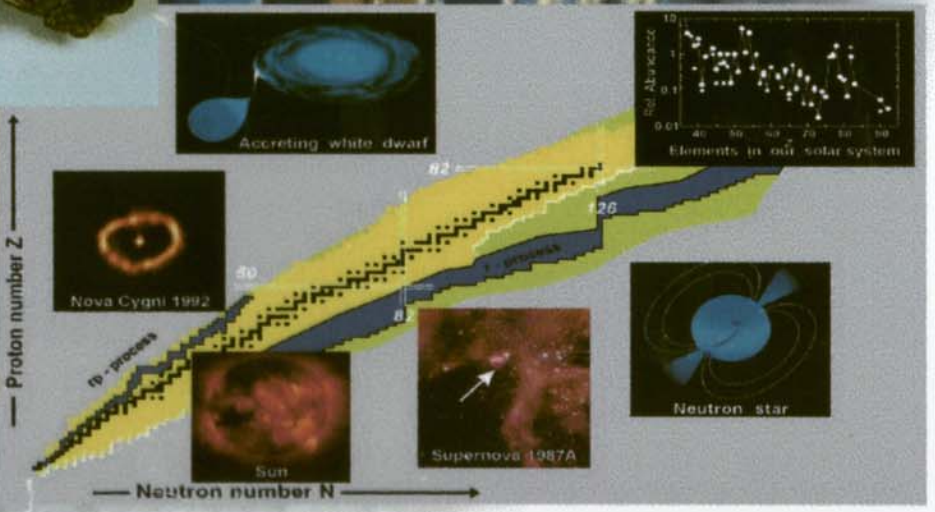
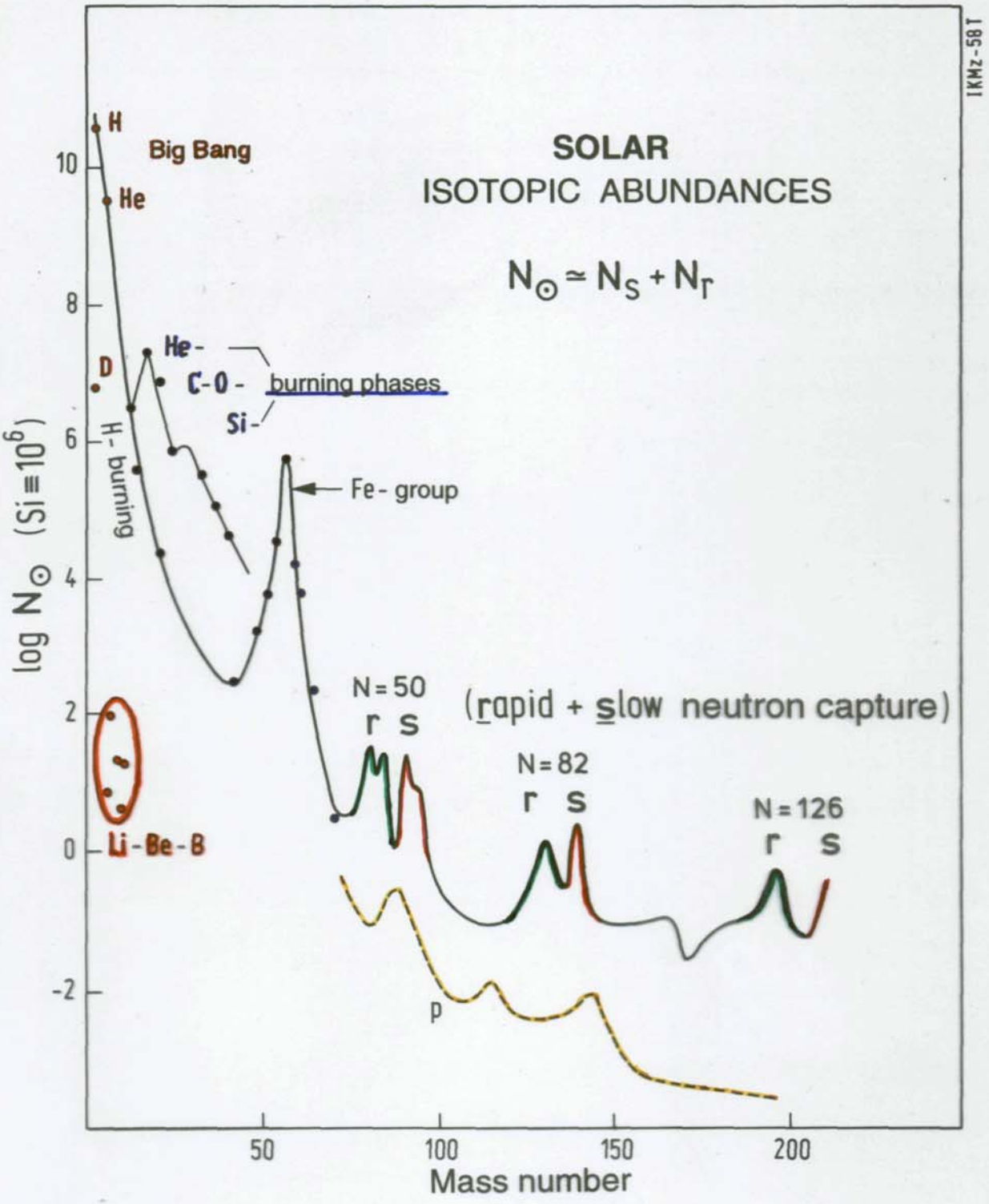
R-Process Signatures:

Observations versus Predictions



K.-L. Kratz
Institut für Kernchemie
Universität Mainz, Germany


IKMz-58 T
SOLAR
ISOTOPIC ABUNDANCES
$N_\odot \simeq N_S + N_r$
H
Big Bang
He
D
He-
C-O-
Si-
burning phases
H-burning
Fe-group
N=50
r s
N=82
r s
N=126
r s
(rapid + slow neutron capture)
Li-Be-B
p
log $N_\odot$ (Si≡10^6)
10
8
6
4
2
0
-2
50
100
150
200
Mass number

r-process

Supernova II

moderate n-densities ($n_n \approx 10^{23}$)
explosive (He, C, Si) shell burning
high-entropy bubble, core scenario

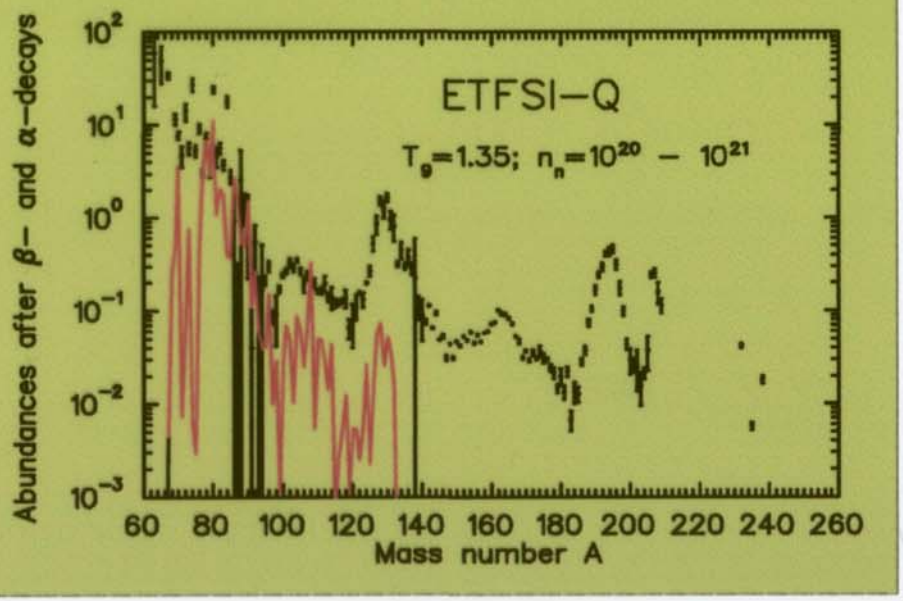
Neutron Star Mergers

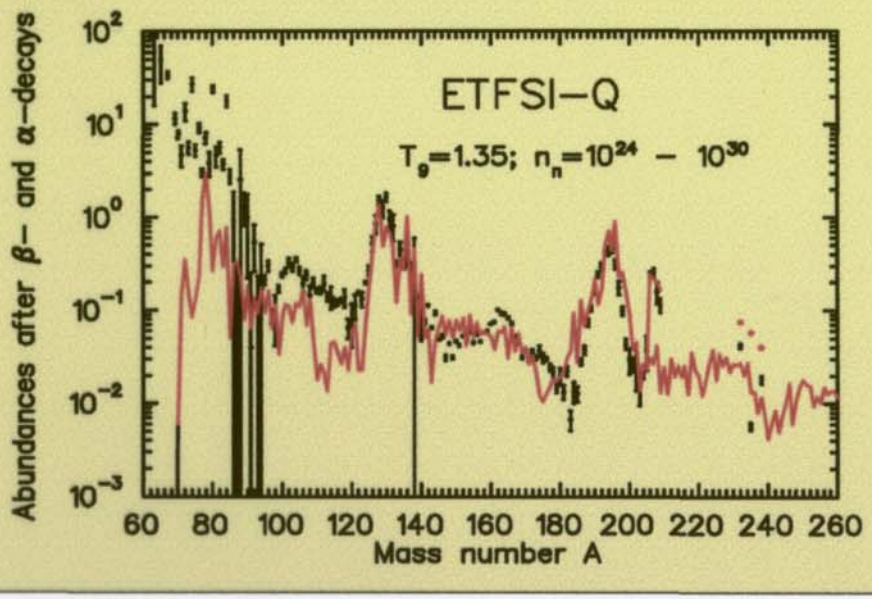
high n-densities ($n_n \approx 10^{30}$)
very n-rich ejecta
fission "recycling"

nuclear data needs

direct: Q_β, S_n, $T_{1/2}$, P_n, $\sigma_{n\gamma}$ on "waiting-point nuclei" at N_{magic}

indirect: development of nuclear structure with isospin





Observations r-Nucleosynthesis

Solar-system isotopic r-abundances ($N_{r,\odot} \simeq N_{\odot} - N_{s,\odot}$)

Arlandini et al., 1999

Elemental r-abundances in UMP Halo stars

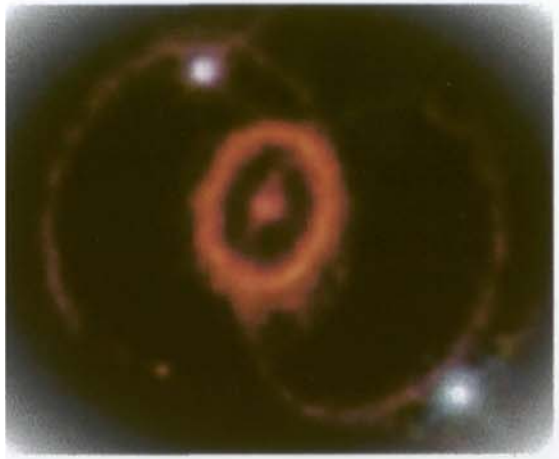
Cowan et al., 1999
Cayrel et al., 2001

Isotopic r-abundances in MP Halo stars

Sneden et al., 2002
Lambert et al., 2002

Isotopic abundance anomalies in Meteorites

Wasserburg et al., 1977
1996
Ott et al., 1996



Calculations r-Process „Observables"

Time-dependent, classical „waiting-point" model

Kratz et al., 1993

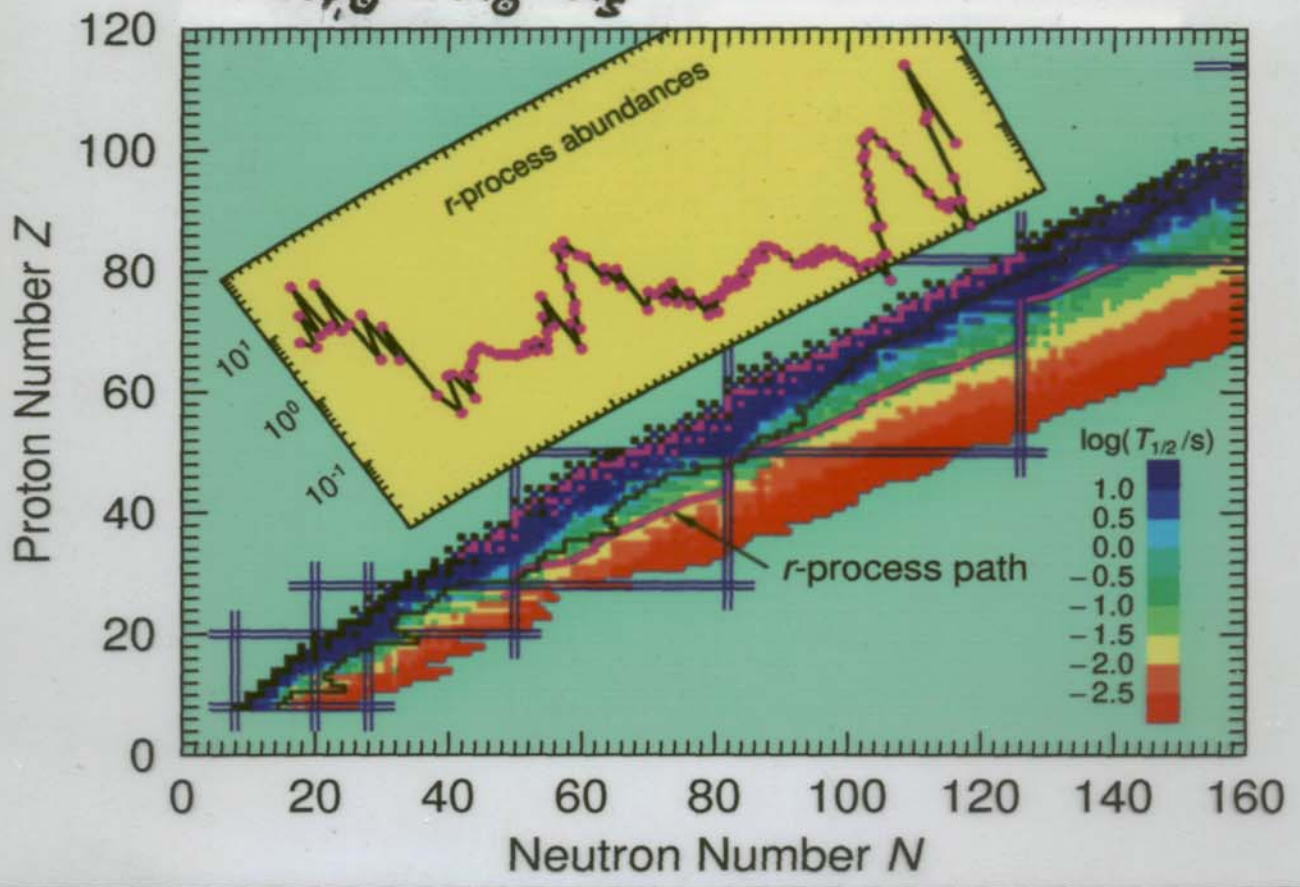
Experimental and microscopic-model nuclear-data input

