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Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

UNIVERSITÀ DEGLI STUDI DI TRIESTE

GIANTS Gruppi Italiani di Astrofisica Nucleare Teorica e Sperimentale

Chemical evolution of the Galaxy and the spectroscopic surveys

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Federico Rizzuti, Lorenzo Cavallo

Osservatorio Astronomico di Trieste
Astronomical Observatory of Trieste

INFN TRIESTE

ChETEC INFRA

Catania, 3 July 2025

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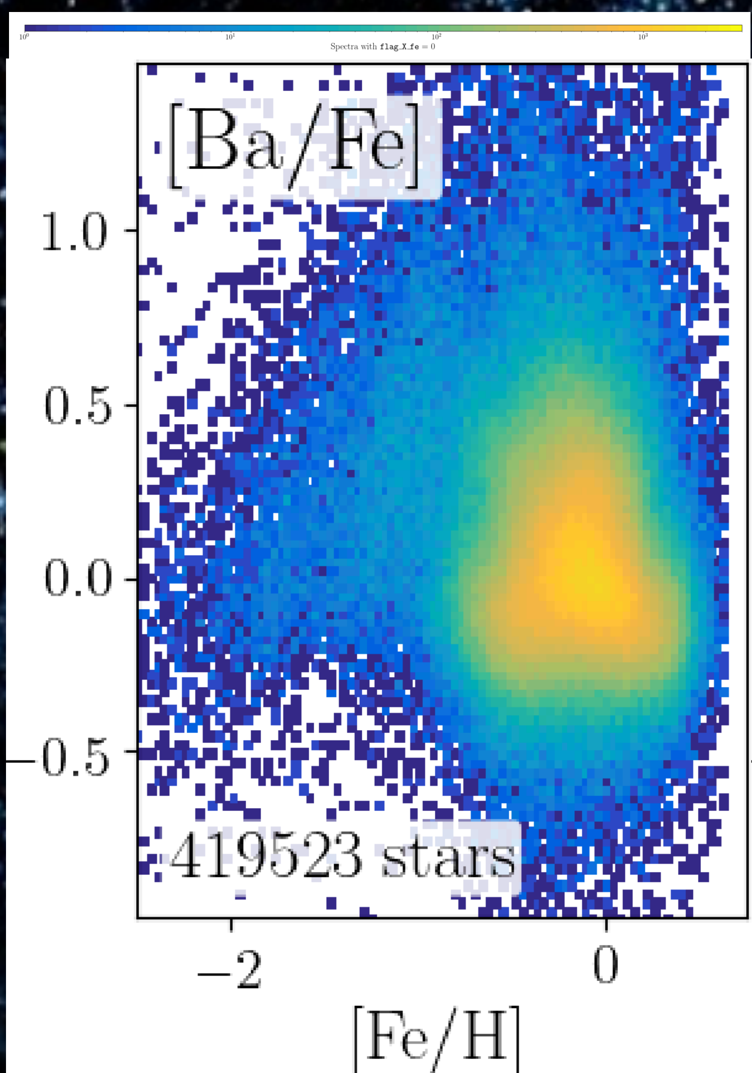
Chemical abundances in stars

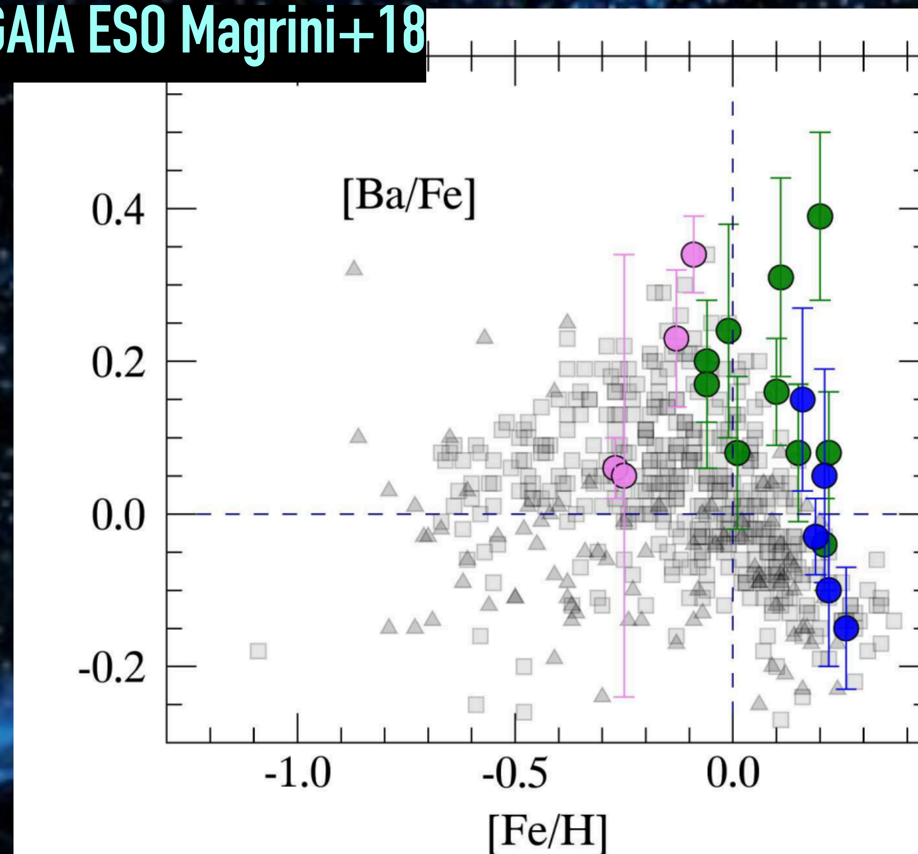
HERMES: 350 objects
28'000R
4m telescope
optical

Galah Buder+21



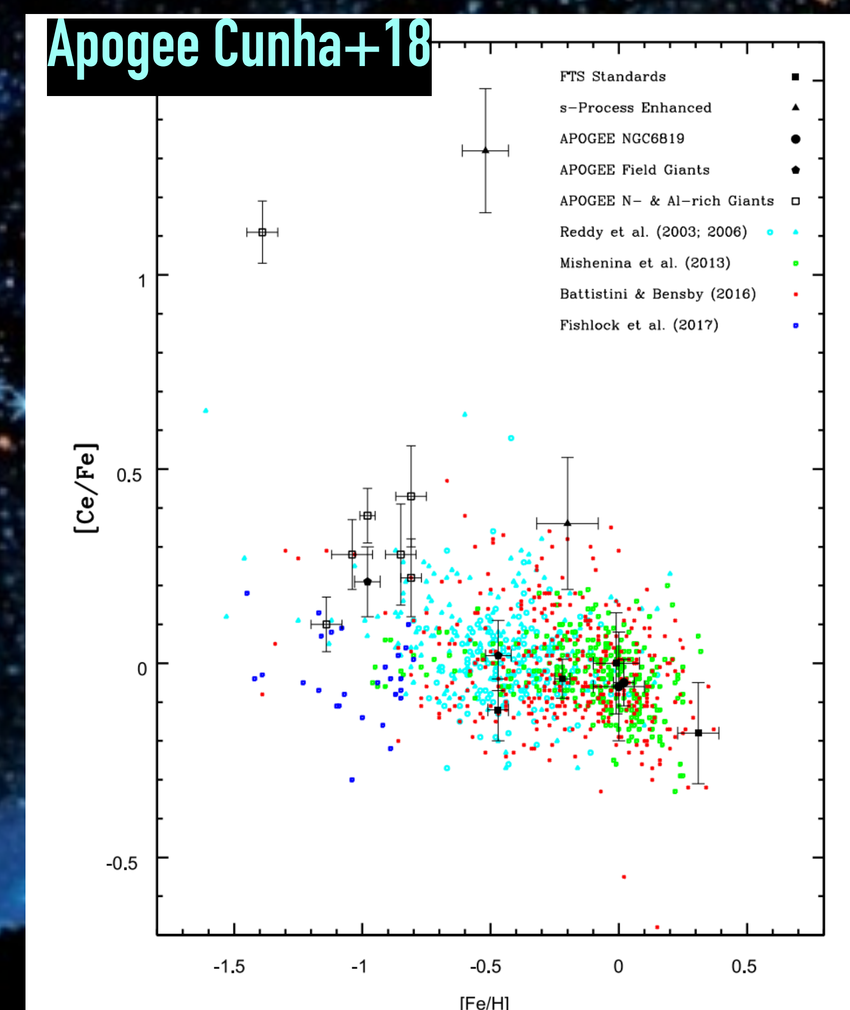
FLAMES: 140 objects
130 20'000R and 8 45'000
8m telescope
optical

GAIA ESO Magrini+18



APOGEE
R=22'500
2.5m telescope
infrared (different elements)

Apogee Cunha+18



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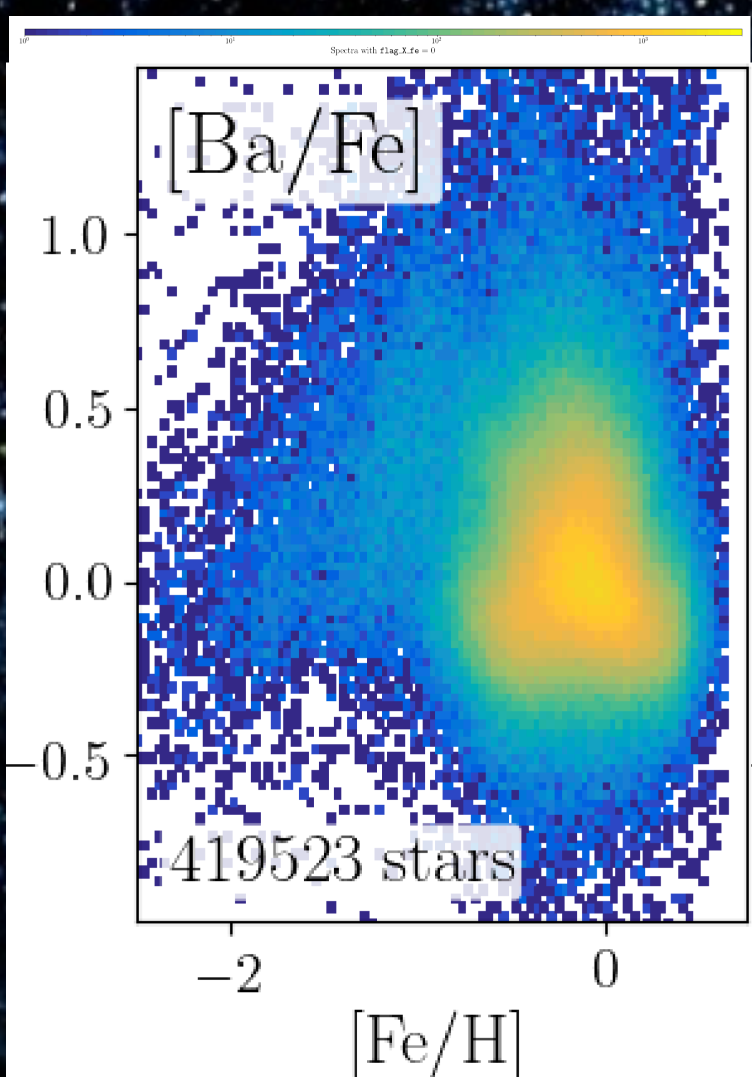
Chemical abundances in stars

Terrific impact for Galactic science!

2m in space
parallax, positions, proper motions
radial velocities —> spectrograph of R 8'000 in calcium triplet region

Galah Buder+21



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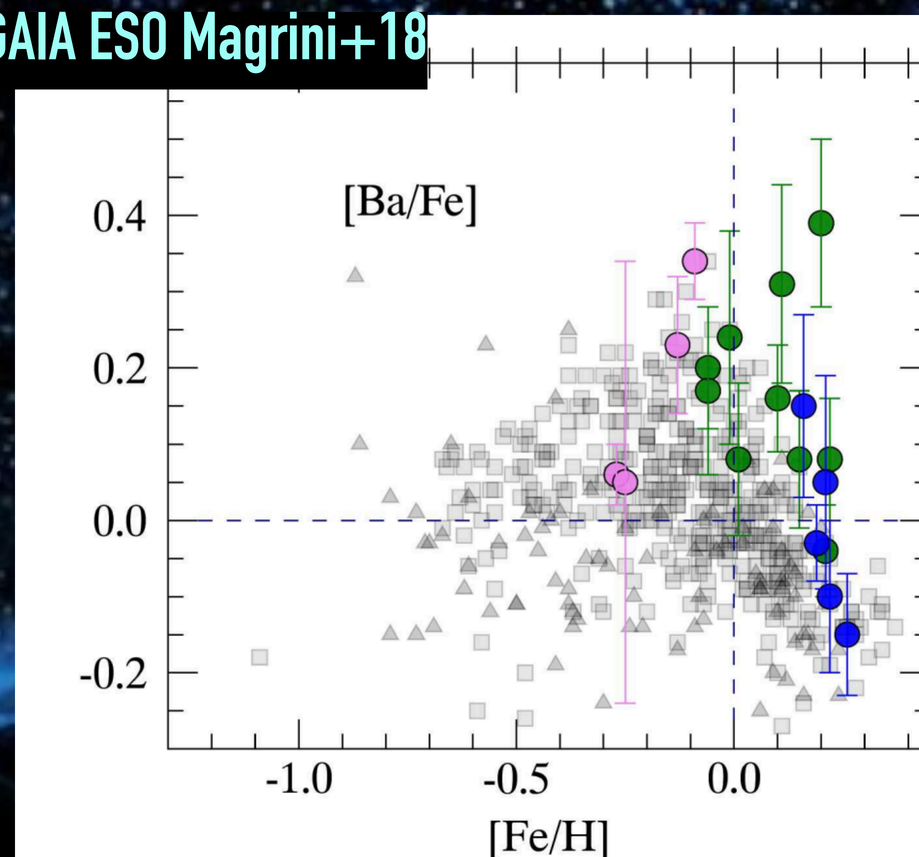

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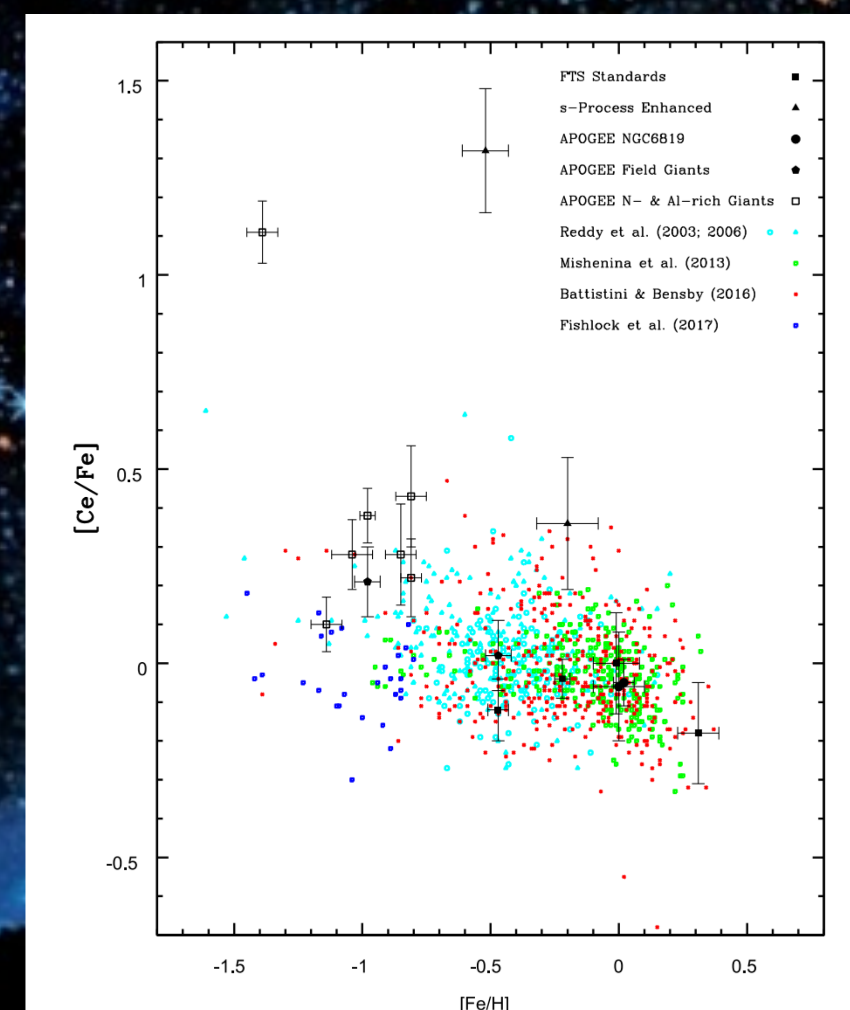
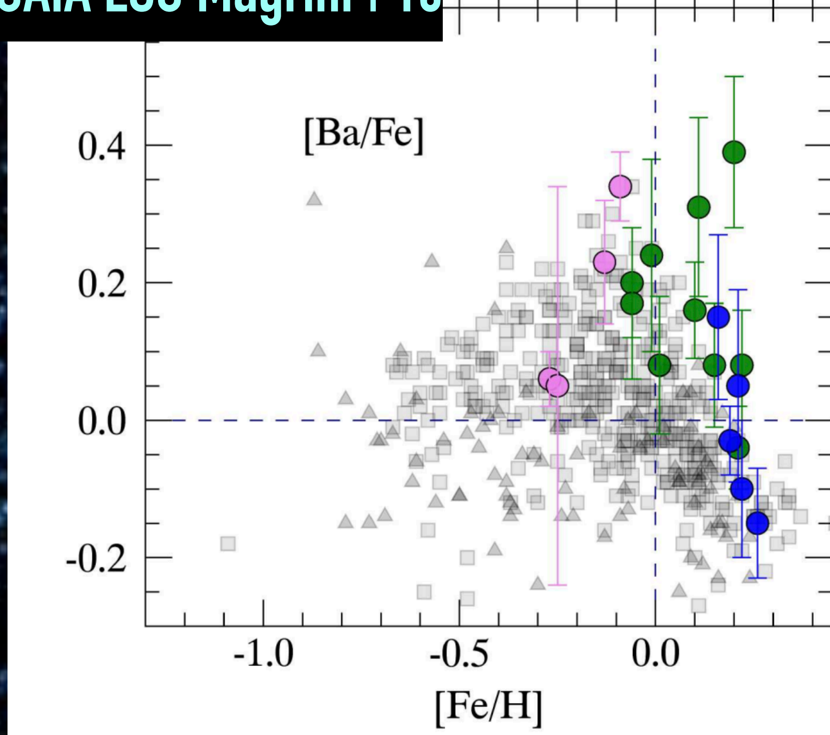
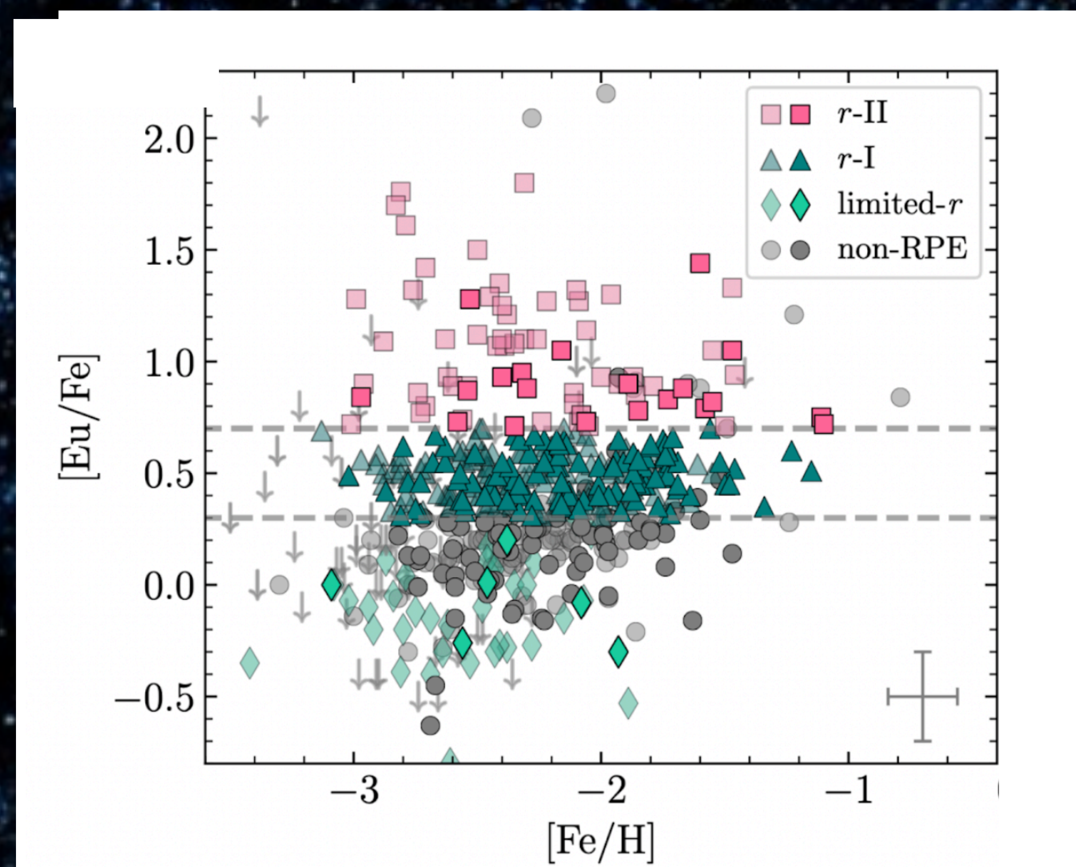


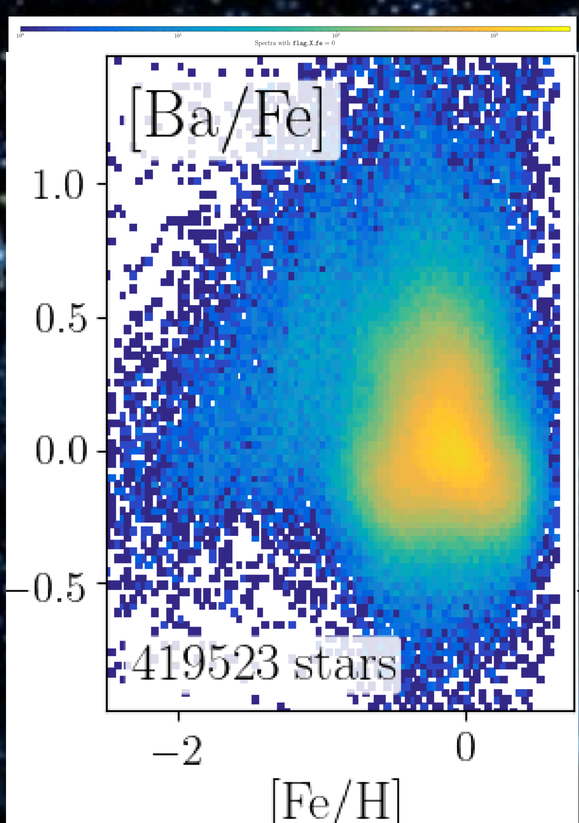
NextGenerationEU
e della Ricerca

GAIA ESO Magrini+18

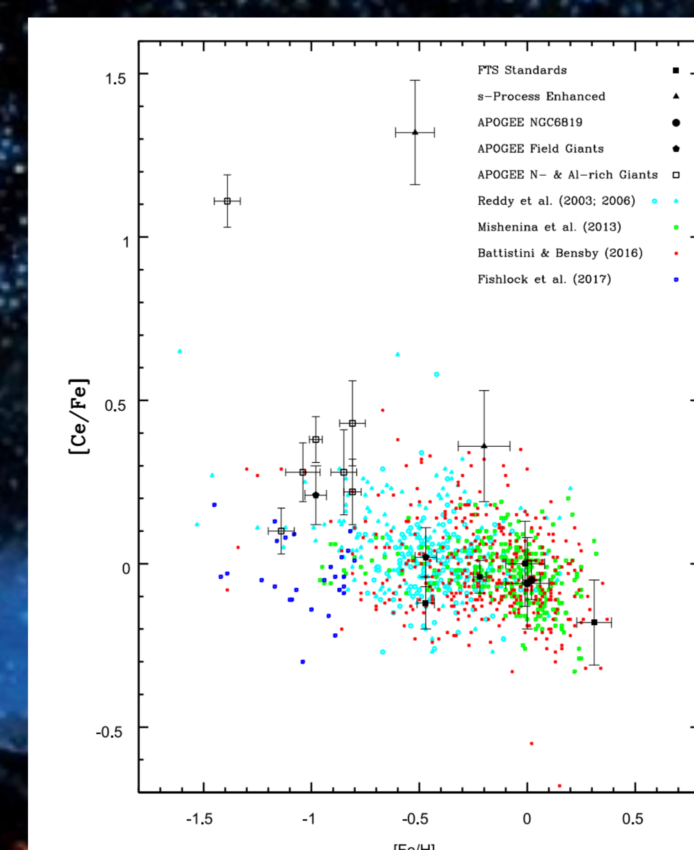


R-process alliance Holmbeck+20
R~30,000 1 object
2.5 m telescopes





Galah Buder+21



Apogee Cunha+18

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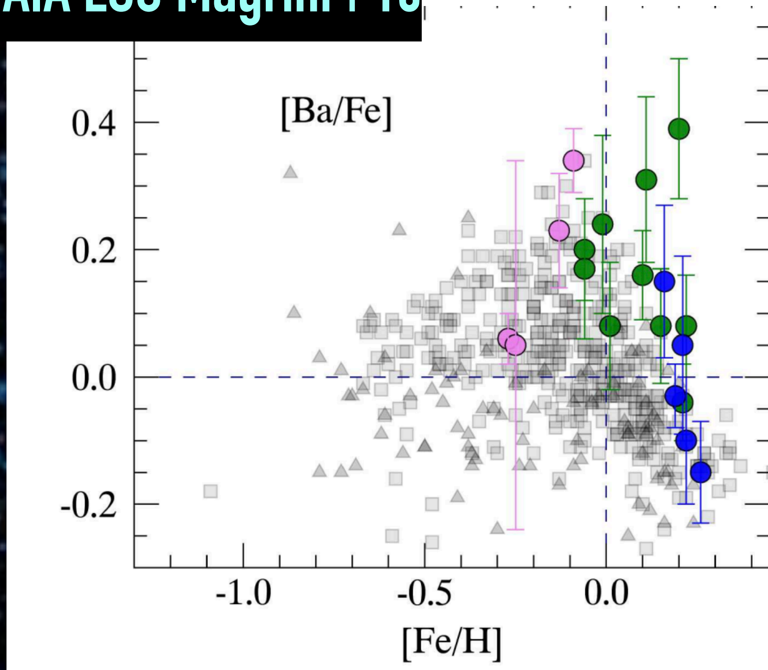
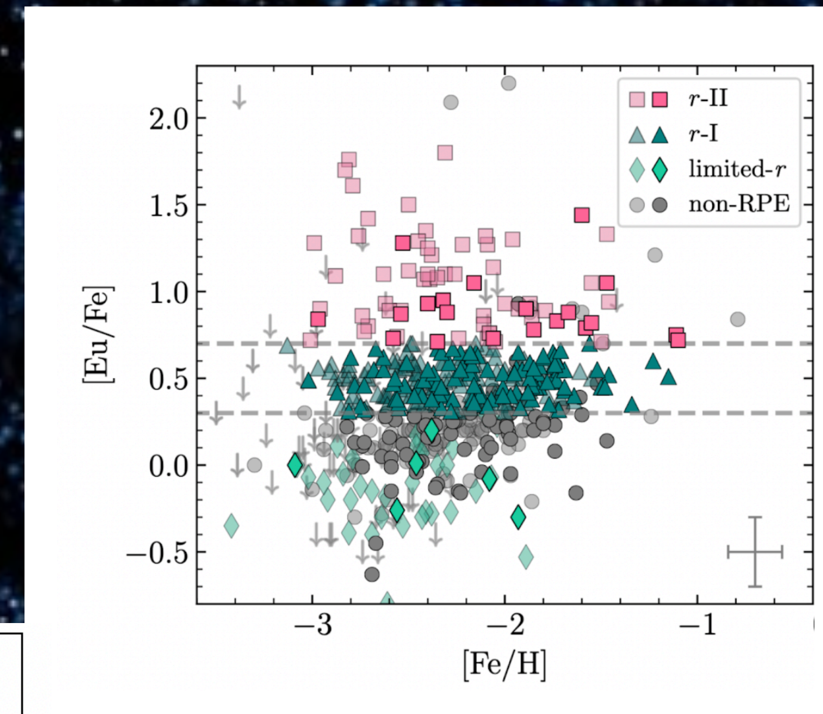
GAIA ESO Magrini+18



R-process alliance Holmbeck+20



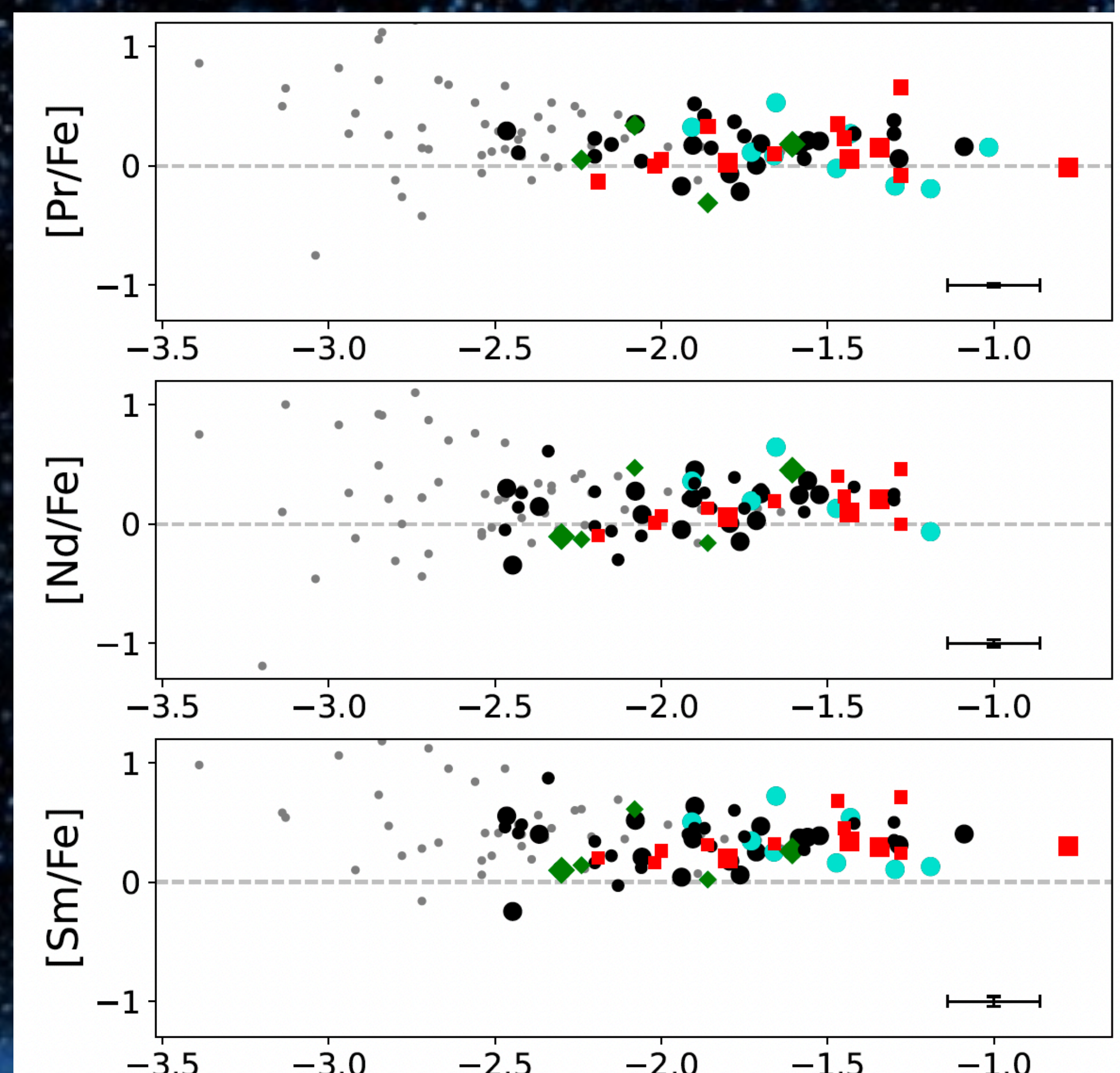
UVES: single object

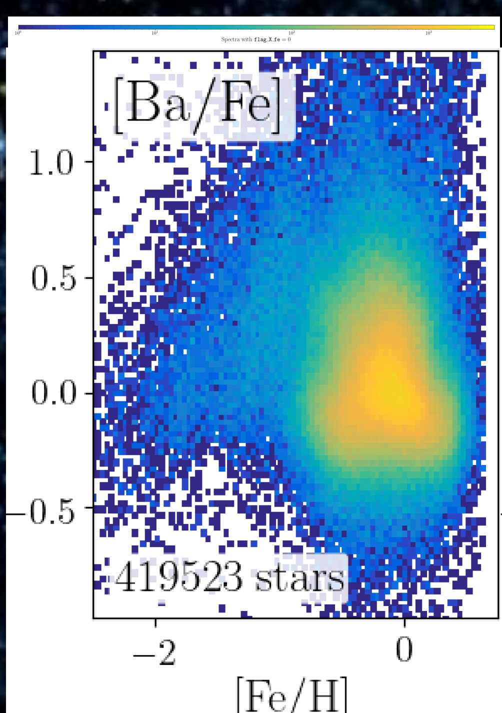
8m telescope

R> 80'000

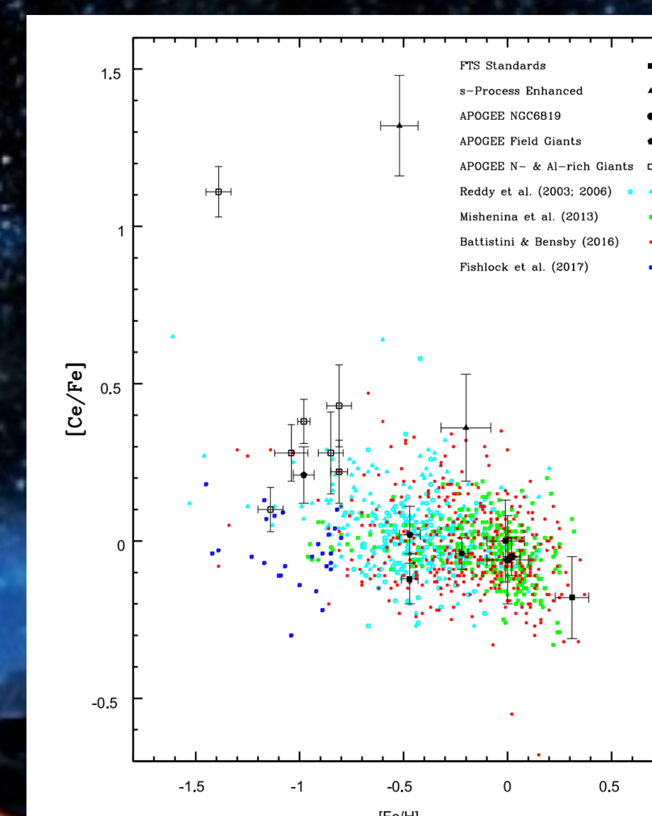
UV-optical

MINCE Lucertini+25





Galah Buder+21



Apogee Cunha+18

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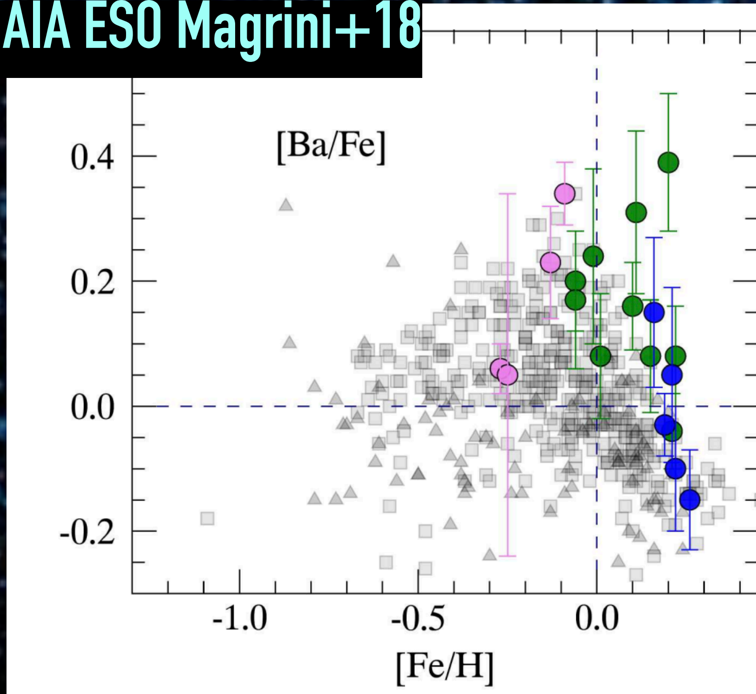
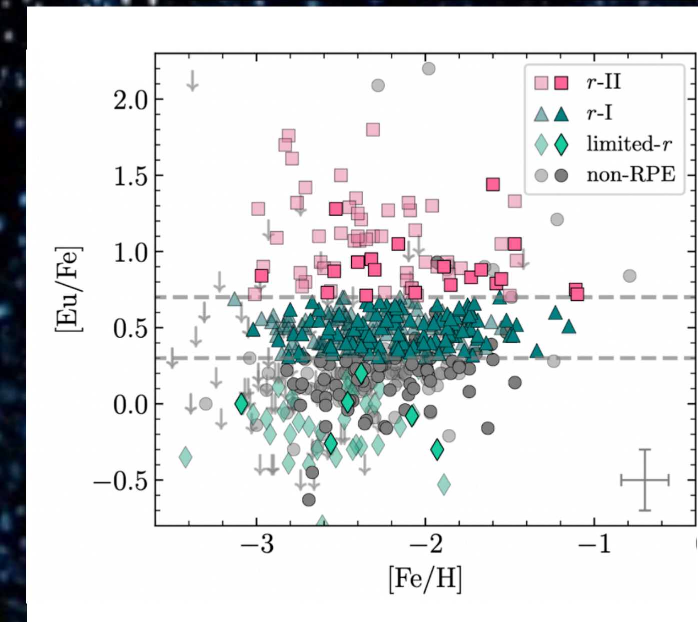
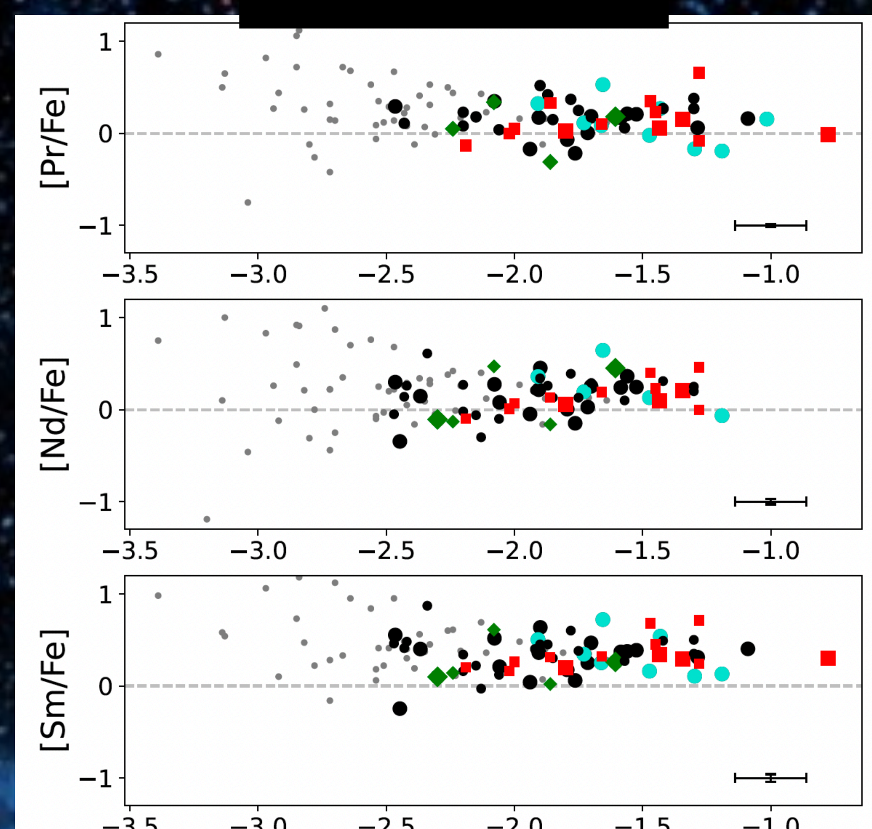
GAIA ESO Magrini+18

