Neutron-Capture Elements in Low-Metallicity Stars: Which sources can we identify?

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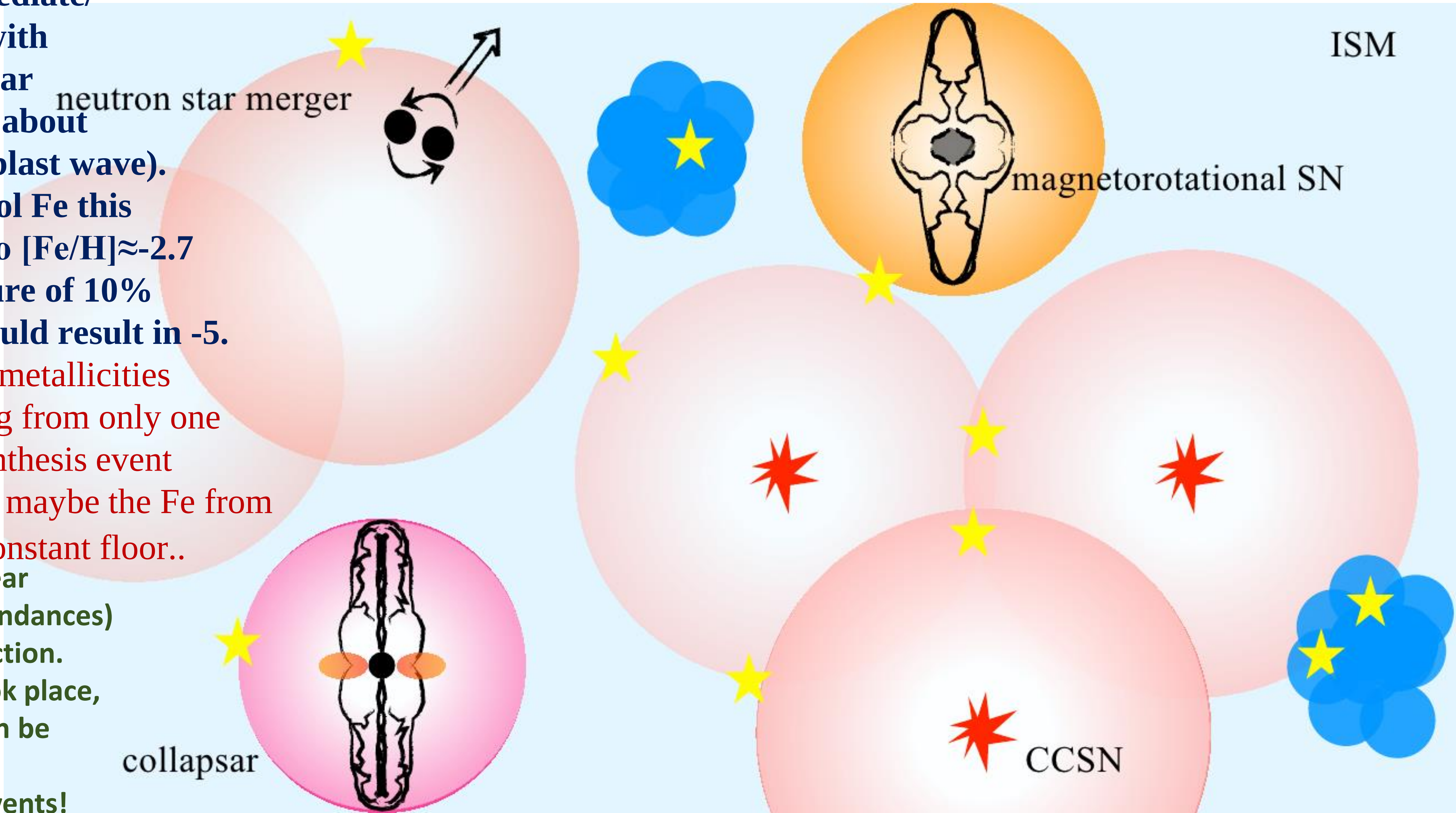
see also our r-process review by Cowan et al. (2021) for Rev. Mod. Phys. 2019arXiv190101410C,
Perego, Thielemann, Cescutti (2021), Handbook of Grav. Wave Astron. 2021arXiv210909162P
Farouqi, Thielemann, Rosswog, Kratz (2022), A&A, 2021arXiv210703486F,
Arcones & Thielemann (2023), A&A Rev. https://link.springer.com/article/10.1007/s00159-022-00146-x
Mishenina, Pignatari, Usenko, Soubiran, Thielemann, Kniazev, Korotin, Gorbaneva (2023), in preparation

Stellar (surface) abundances are enherited from the interstellar medium in which they are born, i.e. one can look back in time. In the early phases of galactic evolution or for events with rare occurrence frequencies one sees initally large scatters and spatial inhomogeneities

Inhomogeneous "chemical evolution" models do not assume immediate/ complete mixing of ejecta with the whole galactic interstellar medium. They pollute only about 5 10^4 Msol (Sedov-Taylor blast wave). With the ejection of 0.1 Msol Fe this leads in a CCSN remnant to [Fe/H]≈-2.7 (Ryan et al. 1996). Admixture of 10% or 1% to new-born stars could result in -5.

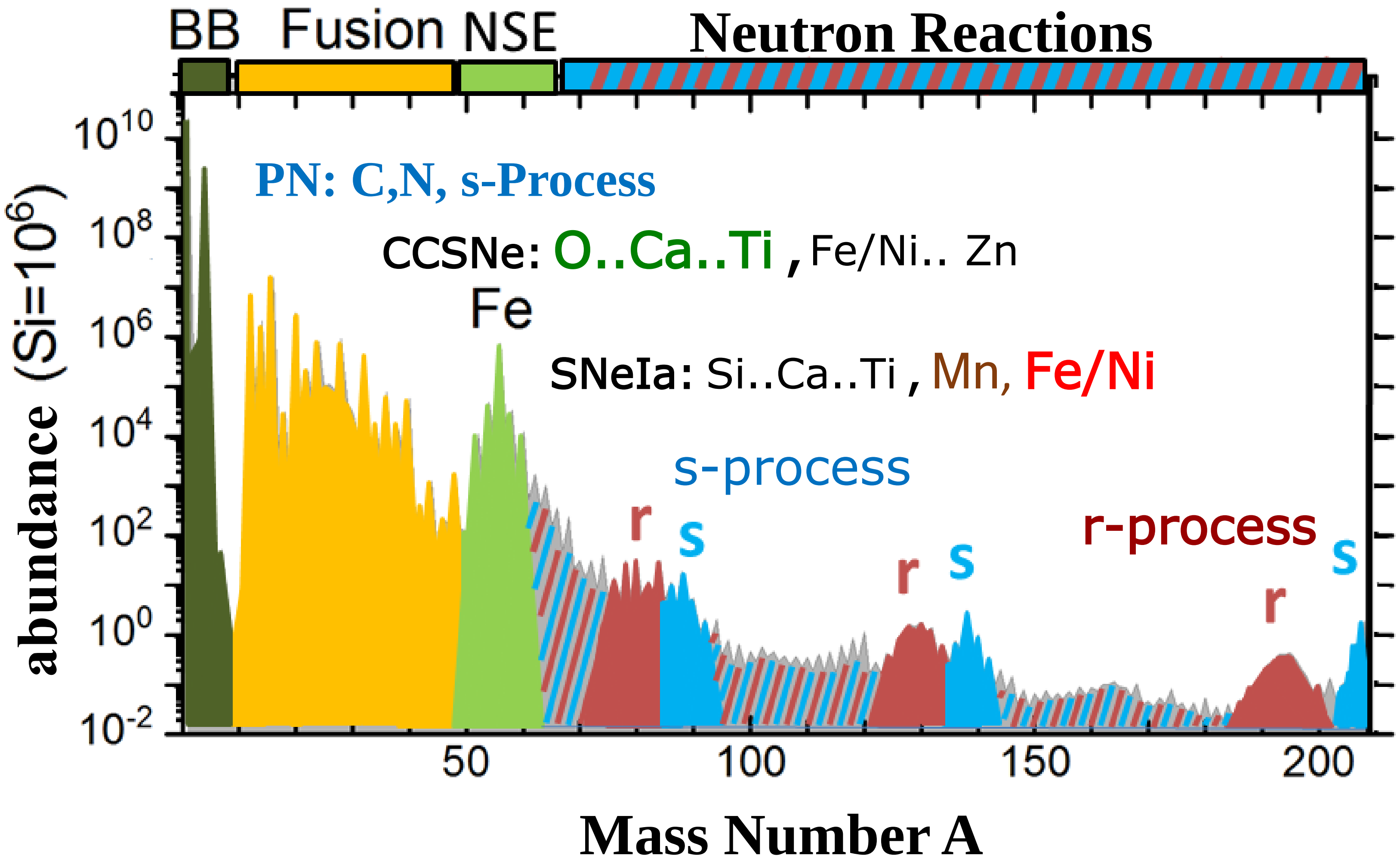
Possibly stars with such low metallicities can be interpreted as resulting from only one single contributing nucleosynthesis event (our starting hypothesis), but maybe the Fe from CCSNe provides already a constant floor..

In this case correlations (i.e.linear relations between element abundances) can be interpreted as co-production. After many different events took place, also «spurious» correlations can be observed, but they are just the result of averages over many events!



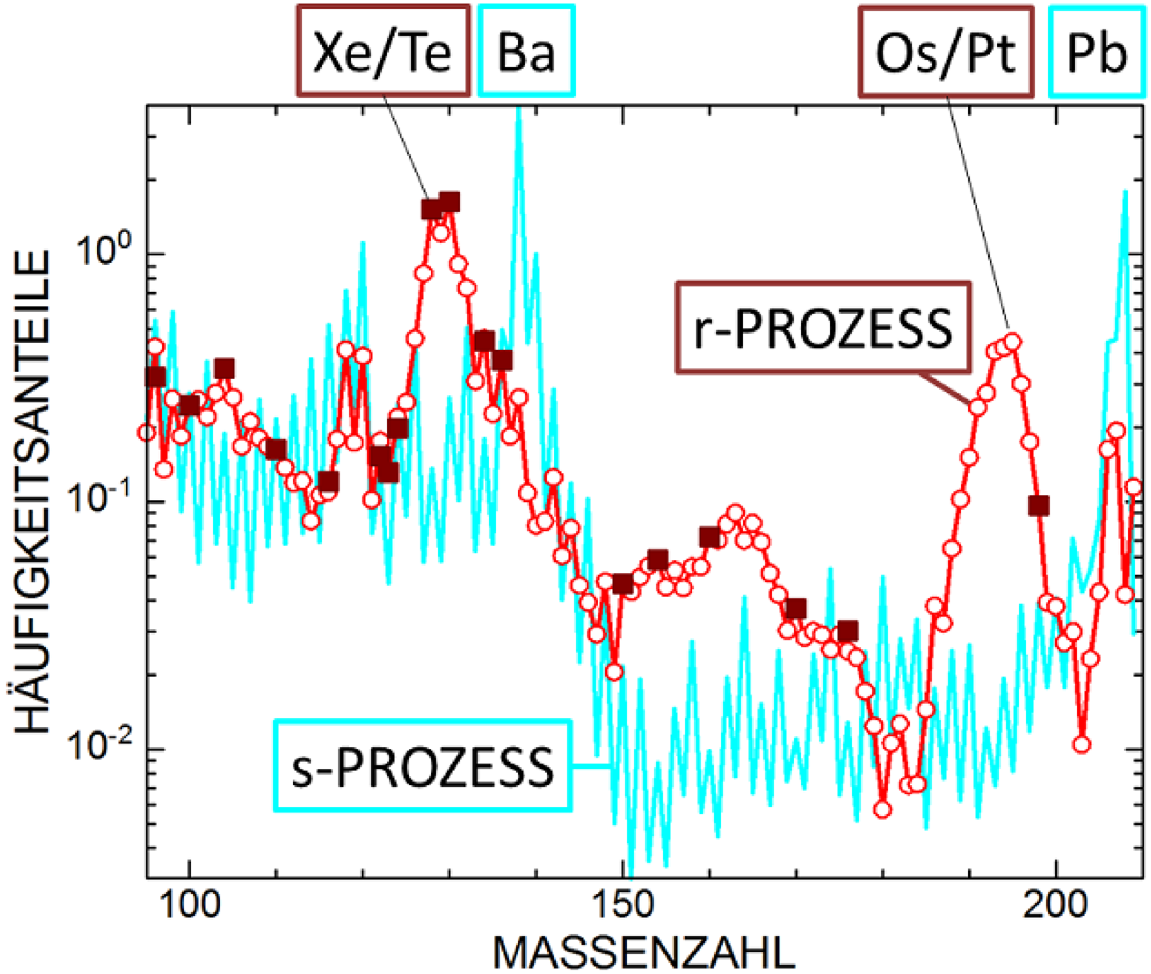
BBN $^{1,2}H$, $^{3,4}He$, ^{7}Li

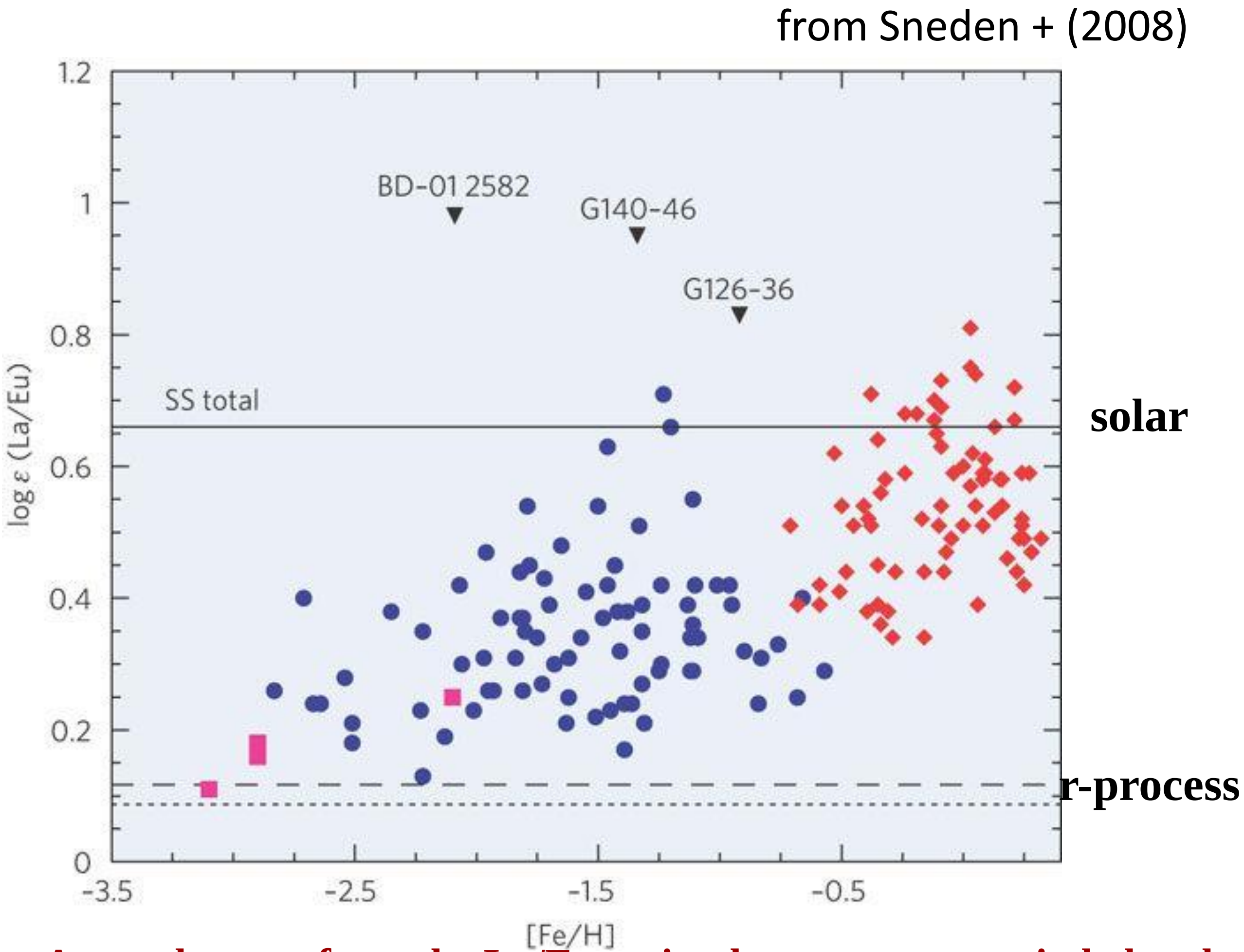
How are elements heavier then Fe made?



