Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

Probing the Nature of the First Stars

the point of view of neutron capture elements

Gabriele Cescutti

AstroFIt 2
Astronomy Fellowships in Italy

4MOST – 4m Multi-Object Spectroscopic Telescope

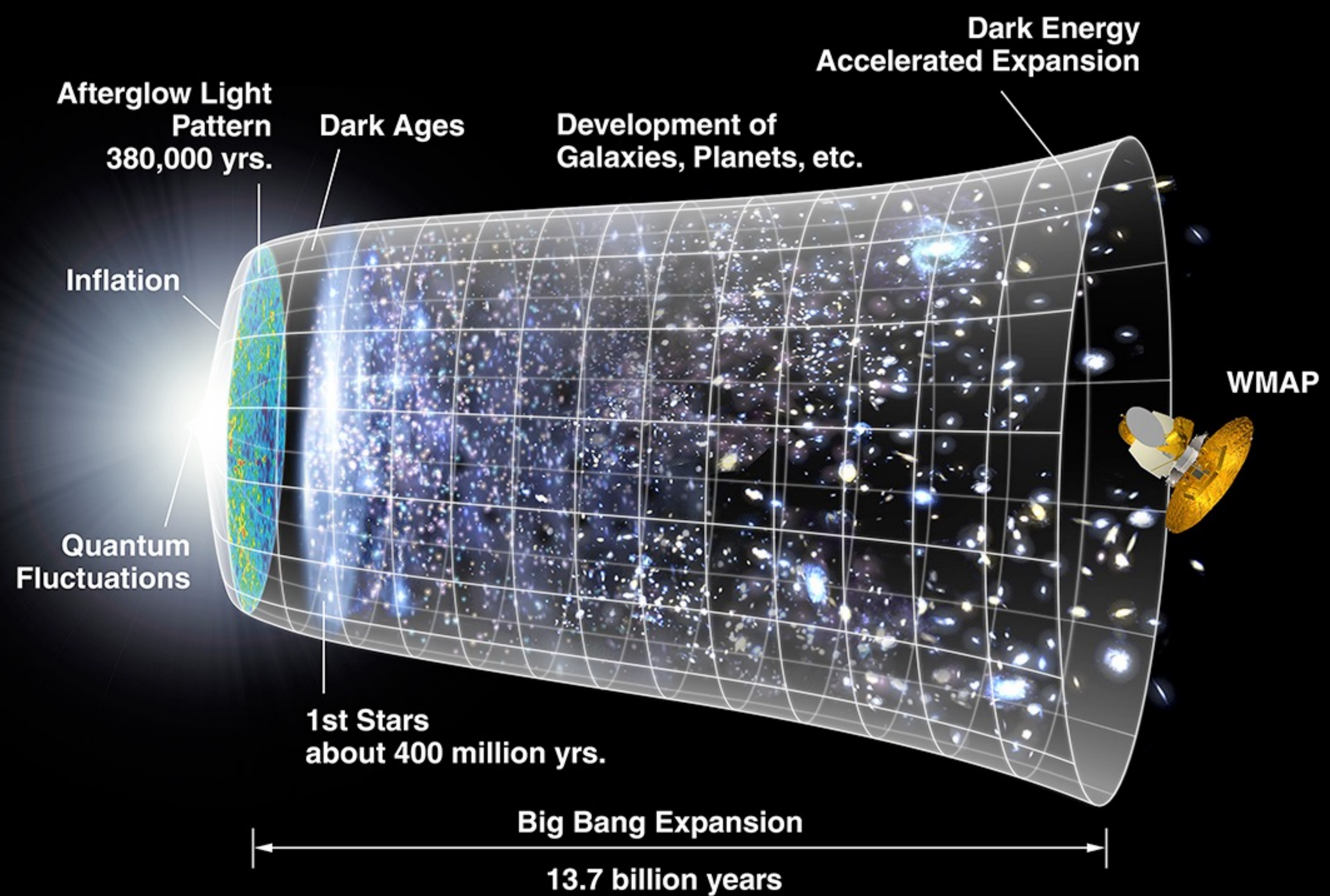
SHYNE

erc
European Research Council

BRIDGCE UK Network

TS ASTRO 2017

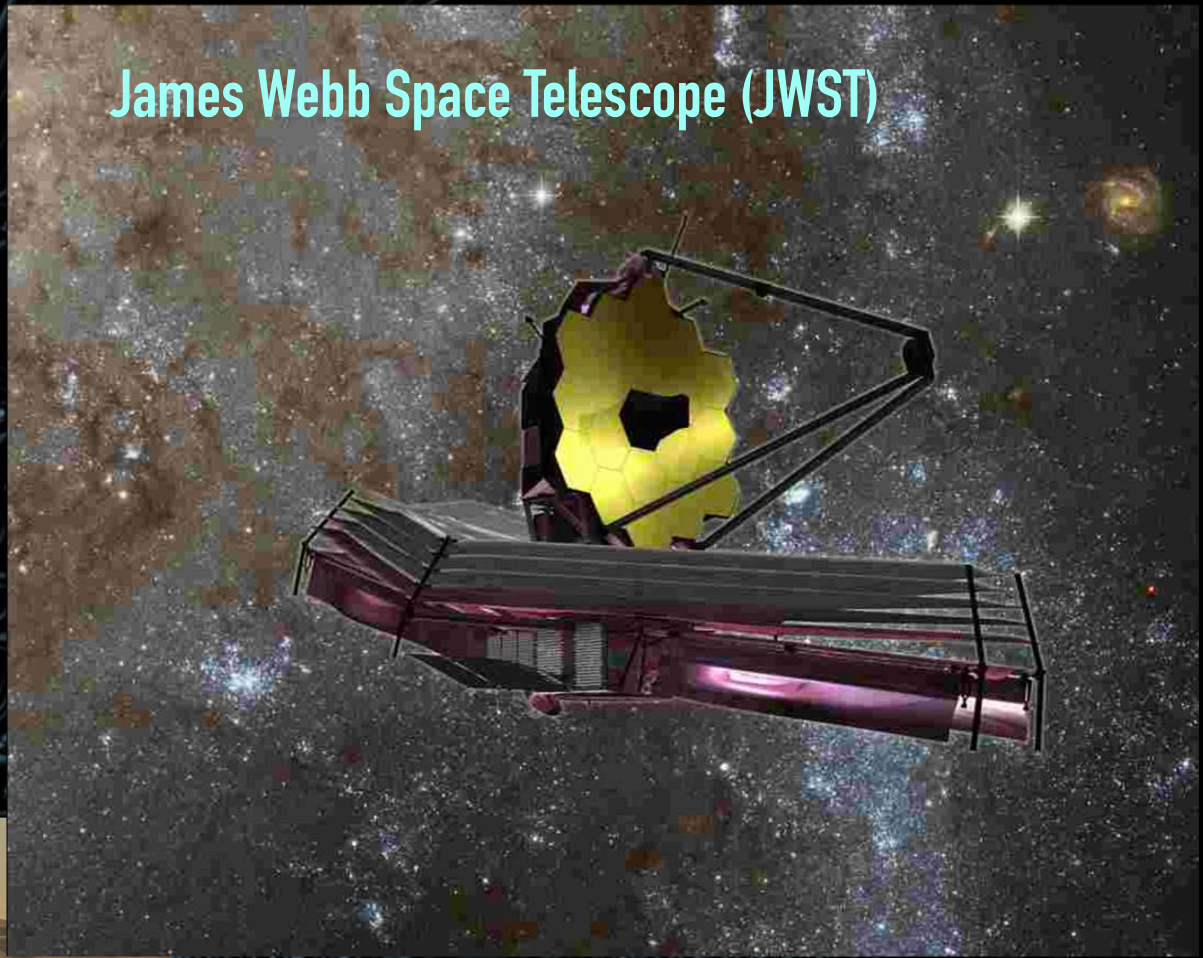
First Stars

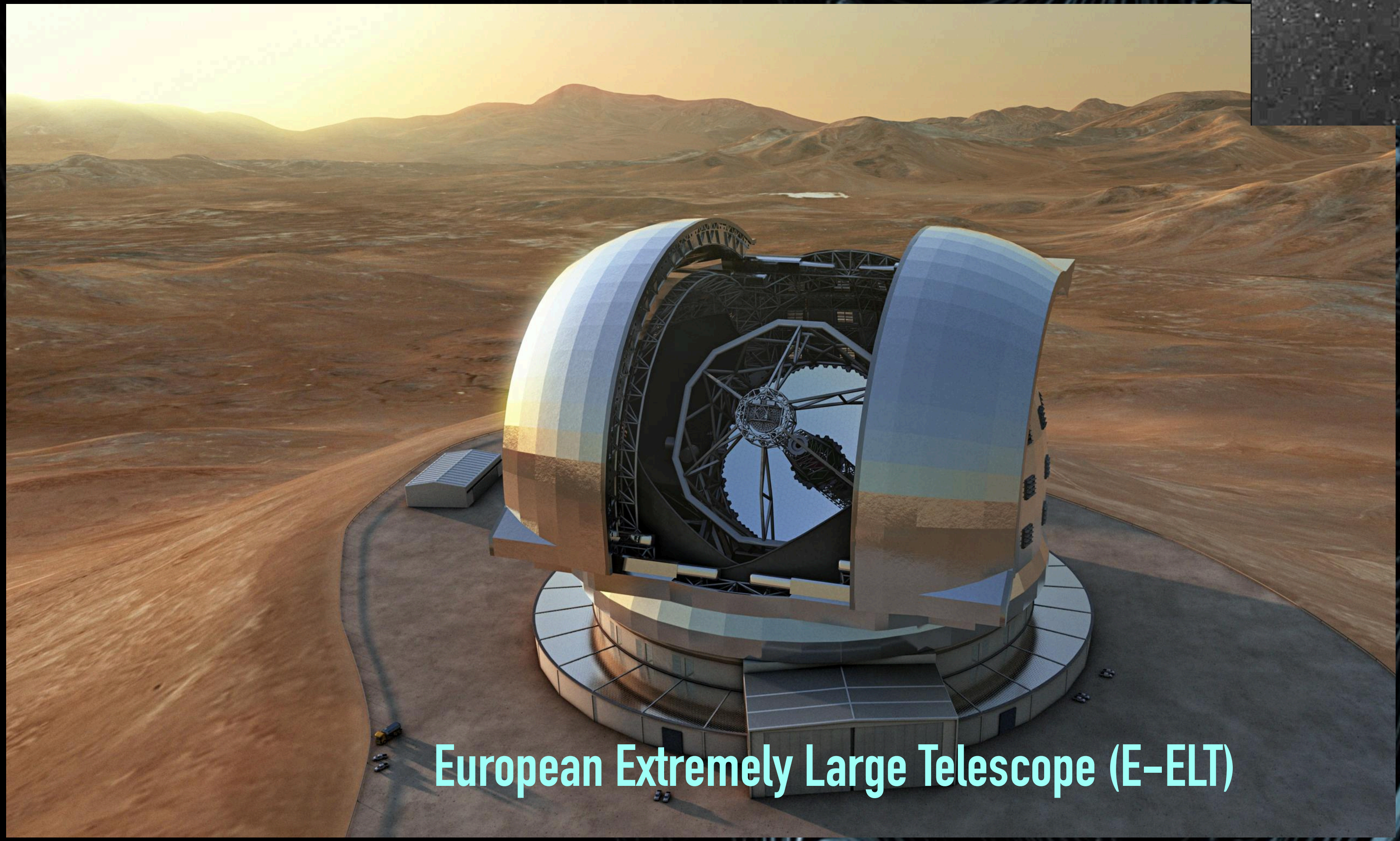


"Understanding these first sources is critical, since they greatly influenced the formation of later objects such as galaxies."

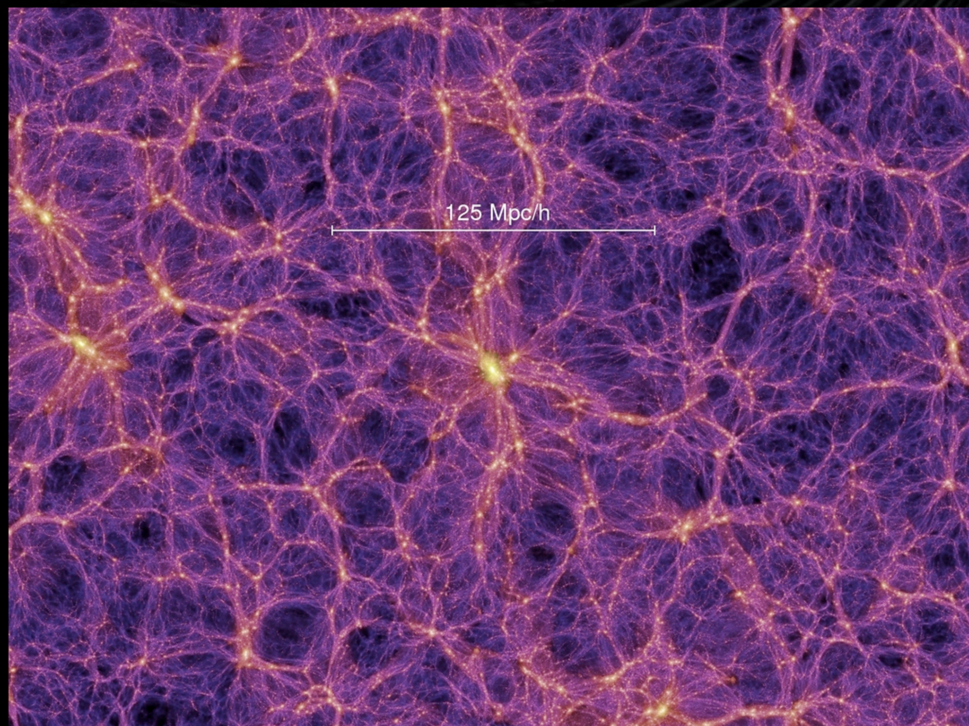
"The chemical elements of life were first produced in the first generation of stars after the Big Bang.
We are here today because of them – and we want to better understand how that came to be!"
John Mather

Quest for future telescopes


James Webb Space Telescope (JWST)


European Extremely Large Telescope (E-ELT)

