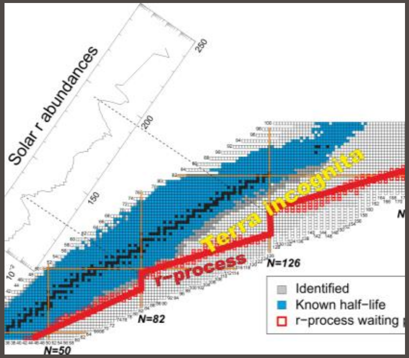
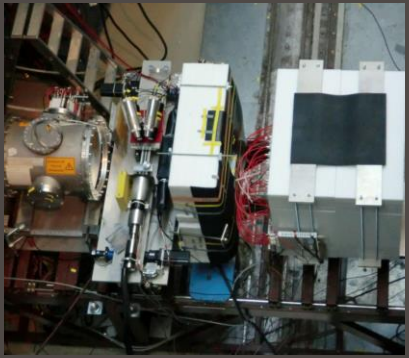
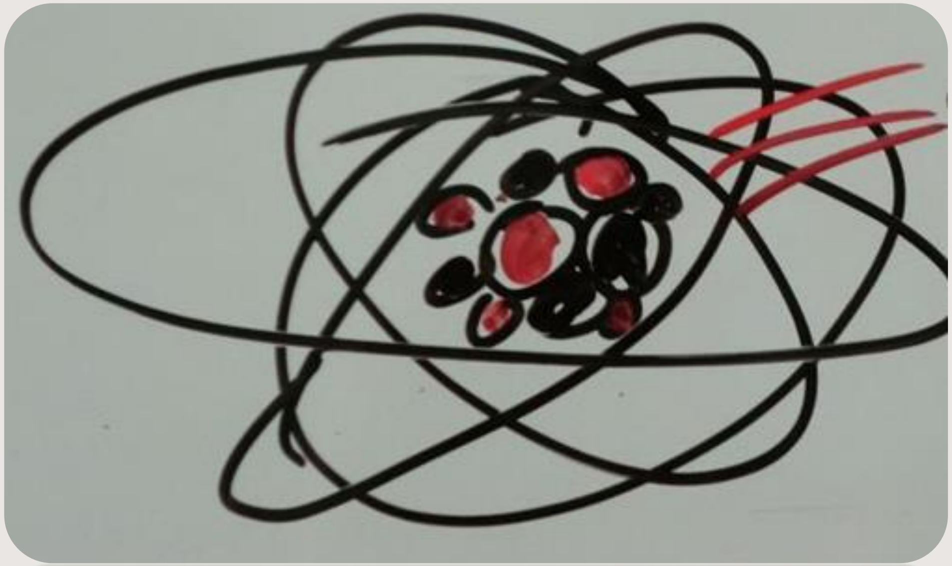
β-delayed neutron emission and its role in the r-process

Iris Dillmann
Research Scientist
TRIUMF



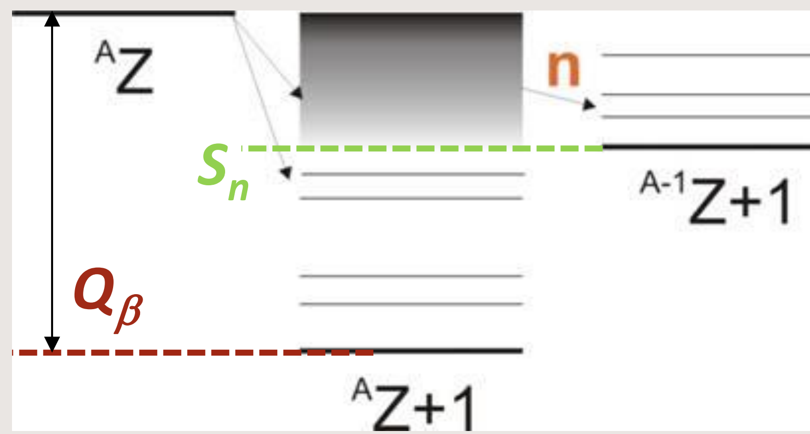


β-delayed neutron emission



Catch me if you can!

- $S_n < Q_\beta$
- "Delayed": emission with β-decay half-life of the precursor ^{A}Z



Discovery (1939)

Further Observations on the Splitting of Uranium and Thorium

Continuing a survey of the effects produced by bombarding uranium and thorium with neutrons we have measured the range of the energetic particles emitted.

To test the possibility of the delayed emission of neutrons a boron-lined ionization chamber was placed a few centimeters from a lithium target used as a source of neutrons, both the chamber and the target being surrounded with paraffin. With this arrangement no pulses were observed after the deuteron bombardment was stopped. However, when a bottle containing about 100 grams of uranium nitrate was placed between the source and the chamber, neutrons were observed as long as $1\frac{1}{2}$ minutes after the bombardment of the uranium, the initial intensity being about one neutron per second. The decay period of these neutrons was observed to be 12.5 ± 3 sec.

R.B. Roberts, R.C. Meyer, P. Wang, Phys. Rev. **55**, 510 (1939).

- Irradiation of 100 g uranium nitrate with neutrons
- Maybe due to (γ,n) reactions?

Discovery (1939)

The Delayed Neutron Emission which Accompanies Fission of Uranium and Thorium

In our previous letter[1] we suggested that the delayed neutrons produced by neutron bombardment of uranium might originate either in direct neutron emission (by one of the disintegration products), or in a photodisintegration process. Further evidence has now been obtained which indicates that direct neutron emission is responsible for the delayed neutrons which we observed.

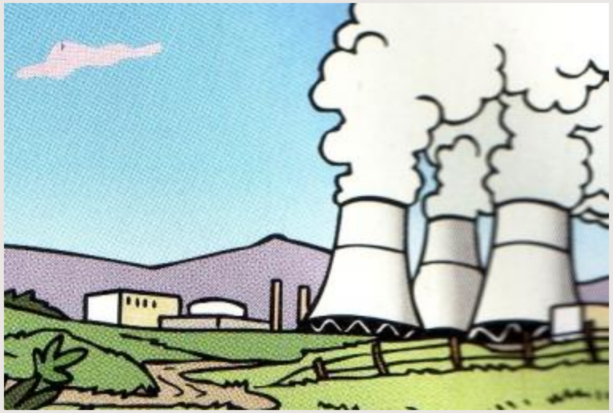
Cloud-chamber observations of the recoils from the delayed neutrons indicated that their energy is less than one million electron volts and probably near one-half million electron volts.

Delayed neutrons were also observed from thorium nitrate which had been activated by fast lithium neutrons. The intensity was roughly one-fourth of that observed from uranium. The period seemed to be roughly the same as that of the delayed neutrons from uranium.

R.B. Roberts, R.C. Meyer, P. Wang, Phys. Rev. **55**, 664 (1939).

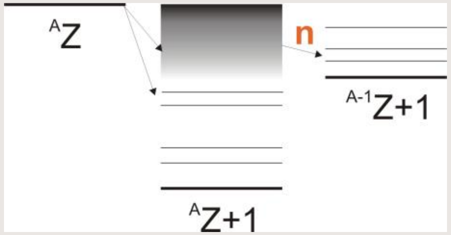
Happy Birthday, beta-delayed neutron!

Why do we need βn?



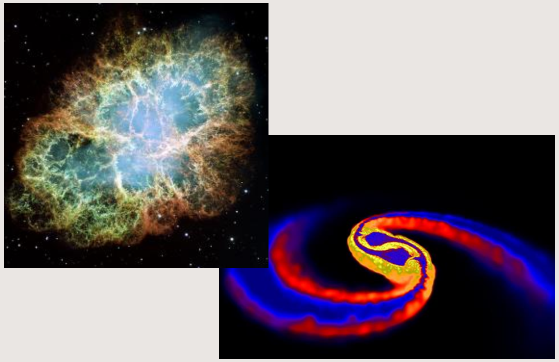
Reactor kinetics:

- Important role in reactor control
- Reactor runs in prompt subcritical, delayed critical conditions



Nuclear structure

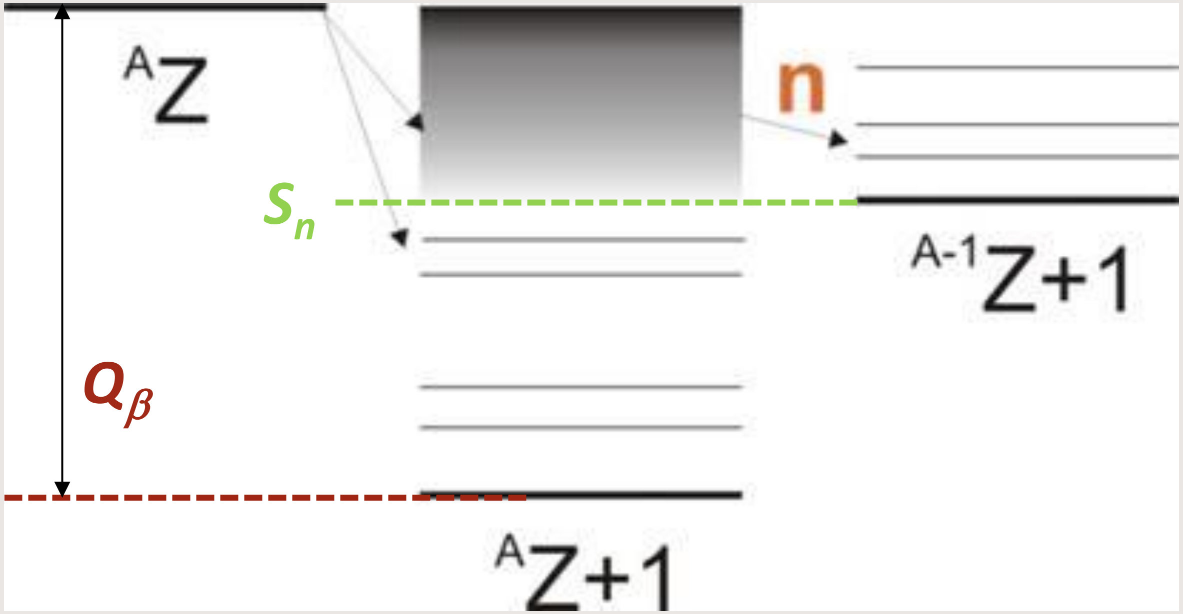
- Dominant decay process for very n-rich nuclei
- Competition with other β-delayed emission processes



Astrophysics (r process)

- Re-capture of neutrons in late-stage evolution
- Influence on solar r-abundance curve

What can we learn from βn?