slow neutron capture (s-process) and rapid neutron capture (r-process)

Decomposition in s- and r-process and their time evolution

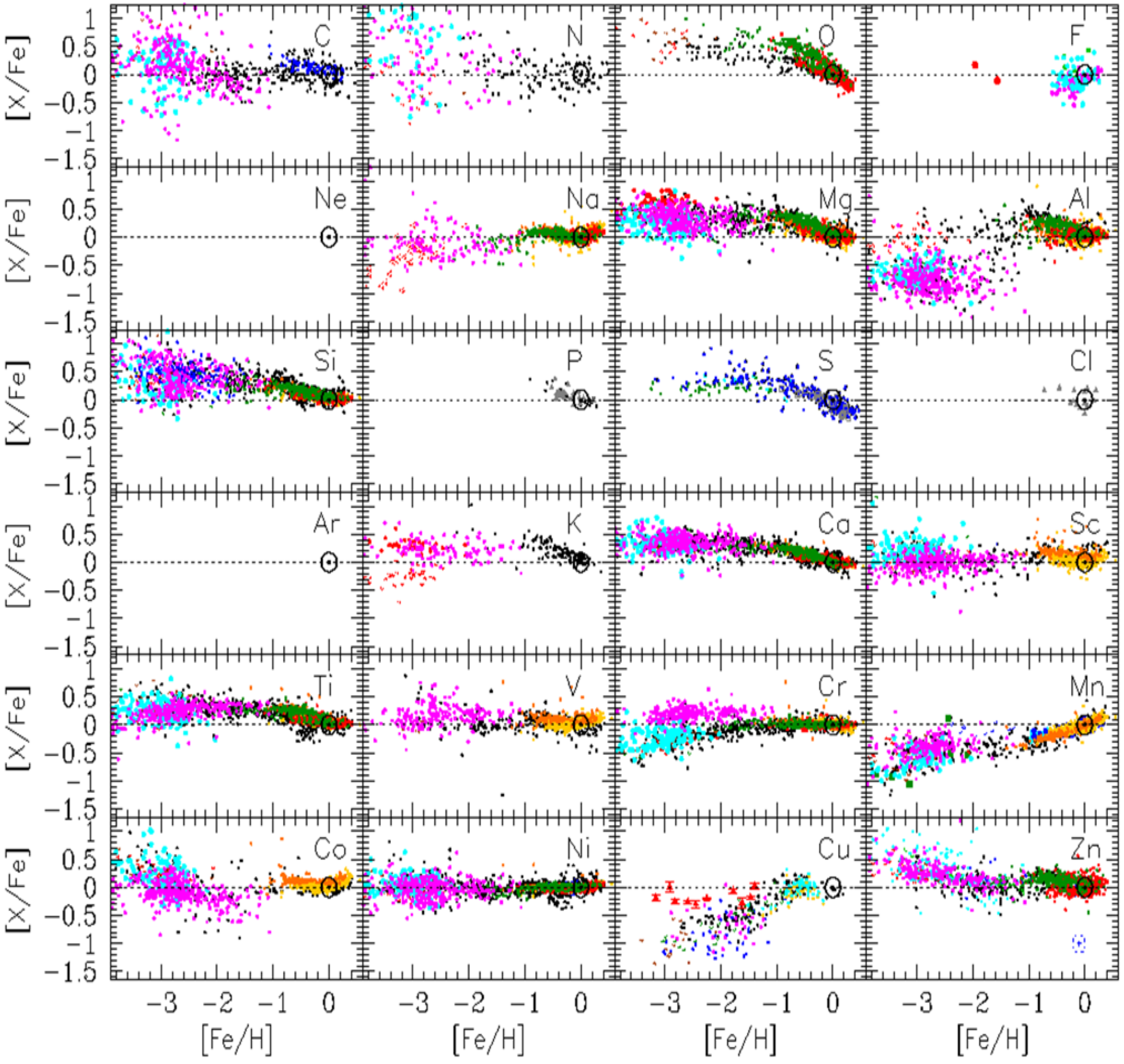




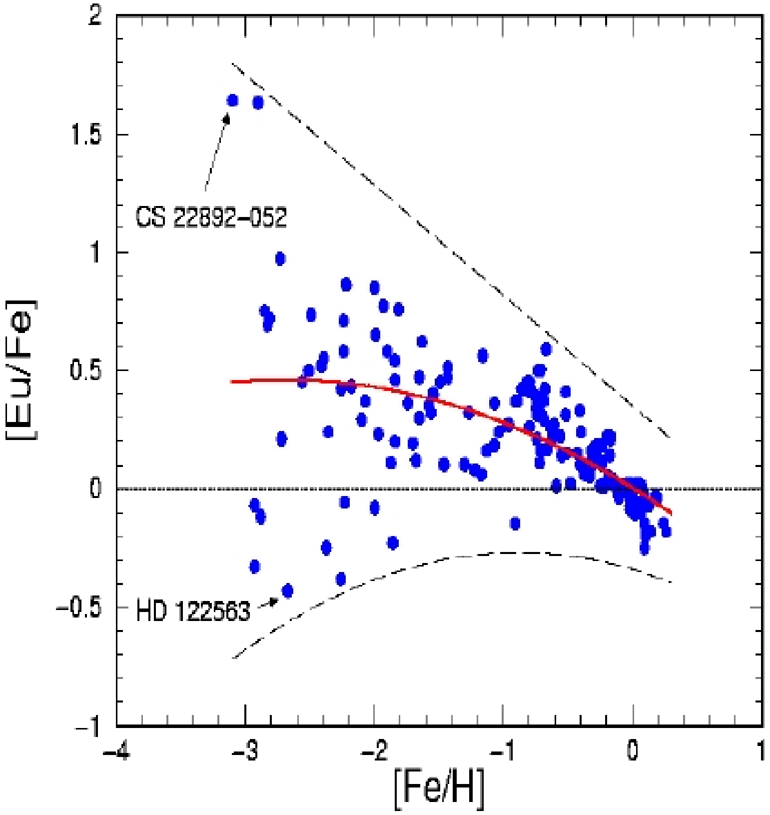
There exist pure s and r nuclei, others having s and r-process contributions. As the s-process is understood (known nuclear physics close to stability as well as stellar models), the r-process component is obtained via subtraction from solar abundances.

As can be seen from the La/Eu ratio, the s-process sets in belated for finally attaining the solar abundance ratio. **The early galaxy is dominated by the r-process. Low mass stars have a long evolution time before ending as planetary nebulae,**
The r-process is correlated with fast evolving massive stars.

How do we understand: low metallicity stars … galactic evolution?



from Prantzos + (2018)



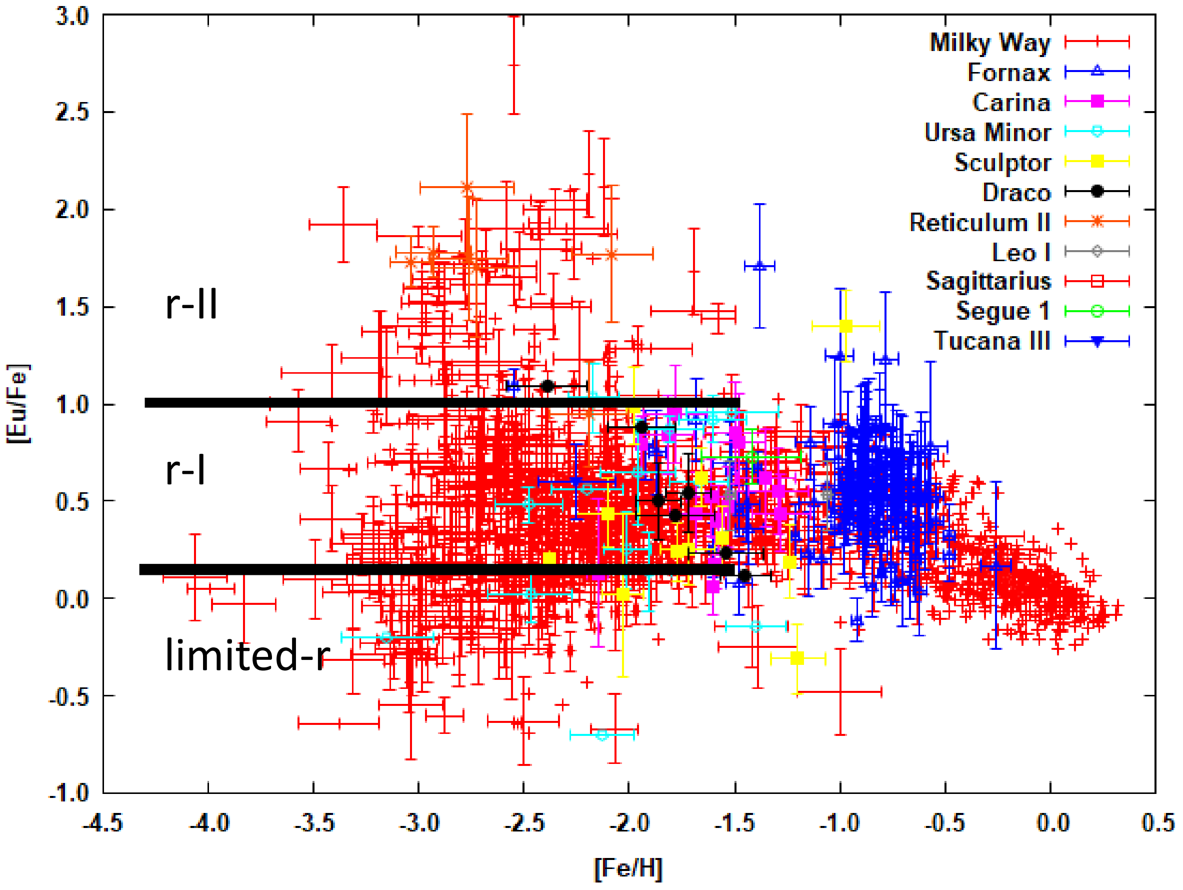
***Average** r-process (Eu) behavior resembles CCSN contribution of alpha elements (O, Mg, SI, S, Ca, Ti), but large scatter at low metallicities!!*

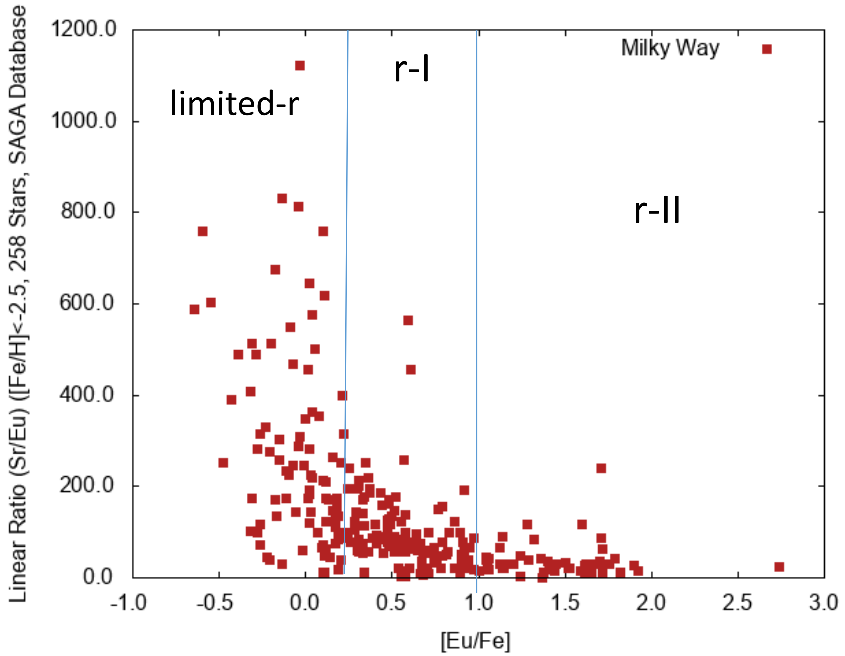
(Cowan & Thielemann 2004)

Highly increased number of observations since 2004!

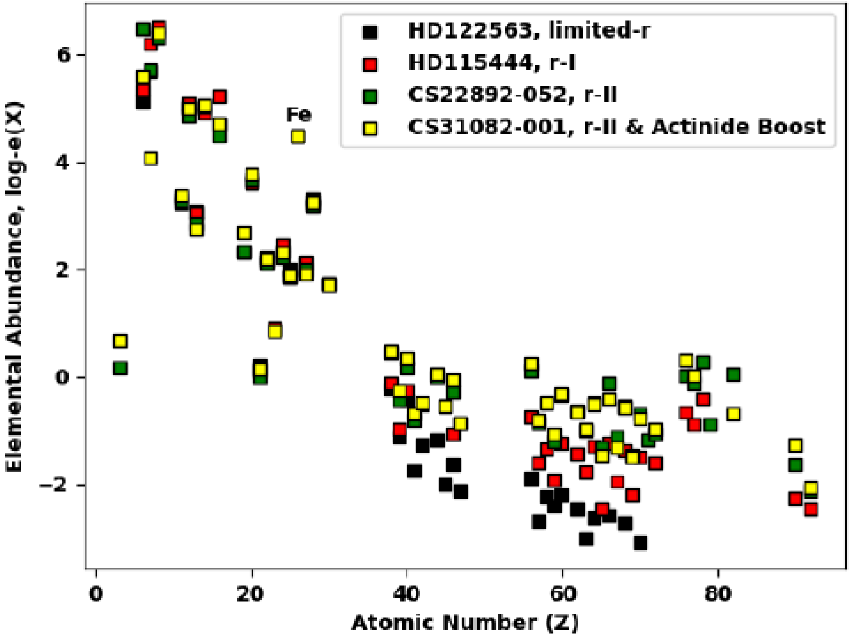
If (at low metallicities) interpreted as imprints of individual events, the large scatter points to either rare events with different amounts of admixtures and/or to different types of events.

