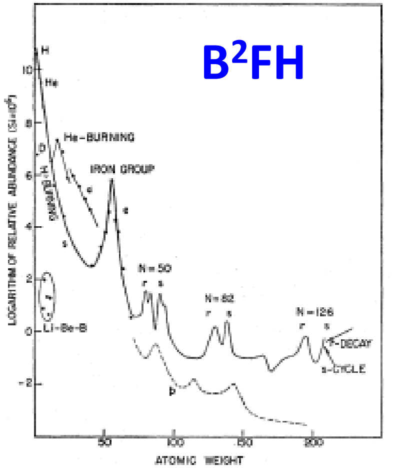
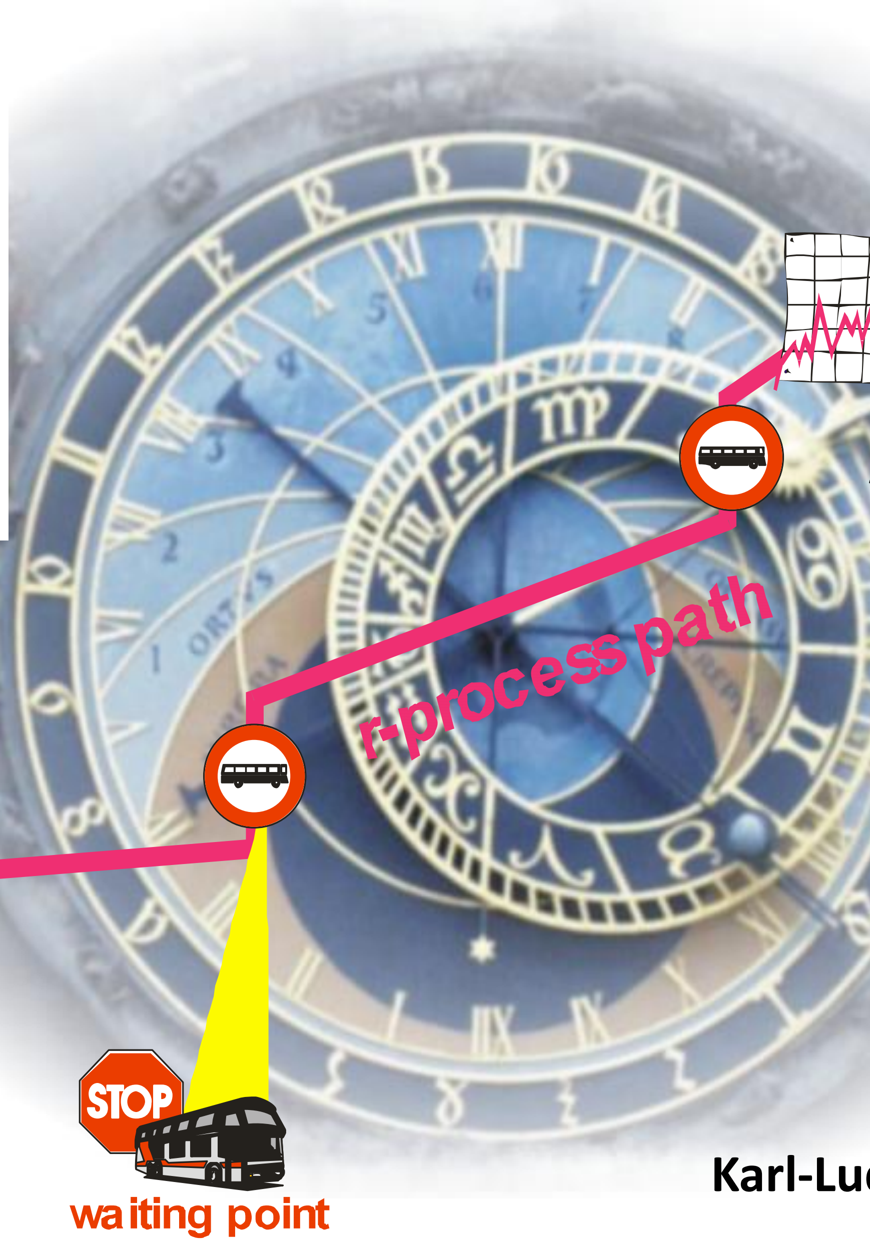
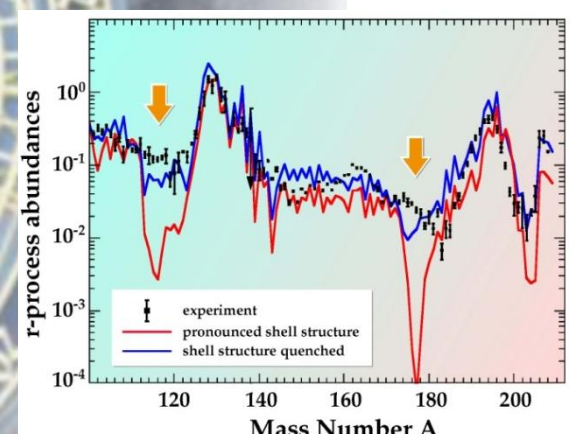
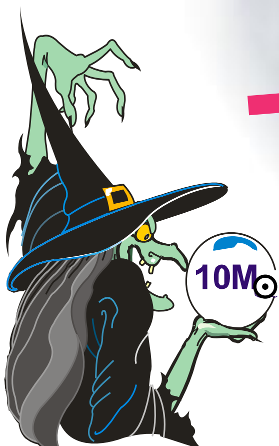
Introduction to the r-process









MAX-PLANCK-GESELLSCHAFT

Karl-Ludwig Kratz

MAX-PLANCK-INSTITUT FÜR CHEMIE

Russbach, 2013

Some early milestones

0.000 creation of the Universe → Friday, summary session

1859 first **spectral analysis** of the sun and stars
by **Kirchhoff & Bunsen** → ”chemistry of the cosmos“

1920 hypothesis that the sun is powered by **nuclear reactions**
by **Eddington**

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

1937 first systematic tabulation of **solar abundances**
by **Goldschmidt**

1957 fundamental paper on **nucleosynthesis**
by **Burbidge, Burbidge, Fowler & Hoyle** (**B^2FH**)

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.**

...56 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

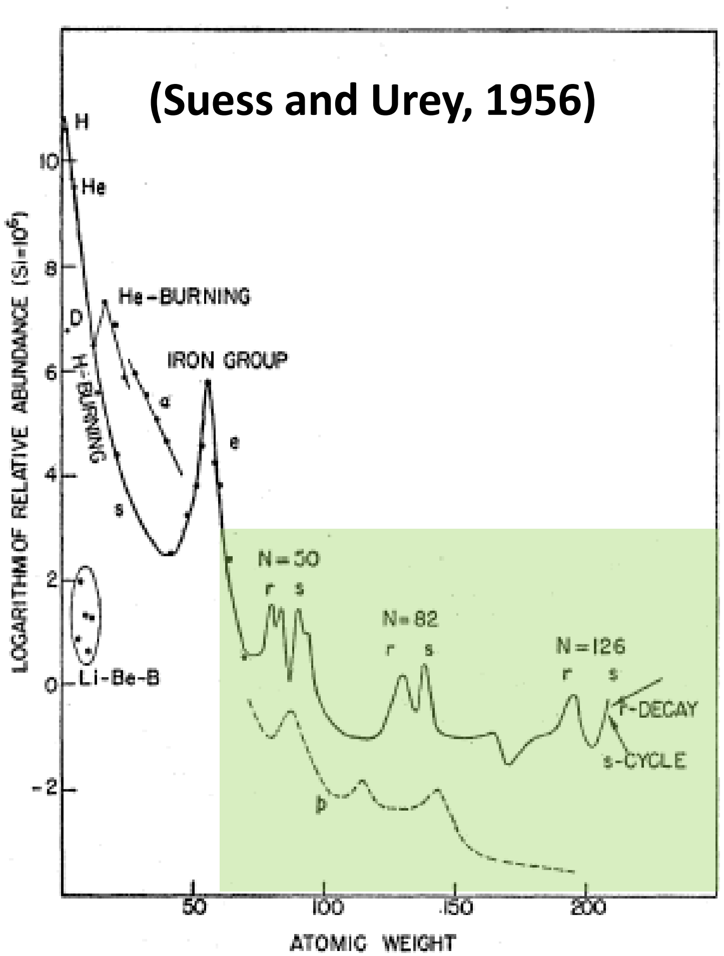
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"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

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

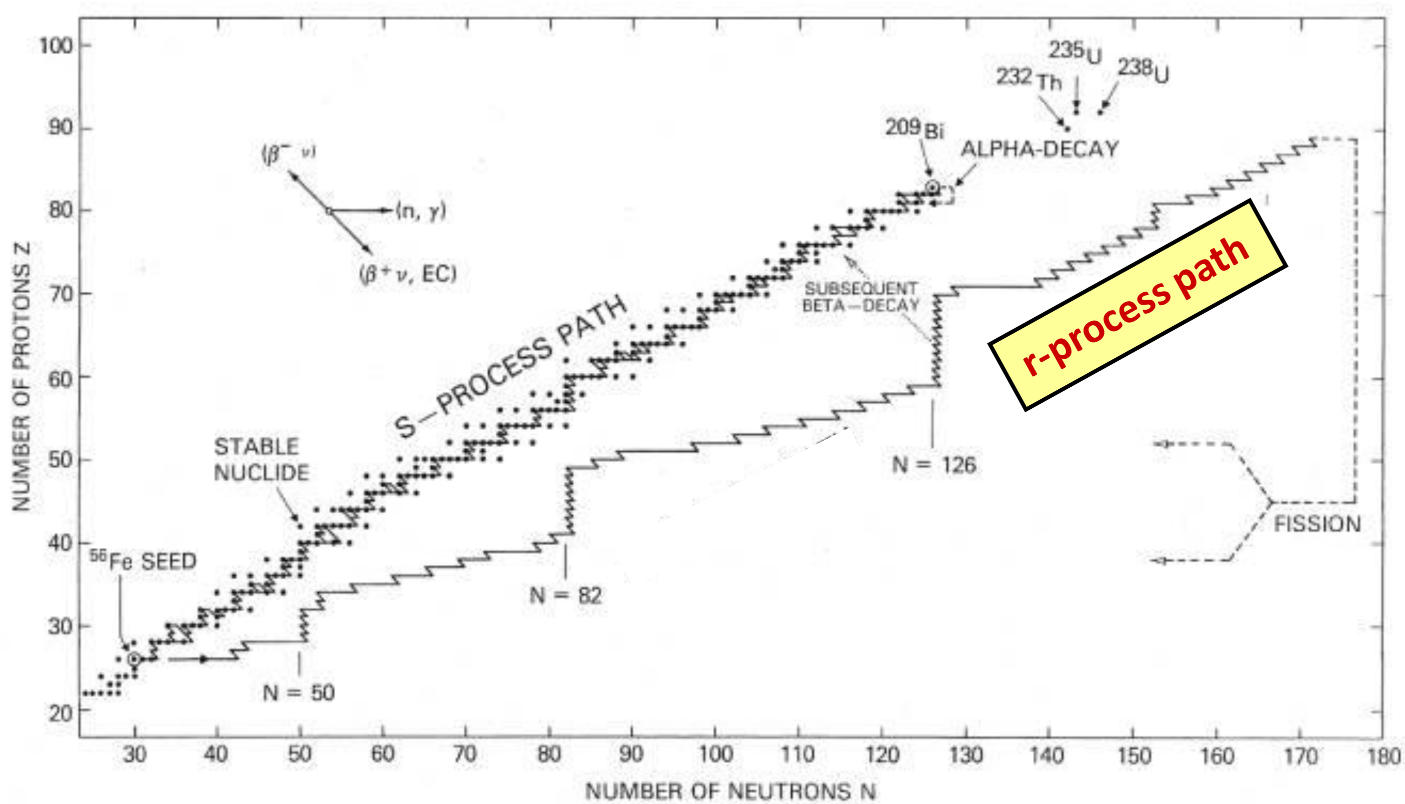


FIGURE 9.13. Neutron-capture paths for the *s*-process and the *r*-process are shown in the (*N*, *Z*)-plane. Both paths start with the iron-peak nuclei as seeds (mainly ^{56}Fe). The *s*-process follows a path along the stability line and terminates finally above ^{209}Bi via α-decay (Cla67). The *r*-process 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	**$2 \cdot 10^{-7}$**

(from **“Cauldrons in the Cosmos”**)

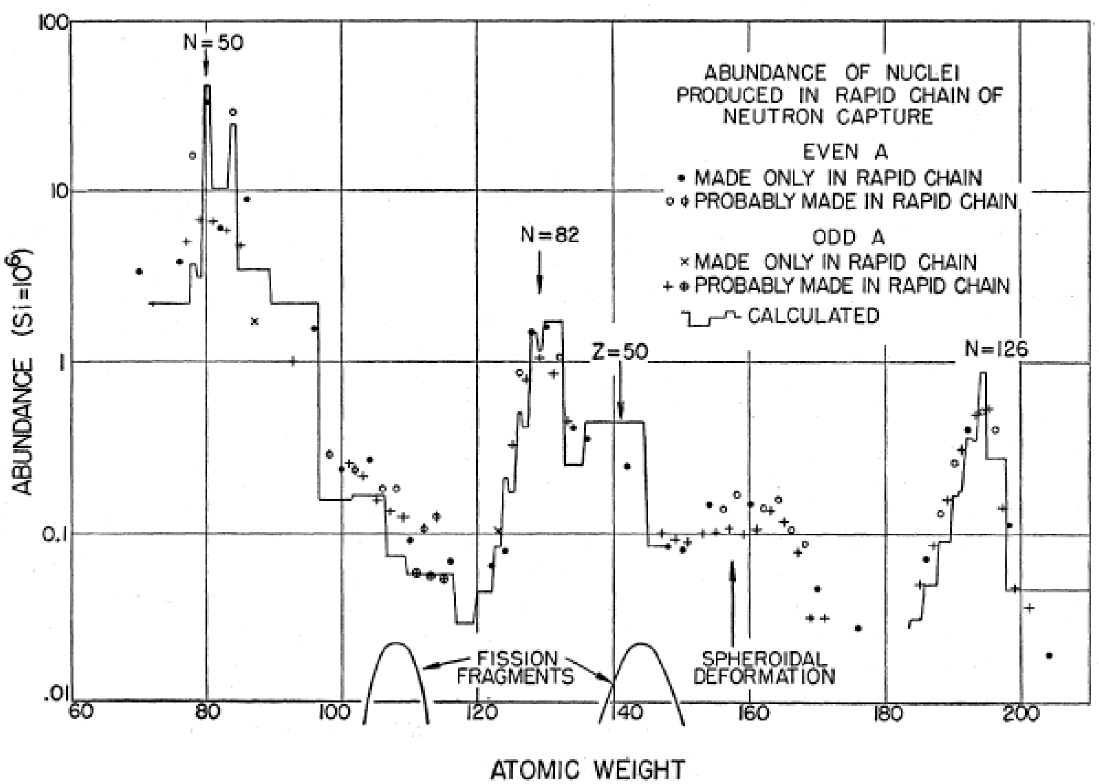
Fit of $N_{r,\odot}$ from B²FH

„Static“ **calculation**

Reproduction of Solar system isotopic r-process abundances

(mainly from r-only nuclei)

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



The r-process "waiting-point" concept (1)

Concept already used by B[2]FH

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:

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

cross section averaged over Maxwell-Boltzmann velocity distribution to T_9

Photodisintegration:

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

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

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

Nuclear Saha equation

The r-process "waiting-point"concept (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
- low S_n
- 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 β-decays from isotopic chain Z to (Z+1)

***β*-decay flow equilibrium**

implies (n,γ)-(γ,n) equilibrium

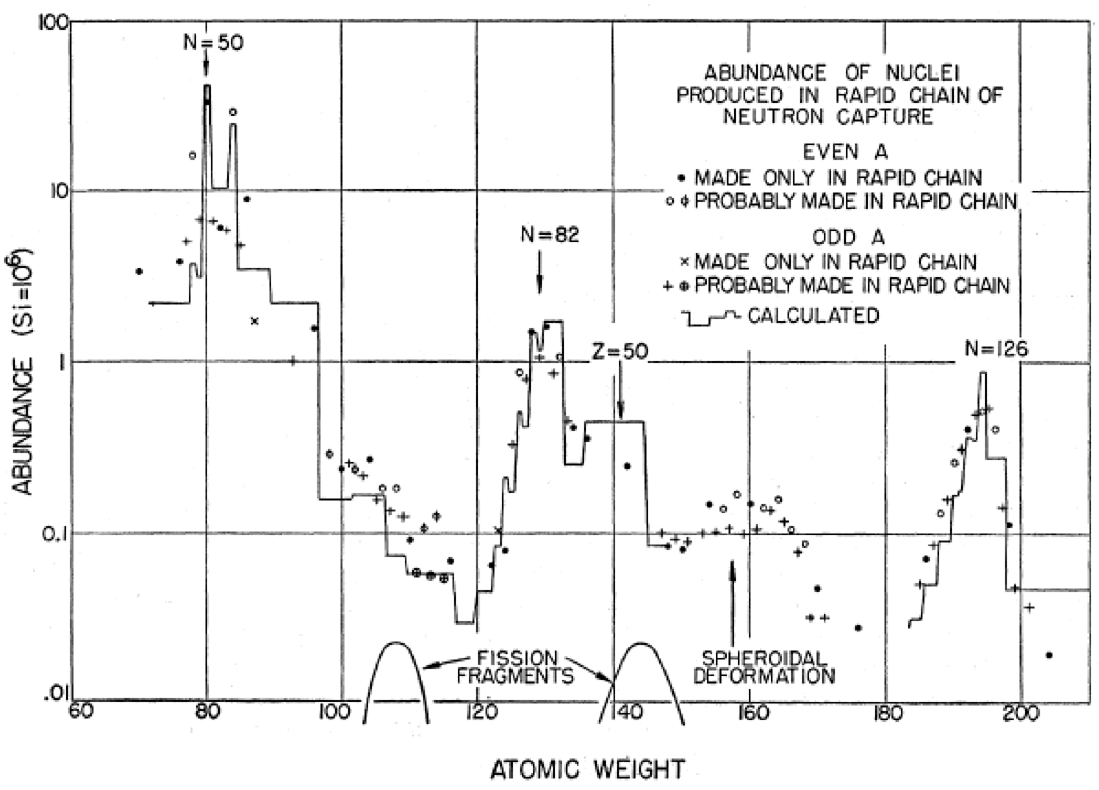
$$\tau_\beta > \tau_{n,\gamma}, \tau_{\gamma,n}$$