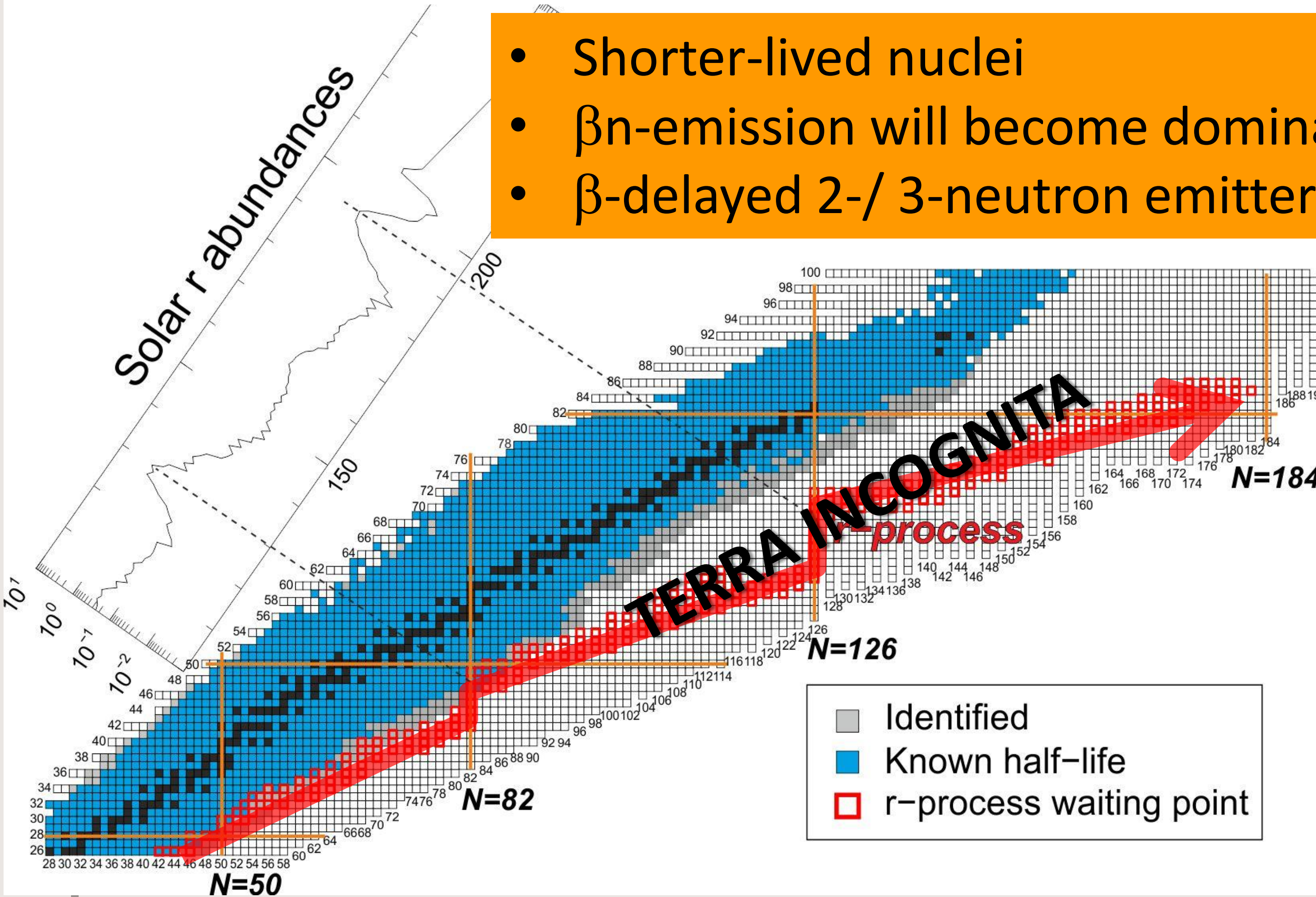


- For new isotopes: fastest (easiest?) access to first nuclear properties
- Important nuclear structure information:
  - Time-dependence of n-emission ⇨ $t_{1/2}(^{A}Z)$ ≈ few ms – 90 s (^{210}Tl)
  - Emission probability P_n and neutron spectrum: β-strength above S_n

Oldie but Goldie!

Recent revival of βn-studies thanks to new RIB facilities

- Shorter-lived nuclei
- βn-emission will become dominant process
- β-delayed 2-/ 3-neutron emitters



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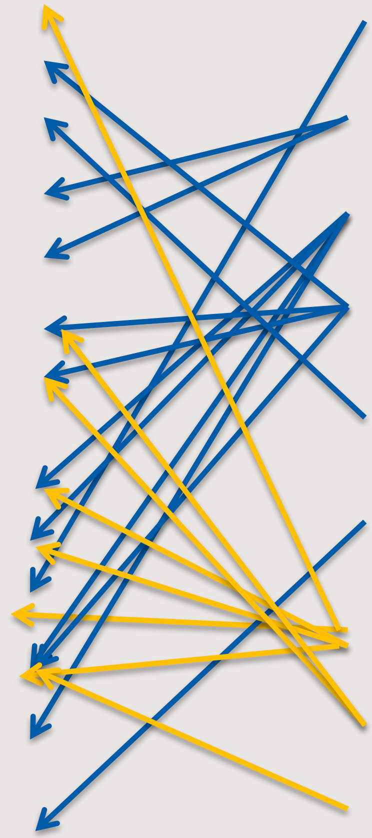
Some ongoing/ planned programs

Choose your facility

ISOLDE @ CERN
FRS @ GSI Darmstadt
Lohengrin @ ILL Grenoble
ALTO @ Orsay
DESIR @ GANIL
IGISOL @ Jyväskylä
SuperFRS @ FAIR

HRIBF @ Oak Ridge
CARIBU @ Argonne
NSCL @ MSU
ISAC + ARIEL @ TRIUMF
FRIB @ NSCL

BigRIPS @ RIKEN



Choose your βn-setup

NERO
TETRA
3Hen
BELEN
LOENIE
BRIKEN

^{3}He-filled counters

VANDLE
MONSTER
DESCANT

Scintillators (liquid/ solid)

...sorry if I missed one...

Methods without neutron detection

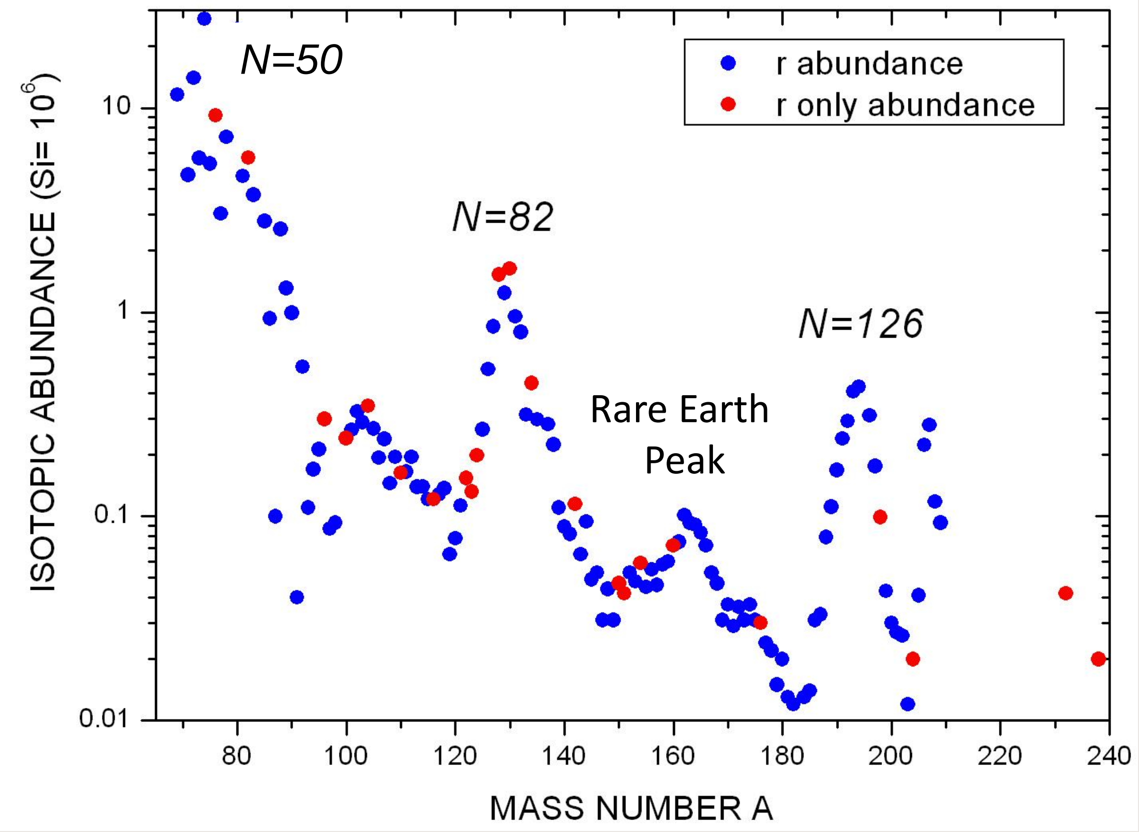
- $\beta\gamma\gamma$-coincidences, e.g. 8π, EURICA, GRIFFIN, ...
  Requires knowledge of absolute intensities, co-production of βn-daughter(s) and/or isomers, direct feeding into g.s., γ-deexcitation from above S_n
- Beta-decay Paul trap: CARIBU @ Argonne
  β-/recoil ion coincidence; neutron energy spectrum and branching ratios; proof-of-principle: ^{137}I; new measurements: $^{134\text{-}136}$Sb, ^{138,140}I, ^{144,145}Cs
  R.M. Yee, N. Scielzo et al., Phys. Rev. Lett. 110, 092501 (2013)
- Particle detector and/ or Schottky-pickups in storage ring: ESR @ GSI Darmstadt, CR@ FAIR
  Design study; detector ready but no beamtime available...
  A. Evdokimov, I. Dillmann, et al., Proc. Nuclei in the Cosmos XII, Cairns/ Australia, PoS (NIC XII)115 (2012)

β-delayed neutrons in the r-process

r-process residuals

$$N_r = N_\odot - N_s - N_p$$

measured *well-known* *negligible*



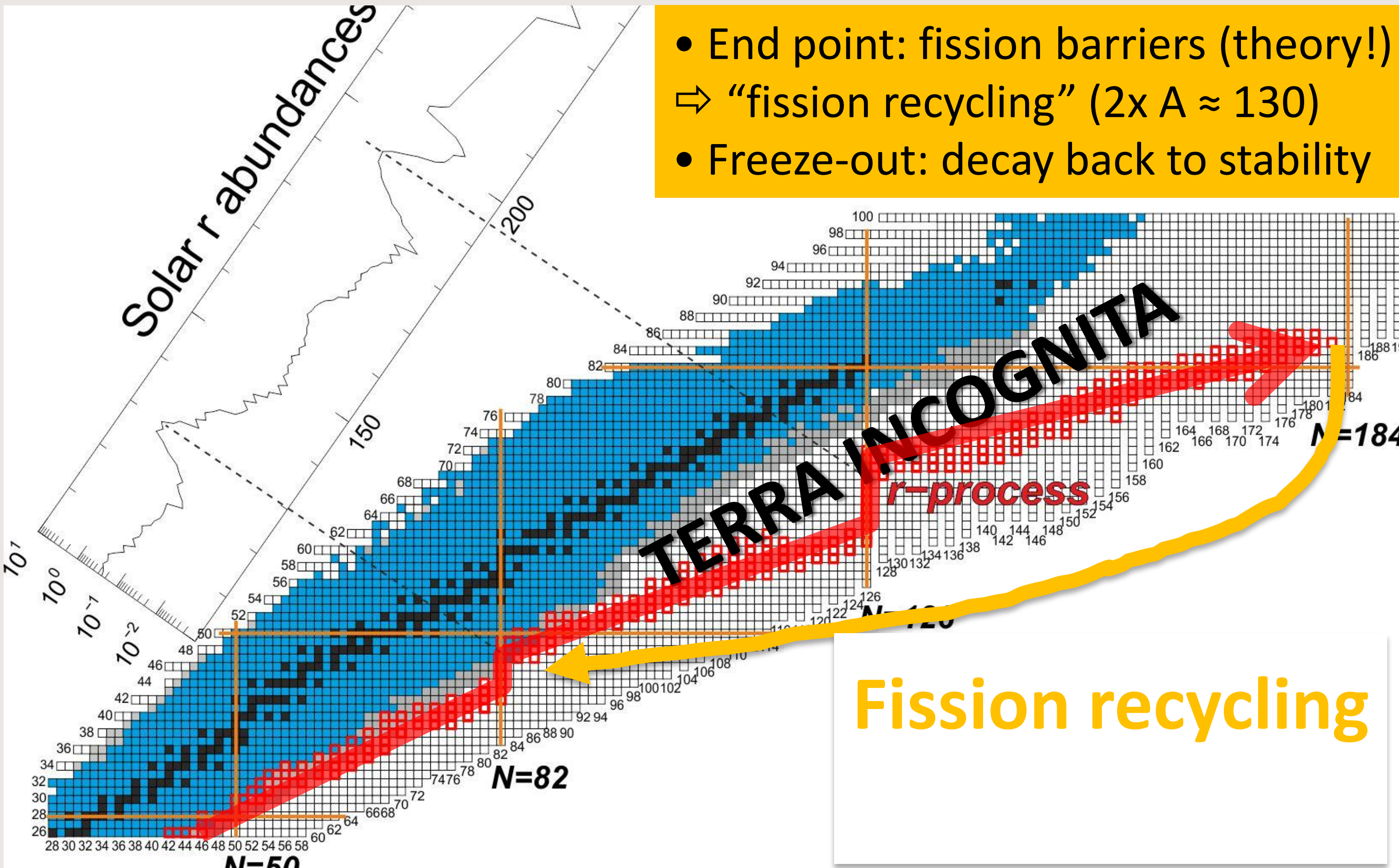
How are these abundances created in stars?