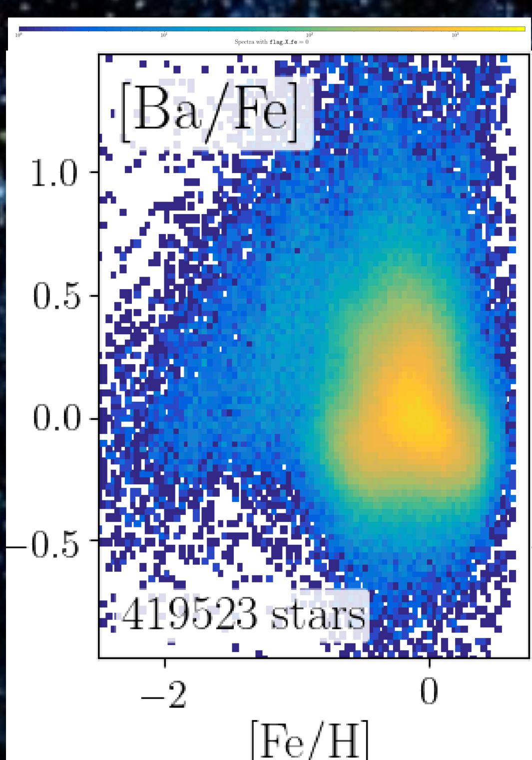


R-process alliance

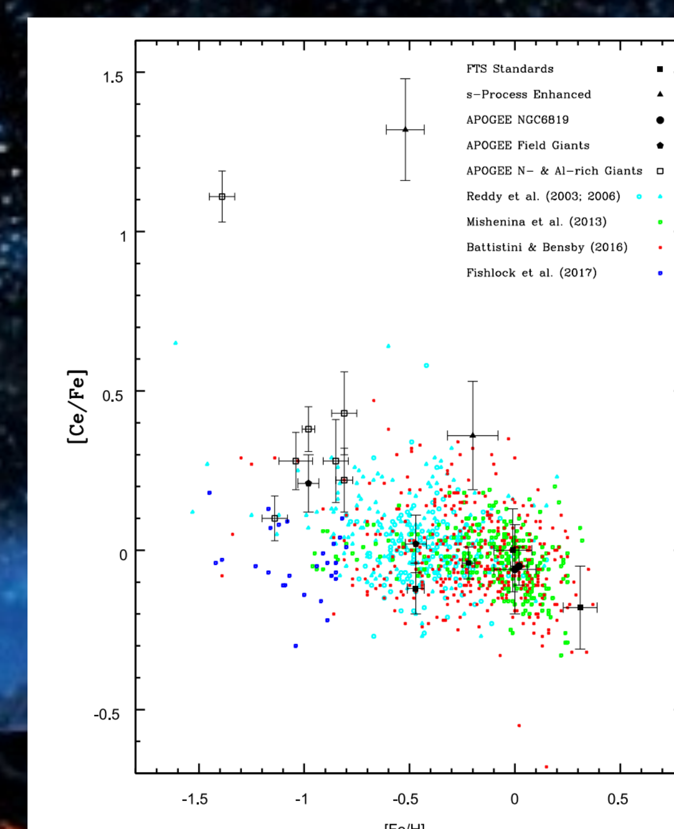


MINCE Lucertini+25





Galah Buder+21



Apogee Cunha+18

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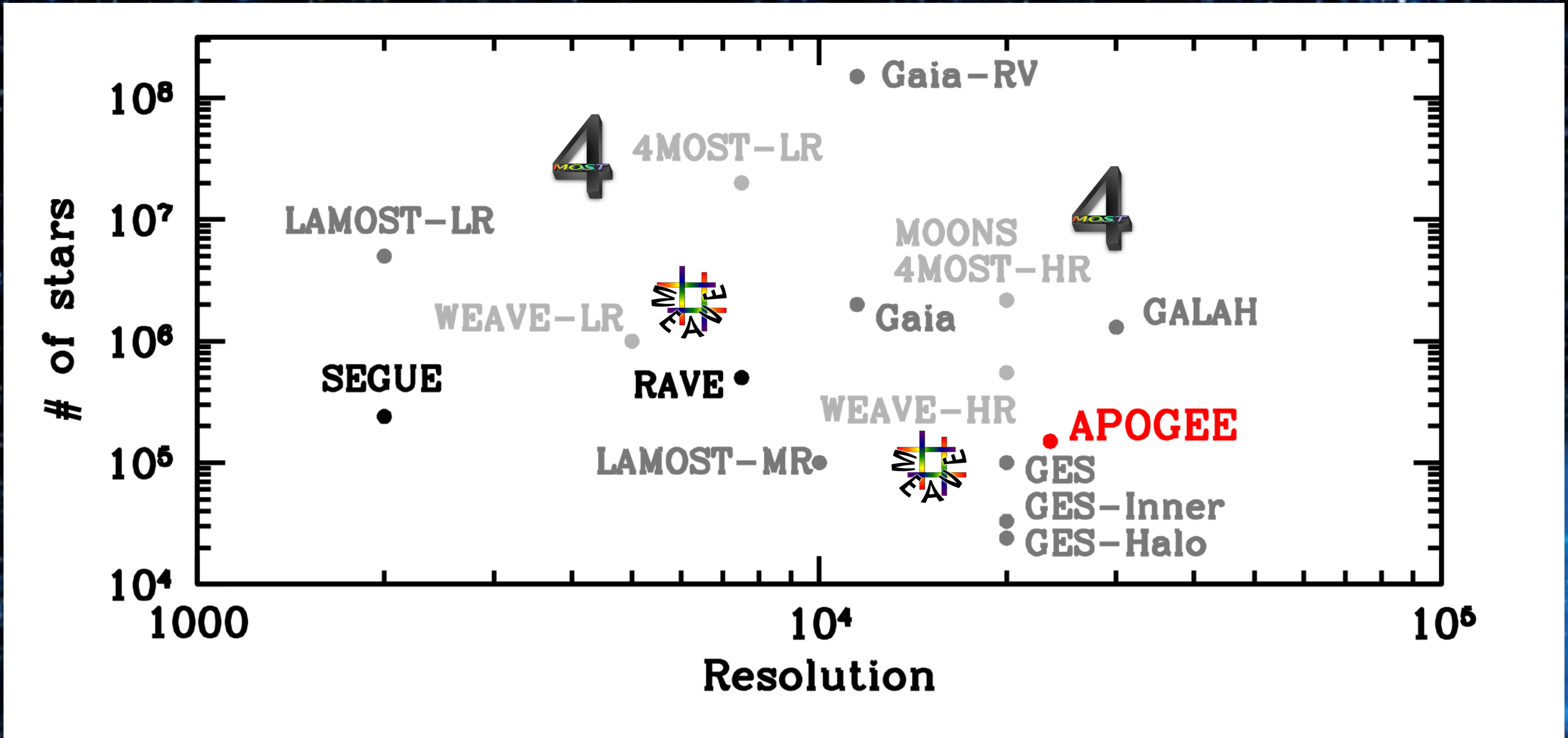
~2400 objects
R 20'000 for 800 fibers
R 8'000 for 1600 fibers
4m telescope VISTA at Paranal
optical

1000-multiplex fibre positioner,
366—959 nm at ~ R 5000,
2 shorter ranges at R ~ 20 000.



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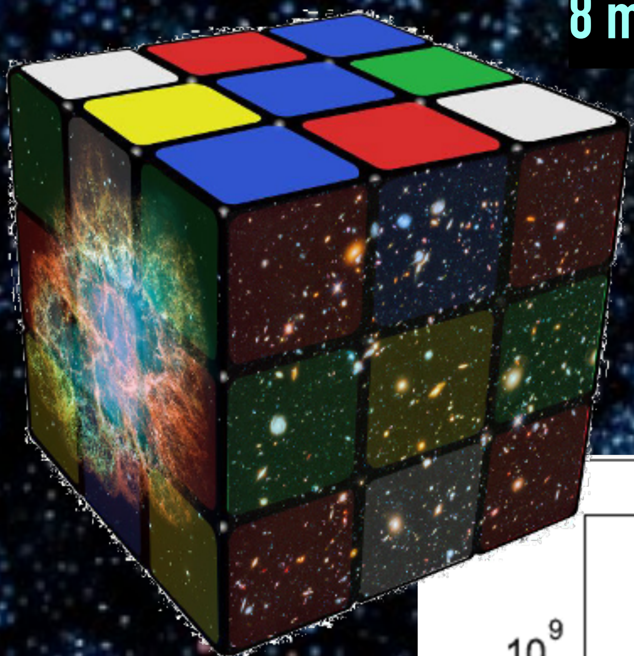
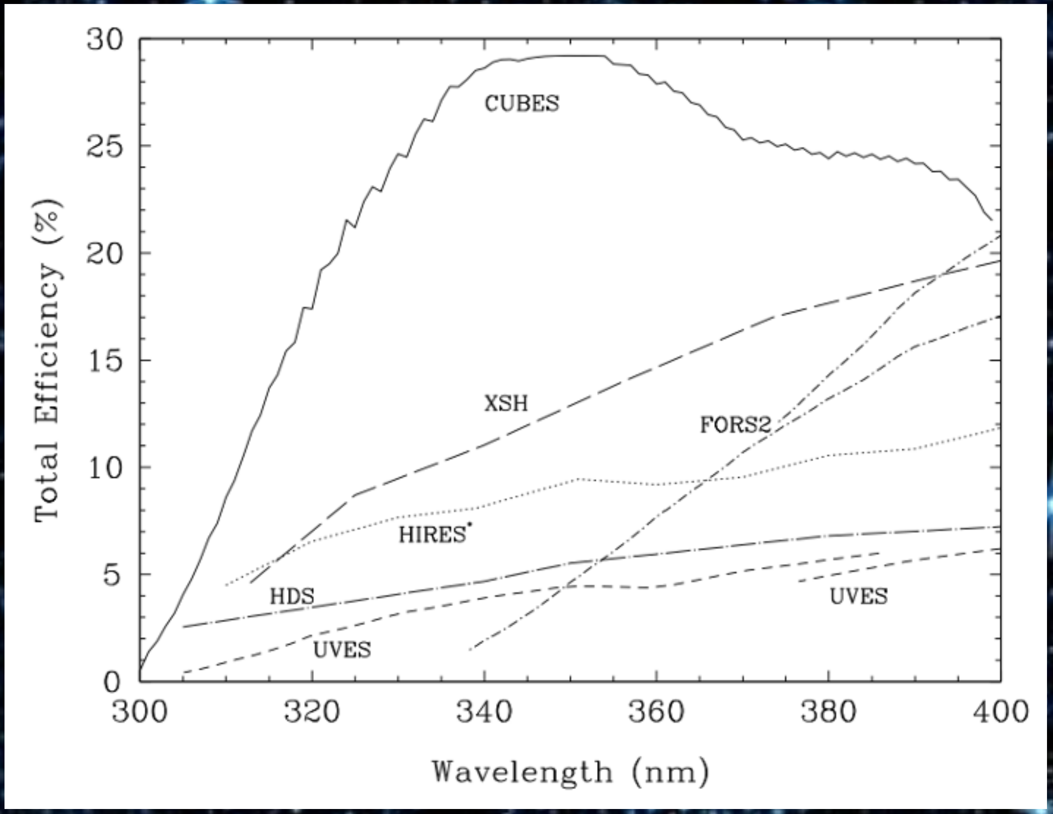
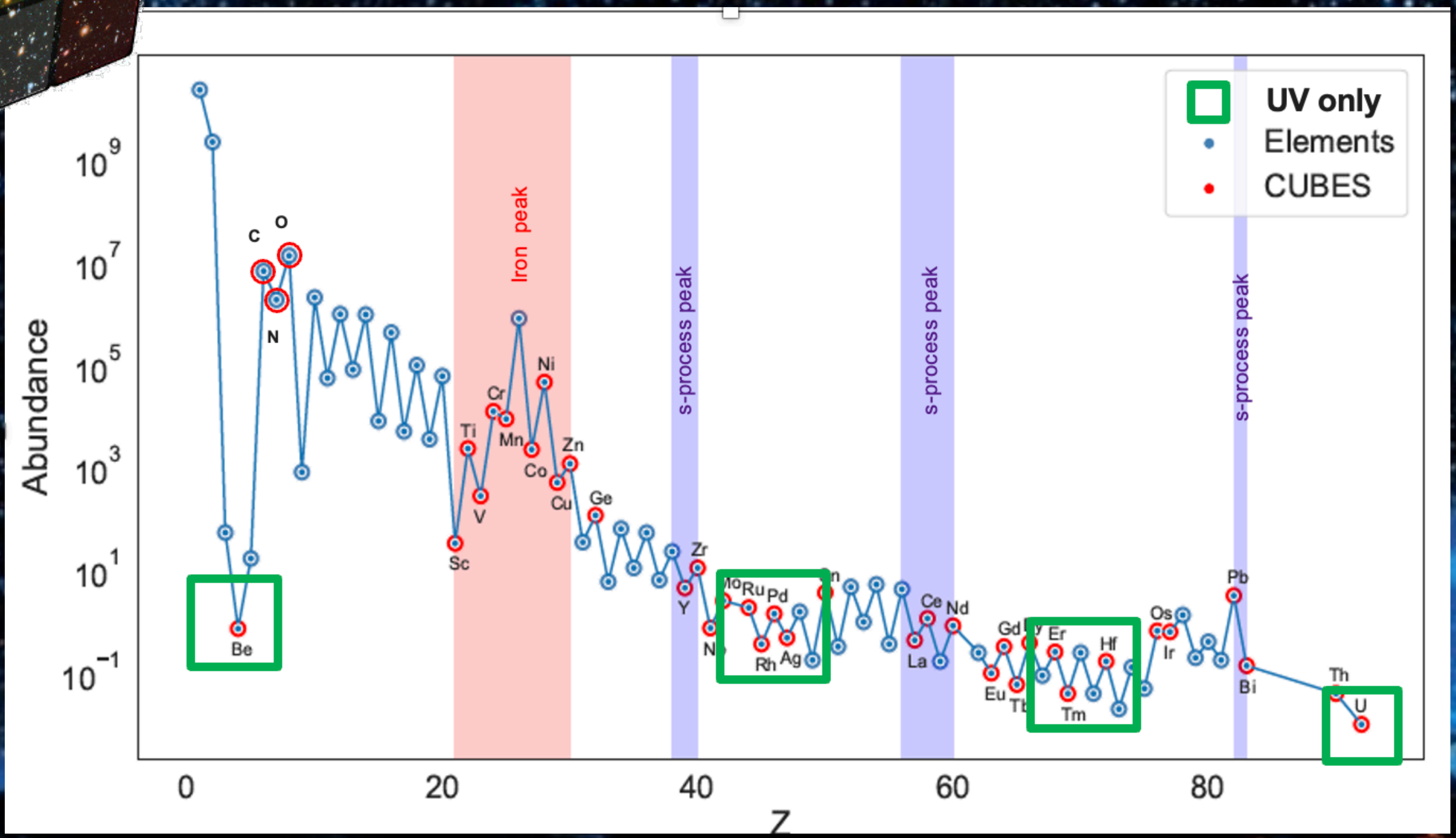
CUBES

Cassegrain U-Band Efficient Spectrograph
R~25,000 1 object
8 m telescopes from 300nm to 400nm







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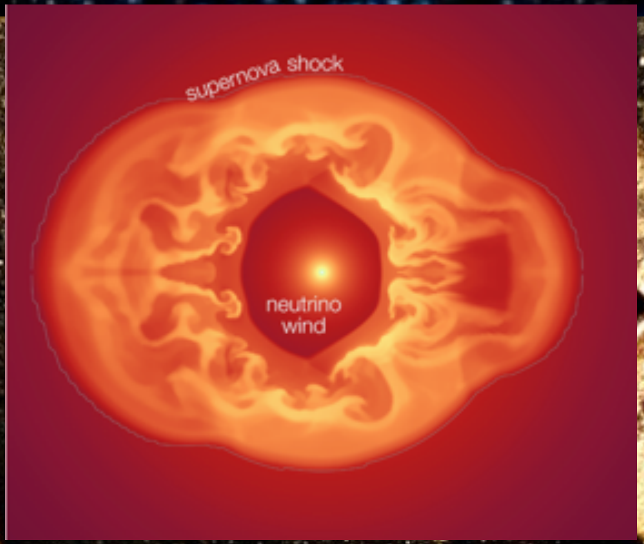
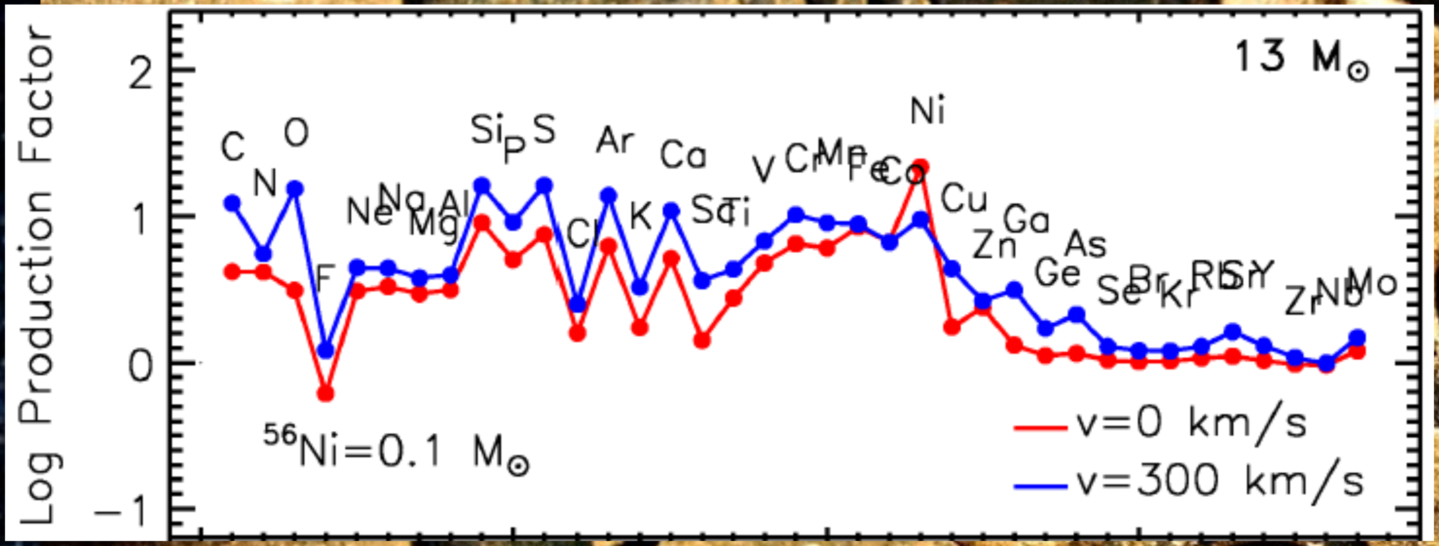
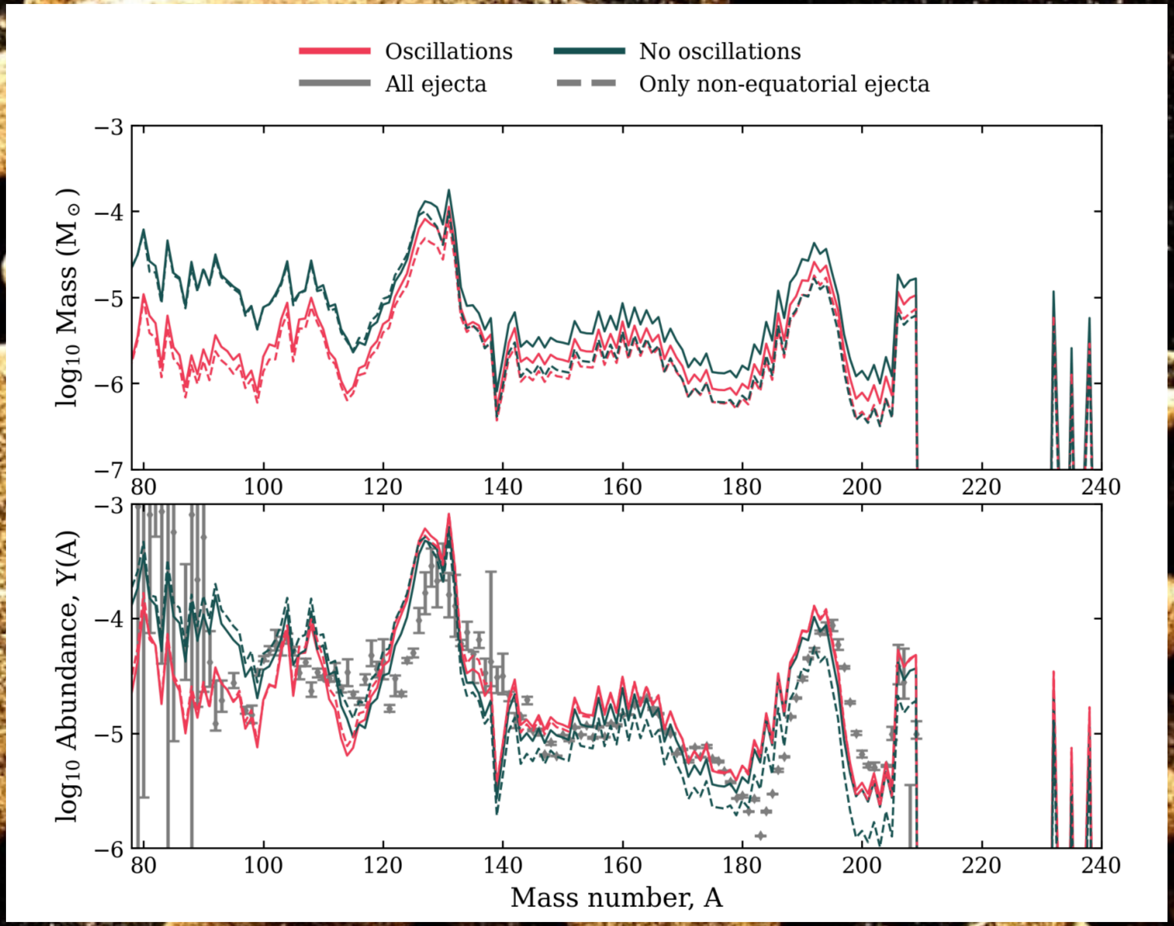
Stellar evolution and neutron star mergers models with nucleosynthesis





Limongi&Chieffi 12



Lund+25

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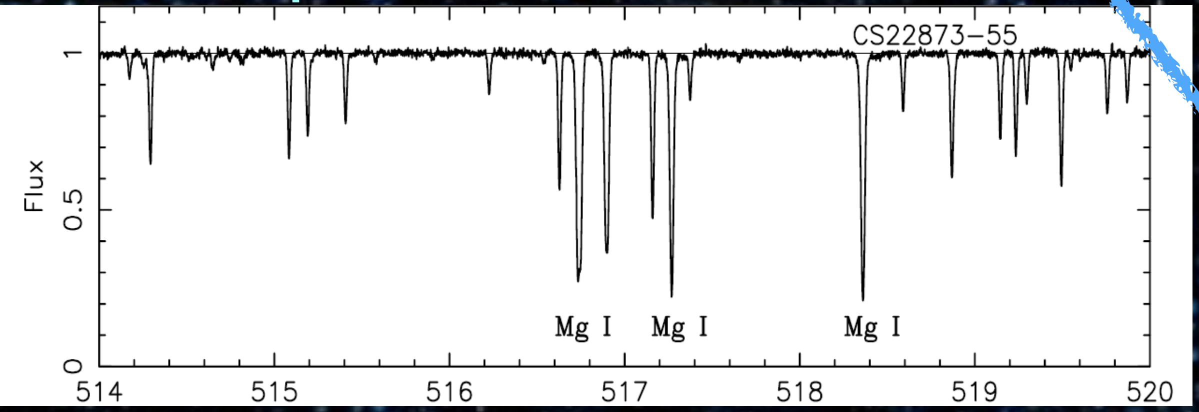
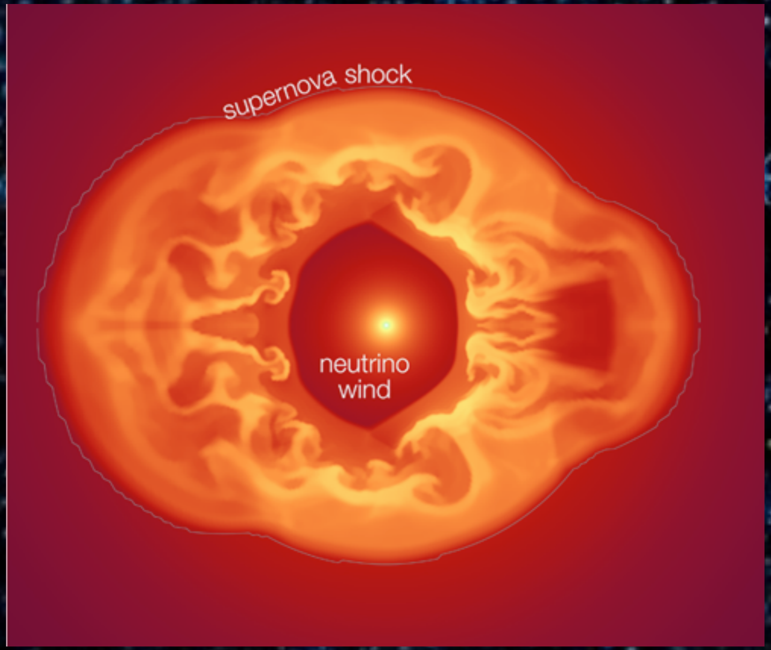
How to compare?

Stellar spectra

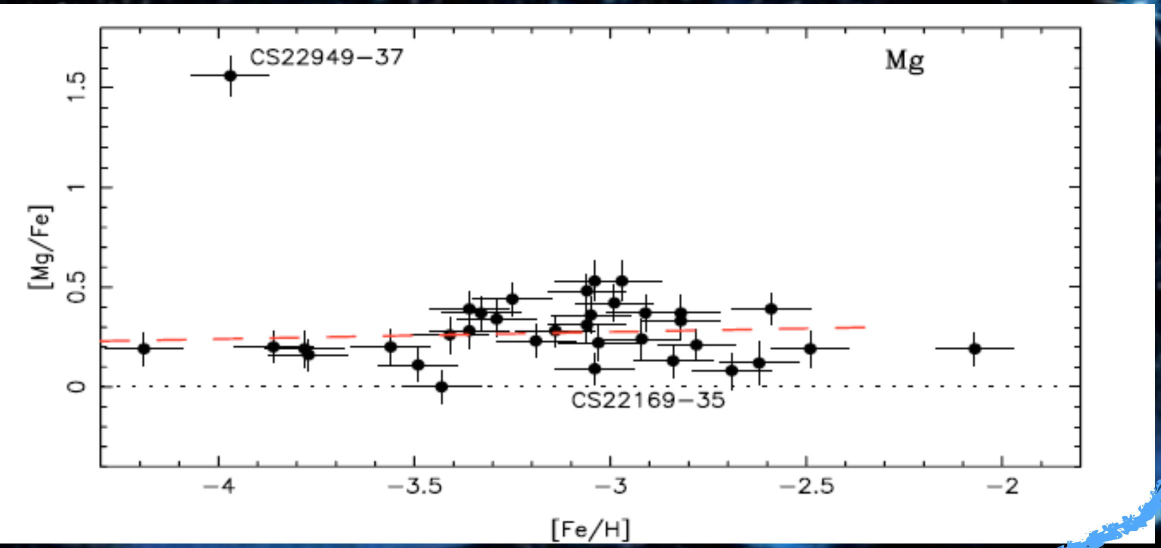


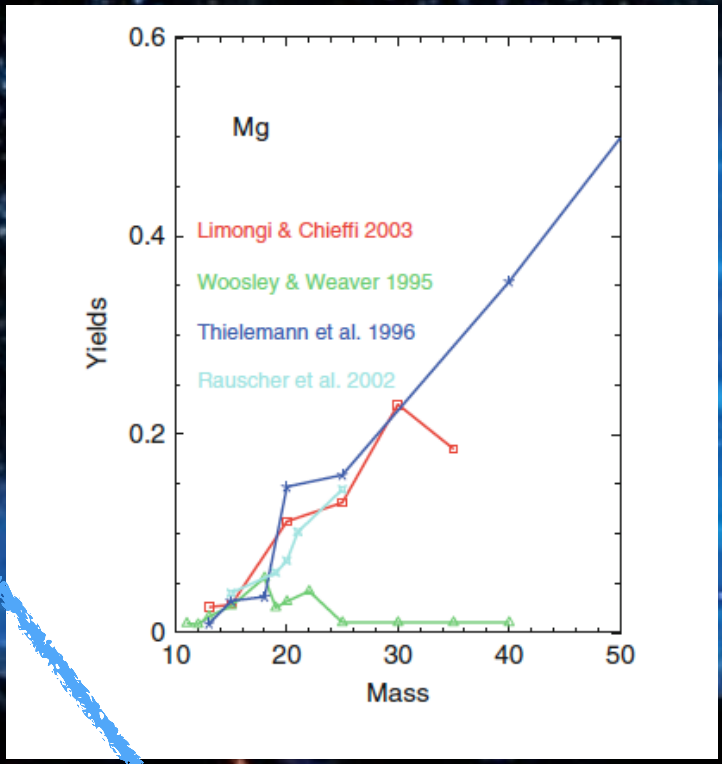
Stellar evolution



Nucleosynthesis

Stellar chemical abundances





Cayrel+04

Romano+10

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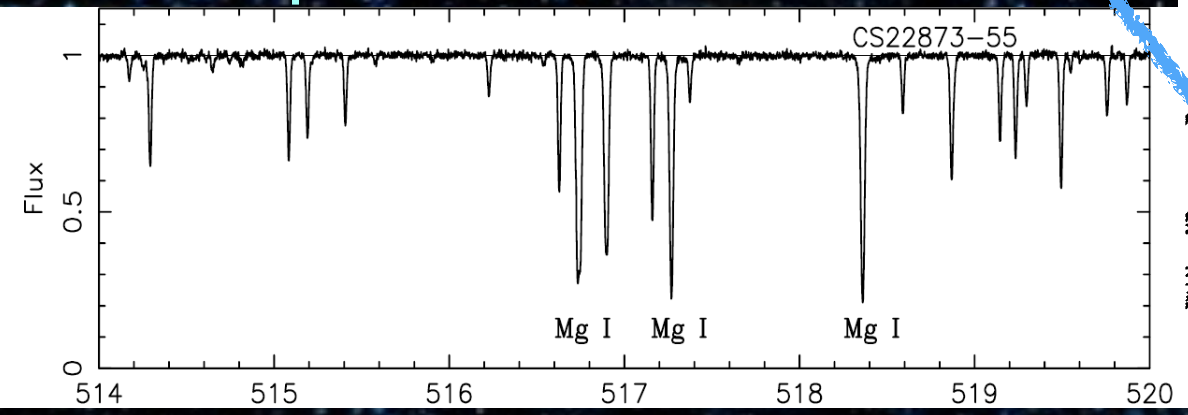
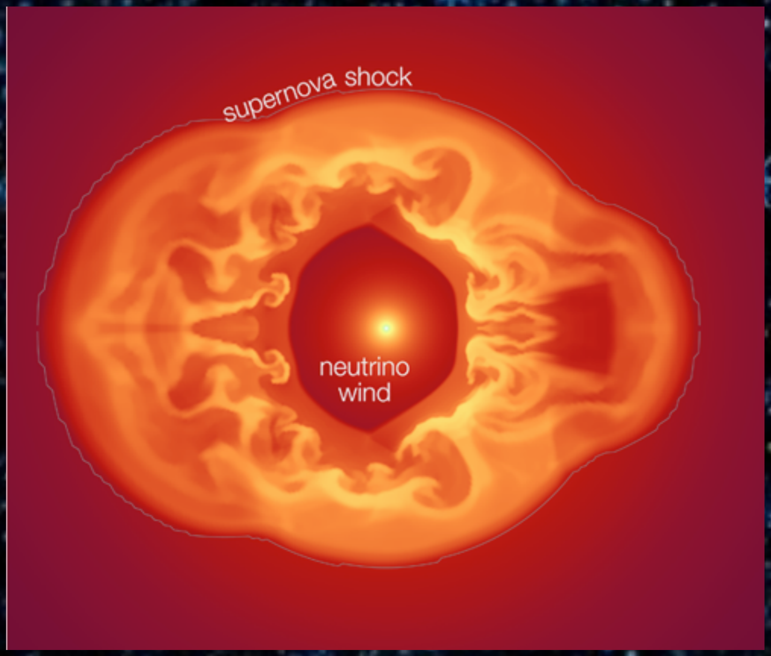
How to compare?

