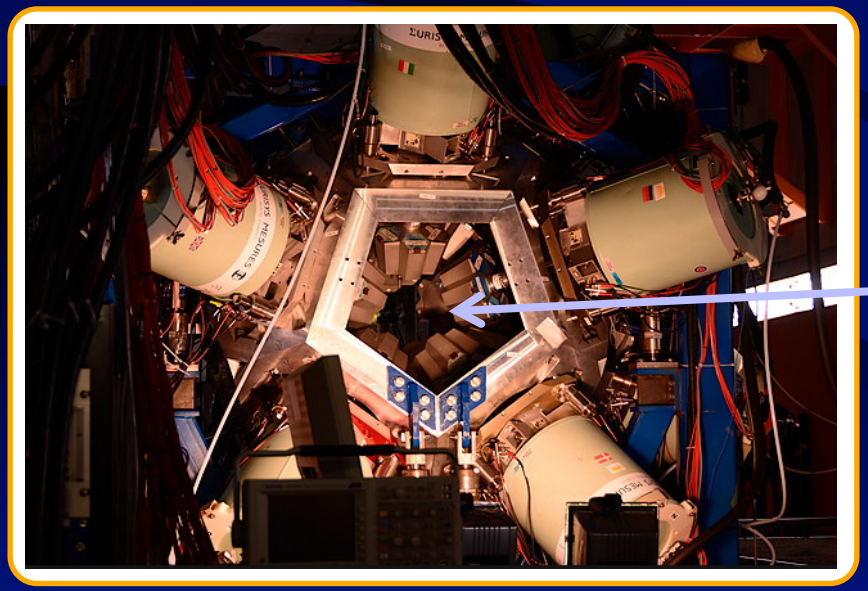
11th Russbach School on Nuclear Astrophysics (Mar. 12, 2014)

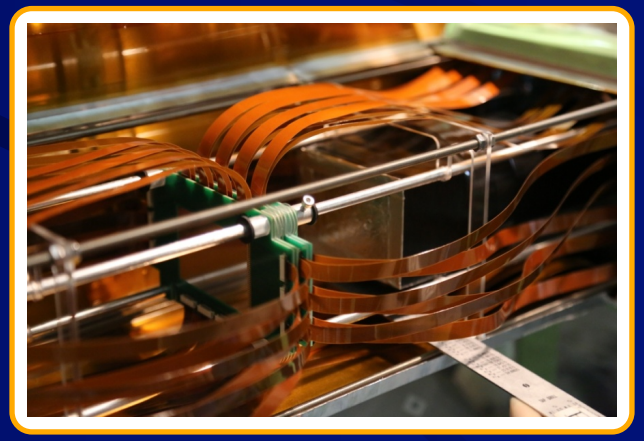
Decay spectroscopy relevant to the r-process nucleosynthesis

Shunji NISHIMURA
(RIKEN, Japan)

Gamma-ray detection system
(Ge: EURICA)



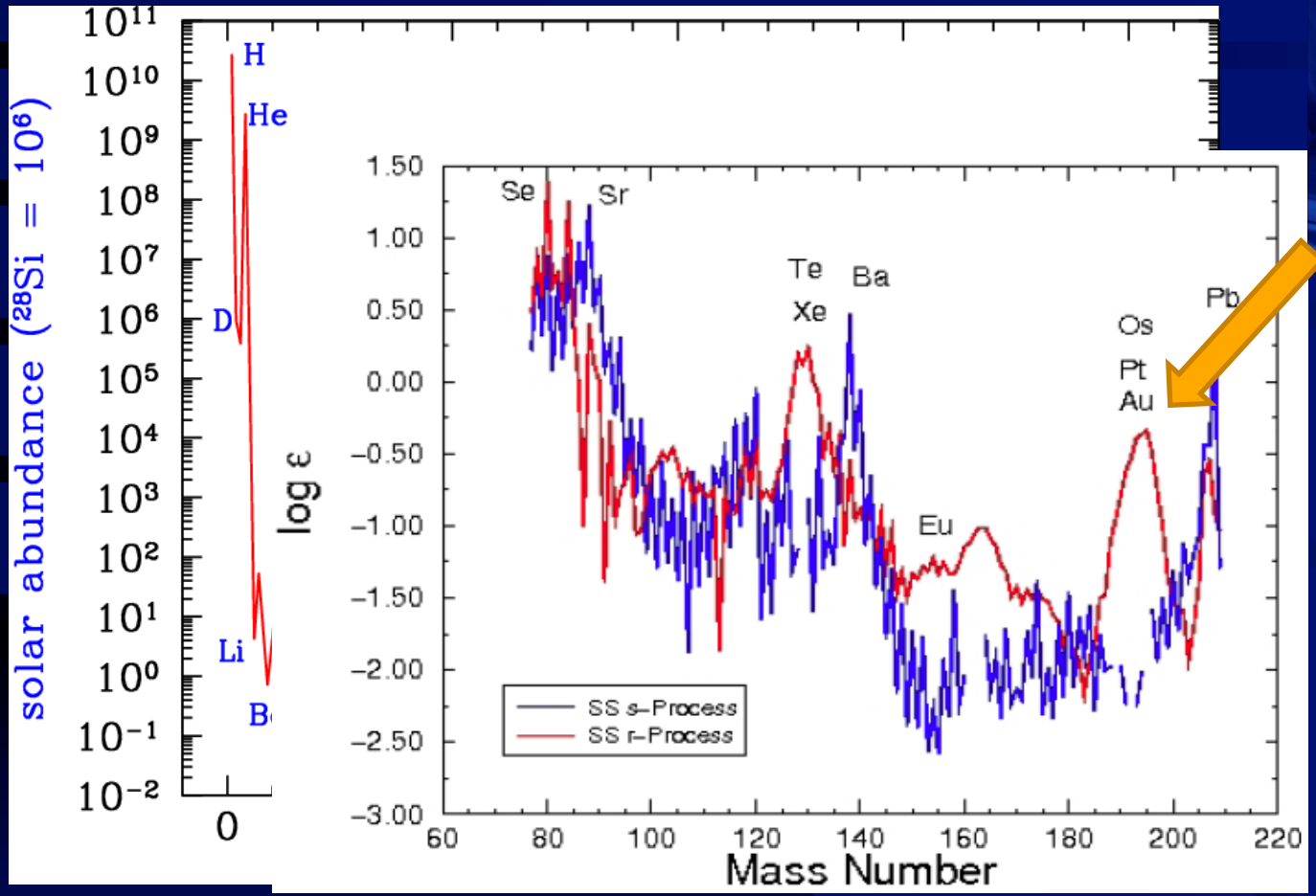
Beta-counting system
(Si: WAS3ABi)



How is the elements created in the universe?

Gold

Solar Abundance

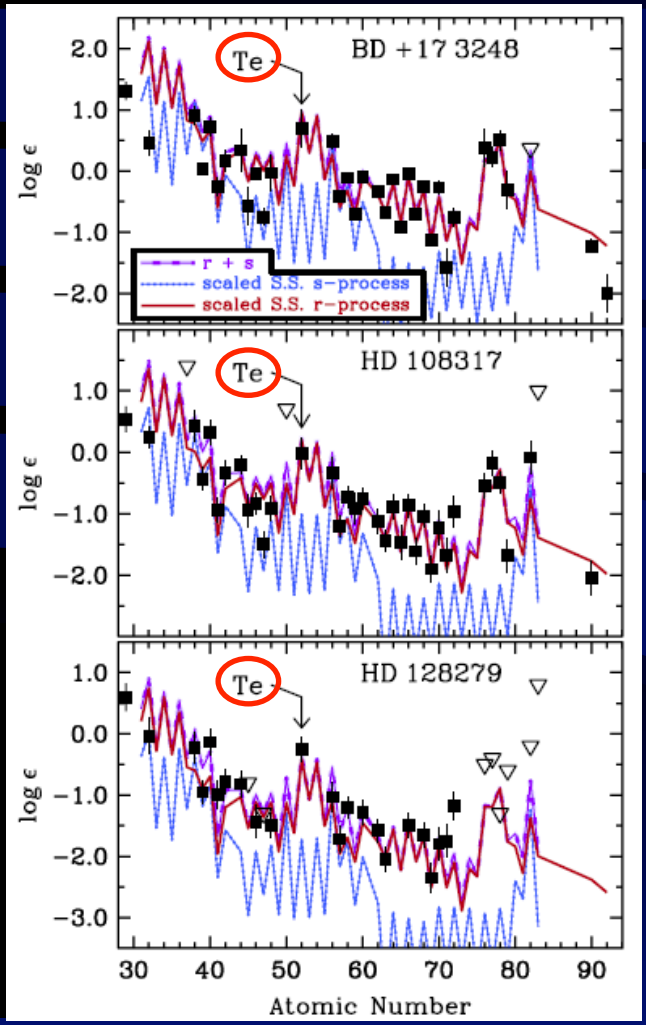


r-process peaks (A~80, 130, 195) are associated to very neutron-rich magic nuclei
N = 50, 82, 126

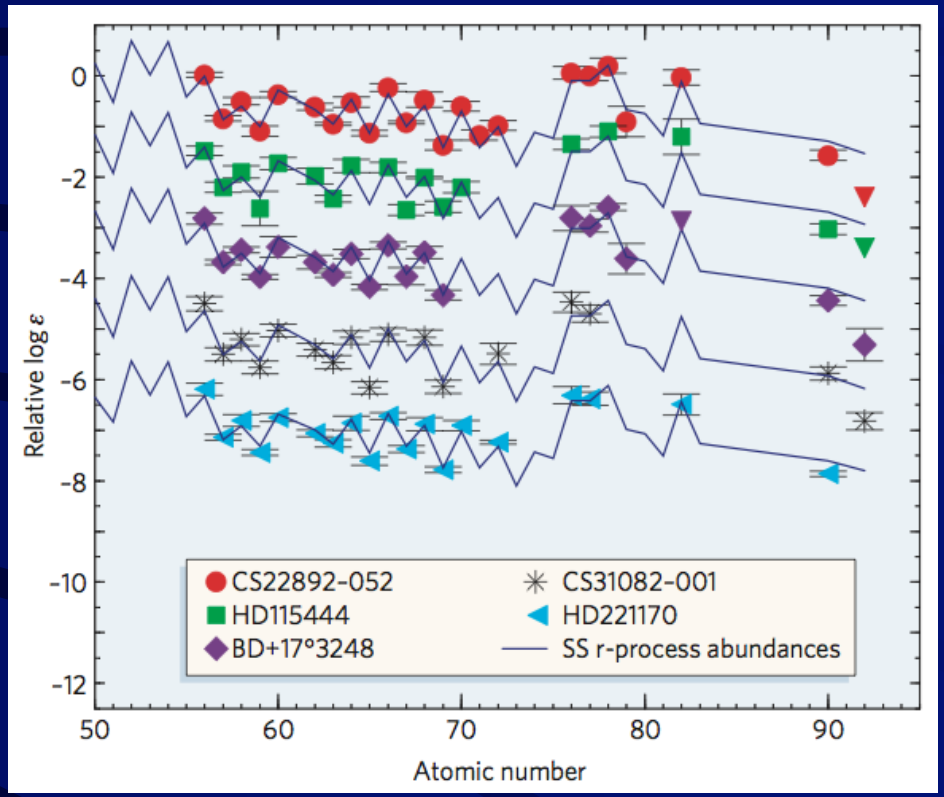
Abundance Patterns in Galactic Halo Stars

(The origin of about half of elements > Fe)

Open question: Where does the r process occur ?



I.U. Roederer, ApJ L 747 (2012)



J.J.Cowan C.Sneden, Nature 440 (2006)

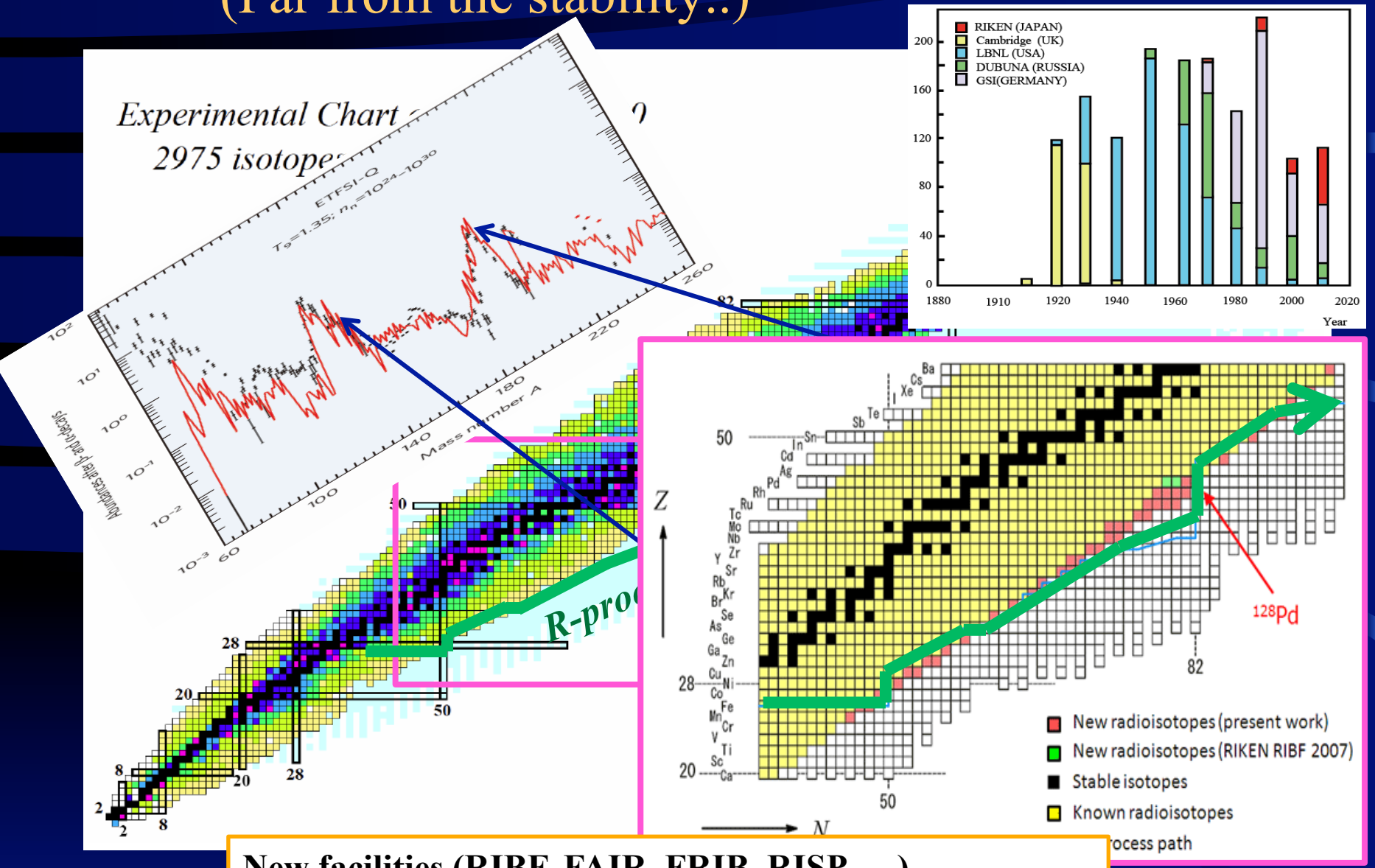
Heavy elements in oldest stars ($Z \geq 56$)

→ Closely match the Solar System (SS) r-process pattern.

→ Te (Z=52) data.

We lack physical reliable data for the most neutron-rich nuclei.

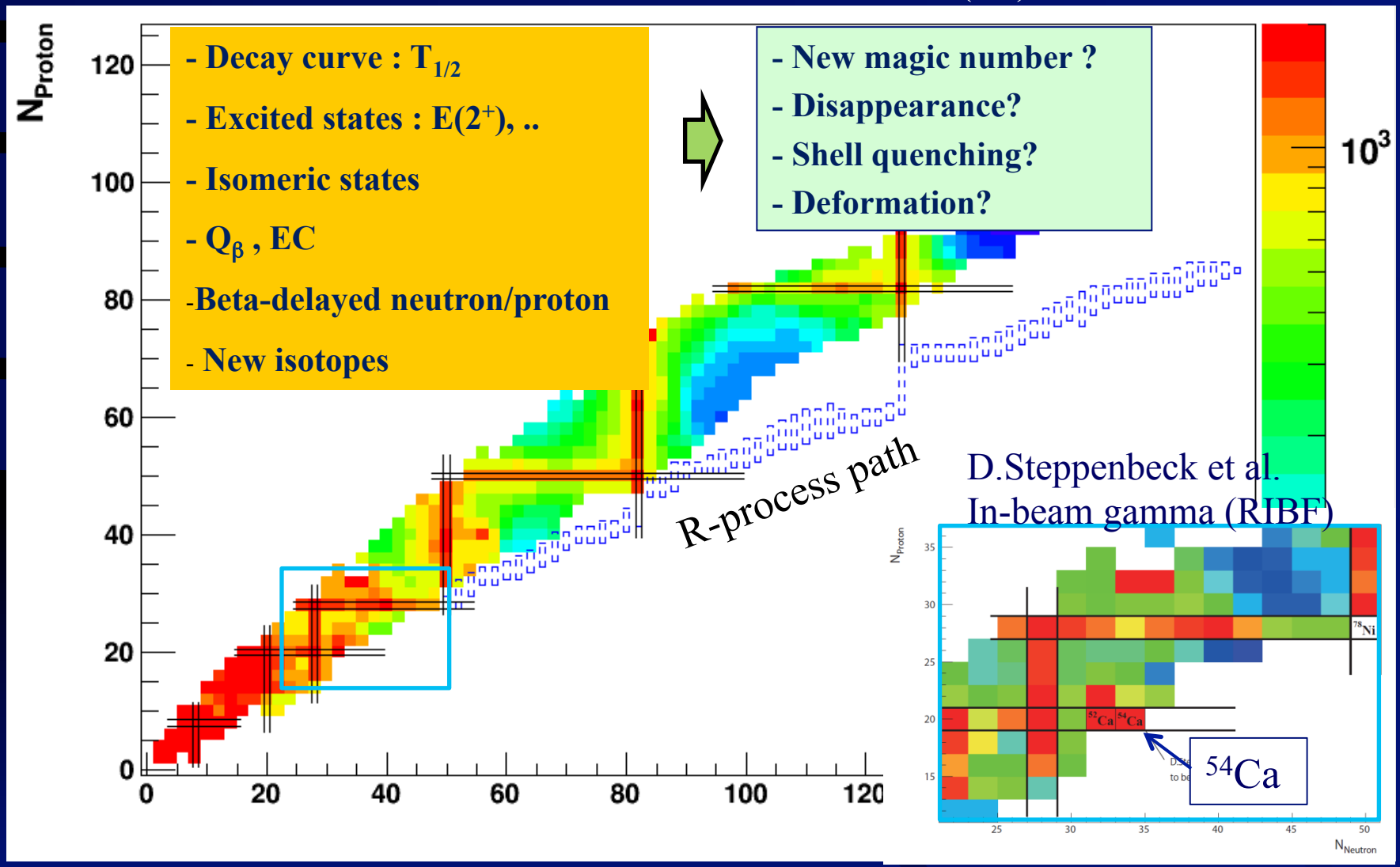
Very Neutron-Rich Nuclei
(Far from the stability..)



