UNIVERSITÀ DEGLI STUDI DI TRIESTE

Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

INFN TRIESTE

Galactic Archaeology with neutron capture elements

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in collaboration with

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PRIN Cosmic pot

Ministero dell'Università e della Ricerca

EMMI Workshop and International Workshop LI on Nucleosynthesis of Heavy Elements: r-process

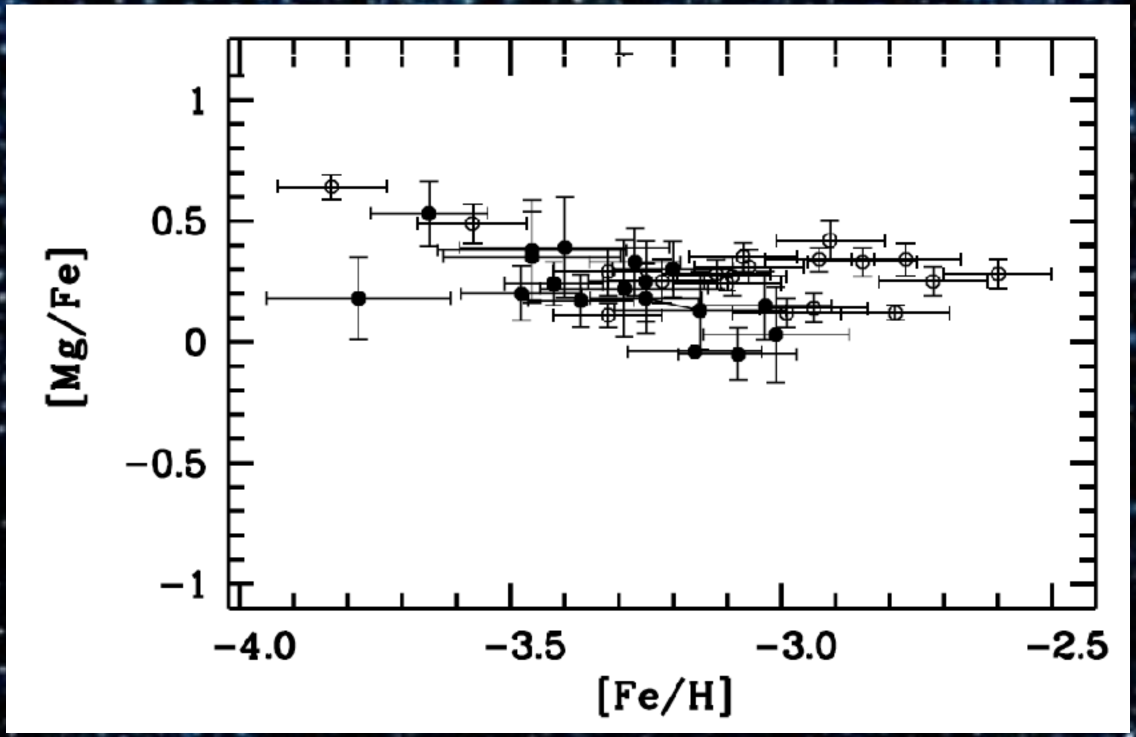
Hirschegg, 20 January 2025

ChETEC INFRA

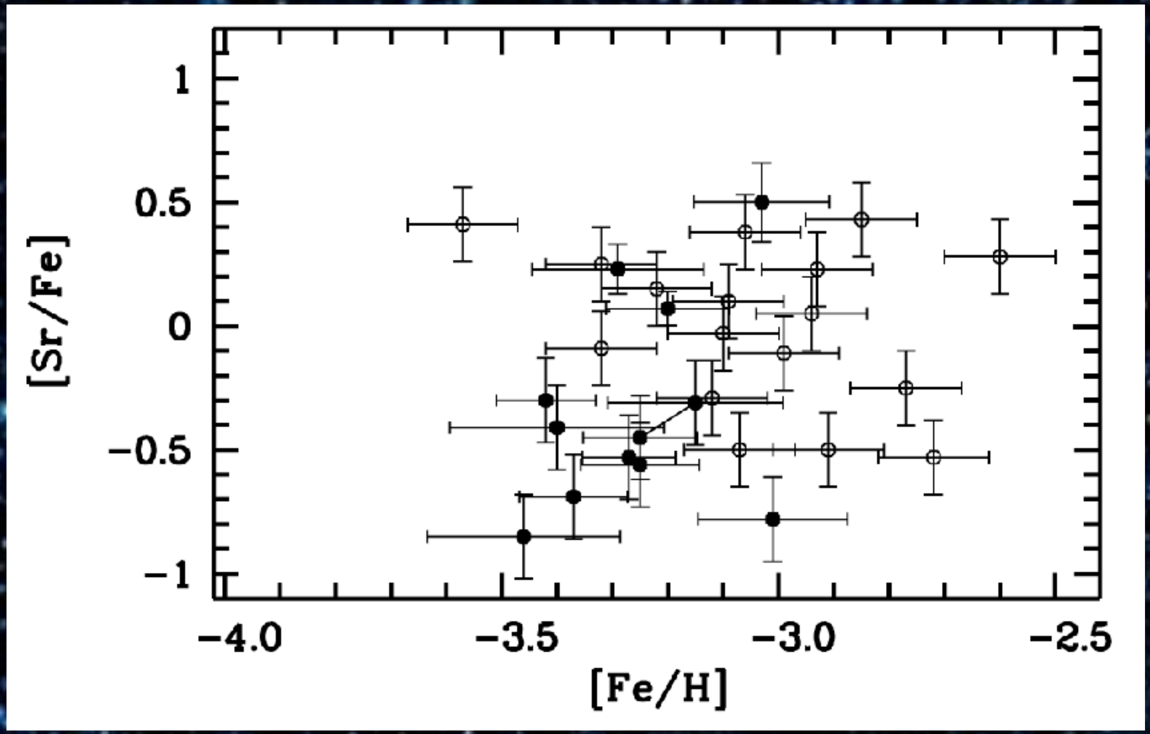

Why neutron capture elements?
Hirschegg, 20 January 2025

Why neutron capture elements?

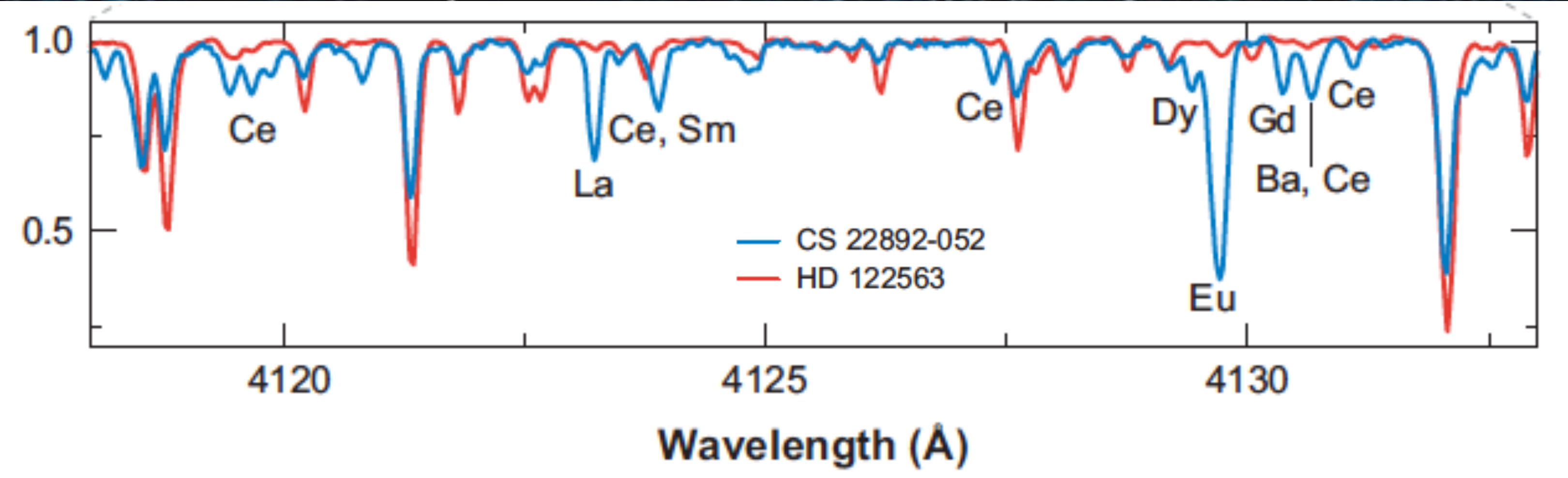
Mg: alpha-element



Sr: neutron capture element

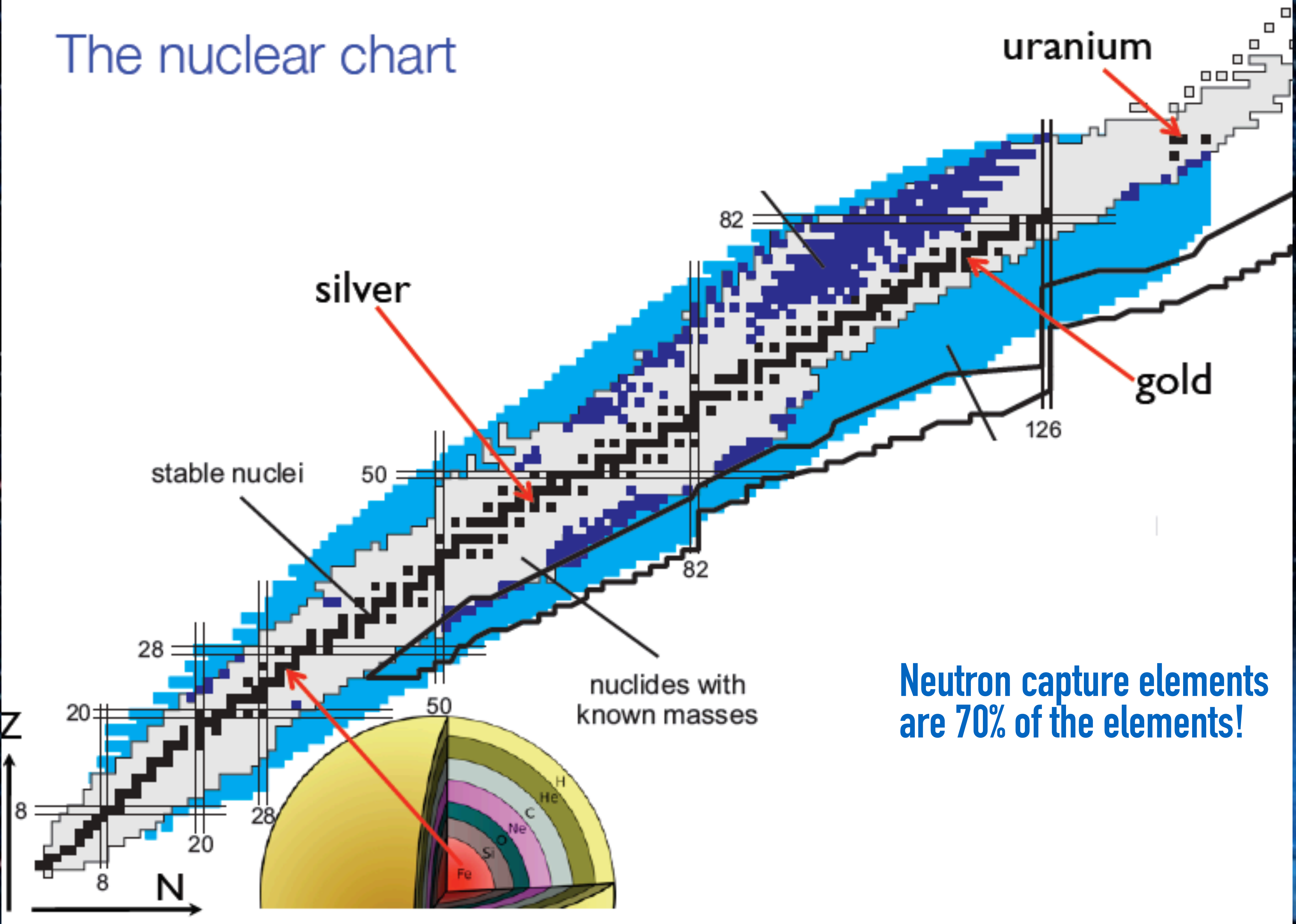


Bonifacio+12



Sneden+08

The nuclear chart

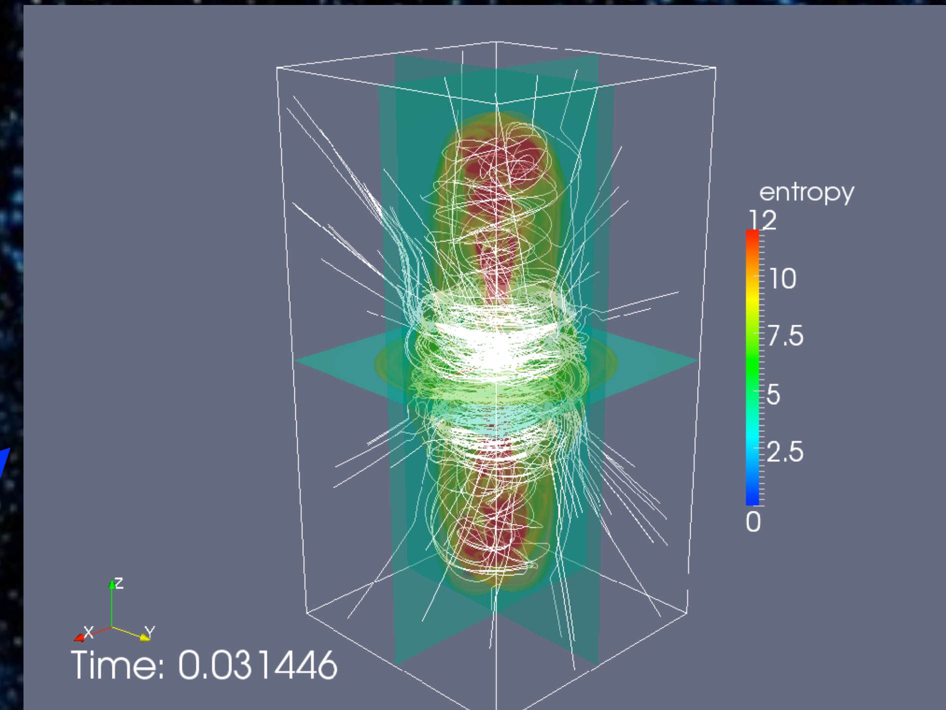


Neutron capture elements are 70% of the elements!

Electron Capture SNe (Wanajo+11)

Cescutti+13

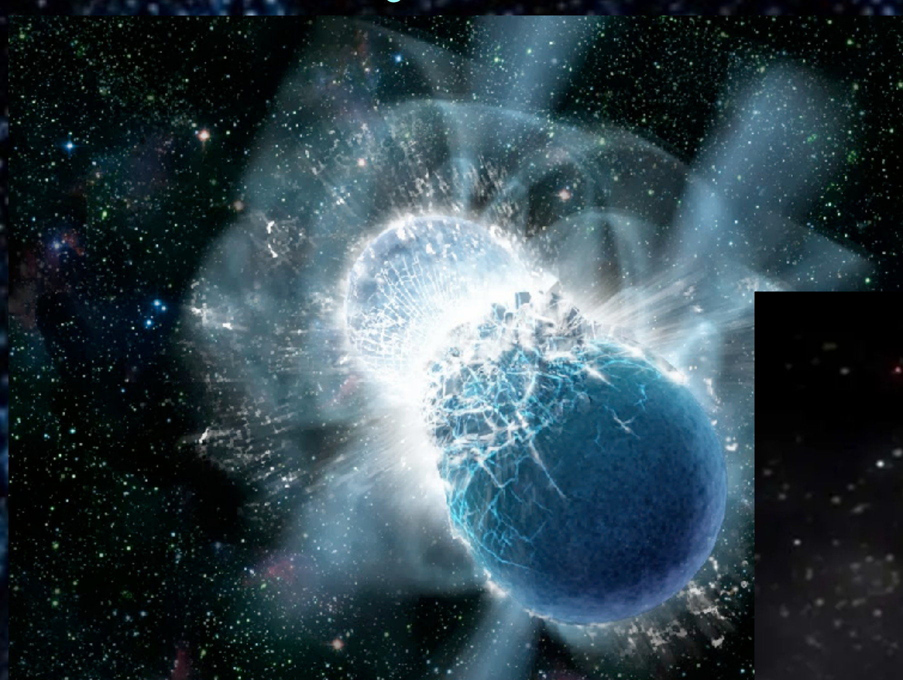
Magnetorotat. driven SNe (Winteler+12)



Cescutti+14

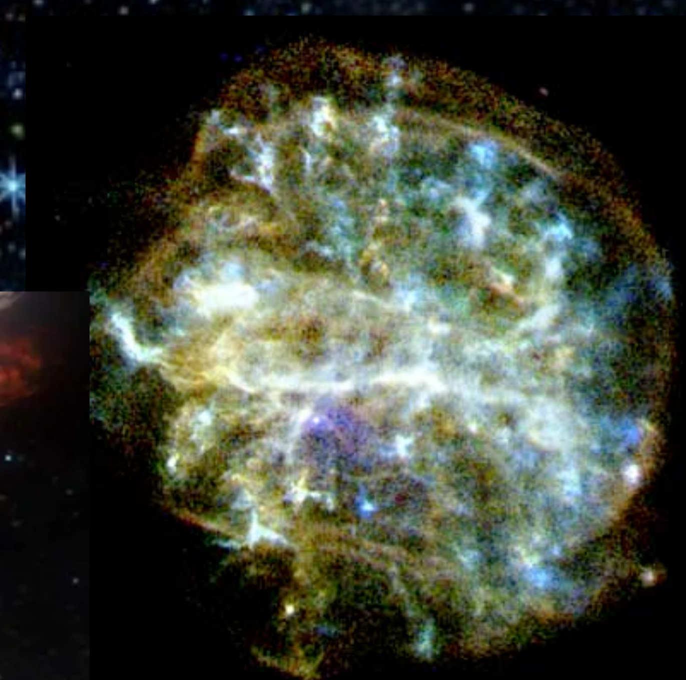
Site(s) of the r-process?

Neutron star mergers (Rosswog+13)



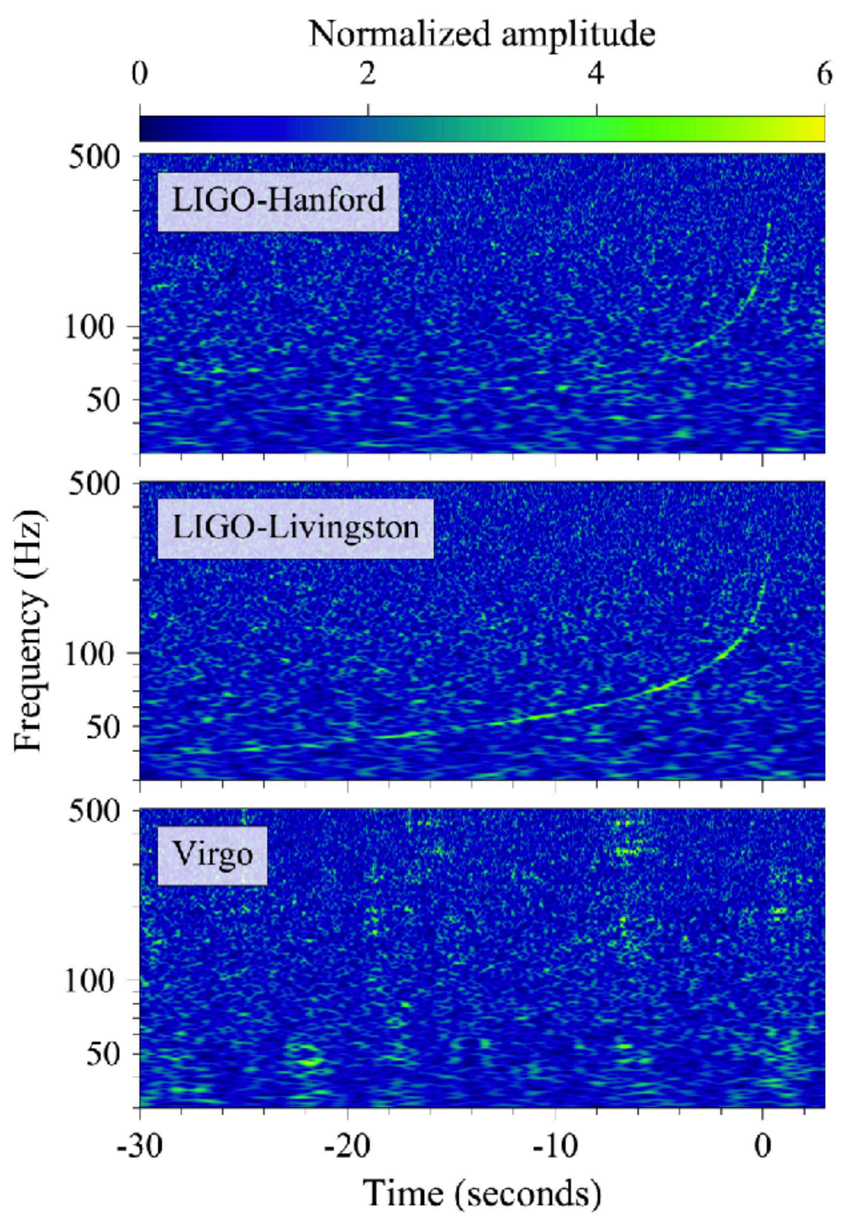
(Cescutti+15, Matteucci+14,. . .)

