

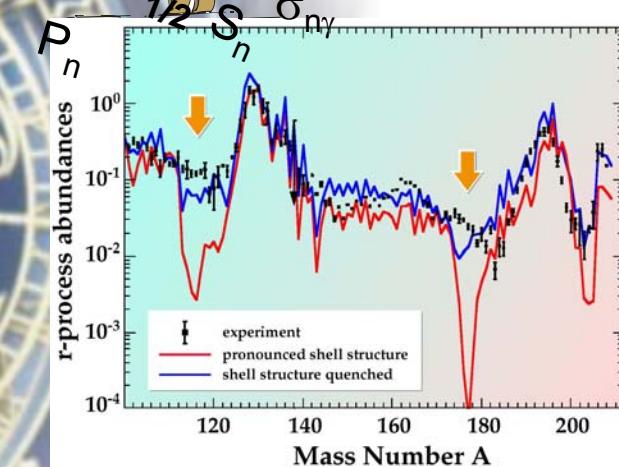
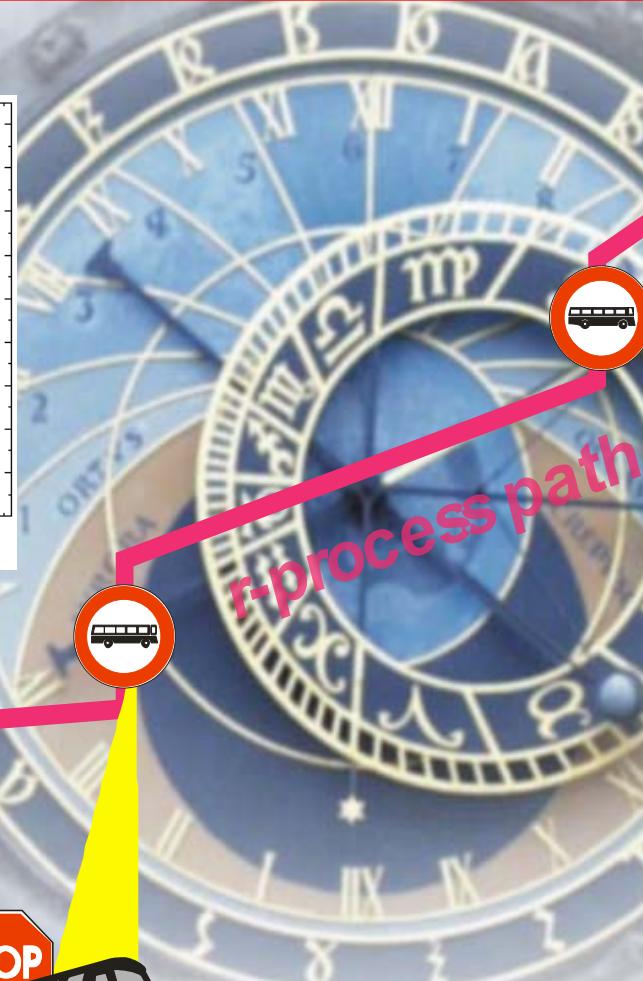
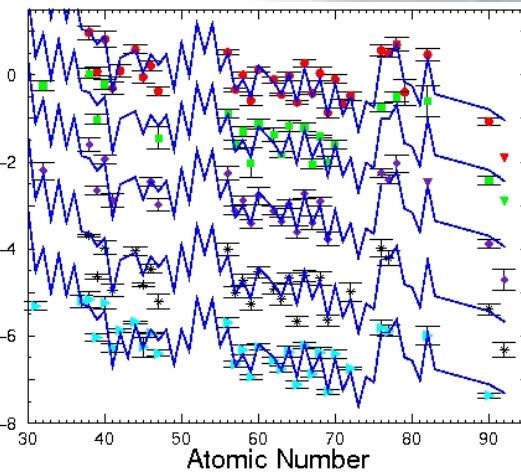


MAX-PLANCK-GESELLSCHAFT

Recent r-Process Calculations: From the “Waiting-Point” Approach to the SNII High-Entropy-Wind Model



Relative log ε



Karl-Ludwig Kratz

- Max-Planck-Institut für Chemie, Mainz, Germany
- Department of Physics, Univ. of Notre Dame, USA

waiting point

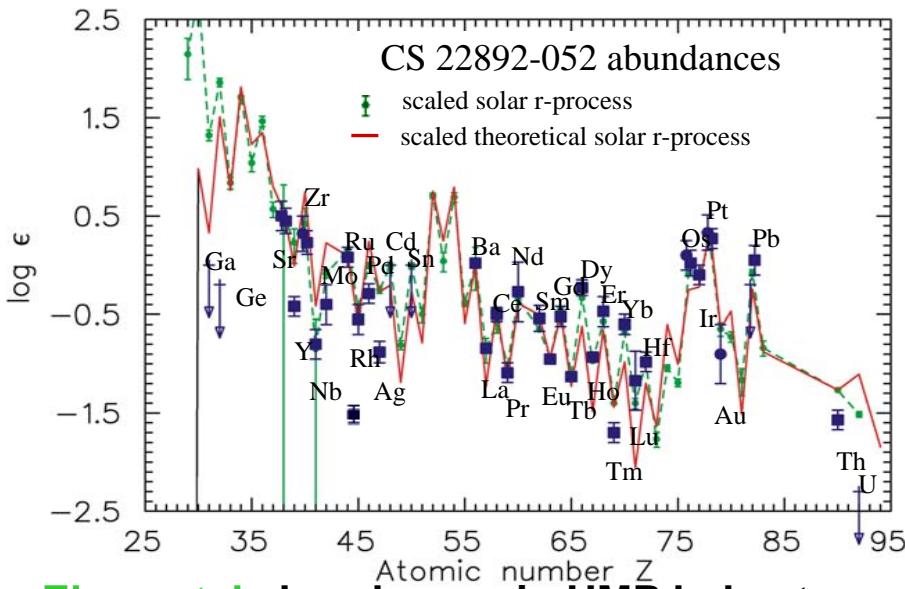


Frontiers 2007

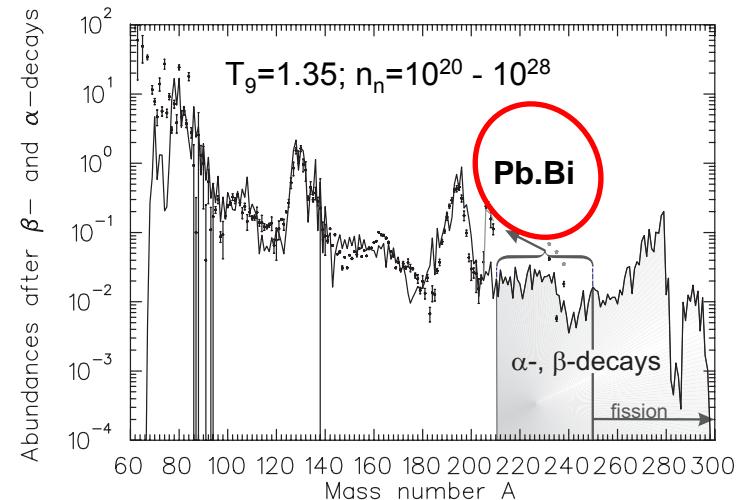
r-Process observables today

Observational instrumentation

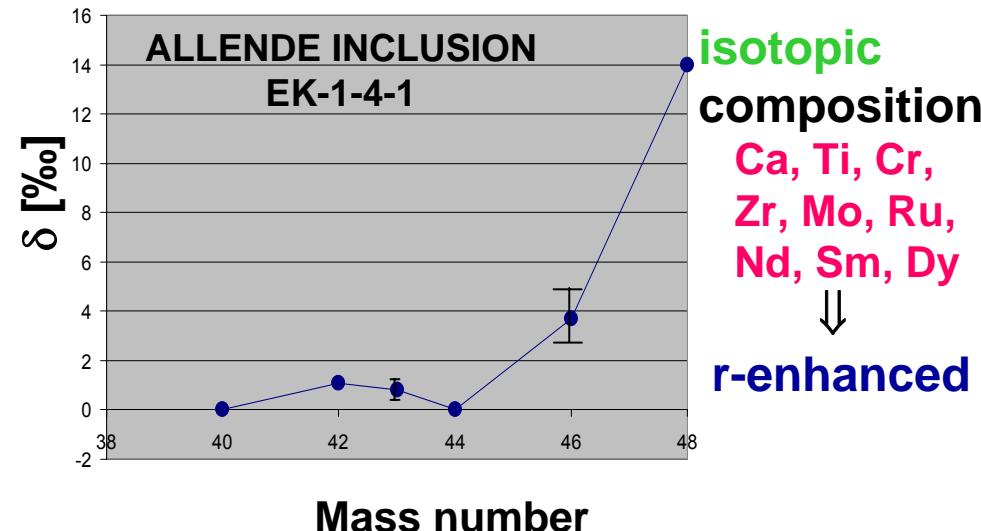
- meteoric and overall solar abundances
- ground- and satellite-based telescopes like *Imaging Spectrograph (STIS)* at **Hubble** or *HIRE*S at **Keck**, and γ -ray satellites like *INTEGRAL*, or X-ray observatories **CHANDRA** and **XMM-Newton**.



Solar system isotopic abundances, $N_{r,\odot}$



r-process observables



isotopic composition

Ca, Ti, Cr,
Zr, Mo, Ru,
Nd, Sm, Dy



r-enhanced

“FUN” anomalies in meteoritic samples

Fit of $N_{r,\odot}$ from B²FH

- assumption $(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium
„waiting-point“ concept

