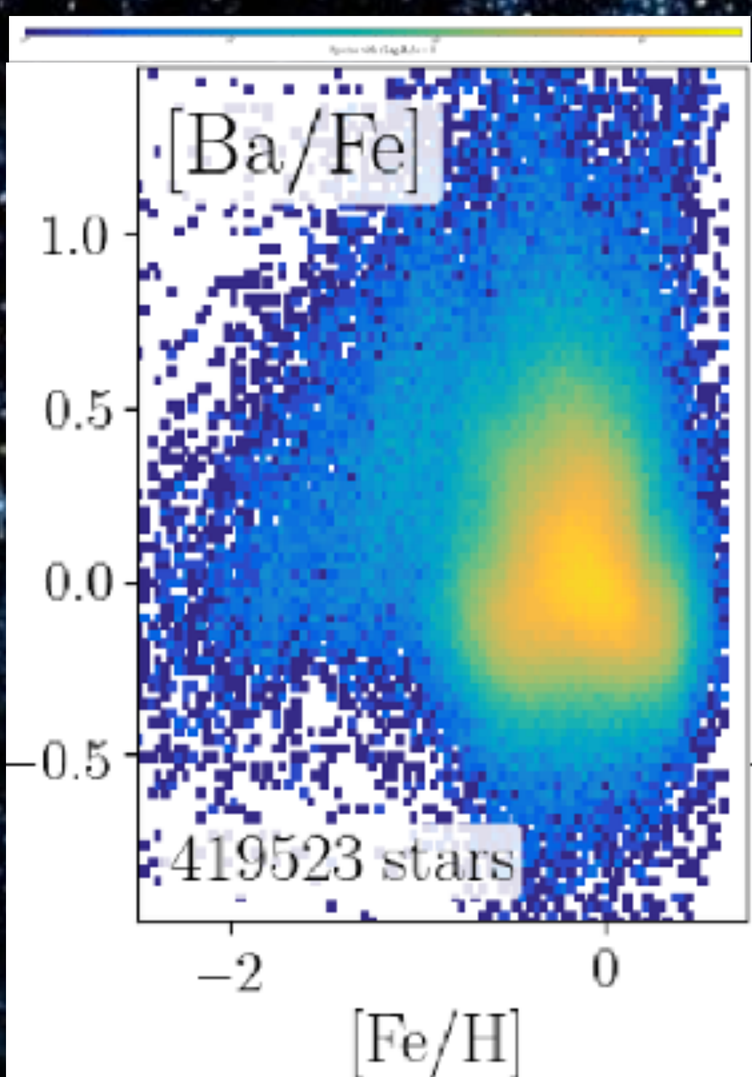
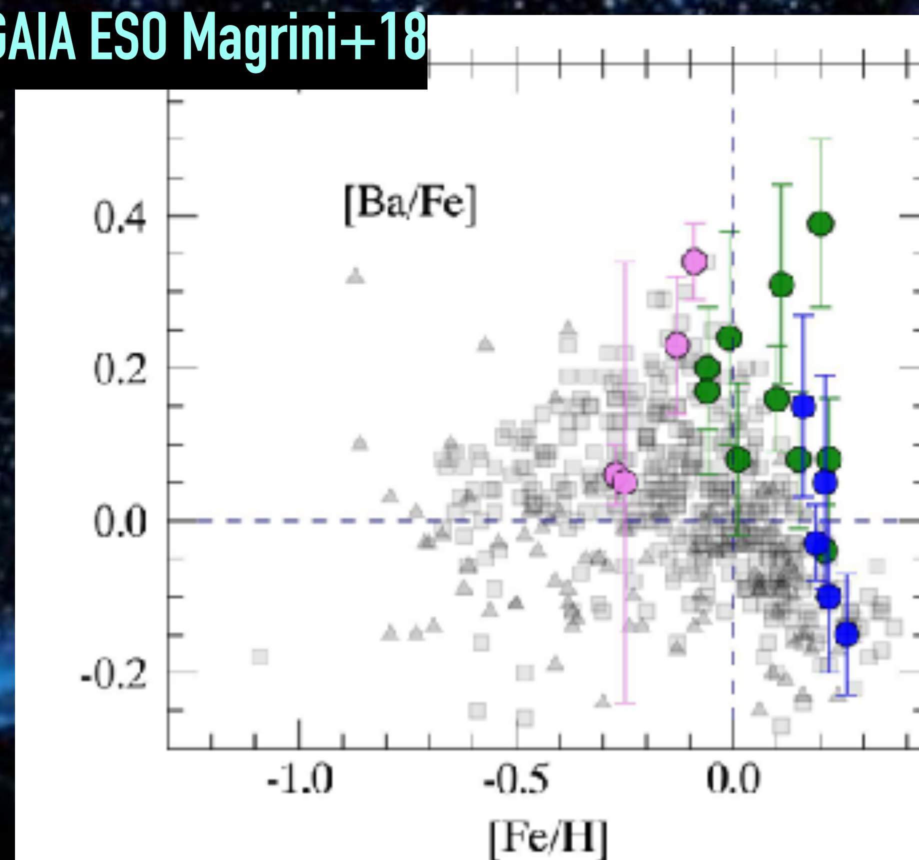
# Recent advances in
# Chemical evolution models
# (for neutron capture elements)

# Chemical abundances in stars

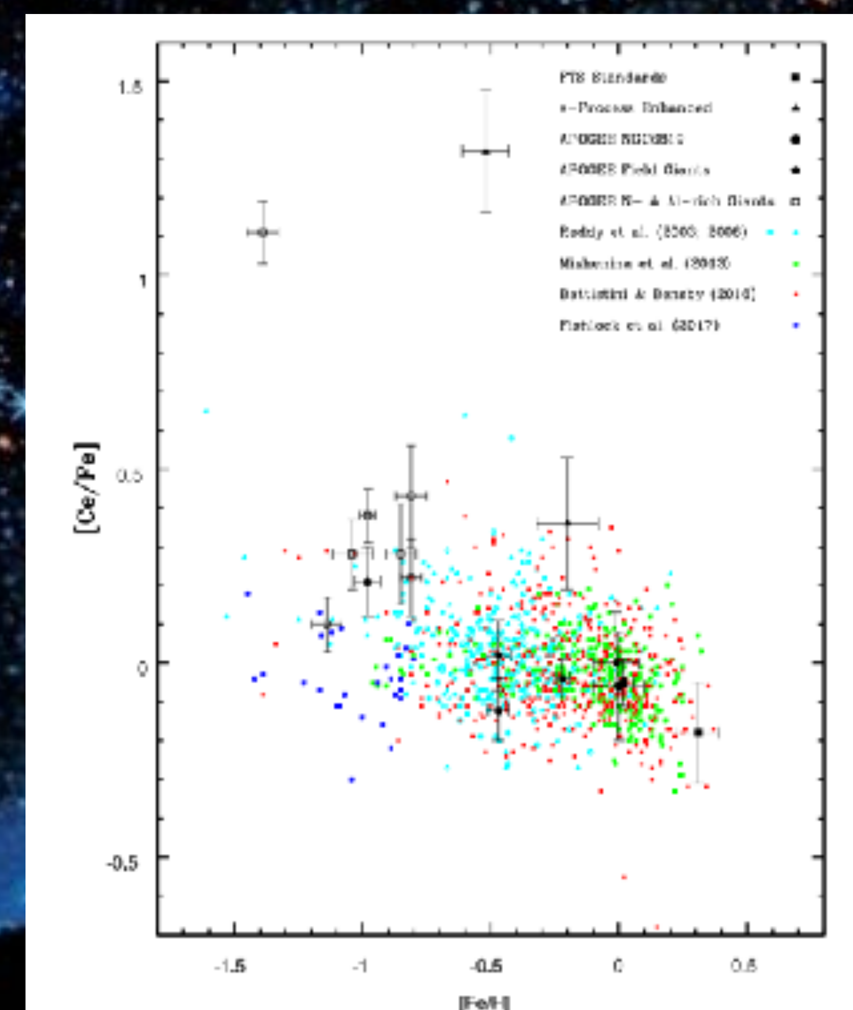
Galah Buder+21




GAIA ESO Magrini+18



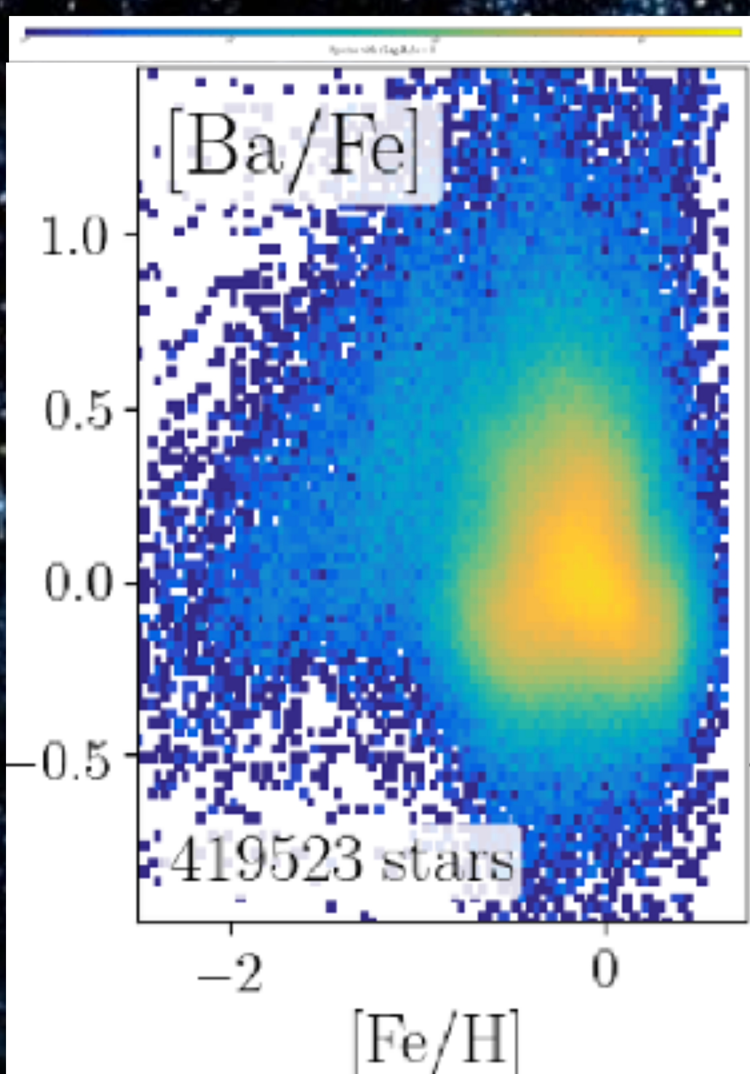

Apogee Cunha+18



# Chemical abundances in stars

Terrific impact for Galactic science!

Galah Buder+21

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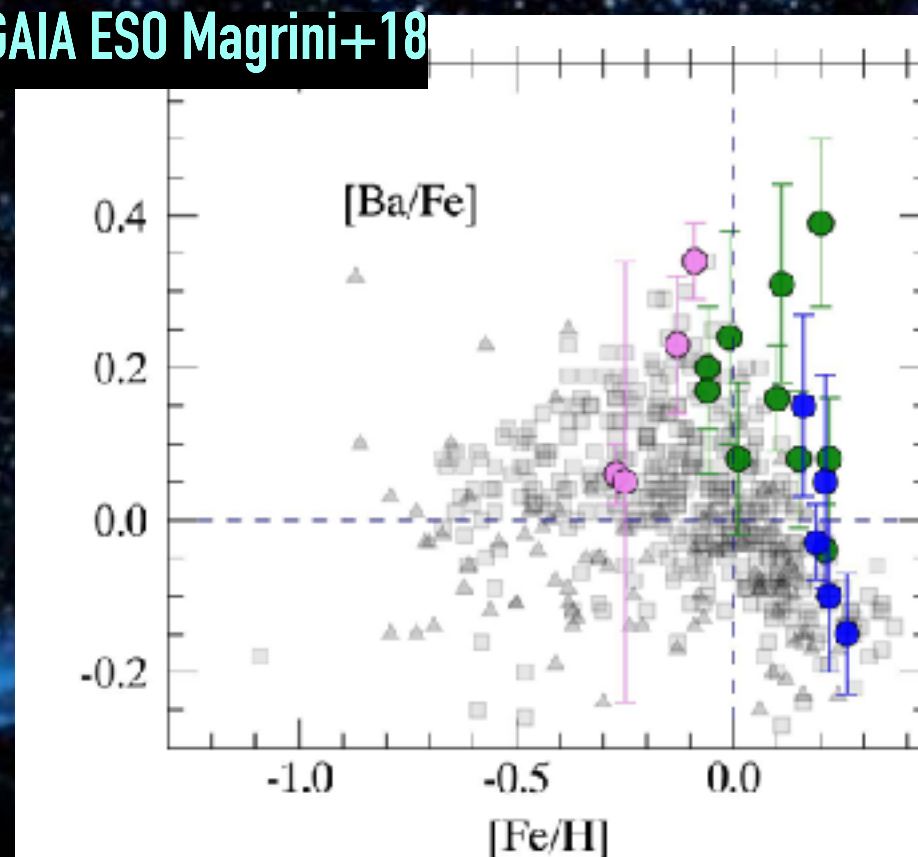


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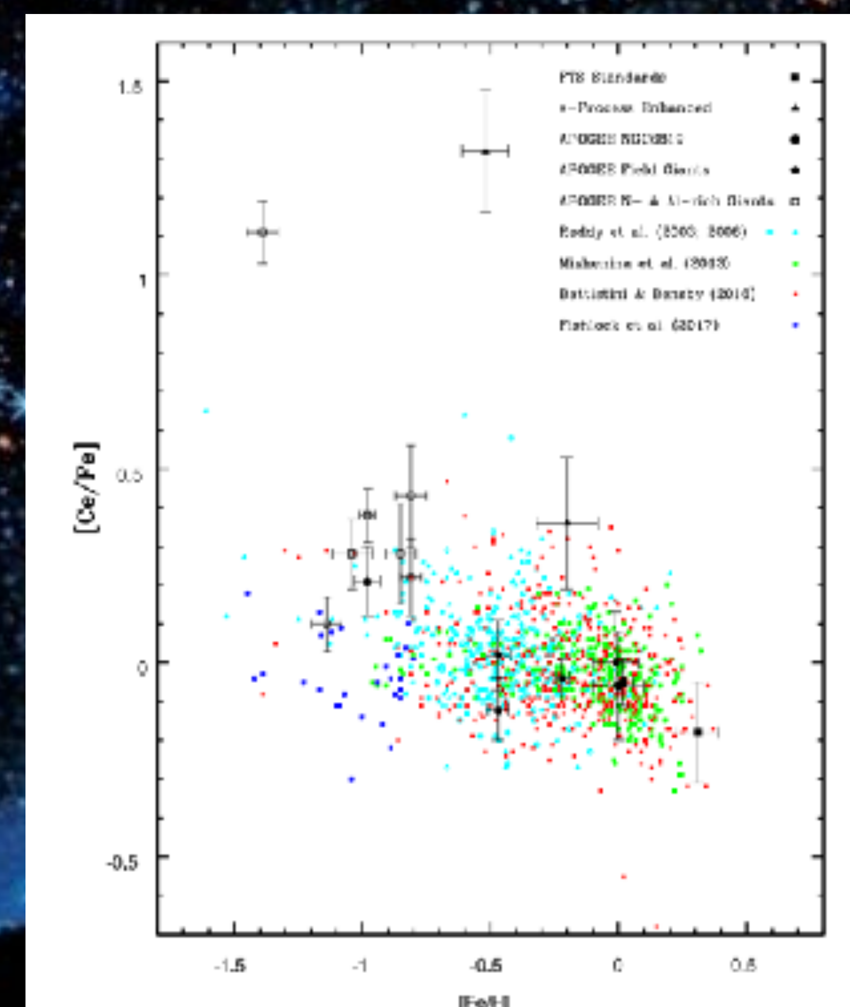

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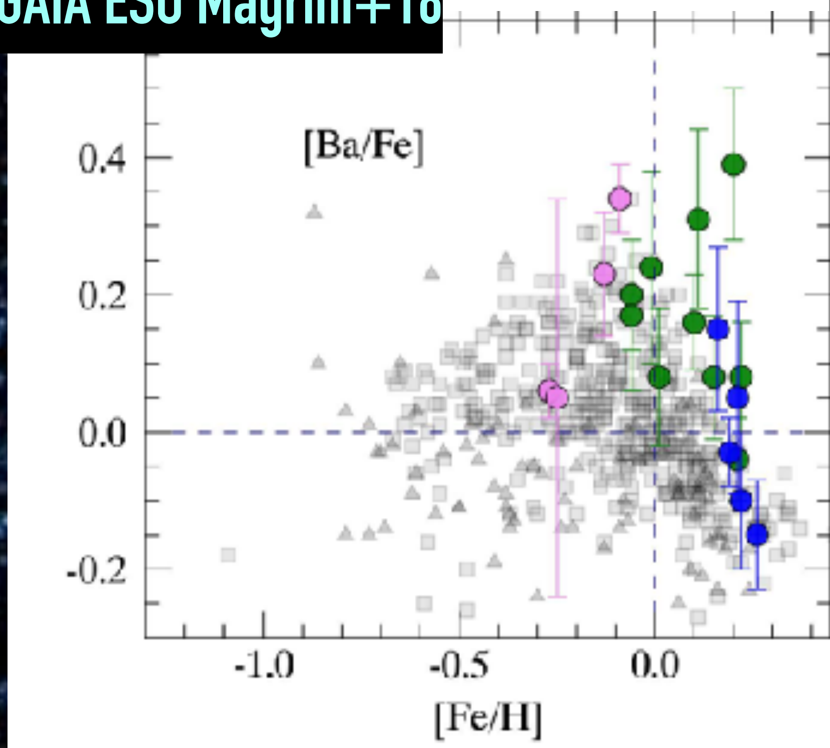
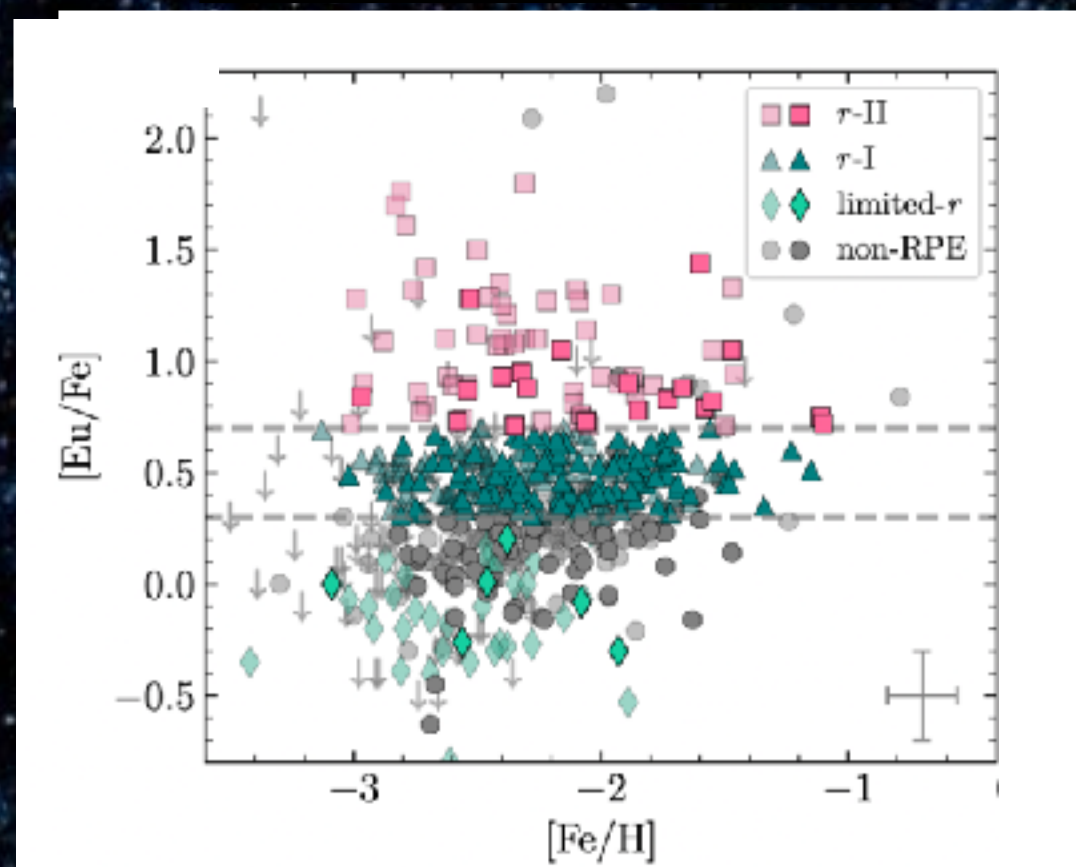
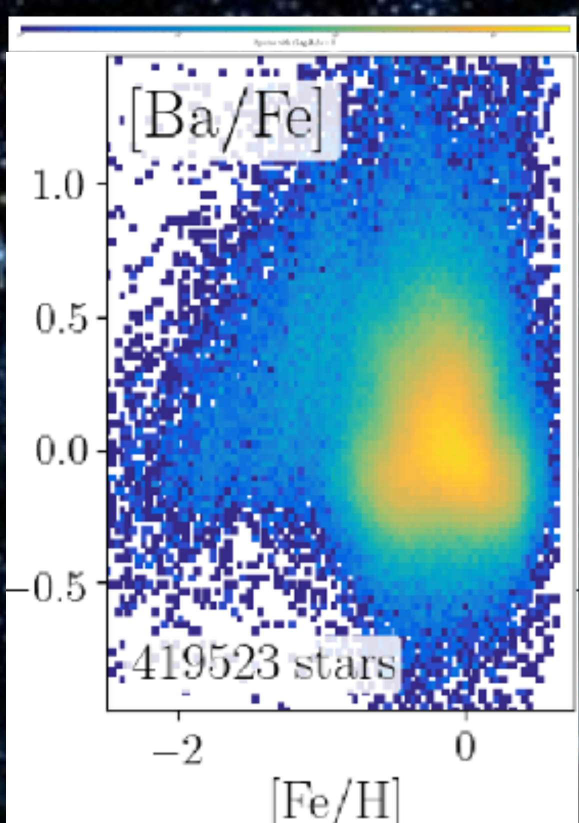
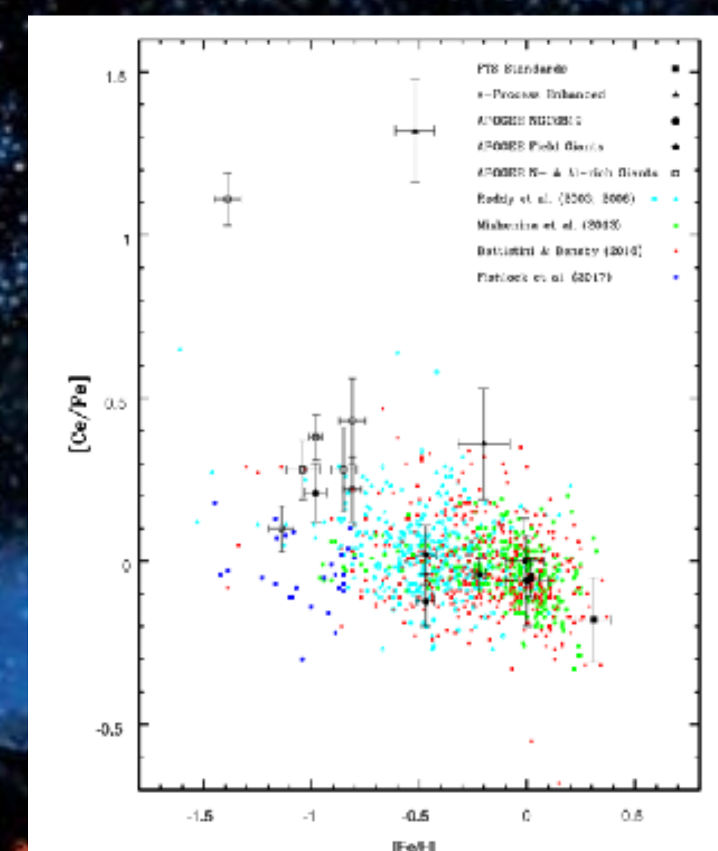



R-process alliance Holmbeck+20




Galah Buder+21




Apogee Cunha+18

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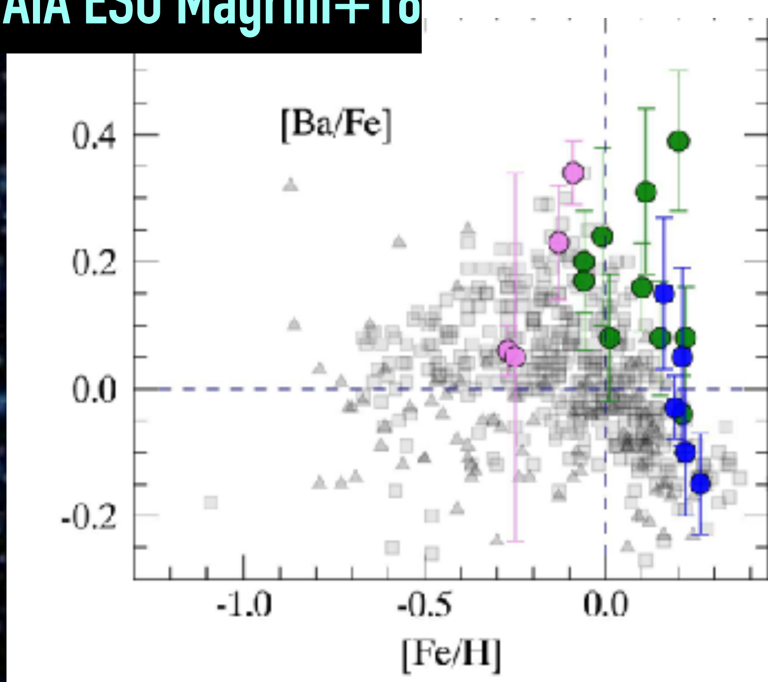


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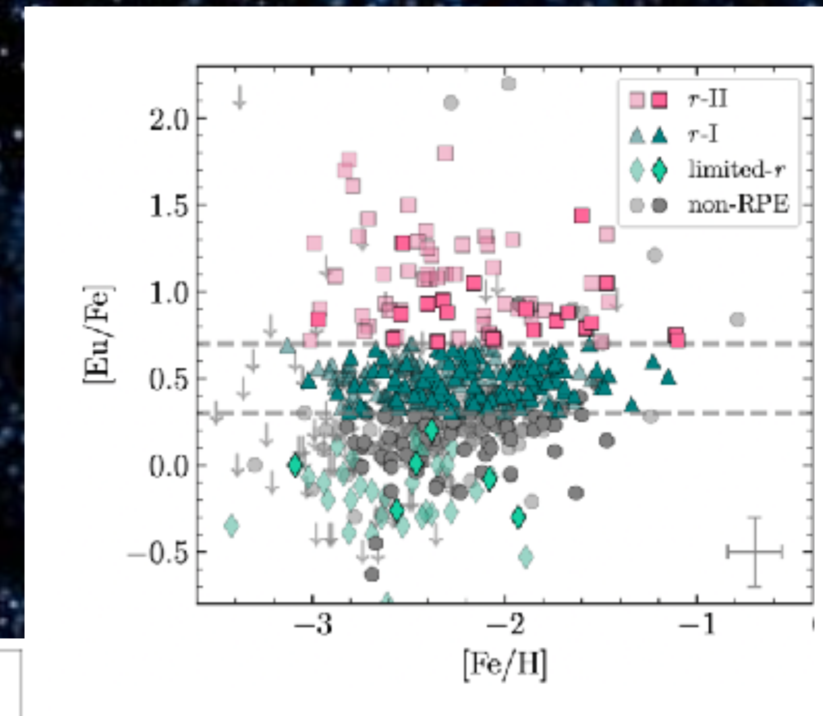
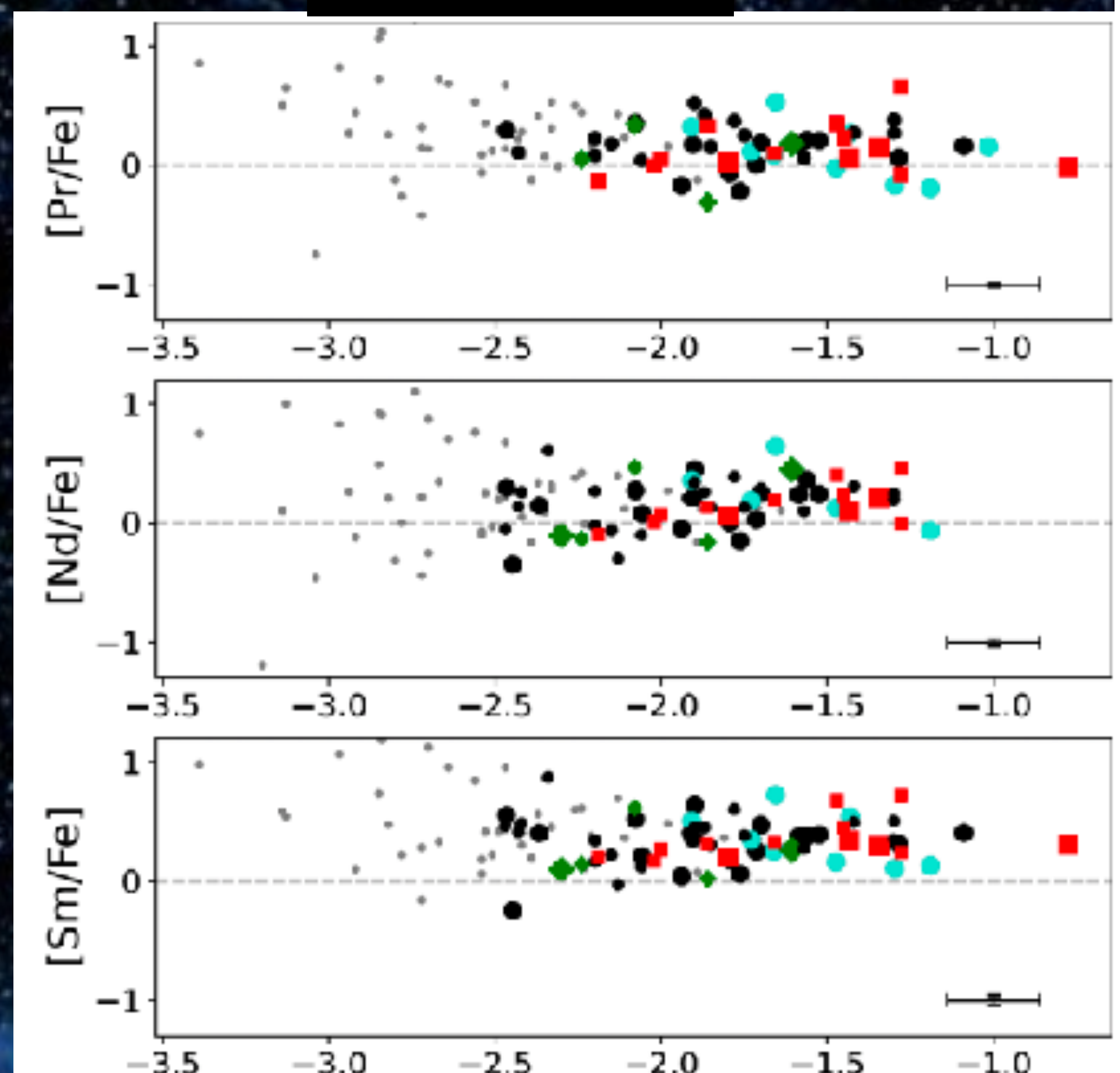
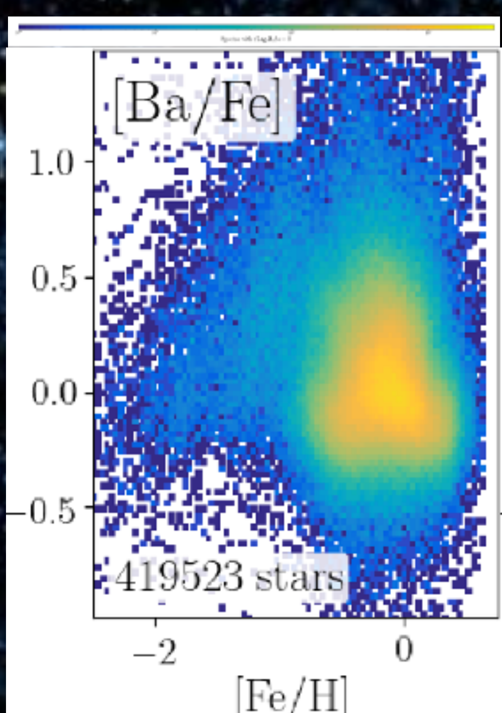



MINCE Lucertini+25

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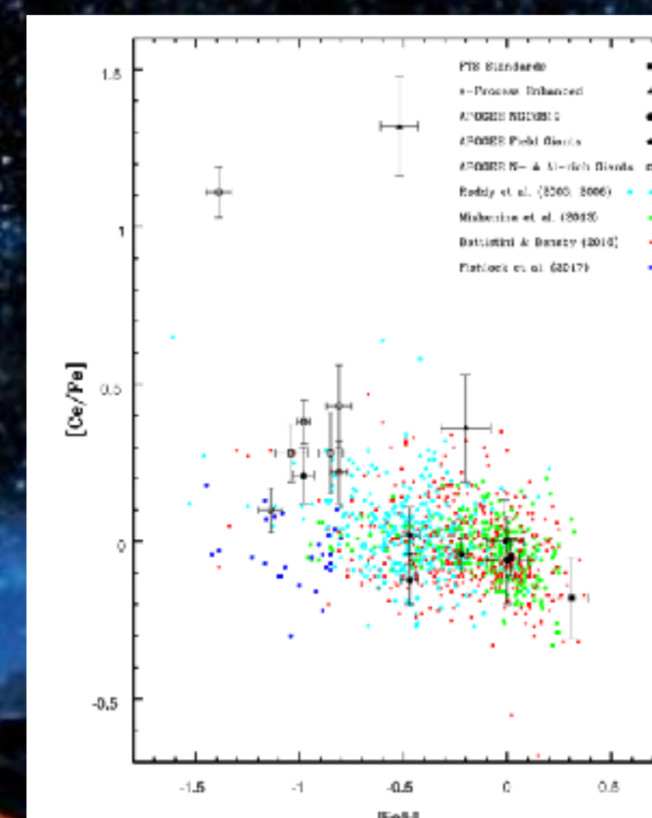


Apogee Cunha+18

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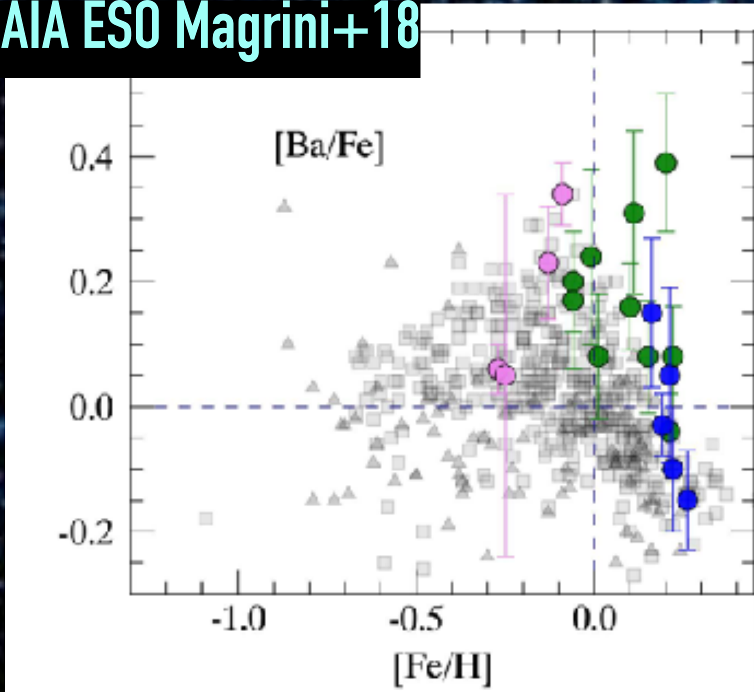
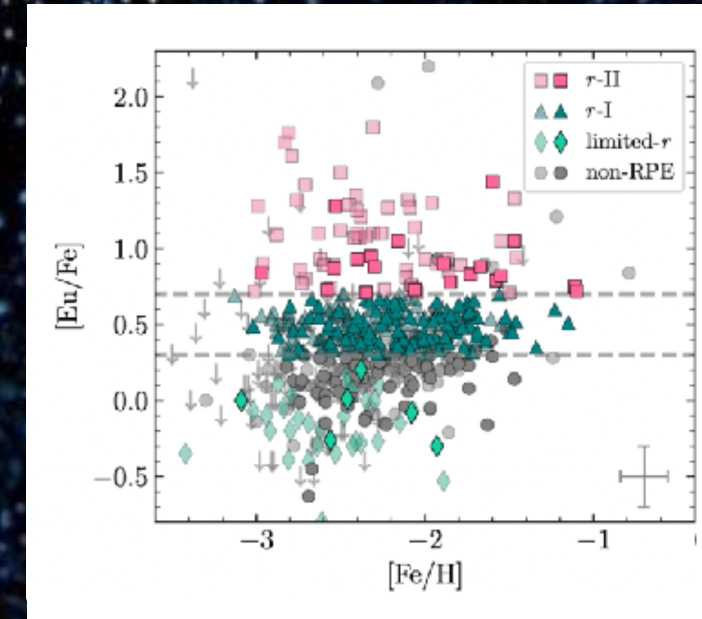



R-process alliance

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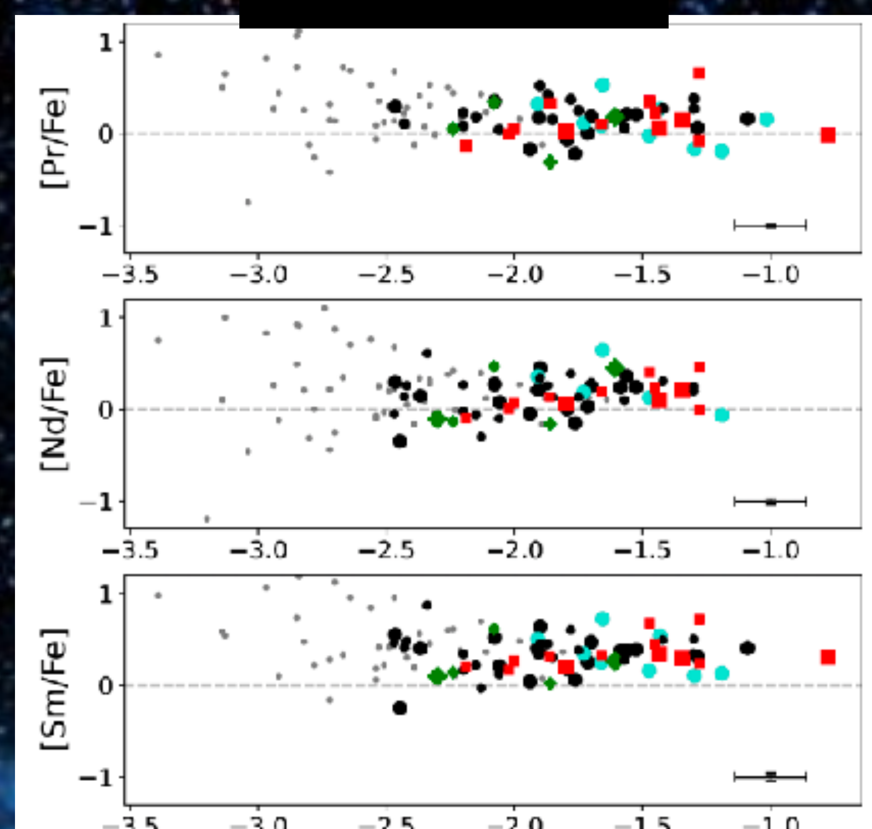


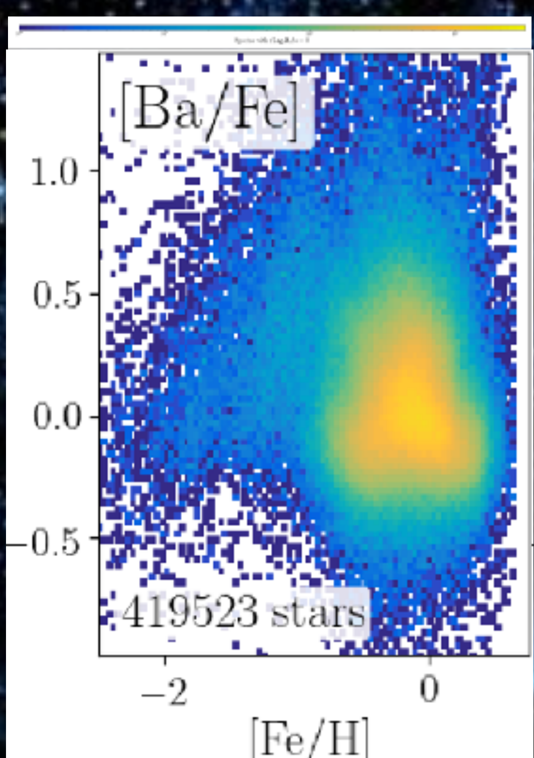


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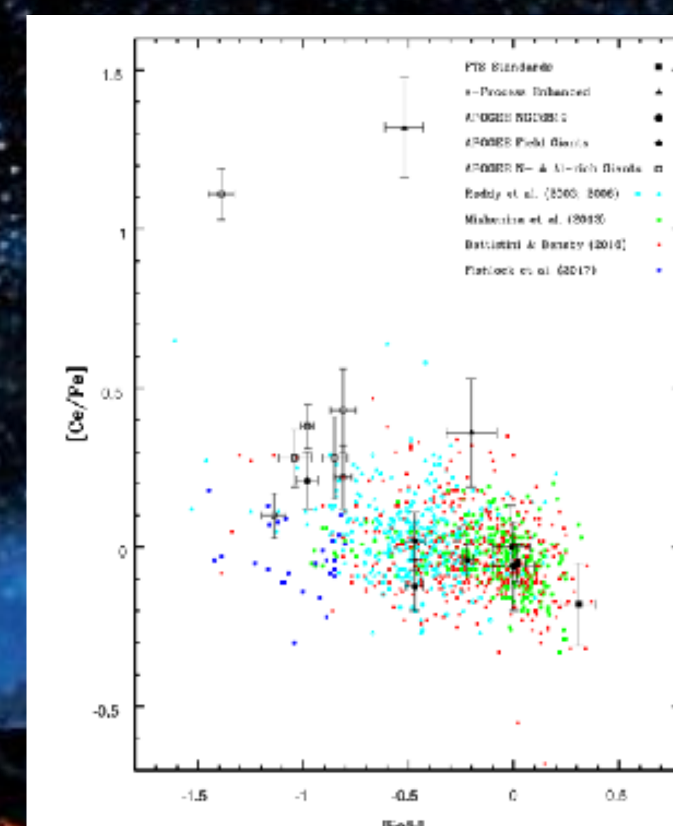



Apogee Cunha+18

# Neutron capture elements: r-s process

The elements beyond the iron peak (A>60) are manly formed through neutron capture on seed nuclei (iron and silicon).