Pfeiffer et al., 2001
Möller et al., 2002

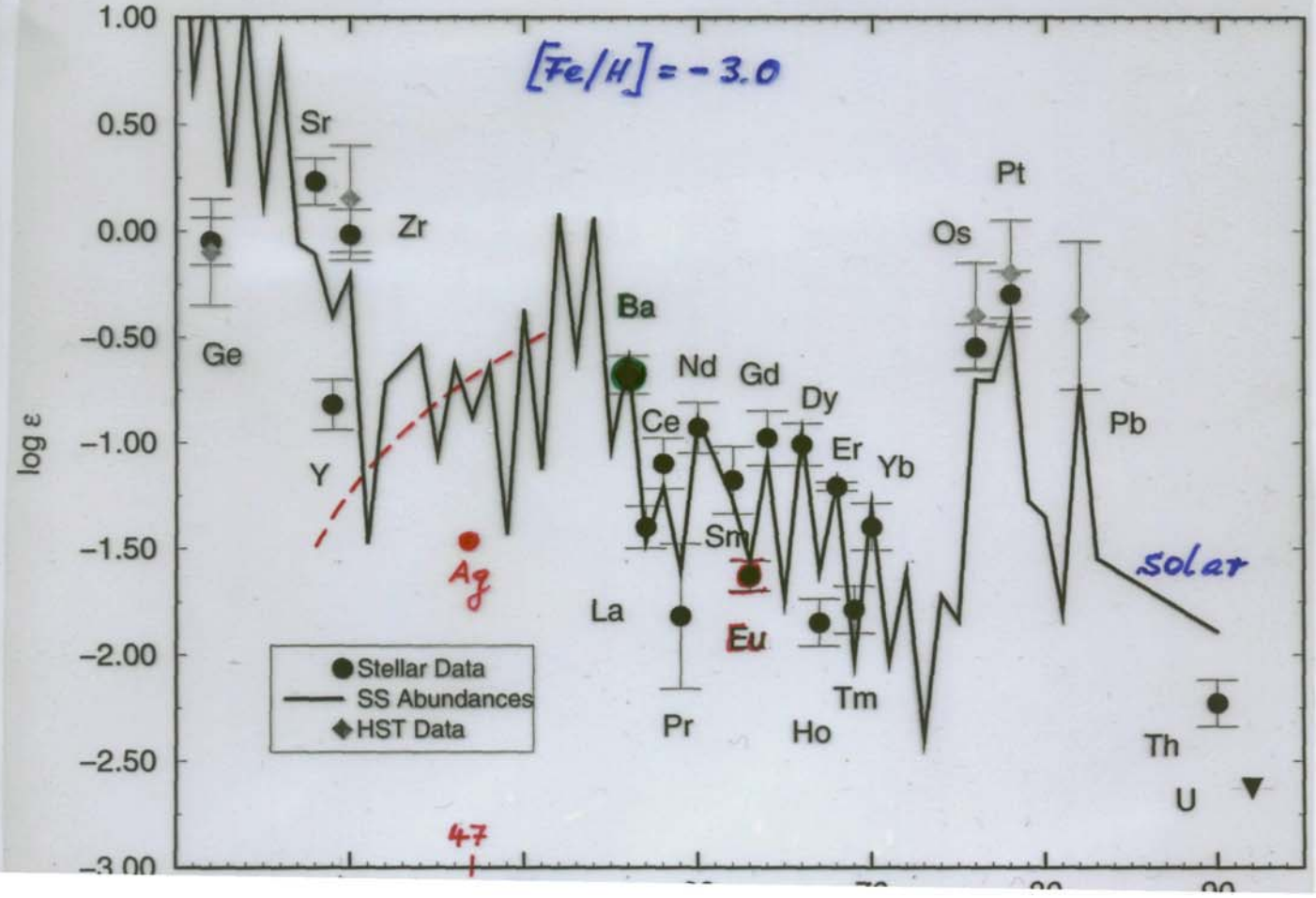
High-entropy bubble, full dynam. network

Freiburgh. et al. 1999
Farouqi 2003

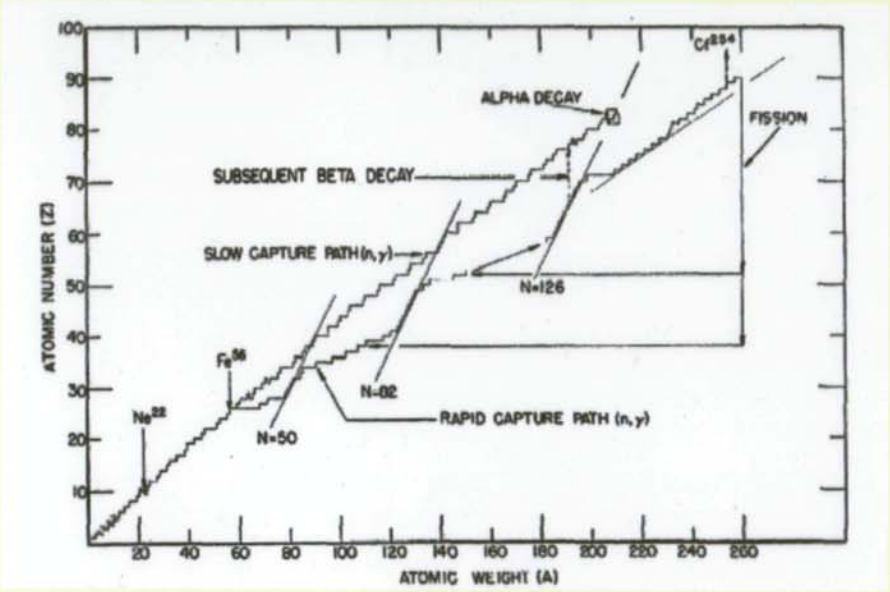
$N_{r,\odot} \approx N_\odot - N_s$

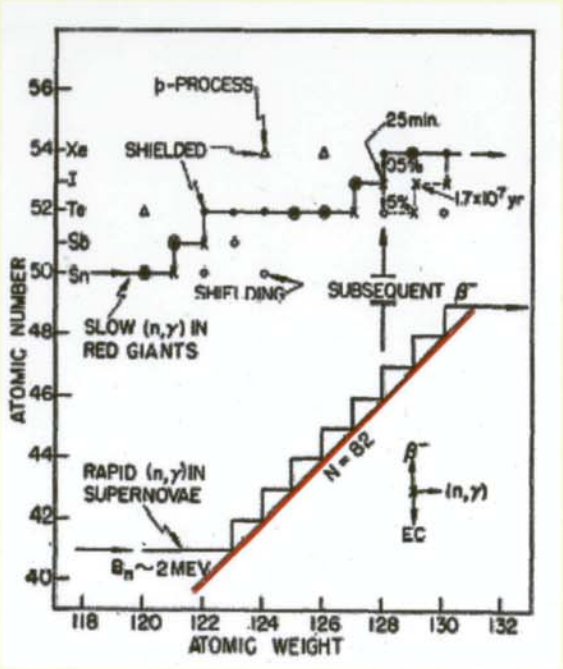


Low-Metallicity Giant HD 115444



R-process at magic numbers

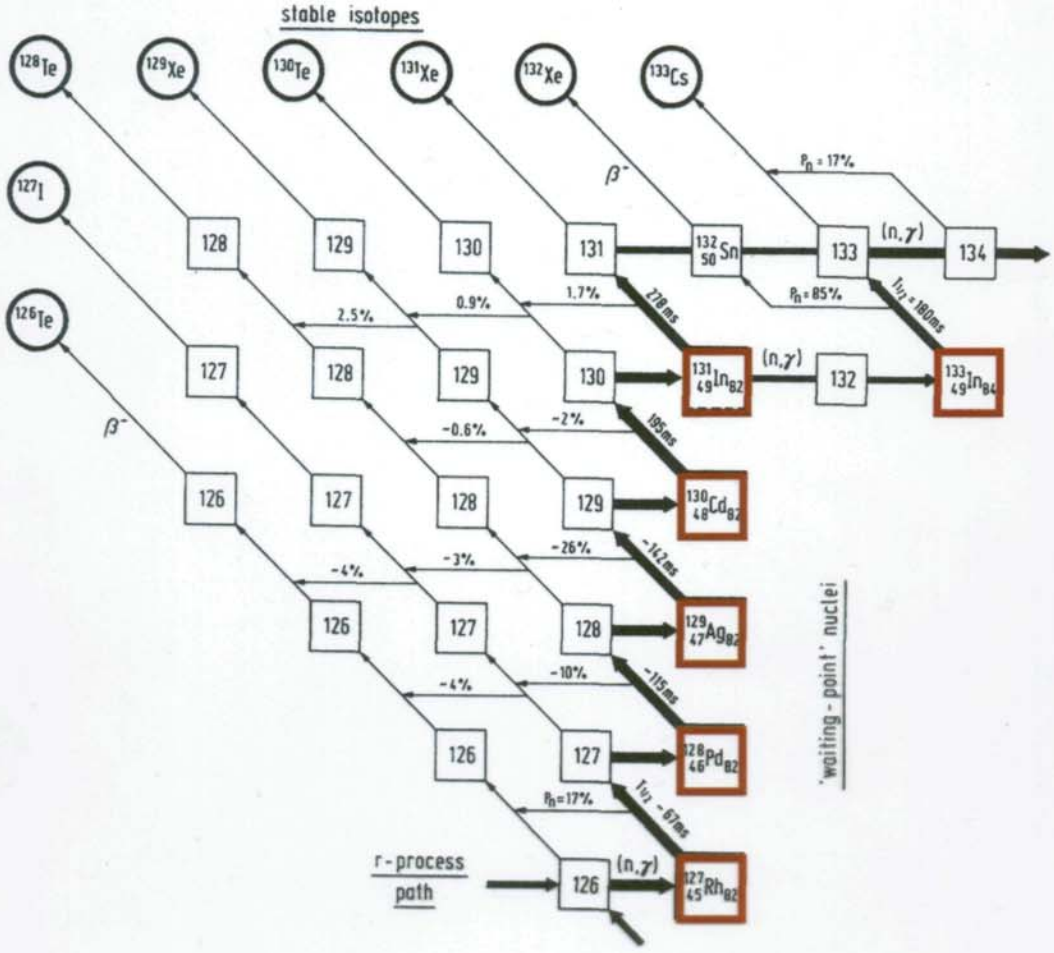


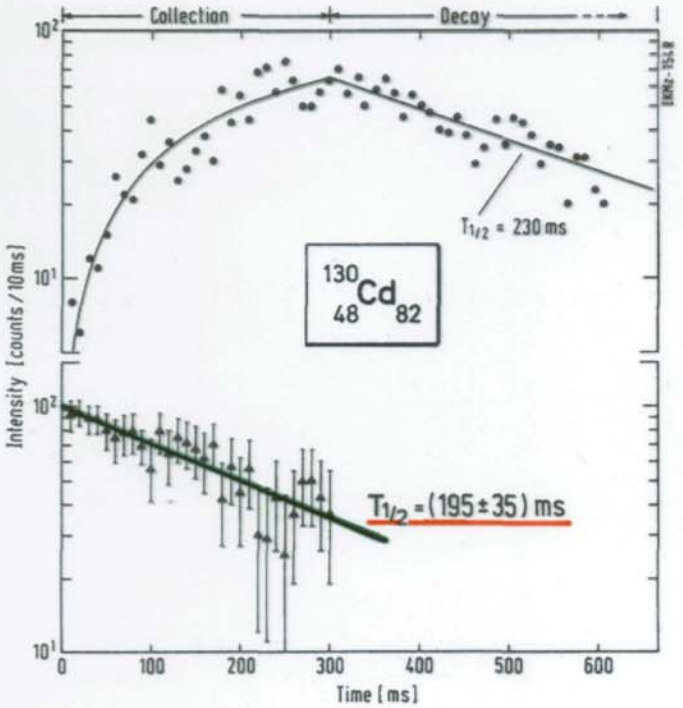


B²FH predicted correctly even the detailed behaviour at N=50, 82 and 126.
The *„climb up the staircases"*, the major waiting-point nuclei involved, as well as the *„break-through pairs"*, and their *„association with the rising sides of major peaks in the abundance curve for the r-process"* are still today important properties to be studied experimentally and theoretically.

"Waiting-point" concept

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





1986

first experiments
in the r-process path
at CERN-ISOLDE

use of chemically
non-selective
plasma ion source

⇒ urgent request

!! SELECTIVITY !!

J. Phys. G 24 (1988)

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

test of

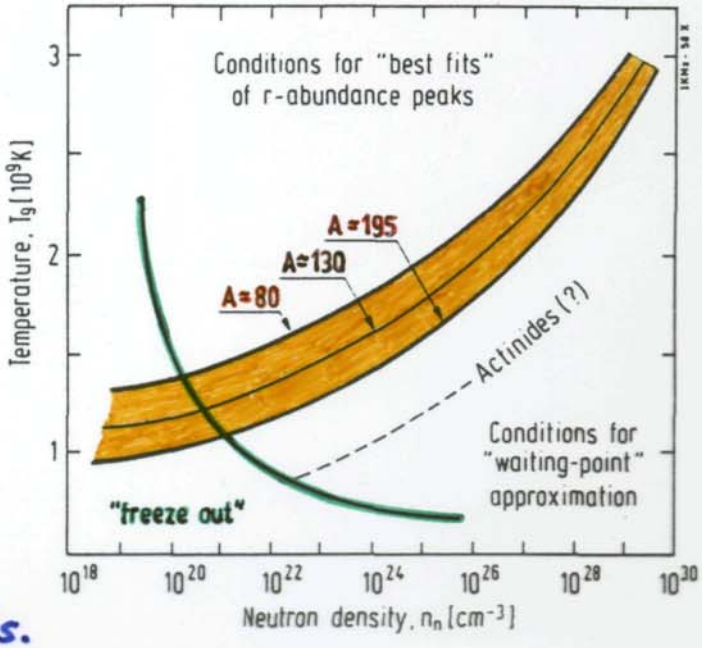
"waiting-point concept":

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

→ deduce $T_g - n_n$ band

conditions to fit the

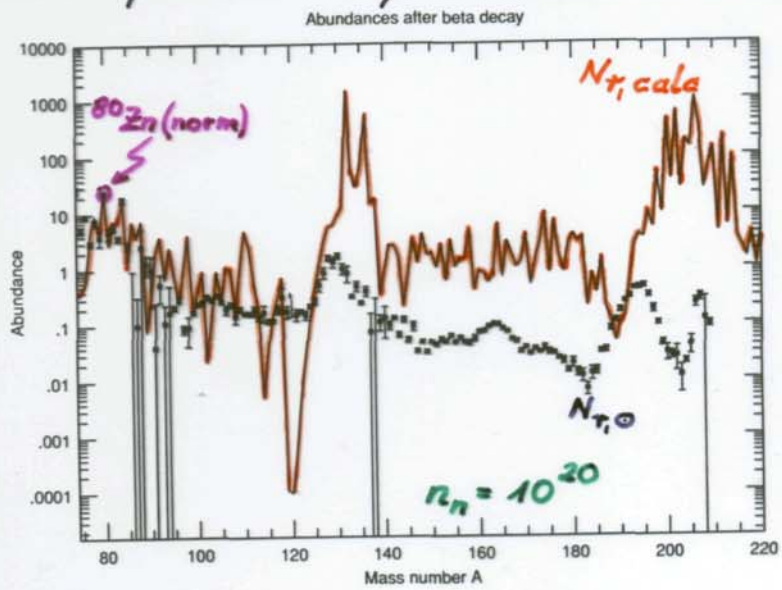
$A \simeq 80$ and 130 $N_{r,\odot}$-peaks.