$T_{1/2}$ ("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)



„Static" calculation

- **assumptions**

  iron seed (secondary process)

  „waiting-point" concept

  (global $(n,\gamma) \leftrightarrow (\gamma,n)$ and ß-flow equilibrium)

  instantaneous freezeout

- **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:**

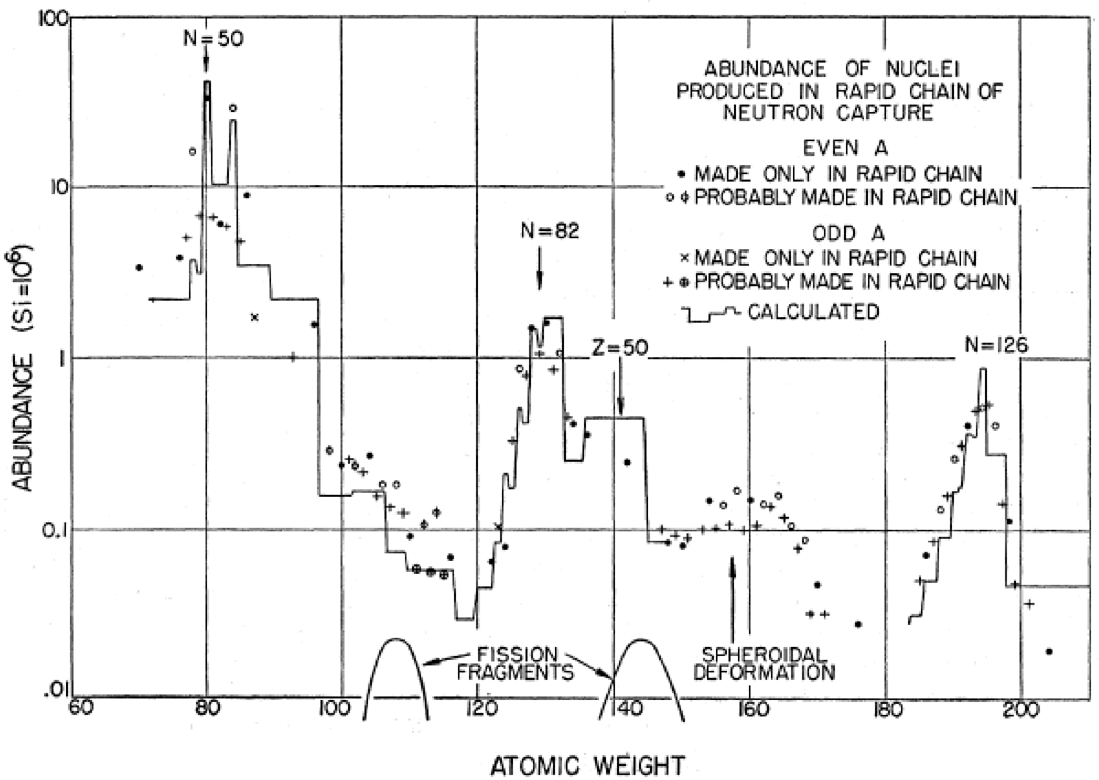
  $^{21}Ne(\alpha,n)$

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

„Static“ calculation

Reproduction of Solar system
isotopic r-process abundances

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



- **assumptions**
  - **iron seed** (secondary process)
  - **„waiting-point“ concept**
    (global $(n,\gamma) \leftrightarrow (\gamma,n)$ and
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    - $n_n \approx 10^{24}$ cm^{-3} (constant)
    - $\tau_r \approx 100$ s

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

- **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-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

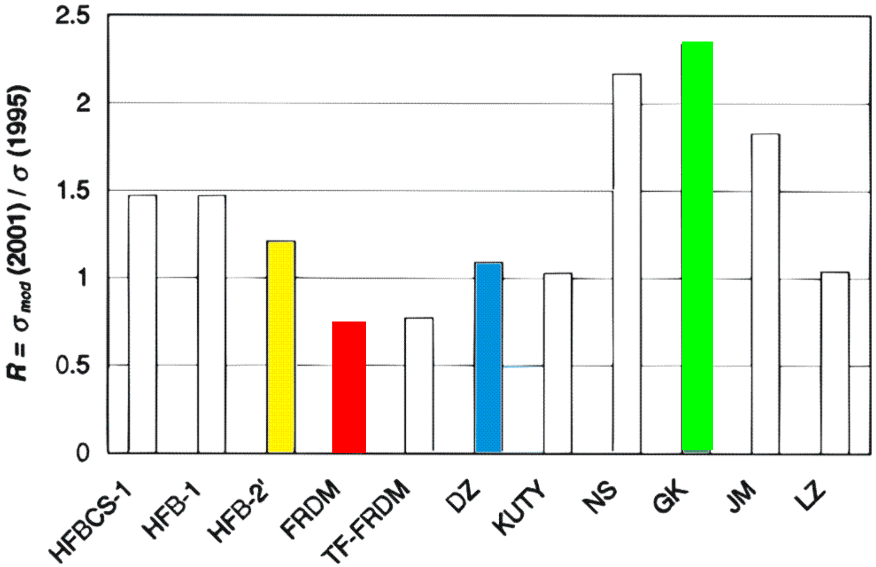
- **nuclear structure development**

  - 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. GTNM; KUTY; INM; DZ)
- Macroscopic-microscopic models
  (e.g. **FRDM**; TF; ETFSI)
- Microscopic models
  (e.g. RMF; **HFB**)



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

Comparison to NUBASE (2003)

FRDM (1995) σ_{rms} = 0.669 [MeV]
ETF-Q (1996) σ_{rms} = 0.818 [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]

No significant improvement of σ_{rms}

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

HFB-21 (2011) σ_{rms} = 0.577 [MeV]
FRDM (2012) σ_{rms} = 0.559 [MeV]

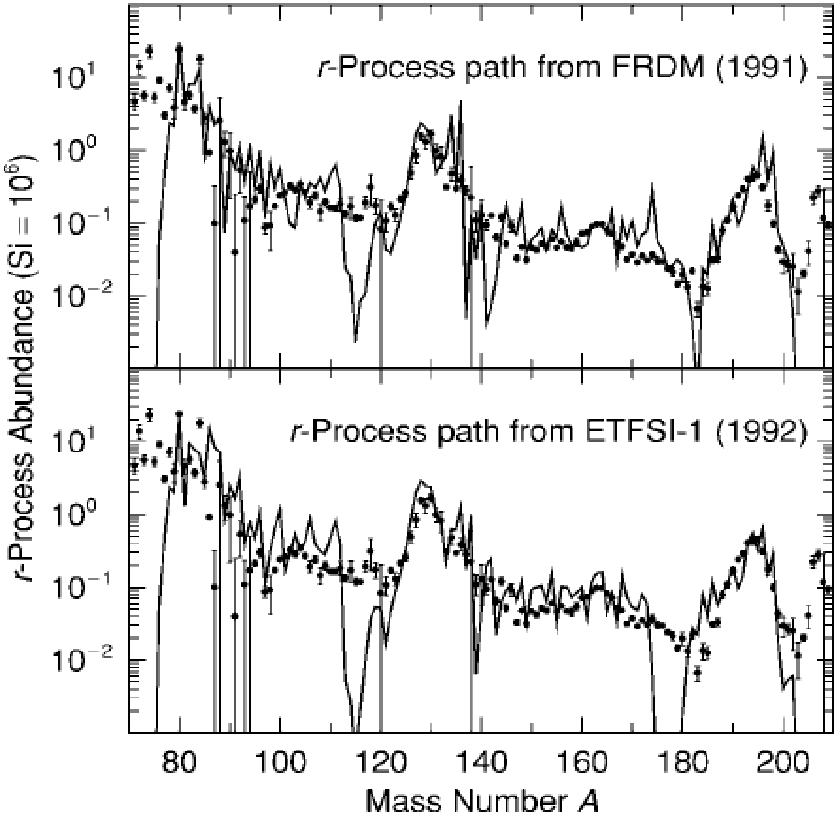
However, still today main deficiencies at N_{magic} and in shape-transition regions !

Mass models for r-process calculations

Apart from the frequently used “Hilf mass formula” (GTNM),
best macroscopic-microscopic global mass models 20 years ago,
used for r-process calculations.

Still local deficiencies below and above the A≈130 and A≈195 $N_{r,\odot}$ peaks.

Nuclear structure origin ?



From Möller-Nix-Kratz, ADNDT 66 (1997)

Figure 36. Calculated r-process abundances (solid lines) compared to measured values (solid circles). For both the upper and lower parts of the figure β-decay half-lives and delayed-neutron emission probabilities are calculated in a QRPA model based on folded-Yukawa single-particle energies, but experimental information has been used when available. In the upper part of the figure the r-process path was determined from the FRDM (1991) [50, 77], and in the lower part of the figure it was determined from the preliminary, privately circulated version of the ETFSI-1 (1992) model [52, 53].

Nuclear-data needs for the classical r-process

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

Theoretically, the gross β-decay quantities, $T_{1/2}$ and P_n, are interrelated via the so-called

β-strength function [$S_\beta(E)$]

"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)

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

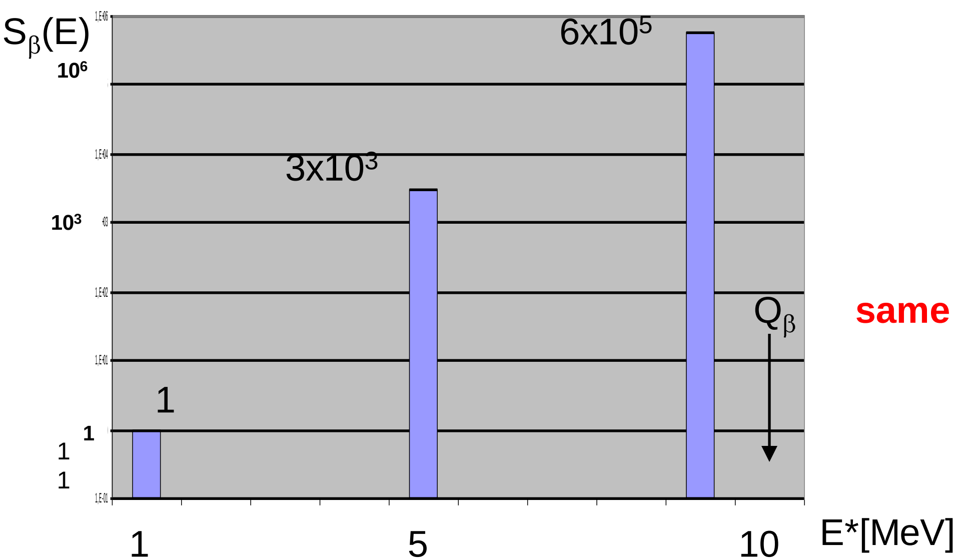
b(E) absolute β-feeding per MeV,

$f(Z, Q_\beta\text{-}E)$ Fermi function,

$T_{1/2}$ β–decay half-life.

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

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



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

same $T_{1/2}$!

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

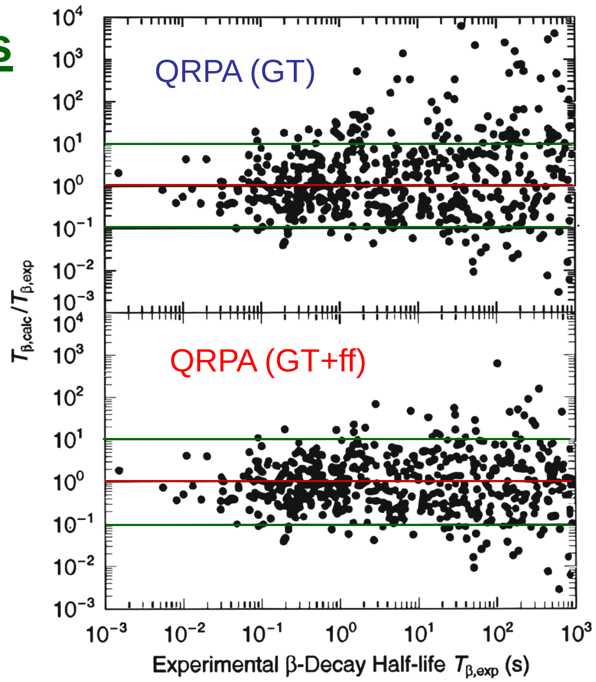
Global $T_{1/2}$ & P_n – calc. vs. exp.

$T_{1/2}$, 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

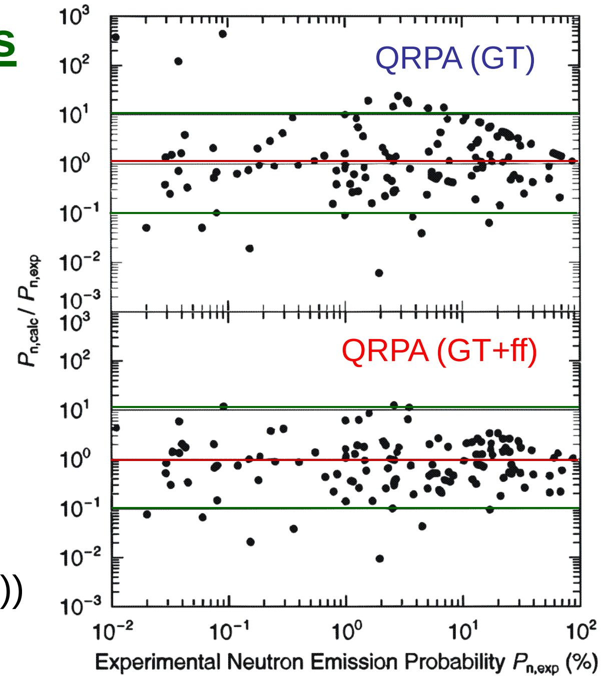


Total Error = 3.08

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

Total Error = 5.54

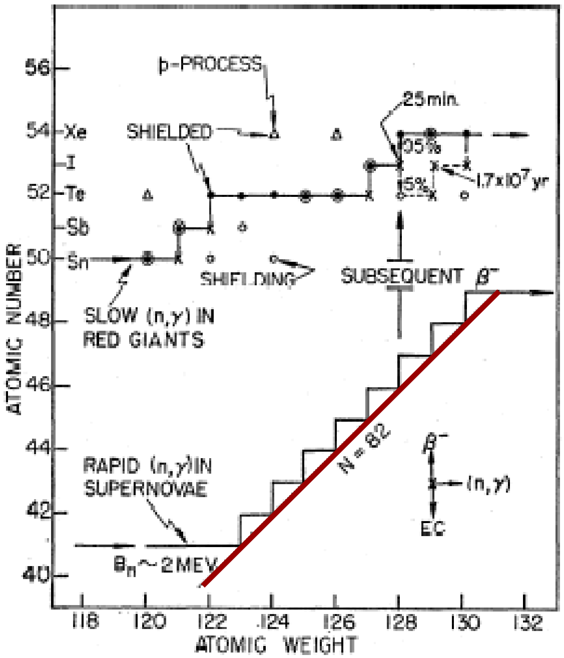
P_n-Values



Total Error = 3.52

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

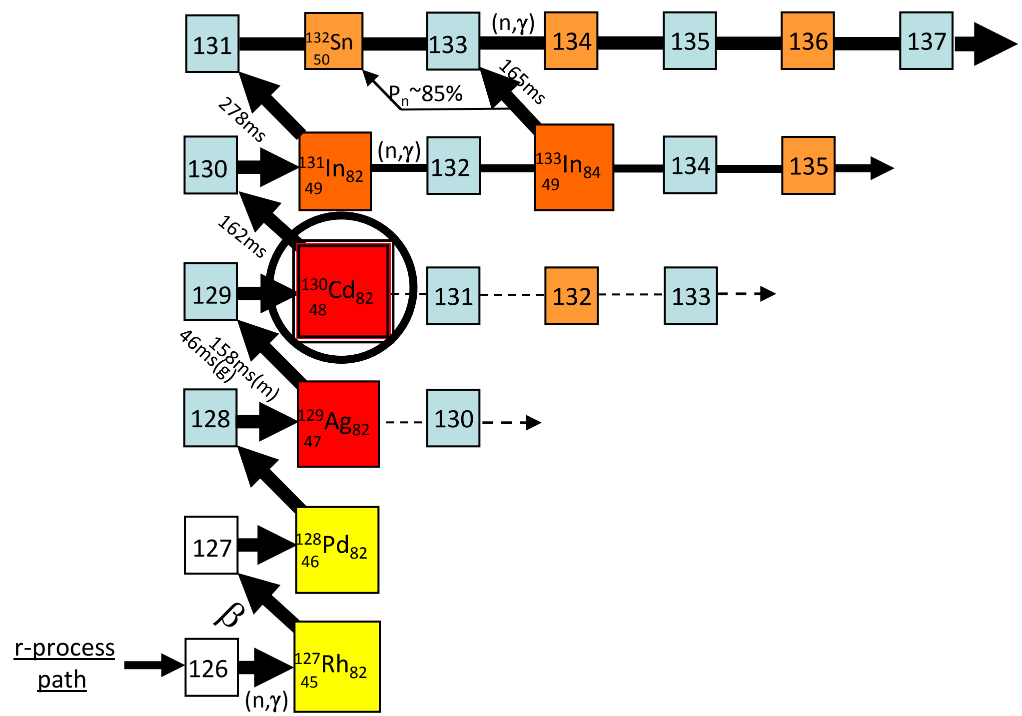
already B²FH (Revs. Mod. Phys. 29; 1957)
C.D. Coryell (J. Chem. Educ. 38; 1961)



"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 (Rev. Mod. Astr. 1; 1988)

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

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

"Waiting-point" estimate $T_{1/2}(^{130}Cd)$

Model predictions (S.M. & Gr.Th.) in the mid 1980s: **$30\ ms \leq T_{1/2} \leq 1.2\ s$**

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.

$$\frac{T_{½}\,(^{131}\mathrm{In}_{82})}{N_{r,\odot}(^{131}\mathrm{Xe})} = \frac{T_{½}\,(^{130}\mathrm{Cd}_{82})}{N_{r,\odot}(^{130}\mathrm{Te})} = \frac{T_{½}\,(^{129}\mathrm{Ag}_{82})}{N_{r,\odot}(^{129}\mathrm{Xe})} \ldots$$

From this assumption, in 1986 the waiting-point prediction for $T_{½}(^{130}Cd)$ ≈ **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 ≈ 90%

$$T_{½}\,(^{130}\mathrm{Cd}) \approx \frac{N_{r,\odot}(^{130}\mathrm{Te})}{\left[N_{r,\odot}(^{131}\mathrm{Xe})/T_{½}(^{131}\mathrm{In})\right]+\left[1.1N_{r,\odot}(^{132}\mathrm{Xe})/T_{½}(^{133}\mathrm{In})\right]} \approx \mathbf{170\ ms}$$

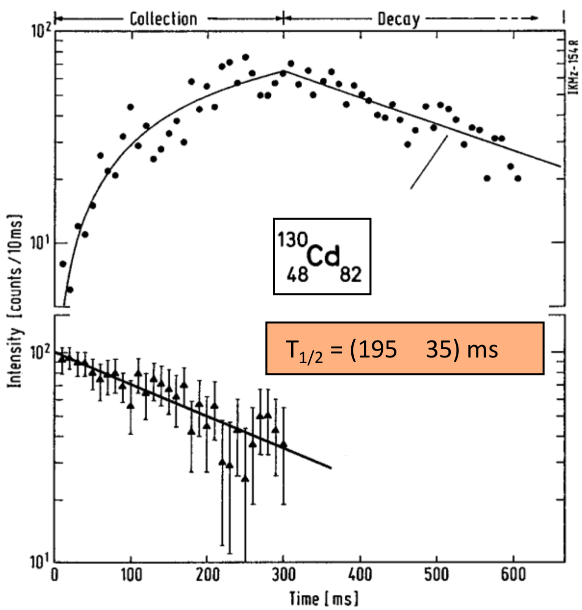
…later to be compared to experimental value

What we knew already in 1986 …

Z. Phys. A325, 489 (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



In 2001 with RILIS, improved
$T_{1/2}$ = (162 7) ms

Exp. at old SC-ISOLDE
with **plasma ion-source**
quartz transfer line
and **βdn counting**

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

Exp. $T_{1/2}$
excludes explosive He-burning
favored at that time;
supports cc-SN scenario.

