



**UNIVERSITÀ
DEGLI STUDI
DI TRIESTE**



Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste



Galactic Archaeology with neutron capture elements

Gabriele Cescutti

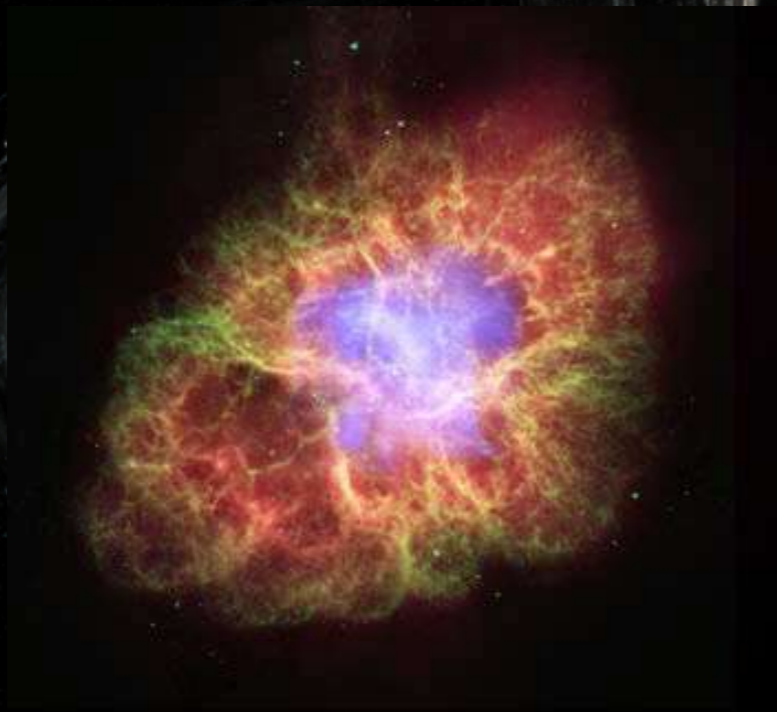
in collaboration with **Francesca Matteucci,
Federico Rizzuti & Lorenzo Cavallo**



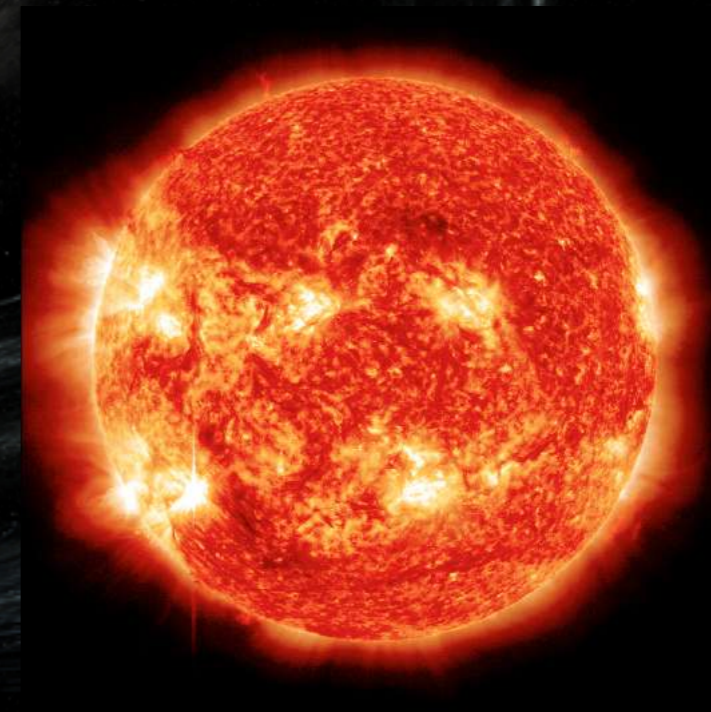
How we can check the
Nucleosynthesis?
GALACTIC ARCHAEOLOGY

The stars in our Galaxy formed from the gas
enriched by previous stellar generations

Low mass stars – long lifetimes



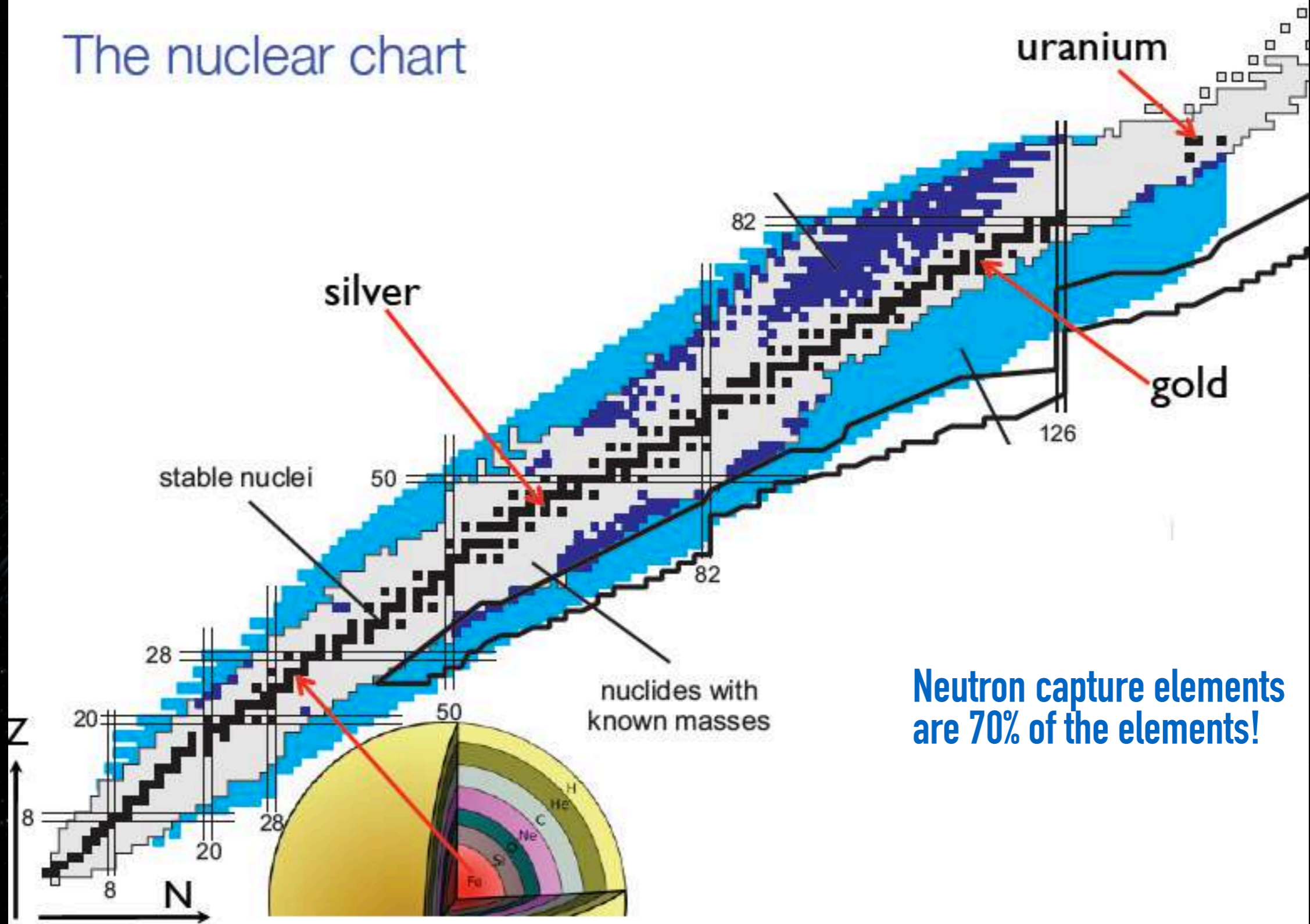
Polluters in the Universe



Imprints of the previous generations

Why neutron capture elements?

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 mainly formed through neutron capture on seed nuclei (iron and silicon).

Two cases:

s-process

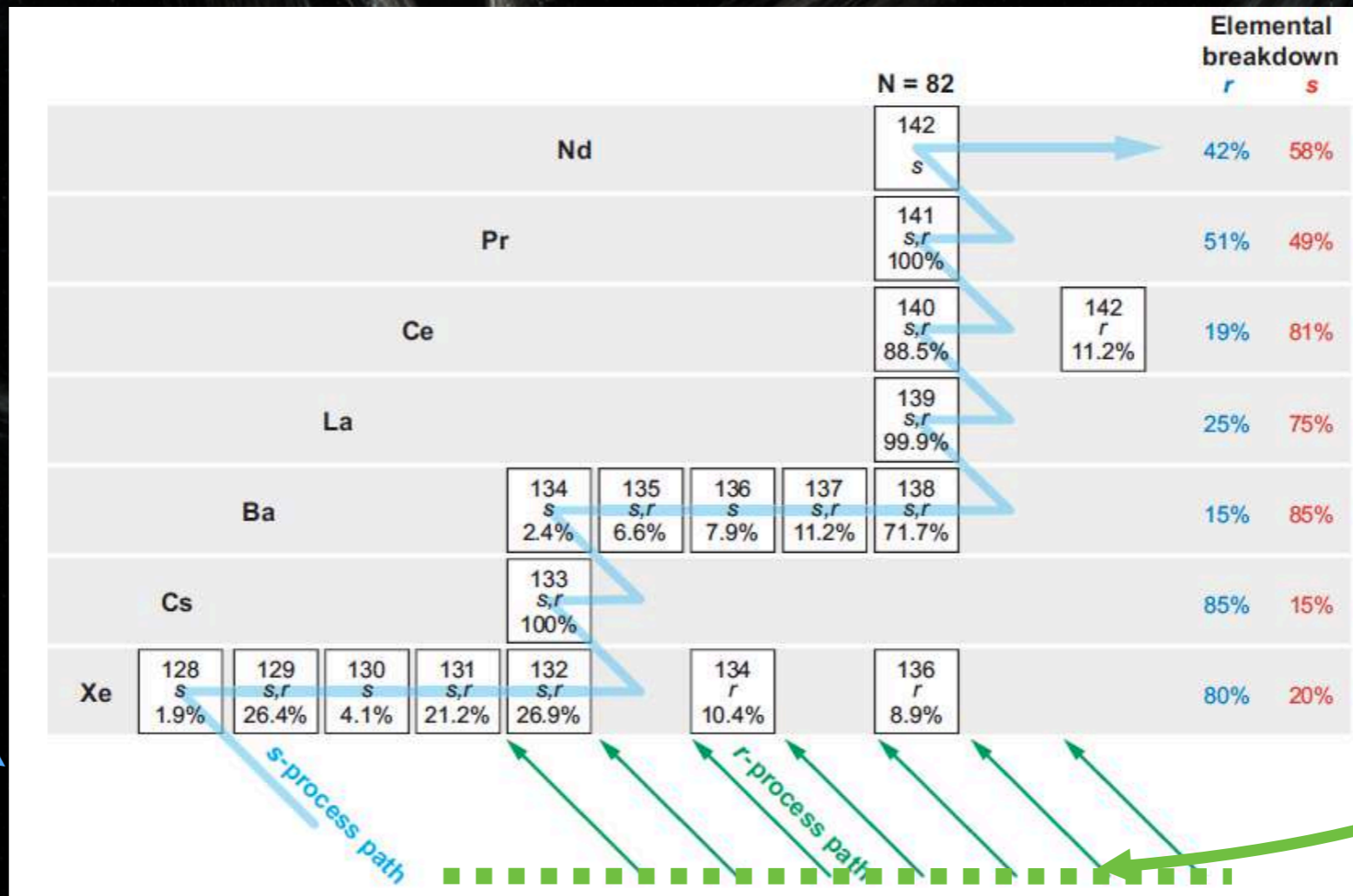
Different Timescale of the neutron capture

r-process

$$\tau_{\beta} \ll \tau_c$$

Different process path

$$\tau_{\beta} \gg \tau_c$$

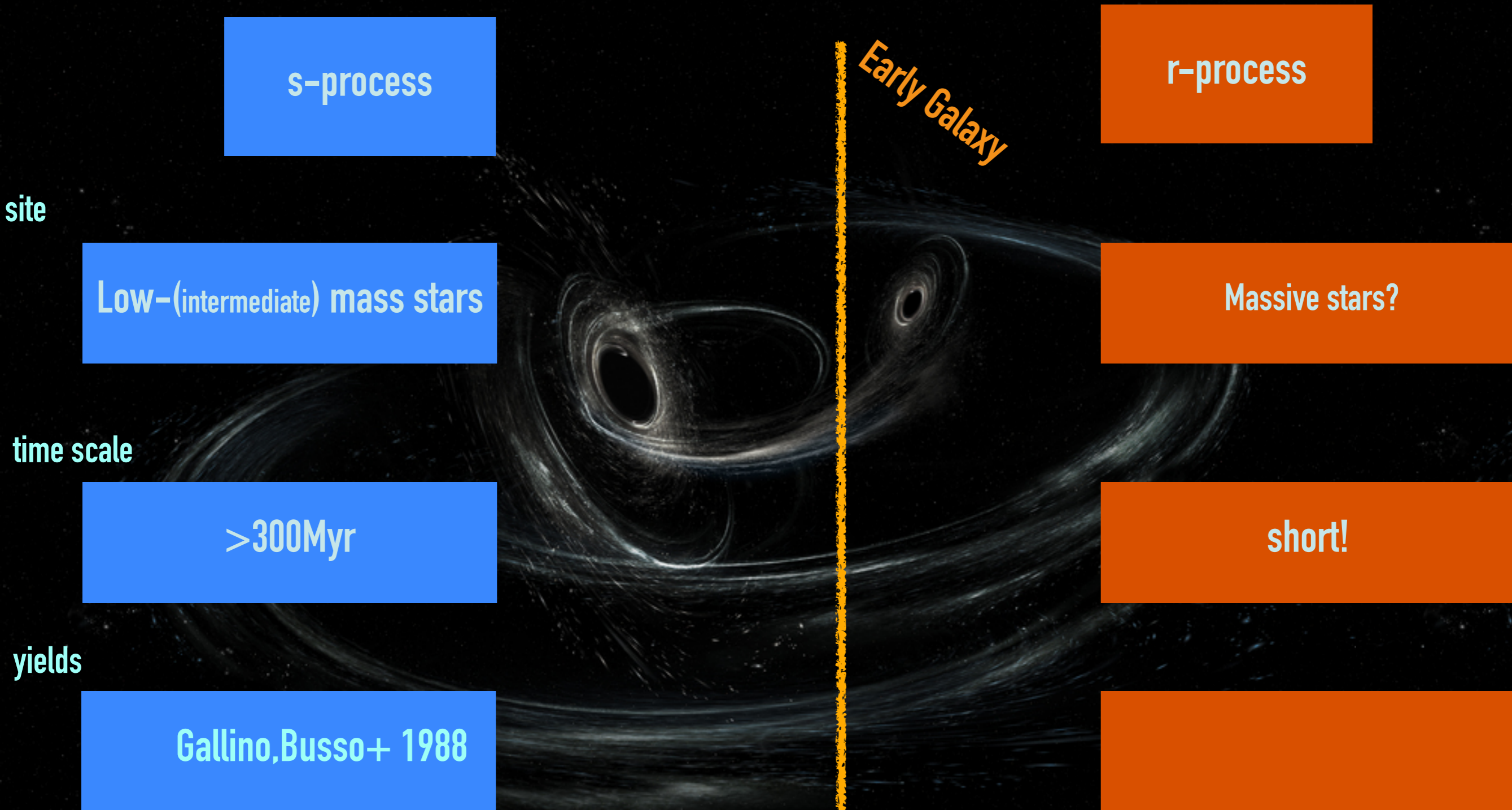


p

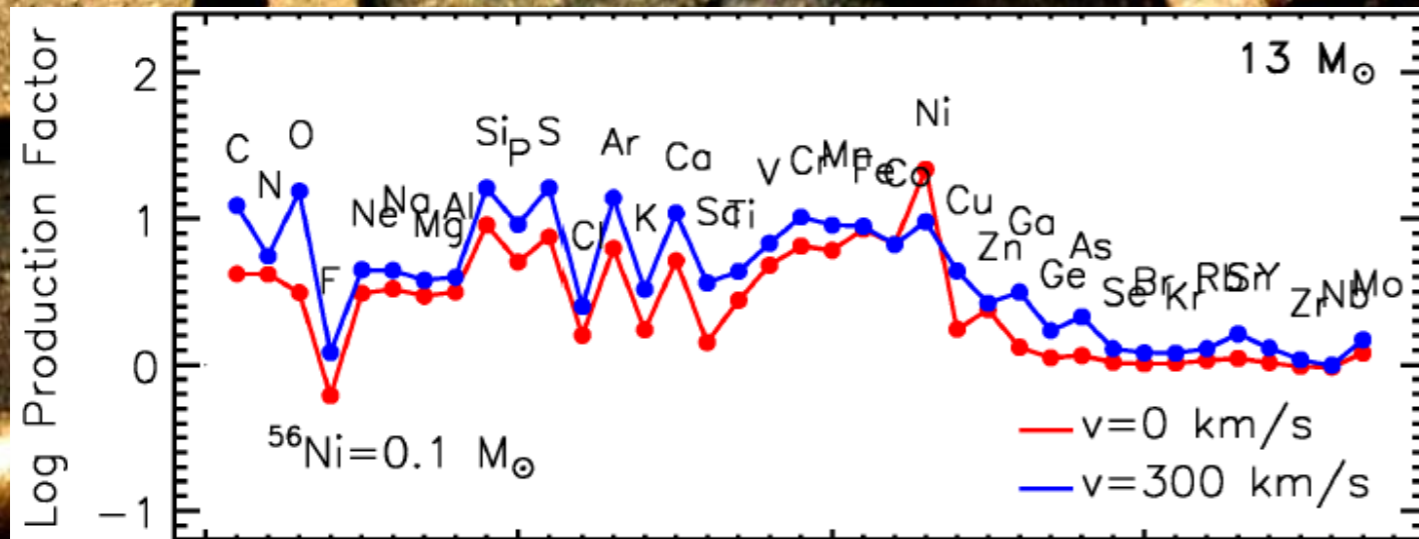
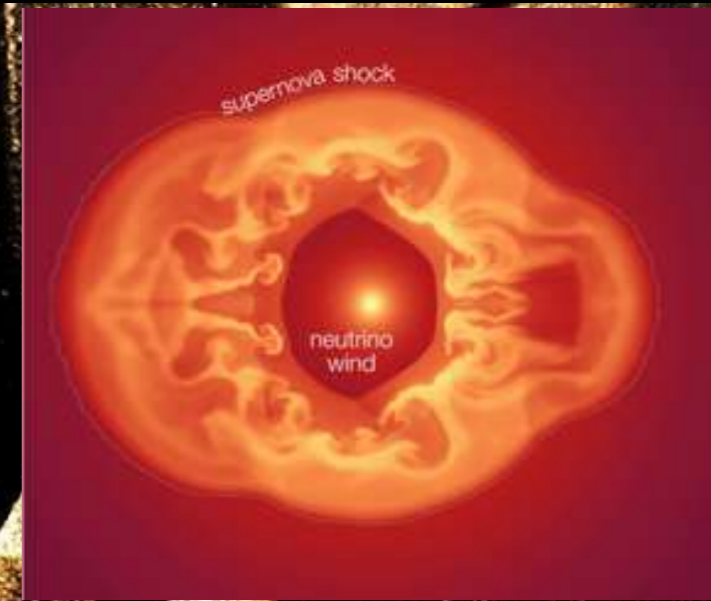
n

