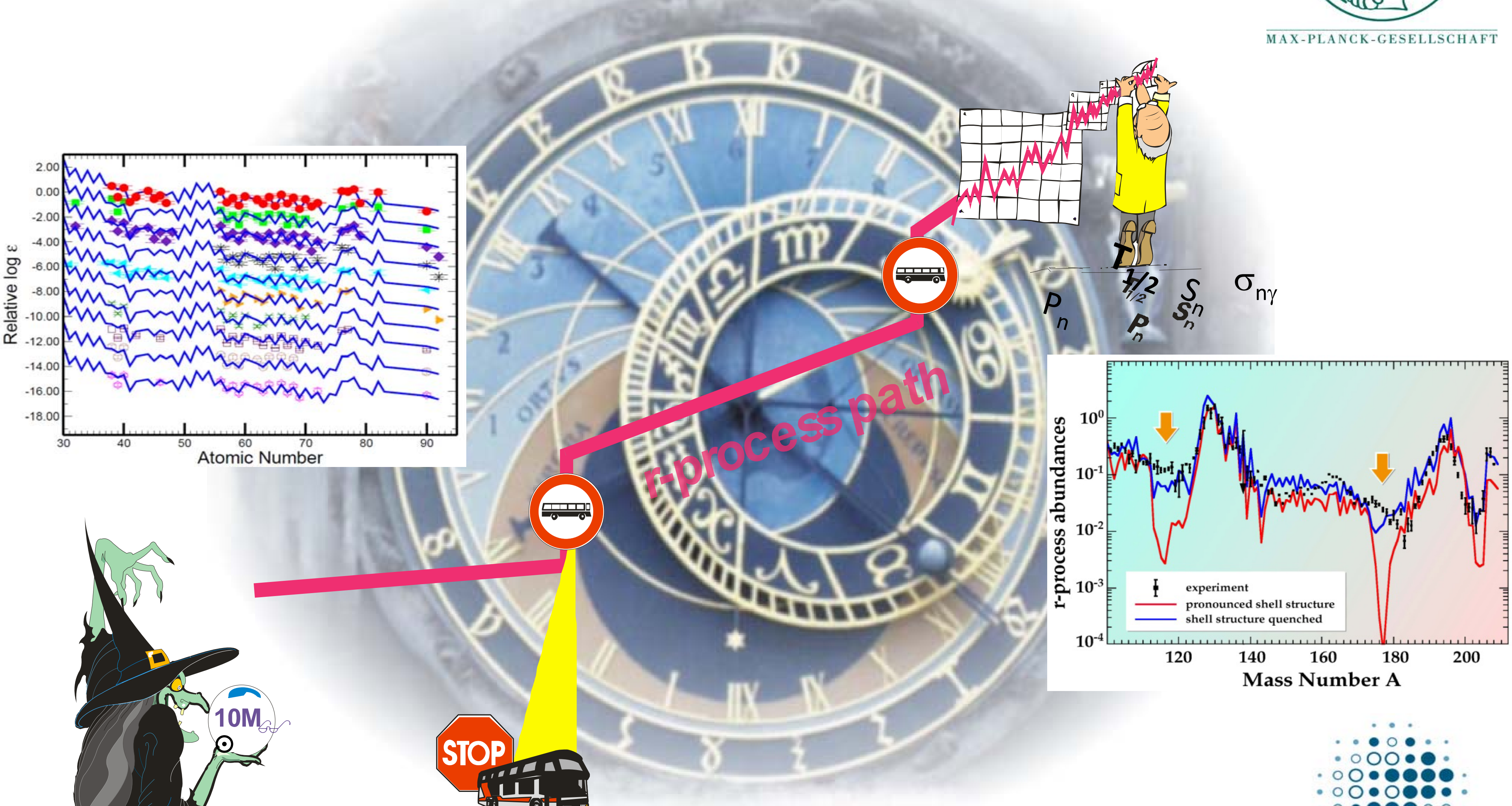
Nucleosynthesis modes in the HEW of SN-II: Calculations vs. observations



Karl-Ludwig Kratz

MAX-PLANCK-GESELLSCHAFT

MAX-PLANCK-INSTITUT FÜR CHEMIE

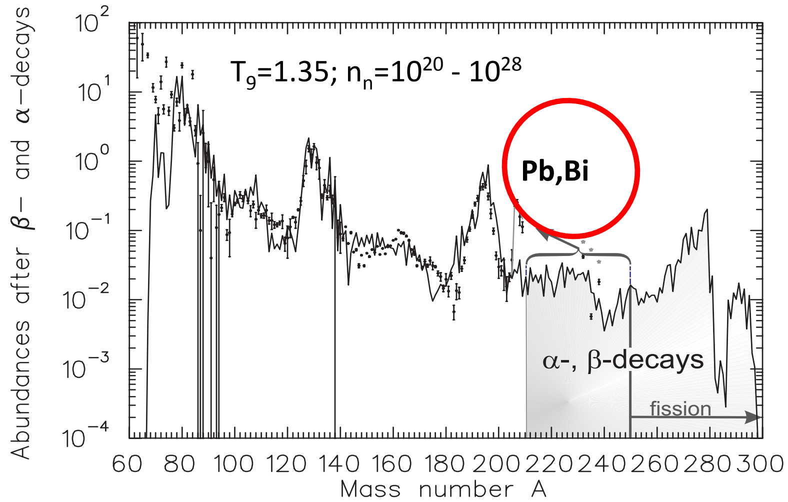
SCOPES, 2011

r-Process observables today

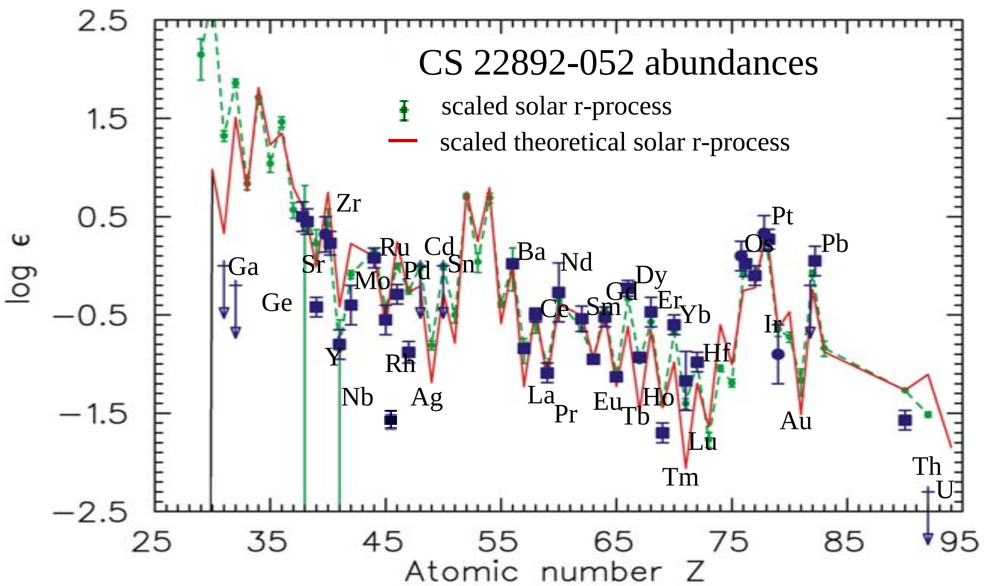
Observational instrumentation

- **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***

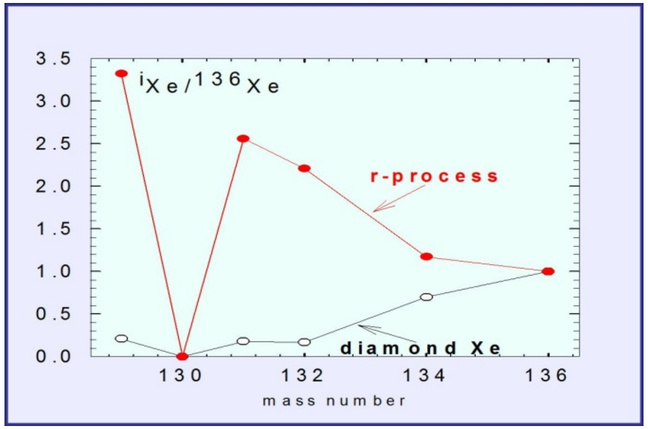
Solar system isotopic $N_{r,\odot}$ "residuals"



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, Pt

Isotopic anomalies in meteoritic samples and stardust

The high-entropy / neutrino-driven wind model

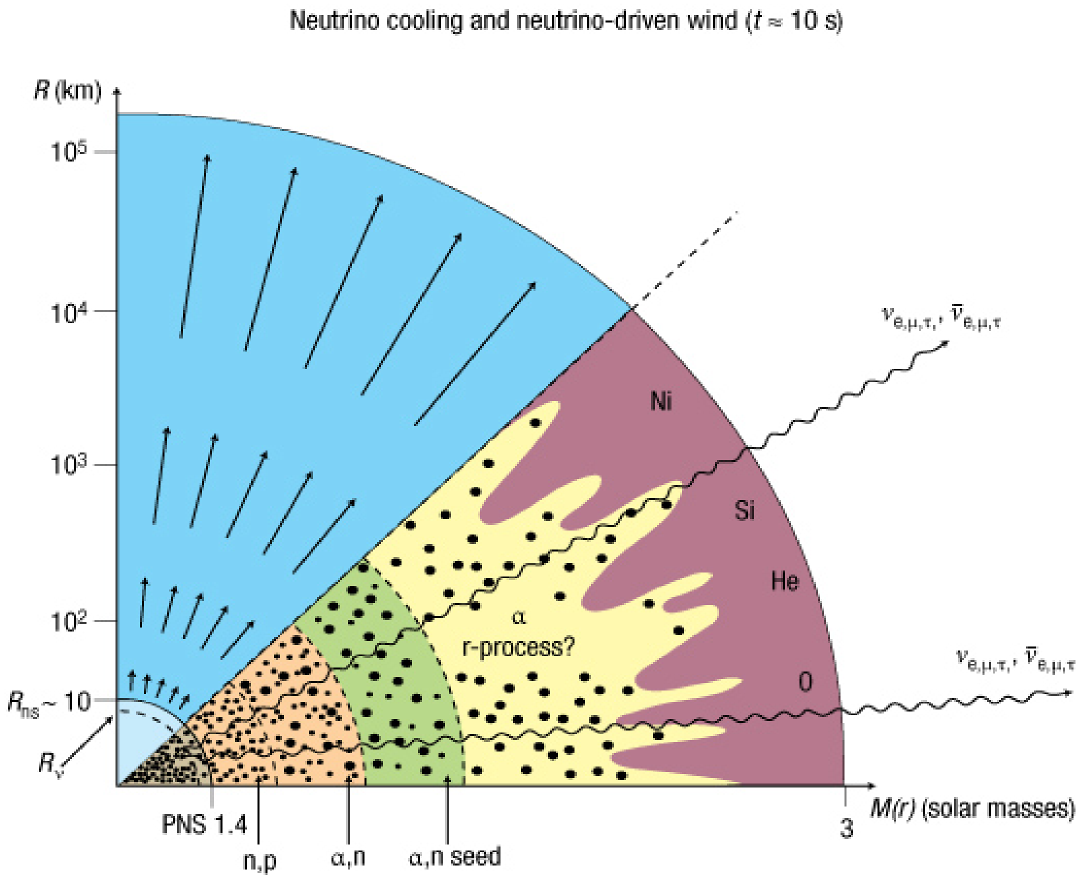
…one of the presently favoured scenarios for the "r-process"

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

As the nucleons cool ($\approx 10 \geq T_9 \geq 6$), 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)

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 !

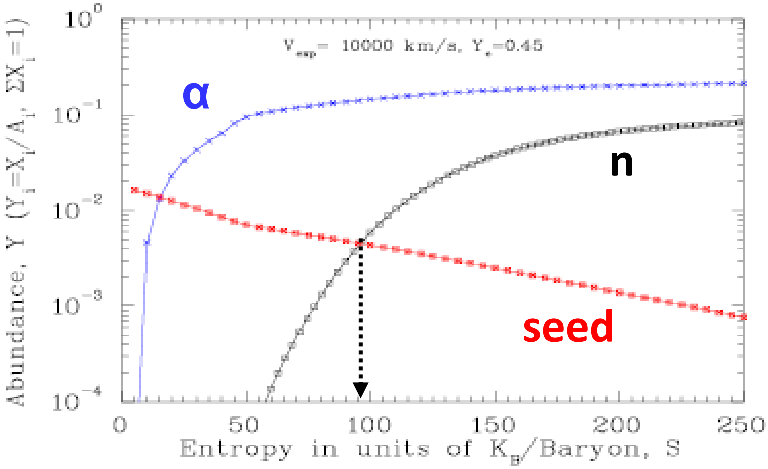
$\Rightarrow$ **r-process “strength” formula**

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

(Farouqi, PhD Mainz 2005)

Parameters HEW model ⇨ Y(Z)

Y_e=0.45



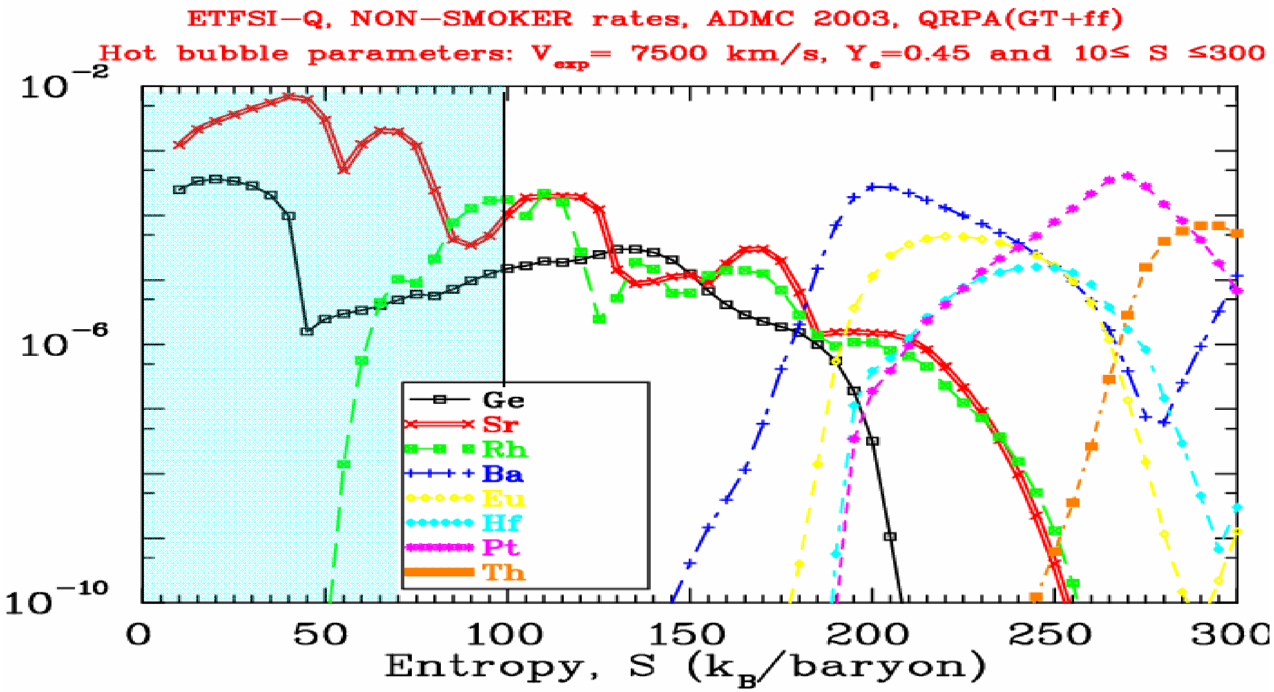
No neutrons ⟶ no n-capture r-process!

Nucleosynthesis components:

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

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

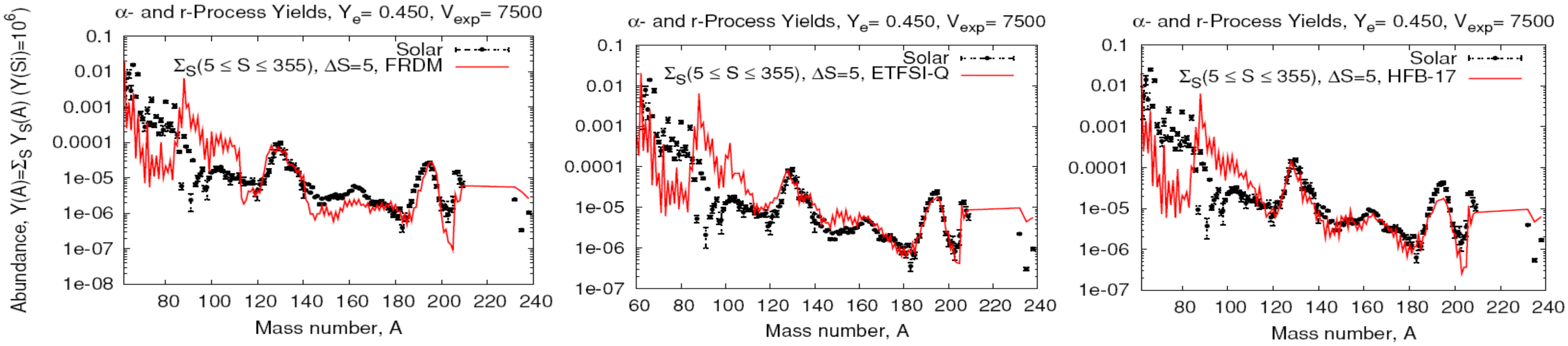
$150 < S < 300$; $15 < Y_n/Y_{seed} < 150$
"main" r-process



Reproduction of $N_{r,\odot}$

Superposition of S-components with Y_e=0.45;

weighting according to Y_{seed}

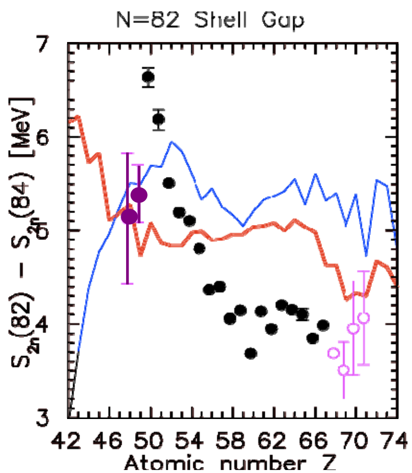


No exponential fit to $N_{r,\odot}$!