Stellar spectra

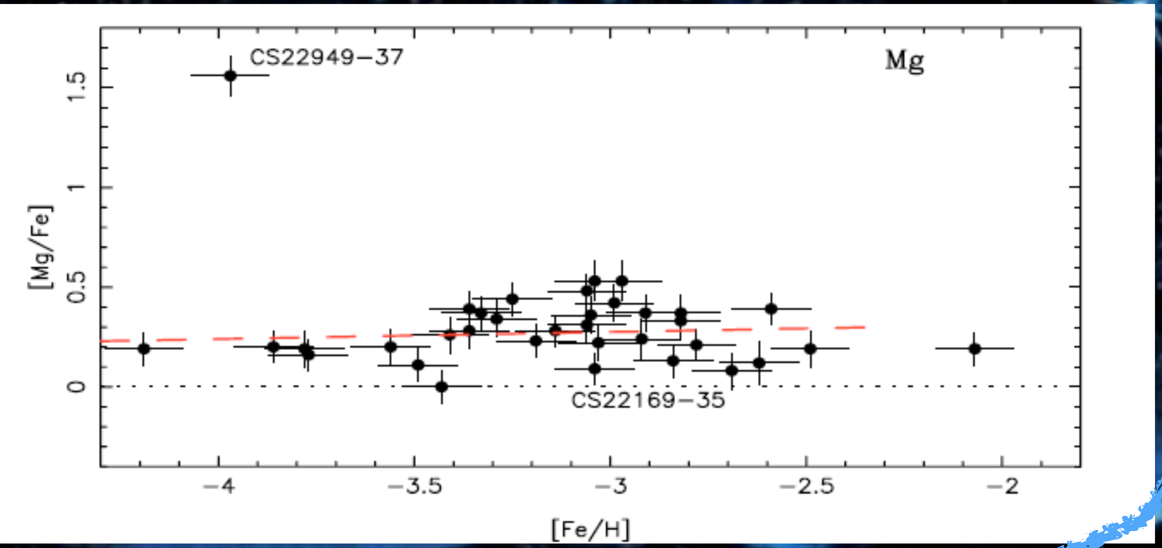


Stellar evolution

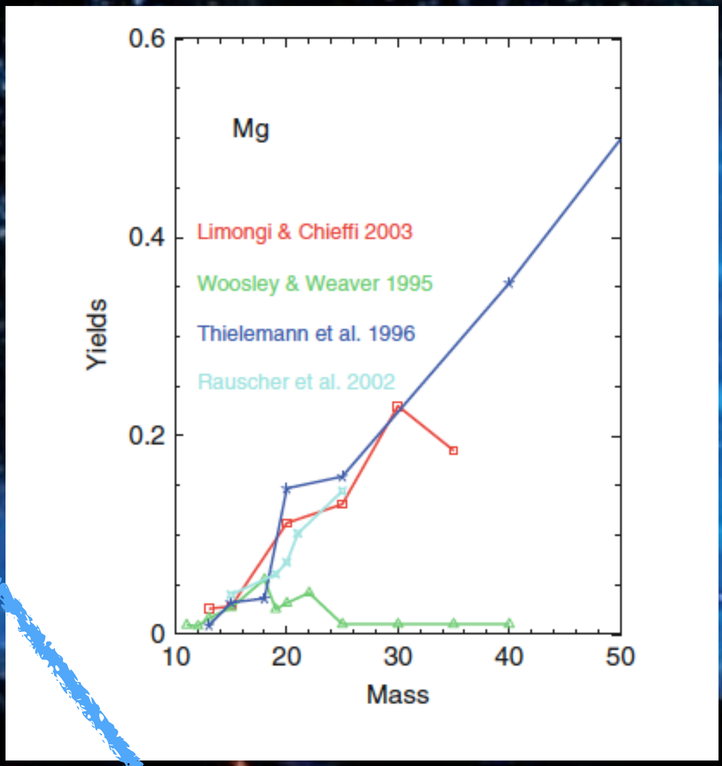


Nucleosynthesis

Stellar chemical abundances



Cayrel+04



Romano+10

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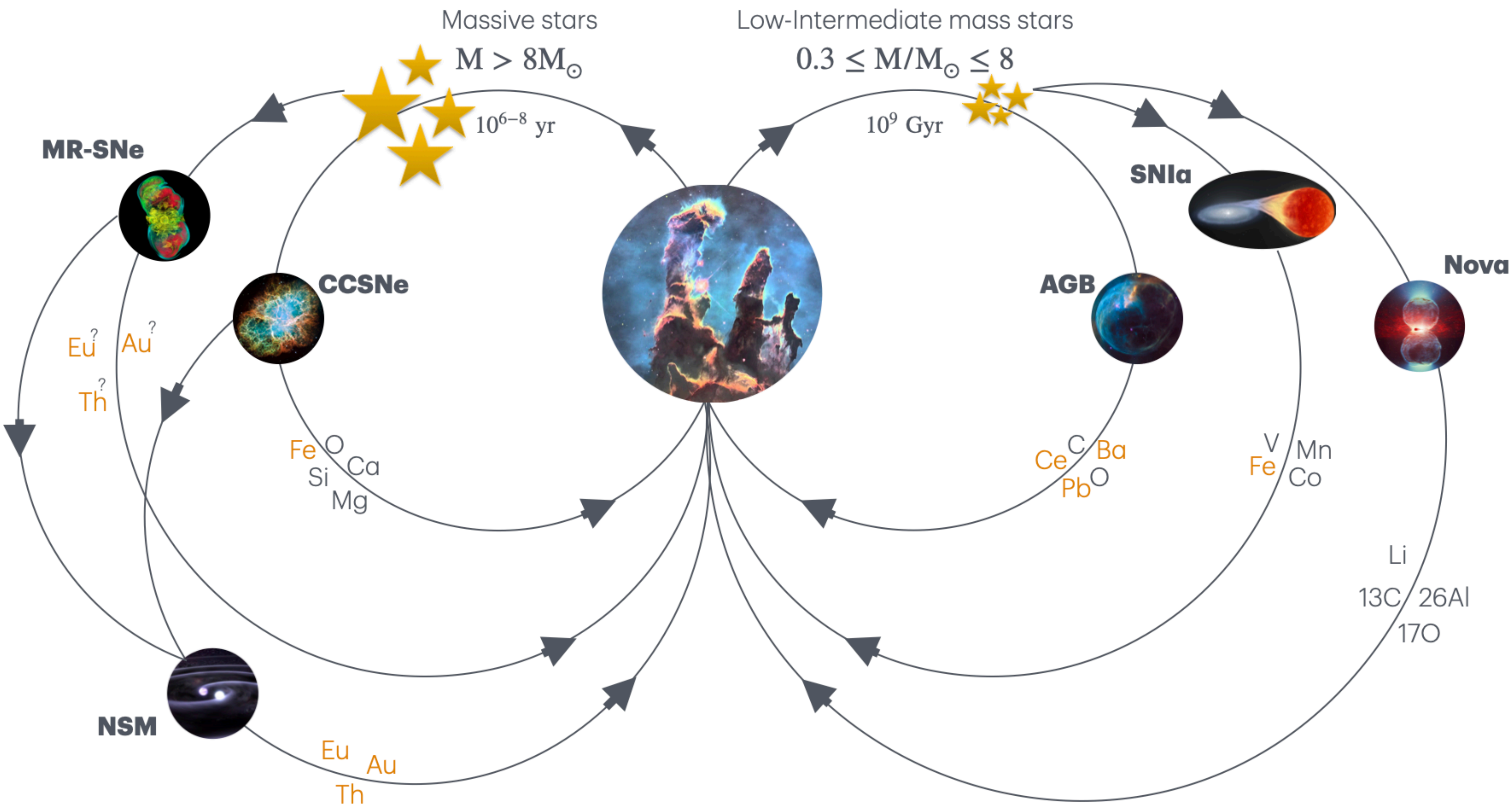
Chemical evolution

Credits: Marta Molero



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Galactic chemical evolution

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

$$\dot{G}_A(R,t) =$$

1) Locked in stars

2) Infalling in the system

3)Flowing from the system

4) Produced by stars

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Galactic chemical evolution

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

$$\dot{G}_A(R,t) =$$

$$-X_A(R,t)\,\Psi\,(R,t) +$$

1) Locked in stars

2) Infalling in the system

3)Flowing from the system

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Galactic chemical evolution

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

$$\dot{G}_A(R,t) =$$

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

$$-X_A(R,t)\,\Psi(R, t) +$$

1) Locked in stars

2) Infalling in the system

3)Flowing from the system

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Galactic chemical evolution

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

$$\dot{G}_A(R,t) =$$

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

$$-X_A(R,t)\, \Psi (R, t) + \dot{G}_{A,infall} (R,t)$$

1) Locked in stars

2) Infalling in the system

3)Flowing from the system

4) Produced by stars

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Galactic chemical evolution

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

$$\dot{G}_A(R,t) =$$

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

$$-X_A(R,t)\,\Psi(R, t) + \dot{G}_{A,infall}(R,t) \quad - X_A(R,t)\,\dot{W}_A(R, t)$$

1) Locked in stars

2) Infalling in the system

3)Flowing from the system

4) Produced by stars

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Galactic chemical evolution

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$$-X_A(R,t)\,\Psi(R,t) + \dot{G}_{A,infall}(R,t) \quad -X_A(R,t)\,\dot{W}_A(R,t)$$

1) Locked in stars **2) Infalling in the system** **3)Flowing from the system**

$$+ \int_M \Psi(R, t - \tau(m))\, \varphi(m)\, Q(m, z(t - \tau(m)))_A\, dm$$

4) Produced by stars

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Galactic chemical evolution

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

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$$-X_A(R,t)\, \Psi(R, t) + \dot{G}_{A,infall}(R,t) \quad -X_A(R,t)\, \dot{W}_A(R, t)$$

1) Locked in stars

2) Infalling in the system

3)Flowing from the system

$$+ \int_M \Psi(R, t - \tau(m))\, \varphi(m)\, Q(m, z(t - \tau(m)))_A\, dm$$

4) Produced by stars

Stellar nucleosynthesis
(nuclear reaction rate!)

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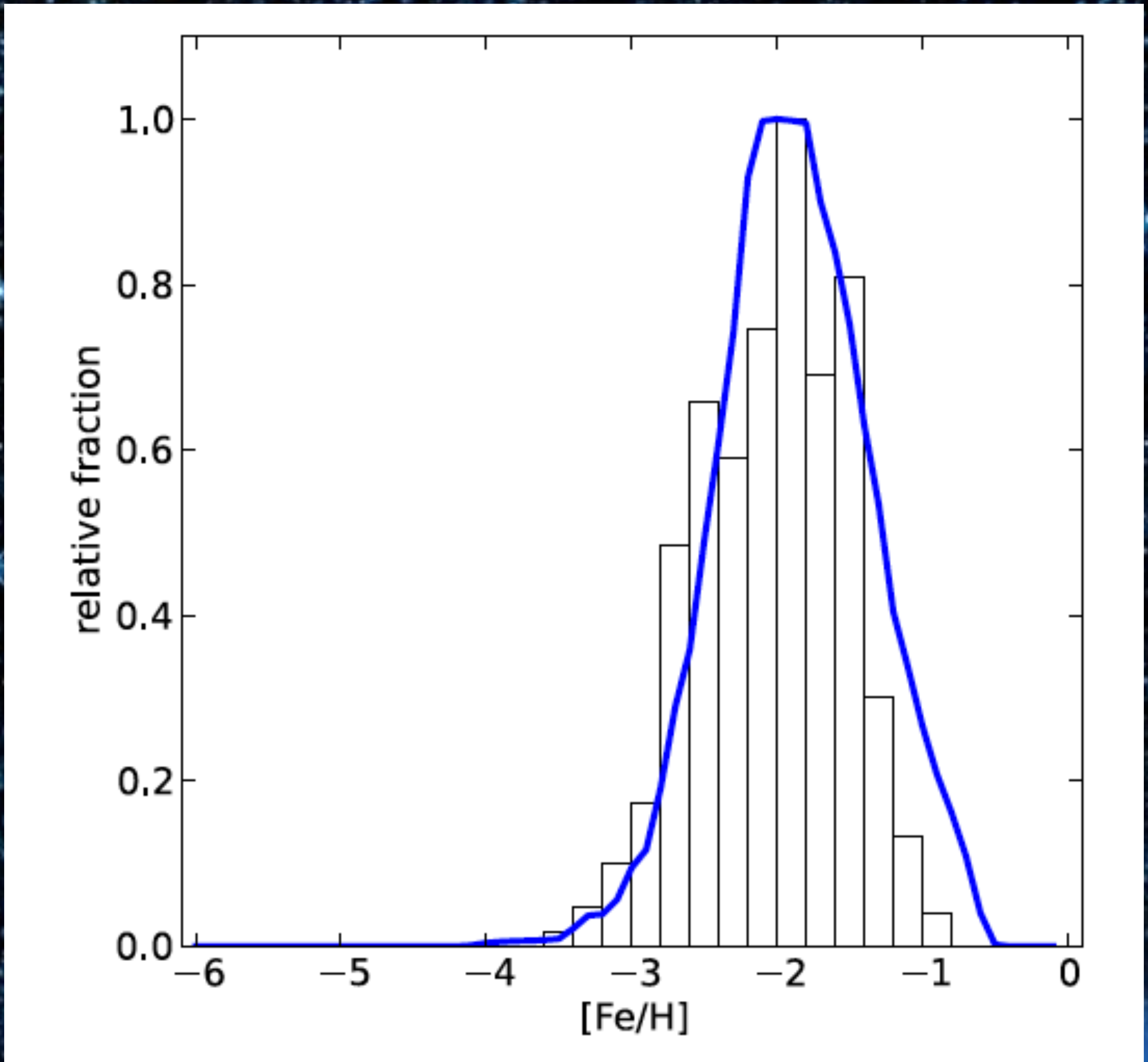
Metallicity distribution function of the Galactic halo



Li et al. (2010): main-sequence turnoff stars in the HESS (Hamburg ESO)

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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).

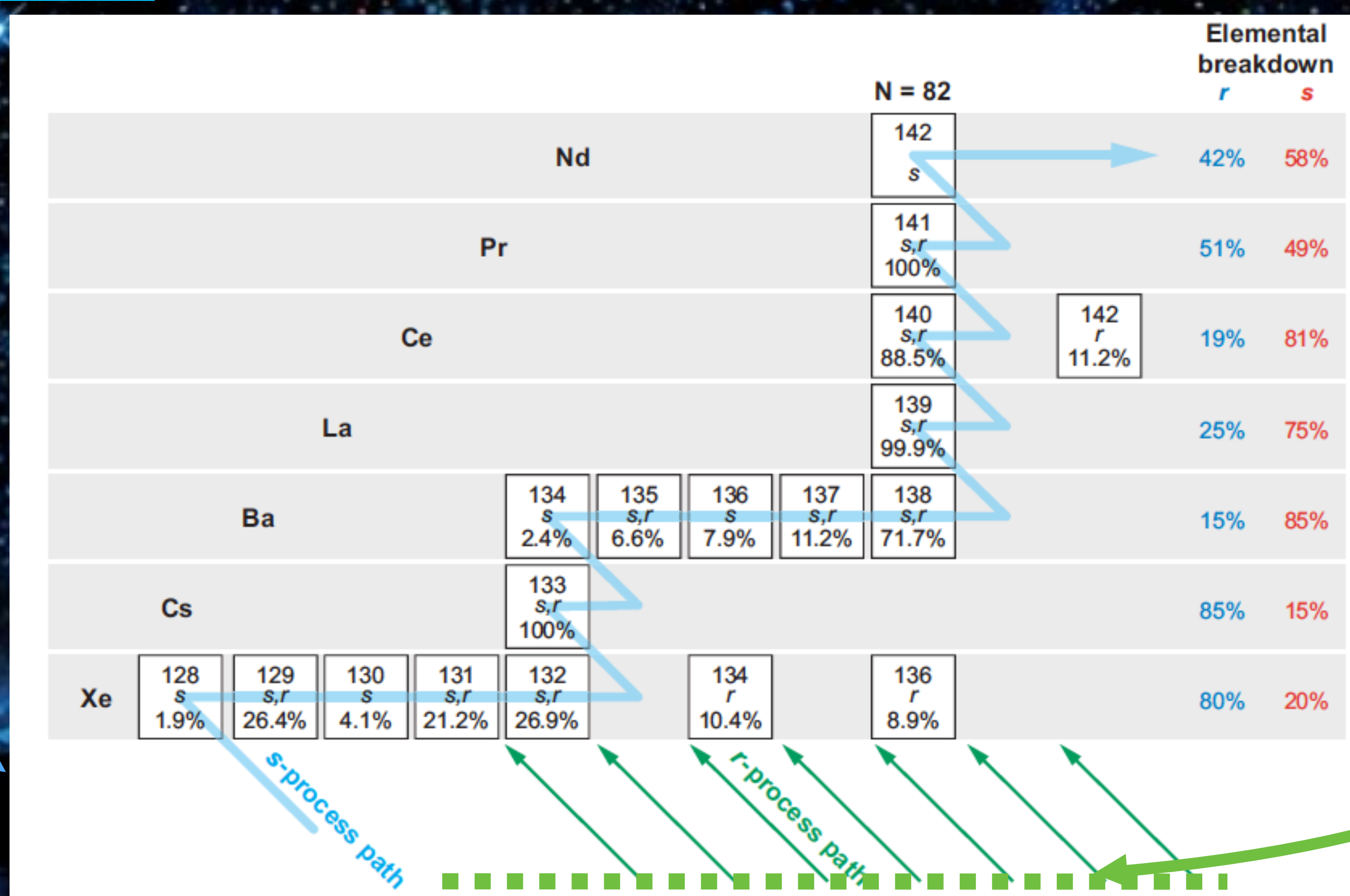
Two cases:

s-process | **r-process**

Different Timescale of the neutron capture

$\tau_\beta << \tau_c$ | $\tau_\beta >> \tau_c$

Different process path



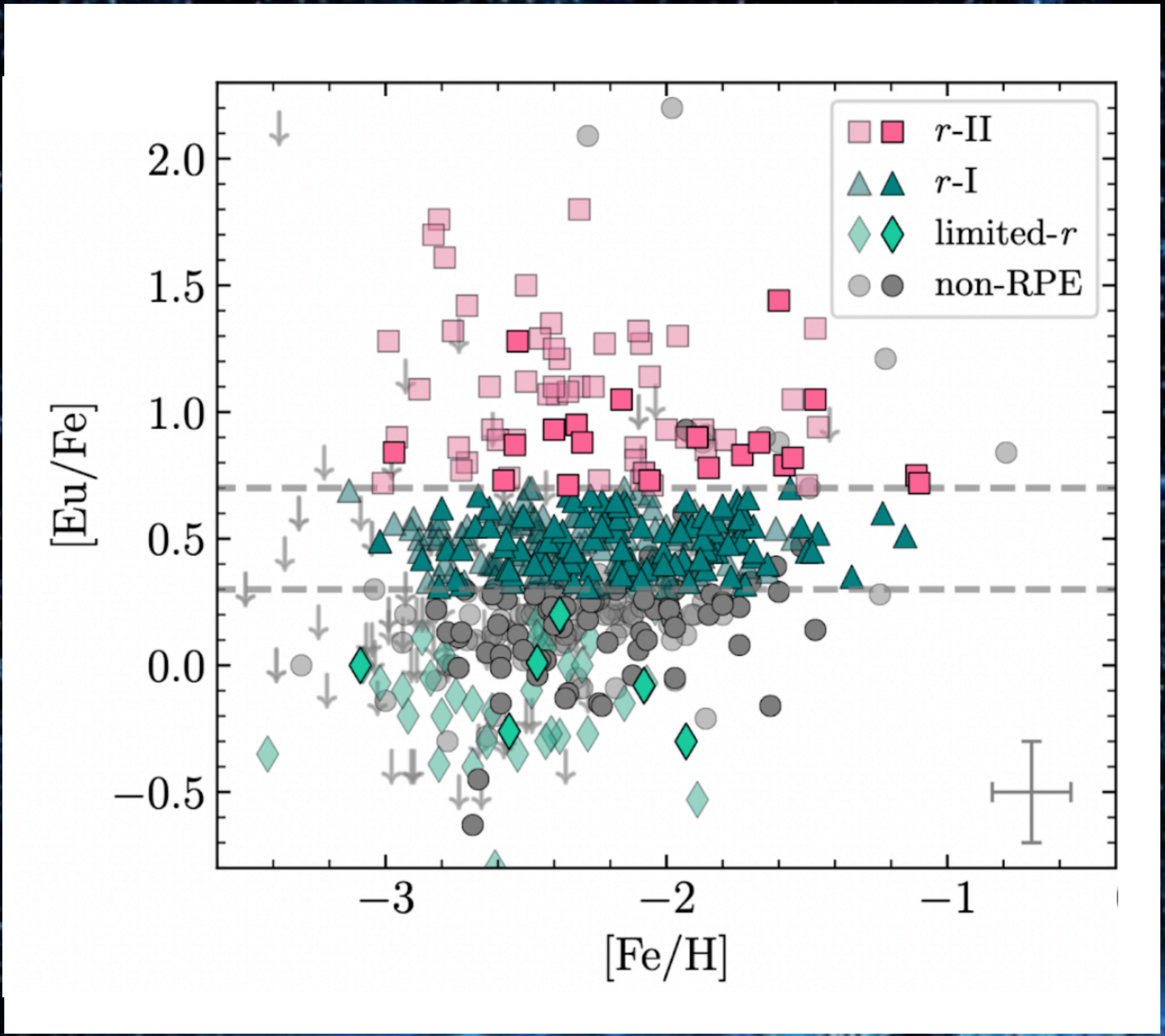
p

n

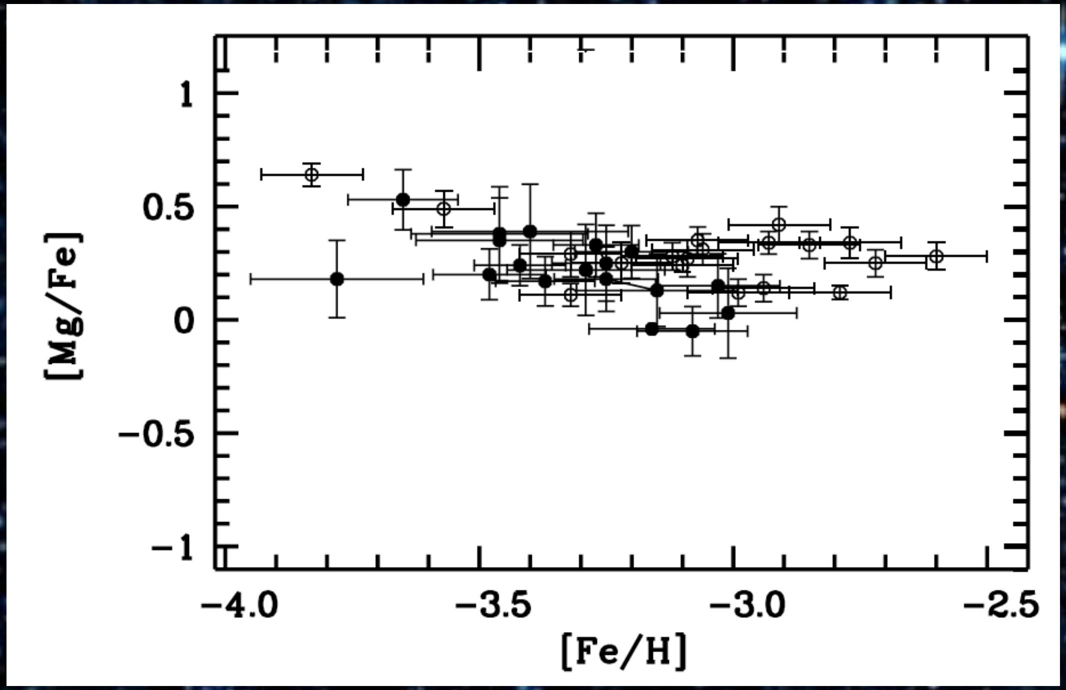
see also Prantzos+20

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

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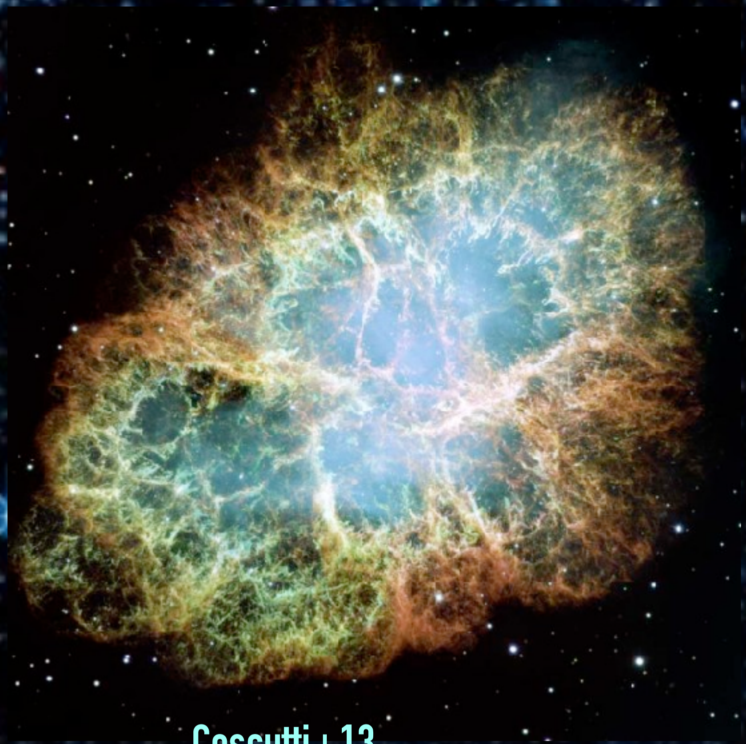
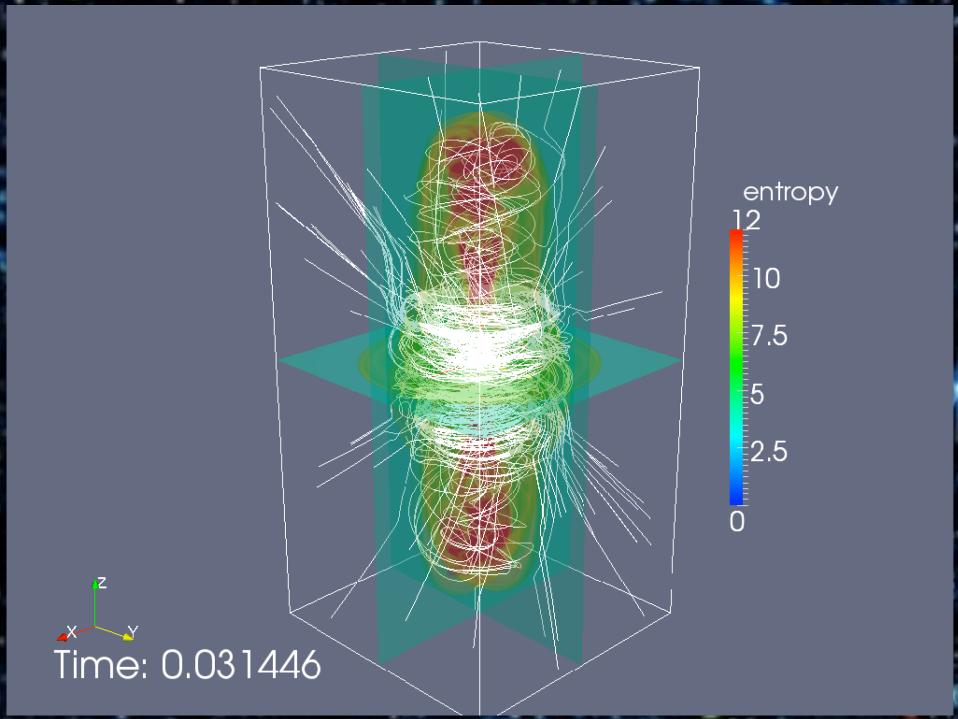
Site(s) of the r-process?

Electron Capture SNe (Wanajo+11)



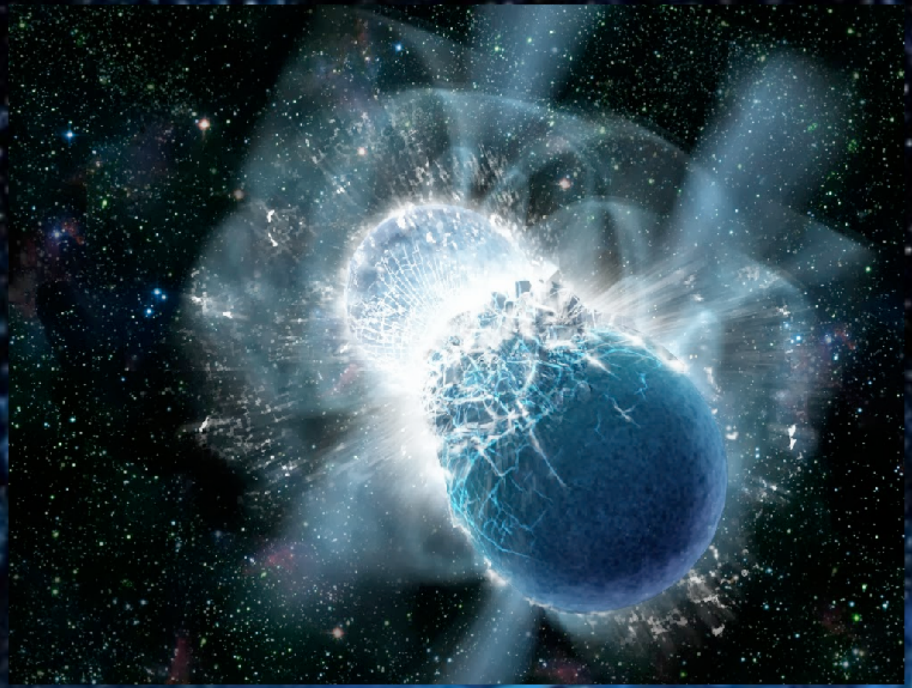
Cescutti+13

Magnetorotat. driven SNe (Winteler+12)



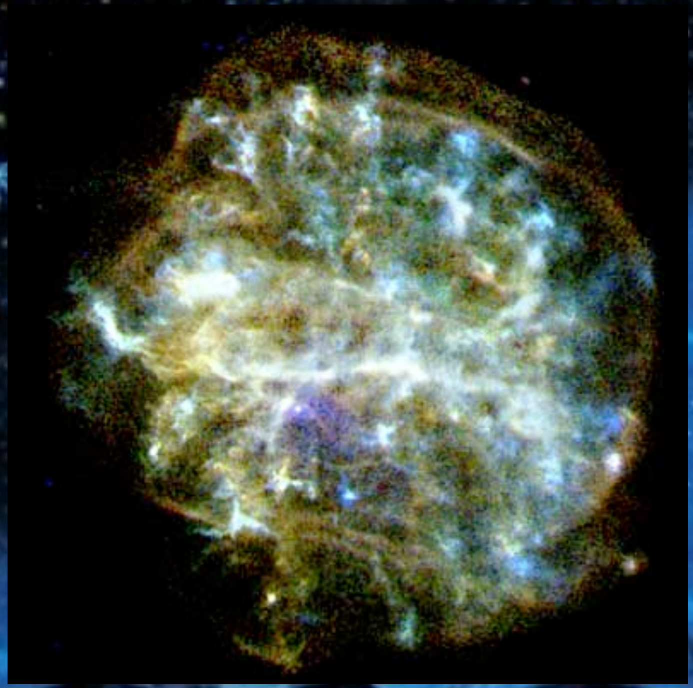
Cescutti+14

Neutron star mergers (Rosswog+13)



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

Neutrino winds SNe (Arcones+07,Wanajo 13)



other possible sites?

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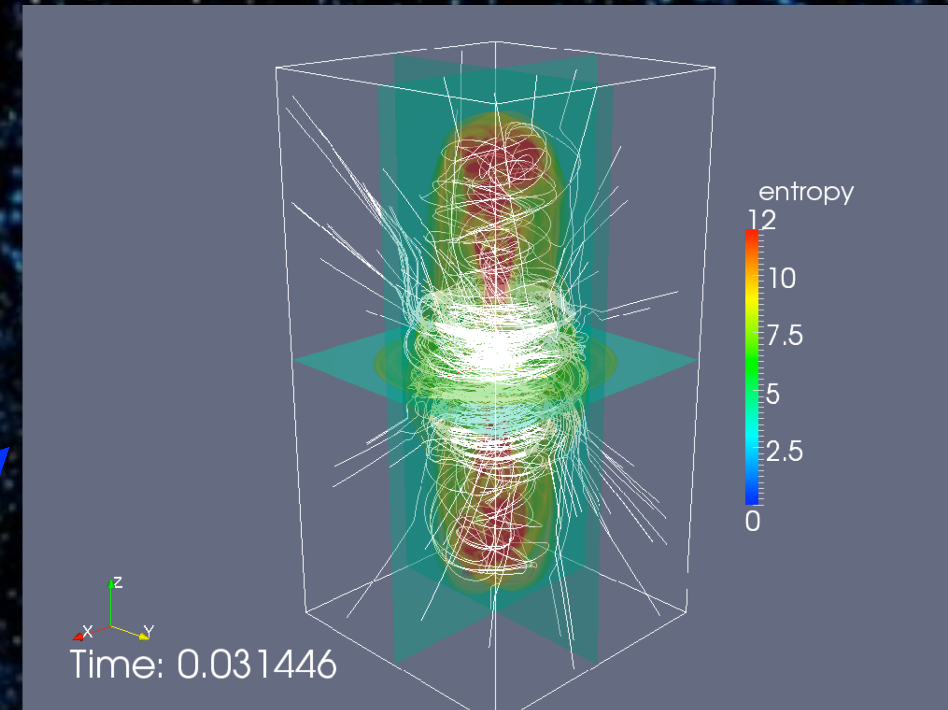
Site(s) of the r-process?

Electron Capture SNe (Wanajo+11)

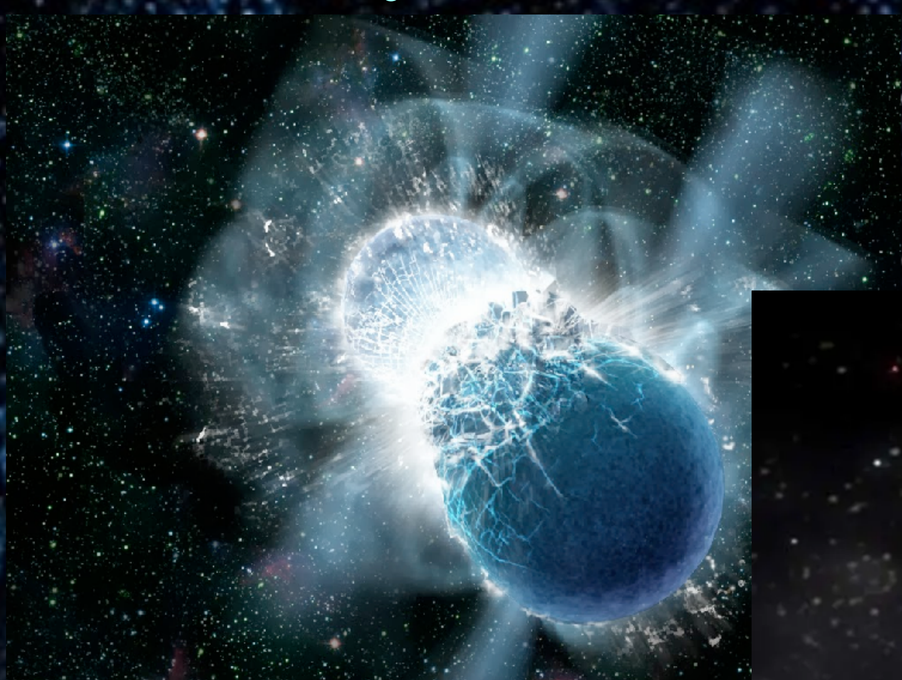
Cescutti+13

Magnetorotat. driven SNe (Winteler+12)



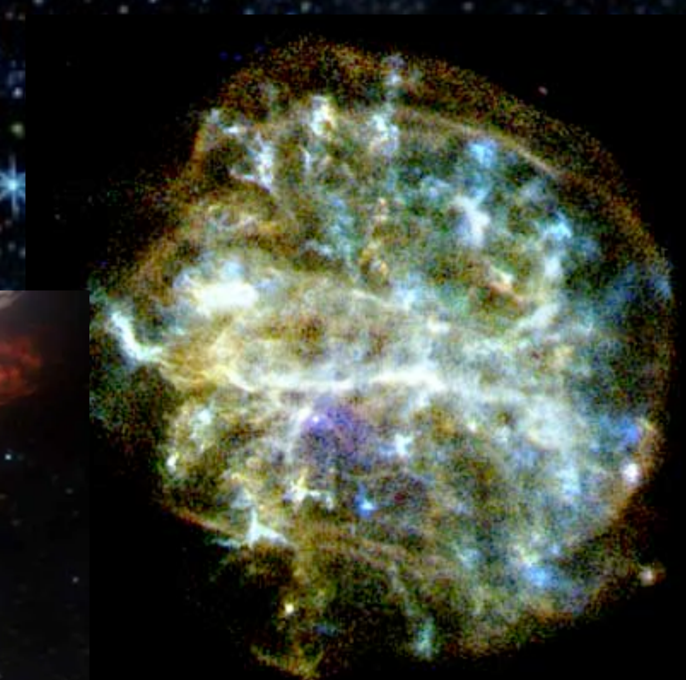
Cescutti+14

Neutron star mergers (Rosswog+13)

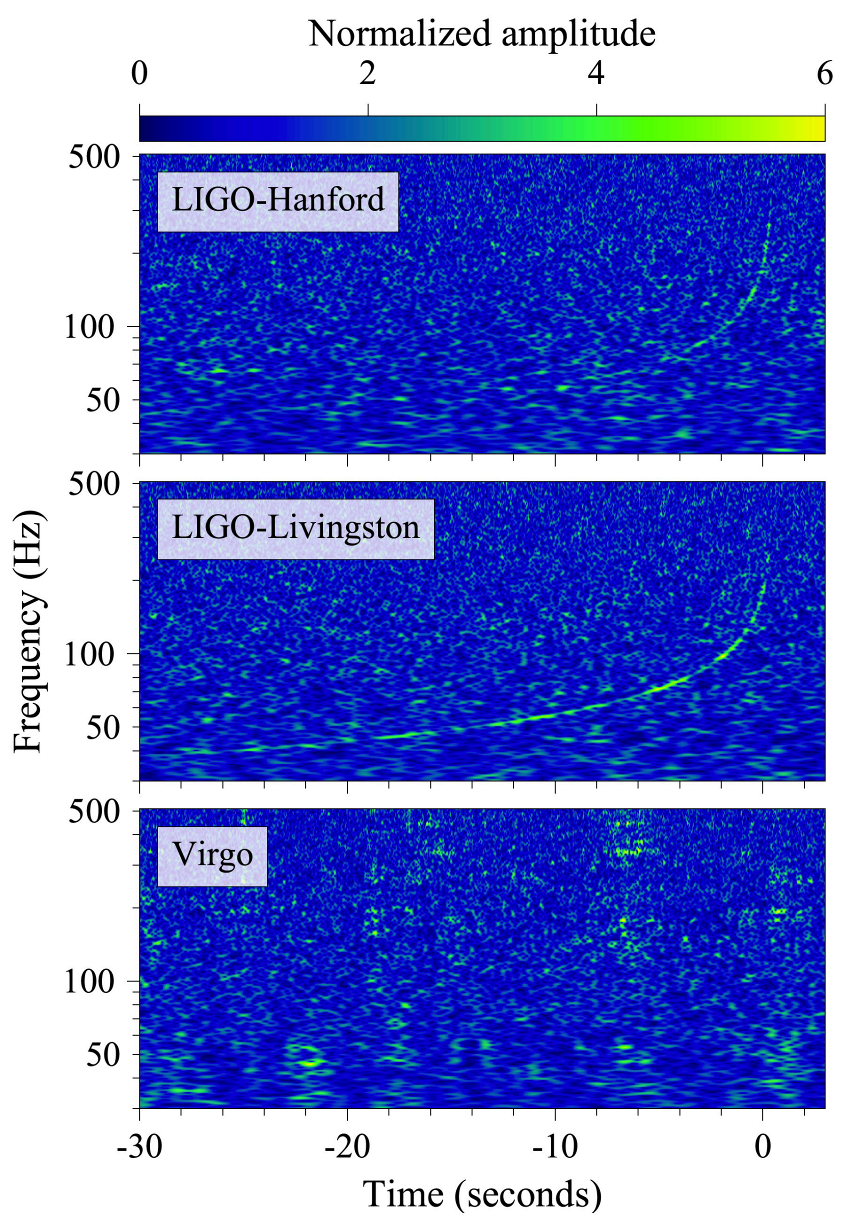


(Cescutti+15, Matteucci+14,…)

Neutrino winds SNe (Arcones+07,Wanajo 13)



Collapsar (Siegel+2019)



After GW170817...

