EVOLUZIONE CHIMICA DELLE GALASSIE

INTRO

EVOLUZIONE CHIMICA
delle GALASSIE

Ingredienti fondamentali:

- Condizioni iniziali
- Funzione di nascita stellare
- La massa restituita al mezzo interstellare dalle singole stelle sotto forma di elementi chimici (stellar yields)
- Possibili Flussi di Gas (entranti o uscenti)
- La composizione chimica di tali flussi di gas

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Condizioni iniziali:

- Caratteristiche del gas iniziale. Potrebbe essere gas primordiale (abbondanze chimiche del Big Bang) oppure gas arricchito chimicamente

- Massa di gas al tempo iniziale (t=0). Si può ipotizzare che il gas da cui si forma la galassia sia stato già tutto presente al momento iniziale oppure che si sia accumulato lentamente nel tempo.
  primo caso e' piu' adatto a sistemi sferoidali, il secondo ai dischi galattici.

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delle GALASSIE

La funzione di nascita stellare

- definita come il numero di stelle formatesi nell'intervallo di massa m, m+dm e nell'intervallo di tempo t, t+dt, ovvero:

$$\varphi(m)\psi(t)dmdt$$

in cui la $\varphi(m)$ è detta funzione iniziale di massa (initial mass fuction o IMF), mentre la $\psi(t)$ è il tasso di formazione stellare (star formation rate o SFR).

La IMF, ovvero il numero di stelle formatesi nell'intervallo m m+dm viene normalmente espressa con $\varphi(m) \propto m^{-(1+x)}$ ed è normalizzata nel seguente modo:

$$\int_0^\infty m\varphi(m)dm = 1$$

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delle GALASSIE

Come derivare la IMF

Supponiamo di sapere l'attuale distribuzione di massa di stelle di sequenza principale per unita' di area sia n(m).
Le stelle di massa 0.1Msun <M< 1.0Msun sono ancora tutte vive in main sequence, quindi possiamo scrivere che:

$$n(m) = \int_0^\infty \varphi(m)\psi(t)dt$$

Se la IMF è costante nel tempo allora possiamo scrivere:

$$n(m) = \varphi(m) < \psi > t_{Hubble}$$

e derivarci la IMF in questo range di masse.

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Come derivare la IMF

Nel caso opposto, per stelle che muoiono (quasi) immediatamente (M > 2.0Msun), possiamo scrivere che:

$$n(m) = \int_{t_{Hubble}-\tau_m}^{t_{Hubble}} \varphi(m)\psi(t)dt$$

Se la IMF è costante nel tempo allora possiamo scrivere:

$$n(m) = \varphi(m)\psi(t_{Hubble})\tau_m$$

e derivarci la IMF anche in questo range di masse.

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Come derivare la IMF

Per stelle fra 1 e 2 Msun, la situazione è complicata, e si tende ad interpolare fra le due situazioni precedenti.

Per stelle di M < 0.1 Msun, è molto difficile perché è difficile osservare queste stelle, sono molto poco luminose.

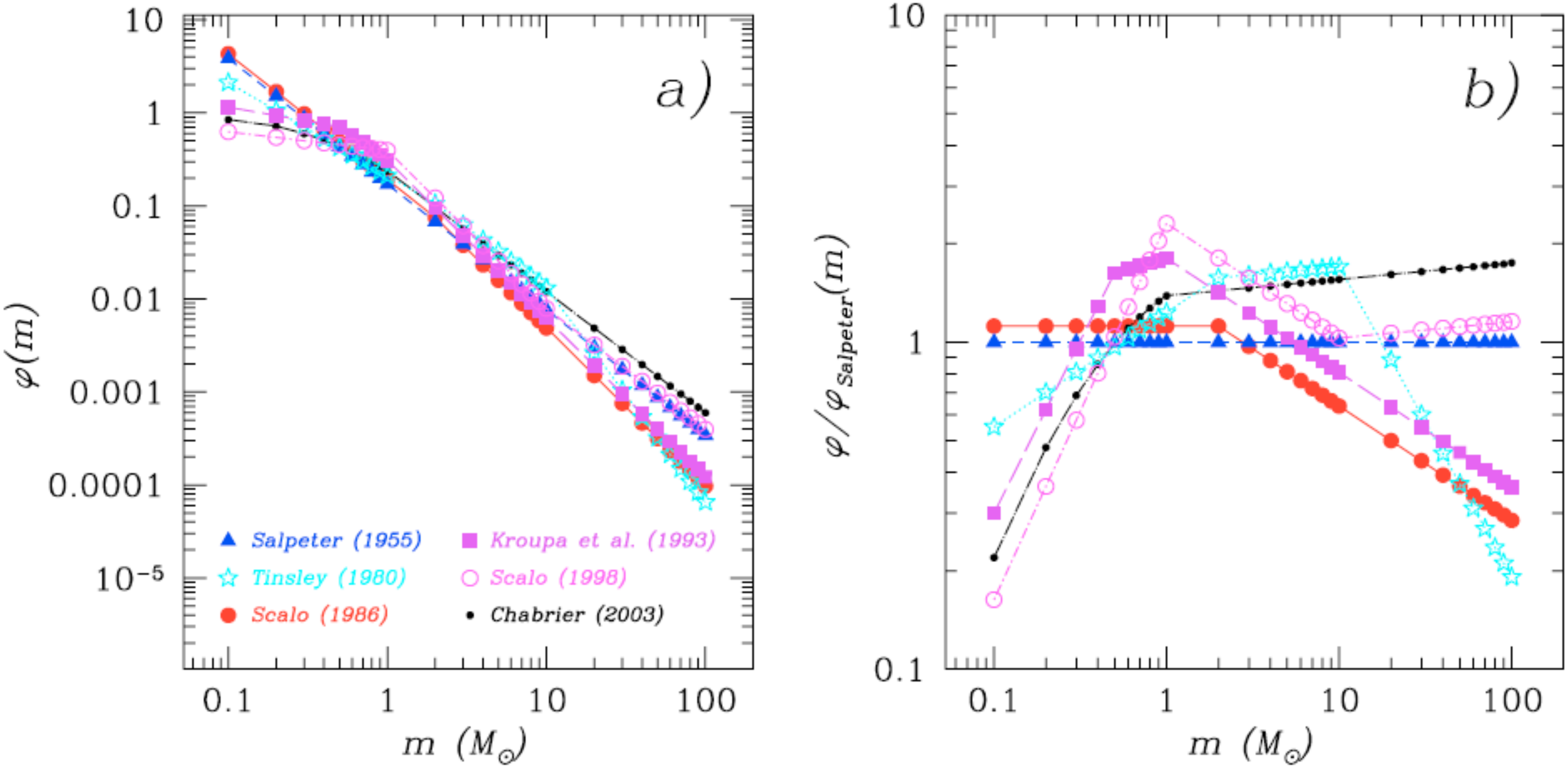
La IMF che si deriva ha tipicamente questa forma:

$$\varphi(m) \propto m^{-(1+x)}$$

La IMF piu' nota e' quella derivata da Salpeter(1955)
con x = 1.35

Initial mass function

Salpeter's IMF: φ (m) ~ $m^{-1.35}$



Romano et al. (2003)

Describe the probability to create a star with a certain mass.
1 star of 100Msun every ~50000 stars of 1Msun

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delle GALASSIE

Tasso di formazione stellare

Anche per derivare la SFR, bisogna fare delle assunzioni. La più semplice è assumerla costante. Una possibilità più realistica è collegarla alla densità del gas:

$$\psi(t) = \nu \rho_{gas}^{n}$$

Dove nu è chiamata efficienza di SF e viene calibrato per riprodurre quello osservato al tempo attuale (per esempio). Una versione più matematica è:

$$\psi(t) = \nu e^{-t/\tau}$$

Nei modelli di evoluzione chimica si usa in genere la densita' superficiale del gas, poiché n(m) è una quantità proiettata sul piano galattico.

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delle GALASSIE

Tasso di formazione stellare

Per derivare la SFR nel disco galattico vicino al Sole (solar vicinity) è possibile utilizzare di nuovo il n(m) e assumere una IMF. Miller e Scalo (1979) ottennero usando una IMF a più pendenze un valore:

$$3 < \psi(t_{Hubble}) < 7 M_{\odot} pc^{-2} Gyr^{-1}$$

Mentre Tinsley (1980) ottenne con una IMF leggermente diversa:

$$\psi(t_{Hubble}) \sim 10 M_{\odot} pc^{-2} Gyr^{-1}$$

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delle GALASSIE

Tasso di formazione stellare

Per valutare in altre regioni del disco Galattico ed in galassie esterne si ricorre ad indicatori di formazione stellare quali:

(a) stelle supergiganti che possono essere viste anche in galassie vicine, assumendo che il numero sia proporzionale al tasso di formazione stellare attuale.

(b) Il flusso Hα e Hβ proveniente da regioni HII, ionizzate da stelle giovani e calde, è proporzionale al tasso di formazione stellare. Kennicutt (1998) suggerisce

$$\psi(t) = 7.9 \cdot 10^{42} L_{H_\alpha}(ergsec^{-1}) M_\odot yr^{-1}$$

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delle GALASSIE

Tasso di formazione stellare

c) La luminosità del continuo UV e' anche usato per derivare il tasso di formazione stellare

d) La luminosità infrarossa che proviene dalla polvere che circonda le regioni di formazione stellare

e) I tassi di esplosione delle supernovae di tipo II possono anche darci un'idea del tasso di formazione stellare attuale.

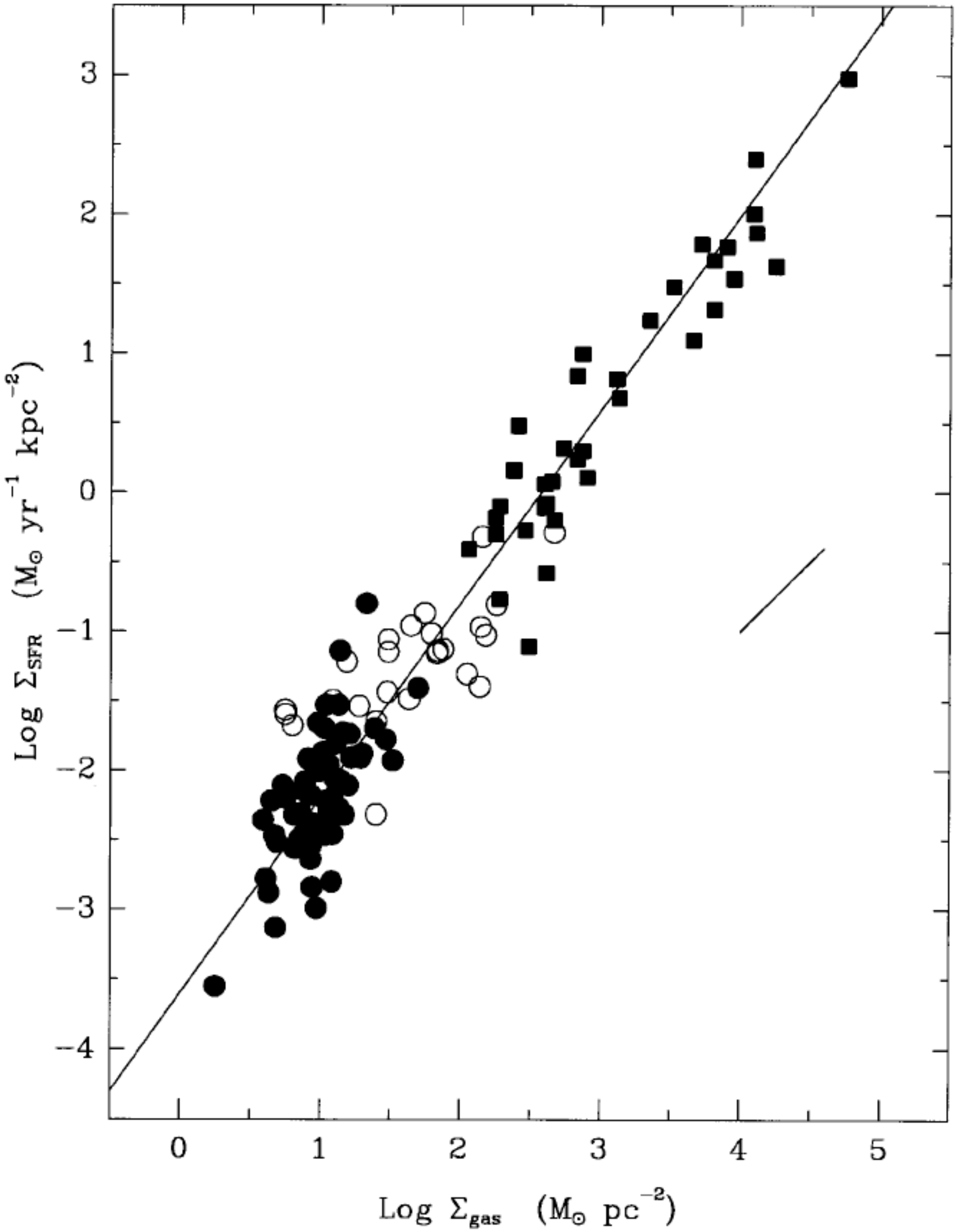
…

Chiaramente per derivare la SFR, dobbiamo assumere un IMF con le incertezze che vi si collegano.

Legge di formazione stellare

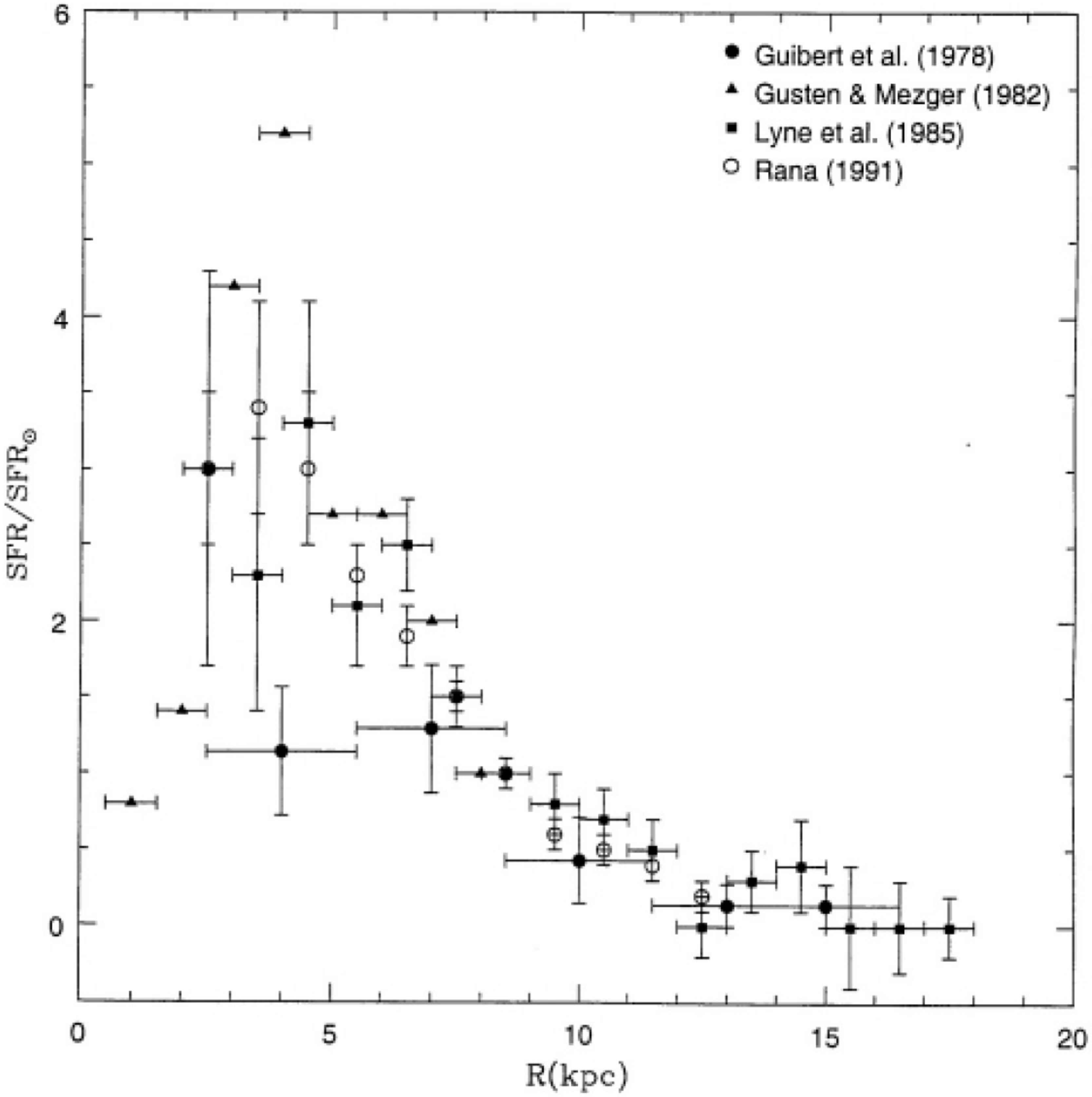
The SFR as measured in star forming galaxies. The continuous line represents the best fit to the data and it can be achieved with the SF law with k=1.4

$$\Psi\ (R, t) = \nu(R,t)\ G(R,t)^k$$



Kennicutt (1998)

Formazione stellare nel disco Galattico



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delle GALASSIE

Nucleosintesi Stellare

Si definisce R, ovvero la «frazione di ritorno», la massa restituita al mezzo interstellare sotto forma di elementi vecchi e nuovi ed è calcolata come:

$$R = \frac{\int_1^{\infty} (m - m_{rem})\varphi(m)dm}{\int_0^{\infty} m\varphi(m)dm}$$

dove m_{rem} è la massa del resto stellare.
Per come abbiamo normalizzato la IMF abbiamo quindi che

$$R = \int_1^{\infty} (m - m_{rem})\varphi(m)dm$$

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Nucleosintesi Stellare

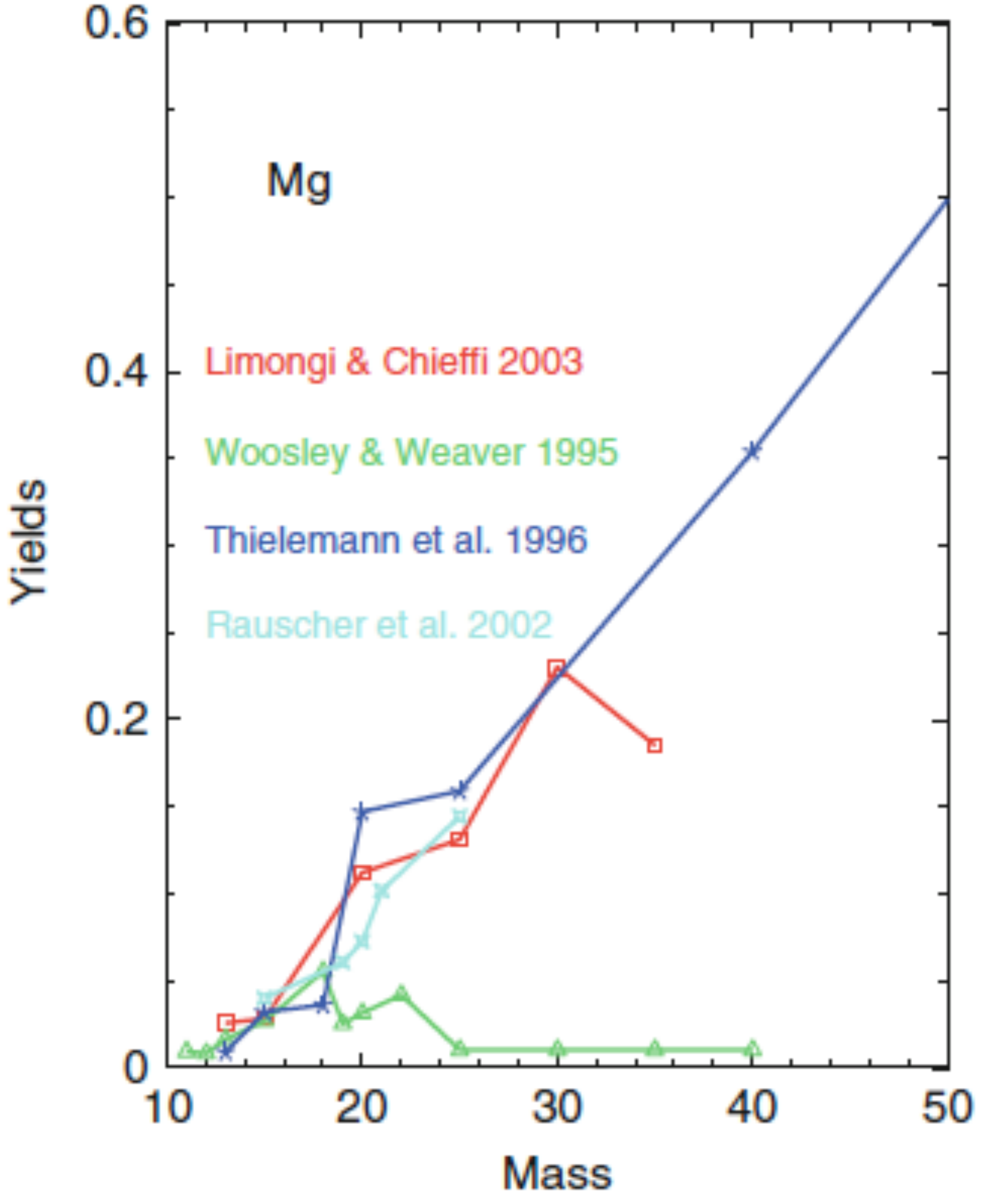
Si definisce yields (o guadagno) il rapporto tra la frazione di massa espulsa sotto forma di nuovi elementi chimici che una generazione di stelle restituisce al mezzo interstellare e la frazione massa che rimane sotto forma di stelle di piccola massa e resti stellari:

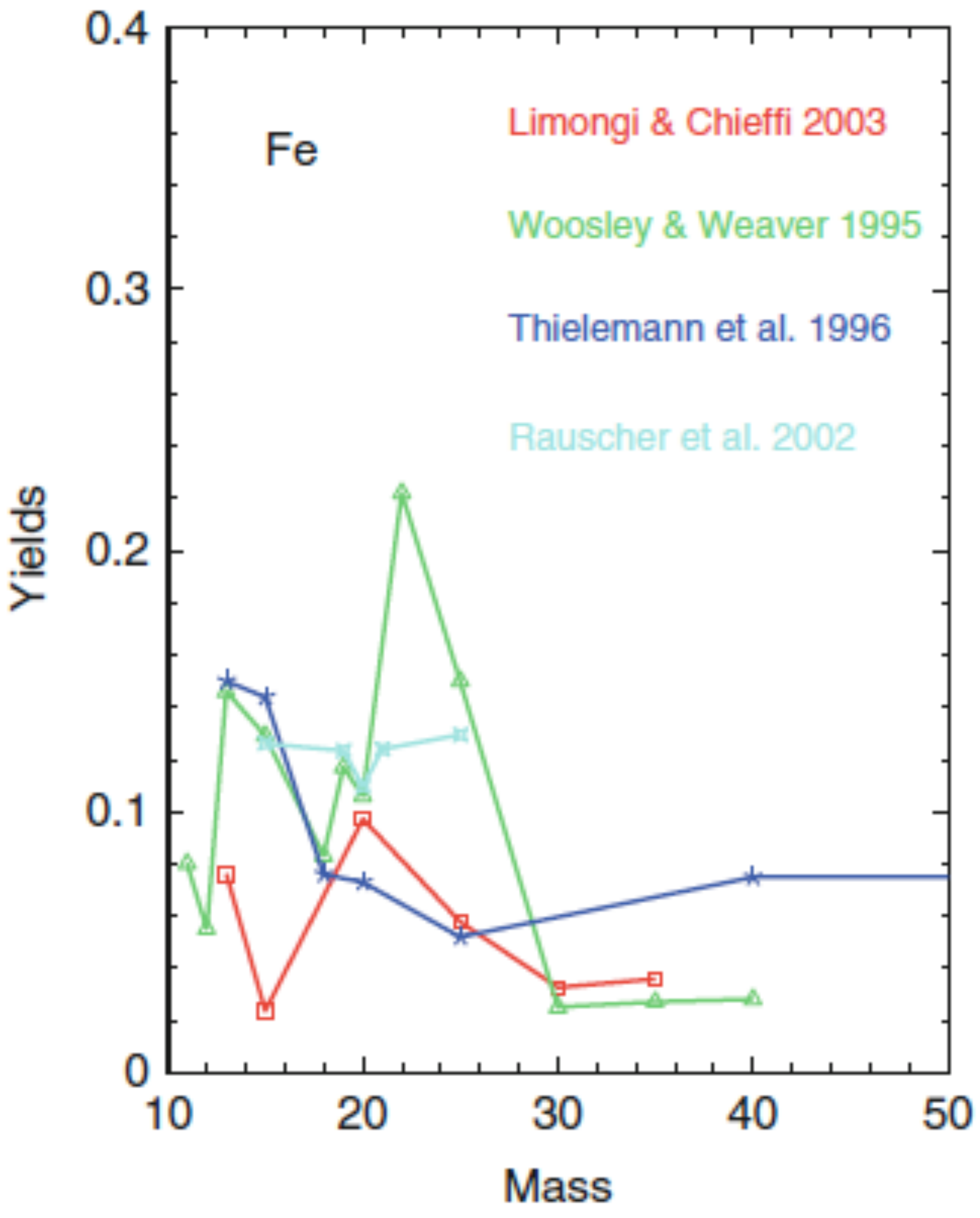
$$y_i = \frac{1}{1-R} \int_1^{\infty} m p_{im} \varphi(m) dm$$

dove p_{im} è e' la frazione di massa prodotta ed espulsa da una stella di massa **m** sotto forma di elemento **i**-esimo nuovo prodotto

Stellar nucleosynthesis

Due esempi di nucleosintesi stellare (magnesio e ferro)
per autori diversi , nell'ambito delle stelle massicce.





EVOLUZIONE CHIMICA DELLE GALASSIE

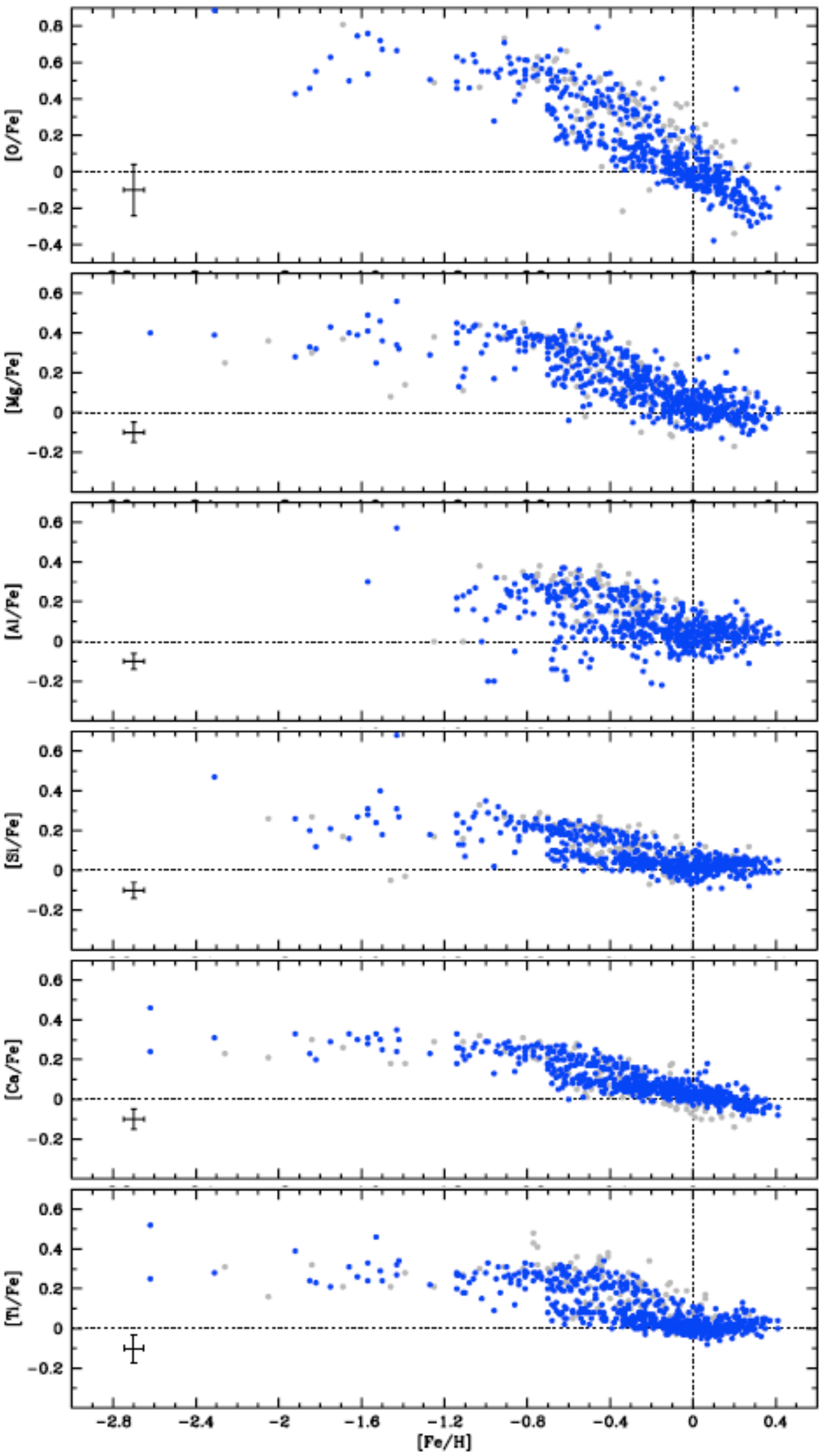
risultati con modelli numerici

Can we explain a plot like this one with a simple model? *Why?*

Simple models cannot cannot reproduce variations (excluding the behavior of secondary elements).