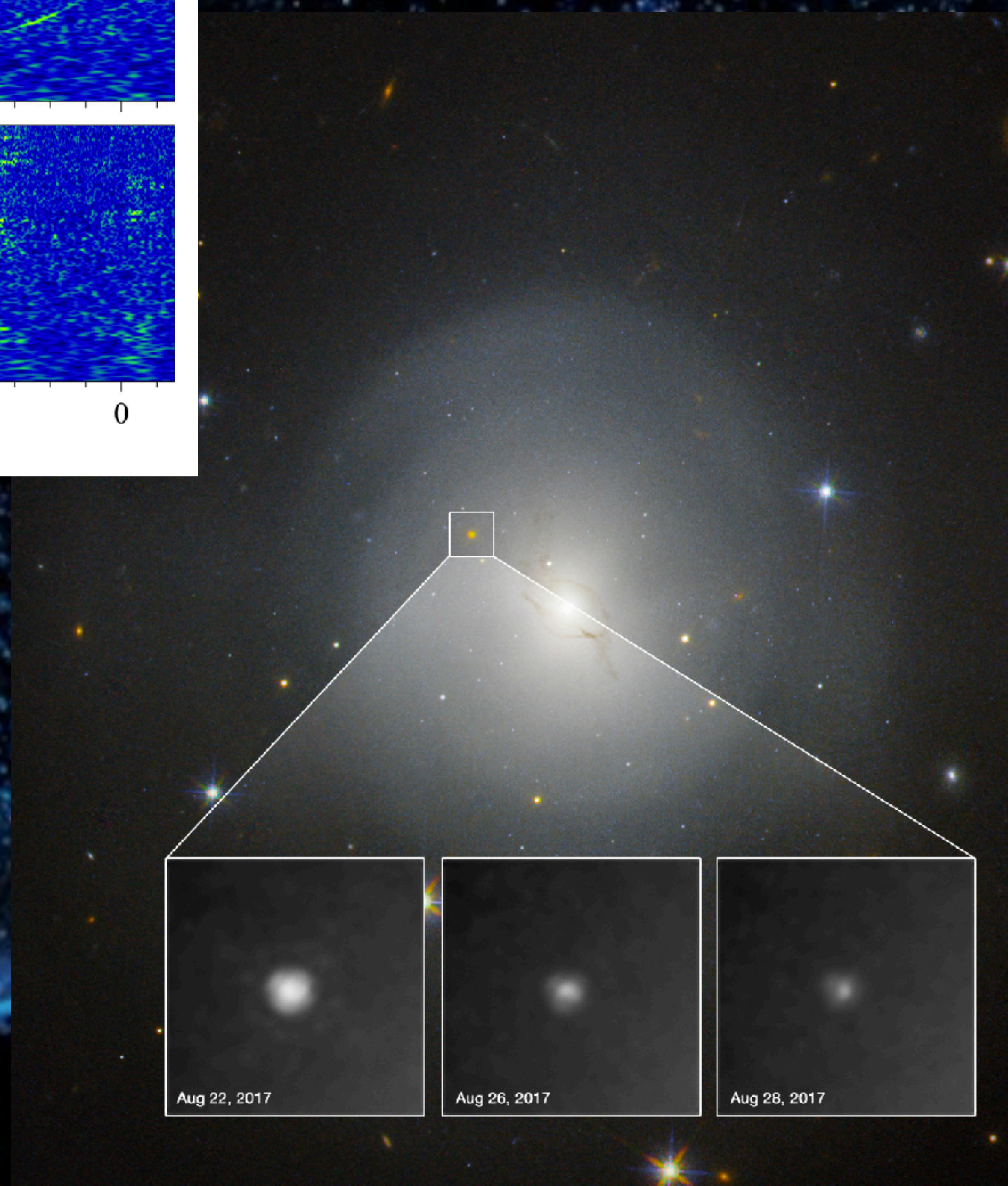
Neutrino winds SNe (Arcones+07,Wanajo 13)

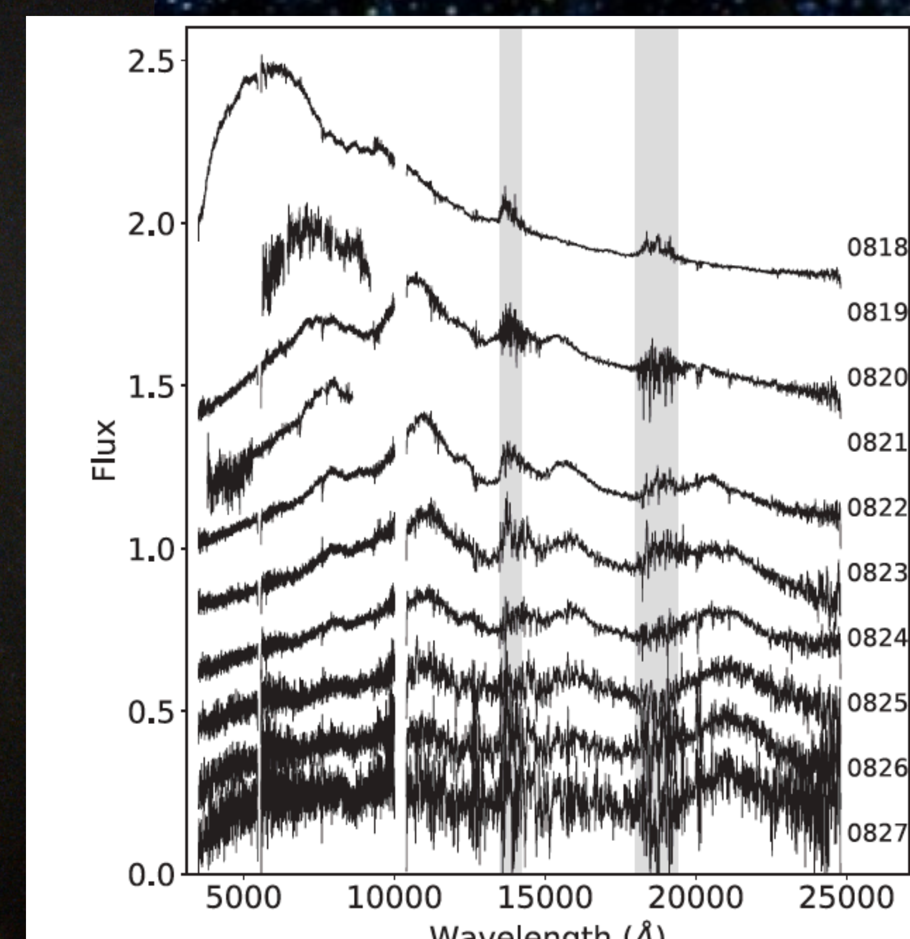


Collapsar (Siegel+2019)

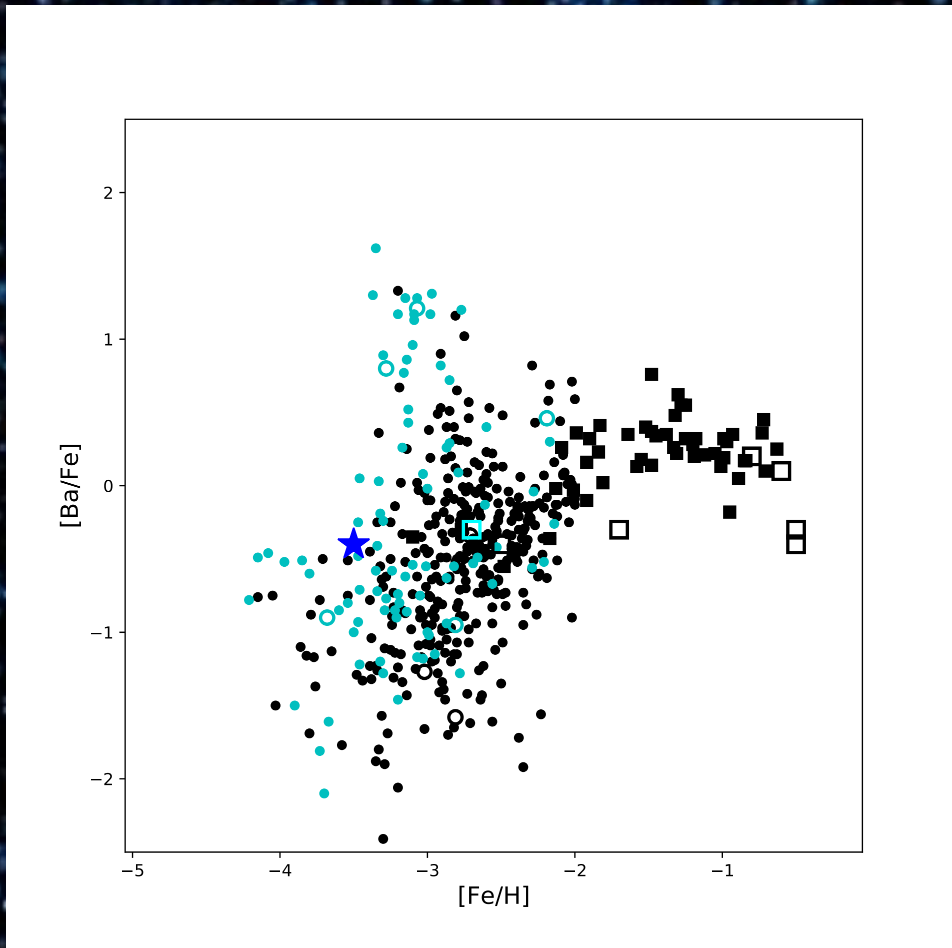
After GW170817…

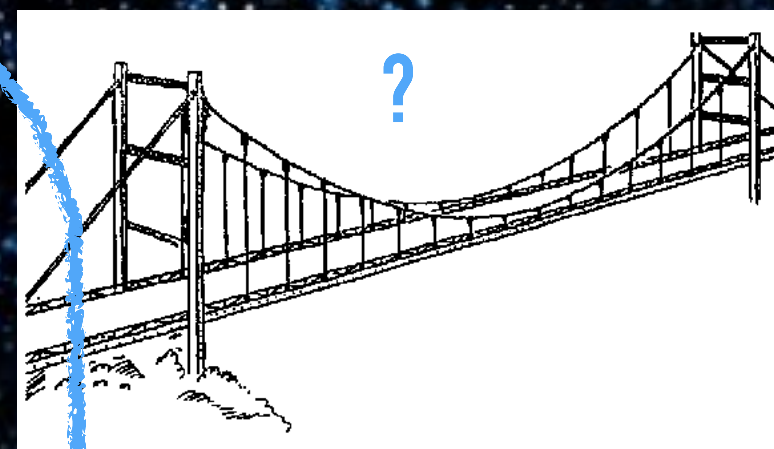




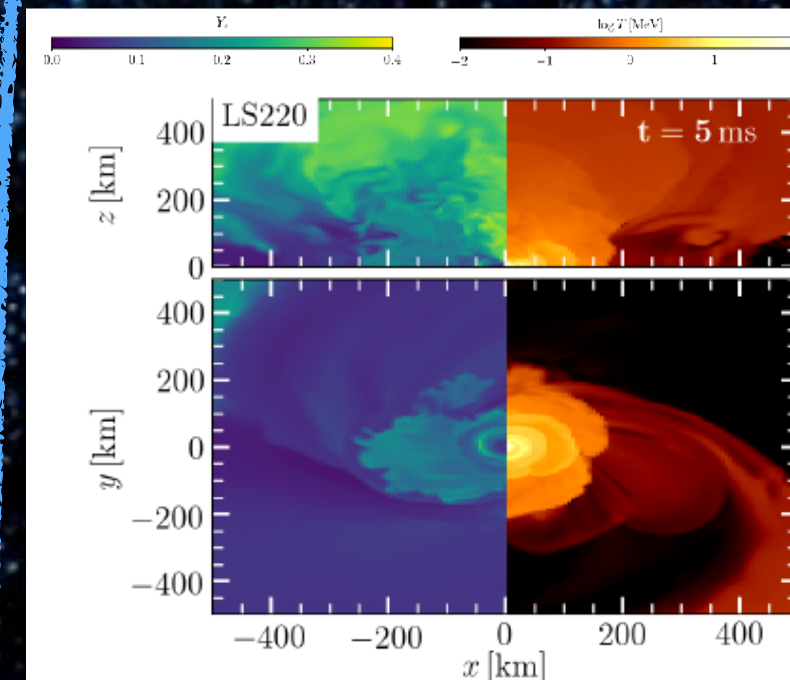


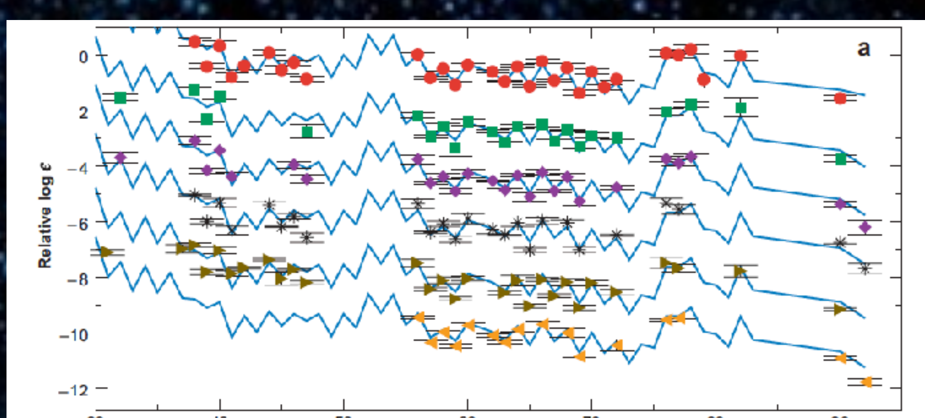
How to?



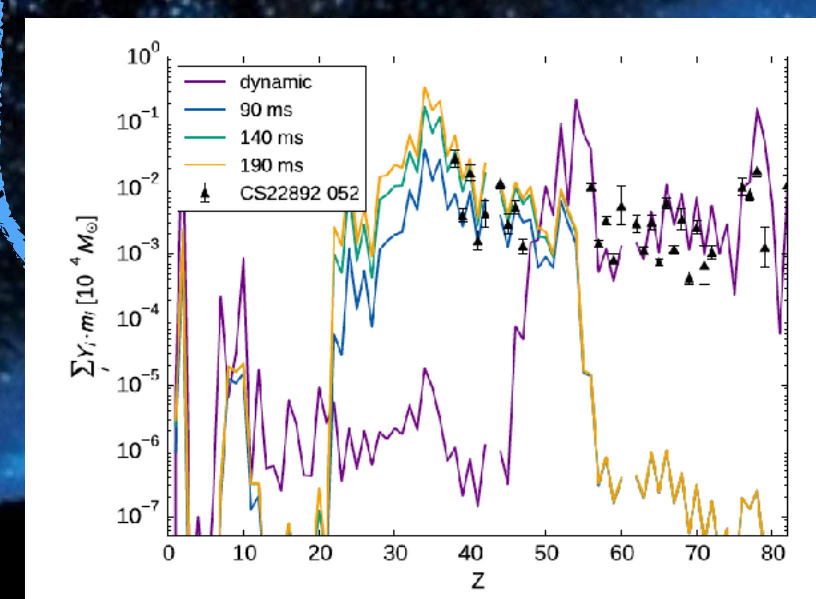


Neutron star mergers

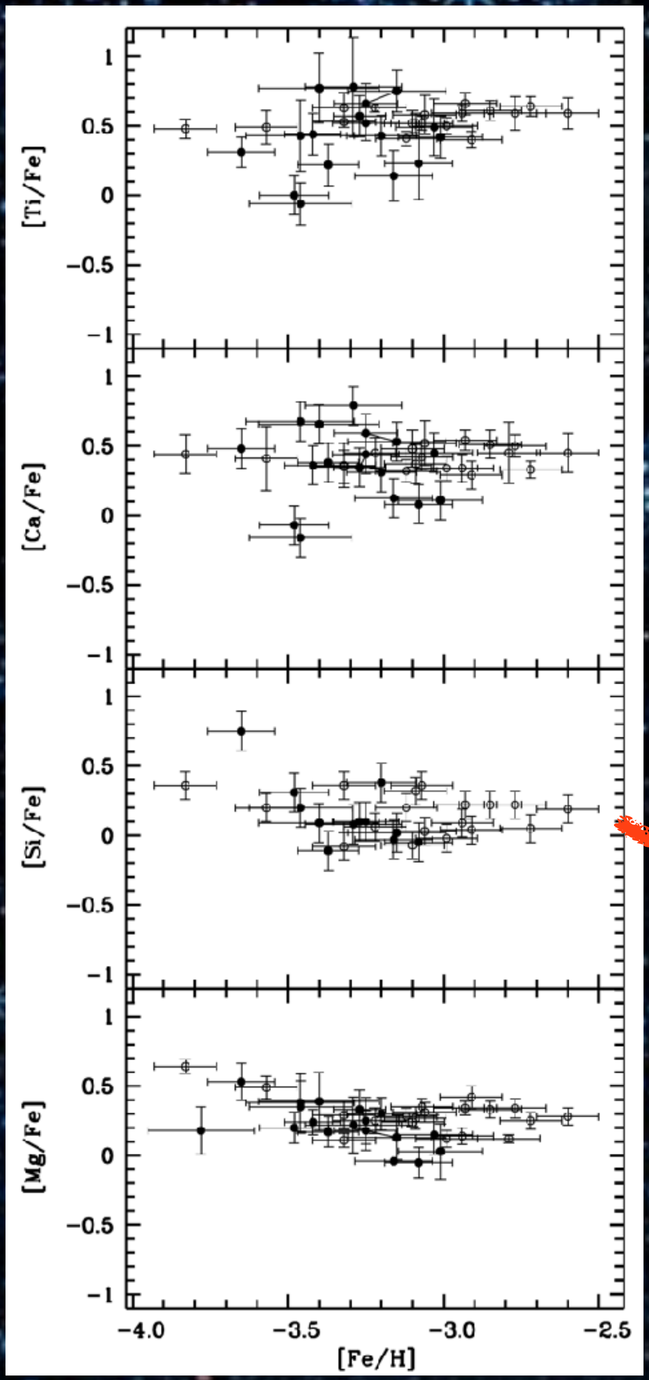




r-process

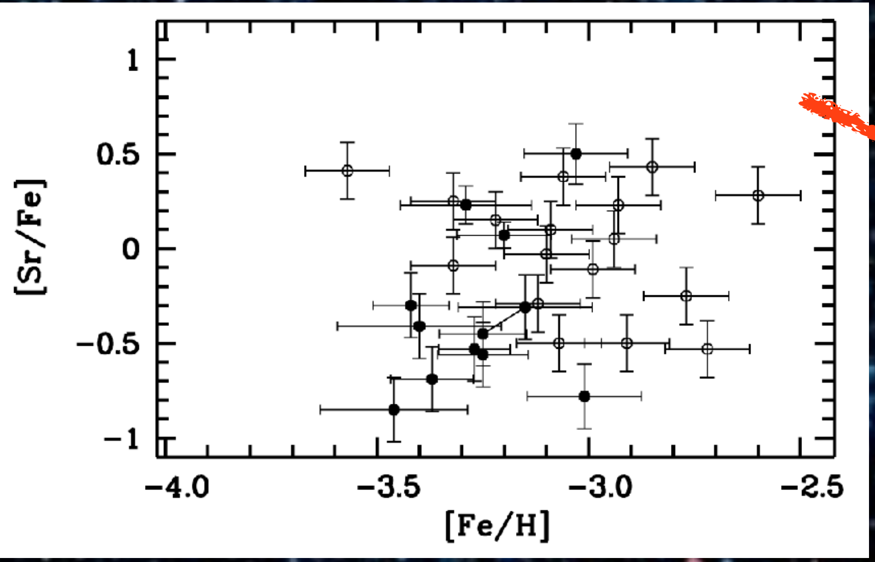


Stochastic chemical evolution models

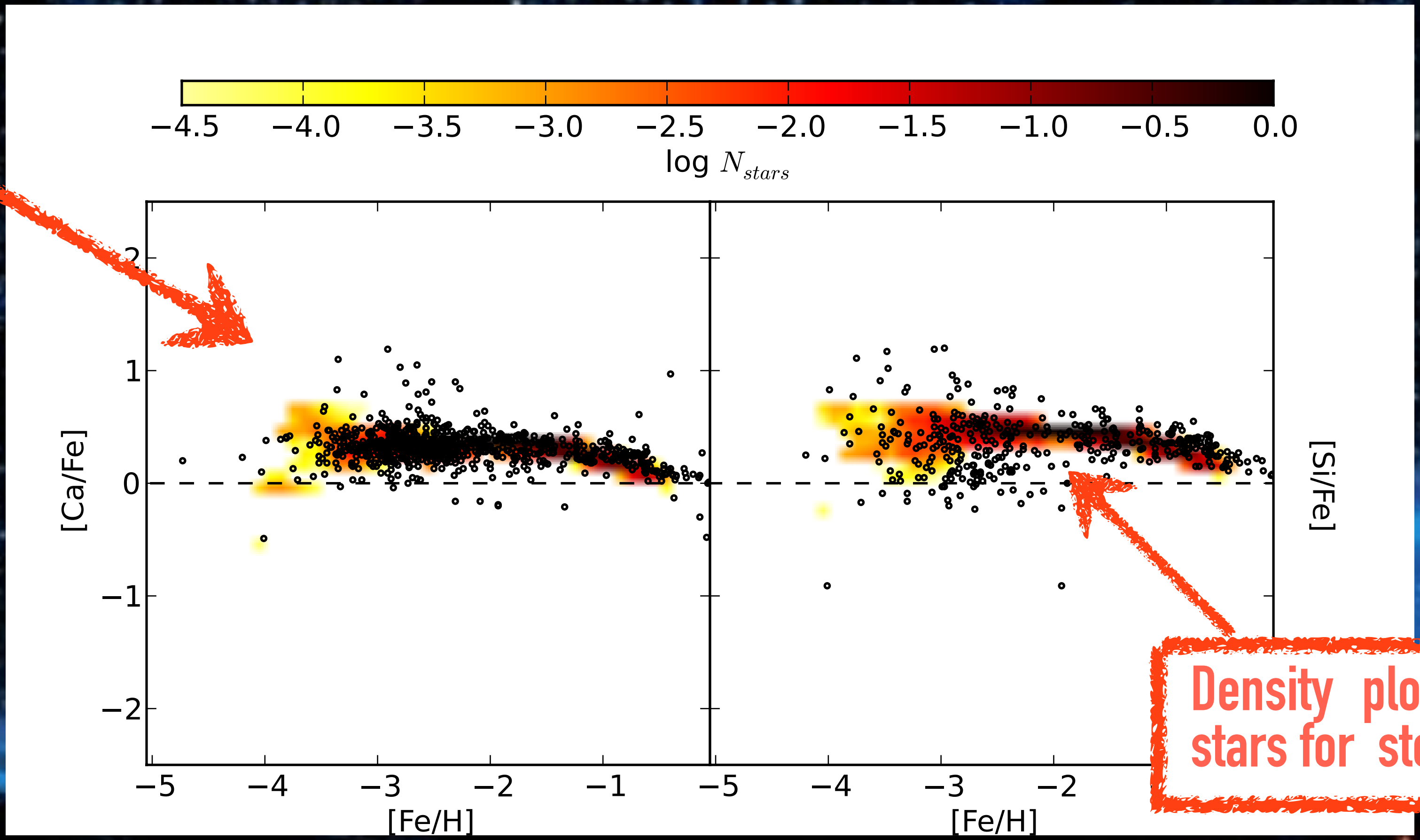


Bonifacio+12

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



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.