Two cases:

**s-process**

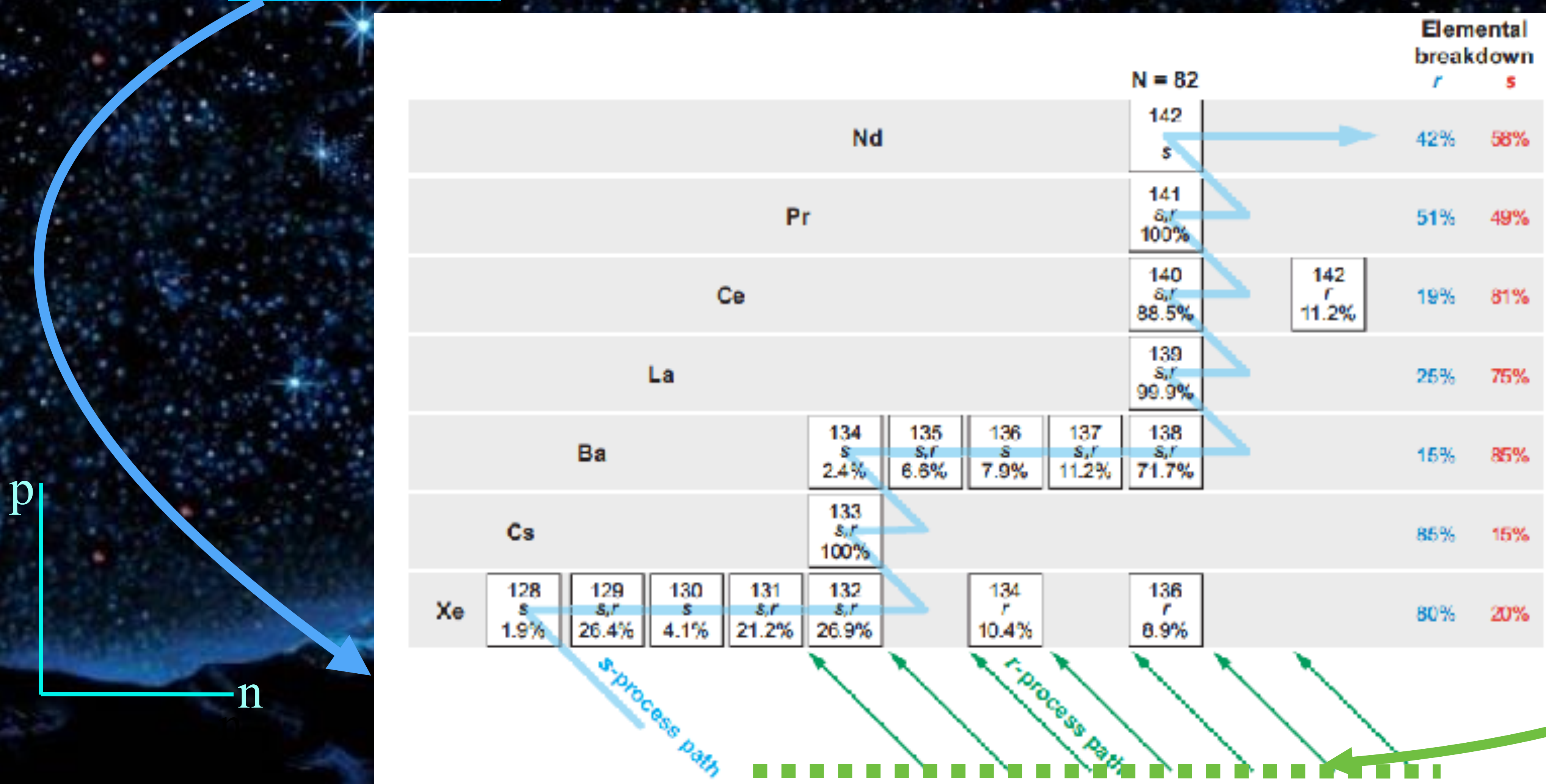
**r-process**

Different Timescale of the neutron capture

$\tau_\beta << \tau_c$

$\tau_\beta >> \tau_c$

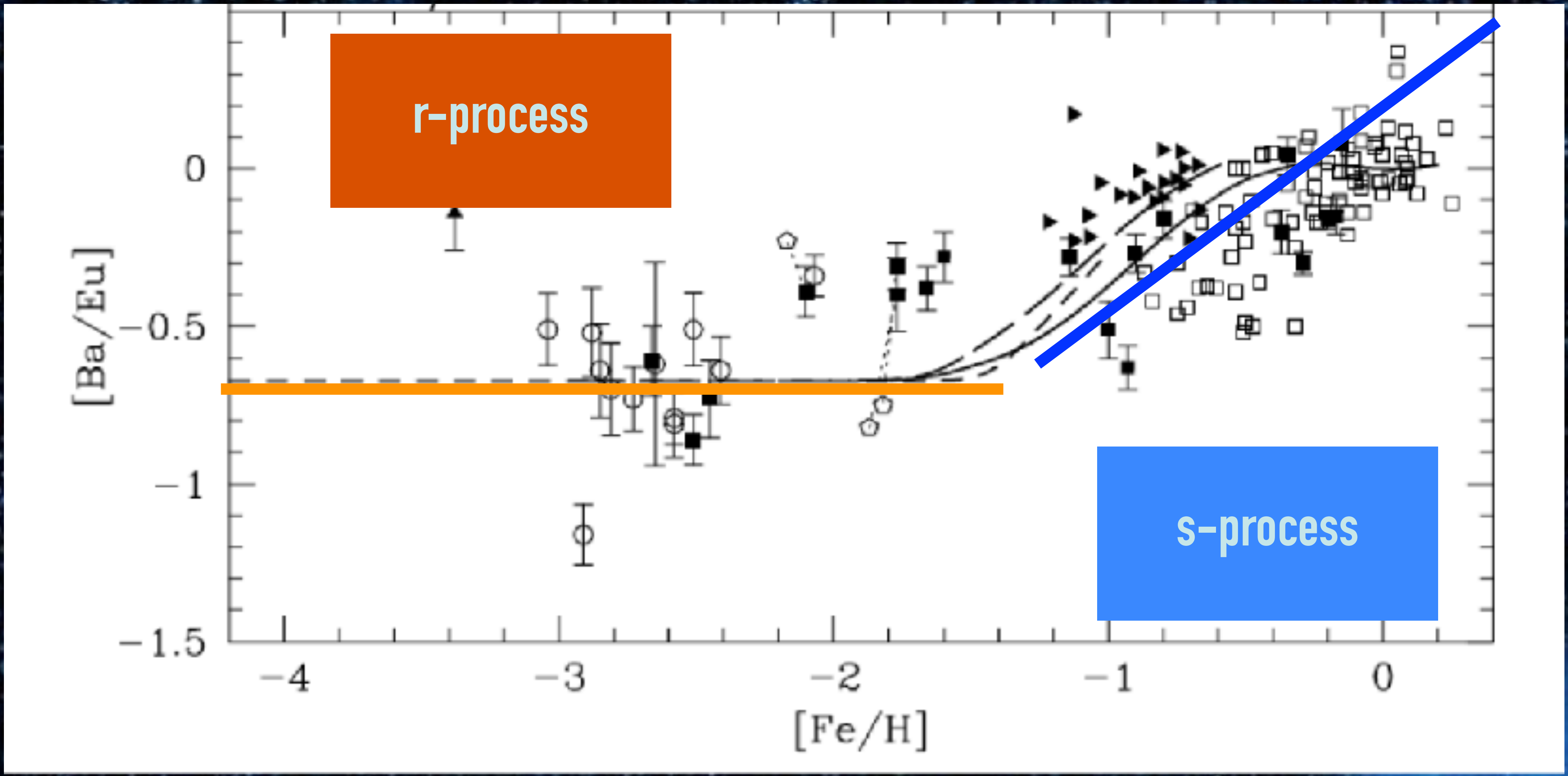
Different process path



# Neutron capture elements

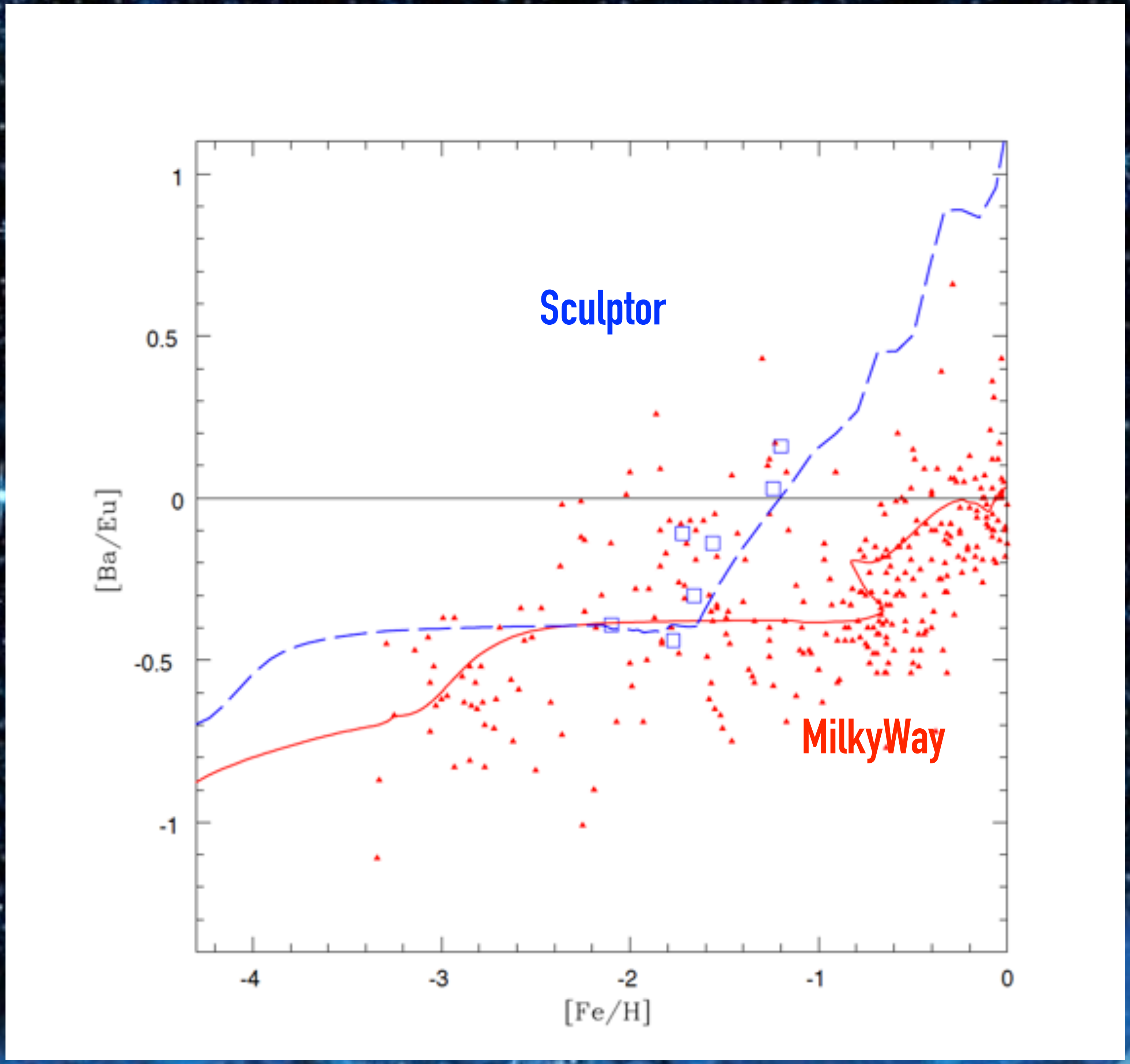
| | s-process | r-process |
|---|---|---|
| site | Low-(intermediate) mass stars | NS mergers (& Massive stars?) |
| time scale | >300Myr | DTD NSM or/and < 30Myr for MRD SNe |
| yields | Cristallo+11<br>Karakas+12 | nucleosynthesis available (but . . .) |

# The case of [Ba/Eu] knee



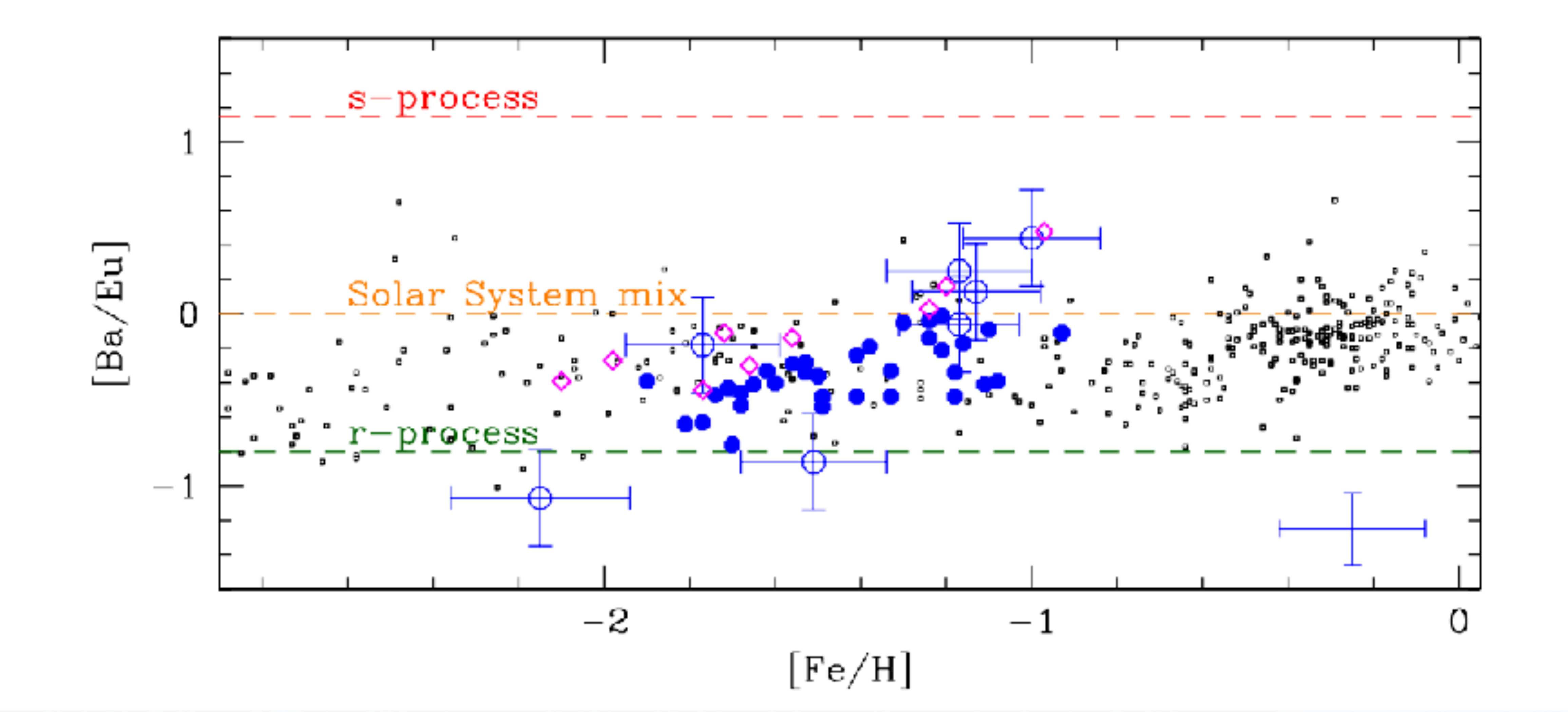

Travaglio+99

# The case of [Ba/Eu] knee



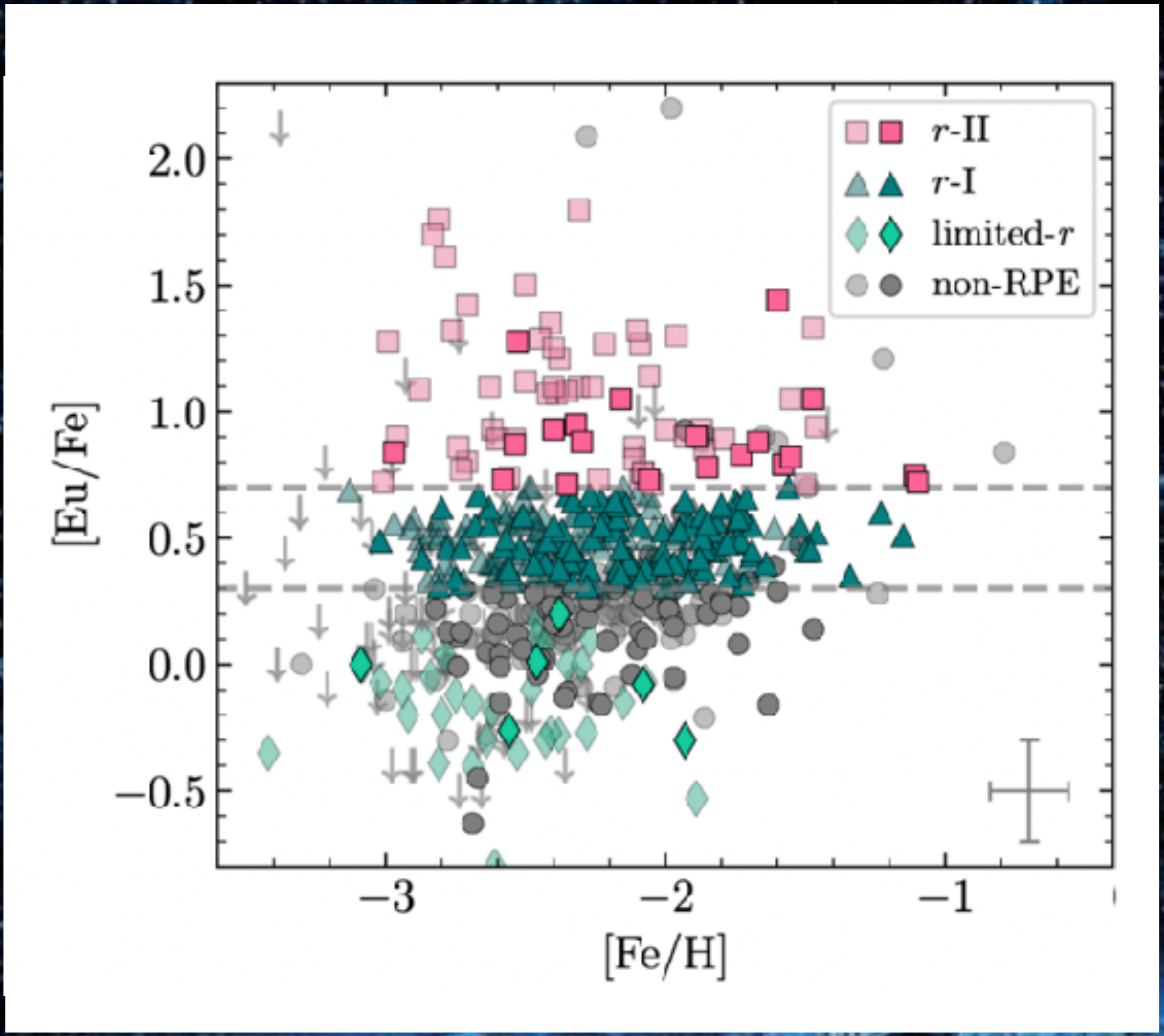

Lanfranchi+07,Cescutti07

# [Ba/Eu] in Sculptor galaxy

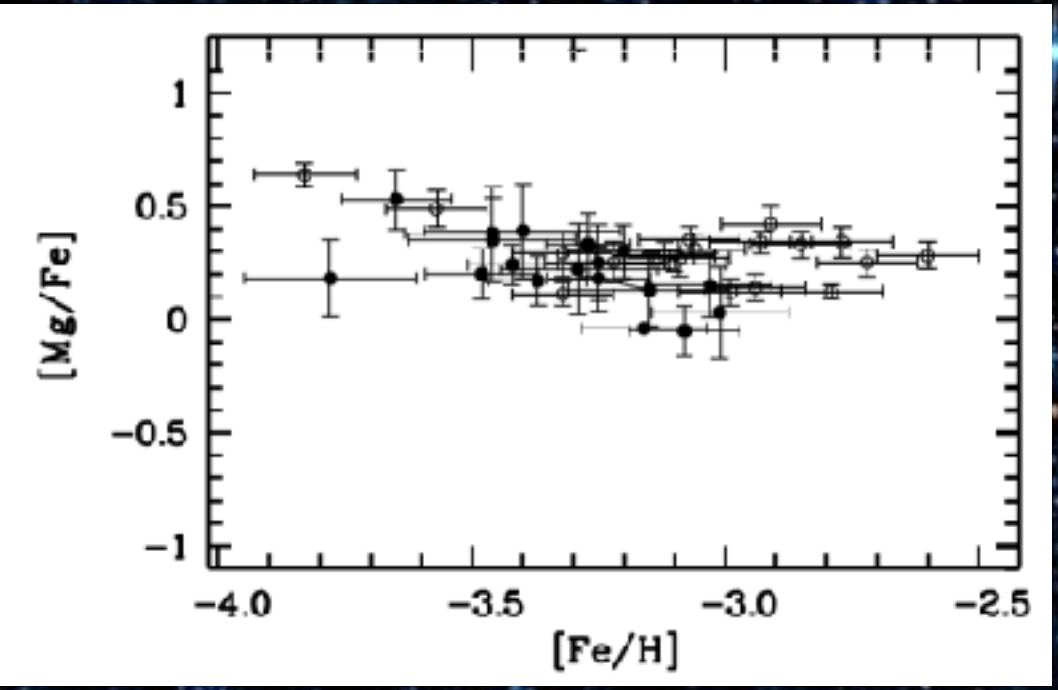


# r-process
# [Eu/Fe] in the Galactic halo

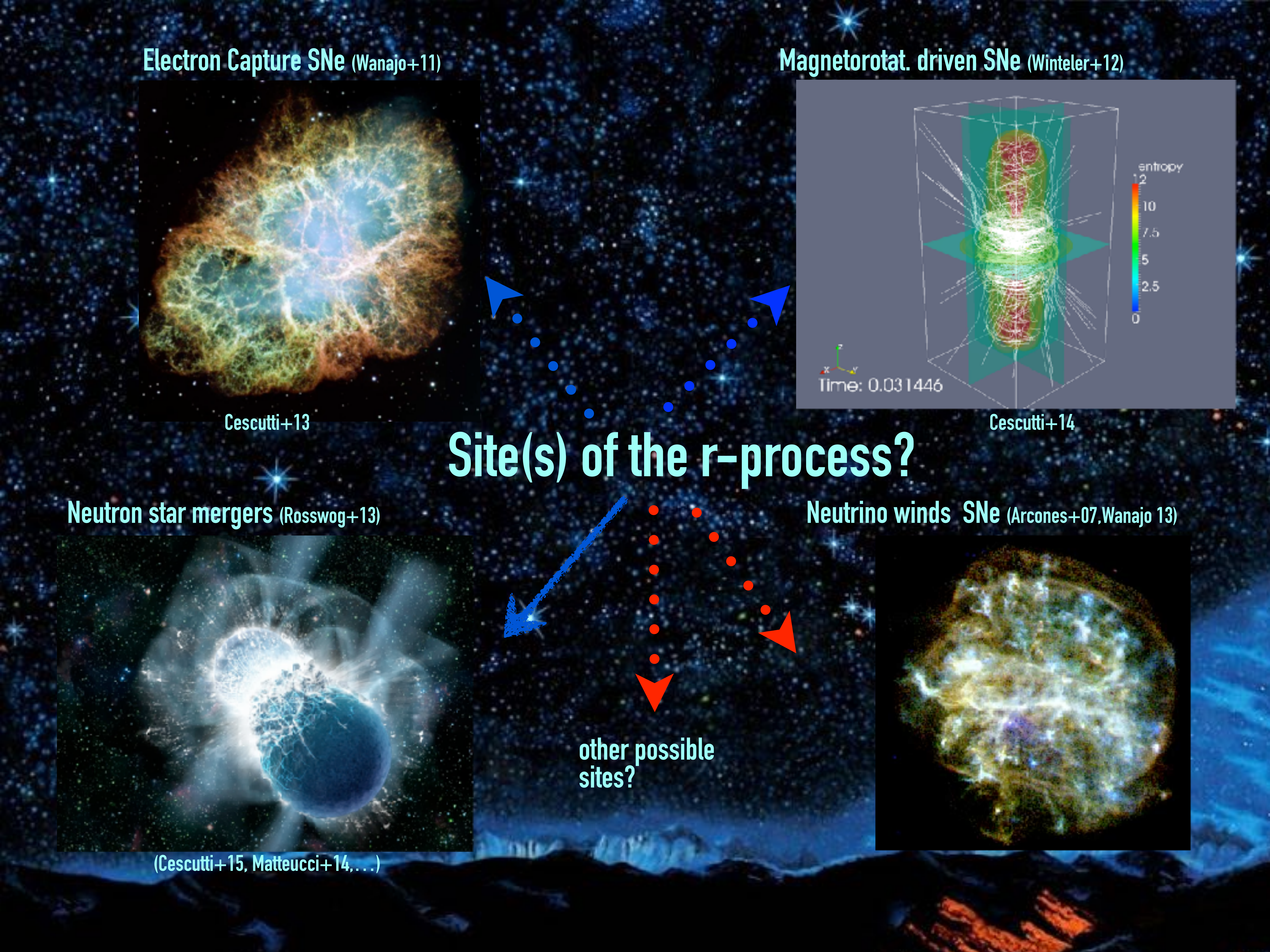
Since McWilliam95 idea of RARE events for r-process events
(see also Primas+94, Ryan+91, Norris+93)




R-process alliance Holmbeck+20




Bonifacio+12

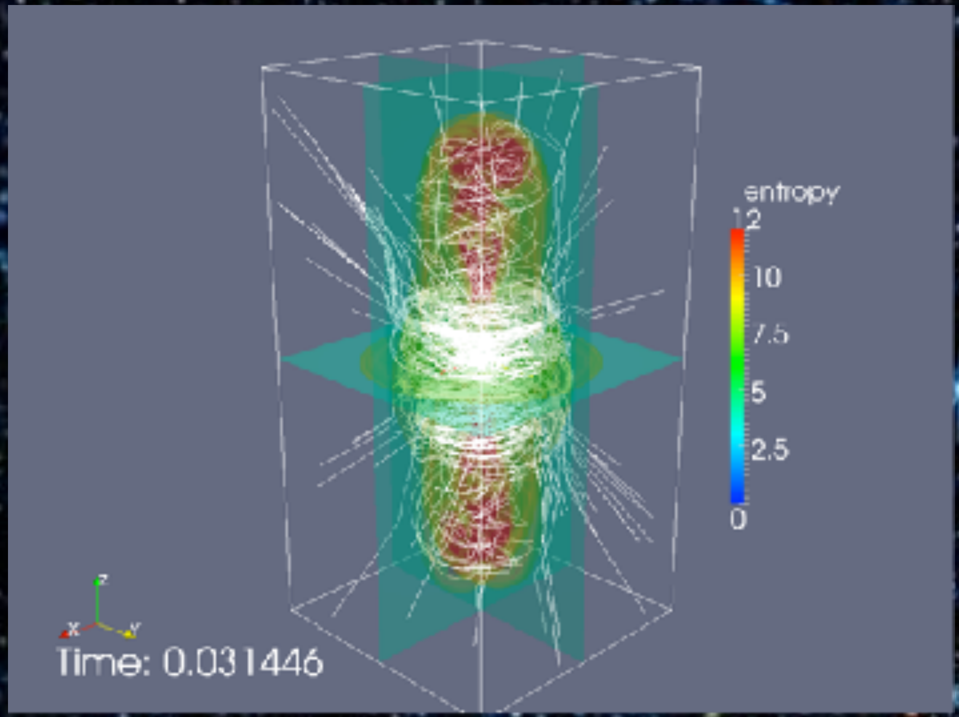

Electron Capture SNe (Wanajo+11)
Cescutti+13
Magnetorotat. driven SNe (Winteler+12)
entropy
12
10
7.5
5
2.5
0
Time: 0.031446
Cescutti+14
Site(s) of the r-process?
Neutron star mergers (Rosswog+13)
(Cescutti+15, Matteucci+14,. . . )
Neutrino winds SNe (Arcones+07,Wanajo 13)
other possible sites?

# Site(s) of the r-process?

Electron Capture SNe (Wanajo+11)

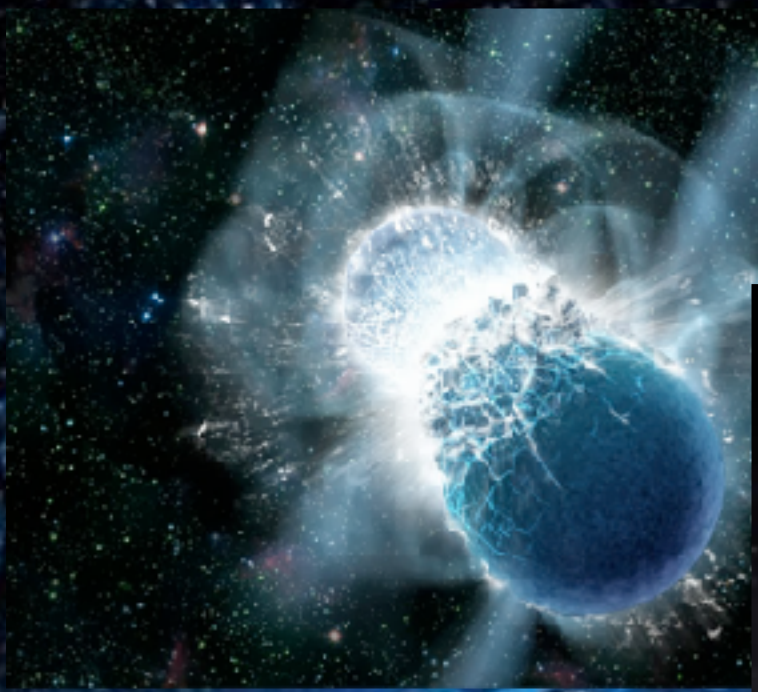
Cescutti+13

Magnetorotat. driven SNe (Winteler+12)



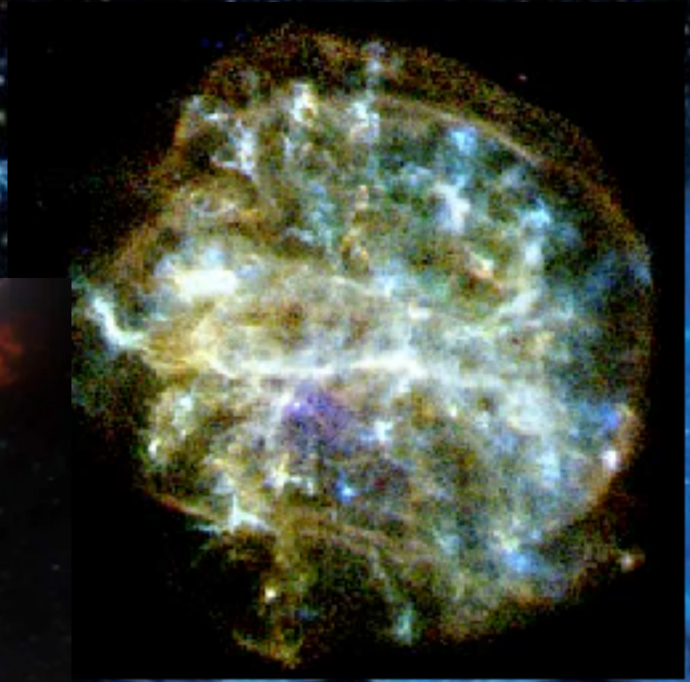

Cescutti+14

Neutron star mergers (Rosswog+13)



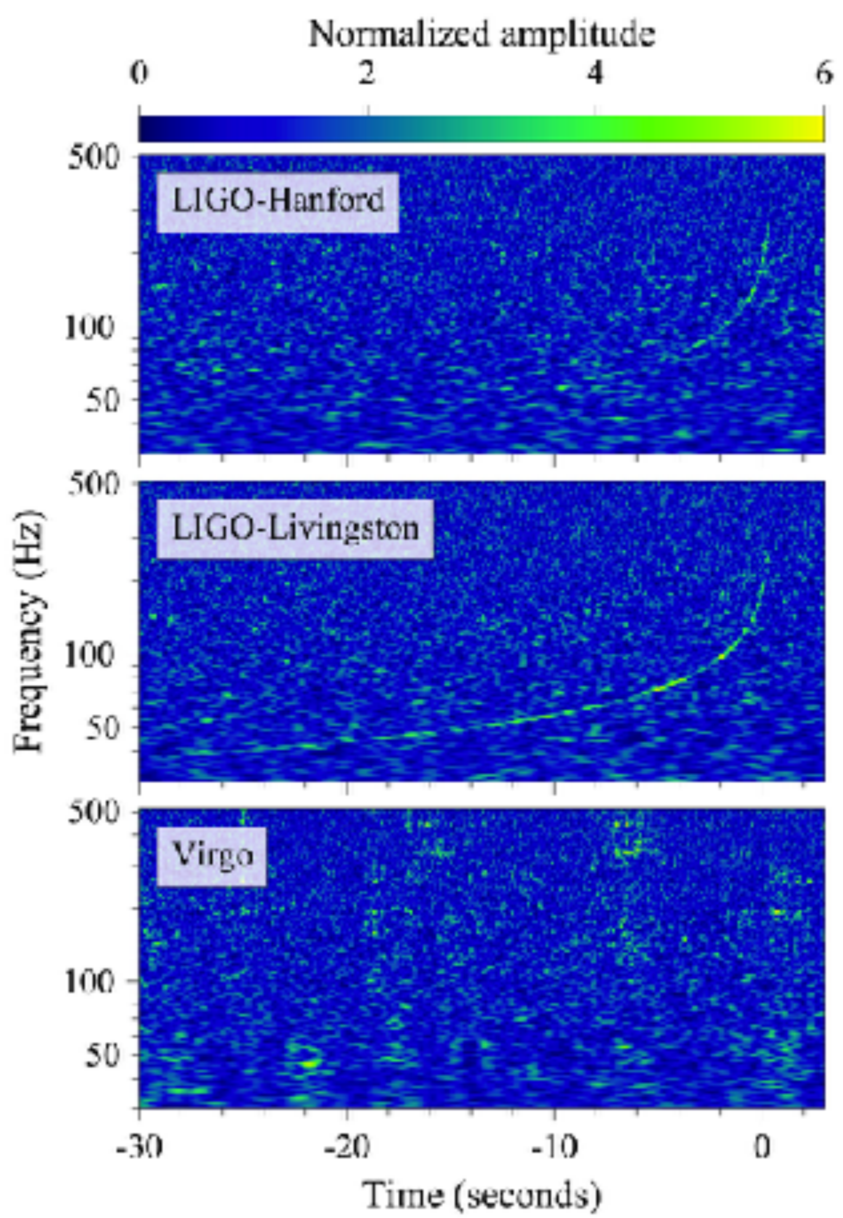
(Cescutti+15, Matteucci+14,. . . )

Neutrino winds SNe (Arcones+07,Wanajo 13)



Collapsar (Siegel+2019)

# After GW170817...

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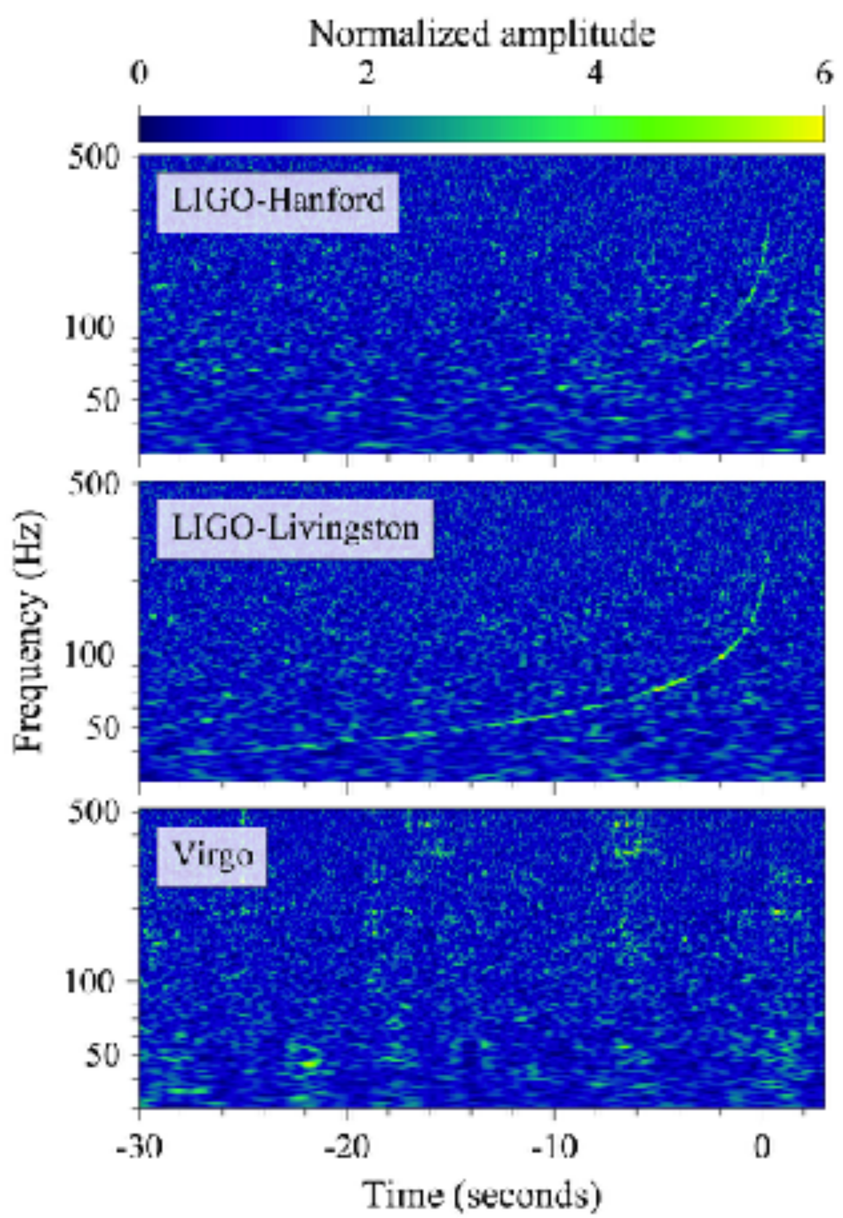


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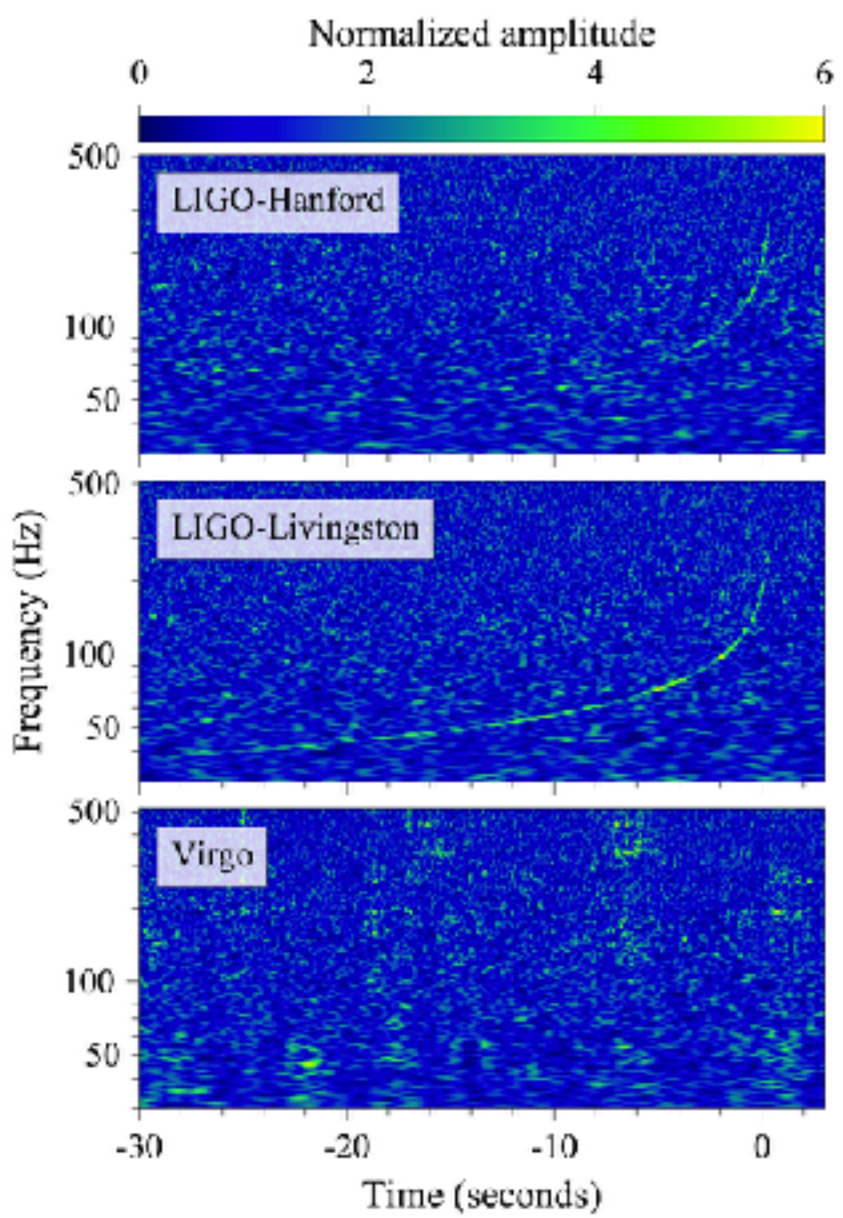



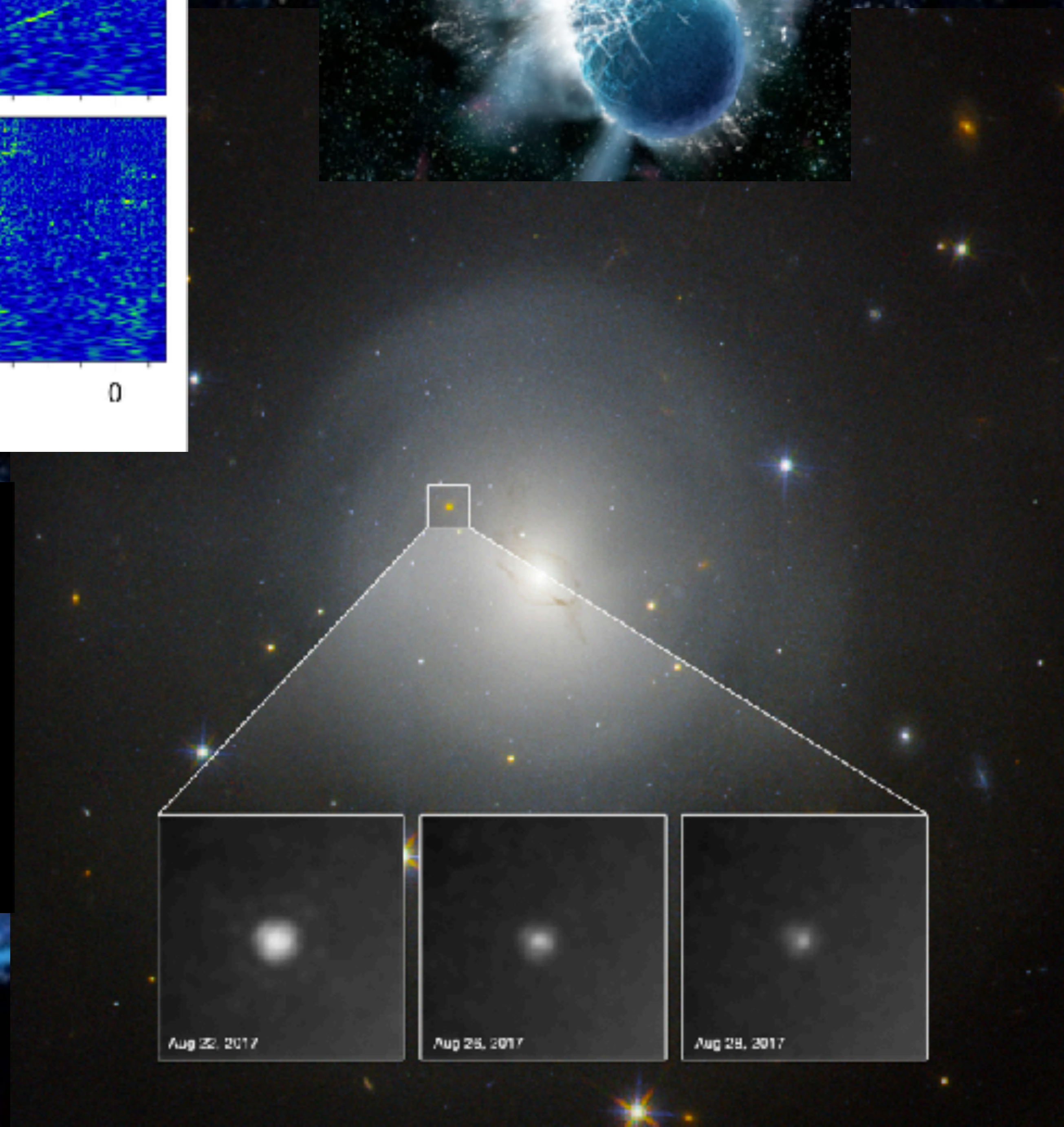

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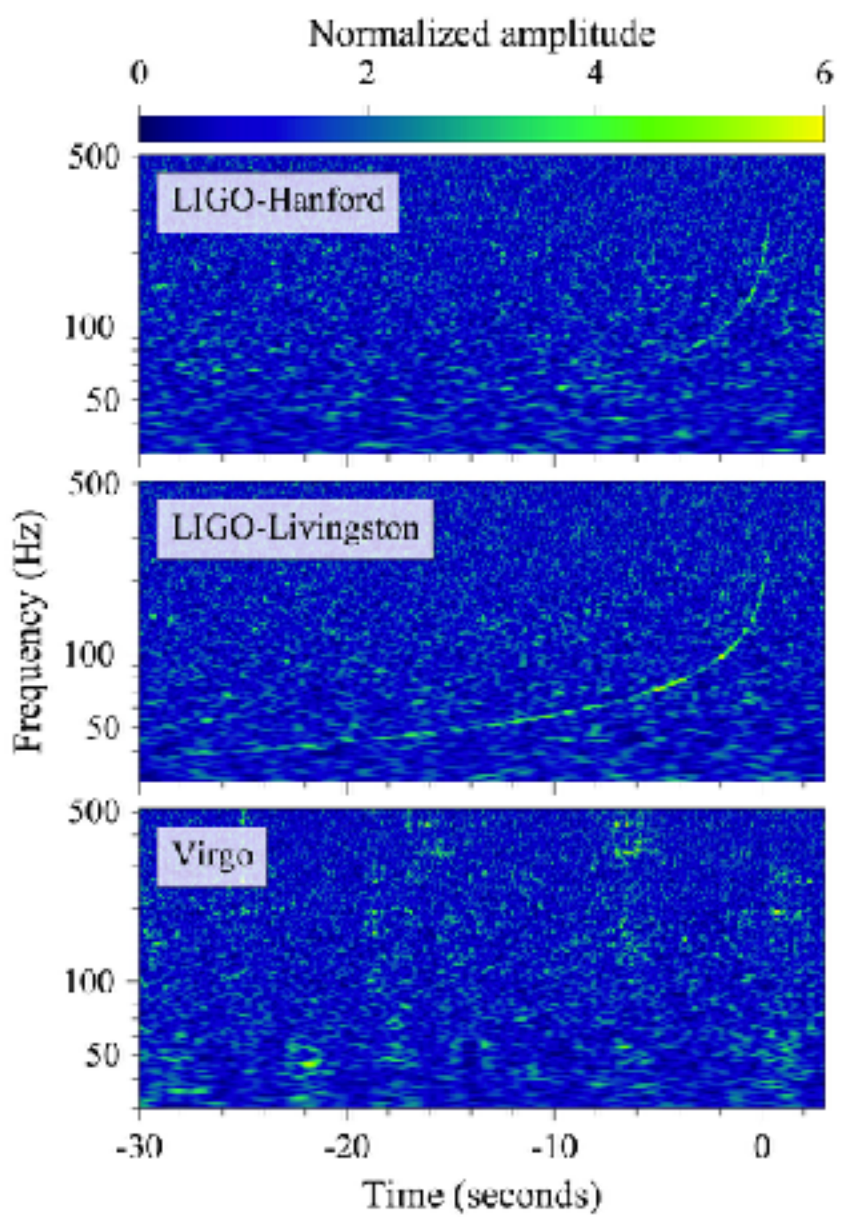


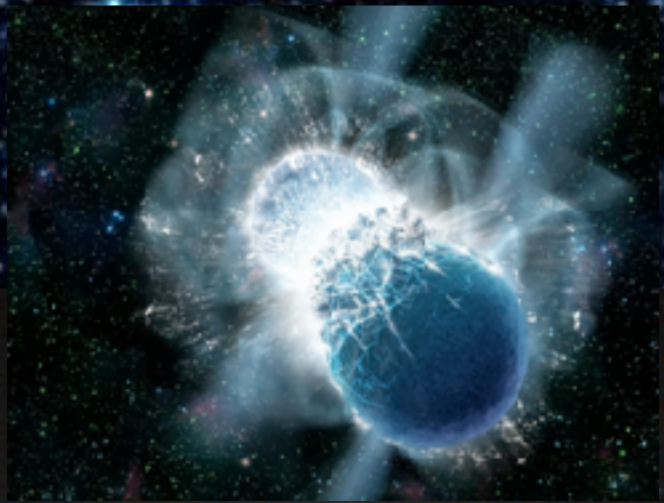

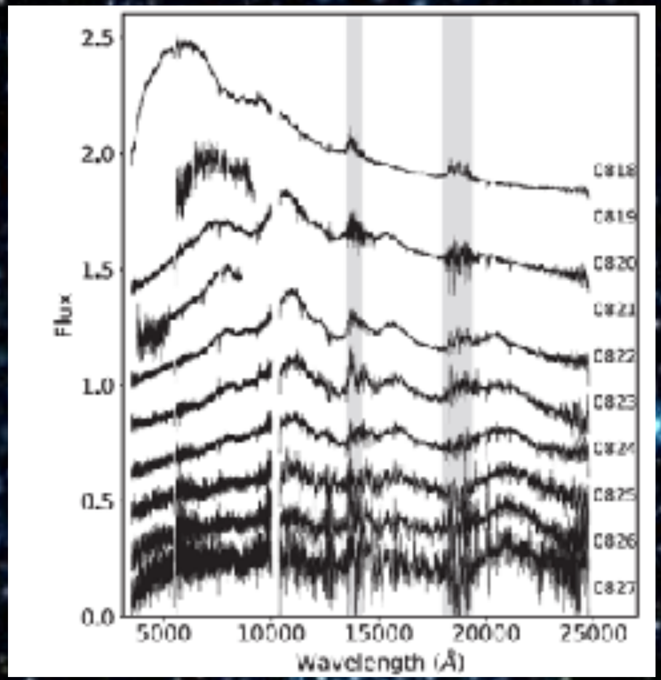



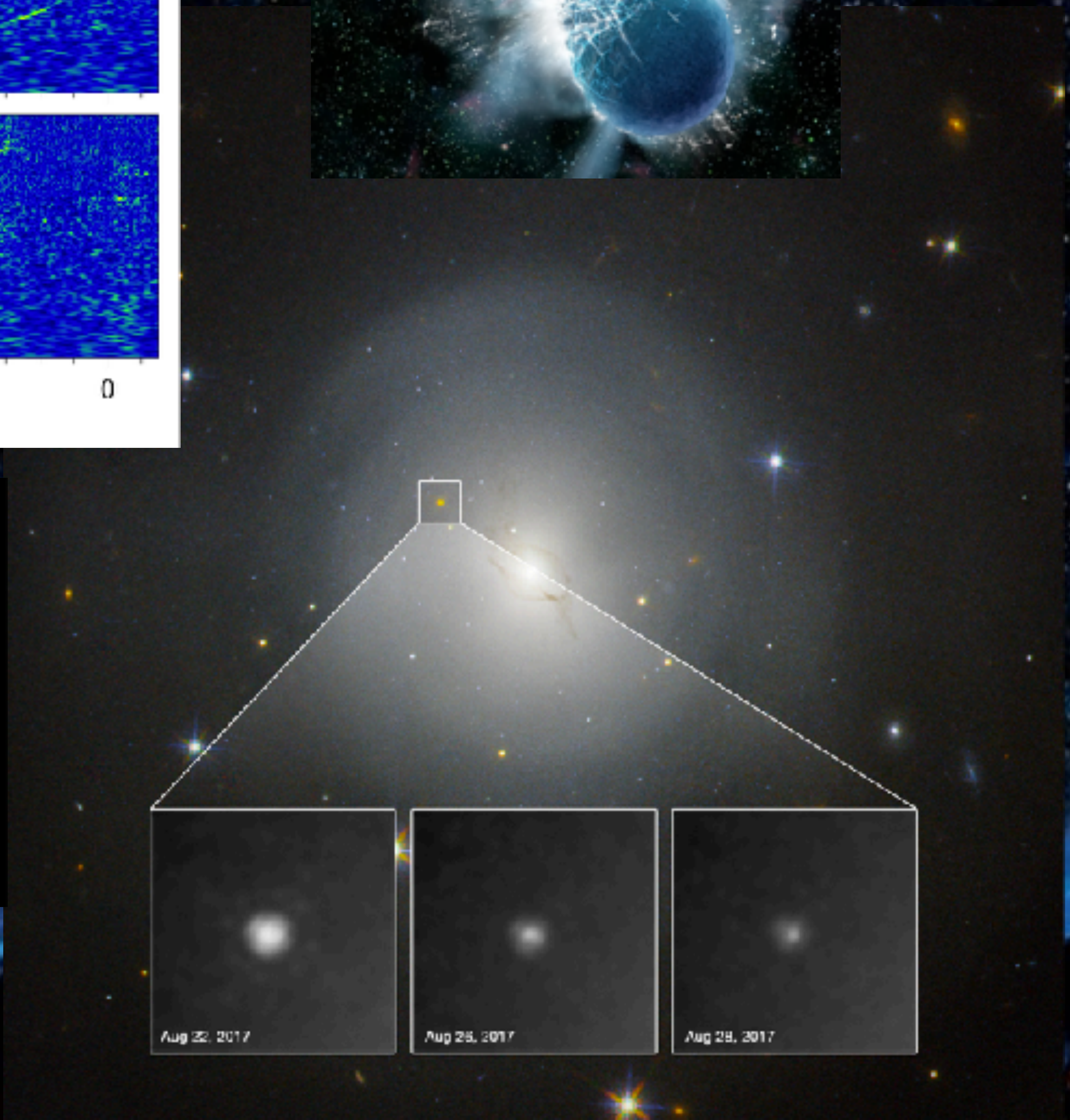

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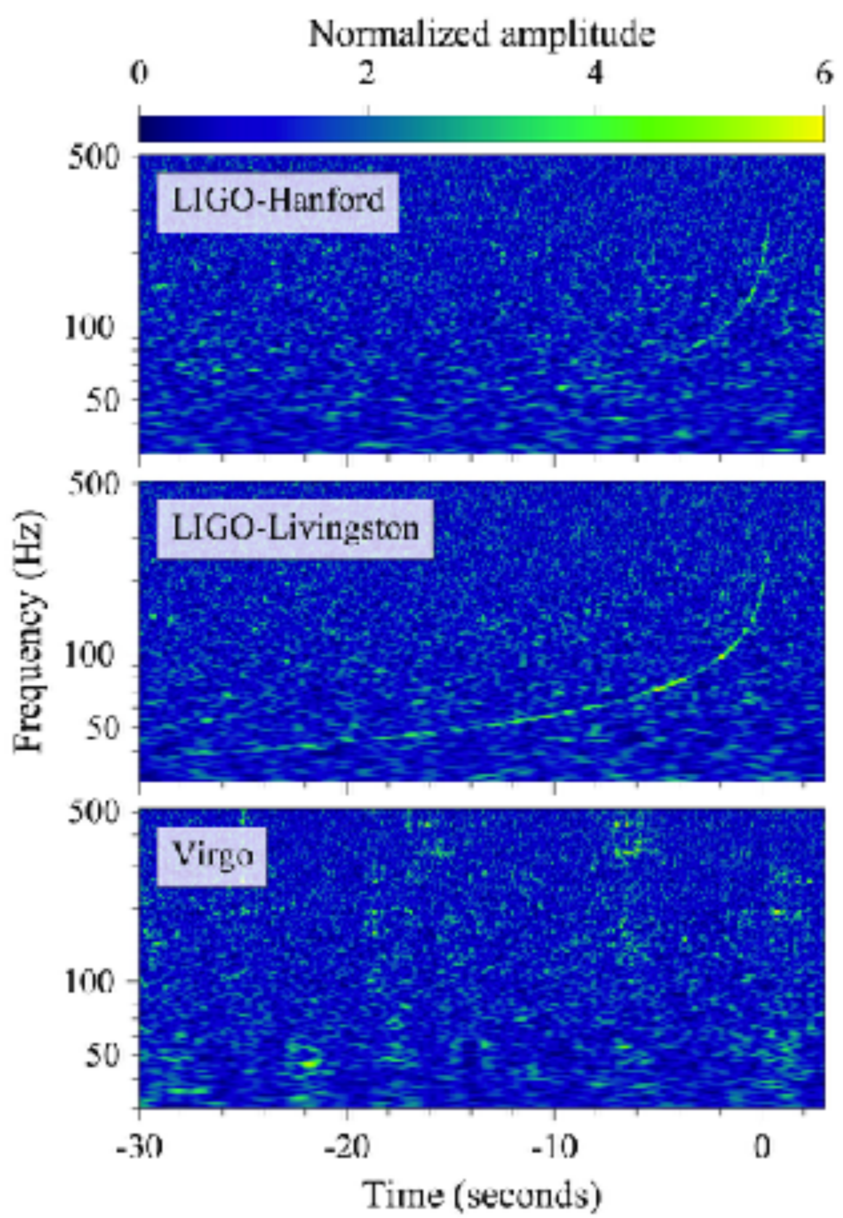
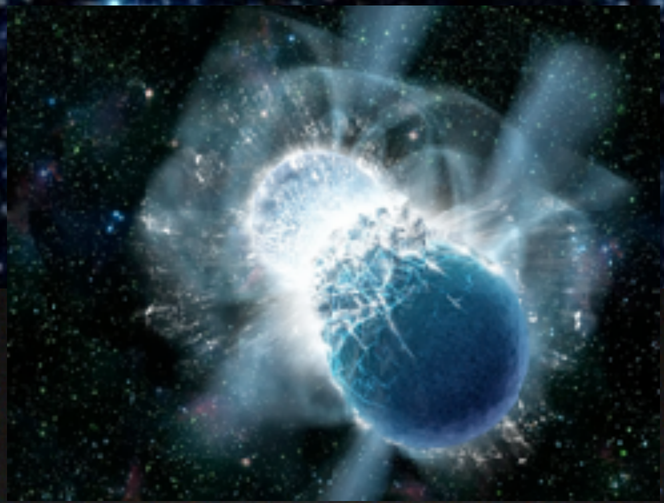
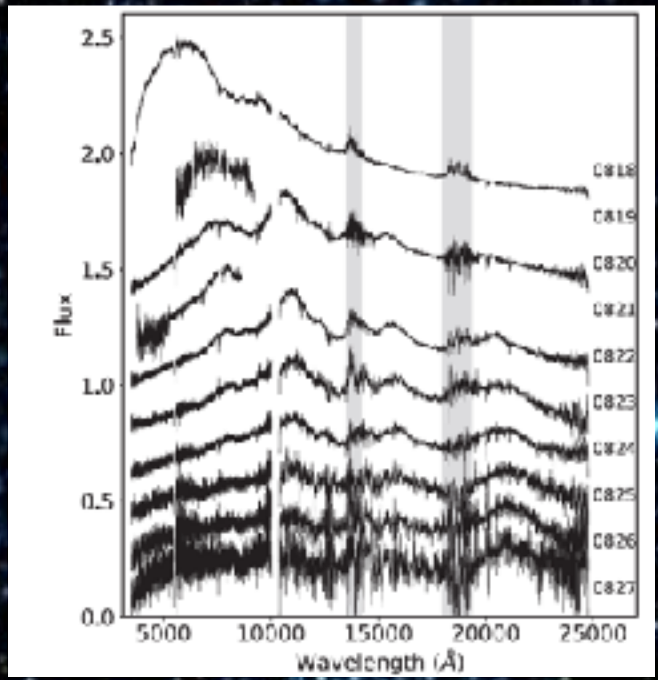
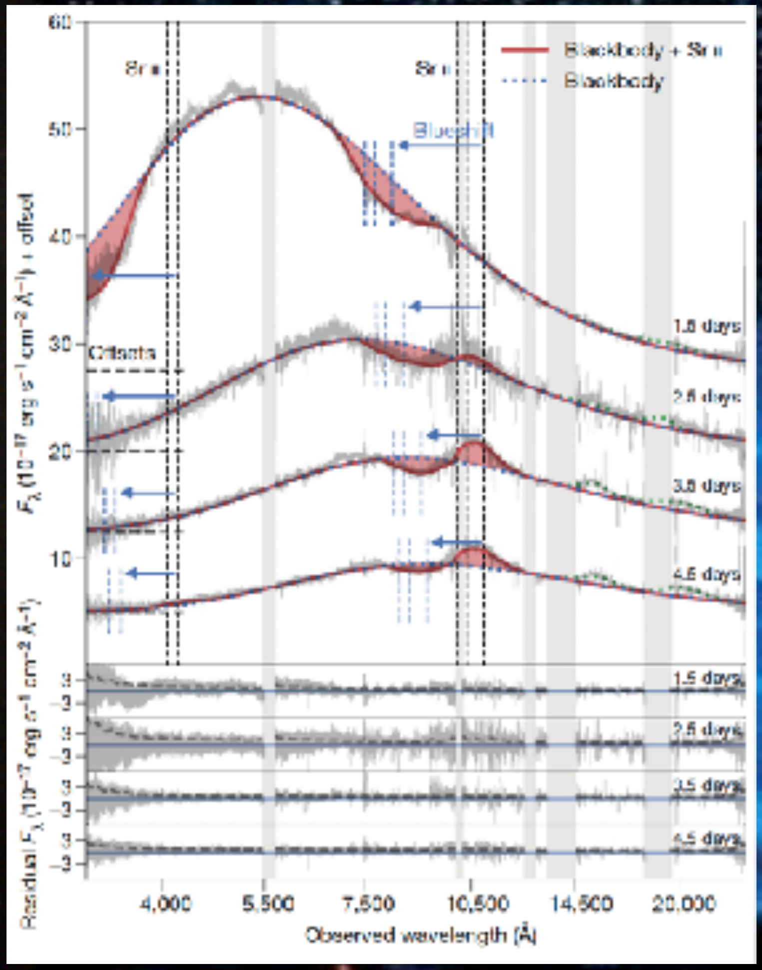






