つくば不安定核セミナー, 2015年９月２日

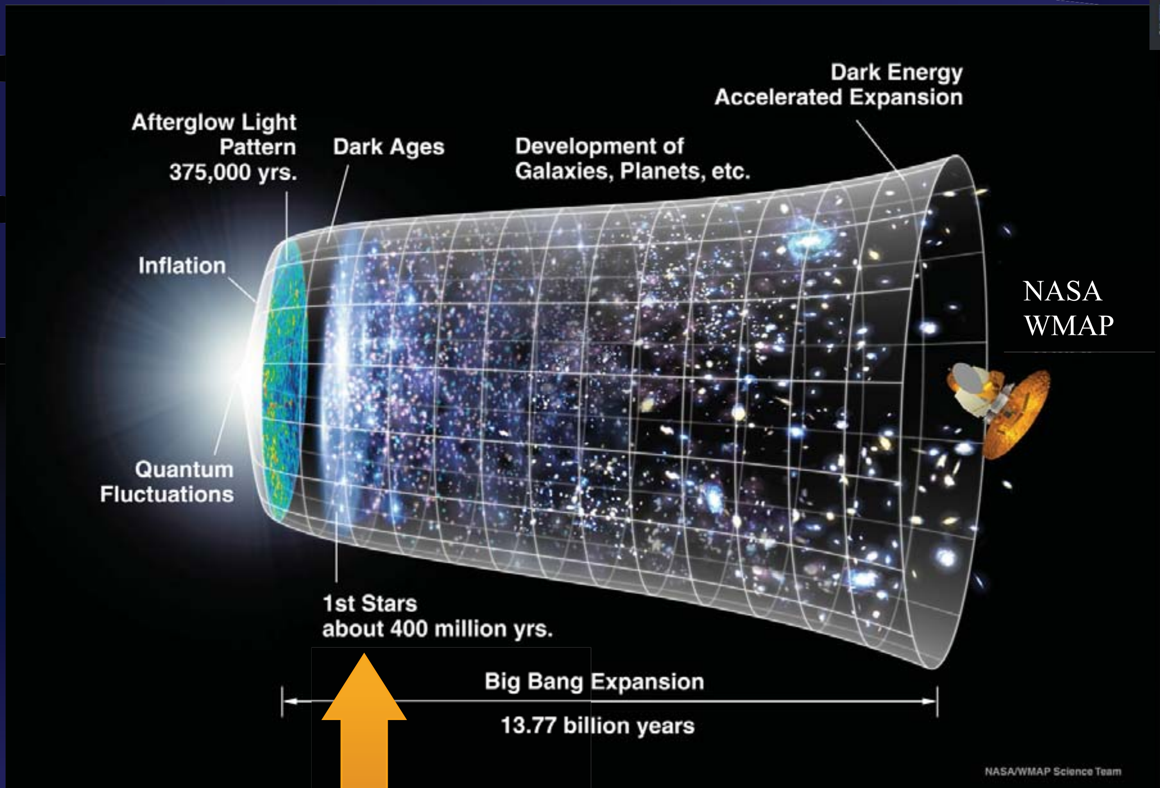
RIBFにおける不安定核の崩壊実験と重元素合成

Study of decay properties and synthesis of heavy elements

Shunji NISHIMURA
(RIKEN Nishina Center)

Where are we from?

O 酸素
C 炭素
H 水素
N 窒素
Ca カルシウム
P リン
S 硫黄
K カリウム
Na ナトリウム
Cl 塩素
Mg マグネシウム
Si ケイ素
Fe 鉄
F フッ素
Zn 亜鉛
Rb ルビジウム
Sr ストロンチウム
Br 臭素
Pb 鉛
Cu 銅
Al アルミニウム
Cd カドミウム
ホウ素 B
Ba バリウム
Sn スズ
Mn マンガン
I ヨウ素
Ni ニッケル
Au 金
Mo モリブデン
Cr クロム
Cs セシウム
Co コバルト
U ウラン
Be ベリリウム
Ra ラジウム

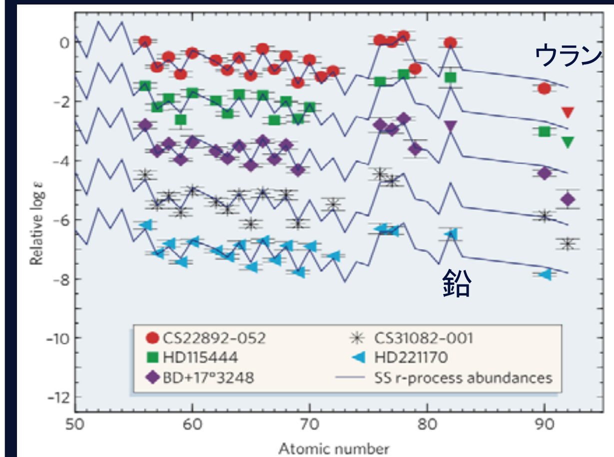


NASA
WMAP

1st Stars

Metal-poor star

J.J.Cowan, C.Sneden (2006年)

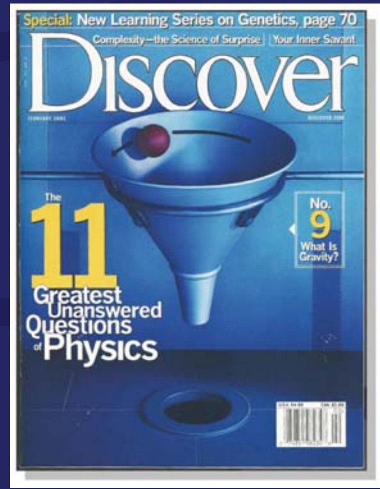


Atomic number (Z)

Elements


元素周期表
BigBang nucleosynthesis
Stellar nucleosynthesis
heavy elements !?
113
115
117
118

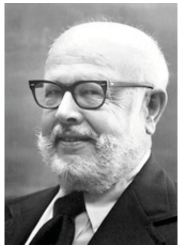
11 Greatest Unanswered Questions 「Physics」



Discover Vol.22 No. 02 February 2002

1. What is dark matter?
2. What is dark energy?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass?
5. Where do ultrahigh-energy particles come from?
6. Is a new theory of light and matter needed to explain what happens at very high energies and temperatures?
7. Are there new states of matter at ultrahigh temperatures and densities?
8. Are protons unstable?
9. What is gravity?
10. Are there additional dimensions?
11. How did the universe begin?

How were heavy elements created in the universe?

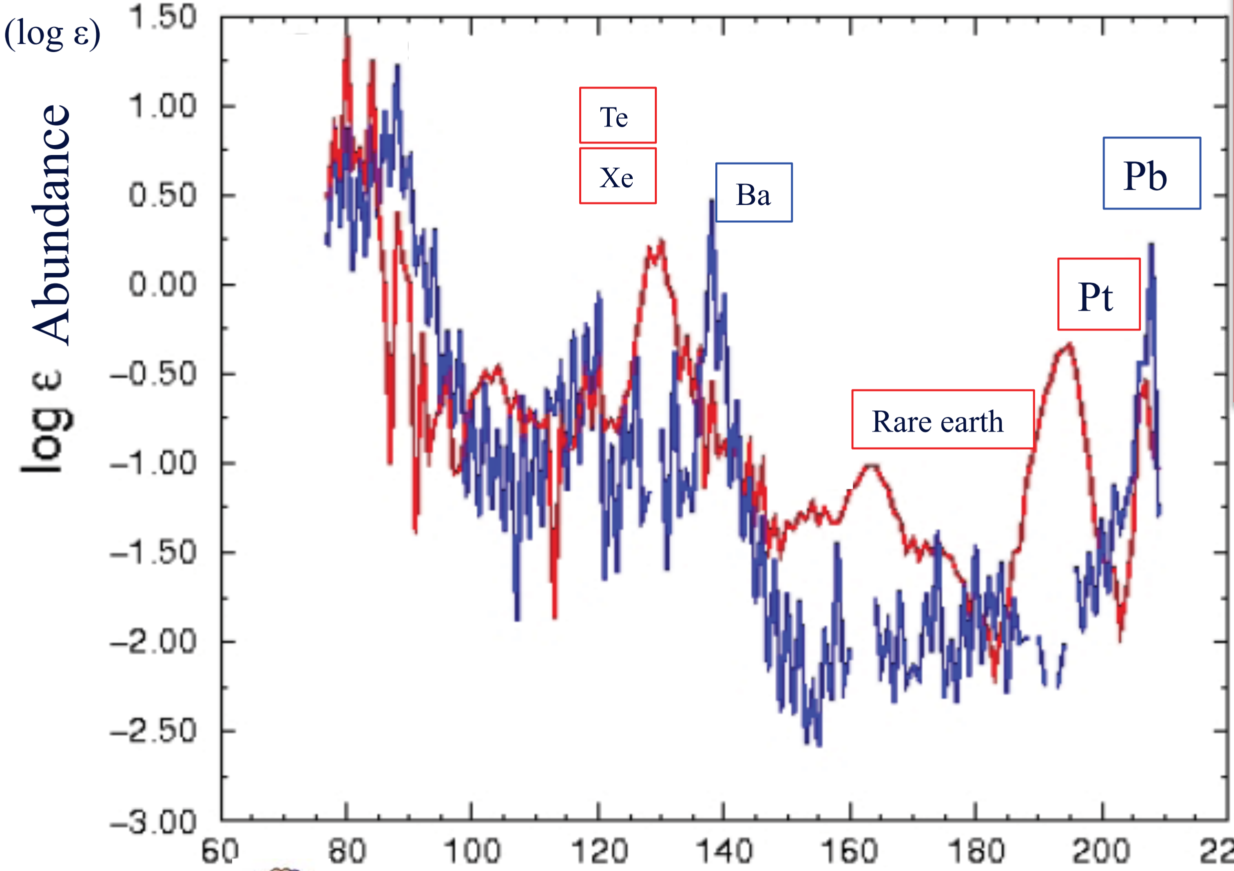


William Fowler（1967）

Nobel Prize（1983）

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

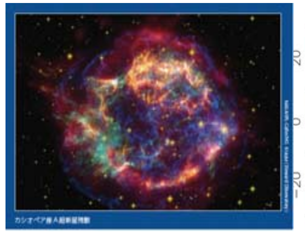
Sneden, J.J. Cowan, Science Vol. 299 (2003年)



Mass A = proton num.（Z)＋neutron num.（N）

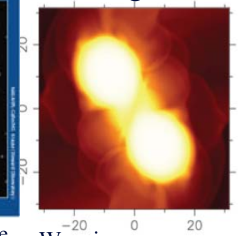
Mystery of site: Where

Supernovae？



NASA/JPL-Caltech/O.Krause (Steward observatory)

Neutron-star merger?



Wanajo

r-process（rapid: ）

温度と密度が高い環境において原子核が多量の中性子を捕獲・不安定になった原子核(RI)が崩壊して一挙に金やウランを生成した。（0.1秒～10秒）

Origin of Heavy Elements (Pt, Th, U…)

Supernovae vs Neutron Star Merger

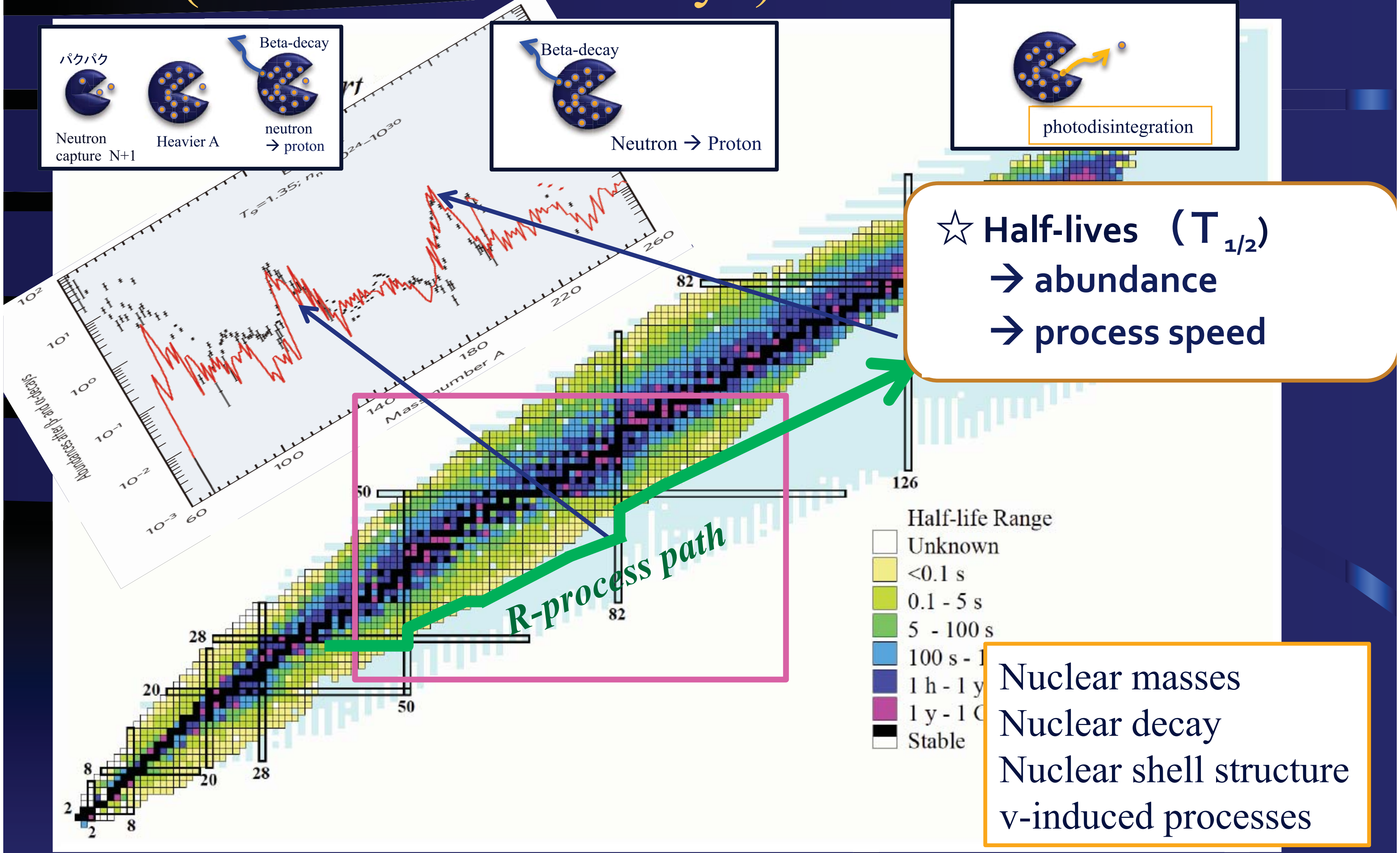
NASA/JPL-Caltech/O.Krause (Steward observatory)

- Mechanism of Explosion.. ?
- Lack of Neutrino, Neutron : Ye < 0.5?