The large Sr/Eu in limited-r stars hints at a different type of event (from Farouqi + 2022)



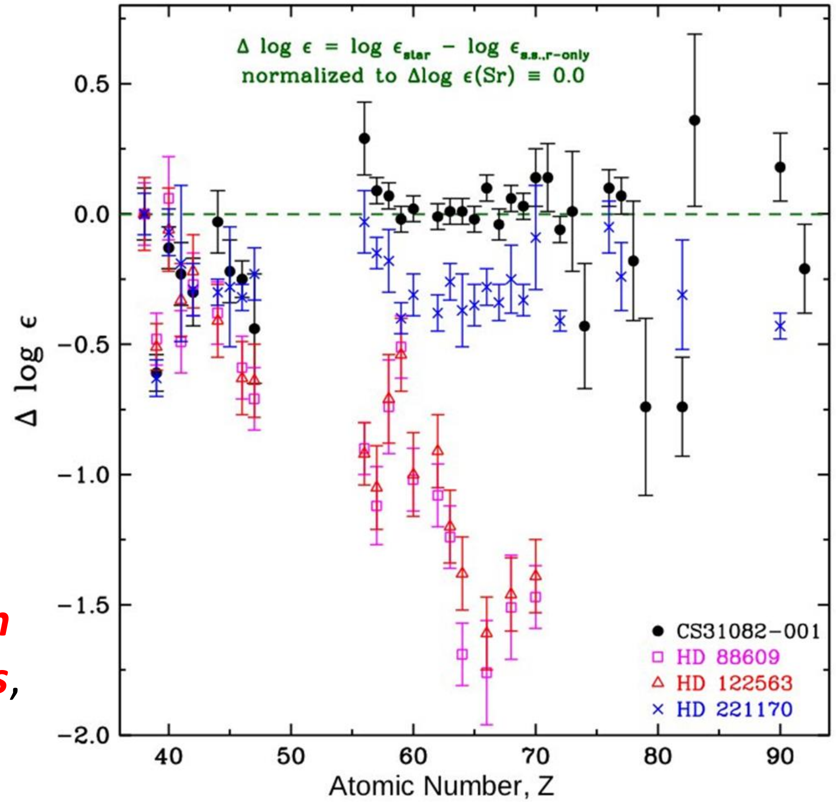


for [Fe/H]>-2 an apparent averaging over all type of events (with possibly different rarity) has taken place



Abundance variations
In r-process elements

a) from Farouqi + (2022)
b) from Cowan + (2021)
c) from Mishenina + (2023)



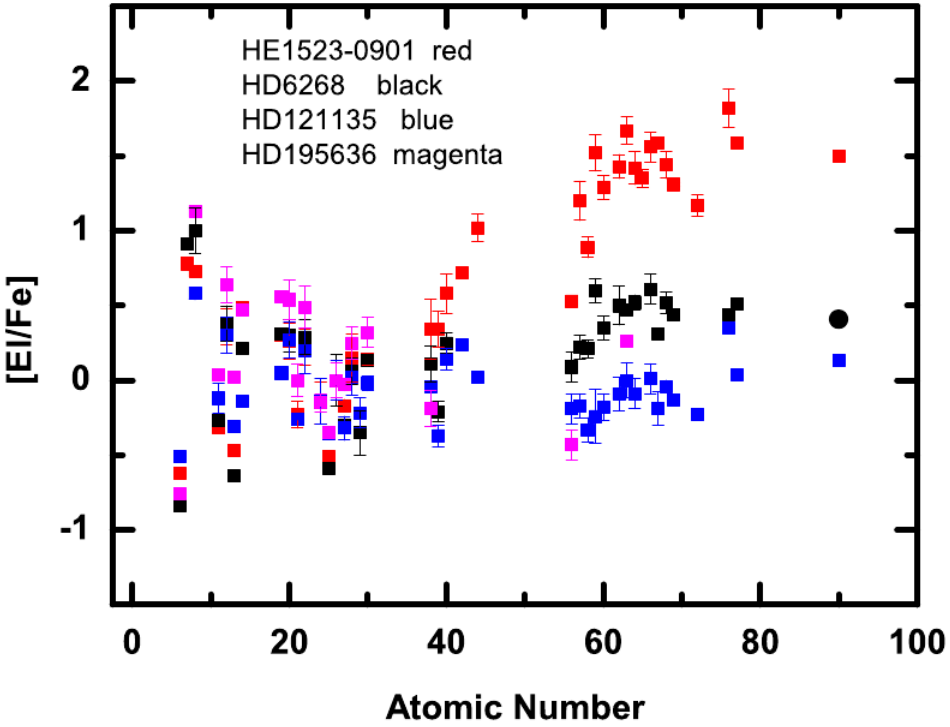
Among observations there exist variations in comparison to solar r-process abundances,

e.g.

so-called limited-r stars (Honda-type stars) with a much steeper abundance decline and no observed 3rd peak, [Eu/Fe]<0-0.3

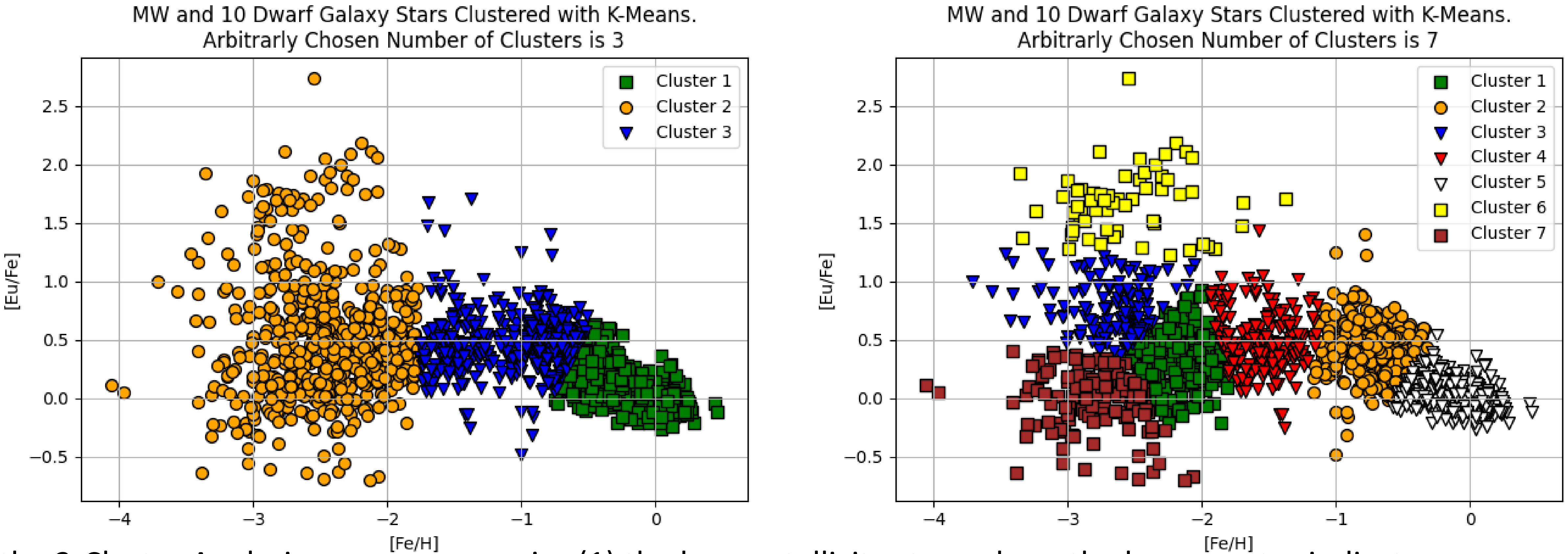
r-I stars with 0-0.3<[Eu/Fe]<1

r-II stars with [Eu/Fe]>1



indicating a variety of enhancements over solar the r-process pattern.

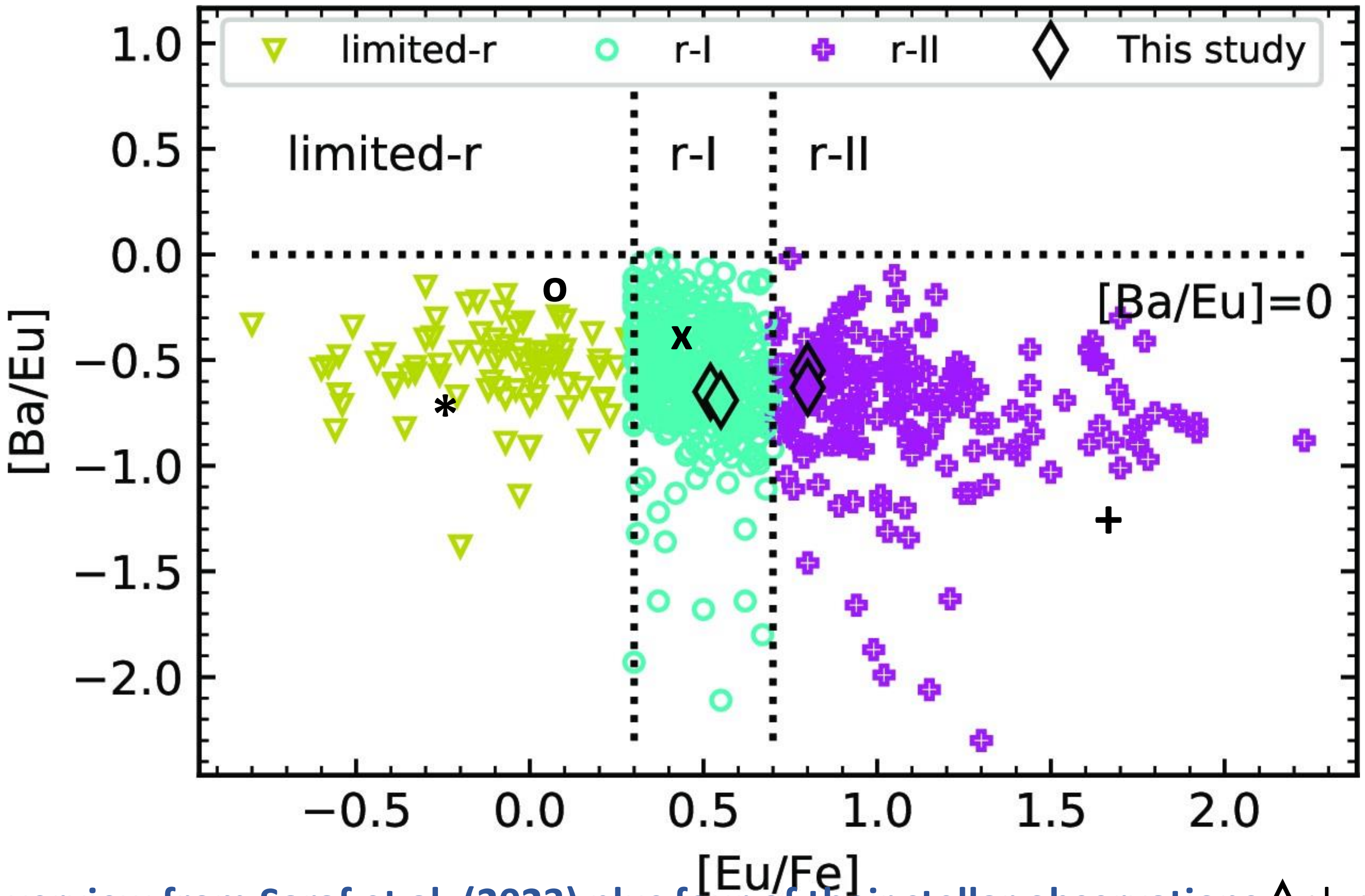
K-Means Cluster Analysis **(a K-Means cluster analysis divides data into K groups of similar data patterns – here applied to abundances)**



In the 3-Cluster Analysis one can recognize (1) the low metallicity stars where the large scatter indicates contributions from individual rare or different events, (2) for [Fe/H]>-2 where already an averaging/mixing of event products set in and the scatter becomes small, (3) Fe is contributed also from SNe Ia.

In the 7-cluster analysis one recognizes different stages of the approach to averaging/mixing (clusters 1, 2, 4, 5) and for low-metallicity stars with [Fe/H]<-2.5 three clusters (3, 6, 7), with properties close to the observational limited-r, r-I, and r-II classes.