To understand this plot, it is better to have a step back and to introduce

1) stellar lifetimes
2) general facts of the nucleosynthesis.



Bensby et al. 2014
(grey stars with T<5400K)

Can we explain a plot like this one with a simple model? *Why?*

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1) stellar lifetimes

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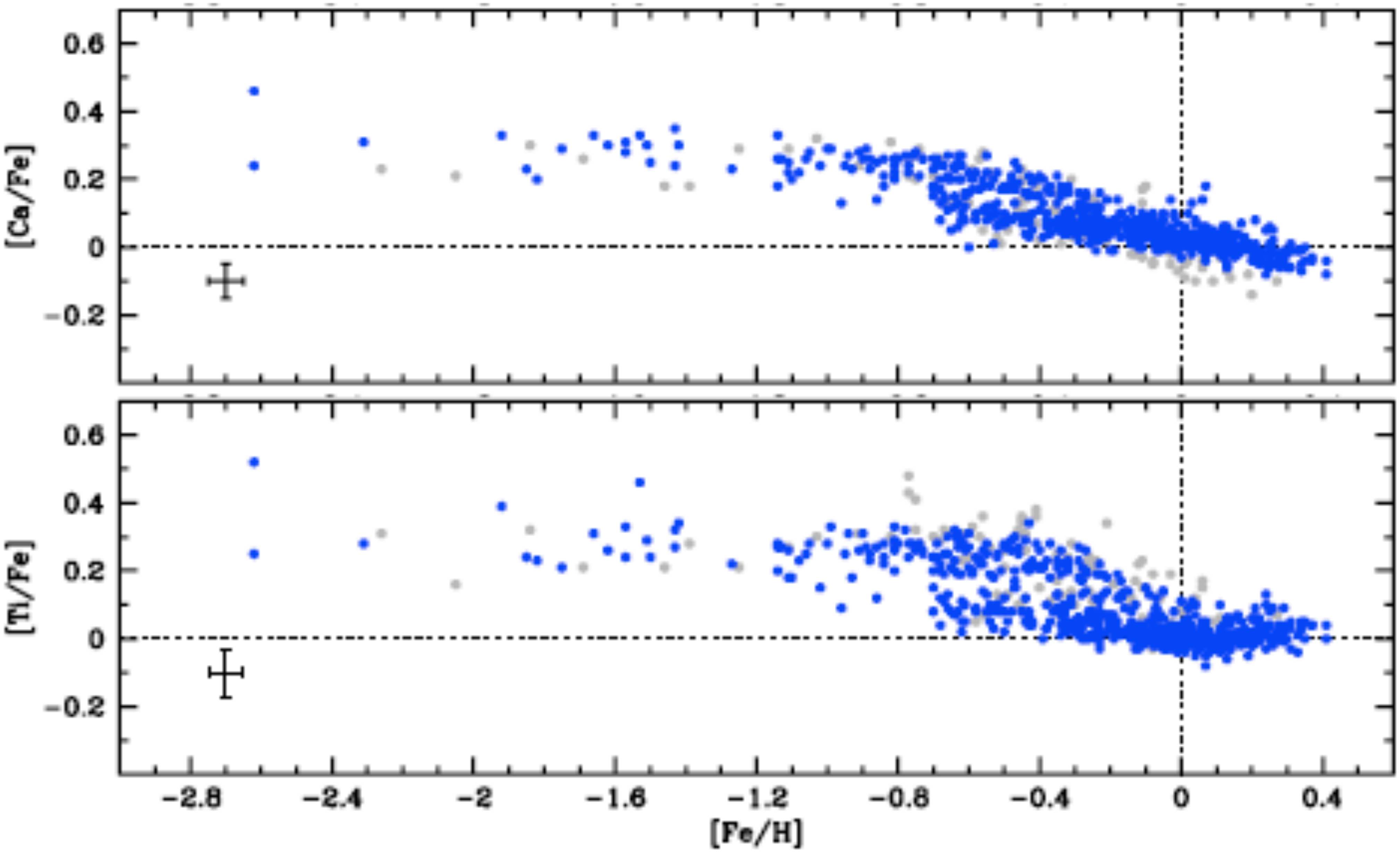


Stellar lifetimes

How bad are we doing if we ignore the stellar lifetime?

... indeed bad ...

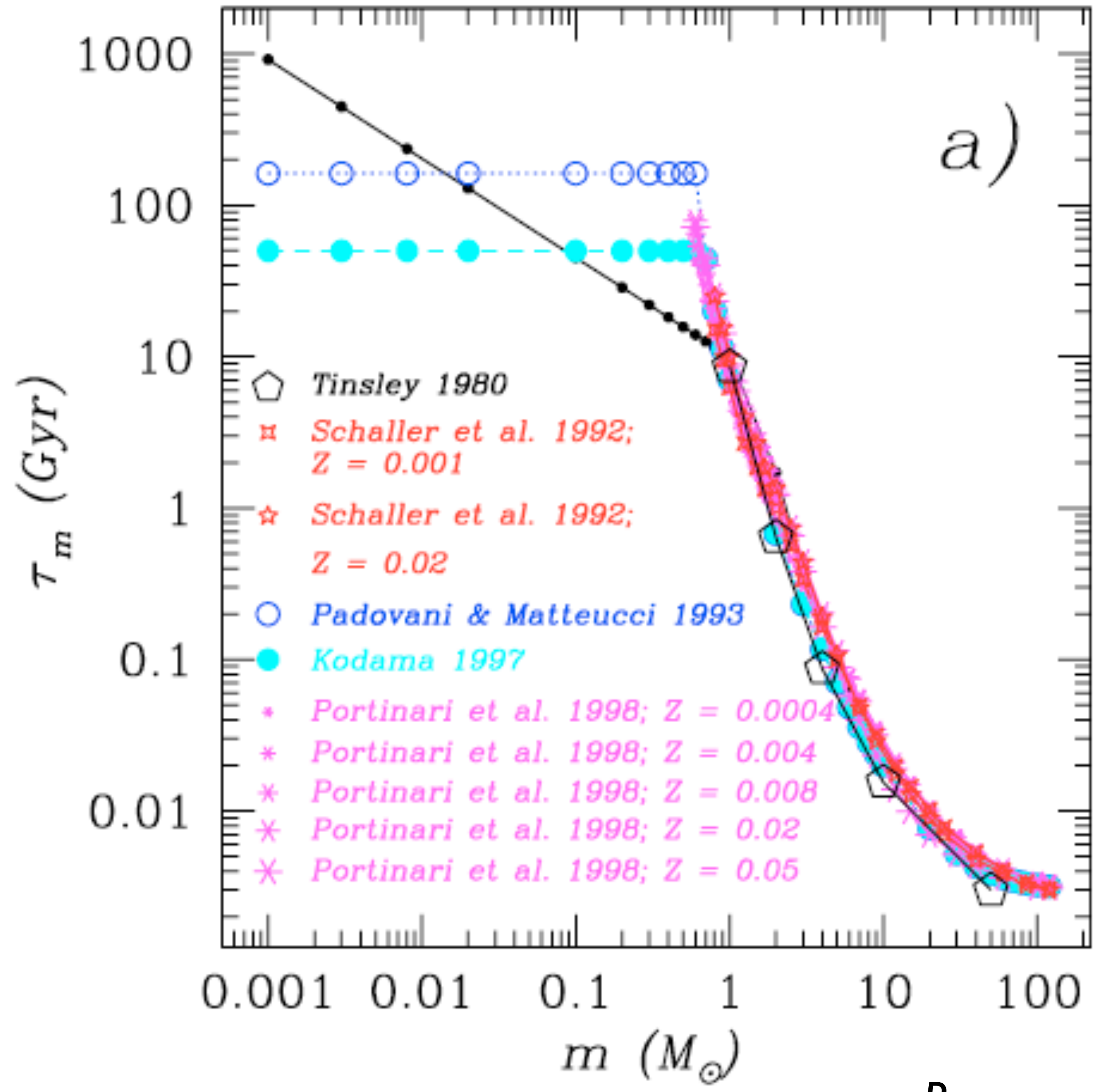
Compilation of stellar lifetimes from different authors.

Note the lifetime

massive stars < 30 Myr
So yes they almost contribute instantaneously.

low-intermediate mass >30Myr

more complex treatment important for elements as carbon, nitrogen and all the elements above the Fe (neutron capture elements)



Romano et al. (2003)

Nucleosynthesys II

Summary of stellar production (for the elements):

^{1}H Just destroyed in stellar evolution

^{4}He Produced by all stars

^{12}C Produce by all stars above the threshold for the He burning, in particular between 5-8Msun

^{14}N produced during the CNO cycle (bottle-neck of the reaction) by intermediate mass stars (5-8Msun) but also by massive stars, as secondary element. Possible primary production in case of stellar rotation.

$^{20}Ne,\ ^{24}Mg,\ ^{28}Si,\ ^{32}S,\ ^{40}Ca$ - alpha elements - produced by chains of alpha captures in massive stars, as oxygen

^{56}Fe and all the iron peak elements are produced in the explosive nucleosynthesis during SNII explosion (so massive stars).

Can this explain what we observe in [alpha/Fe] plots?
No, because still I did not introduce something which is important!

Nucleosynthesys IIbis

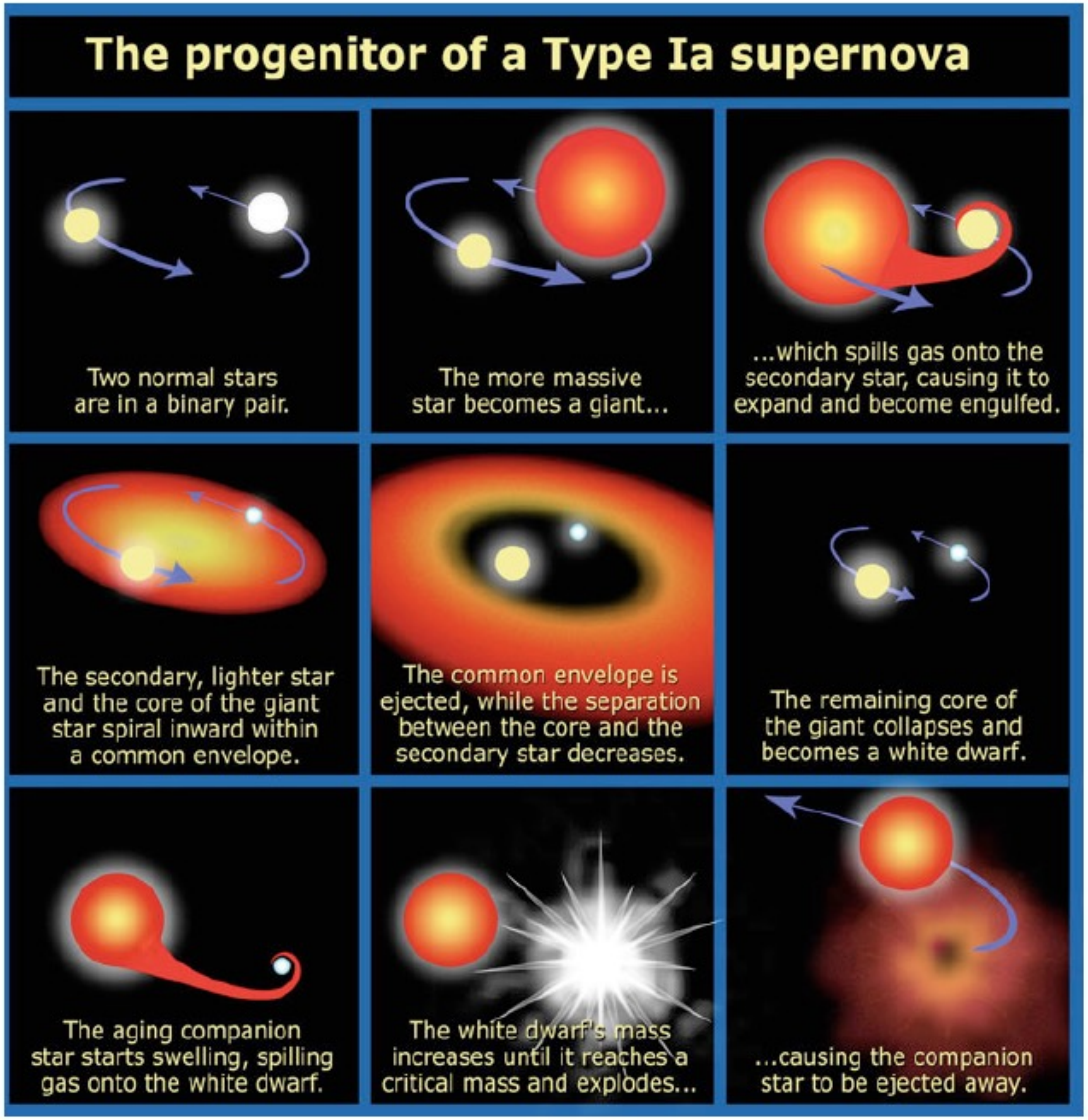
Supernovae type Ia
(not only important in cosmology!)

They have produces most of the iron and iron peaks elements present nowadays.

Each SNIa produce ~0.6Msun of iron.

The timescale is not fixed but depends of the progenitors masses (actually in the mass of the smaller companion of the binary systems in the single degenerate scenario),

BUT the bulk of production arises after ~ 1Gyr

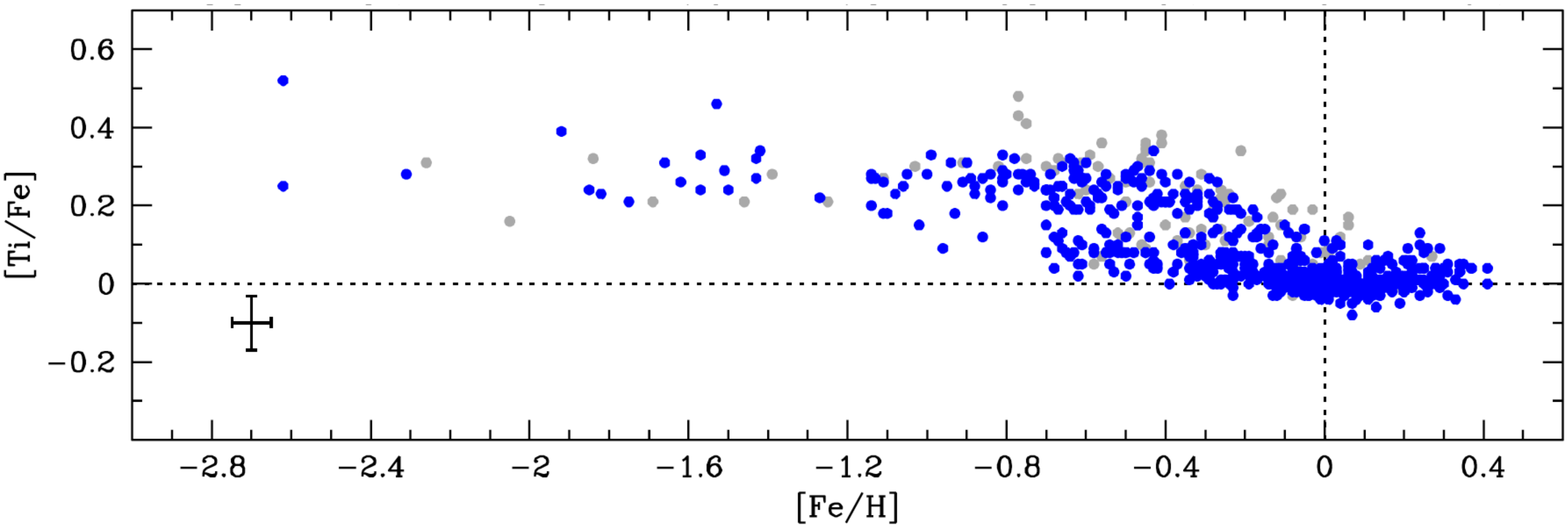


The progenitor of a type Ia SN in the context of the single-degenerate model (Illustration credit: NASA, ESA, and A. Field (STSci))

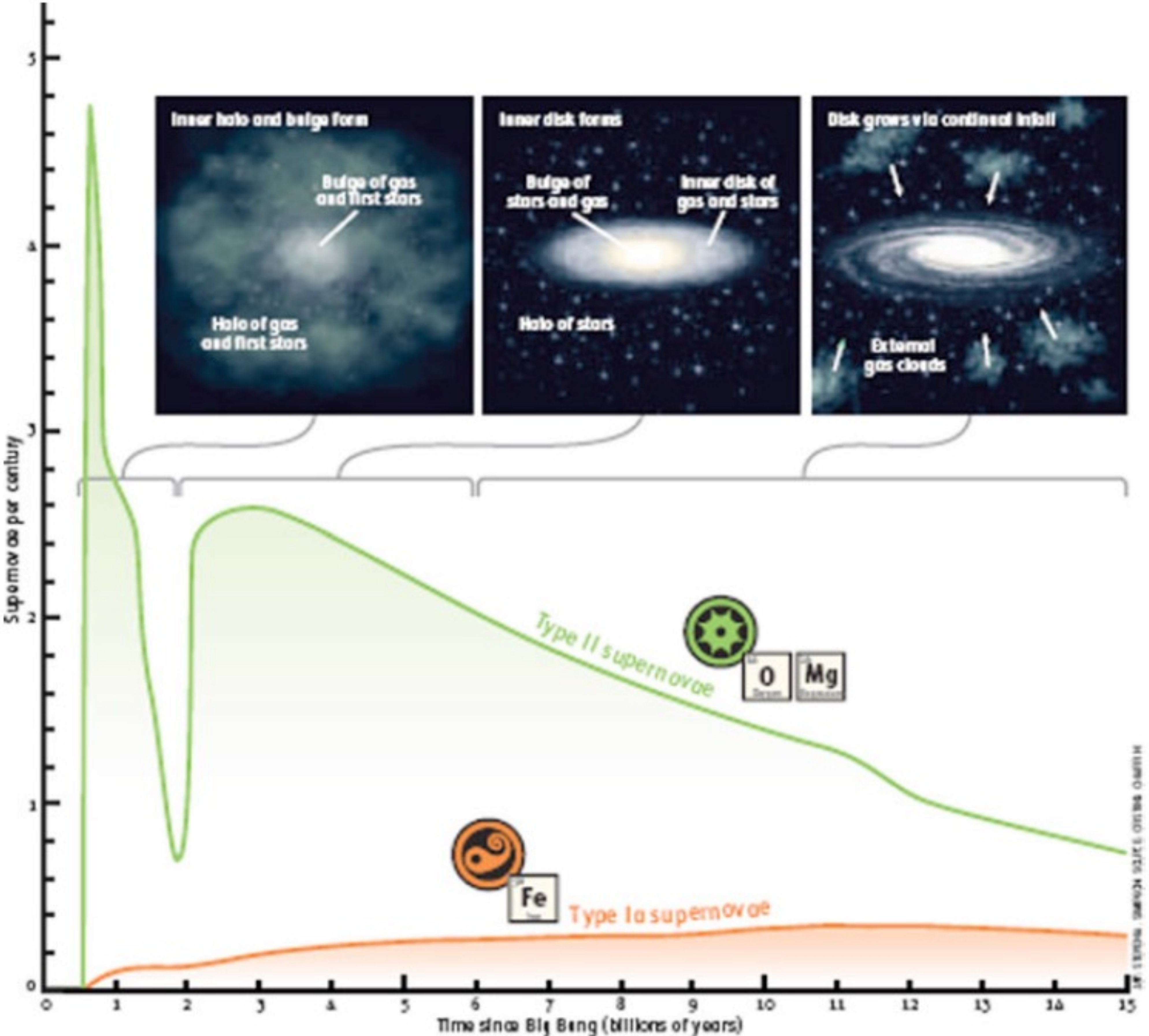
The real open model that we need to solve is:

$$
\begin{aligned}
\dot{M}_i(t) = {} & -\psi(t)X_i(t) + \int_{M_{\mathrm{L}}}^{M_{\mathrm{Bm}}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\varphi(m)\mathrm{d}m \\
& + A_B \int_{M_{\mathrm{Bm}}}^{M_{\mathrm{BM}}} \varphi(m)\Big[\int_{\mu_{\mathrm{B_{min}}}}^{0.5} f(\mu_{\mathrm{B}})\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})\mathrm{d}\mu_{\mathrm{B}}\Big]\mathrm{d}m \\
& + (1-A_B)\int_{M_{\mathrm{Bm}}}^{M_{\mathrm{BM}}} \psi(t-\tau_m)Q_{mi}(t-\tau_{m)}\varphi(m)\mathrm{d}m \\
& + \int_{M_{\mathrm{BM}}}^{M_{\mathrm{U}}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\varphi(m)\mathrm{d}m + X_{iA}(t)A(t) \\
& - X_i(t)W(t) + X_i(t)I(t),
\end{aligned}
$$

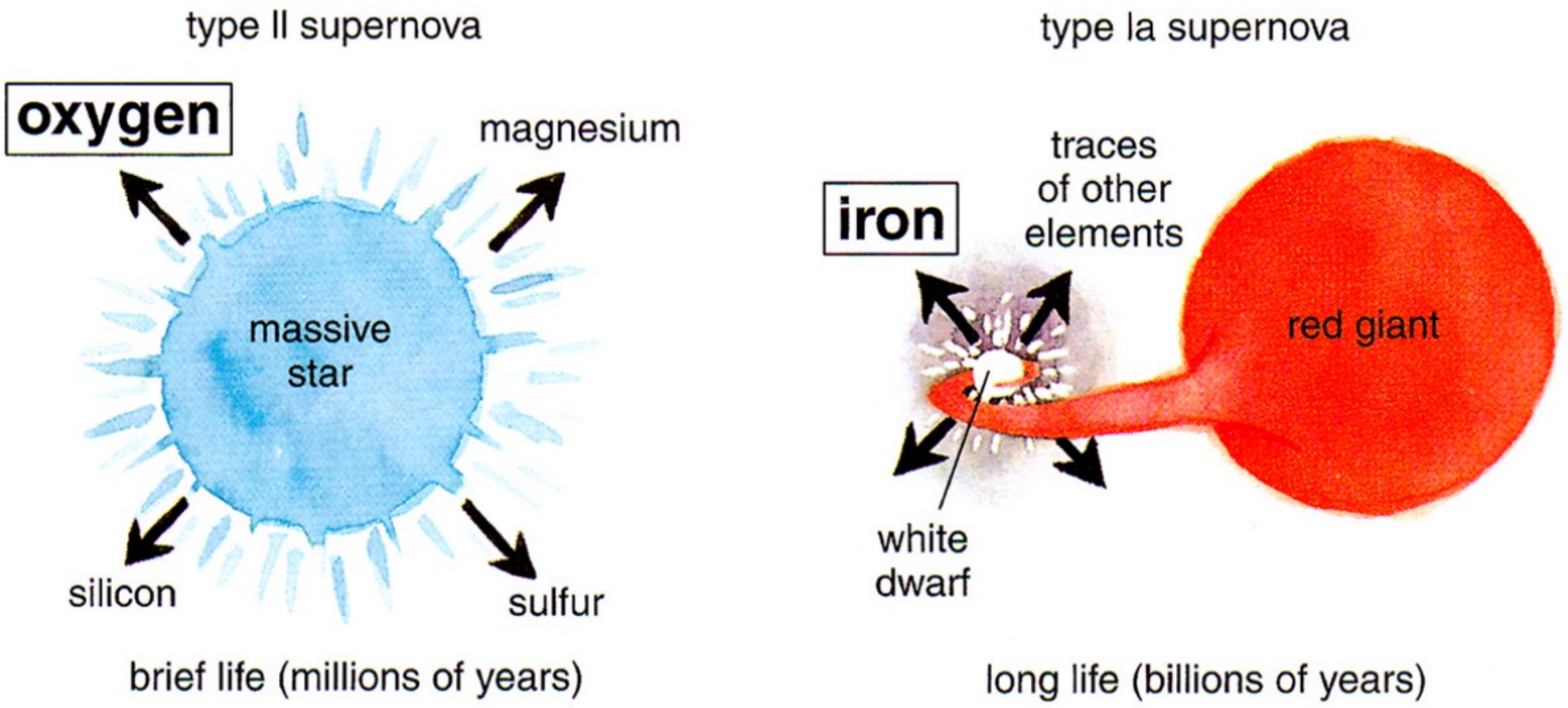
How can we explain this plot?



Initial conditions (Chiappini et al . 1997)