- Extremely neutron-rich nuclei
- Very Rare to have two neutron stars close together.
- Not possible in 1^{st} stars.

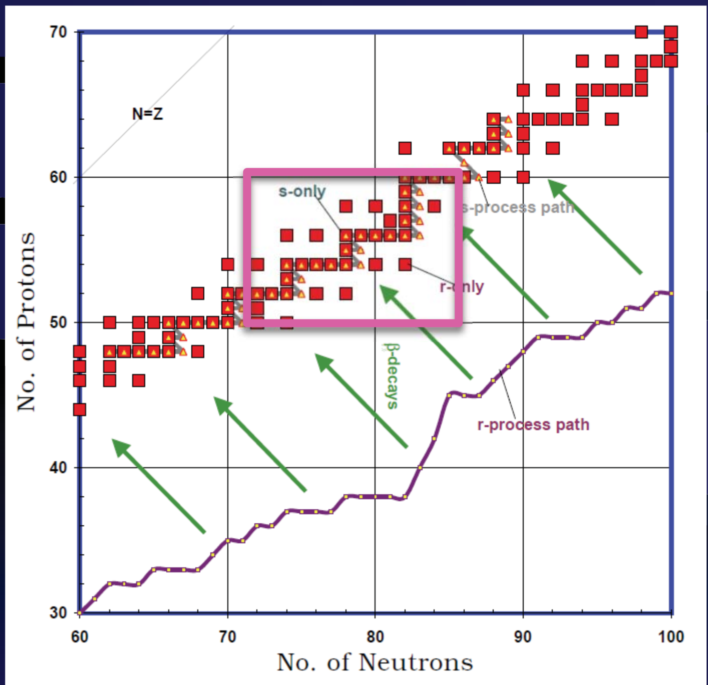
Very Neutron-Rich Nuclei

(Far from the stability..)

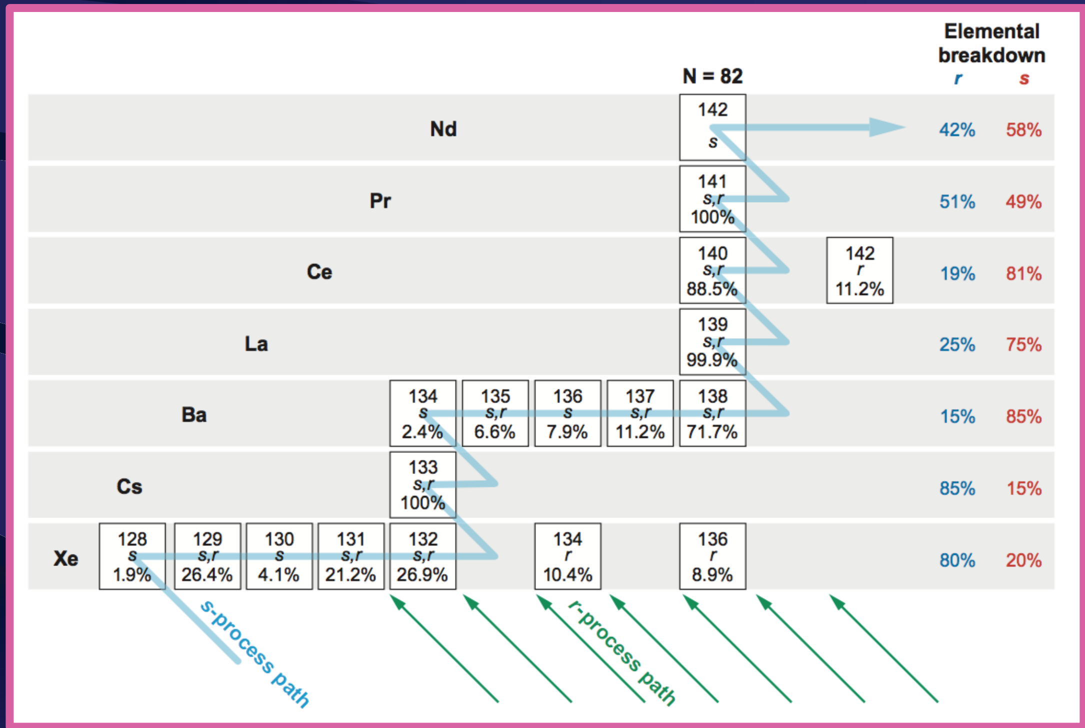


s-process & r-process (slow vs rapid)

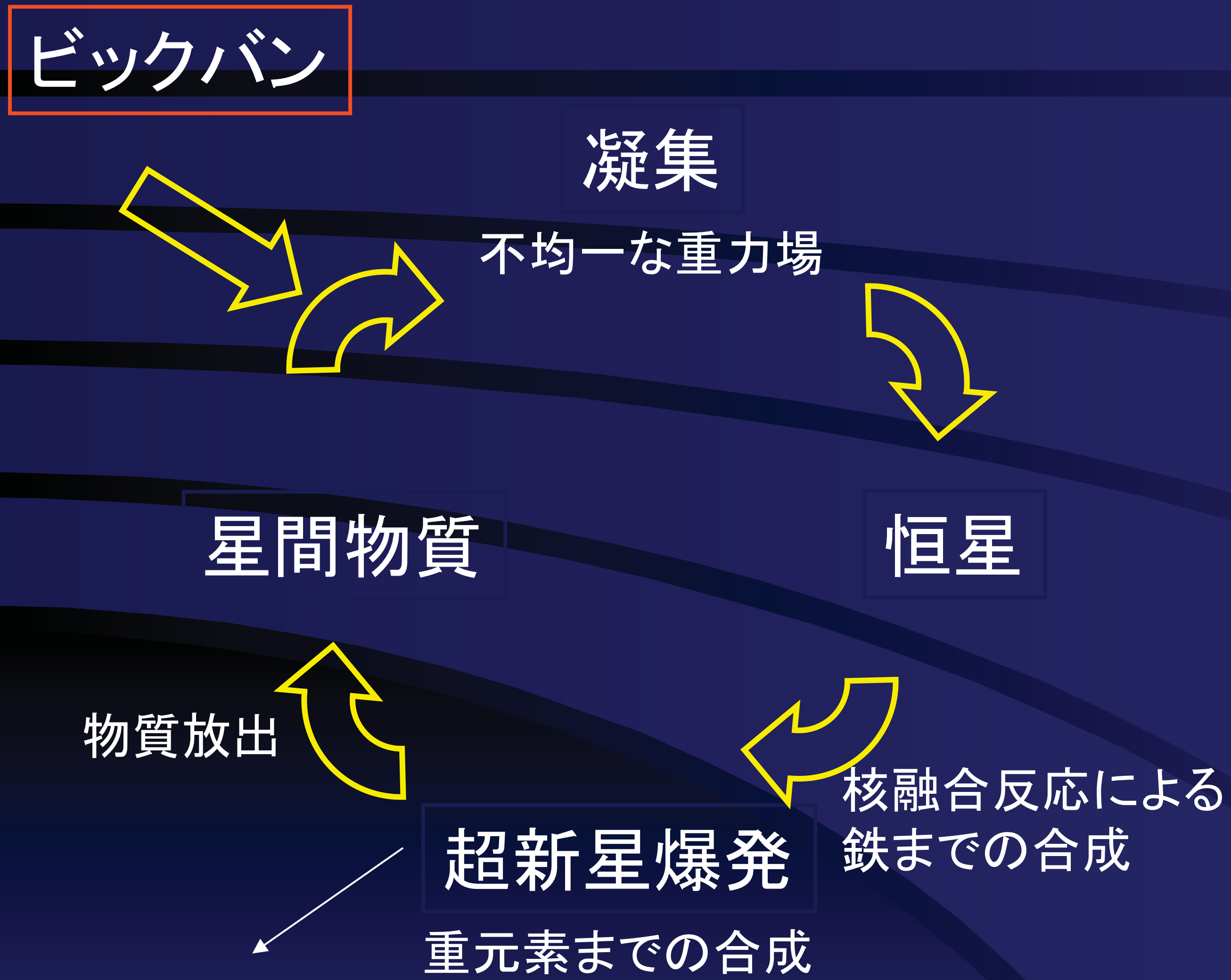
Langanke Lecture



Sneden et al. (2008)

