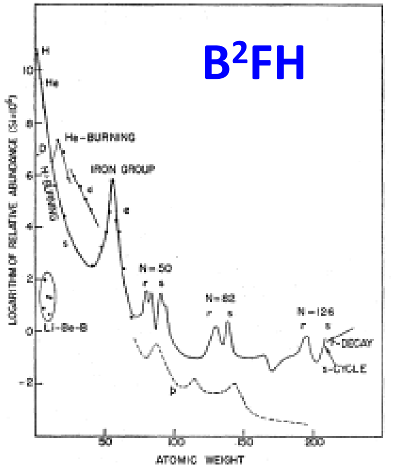
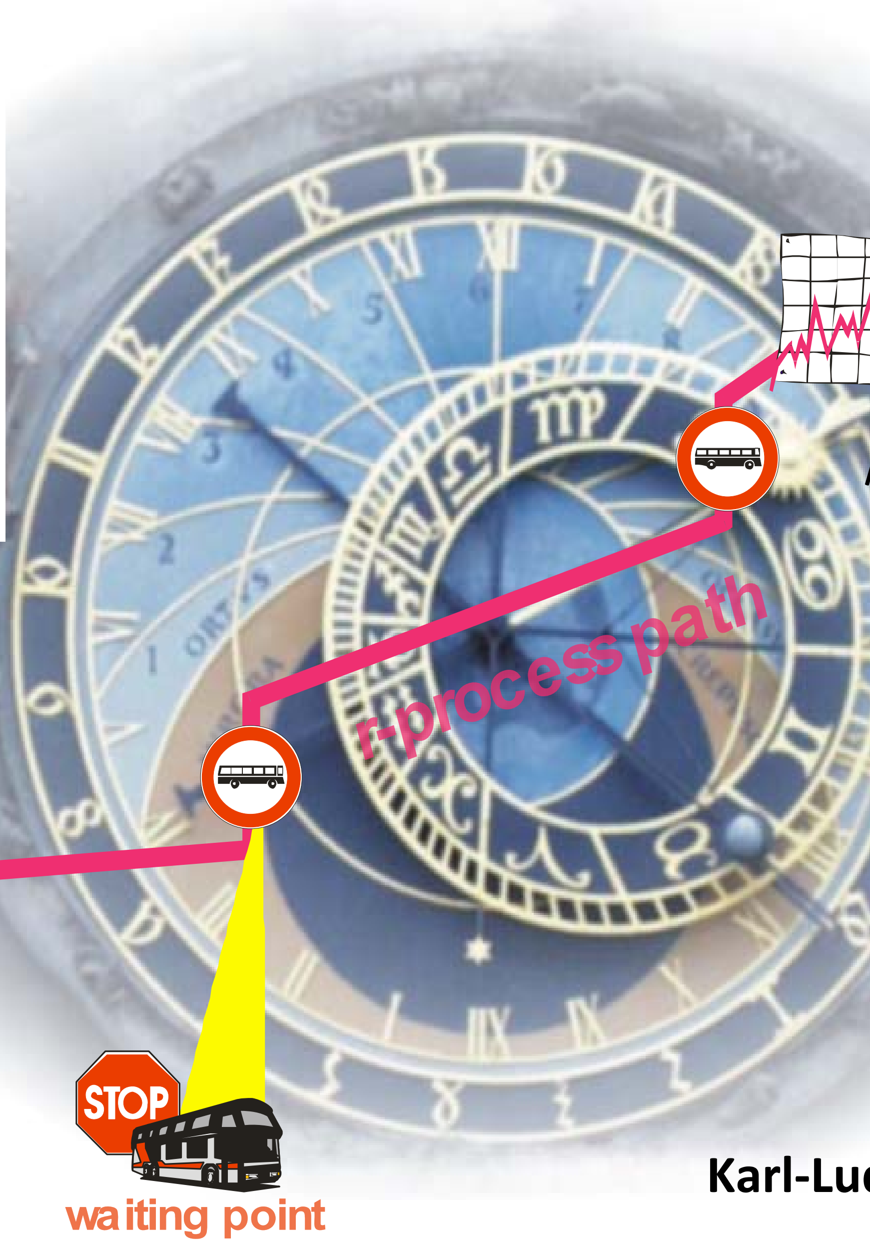
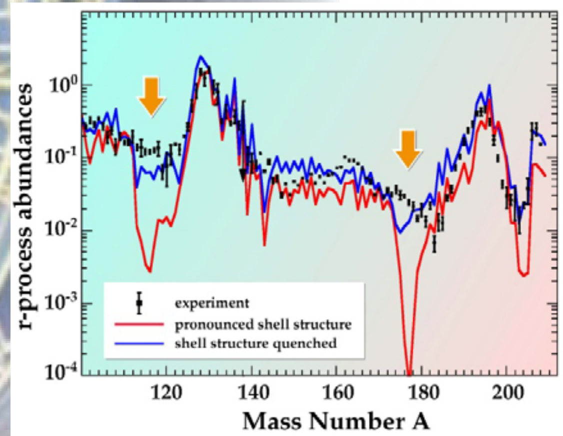
Introduction to the r-process







Karl-Ludwig Kratz

MAX-PLANCK-GESELLSCHAFT

MAX-PLANCK-INSTITUT FÜR CHEMIE

Santa Tecla, 2011

History of nucleosynthesis – where to start?

Heidelberg, main street 59

Nucleosynthesis around 1900

…the early

Cauldrons in the Cosmos

… a potent witches' chemical brew…..

"Alchemy"

Some early milestones

1932 discovery of the previously unknown **neutron** by Chadwick

1937 first systematic tabulation of solar abundances by Goldschmidt

1937 – 39 pp chain and CNO cycle identified as stellar energy sources by Bethe & Critchfield and by von Weizsäcker

1957 fundamental paper on nucleosynthesis by Burbidge, Burbidge, Fowler & Hoyle **(B^2FH)** Rev. Mod. Phys. **29**, 547 (1957)

B²FH, the „bible“ of nuclear astrophysics

Historically,
nuclear astrophysics has always been concerned with

- **interpretation of the origin of the chemical elements from astrophysical and cosmochemical observations,**
- **description in terms of specific nucleosynthesis processes.**

...54 years ago:

REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

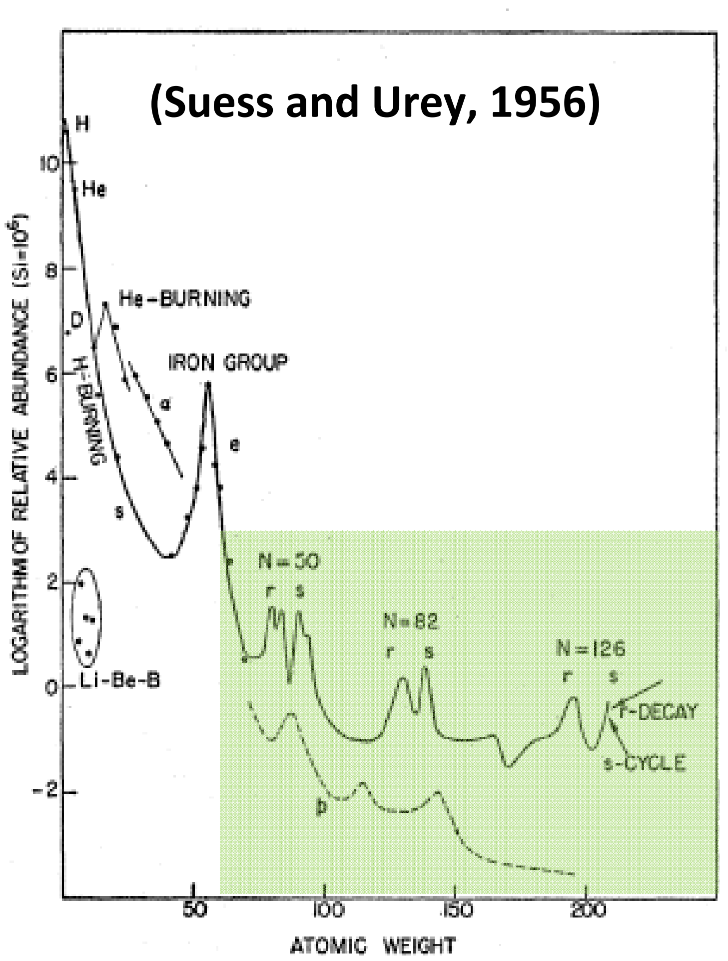
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Solar abundance observables at B²FH (1957)



neutrons

„…it appears that in order to explain all the features of the abundance curve, at least eight different types of synthesizing processes are demanded…“

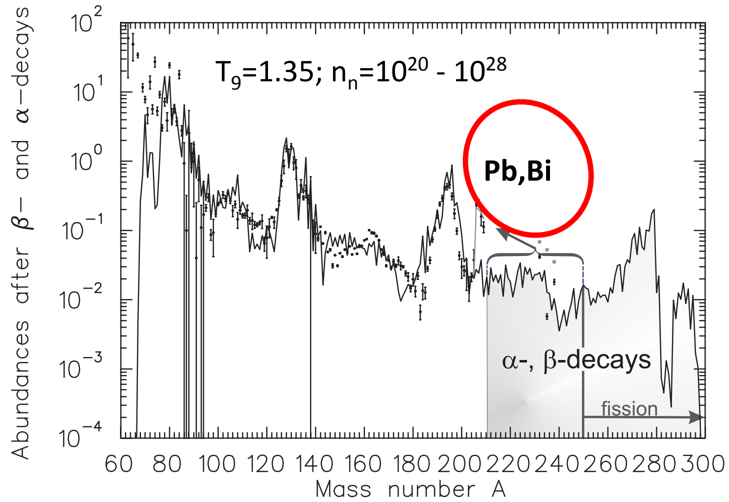
1. H-burning
2. He-burning
3. α-process
4. e-process
5. s-process
6. **r-process**
7. p-process
8. x-process

r-Process observables today

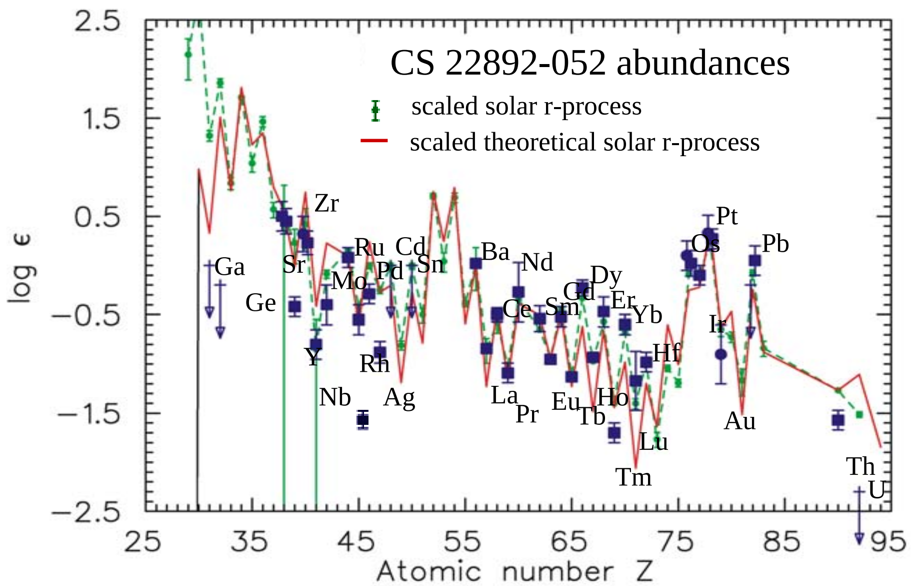
Observational instrumentation

- 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*

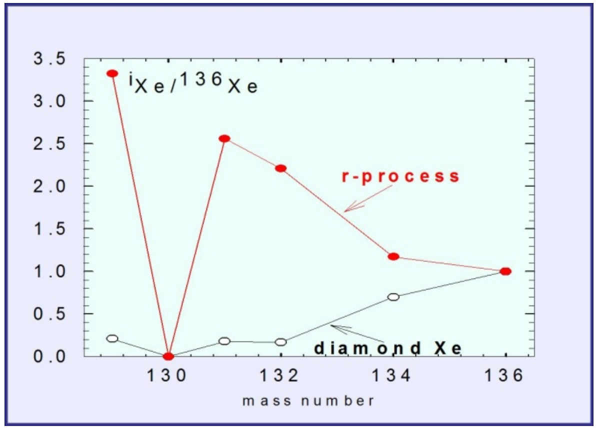
Solar system isotopic $N_{r,\odot}$ "residuals"



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

Neutron-capture paths for the s- and r-processes

Neutrons produce ≈75% of the stable isotopes,
but only 0.005% of the total SS abundances….

s- and r-abundances today about equal

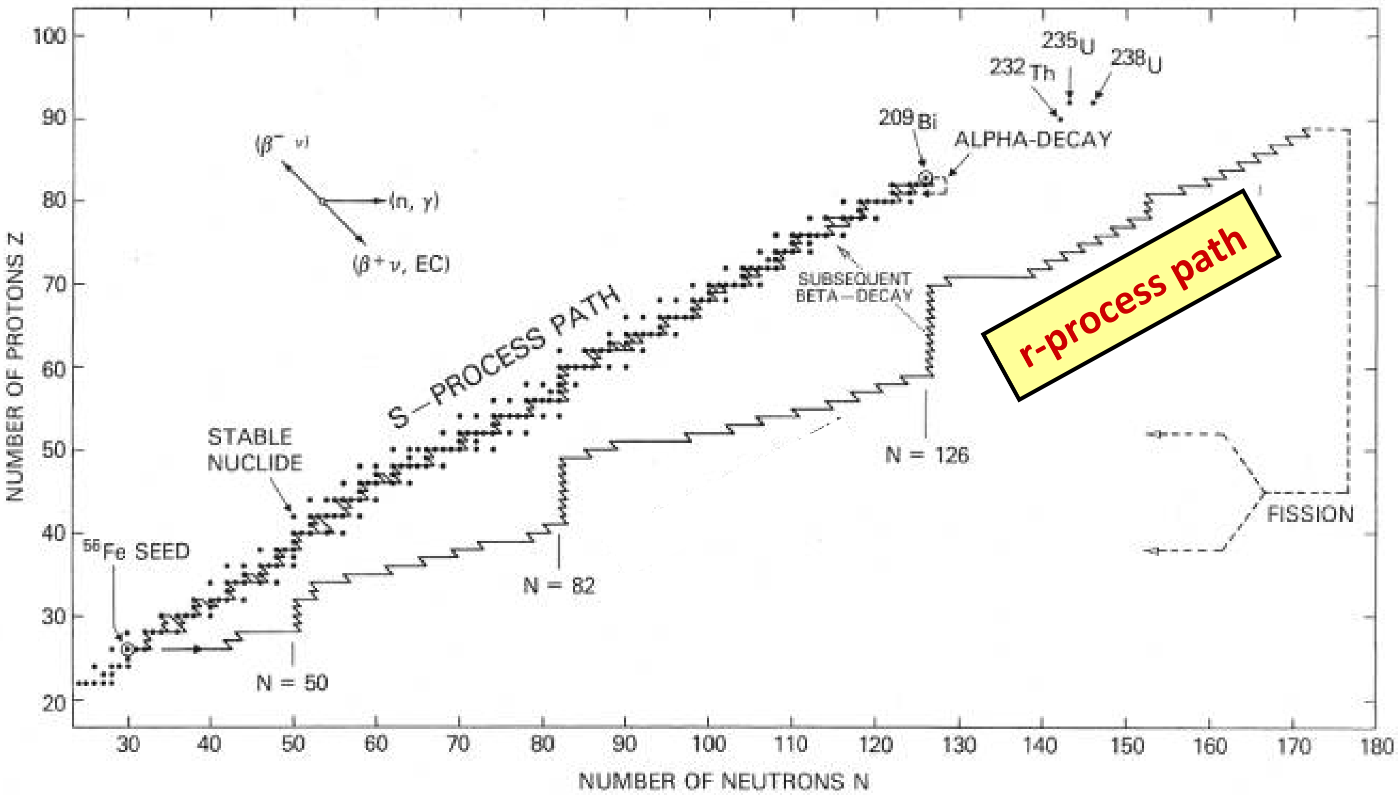
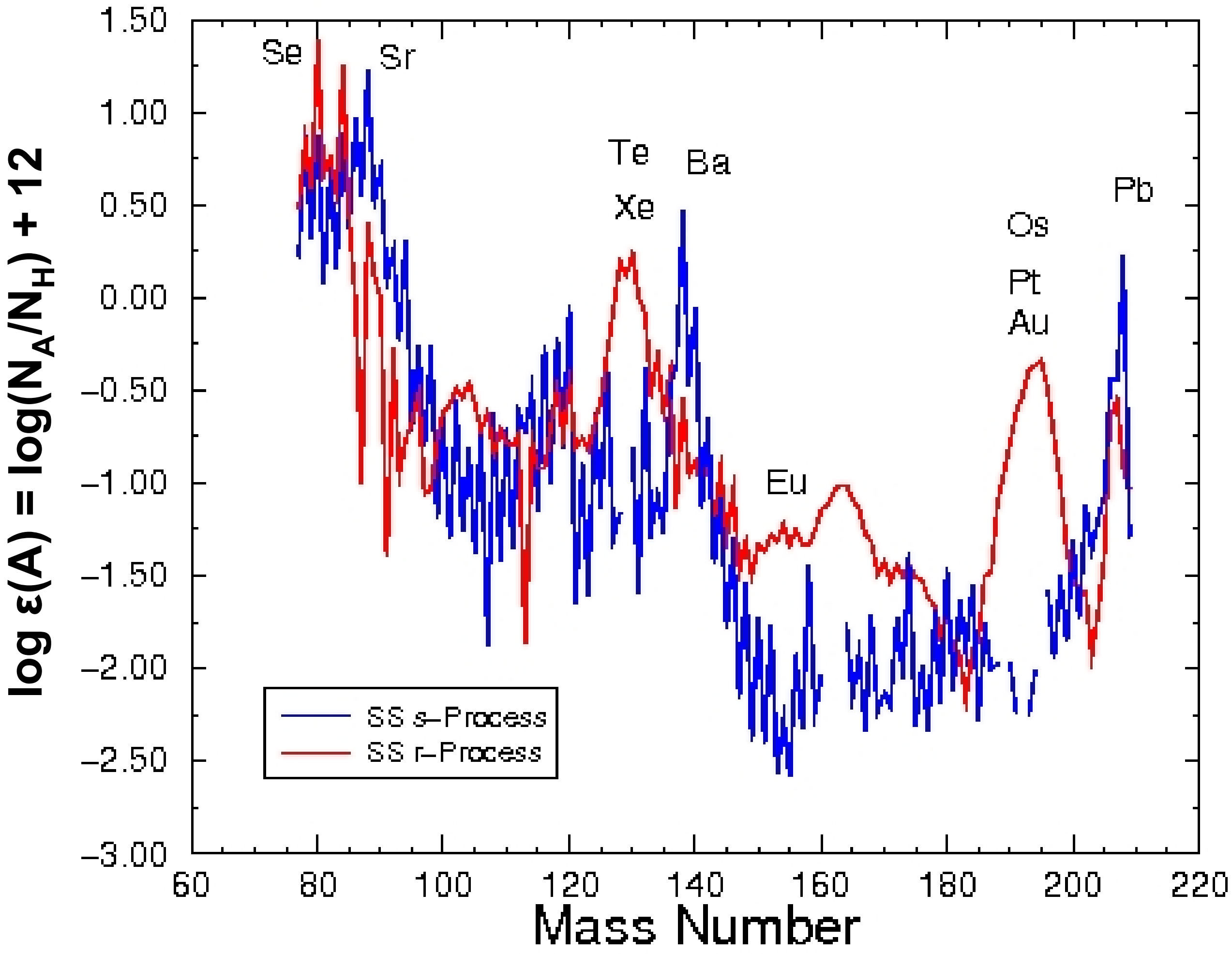


FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the (*N*, *Z*)-plane. Both paths start with the iron-peak nuclei as seeds (mainly ^{56}Fe). The *s*-process follows a path along the stability line and terminates finally above ^{209}Bi via α-decay (Cla67). The *r*-process drives the nuclear matter far to the neutron-rich side of the stability line, and the neutron capture flows upward in the (*N*, *Z*)-plane until β-delayed fission and neutron-induced fission occur (Thi83). The *r*-process path shown was computed (See65) for the conditions $T_9 = 1.0$ and $N_n = 10^{24}$ neutrons cm^{-3}.

