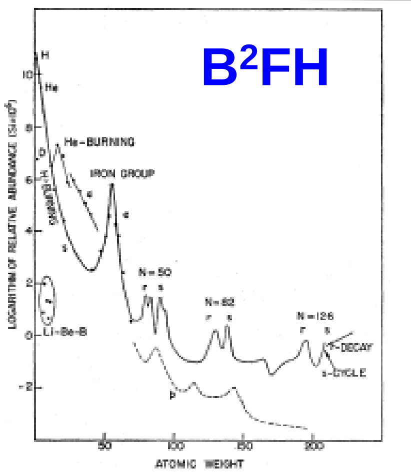
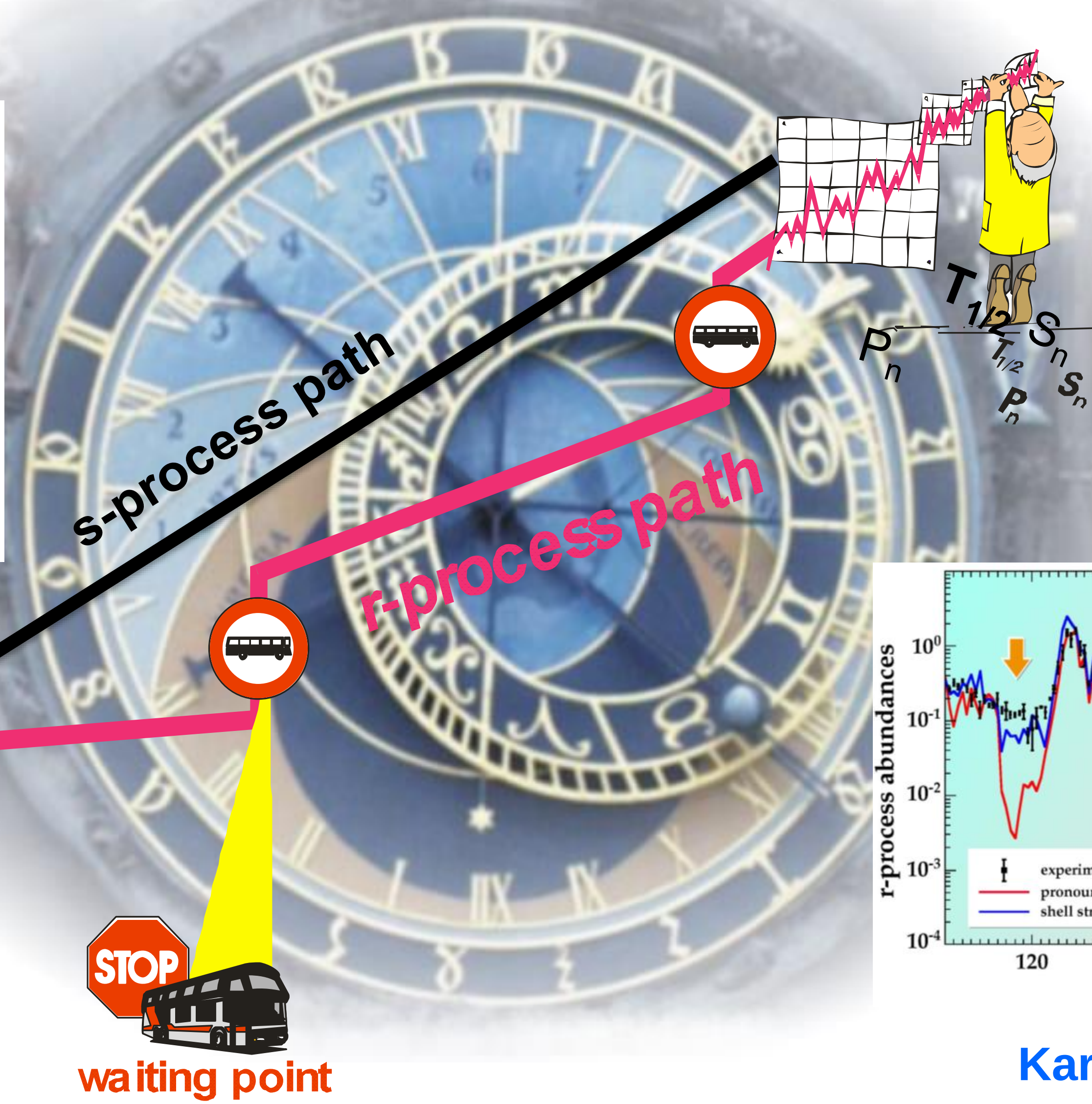
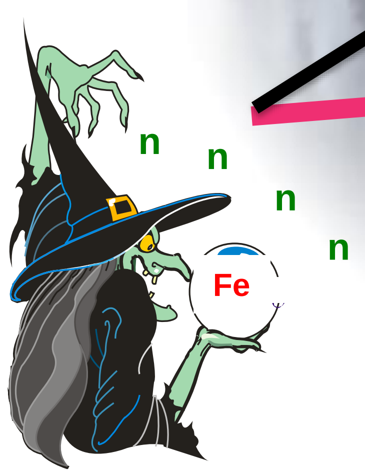
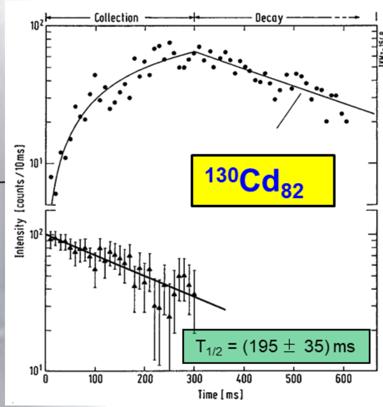
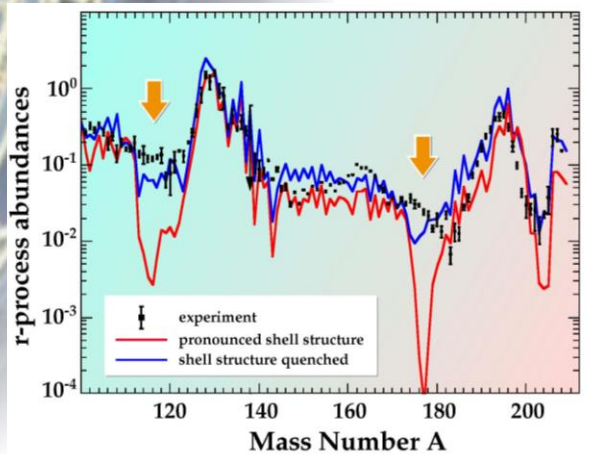
The classical r-process revisited:
what's left over — what's new?











Karl-Ludwig Kratz

Rußbach 2022

Early milestones of r-process nucleosynthesis

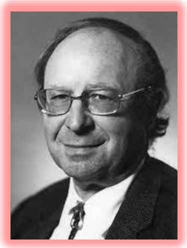
1932 discovery of the neutron by Chadwick

1934 prediction of neutron stars by Zwicky & Baade

1937 first systematic tabulation of solar abundances by Goldschmidt

1953 reflection of closed n-shells in r-process peaks; postulation of steady-state element formation by Coryell

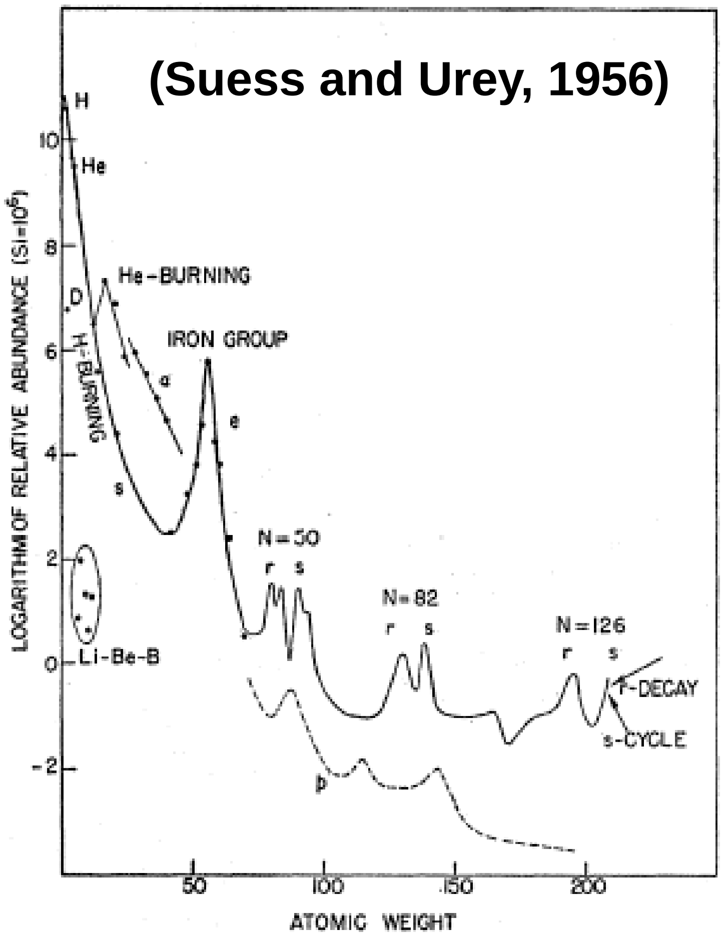
1956 determination of geochemical abundances by Suess & Urey



1957 fundamental papers on nucleosynthesis by Burbidge, Burbidge, Fowler & Hoyle (B^2FH) and by Cameron

Solar abundance observables at B²FH (1957)

(Suess and Urey, 1956)



neutrons

B²FH, Rev. Mod. Phys. 29 (1957)

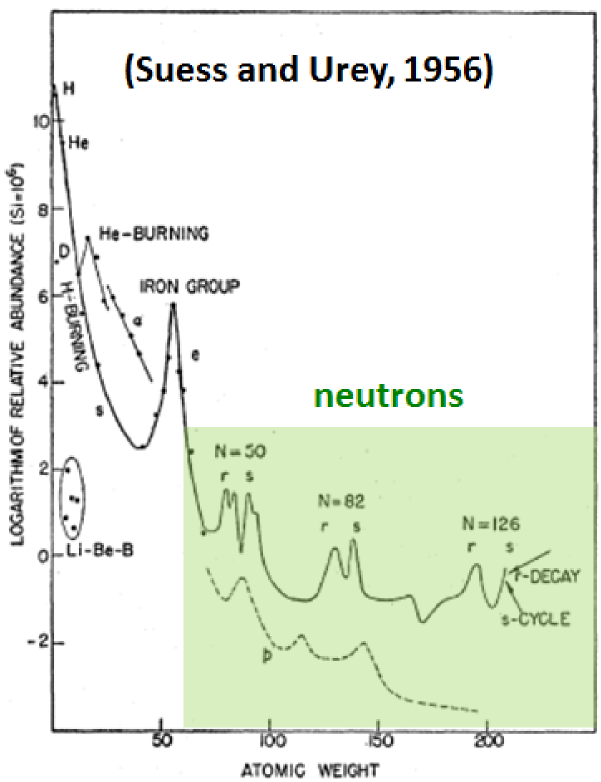
„…it appears that in order to explain all the features of the abundance curve, at least eight different types of synthesizing processes are demanded…“

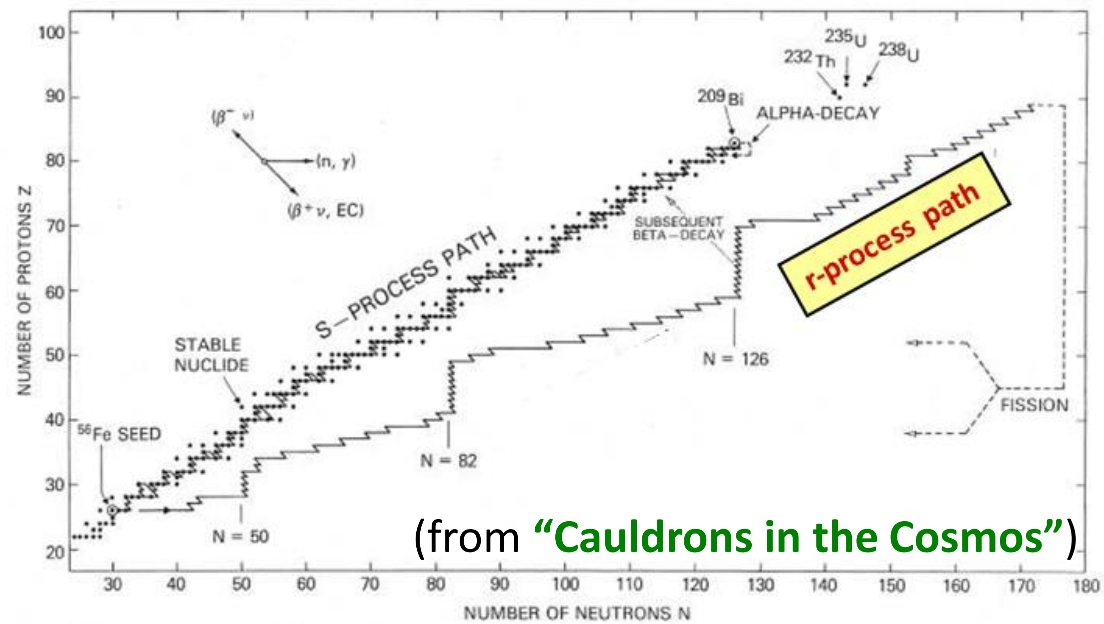
1. **H-burning**
2. **He-burning**
3. **α-process**
4. **e-process**
5. **s-process**
6. **r-process**
7. **p-process**
8. **x-process**

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-process abundances
today about equal





(from "Cauldrons in the Cosmos")