Simulations of the First Stars



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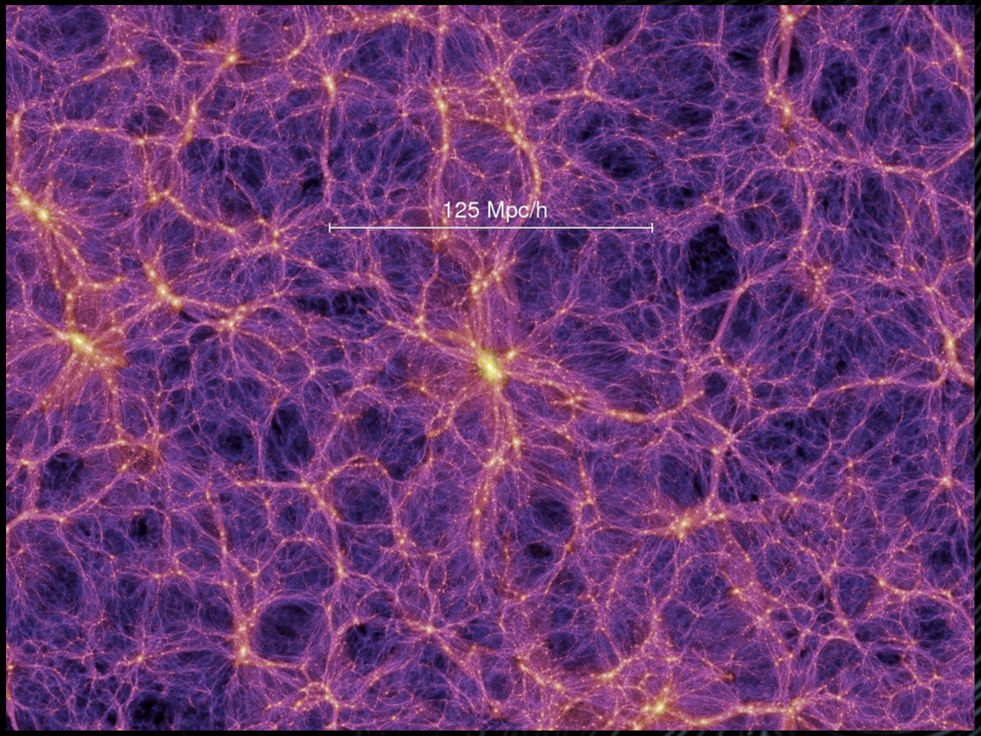
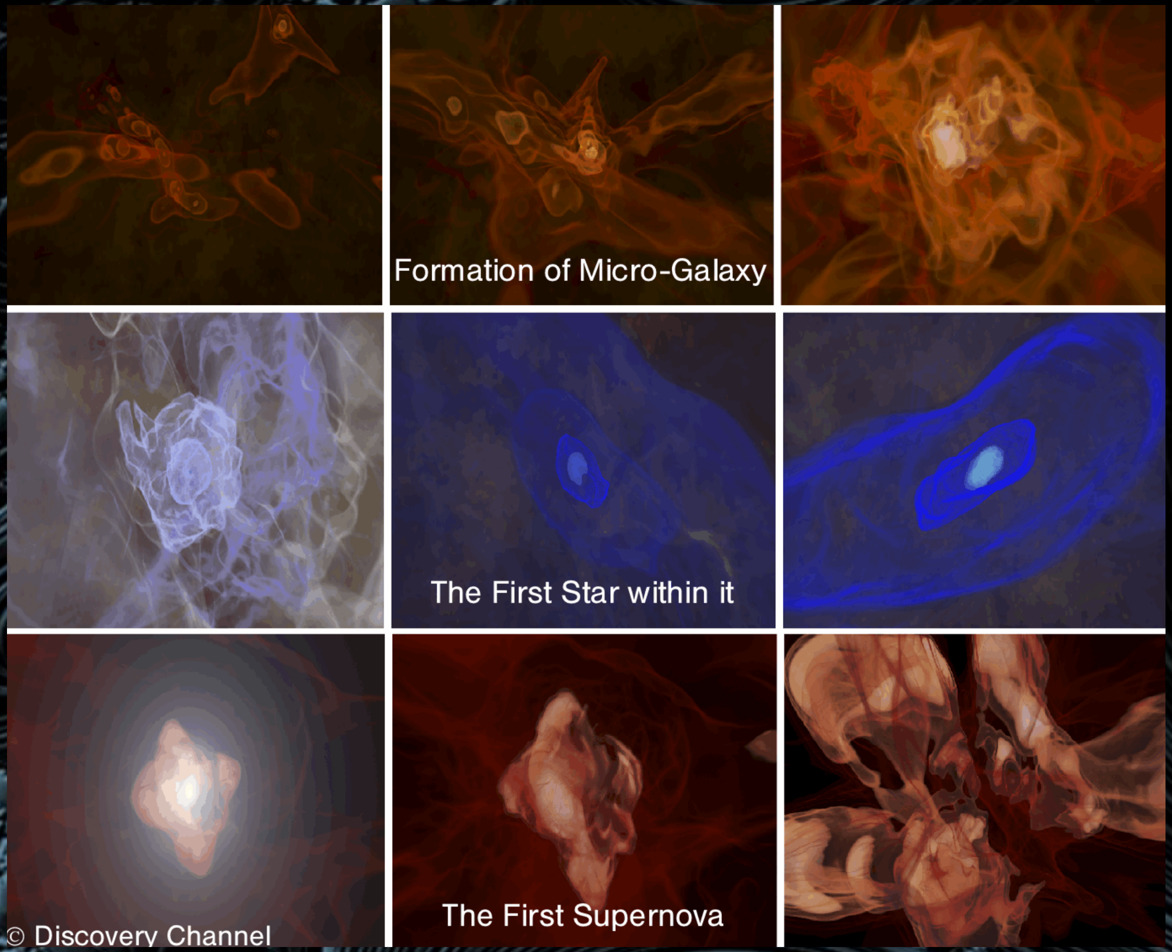


The theoretical challenge:
Total dynamical range 10^{12} !



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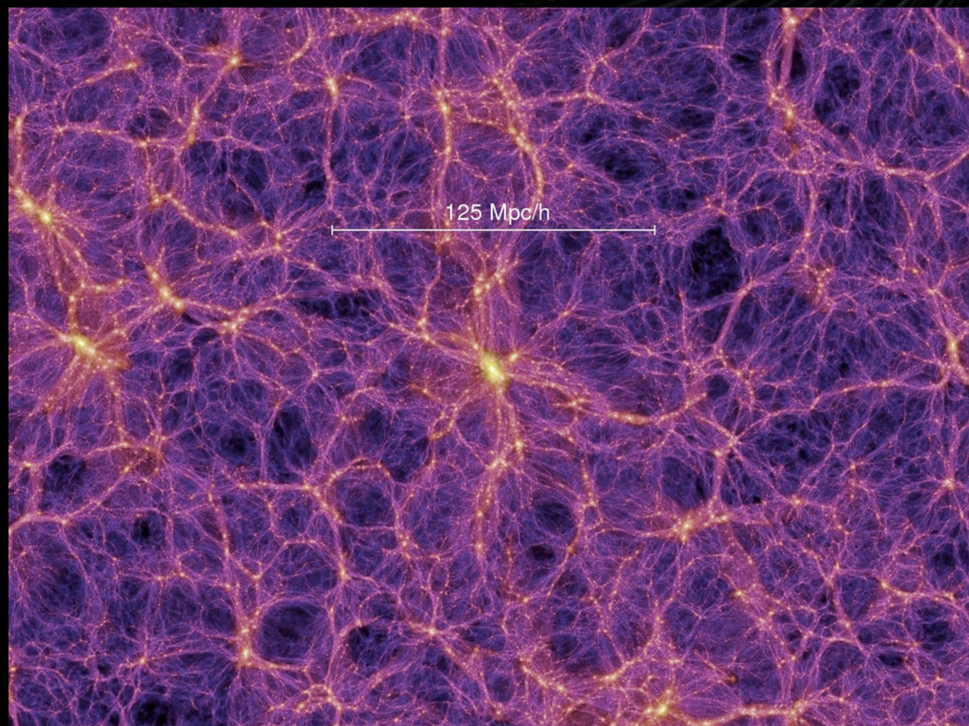

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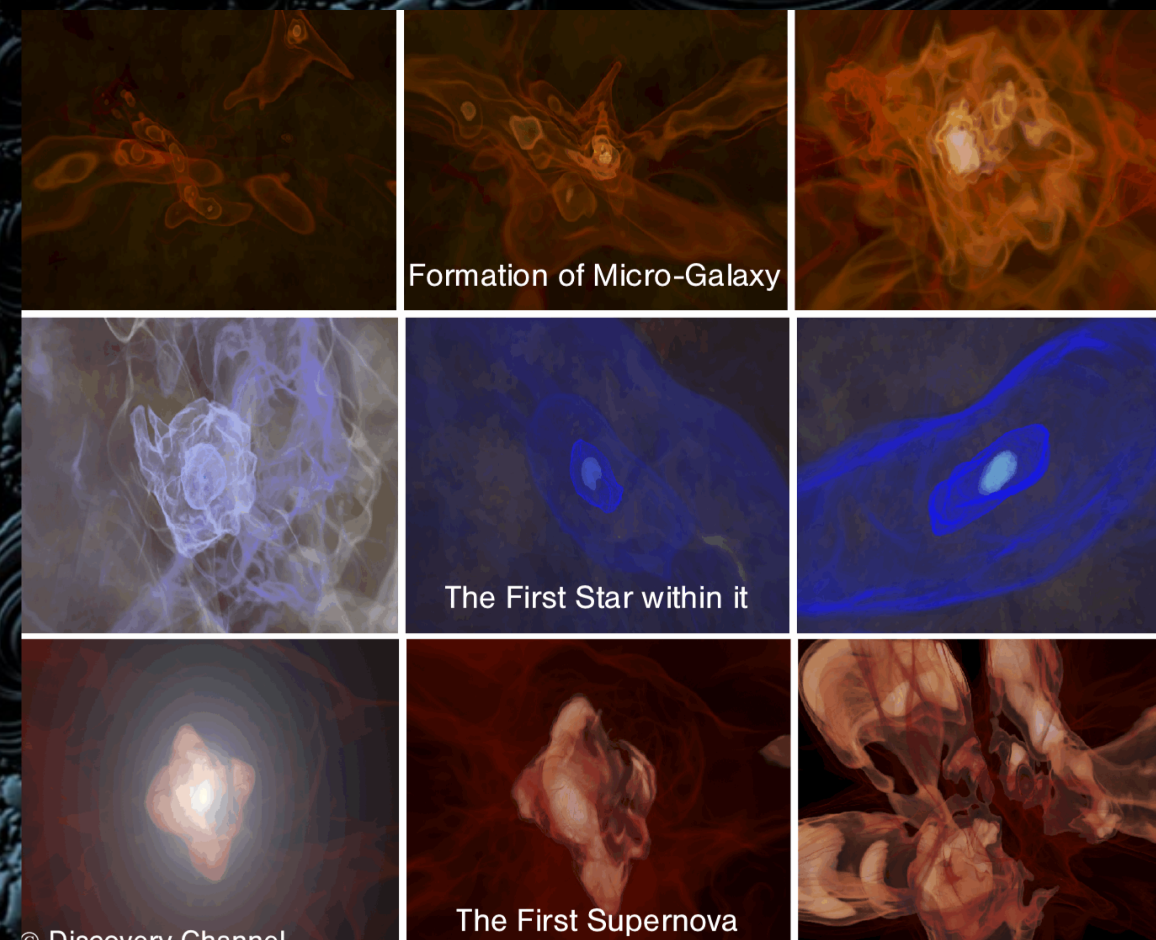

Start with a stadium and then focus on a single atom within a stadium!

Alternative way

Galactic Archaeology

The oldest stars in our Galaxy formed from the gas ejected by the first stellar generations:

Alternative way

Galactic Archaeology

The oldest stars in our Galaxy formed from the gas ejected by the first stellar generations:

Massive Stars – short lifetimes

Core collapse Supernova

First polluters in the Universe

Alternative way

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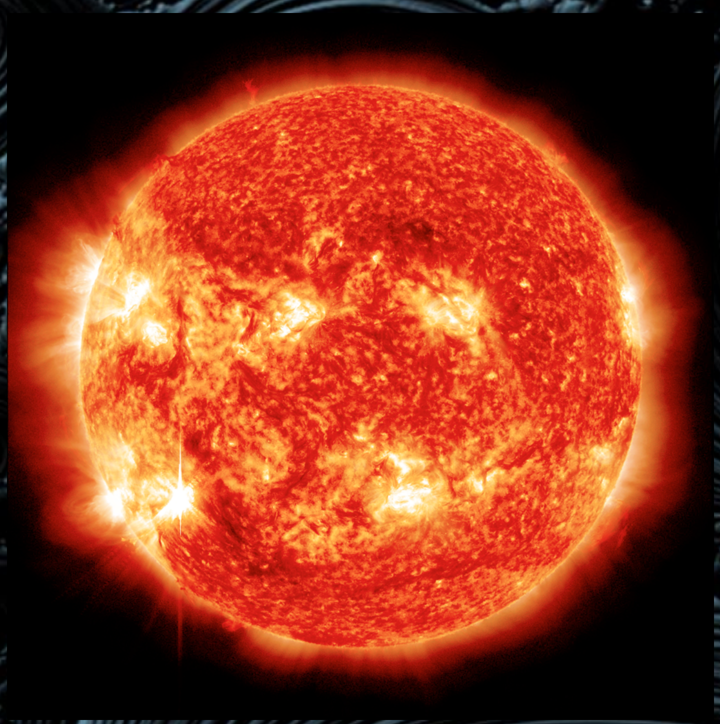
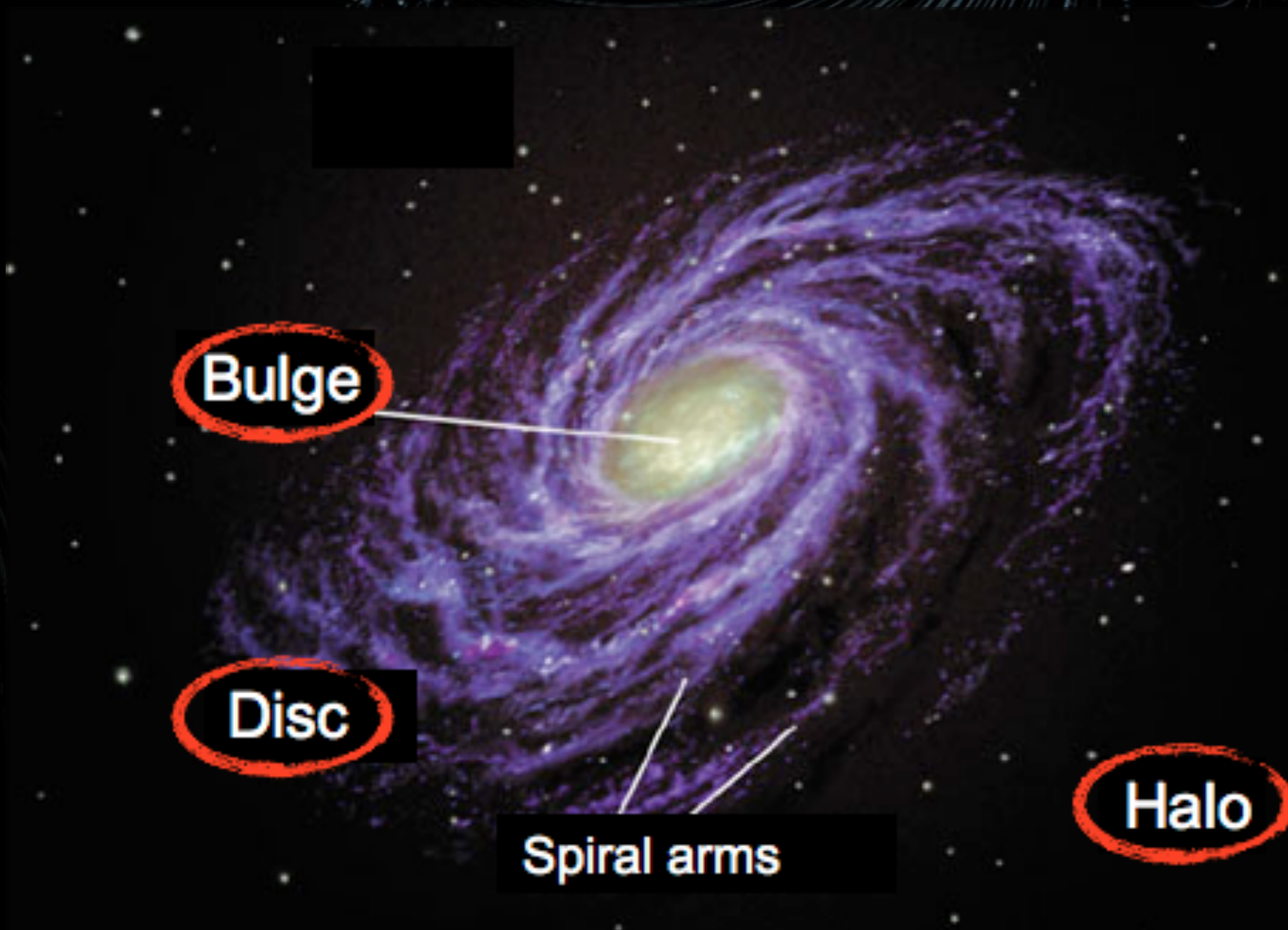
Low mass stars – long lifetimes



The Sun

Imprints of the first stars

Where are the oldest fossil stars in the MW?