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

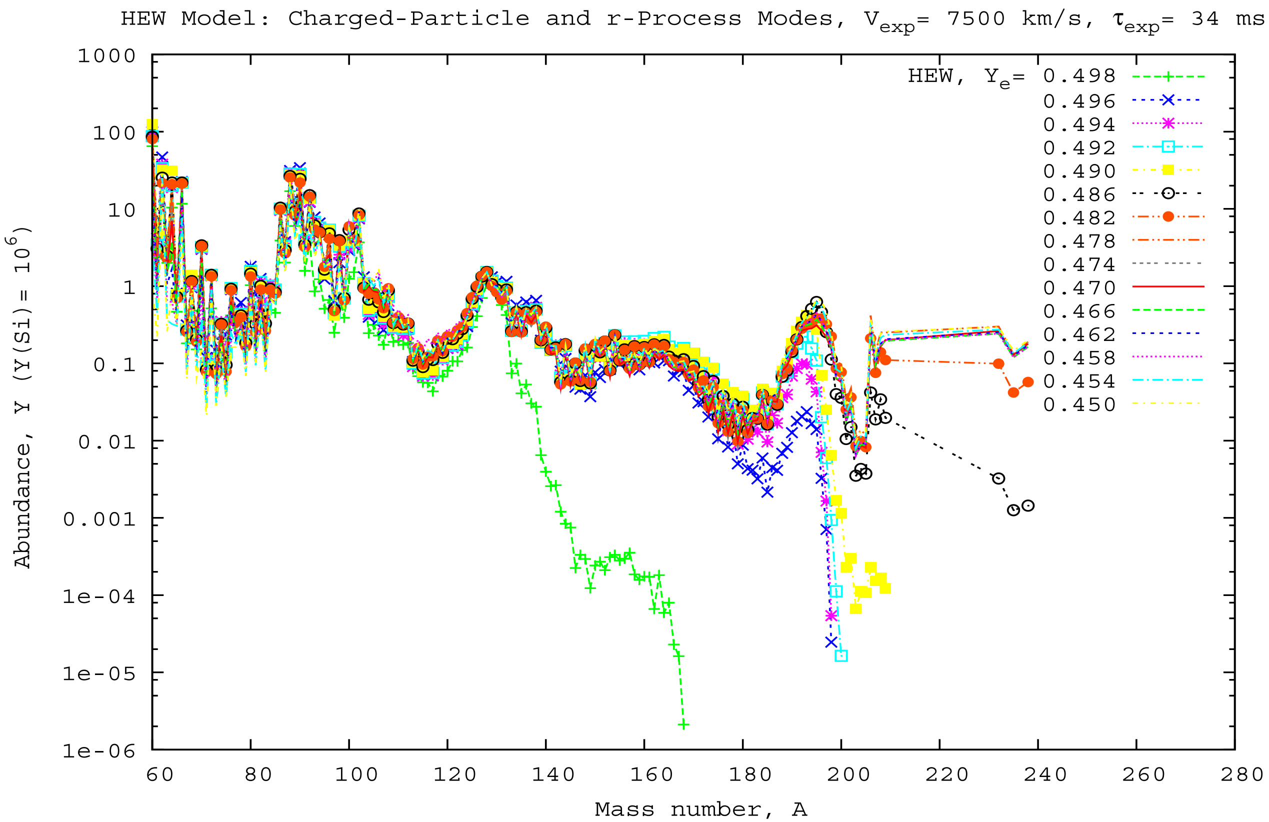


Superposition of HEW components $0.450 \leq Y_e \leq 0.498$

"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 $Y_e \leq 0.470$
full r-process,
up to Th, U

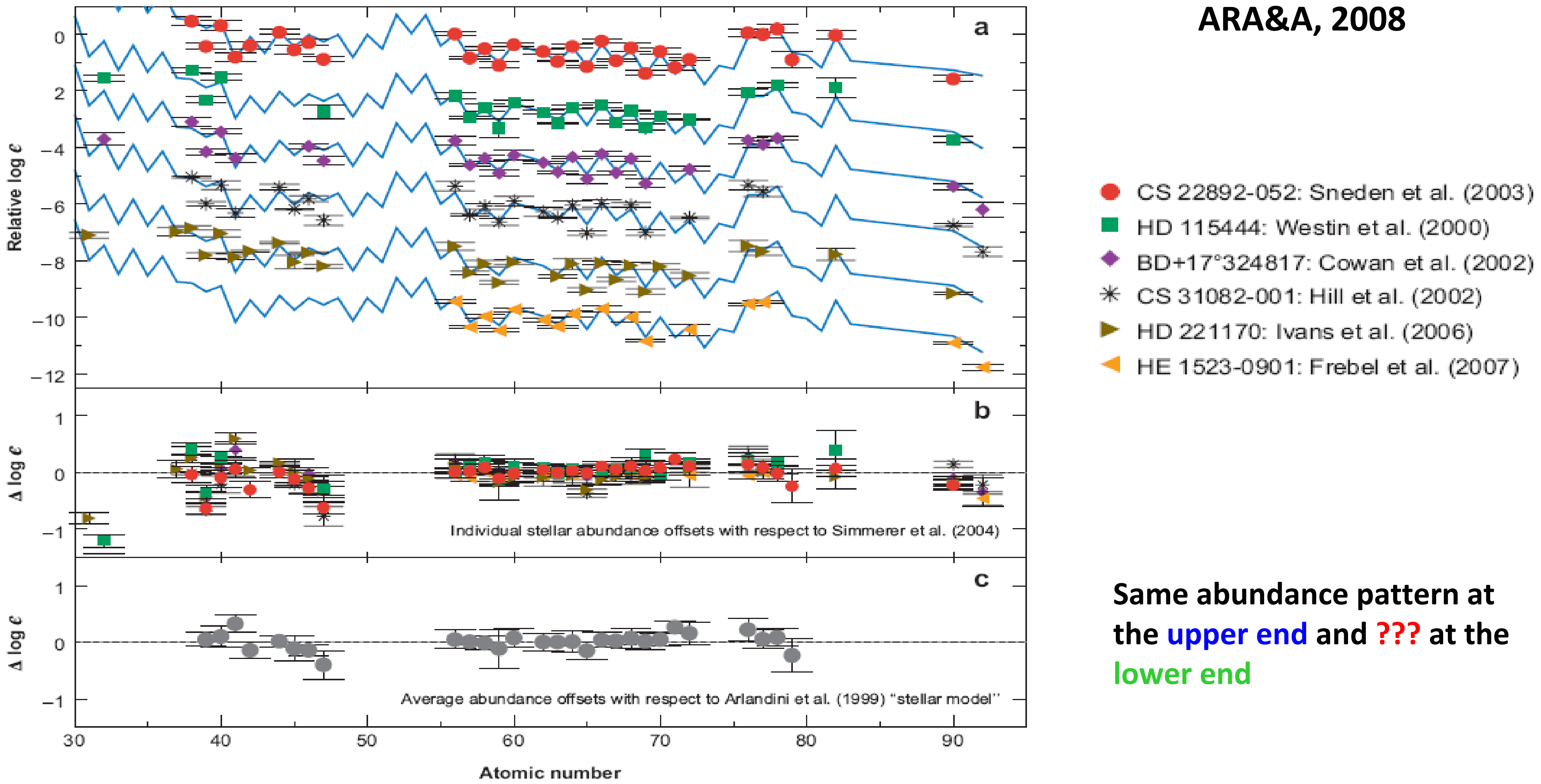
For $Y_e \approx 0.490$
still 3rd peak,
but no Th, U

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)

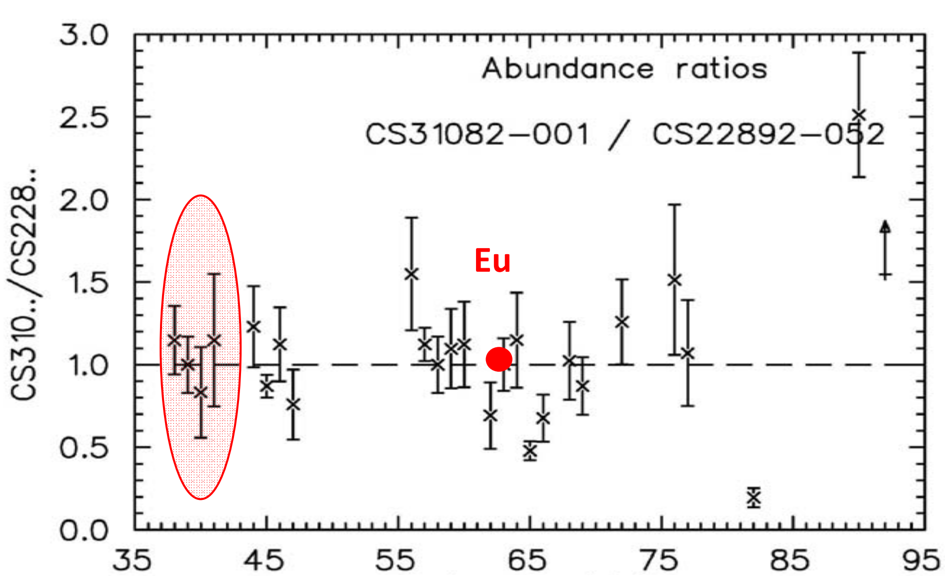
Observations: Selected "r-enriched" UMP halo stars

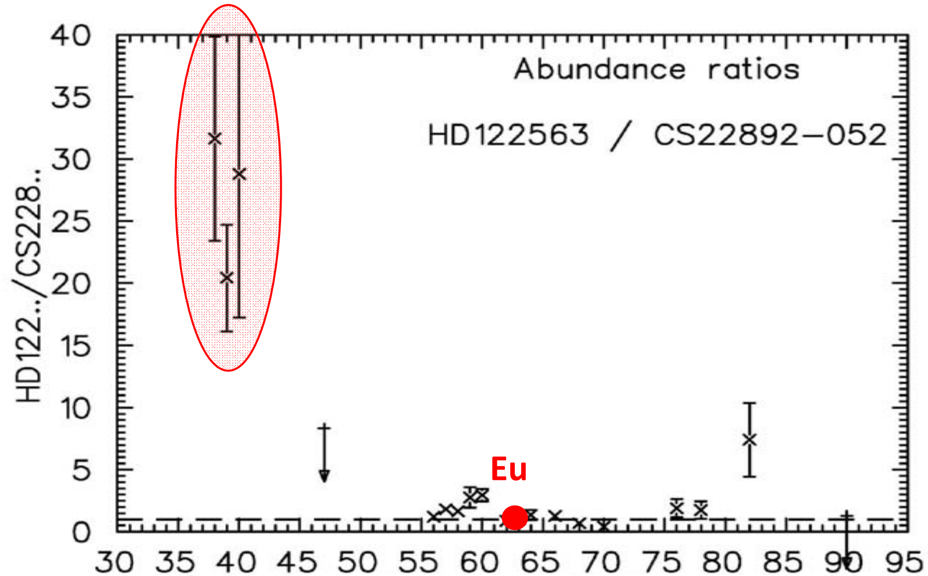


Sneden, Cowan & Gallino
ARA&A, 2008

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

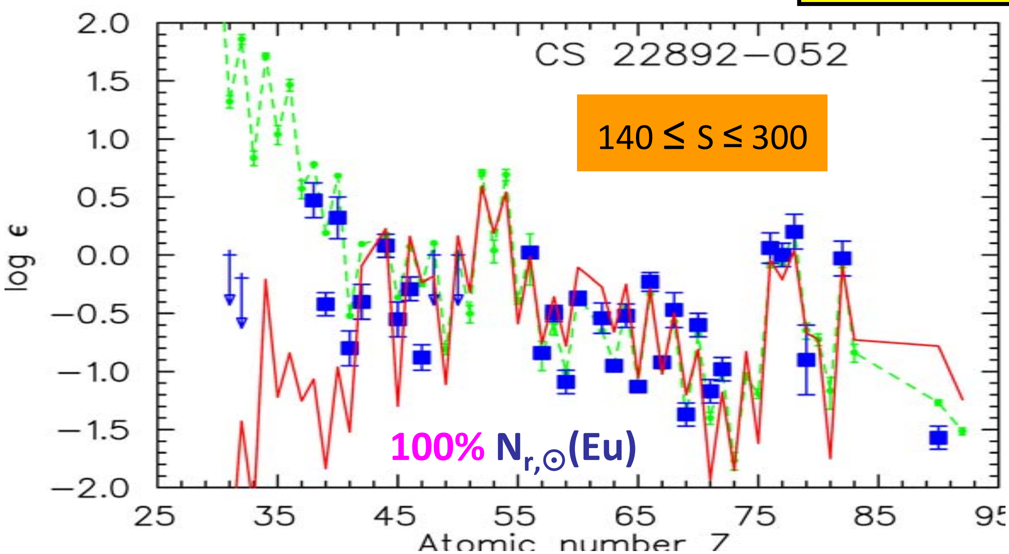
Halo stars vs. HEW-model: total $N_{r,\odot}$





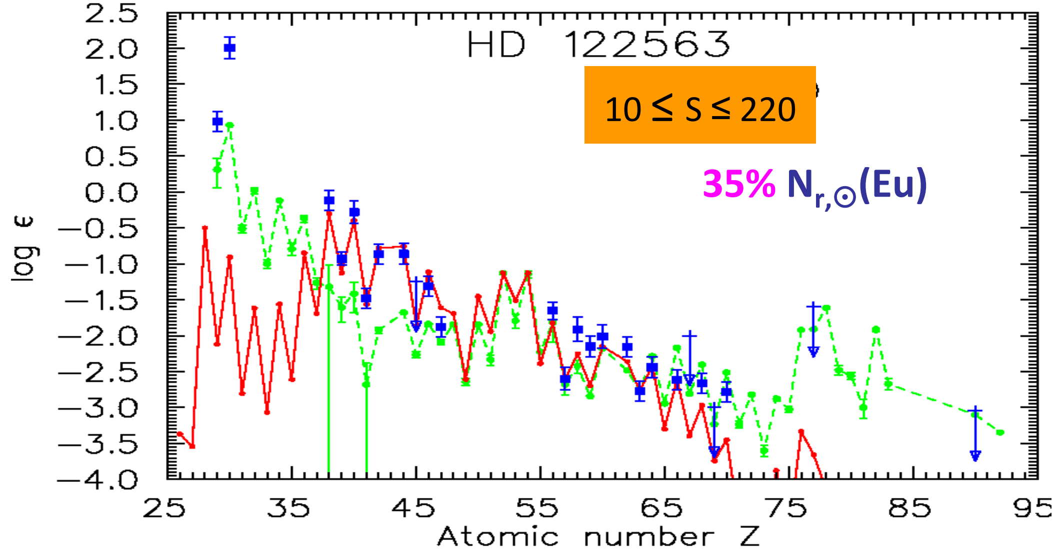
Factor 25 for LEPP region !

r-rich **"Sneden star"**



full main r-process

r-poor **"Honda star"**

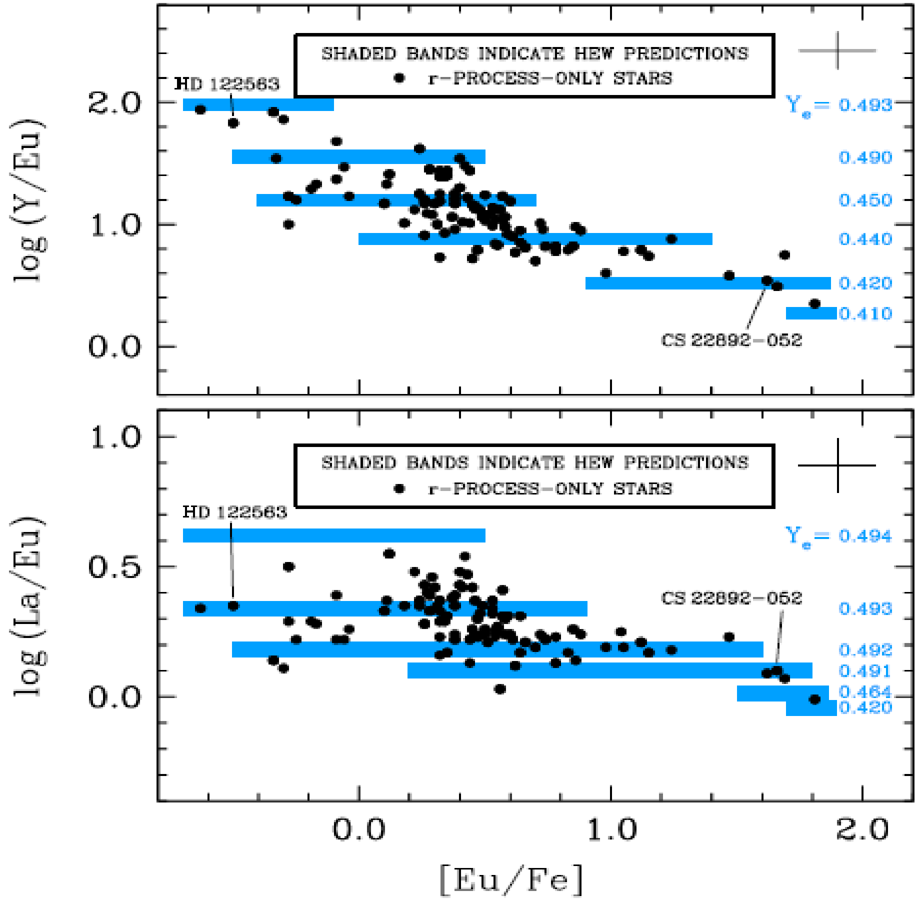


incomplete main r-process

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)