Neutron capture elements

Since Truran 1980 short timescale

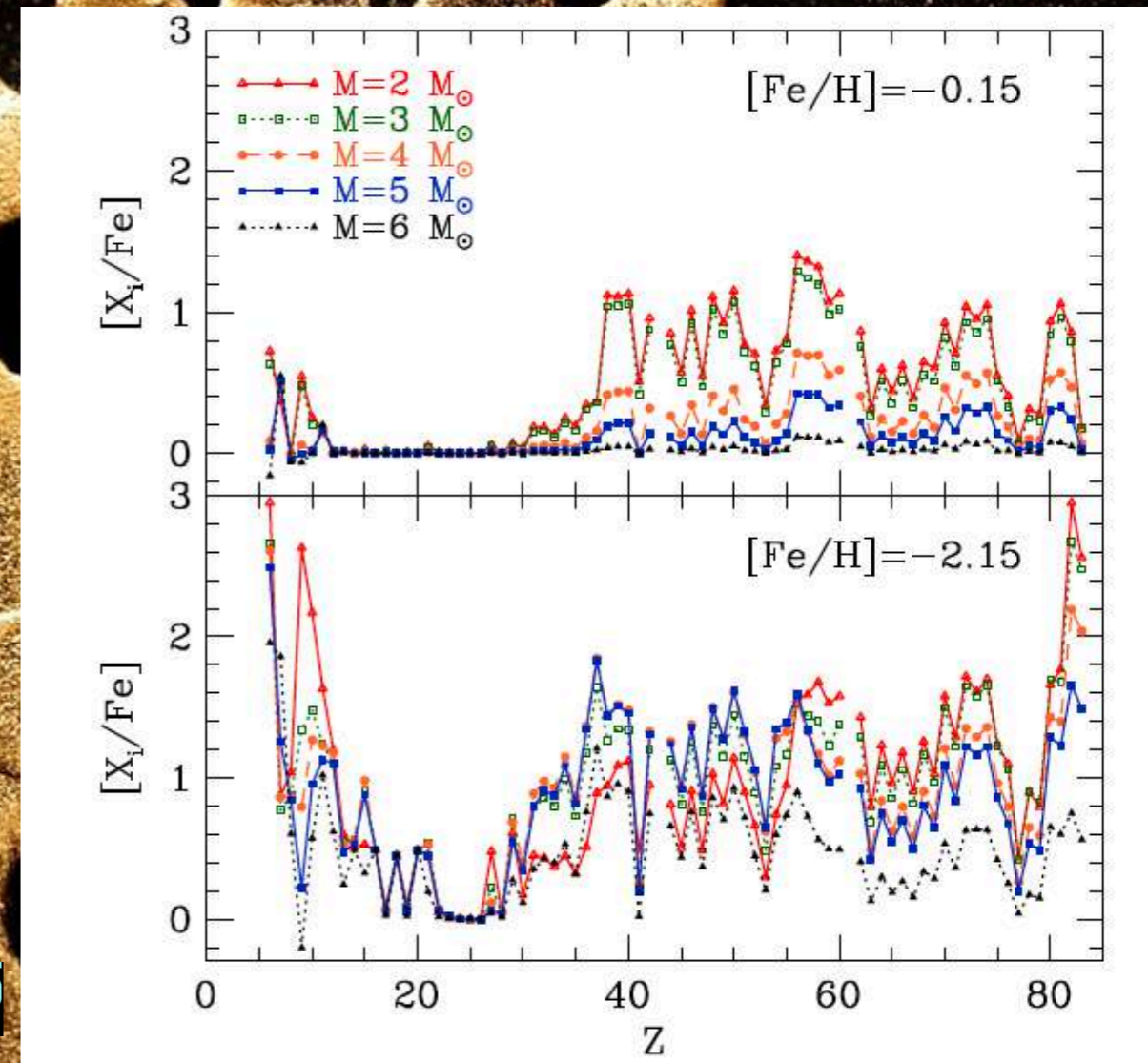


Stellar evolution model with nucleosynthesis

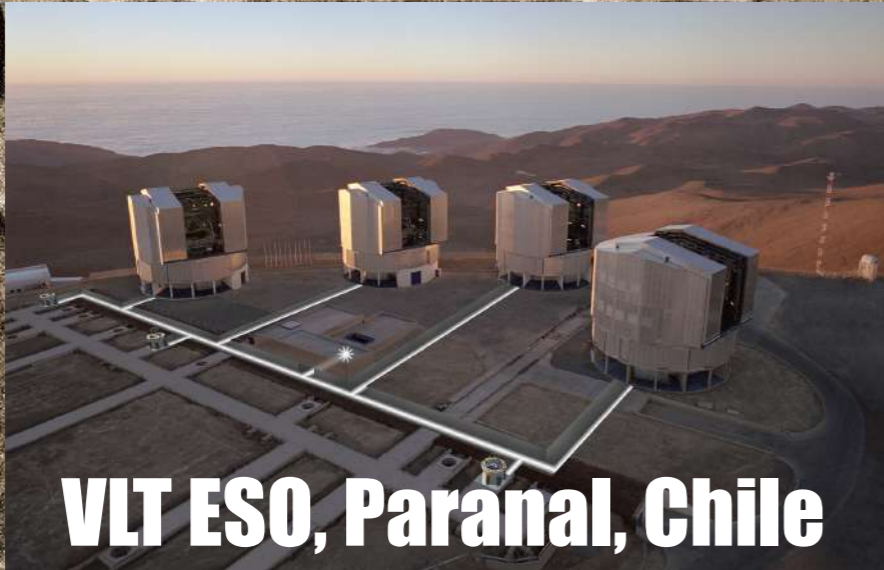


Limongi&Chieffi 12

Cristallo+15

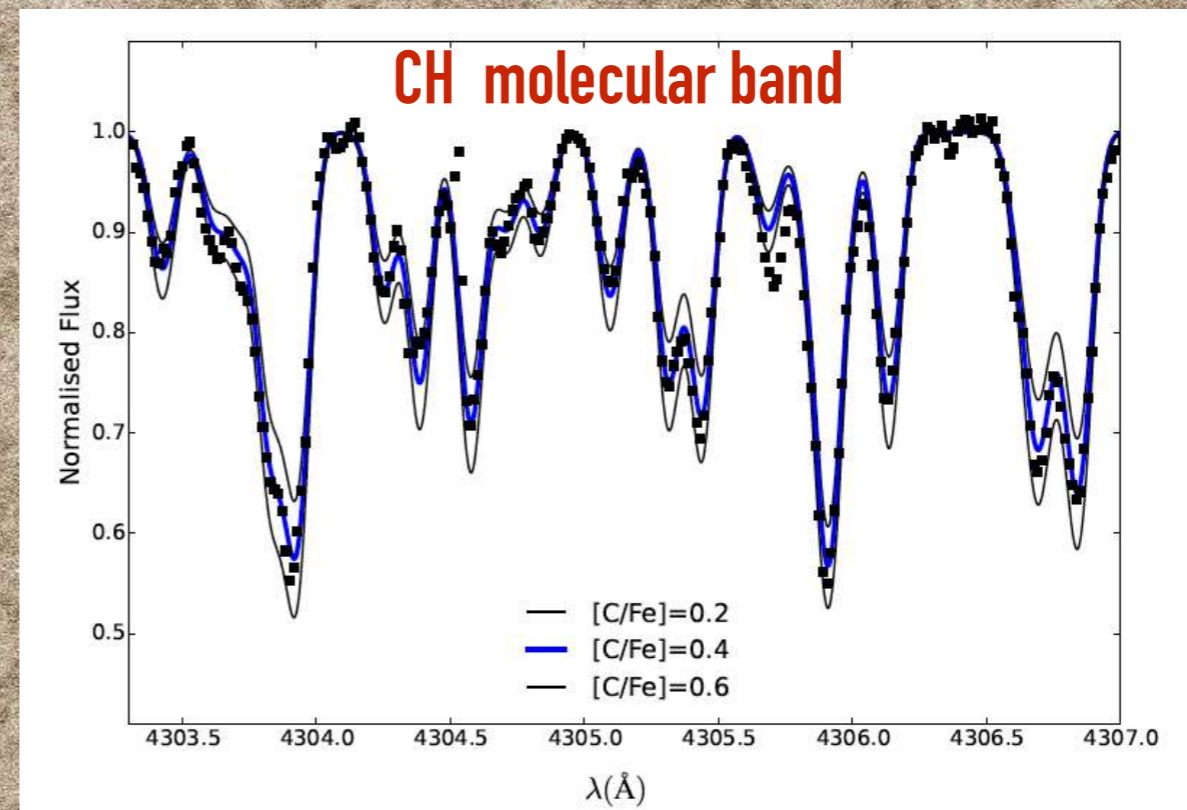


Chemical abundances in stars



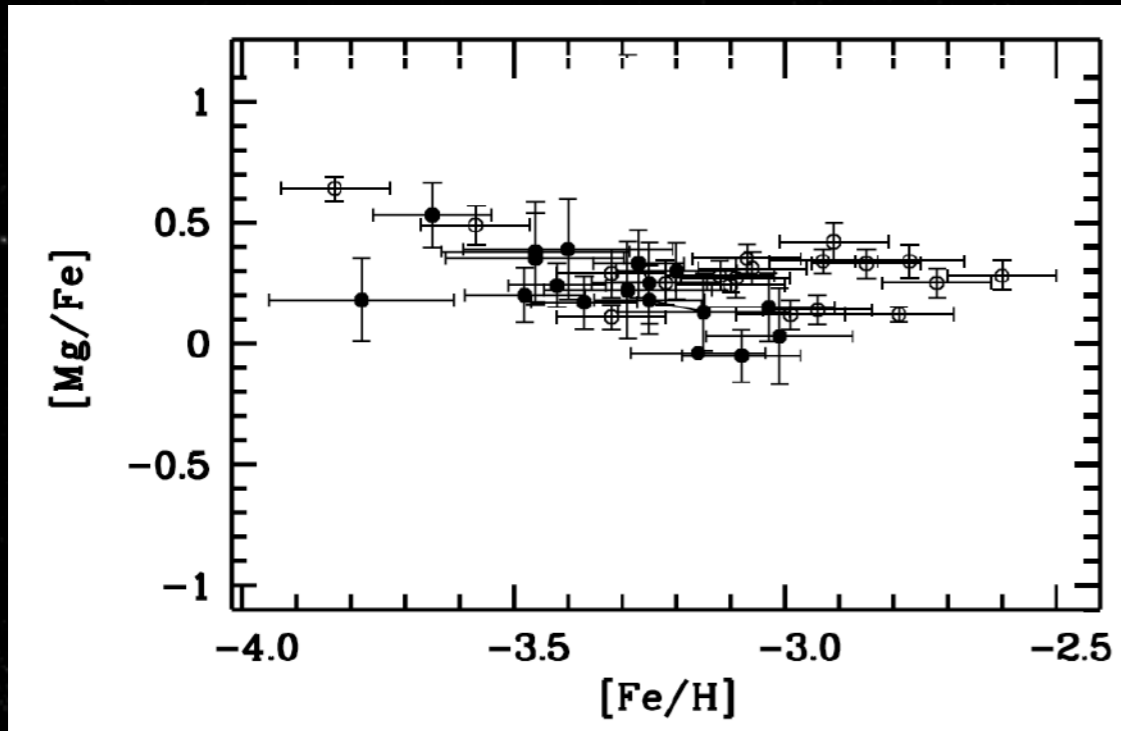
**High resolution
spectra of stars**

**Abundances of
chemical elements**

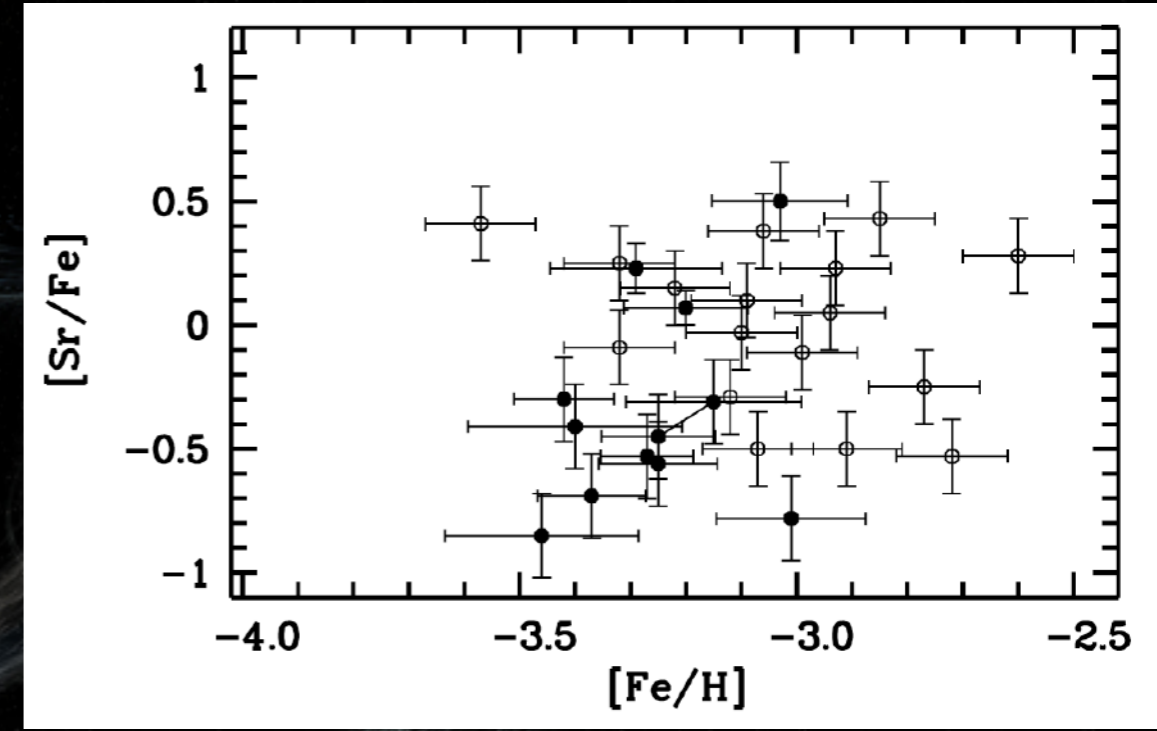


Why neutron capture elements?

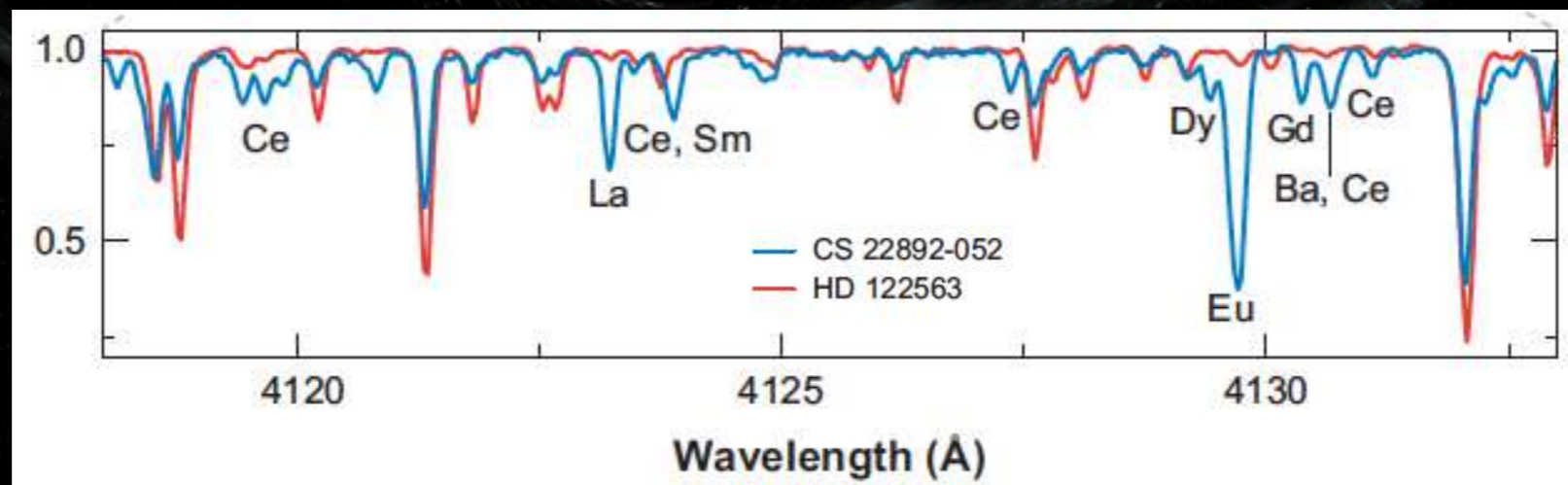
Mg: alpha-element



Sr: neutron capture element

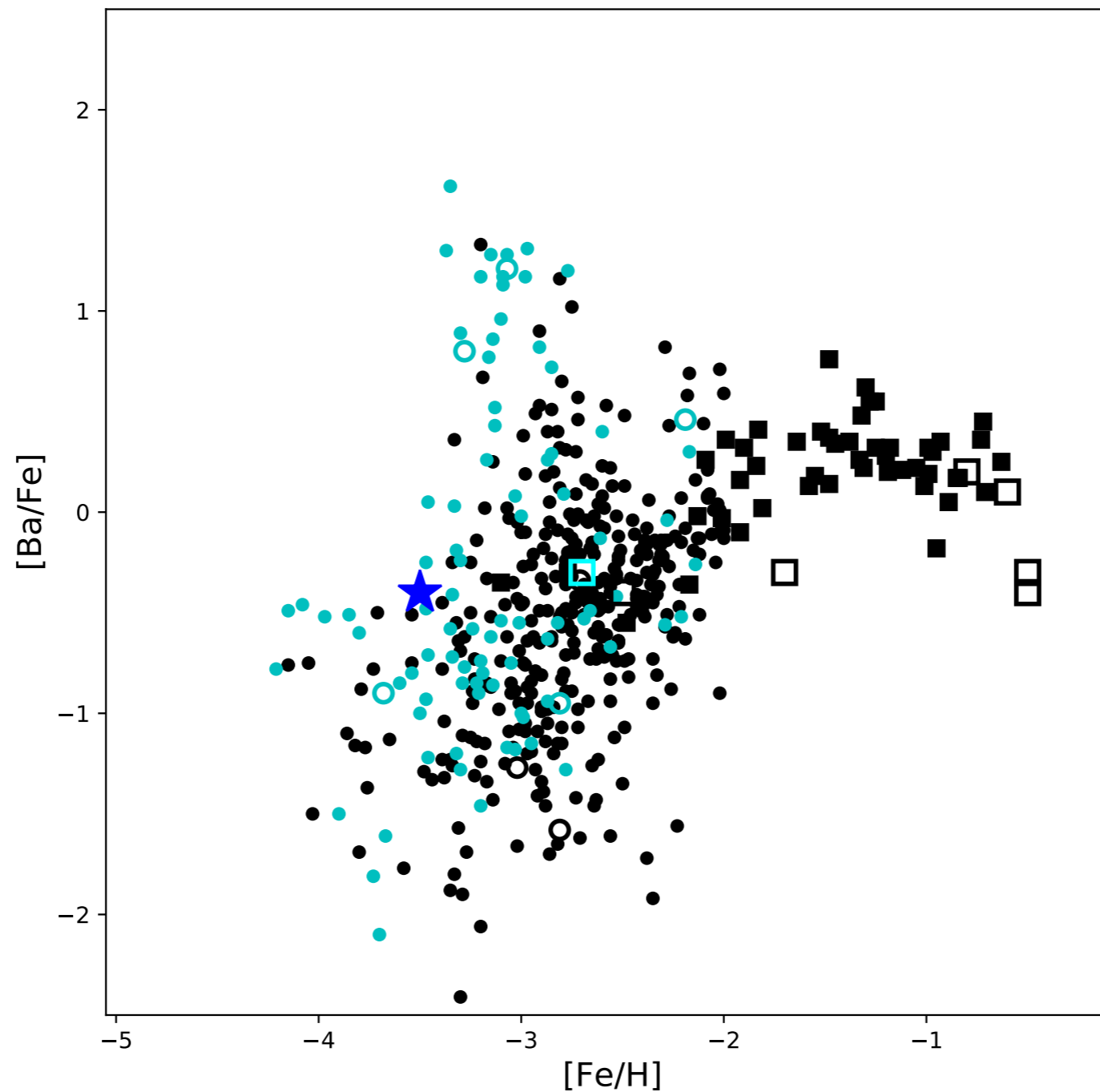


Bonifacio+12



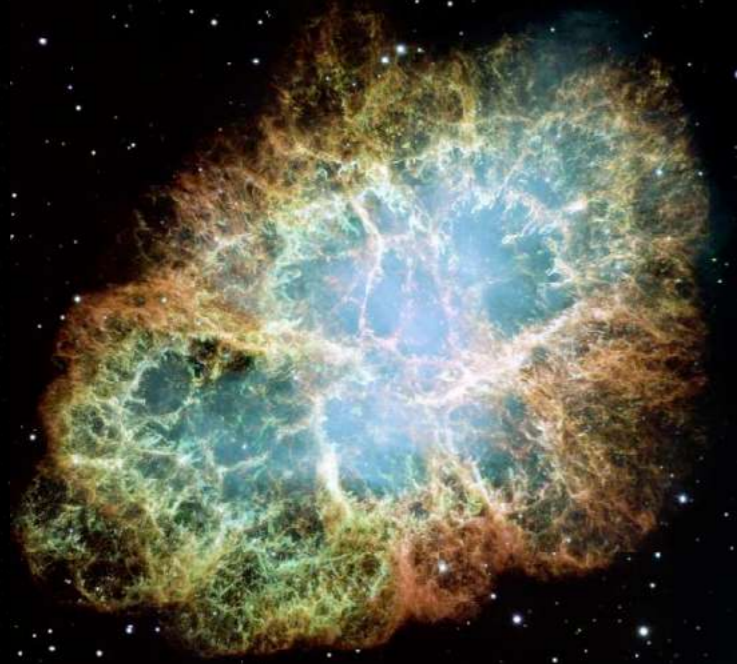
[Ba/Fe] in the Galactic halo

Since McWilliam95 idea of RARE events for r-process events
(see also Primas+94, Ryan+91, Norris+93)



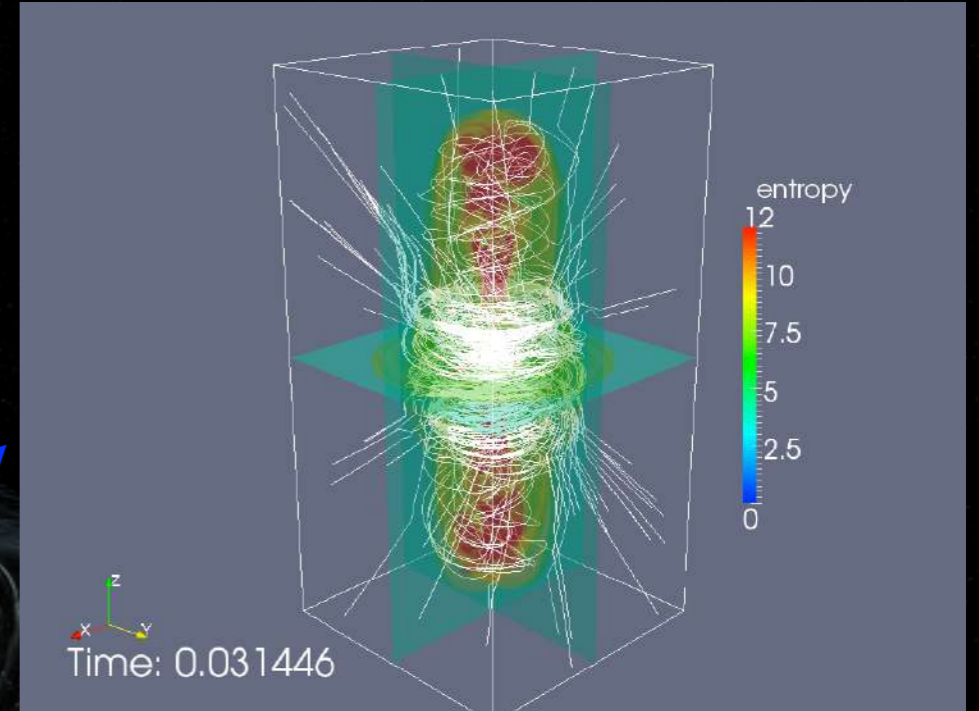
data from in
Placco+14 ● ●
Hansen+12 ■ ■
Hansen+16 □ □
Cescutti+16 ★

Electron Capture SNe (Wanajo+11)



Cescutti+13

Magnetorotat. driven SNe (Winteler+12)



Cescutti+14

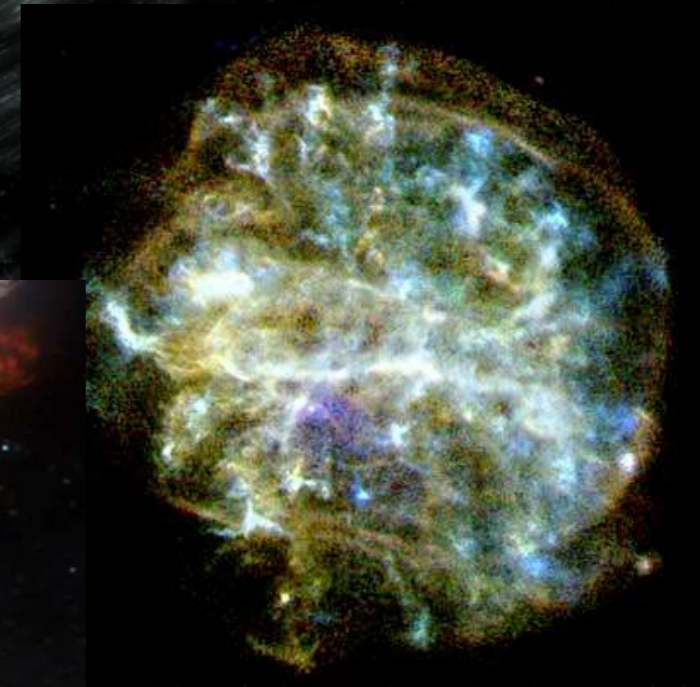
Site(s) of the r-process?