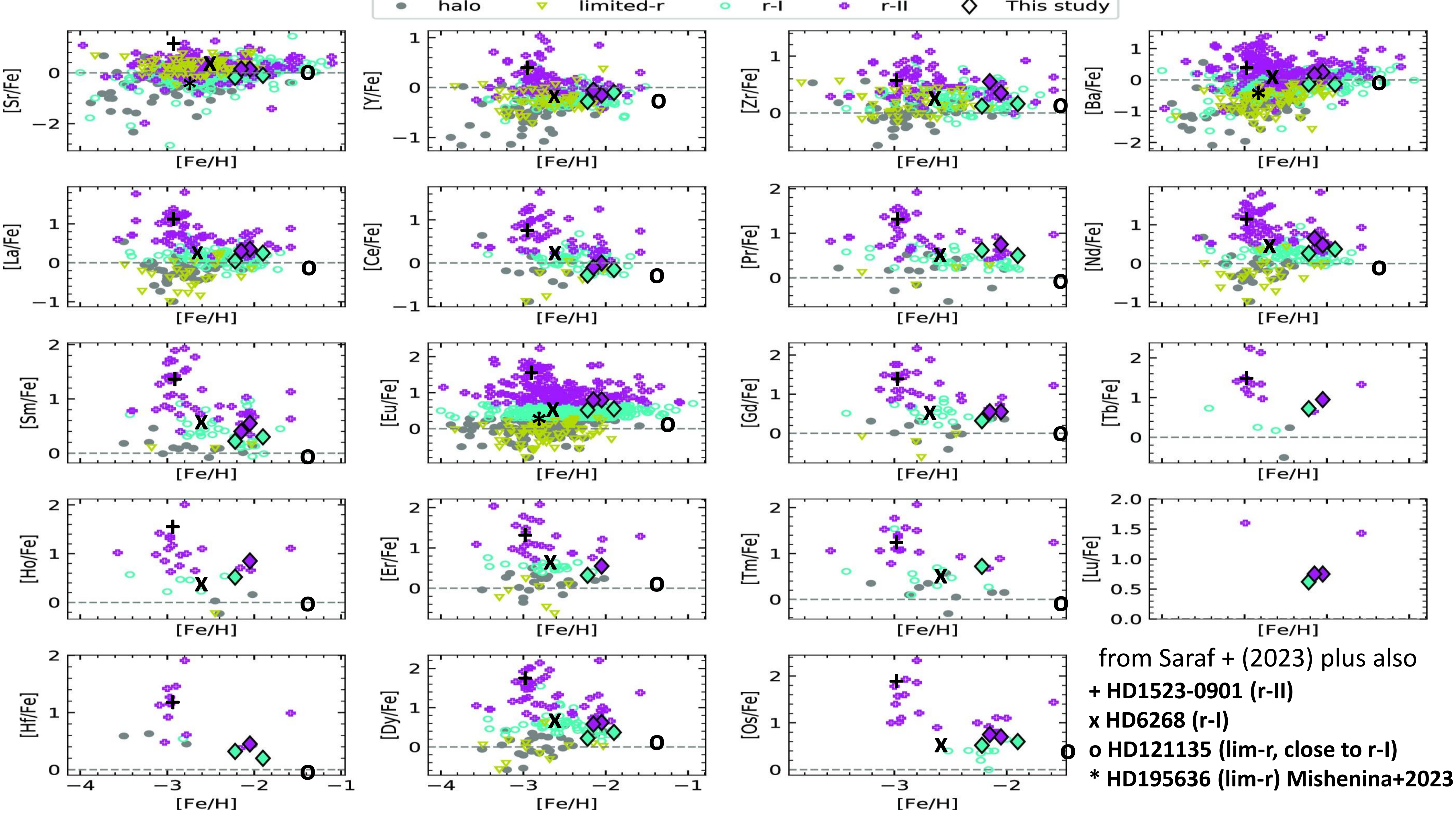
Distribution of [Ba/Eu] as a function of [Eu/Fe]. The limited-r stars are shown in yellow colours, the r-I in green, r-II in blue



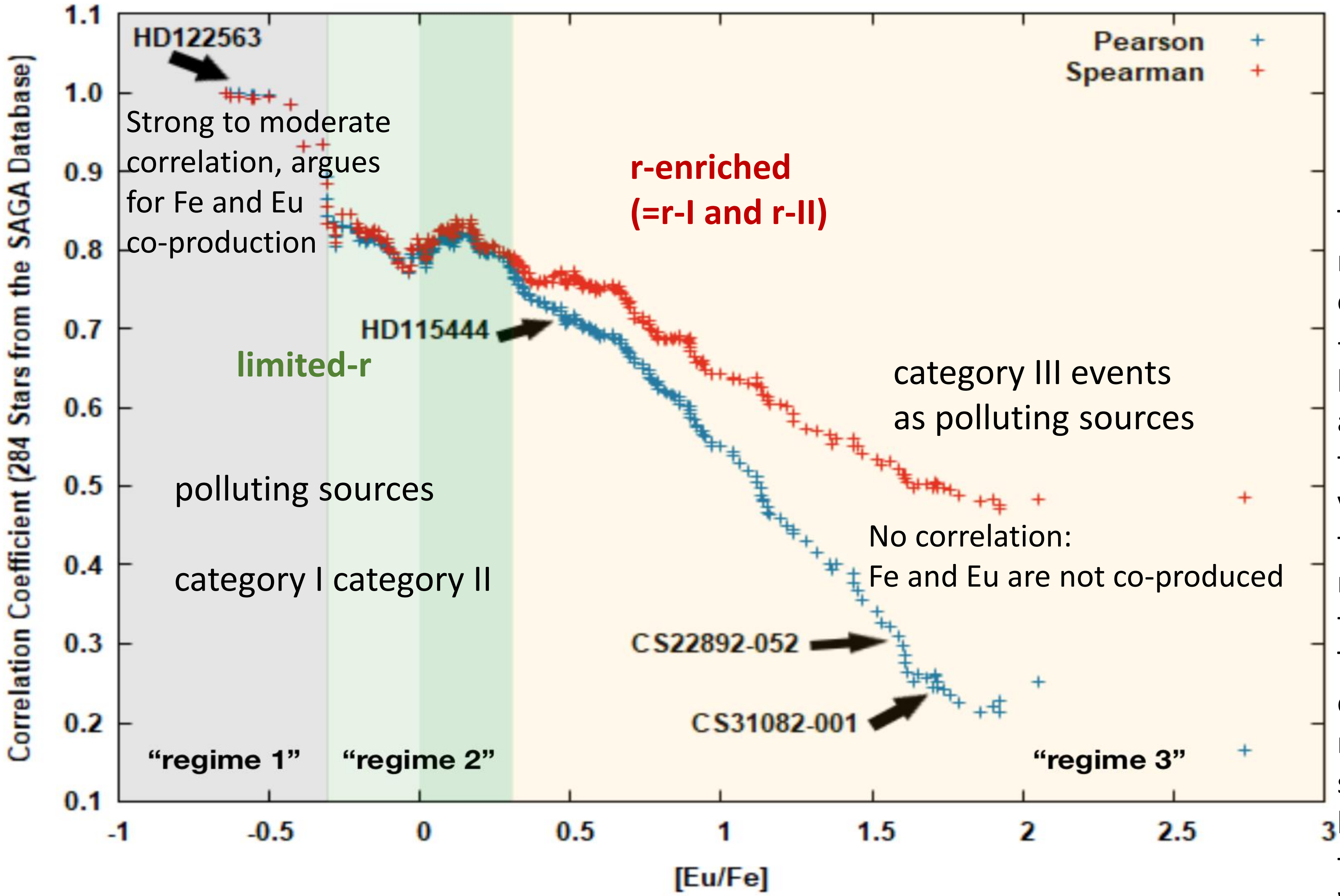
There is a debate whether the lim-r/r-I dividing line should be closer to [Eu/Fe]=0 (see later Farouqi + 2022)

collected literature overview from Saraf et al. (2023) plus four of their stellar observations ◊plus 4 obs. from Mishenina + (2023)

+ HD1523-0901, x HD6268, o HD121135, * HD195636 (fast rotator)with [Fe/H] = -3, -2.6, -1.4, and -2.8 (HD121135 with [Fe/H]=-1.4 might have already a slight Ba s-process contribution)


halo
limited-r
r-I
r-II
This study
[Sr/Fe]
[Y/Fe]
[Zr/Fe]
[Ba/Fe]
[La/Fe]
[Ce/Fe]
[Pr/Fe]
[Nd/Fe]
[Sm/Fe]
[Eu/Fe]
[Gd/Fe]
[Tb/Fe]
[Ho/Fe]
[Er/Fe]
[Tm/Fe]
[Lu/Fe]
[Hf/Fe]
[Dy/Fe]
[Os/Fe]
[Fe/H]
from Saraf + (2023) plus also
+ HD1523-0901 (r-II)
x HD6268 (r-I)
o HD121135 (lim-r, close to r-I)
* HD195636 (lim-r) Mishenina+2023

Correlation between Eu and Fe

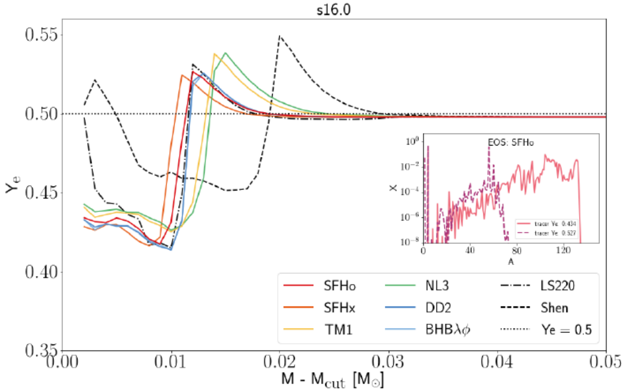


The Pearson correlation measures the agreement of a linear relation - here abundances - between Fe and Eu for all stars with [Eu/Fe] less than the abzissa value. A value of 1 would indicate that in all stars the Eu/Fe ratio is identical, pointing to the same origin. The Spearman correlation coefficient measures them in a slightly «milder» way, based on ranks rather than a linear relation. When both methods deviate, it also indicates the start of a different correlation pattern.

Among the limited-r stars there seem to dominate two types of contributions?

Sources of r-Process Abundances?

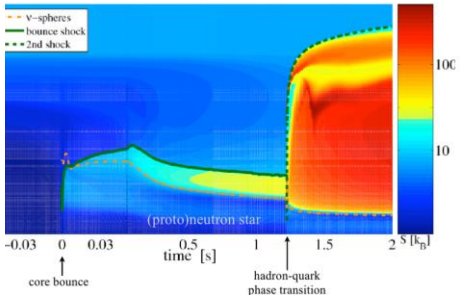
CCSNe



e.g. Curtis+ 2019, Ebinger+ 2020 Ghosh+ 2022, but see also Wang & Burrows 2023

very weak r-process and νp-process, possibly up to Sr

quark-deconfinement supernovae



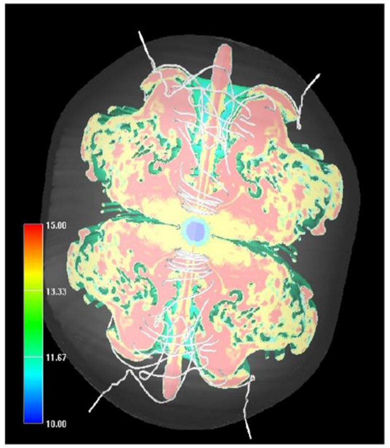
e.g. Fischer+ 2020

weak r-process

????????

strongly dependent on EoS

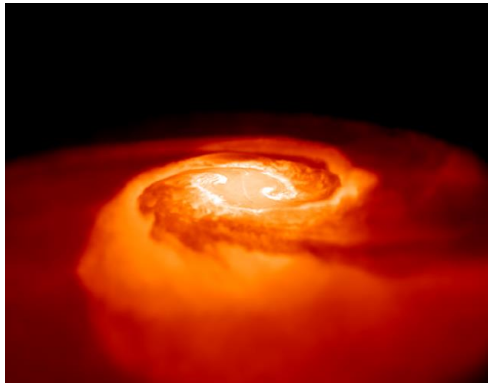
magnetorotational supernovae



e.g. Winteler+ 2012, Nishimura+ 2017, Mösta+ 2018, Reichert+ 2021, Reichert+ 2023, Ober-Gaulinger & Reichert 2023

weak r-process

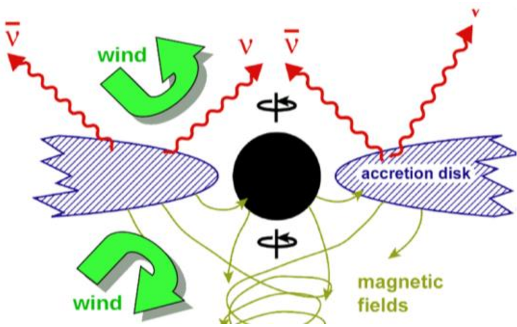
compact binary mergers



e.g. Rosswog+ 2017, Thielemann + 2017, ….. Metzger, Wu, Radice, Hotokezaka, Just, Janka, Wanajo, Goriely, Bauswein. Holmbeck, Lund, Perego, Siegel …

negligible Fe ejection

Collapsars/hypernovae



e.g. Heger & Woosley 2006, Siegel+ 2019, 2022

Although hypernovae eject much Fe, the Fe/r ratio is negigible in comparison to solar

← strong r-process →

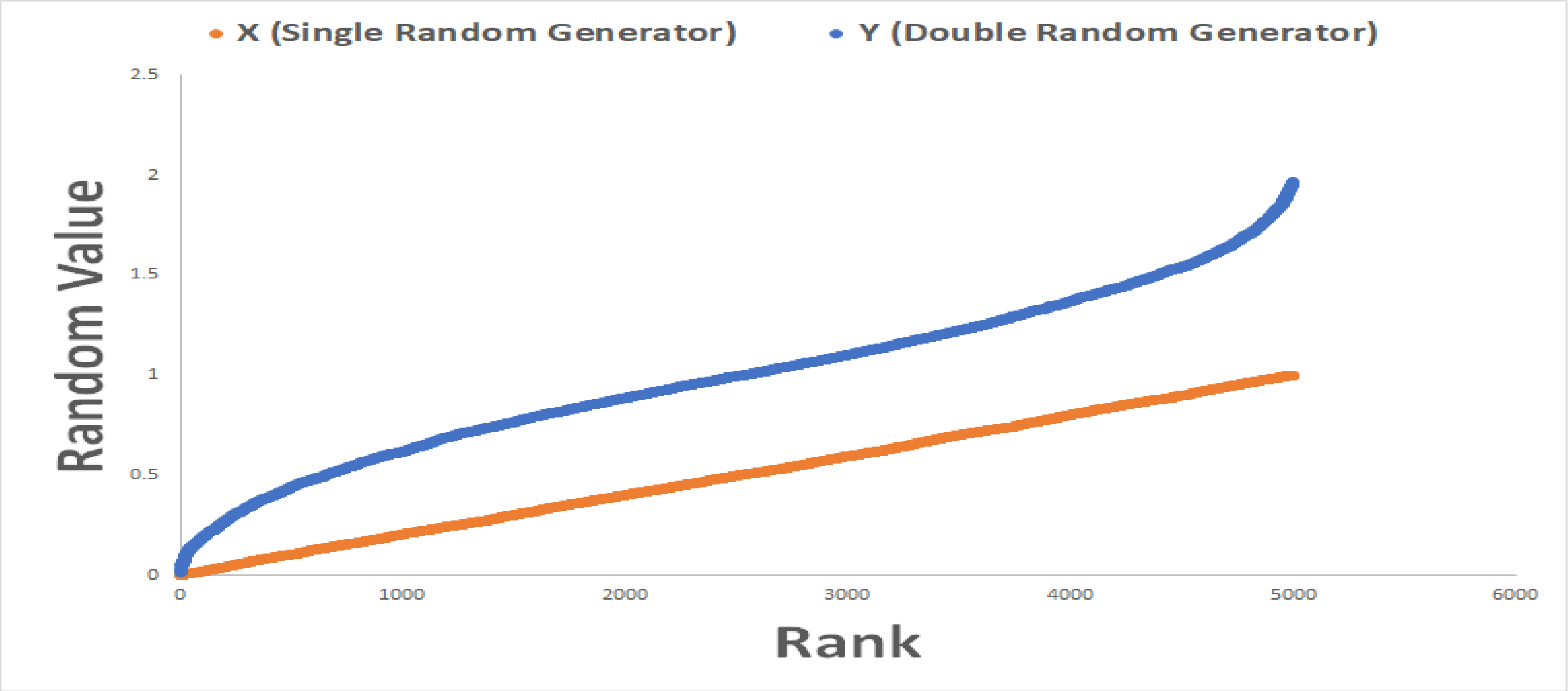
all these objects eject also Fe (MR supernovae smaller amounts but noticable)

← should come with Fe →

Dependent on final central object (NS or BH) and timescale of collapse, highly neutron-rich matter can be ejected from accretion disk (actinide boost?)