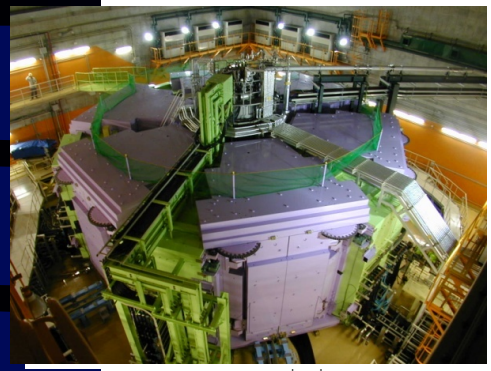
New facilities (RIBF, FAIR, FRIB, RISP, …)
Exciting time to access the nuclei on the r-process !

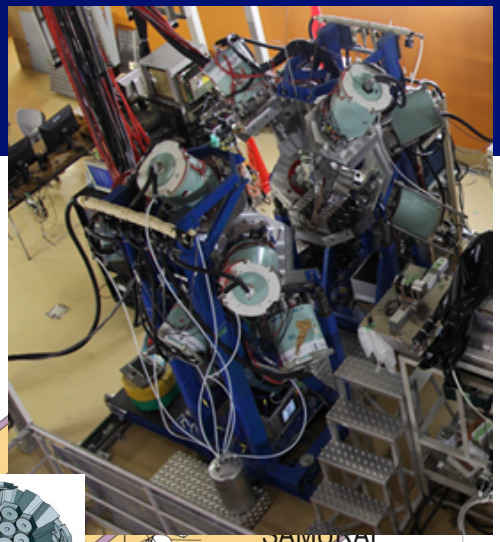
Nuclear Parameters (Decay Spectroscopy)

First E(2+) for even-even nuclei



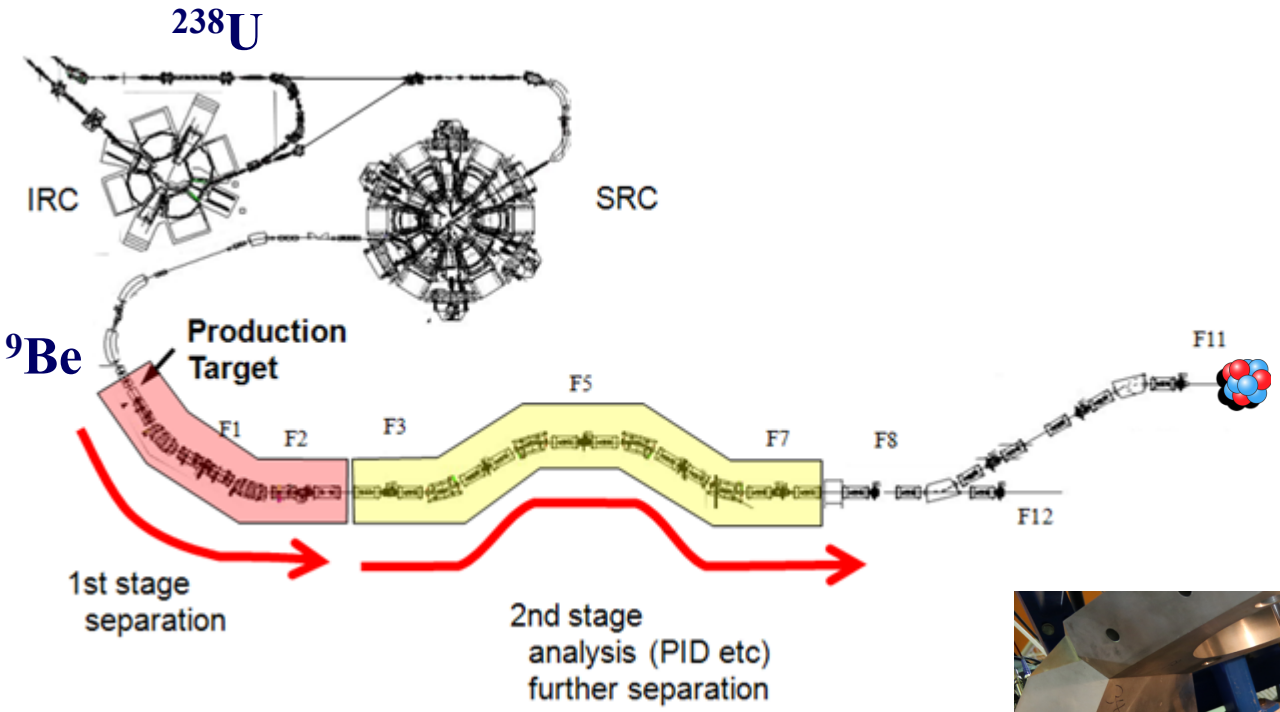
Location of Decay Station at RIBF

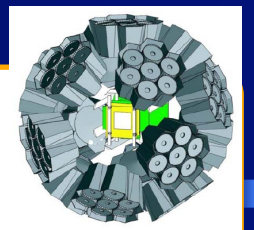


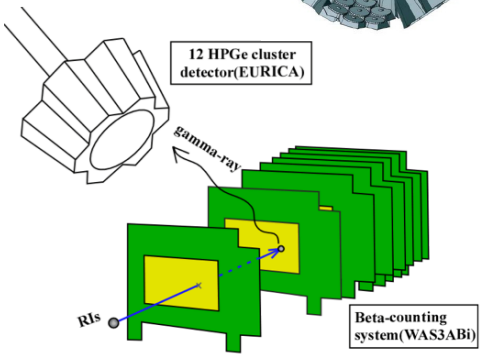


^{238}U … 345 MeV/u,
… Intensity = 5 – 12 pnA !

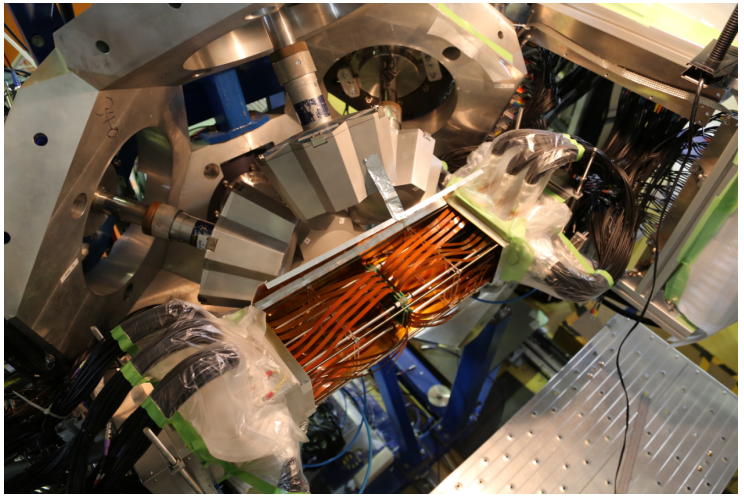
Beam Production at RIBF







- The implantation of an identified RI is associated with the following β-decay events that are detected in the same silicon pixel (DSSSD).



Decay Spectroscopy at RIBF

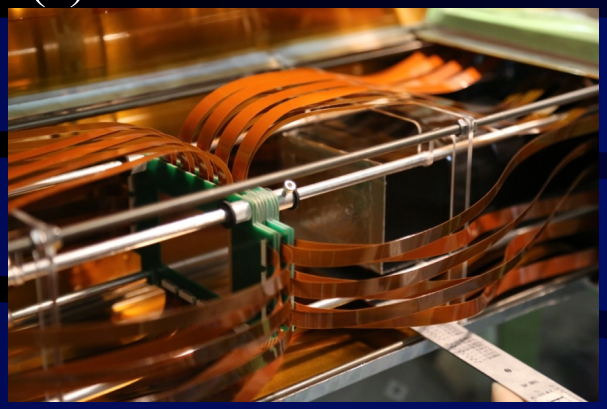
- Production of Isotopes
  - Isotope separation by BigRIPS
    - Cocktail beam (20 ~ 40 isotopes with Z ±3~5)
    - Secondary beam intensity : 10 ~ 1k cps
  - Particle identification
    - Brho, Time-of-Flight, dE, and E
    - Issue of charge states in heavy RI (A > 170)
- Transportation
  - RI Beam energy ~ 150 MeV/u
    - Suitable for short-lived nuclei / isomer (> 50ns)
    - Adjust degrader to optimize the range in active stopper.

Beta-counting system: WAS3ABi

(Wide-range Active Silicon-Strip Stopper Array
for Beta and ion detection)

RIKEN/IBS/TU München

(a)

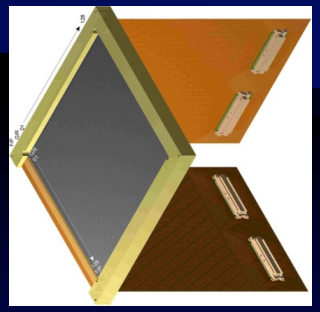


(b)

(c)

Nitrogen air cooling ~ 10 degree.

(d)



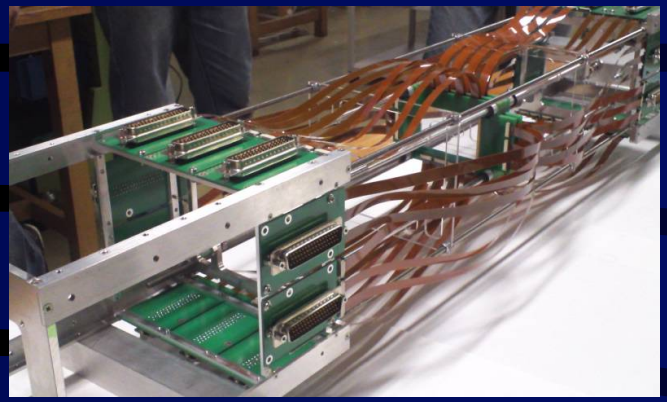
(a) 14,000pixels + Plastic (Qbeta) … 2012 U-beam

(b) 12,000pixels + Plastic (Fast timing) … 2013 U-beam

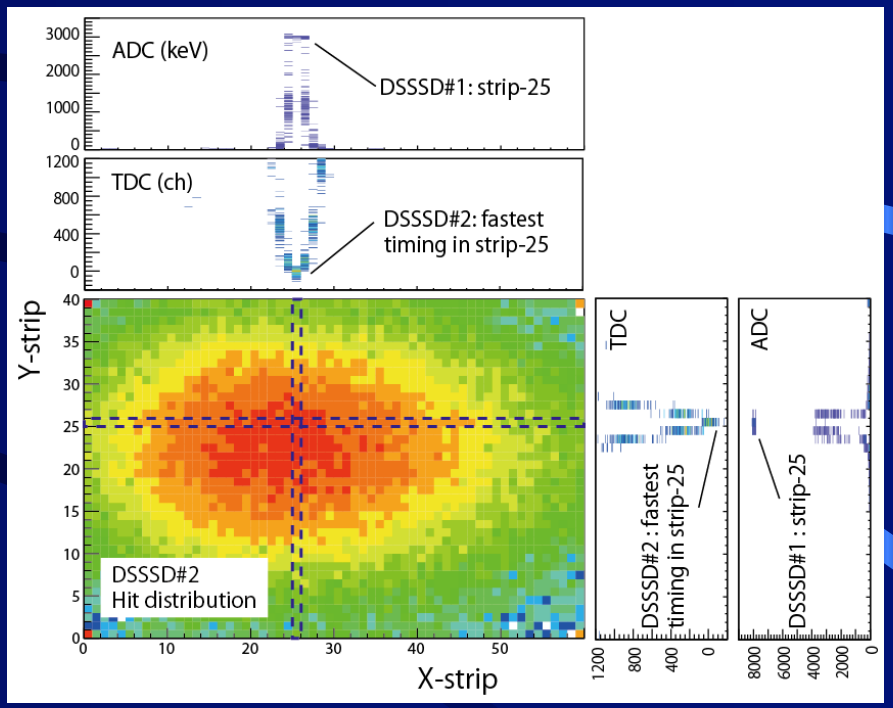
(c) 7,200 pixels + 10 x SSD (Qbeta)
WAS3ABi + SIMBA … 2013 Xe-beam

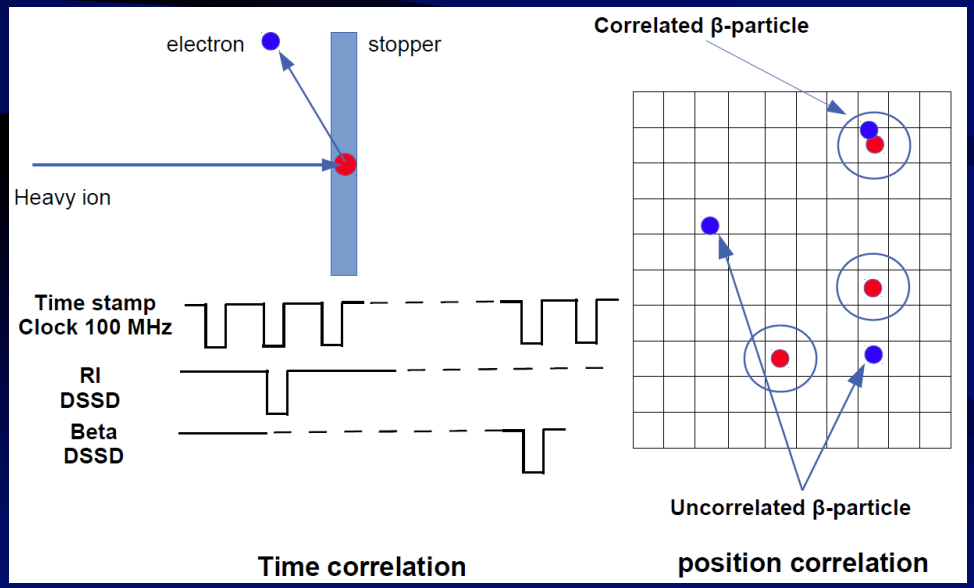
(d) 16,000 pixels + Plastic (Veto) … 2013 Xe-

Event association of isotopes and subsequent beta-decays in WAS3ABi



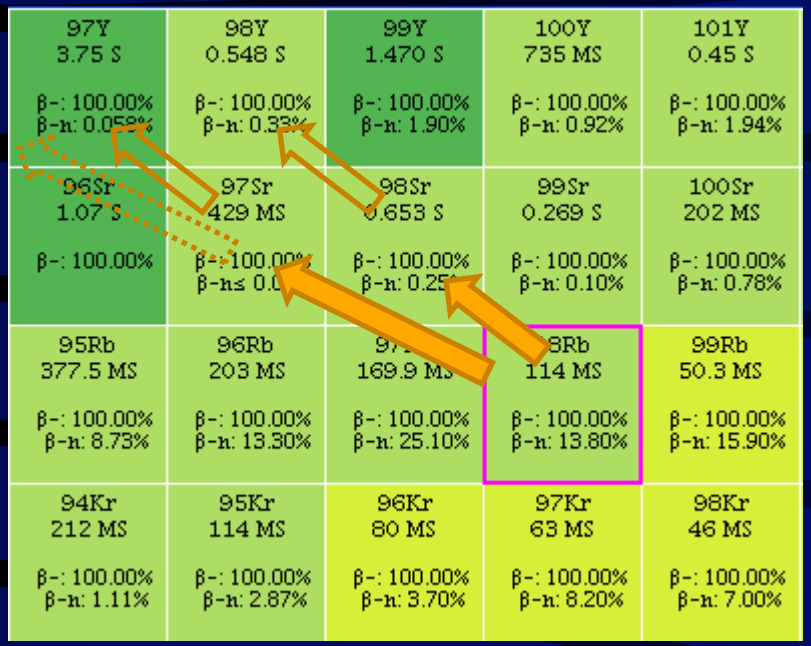
Timing information is used for reconstruction of hit position.