Neutron star mergers (Rosswog+13)



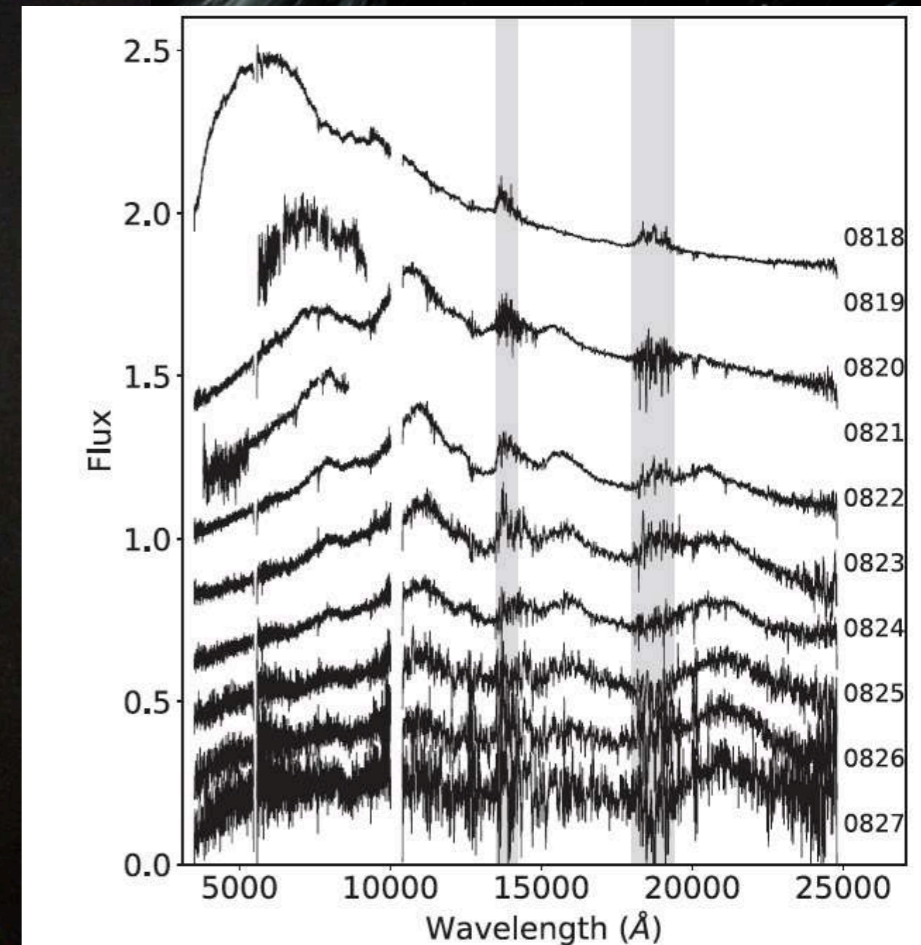
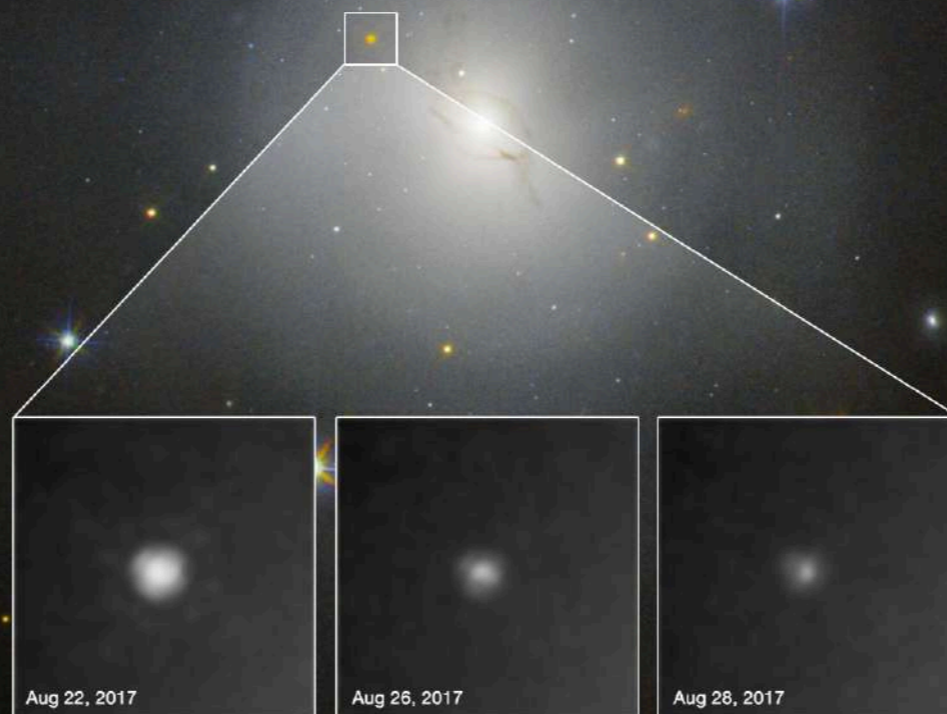
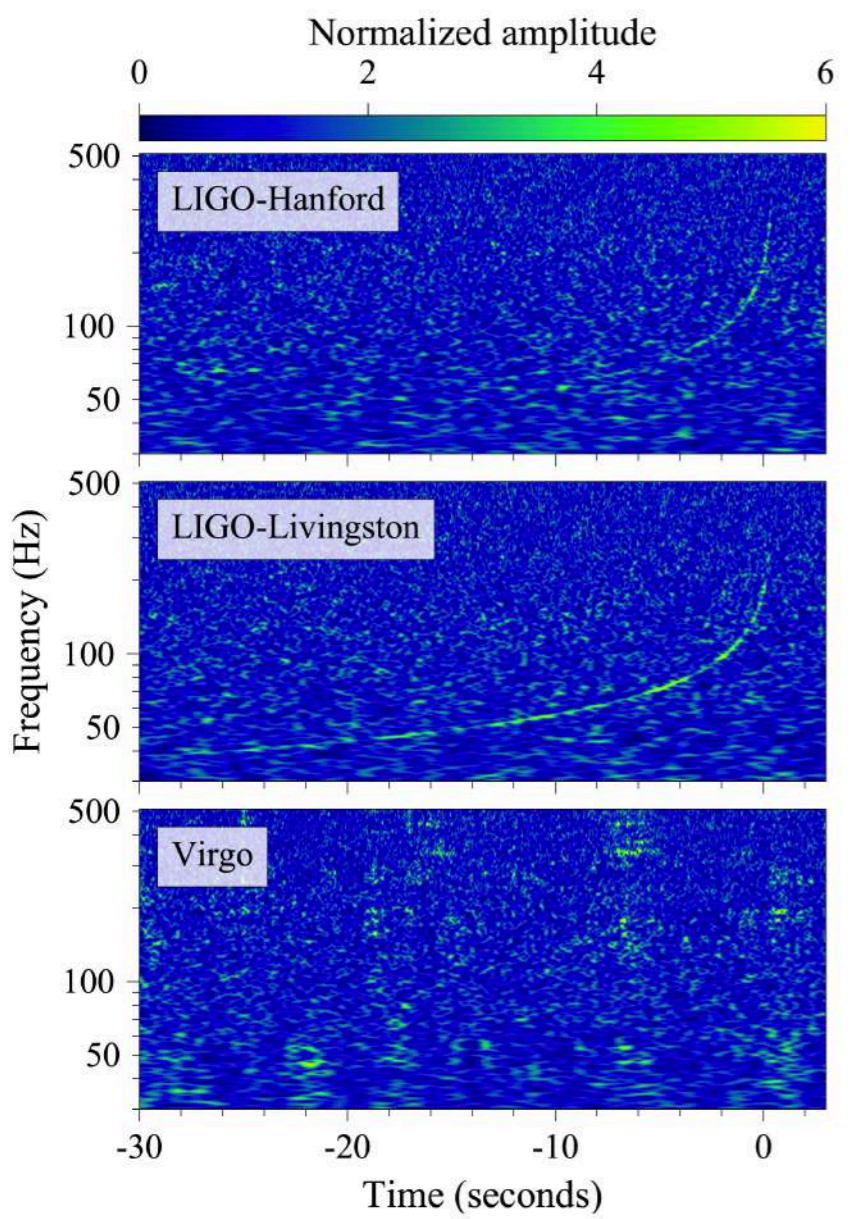
(Cescutti+15, Matteucci+14,...)

Neutrino winds SNe (Arcones+07, Wanajo 13)



Collapsar (Siegel+2019)

After GW170817...

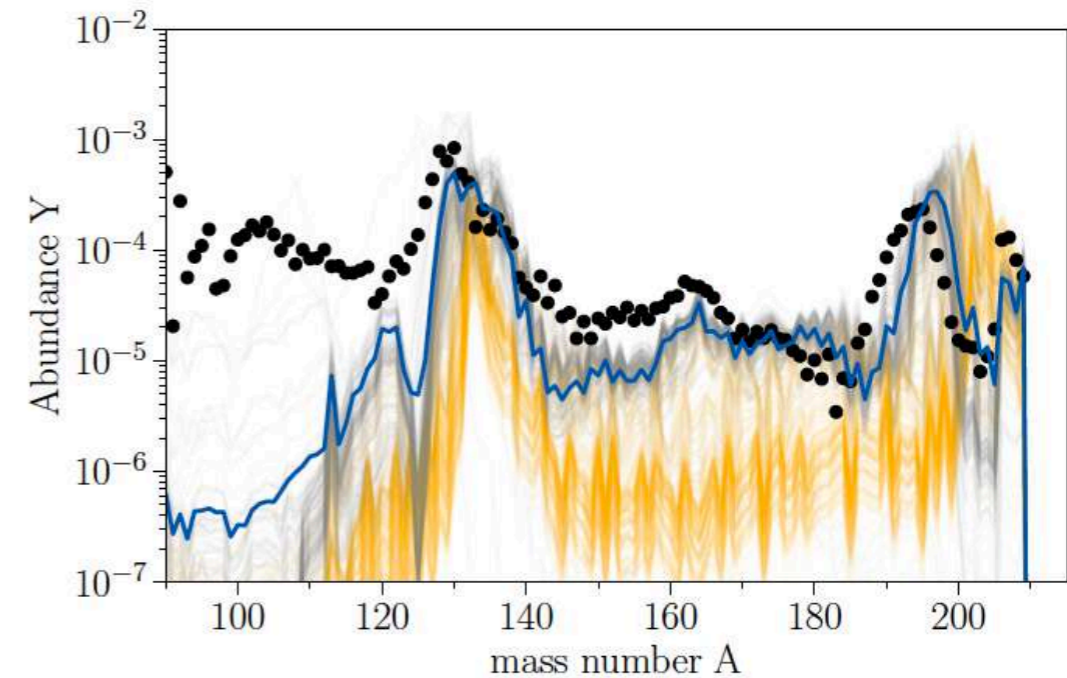
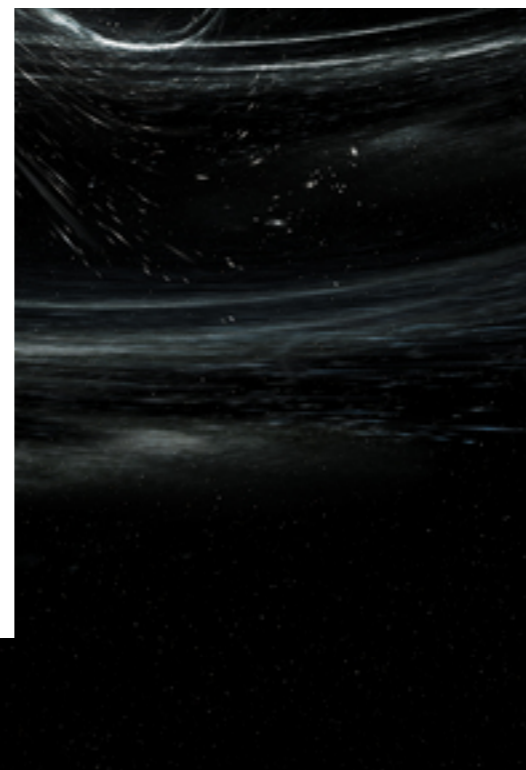
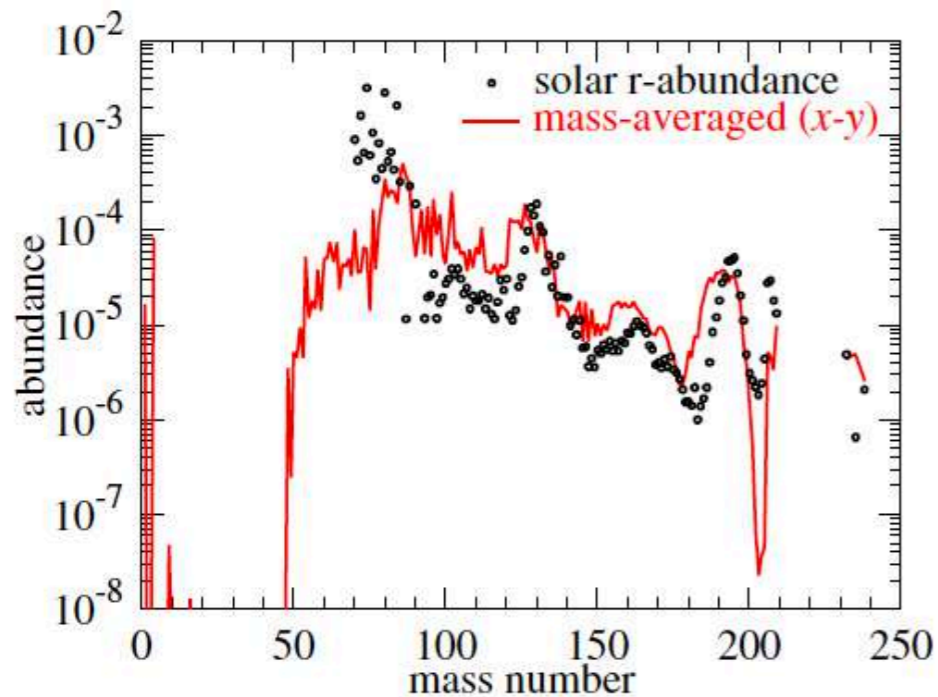
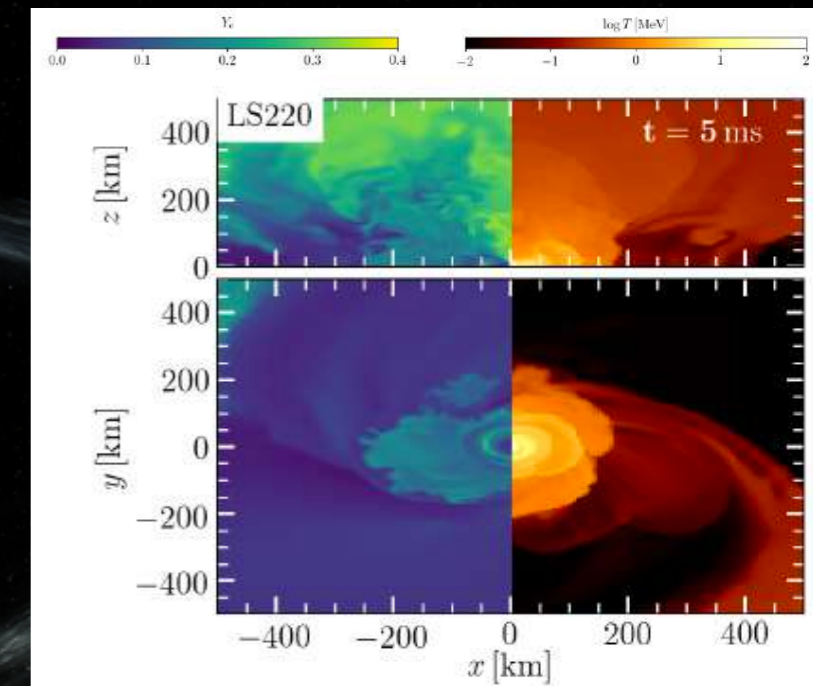
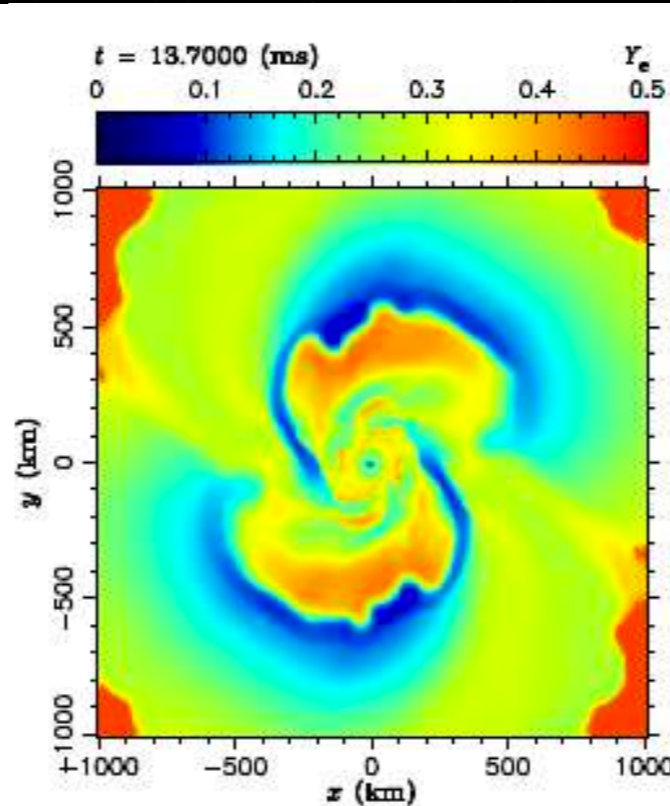
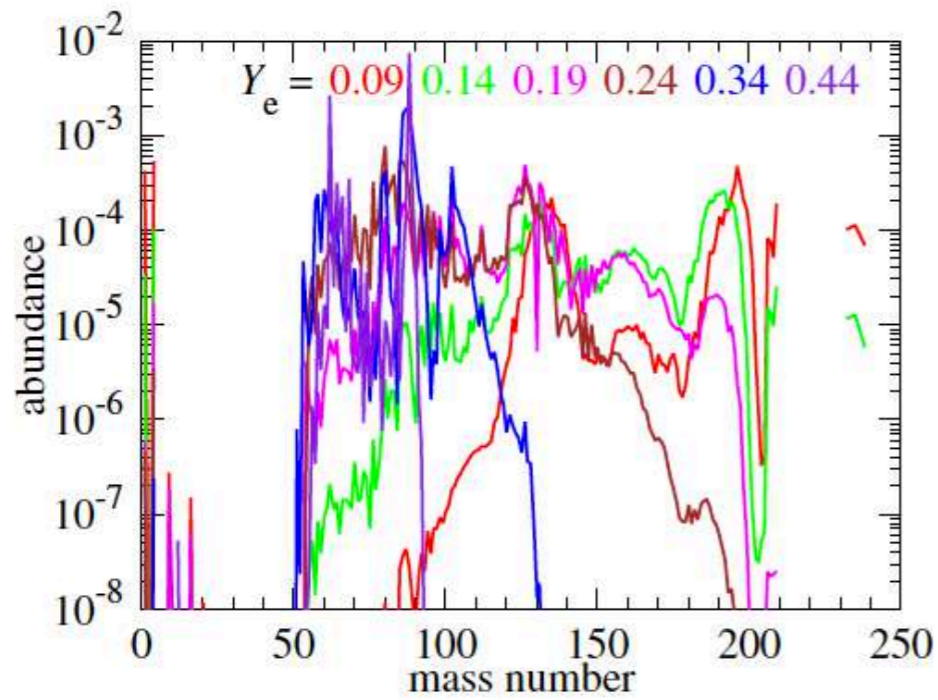


Neutron stars mergers

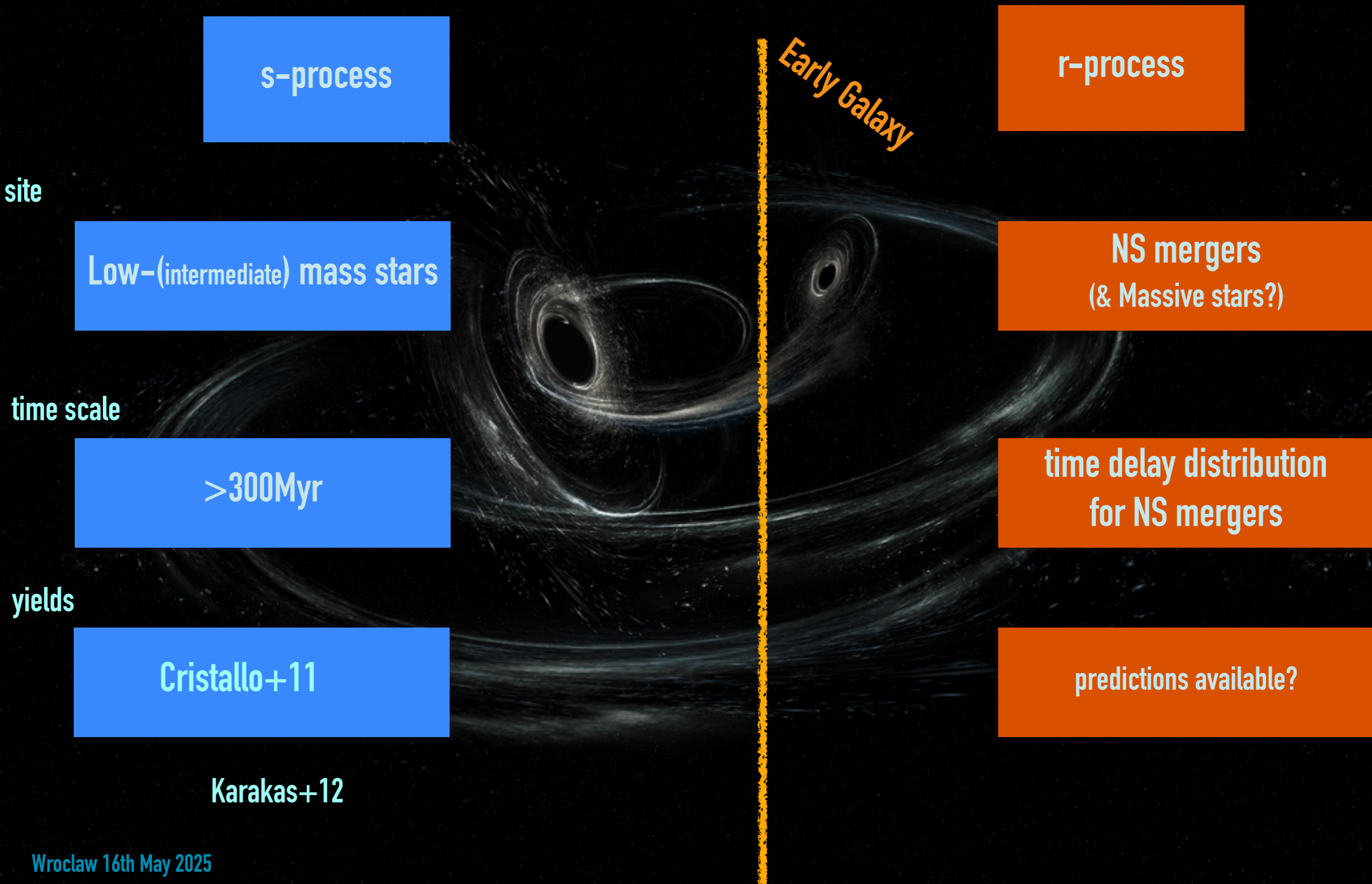
(GR considered, nucleosynthesis computed for the dynamical ejecta)

Wanajo+14

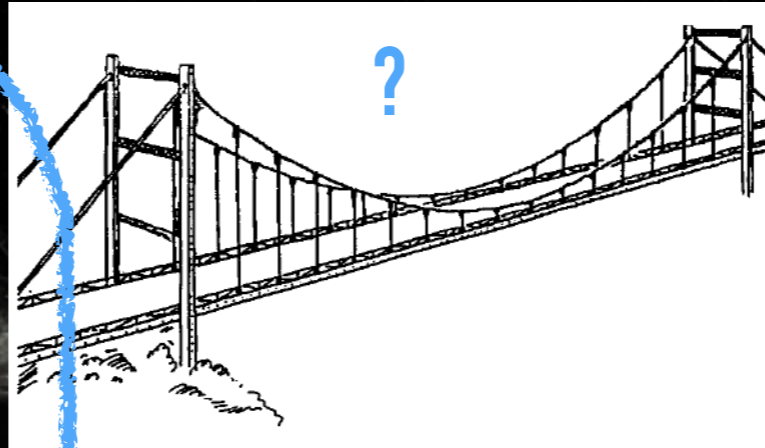
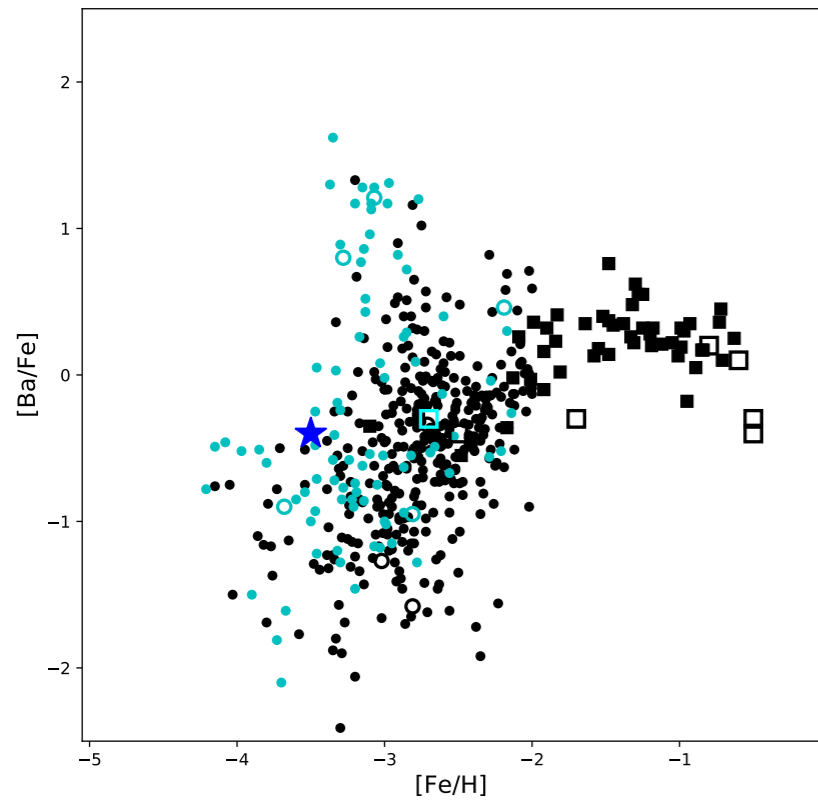
Bovard+17