„static“ calculation

- astrophysical conditions
explosive He-burning in SN-I

$$T_9 \approx 1$$

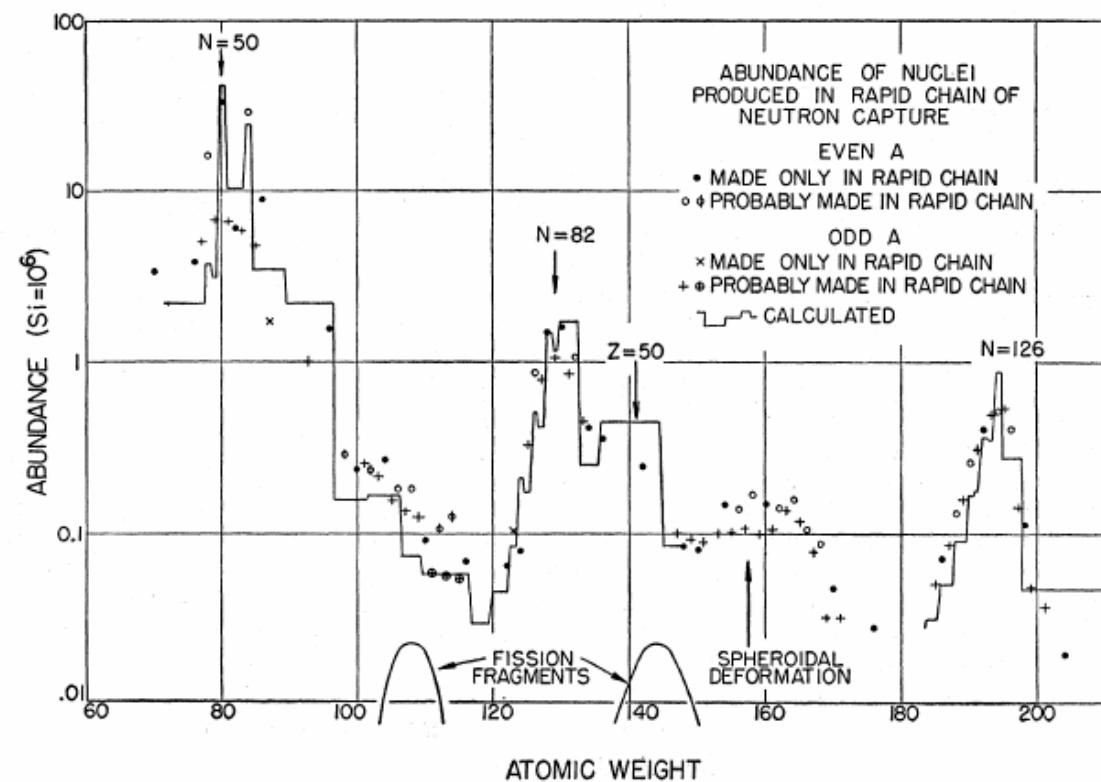
$$n_n \approx 10^{24} \text{ cm}^{-3}$$

$$\tau_r \approx 10 - 100 \text{ s}$$

- neutron source:
 $^{21}\text{Ne}(\alpha, n)$ mainly

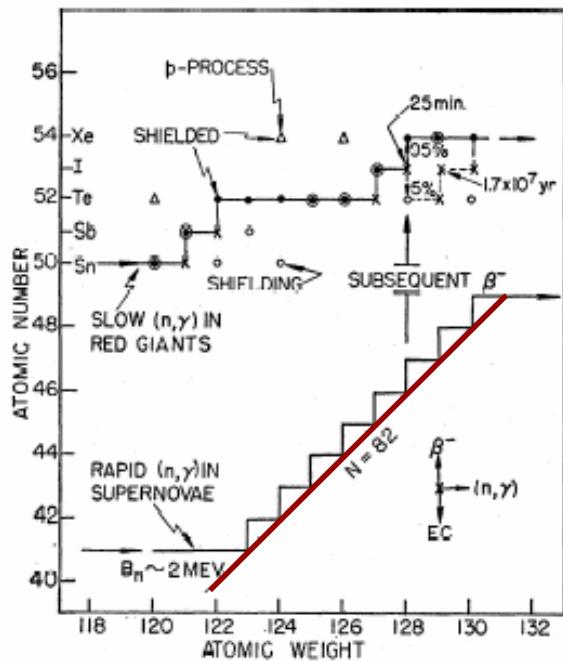
- nuclear physics:
 Q_β - Weizsäcker mass formula + empirical corrections (*shell, deformation, pairing*)

$T_{1/2}$ - 1 allowed transition to excited state, $\log ft = 3.85$



R-abundance peaks and neutron-shell closures

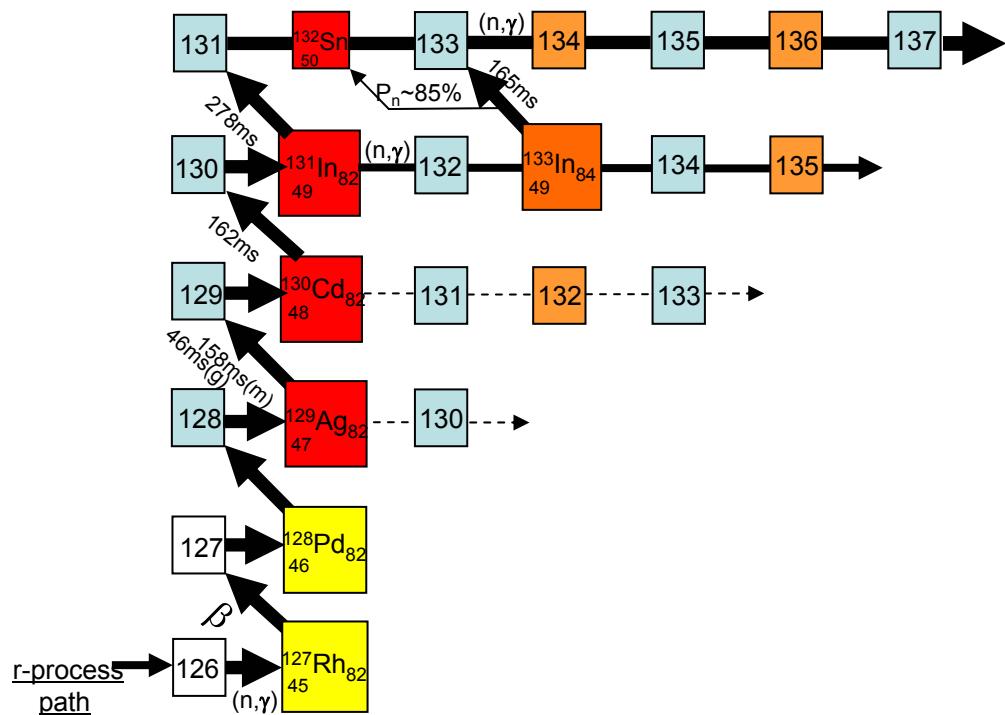
already B²FH (Rev. Mod. Phys. 29; 1957)
 C.D. Coryell (J. Chem. Educ. 38; 1961)



“climb up the staircase“ at N=82;
 major waiting point nuclei;
 “break-through pair“ ^{131}In , ^{133}In ;

“association with the rising side of major peaks in the abundance curve“

...still today important r-process properties to be studied experimentally and theoretically.



K.-L. Kratz (Rev. Mod. Astr. 1; 1988)

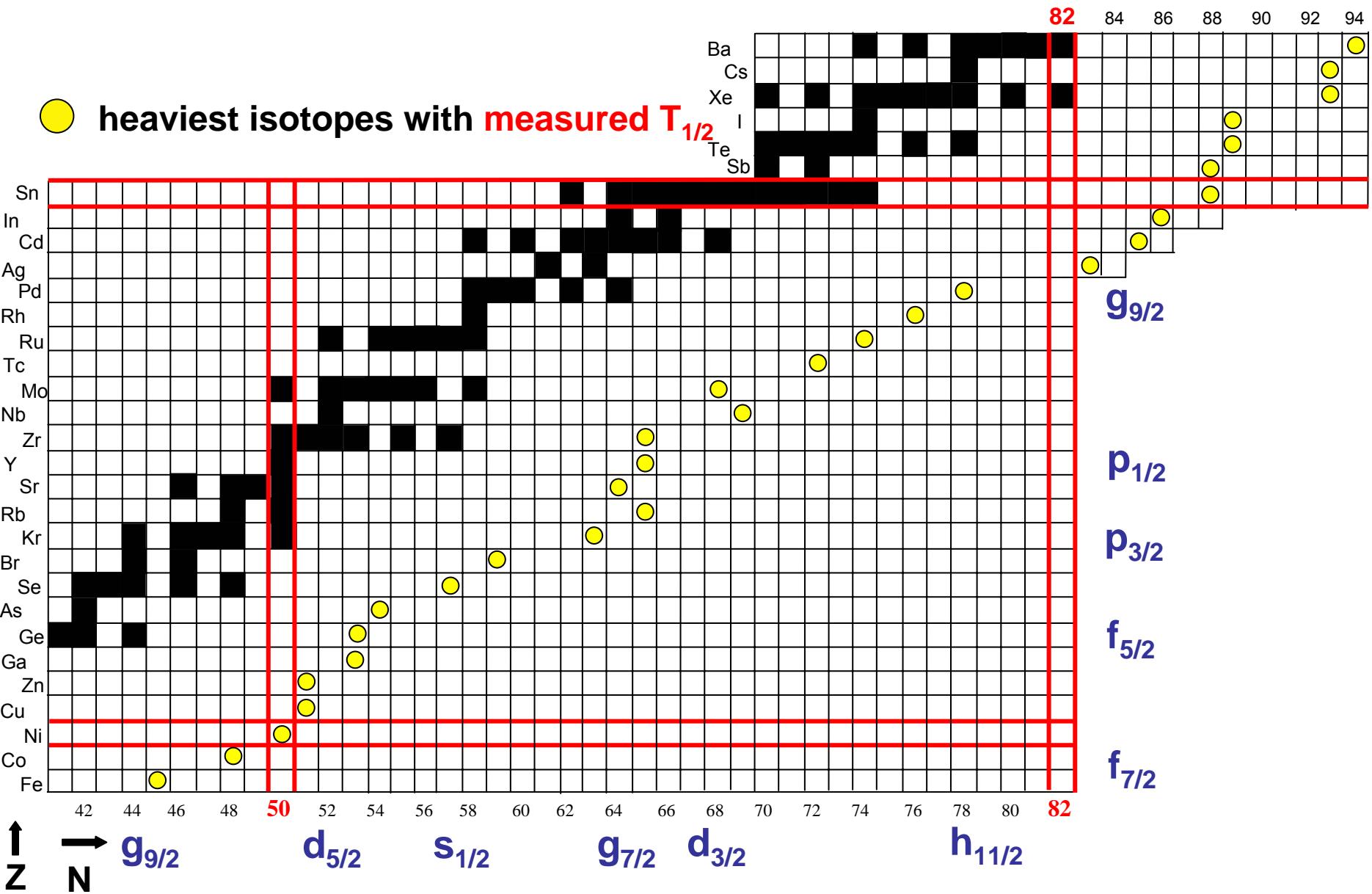
climb up the N= 82 ladder ...