H	**30,000**
C	**10**
Fe	**1**
Au	**$2\cdot10^{-7}$**

(from **"Cauldrons in the Cosmos"**)

Deconvolution SS isotopic abundances



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

r-process "residuals":
subtract N_s from SS

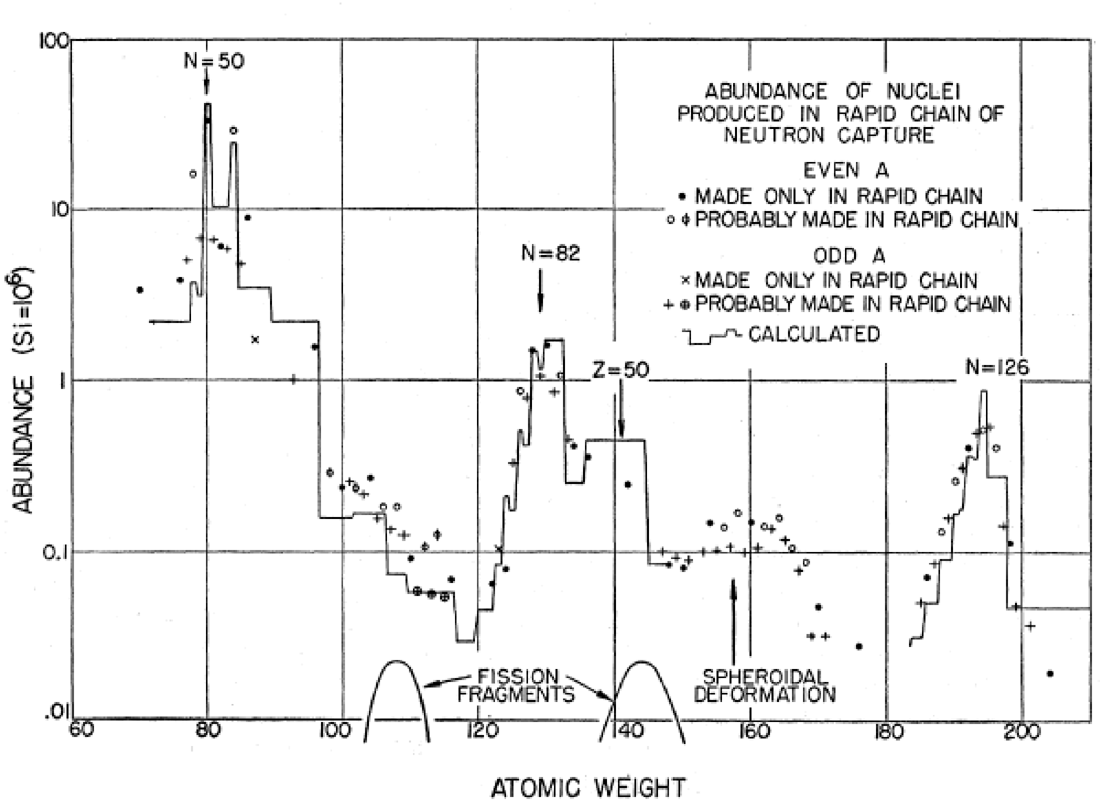
$N_{r,\odot} = N_\odot - N_s$

Still valid today?

Fit of $N_{r,\odot}$ from B^2FH

Reproduction of Solar system
isotopic r-process abundances

(mainly from **r-only** nuclei)



„Static“ calculation

- **assumptions**
  - **iron seed** (secondary process)
  - **„waiting-point“ concept**
    (global (n,γ) ↔ (γ,n) and
    ß-flow equilibrium)
  - **instantaneous freezeout**

The "waiting-point"concept in astrophysics (1)

Concept already used by B²FH

to explain the SS-r abundances $N_{r,\odot}$

assumes equilibrium between (n, γ)- and (γ,n)-reactions

in all isotopic chains; not only at N_{magic}

↷ much easier to handle than full reaction network

Rate of n-captures:

$$r_{n,\gamma}(A,Z) = \langle \sigma_{n,\gamma} v \rangle \, n_n \, N(A,Z) \quad (1)$$

cross section averaged over Maxwell-Boltzmann velocity distribution to T_9

Photodisintegration:

$$r_{\gamma,n}(A+1,Z) = \frac{G(A,Z)G_n}{G(A+1,Z)} \left(\frac{A}{A+1}\right)^{3/2} \left(\frac{2\pi kTm_u}{h^2}\right)^{3/2} \langle \sigma_{n,\gamma} v \rangle \; N(A+1,Z)\, e^{-S_n/kT} \quad (2)$$

(n, γ)-(γ,n) equilibrium ↷ combine (1) and (2) :

$$\frac{N(A+1,Z)}{N(A,Z)} = n_n \frac{G(A+1,Z)}{2G(A,Z)} \left(\frac{A+1}{A}\right)^{3/2} \left(\frac{h^2}{2\pi kTm_u}\right)^{3/2} e^{S_n/kT}$$

Nuclear Saha equation

The "waiting-point"concept in astrophysics (2)

Nuclear Saha equation:

simplified $$\frac{N(A+1,Z)}{N(A,Z)} \propto n_n \exp\left\{{S_n}/{kT}\right\}$$

- high n_n ↷ "waiting-point" shifted to higher masses
- low S_n ↷ "waiting-point" shifted to lower masses
- low T ↷ "waiting-point" shifted to higher masses

Equilibrium-flow along r-process path:

$$\dot{N}(Z) = \sum_A \left\{\frac{N(Z-1,A)}{\tau_\beta(Z-1,A)} - \frac{N(Z,A)}{\tau_\beta(Z,A)}\right\} = 0 ;$$

- governed by b-decays from isotopic chain Z to (Z+1)

↷ ***β-decay flow equilibrium***

implies (n,γ)-(γ,n) equilibrium

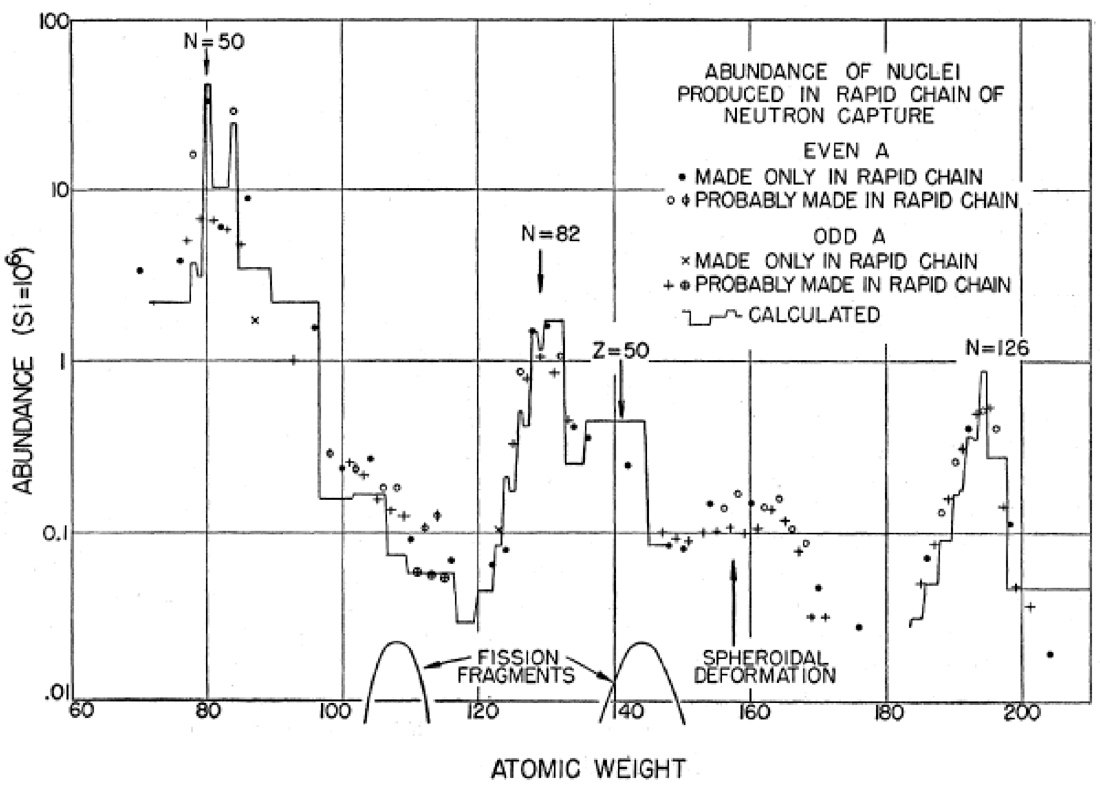
$$\tau_\beta > \tau_{n,\gamma}, \tau_{\gamma,n}$$

$T_{1/2}$("w.-p.") ↔ $N_{r,\odot}$

Fit of $N_{r,\odot}$ from B^2FH

Reproduction of Solar system
isotopic r-process abundances

(mainly from **r-only** nuclei)



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- **astrophysical conditions**
  - **explosive He-burning in SN-I**
  - $T_9 \approx 1$ (constant)
  - $n_n \approx 10^{24}\ cm^{-3}$ (constant)
  - $\tau_r \approx 100$ s

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

Seeger, Fowler & Clayton, ApJ 98 (1965)

Speculations about r-process scenario:

- SN-I (as in B^2FH) unlikely
- Explosion of massive stars $M > 10^4\ M_\odot$
- Conventional SNe

Speculations about various r-process components:

"short-time" solution

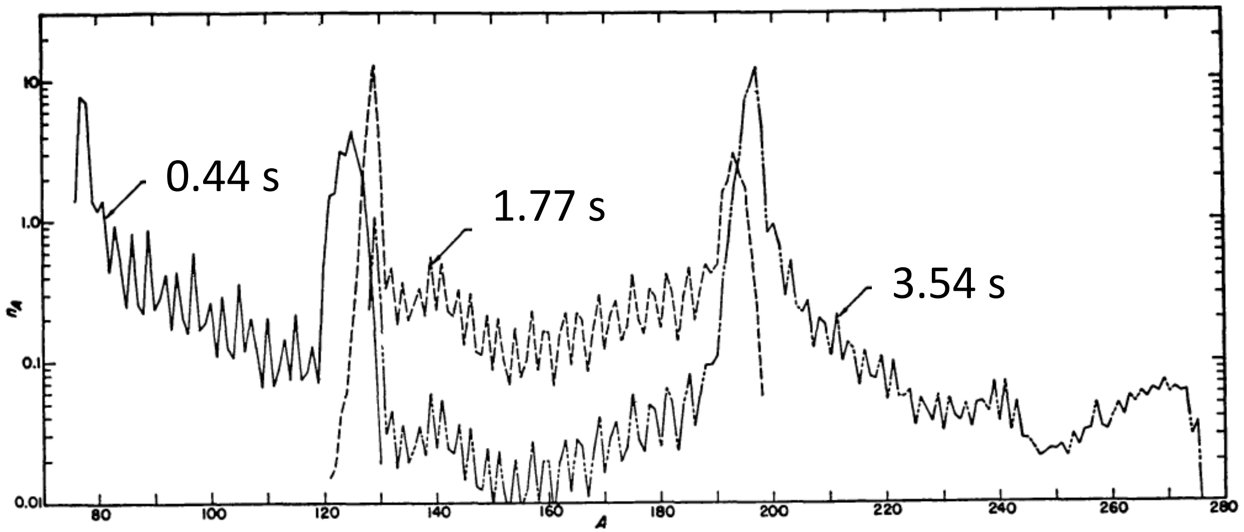


FIG. 12

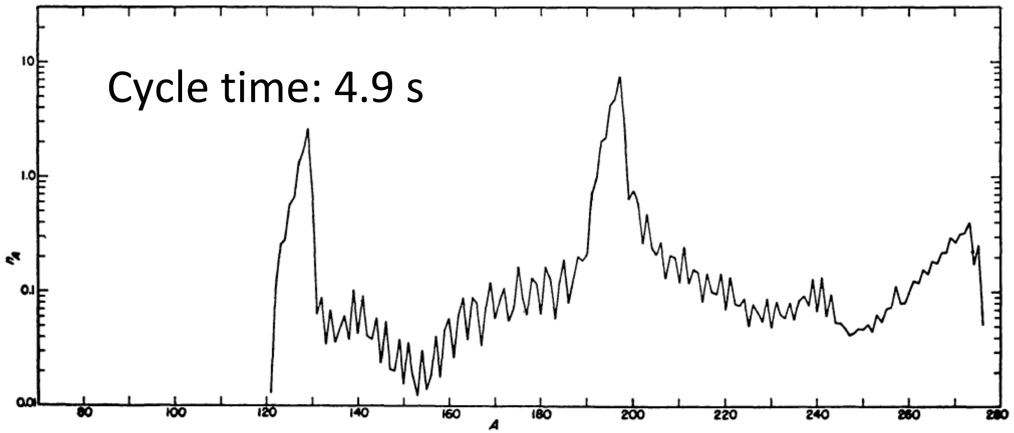


FIG. 13

"long-time" solution

…however, all components with the same neutron-density of 10^{24} n/cm^3 !

r-Process scenarios since B^2FH

For long time suspect, that puzzle of r-process **site**
is closely intertwined with puzzle of **SN explosion mechanism**
(see e.g. Reviews by Hillebrandt 1978; Meyer & Brown 1997)

…original papers **"core-collapse SN"**, e.g. Bethe & Wilson (1985); Mayle & Wilson (1988, 1991);
…first papers **"neutrino-driven winds"**, e.g. Duncan, Shapiro & Wasserman (1986);
Woosley & Hoffman(1992); Takahashi, Witti & Janka (1994).

…other suggested scenarios:

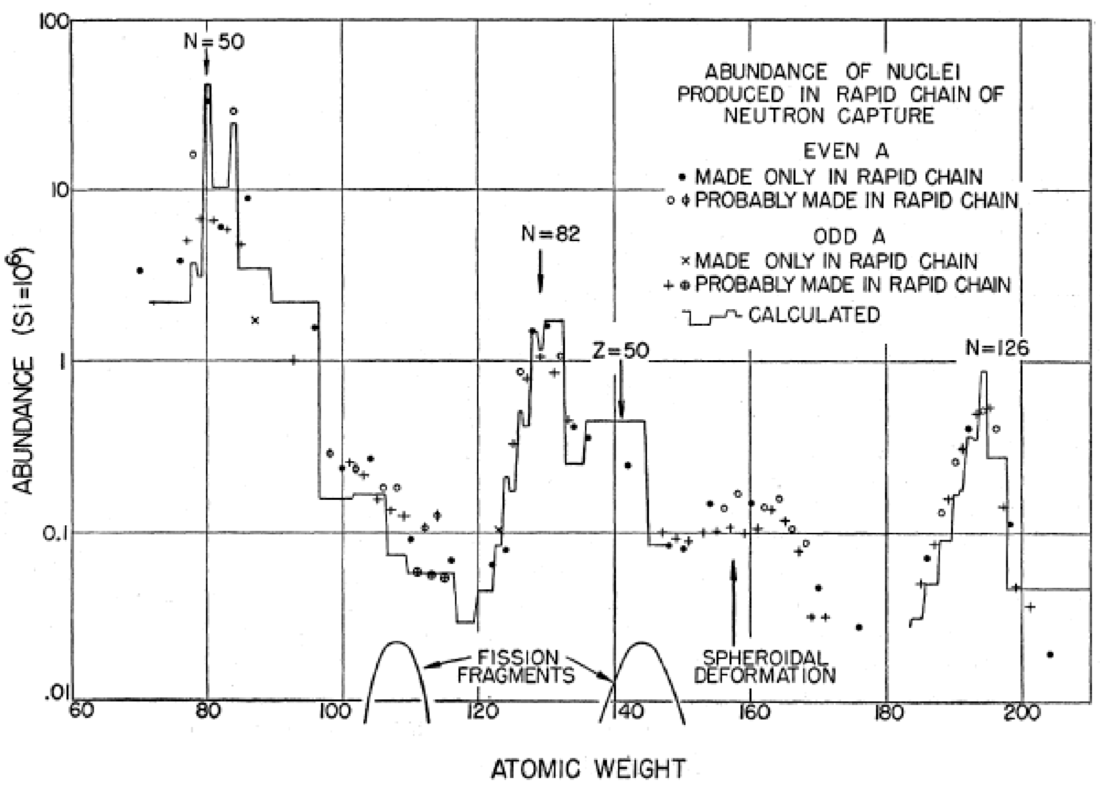
- He-core flashes in low-mass stars
- He- and C-shells of stars undergoing SN explosions
- Jets of matter from collapse of rotating magnetized stellar cores
- Neutron-star mergers
- Black-hole neutron-star mergers
- Hypernovae
- Electron-capture SNe
- r-Process without excess neutrons
- Gamma-ray bursts
- SNe with active-sterile neutrino oscillations

…becoming more and more **"exotic"**

Fit of $N_{r,\odot}$ from B^2FH

Reproduction of Solar system isotopic r-process abundances

(mainly from **r-only** nuclei)



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- **nuclear physics:**
  - Q_β – **Weizsäcker mass formula + empirical corrections (*shell, deformation, pairing*)**
  - $T_{1/2}$ – **one allowed transition to excited state, log*ft* = 3.85**

Nuclear-data needs for the classical r-process

- **nuclear masses**

  S_n-values $\Rightarrow$ r-process path / "boulevard"

  Q_β, S_n-values $\Rightarrow$ theoretical β-decay properties, n-capture rates

- **β-decay properties**

  $T_{1/2} \Rightarrow$ r-process progenitor abundances, $N_{r,prog}$

  $P_n \Rightarrow$ smoothing $N_{r,prog} \xrightarrow[\text{freeze-out}]{\beta\text{-decay}} N_{r,final}$ $(N_{r,\odot})$

  modulation N_r through re-capture

- **neutron capture rates**

  $\sigma_{RC} + \sigma_{DC} \Rightarrow$ smoothing $N_{r,prog}$ during freeze-out in "non-equilibrium" phase(s)

- **fission modes**

  SF, βdf, n- and ν-induced fission

  $\Rightarrow$ "fission (re-) cycling"; r-chronometers

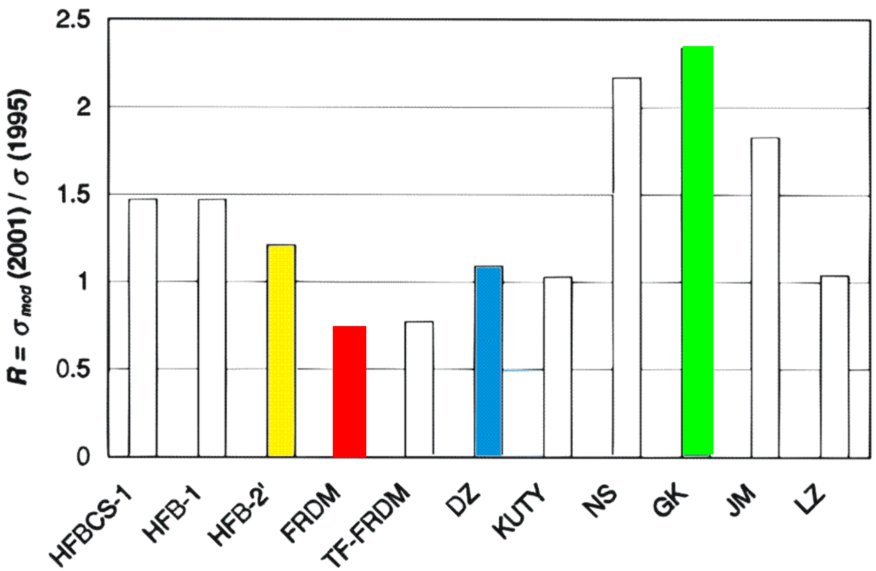
- **nuclear structure development**

  - level systematics
  - "understanding" β-decay properties
  - short-range extrapolation into unknown regions

Nuclear masses

Over the years, development of various types of mass models / formulas:

- Weizsäcker formula
- Local mass formulas
  (e.g. Garvey-Kelson; $N_\pi N_\nu$)
- Global approaches
  (e.g. Duflo-Zuker; KUTY)
- Macroscopic-microscopic models
  (e.g. FRDM, ETFSI)
- Microscopic models
  (e.g. RMF; HFB)



D. Lunney et al., Rev. Mod. Phys. 75, No. 3 (2003)

Comparison to NUBASE (2001) // (2006)

FRDM (1992) σ_{rms} = 0.669 // **0.564** [MeV]
ETF-Q (1996) σ_{rms} = 0.818 // **0.729** [MeV]
HFB-2 (2002) σ_{rms} = 0.674 [MeV]
HFB-3 (2003) σ_{rms} = 0.656 [MeV]
HFB-4 (2003) σ_{rms} = 0.680 [MeV]
•
•
•
HFB-8 (2004) σ_{rms} = 0.635 [MeV]
HFB-9 (2005) σ_{rms} = 0.733 [MeV]
•
•
HFB-21 (2011) σ_{rms} = **0.577** [MeV]

No significant improvement of σ_{rms}

J. Rikovska Stone, J. Phys. G: Nucl. Part. Phys. 31 (2005)

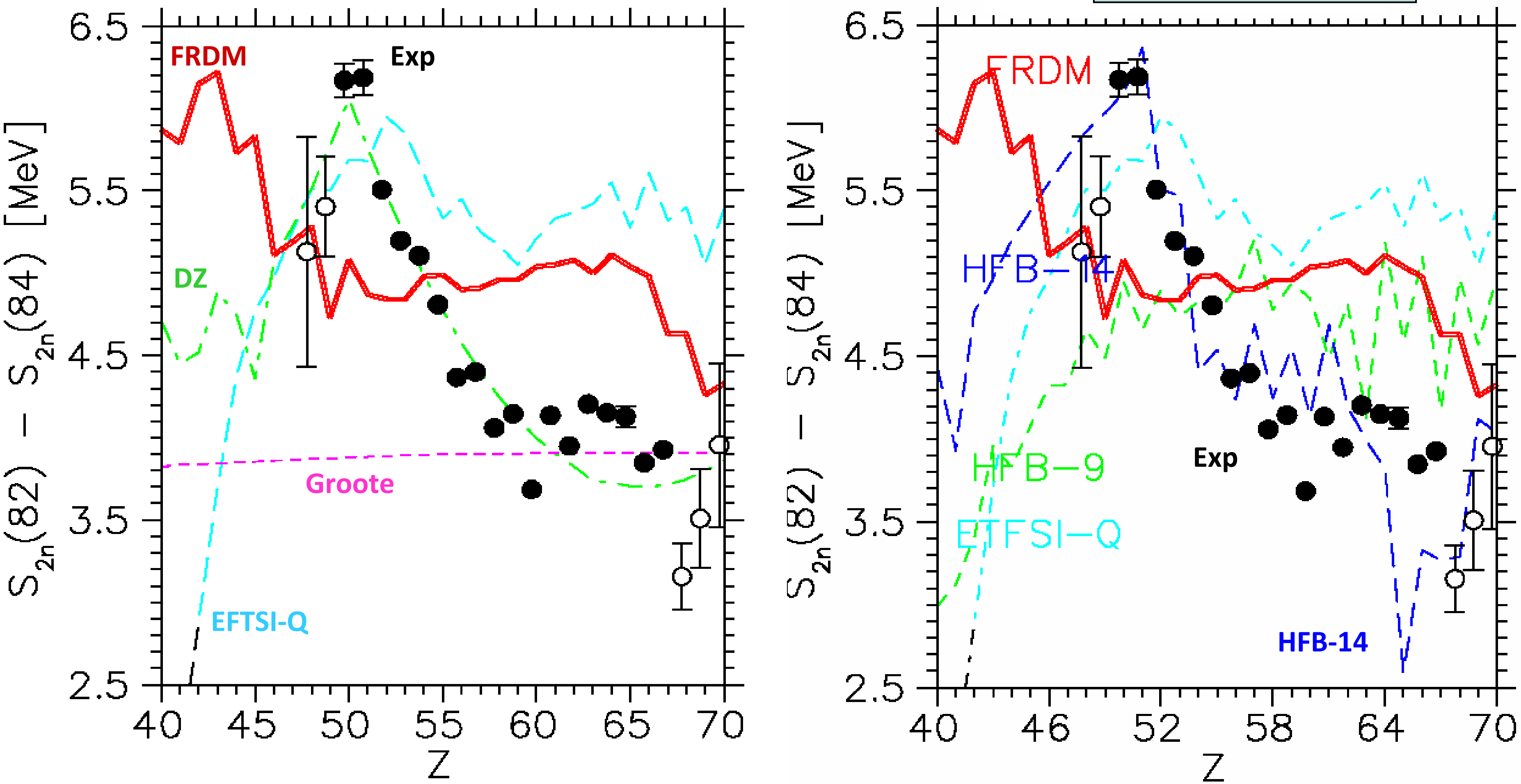
Main deficiencies at N_{magic} !