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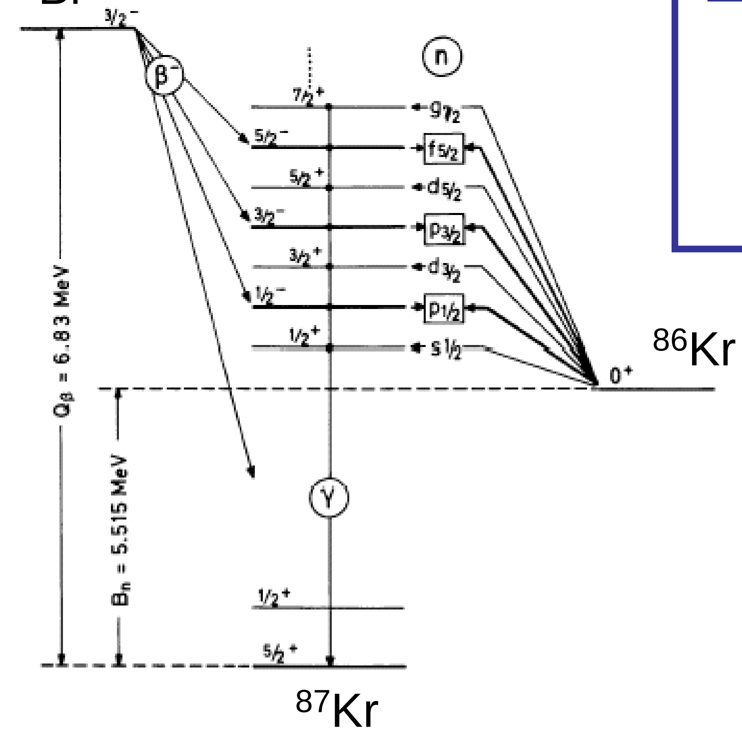
  - "understanding" β-decay properties
  - short-range extrapolation into unknown regions

Determination of stellar neutron-capture rates for radioactive nuclei with the aid of β-delayed neutron emission

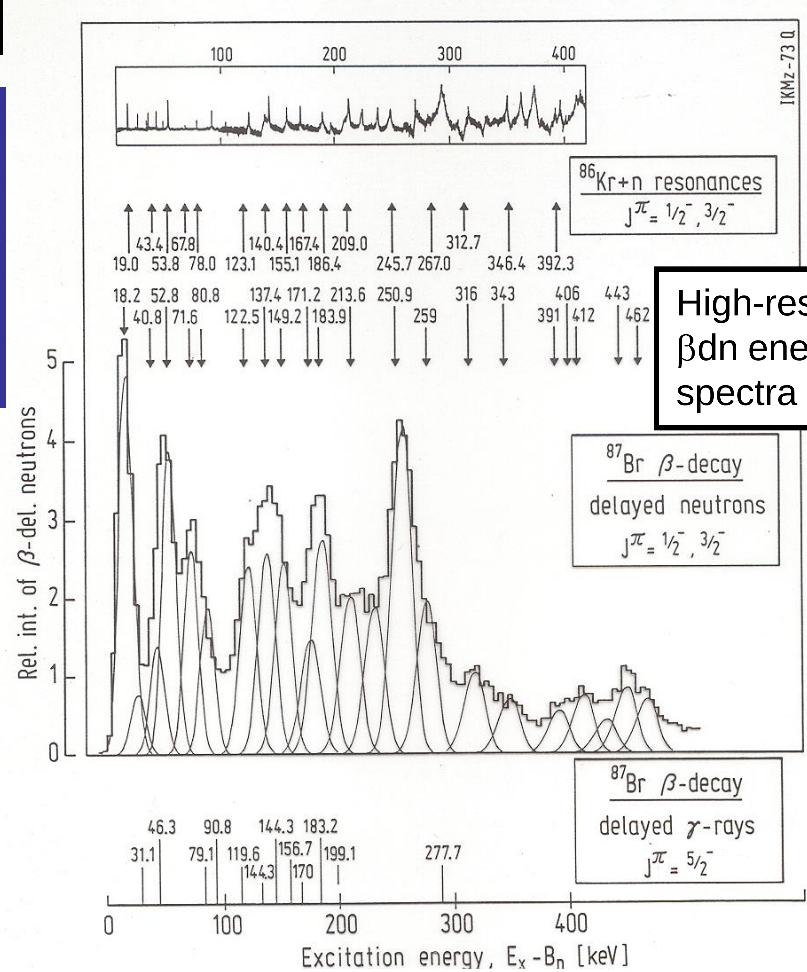
Astron. Astrophys. 125, 381-387 (1983)
Kratz, Ziegert, Hillebrandt and Thielemann

Neutron capture cross sections for neutron-rich isotopes

Z. Physik A –Atoms and Nuclei 332, 531-532 (1983)
Leist, Ziegert, Wiescher, Kratz and Thielemann



Measure:
S_n, J^π
E_n, ℓ_n
Γ_n, Γ_γ
a



High-resolution βdn energy spectra

^{86}Kr(n,γ) → all J^π in ^{87}Kr

^{87}Br(βn) → only J^π acc. to GT selection rules

Replace **Hauser-Feshbach σ_n(H-F)** by **Breit-Wigner σ_n(B-W)** resonance formalism

The historical FK²L waiting-point approach (I)

With the nuclear physics knowledge at that time…

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

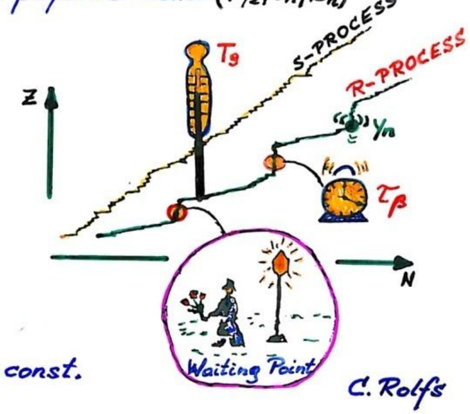
Aim:
Understanding of nucleosynthesis ("r-abundances")

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
(B^2FH, 1957)

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



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

known r-process isotopes:
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

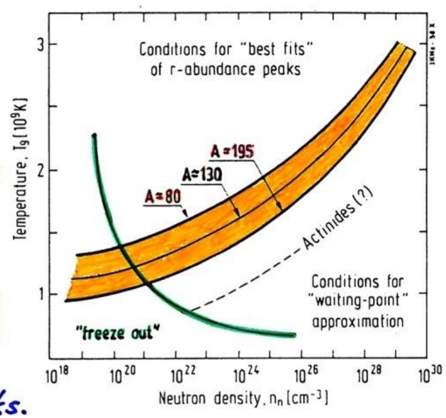
"waiting-point concept":

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

→ deduce $T_9 - n_n$ band

conditions to fit the

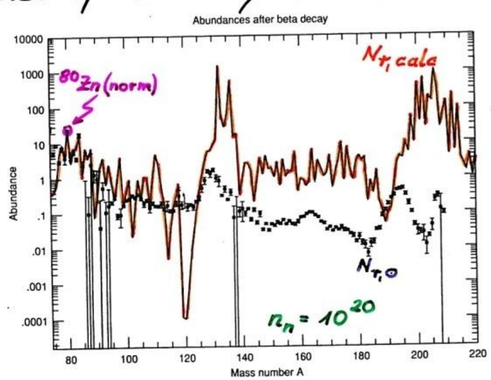
A≃80 and 130 $N_{r,\odot}$-peaks.



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≃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:

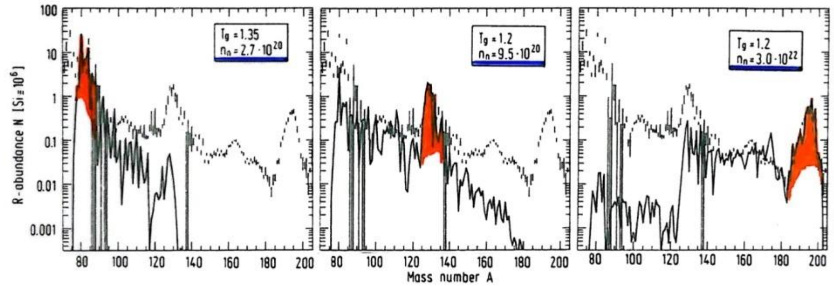
r-process matter flow at freeze-out temperature ;

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

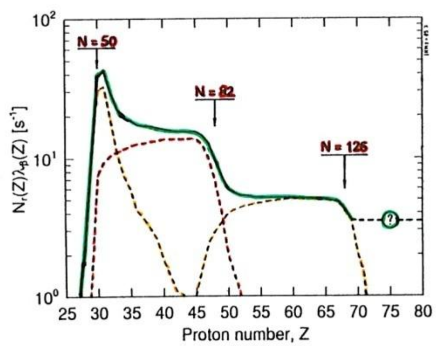
The FK²L waiting-point approach (III)

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}



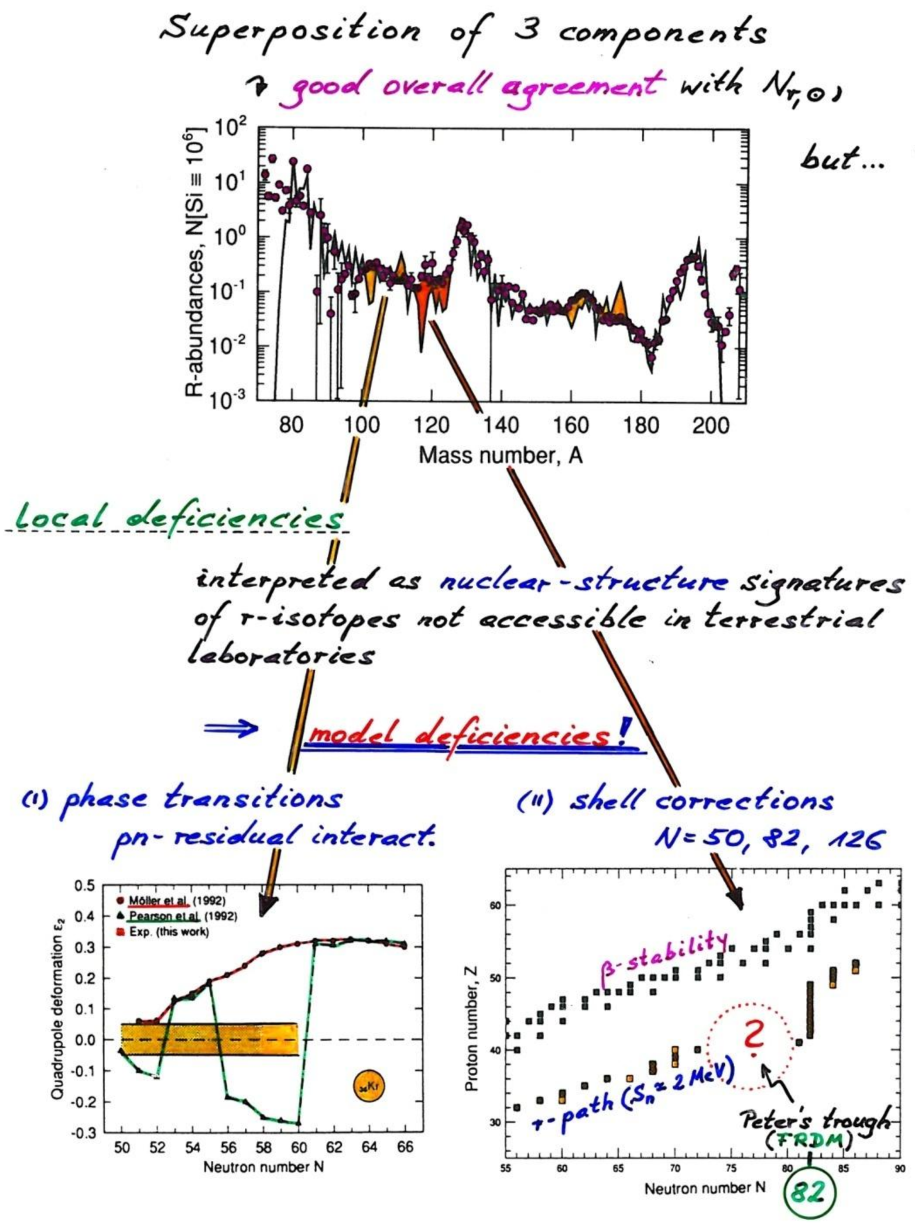
analogous to s-process
with $N_s \sigma = const.$

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, ^{135}Tm)

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



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

W. Hillebrandt

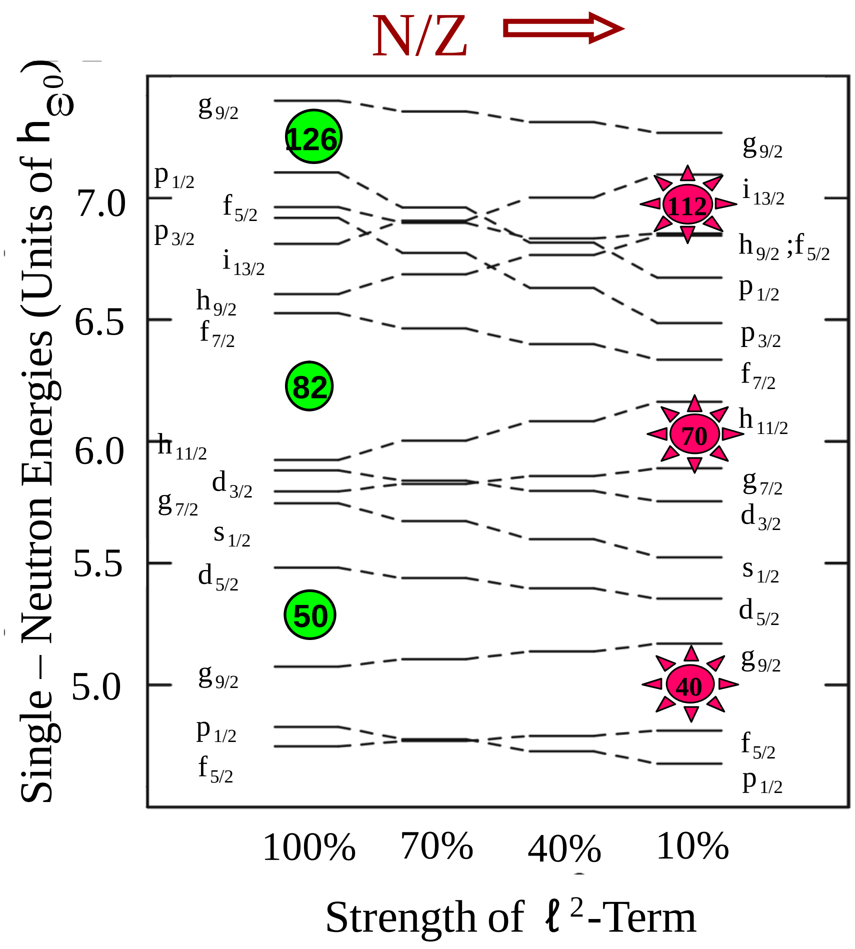
"…call for a deeper study…
before rushing into numerical results…
and premature comparisons with the observed abundances"

M. Arnould

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

…this catchword coined by W. Nazarewicz later led to semantics and misinterpretations

Effects of N=82 "shell quenching"



B. Pfeiffer et al.,
Acta Phys. Polon. **B27** (1996)

"Shell quenching"

…reduction of the spin-orbit coupling strength;
caused by strong interaction between bound and continuum states;
due to diffuseness of "neutron-skin" and its influence on the central potential…