The r-process

- High neutron densities ($n_n \gg 10^{20}$ cm^{-3}) ⇨ ≈1 ms per capture
- "Moderate" temperatures
  - ⇨ ^{56}Fe to ≈ Pu (Z=94, A ≈ 260) in few seconds

Explosive scenario

- End point: fission barriers (theory!)
- ⇨ "fission recycling" (2x A ≈ 130)
- Freeze-out: decay back to stability

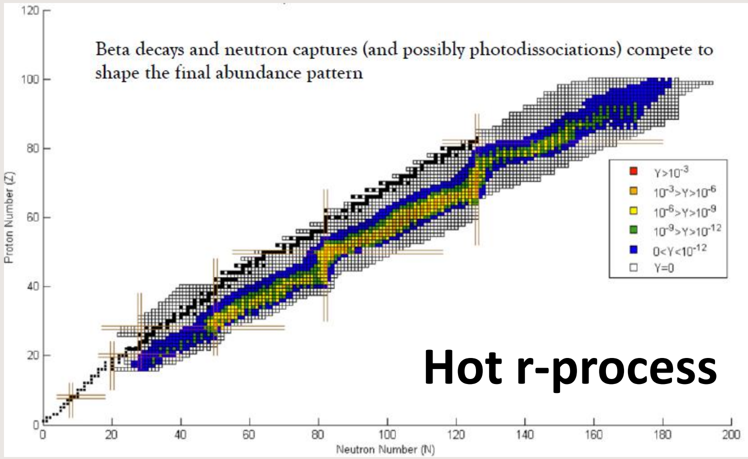


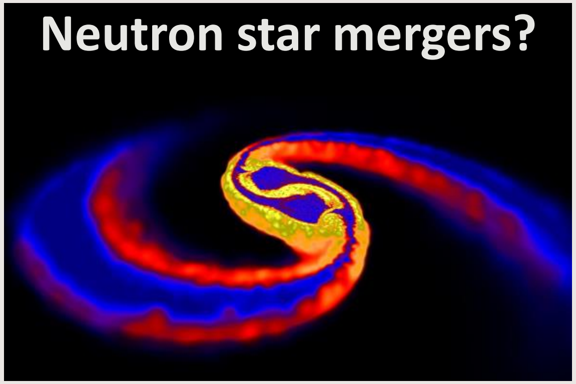
Open question: Where and how?

Core collapse supernova ?


Credit: Hubble Space Telescope

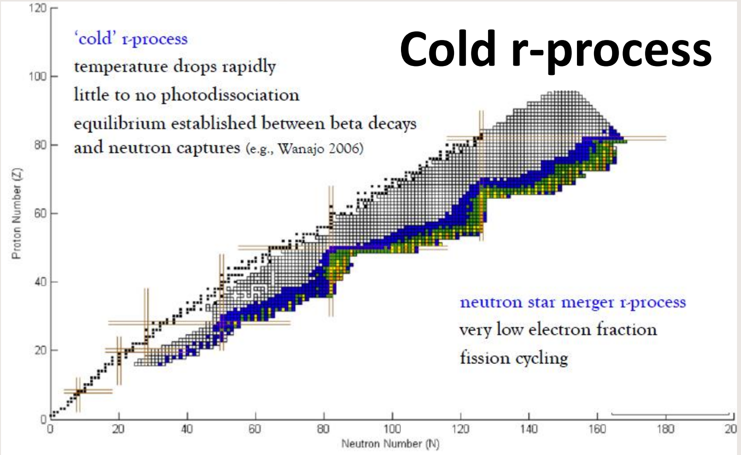
- T > 0.5 GK
- (n,γ)-(γ,n) equilibrium





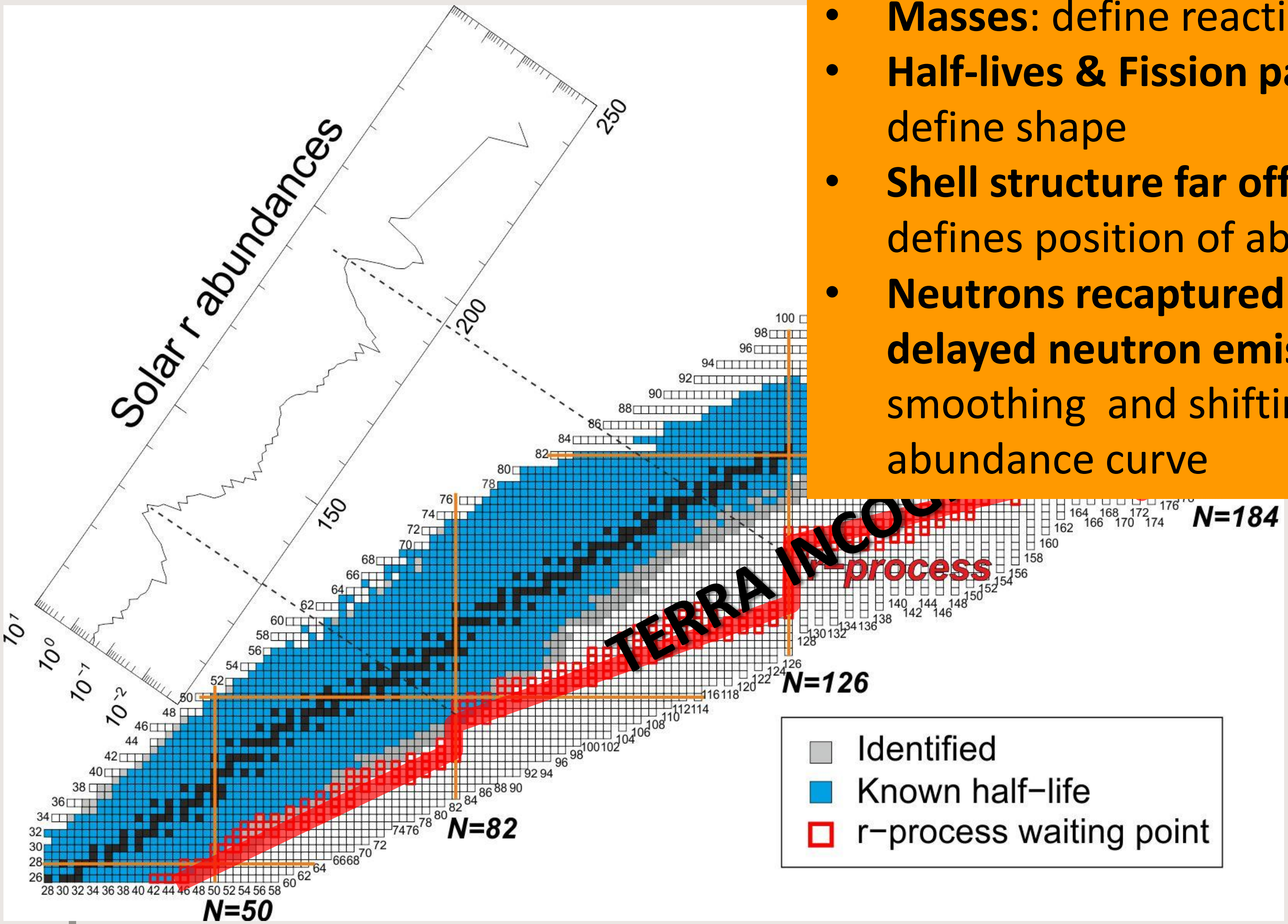
Credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen).

- T< 0.5 GK
- little photodissociation
- equilibrium: β-decays and (n,γ)



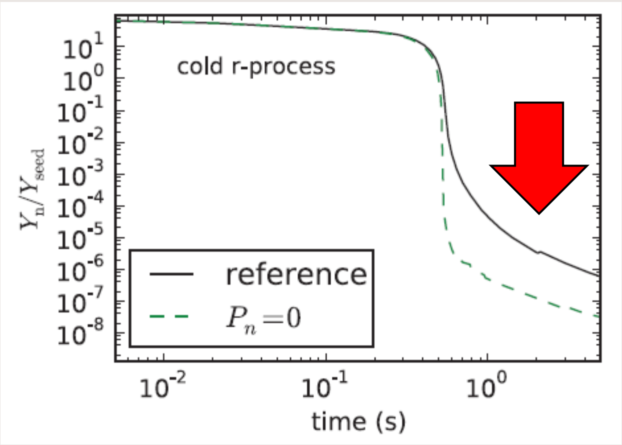
R. Surman

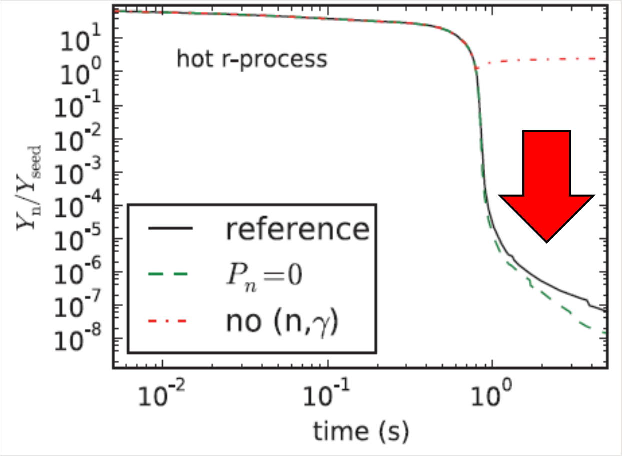
Nuclear Physics Input



- **Masses**: define reaction path
- **Half-lives & Fission parameters**: define shape
- **Shell structure far off stabilty**: defines position of abundance peaks
- **Neutrons recaptured from β-delayed neutron emission or (γ,n)**: smoothing and shifting of abundance curve