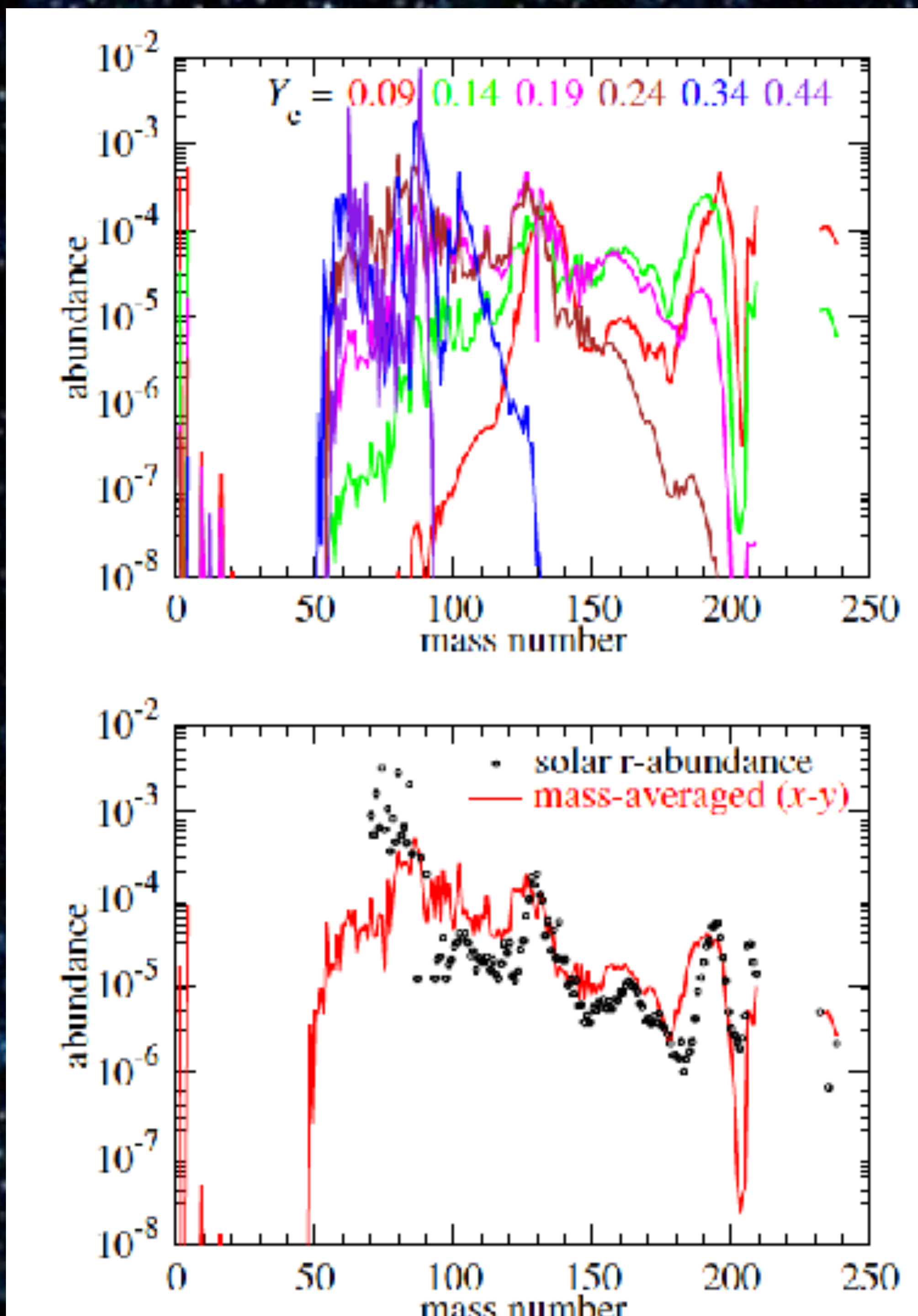


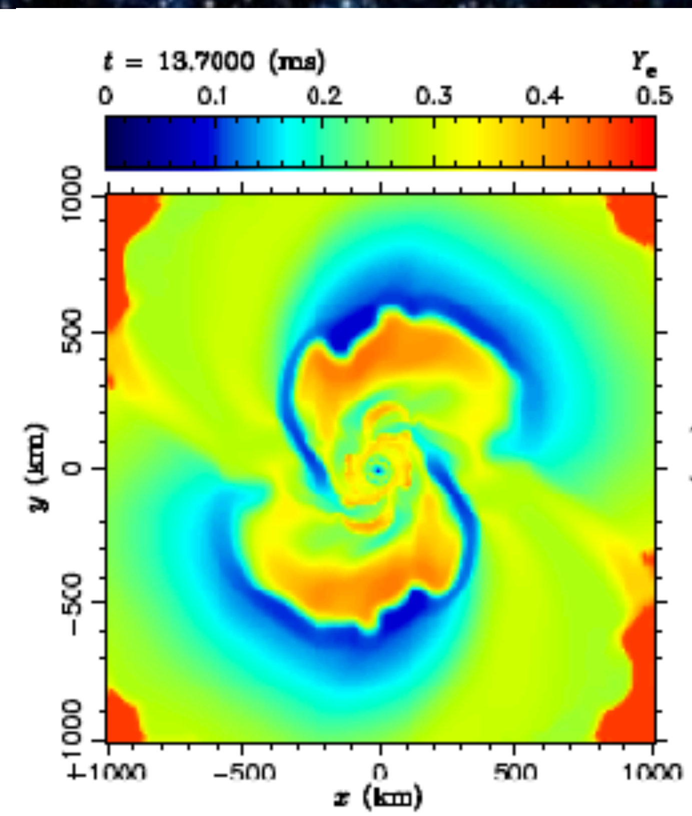

Watson+19

# Neutron stars mergers

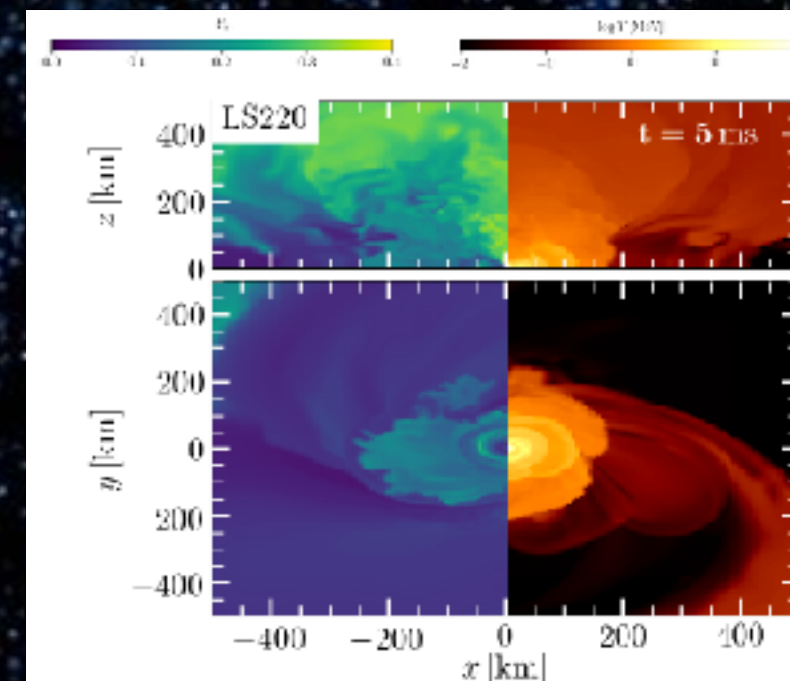
(GR considered, nucleosynthesis computed for the dynamical ejecta)

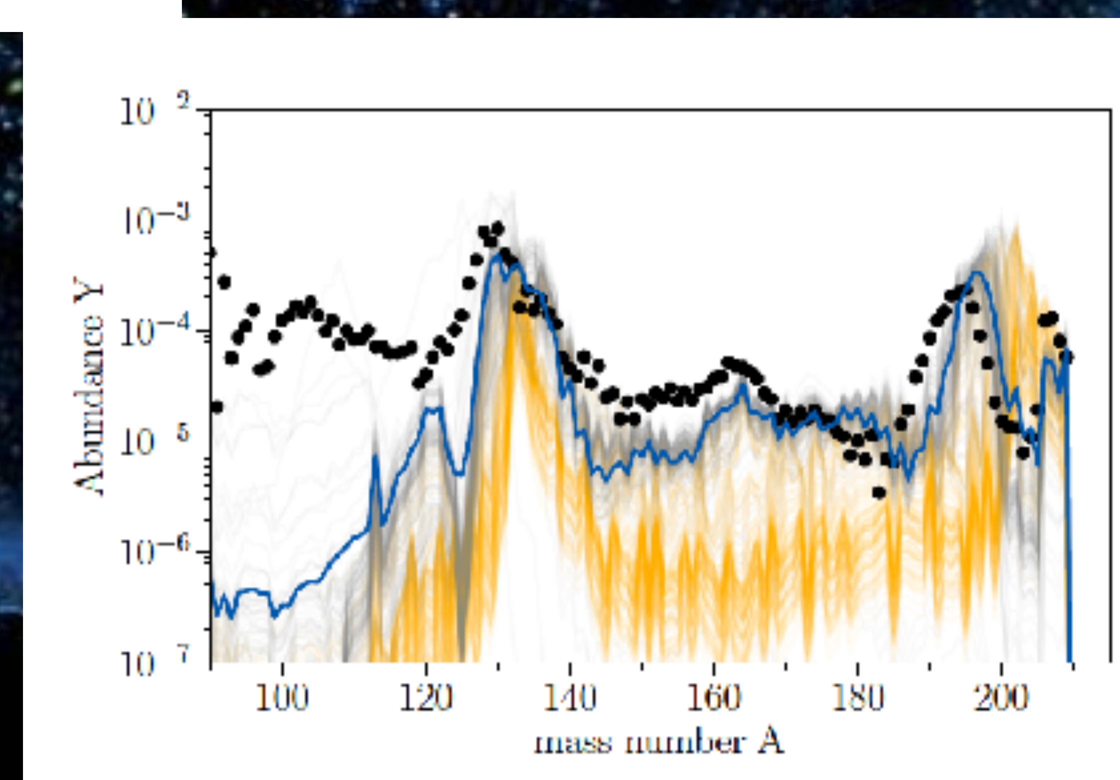
Wanajo+14



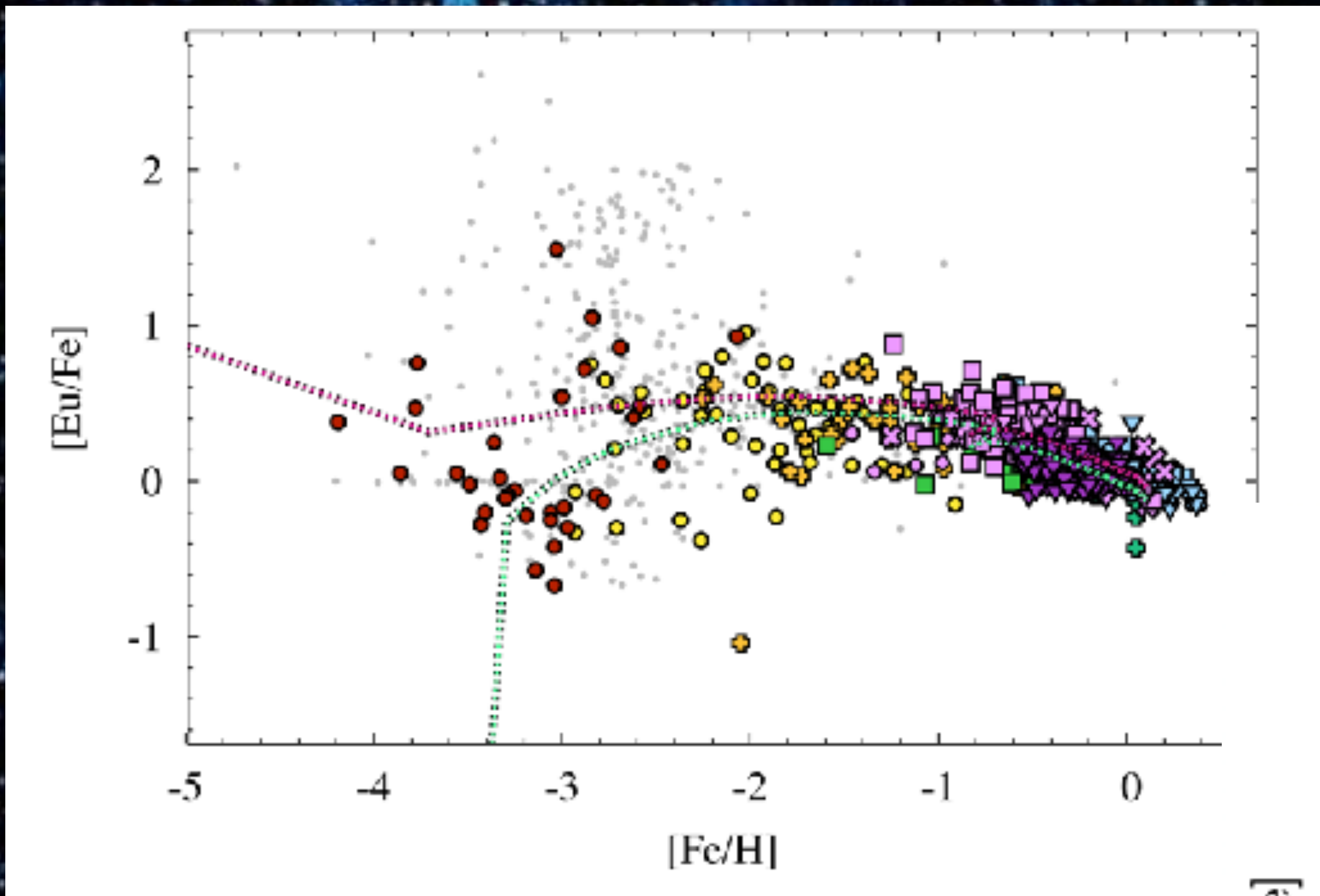

Bovard+17

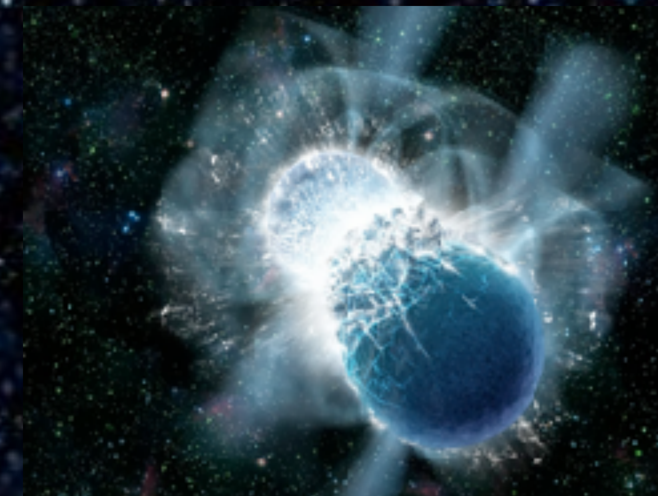


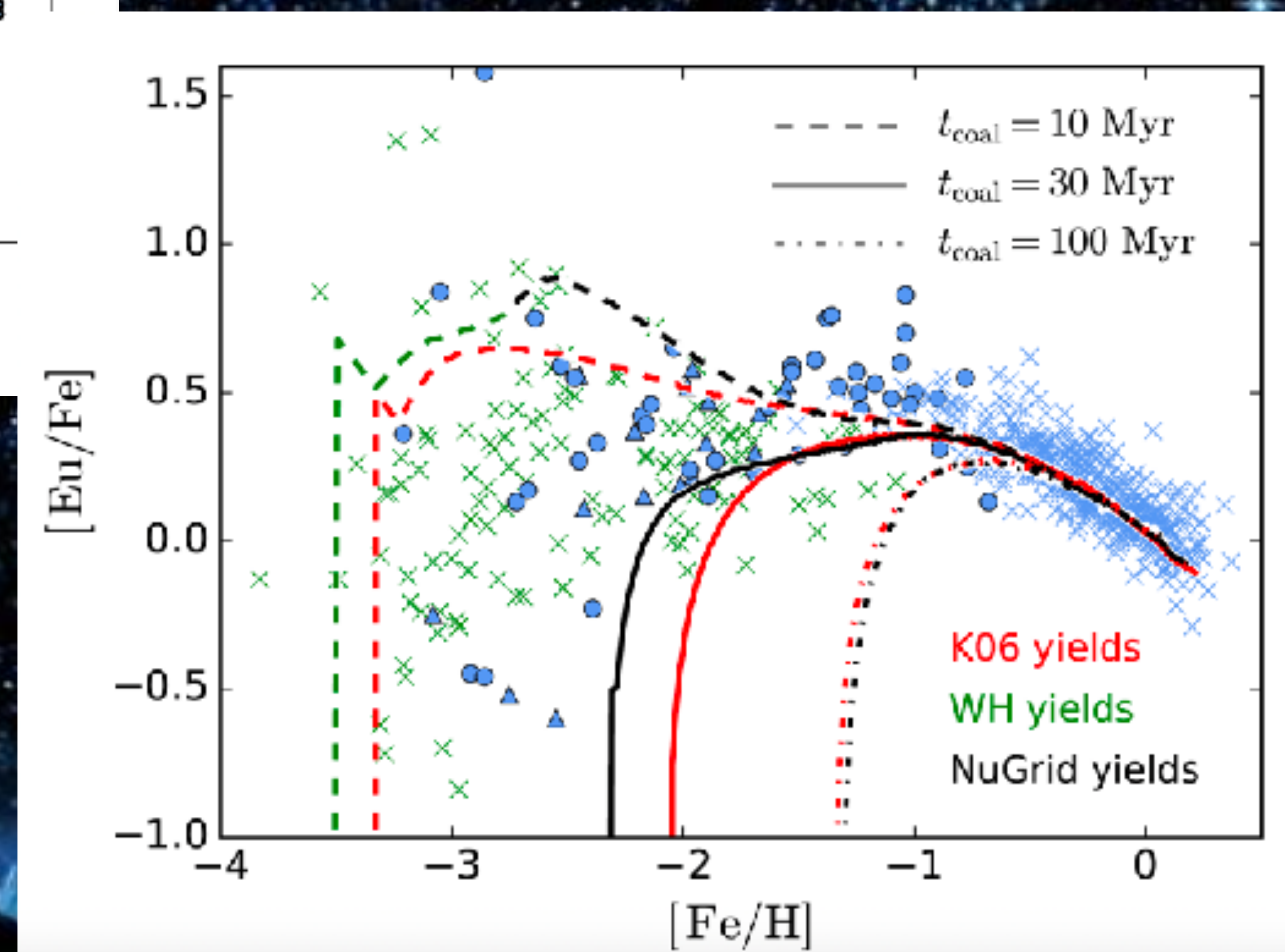
# Homogeneous chemical evolution model

Matteucci+14



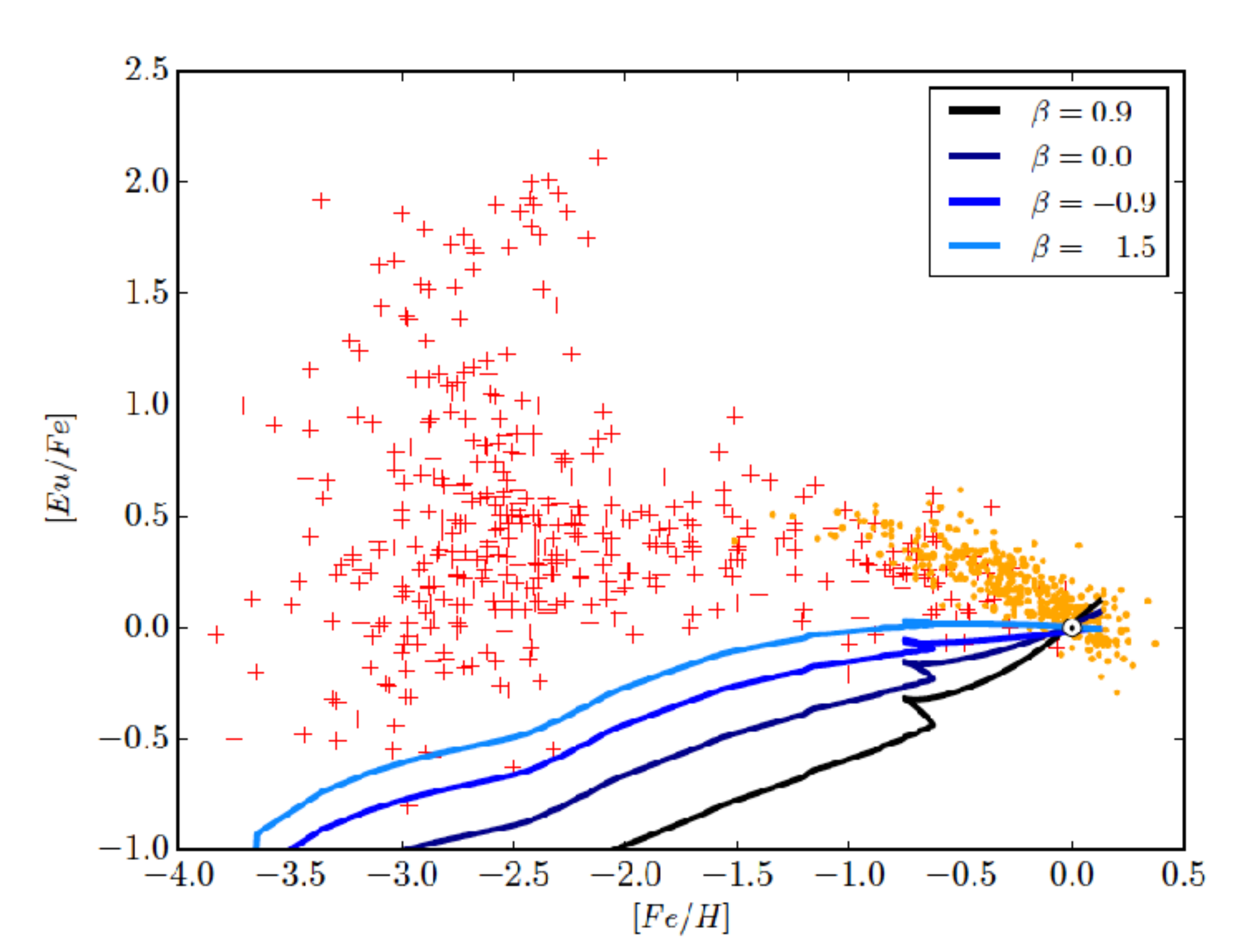
Cotè+17



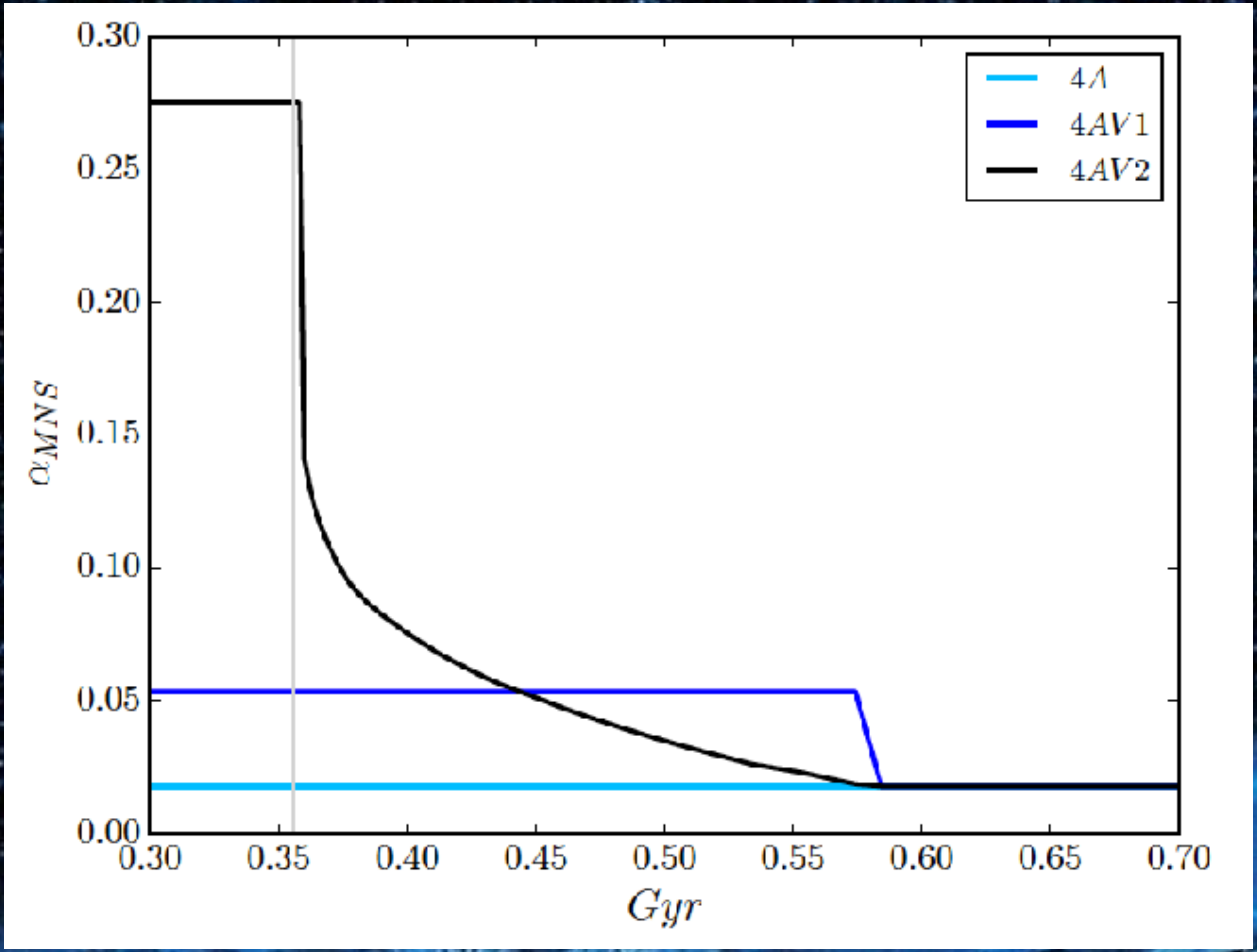
# Detailed DTD for NSM

Simonetti+19

see also Cotè+19

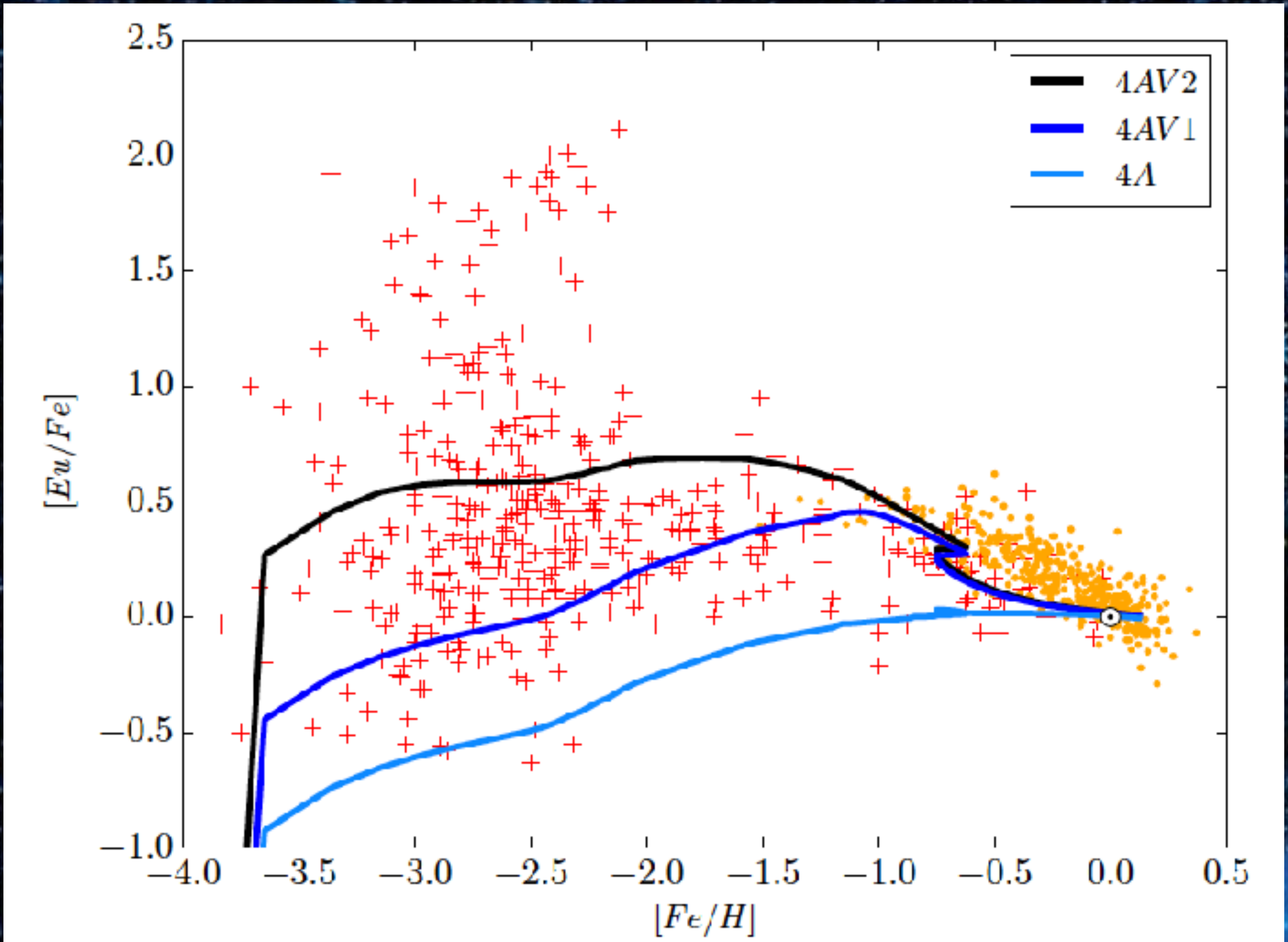


# Models with detailed DTD for NSM variation of the alpha (fraction NSM/SNe)




Simonetti+19

# Models with detailed DTD for NSM




variation of alpha, possible solution!

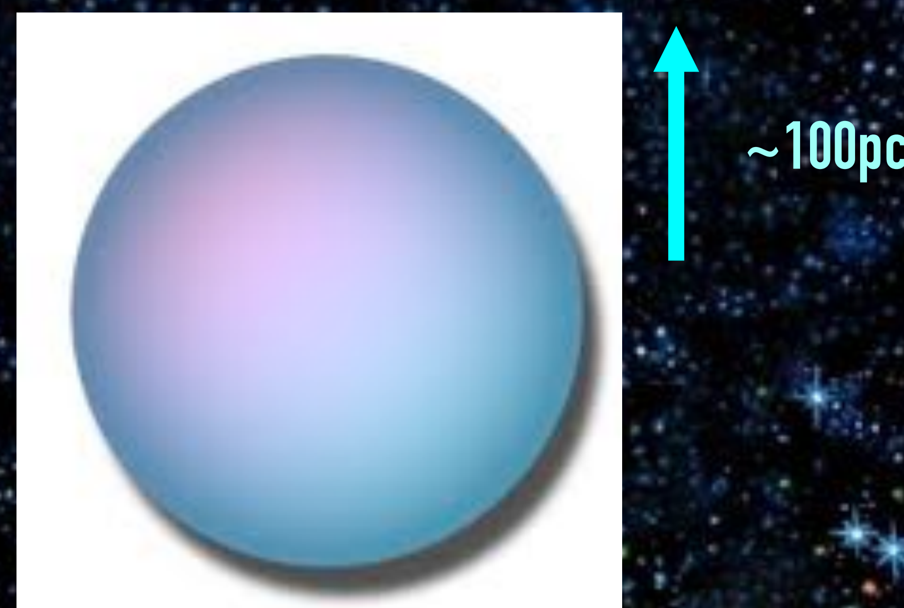
see also Schoenrich&Weinberg19

Simonetti+19

# 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 (~radius of SN bubble) and we treat each volume as isolate from the others.

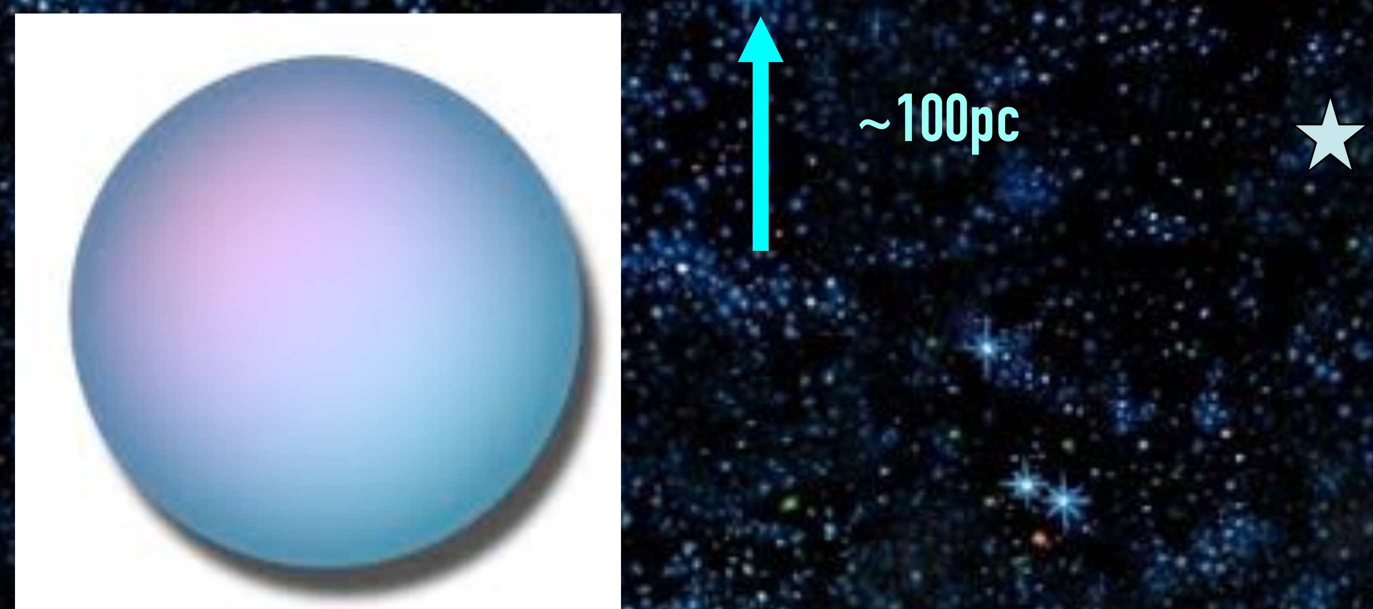



Cescutti (2008)

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 chemical evolution models

minimum of 100 volumes up to 10'000



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~100pc

~100pc

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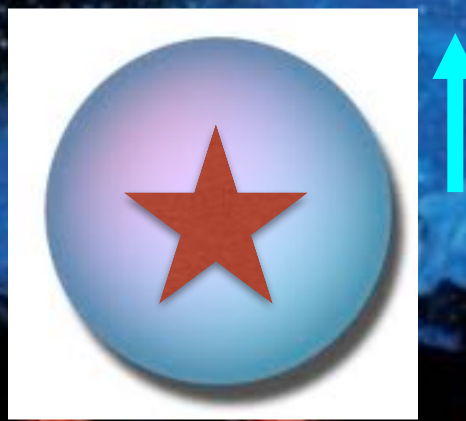

~100pc

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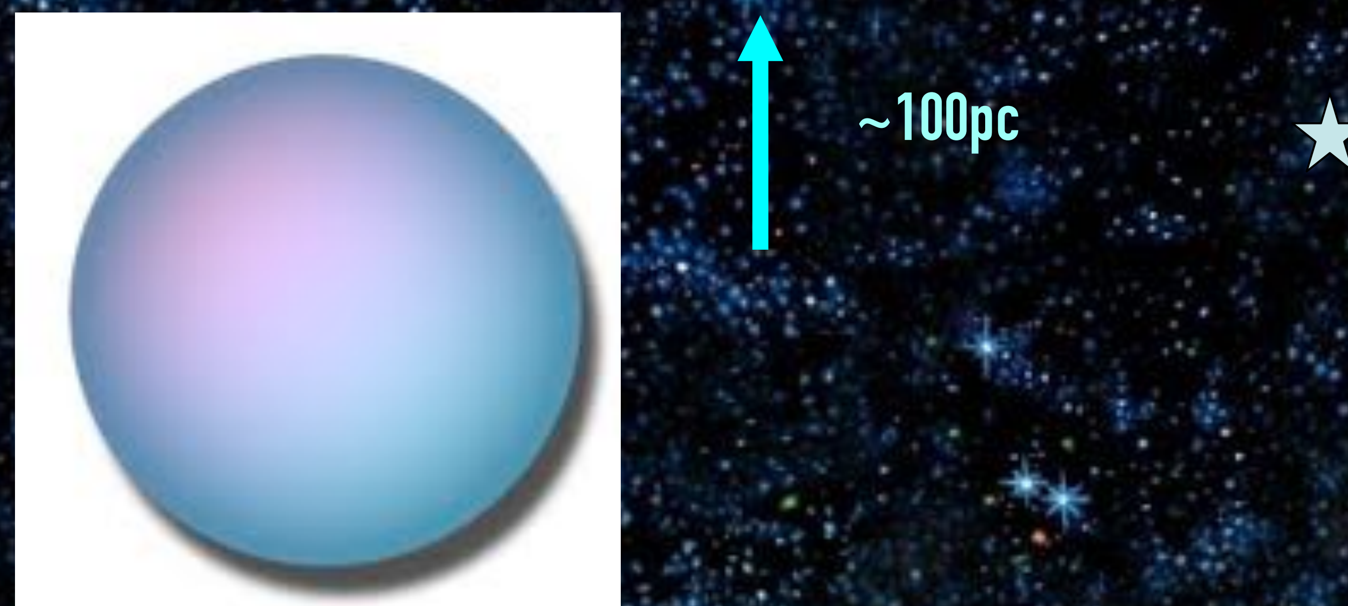



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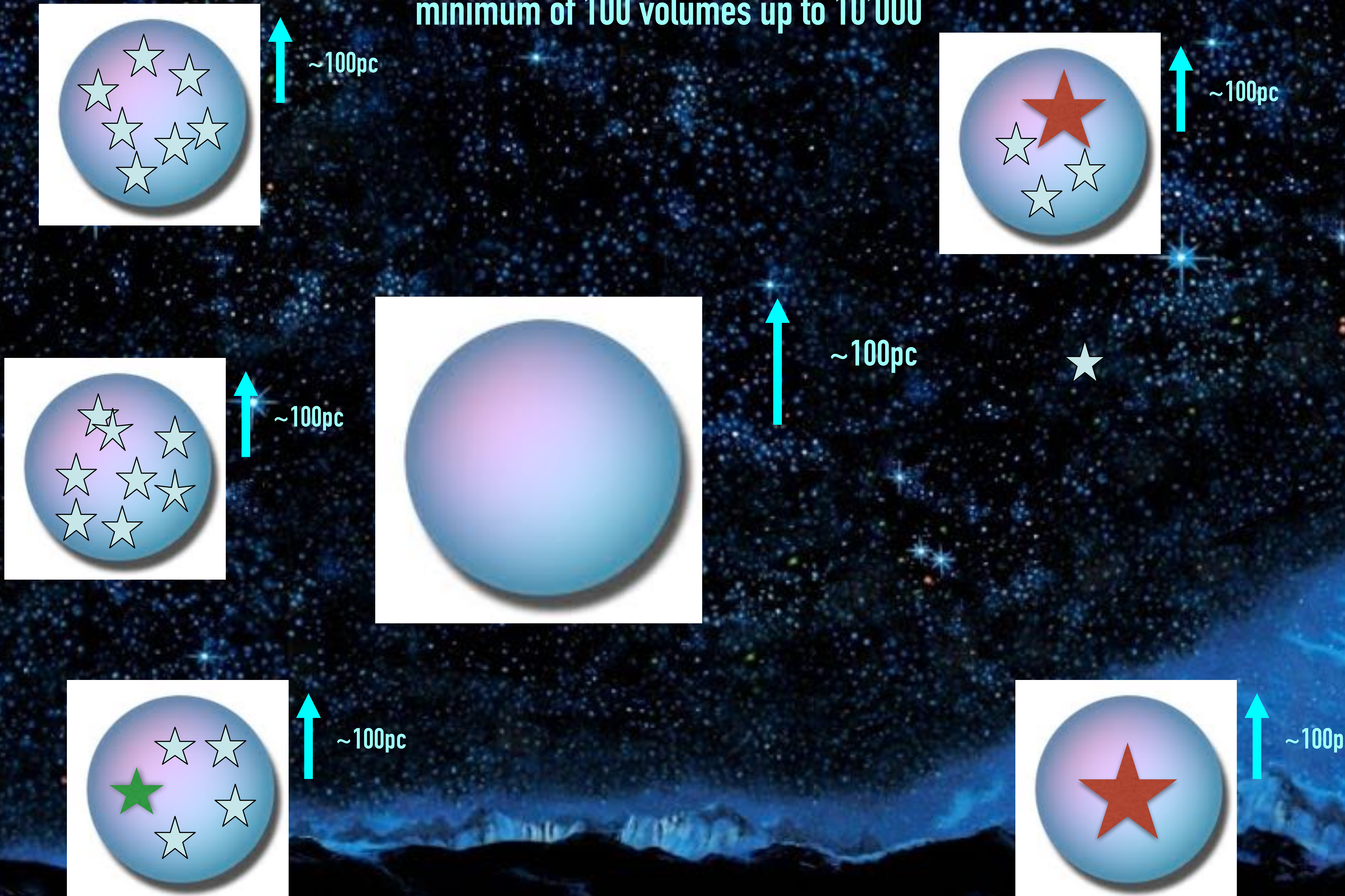