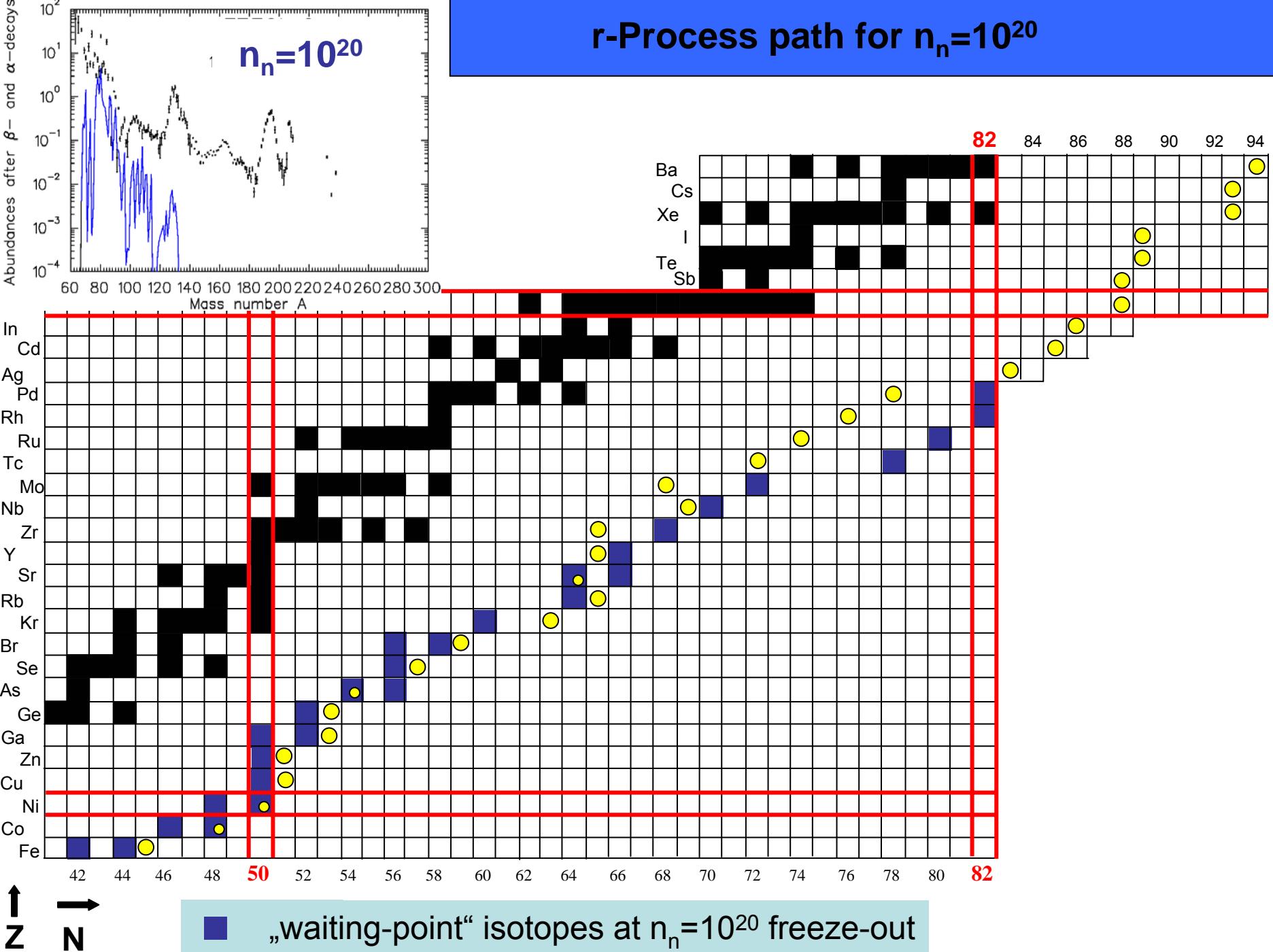
$A \approx 130$ “bottle neck“

$$T_{1/2}$$

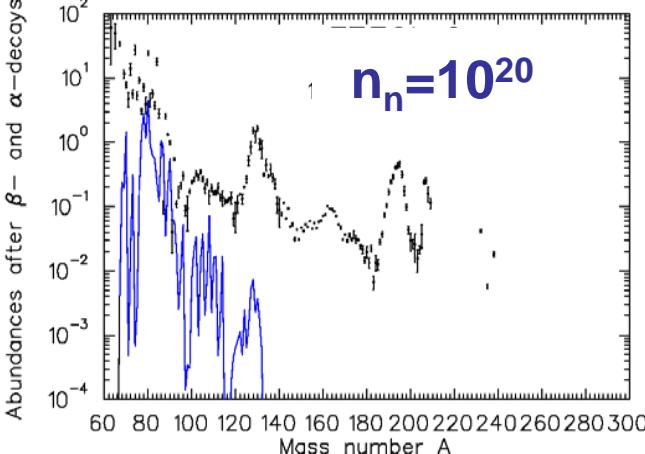
⇒ total r-process duration τ_r

Snapshots: r-Process paths for different neutron densities



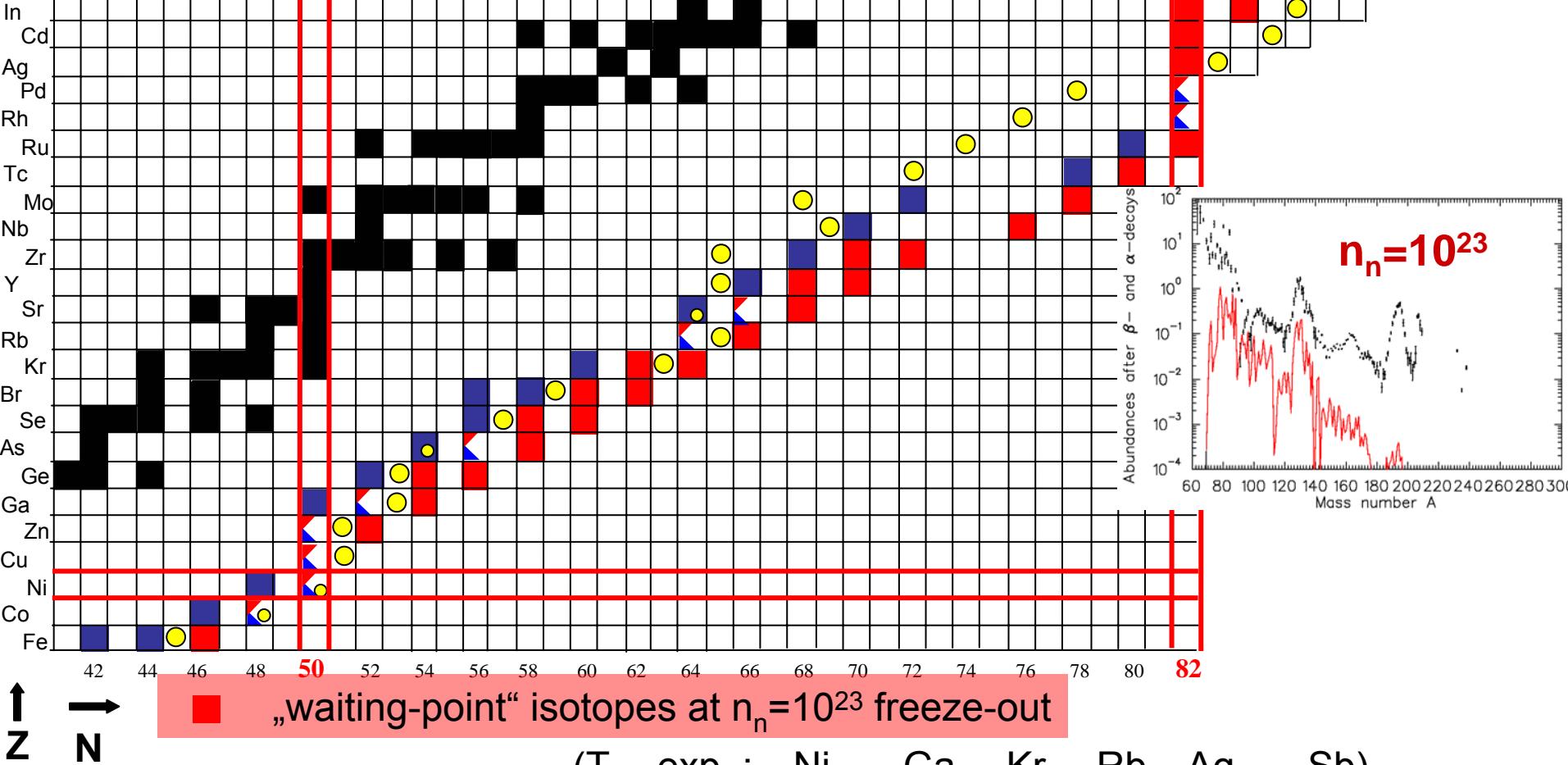


r-Process paths for $n_n=10^{20}$ and 10^{23}

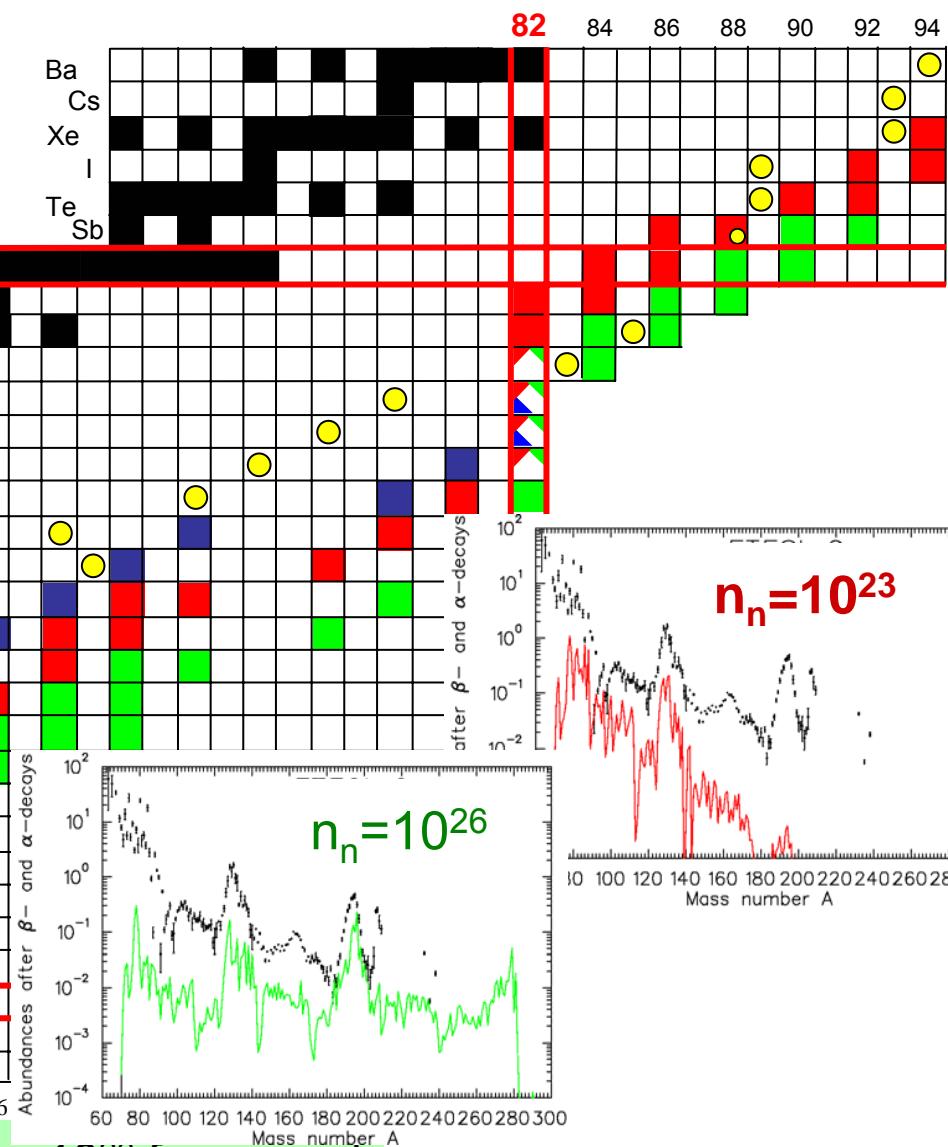
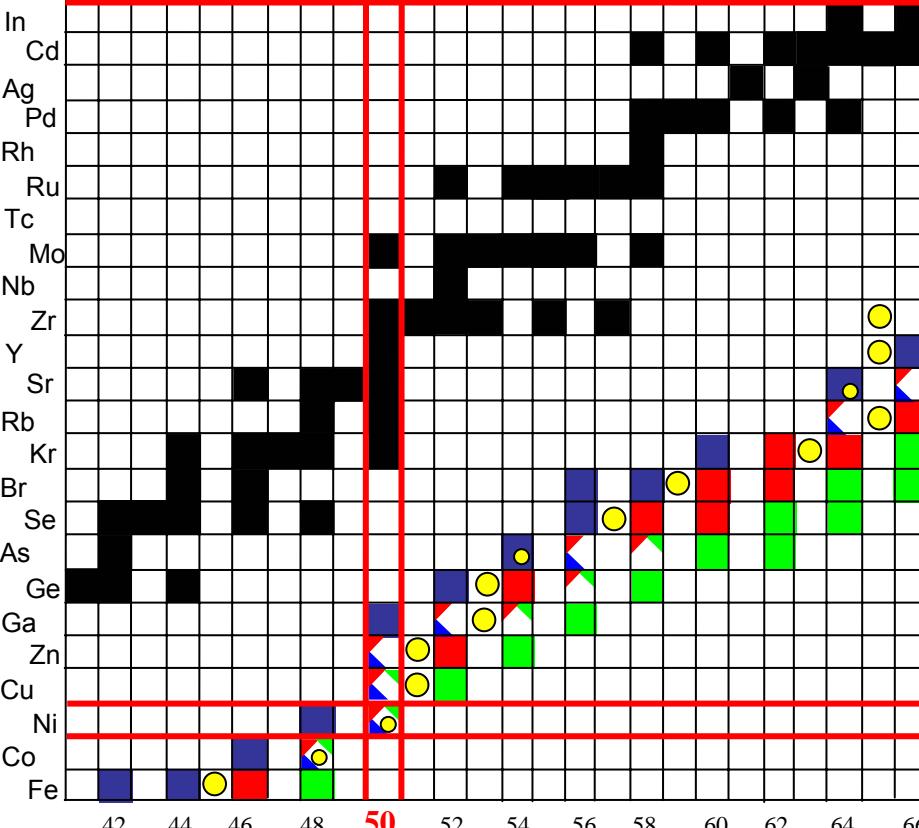
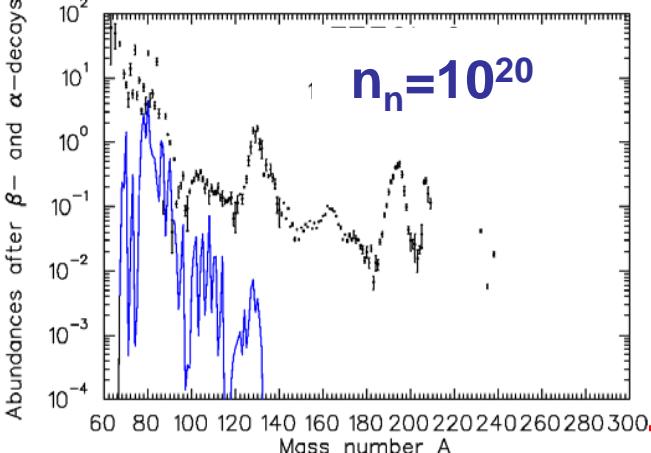