Ap. J. 403 (1993)

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

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

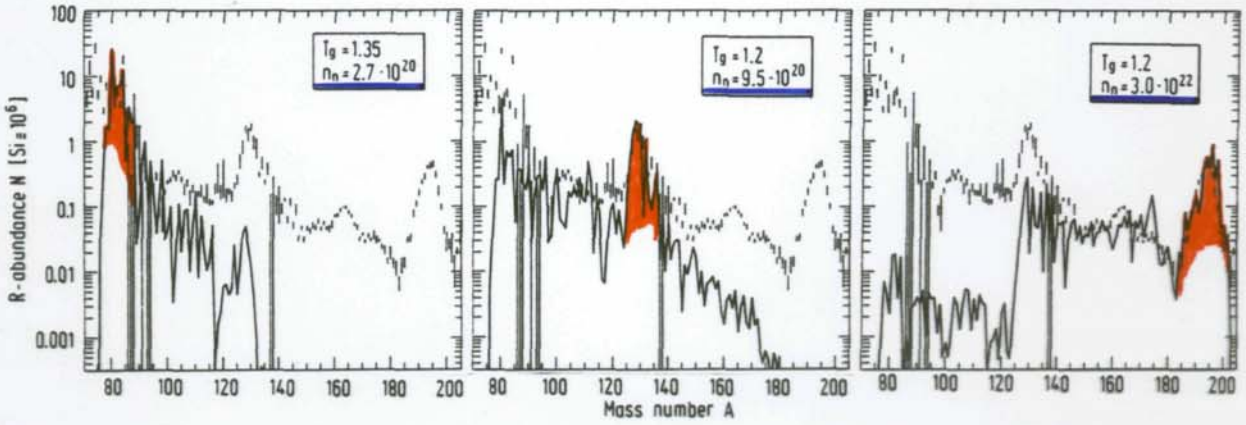


Steady-flow NOT global

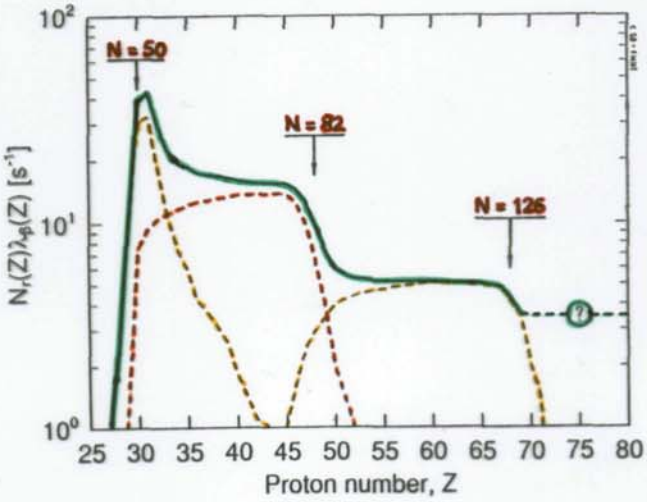
- wrong trend, increasing N_r with A
- $A \simeq 130$ and 135 peaks shifted, too large;
  → indicates too low n_n

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}



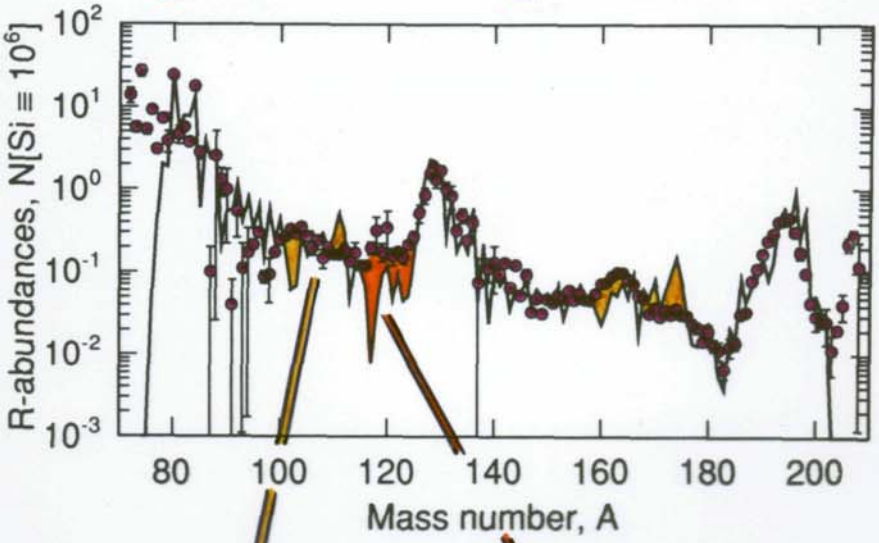
analogous to s-process with $N_s \sigma$ = const.

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

Superposition of 3 components

→ good overall agreement with $N_{r,\odot}$)

but...



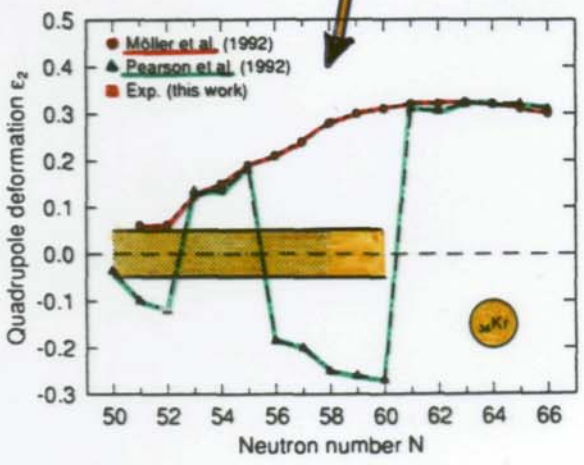
local deficiencies

interpreted as nuclear-structure signatures of r-isotopes not accessible in terrestrial laboratories

⇒ model deficiencies!

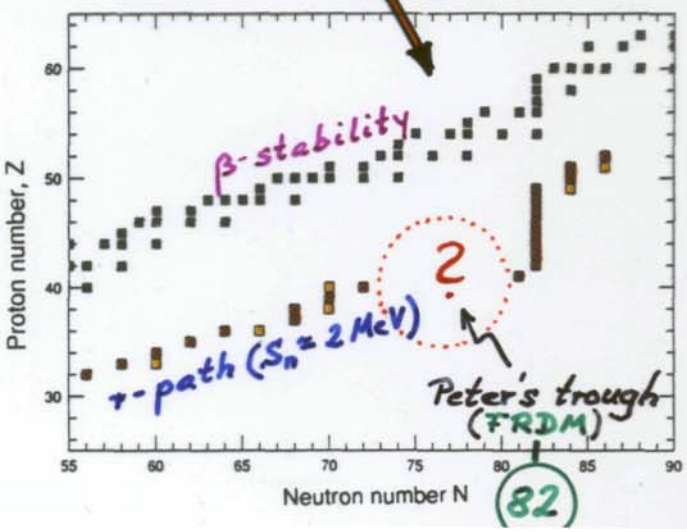
(I) phase transitions

pn-residual interact.



(II) shell corrections

N = 50, 82, 126



Conclusion

"waiting-point" concept

with $(n,\gamma)\Leftrightarrow(\gamma,n)$ and β-flow equilibrium

and T_9=const., n_n=const., instant. freeze-out

is valid.

simple, good "working horse" for parameter studies!

However,

- steady flow **not** global
  ⇒ need more than 1 r-component
- from Fe-seed, $\tau_t \geqslant 3.5$ s ⇒ too long?
- $n_n \approx 10^{20}$ -- 10^{28} cm^{-3} ⇒ too high?
- nuclear structure far off β-stability?

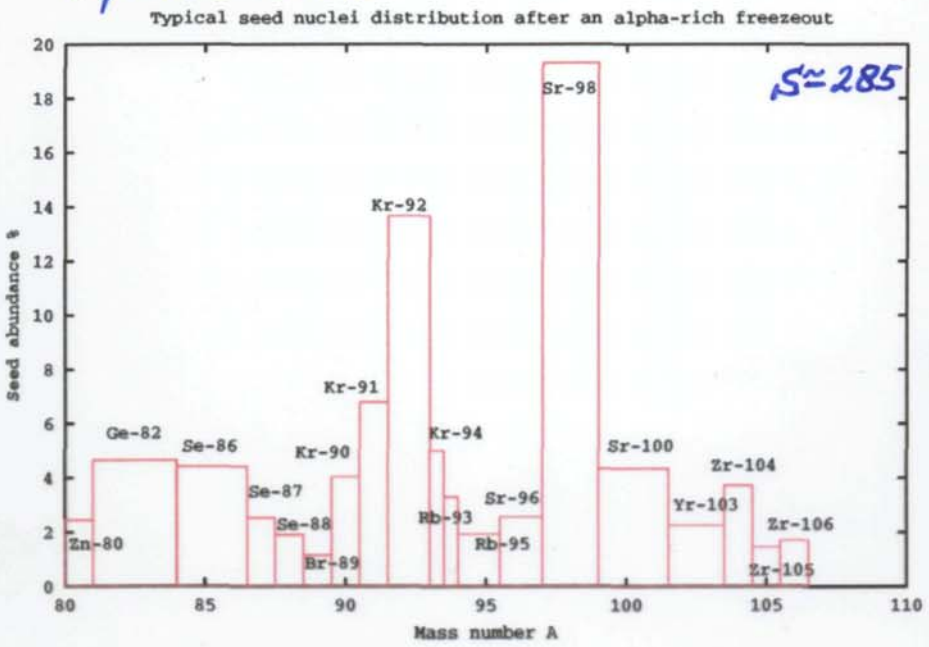
<u>Requests:</u>

1. better r-process models
2. better nuclear structure models
3. experiments

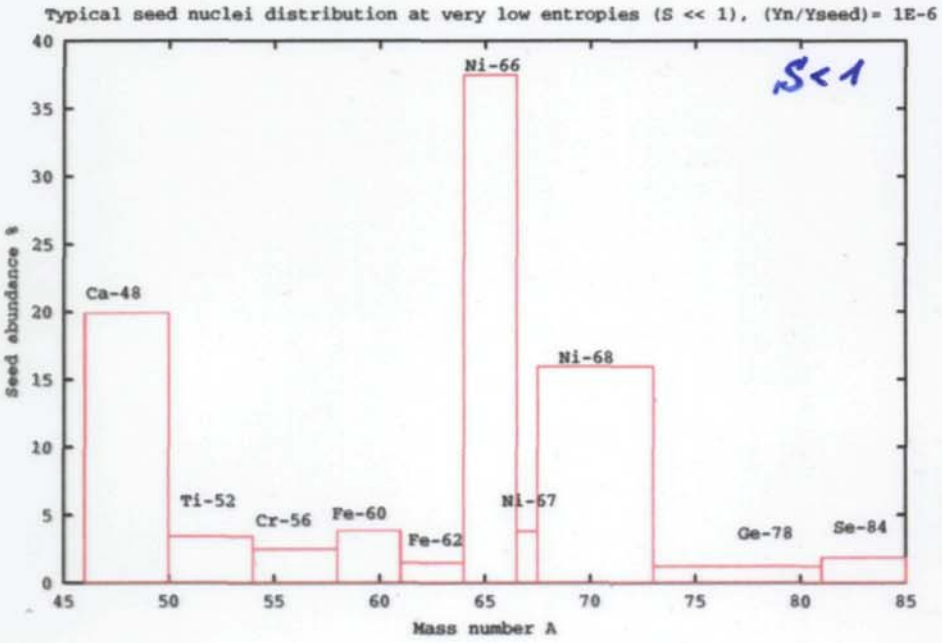
After α-process ...

r-process seed

Subsequent r-process?



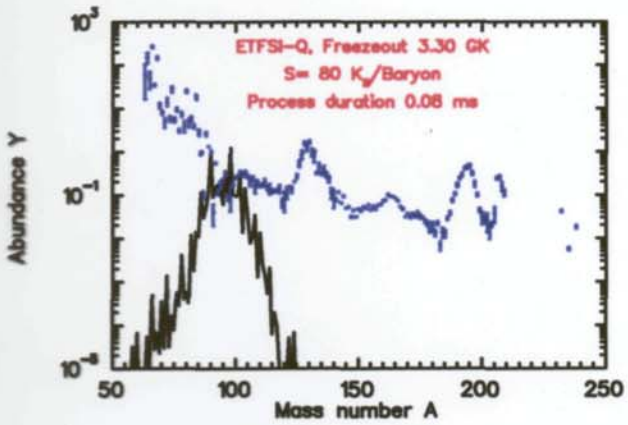
yes !

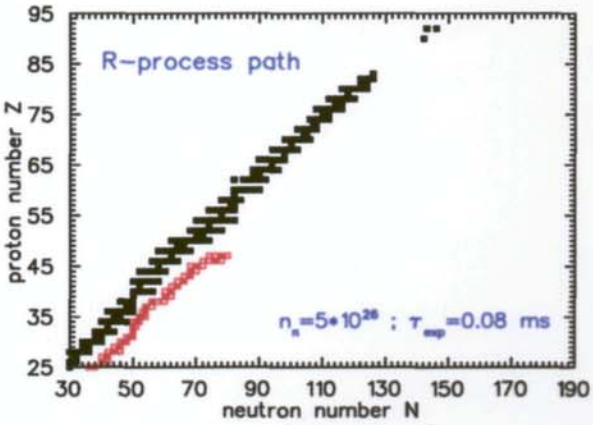


no !

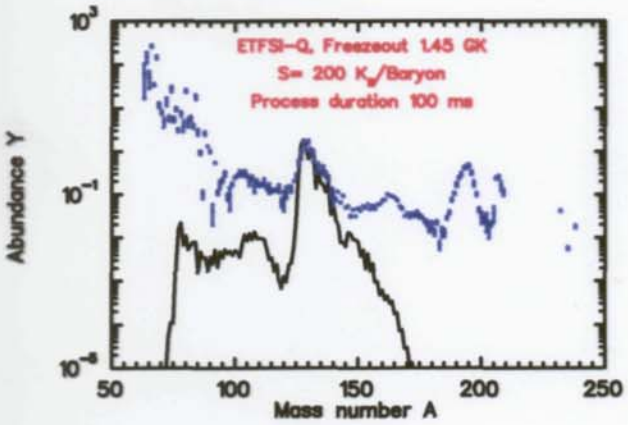
Subsequent r-process for $V_{exp} = 4500\ km/s$ and $Y_e = 0.43$

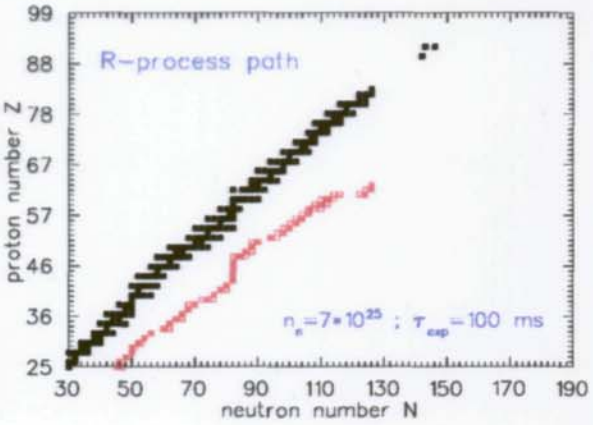
A=90-Peak, $\dfrac{Y_n}{Y_{seed}} = 1$



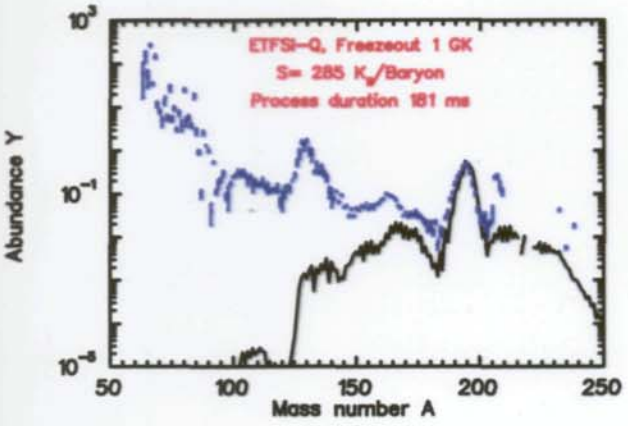


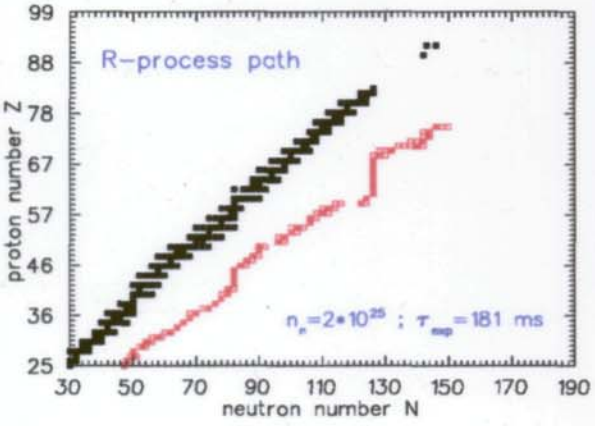
A=130-Peak, $\dfrac{Y_n}{Y_{seed}} = 34$



