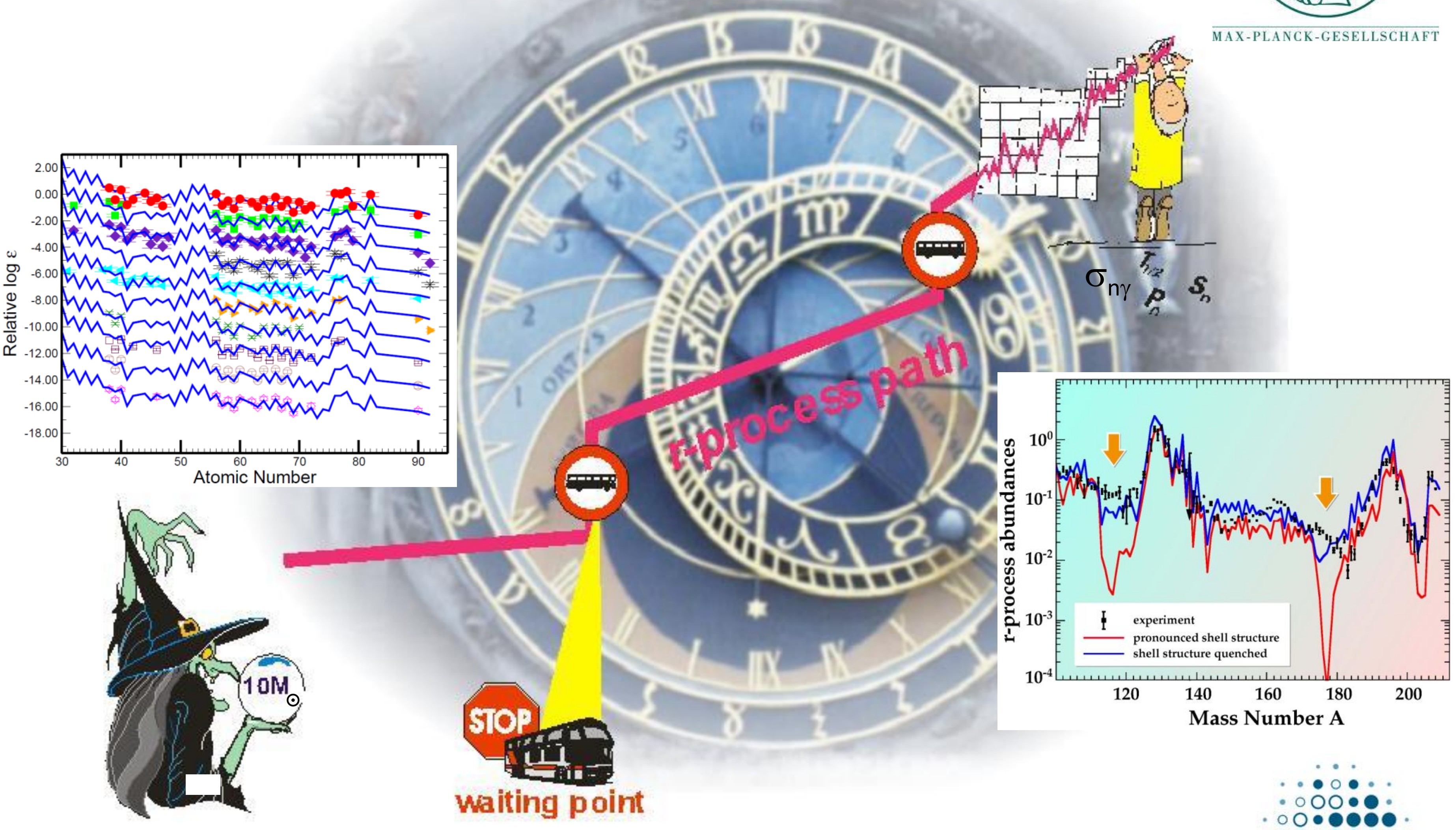
Nucleosynthesis modes in the HEW of SNe: Calculations vs. observations



Karl-Ludwig Kratz
Khalil Farouqi

MAX-PLANCK-GESELLSCHAFT
MAX-PLANCK-INSTITUT FÜR CHEMIE

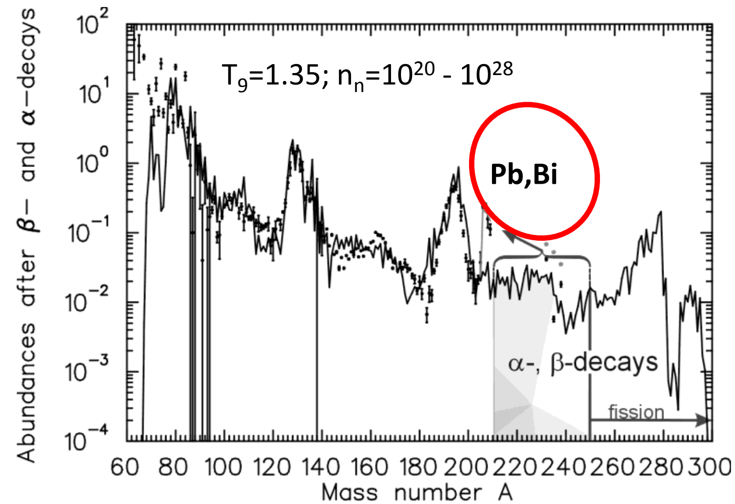
EMMI Workshop, 2011

r-Process observables today

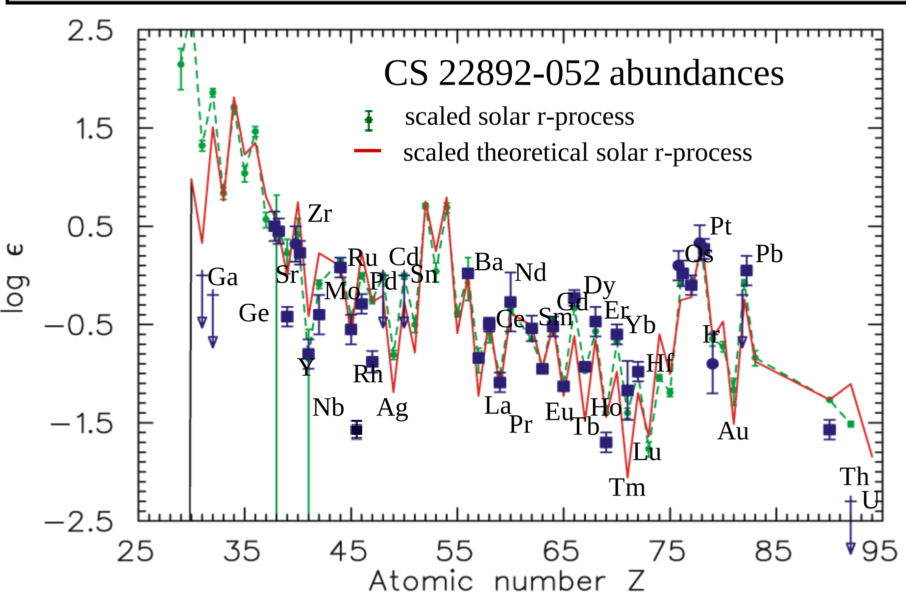
Observational instrumentation

- **meteoritic** and overall **solar-system** abundances
- **ground- and satellite-based telescopes like *Imaging Spectrograph* (STIS) at Hubble, *HIRES* at Keck, and *SUBARU***
- **recent „Himmelsdurchmusterungen“ *HERES and SEGUE***

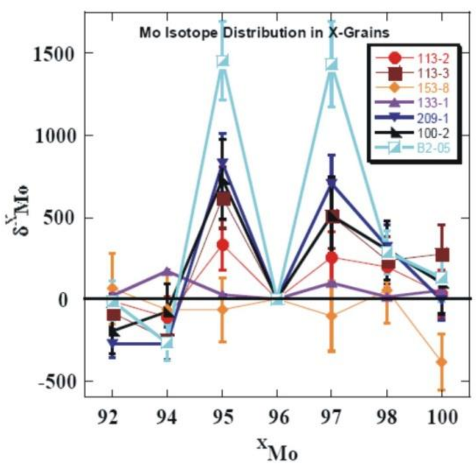
Solar system isotopic $N_{r,\odot}$ "residuals"



r-process observables



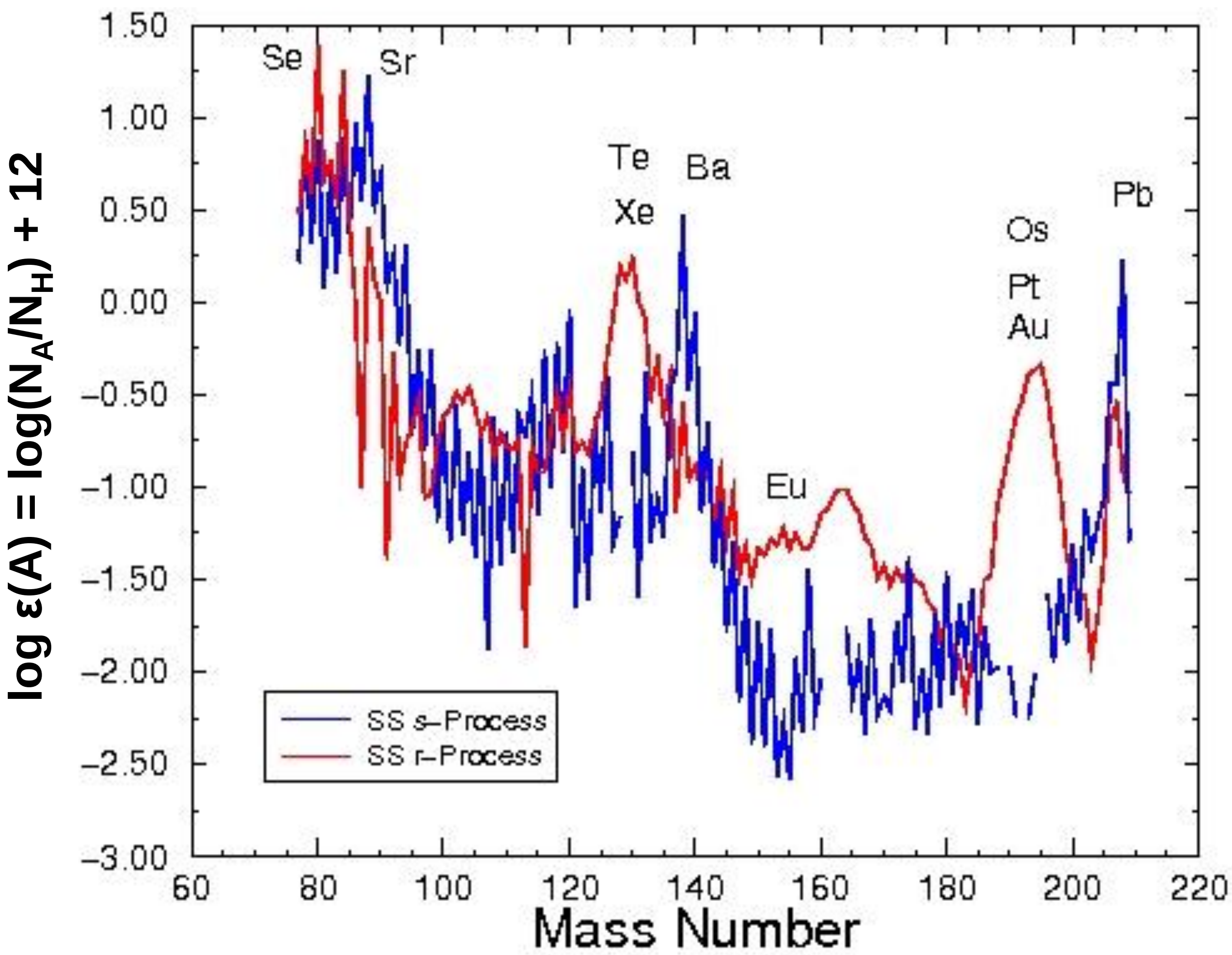
Elemental abundances in UMP halo stars



Presolar SiC grains and nano-diamonds e.g. isotopic composition of heavy metals Zr, **Mo**, Ru, Xe, Ba, Pt

Isotopic anomalies in meteoritic samples and stardust

Deconvolution SS isotopic abundances



Historical SS isotopic abundance breakdowns by s- and r-process

r-process "residuals": subtract N_s from SS

$$N_{r,\odot} = N_\odot - N_s$$

Still valid today?

