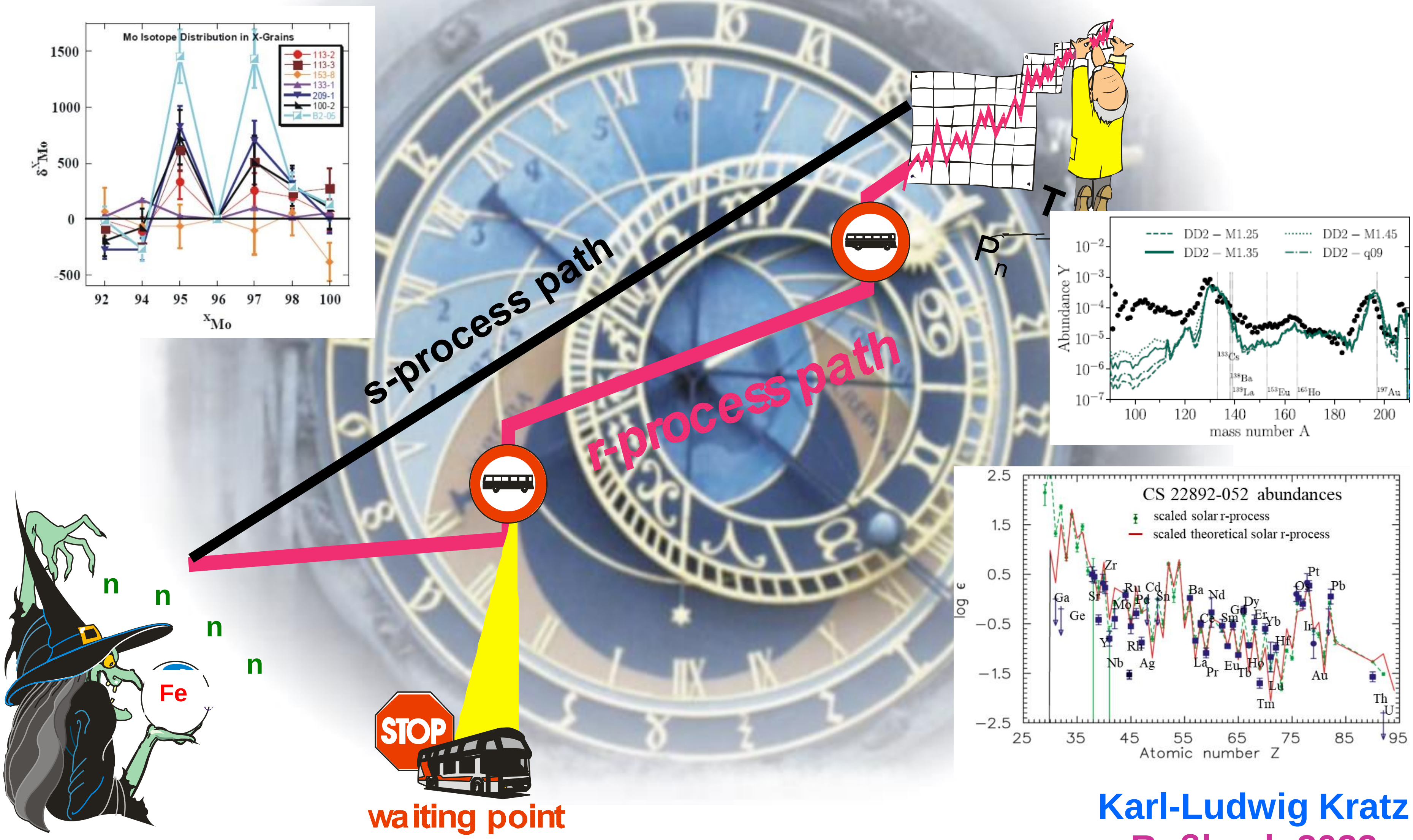
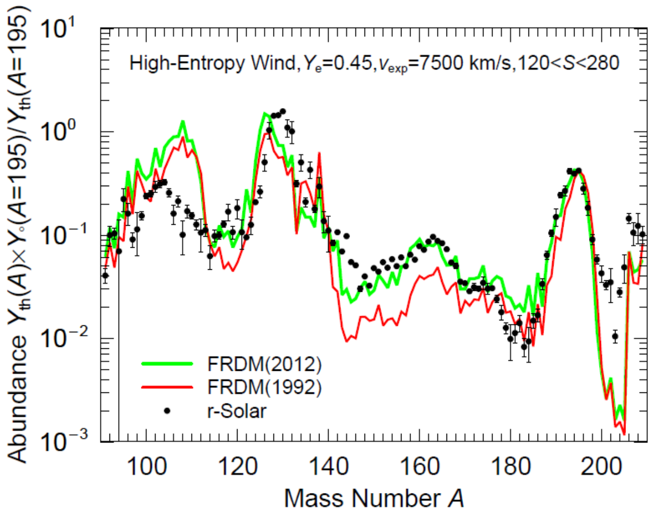
From the classical r-process to the multimessenger era



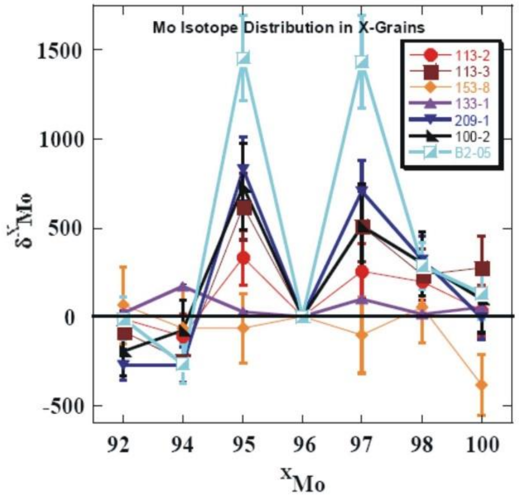
Karl-Ludwig Kratz
Rußbach 2022

r-process observables today

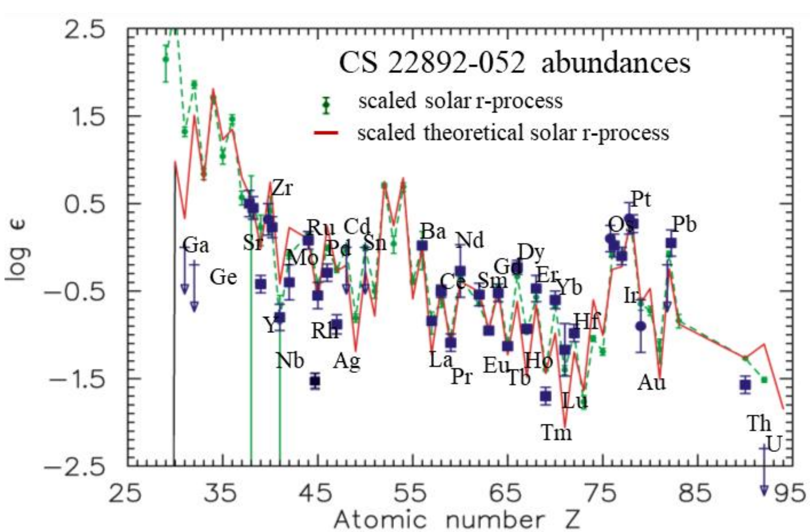
Isotopic S.S.-abundances with better nuclear physics input



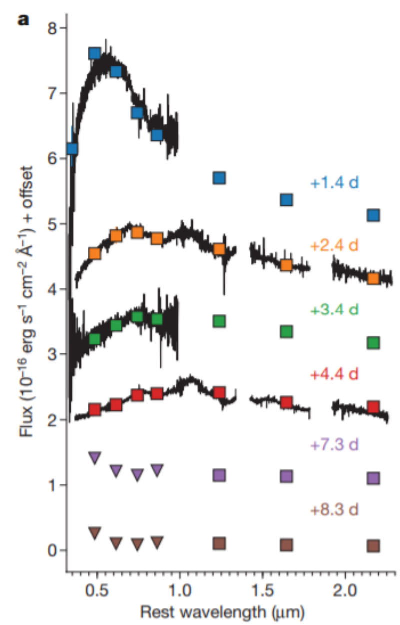
"FUN" anomalies in meteoritic samples and stardust



Presolar SiC grains; **isotopic composition** of Sr, Zr, Mo, Ru, Ba…



Elemental abundances in UMP halo stars

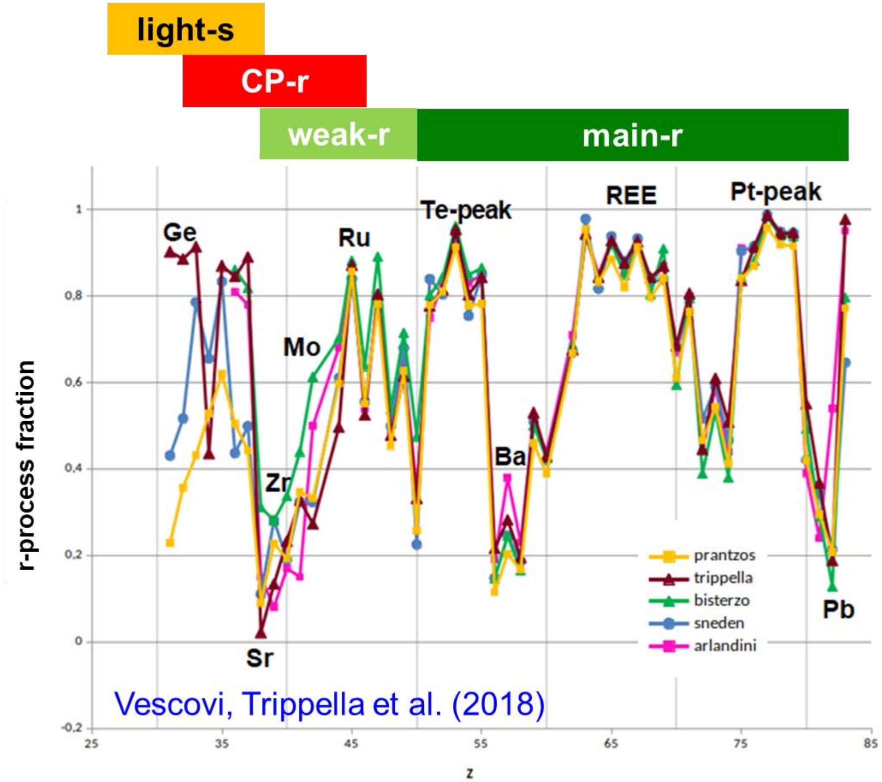


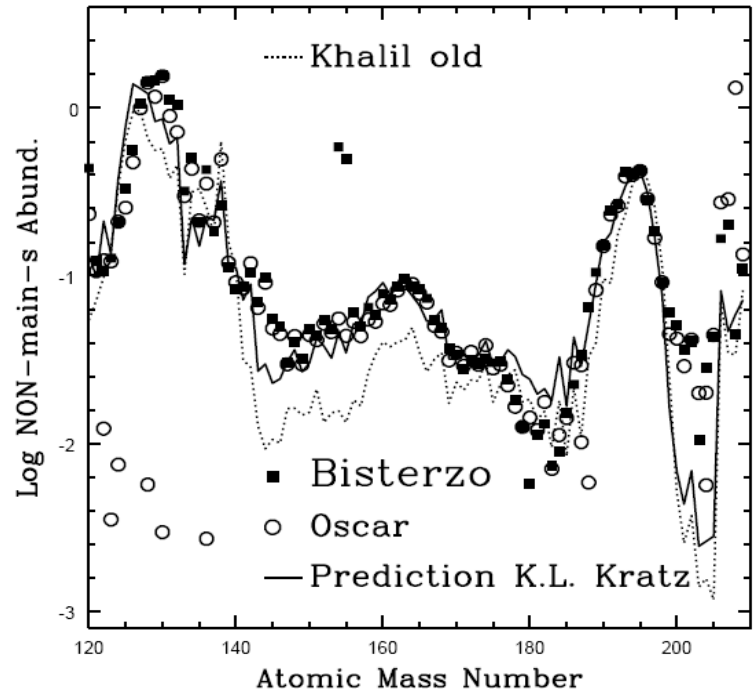
Neutron star merger event GW170817

kilonova AT2017gfo

Comparison of S.S.-r "residuals" with primary S.S.-r abundances

Ongoing Perugia-Mainz project
… identifying S.S.-s and S.S.-r uncertainties





"Khalil old" ⇨ HEW with FRDM(1992)
"Pred. KLK" ⇨ HEW with FRDM(2012)

Example ^{96}Zr r-"residual":

