Beta-delayed neutron measurements with the BELEN detector

Iris Dillmann
Helmholtz Young Investigators Group LISA

Universität Giessen and GSI Helmholtzzentrum Darmstadt/ Germany

HELMHOLTZ ASSOCIATION

Overview

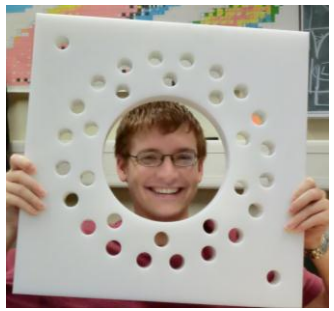
- Who?
- What?
- Why?
- Where and how?
- Which?
- What else and when?

Who? (The collaboration)

Jorge Agramunt[1], Alejandro Algora[1], Frederic Ameil[2], Yassid Ayyad[3], Jose Benlliure[3], Michael Bowry[4], Roger Caballero-Folch[5], Francisco Calviño[5], Daniel Cano-Ott[6], Tom Davinson[7], Iris Dillmann[8,2], Cesar Domingo-Pardo[1], Alfredo Estrade[2], Alexey Evdokimov[8,2], Thomas Faestermann[9], Fabio Farinon[2], Daniel Galaviz-Redondo[10], Aczel García-Rios[6], Hans Geissel[2], William Gelletly[4], Roman Gernhäuser[9], M. Belén Gómez-Hornillos[5], Carlos Guerrero[11], Michael Heil[2], Christoph Hinke[9], Ronja Knöbel[2], Ivan Kojouharov[2], Jan Kurcewicz[2], Nikolaus Kurz[2], Yuri Litvinov[2], Giuseppe Lorusso[12], Ludwig Maier[9], Justyna Marganiec[2], Michele Marta[2,8], Trino Martinez[6], Fernando Montes[13], Ivan Mukha[2], Daniel R. Napoli[14], Chiara Nociforo[2], Robert D. Page[15], Carlos Paradela[3], Anuj Parikh[9], Georgios Perdikakis[13], Stephane Pietri[2], Andrej Prochazka[2], Simon Rice[4], Berta Rubio[1], Henning Schaffner[2], Hendrik Schatz[13], Christoph Scheidenberger[2], Karl Smith[16,17], Eugeny Sokol[18], Konrad Steiger[10], Baohua Sun[2], Jose Luis Taín[1], Maya Takechi[2], Dmitry Testov[19,18], Helmut Weick[2], Emma Wilson[4], John Winfield[2], Rachel Wood[4], Phil Woods[7]

[1] Instituto de Fisica Corpuscolar, Valencia, Spain
[2] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[3] Universidad de Santiago de Compostela, Spain
[4] Department of Physics, University of Surrey, Guildford GU27XH, UK
[5] Universitat Politecnica de Catalunya, Barcelona, Spain
[6] CIEMAT, Madrid, Spain
[7] School of Physics and Astronomy, University of Edinburgh, UK
[8] II. Physikalisches Institut, Justus-Liebig Universität Giessen, Germany
[9] Department of Physics E12, Technische Universität München, Germany
[10] CFNUL, Centro de Fisica Nuclear da Universidade de Lisboa, Portugal
[11] CERN
[12] RIKEN Nishina Center, Wako, Saitama 351-0198, Japan
[13] National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan, USA
[14] Laboratory Nazionali di Legnaro, INFN, Italy
[15] Department of Physics, University of Liverpool, UK
[16] Department of Physics, University of Notre Dame, South Bend, Indiana, USA
[17] Joint Institute for Nuclear Astrophysics, University of Notre Dame, South Bend, Indiana, USA
[18] Flerov Laboratory, Joint Institute for Nuclear Research, Dubna, Russia
[19] IPN Orsay, France



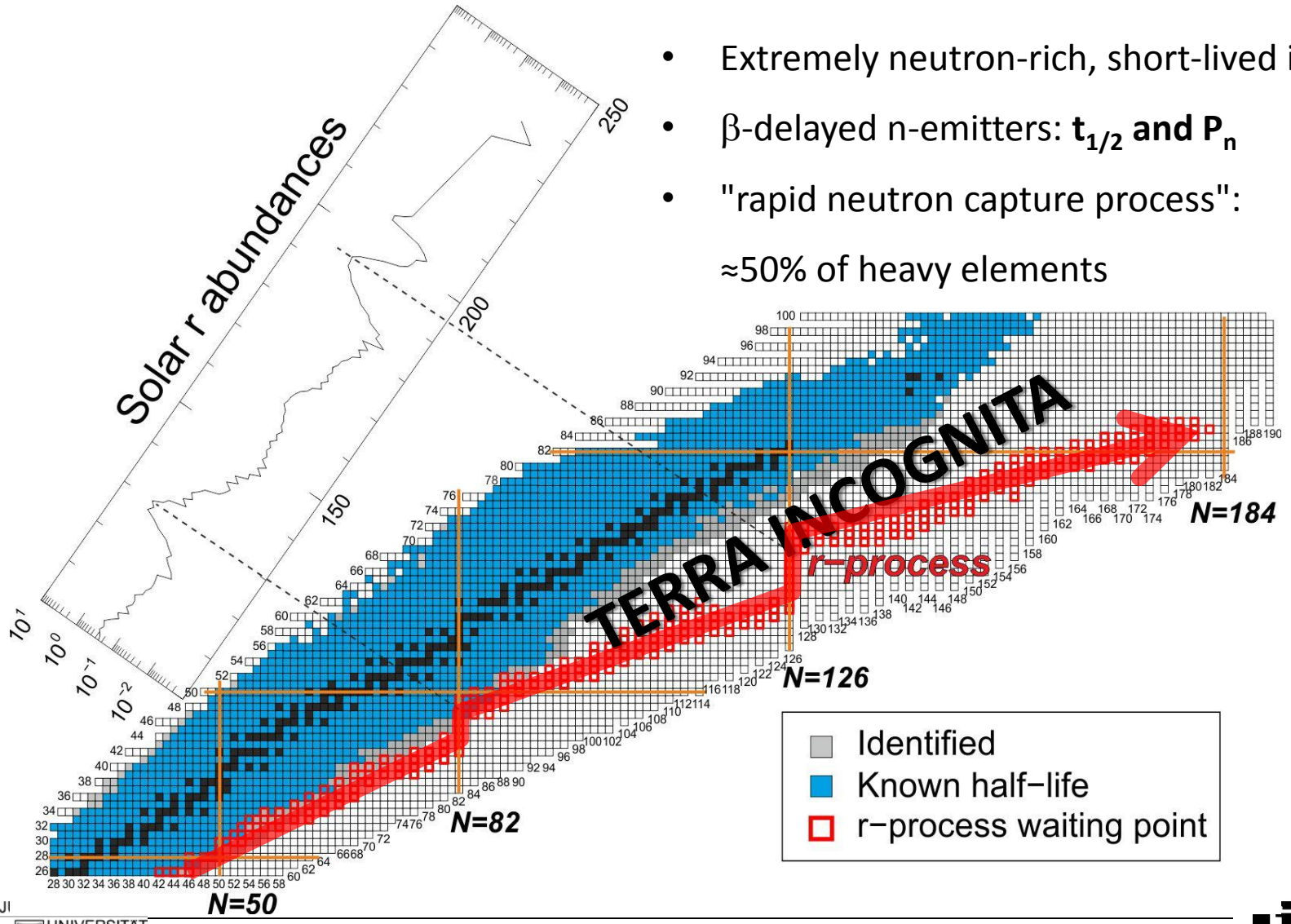


S323/S410 Collaboration

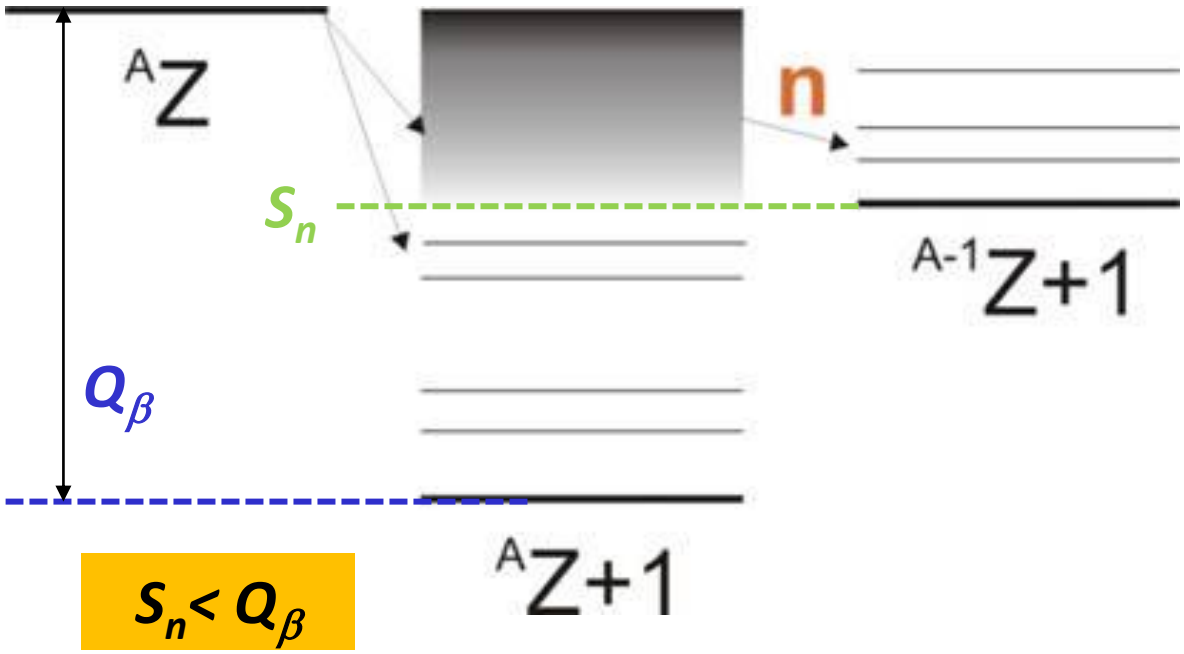
What?

- Extremely neutron-rich, short-lived isotopes
- β-delayed n-emitters: $t_{1/2}$ **and** P_n
- "rapid neutron capture process":

  ≈50% of heavy elements



β-delayed neutron emission



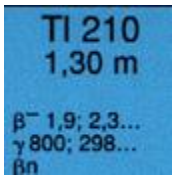
- Discovered in 1939
- "Delayed": emission with β-decay half-life of the precursor ^{A}Z
- $t_{1/2}$≈ few ms – 55.65 s (^{87}Br)
- ^{8}He- ^{150}La: ≈200 datasets available, ≈ 75 in non-fission region (A<70)

- Important nuclear structure information:

  Time-dependence of n-emission ⇨ $t_{1/2}(^{A}Z)$

  P_n : β-strength above S_n

Only 1 measurement for A>150:



P_n= 0.007 (+0.007 -0.004) %

Validation missing

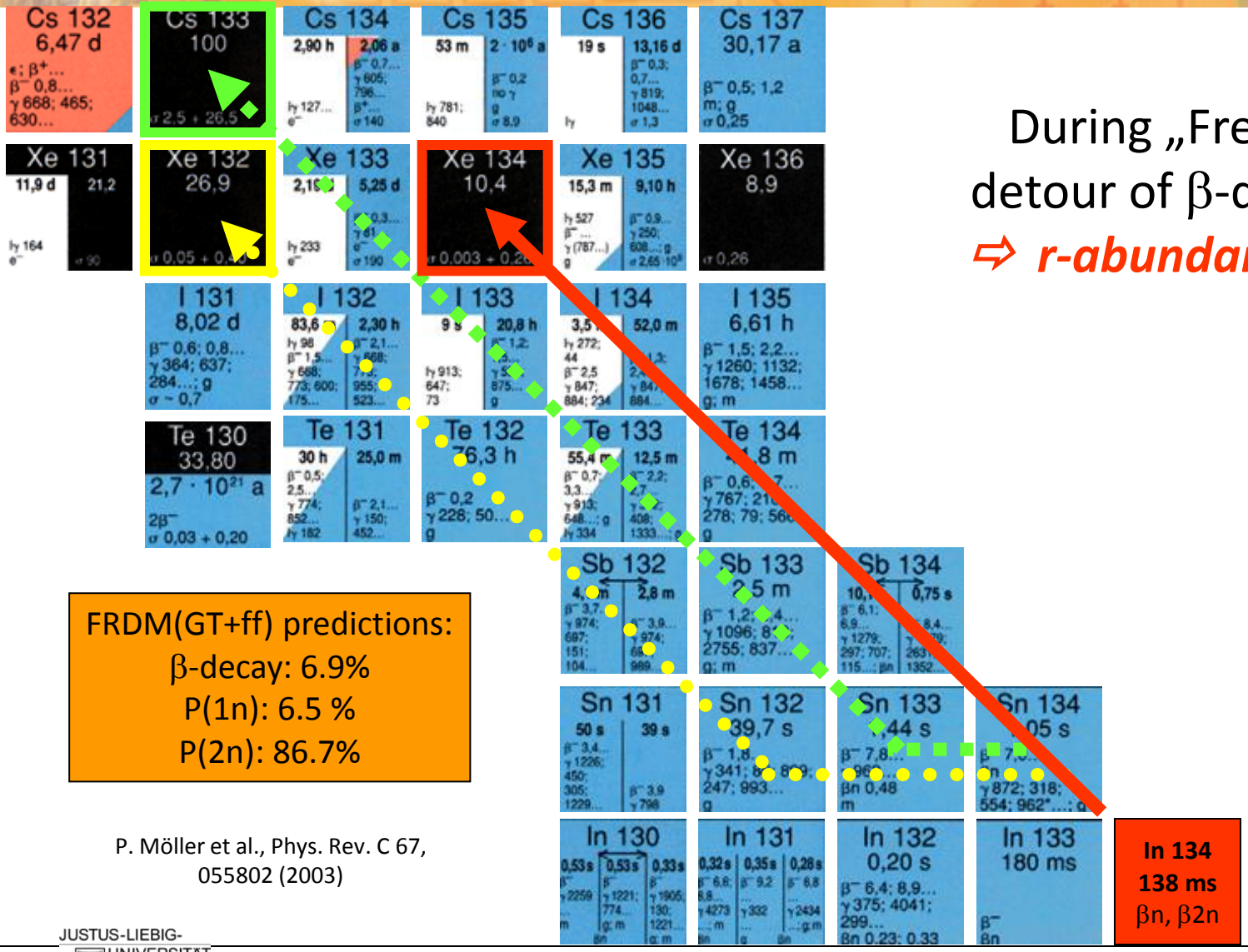
G. Stetter, Nucl. Sci. Abstr. 16, 1409, Abstr. 10963 (1962)

Why?