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 ≤ S ≤ 100	100 ≤ S ≤ 150	150 ≤ S ≤ 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** → →

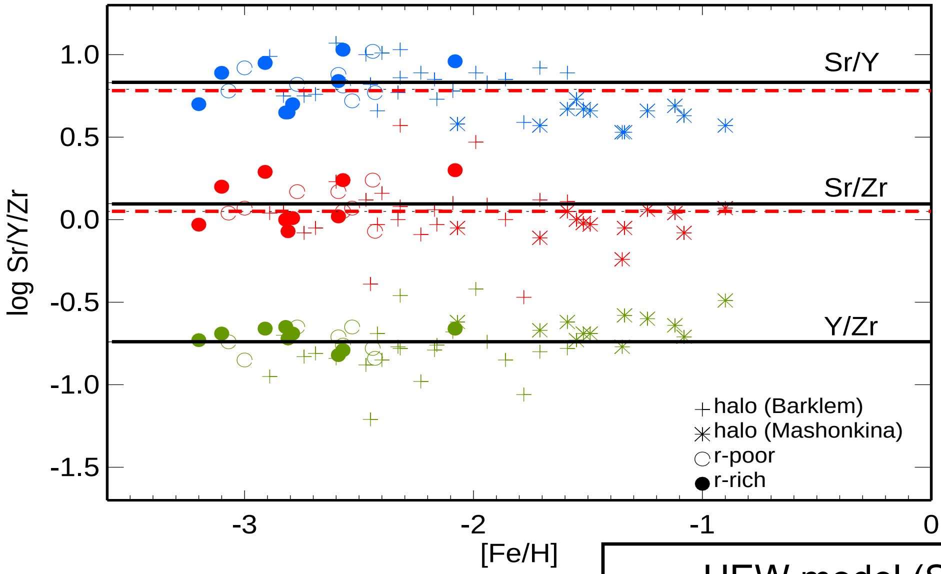
CP component
uncorrelated

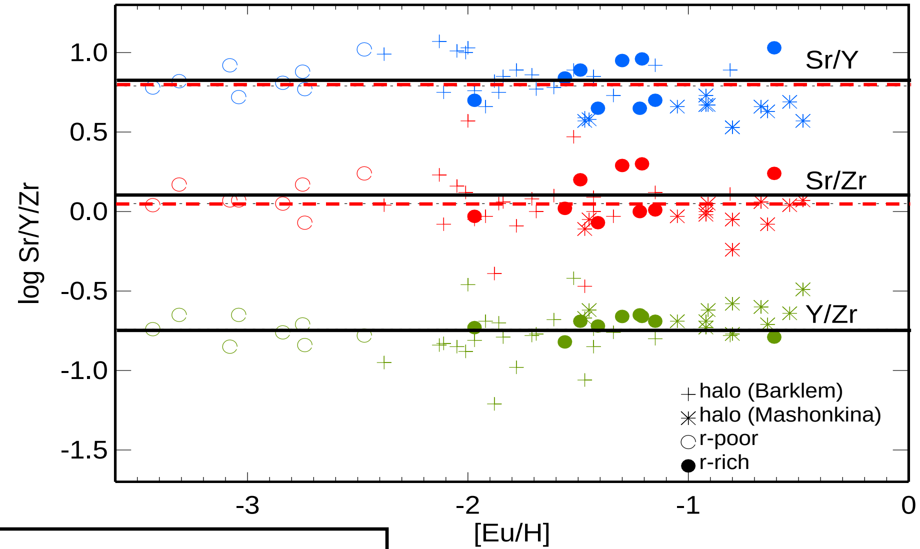
weak-r component
weakly correlated

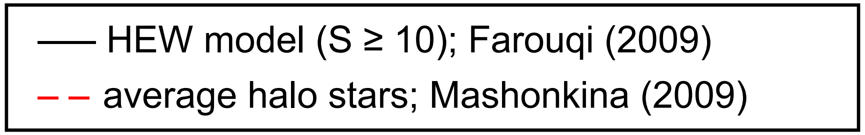
main-r component
strongly correlated

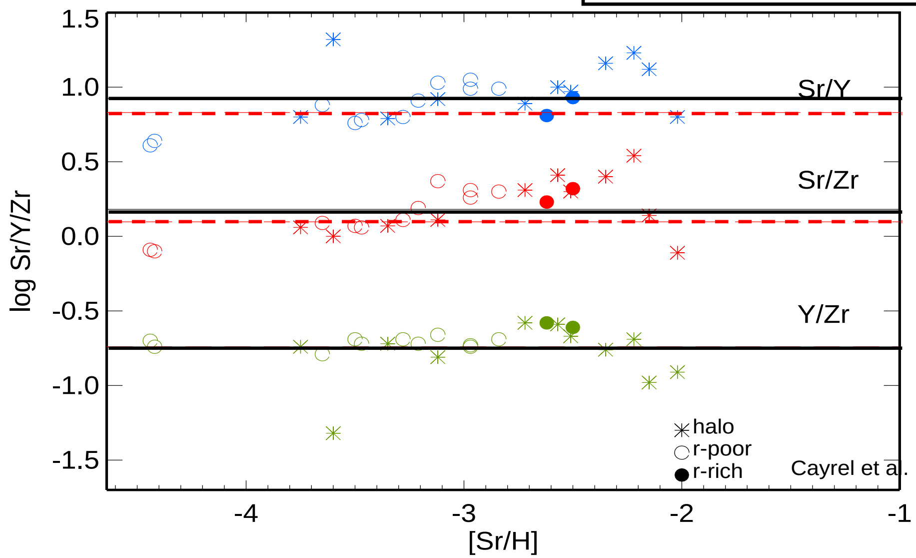
with Eu ?

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









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

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

same behavior for Pd – Ag ?

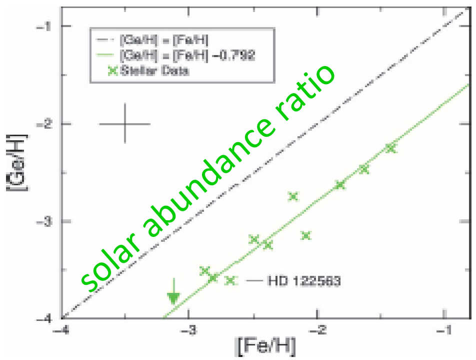
Observations: Correlation Ge, Zr with r-process?

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

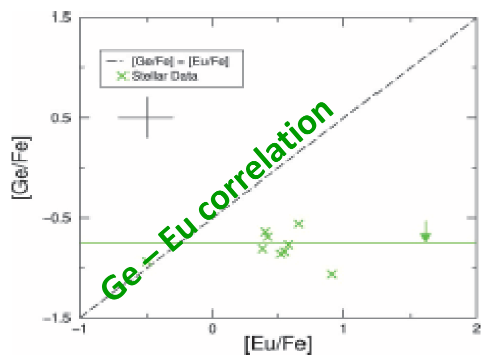


Relative abundances [Ge/H] displayed as a function [Fe/H] metallicity for our sample of 11 Galactic halo stars. The arrow represents the derived upper limit for CS 22892-052. The dashed line indicates the solar abundance ratio of these elements: [Ge/H] = [Fe/H], while the solid green line shows the derived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

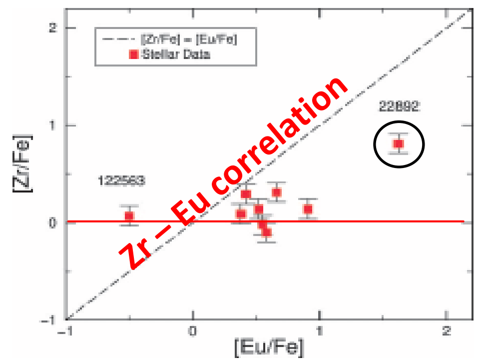
"… the Ge abundances…
track their Fe abundances very well.
An explosive process on iron peak nuclei (e.g. the α-rich freezeout in SNe), rather than neutron capture, appears to have been the dominant mechanism for this element…"

"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.



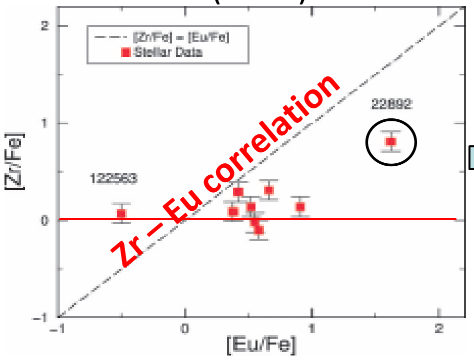
Correlation between the abundance ratios of [Zr/Fe] (obtained exclusivley with HST STIS) and [Eu/Fe].
The dashed line indicates a direct correlation between Zr and Eu abundances.

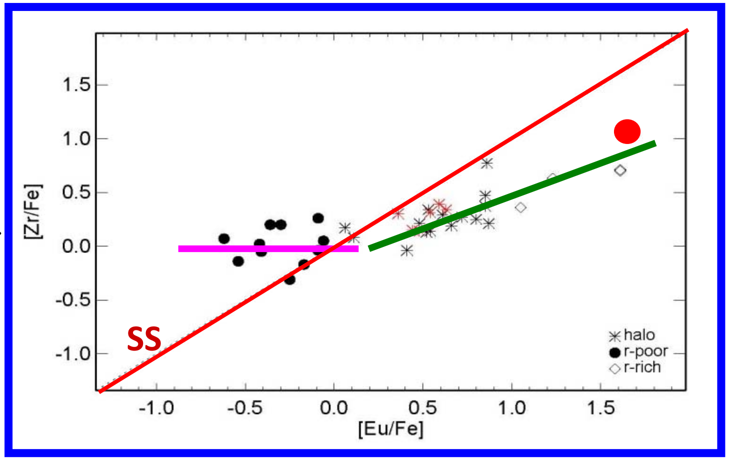
Can our HEW model explain observations ?

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)



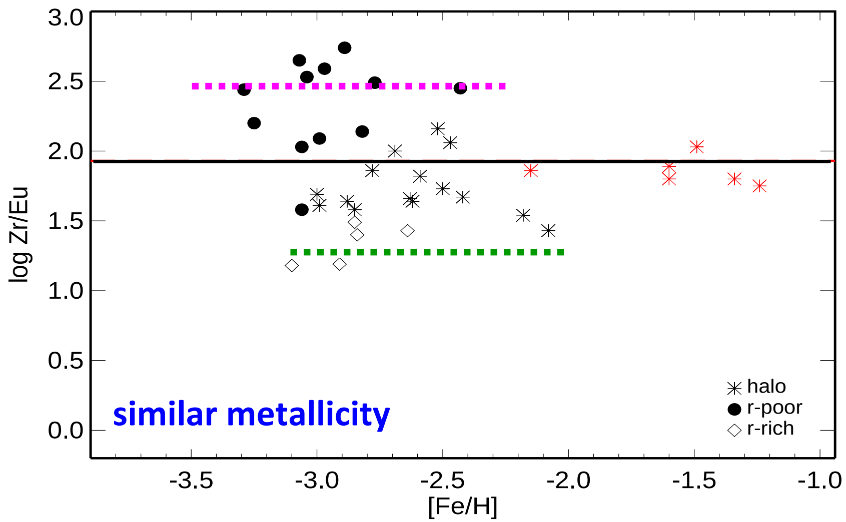


Zr in r-poor stars **overabundant**
↷ type **"Honda star"**

Zr in halo & r-rich stars **underabundant**
↷ type **"Sneden star"**

Strong Zr – Eu correlation
↷ **SS diagonal**

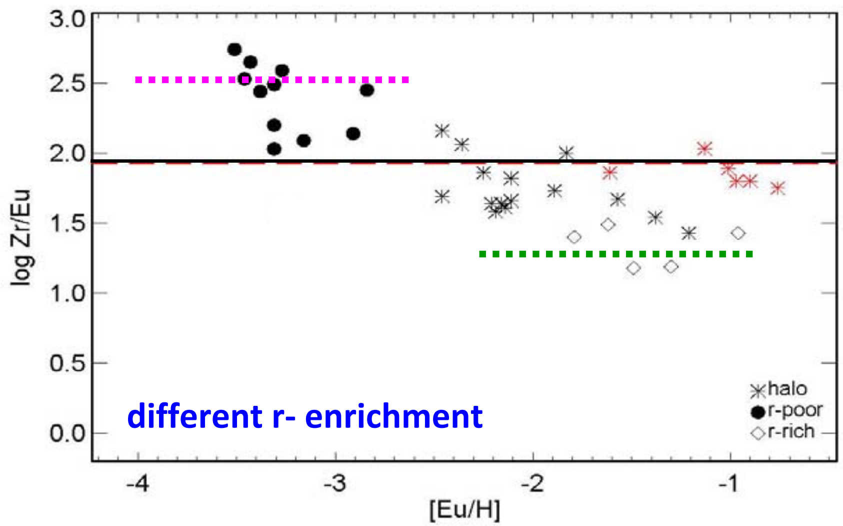
Halo, r-rich and r-poor stars are clearly separated!



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 ≤ S ≤ 100	100 ≤ S ≤ 150	150 ≤ S ≤ 300
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$_{47}$Ag	3.7	**71**	25
$_{52}$Te	0.001	10	**90**
$_{56}$Ba	-	-	100