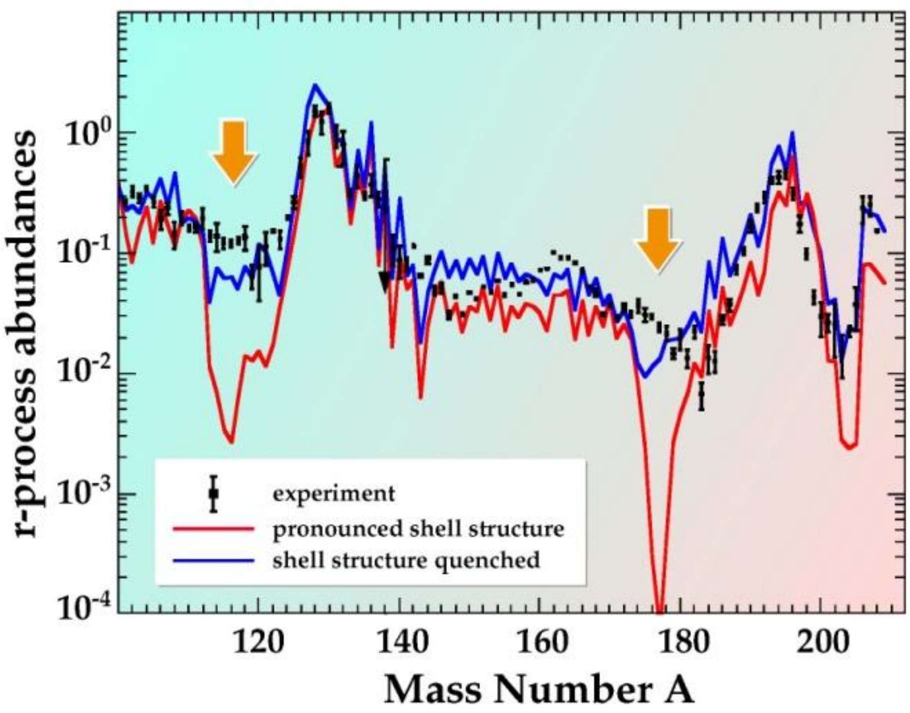
Necessity of separate "LEPP"?

Until yesterday…

Historical r-process:

Fe-seed (implies secondary process)

superposition of n_n-components



our Basel – Mainz (FK^{2}L) parameter studies

…largely **site-independent**!
T_9 and n_n constant;
instantaneous freezeout

"main" r-process

from A ≈ 130 peak up;
early **primary** process; SN-II ?

"weak" r-process

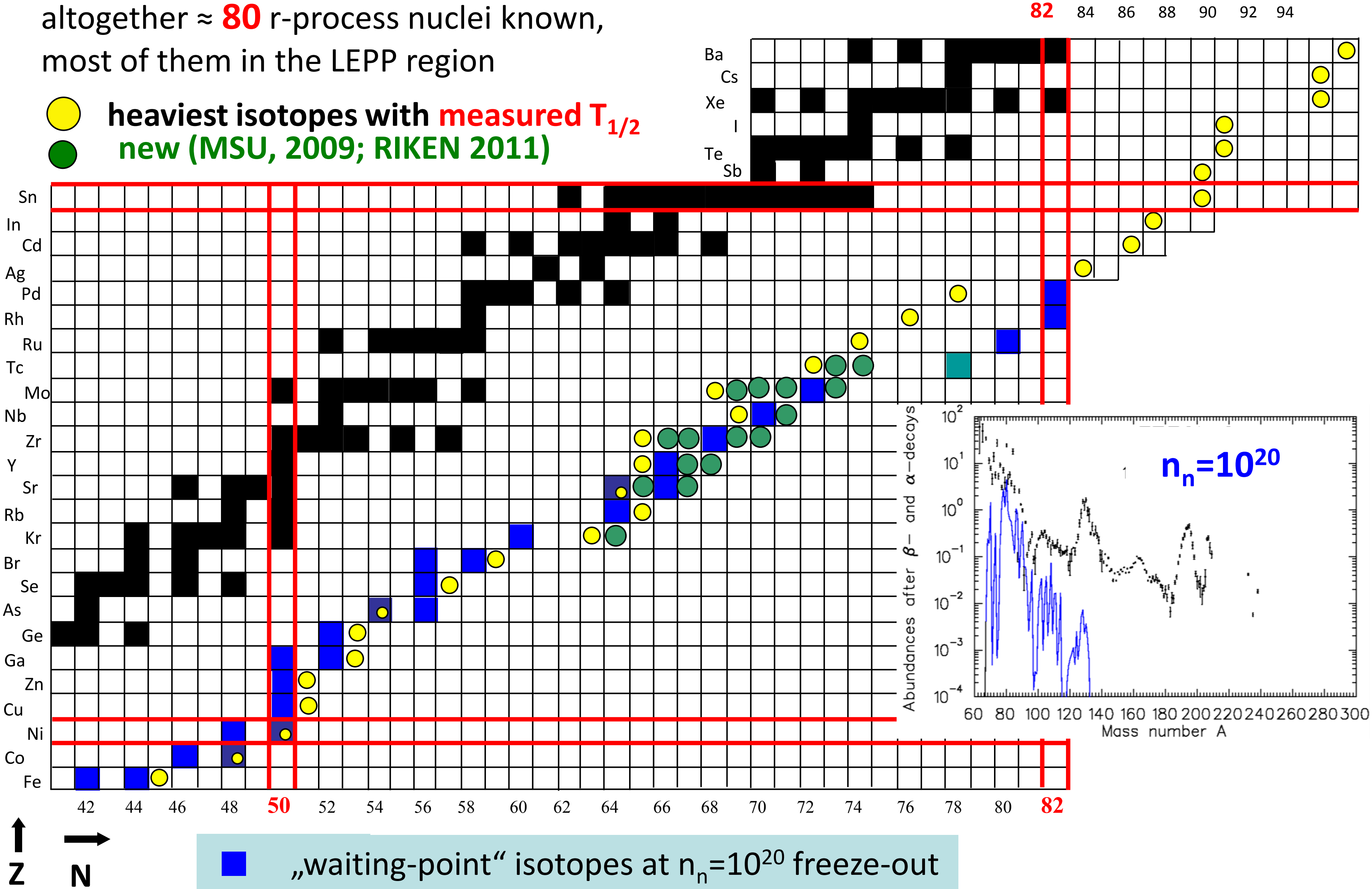
from Fe via A ≈ 50 peak to A ≈ 120;
later **secondary** process;
explosive shell burning ?

Summary "waiting-point" model, see e.g. **Kratz et al., Ap.J. 662 (2007)**

Experimental situation for r-process progenitors of LEPP isotopes

Today,
altogether ≈ **80** r-process nuclei known,
most of them in the LEPP region

heaviest isotopes with measured $T_{1/2}$
new (MSU, 2009; RIKEN 2011)



„waiting-point" isotopes at $n_n=10^{20}$ freeze-out

Experimental information on r-process nuclides

Progress in Particle and Nuclear Physics 66 (2011) 358–362

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Review

r-Process nucleosynthesis: Present status and future experiments at the FRS and ESR

Iris Dillmann [a,b,*], Yuri A. Litvinov [b,c]

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[c] *Max-Planck Institut für Kernphysik, Heidelberg, Germany*

“Up to now, one could only “scratch” the regions where the r-process takes place.”

No comment !

The high-entropy / neutrino-driven wind model

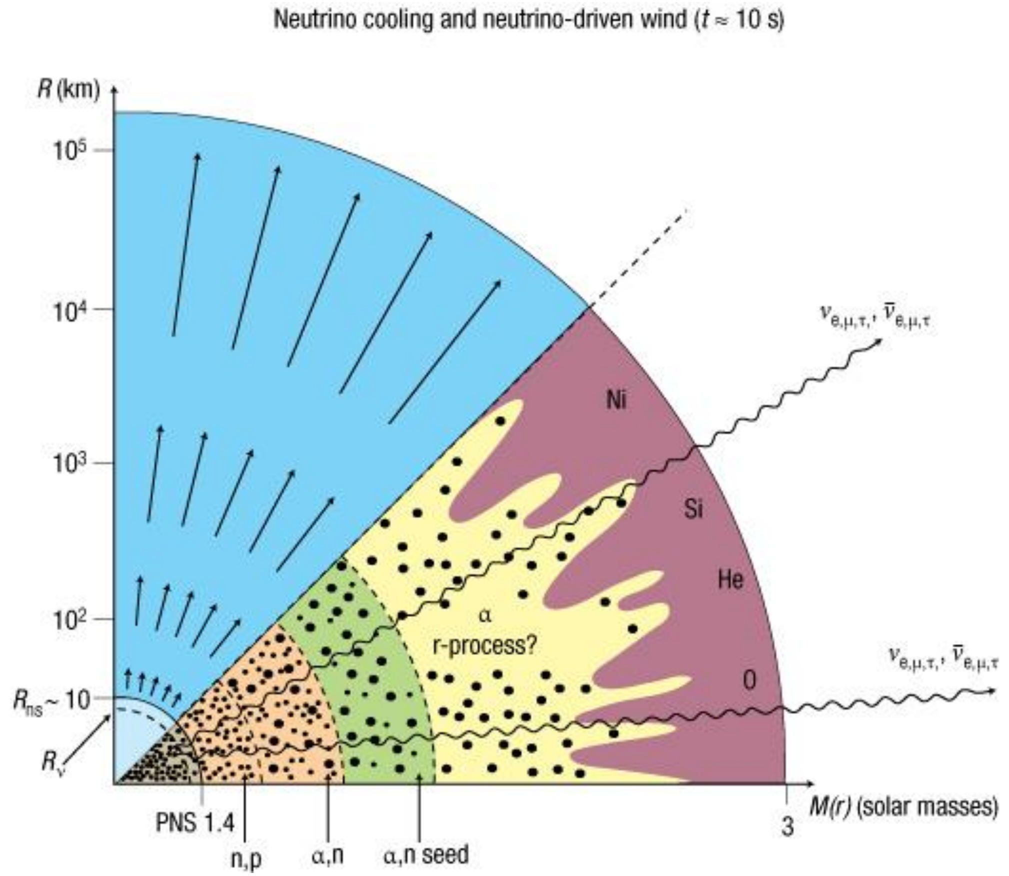
…one of the presently favoured scenarios for the "r-process"

The **neutrino-driven wind** starts from the surface of the proto-neutron star with a flux of neutrons and protons.

As the nucleons cool ($10 \geq T_9 \geq 6$), they combine to α-particles + an excess of unbound neutrons.

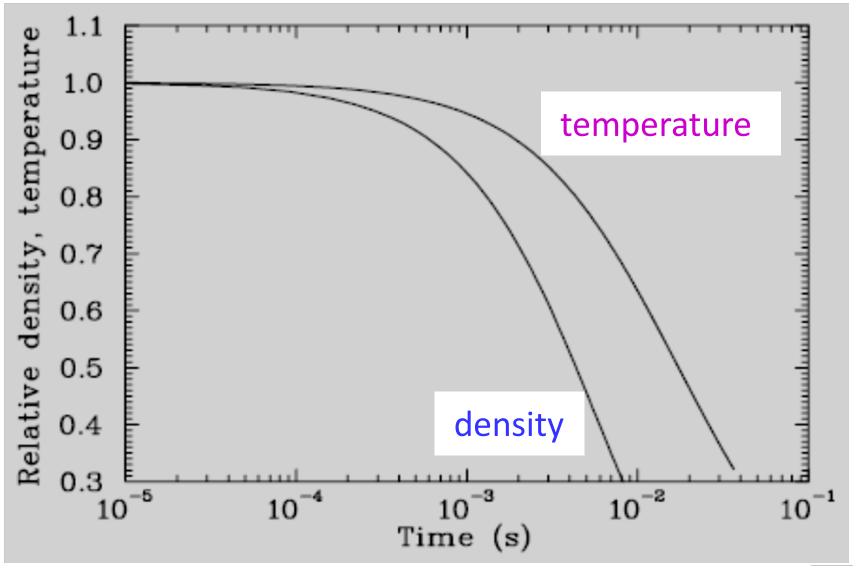
Further cooling ($6 \geq T_9 \geq 3$) leads to the formation of a few Fe-group "seed" nuclei in the so-called **α-rich freezeout**.

Still further cooling ($3 \geq T_9 \geq 1$) leads to neutron captures on this seed composition, making the heavy **r-process** nuclei.