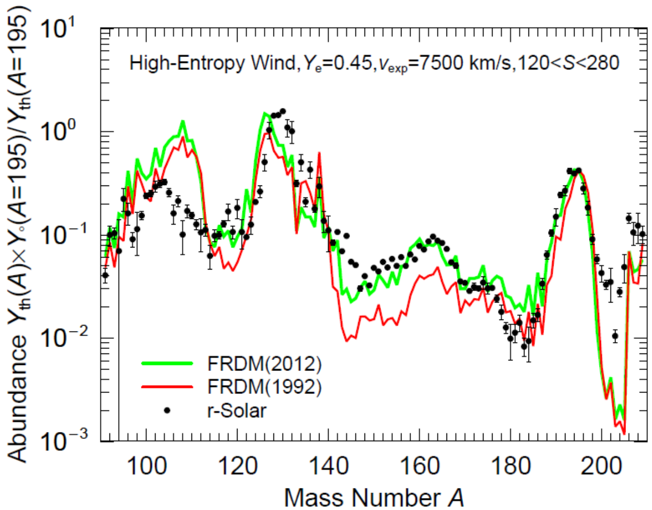
Käppeler '89	**100 %**
Arlandini '99	**45.0 %**
Bisterzo '11	**48.7 %**
Bisterzo '14	**61.3 %**
Tripella '16	**98.6 %**

to be compared to r-"primary":

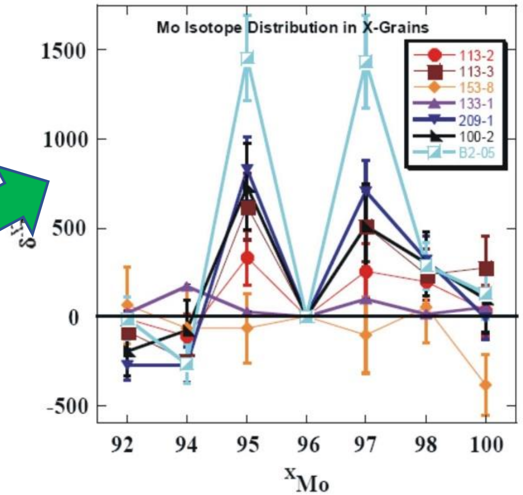
Kratz '19	**98.4 %**

r-process observables today

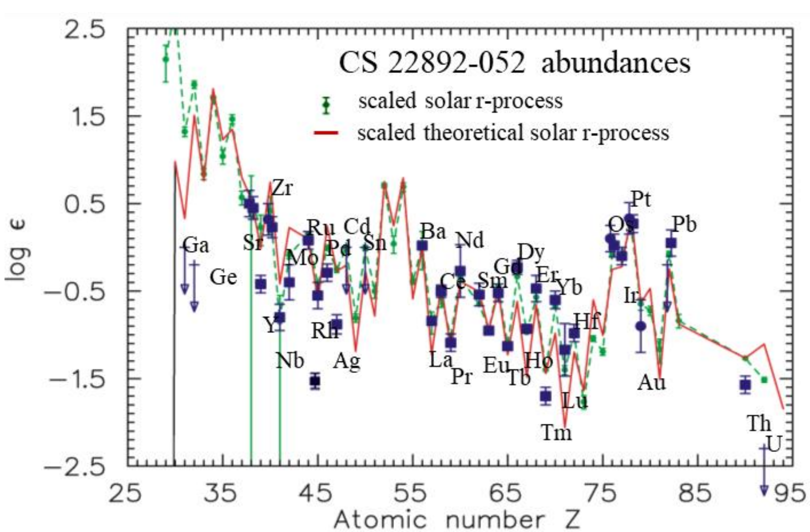
Isotopic S.S.-abundances with better nuclear physics input



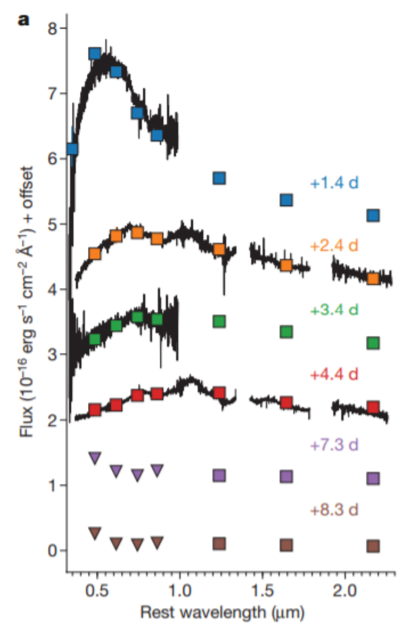
"FUN" anomalies in meteoritic samples and stardust



Presolar SiC grains; **isotopic composition** of Sr, Zr, Mo, Ru, Ba…



Elemental abundances in UMP halo stars



Neutron star merger event GW170817

kilonova AT2017gfo

Light p-process isotopes in the S.S.

Historical papers "p-process"

B^2FH (1957)
Arnould (1976)
Woosley & Howard (1978)

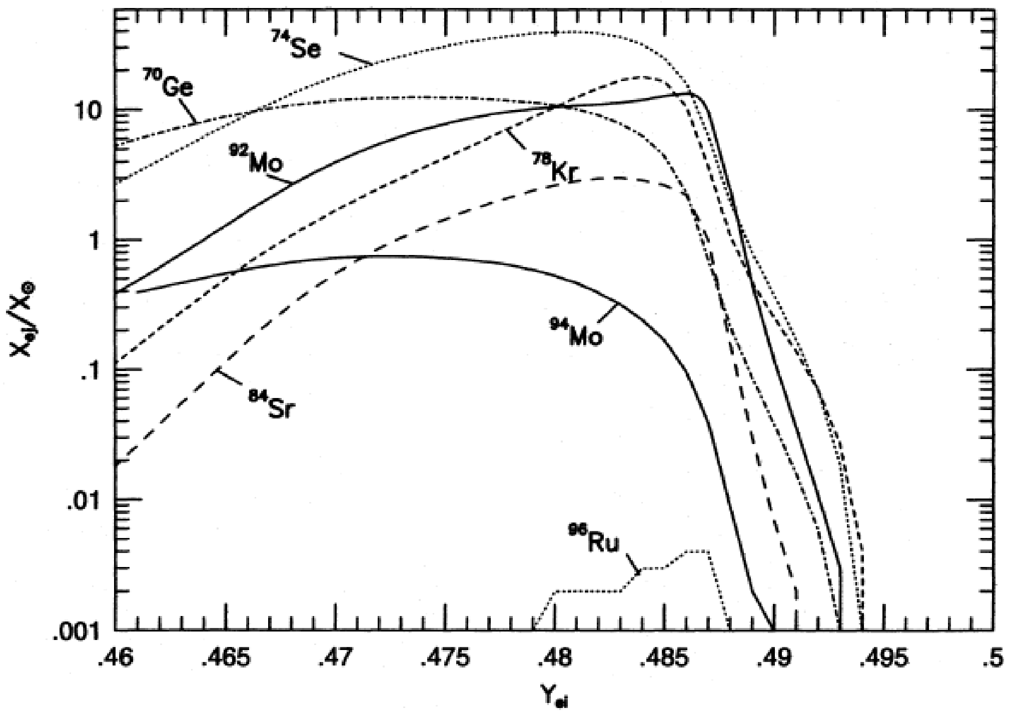
Main goal:
explanation of nucleosynthetic origin of light p-nuclei, including **$^{92}Mo/^{94}Mo$**

Selected subsequent papers / scenarios

Paper	Scenario
Howard *//* Meyer et al. (1992, **2000**)	n-burst in exploding massive stars
Hoffman et al. (1996, **2008**)	ν-driven winds in SN II
Schatz et al. (1998, 2003)	rp-process in X-ray bursters
Rauscher et al. (2002)	γ-process in pre-SN and SN
Fisker et al., (2006)	νp-process in SN II
Wanajo et al. (2009)	p-production in EC-SN
Farouqi et al. (**2009**)	light p, s, r in SN II at low S
Travaglio et al. (2011, **2018**)	p-process in SN Ia
Eichler et al. (2017)	nucleosynthesis in ccSN
Pignatari et al. (2018)	n-burst in He-shell of ccSN
Kratz et al. (**2018**)	light trans-Fe elements in SN-HEW
Sasaki et al. (2022)	hypernova νp-process

Production of the light p-process nuclei in neutrino-driven winds

Hoffman, Woosley, Fuller, Meyer, ApJ 460 (1996)



“normalized production factors“

$X_{ej}/X_{\odot} = f(Y_e)$

individual Y_e‘s; $S/(N_A k) \approx 50$

“No initial abundances of r- or s-process seed need be invoked
⇒ this component of the p-process is primary rather than secondary.“

Result on ^{92}Mo:

Underproduction relative to solar

The authors give 3 possible explanations:

1) The νp-process is active, but ^{92}Mo is primarily produced at other sites
2) The νp-process is not active, so another explanation is needed
3) The νp-process is active, but the nuclear parameters (…) are incorrect

Abundances of light trans-Fe ISOTOPES in the ccSN-HEW scenario

Continuing the work of Hoffman, Woosley et al. (1996)…

Farouqi, Kratz & Pfeiffer;
Publications of the Astron. Soc. of Australia (PASA) 26 (**2009**)
"Co-production of light p-, s- and r-process isotopes in the high-entropy wind of type II supernovae"

Typical yields ($M_\odot$) for Y_e = 0.46			
^{64}Zn	$5.6*10^{-5}$	^{78}Kr	$4.0*10^{-8}$
^{70}Ge	$8.9*10^{-6}$	^{84}Sr	$1.2*10^{-8}$
^{74}Se	$5.4*10^{-8}$	^{92}Mo	$2.6*10^{-8}$

sizeable abundance yields, comparable to SN Ia of Travaglio et al. (2011, 2015)

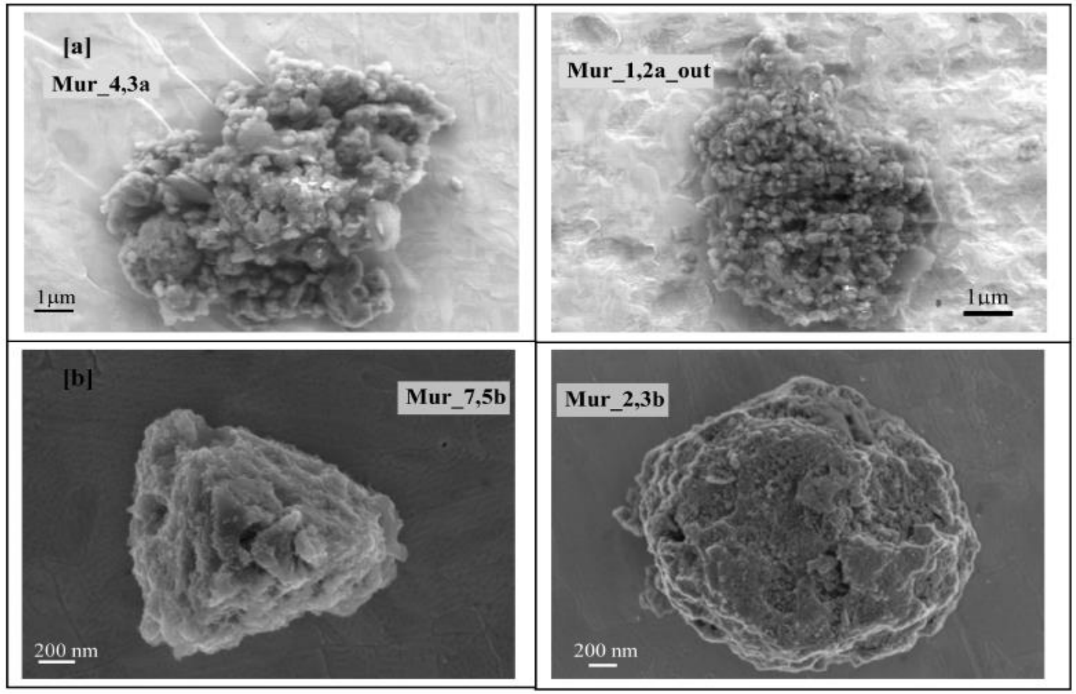
Isotopic pairs (nucleosynth. origin)	Isotopic abundance ratios	
	S.S.	HEW
^{64}Zn(**p**) / ^{70}Zn(**r**)	78.4	79.4
^{70}Ge(**s**,**p**) / ^{76}Ge(**r**)	2.84	4.61
^{74}Se(**p**) / ^{76}Se(**s**)	$9.4*10^{-2}$	$9*10^{-2}$
^{74}Se(**p**) / ^{82}Se(**r**)	0.101	0.113
^{78}Kr(**p**) / ^{86}Kr(**r**,**s**)	$2.1*10^{-2}$	$8*10^{-4}$
^{84}Sr(**p**) / ^{86}Sr(**s**)	$5.7*10^{-2}$	$4*10^{-2}$
^{90}Sr(**s**,**r**) / ^{96}Zr(**r**,**s**)	18.4	5.56
^{92}Mo(**p**) / ^{94}Mo(**p**)	1.60	1.73
^{96}Ru(**p**) / ^{98}Ru(**p**)	2.97	2.57

all historical p-, s- and r-"**only**" isotopes are co-produced, from ^{64}Zn to ^{104}Ru

Star-dust observables of Zr, Mo and Ru in SiC-X grains

Zr, Mo, Ru in **presolar SiC X-grains** (sub-micron size)
measured with **NanoSIMS** or **RIMS**

... ejecta of stars that contributed to the proto-solar nebula;
due to SiC's refractory nature, these grains survived S.S. formation;
type X-grains are believed to contain isotopic patterns from **presolar** explosive nucleosynthesis events.