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

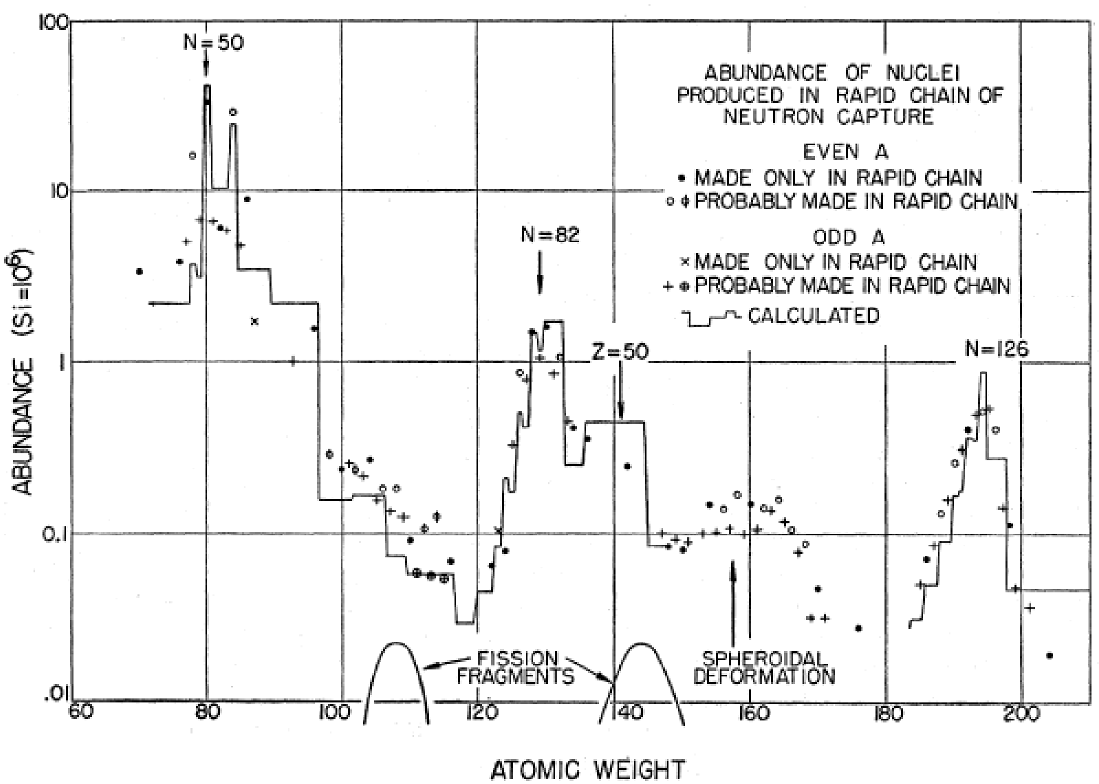
Differences	s-process	r-process
path	at stability	**far from stability**
duration	10^{12} s	**1 s**
n-density	10^{8} cm^{-3}	**10^{28}**
temperature	10^{8} K	**10^{9} K**

Fit of $N_{r,\odot}$ from B²FH

„Static“ calculation

Reproduction of Solar system isotopic r-process abundances

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



Assumption: whole r-process in „one shot“

- **assumptions**
  - **iron seed** (secondary proc.)
  - **„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(α,n)

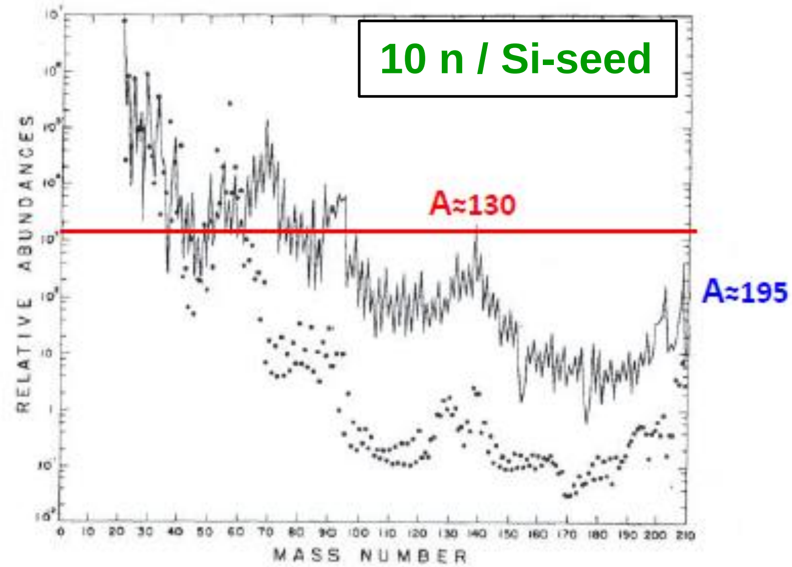
- **nuclear physics:**
  - **Q_β - Weizsäcker mass formula + empirical corrections (*shell, deformation, pairing*)**
  - **$T_{1/2}$ – one allowed transition to excited state, log*ft* = 3.85**

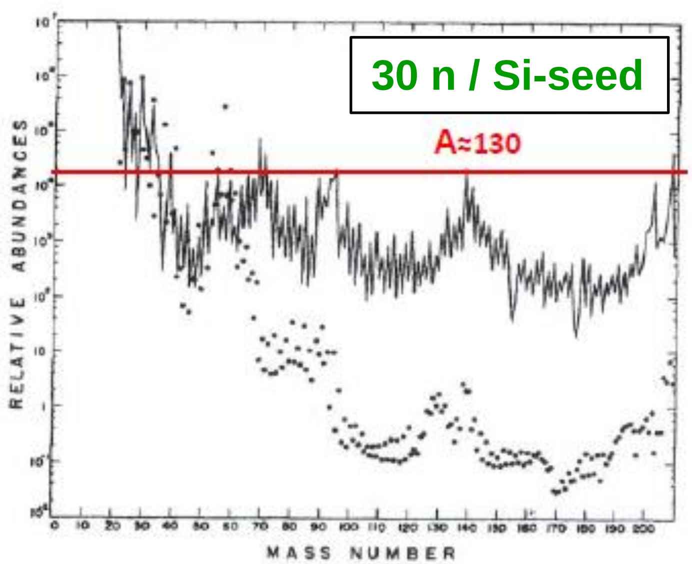
Cameron (1957)

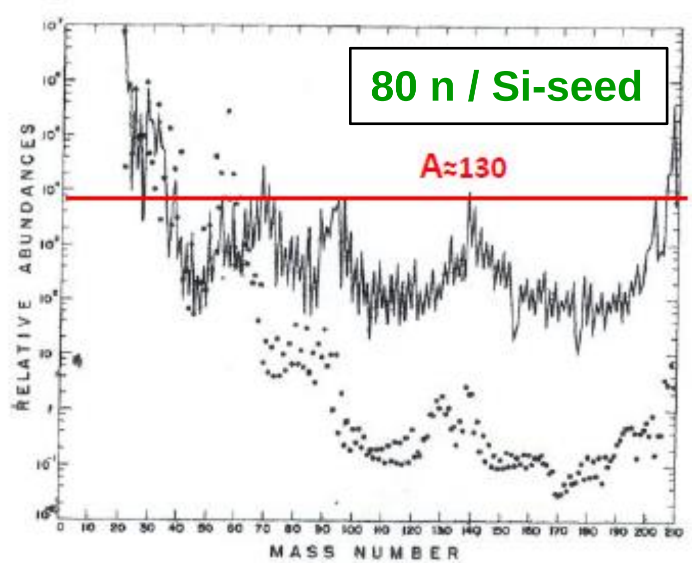
From the Chalk River Report CRL-41:
Lecture series given at Purdue Univ.

First (?) assumption of different r-process components in a **SN-I**, as function of the number of neutrons injected per initial **Si-seed** atom.

Neutron source $^{13}C(\alpha,n)$







Seeger, Fowler & Clayton, ApJ 98 (1965)

Speculations about r-process scenario:

- SN-I (as in B²FH) unlikely
- explosion of massive stars M > 10^3 $M_\odot$
- conventional SNe

First (?) time-dependent calculations of several r-process components

"short-time" solution

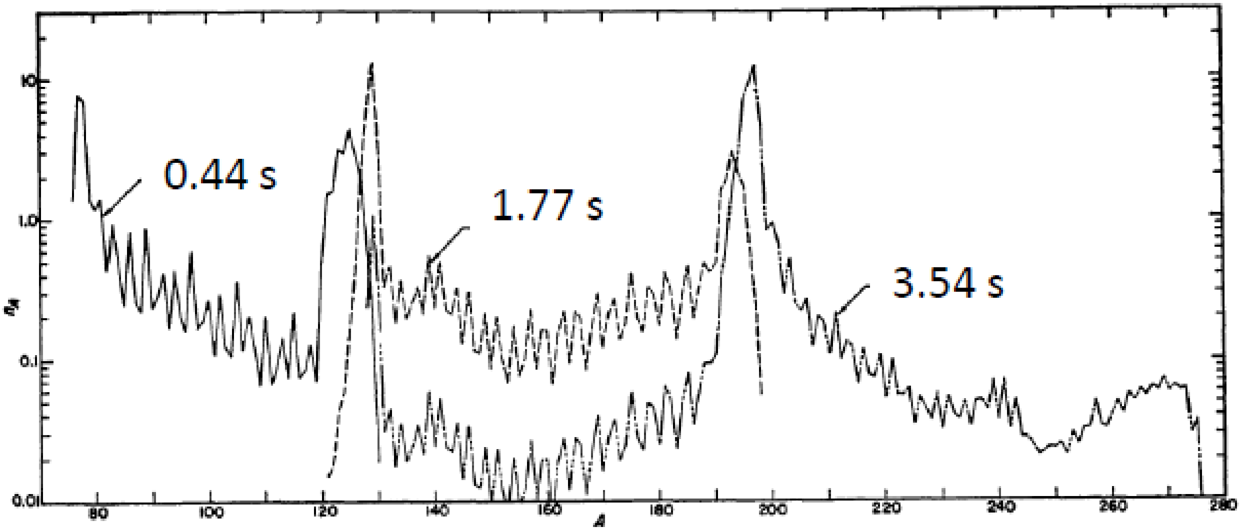


FIG. 12

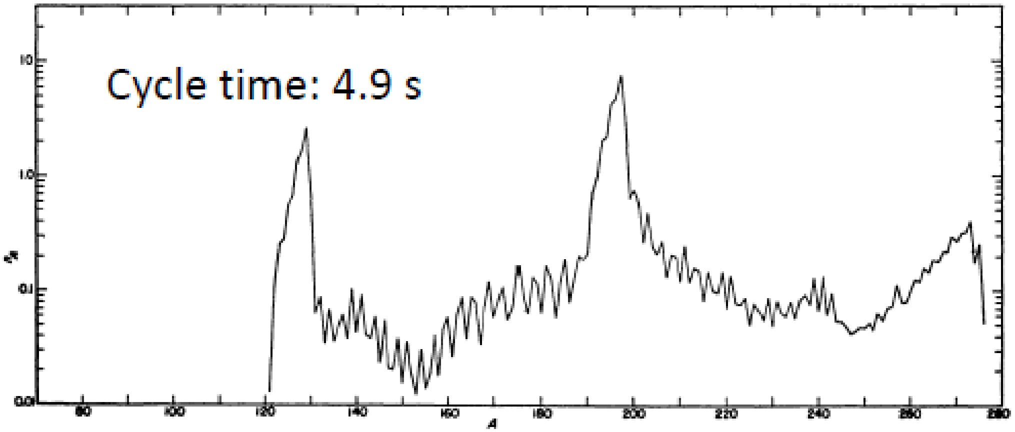


FIG. 13

"long-time" solution

...however, all components with the same neutron-density of 10^{24} n/cm³ !

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

Concept already used by B^2FH

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:

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

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

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

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

in addition to (n,γ)-(γ,n) equilibrium

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

$\boxed{T_{1/2}\,(\text{"w.-p."}) \leftrightarrow N_{r,\odot}}$

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

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

- breakout from N=82 involves ^{131}In and ^{133}In (≈ 1:1)
- ^{133}In has a known P_n ≈ 90

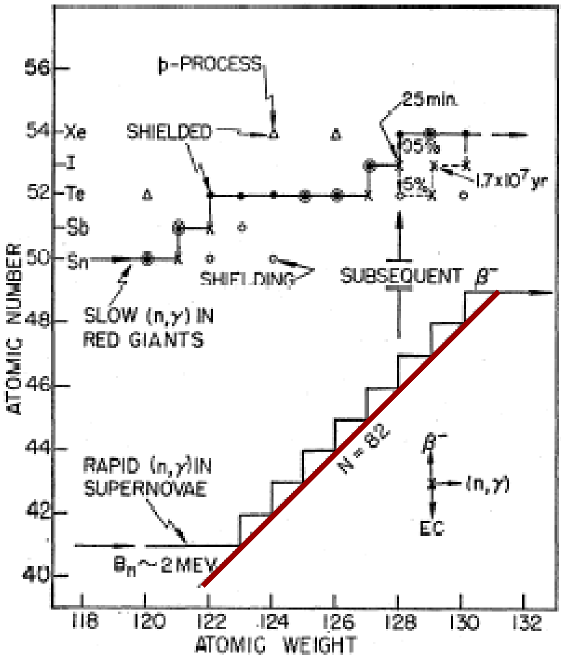
$$T_{½}(^{130}\mathrm{Cd}) \approx \frac{N_{r,\odot}(^{130}\mathrm{Te})}{[N_{r,\odot}(^{131}\mathrm{Xe})/T_{½}(^{131}\mathrm{In})]+[1.1N_{r,\odot}(^{132}\mathrm{Xe})/T_{½}(^{133}\mathrm{In})]} \approx \mathbf{170\ ms}$$

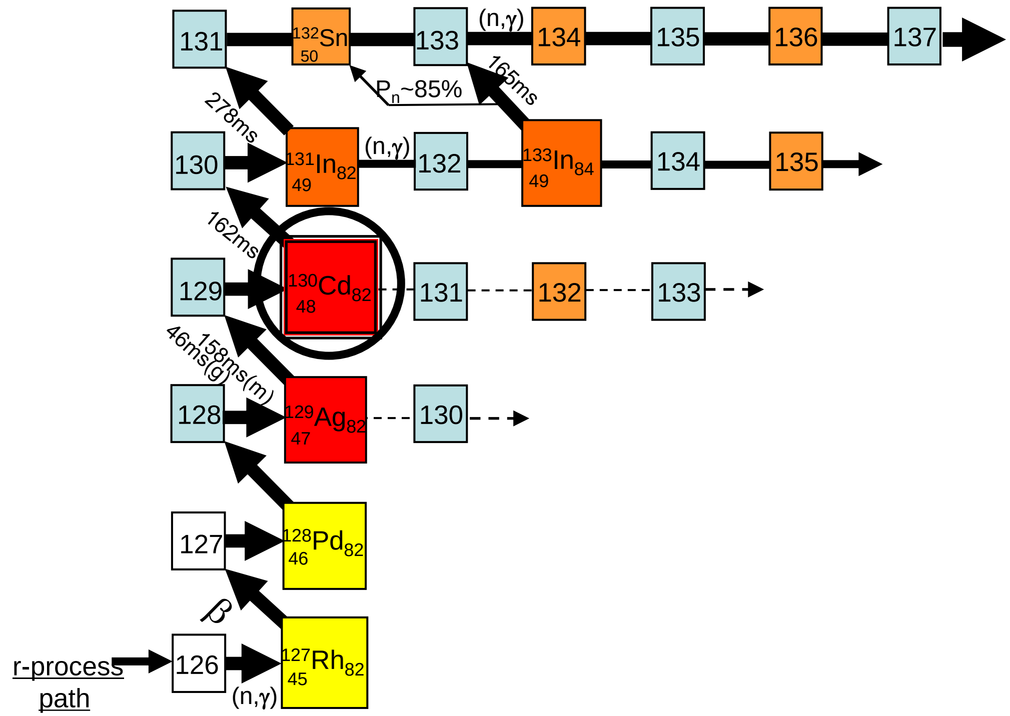
…to be compared to our **1986** exp. value of **195 (35) ms**,
and to our **2000** improved value of **162 (7) ms**,
today ≈ **130 (3) ms**

^{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)

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





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

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

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

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

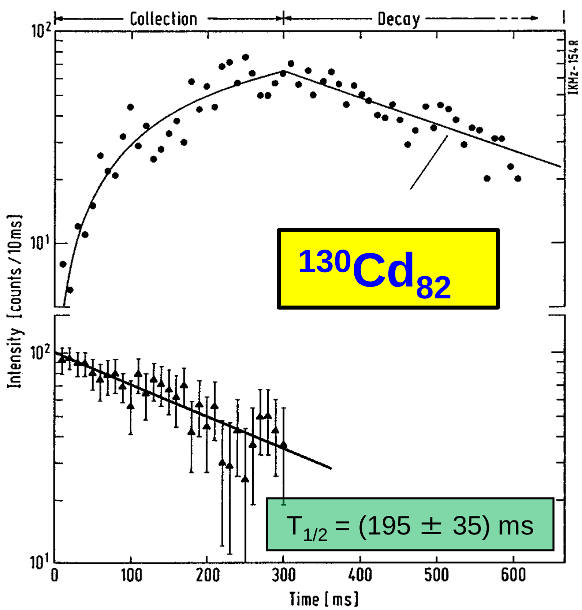
$T_{1/2}$ ⇨ **total r-process duration τ_r**

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



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 $[^{40}Ca^{90}Br]^+$

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

Exp. $T_{1/2}$ of ^{130}Cd as gate-keeper of the r-process
excludes explosive He-burning
favored at that time;
supports supernova scenario.

