UNIVERSITÀ DEGLI STUDI DI TRIESTE

INFN TRIESTE

Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

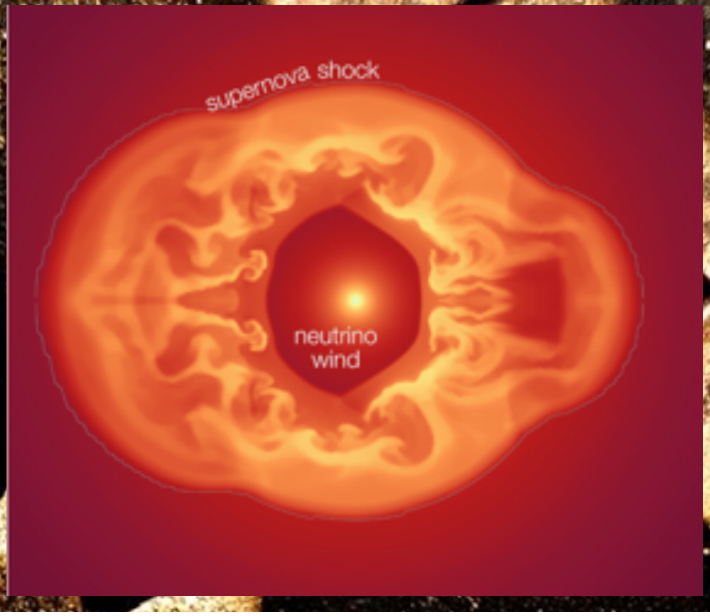
Galactic Archaeology with neutron capture elements

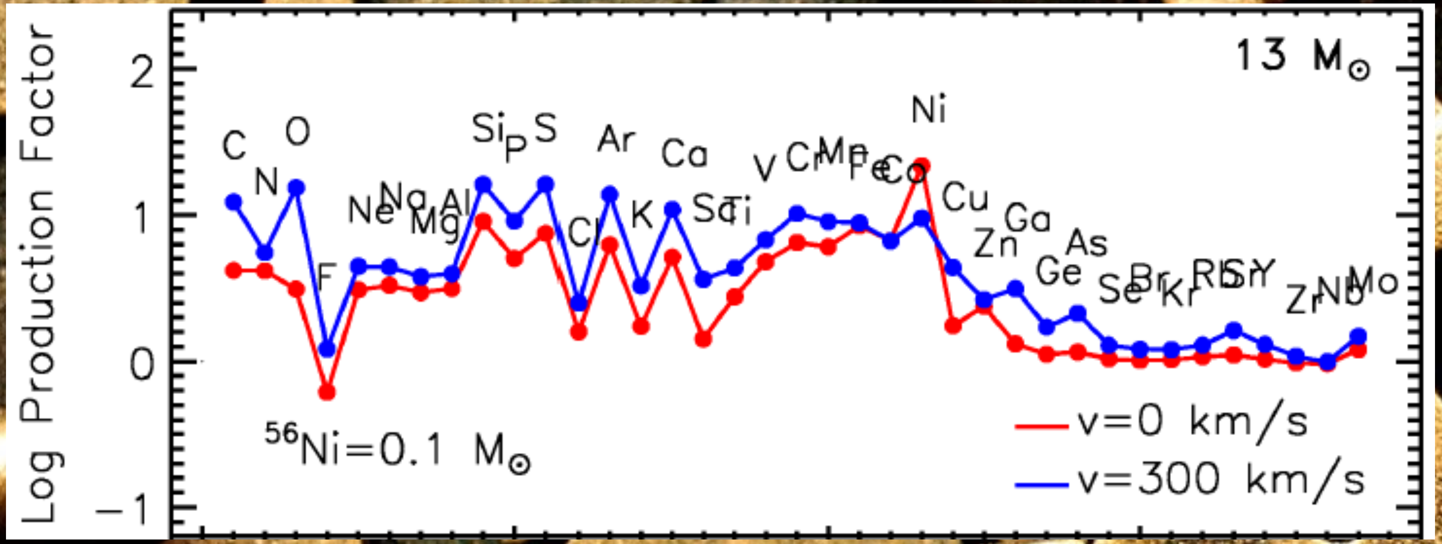
Gabriele Cescutti
in collaboration with
Federico Rizzuti & Lorenzo Cavallo

THE 13TH TORINO WORKSHOP ON AGB STARS
PERUGIA, 19TH-24TH JUNE 2022

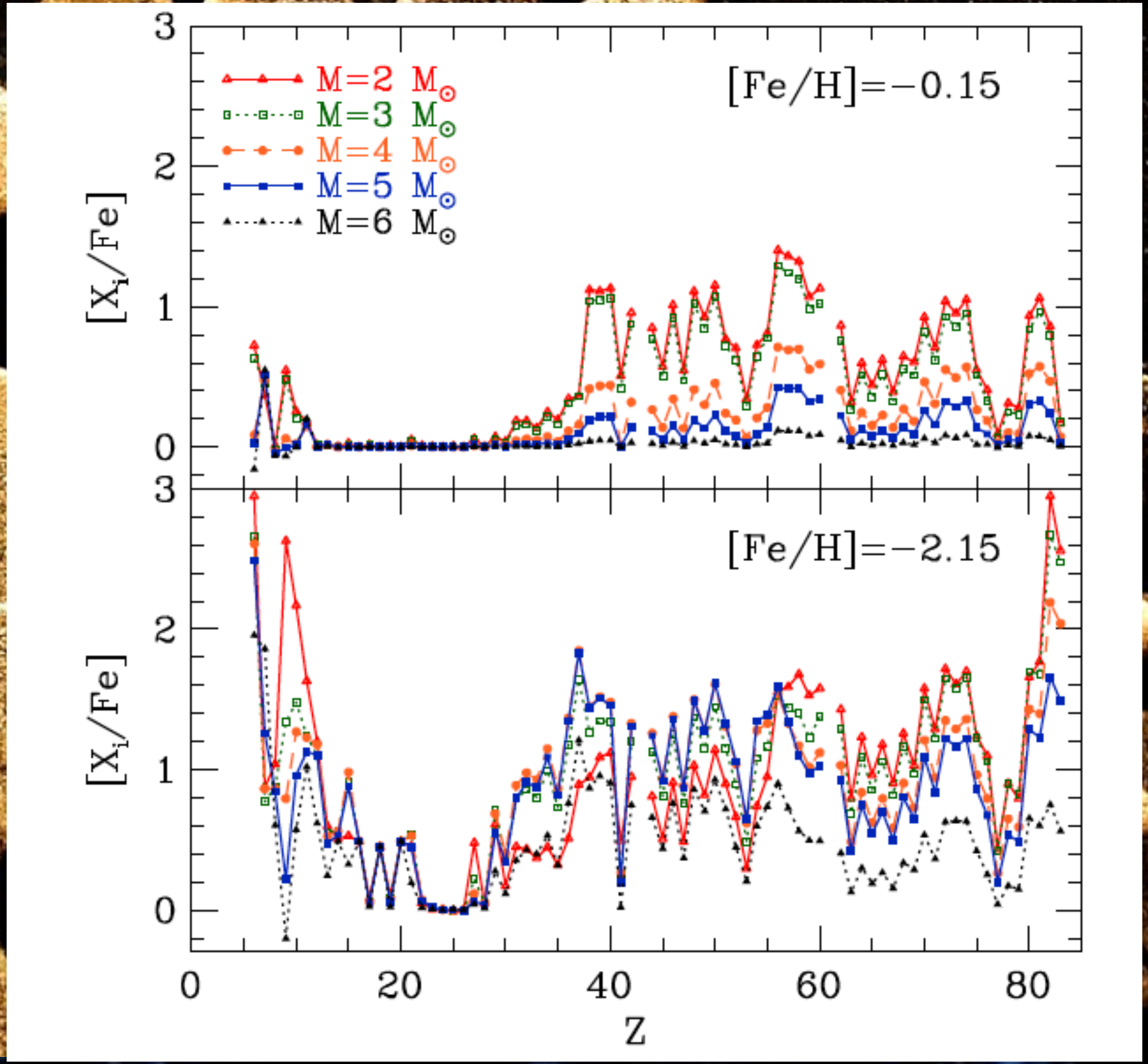
CHETEC INFRA

Stellar evolution model with nucleosynthesis



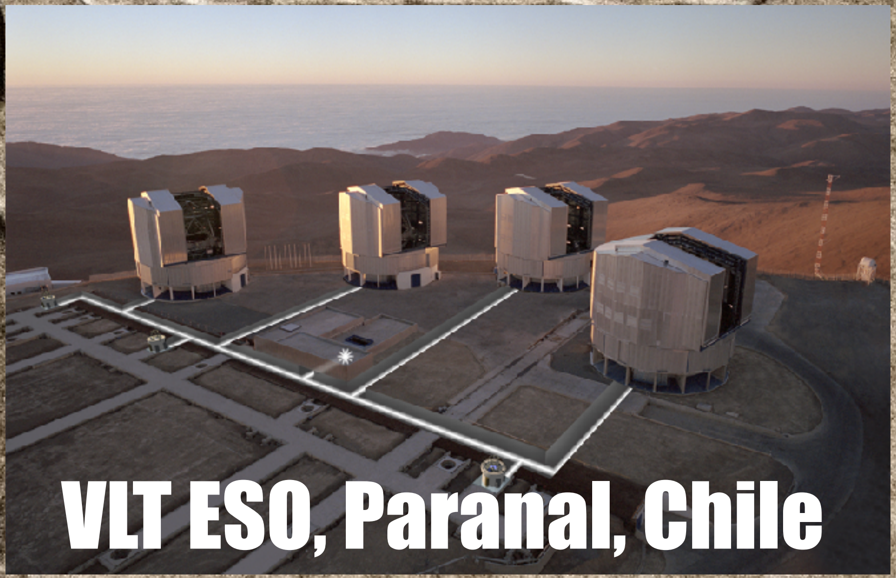


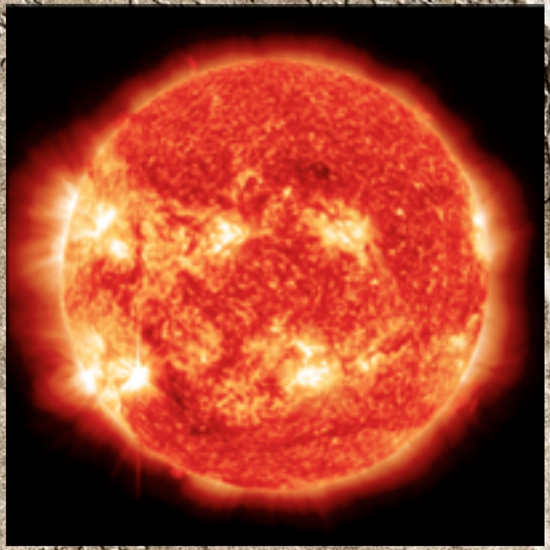
Limongi+12



Cristallo+15

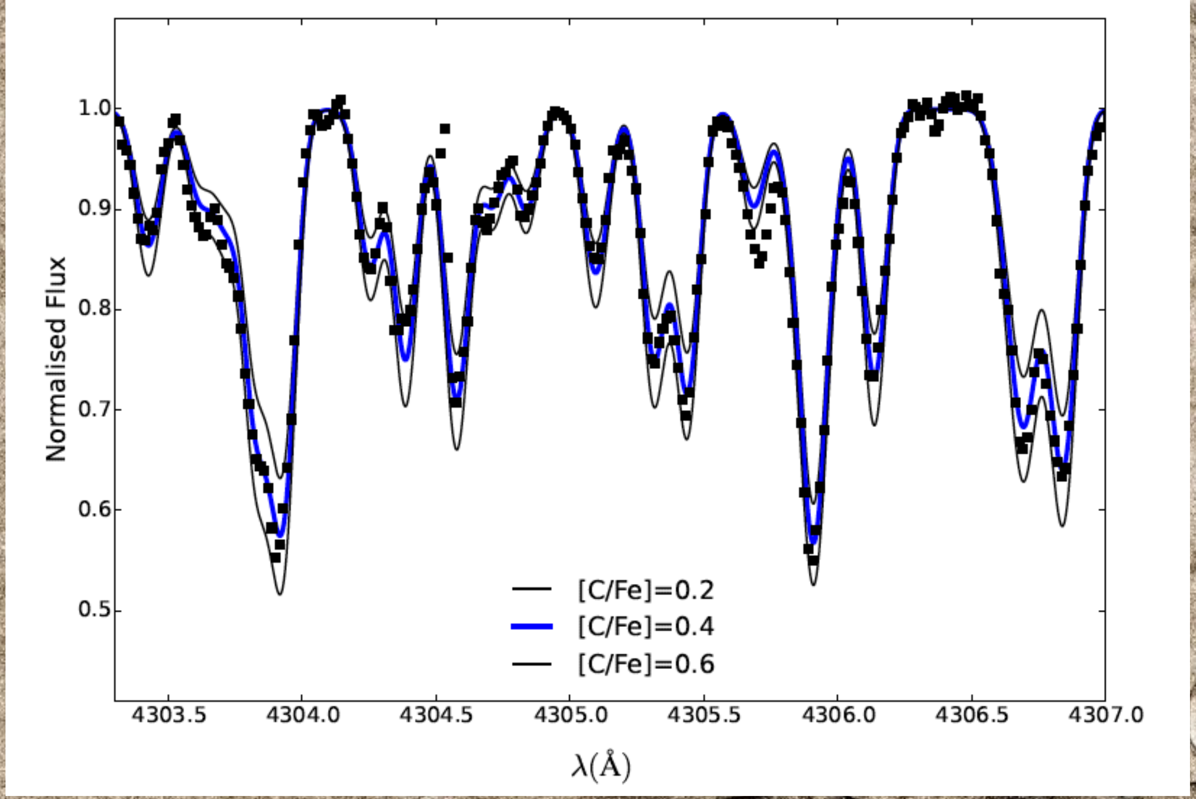
Chemical abundances in stars


VLT ESO, Paranal, Chile



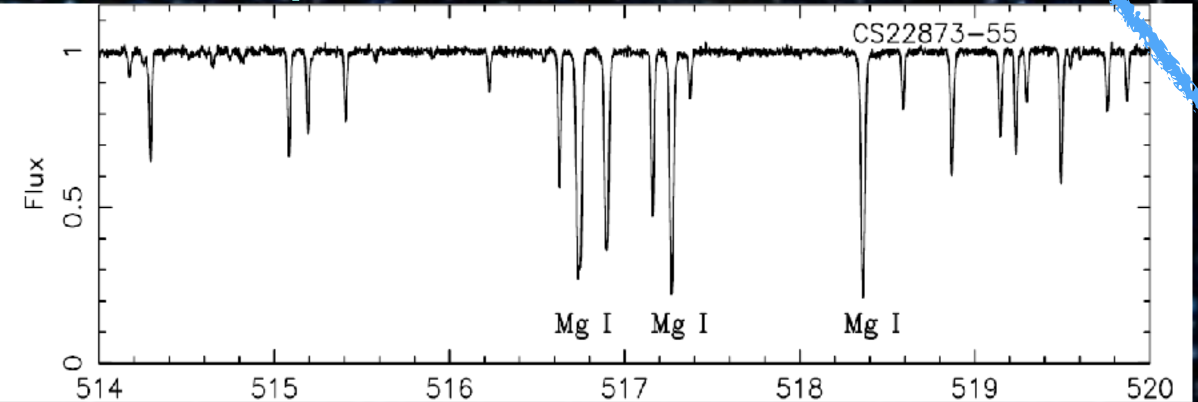
High resolution spectra of stars

Abundances of chemical elements

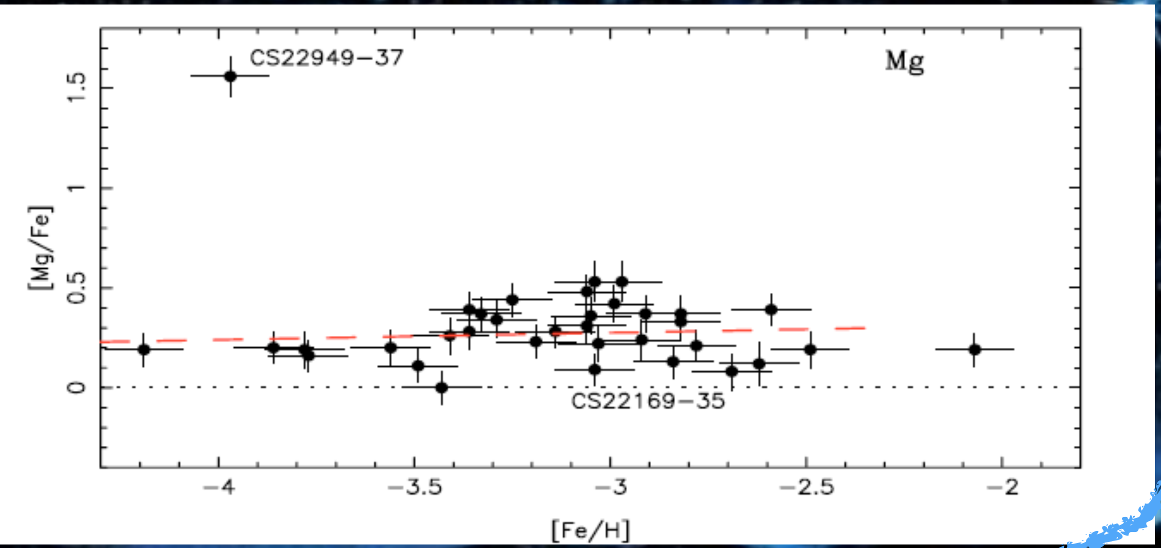


How to compare?

Stellar spectra

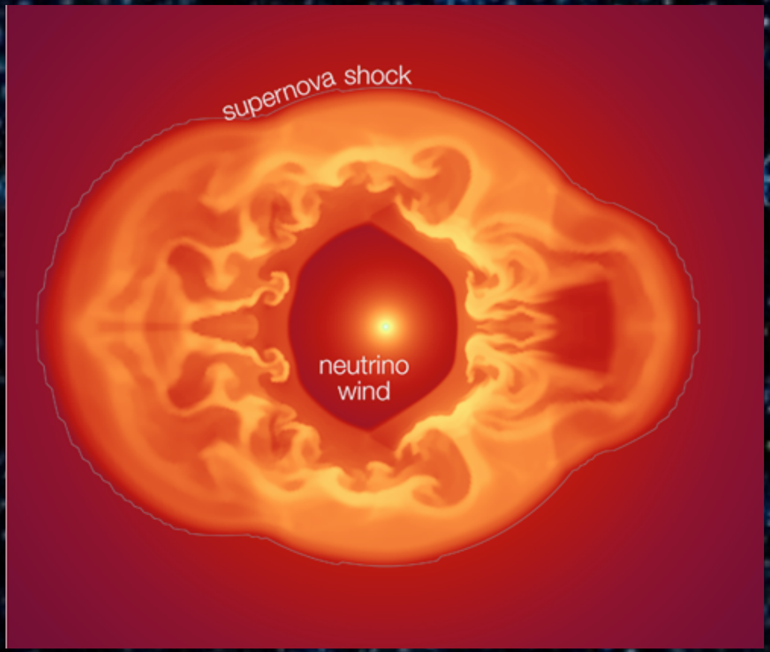


Stellar chemical abundances

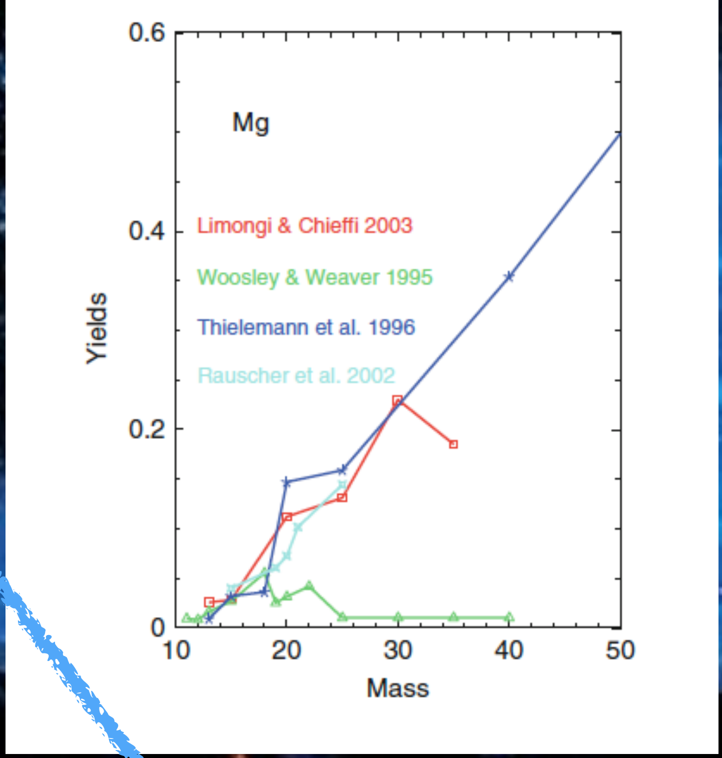


Cayrel+04

Stellar evolution



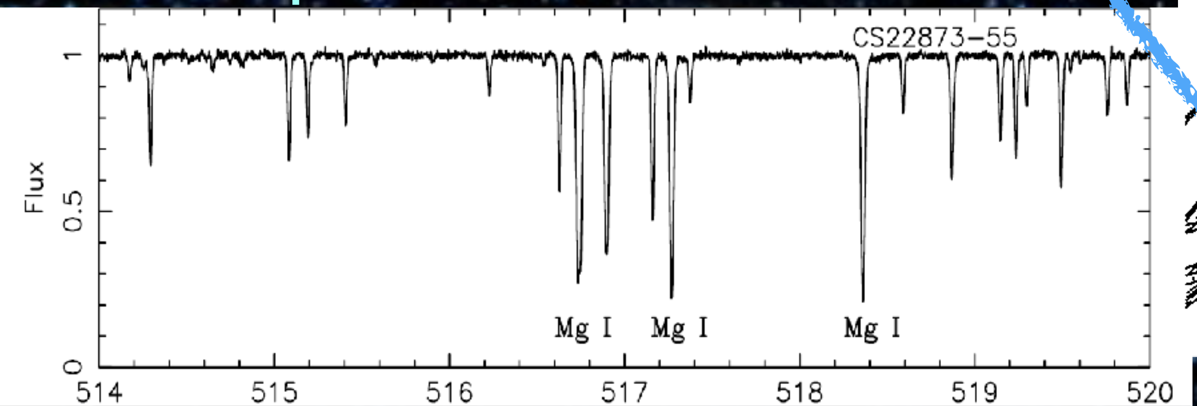
Nucleosynthesis

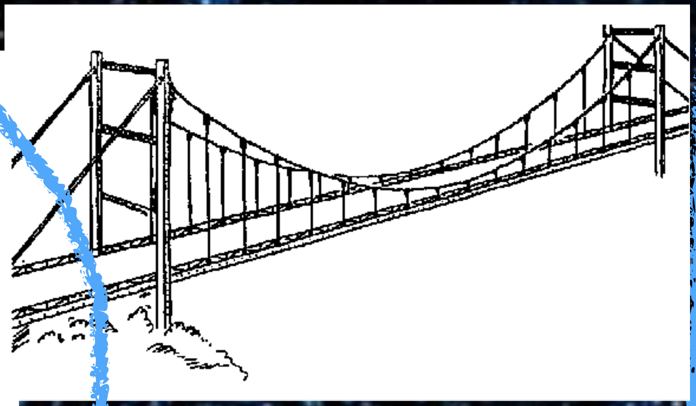


Romano+10

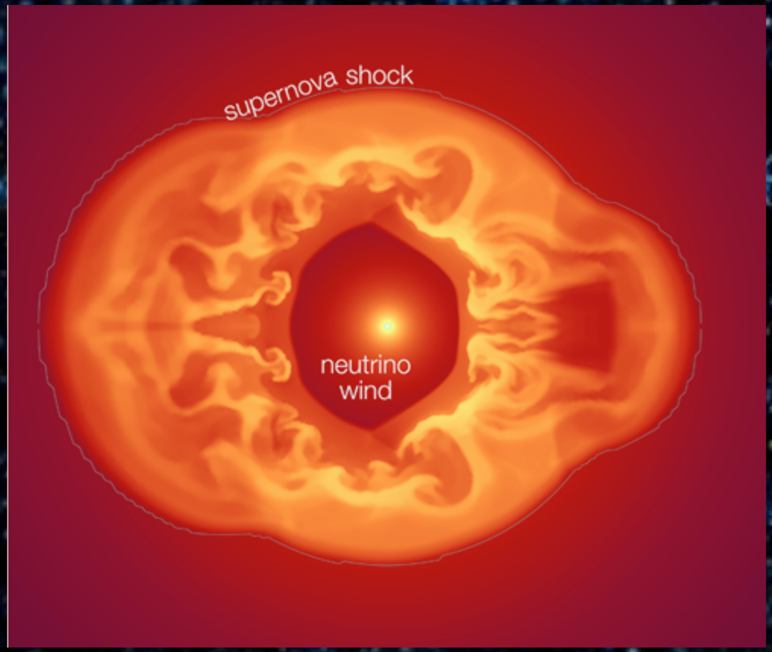
How to compare?