Marhas, Ott & Hoppe, MPS 42 (2007)

Remember:

Mo of particular interest:
7 stable isotopes with ^{92,94}Mo **"p-only"**
^{96}Mo **"s-only"**
^{95,97,98}Mo **s+r**
^{100}Mo **"r-only"**

Among suggested nucleosynthesis scenarios:

- "n-burst" in shocked He shell in SNe
- rp-process in X-ray bursters
- p-process in SN-Ia or EC-SN
- **ν-driven wind in cc-SN-II**

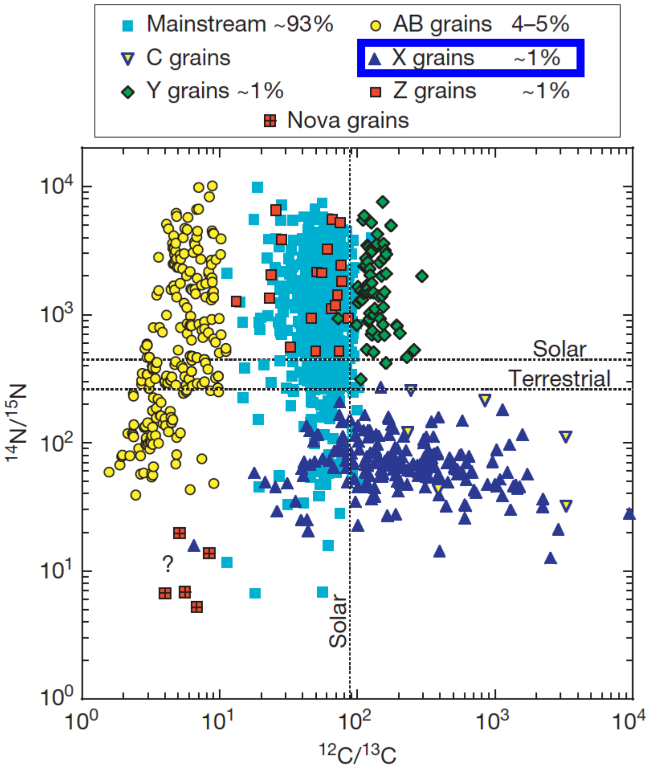
Question:

can the low-S CP-r component of the HEW r-process produce all 7 Mo isotopes at the same time?

Types of presolar SiC grains

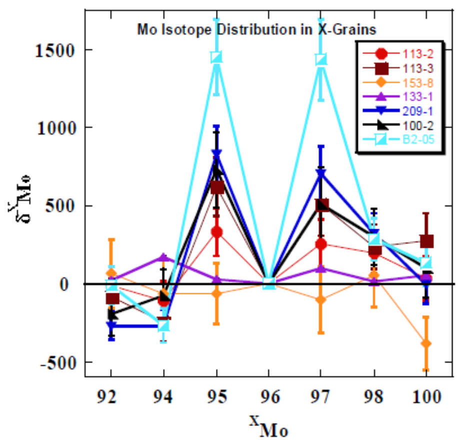
SiC grains:

- Fourth most abundant and one of the best-studied type of presolar grains
- Further divided into subgroups based on C, N, O & Si isotope ratios
- Most (93%) have C, N, O & Si isotope signatures consistent with TP-AGB stars → **mainstream grains**
- Just 1% have isotopic signatures consistent with explosive scenarios → **Type X grains**
- However, the light trans-Fe element composition (e.g. Zr, Mo, Ru) of Type X grains have so far defied a straightforward interpretation.



Zinner: Treatise on Geochemistry (2004)

Pellin et al.: LPS (2006)



δ notation: permill deviation from S.S.

Taking Mo as an example, rel. to ^{96}Mo:

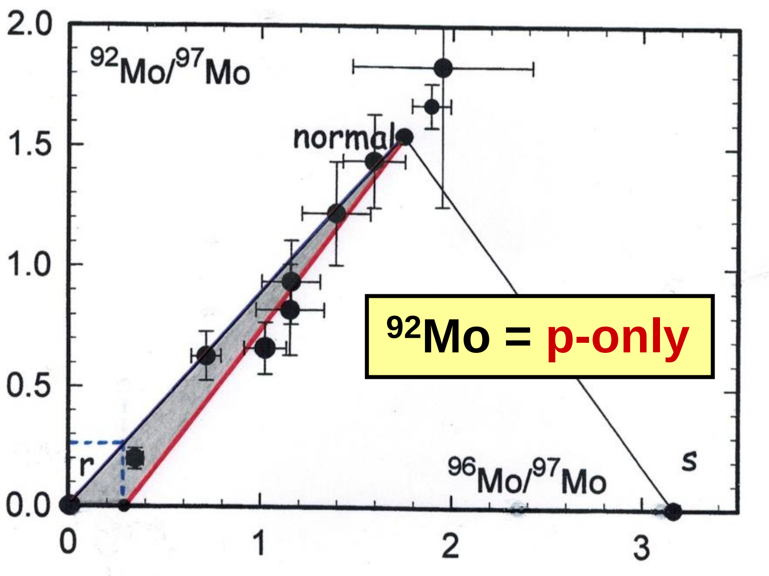
$^{92,\,94}$Mo depleted

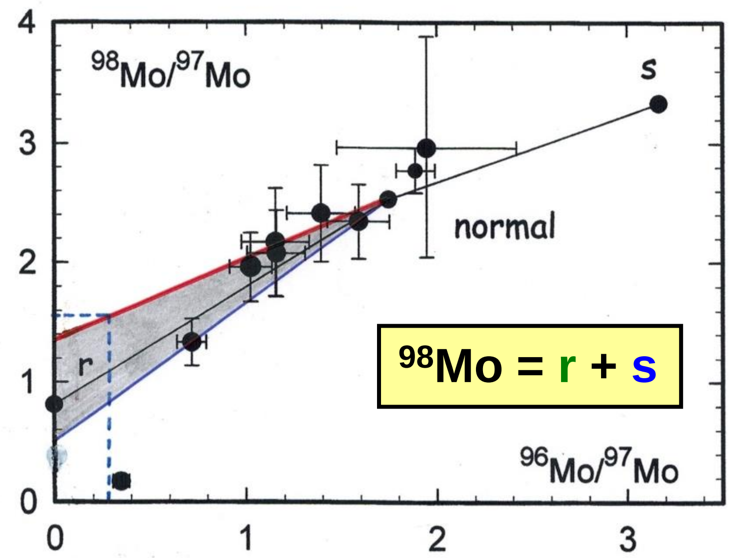
$^{95,\,97,\,98}$Mo enriched

^{100}Mo approx. S.S.

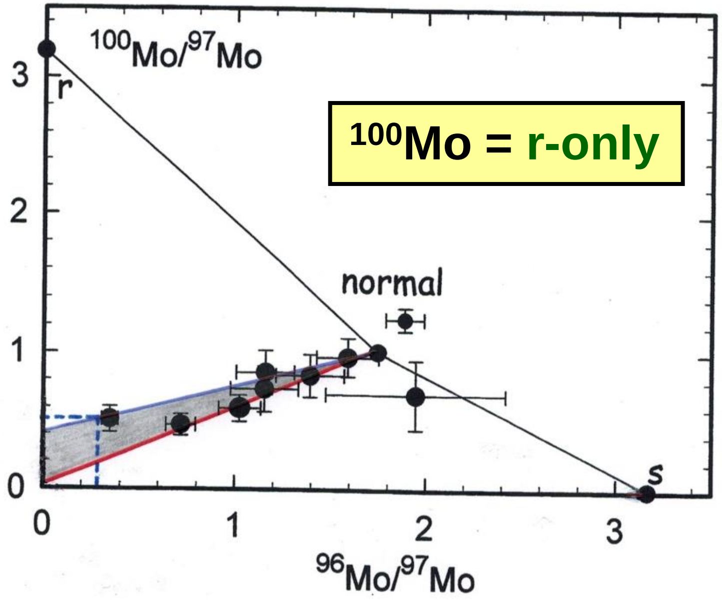
“Clean“ signature of ccSN–low-S component?

Cosmochemical Mo "three-isotope plots"





Ott, Kratz (2007)



Convention of cosmochemists:

"three-isotope plots"

extrapolation of mixing lines with S.S.
yields "clean" nucleosynthesis signature

Here, S.S. data point **included** in mixing-line fits

X-axis: ^{96}Mo / ^{97}Mo

Y-axis: ^{X}Mo / ^{97}Mo

To be compared to model predictions:
definitely neither classical s nor r !

Comparison of Mo mixing-line results with model predictions

Astro-models (new analyses):

- **"primary"** **ccSN, HEW-CP**; $Y_e = 0.454 – 0.460$; $S_{max} = 50 - 80$; $Y_n/Y_{seed} < 1$
- **"secondary"** **new n-burst**; Meyer (2018)

$^{x}Mo/^{97}Mo$	Isotopic abundance ratios		
	SiC X-grains	**This work**	**New "n-burst"**
$^{92}Mo/^{97}Mo$	0.15	0.06	1.43 E-3
$^{94}Mo/^{97}Mo$	0.09	0.02	3.28 E-3
$^{95}Mo/^{97}Mo$	1.86	2.96	1.54
$^{96}Mo/^{97}Mo$	0.10	0.02	0.01
$^{98}Mo/^{97}Mo$	0.50	0.66	0.38
$^{100}Mo/^{97}Mo$	0.10	0.17	0.10
$^{92}Mo/^{94}Mo$	1.67	1.73	0.44 !

For $^{95, 96, 98, 100}Mo/^{97}Mo$, HEW-CP and new n-burst yield similar results.

Not so for $^{92, 94}Mo/^{97}Mo$ and $^{92}Mo/^{94}Mo$!

Comparison of Ru mixing-line results with model predictions

Astro-models (new analyses):

- **"primary"** **ccSN, HEW-CP**; Y_e = 0.460 – 0.480; S_{max} = 50 - 80; Y_n/Y_{seed} < 1
- **"secondary"** **new n-burst**, Meyer (2018)

$^{x}Ru/^{101}Ru$	Isotopic abundance ratios		
	SiC X-grains	This work	New "n-burst"
$^{96}Ru/^{101}Ru$	1.28	1.09	3.70 E-9
$^{98}Ru/^{101}Ru$	0.20	0.22	5.72 E-7
$^{99}Ru/^{101}Ru$	1.33	1.46	0.47
$^{100}Ru/^{101}Ru$	0.15	0.16	1.42 E-3
$^{102}Ru/^{101}Ru$	3.16	3.03	10.2
$^{104}Ru/^{101}Ru$	3.68	2.96	7.41
$^{96}Ru/^{98}Ru$	**6.12**	**4.83**	**6.47 E-3 !**

As for Mo, our HEW-CP results for Ru agree with measured grain data, whereas the new n-burst clearly fails.

Summary light trans-Fe isotopes

We find

- all historical p-, s- & r-isotopes in the light trans-Fe region (from ^{64}Zn to ^{104}Ru) co-produced in the **primary** CP component of a ccSN-HEW

As select example

- the ccSN-CP scenario can provide a consistent picture for all stable Zr, Mo and Ru isotopes in presolar SiC-X grains
- it can also reproduce the S.S. ratio of $^{92}Mo/^{94}Mo \approx 1.6$

"Clean" signature of low-S ccSN scenario

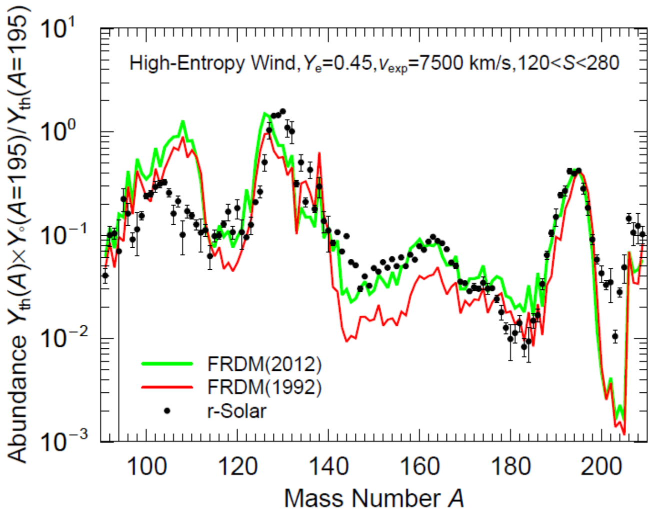
- from **"intercepts"** of SiC-X grain mixing lines