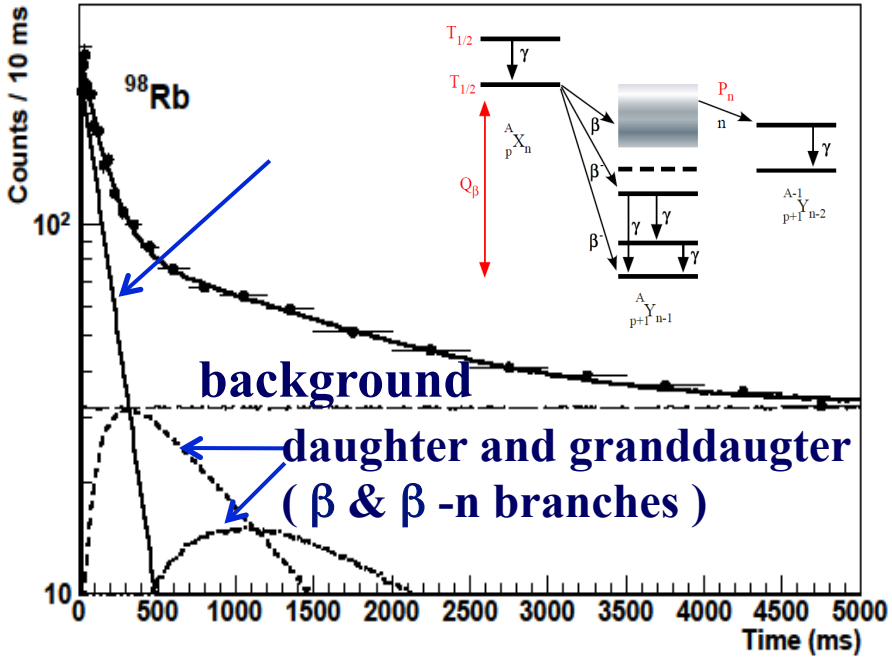




Heavy-ion … ~ 1GeV ~ 10 GeV
Beta-ray … 20 keV ~ 3 MeV

Decay curve and $T_{1/2}$





Likelihood method with 10ms bins (0 – 5 sec)

Free parameters for fitting

- Background … ~ 0.5 cps
- Neutron emission Probability (Pn)
- Detection efficiency (ε) … 40% - 80%

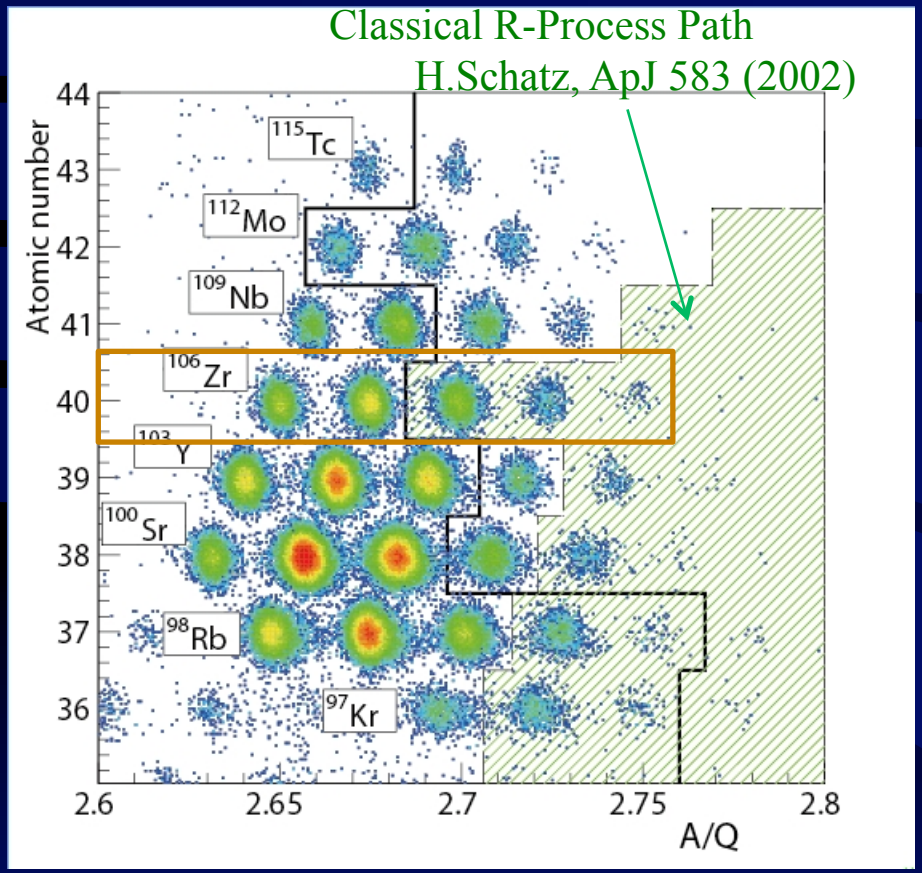
Consistency check

- Monte Carlo Simulation / beta-delayed gamma

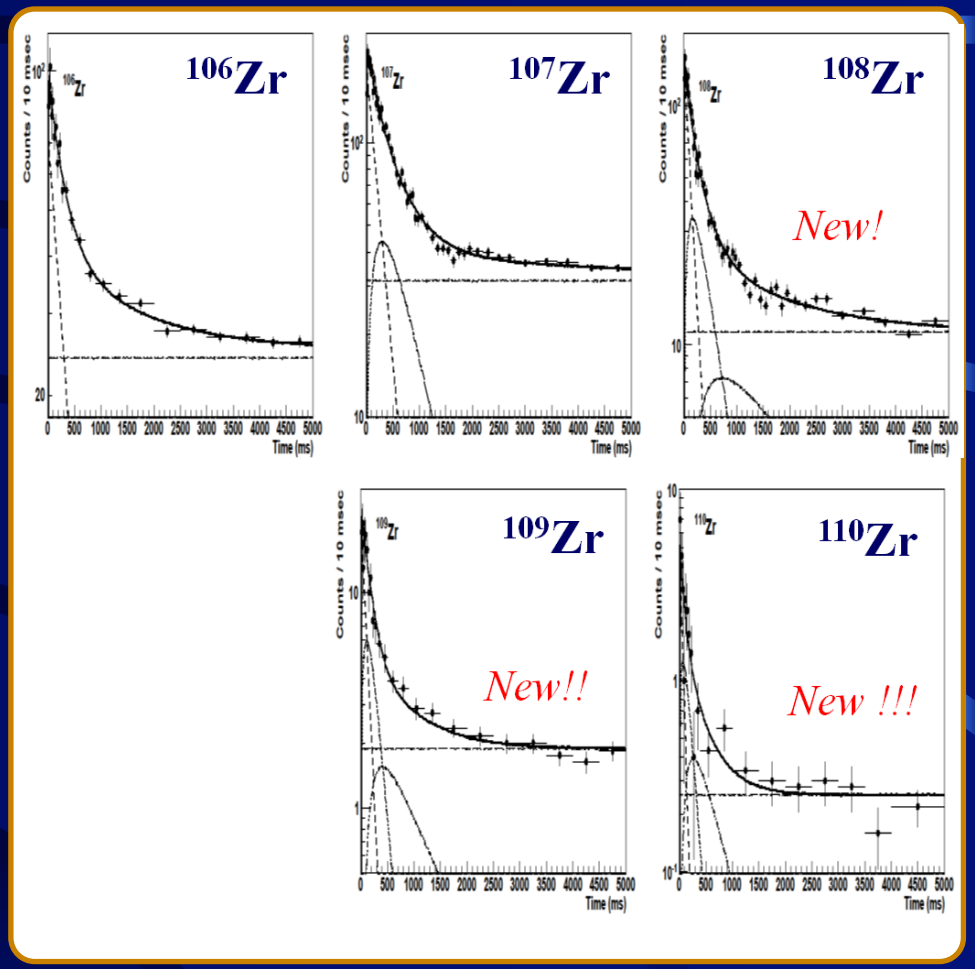
$T_{1/2}$

Beta-decay Half-life $T_{1/2}$ for Kr-Tc

Part of data set (8 hours)
Implantation rate ~ 8 cps



Decay Curves 0 – 5 sec



Decay Experiment in 2009

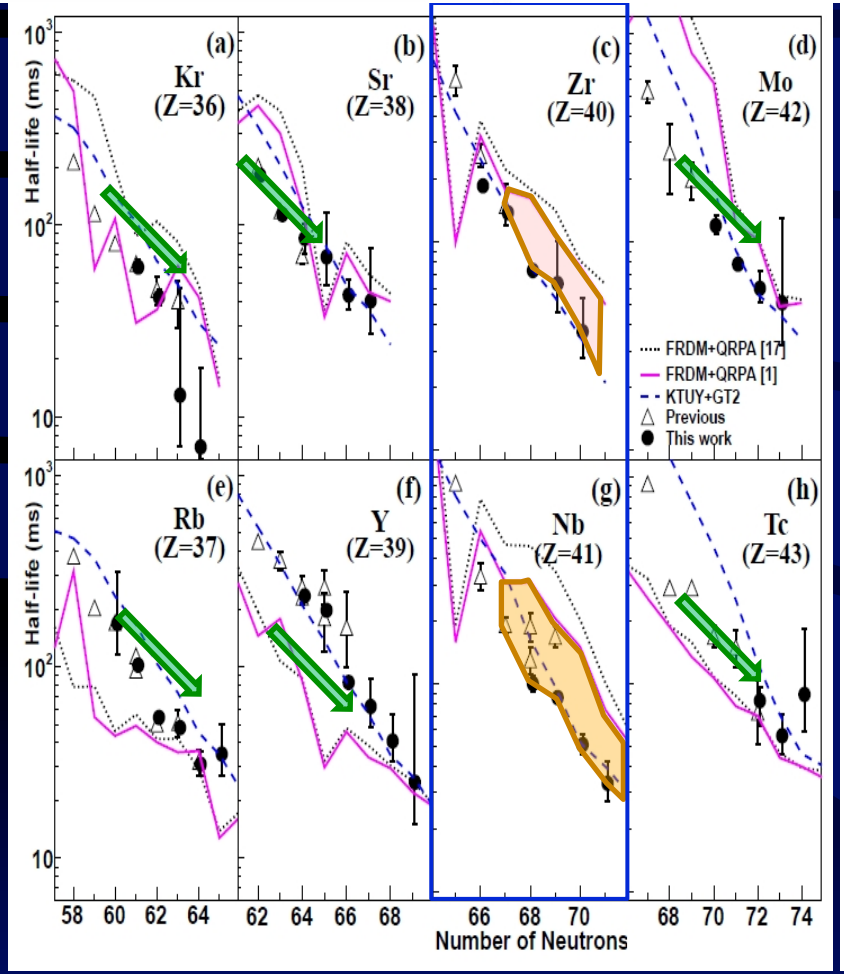
$$\frac{1}{T_{1/2}} = \sum_{0 \le E_i \le Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i),$$

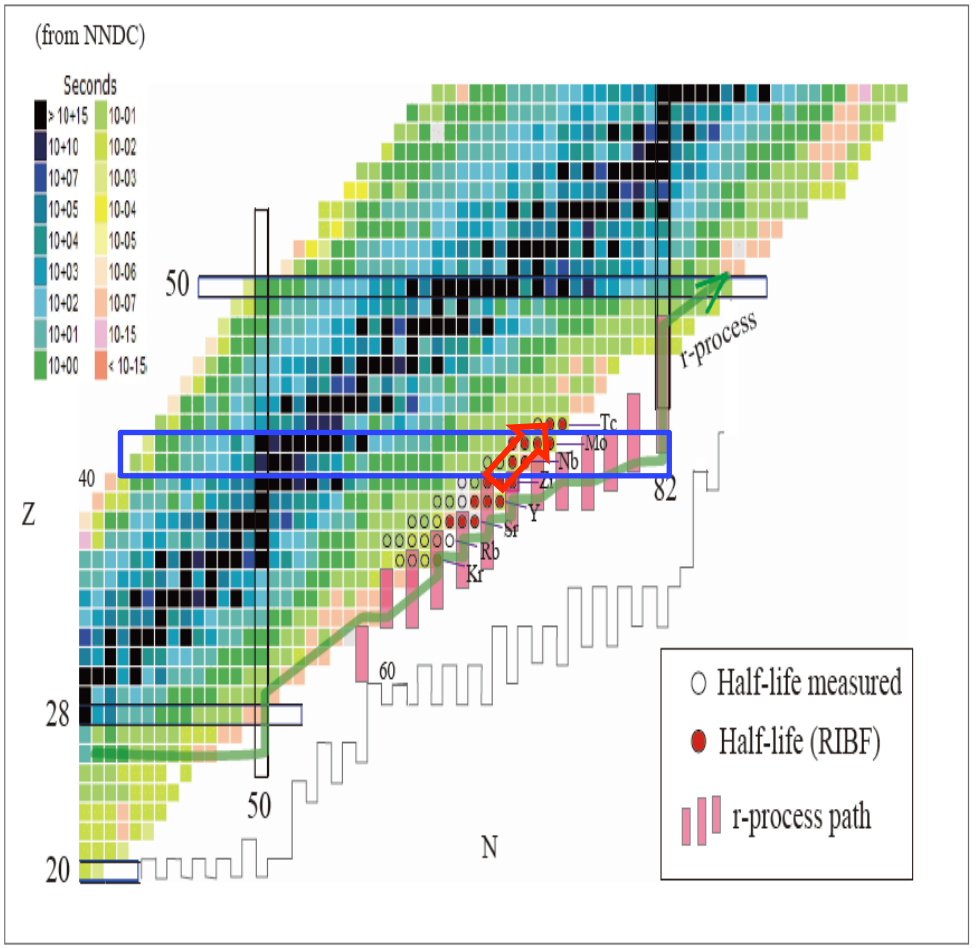
Half-lives (isotope)

β-strength function

Phase-space factor
$f \sim (Q_\beta - E_i)^5$,
dominant at neutron rich region (large Q_β)

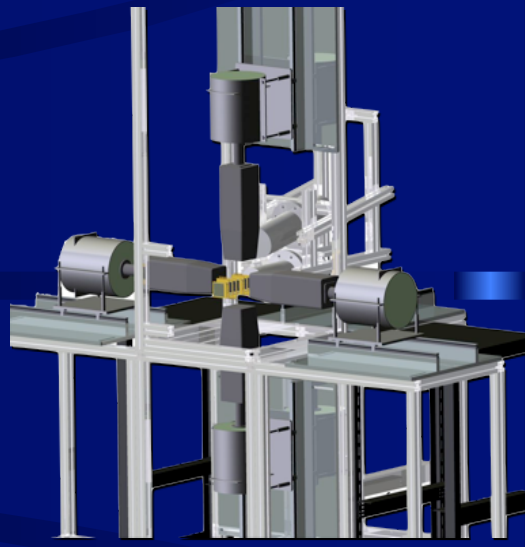
SN PRL106 (2011)





Zr and Nb decay faster than expected by FRDM+QRPA ($T_{1/2}$: 1/2 ~ 1/3)

Upgrade : 2009 → 2012



U-beam intensity

- 0.2 pnA → ~ 10 pnA … x 50 times

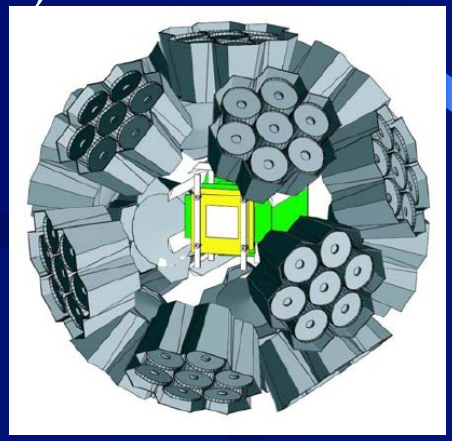
Gamma-ray detector

- 4 Clover detectors

→ 12 Cluster detectors (Det. Eff. ~ 8 % at 1 MeV)

… x 10 times

(→ gamma-gamma coincidence … x 100 times)