Do we have a way from observations to distinguish between these sources?

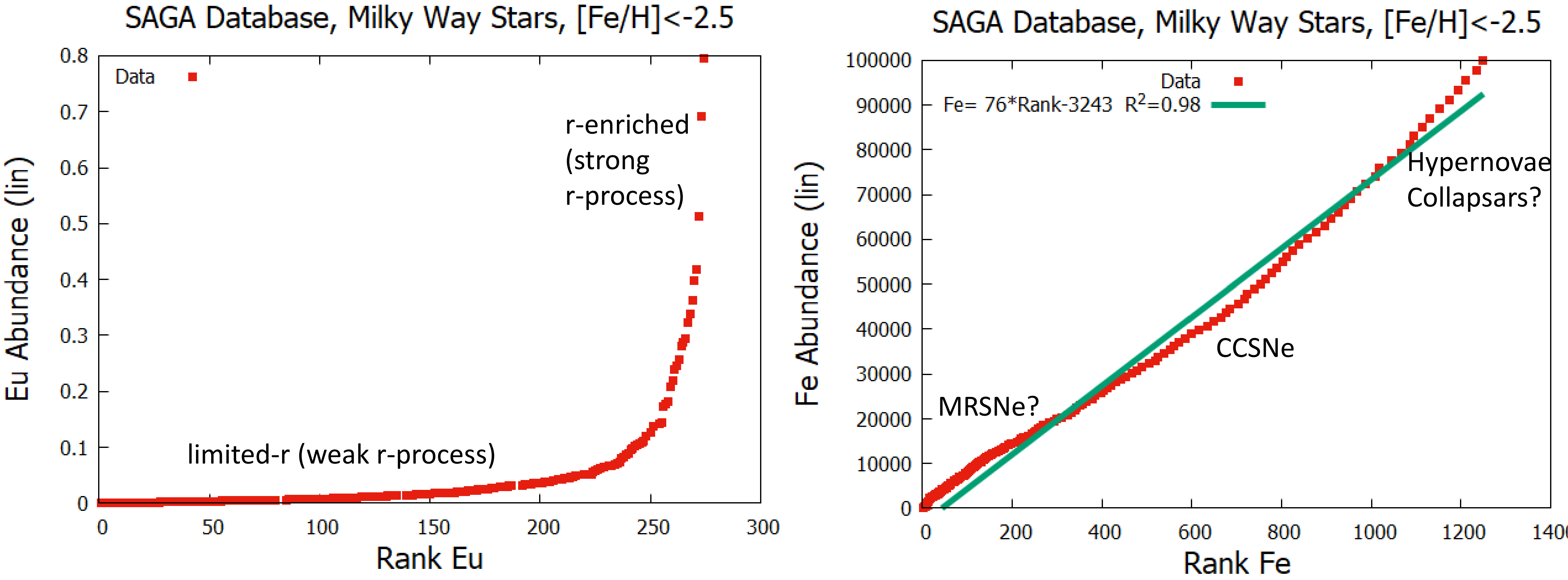
Rank Tests (How can we decide whether one or two/several events contributed?)



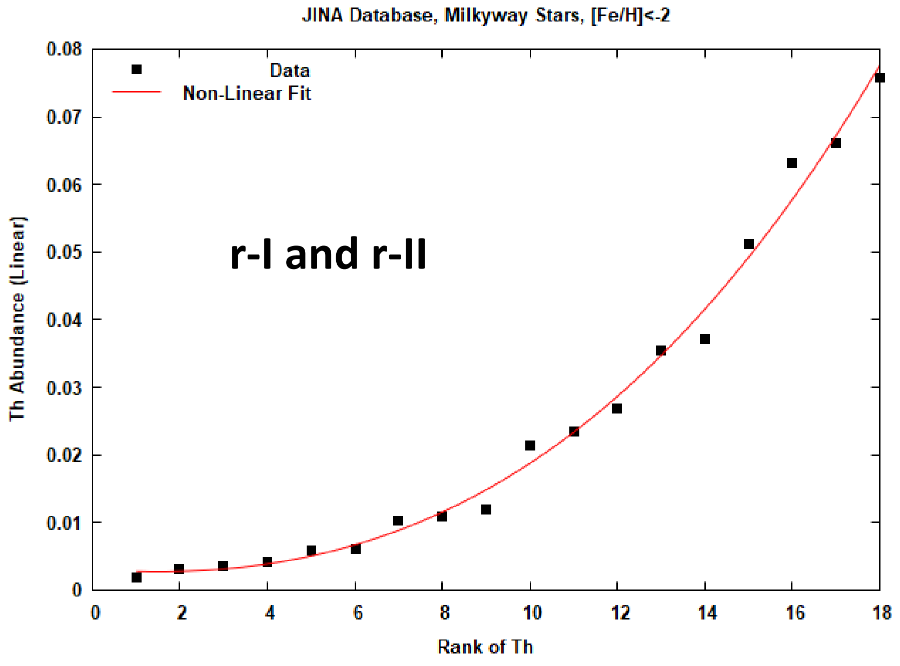
1 (orange): utilzing a single random number generator X (0-1, multiplied with a specific source value to obtain an X1 distribution), ordering the values according to their size, giving them integer entries (ranks), and plotting them as a function of their ranks, leads to a linear relation between the random numbers and their ranks.

2 (blue): utilizing two random number generated distributions (with a second specific source value), adding their values Y=X1+X2 and plotting Y as a function of its ranks, deviates from a linear relation between Y and its ranks. The deviation at low ranks depends on the fact whether the second contribution includes more or less low-value entries. The deviation at high ranks depends on the number of high-value entries.

If one applies this method to abundance observations of individual elements as a function of rank, it can indicate whether only one type of nucleosynthesis source or two or several contributed to this element.



Left: Eu abundances versus their corresponding ranks. The integer rank passes, with increasing Eu abundances, through all observational points from the smallest to the highest abundance. The fit deviates strongly from a linear behavior at high Eu ranks. This argues for a superposition with an additional Eu source, especially responsible for the high Eu abundances. A missing deviation from the linear slope at small ranks underlines that this additional Eu source contains essentially no contributions with negligible Eu production. Right: Fe abundances versus their corresponding ranks . The figure shows a close to linear relation. This would argue for a single or dominating production site (explosive Si-burning in CCSNe?). The slight deviation at high ranks could be interpreted as an additional source with high Fe production (hypernovae?), the slight deviation at low ranks as an addinitional source with small Fe production (magneto-rotational supernovae?)

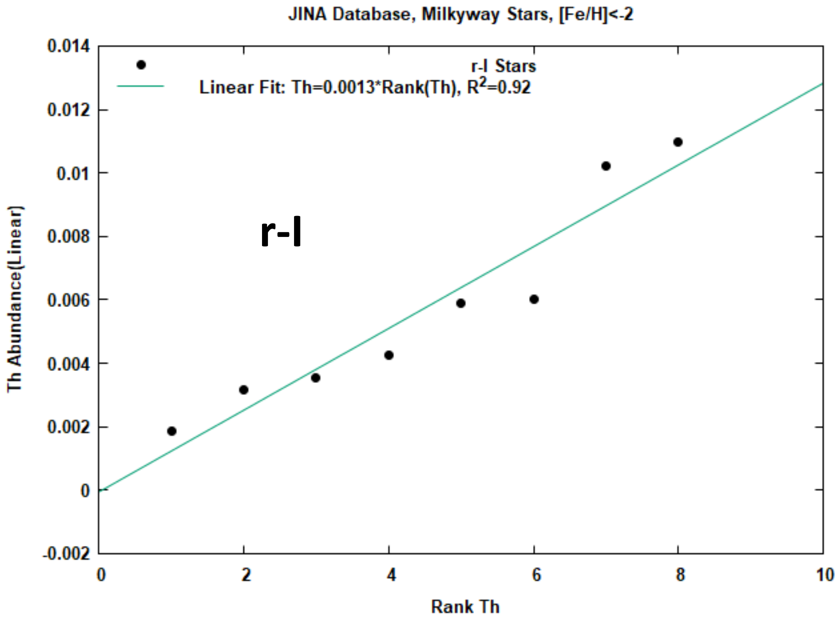


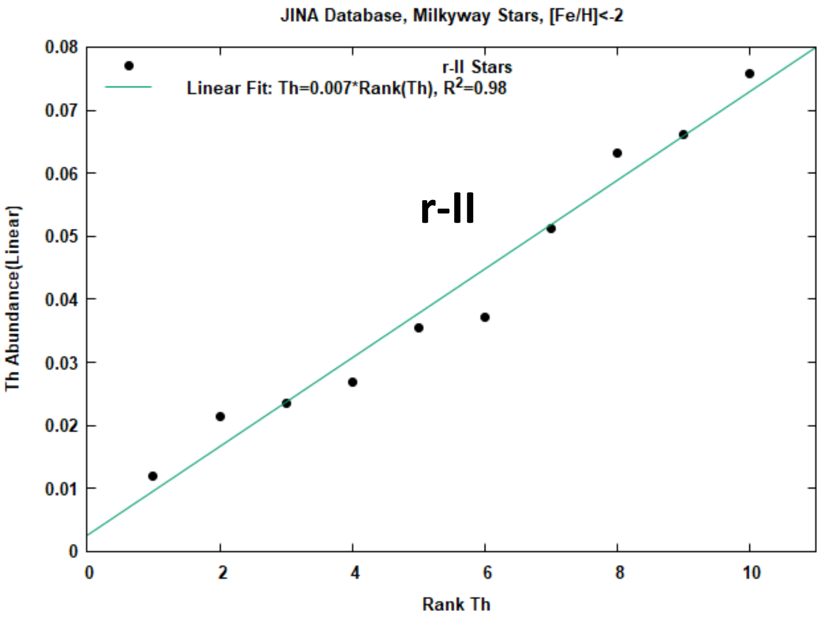
Rank test for Th in r-enriched (r-I and r-II stars)

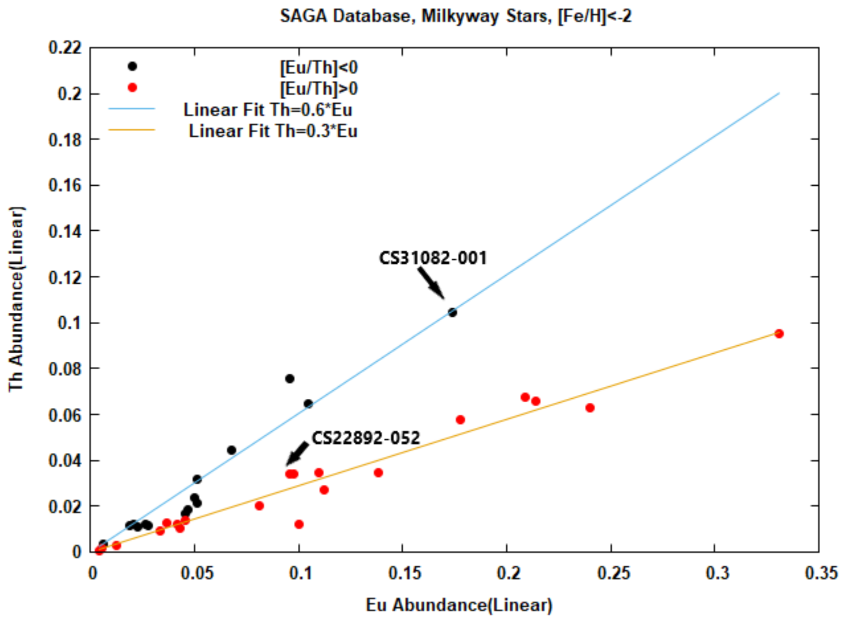
Need for a superposition of two types of events!

But linear rank relation when plotted for r-I and r-II stars separately (with slight scatter)

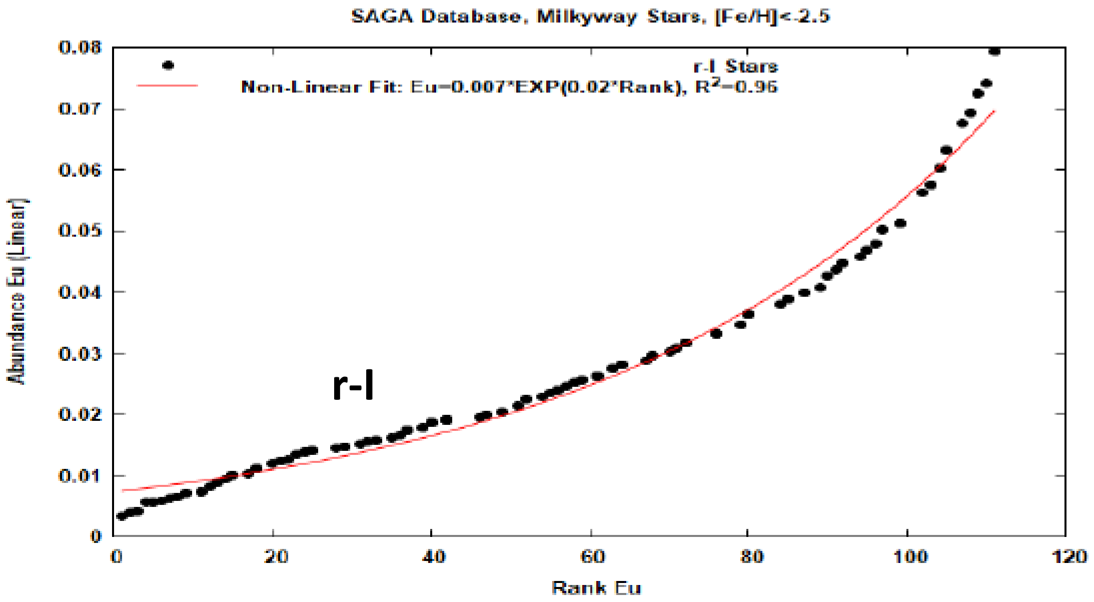
r-I and r-II stars seem each to be dominated by one type of event responsible for the Th production (leading to actinide boost and normal patterns)