(Woosley & Janka, Nature, 2005)

Formation of r-process "seed"

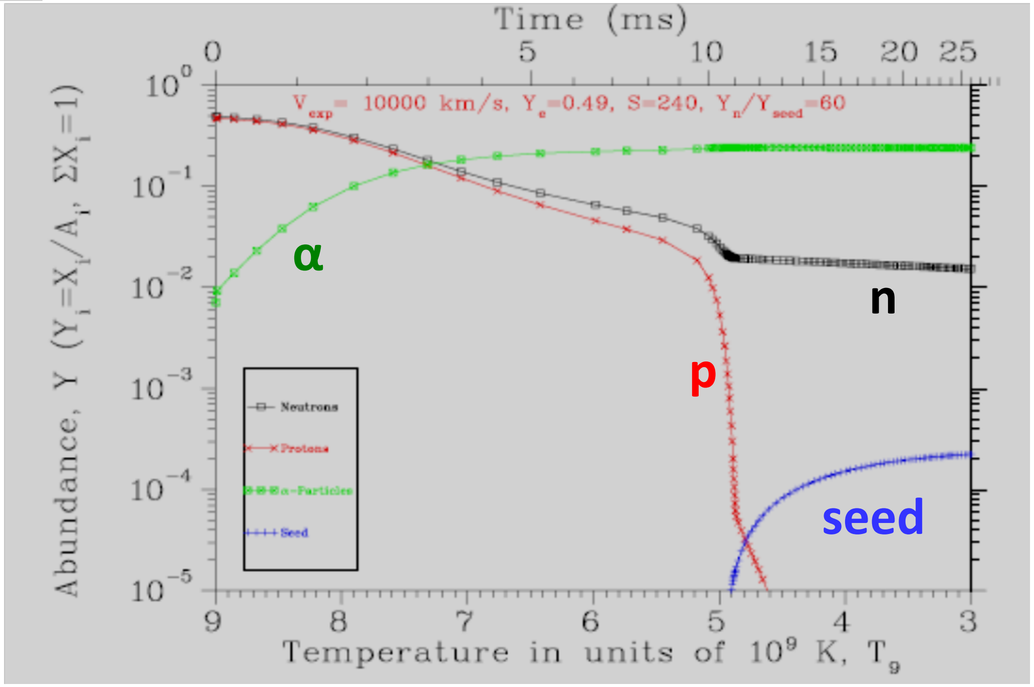


Time evolution of
temperature and density
of HEW bubble
(V_{exp}=10,000 km/s)

⇨ **extended "freeze-out" phase !**

Recombination of protons
and neutrons
into α-particles
as functions of temperature and time

For $T_9 \leq 7 \Rightarrow$ **α** dominate;
at $T_9 \approx 5 \Rightarrow$ **p** disappear,
n survive,
"seed" nuclei emerge.



(Farouqi et al., 2009)

The Basel – Mainz HEW model

full dynamical network (extension of Freiburghaus model)

- time evolution of temperature, matter density and neutron density
- extended freezeout phase

"best" nuclear-physics input (Mainz, LANL, Basel)

- nuclear masses
- β-decay properties
- n-capture rates
- fission properties

Three main parameters:

electron abundance	$Y_e = Y_p = 1 - Y_n$
radiation entropy	$S \sim T^3/\rho$
expansion speed	$v_{exp} \Rightarrow$ durations τ_α and τ_r

parameters correlated !

First results of dynamical r-process calculations

- Conditions for successful r-process

  ⇒ **„strength“ formula**

$$\frac{Y_n}{Y_{Seed}} = k_{SN} V_{Exp} \left(\frac{S}{Y_e} \right)^3$$

(Farouqi, PhD Mainz 2005)

- Neutron-rich r-process seed beyond N=50 (^{94}Kr, ^{100}Sr, ^{95}Rb…)

  ⇒ avoids first bottle-neck in classical model

- Initial r-process path at particle freezeout ($T_9 \approx 3$)

  ⇒ **$Y_n/Y_{seed} \leq 150$**

- Total process duration up to Th, U

  ⇒ **$\tau_r \leq 750$ ms**

  instead of ≈ 3500 ms in classical model

- Due to improved nuclear-physics input (e.g. N=82 shell quenching!)

  ⇒ **max. S ≈ 280**

  to form full 3rd peak and Th, U

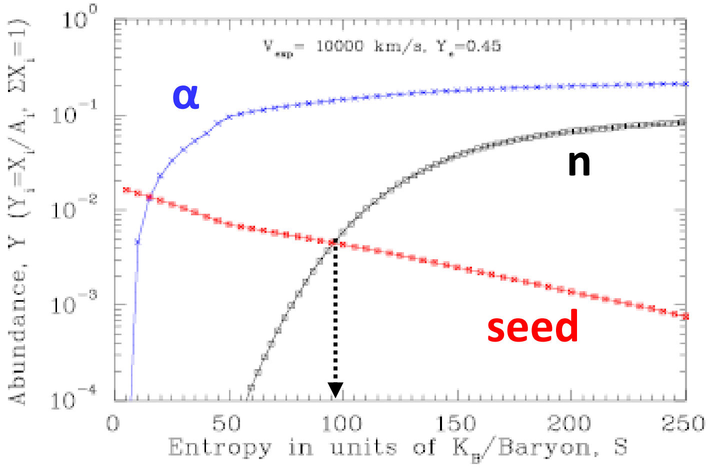
- Freezeout effects (late non-equilibrium phase)

  ⇒ capture of “free” neutrons

  ⇒ recapture of βdn-neutrons

Parameters HEW model ⇨ Y(Z)

Y_e=0.45



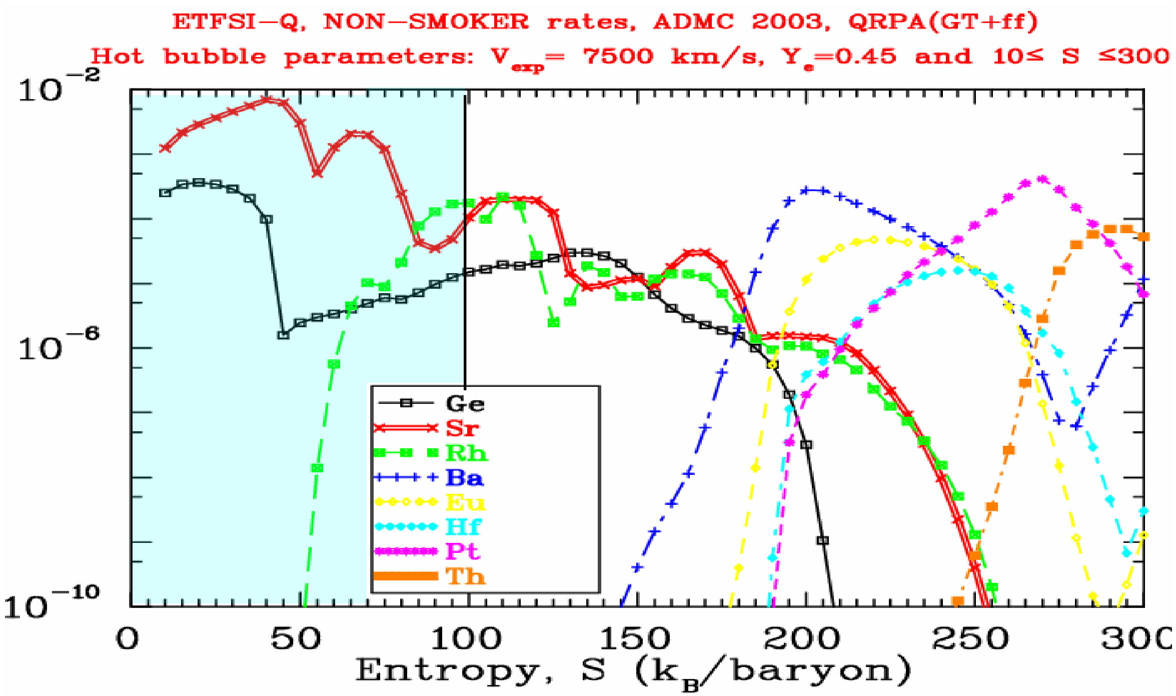
No neutrons ↷ no n-capture r-process!

Nucleosynthesis components:

$S \leq 100$; $Y_n/Y_{seed} < 1$
charged-particle (CP) process

$100 < S < 150$; $1 < Y_n/Y_{seed} < 15$
"weak" r-process

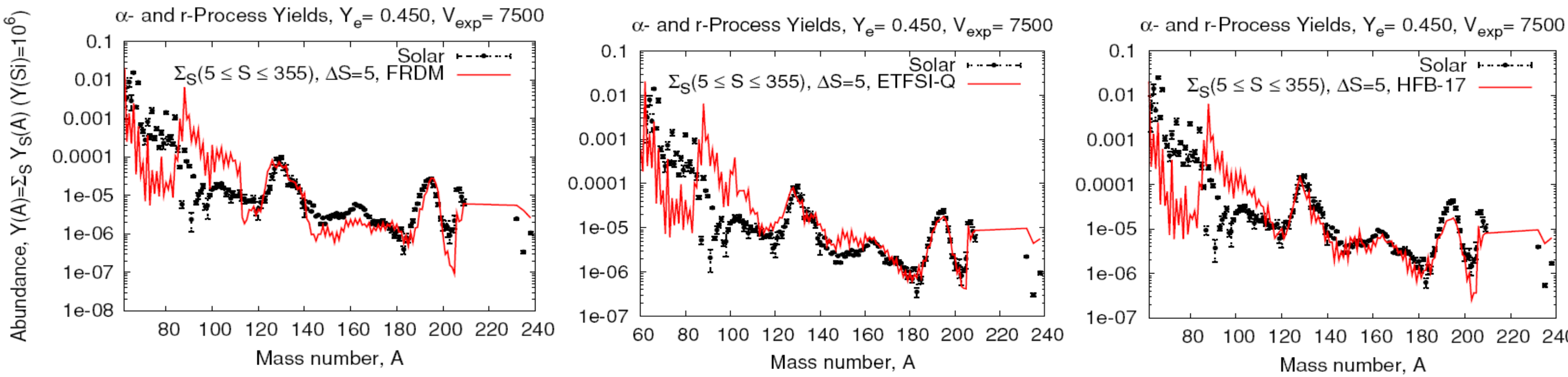
$150 < S < 300$; $15 < Y_n/Y_{seed} < 150$
"main" r-process



Reproduction of $N_{r,\odot}$

Superposition of S-components with Y_e=0.45;

weighting according to Y_{seed}

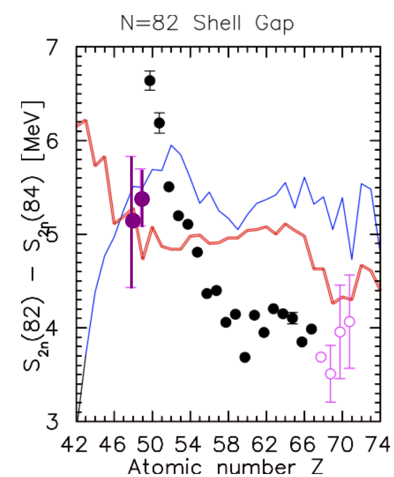


Caveat: deficiences in REE

No exponential fit to $N_{r,\odot}$!

Entropy S	Process duration [ms] FRDM	ETFSI-Q	Remarks
150	54	57	A≈115 region
180	209	116	**top of A≈130 peak**
220	422	233	REE pygmy peak
245	691	339	**top of A≈195 peak**
260	1290	483	Th, U
280	2280	710	fission recycling
300	4310	1395	" "