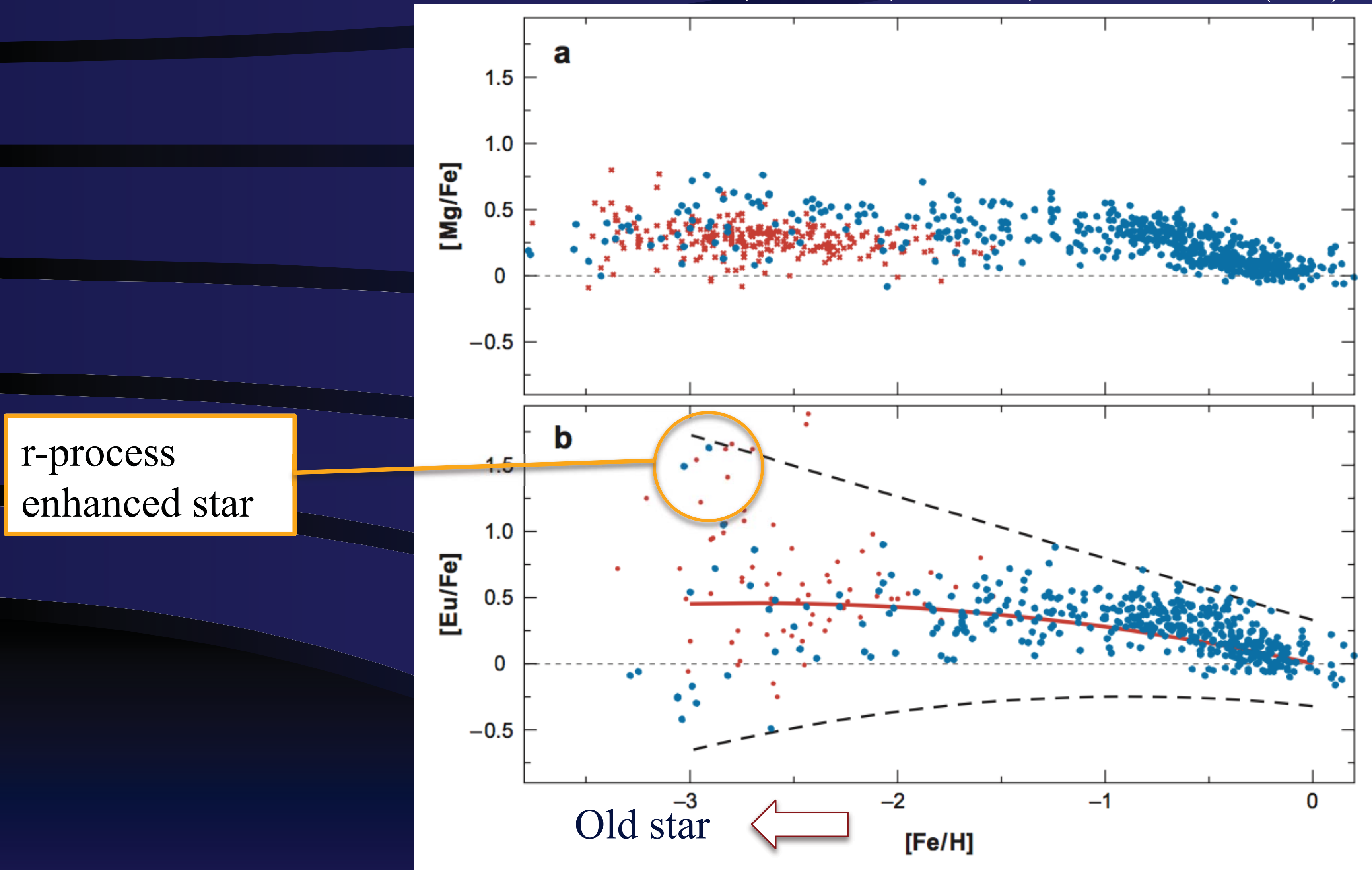


Cycle in Universe



Eu/Fe abundances as a function of [Fe/H] metalicity

C. Sneden, J.J. Cowan, R. Gallino, Annu. Rev. Astro. (2008)

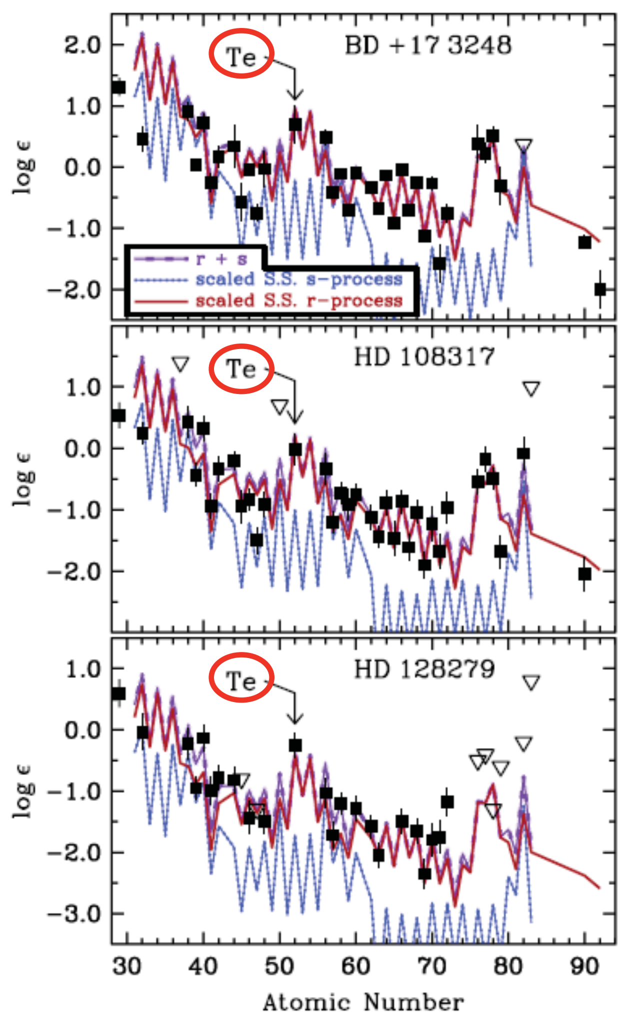


Significant [Eu/Fe] abundance scatter at low metalicity

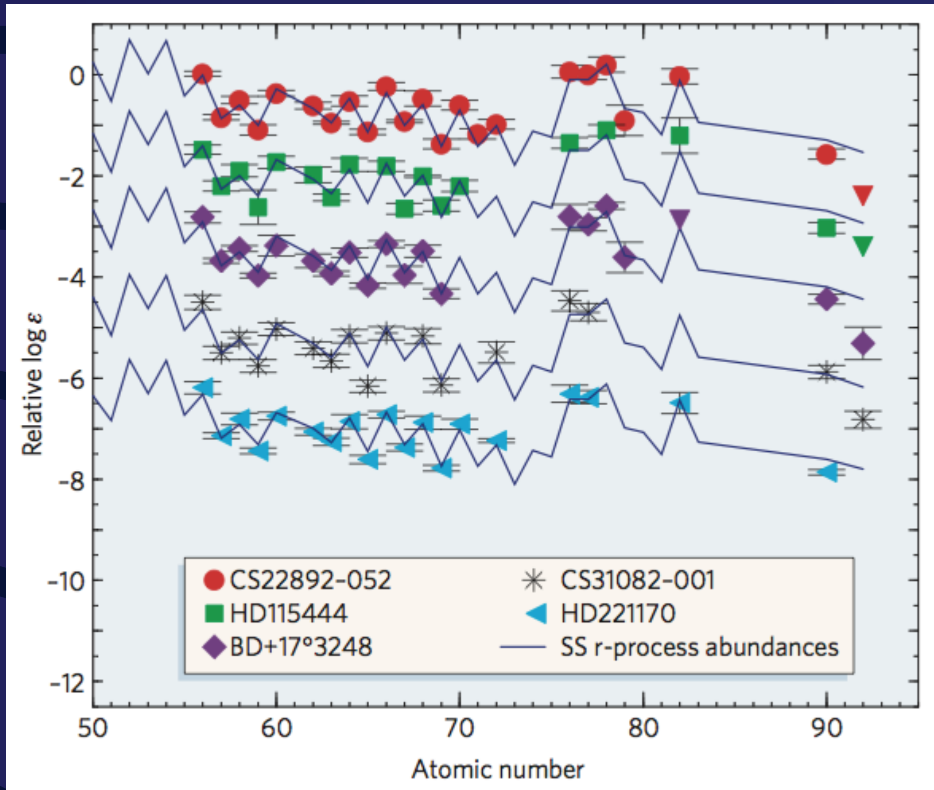
Abundance Patterns in Galactic Halo Stars

(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)

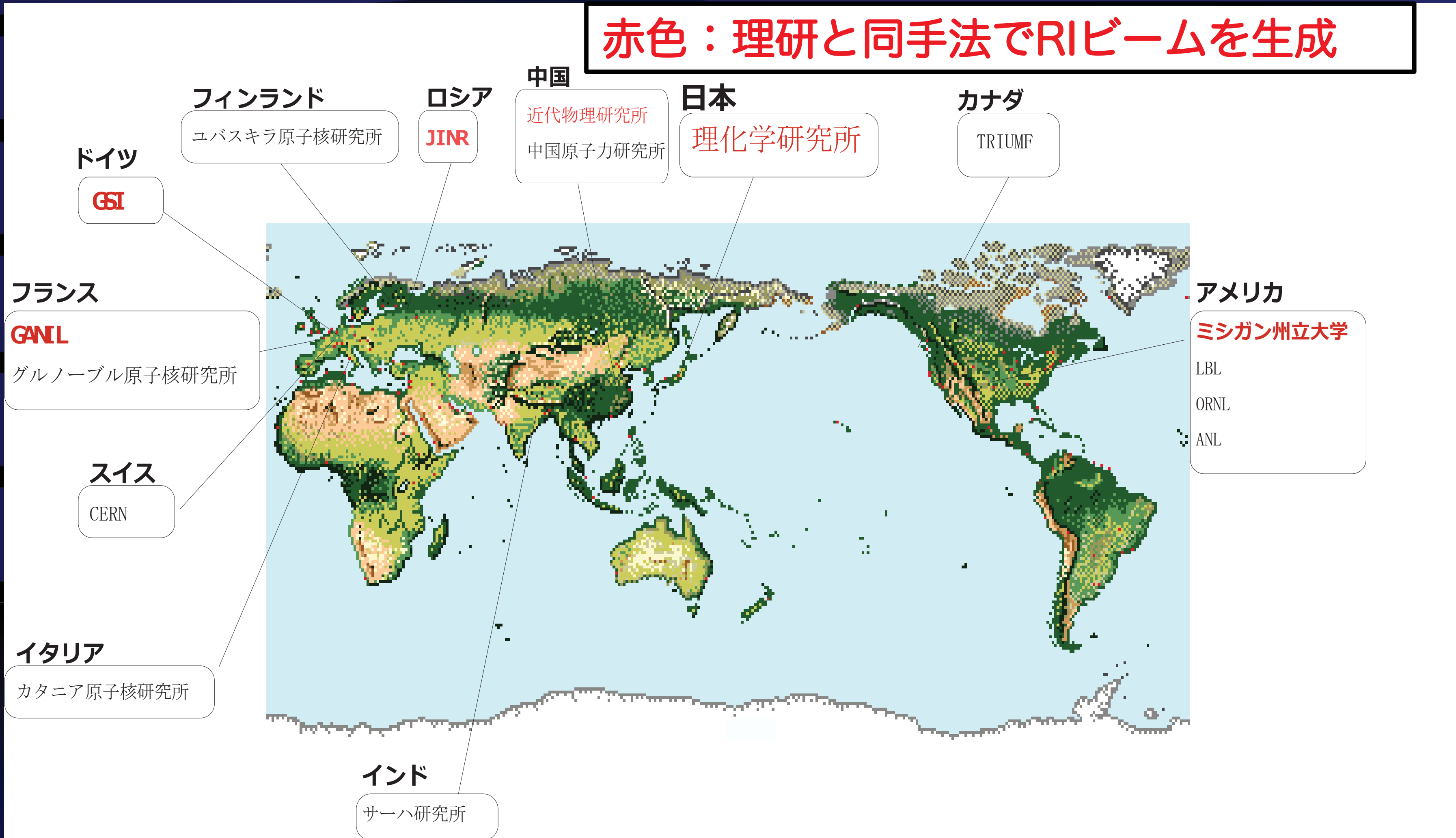
→ Closely match the Solar System (SS) r-process pattern.

→ Te (Z=52) data.

Key: We need properties of most neutron-rich nuclei.