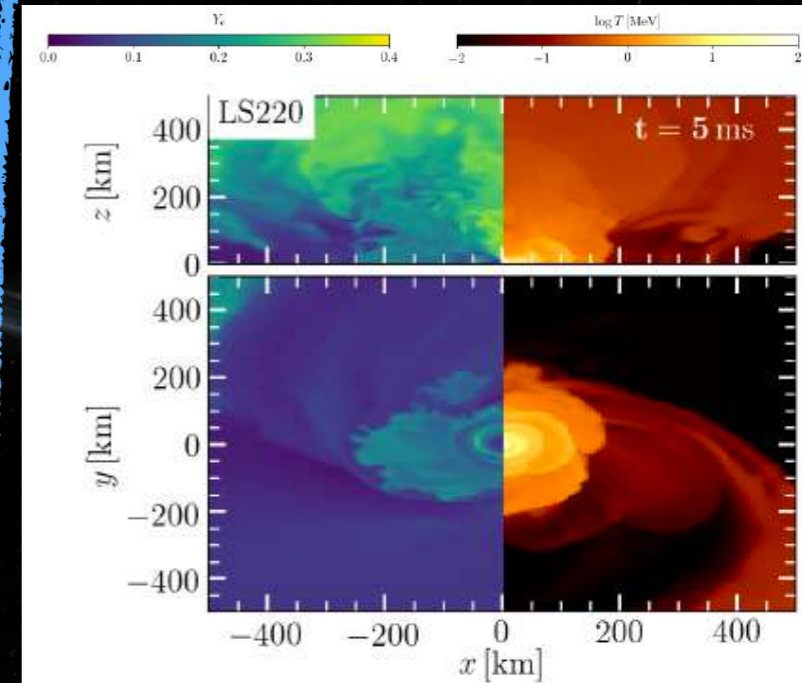
Neutron capture elements



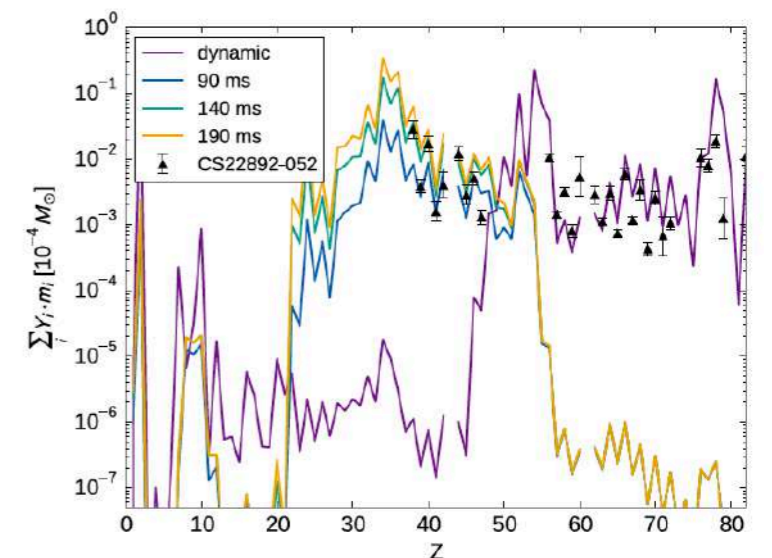
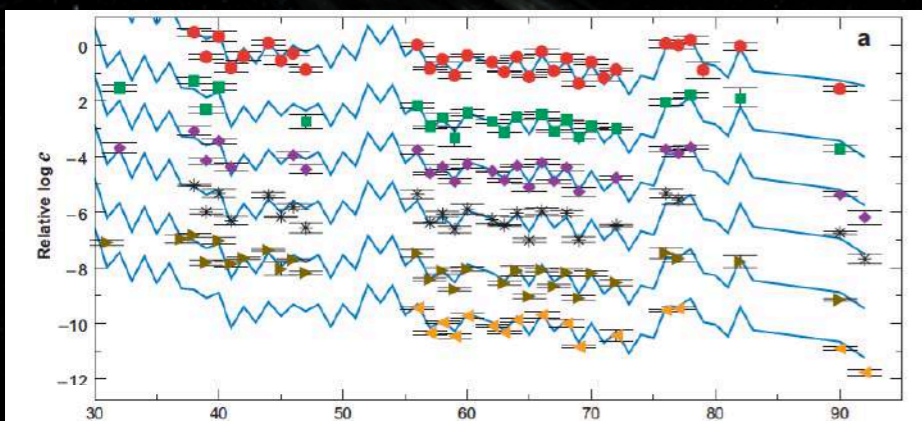
How to?



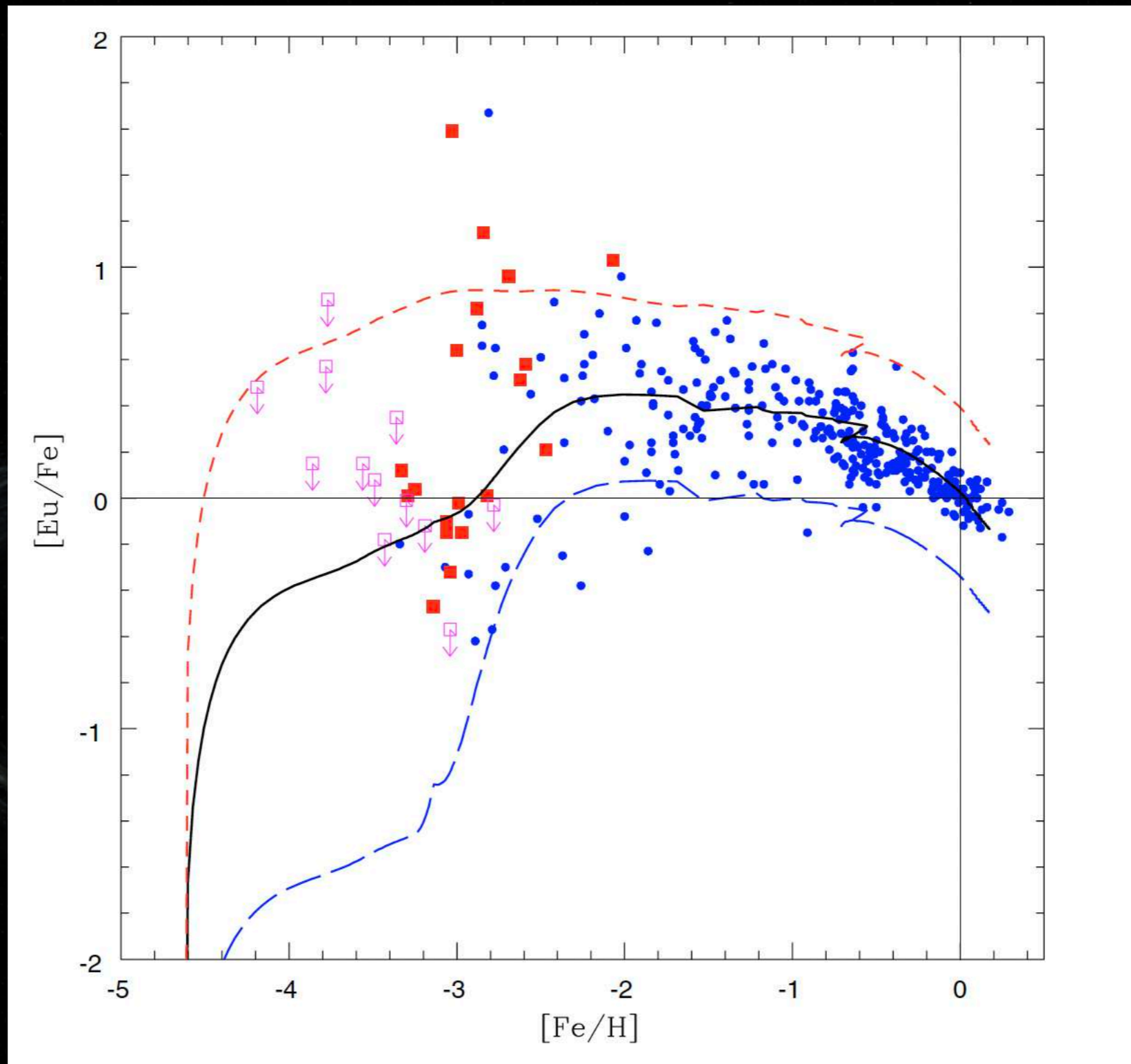
Neutron star mergers



r-process



Usual answer: chemical evolution model



Galactic chemical evolution

An homogeneous model follows the time evolution of the gas fraction of element A with this equation:

1) Locked in stars

2) Infalling in the system

3) Flowing from the system

4) Produced by stars



**Stellar nucleosynthesis
(nuclear reaction rate!)**

Stochastic chemical evolution model

Stars and Neutron star mergers are discrete entities!

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



~ 100 pc

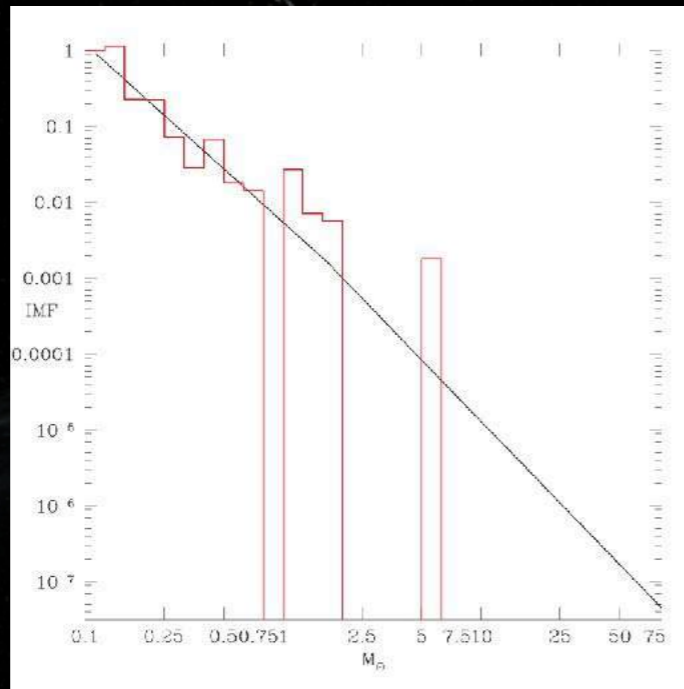
Cescutti (2008)

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

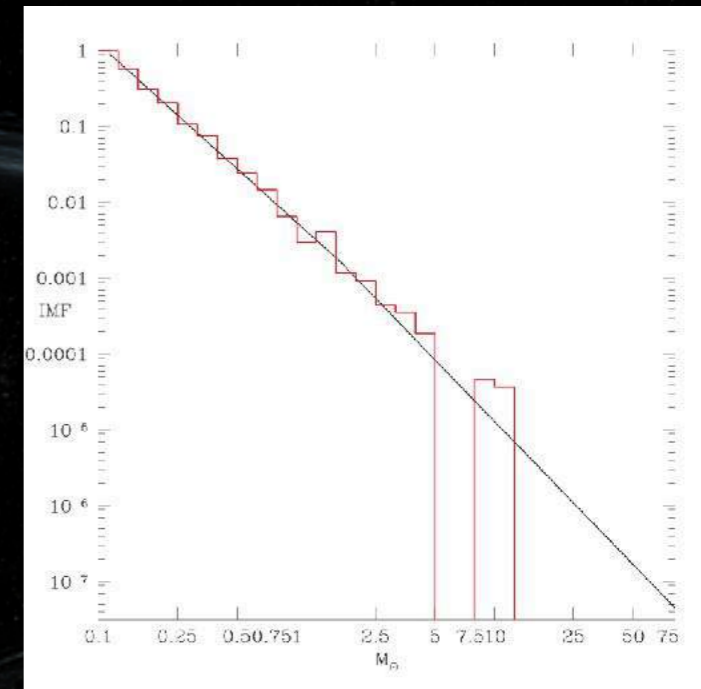
Stochastic formation of stars

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.

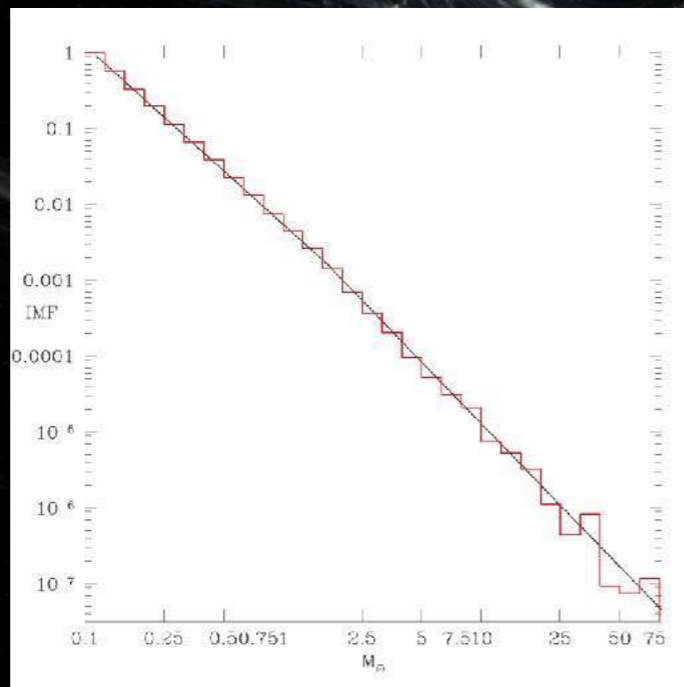
50 stars



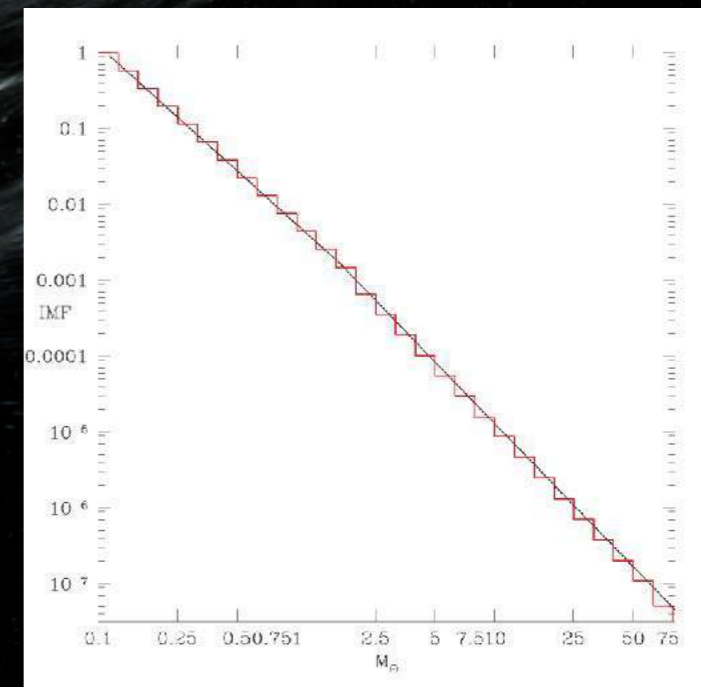
1000 stars



10^5 stars

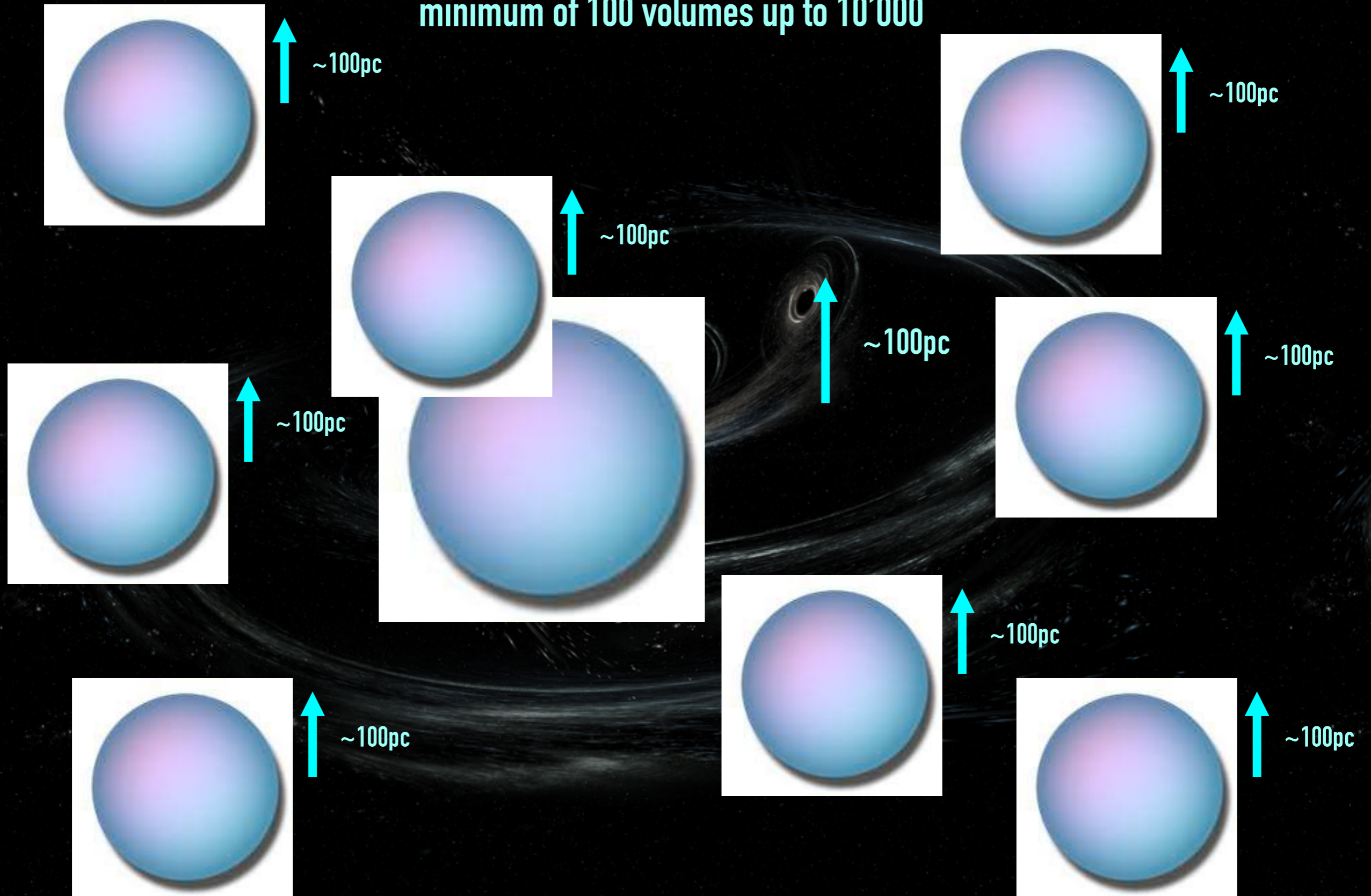


10^7 stars



Stochastic chemical evolution models

minimum of 100 volumes up to 10'000

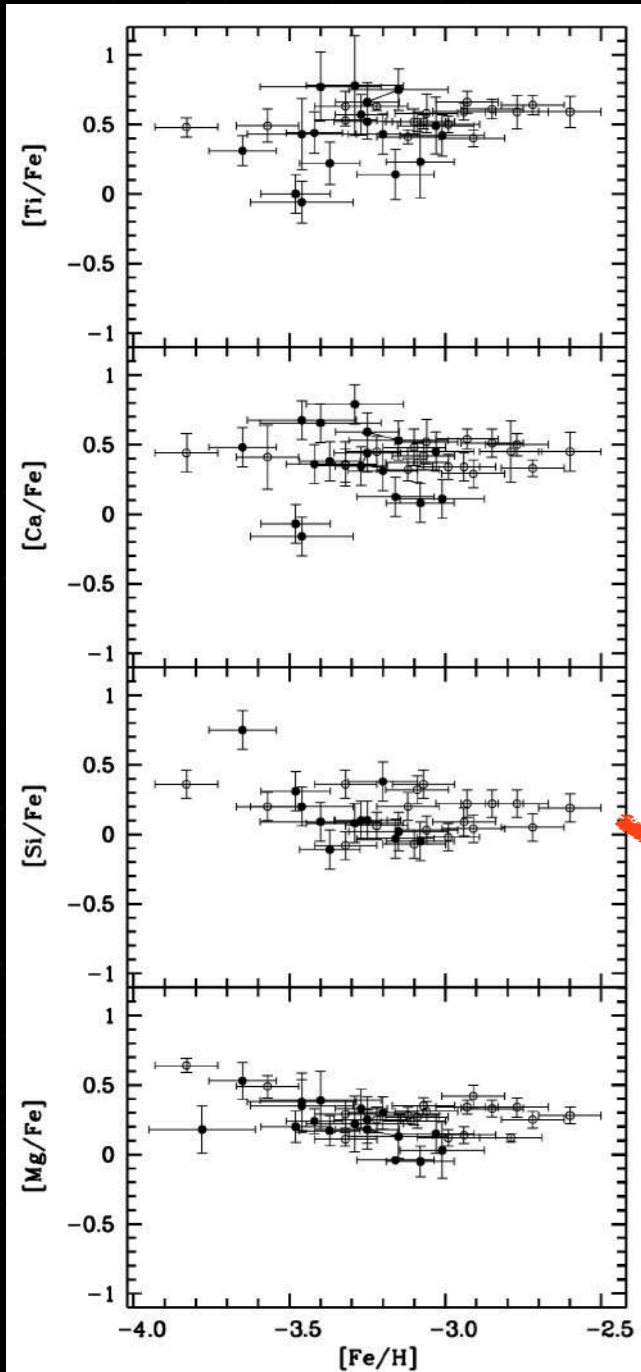


Stochastic chemical evolution models

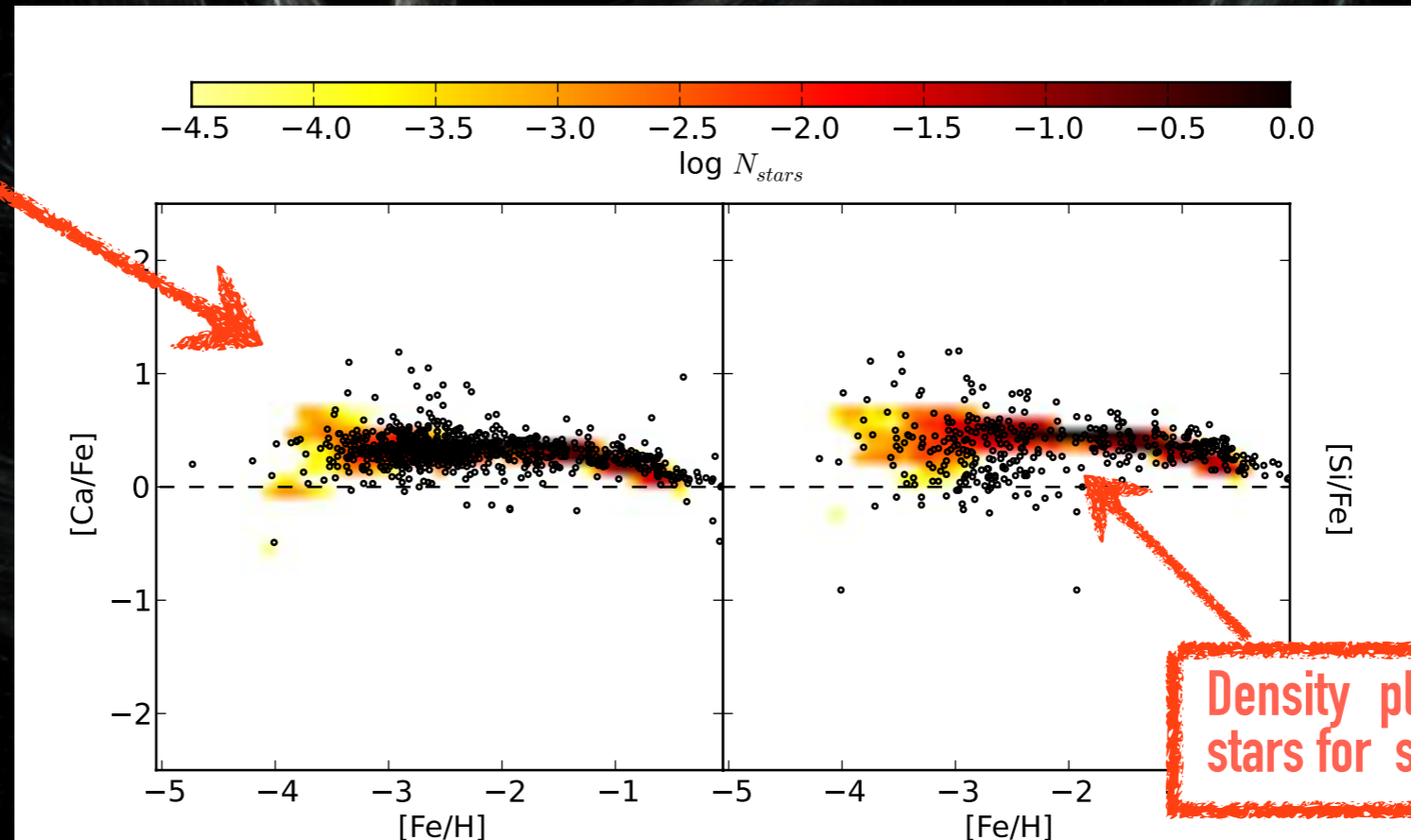
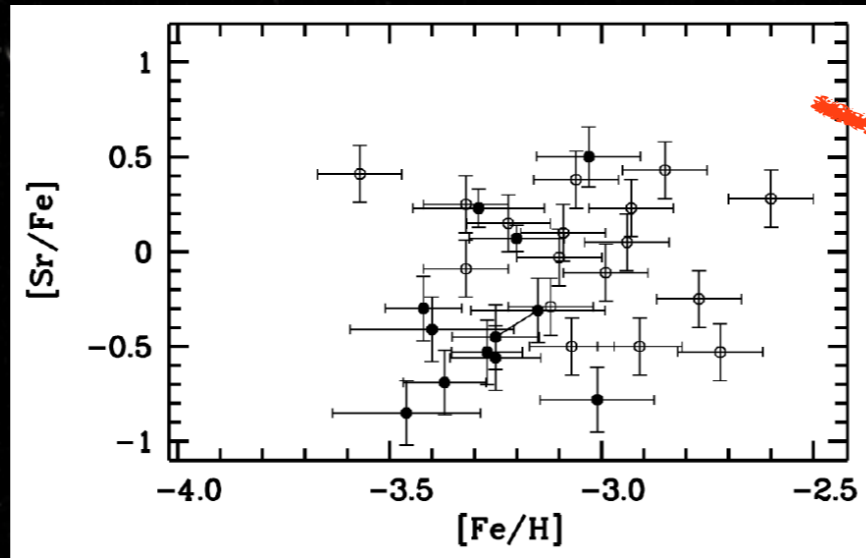
Problem:
Neutron capture elements present
a spread alpha elements do not