Main collaborators

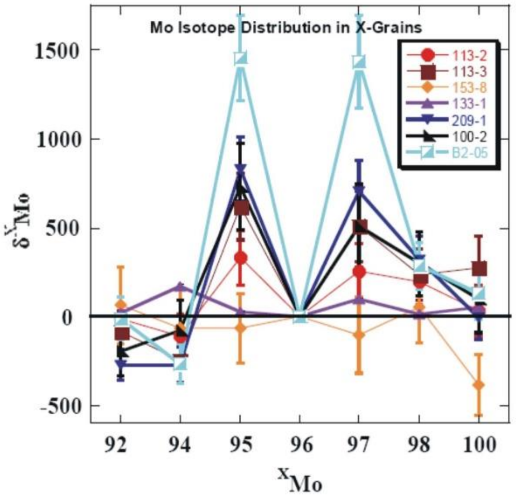
W. Akram, K. Farouqi, O. Hallmann, U. Ott, B. Pfeiffer

r-process observables today

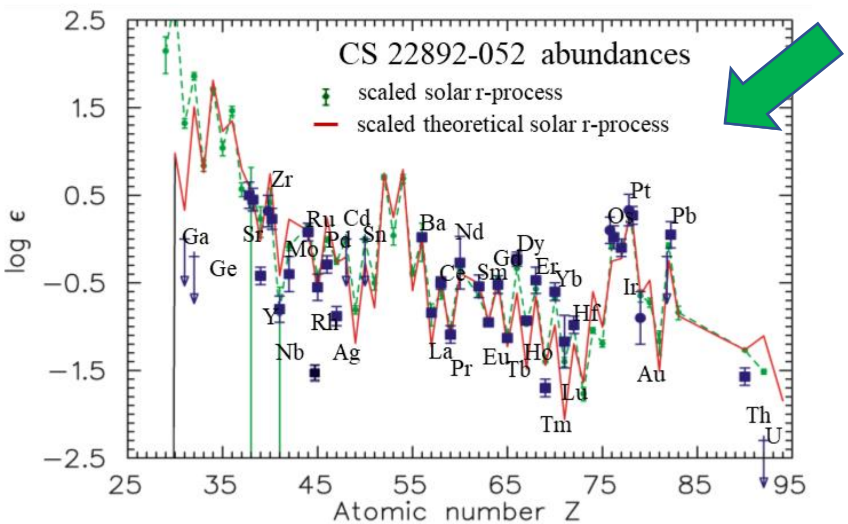
Isotopic S.S.-abundances with better nuclear physics input



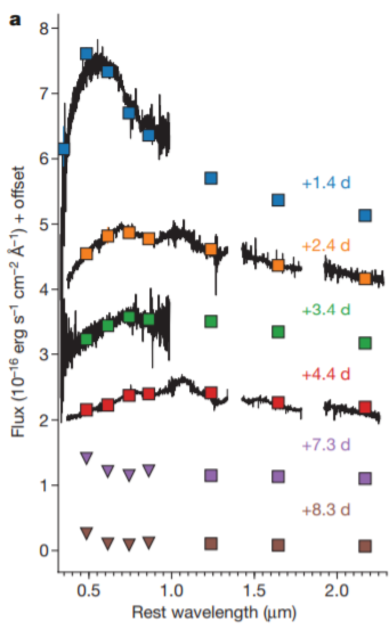
"FUN" anomalies in meteoritic samples and stardust



Presolar SiC grains; **isotopic composition** of Sr, Zr, Mo, Ru, Ba…



Elemental abundances in UMP halo stars



Neutron star merger event GW170817

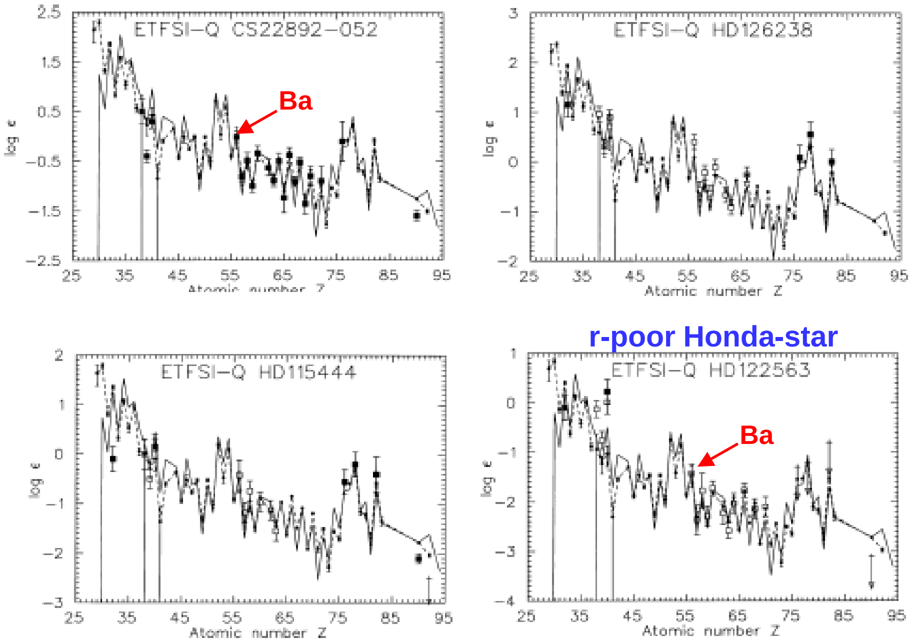
kilonova AT2017gfo

Early metal-poor halo stars (1999)

…our first involvement in UMP halo-star astronomy:

Cowan, Pfeiffer, Kratz, Thielemann, Sneden & Burles; ApJ 521 (1999)

"r-Process abundances and chronometers in metal-poor stars"



Comparison of observed abundances (filled squares) with $N_{r,\odot}$ (small filled circles, joined by a dashed line), and with $N_{r,calc}$ (solid line).

[Fe/H] ≤ -2; [Eu/Fe] ≥ +1; [Ba/Eu] ≤ -0.7

Conclusions at that time (!) :

The abundance comparisons indicate several striking results:

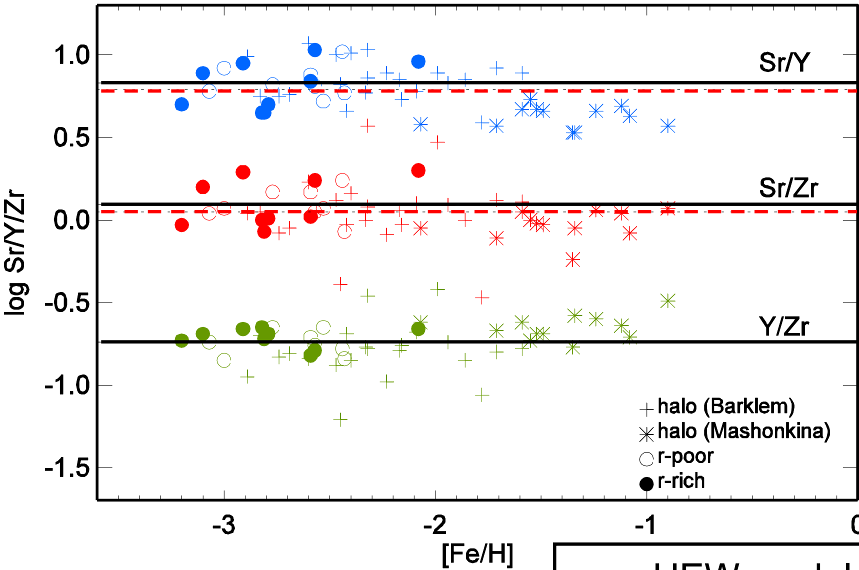
- **Halo stars with -1.7 ≤ [Fe/H] ≤ -3.1 show the same S.S.-r pattern for Z ≥ 56;**
  ↷ in each hypothetical r-process site a continuous set of conditions.
- **For Z ≥ 56, the r-abundances seem not to have changed with GCE;**
  ↷ one r-process site (later denoted as "main" r-process).
- **The trend of the lighter n-capture elements is unclear; explainable in terms of metallicity dependent weak s-process?**
- **Or…, there are two r-process signatures (weak & main) reflecting different sites**

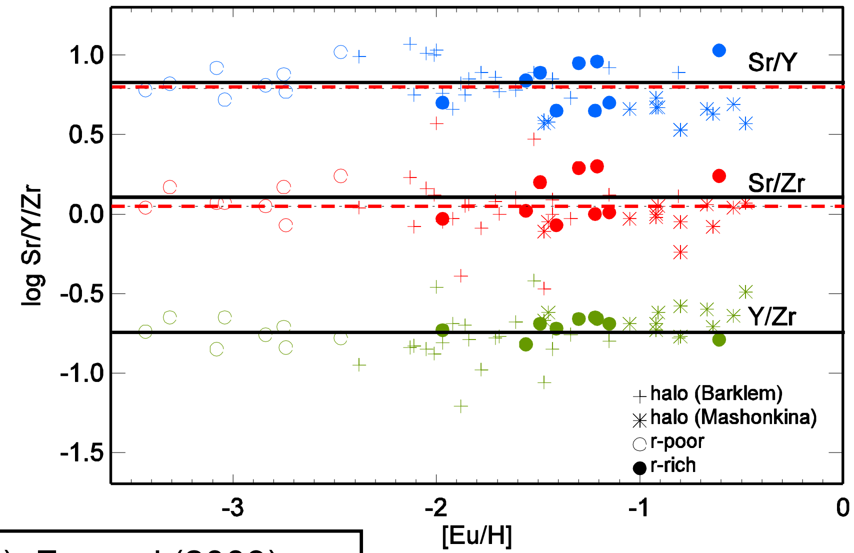
Standard spectroscopic notation:

$$[A/B] \equiv \log(N_A/N_B)_{star} - \log(N_A/N_B)_{\odot}$$

- **First Comparison with theoretical predictions: WP and HEW**

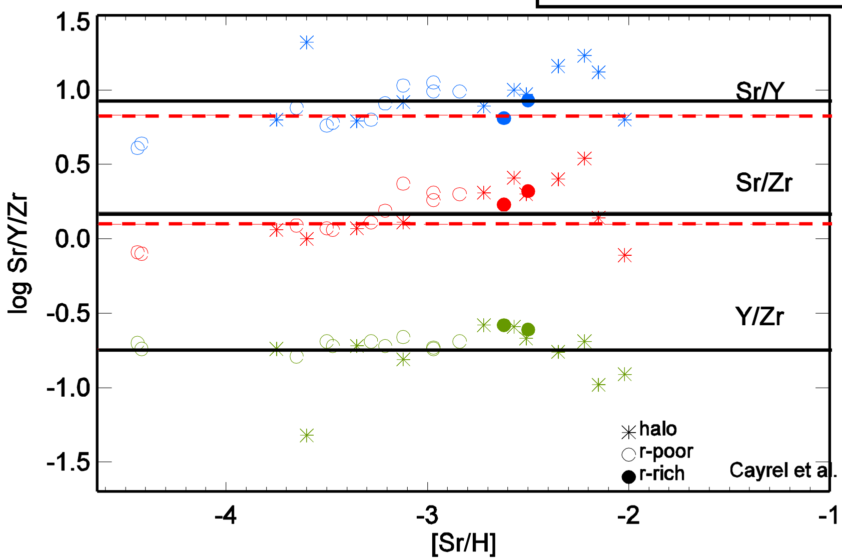
Halo stars vs. HEW model: Sr/Y/Zr as fct. of [Fe/H], [Eu/H] and [Sr/H]





—— HEW model (S ≥ 10); Farouqi (2009)

– – average halo stars; Mashonkina (2009)



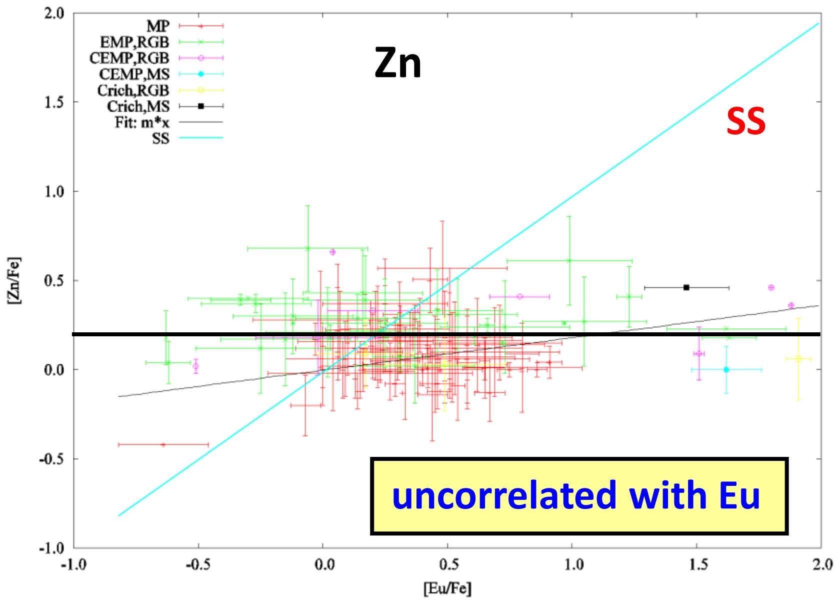
Robust Sr/Y/Zr abundance ratios,
independent of metallicity,
r-enrichment,
α-enrichment.