The N=82 shell gap as a function of Z

The **N=82** shell closure dominates the matter flow of the „main“ r-process ($n_n \geq 10^{23}$).
Definition „shell gap“: $S_{2n}(82) - S_{2n}(84)$ ↷ **paired neutrons**.
Therefore request:

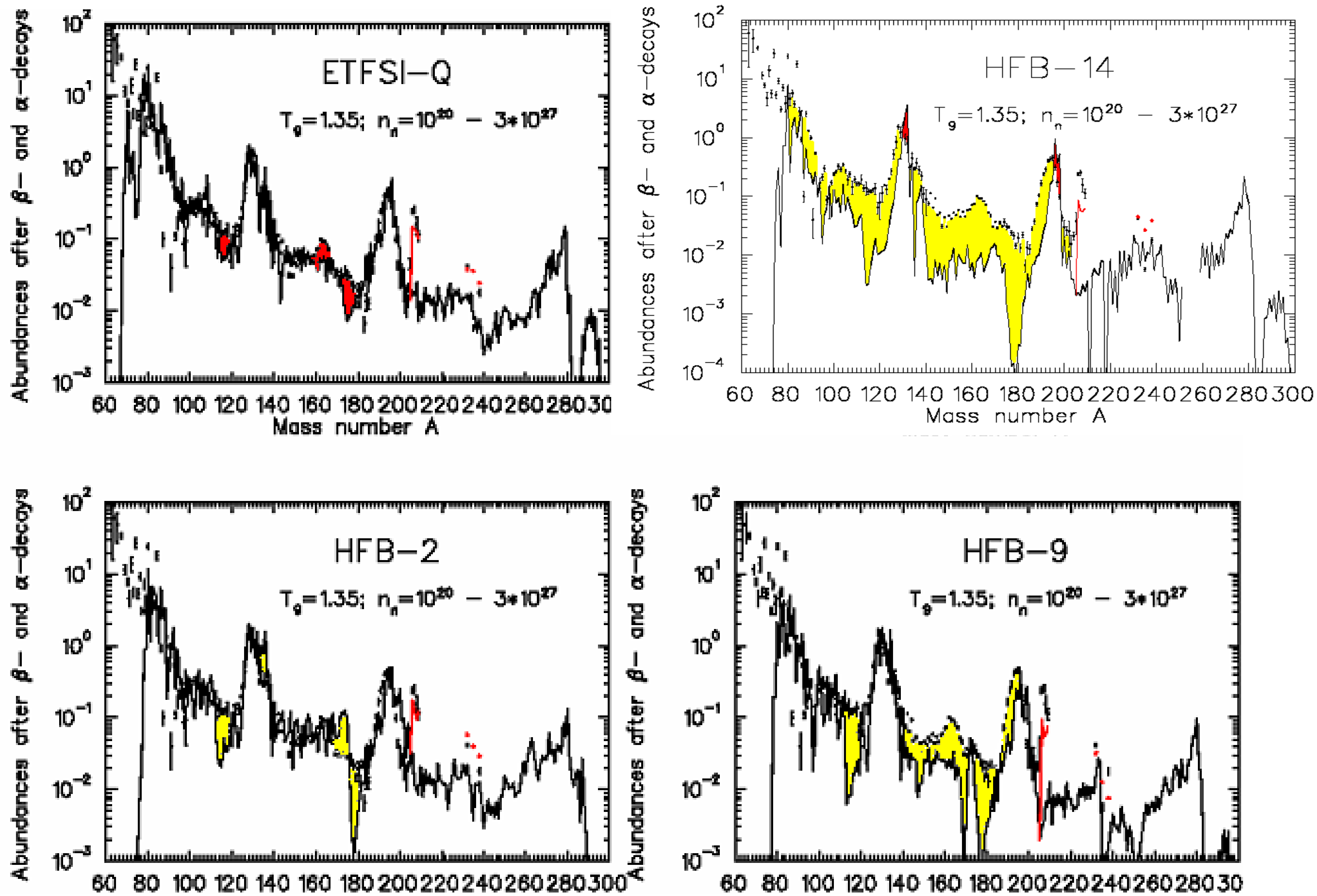
experimental masses and reliable model predictions for the respective
N=82 waiting-point nuclei ^{125}Tc to ^{131}In

→ A≈130 $N_{r,\odot}$ peak



Effects of nuclear masses on $N_{r,\odot}$ fits

$T_{1/2}+P_n$ and all astro parameters kept constant !



Fit of $N_{r,\odot}$ from B^2FH

Reproduction of Solar system isotopic r-process abundances

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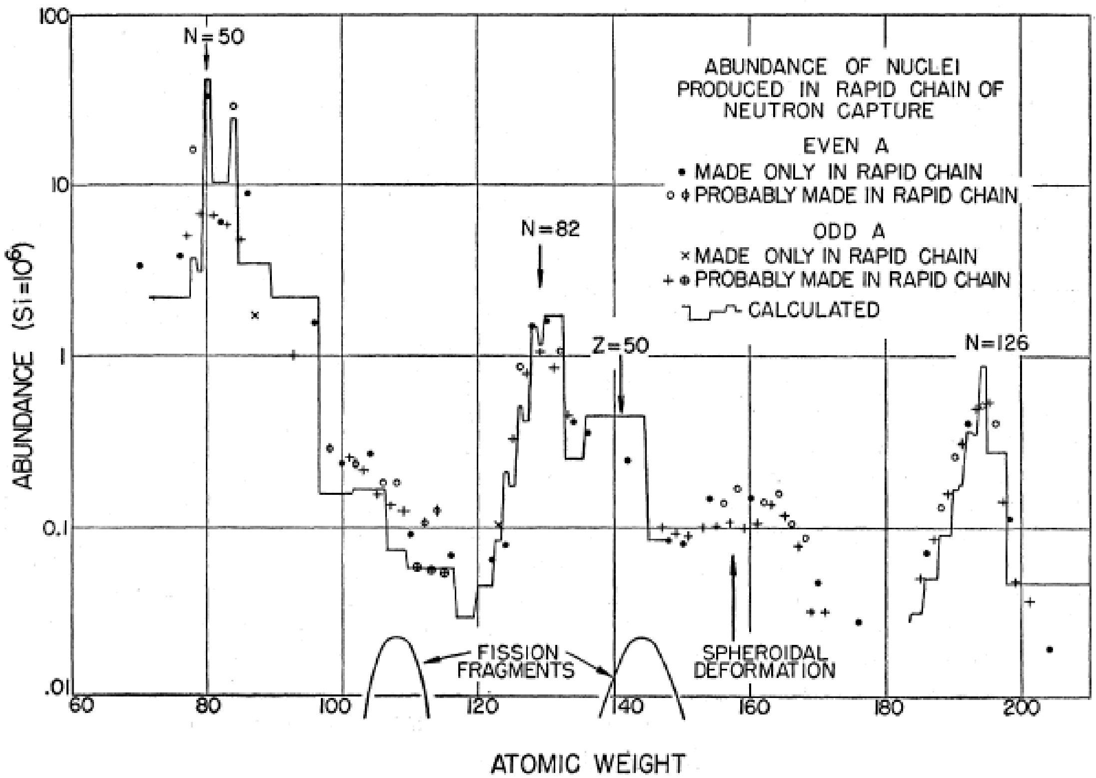

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  - $^{21}Ne(\alpha,n)$

- **nuclear physics:**
  - Q_β – **Weizsäcker mass formula + empirical corrections (*shell, deformation, pairing*)**
  - $T_{1/2}$ – **one allowed transition to excited state, log*ft* = 3.85**

Nuclear models to calculate $T_{1/2}$ and P_n

Application to β-decay:

"Theoretical" definition (Yamada & Takahashi, 1972)

$$S_\beta(E) = D^{-1} \cdot |M(E)|^2 \cdot \omega(E) \; [s^{-1}MeV^{-1}]$$

- $|M(E)|$ average β-transition matrix element
- $\omega(E)$ level density
- D const., determines Fermi coupling constant g_v^2

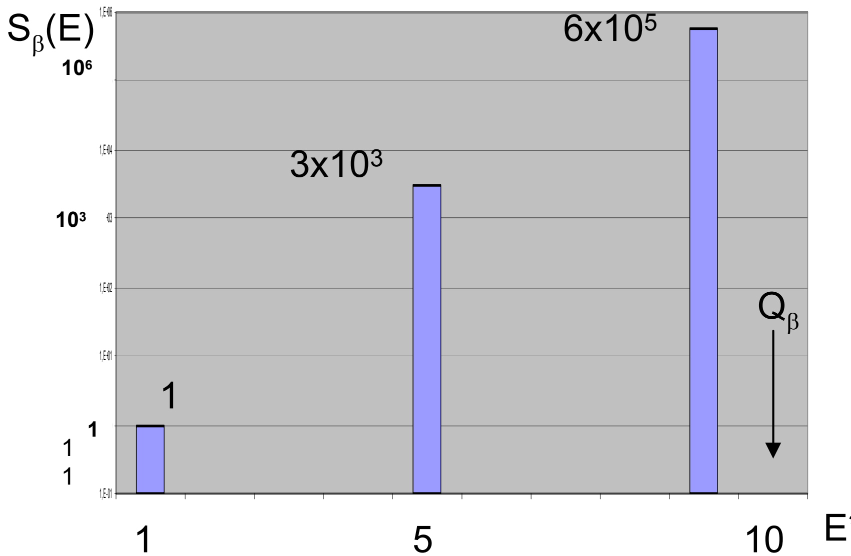
"Experimental" definition (Duke et al., 1970)

$$S_\beta(E) = \frac{b(E)}{f(Z, Q_\beta - E) \cdot T_{1/2}} \quad [s^{-1}MeV^{-1}]$$

- b(E) absolute β-feeding per MeV,
- $f(Z, Q_\beta\text{-}E)$ Fermi function,
- $T_{1/2}$ β–decay half-life.

$T_{1/2}$ as reciprocal ft-value per MeV

$$T_{1/2} = \frac{1}{\sum_{0 \le E_i \le Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)}$$



E*[MeV]

same $T_{1/2}$!

$f(Z, Q_\beta\text{-}E_i) \sim (Q_\beta - E_i)^5$ Fermi function

$T_{1/2}$ sensitive to lowest-lying resonances in $S_\beta(E_i)$
P_n sensitive to resonances in $S_\beta(E_i)$ just beyond S_n

↷ easily "correct" $T_{1/2}$ with wrong $S_\beta(E)$

$T_{1/2}$ and P_n calculations in 3 steps

"Typical example":

(1) FRDM /ETFSI-Q

↷ Q_β, S_n, ε_2

Folded-Yukawa wave fcts.

QRPA pure GT

with input from mass model

potential: Folded Yukawa

Nilsson (different κ, μ)

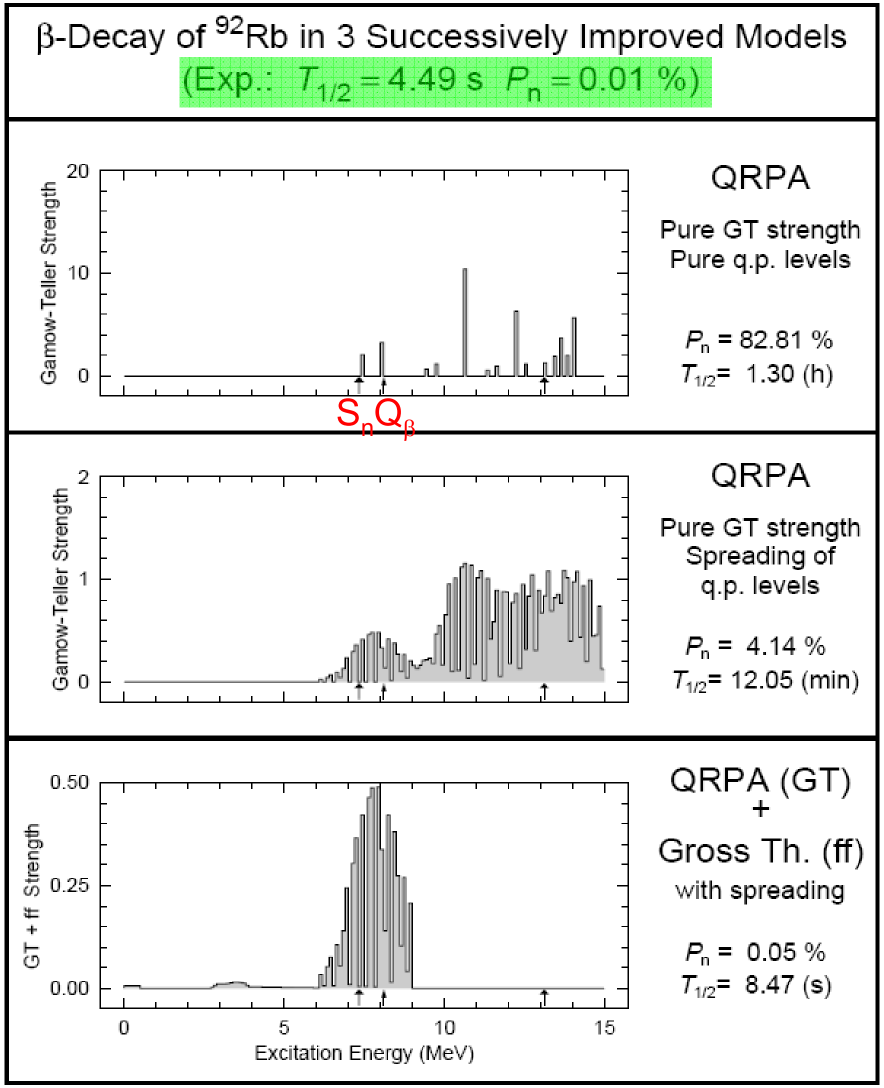
Woods-Saxon

pairing-model: Lipkin-Nogami

BCS

(2) as in (1) with empirical spreading of SP transition strength, as shown in experimental $S_\beta(E)$

(3) as in (2) with addition of first-forbidden strength from Gross Theory



note: effect on P_n !

β-Decay properties

$T_{1/2}$, P_n ⟶ gross **β-strength** properties from theoretical models, e.g. QRPA in comparison with experiments.

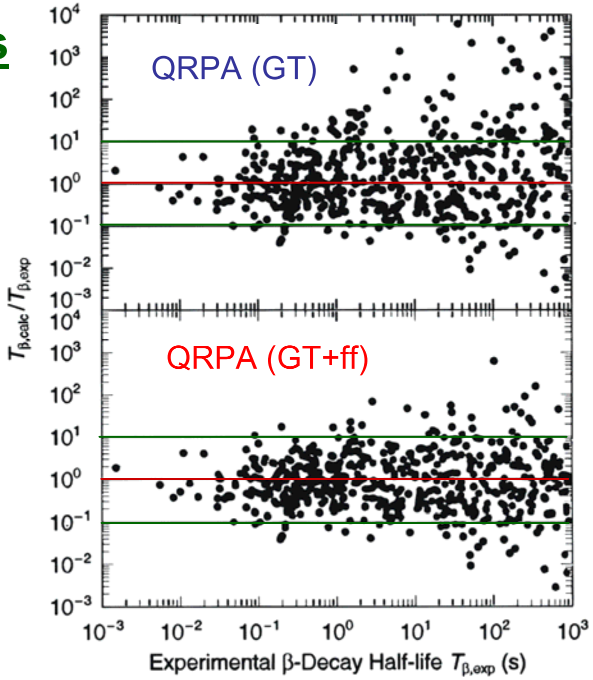
Requests: (I) prediction / reproduction of correct experimental "**number**"

(II) full nuclear-structure understanding

↷ full spectroscopy of "key" isotopes, like $^{80}Zn_{50}$, $^{130}Cd_{82}$.

Total Error = 3.73

Half-lives

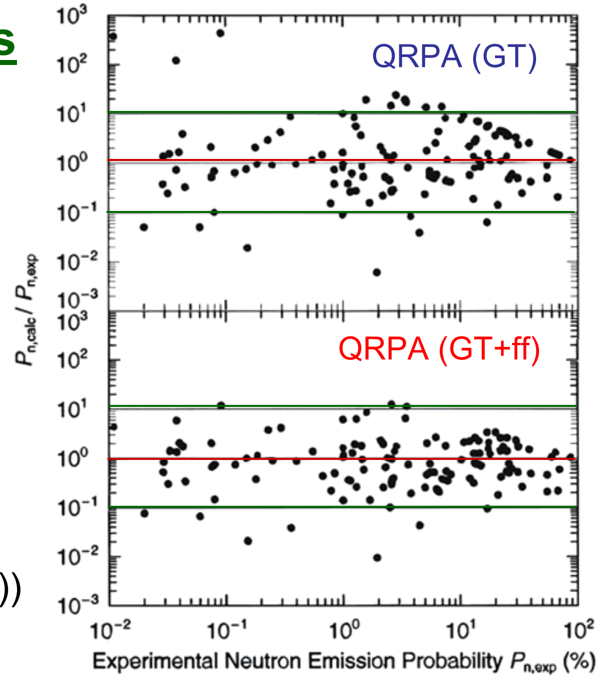


Total Error = 3.08

(P. Möller et al., PR **C67**, 055802 (2003))

Total Error = 5.54

P_n-Values

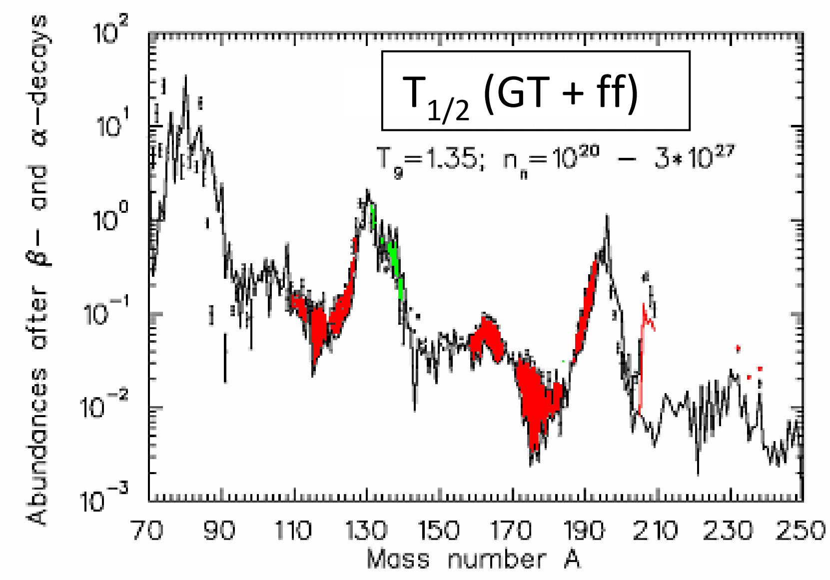


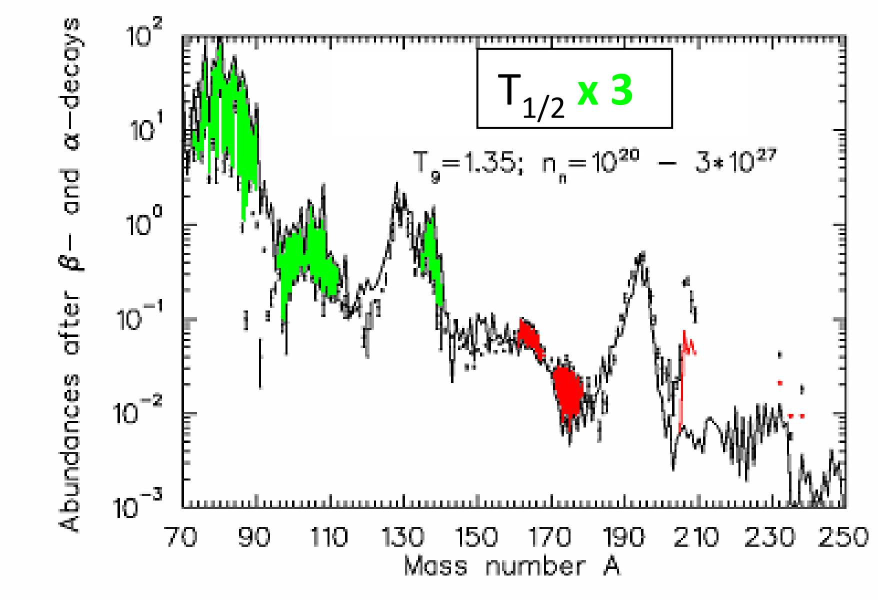
Total Error = 3.52

Effects of $T_{1/2}$ on r-process matter flow

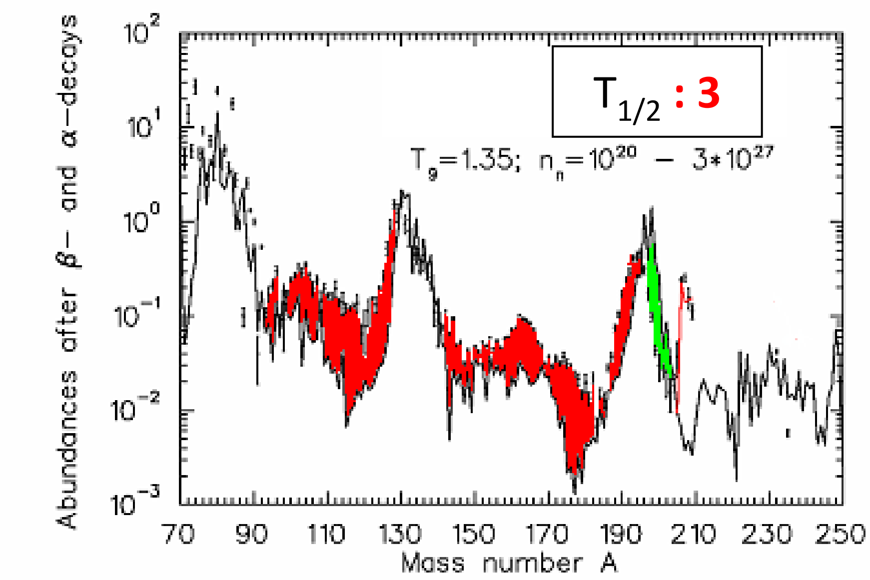
Mass model: **ETFSI-Q**
-all astro parameters kept constant

r-process model:
"waiting-point approximation"