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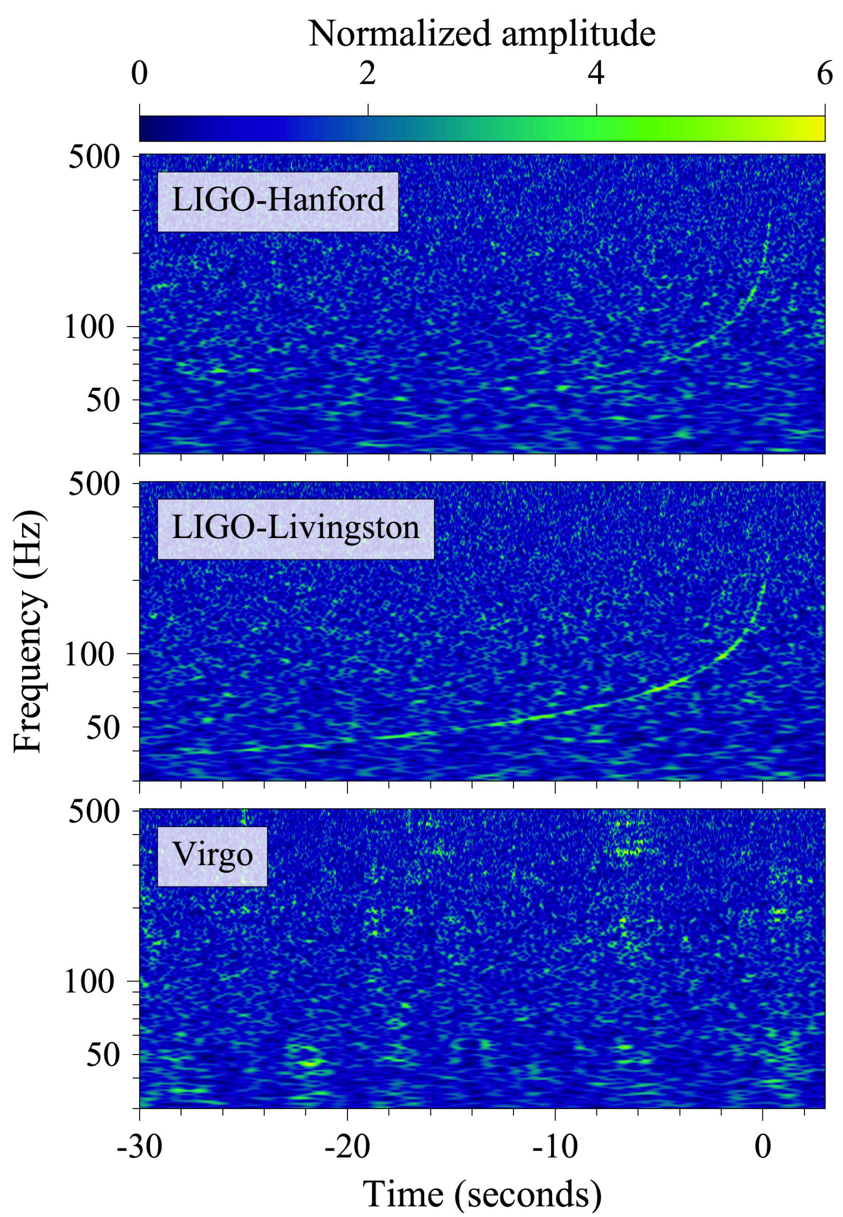
After GW170817...



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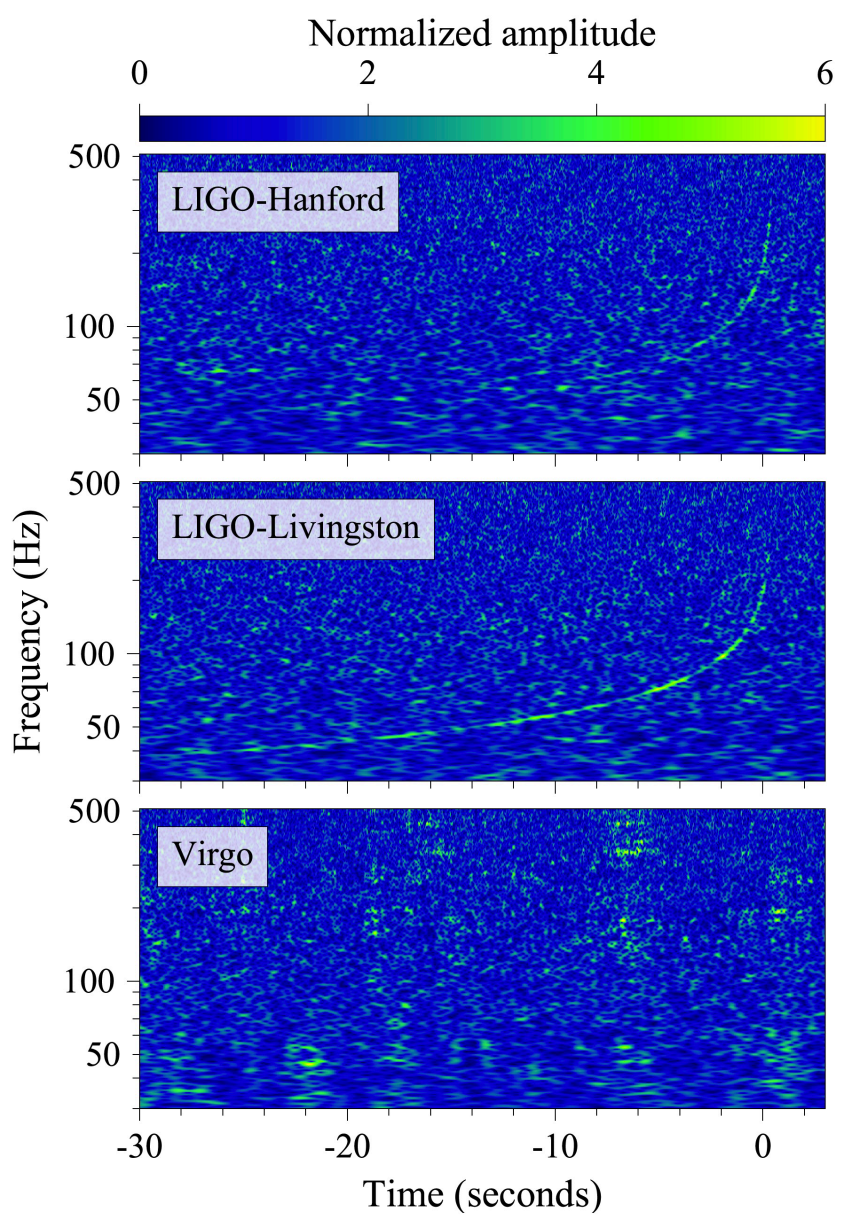
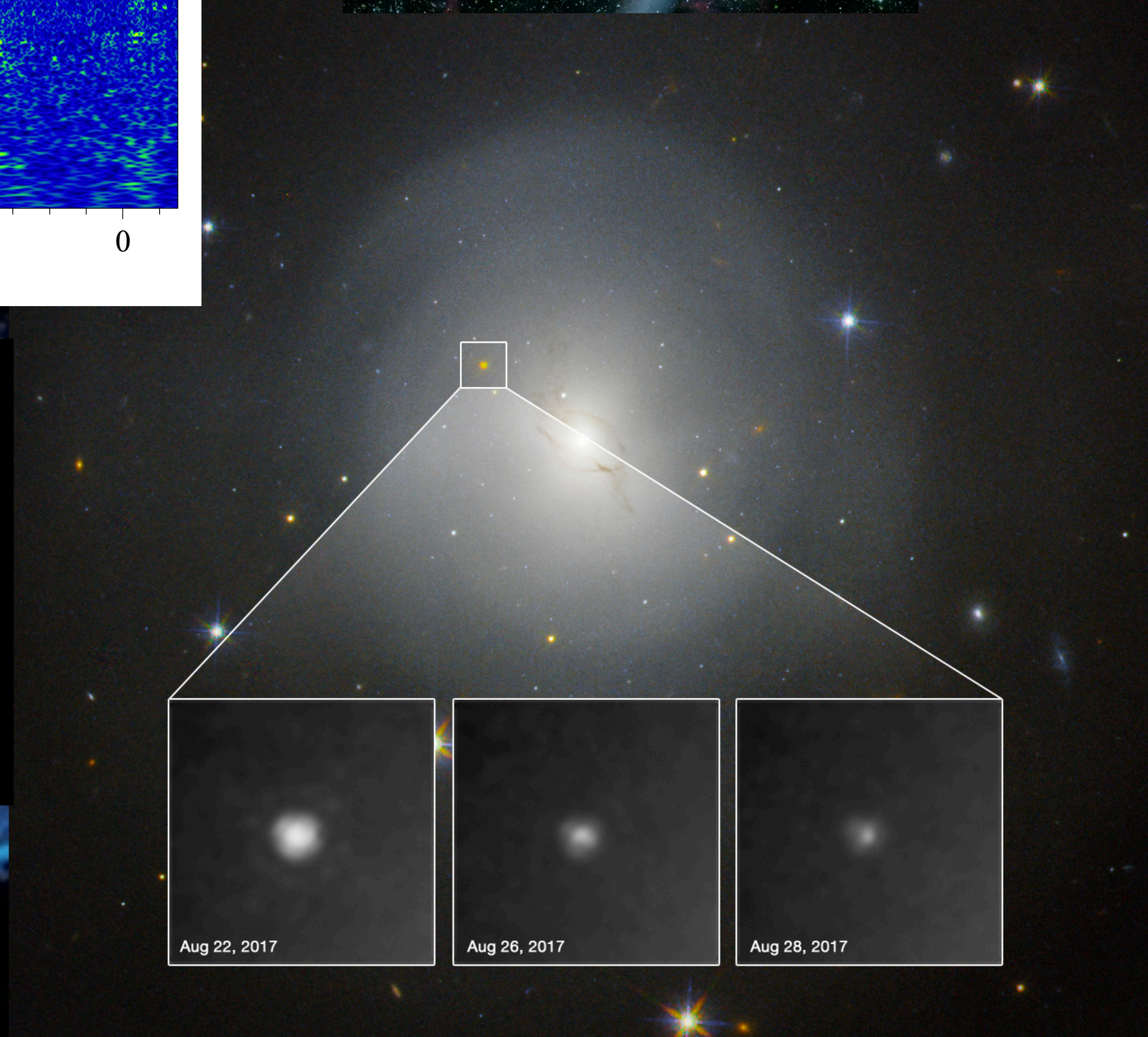
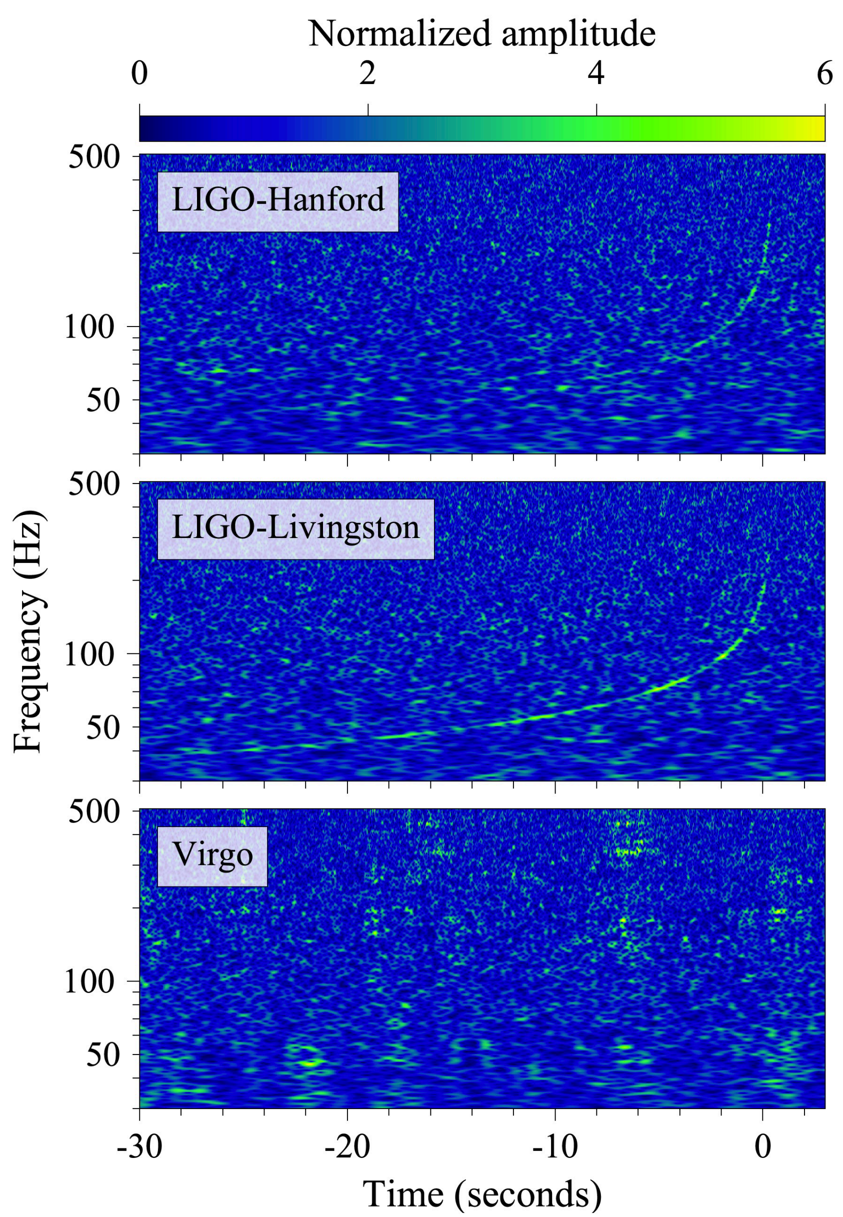
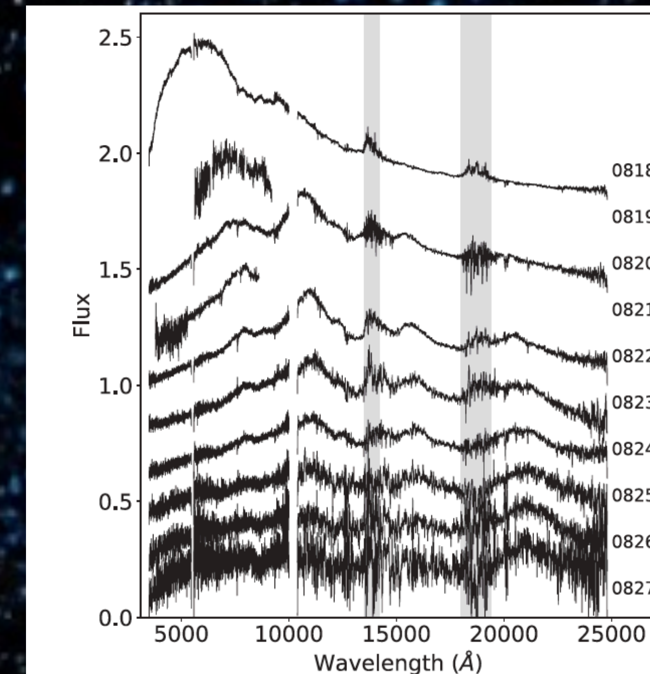
After GW170817...

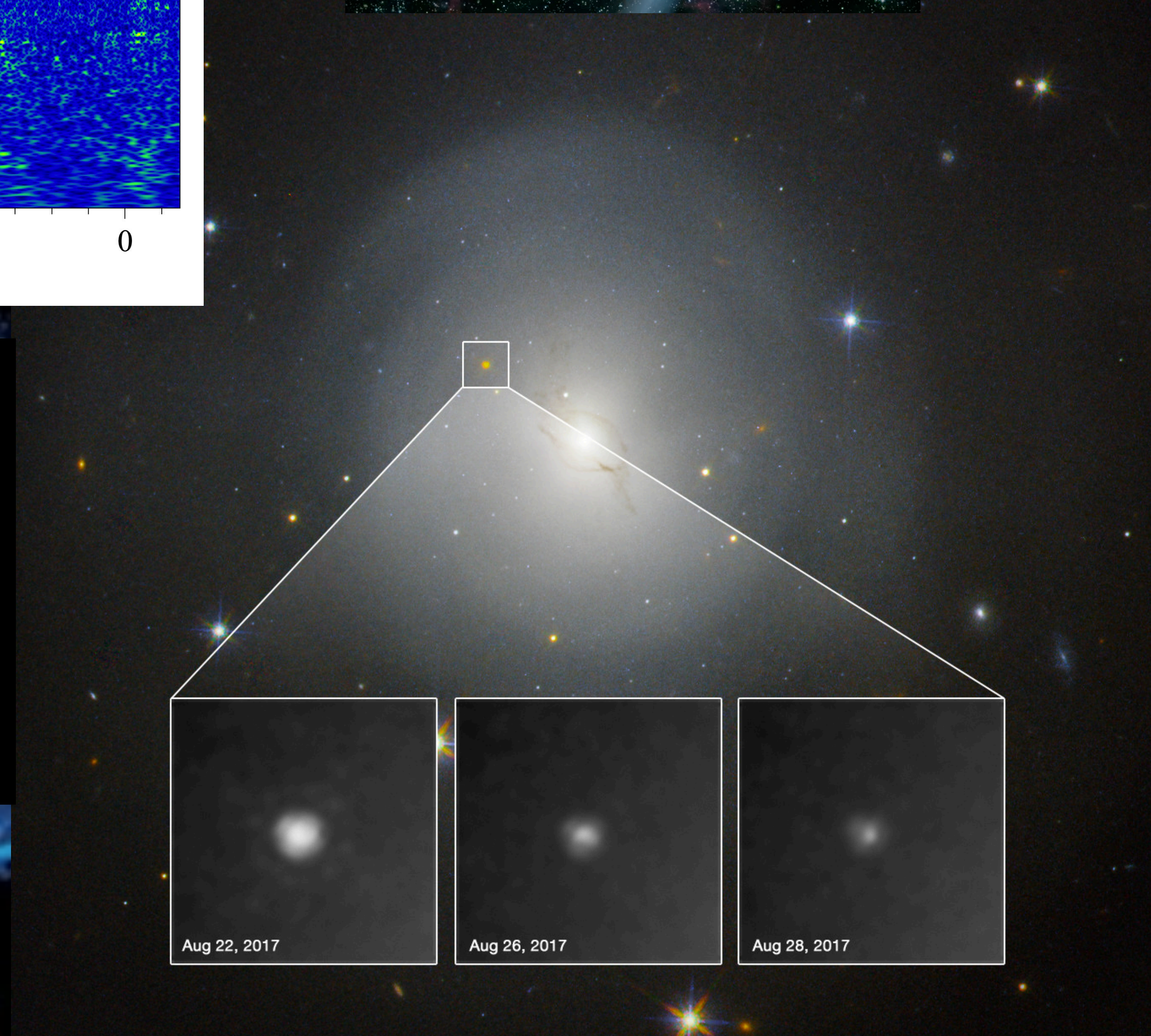




After GW170817…







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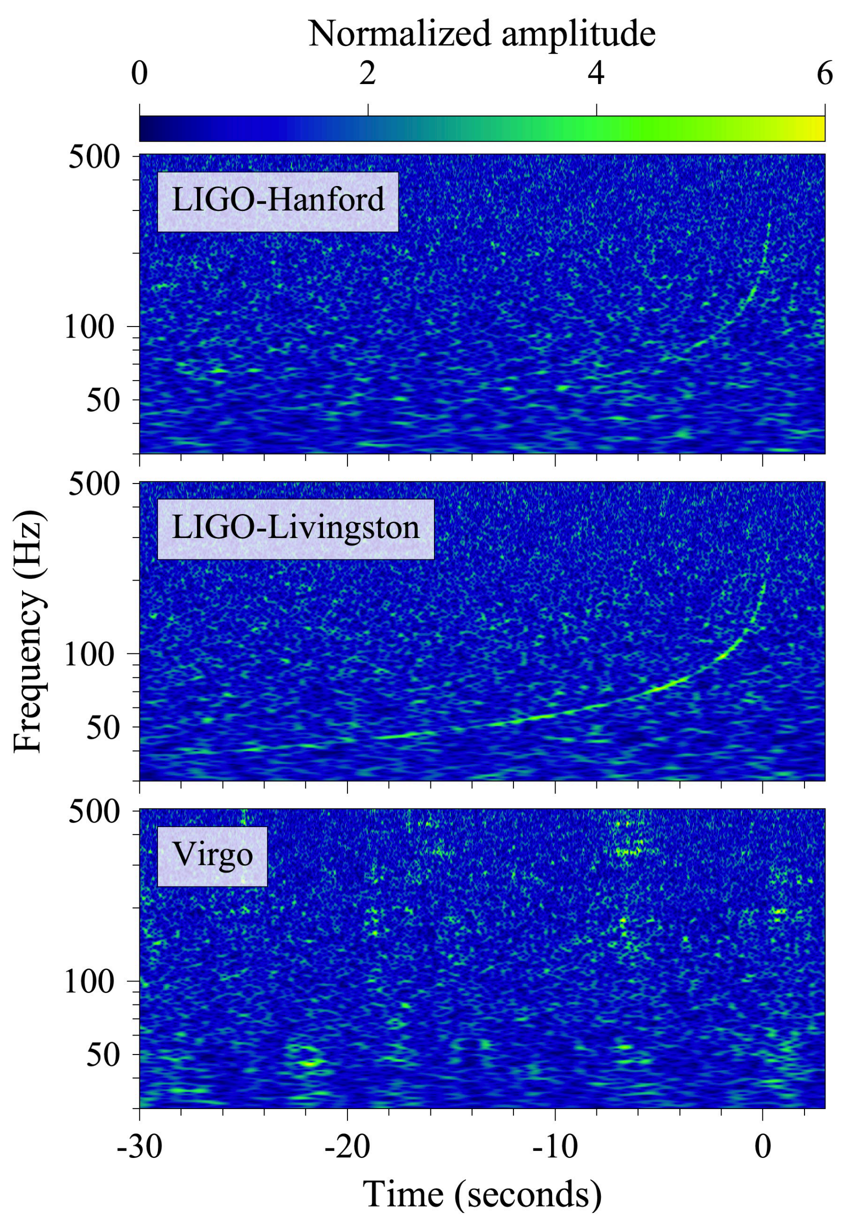
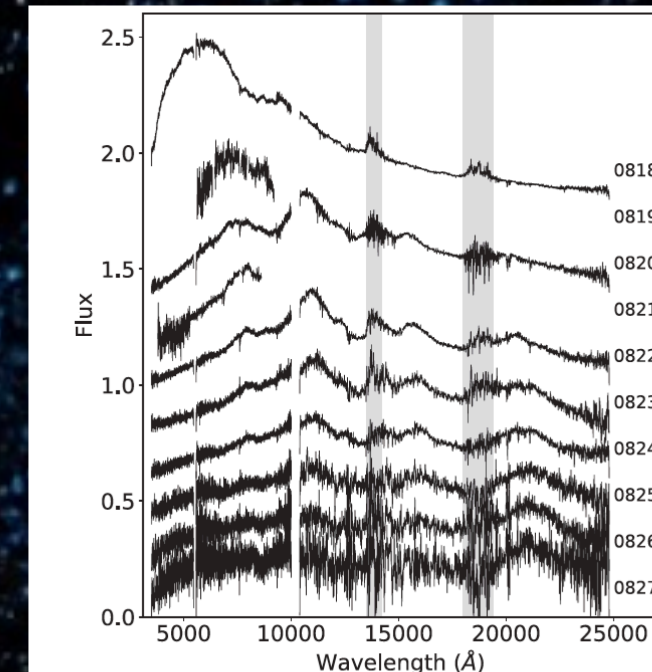
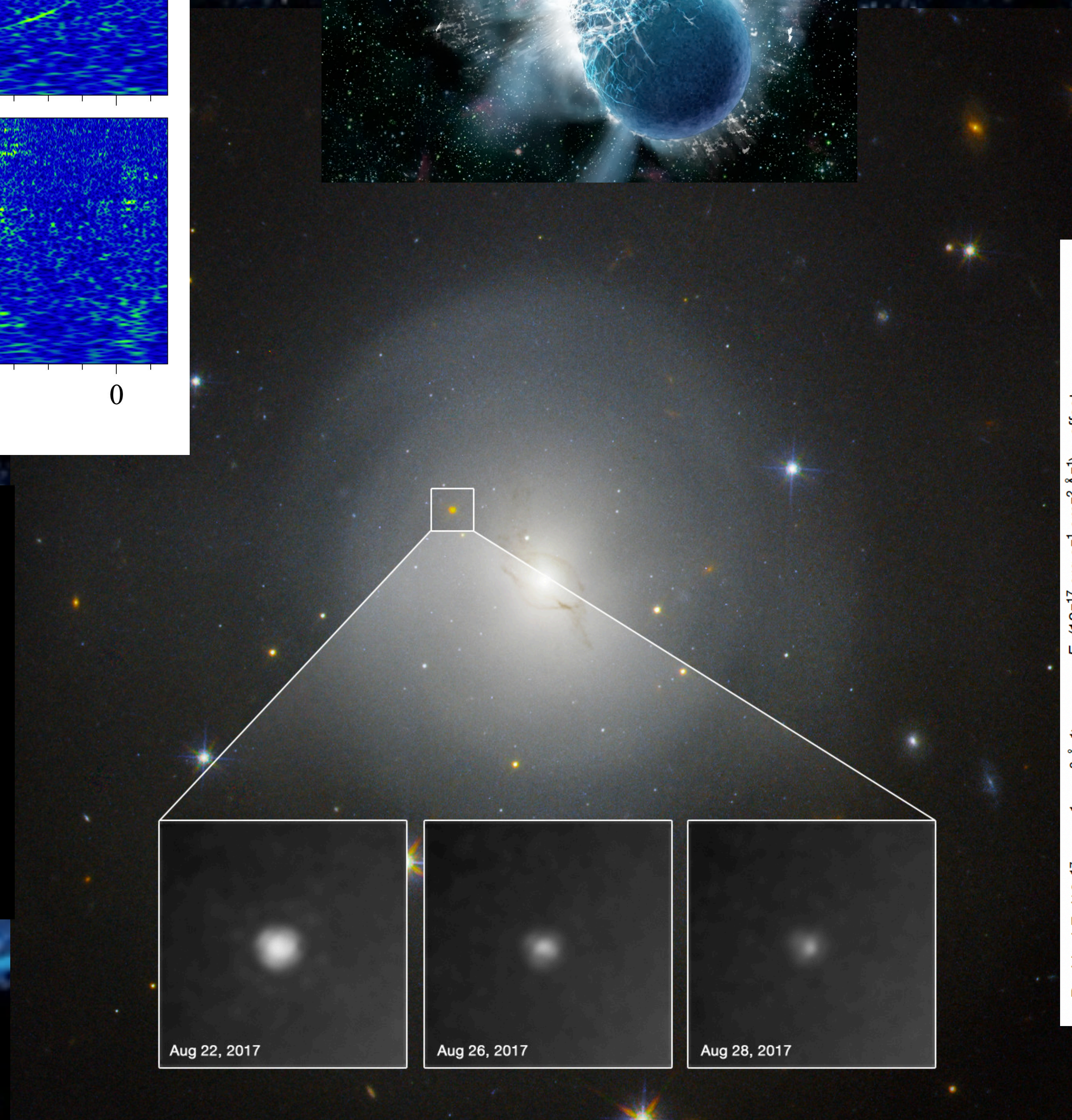
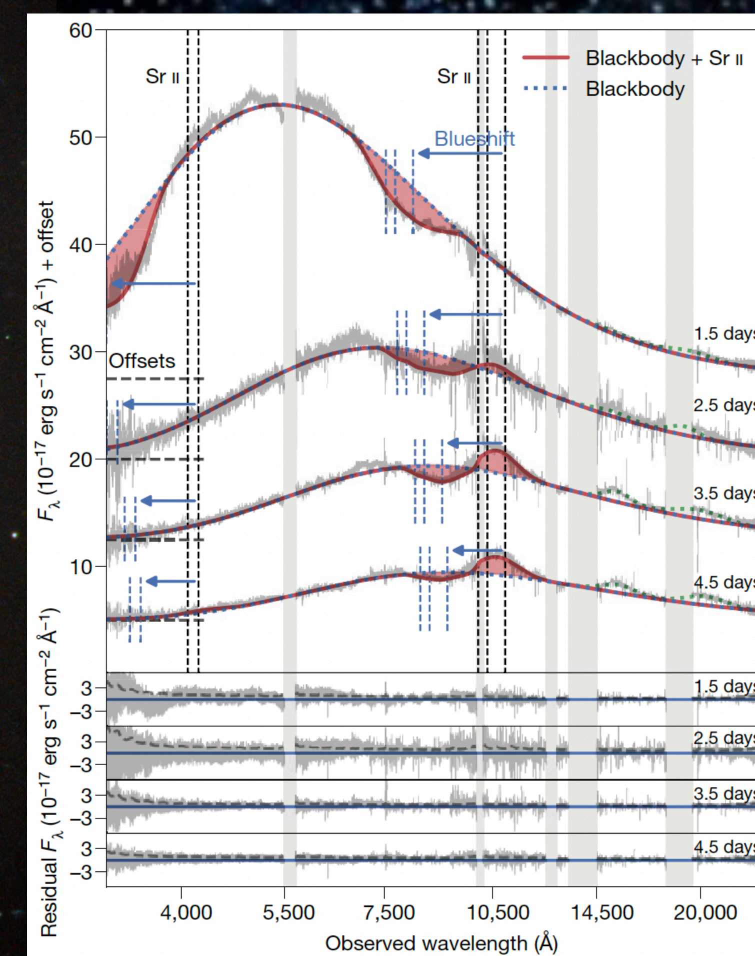
After GW170817…





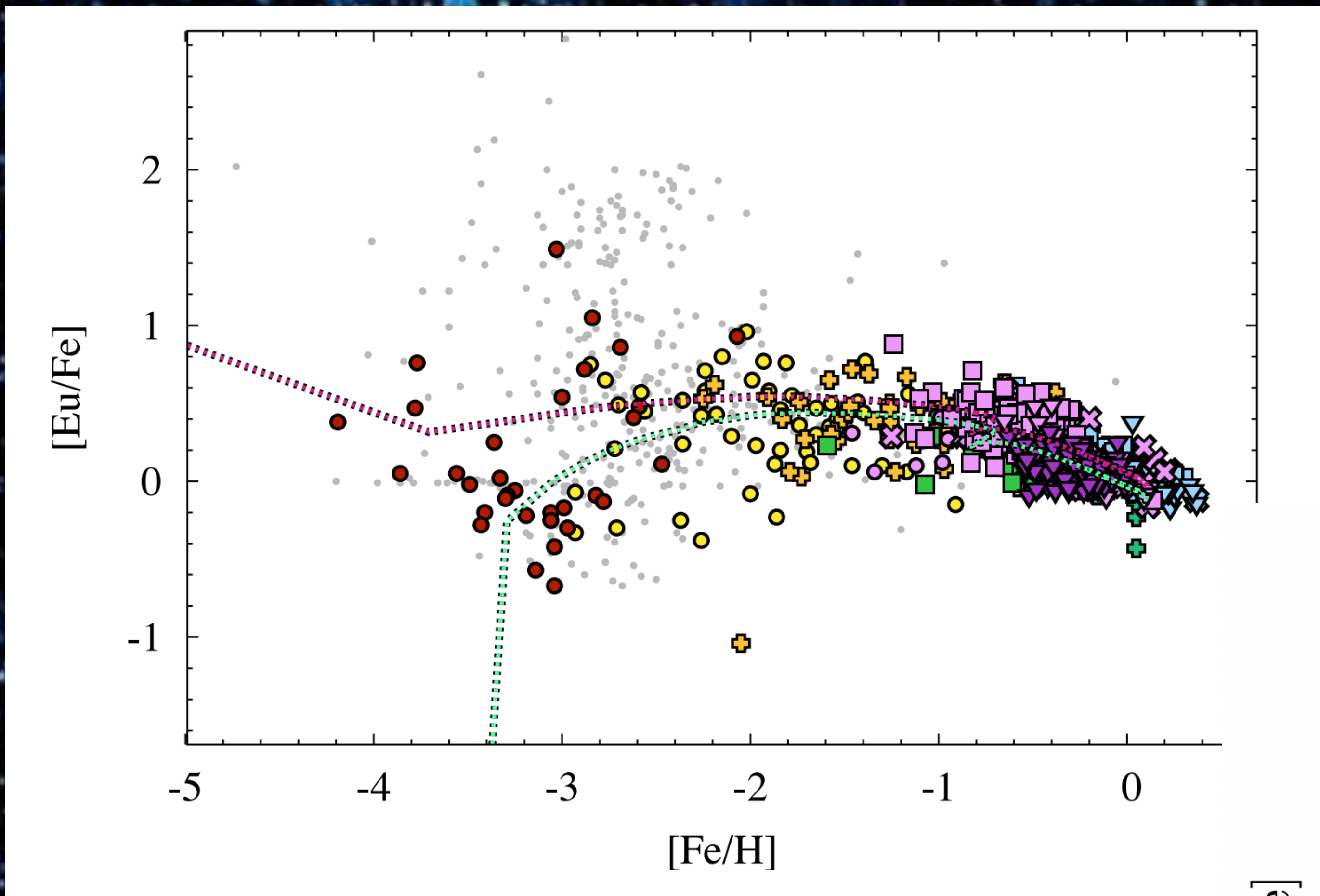




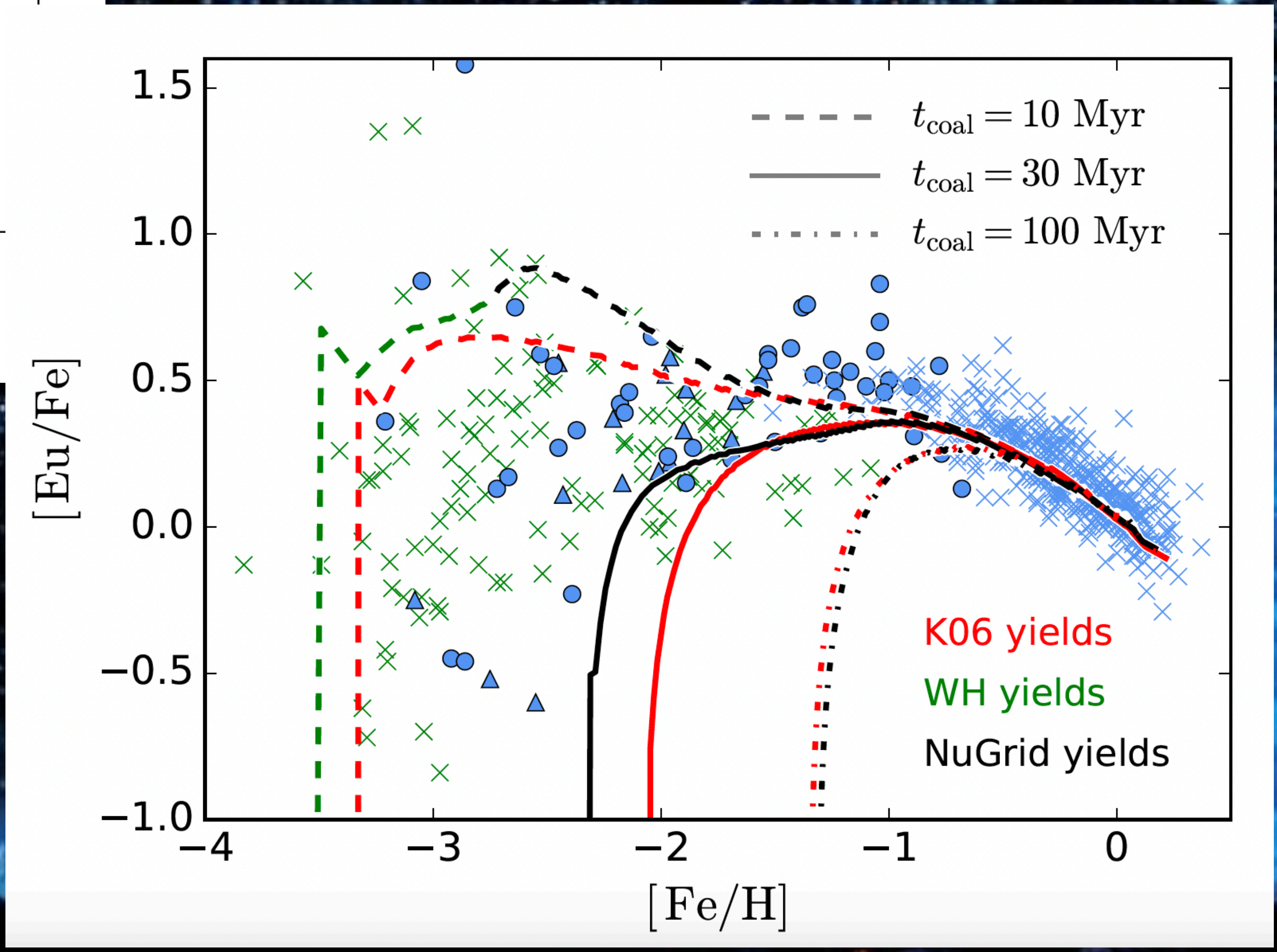
Watson+19

Homogeneous chemical evolution model

Matteucci+14



Cotè+17



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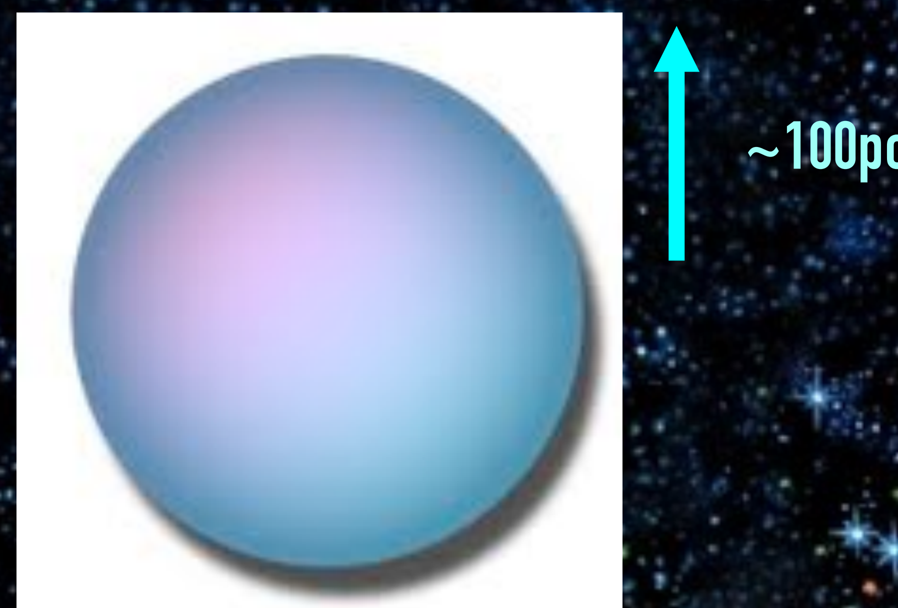
Stochastic chemical evolution model