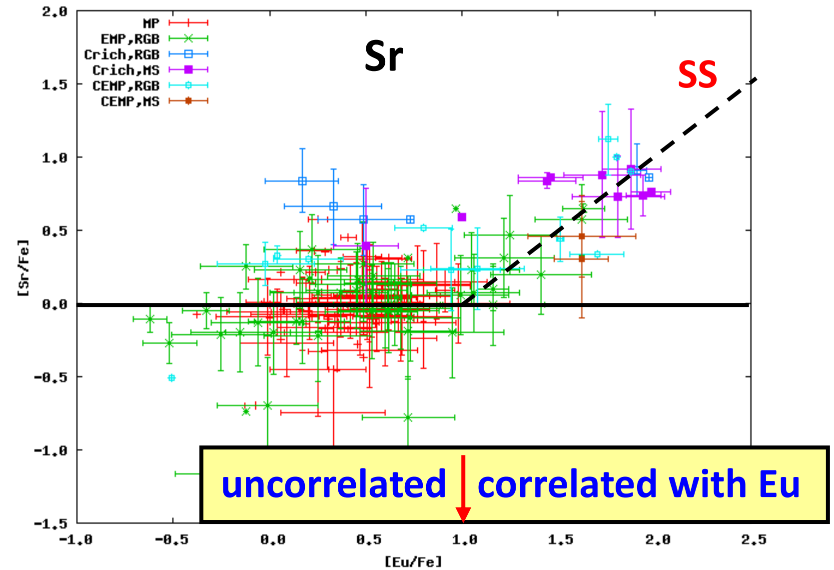
↷ Same nucleosynthesis component:
CP-process, **NOT** n-capture r-process

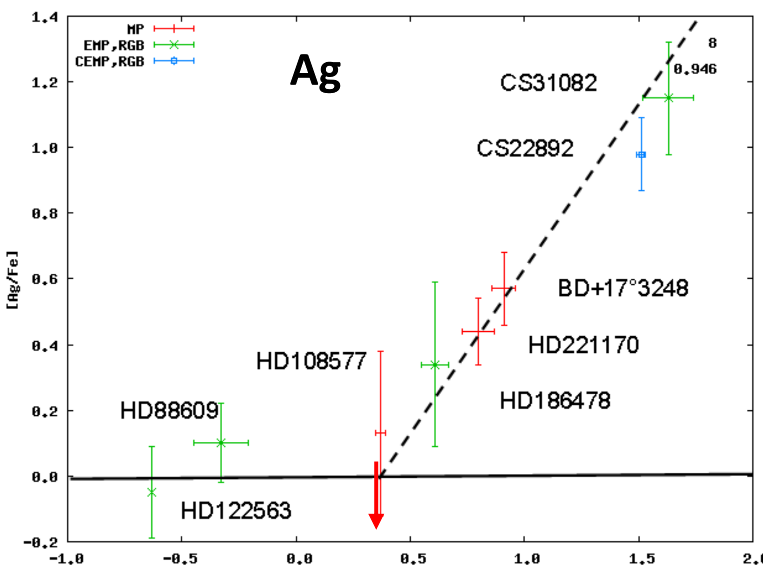
Correlation with main r-process (Eu) ?

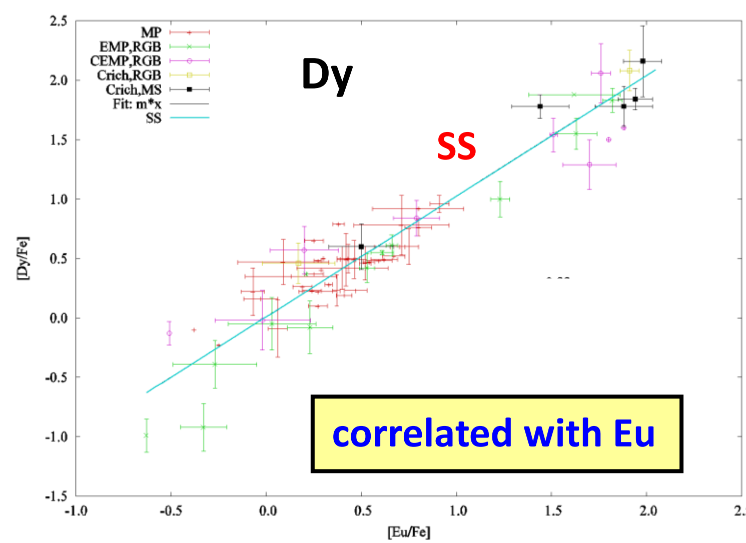
Astronomical observations, SAGA database: [X/Fe] vs. [Eu/Fe]

Transition from CP-r component via “weak” to “main” n-capture r-process





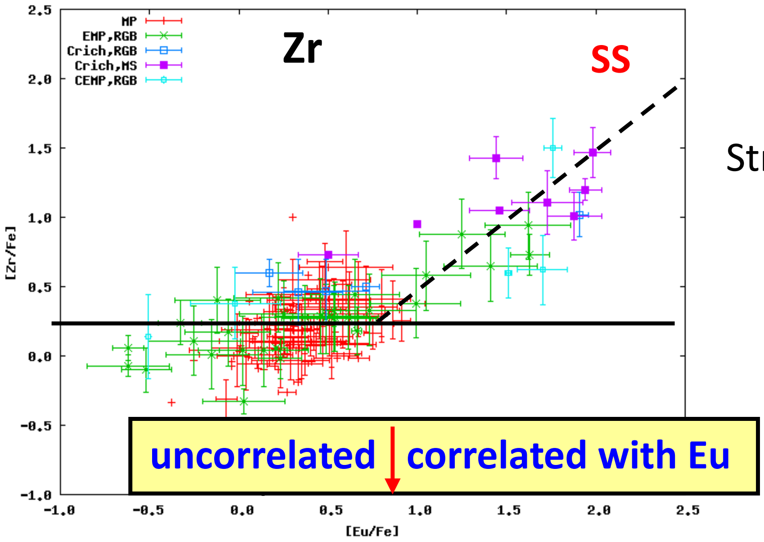




Eu ⇨ r-enrichment; Fe ⇨ metallicity

$[A/B] = \log(N_A/N_B)_* - \log(N_A/N_B)_\odot$

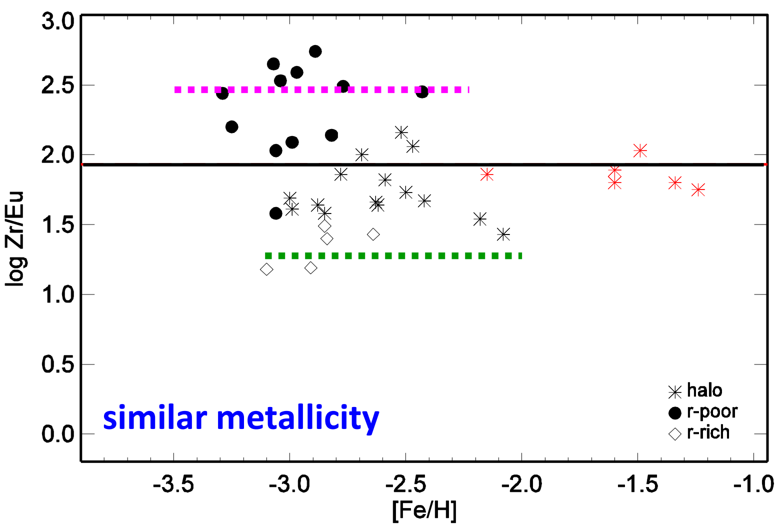
SAGA database: Zr in more detail



Strong Zr – Eu correlation
SS diagonal

Zr in r-poor halo stars overabundant
type "Honda star"
Zr in r-rich halo stars underabundant
type "Sneden star"

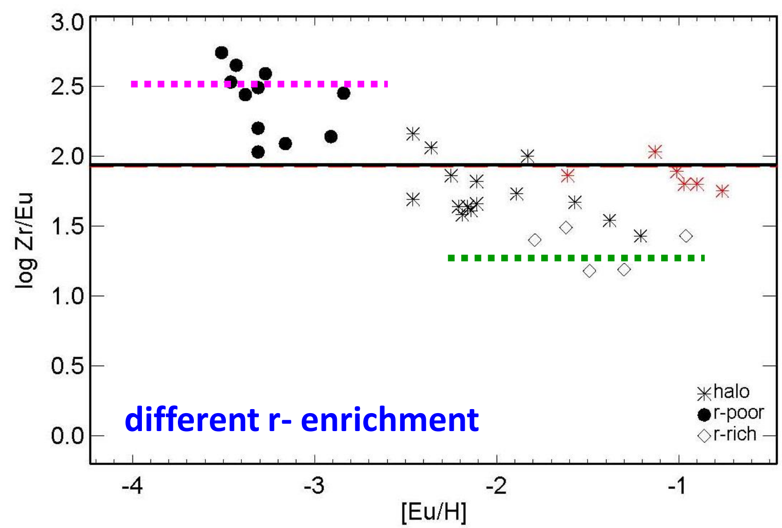
Mashonkina (2009); Farouqi (2009)



r-poor

HEW (av.)

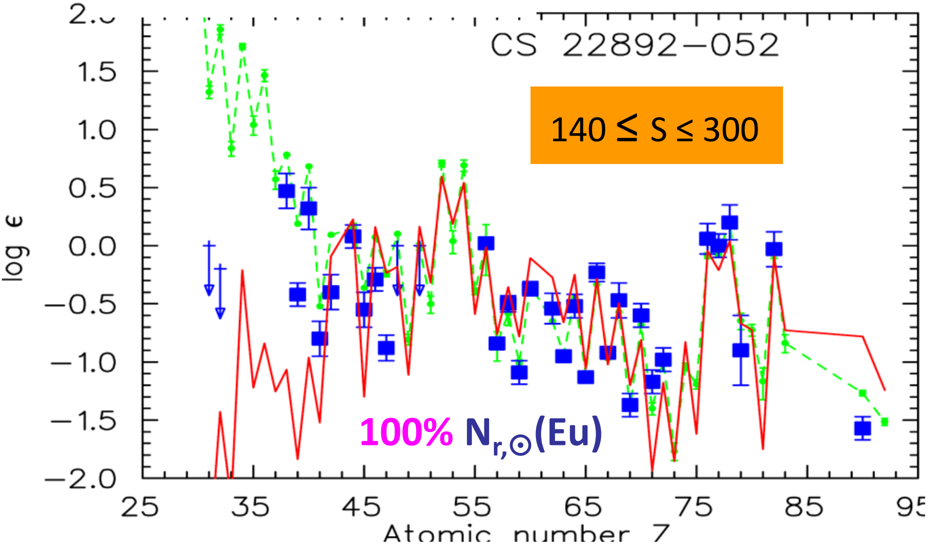
r-rich



Clear differences observed already a decade ago…
However, today's r-process consequences not fully understood

Extremes "r-rich" and "r-poor": S-range optimized

r-rich "Sneden star"



full main r-process

Sr – Ag region **underabundant** by a mean factor ≈ **2** relative to $N_{r,\odot}$

[Eu/Fe] = 1.52; [Sr/Fe] = 0.73;

Sr/Eu = 26

(assumption by Travaglio et al. that this pattern is unique for all UMP halo stars)

➡ **missing part to $N_{r,\odot}$ = "LEPP"**

incomplete main r-process

Sr – Cd region **overabundant** by a mean factor ≈ 10 relative to $N_{r,\odot}$

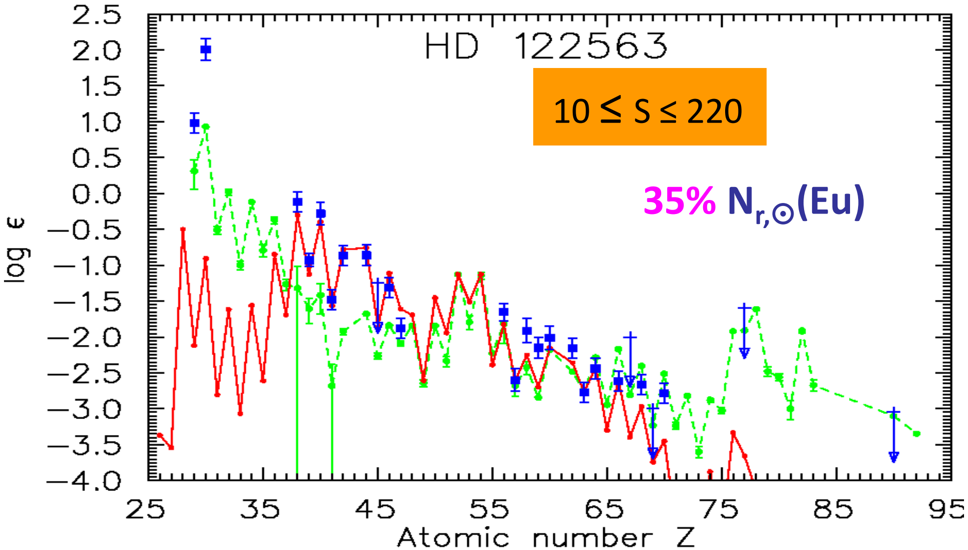
[Eu/Fe] = – 0.64; [Sr/Fe] = – 0.27;