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

…about 3 decades later:

When we (FK^{2}L) 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")

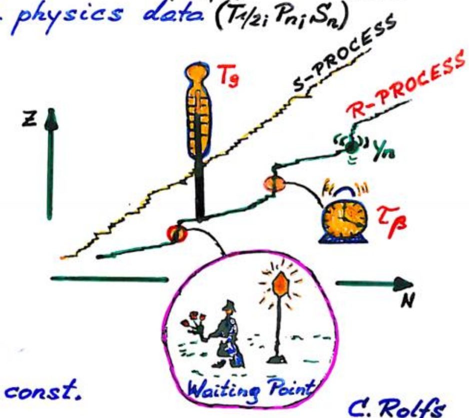
Problems:
Knowledge of
– astrophysical conditions
– nucl. physics far off β-stability

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)

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



C. Rolfs

FK^{2}L => **F**riedrich-**K**arl & **K**arl-**L**udwig
by analogy to B^{2}FH
coined at 22nd Masurian Lake Summer School (1991)

Classical assumptions:

- **global steady flow**
  of r-process through
  N = 50 ^{80}Zn
  N = 82 ^{130}Cd
  N = 126 ^{195}Tm
- r-matter flow at freeze-out temperature

The FK²L waiting-point approach (II)

J. Phys. G 24 (1988)

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

test of

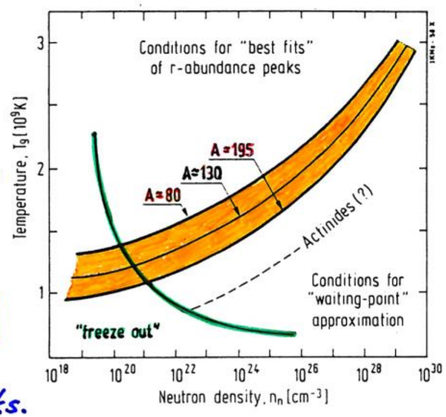
"waiting-point concept":

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

→ deduce $\boxed{T_9 - n_n \text{ band}}$

conditions to fit the

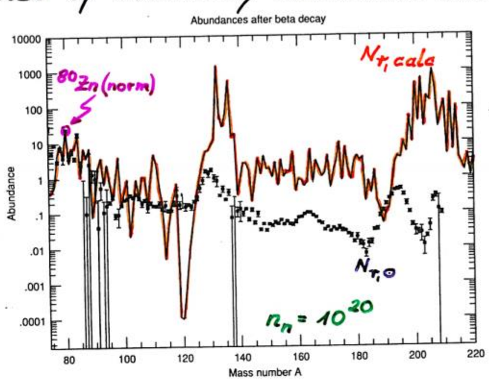
A≃80 and 130 $N_{r,\odot}$-peaks.



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.

Our model:

„site-independent“ waiting-point approach, using first experimental nuclear data of r-process isotopes:

N = 56,57 ^{91,92}Br

N = 60-63 $^{97\text{-}100}$Rb

N = 50 ^{79}Cu, ^{80}Zn, ^{81}Ga

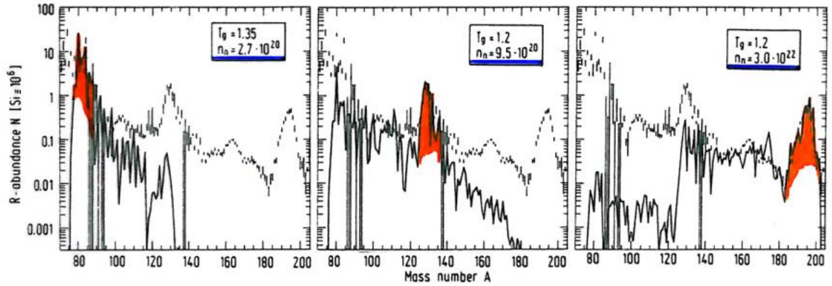
N = 82 ^{130}Cd, ^{131}In

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

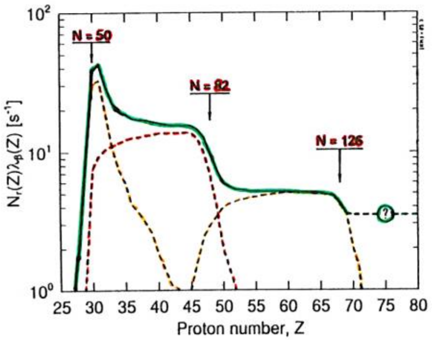
The FK²L waiting-point approach (III)

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}



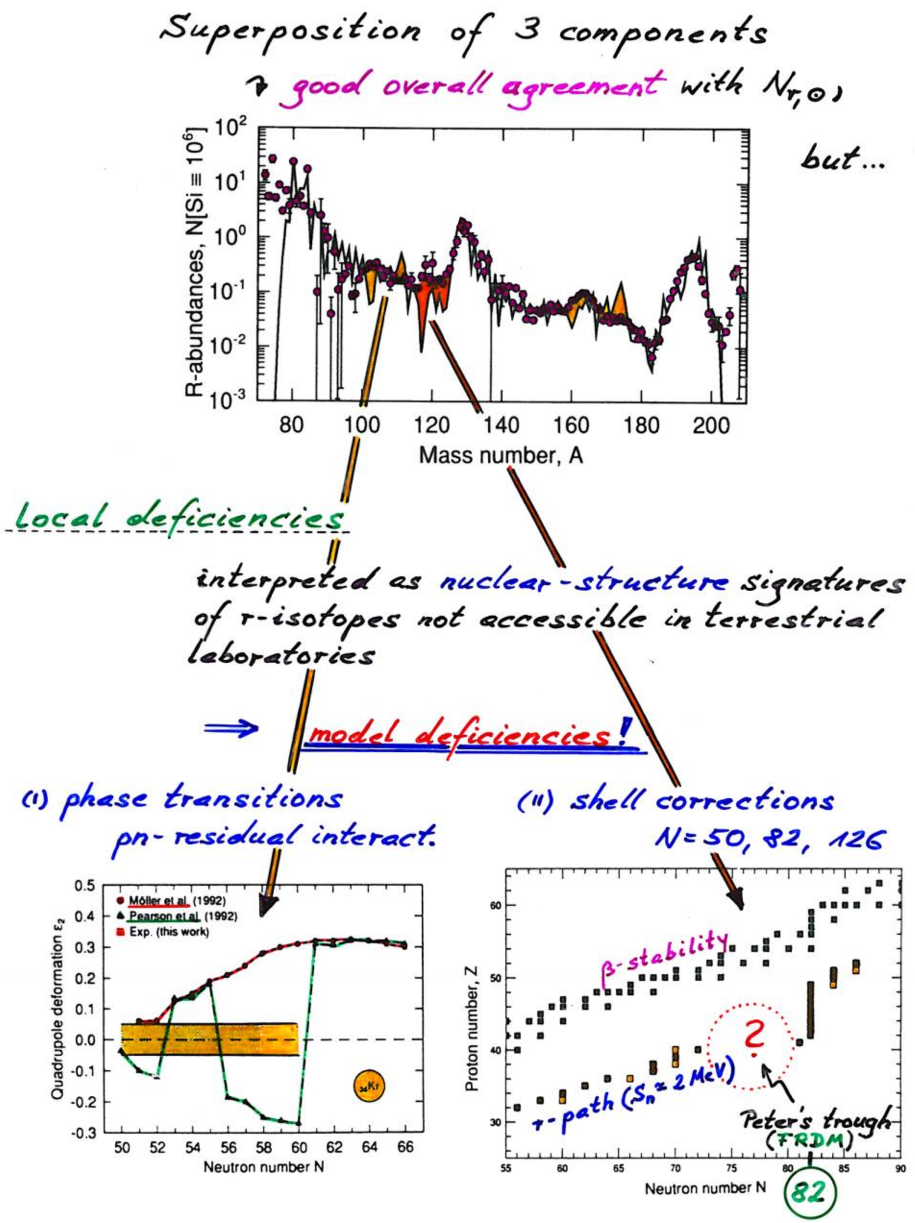
analogous to s-process
with $N_s \sigma = const.$

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

$\boxed{N_r \lambda_\beta = const.}$

weighting acc. to
$T_{1/2}$ (^{80}Zn, ^{130}Cd, ^{135}Tm)

The FK²L waiting-point approach (IV)



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

My speculative interpretation at that time:
"The FRDM + QRPA (1992) model"
deficiency may have its origin in the neglect of the p-n residual interaction which manifests itself in an **overestimation of the Z=50 and N=82 shell strength below ^{132}Sn."**

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

…this catchword coined by **W. Nazarewicz** later led to numerous misinterpretations

To be fair...

J. Phys. G: Nucl. Part. Phys. **19** (1993) S197-S208

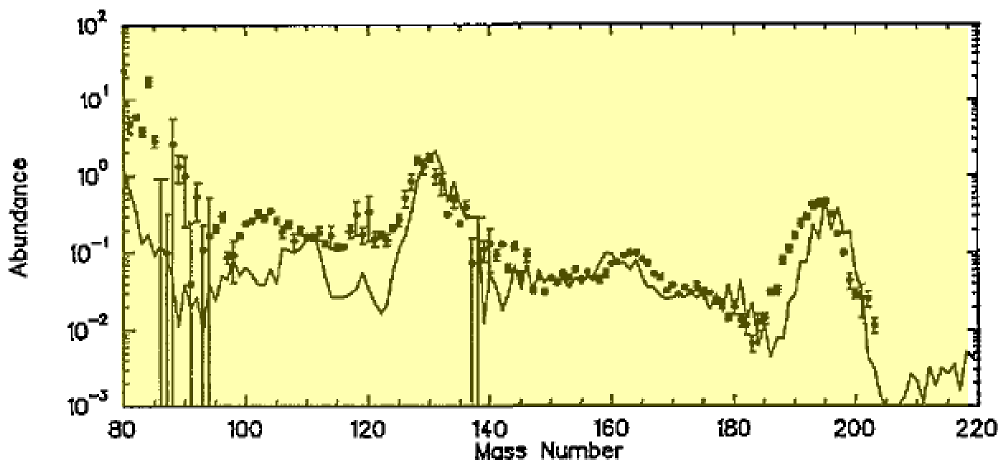
The r-process in the hot bubble

Bradley S. Meyer†[1]

Abstract. The high-entropy, evacuated region forming just outside the proto-neutron star during a core-collapse supernova makes an excellent site for the r-process. The high entropy per baryon allows this region to have a high free neutron/seed nucleus ratio, a necessary requirement for the r-process, even though the material is not particularly neutron rich. The neutrino-driven wind blowing from the hot bubble lasts several seconds and has a mass loss rate of roughly $10^{-5}\ M_\odot\ s^{-1}$. The total mass of r-process matter produced during the supernova is thus $\sim 10^{-4}\ M_\odot$, in good agreement with arguments from galactic chemical evolution. The hot-bubble r-process achieves local steady beta flow, in agreement with results from experimental nuclear physics. Deficiencies in the present model may reflect in part failings of the nuclear mass extrapolation used. It may be possible to constrain nuclear and neutrino physics through the r-process.

Same conclusions as in FK^{2}L !

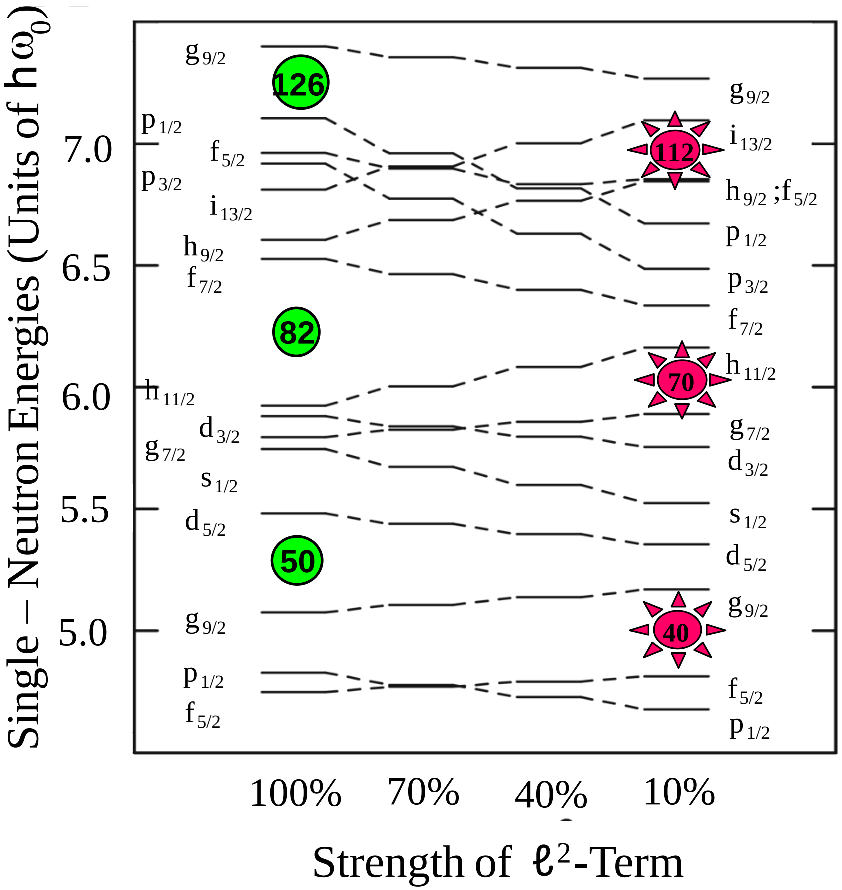
Figure 1.
Weighted-sum r-process and solar r- abundances