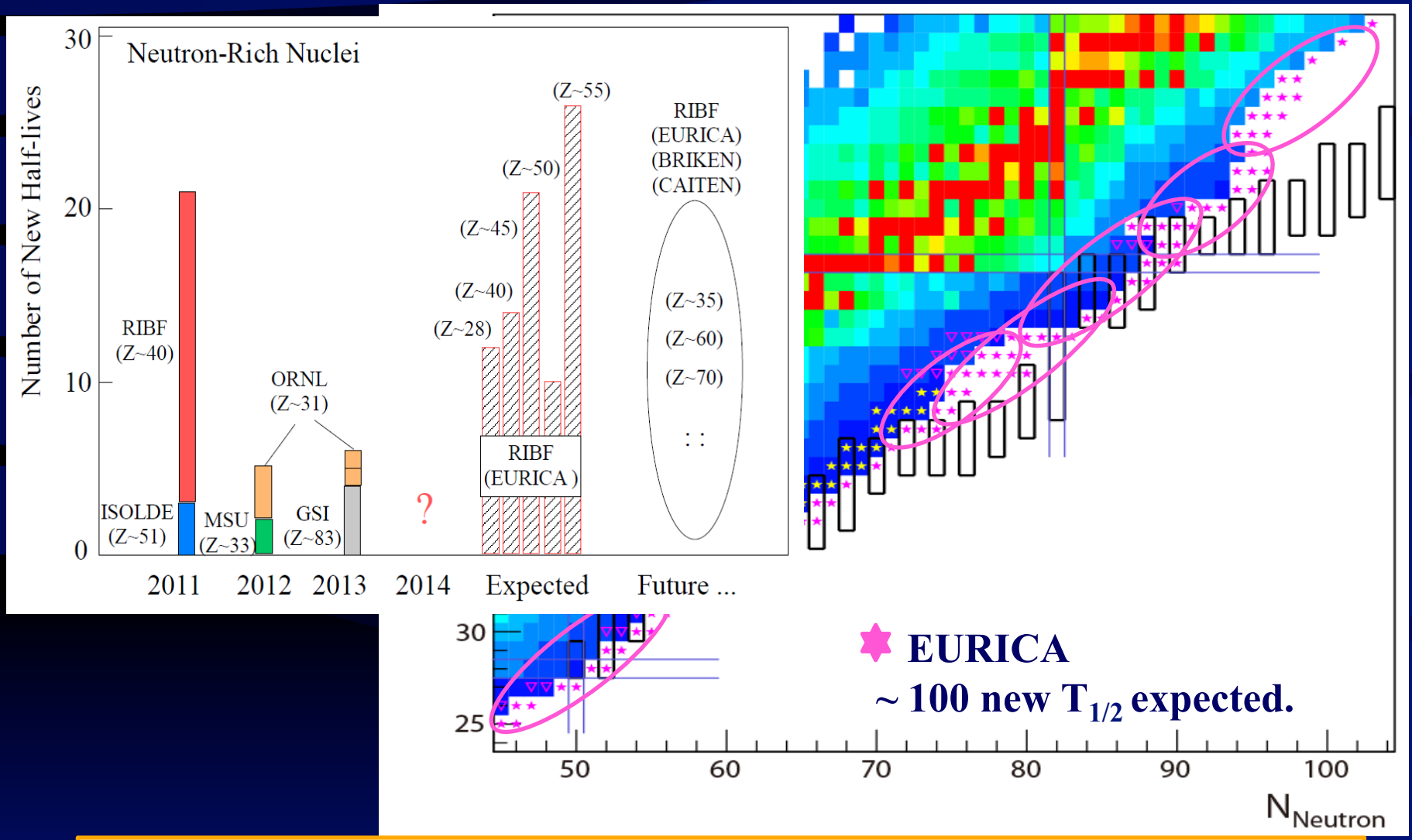
Beta counting system

- 16 x 16 pixels x 7 layers = 1792 pixels

→ 40x60 pixels x 8 layers = 19200 pixels

… x 10 times

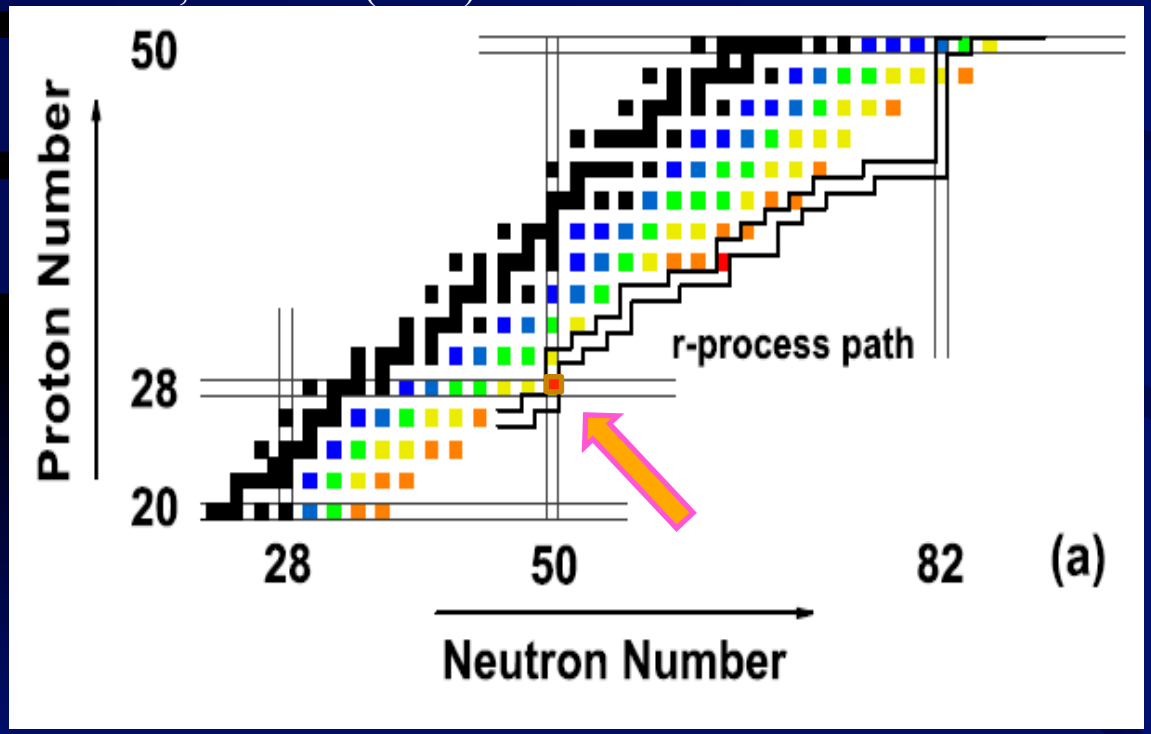
New Half-lives Measurements (2011 ~)



New half-lives of RI → Directory feed into r-process nucleosynthesis calc.
→ Feedback to theory.

Decay Spectroscopy in the vicinity of double magic ^{78}Ni (Z=28, N=50)

Z.M.Niu, PLB 723 (2013)



[History of ^{78}Ni]

-1997

Identified as sew isotope (3 events)

M.Bernas et al., PLB415 (1997)

- 2005

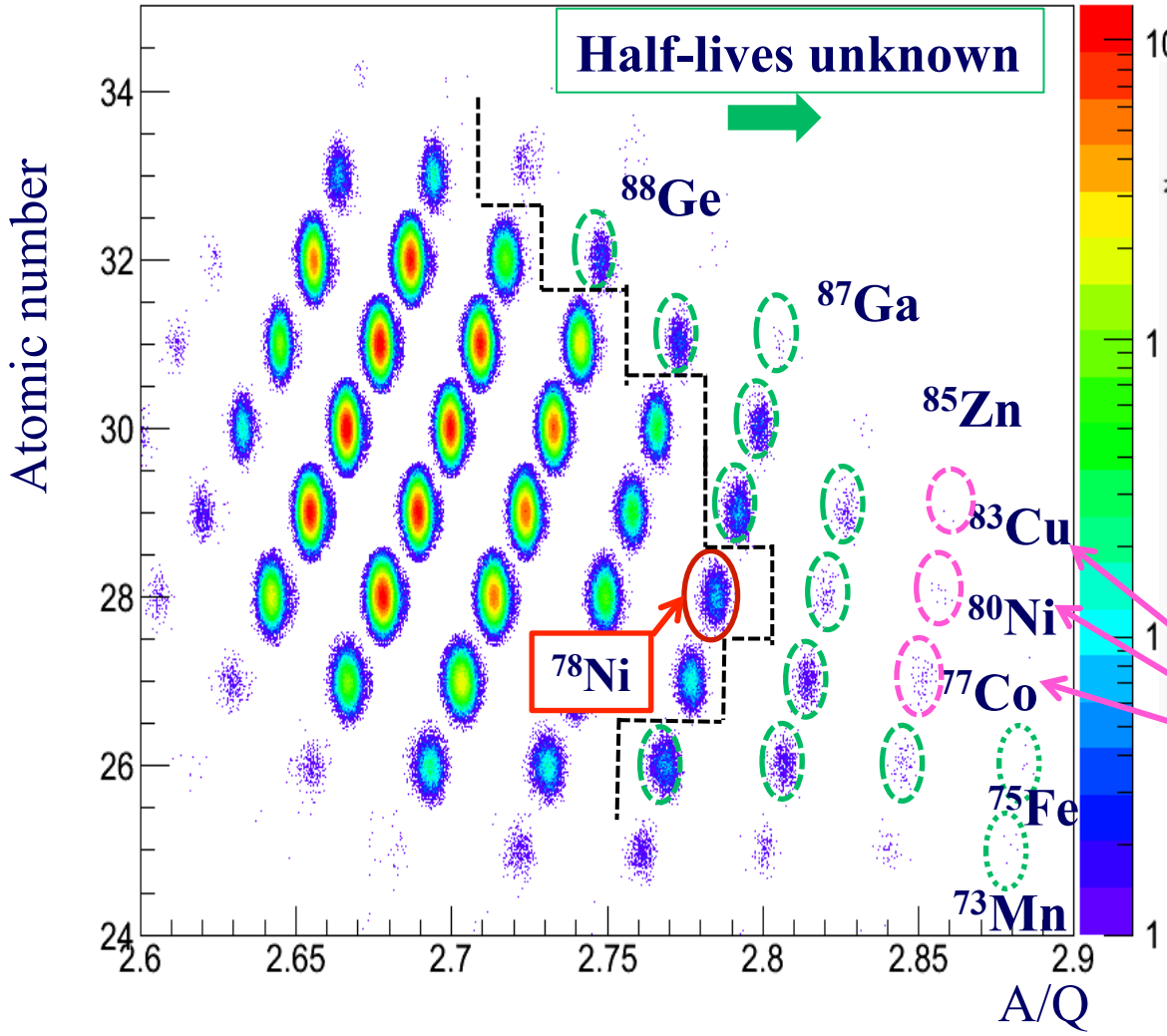
Beta-decay half-life (11 events)

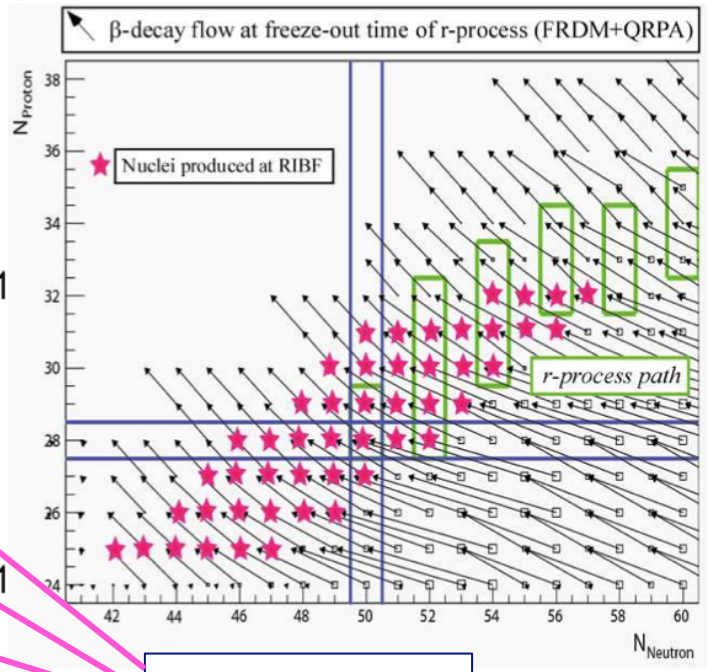
$T_{1/2} \sim 110^{+100}_{-60}$ ms

T.Hosmer et al., PRL94 (2005)

RIBF: Decay Experiment around ^{78}Ni region

Spokesperson : SN / Niikura





New isotopes (Candidates)

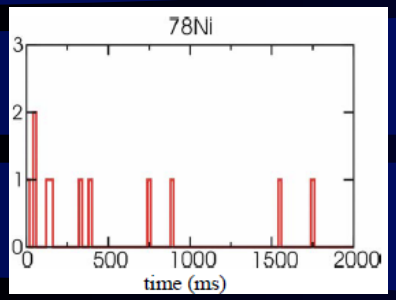
Implantation rate
= 20 ~ 50 pps

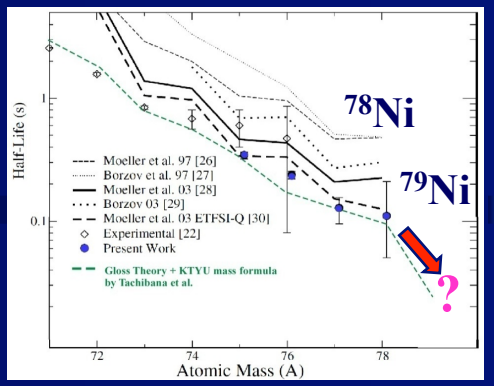
~ 12 k of ^{78}Ni produced at the RIBF.

Low production yield of ^{79}Ni (^{78}Ni + neutron)

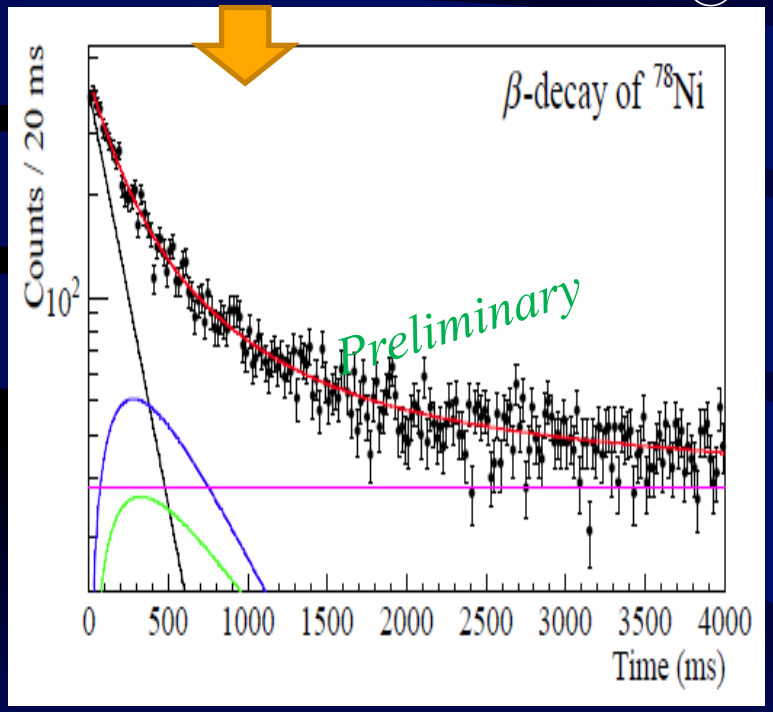
^{78}Ni beta-decay half-life

Hosmer (MSU)
PRL (2006)





Z.Xu PhD@U.Tokyo



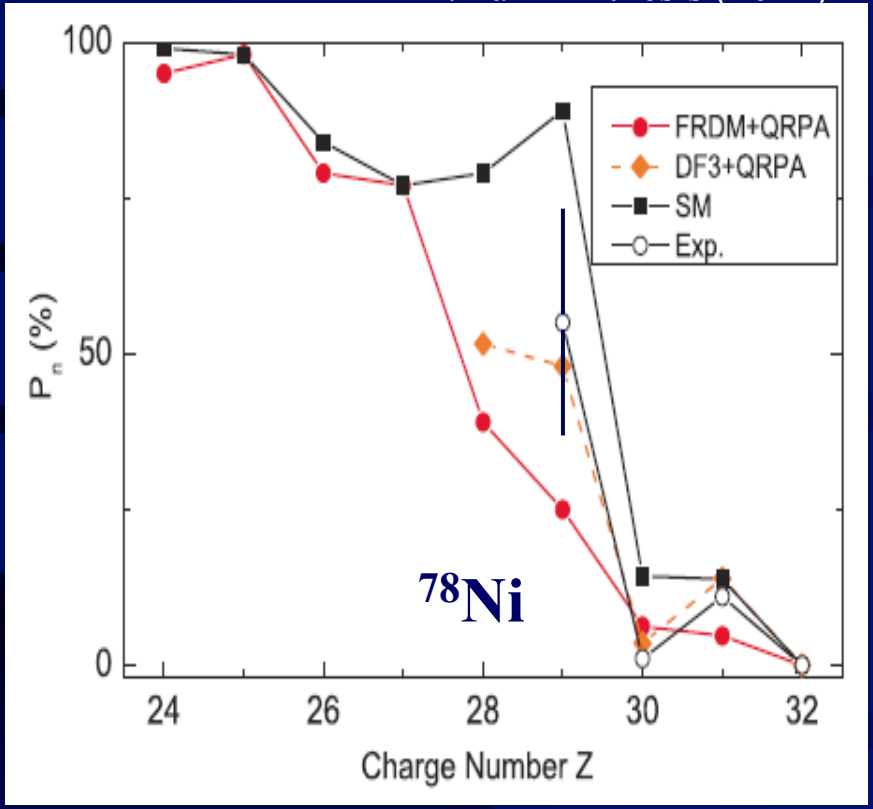
Gated on β-delayed γ

Decay spectra obtained in WAS3ABi and with EURICA.
What about N=51 (^{79}Ni)? Z=27 (^{77}Co)?