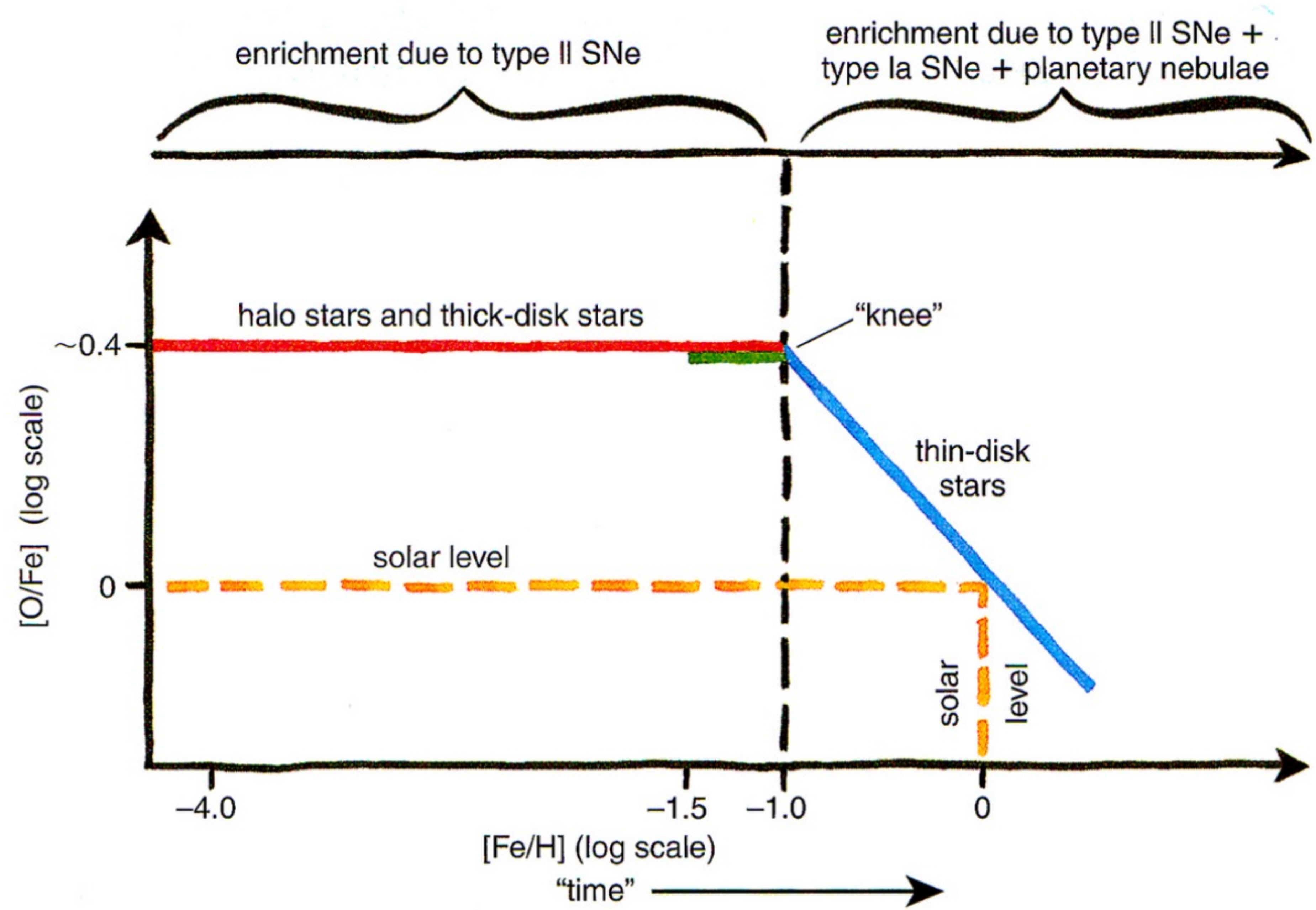


The [O/Fe] knee

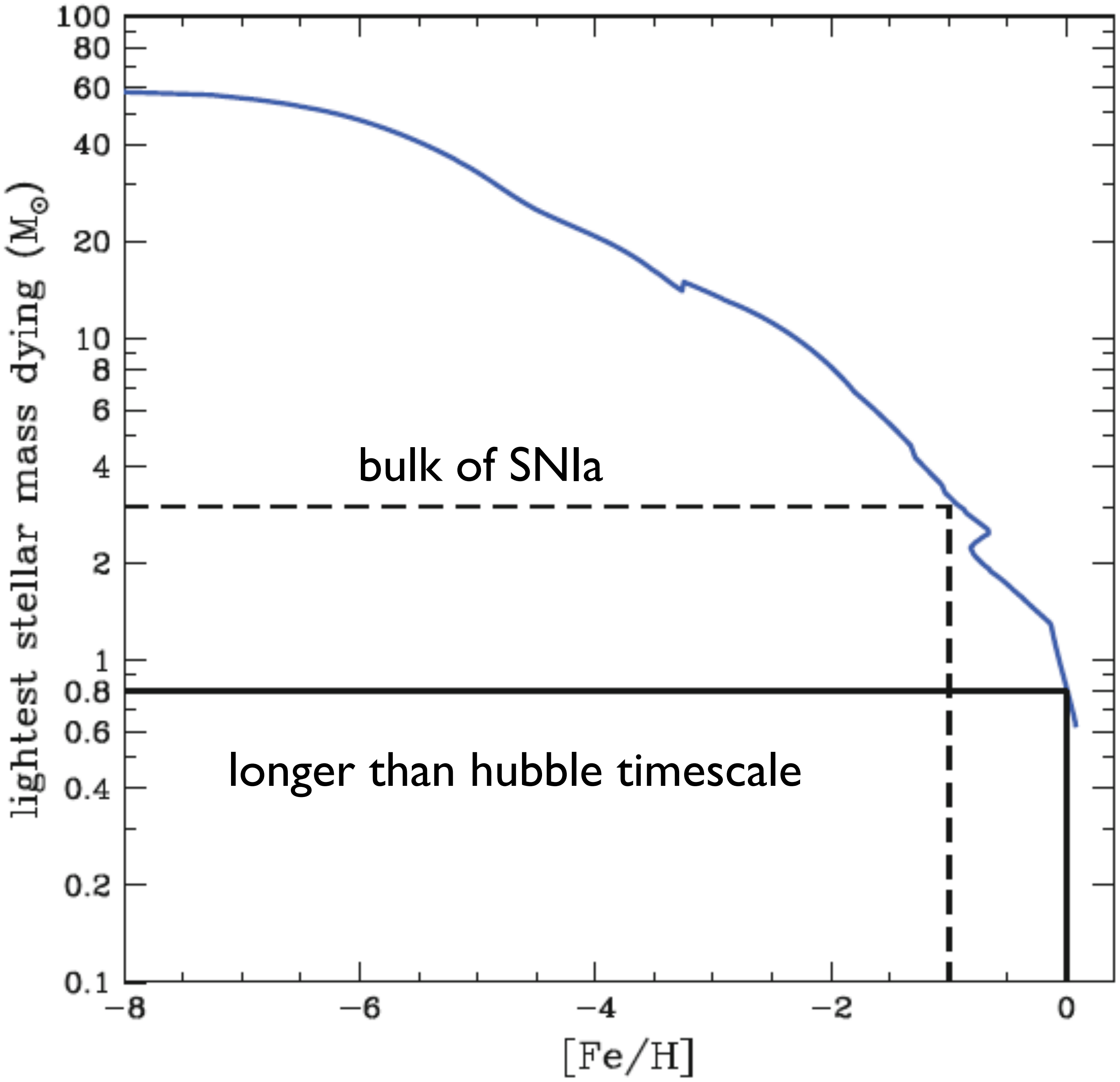


Chiappini01

The [O/Fe] knee

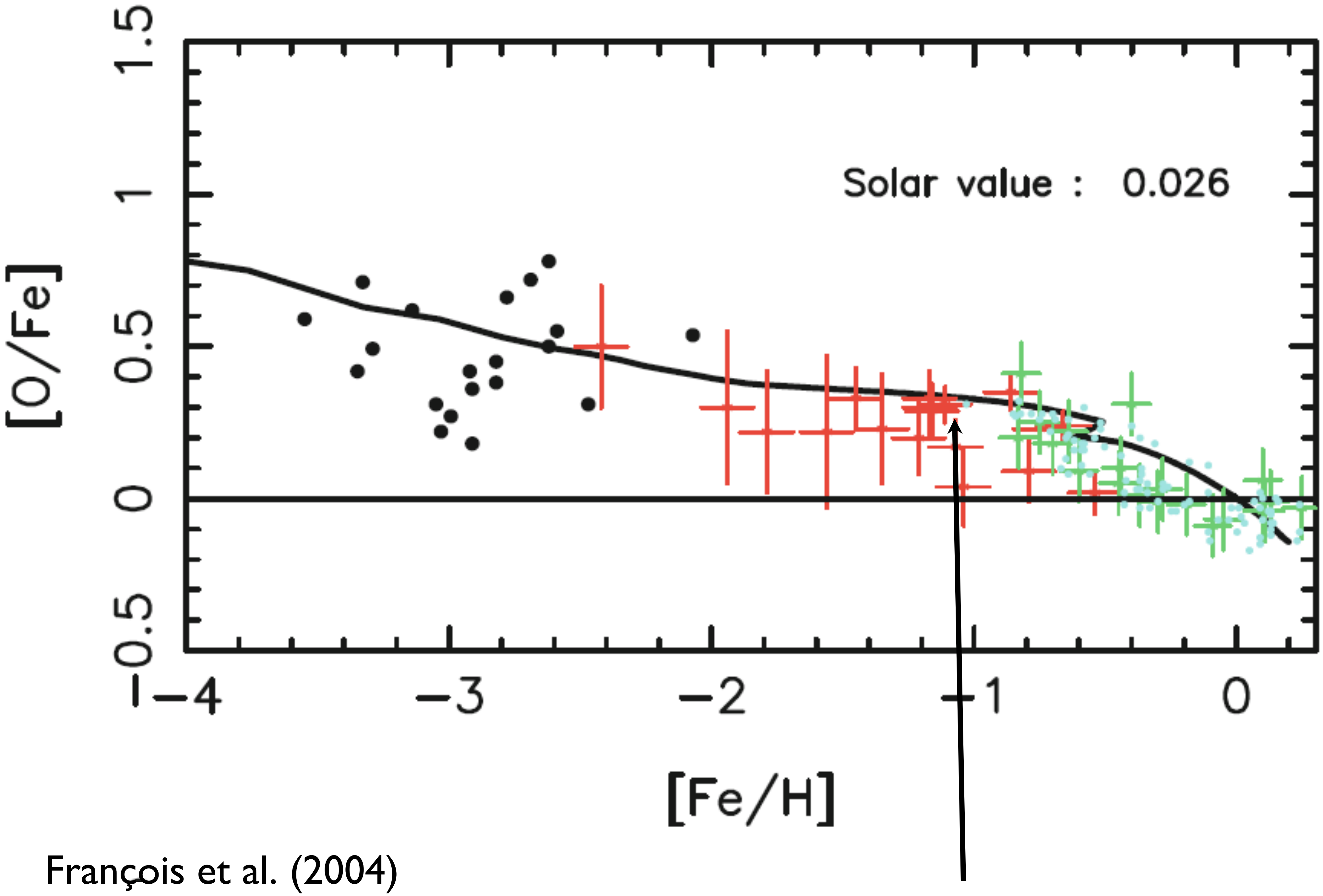

enrichment due to type II SNe
enrichment due to type II SNe + type Ia SNe + planetary nebulae
halo stars and thick-disk stars
"knee"
thin-disk stars
solar level
solar level
~0.4
0
[O/Fe] (log scale)
–4.0
–1.5
–1.0
0
[Fe/H] (log scale)
"time"

Timescales



Cescutti et al. 2006

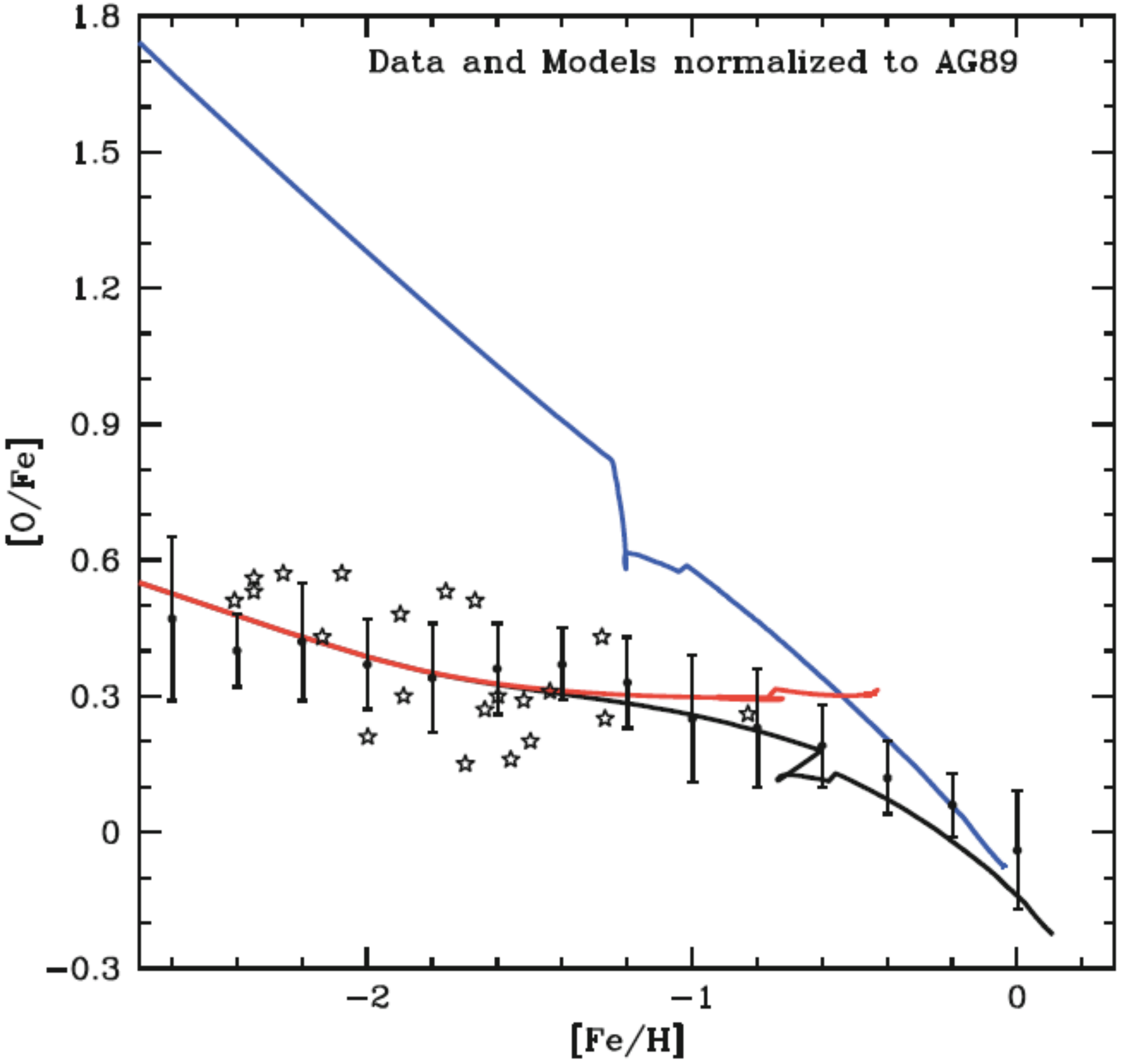
[α/Fe] knee in the solar vicinity



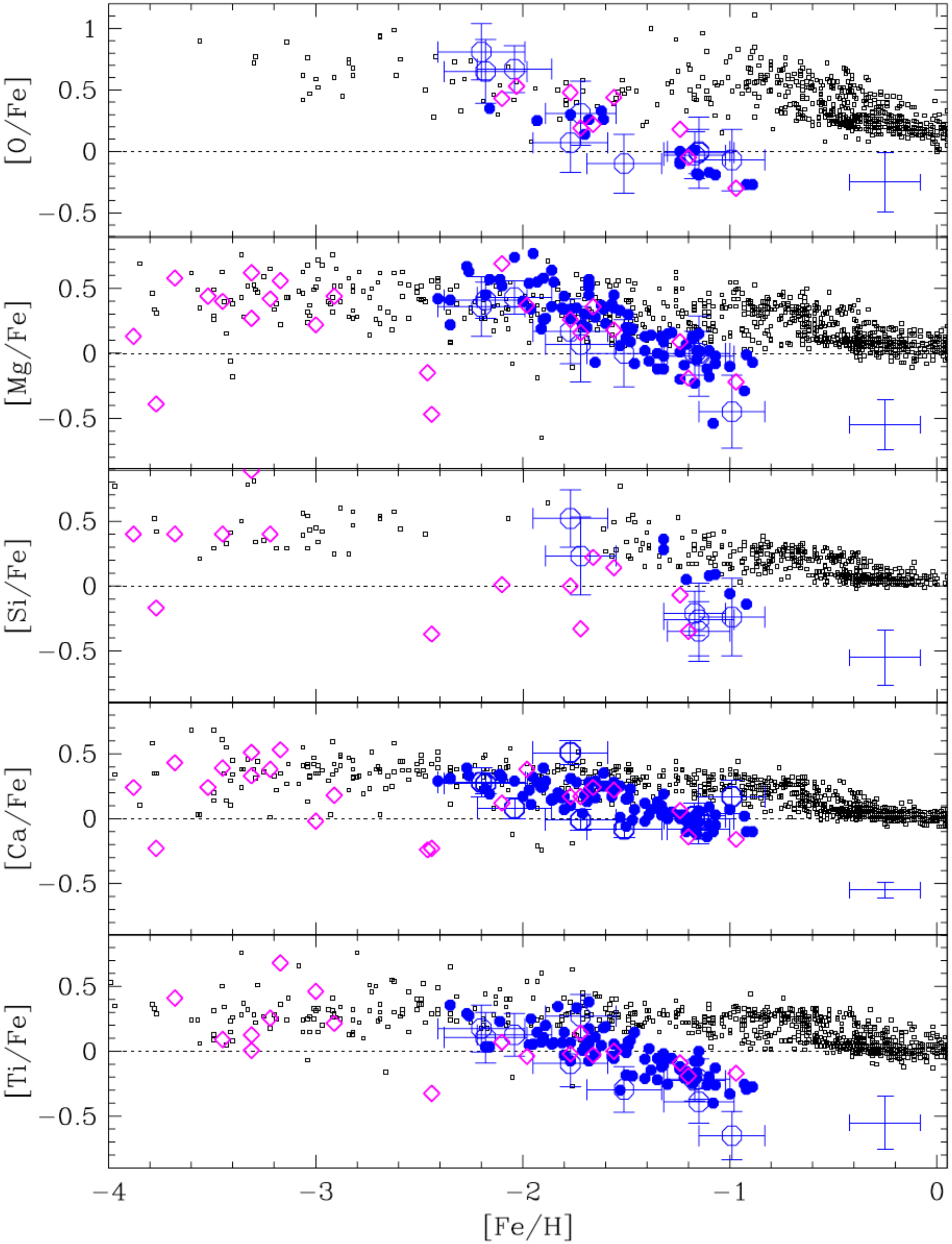
François et al. (2004)

where the SNIa start to contribute

[α/Fe] with and without SNIa

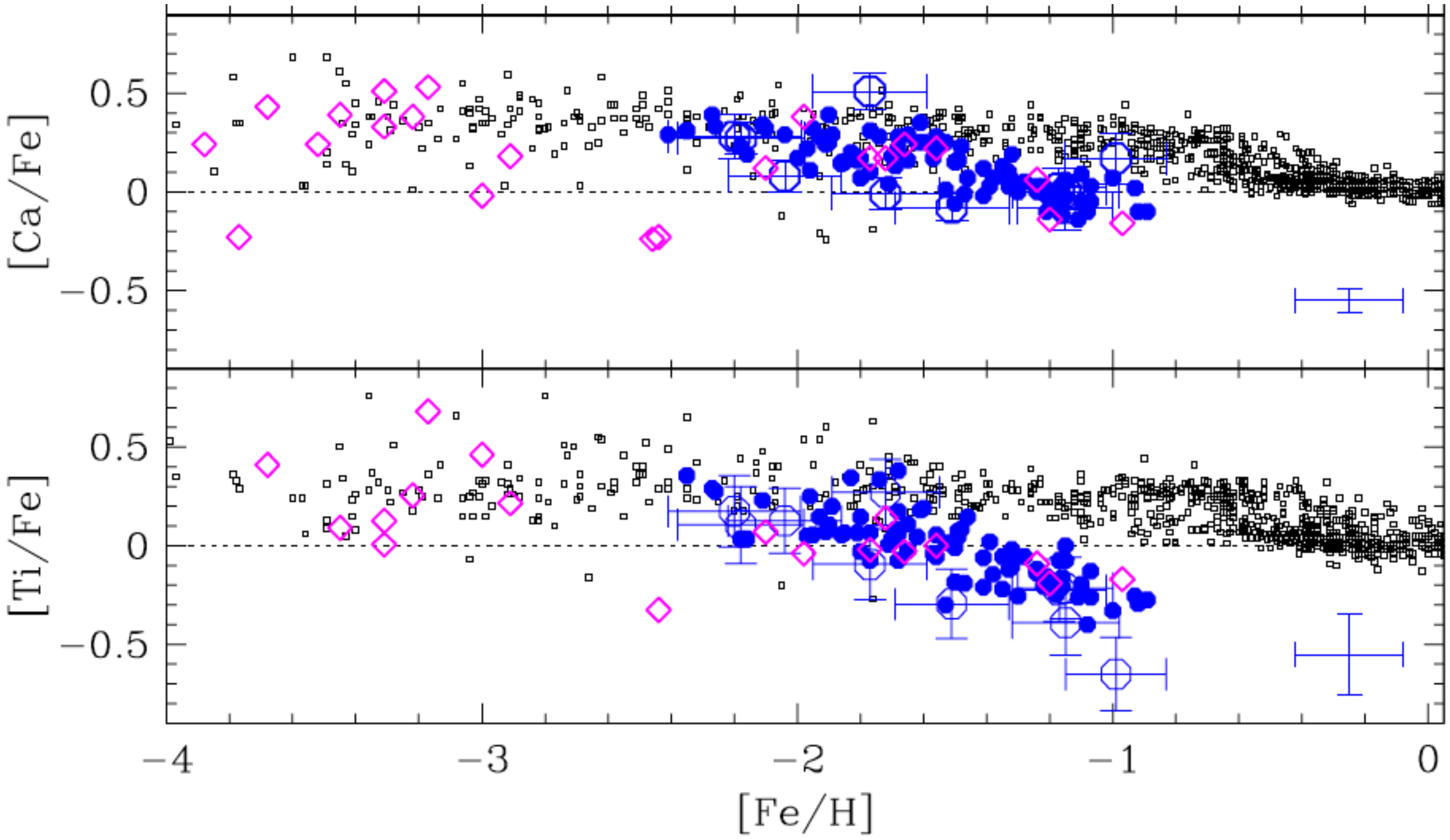


alpha-elements in Sculptor galaxy



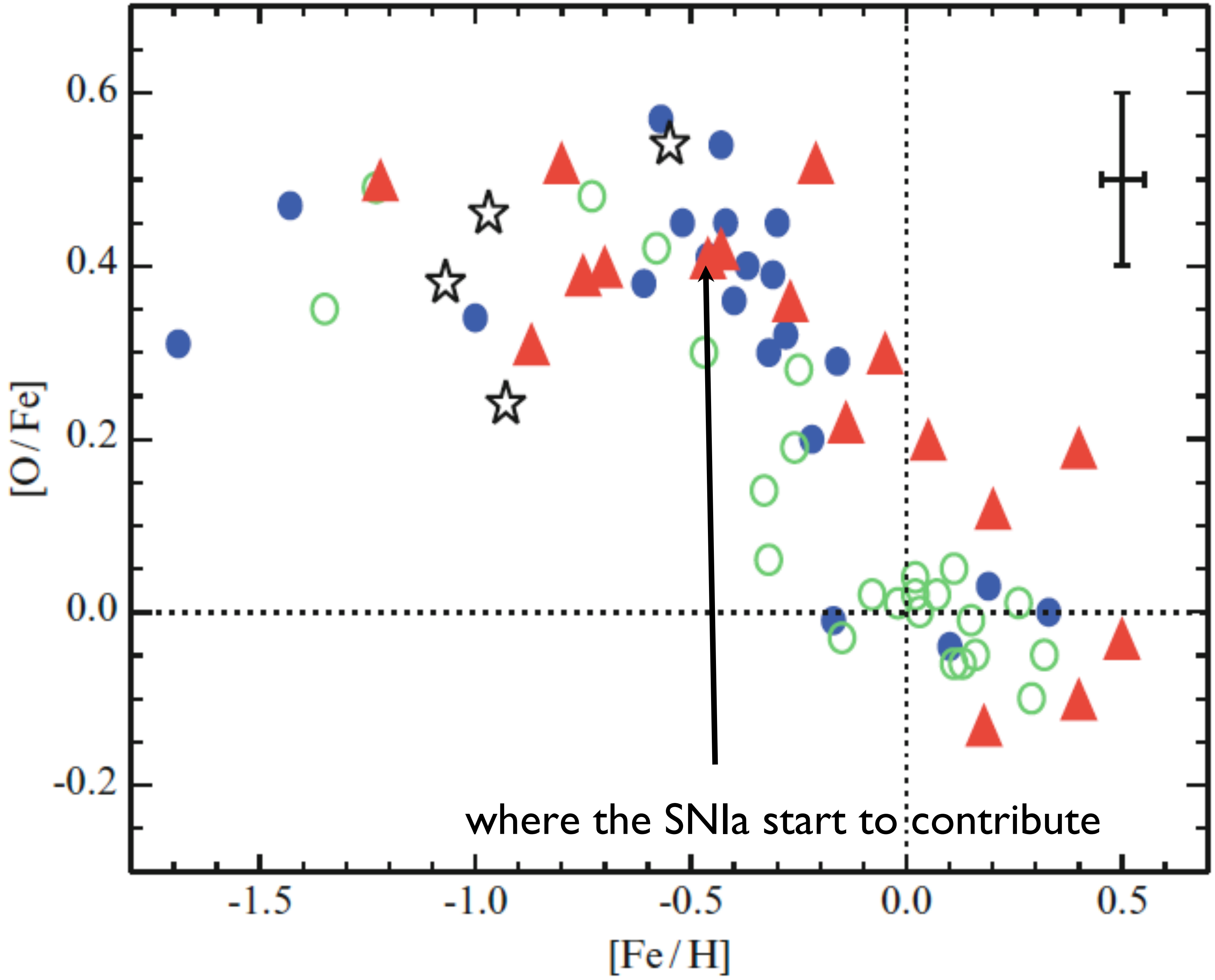
Hill+19

alpha-elements in Sculptor galaxy



Hill+19

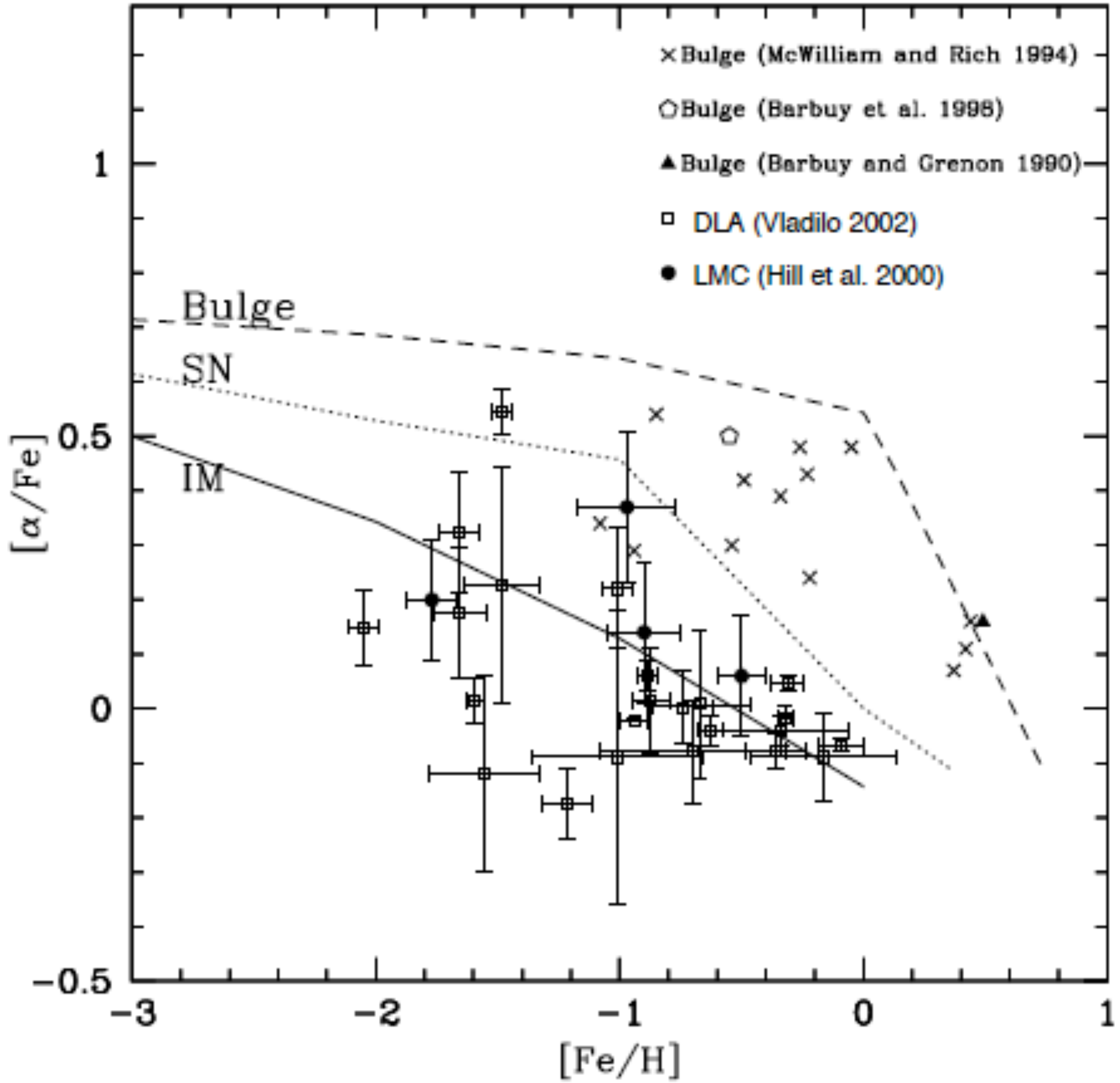
Bulge of the Milky Way



where the SNIa start to contribute

Melendez et al. (2008)

Time-delay model



Matteucci et al. (2012), first claim in
Matteucci e Brocato1990

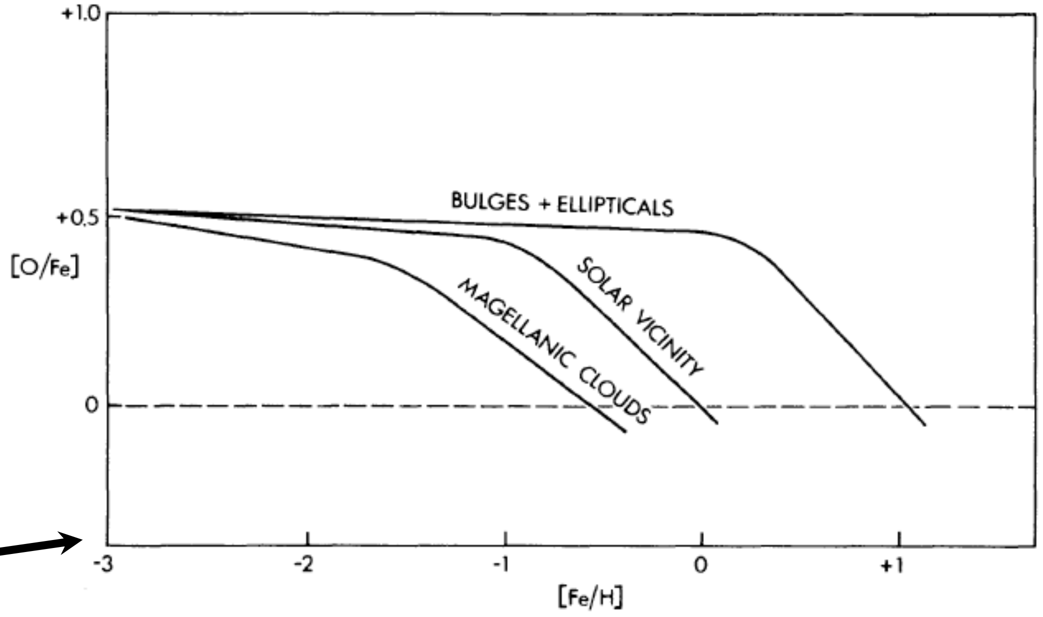
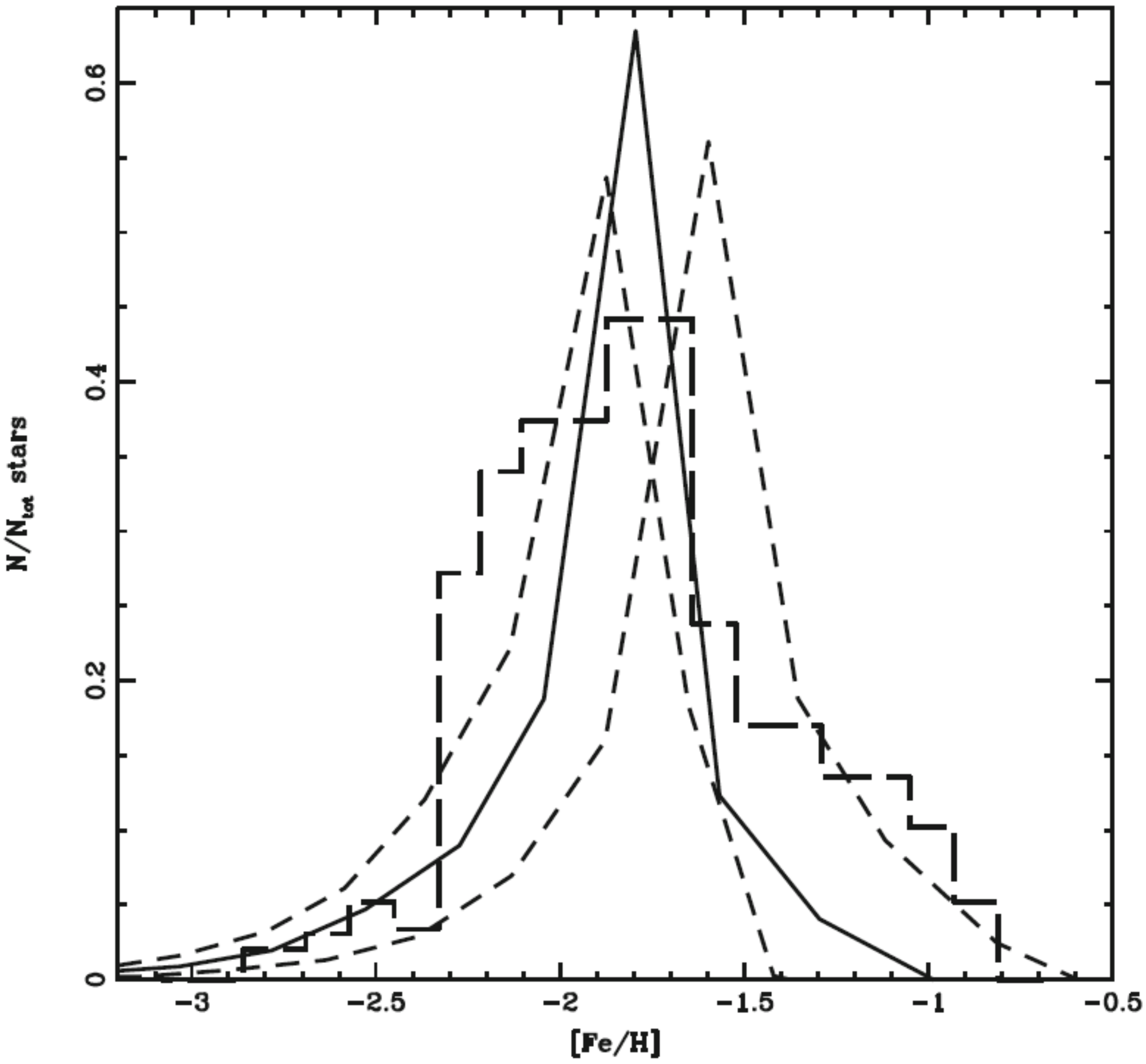