Mass number A

$n_n=10^{20}$



r-Process paths for $n_n=10^{20}$, 10^{23} and 10^{26}



($T_{1/2}$ exp. : ^{28}Ni , ^{29}Cu , $^{47}\text{Ag} - ^{50}\text{Sn}$)

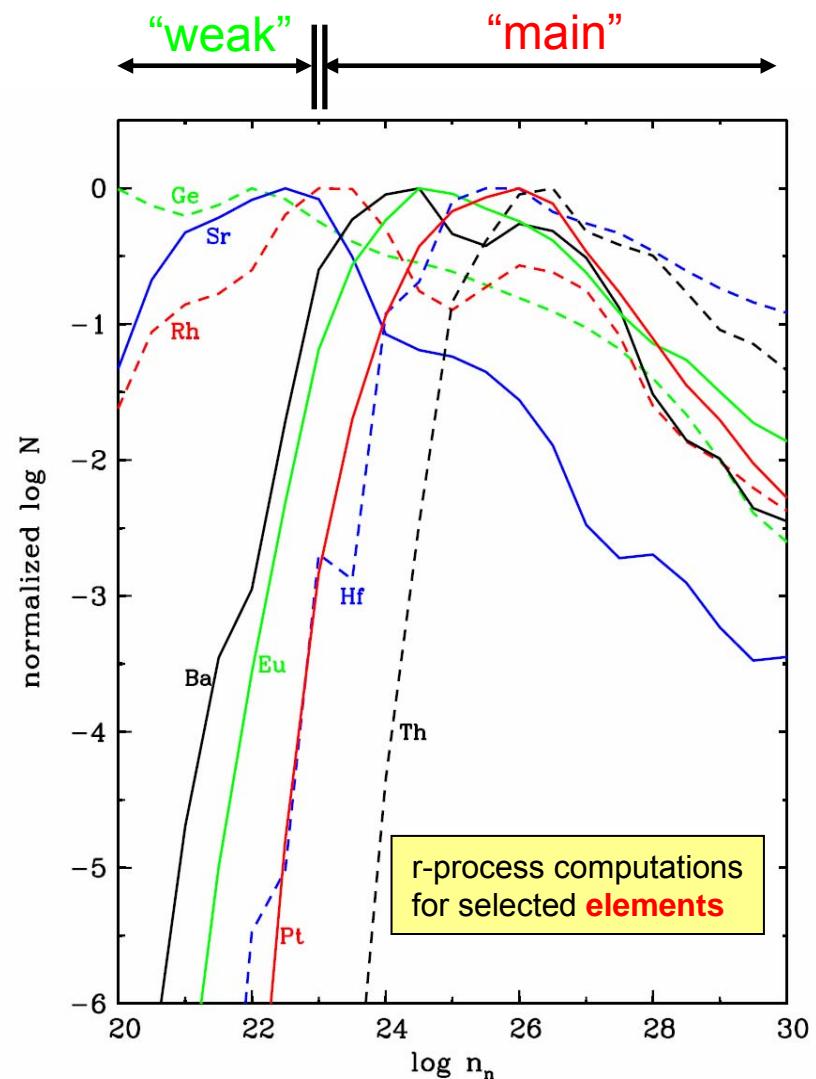
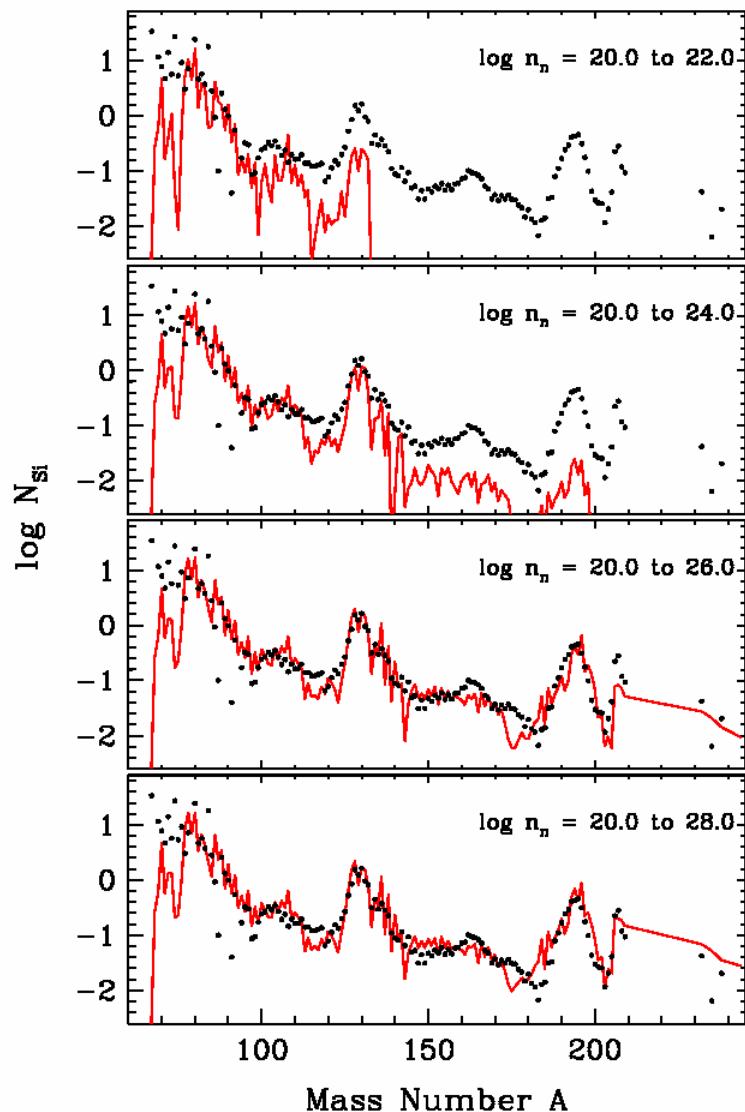
Kratz (2005)

Abundance clues and constraints

... based on „waiting-point“ model

- Observations versus calculations
 - solar system
 - UMP halo stars
- Conditions for „main“ and „weak“ r-process
- Split between the two r-processes
 - ^{129}I (Wasserburg et al.)
 - below N=82
- (Un-) importance of fission recycling
- Suggestions on r-process sites
- Galactic chemical evolution
- R-process chronometric pairs
 - Th/Eu, Th/U
 - new: Th/Hf
- Ages of UMP stars, Galaxy and Universe

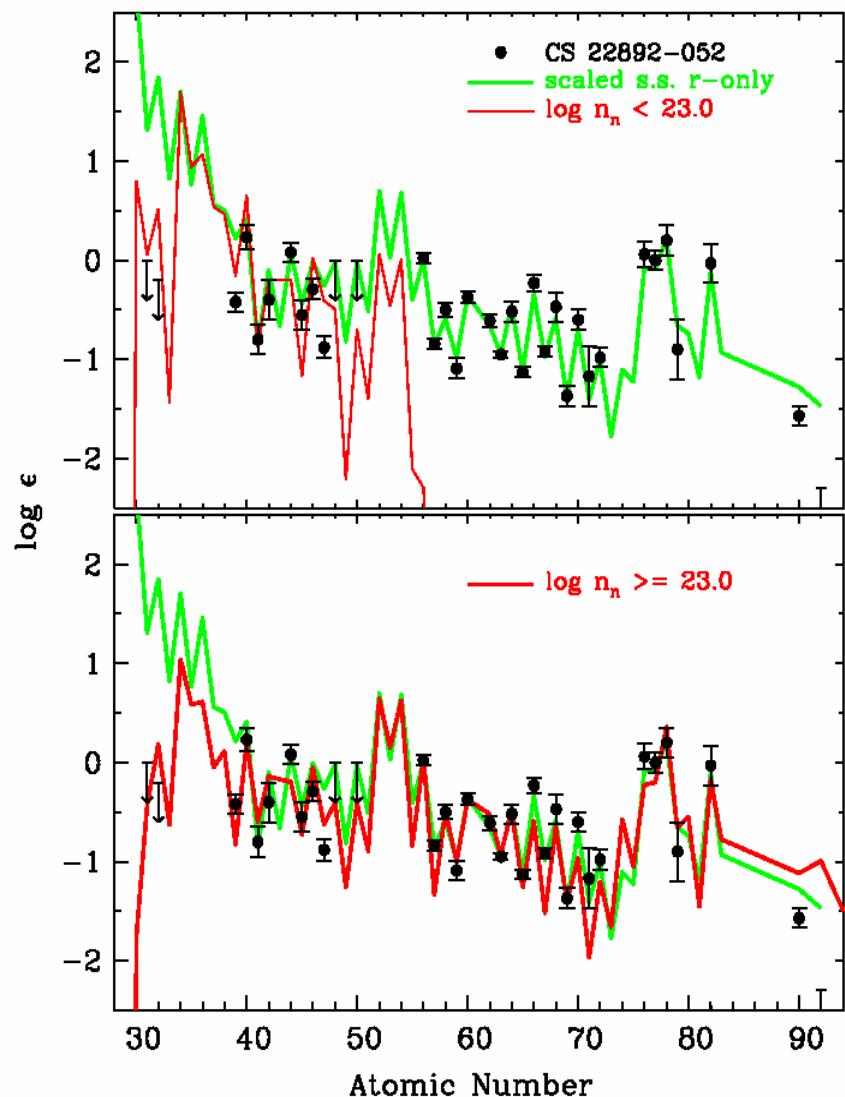
Calculated r-process abundances as function of neutron density



(K.-L. Kratz, B. Pfeiffer, 2005)

r-Process elemental abundances

... based on „waiting-point“ model



Conditions for

“weak” r-process

“main” r-process

Solar system Simmerer et al., 2004
CS 22892-052 Sneden et al., 2003
Calculations Pfeiffer & Kratz, 2005

From waiting-point to high-entropy wind model

SO FAR, site-independent parameter study
within **classical Waiting-Point Model**



understand effects of nuclear-physics input on $N_{r,\text{calc}}$

NOW, more realistic r-process model

High-Entropy Wind of SN II

“best” nuclear-physics input
full dynamical network

start with **α -process**

charged-particle freeze-out at $T_9 \approx 3$

→ n-rich seed beyond $N=50$ (^{94}Kr , ^{100}Sr)
for subsequent **r-process**
avoids $N=50$ “bottle neck” in classical model !