Nuclear physics input for network calculations:
Theory + few experimental information

- **$t_{1/2}(\beta)$** (s- ms): **Shape**
- Masses ($S_n \approx 2$-3 MeV): **Path**
- **β-delayed neutron emission (P_n): Extra-neutrons, detour of path**
- $(n,\gamma)/(\gamma,n)$ cross sections
- Z>80: fission barriers, β-delayed fission, (n,f)-cross sections
- $t_{1/2}(\alpha)$ for A>210

Astrophysical influence



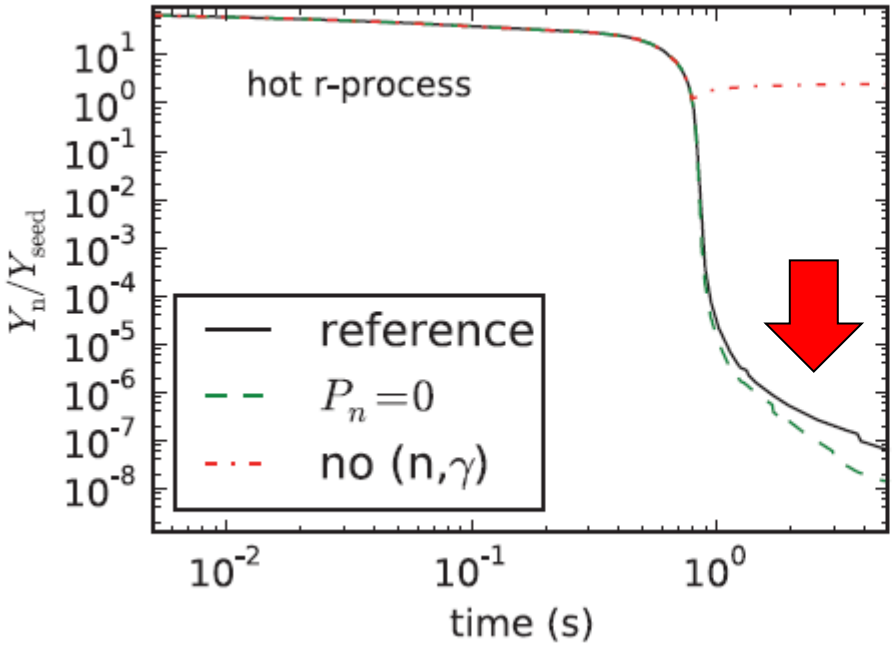
During „Freeze-out“:
detour of β-decay chains
⇨ ***r-abundance changes***

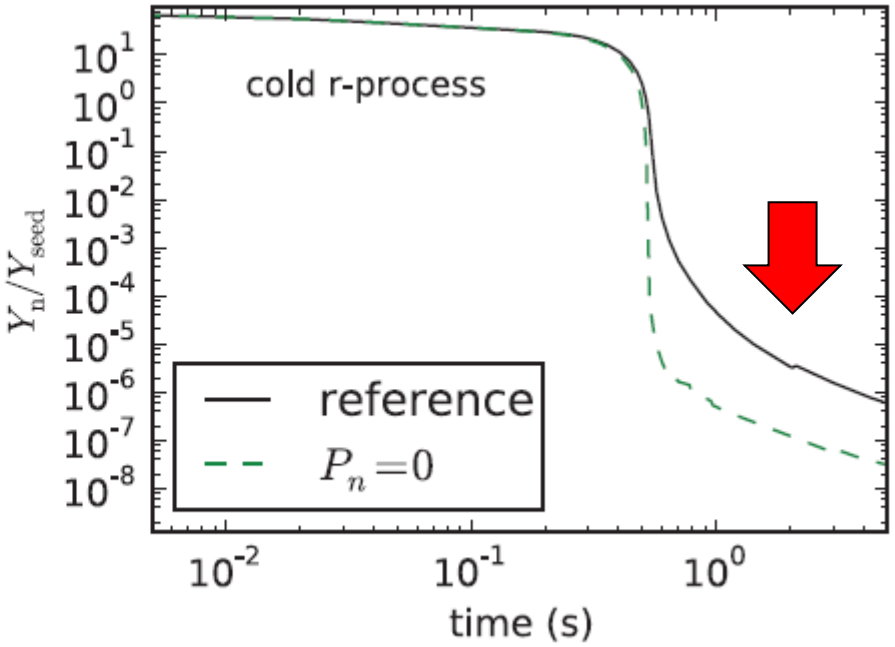
FRDM(GT+ff) predictions:
β-decay: 6.9%
P(1n): 6.5 %
P(2n): 86.7%

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

Late-time influence

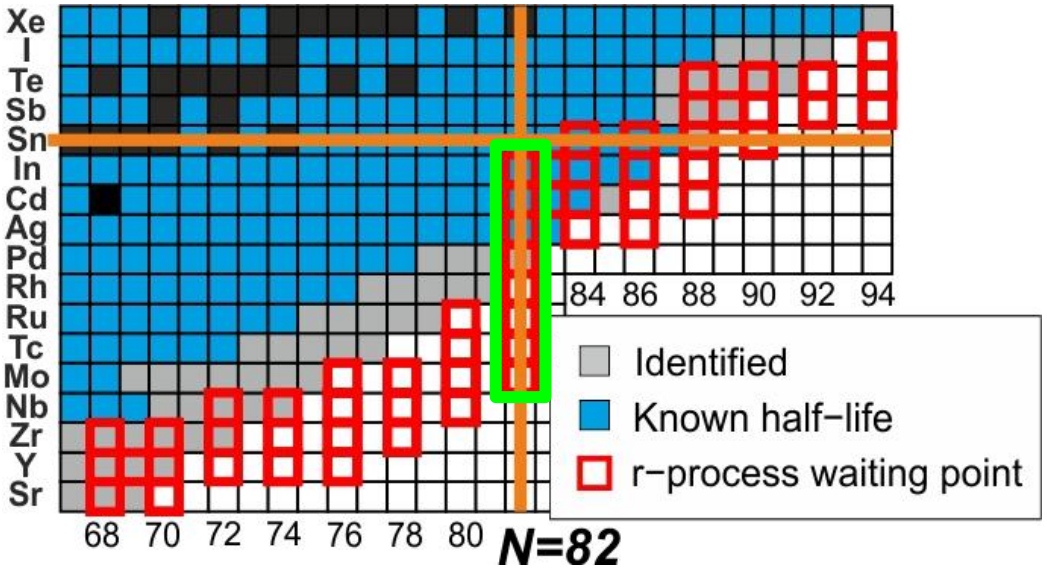
- Production of additional neutrons, influence on n/seed ratio at later times

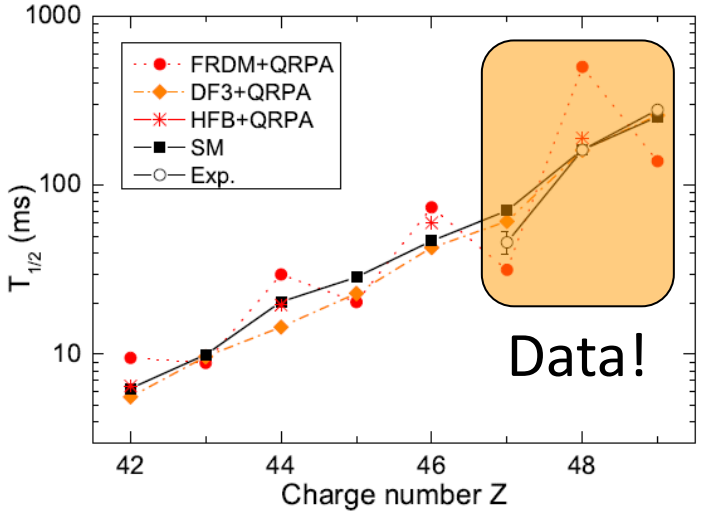


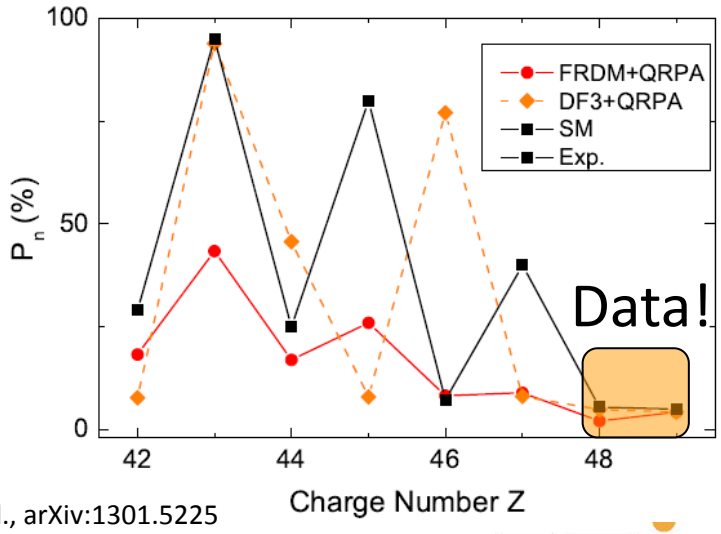


A. Arcones and G. Martinez-Pinedo, PRC83, 045809 (2011)

N=82



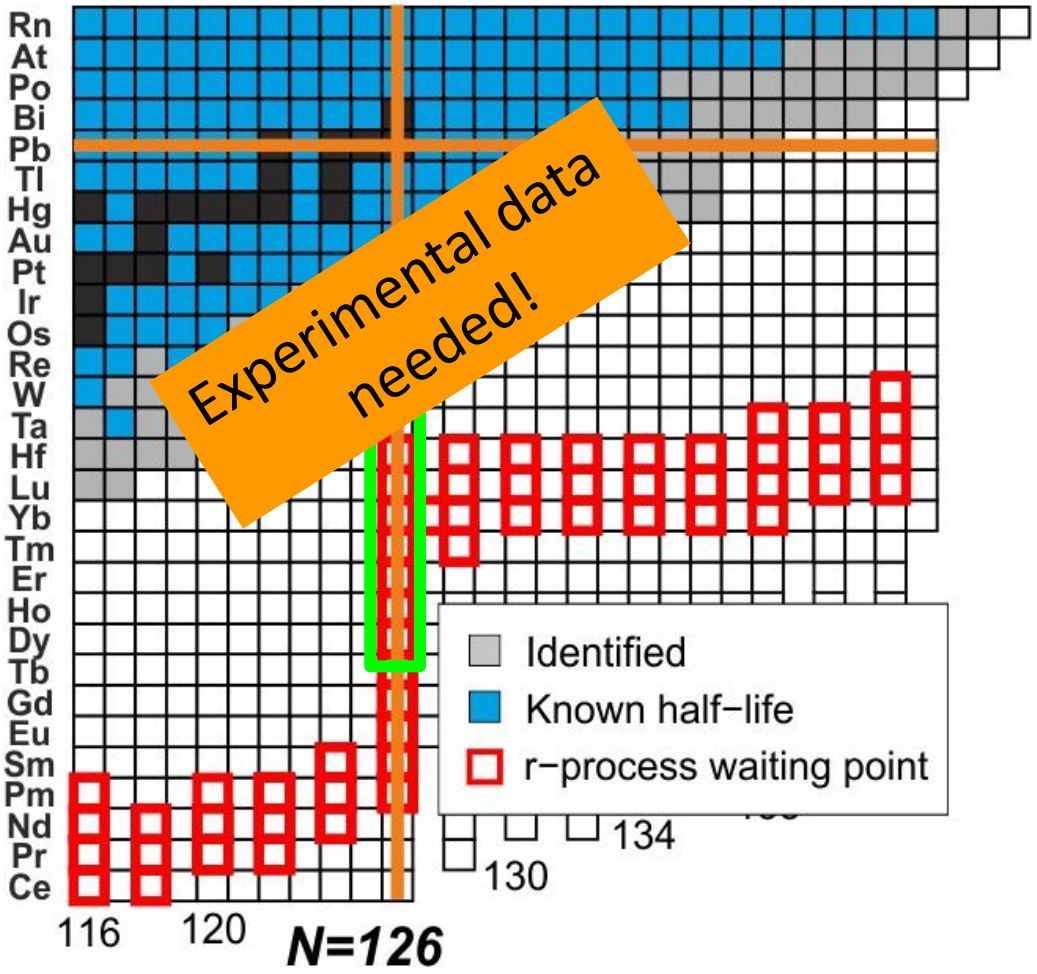


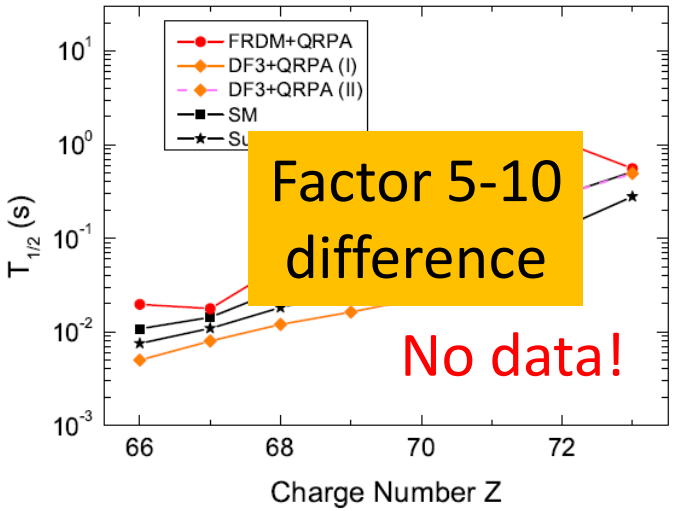


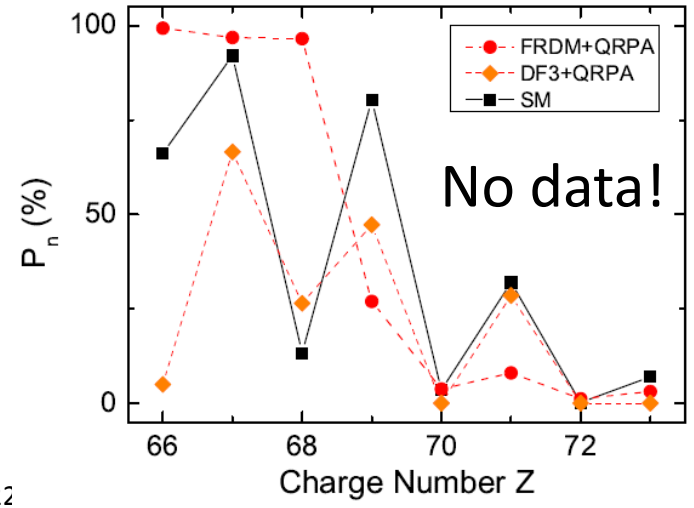
- Existing data contrains models (strong even-odd staggering?)
- Next N=82 isotope in reach: ^{128}Pd
- P_n value of ^{129}Ag?