normal α -rich freezeout | **n-rich α-freezeout**

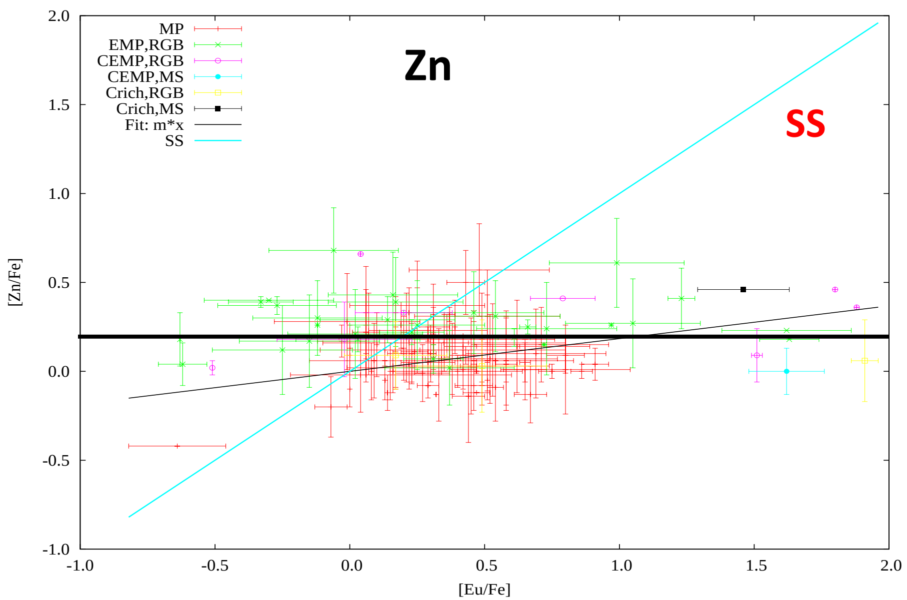
CP component
uncorrelated

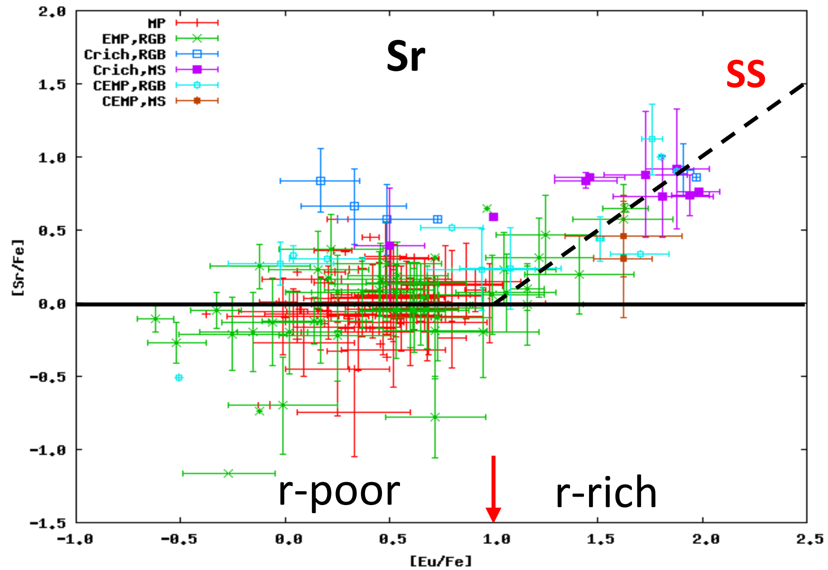
weak-r component
weakly correlated

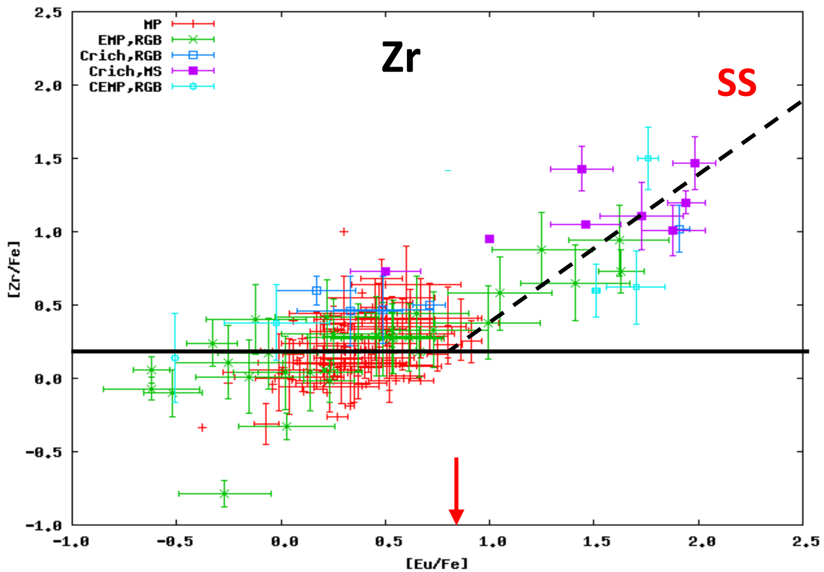
main-r component
strongly correlated

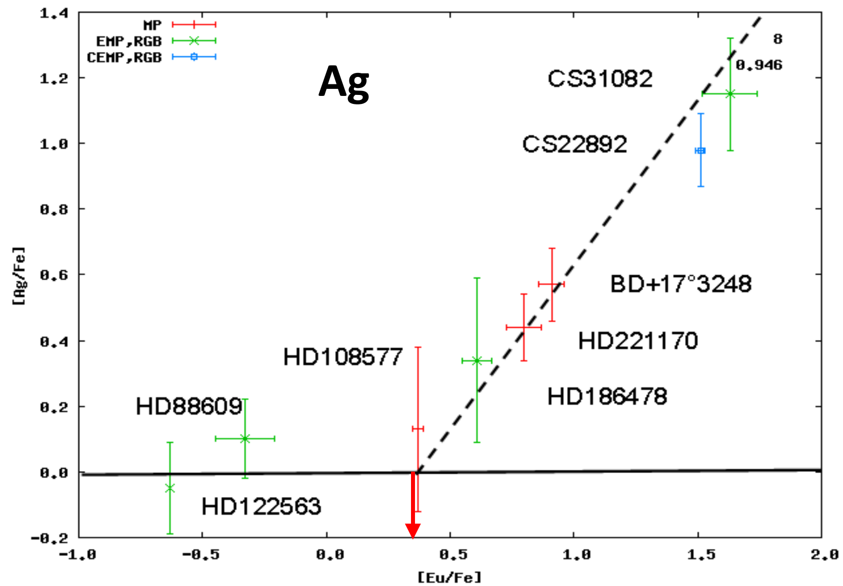
with Eu ?

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

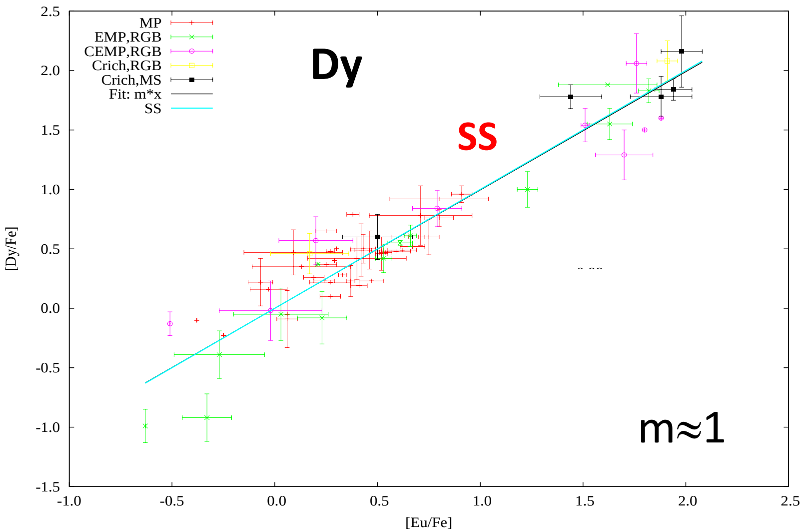


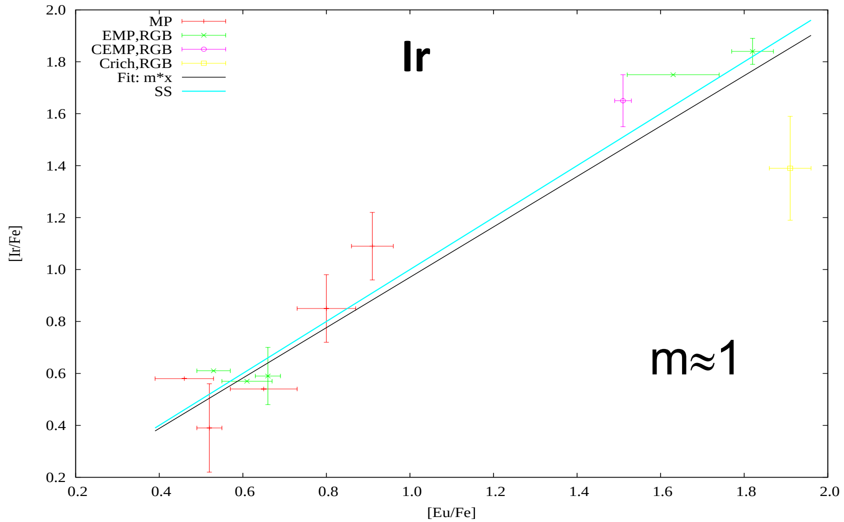


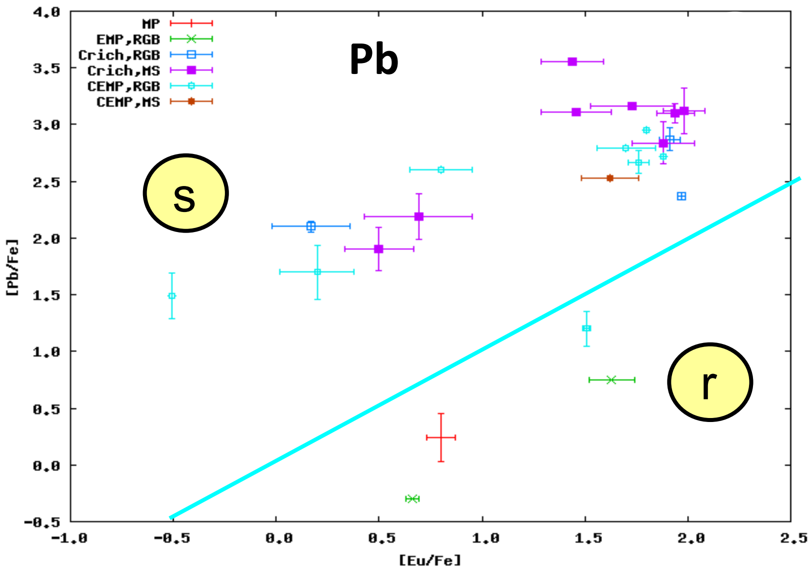


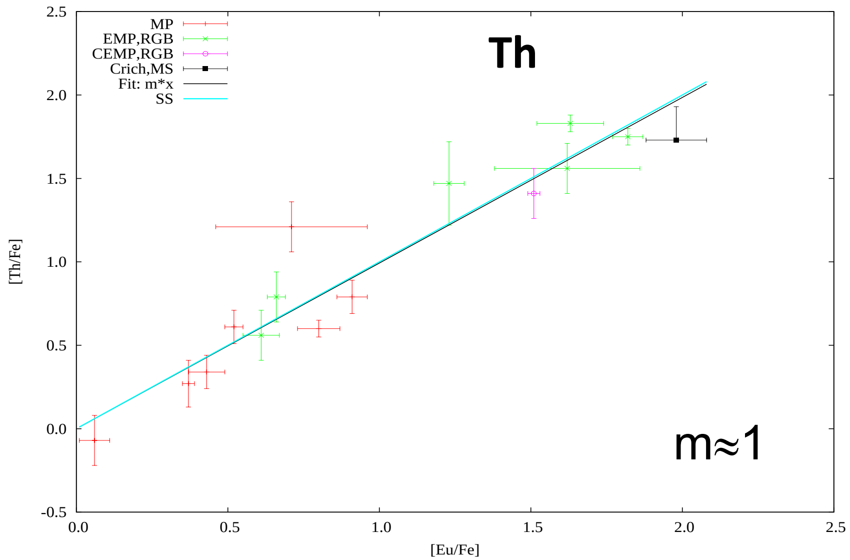


SAGA data base: [X/Fe] vs. [Eu/Fe] (II)









...Th – U cosmochronology ?!

What did we learn about Th/U r-chronometer since 1965?

Take the most recent Th/U observation in HE 1523-0901 ([Fe/H] = -2.95) from **Frebel** et al. (2007)

$\log(Th/U)_{obs} = +0.86$ → **Th/U-age 13.2 ± 2.8 Gyr**

$(Th/U)_{calc}^{initial}$	$\log(Th/U)_{calc}^{initial}$	Ref.(year)		Age HE 1523-0901
1.65	0.218	Seeger	1965	14.0 Gyr
1.90	0.279	Schramm	1981	12.7 Gyr
1.40	0.146	Thielemann	1983	15.6 Gyr
1.81	0.257	C-Pf-Kz	1999	13.2 Gyr
2.00	0.301	Goriely	2001	12.2 Gyr
1.73	0.215	Kz-F-Pf	2007	13.6 Gyr

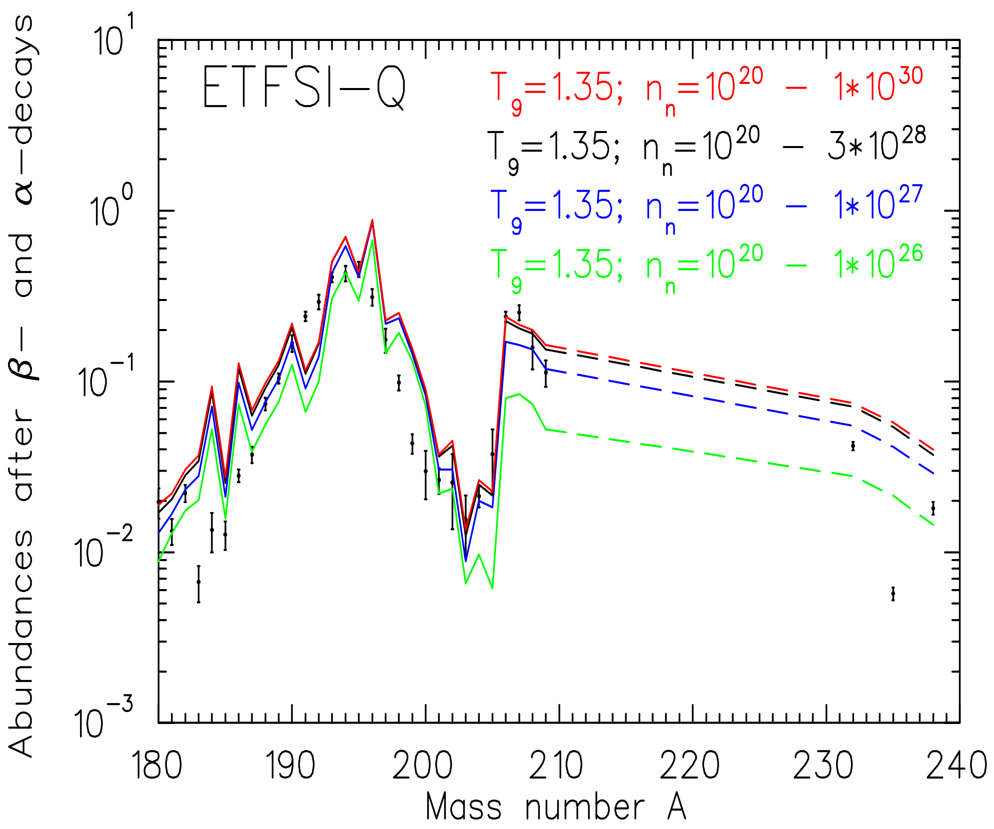
average 13.5 Gyr

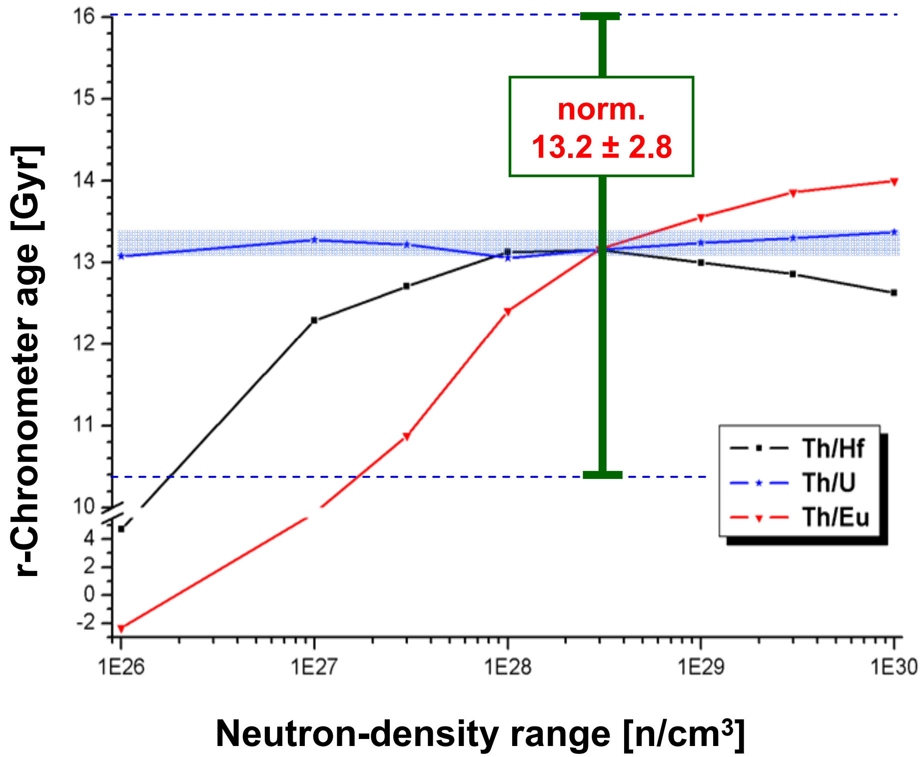
… just from Th and U **numbers** we have learned **nothing** over the last 40 years; however continuously improved r-abundance calculations.

Requests:

1) Sensitivity studies of Y(X) calculations:
   - mass models
   - n_n- and/or S-ranges
2) Correlation Th,U with other elements:
   - Eu, Hf
   - 3rd r-peak (Os,Ir,Pt)
   - **Pb, Bi**

Th/U – a robust and reliable r-process chronometer?