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

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Stochastic chemical evolution models

minimum of 100 volumes up to 10’000

Stochastic chemical evolution models

minimum of 100 volumes up to 10’000

~100pc

~100pc

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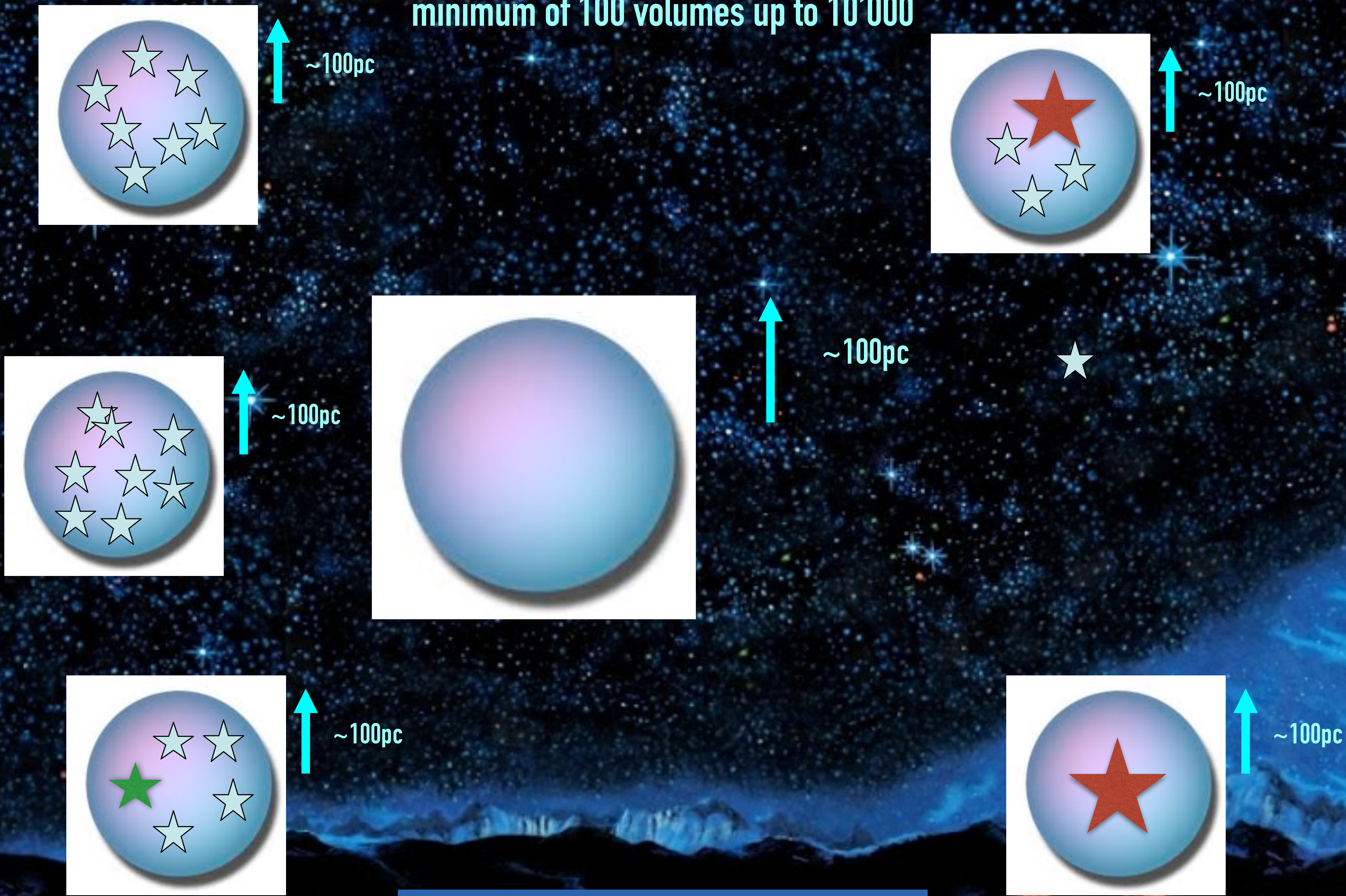

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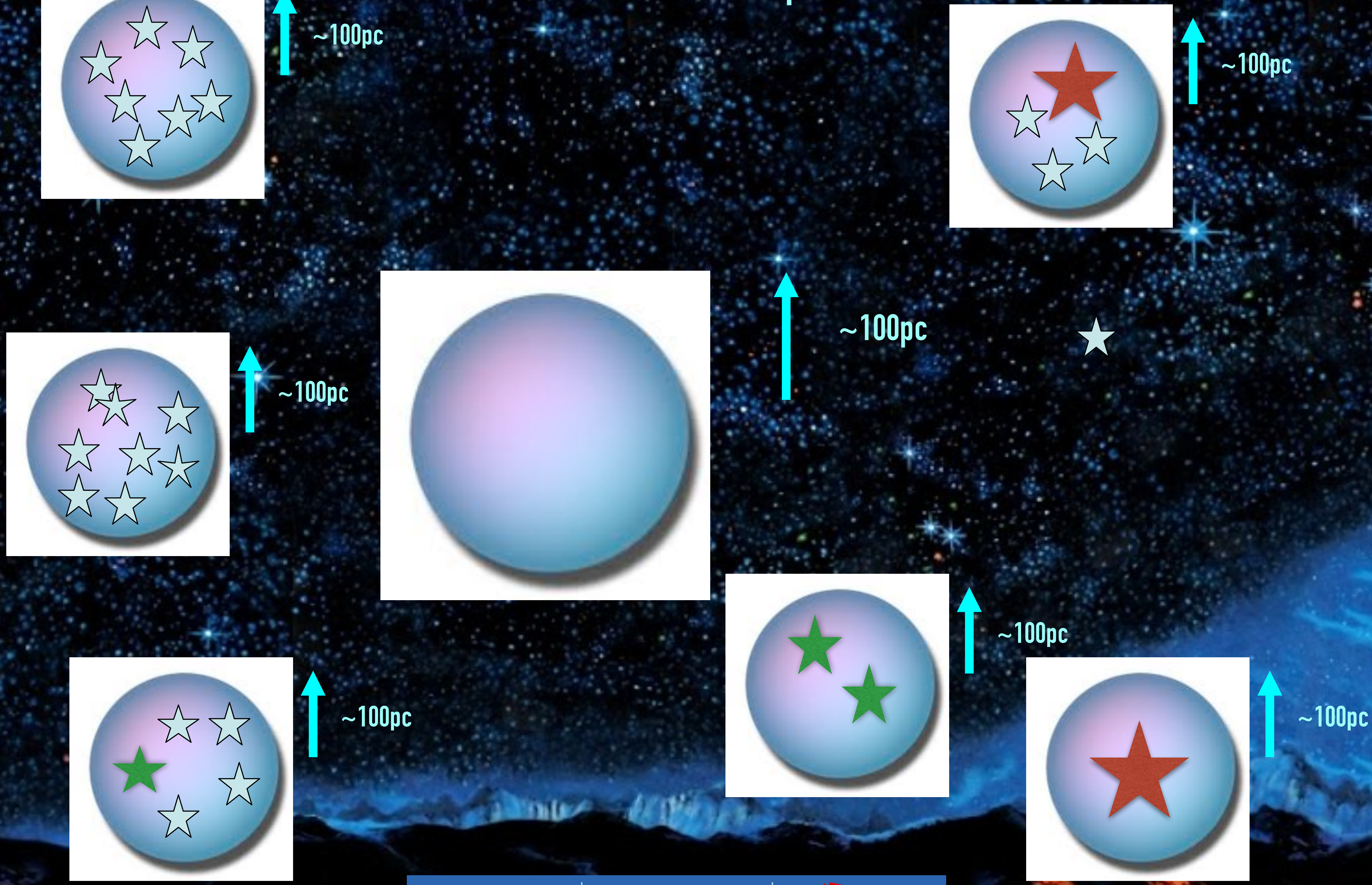

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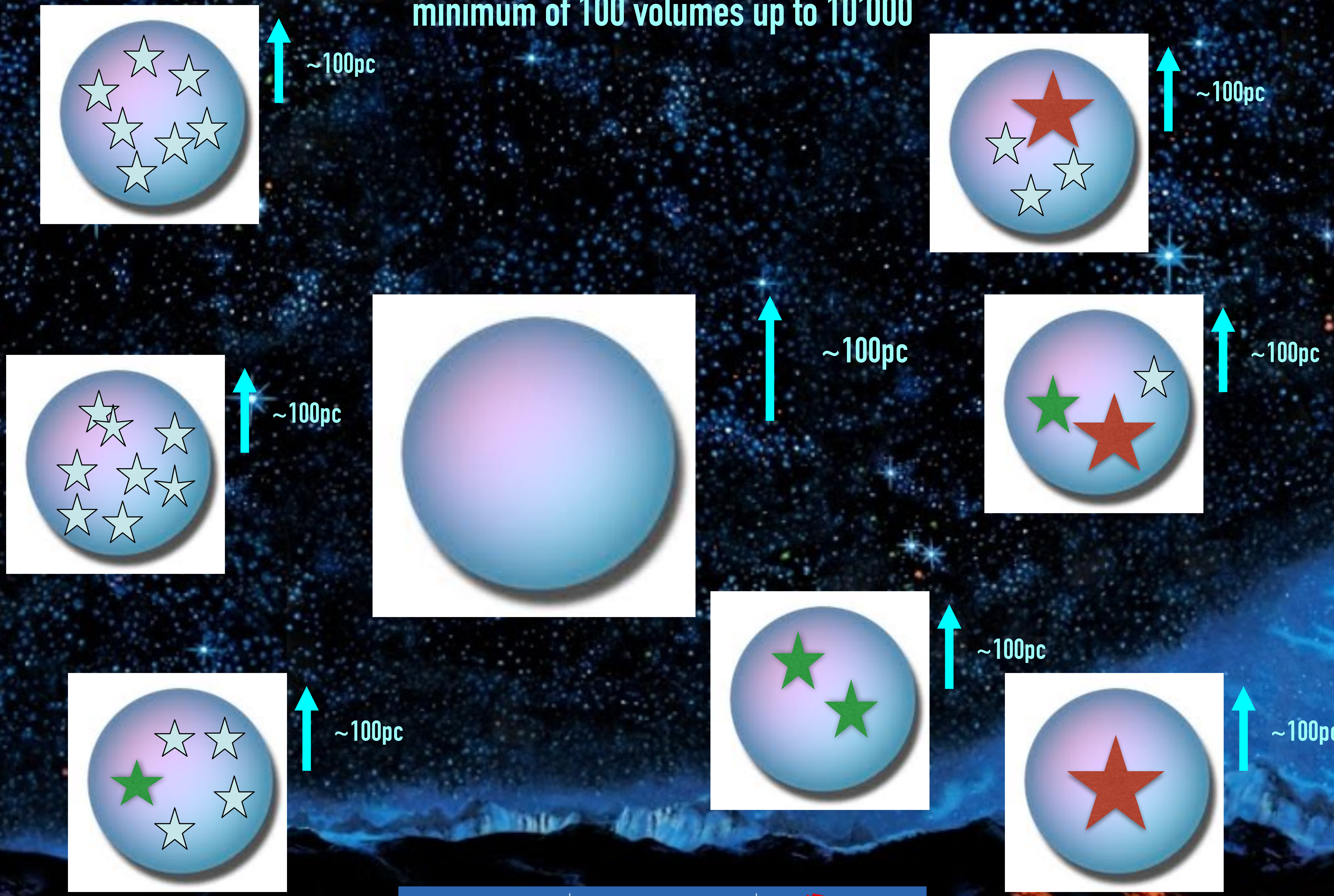

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Stochastic chemical evolution models

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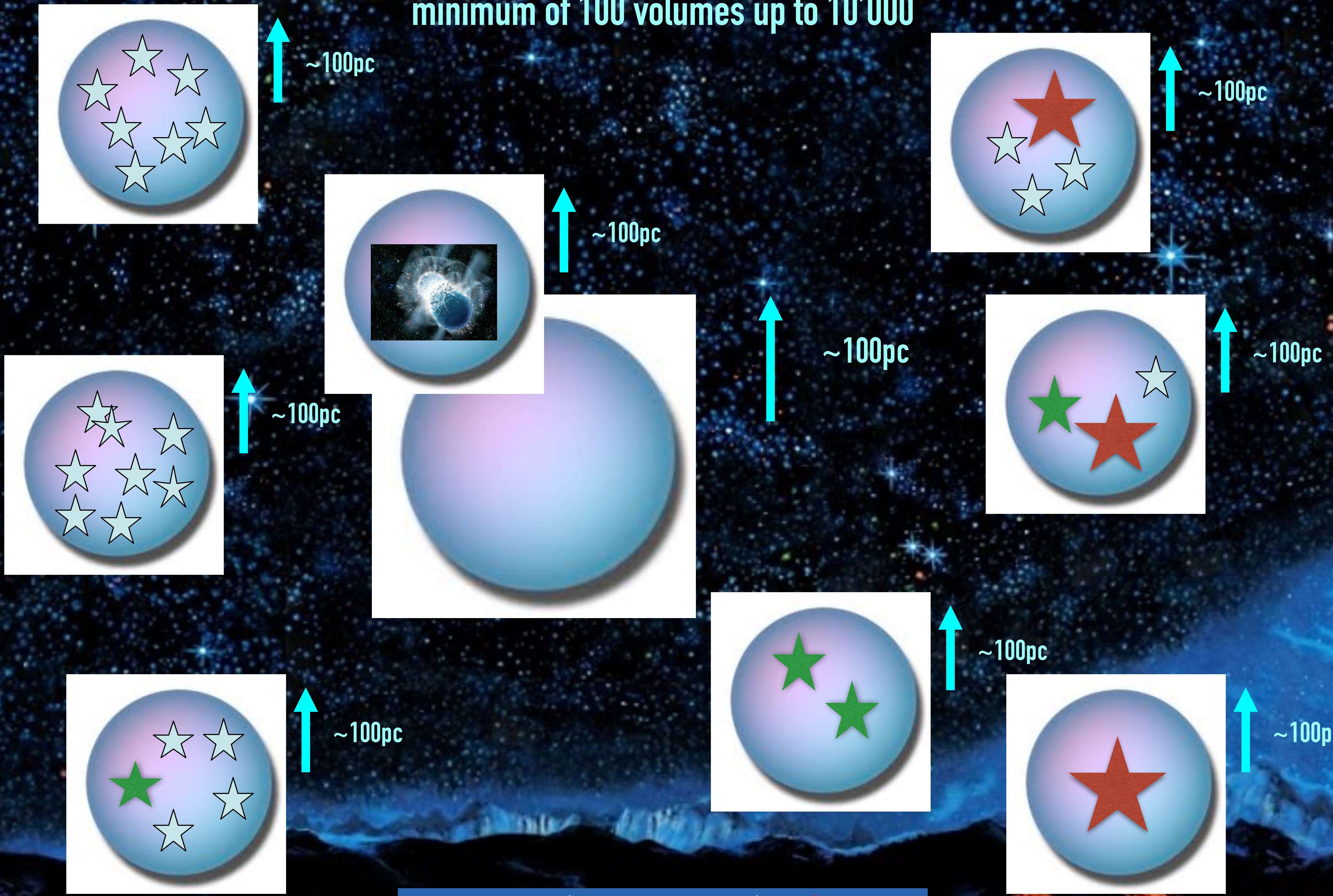

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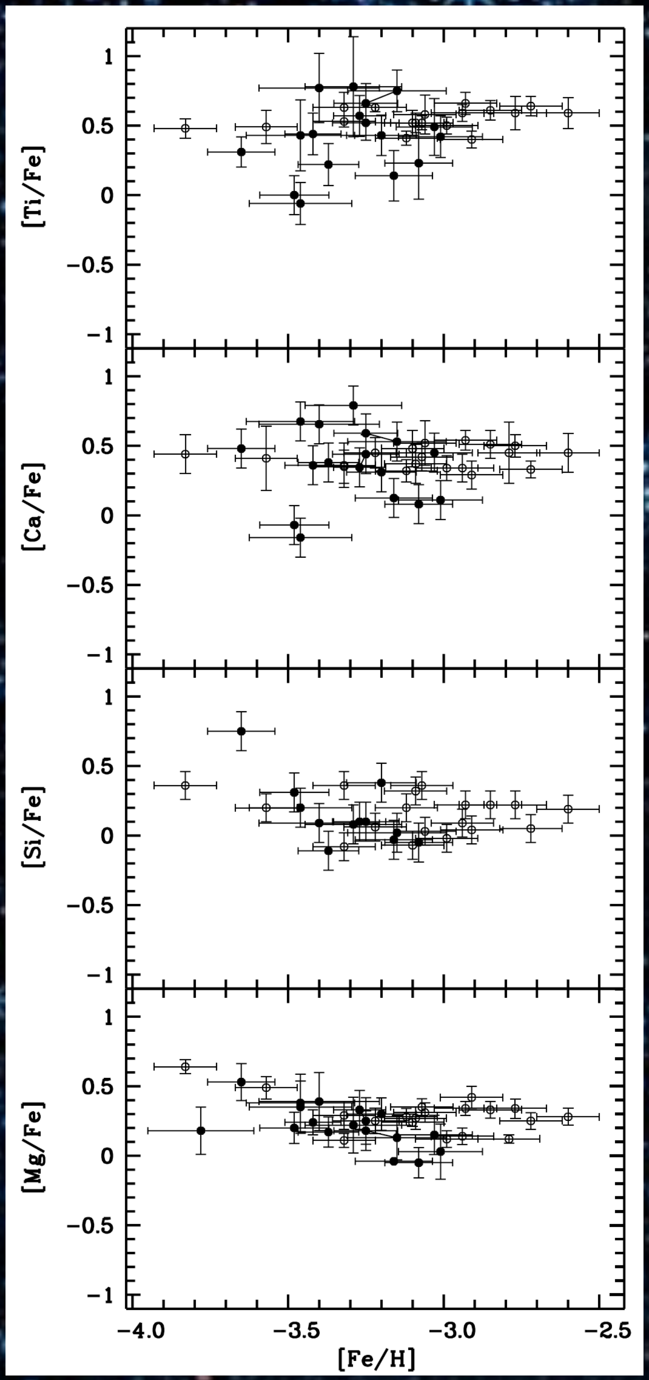
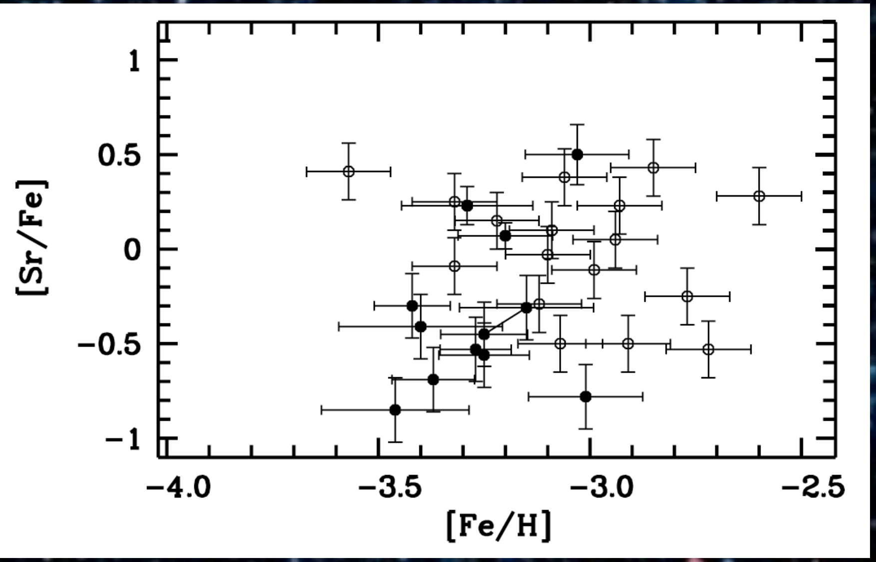
Galaxy Evolution via Montecarlo Sampling

GEMS

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





Bonifacio+12

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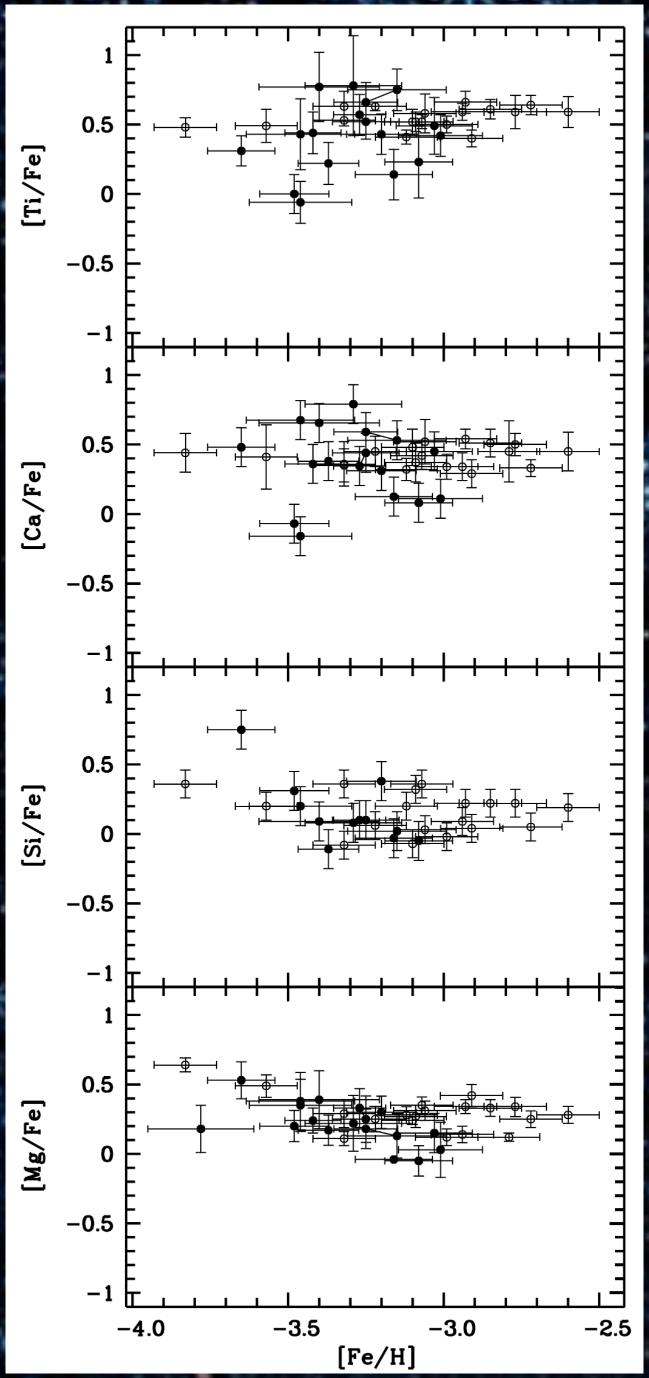

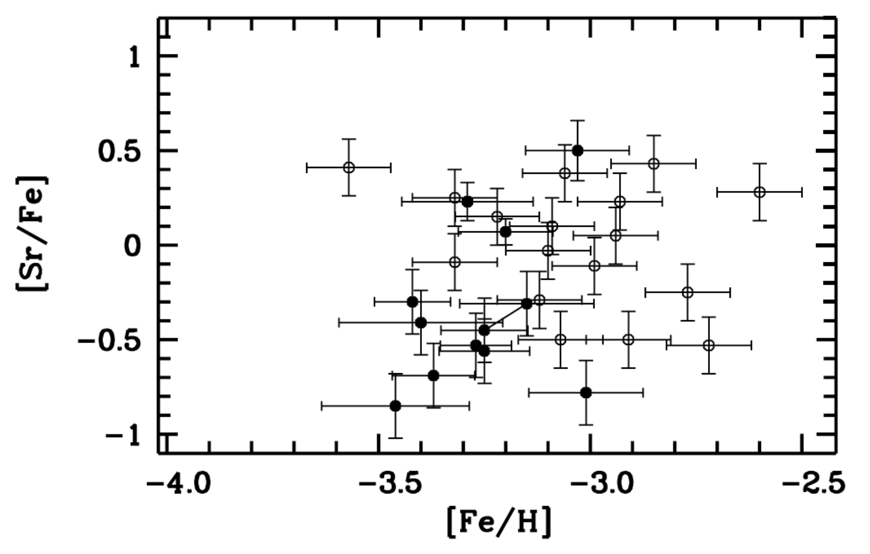

Solution:
The volumes in which the ISM is well mixed are discrete. Assuming a SNe bubble as typical volume with a low regime of star formation the IMF is not fully sampled.
This promotes spread among different volumes if nucleosynthesis of the element is is different among different SNe.

Bonifacio+12

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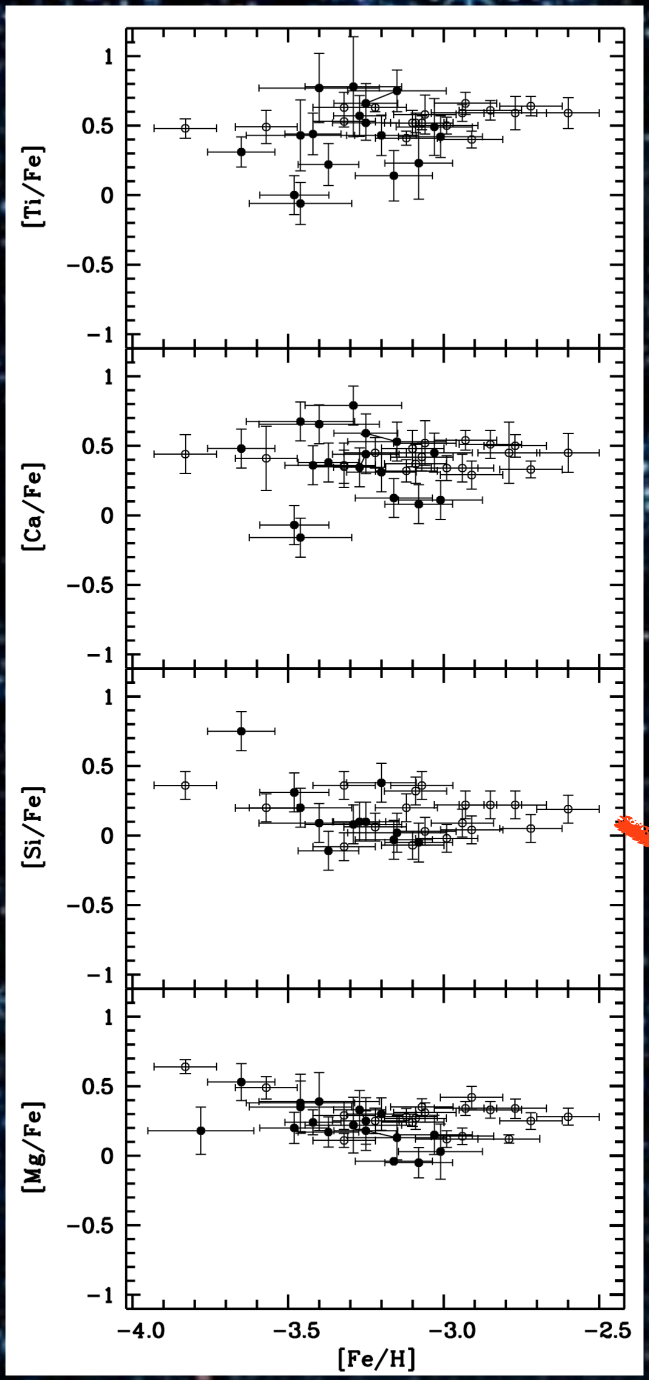
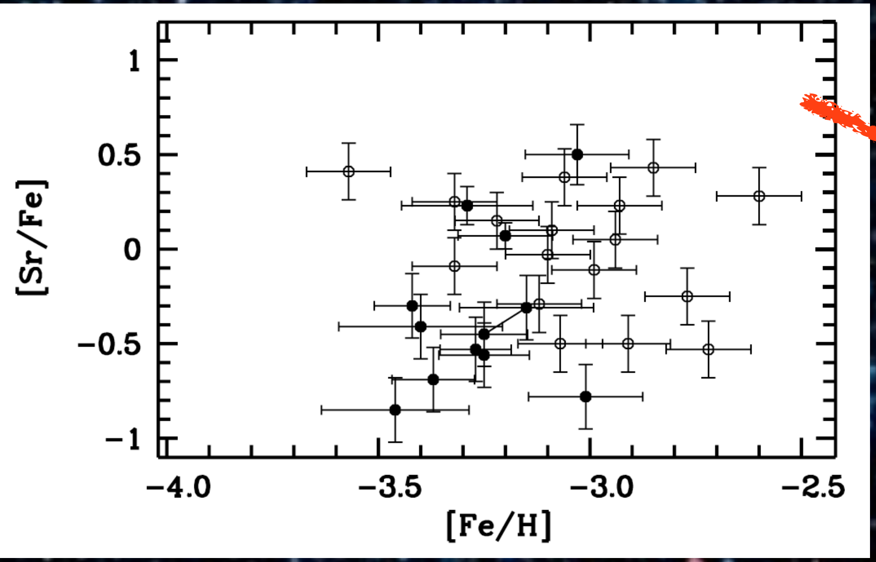


Bonifacio+12



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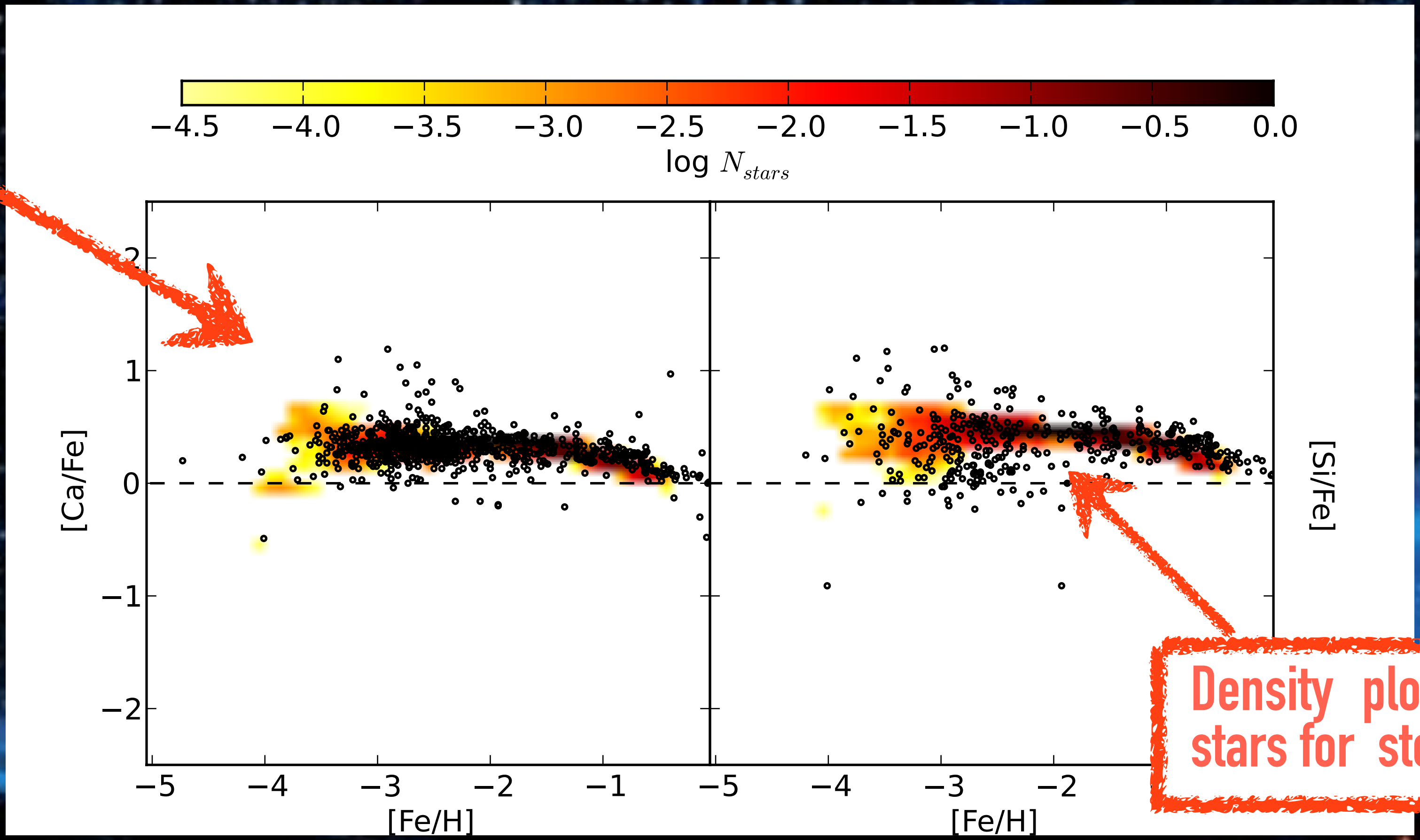

Density plot of long living stars for stochastic model

Cescutti 2008
Cescutti et al. 2013

data collected in Frebel 2010

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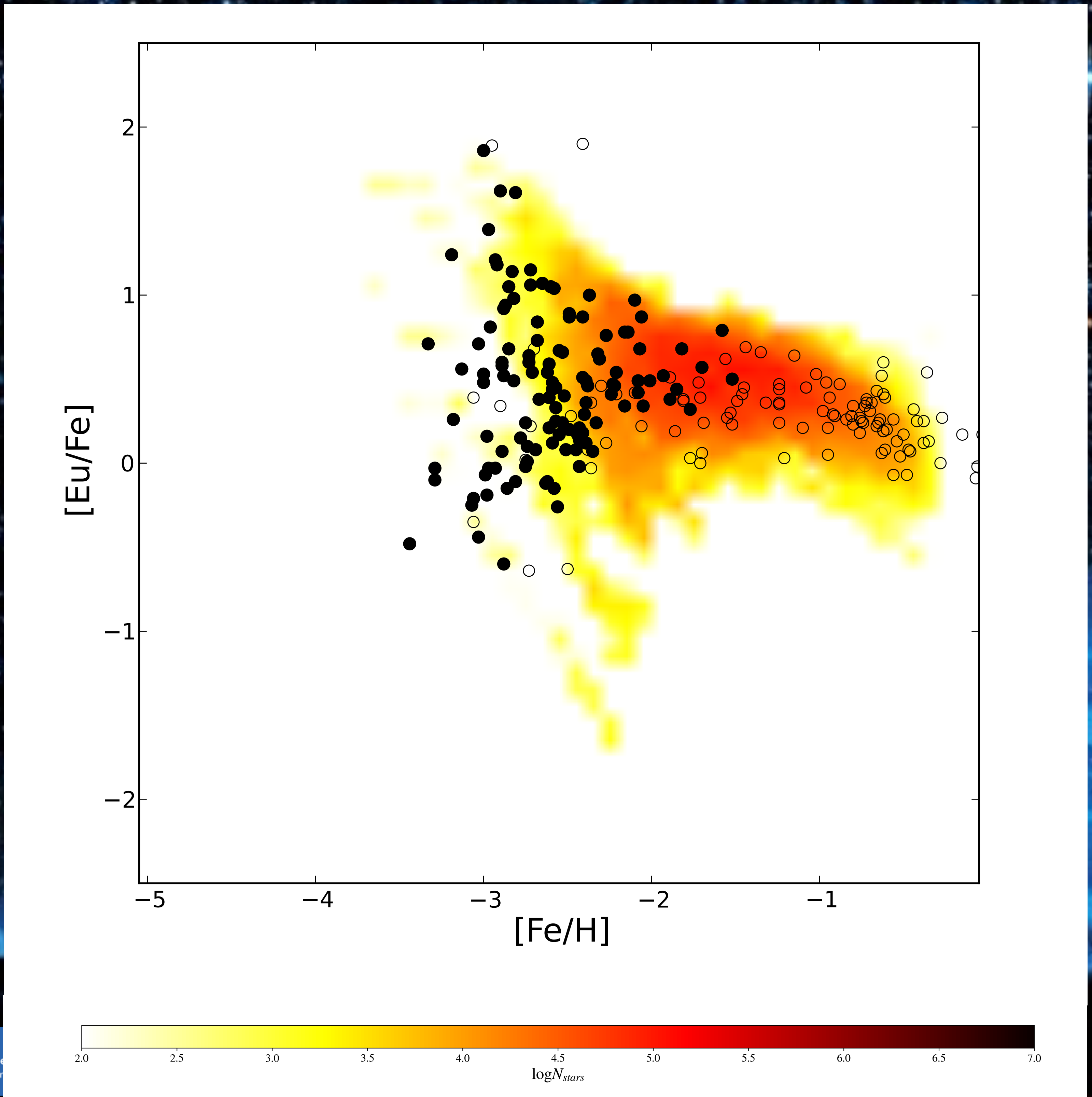
Neutron stars mergers

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?