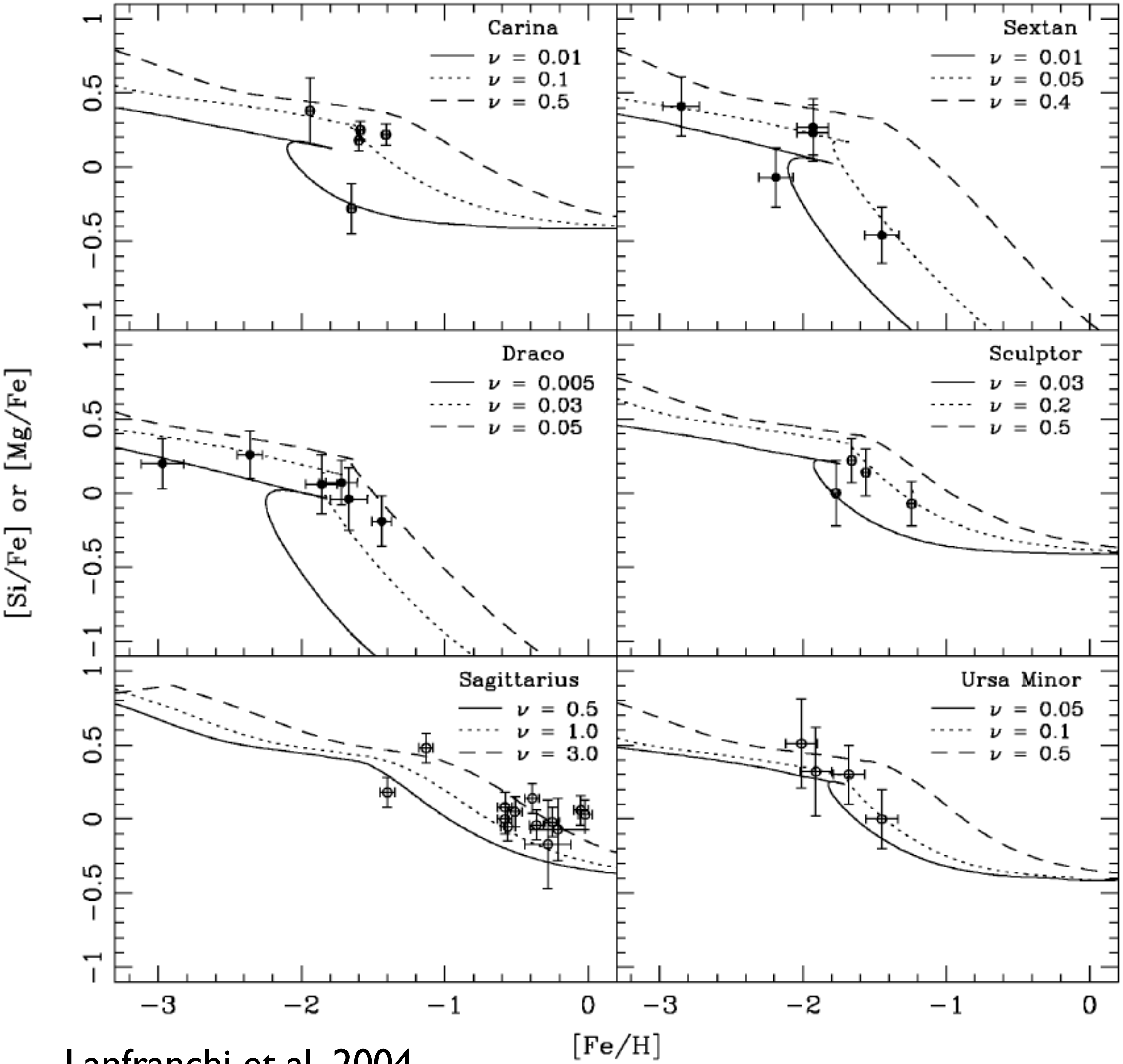
FIG. 4.—A sketch of the predicted [O/Fe] vs. [Fe/H] relations in different systems as a consequence of their different [Fe/H]-t relations.

Distribution functions for Sculptor



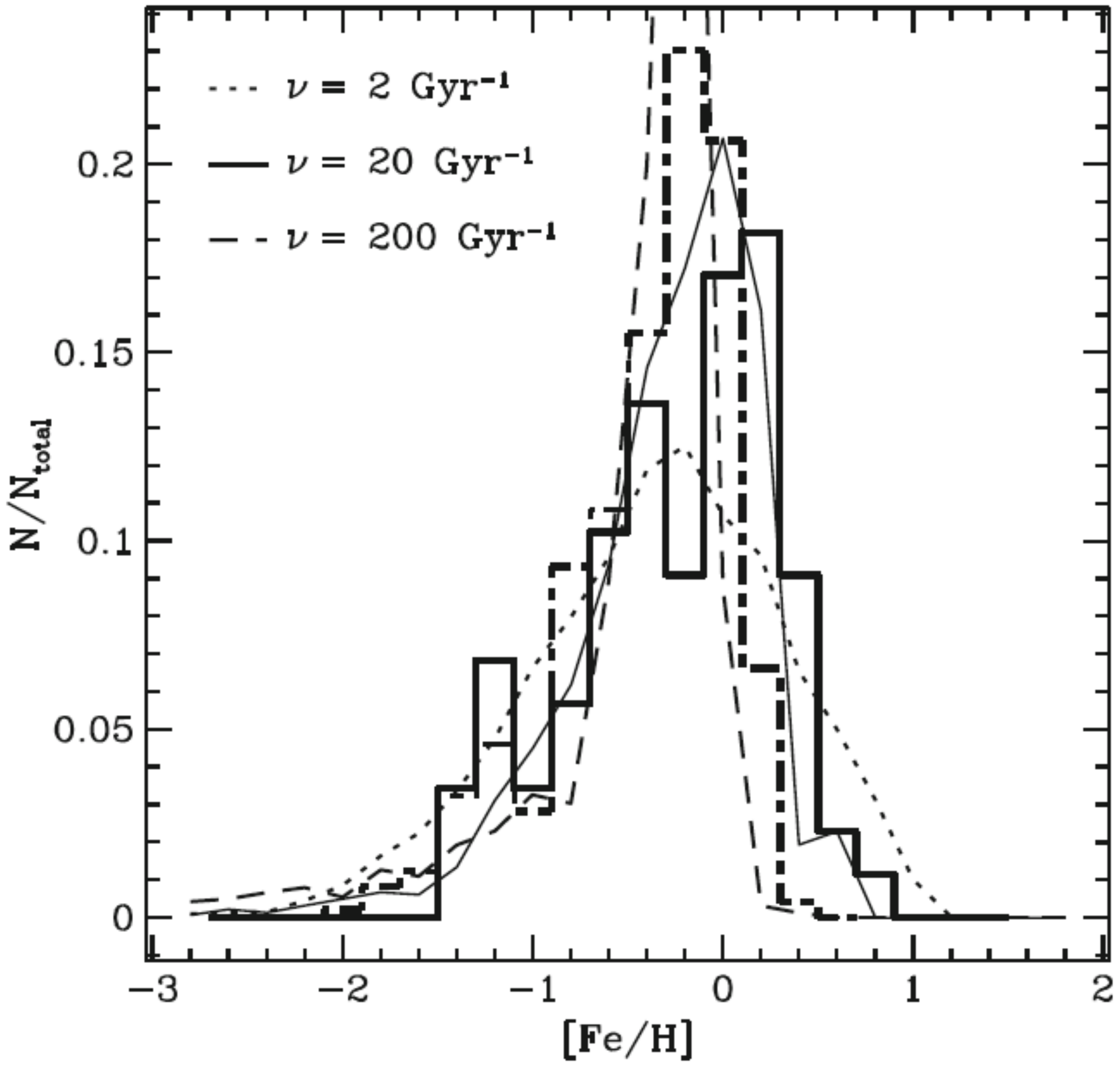
Lanfranchi et al. 2004

Chemical evolution for Sculptor



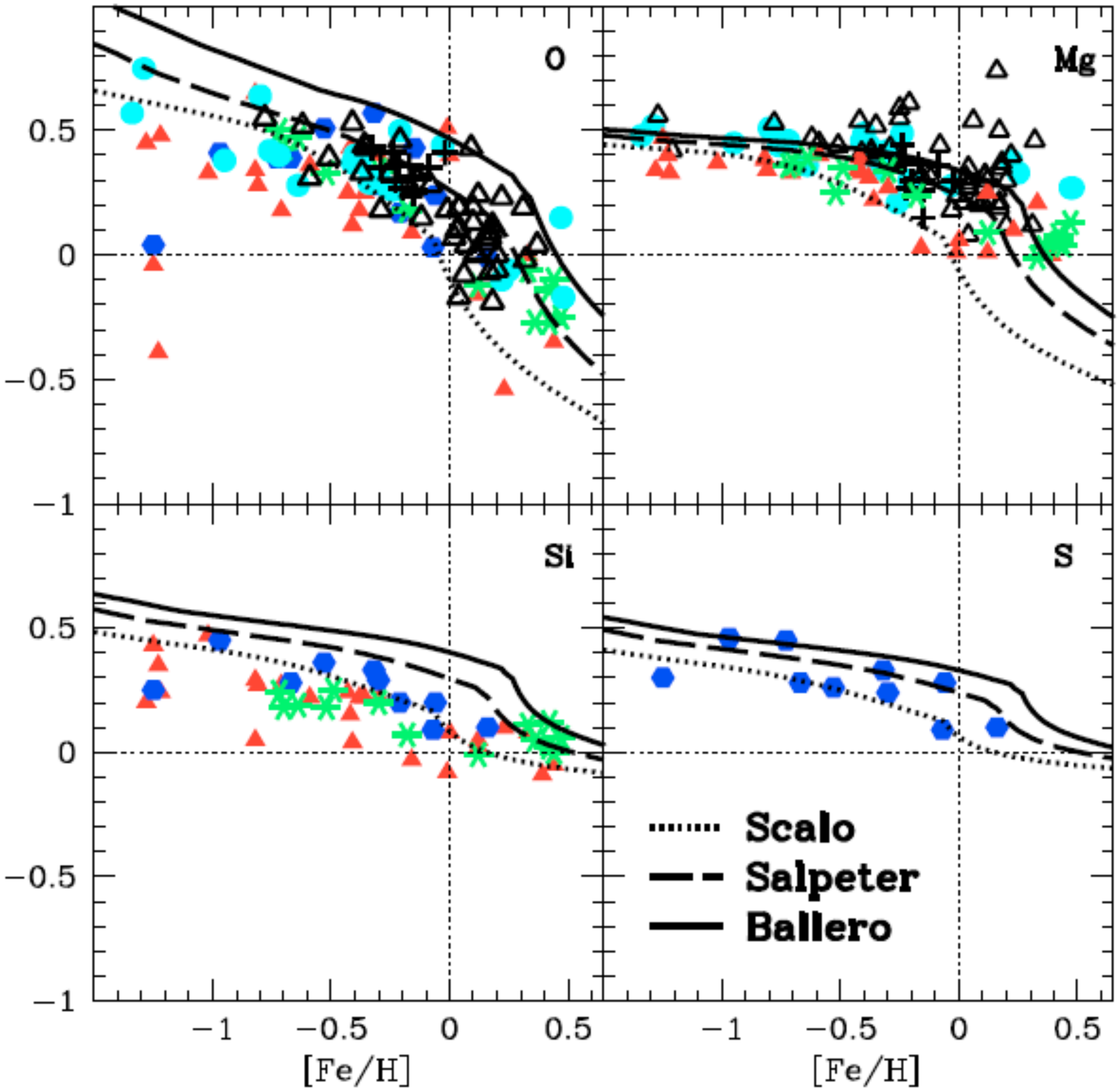
Lanfranchi et al. 2004

Distribution functions for Galactic bulge



Ballero et al. 2007

Chemical evolution for the Bulge



Cescutti et al. 2011

The chemical evolution of different galaxies produce α-knees at different positions.

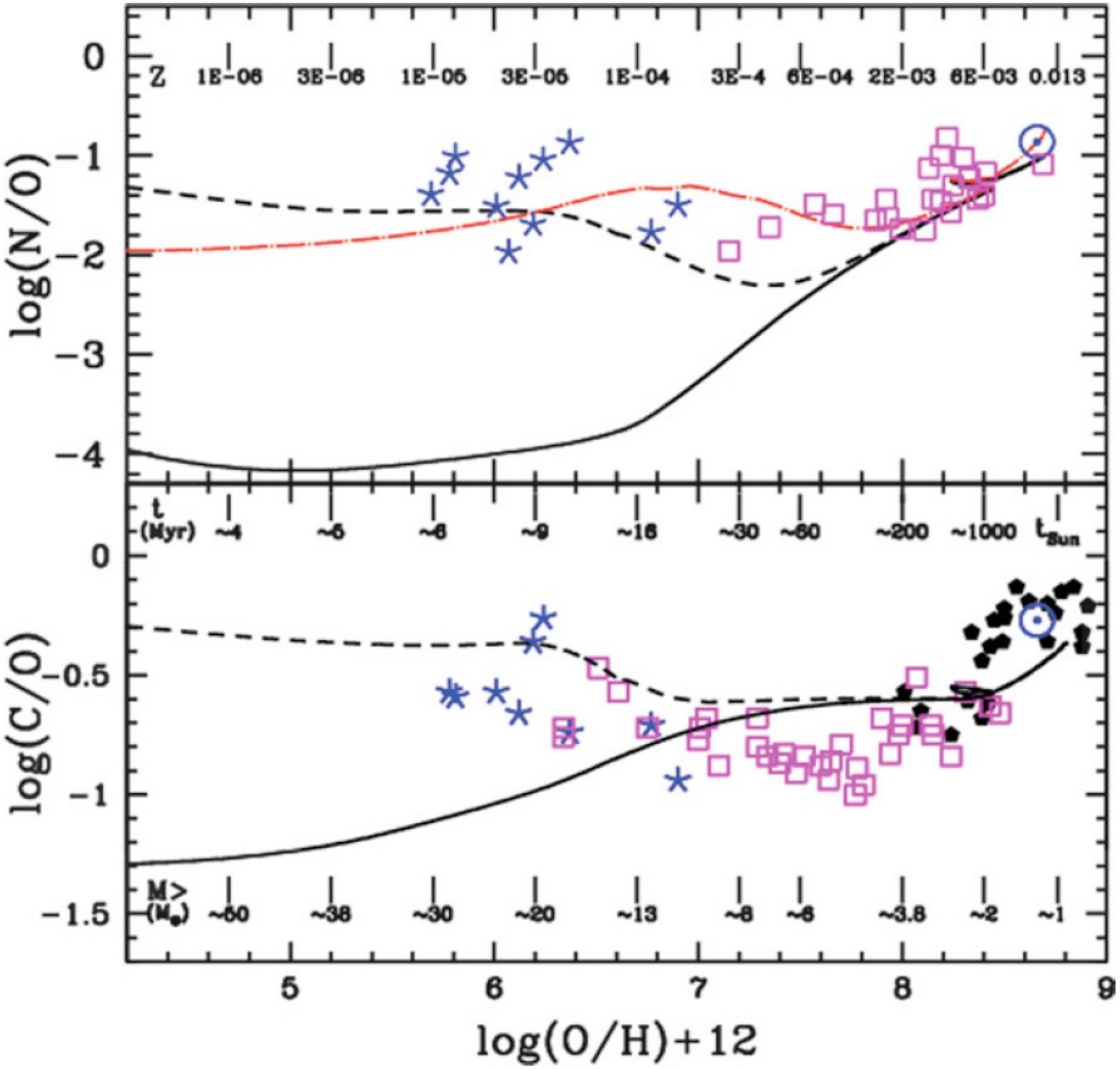
By means of chemical evolution model which implement the time delay for SNIa, we can constrain the **star formation history** (and more) of different galaxies thanks to the position of their α-knees.

Impact on nucleosynthesis

a secondary(?) element Nitrogen

Nitrogen does not follow the trend expected for a secondary element.

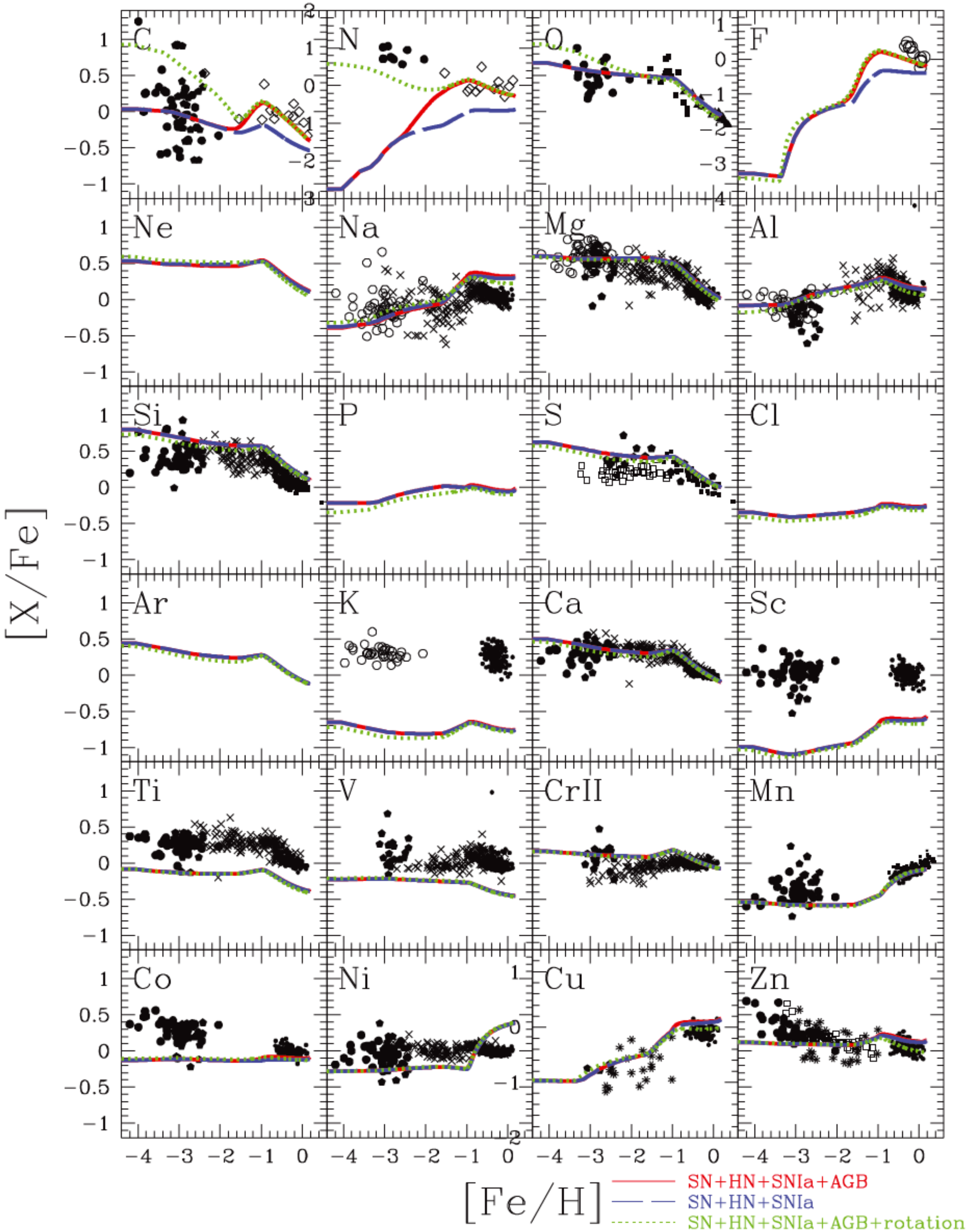
Stellar model with rotation at low metallicity can explain its behaviour, the rotation allows the N to be produce as a primary element.


Chiappini et al. (2006)

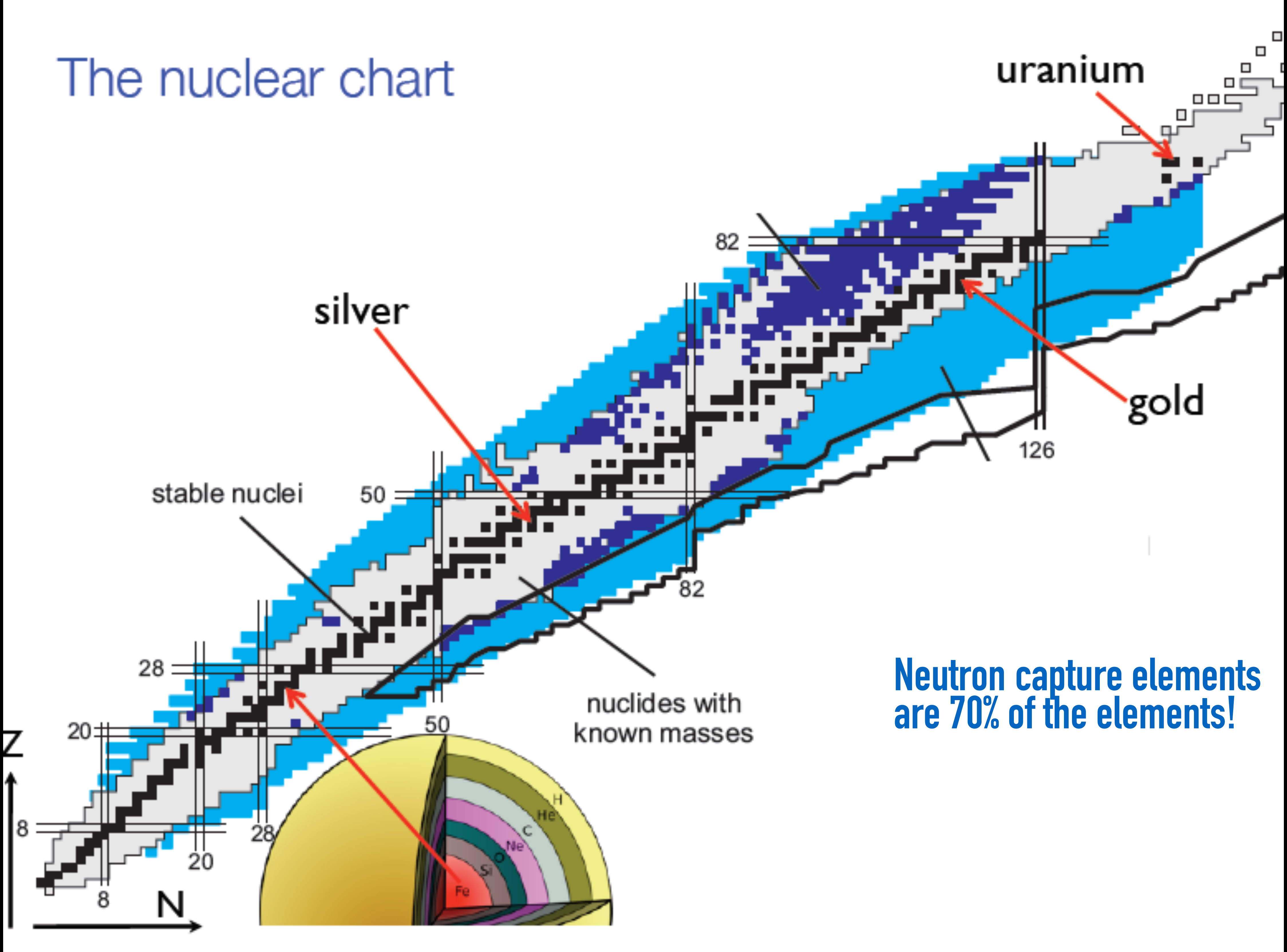
Prediction of the Chemical trends

Kobayashi+11
see also

Romano
Prantzos
Coté
Spitoni



Neutron capture elements

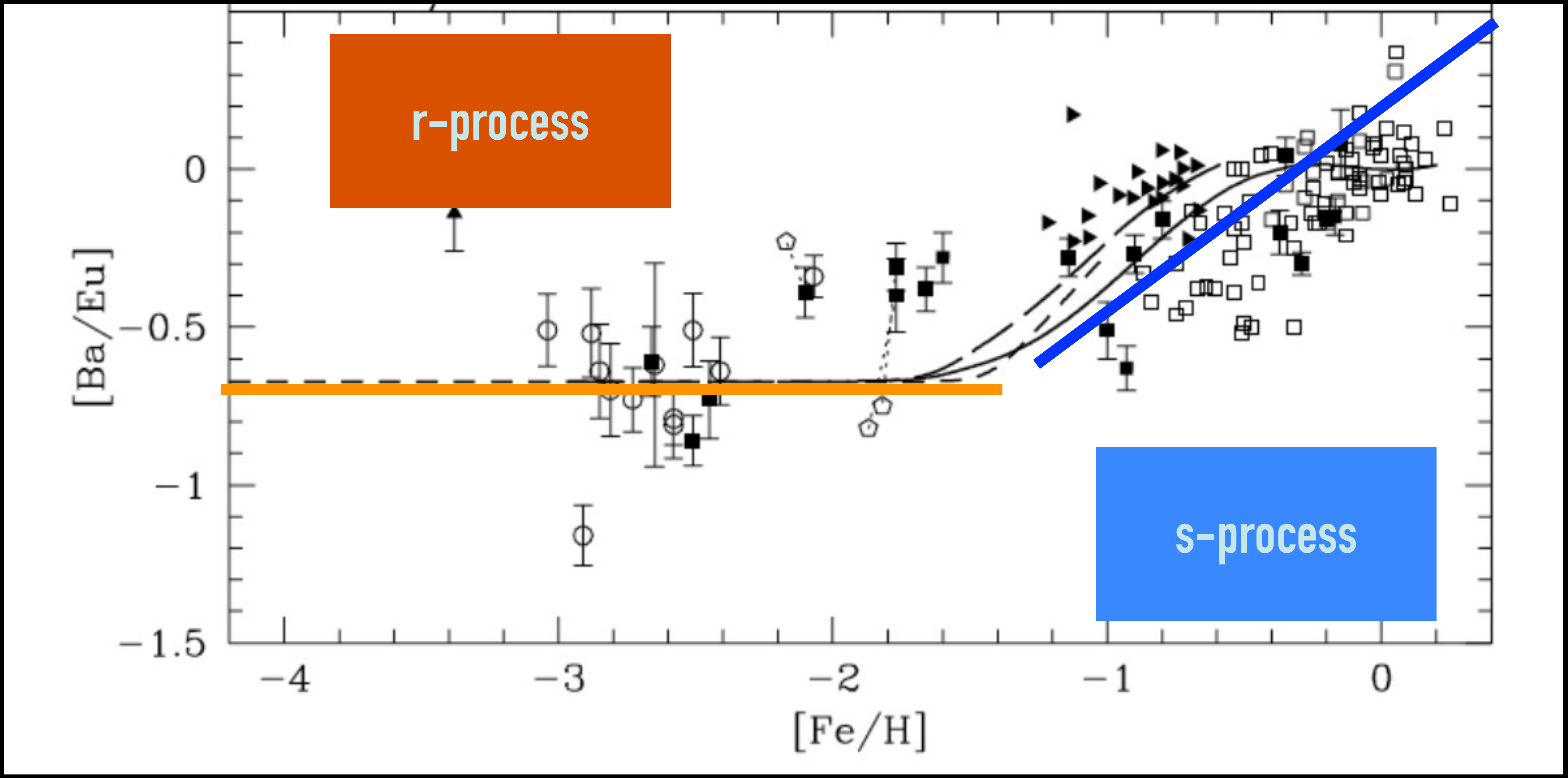


Neutron capture elements are 70% of the elements!