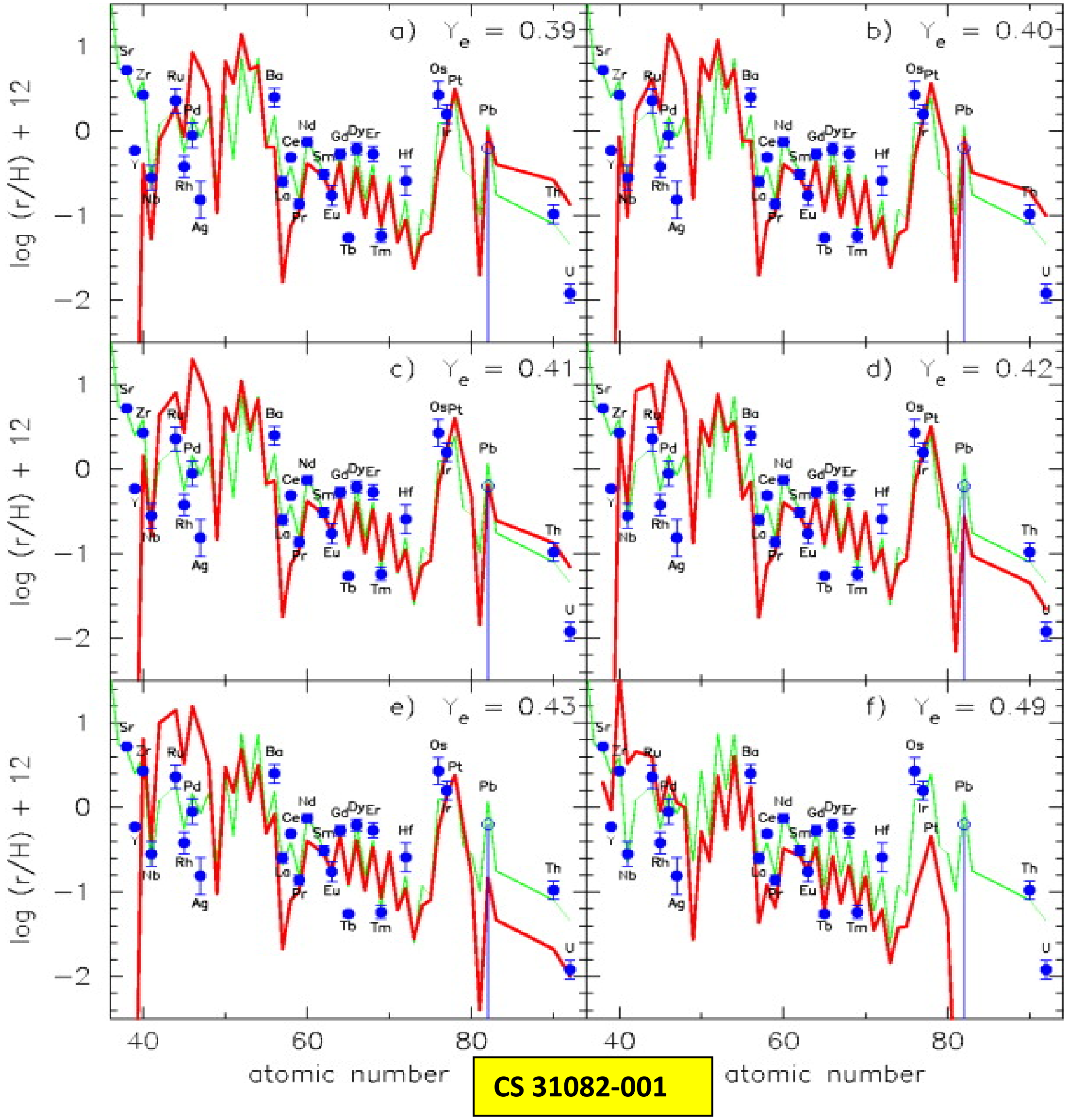
Th/U **robust – yes**
reliable – no
(not always)

Correlate Th, U with other elements, e.g. 3rd peak, Pb !

U - Th cosmochronology

S. Wanajo et al.; ApJ 577 (2002)

“The r-process in the neutrino winds of core-collapse supernovae and U – Th cosmochronology”



“In practice, the U – Th pair is expected to be the most precise chronometer… …since these species are separated by only two units in atomic number…”

Caveat !

also correct U/Th chronometer age when calculated U & Th abundances are lower than the observed values in the respective star…

How about Pb as r-chronometer ?

In principle, **direct correlation** to Th, U

≈ 85% abundance from a-decay from actinide region

Sensitivity to age:

Pb

0 Gyr Y(Pb) = **0.375** (Mainz) // Sneden et al. (2008) Y(Pb) = **0.622** **?**

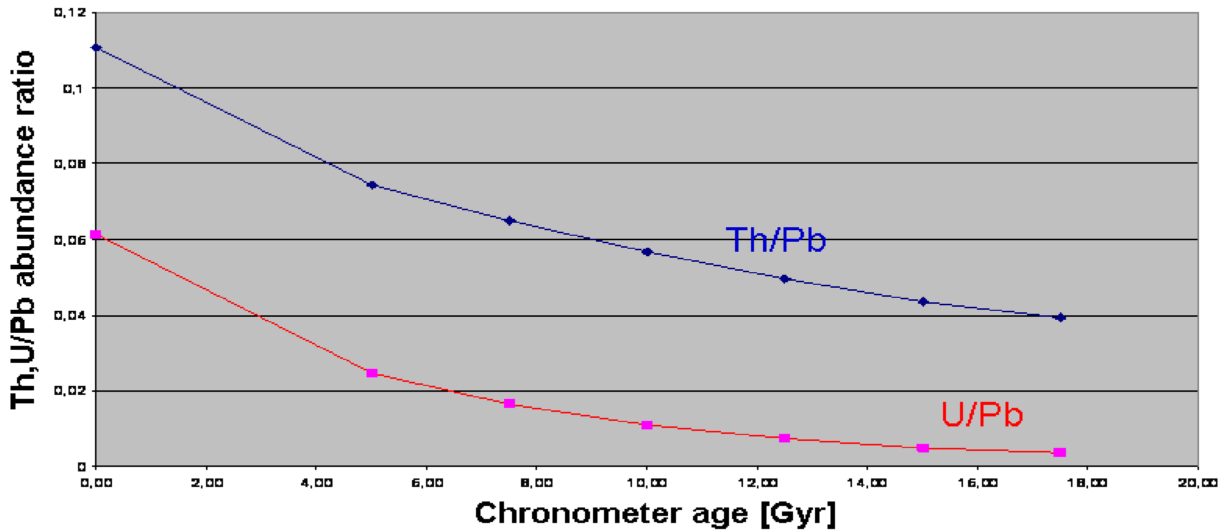
5 Gyr 0.433

13 Gyr 0.451

Th,U/Pb

13 Gyr: **Th/Pb ≈ 0.048**

U/Pb ≈ 0.007



New HEW results:

1) agreement Th/U and Th/Pb with NLTE analysis of Frebel-star.
2) consistent picture for Th/Ba – Th/U for 4 **"r-rich"** halo-stars with **Y_e ≈ 0.45**;

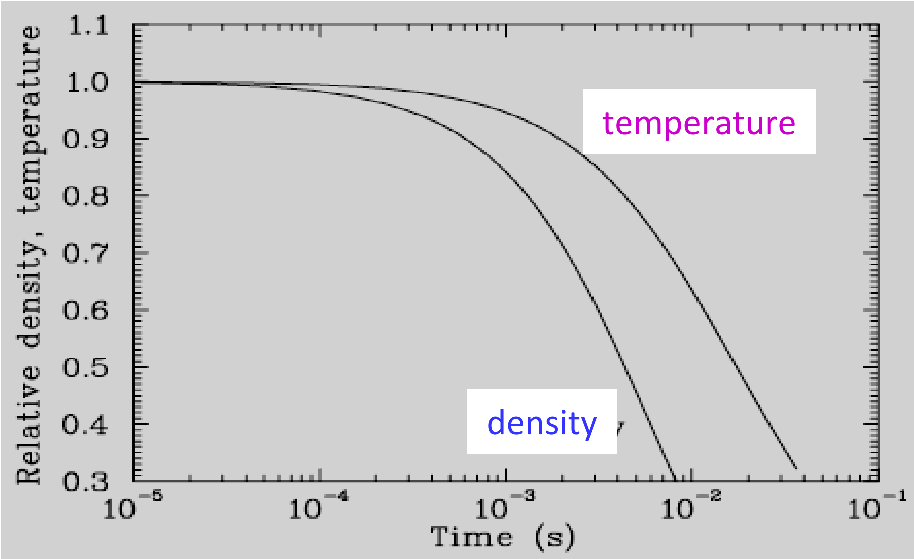
and for the **"actinide-boost"** Cayrel-star with **Y_e ≈ 0.44**.

Current projects / Collaborations

1.	$T_{1/2}$ & P_n of n-rich Sn - Xe isotopes	W.B. Walters, H. Schatz, U.Köster, P. Möller
2.	Zr - Mo – Ru isotopes in SiC – grains and CAI	U. Ott, M. Schönbächler, M. Savina, O. Hallmann, K. Farouqi
3.	Xe, Ba & Pt isotopes in nanodiamonds	U. Ott, A. Wallner, P. Hoppe, O. Hallmann, K. Farouqi
4.	A ≈ 130 and A ≈ 195 SS-r peaks	K. Farouqi, W.B. Walters
5.	Observations vs. calculations Sr – Cd in UMP halo-stars	L. Mashonkina, C.J. Hansen, N. Christlieb, I.U. Roederer, K. Farouqi
6.	Ba f_{odd} in "r-poor halo-stars"	L. Mashonkina, M. El Eid, K. Farouqi
7.	Th - U – Pb r-chronometry in "r-rich" halo-stars	A. Frebel, L. Mashonkina, N. Christlieb, K. Farouqi
8.	FRDM fission barriers & yields	P. Möller

Reserve

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

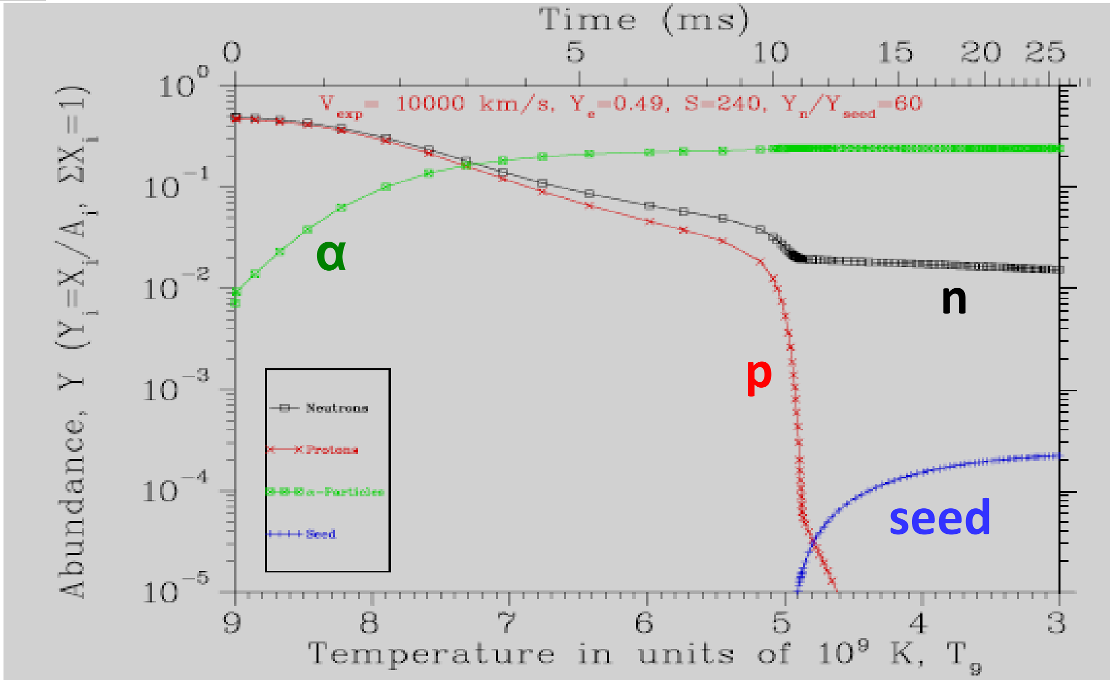
as functions of temperature and time

For $T_9 \leq 7 \Rightarrow$ **α** dominate;

at $T_9 \approx 5 \Rightarrow$ **p** disappear,

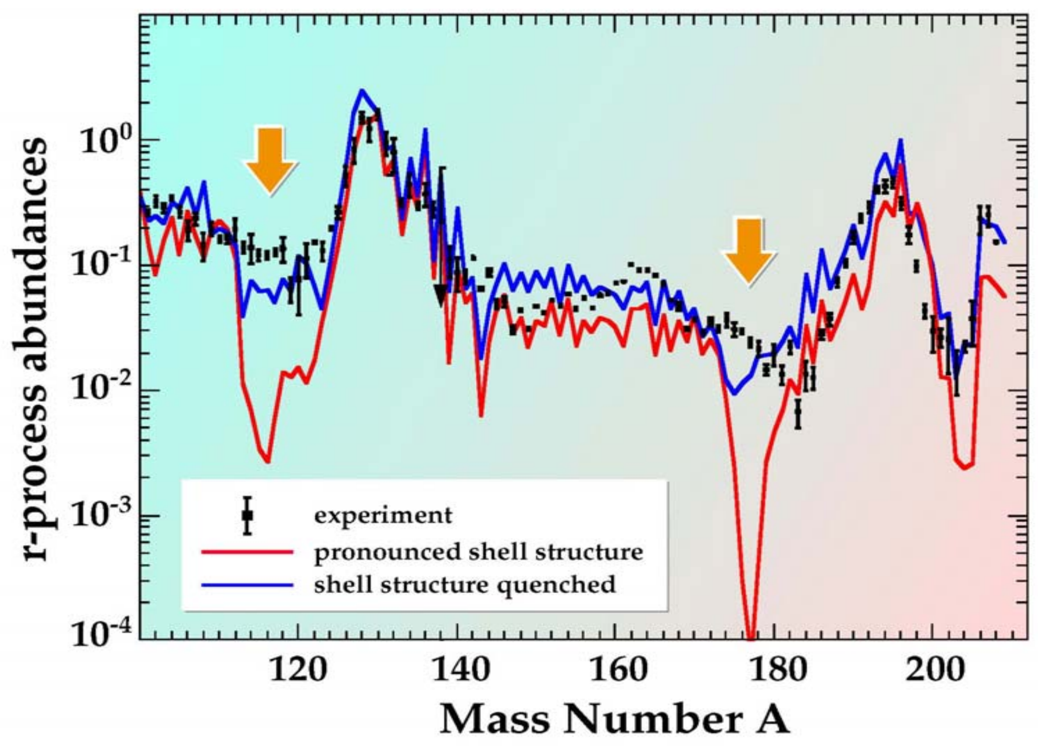
n survive,

"seed" nuclei emerge.

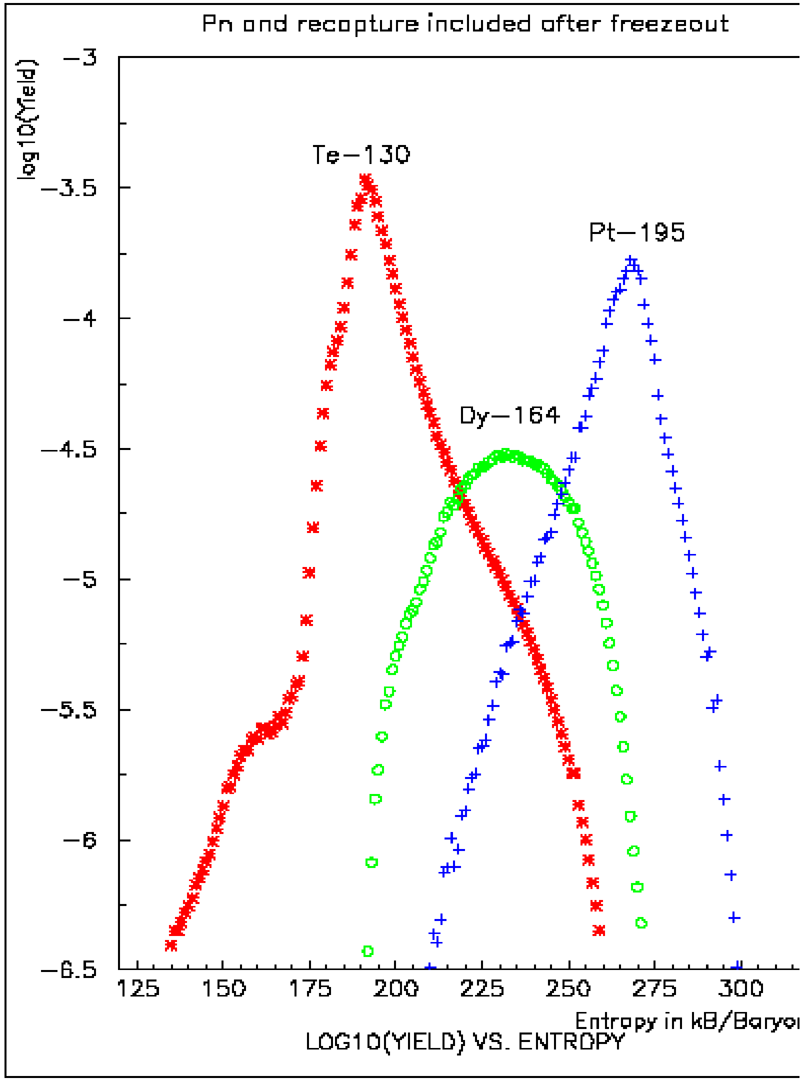


(Farouqi et al., 2009)

R-process robustness due to neutron shell closures



Width of A=130 and 195 peaks ca. 15 m.u.;
width of REE pygmy peak ca. 50 m.u.;



Widths of all three peaks (A=130, REE and A=195) $\Delta S \approx 40\ k_B$/Baryon

Kratz, Farouqi, Ostrowski (2007)