Stellar spectra



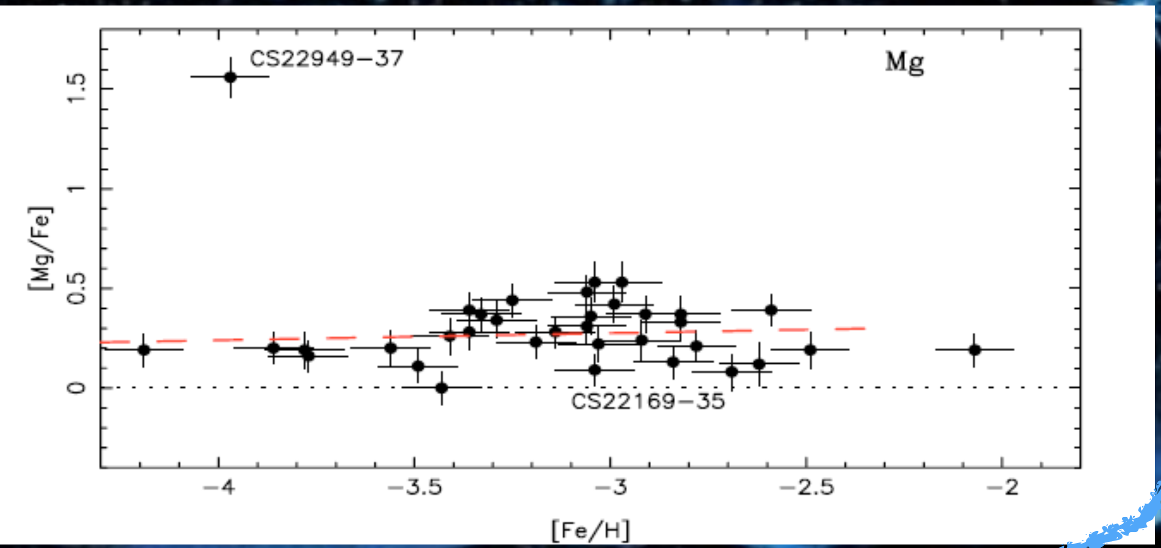


Stellar evolution

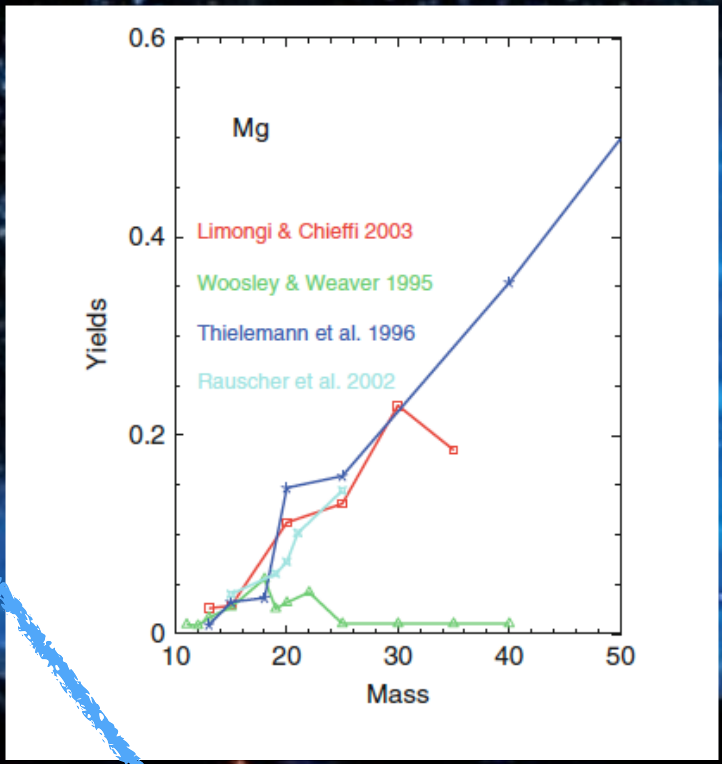


Nucleosynthesis

Stellar chemical abundances



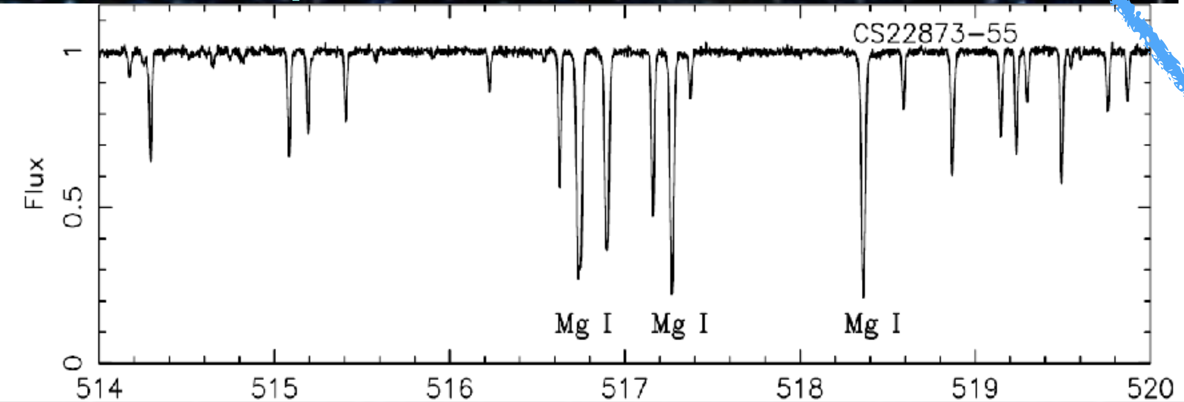
Cayrel+04

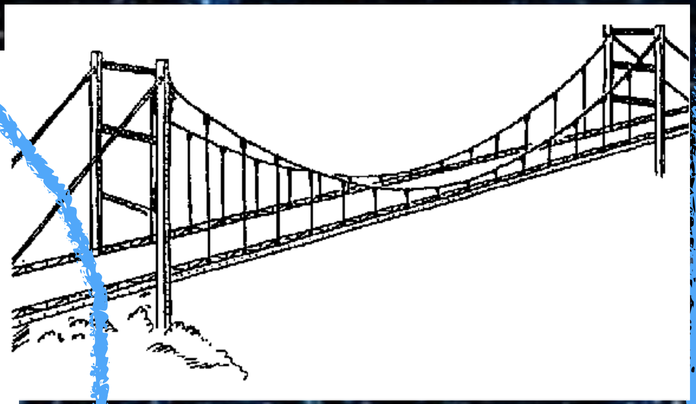


Romano+10

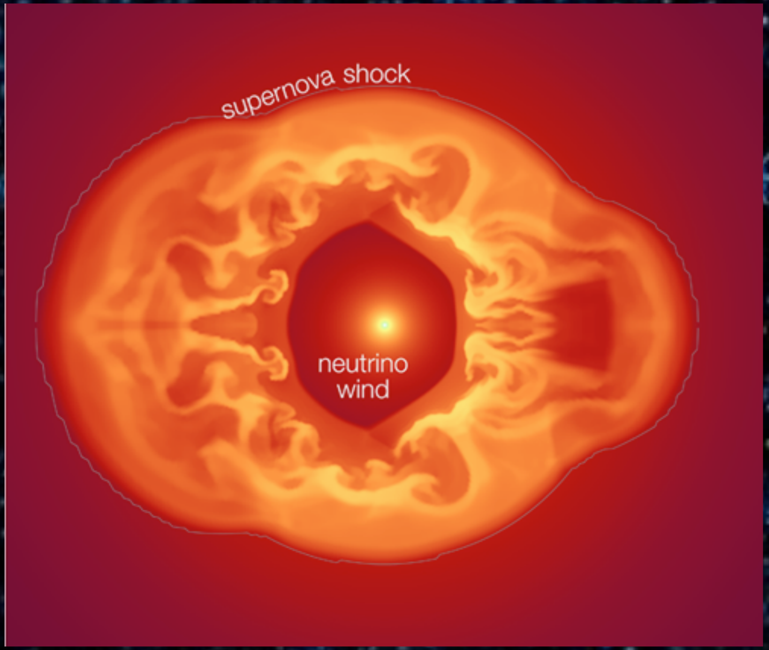
Chemical evolution models

Stellar spectra

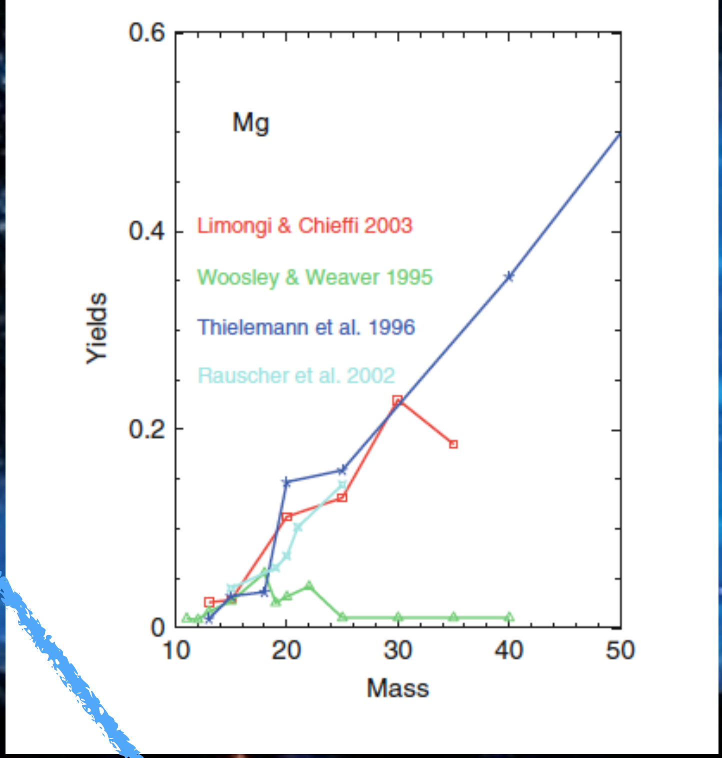




Stellar evolution

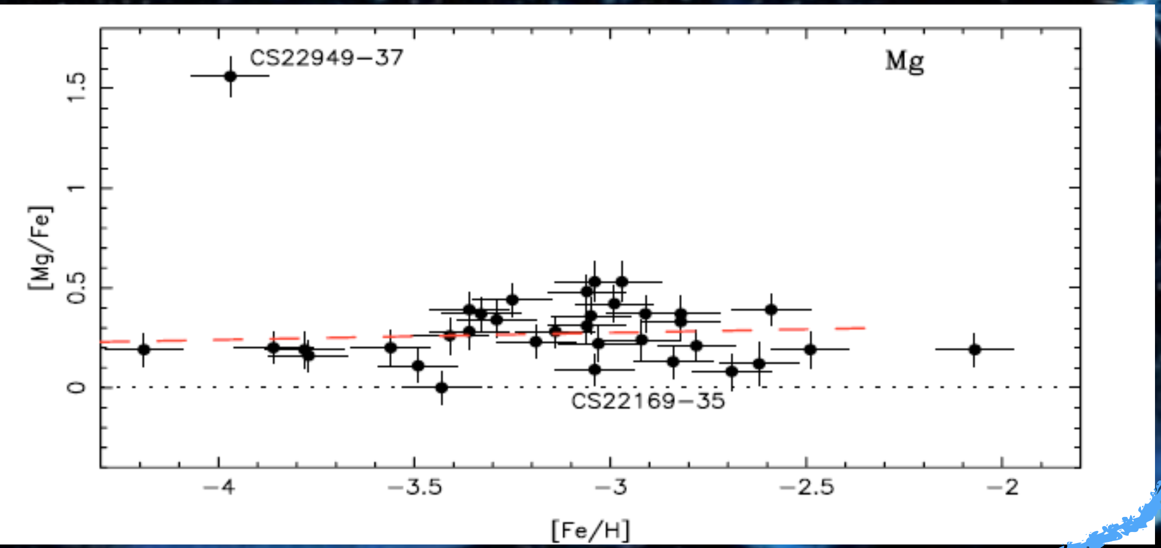


Nucleosynthesis



Romano+10

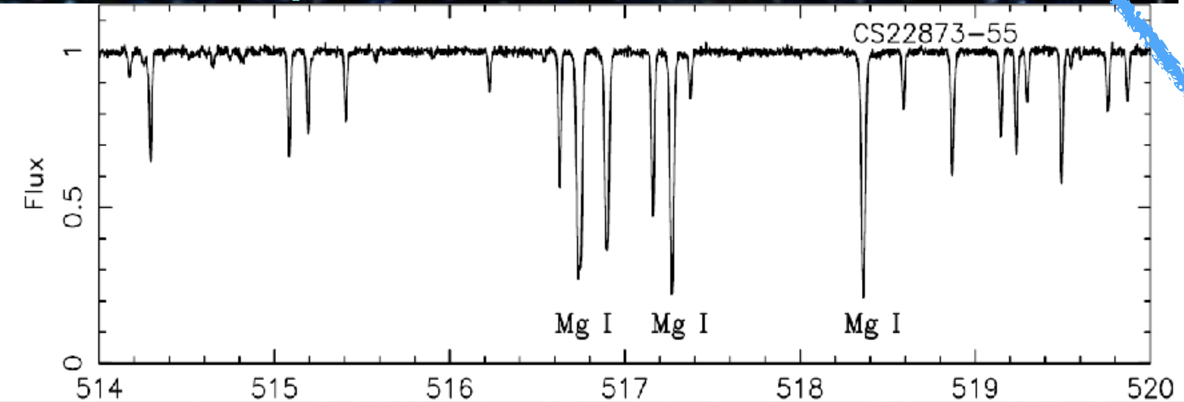
Stellar chemical abundances

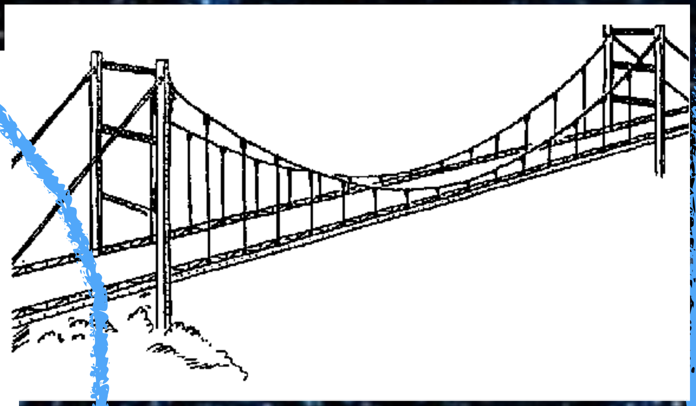


Cayrel+04

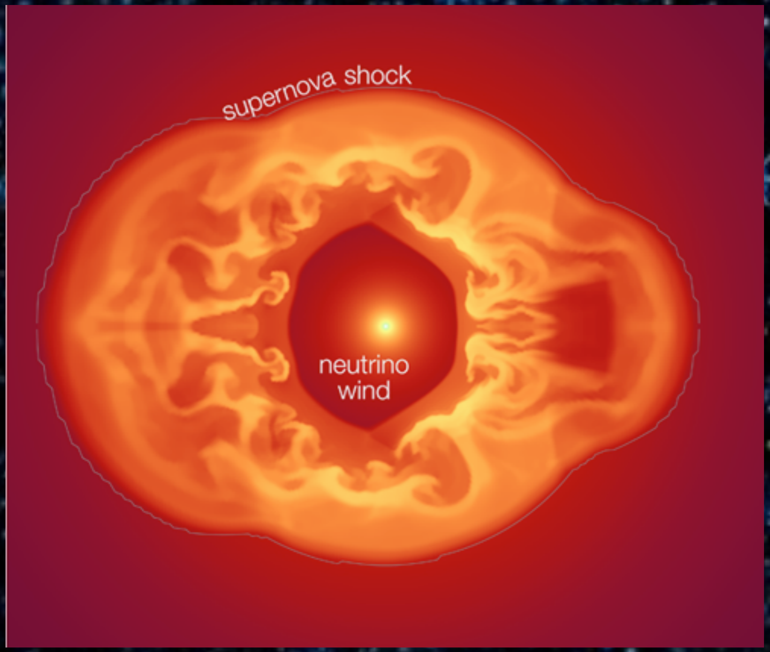
Chemical evolution models

Stellar spectra



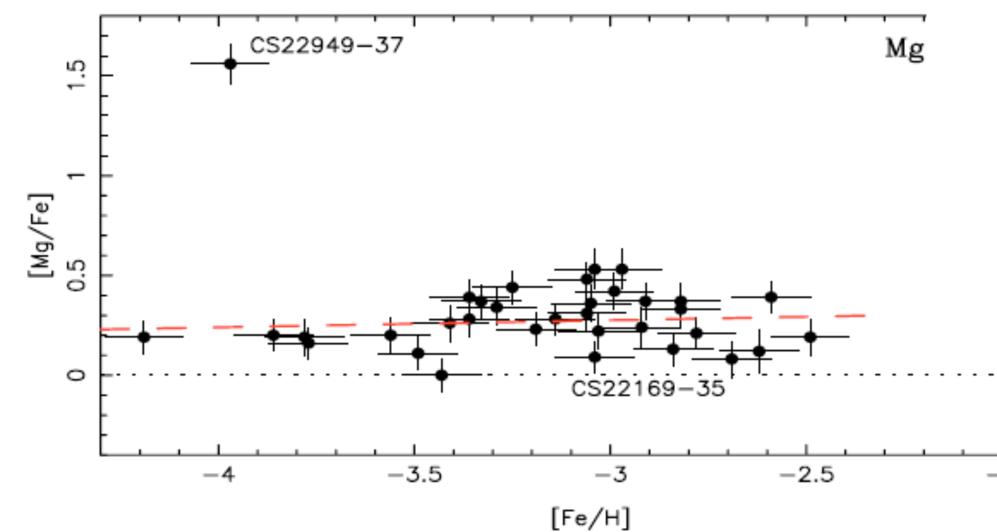


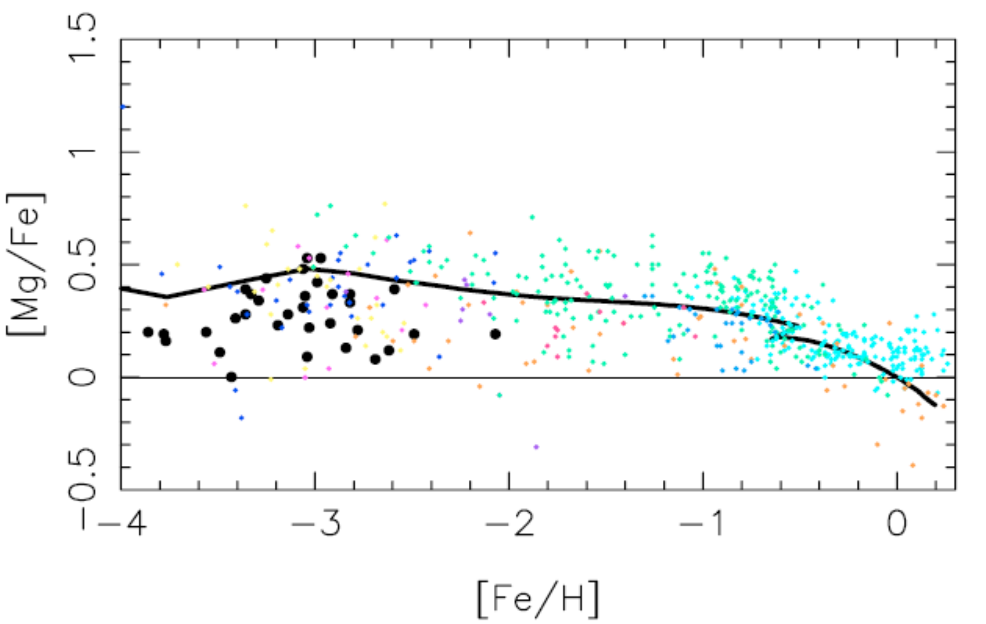
Stellar evolution



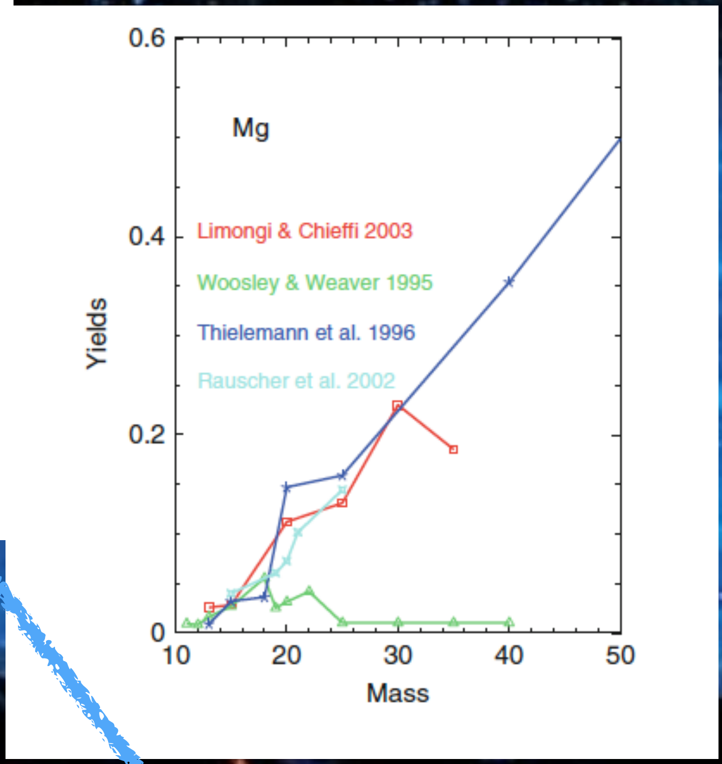
Nucleosynthesis

Stellar chemical abundances





Francois+04

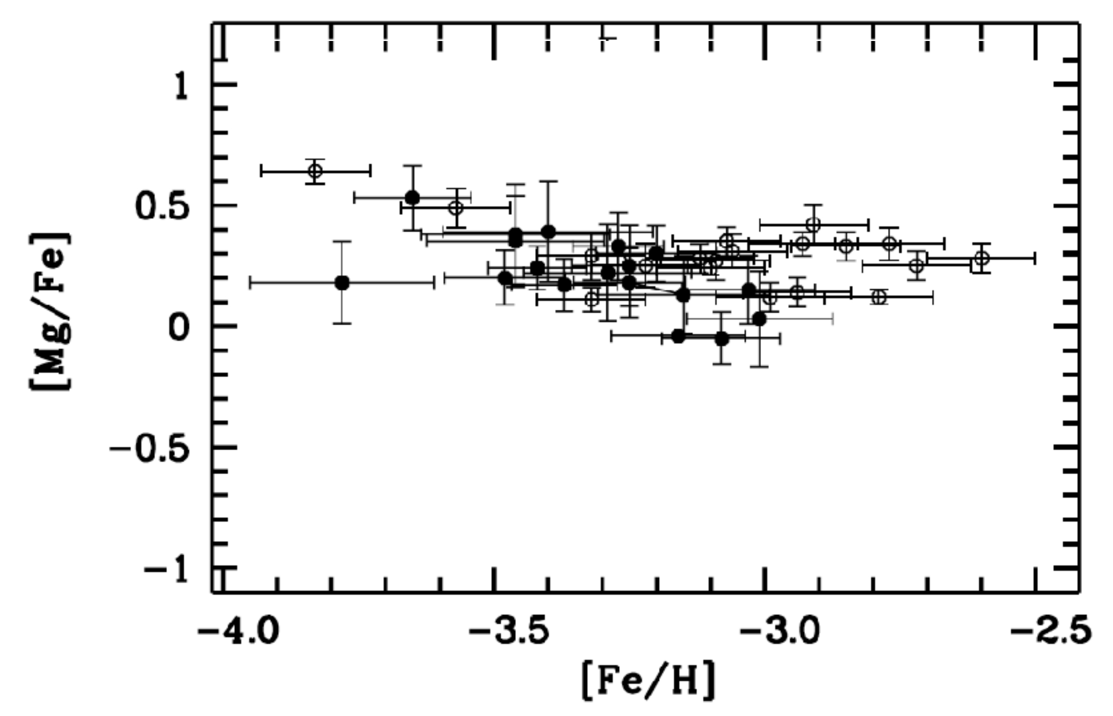


Cayrel+04

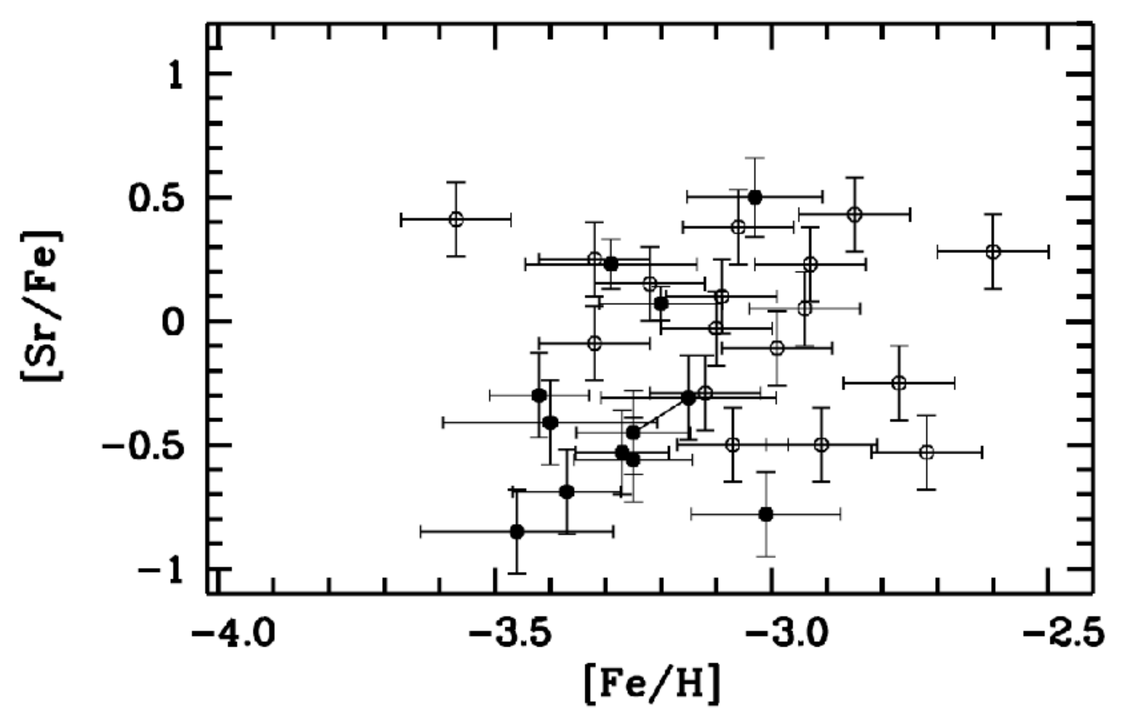
Romano+10

Why neutron capture elements?