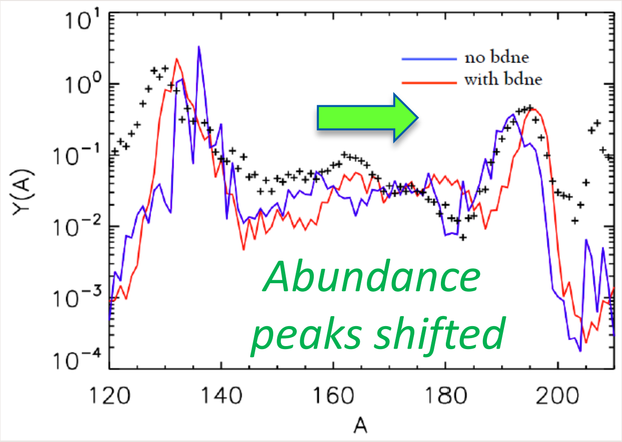
Influence of βn on r-process

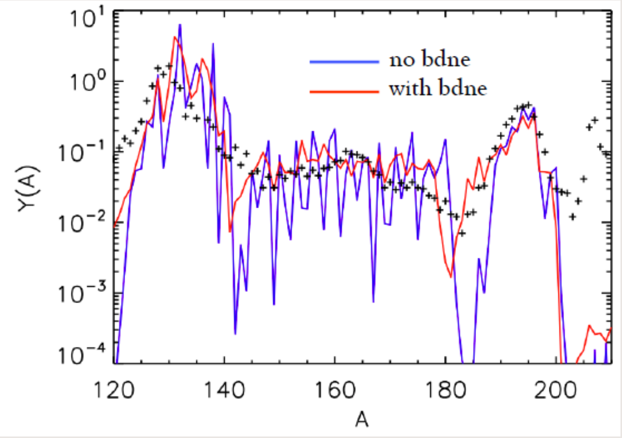




A. Arcones and G. Martinez-Pinedo, PRC83, 045809 (2011)

- Production of additional neutrons: influence on n/seed ratio at later times



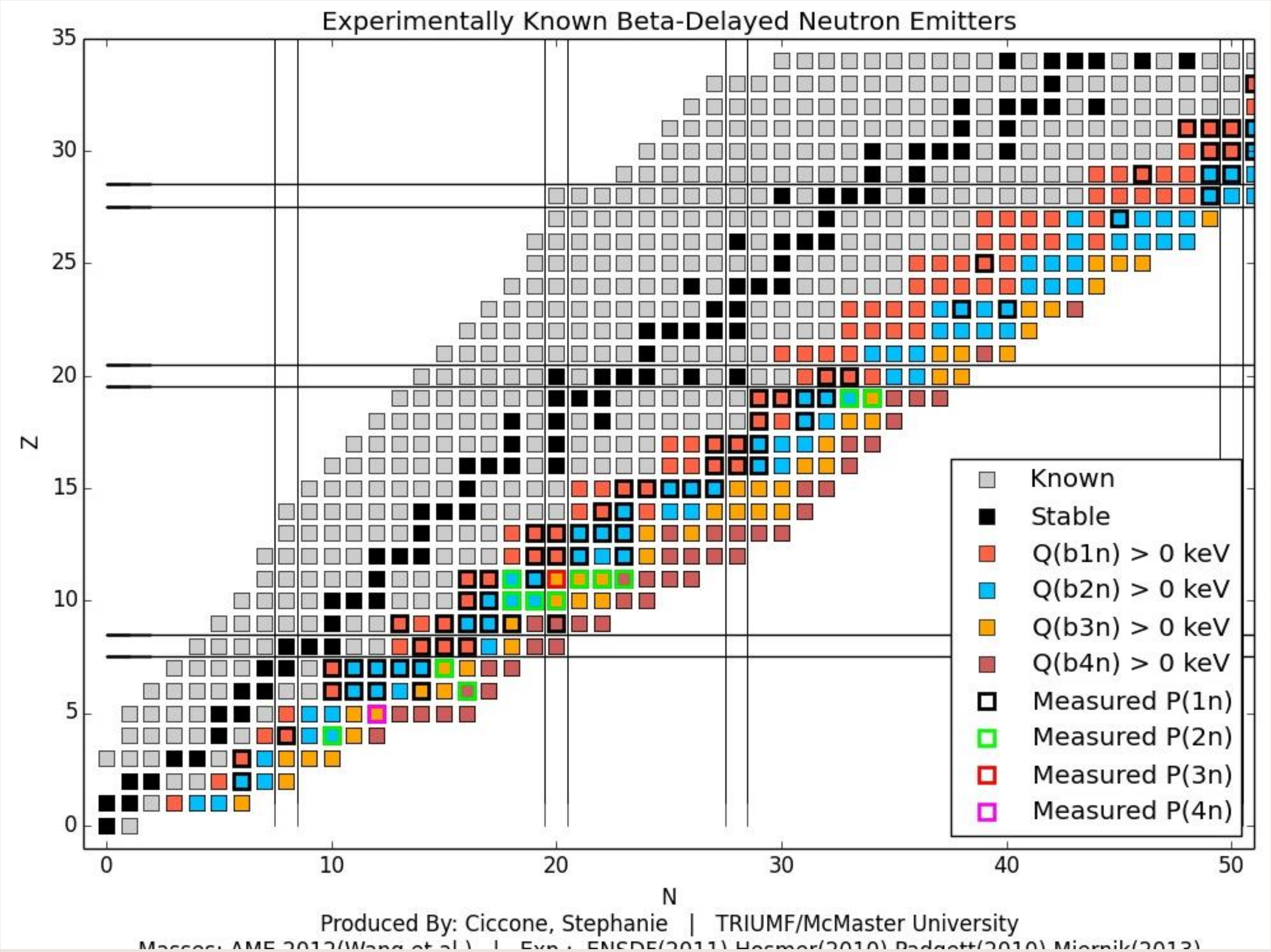


R. Surman, M. Mumpower, in preparation

- Smoothing of abundance curve
- Formation of Rare-Earth peak
- Shift of abundance peaks

Status of βn-emitters

Experimental status (I)



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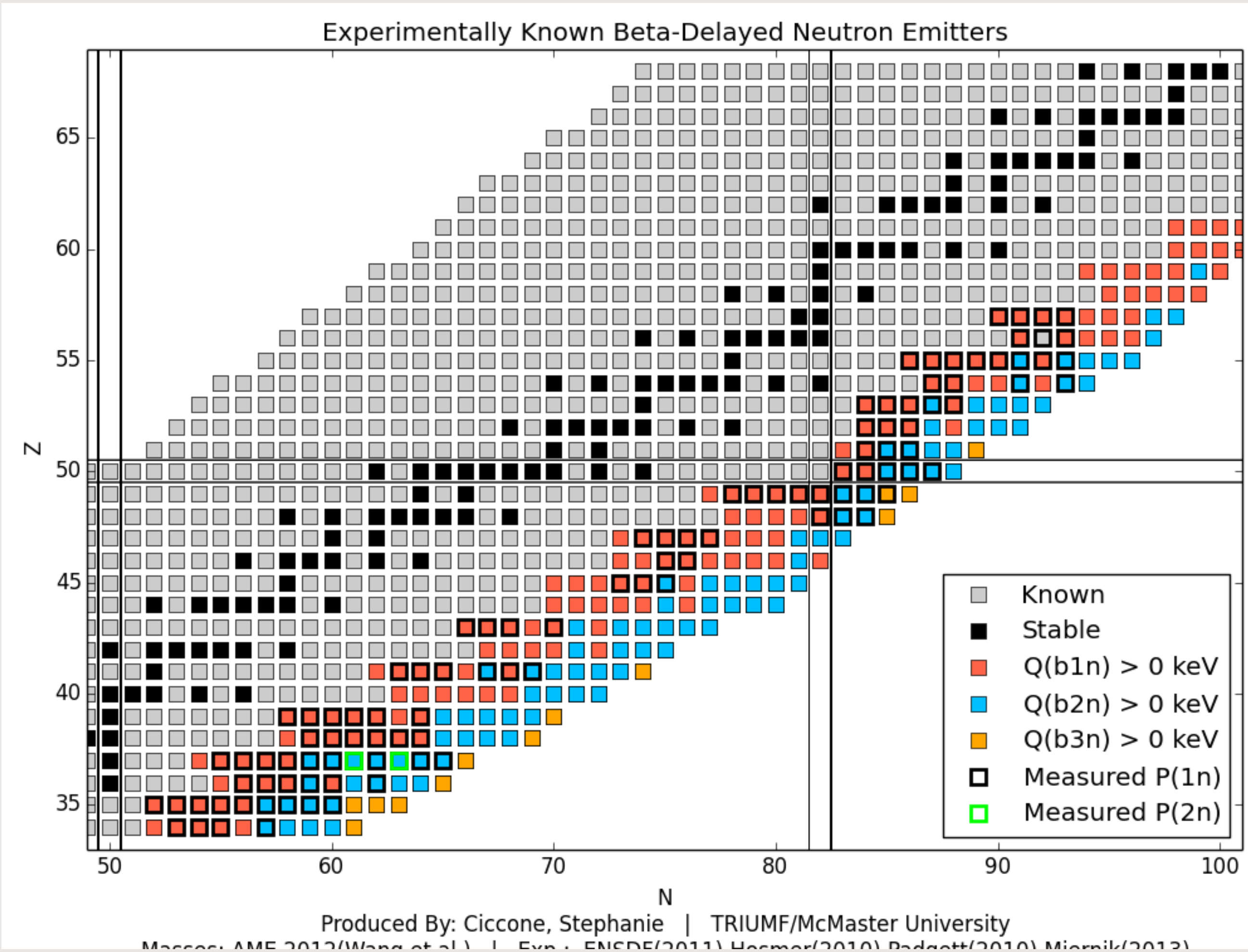
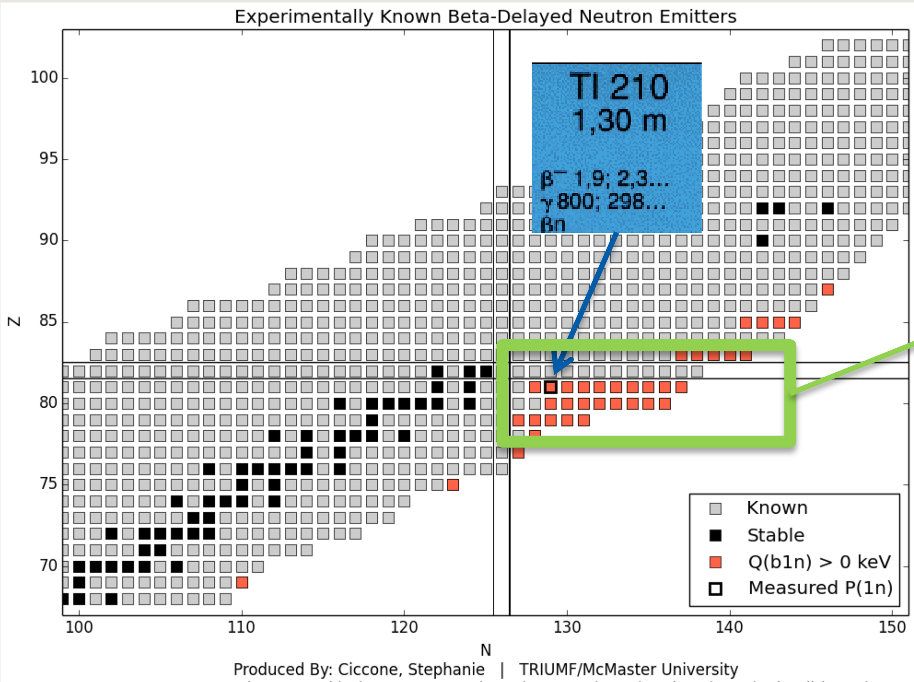
Experimental status (II)