理研・世界最強の
リングサイクロトロン加速器

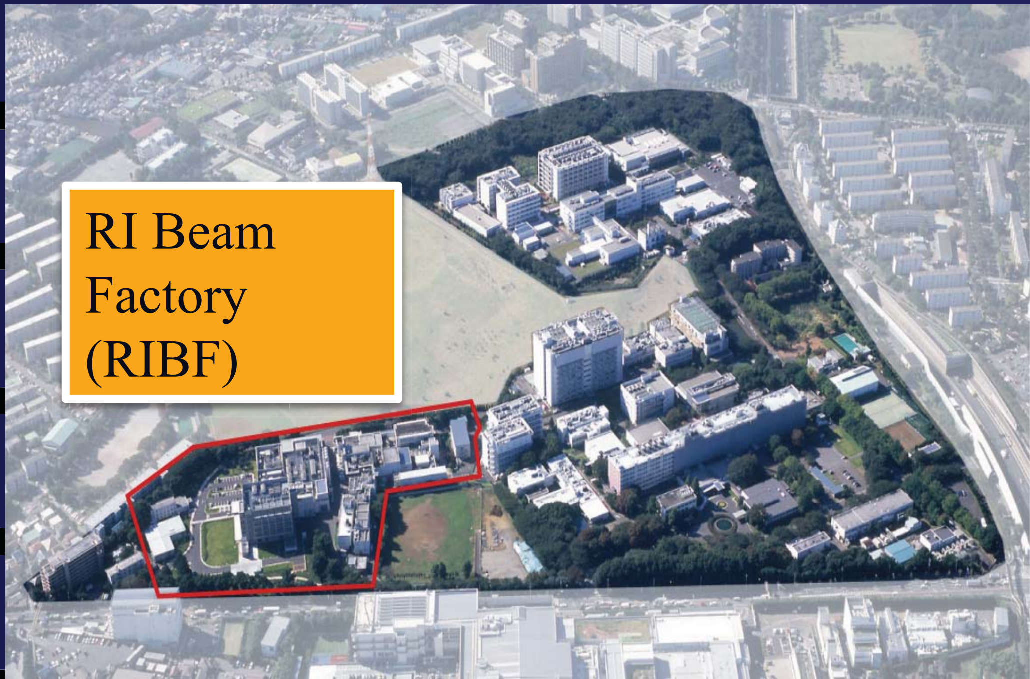
世界における不安定核の研究



欧米次期計画

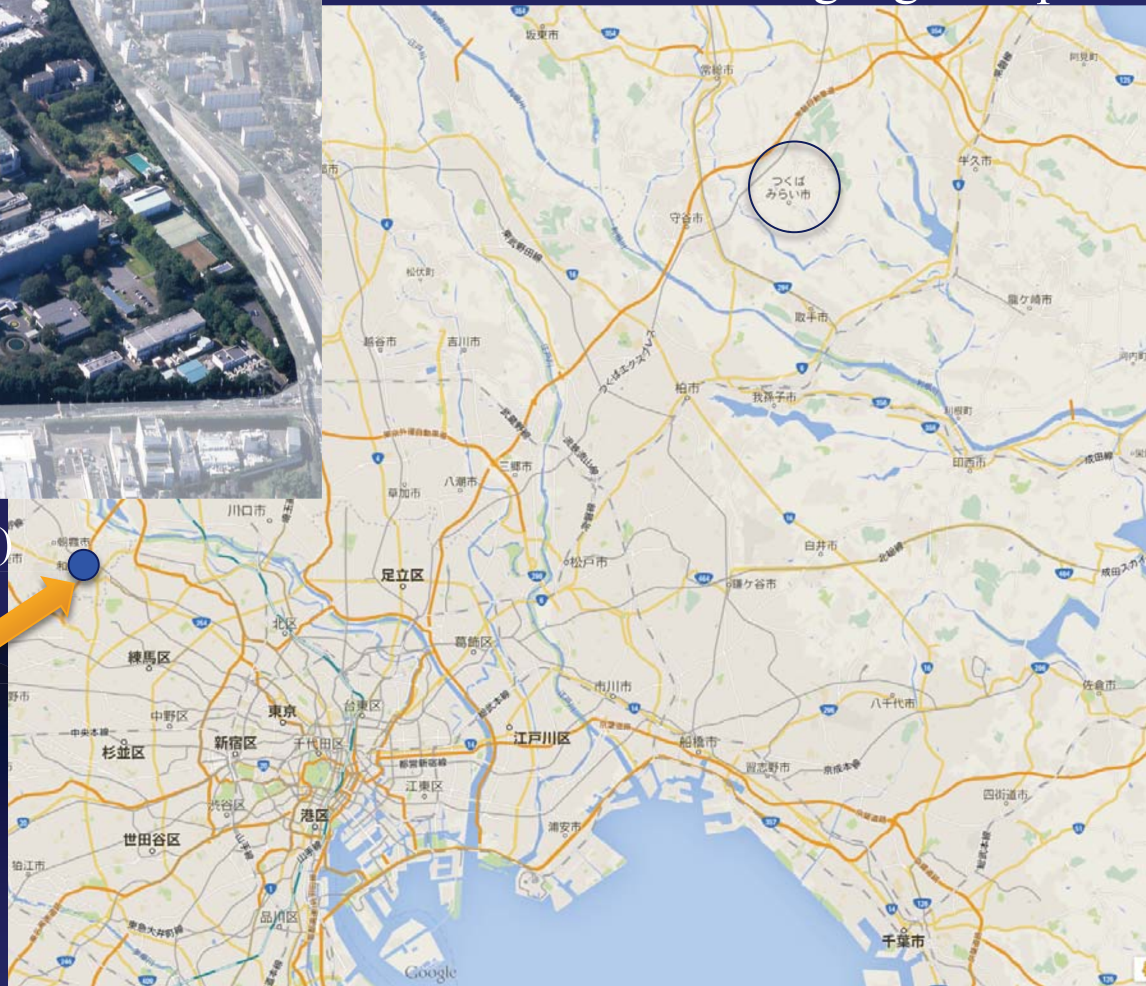
GSI-FAIR(ドイツ) 20XX？
FRIB (米国) 20XX？

RIKEN Nishina Center

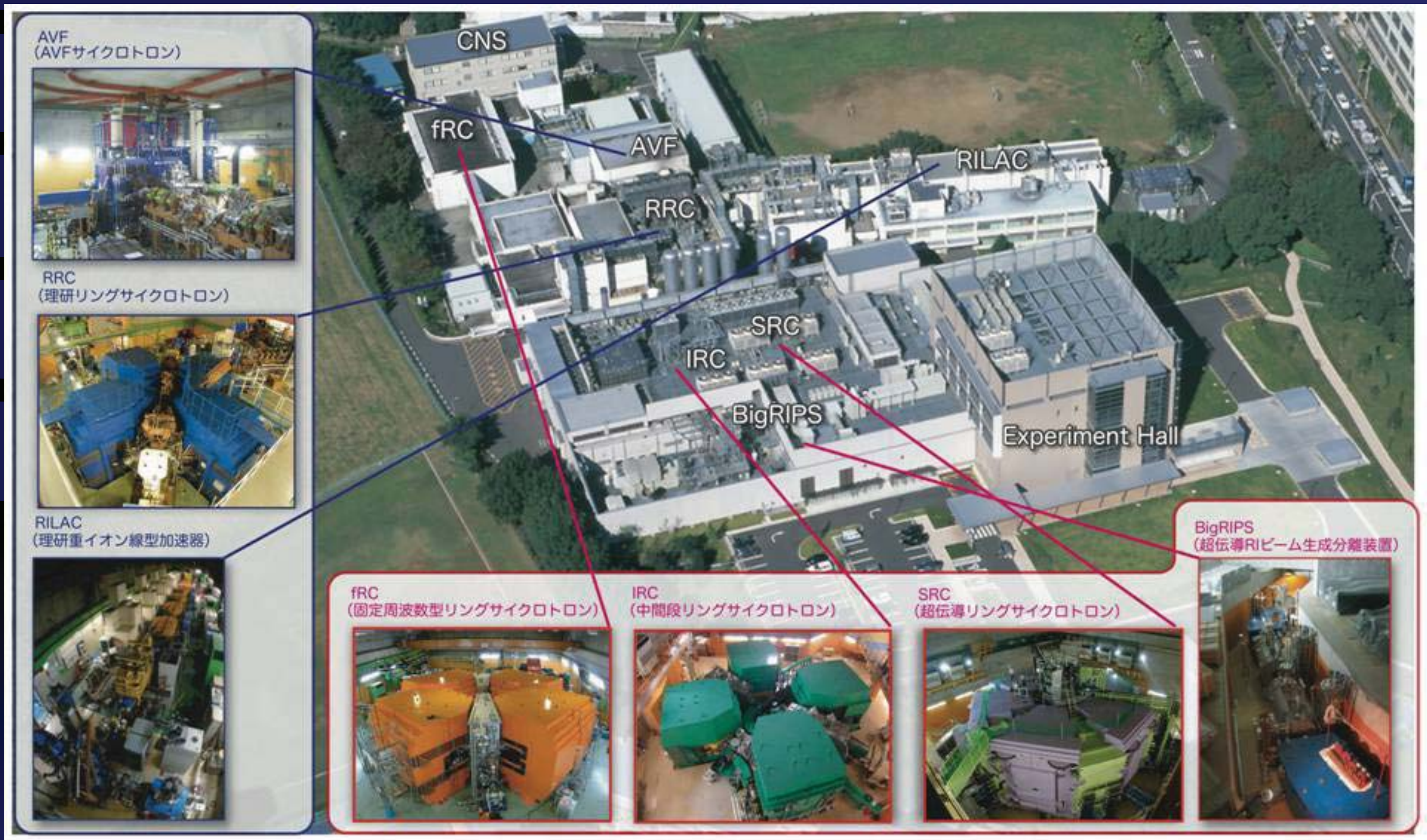


埼玉県･和光市キャンパス (1960 ～)

google map

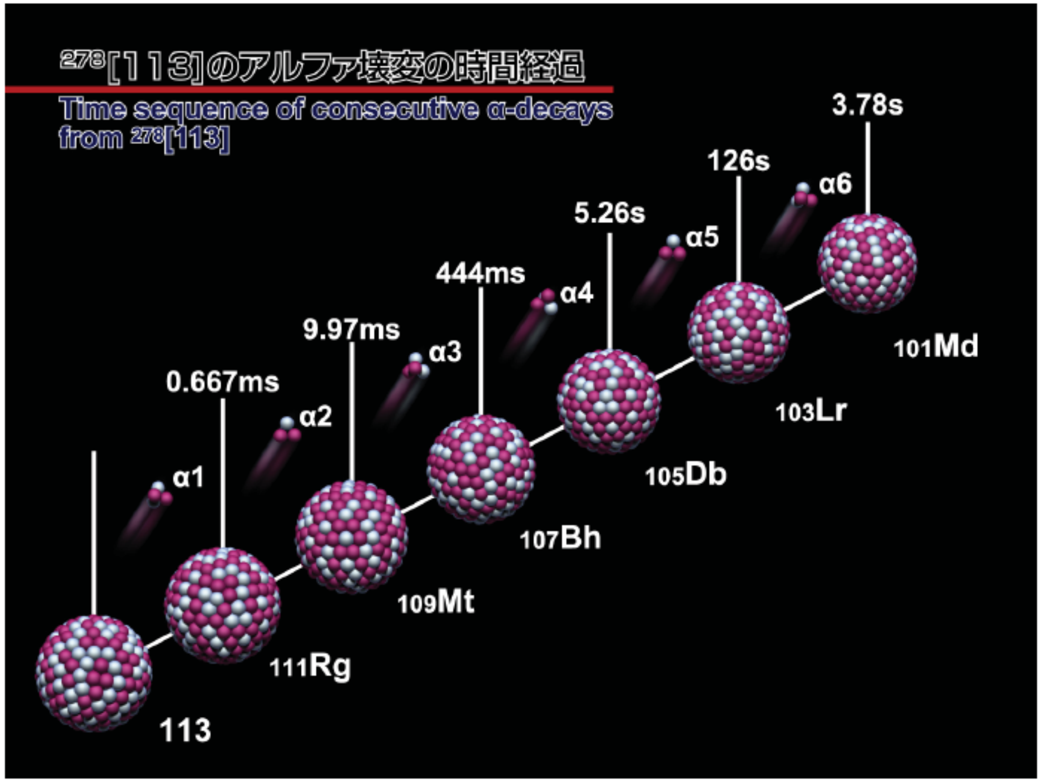


RIビームファクトリー ・ 加速器群
（ 世界最強の加速器施設！： 埼玉県･和光市 ）



※加速器と実験設備はすべて地下室に収容されます。

Superheavy elements (RIKEN)



Element 113
→ Naming?

1 回目：^{278}113 から 0.667 ミリ秒後に原子番号 111 のレントゲニウム（質量数 274 の ^{274}Rg）に壊変

2 回目：^{274}Rg が 9.97 ミリ秒後に原子番号 109 のマイトネリウム（質量数 270 の ^{270}Mt）に壊変

3 回目：^{270}Mt が 444 ミリ秒後に原子番号 107 のボーリウム（質量数 266 の ^{266}Bh）に壊変

4 回目：^{266}Bh が 5.26 秒後に原子番号 105 のドブニウム（質量数 262 の ^{262}Db）に壊変

5 回目：^{262}Db が 126 秒後に原子番号 103 のローレンシウム（質量数 258 の ^{258}Lr）に壊変

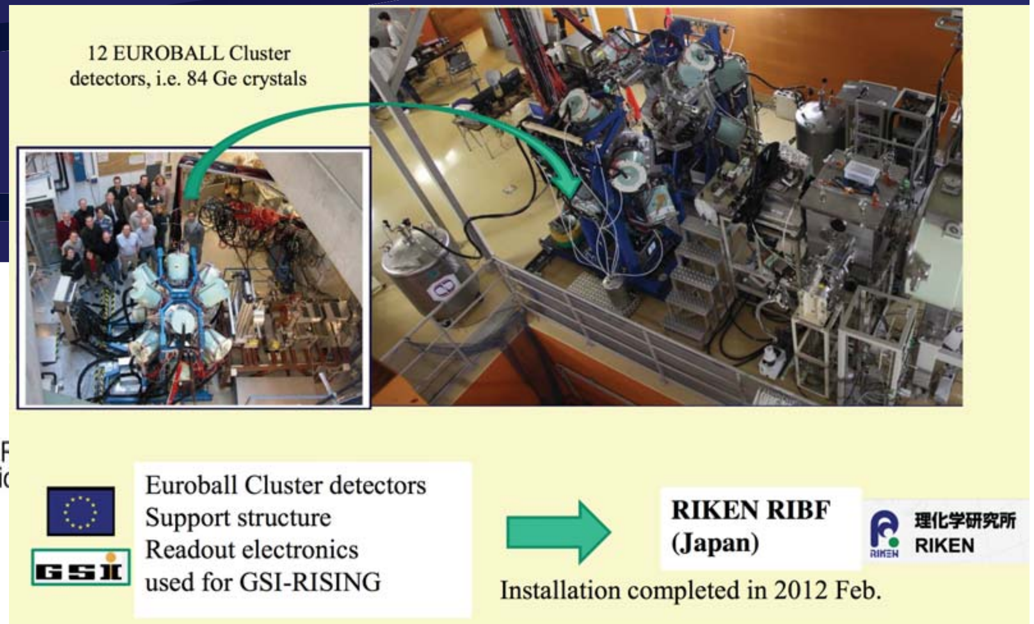
6 回目：^{258}Lr が 3.78 秒後に原子番号 101 のメンデレビウム（質量数 254 の ^{254}Md）に壊変