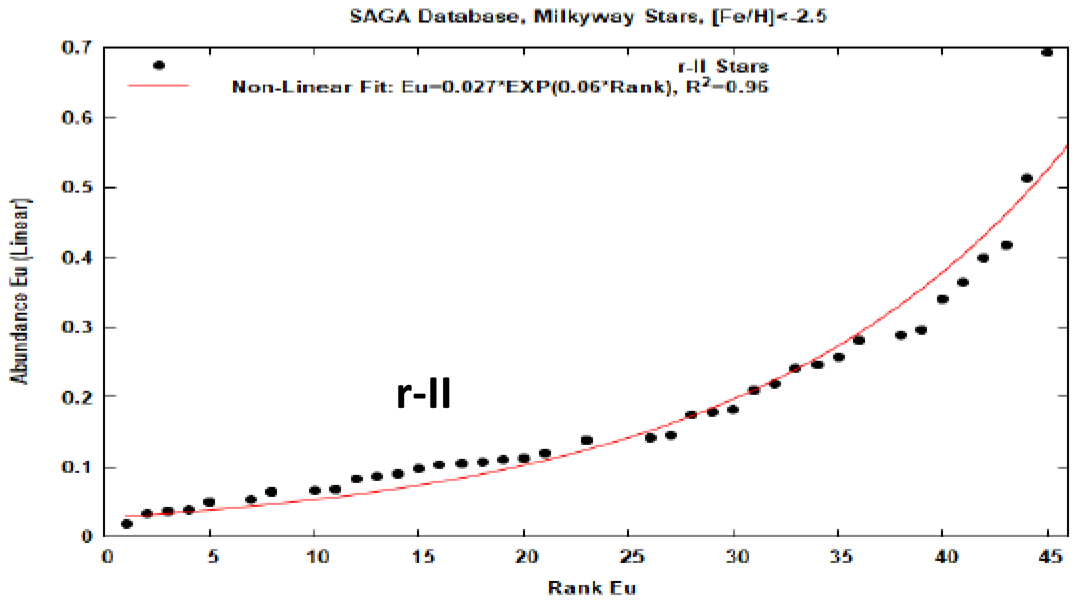






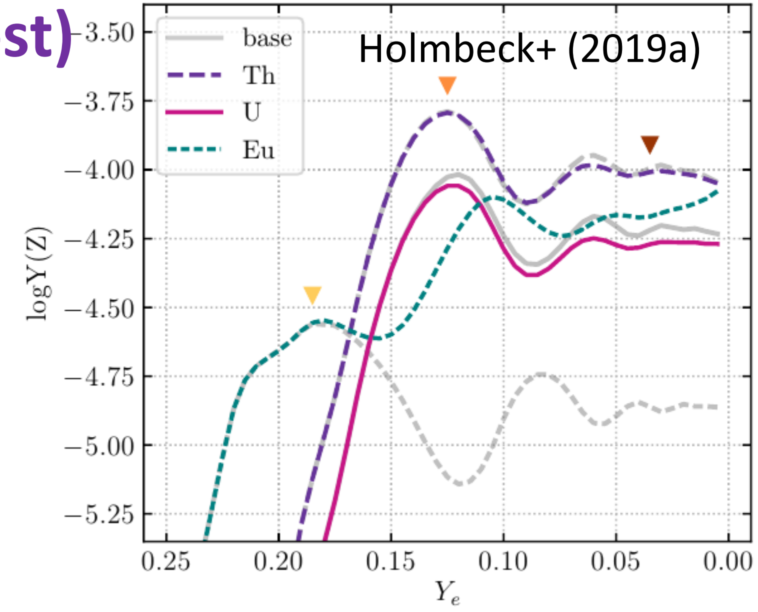
Rank test for Eu in r-I and r-II stars



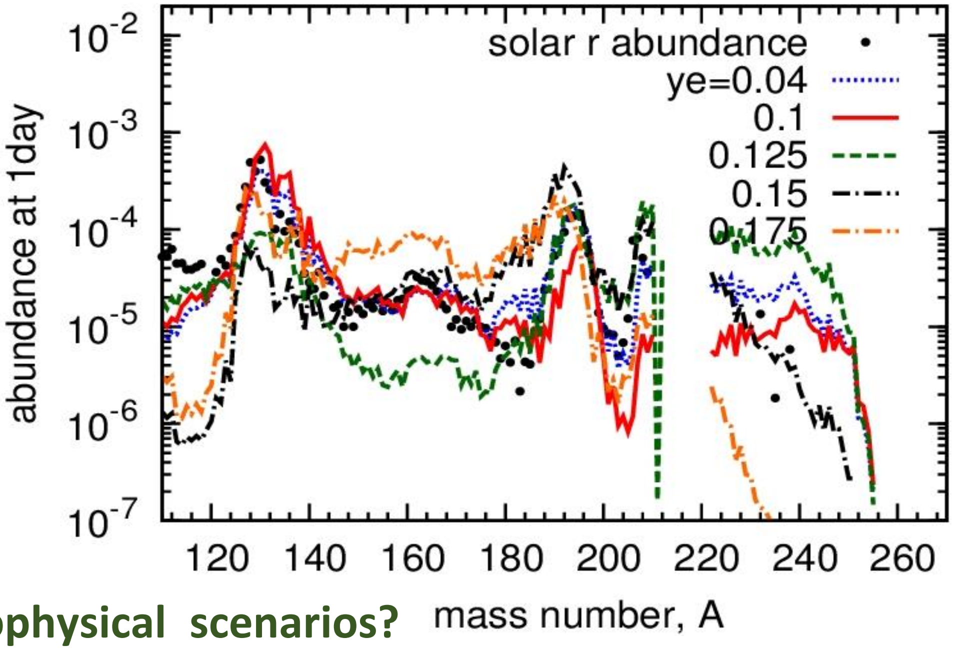


Opposite to Th, Eu does not show a linear rank relation, when only considering r-I and r-II stars separately. This argues for the fact that also among r-enriched (strong r-process r-I and r-II) stars weak r-process events «spill in» a Eu contribution.

Fission cycling affecting Th/Eu (actinide boost)



One finds different production of Eu, U, Th for different Ye conditions in r-process



From Wu+ 2017:
The DZ mass model permits large variations of actinide production, even at low Ye's.
Do we have different Ye-superpositions in the same type of event, or are certain types of events dominated by low Ye's while others show a larger superposition spread just going down to Ye=0.15 or 0.125?

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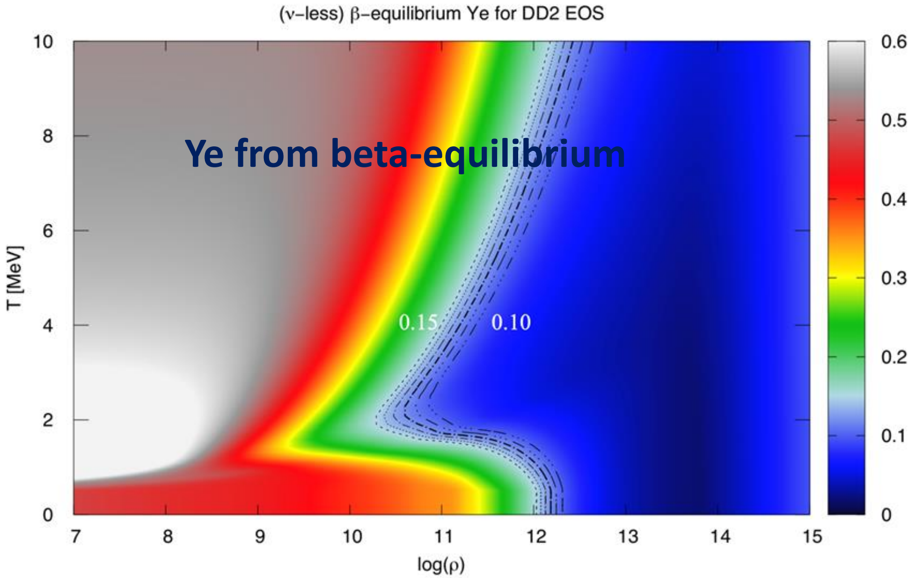
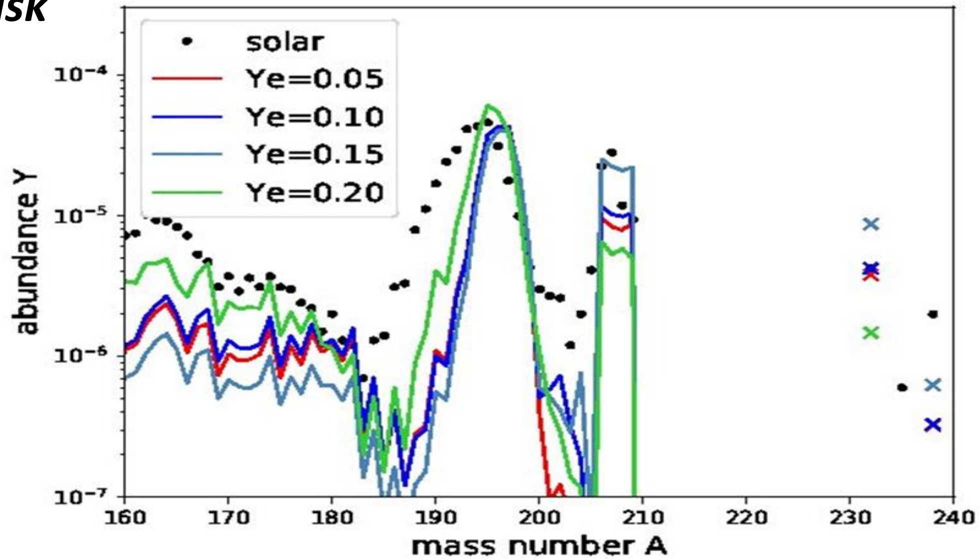
Which Ye-intervals are incorporated in astrophysical scenarios?

Maximum actinide to Eu ratio in Ye-interval 0.1-0.15 (favored in BH accretion disk outflows)

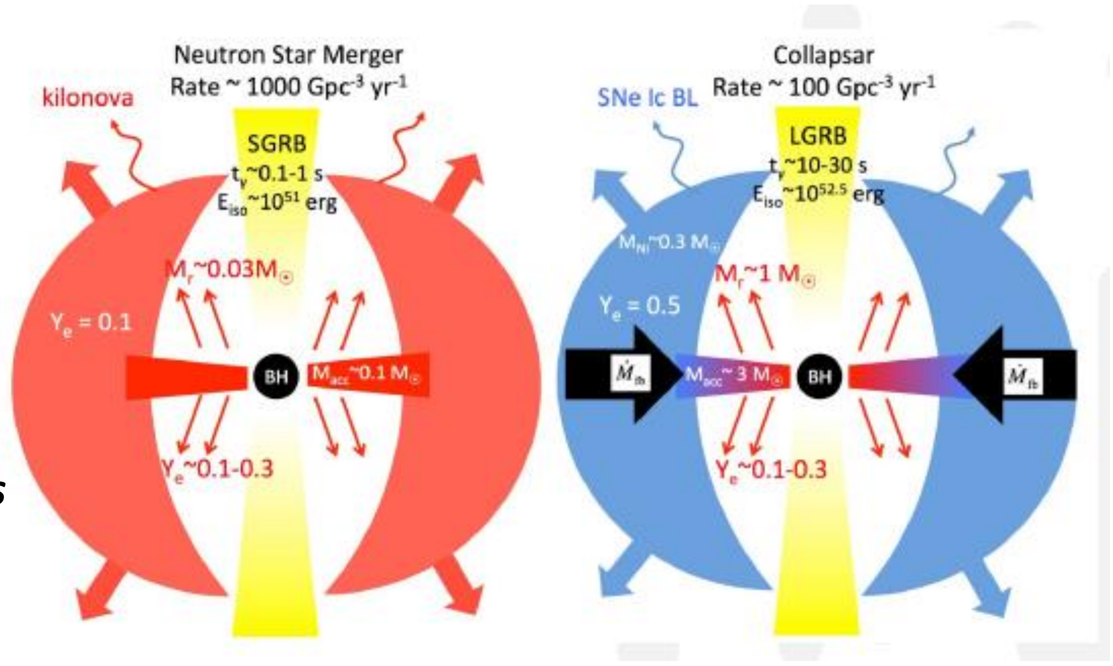


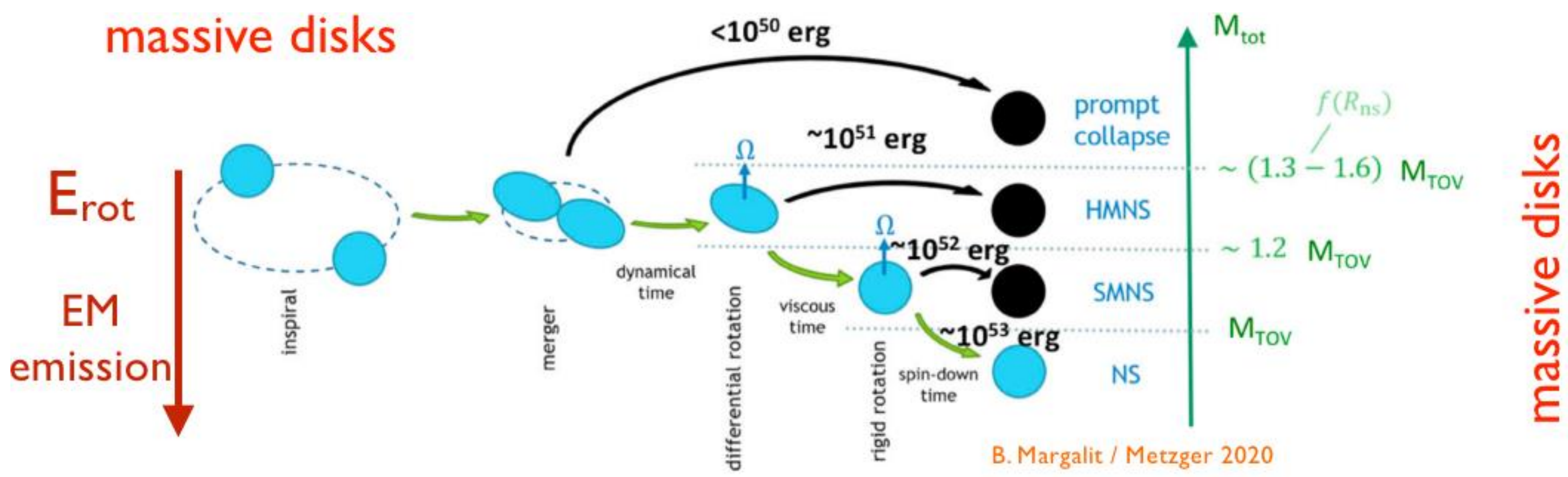
see also Eichler et al. (2019)



Mergers vs. Collapsars (Siegel 2019)

BH formation produces massive accretion disks
Maximum actinide to Eu ratio in Ye-interval 0.1-0.15 (favored in BH accretion disk outflows, up to 20-40% of disk material). In collapsars about 30 times more disk matter than in mergers. How much matter with Ye>0.2-0.3 is contained in overall ejecta? Which Ye spread seen in mergers vs. collapsars, determining actinide-normal or actinide boost composition?