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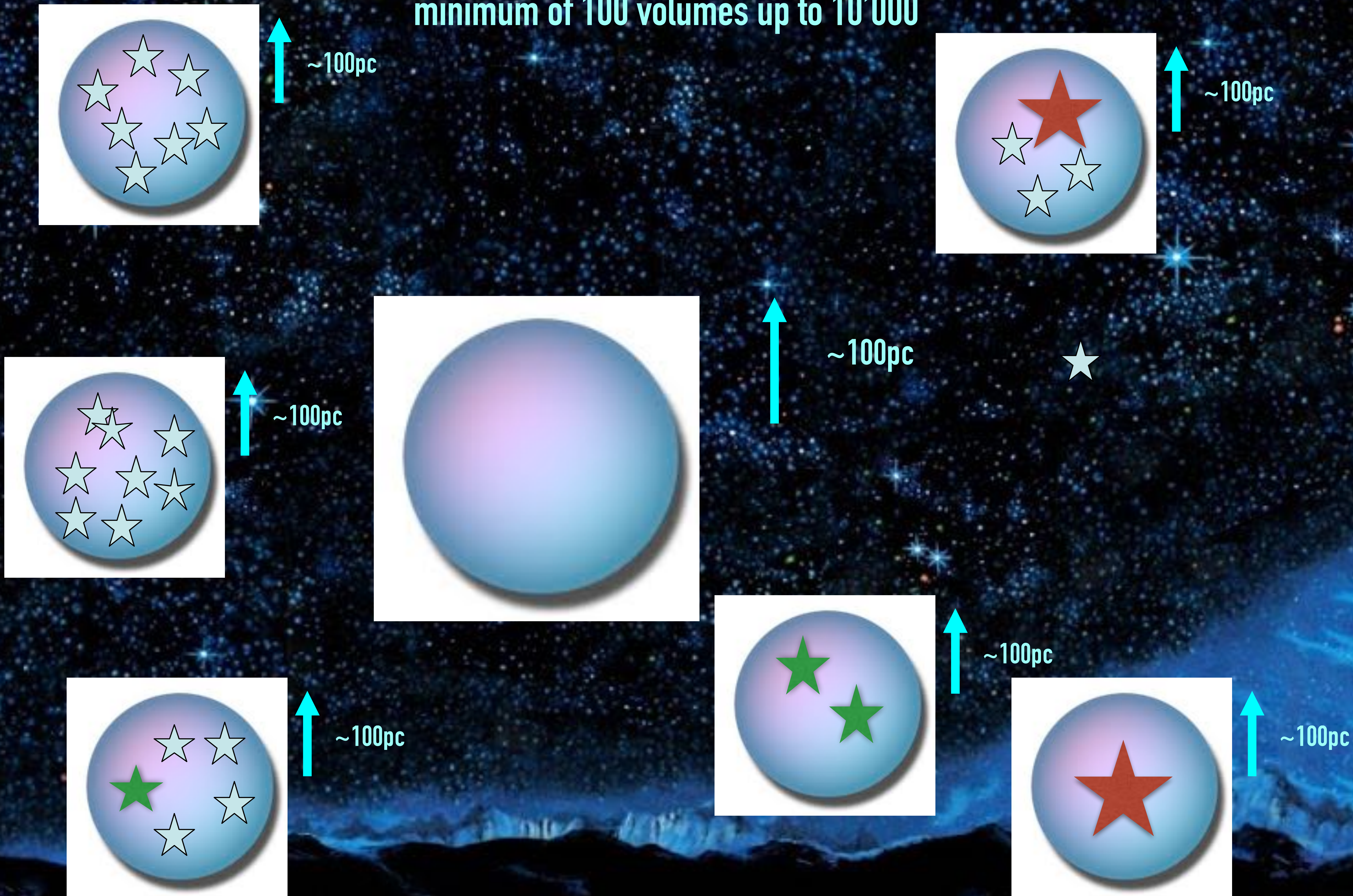

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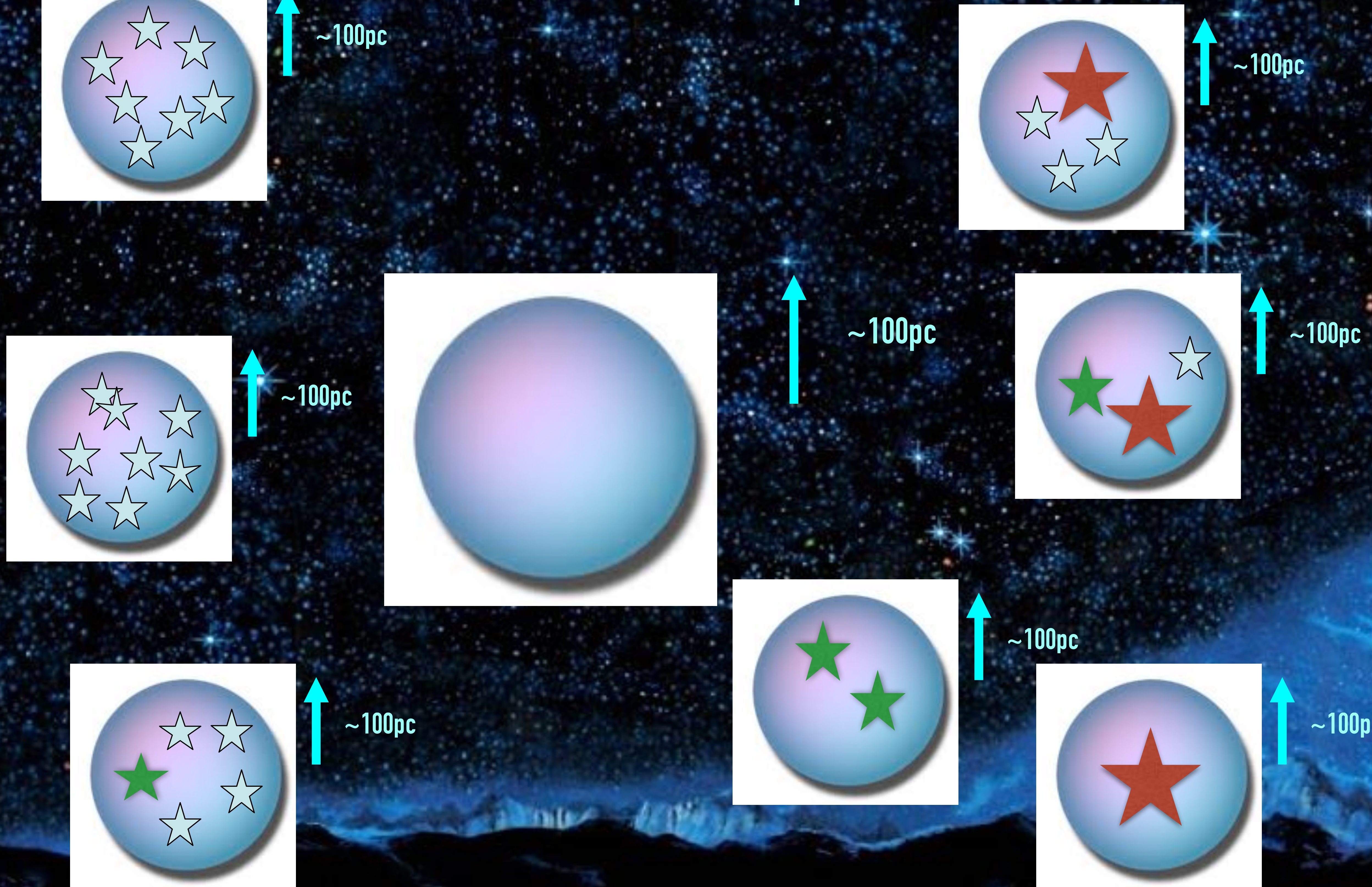

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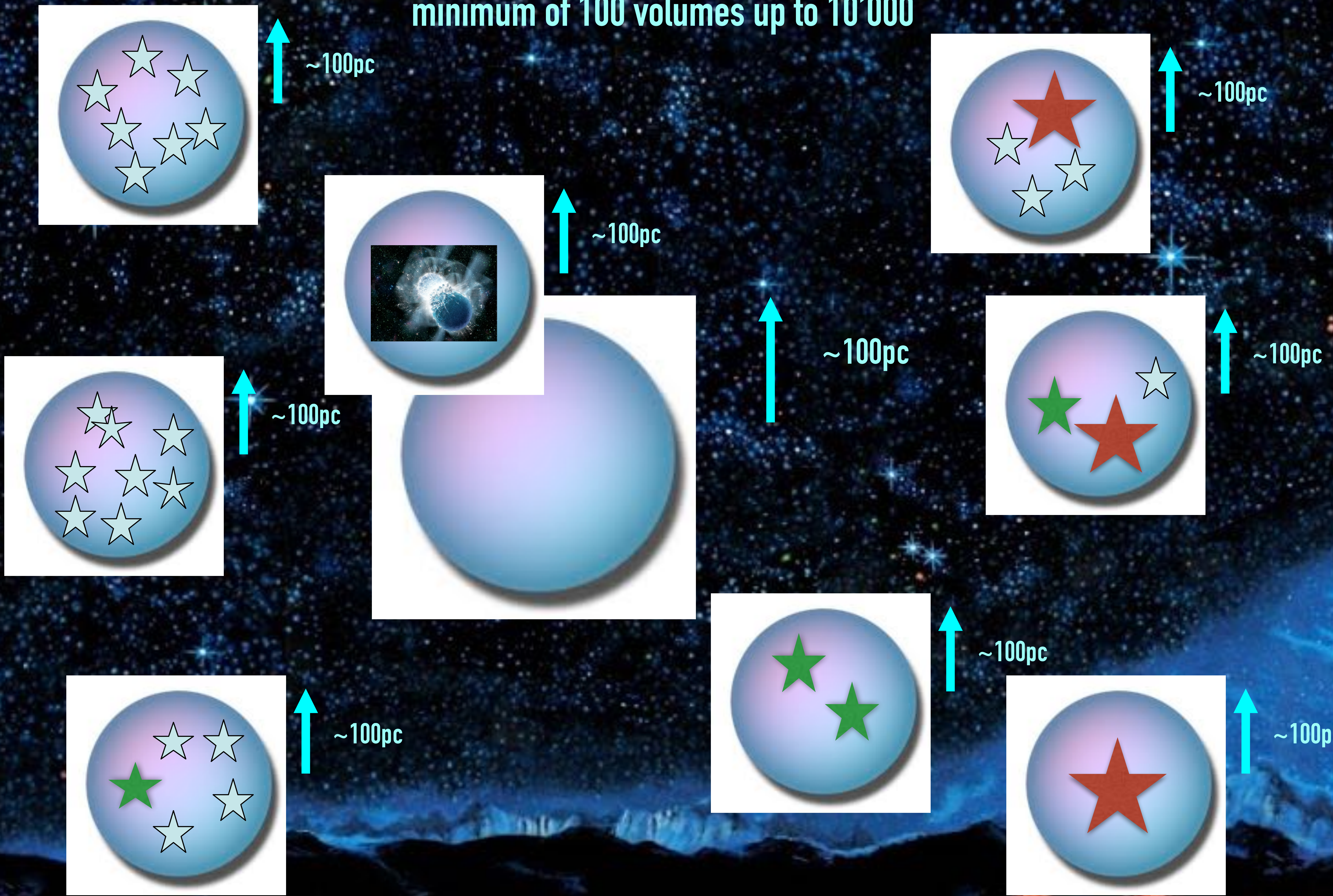
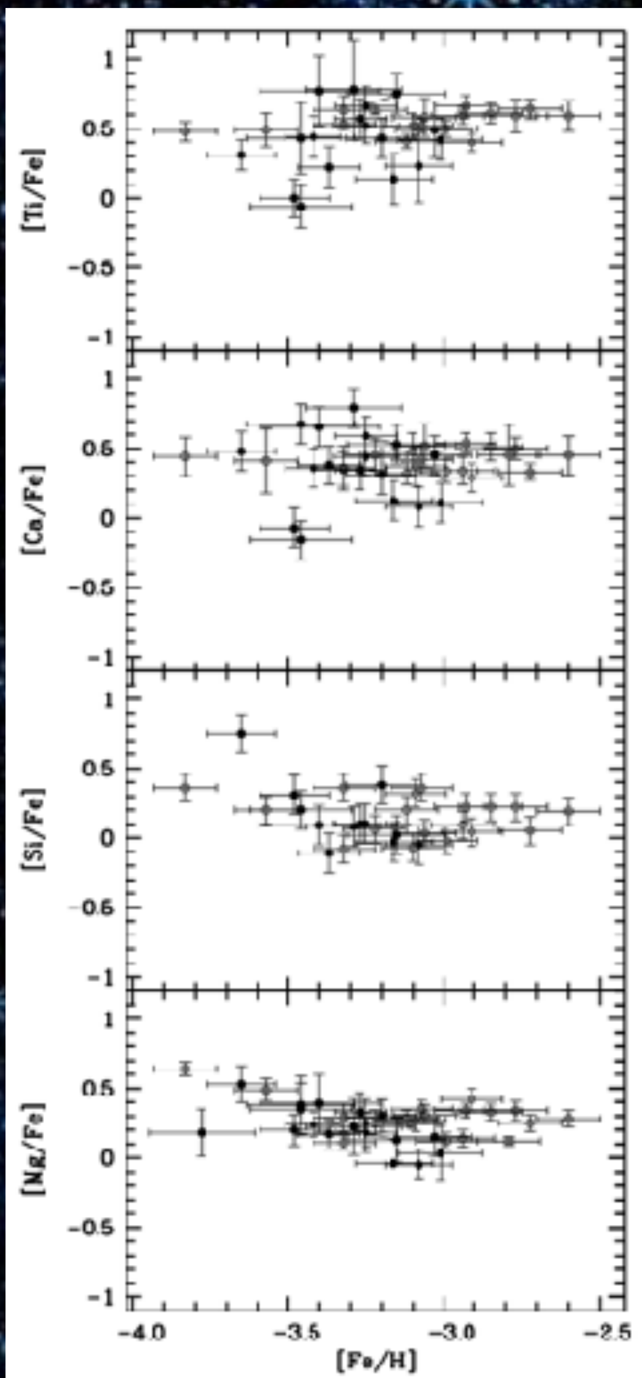
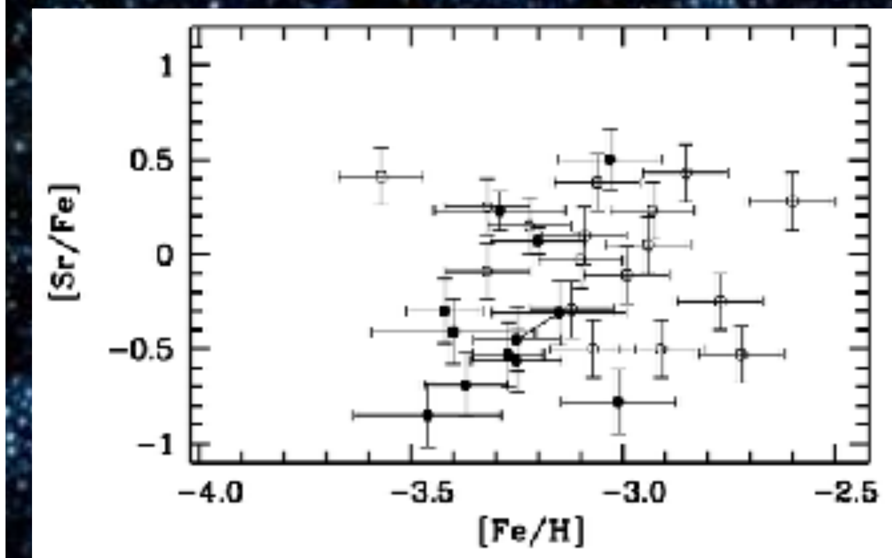


# Galaxy Evolution via Montecarlo Sampling

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

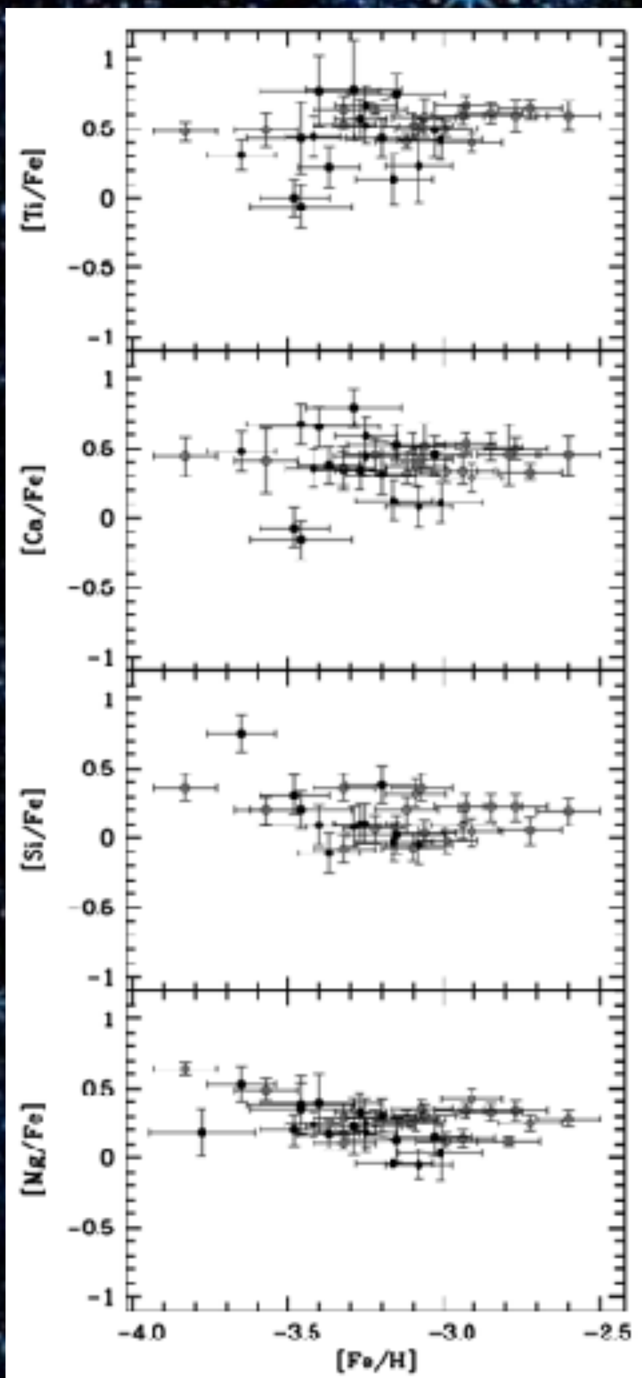



Bonifacio+12

# Galaxy Evolution via Montecarlo Sampling

GEMS




Bonifacio+12

Problem:
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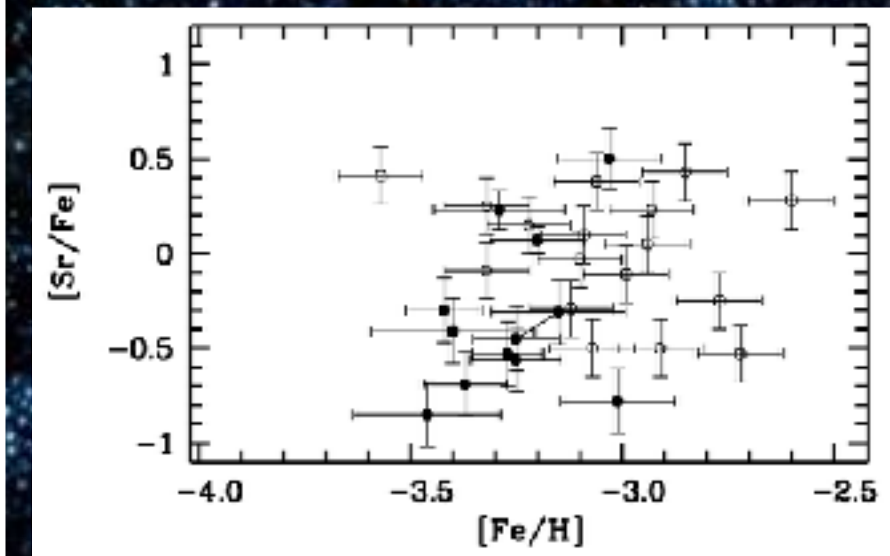
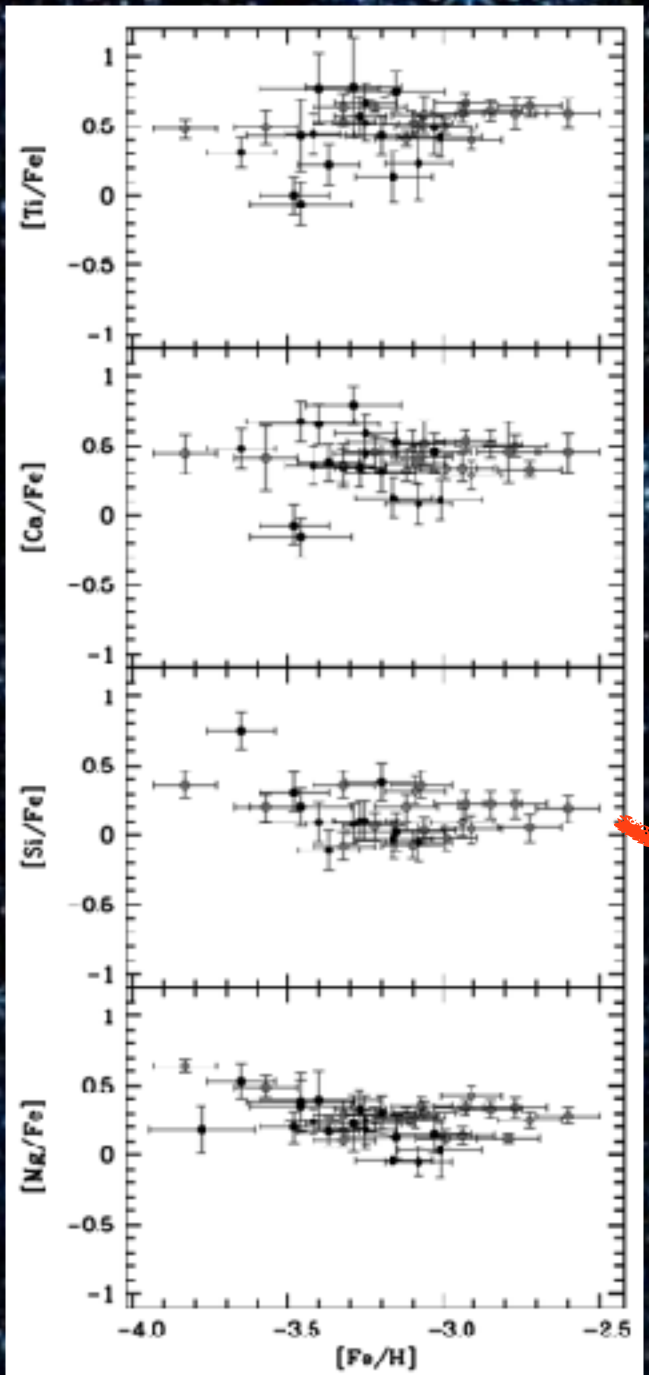


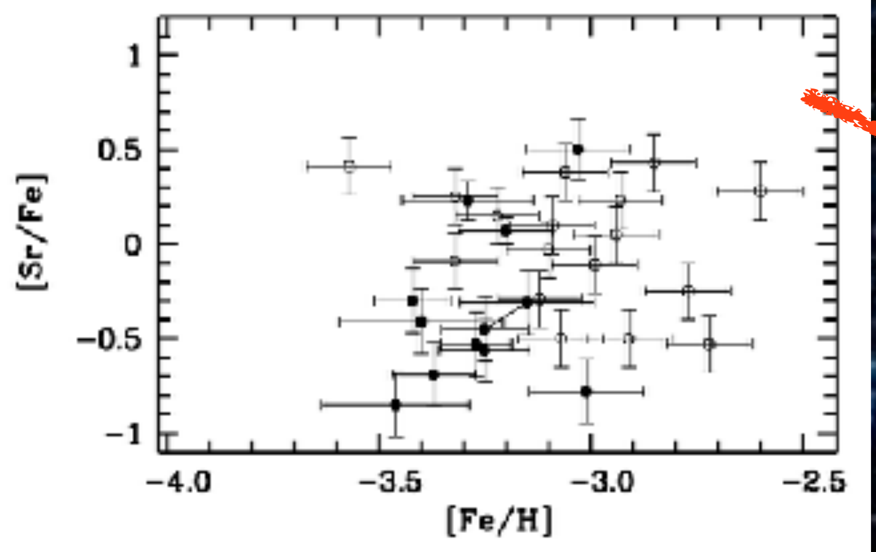

Solution:
The volumes in which the ISM is well mixed are discrete. Assuming a SNe bubble as typical volume with a low regime of star formation the IMF is not fully sampled.
This promotes spread among different volumes if nucleosynthesis of the element is is different among different SNe,

# Galaxy Evolution via Montecarlo Sampling

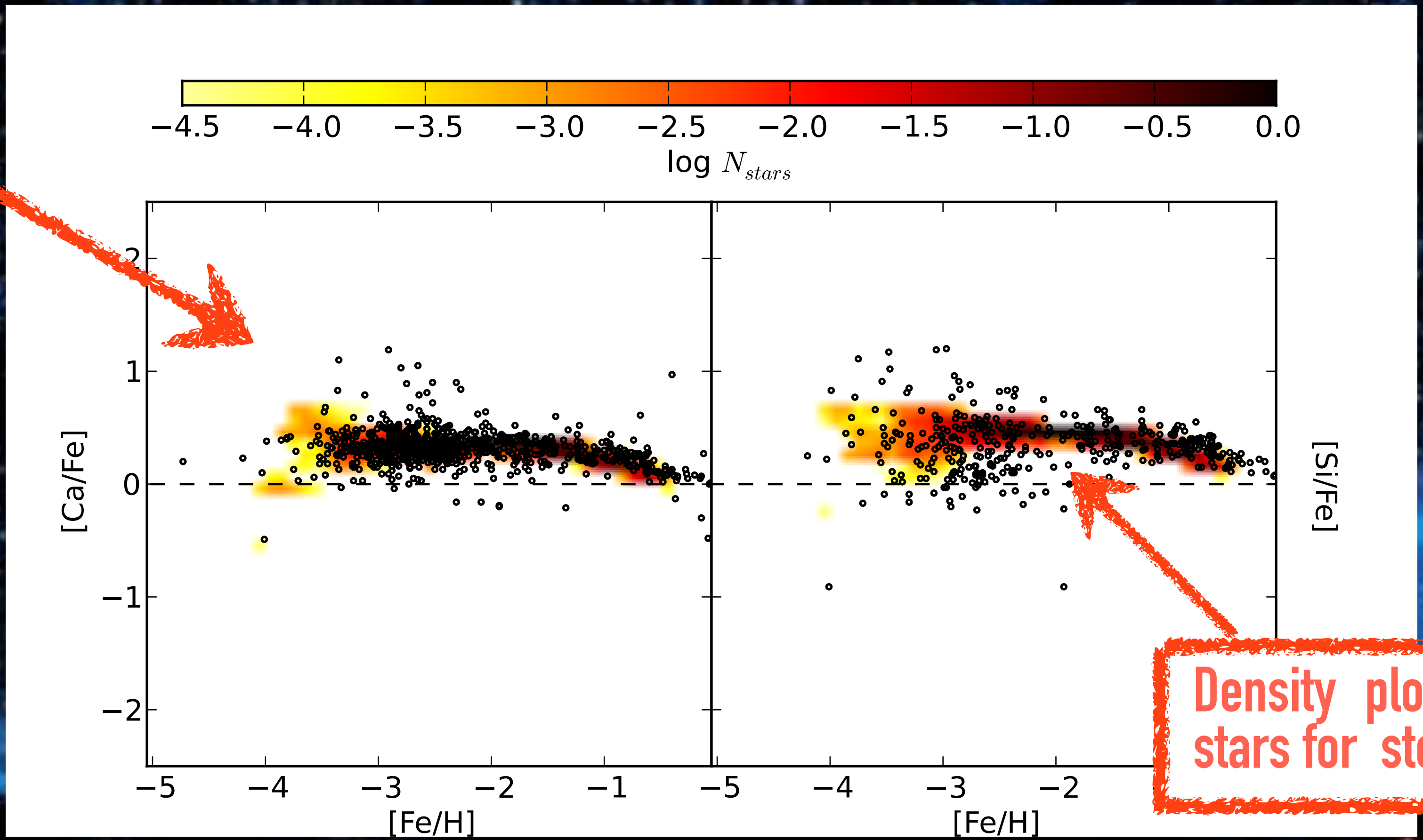
Problem:
Neutron capture elements present a spread alpha elements do not




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

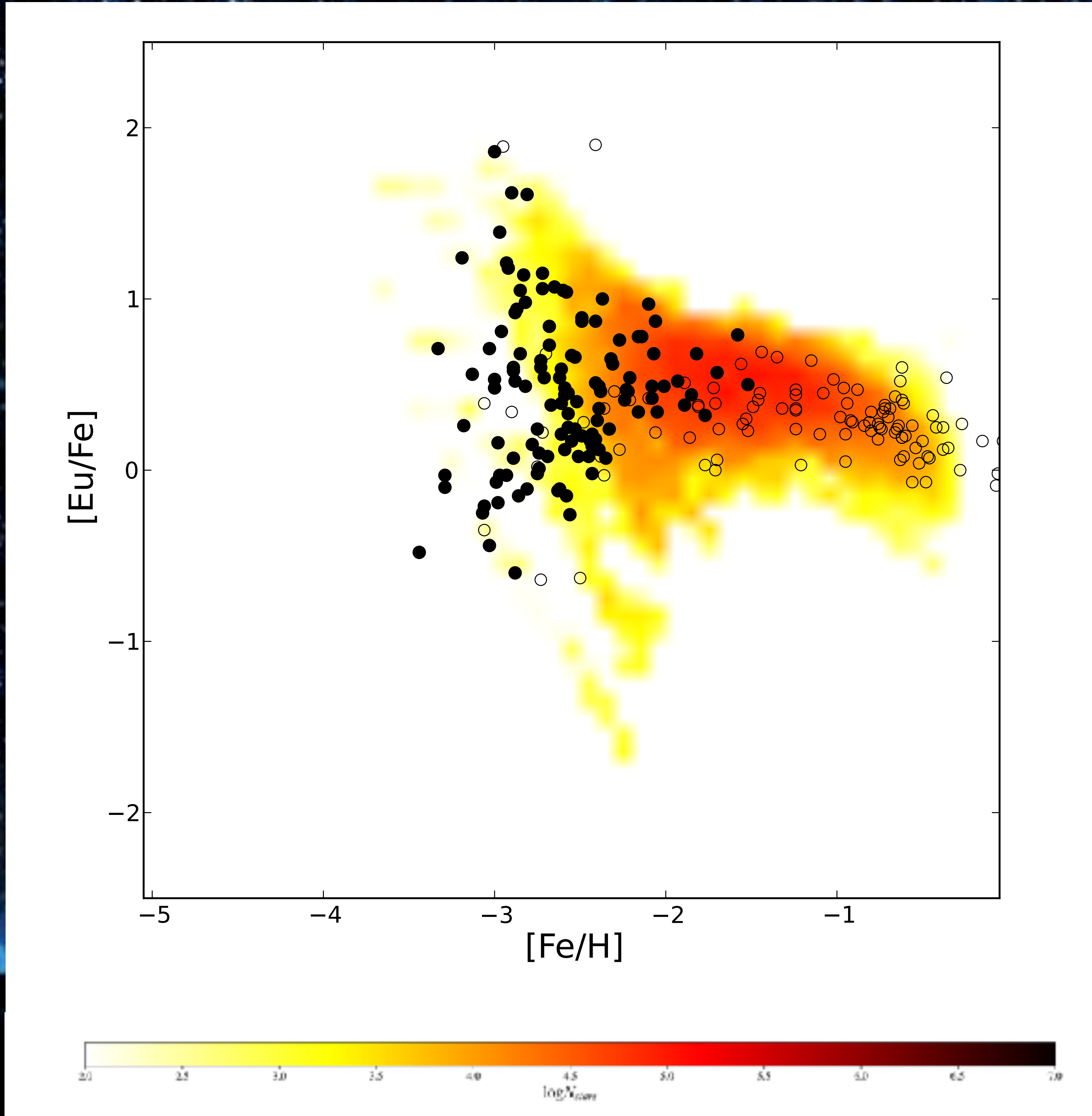
# Neutron stars mergers

## delay for the merging 1Myr

Cescutti+15

Results with alpha=0.04 (NSM/SNe)

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



# Neutron star mergers

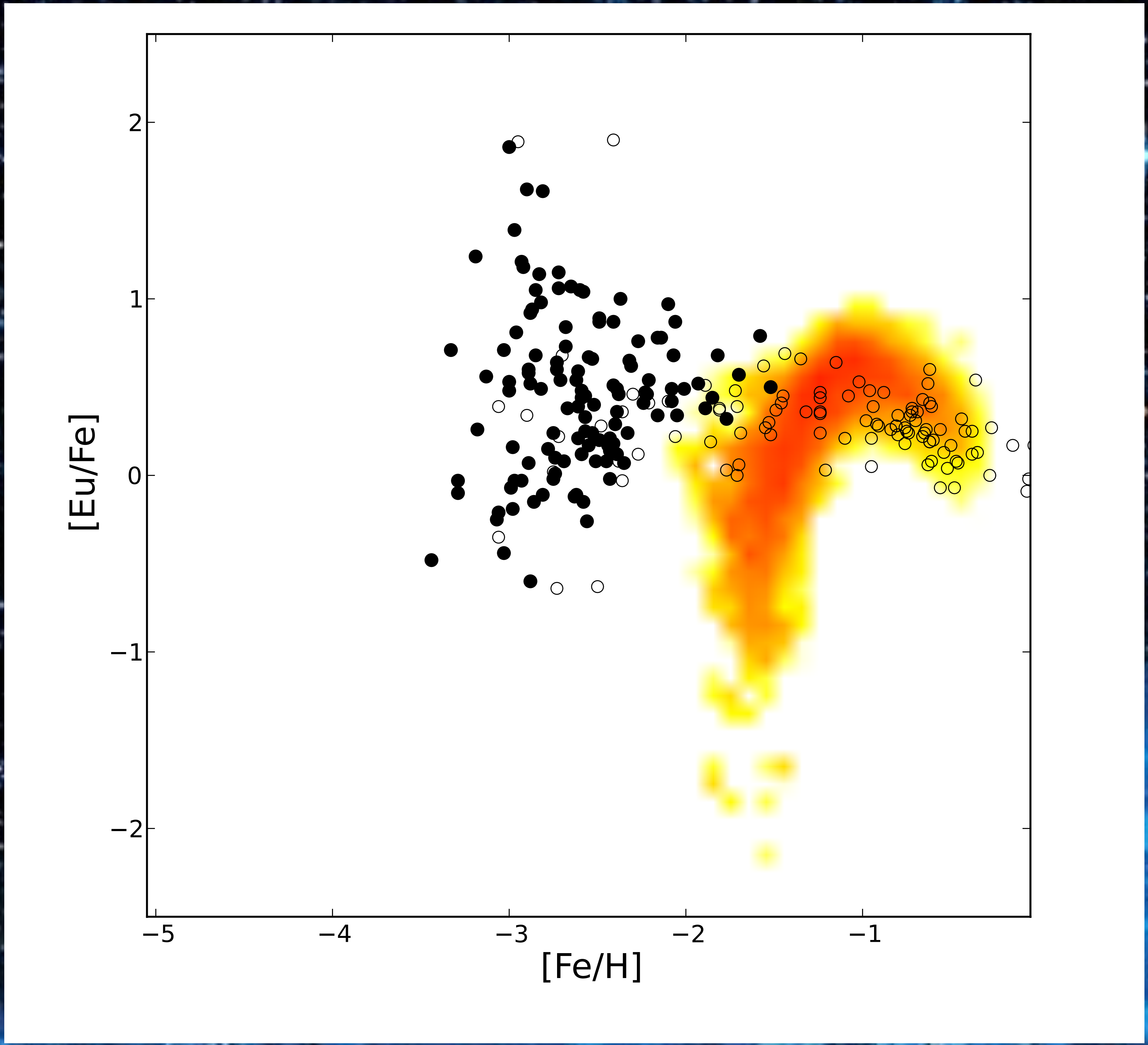
delay for the merging 100 Myr

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?

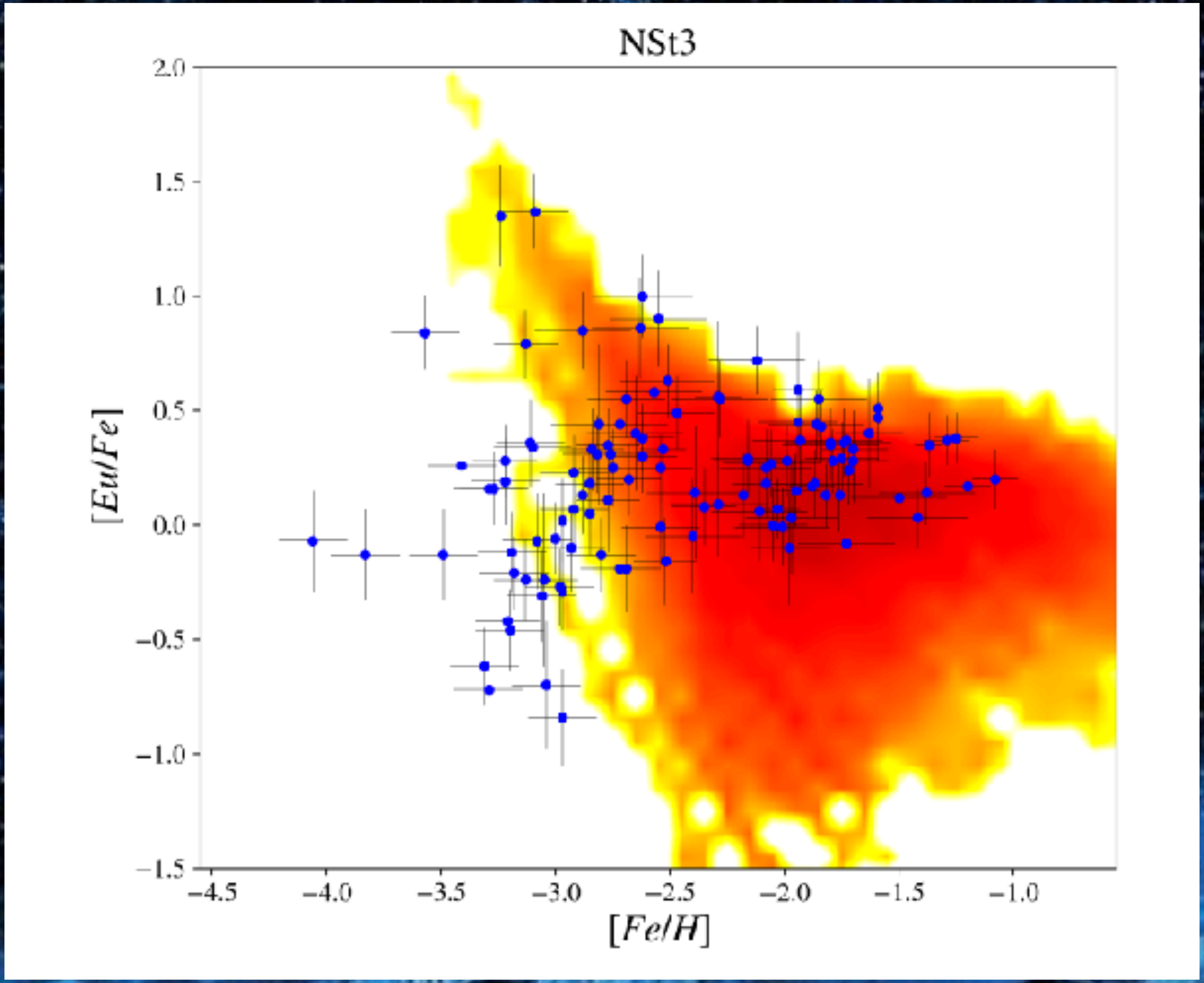



This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the astro-ph Shen+2014

# Neutron star mergers

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

Cavallo+22

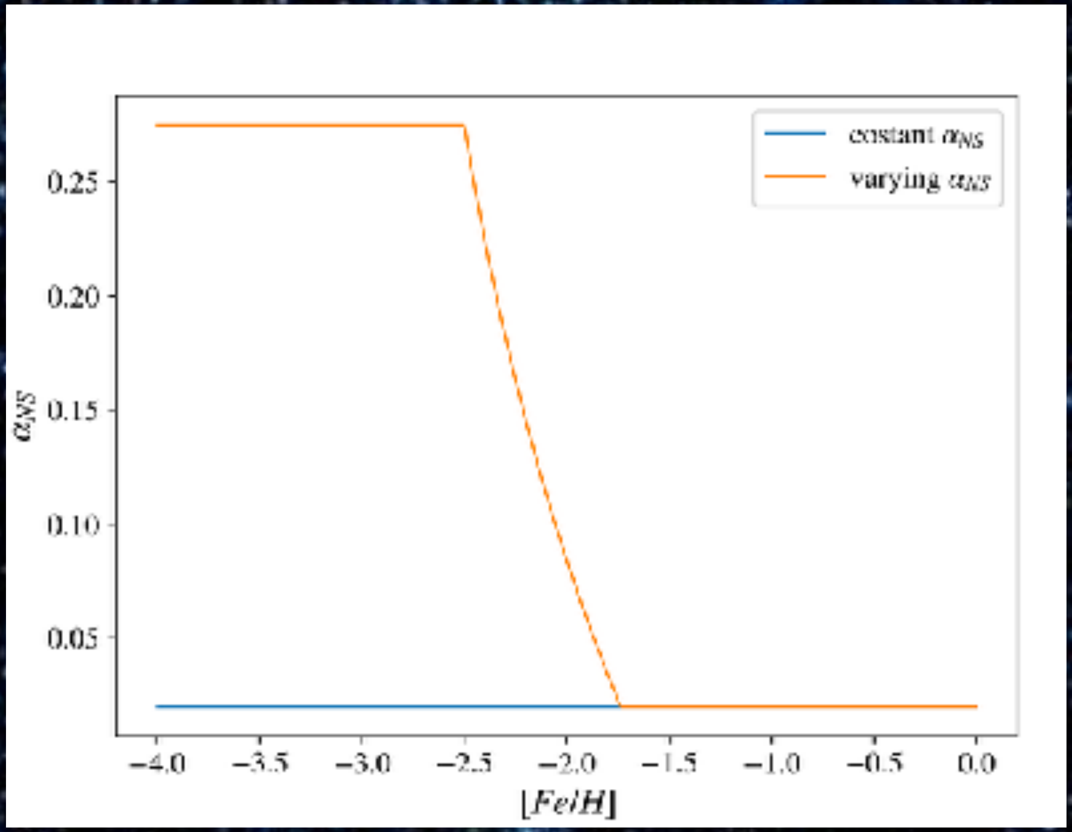



see also Simonetti+19 and Cotè+19

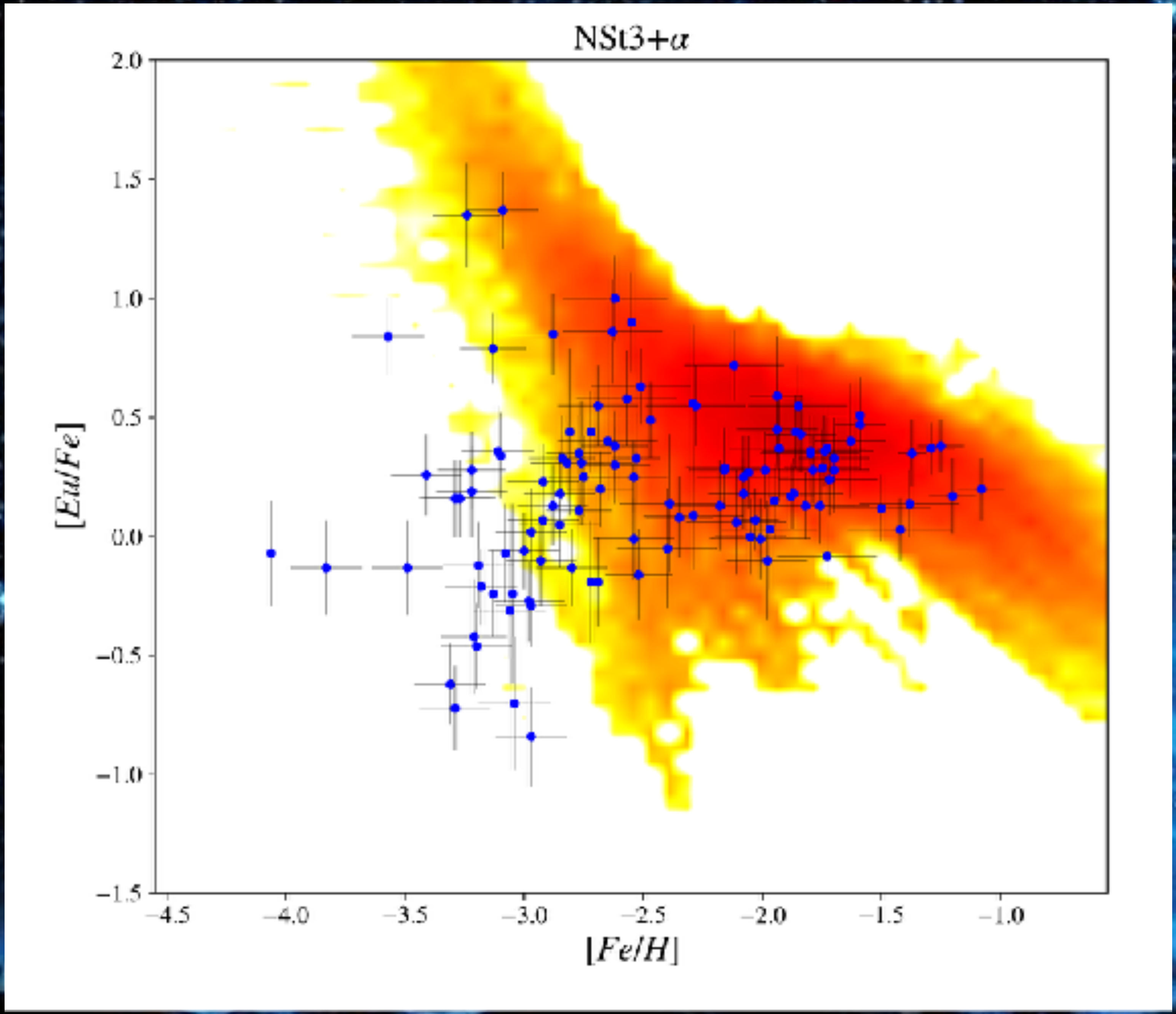
# NSM with alpha variations

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

Cavallo+22




similar to Simonetti+19




Cavallo+22


Other solutions?

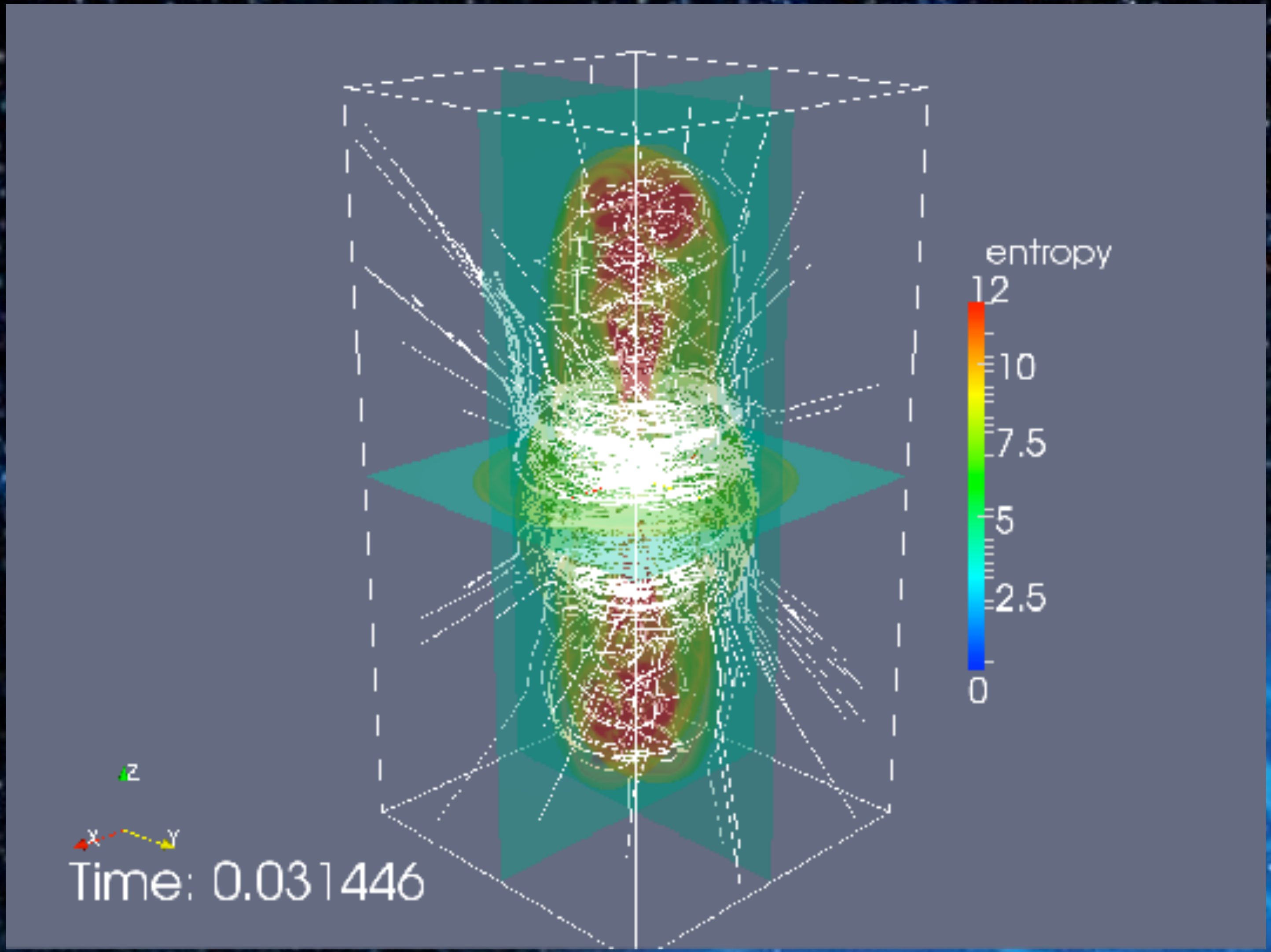
# Magneto Rotationally Driven SN scenario (MRD)

(Winteler+12, Nishimura+15, Reichert+21…)

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.