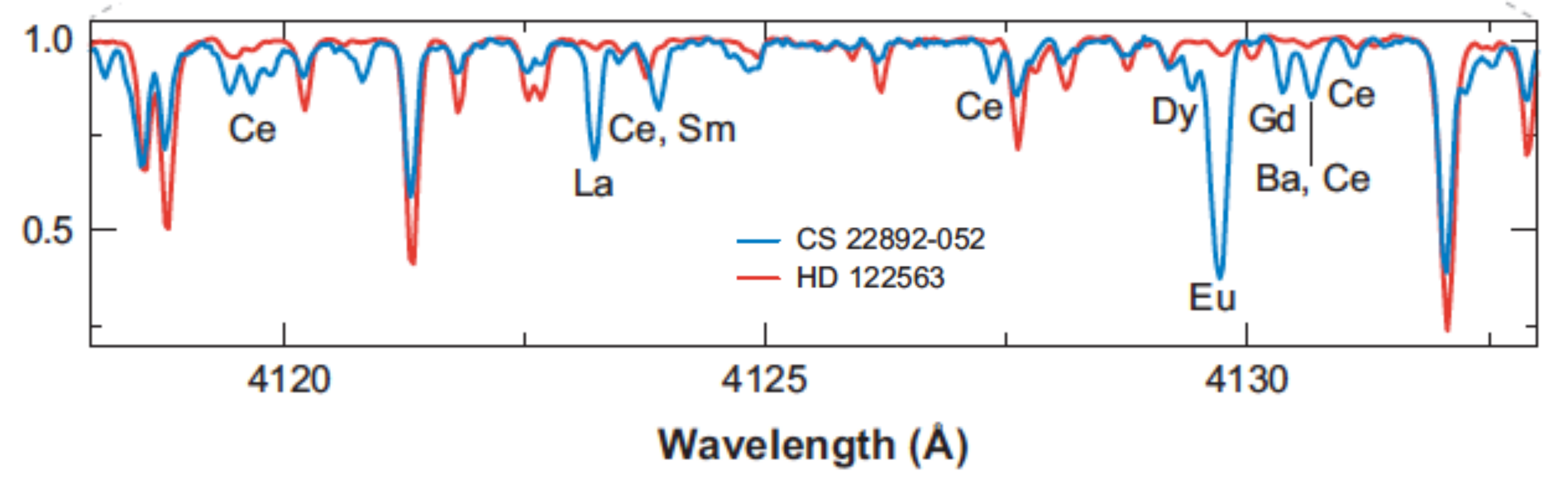
Mg: alpha-element



Sr: neutron capture element



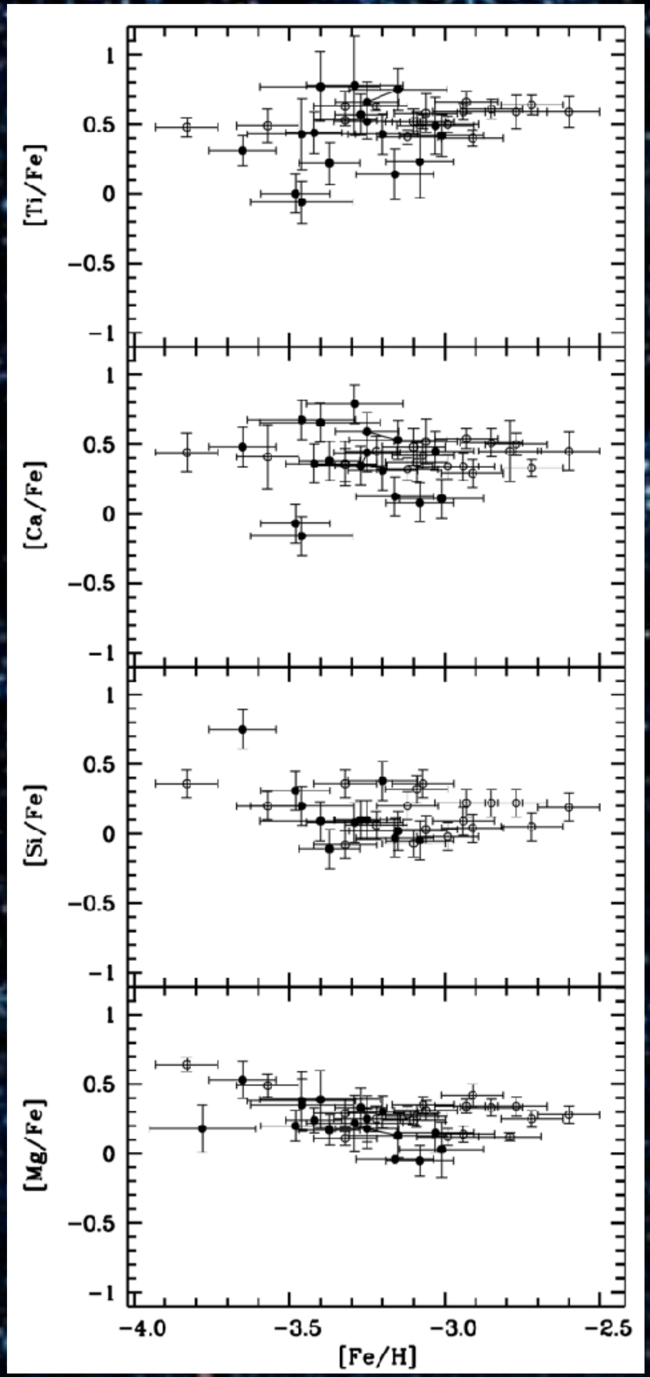
Bonifacio+12

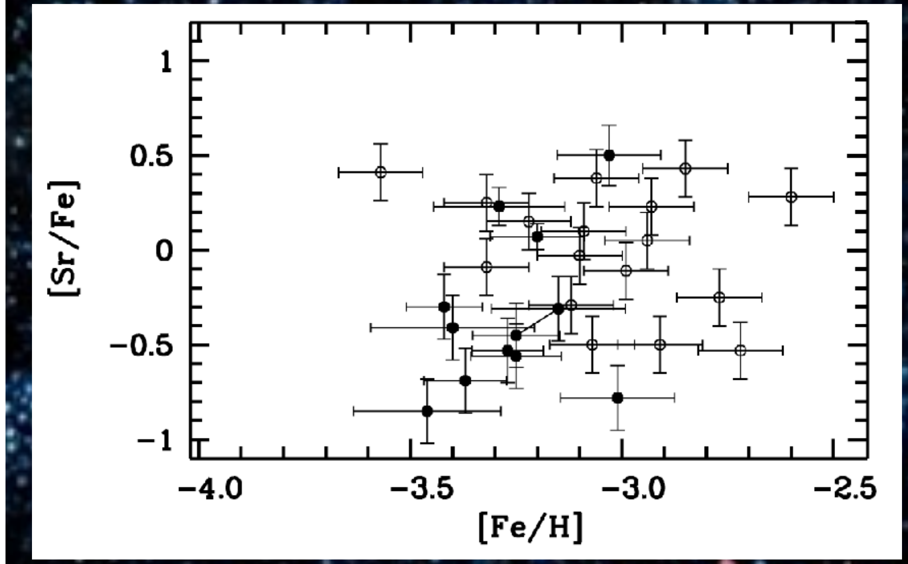


Sneden+08

Stochastic chemical evolution models

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

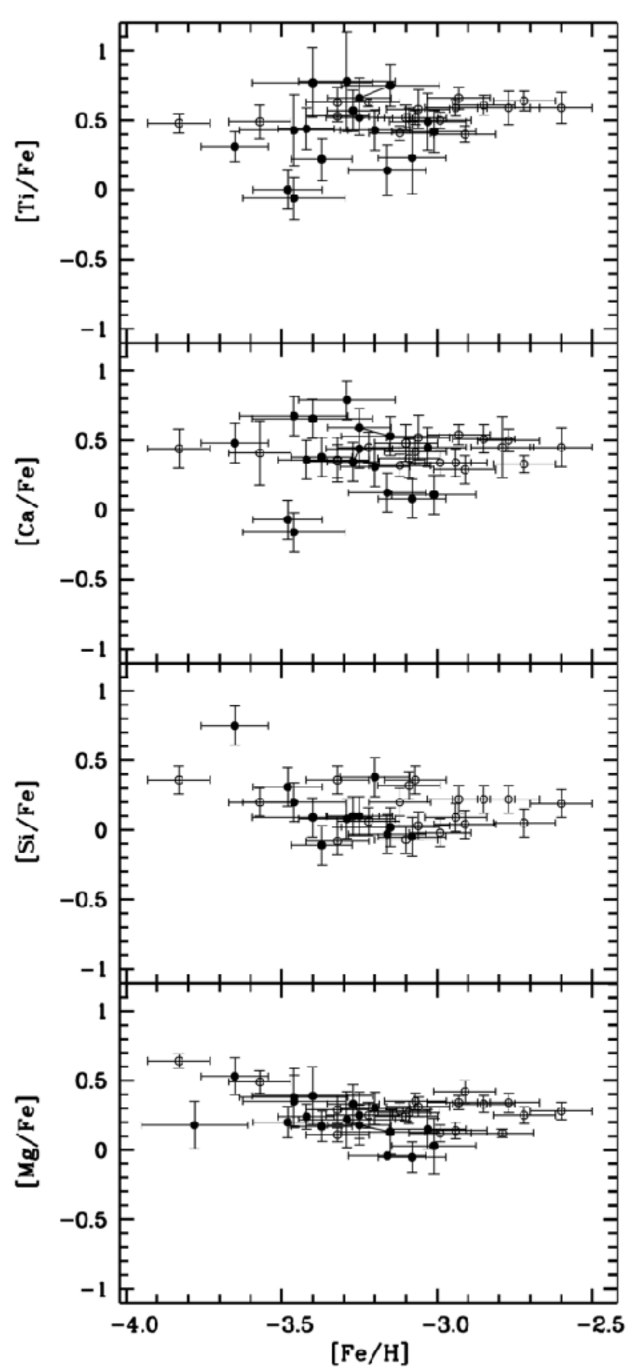


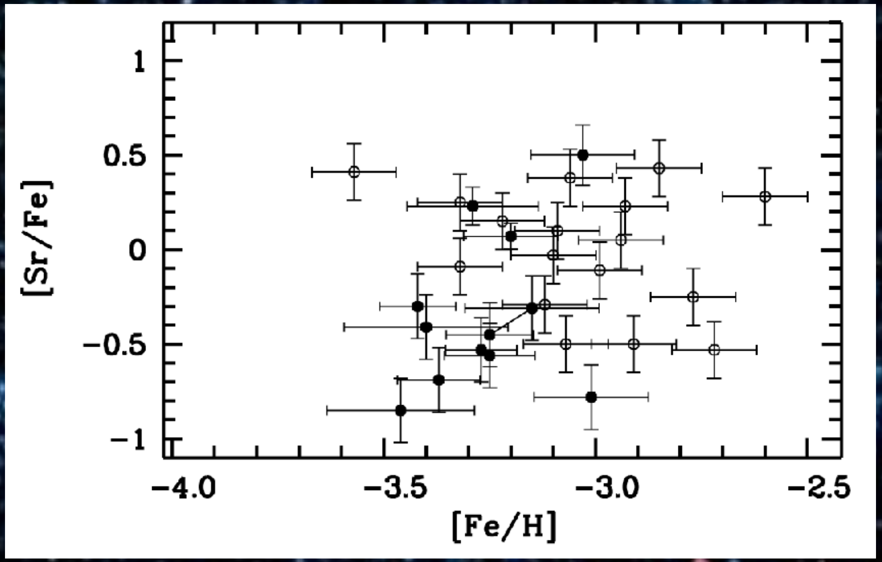


Bonifacio+12

Stochastic chemical evolution models

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



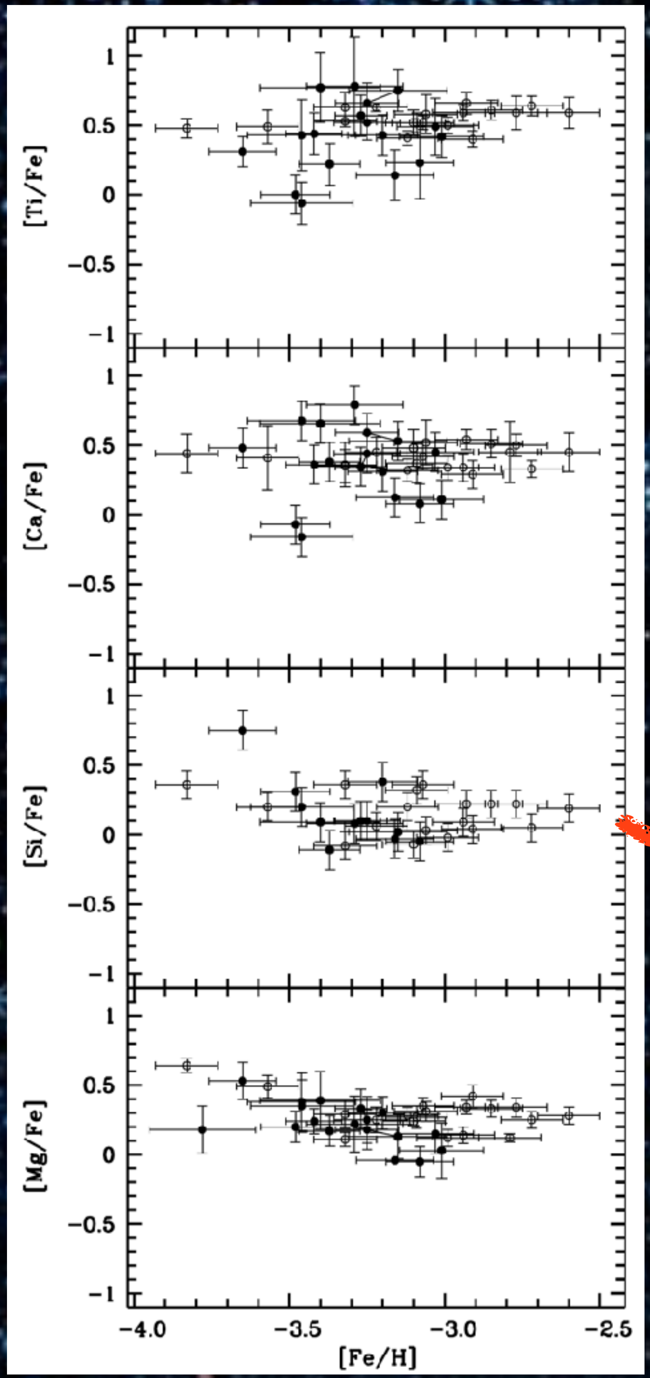


Solution:
The volumes in which the ISM is well mixed are discrete. Assuming a SNe bubble as typical volume with a low regime of star formation the IMF is not fully sampled.
This promotes spread among different volumes if nucleosynthesis of the element is is different among different SNe.

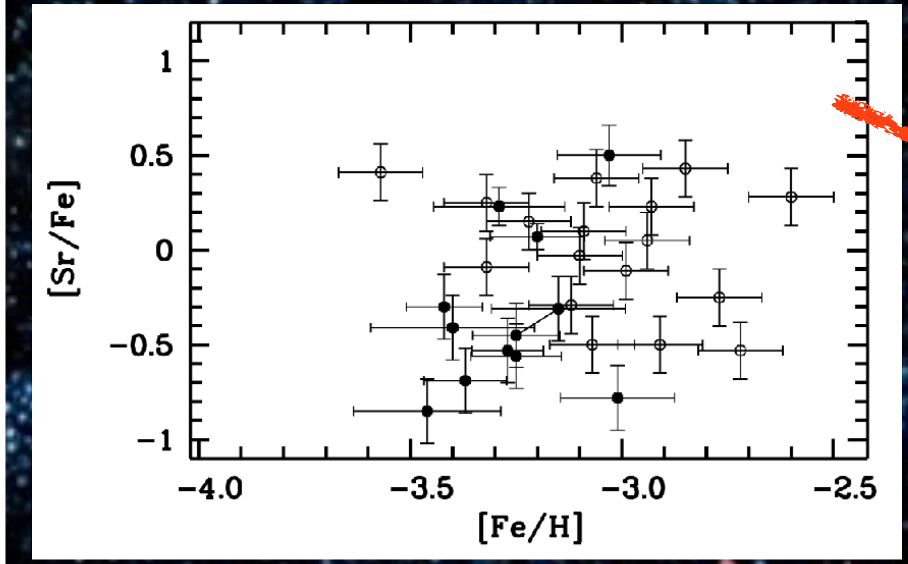
Bonifacio+12

Stochastic chemical evolution models

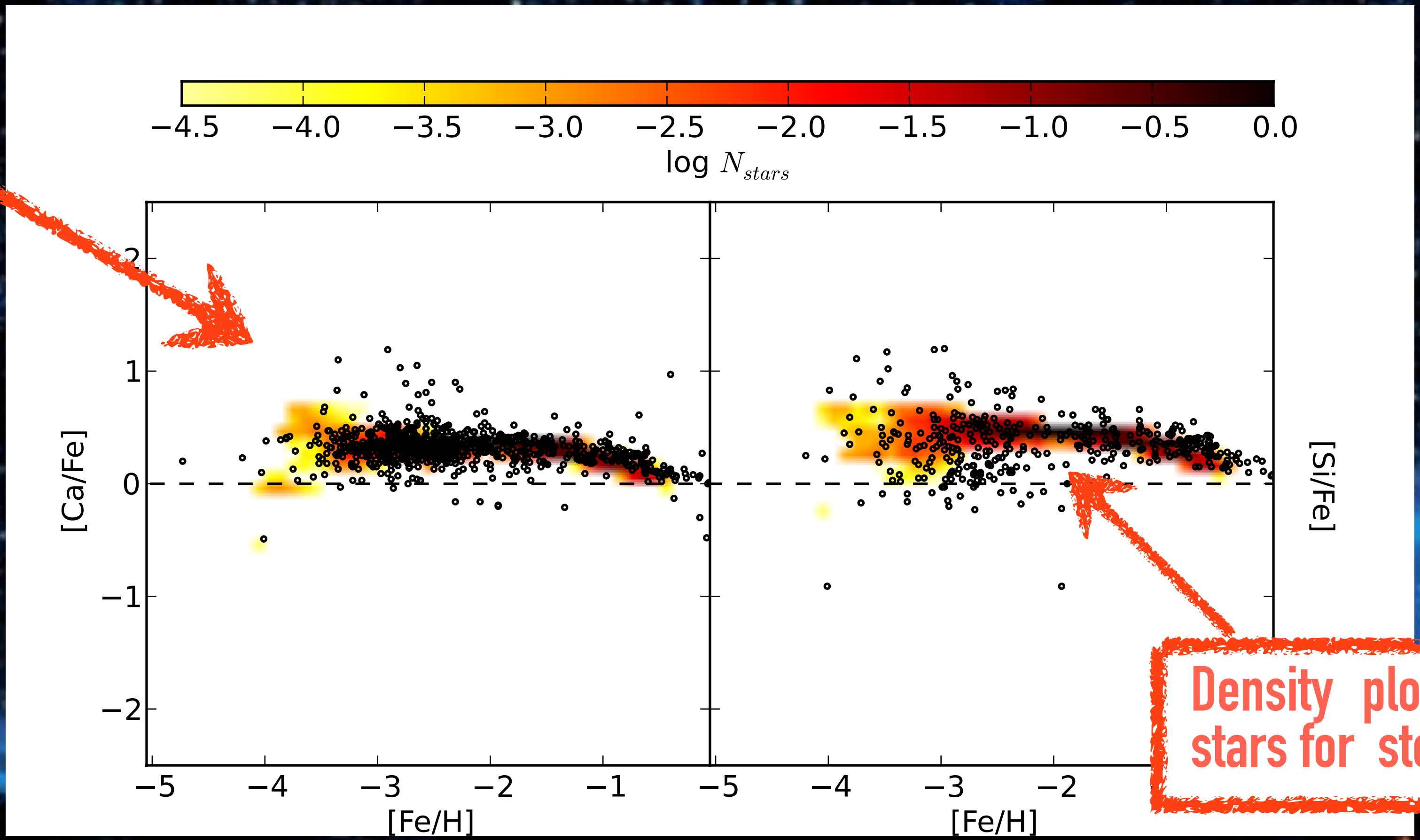
Problem:
Neutron capture elements present a spread alpha elements do not



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.