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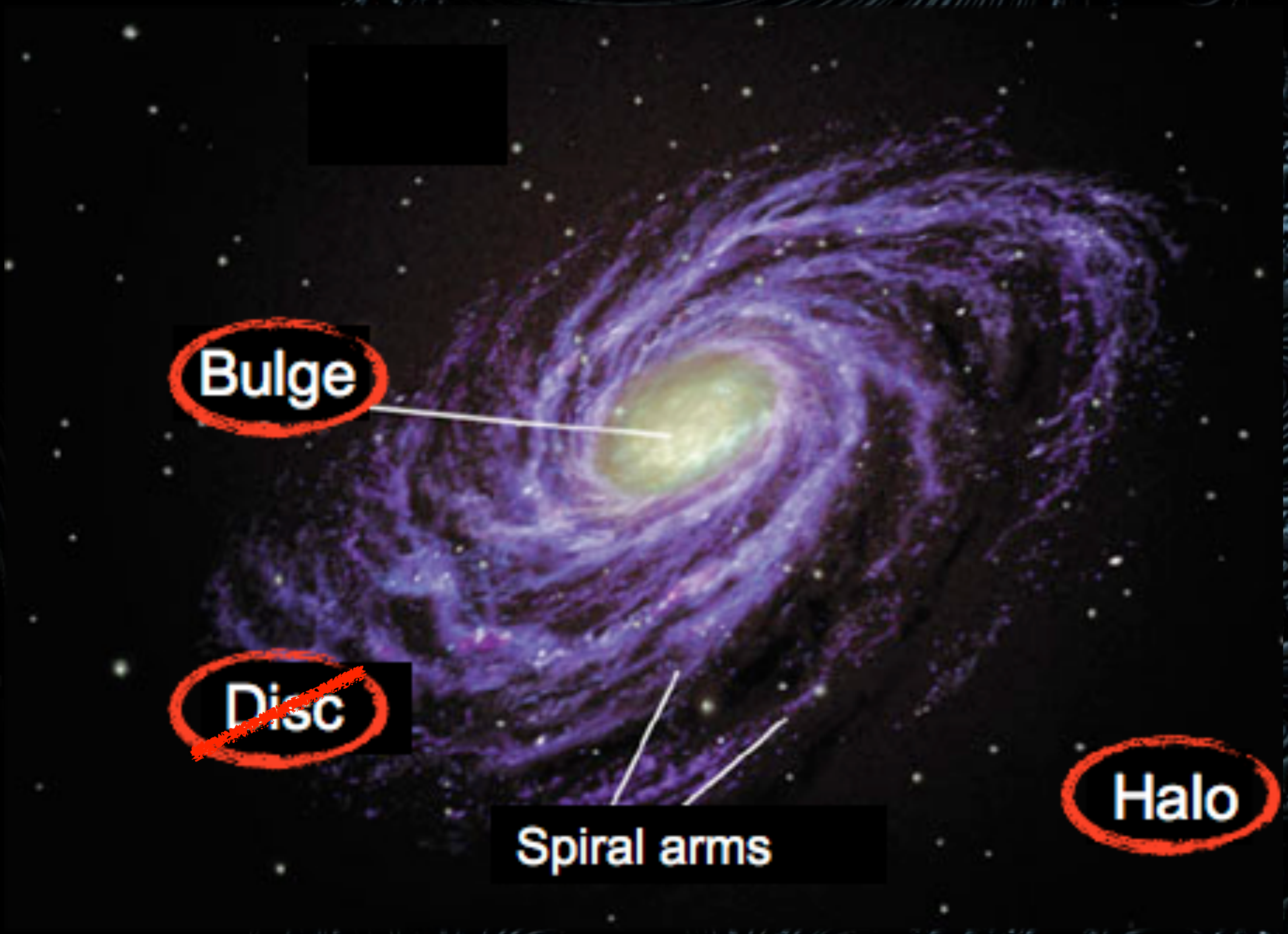

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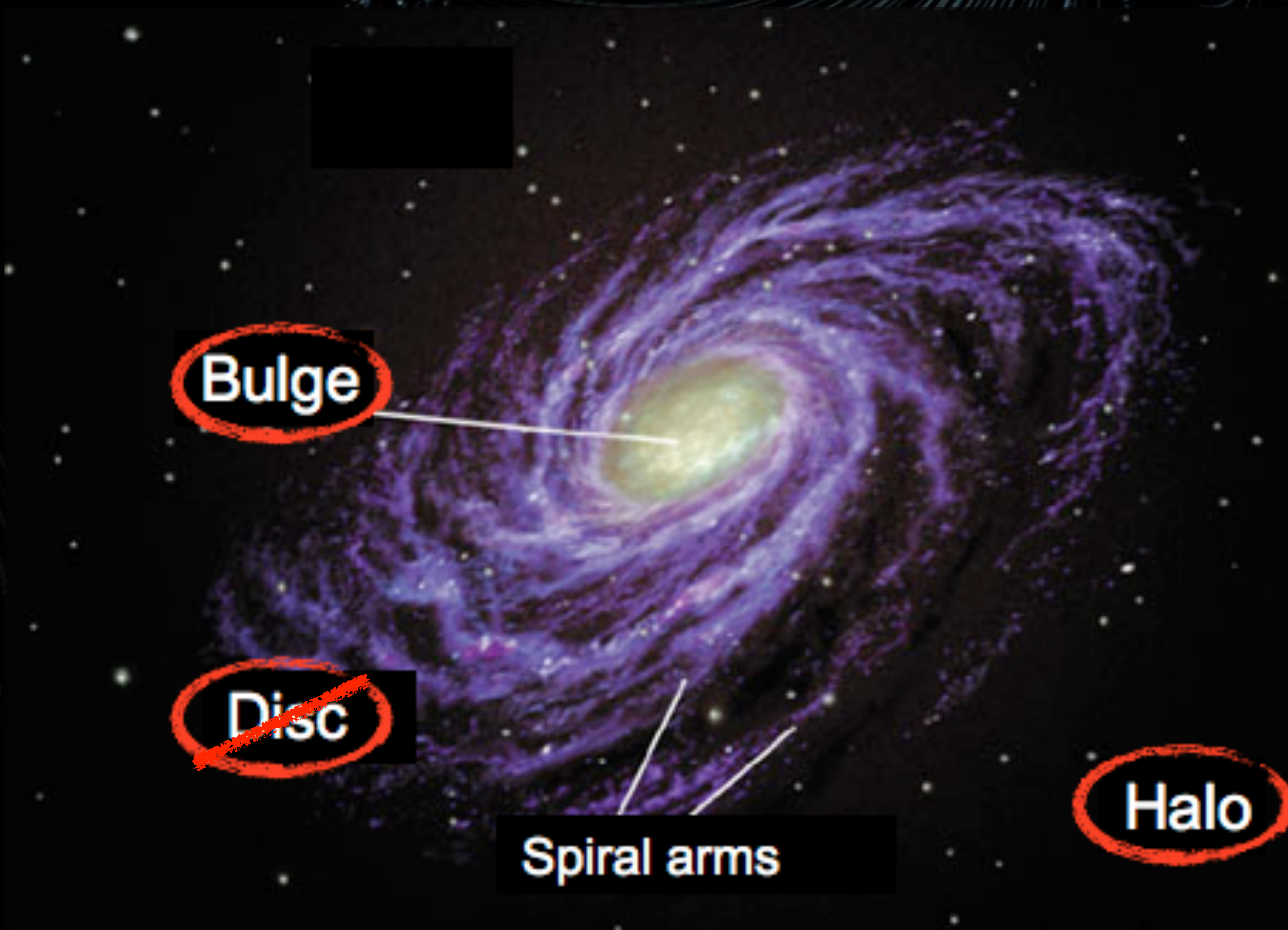
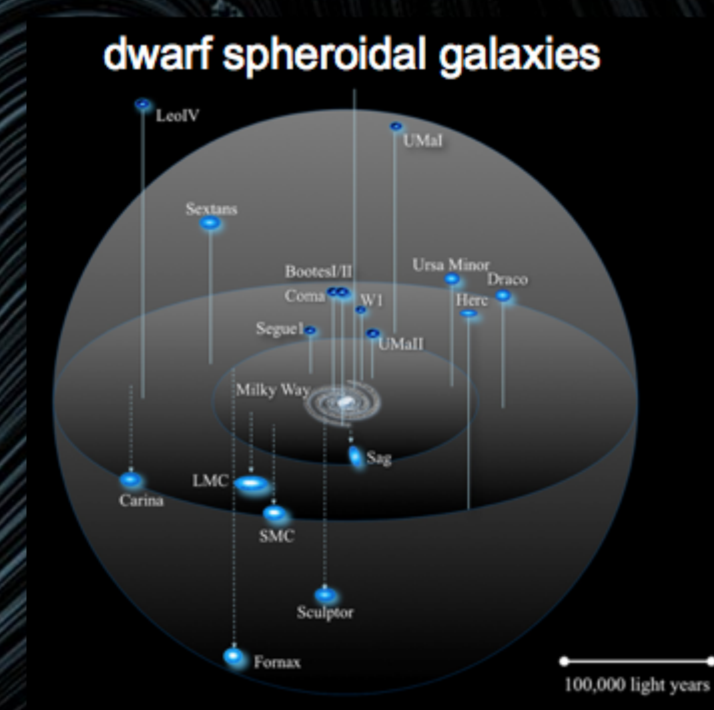
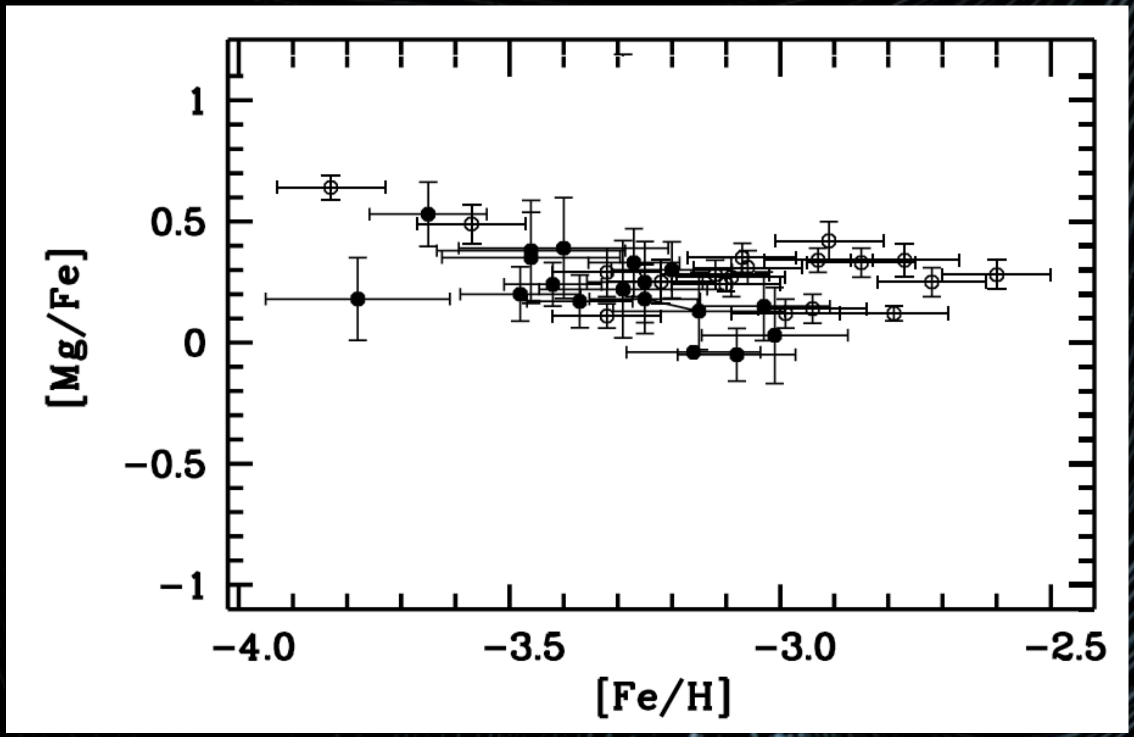


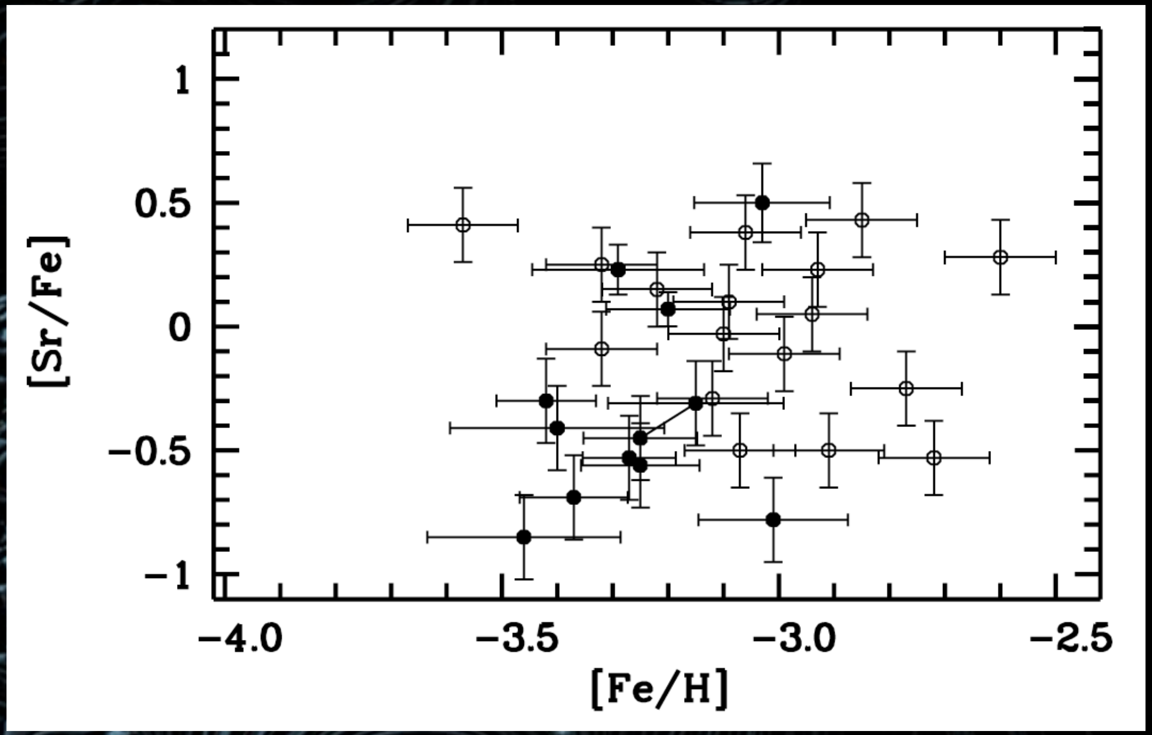


Why neutron capture elements?

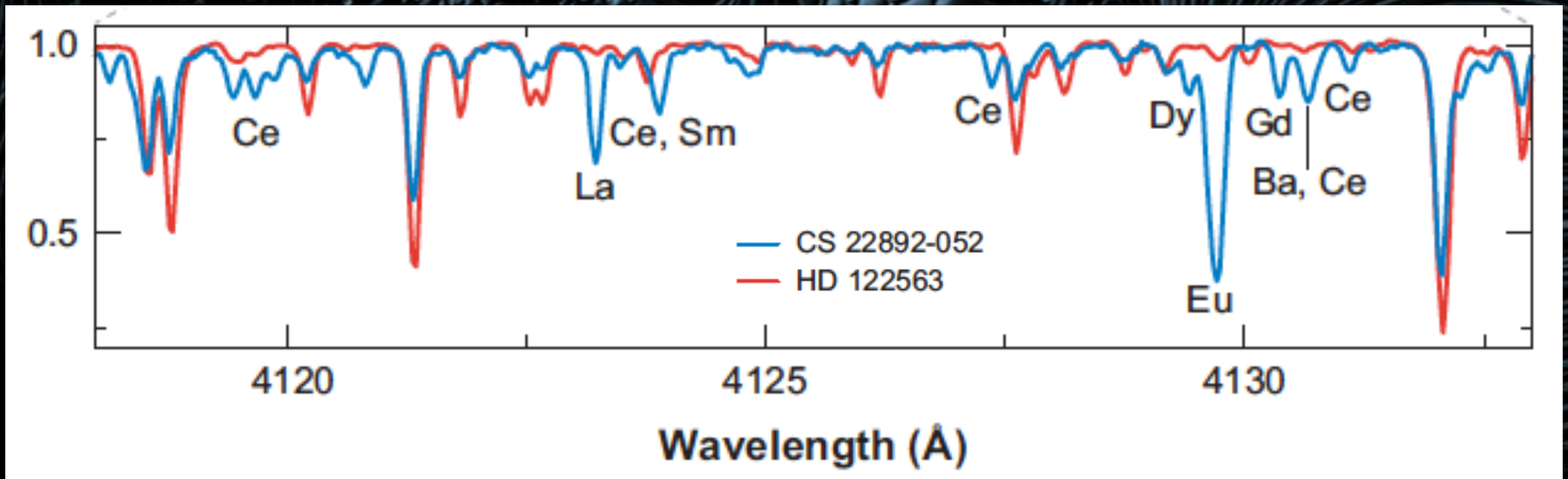
Mg: alpha-element



Sr: neutron capture element



Bonifacio+12



Sneden+08

Nucleosynthesis of neutron capture elements

from Truran 1981 to ~6 years ago

Early Galaxy

	s-process	r-process
site	Low-(intermediate) mass stars	Massive stars (& NS mergers) O-Ne-Mg core explosions? NS stars mergers?Magneto rot. driven SN? many scenarios...
time scale	>300Myr	< 30Myr (excluding NS mergers)
yields	Busso et al. 2001 Cristallo+11 Karakas+12	....