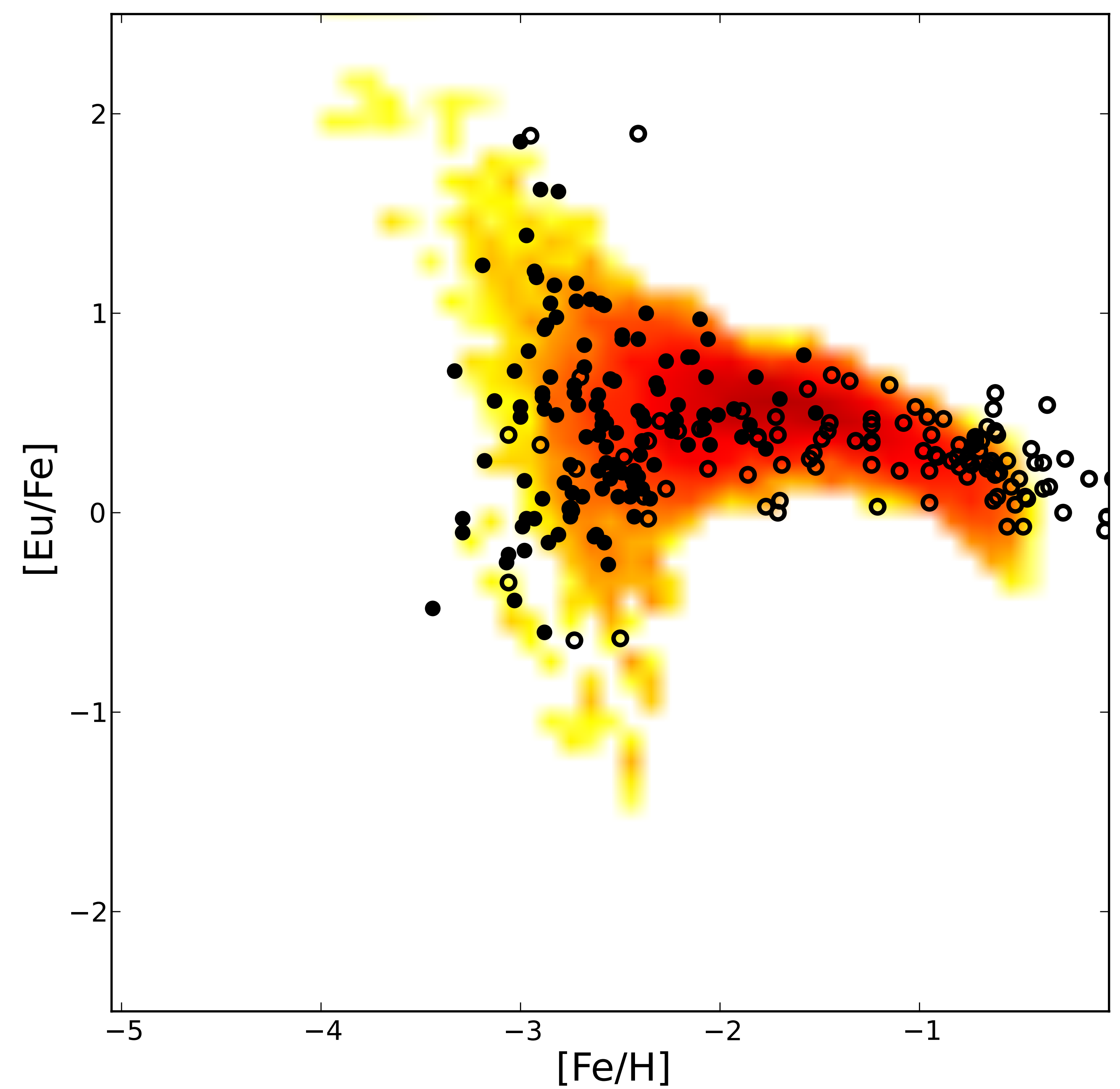


# Magneto Rotationally Driven SN scenario (MRD) 10%

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

site

time scale

yields

| | 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 | nucleosynthesis available (but . . .) |

Karakas+12

Early Galaxy

# 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

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

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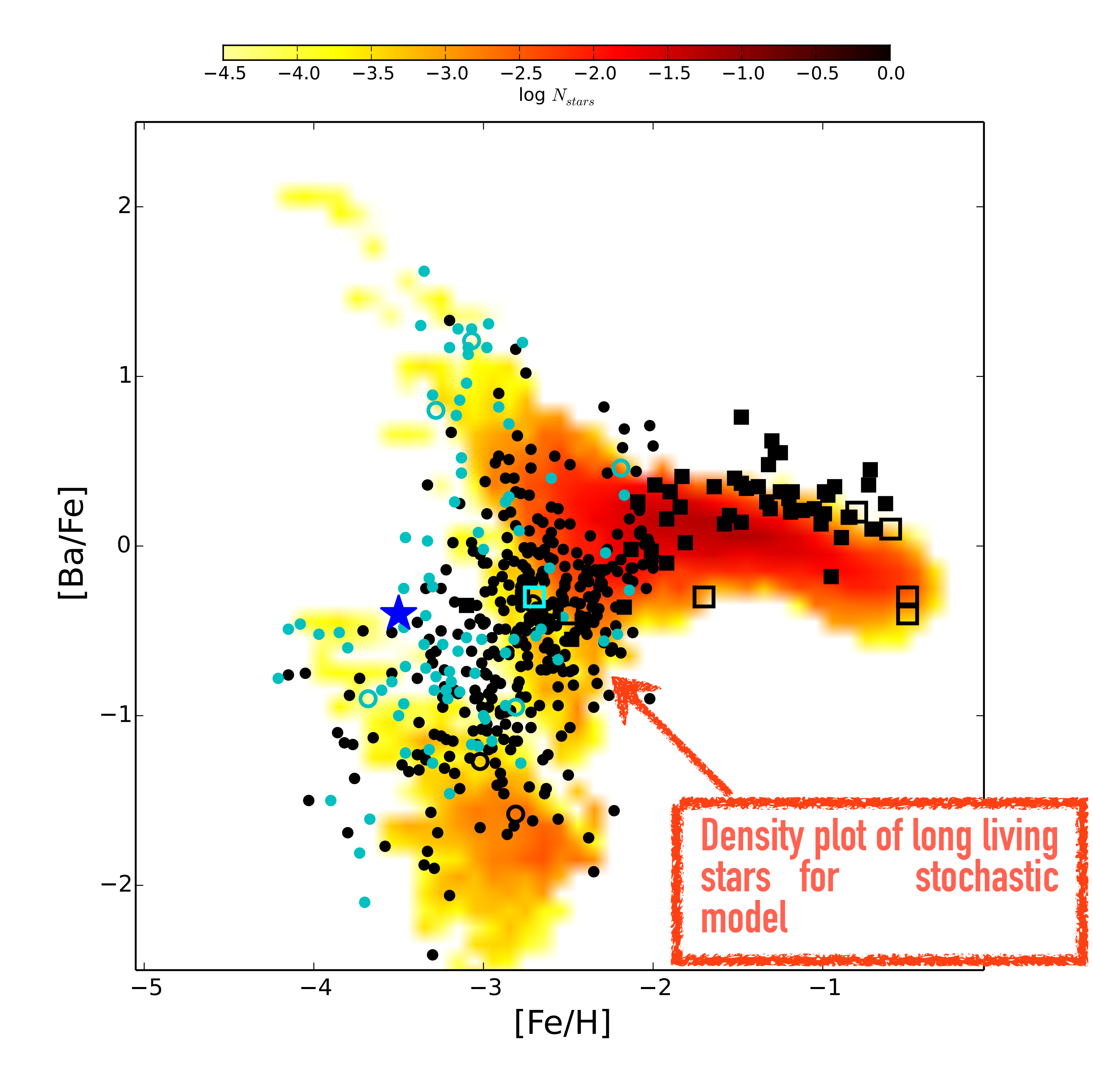


Density plot of long living stars for stochastic model

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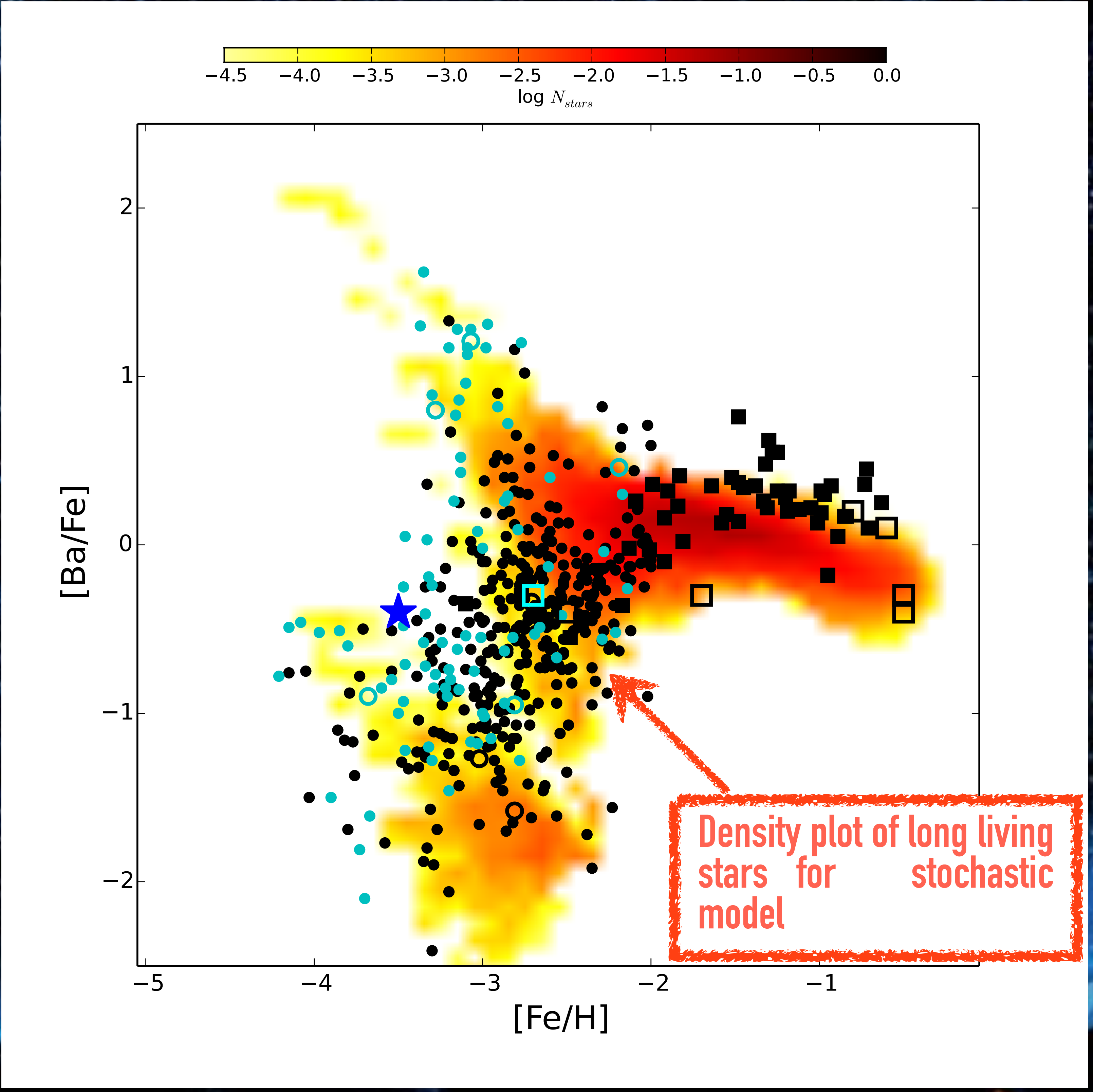
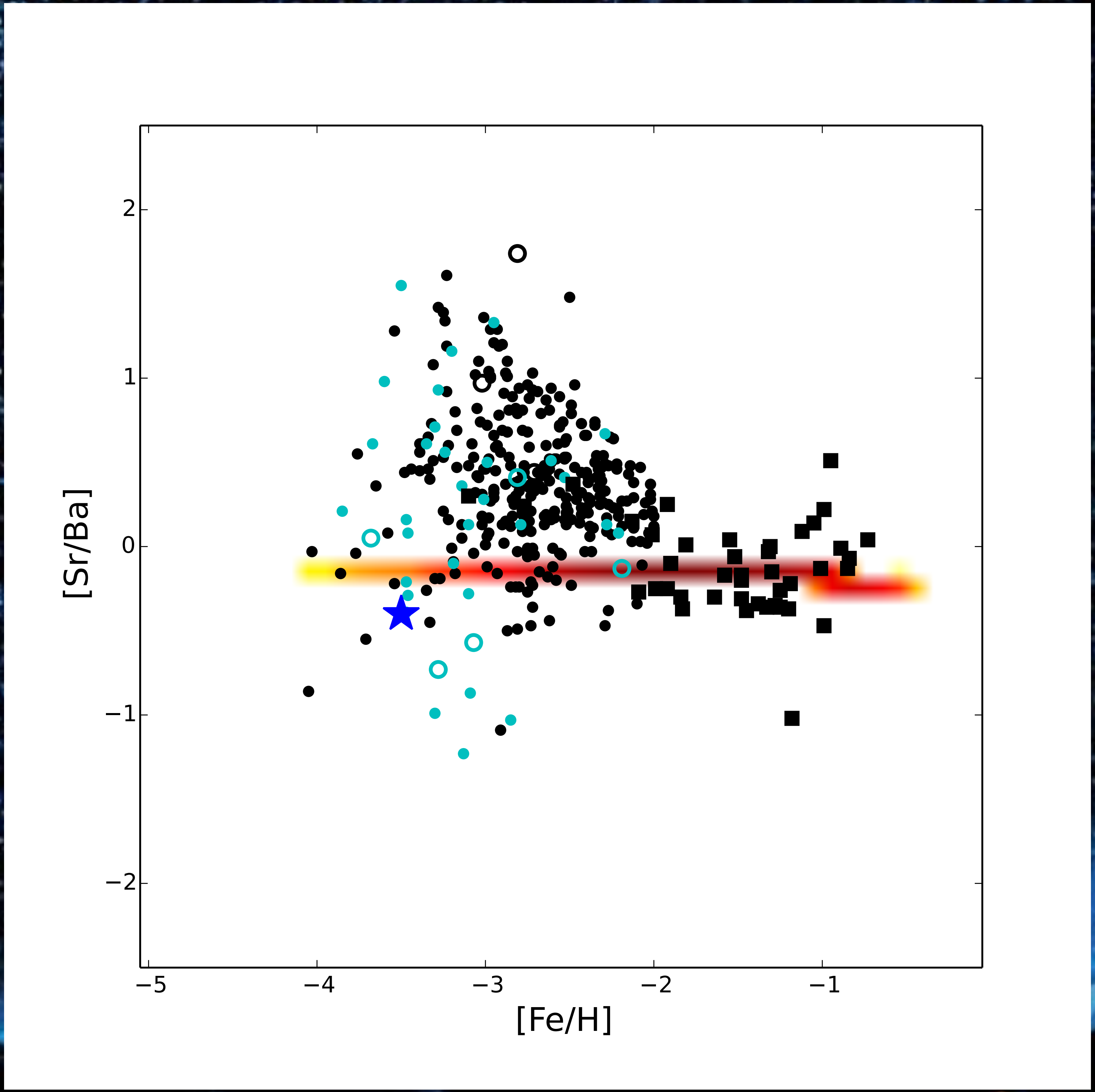



We can reproduce the [Ba/Fe] spread...

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)



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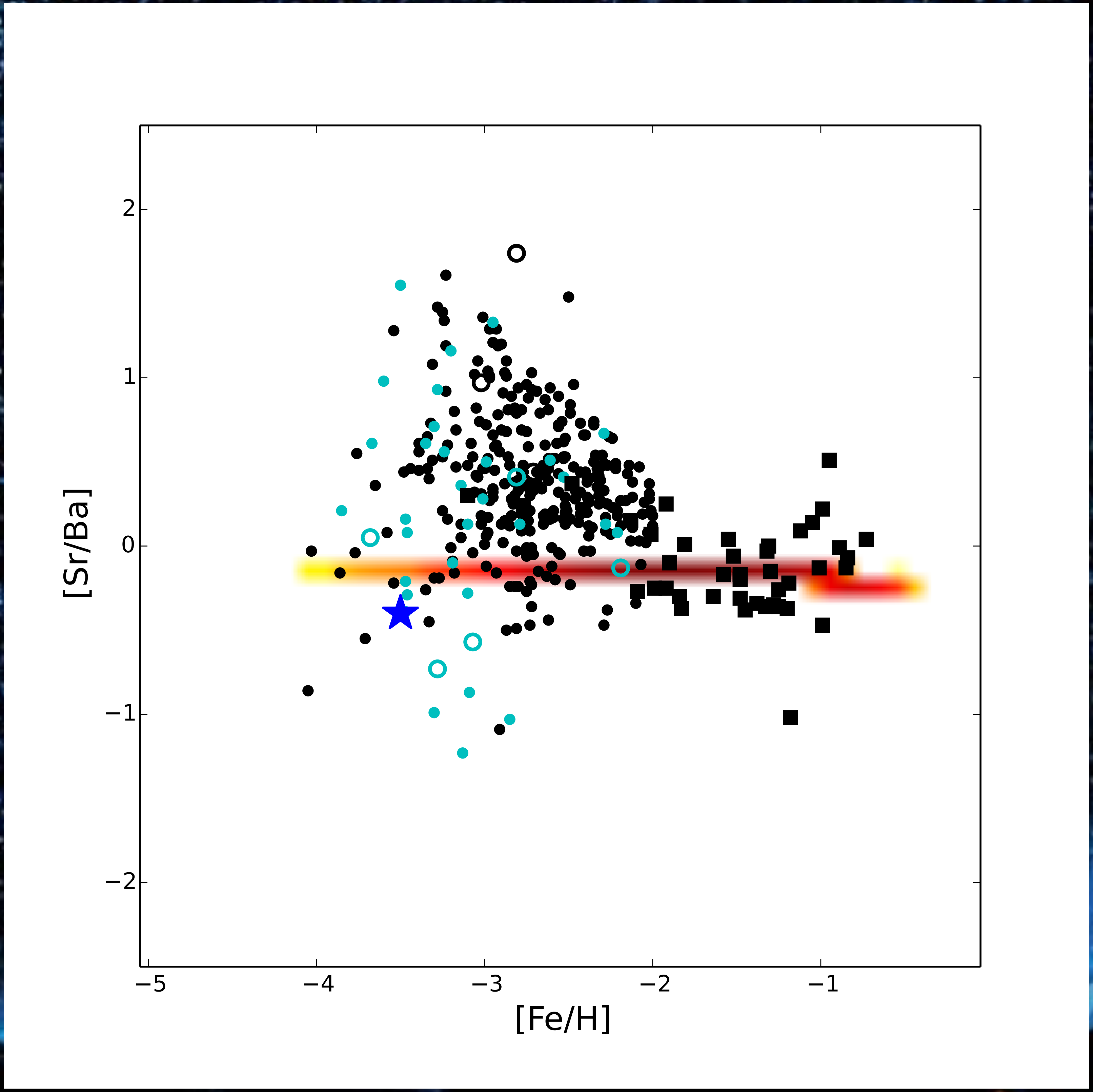


It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

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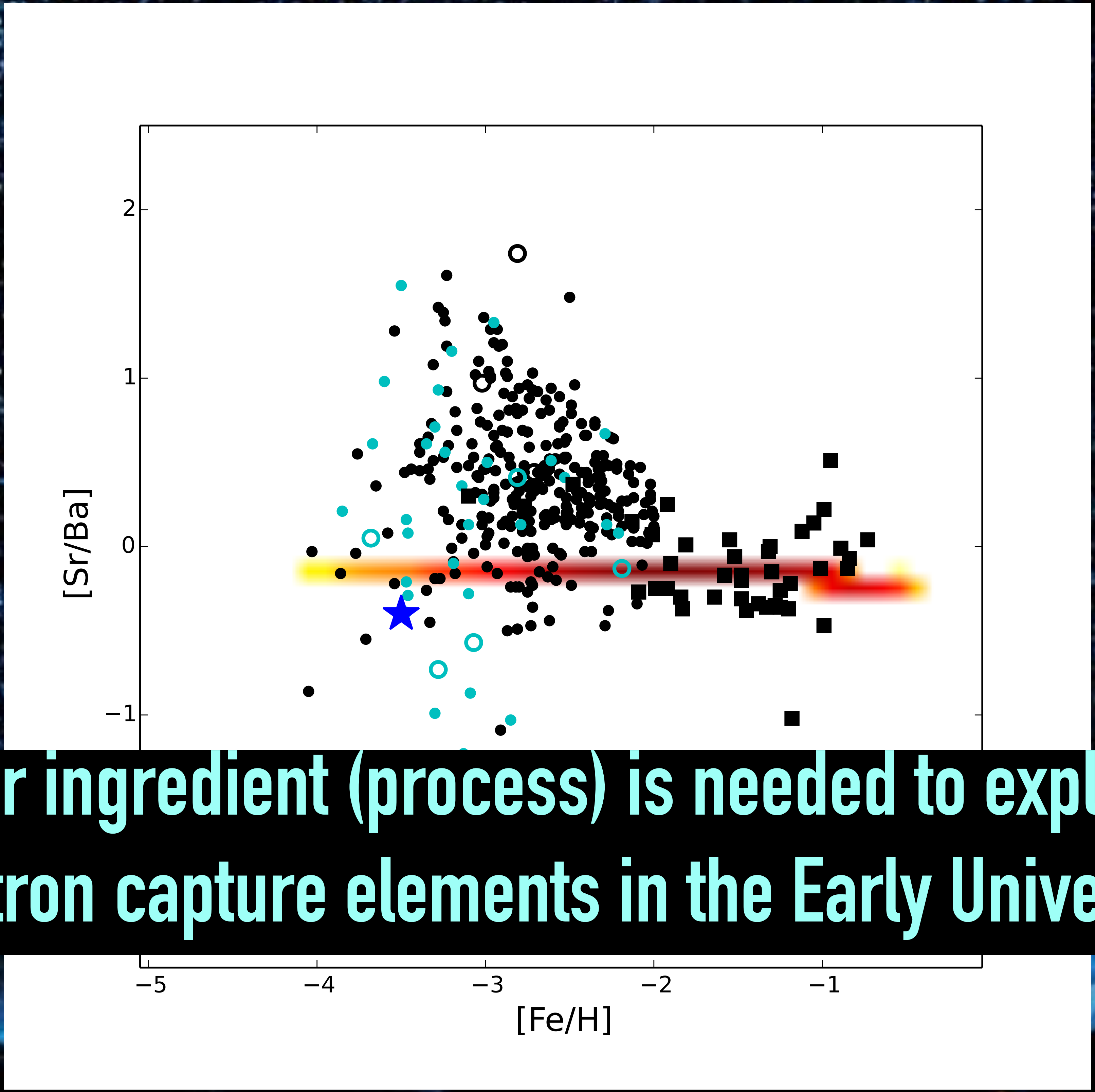



It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

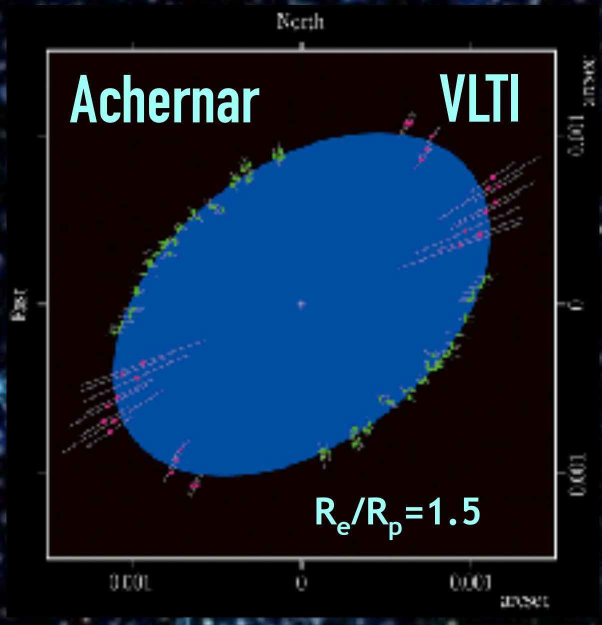
**Another ingredient (process) is needed to explain the neutron capture elements in the Early Universe!**

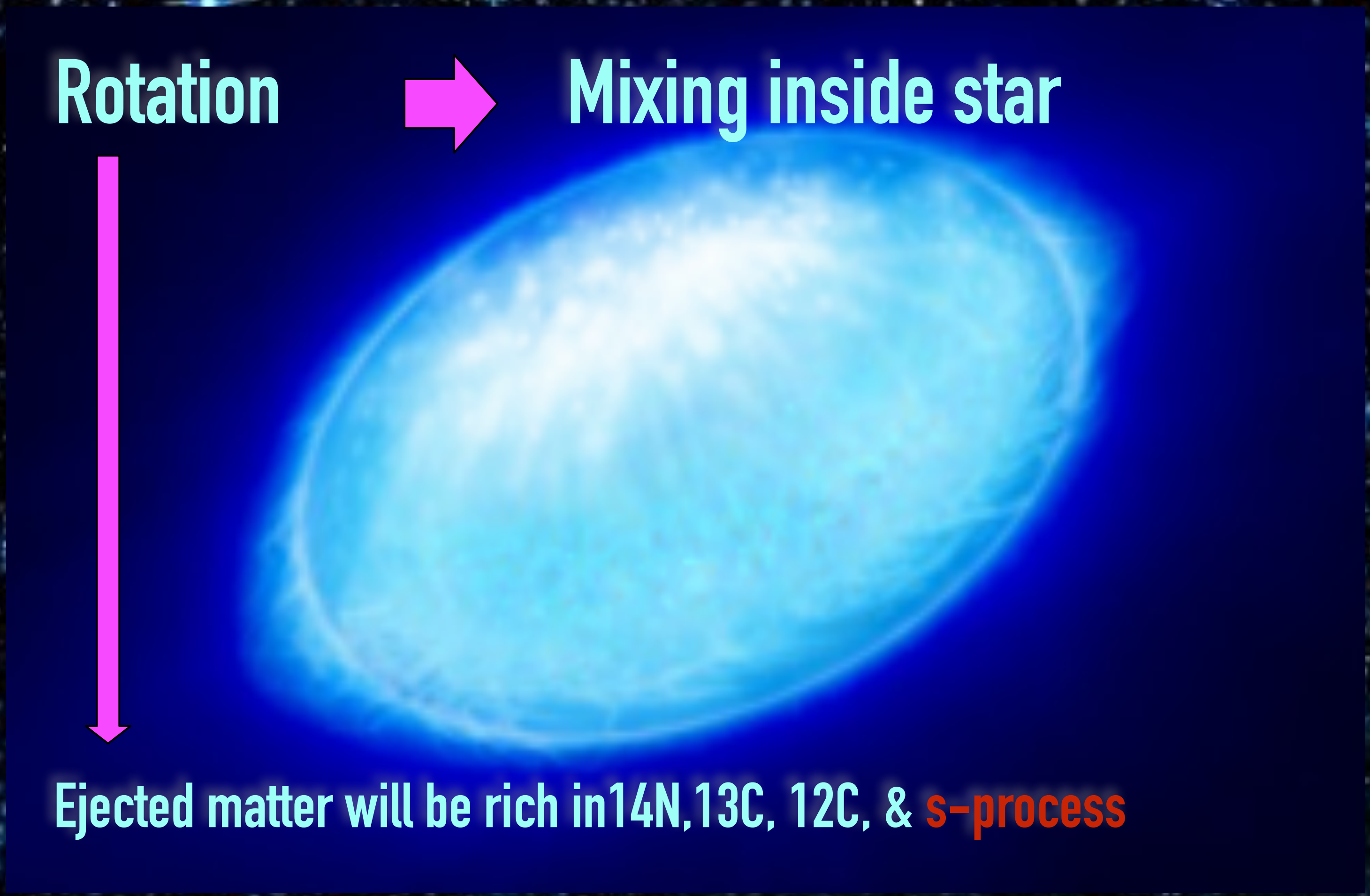
# Rotating massive stars in the early Universe

In the Early Universe

Low metals: stars rotate faster (more

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 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)

# Rotating massive stars in the early Universe

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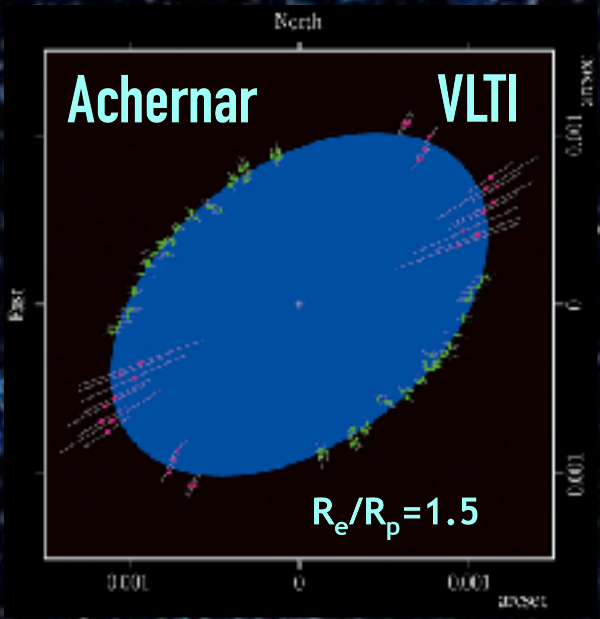


Rotation → Mixing inside star

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)
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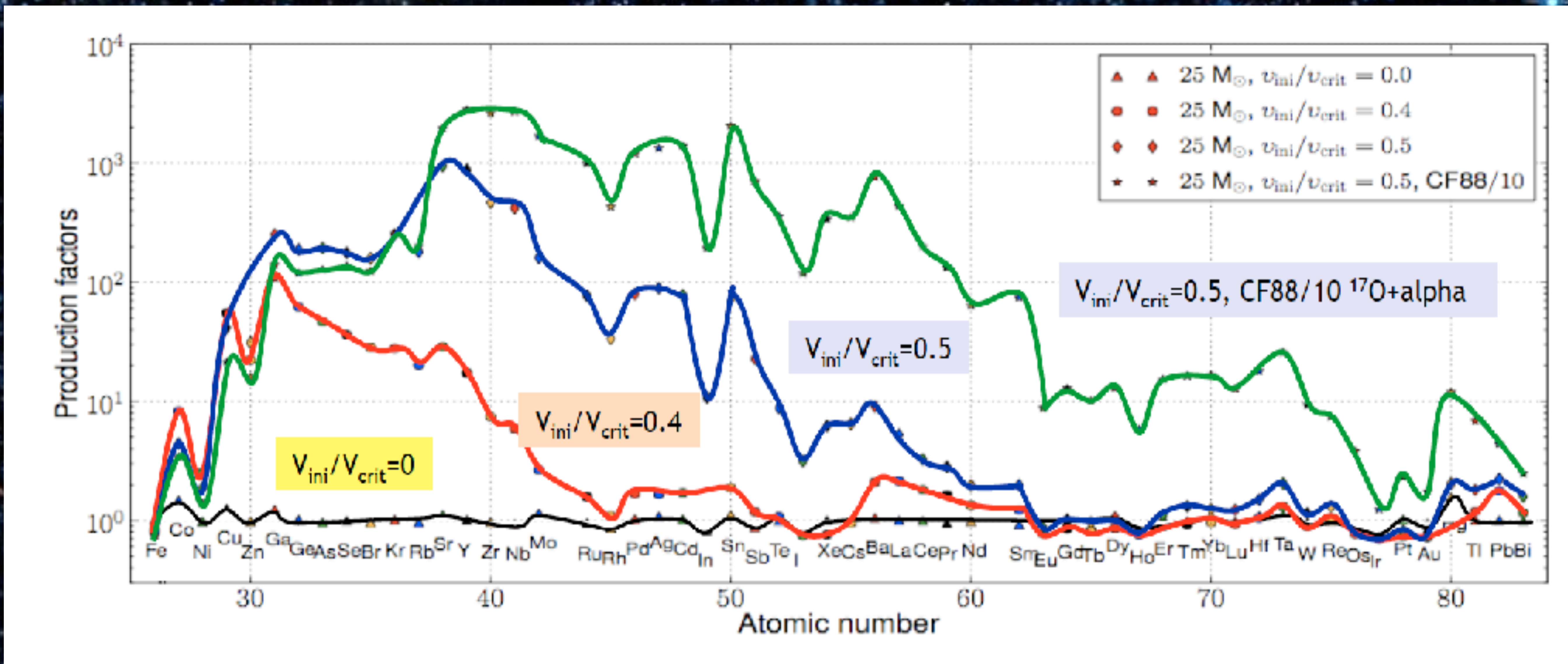
(4) Early production of Be and B by cosmic ray spallation (Prantzos 2012)

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)



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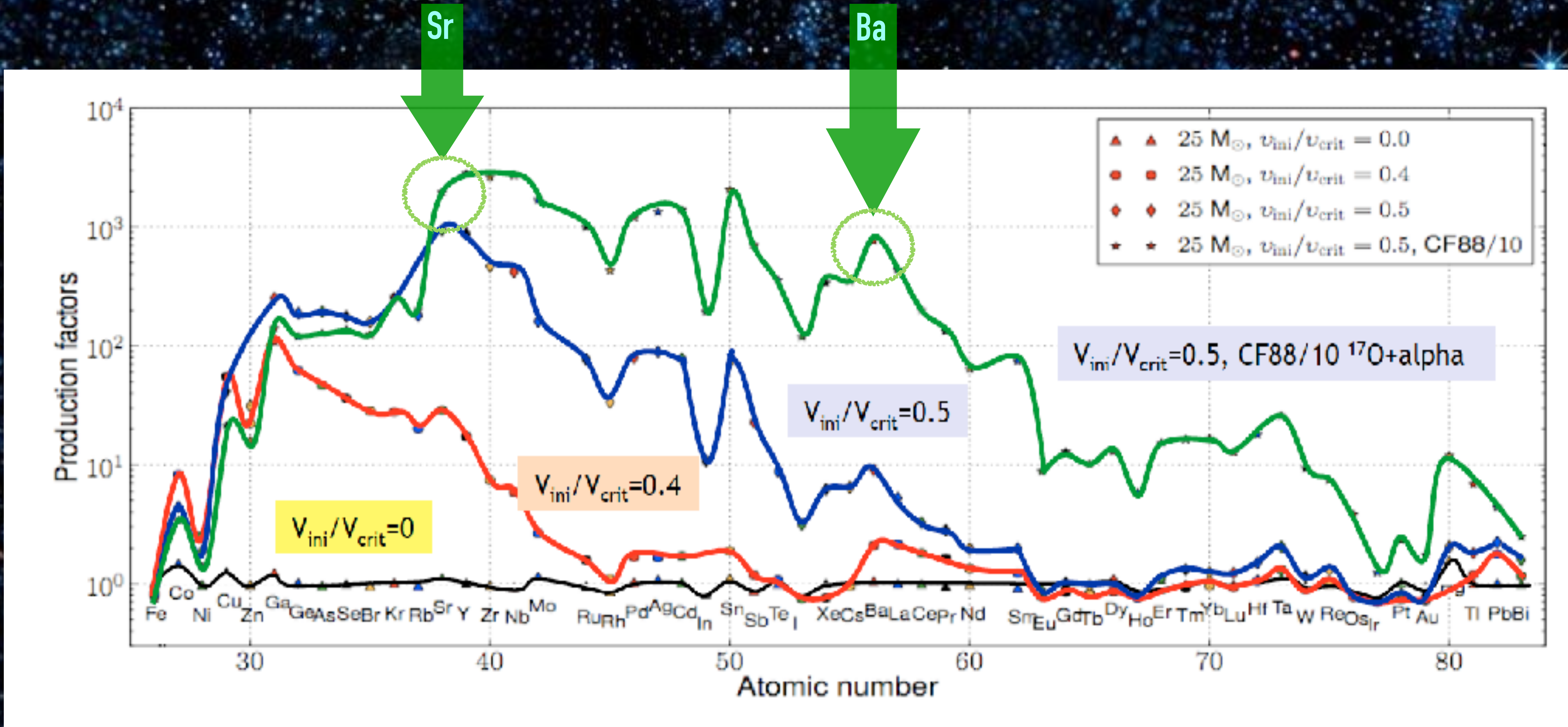
Rotating massive stars can contribute to s-process elemen



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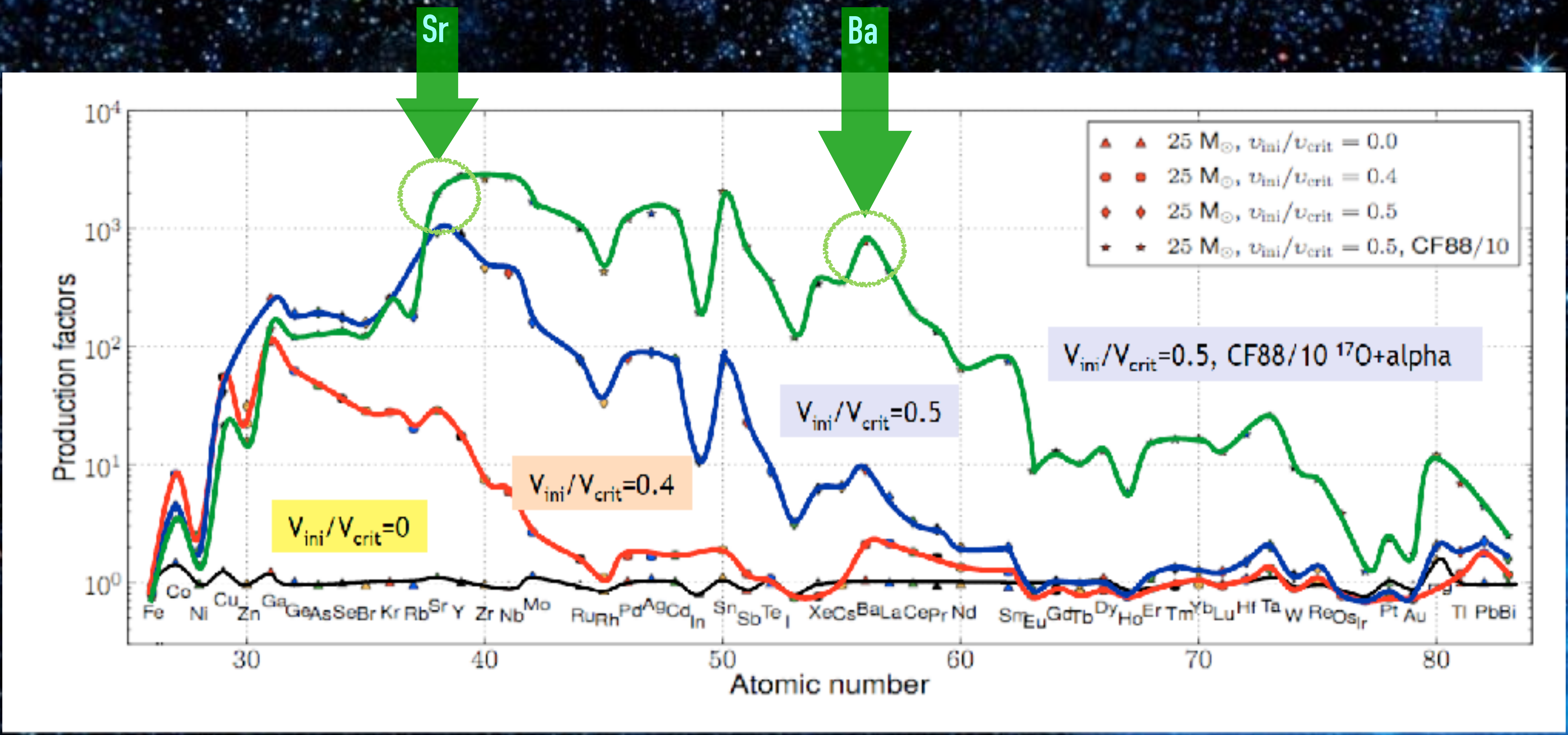



Can they explain the puzzles for Sr and Ba in halo?

# Neutron capture elements

| | 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 | |

Early Galaxy

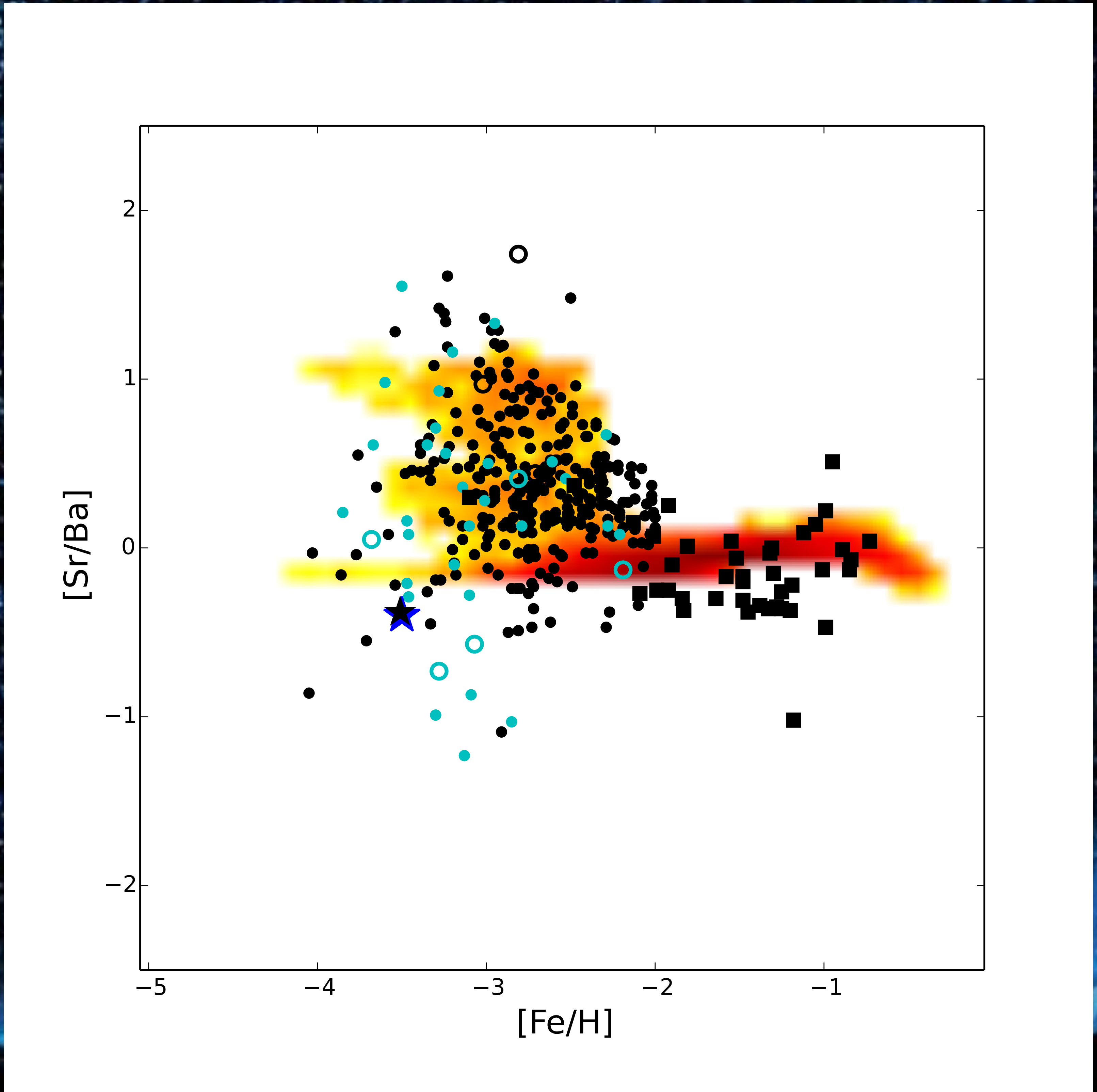
# s-process from rotating massive stars

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

Cescutti +14

# s-process from rotating massive stars

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

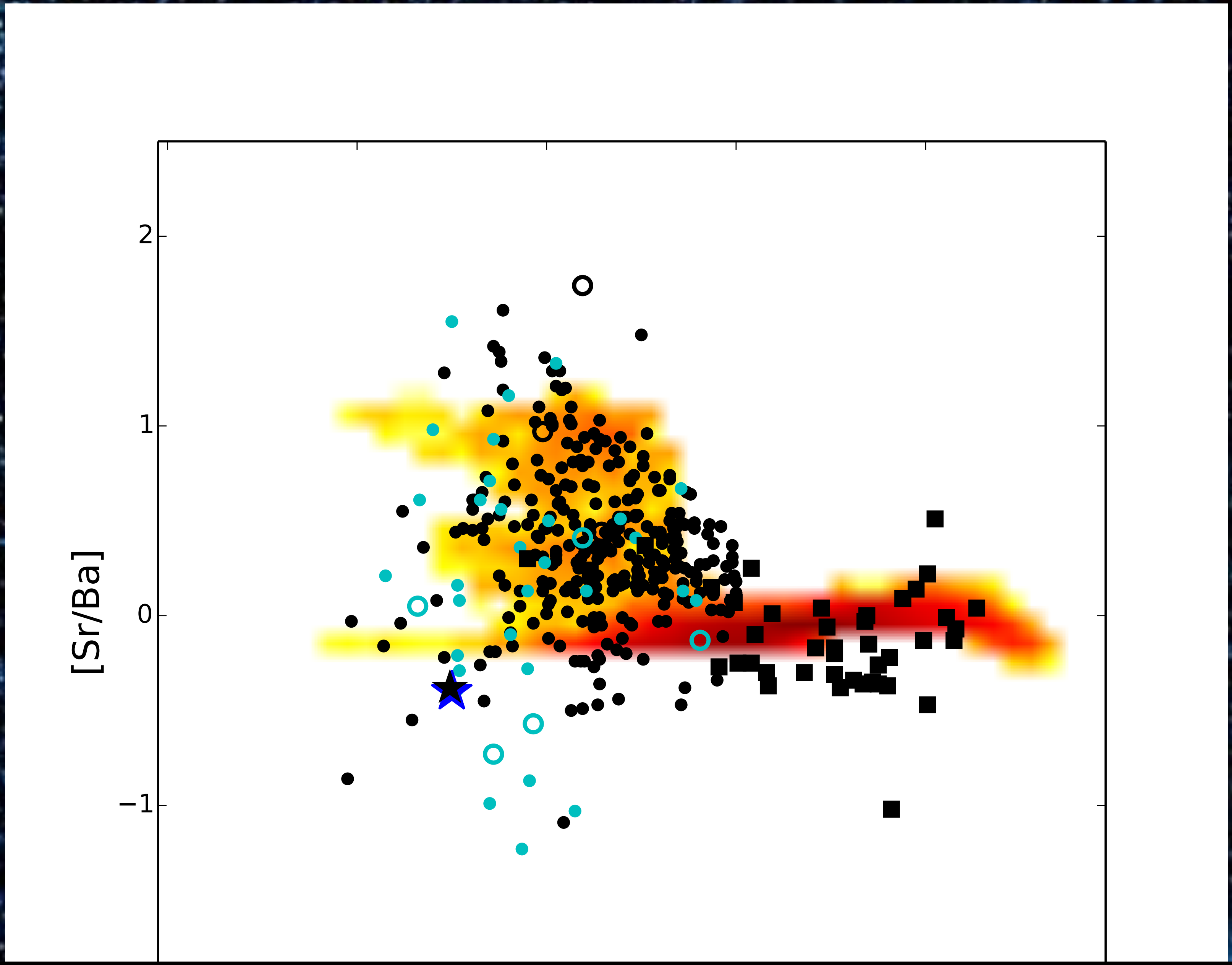



Cescutti +14

# s-process from rotating massive stars

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

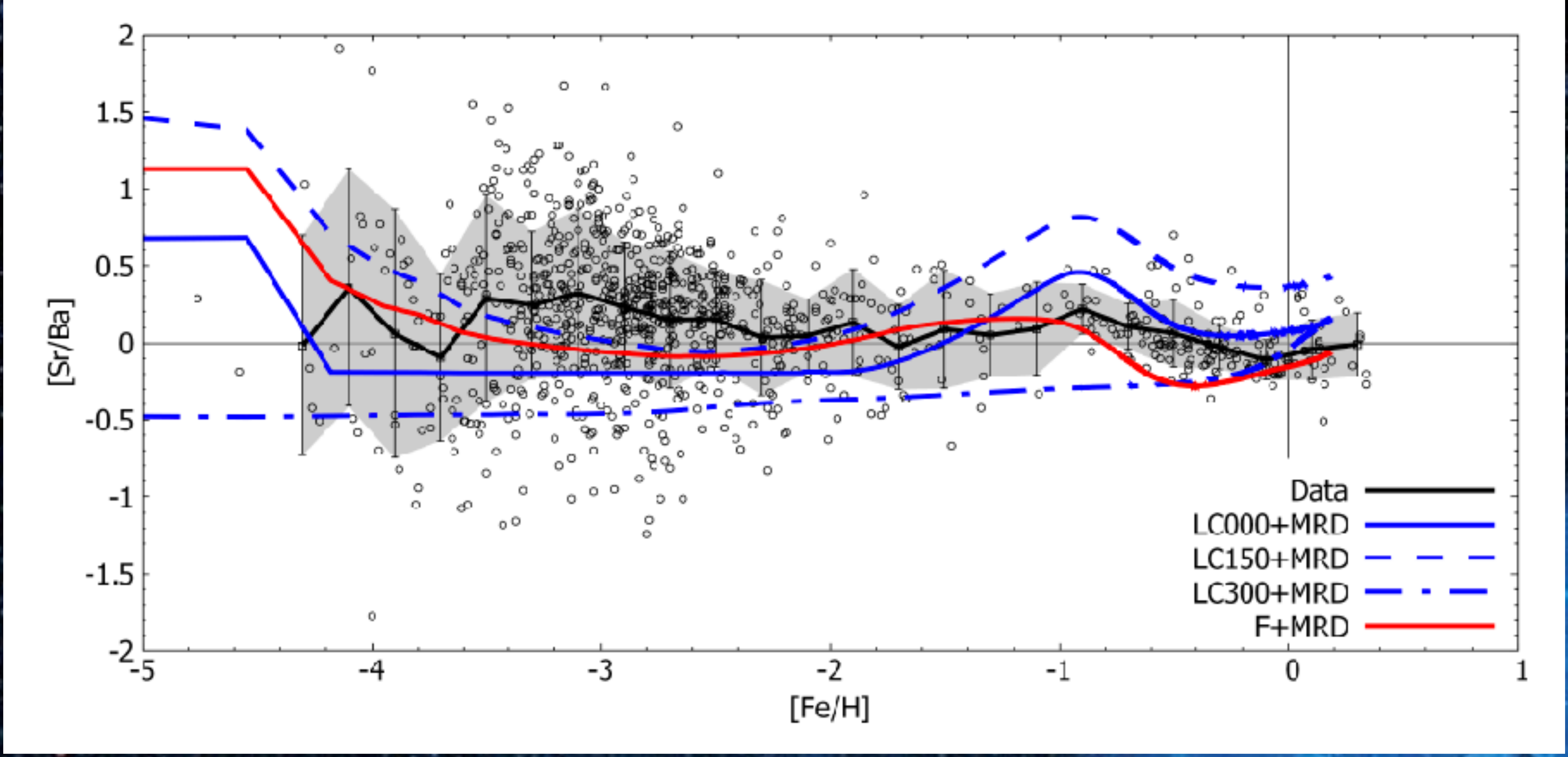
Cescutti +14




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

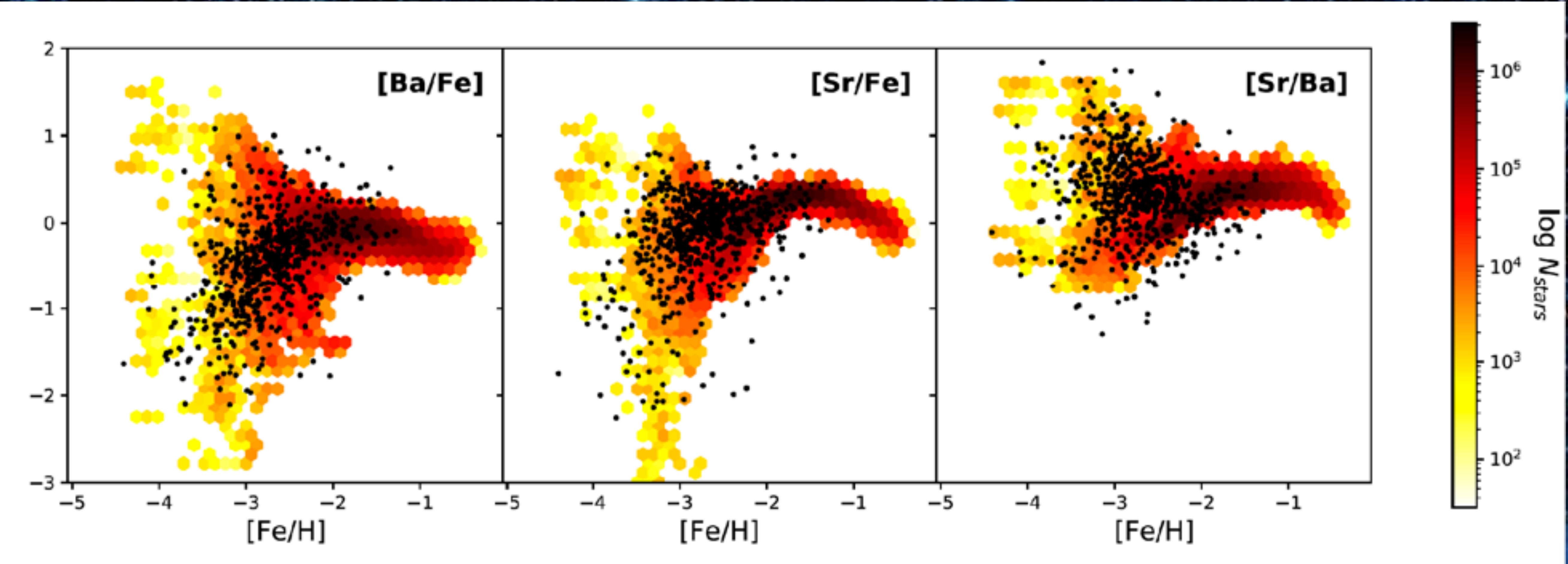
# Confirmed in Rizzuti et al. (2019)

