see Benoit talk!).
  Other possible solution are MRD SNe.

- 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.