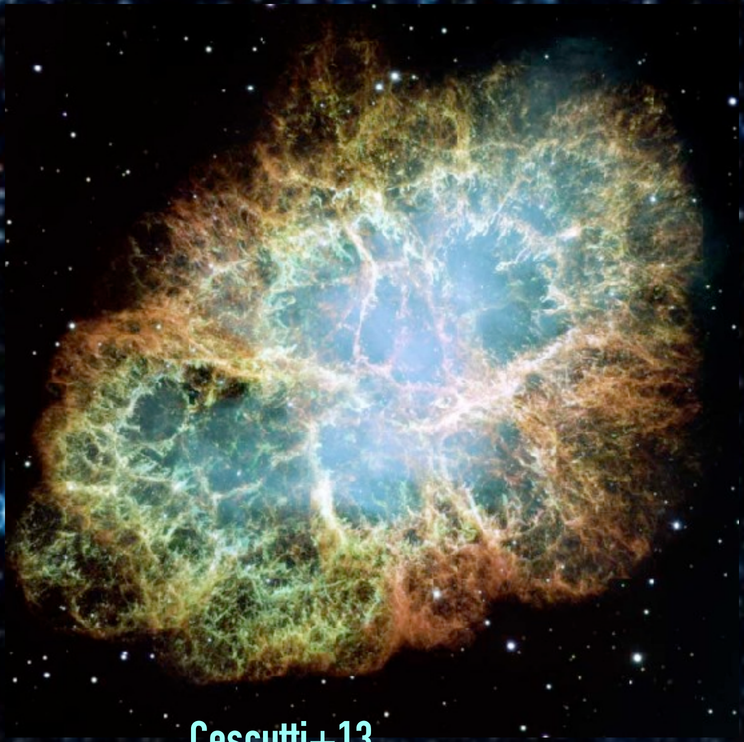


Density plot of long living stars for stochastic model

Cescutti 2008
Cescutti et al. 2013

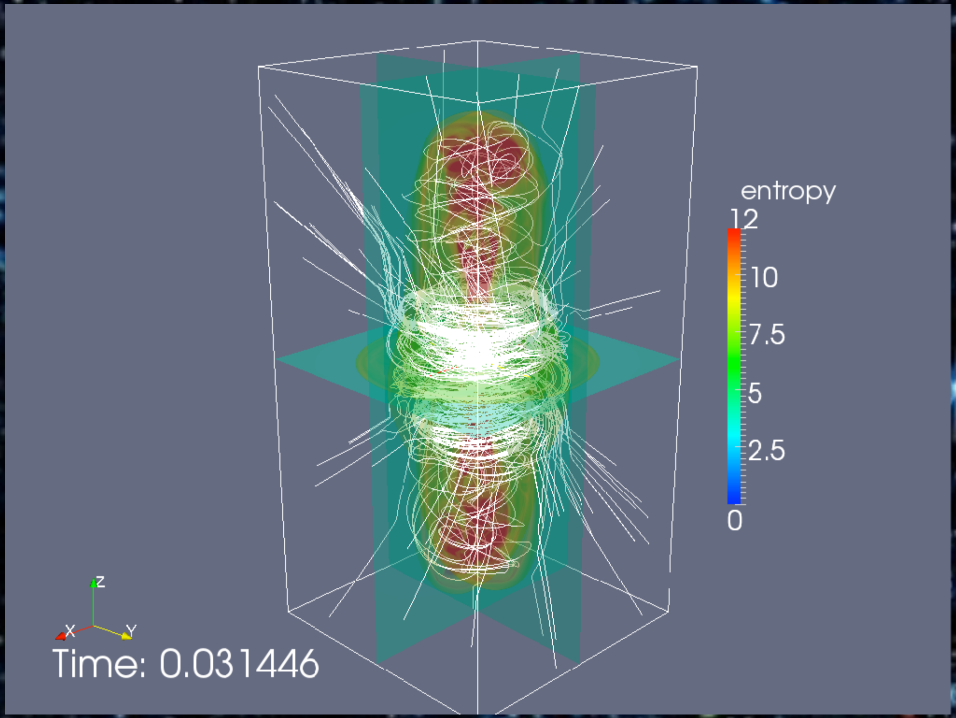
data collected in Frebel 2010

Electron Capture SNe (Wanajo+11)



Cescutti+13

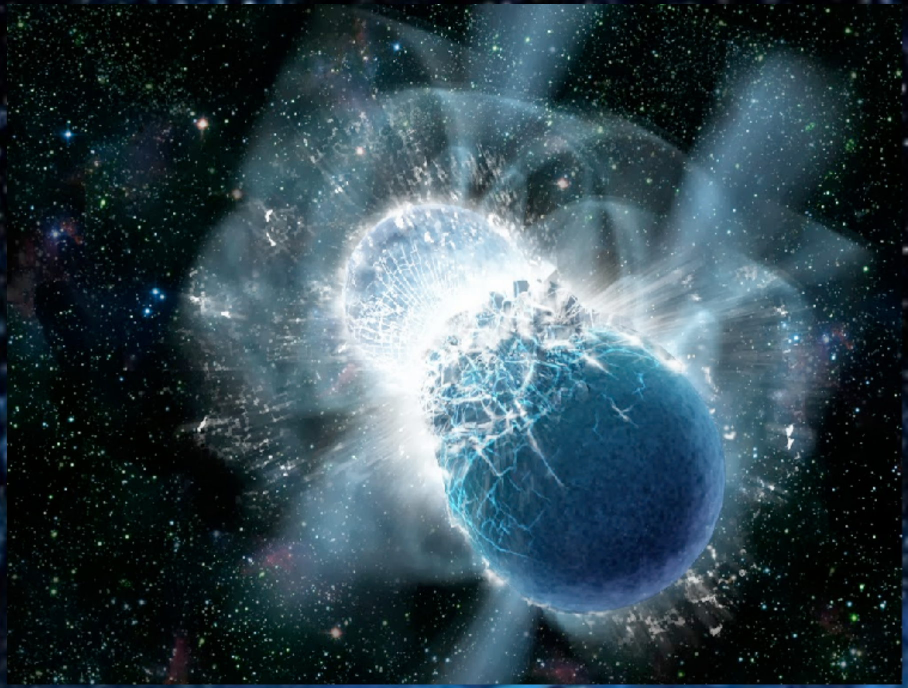
Magnetorotat. driven SNe (Winteler+12)



Cescutti+14

Europium (r-process)

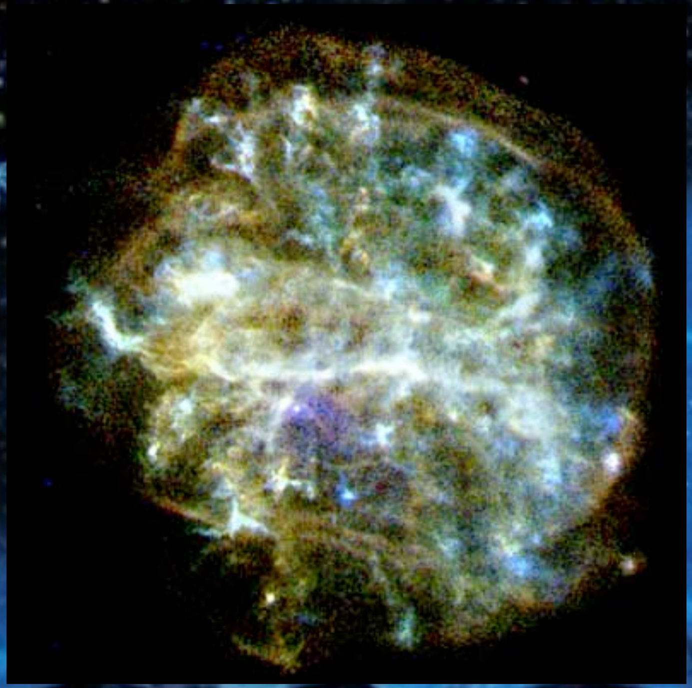
Neutron star mergers (Rosswog+13)



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

other possible sites?

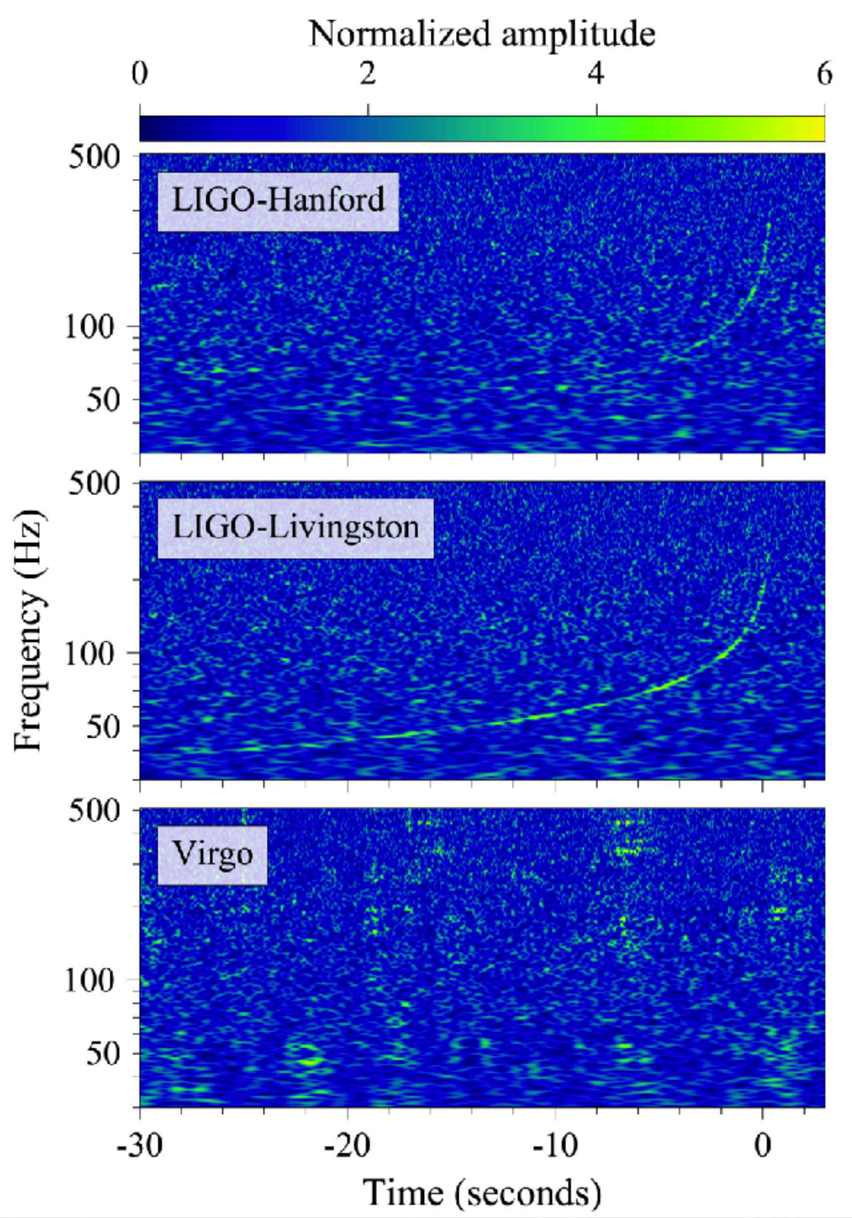
Neutrino winds SNe (Arcones+07,Wanajo 13)



After GW170817...

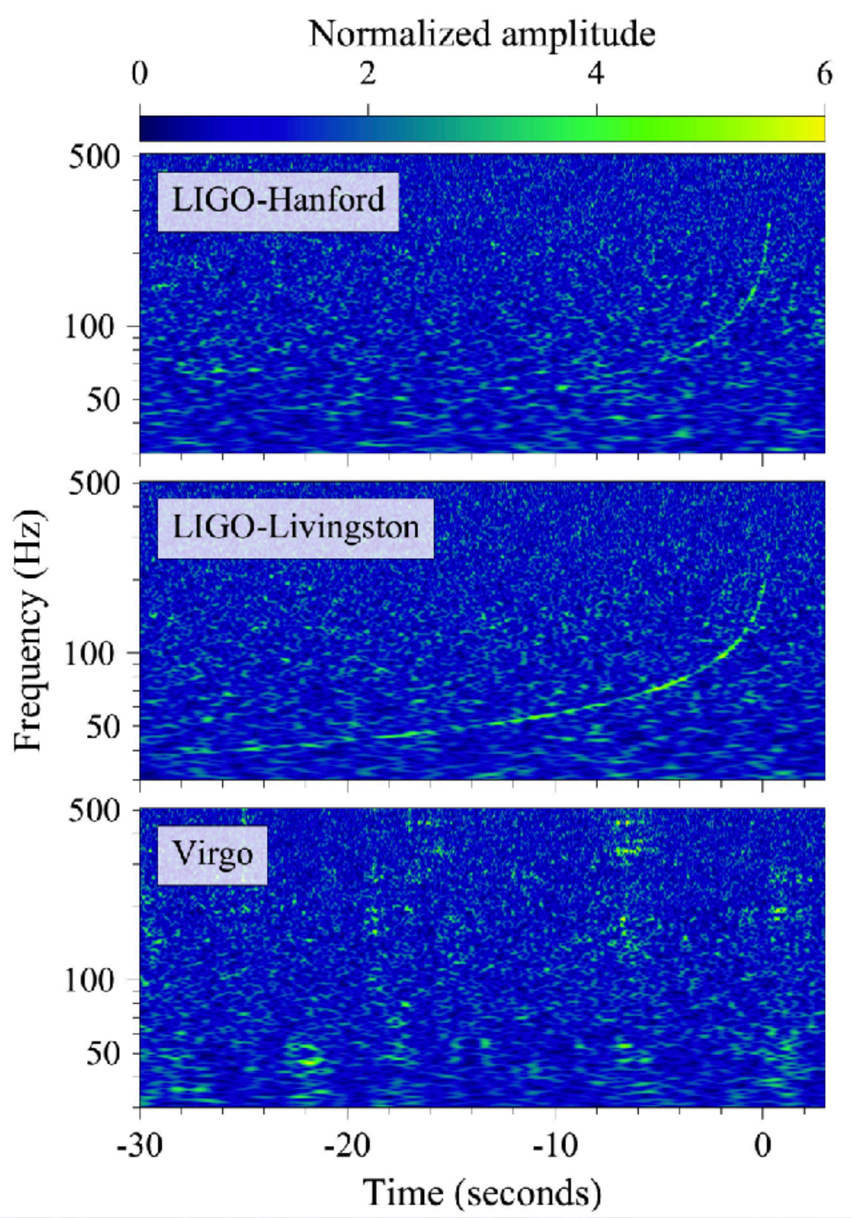
Credit: LIGO/Virgo/NASA/Leo Singer

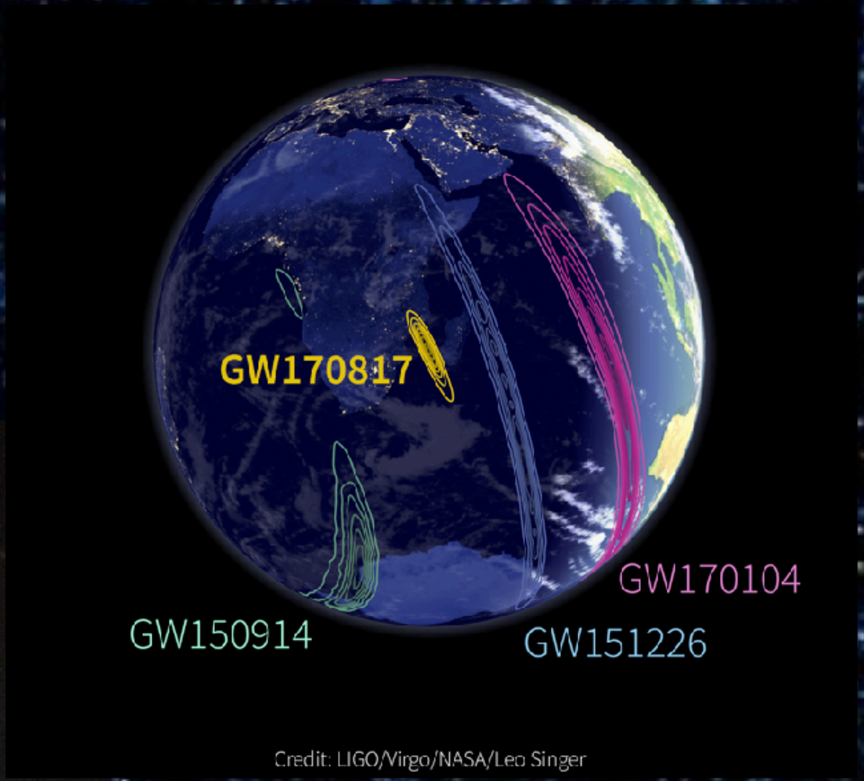
After GW170817. . .



Credit: LIGO/Virgo/NASA/Leo Singer

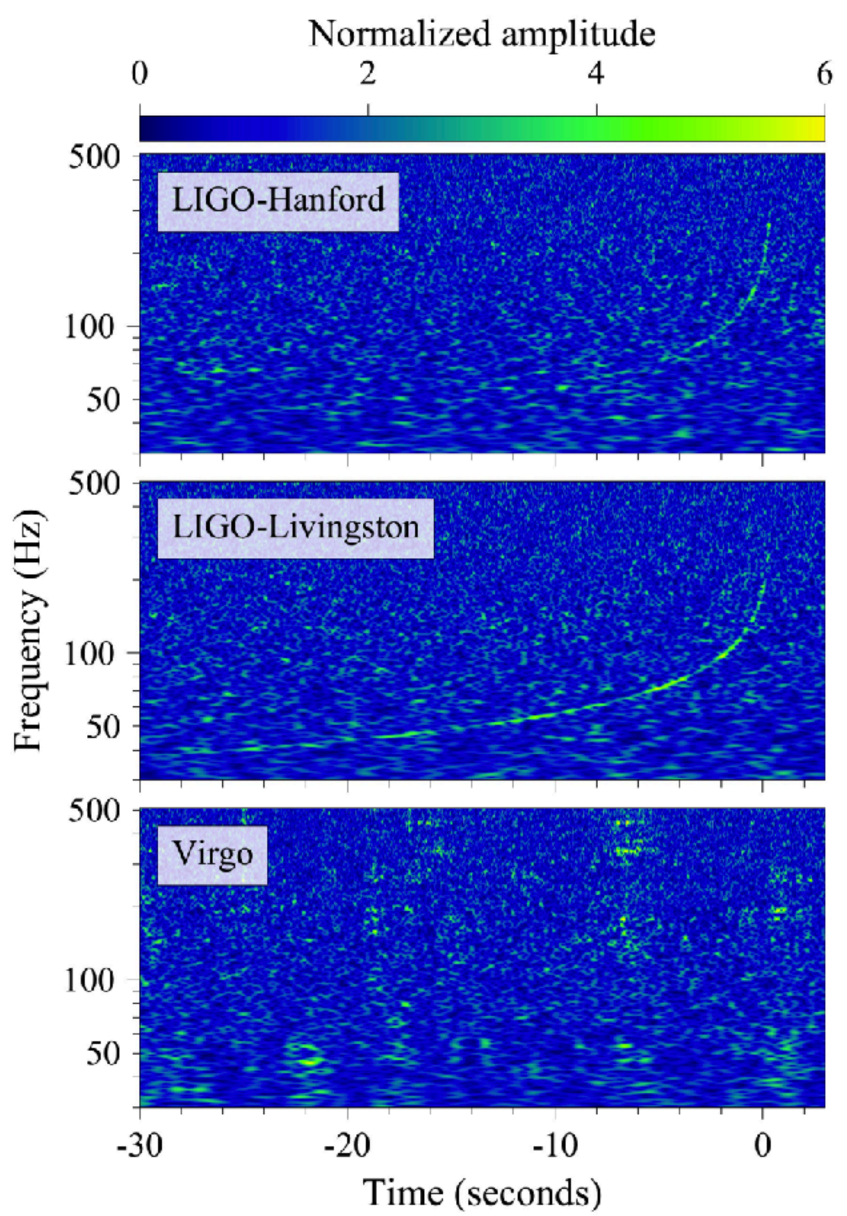
After GW170817. . .



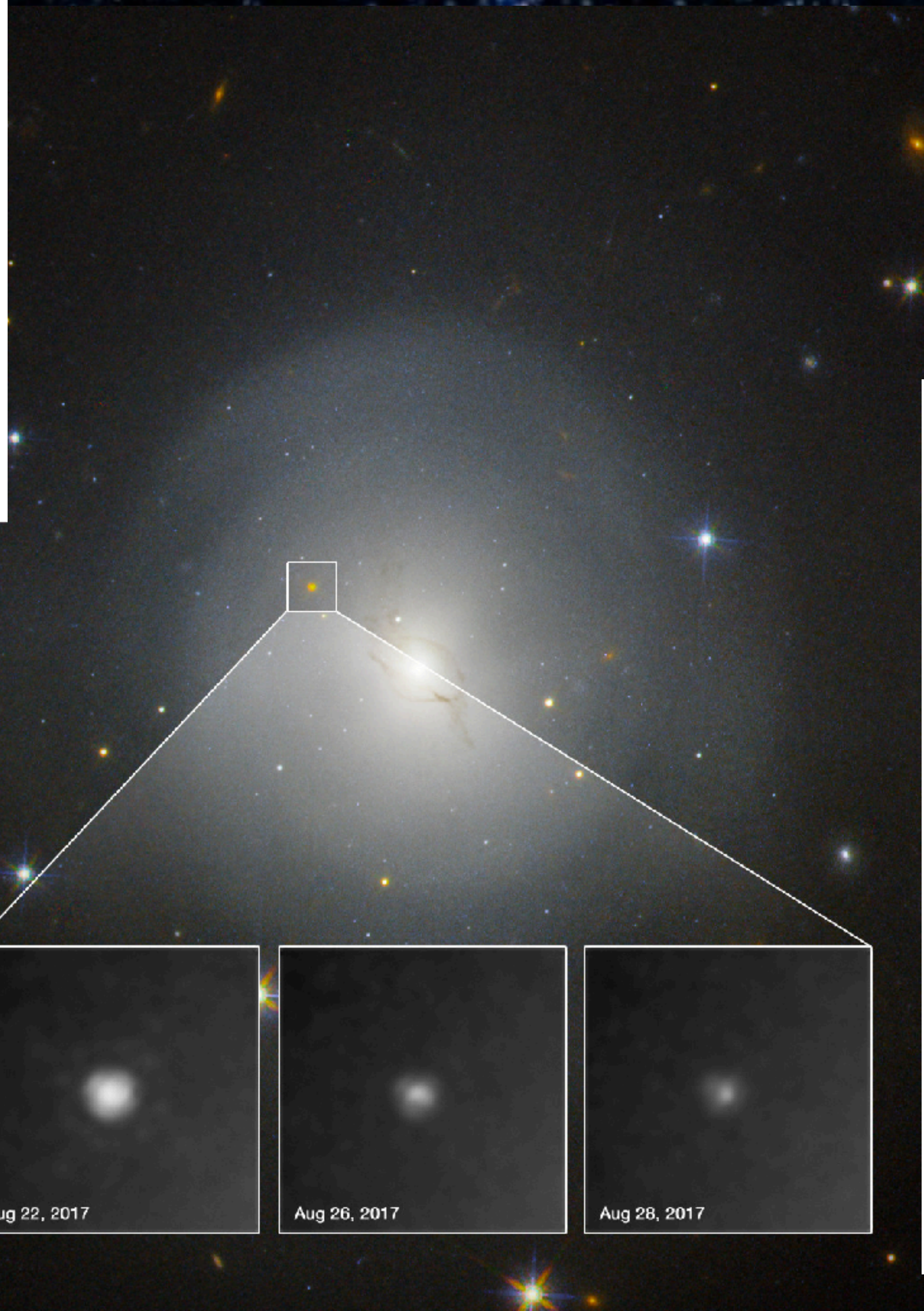


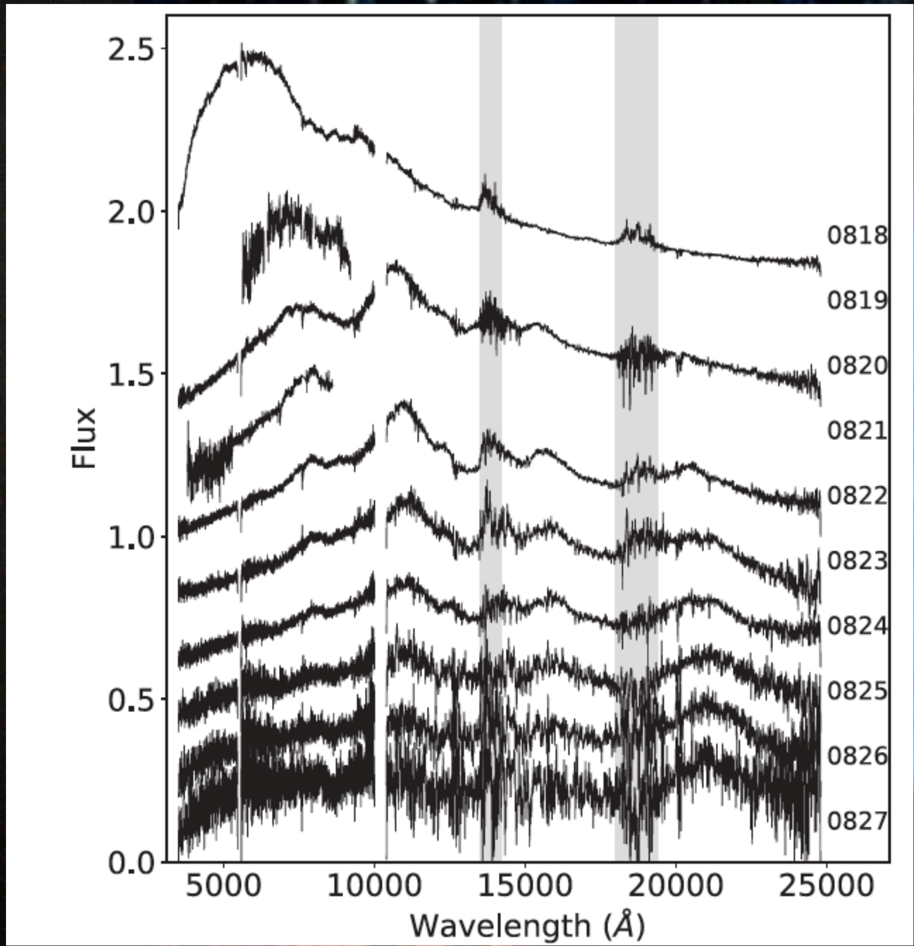
Credit: LIGO/Virgo/NASA/Leo Singer

After GW170817. . .