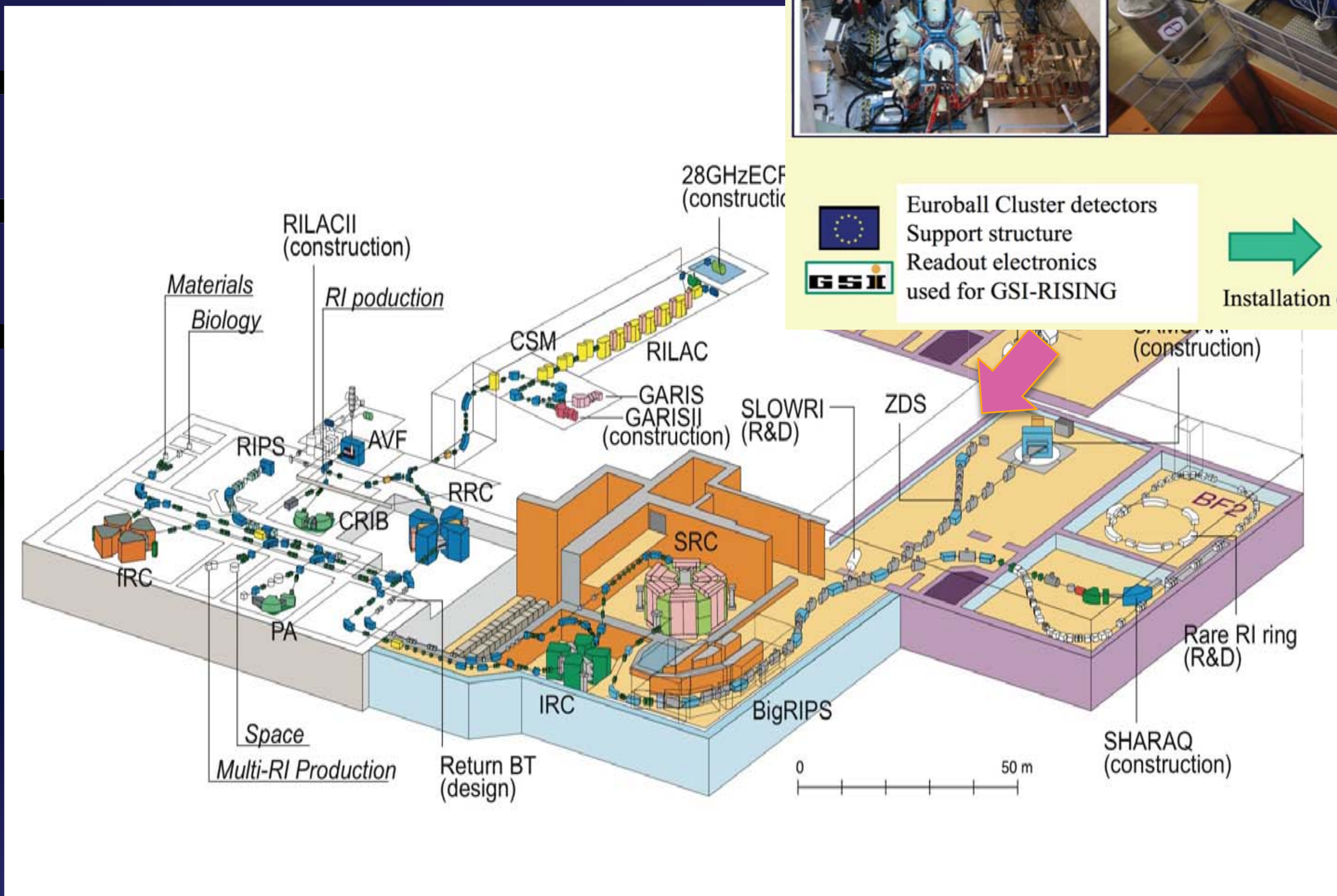
崩壊測定実験

原子核の核構造

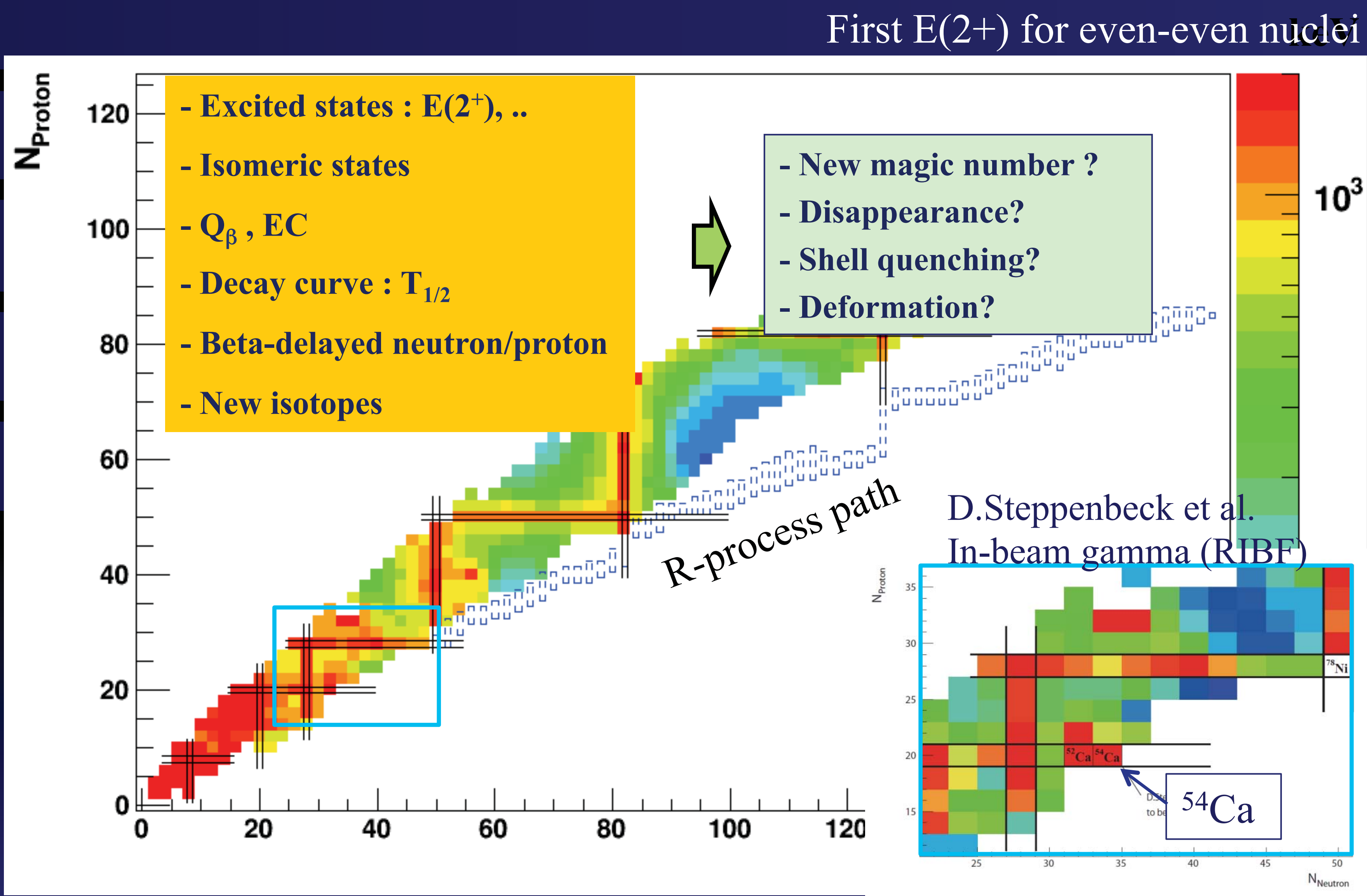
元素合成

RIBF & Decay Station

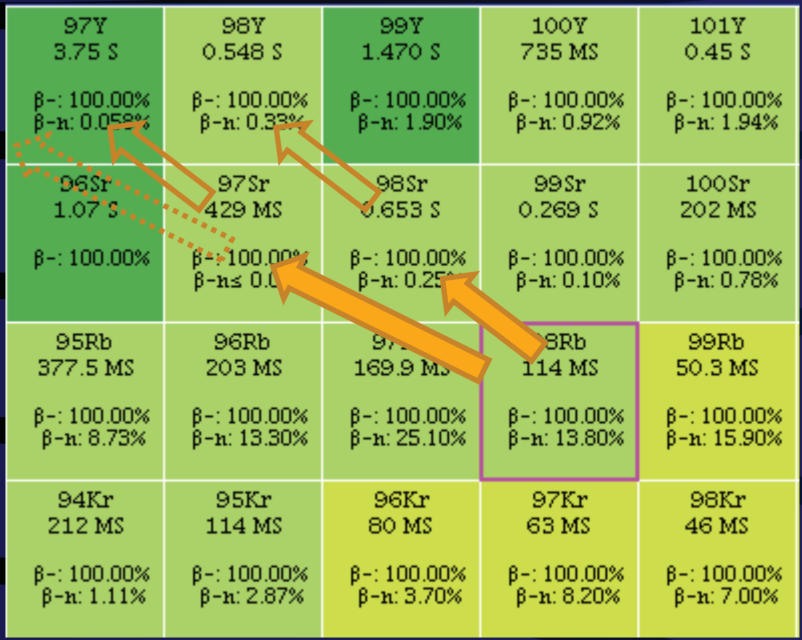


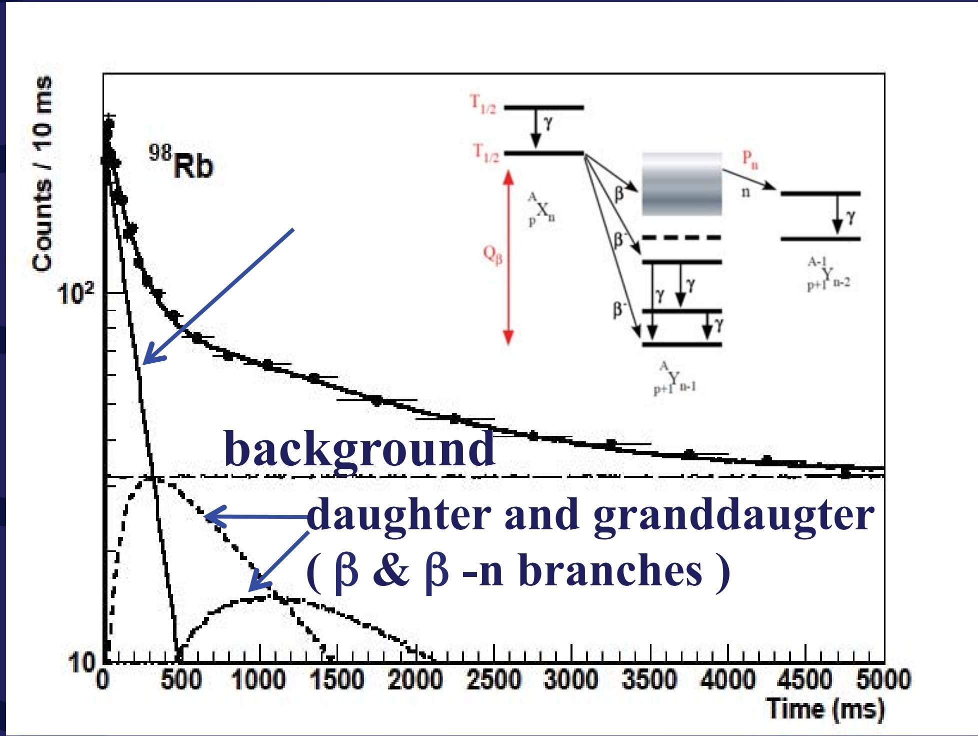


Survey of Nuclear Properties (Decay Spectroscopy)



Decay curve and $T_{1/2}$





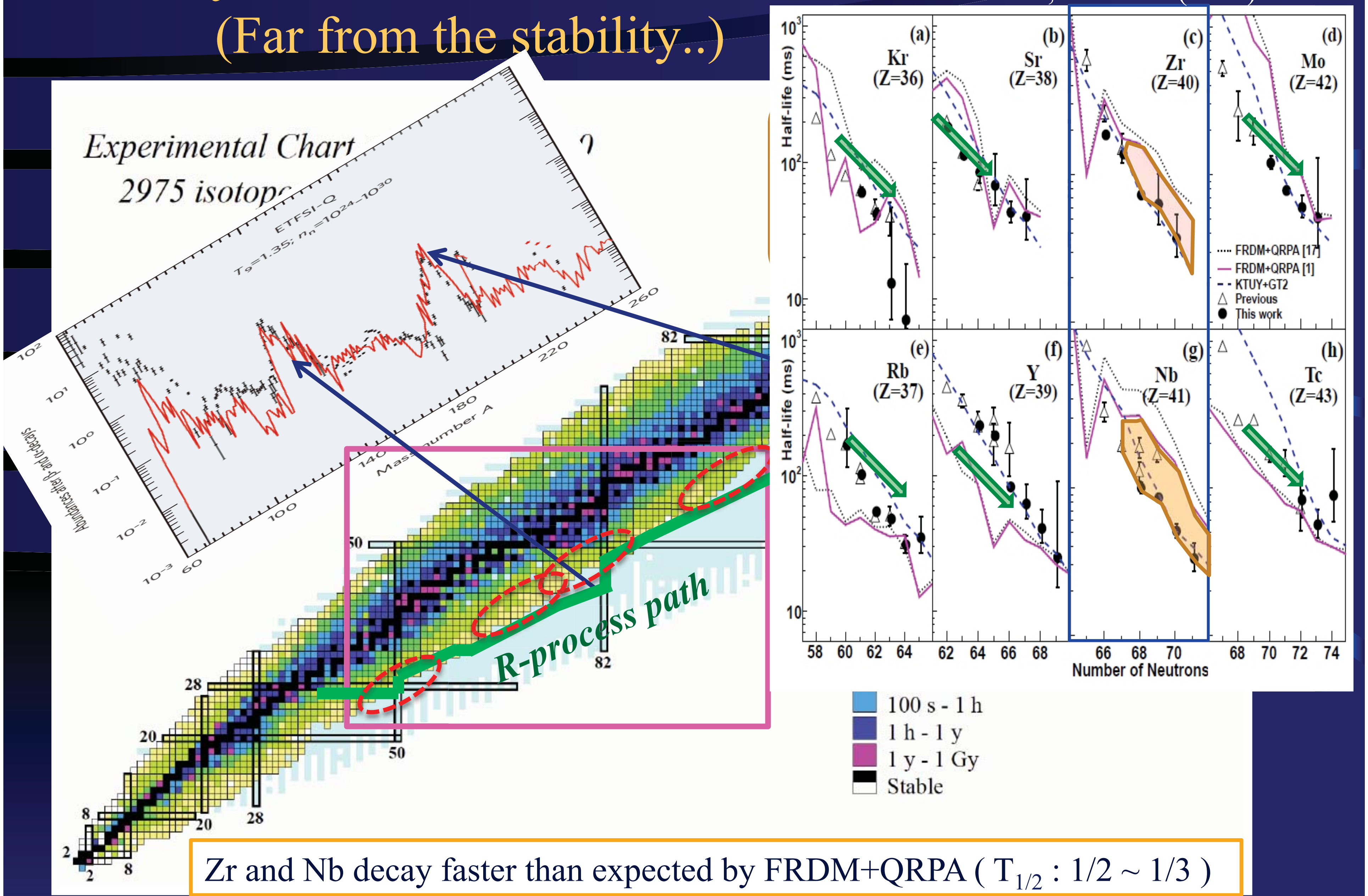
Likelihood method with 10ms bins (0 – 5 sec)
Free parameters for fitting
- Background … ~ 0.5 cps
- Neutron emission Probability (Pn)
- Detection efficiency (ε) … 40% - 80%

Consistency check
- Monte Carlo Simulation / beta-delayed gamma

→ $T_{1/2}$

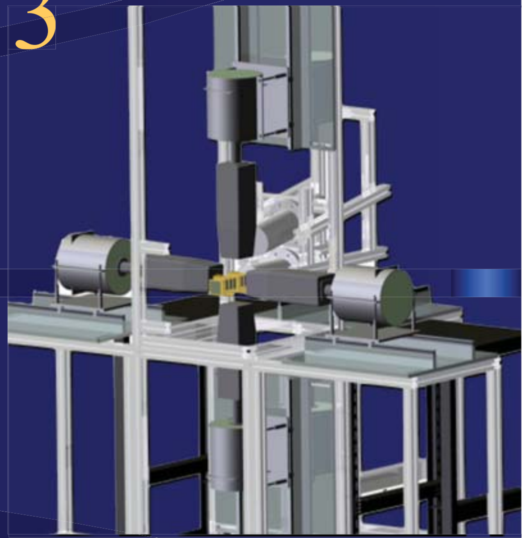
Very Neutron-Rich Nuclei
(Far from the stability..)

SN, PRL 106 (2011)



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

Upgrade : 2009 → 2012-2013



U-beam intensity

- 0.2 pnA → ~ 10 pnA … x 50 times

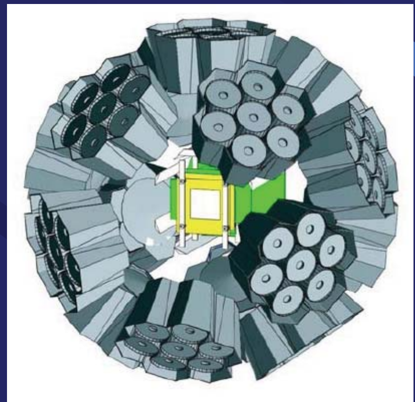
Gamma-ray detector

- 4 Clover detectors
  → 12 Cluster detectors (Det. Eff. ~ 8 % at 1 MeV)
  … x 10 times

(→ gamma-gamma coincidence … x 100 times)

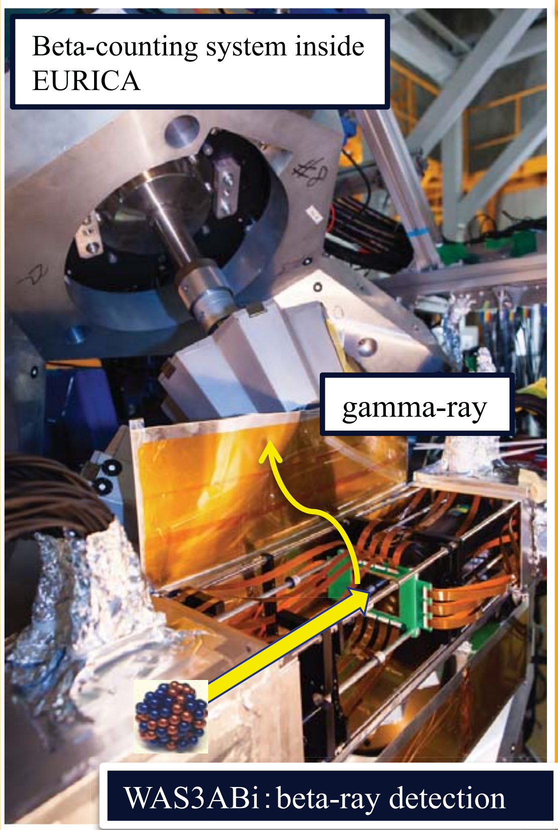
Beta counting system

- 16 x 16 pixels x 7 layers = 1792 pixels
  → 40x60 pixels x 8 layers = 19200 pixels
  … x 10 times