⇨ significant effect of **"shell-quenching"** below doubly-magic ^{132}Sn

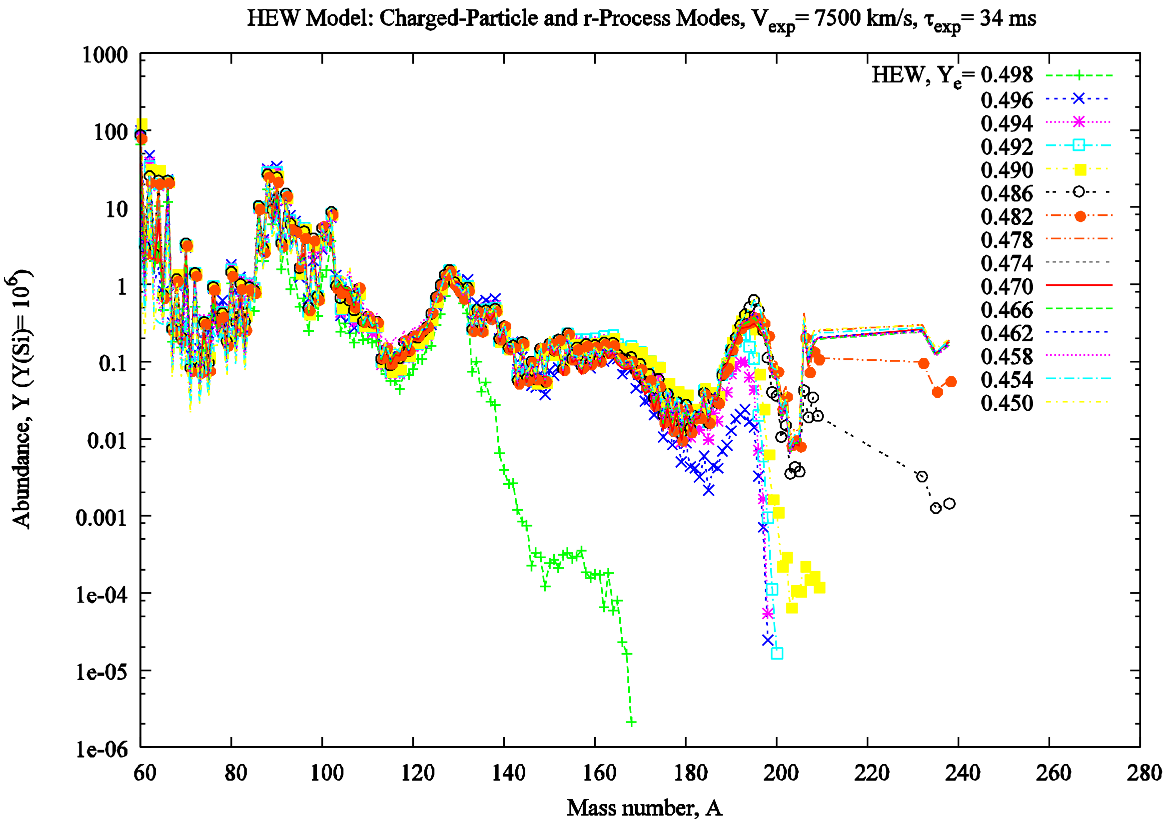


Superposition of HEW components $0.450 \le Y_e \le 0.498$

"weighting" of r-ejecta according to mass predicted by HEW model:

for Y_e=0.400 ca. 5×10^{-4} M_o

for Y_e=0.498 ca. 10^{-6} M_o



For $Y_e \le 0.470$
full r-process,
up to Th, U

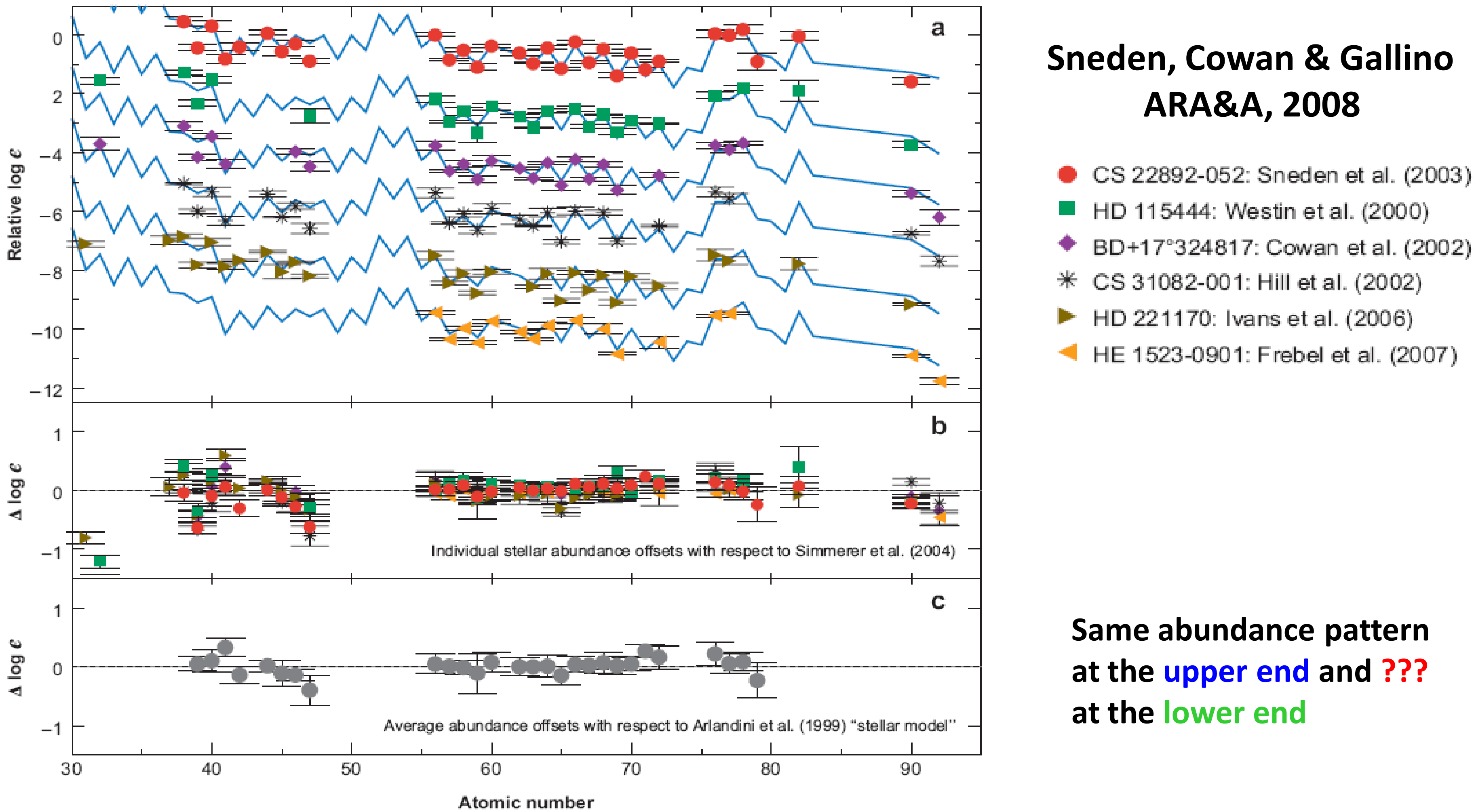
For $Y_e \approx 0.490$
still 3rd peak,
but no Th, U

For $Y_e = 0.498$
still 2nd peak,
but no REE

„what helps…?" low Y_e, high S, high V_{exp}

Farouqi et al. (2009)

Observations: Selected “r-enriched” UMP halo stars



Sneden, Cowan & Gallino
ARA&A, 2008

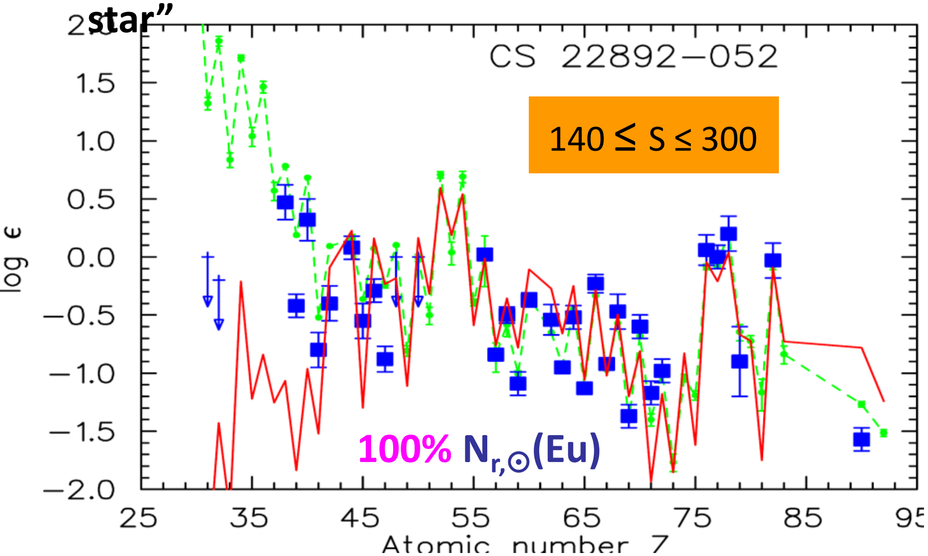
Same abundance pattern at the upper end and ??? at the lower end

Two options for HEW-fits to UMP halo-star abundances:

- const. Y_e = 0.45, optimize S-range;
- optimize Y_e with corresponding full S-range.

Extremes “r-rich” and “r-poor”: S-range optimized

r-rich “Sneden star”



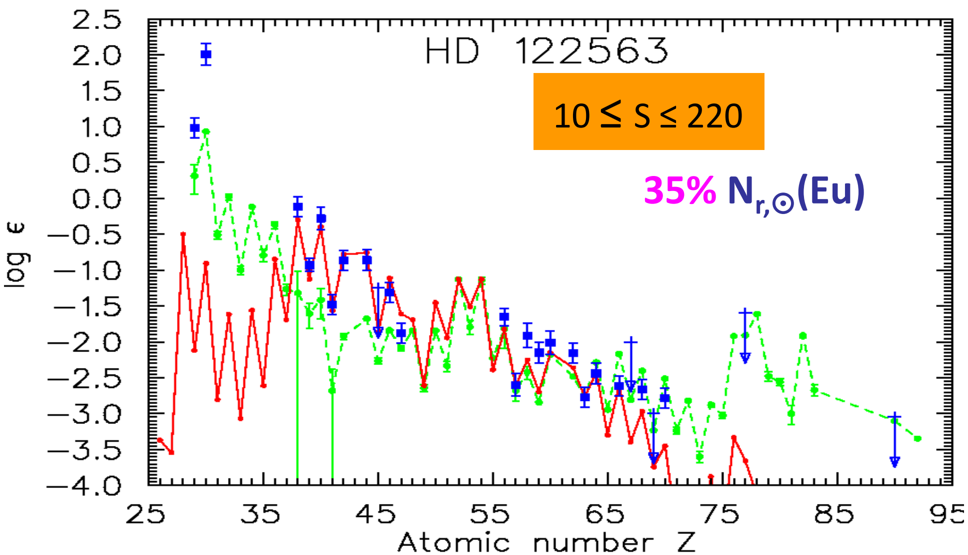
full main r-process

Sr – Cd region **underabundant** by a mean factor ≈ 2 relative to SS-r

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

➡ **“missing” part to SS-r = LEPP**

r-poor “Honda star”



incomplete main r-process

Sr – Cd region **overabundant** by a mean factor ≈ 8 relative to SS-r

Relative elemental abundances, Y(Z)

From Ge – Zr via Ag to Eu ↷ different nucleosynthesis modes

HEW with Y_e =0.45; v_{exp} =7500

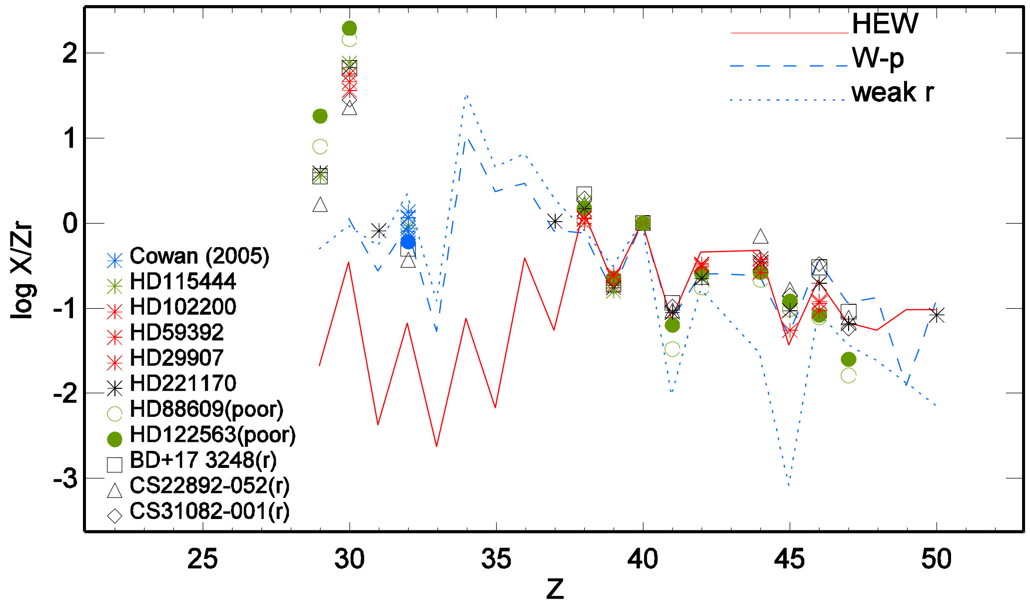
ELEMENT	Y(Z) as fct. of S in %		
	$10 \leq S \leq 100$	$100 \leq S \leq 150$	$150 \leq S \leq 300$
$_{32}$Ge	99	1.2	-
$_{38}$Sr	98	1.4	0.3
$_{40}$Zr	**95**	4.7	0.3
$_{42}$Mo	64	32	4.7
$_{47}$Ag	3.7	**71**	25
$_{52}$Te	0.001	10	**90**
$_{56}$Ba	-	-	100

normal α -rich freezeout	n-rich α-freezeout	
CP component uncorrelated	weak-r component weakly correlated	main-r component strongly correlated

with Eu ?