Credit: LIGO/Virgo/NASA/Leo Singer





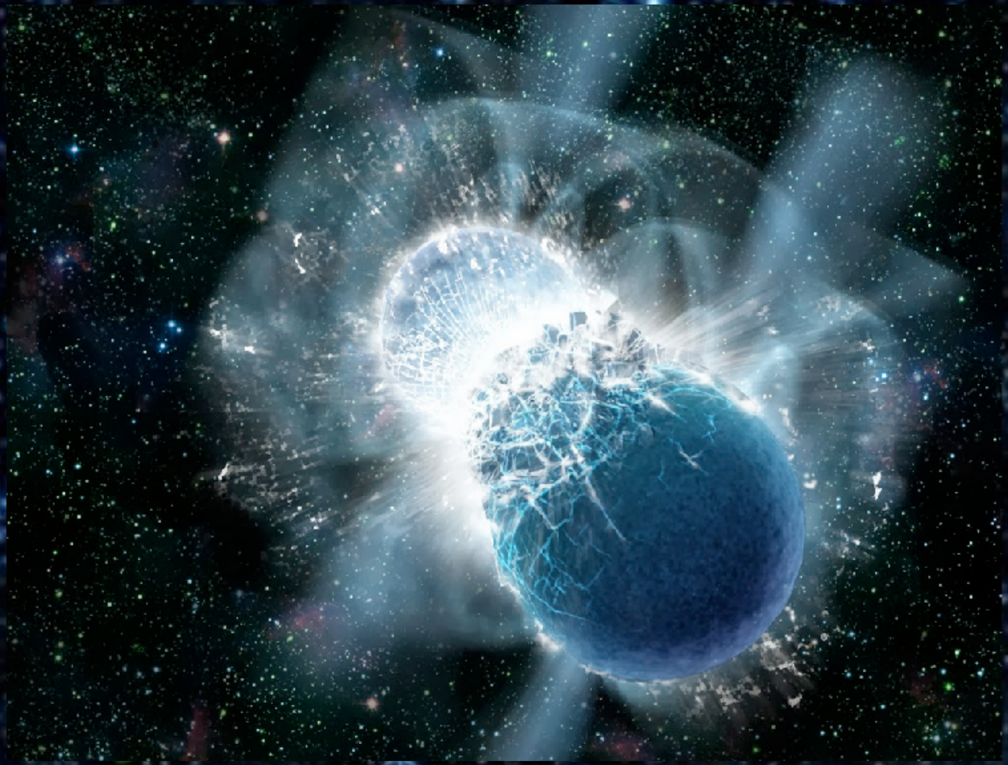
Neutron stars mergers

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.
We investigate delay of 1, 10 and 100Myr.

Neutron star mergers (Rosswog+13)



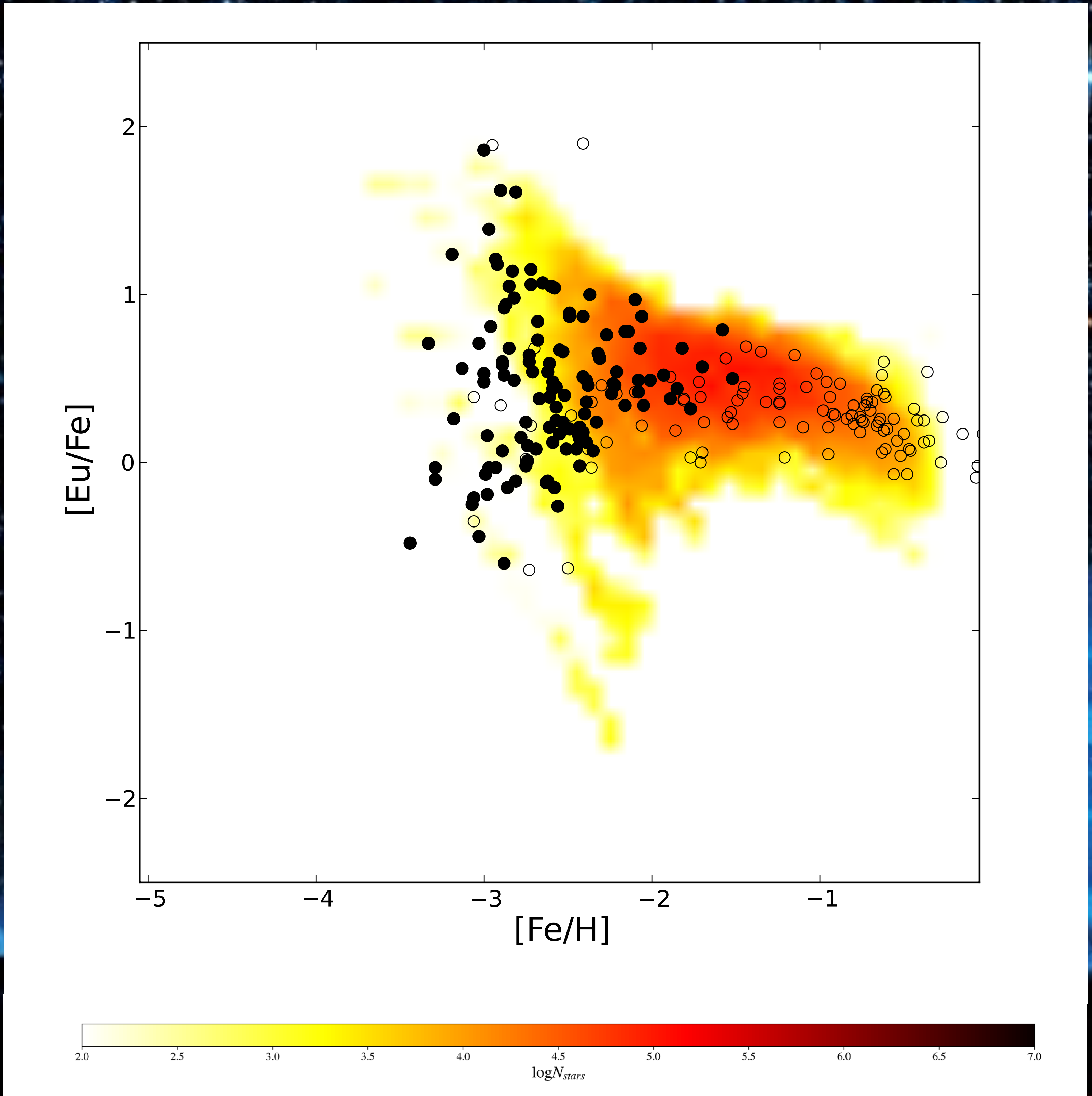
Neutron stars mergers

delay for the merging 1Myr

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?



Neutron star mergers

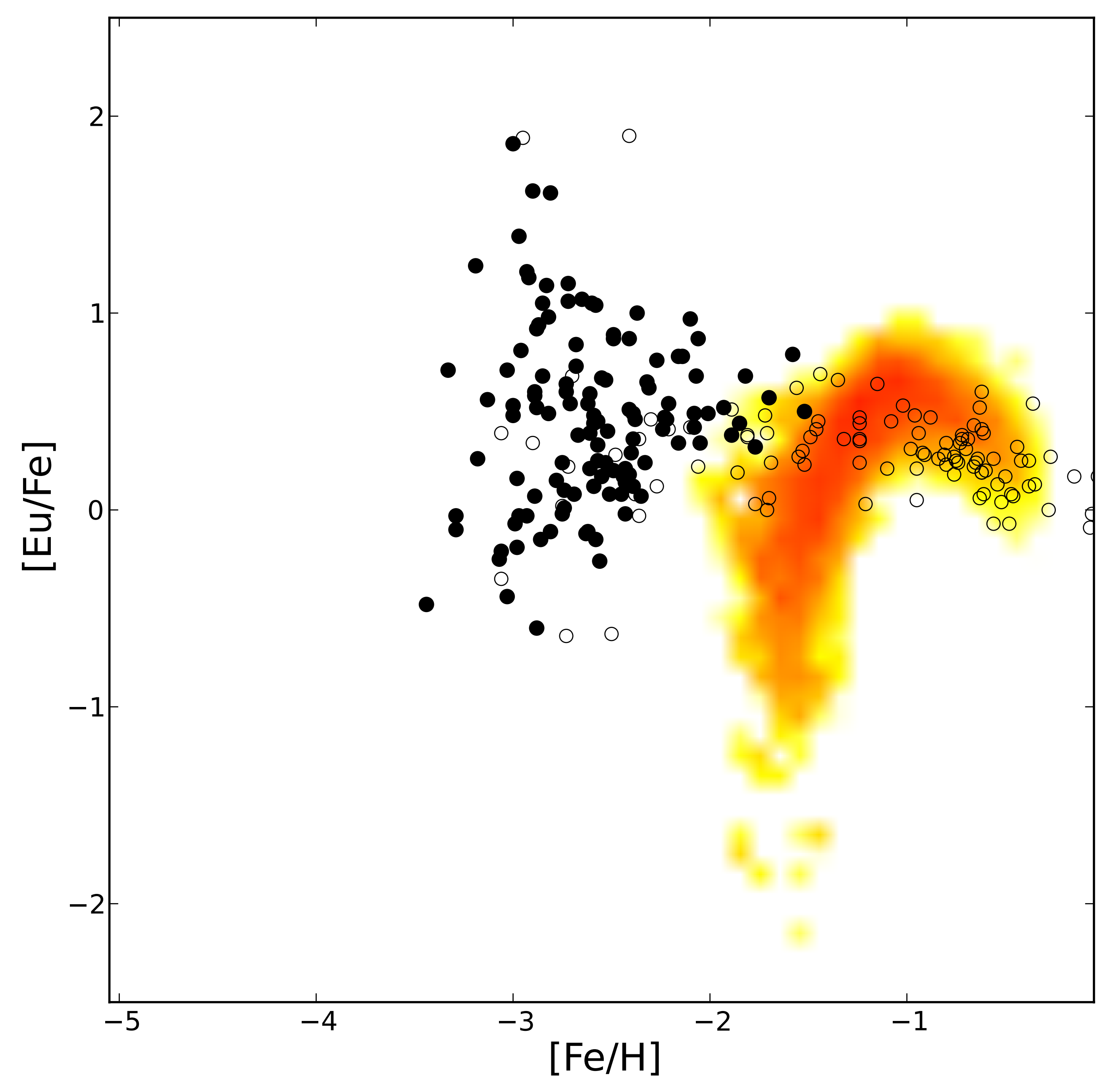
delay for the merging 100 Myr

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.

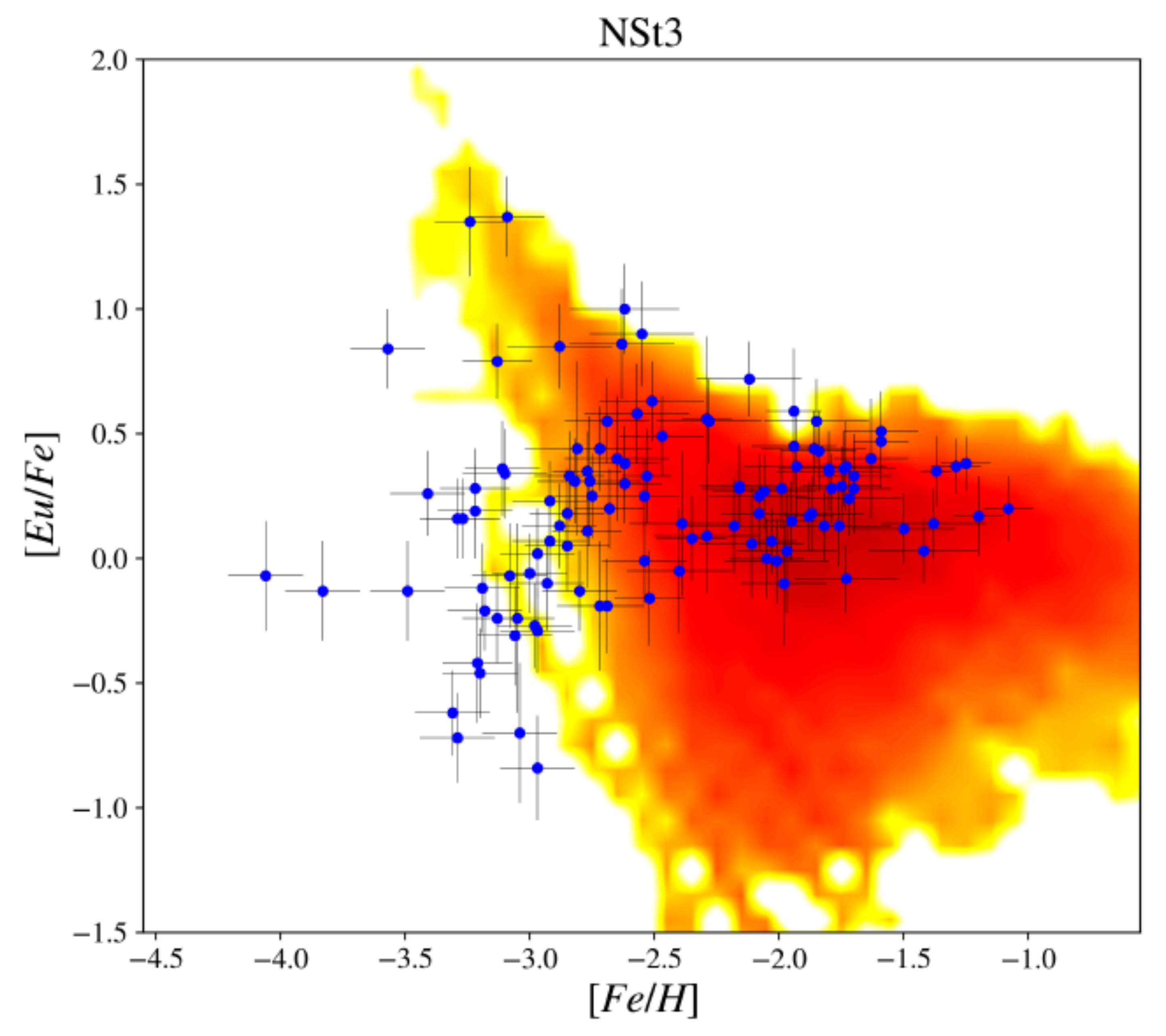
What about a distribution of delays?



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

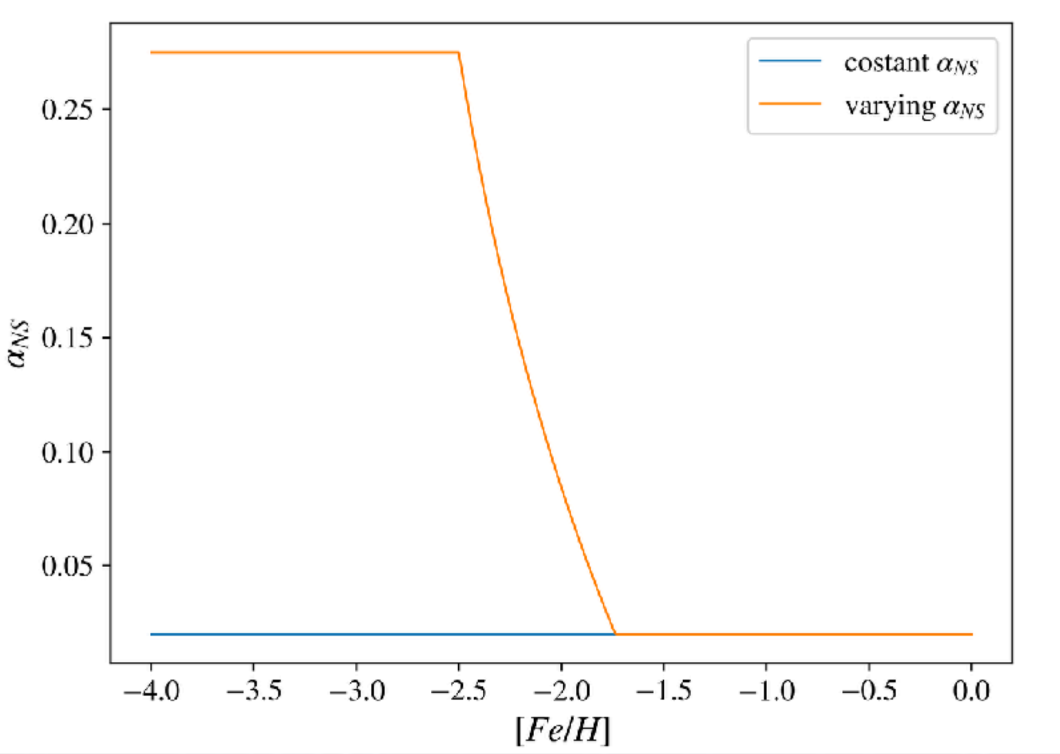
with a delay time distribution: $t^{-1.5}$



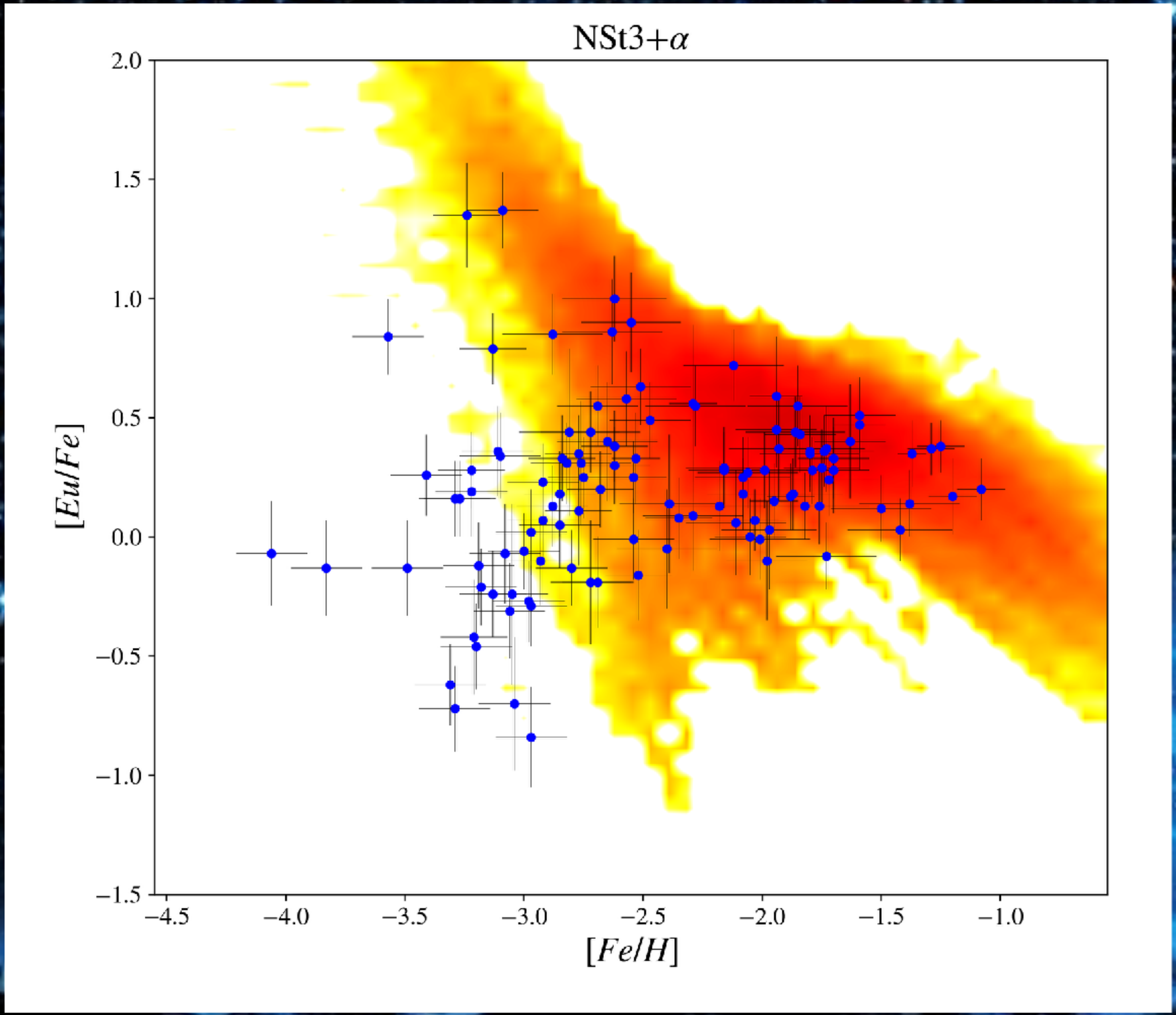
Cavallo+21

NSM with alpha variations

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



similar to Simonetti+19



Cavallo+ 21

Other solutions?

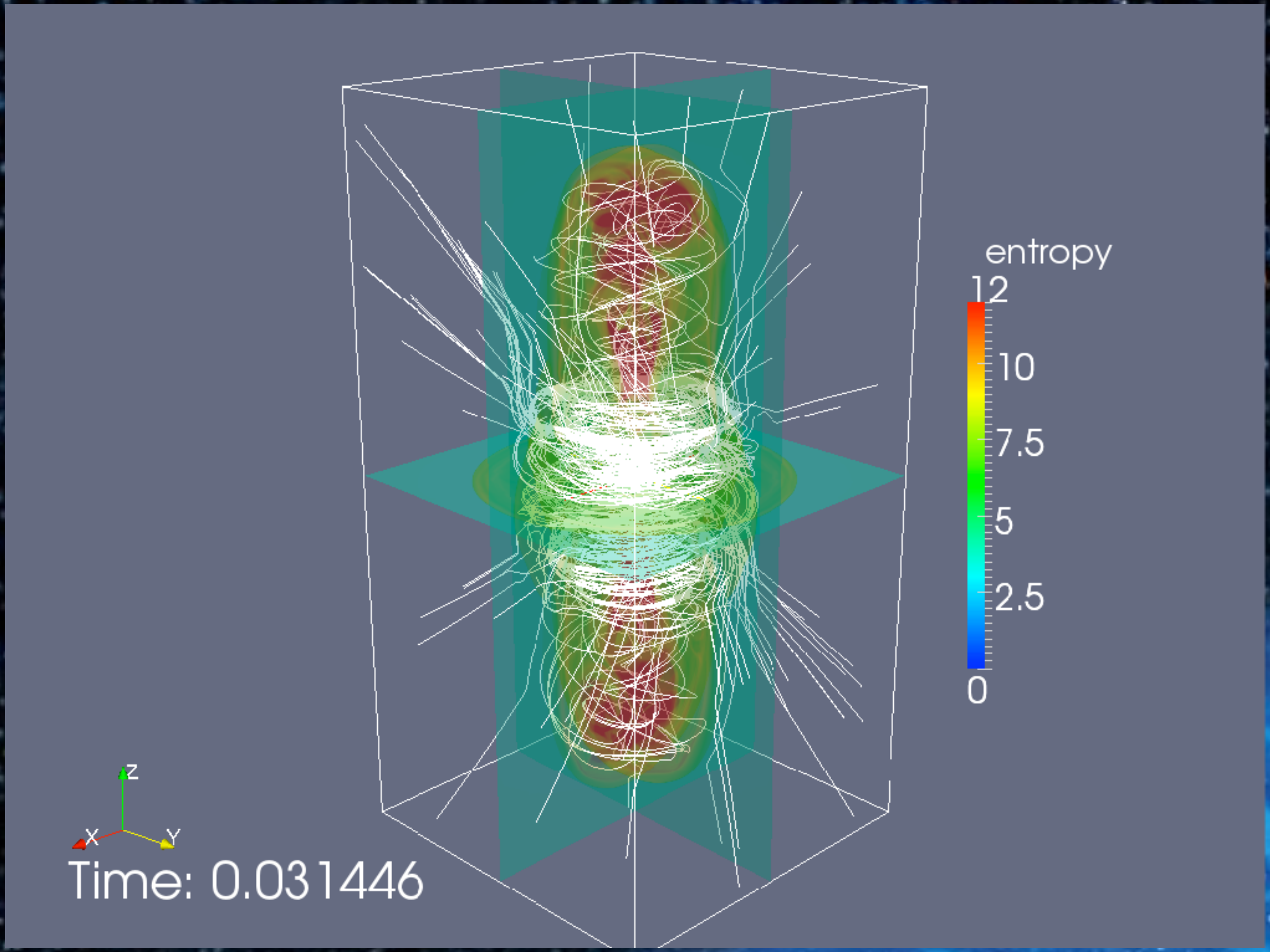
Magneto Rotationally Driven SN scenario (MRD)

(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.