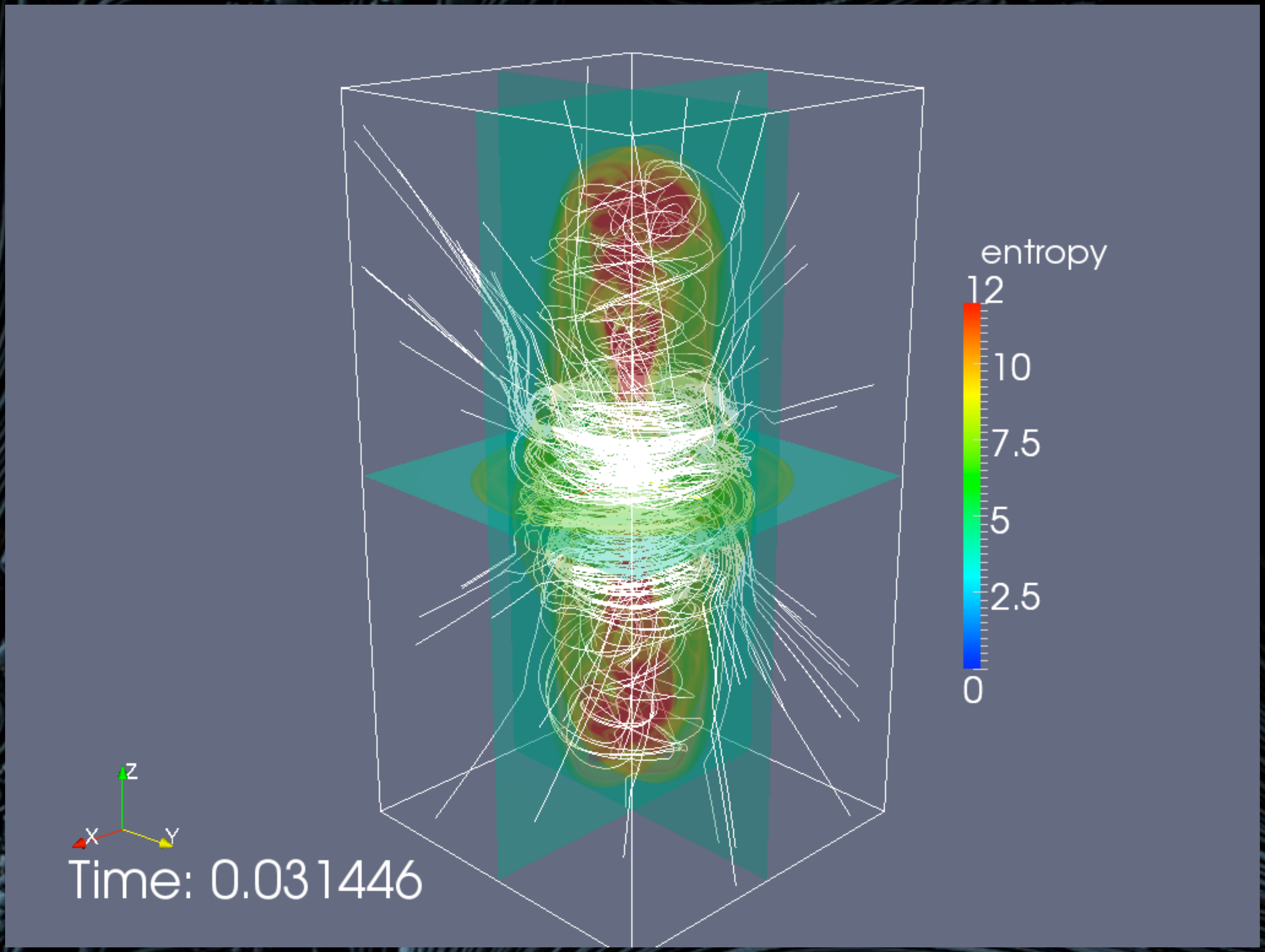
Magneto Rotationally Driven SN scenario (MRD)

(Winteler+12, Nishimura+15)

The progenitors of MRD SNe are believed to be rare:
only a small percentage of the massive stars (~1-5%)

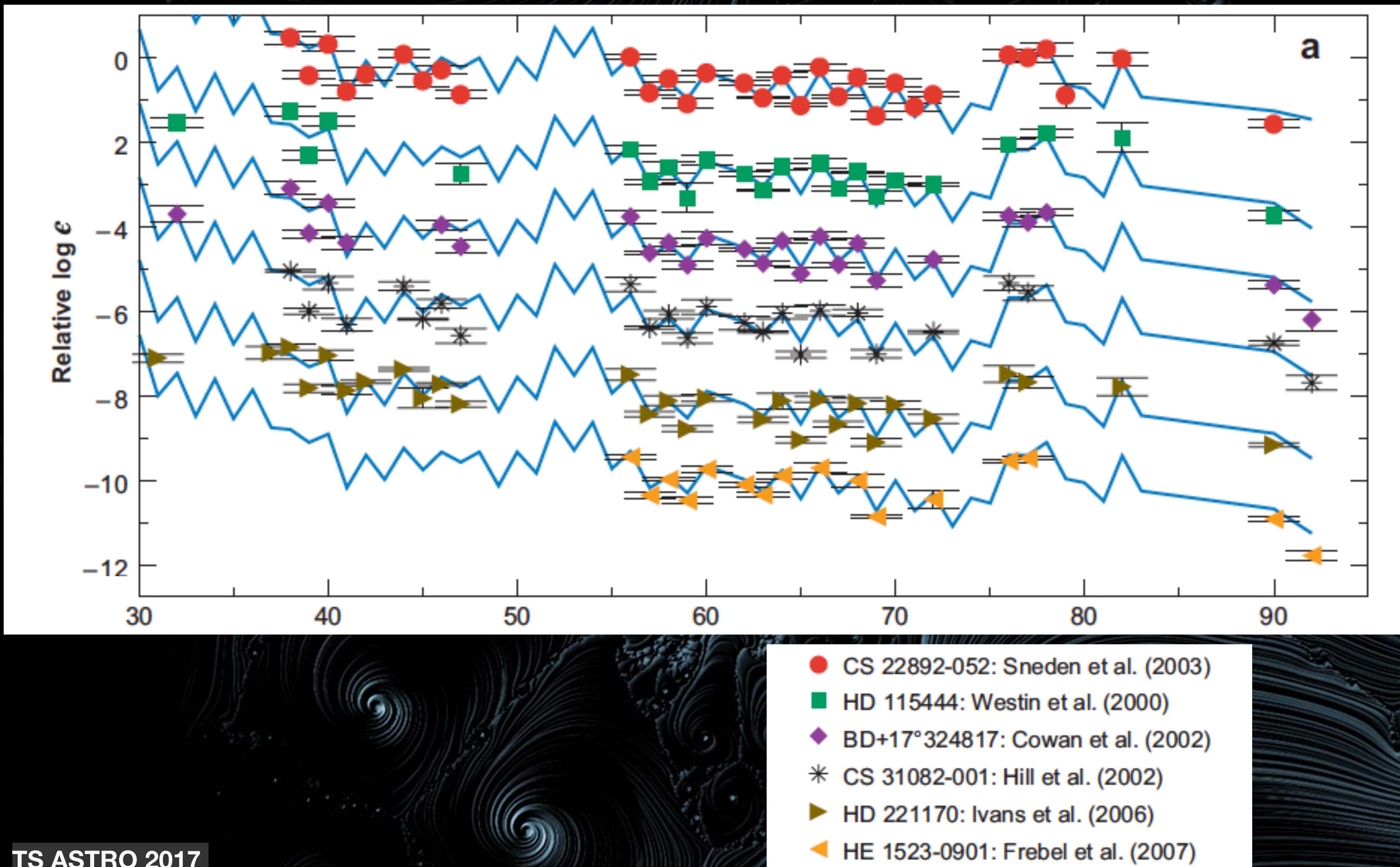
We have results for 5% and for an higher value (10%).

This percentage is not well constrained, in particular for the early Universe.



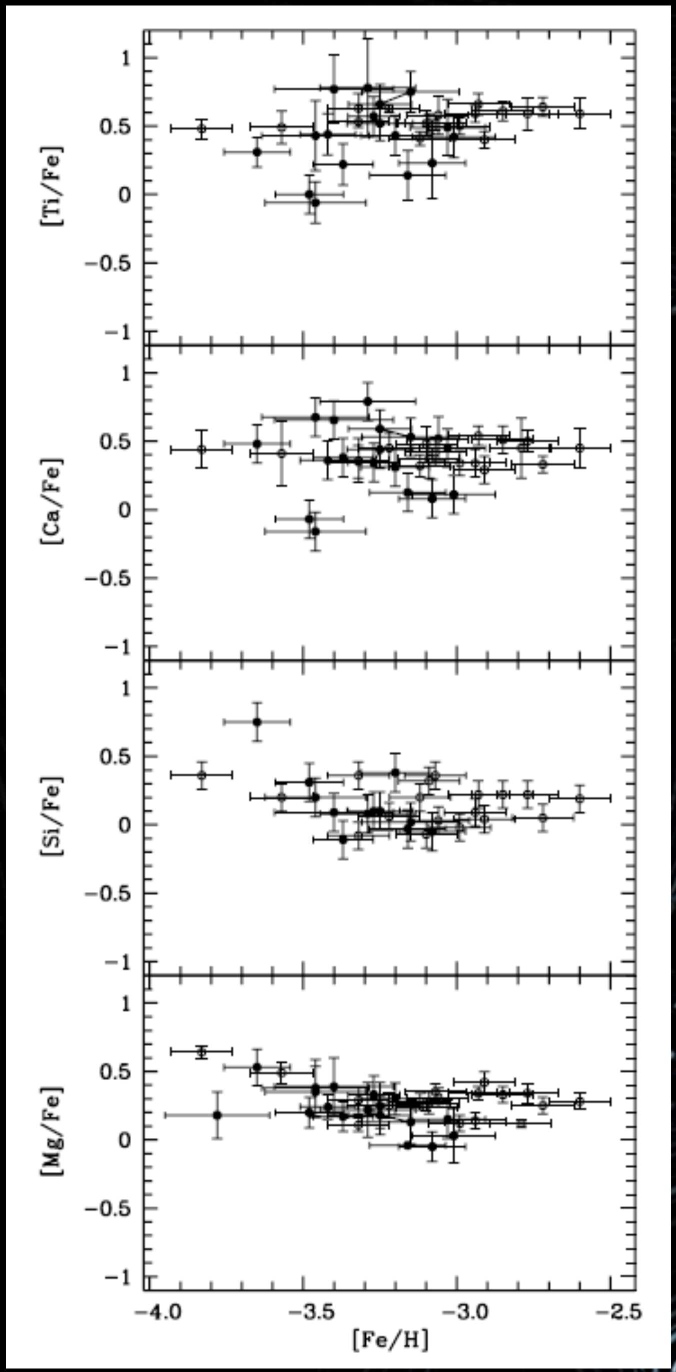
r-process

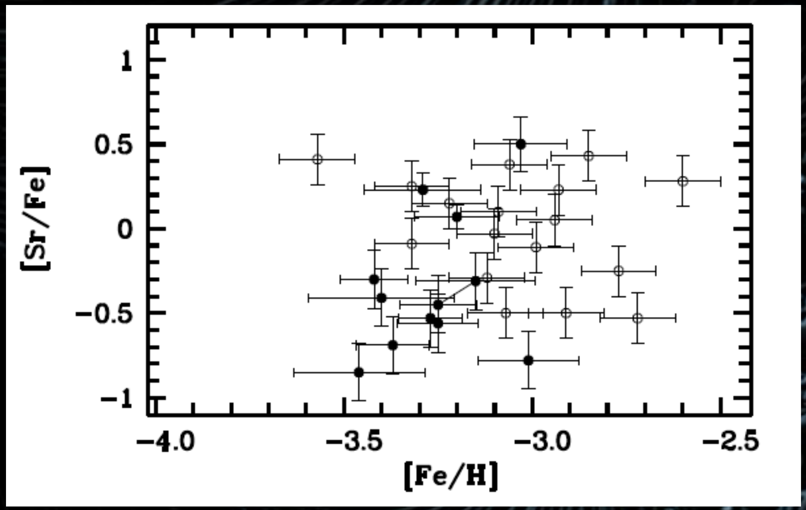
pattern in r-process rich stars



Stochastic chemical evolution models

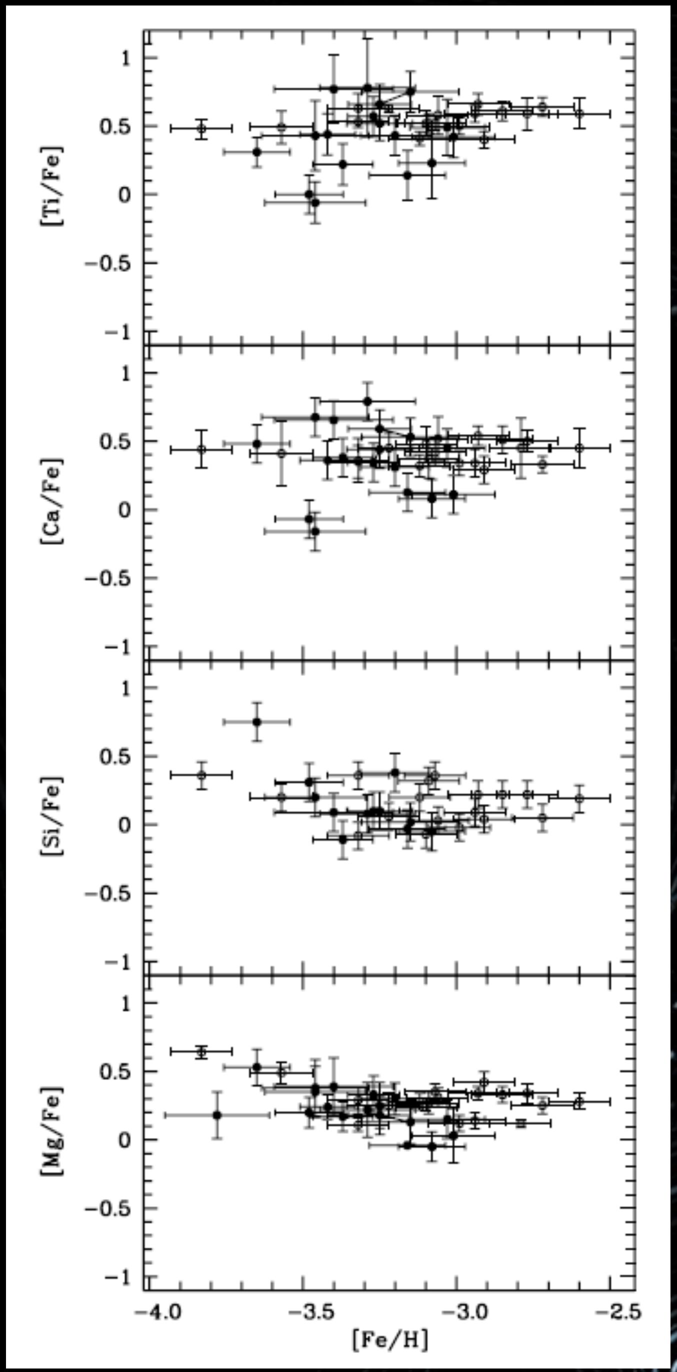
Problem:
Neutron capture elements present
a spread alpha elements do not





Bonifacio+09

Stochastic chemical evolution models



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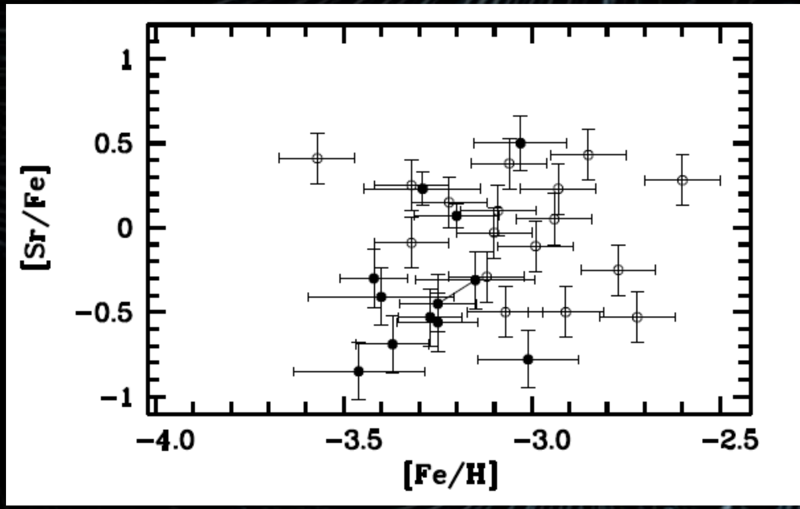
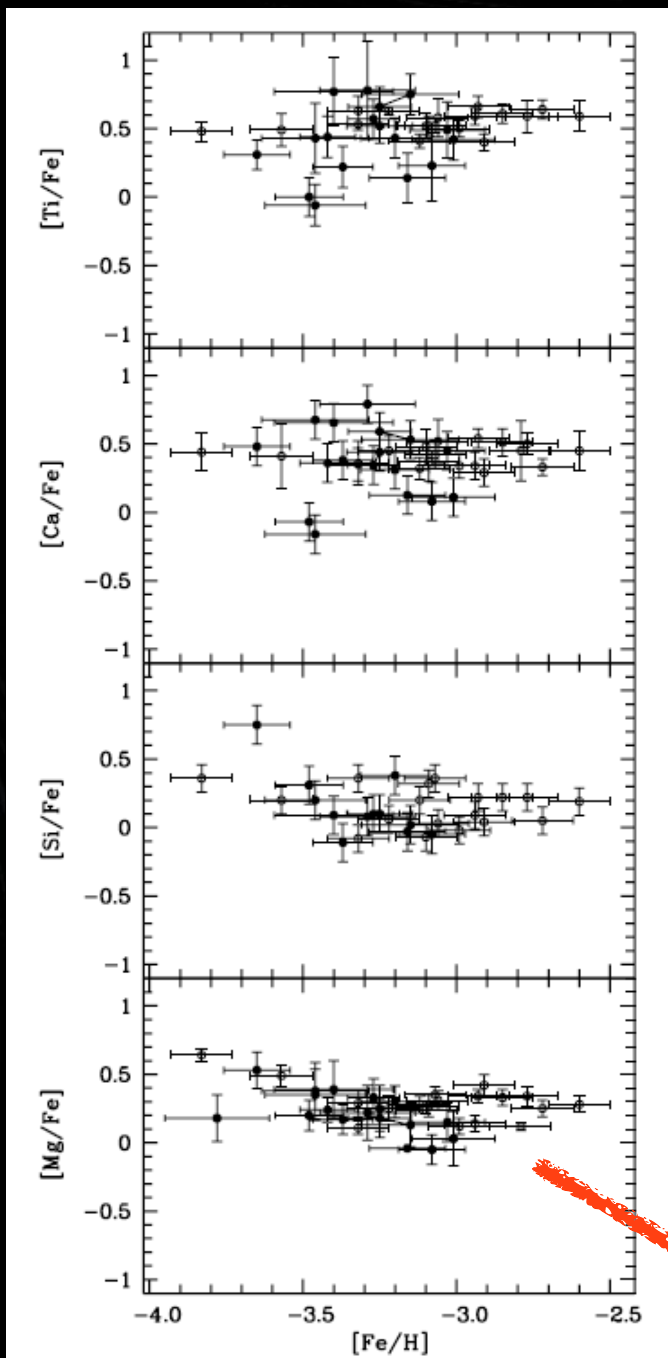


Solution:
The volumes in which the ISM is well mixed are discrete. Assuming a SNe bubble as typical volume with a low regime of star formation the IMF is not fully sampled.
This promotes spread among different volumes if nucleosynthesis of the element is is different among different SNe.