Experimental status (III)

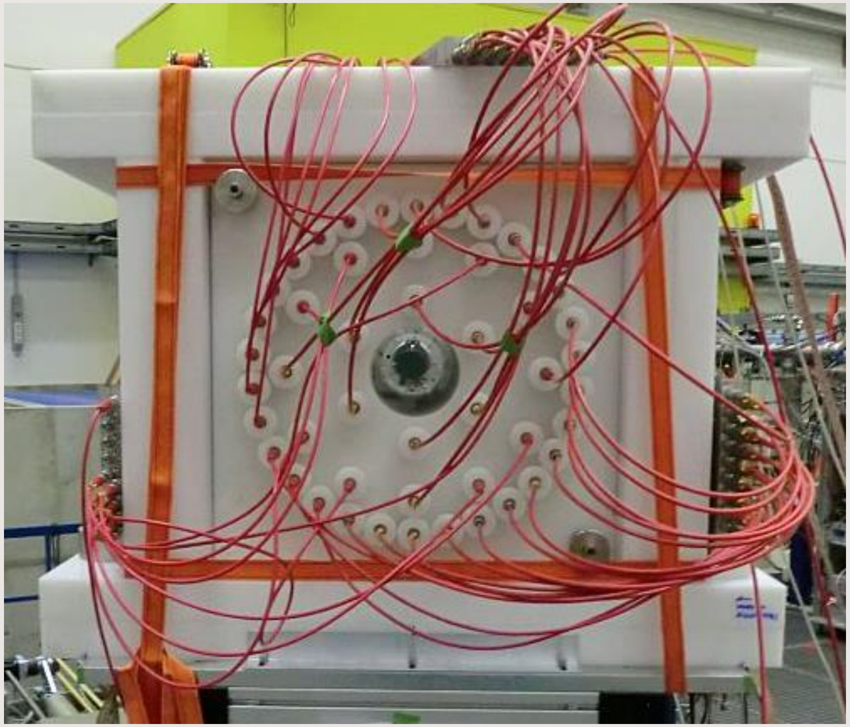


BELEN @ GSI-FRS

	Energetically possible	Measured	Fraction measured (%)	Mass region
β1n	606	227	37.5%	^{8}He-^{150}La (^{210}Tl)
β2n	295	24	8.1%	^{11}Li-^{100}Rb
β3n	104	6	5.8%	^{11}Li, ^{14}Be, ^{17,19}B, ^{23}N, ^{31}Na
β4n	60	1	1.7%	^{17}B

Table 1: Number of energetically possible vs. measured βxn-emitters. ("Energetically possible" means every case where $Q_{\beta xn} > 0$ keV (using masses from the AME2012[10]).

BEta deLayEd Neutron detector (BELEN)

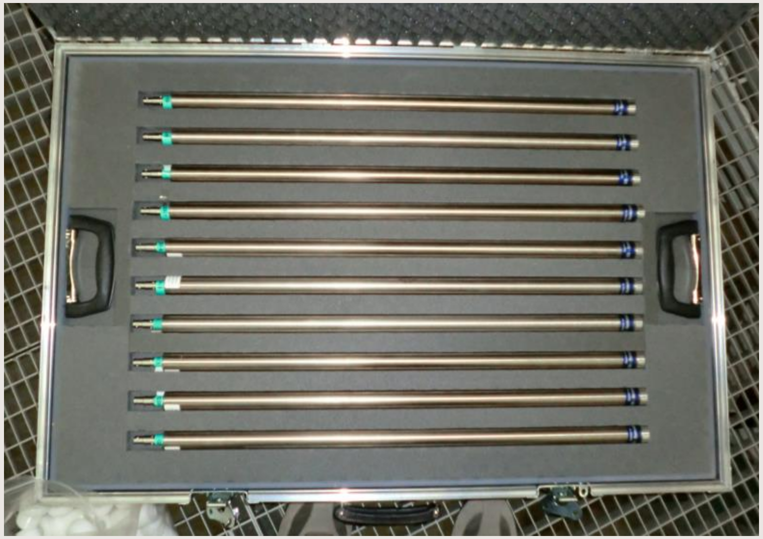


Universidad Politecnica de Cataluna, Barcelona

IFIC Valencia

CIEMAT Madrid

GSI Helmholtz Center Darmstadt



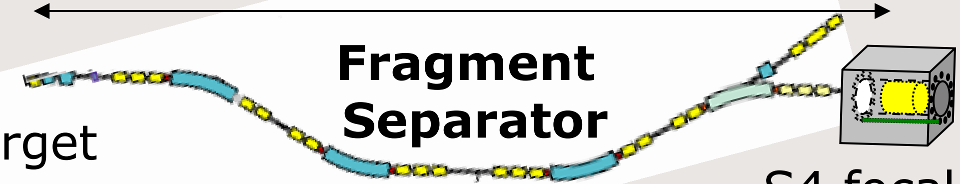
High-pressure ^{3}He long counters in polyethylene moderator:

$^{3}He + n \rightarrow {}^{3}H + p + 765$ keV

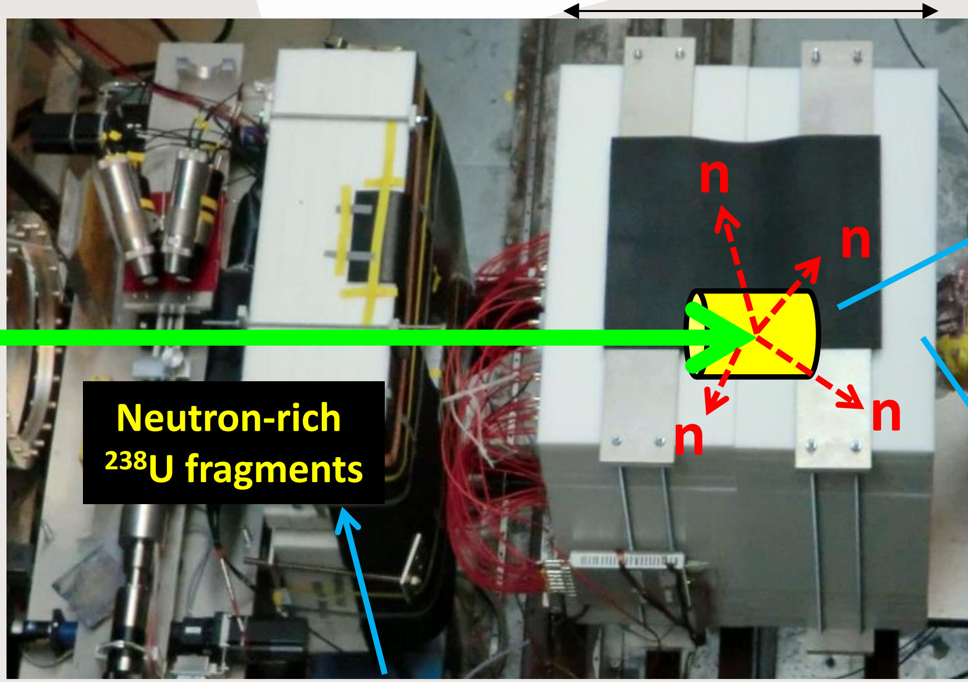
BELEN-30 @ GSI Darmstadt (2011)

1 GeV/ u $^{238}U^{73+}$
10^9 pps
Be target

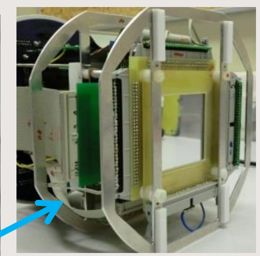
≈ *70 m*



≈ *1 m*

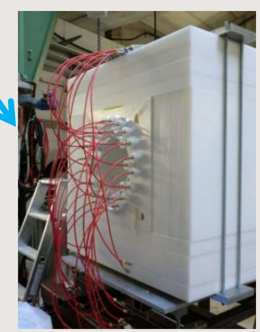


Shielding (PE + borated rubber)



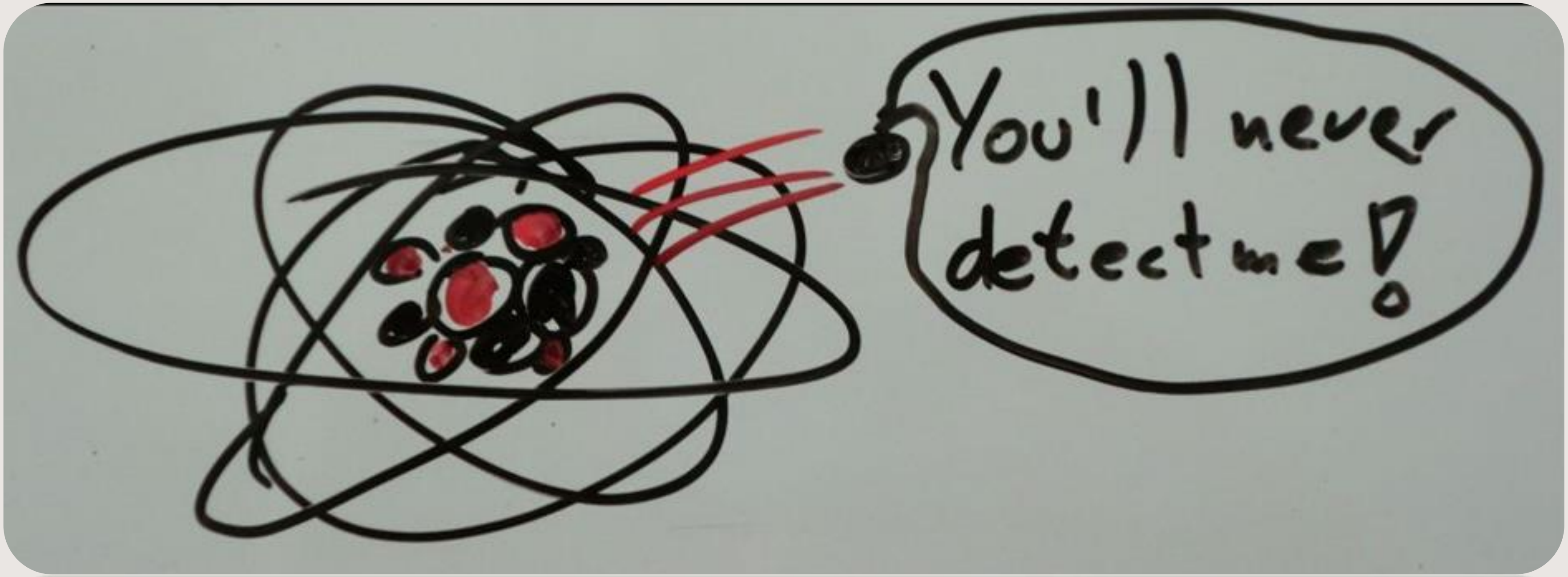
Implantation detector
SIMBA

Lehrstuhl E12
Technische Universität München

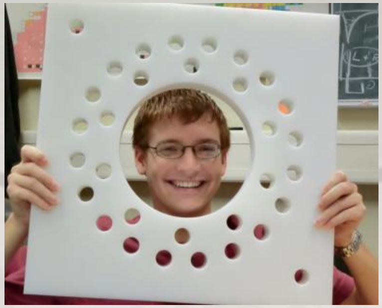


Neutron detector
BELEN-30
(ε_n≈40%)