Cescutti 2008
Cescutti et al. 2013

data collected in Frebel 2010

Neutron stars mergers

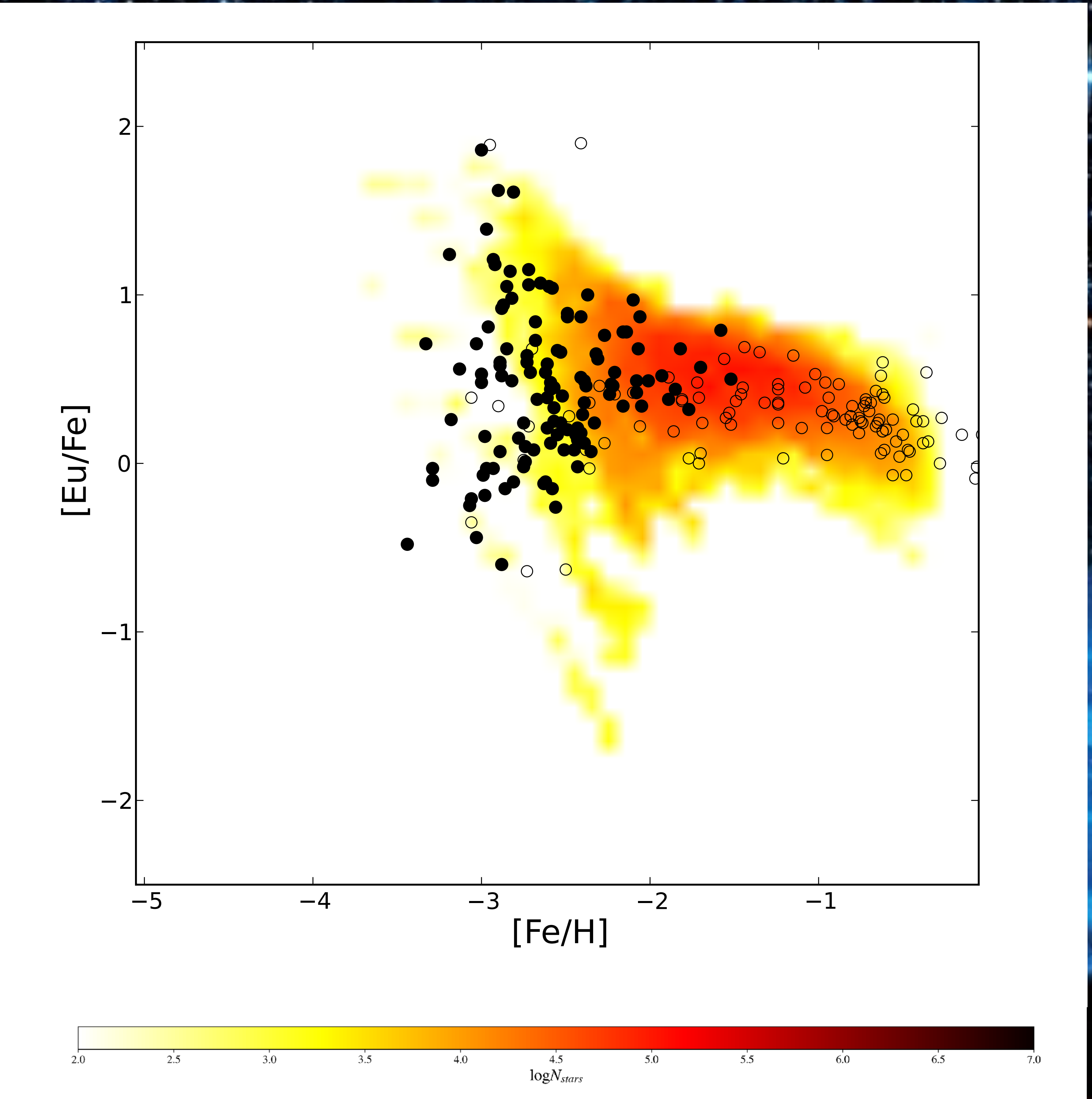
delay for the merging 1Myr

Cescutti, Romano, Matteucci, Chiappini and Hirschi 2015

Progenitors are rare:
only few percent of the massive stars are formed in binary system which can produce a NS merger.
Results with alpha=0.04 (NSM/SNe)

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

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



Neutron star mergers

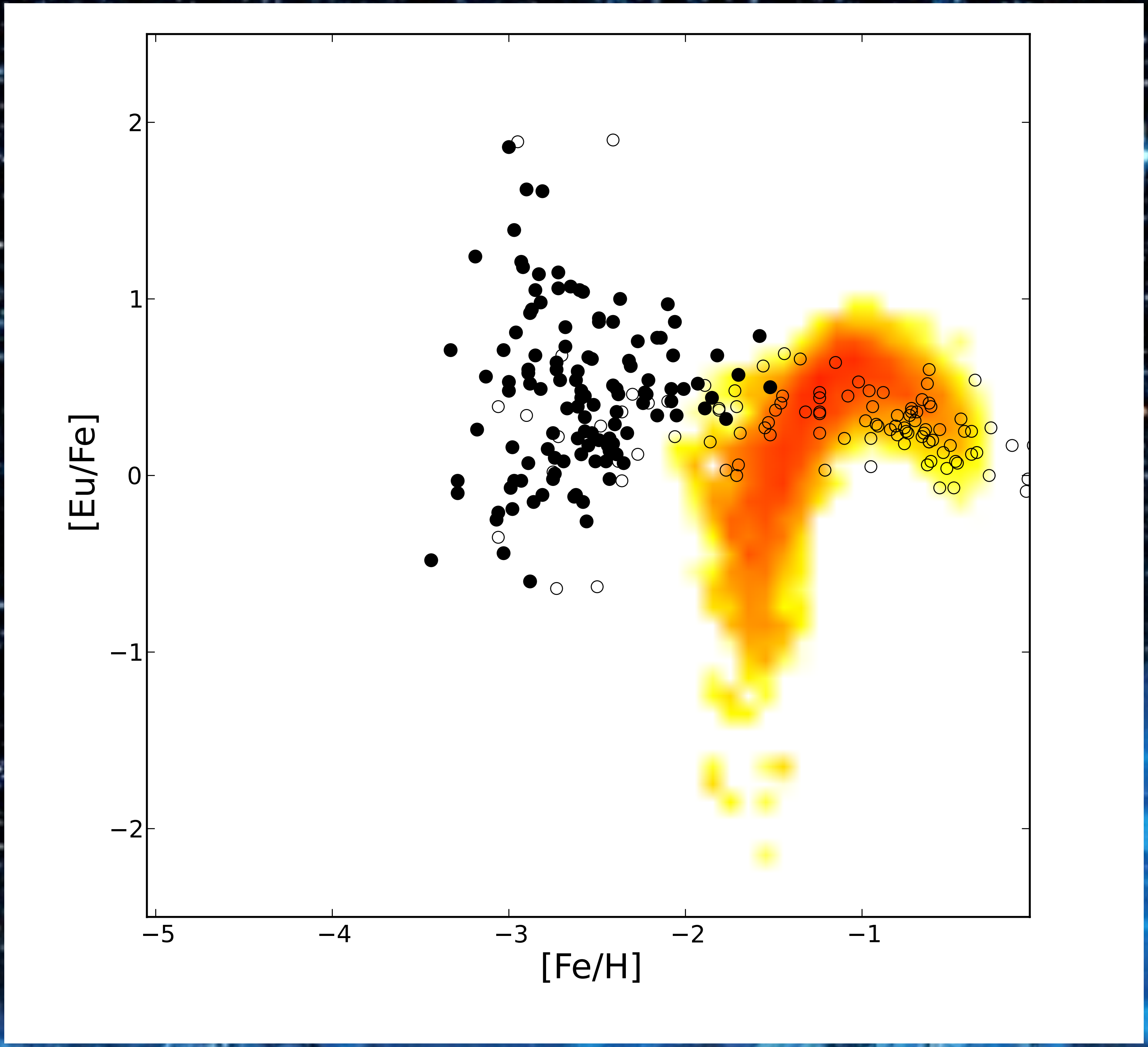
Cescutti+15

delay for the merging 100 Myr

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

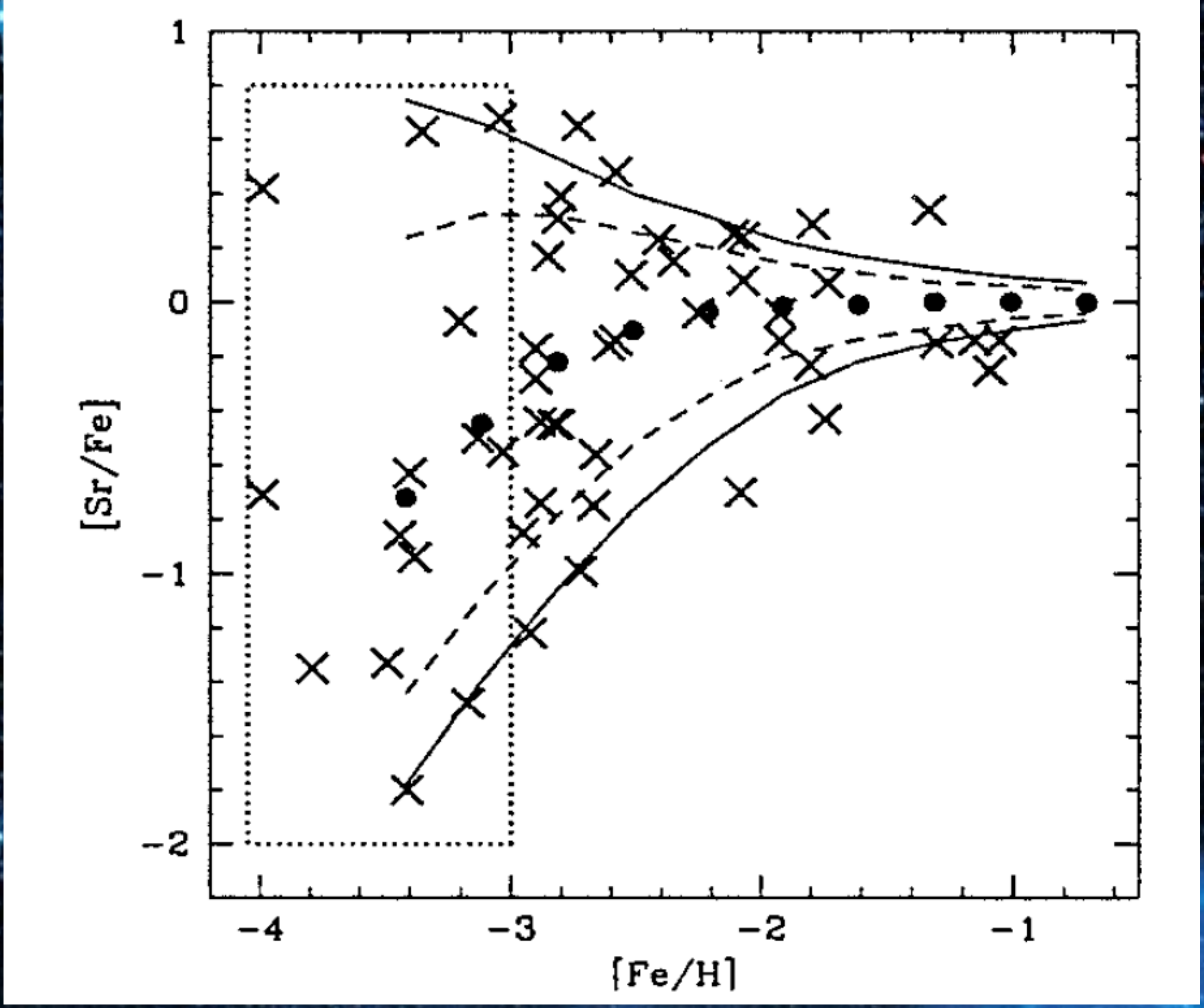
Therefore, only if most of the NS mergers enriches in timescale <10Myr, the scenario can be supported.

What about a distribution of delays?



not a novelty . . .

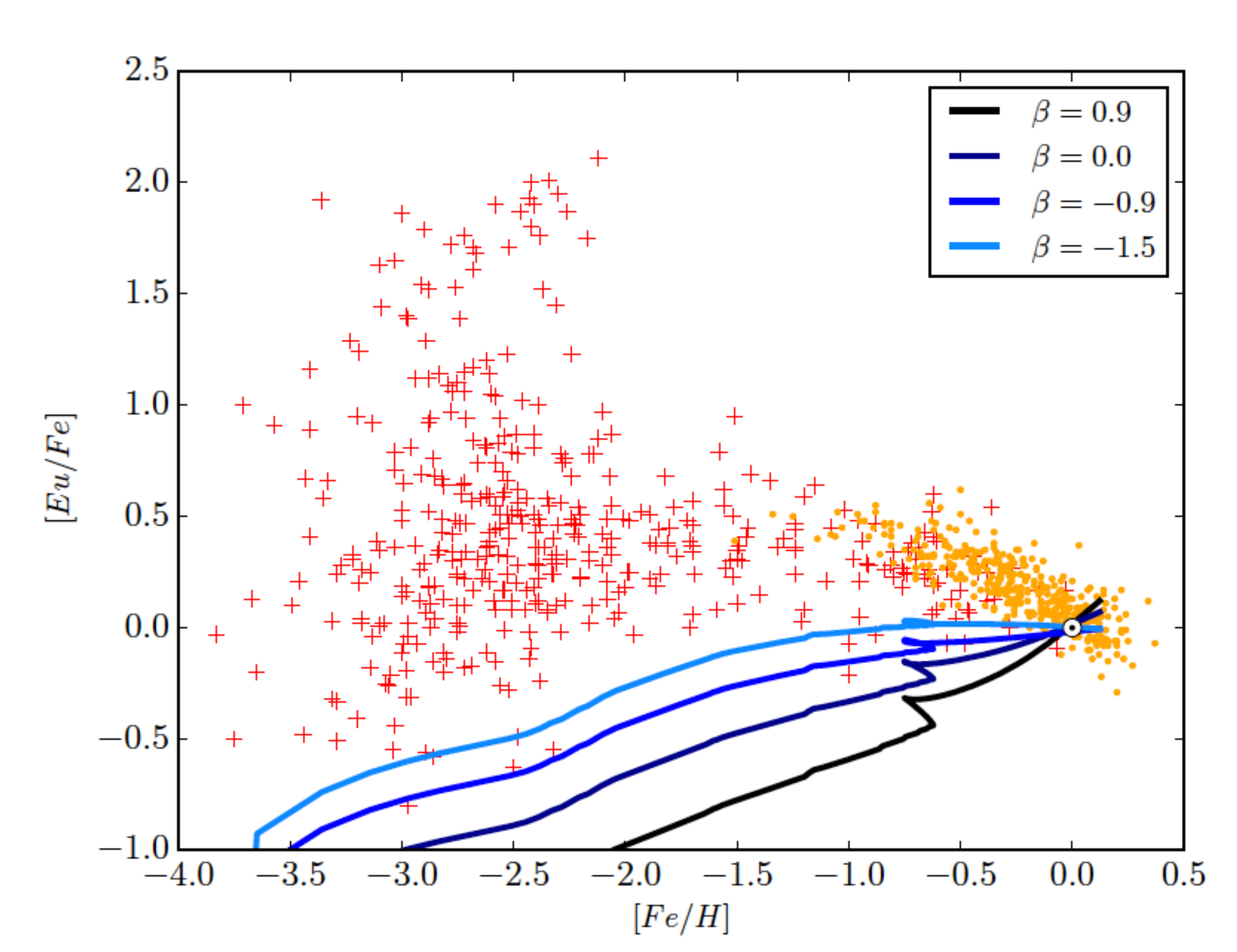
McWilliam&Searle1999



See also Tsujimoto+99,Ishimaru&Wanajo 99,Argast+01,
(see Benjamin results!), Matteucci+2014, Komiya+2014... few exceptions