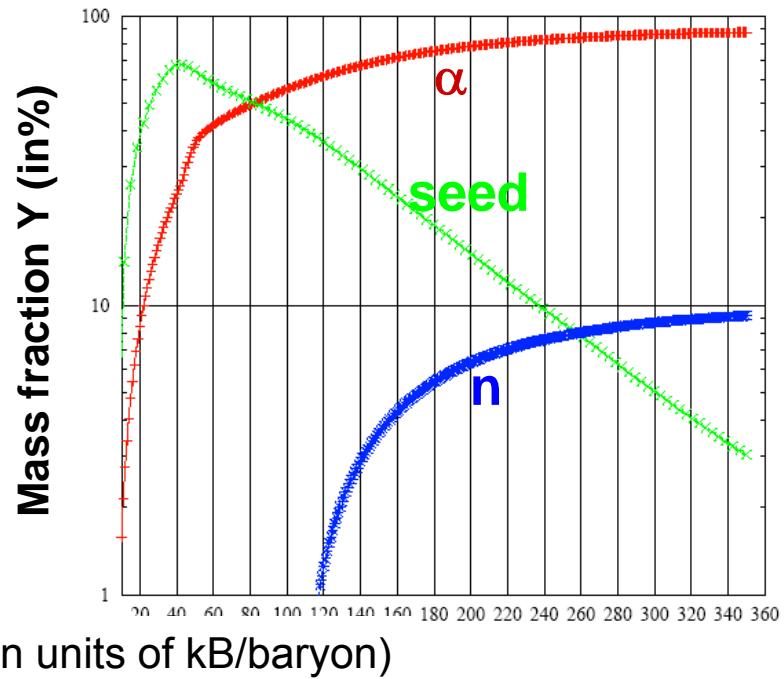
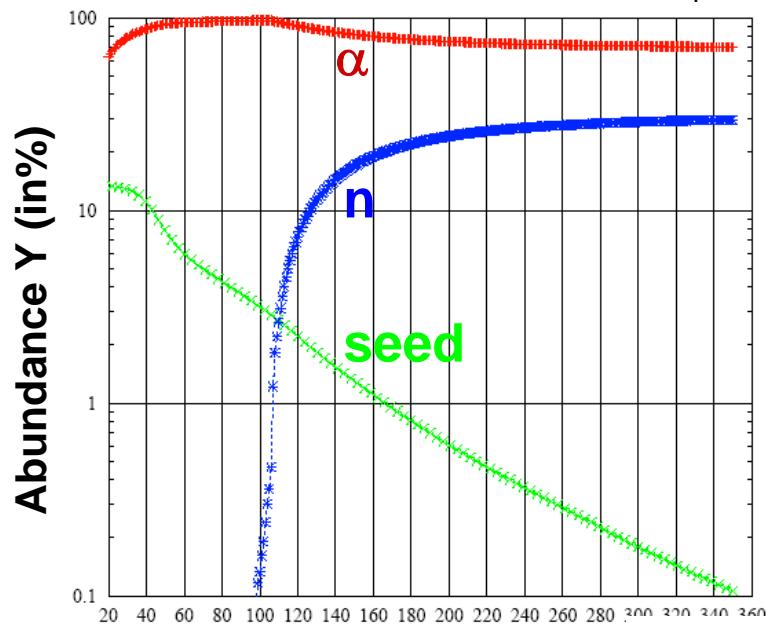
Three main parameters:

electron abundance
radiation entropy
expansion speed

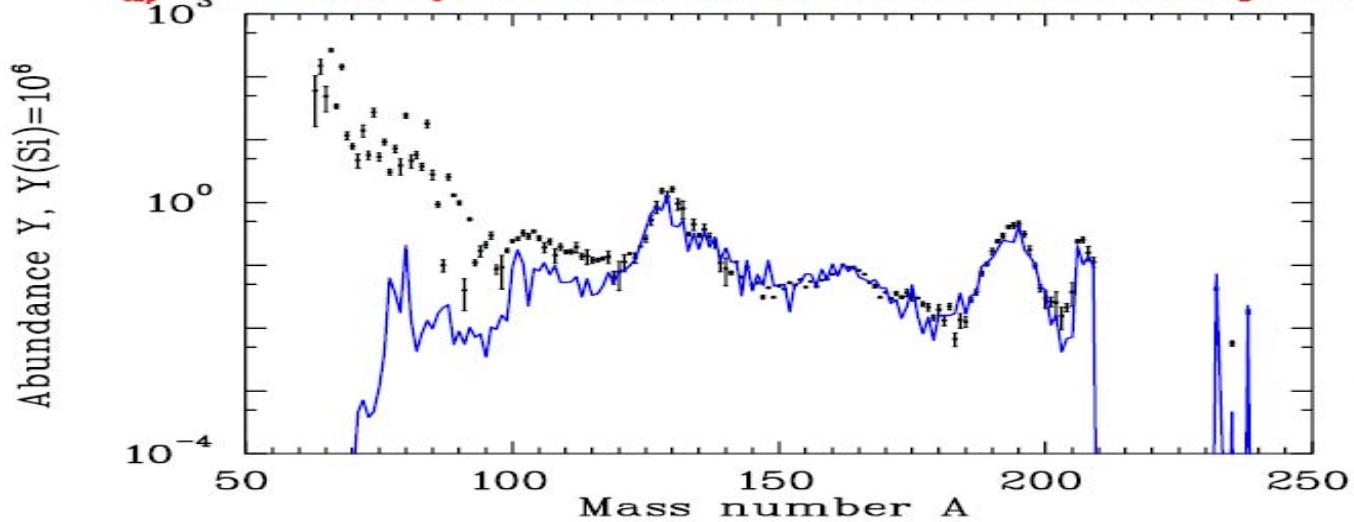
$$Y_e = Y_p = 1 - Y_n$$
$$S \sim T^3/\rho$$
$$v_{\text{exp}} \Rightarrow \text{process durations } \tau_\alpha \text{ and } \tau_r$$

Parameters high-entropy bubble

$V_{\text{exp}} = 7500 \text{ km/s}$ $Y_e = 0.45$



ETFSI-Q, NON-SMOKER rates, ADMC 2003, QRPA(GT+ff)
 $V_{\text{exp}} = 7500 \text{ Km/s}$, $Y_e = 0.45$ and 27 entropy sequences: $160 < S < 290 \text{ k}_B/\text{Baryon}$