Q. Zhi et al., arXiv:1301.5225

N=126





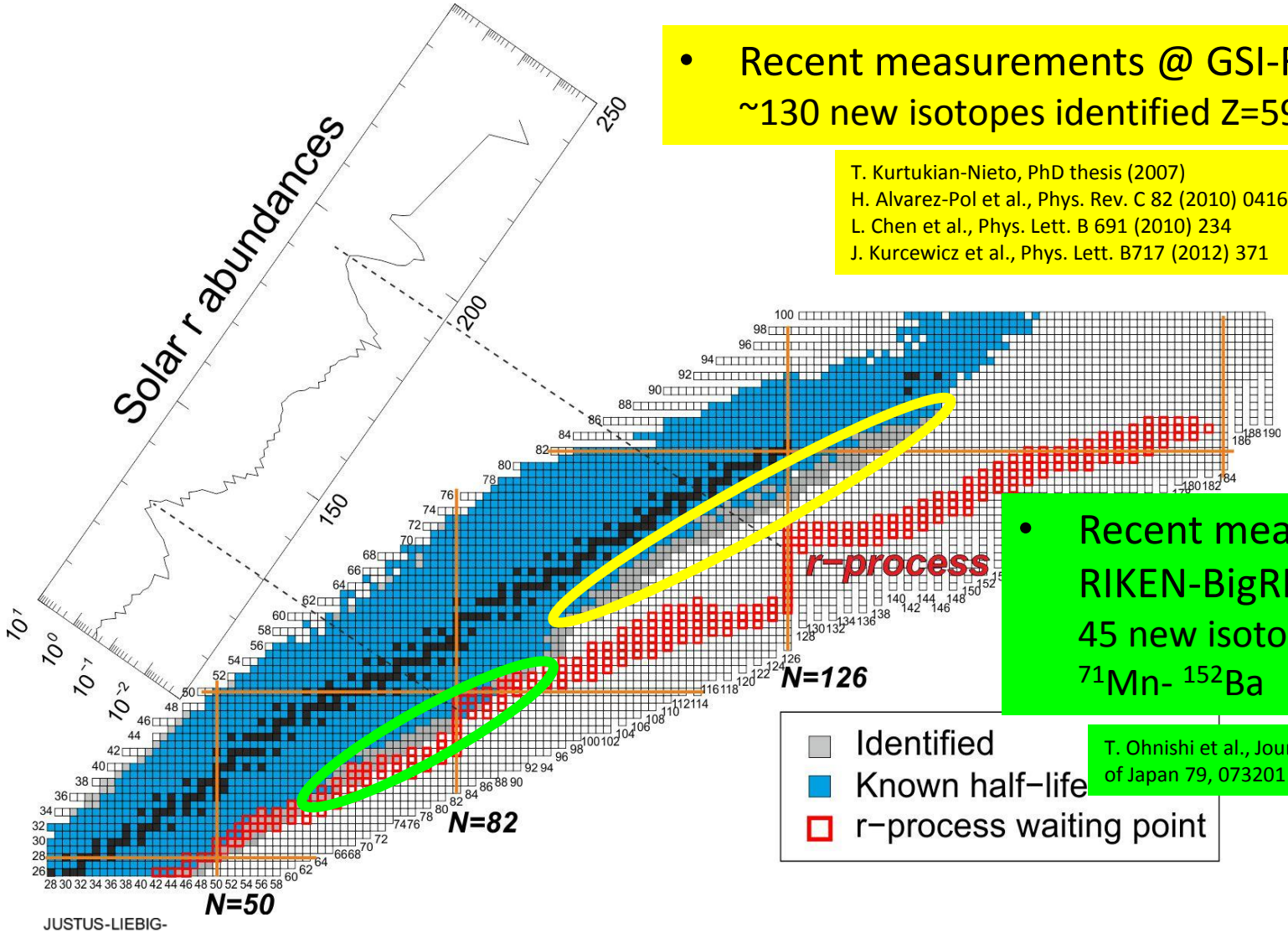


Q. Zhi et al., arXiv:1301.522

Recent progress on the n-rich side

- Recent measurements @ GSI-FRS:
  ~130 new isotopes identified Z=59-87 (Pr-Fr)

T. Kurtukian-Nieto, PhD thesis (2007)
H. Alvarez-Pol et al., Phys. Rev. C 82 (2010) 041602 (R)
L. Chen et al., Phys. Lett. B 691 (2010) 234
J. Kurcewicz et al., Phys. Lett. B717 (2012) 371



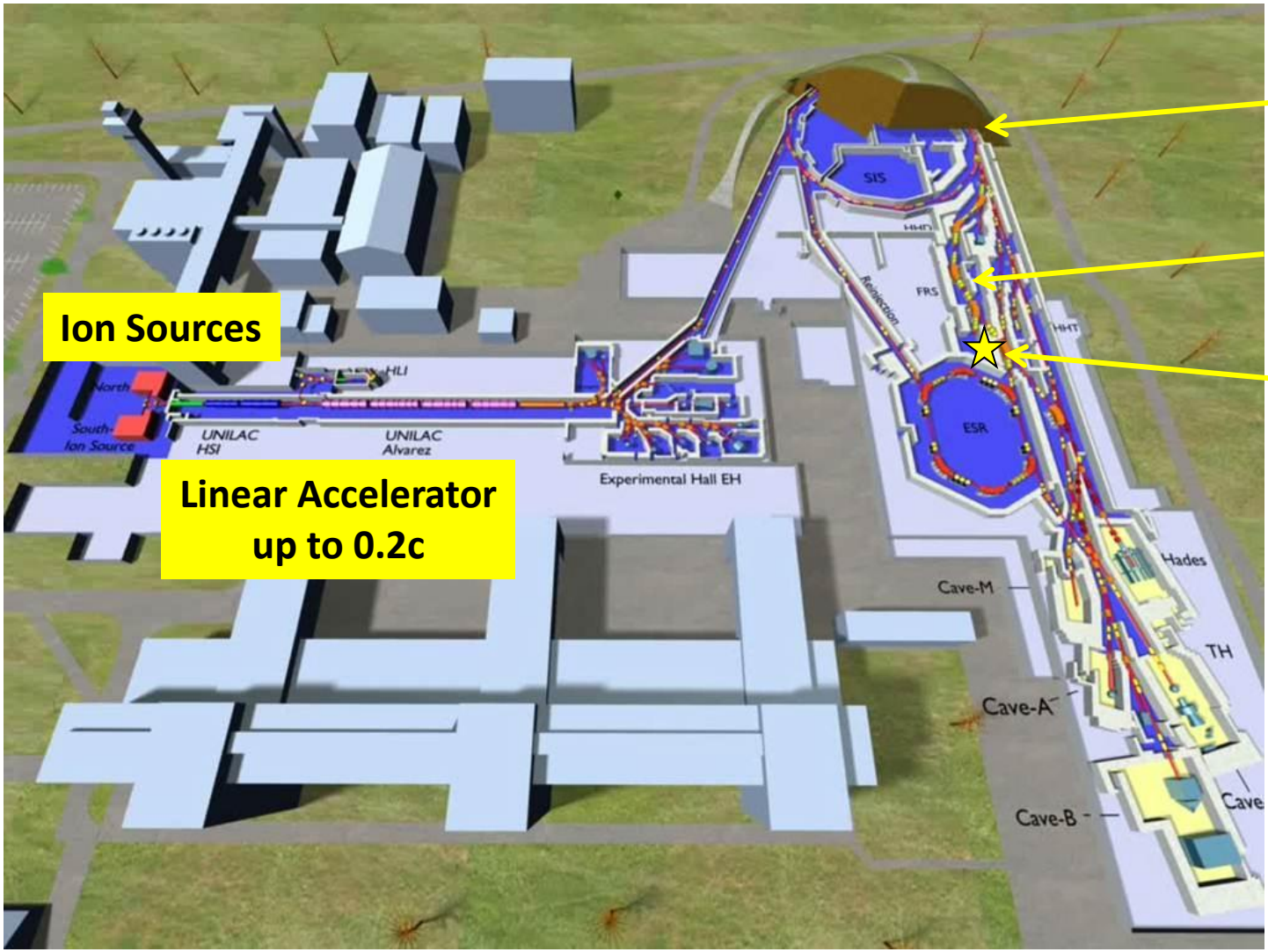
- Recent measurements @ RIKEN-BigRIPS:
  45 new isotopes identified:
  ^{71}Mn- ^{152}Ba

T. Ohnishi et al., Journal of the Physical Society of Japan 79, 073201 (2010)

Where and how?

Experimental campaign @ GSI Darmstadt 2011

GSI Helmholtzzentrum für Schwerionenforschung Darmstadt/Germany



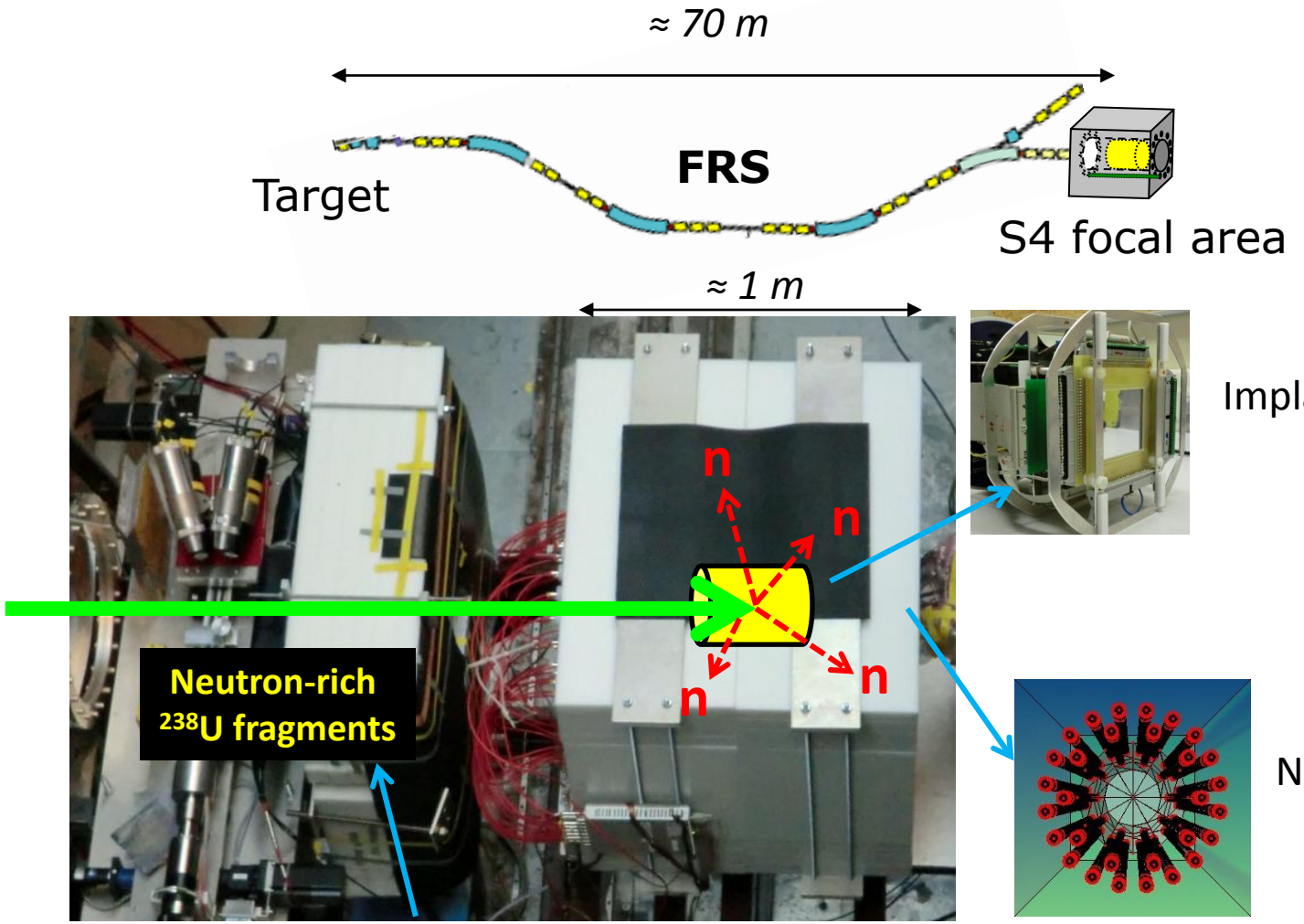
SchwerIonen Synchrotron (up to 0.9c)