Neutron capture elements

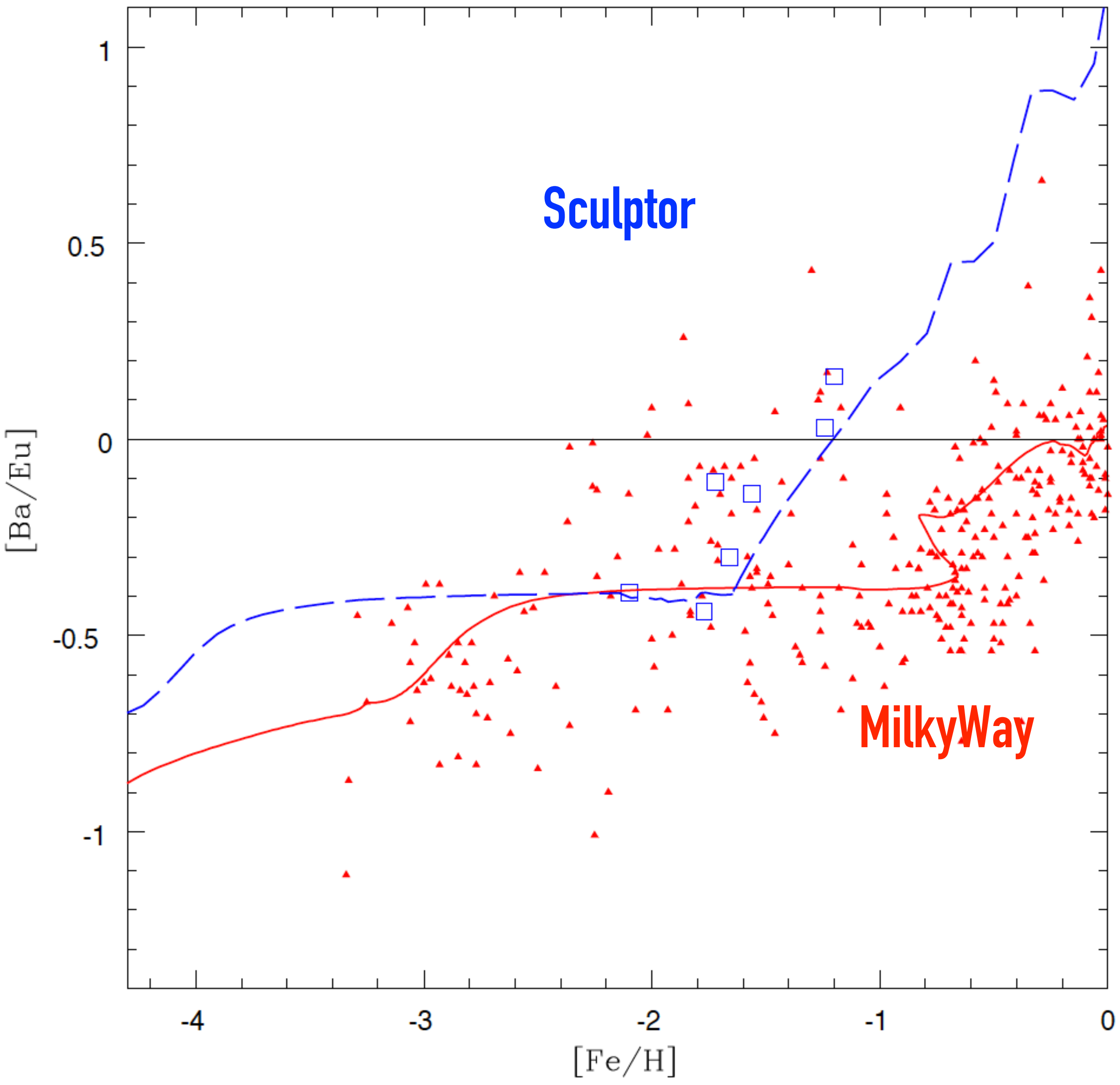
	s-process	r-process
site	Low-(intermediate) mass stars	NS mergers (& Massive stars?)
time scale	>300Myr	DTD NSM or/and < 30Myr for MRD SNe
yields	Cristallo+11 Karakas+12	nucleosynthesis available (but . . .)

The case of [Ba/Eu] knee



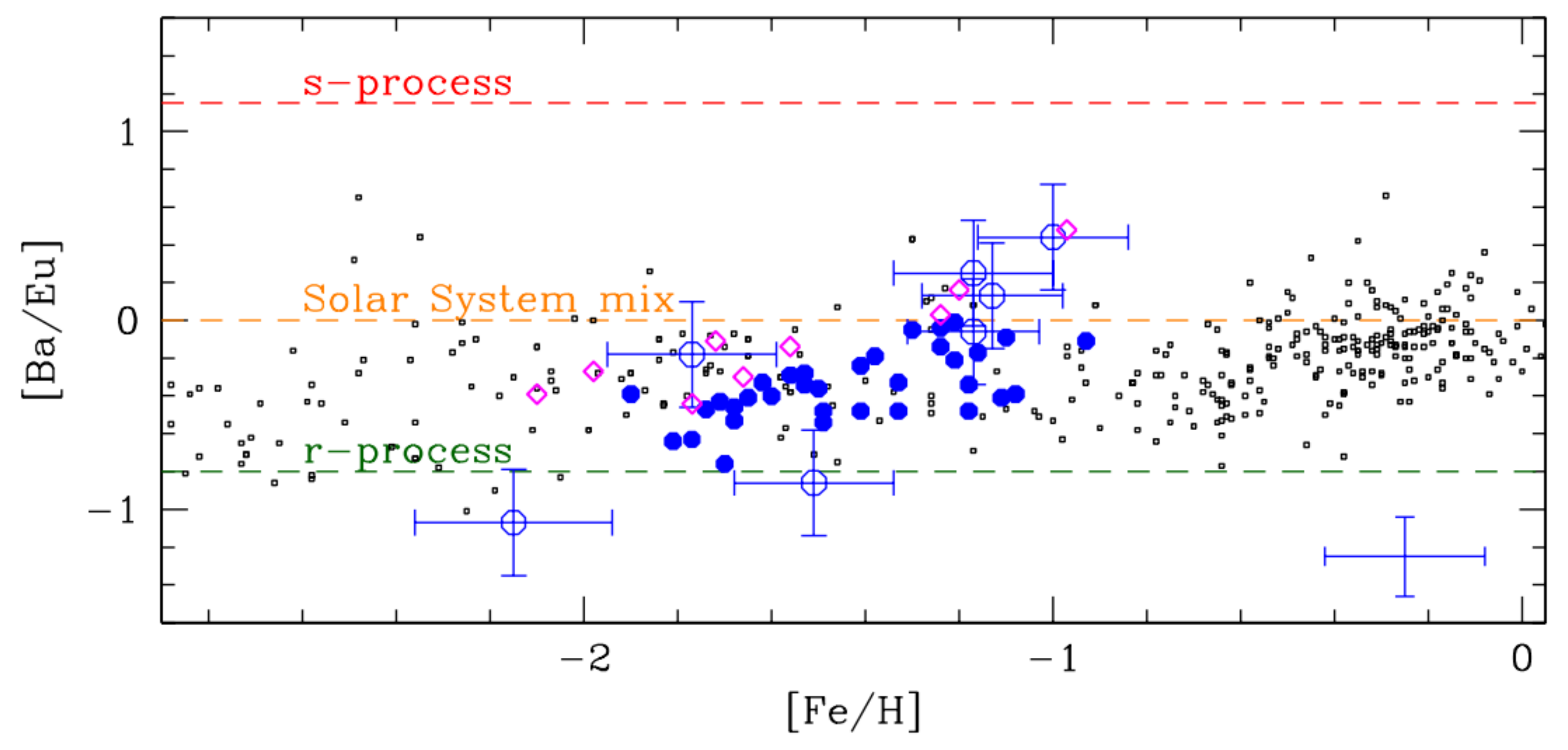
Travaglio+99

The case of [Ba/Eu] knee



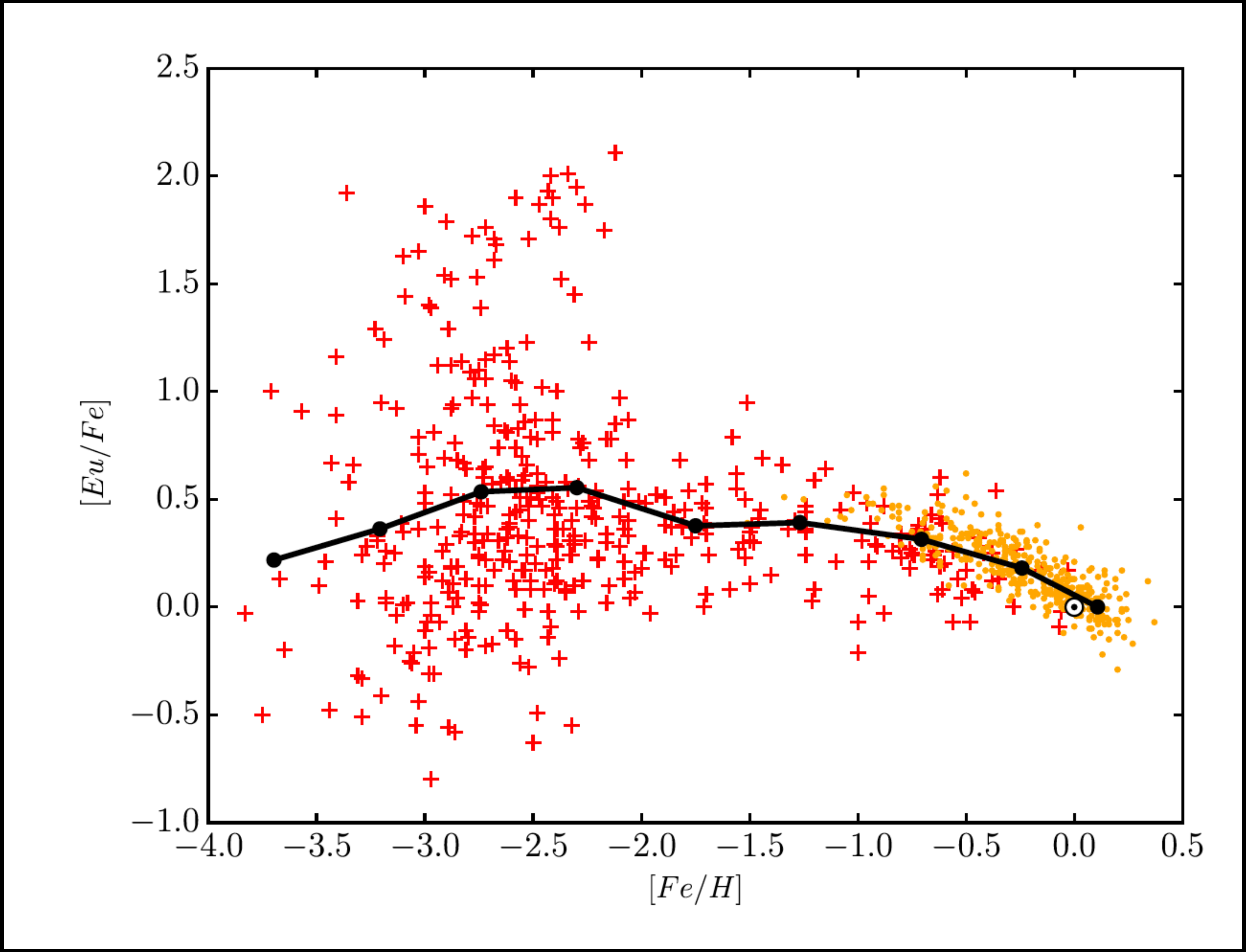
Lanfranchi+07,Cescutti07

[Ba/Eu] in Sculptor galaxy



Eu/Fe in the Galactic halo

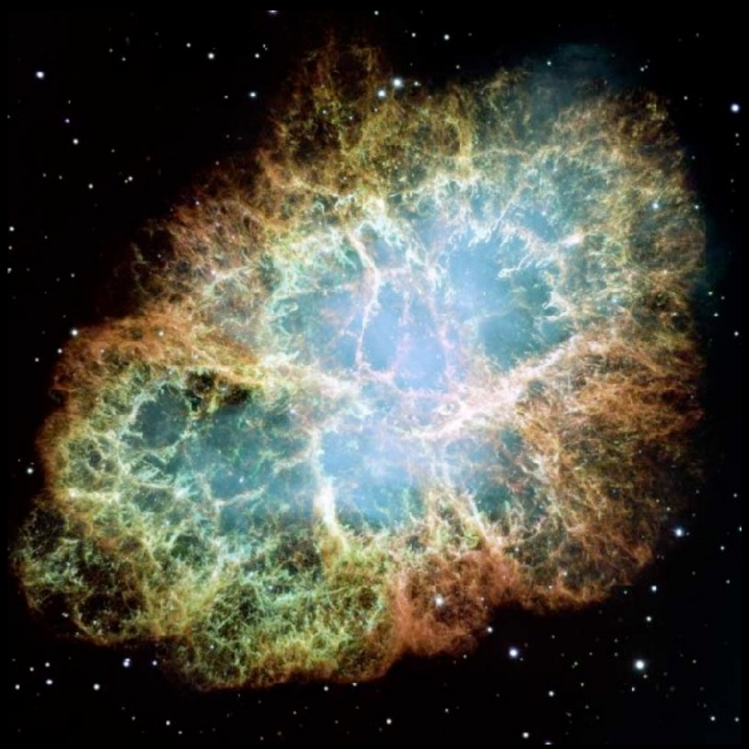
Europium only r-process...
Since McWilliam98 idea of rare events



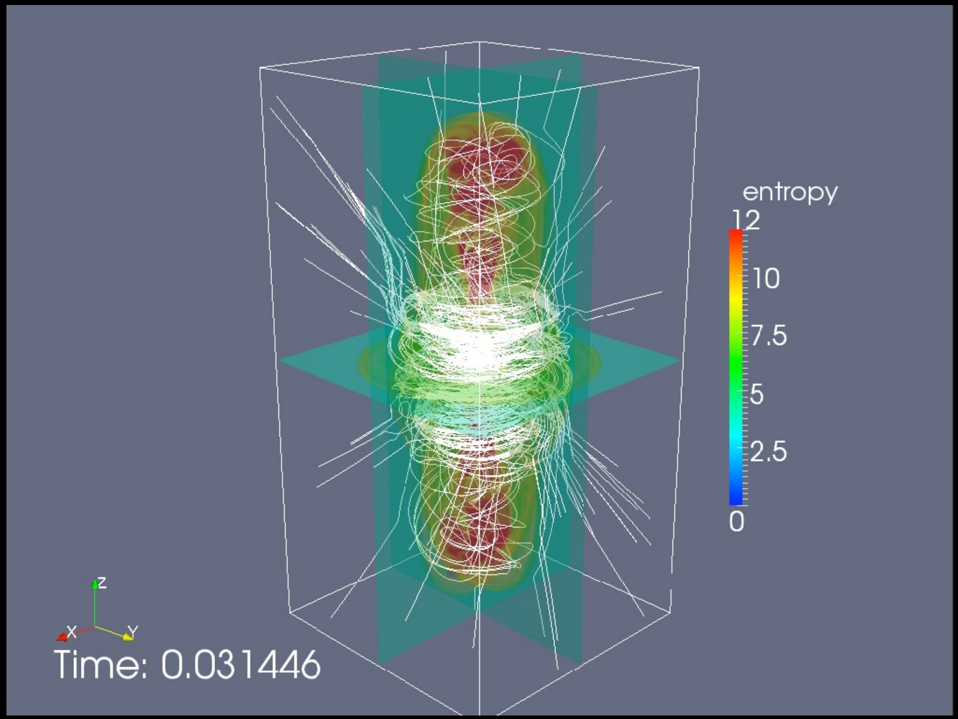
JINA collections
+Battistini&Bensby16

Site(s) of the r-process?

Electron Capture SNe (Wanajo+11)



Magnetorotat. driven SNe (Winteler+12)

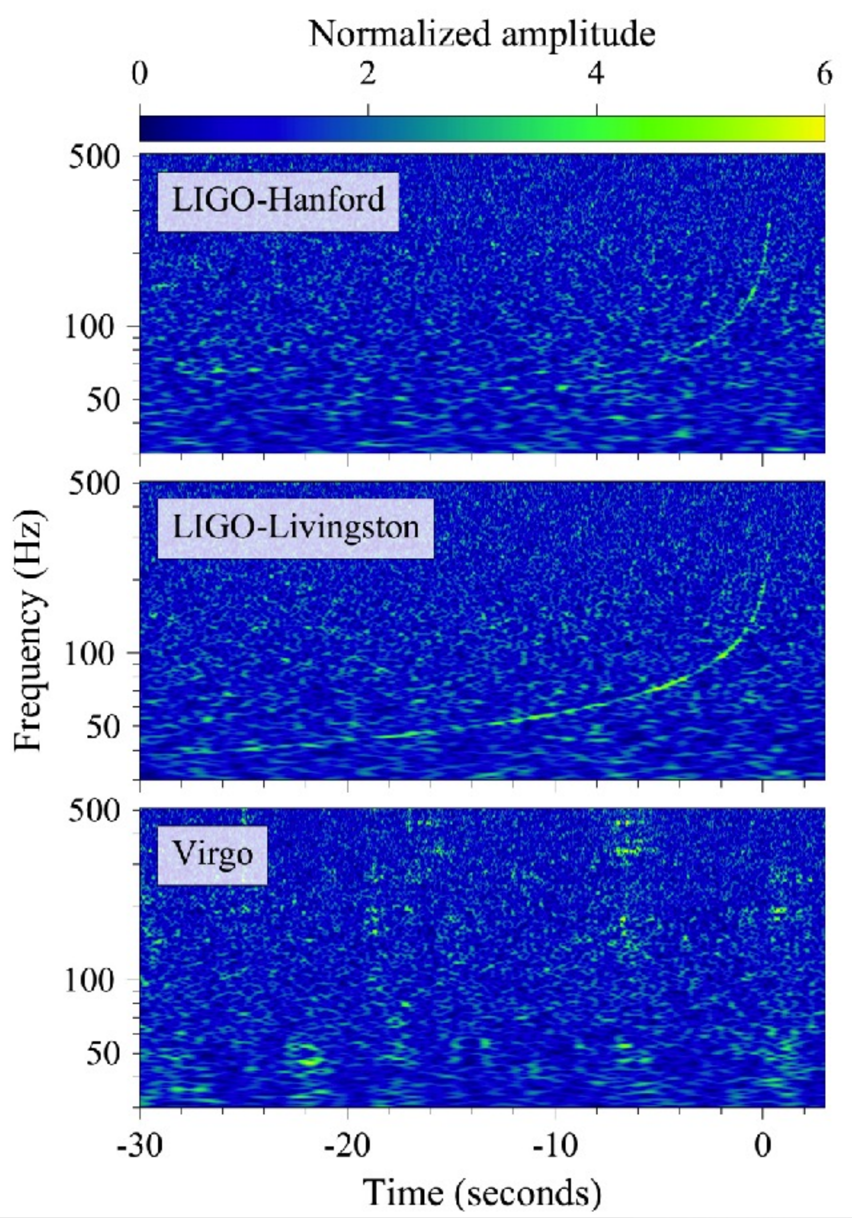


Neutron star mergers (Rosswog+13)

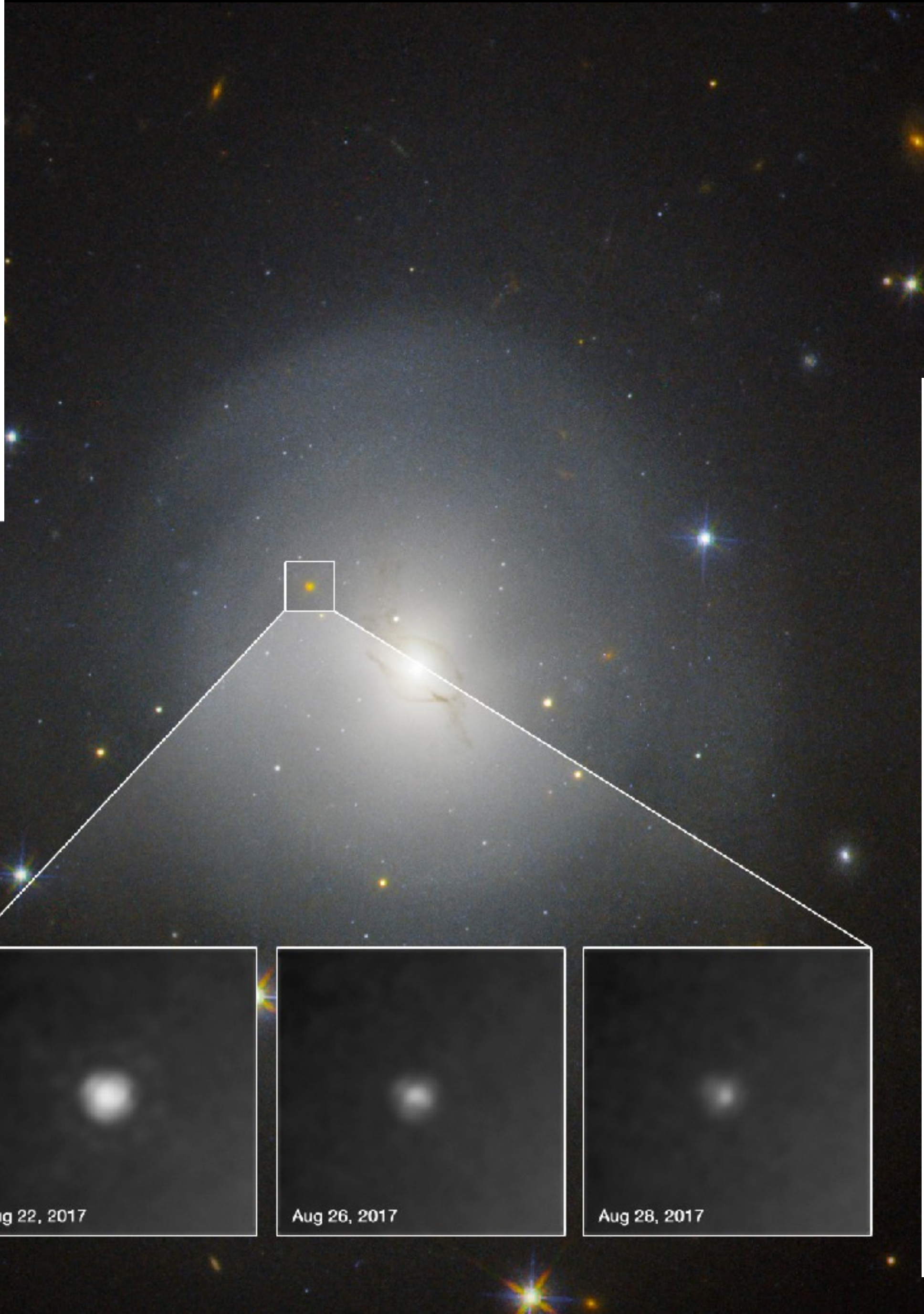
other possible sites?

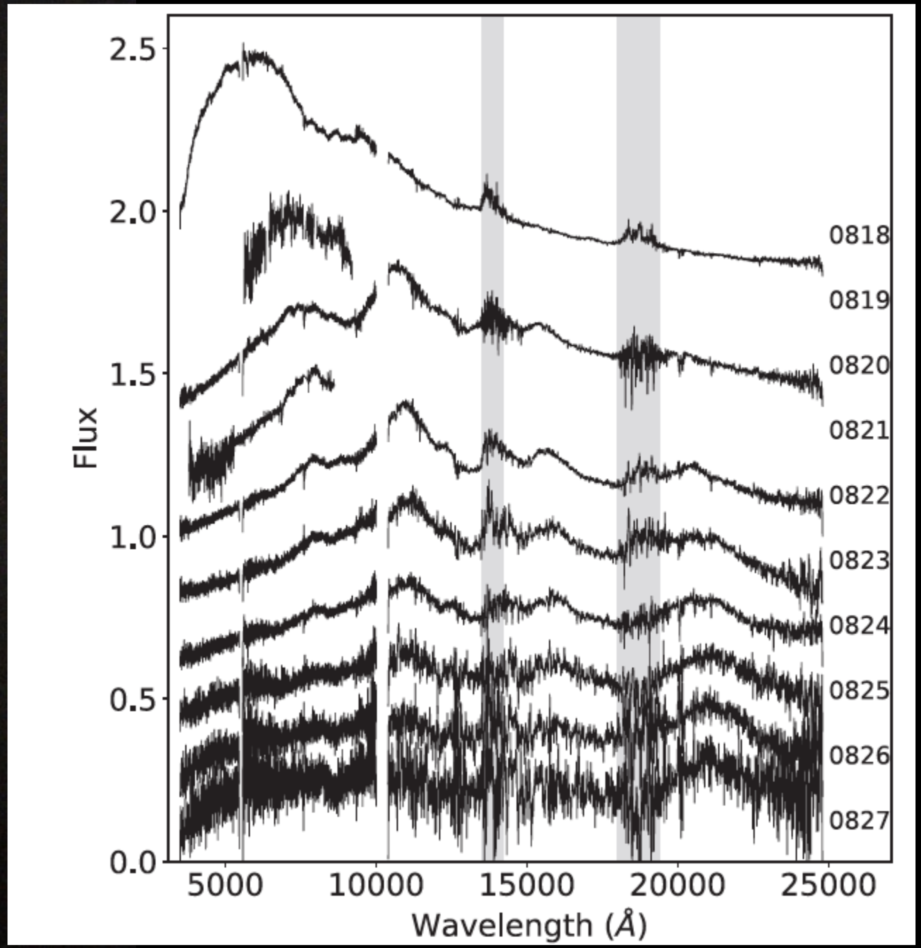
Neutrino winds SNe (Arcones+07,Wanajo 13)

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 fraction (NSM/SNeII)
is defined as alpha

This fraction is not constrained at all the times, the rate can be constrained only at the present time.

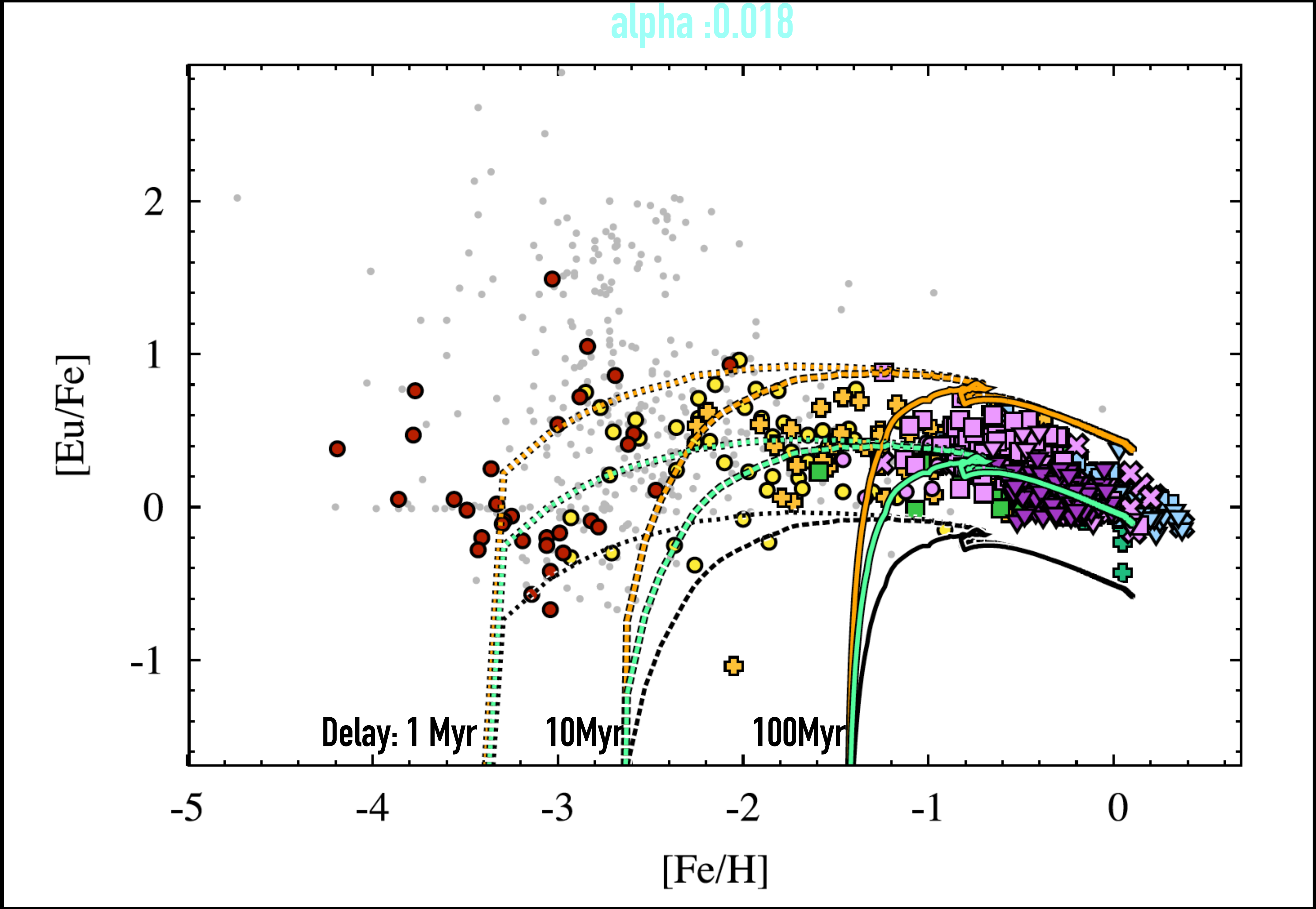
Another key feature of NS merger is the delay between the formation of the binary system of neutron stars and the merging event.
We investigate delay of 1, 10 and 100Myr.