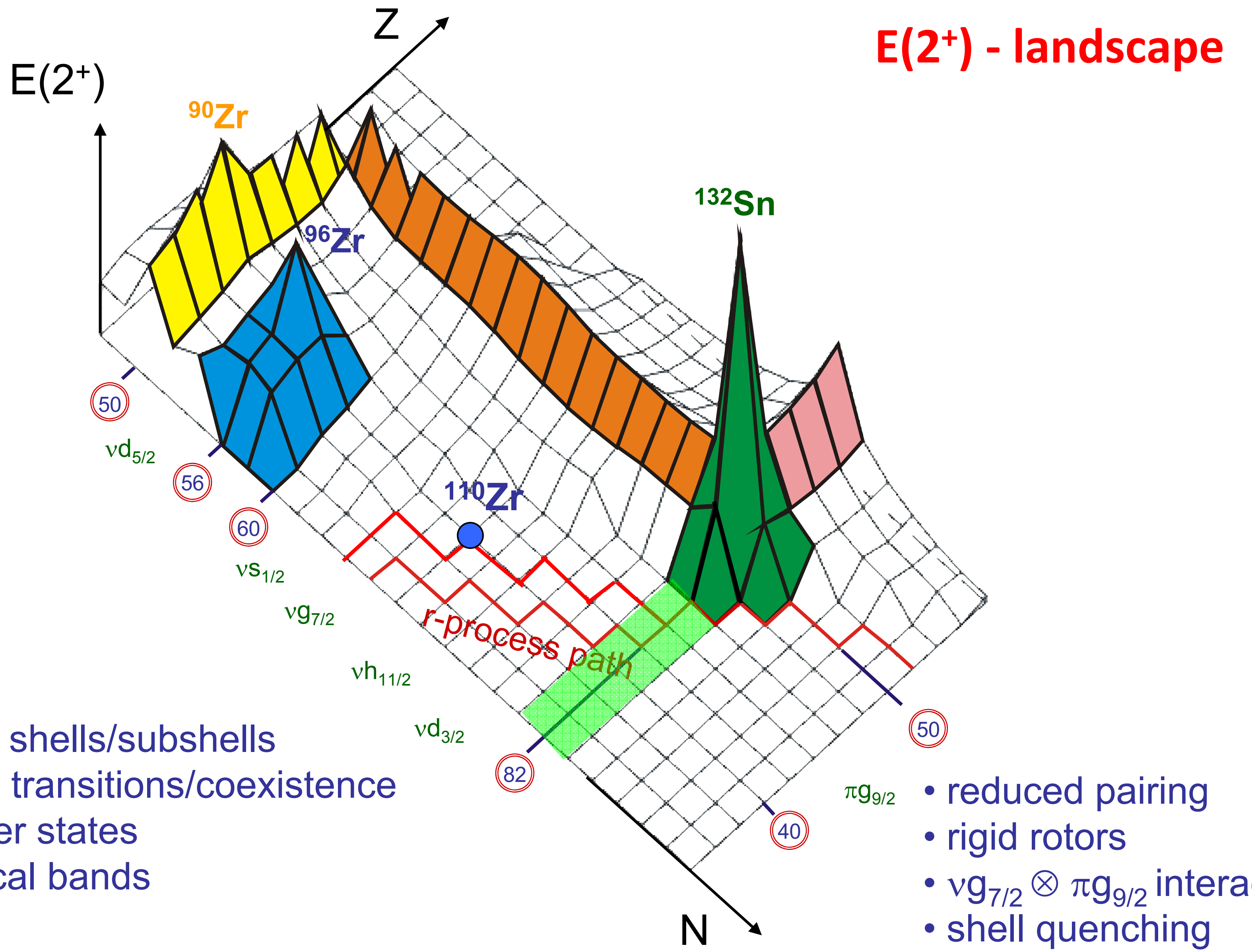


r-matter flow too **slow**



r-matter flow too **fast**

Nuclear structure development



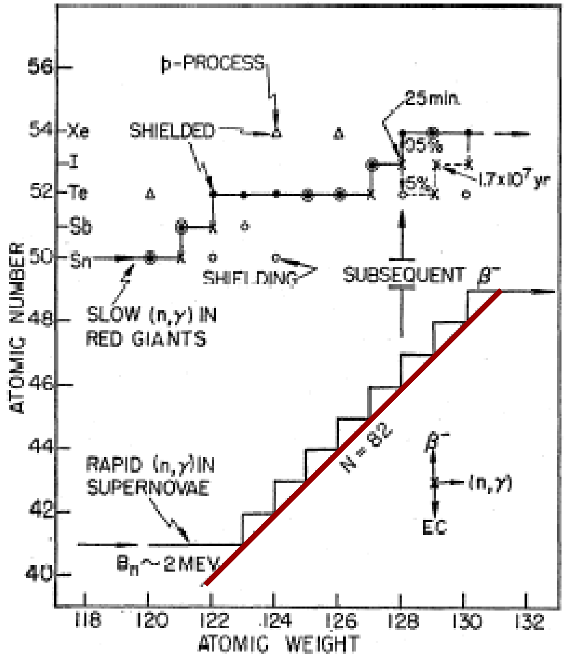
- magic shells/subshells
- shape transitions/coexistence
- intruder states
- identical bands

- reduced pairing
- rigid rotors
- $\nu g_{7/2} \otimes \pi g_{9/2}$ interaction
- shell quenching

^{130}Cd – the key isotope at the A=130 peak

already B²FH (Revs. Mod. Phys. 29; 1957)

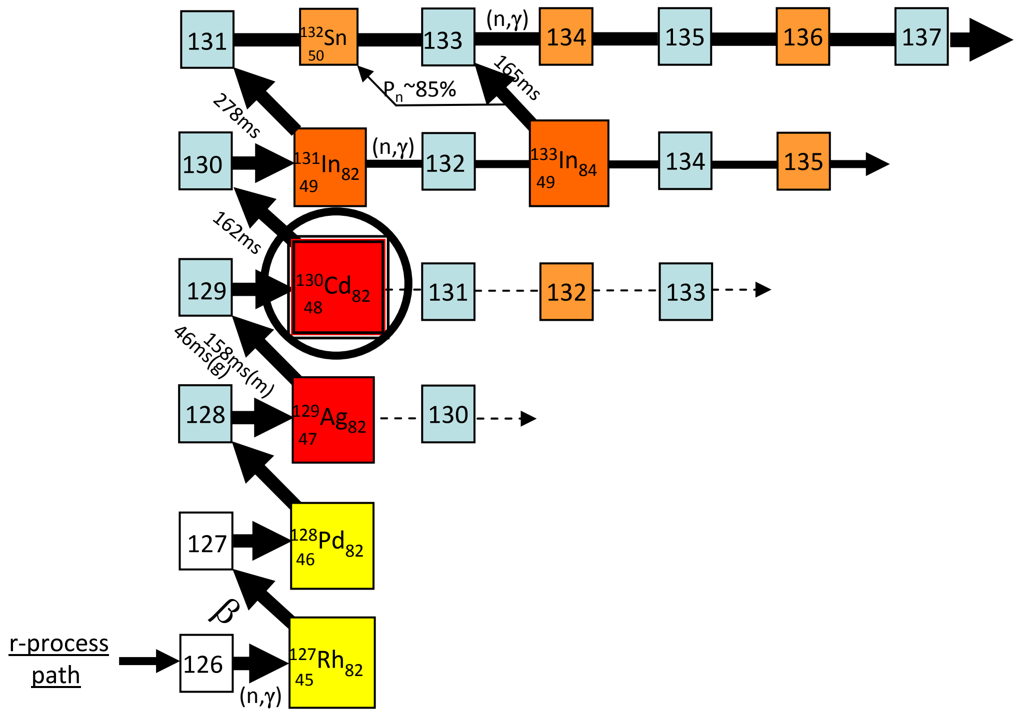
C.D. Coryell (J. Chem. Educ. 38; 1961)



"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"

...hunting for nuclear properties of waiting-point isotope **^{130}Cd...**



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

climb up the N= 82 ladder ...
A ≅ 130 "bottle neck"

$T_{1/2}$ ⇨ **total r-process duration τ_r**

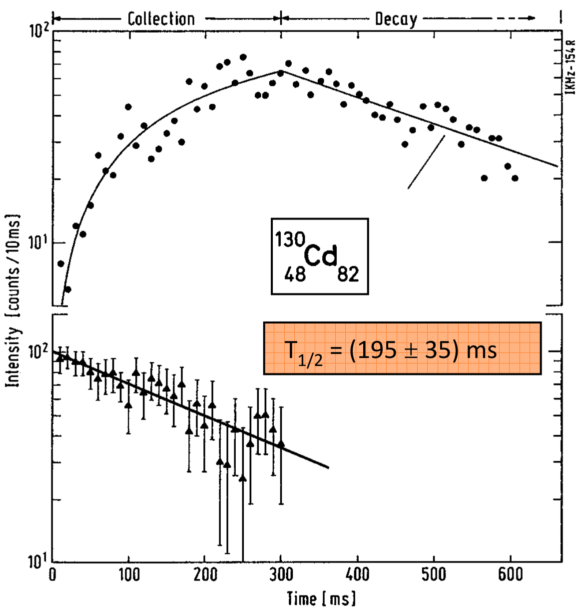
What we knew already in 1986 ...

Z. Phys. A – Atomic Nuclei 325, 489–490 (1986)

Zeitschrift für Physik A
Atomic Nuclei
© Springer-Verlag 1986

The Beta-Decay Half-Life of $^{130}_{48}Cd_{82}$ and its Importance for Astrophysical *r*-Process Scenarios

K.-L. Kratz[1], H. Gabelmann[2], W. Hillebrandt[3], B. Pfeiffer[1], K. Schlösser[2], and F.-K. Thielemann[4]
and the ISOLDE Collaboration, CERN



Model predictions at that time:
$30\ ms \lesssim T_{1/2} \lesssim 1.2\ s$

Astrophysical requests:

- r-process must go through $^{130}Cd \rightarrow {}^{130}Te$ at top of A ≈ 130 peak
- hence, $n_n \approx 10^{21}\ cm^{-3}$ required
- $T_{1/2}(^{130}Cd)$ must correlate with $N_{r,\odot}(^{130}Te)$

Above conditions
exclude explosive shell-burning
favored at that time;
supports cc-SN scenario.

$T_{1/2}(^{130}Cd) \leftrightarrow N_{r,\odot}(^{130}Te)$?

If the historical **"waiting-point" concept** is valid for the A ≈ 130 $N_{r,\odot}$-peak,
then in the simplest version with $S_n(N=82)$=const.

$$\frac{T_{1/2}(^{131}In_{82})}{N_{r,\odot}(^{131}Xe)} = \frac{T_{1/2}(^{130}Cd_{82})}{N_{r,\odot}(^{130}Te)} = \frac{T_{1/2}(^{129}Ag_{82})}{N_{r,\odot}(^{129}Xe)} \ldots$$

From this assumption, in 1986 the waiting-point prediction for $T_{1/2}(^{130}Cd) \approx$ **595 ms**.

With a more realistic approach,
taking into account that

- the breakout from N=82 involves ^{131}In und ^{133}In (≈ 1:1)
- ^{133}In has a known $P_n \approx 90\%$

$$T_{1/2}(^{130}Cd) \approx \frac{N_{r,\odot}(^{130}Te)}{[N_{r,\odot}(^{131}Xe)/T_{1/2}(^{131}In)] + [1.1 N_{r,\odot}(^{132}Xe)/T_{1/2}(^{133}In)]} \approx 170 \text{ ms}$$

…to be compared to the **1986** exp. value of **195 (35) ms**,
and to the **2001** improved value of **162 (7) ms**.

Experiment request: Selectivity !

Remember

First $T_{1/2}$ of ^{130}**Cd** at SC-ISOLDE (1986)

- non-selective plasma ion-source
- selective quartz transfer line
- selective ßdn-counting

Obviously not sufficient

High background from

- surface-ionized ^{130}In, ^{130}Cs
- molecular ions $[^{40}Ca^{90}Br]^+$

Request: additional selectivity steps

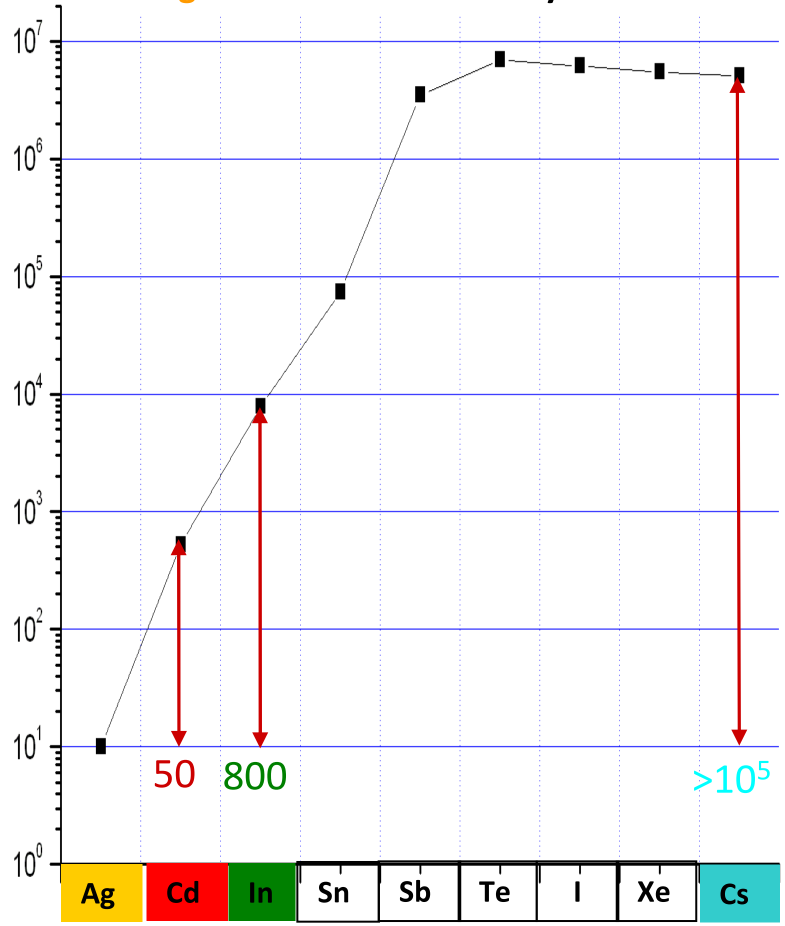
developed since 1993

- Fast UC_x target
- Neutron converter
- **Laser ion-source**
- Hyperfine splitting
- Isobar separation
- Repeller
- **Chemical separation**
- Multi-coincidence setup

… hunting for N=82 ^{129}**Ag**

Relative production rates

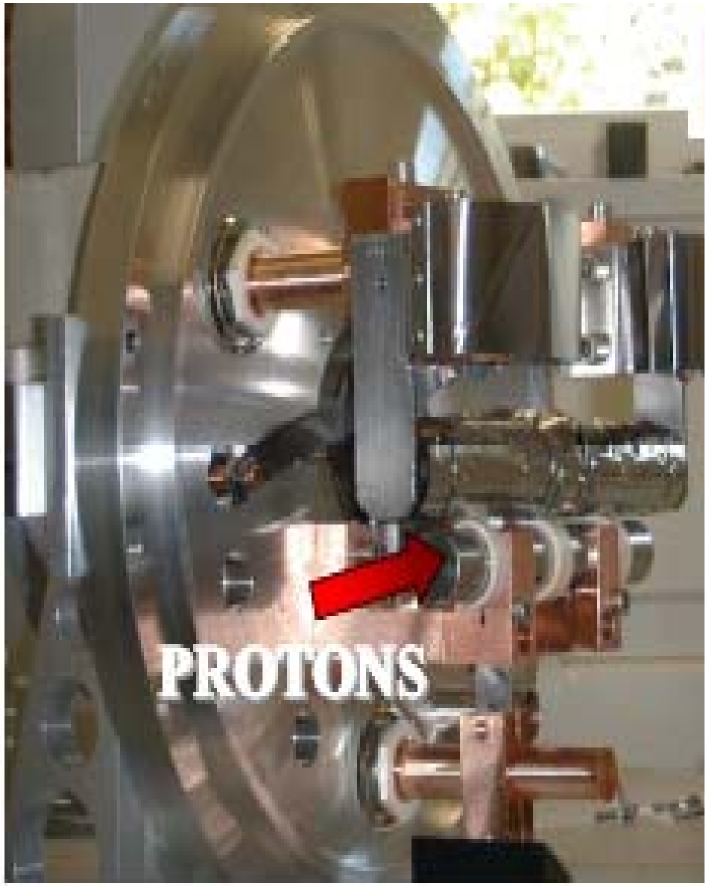
the Ag "**needle**" in the Cs "**haystack**"



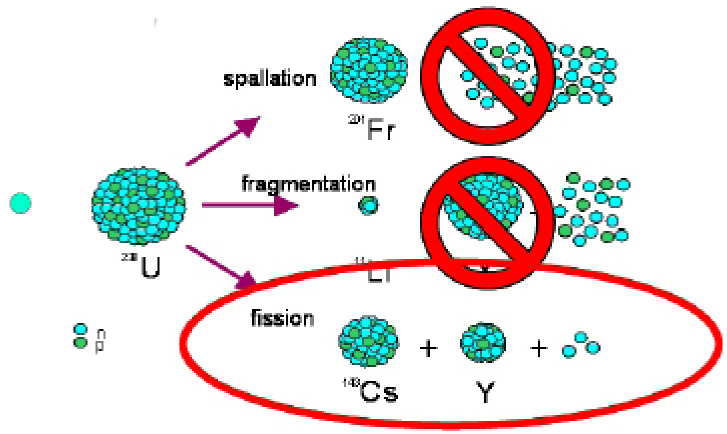
experimental "lifework" of Mainz group

Request: **Selectivity !**

UC_x target and "neutron converter"

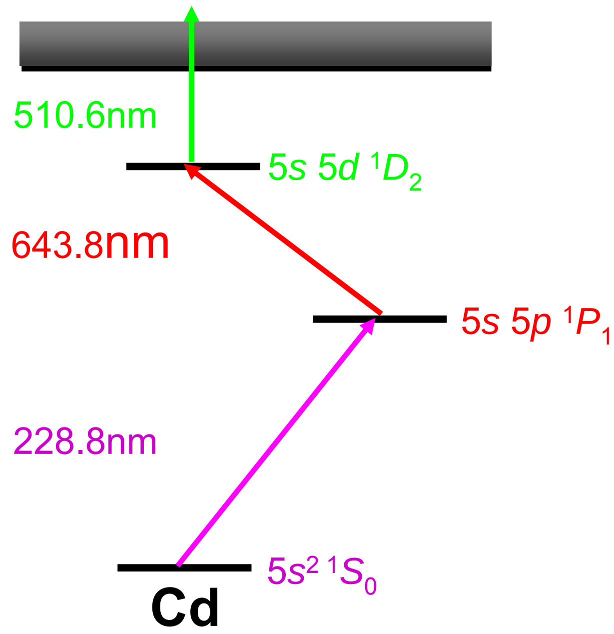


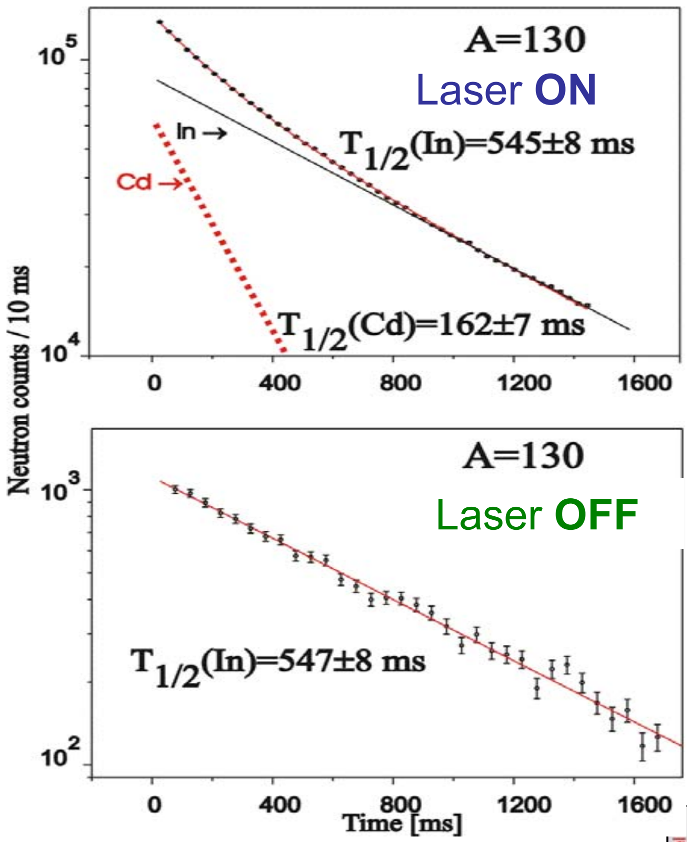
Proton-beam on "neutron converter" (tungsten rod)
↷ only fission, avoids p-rich isobars



Experiment request: Selectivity !