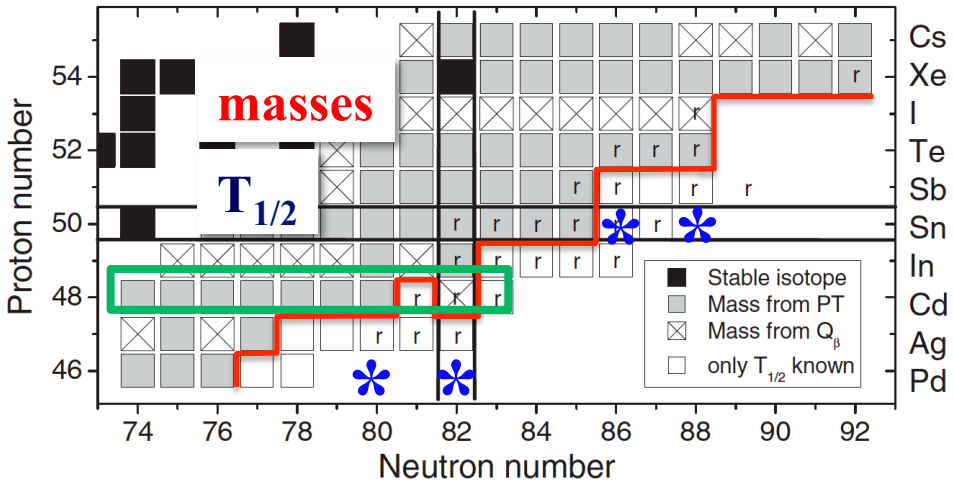
Half-lives and Pn on N = 50

(Experiment ←→ Theory)

Z.Xu PhD thesis (2014)



Decay properties around double magic ^{132}Sn (Z=50, N=82)



J. Hakala et al., Phys. Rev. Lett. 109 (2012) 032501

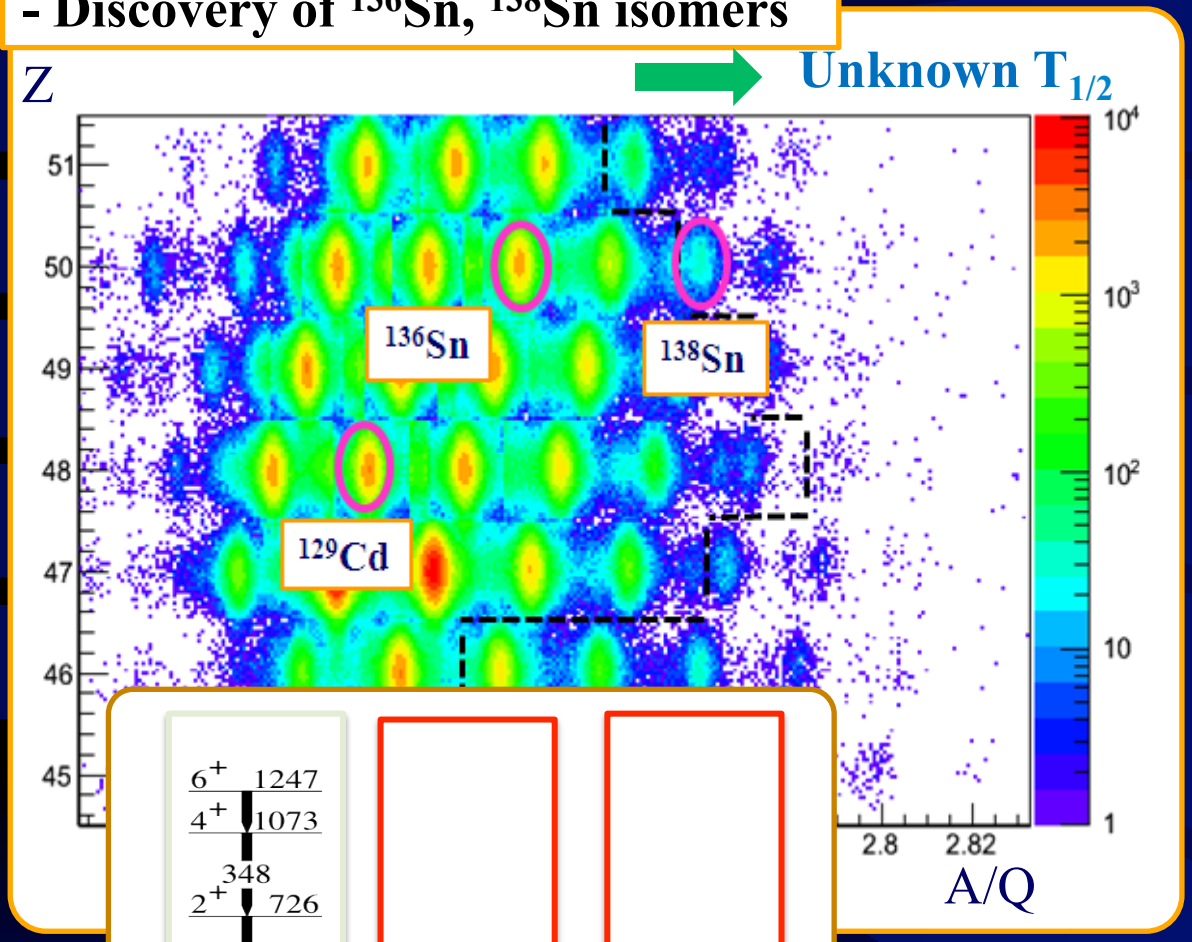
New isomers around 132Sn region

Half-lives of Cd isotopes

$^{136\text{-}138}$Sn Region (Z=50)

Spokespersons:
G.Simpson /A.Jungclaus/Gadea

- Discovery of ^{136}Sn, ^{138}Sn isomers



875.000 ions

^{136}Sn

Very short T ½ !

^{138}Sn

5.000 ions

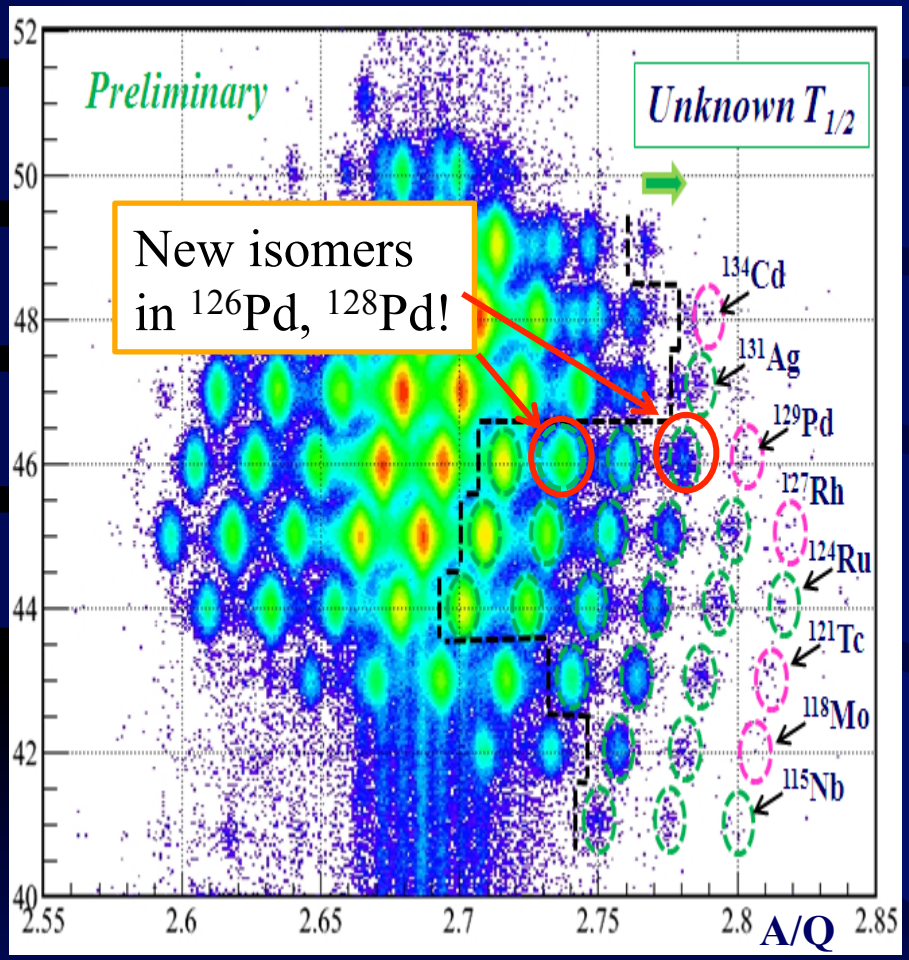
G. Simpson, G.Gey, A.Jungclaus .. submitted to Phys. Rev. Lett.

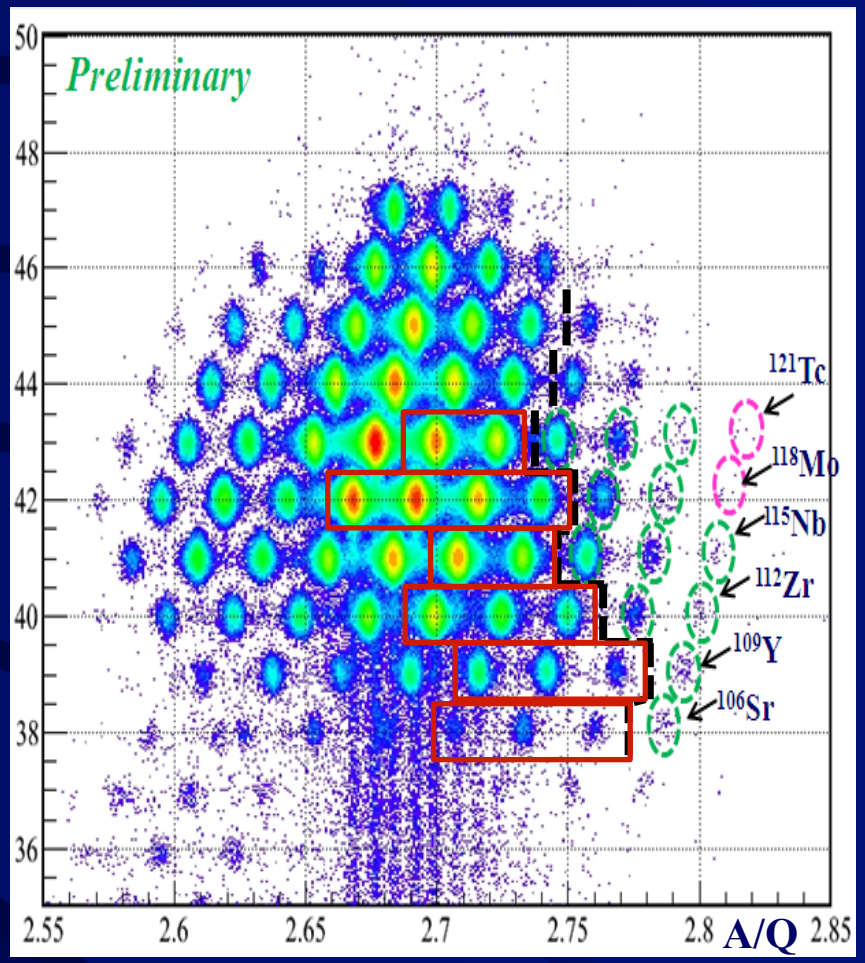
^{136}Sn … H.Wang , PTEP (2014) … RIKEN

Decay Spectroscopy around ^{128}Pd and ^{115}Nb

New Isotopes

Spokespersons: H.Watanabe/G.Lorusso

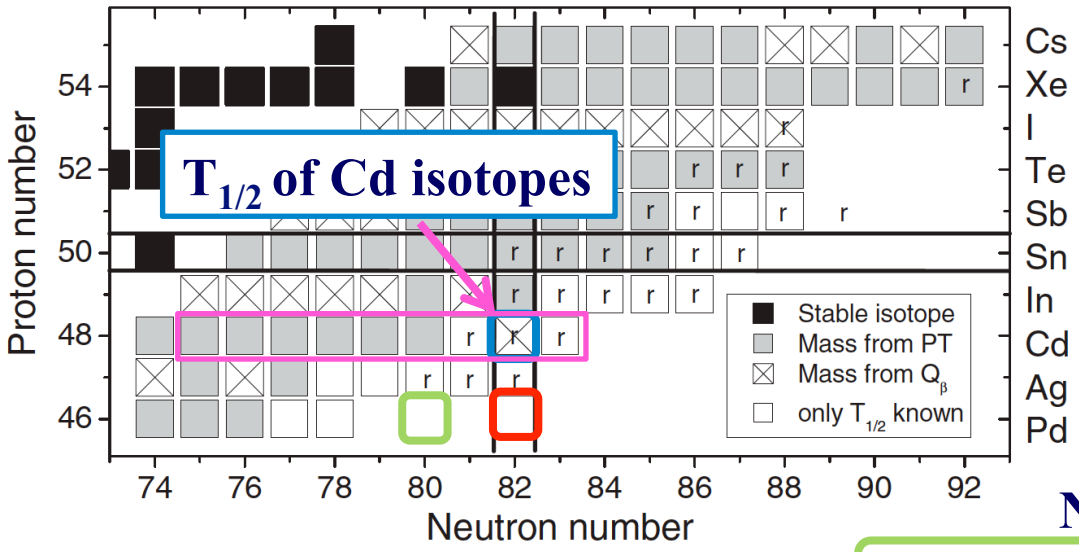




PRL **106,** 052502 (2011) PHYSICAL REVIEW LETTERS week ending 4 FEBRUARY 2011

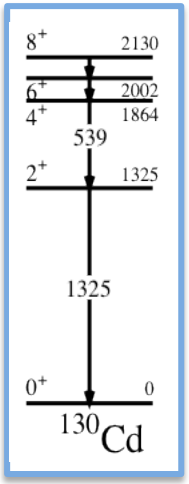
β-Decay Half-Lives of Very Neutron-Rich Kr to Tc Isotopes on the Boundary of the *r*-Process Path: An Indication of Fast *r*-Matter Flow

Most Neutron-Rich N=82 Isomer with EURICA
(r-Process waiting point)

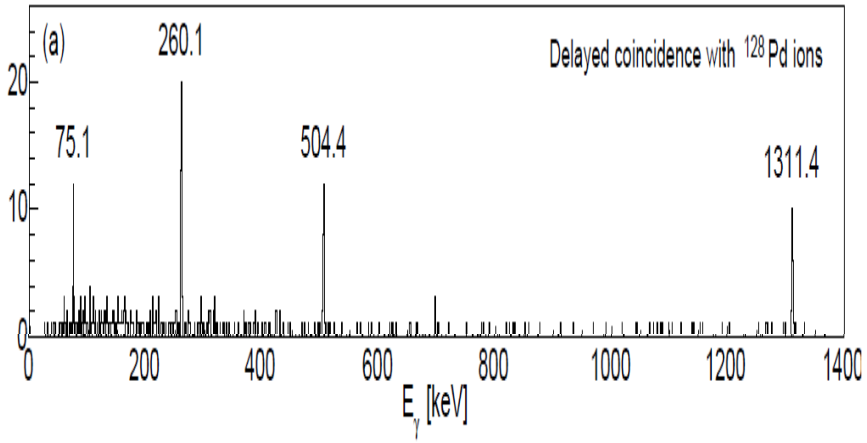


A.Jungclaus,
PRL99, (2007)

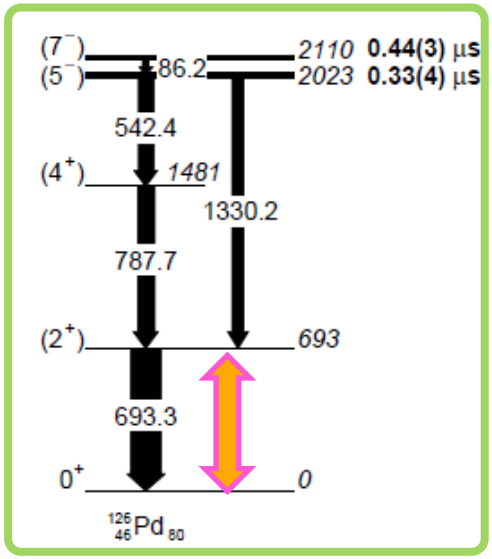
No evidence
for shell quenching



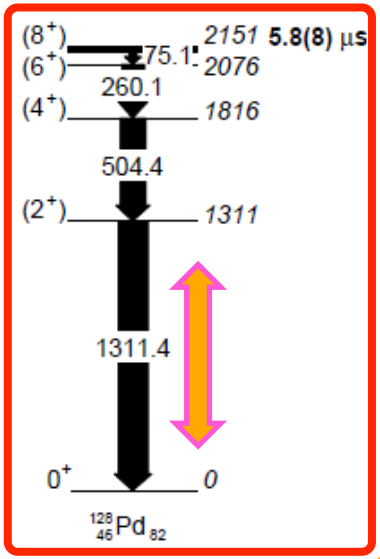
H. Watanabe, G. Lorusso et al., PRL111 (2013)



N=80



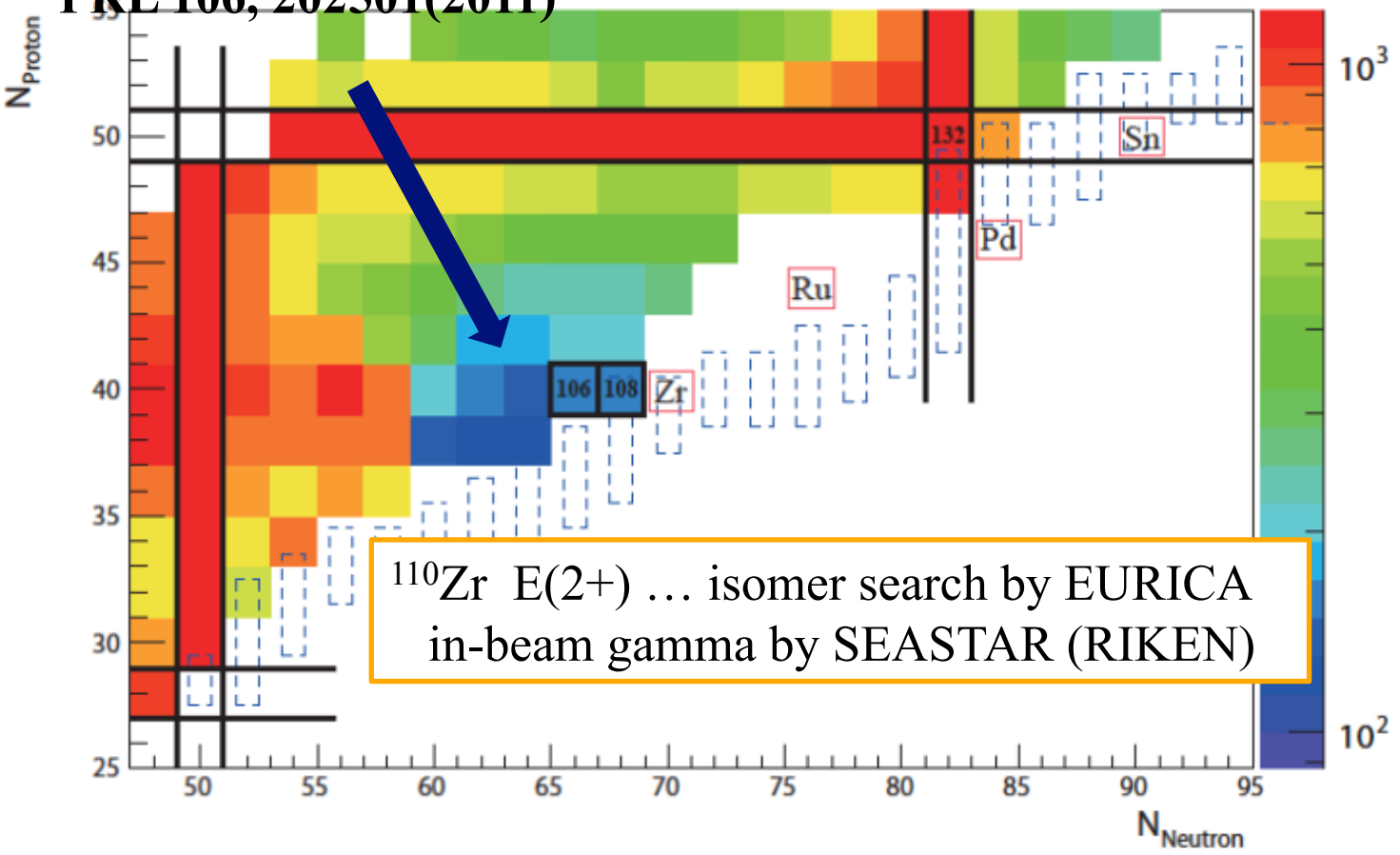
N=82



→ No evidence for shell-quenching in ^{128}Pd….