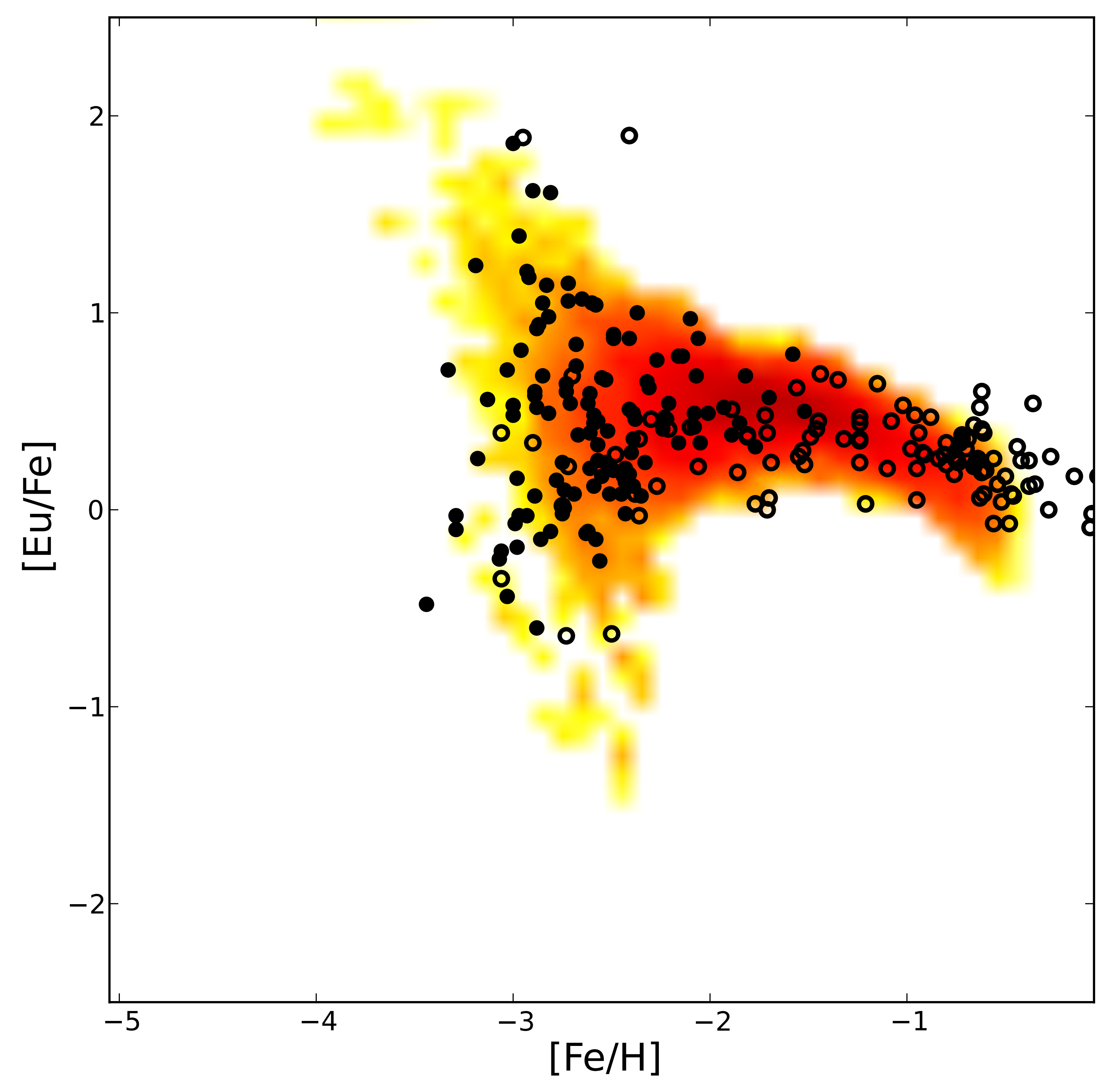


Magneto Rotationally Driven SN scenario (MRD) 10%

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

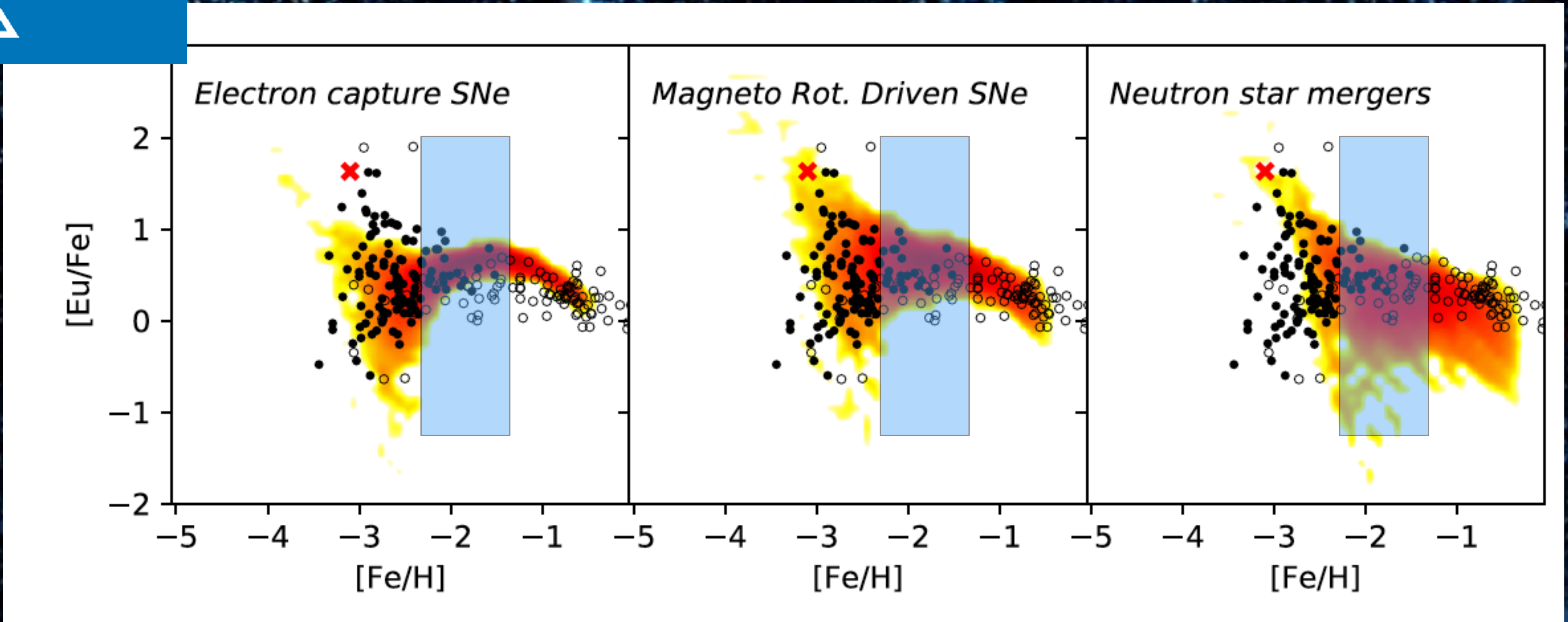
The assumed percentage of events in massive stars is higher than expected (at least at the solar metallicity), but it is reasonable to increase toward the metal poor regime
(Woosley and Heger 2006)



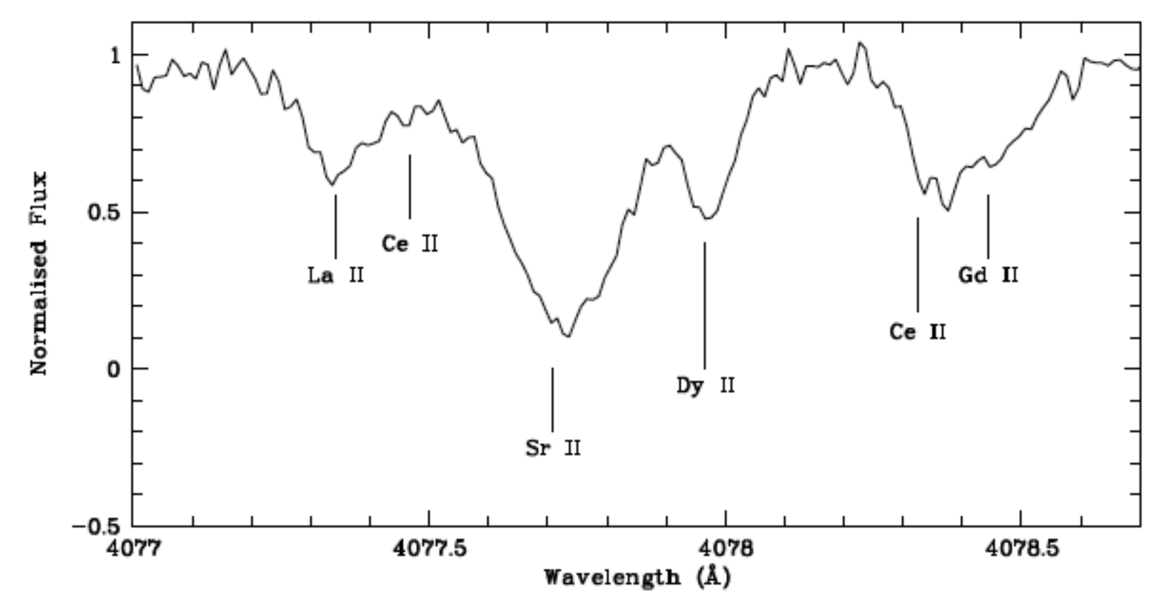
MINCE

Measuring at Intermediate Metallicity Neutron Capture Elements

Main investigators Bonifacio & Cescutti

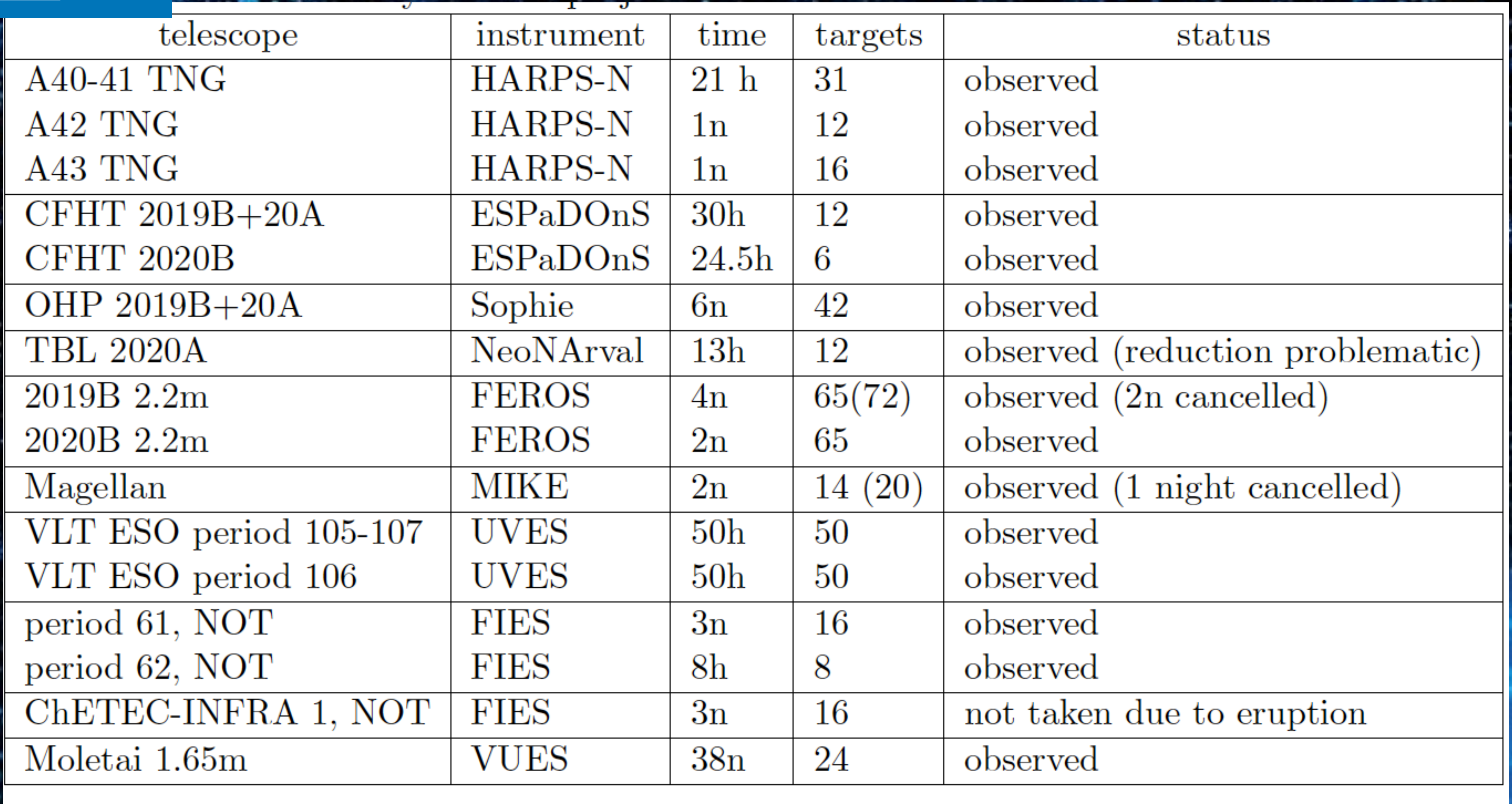


Observational proposals at
TNG,CFHT,3.6m,Magellan,UVES…
Goal is 1000 stars in 5y at high quality:
100S/N at 400nm and R>50'000.



Summary

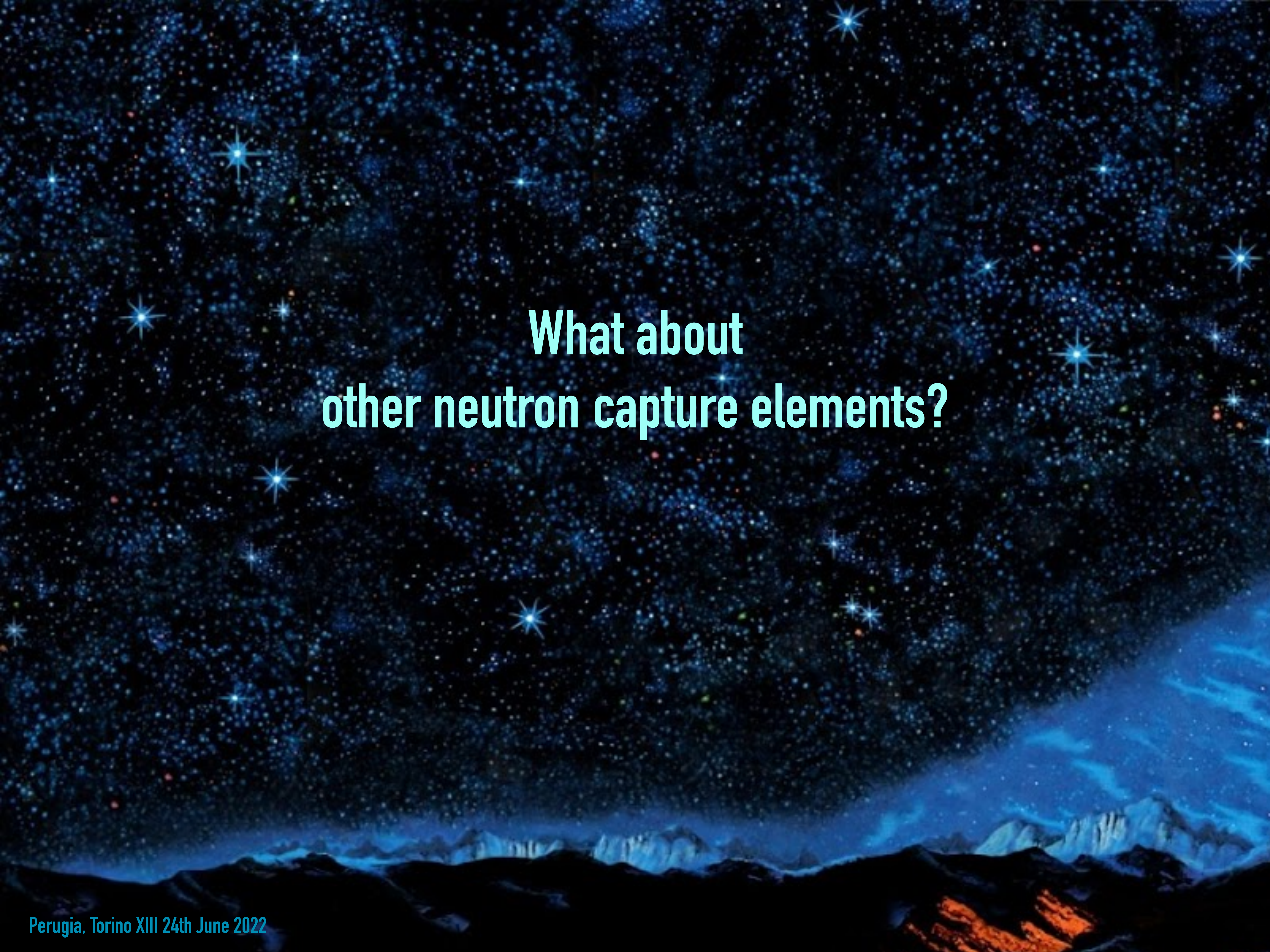
(missing the 3n awarded with a proposal @NOT thanks to ChETEC INFRA time!)



telescope	instrument	time	targets	status
A40-41 TNG	HARPS-N	21 h	31	observed
A42 TNG	HARPS-N	1n	12	observed
A43 TNG	HARPS-N	1n	16	observed
CFHT 2019B+20A	ESPaDOnS	30h	12	observed
CFHT 2020B	ESPaDOnS	24.5h	6	observed
OHP 2019B+20A	Sophie	6n	42	observed
TBL 2020A	NeoNArval	13h	12	observed (reduction problematic)
2019B 2.2m	FEROS	4n	65(72)	observed (2n cancelled)
2020B 2.2m	FEROS	2n	65	observed
Magellan	MIKE	2n	14 (20)	observed (1 night cancelled)
VLT ESO period 105-107	UVES	50h	50	observed
VLT ESO period 106	UVES	50h	50	observed
period 61, NOT	FIES	3n	16	observed
period 62, NOT	FIES	8h	8	observed
ChETEC-INFRA 1, NOT	FIES	3n	16	not taken due to eruption
Moletai 1.65m	VUES	38n	24	observed

9 facilities used!

~400 stellar spectra with high S/N and Resolution



What about
other neutron capture elements?

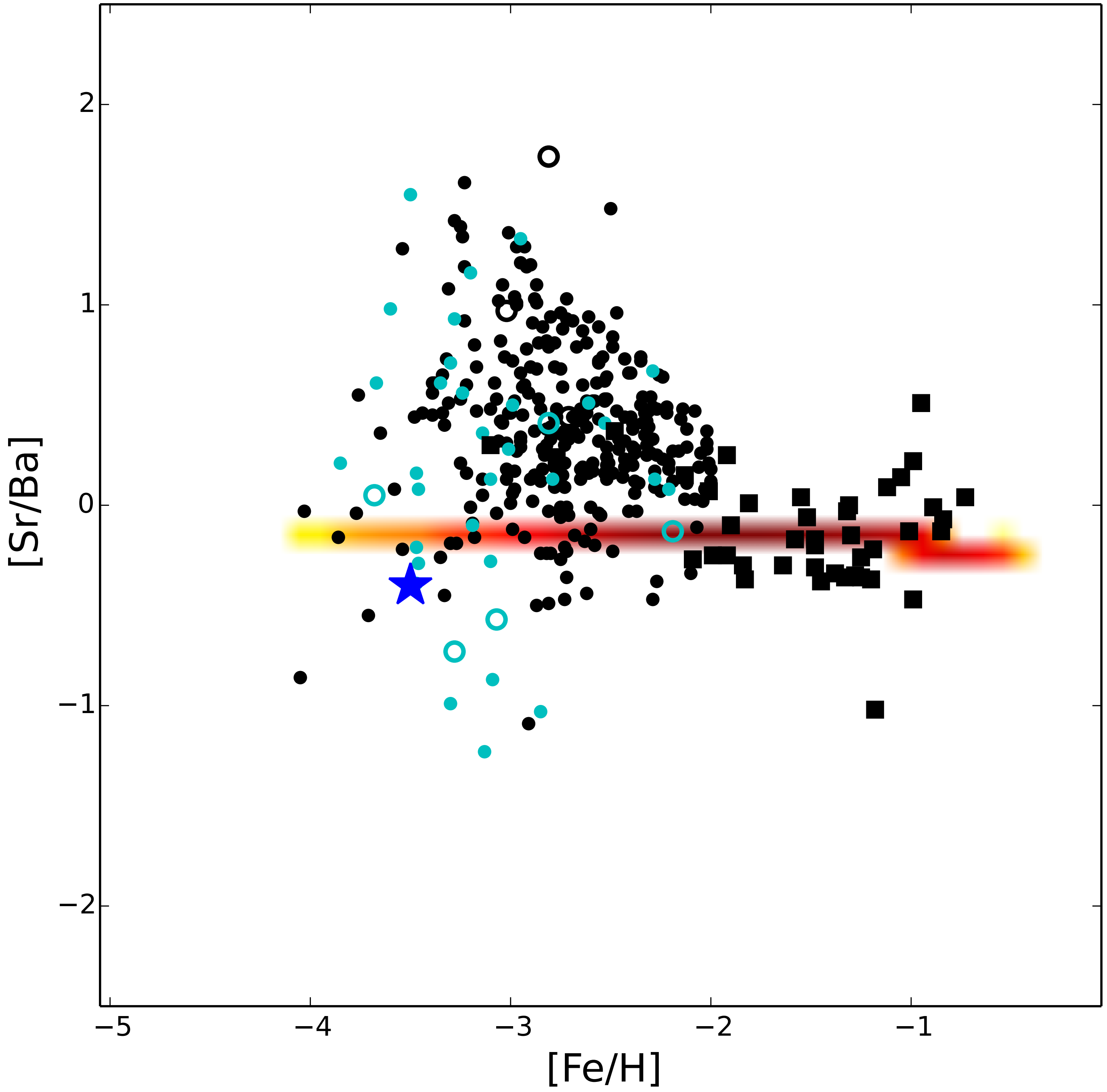
Neutron capture elements

Early Galaxy

	s-process	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 Karakas+12	nucleosynthesis available (but . . .)