Neutron star mergers (Rosswog+13)

GCE for Europium with NSM with fixed delay

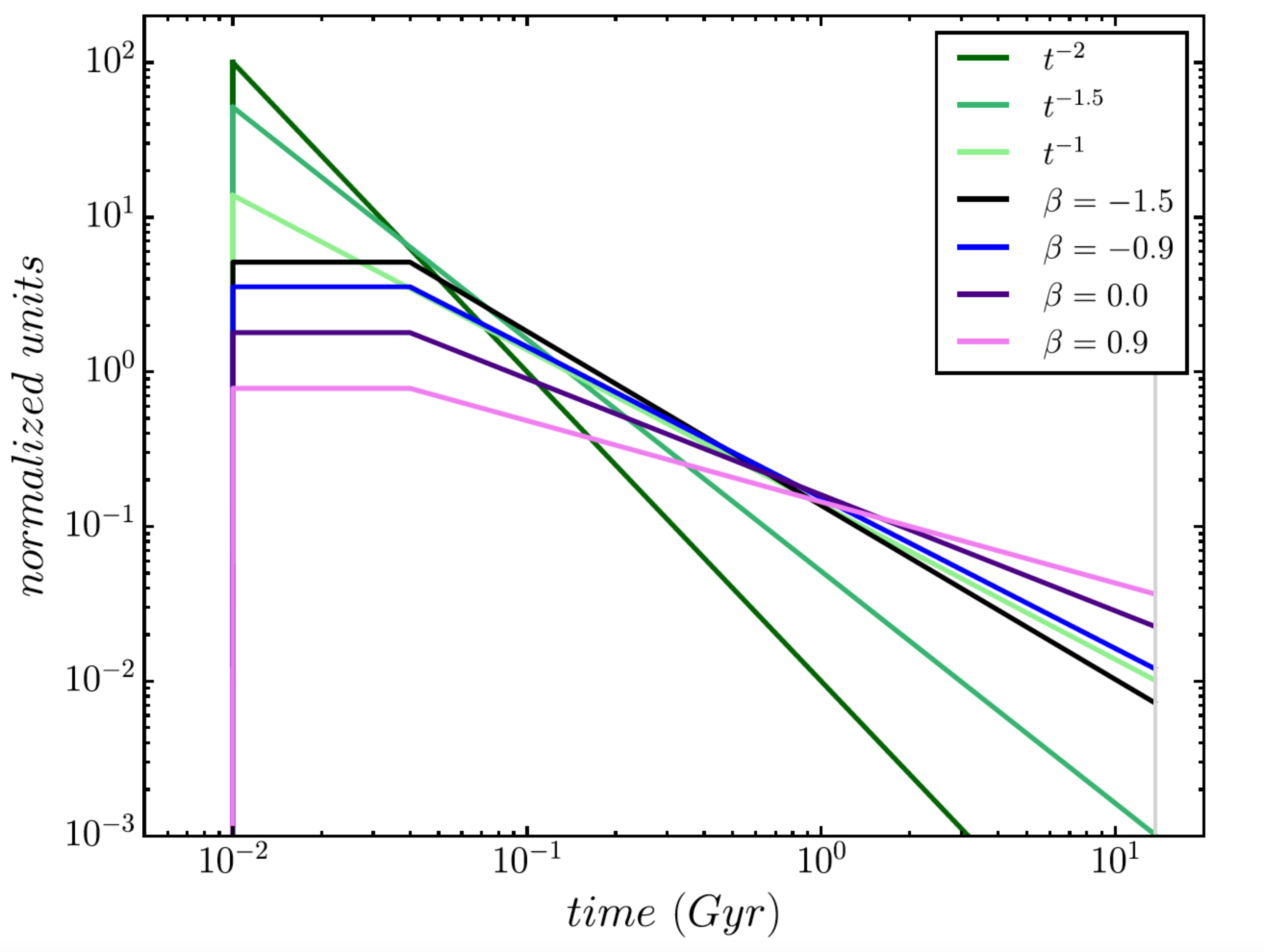
Eu yields (green): 3 10^-7Msun

alpha :0.018



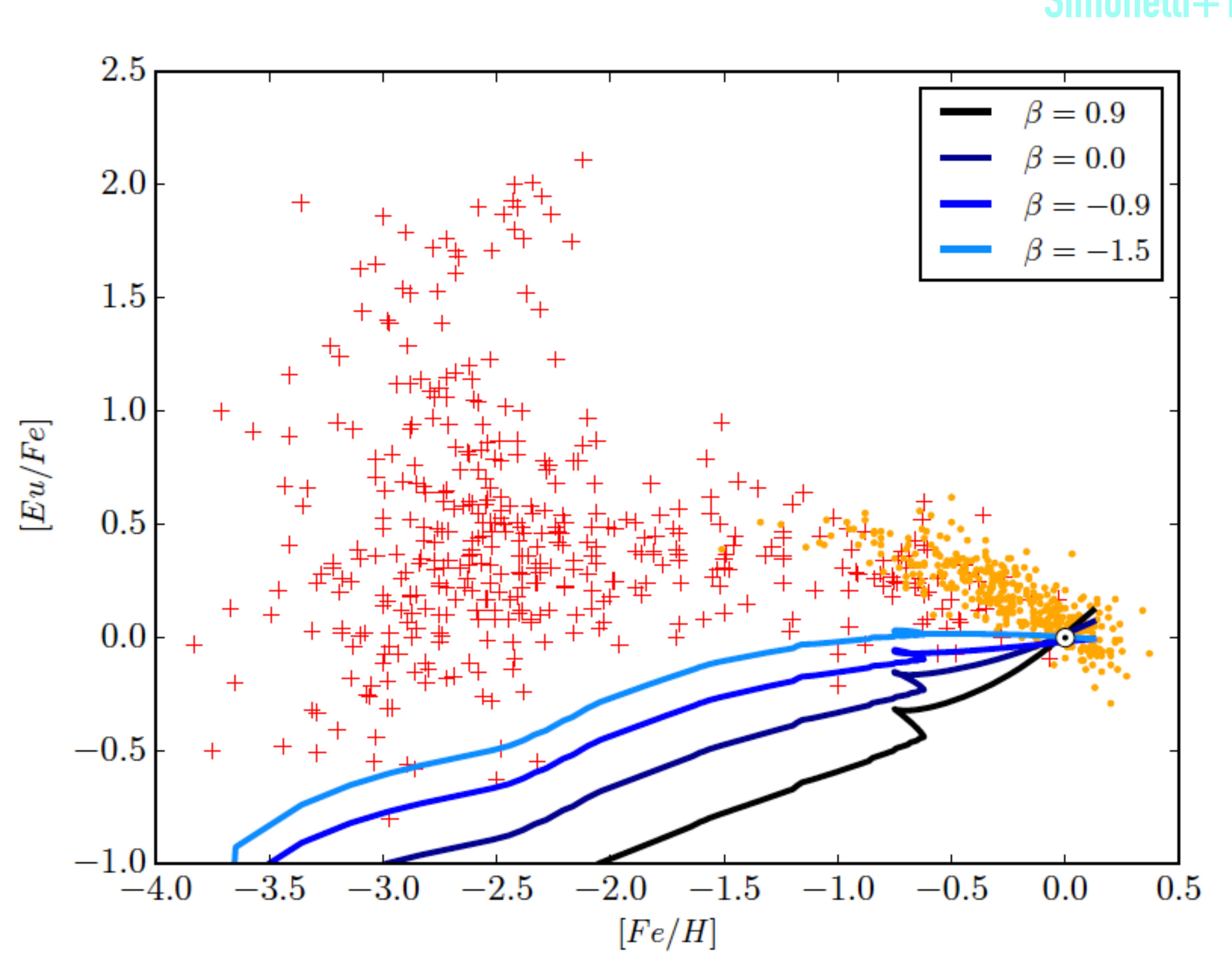
Matteucci+14

Detailed DTD for NSM



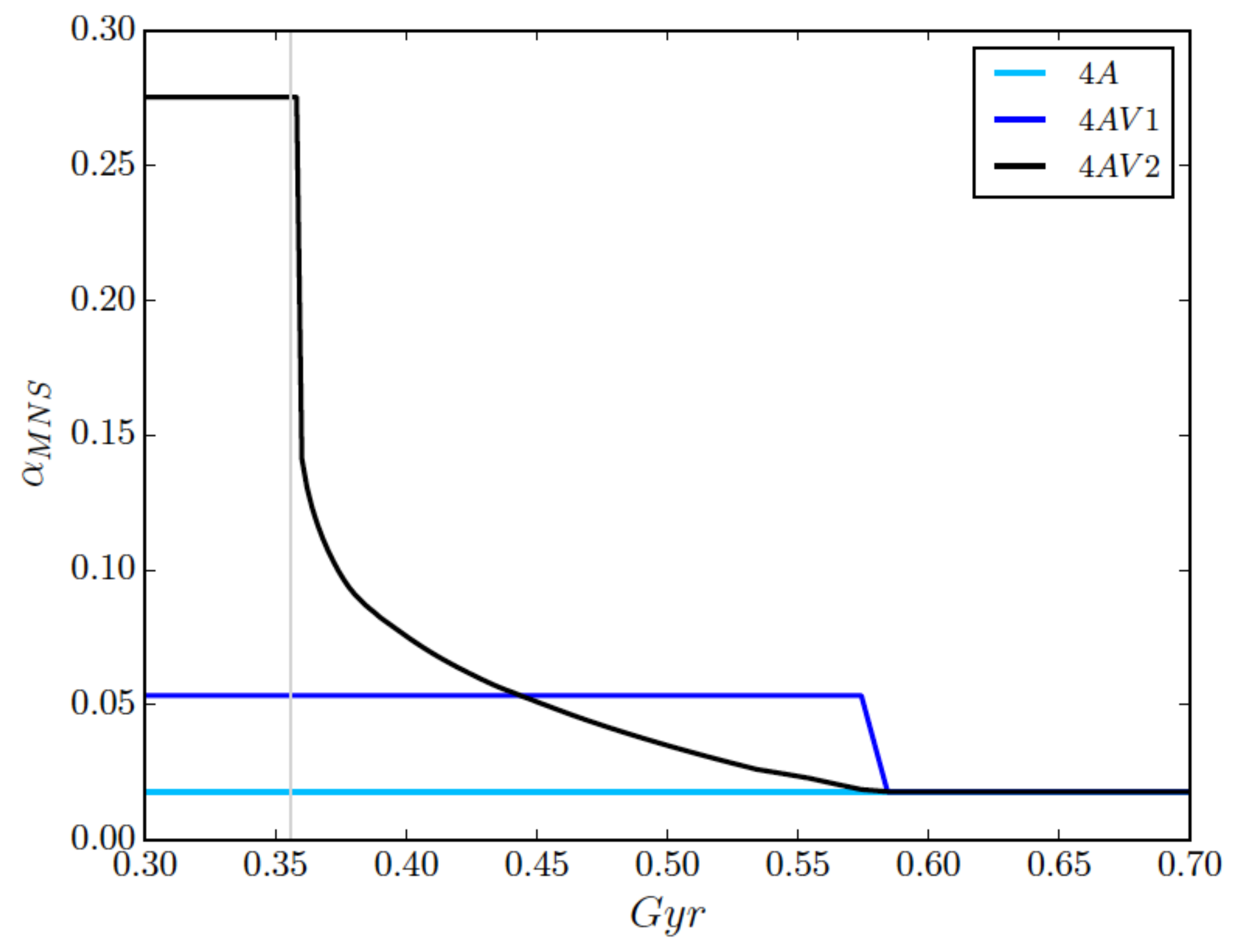
Detailed DTD for NSM

Simonetti+19



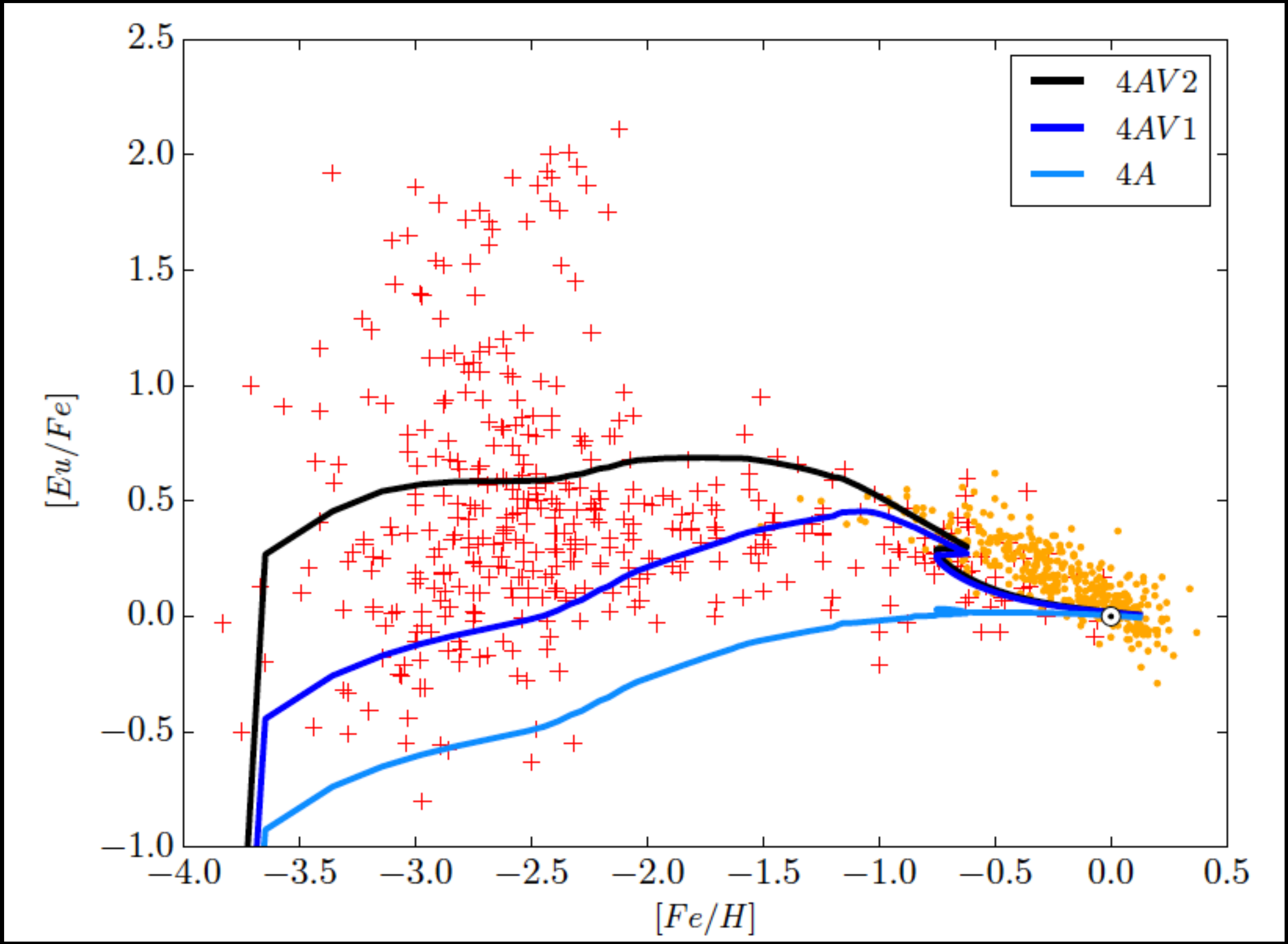
see also Cotè+19

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



Simonetti+19

Models with detailed DTD for NSM



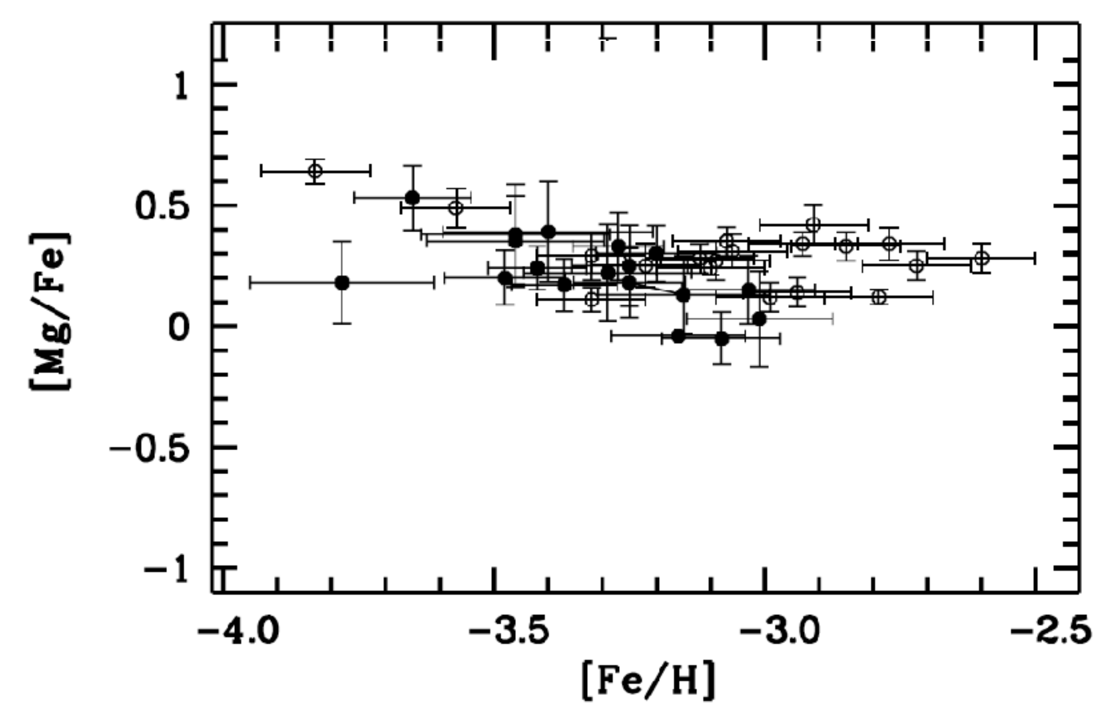
variation of alpha, possible solution!

see also Schoenrich&Weinberg19

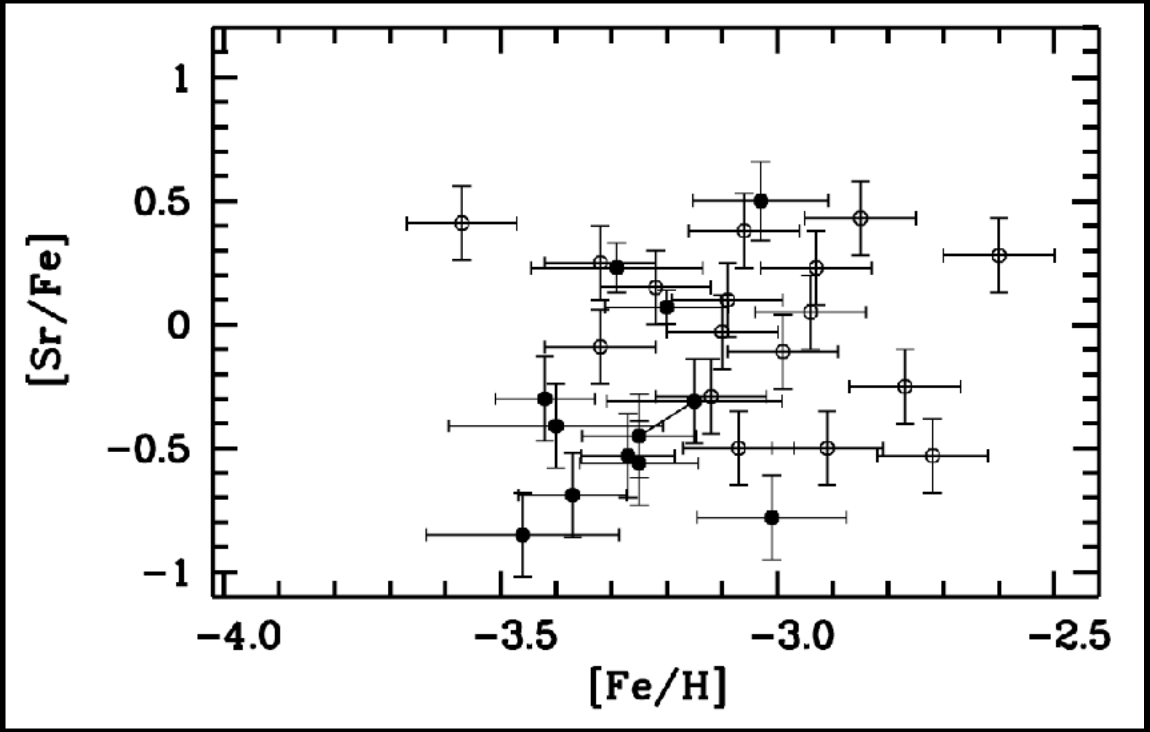
Simonetti+19

Spread in the neutron capture elements!

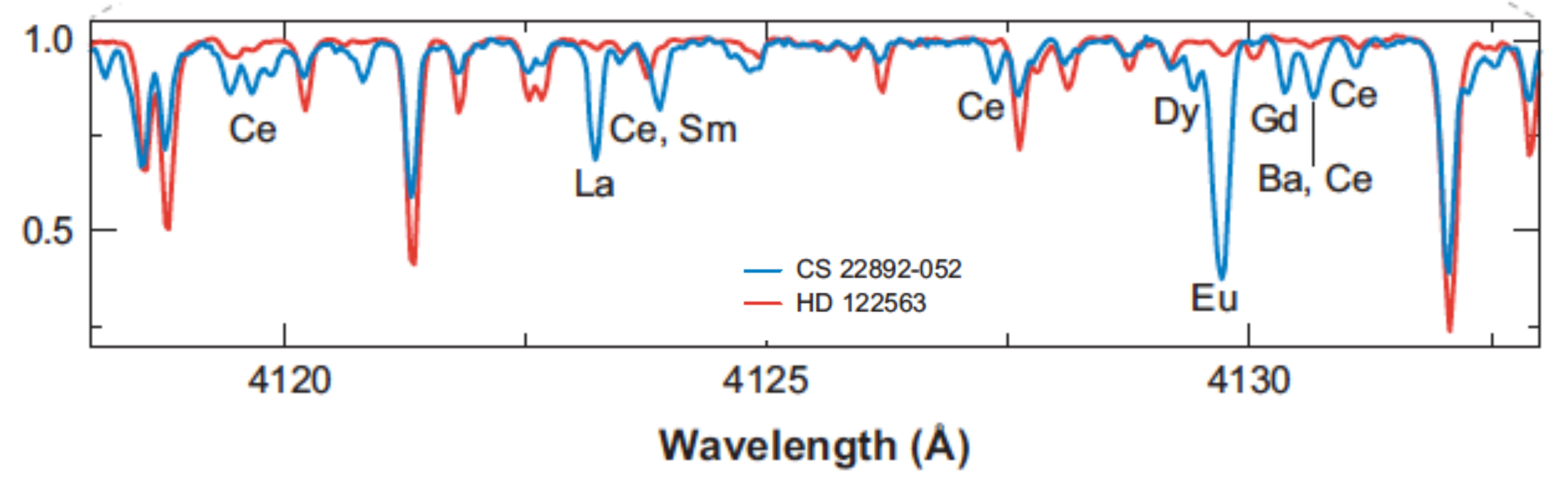
Mg: alpha-element



Sr: neutron capture element



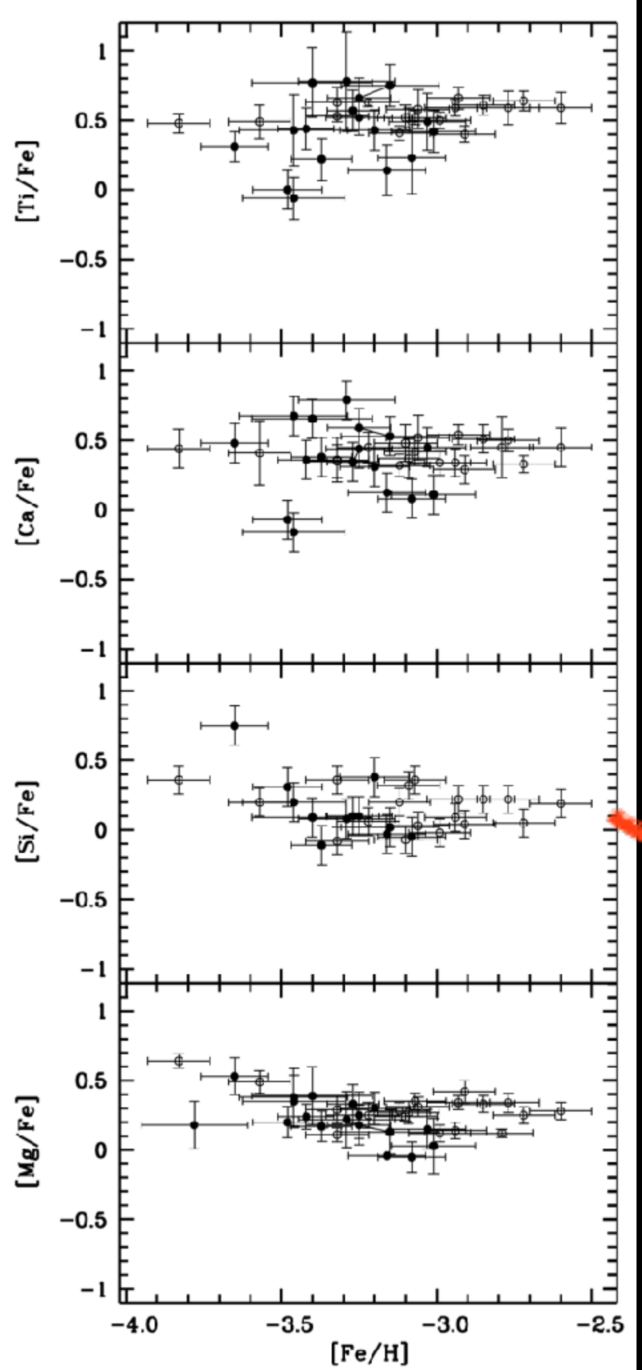
Bonifacio+12



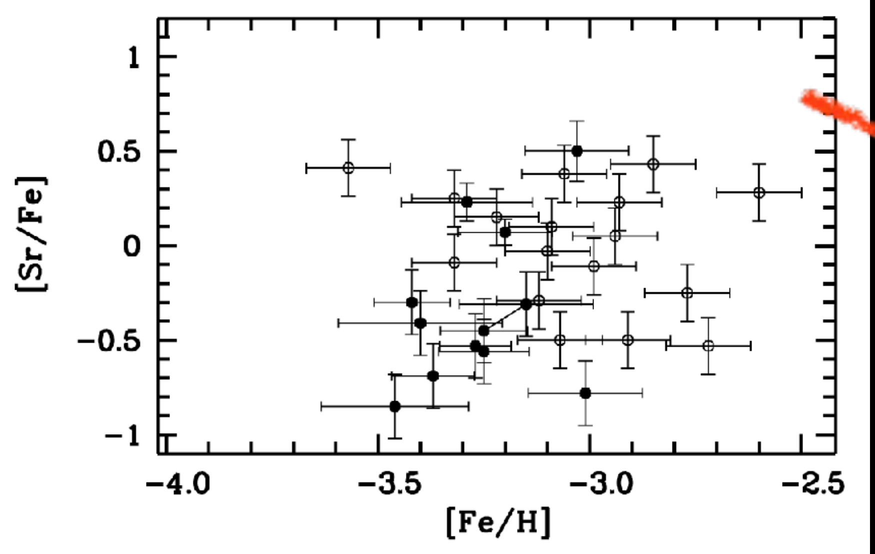
Sneden+08

Stochastic chemical evolution models

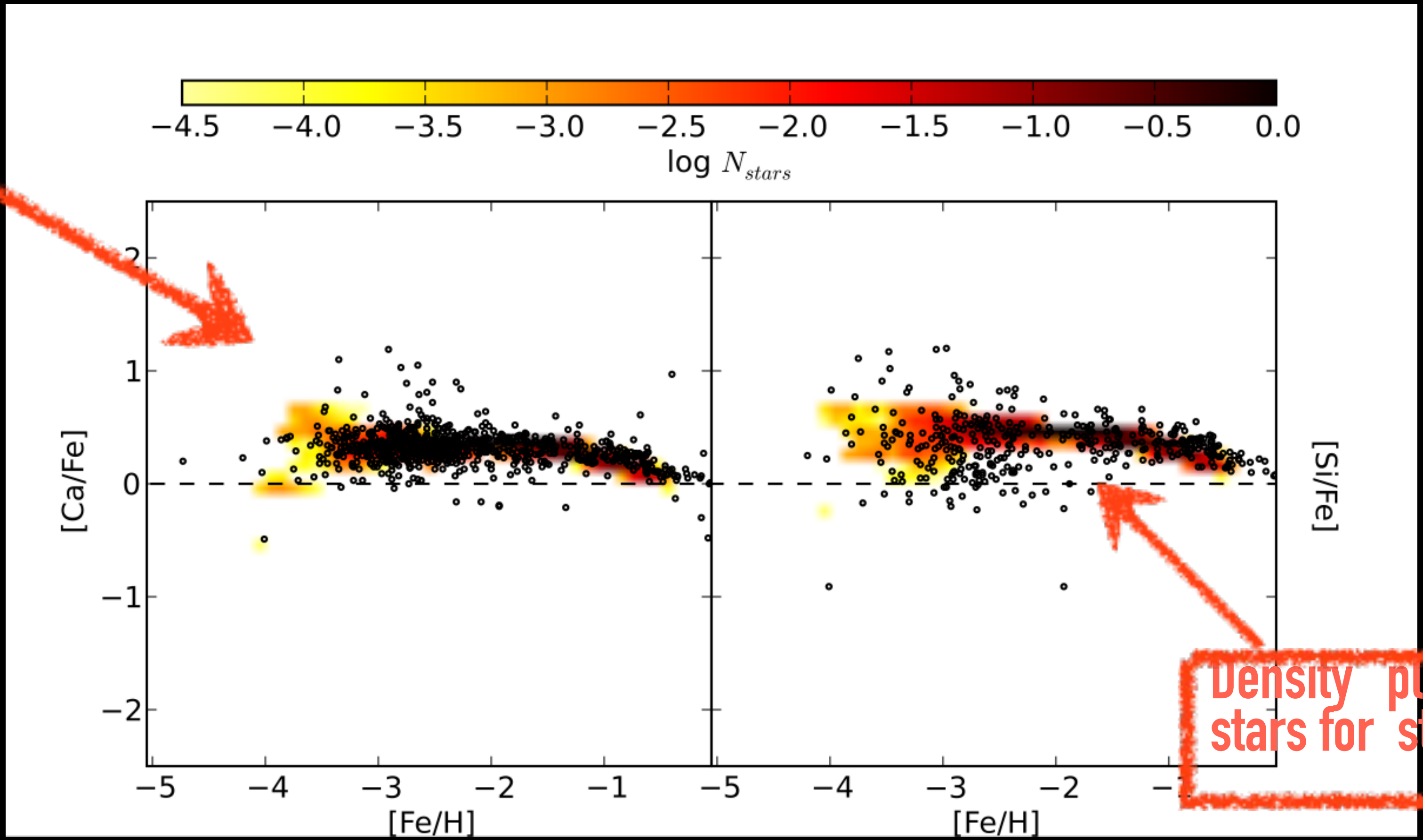
Problem:
Neutron capture elements present
a spread alpha elements do not