The A ≈ 130 SS r-abundance peak

HEW reproduction of the solar-system A ≈ 130 r-abundance peak

"cold" r-process

V_{exp} = 20000; S(top) ≈ 140

peak top at **A ≈ 126**

"hybrid" r-process

V_{exp} = 7500; S(top) ≈ 195

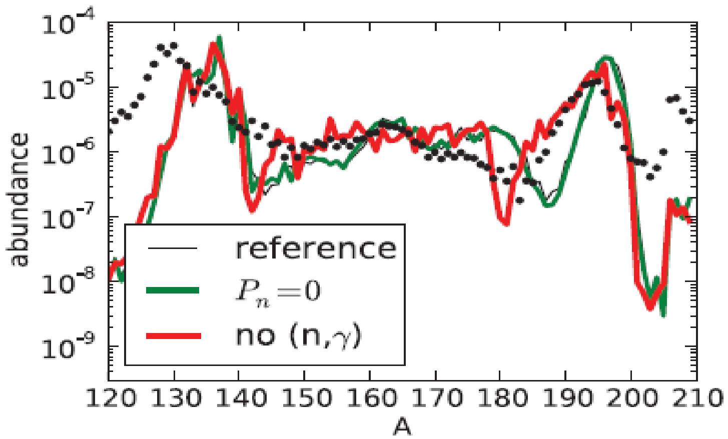
peak top at **128 < A < 130**

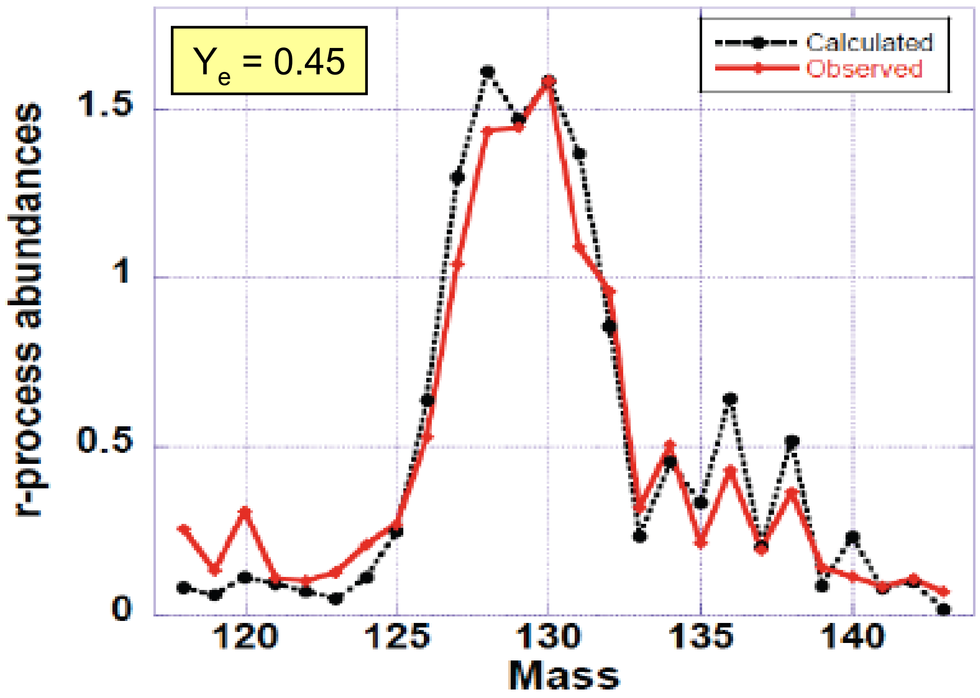
"hot" r-process

V_{exp} = 1000; S(top) ≈ 350

peak top at **A ≈ 136**

as, e.g. in Arcones & Martinez-Pinedo, Phys. Rev. C83 (2011)

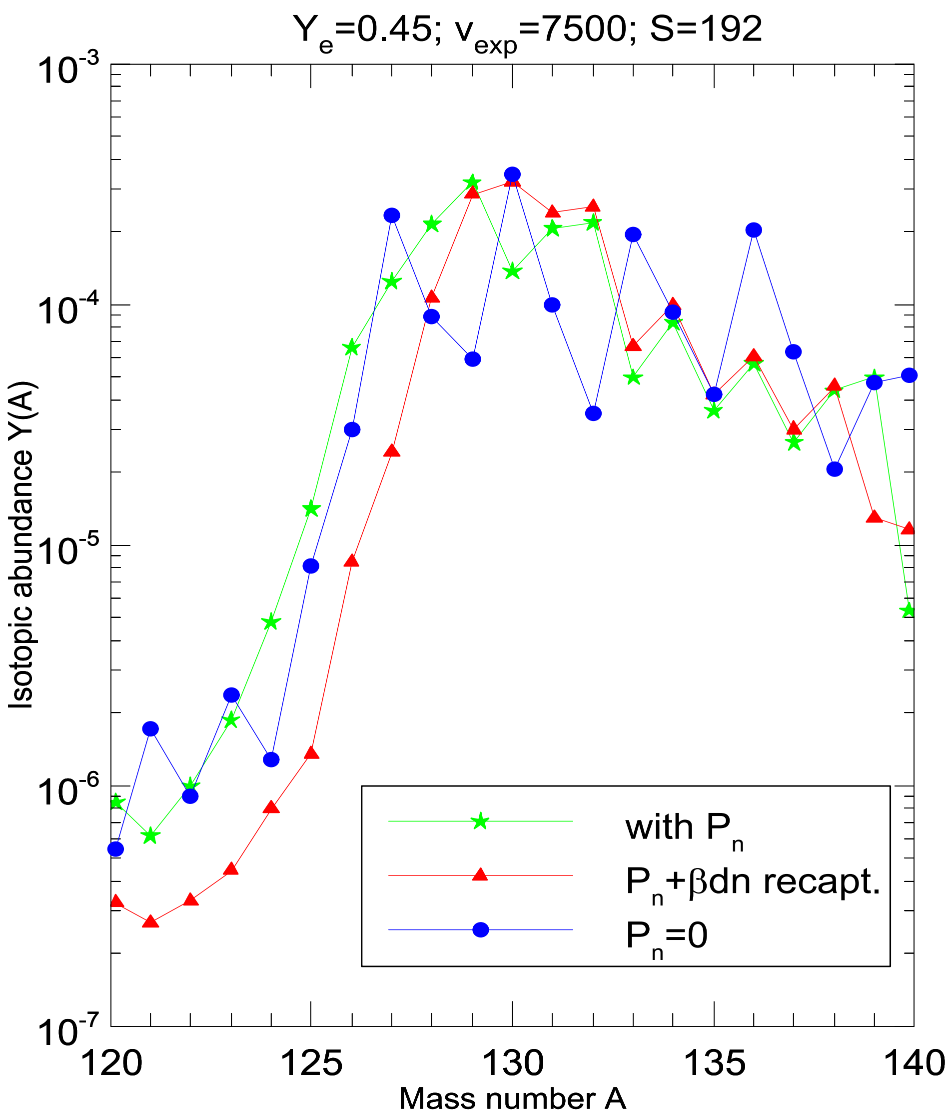




Nuclear-physics input:

ETFSI-Q; updated QRPA(GT+ff); experimental data

Effect of βdn-emission for the A≈130 peak

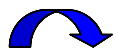


Significant differences

(1) smoothing of odd-even Y(A) staggering

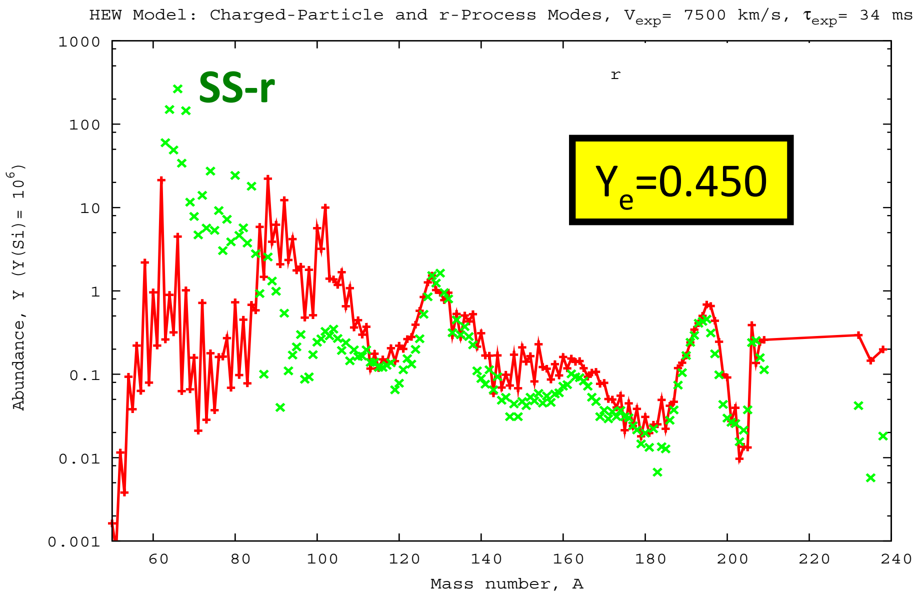
(2) importance of **individual** waiting-point nuclides, e.g. ^{127}Rh, ^{130}Pd, ^{133}Ag, ^{136}Cd

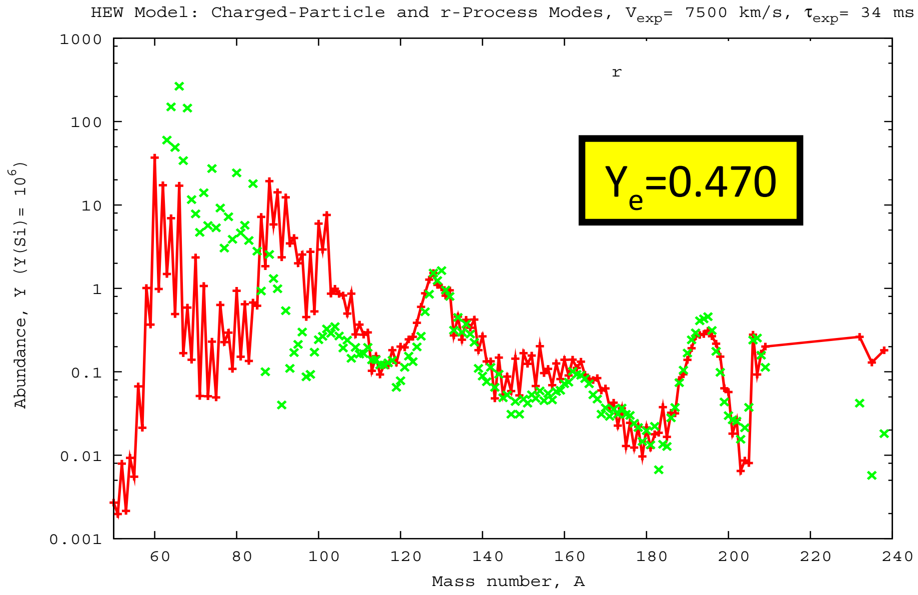
(3) shift left wing of peak

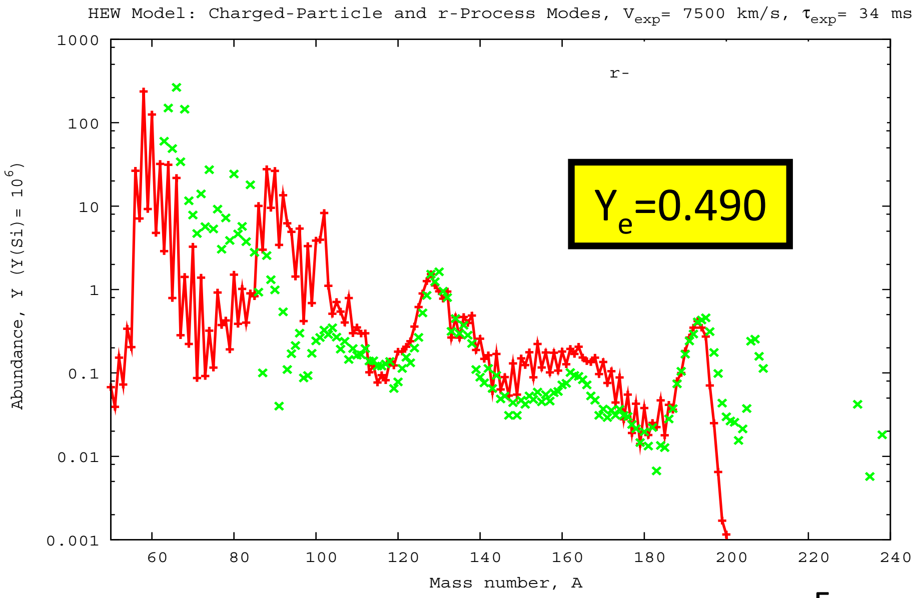


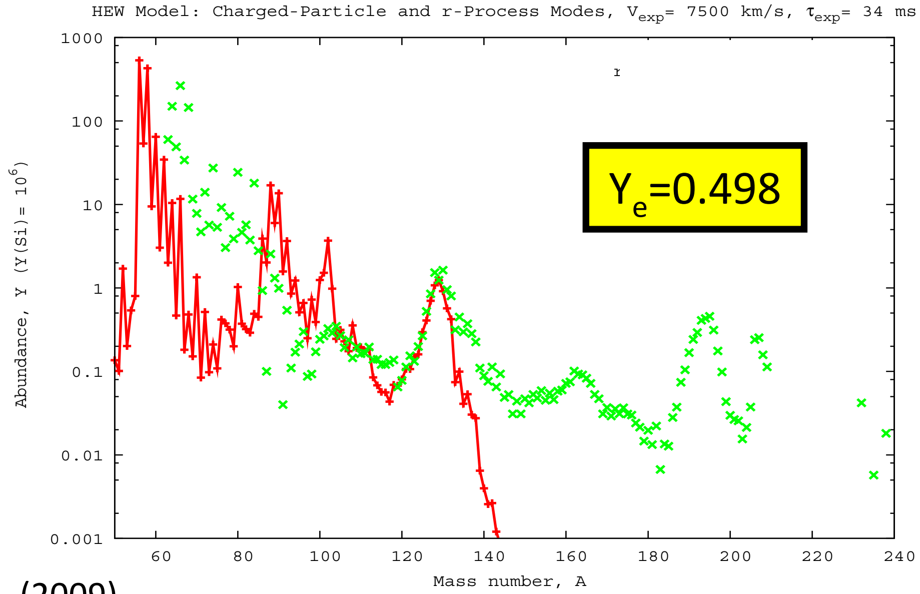
in clear contrast to Arcones & Martinez-Pinedo Phys. Rev. C83 (2011)

HEW model with ETFSI-Q: isotopic abundances









Farouqi et al. (2009)

Selected recent HEW r-process publications

1 Farouqi, Kratz, Thielemann et al.
"Charged-particle and neutron-capture processes in the HEW of cc SN II"
ApJ 712 (2010)
parameterized Basel model; Y_e, S, V_{expand} , T_9 **correlated**
Y_e = 0.40 – 0.499; S = 10 – 350; V_{exp} = 1000 – 30,000 km/s; T_9 = 0.2 – 1

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

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2 Beun, McLaughlin et al.
"Fission cycling in a supernova r-process"
Phys.Rev. C77 (2008)
parameterized Woosley model (1994)
Y_e = 0.027 – 0.17; S = 100; $T_9 \lesssim 2$

sterile neutrino oscillations required !

3 Kuroda, Wanajo & Nomoto
"The r-process in supersonic neutrino-driven winds"
ApJ 672 (2008)
semi-analytical neutrino model
Y_e = 0.21 – 0.39 (free parameter);
V_{radial} = 10,000 km/s; T_9 = 1.3

4 Wanajo
"Cold r-process in neutrino-driven winds"
ApJ 666 (2007)
semi-analytical neutrino model
Y_e = 0.15 – 0.22 ("artificial assumption");
T_9 = 0.1 – 0.4

5 Ning, Qian & Meyer
"r-Process nucleosynthesis in shocked surface layers of O-Ne-Mg cores"
ApJ 667 (2007)
parameterized Nomoto core model;
Clemson reaction network
Y_e = 0.495; S = 139; V_{shock} = 100,000 km/s τ = 4

τ = 4 ms !

Attempt to reproduce the $N_{r,\odot}$ pattern

PHYSICAL REVIEW D 73, 093007 (2006)

Fission cycling in supernova nucleosynthesis: Active-sterile neutrino oscillations

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[2]*Department of Physics, Union College, Schenectady, New York 12308, USA*
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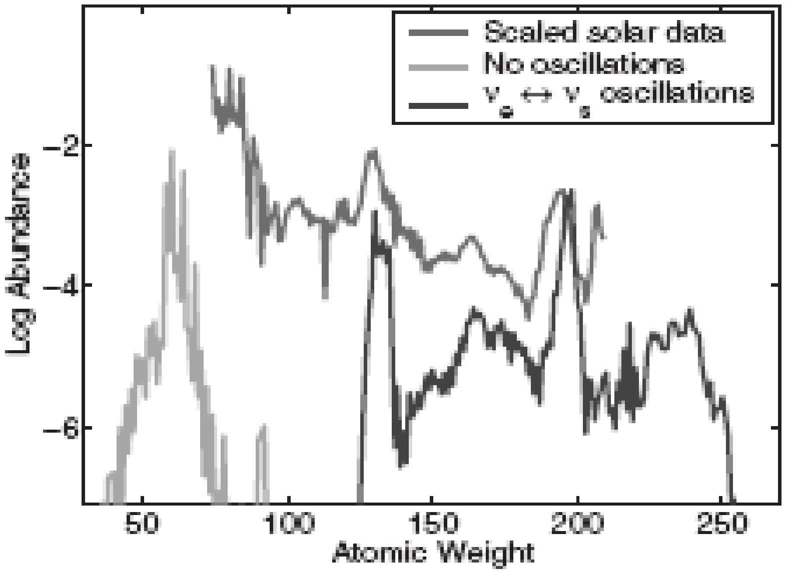
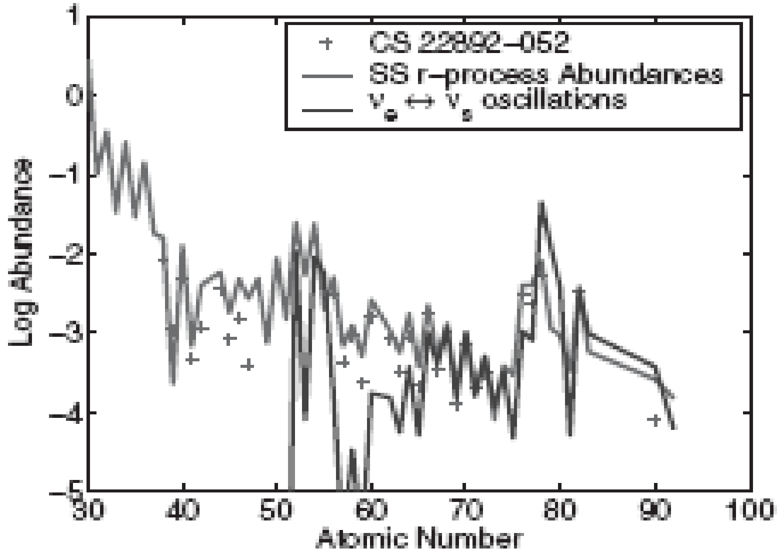
(Received 6 February 2006; published 26 May 2006)



At which level is disagreement starting ???