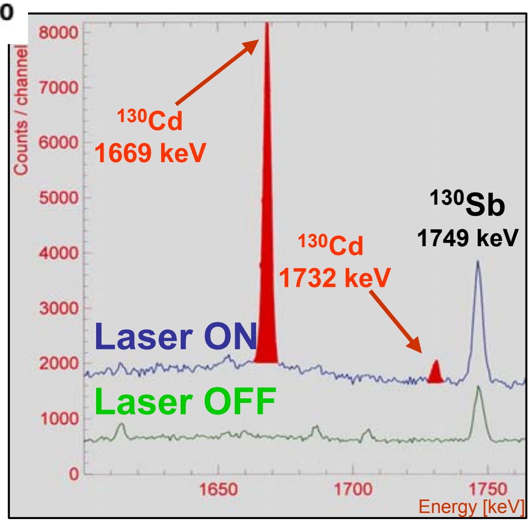
Laser ion-source (RILIS)





Comparison of **Laser ON** to **Laser OFF** spectra

γ-singles spectrum



Chemically selective, three-step laser ionisation of Cd into continuum

Properties of the laser system:
Efficiency ≈ 10%
Selectivity ≈ 10^3

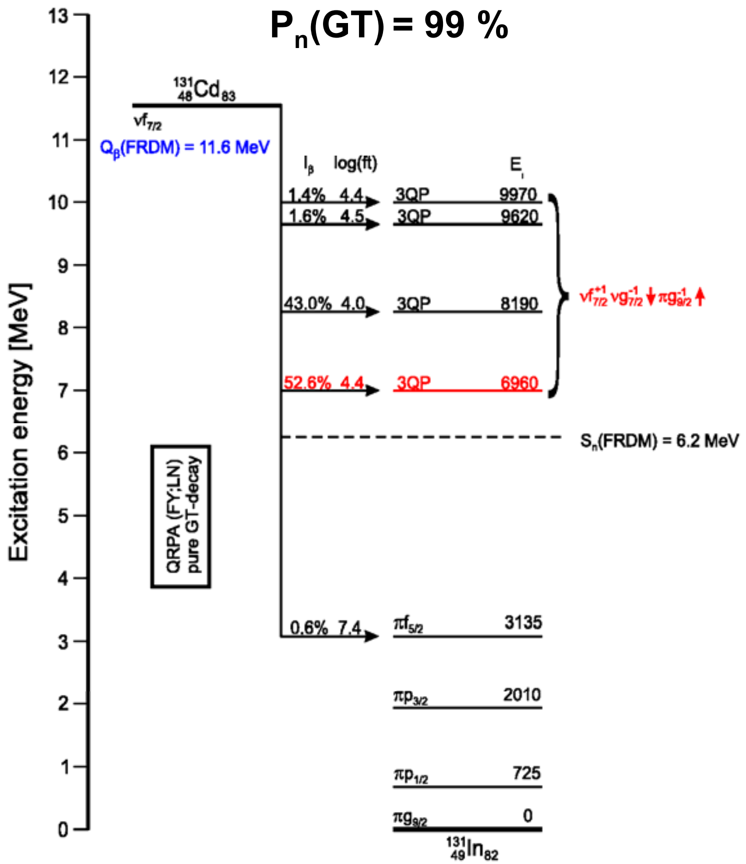
Surprising β-decay properties of ^{131}Cd

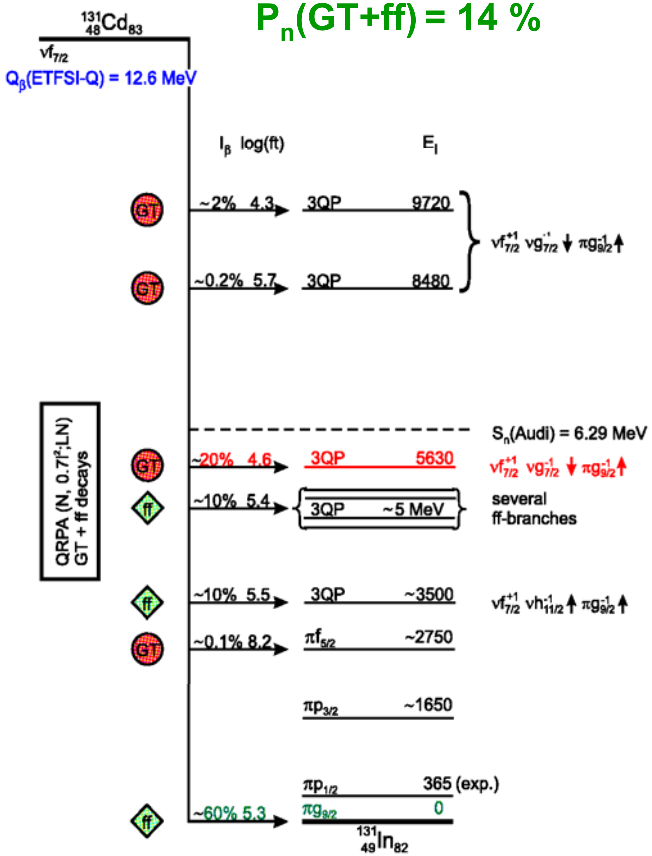
…just **ONE** neutron outside N=82 magic shell

Experiment: $T_{1/2}$ = 68 ms; P_n = 3.4 %

QRPA predictions: **$T_{1/2}$(GT) = 943 ms;** **$T_{1/2}$(GT+ff) = 59 ms;**

P_n(GT) = 99 % **P_n(GT+ff) = 14 %**





Nuclear-structure requests: higher Q_β, main GT lower, low-lying ff-strength

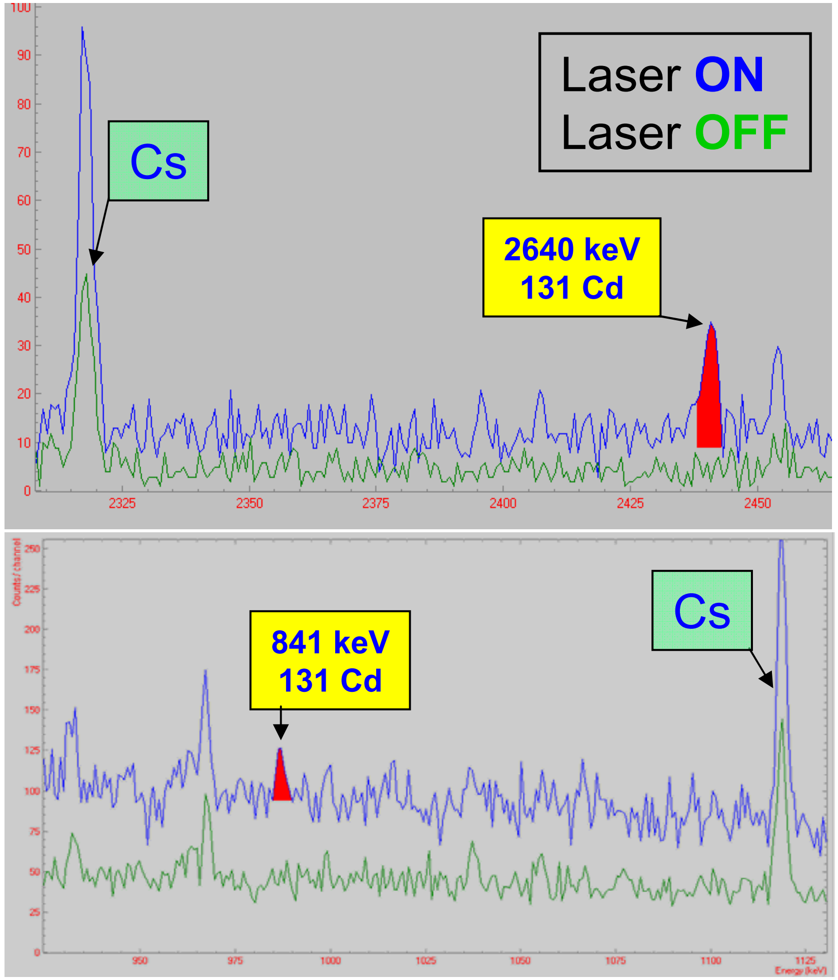
γ-spectroscopic confirmation of decay scheme with normal separator set-up failed

Experiment request: More selectivity !

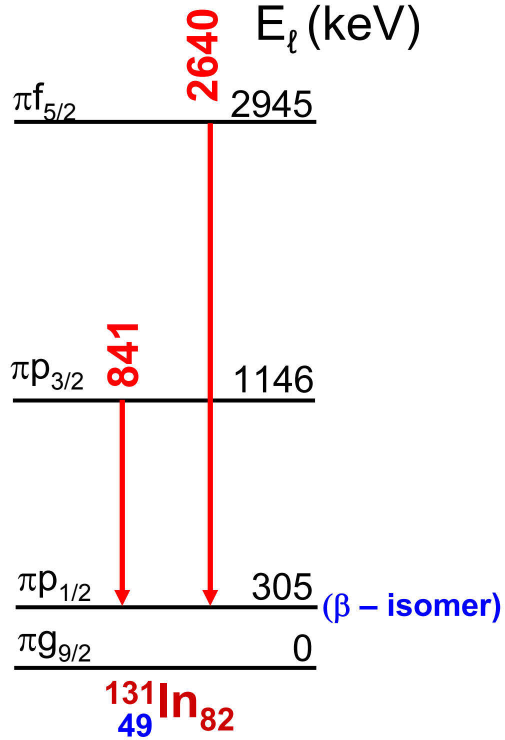
Surface chemistry

UC_x-target; neutron converter;
quartz transfer line at 820°C,
gas-phase chemistry.

68 ms ^{131}Cd decay



$\upsilon g_{7/2} \rightarrow \pi g_{9/2}$ main β-feeding below S_n !



Energy-splitting	Hyde (1980)	Leander (1984)	Brown (1998)	Exp.
$\pi p_{1/2} - \pi p_{3/2}$	0.6 MeV	1.4 MeV	1.1 MeV	**0.841 MeV**
$\pi p_{1/2} - \pi f_{5/2}$	1.3 MeV	2.6 MeV	2.6 MeV	**2.640 MeV**

The FK²L waiting-point approach (I)

When we (FK²L) started in **1986,**

already *numerous attempts,*
>10 different stellar sites ...
(none successful)

Since **30** *years, search for the site(s) of the r-process*

Aim:
Understanding of nucleosynthesis ("r-abundances")

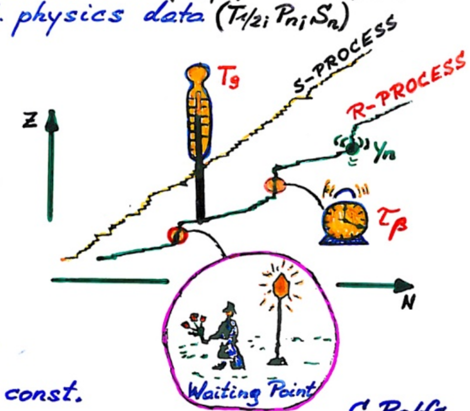
Problems:
Knowledge of – *astrophysical conditions*
– *nucl. physics far off β-stability*

Our approach:
No new astrophys. model ....
From observed r-abundances ($N_{r,\odot}$)
measured nucl. physics data ($T_{1/2}$; P_n; S_n)
deduce
r-proc. conditions

↱ constraints on existing models.

Assume "waiting-point" approximation
(B²FH, 1957)

$N_{r,\odot} \times \lambda_\beta \simeq const.$



C. Rolfs

E.g.:
Cameron, Clayton, Schramm, Truran, Kodama, Arnould, Woosley, Hillebrandt, Thielemann...

r-process isotopes known at that time:
N=50 ^{79}Cu, ^{80}Zn, ^{81}Ga
N=82 ^{130}Cd, ^{131}In

The FK^{2}L waiting-point approach (II)

J. Phys. G 24 (1988)

With $T_{1/2}$(exp) and $N_{r,\odot}$

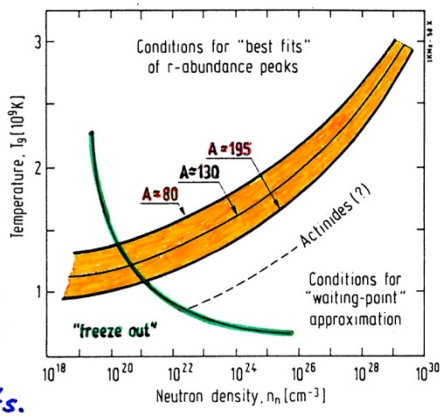
test of

"waiting-point concept":

correlate $T_{1/2} \rightleftharpoons N_{r,\odot}$

→ deduce $T_9 - n_n$ band

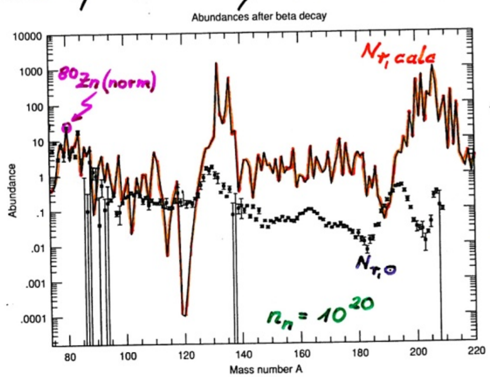
conditions to fit the $A \simeq 80$ and 130 $N_{r,\odot}$-peaks.



Ap. J. 403 (1993)

Static and time-dependent r-process calculations for "freeze-out" conditions.

Use of internally consistent nuclear-physics input (FRDM + QRPA).



Steady-flow NOT global

- wrong trend, increasing N_r with A
- $A \simeq 130$ and 195 peaks shifted, too large;

→ indicates too low n_n

ctd.

Classical assumptions:

global steady flow

of r-process through

N=50 ^{80}Zn, **N=82** ^{130}Cd

and **N=126** ^{195}Tm

Calculation:

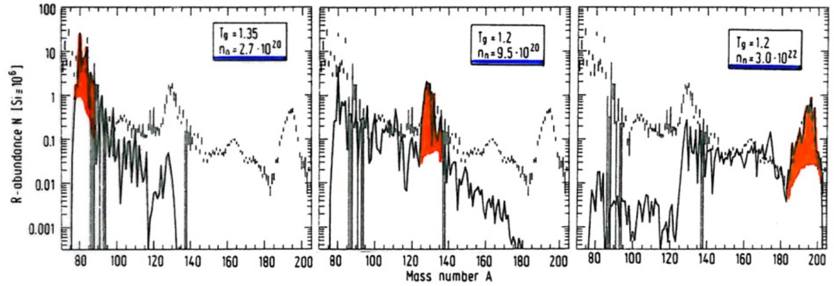
r-process matter flow at freeze-out temperature ;

at N=82 "imperfect" peak, r-process through 40 s ^{132}Sn, instead of 195 ms ^{130}Cd…

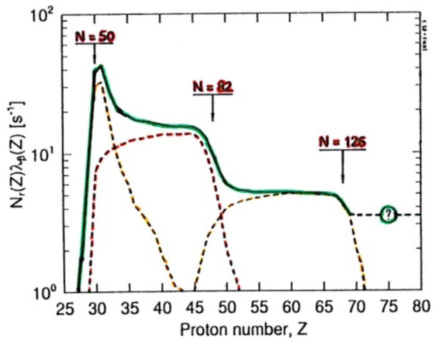
The FK²L waiting-point approach (III)

Consequences:

- r-process must have several components
  with different n-densities
  and different r-process paths.



- steady-flow is only local,
  breaks down at each N_r-peak
  ↗ at N_{magic}



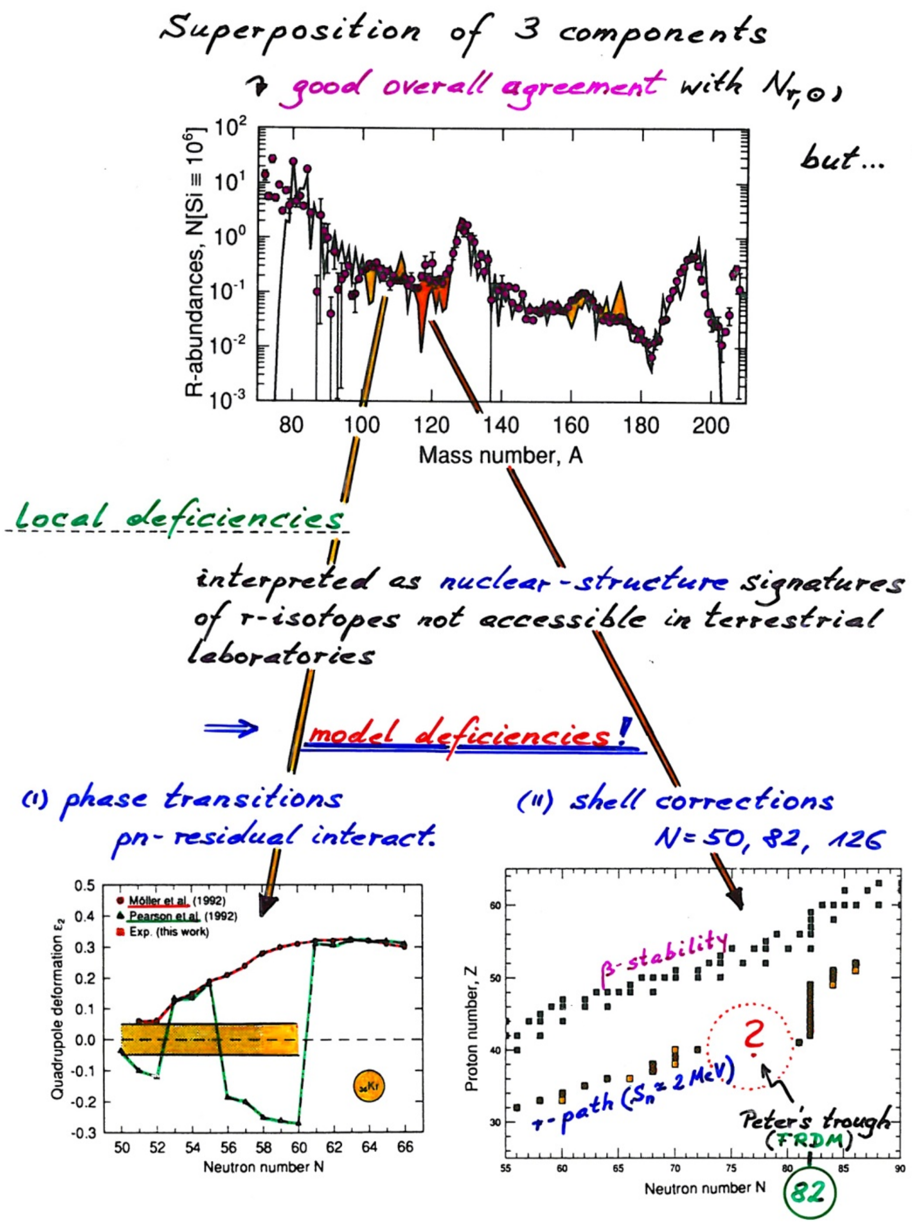
analogous to s-process
with $N_s\sigma = const.$

empirical r-process picture
with superposition of
(minimum) 3 components

$N_r\lambda_\beta = const.$

weighting acc. to
$T_{1/2}$ (^{80}Zn, ^{130}Cd, ^{195}Tm)

The FK²L waiting-point approach (IV)



"…best fit so far…;
long-standing problem solved…"
W. Hillebrandt

"…call for a deeper study…
before rushing into numerical results…
and premature comparisons with the observed abundances"
M. Arnould

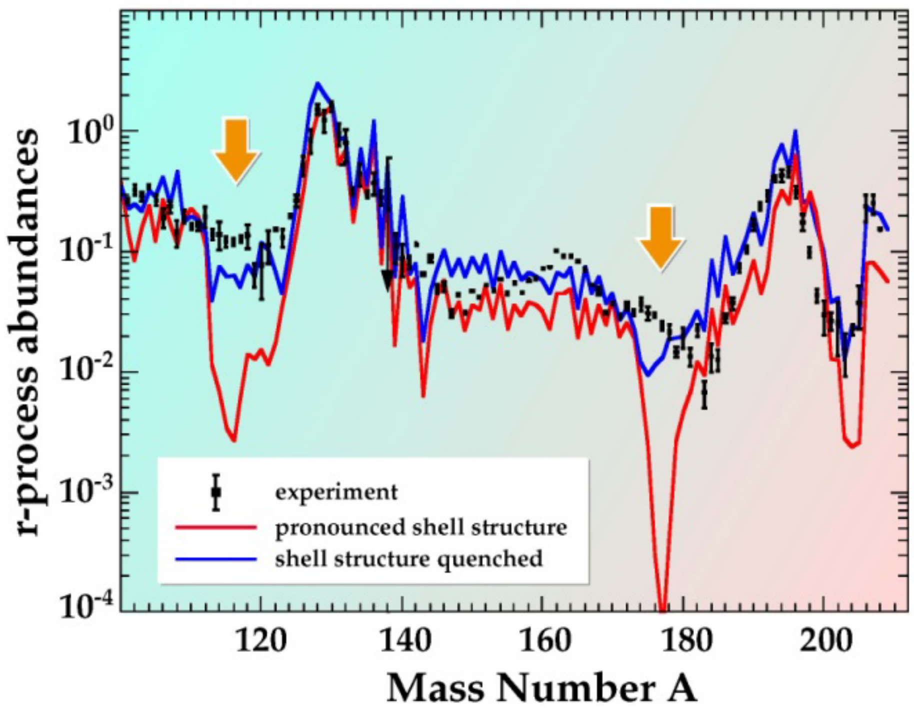
↷ birth of N=82
"shell-quenching"
idea …

Summary "waiting-point" model

seed Fe (still implies secondary process)

superposition of n_n-components

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



"weak" r-process

(later **secondary** process;
explosive shell burning?)