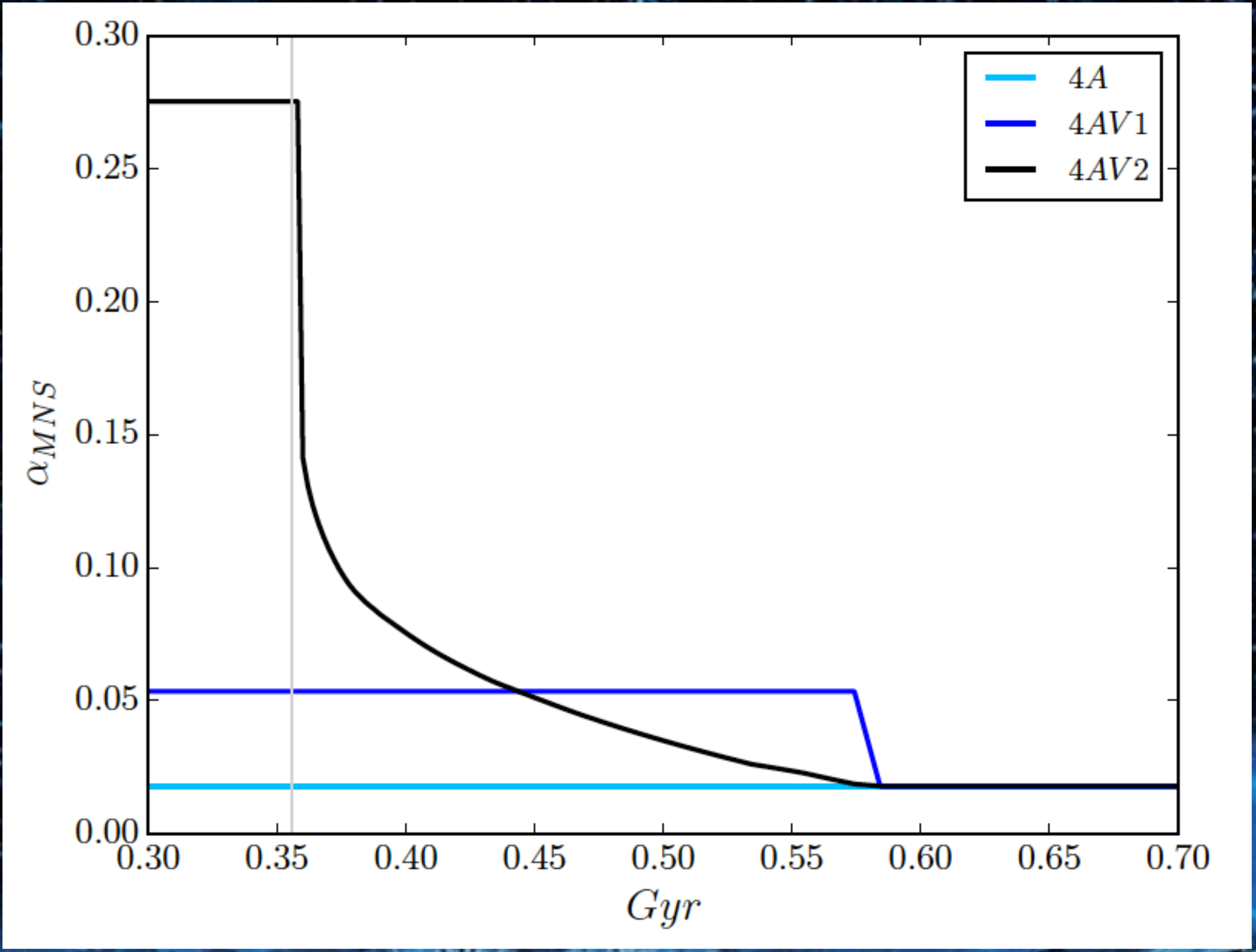
Detailed DTD for NSM

Simonetti+19



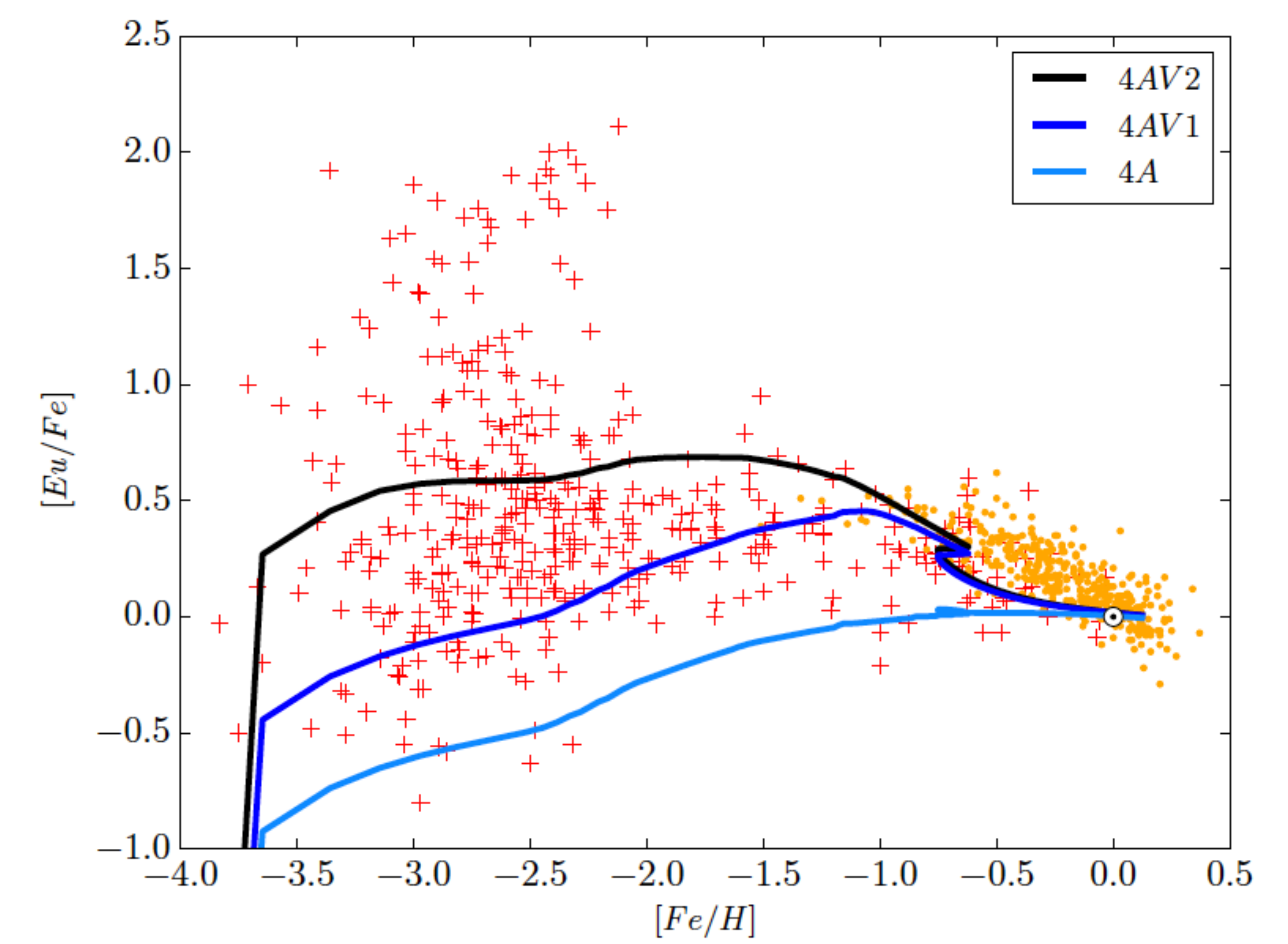
see also Cotè+19

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



Simonetti+19

Models with detailed DTD for NSM



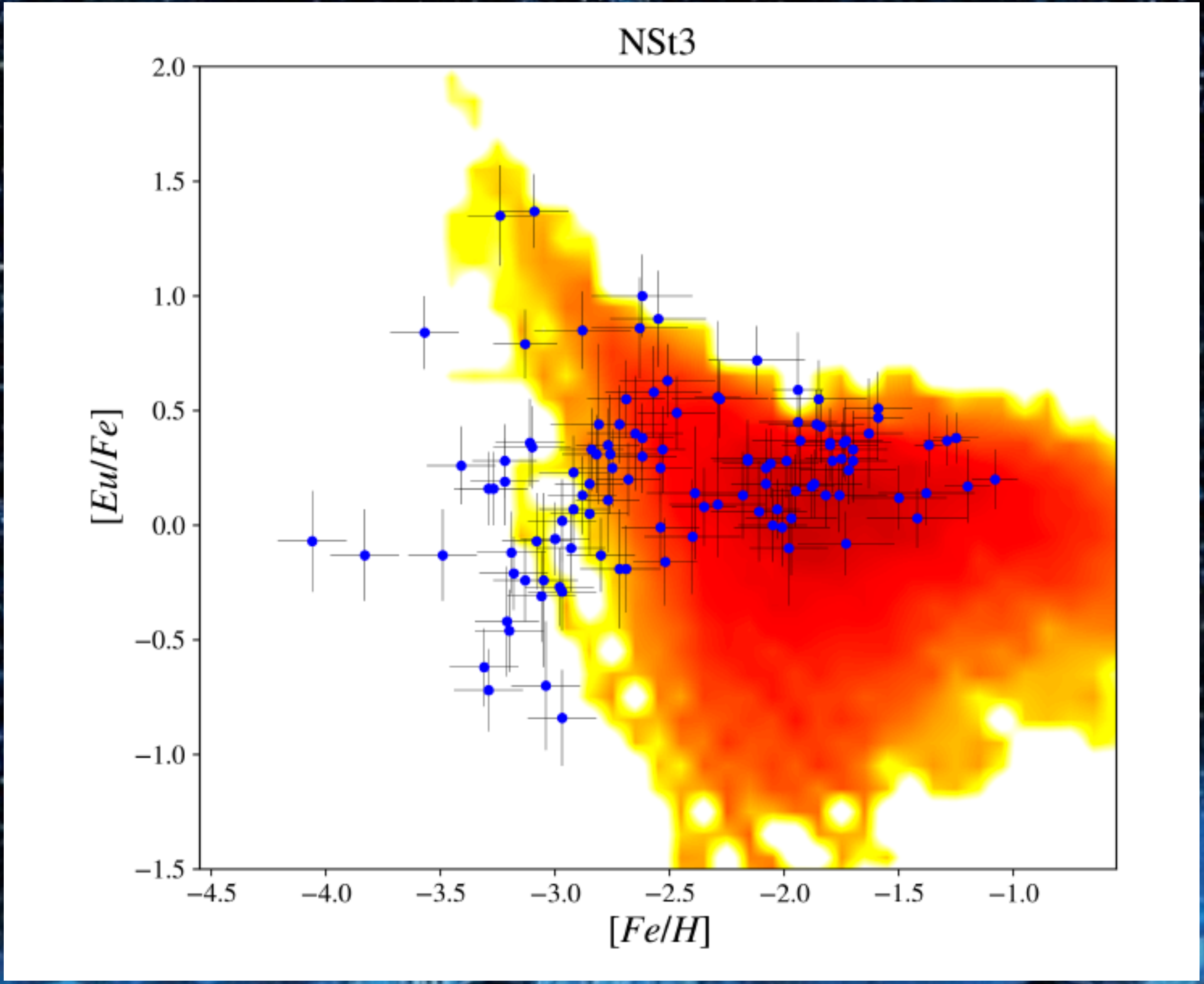
Simonetti+19

variation of alpha, possible solution!

see other solution in Schoenrich&Weinberg19

Stochastic model

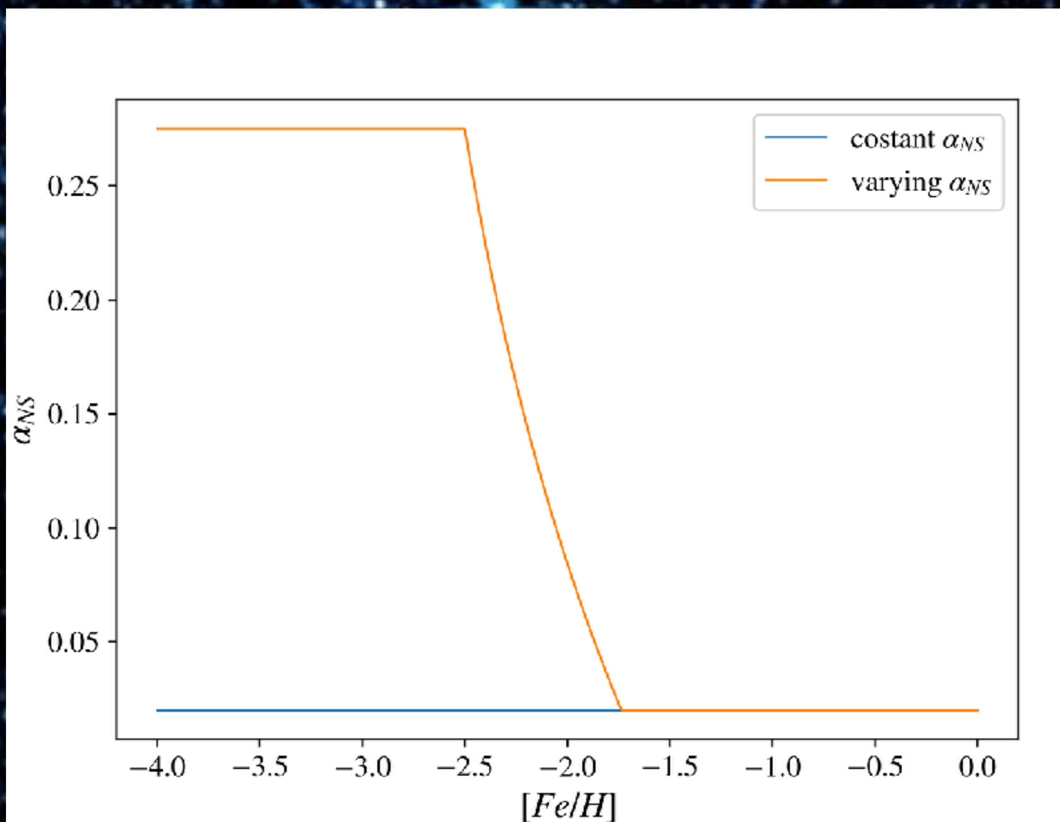
with a delay time distribution: $t^{-1.5}$



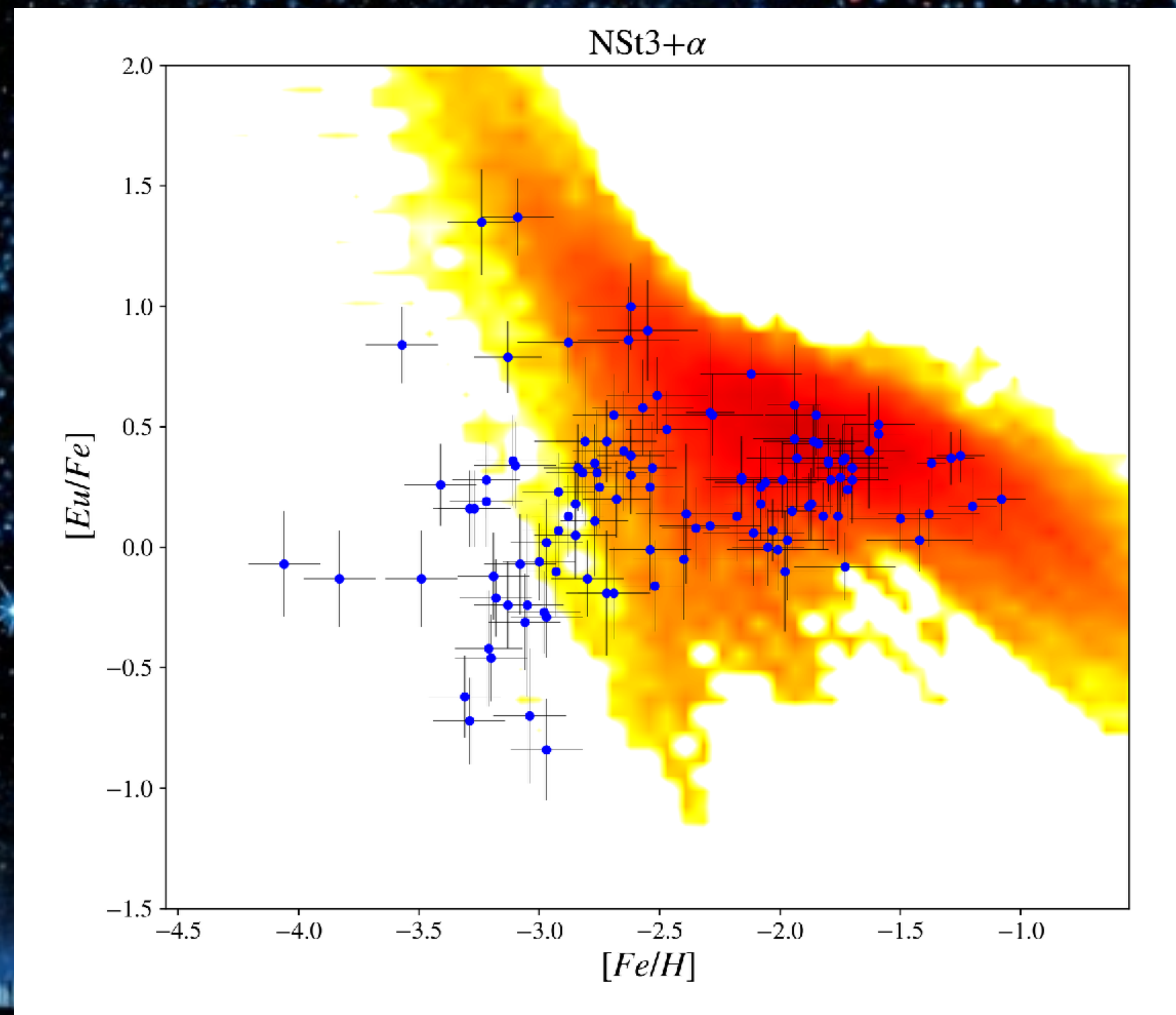
Cavallo+22

NSM with alpha variations

a delay time distribution: $t^{-1.5}$



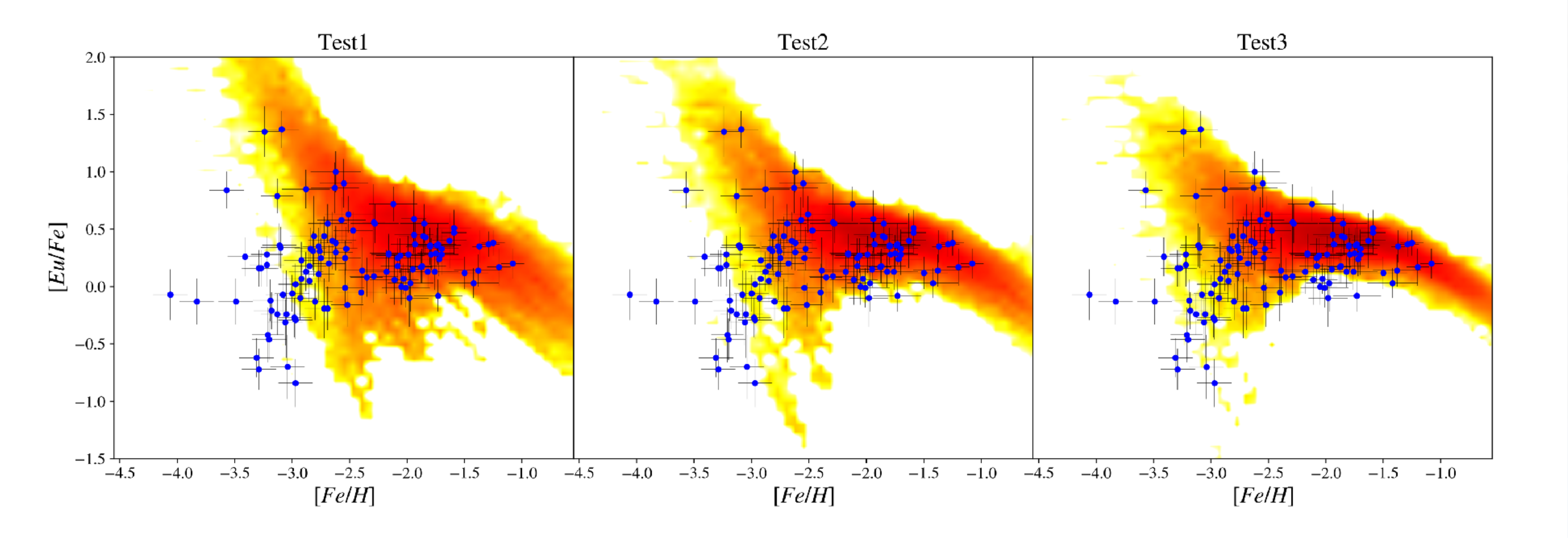
similar to Simonetti+19



Cavallo+21

How to constrain the fraction of NSM?

alpha=0.02 alpha=0.06 alpha=0.1 Cavallo+21

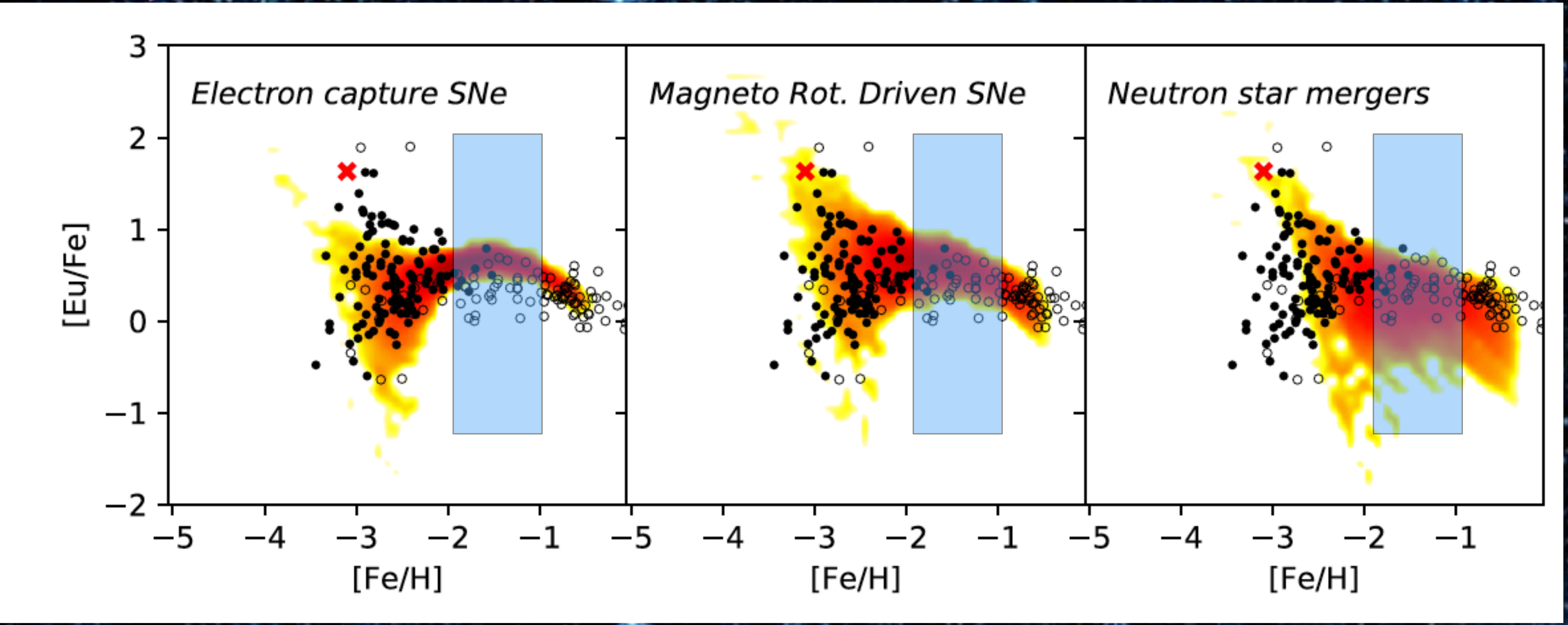


[Fe/H] (dex)	Test1		Test2		Test3	
	mean [Eu/Fe] (dex)	sigma(dex)	mean [Eu/Fe] (dex)	sigma(dex)	mean [Eu/Fe] (dex)	sigma(dex)
-3.00	1.42	0.22	1.05	0.23	0.84	0.22
-1.00	0.15	0.15	0.16	0.10	0.17	0.08

Weave and 4MOST !!

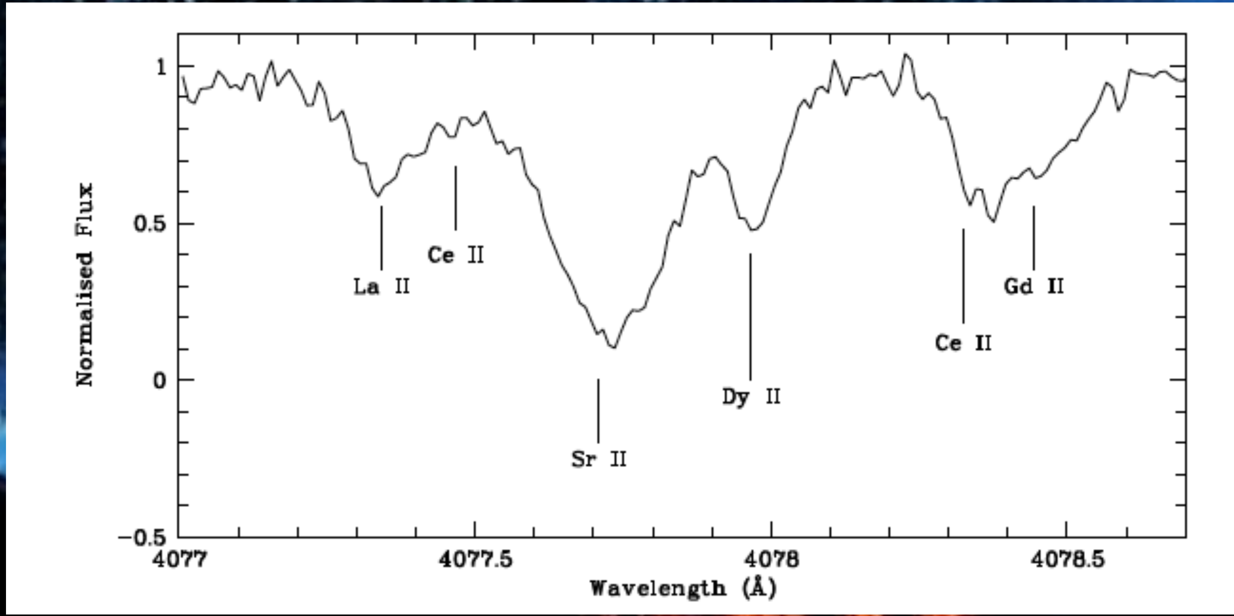
PI of MINCE

Measuring at Intermediate Metallicity Neutron Capture Elements
Main investigators Bonifacio & Cescutti



Observational proposals at TNG,CFHT,3.6m,Magellan,UVES…
Goal is 1000 stars in 5y at high quality:
100S/N at 400nm and R>50'000.