- high-j orbitals ⇑ (e.g. $\nu h_{11/2}$)
- low-j orbitals ⇓ (e.g. $\nu d_{3/2}$)
- evtl. crossing of orbitals
- new “magic” numbers / shell gaps (e.g. $^{110}Zr_{70}$, $^{170}Ce_{112}$)

change of

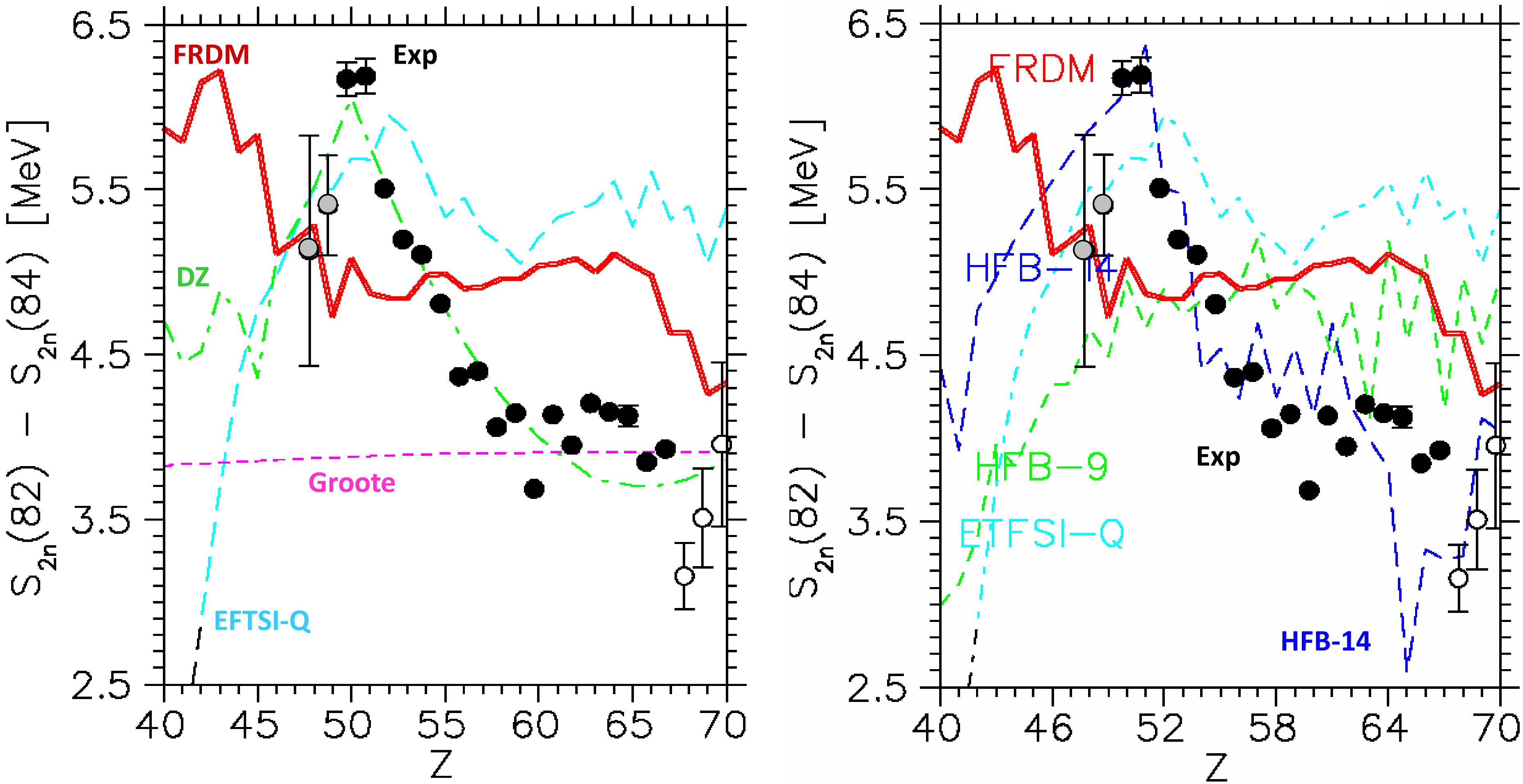
- shell-gaps
- deformation
- r-process path (S_n)
- r-matter flow (τ_n)

The N=82 shell gap as a function of Z

The **N=82** shell closure

- dominates the matter flow of the „main“ r-process ($n_n \geq 10^{23}$)
- determines the build-up of A≈130 $N_{r,\odot}$ peak
- influences break-out and formation of REE

Definition „shell gap“: S_{2n}(82) – S_{2n}(84)

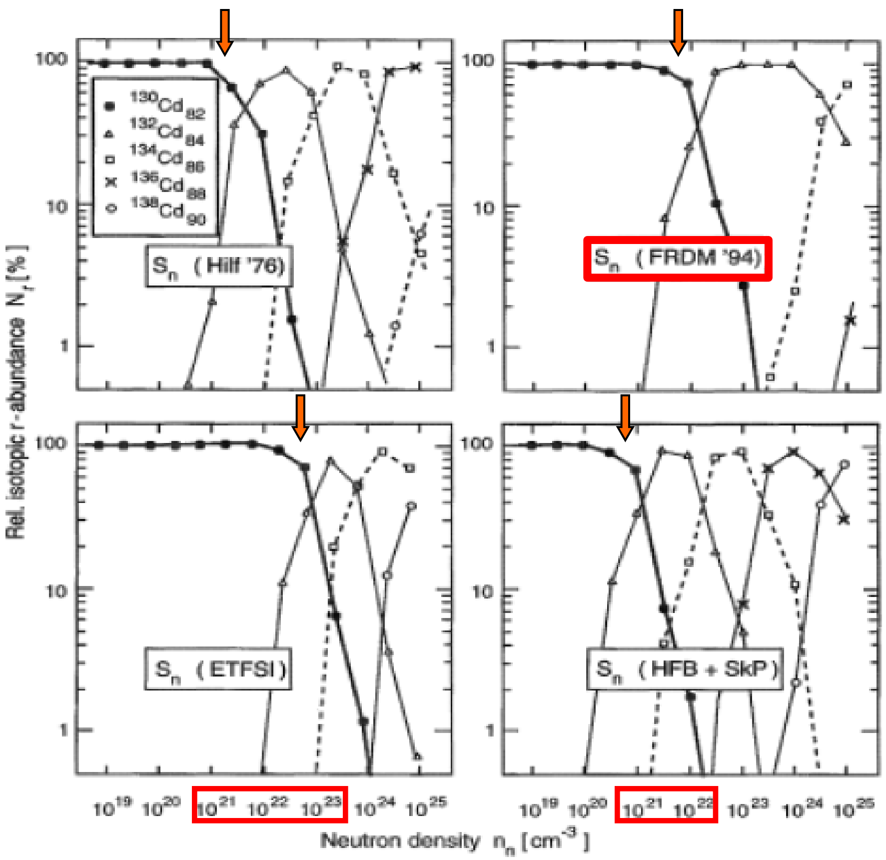


Impact of nuclear masses at N = 82

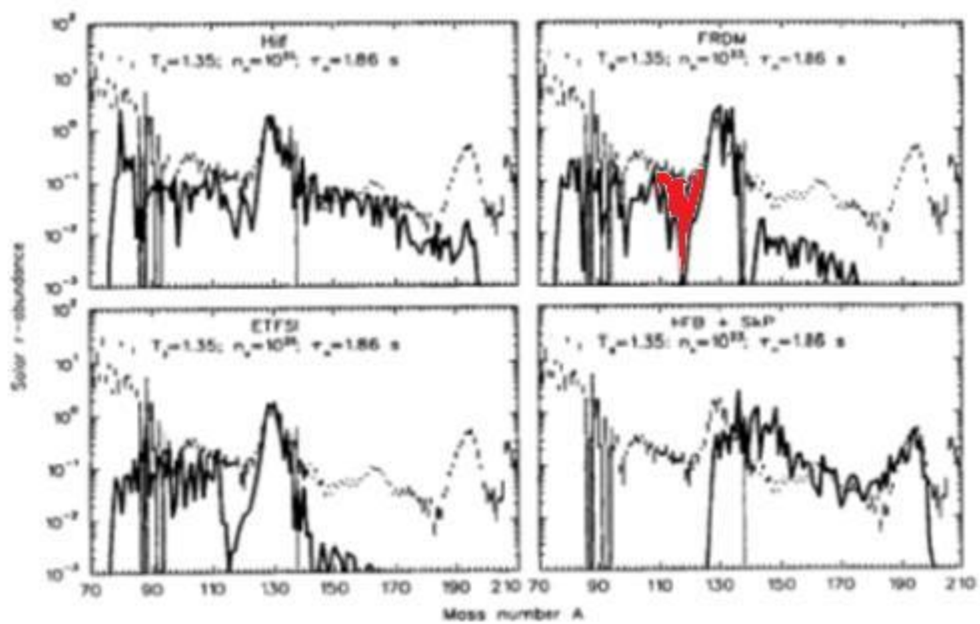
Already FK^2L (ApJ 403) concluded from their fits to $N_{r,\odot}$:

”the calculated r-abundance ”trough“ in the A ≈ 120 region reflects the weakening of the shell strength below $^{132}Sn_{82}$.“

Effect of S_n around N=82 shell closure



astrophys. parameters (T_9, n_n, τ_n) and $T_{1/2}$ kept constant



“static” calculations (Saha equation)
⟹ break-out at N=82 ^{130}Cd

“time-dependent” calculations (w.-p.)
⟹ r-matter flow to and beyond A=130

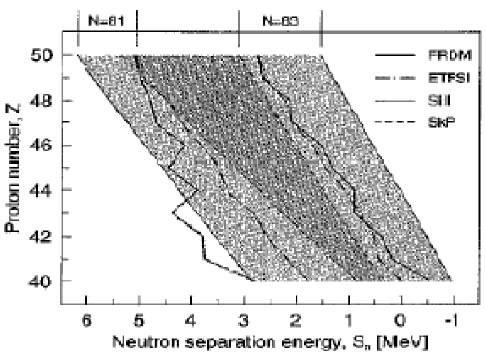
N=82 „shell-quenching“

Phys. Lett. B355, 37 (1995)

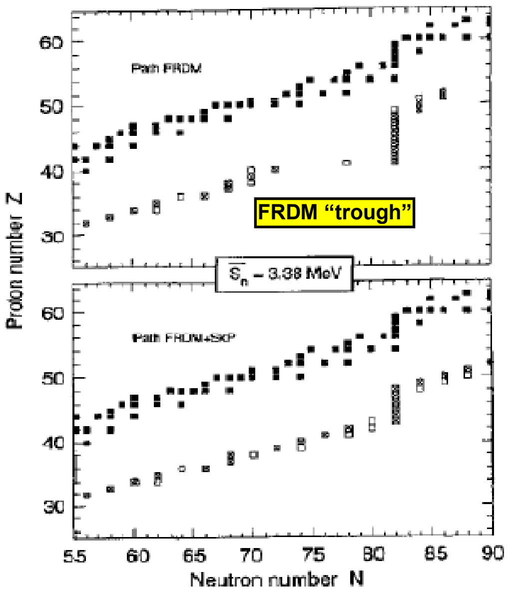
Influence of shell-quenching far from stability on the astrophysical r-process

B. Chen [a], J. Dobaczewski [b], K.-L. Kratz [c], K. Langanke [a], B. Pfeiffer [c], F.-K. Thielemann [d], P. Vogel [e]

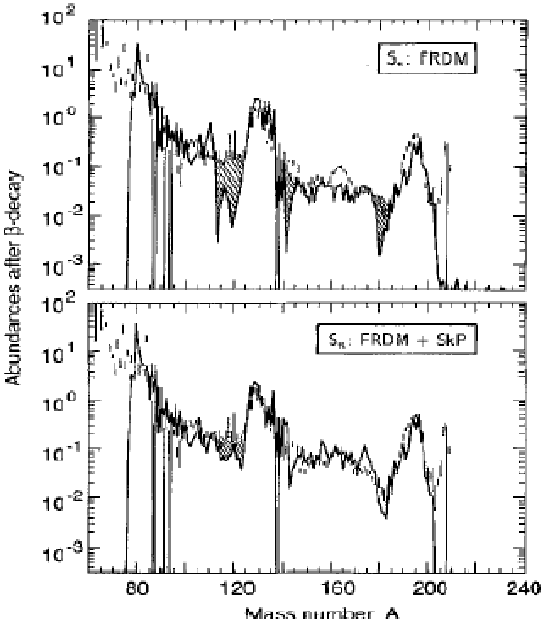
Use spherical **HFB/SkP** mass model ⇨ **FRDM+HFB/SkP** “hybrid model” around N=82



ΔS_n as a measure of the N=82 shell strength



population of **r-path**



$N_{r,\odot}$ **fits**

WARNING: FRDM (1992) not appropriate for r-process calculations !

N=82 shell-quenching

Phys. Lett. B387, 455 (1996)

Nuclear mass formula with Bogolyubov-enhanced shell-quenching: application to r-process ★

J.M. Pearson [a], R.C. Nayak [a], S. Goriely [b]

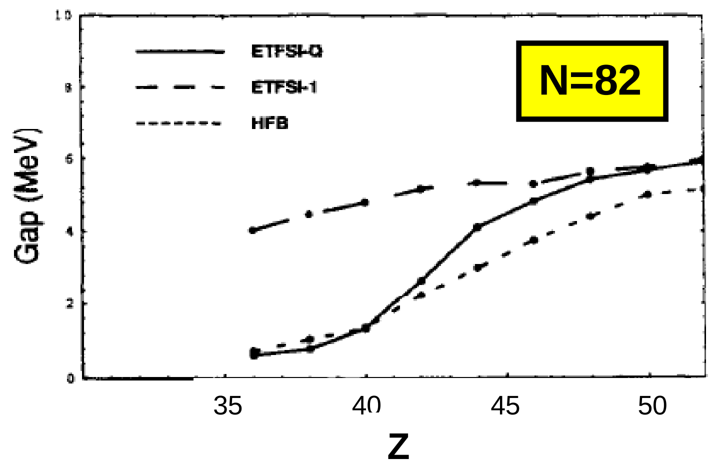
[a] *Laboratoire de Physique Nucléaire, Université de Montréal, Montréal (Que.) H3C 3J7, Canada*

[b] *Institut d'Astronomie et d'Astrophysique, CP-226 Université Libre de Bruxelles, Campus de la Plaine, Boulevard du Triomphe, B-1050 Brussels, Belgium*

In an early self-consistent calculation on neutron-rich nuclei Tondeur [1] found that the shell effects associated with the usual magic numbers effectively vanished as the drip line was approached. However, this result depends critically on the treatment of pairing, and while Tondeur adopted a BCS approach with parametrized constant *G*, Dobaczewski et al. [2] found a much weaker quenching of shell effects in a pure Hartree-Fock (HF) calculation with no pairing at all.

(1978)

strength of quenching seems to be force-dependent !

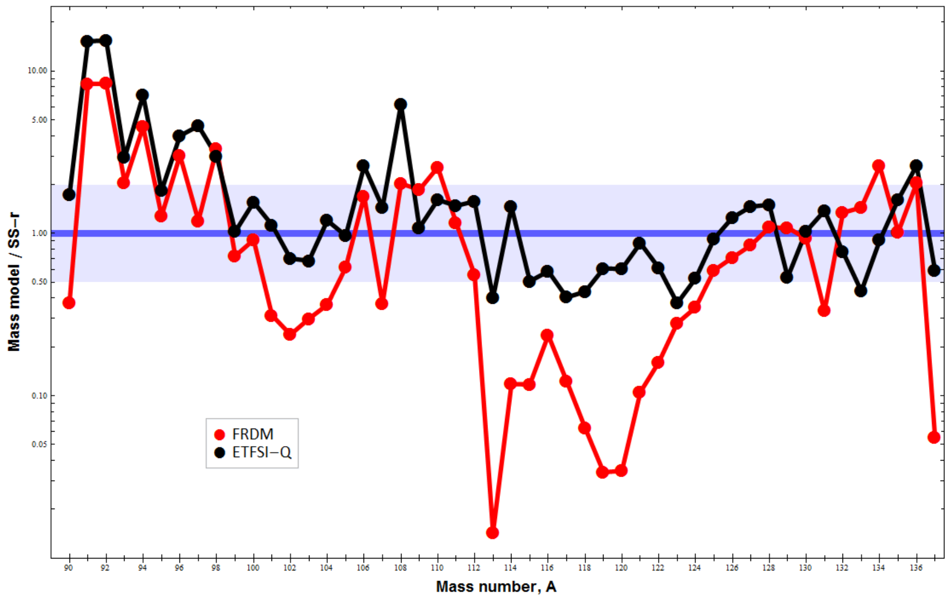


For **Z=40** (^{122}Zr) ⇨ quenching **2 MeV**

- **Assume that quenching is shape-independent;**
- **Incorporate HFB shell effects into spherical ETFSI framework;**
- **Reconstruct ETFSI by minimizing energy with respect to deformation;**

"…inevitable consequence of quenching": **deformation reduced !**

Deviation from SS-r: FRDM vs. ETFSI-Q



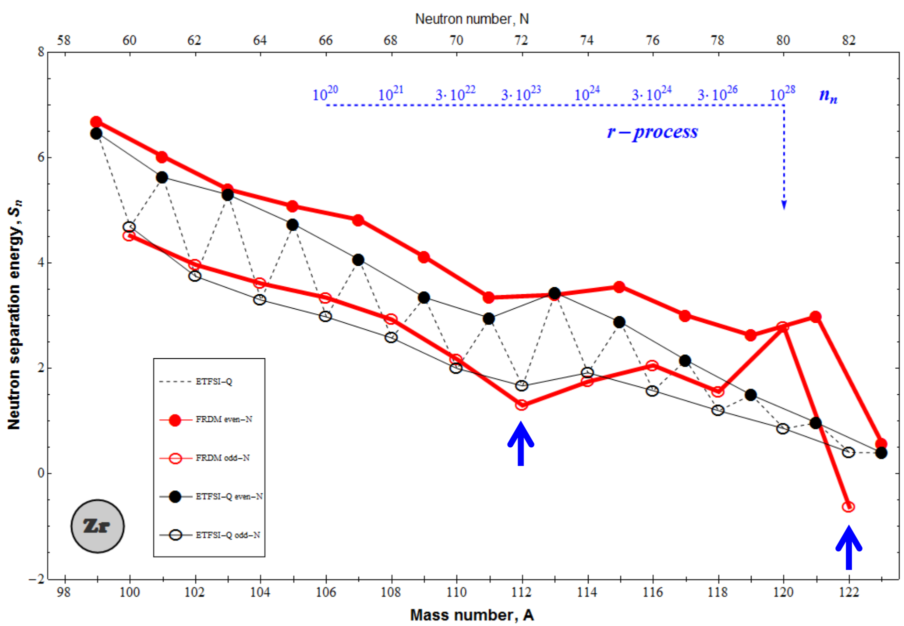
How to fill up the FRDM A ≈ 115 "trough" ?