"main" r-process

(early **primary** process; SN-II?)

Kratz et al., Ap.J. 662 (2007)

Second part

Now…

from historical r-process approaches

to “modern” nucleosynthesis calculations

The high-entropy / neutrino-driven wind model

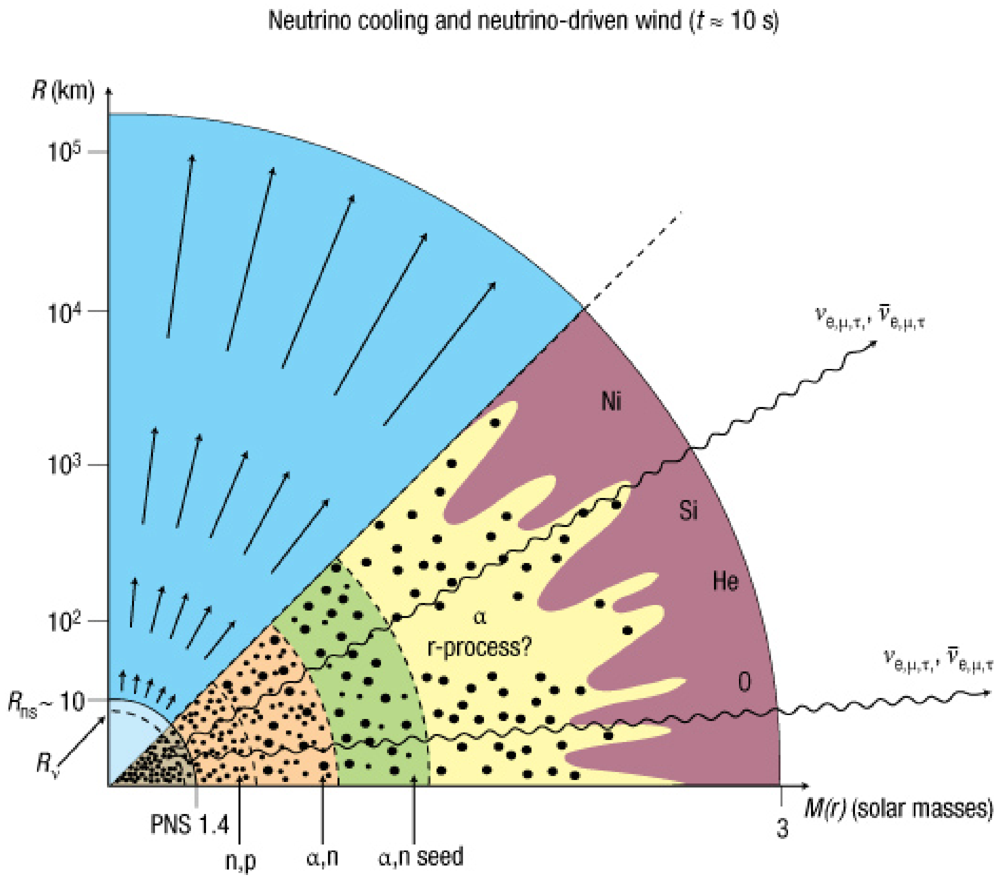
…one of the presently favoured scenarios for the "r-process"

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 ≥ T_9 ≥ 6), they combine to α-particles + an excess of unbound neutrons.

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

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



(Woosley & Janka, Nature, 2005)

(see lectures of Hix, Wanajo & Langanke)

The Basel – Mainz HEW model

full dynamical network (extension of Basel model)

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

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

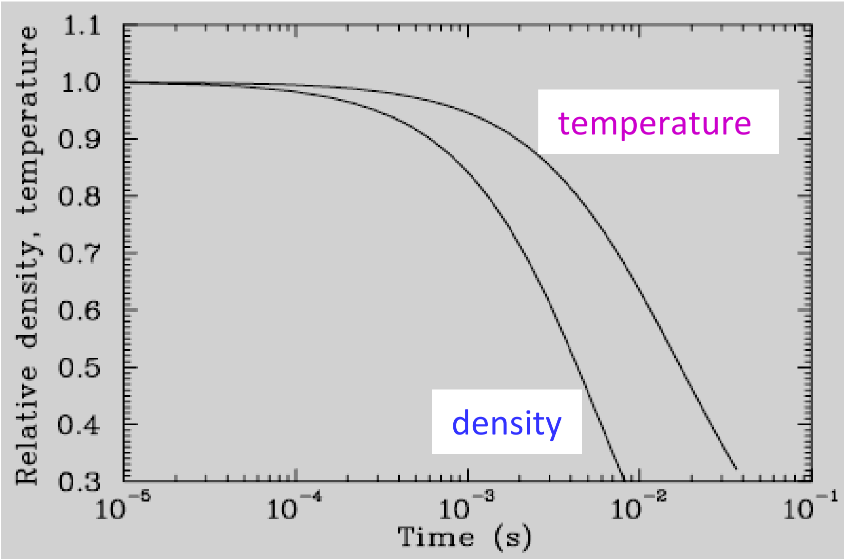
- nuclear masses
- β-decay properties
- n-capture rates
- fission properties

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

(Farouqi, PhD Mainz 2005)

Formation of r-process "seed"

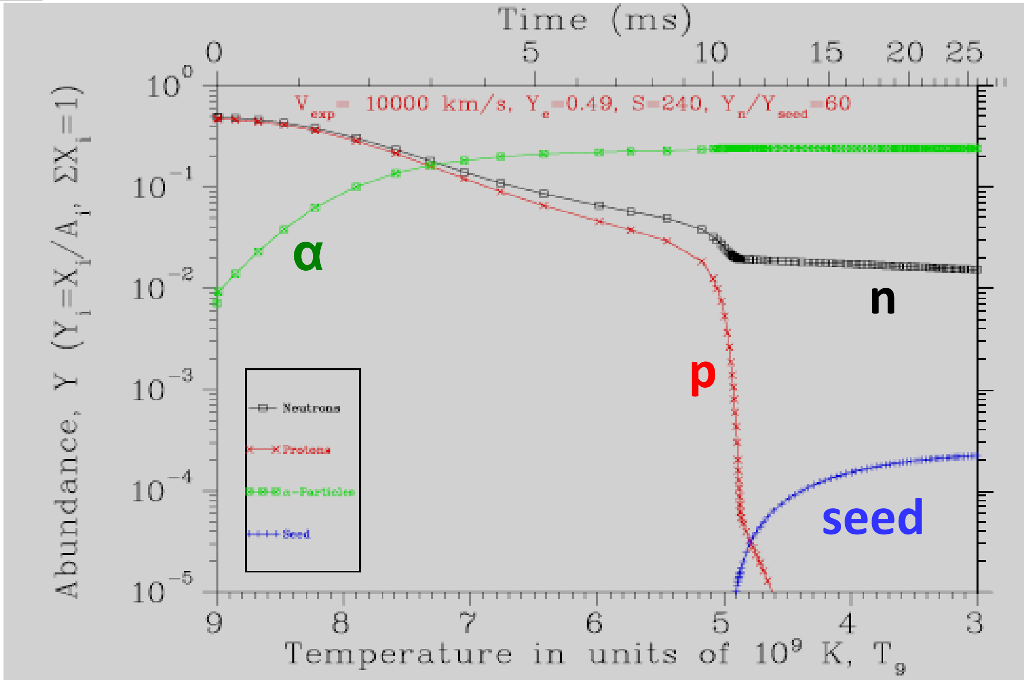


Time evolution of
temperature and density
of HEW bubble
(V_{exp}=10,000 km/s)

⇨ 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)

First results of dynamical r-process calculations

- Conditions for successful r-process

  $\Rightarrow$ **„strength" formula**

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

  parameters **correlated**

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

  $\Rightarrow$ avoids first bottle-neck in classical model

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

  $\Rightarrow$ **$Y_n/Y_{seed} \leq 150$**

- Total process duration up to Th, U

  $\Rightarrow$ **$\tau_r \leq 750$ ms**

  instead of $\approx$ 3500 ms in classical model

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

  $\Rightarrow$ **max. S $\approx$ 280**

  to form full 3rd peak and Th, U

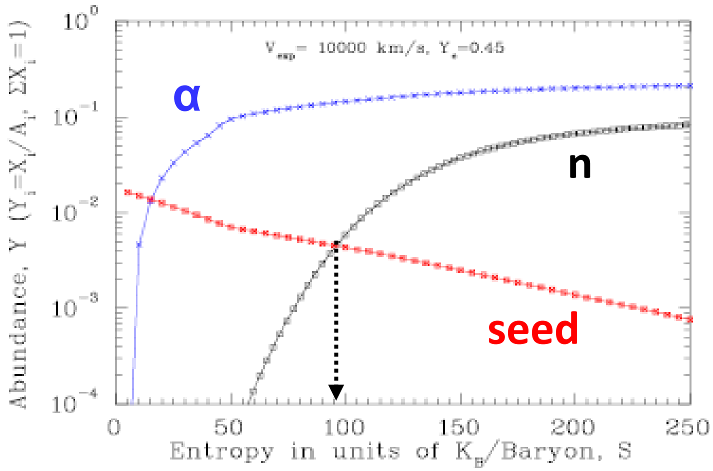
- Freezeout effects (late non-equilibrium phase)

  $\Rightarrow$ capture of "free" neutrons

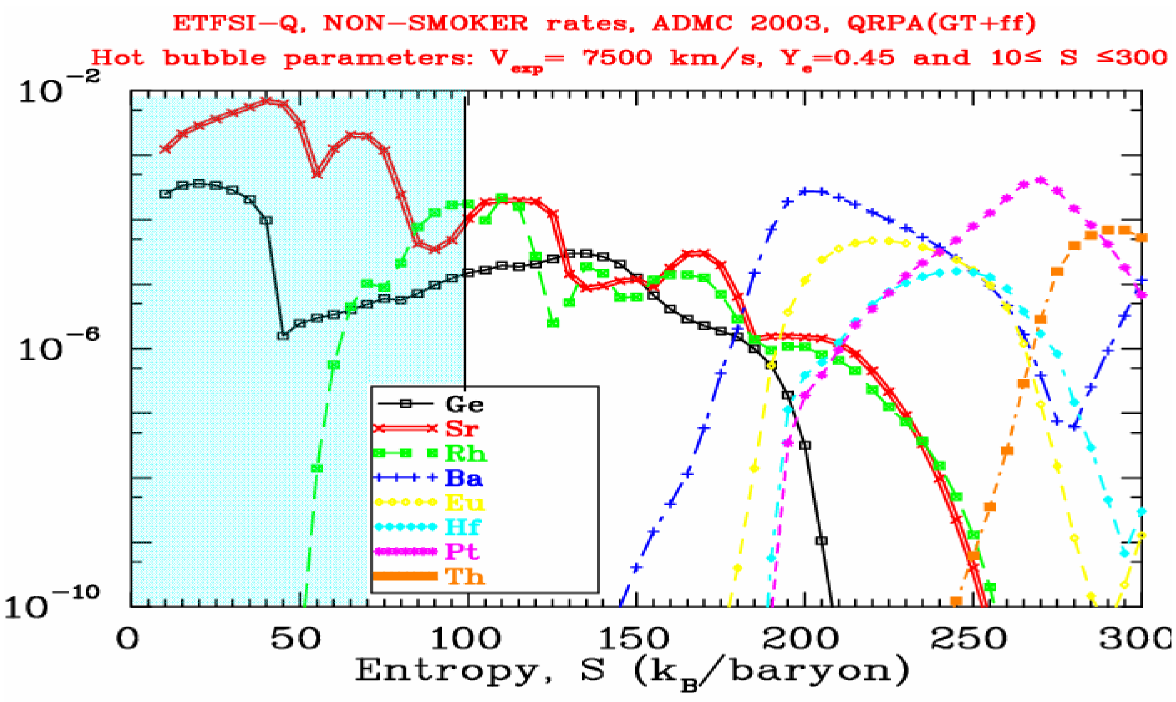
  $\Rightarrow$ recapture of βdn-neutrons

Parameters HEW model ⇨ Y(Z)

Y_e=0.45



No neutrons ⟶ no n-capture r-process!



Nucleosynthesis components:

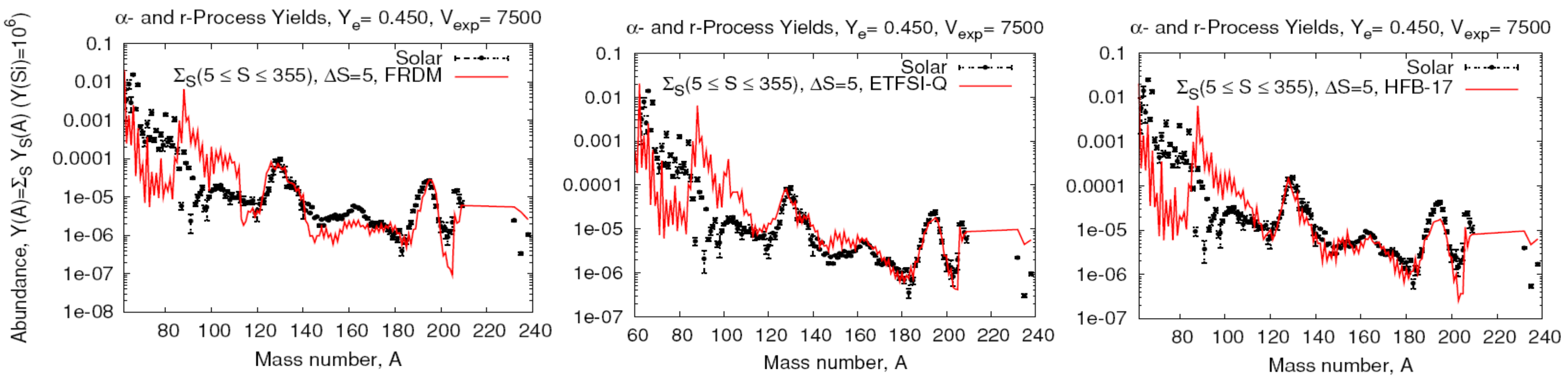
S ≤ 100; Y_n/Y_{seed} < 1
charged-particle (α) process

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 $N_{r,\odot}$

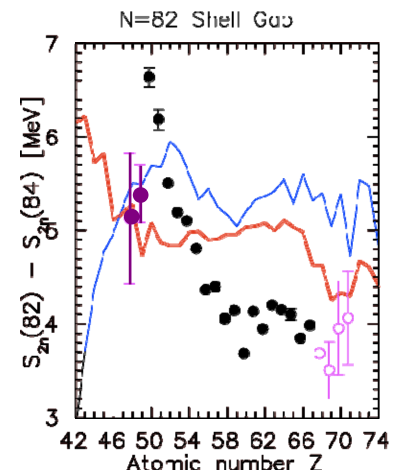
Superposition of S-components with Y_e=0.45;
weighting according to Y_{seed}



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

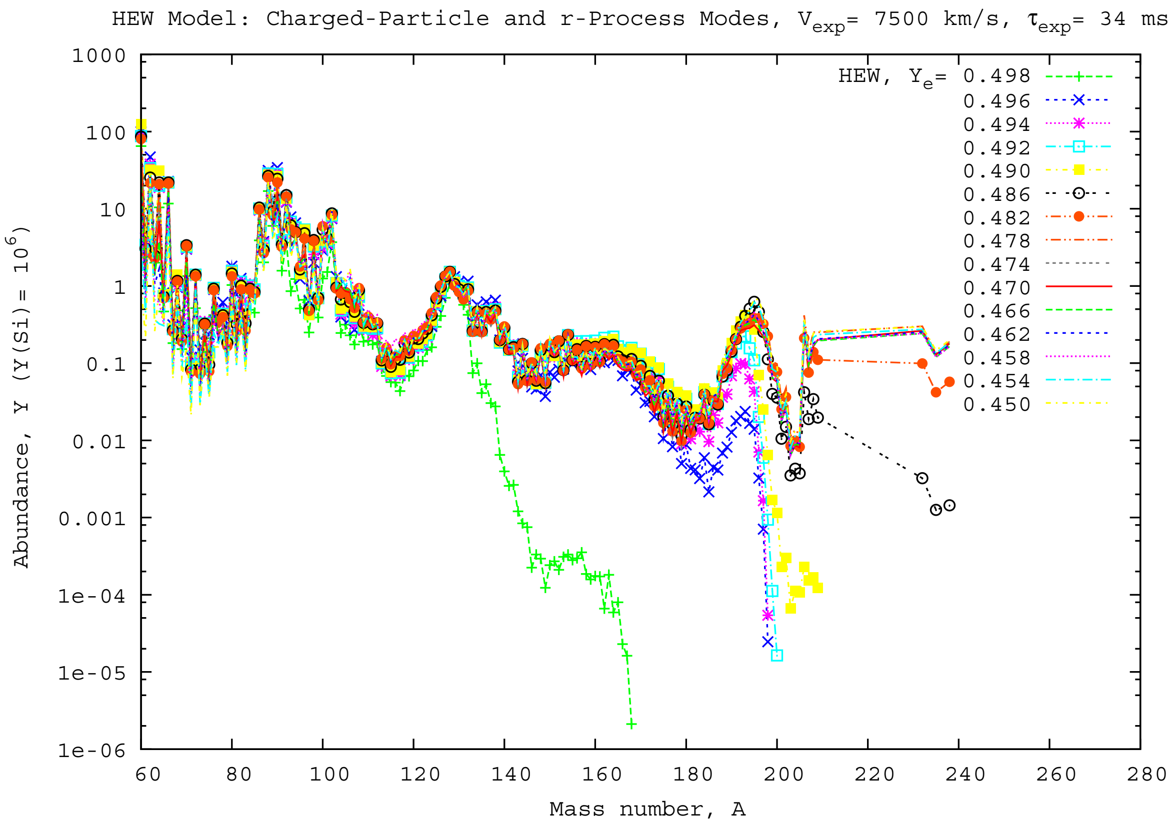


Superposition of HEW components 0.450 ≤ Y_e ≤ 0.498

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

for Y_e=0.400 ca. 5×10^{-4} $M_\odot$

for Y_e=0.498 ca. 10^{-6} $M_\odot$



For Y_e≤0.470
full r-process,
up to Th, U

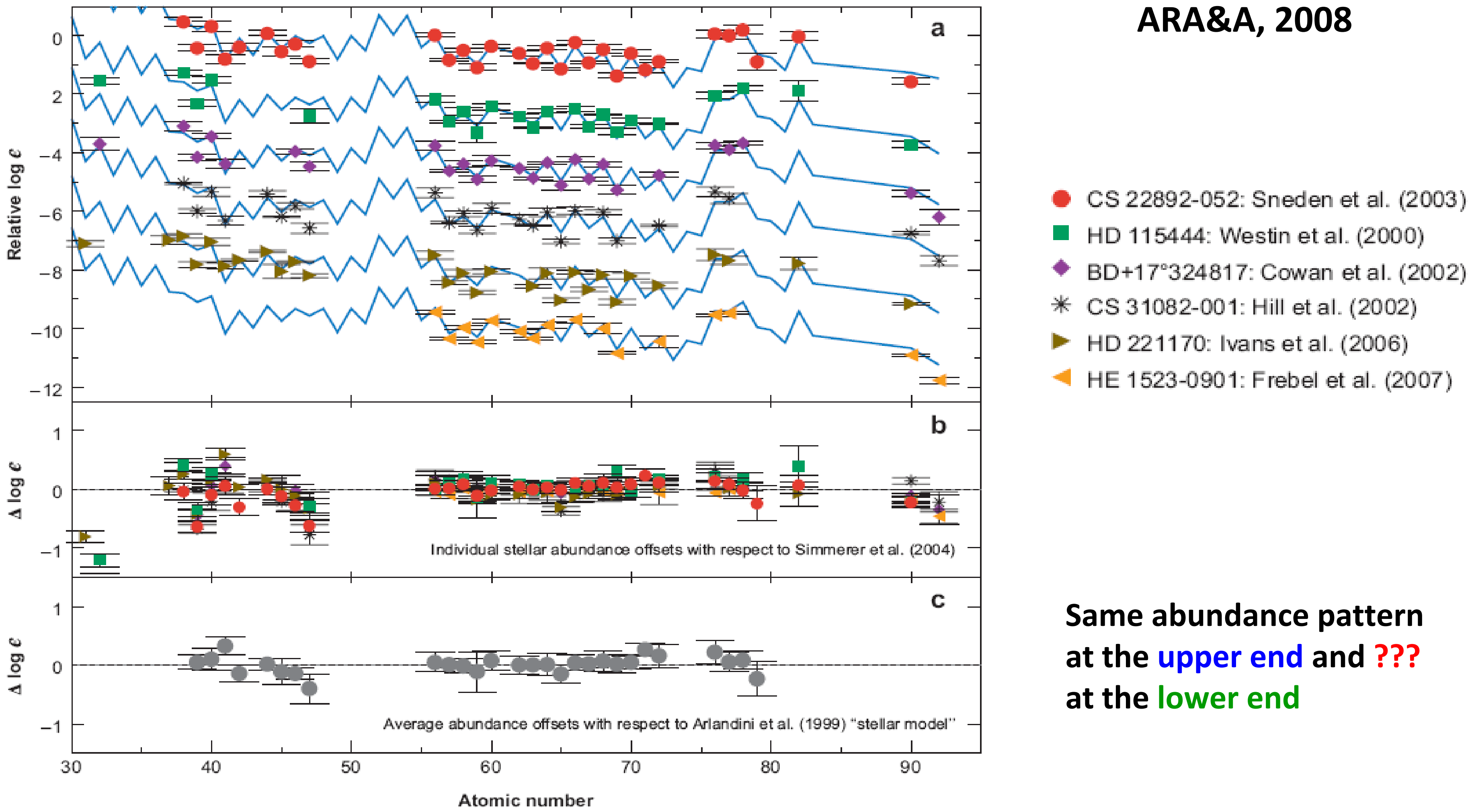
For Y_e≈0.490
still 3rd peak,
but no Th, U