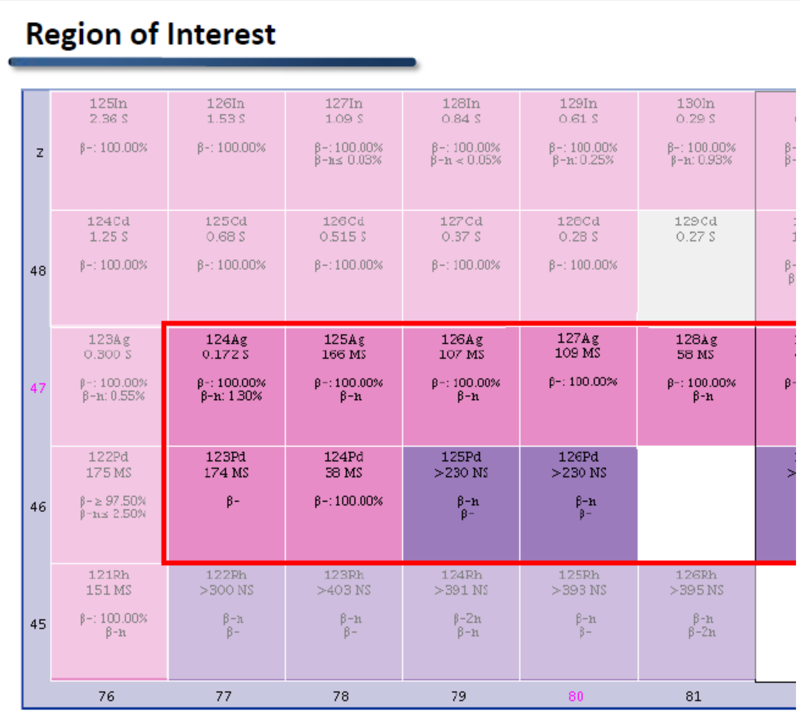
Data



Data analyzed by PhD students
K. Smith (U Notre Dame/ GSI, now at UTK)
R. Caballero Folch (UPC Barcelona, soon at TRIUMF)



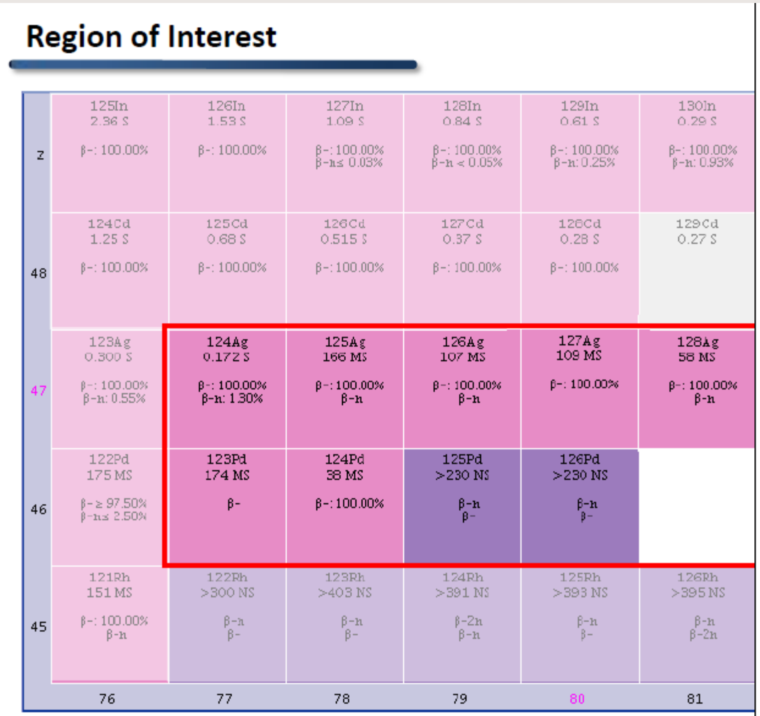
New half-lives "south-west" of ^{132}Sn



- Good agreement with literature values
- New $t_{1/2}$: $^{125-128}$Pd

K. Smith (APS Meeting, Savannah 2014)

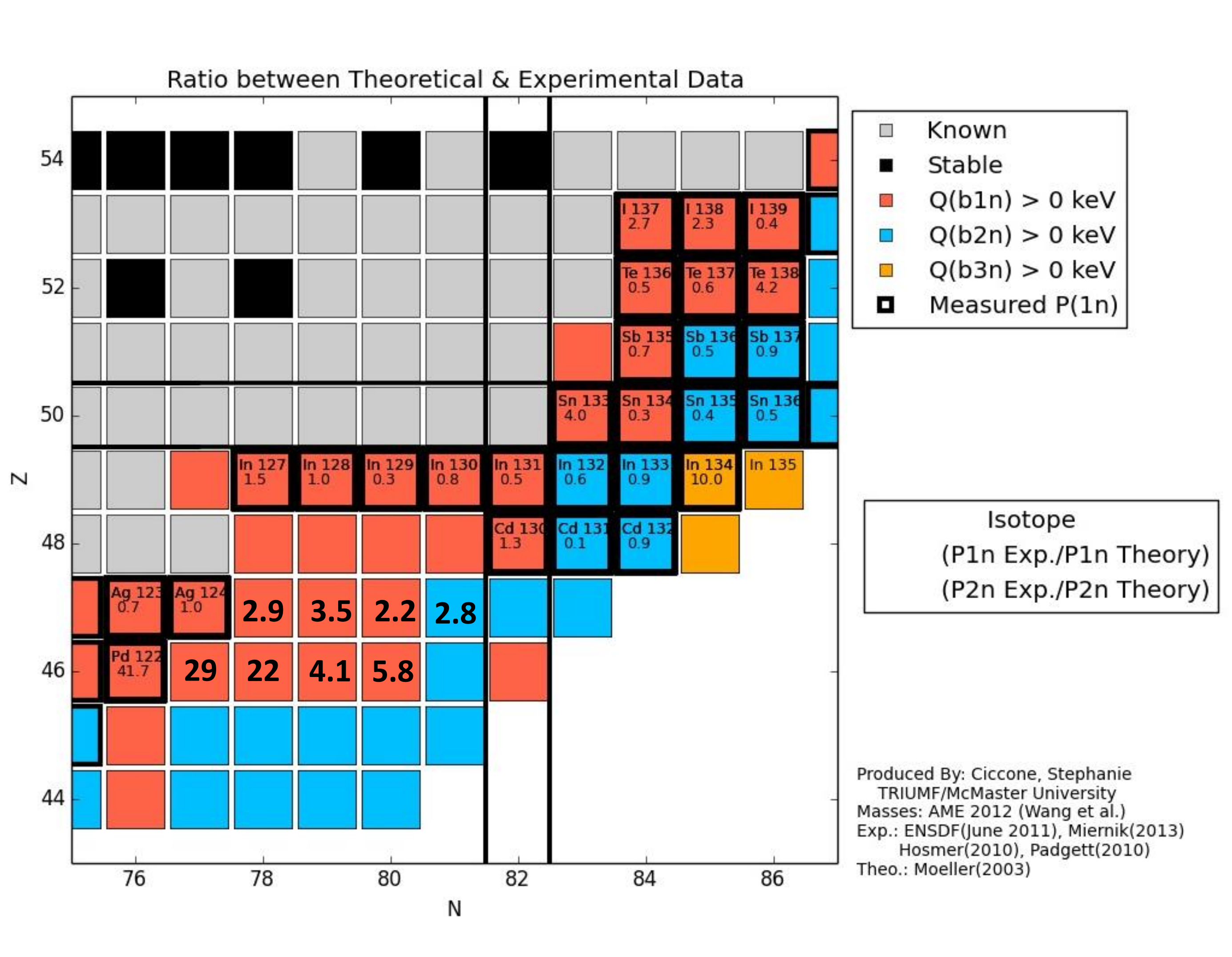
New P_{1n} values "south-west" of ^{132}Sn



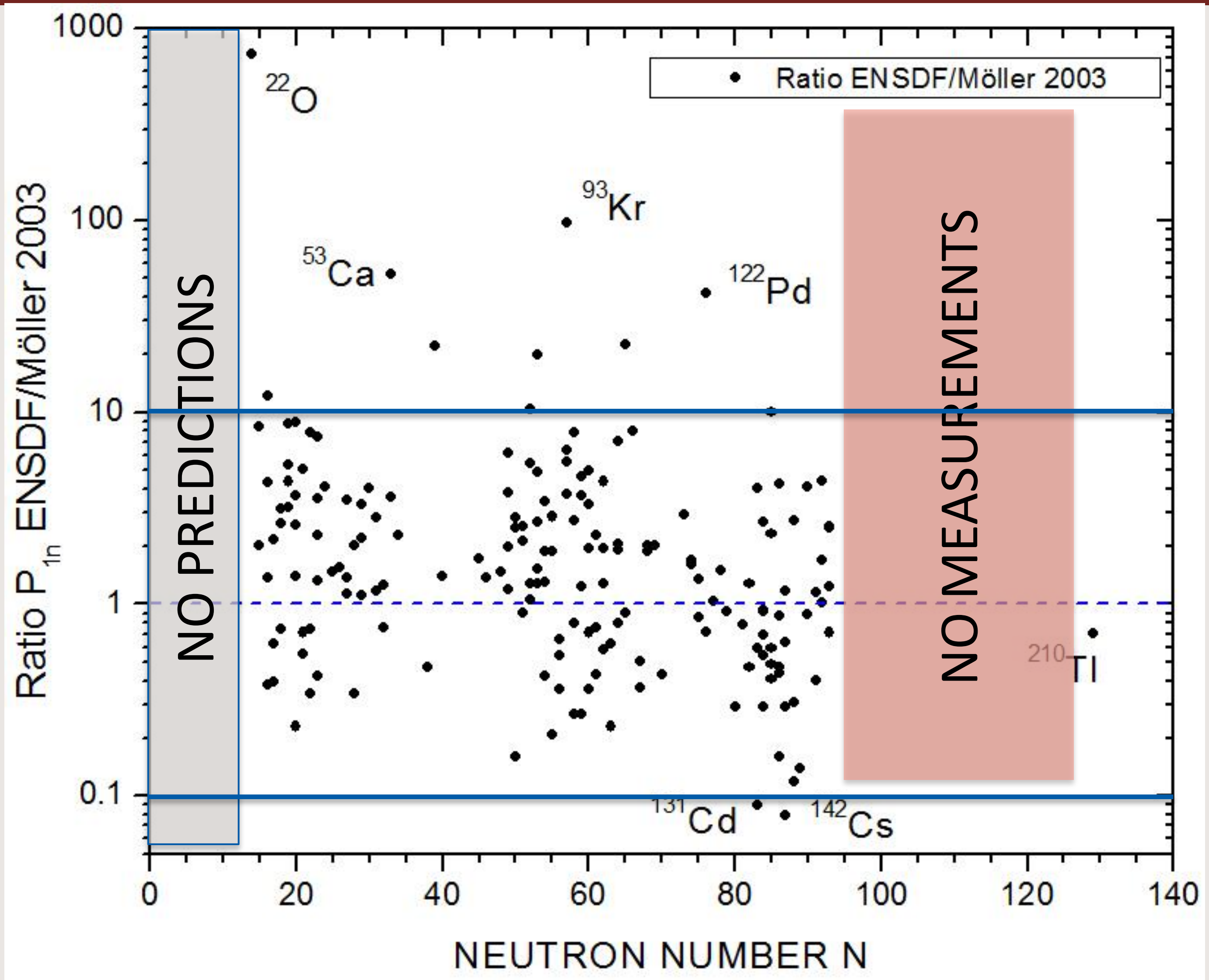
Experimental P_n values **higher** than predictions