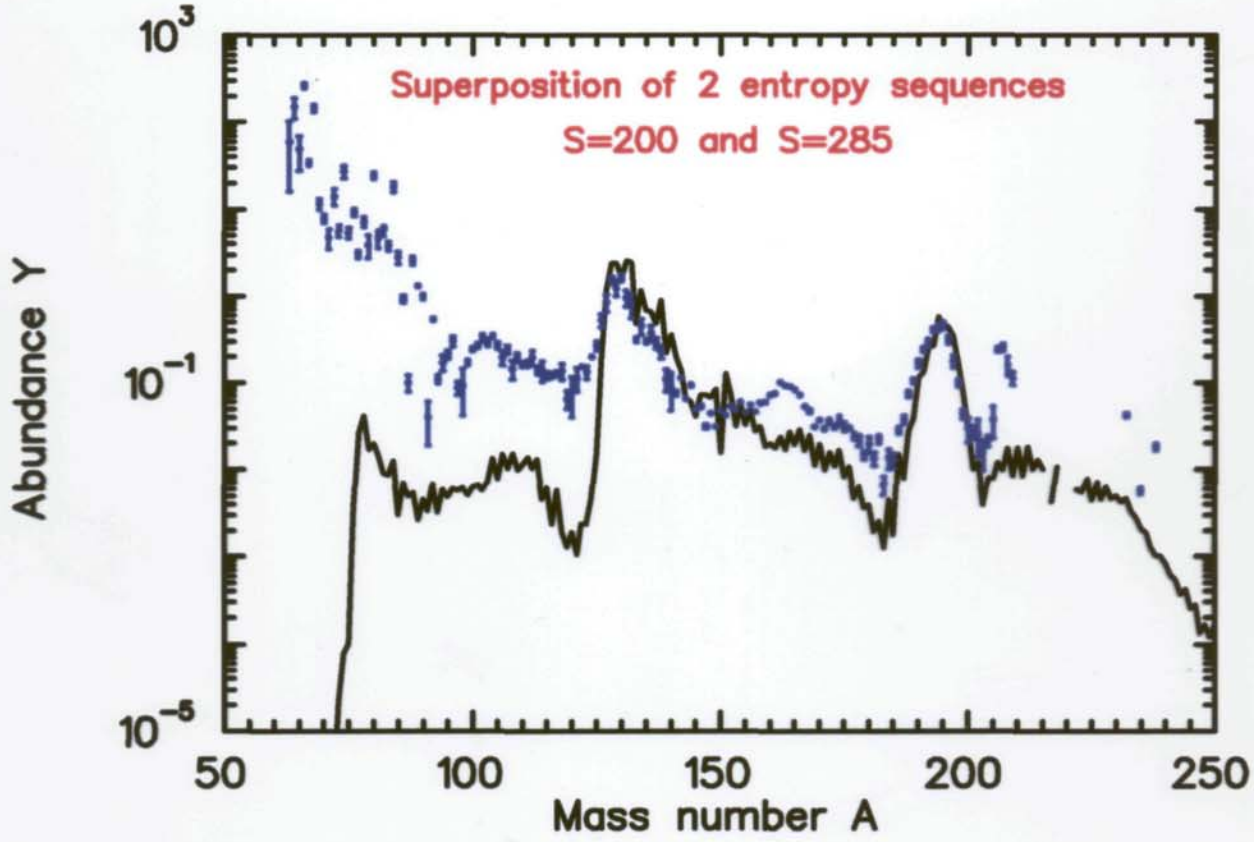


A=190-Peak, $\dfrac{Y_n}{Y_{seed}} = 100$





Superposition of different entropy sequences for $Y_e = 0.43$



Fit function: $g(S_i) = a_1\, e^{a_2 S_i} \quad i = 1, \ldots, 20$

Fit parameter: $a_1 = 100, \quad a_2 = 1{,}2 \times 10^{-2}$

Conclusions

High-entropy neutrino-wind scenario with an initial
α-process and a subsequent r-process
more realistic, but
more time-consuming to calculate

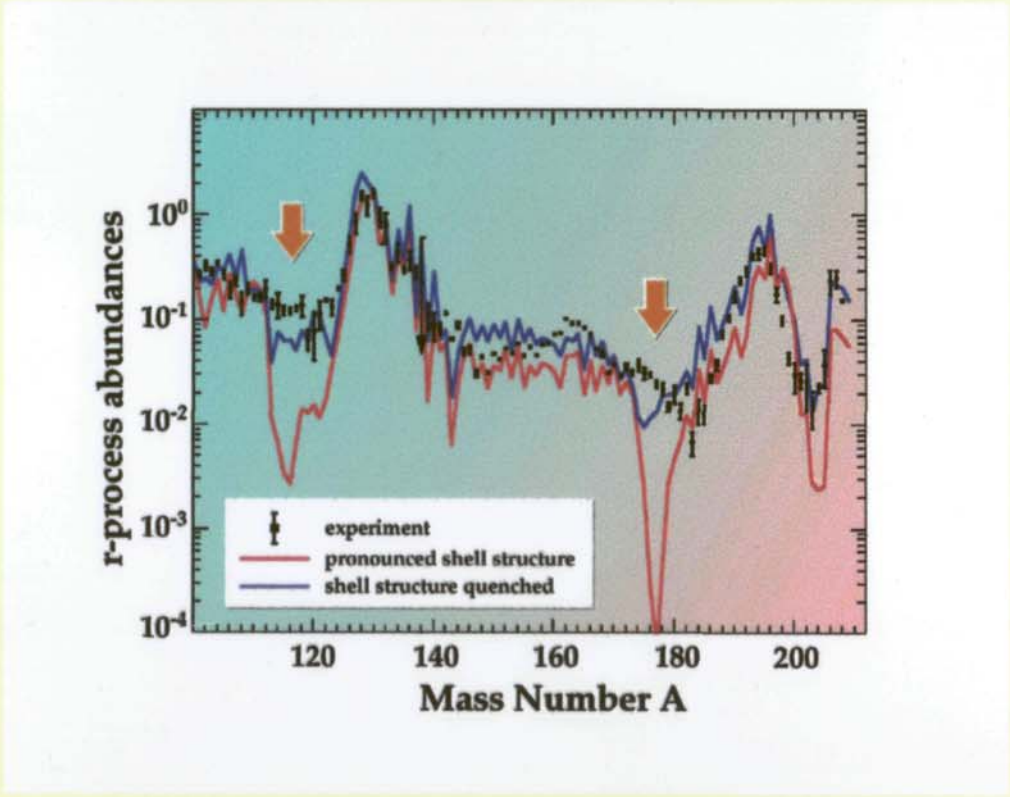
Analytical relation of parameters

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

- again, need more than 1 r-component
- again, need high n_n // S
- no longer Fe-seed; n-rich A≈90 avoids N=50 "bottle-neck" for r-matter flow
- r-process duration 200 ms

Shell Quenching?

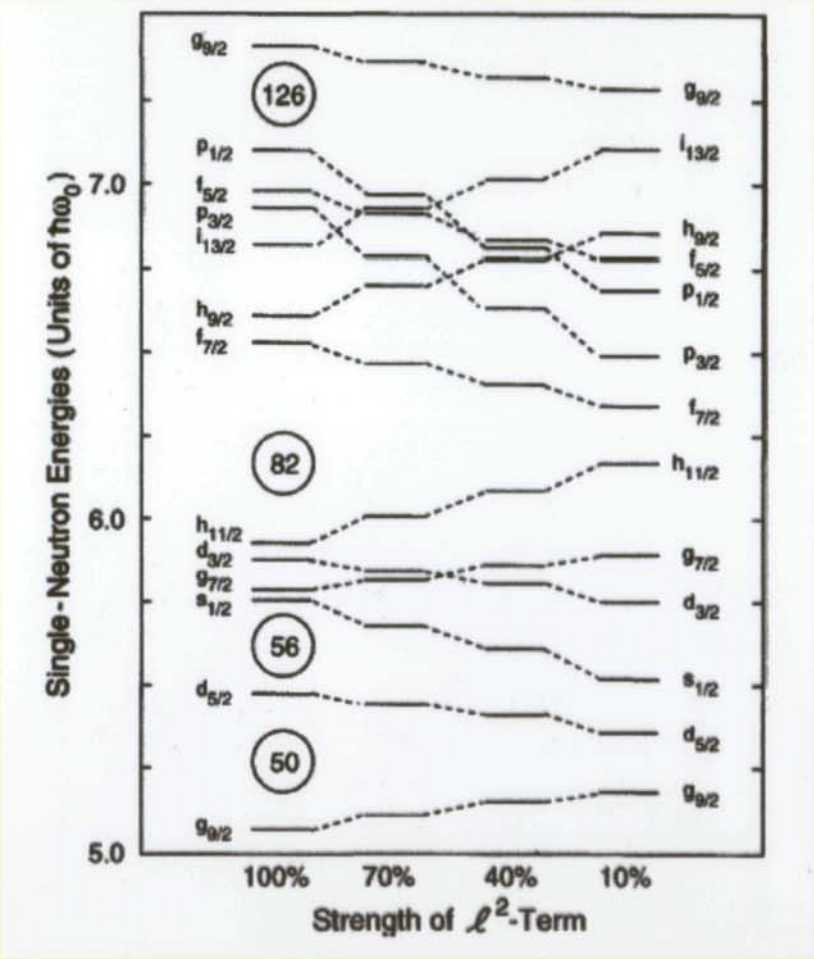
Defiencies prior to the main peaks were attributed by our group to nuclear structure efffects: too strong shell strength for neutron-rich magic nuclei far from stability

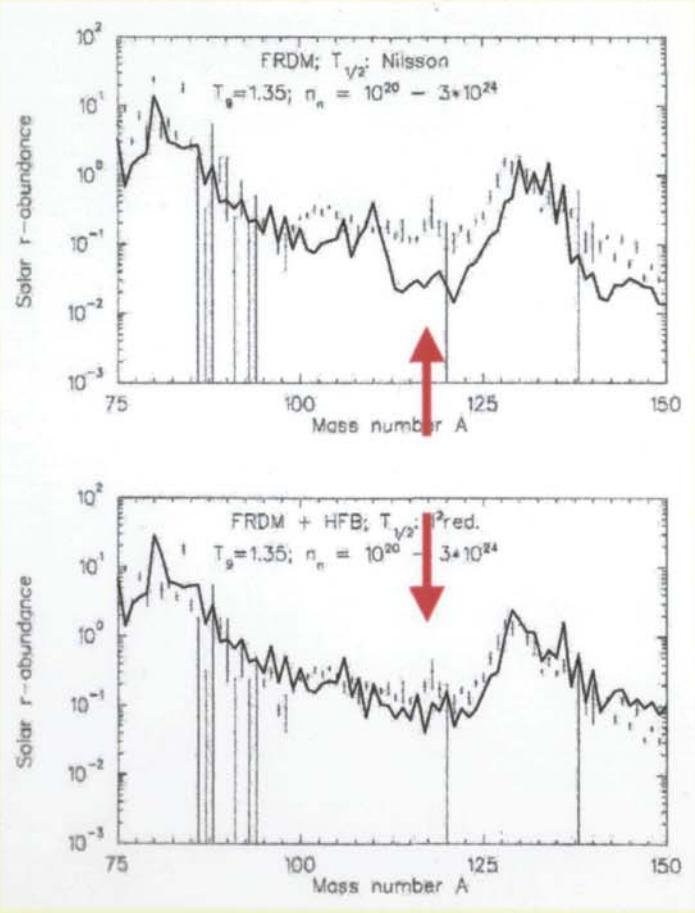


Question:

Can one learn neutron-dripline physics from astrophysical observables?

- The weakening (quenching) of the shell gaps can be simulated by reducing the l^2-term in the Nilsson potential
- The trough in the abundances prior to N=82 vanishes





Motivation for r-Process-Experiments

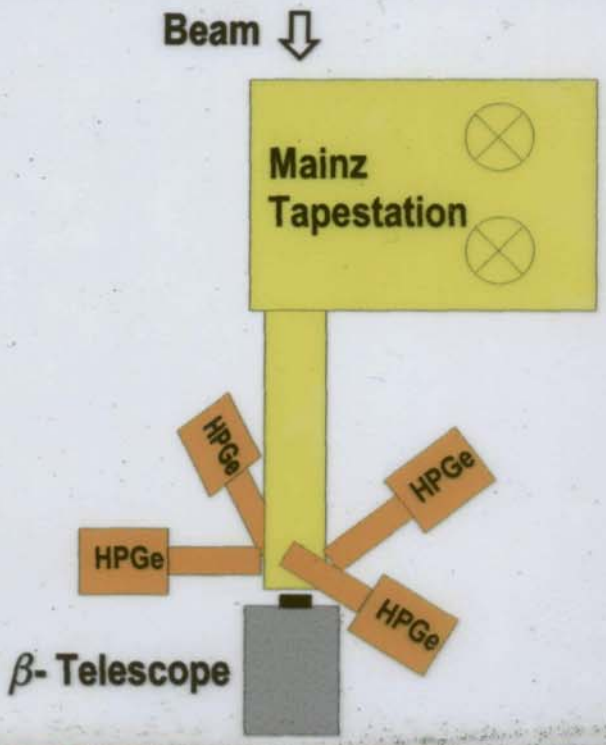
1 **Direct information**
(Q_β, S_n, $T_{1/2}$, P_n)
of "waiting-point" isotopes in the r-path.

2 **Indirect information**
nuclear-structure development
(Q_β, E_{level}, ε_2, shell-closures, etc.)
towards the r-path.