FRagment Separator

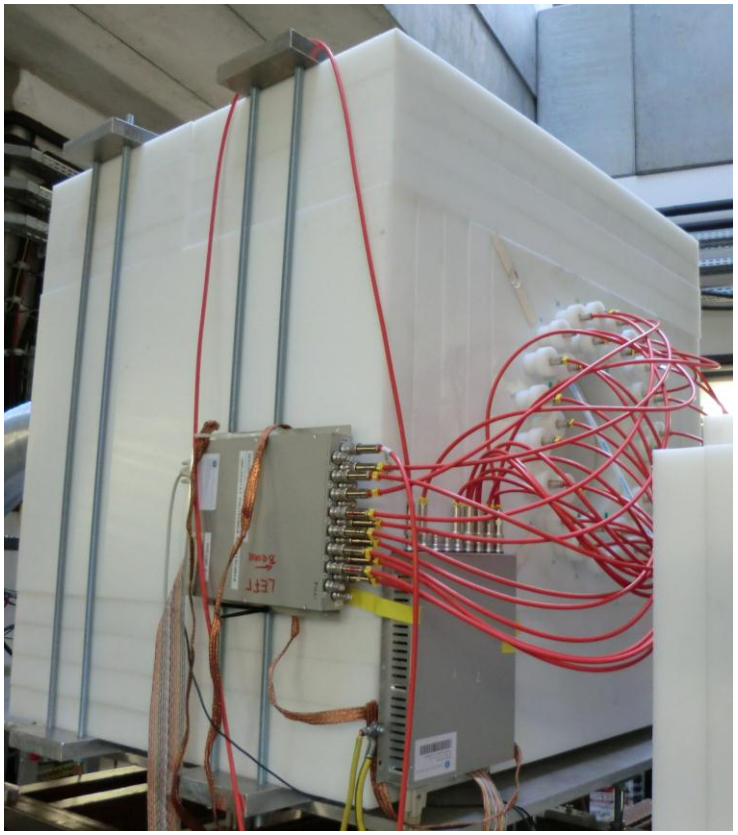
Experimental Area

1 GeV/u $^{238}U^{73+}$
10^9 ions/spill
on 1-3 g/cm² Be

Setup


≈ 70 m
Target
FRS
S4 focal area
≈ 1 m
n
n
n
n
Neutron-rich
238U fragments
Shielding (PE + borated rubber)
Implantation detector
SIMBA
Neutron detector
BELEN-30

BEta deLayEd Neutron detector (BELEN-30)



30 high pressure ^{3}He long counters
PE matrix, size ≈1m^3

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

GSI

UPC

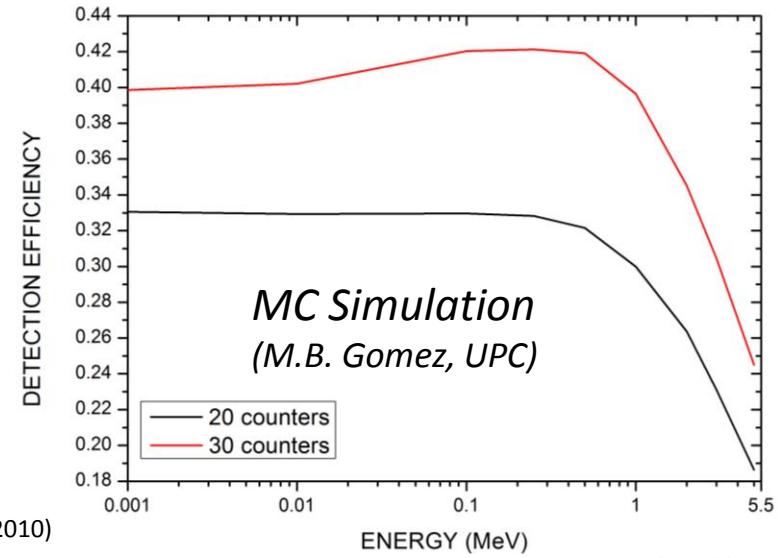
Universidad Politecnica de Cataluna, Barcelona

IFIC

IFIC Valencia

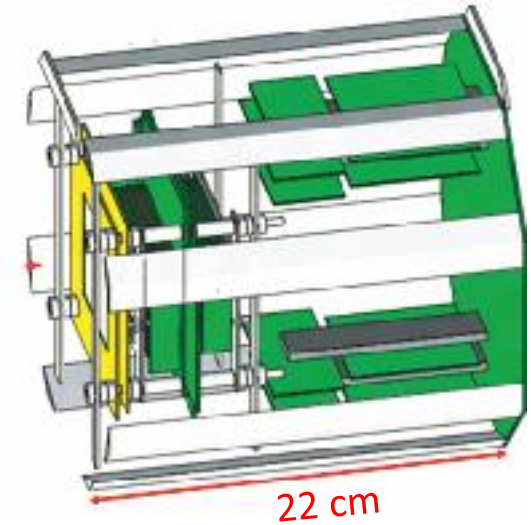
Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CIEMAT Madrid



M.B. Gómez Hornillos et al., Proc. Int. Conf. on Nucl. Data for Science and Techn. (2010)

Silicon IMplantation detector and Beta Absorber



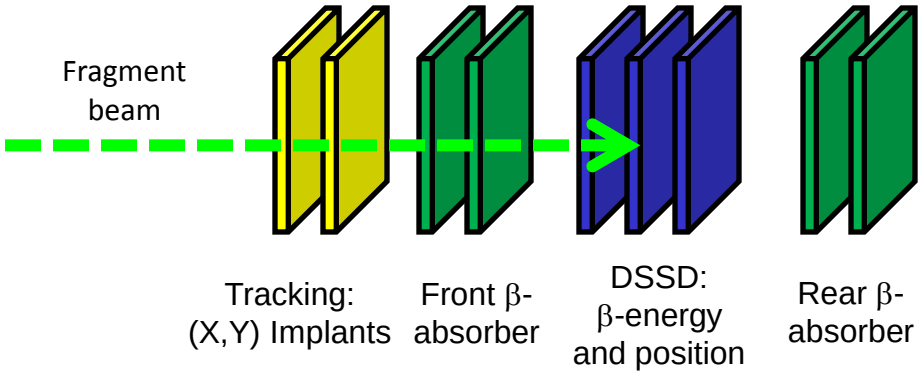
SIMBA

- 60x segm. X and Y-detector
- 7x segm. β-absorber (front and back)
- Implantation area: DSSD, 60x40 segm.

Constructed and developed at

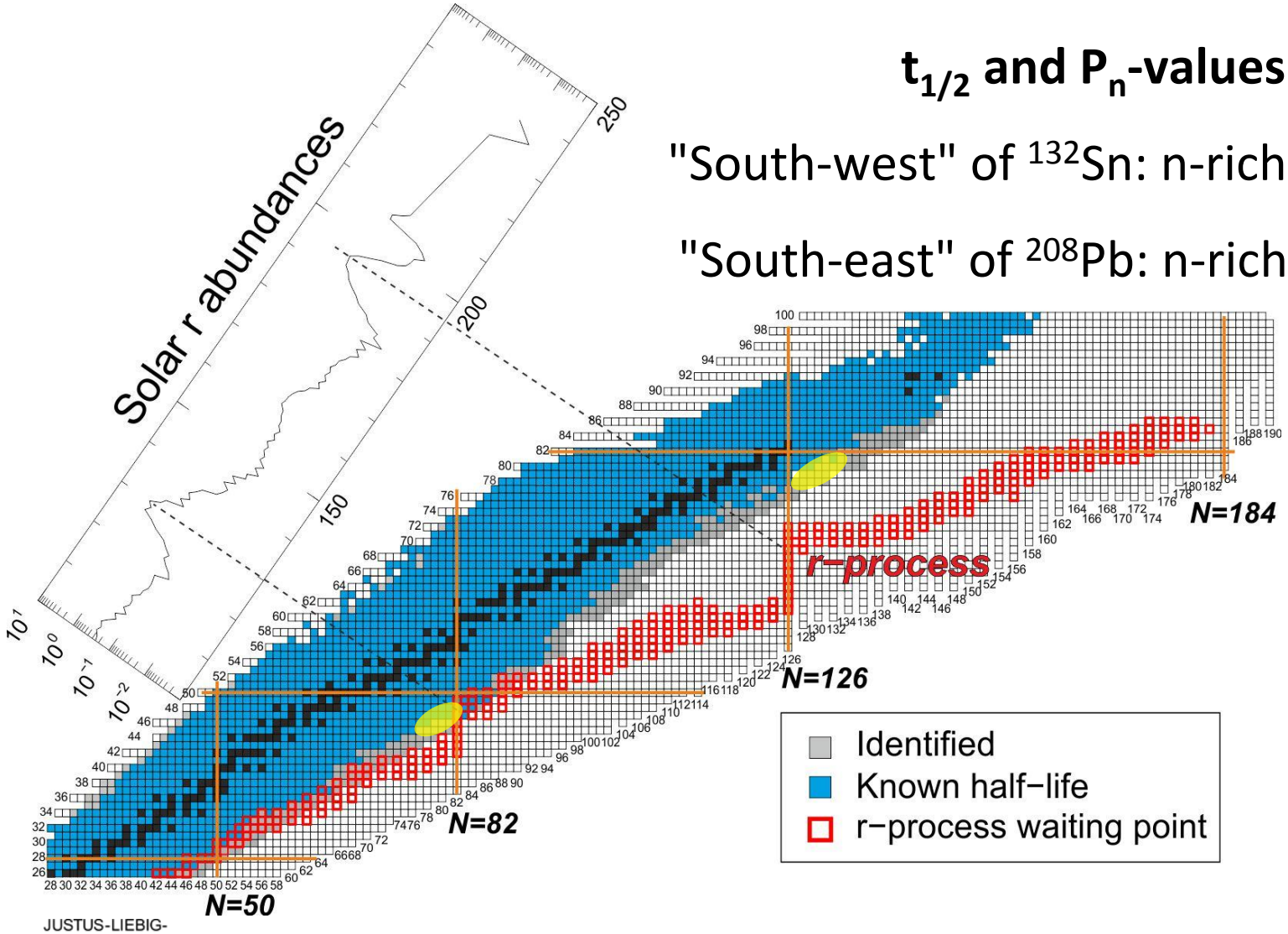
Technische Universität München

Lehrstuhl E12



PhD thesis C. Hinke, TUM (2010)
Diploma thesis K. Steiger, TUM (2009)

Which (isotopes)?

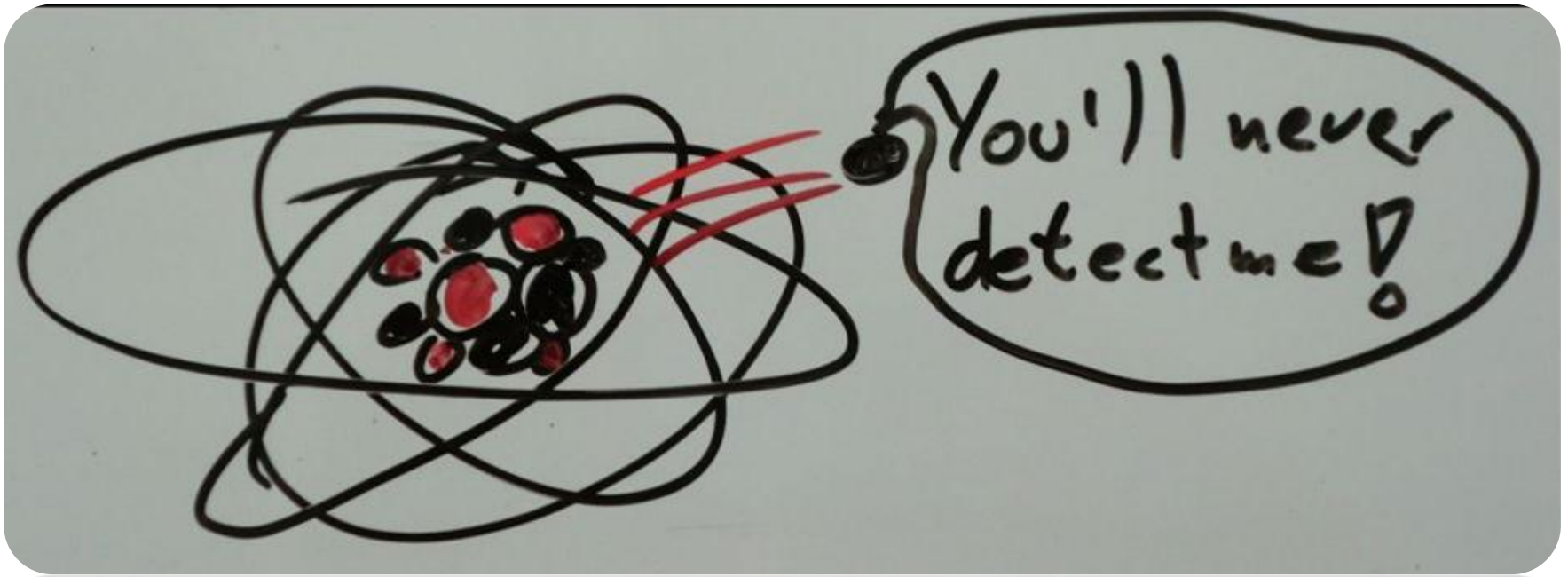


$t_{1/2}$ and P_n-values

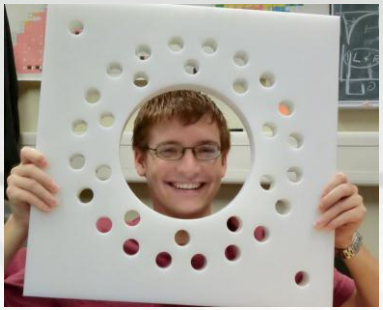
"South-west" of ^{132}Sn: n-rich Ag, Pd, Rh