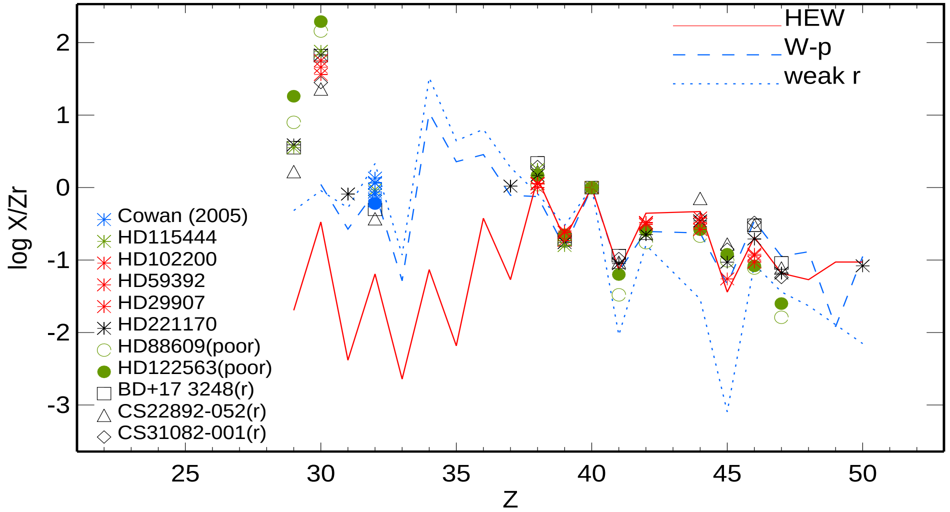


An r-process pattern (dark line) producing only the second and third of the three r-process peaks occurs in the neutrino-driven wind when there is active sterile neutrino mixing.

The **general features** of the r-process pattern found in halo stars are **reproduced** in the neutrino-driven wind when active-sterile neutrino oscillations occur.

Halo stars vs. HEW model: “LEPP” elements

LEPP-abundances vs. α- enrichment (Zr)

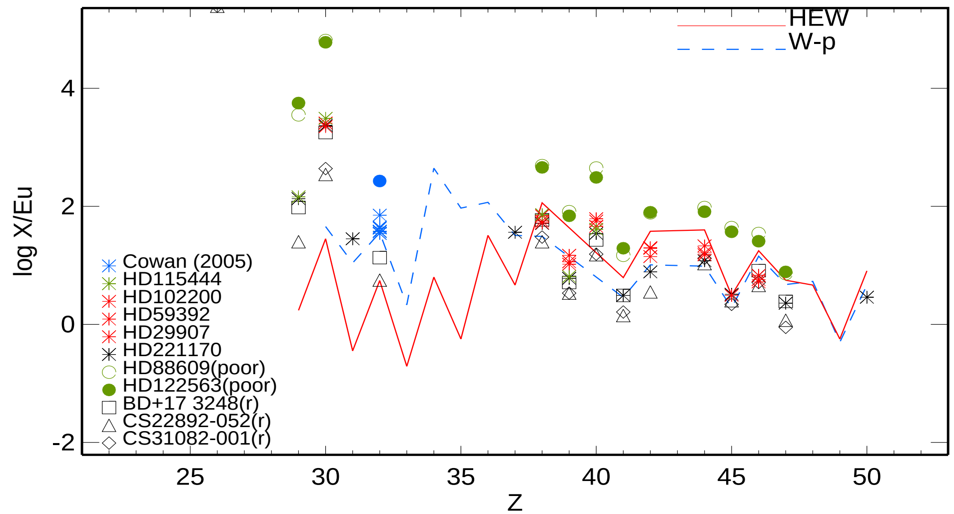


HEW (10 < S < 280)
WP (Fe seed; $10^{20} < n_n < 10^{28}$)
weak-r (Si-Cr seed; $n_n \approx 10^{19}$)

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

additional nucleosynthesis processes ?

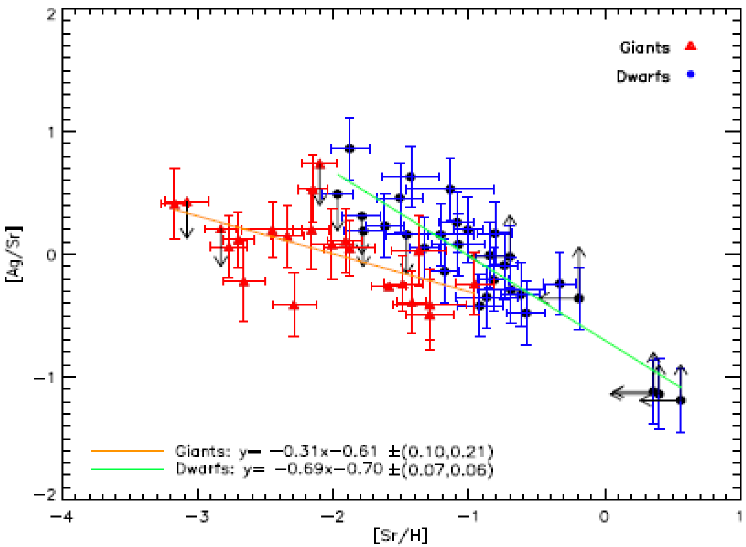
LEPP-abundances vs. r-enrichment (Eu)



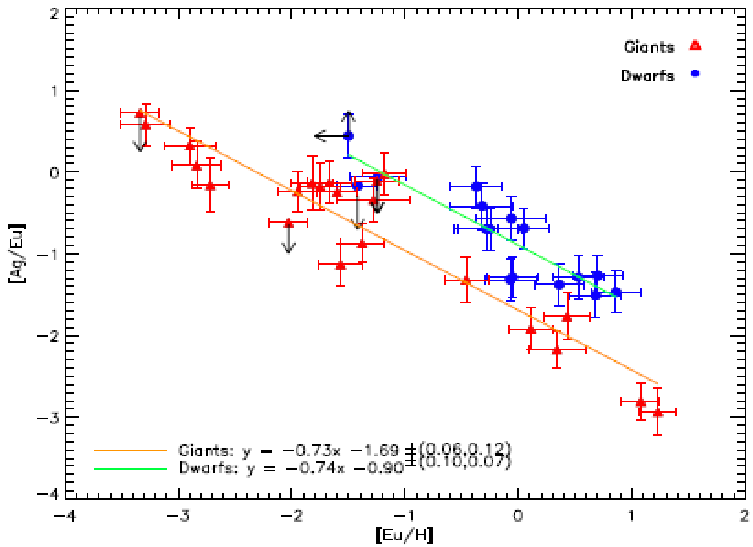
HEW predictions of high-Z LEPP (Sr – Sn)
in between “r-poor” (X/Eu high) and
“r-rich” stars (X/Eu low);
again underestimates low-Z LEPP.

Request: more and higher-quality observations of low-Z LEPP

Observations of Pd & Ag in giant and dwarf stars



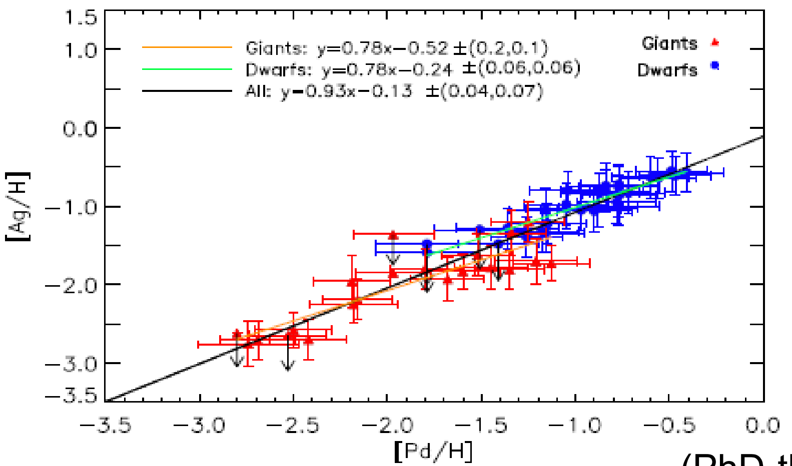
anticorrelation between Ag and Sr



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

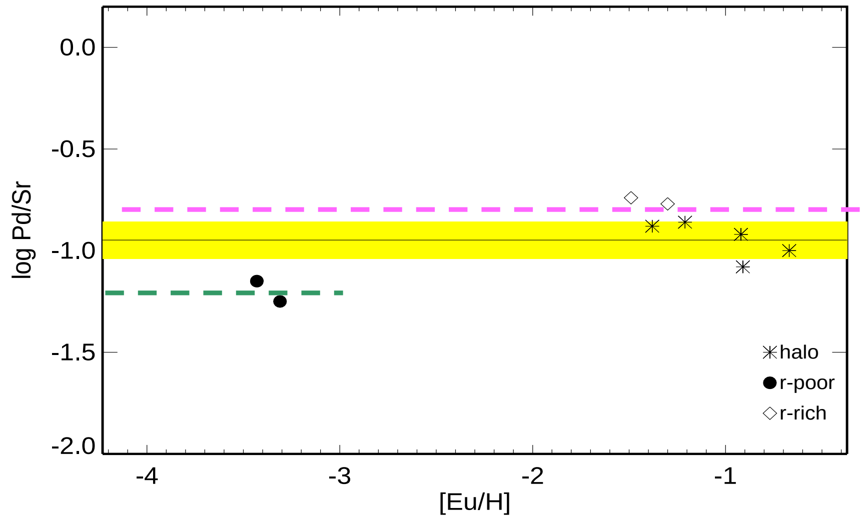
(predominantly) weak r-process

in agreement with our HEW predictions !

(PhD-thesis C.J. Hansen, LMU, 2011)

Halo stars vs. HEW-model predictions: Pd in “r-pure” stars

Pd relation to **α-element Sr**



average Halo stars

-1.5 < [Eu/H] < -0.6

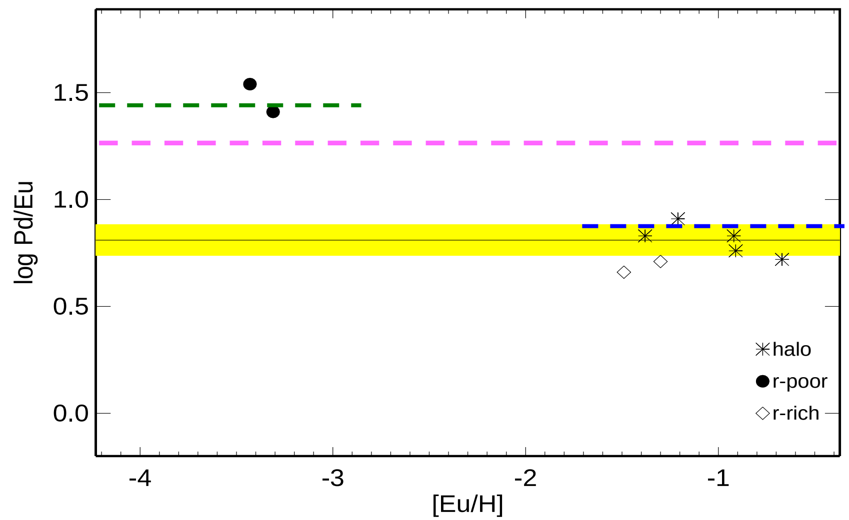
log(Pd/Sr) ≈ - 0.95(0.09)

HEW model

log(Pd/Sr) = - 0.81 (“r-rich”)

- 1.16 (“r-poor”)

Pd relation to **r-element Eu**



average Halo stars

-1.5 < [Eu/H] < -0.6

log(Pd/Eu) ≈ +0.81(0.07)

HEW model

log(Pd/Eu) = +1.25 (Pd α+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

r-Abundances Pb, Bi – $N_{r,\odot}$ vs. $N_{r,calc}$

Reference	^{206}Pb	^{207}Pb	^{208}Pb	ΣPb	^{209}Bi
$N_{\odot}$ (Lodders, 2003)	0.610	0.671	1.912	3.258	0.139
$N_{r,\odot}$ „residuals“					
(Käppeler et al. 1989)	0.223	0.280	0.118	0.622	0.093
(Beer et al. 2001)	0.178	0.171	0.133	0.482	0.101
(Gallino et al. 2003)	0.178	0.116	0.091	0.385	0.118
(Gallino et al. 2008)	0.181	**0.225**	**0.455**	**0.861**	0.117
$N_{r,calc}$ (w.p. model)					
(Cowan et al. 1999)	0.158	0.146	0.135	0.439	0.103
(Kratz, Pfeiffer 2008)	0.145	0.106	0.123	0.374	0.102

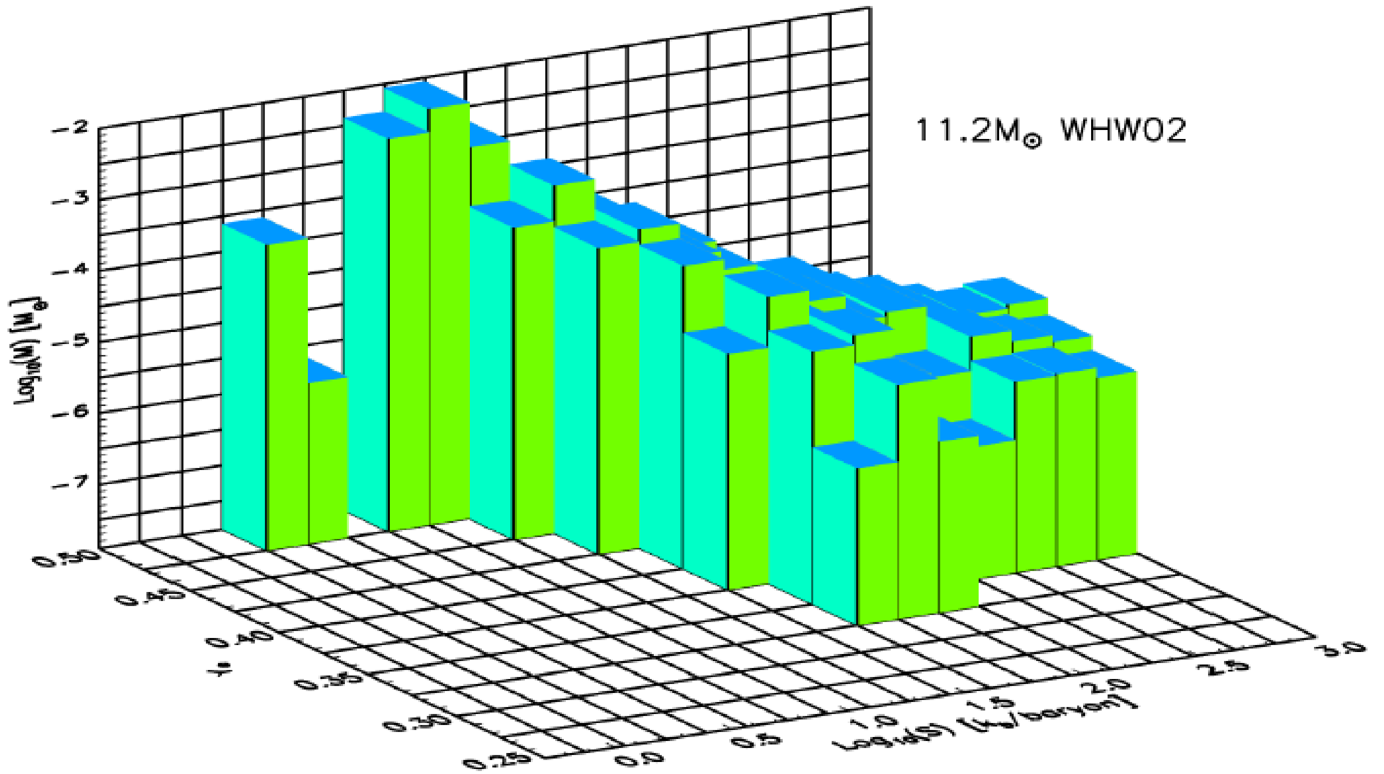
to be used as chronometer ?

Franz / Roberto / Stefano ⇨ which $N_{r,\odot}$ values should be believed ???