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Neutron star mergers

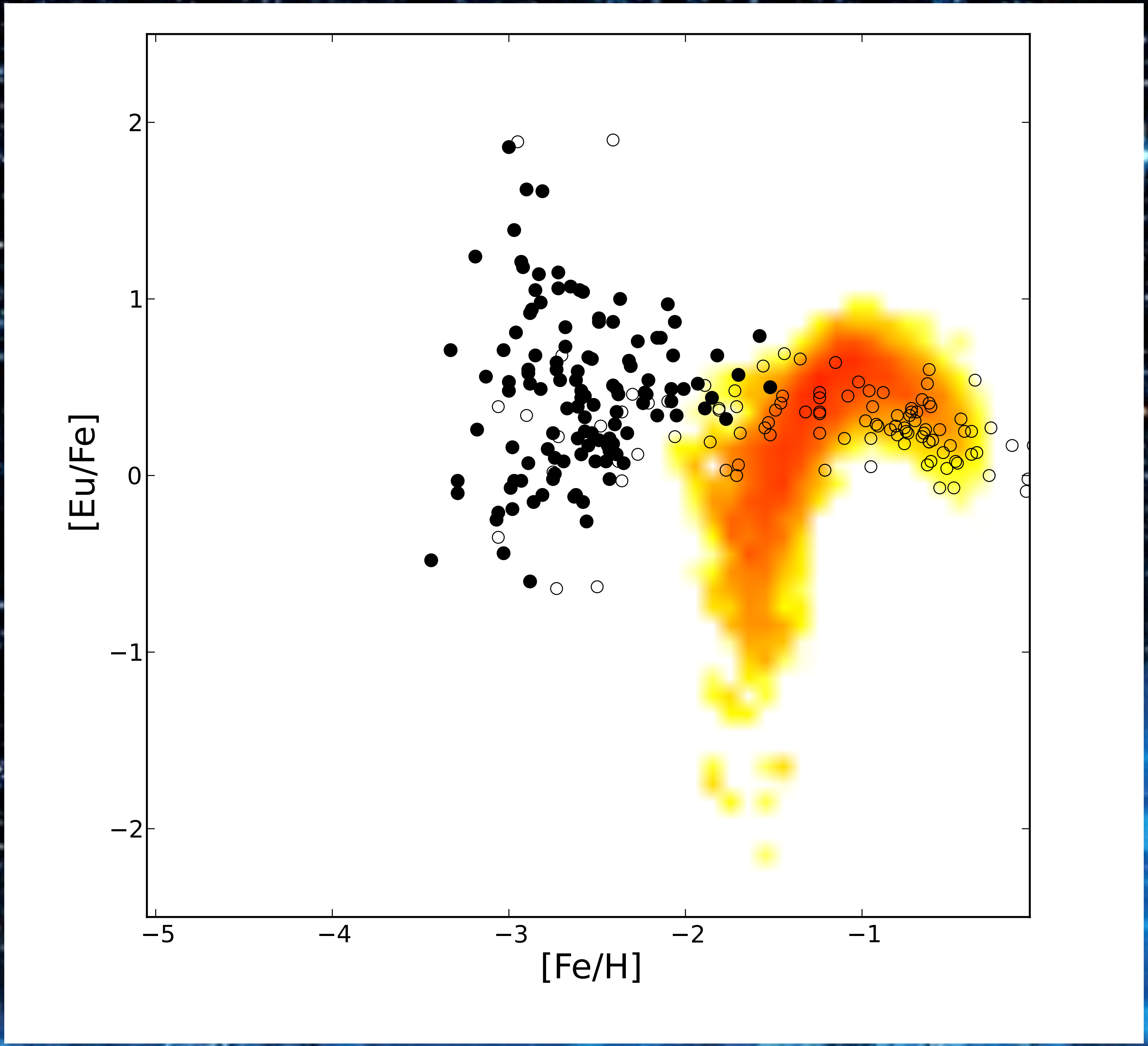
delay for the merging 100 Myr

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?

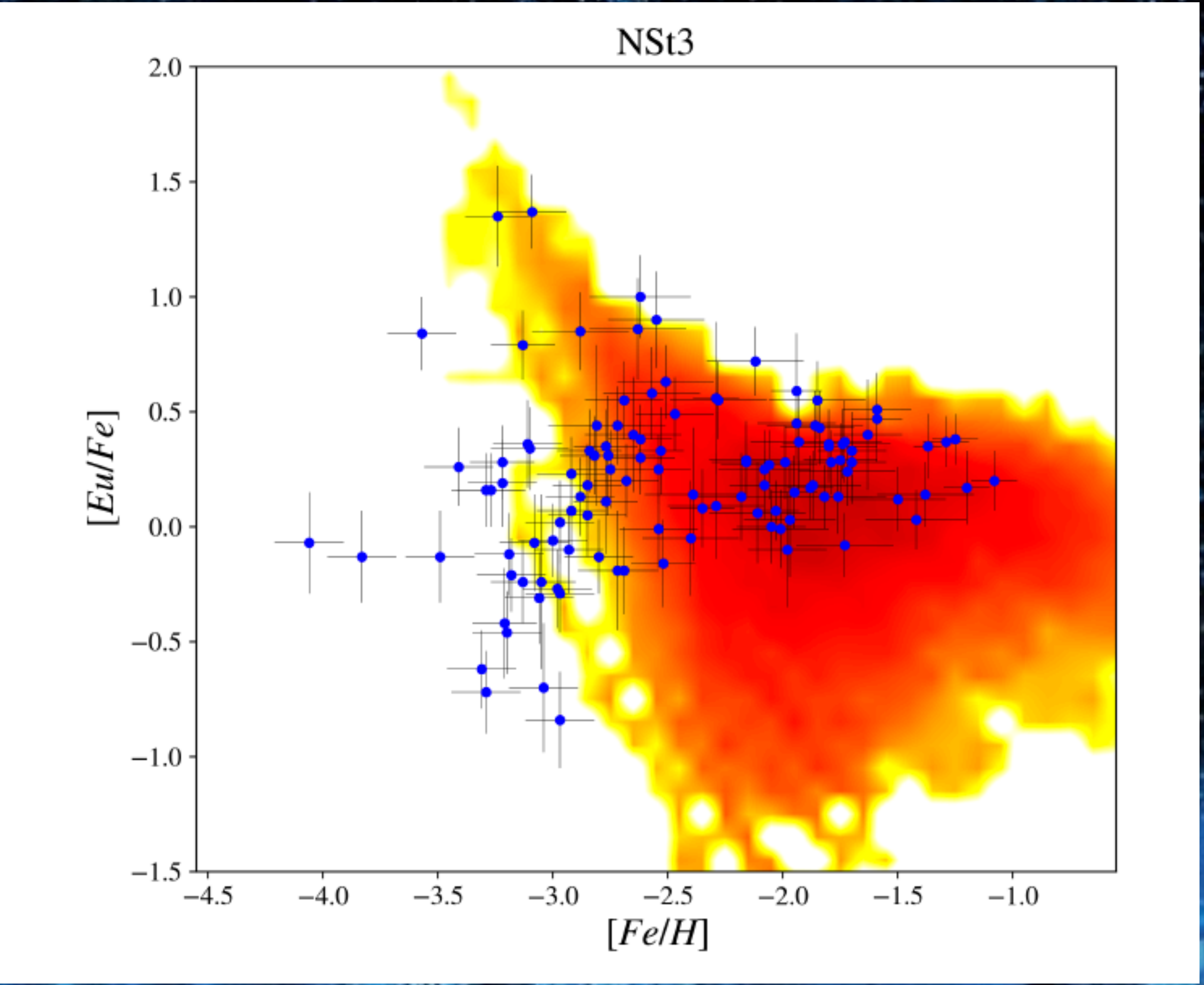


This is not a new result, it has been shown by Argast+ 2004, Matteucci+2014, Komiya+2014... just an exception the astro-ph Shen+2014

Neutron star mergers

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

Cavallo+22



see also Simonetti+19 and Cotè+19

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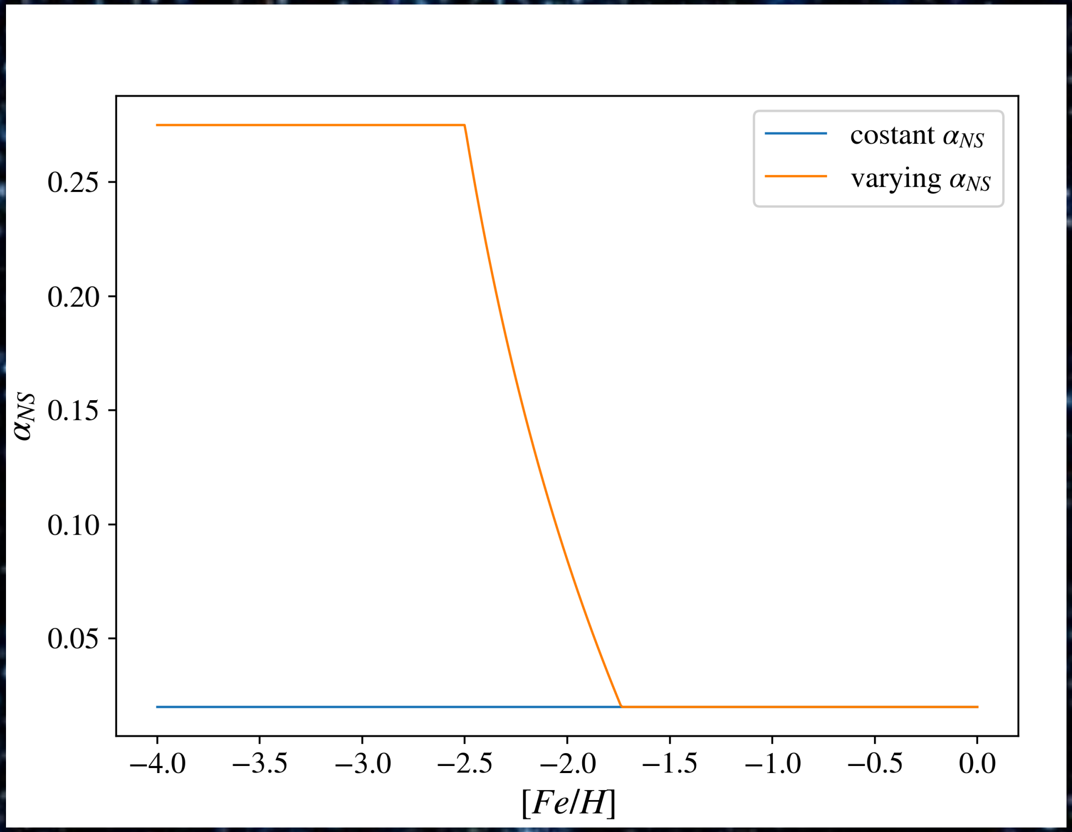
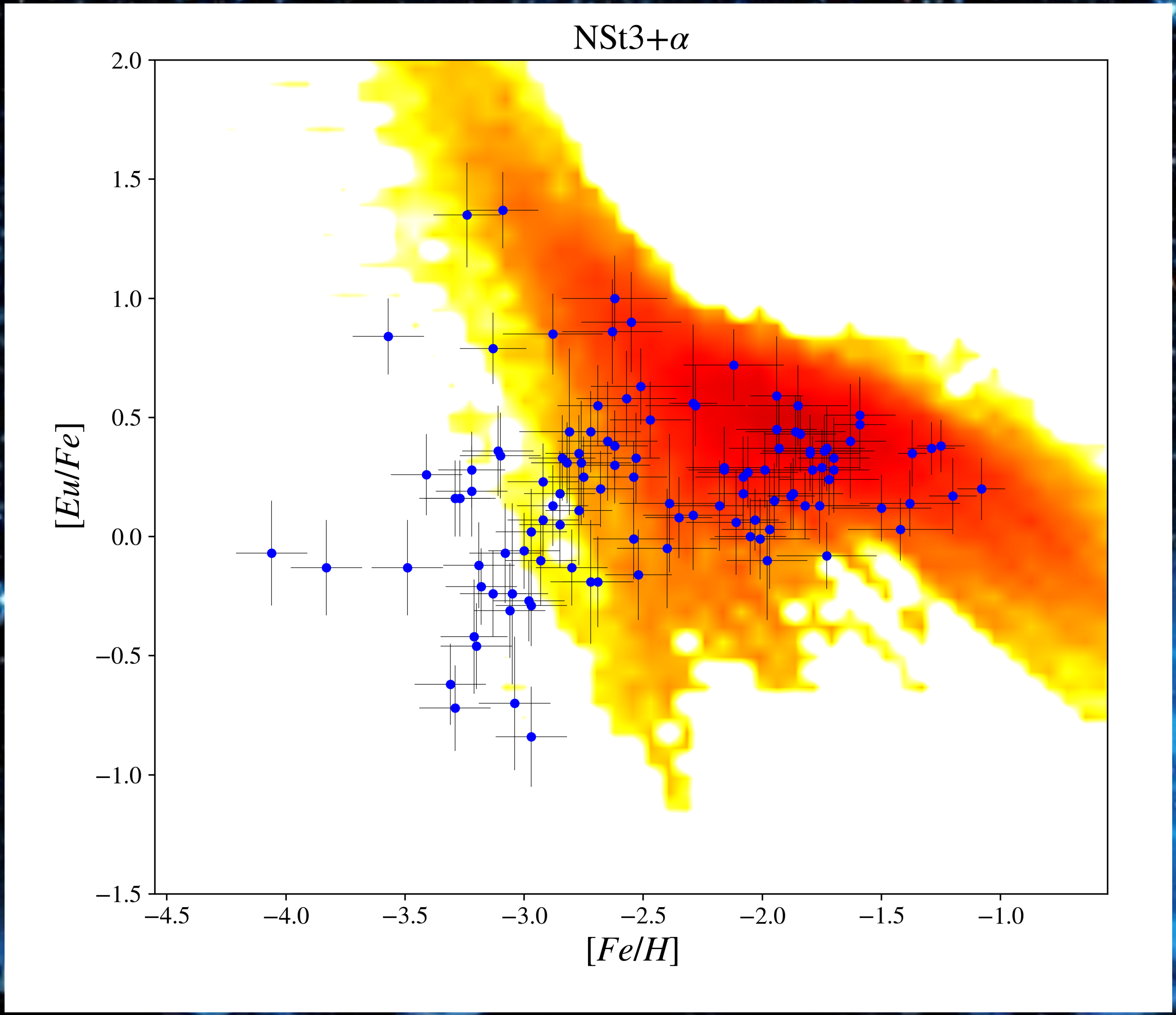
NSM with alpha variations

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

Cavallo+22



similar to Simonetti+19



Cavallo+22

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Other solutions?

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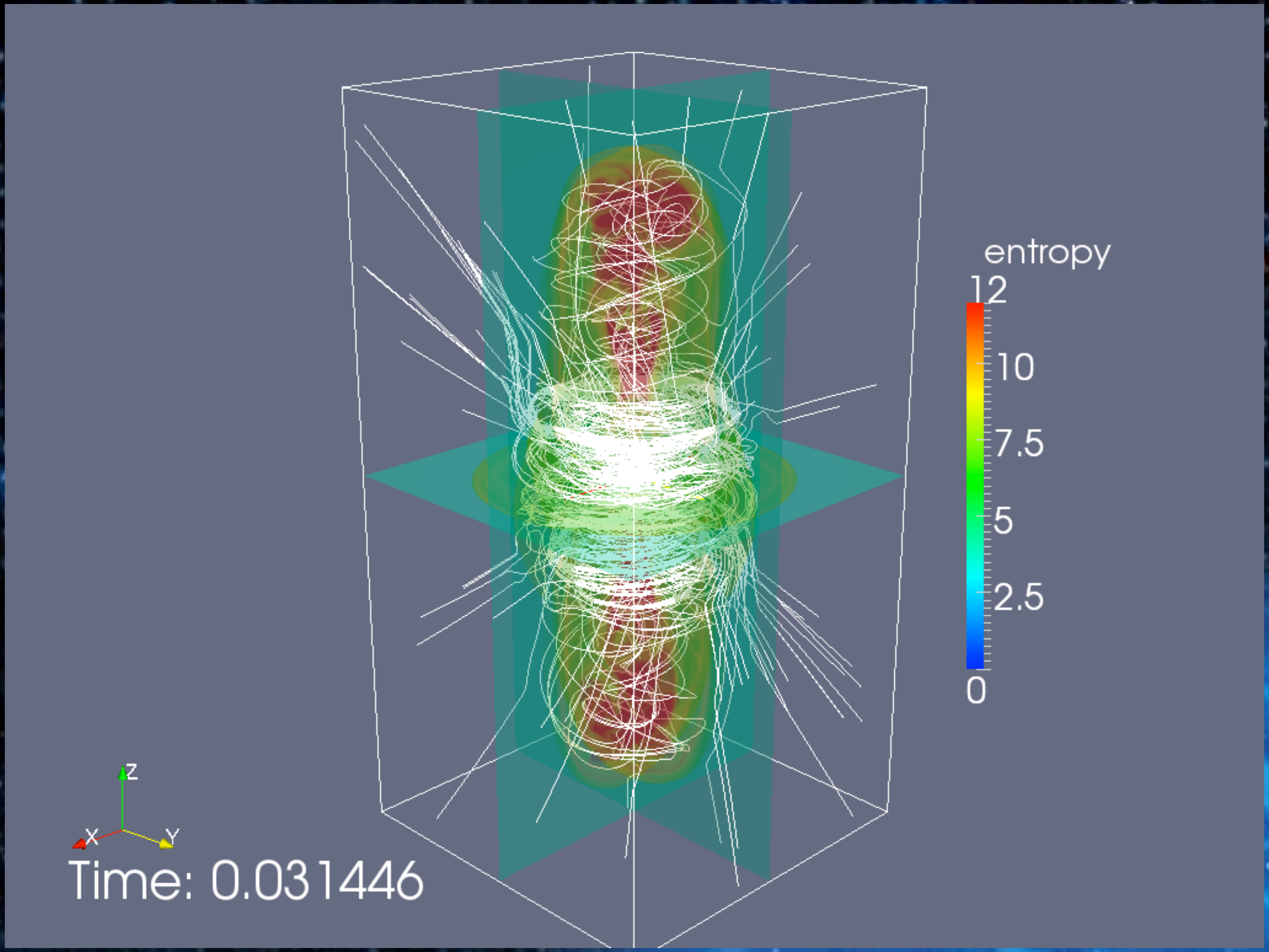
Magneto Rotationally Driven SN scenario (MRD)

(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.



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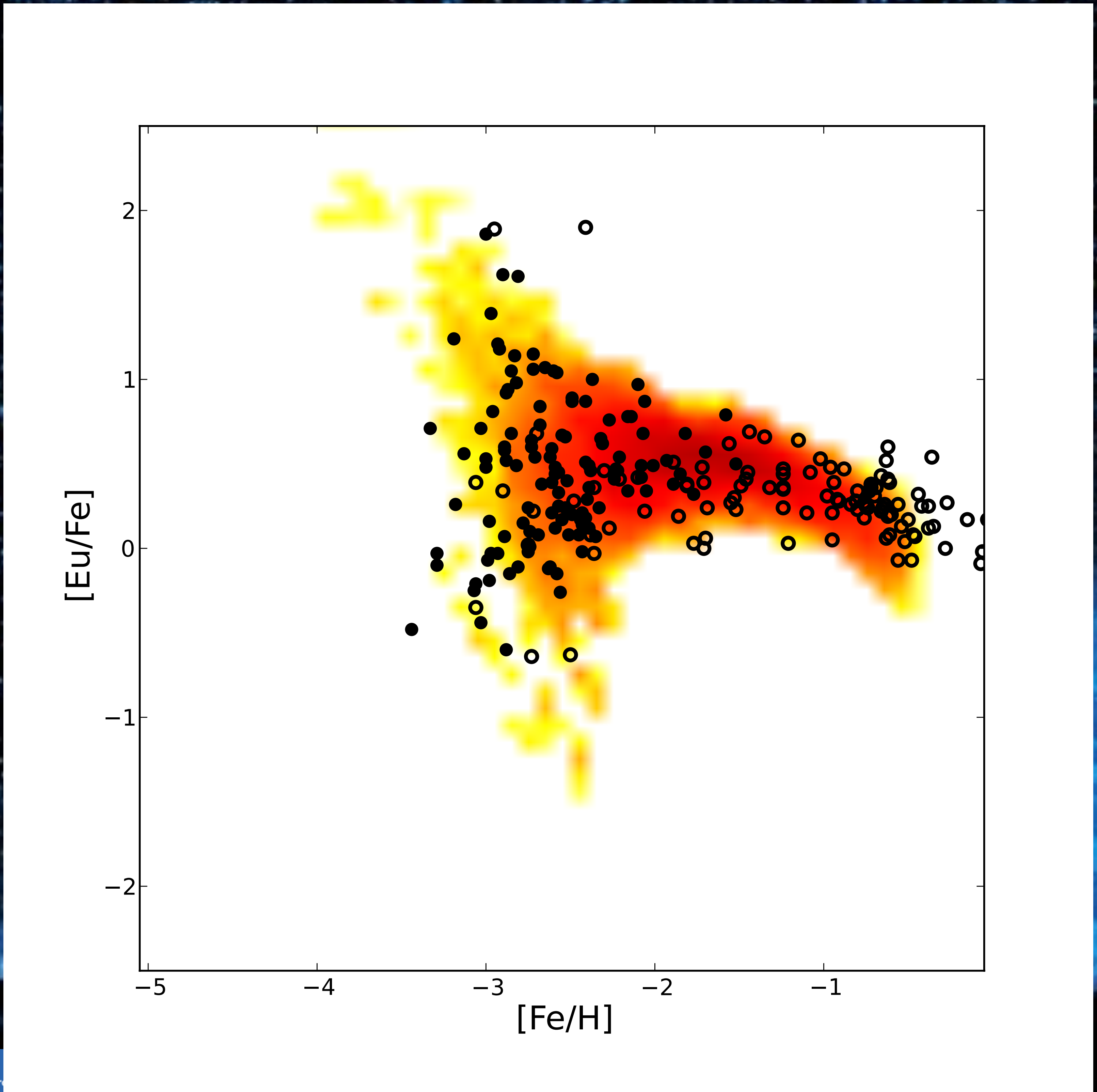
Magneto Rotationally Driven SN scenario (MRD) 10%

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?

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Neutron capture elements

	s-process	r-process
		Early Galaxy
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 . . .)

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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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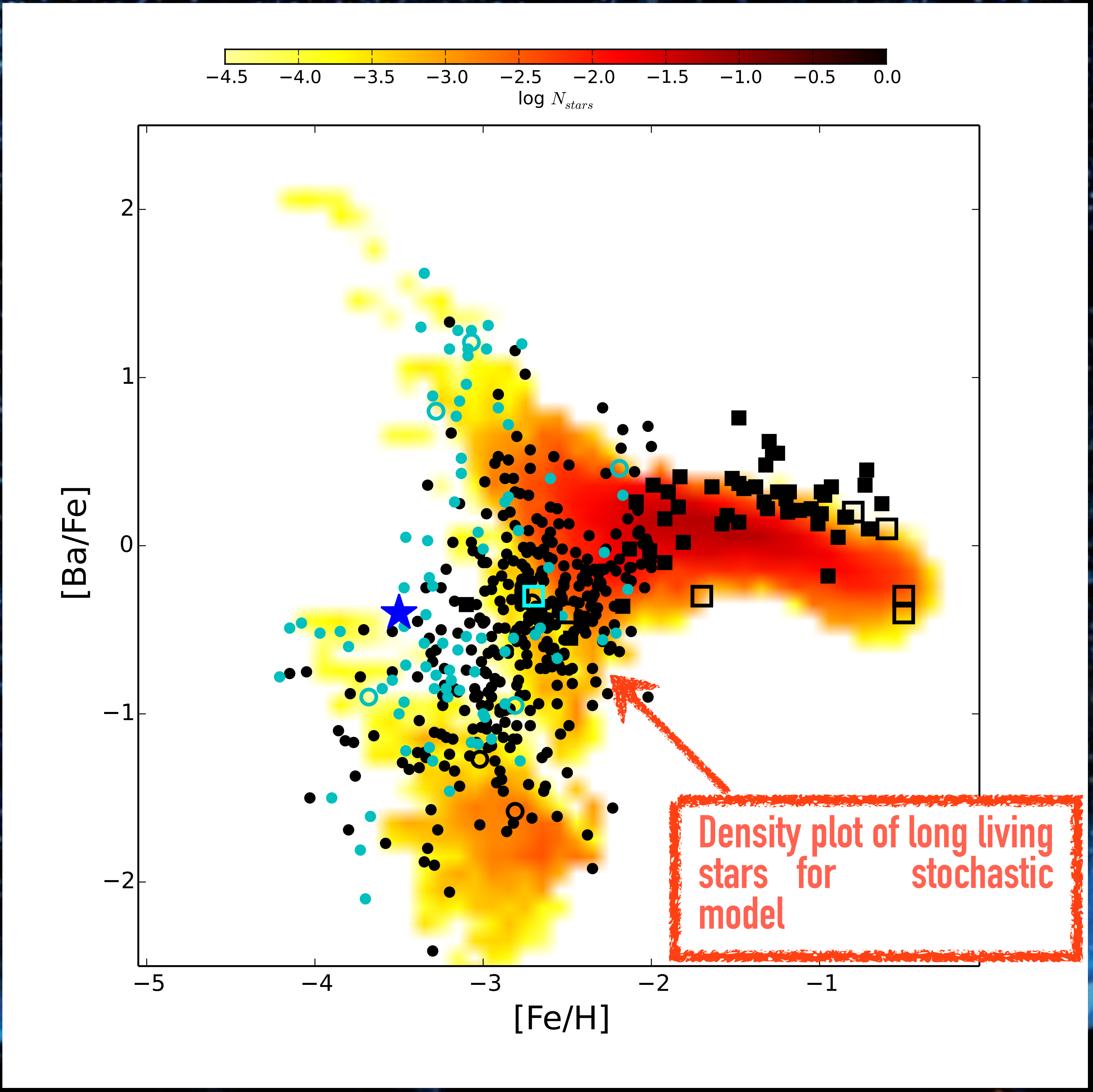

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Hansen+12 ■
Hansen+16 □ □
Cescutti+16 ★

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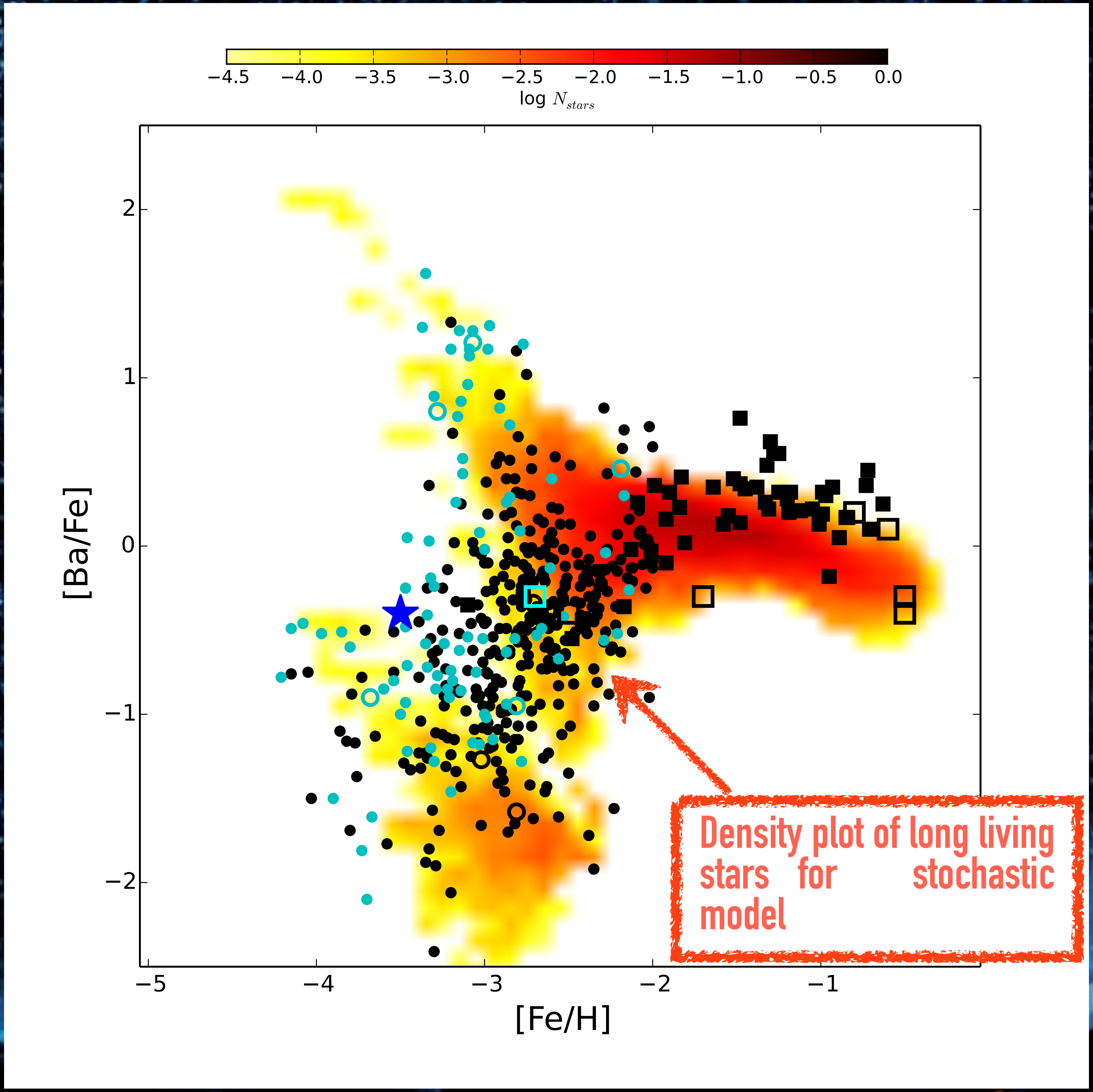

We can reproduce the [Ba/Fe] spread...