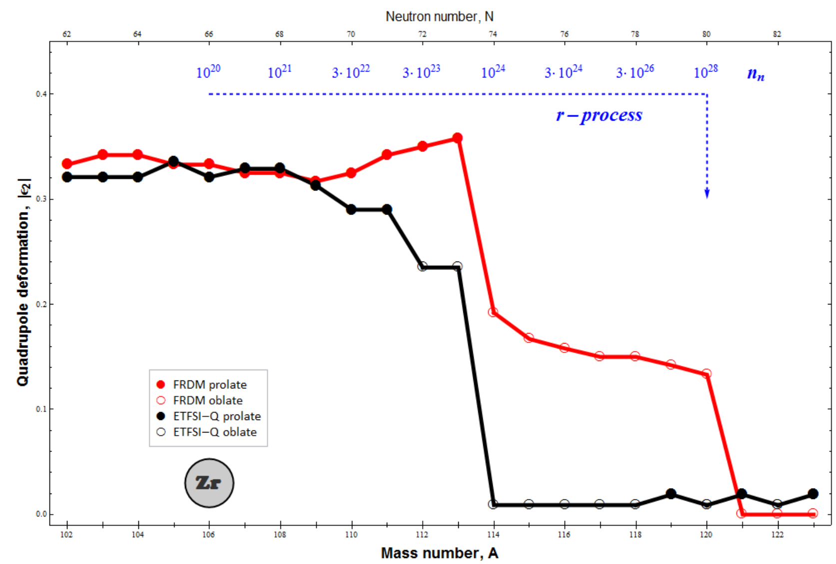
- if via $T_{1/2}$ (as e.g. suggested by Nishimura, Kajino et al.; PRC 85 (2012)), on average all r-progenitors between ^{110}Zr and ^{126}Pd should have

  7.5 x $T_{1/2}$(FRDM) ≈ 350 ms →

  2 x $T_{1/2}$(^{130}Cd) at top of r-peak

- it **must** be the progenitor masses, via S_n (and correlated deformation ε_2)





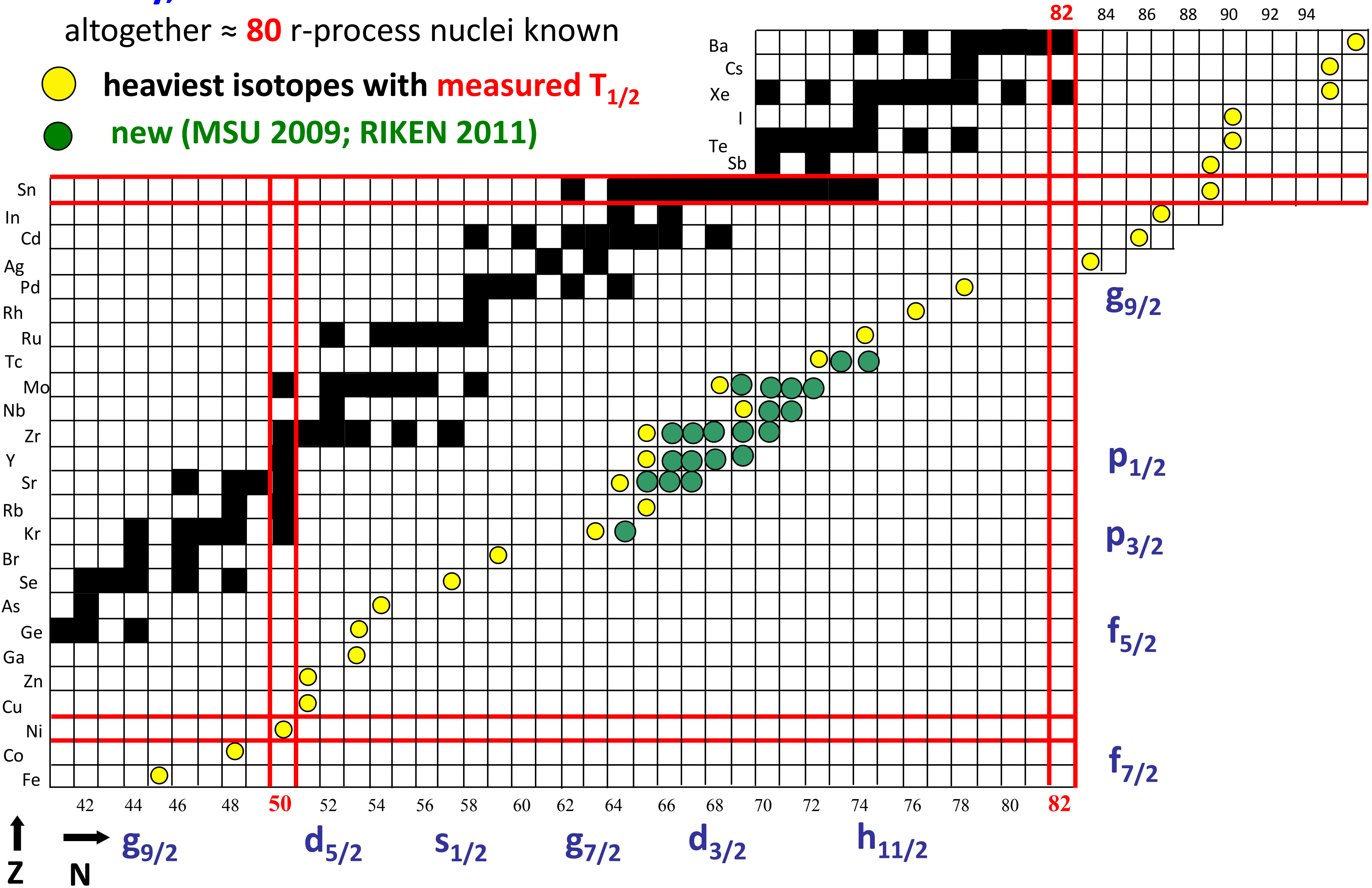
Experimental information on r-process nuclides

Today,

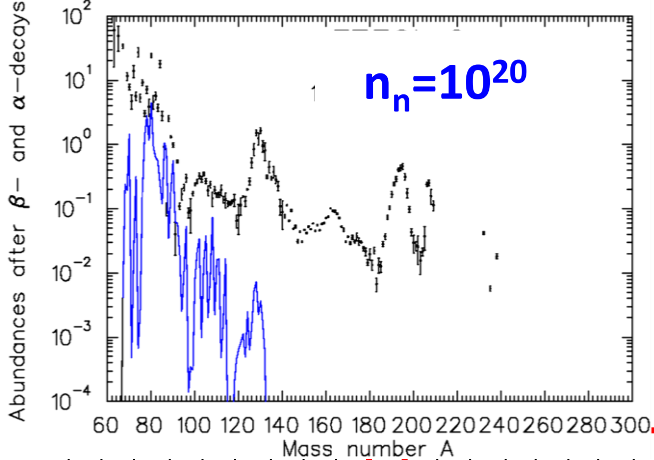
altogether ≈ 80 r-process nuclei known

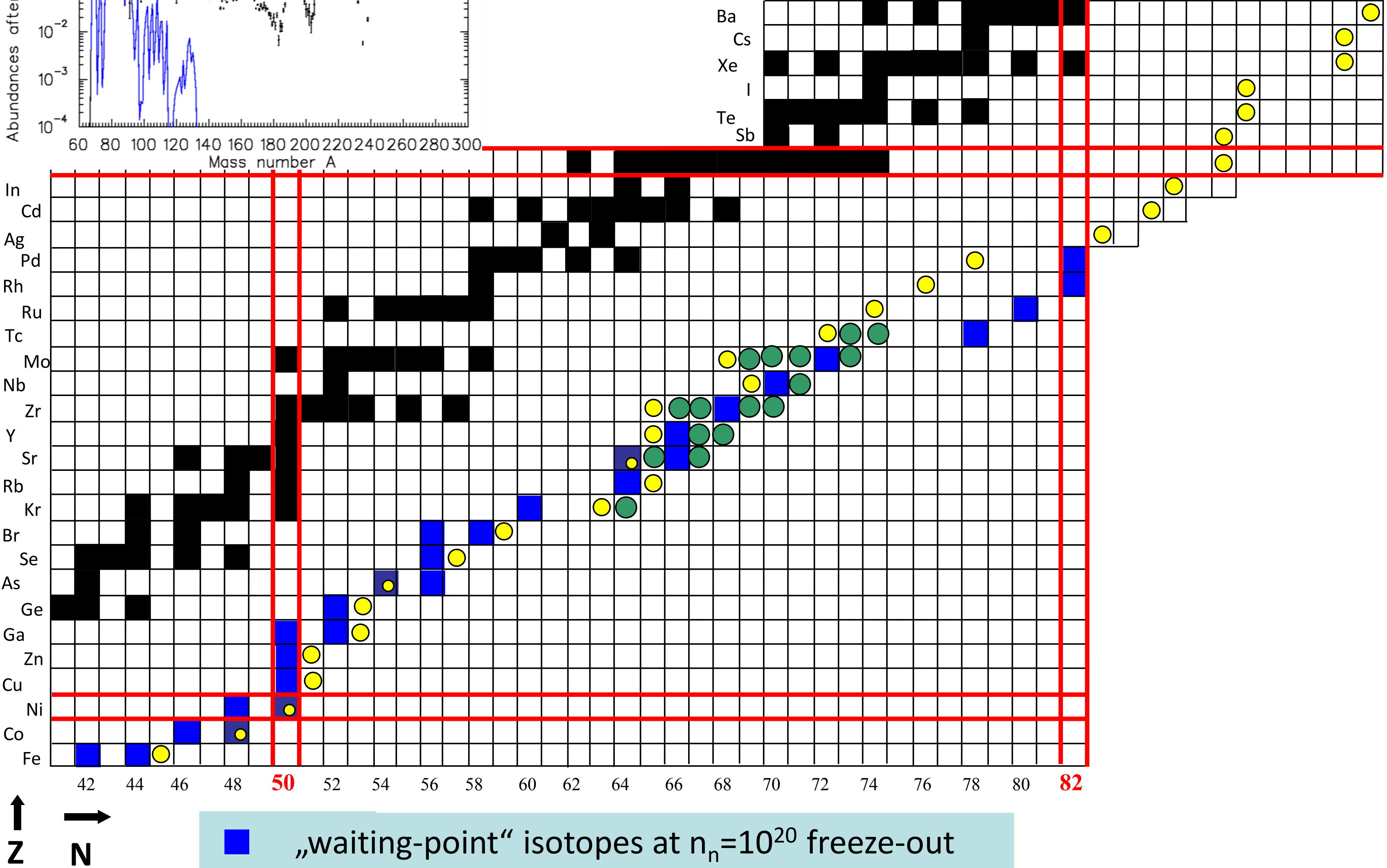
heaviest isotopes with measured $T_{1/2}$

new (MSU 2009; RIKEN 2011)



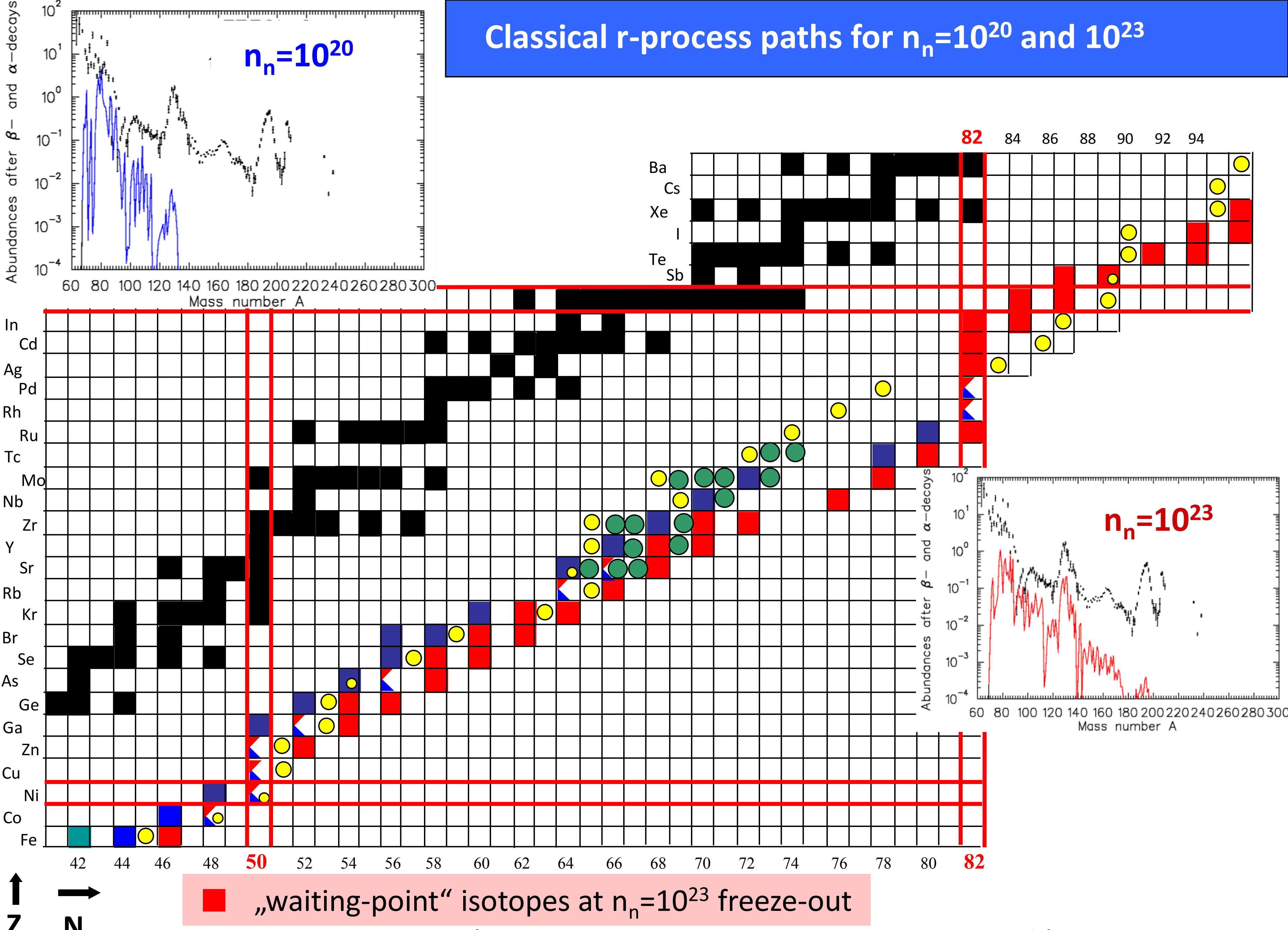
Classical r-process path for $n_n=10^{20}$





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

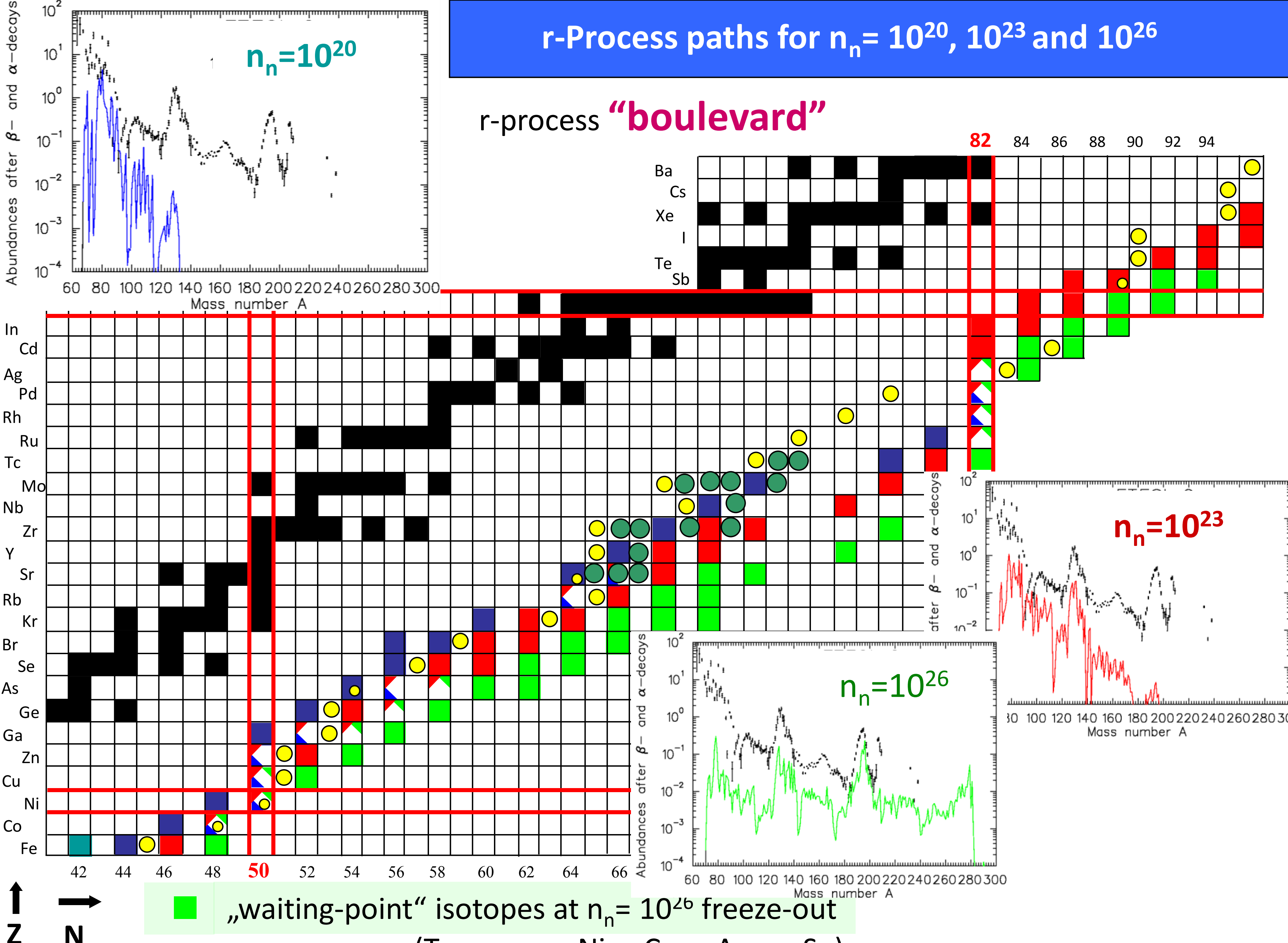
Classical r-process paths for $n_n=10^{20}$ and 10^{23}



„waiting-point" isotopes at $n_n=10^{23}$ freeze-out

($T_{1/2}$ exp. : $_{28}$Ni – $_{31}$Ga, $_{36}$Kr – $_{40}$Zr, $_{47}$Ag – $_{51}$Sb)