N=82 "shell quenching"

What is **"shell quenching" ?**

J. Dobaczewski et al., Phys.Scr. T 56 (1995) → spherical mass model using the HFB theory with the Skyrme interaction SkP



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

change of shell gaps

$\Delta S_n = [S_n(N=81) - S_n(N=83)]$

- high-j orbitals ⇑ (e.g. $\nu g_{9/2}$, $\nu h_{11/2}$)
- low-j orbitals ⇓ (e.g. $\nu d_{5/2}$, $\nu f_{7/2}$)
- new "magic" numbers (e.g. **40, 70, 112**)

In "**unquenched**" FRDM:
Z=50: ^{132}Sn with ΔS_n = 2.35 MeV
Z=40: ^{122}Zr with ΔS_n = 2.50 MeV

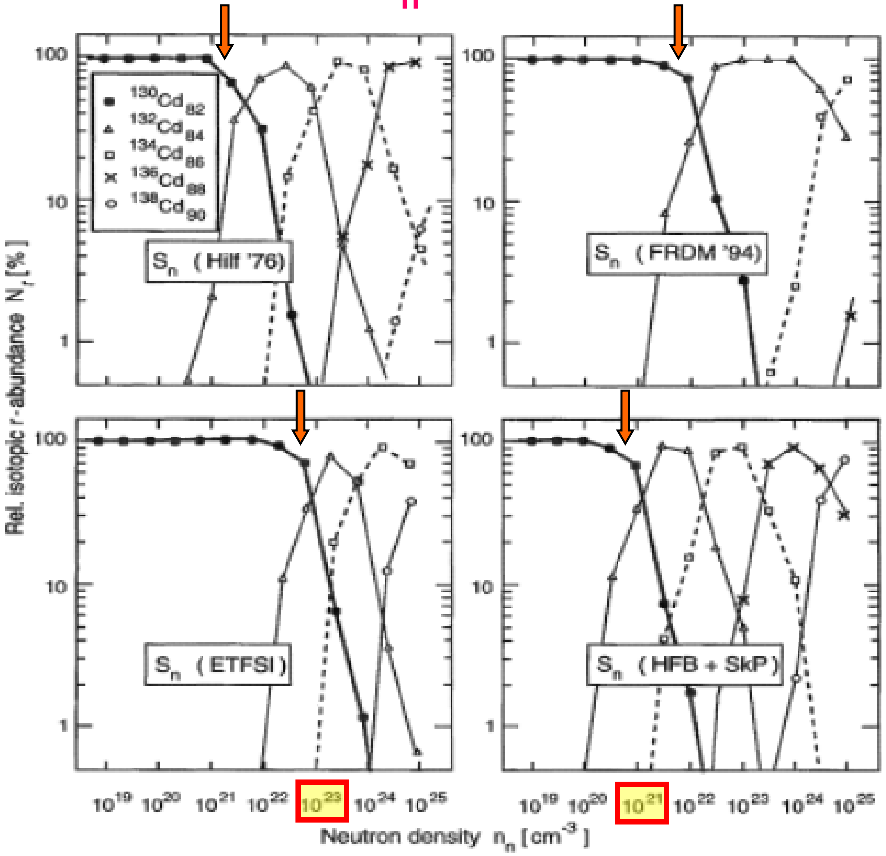
In "**quenched**" HFB/SkP:
Z=50: ^{132}Sn with ΔS_n = 2.40 MeV
Z=40: ^{122}Zr with ΔS_n = 0.62 MeV

Effects of nuclear properties at N=82

…consequences of “shell-quenching”

1998

effect of S_n around N=82



“static” calculations (Saha equation)

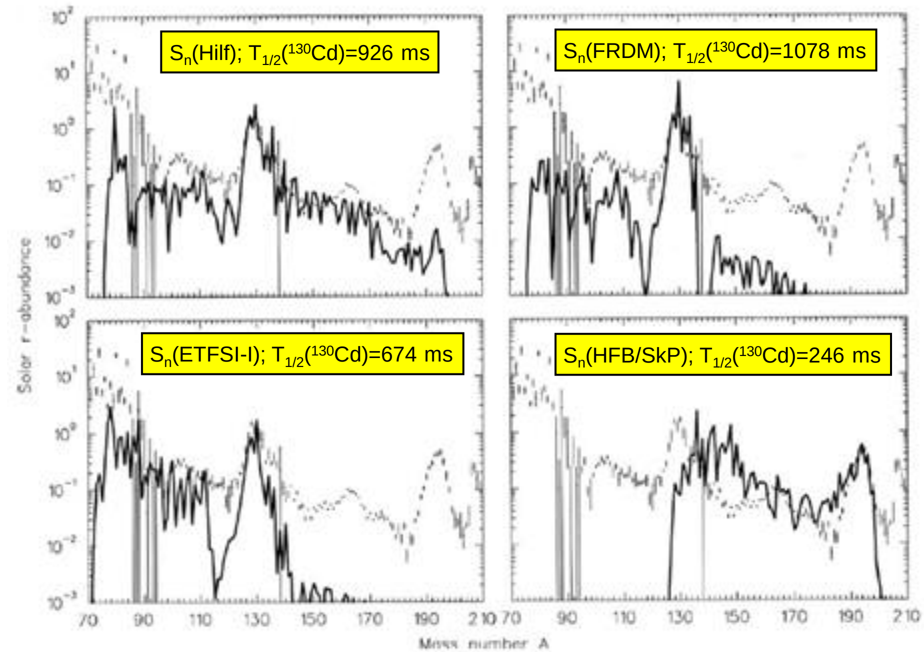
⇨ necessary n_n for r-process break-out at N=82 ^{130}Cd

Kratz et al., Nucl. Phys. **A630** (1998)

correlated effects of S_n / Q_β & $T_{1/2}$

mass models with pronounced N=82 gap

⇨ **longest** $T_{1/2}$(QRPA)



“time-dependent” w.p.-calculations

Under conditions where “unquenched“ mass models produce the 2nd r-peak, “quenched“ HFB/SkP forms already the 3rd peak

Effects of nuclear properties at N=82

Z. Physik A357 (1997)

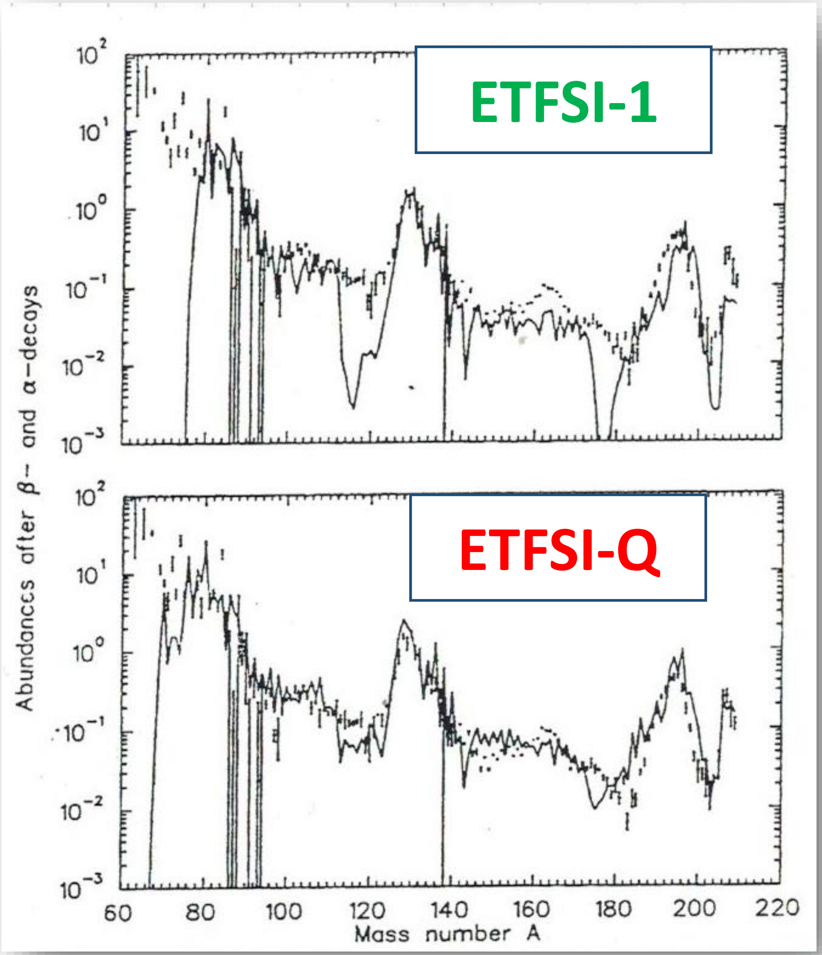
Analysis of the solar-system r-process abundance pattern with the new ETFSI-Q mass formula

For spherical HFB/SKP to Pearson`s deformed ETFSI-Q

Consequences of n-shell quenching:

From ETFSI-1 to ETFS-Q with increasing distance from ß-stability

- Lowering of ground-state deformation
- Lowering of S_n values → larger P_n
- Increase of $Q_ß$ values → shorter $T_{1/2}$ "speeding up" the r-process
- Elimination of r-abundance troughs before and after A ≈130 & A ≈195 r-peaks
- Better reproduction of REE "pygmy peak"
- Better agreement for Pb and Bi
- Considerably improved ^{232}Th & ^{238}U r-chronometer



N = 82 ΔS_{2n} shell gap

Exp. facts from mass measurements in **2015**:

Exp./Mass model	$_{50}$Sn - $_{49}$In	$_{50}$Sn – $_{48}$Cd	$_{50}$Sn – $_{40}$Zr
Mainz & AME (2012)	**- 773 keV**	**- 963 keV**	/
GSI/ESR	- 777 keV	**+ 350 keV**	/
ISOLTRAP	- 777 keV	**- 1.31 MeV**	/
FRDM (1992)	- 353 keV	+ 204 keV	+ 792 keV
HFB/SkP	- 270 keV	- 600 keV	- 3.64 MeV
ETFSI-Q	- 190 keV	- 180 keV	- 4.28 MeV
KTUY (2005)	- 500 keV	- 690 keV	- 1.41 MeV
HFB-27	- 200 keV	- 420 keV	- 4.28 MeV

Publicized statements:

"There is absolutely **no evidence** of the hypothesized quenching effect in either the **β-decay rates** or **nuclear masses**."
(Kajino, Mathews et al.)

"Our study … manifests **for the first time** changes in the shell structure in this (N=82) region. … A significant reduction of the N=82 gap … is **expected**."
(Aprahamian, Mumpower et al.)

"The masses measured in this work allow a **first probing** of the N=82 shell towards the drip line. …The new masses **show** a significant reduction of the N=82 shell gap for Z<50."
(Blaum, Goriely et al.)

Consequences of neutron-shell quenching - TODAY

ELSEVIER

Progress in Particle and Nuclear Physics
Volume 107, July 2019, Pages 109-166

Review

Current status of *r*-process nucleosynthesis

T. Kajino [a, b, c], W. Aoki [a], A.B. Balantekin [a, d], R. Diehl [e, f], M.A. Famiano [a, g], G.J. Mathews [a, h]

Chapter 6.6: Magneto-hydrodynamical jet models

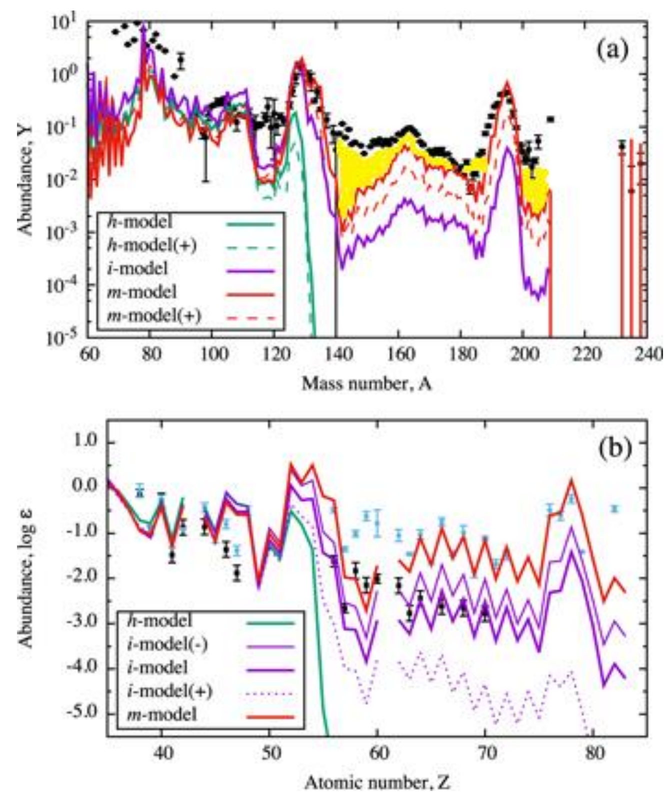
"… As the ejected low Ye material in the jet emerges from the Si layers, an r-process occured that reasonably reproduced the solar r-process abundance distribution up top the 3rd peak."

"… However, many of the jet simulations (Refs. Winteler; Nishimura) tend to underproduce nuclides just below and above the r-process peaks. This tendency seems to be a generic weakness of the MHDJ models."

As shown before, this is NOT a "weakness" of the r-process models, but due to the "unquenched" nuclear physics input !

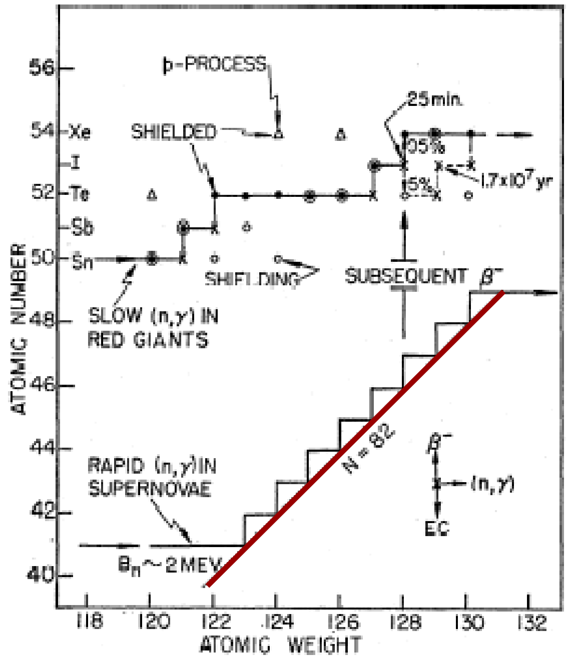
From Nishimura et al., ApJL 836 L21 (2017)

MHDJ simulations based on "unquenched" FRDM (1992)



At the end: Why still hunting for ^{130}Cd ?