Bonifacio+12



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



Density plot of long living stars for stochastic model

Cescutti 2008
Cescutti et al. 2013

data collected in
Frebel 2010

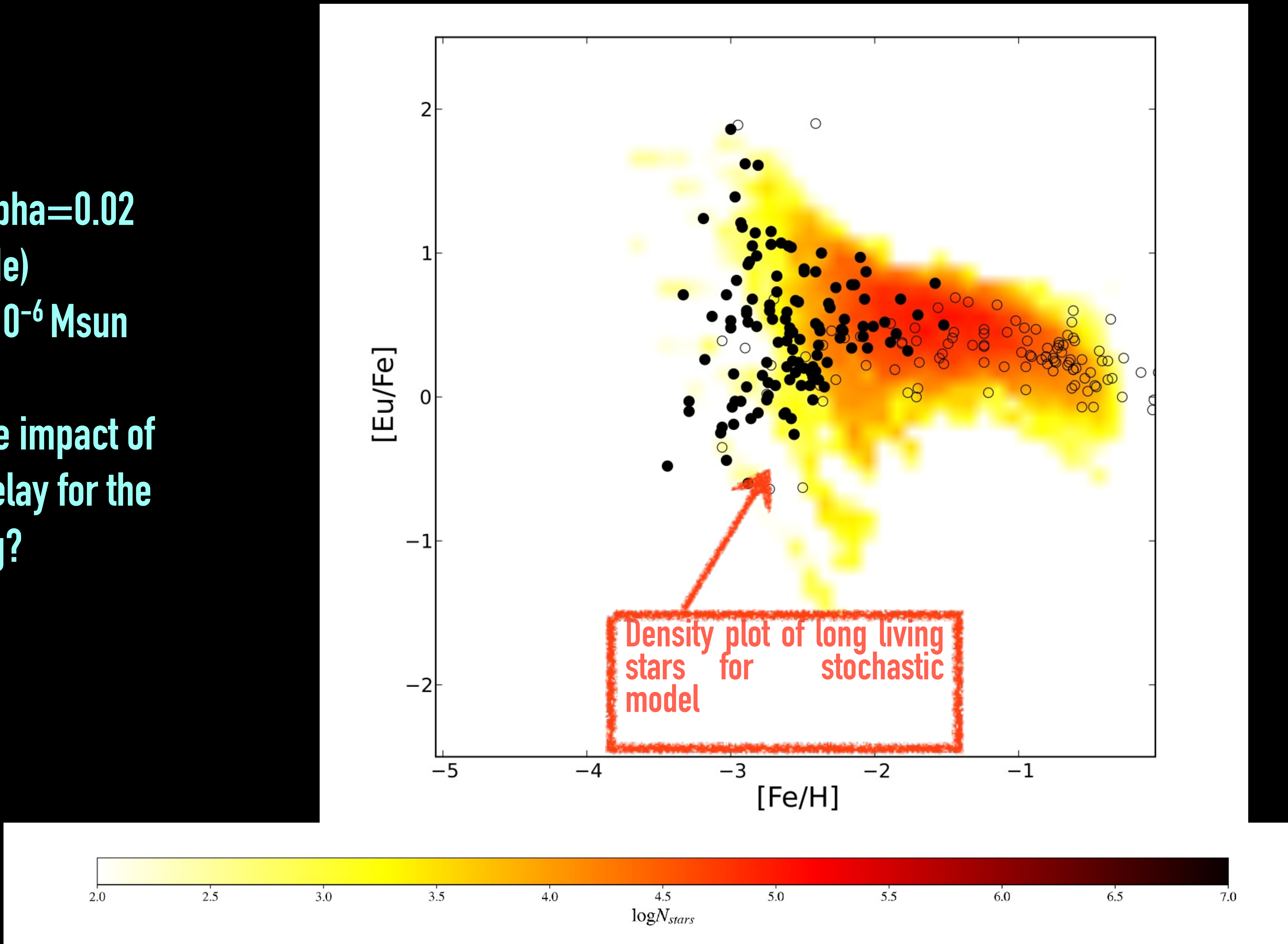
Neutron stars mergers

delay for the merging 1Myr

Cescutti,Romano,Matteucci,
Chiappini and Hirschi 2015

Results with alpha=0.02
(NSM/SNe)
Eu yields 5 10^{-6} Msun

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



Density plot of long living stars for stochastic model

Neutron star mergers

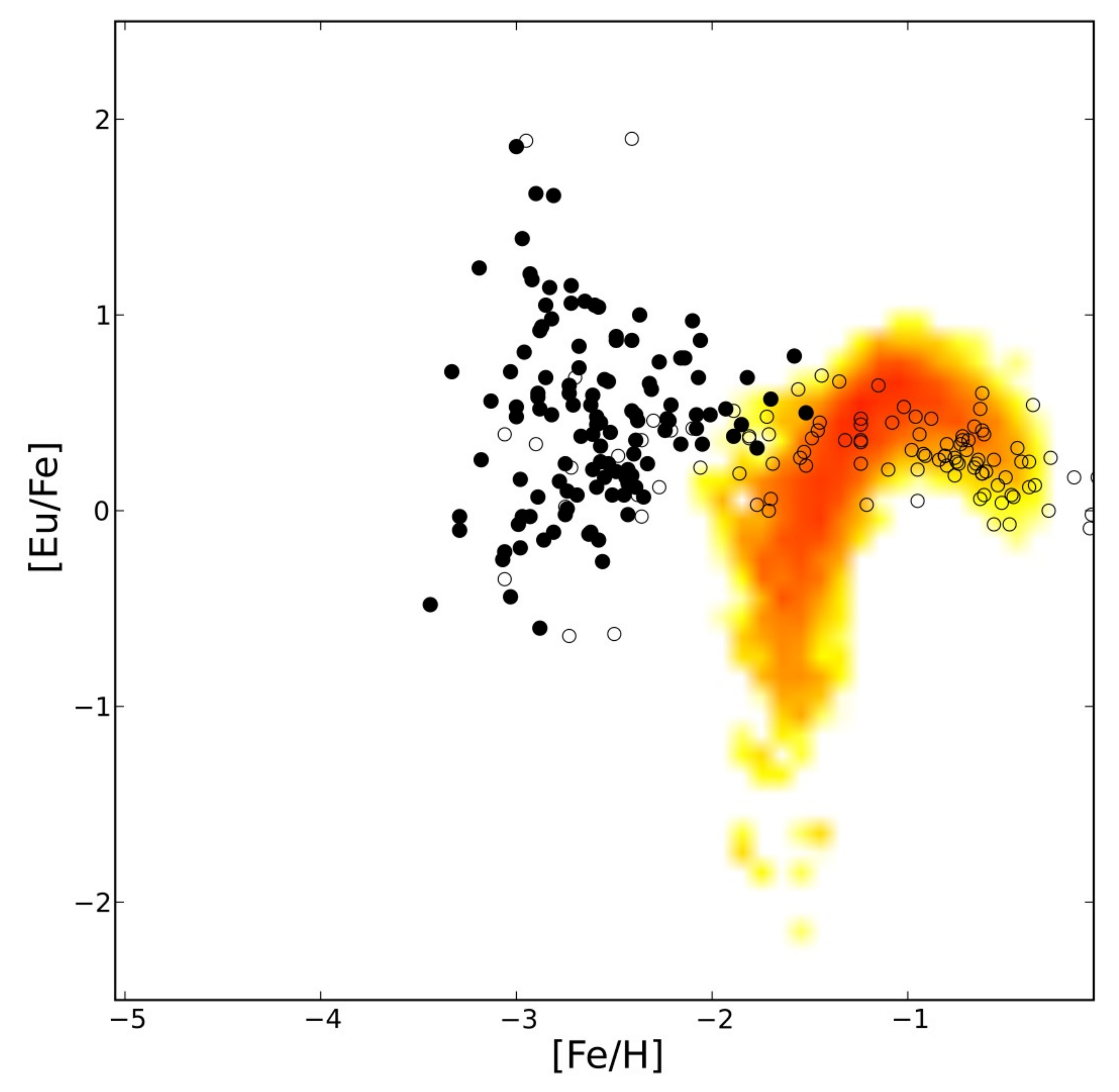
delay for the merging 100 Myr

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.

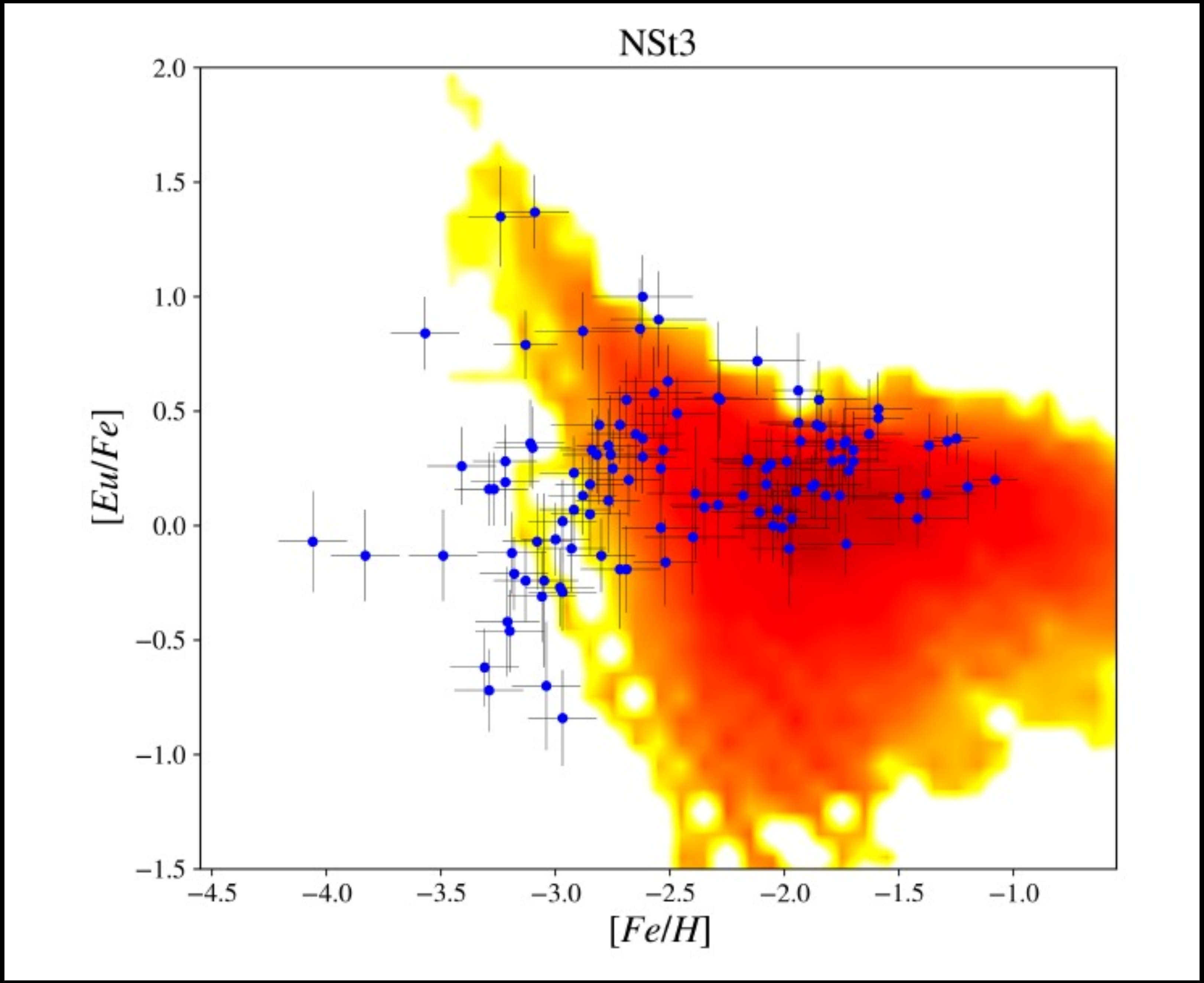
What about a distribution of delays?



This result has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the Shen+2014

Stochastic model

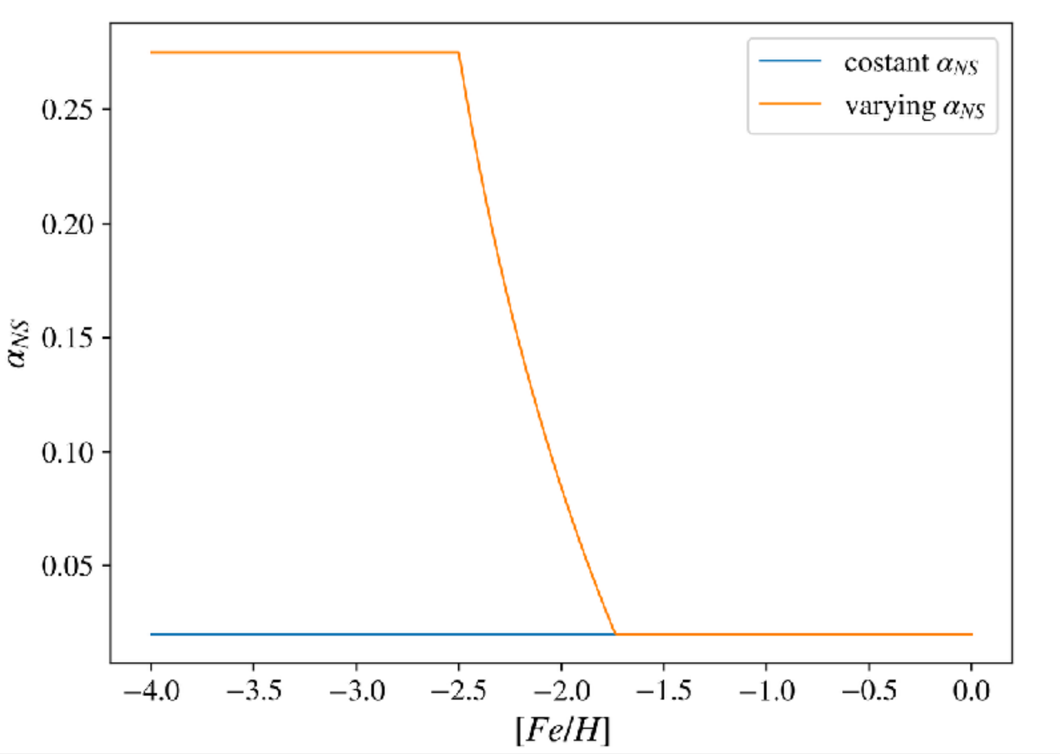
with a delay time distribution: $t^{-1.5}$



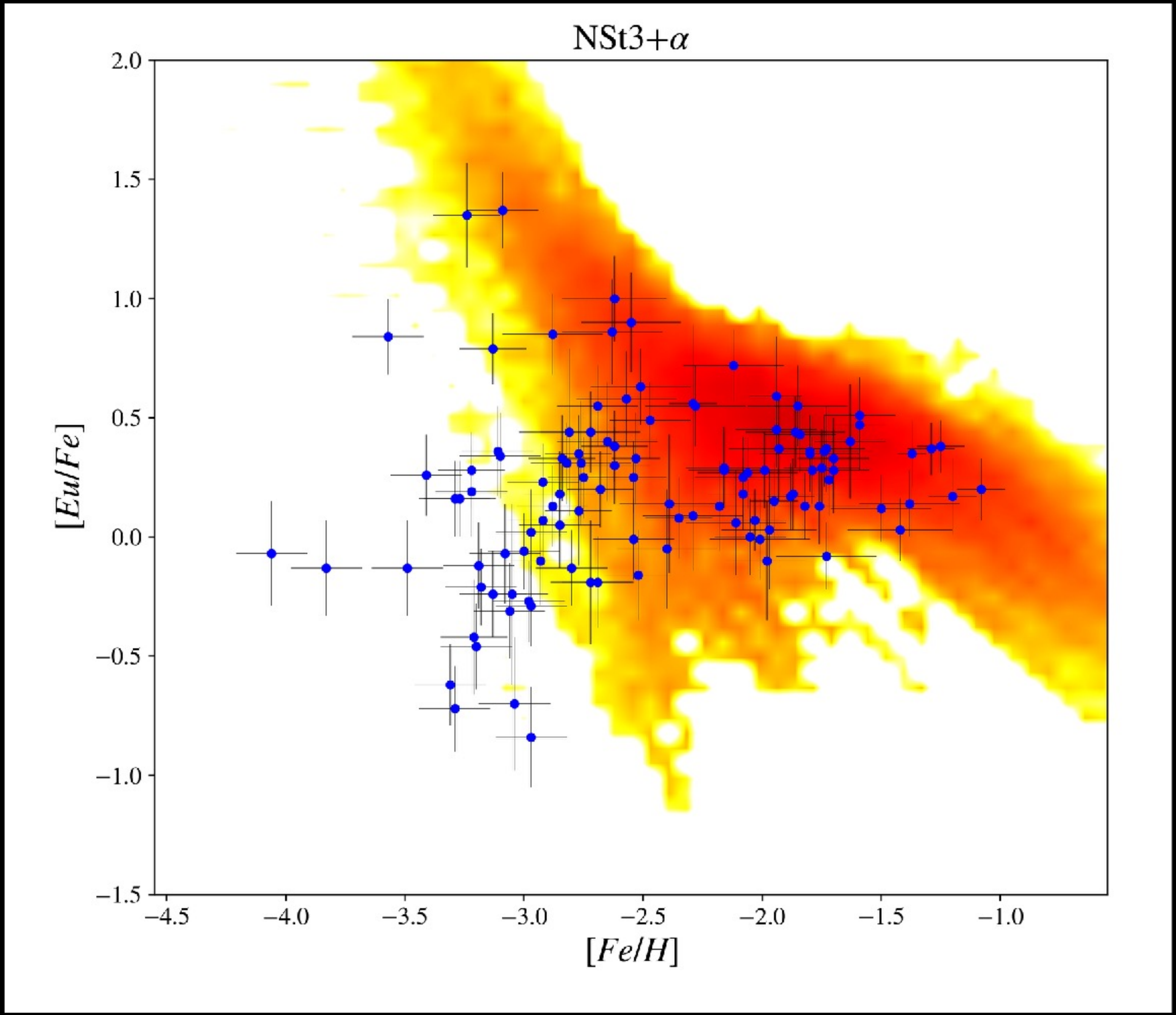
Cavallo+21

NSM with alpha variations

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



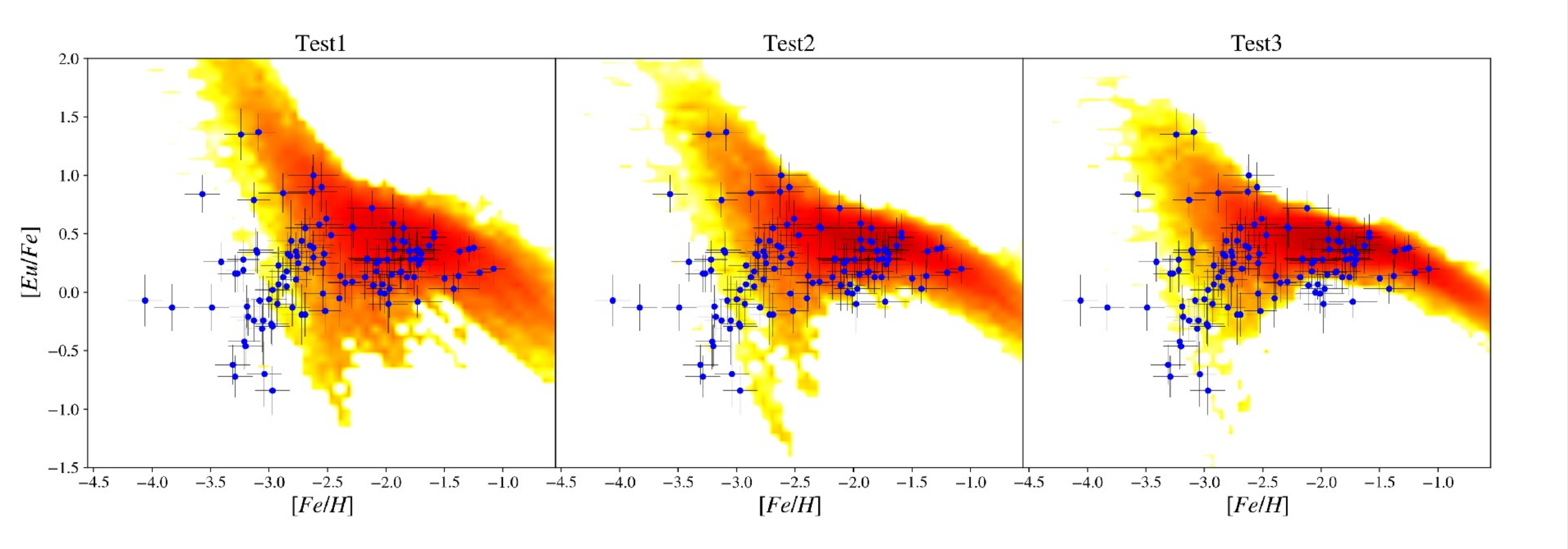
similar to Simonetti+19

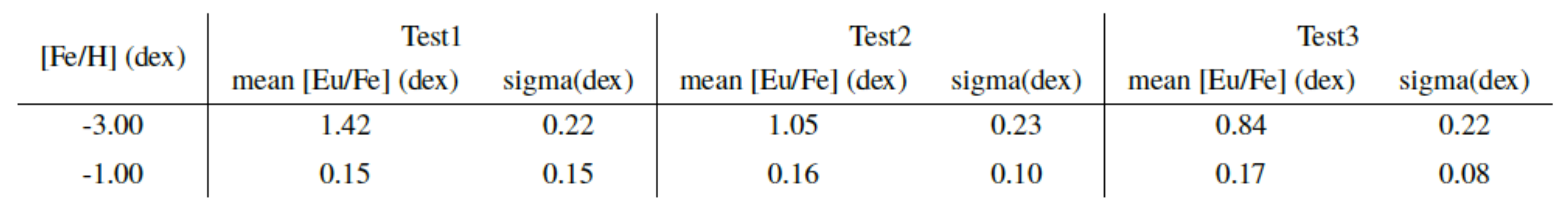


Cavallo+21

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

Weave and 4MOST !!

Other solutions?

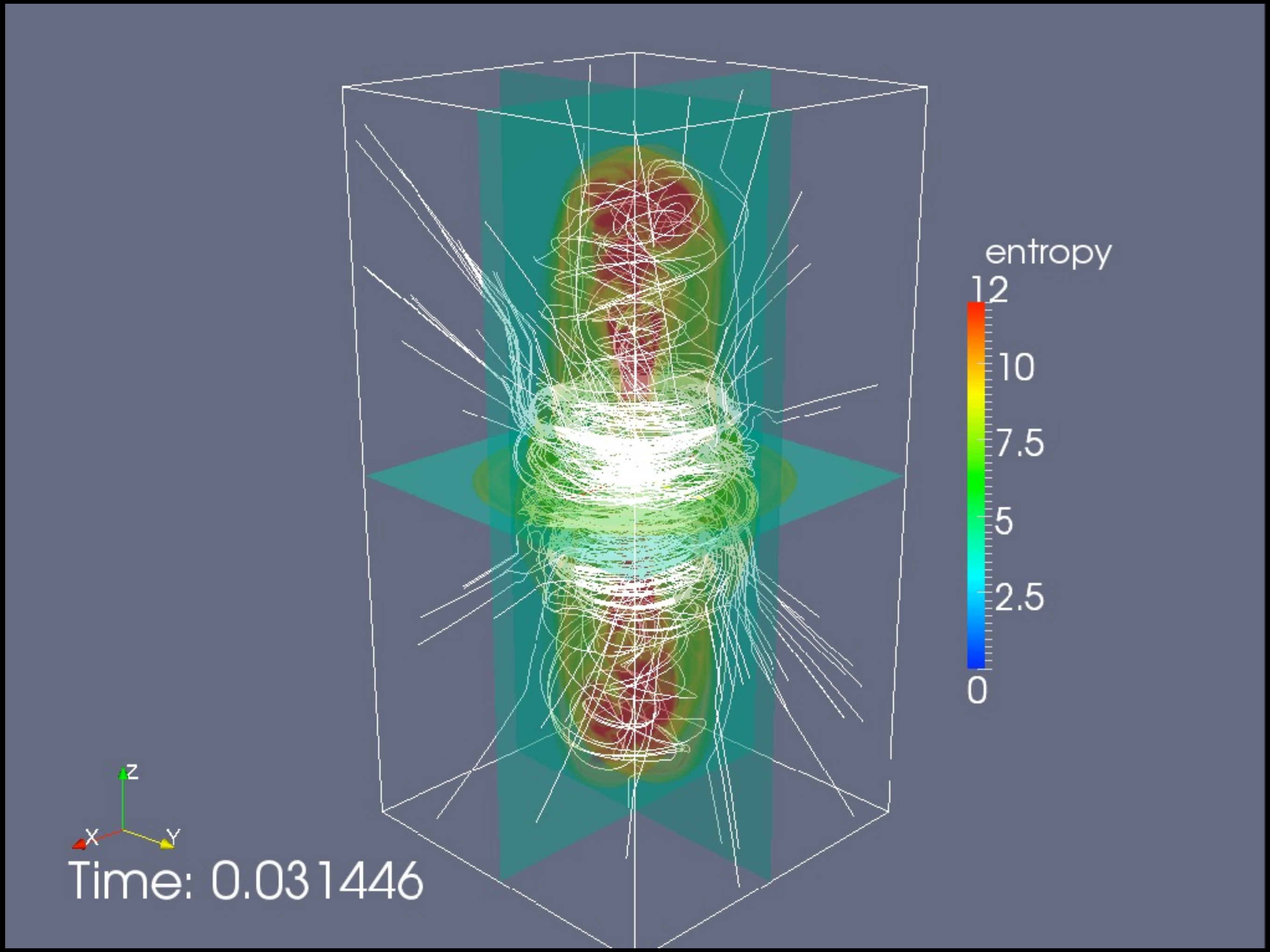
Magneto Rotationally Driven SN scenario (MRD)

(Winteler+12, Nishimura+15)

The progenitors of MRD SNe are believed to be rare and possibly connected to long GRBs.
Only a small percentage of the massive stars (~1-5%)

Our results use an higher value (10%), but this percentage is not well constrained, in particular for the early Universe.

Therefore in the stochastic model not all the massive stars produce neutron capture elements.