~500 stars at present



9 Facilities used

2 from ChETEC-INFRA

MINCE I (2022) & MINCE II (2024)

MINCE III submitted

TNG 3.58m
Spectrograph HARPS-N

NOT 2.2m
Spectrograph:FIES

Moletai 1.65m
Spectrograph: VUES

VLT 8.2m
Spectrograph: UVES

~450 stellar spectra with high S/N and Resolution

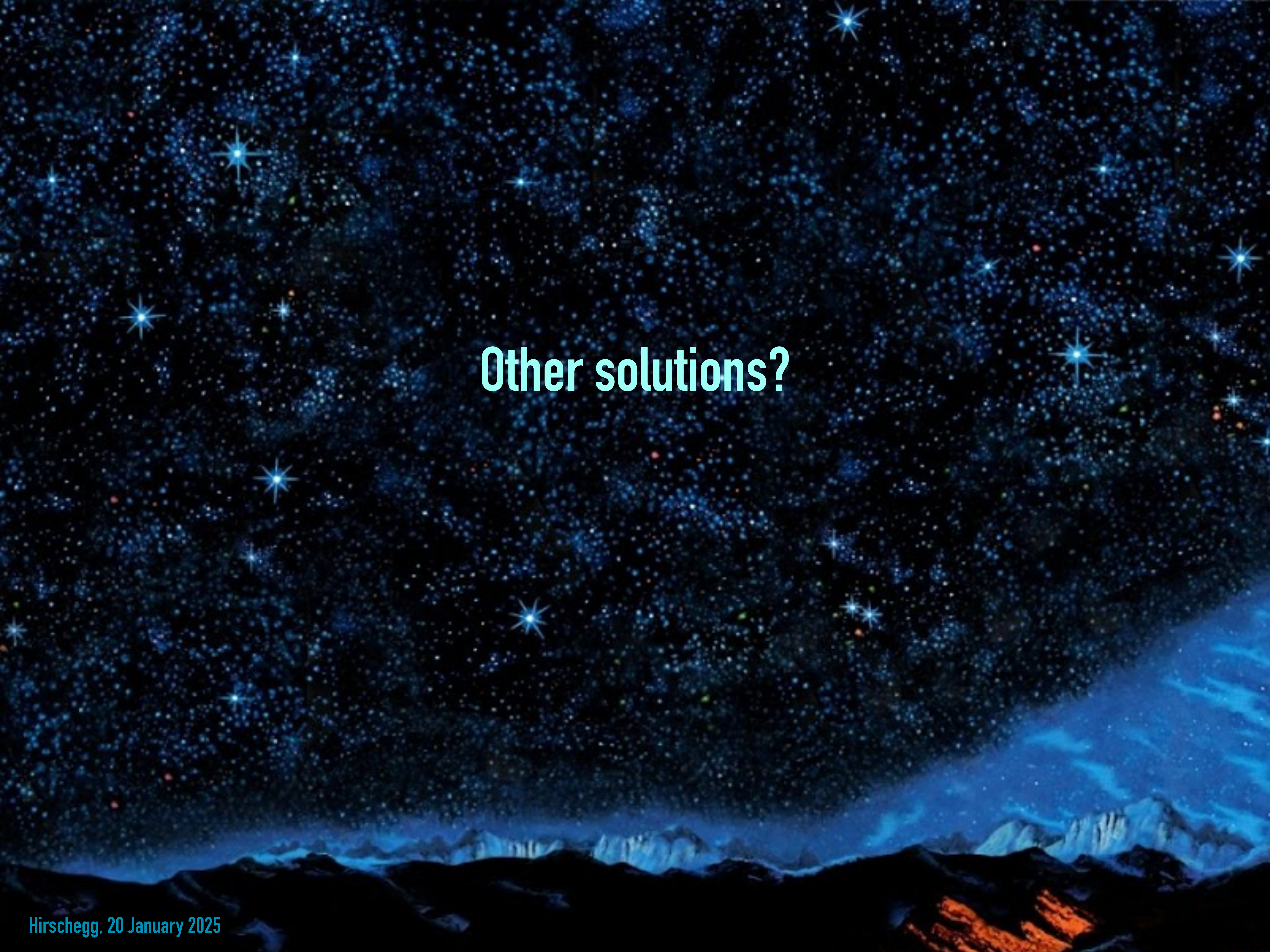
20% from ChETEC-INFRA

OHP 1.93m
Spectrograph SOPHIE

CFHT: 3.58m
Spectrograph ESPaDOnS

MPG/ESO 2.2-metre
FEROS

Magellan 6.5m
Spectrograph: MIKE


Other solutions?
Hirschegg, 20 January 2025

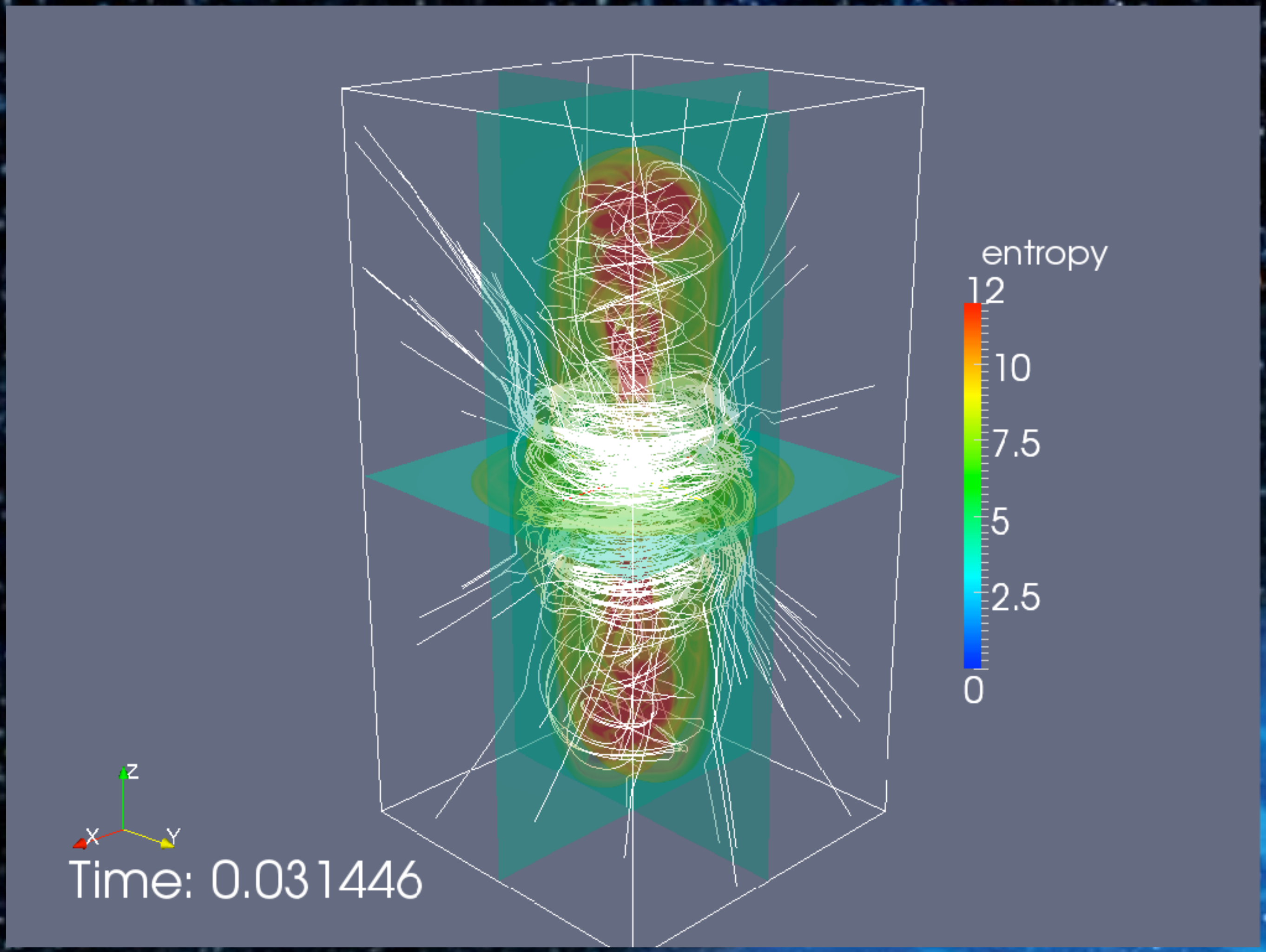
Magneto Rotationally Driven SN scenario (MRD)

(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.

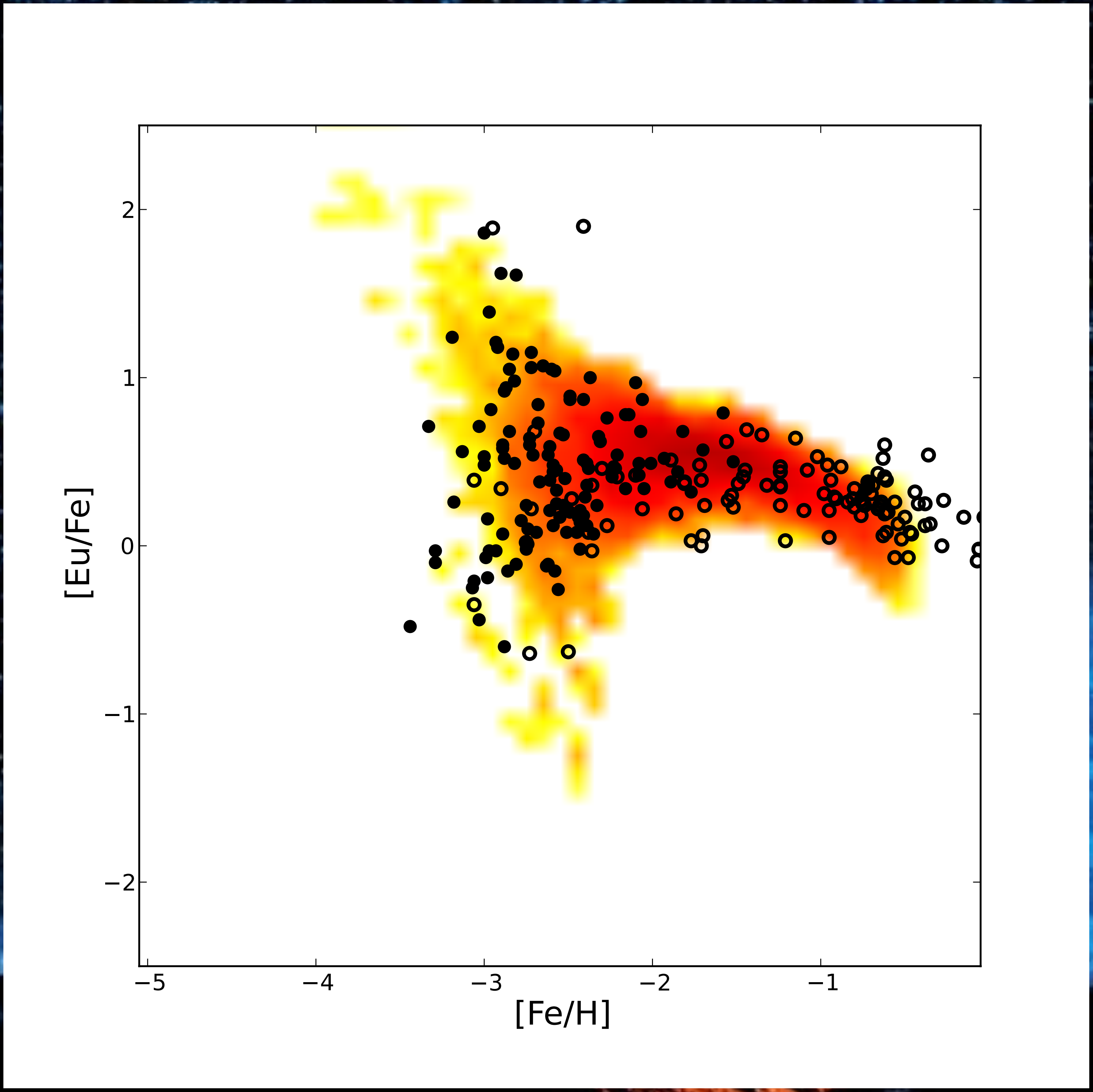


Magneto Rotationally Driven SN scenario (MRD) 10%

Cescutti+14

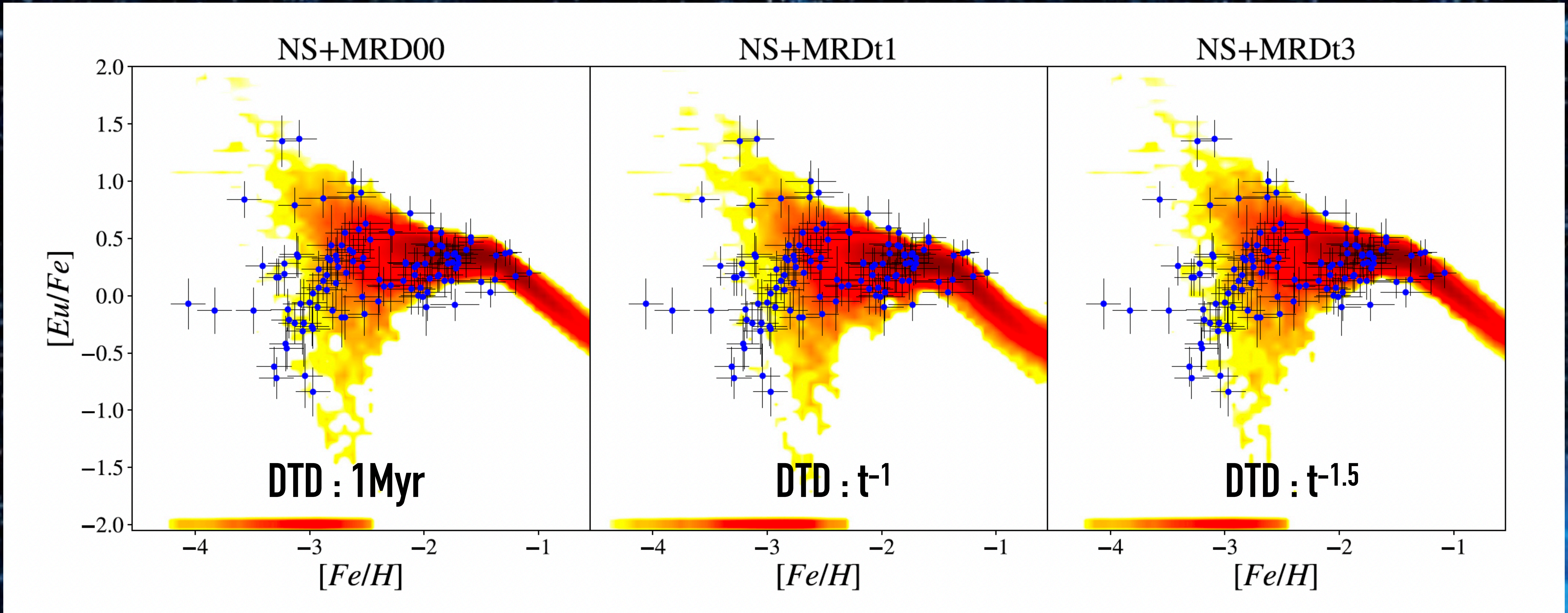
In the best model shown here the amount of r-process in each event is about 2 times the one assumed in NSM scenario

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)



Mixed scenario with both Magneto Rotationally Driven SN and NSM

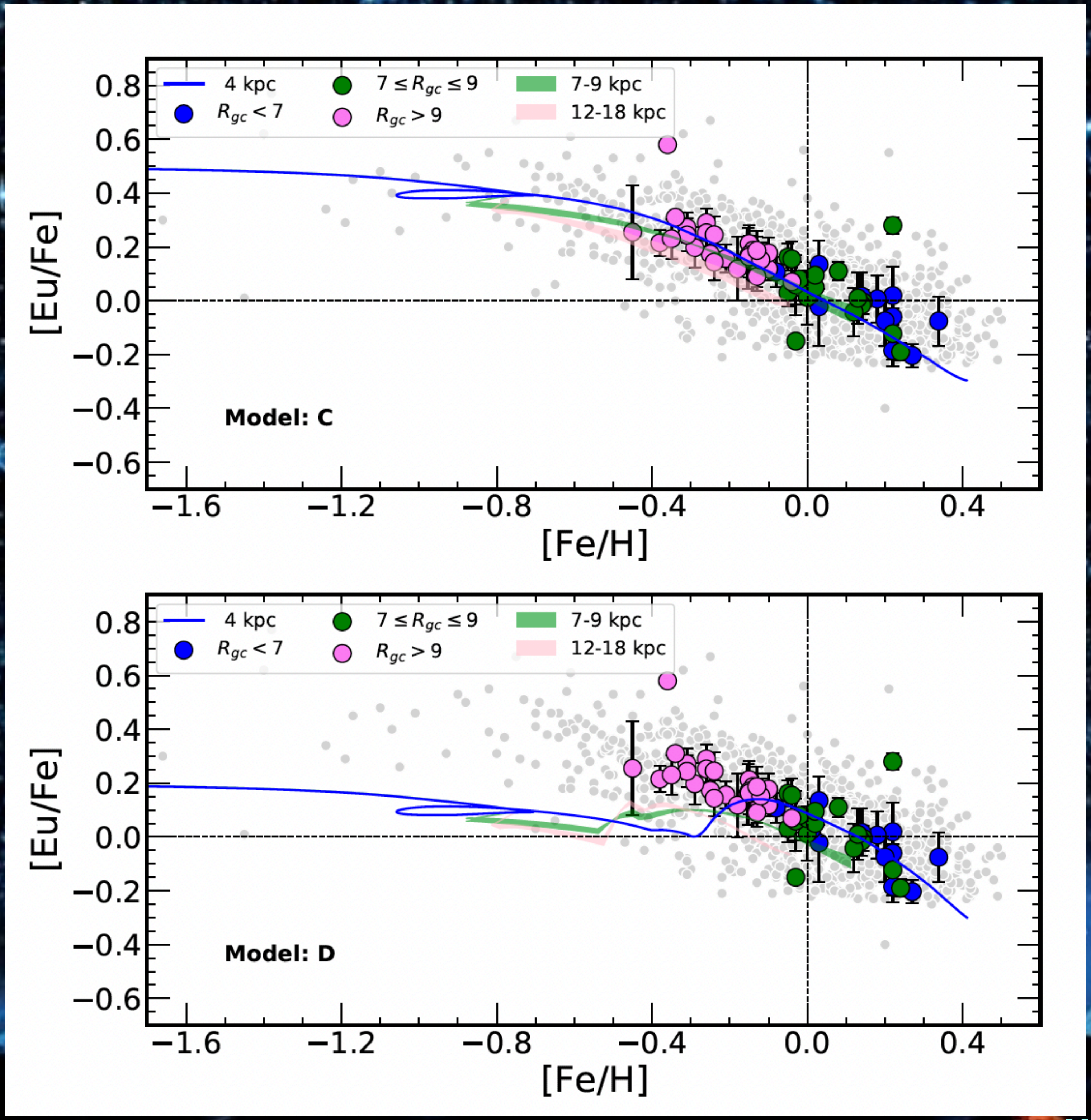
Cavallo+21



See also Cescutti+15 with both processes included
(first with NSM and MRD SNe)

It works, but it is fine tuned…

BUT a mixed scenario (50%-50%) with a longer time scale FAILS to reproduce the MW disc (our best constrain!)



Van der Swaelmen+23

What about
other neutron capture elements?