Bonifacio+09

Stochastic chemical evolution models



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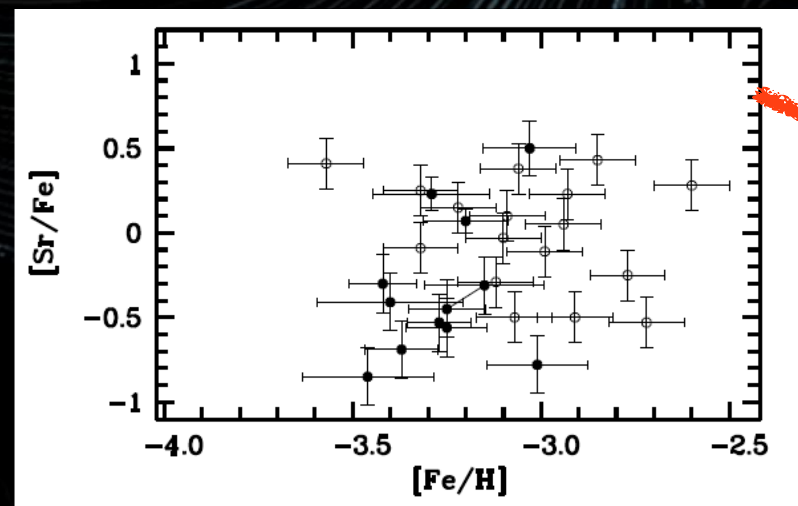

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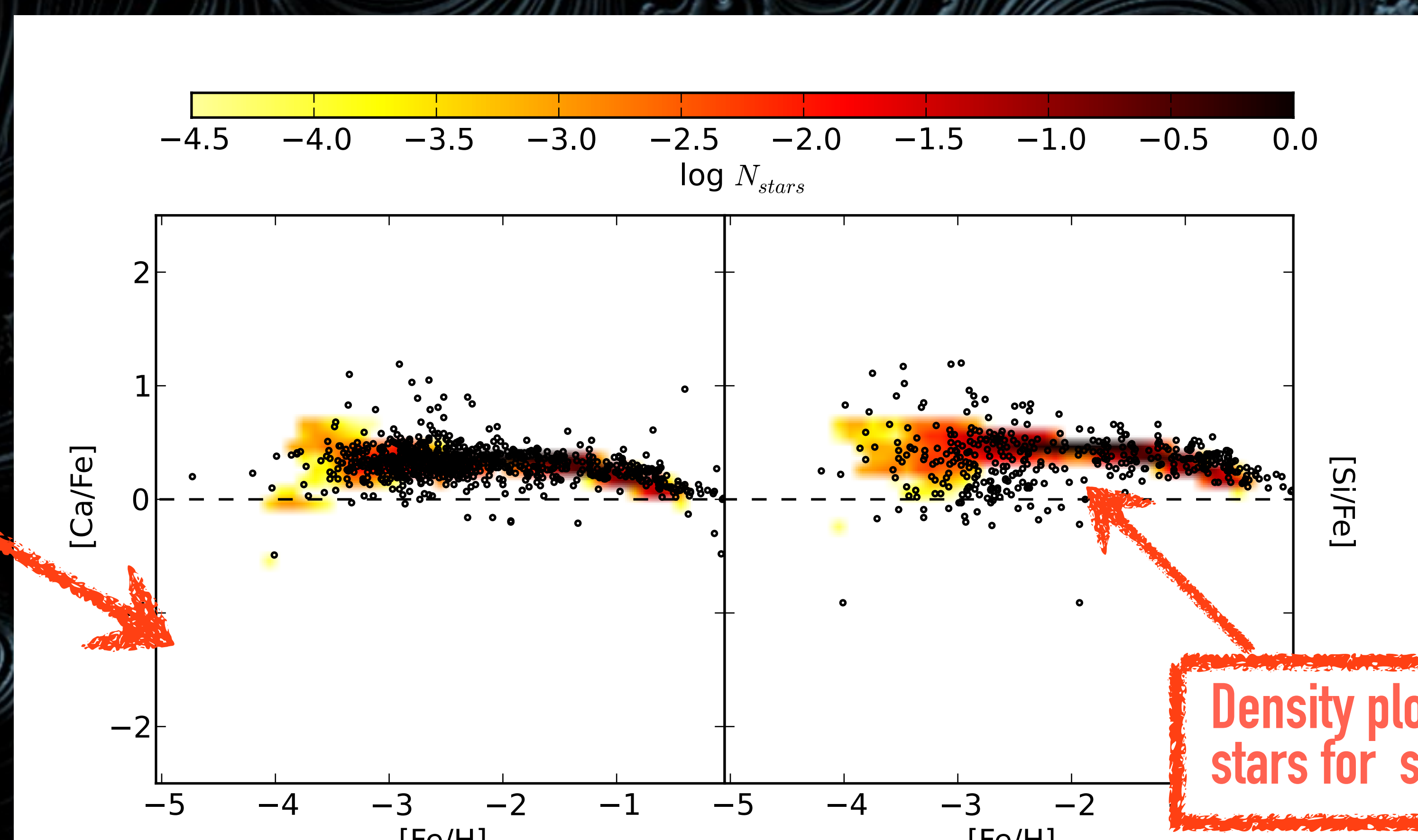

Density plot of long living stars for stochastic model

Cescutti 2008
Cescutti et al. 2013

data collected in Frebel 2010

Stochastic model for Ba in the Galactic halo

We run the stochastic model
(based on Cescutti 08)
with these prescriptions for the Ba:

10% of all the massive stars produce $8\ 10^{-6}$ Msun

data from	Normal	CEMP-no
Placco+14	●	● (cyan)
Hansen+12	■	
Hansen+16	□	□ (cyan)
Cescutti+16	★	

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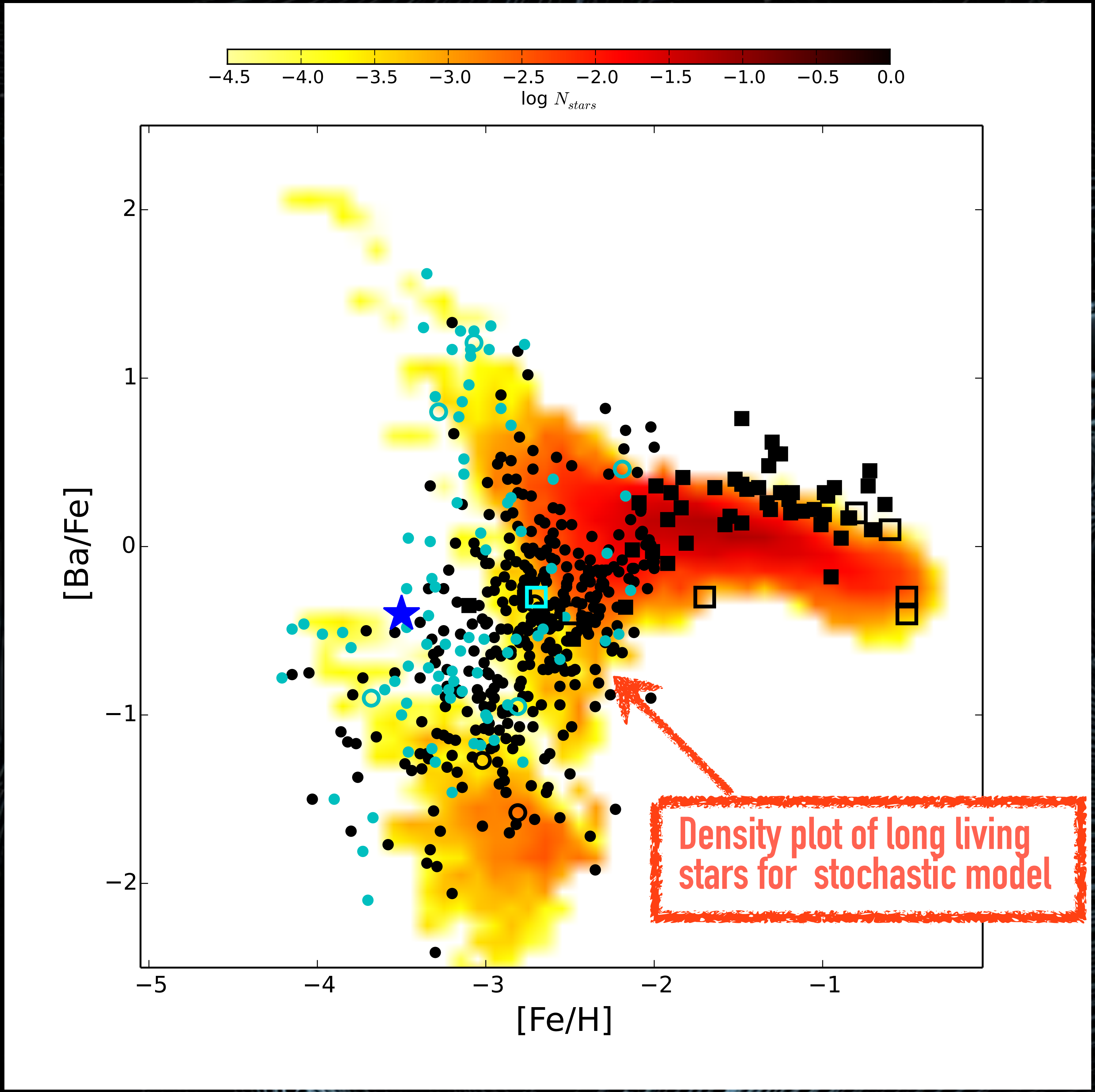

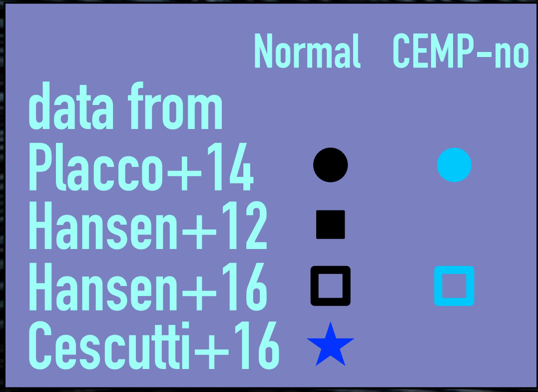

Stochastic model for Ba in the Galactic halo

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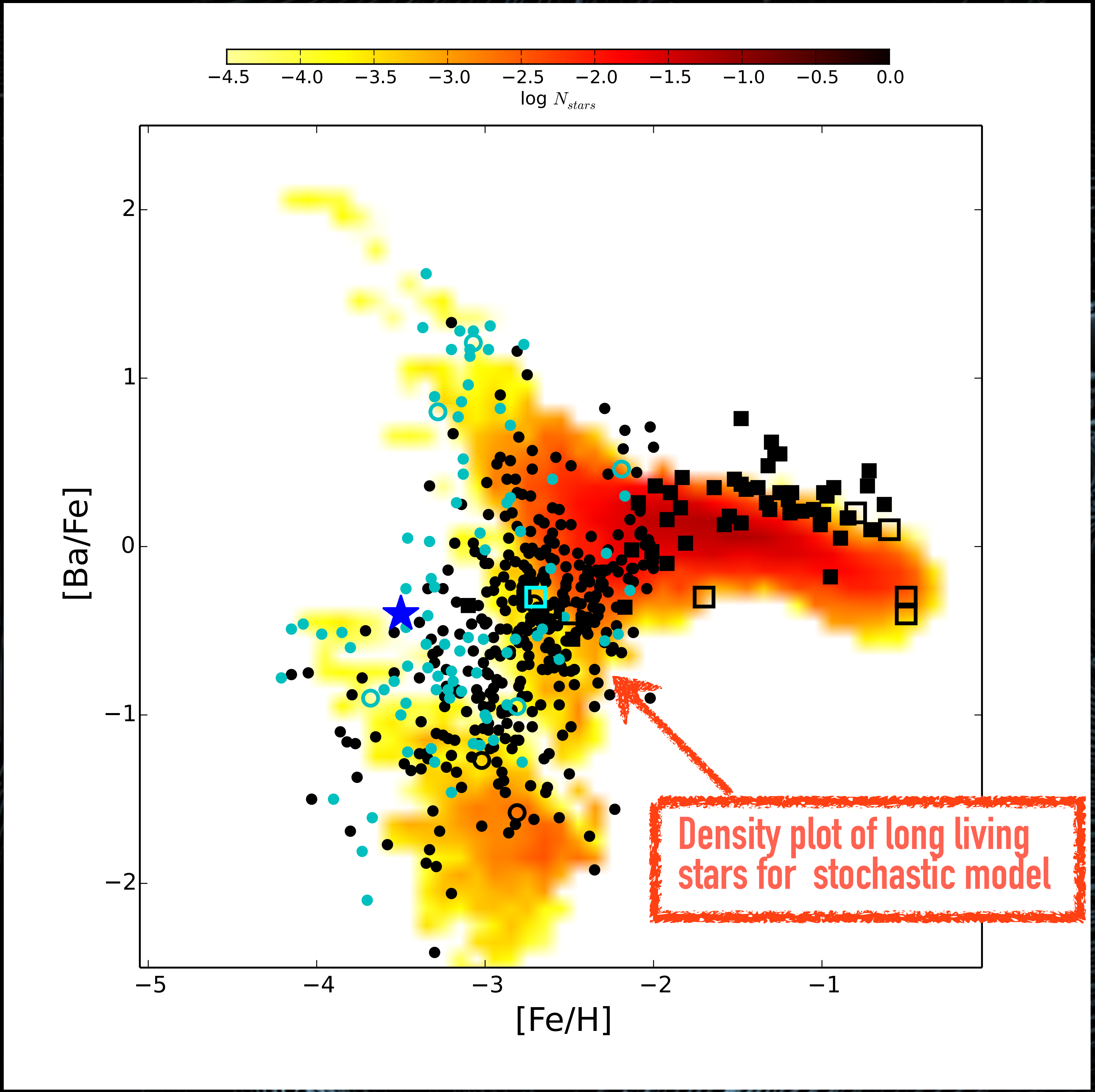
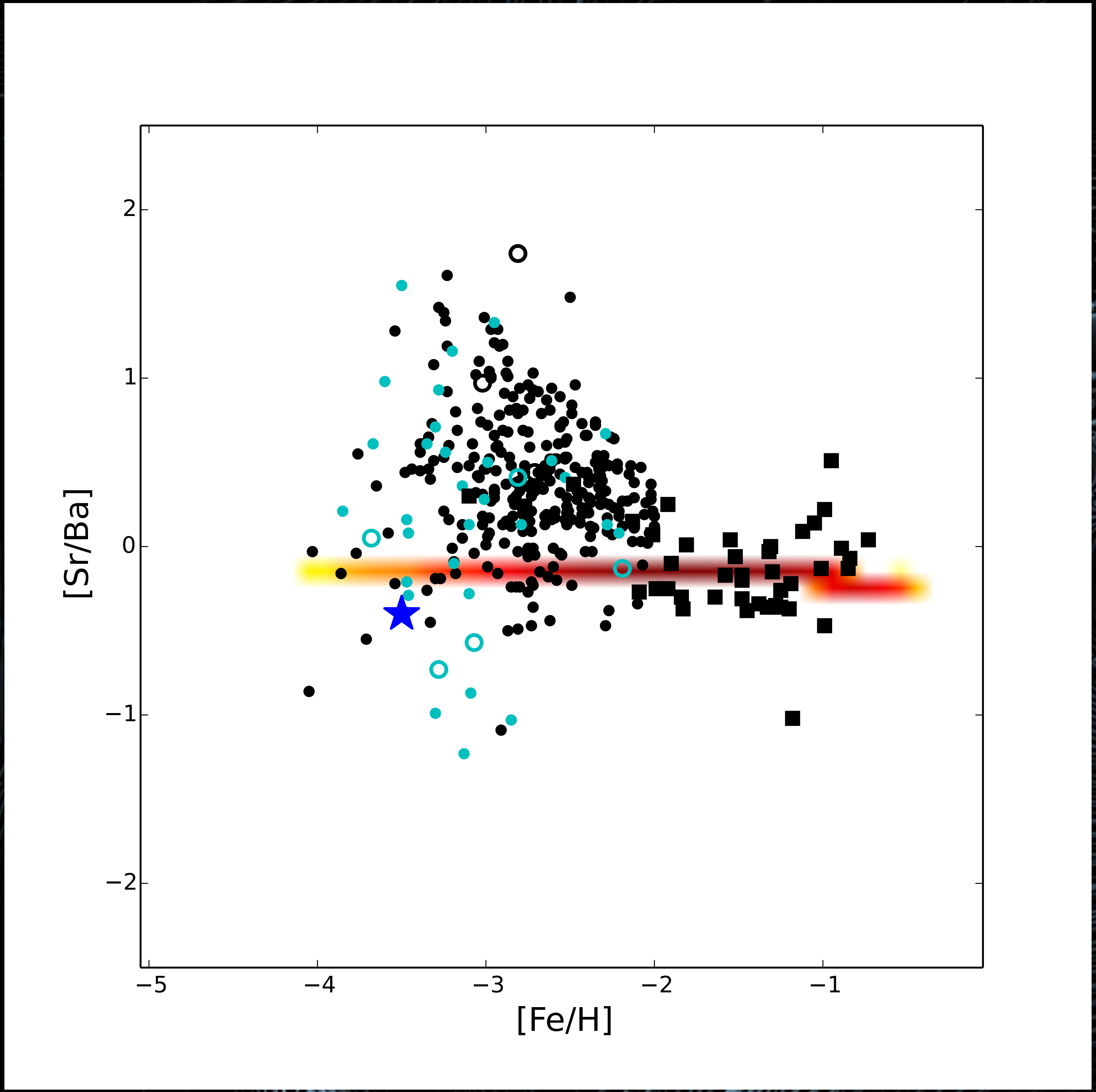