Puzzling result for the "heavy to light" n.c. element ratio

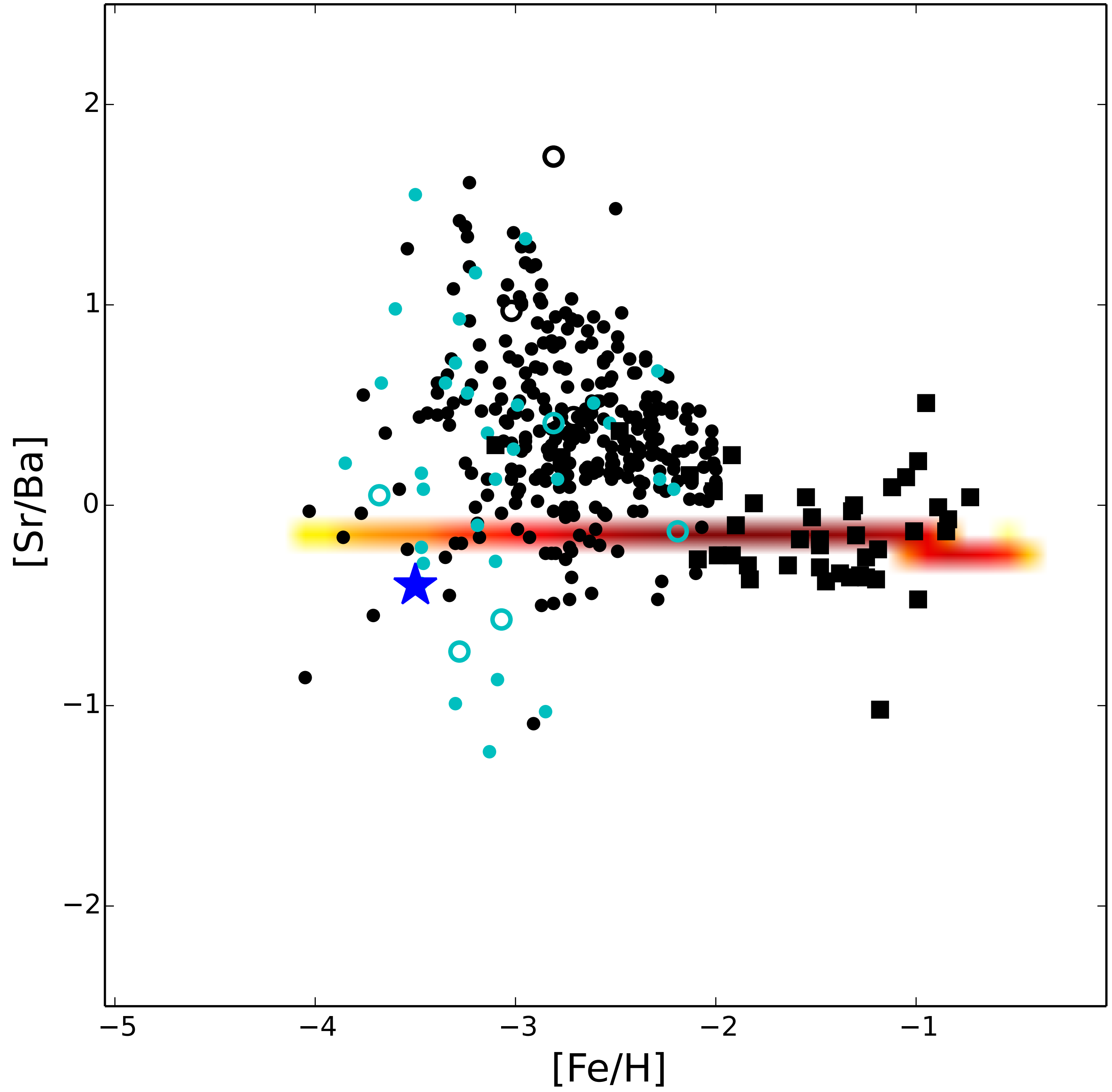
For Sr yields:
scaled Ba yields
according to the
r-process signature of the
solar system
(Sneden et al '08)



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)

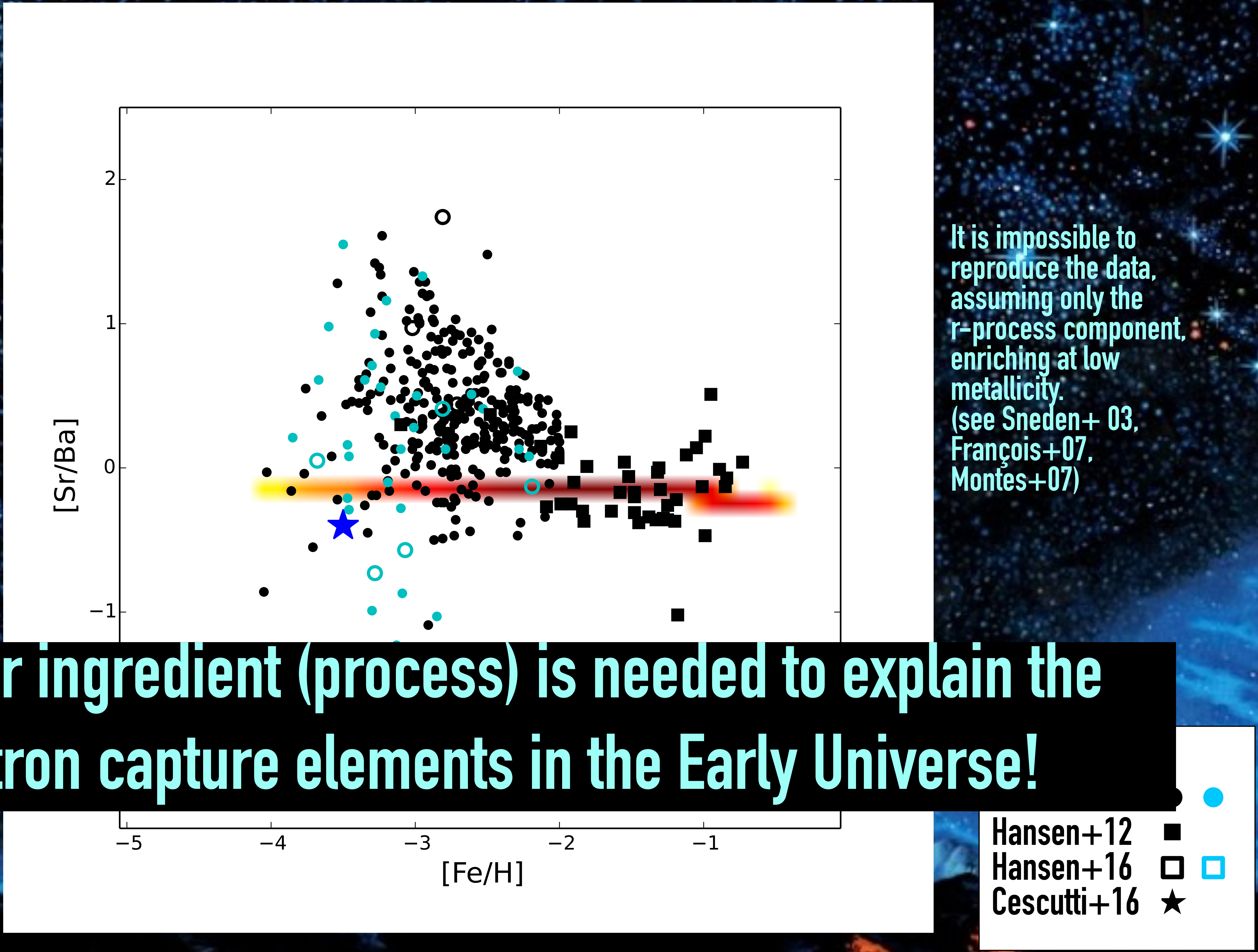


It is impossible to
reproduce the data,
assuming only the
r-process component,
enriching at low
metallicity.
(see Sneden+ 03,
François+07,
Montes+07)

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)

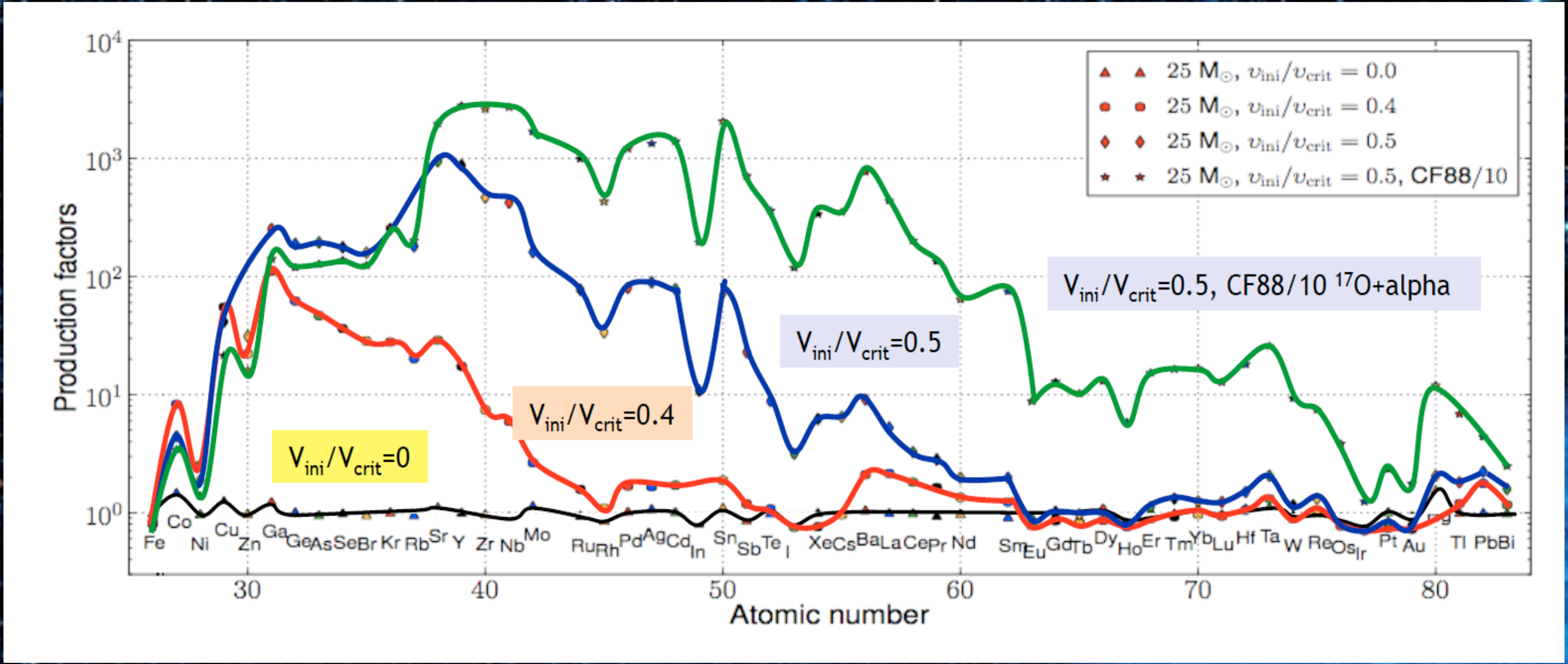


It is impossible to
reproduce the data,
assuming only the
r-process component,
enriching at low
metallicity.
(see Sneden+ 03,
François+07,
Montes+07)

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

Low metallicity and rotating massive stars

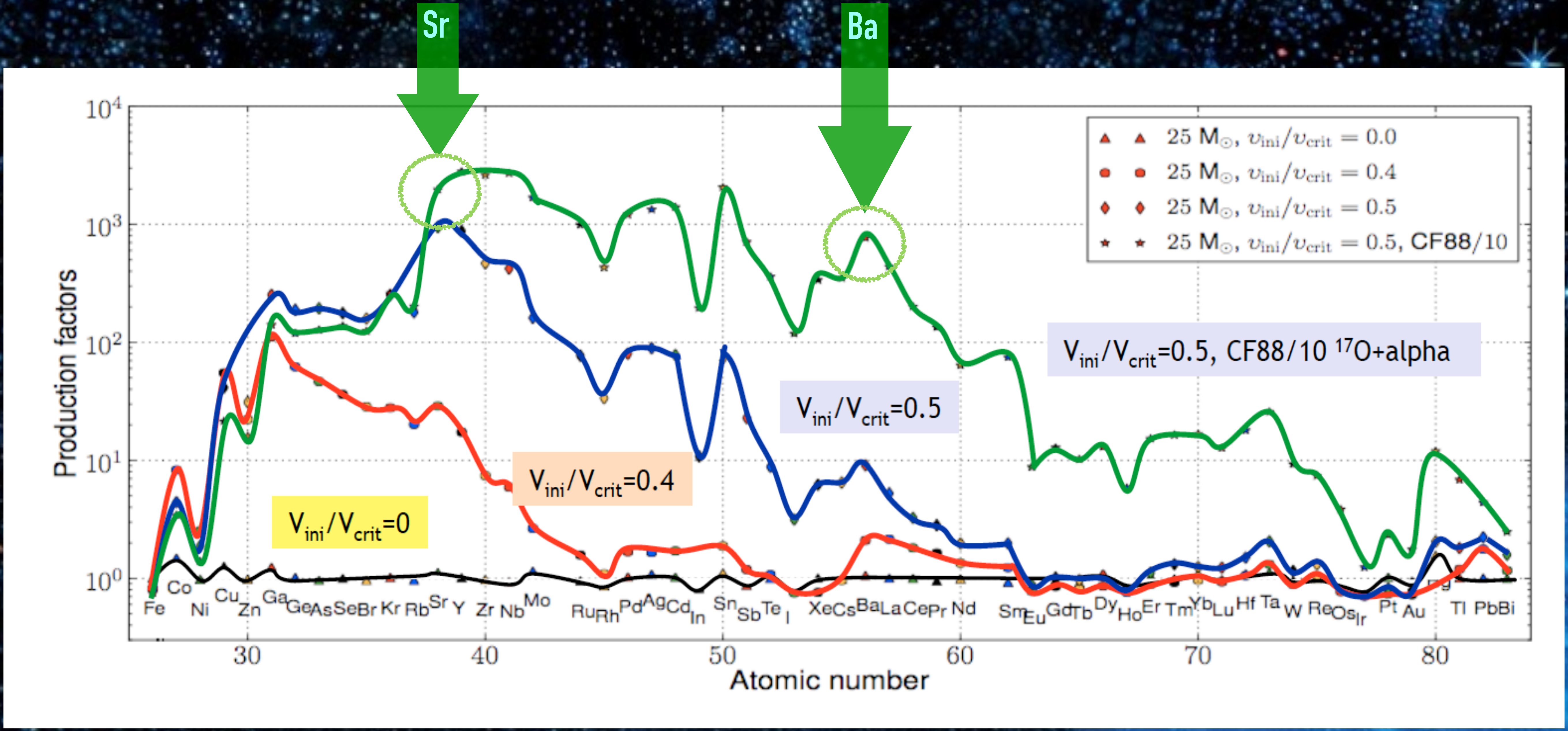
Frischknecht et al. 2012 , 2016 (self-consistent models with reaction network including 613 isotopes up to Bi)



Low metallicity and rotating massive stars

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

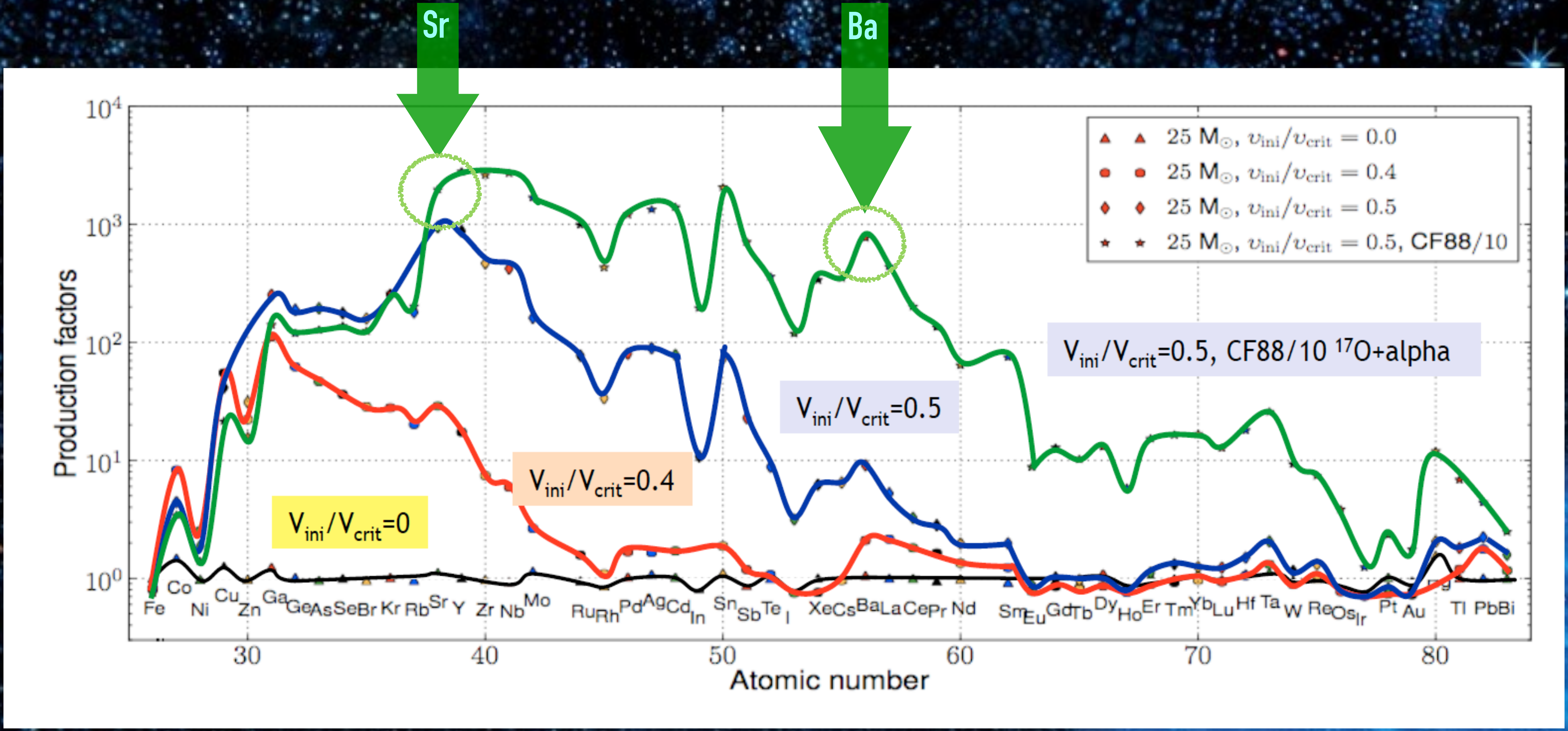
Rotating massive stars can contribute to s-process elements!



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 Karakas+ 2012	(Frischknecht+ 2012) Frischknecht+ 2016 Limongi and Chieffi 2018	....

s-process from rotating massive stars

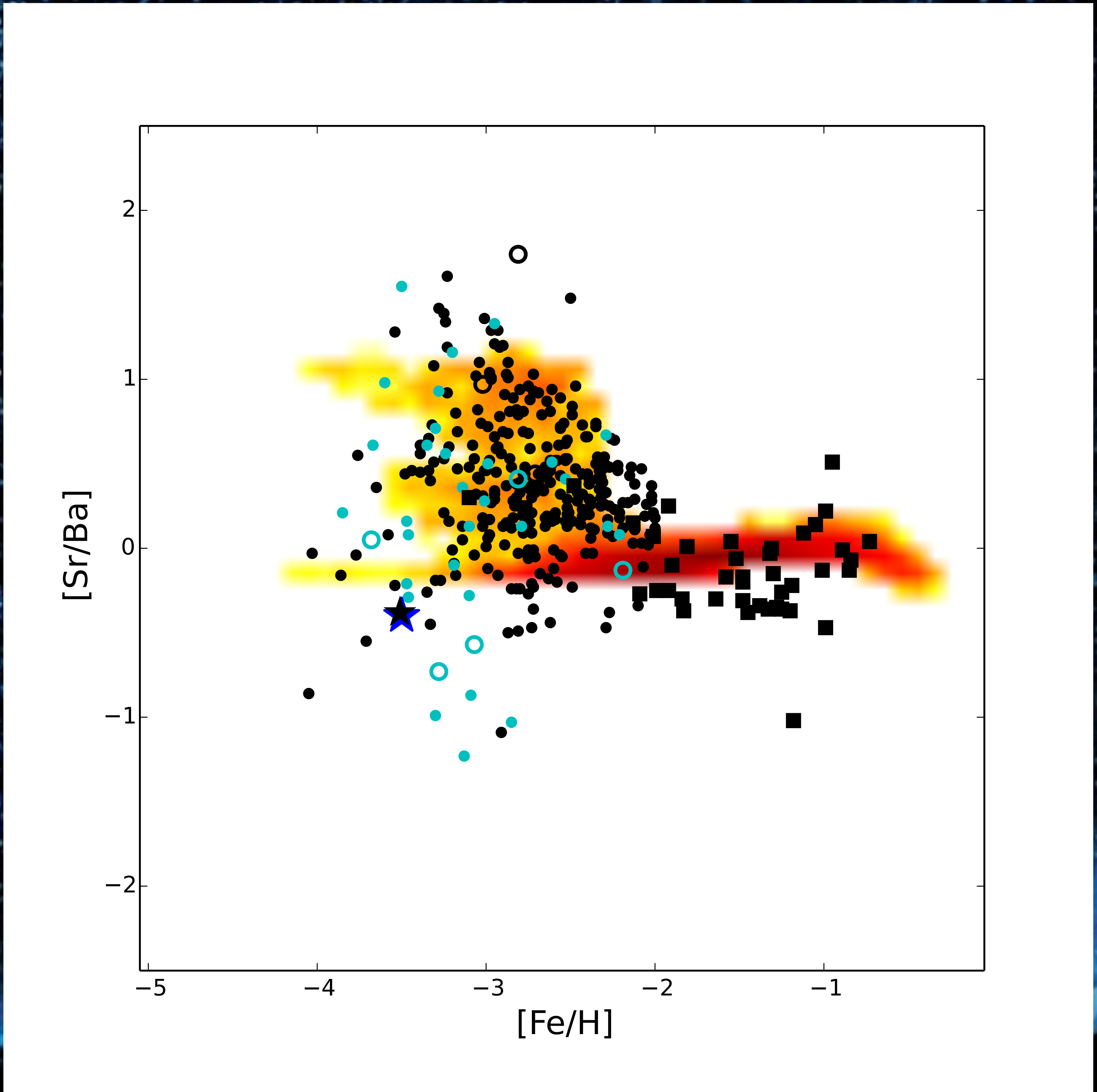
+ an r-process site (the 2 productions are not coupled!)

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

s-process from rotating massive stars

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

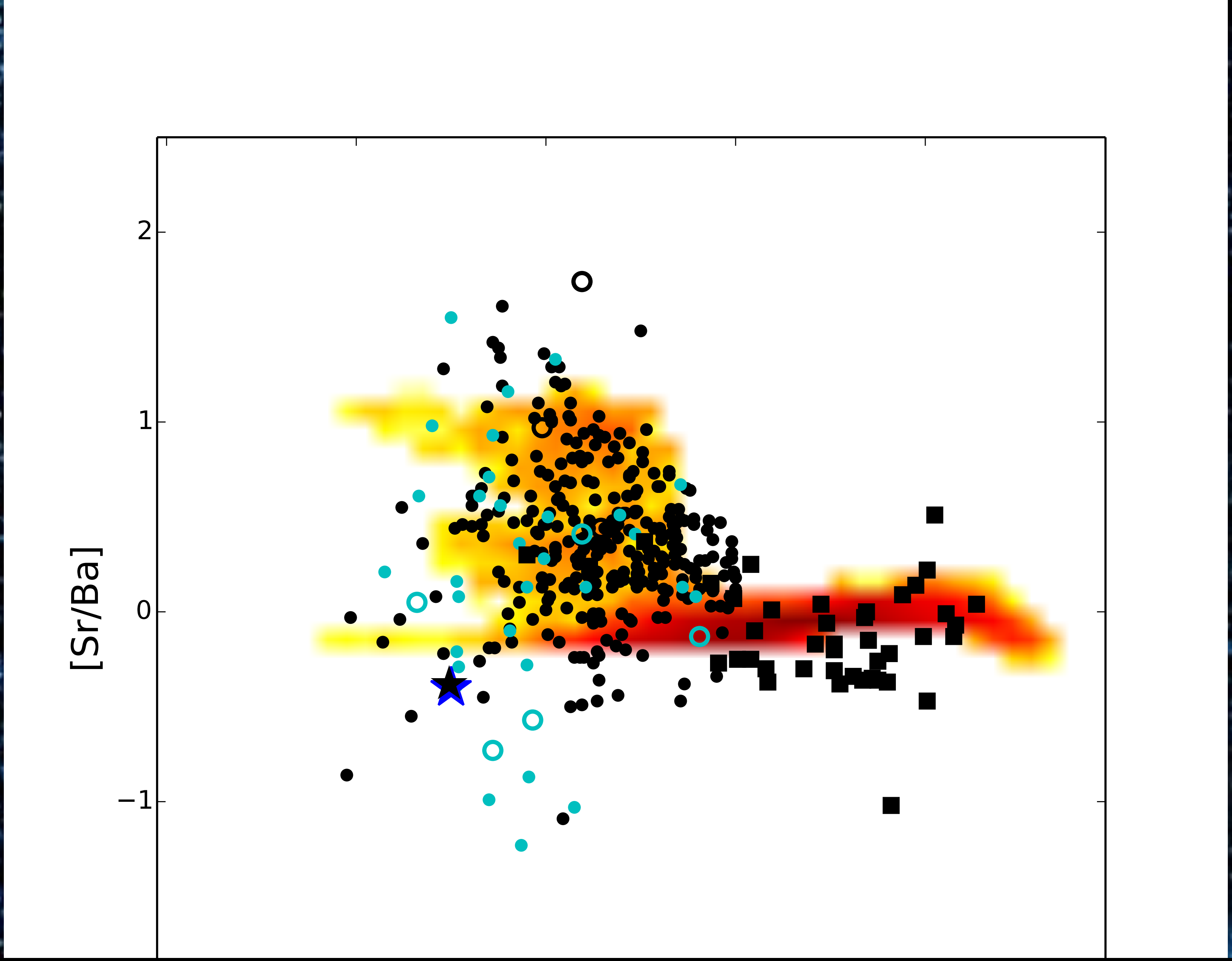
Cescutti et al. (2013)
Cescutti & Chiappini (2014)



s-process from rotating massive stars

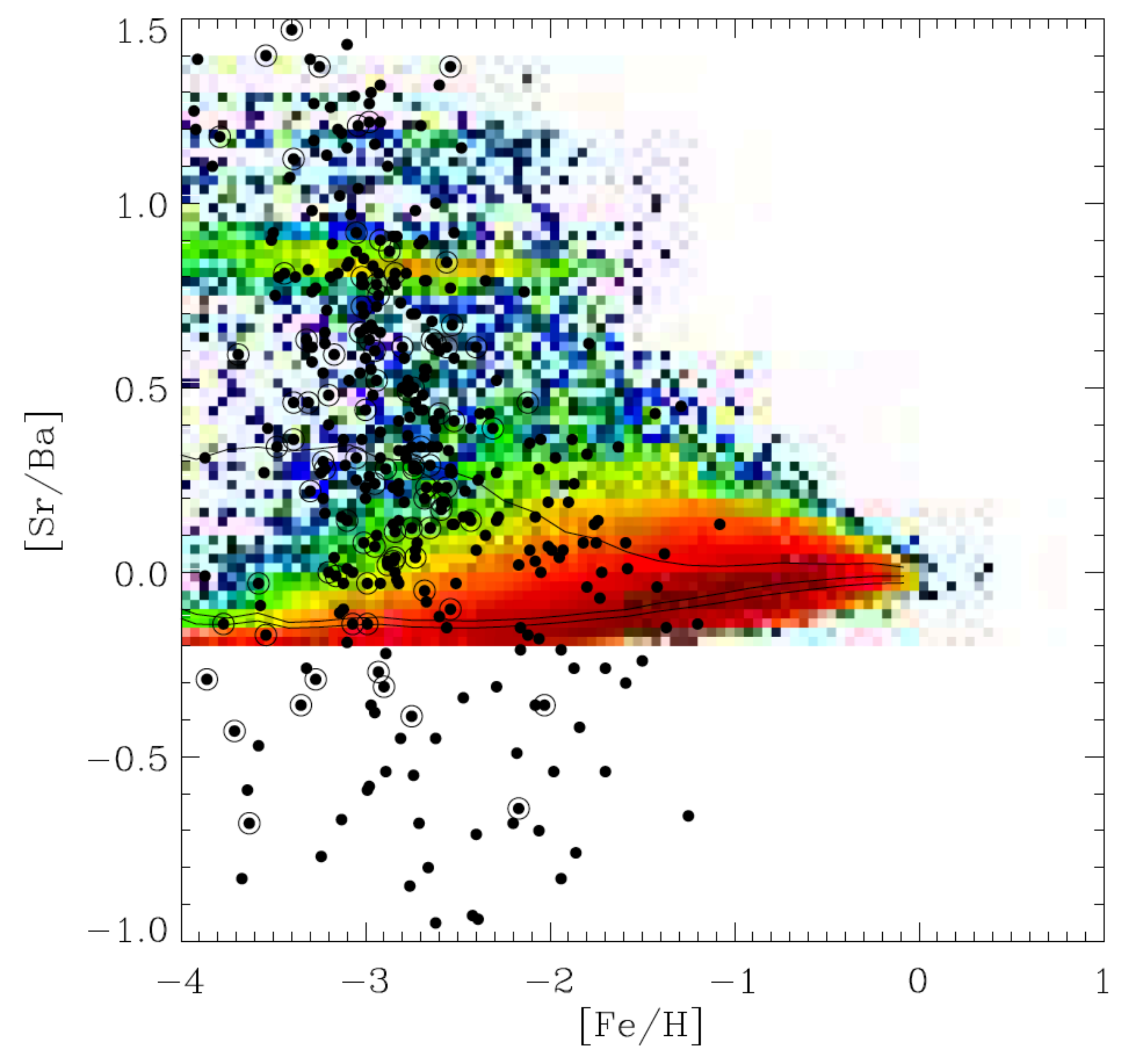
+ an r-process site (the 2 productions are not coupled!)