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

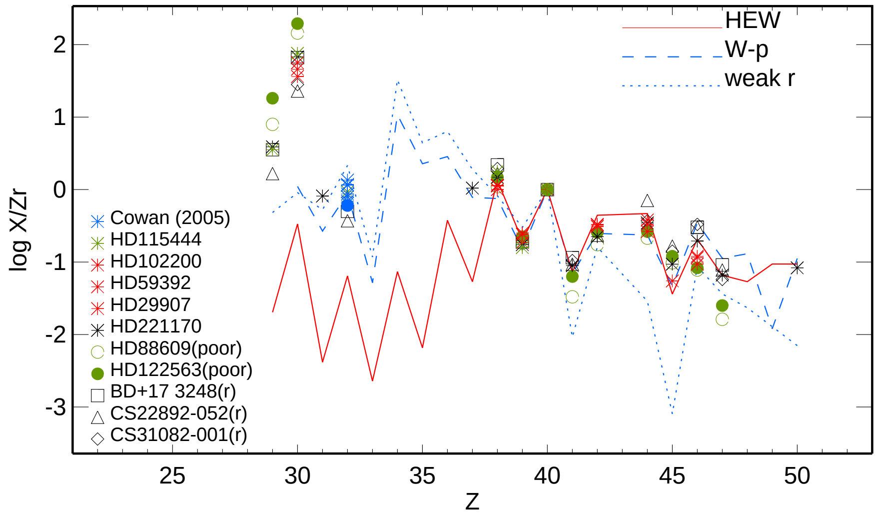


Sneden, Cowan & Gallino
ARA&A, 2008

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

Halo stars vs. HEW model: "LEPP" elements

LEPP-abundances vs. α- enrichment (Zr)

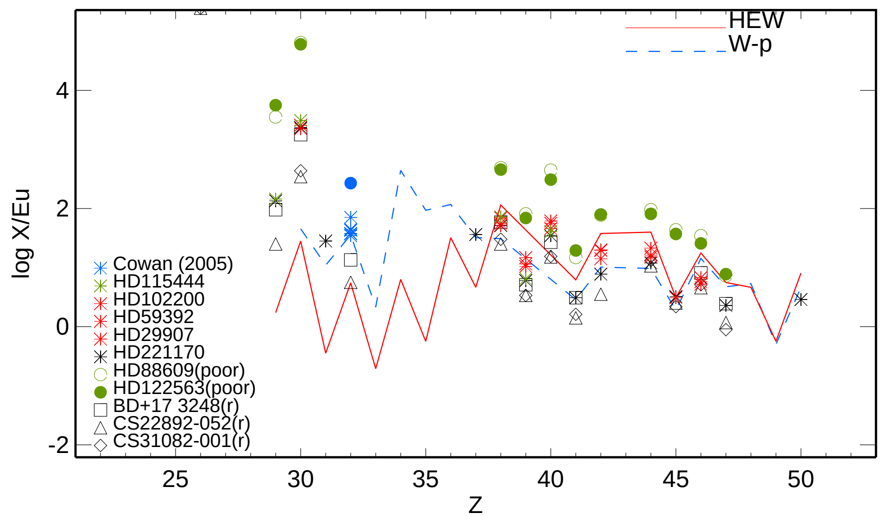


HEW (10 < S < 280)
WP (Fe seed; $10^{20} < n_n < 10^{28}$)
weak-r (Si-Cr seed; $n_n \approx 10^{19}$)

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

↷ **additional nucleosynthesis processes ?**

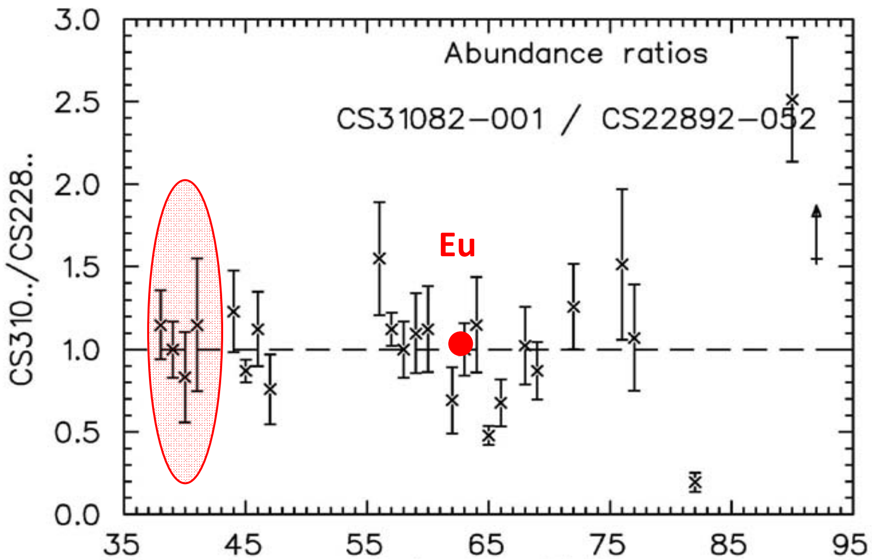
LEPP-abundances vs. r-enrichment (Eu)

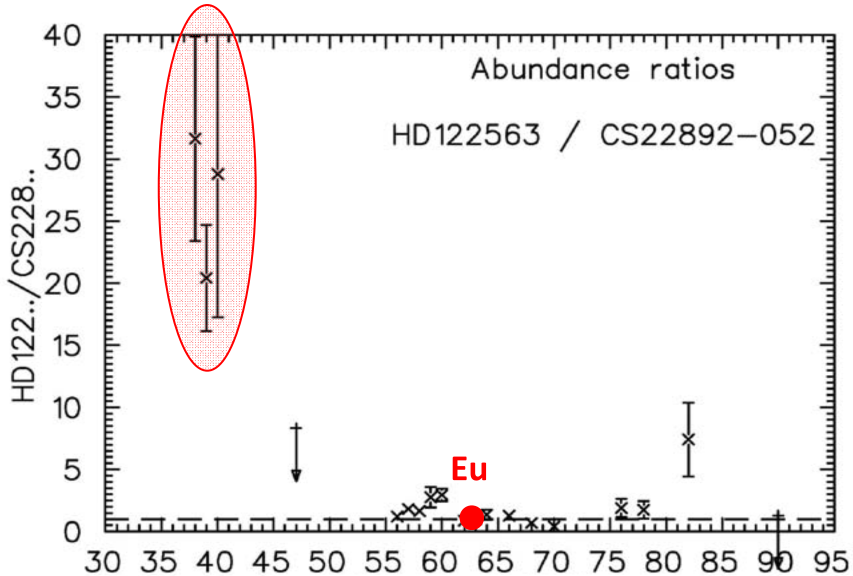


HEW predictions of high-Z LEPP (Sr – Sn)
in between "r-poor" (X/Eu high) and
"r-rich" stars (X/Eu low);
again underestimates low-Z LEPP.

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

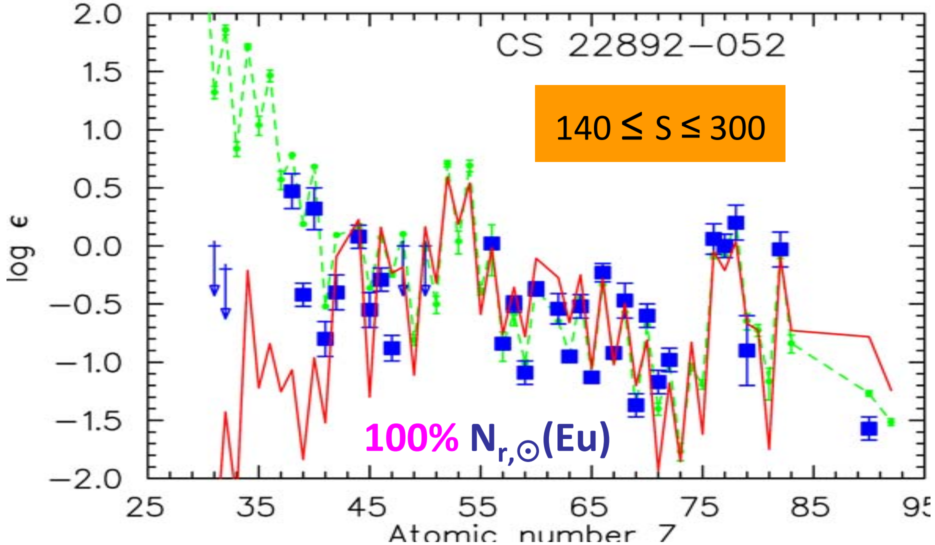
Halo stars vs. HEW-model: Extremes “r-rich” and “r-poor”





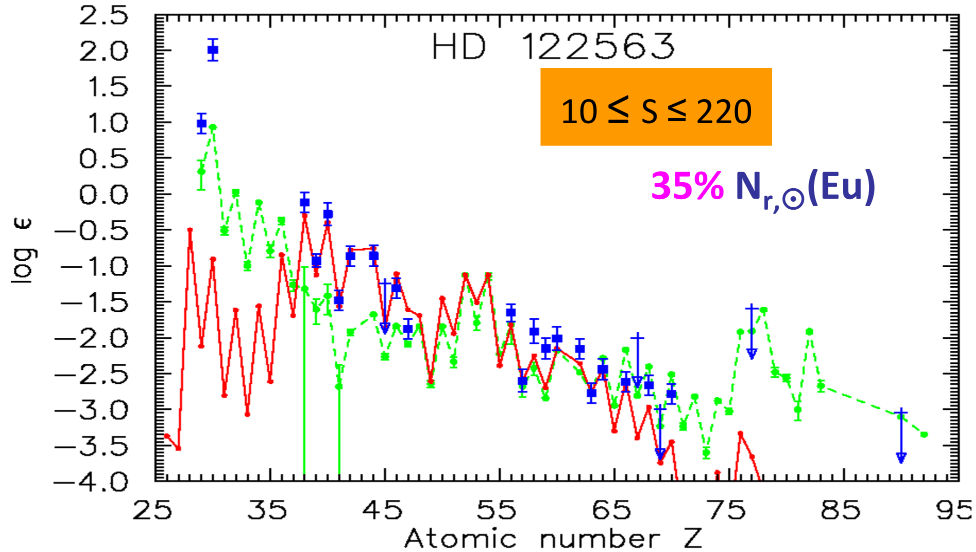
Factor 25 for LEPP region !

r-rich **“Sneden star”**



full main r-process

r-poor **“Honda star”**

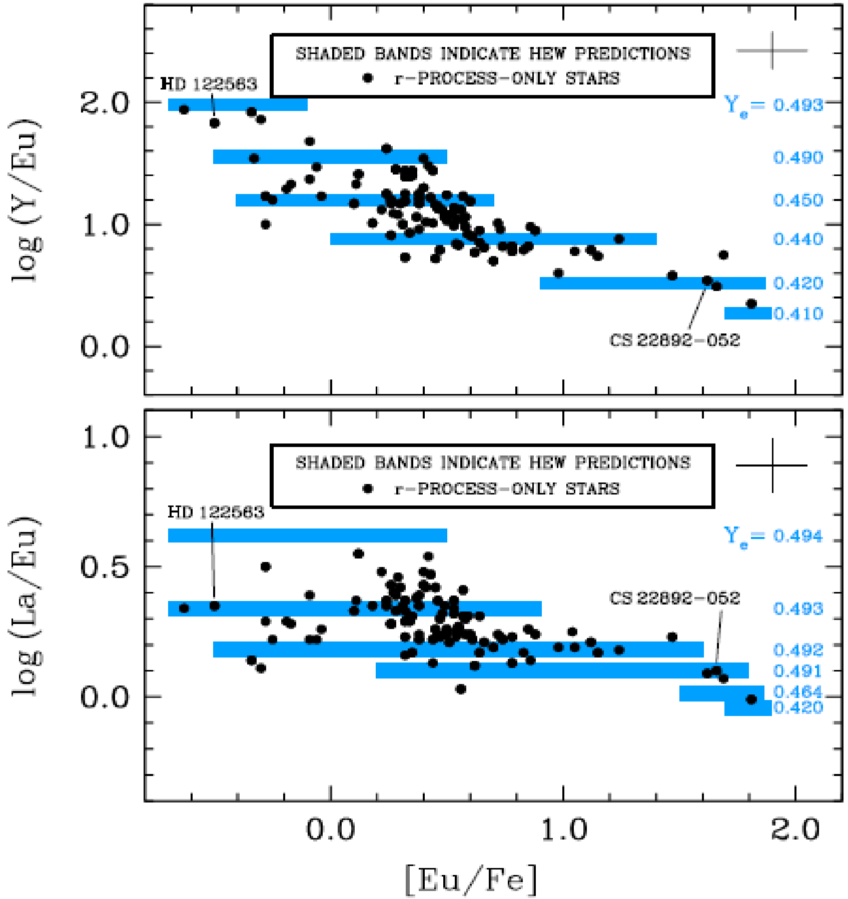


incomplete main r-process

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 charged-particle 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** → →

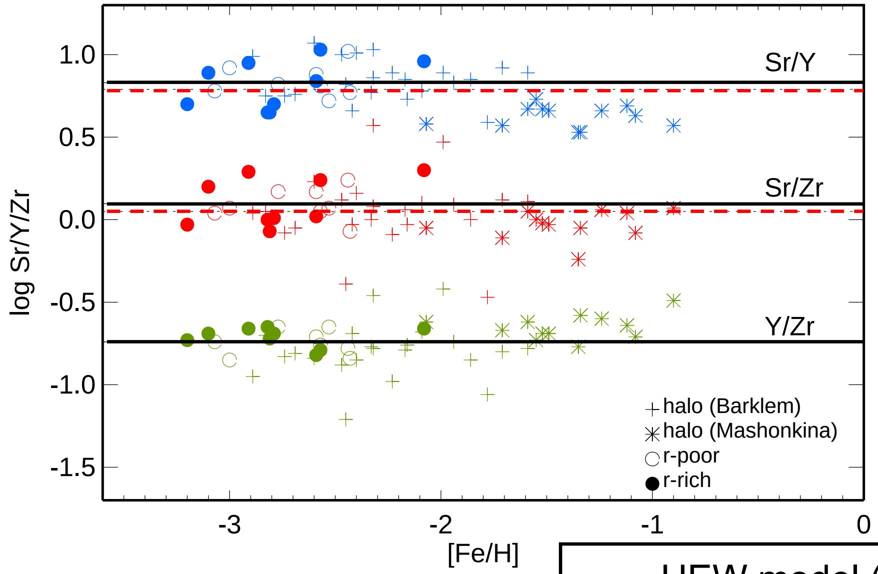
CP component
uncorrelated

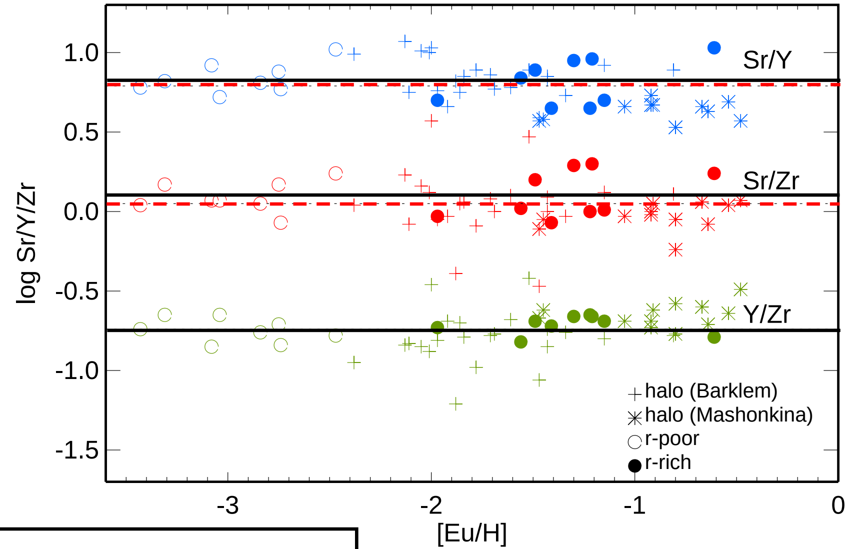
weak-r component
weakly correlated

main-r component
strongly correlated

with Eu ?

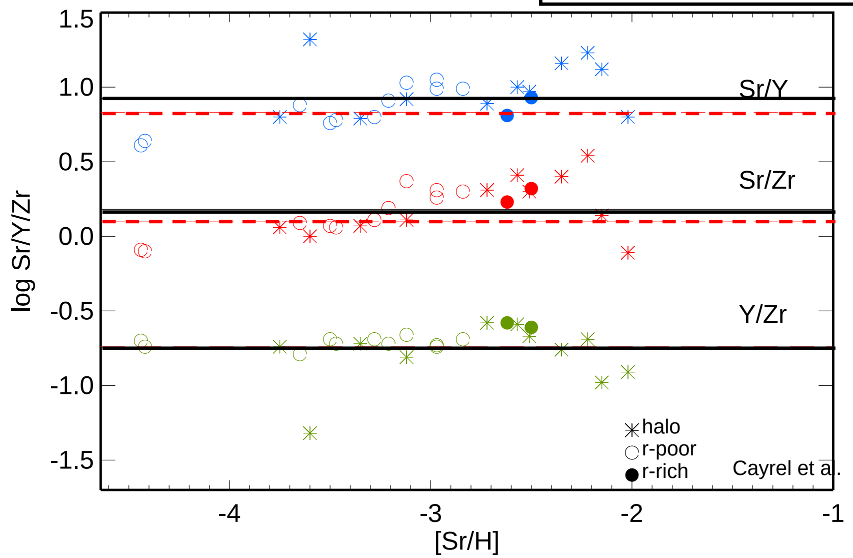
Halo stars vs. HEW model: Sr/Y/Zr as fct. of [Fe/H], [Eu/H] and [Sr/H]





—— HEW model (S ≥ 10); Farouqi (2009)

– – average halo stars; Mashonkina (2009)



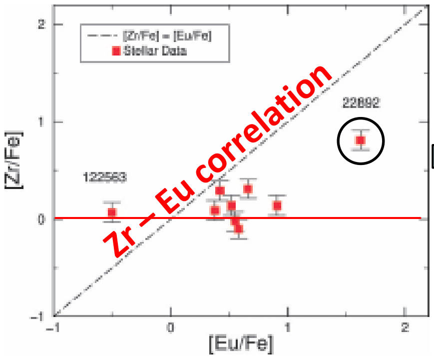
Robust Sr/Y/Zr abundance ratios, independent of metallicity, r-enrichment, α-enrichment.

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

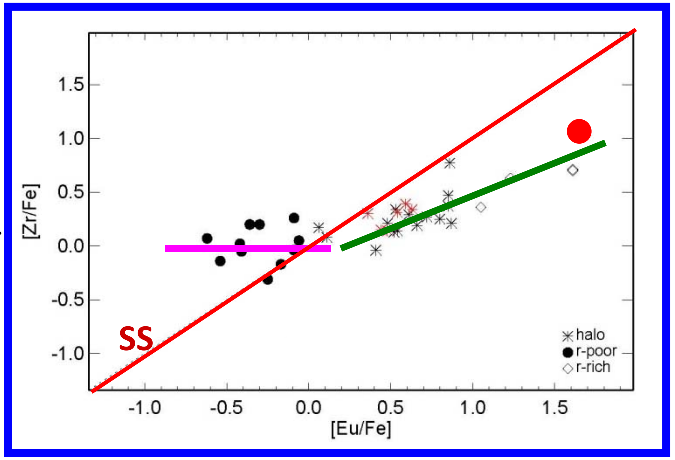
Correlation with main r-process (Eu) ?