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

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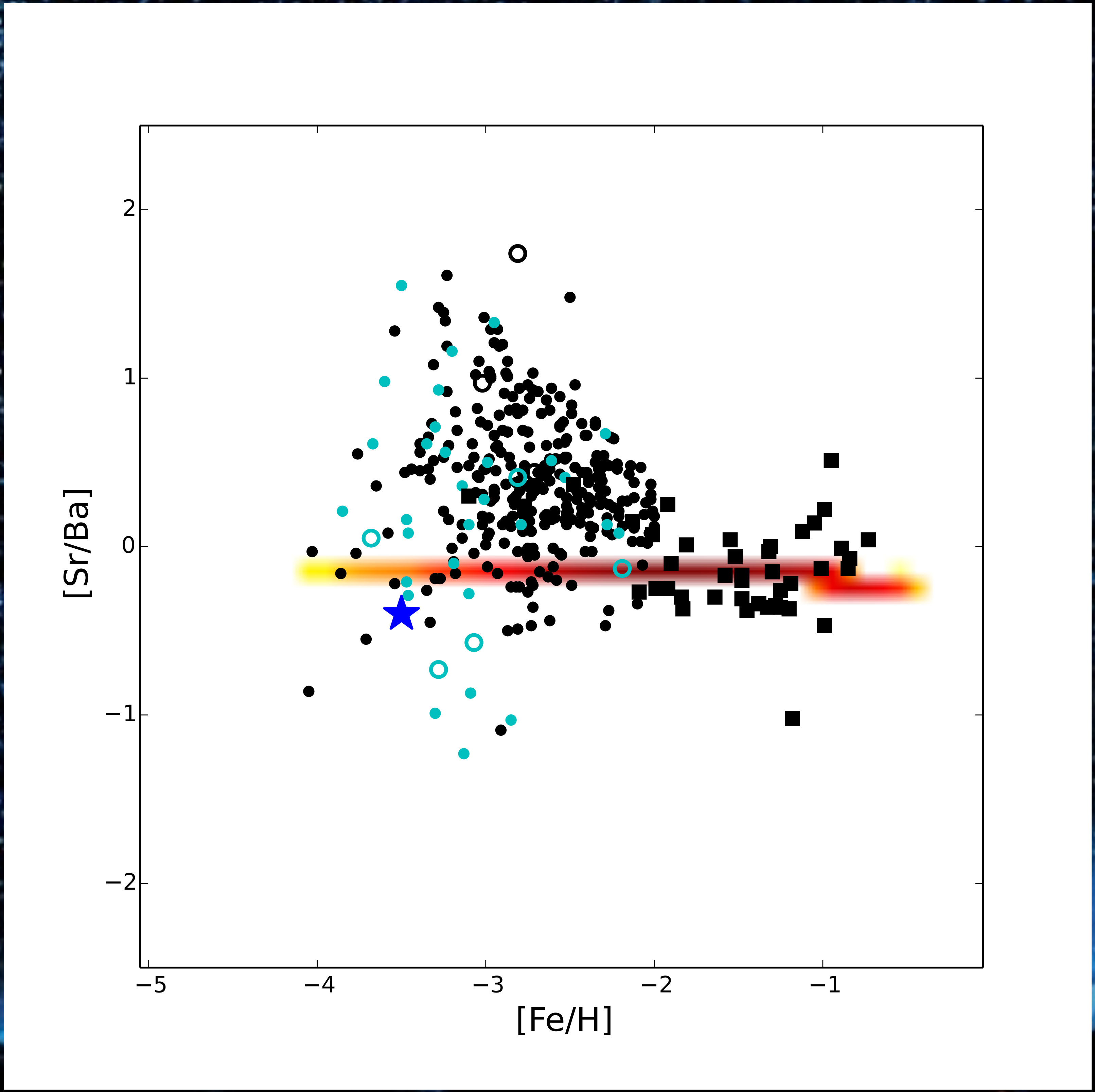
Puzzling result for the "heavy to light" n.c. element ratio

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



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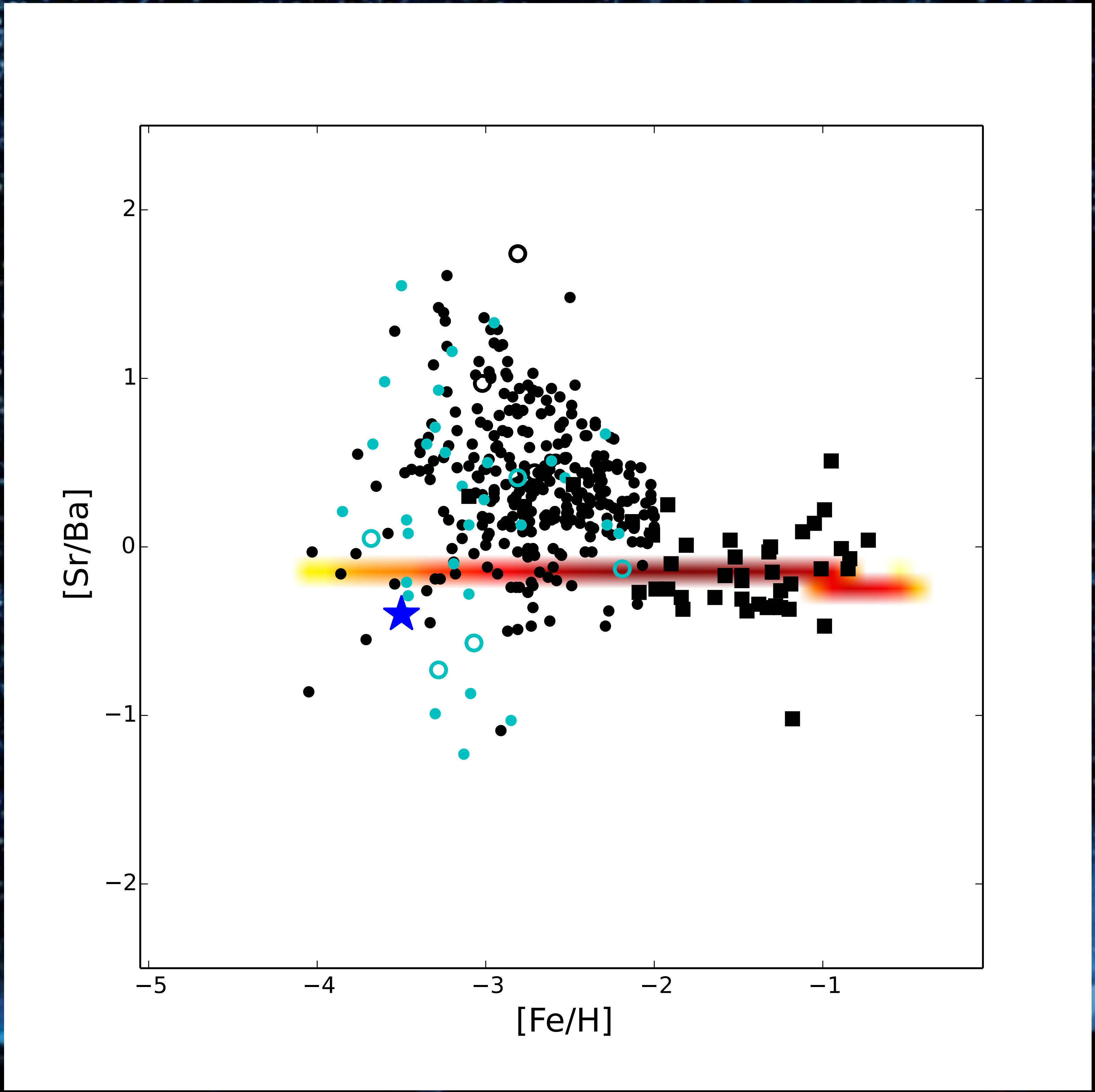

It is impossible to reproduce the data, assuming only the r-process component, enriching at low metallicity.
(see Sneden+ 03, François+07, Montes+07)

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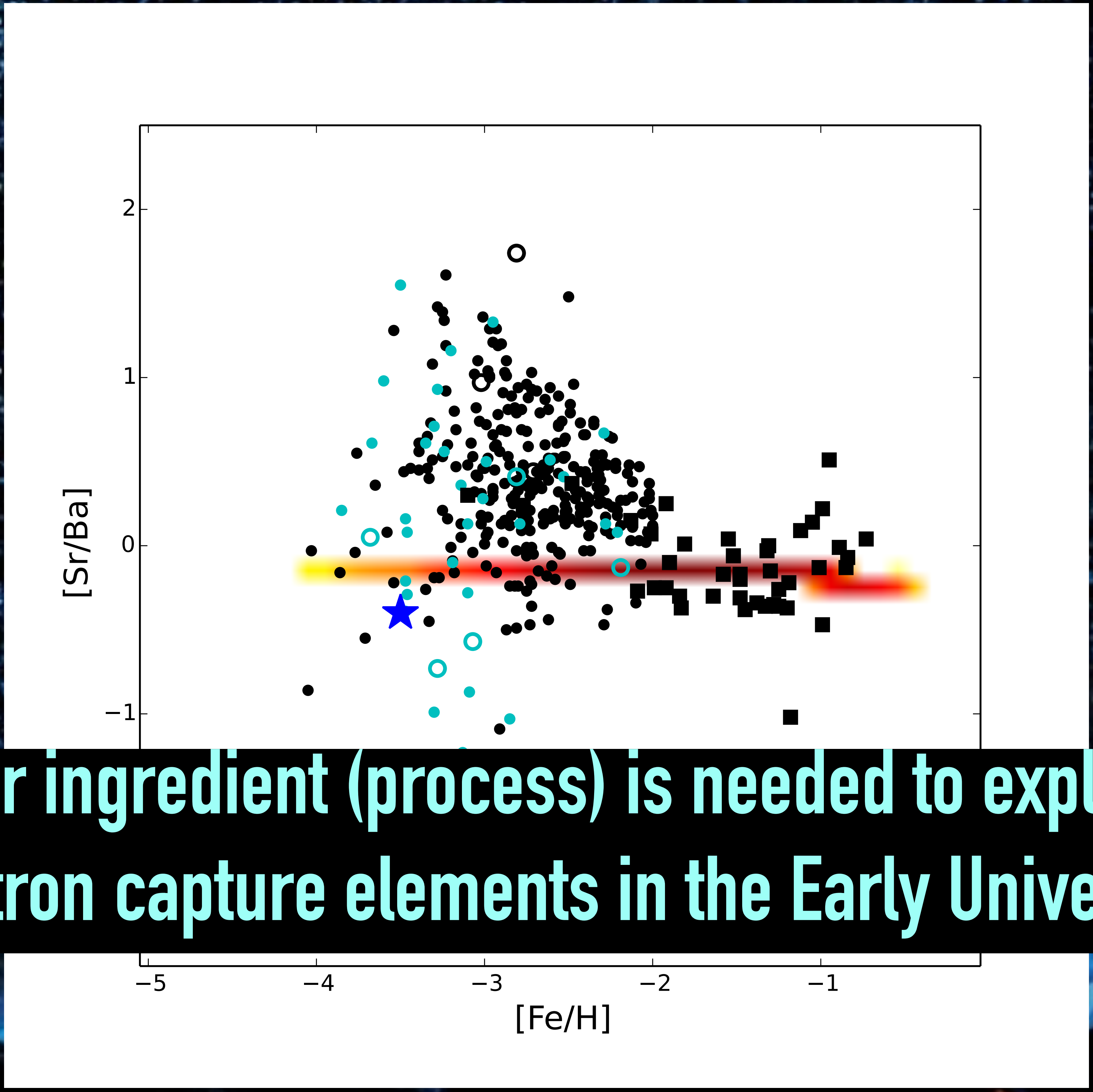

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(see Sneden+ 03, François+07, Montes+07)

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

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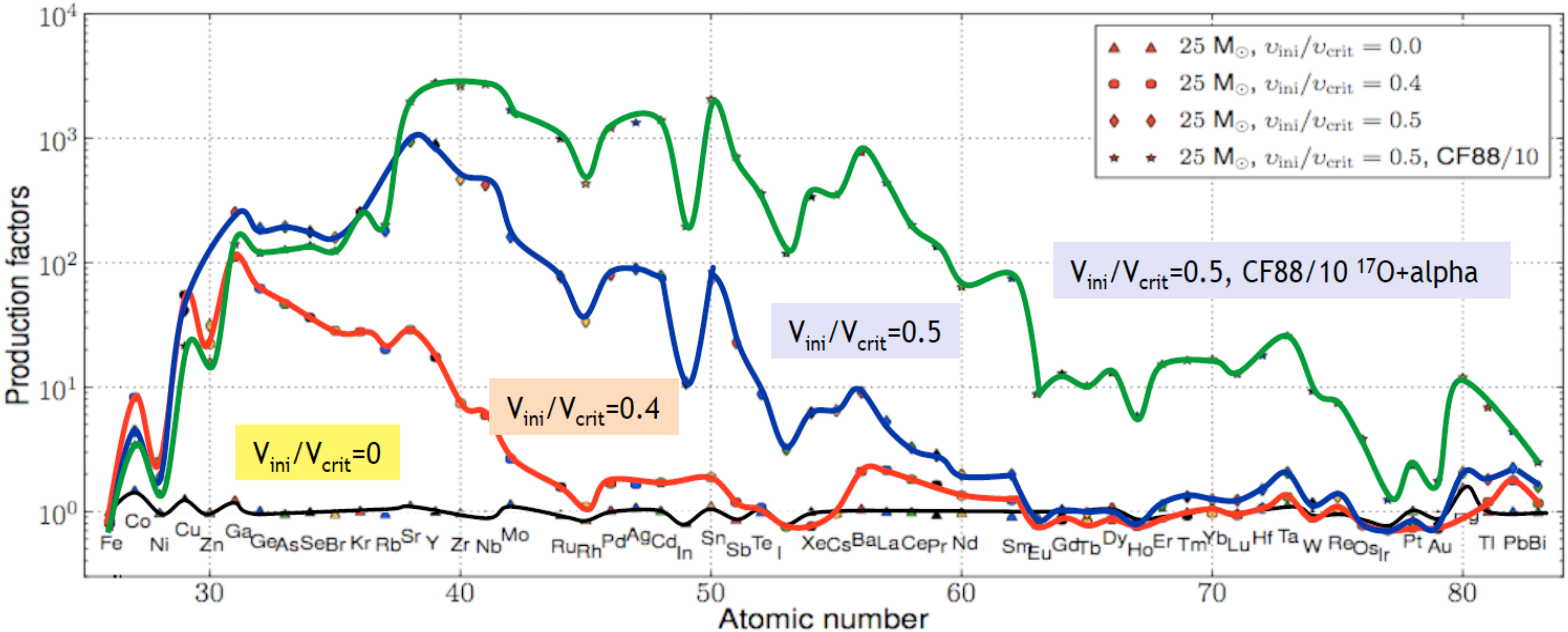
Low metallicity and rotating massive stars

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



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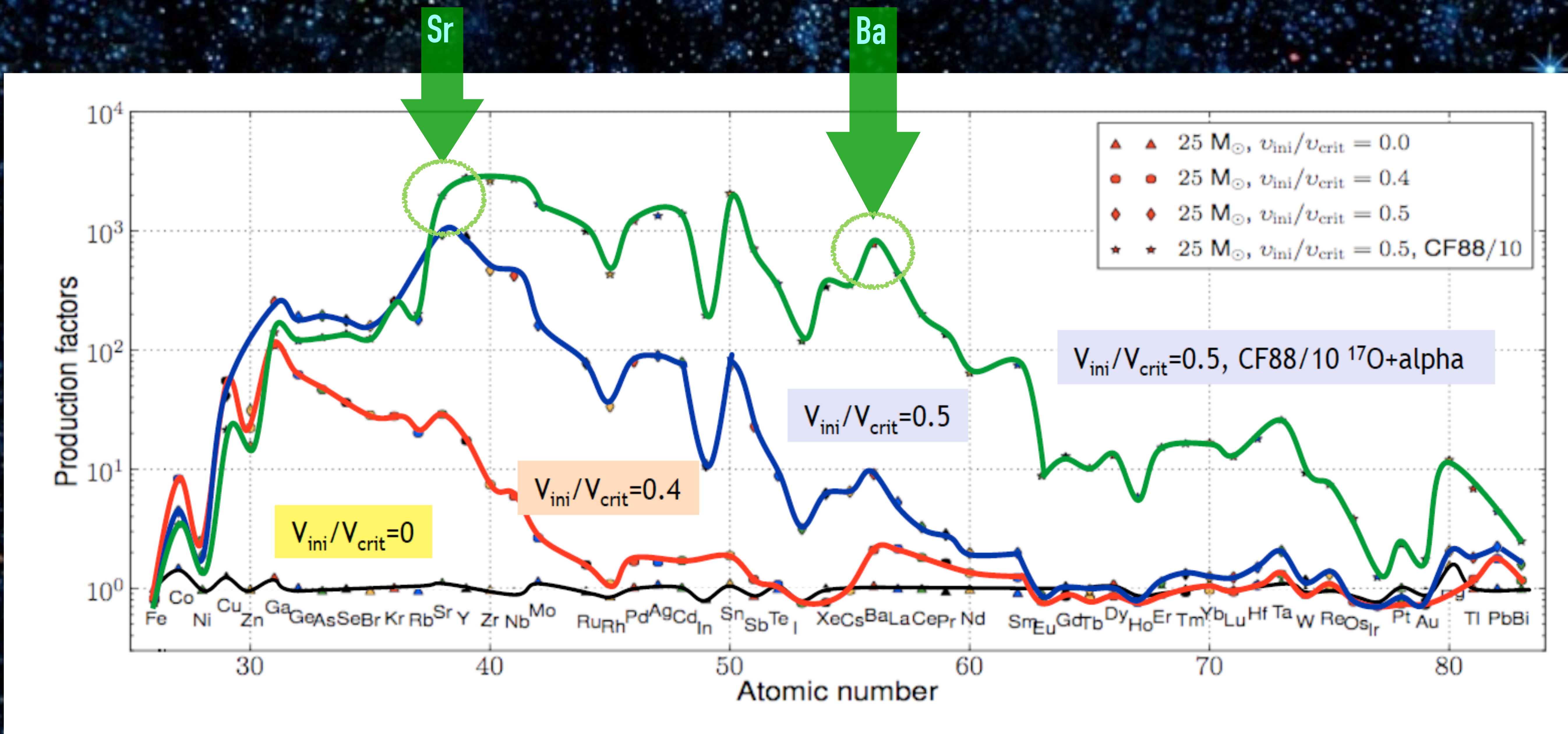
Rotating massive stars can contribute to s-process elemen



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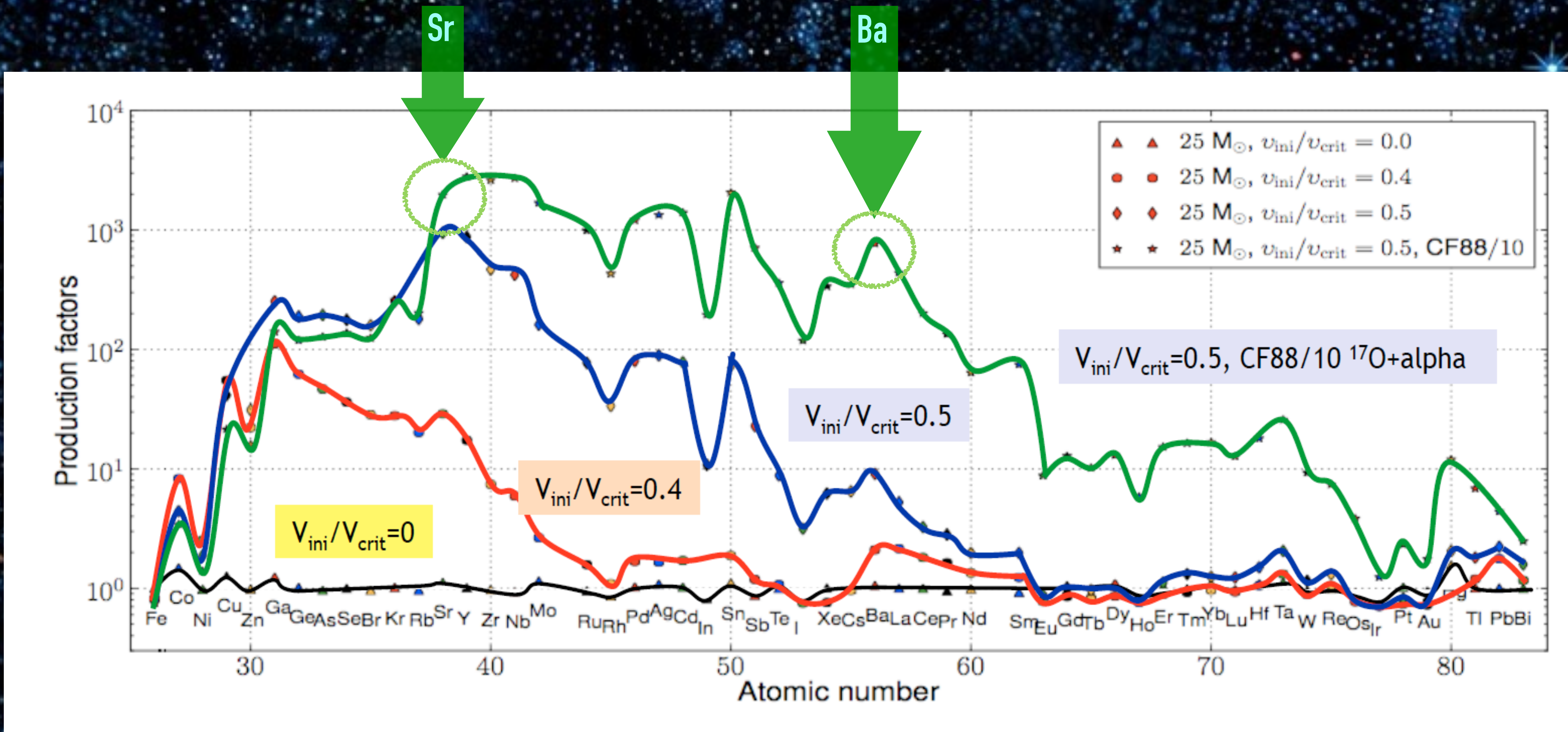

Can they explain the puzzles for Sr and Ba in halo?

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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

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s-process from rotating massive stars

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

Cescutti +14

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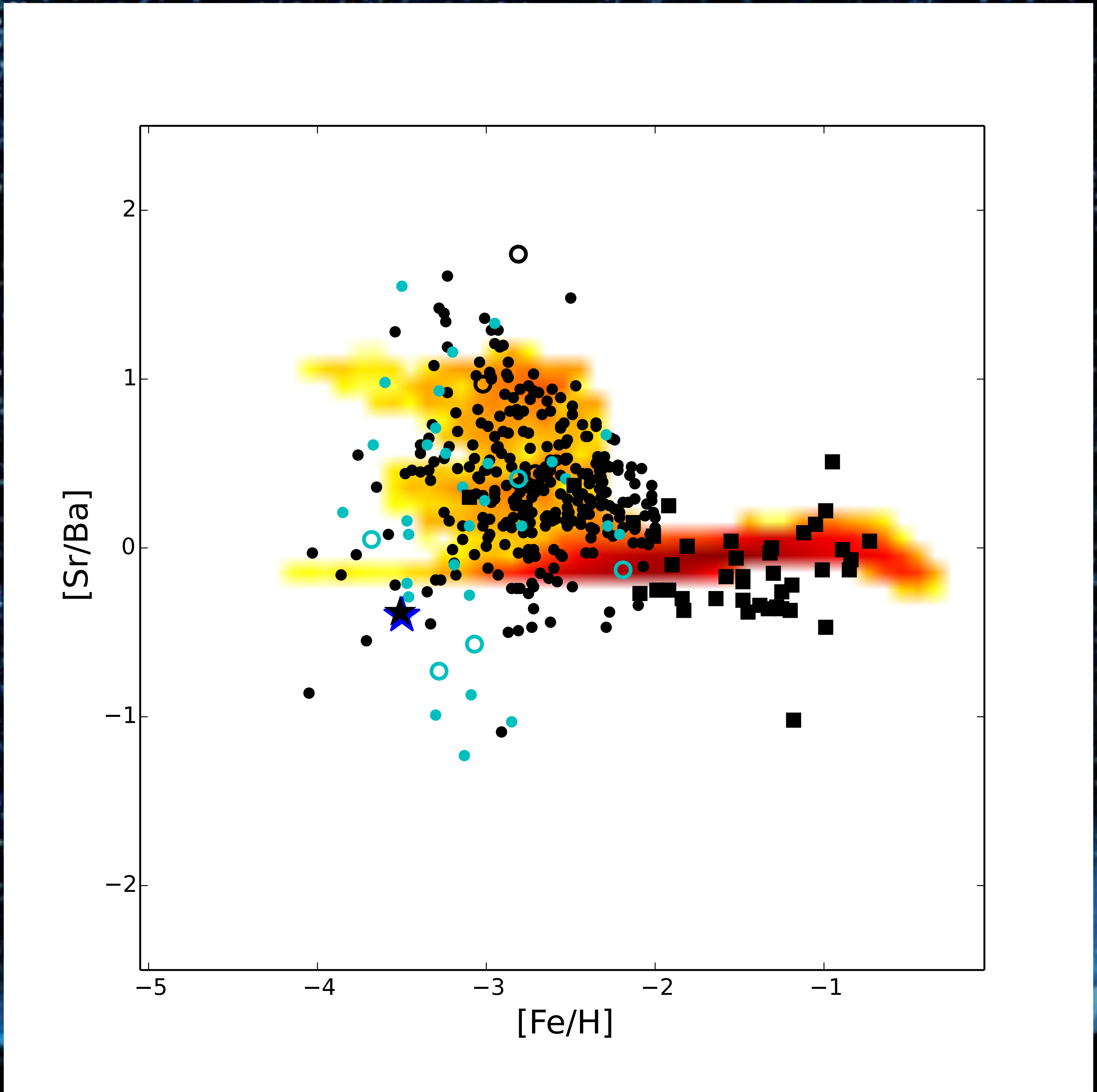
s-process from rotating massive stars

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

Cescutti +14



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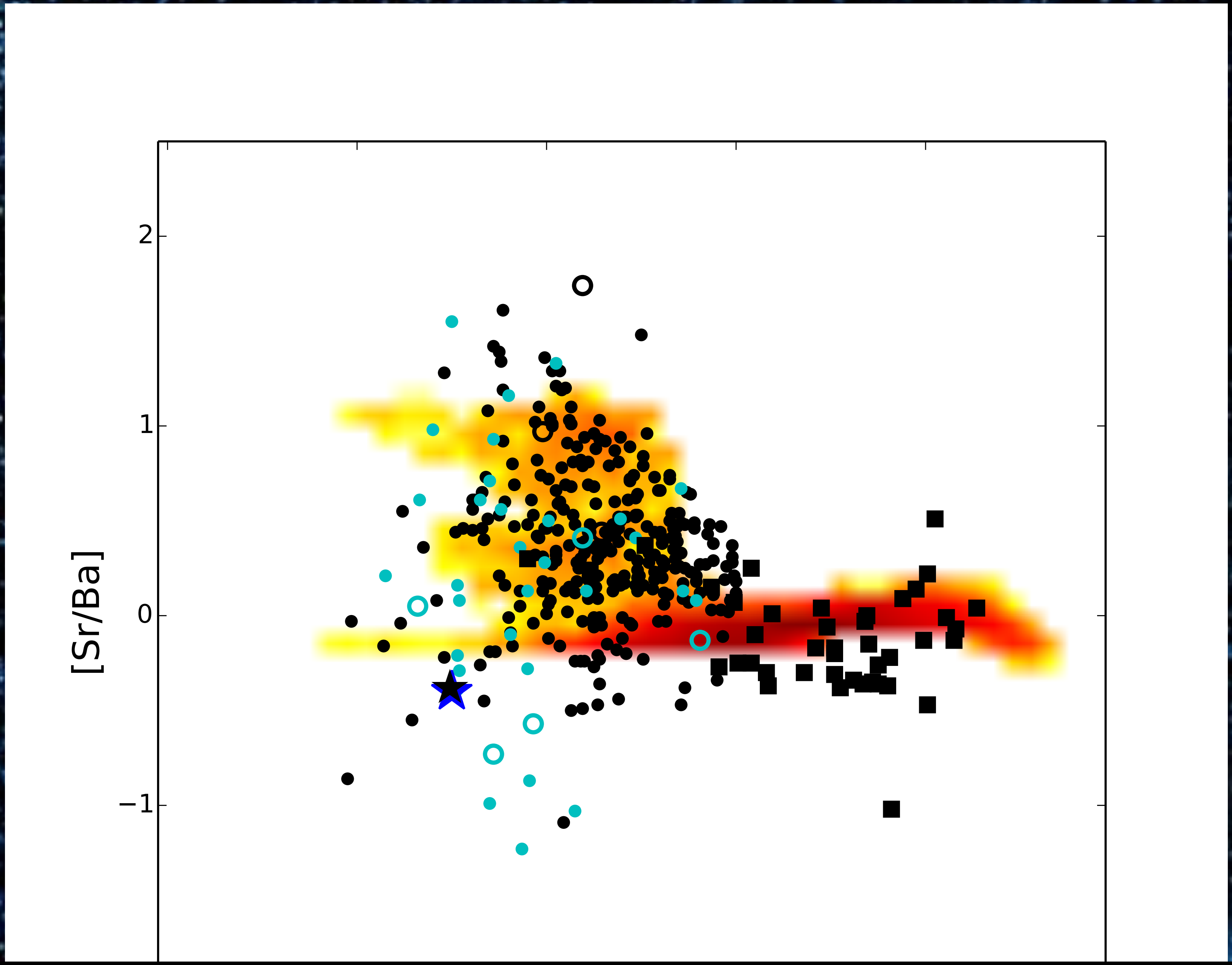

Cescutti +14

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

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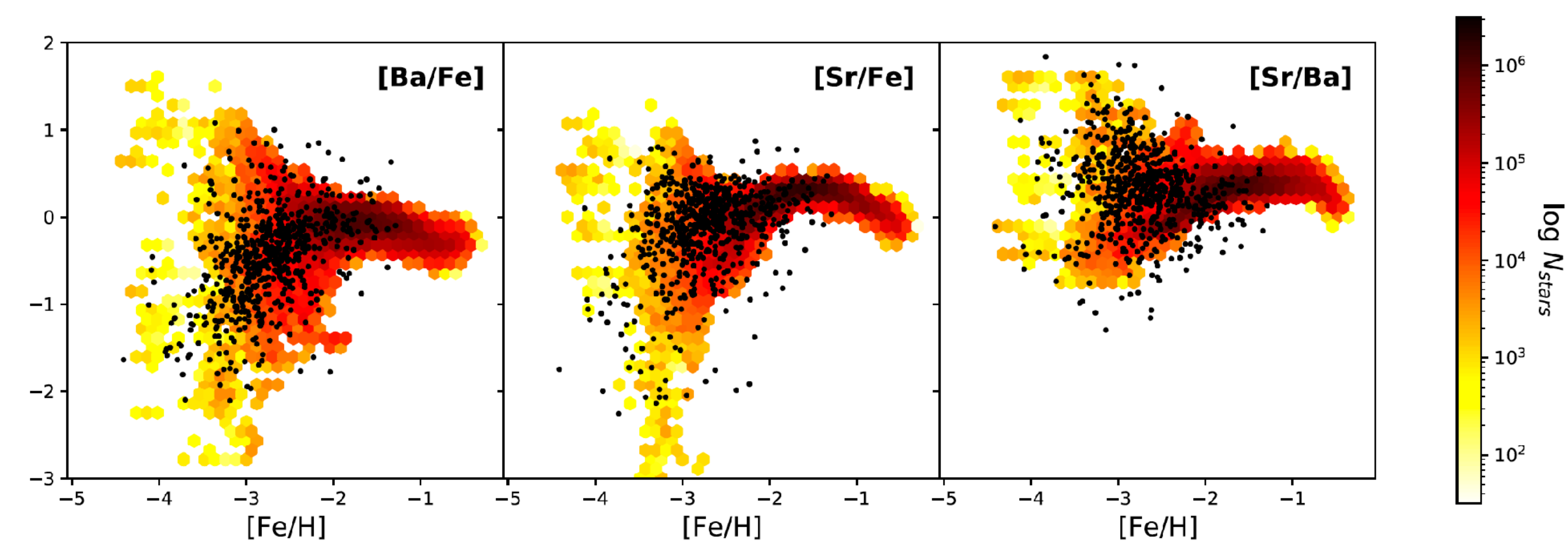
Rizzuti et al. (2021)

adopting Limongi&Chieffi18



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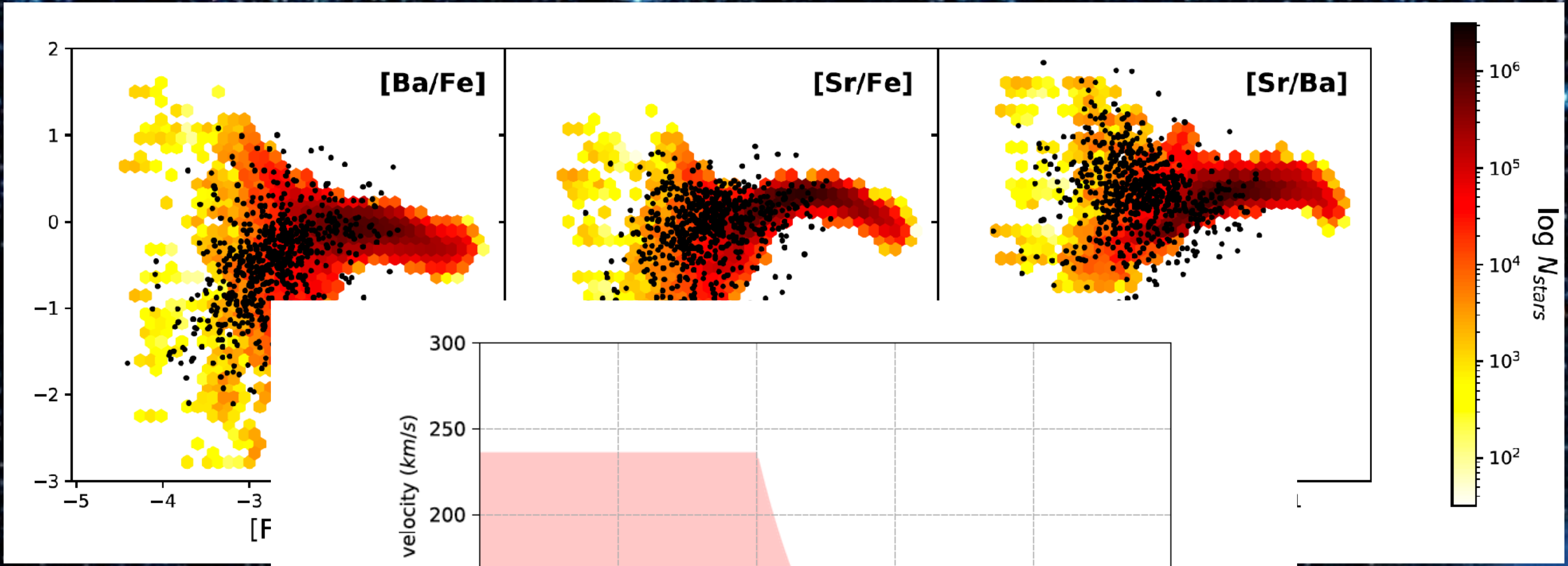
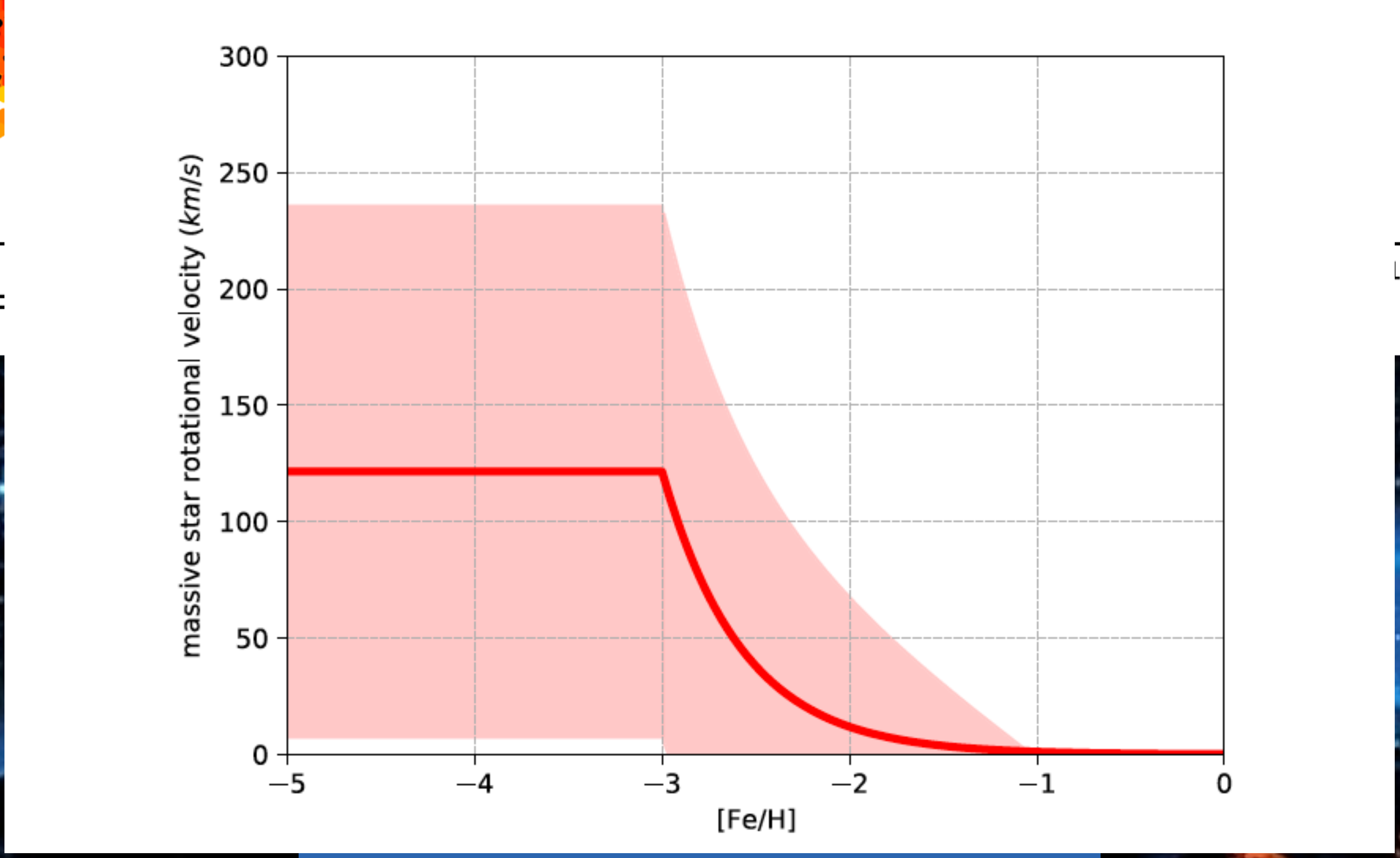
adopting Limongi&Chieffi18





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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.

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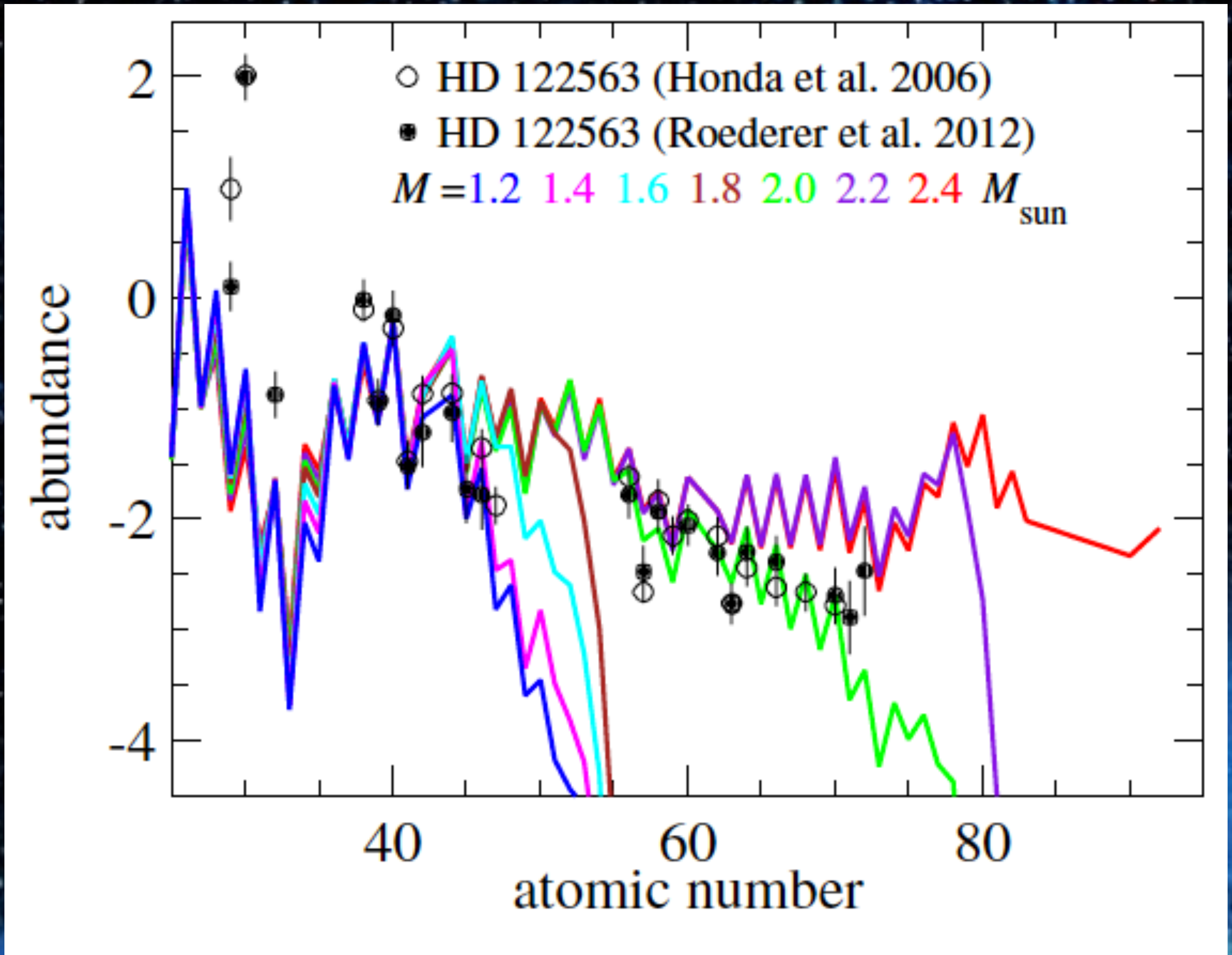
The only possible answer?