Regions of major interest

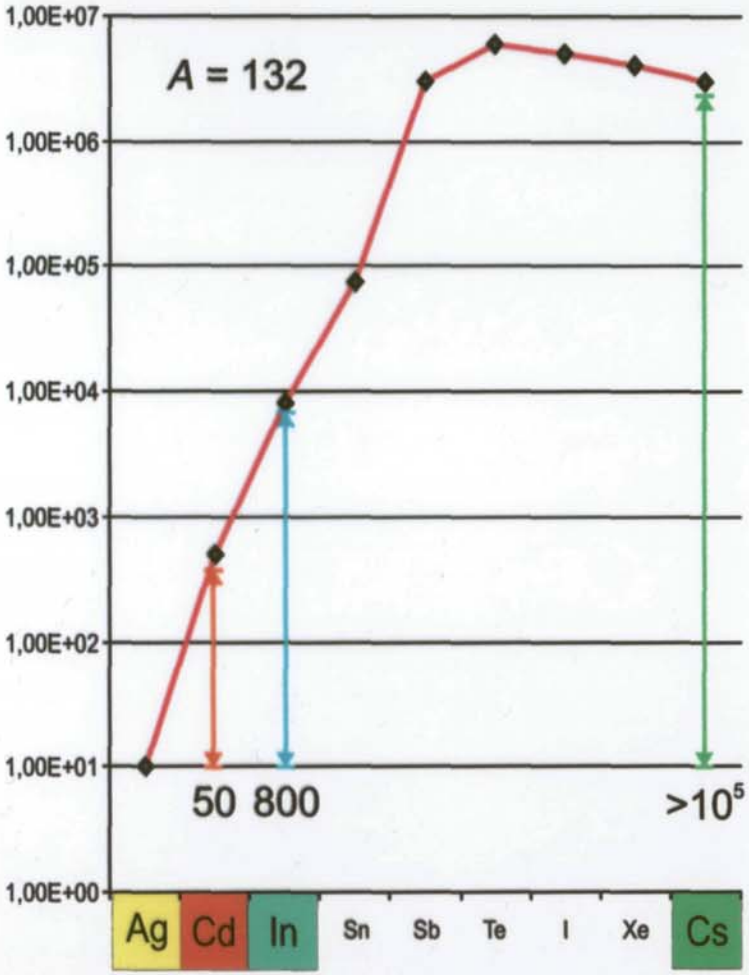
Fe-region	N = 40, N = 50, Z = 28 shell closures; r-process seed , α-rich freeze-out (?)
A = 115	deformation, shape transition N > 66; r-abundance trough
Sn-region	N = 82, Z = 50 shell closures; s.p.-structure around ^{132}Sn; r-process waiting-point isotopes; build-up, shape, matterflow out of $N_{r,\odot}$ -peak.

Experimental Setup



Relative production rates

Silberberg, Tsao



Selectivity

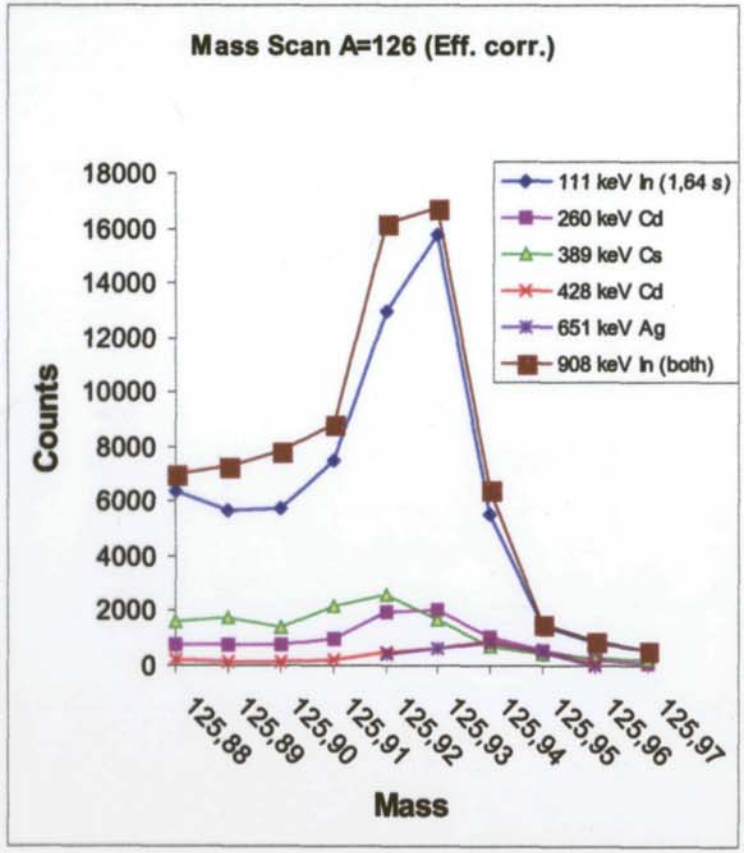
fast target

n-converter

LASER ion-scoure

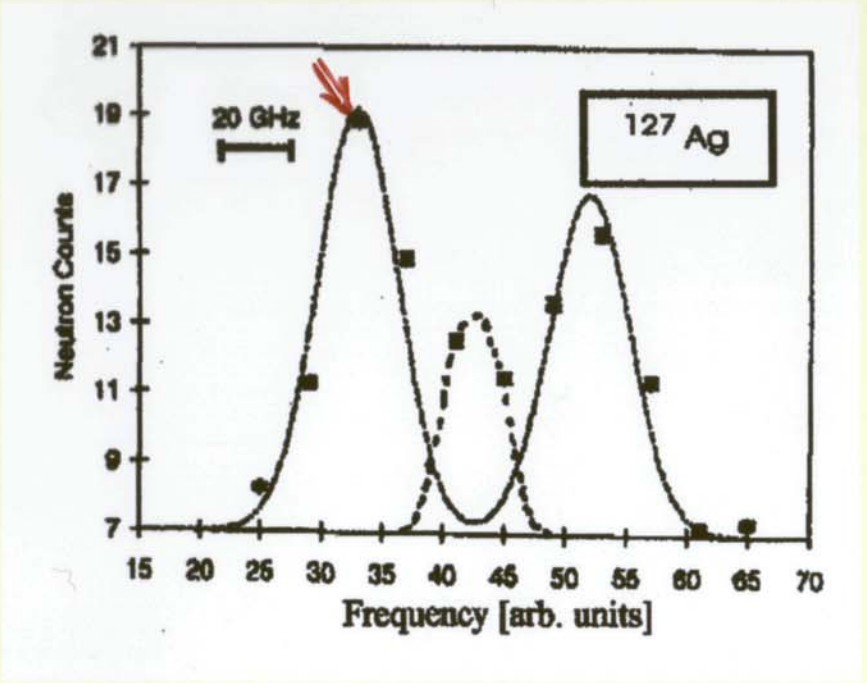
isobar separation

multi coincidence setup



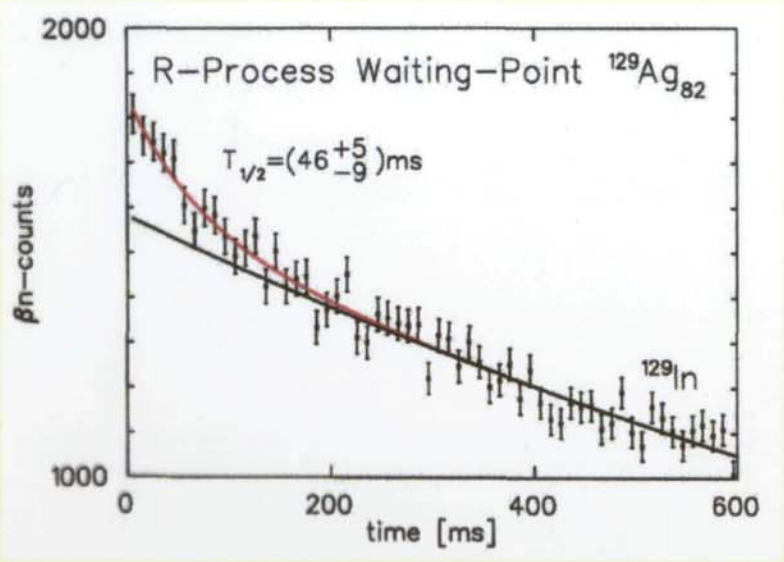
Additional selectivity from hyperfine splitting

- Solid line:
  - HF-splitting of the $\pi g_{9/2}$ configuration
- Dashed line:
  - $\pi p_{1/2}$ component

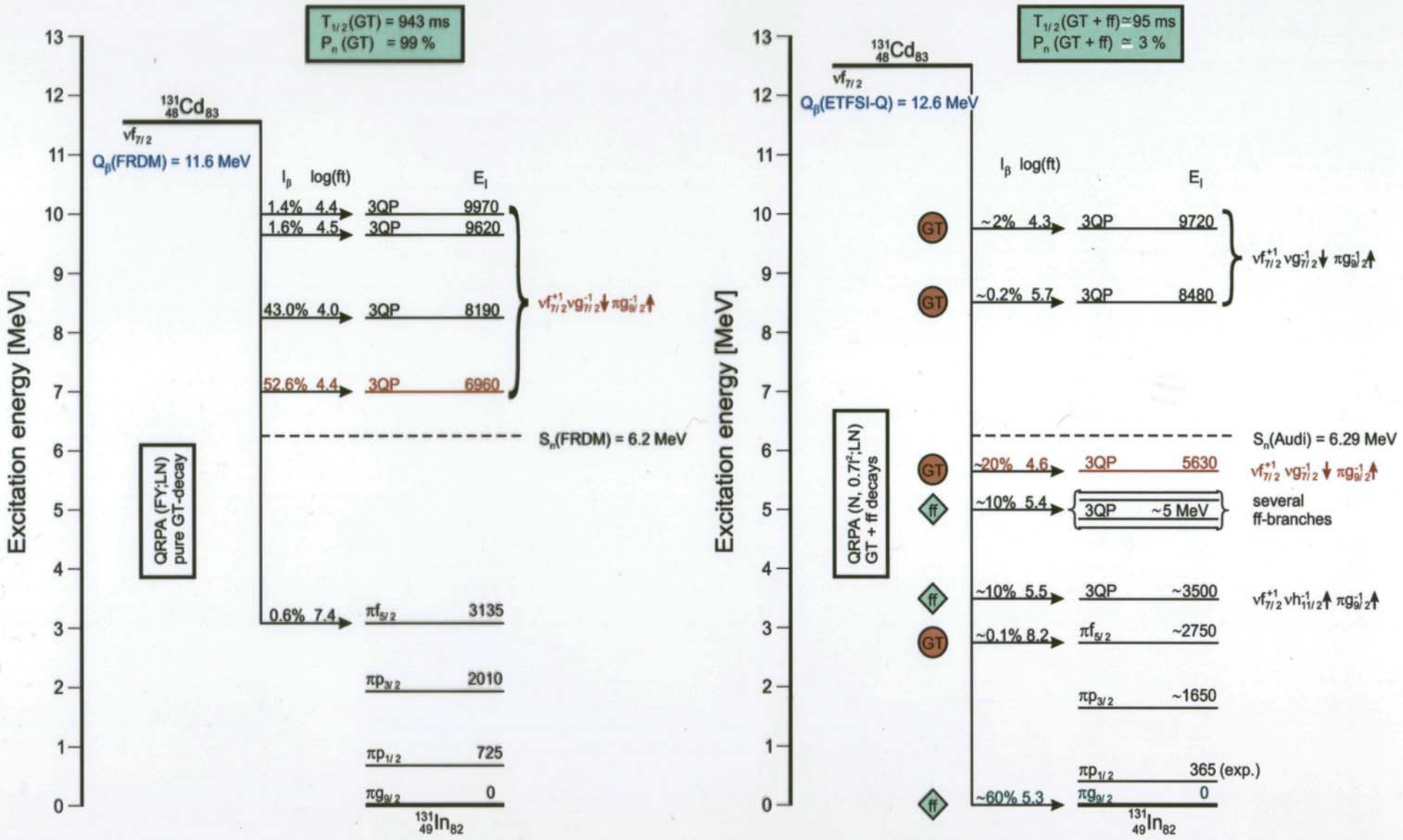


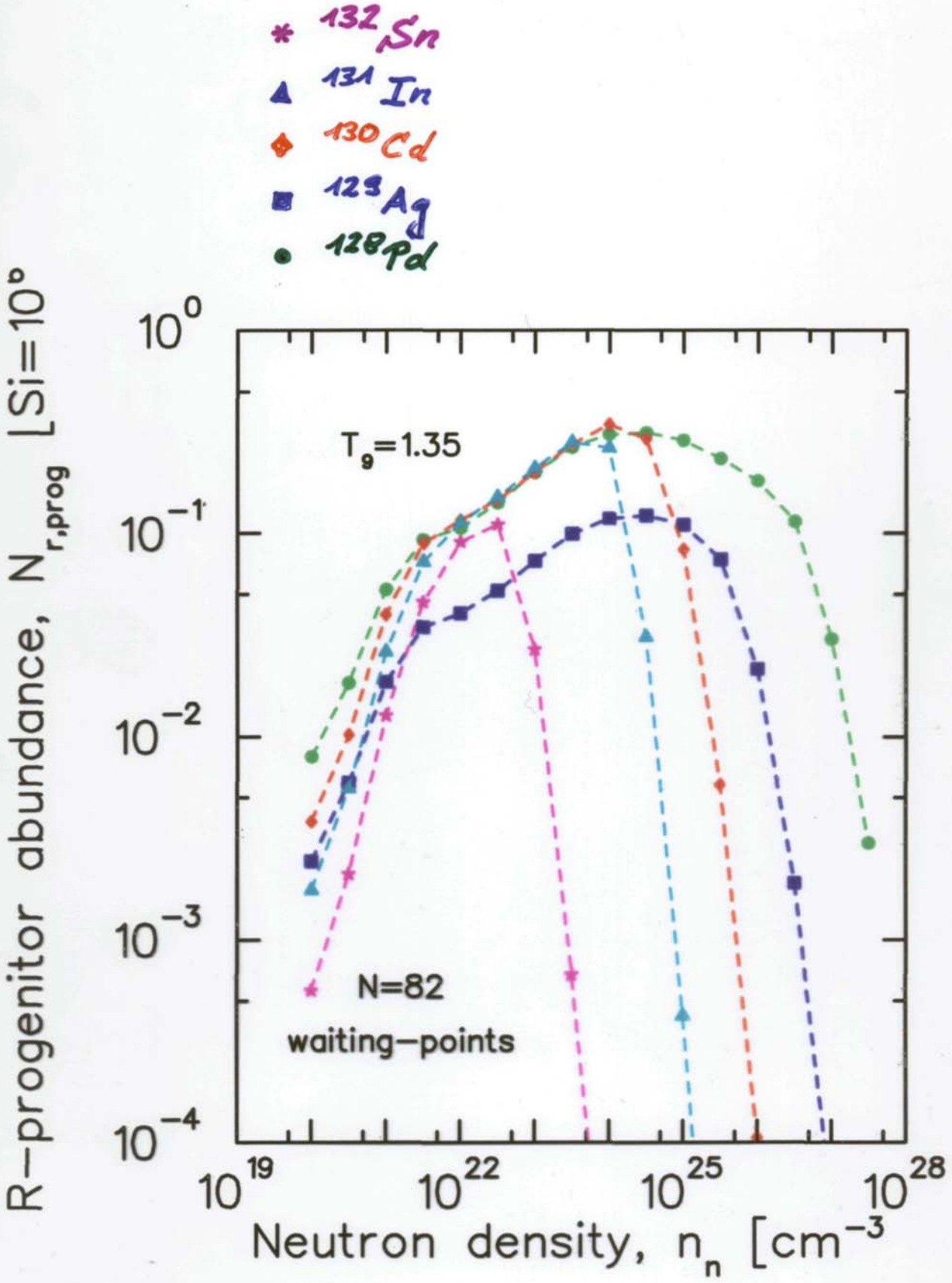
Laser ion source

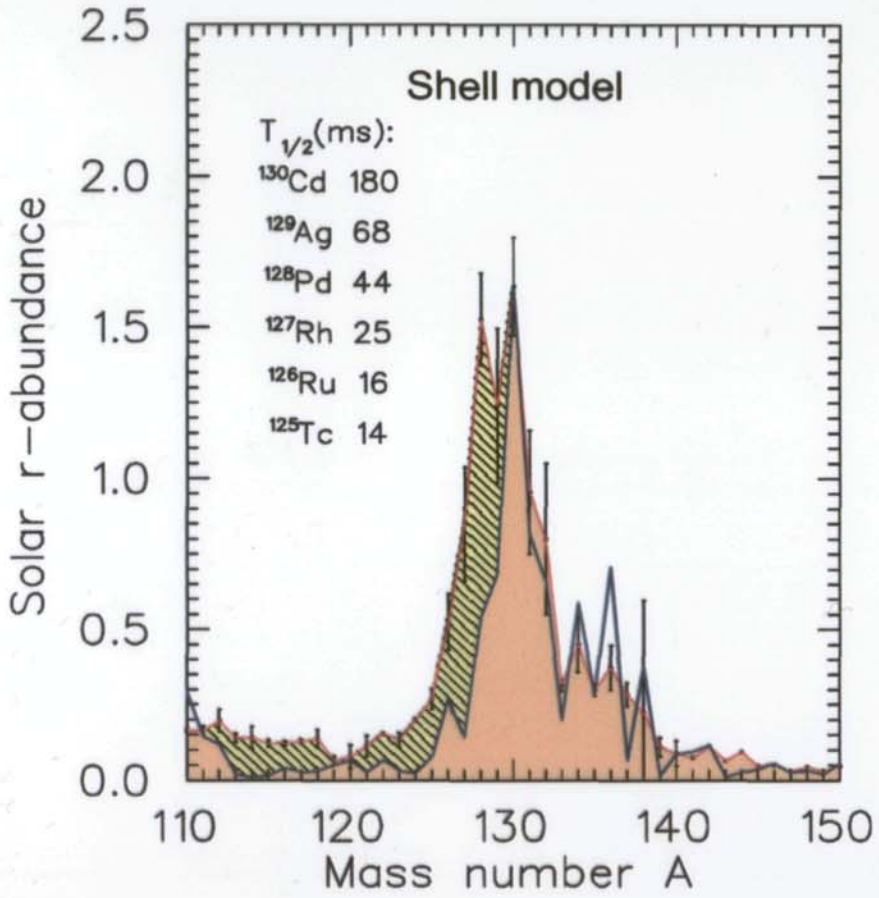
- Laser set to off-center frequency
  $g_{9/2}$ ground-state decay
- Laser on central frequency
  Indication of isomeric decay