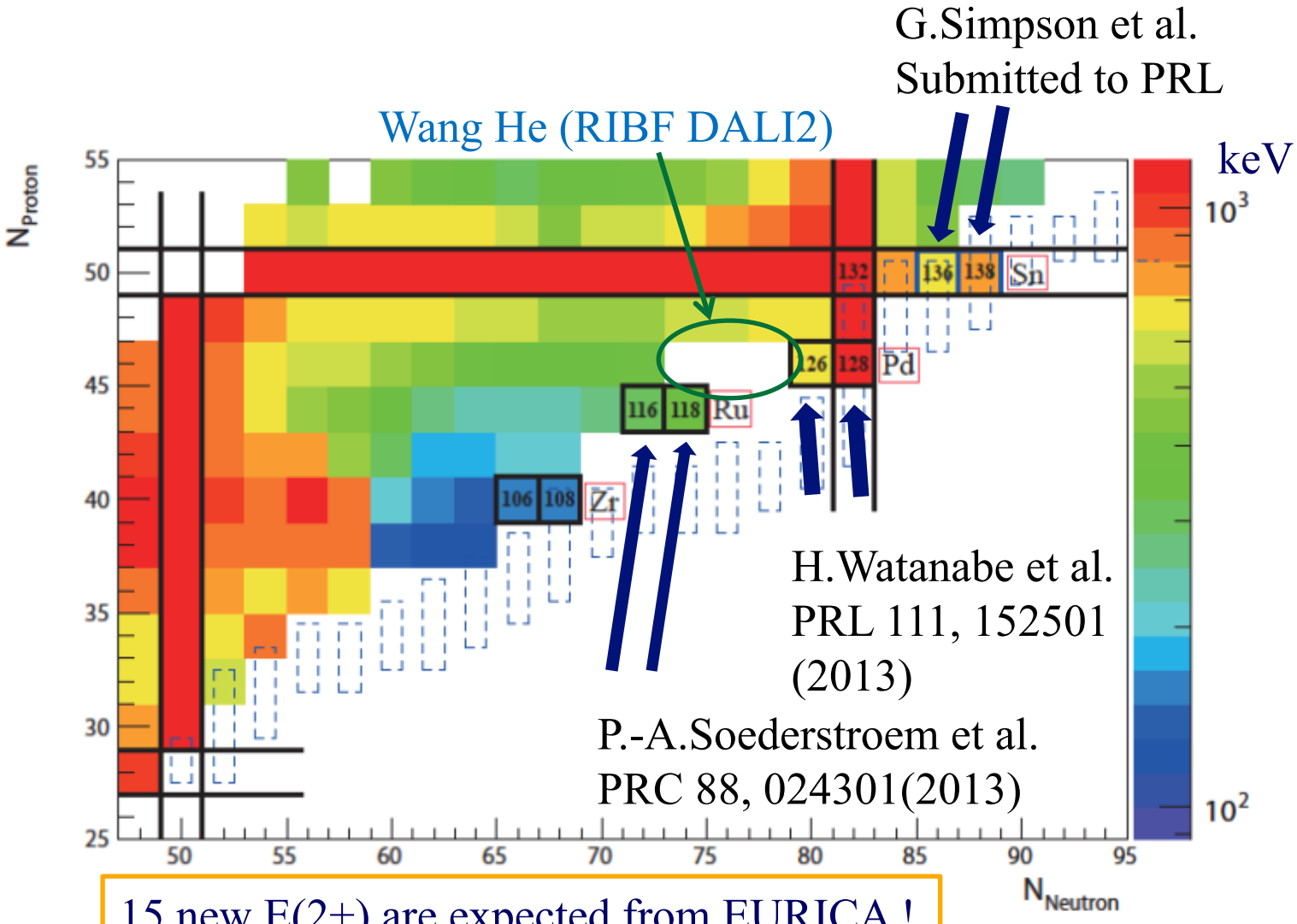
First Excited State: E(2+)

T.Sumikama et al.
PRL 106, 202501(2011)



^{110}Zr E(2+) … isomer search by EURICA
in-beam gamma by SEASTAR (RIKEN)

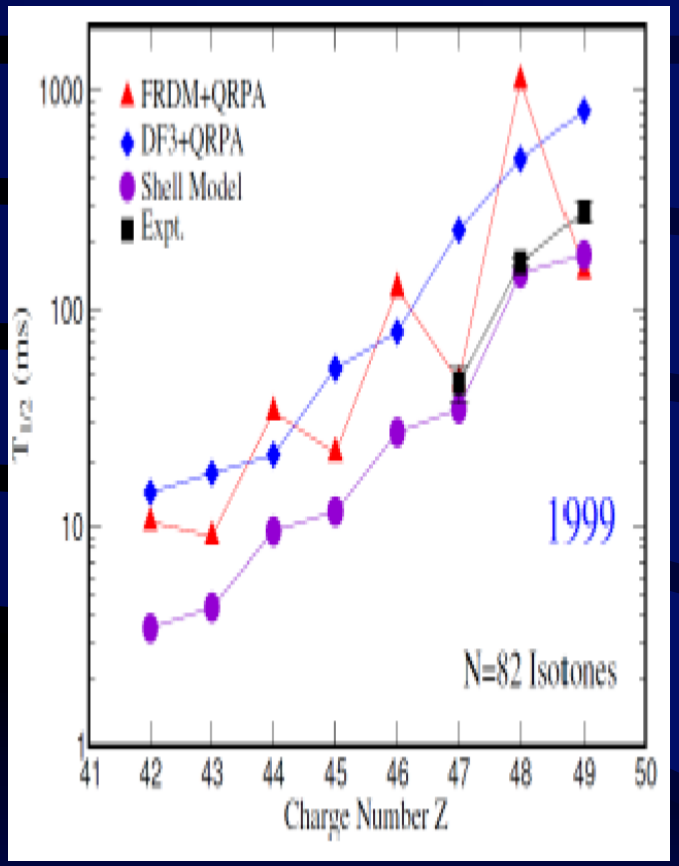
First Excited State: E(2+)

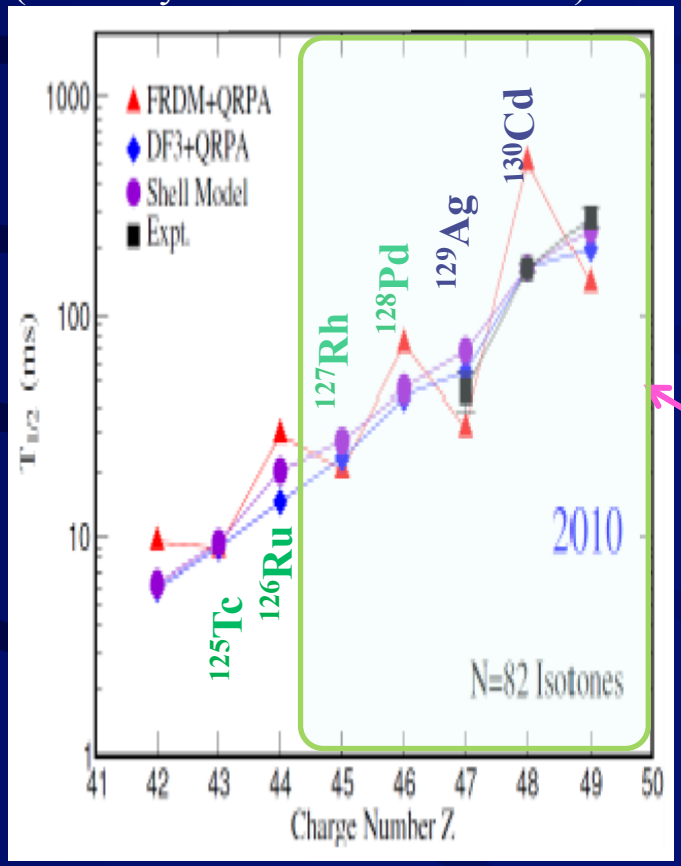


15 new E(2+) are expected from EURICA !
And more …

Beta-decay Half-lives N = 82
→ Feedback to the Theory

K.Langanke Phys. Scr. T152 (2013) 014011
(Courtesy of G. Martines-Pinedo)



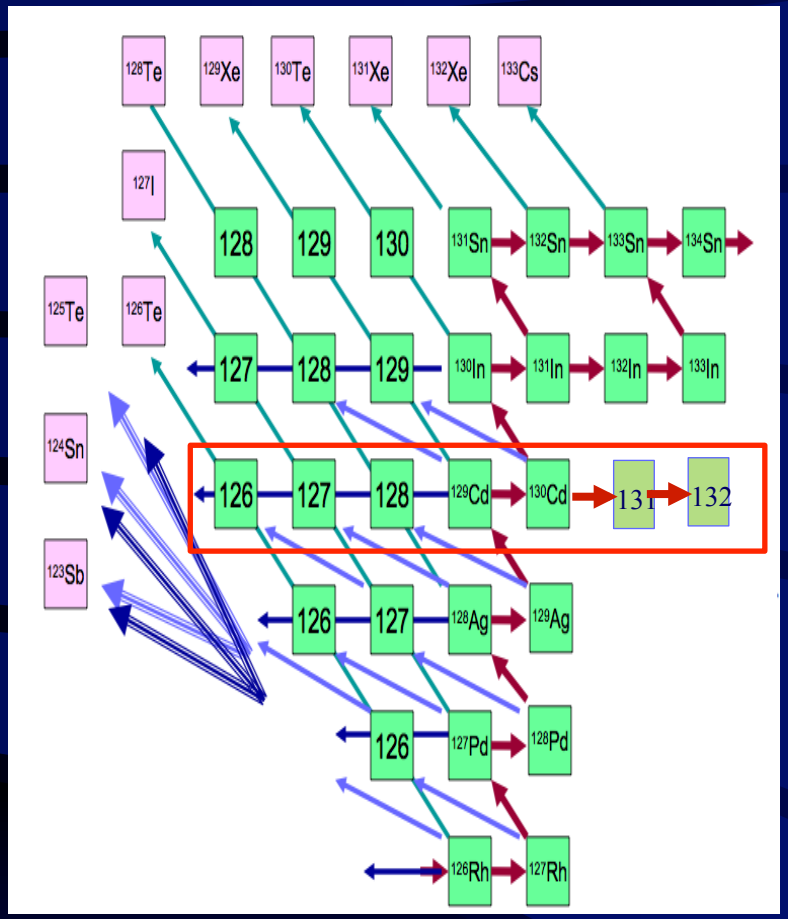


RIBF
EURICA

So call r-process waiting point nuclei (N=82)
- r-process path
- residual r-matter flow in freeze-out

$T_{1/2}$ of Cd isotopes (EURICA)

Beta-decay half-lives of Cd isotopes (RIBF)



^{130}Cd isomer: Consistent
RISING – EURICA
(GSI) (RIBF)

Significant impact to SM calc. & r-process simulation !

Beta-delayed gamma of ^{131,132}Cd → ^{131}In.

Low lying state in ^{131}In
(^{131}Cd beta-decay, ^{132}Cd beta-delayed neutron)

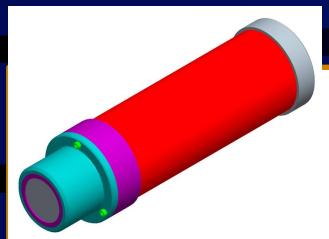
RIBF (EURICA) + Shell Model calc.

J.Taprogge, A.Jungclaus, H.Grawe, et al.
To be published in Phys. Rev. Lett.
(please wait..)

Robust evidence for the disappearance of the Z = 38, 40 proton subshell closures at N = 82 (^{120}Sr and ^{122}Zr) .

Complementary $LaBr_3$ array for fast timing with EURICA

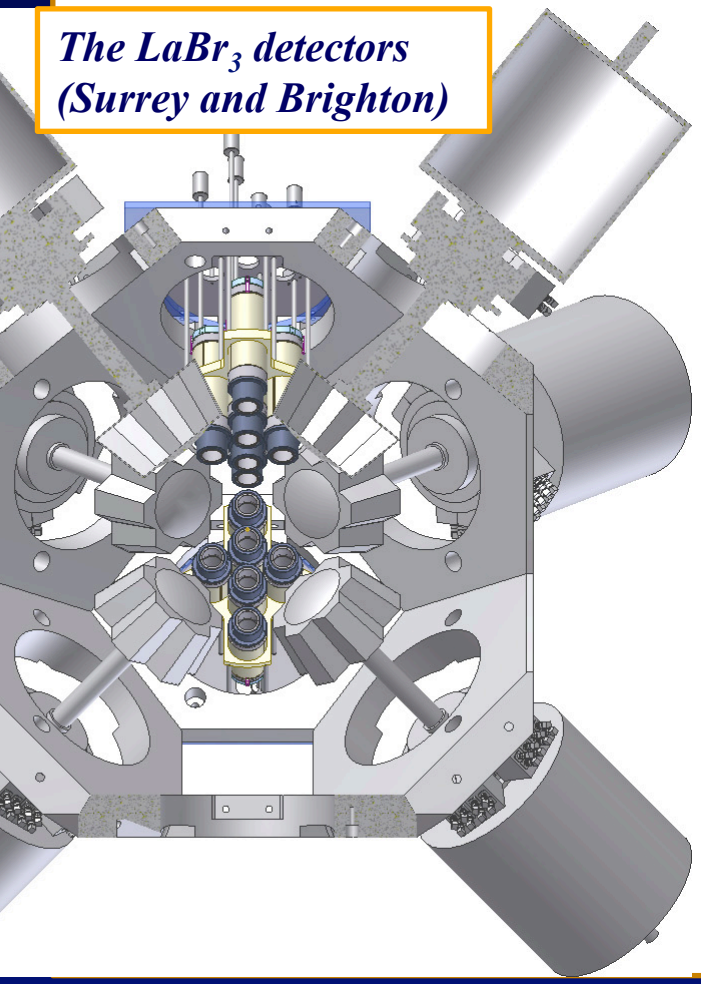
18 detectors
φ1.5” x 2”

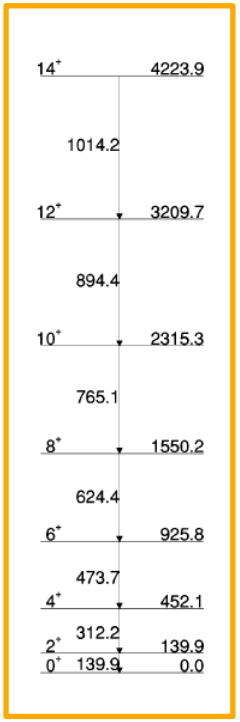


Spokesperson: T.Sumikama

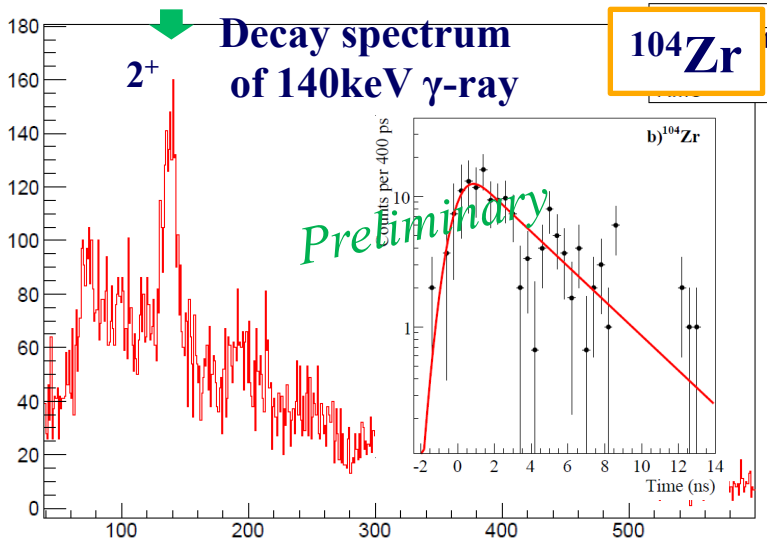
- **For short life-times a $LaBr_3$ array for fast timing has been installed to complement the HPGe detectors**

The $LaBr_3$ detectors (Surrey and Brighton)





^{104}Y beta-decay is used as start.