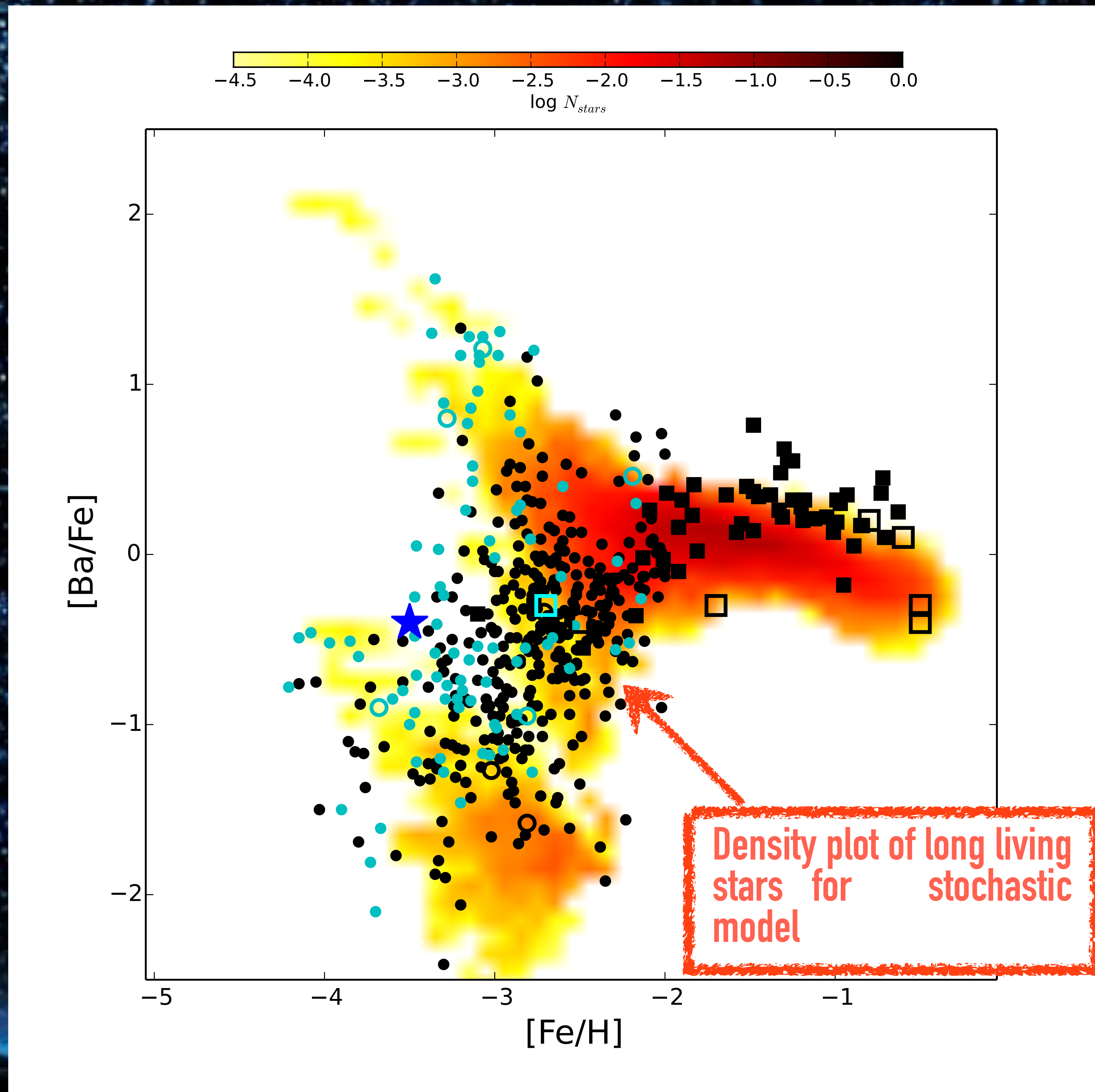
Neutron capture elements

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

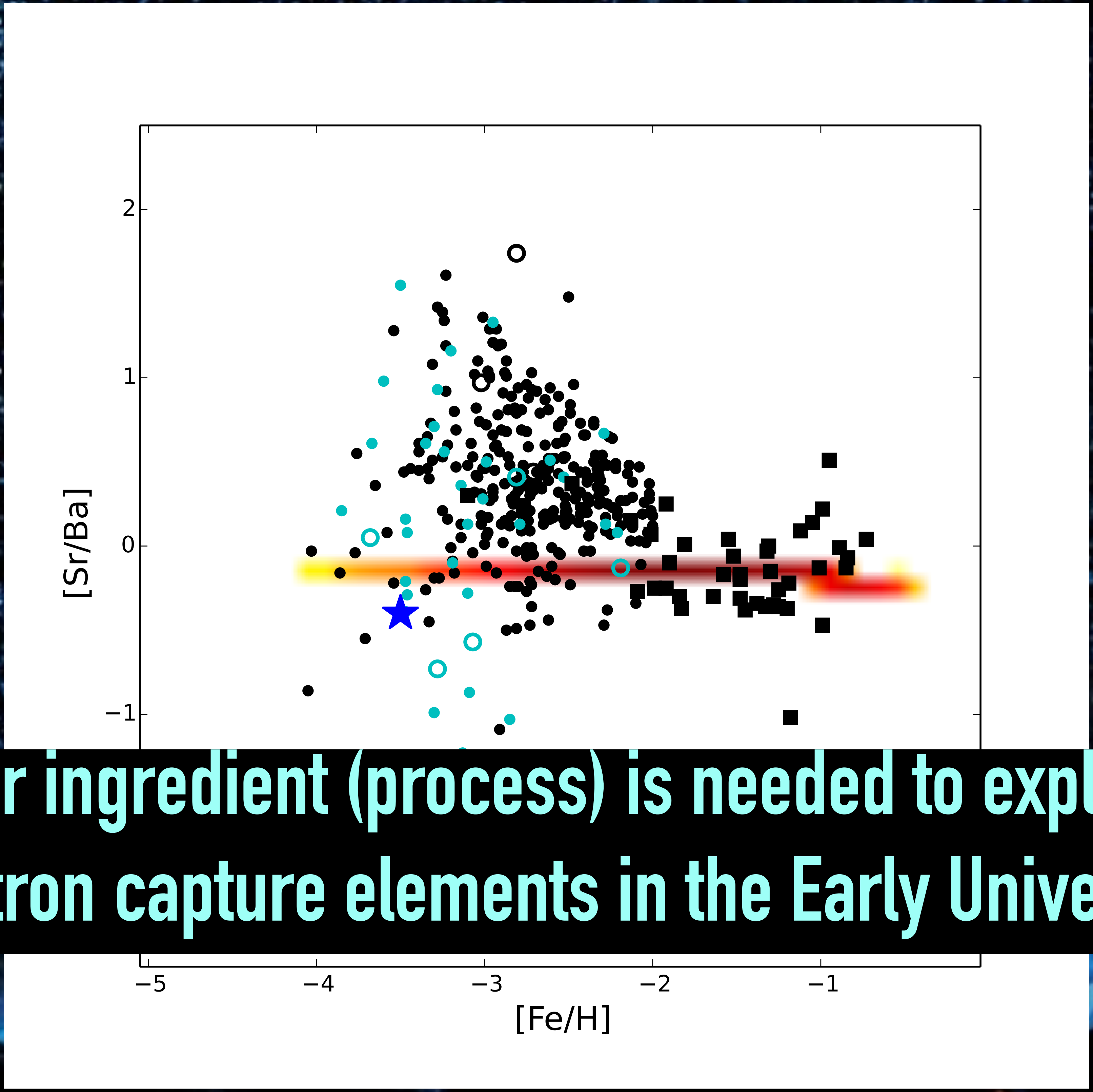


We can reproduce the [Ba/Fe] spread...

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

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)

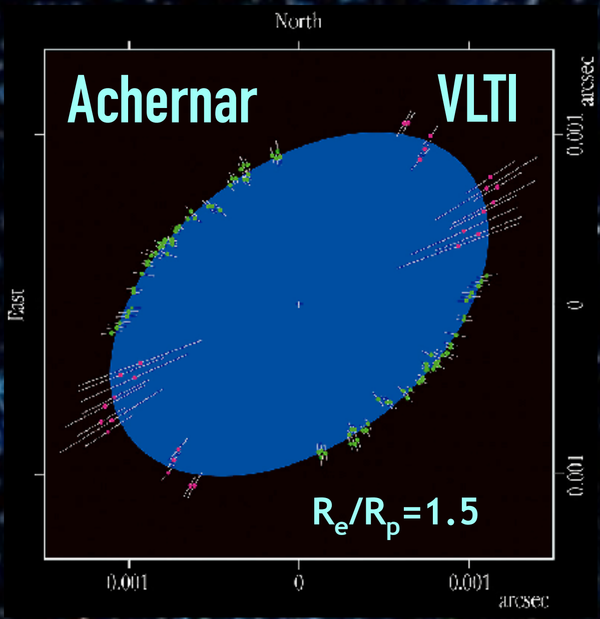


It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

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:

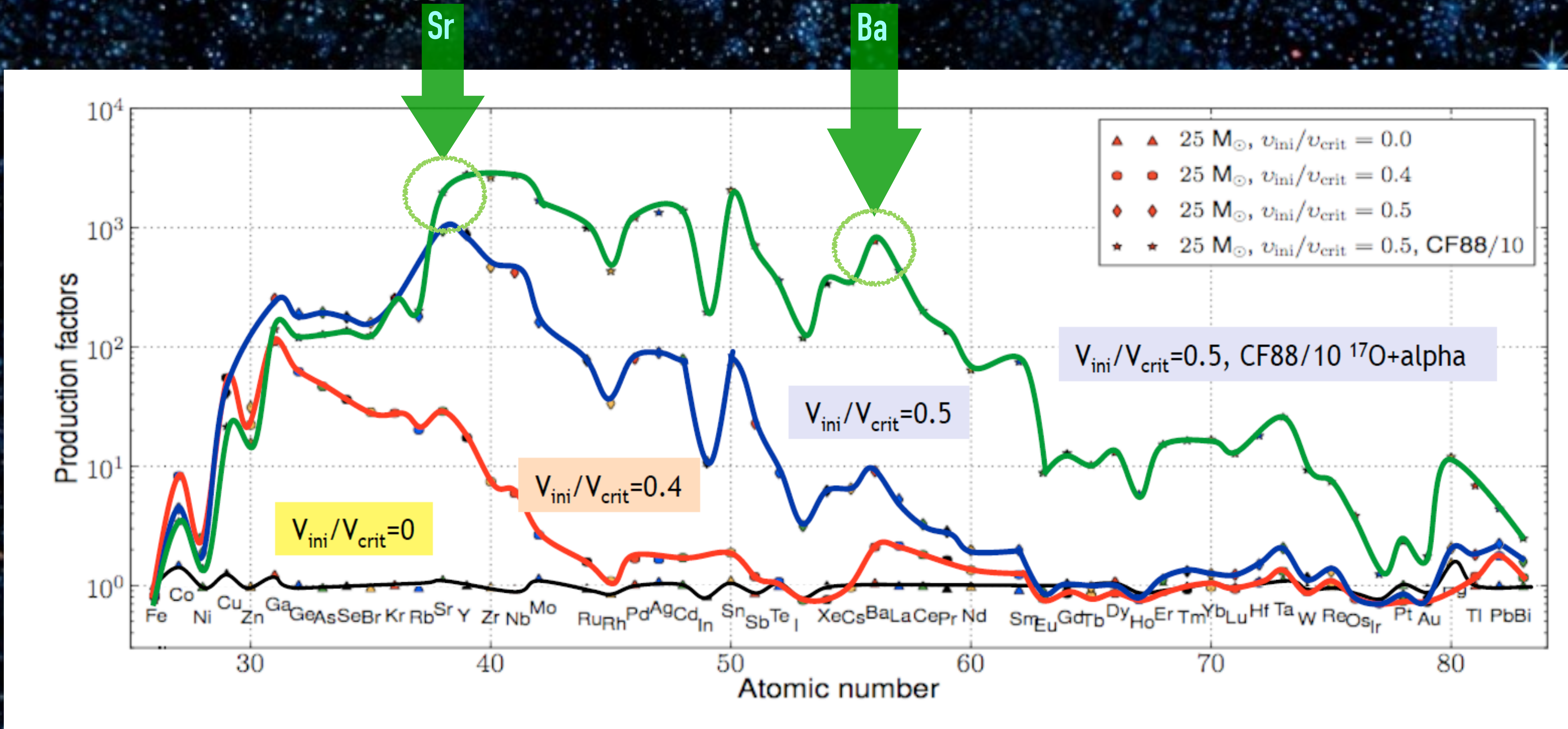
(1) Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)
(2) Increase in the C/O ratio in the early Universe
(3) Large amounts of 13C in the early Universe (Chiappini et al. 2008 A&A Letters)
(4) Early production of Be and B by cosmic ray spallation (Prantzos 2012)

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

from Cescutti+13

Early Galaxy

	s-process		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	....

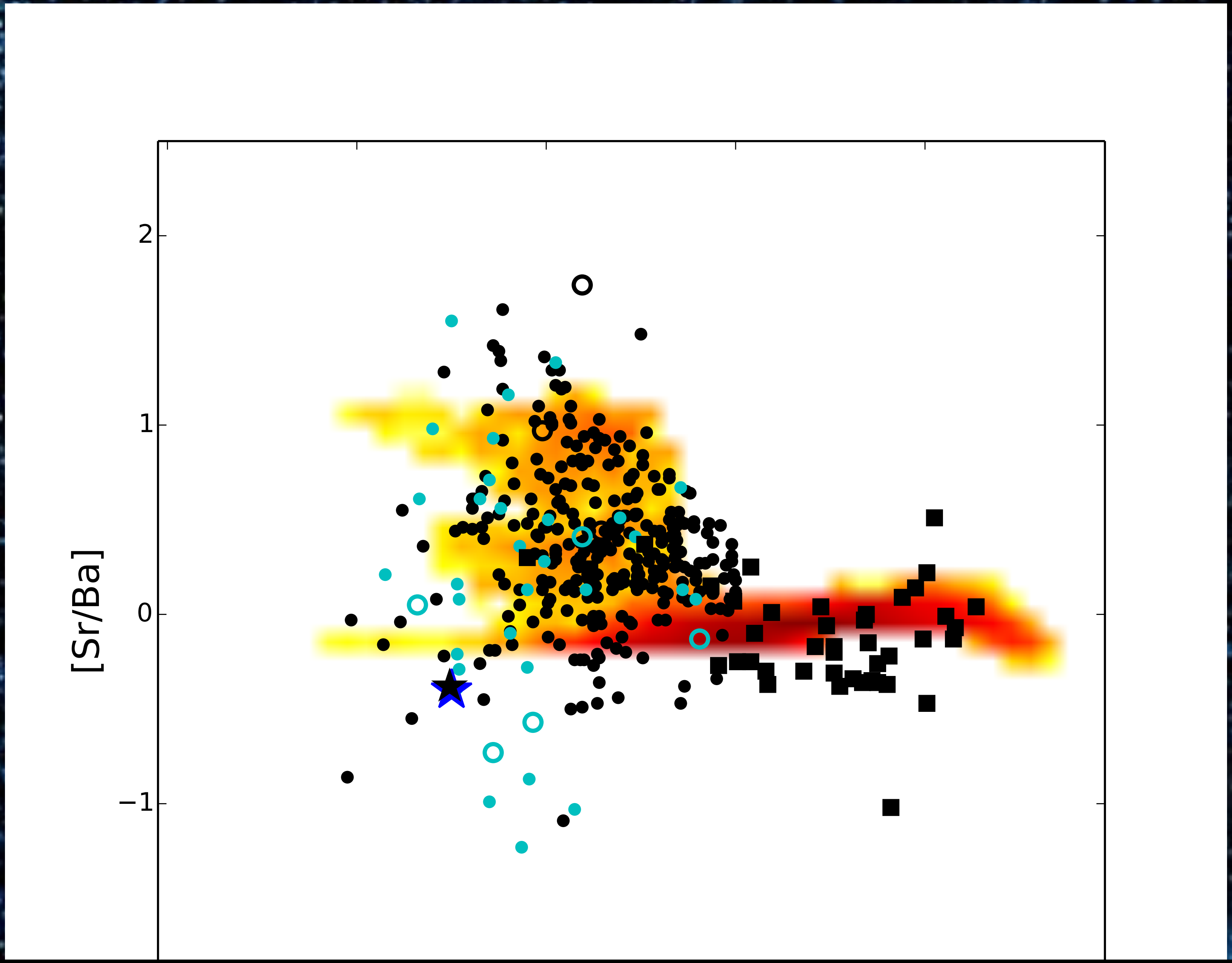
Karakas+ 2012

Limongi and Chieffi 2018

s-process from rotating massive stars

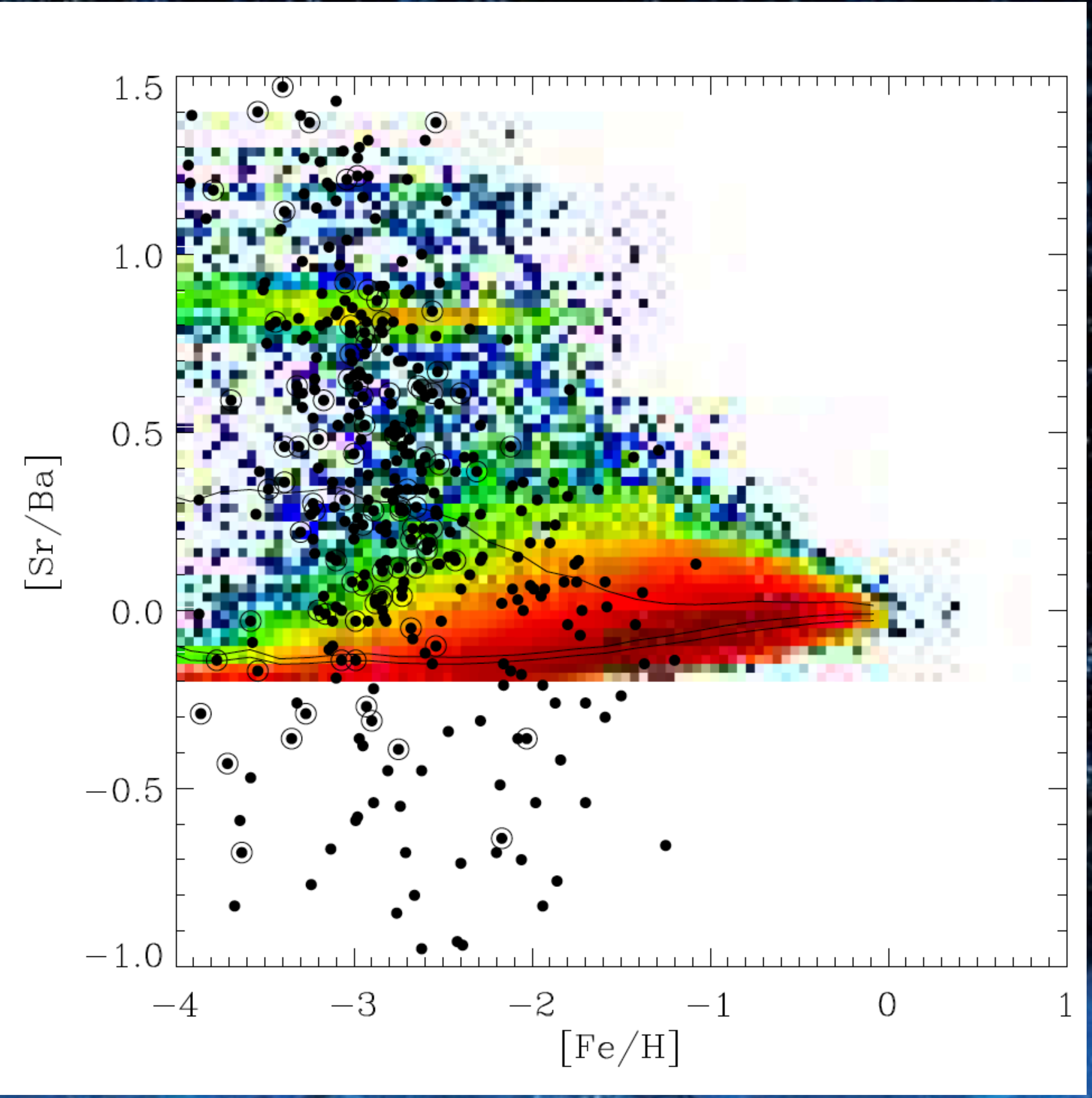
+ an r-process site (the 2 productions are not coupled!)