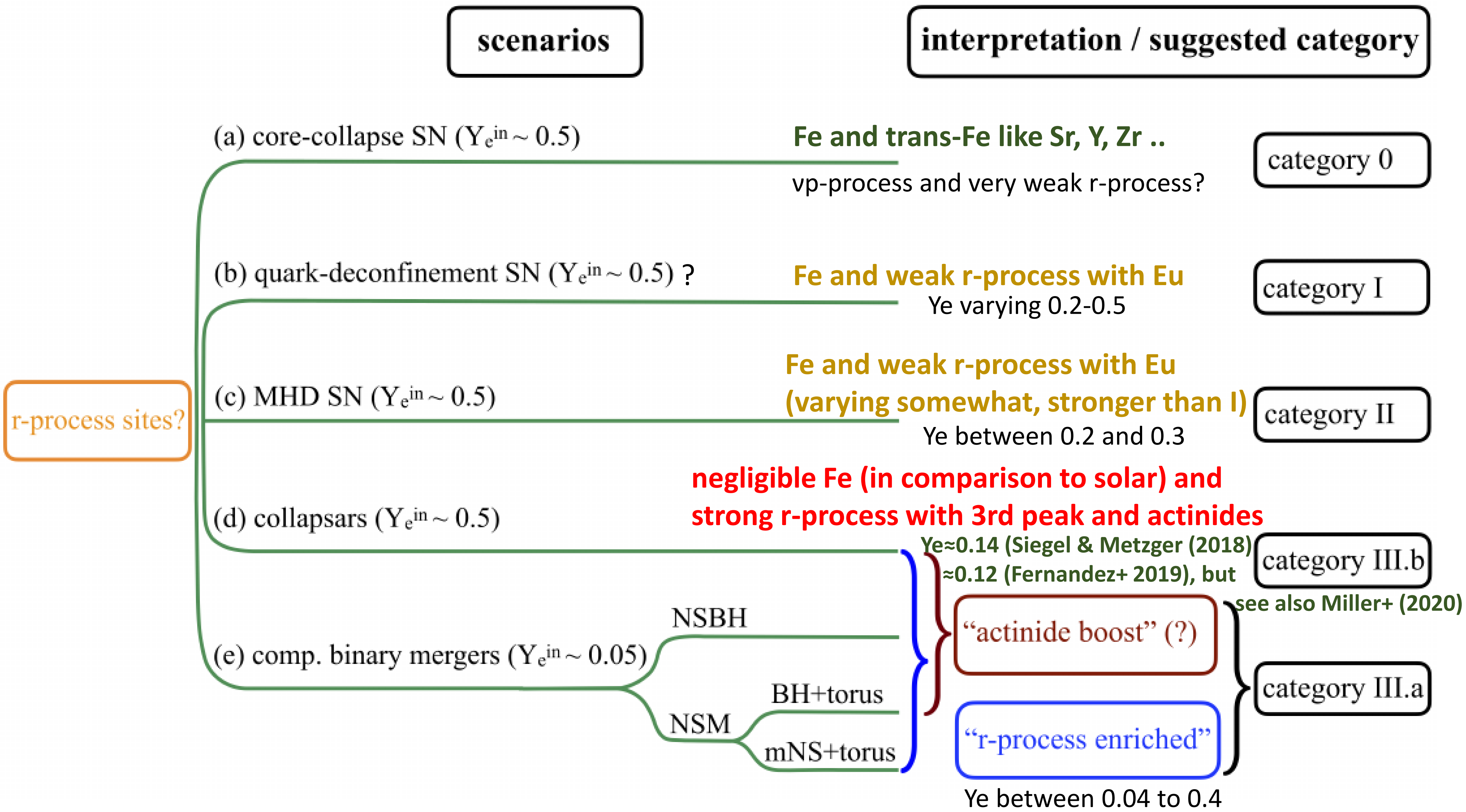




delayed
BH formation

(from Siegel at MICRA/Trento 2023)

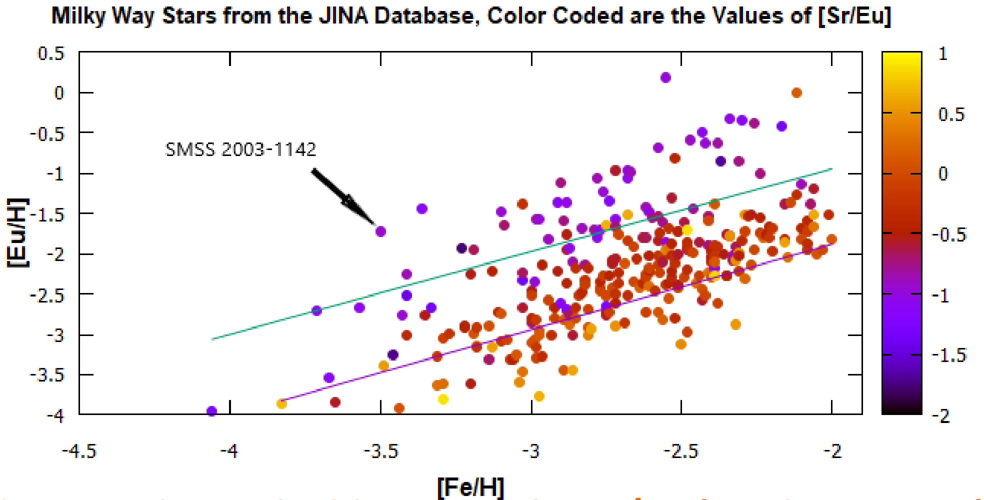
Suggested scenarios for r-process sites (Farouqi+ 2022)



There exist actinide-boost stars with Th/Eu supersolar (>0.42, according to Lodders 2020), mostly among r-II stars
(**limited-r** with [Eu/Fe]<0-0.3; **r-I** with [Eu/Fe]<1 and **r-II** with [Eu/Fe]>1 **r-enriched**)
probably affected by fission cycling, high Th/Eu values obtained in simulations for Ye in the range 0.1-0.15 (Wu 2017, Holmbeck+ 2019, Eichler+ 2019)

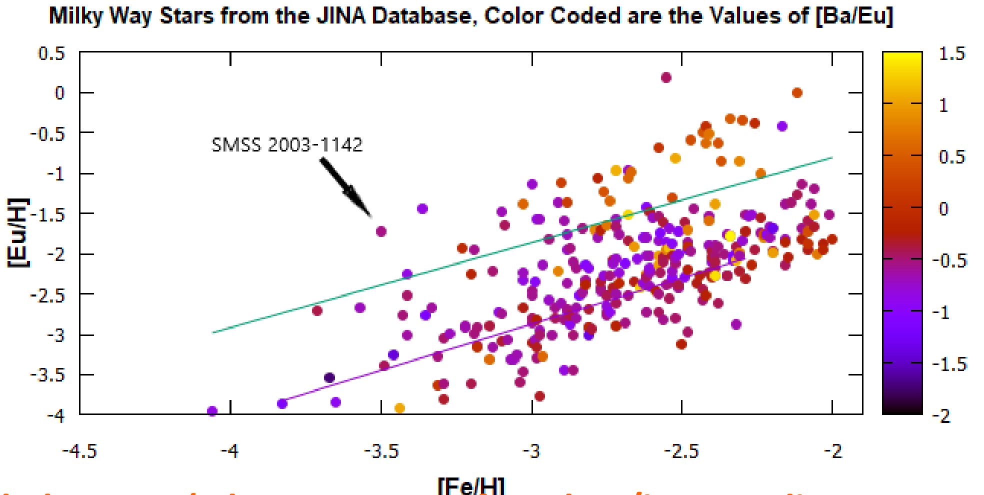
Star	Eu	Th	(Th/Eu)	regime 3 (complete r-process) subclass	[Eu/Fe]
TYC5329 – 1927 – 1	−1	−1.91	0.12	r – I	0.89
J0858 – 0809	−2.41	−3.07	0.22	r – I	0.23
HD108317	−1.37	−1.99	0.24	r – I	0.64
HD110184	−1.91	−2.5	0.26	r – I	0.08
HE1523 – 0901	−0.62	−1.2	0.26	r – II	1.86
CS22892 – 052	−0.86	−1.42	0.28	r – II	1.53
HD186478	−1.34	−1.85	0.31	r – I	0.63
CS29491 – 069	−0.96	−1.46	0.32	r – II	1.12
RAVEJ203843.2 – 002333	−0.75	−1.24	0.32	r – II	1.64
CS29497 – 004	−0.68	−1.17	0.32	r – II	1.44
J1432 – 4125	−1.01	−1.47	0.35	r – II	1.44
HE0240 – 0807	−1.44	−1.9	0.35	r – I	0.55
BD – 15$_5$781	−2.28	−2.73	0.35	r – I	0.12
HE2224 + 0143	−1.02	−1.47	0.35	r – I	0.87
HE2327 – 5642	−1.29	−1.67	0.42	r – II	1.07
HD6268	−1.56	−1.93	0.43	r – I	0.54
HD115444	−1.64	−1.97	0.47	r – I	0.68
HE2252 – 4225	−1.3	−1.63	0.47	r – II	1.12
CS22953 – 003	−1.69	−1.92	0.59	r – I or r – II	0.92
CS31082 – 001	−0.76	−0.98	0.60	r – II	1.62
CS30315 – 029	−2.24	−2.45	0.62	r – I	0.67
HE1219 – 0312	−0.98	−1.19	0.62	r – II	1.47
CS31078 – 018	−1.17	−1.35	0.66	r – II	1.15
2MASSJ09544277 + 5246414	−1.19	−1.31	0.76	r – II	1.28

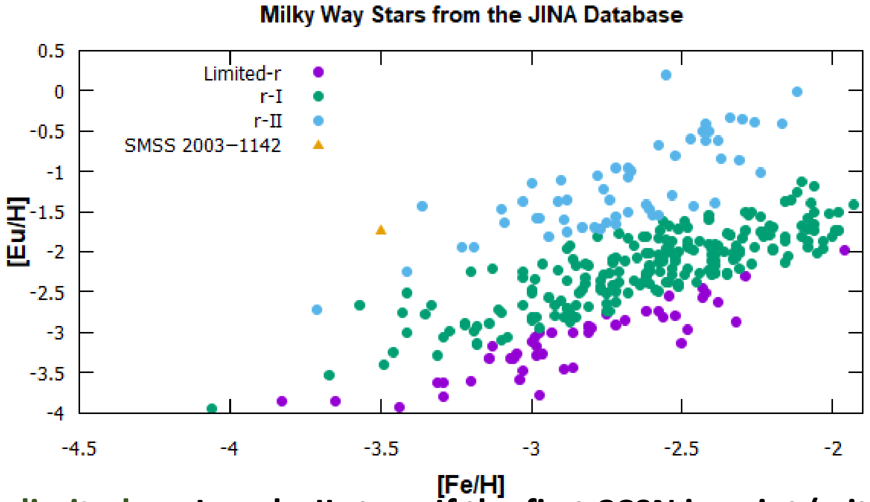
[X/H] vs [Fe/H] plots from JINA and SAGA databases with SMSS 2003-1142 (Yong + 2021)



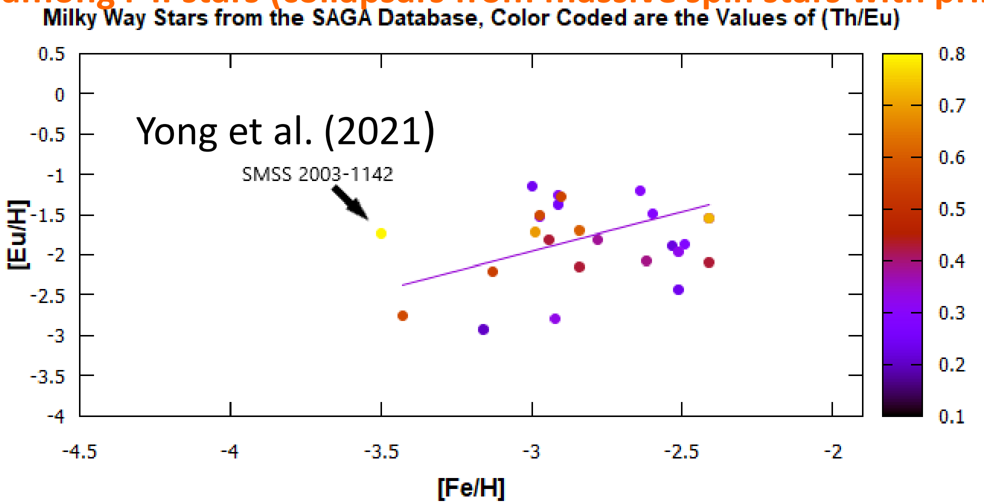
Limited-r stars show a highly supersolar Sr/Eu (weak r-process)

We find solar to supersolar Ba/Eu (s-process) already at metallicities below -1.5 (where s-process from low/intermediate mass stars sets in) among r-II stars (collapsars from massive spin stars with primary $^{14}N/^{22}Ne$)





Division into limited-r, r-I, and r-II stars. If the first CCSN imprint (with 1% pollution to a new-born star) appears at [Fe/H]=-5, and MHD supernovae, leading to magnetars occur less by 1/10, we expect the first imprint at -4. Even less frequent events show up at -3.5 to -3.