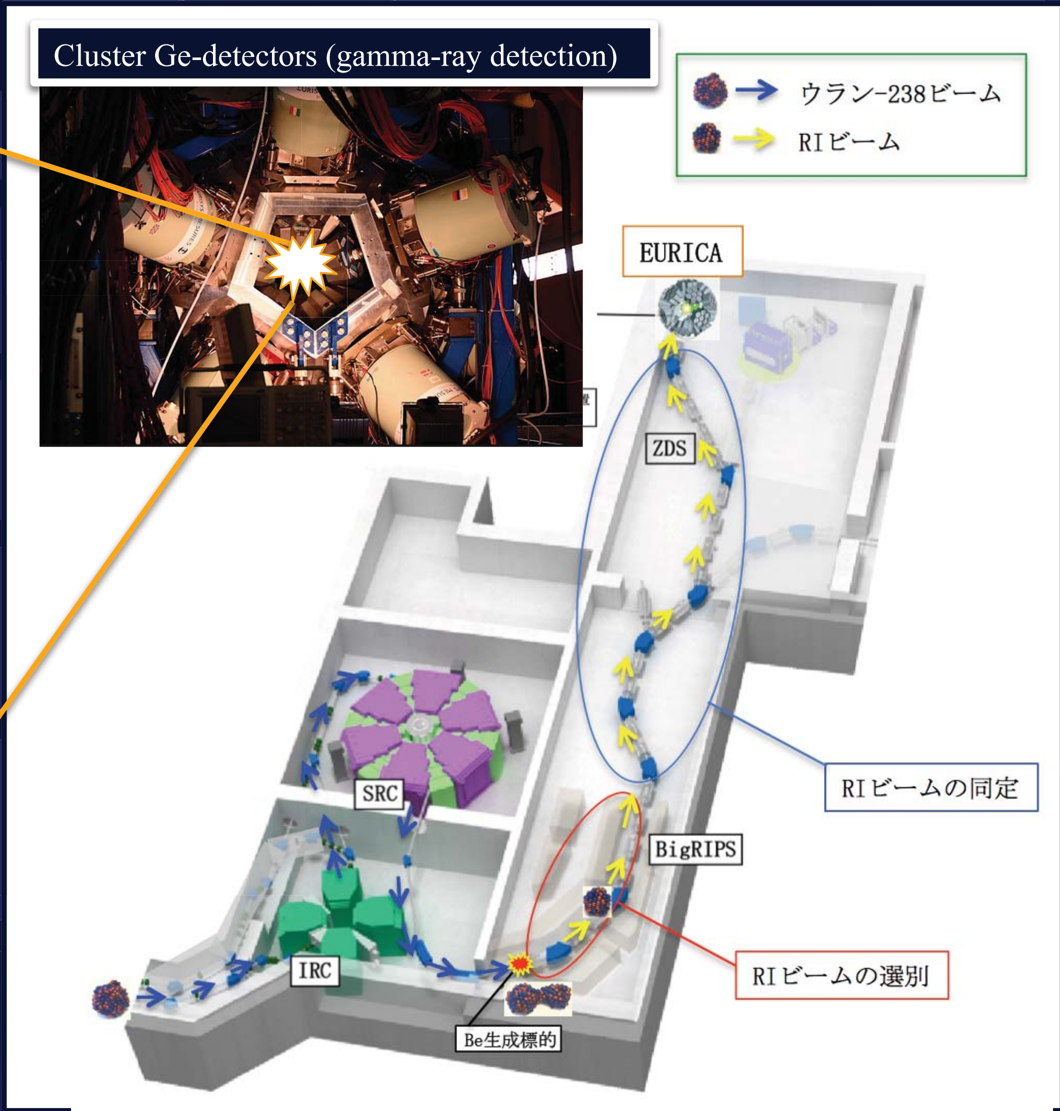


Decay spectroscopy of key nuclei relevant to r-process nucleosynthesis

High resolution, High efficiency gamma-ray detector!
(x 10 times)



Beta-decay half-lives, etc..



World highest efficiency detectors
(1 months → 40 minutes)

x

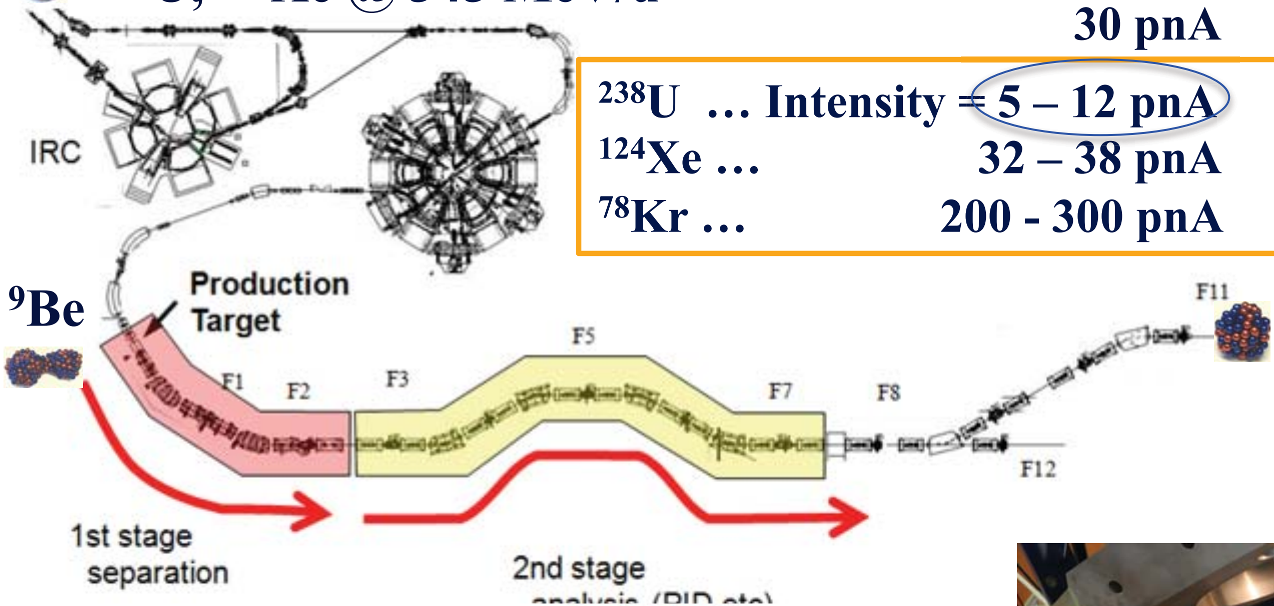
World high intensity RI beam
1000 times

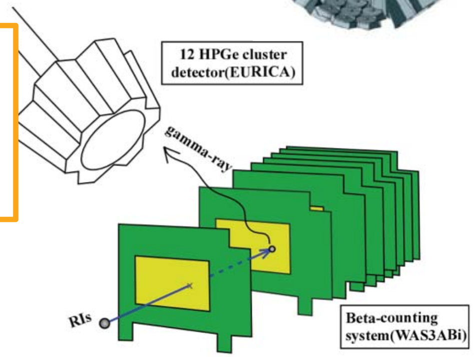
RI Production and Decay Spectroscopy

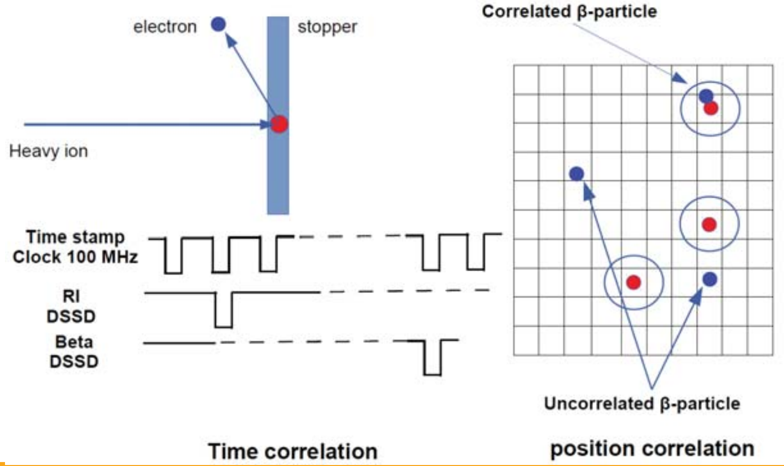
^{238}U, ^{124}Xe @ 345 MeV/u

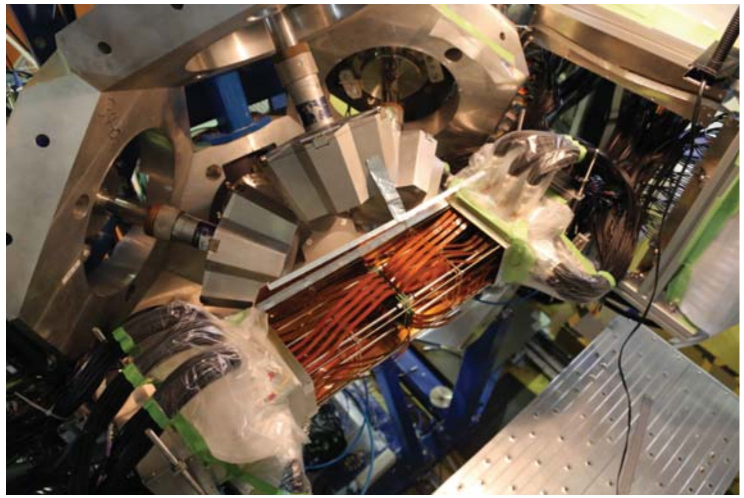
30 pnA

^{238}U … Intensity =	5 – 12 pnA
^{124}Xe …	32 – 38 pnA
^{78}Kr …	200 - 300 pnA







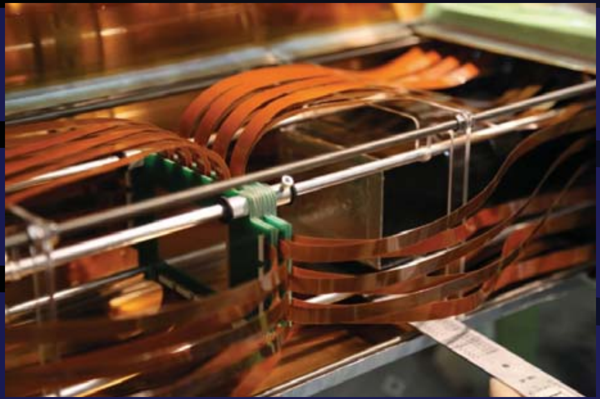


Beta-counting system: WAS3ABi in EUIRCA

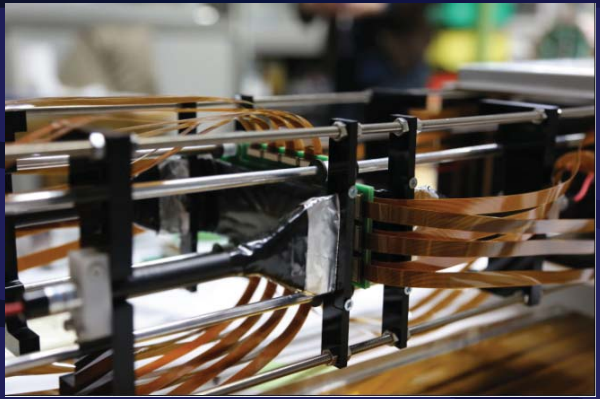
(Wide-range Active Silicon-Strip Stopper Array
for Beta and ion detection)

RIKEN/IBS/TU-Munchen

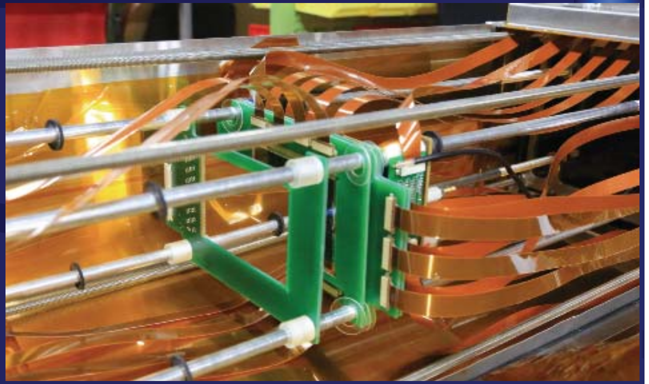
(a)



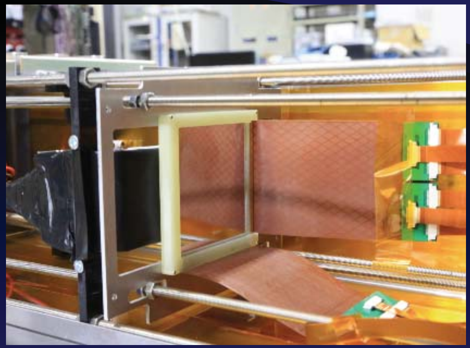
(b)



(c)



(d)



DSSSD (Univ. York)

Heavy-ion … ~ 6 GeV ~ (Nov. / 2014)

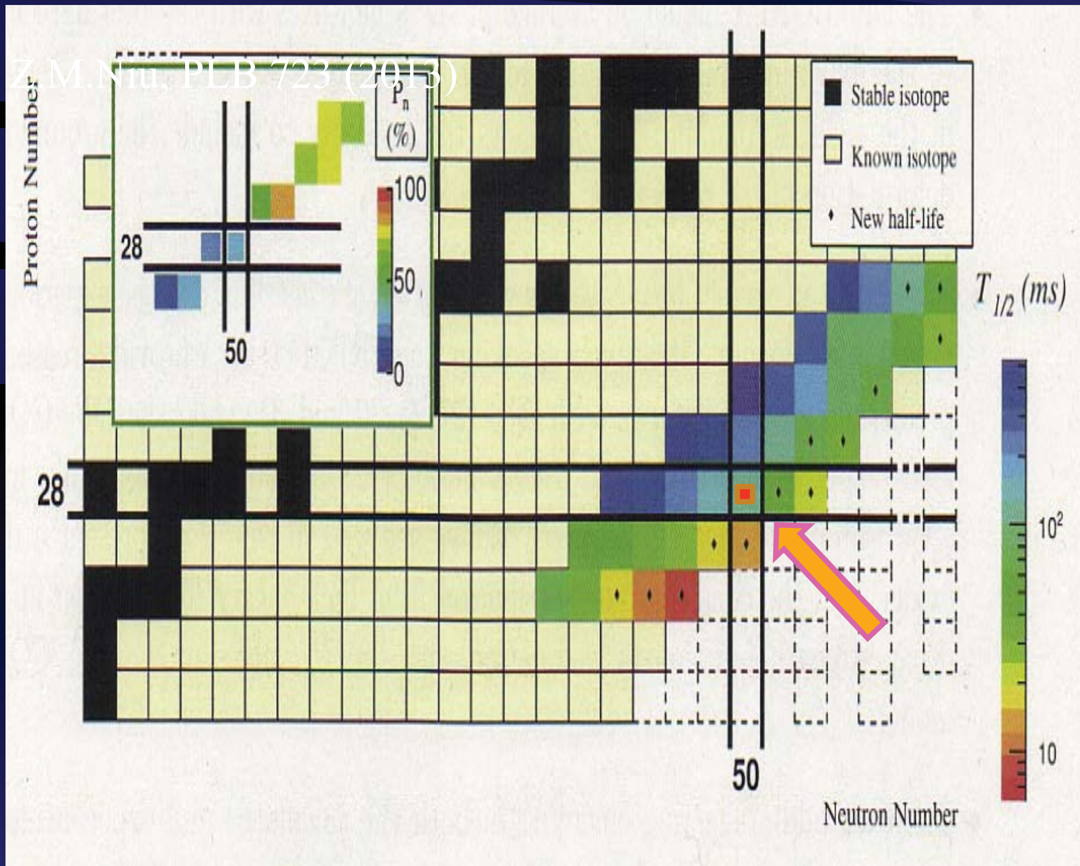
Beta-ray … 20 keV ~ 3 MeV

High segmentation … 60 x 40mm2, 1mm strips
Up to 16,000 pixels

Qbeta …. Plastic scintillator or SSSD x 10

Fast timing … Plastic scintillators

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



[History of ^{78}Ni]