## adopting Limongi&Chieffi18




see also Prantzos et al. 2018

# Rizzuti et al. (2021)
## adopting Limongi&Chieffi18



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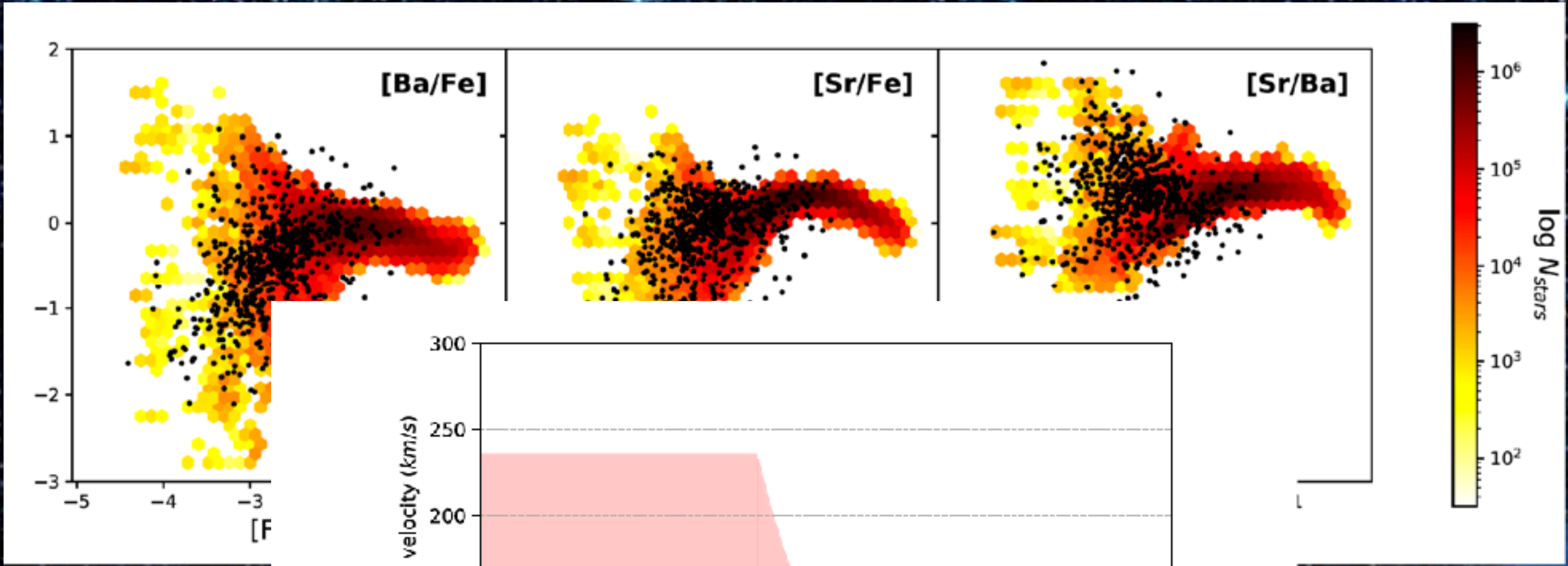
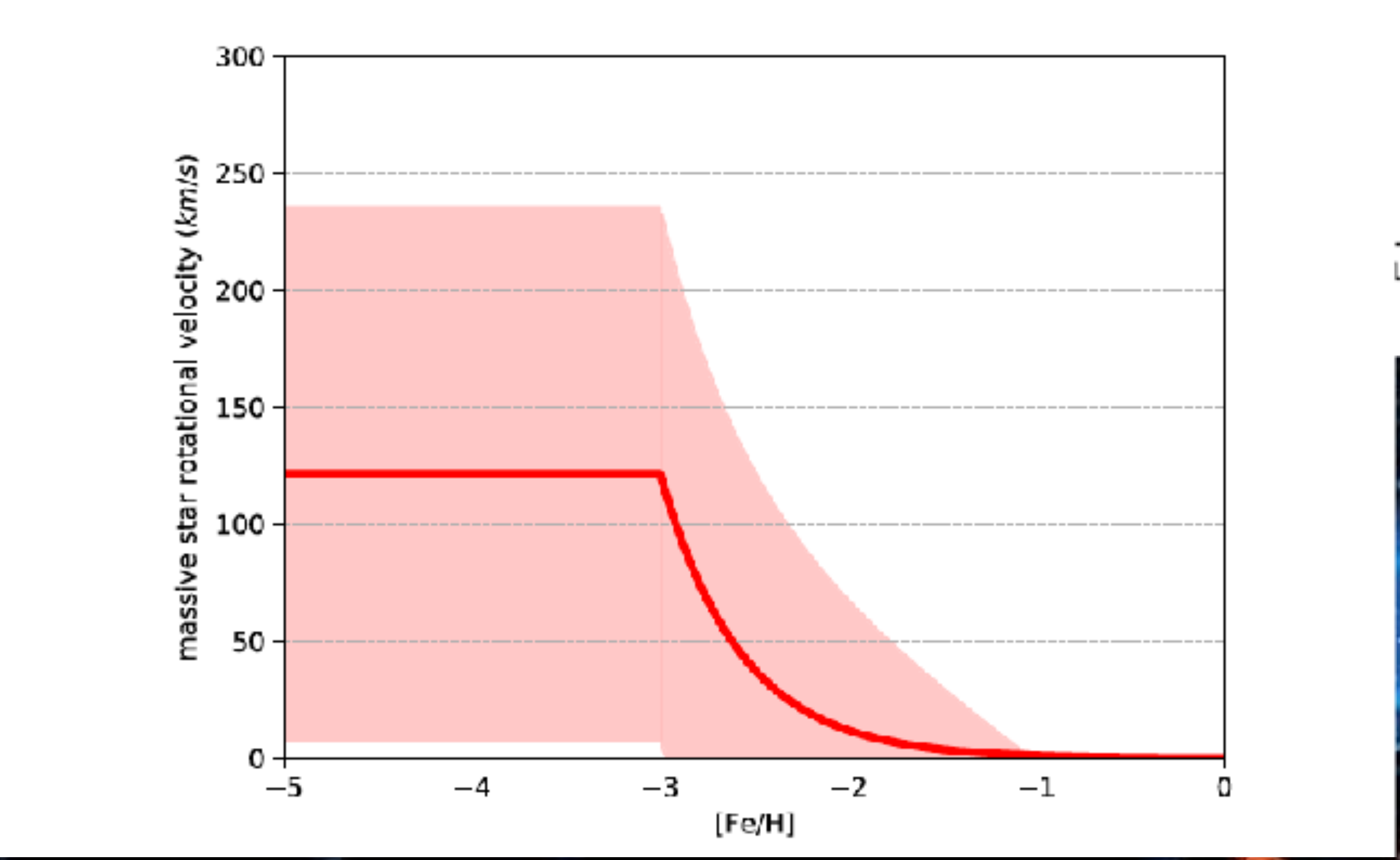
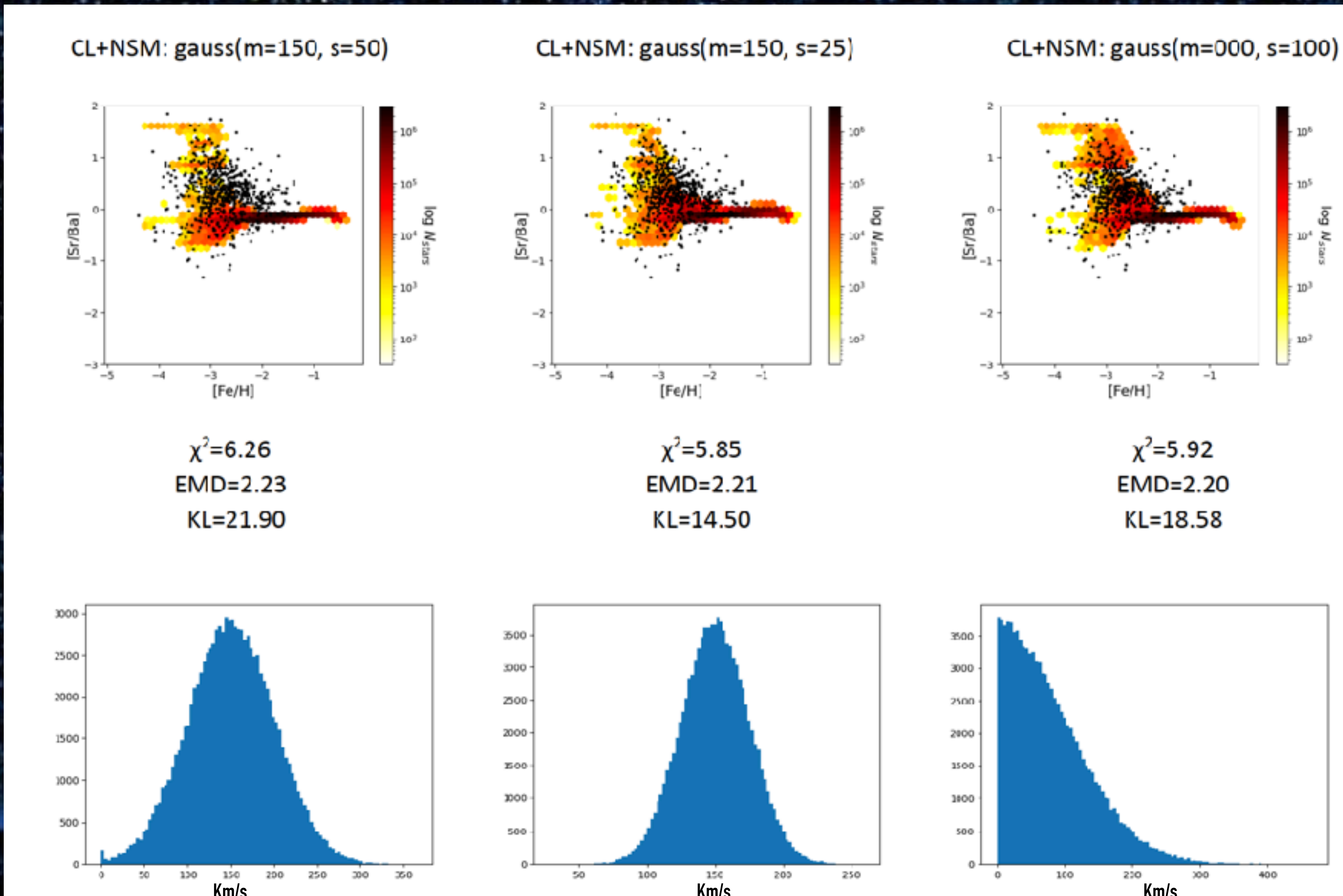


# Data+stochastic modelling

# —>constrain stellar velocity distribution at [Fe/H]~-3 !!

Rizzuti +21



# 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 a candidate to play this role if they have a very short time scale, or if their frequency was higher at extremely low metallicity.
However, a unique prompt source (e.g. MRD SNe) can be the simplest solution.

Another process more frequent and that can produce both Sr and Ba with a production that is compatible with the s-process by rotating massive stars.

CAVEAT

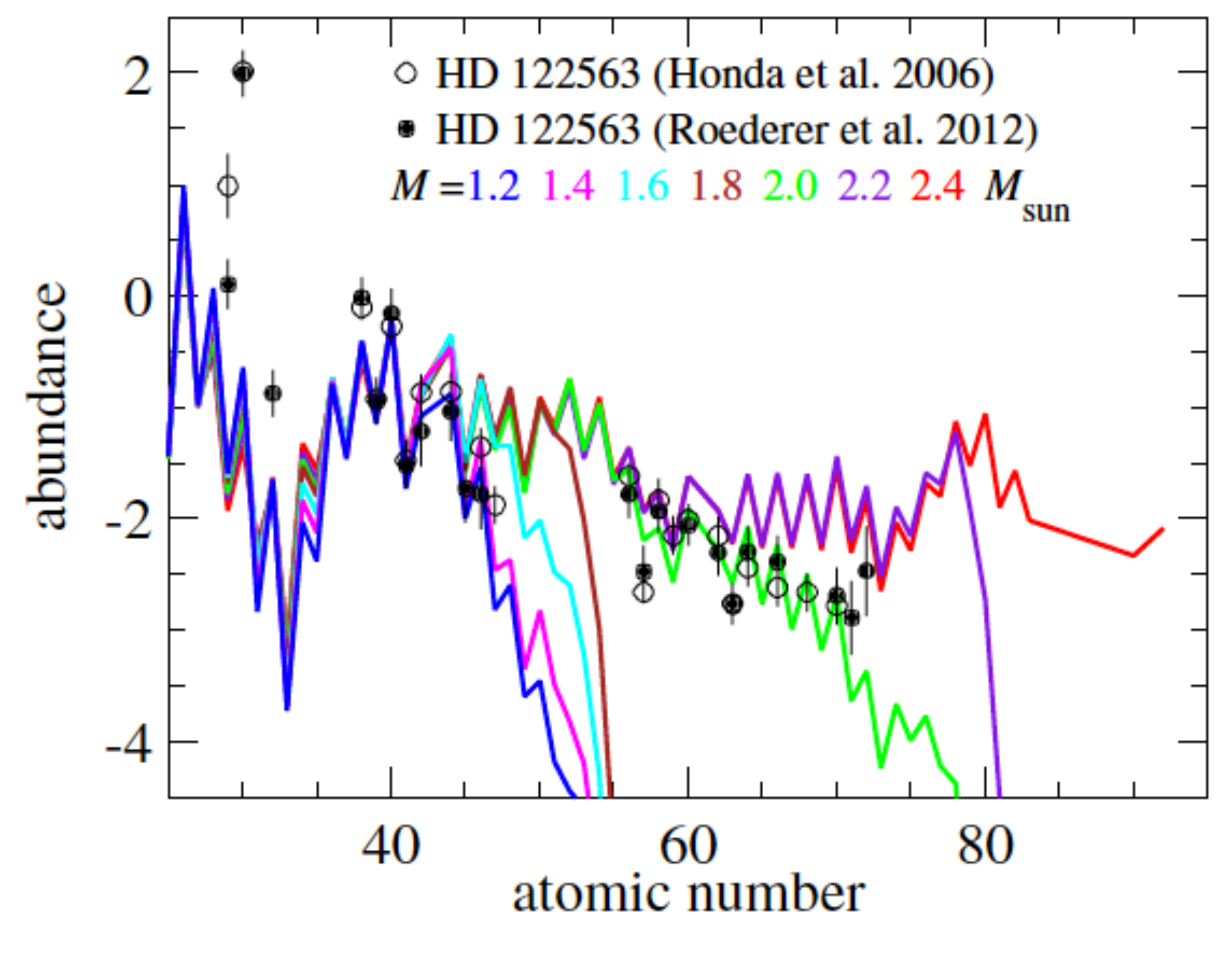
# The only possible answer?

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

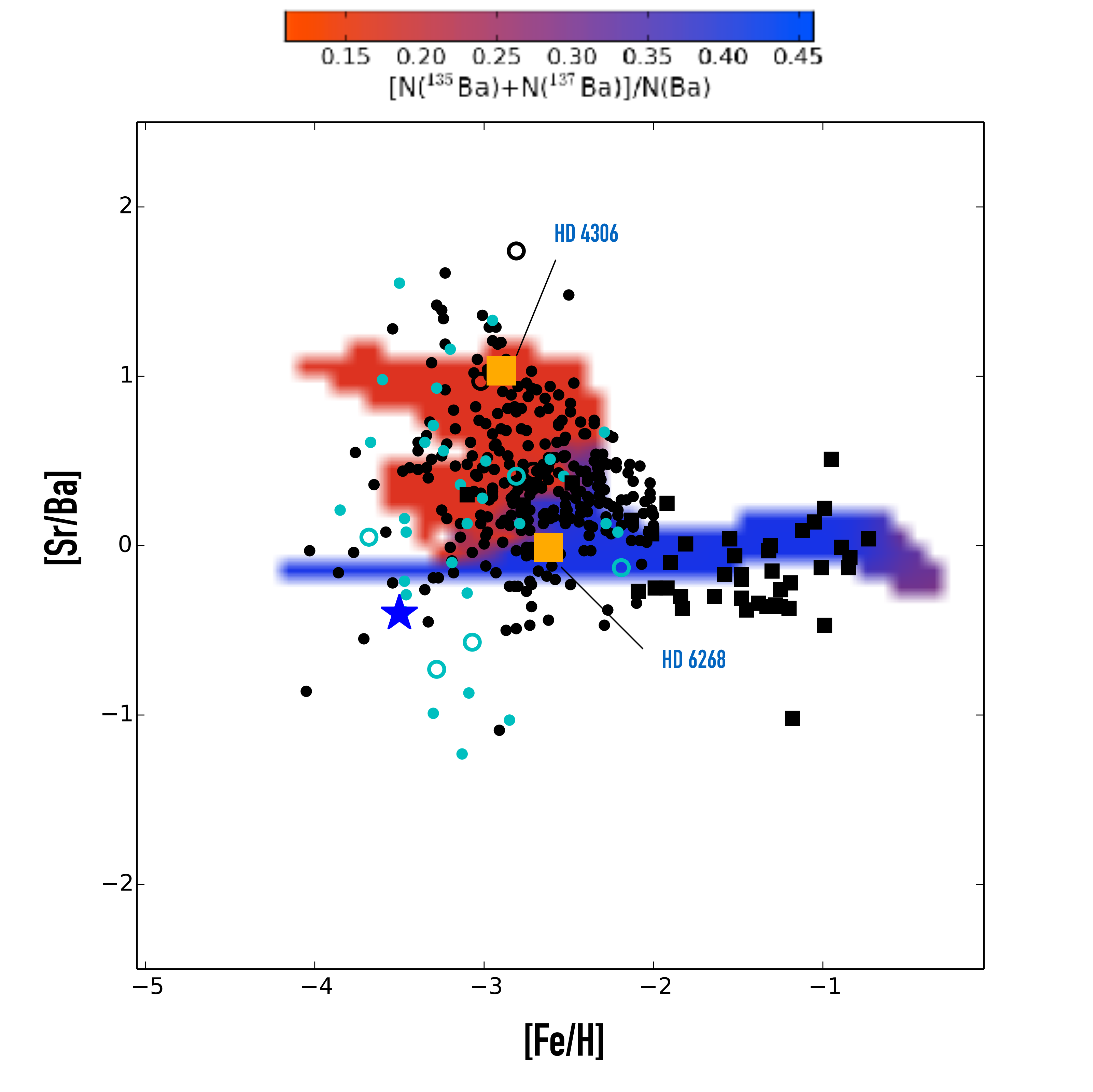
# Isotopic ratio for Ba

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)




Cescutti +14

2 stars
with a R~100'000 &
S/N~900
with UVES at VLT

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

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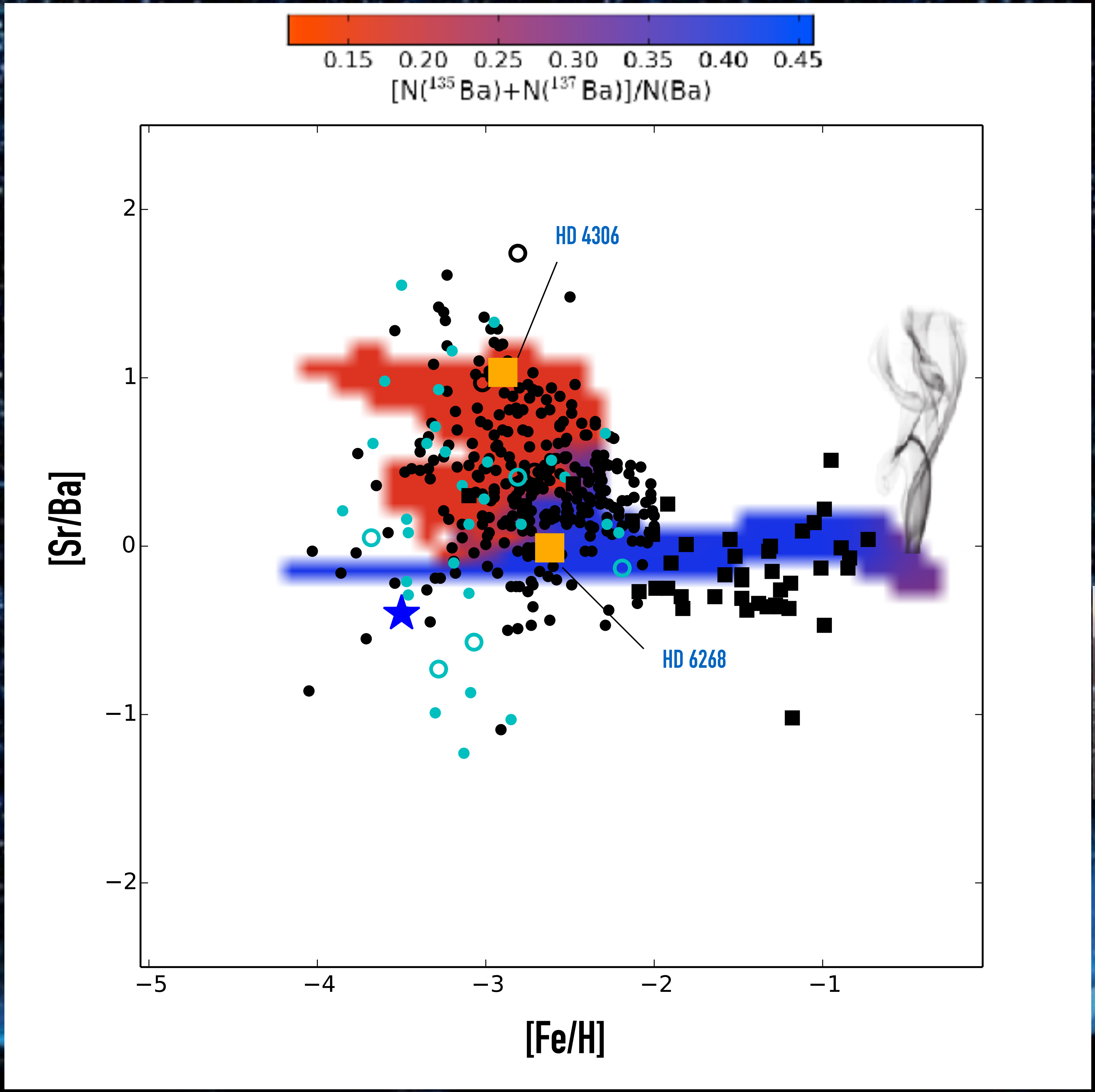


2 stars
with a R~100'000 &
S/N~900
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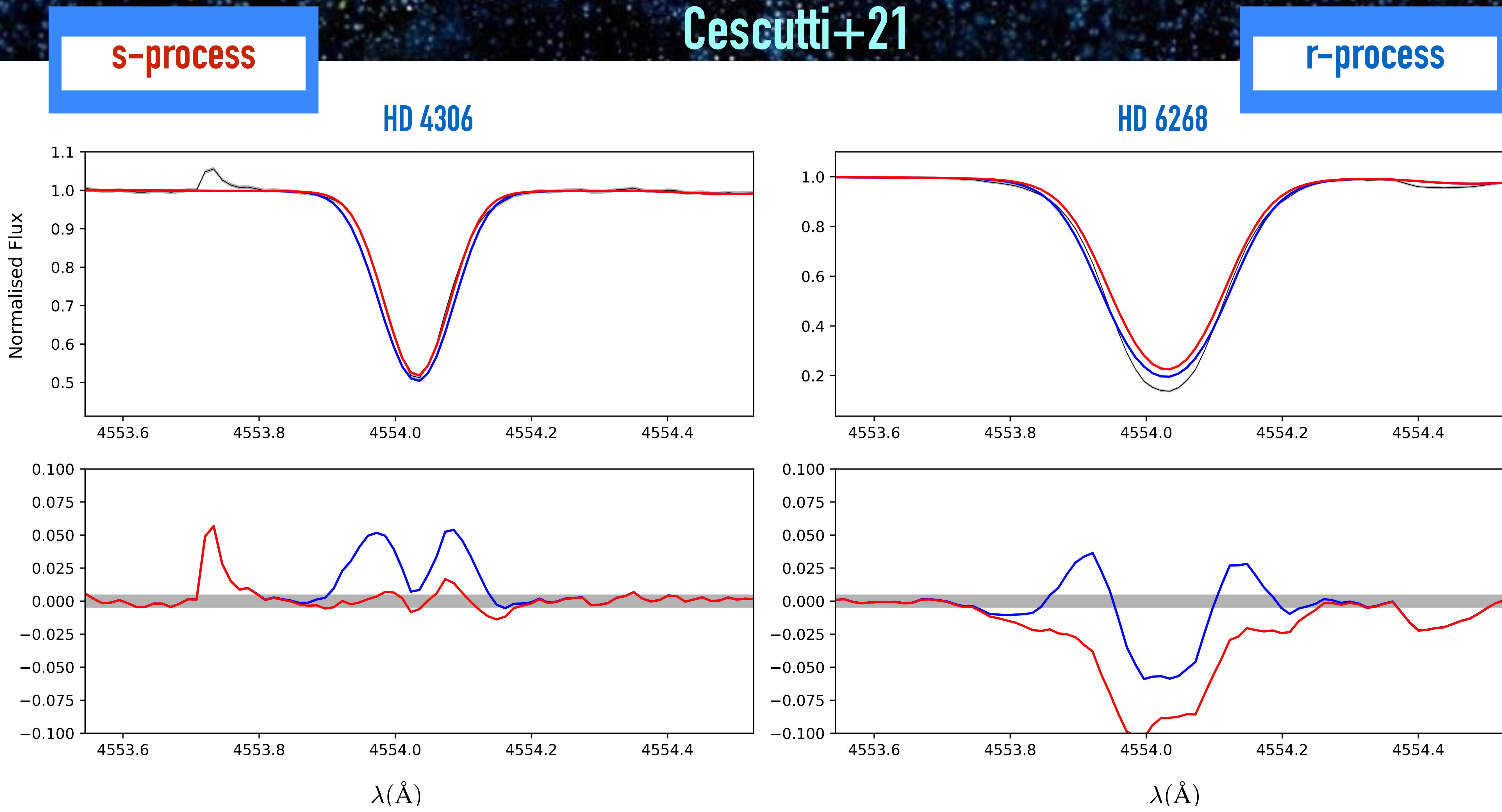
"normal" value
high R ~ 30'000
high S/N ~ 80-100

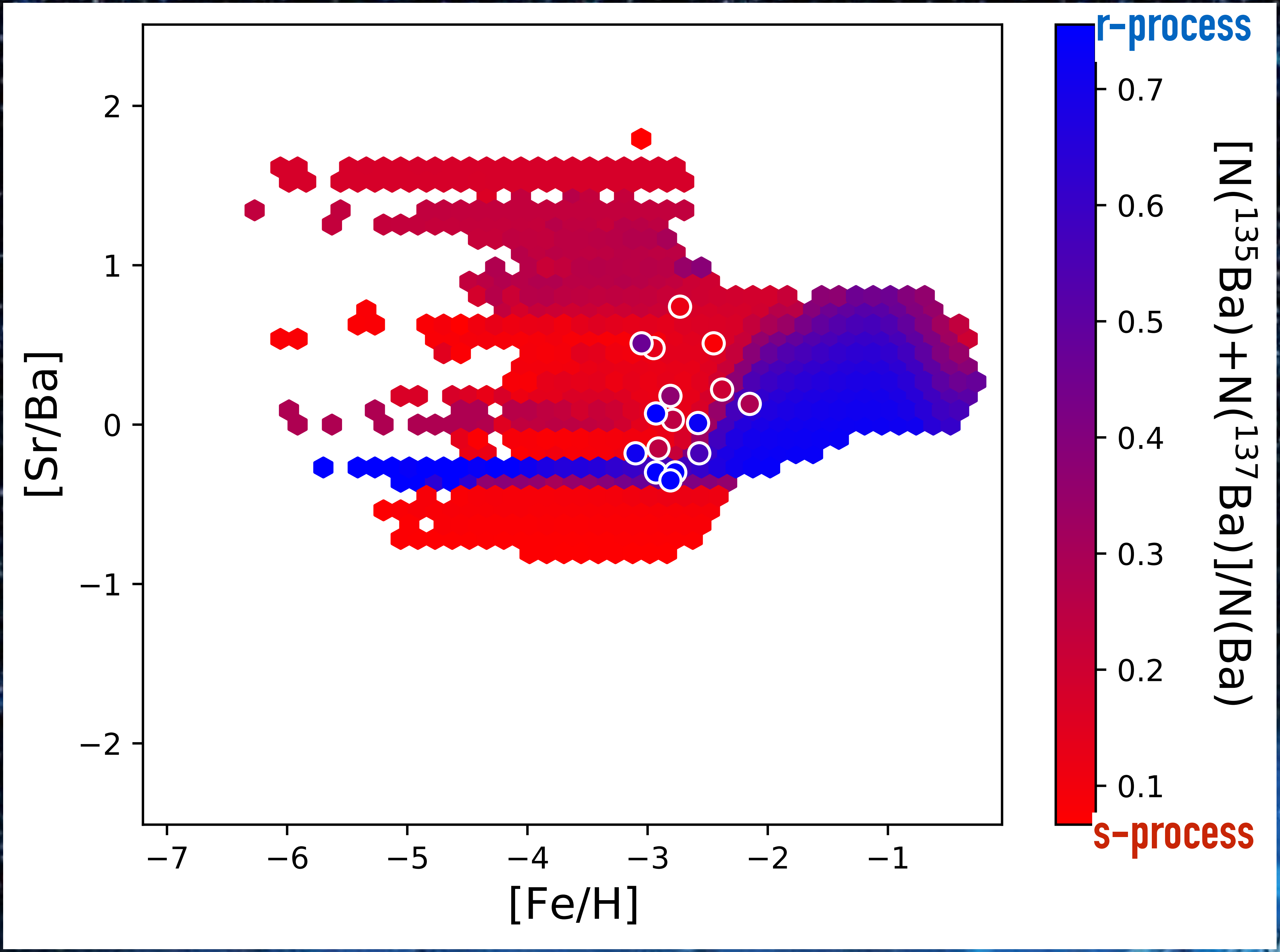
# Spectral analysis results ratio for Ba (1D and LTE)

Cescutti+21



# Isotopic ratio for Ba

Sitnova+25



# 9 Facilities used
# 2 from ChETEC-INFRA
# MINCE I (2022), MINCE II (2024) & MINCE III (2025)

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

20% from ChETEC-INFRA

OHP 1.93m
Spectrograph SOPHIE

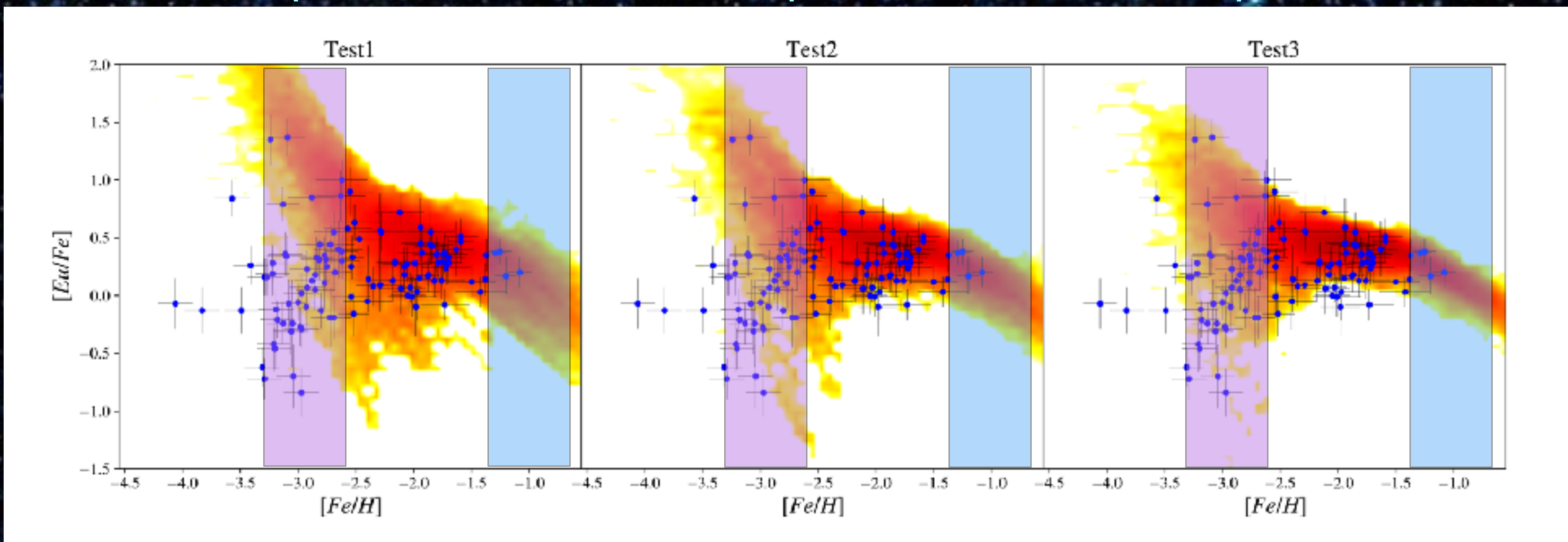
CFHT: 3.58m
Spectrograph ESPaDOnS

MPG/ESO 2.2-metre
FEROS

Magellan 6.5m
Spectrograph: MIKE

# How to constrain the fraction of NSM?

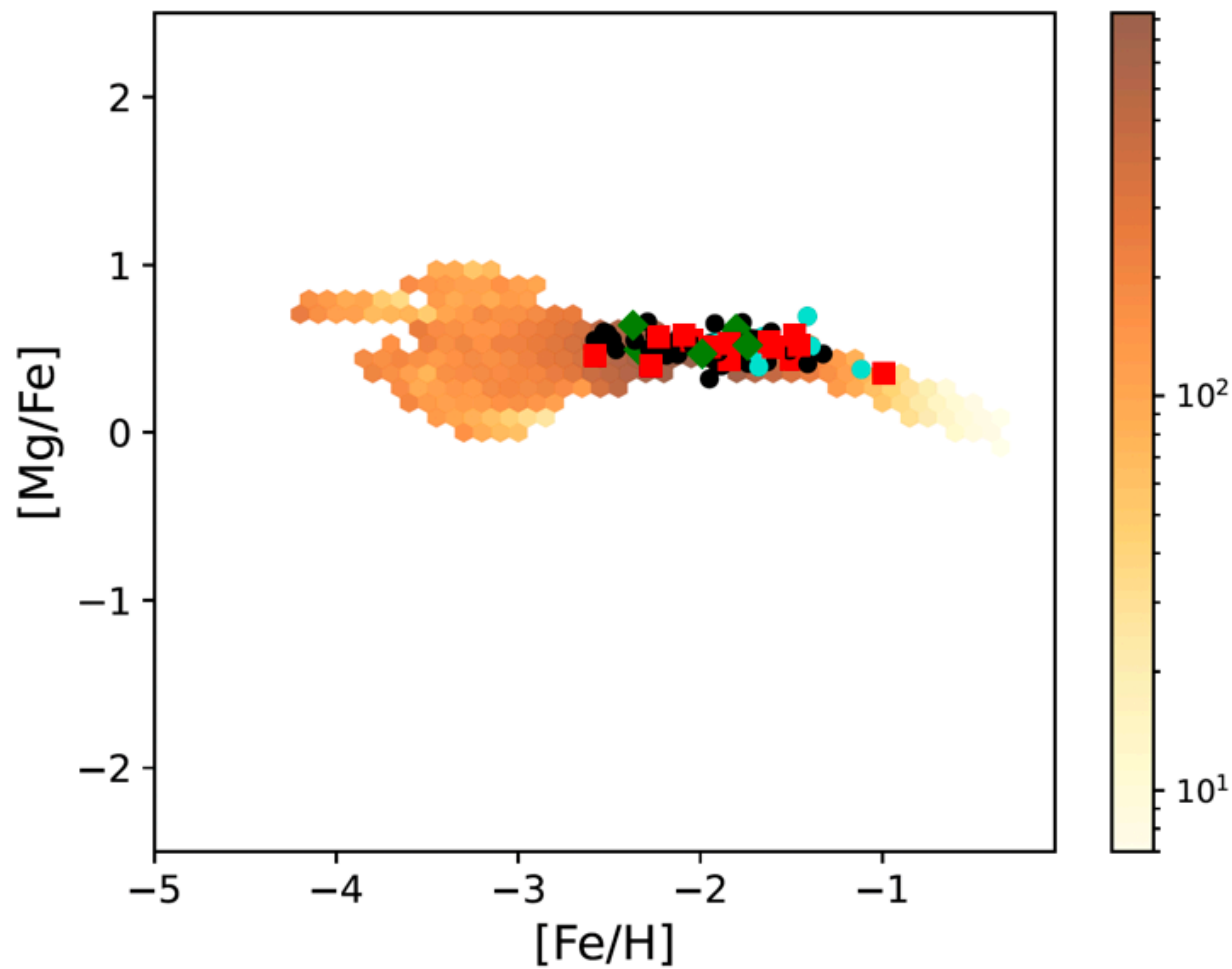
alpha=0.02 alpha=0.06 alpha=0.1



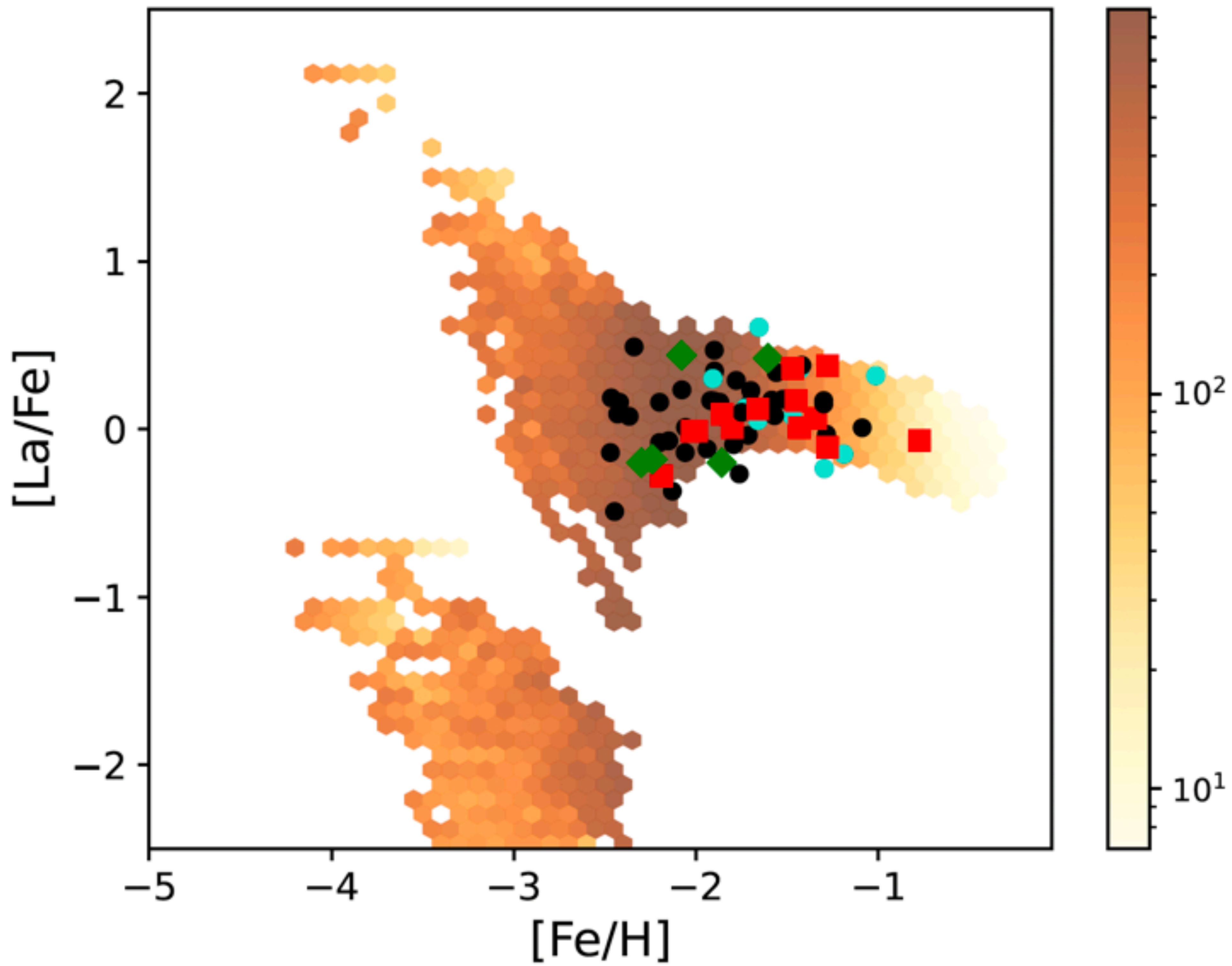

| [Fe/H] (dex) | Test1 | | Test2 | | Test3 | |
|---|---|---|---|---|---|---|
| | mean [Eu/Fe] (dex) | sigma(dex) | mean [Eu/Fe] (dex) | sigma(dex) | mean [Eu/Fe] (dex) | sigma(dex) |
| -3.00 | 1.42 | 0.22 | 1.05 | 0.23 | 0.84 | 0.22 |
| -1.00 | 0.15 | 0.15 | 0.16 | 0.10 | 0.17 | 0.08 |

**Weave and 4MOST !!**

# Lucertini+25 aka MINCE 3



# Lucertini+25 (MINCE 3)



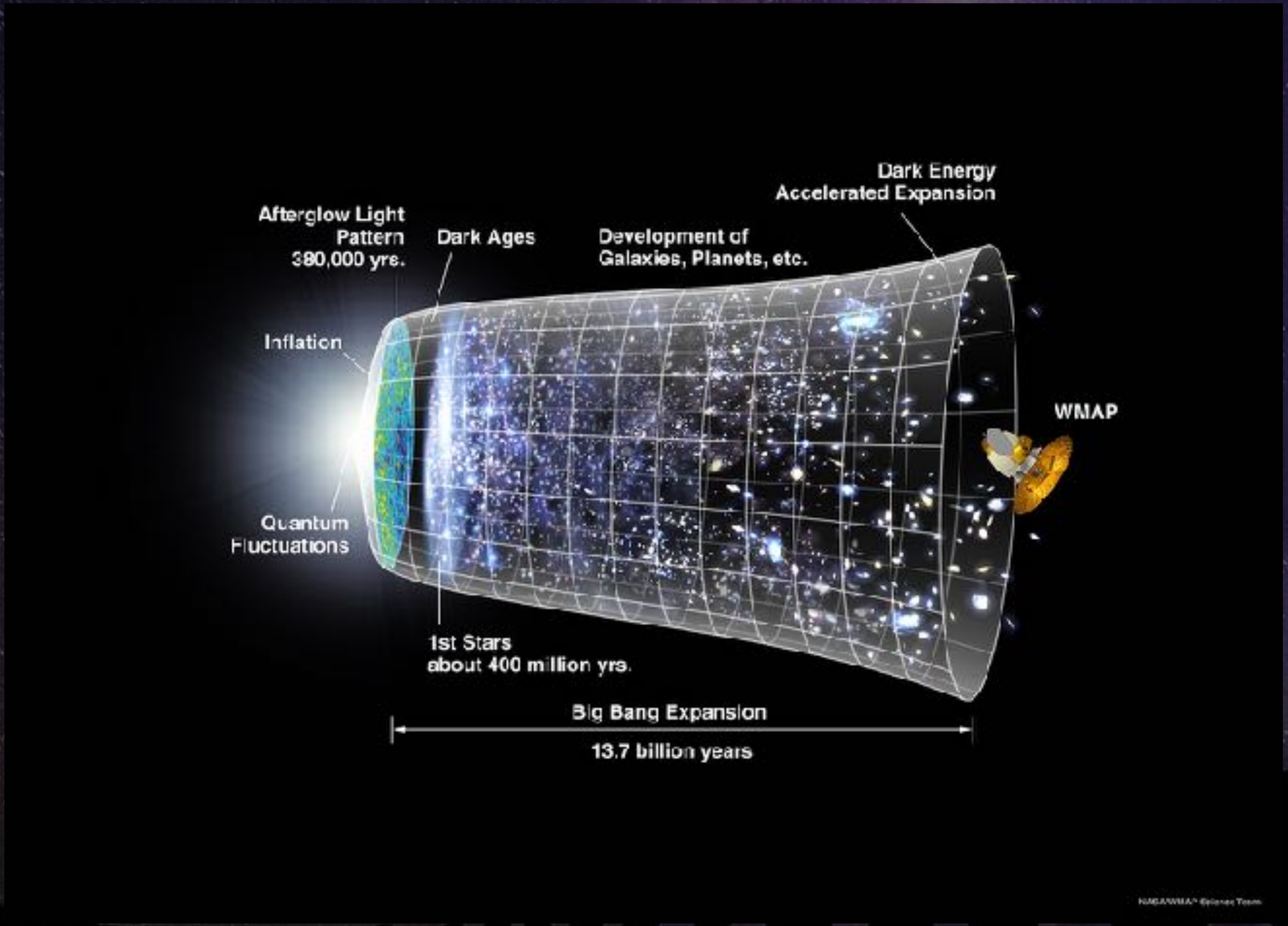
UNIVERSITÀ DEGLI STUDI DI TRIESTE

# CEMP-no stars & Nitrogen in the Early Galaxy


Gabriele Cescutti
F.Rizzuti, F.Matteucci, C.Chiappini, & P. Molaro

# The Nature of the First Stars

## Chemical enrichment of the Early Universe



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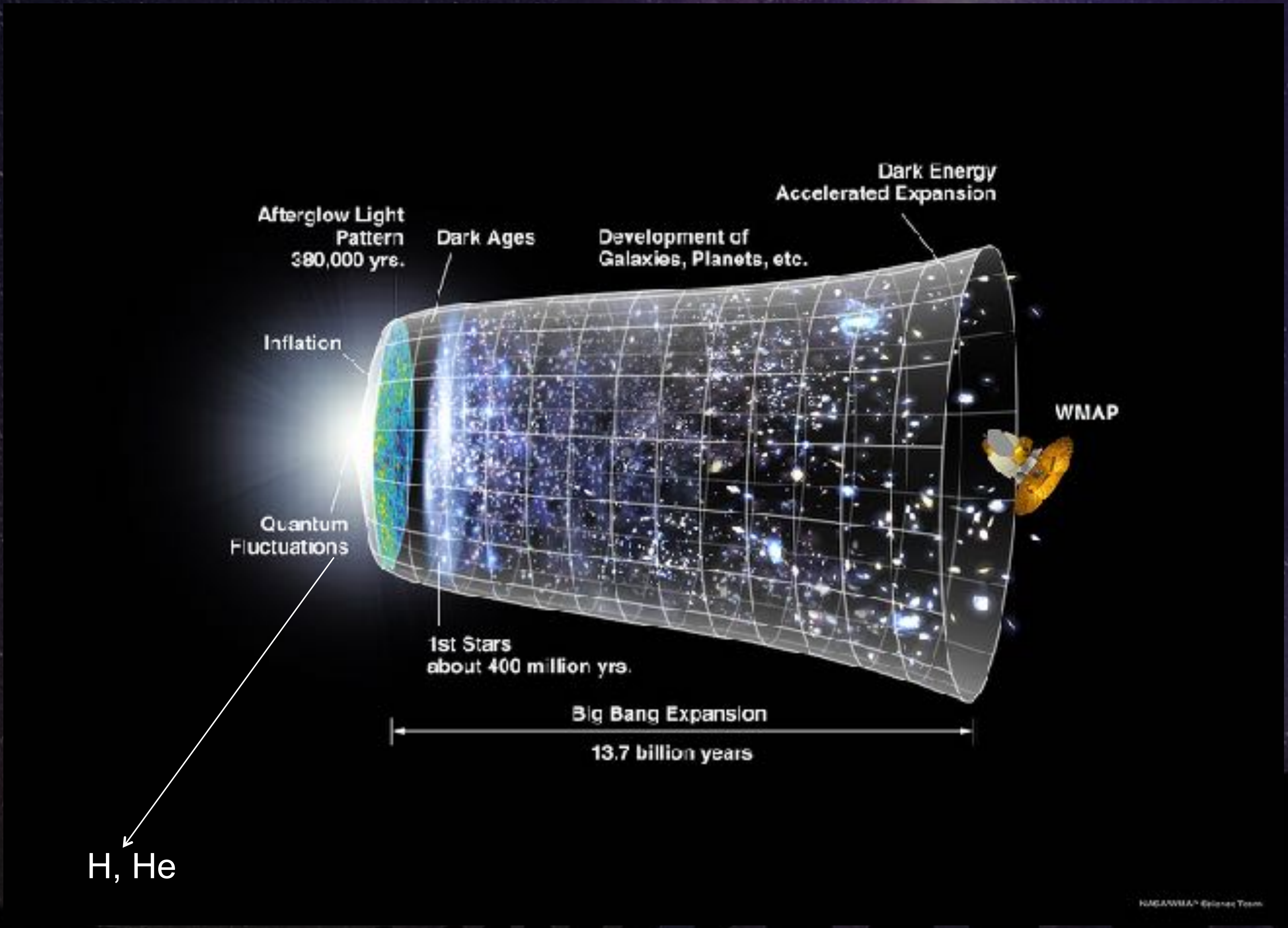