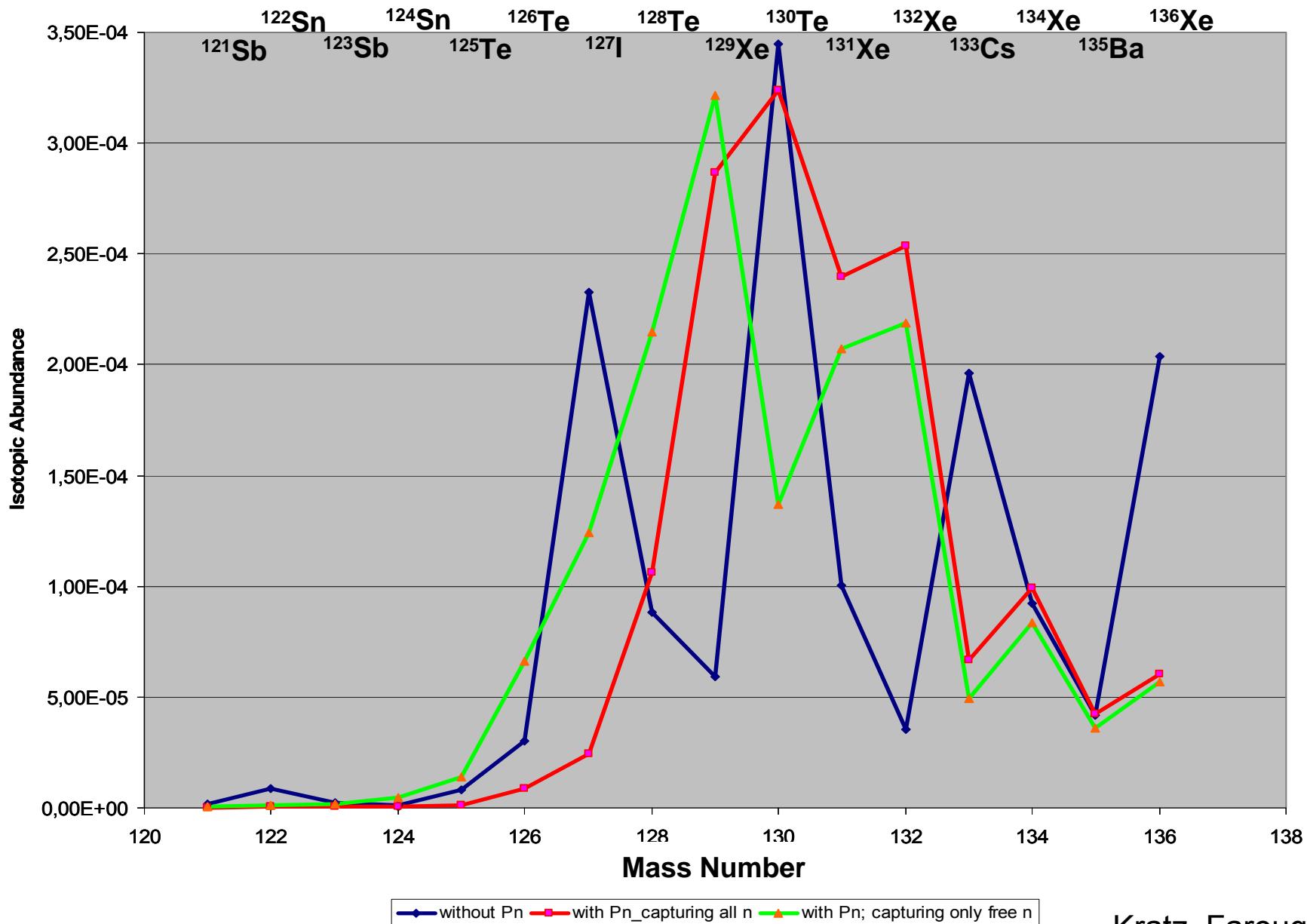


No fit of $N_{r.o}!$

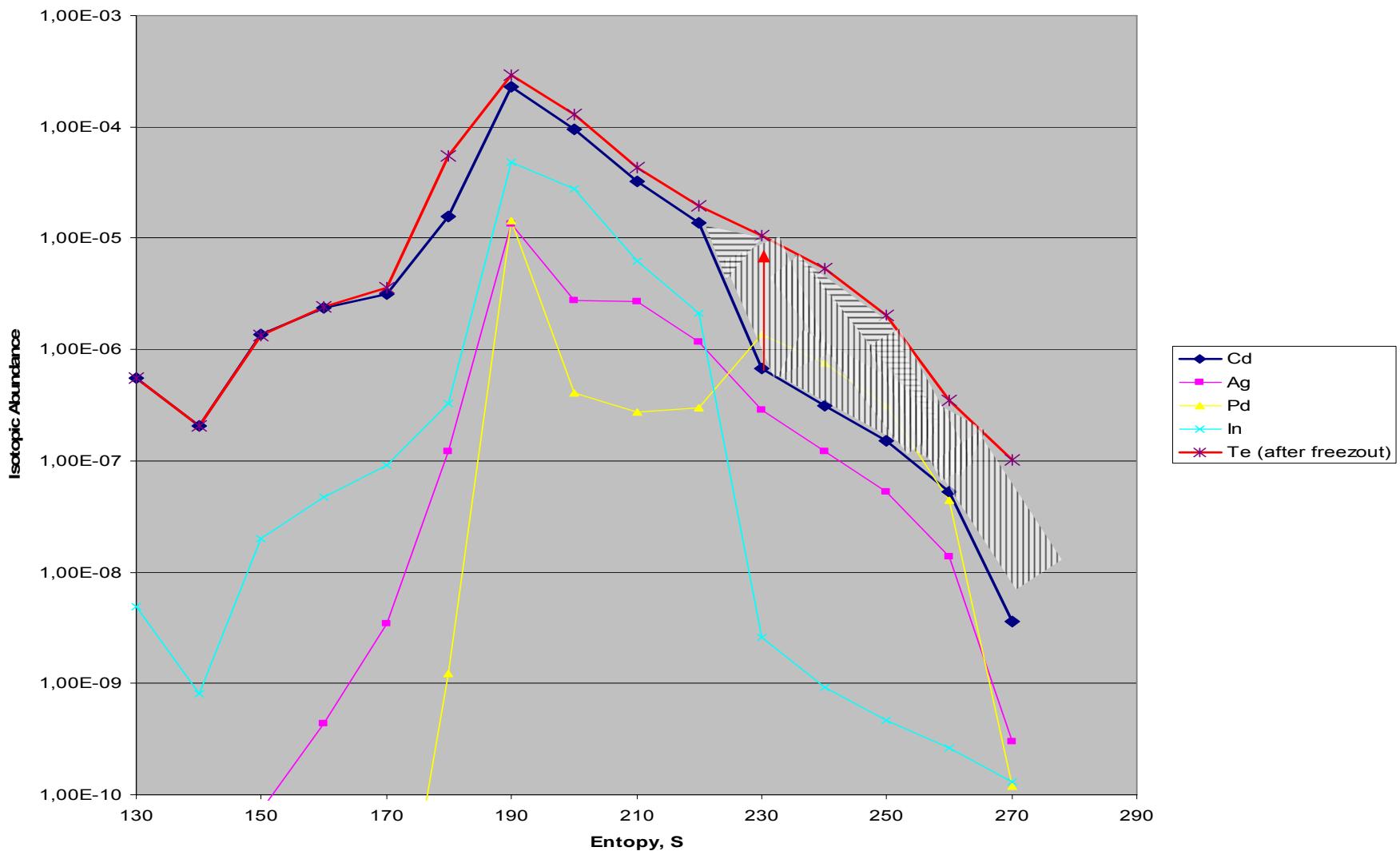
(Farouqi, Kratz, Thielemann
to be subm. to Ap. J., 2007)

P_n – effects at A=130 peak

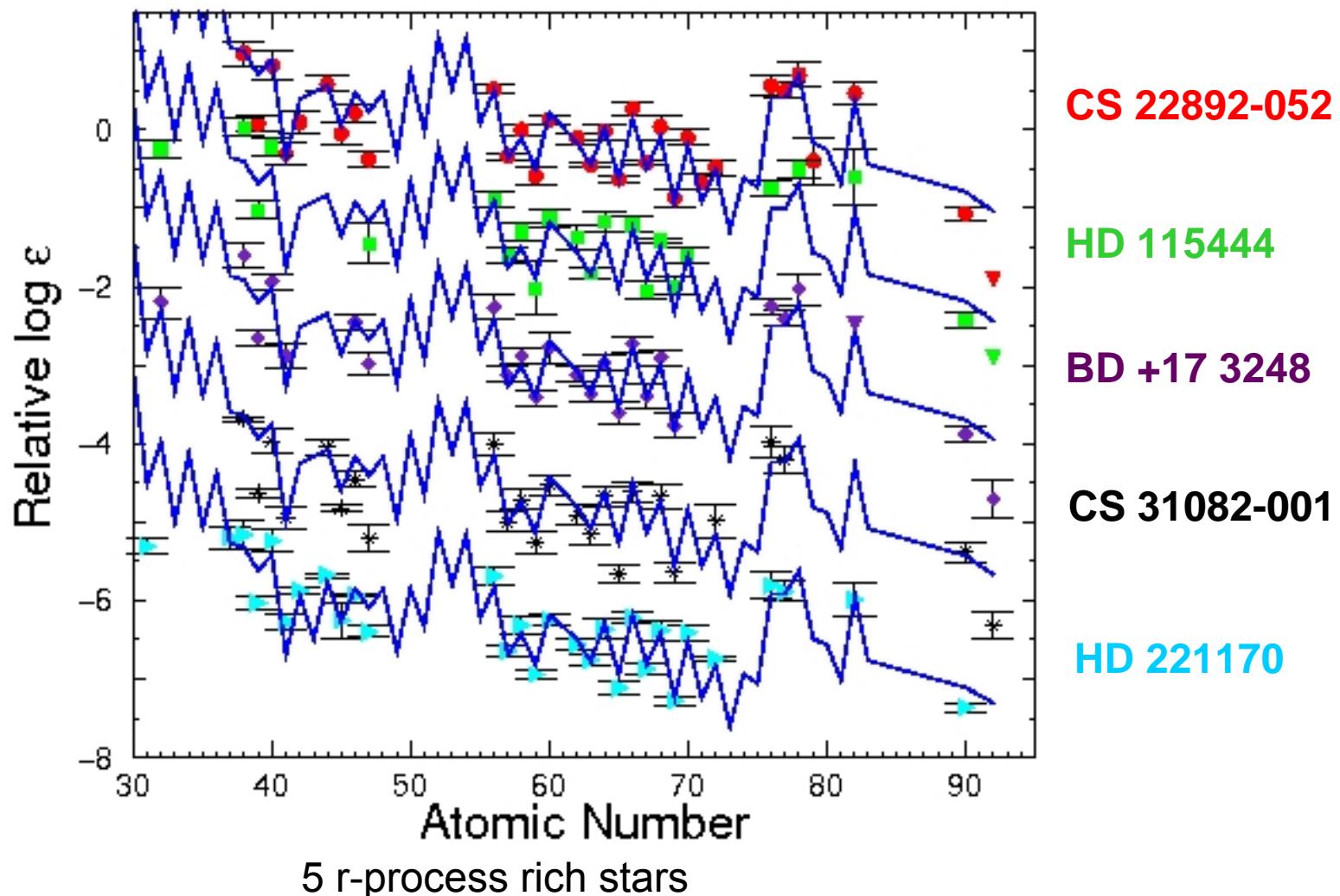
Isotopic Abundance in the A=130 Area



Isotopic abundance at A=130

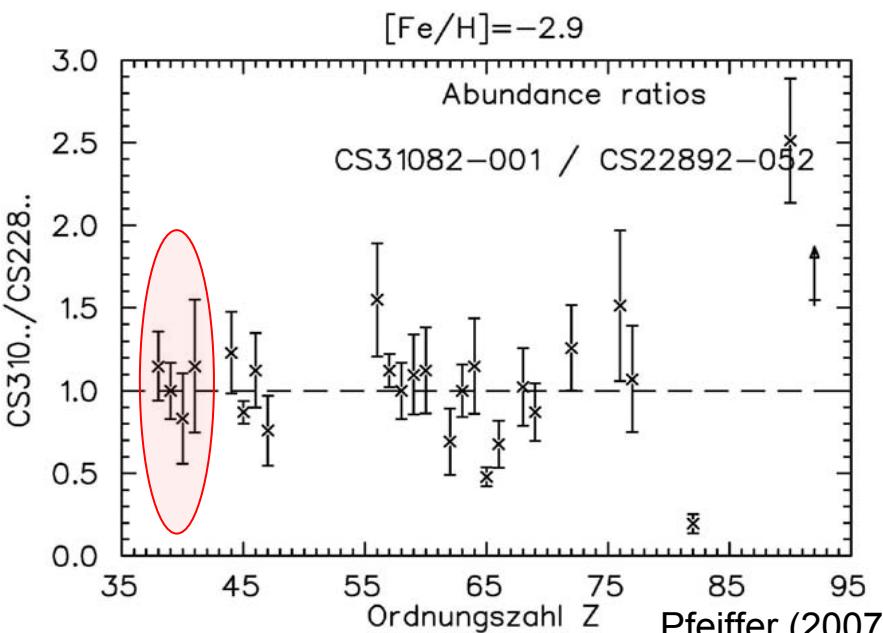
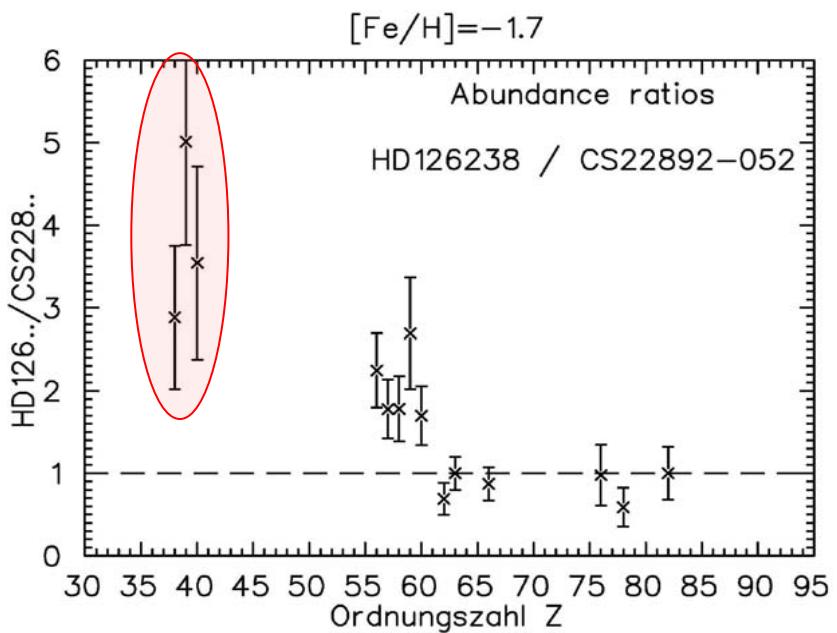
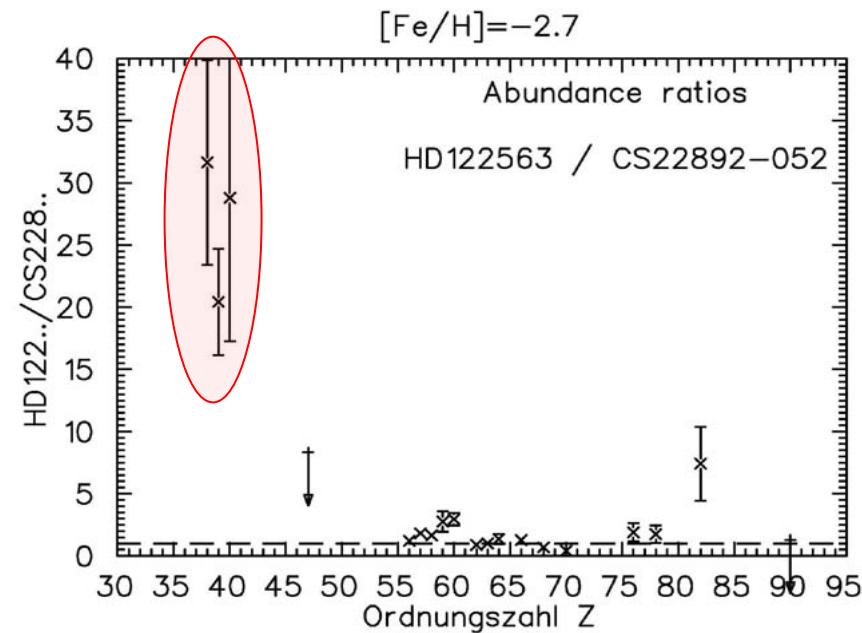
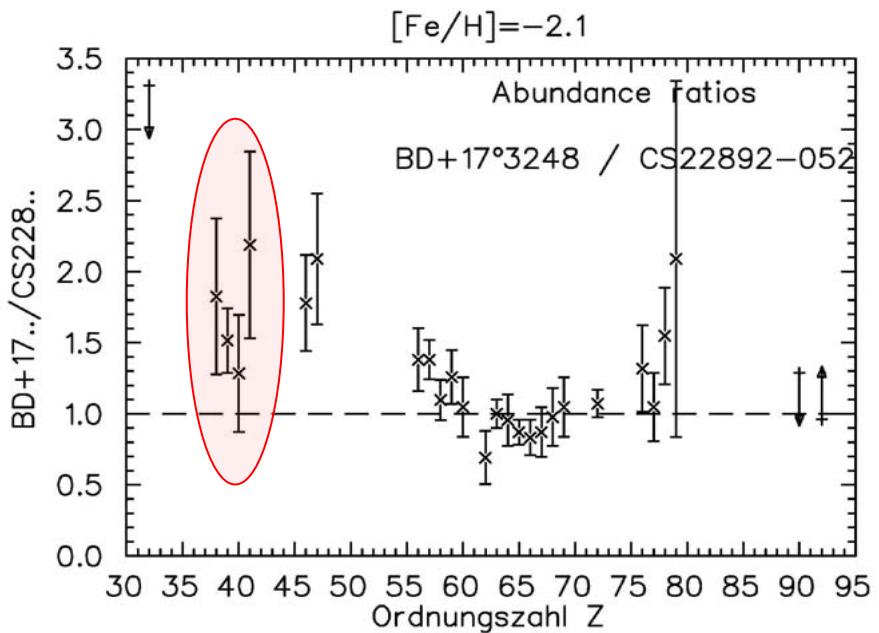