Halo stars vs. HEW model: "LEPP" elements

LEPP-abundances vs. CP- enrichment (Zr)



HEW (10 < S < 280)
WP (Fe seed; $10^{20} < n_n < 10^{28}$)
weak-r (Si seed; $n_n \approx 10^{18}$)

HEW reproduces high-Z LEPP observations (Sr – Sn);
underestimates low-Z LEPP observations (Cu – Ge)

↷ **additional nucleosynthesis processes ?**

(e.g. Fröhlich et al. νp-process;
Pignatari et al. rs-process;
El Eid et al. early s-process)

(Farouqi, Mashonkina et al. 2008)

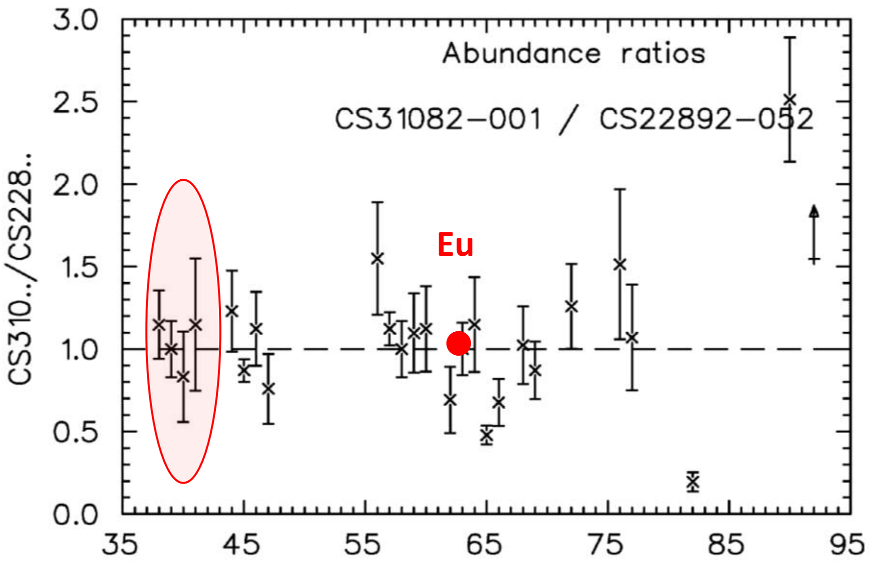
Halo stars vs. HEW-model: Extremes "r-rich" and "r-poor"

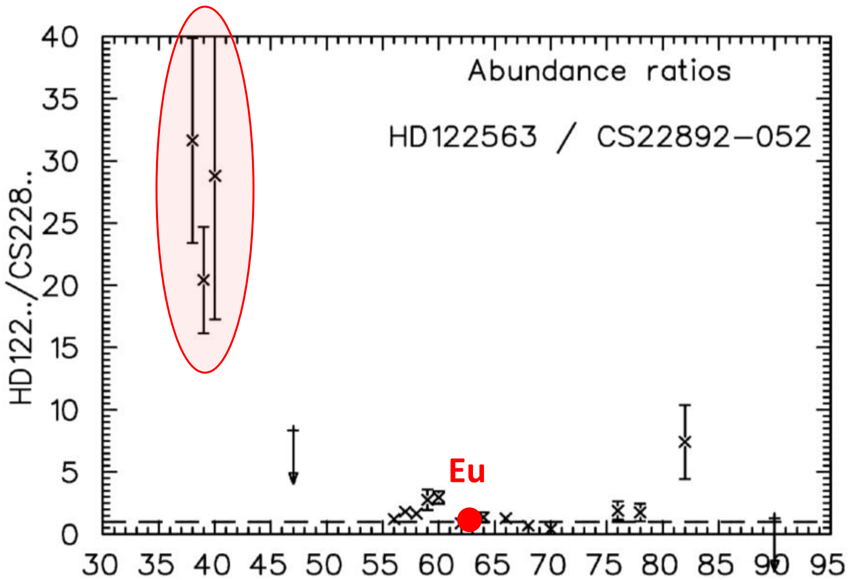
Elemental abundance ratios UMP halo stars

r-rich "Cayrel star" / r-rich "Sneden star"

r-poor "Honda star" / r-rich "Sneden star"

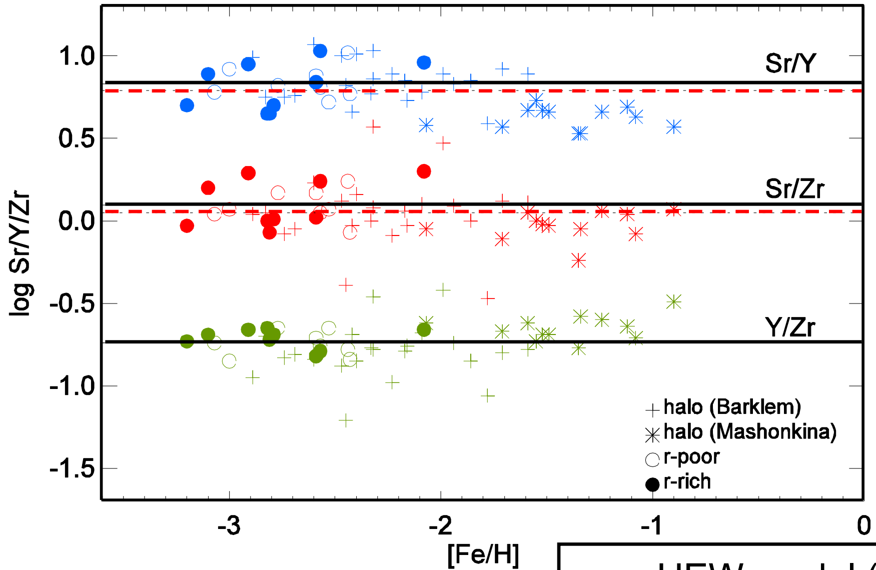
normalized to Eu

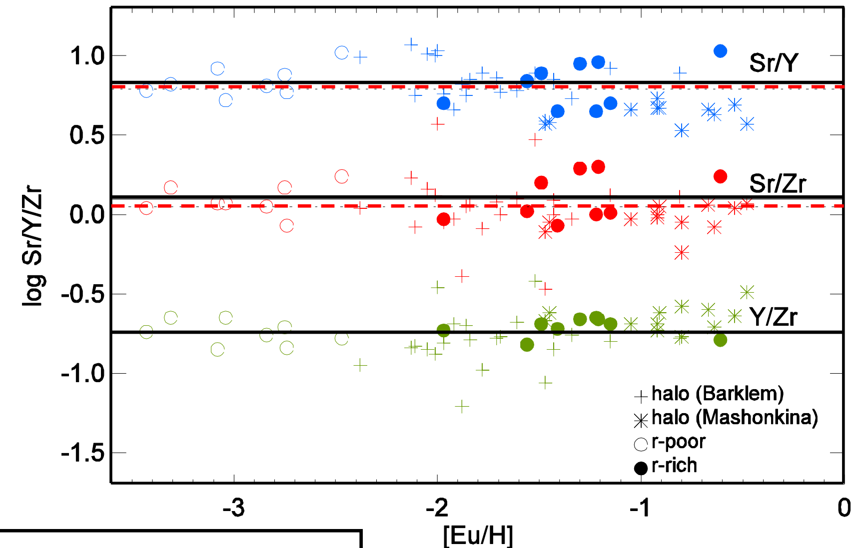




Factor 25 difference for Sr - Zr region !

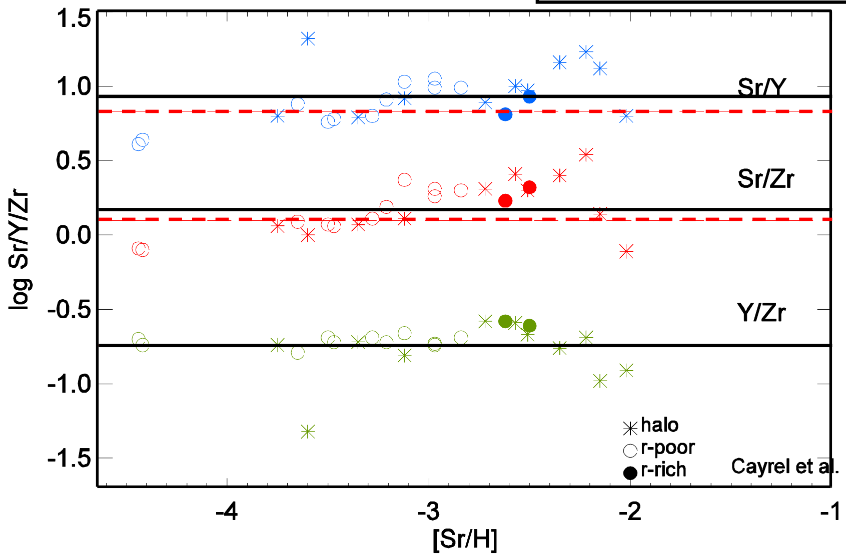
Halo stars vs. HEW model: Sr/Y/Zr as fct. of [Fe/H], [Eu/H] and [Sr/H]





—— 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) ?

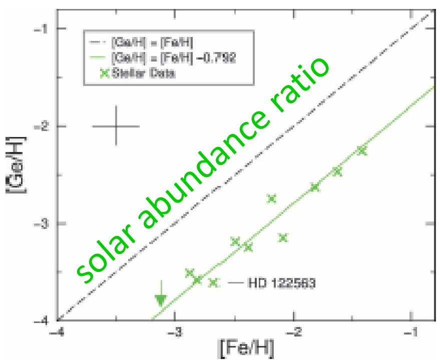
Observations: Correlation Ge, Zr with r-process?

Ap.J., 627 (2005)

HUBBLE SPACE TELESCOPE OBSERVATIONS OF HEAVY ELEMENTS IN METAL-POOR GALACTIC HALO STARS

John J. Cowan,[1] Christopher Sneden,[2] Timothy C. Beers,[3] James E. Lawler,[4] Jennifer Simmerer,[2] James W. Truran,[5] Francesca Primas,[6] Jason Collier,[1] and Scott Burles[7]

Received 2004 September 8; accepted 2005 February 24

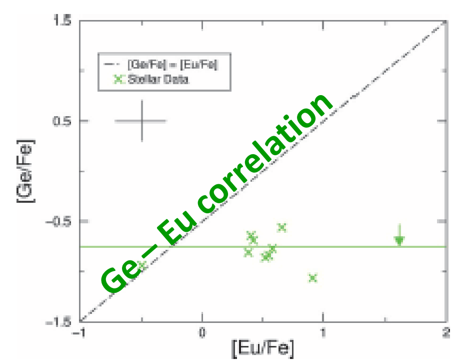


Relative abundances [Ge/H] displayed as a function [Fe/H] metallicity for our sample of 11 Galactic halo stars. The arrow represents the derived upper limit for CS 22892-052. The dashed line indicates the solar abundance ratio of these elements: [Ge/H] = [Fe/H], while the solid green line shows the derived correlation [Ge/H]=[Fe/H]= -0.79. A typical error is indicated by the cross.

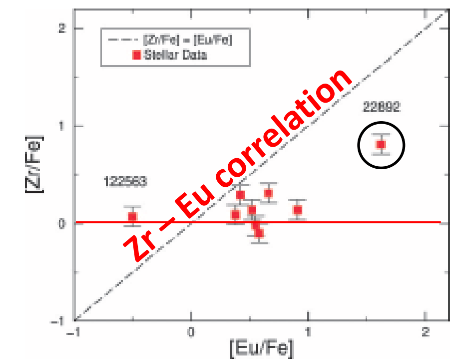
"… the Ge abundances…
track their Fe abundances very well.
An explosive process on iron peak nuclei (e.g. the α-rich freezeout in SNe), rather than neutron capture, appears to have been the dominant mechanism for this element…"

"Zr abundances also do not vary cleanly with Eu"

"Ge abundance seen completely uncorrelated with Eu"



Correlation between the abundance ratios [Ge/Fe] and [Eu/Fe]. The dashed line indicates a direct correlation between Ge and Eu abundances. As in the previous Figure, the arrow represents the derived upper limit for CS 22892-052. The solid green line at [Ge/Fe]= -0.79 is a fit to the observed data. A typical error is indicated by the cross.



Correlation between the abundance ratios of [Zr/Fe] (obtained exclusivley with HST STIS) and [Eu/Fe]. The dashed line indicates a direct correlation between Zr and Eu abundances.