We can reproduce the [Ba/Fe] spread…

	Normal	CEMP-no
data from		
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
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(Sneden et al '08)

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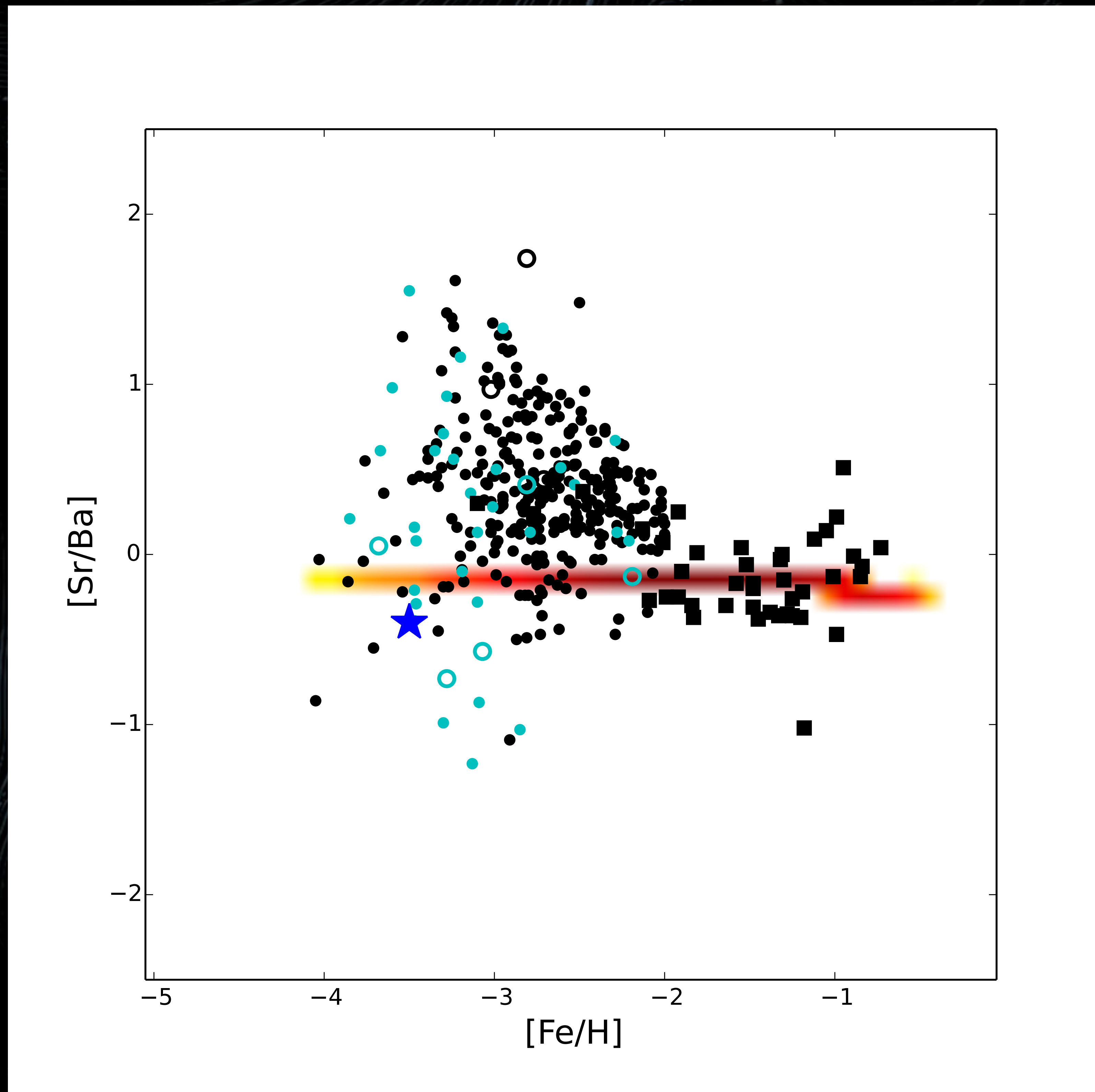

It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity. (see Sneden+ 03, François+07, Montes+07)

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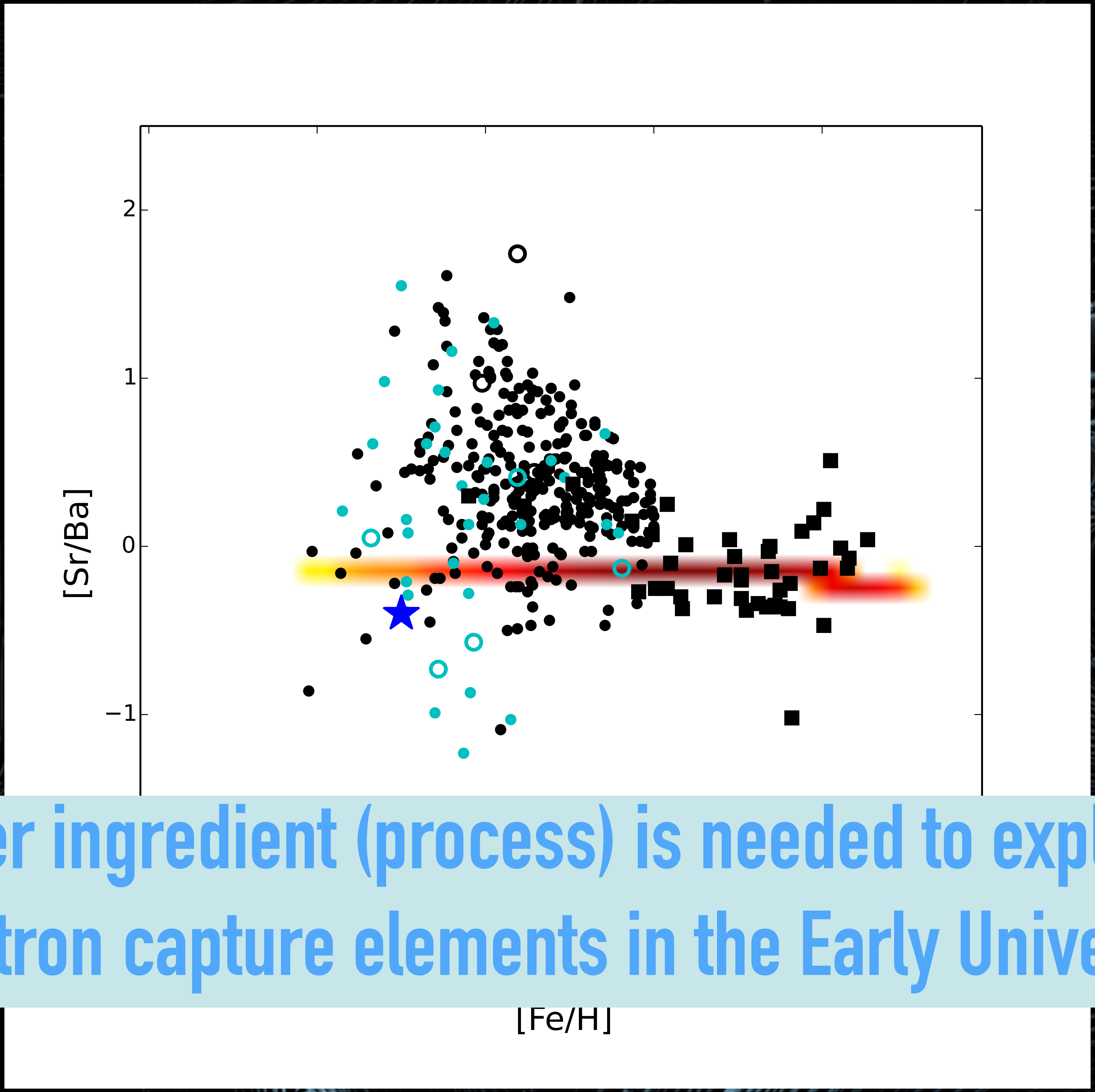


It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity. (see Sneden+ 03, François+07, Montes+07)

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

Possible solution?

Fast rotating massive stars in the early Universe

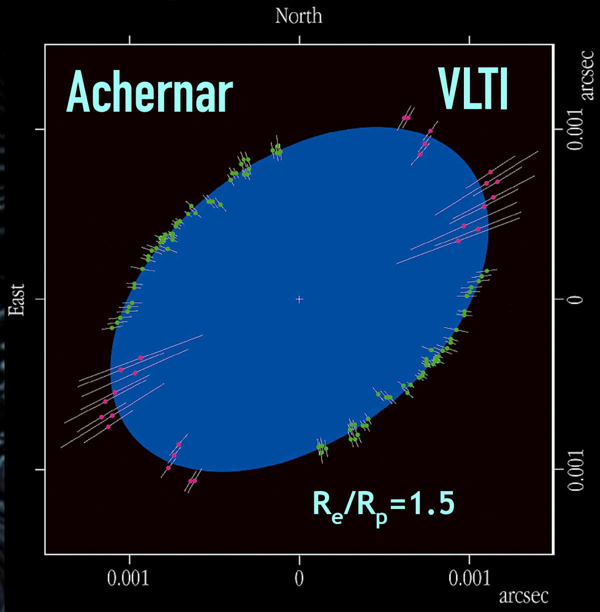
In the Early Universe

Low metals: stars rotate faster (more compact)

Rotation → Mixing inside star

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

Massive stars rotate in the Local Universe



Signatures in the Galactic Halo

- Large amounts of N (Chiappini+06 A&A)
- Increase of the C/O ratio (as above)
- Large amounts of ^{13}C (Chiappini+08)
- Early production of Be & B by cosmic ray spallation (Prantzos 12)

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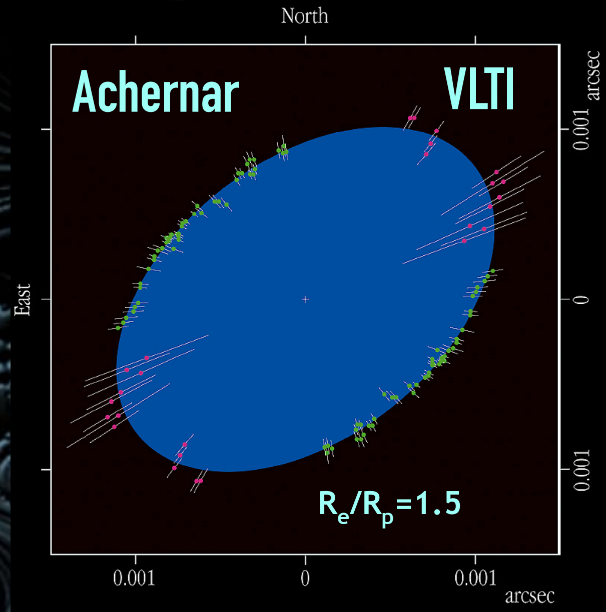

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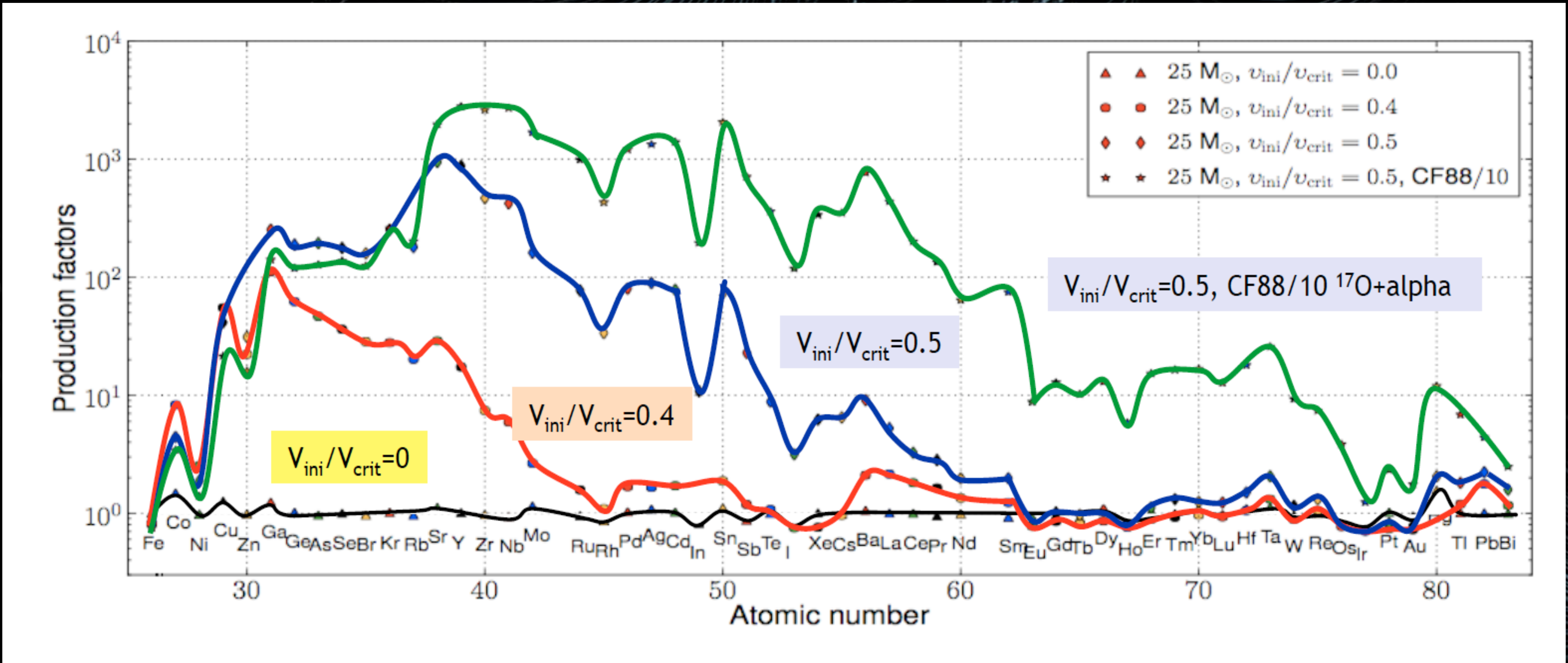
Test the production of neutron capture elements from rotating massive stars! (Cescutti+13)