Sr/Eu = 447

➡ **missing part to $N_{r,\odot}$ = "HEPP"**

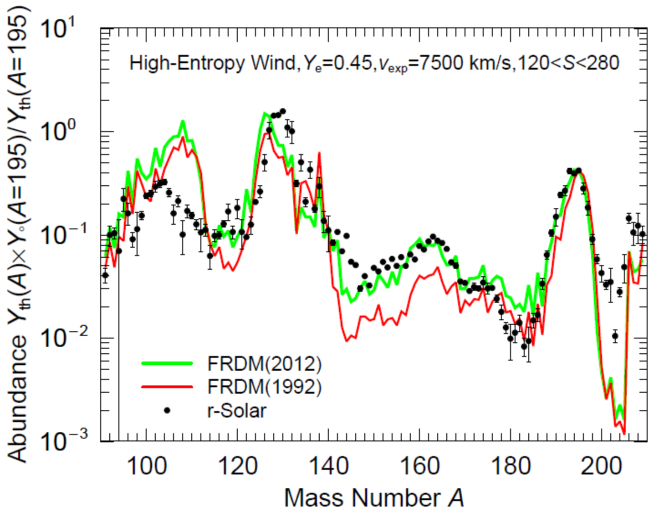
(today, NSM r-component)

r-poor "Honda star"

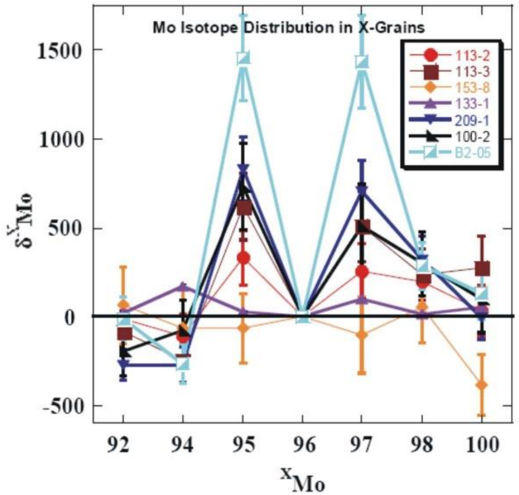


r-process observables today

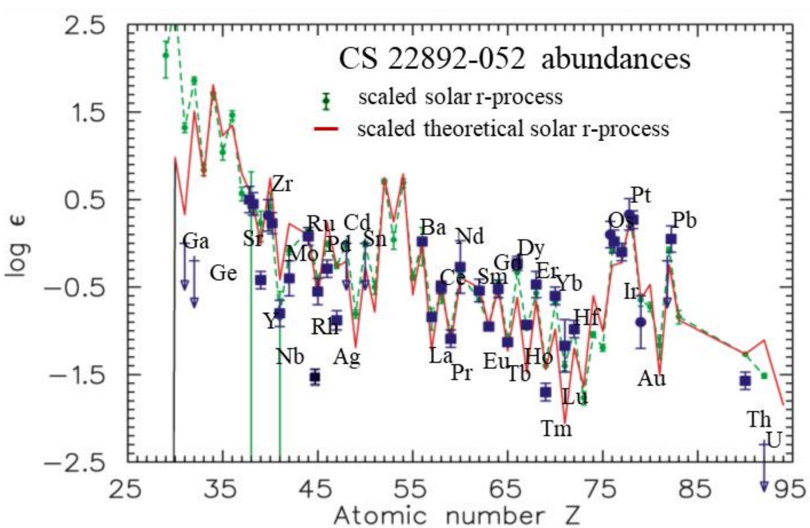
Isotopic S.S.-abundances with better nuclear physics input



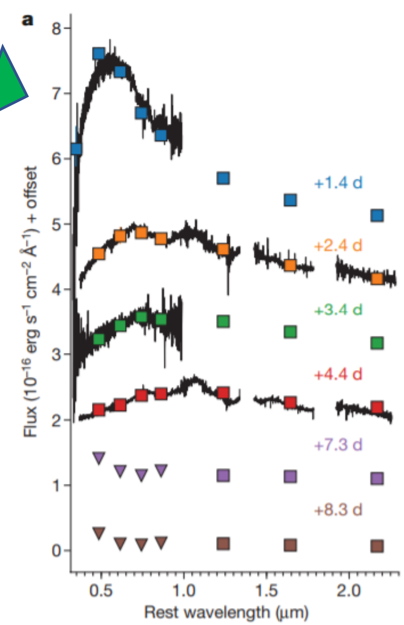
"FUN" anomalies in meteoritic samples and stardust



Presolar SiC grains; **isotopic composition** of Sr, Zr, Mo, Ru, Ba…



Elemental abundances in UMP halo stars



Neutron star merger event GW170817

kilonova AT2017gfo

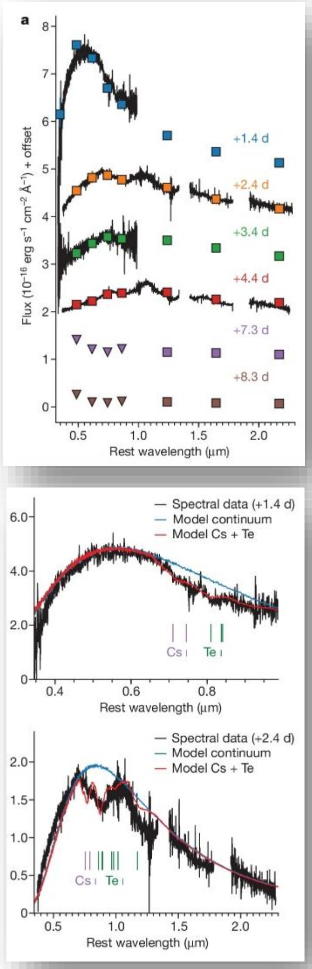
The Multimessenger Era → GW – NSM – Kilonovae (I)

Prediction NSM as promising r-process site **Lattimer & Schramm** ApJ 213 (1974)

Over many years considered „exotic“, e.g. because the extreme gravity makes it difficult to eject possible r-process matter.

August 2017

- r-process nucleosynthesis in NSM in the multiwave follow-up observations of **kilonova** / **gravitational wave**, **GRB 170807A** / **GW 170817**
- **LIGO & VIRGO** ↷ GW (Tanvir et al., APJL 847; Abbott et al., PRL 119)
- **Fermi-GBM** & **INTEGRAL/SPI** ↷ γ-burst signal (Goldstein et al., ApJL 848; Savchenko et al., ApJL 848)
- **GROND** ↷ electromagn. Signal = **kilonova** spectrum peaked in infrared region ⟶ heavy elements (Ba & lanthanides)



Smartt et al.,Nature 551

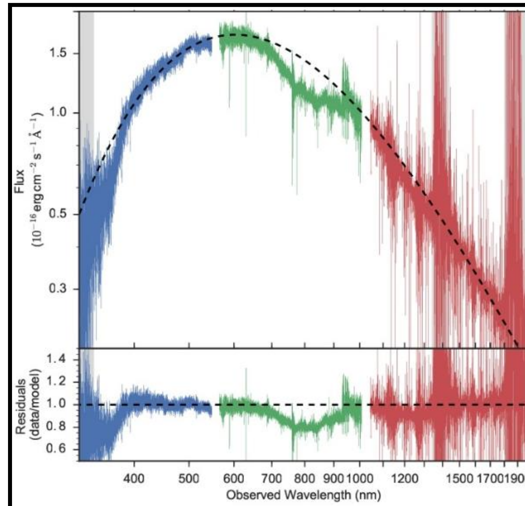
From Kajino et al.
Prog. Part. & Nucl. Phys. 107 (2019)

The Multimessenger Era – Identifications of Sr (II)

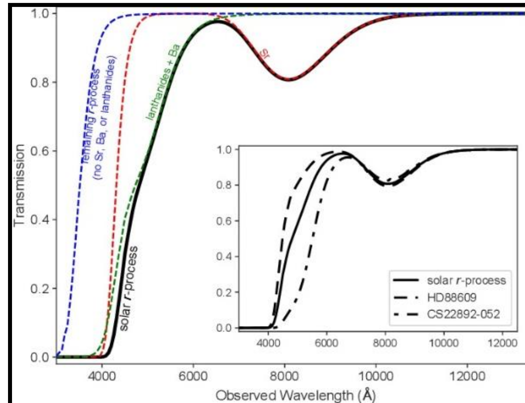
D. Watson et al., Nature 574 (2019)

- Z = 38, N = 88 **Sr** identified as first individual element from electromagnetic radiation of a NSM
- NSM ejecta with $Y_e \leq 0.1$ ↷ heavy r-elements; increase of Y_e by weak interactions (changes of n to p) to eject the light r-elements
- Expanding material diluted – only after a few days „**red** wavelength emission“ of Ba & lanthanides. Lighter elements – at higher Y_e - visible earlier as „**blue** wavelength emission“

From S. Rosswog
Physik Journal 19 (2020)



Spectrum of the kilonova AT2017gfo, 1.5 days after the merger



Thermal r-process element emission spectrum.

Sr	red dashed
lanthanides	green dashed
remaining elements	blue dashed

UMP halo-stars – observations vs. calculations

Abundance ratio CP-r Sr / main-r Eu

- Lodders (2009); Bisterzo (2014); Trippella (2016)

  $N_{\odot} - N_{s,\odot} \approx N_{r,\odot}$ "residuals" ↷ (Sr/Eu) ≈ 45

- Farouqi (2010)

  ccSN-HEW, Y_e = 0.45 ↷ (Sr/Eu) ≈ 115

- T. Hansen et al. (**2018**)

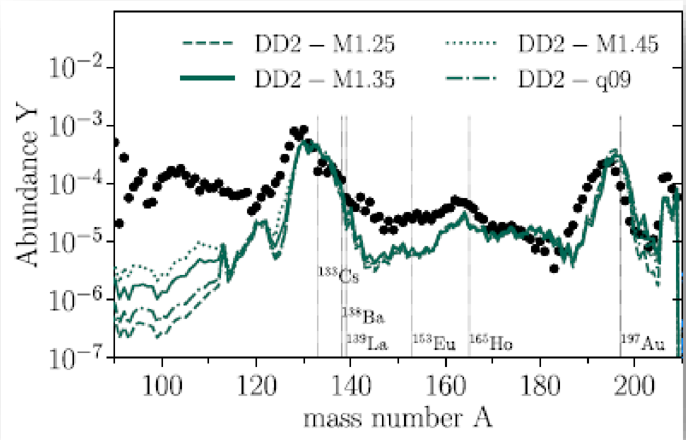
  "The r-process alliance"

r-poor stars	[Eu/Fe] < 0.3	$(Sr/Eu)_{max}$ ≈ **780**	indicates ccSN
r-I stars	0.3 < [Eu/Fe] < 1.0	$(Sr/Eu)_{av}$ ≈ **45**	S.S.-r blend
r-II stars	[Eu/Fe] > 1.0	$(Sr/Eu)_{min}$ ≈ **2**	indicates NSM

- Bovard et al. (2017)

  rel. r-abundances for diff. NSM models

  (Sr/Eu) ≈ **10^{-2} – 10^{-1}**



Important question: where "clean" signatures for ccSN and NSM?

Relative r-process contributions of ccSN, MHDJet-SN & NSM

Farouqi, Kratz et al. (2010, 2019)

halo-star obs. & ejected r-matter as fct. Y_e

≈ 90 % r-poor (Honda-type) stars
≈ 8 % r-rich (Sneden-type) stars
≈ 2 % r-strong (actinide-boost) stars

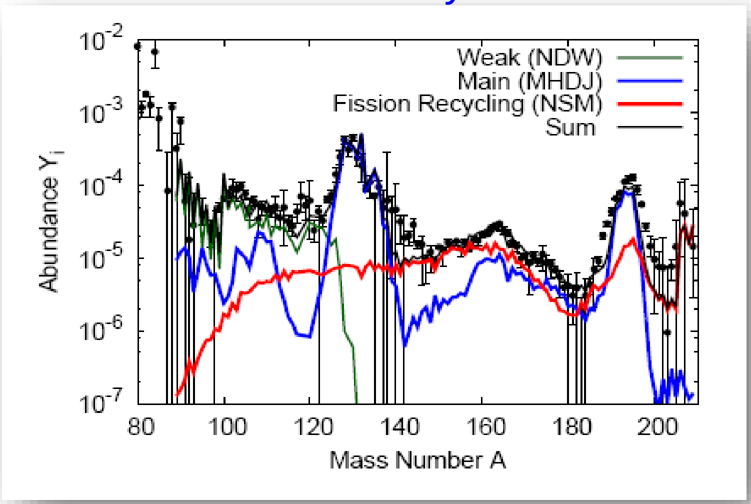
Wehmeyer, Pignatari & Thielemann (2015)

acc. to their GCE understanding

≈ 98 % cc-SN (light r-elements)
≈ 1 % Jet-SN (full r-process)
≈ 1 % NSM (main r-process)

Shibagaki, Kajino et al. (2015)

fit of S.S.-r distribution by fractions of



≈ 79 % HEW (weak r-process)
≈ 18 % MHDJ (main r-process)
≈ 3 % NSM (fission-recycling r-process)

…unfortunately, with highly questionable nuclear-physics input!