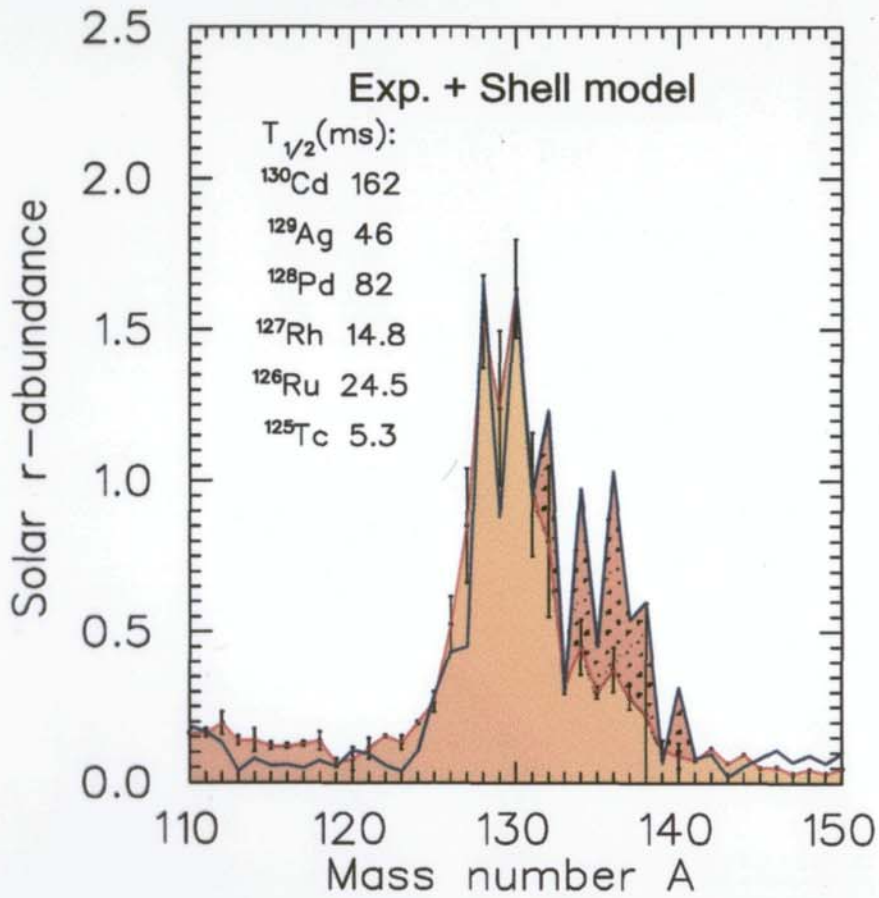


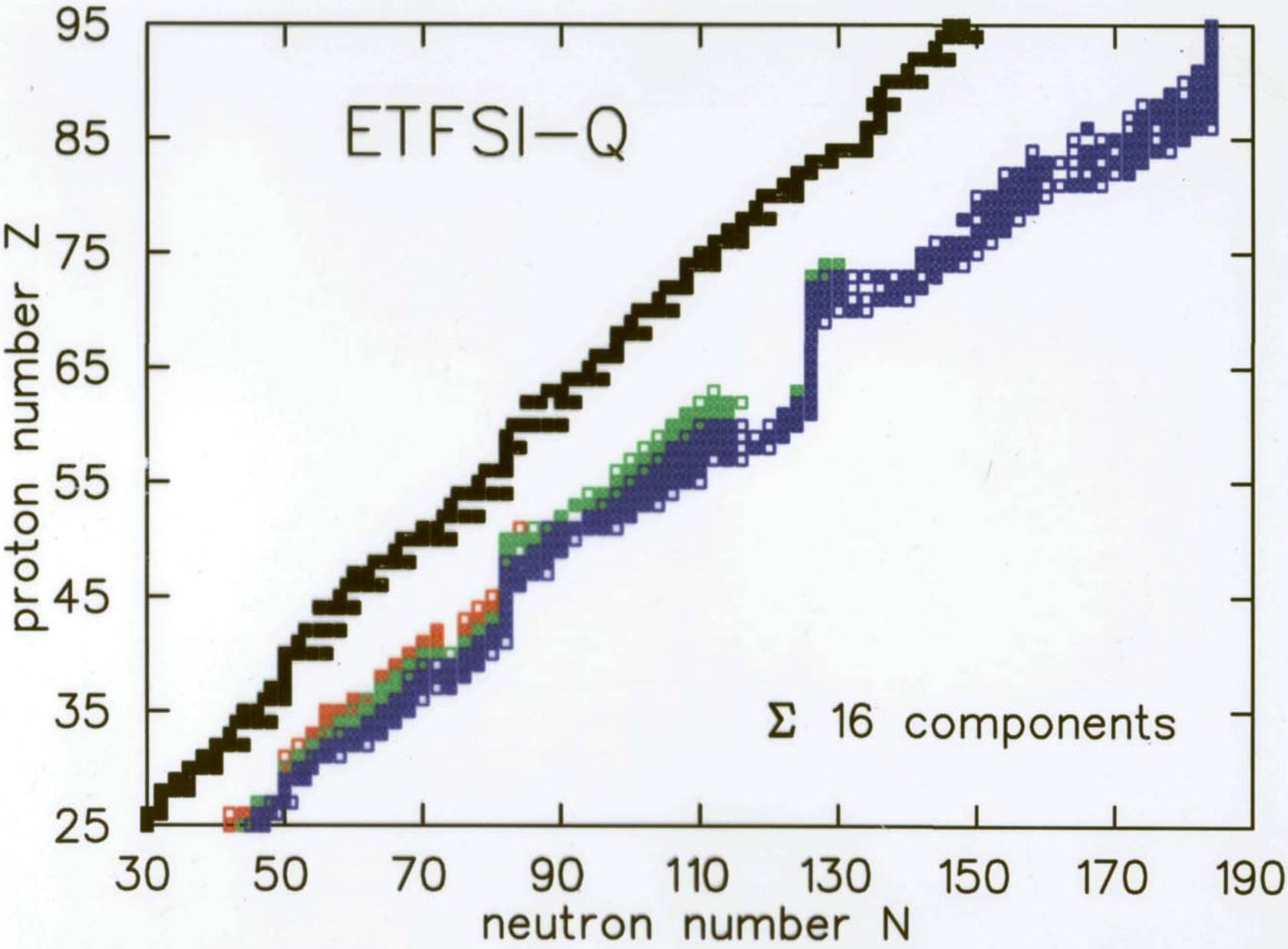
$T_{1/2}$ = 68 ms; P_n(exp) = 3.4 %




^{132}Sn
^{131}In
^{130}Cd
^{129}Ag
^{128}Pd
T_9=1.35
N=82
waiting–points
R–progenitor abundance, $N_{r,prog}$ [Si=10^6]
Neutron density, n_n [cm^{-3}]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{19}
10^{22}
10^{25}
10^{28}


Shell model
T1/2(ms):
130Cd 180
129Ag 68
128Pd 44
127Rh 25
126Ru 16
125Tc 14
Solar r−abundance
Mass number A
0.0
0.5
1.0
1.5
2.0
2.5
110
120
130
140
150


Exp. + Shell model
T1/2(ms):
130Cd 162
129Ag 46
128Pd 82
127Rh 14.8
126Ru 24.5
125Tc 5.3
Solar r−abundance
Mass number A
0.0
0.5
1.0
1.5
2.0
2.5
110
120
130
140
150


ETFSI–Q
Σ 16 components
proton number Z
neutron number N
95
85
75
65
55
45
35
25
30
50
70
90
110
130
150
170
190

With this basis,

"application" of our r-abundance calculations
to recent observations

from Hubble Space Telescope (HST)
and high-resolution ground-based spectrographs
(e.g. KECK)

- Elemental abundances of UMP halo stars
  - Th,U cosmochronometers
  - age of the Universe
- Isotopic abundances in halo stars
  - stellar evolution of early Milky Way
  - r/s-process abundance mixtures
  - first stars →solar system

Determining the age of the Universe has long been considered the

"holy grail of cosmology"

BPS CS22892-052 in AQUARIUS

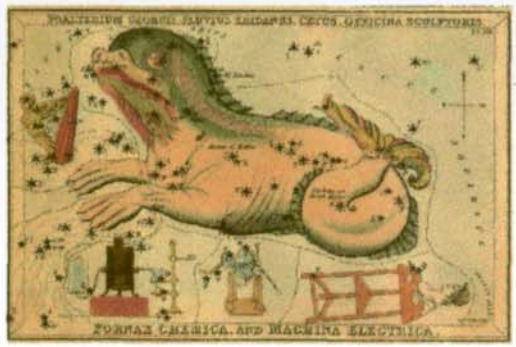
RA 22:17:01.5 DE -16:39:26

V=13.2, [Fe/H]=-3.1, dist.=4.7 kpc

HD115444 in CANES VENATICI

RA 13:16:42.46 DE +36:22:53

V=8.98, [Fe/H]=-3.0, dist.=286 pc



BPS CS31082-001 in CETUS

RA 01:29:31.2 DE -16:00:48

V=11.7, [Fe/H]=-2.9, dist.=4 kpc

HD122563 in BOÖTES

RA 14:02:31.8 DE +09:41:10

V=6.18, [Fe/H]=-2.7, dist.=266 pc

HD126238 in BOÖTES

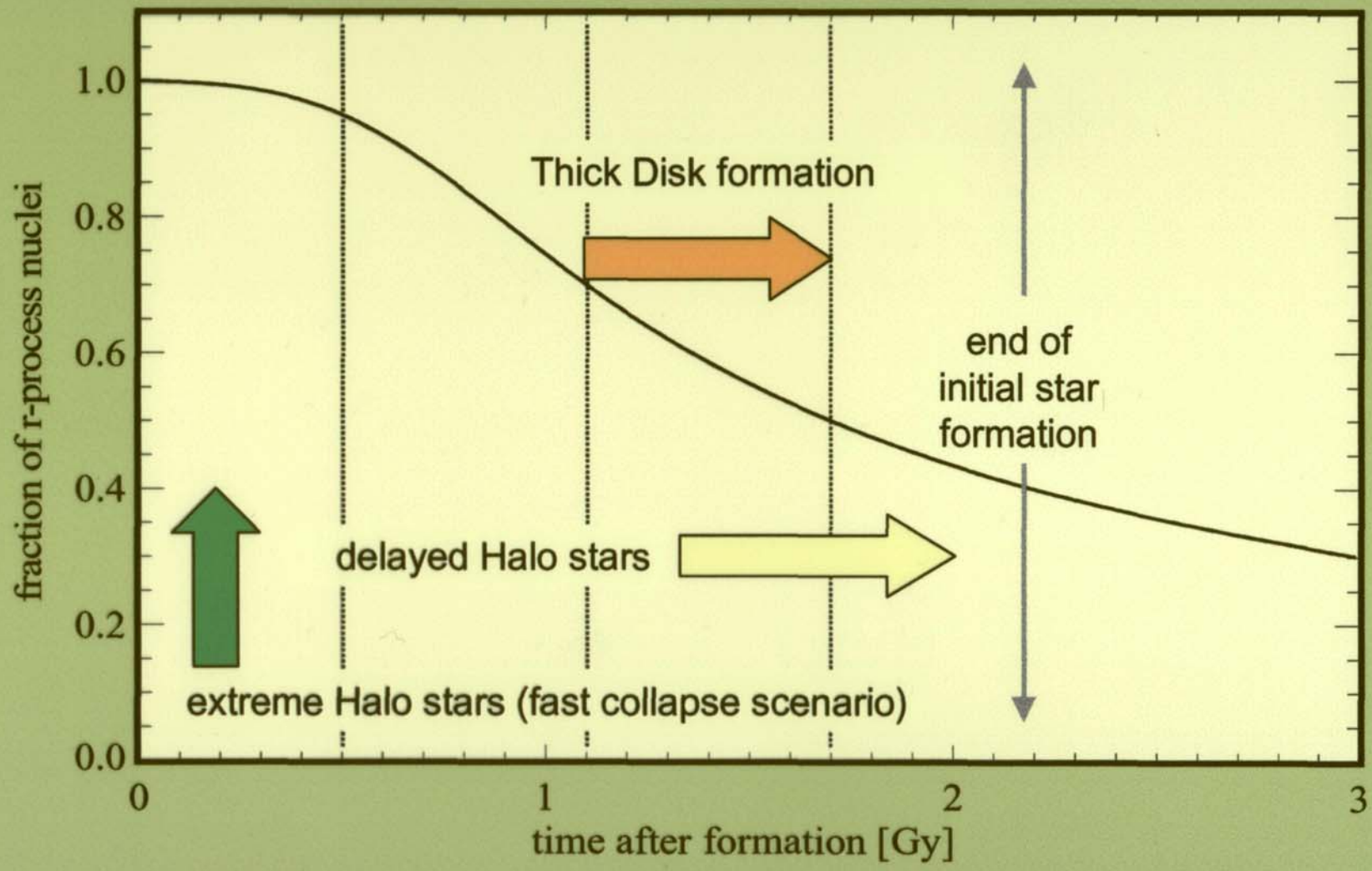
RA 14:25:30.0 DE +43:38:37

V=7.66, [Fe/H]=-1.7, dist.=263 pc

*W*e compare r-process model predictions with recent astronomical observations from the solar system, ultra-metal-poor (UMP) halo stars and meteoritic r-process signatures, i.e. containing elemental as well as isotopic abundances. We deduce (1) astrophysical conditions (n_n-ranges for weak and main r-process components) under which such r-patterns can be obtained, and (2) criteria to determine Th/U chronometric ages.

These historic illustrations of the constellations are from Catherine Tennants *"The Box of Stars: A Practical Guide to the Night Sky and to Its Myths and Legends / Book, Cards and Maps."* They are reproductions from *Urania's Mirror*, published 1825 in London.