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

Cowan et al. (2005)



Mashonkina (2009)



Zr in r-poor stars **overabundant**

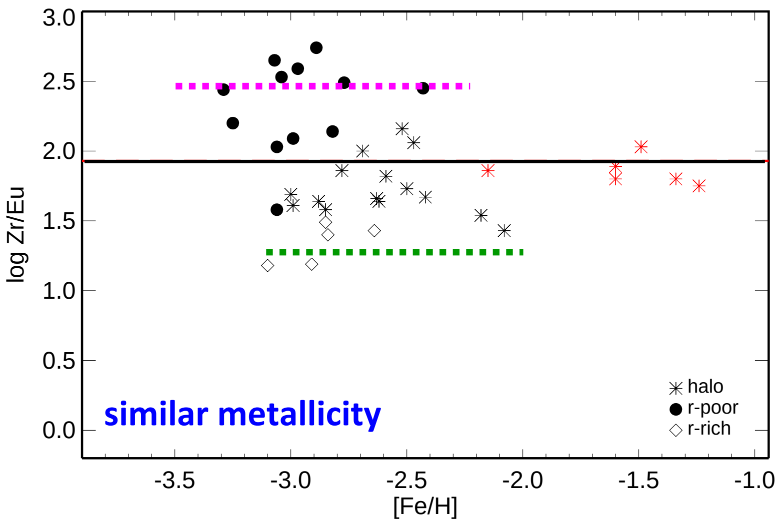
type **"Honda star"**

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

type **"Sneden star"**

Strong Zr – Eu correlation would be indicated by **SS diagonal**

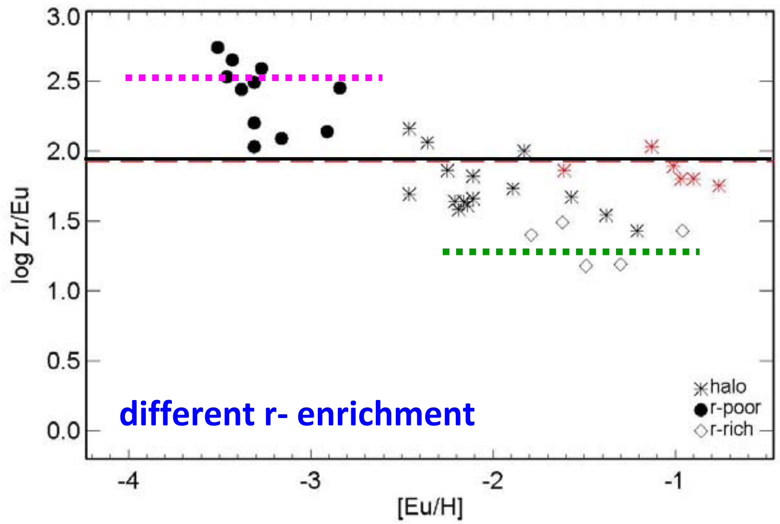
Halo, r-rich and r-poor stars are clearly separated!



r-poor

HEW (av.)

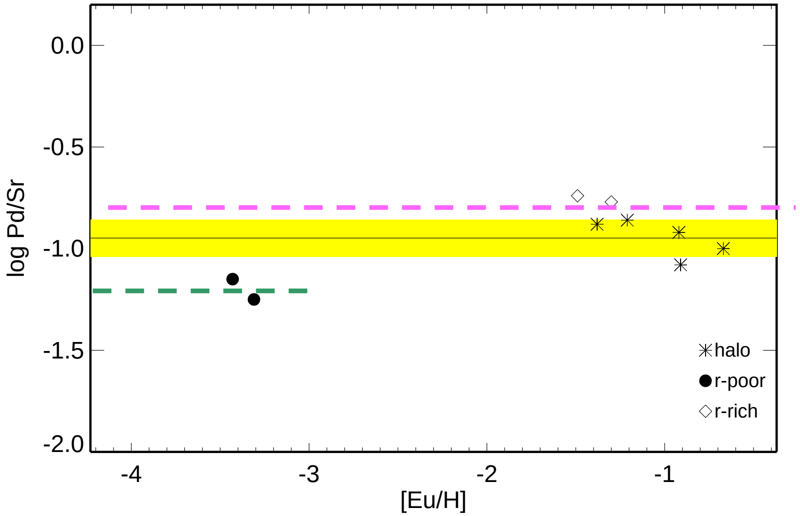
r-rich



Farouqi et al. (2009)

Halo stars vs. HEW-model predictions: Pd

Pd relation to **α-element Sr**



——— **average Halo stars**

-1.5 < [Eu/H] < -0.6

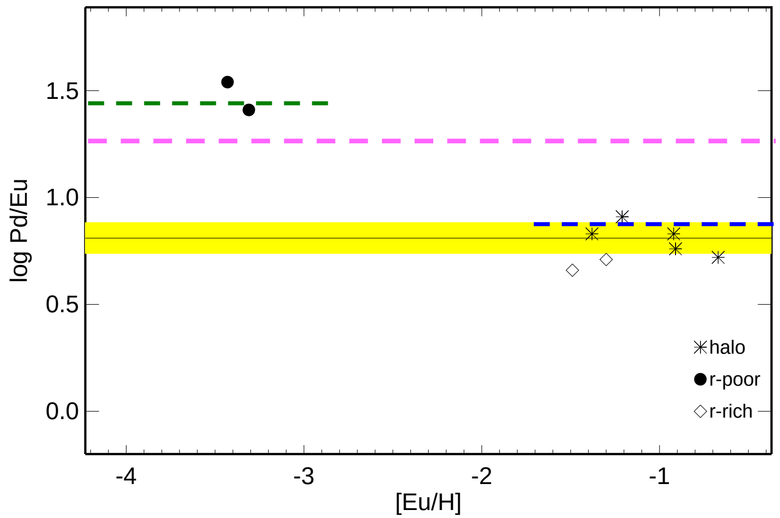
log(Pd/Sr) ≈ - 0.95(0.09)

- - - - **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**

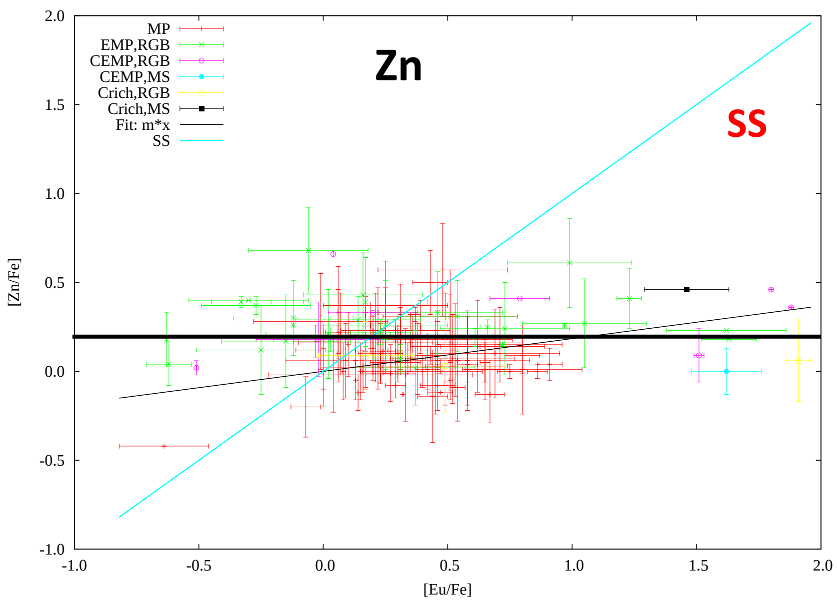
log(Pd/Eu) = +1.25 (Pd α+r)

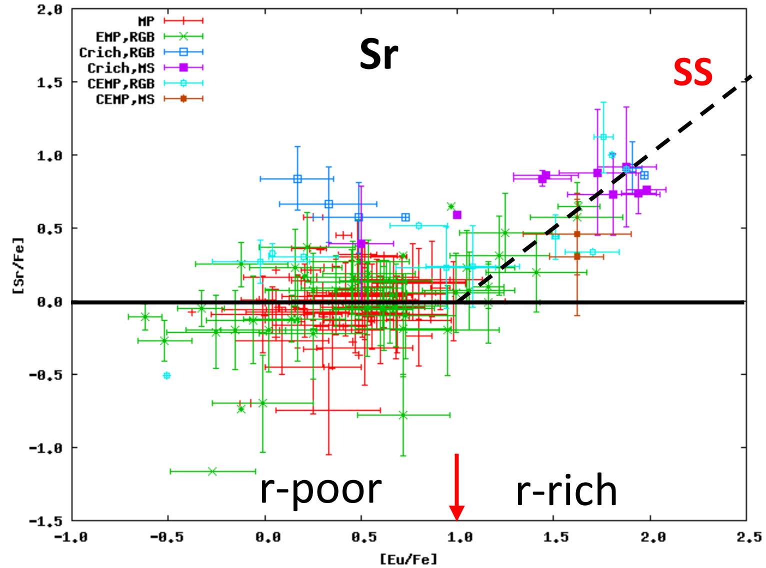
+0.89 (“r-rich”)

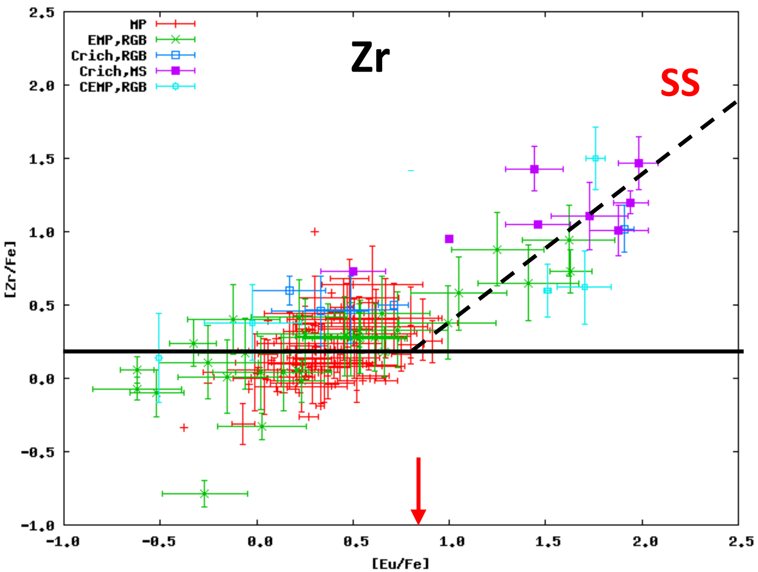
+1.45 (”r-poor”)

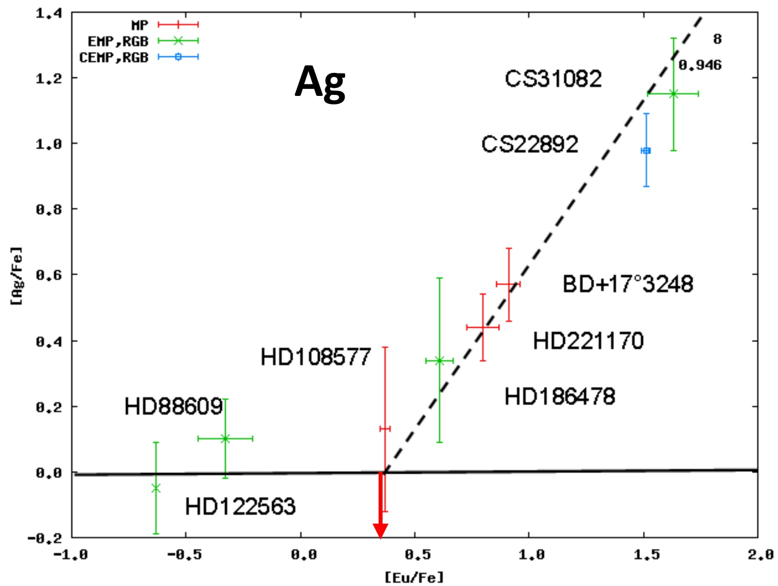
r-poor stars ([Eu/H]<-3) indicate TWO nucleosynthesis components for $_{46}$Pd:
Pd/Sr ⇨ uncorrelated, Pd/Eu ⇨ (weakly) correlated with “main” r-process

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

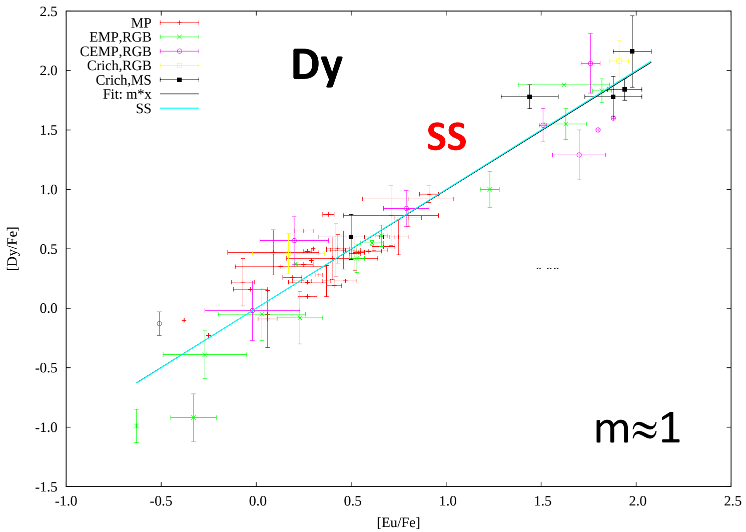


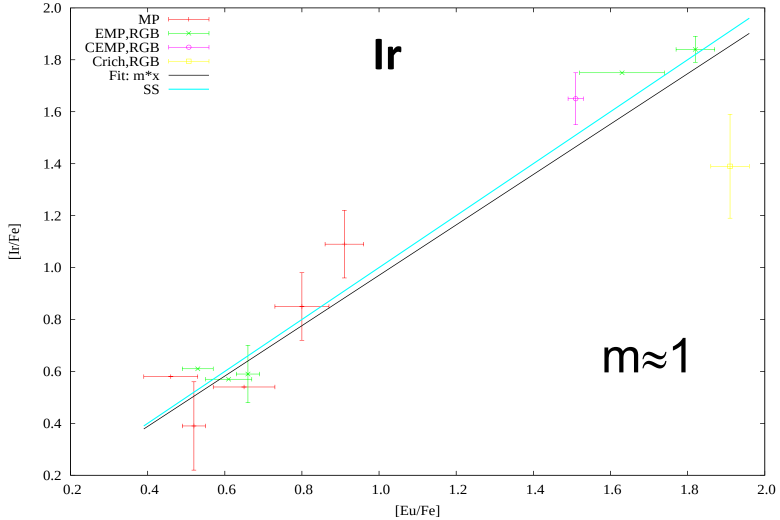


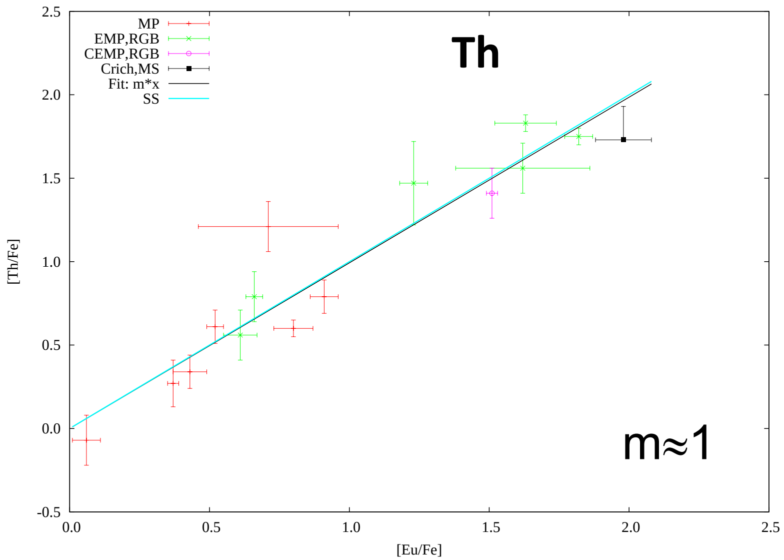




SAGA data base: [X/Fe] vs. [Eu/Fe] (II)

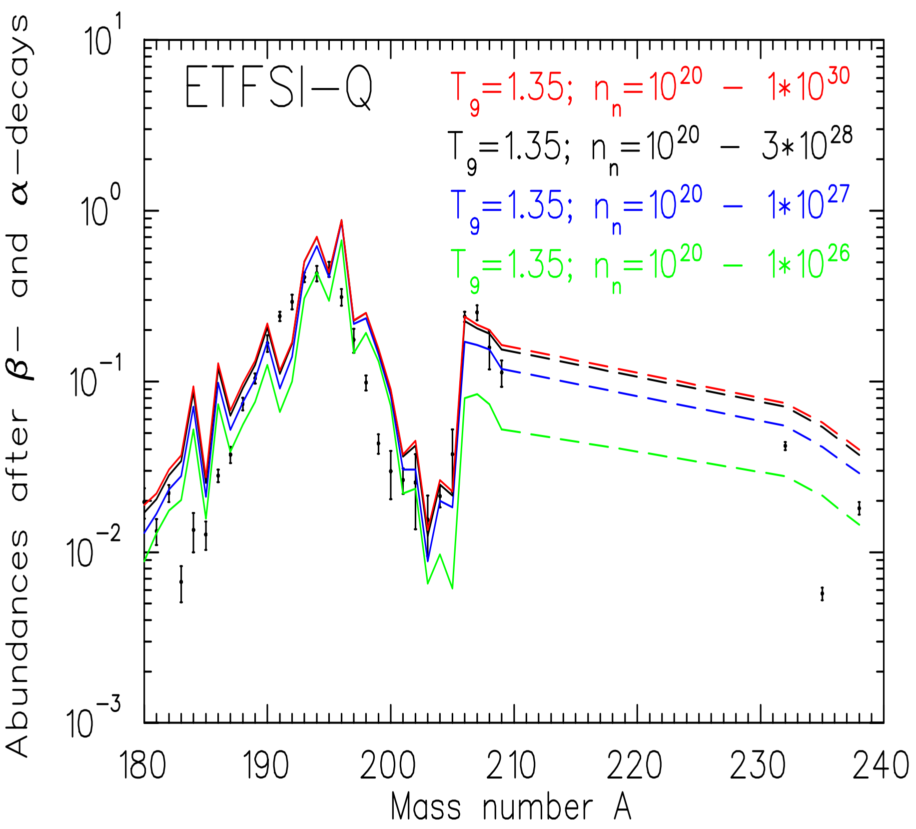




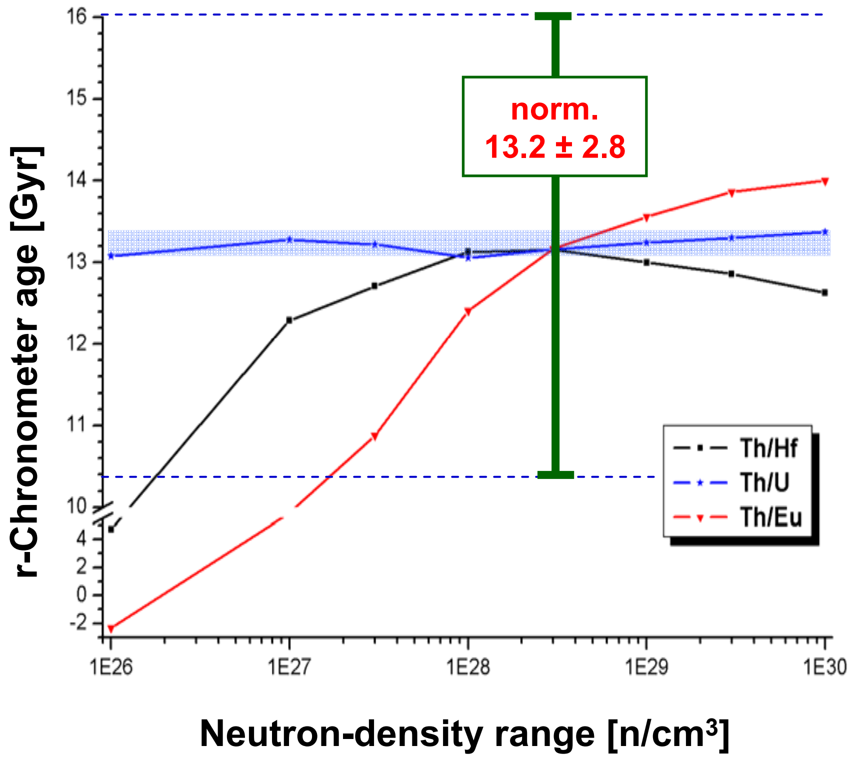


…Th – U – Pb cosmochronology ?!

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



Pfeiffer, Kratz (1999)



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

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

How about Pb as r-chronometer ?

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

≈ 85% abundance from α-decay from actinide region

Sensitivity to age:

Pb

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

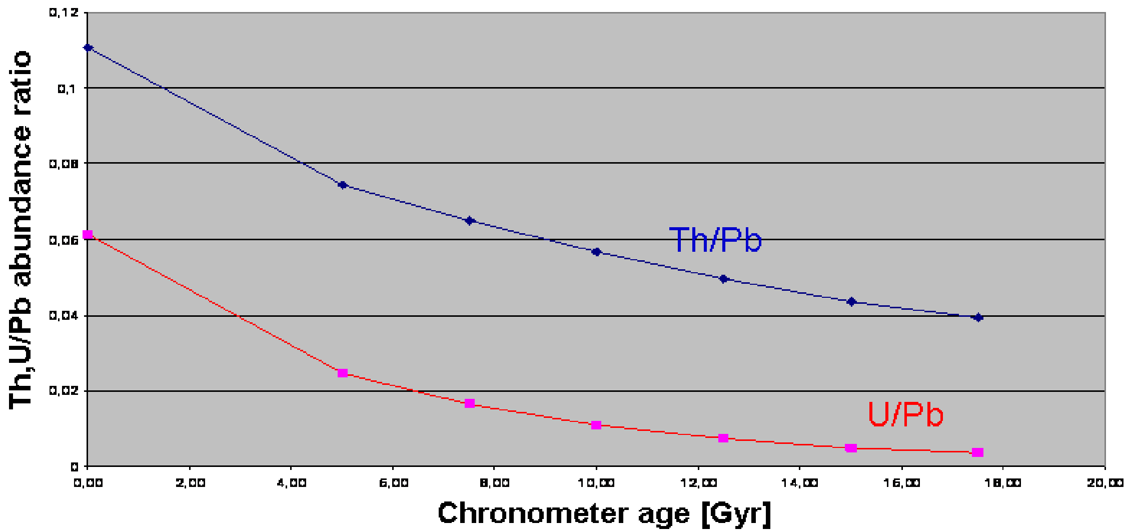
5 Gyr 0.433

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 (HE 1523-0901; [Fe/H] ≈ -3)
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