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 different among different SNe,



Bonifacio+12



Cescutti 2008
Cescutti et al. 2013

data collected in
Frebel 2010

Density plot of long living
stars for stochastic model

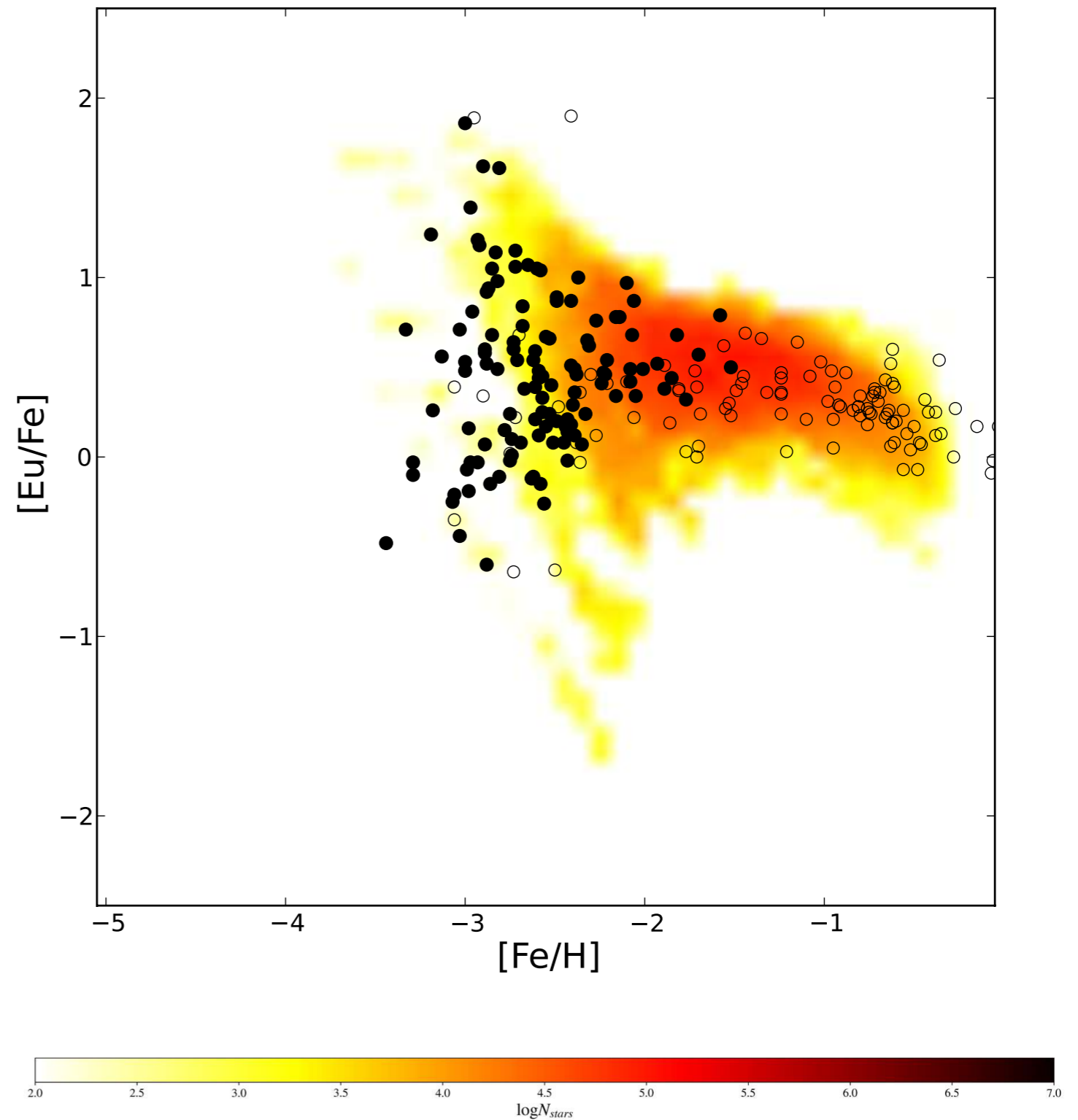
Neutron stars mergers

delay for the merging 1 Myr

Cescutti, Romano, Matteucci,
Chiappini and Hirschi 2015

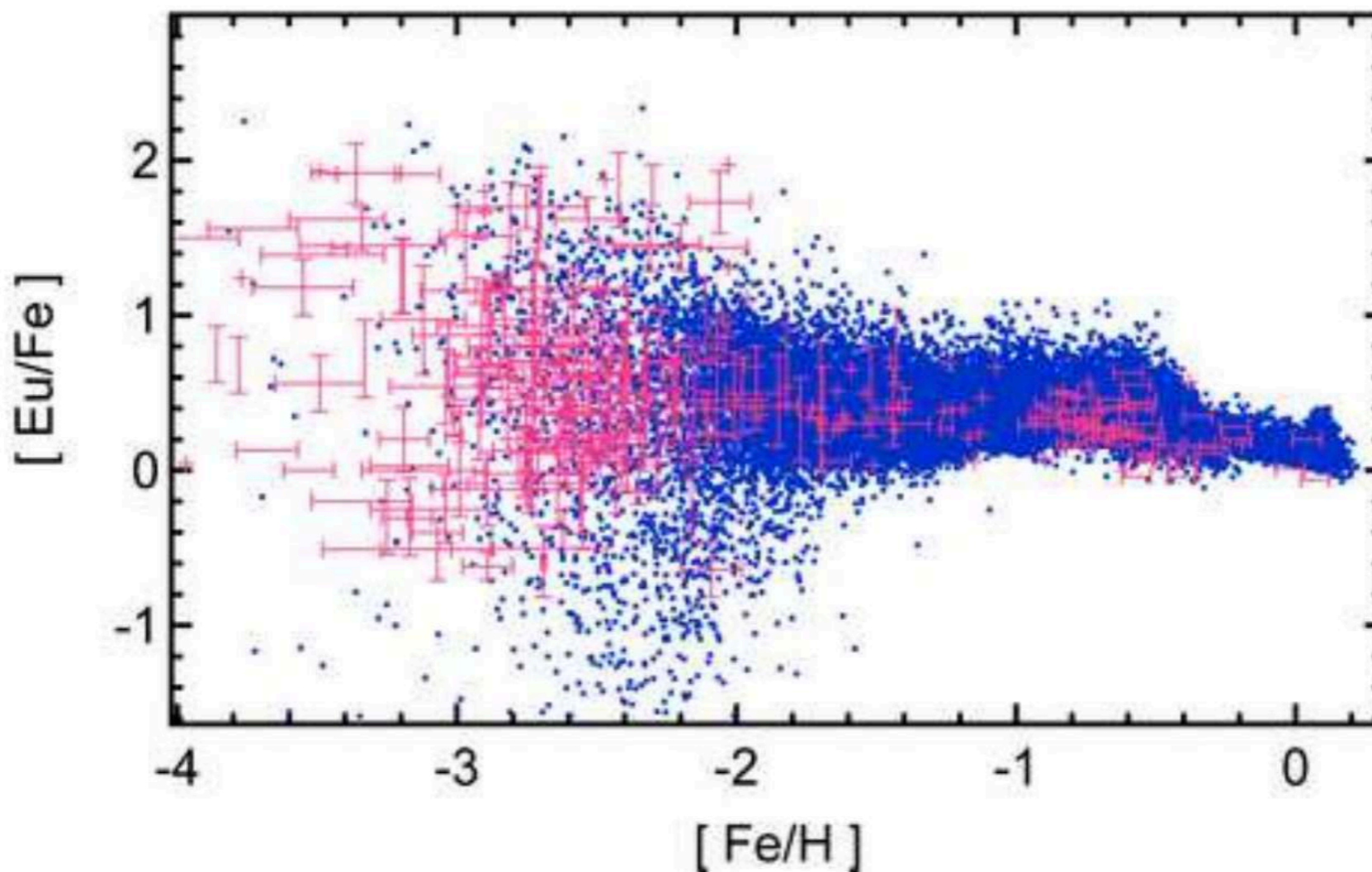
Results with $\alpha=0.04$
(NSM/SNe)

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



not a novelty . . .

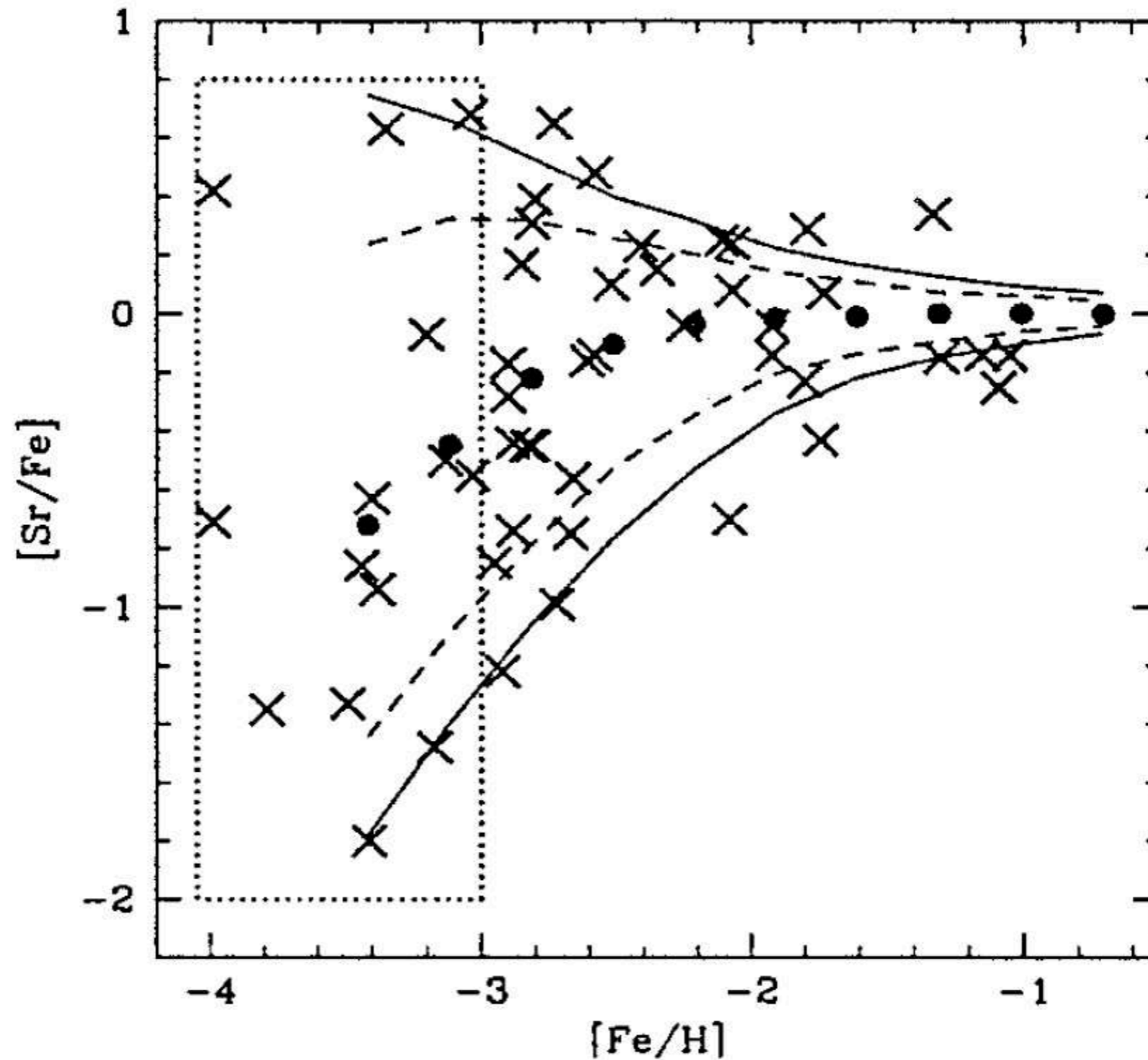
Wehmeyer+15



See also Tsujimoto+99, Ishimaru&Wanajo 99, Argast+01

not a novelty . . .

McWilliam&Searle1999



See also Tsujimoto+99, Ishimaru&Wanajo 99, Argast+01,
Komiya+2014,

Neutron star mergers

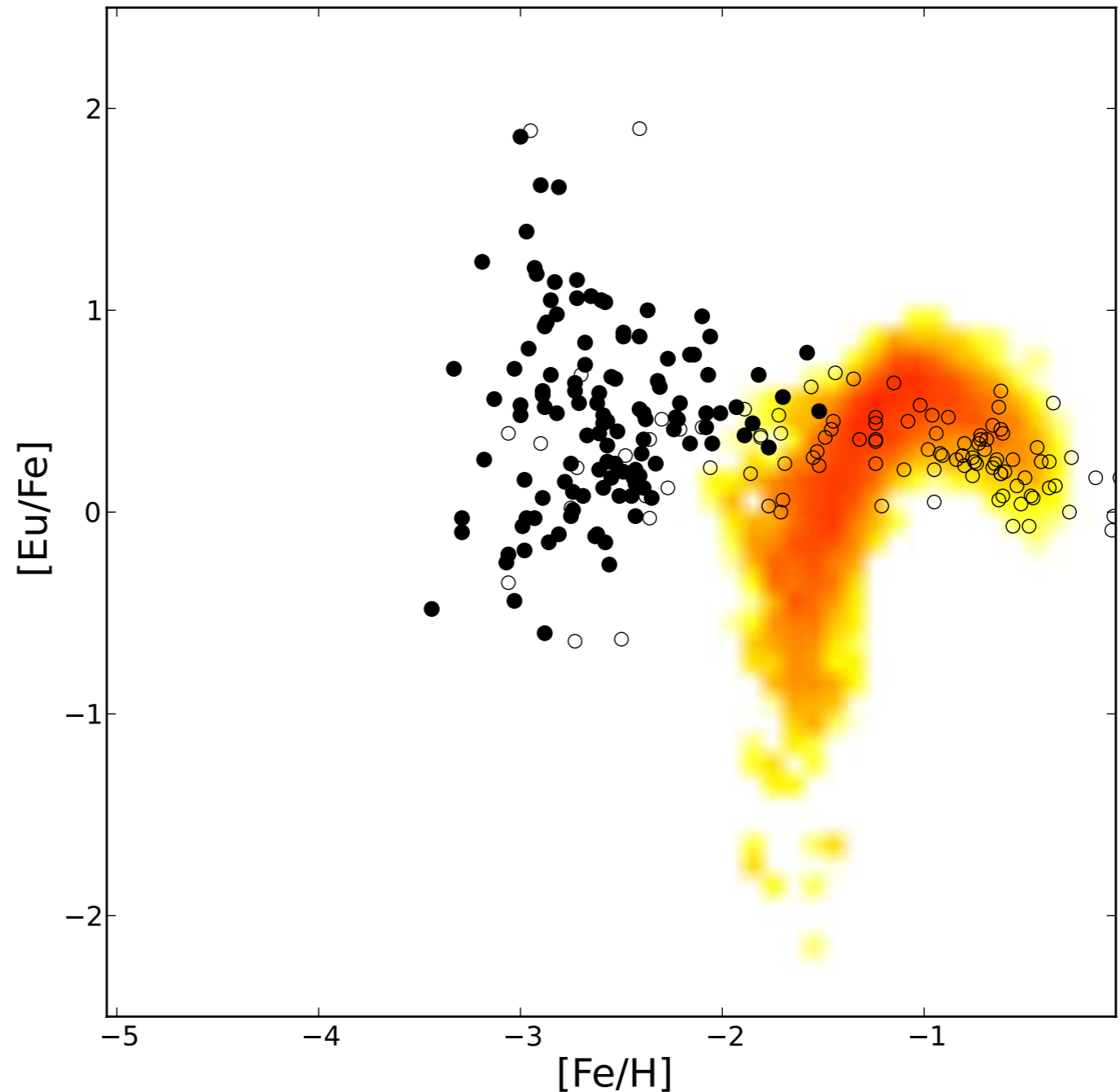
delay for the merging 100 Myr

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 < 10 Myr, the scenario can be supported.

What about a distribution of delays?