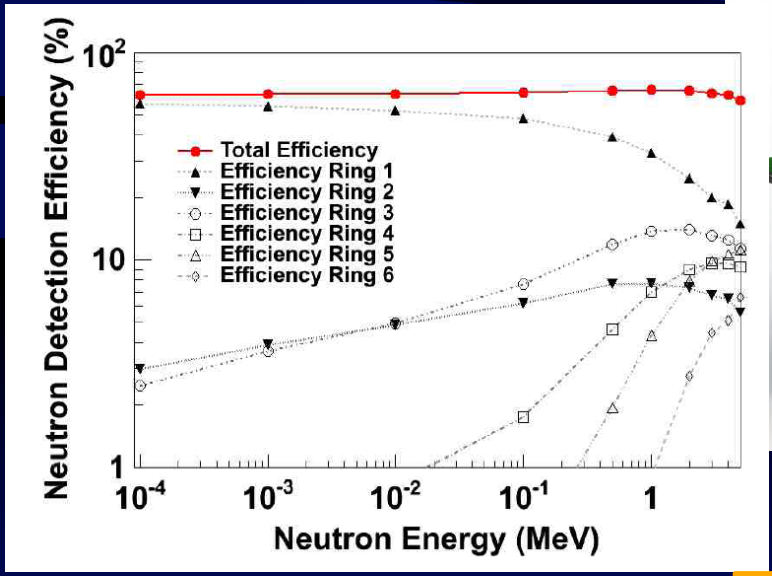
F.Browne

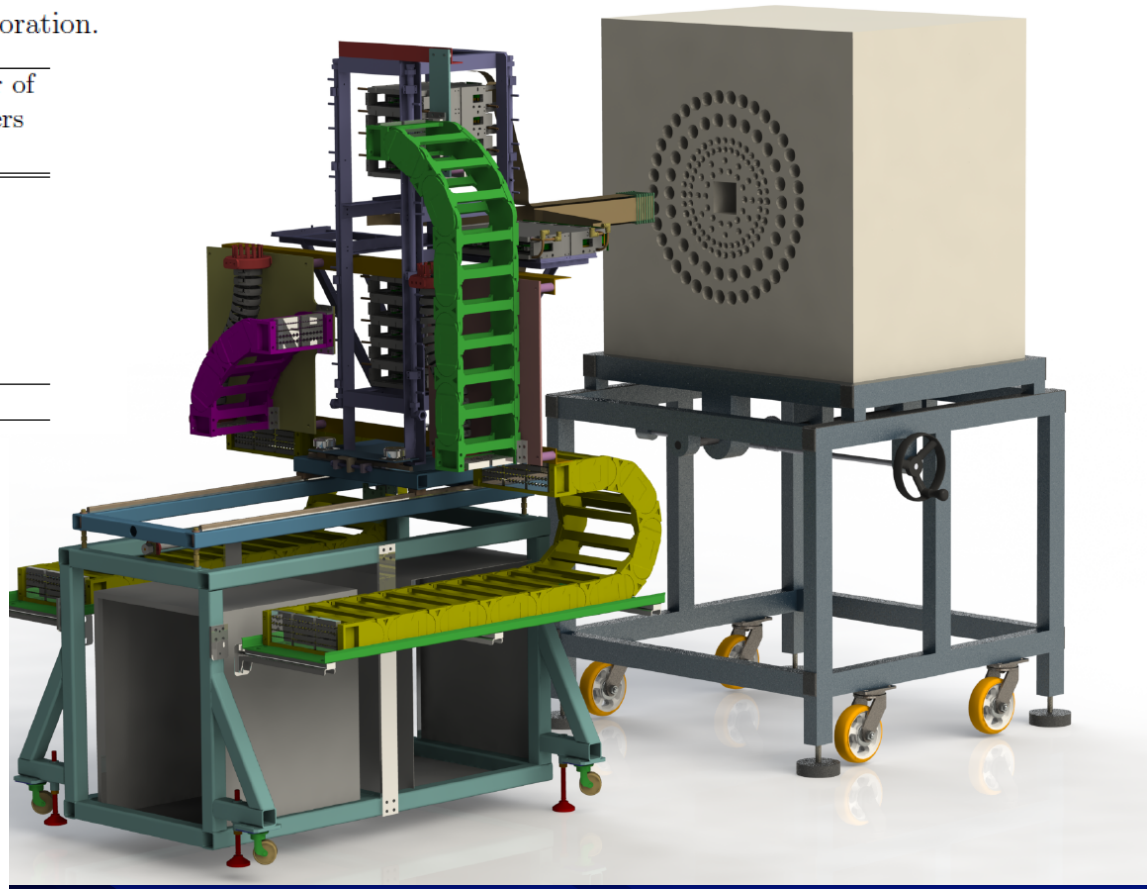
BRIKEN Project (RIBF)

Monster of 3He Detectors

Table 1: ^{3}He tubes available within the BRIKEN Collaboration.

Owner	Pressure (atm)	Size		Number of Counters
		Diameter (inch/cm)	Eff. Length (inch/mm)	
GSI	10	1 / 2.54	23.62 / 600	10
JINR	4	1.18 / 3.0	19.69/500	20
ORNL	10	2 / 5.08	24/609.6	67
ORNL	10	1 / 2.54	24/609.6	17
RIKEN	5.13	1 / 2.54	118.1/300	26
UPC	8	1 / 2.54	23.62/600	42
		Total		182

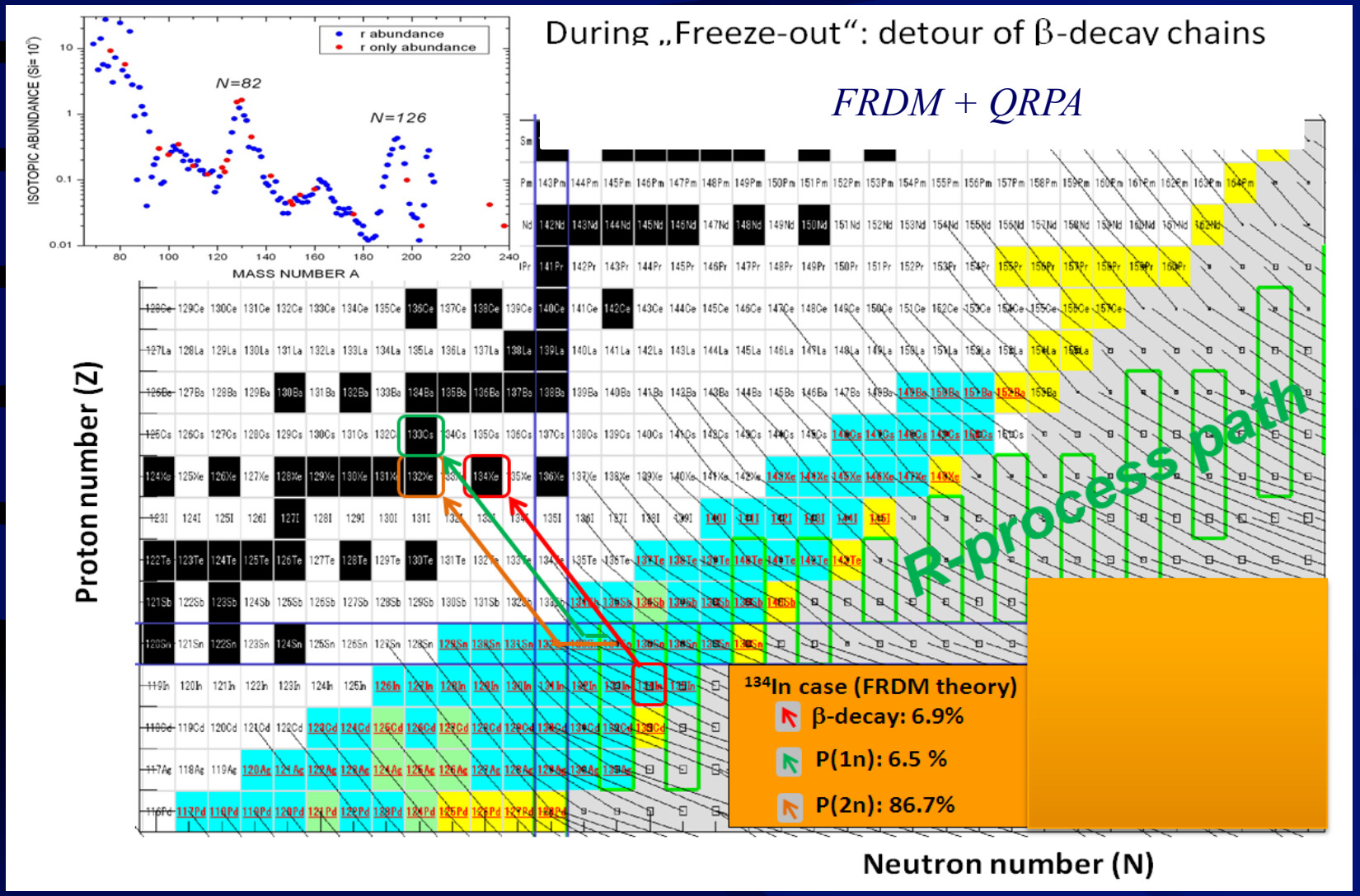




Silicon detectors
(AIDA from UK)

Very high efficiency neutron detector
→ Survey of beta-delayed multi-neutron & T1/2

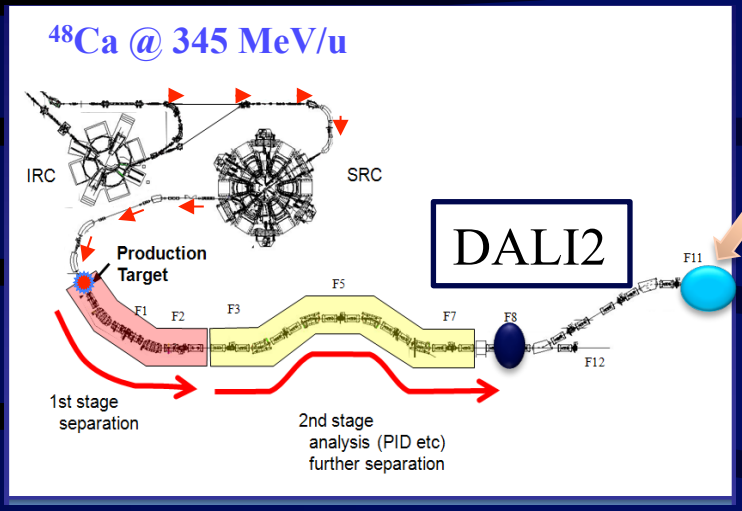
Beta-decay flow

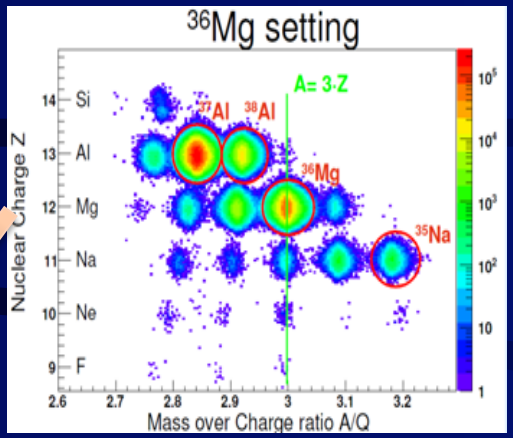


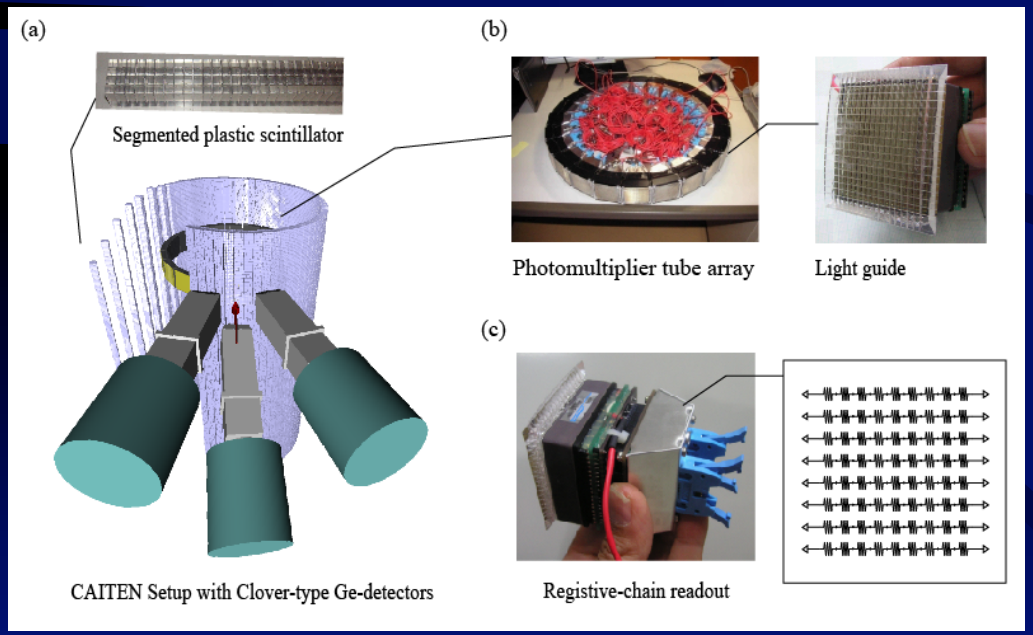
EURICA Project + BRIKEN Project

→ Beta-delayed multi-neutron emission measurement

Fast-timing beta-counting system: CAITEN





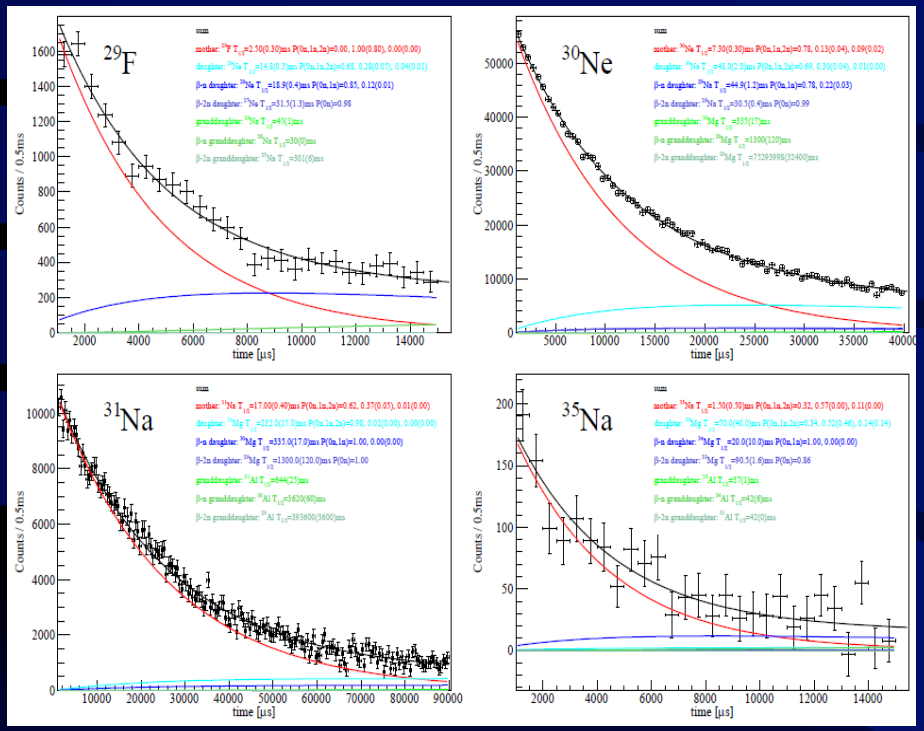


K.Steiger, Z.Li

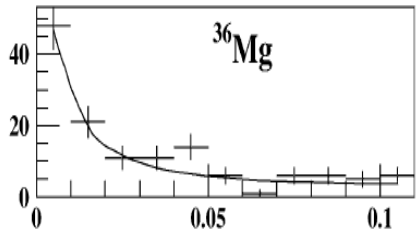
Beta-delayed gamma of ^{37}Al

Beta-decay half-lives (CAITEN)

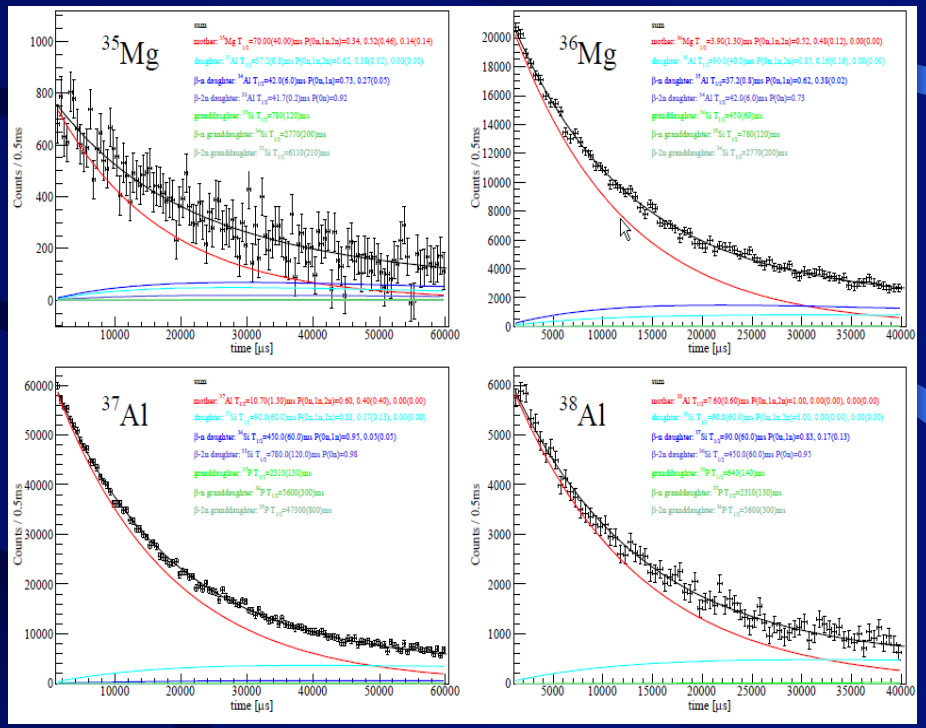
K.Steiger, SN et al., Bormio Proc. 032 (2013)



S.Grevy, et al. (2004)



High statistic



High precision $T_{1/2}$ measurement
(implantation rate 300 ~ 1 kcps)