The early years of the Milky Way



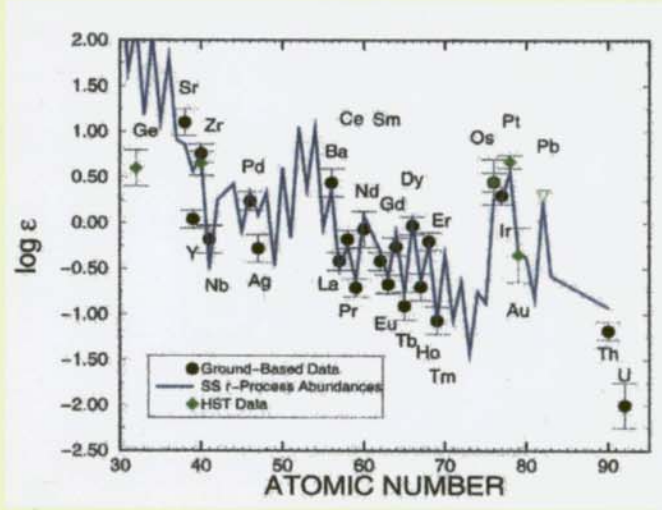
from Travaglio et al. (1999)

Ultra-metal-poor Halo stars
Th-U cosmochronometer

- Th-U chronometer ideal for dating of solar system.
- Lower limit for age of the Universe requires models of Galactic chemical evolution.

- High-resolution optical spectroscopy of ultra-metal-poor, very old Halo red giants stars opens new perspectives:

  - One (or few) nucleosynthesis events seeded ISM.
  - Scaled solar system r-process abundances for $56 \leq Z \leq 79$.
  - Radioactive dating requires „production ratios“.
  - Th/U ratio (hopefully) less effected by extra-polations of nuclear structure



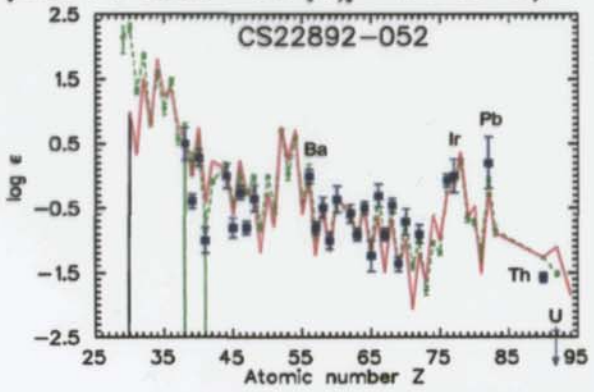
Abundances in BD+17°3248

Cosmochronology with Thorium

Several UMP halo stars consistently show solar elemental abundance pattern, among them

CS 22892-052

with 17 elements between Ba and Ir, plus Pb and ^{232}Th ($T_{½} = 14 \cdot 10^9$ a)



🗁 age from average of Th/Ba-Ir

14.6 ± 3.0 Gyr

☾ age of the Universe

Tuning the clock with Uranium

Because of shorter half-life ($T_{½} = 4.5 \cdot 10^9$ a), ^{238}U may yield more precise age.
Recently, first observation of U in CS 31082-001

(Cayrel et al., 2001)

🗁 age from U/Th

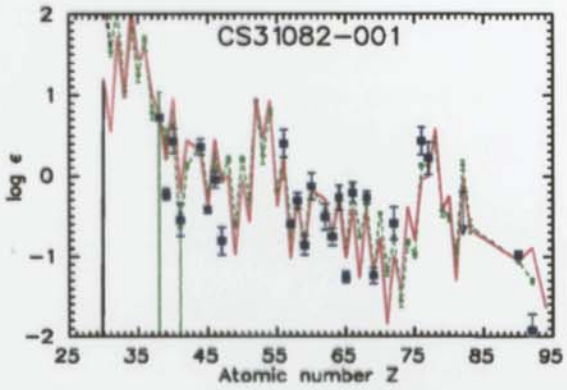
15.0 ± 3.0 Gyr

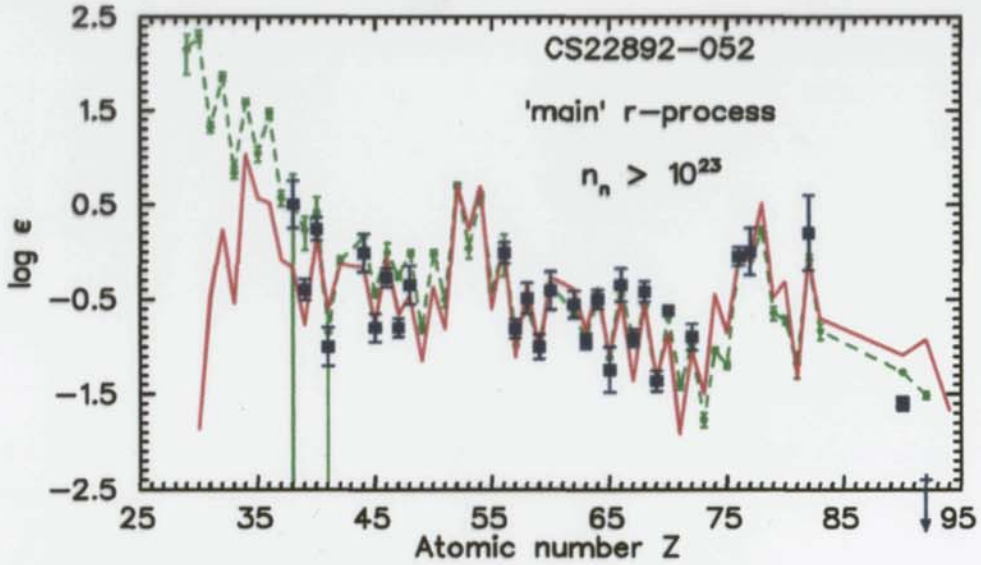
(Schatz et al., 2002)

In the meantime, second observation of U in BD +17°3248 🗁 age from U/Th and U,Th/3rd peak

13.8 ± 4.0 Gyr

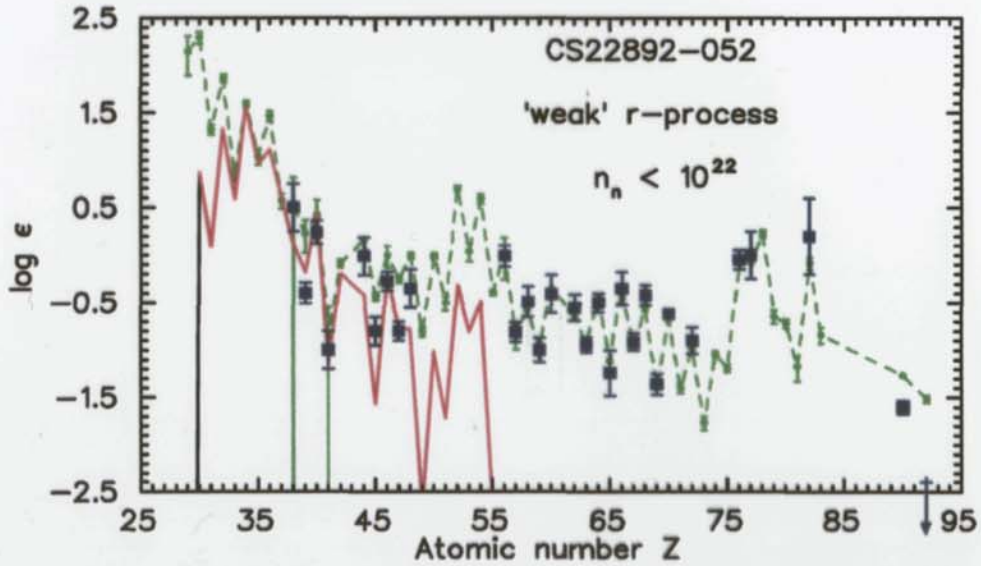
(Cowan et al., 2002)





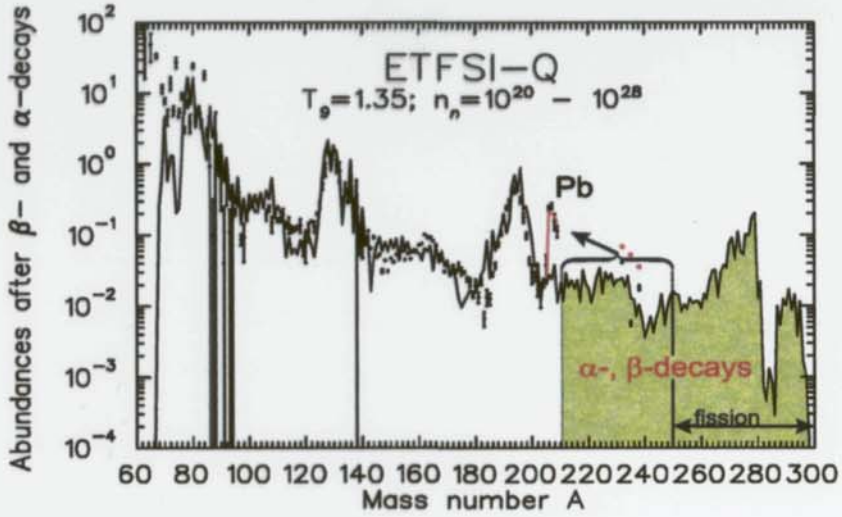
■ observation
--- $N_{r,\phi}(Z)$
— $N_{r,calc}(Z)$

difference $(N_{r,\phi}(Z)-N_{r,main}(Z))$
= "weak" r-process



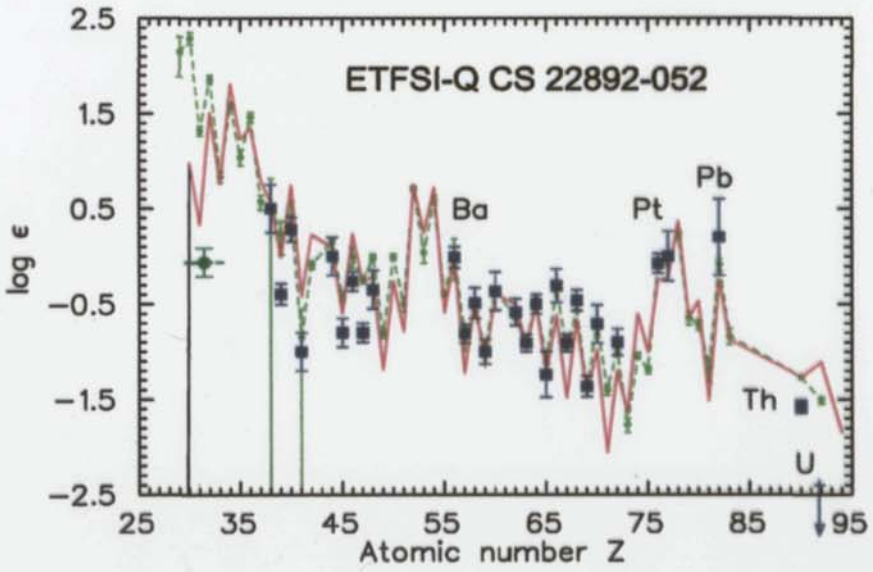
What do we calculate?

eproduce isotopic $N_{r,\odot}$ distribution
sing waiting-point approach
sq-fits; A ⩾ 80, A ⩾ 120)



Pb abundances as reliability criterion for Th, U region!

Convert to elemental $N_{r,\odot}$ curve(–), and scale to halo abundances (▪)



comparision to $N_{r,\odot}(Z)$

⇒ excellent agreement above Ba

⇒ Th, U cosmo-chronometry

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s/r Isotopic Mixtures in UMP Halo Stars

Two recent cases:

① Sneden et al. (2002)

In 3 UMP stars, abundance ratio

$^{153}Eu / ^{151}Eu \simeq 1.0$

to be compared to

$^{153}Eu(s) / ^{151}Eu(s) = 0.85 \pm 0.09$

$^{153}Eu(r) / ^{151}Eu(r) = 1.11 \pm 0.02$

possible s-process contamination difficult to identify

↷ Eu(s) / Eu(r) ≃ 6 / 94

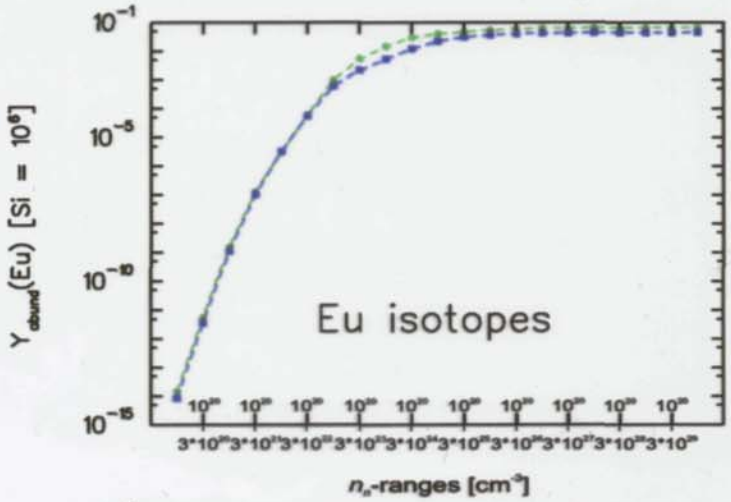
What do we calculate?

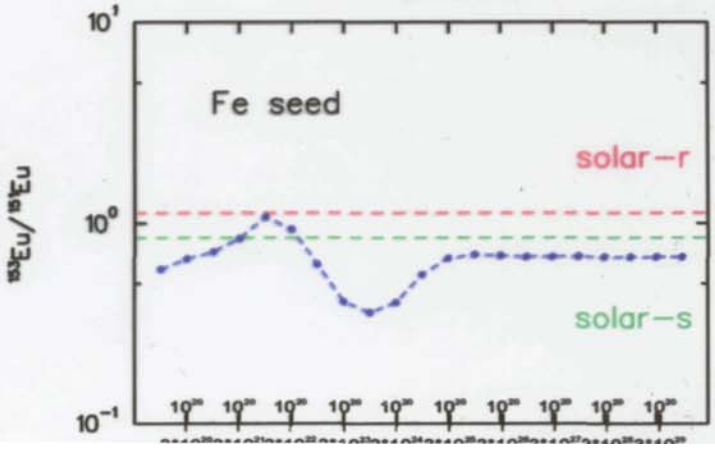
- Eu(r) as function of n_n-ranges

↷ "main" r-process conditions

- calculated integral r-ratio

$^{153}Eu / ^{151}Eu \simeq 0.86$





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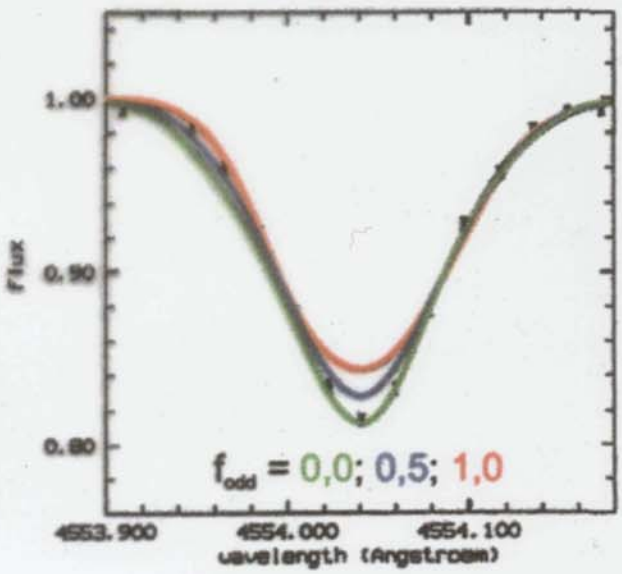
P. Magain (1995):

"the r/s-process controversy"

much stronger r/s constraints from isotopic abundances as a function of metallicity;
use isotopic hyperfine splitting, affecting line widths to determine odd-to-even isotopic ratios.