K. Smith (APS Meeting, Savannah 2014)

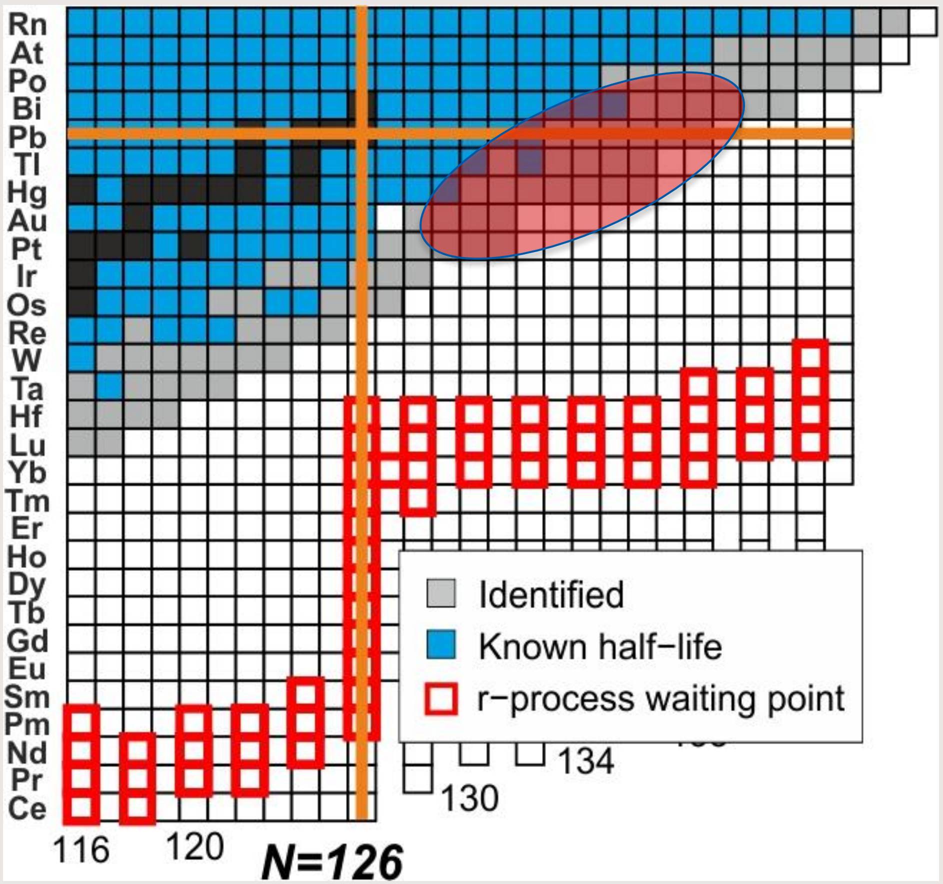
Ratio P_{1n}(exp)/ P_{1n}(theo)

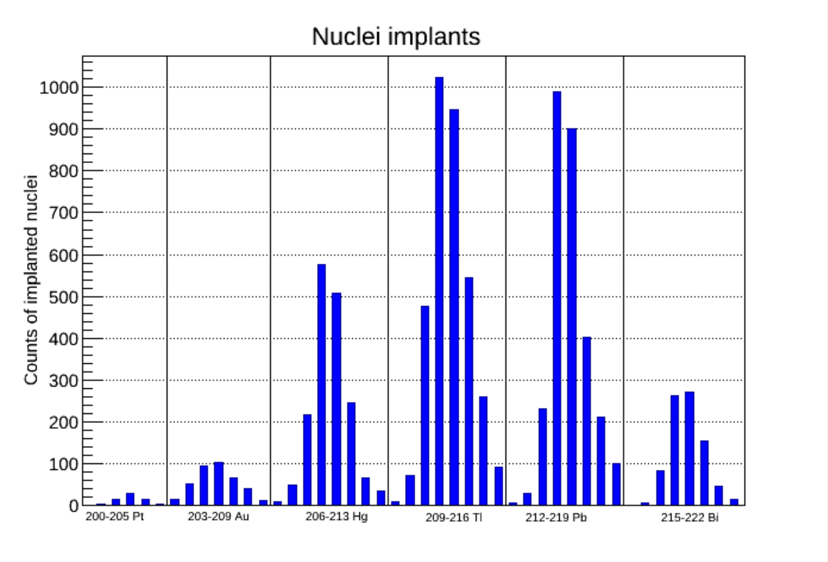


P_{1n} Discrepancy



"South-east" of ^{208}Pb





R. Caballero, NIC-XII proceedings (2012), NIC XII_109

R. Caballero, 3rd North American Workshop on β-delayed neutron emission, July 2014

New $t_{1/2}$ and P_{1n}-values

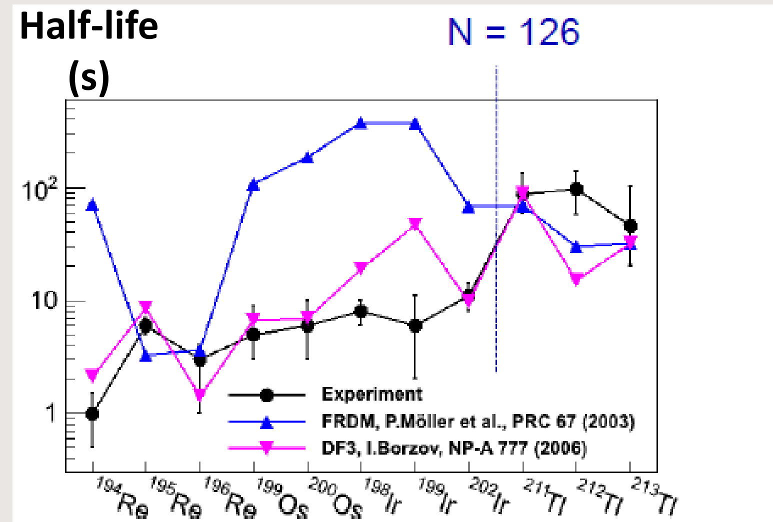
Heaviest βn-emitters measured so far!

- 9 first $t_{1/2}$ measurements
- 10 first P_{1n}-value measurements

Systematic trends in $t_{1/2}$?

Half-lives in comparison to QRPA calc. (e.g. Möller 2003)

- Overestimation for N≤126
- Underestimation for N>126



T. Kurtukian-Nieto et al., arXiv:0711.0101v1
J.Benlliure et al. NPA-V, 2012

G.Benzoni et al., Phys.Lett. B 715 (2012)

Ratio theo/exp

long $t_{1/2}$

Element	Z / N ->	122	123	124	125	126
At	85					
Po	84					
Bi	83					
Pb	82					
Tl	81		0.003		90.295	27.243
Hg	80		0.190		21.726	7.413
Au	79	8.315	56.611	25.350	**6.796**	**6.343**
Pt	78	1.599	3.833	0.055	**56.397**	**31.244**
Ir	77	61.775			**6.218**	
Os	76		21.352	31.180		

Ratio theo/exp

Element	127	128	129	130	131	132	133	134	135	136	137
Bi			1.332	2.665	0.696	2.417	0.737	1.810	**0.077**	**2.654**	**0.517**
Pb	20.076	29.401	4.572	3.064	0.965	5.839	**2.018**	**7.818**	**5.246**	**6.026**	
Tl	0.544	0.704	0.738	**1.027**	**0.937**	**1.472**	**1.311**	**0.518**			
Hg	0.231	**1.352**	**0.960**	**0.676**	**0.622**						
Au	**0.419**										

^{208}Hg

^{213,214}Tl

Outlook

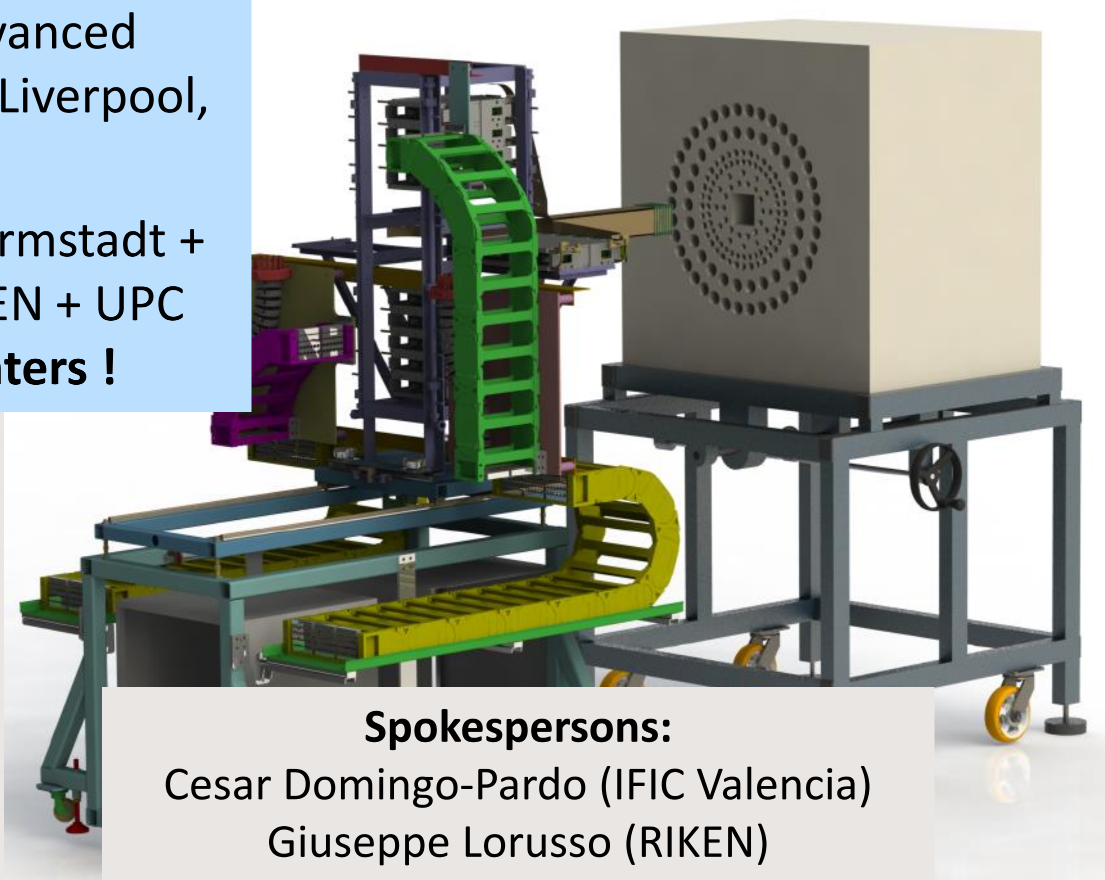
The BRIKEN project (2015/16)