-1997

Identified as new isotope (3 events)

M.Bernas et al., PLB415 (1997)

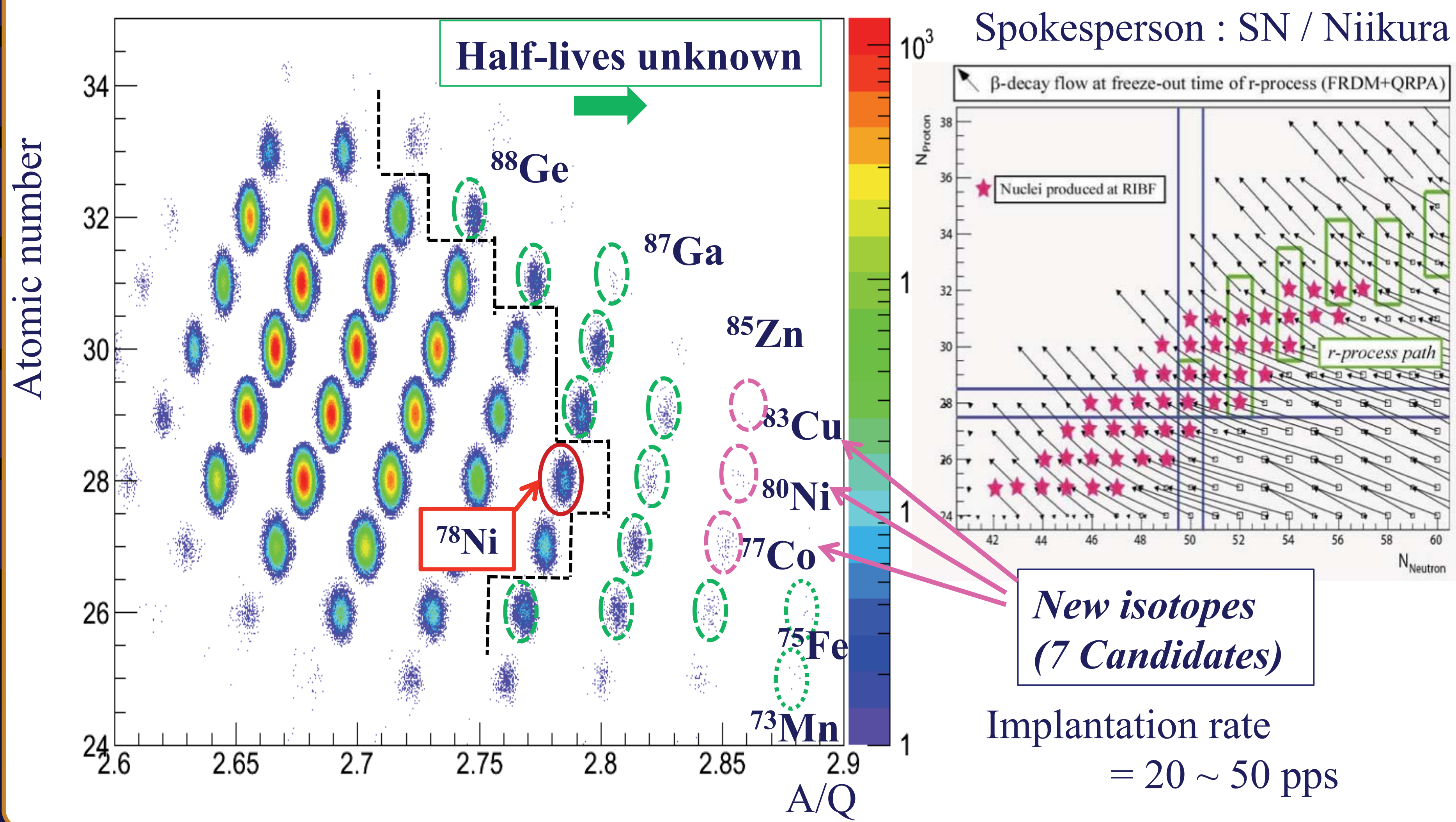
- 2005

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

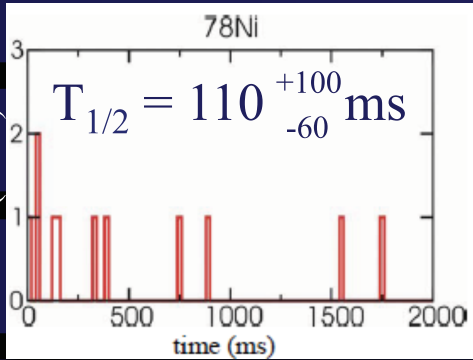


Implantation rate
= 20 ~ 50 pps

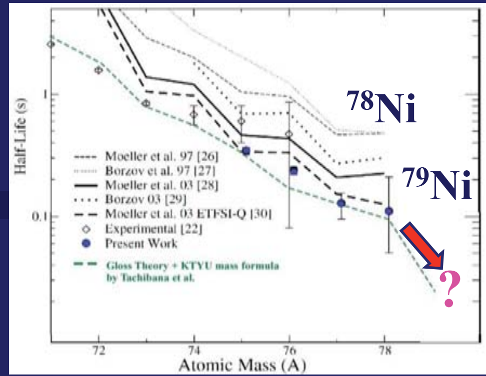
~ 12 k of ^{78}Ni produced at the RIBF.
Low production yield of ^{79}Ni (^{78}Ni + neutron)

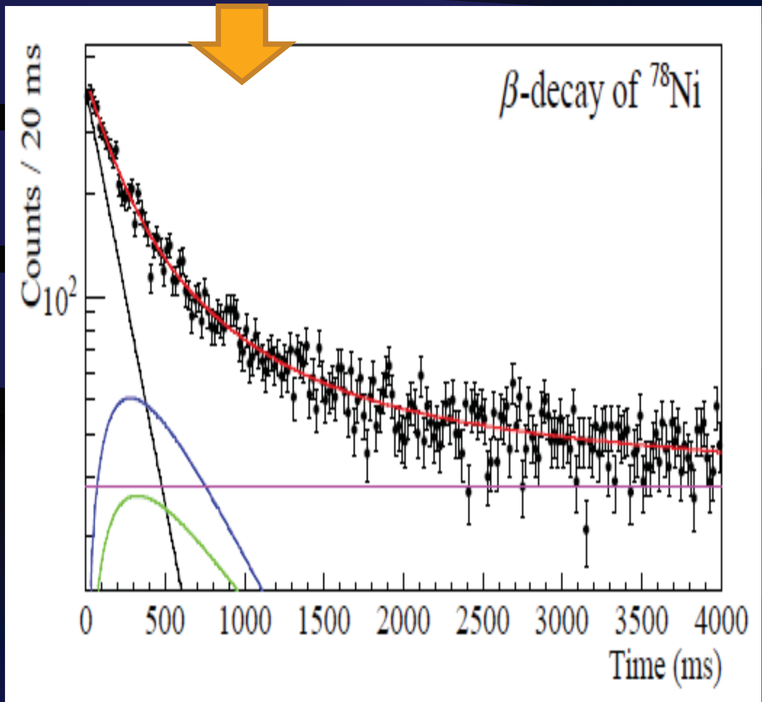
^{78}Ni beta-decay half-life

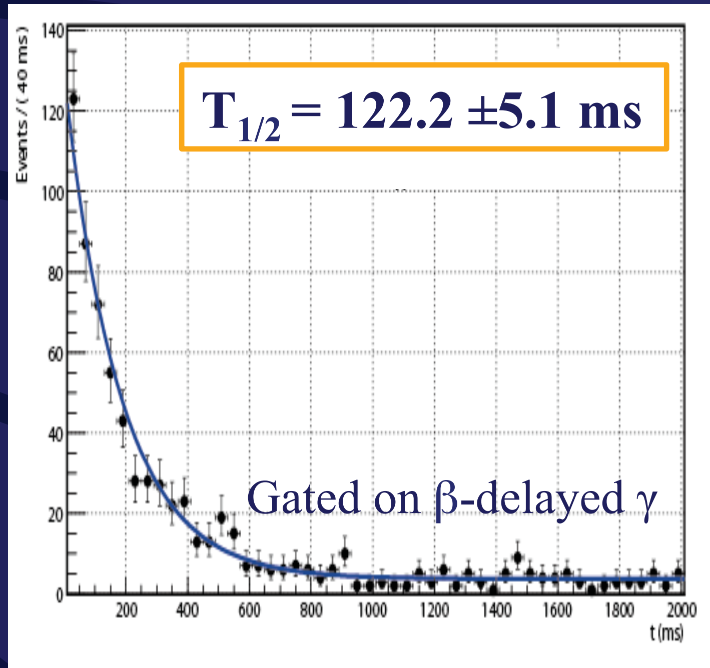
Hosmer (MSU)
PRL (2006)



Z.Y.Xu et al.
Phys. Rev. Lett. 113 (2014) 032505



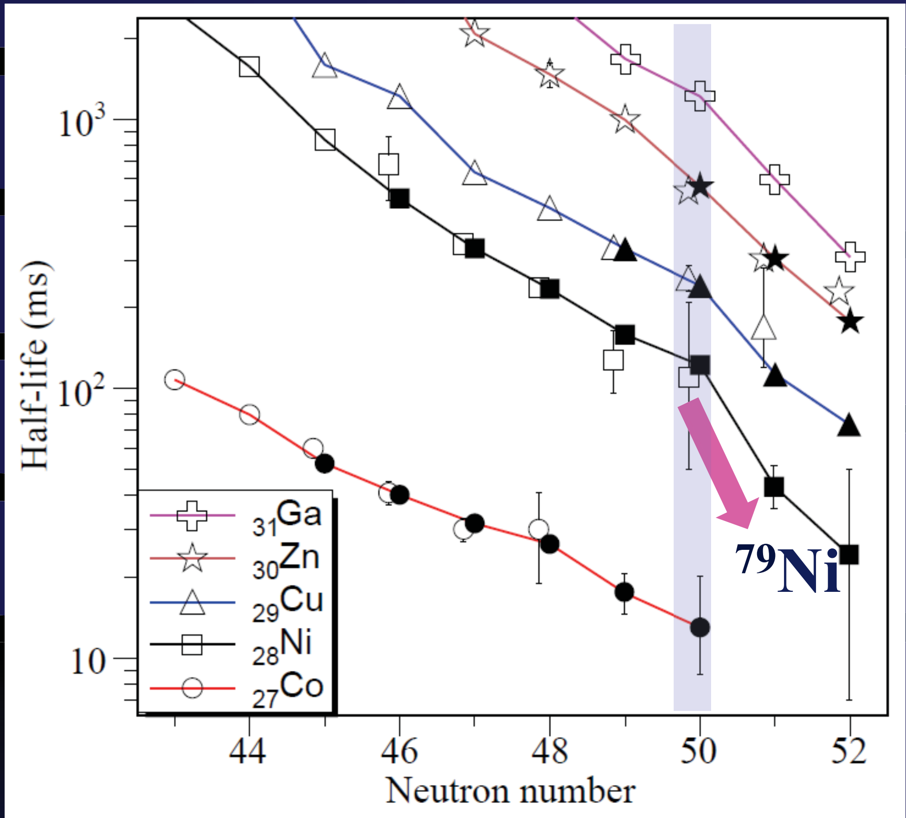


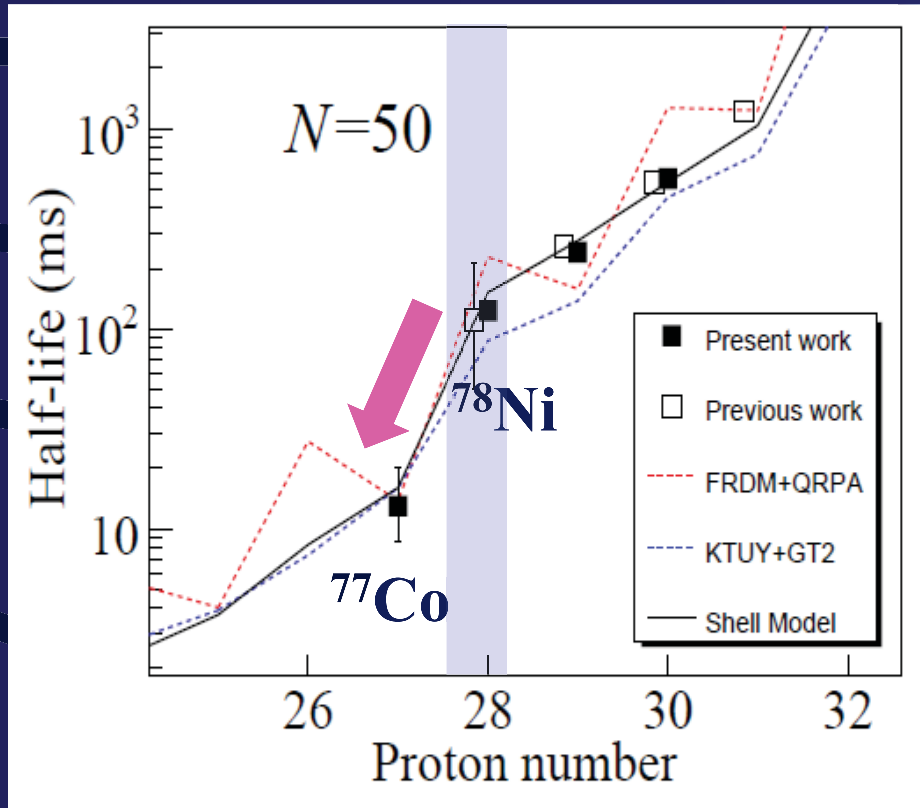


Decay spectra obtained in WAS3ABi.
What about N=51 (^{79}Ni)? Z=27 (^{77}Co)?