Barium is particularly well suited
Ba II spectral line at 4554 Å
s-process dominates even isotopes ↝ narrow line
r-process dominates odd isotopes ↝ broad line

⇒ width of the line is a measure of the oe isototopic ratio, and thus of the r-process contribution.

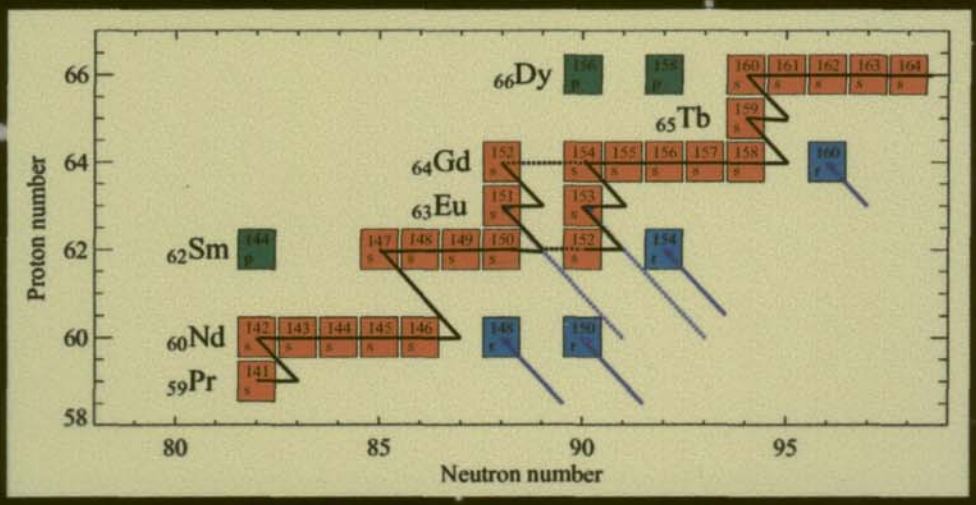


Definition:

$$f_{odd} = \frac{N(135Ba) + N(137Ba)}{N(Ba)}$$

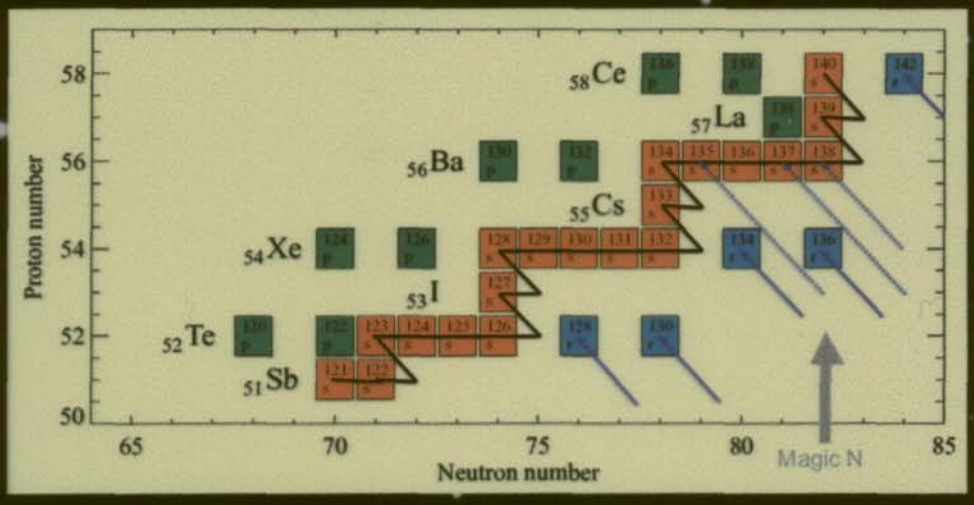
$f^{\odot}_{odd} = 0.18 \pm 0.02$ $f^{s,\odot}_{odd} = 0.11 \pm 0.02$ $f^{r,\odot}_{odd} = 0.54 \pm 0.13$

Europium isotopes and their nucleosynthesis



Europium isotopes are processed in a broken s-process chain.
Both isotopes can be produced by the r-process,
but also may have some s-process contributions.

Barium isotopes and their nucleosynthesis



Map of nuclides with valley of β-stability (s-process path).
Also displays isotopes that can be produced in both s- and r-process (dotted arrows)

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Analyses of 4554 Å line of HD 140283

P. Magain (1995)

$f_{odd} = 0.08 \pm 0.06$

"... in agreement with a pure s-process production ..."

D. L. Lambert (2002)

$f_{odd} = 0.30 \pm 0.21$

"... consistent with the solar r-process contributions to barium ..."

in addition,
from measured [Ba/Fe] and [Eu/Fe] ratios

↷ [Ba/Eu] = -1.05

"... HD 140283 has the [Ba/Eu] ratio expected of the r-process ...;
... suggestion about s-process contamination ...(?)"

For solar-like r-process yields of Ba and Eu

↷ $[Ba/Eu]_r = -0.73 \pm 0.04$

Definition: $[Ba/Eu]_r = \log \left[\frac{Ba\ (r)}{Ba\ (\odot)} \Big/ \frac{Eu\ (r)}{Eu\ (\odot)} \right]$

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What do we calculate?

① integral f^{r}_{odd}(Ba)

average from 20 calculations ($10^{20} < n_n < 10^{30}$), using 11 different mass models / hybrid mass models and different global fit criteria to reproduce the overall isotopic $N_{r,\odot}$ pattern

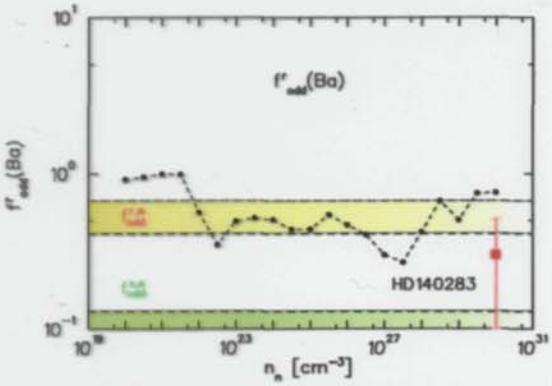
↷ quite robust result

$$f^{r}_{odd}(Ba) = 0.51 \pm 0.06$$

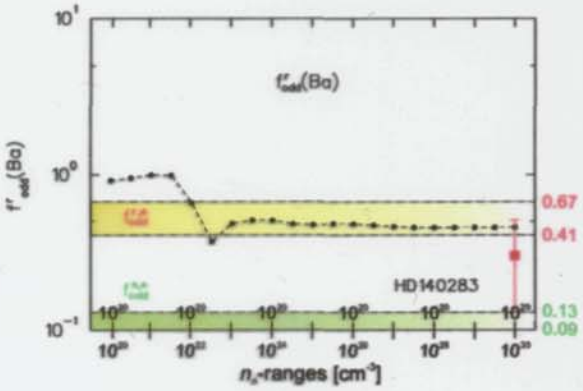
- good agreement with $f^{r,\odot}_{odd}$(Ba)
- overlaps with upper limit of Lambert´s f^{r}_{odd}(Ba) in HD 140283
- excludes $f_{odd}(Ba) < 0.4$

② f^{r}_{odd}(Ba) as function of neutron-density

(ETFSI-Q mass model)

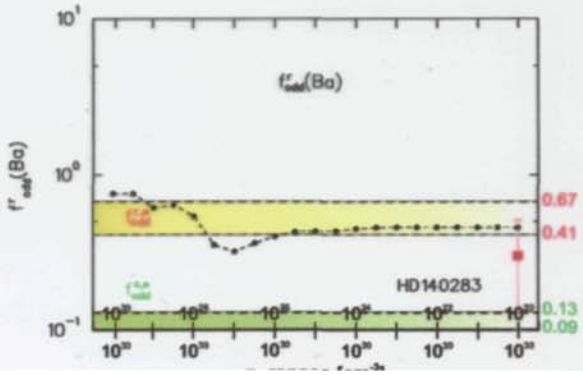


individual n_n-components



different n_n-ranges

… to simulate "weak" and "main" r-process conditions …



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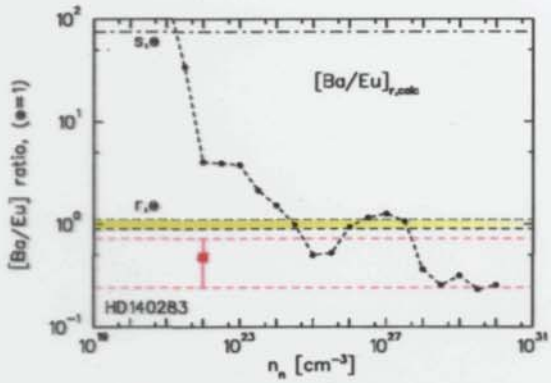
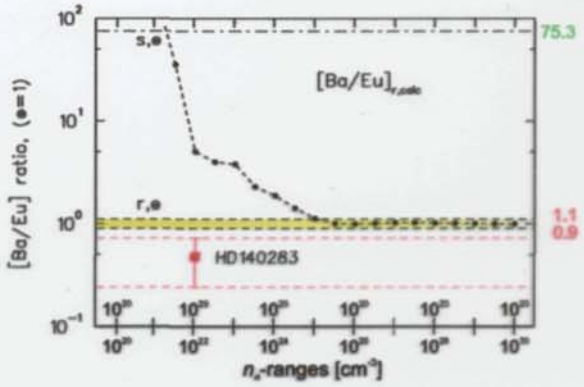
What do we calculate? ...ctd.

③ [Ba / Eu] as function of neutron-density

(ETFSI-Q mass model)

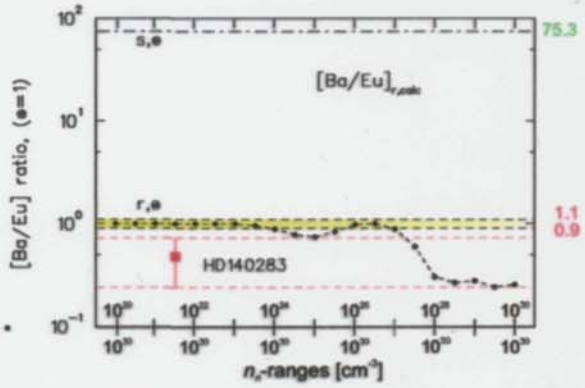




individual n_n-components

different n_n-ranges

… to simulate "weak" and "main" r-process conditions …



Conclusions:

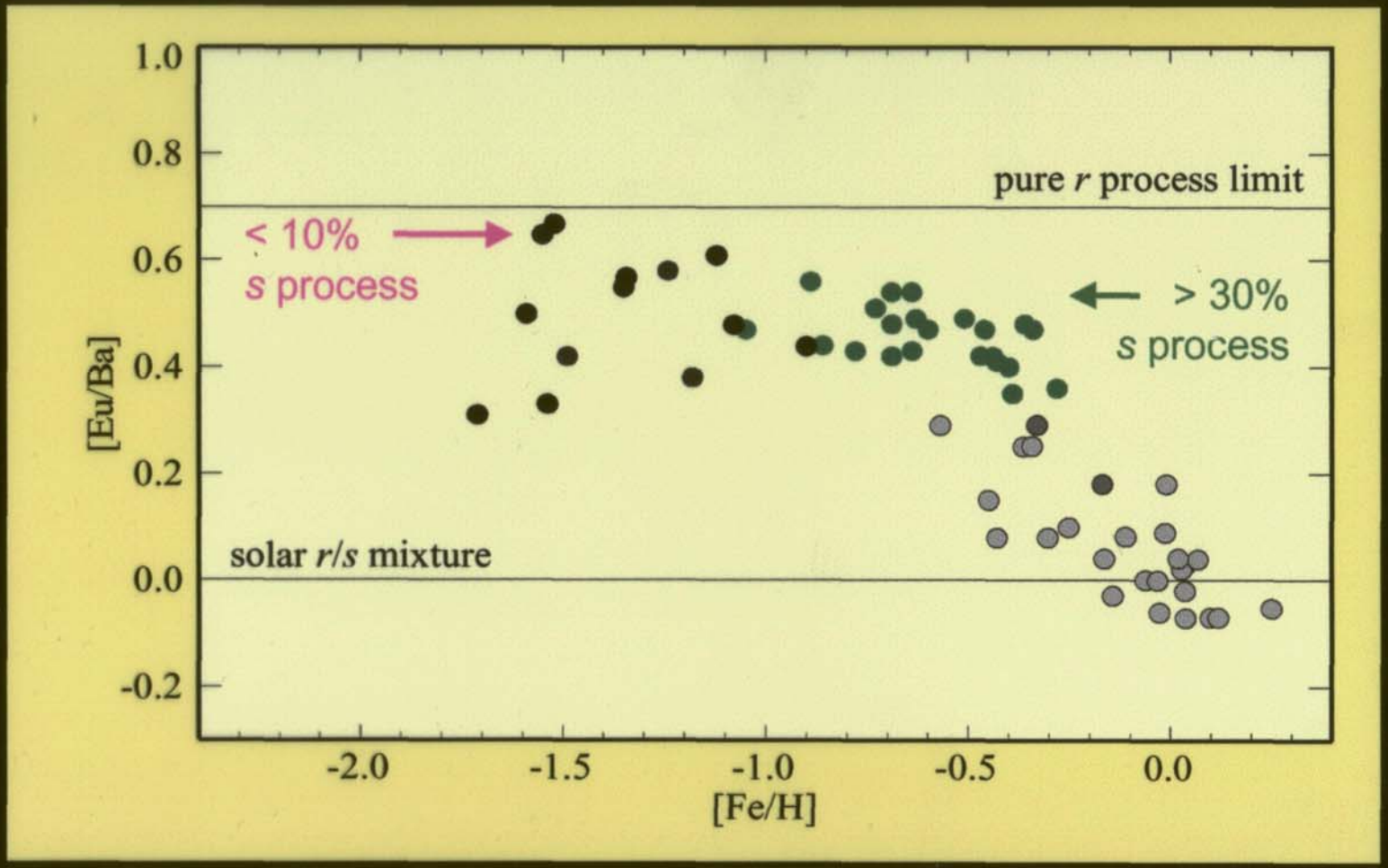
- measured $f_{odd}(Ba) = 0.30 \pm 0.21$

  just in between f^{r}_{odd} and f^{s}_{odd}

- measured [Ba/Eu] = -1.05

  favors high-n_n r-process
  incompatible with s-process

- a "weak" r-process ($n_n < 10^{22}$) shows $[Ba/Eu]_r$ similar to $[Ba/Eu]_{s,\odot}$



Stellar evolution predicts the first s nuclei 0.5 Gyr after the proto-Galactic collapse, with another 0.6 Gyr to reach s/r = 30 : 70, and another 0.5 Gyr to arrive at 50 : 50

from Gehren et al. (2003)

Conclusions

Direct comparison between astronomical and nuclear structure observations and astro-model predictions

- information about stellar parameters

  temperatures,
  particle (e.g. p, α, n) and matter densities,
  time scales,
  hydrodynamical conditions

- possible information on nuclear physics far from stability

  position of particle drip-lines
  regions of shape transition
  monopole shifts
  shell quenching

It is clear that also in the future astrophysics will have to rely on nuclear physics input;
mainly from nuclear theories,
still not sufficiently well understood.

Therefore, continued **request** for
radioactive-beam
nuclear mass
β-decay
experiments

Present ISOL-RIB facilities (ISOLDE, SPIRAL, ...) ⟶ TARGISOL ⟶ EURISOL