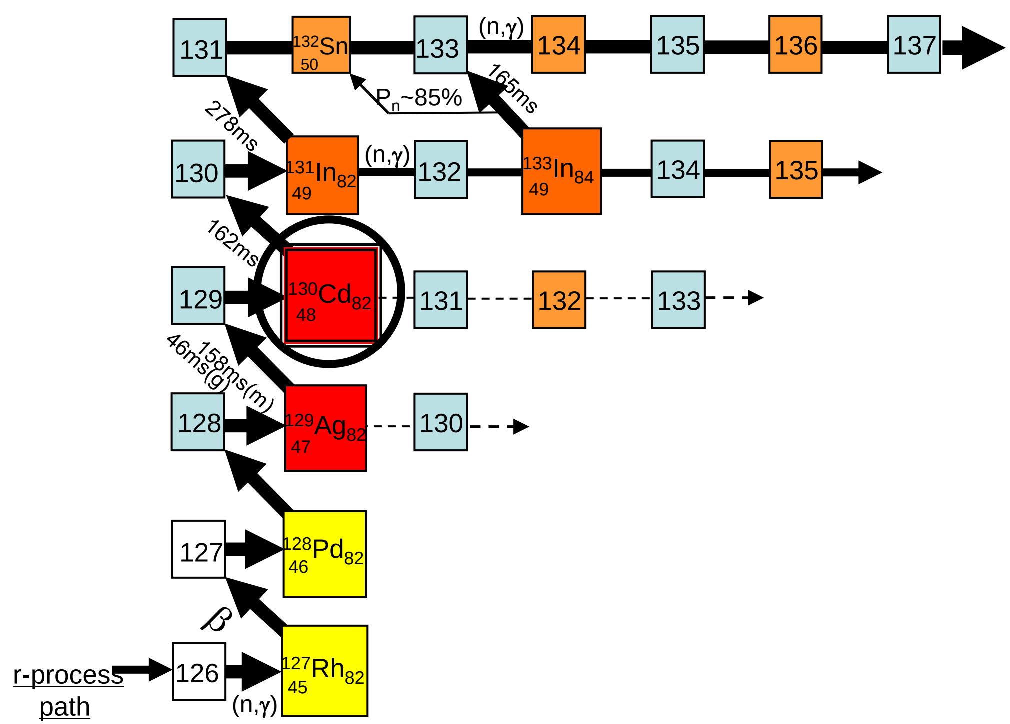
already B²FH (Revs. Mod. Phys. 29; 1957)
C.D. Coryell (J. Chem. Educ. 38; 1961)



"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"

A = 130, **N = 82** as most important bottleneck for the r-process matter flow



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**

$S_\beta(E)$ & $T_{1/2}$ of N=82 ^{130}Cd

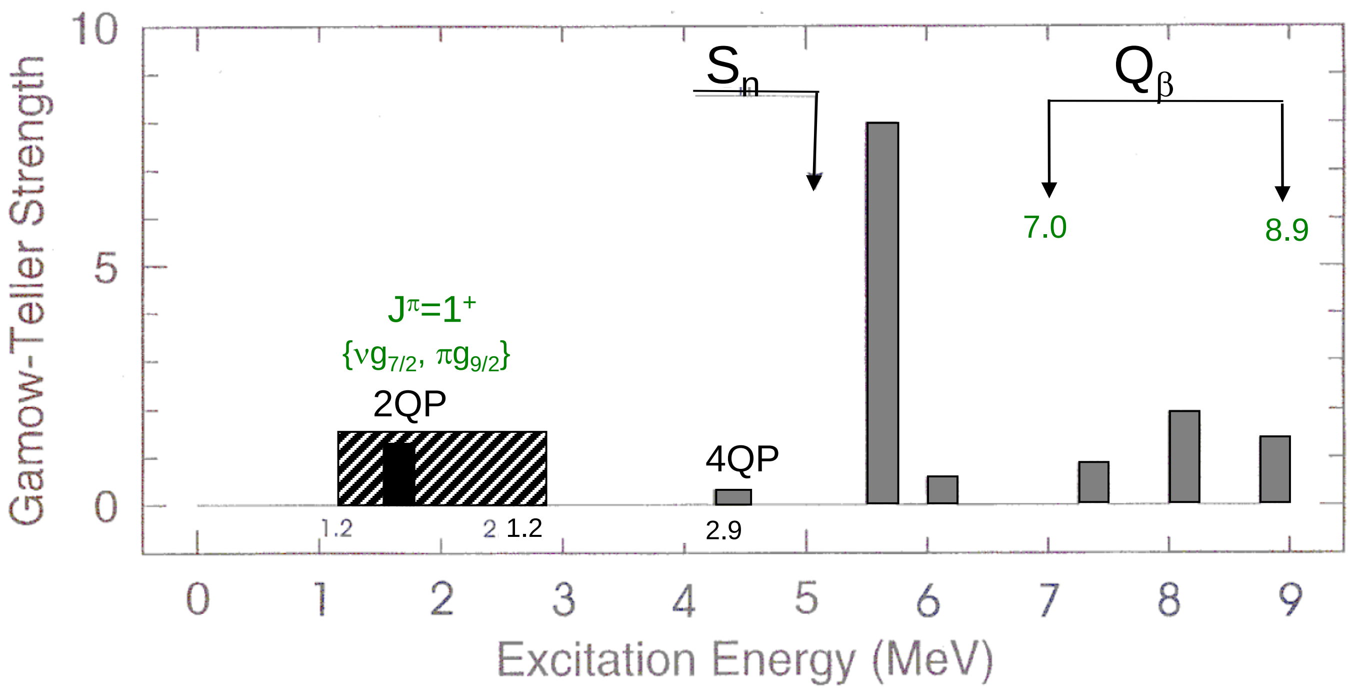
By combination of all nuclear-physics quantities, a physically consistent picture !

Nilsson model (BCS)

$^{130}_{48}Cd_{82} \rightarrow ^{130}_{49}In_{81}$

Important ingredients:

Q_β, $E(1^+)$, $I_\beta(1^+)$, log ft



Early $T_{1/2}$ predictions

GTNM	**1.2 s**
FRDM/QRPA	**1.1 s**
Livermore SM	**30 ms**

1986, 195±35 ms

2000, 162±7 ms

today 127±2 ms

135±8 ms

126±4 ms

However, with $T_{1/2}$(exp) alone, no unambiguous solution !

Therefore, correct Q_β, $E(1^+)$, log ft and ff-transitions through detailed spectroscopy

"free choice" of combinations:

(log ft=4.0)

	$T_{1/2}$(GT)
low $E(1^+)$ with **low** Q_β	**185 ms**
high $E(1^+)$ with **low** Q_β	**900 ms**
low $E(1^+)$ with **high** Q_β	**60 ms**
high $E(1^+)$ with **high** Q_β	**195 ms**

Request: Selectivity !

Remember

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

- 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

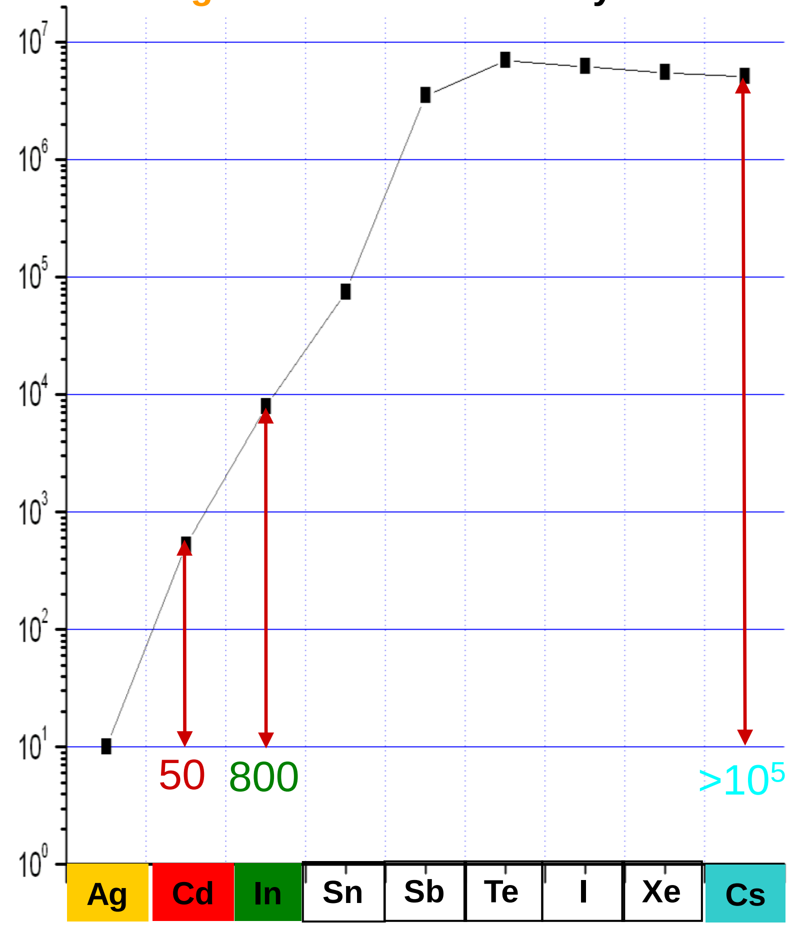
developed since 1993

- 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

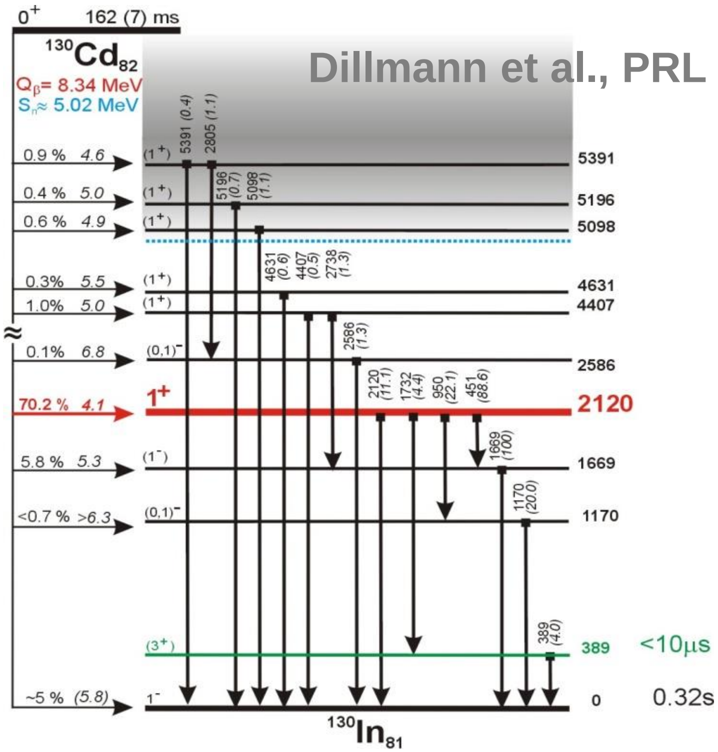
the **Ag** “**needle**” in the **Cs** “**haystack**”



Additional spectroscopy of ^{130}Cd decay

…17 years after the first $T_{½}$ measurement, a physically consistent picture;

but, all experimental ingredients correct ?



- short $T_{1/2}$
- high Q_β
- high $E(1^+)$
- low log ft
- low-lying ff

ENSDF(2008):

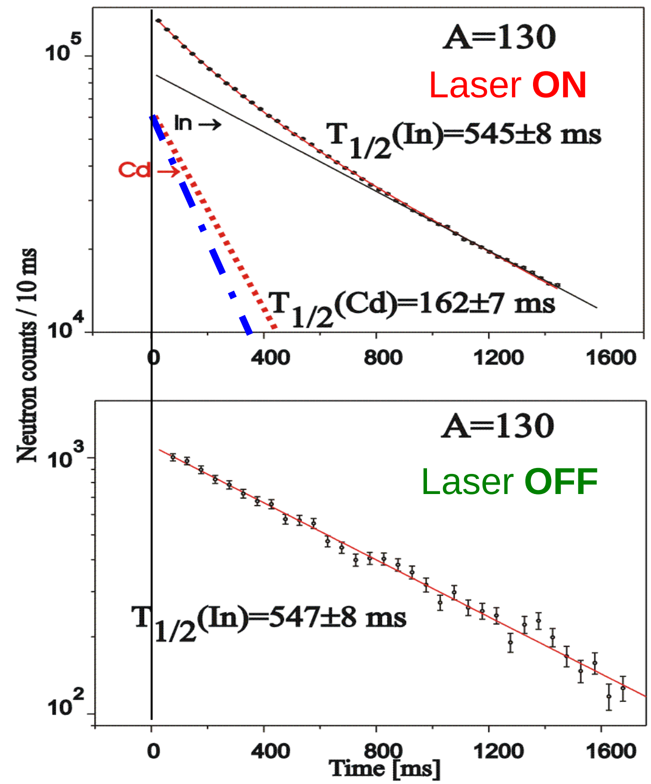
^{130g}In ($J^\pi = 1^-$) $T_{1/2} = 290 \pm 20$ ms;
populated as β–decay daughter of ^{130}Cd

^{130m,n}In ($J^\pi = 10^-, 5^+$) $T_{1/2} = 540 \pm 10$ ms;
no feeding from ^{130}Cd

For example,
question about "correct" ^{130}Cd half-life

ISOLDE $T_{1/2} = 162 \pm 7$ ms

subtraction of primary ionized high-spin **^{130m,n}In**;
Cd component may also contain small **^{130g}In** daughter activity;
new analysis yields **$T_{1/2}$(Cd) = 137 +8/-5 ms**
(now closer to the new RIKEN value !)