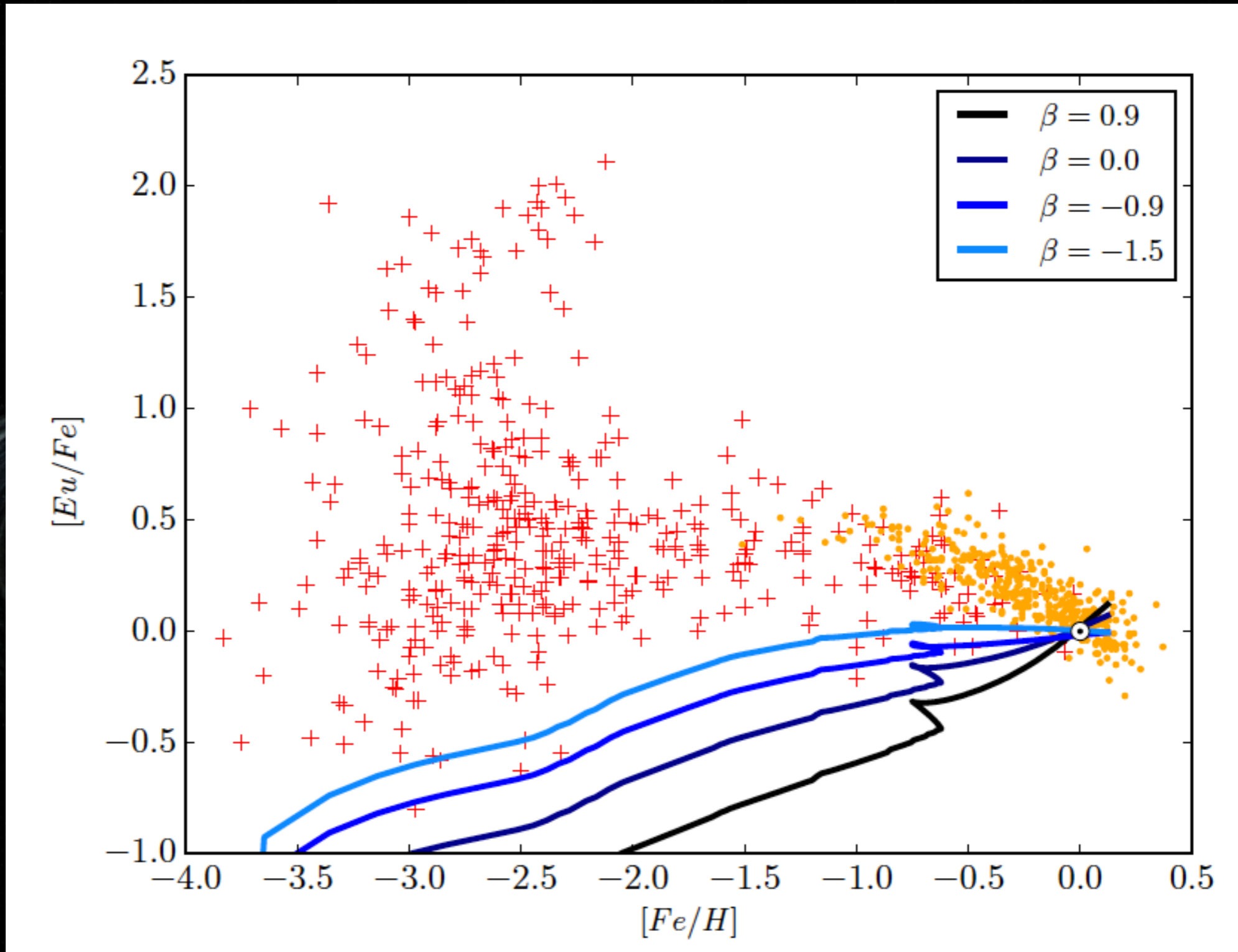


This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the astro-ph Shen+2014

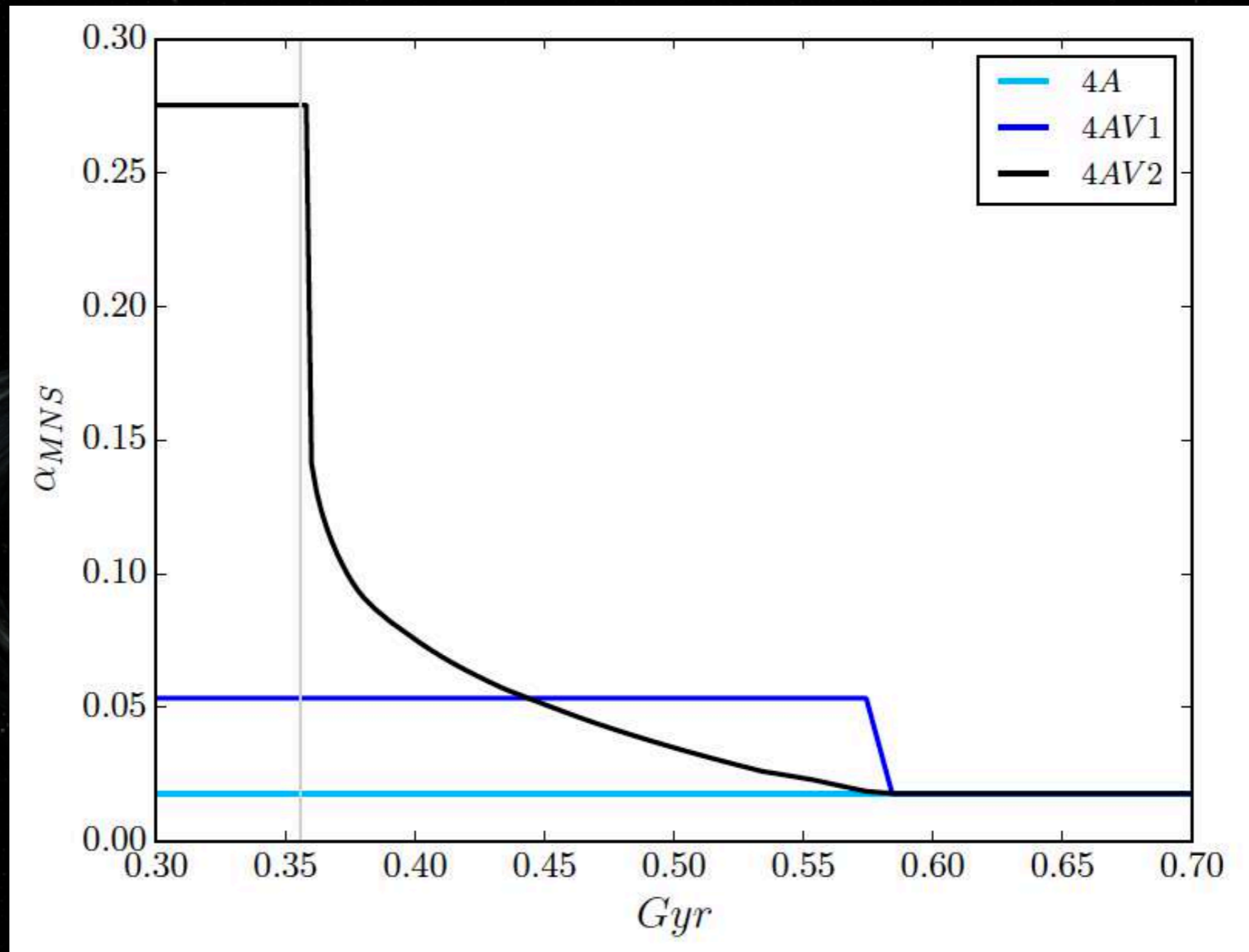
Detailed DTD for NSM

Simonetti+19

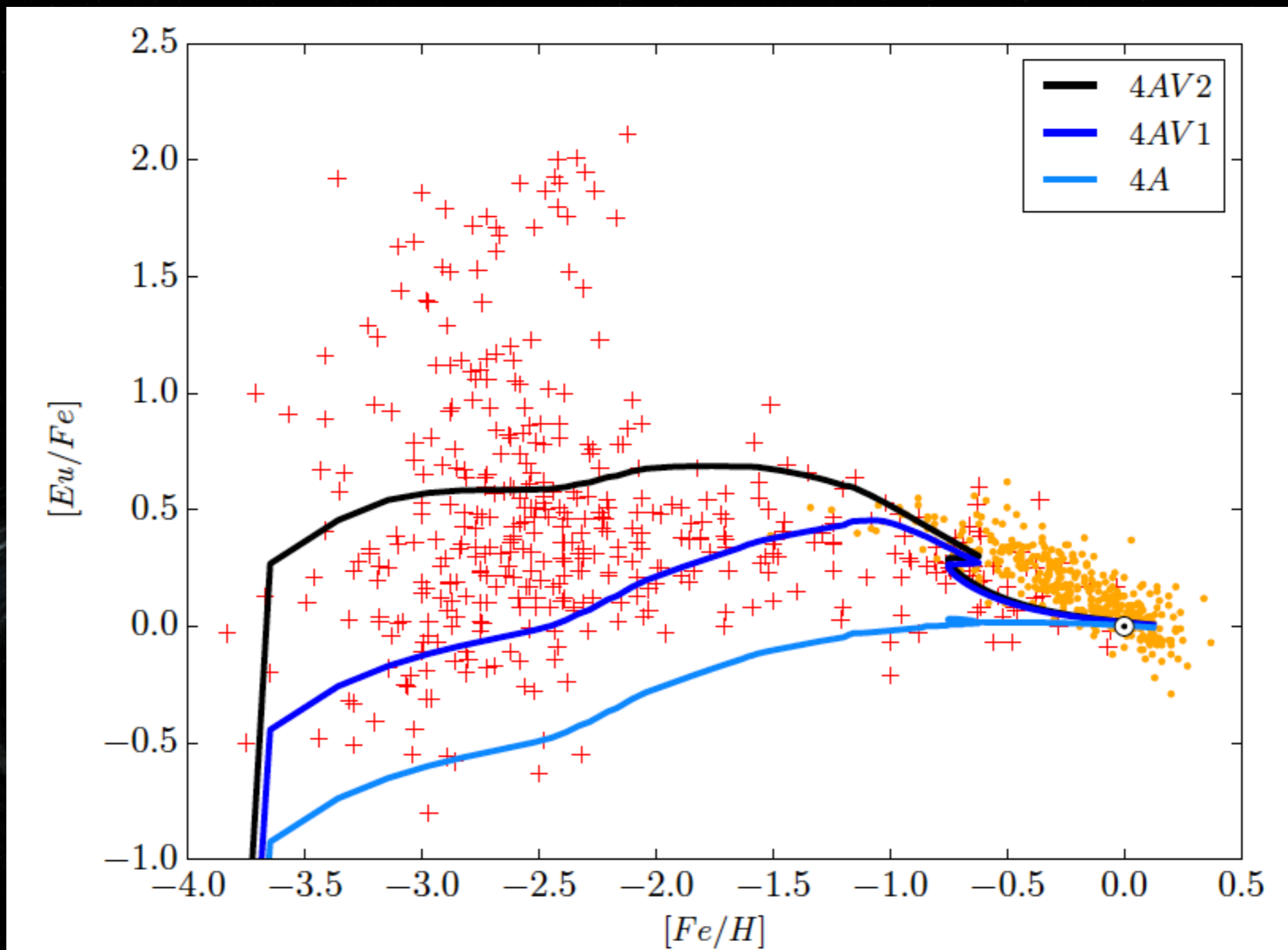
see also Cotè+19



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



Models with detailed DTD for NSM



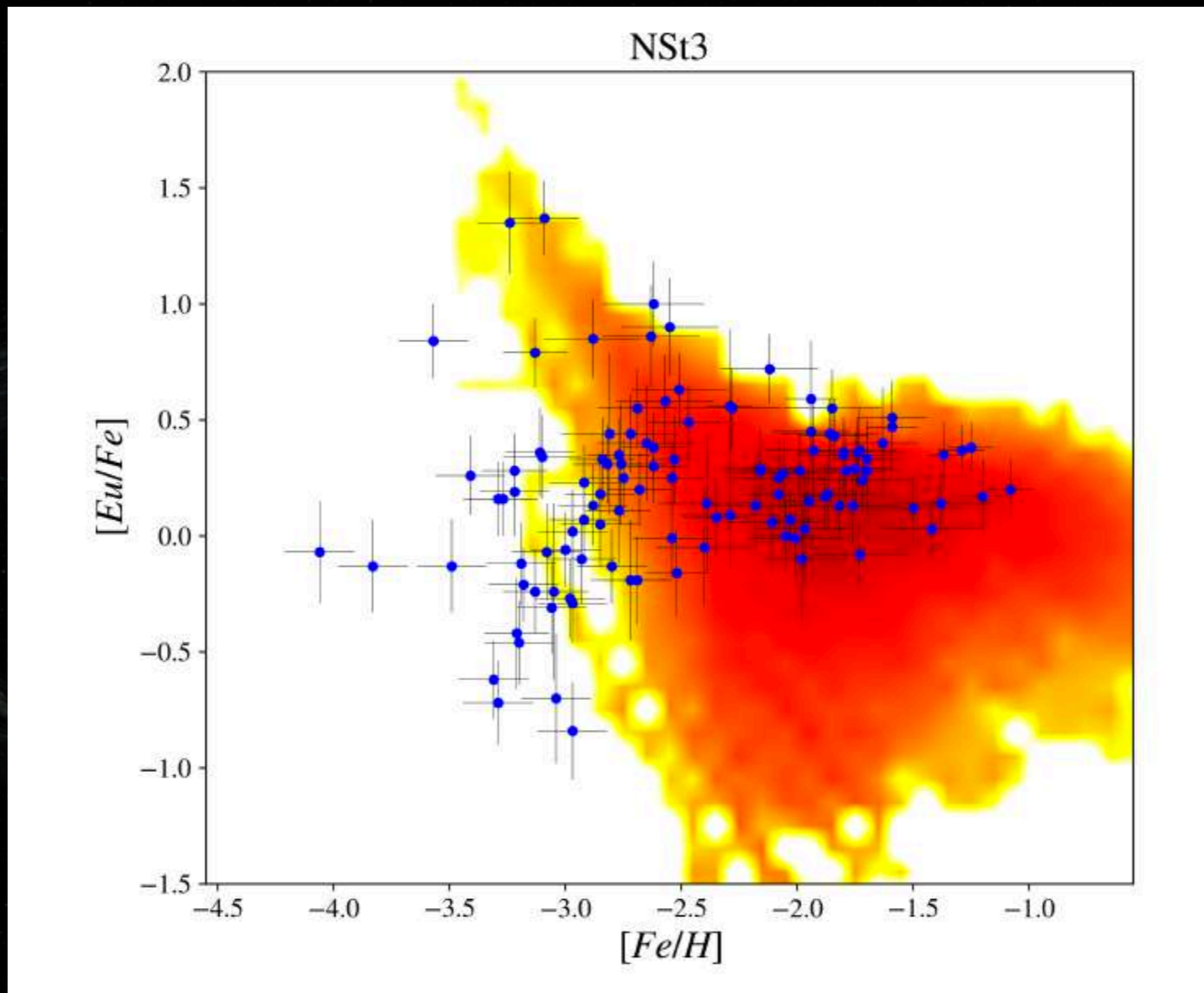
variation of alpha, possible solution!

see also Schoenrich&Weinberg19

Simonetti+19

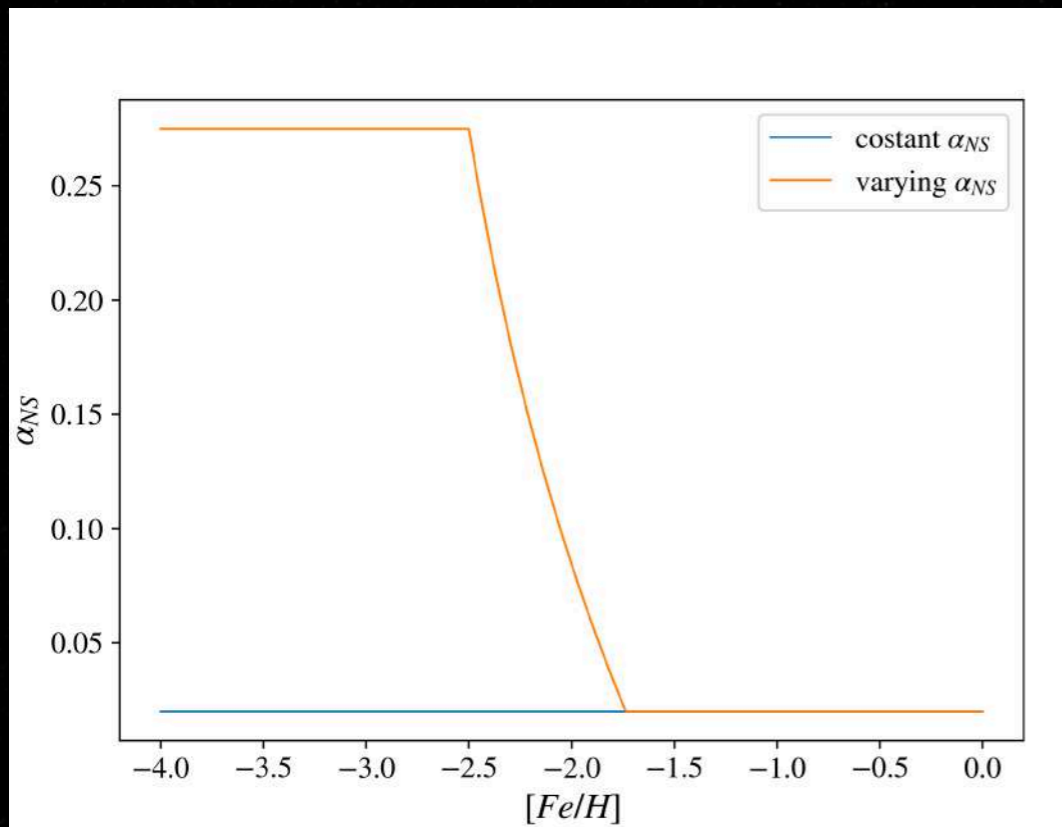
Stochastic model

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

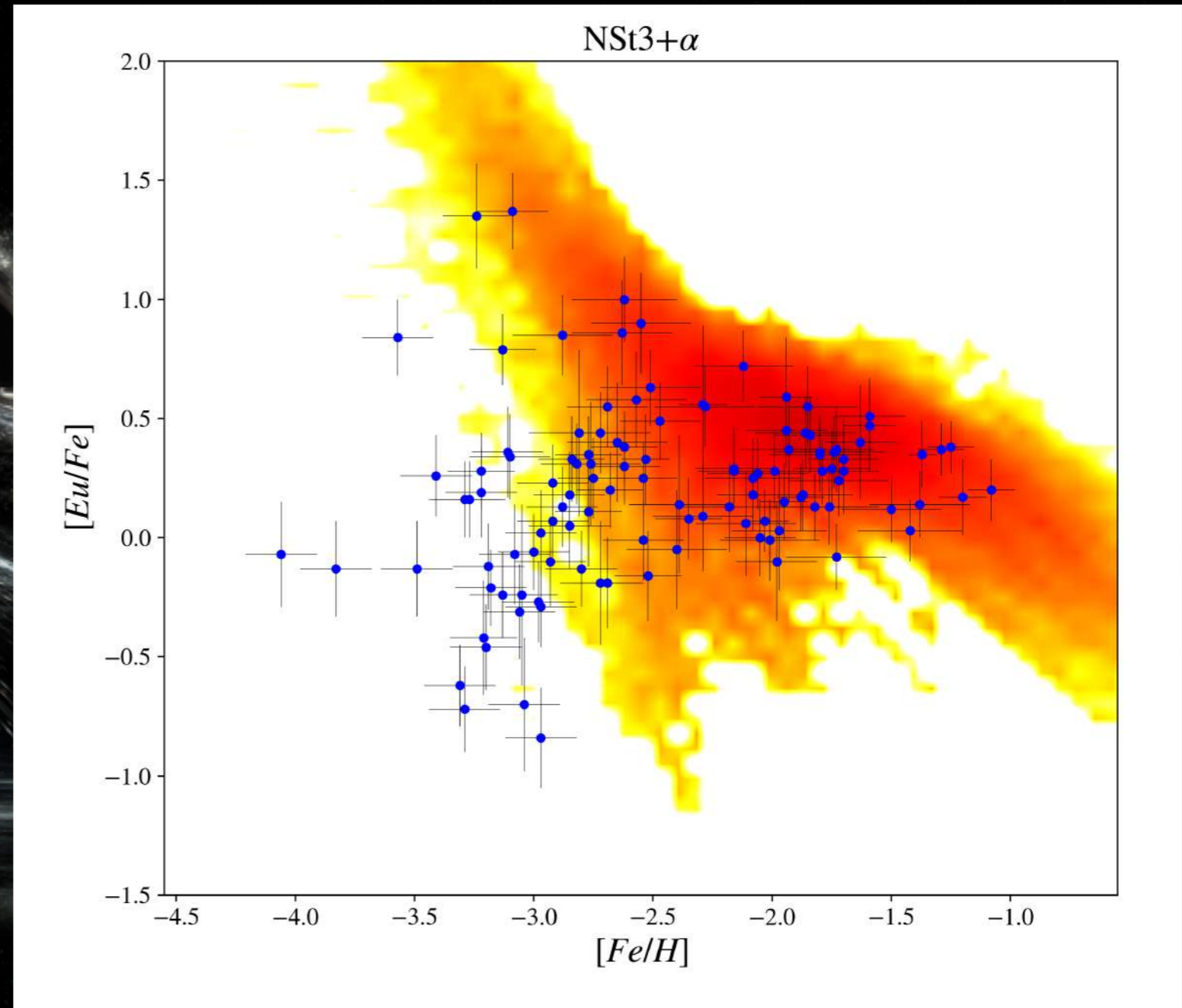


NSM with alpha variations

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



similar to Simonetti+19



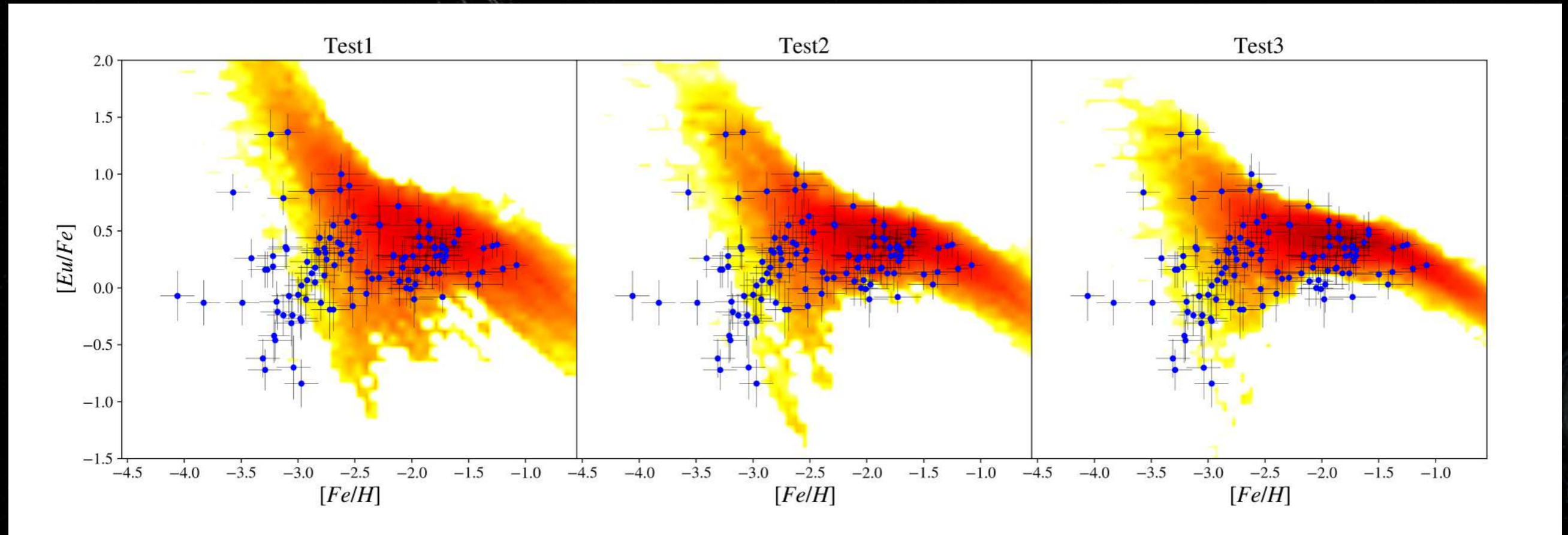
Cavallo+22

How to constrain the fraction of NSM?

alpha=0.02

alpha=0.06

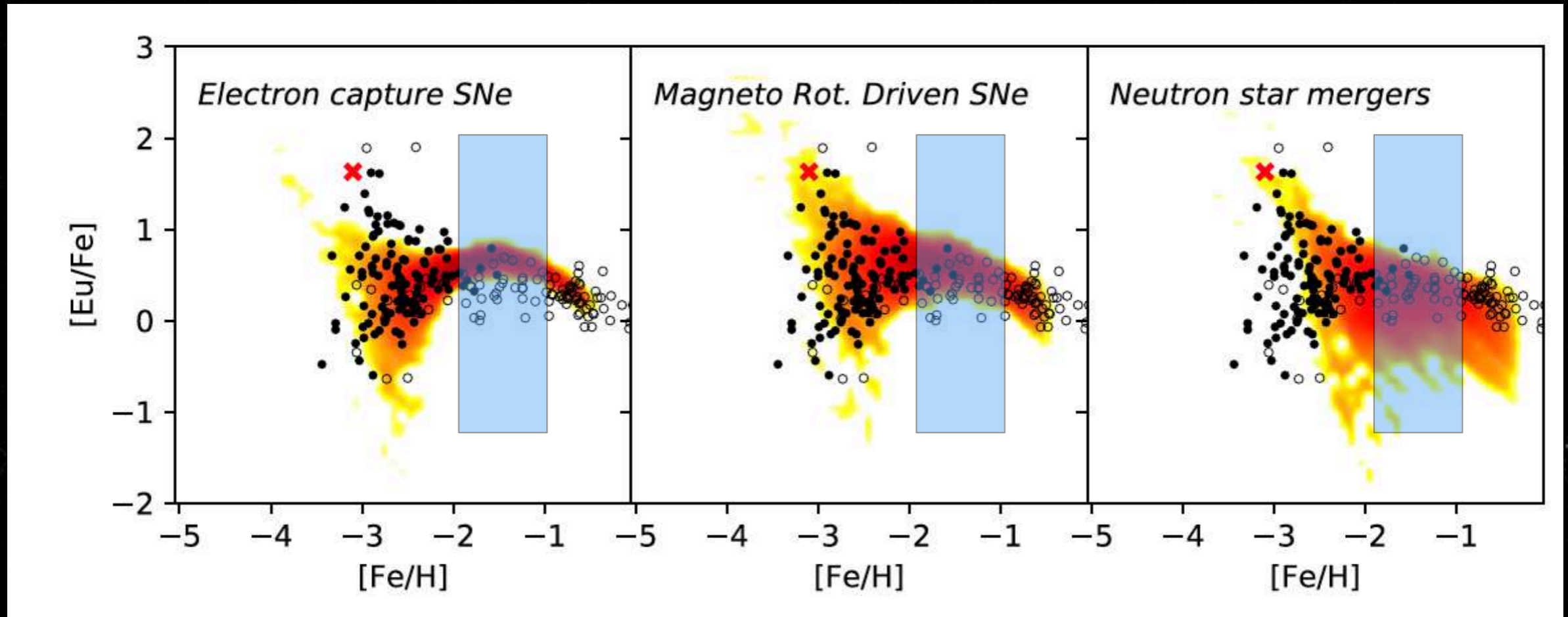
alpha=0.1



[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

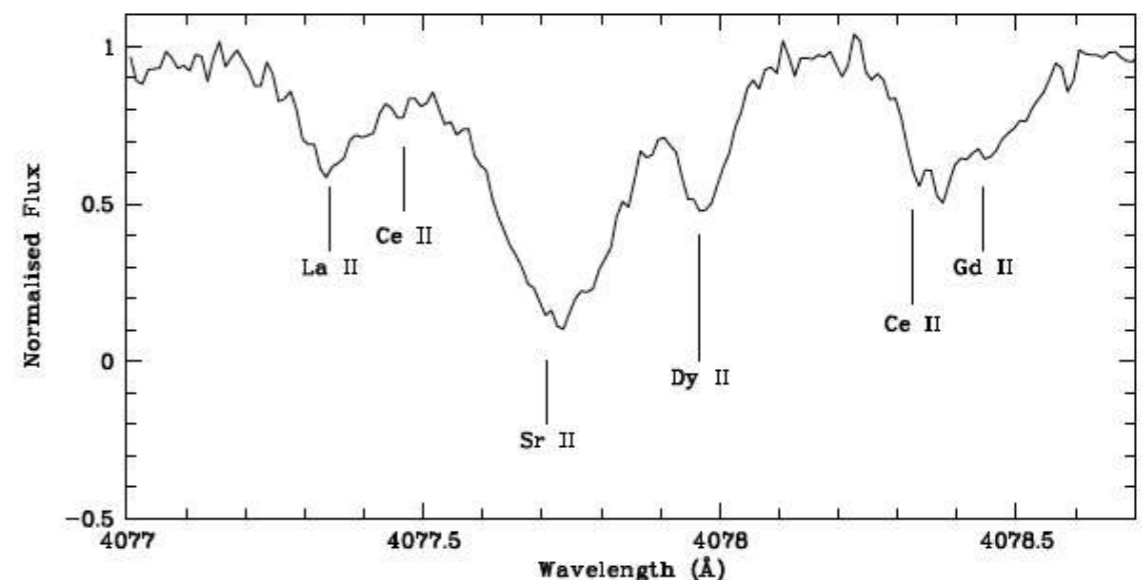
MINCE

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 (2025)



TNG 3.58m
Spectrograph HARPS-N



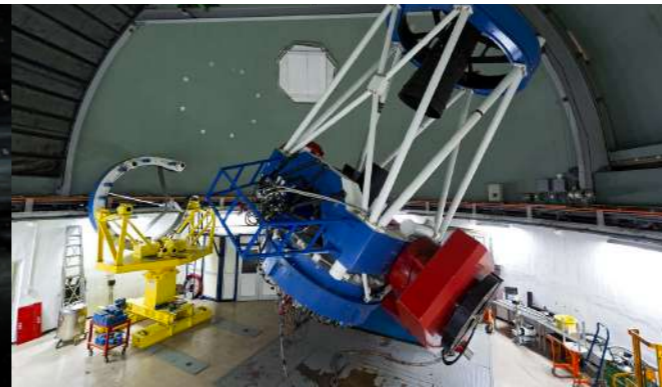
VLT 8.2m
Spectrograph: UVES



OHP 1.93m
Spectrograph SOPHIE



CFHT: 3.58m
Spectrograph ESPaDOnS



MPG/ESO 2.2-metre
FEROS



Magellan 6.5m
Spectrograph: MIKE



NOT 2.2m
Spectrograph: FIES



Moletai 1.65m
Spectrograph: VUES

~450 stellar spectra with high S/N and Resolution
20% from ChETEC-INFRA

The background features a dark, almost black, field with intricate, glowing patterns. These patterns consist of multiple overlapping, swirling, and looping lines that resemble light trails or perhaps the paths of particles in a complex system. The lines are primarily white and light grey, with some areas appearing more intense and brighter. The overall effect is one of dynamic movement and complexity, set against a stark, dark backdrop.