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



„waiting-point“ isotopes at $n_n = 10^{26}$ freeze-out

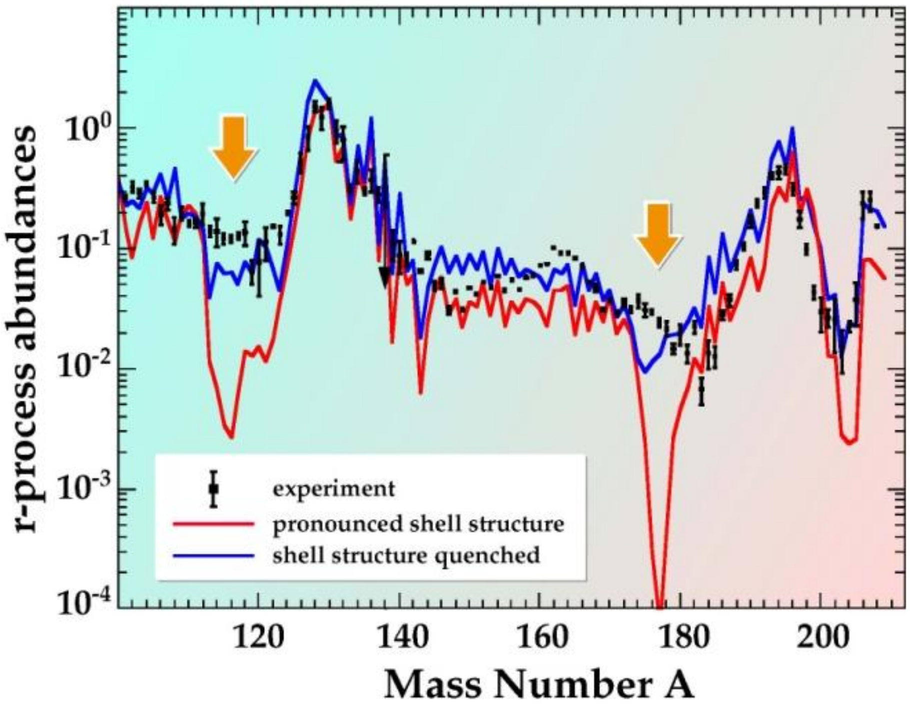
($T_{1/2}$ exp. : $_{28}$Ni, $_{29}$Cu, $_{47}$Ag – $_{50}$Sn)

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 the historical, site-independent r-process "waiting-point" approach

to more recent (hydro-) dynamical nucleosynthesis calculations

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
- 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
- Jets of matter from collapse of rotating magnetized stellar cores

...becoming more and more **"exotic"**

r-Process calculations with MHD-SN models

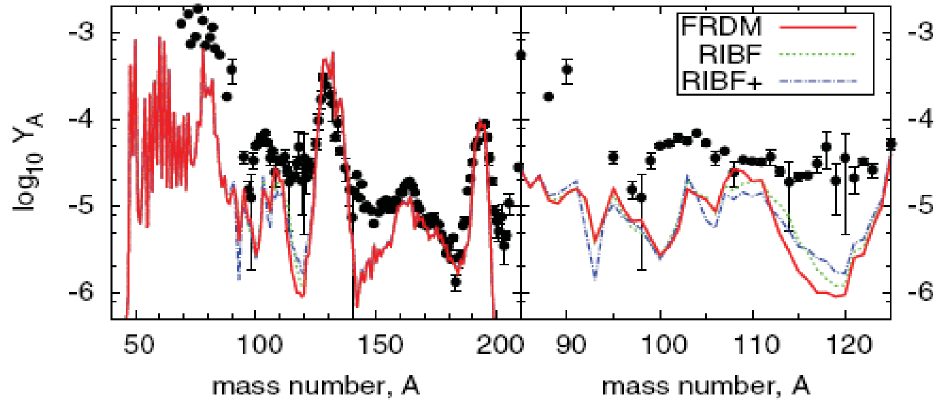
2012 … new "hot r-process topic" ➔ **magnetohydrodynamic SNe**
… but, unfortunately not with the optimum nuclear-physics input…

Phys.Rev. C85 (2012)

Impact of new β-decay half-lives on r-process nucleosynthesis

Nobuya Nishimura,[1,2,*] Toshitaka Kajino,[3,4] Grant J. Mathews,[5] Shunji Nishimura,[6] and Toshio Suzuki[7]

"We investigate the effect of newly measured ß-decay half-lives on r-process nucleosynthesis. We adopt … a magnetohydrodynamic supernova explosion model… The ($T_{1/2}$) effect slightly alleviates, but does not fully explain, the tendency of r-process models to underproduce isotopes with A = 110 – 120…"



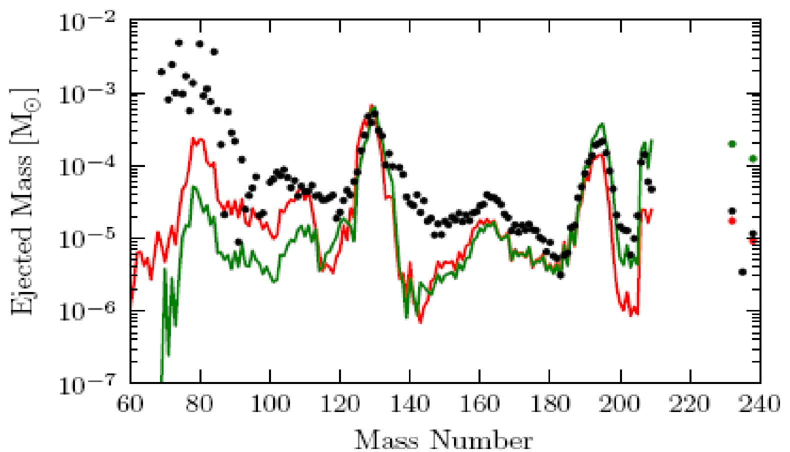
In both cases FRDM 1992 masses have been used
partly misleading conclusions

Ap.J. Letter 750 (2012)

MAGNETOROTATIONALLY DRIVEN SUPERNOVAE AS THE ORIGIN OF EARLY GALAXY r-PROCESS ELEMENTS?

C. Winteler[1], R. Käppeli[2], A. Perego[1], A. Arcones[3,4], N. Vasset[1], N. Nishimura[1], M. Liebendörfer[1], and F.-K. Thielemann[1]

"We examine magnetohydrodynamically driven SNe as sources of r-process elements in the early Galaxy… … the formation of bipolar jets could naturally provide a site for the strong r-process…"



The high-entropy / neutrino-driven wind model

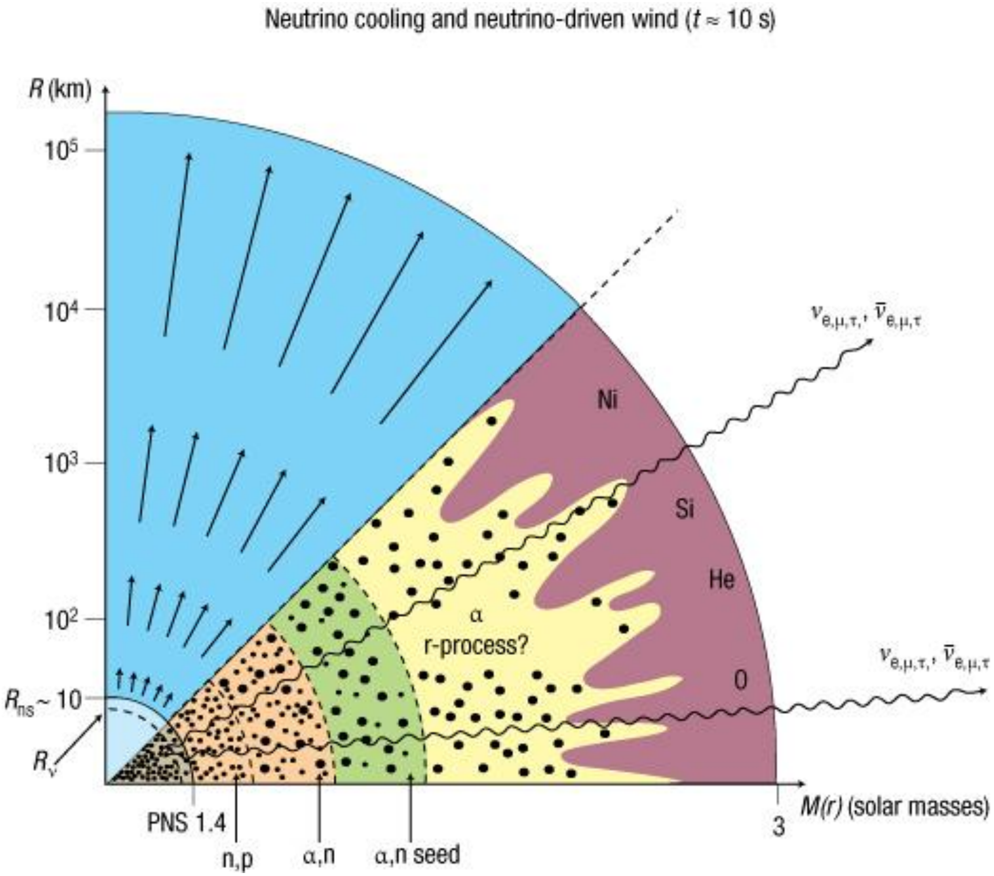
Core-collapse SN "HEW" …still one of the presently favoured scenarios for a rapid neutron-capture nucleosynthesis process

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

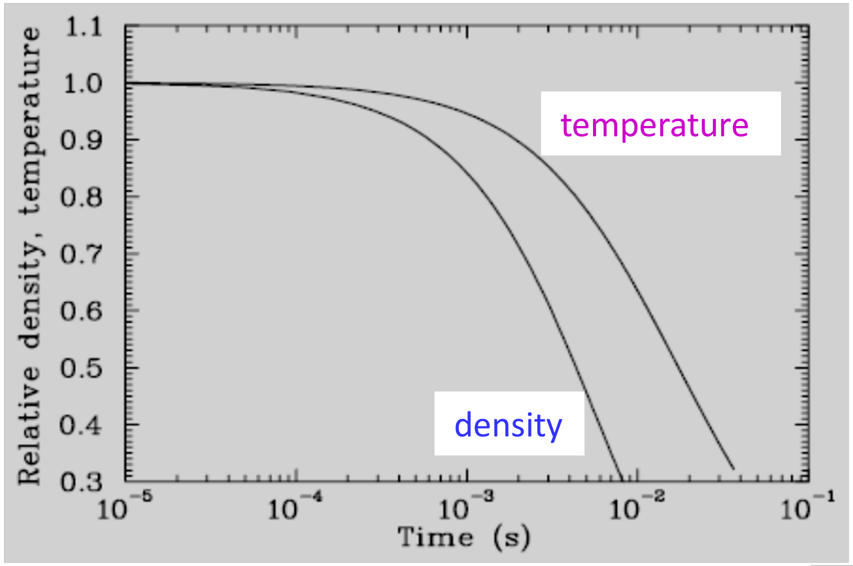
parameters **correlated !**

$\Rightarrow$ **„strength“ formula**

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

(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

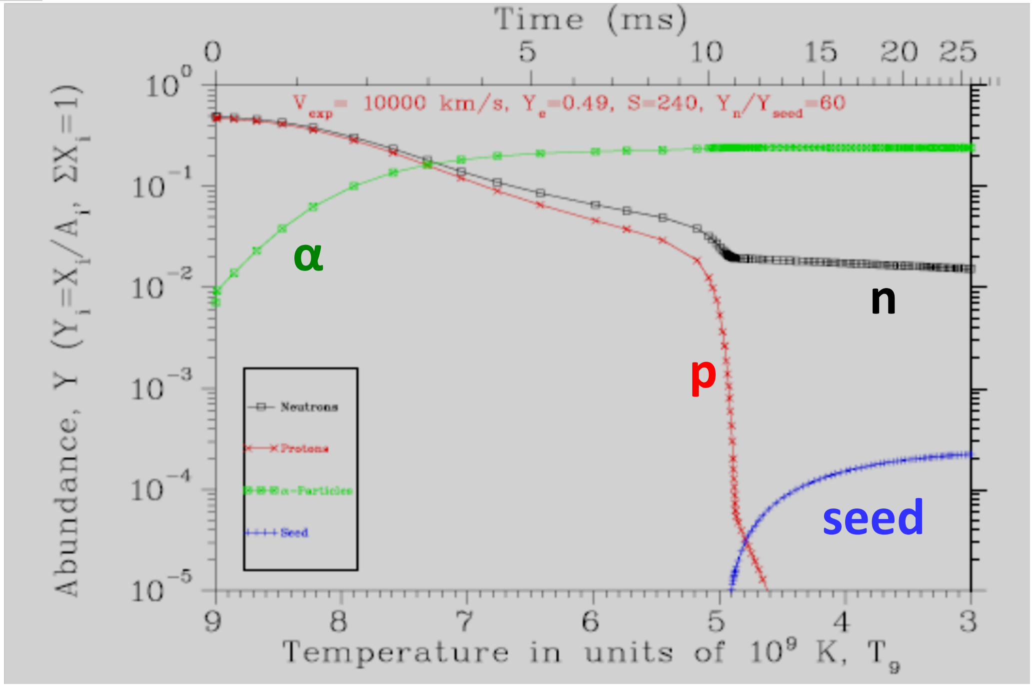
as functions of temperature and time

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

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

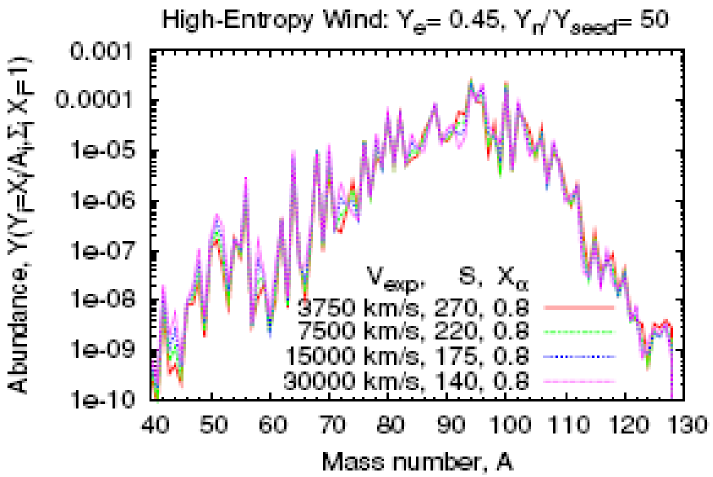
n survive,

“seed“ nuclei emerge.



(Farouqi et al., 2009)

Distribution of seed nuclei

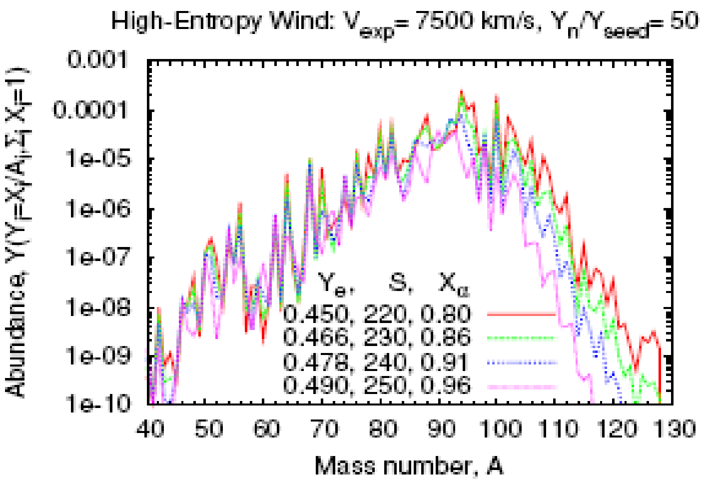


effect of different expansion velocities of the hot bubble, V_{exp}

distributions are robust !

effect of different electron abundances, Y_e

distributions show differences, mainly for A > 100

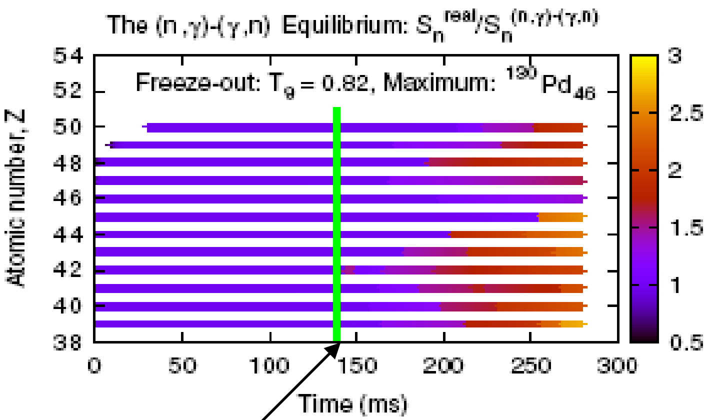


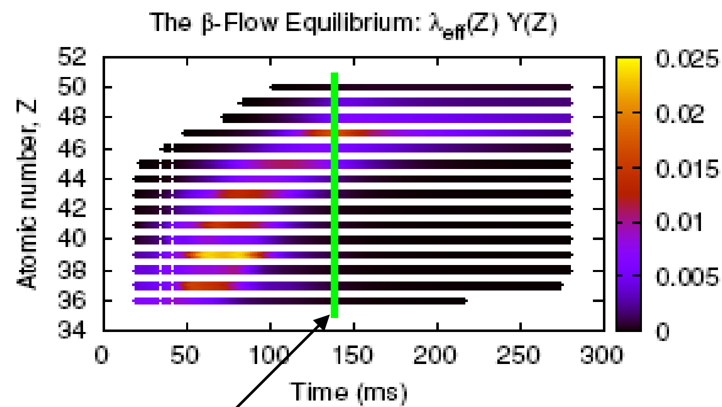
Main seed abundances at A > 80 lie beyond N = 50 !