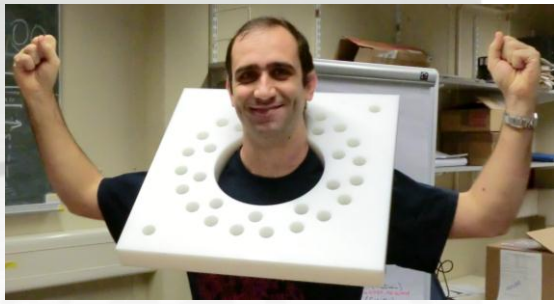
"South-east" of ^{208}Pb: n-rich Tl, Hg, Au

Preliminary status

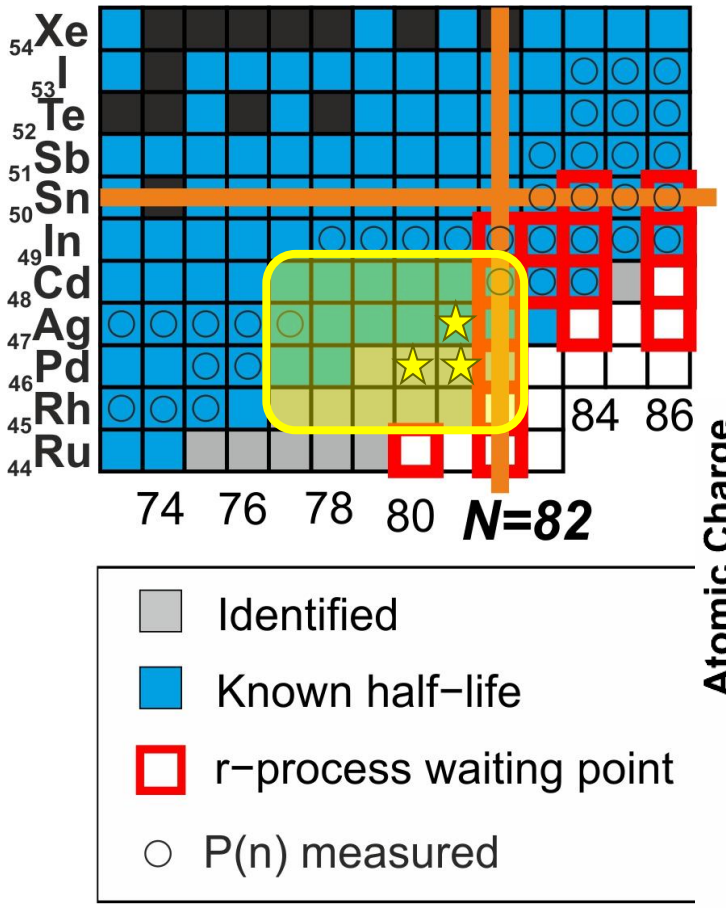


Showing prelim. data from
K. Smith (Notre Dame/ GSI)
R. Caballero-Folch (UPC Barcelona)





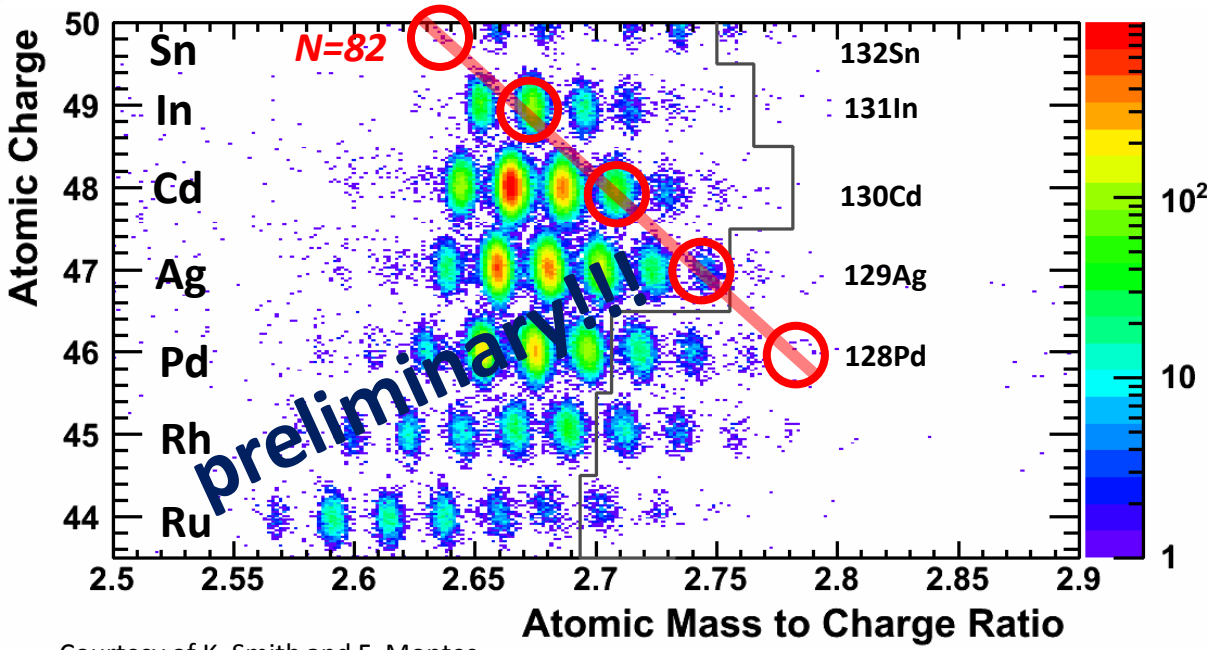
"South-west" of ^{132}Sn



4 days beamtime:

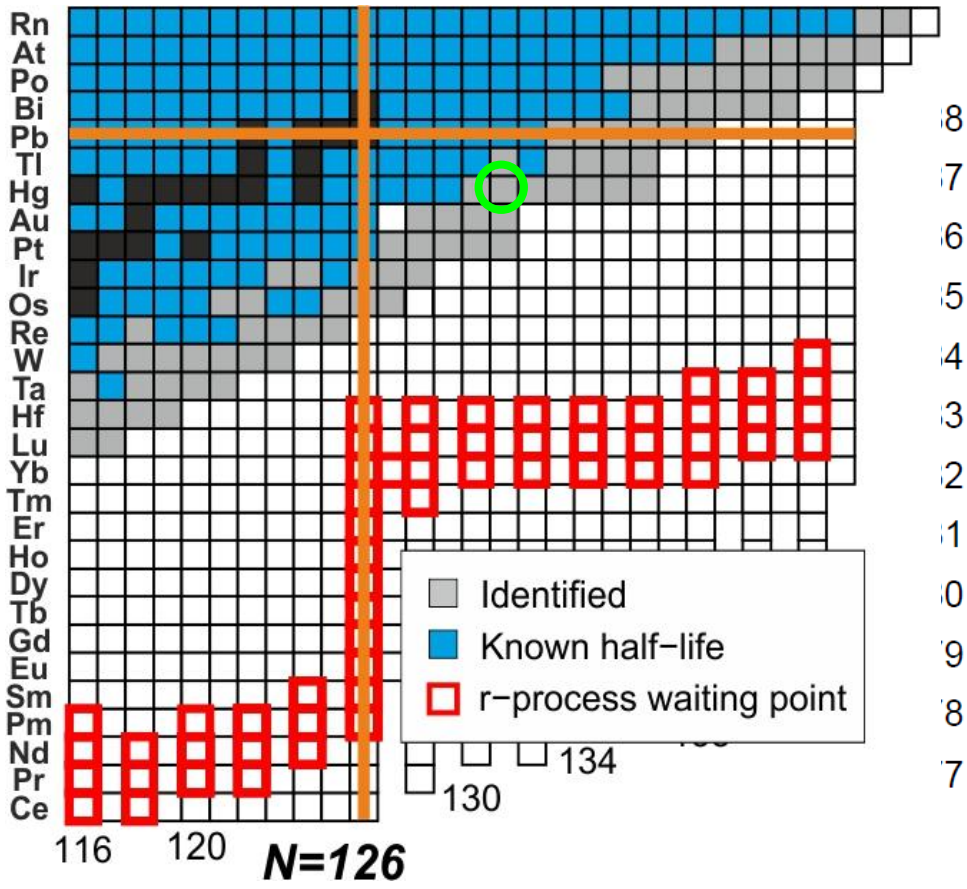
- Aim: new $t_{1/2}$ $^{128\text{-}126}$Pd, $^{122\text{-}12x}$Rh
- New P_n values
- Improved $t_{1/2}$ and P_n values

Identification of fragments

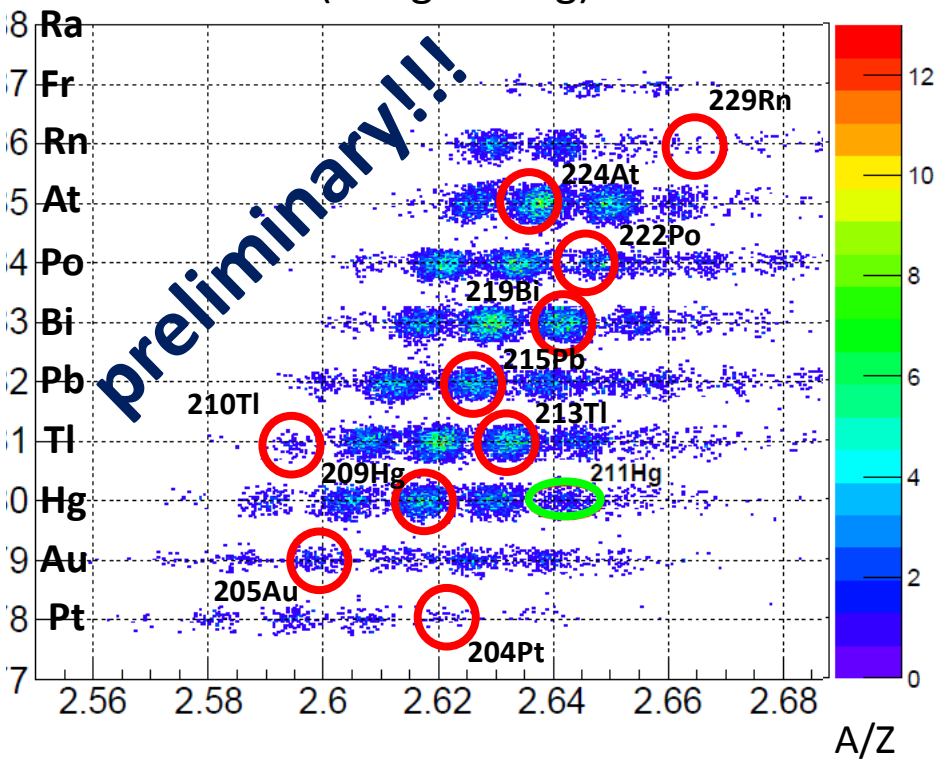


Courtesy of K. Smith and F. Montes

"South-east" of ^{208}Pb



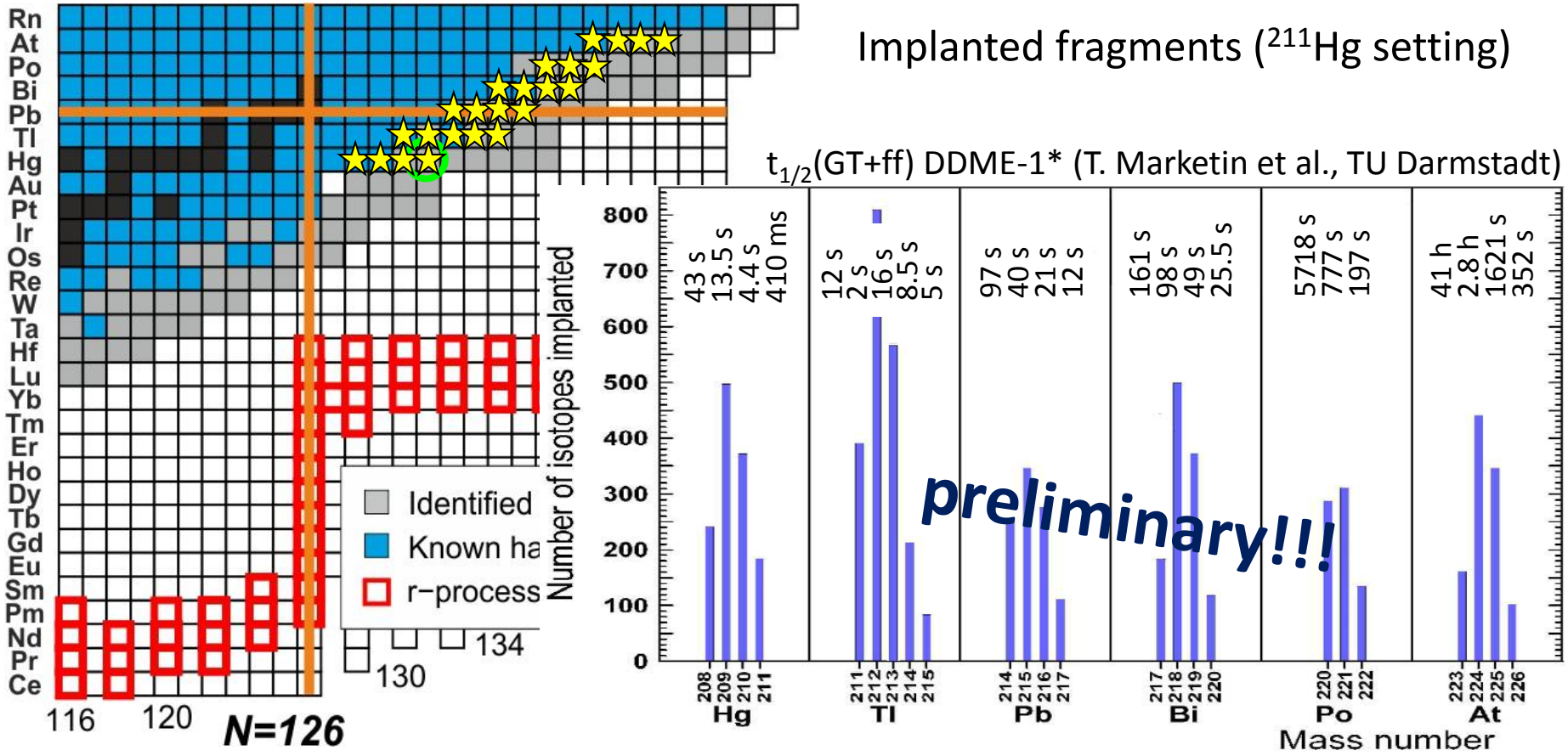
Identification of fragments
(^{211}Hg setting)