Low metallicity and fast rotating massive stars

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



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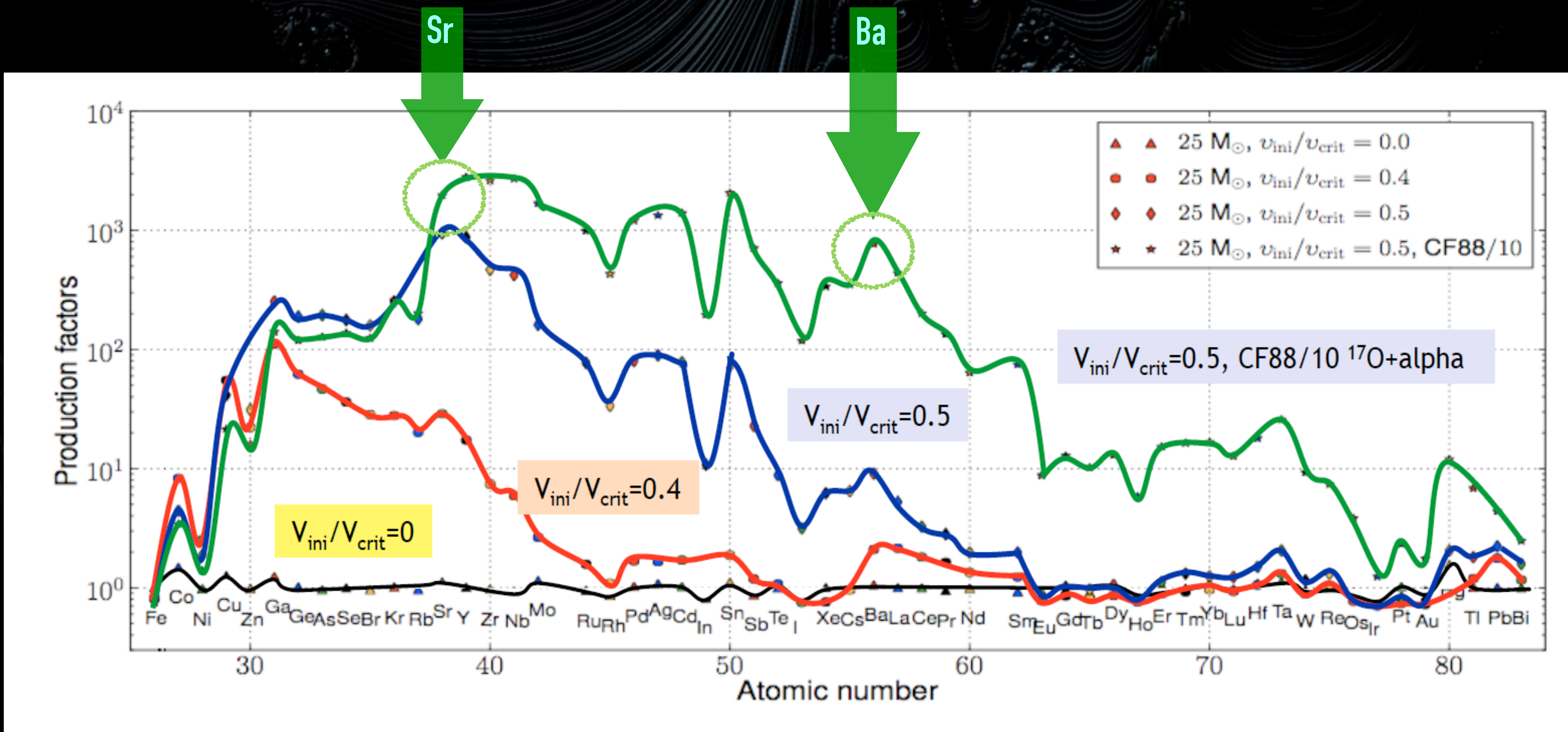
Fast rotating massive stars can contribute to s-process elements!



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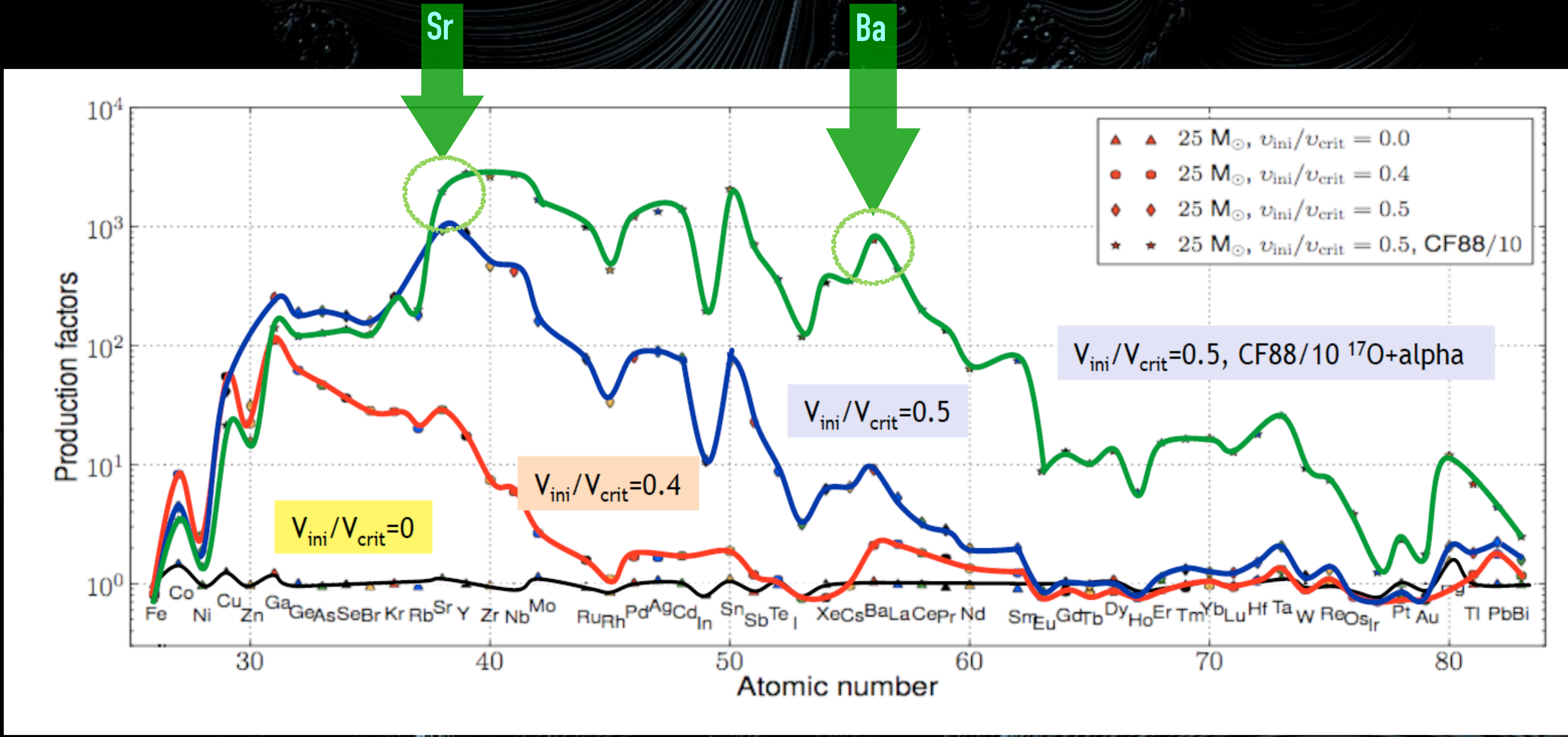

Can they explain the puzzles for Sr and Ba in halo?

Neutron capture elements

from Chiappini+11

	s-process	Early Galaxy	r-process
site	Low-(intermediate) mass stars	fast rotating Massive stars	Massive stars (& NS mergers)
			O-Ne-Mg core explosions? NS stars mergers?Magneto rot. driven SN? many scenarios...
time scale	>300Myr	< 30Myr	< 30Myr (excluding NS mergers)
yields	Busso+ 2001	(Frischknecht+ 2012) Frischknecht+ 2016	....
	Cristallo+ 2011 Karakas+ 2012	Pignatari+ 2008 Limongi yields still unpublished	

s-process from fast rotating massive stars

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

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

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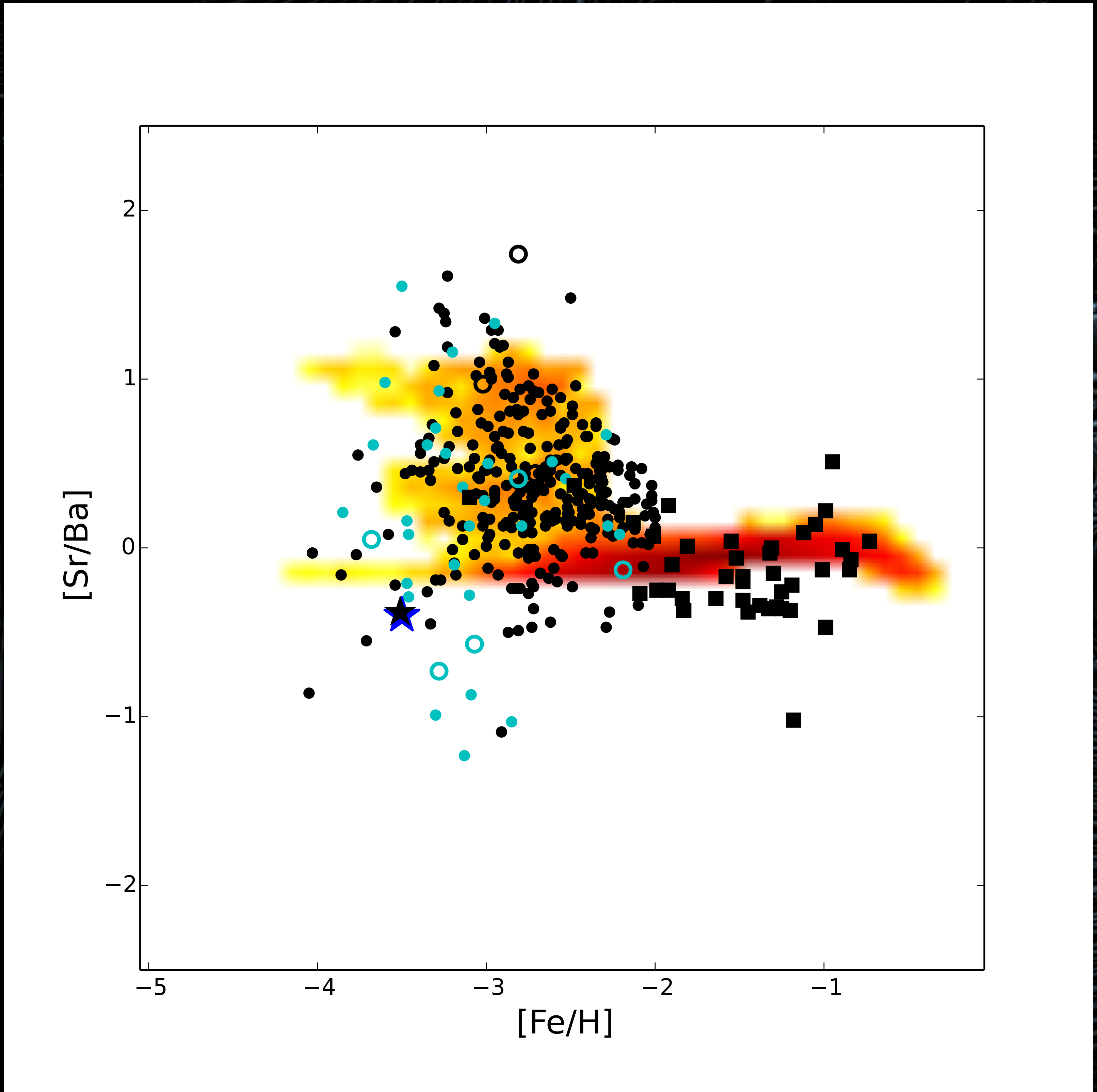

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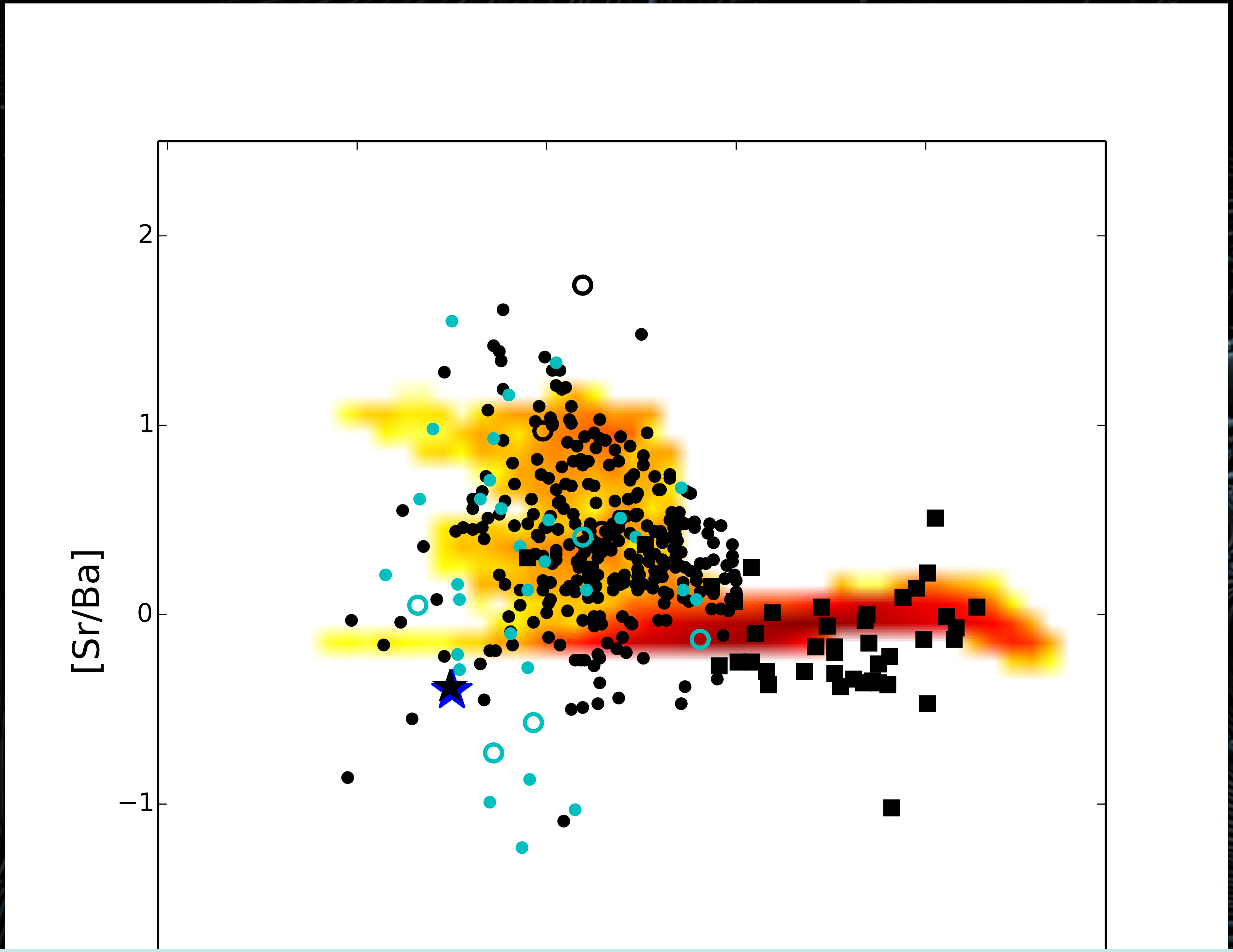

**A s-process (from fast rotating massive stars)
and an r-process (from rare events)
can reproduce the neutron capture elements in the Early Universe**

Conclusions

Fast rotating massive stars

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Fast rotating massive stars

Solution for 4 signatures in the early Universe

(1) Large amounts of N in the early Universe (Chiappini et al. 2006 A&A Letters)

(2) Increase in the C/O ratio in the early Universe

(3) Large amounts of ^{13}C in the early Universe (Chiappini et al. 2008 A&A Letters)

(4) Early production of Be and B by cosmic ray spallation (Prantzos 2010)