Freezeout at A ≈ 130

Validity and duration of
(n,γ) ↔ (γ,n) equilibrium
$S_n(\text{real}) / S_n(n,\gamma) \approx 1$

Validity and duration of
β-flow equilibrium
$\lambda_{eff}(Z) \times Y(Z) \neq 0$





freezeout

(n,γ)-equilibrium valid over ≈ 200 ms,
independent of Z

freezeout

Local equilibrium "blobs" with
Increasing Z, at different times

Definition of different freezeout phases

Neutron freezeout at ≈ 140 ms, $T_9 \approx 0.8$, $Y_n/Y_r = 1$ ⇨ ^{130}**Pd**

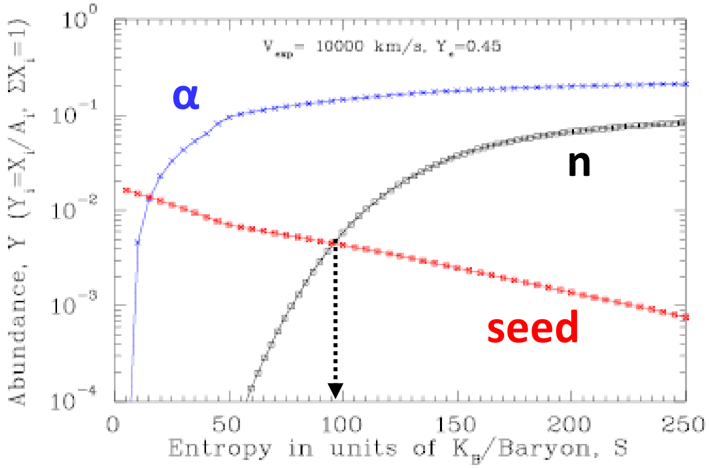
Chemical freezeout at ≈ 200 ms, $T_9 \approx 0.7$, $Y_n/Y_r \approx 10^{-2}$ ⇨ ^{130}**Cd**

Dynamical freezeout at ≈ 450 ms, $T_9 \approx 0.3$, $Y_n/Y_r \approx 10^{-4}$ ⇨ ^{130}**In**

Notes. The model parameters are $Y_e = 0.45$, $V_{exp} = 7500$ km s^{-1}, and S = 195, 236, and 270. The neutron, chemical and dynamical freeze-outs mean $Y_n/Y_{heavy} < 1$, the break-out of the $(n,\gamma)-(\gamma,n)$ equilibrium and $|Y_n(t)/\dot{Y}_n(t)| > |\rho(t)/\dot{\rho}(t)|$, respectively. The superscripts b and e denote the "begin" and "end" of the $(n,\gamma)-(\gamma,n)$ equilibrium, respectively.

Parameters HEW model ⇨ Y(Z)

Y_e=0.45



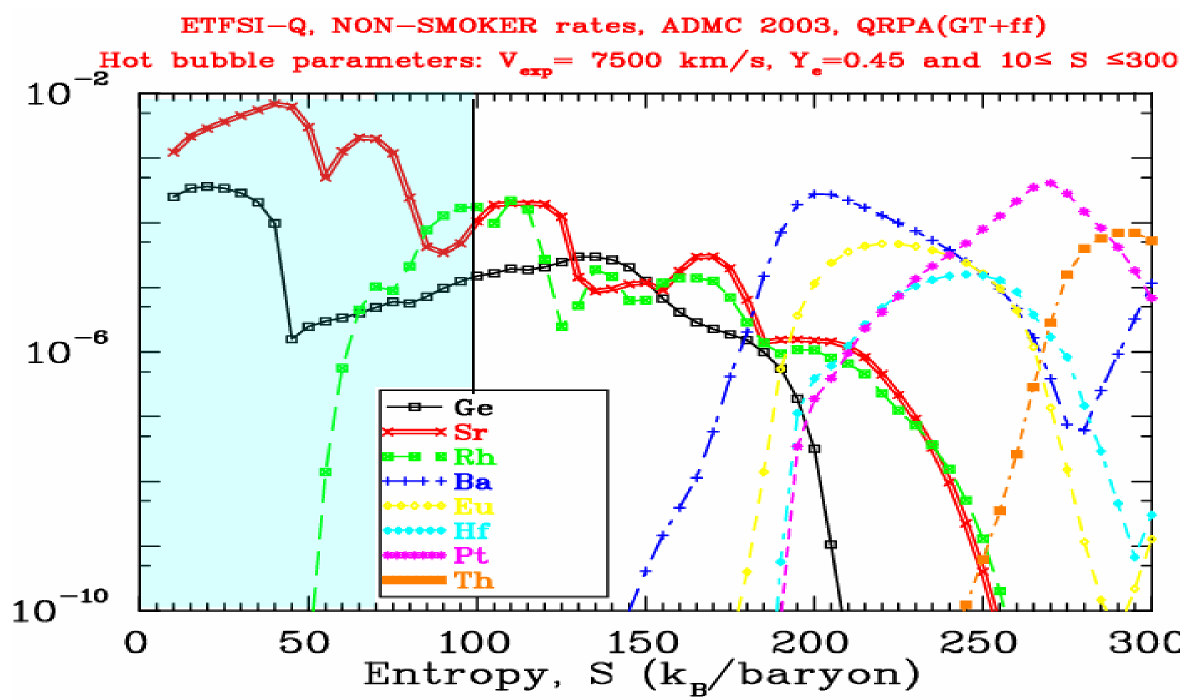
No neutrons → no n-capture r-process!

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

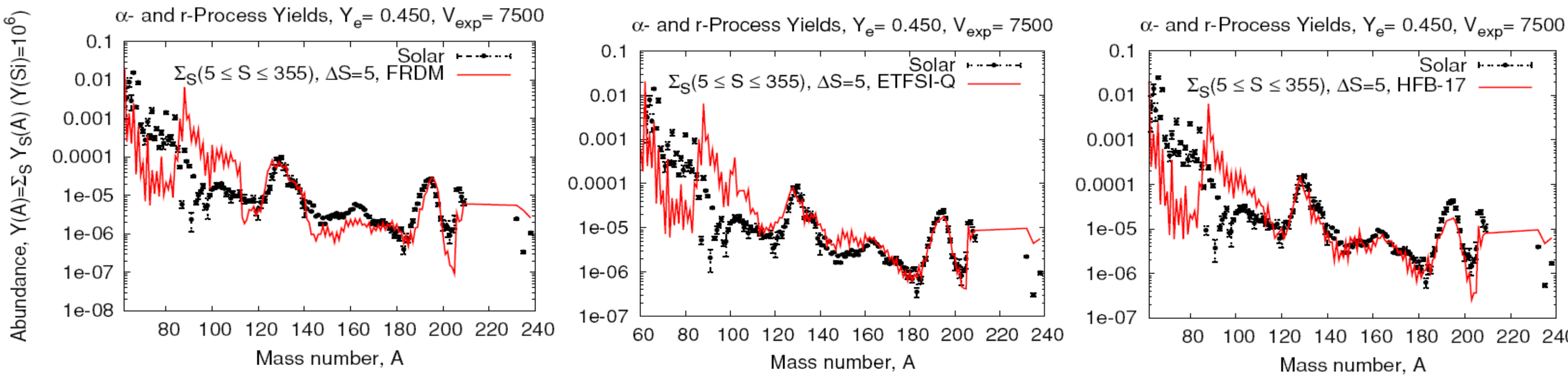
150 < S < 300; $15 < Y_n/Y_{seed} < 150$
"main" r-process



Reproduction of $N_{r,\odot}$

Superposition of S-components with Y_e=0.45;

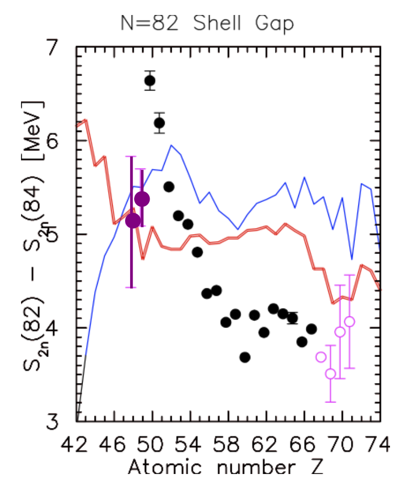
weighting according to Y_{seed}



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

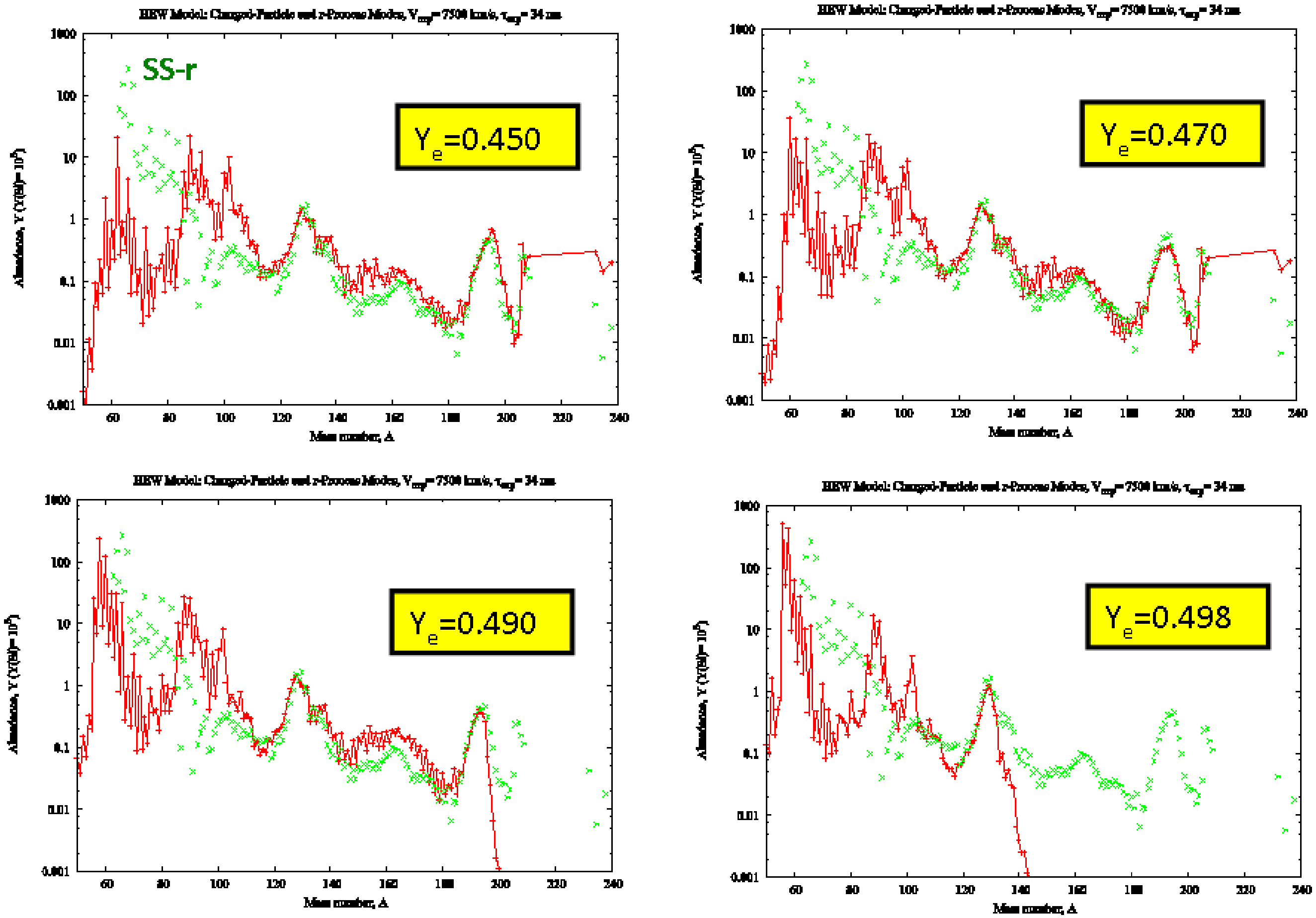


Superposition of HEW components 0.450 ≤ Y_e ≤ 0.498

"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}

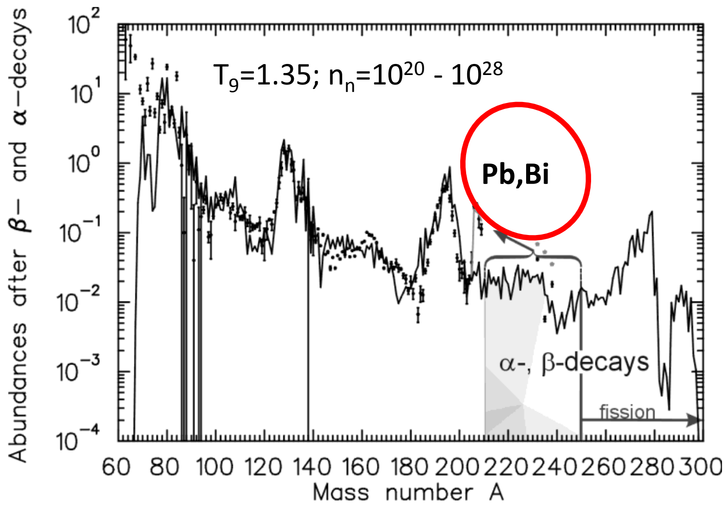
Farouqi et al. (2009)

r-Process observables today

So far…

Historical solar system isotopic r-process "residuals"

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



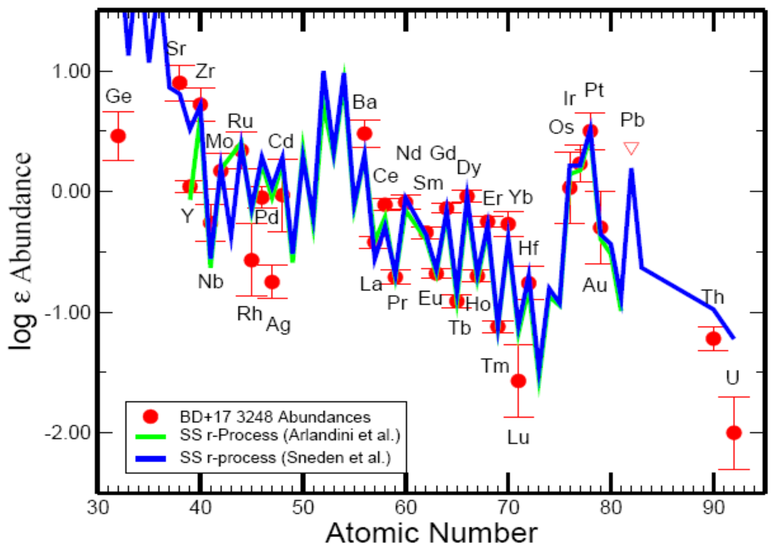
More recently,

Elemental abundances in UMP halo stars,

e.g.

BD+17 3248

(registered by U.S.F.I as "K.-L. Kratz star")



Detection of 33 n-capture elements, the most in any halo star

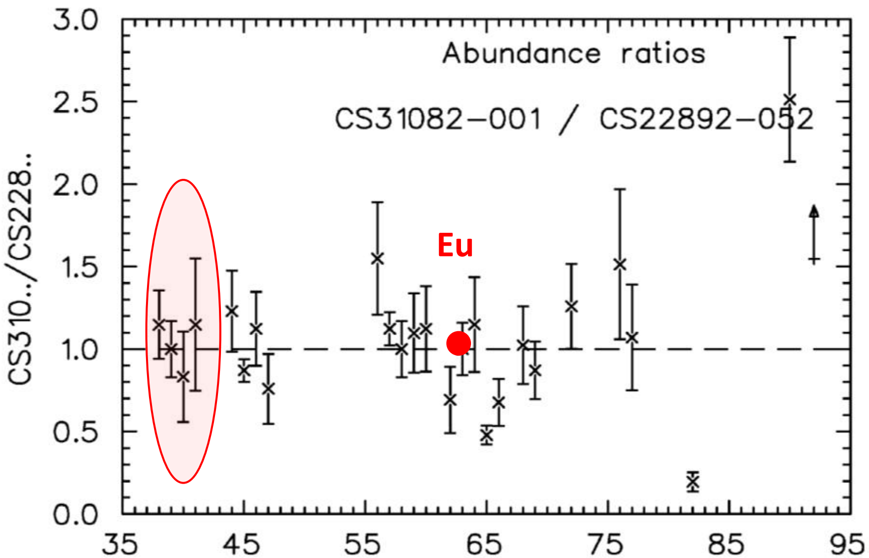
Halo stars vs. HEW-model: Extremes “r-rich” and “r-poor”

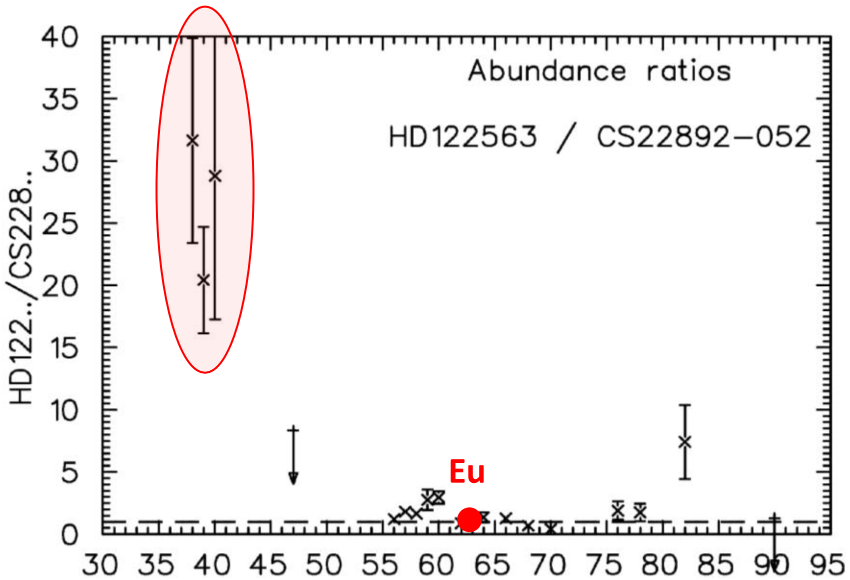
Elemental abundance ratios UMP halo stars

r-rich “Cayrel star” / r-rich “Sneden star”

r-poor “Honda star” / r-rich “Sneden star”

normalized to Eu

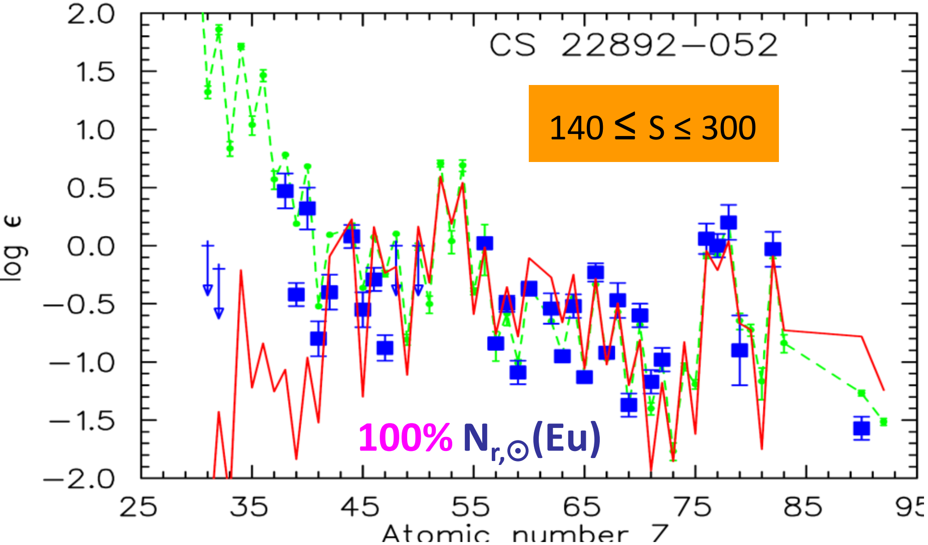




Factor 25 difference for Sr - Zr region !