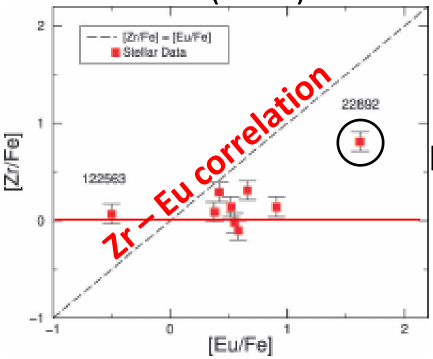
Can our HEW model explain observations ?

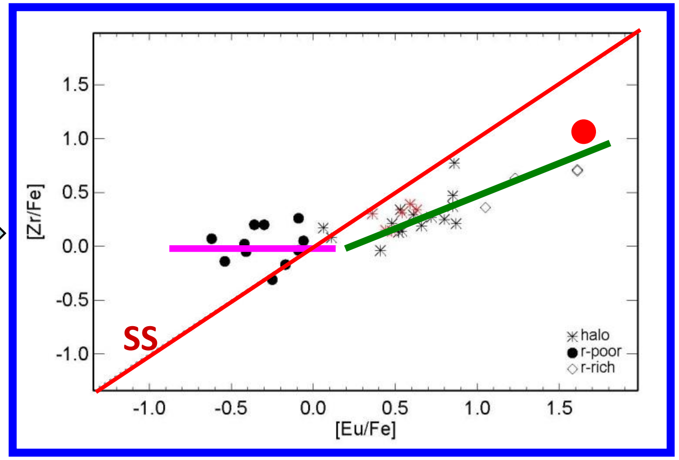
Ge okay!   100% CPR

Zr two components?

Halo stars vs. HEW model: Zr/Fe/Eu vs. [Eu/Fe], [Fe/H] and [Eu/H]

Cowan et al. (2005)





Zr in r-poor stars **overabundant**

type **"Honda star"**

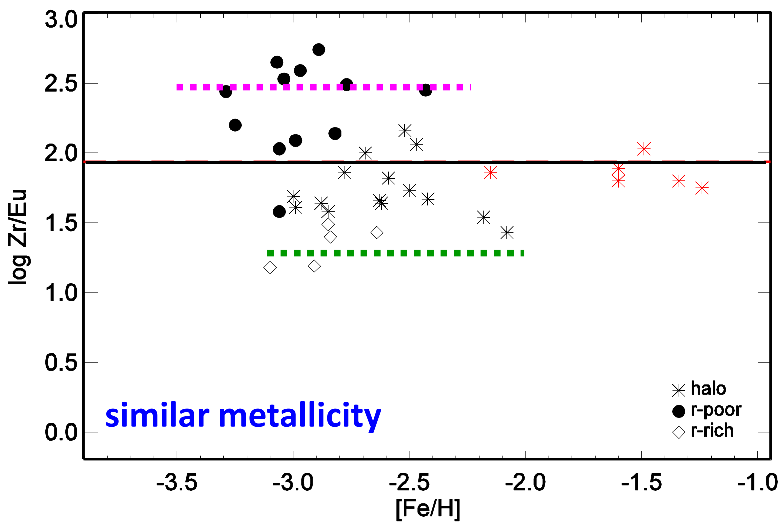
Zr in halo & r-rich stars **underabundant**

type **"Sneden star"**

Strong Zr – Eu correlation

SS diagonal

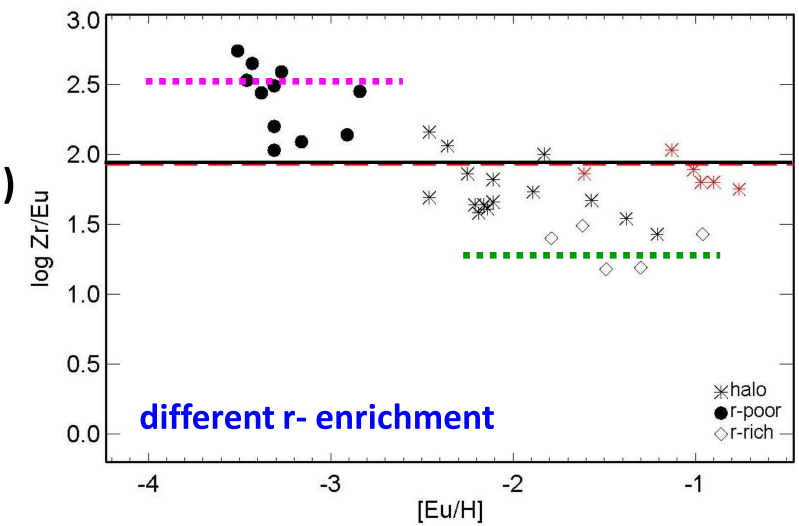
Halo, r-rich and r-poor stars are clearly separated!



r-poor

HEW (av.)

r-rich



Mashonkina (2009); Farouqi (2009)

Relative elemental abundances, Y(Z)

From Ge – Zr via Ag to Eu ↷ different nucleosynthesis modes

HEW with Y_e =0.45; v_{exp} =7500

ELEMENT	Y(Z) as fct. of S in %		
	$10 \leq S \leq 100$	$100 \leq S \leq 150$	$150 \leq S \leq 300$
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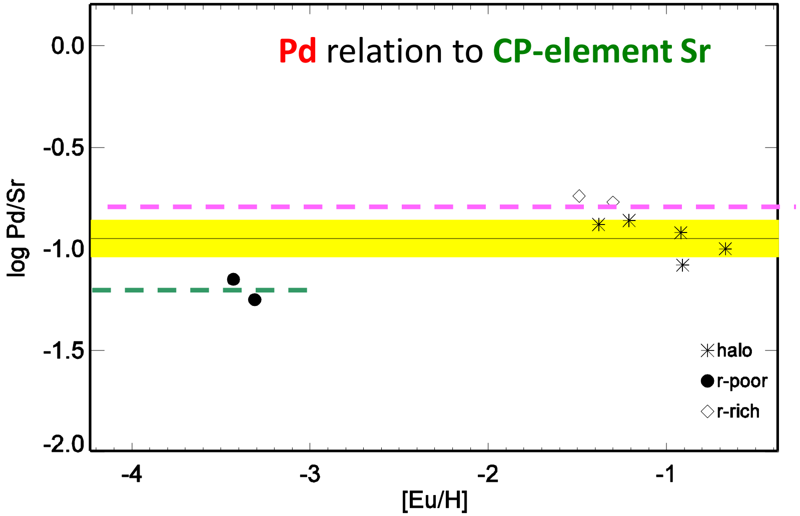
$_{40}$Zr	**95**	4.7	0.3
$_{42}$Mo	64	32	4.7
$_{47}$Ag	3.7	**71**	25
$_{52}$Te	0.001	10	**90**
$_{56}$Ba	-	-	100

normal α -rich freezeout	n-rich α-freezeout	
CP component uncorrelated	weak-r component weakly correlated	main-r component strongly correlated

with Eu ?

Halo stars vs. HEW-model predictions: Pd

Pd/Sr and Pd/Eu different from Sr/Y/Zr



average Halo stars

-1.5 < [Eu/H] < -0.6

log(Pd/Sr) ≈ - 0.95(0.09)

HEW model

log(Pd/Sr) = - 0.81 ("r-rich")

- 1.16 ("r-poor")

average Halo stars

-1.5 < [Eu/H] < -0.6

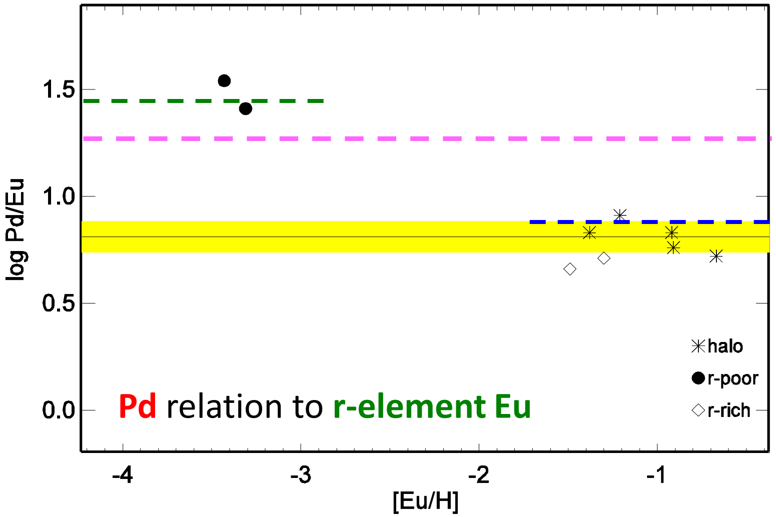
log(Pd/Eu) ≈ +0.81(0.07)

HEW model

log(Pd/Eu) = +1.25 (Pd CP+r)

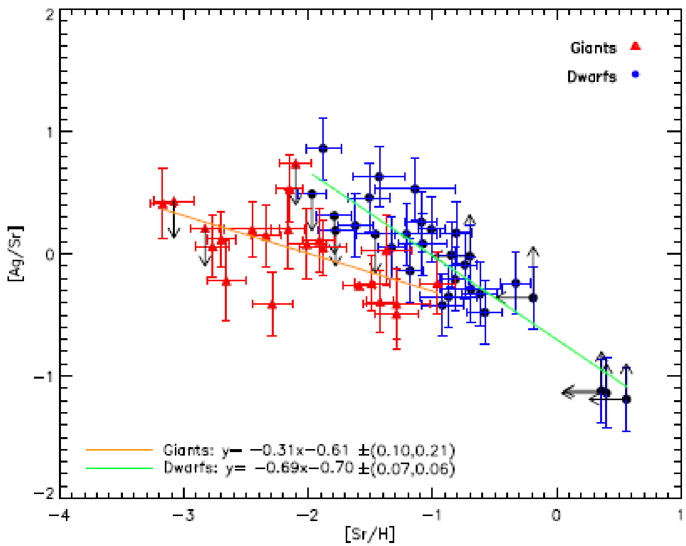
+0.89 ("r-rich")

+1.45 ("r-poor")

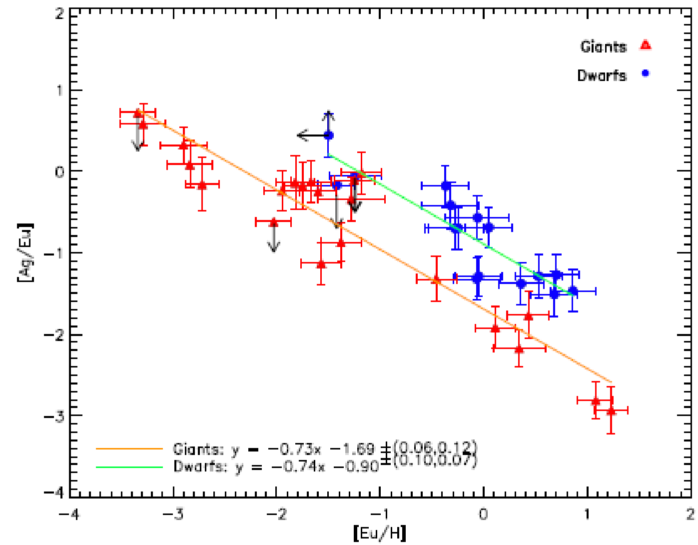


r-poor stars ([Eu/H] < -3) indicate TWO nucleosynthesis components for $_{46}$Pd:
Pd/Sr ⇨ uncorrelated, Pd/Eu ⇨ (weakly) correlated with "main" r-process