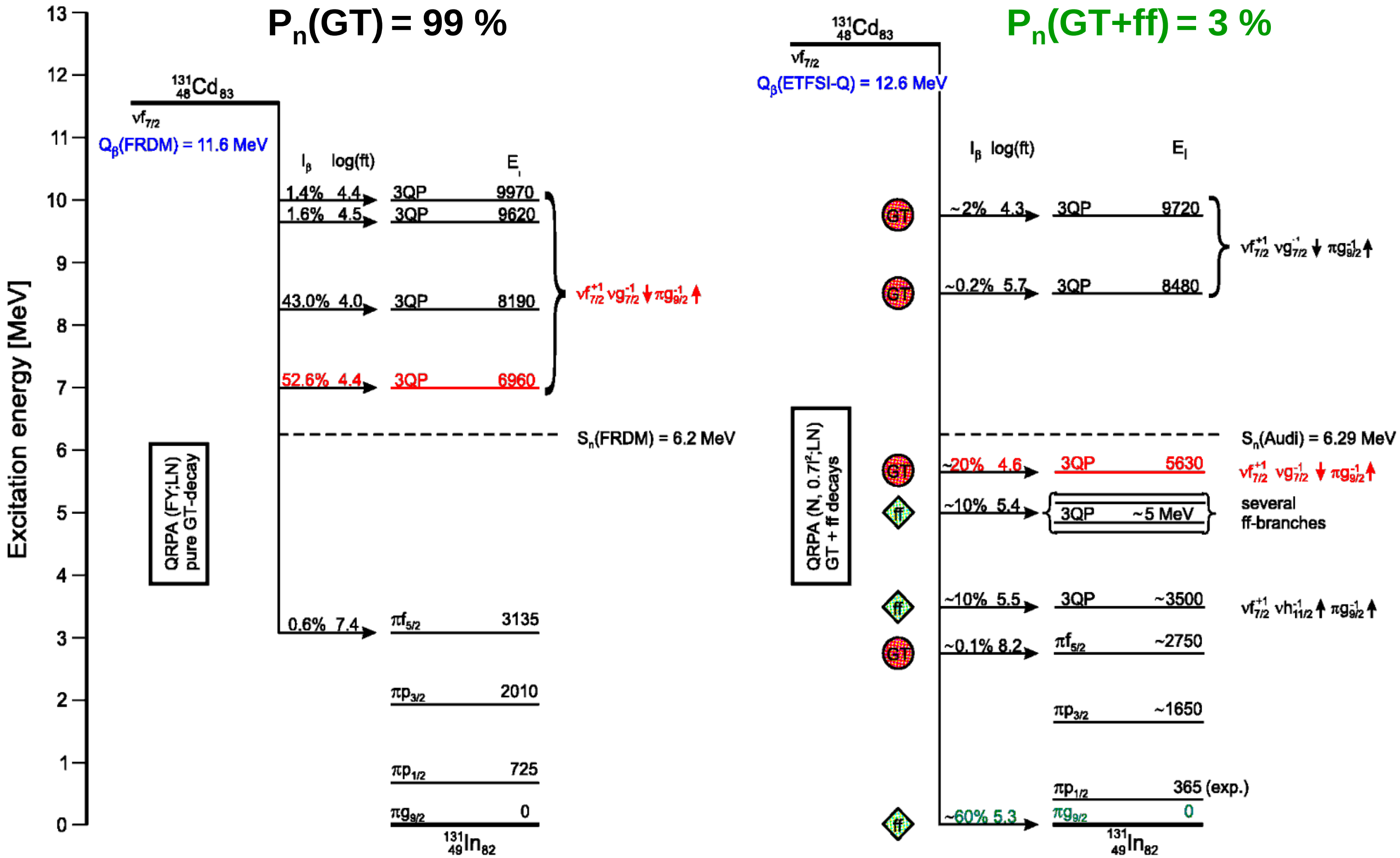
Surprising β-decay properties of ^{131}Cd

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

Experiment: $T_{1/2}$ = 68 / 98 ms; P_n = 3.4 % (PRC 62, 2000)

QRPA predictions: **$T_{1/2}$(GT) = 943 ms;** **$T_{1/2}$(GT+ff) = 95 ms;**

P_n(GT) = 99 % **P_n(GT+ff) = 3 %**



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

later, **γ-spectroscopic confirmation of decay scheme** at **ISOLDE** and **RIKEN**

Short-range extrapolations of β-decay properties

…on the basis of the experimental results on ^{131}**Cd** β–decay,

in 2010, new QRPA calculations of $T_{1/2}$ & P_{xn} for **82≤N≤86** $_{45}$**Rh** to $_{48}$**Cd**;
instead of standard Folded-Yukawa using a **modified Nilsson potential**
with a **25% reduction of the l^2-term** (see e.g. Hannawald et al., PRC 62)

reduction of neutron-pairing energy
upward shift of E(SP) of $\nu g_{7/2}$

.

$T_{1/2}$ of 12 new isotopes from above **Rh** to **Cd** measured at **RIKEN** (PRL 114)

mean deviation from **"old" FY-QRPA** **2.10**
mean deviation from **"new" mod.-N-QRPA** **1.35**

as typical example, N=82 ^{128}**Pd**: $T_{1/2}$(exp) = **35**(3) ms
$T_{1/2}$(old) = **74** ms
$T_{1/2}$(new) = **33** ms

Modified Nilsson-QRPA also used to predict new $\mathbf{P_{xn}}$ values;

partly significant differences to old FY-QRPA predictions

as typical example N=84 ^{133}**Ag**:

	P_{1n}	P_{2n}	P_{3n}
old	8%	69%	19%
new	3%	8%	86%

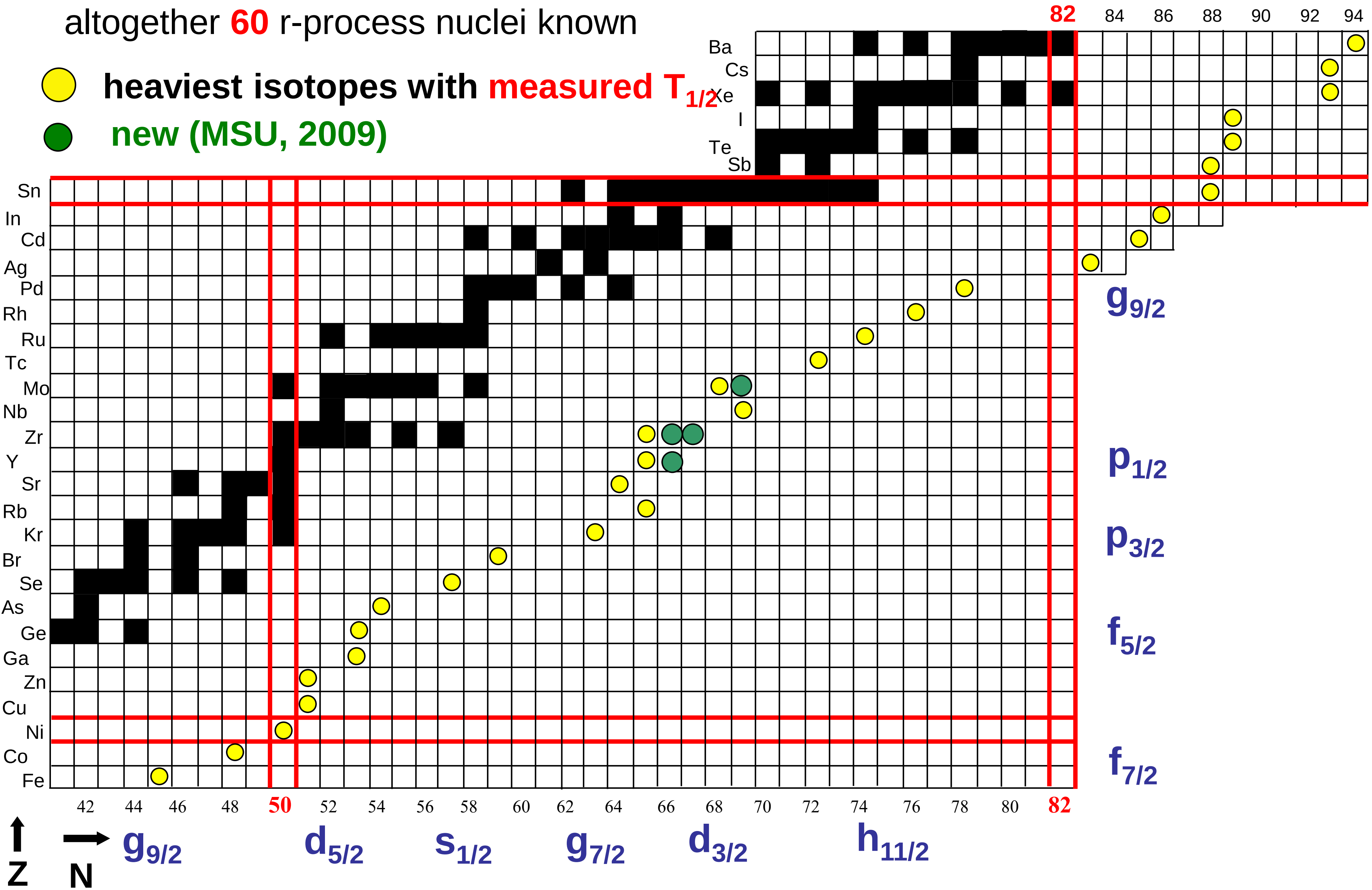
may change the abundance of "r-only" ^{130}Te !

Experimental information on r-process nuclides

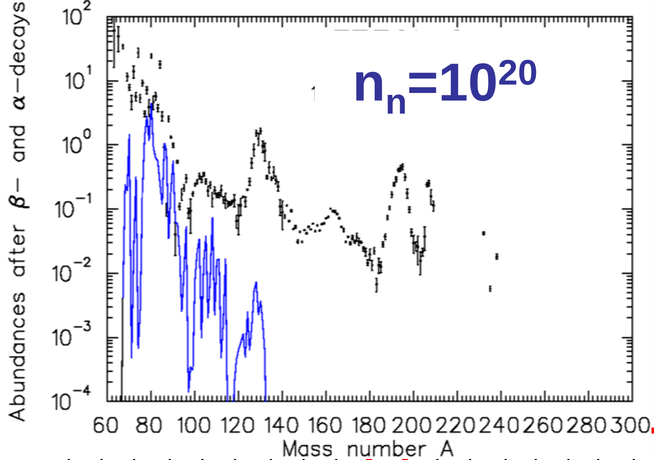
Around 2003,
altogether **60** r-process nuclei known

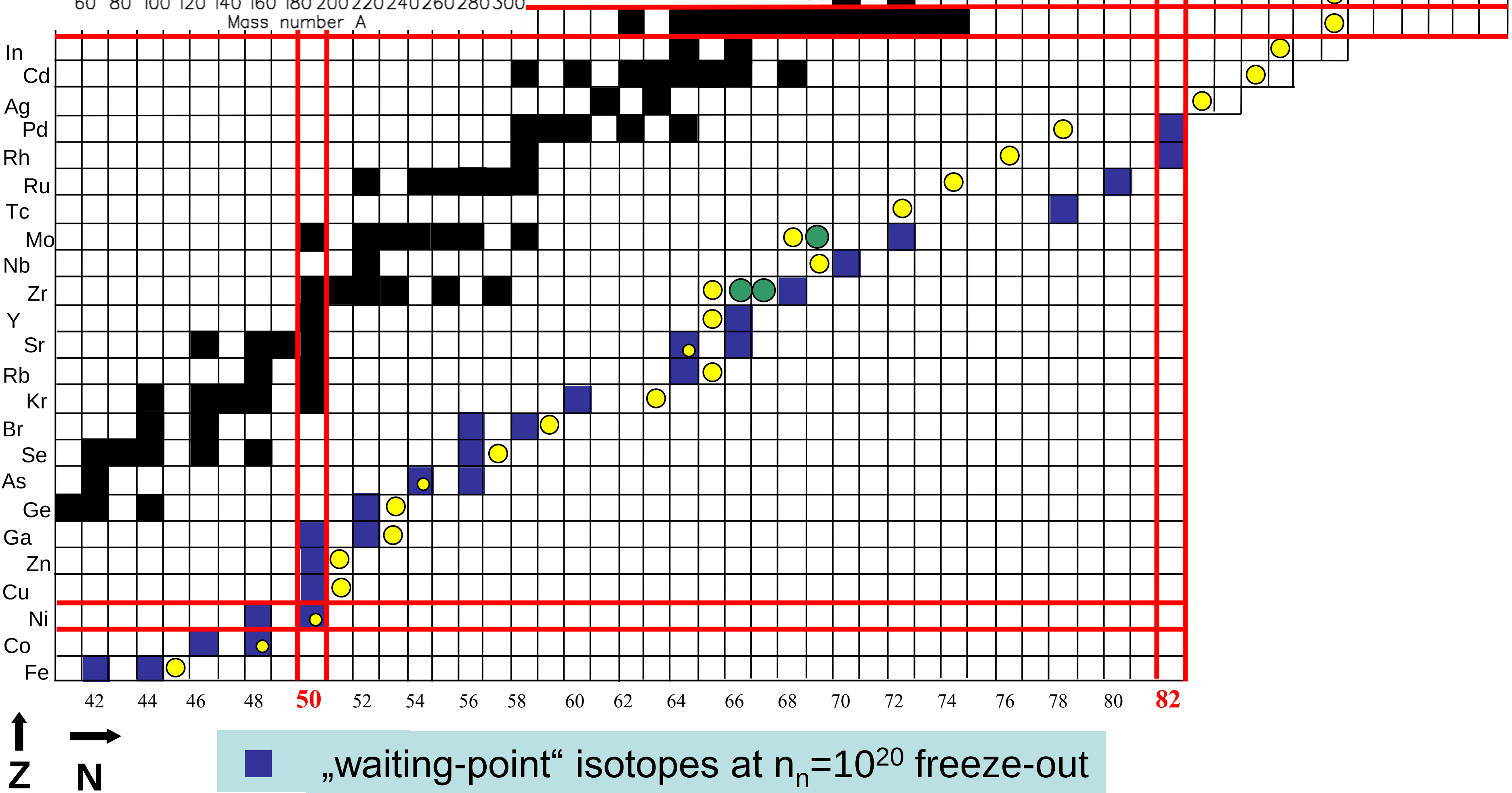
heaviest isotopes with measured $T_{1/2}$

new (MSU, 2009)



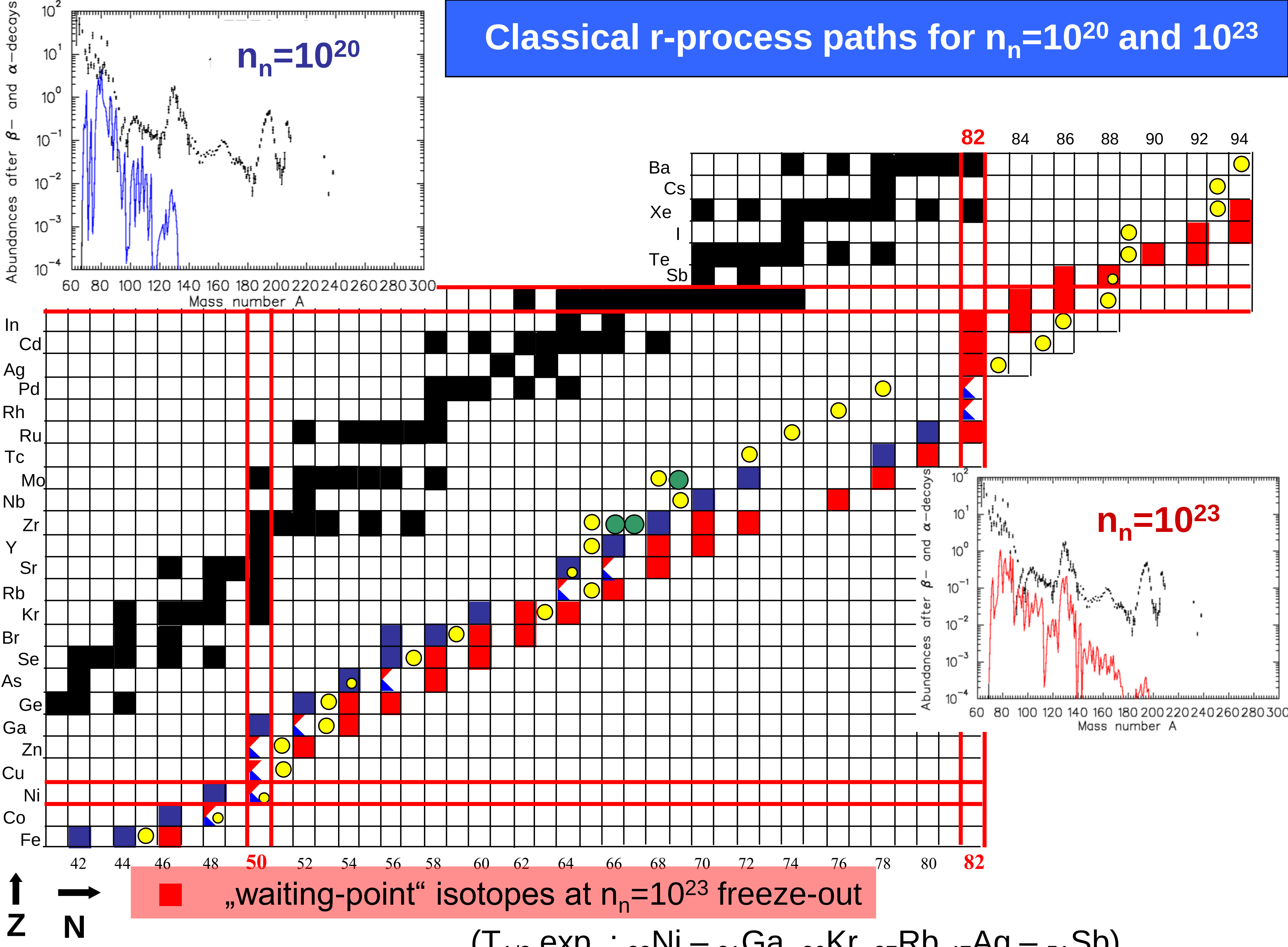
Classical r-process path for $n_n=10^{20}$