Proton rich nuclei

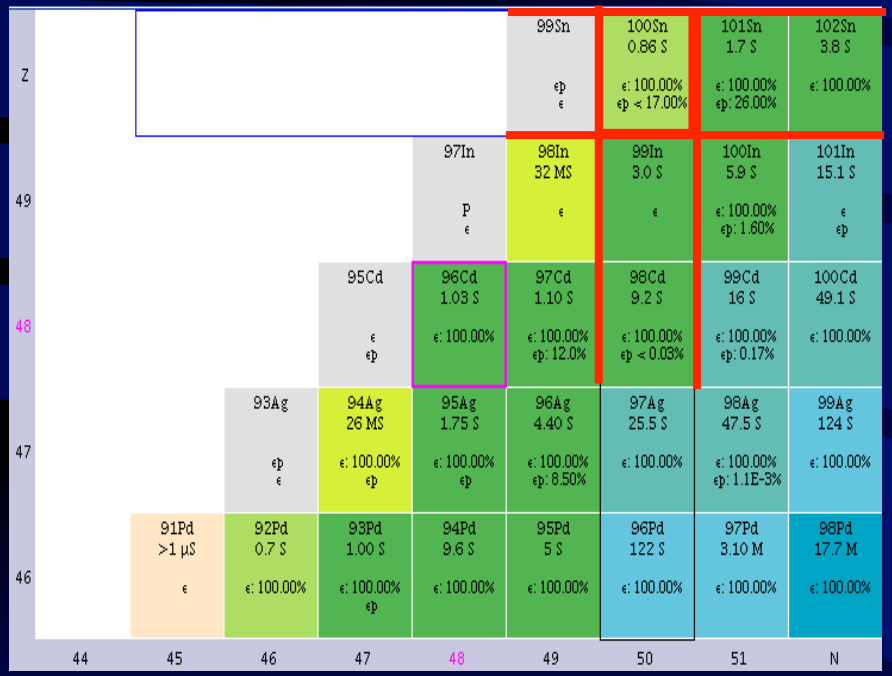
(EURICA)

Decay Spectroscopy in vicinity of ^{100}Sn

^{124}Xe beam int. = 32~ 38 pnA

^{100}Sn ~ 2000 events

M.Lewitwicz, R.Krucken/R.Gernhauser, SN



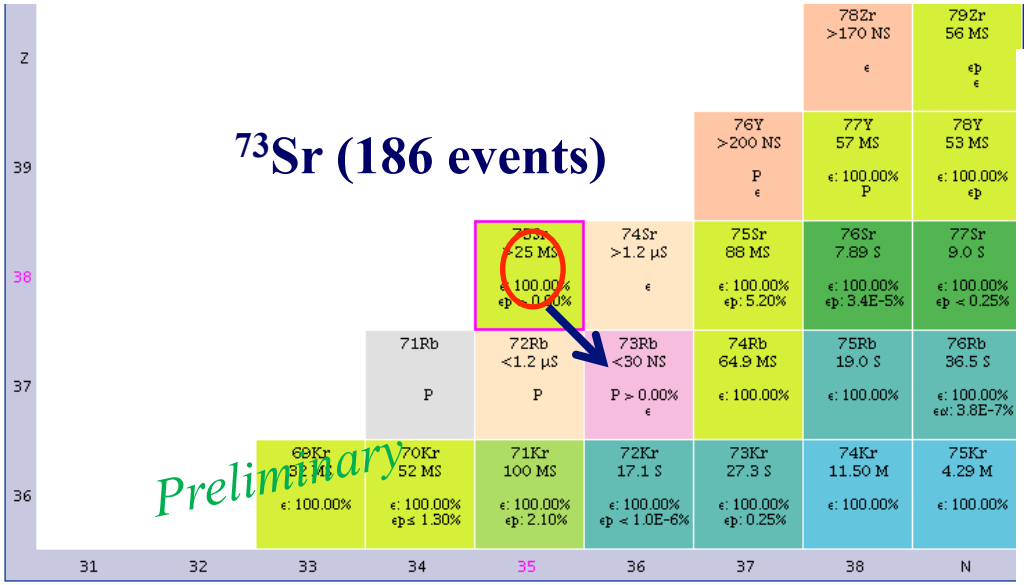
New half-lives: ^{99}Sn and ^{95}Cd

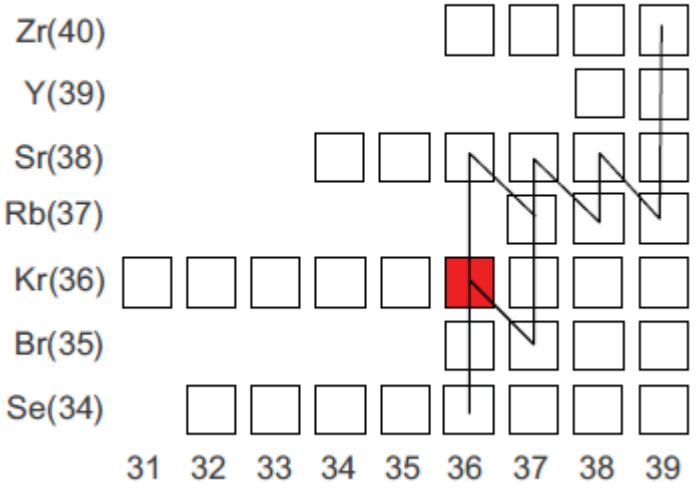
- -Qbeta
- -beta-delayed gamma
- -beta-delayed proton

RIBF097: rp-process (G.Lorusso)

G.Lorusso (RIKEN) … 2.5 days

^{73}Sr (186 events)



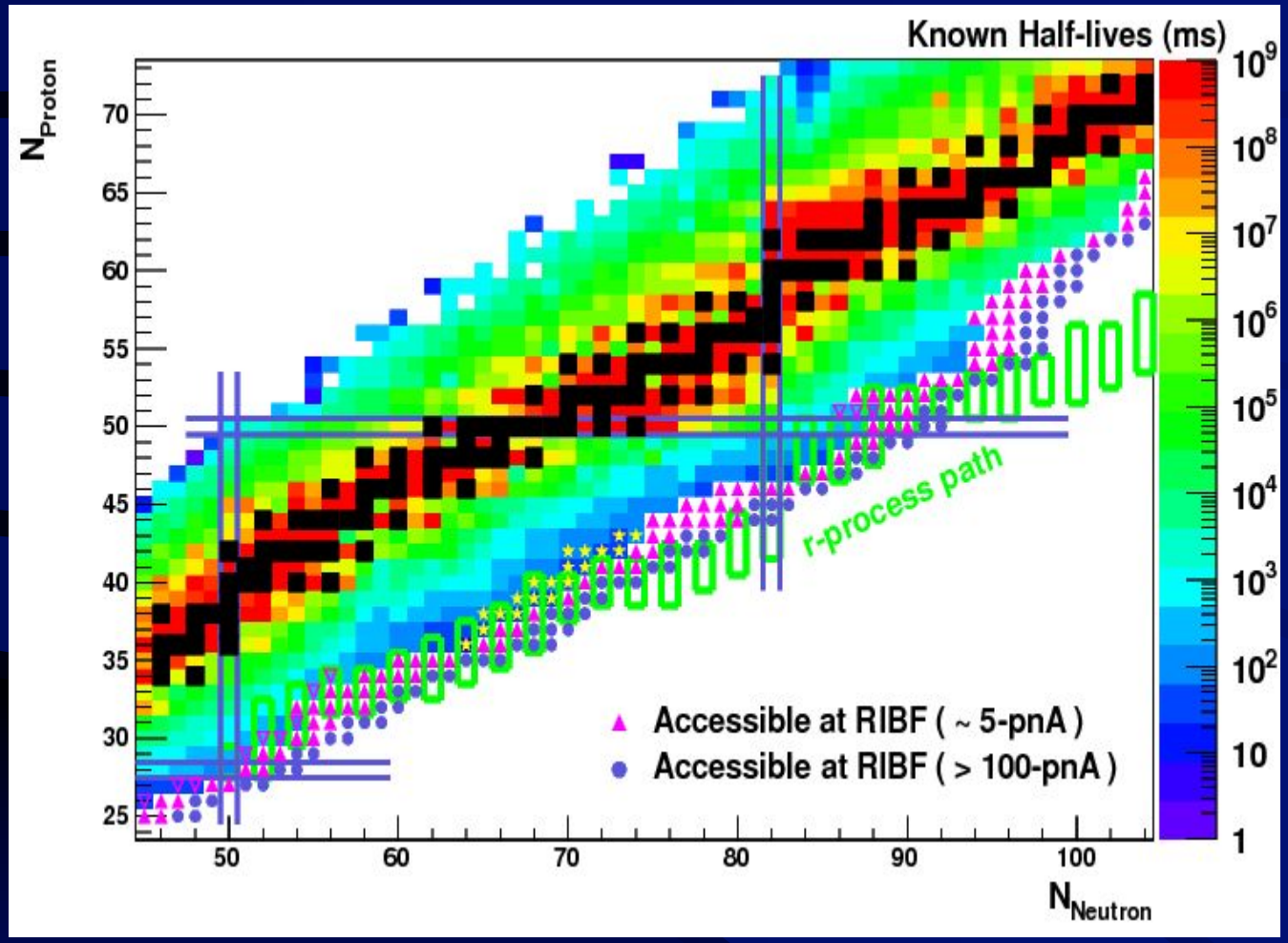


73Sr → 73Rb

→ 72Kr + p … Energy spectrum of beta-delayed proton

… Beta-decay half-lives of ^{73,74}Sr

In five years…
(U-beam int. ≥ 100 pnA!?)

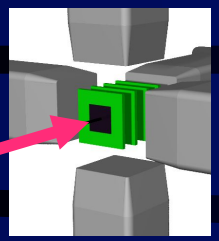


Several hundreds of new beta-decay half-lives in five years.
→ Significant contribution in nuclear structure and r-process nucleosynthesis.

Decay Programs at RIBF

2009 2010 2011 2012 2013 2014

β-γ

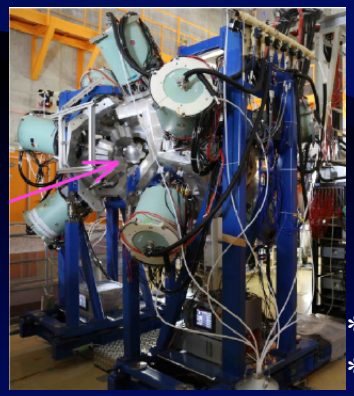


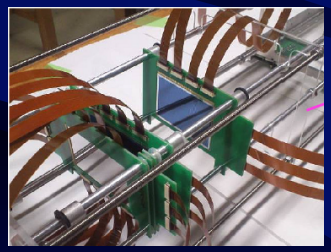
^{110}Zr region
(3-days)

*PLB 696, 186 (2011)
*PRL. 106, 052502 (2011)
*PRL. 106, 202501 (2011)
*PLB 704, 270 (2011)

EURICA Project

WAS3ABi (Si)





*PRC 88, 024301 (2013)
*PRL 111, 152501 (2013)
*PRL *** (2014)

β-n(-γ)
[high efficiency]

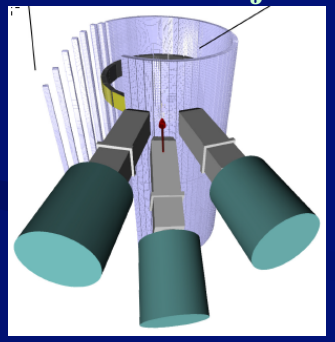
BRIKEN Project

180 ^{3}He counters

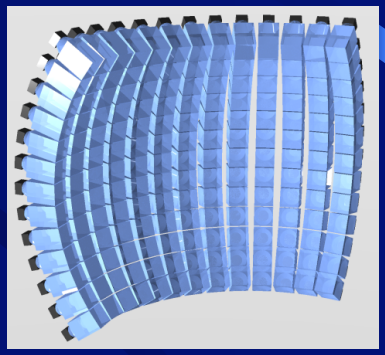
BELEN (Spain)
+3Hen (ORNL)
+GSI/Russia+RIKEN

β-γ-n
[fast timing]

CAITEN Project



- LaBr3 detectors
- Neutron detector
  (NiGIRI)



Summary

- Decay spectroscopy is powerful tool to investigate the properties of exotic nuclei !
  - Beta-decay half-lives (T1/2)
  - Beta-delayed gamma (low lying states), Isomer
  - Qbeta, EC
  - Beta-delayed neutron (proton) –emission
- New projects at RIBF
  - EURICA
  - BRIKEN
  - CAITEN

Rare-RI Ring (Mass)
SLOWRI-MRTOF(Mass)
DALI2 (In-Beam Gamma)

- High intensity radioactive beam facility
  - RIBF , FAIR, FRIB, GANIL, TRIUMF, ISOLDE, RISP, …

→ Golden time for nuclear structure & nuclear astrophysics

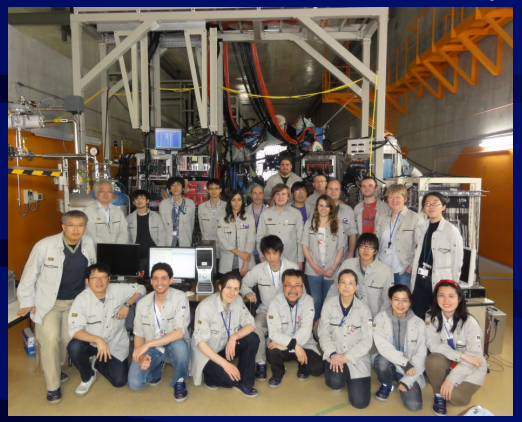
(Magicity, Shell-quenching, Deformation

→ r-process, rp-process, …)

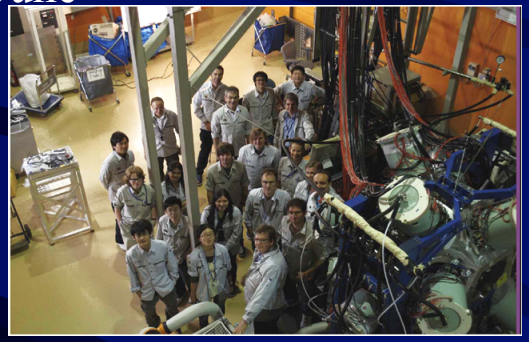
EURICA Collaboration and Support

2012 Nov.-Dec.

2013 May



2012 June



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Collaboration:
Tohoku, Univ. Tokyo, Brighton Univ. Debrecen, Joseph Fourier, Osaka Univ. Peking, LPSC, IBS, Oslo, Consejo Sup. De Inv. Cientificas, IPN Orsay, Padova, Leuven, SKKU, INFN, ANU, Koeln, TU Muenchen, Fisica, Legnaro, ATOMKI, INFN-Milano, INFN-Firenze, INFN-LNL, Univ. di Padova, Surrey, GSI, ANL, Yale, Milano, Univ. Madrid, Tech. Univ. Darmstadt, Univ. Istanbul, CNS, CEA, RCNP, Univ. Notre Dame, Inst. voor Kern-en Stralings Fysica, Hoseo Univ., Univ. Tsukuba, Inst. Plurid. Hubert Curien, and RIKEN

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—

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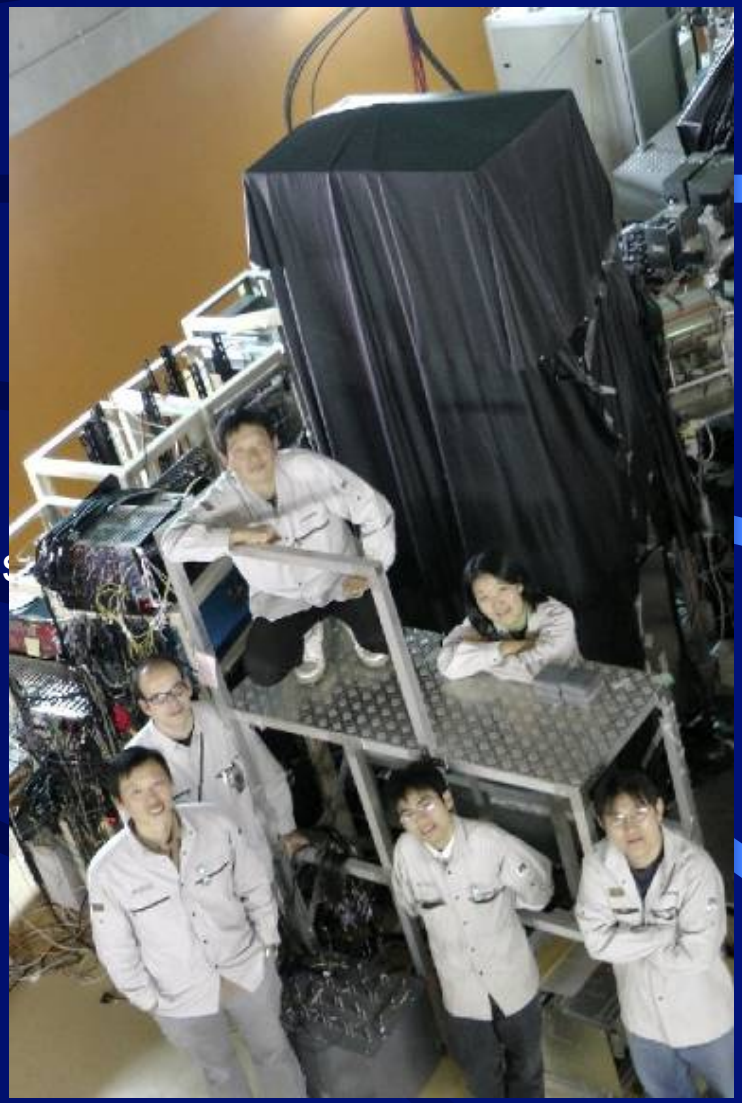

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Thank you.