Weight, Y_e, S in a 3D hydrodynamical SNII model

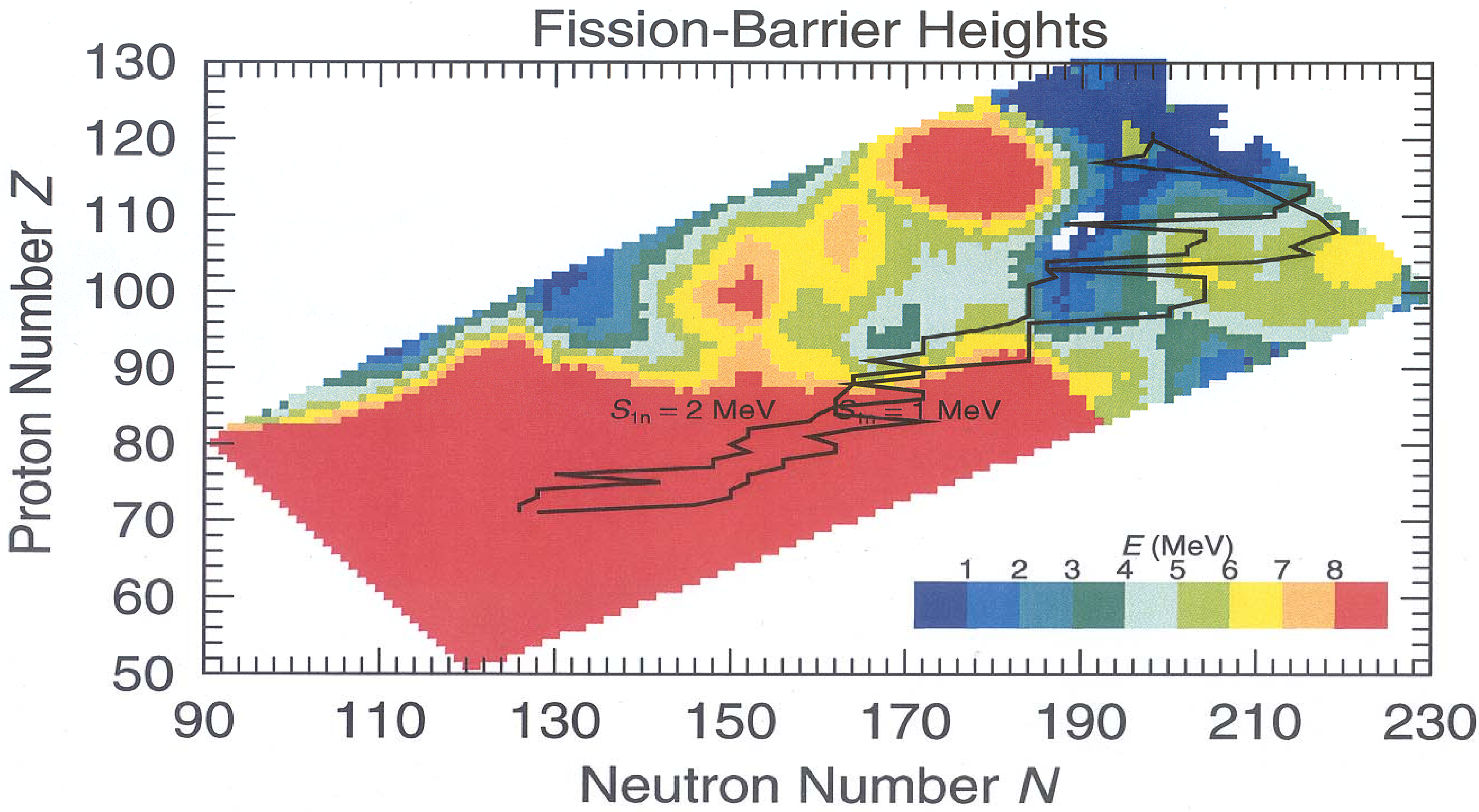
The Acoustic SN Mechanism and the r-Process

[Burrows et al., ApJ 655, 416 2007]



- Example: $11.2\,M_\odot$ star, 1.4 s after core bounce. $2.15 \times 10^{-4}\,M_\odot$ with $s > 100\,k_B$/baryon and $1.1 \times 10^{-5}\,M_\odot$ with $s > 300\,k_B$/baryon.

r-Process boulevard in the fission region



Cosmochemical observations:

Xe-H in nanodiamonds

Pt-H in nanodiamonds

Xe-H nano-diamonds / „old“ models

The **“neutron burst model”**

is the favoured nucleosynthesis scenario among cosmochemists,

so far applied to isotopic abundances of Mo, Zr, Xe, Ba, Pt

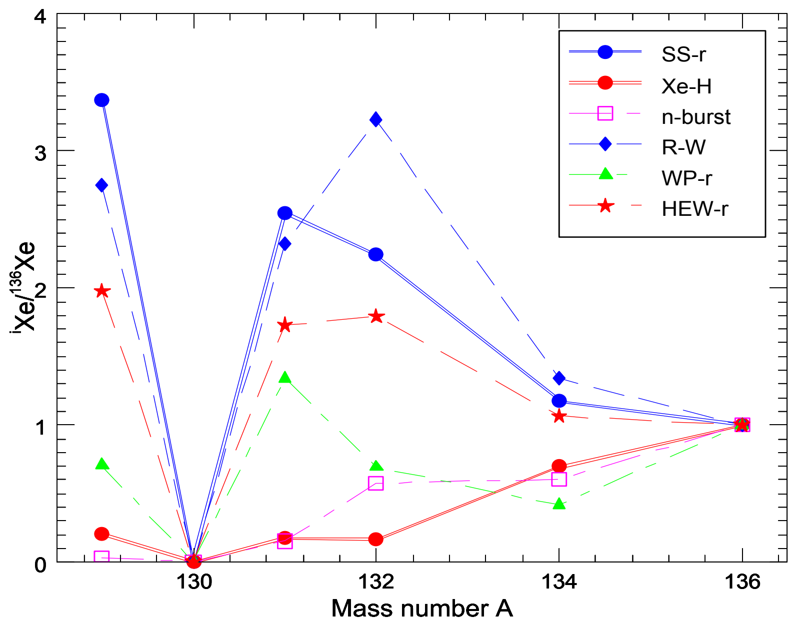
Historical basis:

…neutron burst in shocked He-rich matter in exploding massive stars

first ideas by Cameron

Howard et al., *Meteoritics* (1992)

Rauscher et al., *ApJ* **576** (2002)

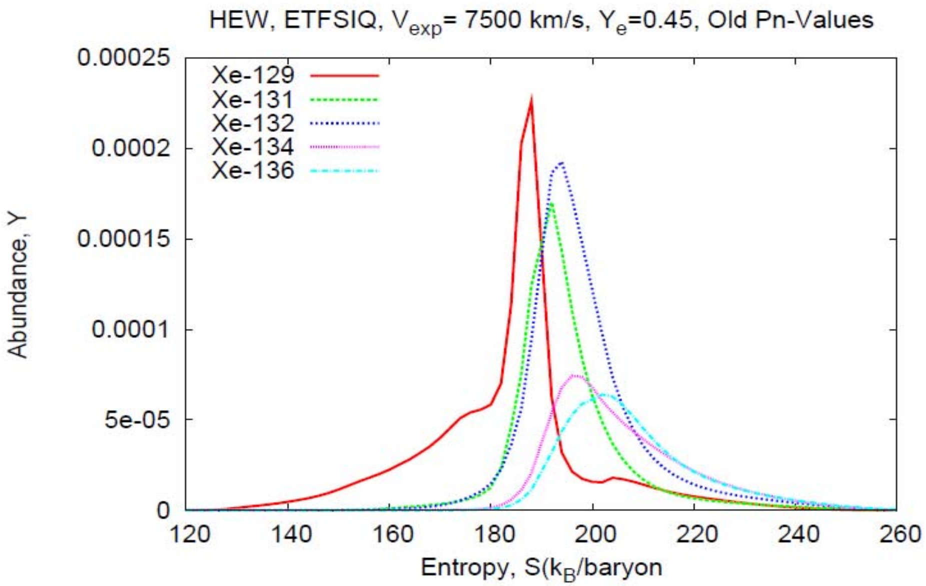


Several steps:

1) start with SS isotope distribution
2) Exposure to weak neutron fluence, mimics pre-SN weak s-processing
3) “s-ashes” heated suddenly to $T_9 \approx 1$
4) rapid release of (α,n)-neutrons during expansion and cooling = **neutron burst**

Shift of post-processed isotope pattern towards higher A

r-Abundances of Xe isotopes



„old“ nuclear-physics input

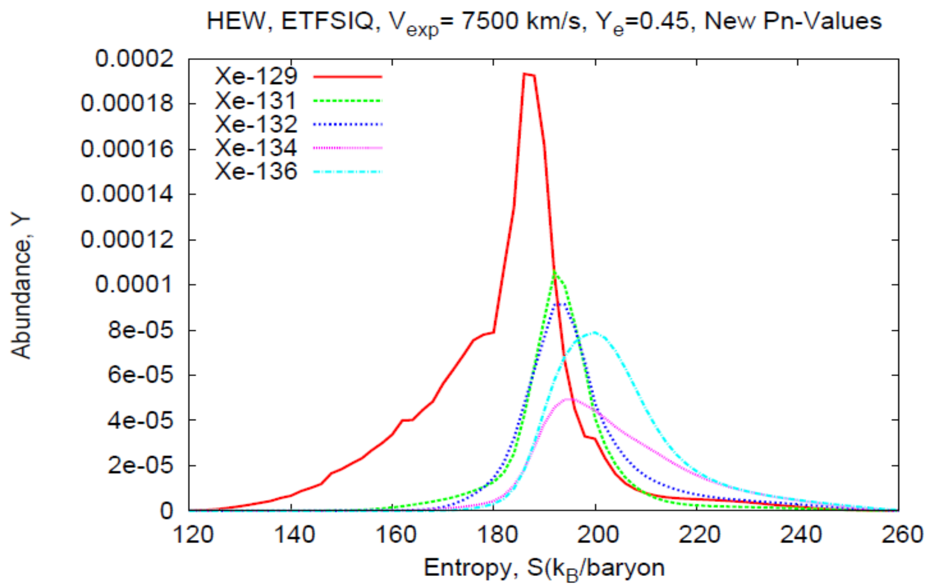
e.g. ^{129}Ag $T_{1/2}$(g.s.) = 46 ms;

^{130}Pd $T_{1/2}$ = 98 ms, $P_{1\text{-}2n}$ = 96; 4 %

„new“ nuclear-physics input

e.g. ^{129}Ag stellar-$T_{1/2}$ = 82 ms;

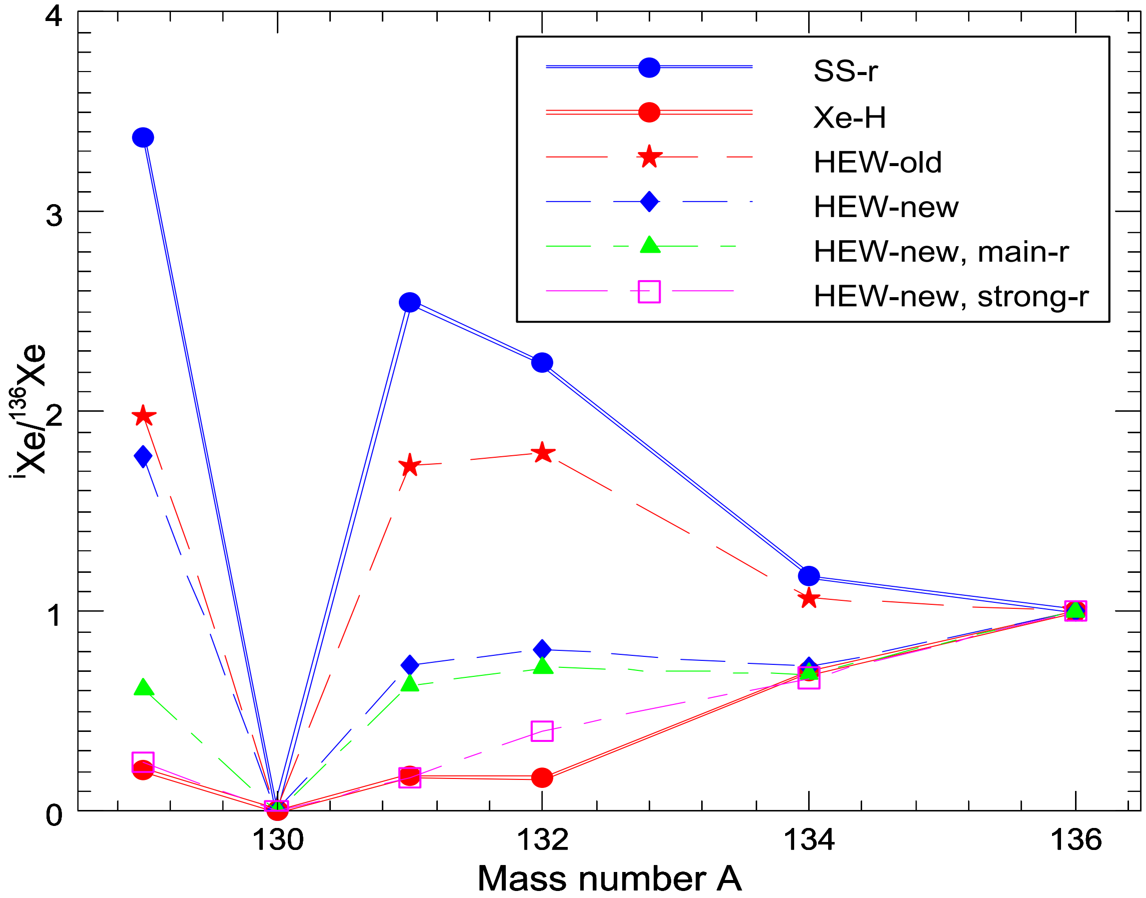
^{130}Pd $T_{1/2}$ = 13 ms, $P_{1\text{-}3n}$ = 79; 16; 1%



Successive “cuts” of low-S components

exclusion of weak r-process

Xe-H nano-diamonds / „new“ models



1) Improvement by "new" nuclear input
   HEW-old → HEW-new

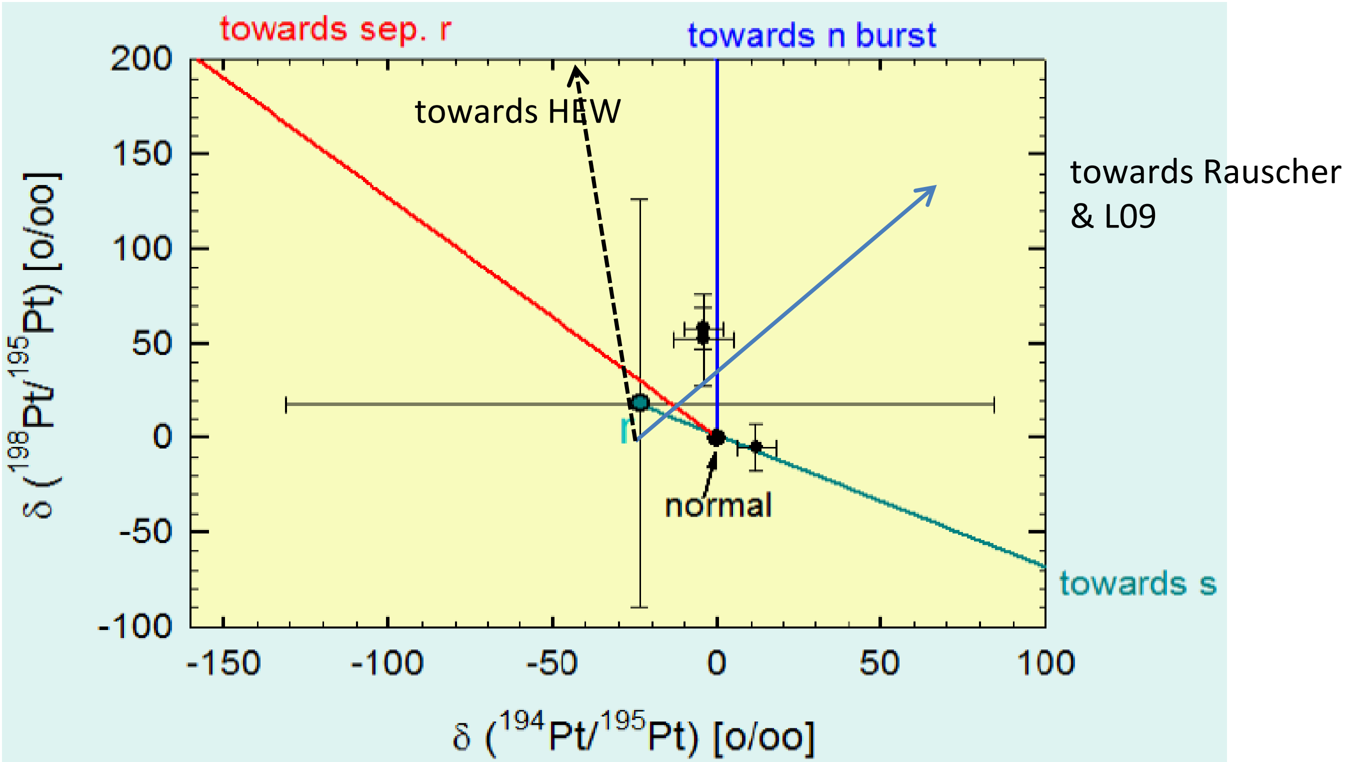
2) Further improvement by cutting off low-S range of weak r-process
   → HEW-new, main-r

3) Best agreement by assuming a strong r-process
   → HEW-new, strong-r

…interesting to note, that under the same HEW-conditions also the recently measured Pt-pattern in nanodiamonds can be reproduced

Pt in nano-diamonds

Recent AMS measurement by Wallner et al.; Vienna



…same HEW „strong“ r-process conditions as Xe-H !