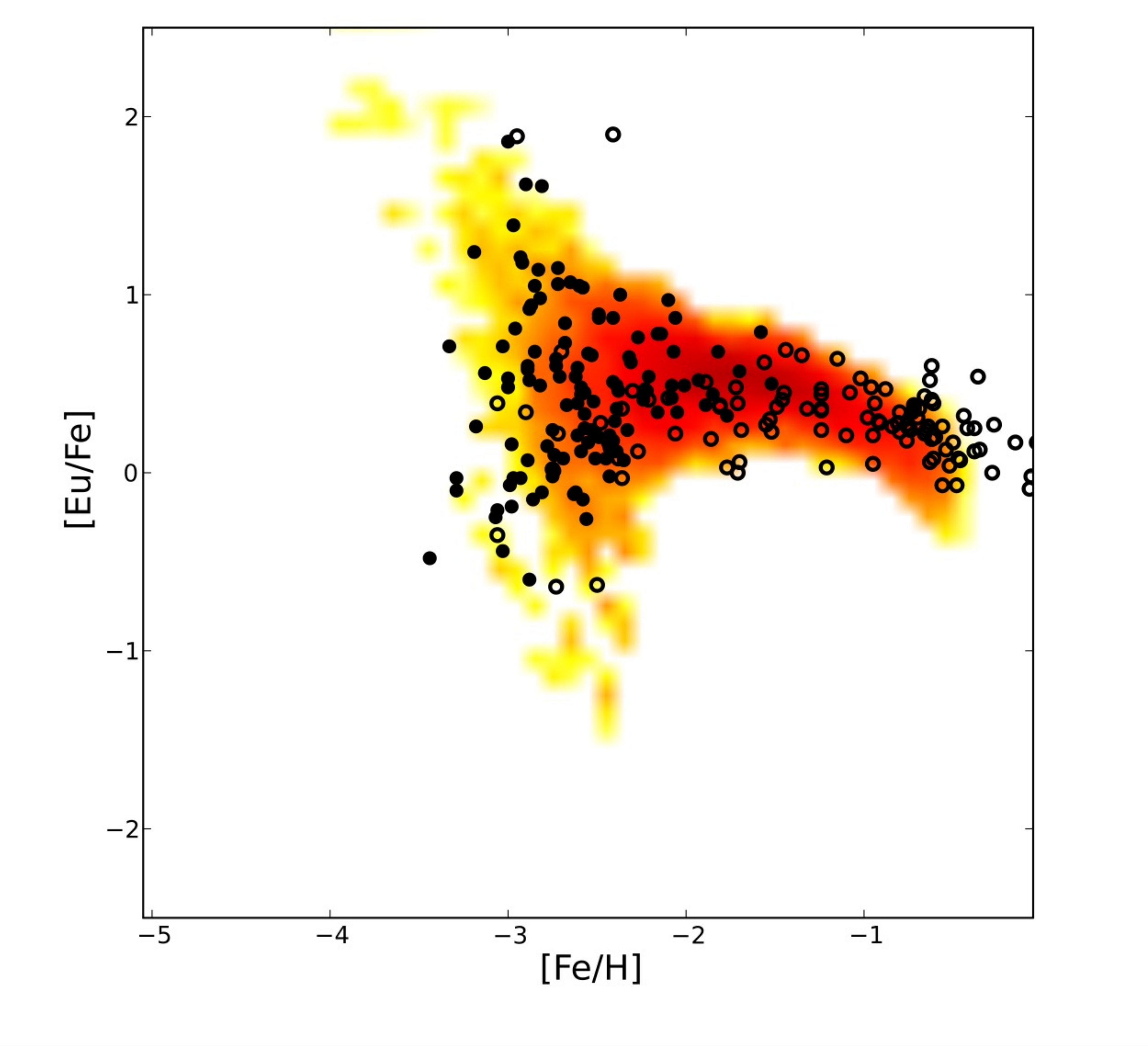


Magneto Rotationally Driven SN scenario (MRD) 10%

Cescutti+14

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

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



What about
other neutron capture elements?

Neutron capture elements

(~until 10 years ago)

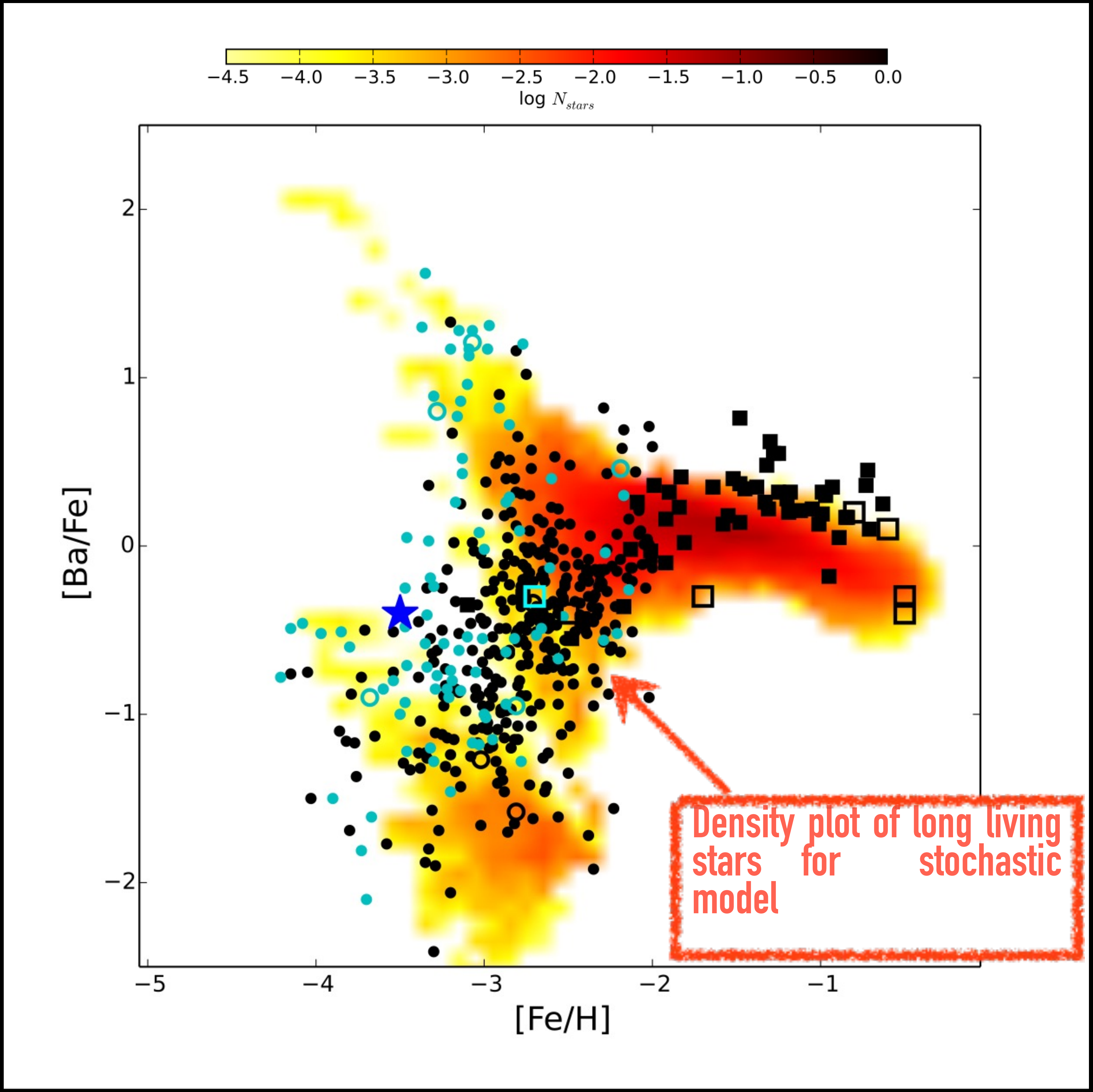
Early Galaxy

	s-process	r-process
site	Low-(intermediate) mass stars	NS mergers (& Massive stars?)
time scale	>300Myr	< 30Myr (excluding NS mergers)
yields	Cristallo+11 Karakas+12	....

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



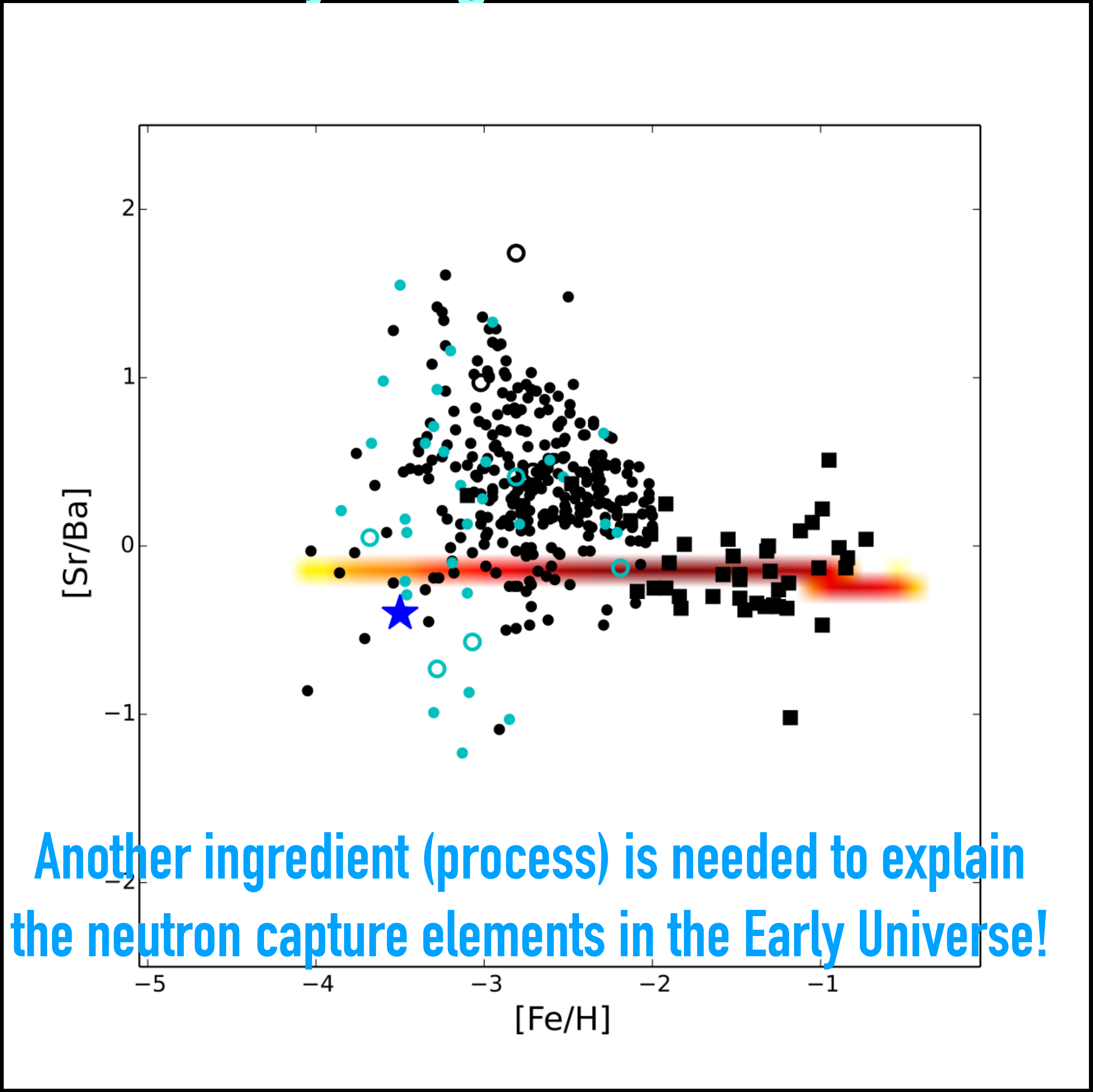
Density plot of long living stars for stochastic model

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)



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

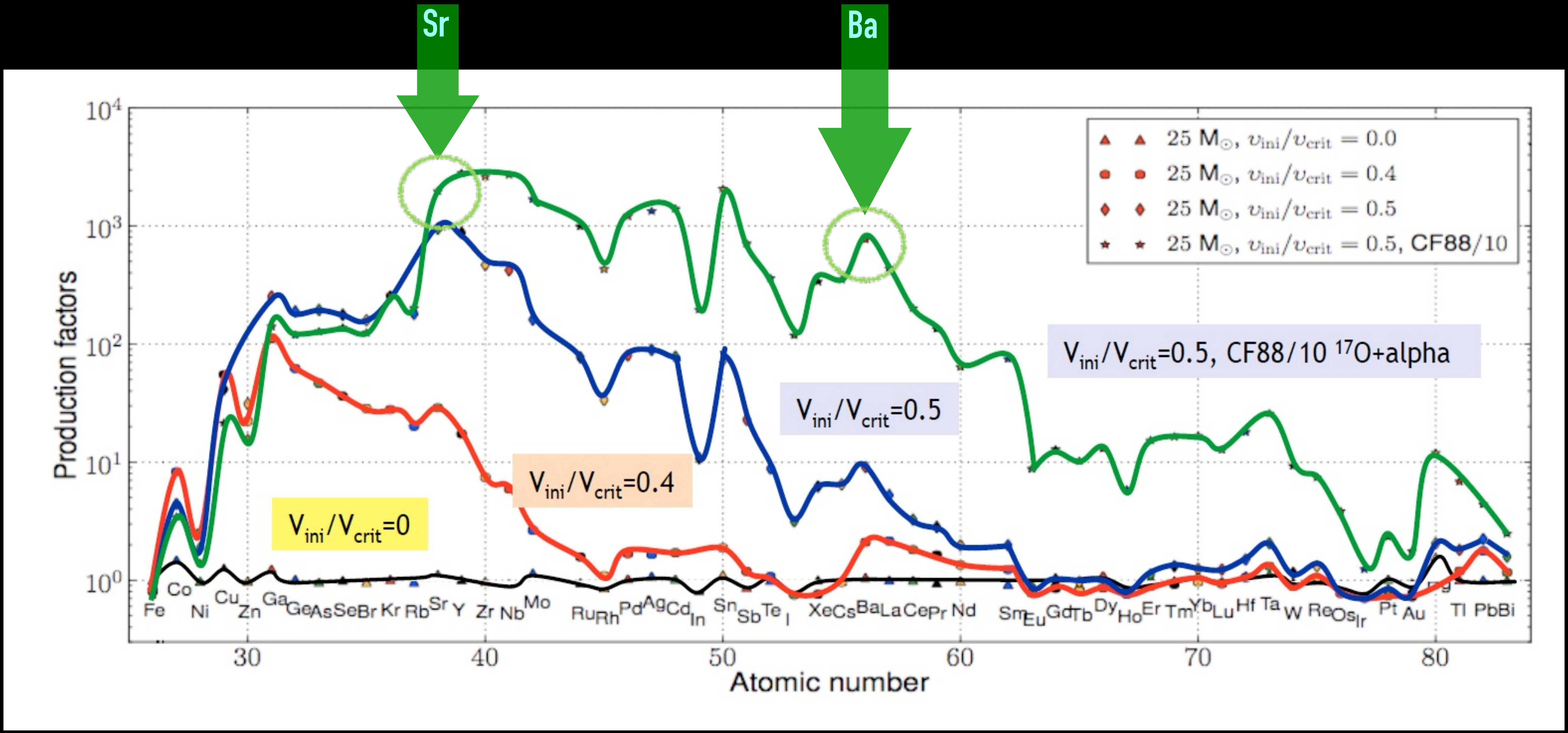
It is impossible to
reproduce the data,
assuming only the
r-process component,
enriching at low
metallicity.
(see Sneden+ 03,
François+07,
Montes+07)

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

Low metallicity and rotating massive stars

Frischknecht et al. 2016 (See also Limongi and Chieffi 2018)

Rotating massive stars can contribute to s-process elements!



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

Neutron capture elements

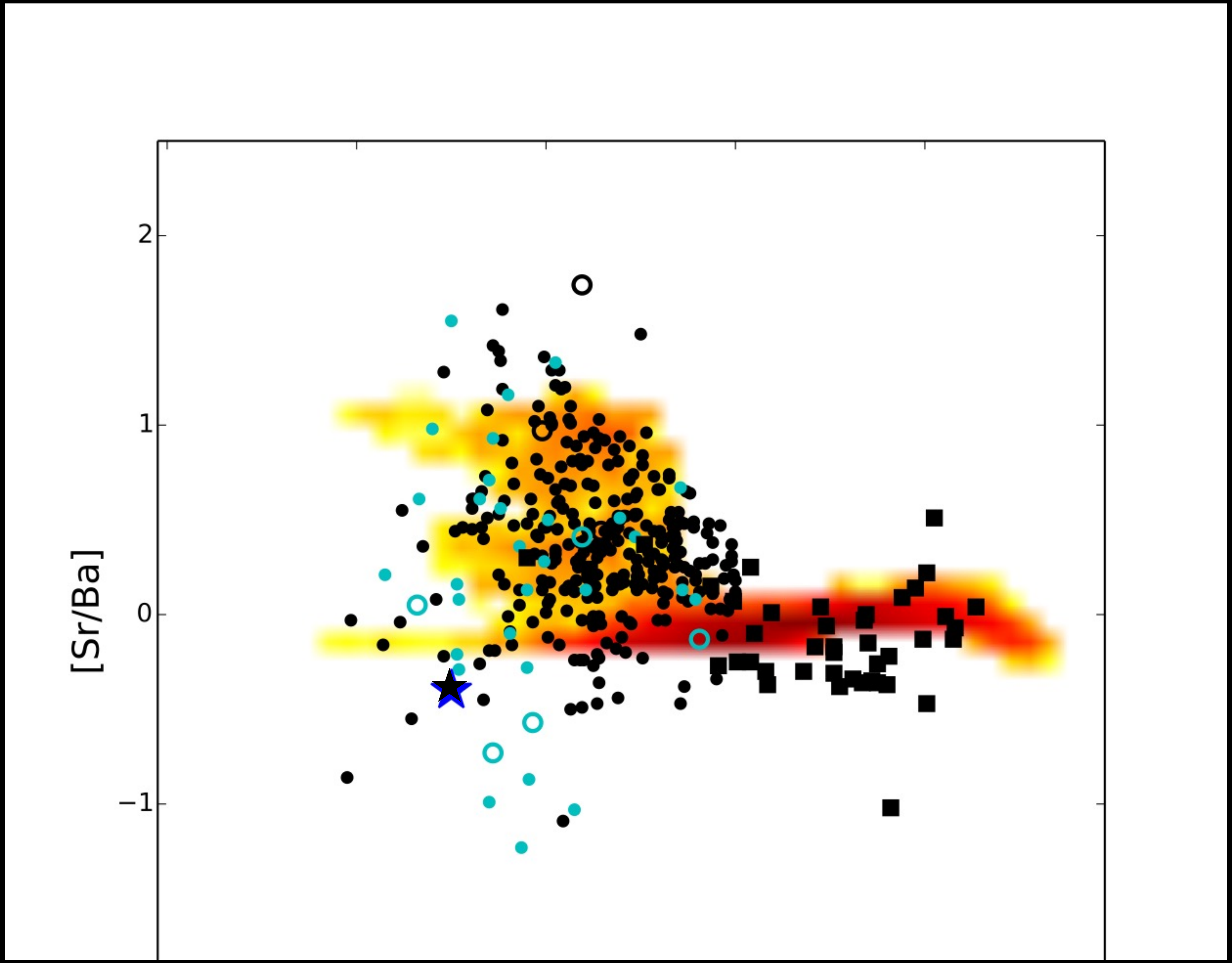
Early Galaxy

	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)

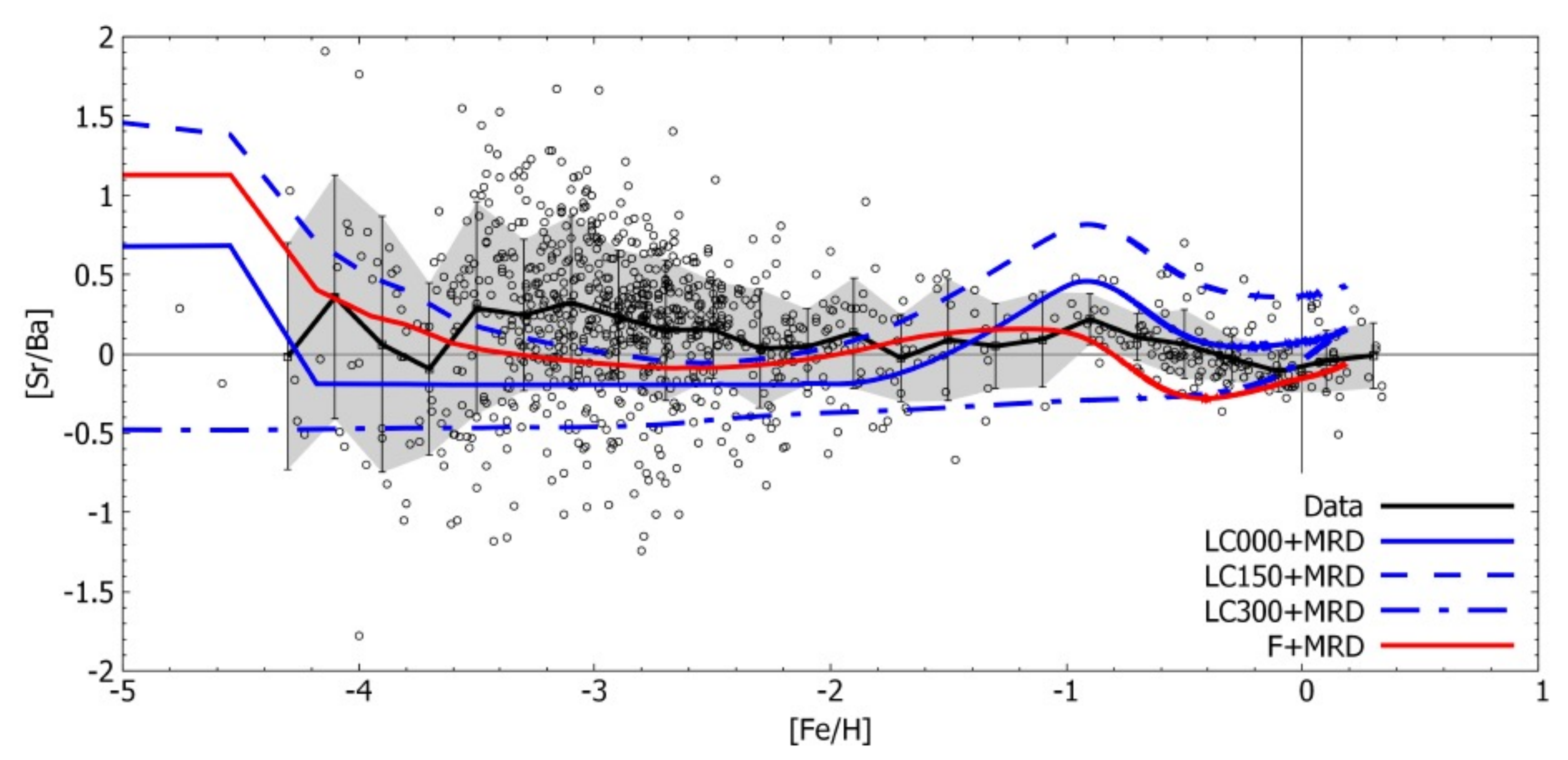


A s-process (from rotating massive stars)
and an r-process (from rare events)
can reproduce the neutron capture elements in the Early Universe

Confirmed in Rizzuti et al. (2019)

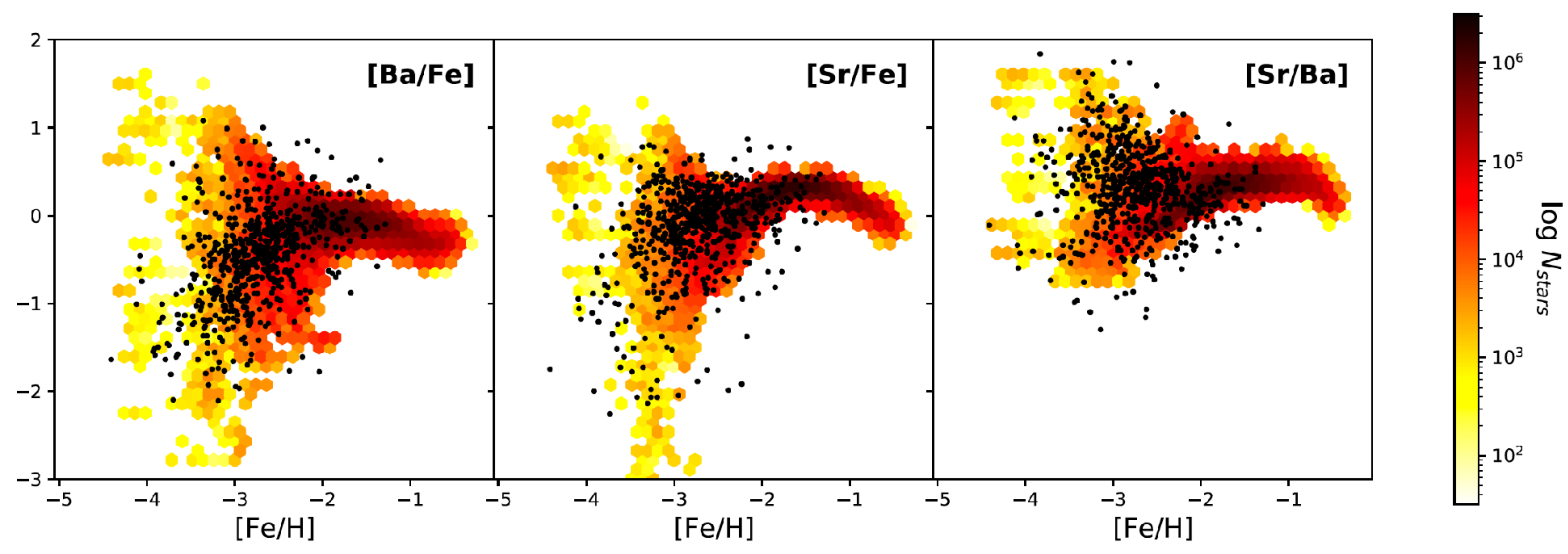
adopting Limongi&Chieffi18

see also Prantzos et al. 2018!

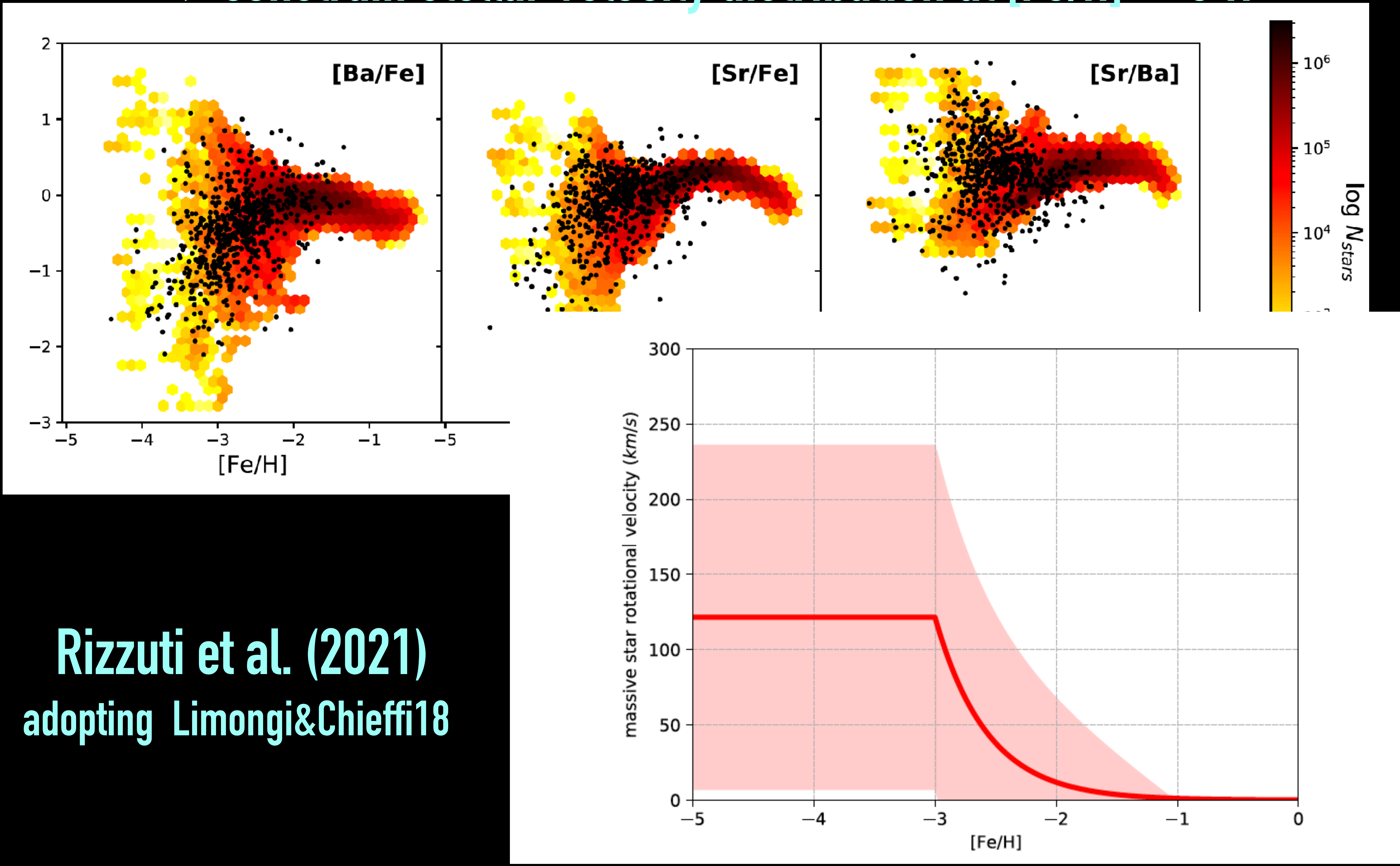


Rizzuti et al. (2021)

adopting Limongi&Chieffi18



Data+stochastic modelling
—>constrain stellar velocity distribution at [Fe/H]~−3 !!



Rizzuti et al. (2021)

adopting Limongi&Chieffi18

Conclusions

Chemical evolution models have shown that 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 or Collapsar** 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.