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

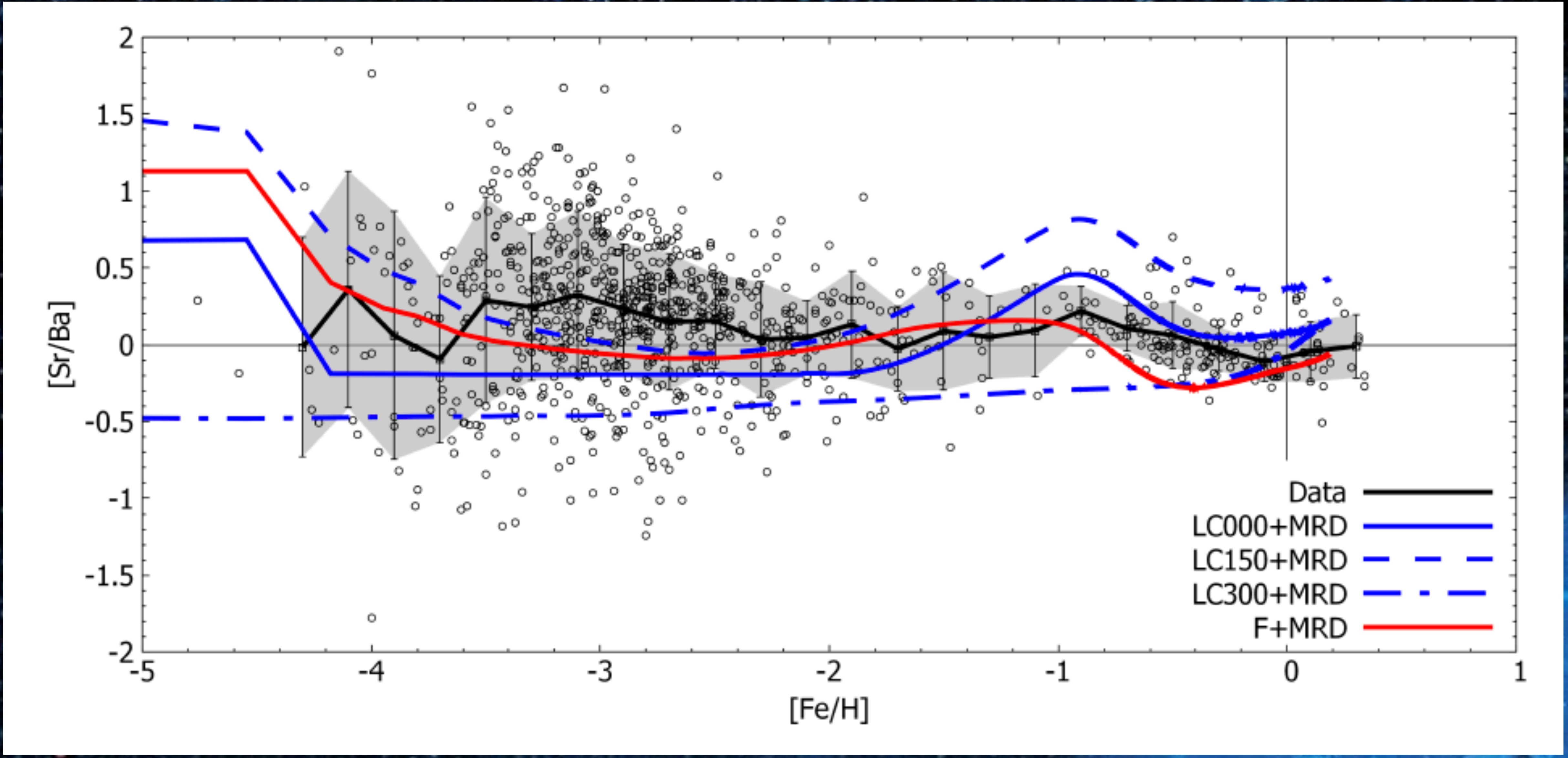
Different model
cosmological simulation of the Galaxy



Scannapieco, Cescutti & Chiappini (2022)

Confirmed in Rizzuti et al. (2019)

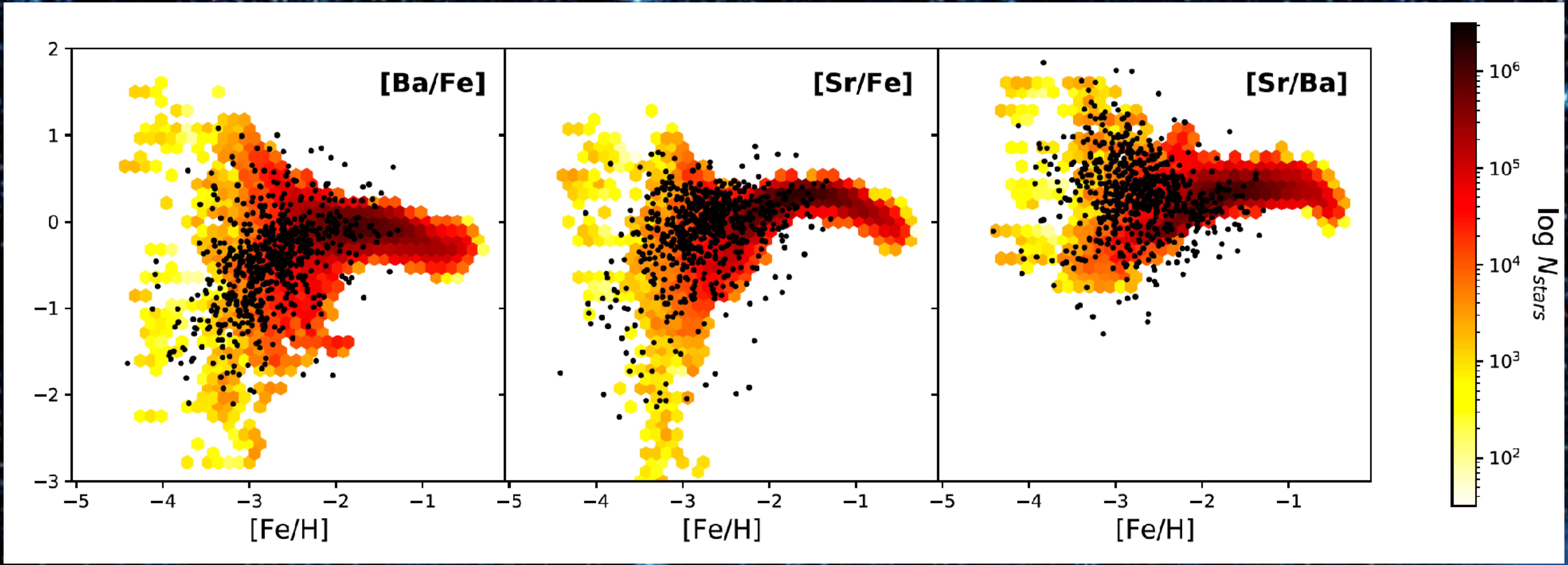
adopting Limongi&Chieffi18



see also Prantzos et al. 2018

Confirmed by Rizzuti et al. (2021)

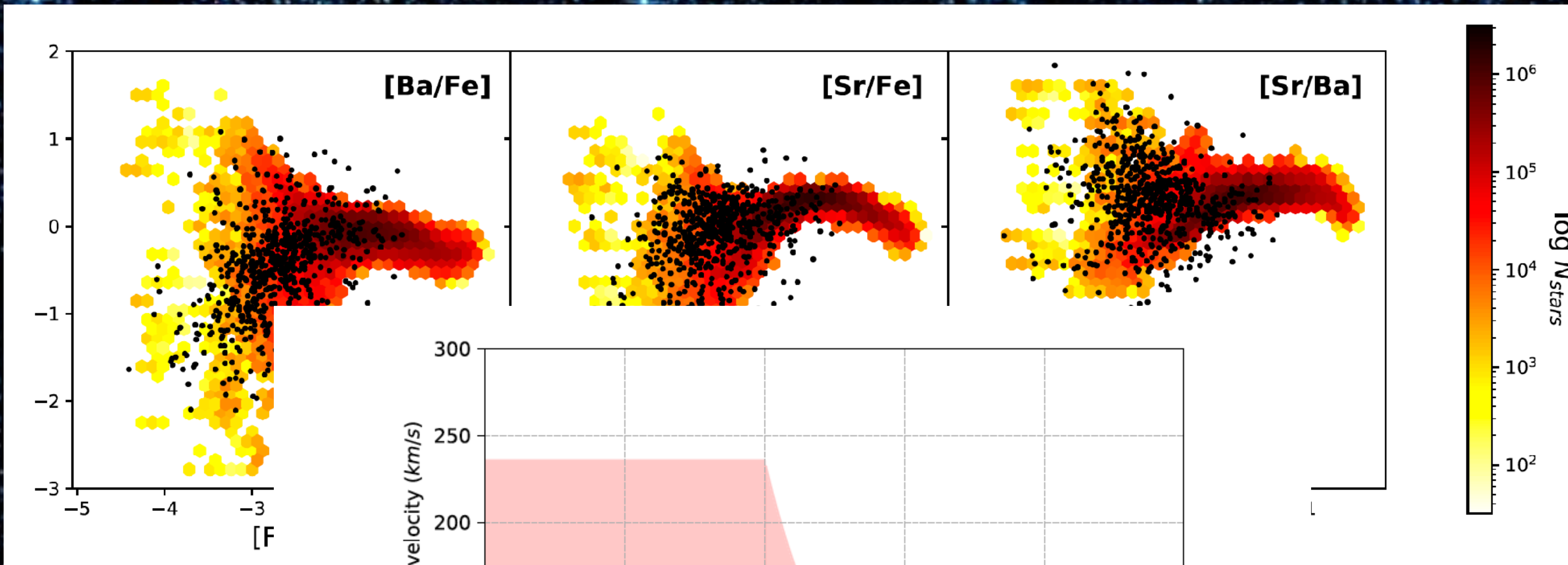
adopting Limongi&Chieffi18

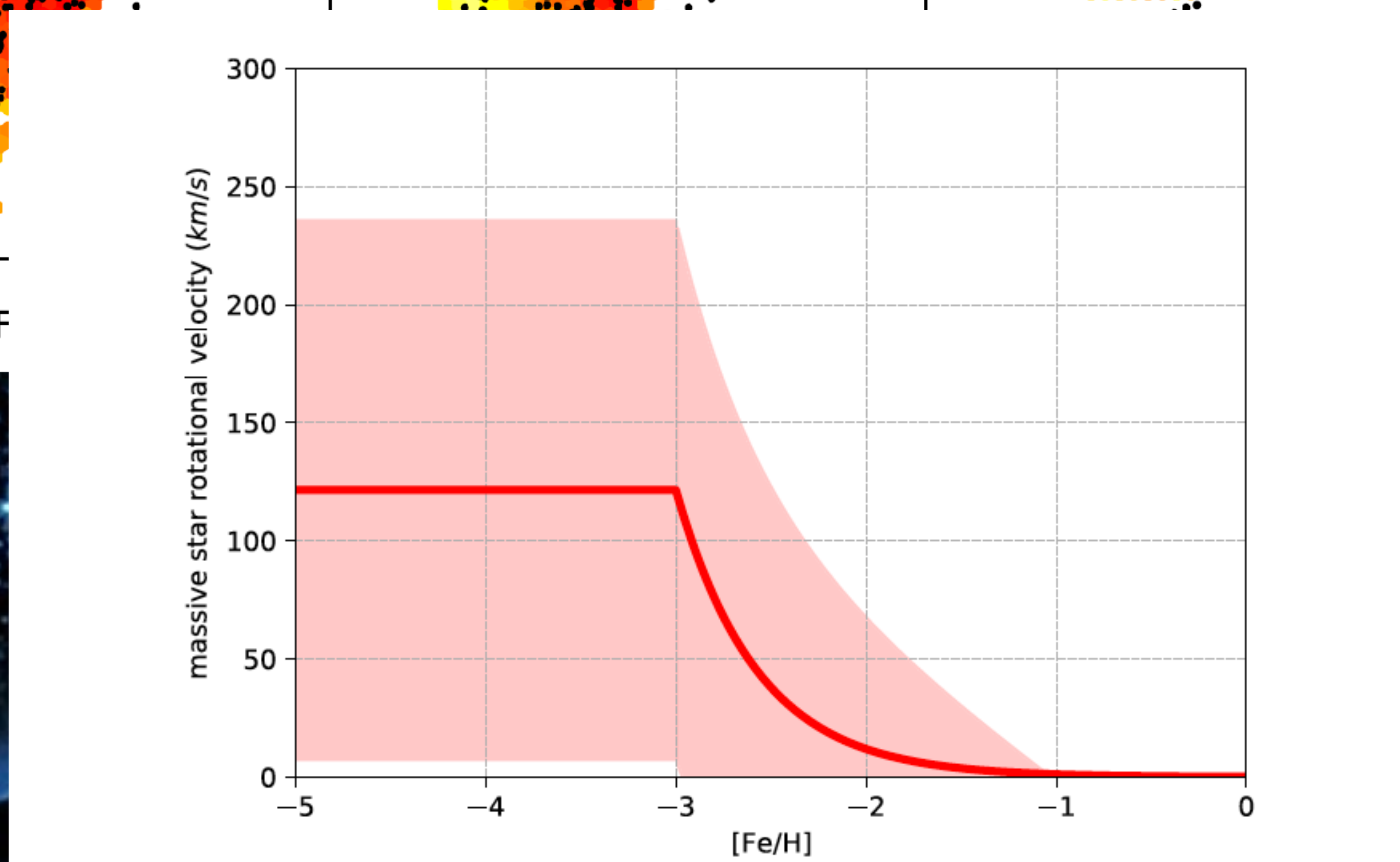


see also Prantzos et al. 2018

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:

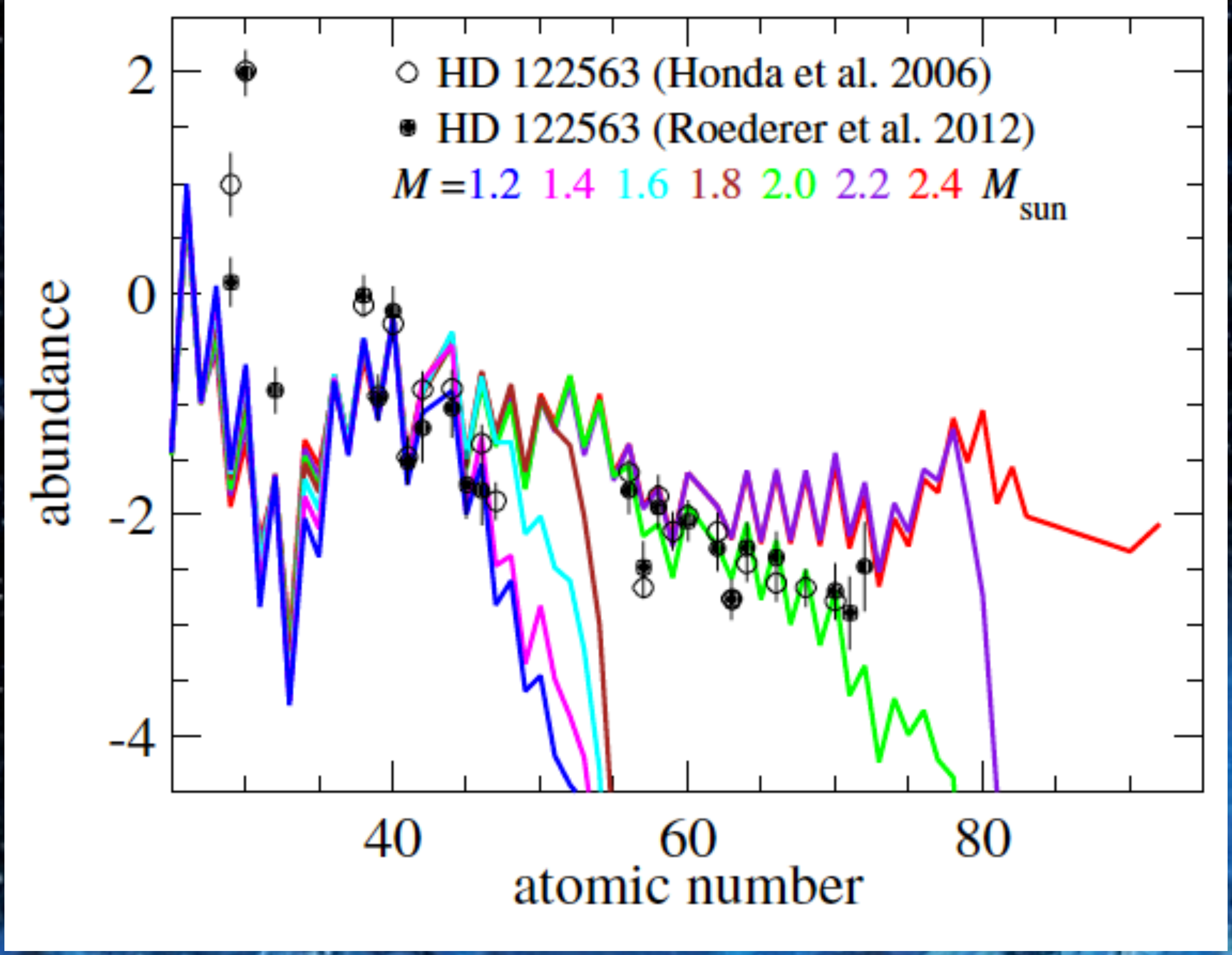
A (main) r-process, rare and able to produce all the elements up to Th with a pattern as the one observed in r-process rich stars.
NSM is the only confirmed candidate, and they can play this role if they have very short time scales or if their frequency is higher at extremely low metallicity.
MRD SNe (or collapsar) can also play this role, and they would be the easiest way to explain r-process elements with a GCE model.

The other process is more frequent and 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

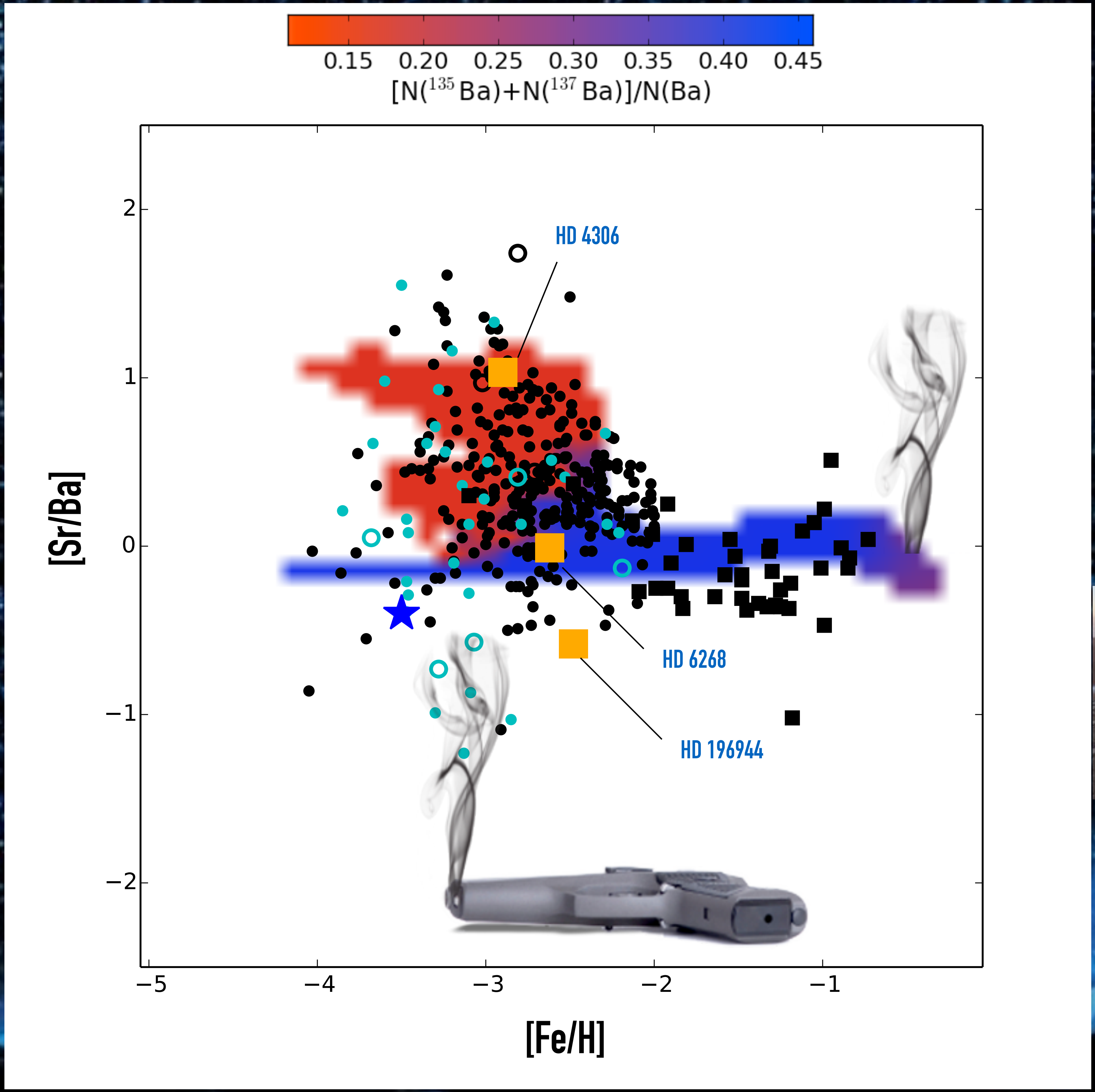
Isotopic ratio for Ba

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)



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

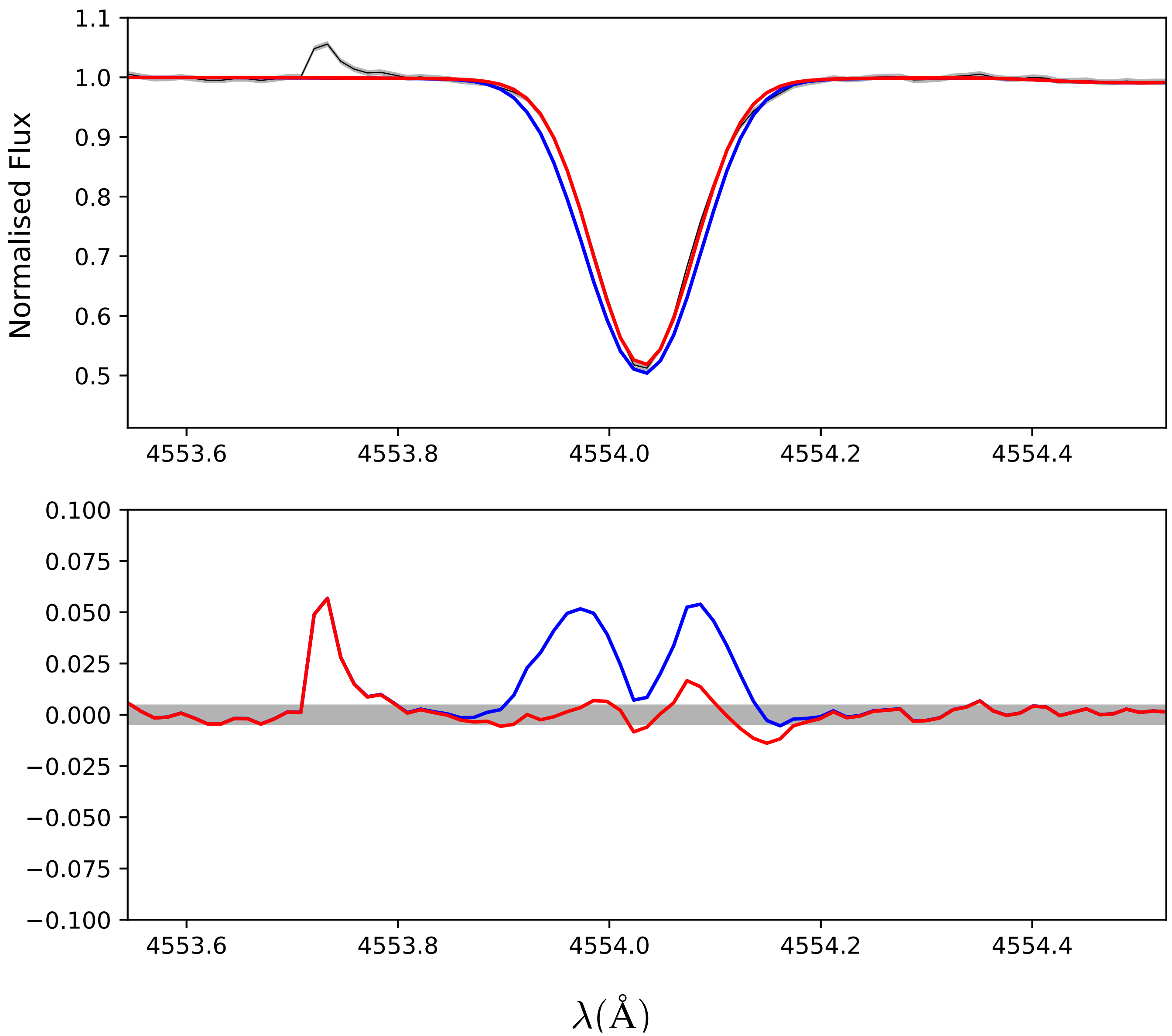
Cescutti and Chiappini (2014)