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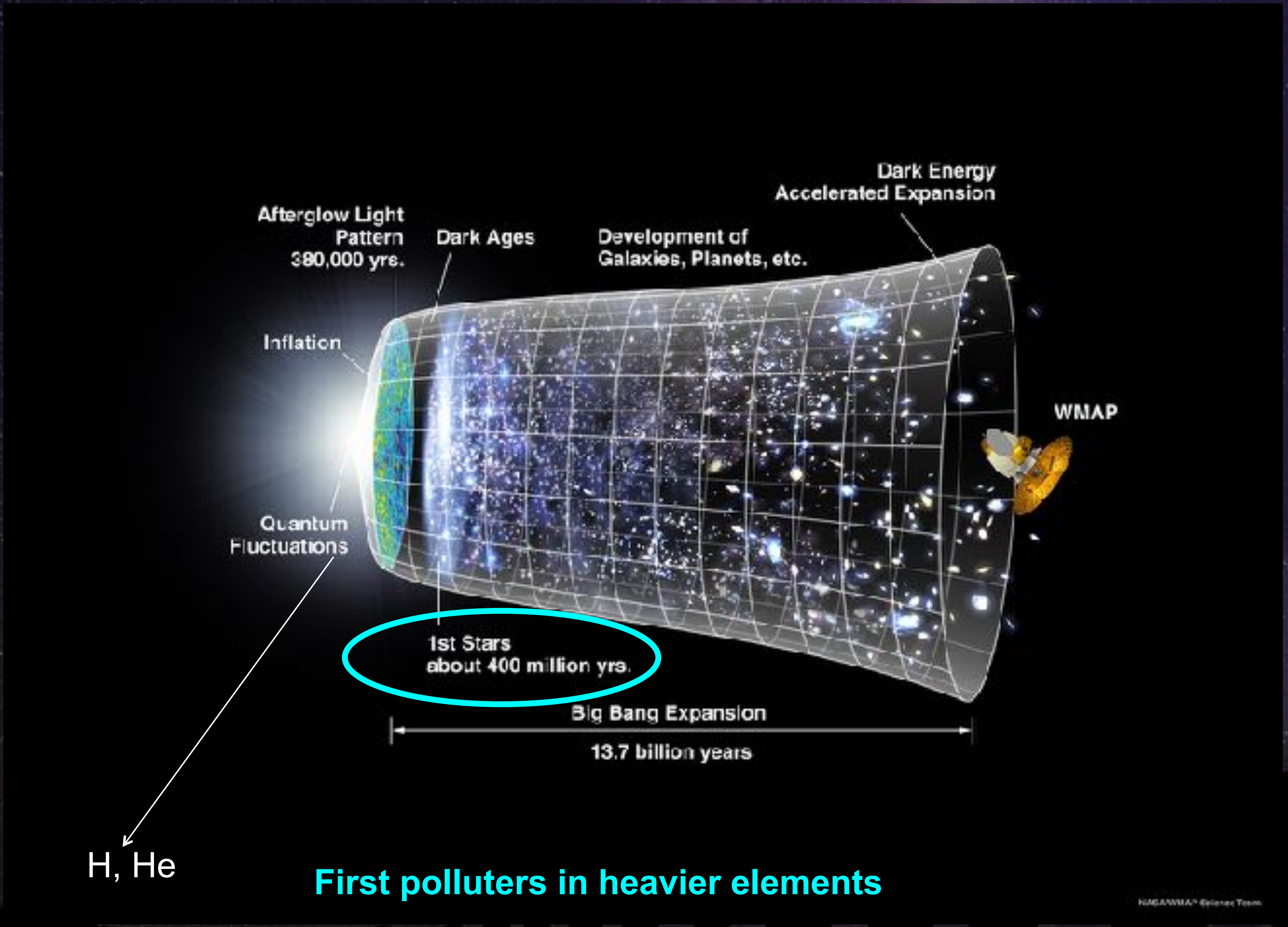

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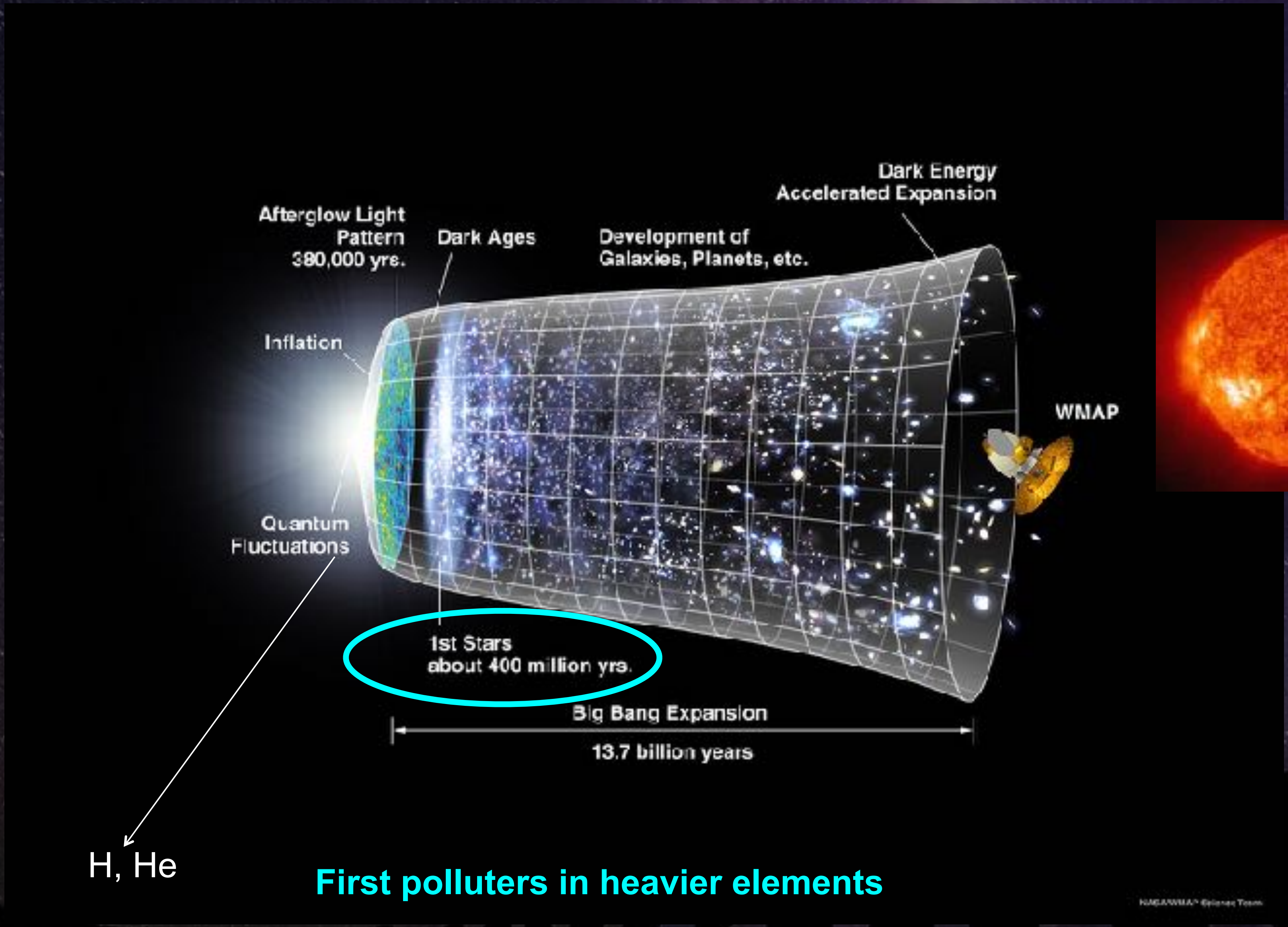


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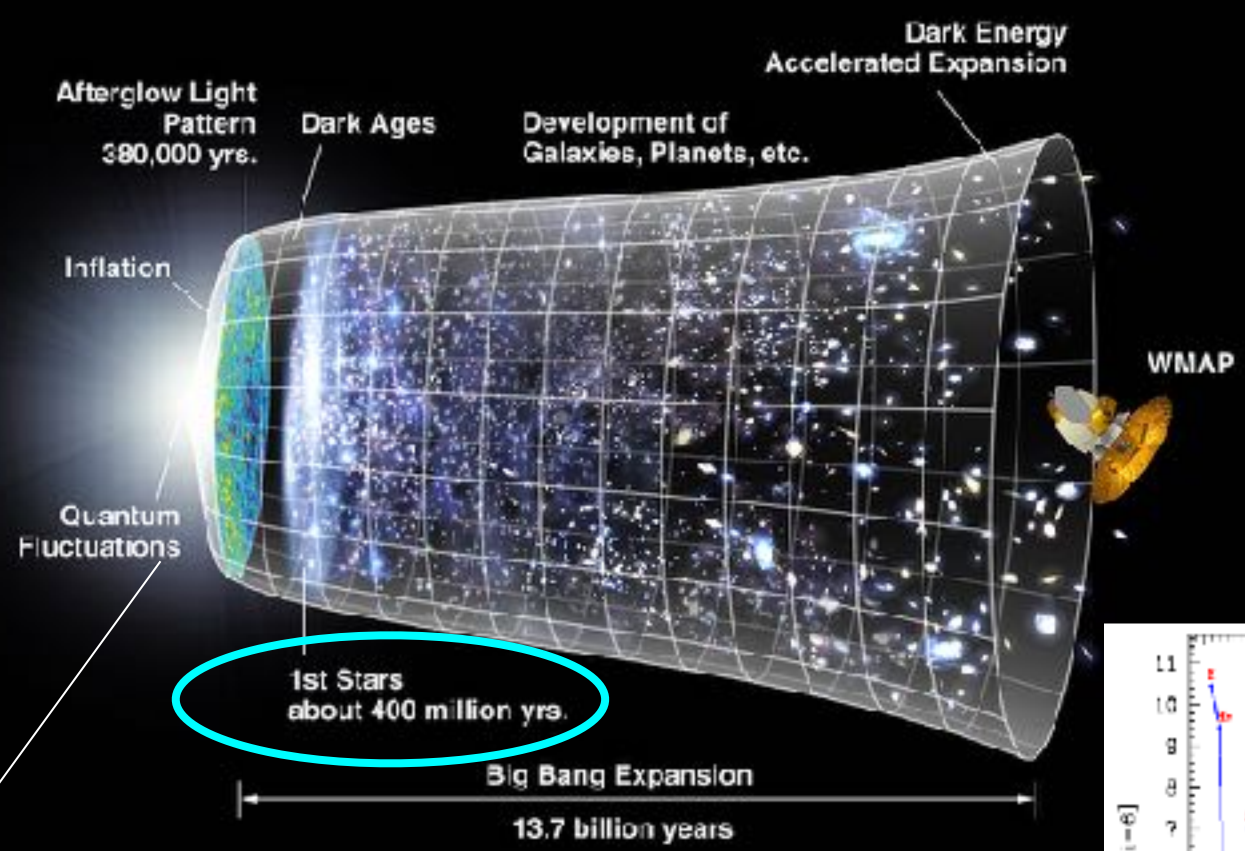
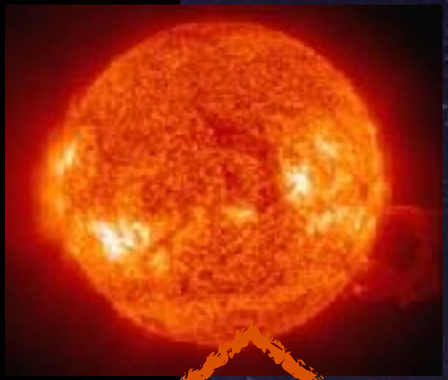
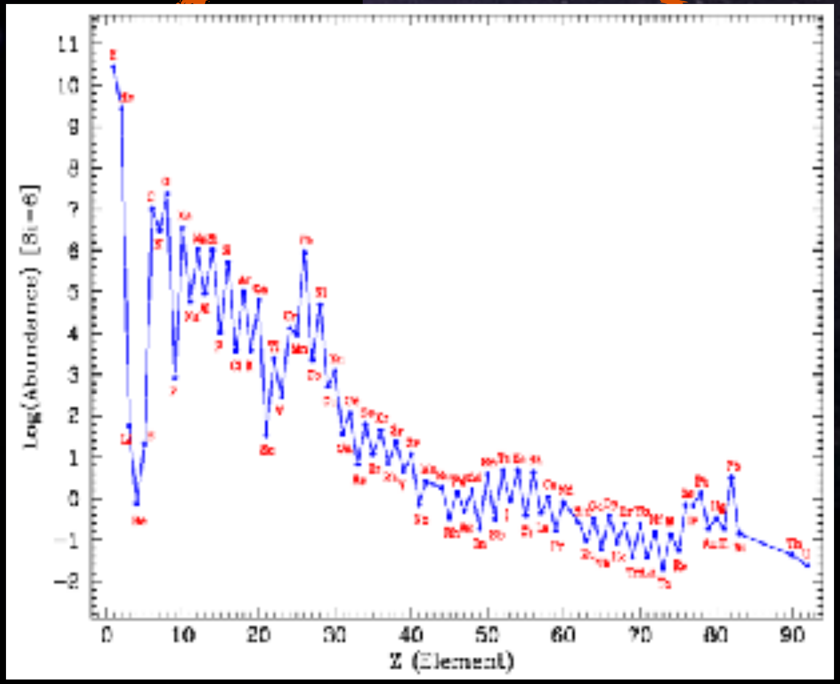


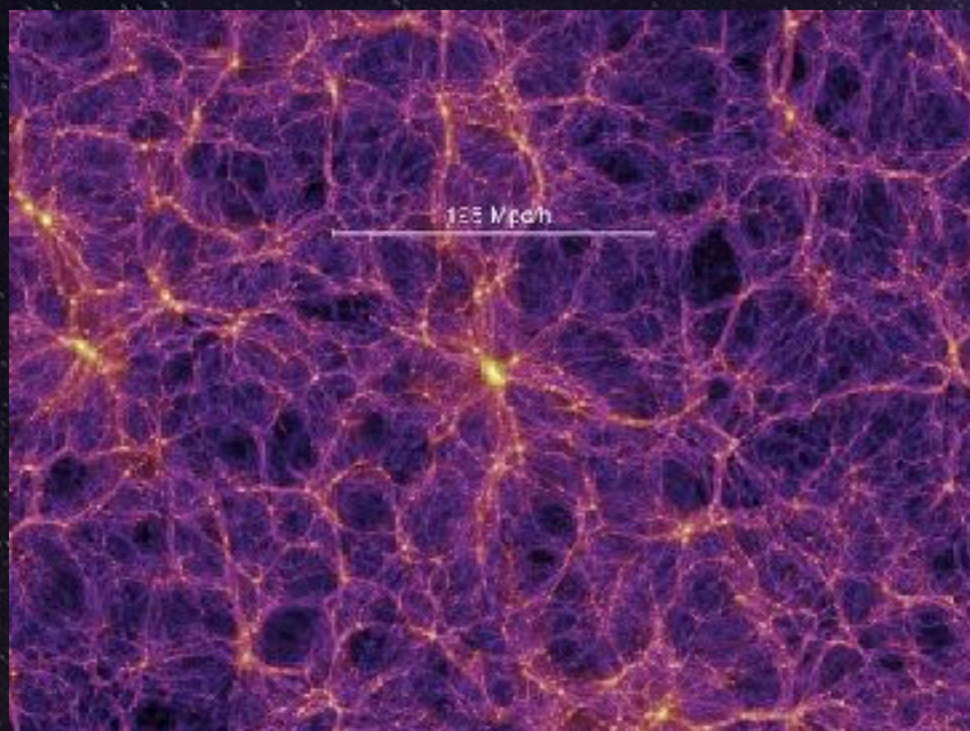






H, He

**First polluters in heavier elements**

# Simulation of the First Stars



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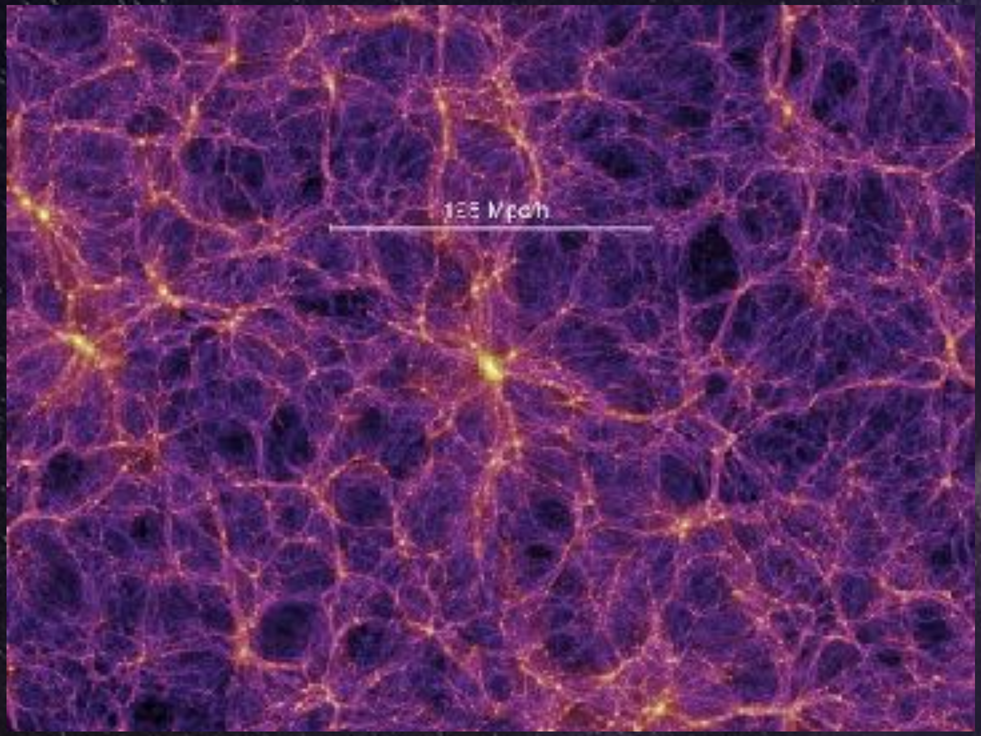
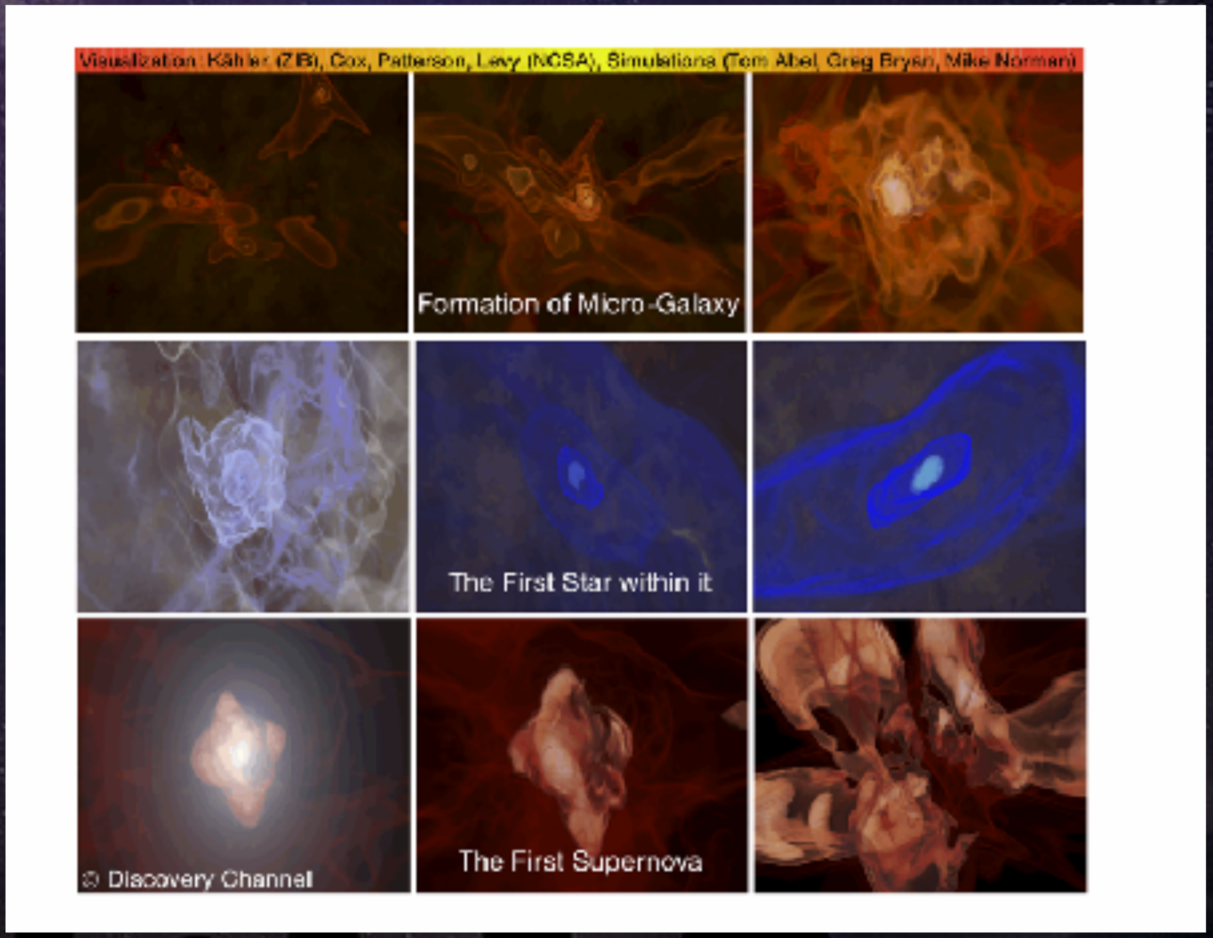
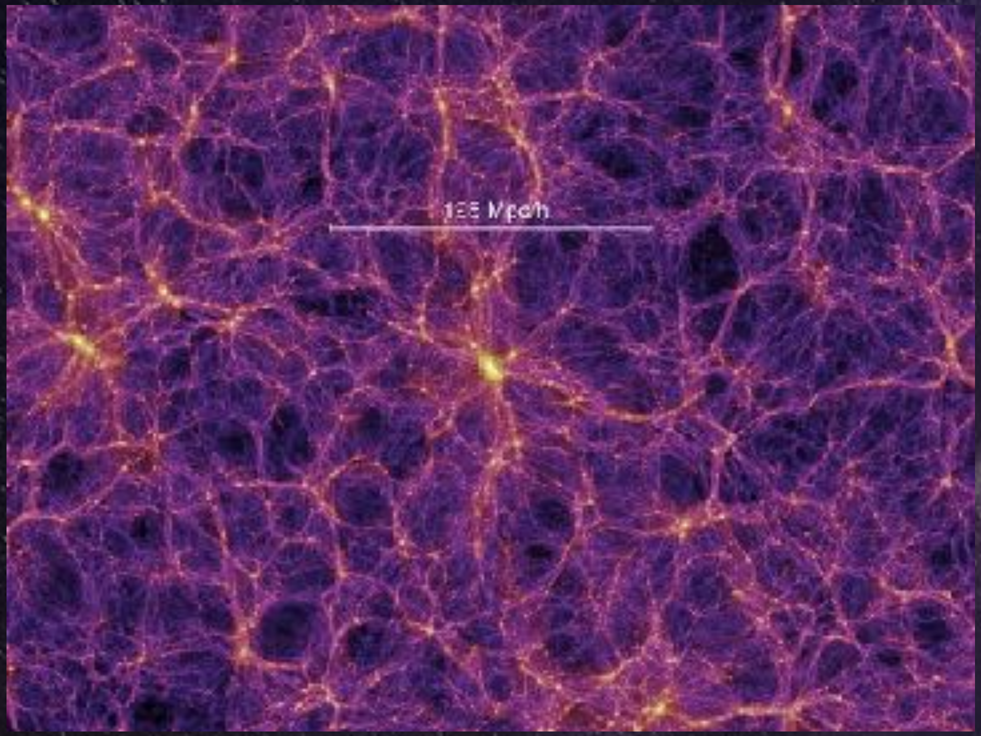


The theoretical challenge:
Total dynamical range $10^{12}$ !

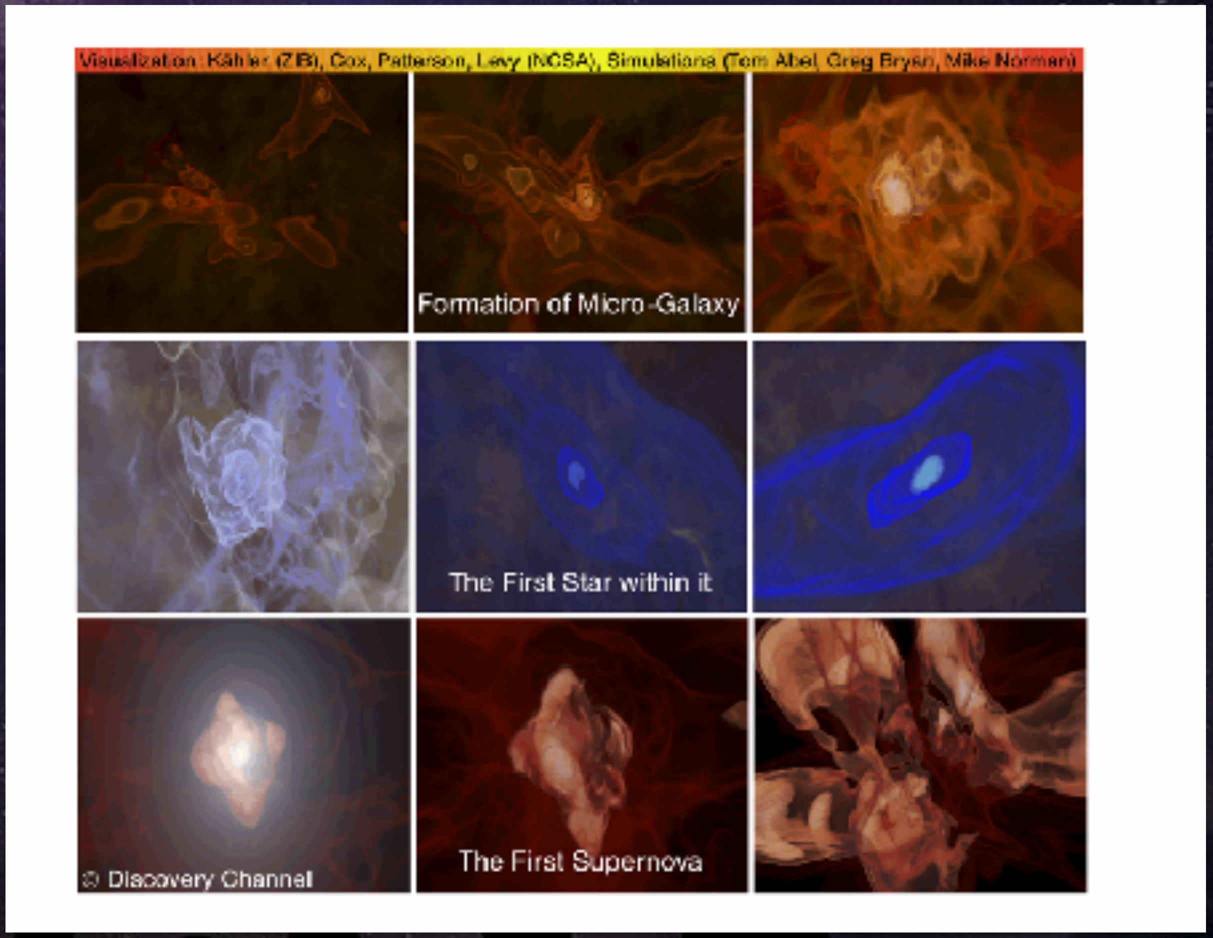


# Simulation of the First Stars

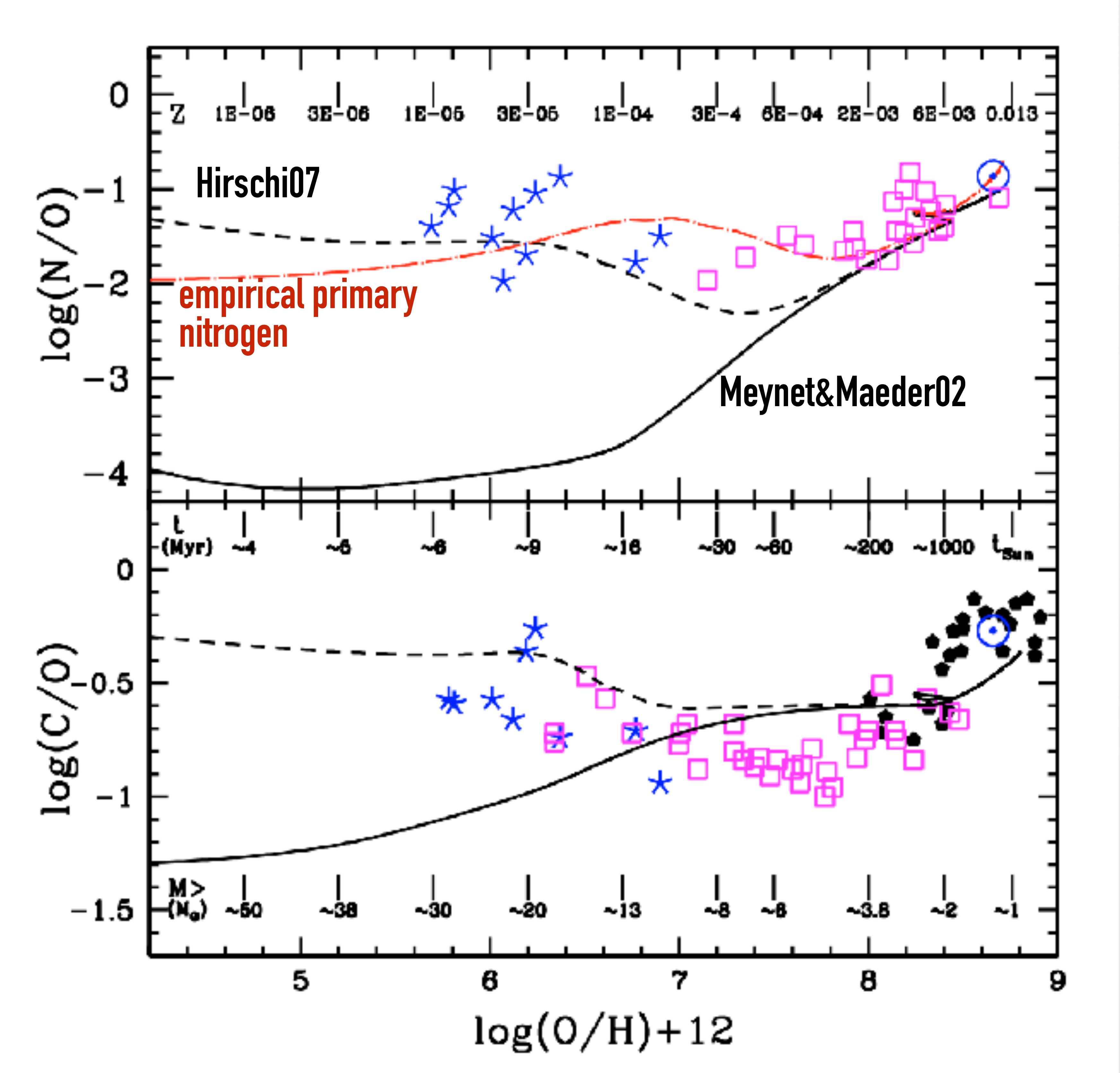


Start with a stadium and then focus on a single atom within that stadium!

The theoretical challenge:
Total dynamical range $10^{12}$ !

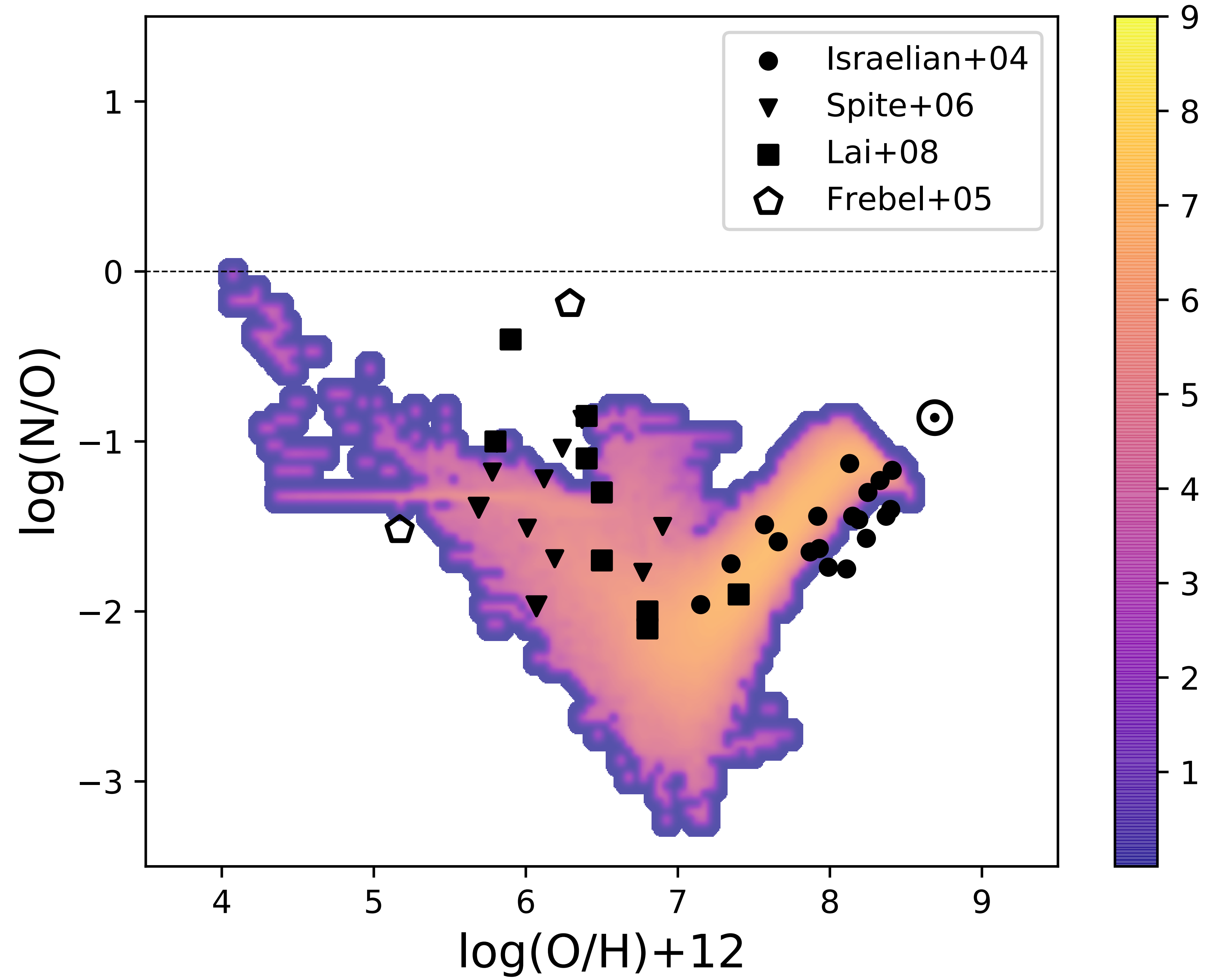


# Problem of the nitrogen —> Rotating massive stars
## at low metallicity (Hirschi 2007)



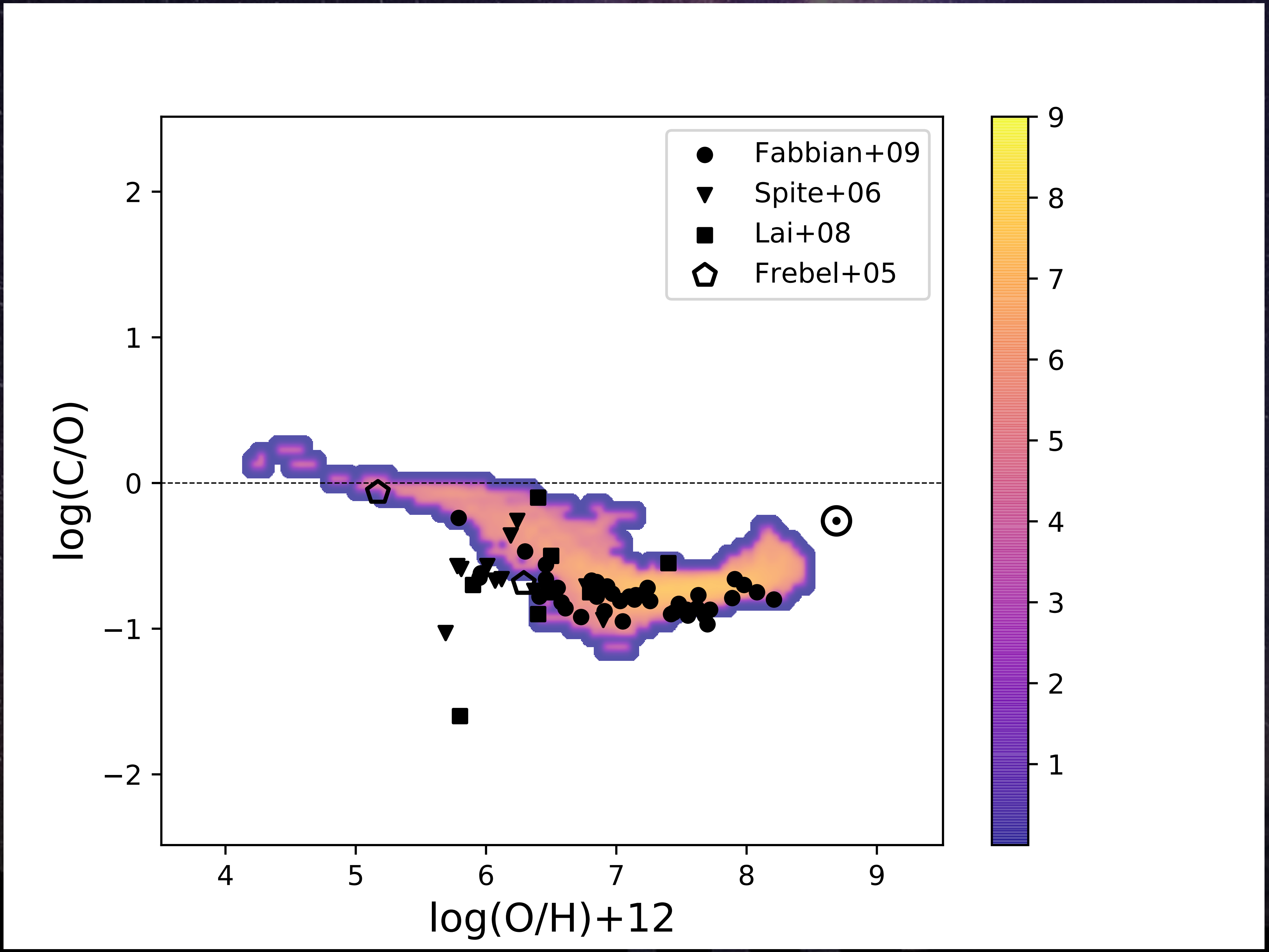

Chiappini+06
based on Hirschi07

# N/O with rotating massive stars




Revised from Cescutti and Chiappini 2010, yields MM02 + Hirschi07

# C/O with rotating massive stars




Revised from Cescutti and Chiappini 2010, yields MM02 + Hirschi07

# The ZOO of the Carbon Enriched Metal-Poor (CEMP) stars

defined for the first time by Beers and Christlieb (2005)

CEMP $[C/Fe]>0.9$

- s: $[Ba/Fe] > 1$ & $[Ba/Eu] > 0$
- rs: $[Eu/Fe] > 1$ & $[Ba/Eu] > 0$
- low−s: $[Ba/Fe]<1$ & $[Ba/Eu]>0$
- no: $[Ba/Fe]<1$
- r $[Ba/Eu]<0$

rII: $[Eu/Fe] > 1$ & $[Ba/Eu] < 0$

rI: $[Eu/Fe] < 1$ & $[Ba/Eu] < 0$

Masseron et al. (2010)

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Masseron et al. (2010)

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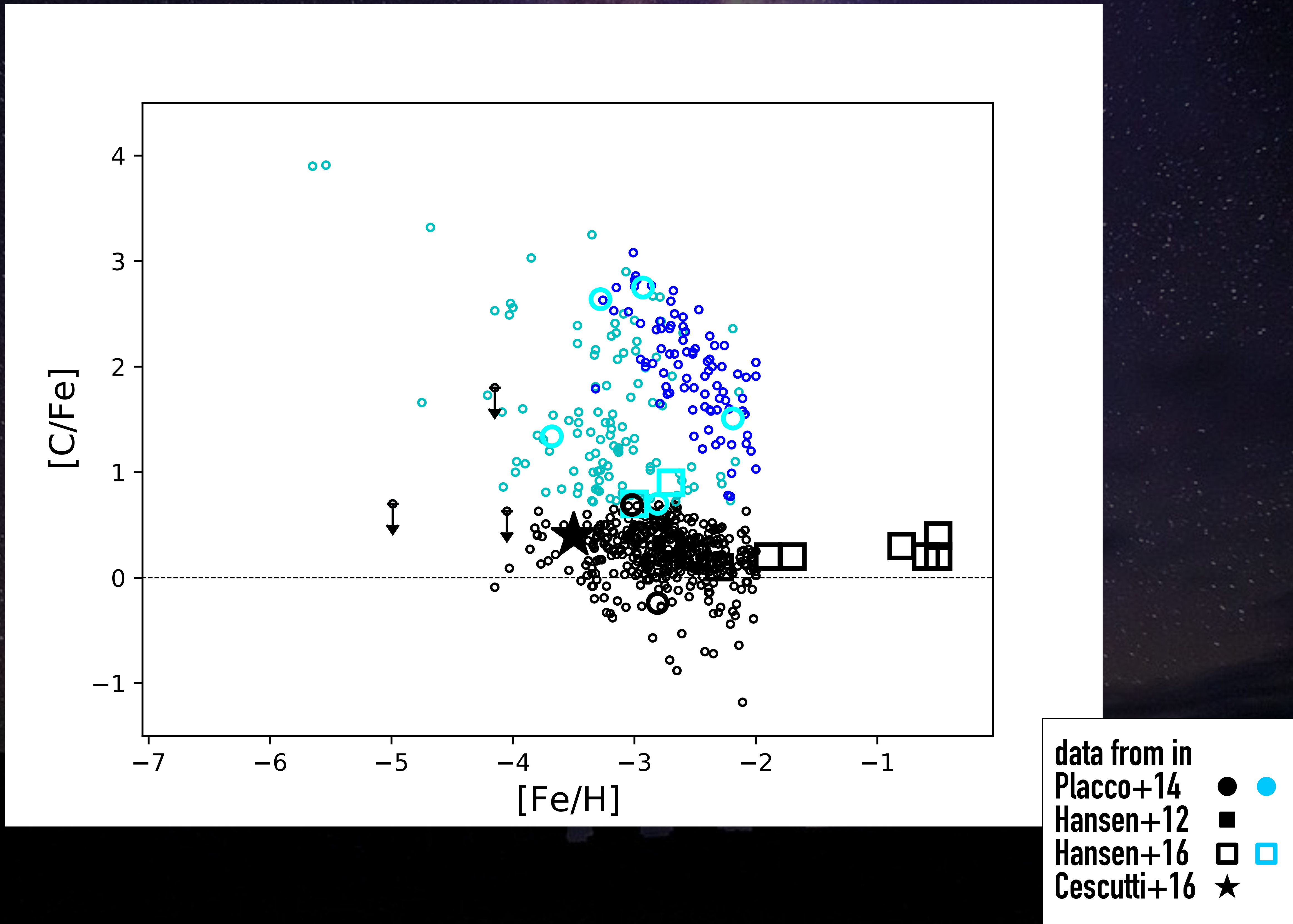
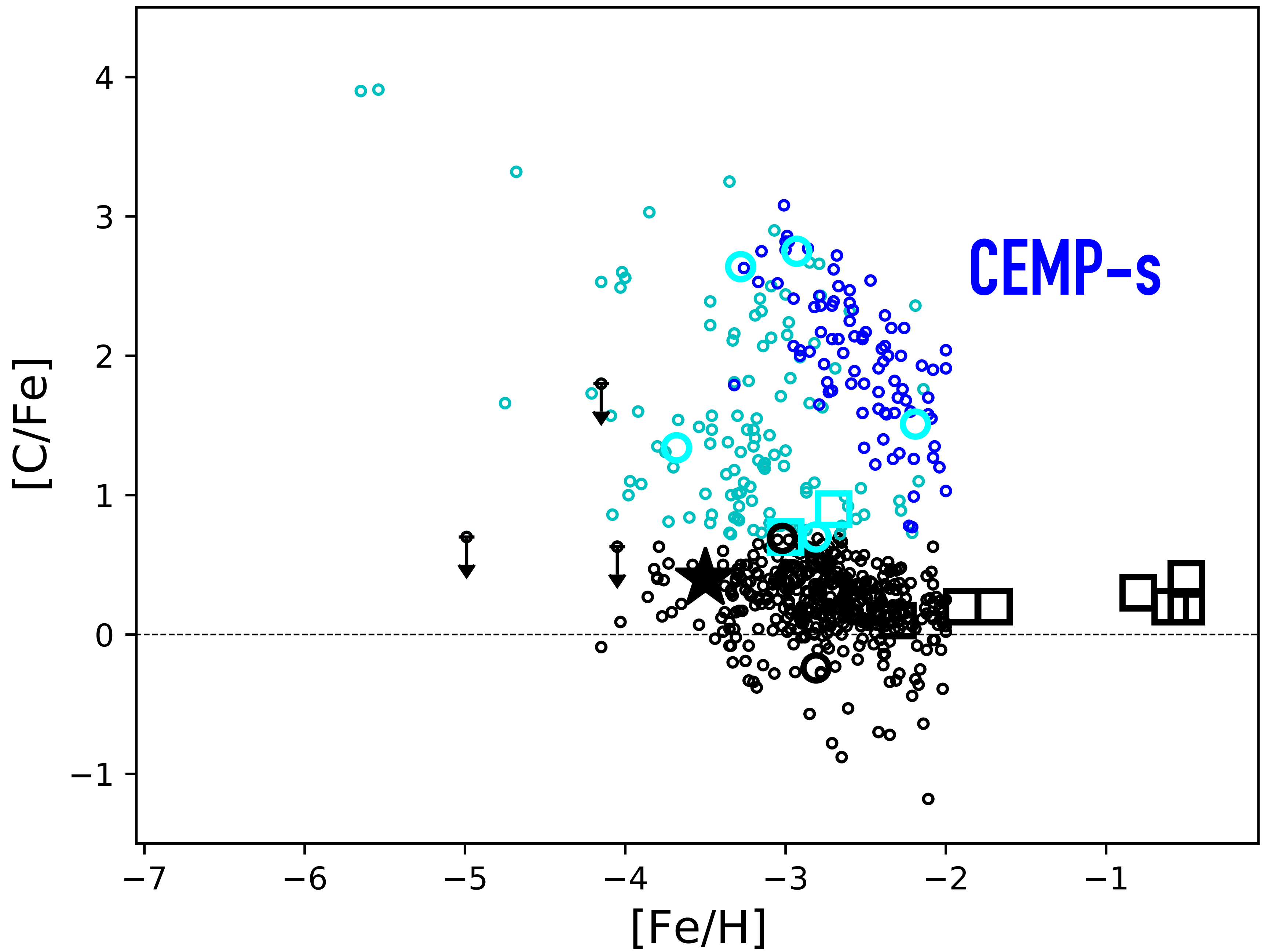
- low−s: [Ba/Fe]<1 & [Ba/Eu]>0
- no: [Ba/Fe]<1