○ Last isotope with measured $t_{1/2}$

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

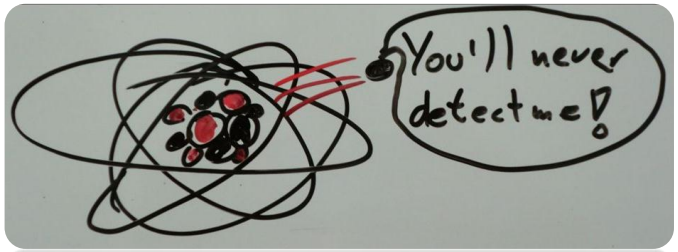
"South-east" of ^{208}Pb

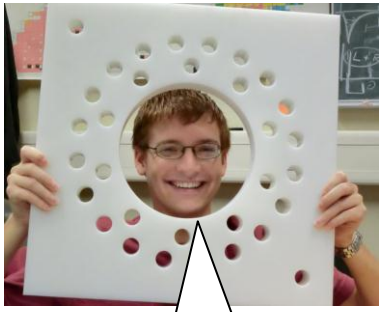


R. Caballero, NIC-XII proceedings (2012), NIC XII_109

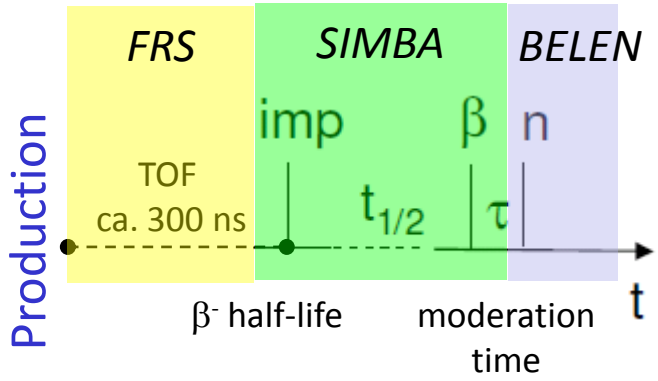
- Heaviest βdn-emitters measured so far!

Detection of βn

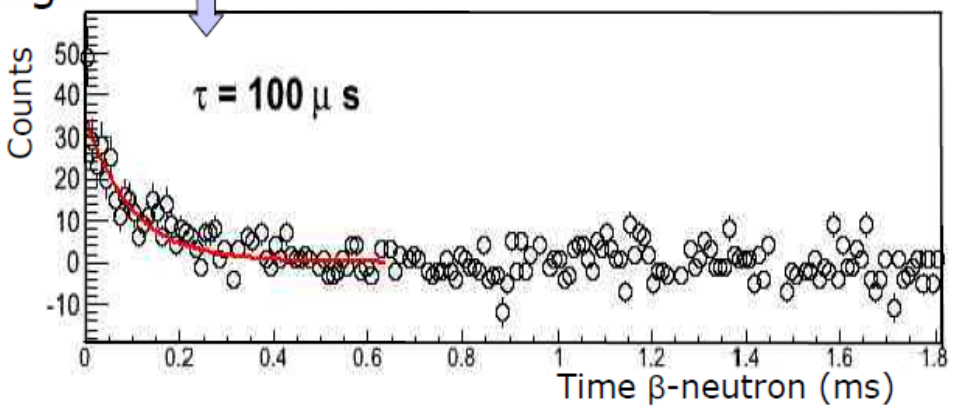




We have detected you!

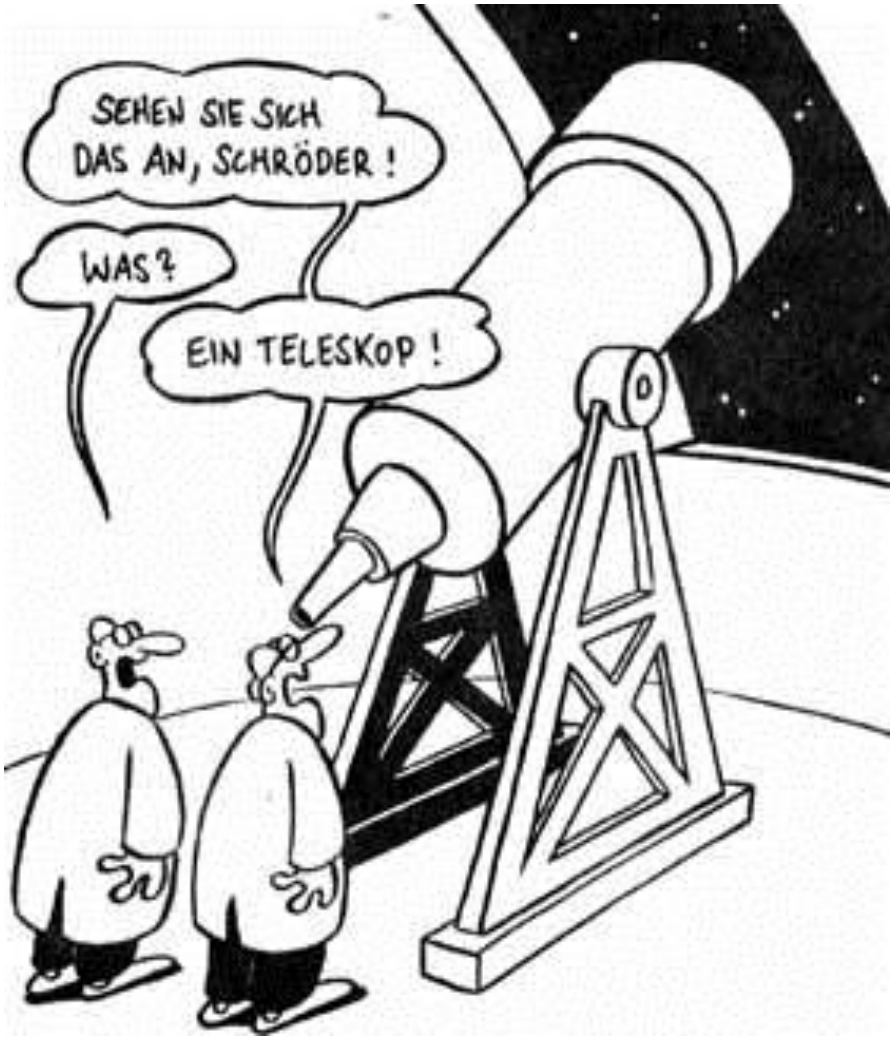


Signal – bkgd =

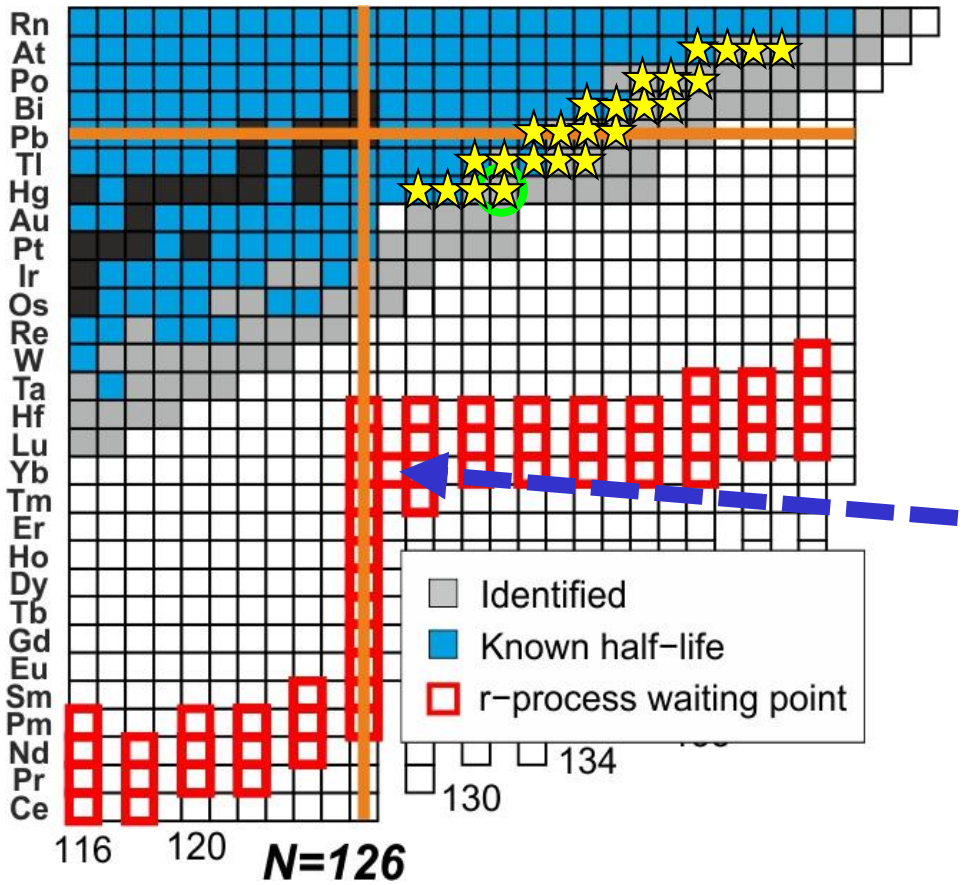


- Analysis in progress: identification of implants, β-n correlations
  - $t_{1/2}$, P_n

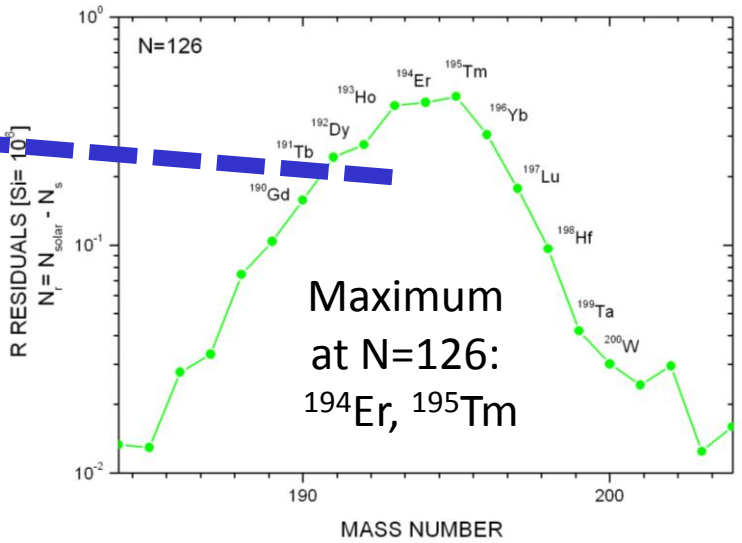
What else and when? (Outlook)



r-process around N=126



- Gap to N=126 progenitors:
  ^{194}Er (-16n: ^{178}Er)
  ^{195}Tm (-14n: ^{181}Tm)
- Need: better detection setup and higher beam intensities



BELEN is growing up !

BELEN versions designed

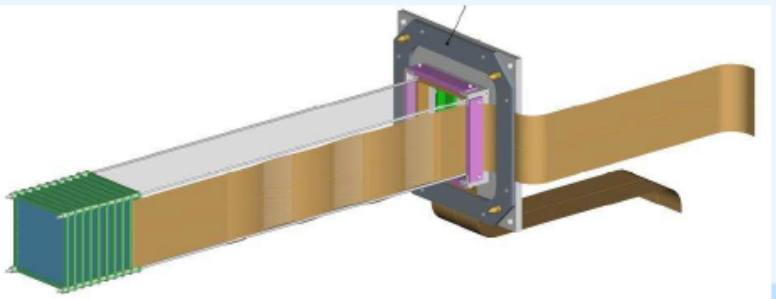
Name	^{3}He counters	Pressure (atm)	Experiment	Average Efficiency	Central hole radius (cm)
BELEN-20	20	20	JYFL-2009	27%	5.5
BELEN-20	20	20	JYFL-2010	35%	5.5
BELEN-30	20+10	20 & 10	GSI-2011	35 %	11.5 (SIMBA)
BELEN-48	40+8	8 & 10	JYFL-2013	37%-52%	6
BELEN-48	40+8	8 & 10	RIKEN	34%-50%	8 (AIDA)
BELEN 48	40+8	8 & 10	RIKEN	???	Local imp. detector
BELEN-96	96	3, 8 & 10	FAIR/ DESPEC	~65%	8 (AIDA)

2009
2010
2011
2013
2014/15
...
>2018

See differences:

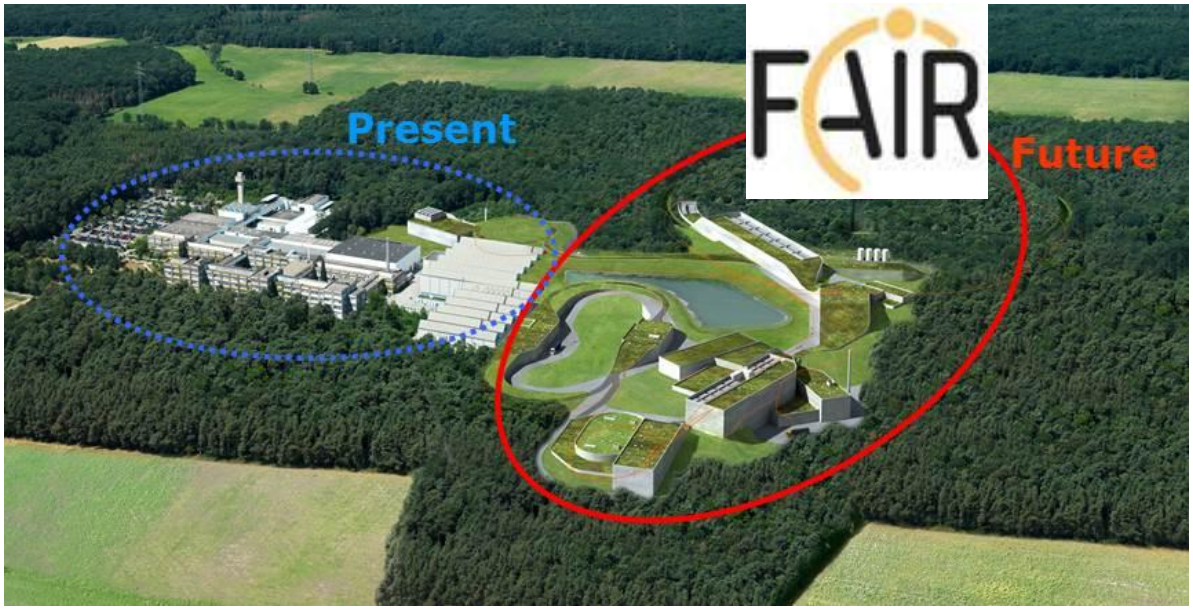
- Central hole
- Number of counters
- Distance of rings

AIDA



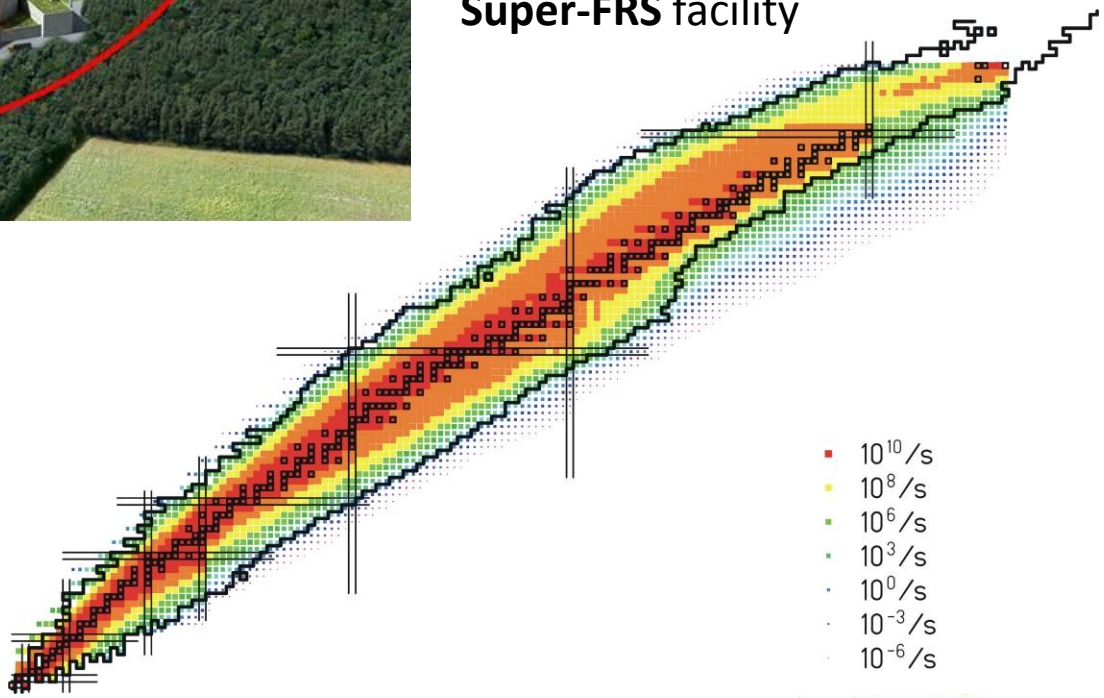
R. Caballero, BRIKEN Workshop (17.12.2012)

Future RIB facilities



Facility for **A**ntiproton and **I**on **R**esearch (>2018)

Super-FRS facility



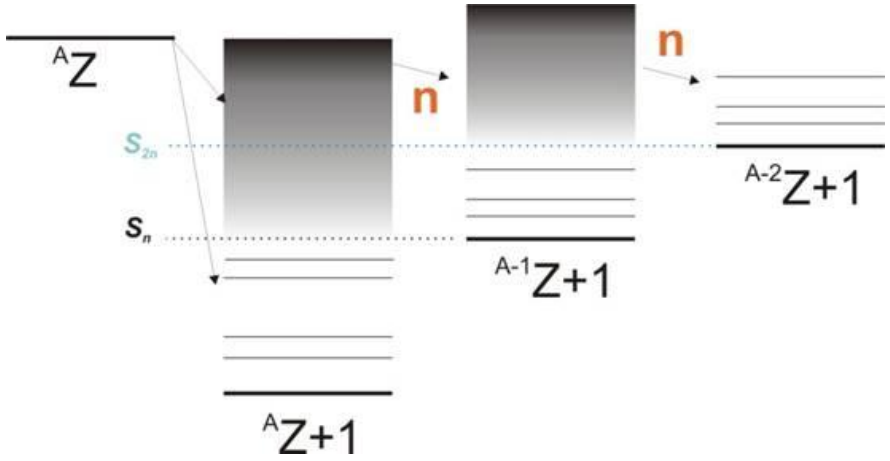
Similar RIB projects:

- **RIBF (Japan, since 2007)**
- Spiral 2 (France)
- FRIB (USA)
- RAON (Korea)

⇨ More βxn-emitters in reach, **priorities shifted**

What else: Measure P_{2n}

$S_{2n} < Q_\beta$



First experimental identification of P_{2n}:

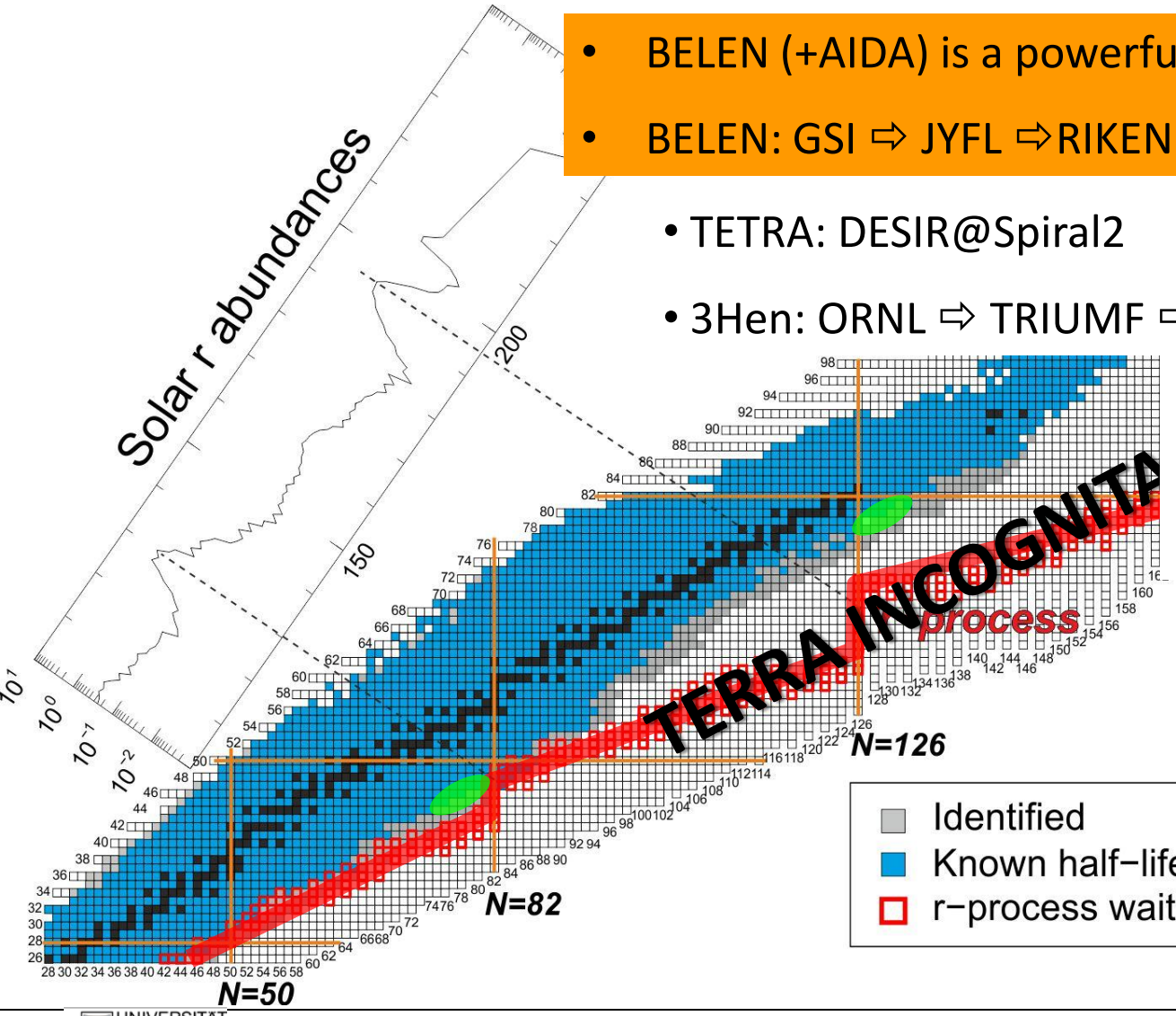
Rb ($t_{1/2}$= 114 ms) @ ISOLTRAP Reeder et al., PRL 47, 483 (1981)

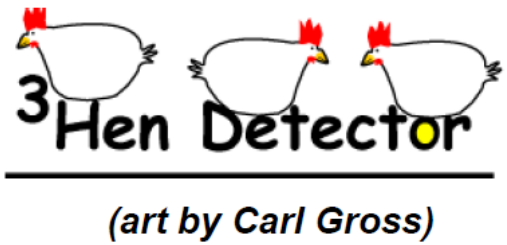
Experiment in JYFL (2013): measure P_{2n} of ^{136}Sb

- 18 β2n and 4 β3n emitter (^{11}Li, ^{14}Be, ^{17}B, ^{31}Na) known
- AME2011: 247 β2n cases energetically possible

Summary

- BELEN (+AIDA) is a powerful setup for βdn and $t_{1/2}$
- BELEN: GSI ⇨ JYFL ⇨RIKEN ⇨... ⇨FAIR
  - TETRA: DESIR@Spiral2
  - 3Hen: ORNL ⇨ TRIUMF ⇨ CARIBU ⇨ FRIB

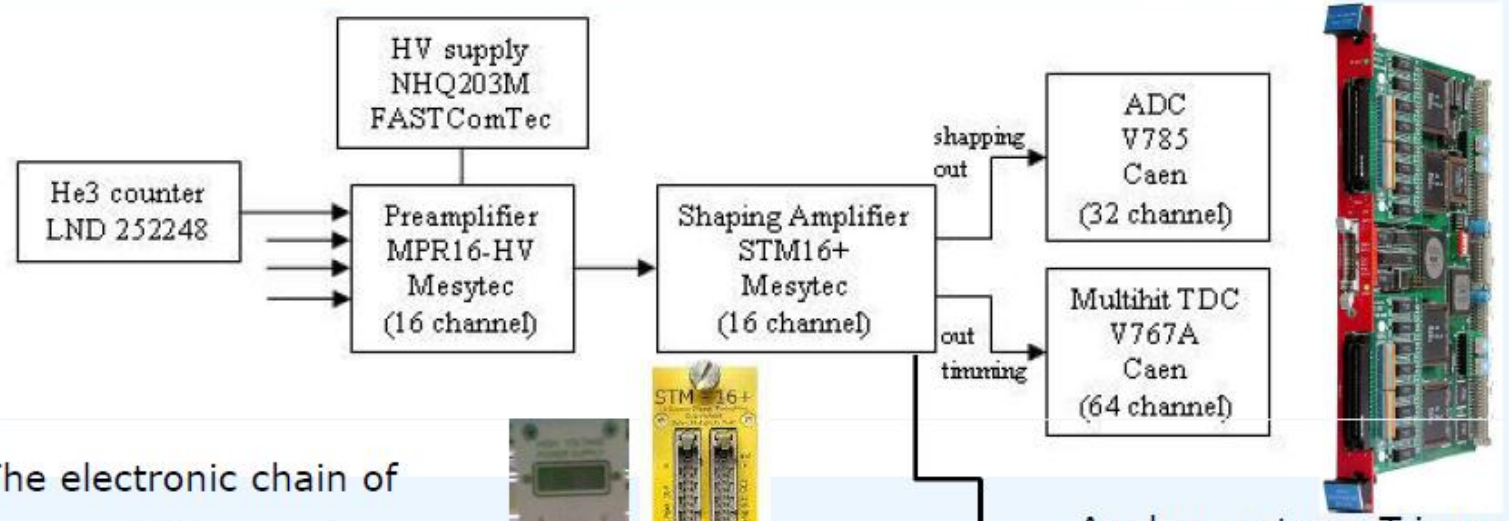




(art by Carl Gross)

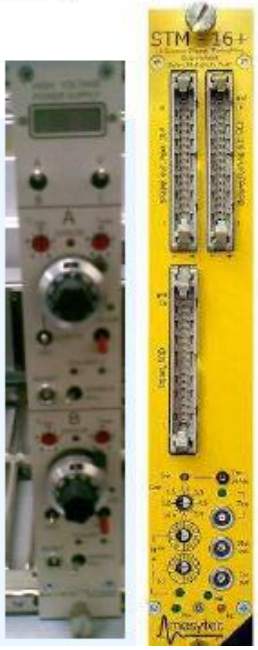
The big improvement: Digital electronics

Electronic chain for data acquisition and signal processing



Analog system: Trigger

The electronic chain of the acquisition system operates independently of the other systems of the experiment and detectors along the beamline. It only needs to sinchronize the timestamp.