Ji & Frebel (2018)

acc. to estimated event production

- only **1 NSM** every ≈ **2000 ccSNe**;
- however, admittedly much lower than currently inferred rates based on Abbott et al. (2017) & Taylor et al. (2014) of ≈ **1/100**

Correlation of r-process elements in VMP halo stars

When Khalil Farouqi and I started in 2018, our main goal was to distinguish between

- r-elements **correlated** (co-produced?) with Fe, and
- r-elements **uncorrelated** (not produced?) with Fe

In contrast to the numerous model-speculation papers after the GW-NSM event,
our approach primarily based on experimental “**facts**“:
databases for UMP halostars SAGA (and JINAbase); **[Fe/H] ≤ -2.5**

Choice of 3 “typical“ r-elements:

- Z = 38 Sr ↷ classical “**weak-r**“ element → SN-type ?
- Z = 63 Eu ↷ classical “**main-r**“ element → Merger-type ?
- Z = 90 Th ↷ classical “**actinide-boost**“ → Merger-type ?

Choice of “typical“ r-parameters:

- [**Eu/Fe**] ↷ “r-enrichment“ → historical stellar classes r-poor, r-I, r-II
- (**Sr/Eu**) ↷ “**weak-r**“/“**main-r**“ → indication of fractions SN & Merger ?
  → indication of “pure“ SN and/or Merger signatures ?
  → correlation with metallicity [Fe/H]?

Combination of exp. “facts“ with statistical-model correlation coefficients SCC & PCC

SAGA database: [Fe/H] mean & (Sr/Eu) mean as function of [Eu/Fe]

What do we learn from the astronomical observations (facts!) ?

[Eu/Fe] range	No. stars	[Fe/H] mean	(Sr/Eu) mean	Stellar classes
- 0.65 to - 0.3 - 0.3 to 0 0 to 0.2	11 34 45	- 3.09 - 2.92 - 2.90	399 278 207	“r-poor“ e.g. Honda-star HD122563
0.2 to 0.4 0.4 to 0.6 0.6 to 0.8	34 37 28	- 2.85 - 2.71 - 2.80	140 106 70	“r-I“ e.g. Westin-star HD115444
0.8 to 1.0 1.0 to 1.4 1.4 to 1.95	23 22 24	- 2.81 - 2.90 - 2.79	57 39 30	“r-II“ e.g. Sneden-star CS22892-052

- **With increasing [Fe / H]**
  - increasing r-process enrichment
  - decreasing (Sr/Eu) ratio
- **Indication of**
  - different r-process sites
  - different galactic times for r-sites
  - different frequencies of r-sites (?)
  - different r-matter ejecta (?)

From observations to mathematical correlations → Spearman & Pearson correlation coefficients

Pearson and Spearman Correlation Coefficients, PCC & SCC

J. Hauke & T. Kosowski; Questiones Geographicae (2011)

Correlations between “variables“ can be measured with the use of different indices (coefficients); among the most popular are:

- Spearman (rank) correlation coefficient (SCC)
- Pearson correlation coefficient (PCC)

Spearman‘s “rho“

- is a non-parametric (distribution-free) rank-statistic
- is a measure of monotone association of variables in a somewhat **„qualitative“** way
- does not require the assumption that the relationship between the variables is linear
- does not require the variables to be measured on interval scales

Pearson‘s product-moment correlation coefficient

- treats data in a **“quantitative“** way
- assumes the normality of the variables
- is a measure of the linear association of variables
- prefers data variance to be homogeneous (“homoscedascity“)
- requires that no outliers be present in the data

A&A Publication

Astronomy & Astrophysics manuscript no. rPocessCorrelation
July 9, 2021

©ESO 2021

arXiv:2107.03486v1 7 Jul 2021

Correlations of r-Process Elements in Very Metal-Poor Stars as Clues to their Nucleosynthesis Sites

K. Farouqi[1], F-K. Thielemann[2,3], S. Rosswog[4] and K.-L. Kratz[5,6]

Accepted for publication by Astronomy and Astrophysics in January 2022

Possible r-process sites

Single stars

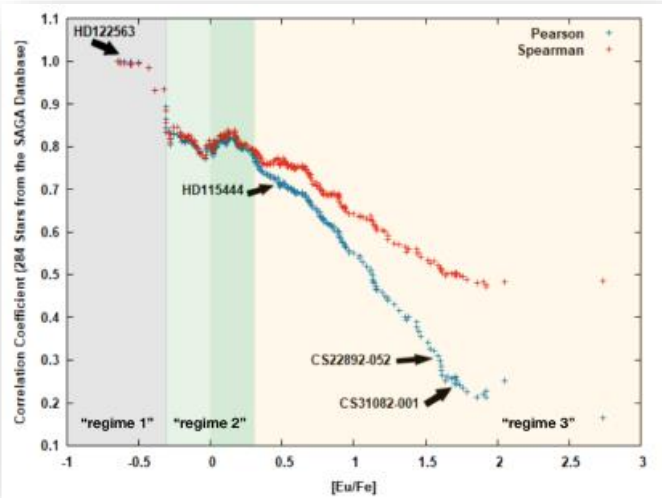
Astrophys. site	r-ejecta/event	frequency
Regular ccSNe	weak	high
QD-SNe	weak	low
MHD-Sne	from weak to strong (?)	medium
EC-SNe	very weak	uncertain (!)
Collapsars / Hypernovae	strong (?)	low

Compact binary mergers

Event type	r-ejecta/event	frequency
NS-NS	strong	low
BH + torus		
mass. NS + torus		
NS-BH	strong	low

Example of PCC & SCC for r-element correlations

PCC and SCC for Eu (r-enrichment) and Fe metallicity) for halo-stars with [Fe/H] ≤ -2.5



Our 4 “typical“ stars:

1) HD122563, Honda-star, r-poor / incomplete-r
2) HD115444, Westin-star, complete r-I
3) CS22892, Sneden-star, complete r-II
4) CS3108-001, Cayrel-star, complete r-II & actinide boost

…at [Eu/Fe] ≈ 0.3 PCC & SCC begin to diverge from each other. At this point the CC ≈ 0.75 is still high. Fe and Eu are well correlated / co-produced (?)

PCCs for [Eu/Fe] > 0.3 weak(er) correlation several contributers, e.g. SNe and NSM

Star-Type	[Eu/Fe]	PCC	strength	No. stars
all stars	- 0.64 – 1.9	0.14	very weak	282
r-I + r-II	0.3 – 1.9	0.15	very weak	166
r-II	> 1.0	0.34	moderate	51
r-I	0.3 – 1.0	0.65	strong	115
r-poor	< 0.3	0.83	very strong	168

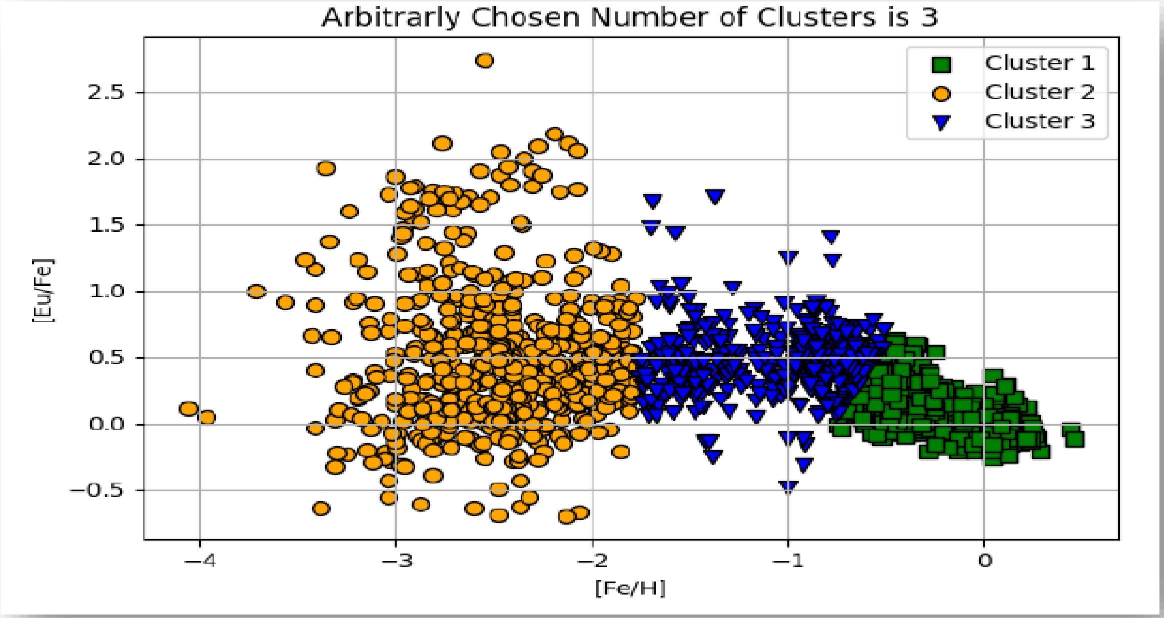
Cluster analysis techniques

Cluster analysis

… a statistical technique to group data with common characteristics; however without explanation, why the clustering exists.Typically used in the exploratory phase of a research project with the aim to guide further analyses.

K-means clustering

… treats observations in data as objects having locations & distances from each other.
Each cluster is characterized by its mean or central point.



In the **3-Cluster Analysis** of [Eu/Fe] vs. [Fe/H] one can recognize:

(1) for low-metallicity stars ([Fe/H] < -2) with large scatter (≈ 10^3) ➡ contributions from **individual rare** or **different events**;

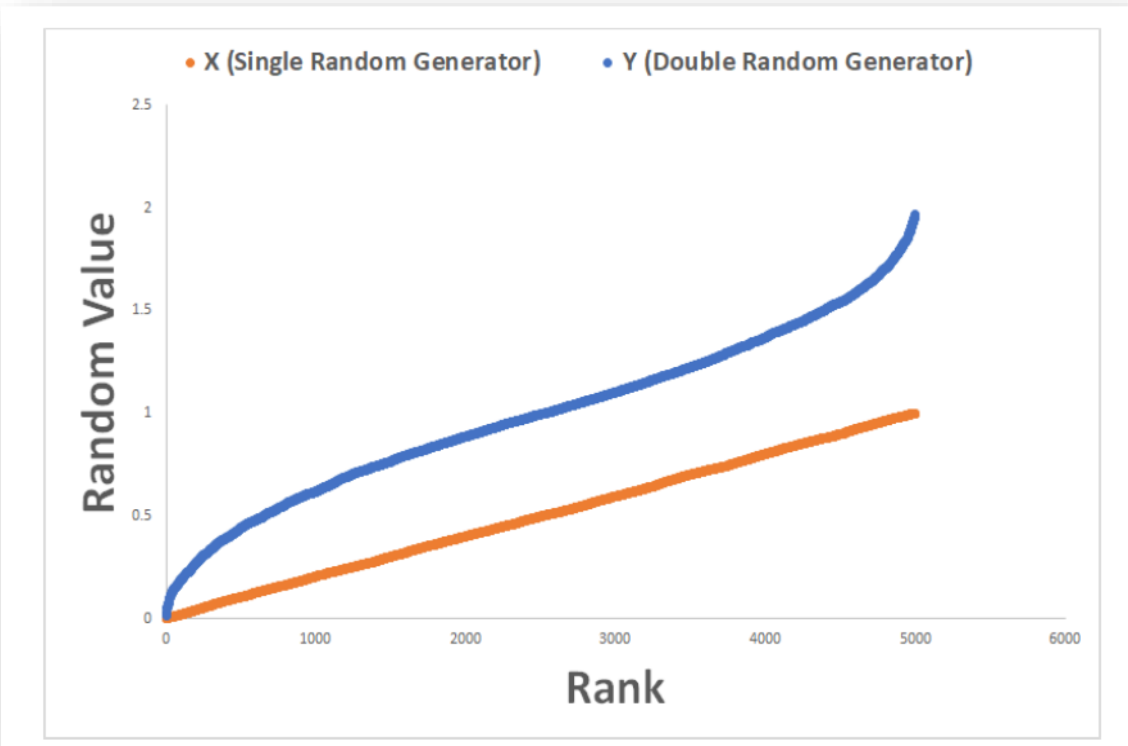
(2) for -2 < [Fe/H] < -1.5 with already small scatter ➡ **averaging / mixing** of events;

(3) for [Fe/H] > -1.5 ➡ additional Fe-contribution from **SN-Ia**

Rank tests

... usually applied to abundance observations of individual elements as function of "rank"

➡ indicates whether only **one** nucleosynthesis source, or **several** contributed to the element