Spectral analysis results ratio for Ba (1D and LTE)

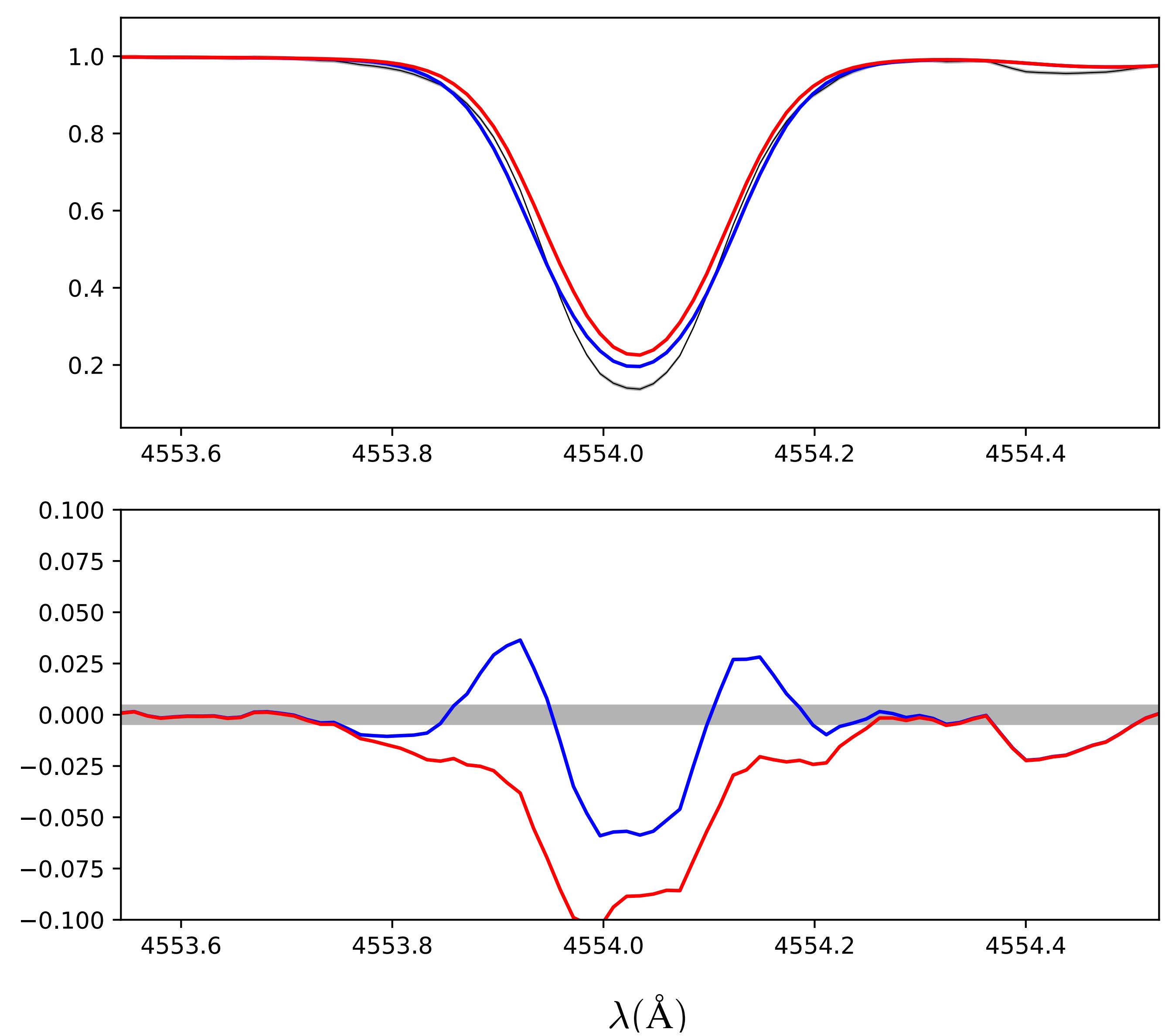
Cescutti+21

Ba II $\lambda4554.00$: $\chi = 0.000$ eV, log $gf = +0.17$	
^{134}Ba:	
4554.000	1.0000
^{135}Ba:	
4553.969	0.1562
4553.970	0.1562
4553.971	0.0625
4554.017	0.4375
4554.020	0.1562
4554.021	0.0313
^{136}Ba:	
4554.000	1.0000
^{137}Ba:	
4553.965	0.1562
4553.967	0.1562
4553.968	0.0625
4554.020	0.4375
4554.022	0.1562
4554.023	0.0313
^{138}Ba:	
4554.000	1.0000

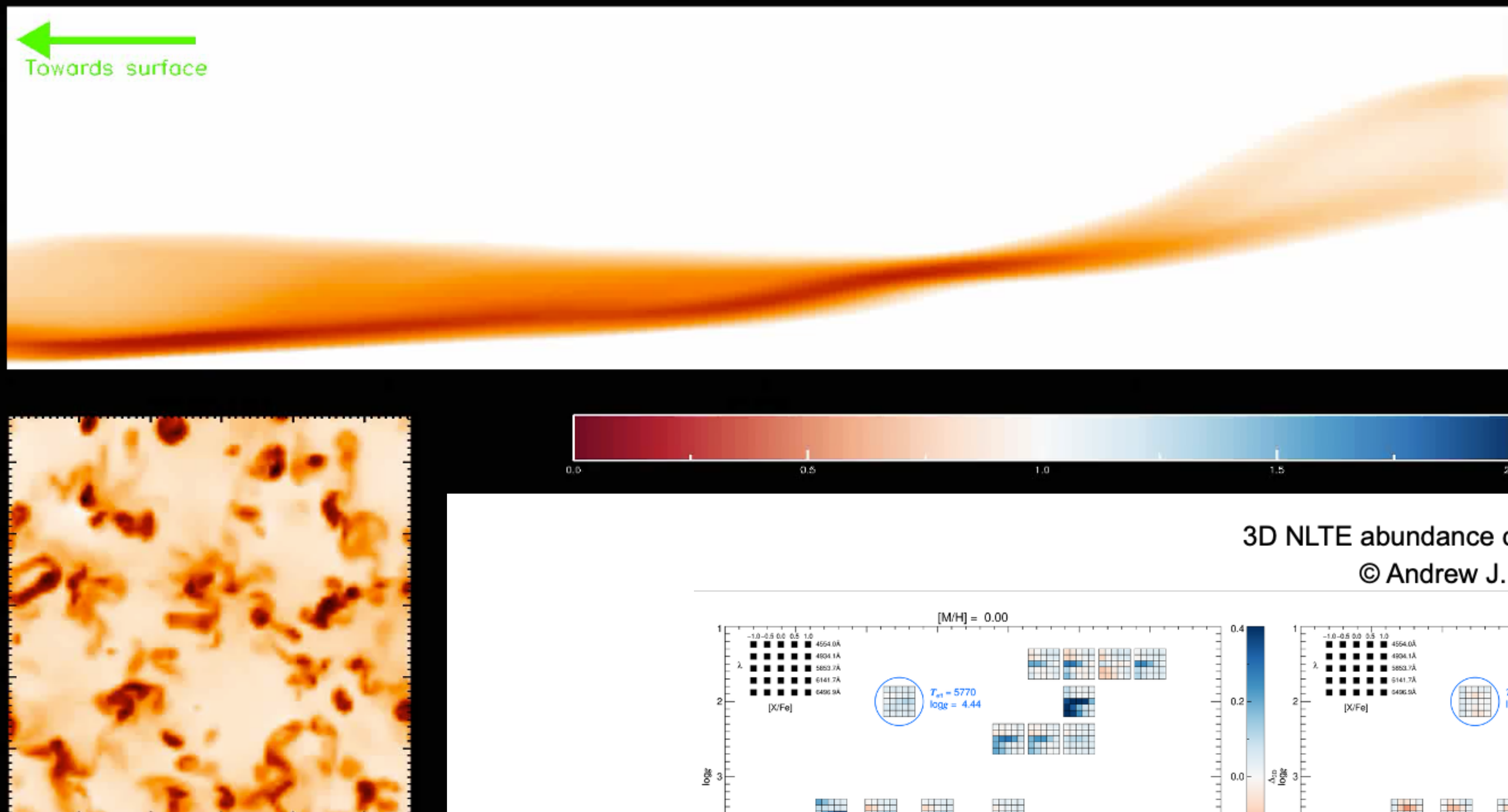
HD 4306



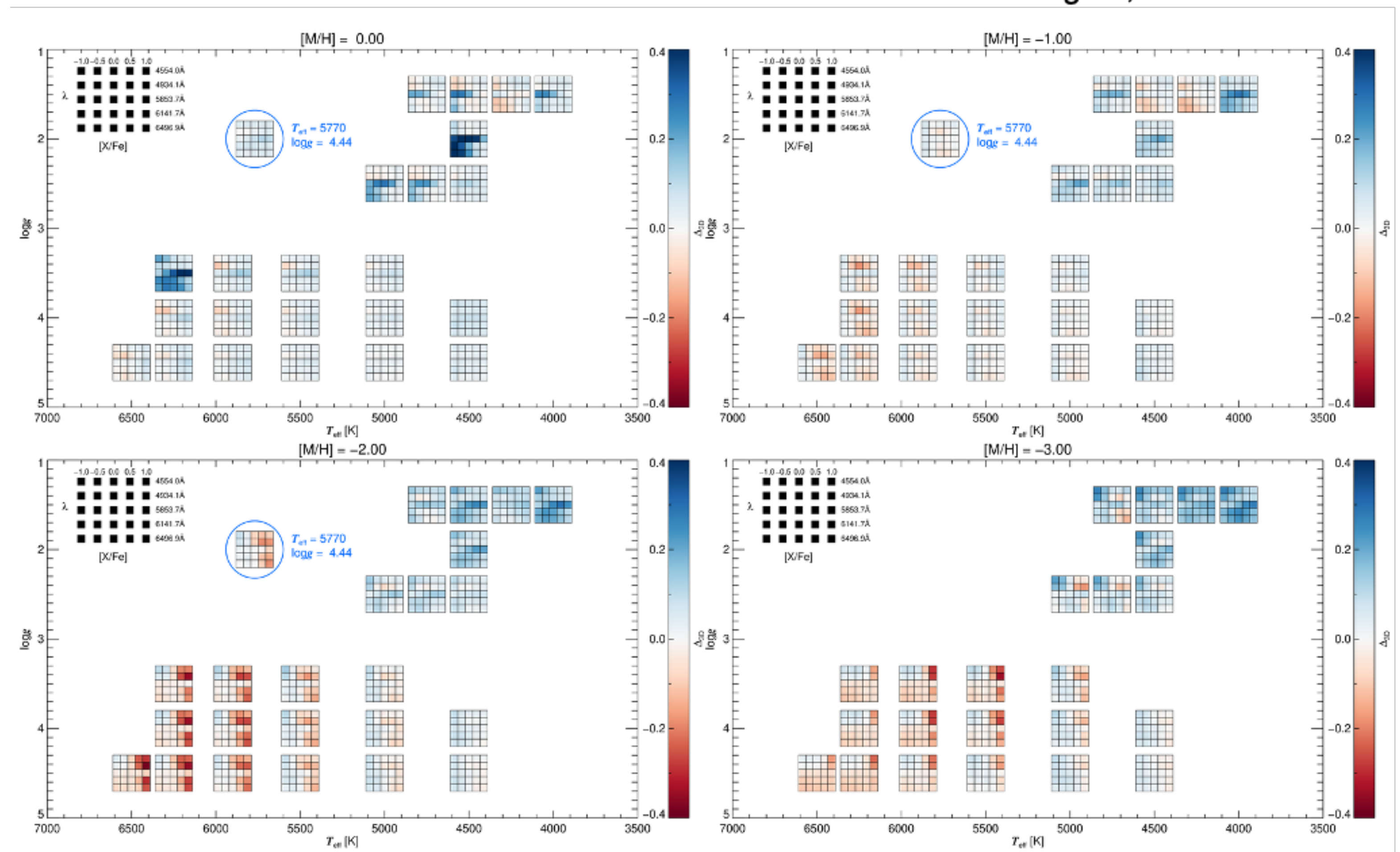
HD 6268



Ba II 4554.033 Å line formation in the atmosphere of red giant star



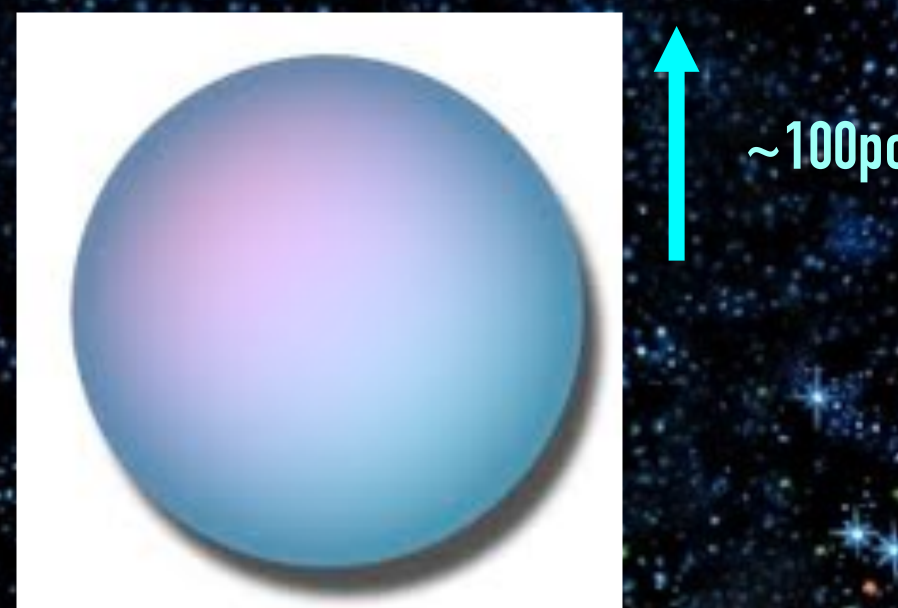
3D NLTE abundance corrections for Ba II lines
© Andrew J. Gallagher, AIP



Stochastic chemical evolution model

Stars are discrete entities!

We simulate the halo as formed by many independent volumes each one of the typical dimension of ~ 100 pc (~radius of SN bubble) and we treat each volume as isolate from the others.



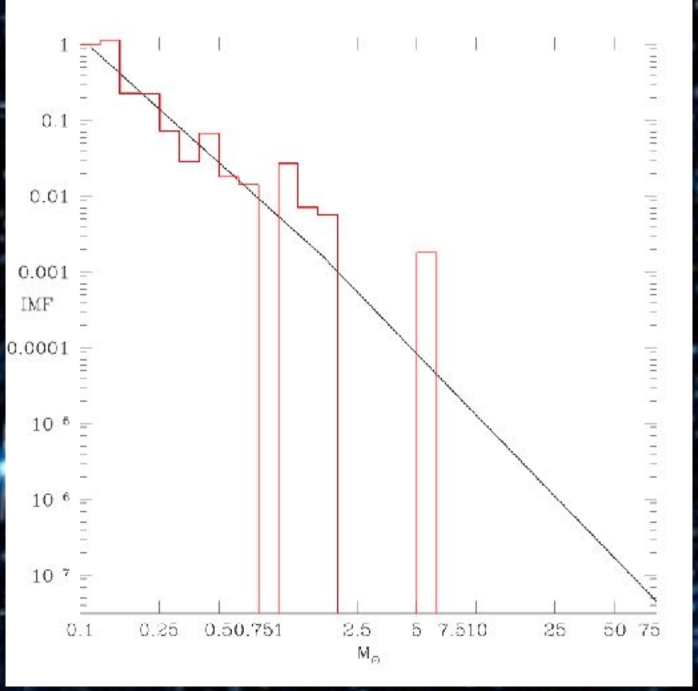
Cescutti (2008)

Inside each volume, we simulate the chemical enrichment.
The main parameters are the same as those of the homogeneous model but in each isolated volume

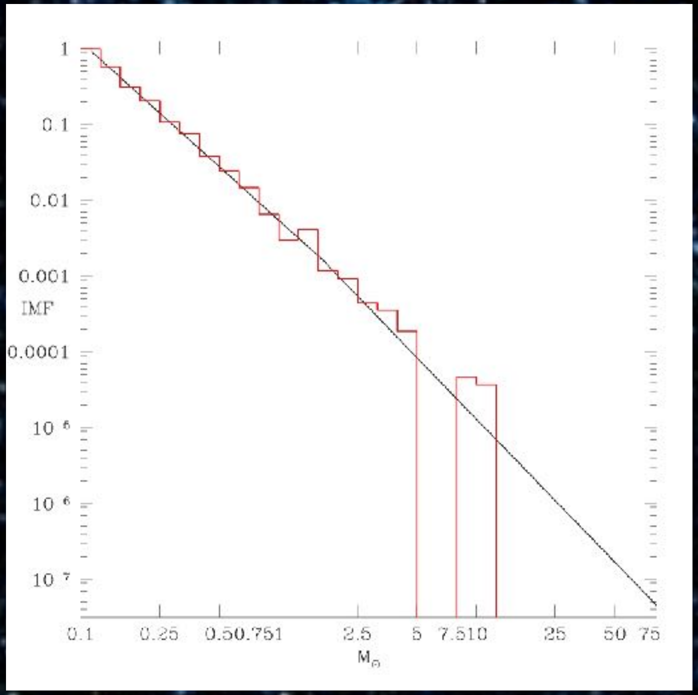
Stochastic formation of stars

The formation of new stars subjects to the condition that the cumulative mass distribution follows a given initial mass function; this fact produces different enrichments in the different volumes.

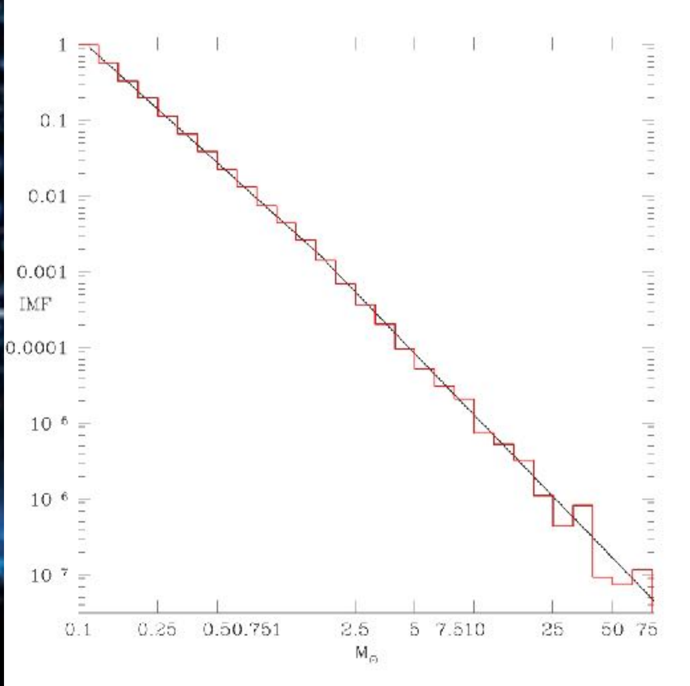
50 stars



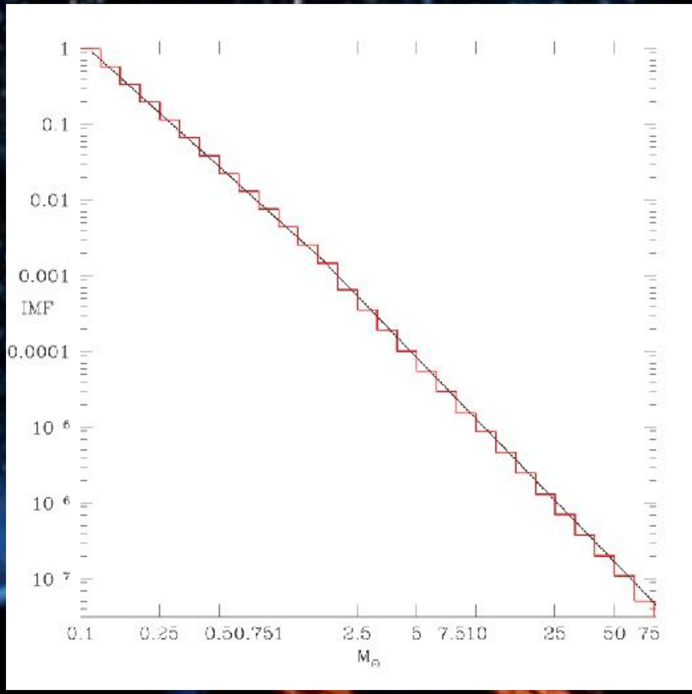
1000 stars



10^5 stars



10^7 stars



Stochastic chemical evolution models

minimum of 100 volumes up to 10’000