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

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Isotopic ratio for Ba

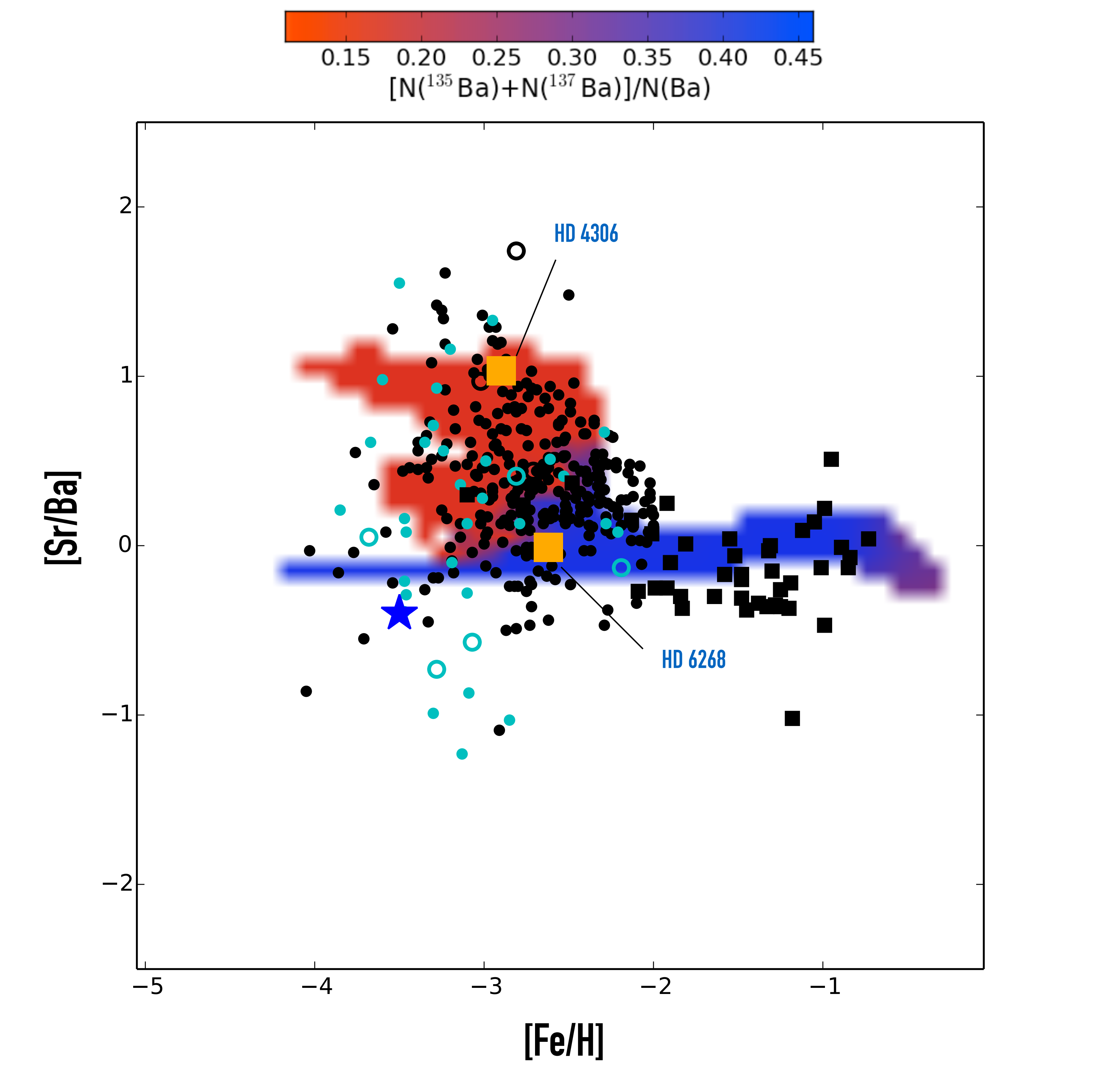
The rotating massive stars scenario naturally predicts different Ba isotopic ratios in halo stars.

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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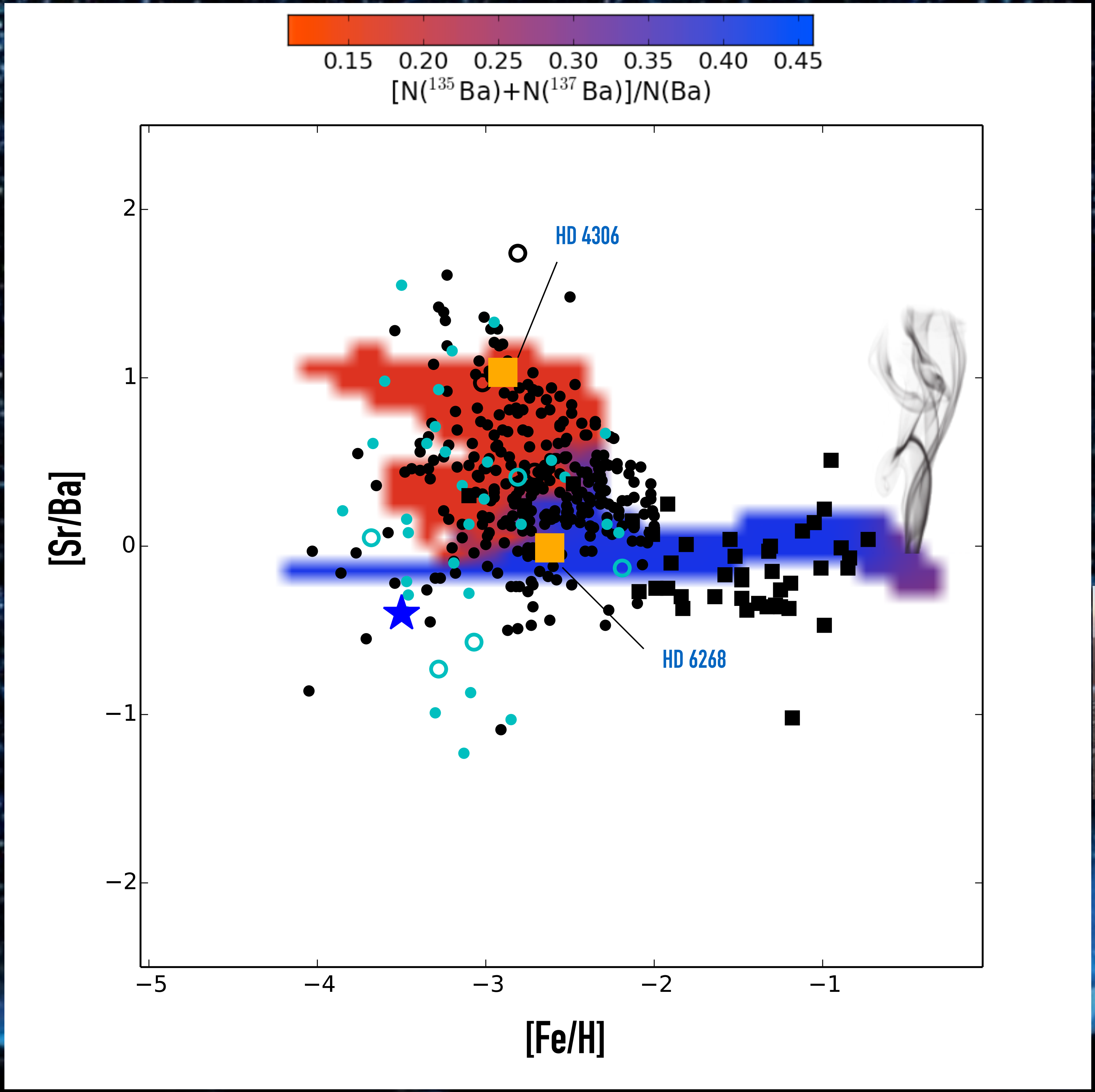

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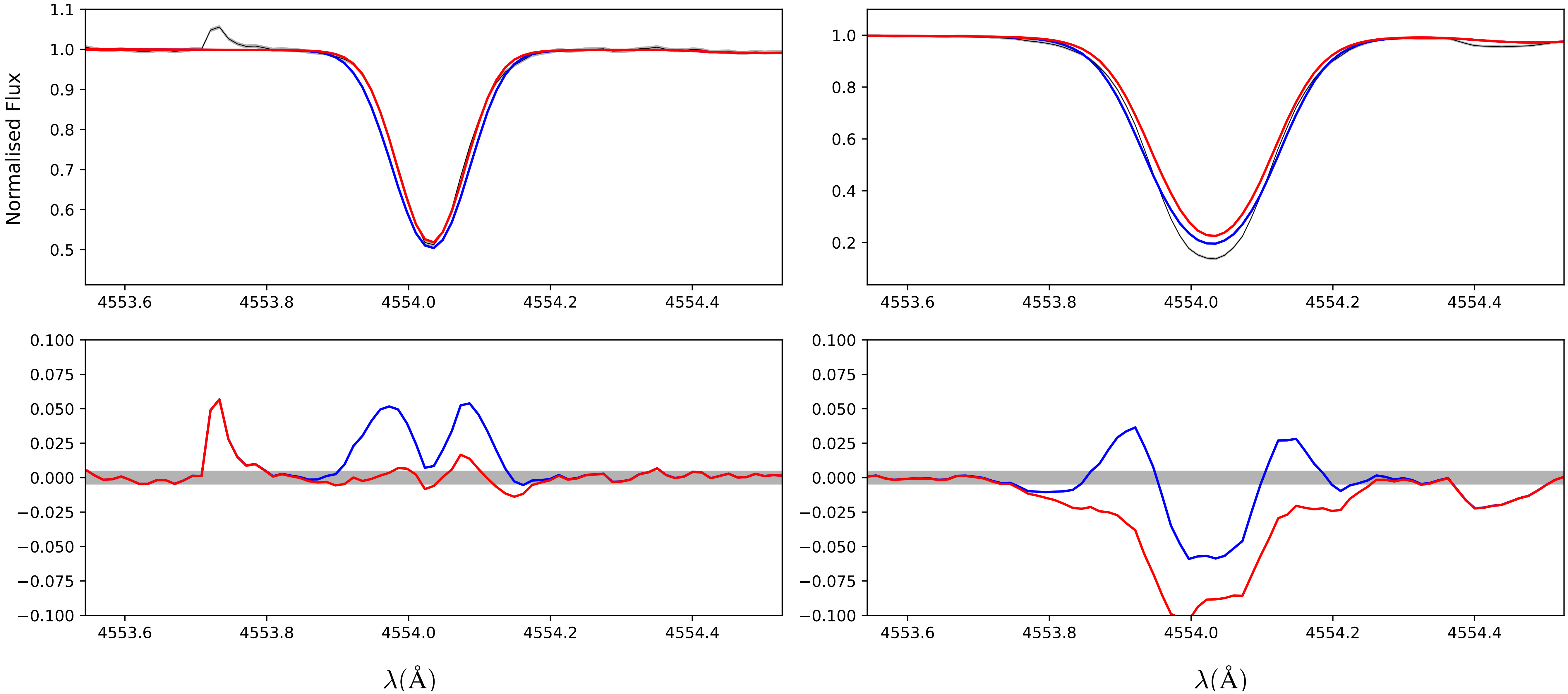
Spectral analysis results ratio for Ba (1D and LTE)

Cescutti+21

s-process | **r-process**

HD 4306 | HD 6268



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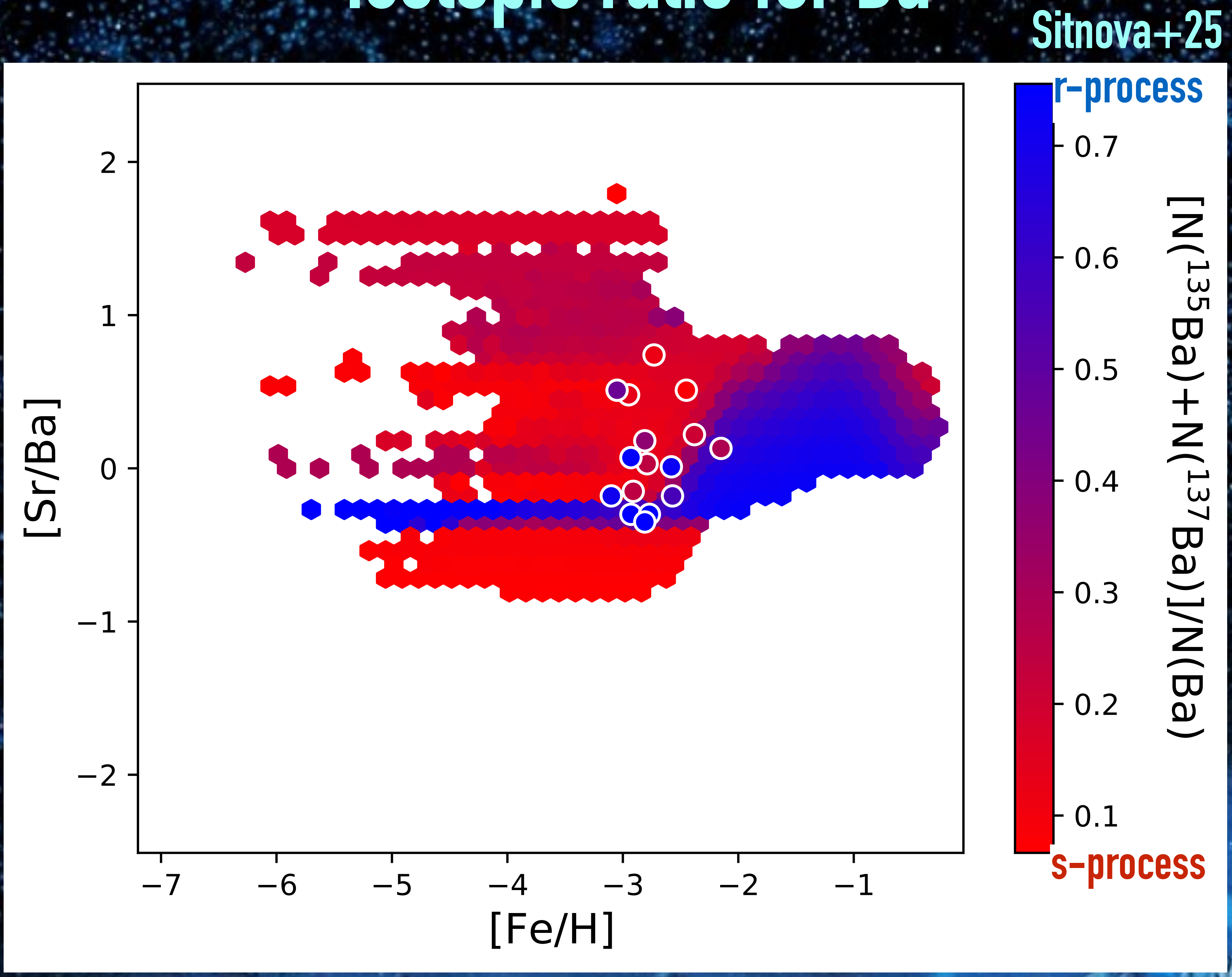
Isotopic ratio for Ba



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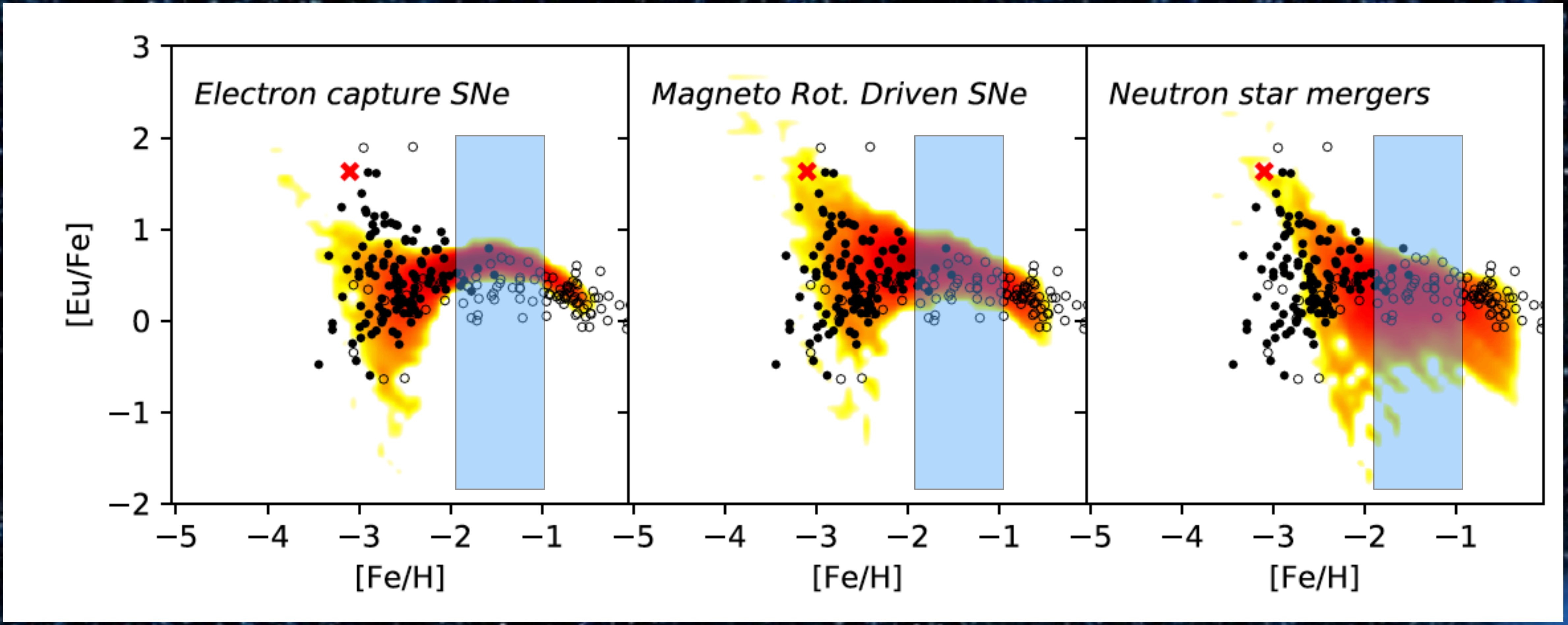
How to constrain the r-process event?



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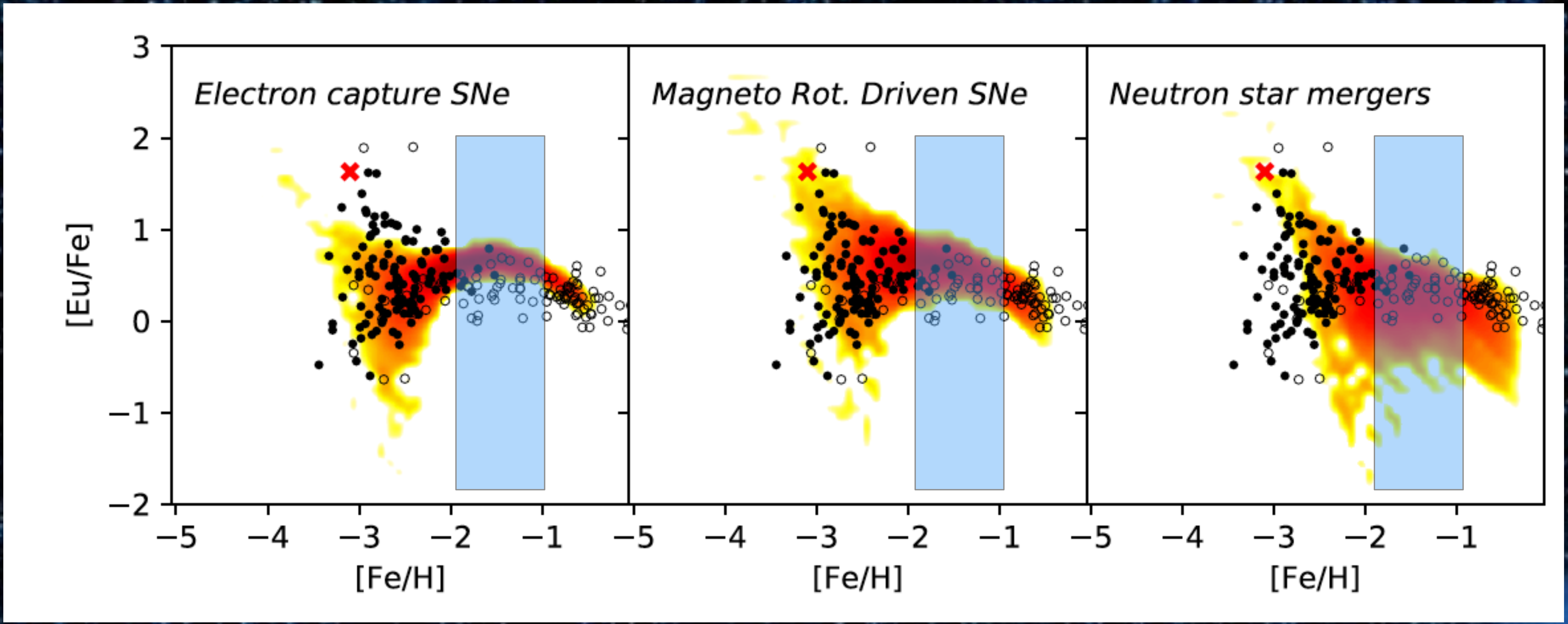

MINCE

Measuring at Intermediate Metallicity Neutron Capture Elements

Main investigators Bonifacio & Cescutti

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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

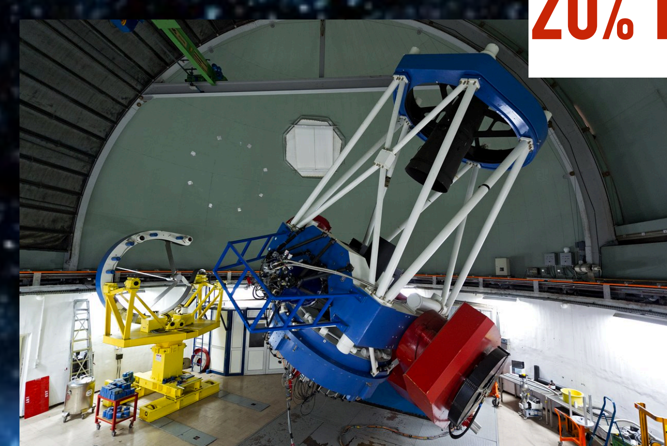
VLT 8.2m
Spectrograph: UVES

~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

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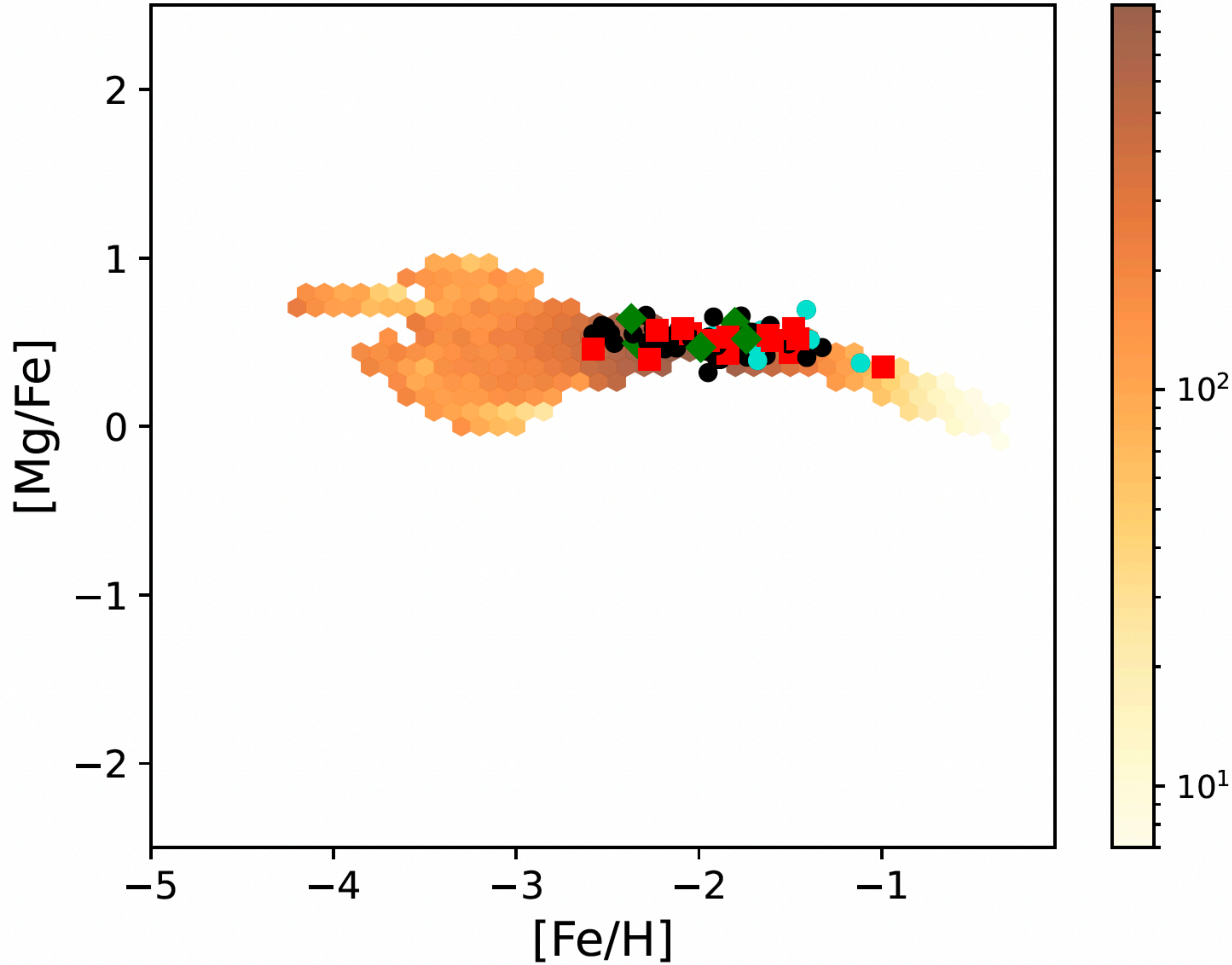
Lucertini+25 aka MINCE 3



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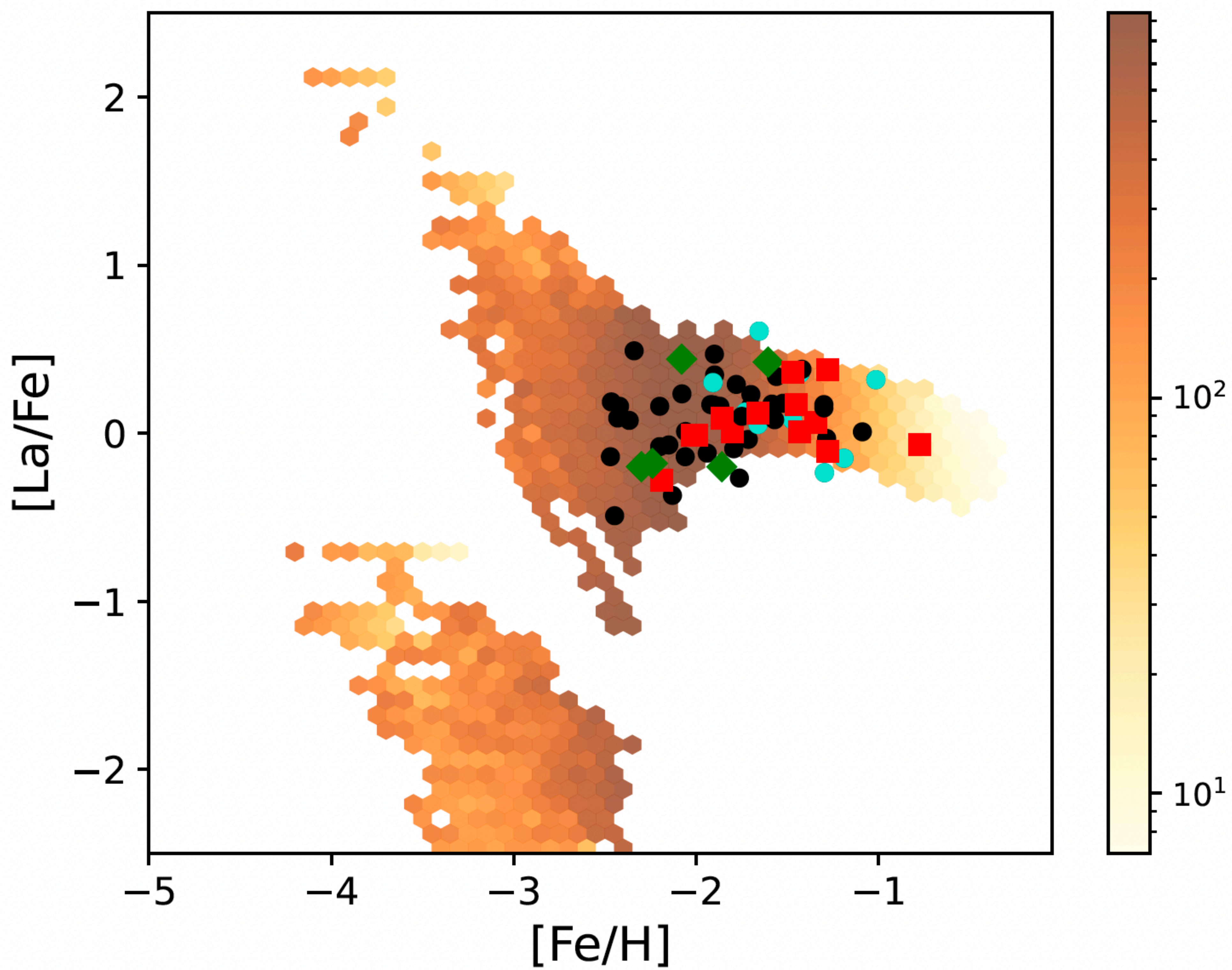
Lucertini+25 (MINCE 3)



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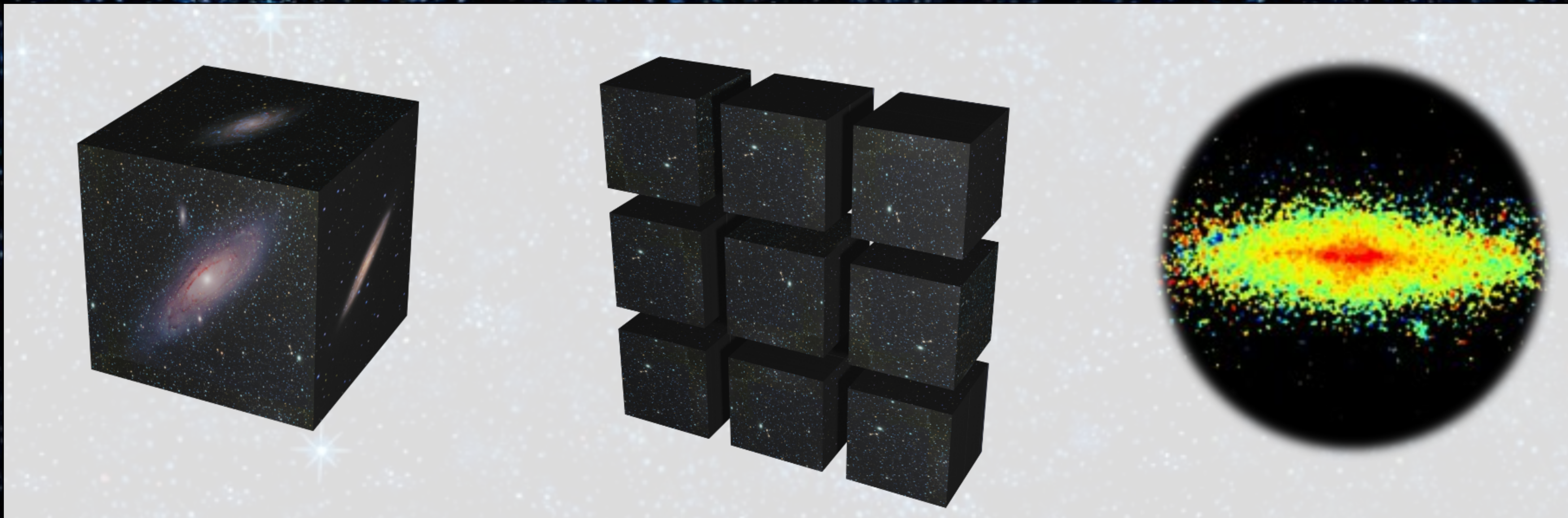
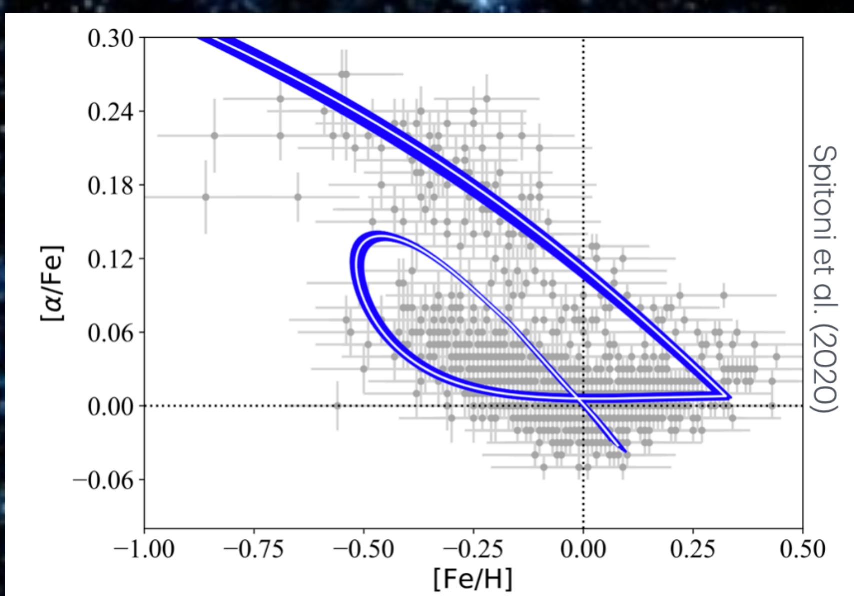
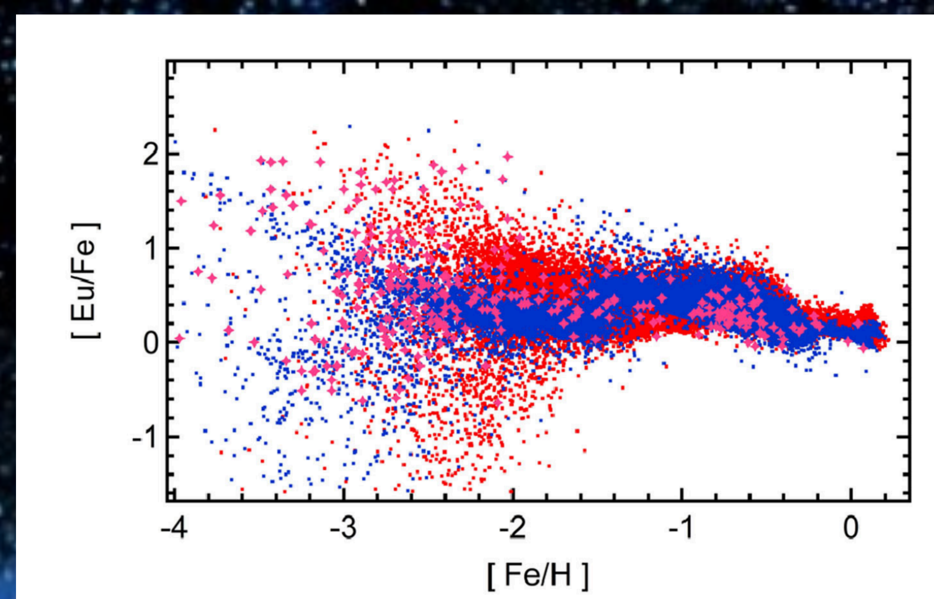
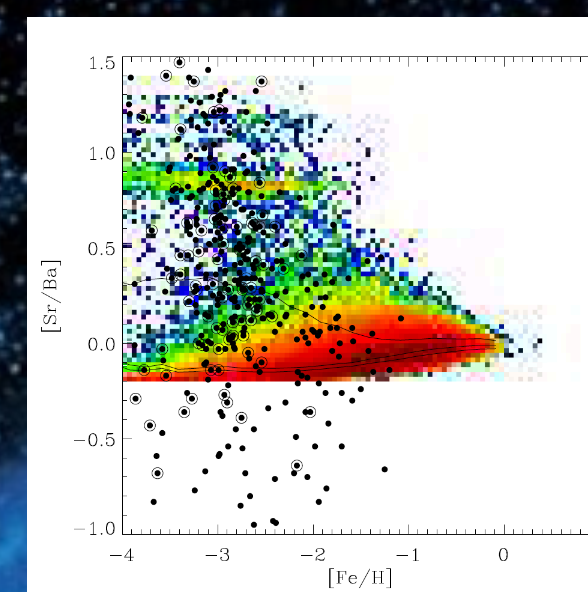
One-zone (homogeneous)	Inhomogeneous/Stochastic	SpH simulations
Matteucci+14, Spitoni+23	Argast+04, Ishimaru+04	Kobayashi+11, van de Voort+20
Prantzos+18, Côté +17	Cescutti 08, Wehmeyer+15	Scannapieco+22, Wehemeyer+25









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