Other solutions?

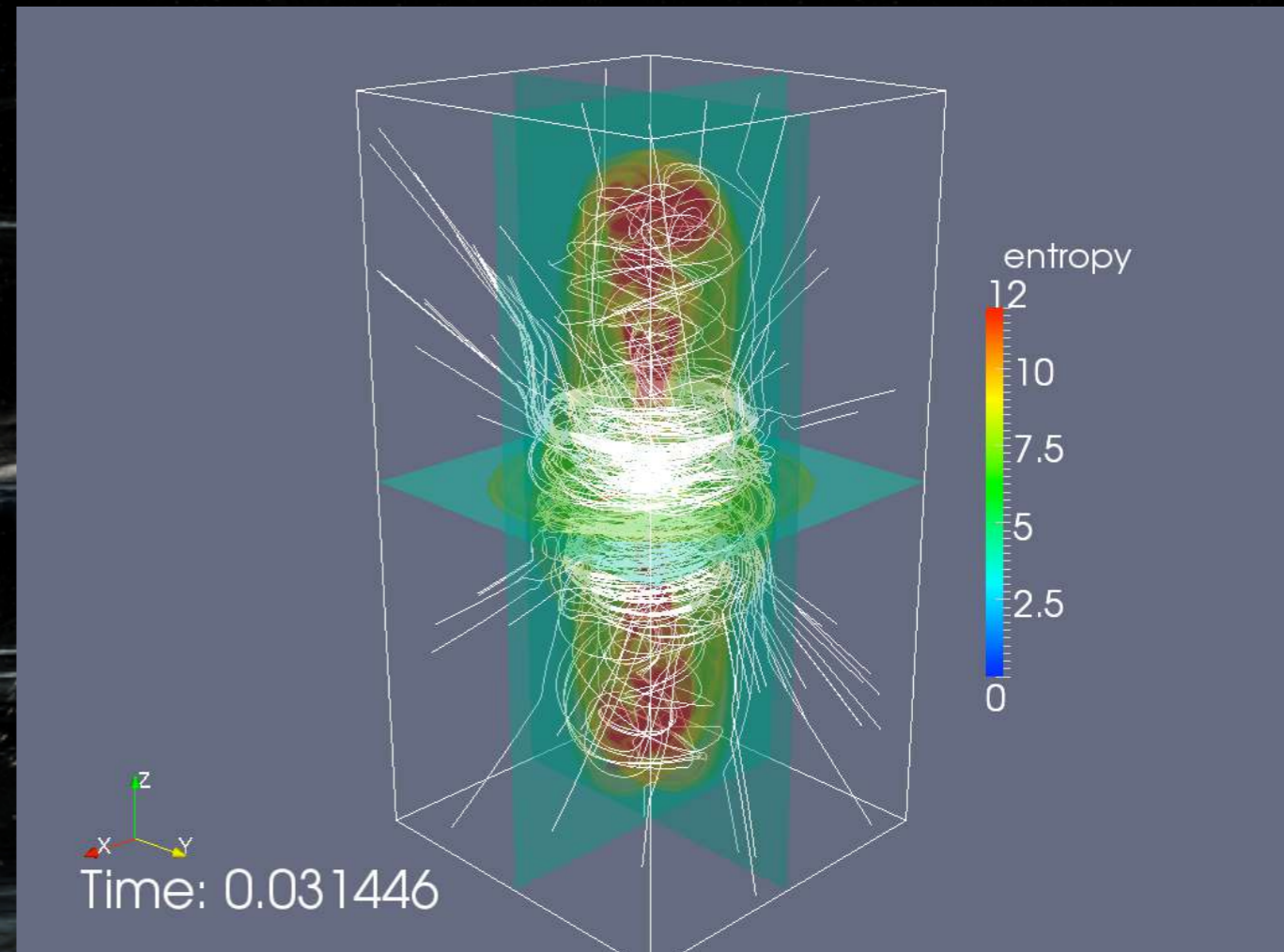
Magneto Rotationally Driven SN scenario (MRD)

(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 ($\sim 1-5\%$)

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.

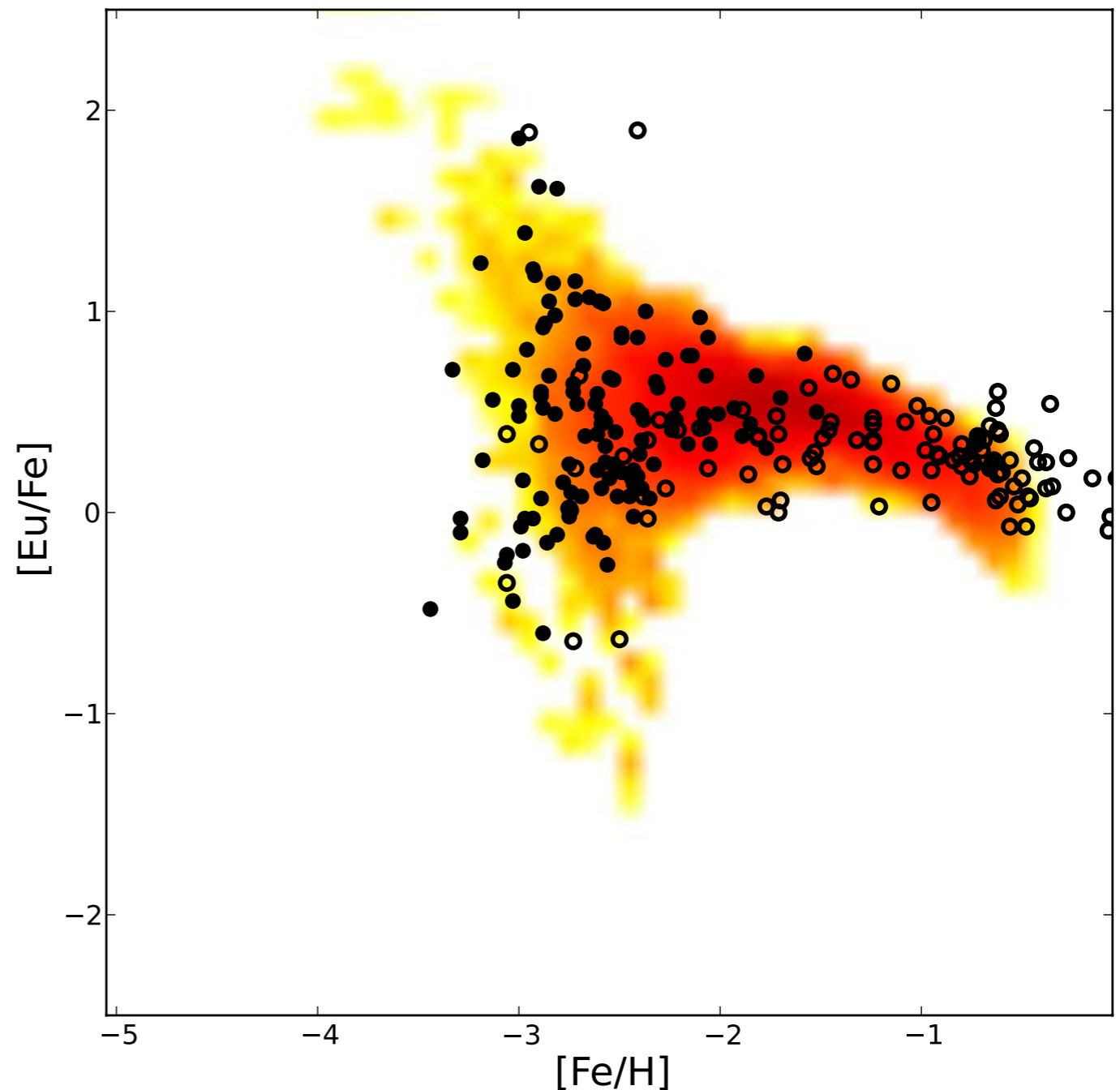


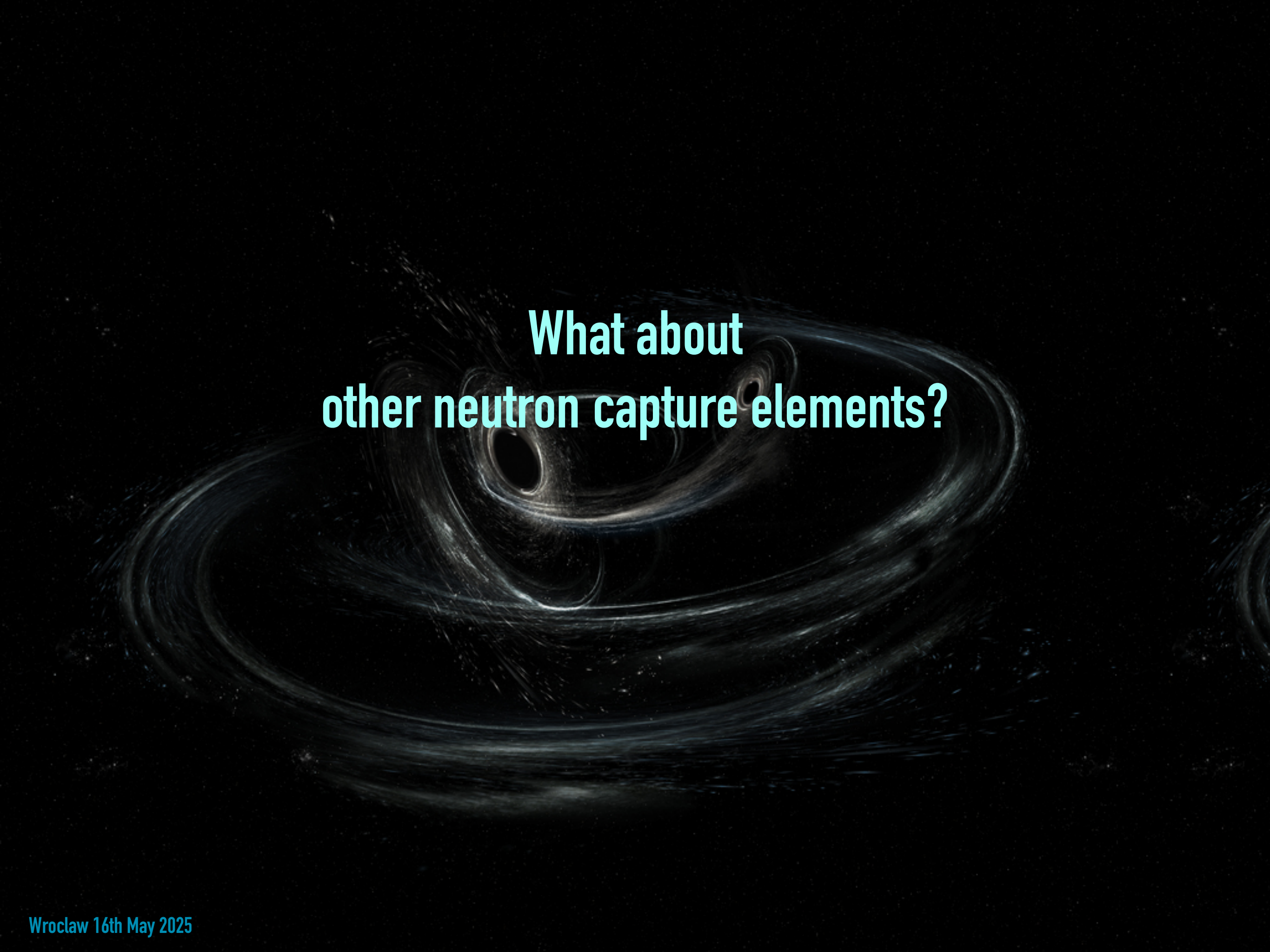
Magneto Rotationally Driven SN scenario (MRD) 10%

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

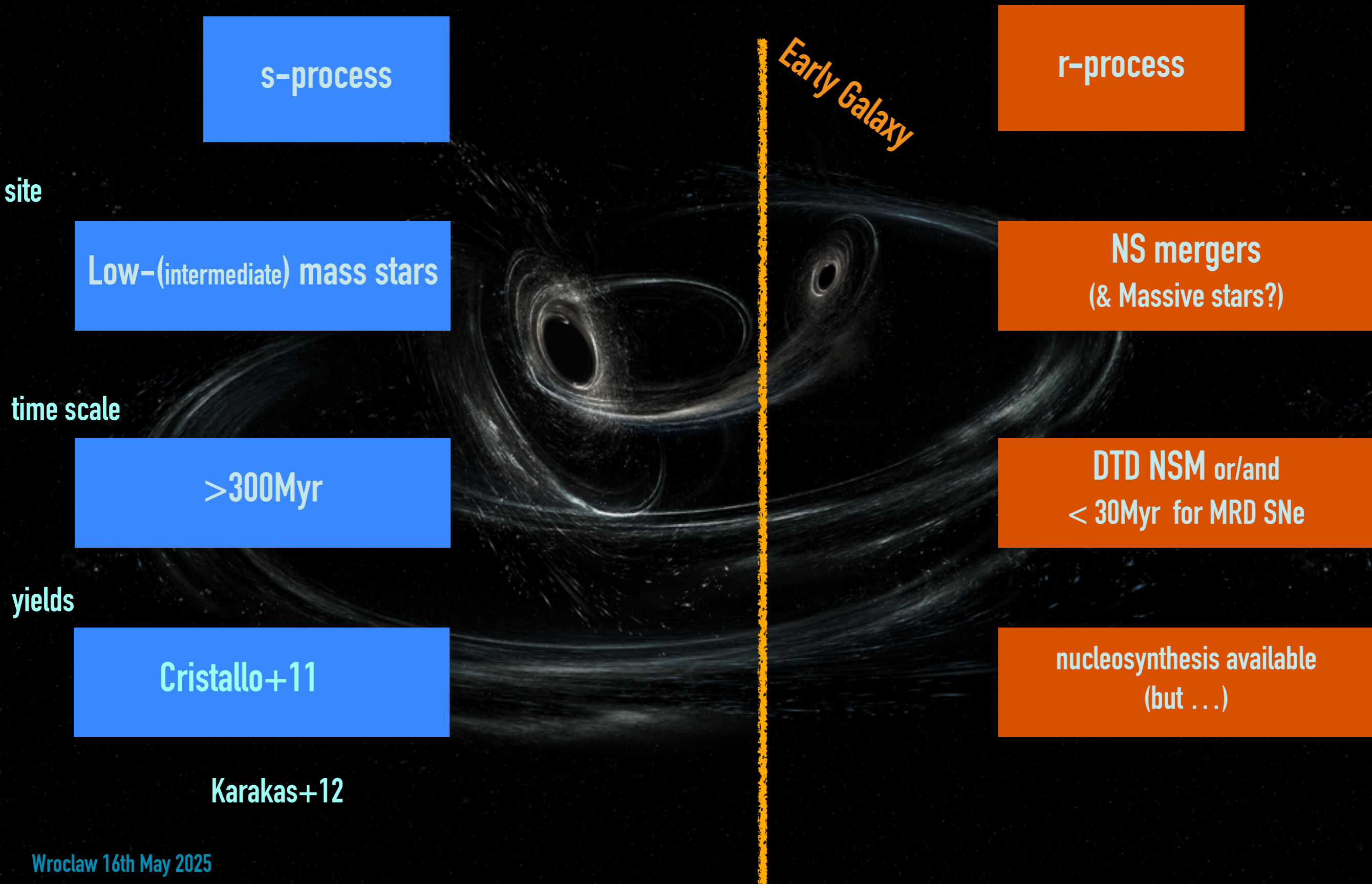
The assumed percentage of events in massive stars is higher than expected (at least at the solar metallicity), but it is reasonable to increase toward the metal poor regime
(Woosley and Heger 2006)





**What about
other neutron capture elements?**

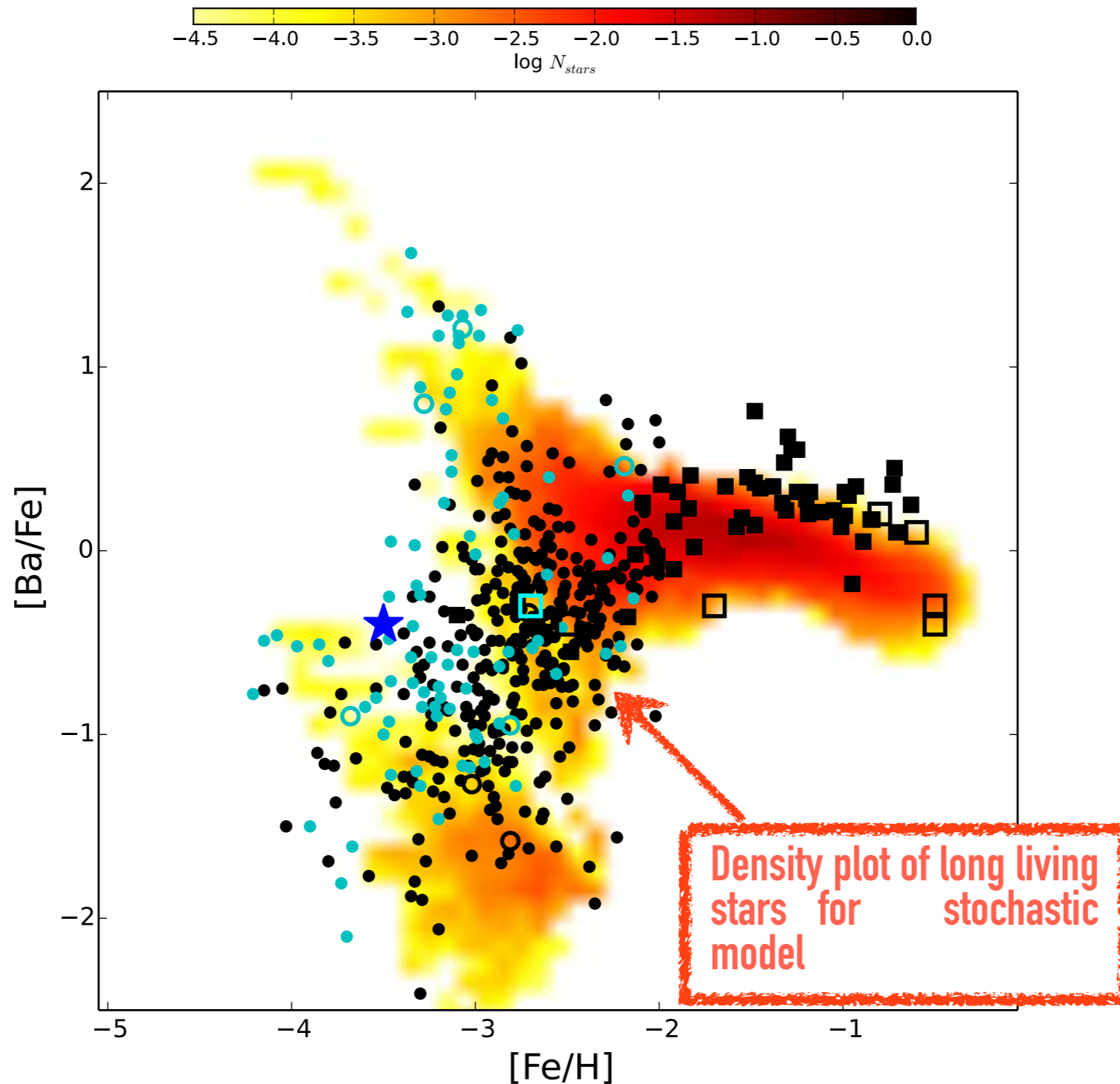
Neutron capture elements



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
 $8 \cdot 10^{-6} M_{\text{sun}}$ of Ba



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

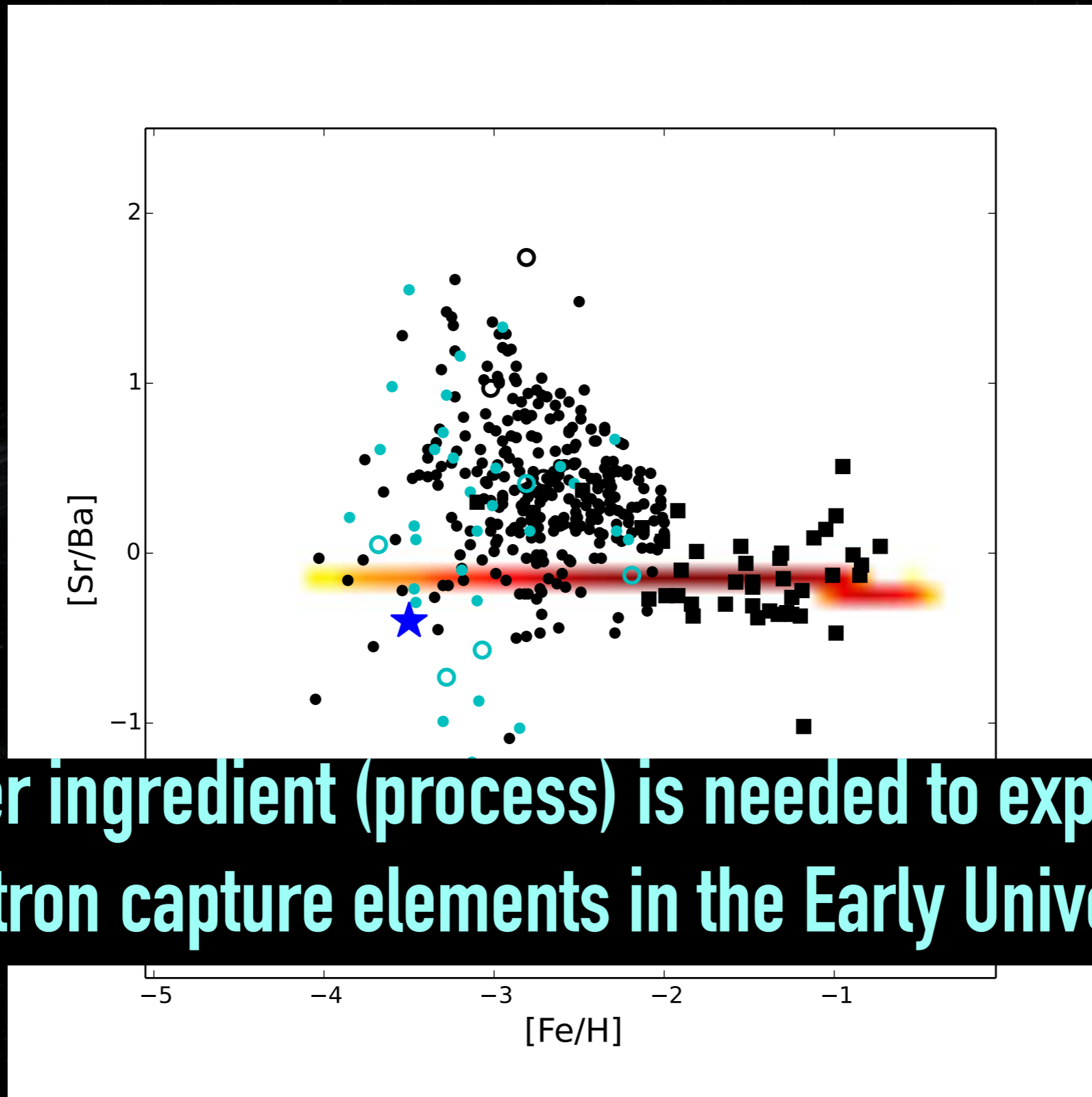
data from in

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)

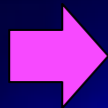
Another ingredient (process) is needed to explain the neutron capture elements in the Early Universe!