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

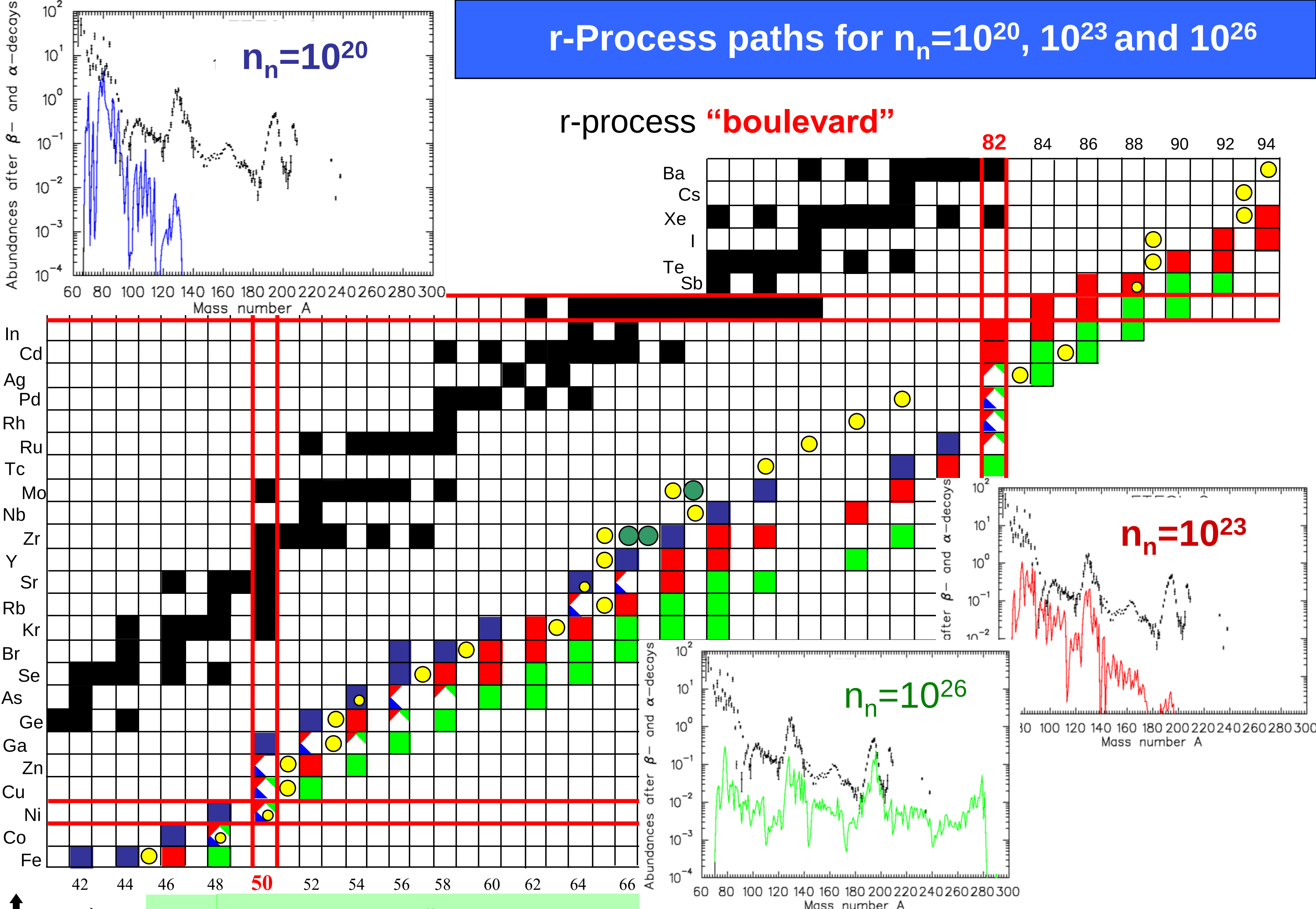
Classical r-process paths for $n_n=10^{20}$ and 10^{23}



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

($T_{1/2}$ exp. : $_{28}$Ni – $_{31}$Ga, $_{36}$Kr, $_{37}$Rb,$_{47}$Ag – $_{51}$Sb)

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



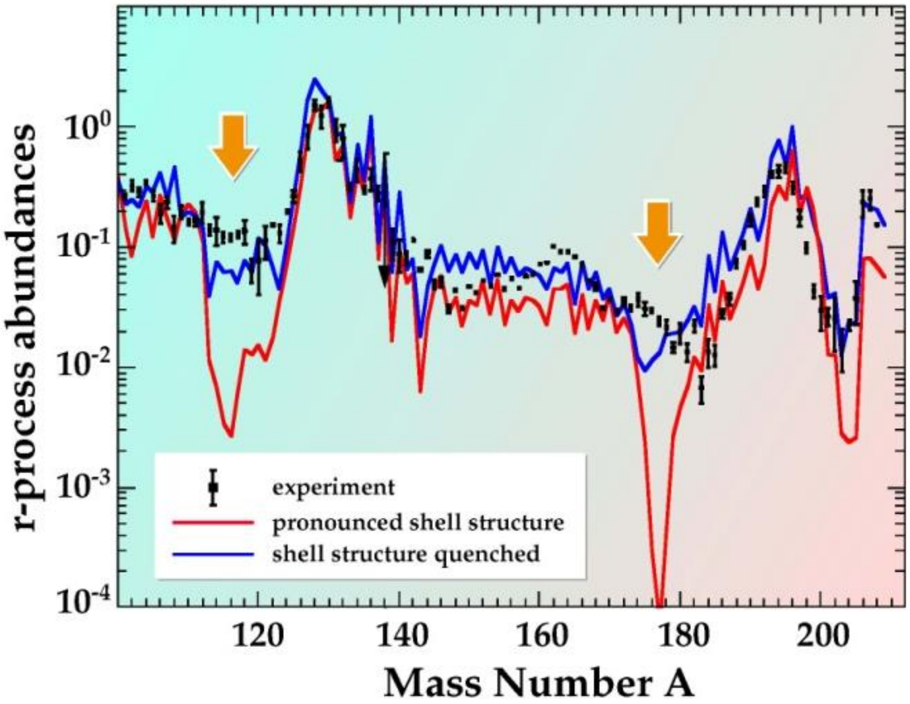
„waiting-point" isotopes at $n_n=10^{26}$ freeze-out

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

Summary “waiting-point” model

Site-independent r-process **”waiting-point” model**, our first working horse…

Fe seed (implies **secondary** nucleosynthesis process),
detailed nuclear and astrophys. parameter studies
T_9 and n_n constant over process duration;
instantaneous freezeout



superposition of n_n-components

$$10^{20} \leq n_n \leq 10^{30}$$

correlated process durations

$$1.2\ \mathrm{s} \leq \tau_r \leq 4.5\ \mathrm{s}$$

temperature neutron-freezeout

$$T_9 = 1.35$$

With this approach, we have learnt a lot about astro-parameters and nuclear structure far from stability.

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

From waiting-point to high-entropy-wind (HEW) model

Core-collapse SN “HEW“ … for a long time **“the“** r-process scenario;

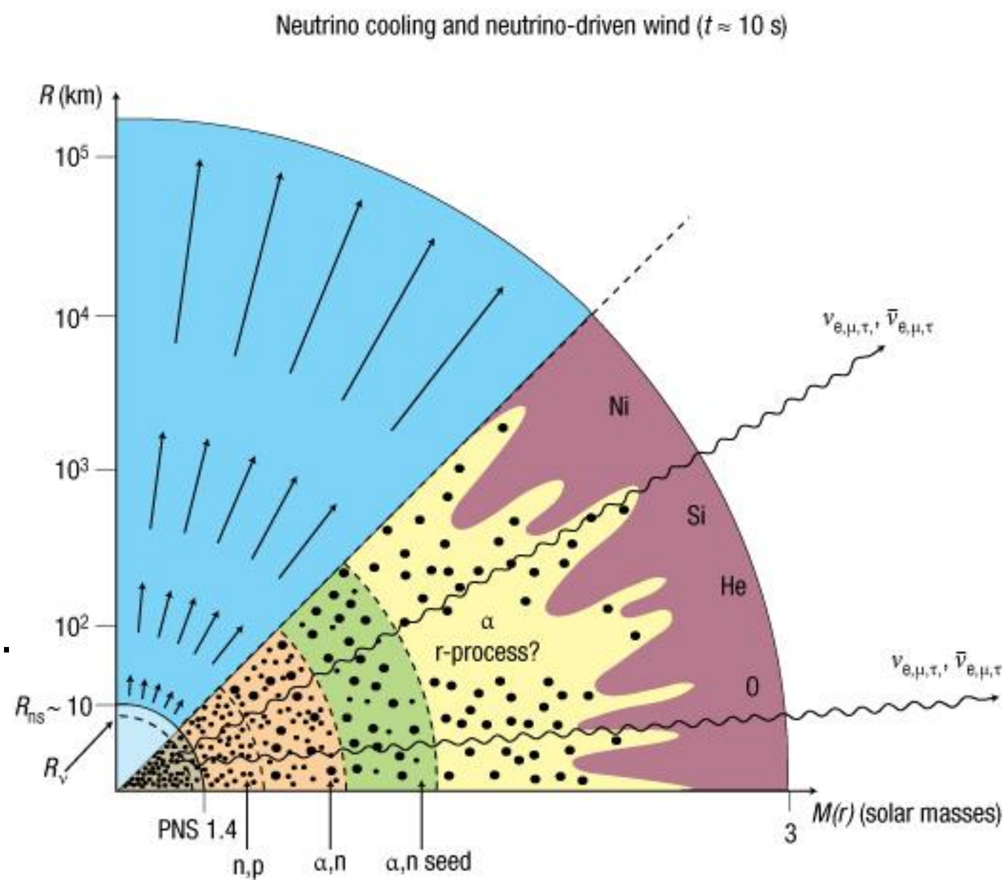
in an interim period completely **“out“** with wrong neutrino-properties;
corrected e.g. by Roberts et al. (2012) with improved ν-nucleus interactions;
today “rehabilitated“ as important scenario for (at least) the **“weak“** r-process

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

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

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

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



(Woosley & Janka, Nature, 2005)

Nucleosynthesis in the HEW of SN II

High-entropy wind of SN II

…still one of the favoured scenarios for the “weak” r-process

full dynamical network (extension of Freiburghaus model 1999)

- time evolution of temperature, matter & neutron densities
- extended freezeout phase
- n-rich “r-seed” beyond N=50 (^{94}Kr, ^{100}Sr, ^{95}Rb…), avoids first bottle-neck of classical model

“best” nuclear-physics input (LANL, Basel, Mainz)

- consistent ETFSI-Q, QRPA(GT+ff) & NON-SMOKER models
- experimental data

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** !

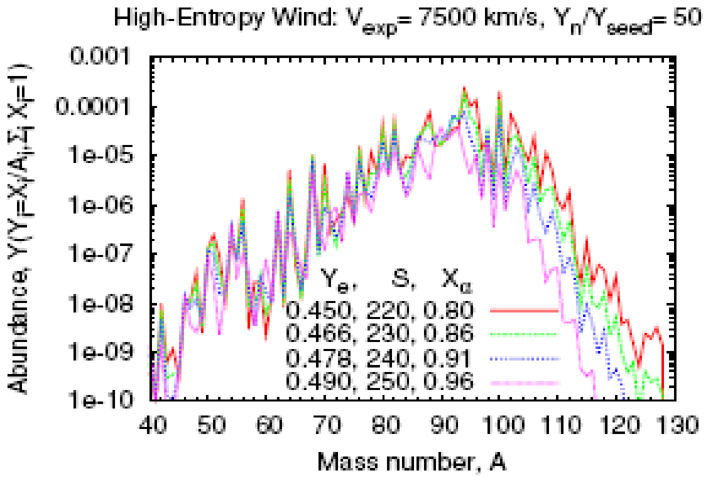
→ **r-process “strength“ formula**

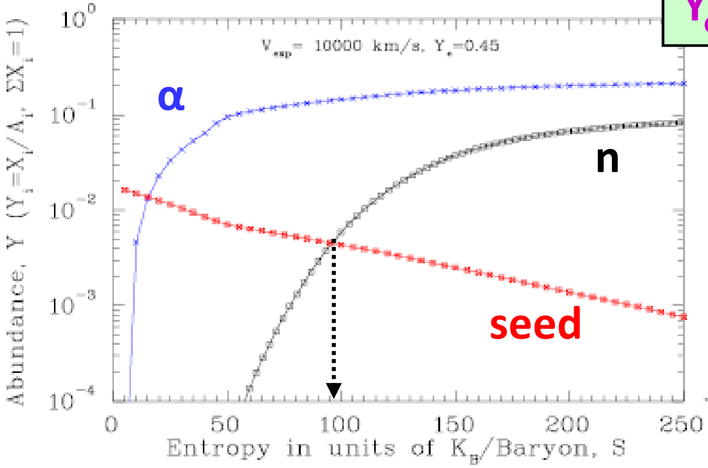
$$\frac{Y_n}{Y_{Seed}} = k_{SN} V_{Exp} \left(\frac{S}{Y_e} \right)^3$$

Parameters HEW model ⇨ Y(Z)

Y_e=0.45

Distributions of r-"seed" nuclei:





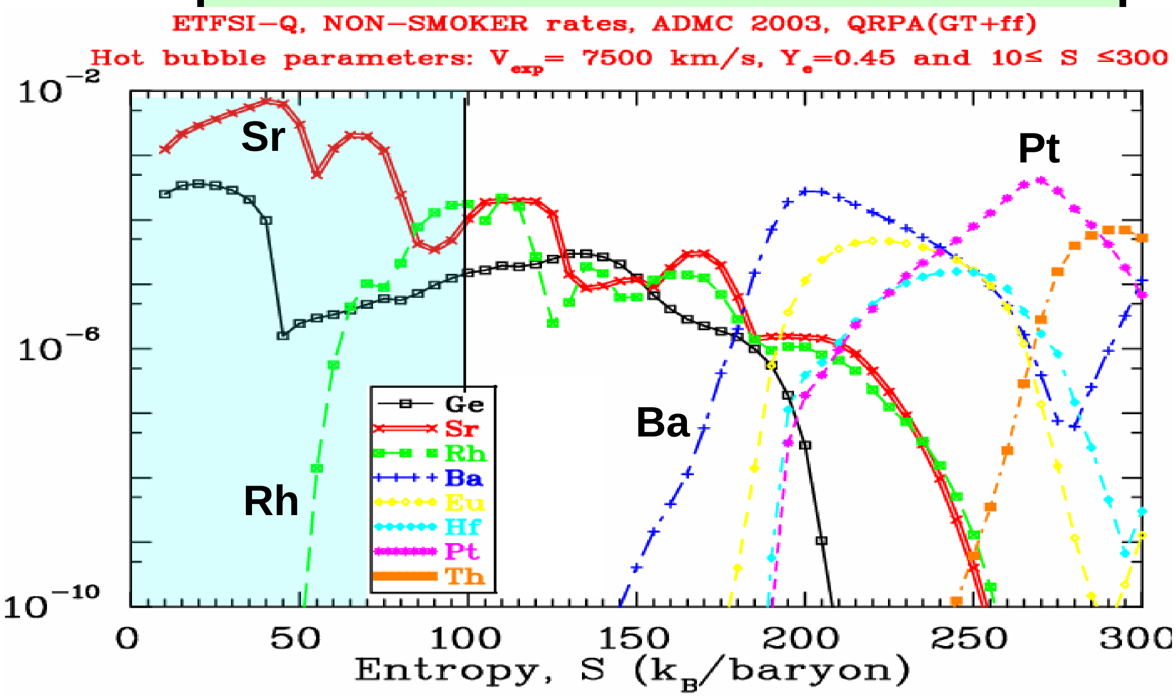
No neutrons → no n-capture r-process!

Nucleosynthesis components of rapid, primary HEW scenario:

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

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

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



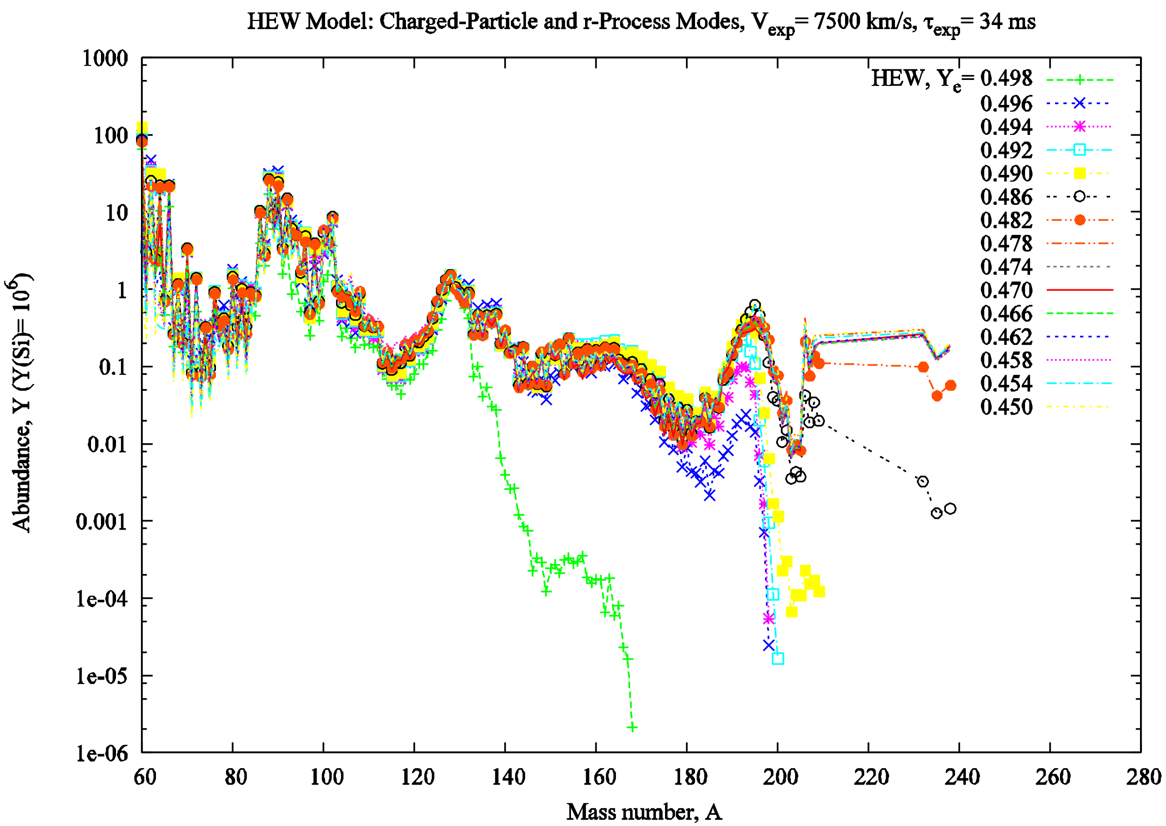
Farouqi et al., ApJ 712 (2010)

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

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

for Y_e=0.400 ca. 5×10^{-4} M_o

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



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

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

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

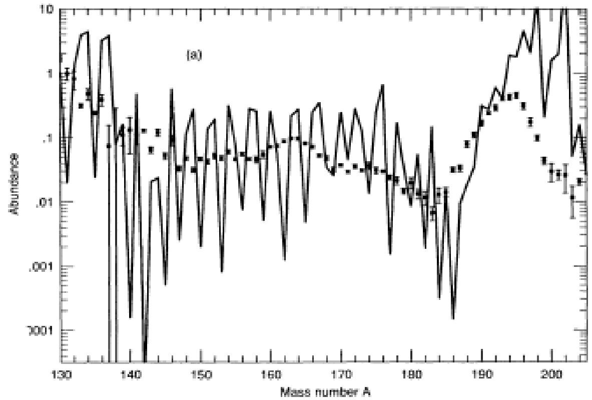
„what helps…?" low Y_e, high S, high V_{exp}

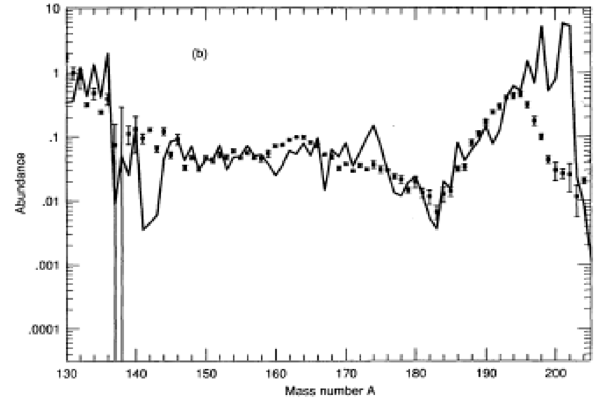
Farouqi et al. (2009)

Effects of P_n on r-abundances

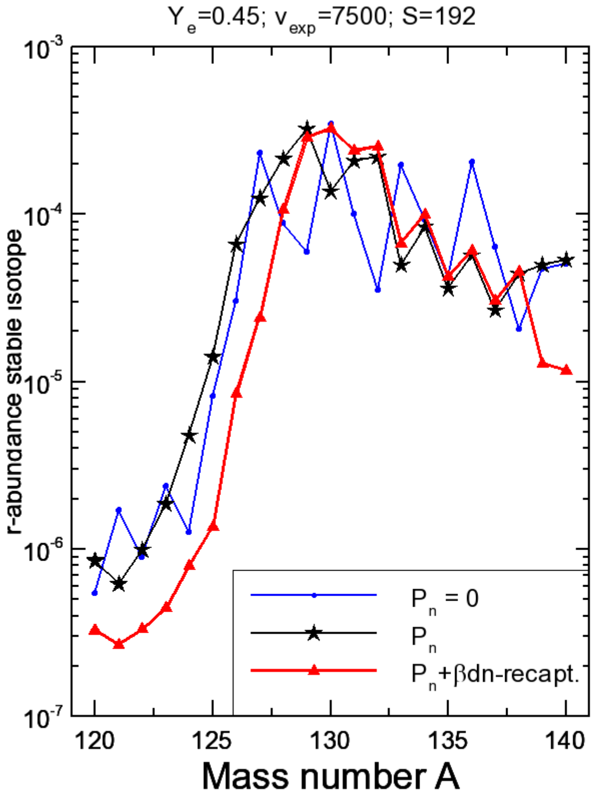
Site-independent "waiting-point" model (ApJ 403, 1993)

overall smoothing of oe-mass
staggering of initial abundances





(a) progenitor abundances before ß-decay (P_n=0)
(b) final abundances after ß-decay and ßdn-emissio



Site-specific cc-SN-II HEW model (ApJ 712, 2010)

significant P_n effects at r-abundance peaks (here A=130):

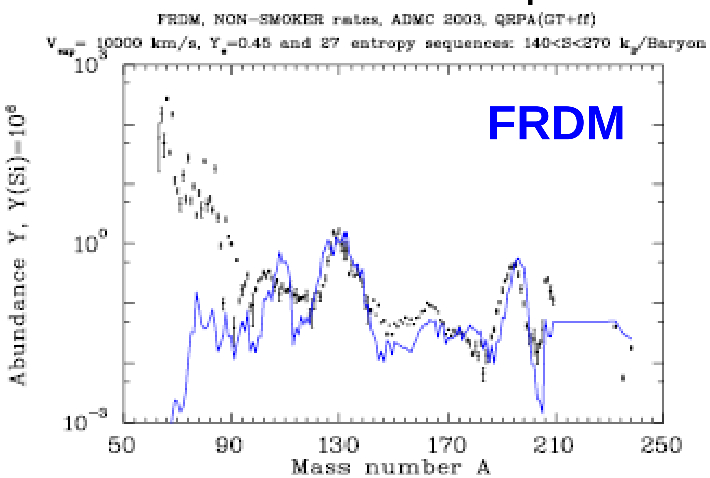
– **from P_n=0 to P_n :**
smoothing of oe-mass staggering;
importance of **individual** "w.-p." isotopes (e.g. ^{127}Rh, ^{130}Pd,^{133}Ag, ^{136}Cd)

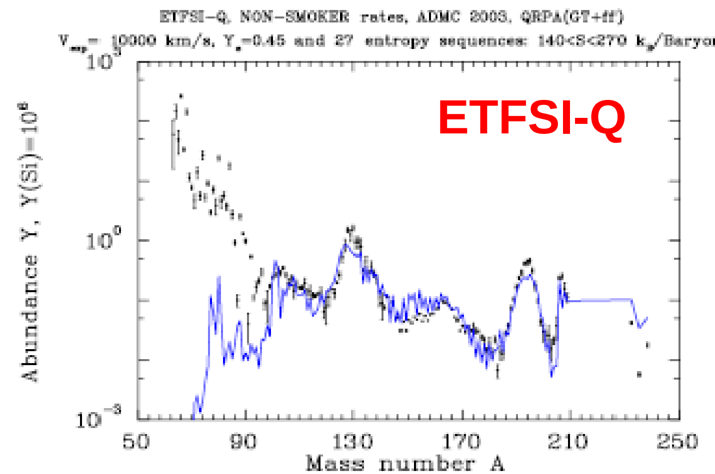
– **from P_n to βdn-recapture :**
shift of left wing of peak to higher A

Effects of correlated nuclear properties (2)

Recent dynamical cc-SN – HEW model

⇨ **„self-regulating“** (main) r-process

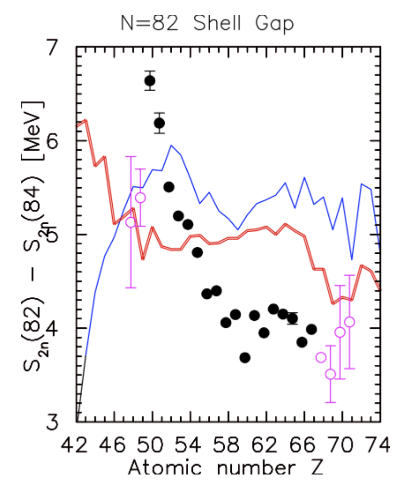




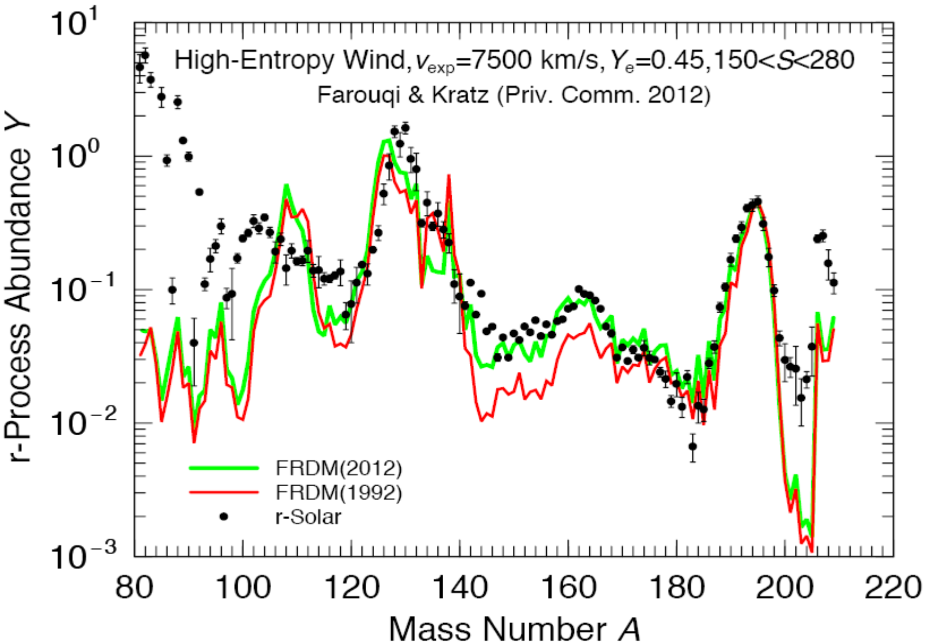
No exponential fit to $N_{r,\odot}$!

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 **N=82 shell-gap** below doubly-magic ^{132}Sn



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**