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

r-rich “Sneden star”



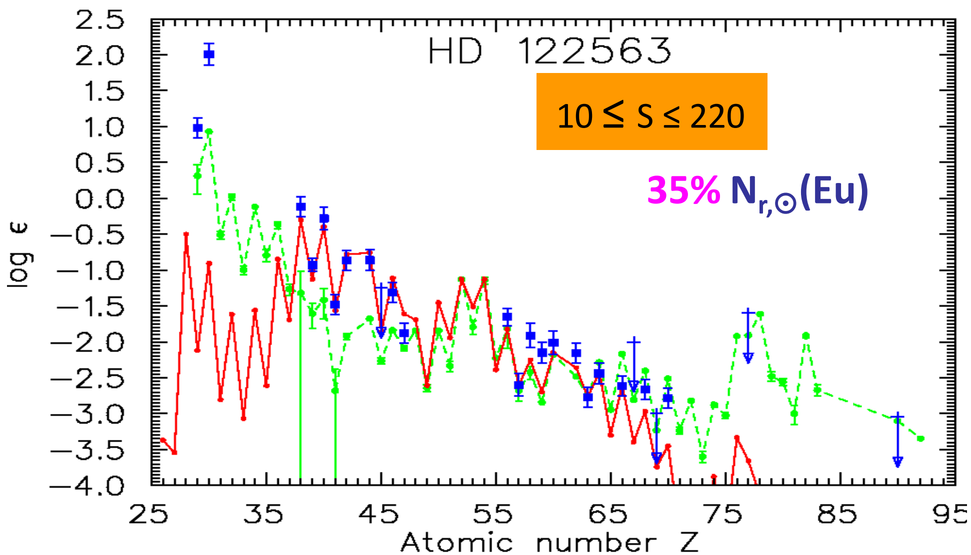
full main r-process

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

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

➡ **“missing” part to SS-r = LEPP**

r-poor “Honda star”



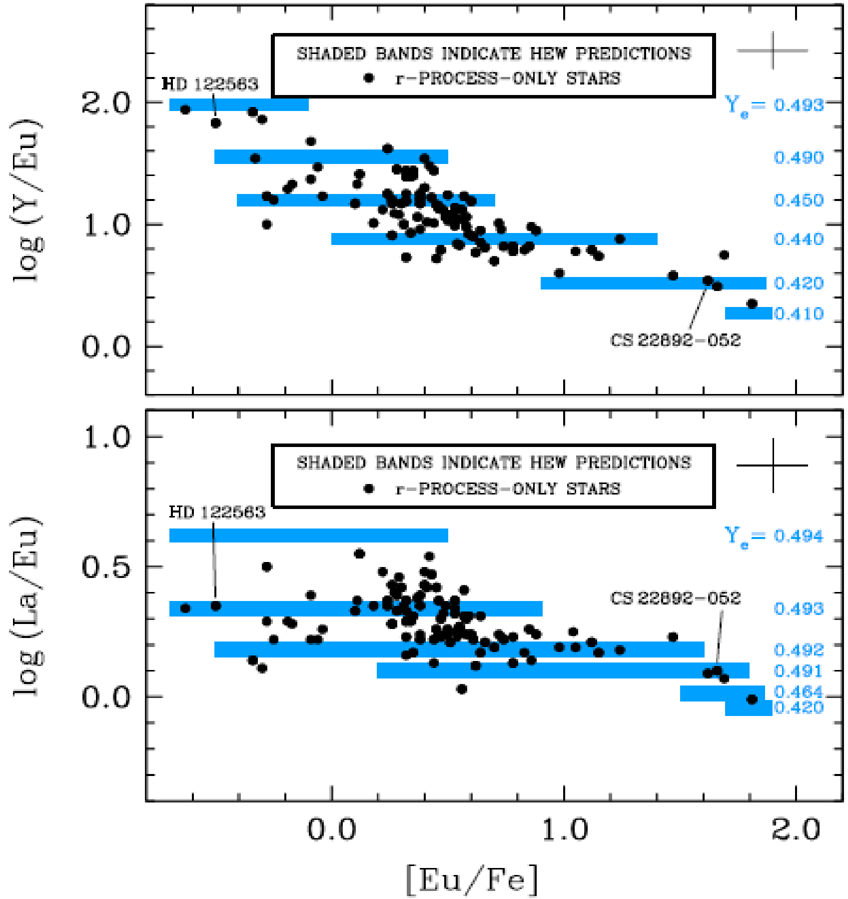
incomplete main r-process

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

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!

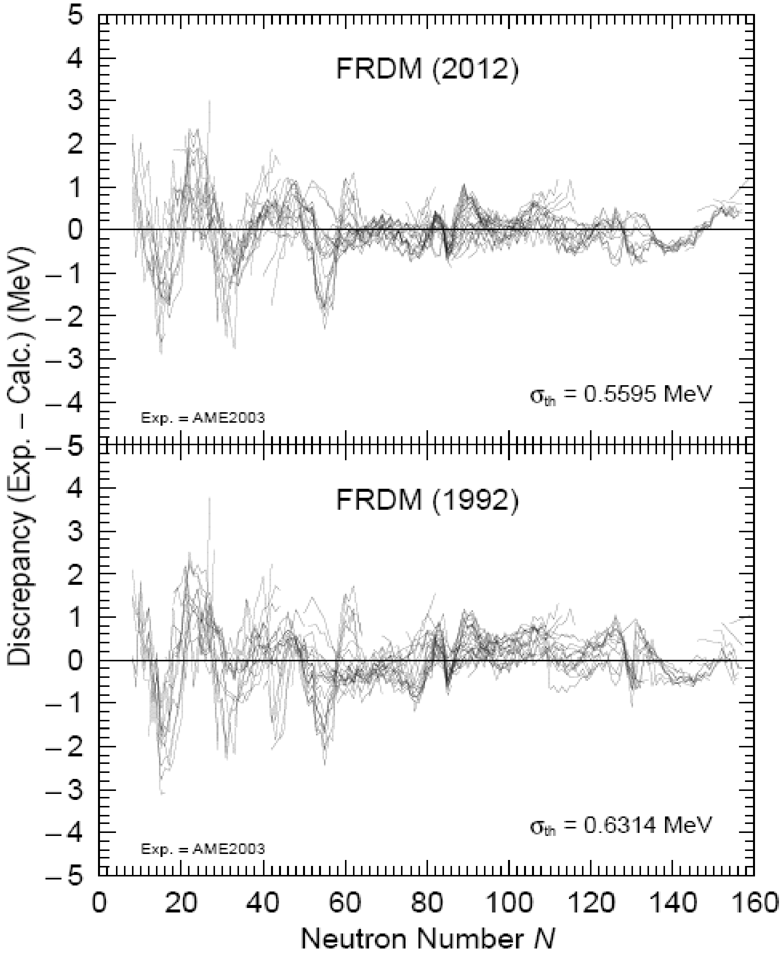
La always 100 % scaled solar;
log(La/Eu) trend correlated with
sub-solar Eu in "r-poor" stars

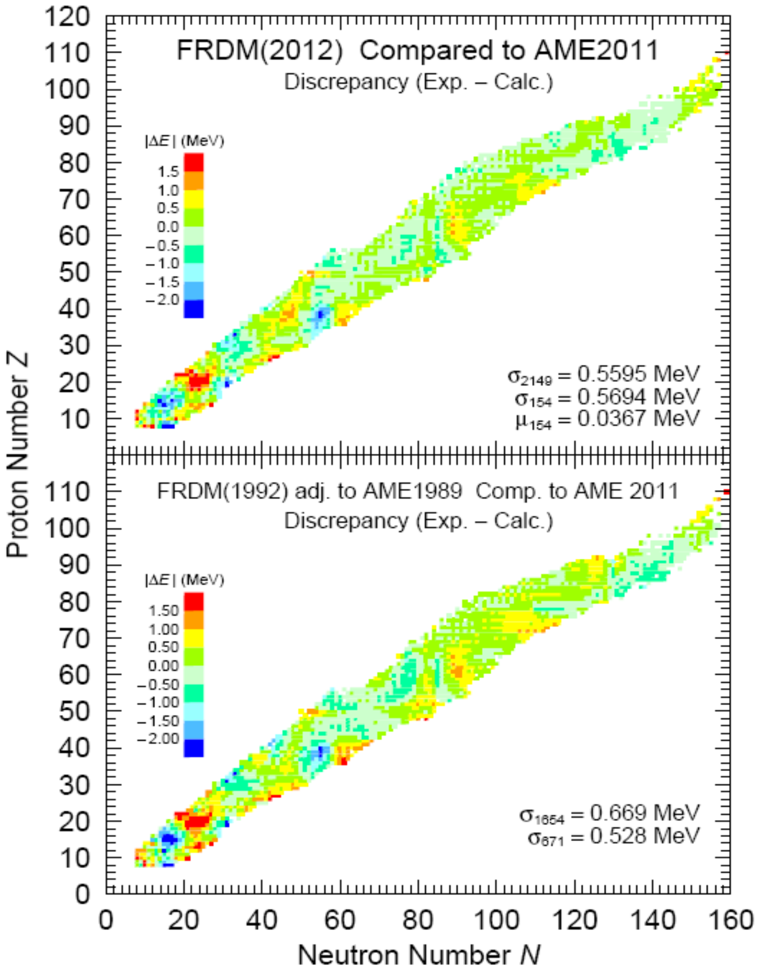
(I. Roederer et al., 2010; K. Farouqi et al., 2010)

Peter Möller s new FRDM 2012 mass model

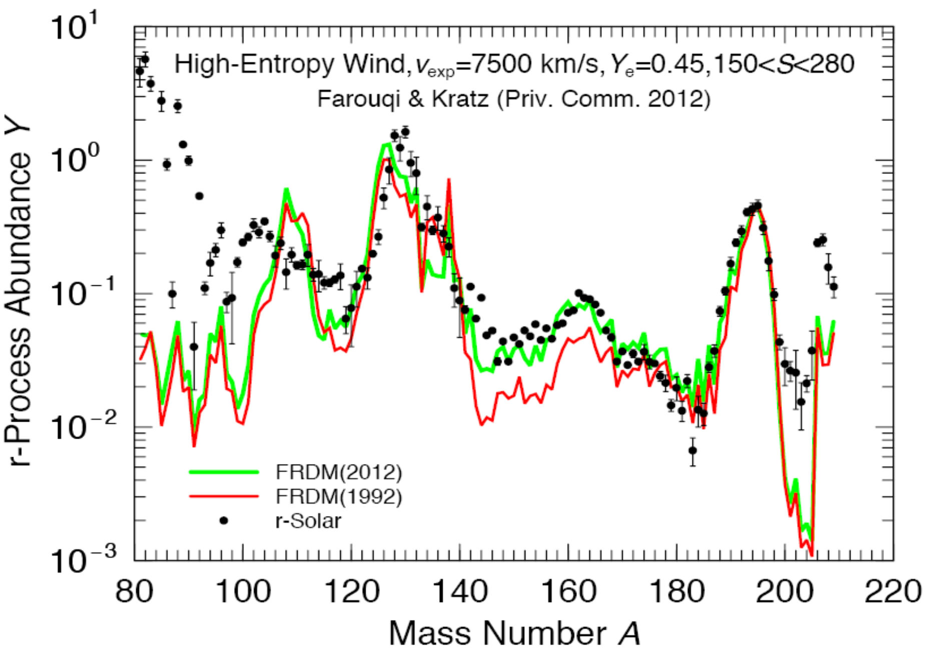
Good news at the end…

to be published in ADNDT





First HEW calculations with the new FRDM 2012



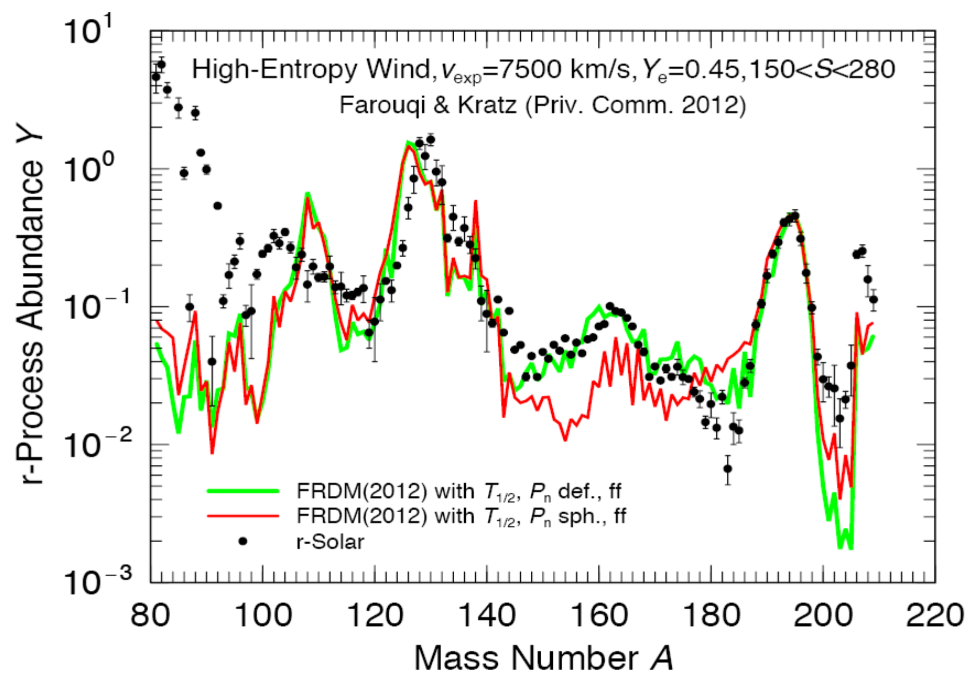
Comparison between $N_{r,\odot}$ and r-abundances calculated with **FRDM 1992** and **FRDM 2012**, respectively.

Note the improvement in the REE region !

Comparison between $N_{r,\odot}$ and r-abundances calculated with masses from **FRDM 2012** and two different sets of QRPA(GT+ff) β-decay properties $T_{1/2}$ & P_n:

a) **deformed**

b) **spherical**

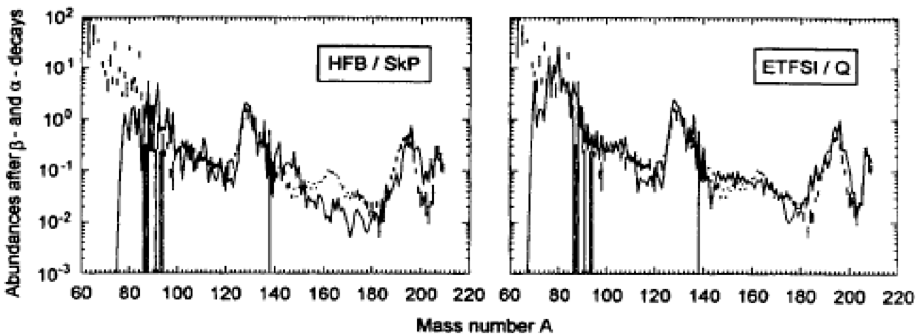


The $N_{r,\odot}$ rare-earth pygmy peak

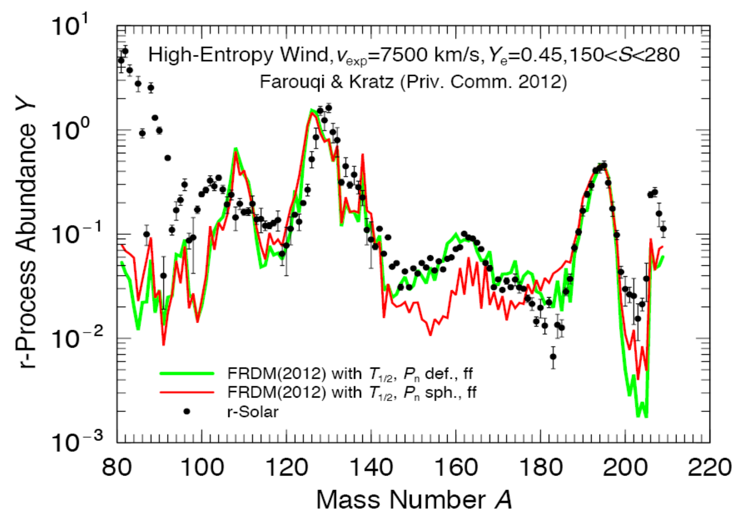
What is the origin of the REE r-abundance peak ?

Already about 15 years ago,
first indications from calculations
using two different mass models
⇨ effect of S_n

SPHERICAL DEFORMED



Today, in principle confirmed by
new calculations using the
"deformed" FRDM 2012 and
two different $T_{1/2}$ & P_n data sets
⇨ effect of **β-decay properties**



REE pygmy peak due to **deformation**, not from fission cycling!

Summary

Still today

- there is no selfconsistent hydro-model for SNe, that provides the necessary astrophysical conditions for a full r-process

Therefore,

- parameterized dynamical studies (like our HEW approach) are still useful to explain r-process observables;

- astronomical observations & HEW calculations indicate that SS-r and UMP halo-star abundance distributions are superpositions of 3 nucleosynthesis components: **charged-particle, weak-r and main-r**

- the yields of the CP-component (up to Zr) are largely uncorrelated with the "main" r-process;

- the yields of the weak-r component (Mo to Cd) are partly correlated with the "main" r-process;
  elements ≥ Te belong to the "main" r-process

- HEW can explain the peculiar isotopic anomalies in SiC-X grains and nanodiamond stardust

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