Orange curve:

a **single** random-number operator X, ordering values according to their size, giving them integer entries ("ranks")

⇨ linear relation between random numbers and ranks

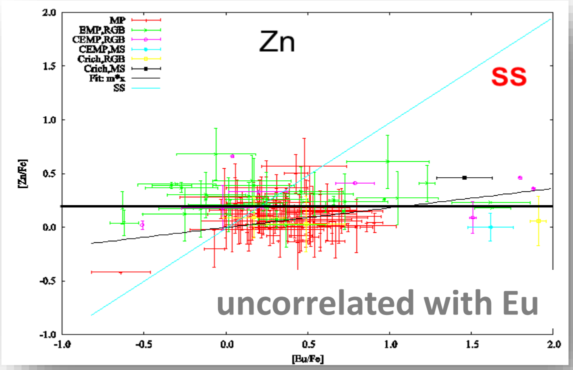
Blue curve:

two random-number generators, adding their values X1 + X2 = Y; plotted as function of its ranks

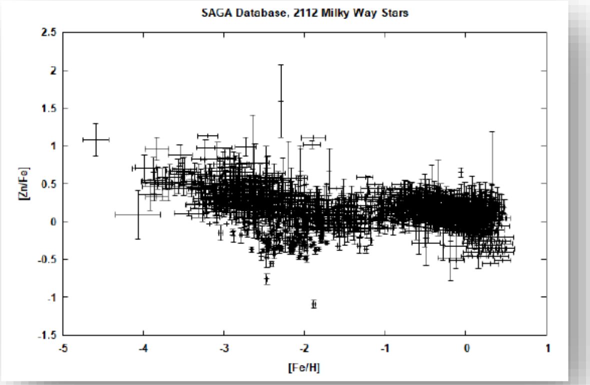
⇨ deviation from a linear relation between Y and its ranks

Zn vs. Fe & Eu: 2008 and today

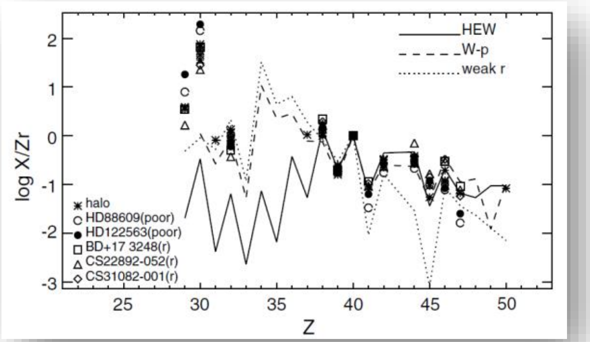
Kratz et al., New Astron.Rev. 52 (2008)
based on the SAGA data at that time



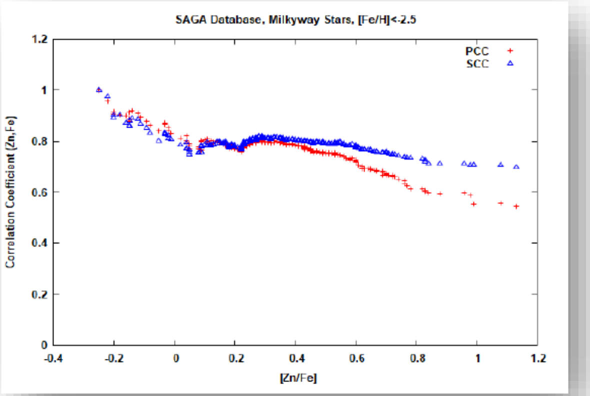
Farouqi et al., arXiv: 2107.03486 (2021)
based on today's SAGA data



... the rise of [Zn/Fe] below [Fe/H] < -2 points to an additional event to ccSNe → alpha-rich freeze-out of hypernovae/collapsars

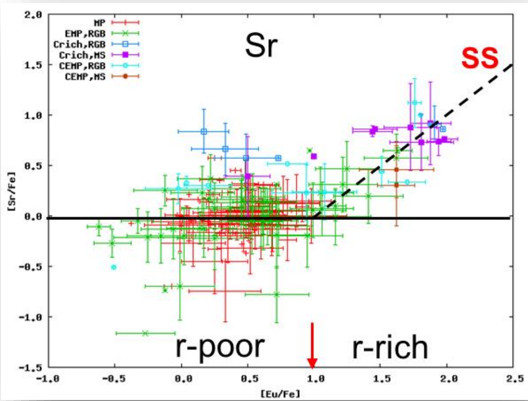


... the minimal conclusion to be drawn right now is that the high abundances of Cu (Z=29) and Zn (Z=30) are not produced together with the Z ≥ 38 (Sr-Ag) elements



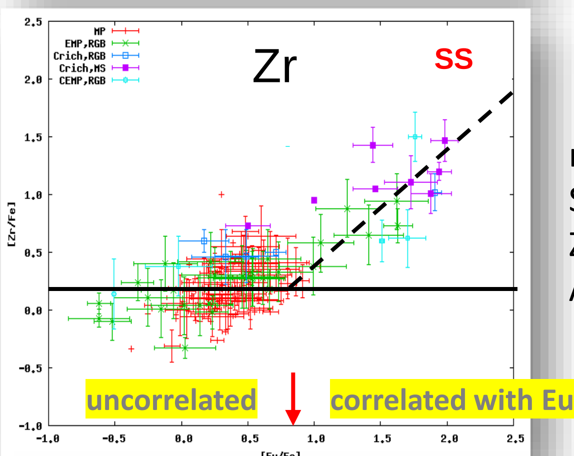
... consistent with decrease of PCCs for high [Zn/Fe] ≥ 0.3 → high Zn not necessarily from regular ccSNe

Sr, Zr → Ag vs. Fe & Eu: 2008 and 2021

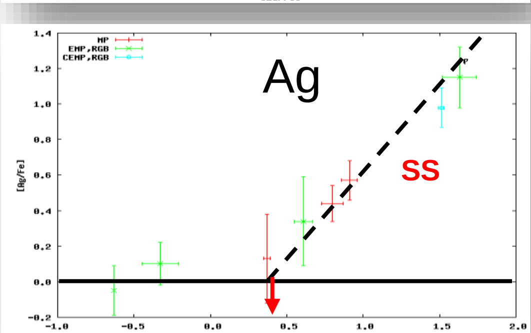


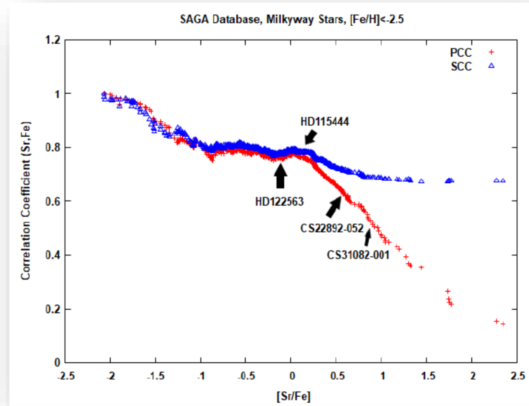
2008

partial correlation with “main-r“ Eu;
from (Z=38) Sr on, increasing fractions of “main-r“ material



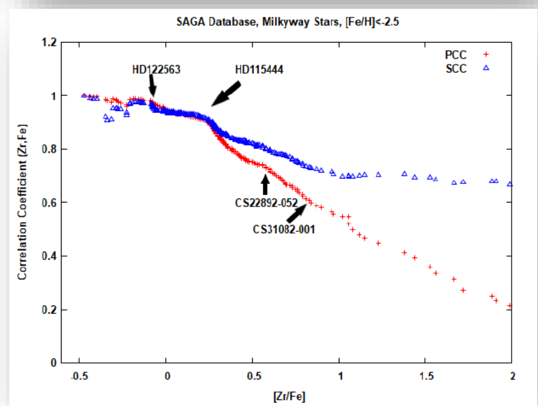
r-poor/r-rich “cuts“:
Sr – [Eu/Fe] ≈ 1.0
Zr – [Eu/Fe] ≈ 0.8
Ag – [Eu/Fe] ≈ 0.4





today

SCC & **PCC** of Fe for Sr and Zr in stars with [Fe/H] < -2.5



SCC / **PCC** „cuts“
Sr - [Sr/Fe] ≈ 0.1
Zr – [Zr-Fe] ≈ 0.25

Correlation coefficients (X/Fe) high for r-poor and r-I → **SNe**

low for r-II → **Mergers**

Selected r-poor & r-I halo stars: Comparison of data with Fe-Sr-Eu correlations

What do we learn from comparison of astronomical observations with r-element correlations ?

Stellar ID	[Eu/Fe]	[Fe/H]	(Sr/Eu)	%Sr with Fe	%Eu with Fe	%Sr w/o Fe	%Eu w/o Fe	
HD 122563	-0.64	-2.53	589	100	100	0	0	"r-poor"
HE 0048-6408	-0.50	-3.75	107	100	100	0	0	
BD - 185550	-0.21	-3.06	40	100	100	0	0	
CS 22897-008	-0.03	-3.83	1122	100	100	0	0	
CS 22891-209	0.10	-3.49	759	100	100	0	0	
HE 0139-2826	0.21	-3.46	4.3	100	100	0	0	"r-I"
CS 22190-007	0.33	-2.57	170	80	51	20	49	
CS 22955-174	0.35	-3.10	251	100	80	0	20	
CS 22879-029	0.59	-2.55	562	15	34	85	66	
HD 115444	0.68	-2.84	56	100	46	0	54	
HE 2158-0348	0.79	-2.71	155	48	33	52	67	

"r-poor" stars

- lowest metallicity $[Fe/H]_{av} \approx -2.93$
  early in galaxy
- large scatter (Sr/Eu), min. 40; max. 1122
- Sr & Eu completely correlated with Fe

"pure" SN signature

"r-I" stars

- slightly higher $[Fe/H]_{av} \approx -2.78$
- again, large scatter (Sr/Eu), min. 4.3; max. 562
- Sr still predominantly correlated with Fe (90%);
  Eu ≈ 60% correlated with Fe

"blends" of SN & NSM

Selected r-I & r-II halo stars: Comparison of data with PCC & SCC

Again – what can we learn?

	Stellar ID	[Eu/Fe]	[Fe/H]	(Sr/Eu)	%Sr with Fe	%Eu with Fe	%Sr w/o Fe	%Eu w/o Fe	
	CS 22190-007	0.33	-2.57	170	80	51	20	49	„r-I“
	CS 22879-029	0.59	-2.55	562	15	34	85	66	
	HD 115444	0.68	-2.84	56	100	46	0	54	
	CS 22875-029	0.92	-2.69	191	29	25	71	75	„r-II“
	HE 0336+0113	1.22	-2.73	776	4	15	96	85	
	CS 22892-052	1.53	-2.91	25	84	14	16	86	
*	CD -24_17504	1.37	-3.19	0.54	100	27	0	73	
*	CD -27_14351	1.71	-2.63	240	3.4	4.3	97	96	
	CS 31082-001	1.72	-2.79	7.9	93	5.9	7.0	94	
	HE 0243-3044	1.92	-2.58	26	17	2.5	83	97	

“r-I“ stars

- 90% Sr correlated with Fe
- 60% Eu correlated with Fe
- “blends“ of SN & Merger

“r-II“ stars

[Fe/H] av. ≈ -2.78, similar to r-I
74 % Sr corr. with Fe ⟹ SN
77 % Eu uncorr. with Fe ⟹ Merger
CD-27_14351 „clean“ NSM with low [Fe/H]
CD-24_17504 no Sr from NSM-HEW

Deconvolution of Sr & Eu from SNe and Mergers

Example: r-II **Sneden star** (CS22892-052) [Eu/Fe] = 1.53

(Sr/Eu) = 25

84% Sr & 14% Eu correlated with Fe ⇨ **SNe**

16% Sr & 86% Eu uncorrelated with Fe ⇨ **Mergers**

↷ „clean“ **SN** part (Sr/Eu) ≈ 147

„clean“ **Merger** part (Sr/Eu) ≈ 4.6

↷ „clean“ **SN** part [Eu/Fe] ≈ 0.30

„clean“ **Merger** part [Eu/Fe] ≈ 1.46

… rough estimate: „Sneden-star Merger“ contaminated by 6 SNe

Near future: similar analyses for „typical“ r-I, r-II and actinide-boost stars

Summary based on astronomical "facts"

- First indications of different r-process types & sites, **already more than a decade ago**
- Statistical analyses (PCC, SCC ranks, K-means clusters) confirm the old ideas; improvements from qualitative to quantitative
- To understand the total abundance pattern (from Sr to Th) of **S.S.-r „blend"**, in addition to Merger-type contributions, also sizeable fractions of SN-types required;

e.g. ≈ 90% S.S.-r Strontium
≈ 50% S.S.-r Europium
} from **SNe**

Summary based on nucleosynthesis models

Six decades of r-process nucleosynthesis research:

From a secondary process with Fe-seed in SN-I (B^2FH, Cameron, Coryell) to a primary process in SN-II to the present „multi-scenarios“.