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

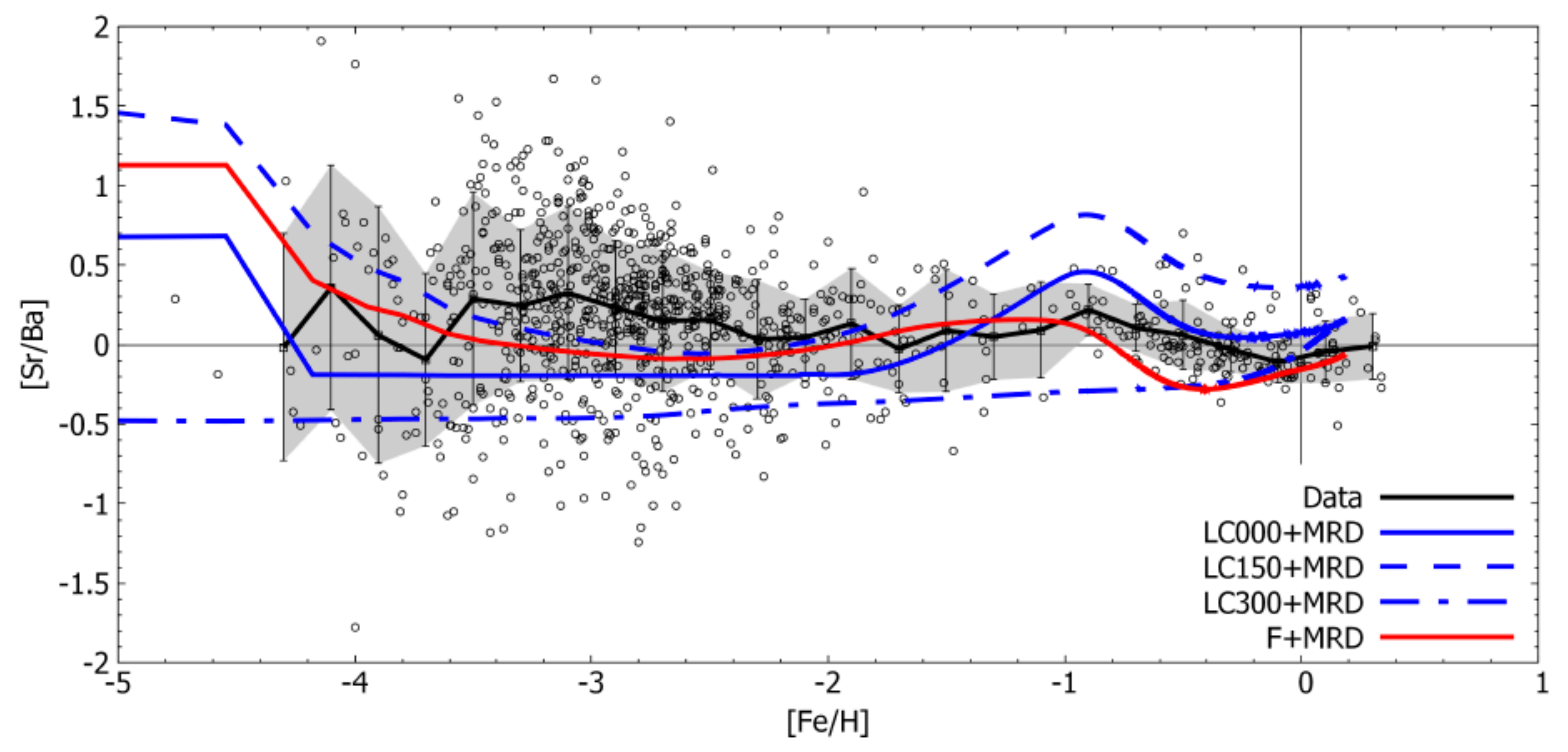
Results with an Sph simulation of the Galactic halo



Scannapieco, Cescutti & Chiappini (202x)

Confirmed in Rizzuti et al. (2019)

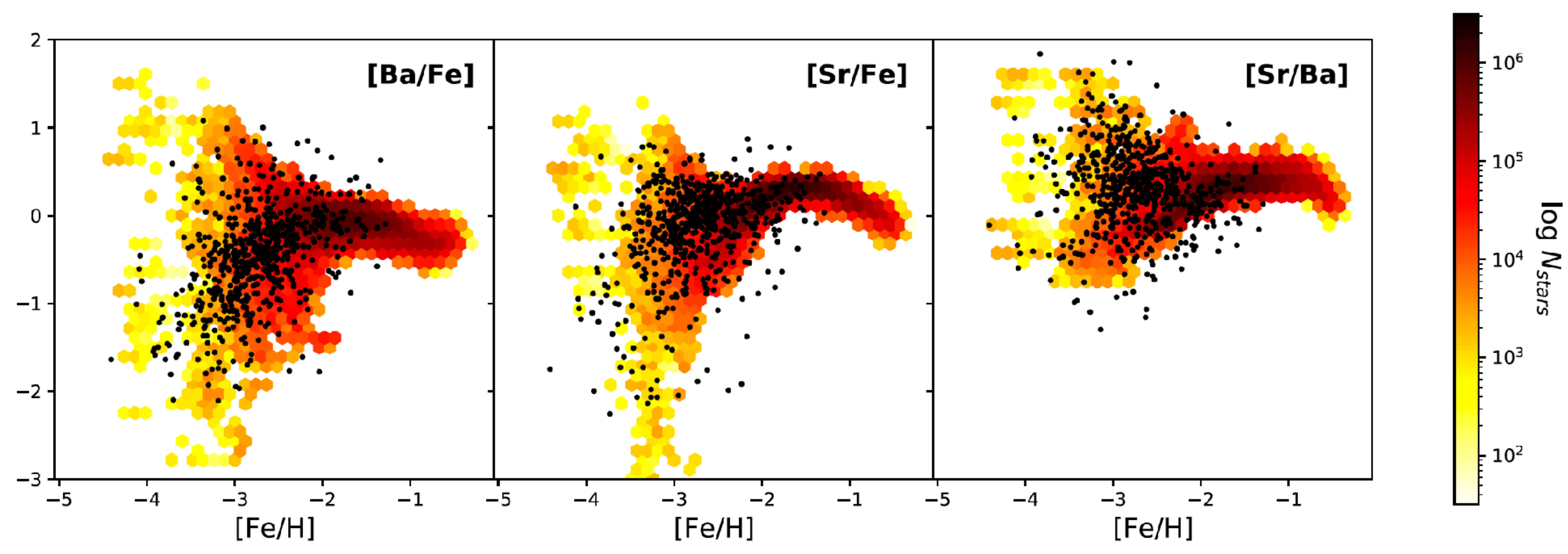
adopting Limongi&Chieffi18



see also Prantzos et al. 2018

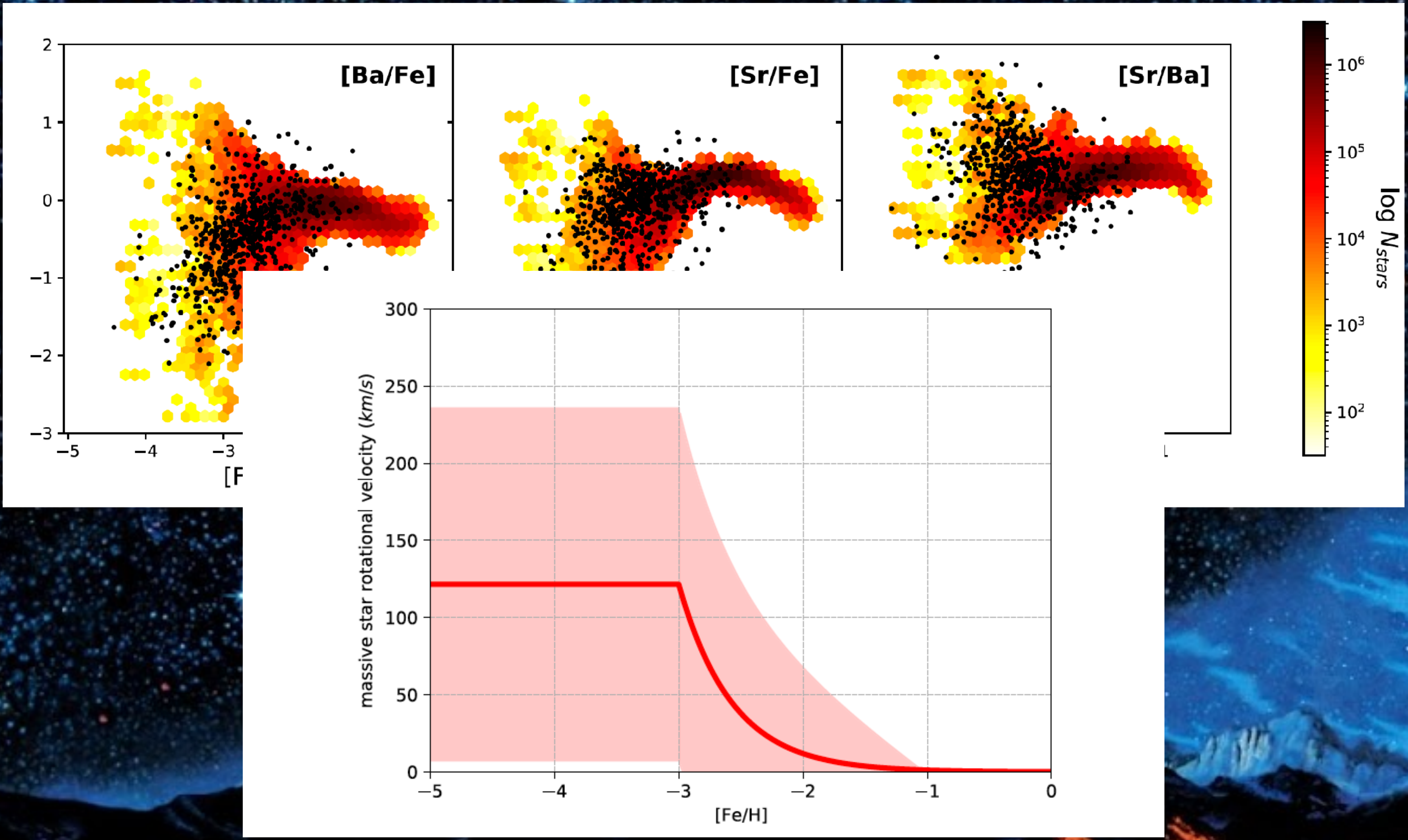
Rizzuti et al. (2021)

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

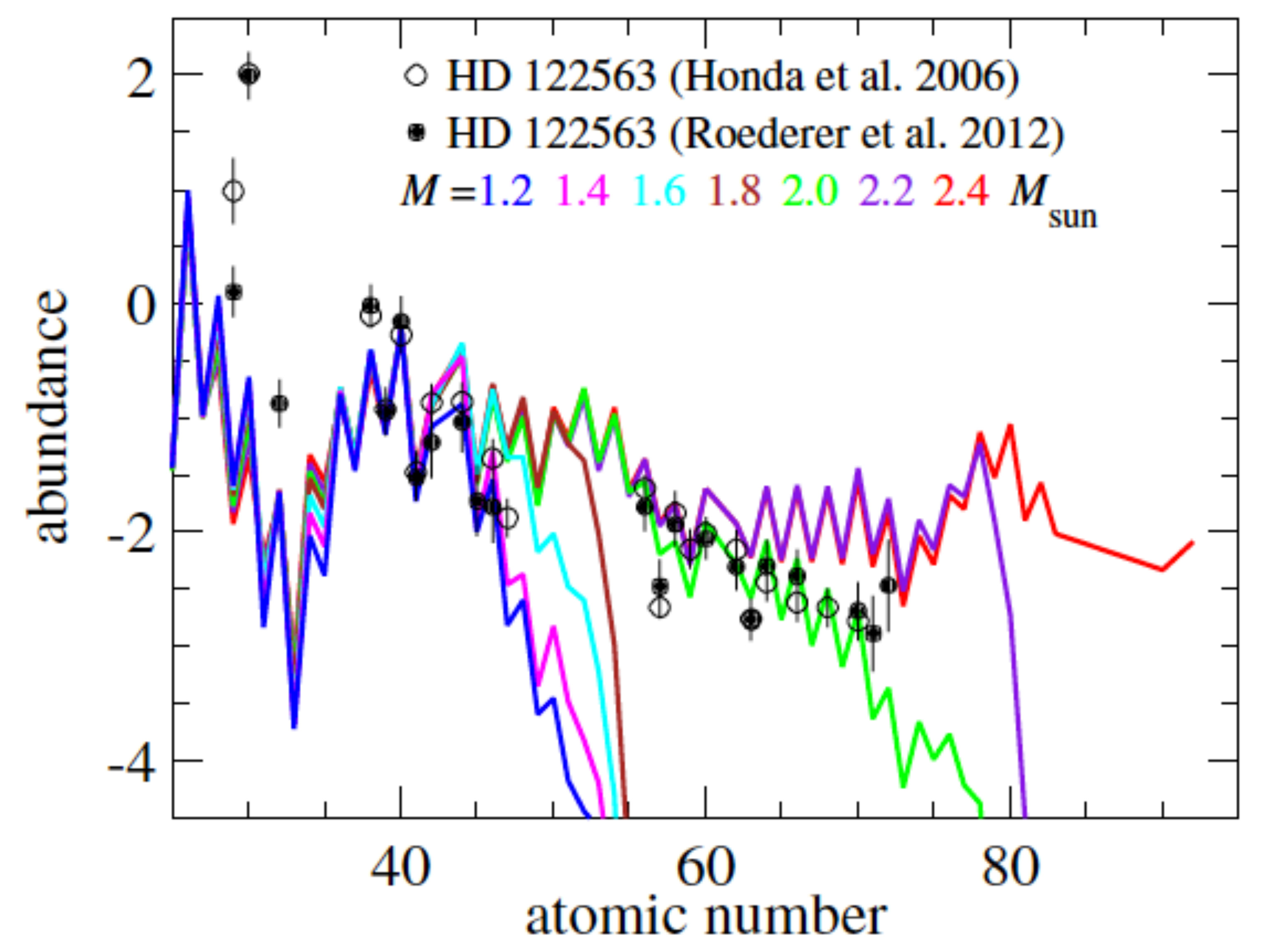
The only possible answer?

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

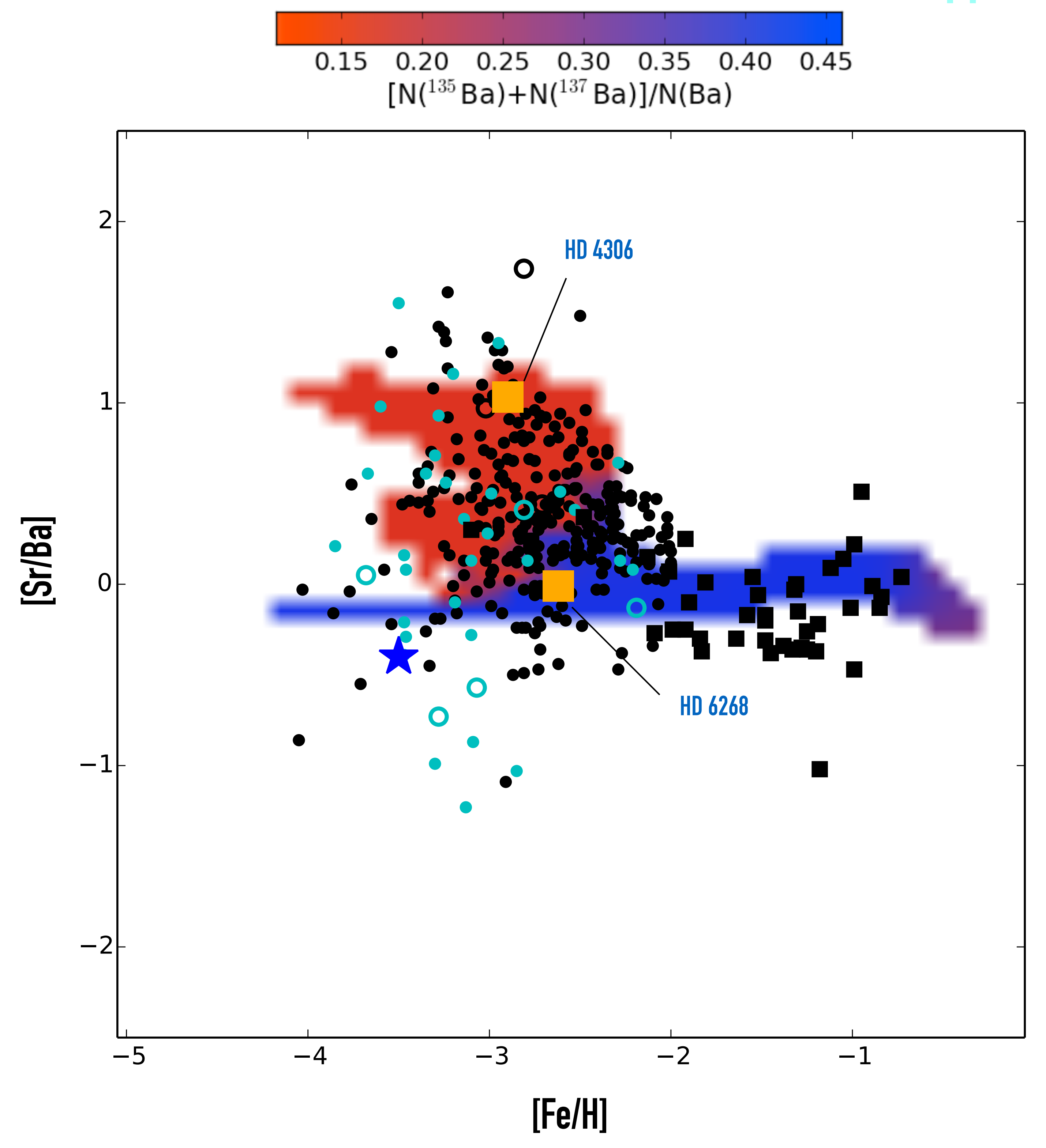
Cescutti and Chiappini (2014)

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)

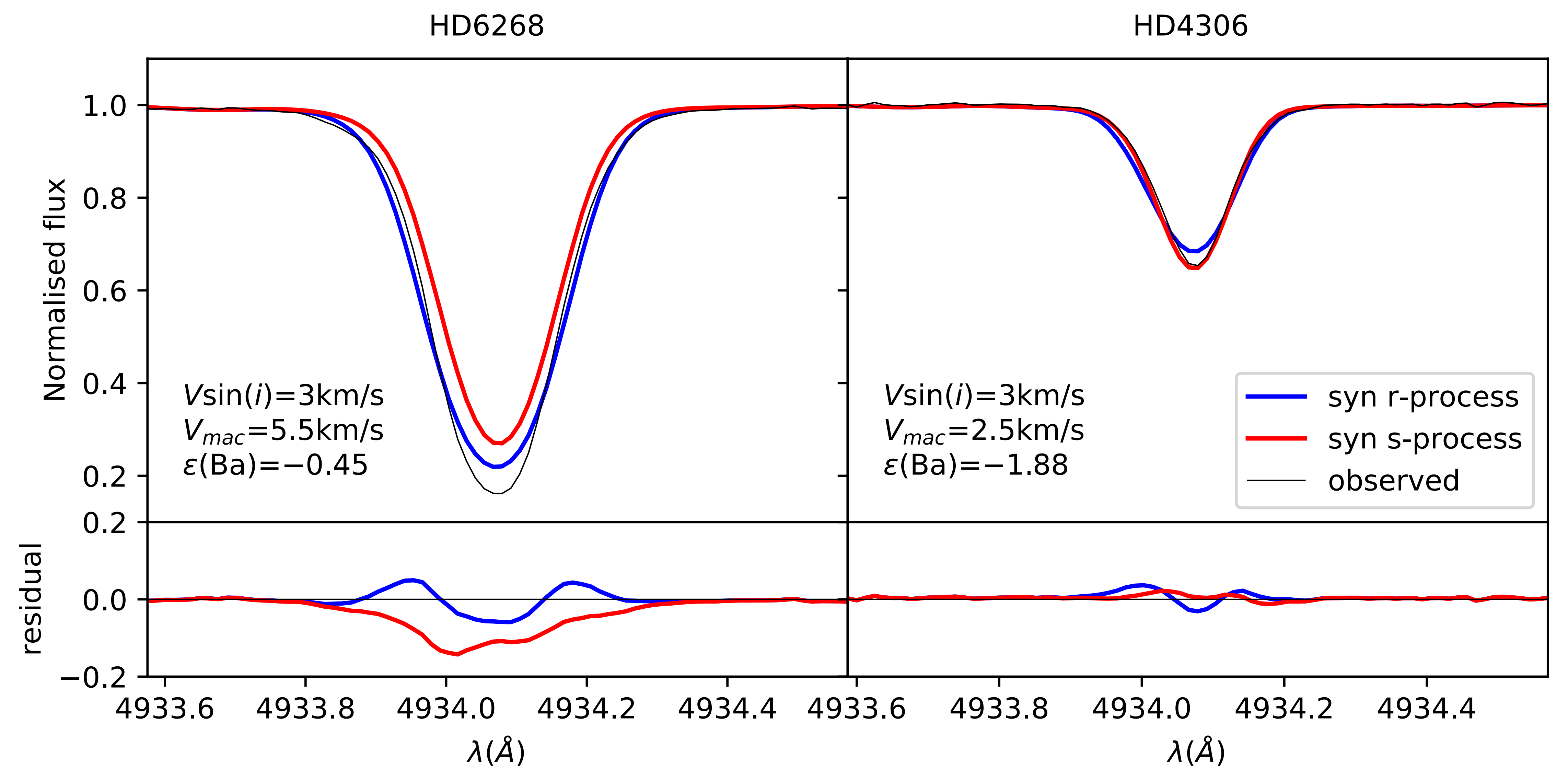


2 stars
with a R~100'000 &
S/N~500
with UVES at VLT

"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.