Observations of Pd & Ag in giant and dwarf stars



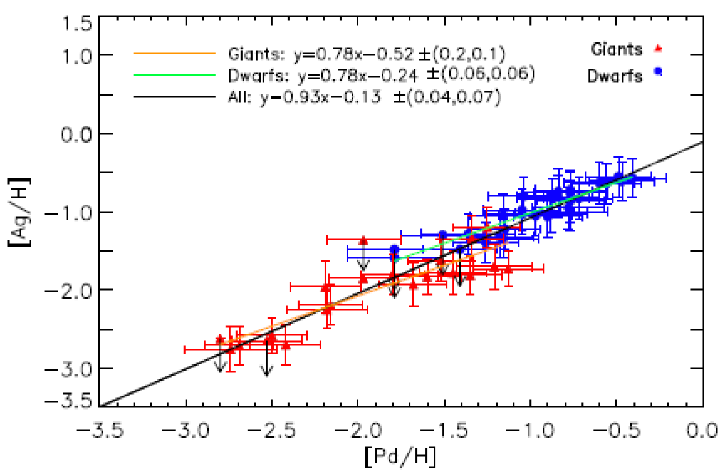
anticorrelation between Ag and Sr



anticorrelation between Ag and Eu

indication of different production processes

(Sr – charged-particle, Ag – weak-r, Eu – main r-process)



correlation of Pd and Ag

Pd and Ag are produced in the same process

(predominantly) weak r-process

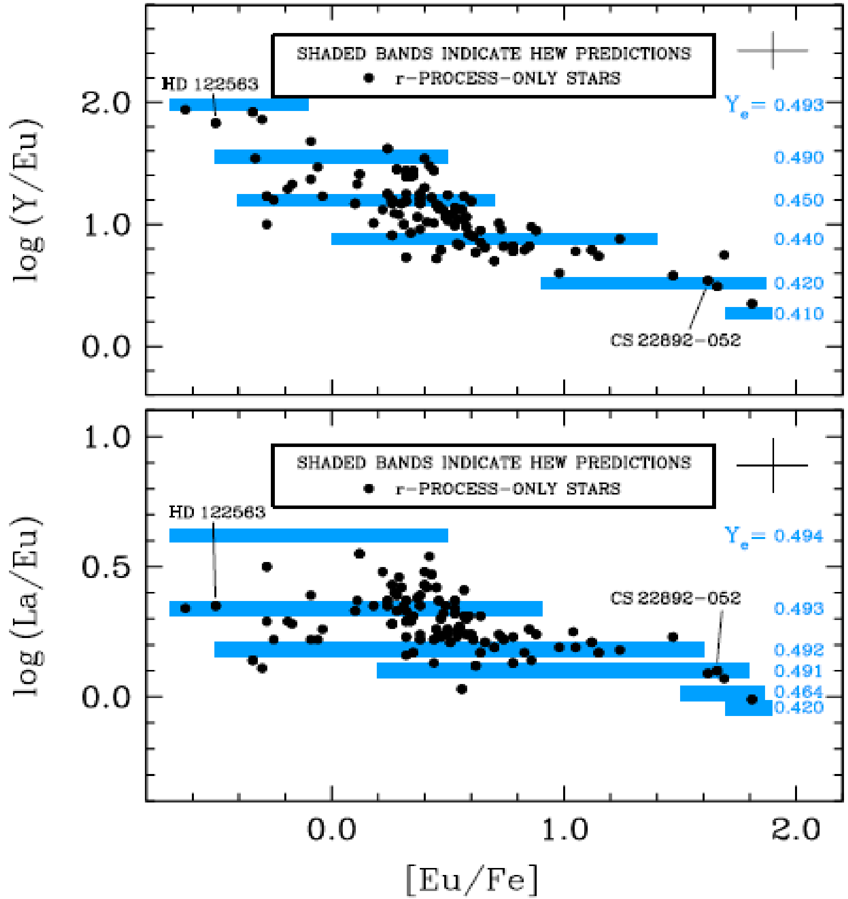
All observations in agreement with our HEW predictions !

(PhD-thesis C.J. Hansen, LMU 2011; and this workshop)

Halo stars vs. HEW-model: Y/Eu and La/Eu

Instead of restriction to a single Y_e with different S-ranges,

probably more realistic, choice of different Y_e's with corresponding full S-ranges



Clear correlation between "r-enrichment" and Y_e

$_{39}$Y represents CPR-component

(historical **"weak"** n-capture r-process)

$_{57}$La represents "main" r-process

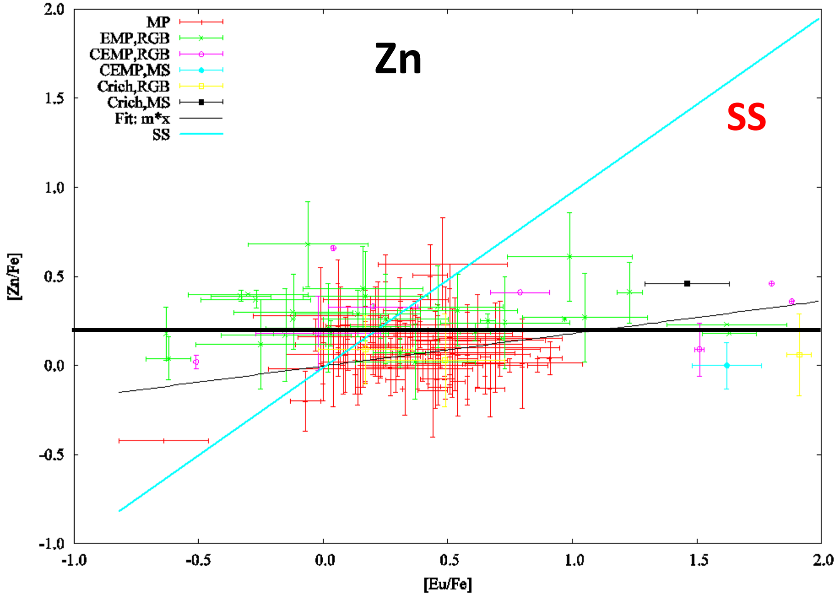
Caution!

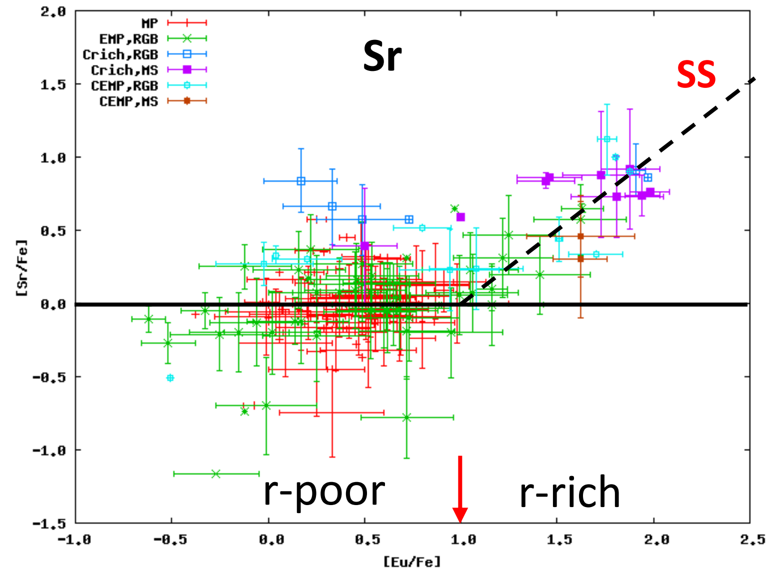
La always 100 % scaled solar;
log(La/Eu) trend correlated with **sub-solar** Eu in "r-poor" stars

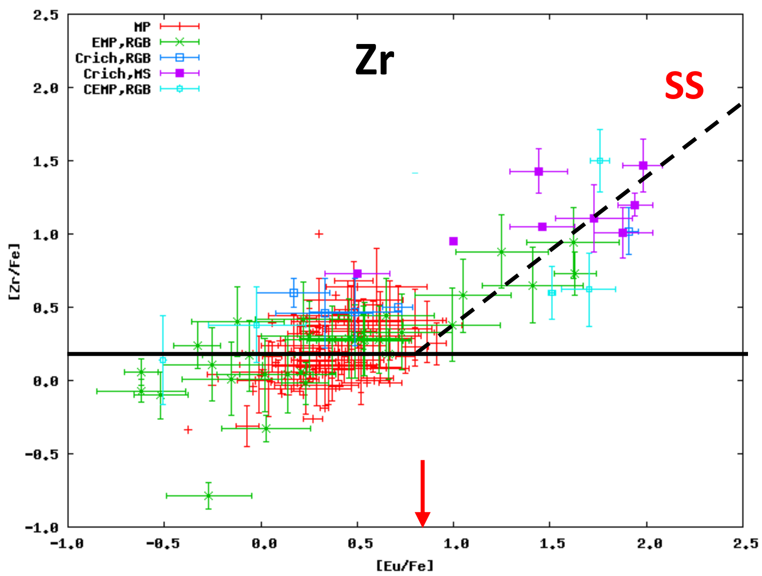
(I. Roederer et al., 2010; K. Farouqi et al., 2010)

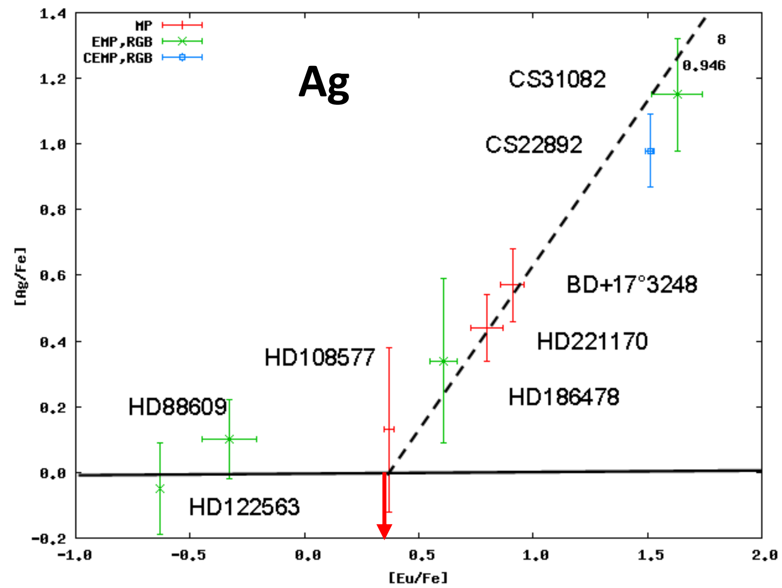
SAGA data base: [X/Fe] vs. [Eu/Fe] (I)