Models predict an enhanced s-process

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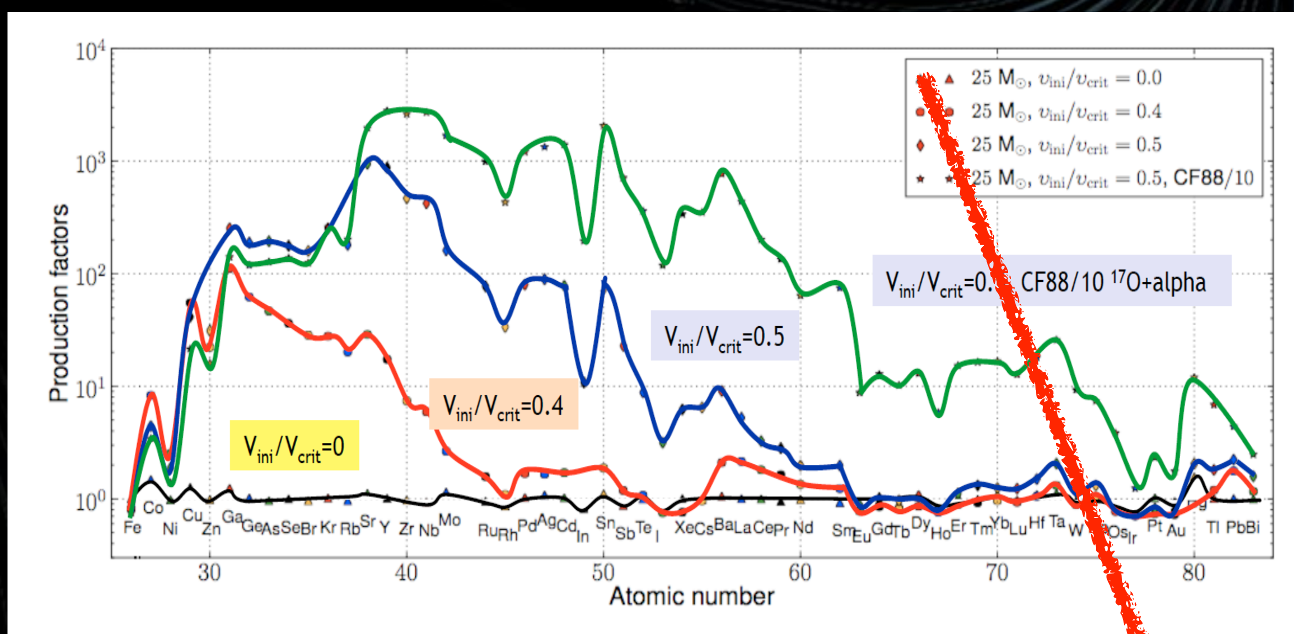

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5th signature: The s-process production from rotating massive stars can solve the puzzle of Sr/Ba

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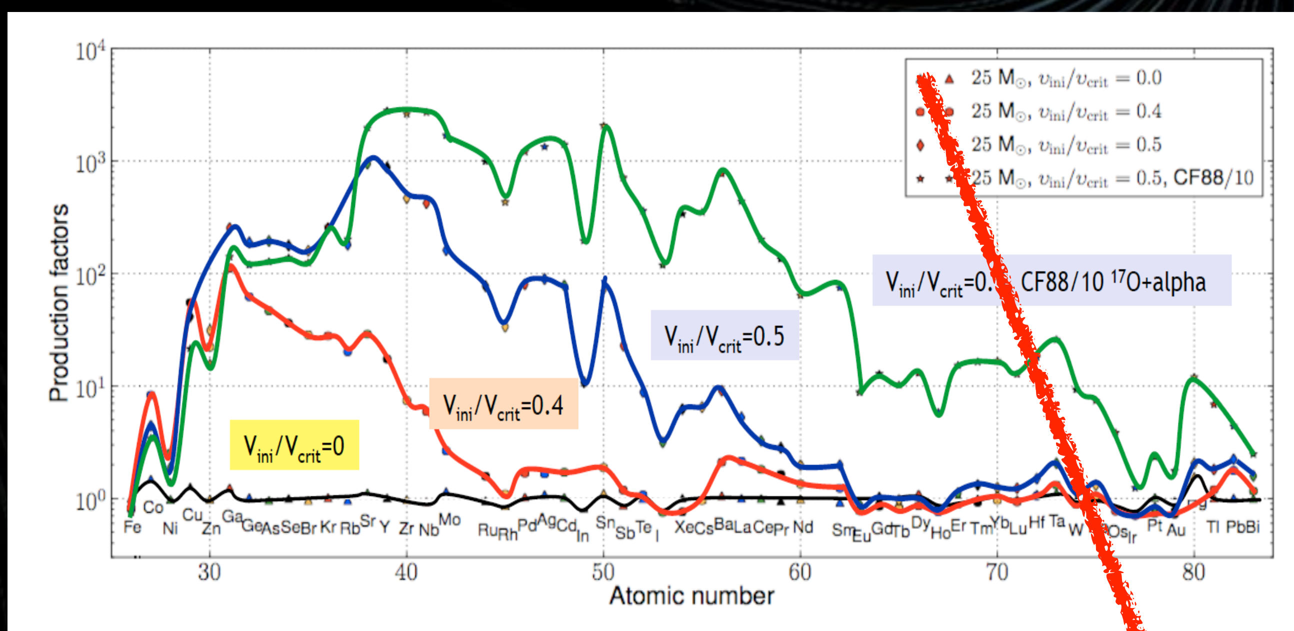

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5th signature: The s-process production from rotating massive stars can solve the puzzle of Sr/Ba

First stars: fast rotating massive stars

CAVEAT

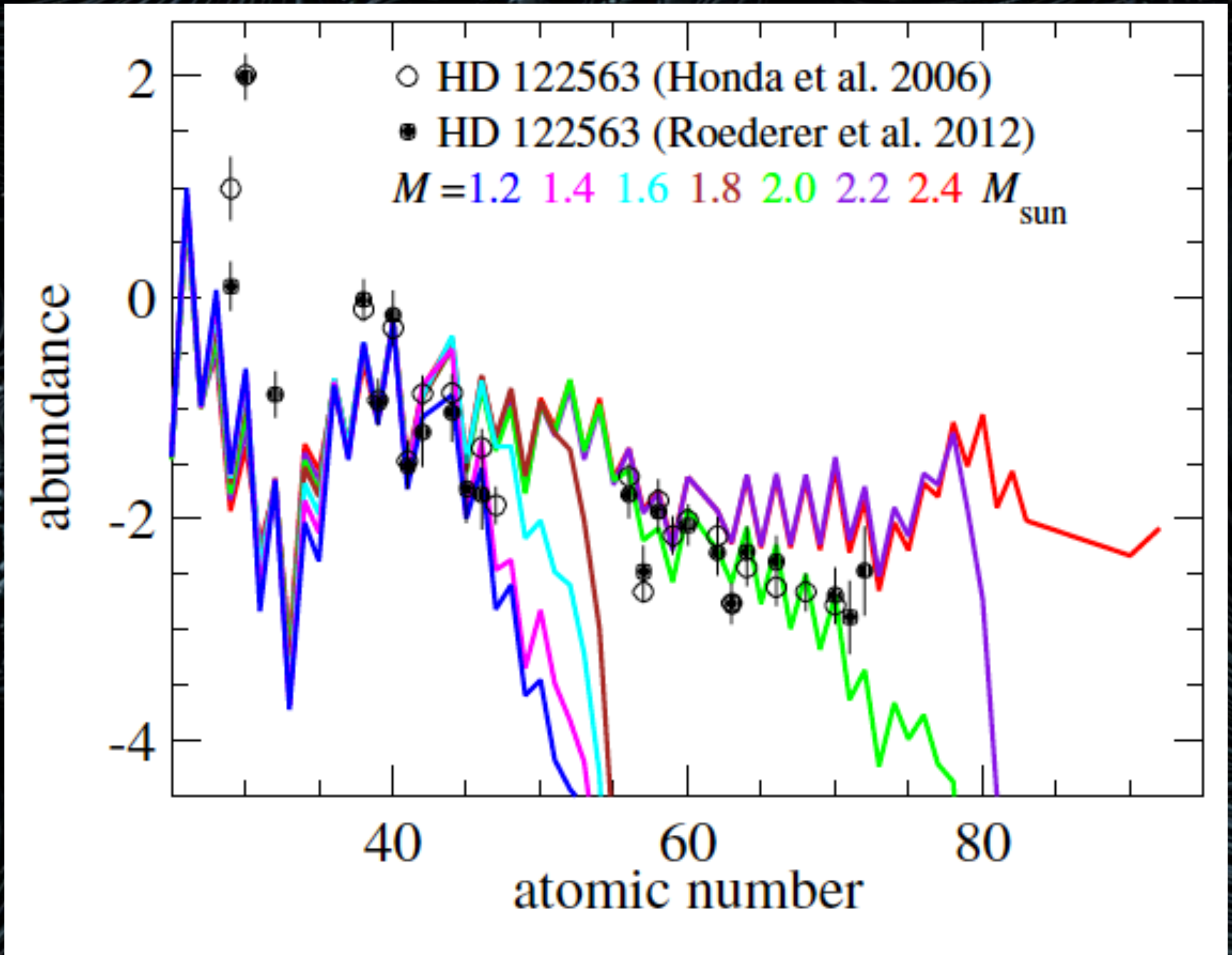
The only possible answer?

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

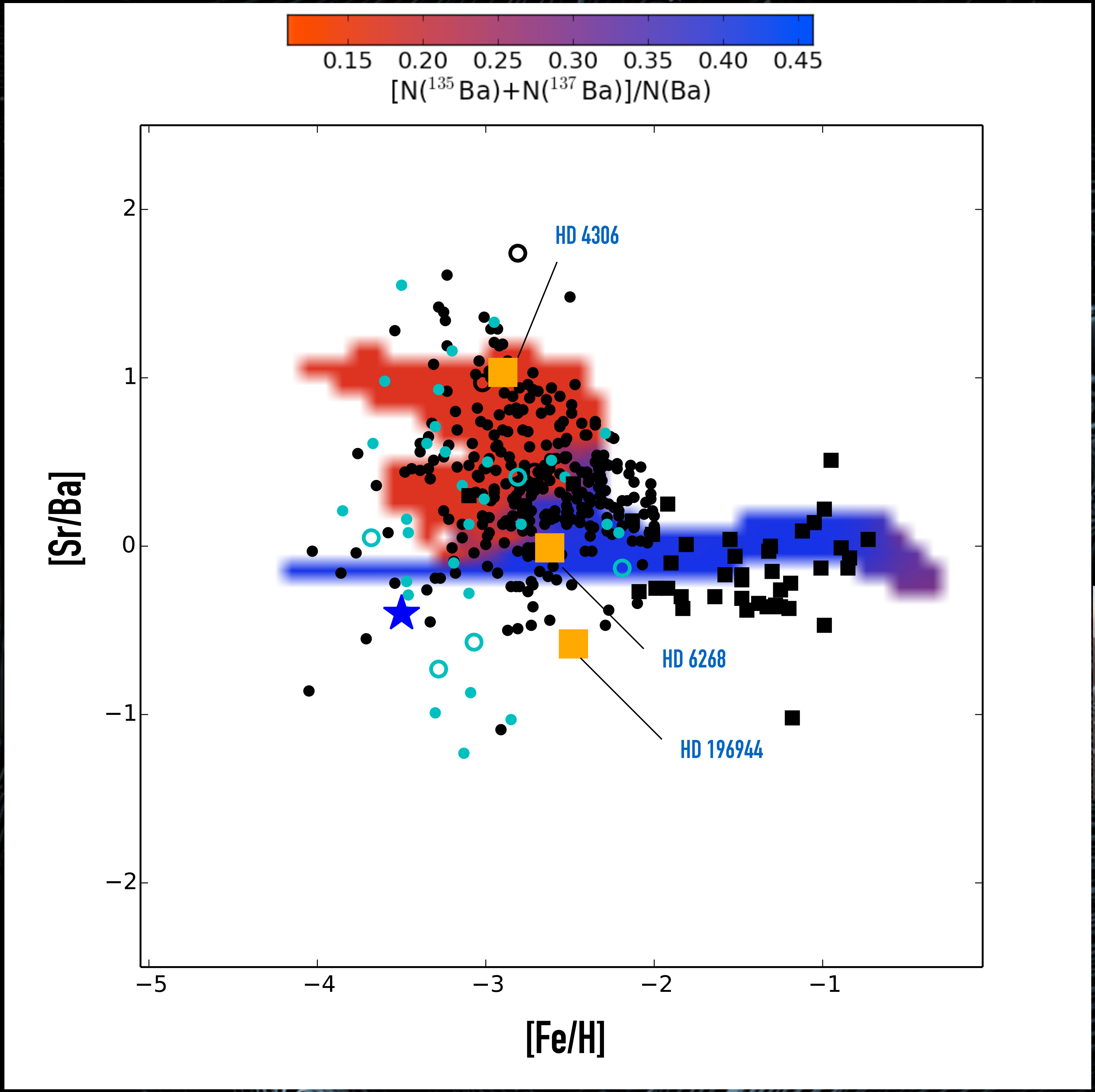
Isotopic ratio for Ba

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)



PI Cescutti
proposal at ESO to measure the Ba isotopic ratio in three stars with a R~100'000 &
S/N~900
with UVES at VLT

1 night in designed
visitor mode last October

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

Cescutti and Chiappini (2014)

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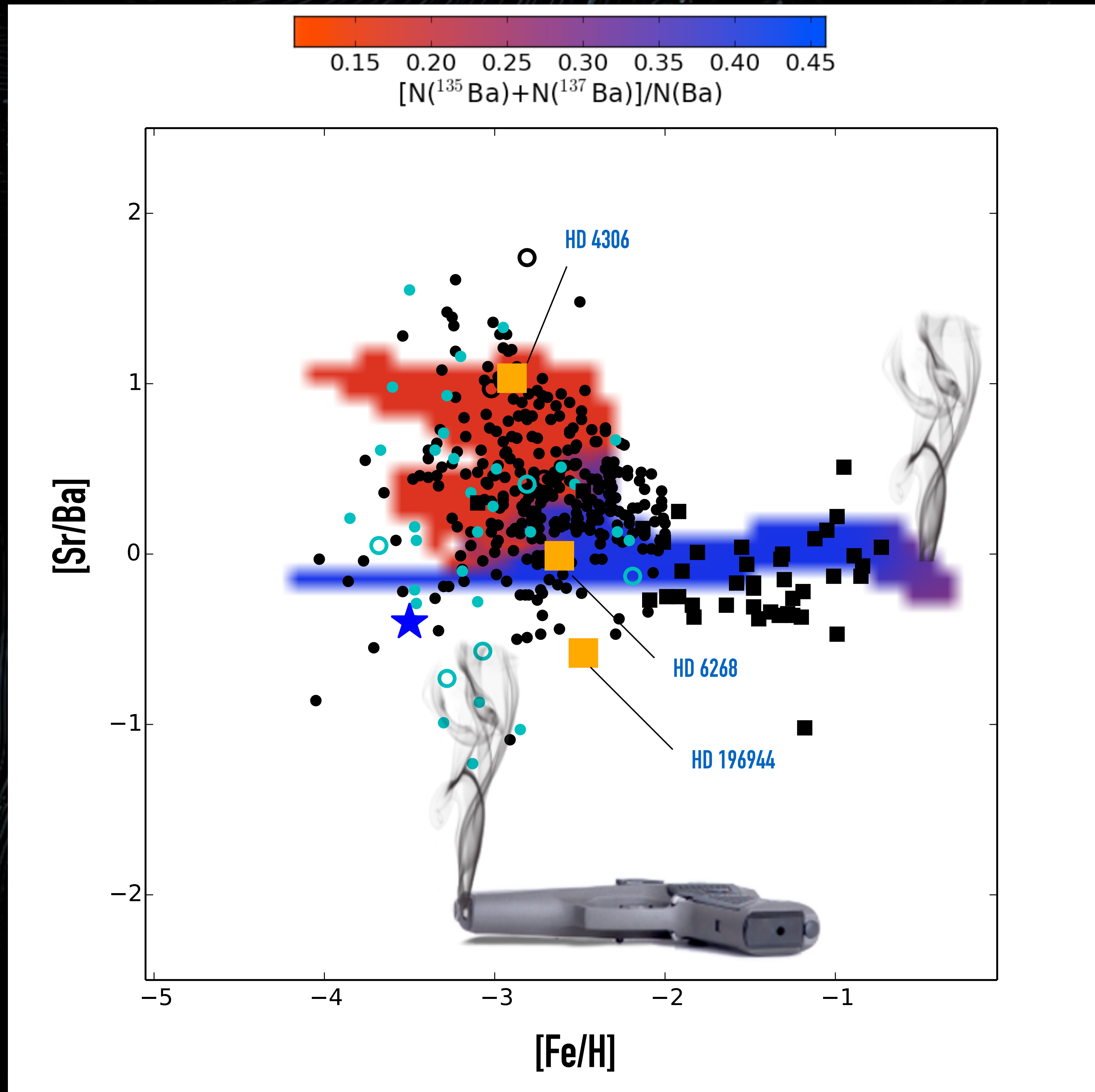

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