BRIKEN project (2015/16)

"Beta delayed neutron emission measurements at RIKEN"

- Implantation setup: **AIDA** (Advanced Implantation Detector Array): Liverpool, Edinburgh, Daresbury/ UK
- ^{3}He neutron detectors: GSI Darmstadt + JINR Dubna + Oak Ridge + RIKEN + UPC Barcelona **= 182 neutron counters !**

Louisiana State University	USA	B.C. Rasco
Mississippi State University	USA	J.A. Winger
MTA-Atomki	Hungary	Z. Fulop
NSCL-MSU	USA	F. Montes
ORNL	USA	K. Rykaczewski
RIKEN Nishina Center	Japan	G. Lorusso
		S. Nishimura
The University of Tokyo	Japan	K. Matsui
TRIUMF	Canada	I. Dillmann
UPC	Spain	G. Cortés
University of Edinburgh	UK	A. Estrade
University of Guelph	Canada	P. Garrett
University of Liverpool	UK	R. Page
University of Tennessee	USA	R. Grzywacz
University of Warsaw	Poland	A. Korgul



Spokespersons:
Cesar Domingo-Pardo (IFIC Valencia)
Giuseppe Lorusso (RIKEN)

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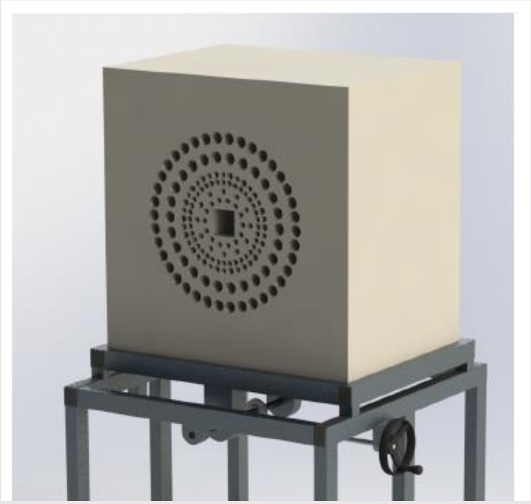
BRIKEN neutron detectors

2 configurations planned:

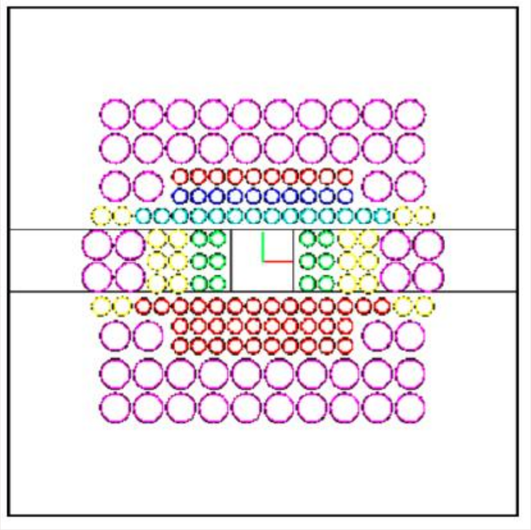
High-efficiency setup (BRIKEN-1)

- $\varepsilon_{\beta n}$~80% (E_n= eV- 5 MeV)
- $\varepsilon_{\beta 2n}$~40% (E_n= eV- 5 MeV)



Hybrid setup (BRIKEN-2)

- incl. 2 HPGe clovers
- ε_n=76-66% (E_n= 0.5- 2.5 MeV)



TRIUMF

Proposed program 2015

Early 2015: Setup phase

2 proposals submitted, **got 6.5 days beamtime** (from 30 days total)

"Measurements of new beta-delayed neutron emission properties around doubly-magic ^{78}Ni"

Spokespersons: Rykaczewski, Tain, Grzywacz, Dillmann

Request: 7 days beamtime

^{76}Co- ^{92}Se (ca. 30 isotopes)

"Measurement of beta-delayed neutron emission probabilities relevant to the A = 130 r-process abundance peak"

Spokespersons: Estrade, Lorusso, Montes

Request: 10 days beamtime

^{121}Rh-^{152}Ba (33 isotopes)

Summary

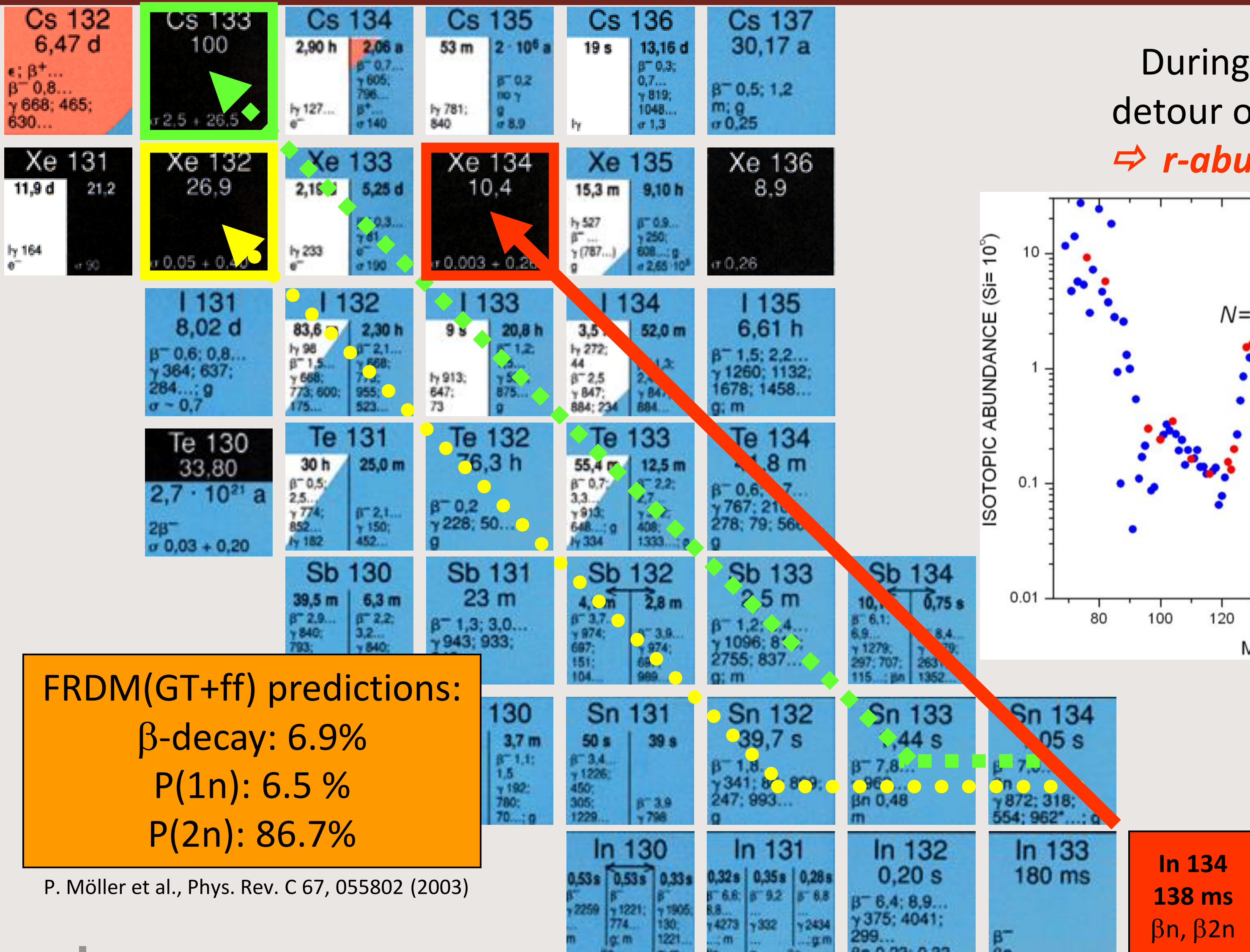
- Renewed strong interest in βn-programs at all RIB facilities
- Going more neutron-rich: βxn-emission will be the dominant process

- BELEN measurements @ GSI Darmstadt:
  - $t_{1/2}$ for 13 isotopes measured for the first time
  - P_{1n} for 20 isotopes measured for the first time
  Heaviest bn-emitters detectec so far!
- BRIKEN neutron detector @ RIKEN: one proposal accepted, setup will start early 2015; high impact of research expected!

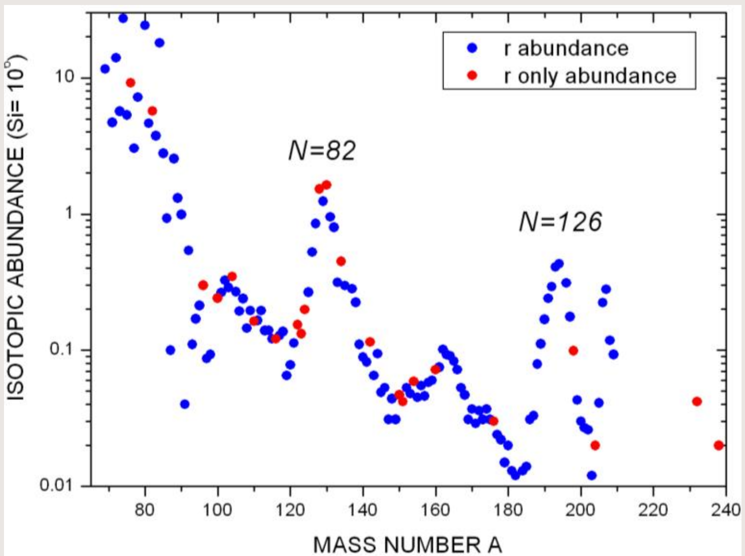
Thank you!
Merci !

TRIUMF: Alberta | British Columbia | Calgary Carleton | Guelph | Manitoba | McMaster Montréal | Northern British Columbia | Queen's Regina | Saint Mary's | Simon Fraser | Toronto Victoria | Winnipeg | York

Astrophysical influence



During „Freeze-out“:
detour of β-decay chains
➩ ***r-abundance changes***



FRDM(GT+ff) predictions:
β-decay: 6.9%
P(1n): 6.5 %
P(2n): 86.7%

P. Möller et al., Phys. Rev. C 67, 055802 (2003)

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New P_{1n} standards

Proposed new standards

The following β-delayed neutron precursors were selected as "standards" for the purpose of data evaluation and measurements:

	New [3,4]	Pfeiffer 2002 [2]
^{9}Li:	P_n= 50.61 (57) %	---
^{16}C:	P_n= 99.27(12) %	---
^{17}N:	P_n= 95.1 (7) %	---
^{87}Br:	P_n= 2.43 (14) %	P_n= 2.52 (7) %
^{88}Br:	P_n= 6.75 (18) %	P_n= 6.55 (18) %
^{94}Rb:	P_n= 10.24 (21) %	P_n= 9.1 (11) %
^{95}Rb:	P_n= 8.87 (29) %	P_n= 8.73 (31)
^{137}I:	P_n= 7.33 (38) %	P_n= 7.02 (54)

- Should be measured with independent methods and agree
- Standard for every mass region:
  Missing: A>150 and A~60

www-nds.iaea.org/publications/indc/indc-nds-0599.pdf