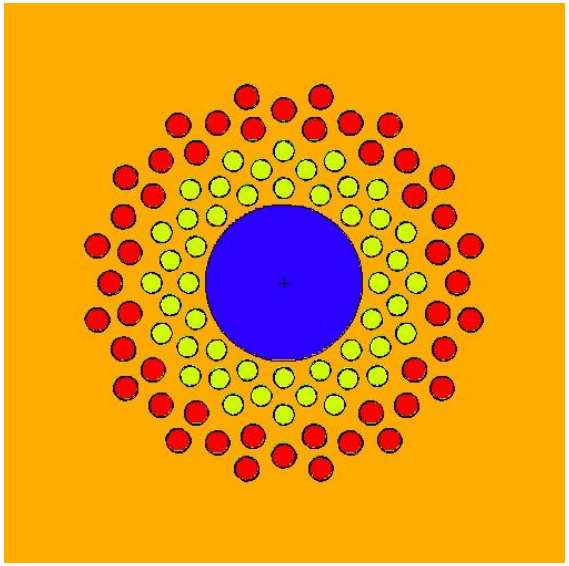
NEW Digital system: Triggerless

Digital Data Acquisition System (DDAS)

R. Caballero, BRIKEN Workshop (17.12.2012)

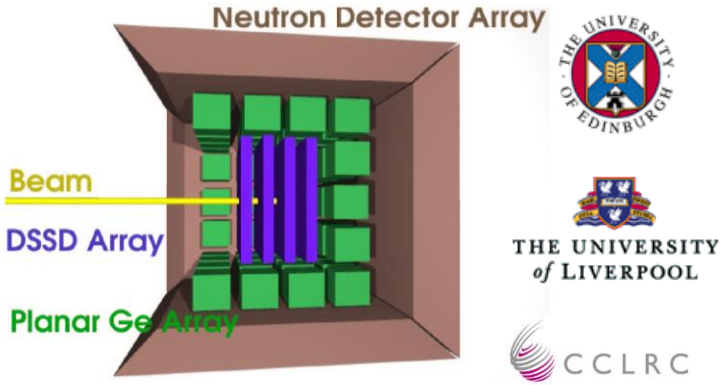
9

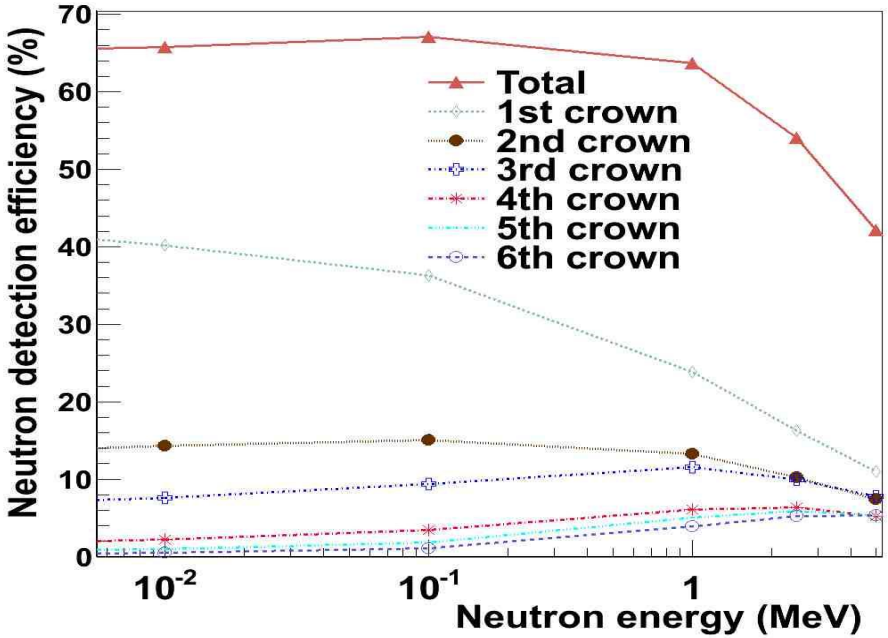
Upgrade for DESPEC@FAIR



- Inclusion of additional counters from JINR Dubna ⇨ upgrade to 96 counters
- New implantation detector AIDA
- Efficiency: BELEN-30: ≈40% ⇨ **BELEN-96: ≈65%**

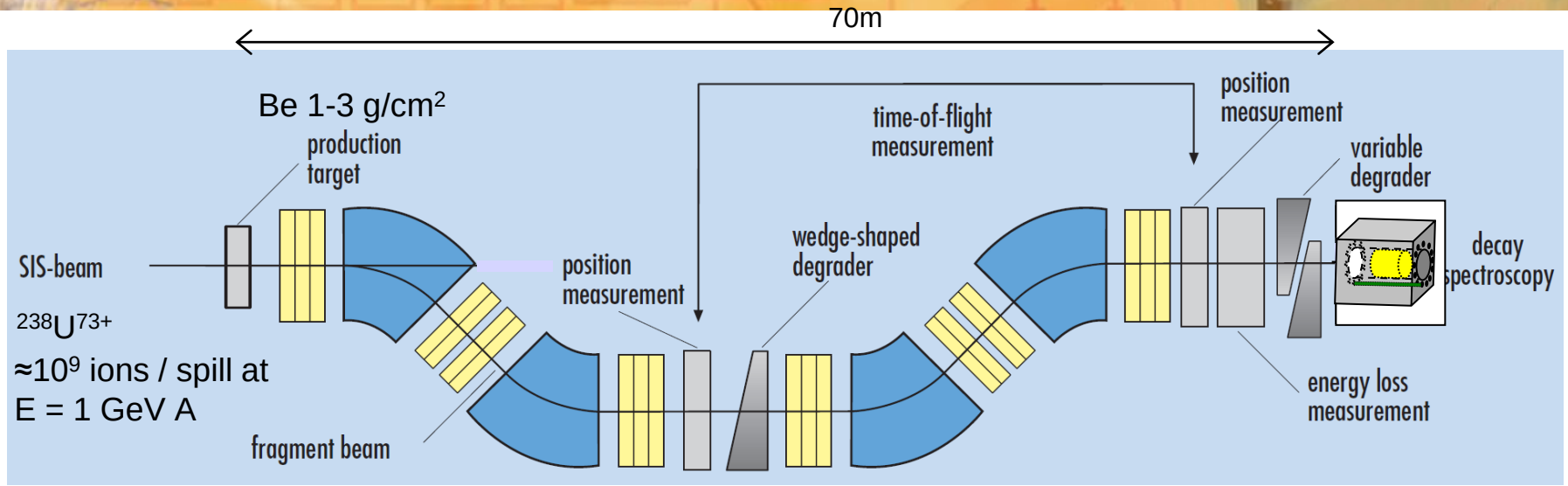
Advanced Implantation Detector Array (AIDA)





Pictures: M.B. Gomez Hornillos and T. Davinson

FRS: fragment production, in-flight separation, and identification



- Separation Bρ – ΔE – Bρ
- In-flight particle identification:
  - 2x Plastic Scintillators — ToF → β
  - 4x Time Projection Chambers — x,y position → ρ
  - 2x MUSIC (MUltiple Sampling Ionisation Chamber) — E loss → Z

$$B\rho = \frac{m}{q} c\beta \frac{1}{\sqrt{1-\beta^2}}$$

→ m/q

- m/q and Z identify the fragment (validation with Isomer TAGging)

H. Geissel et al., NIM B 70, 286 (1992)

What else: Measure P_{2n}

$$P_n = \frac{1}{\varepsilon_n}\frac{N_{\beta n}}{N_\beta} \qquad P_{2n} = \frac{1}{\varepsilon_n{}^2}\frac{N_{\beta nn}}{N_\beta}$$

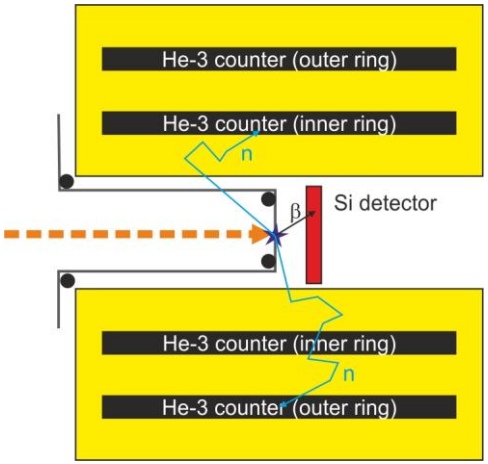
Highly efficient setup needed: upgrade to **BELEN-48**

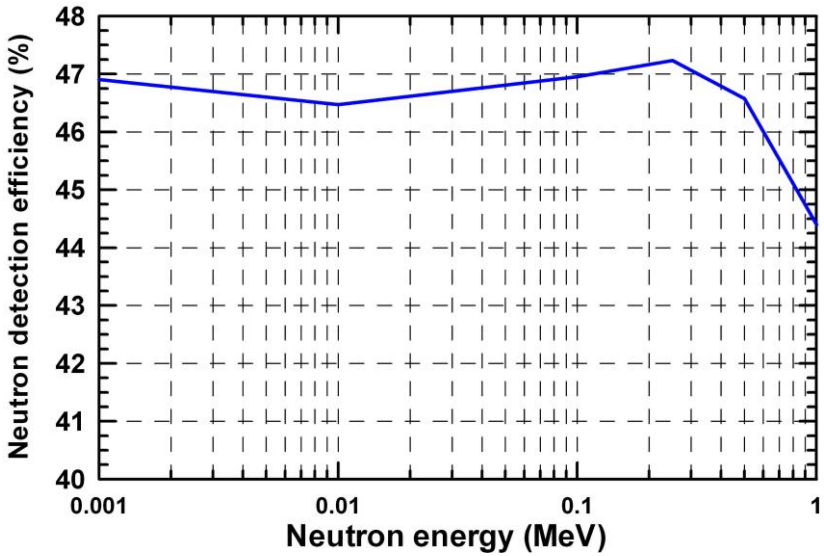
Proposal for IGISOL@Jyväskylä/ Finland:

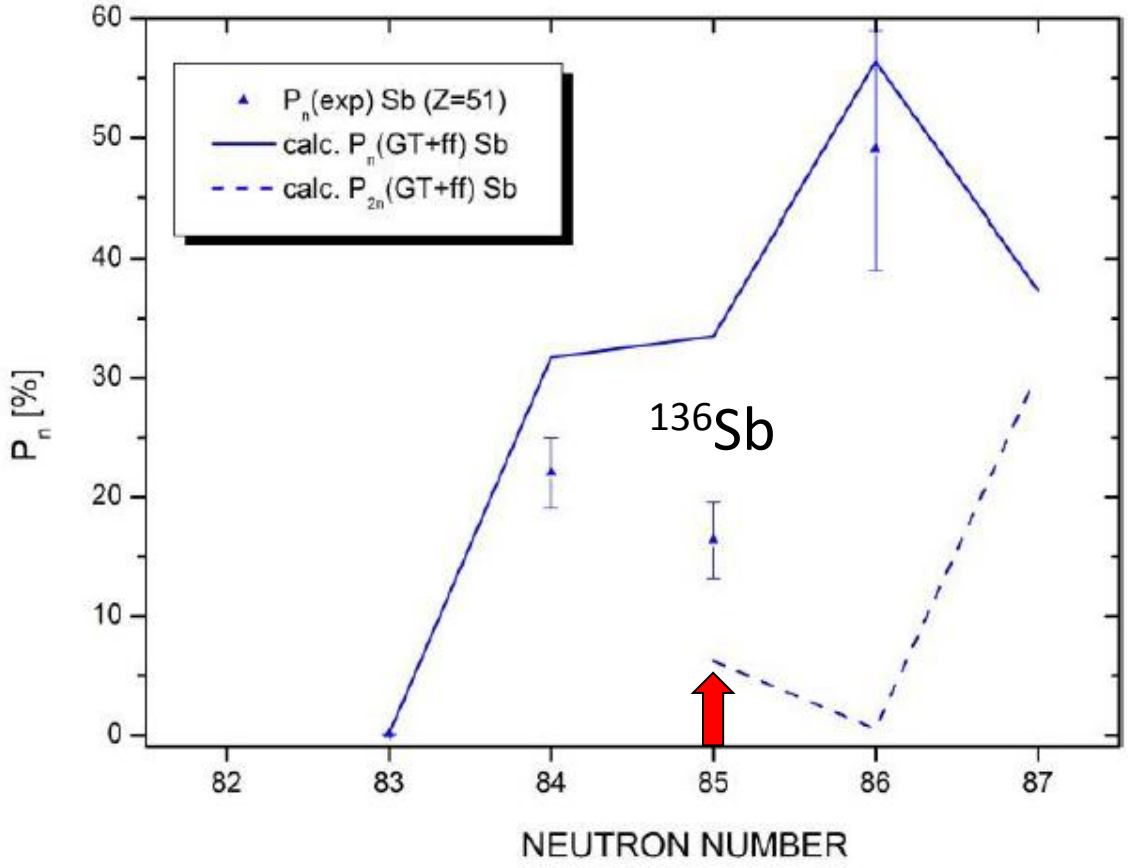
$\varepsilon(\beta n) \approx 11\ \%$
$\varepsilon(\beta nn) \approx 5\ \%$

^{136}Sb

$P_{2n} \approx 1.4\text{- }6.2\ \%$
90-390 events/ 5d






P_n(exp) Sb (Z=51)
calc. P_n(GT+ff) Sb
calc. P_2n(GT+ff) Sb
136Sb
P_n [%]
NEUTRON NUMBER
0
10
20
30
40
50
60
82
83
84
85
86
87

BELEN@RIKEN

- First next-generation RIB facility online (since 2007)
- Same production mechanism as GSI/ FAIR (fragmentation and in-flight separation), with lower primary beam energy (345 MeV/u instead of 1 GeV/u) and higher intensity (≈10 pnA for ^{238}U)
- Advantage: Possibility to test FAIR-like setup (BELEN+AIDA) under realistic conditions