No Binary signature, most of them are single stars

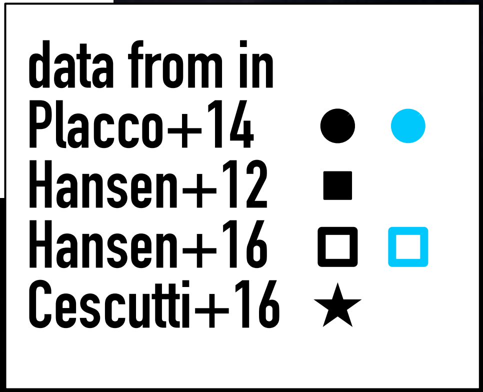
Masseron et al. (2010)



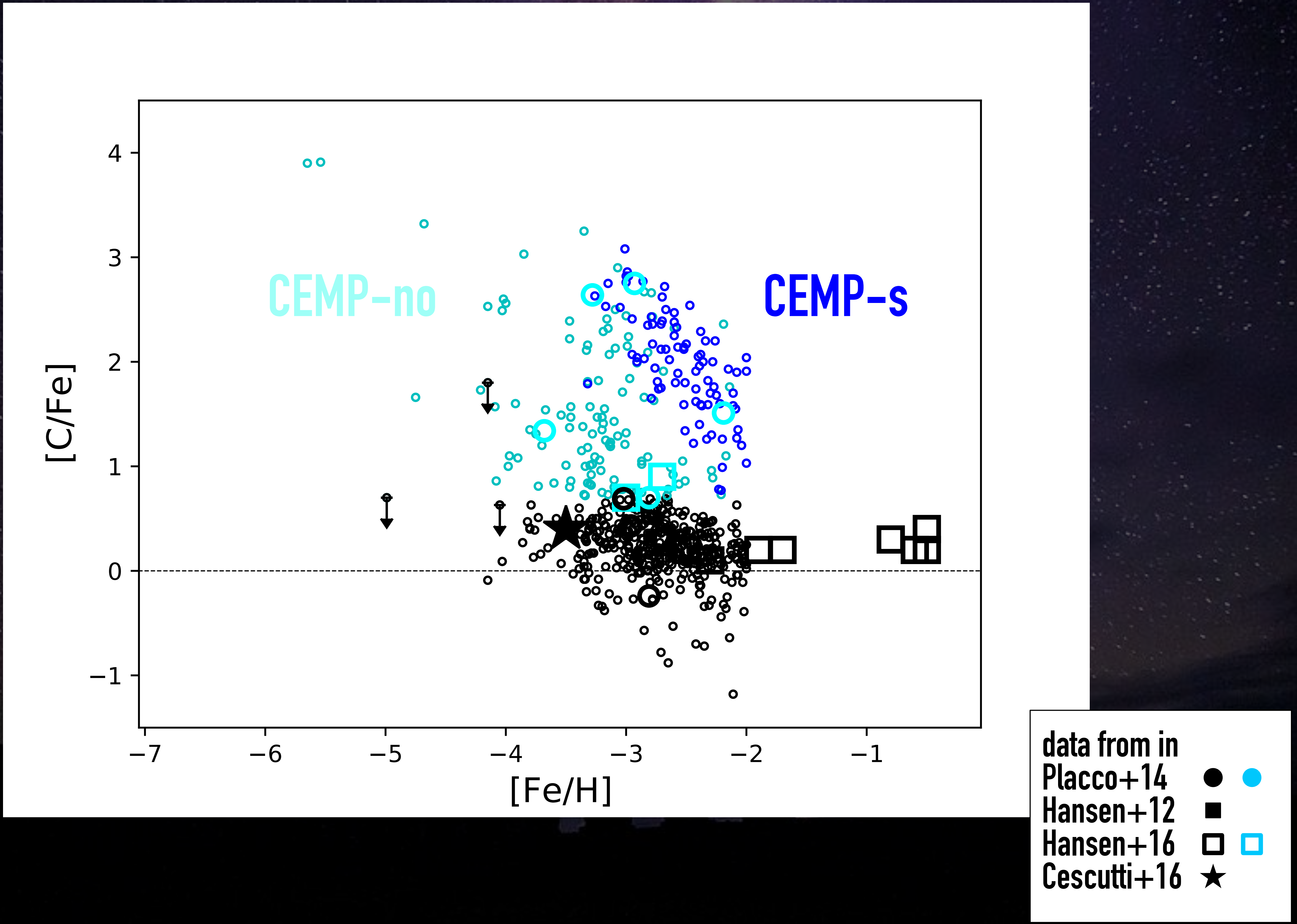
[C/Fe]
4
3
2
1
0
−1
−7
−6
−5
−4
−3
−2
−1
[Fe/H]
data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16



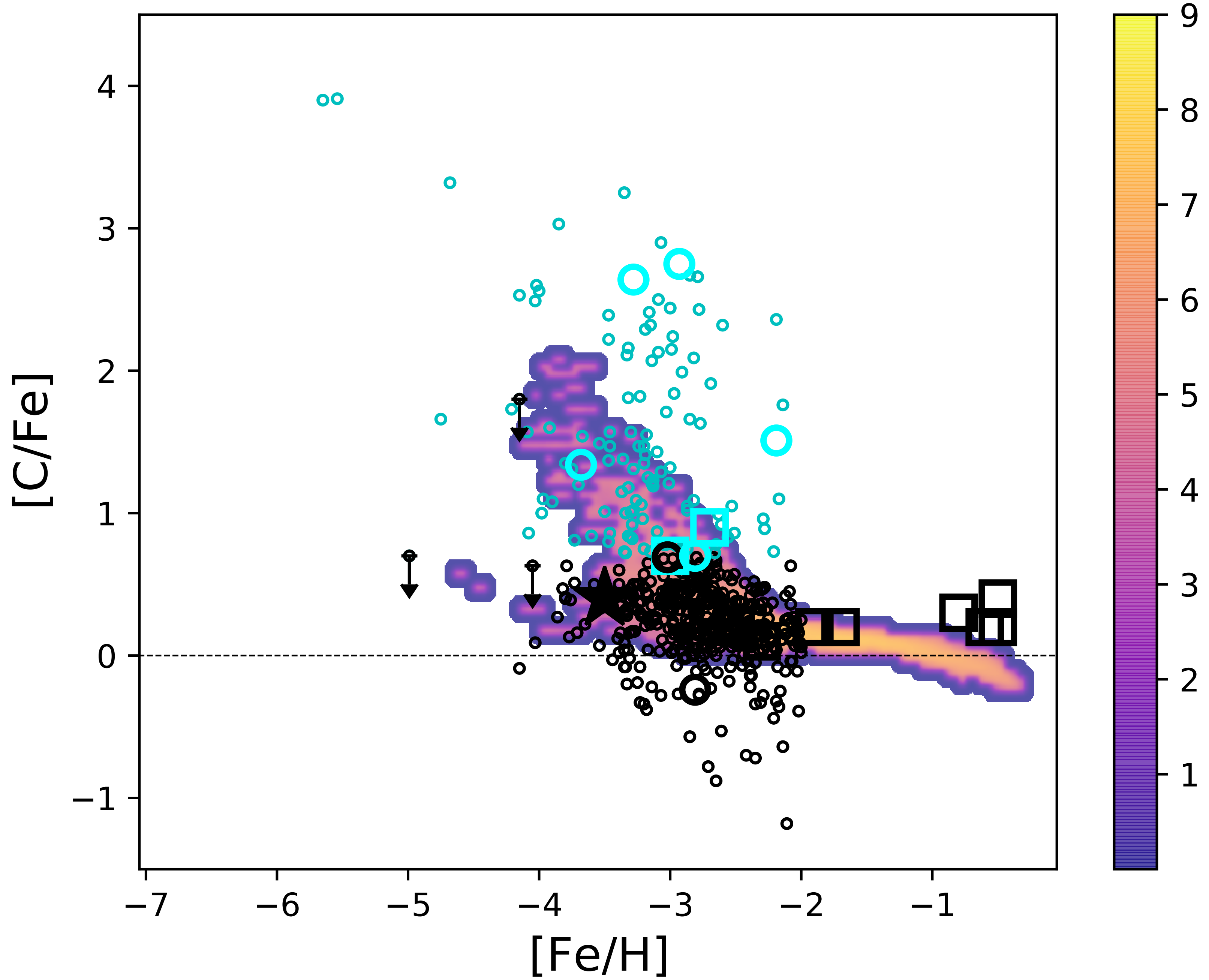
CEMP-s
[C/Fe]
[Fe/H]
4
3
2
1
0
−1
−7
−6
−5
−4
−3
−2
−1

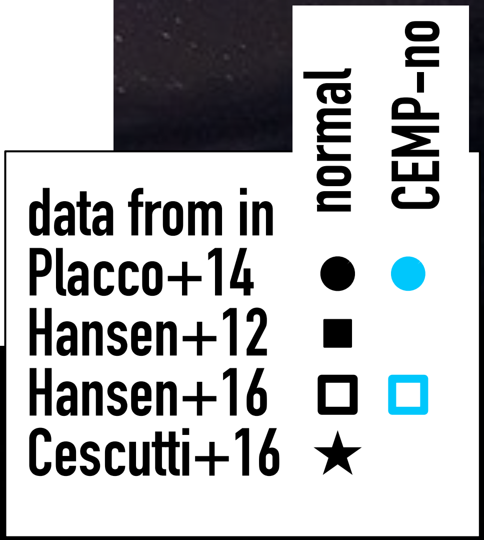



data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16


CEMP-no
CEMP-s
[C/Fe]
[Fe/H]
4
3
2
1
0
−1
−7
−6
−5
−4
−3
−2
−1
data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16

# C/Fe standard

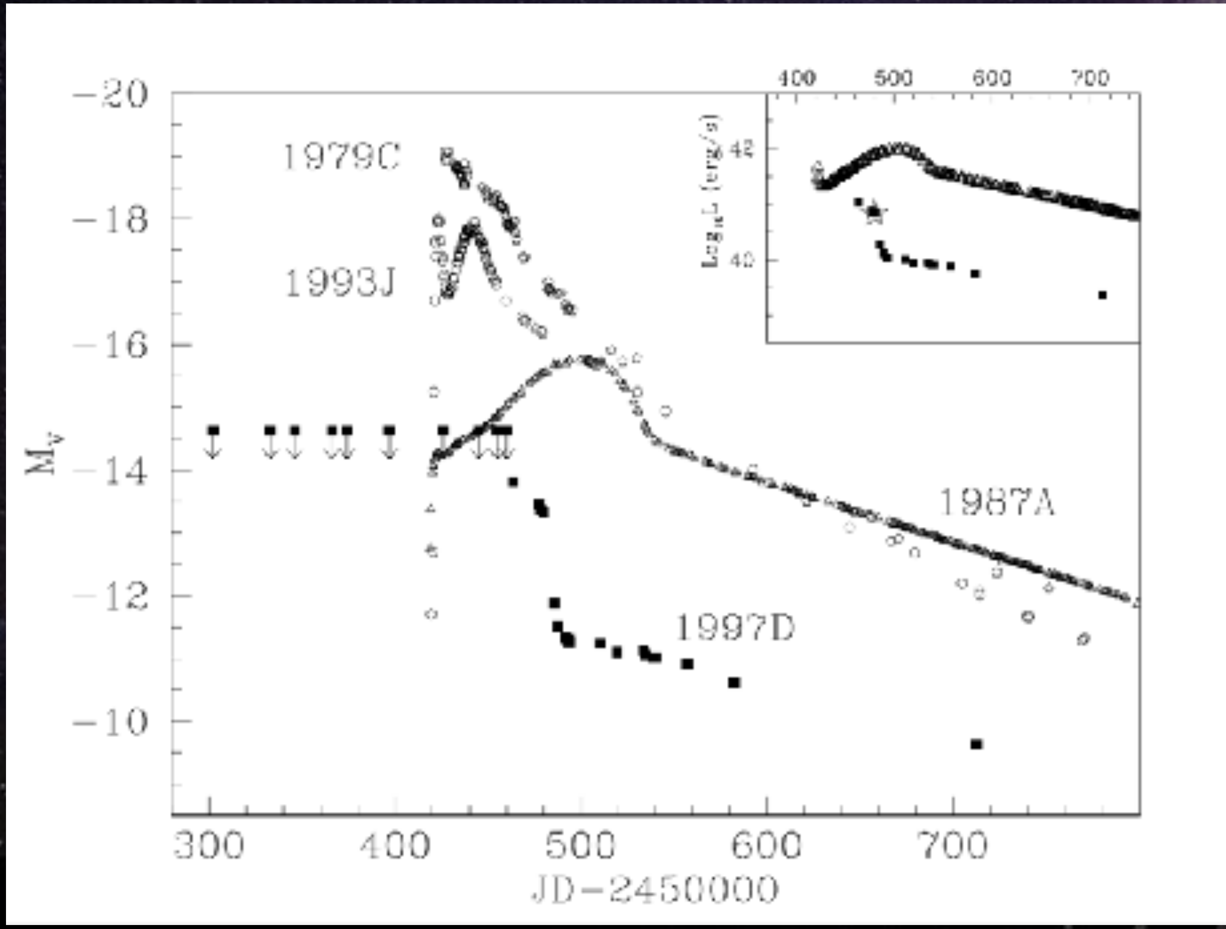


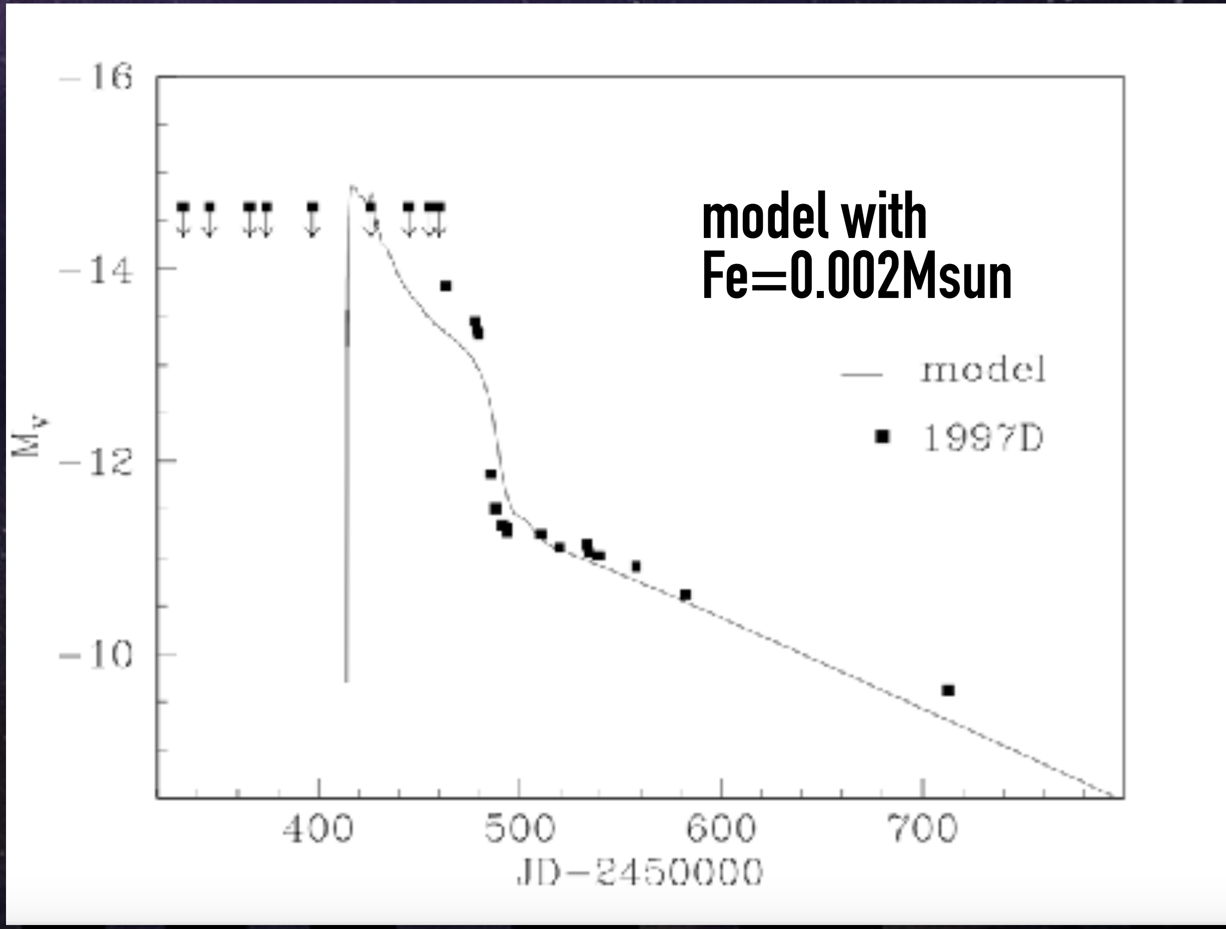




Cescutti + 2016

# Faint SuperNovae

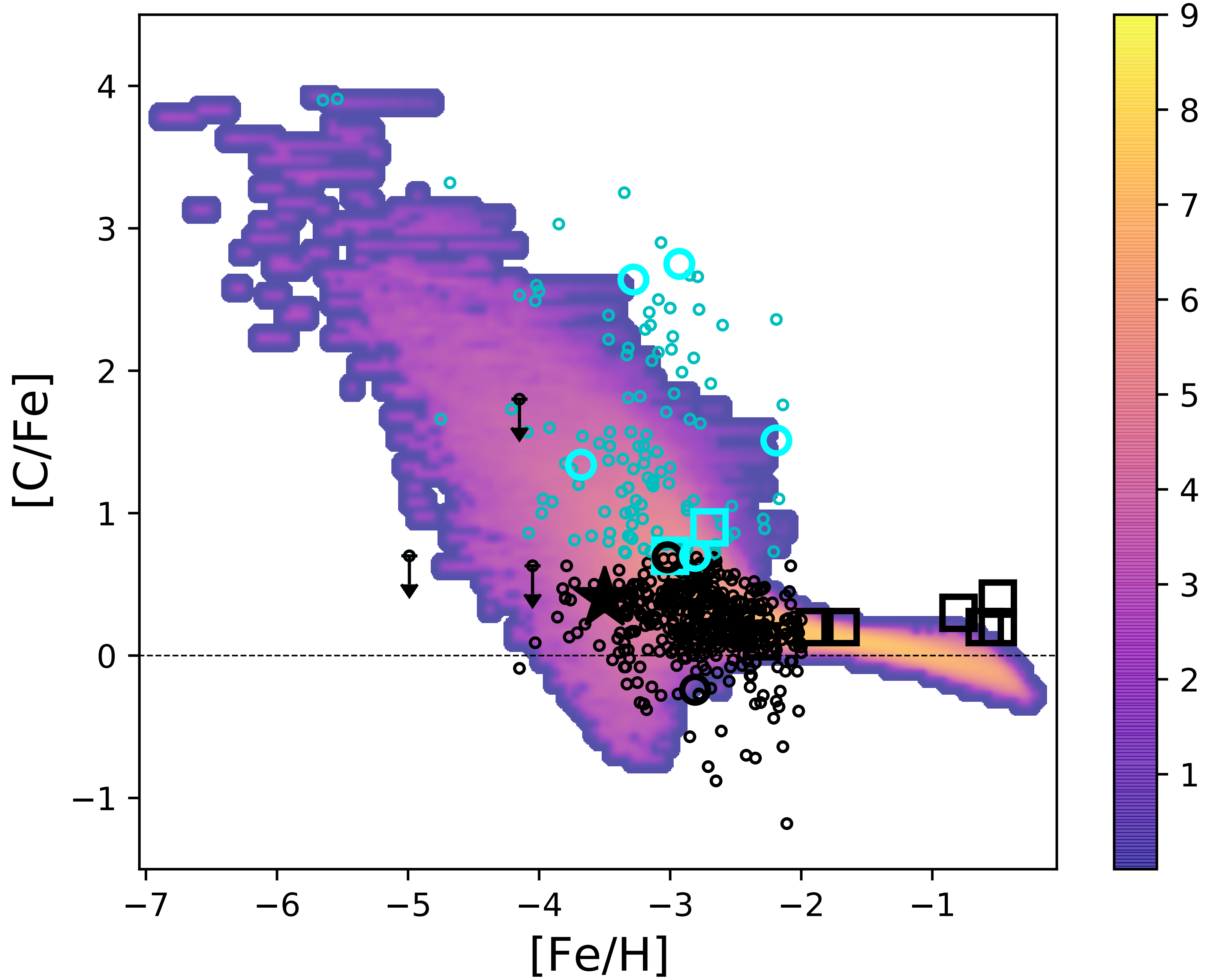
We add another stochasticity in the production of iron by supernovae II.
On average they produce 0.1M⊙ (reference SNe 1987A)
but we assume a distribution of productions from 0.1 to $10^{-5}$M⊙
(see Tominaga+2014, Umeda & Nomoto 2003)




Turatto et al. 1997

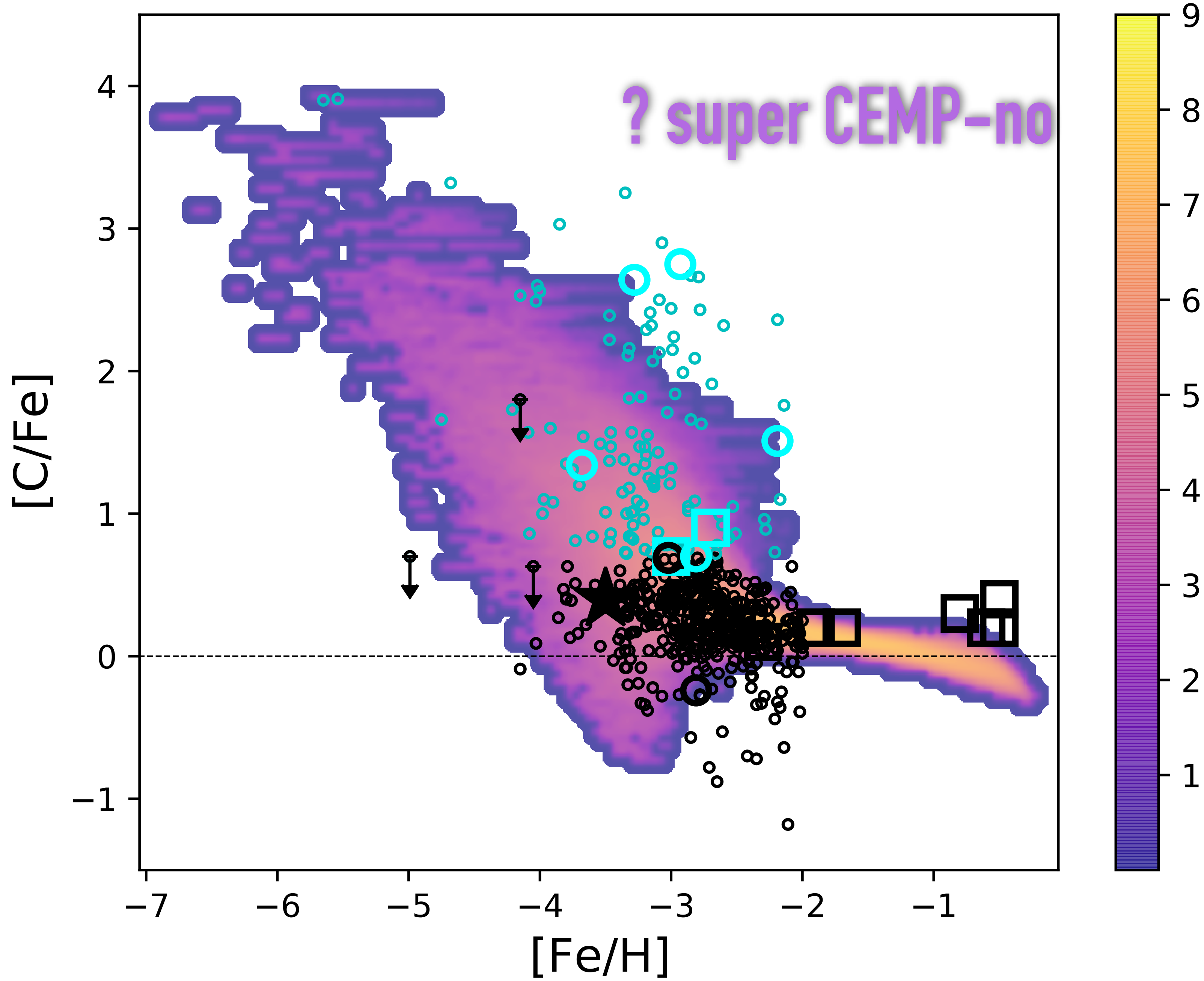
# C/Fe with faint SNe




Cescutti + 2016

data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16

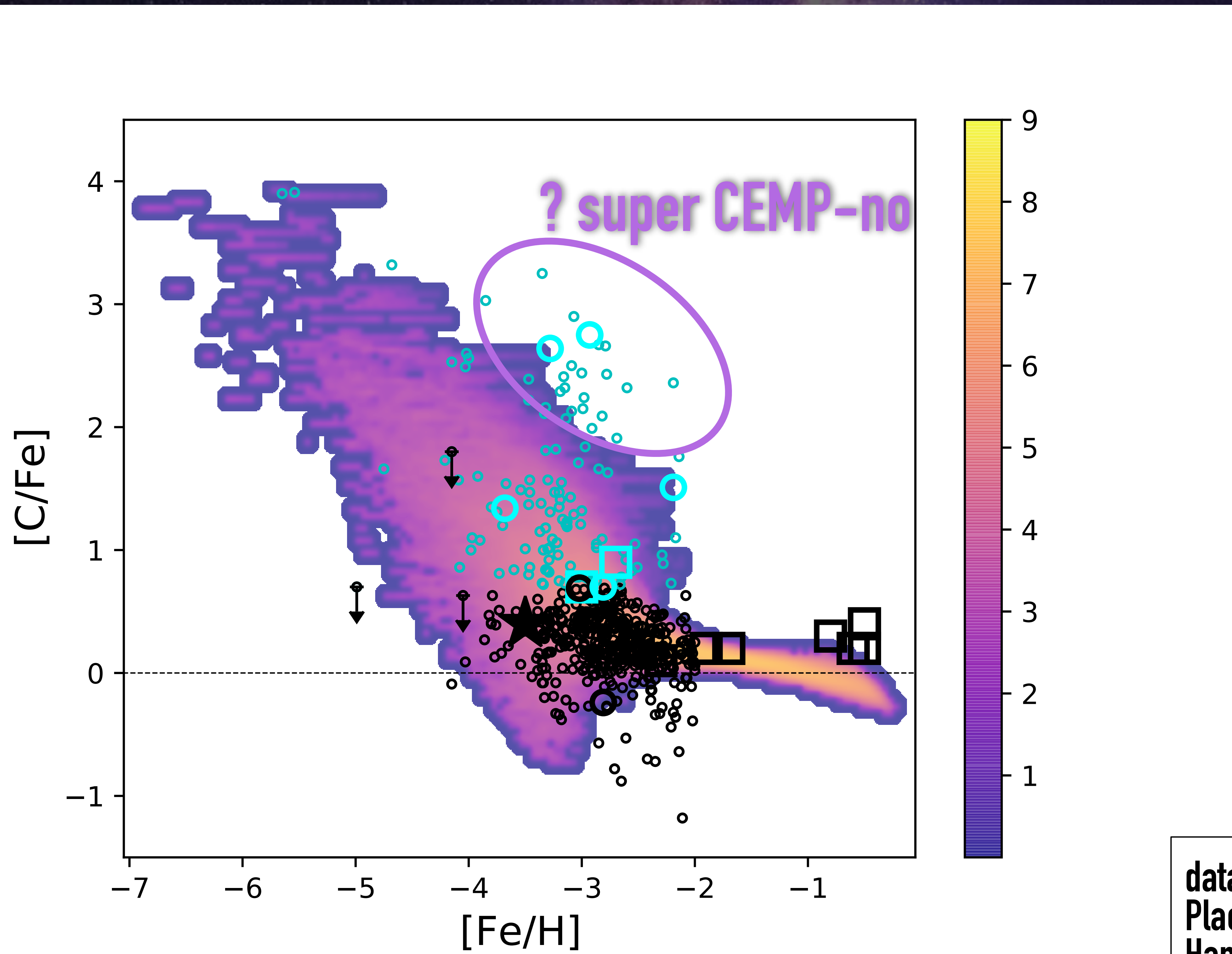
# C/Fe with faint SNe




Cescutti + 2016

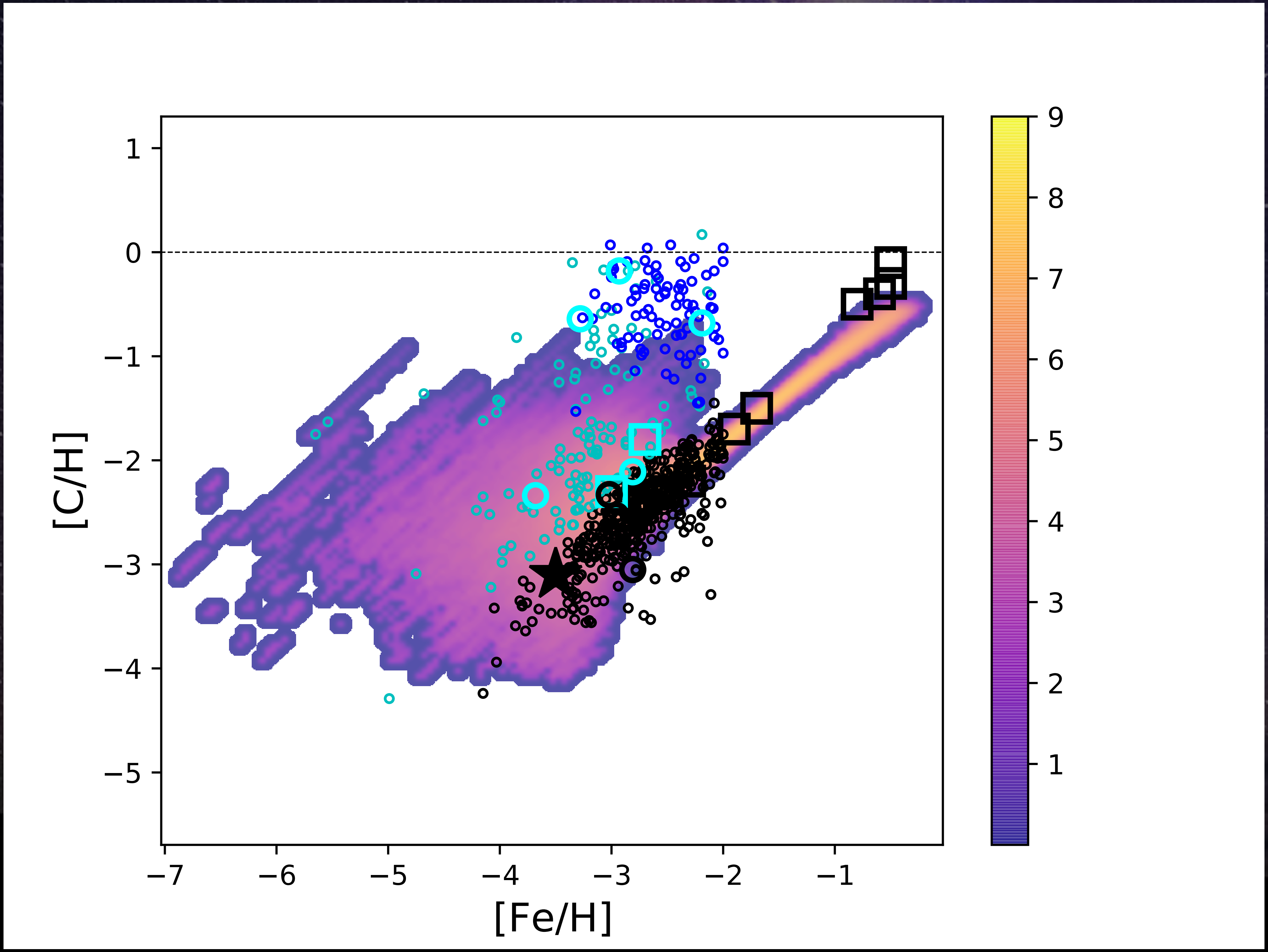
data from in
Placco+14
Hansen+12
Hansen+16
Cescutti+16

# C/Fe with faint SNe

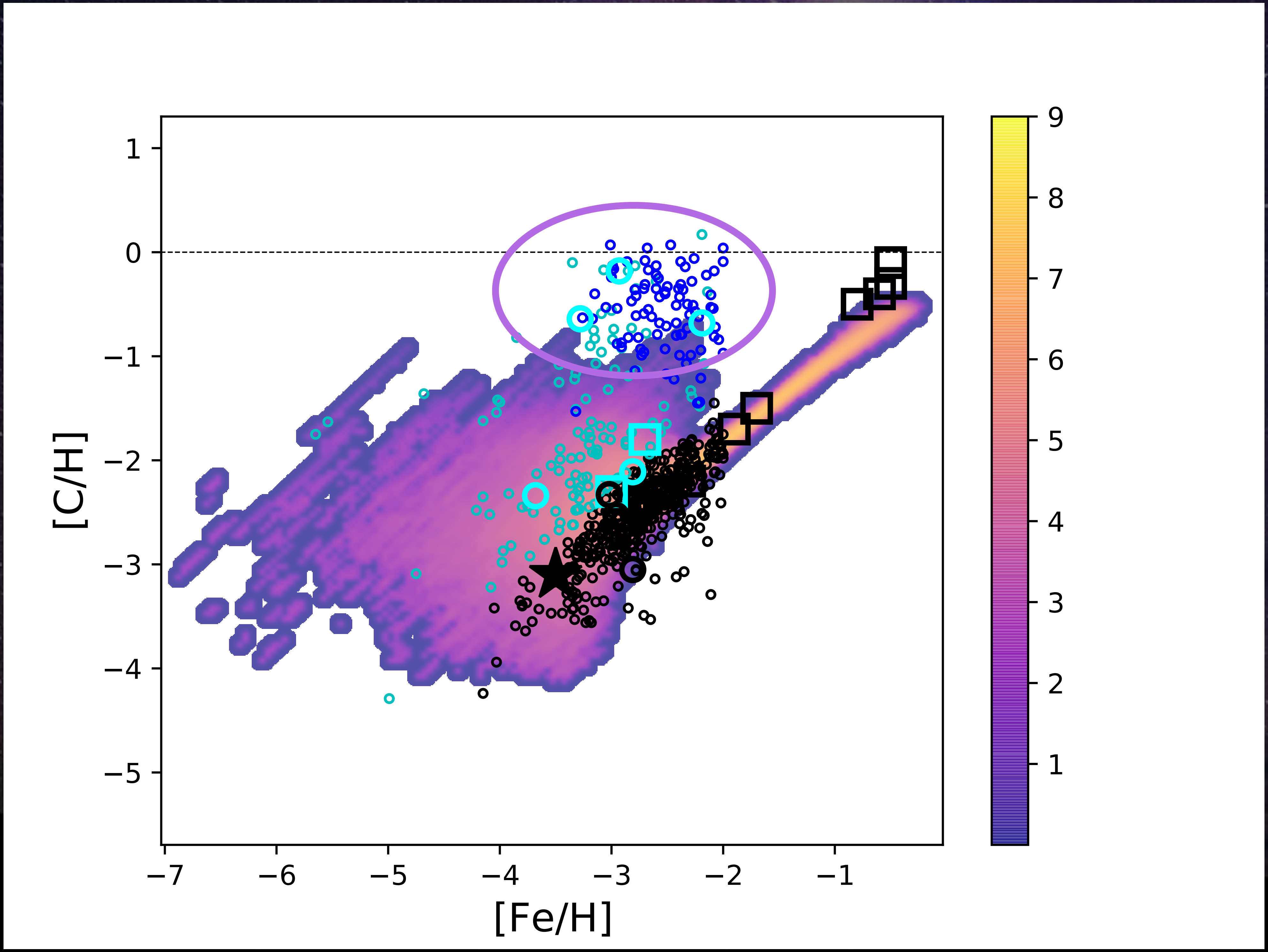



Cescutti + 2016

# Iron Depleted stars?



# Iron Depleted stars?



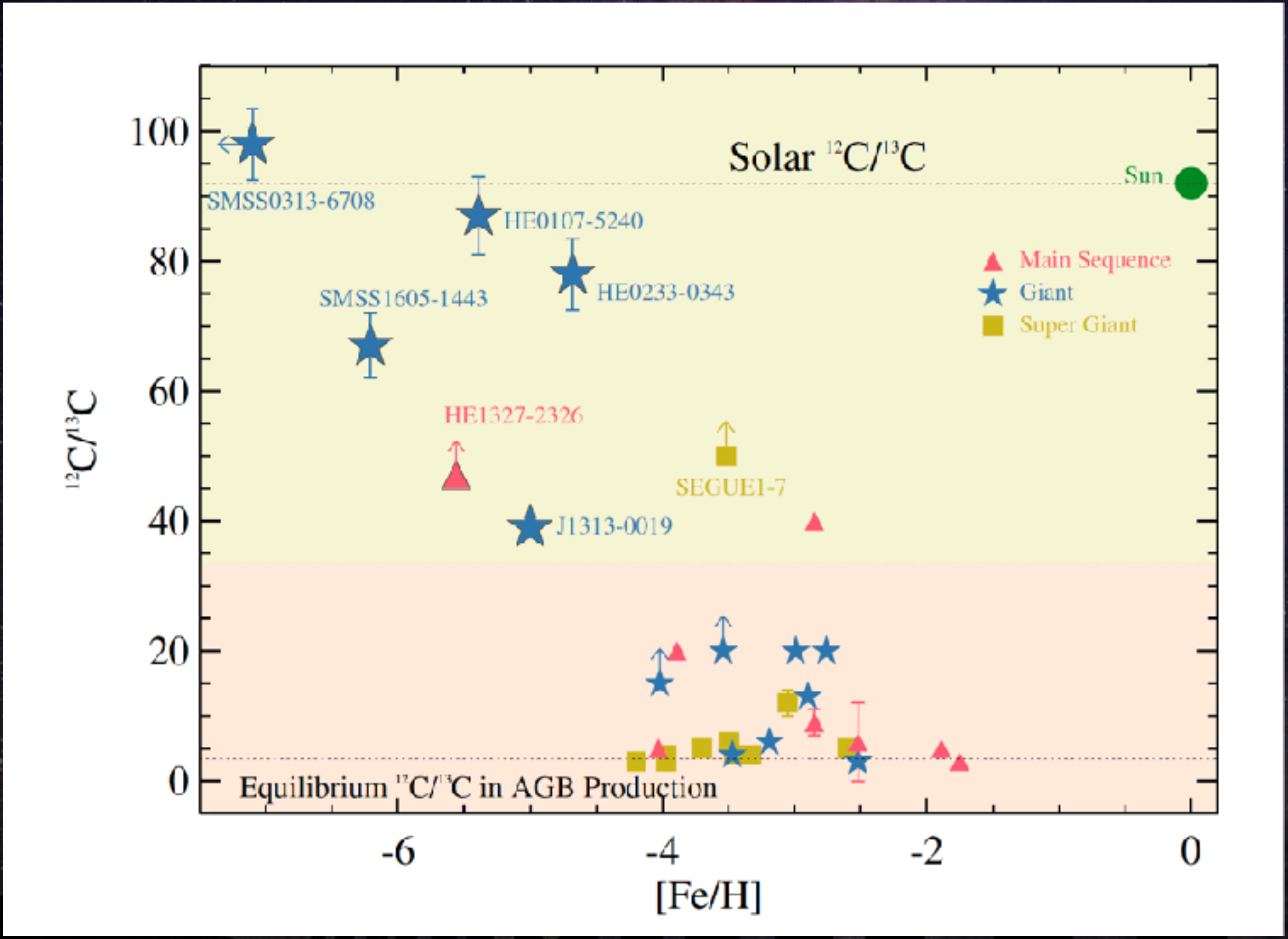
# CONCLUSIONS

The behaviour of CNO can be reproduced in the Early Galaxy by considering stellar rotation.

The same yields can reproduce the Sr/Ba in the Galaxy

We can reproduce CEMP-no stars considering the existence of faint SNe.

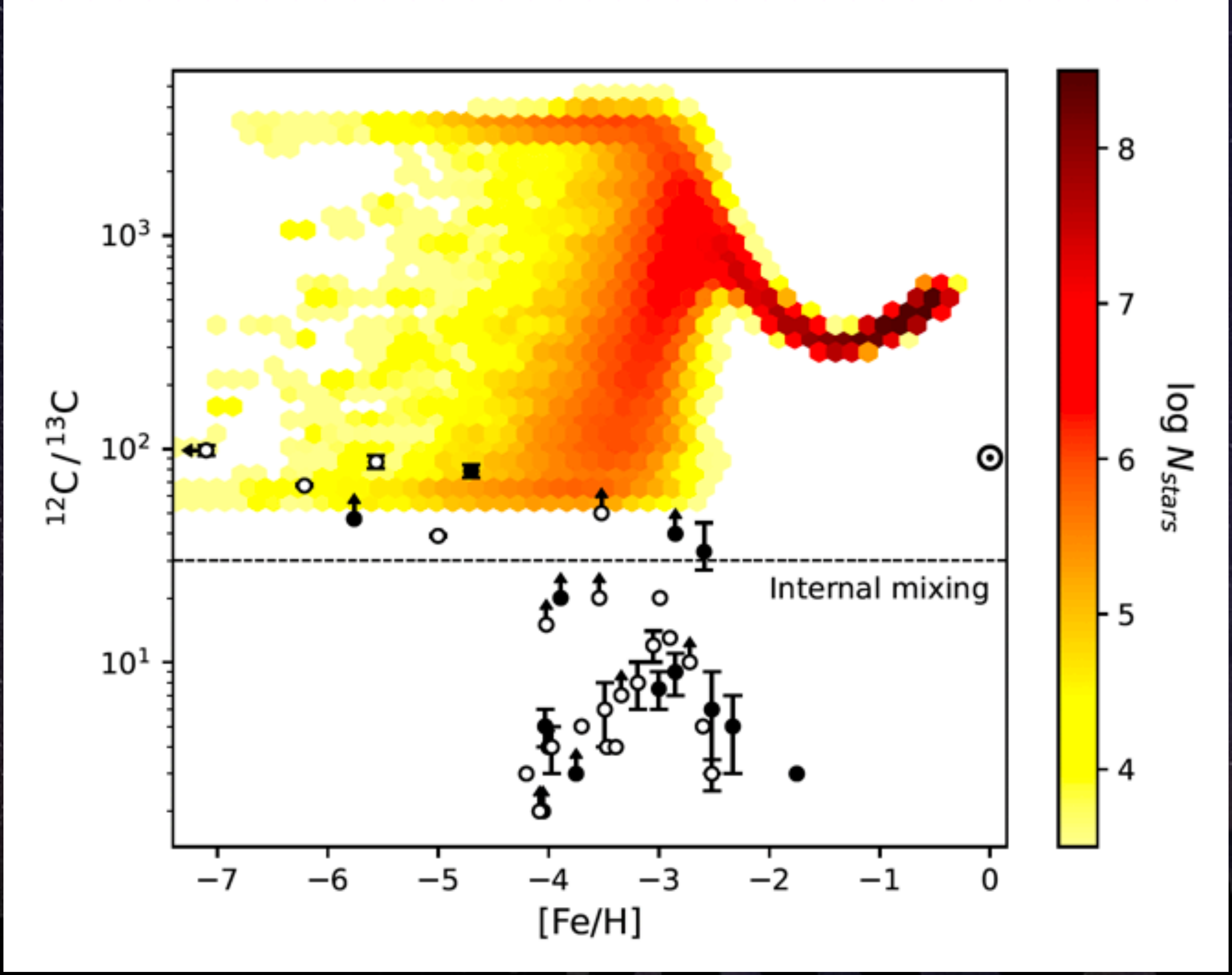
# Not the only constraint! Molaro+2022



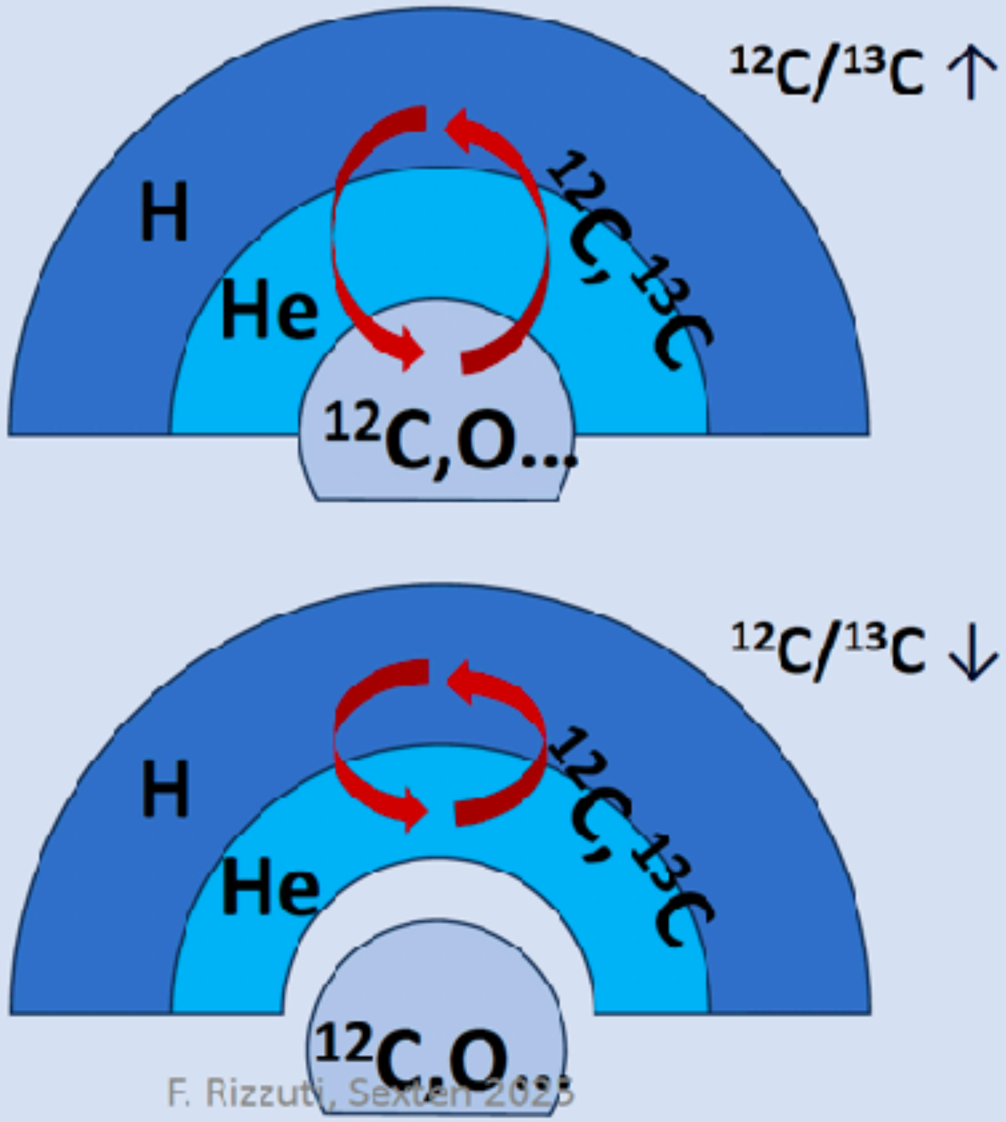

## —> Rizzuti et al. 2025

using Limongi&Chieffi + Roberti models

# C13 with rotating faint SNe



# The data below $^{12}C/^{13}C < 30$




- The CNO cycle has a theoretical equilibrium value of $^{12}C/^{13}C \sim 4$ (Choplin+16)
- The ratio increases bacause the $^{12}C/^{13}C \sim 4$ layers mix with the abundant $^{12}C$ below
- What if the envelope expelled with no mixing? Wolf-Rayet, failed supernovae…

# C13 with rotating failed SNe