Observational summary of total abundances



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

Halo star abundance ratios rel. to „Sneden-star“



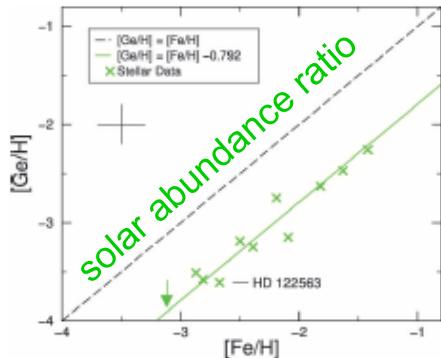
Correlation / uncorrelation Ge, Zr with Eu

The Ap.J., 627 (2005)

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

JOHN J. COWAN,¹ CHRISTOPHER SNEDDEN,² TIMOTHY C. BEERS,³ JAMES E. LAWLER,⁴ JENNIFER SIMMERER,² JAMES W. TRUHAN,³ FRANCESCA PRIMAS,⁶ JASON COLLIER,¹ AND SCOTT BURLES⁷

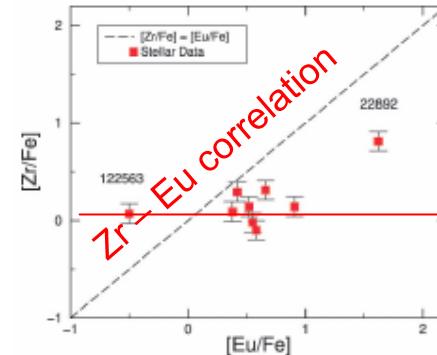
Received 2004 September 8; accepted 2005 February 24



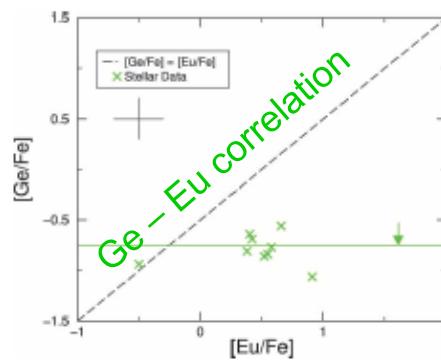
Relative abundances [Ge/H] displayed as a function [Fe/H] metallicity for our sample of 11 Galactic halo stars. The arrow represents the derived upper limit for CS 22892-052. The dashed line indicates the solar abundance ratio of these elements: [Ge/H] = [Fe/H], while the solid green line shows the derived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

“Ge abundance seen completely uncorrelated with Eu”



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



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.

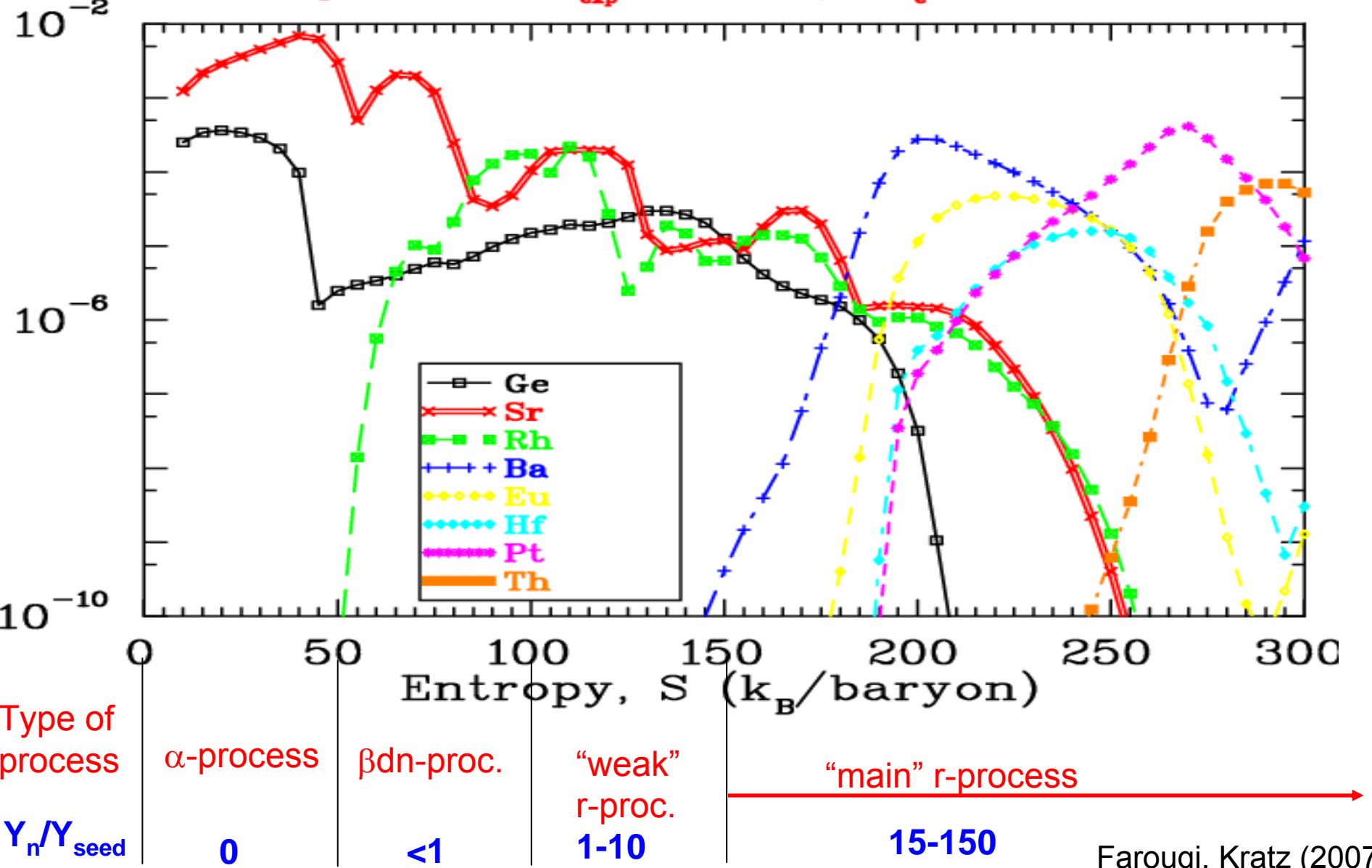
Can our HEW model explain observations ?

“The Zr abundances also do not vary cleanly with Eu abundances, indicating a synthesis origin different than that of heavier neutron-capture elements.”

Calculated r-process abundances as function of entropy

ETFSI-Q, NON-SMOKER rates, ADMC 2003, QRPA(GT+ff)

Hot bubble parameters: $V_{\text{exp}} = 7500 \text{ km/s}$, $Y_e = 0.45$ and $10 \leq S \leq 300$



Relative elemental abundances Y(Z)

| ELEMENT | Y(Z) as fct. of entropy S | | | | |
|------------------|---------------------------|--------------|---------------|---------------------|---------------|
| | 10 ≤ S ≤ 50 | 50 ≤ S ≤ 100 | 100 ≤ S ≤ 150 | 150 ≤ S ≤ 200 | 200 ≤ S ≤ 250 |
| ^{29}Cu | 100% | 0.1% | -- | -- | -- |
| ^{30}Zn | 99.2% | 0.4% | 0.4% | $6 \cdot 10^{-3}\%$ | -- |
| ^{32}Ge | 85% | 3.2% | 11% | 1.2% | -- |
| ^{38}Sr | 80% | 18% | 2.3% | 0.3% | 0.01% |
| ^{39}Y | 61% | 37% | 1.3% | 0.3% | 0.02% |
| ^{40}Zr | 22% | 67% | 11% | 0.35% | 0.01% |
| ^{41}Nb | 0.08% | 88% | 10% | 1.3% | 0.03% |
| ^{42}Mo | 0.7% | 44% | 53% | 2.7% | 0.05% |

α -process

n-rich α -freezeout

βdn -recapt.