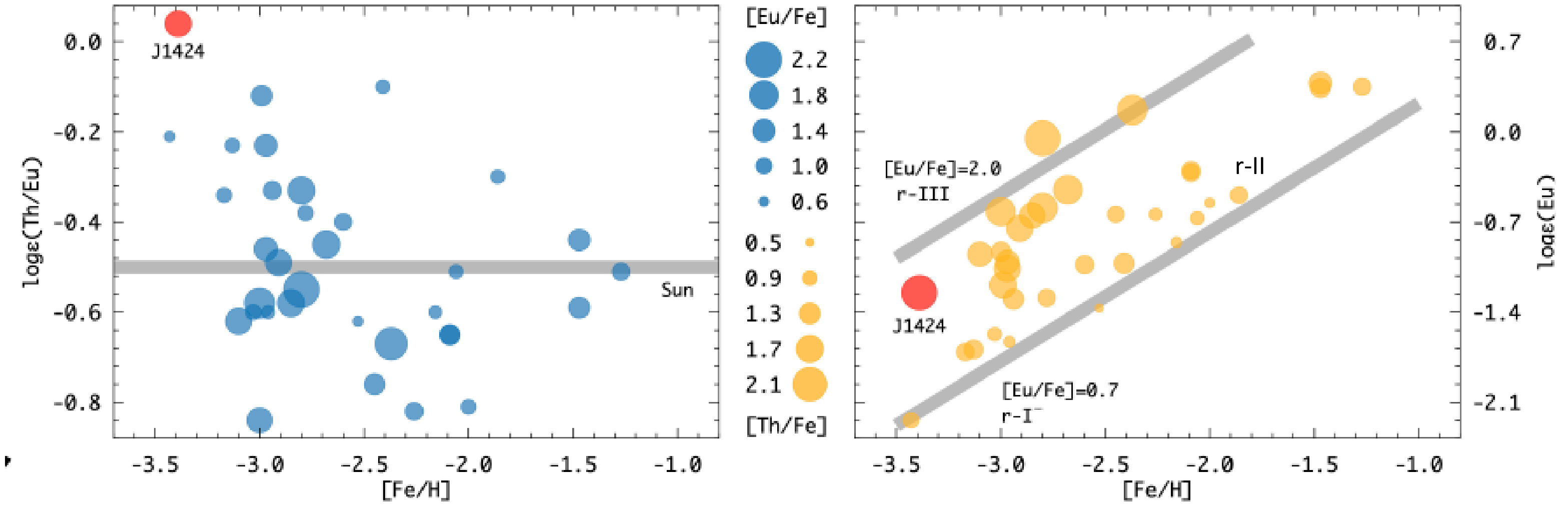
Strongly supersolar Th/Eu (actinide boosts) are dominantly found among r-II and the upper end of r-I stars

Events occur with different occurrence frequencies, ranging from frequent to rare events

The most frequent stellar explosions are CCSNe with imprint already seen in galactic evolution as early as [Fe/H]=-6.

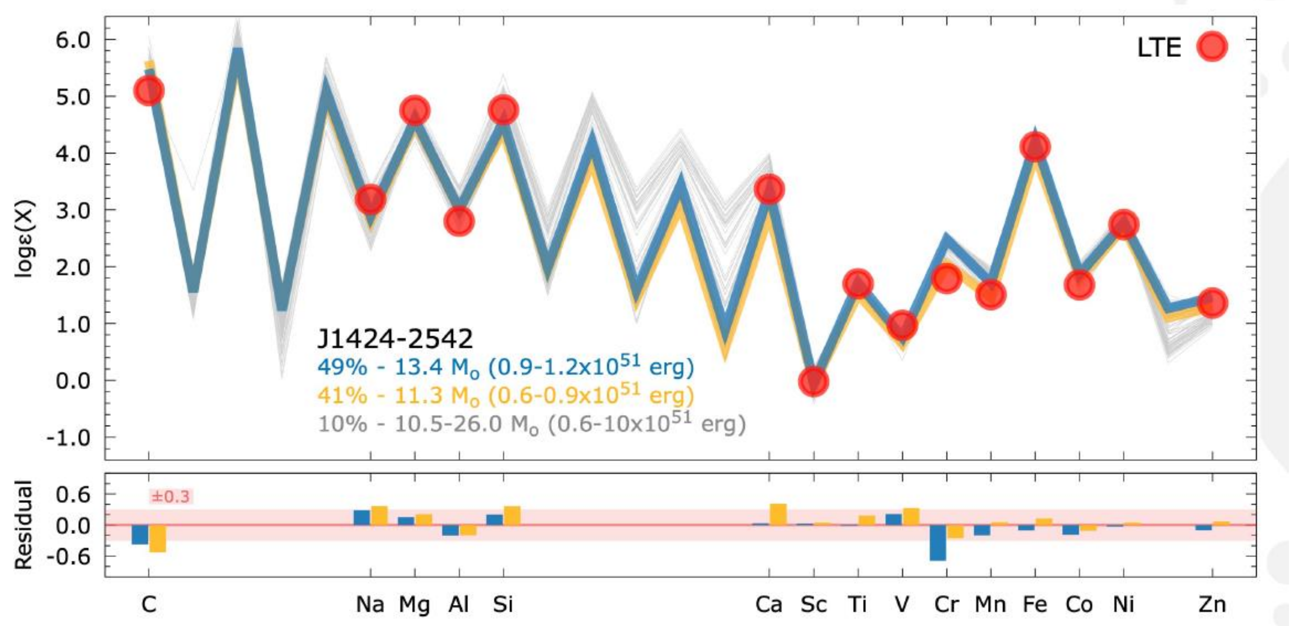
The first limited-r events are observed around [Fe/H]=-4, while r-I and r-II show up around [Fe/H] around -3.5. Thus: limited-r producing events are apparently the most frequent of the r-process sites and probably related to a rare class of supernovae (most probably magnetorotational supernovae),

r-I and r-II pattern producing events are rarer, possibly related to compact mergers and collapsars, with a fraction of the latter possibly (and specific mergers with delayed BH formation and accretion disk outflows?) responsible for actinide boosts.

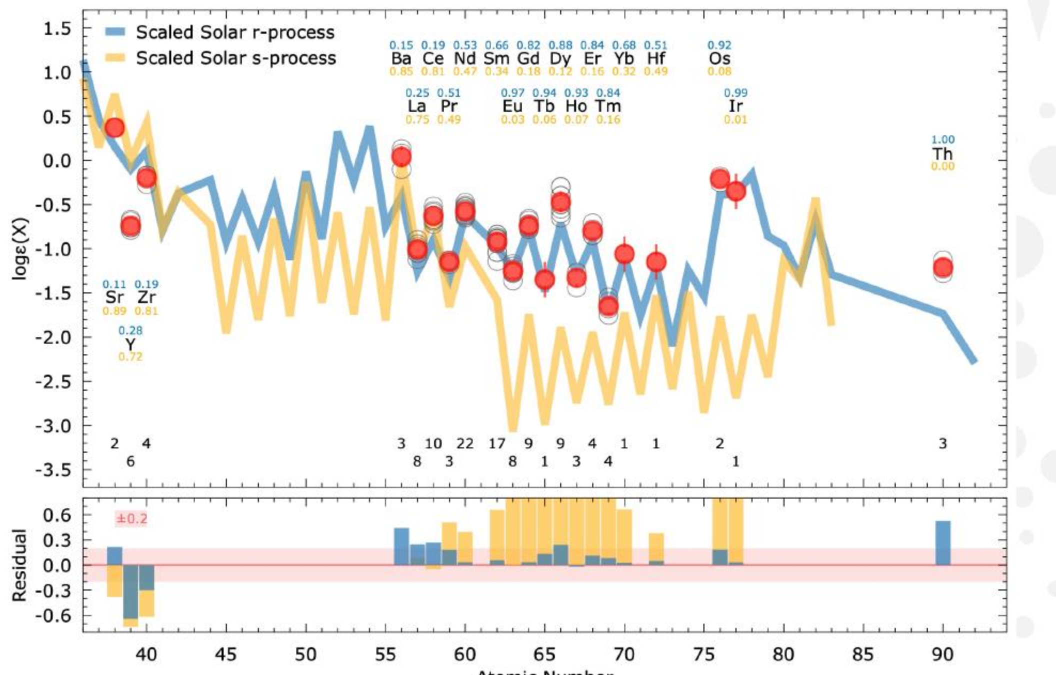


J1424-2542 **a new actinide-boost r-II star** ***(from*** ***Placco's IReNA online Seminar 7 Oct 2023, Placco+ submitted)*** **shows among the light and intermediate mass elements a typical CCSN composition and among the heavy elements a solar r-process composition with actinide boost**

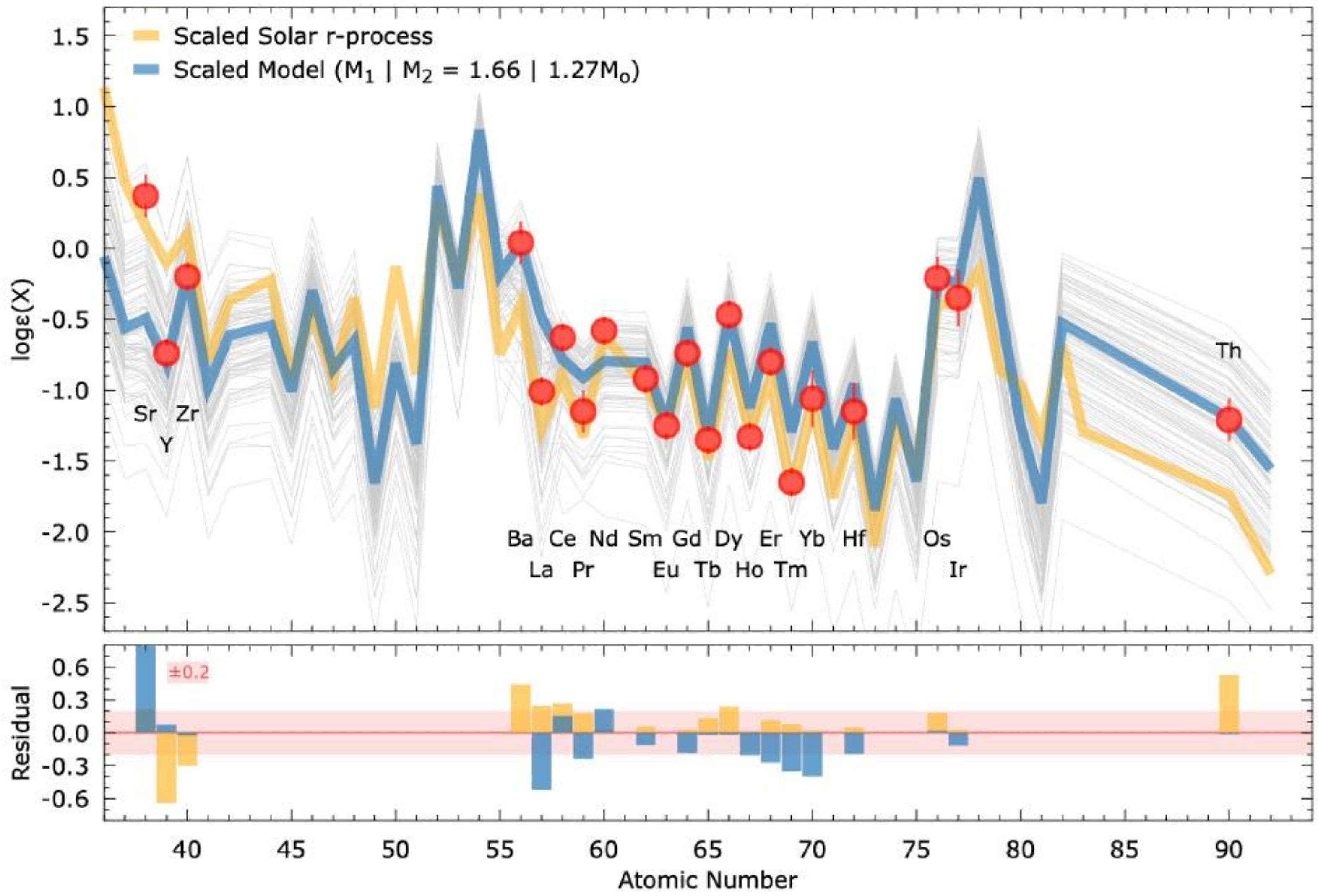
SPLUS J1424-2542 → light-element abundances vs. Pop III SN yields



SPLUS J1424-2542 → heavy-element abundances vs. Solar System



SPLUS J1424-2542 → heavy-element abundances vs. neutron star merger



(Placco's IReNA online Seminar 7 Oct 2023, Placco+ submitted)

The heavy element abundances of r-II star J1424-2542 requires a weak and a strong (actinide-boost) r-process contribution.
The debate will be whether the latter can be matched with BH accretion disk outflows from a massive neutron star binary, leading to an extended BH accretion disk or from a collapsar BH accretion disk as suggested by Farqoui+ (2022)
or both options are possible?

Independent investigations (e.g. Hartwig, Ishigaki et al. 2018, Cescutti, Morossi et al.2021, Han, Yang, Zhang et al. 2021, Scannapieco, Cescutti, Chiapini 2022, Molero, Magrini et al. 2022, Carrillo, Ness et al. 2023, as well as Fukagawa & Prantzos 2023, Skinner & Wise 2023 and Kolborg, Ramirez-Ruiz et al. 2023) tried to follow possible different contributions, including rare events, in early galactic evolution.
Here several suggested scenarios for r-process contributions, apparently fitting observed abundance patterns:

Farouqi+ (2022):

Ratio of magnetorotational (MR) supernovae to CCSNe about 1/10 (ratio between magnetar and overall neutron star formation), ratio compact binary mergers or collapsars to CCSNe 1/120 or 1/125 (i.e. very similar)

Fukagawa & Prantzos (2023):

1/1000 to 1/100 ratio of mergers to CCSNe (Matteucci + 2014 found about 1/100, also Rosswog + 2017), 1/4 to 1/5 ratio between collapsars and mergers.

Siegel (2019):

ratio of MR supernovae to CCSNe of only 3/1000, compact binary mergers to CCSNe 1/45, and collapsars to binary mergers 1/10, finds contribution to overall r-process matter by MR SNe of only a few %, and mergers vs. collapsars ranging from close to 70 vs. 30% to 20 vs. 80% (varying the enrichment efficiency of mergers)

Gross, Xiong, Qian (2023):

(Look only at Fe, Sr, Ba, and Eu, no actinides) Utilize two «hypothetical» sources resembling (a class of) supenovae and compact binary mergers: 1 producing Fe & Sr, 2 producing Sr, Ba & Eu but no Fe, no 3rd source with actinide boost assumed. Fit to observational data provides result that source 1 produces 1/3 of the Sr, source 2 produces 2/3 of the Sr and all of Ba and Eu

Conclusions

- Regular CCSNe produce an alpha/Fe pattern and an Fe «floor», as «early» as [Fe/H]<-5. They could also produce small contributions to Sr,Y,Zr via innermost ejecta and νp-process (but 3D models have to varify this)

- Whether Quark-Deconfinement QD SNe occur is strongly dependent on the nuclear EoS. If yes, they would produce a weak r-process up to Eu

- Magnetorotational MR SNe produce on average a weak r-process, including Eu, but with a large Sr/Eu ratio, with the strength somewhat dependent on rotation and magnetic field strength. Their ratio in comparison to CCSNe is probably close the ratio of observed magnetars to «regular» neutron stars (<1/10?).

- Compact binary mergers (with about 1/100 of the CCSN rate) produce a solar-type r-process composition (except for the lighter - weak r-process - elements), including actinides. Abundance patterns can vary, dependent on the mass of the final compact object and the timing of BH formation.

- Collapsars/Hypernova (with an occurrance of <1/100 of the CCSN rate) have very neutron-rich accretion disk outflows (equilibrium conditions in the mid-disk lead to Ye=0.1-0.15). Are they the source of actinide boosts (or do certain NSM properties also lead to the same effect?)

- ***There are still many things to learn and explore !!!***