Rotating massive stars in the early Universe

In the Early Universe

Low metals: stars rotate faster (more compact)

Rotation

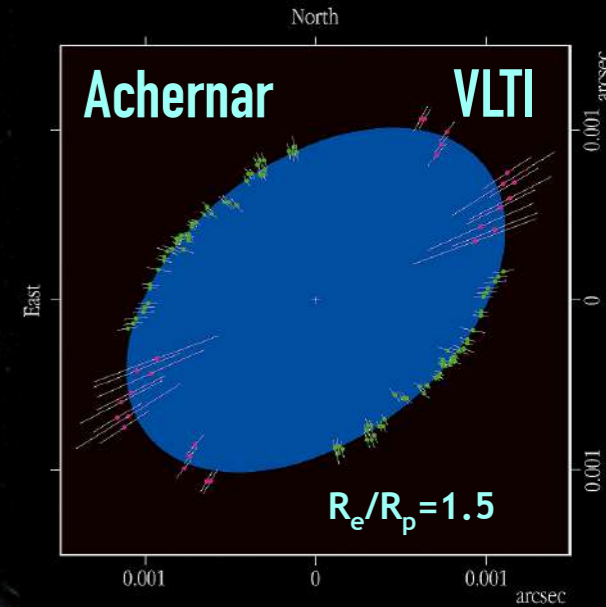


Mixing inside star



Ejected matter will be rich in ^{14}N , ^{13}C , ^{12}C , & s-process

Massive stars rotate in the Local Universe



Signatures:

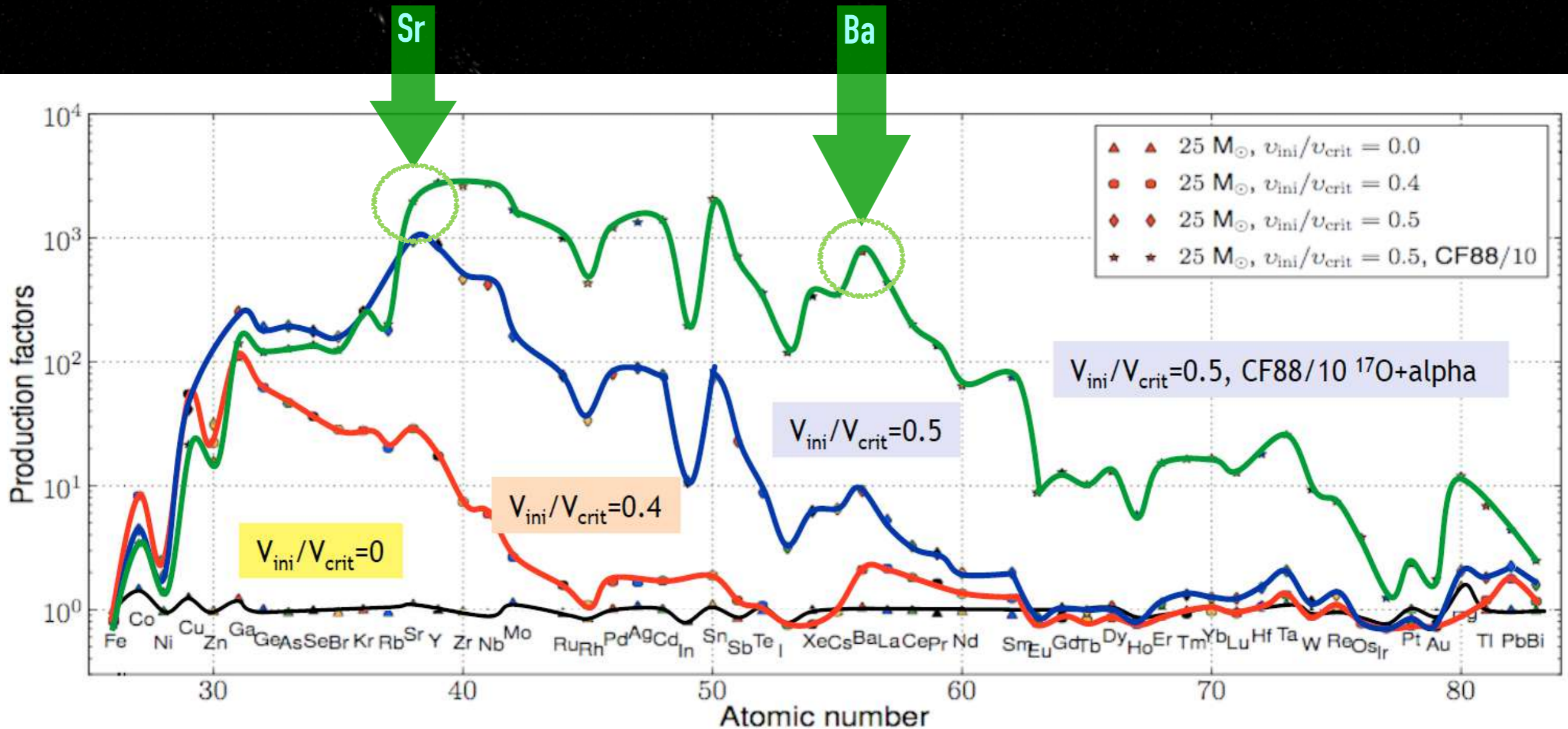
- (1) Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)
- (2) Increase in the C/O ratio in the early Universe
- (3) Large amounts of ^{13}C in the early Universe (Chiappini et al. 2008 A&A Letters)
- (4) Early production of Be and B by cosmic ray spallation (Prantzos 2012)

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)

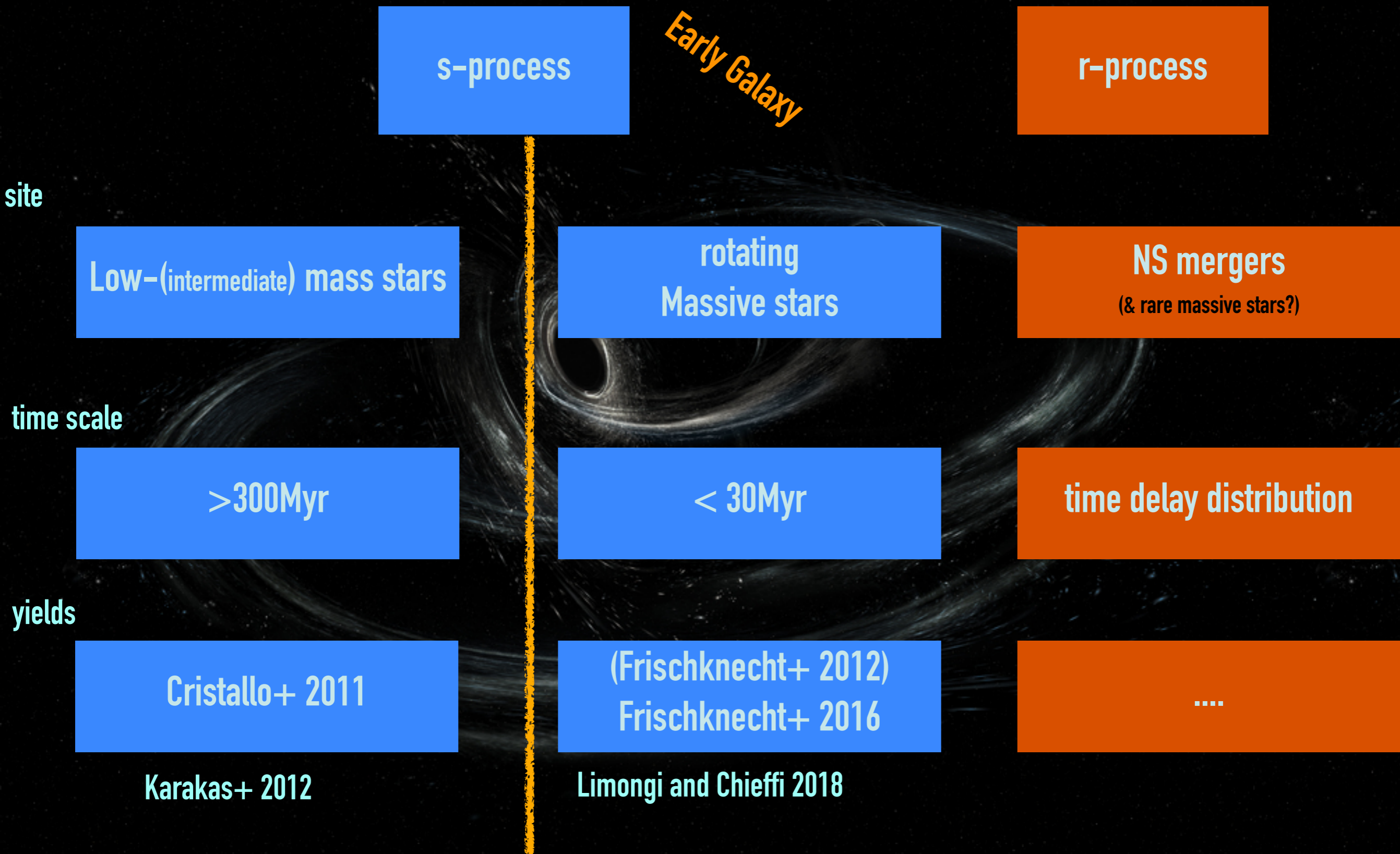
Rotating massive stars can contribute to s-process elements!



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

Neutron capture elements

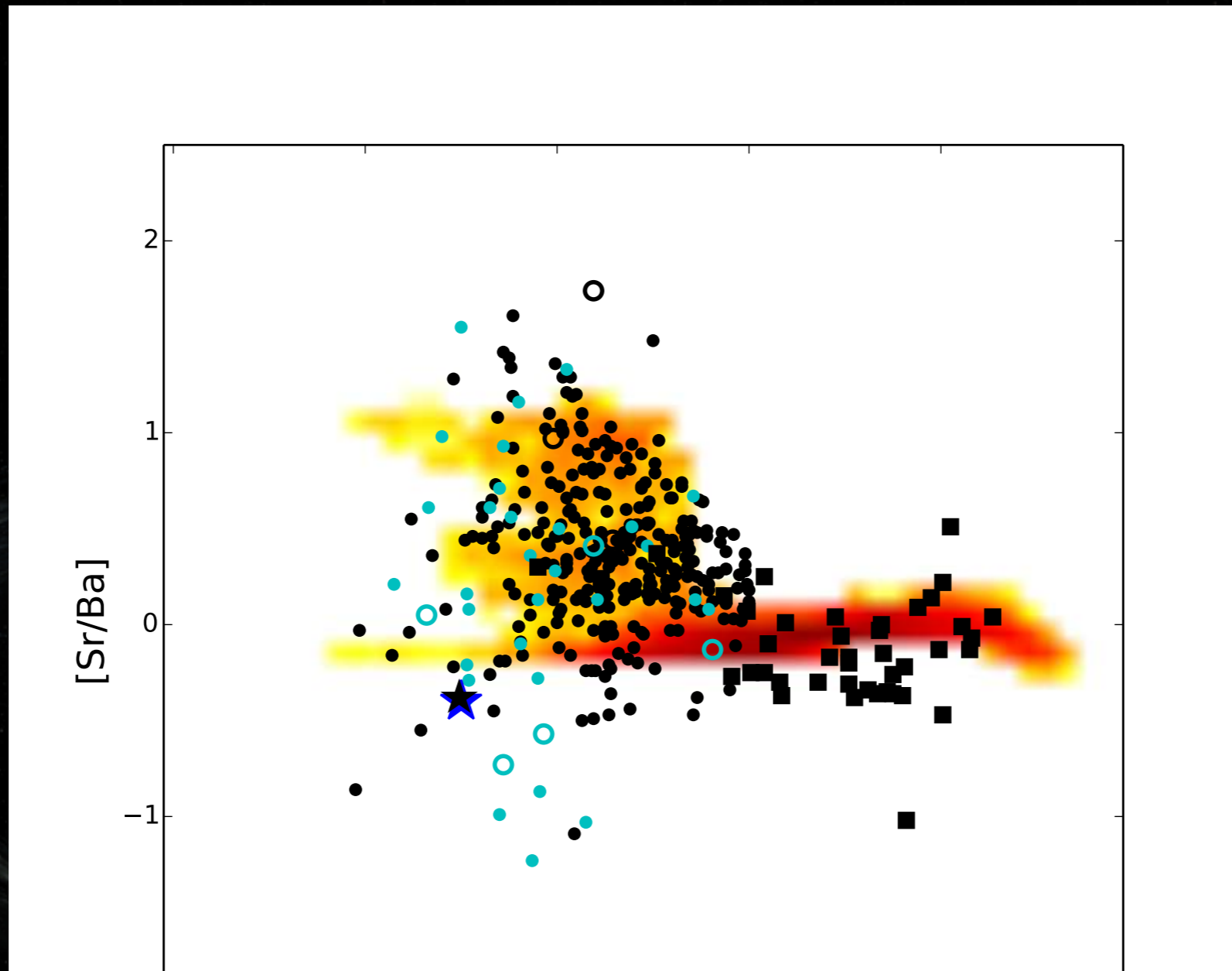
from Chiappini+11



s-process from rotating massive stars

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

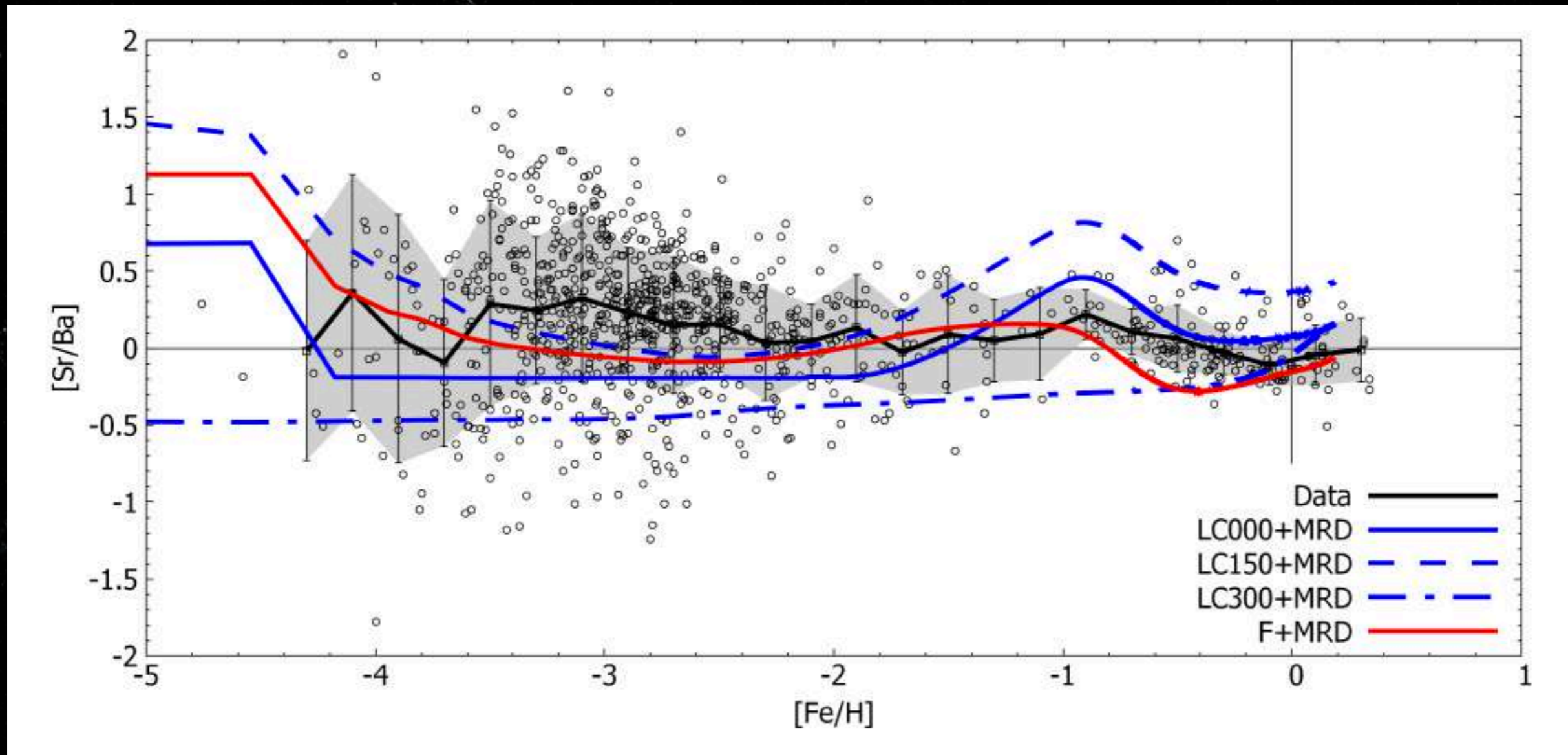
Cescutti et al. (2013)
Cescutti & Chiappini (2014)



A s-process (from rotating massive stars)
and an r-process (from rare events)

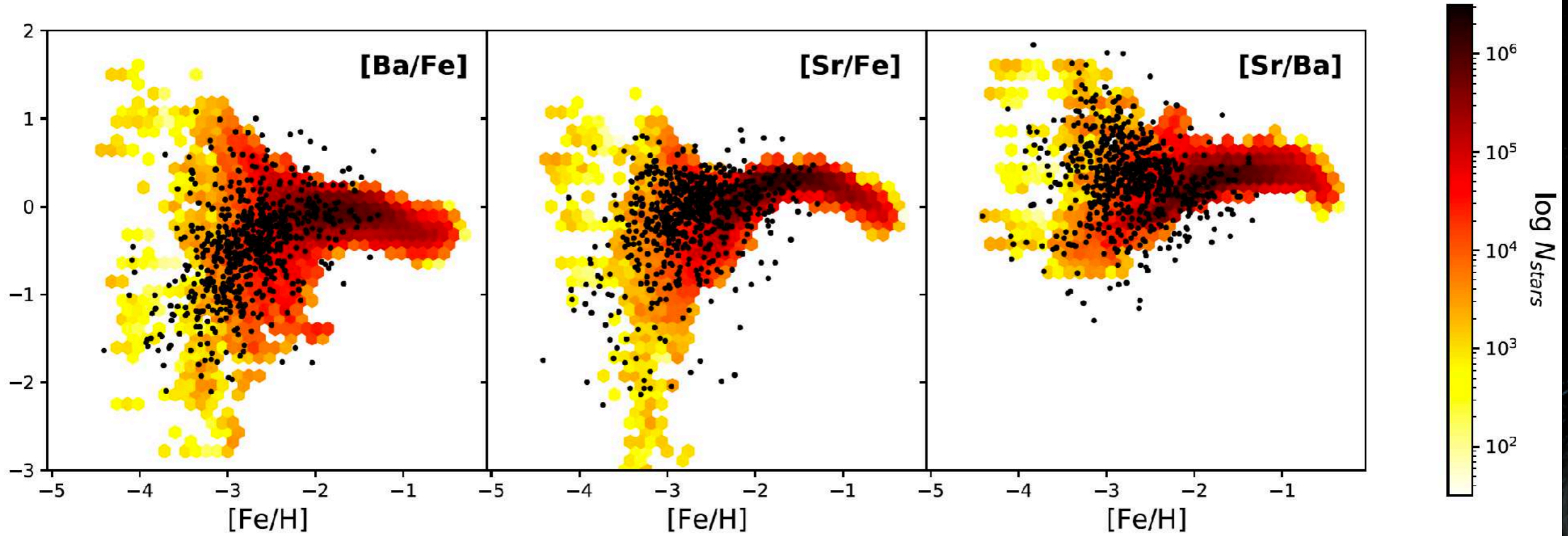
can reproduce the neutron capture elements in the Early Universe

Confirmed in Rizzuti et al. (2019) adopting Limongi&Chieffi18

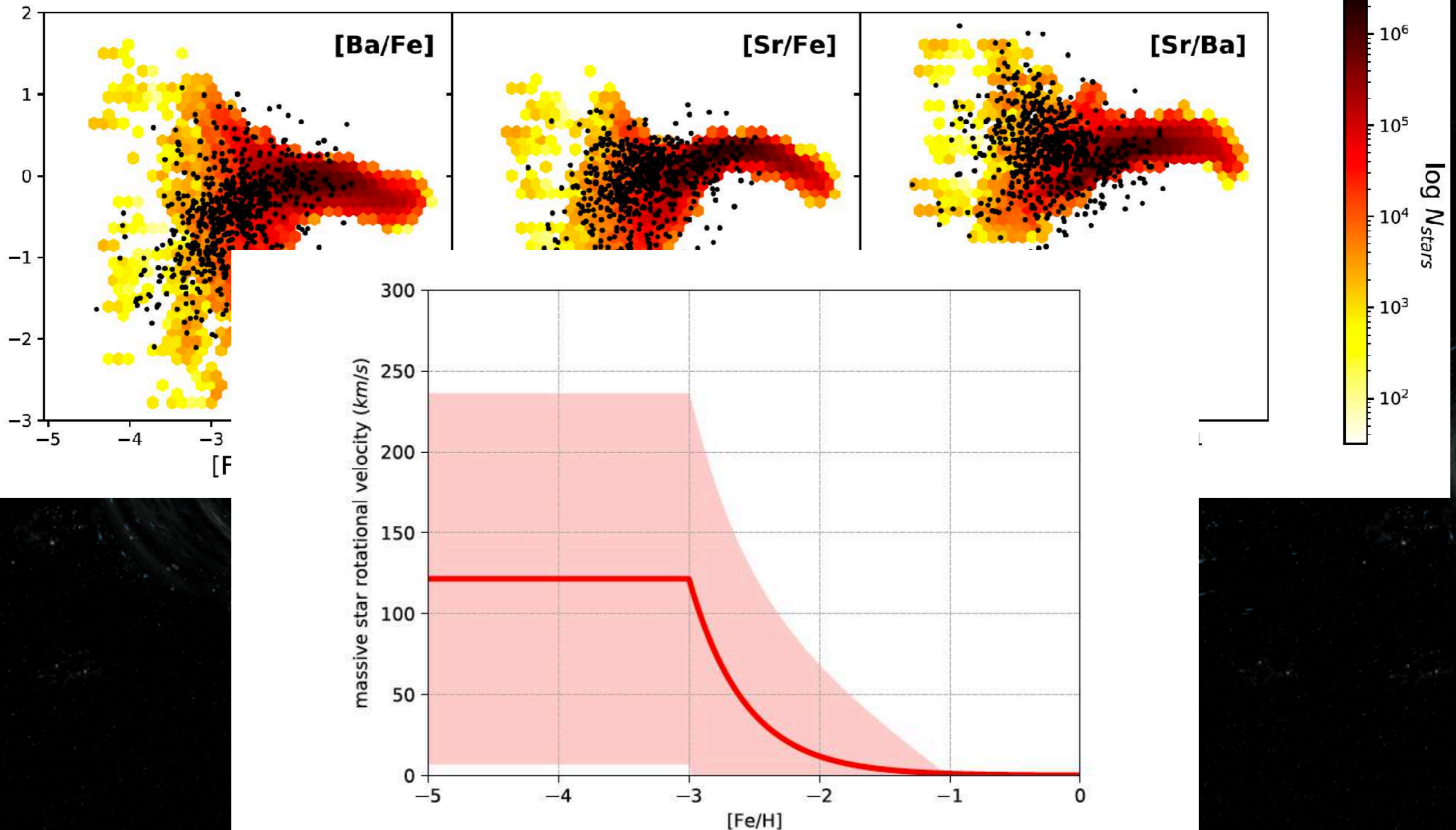


see also Prantzos et al. 2018

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.

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.