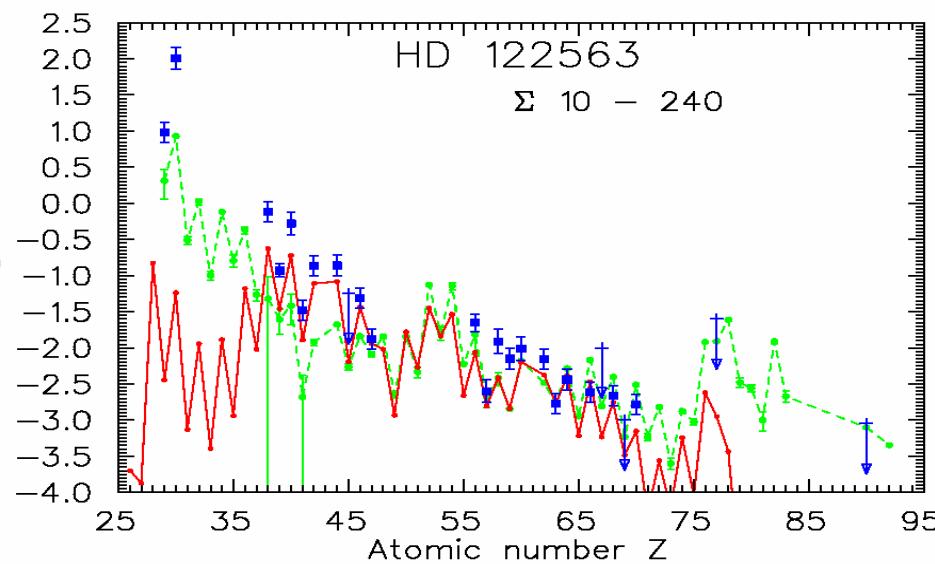
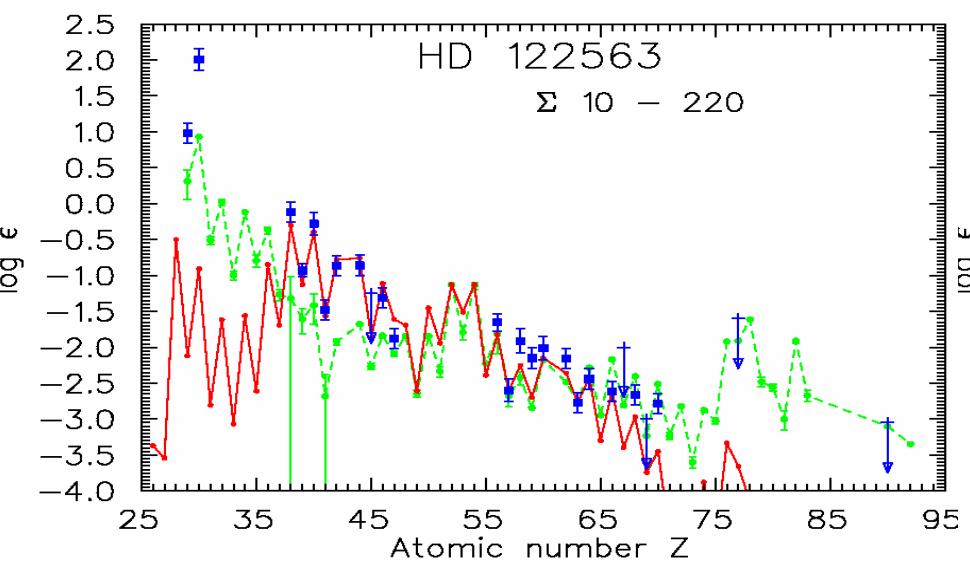
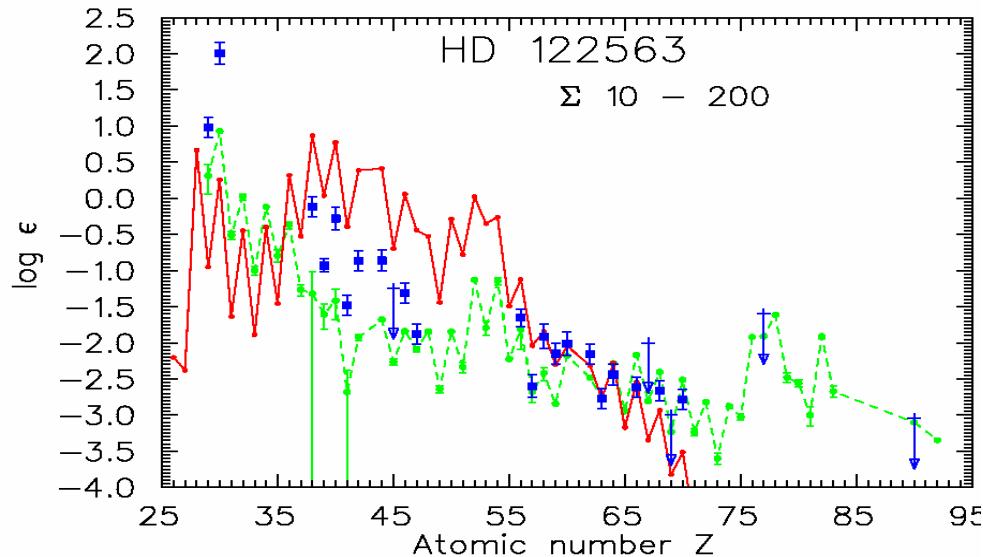
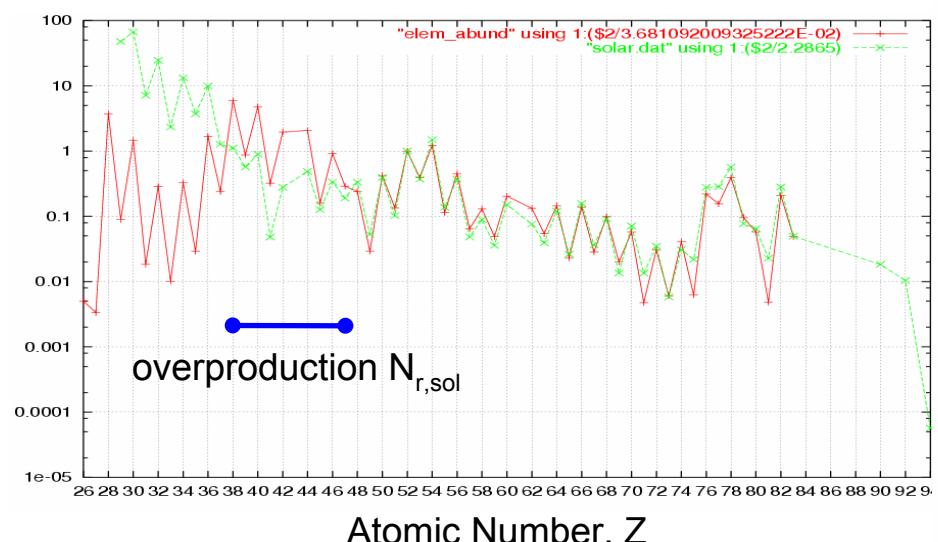
weak comp. main comp. r-process

uncorrelated with Eu

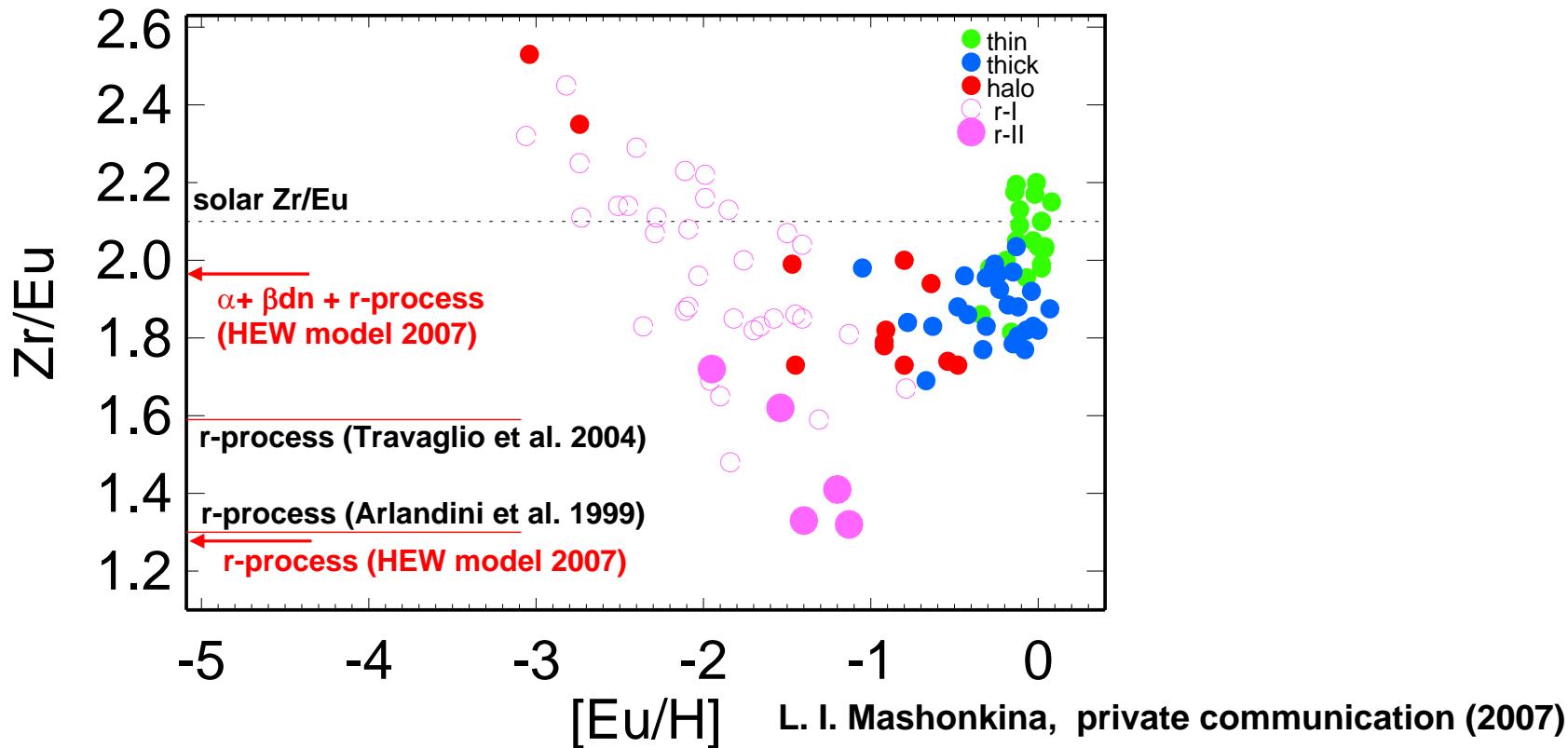
correlated with Eu

Kratz, Farouqi
(2007)

Elemental abundances: observations vs. calculations



Abundance ratio Zr/Eu as a fct. of [Eu/H]



- Prediction of HEW pure r-process agrees with Arlandini et al. „r-residuals“.
- Prediction of Travaglio et al. represents the contributions of the r-residuals + an additional primary process (LEPP), as observed in CS 22892-052.
- Prediction of total HEW ($\alpha + \beta dn + r$) represents the maximum Zr/Eu ratio, as observed in HD 122563.



N_{r,∞} in the Zr-region is a „mixture“ of different LEPP fractions per SN

Summary

➤ The site-independent „**waiting-point model**“ has been a useful working-horse until **yesterday**.

➤ **Today**

- within the „**HEW SNII scenarios**“, the full production of the $N_{r,\odot}$ distribution is possible within 500ms and $S_{\max} \approx 280 \text{ k}_B/\text{Baryon}$;
- under these conditions, **fission recycling** is of minor importance;
- the mass split between „**weak**“ and „**main**“ r-process occurs below the $N=82$, $A \approx 130$ $N_{r,\odot}$ peak;
- the HEW model quantitatively predicts all UMP halo-star observations;
- the solar „r-residuals“ are a superposition of 4 distinct nucleosynthesis components;
- the two low-S components (α and βdn) are **not tightly correlated** with the „**main**“ r-process.

➤ **Tomorrow**,

coupling of the (still parameterized) HEW network to **hydrodynamical SNII** model calculations.

Main collaborators:

K. Farouqi (Mainz/Chicago)
B. Pfeiffer (Mainz)
F.-K. Thielemann (Basel)
P. Möller (Los Alamos)
H.L. Ravn (CERN)
W.B. Walters (Maryland)



J.J. Cowan (Oklahoma)
C. Sneden (Austin, Texas)
J.W. Truran (Chicago & Argonne)
I. Ivans (Caltech)
N. Christlieb (Hamburg/Uppsala)
L.I. Mashonkina (Moscow)