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

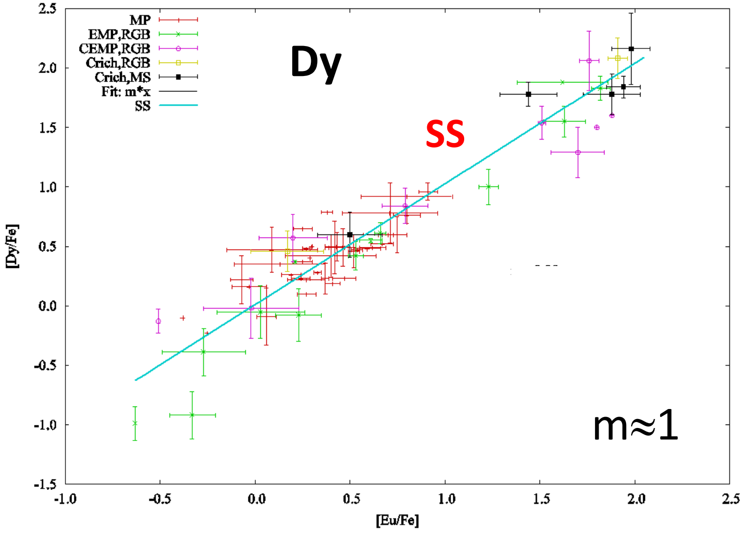


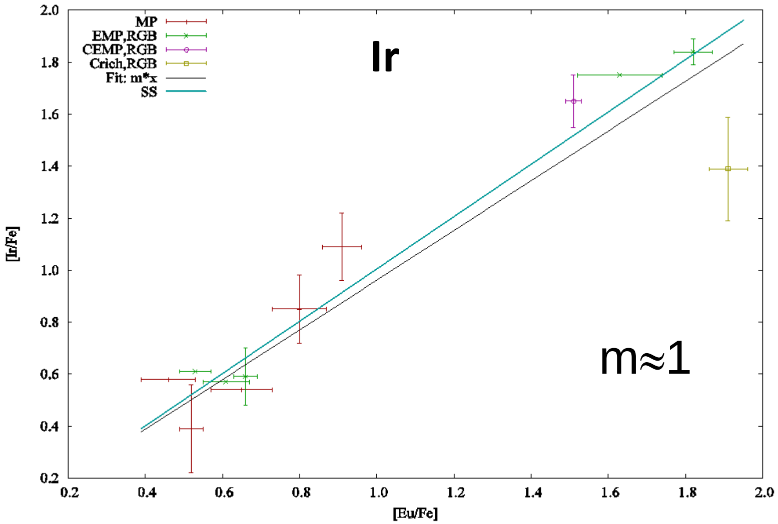


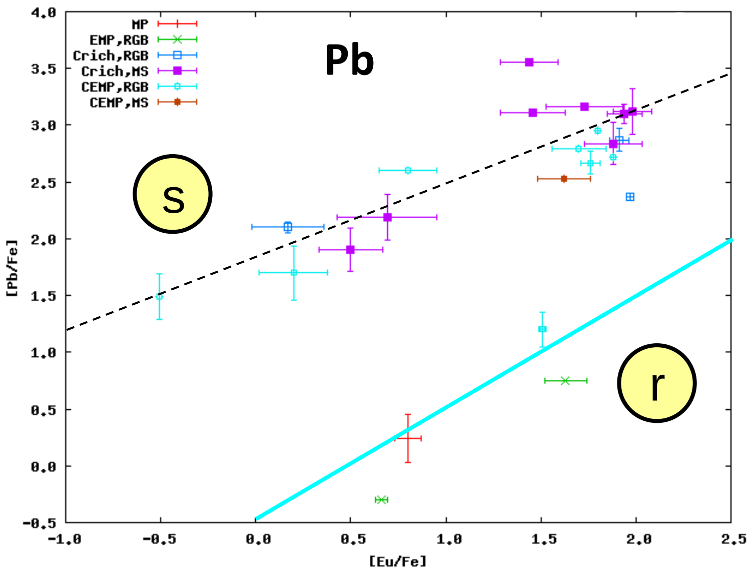


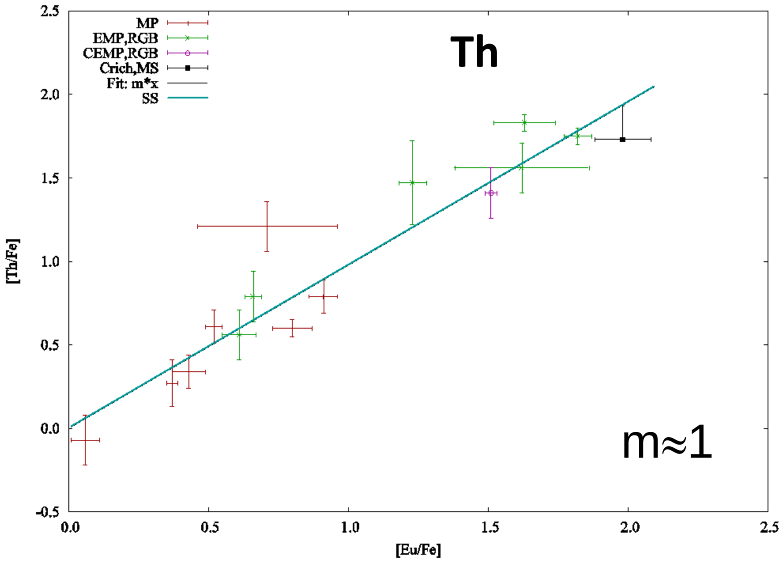


SAGA data base: [X/Fe] vs. [Eu/Fe] (II)









Th/Pb r-chronometer ? (Frebel, Mashonkina & Kratz)

Summary

Still today

- there is no selfconsistent hydro-model for SNe, that provides the necessary astrophysical conditions for a full r-process;
- therefore, parameterized dynamical studies (like our HEW approach) are still useful to explain r-process observables;
- astronomical observations & HEW calculations indicate that SS-r and UMP halo-star abundance distributions are superpositions of 3 nucleosynthesis components: **charged-particle, weak-r and main-r**
- the yields of the CP-component (up to Zr) are largely uncorrelated with the "main" r-process;
  the yields of the weak-r component (Mo to Cd) are partly correlated with the "main" r-process;
  elements ≥ Te belong to the "main" r-process
- no UMP halo-star has been observed so far without a CP- (LEPP) component
- **therefore, no separate LEPP-component is required !**

@John: ***Enjoy your emeritus stage !***

your Mainz collaborators K.-L., Bernd, Khalil & Oliver

Co-production of Light p-, s- and r-Process Isotopes in the Neutrino-Driven Wind of Type II Supernovae

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We have performed large-scale nucleosynthesis calculations within the high-entropy-wind (HEW) scenario of core-collapse supernovae with the primary aim to constrain the conditions for the production of the classical 'p-only' isotopes of the light trans-Fe elements in the Solar System (SS). We find that in moderately neutron-rich winds, sizeable abundances of p-, s- and r-process nuclei between ^{64}Zn and ^{104}Ru are co-produced. Taking the peculiar compositions of the 7 stable Mo isotopes in (i) the SS and (ii) in specific presolar SiC X-grains as particularly challenging examples, our results show that the HEW ejecta can reproduce both, (i) the SS-ratio of ^{92}Mo/^{94}Mo with isotopic yields per SN event in the 10^{-8} $M_\odot$ range, and (ii) the puzzling grain data of the Argonne / Chicago group. These results are in principal agreement with earlier studies, and may provide further means to revise the abundance estimates in the historical "light-p", "weak-s" and "weak-r" process regions.

	Isotopic abundance ratios			
Isotope pairs (nucleosynth. origin)	Solar System [10]	This work [22]	γ-process [13]	EC SN [16]
^{64}Zn(p)/^{70}Zn(r)	78.4	79.4	10.5	6.6 E+7
^{70}Ge(s,p)/^{76}Ge(r)	2.84	4.61	2.53	2.8 E+9
^{74}Se(p)/^{76}Se(s)	9.42 E-2	9.09 E-2	0.128	0.567
^{74}Se(p)/^{82}Se(r)	0.101	0.113	0.120	6.1 E+9
^{78}Kr(p)/^{82}Kr(s)	3.11 E-2	2.92 E-2	1.97 E-2	0.654
^{78}Kr(p)/^{86}Kr(r,s)	2.11 E-2	7.9 E-4	5.8 E-3	5.7 E+4
^{84}Sr(p)/^{86}Sr(s)	5.66 E-2	4.00 E-2	4.05 E-2	0.240
^{90}Zr(s,r)/^{96}Zr(r,s)	18.4	5.56	10.4	> E+20
^{92}Mo(p)/^{94}Mo(p)	1.60	1.86	1.55	49.4
^{96}Ru(p)/^{98}Ru(p)	2.97	2.57	2.54	9.06

Table 1: Selected isotopic abundance ratios of light trans-Fe elements between Zn (Z=30) and Ru (Z=44).

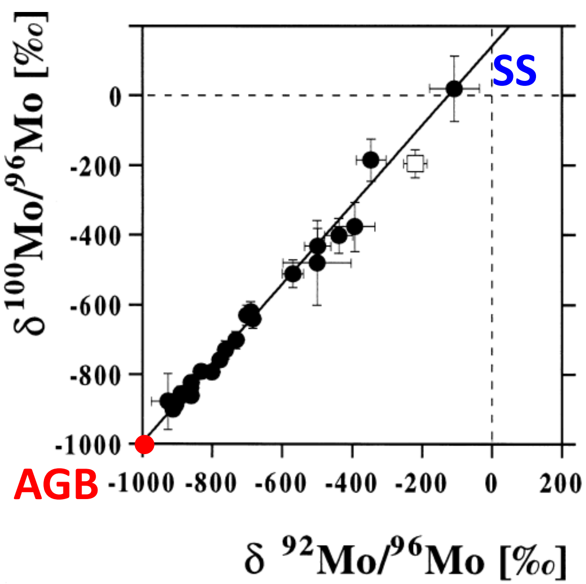
	Isotopic abundance ratios			
^{x}Mo/^{97}Mo	SiC X-grains	SS	"n-burst"	This work
^{92}Mo/^{97}Mo	< 0.19	1.55	1.4 E-3	0.10
^{94}Mo/^{97}Mo	< 0.10	0.97	3.3 E-3	1.3 E-2
^{95}Mo/^{97}Mo	1.83	1.66	1.54	3.65
^{96}Mo/^{97}Mo	$\equiv 0.05$	1.74	1.0 E-2	1.6 E-3
^{98}Mo/^{97}Mo	0.71	2.52	0.38	1.38
^{100}Mo/^{97}Mo	0.13	1.01	9.6 E-2	0.32

Table 2: Molybdenum isotopic abundance ratios (^{x}Mo/^{97}Mo). The initial data were obtained by RIMS measurements of the individual SiC grains [18]. They indicate a mixture of normal (SS) Mo and an (unknown) exotic component. The respective compositions have been derived by weighted fits to the grain data (two outliers omitted), forced through the respective SS value and extrapolated to ^{96}Mo/^{97}Mo $\equiv 0.05$. They are compared with the SS values, the predictions of the "neutron-burst" model [20] and the CP-component in moderately neutron-rich SN winds (for details, see [22]).

PoS NIC-XI (2010) & PASA 26, 194 (2009)

Isotopic information on LEPP elements from presolar grains

SiC mainstream grains → He-IS in AGB stars



Nicolussi et al. (1998)

3-isotope-plot:

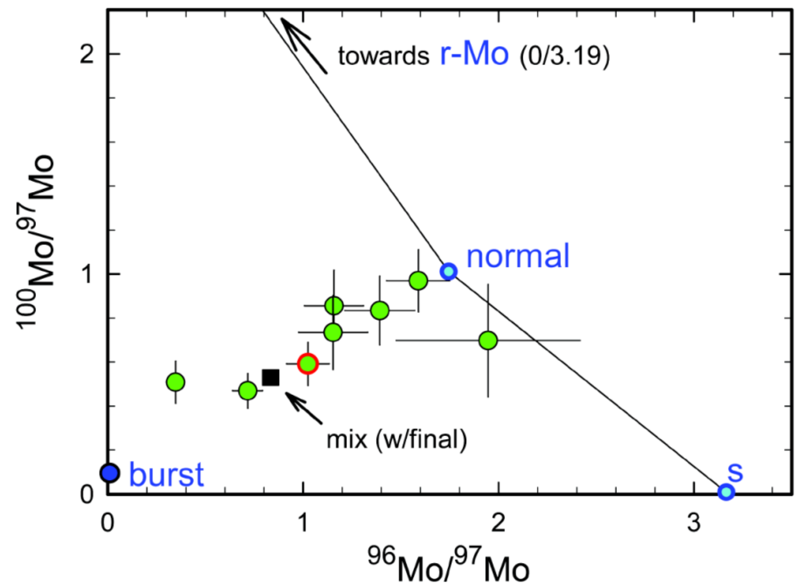
The grains are a **mixture** of material from the nucleosynthesis site and SS-like material !

SiC-X grains → Supernovae origin

Measurements by the Chicago group on SiC-X grains for **Zr, Mo & Ru**

What nucleosynthesis process works as a mixing-component for all isotopic ratios?

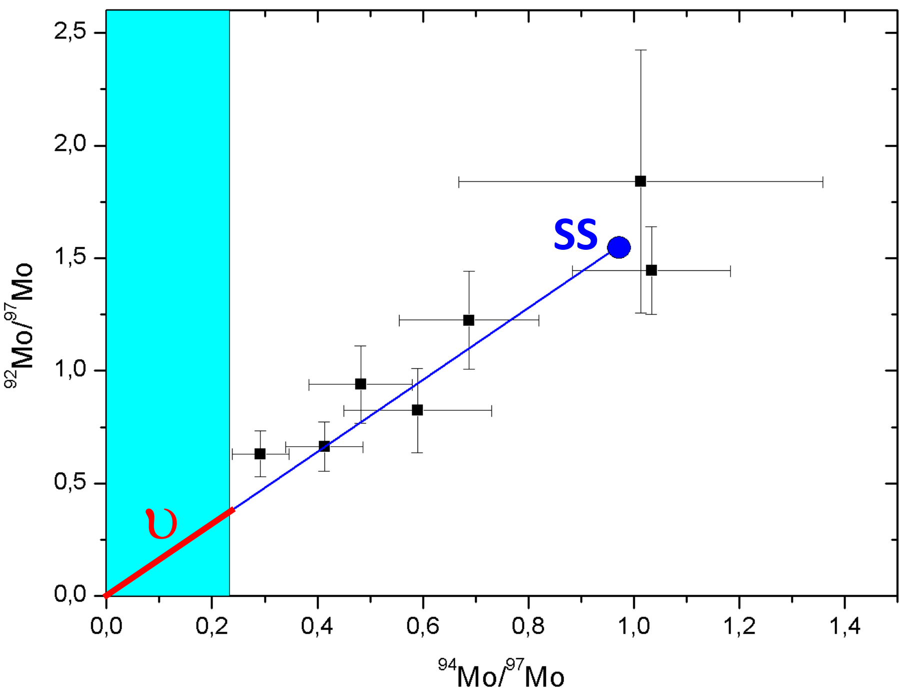
→ Isotopic composition obviously <u>not</u> main-r or s !



Marhas et al. (2007); data from Pellin et al.

Isotopic information on LEPP elements from presolar grains

Mo in SiC-X grains = Mixture of υ-driven wind & SS



Data from Pellin et al. (2000, 2006)

SiC-X grains are a mixture of material from a supernova and SS-like material in the ISM !

Analytic procedure:

- Perform regressions for all isotopic ratio permutations
- thereby: pin-point the isotopic composition of the mixing component
- optimize the astrophysical conditions in the υ-driven wind to find the best fit for the required isotopic composition
- check Zr & Ru under the same conditions

Result:

The astrophysical conditions for the best fit of the isotopic composition of all 3 elements are **Y_e = 0.45** and **s = 0…70 k_B**

- **Charged-particle component of the υ-driven wind**
- **No neutron-capture process !**

Hallmann, Farouqi, Kratz, Ott (2011) unpubl.