Beta-decay half-lives beyond ^{78}Ni

Z.Y.Xu, PRL (2014)

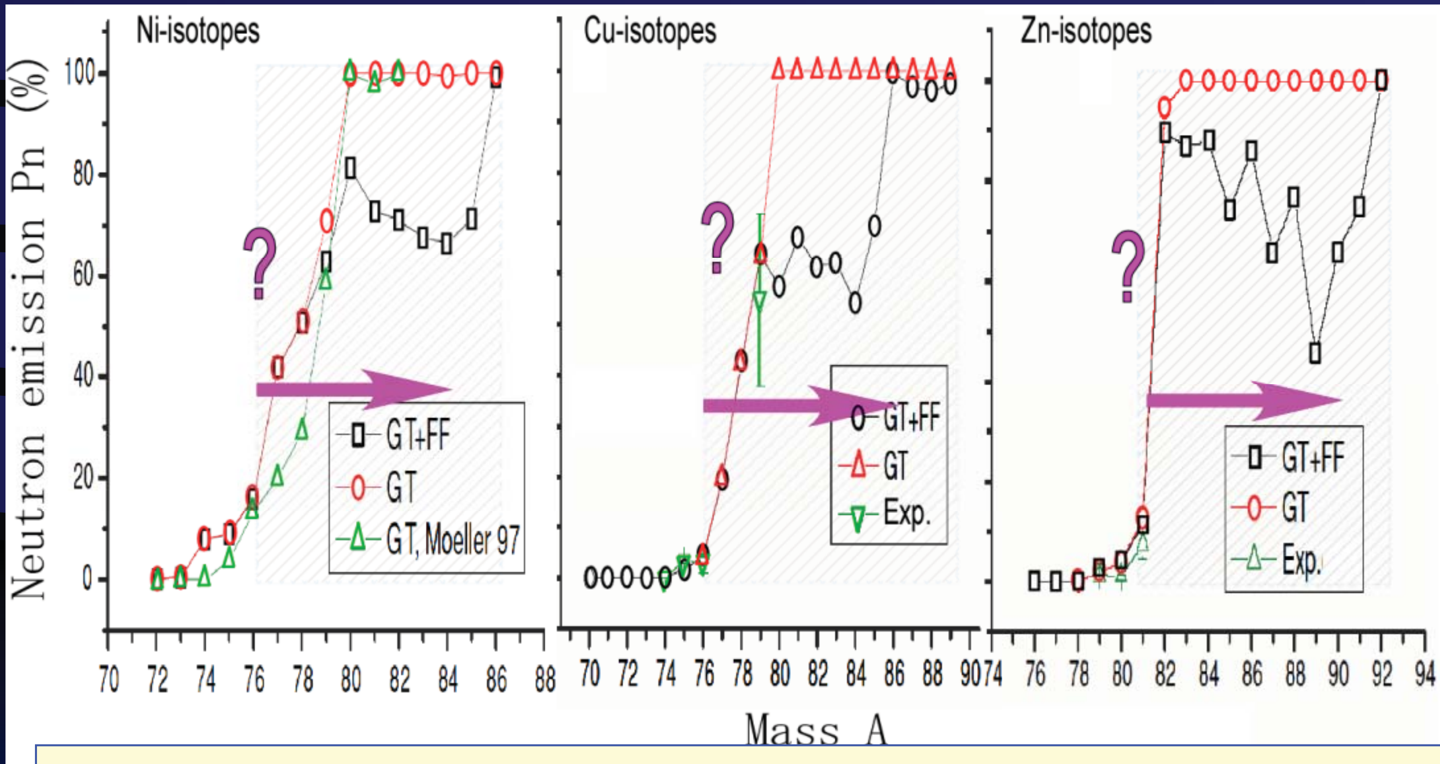




Shorter $T_{1/2}$ beyond ^{78}Ni → Pronounced in Z = 28, N=50
→ ^{78}Ni is double magic nuclei !?

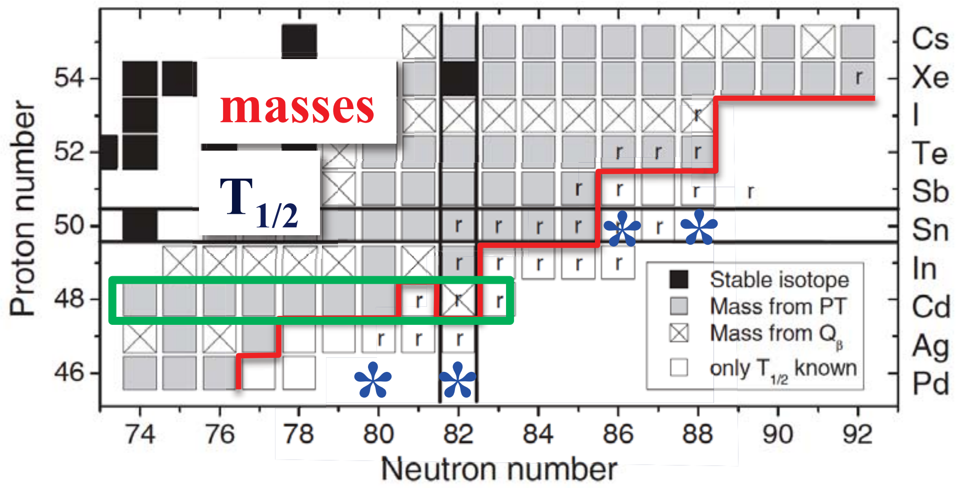
Neutron detection system

I.N.Borzov Phys. Rev. C71 (2005) 065801



Rapid increase of neutron emission prob. around 78Ni.

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



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

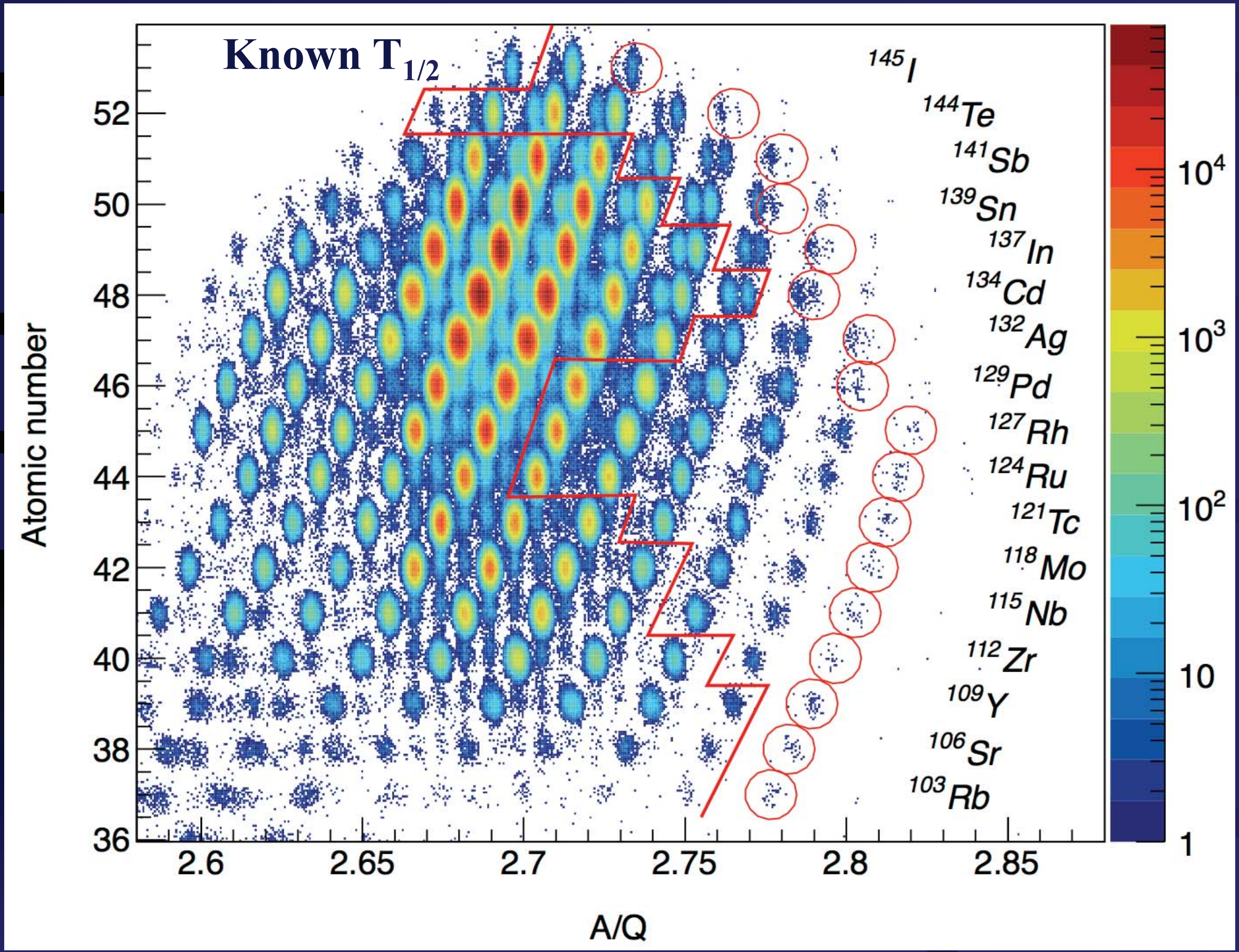
New isomers around
- $^{126,128}Pd$, $^{136,138}Sn$ region

110 Half-lives measured

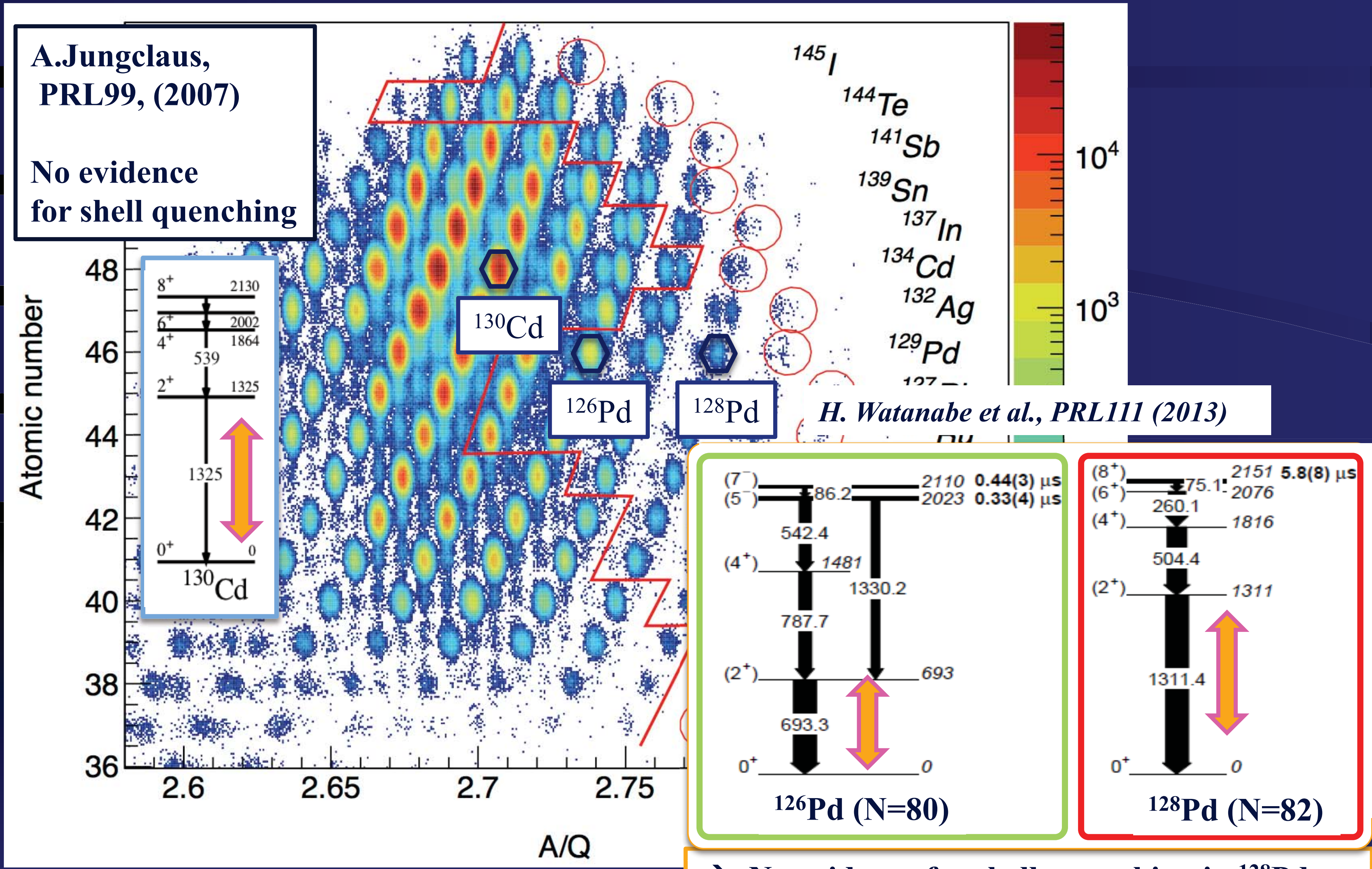
Decay Spectroscopy around A = 100 ~ 145

U-beam: 8 – 10 pnA
~ Two weeks

Two EURICA data sets: G.Simpson/A.Jungclaus & H.Watanabe/G.Lorusso

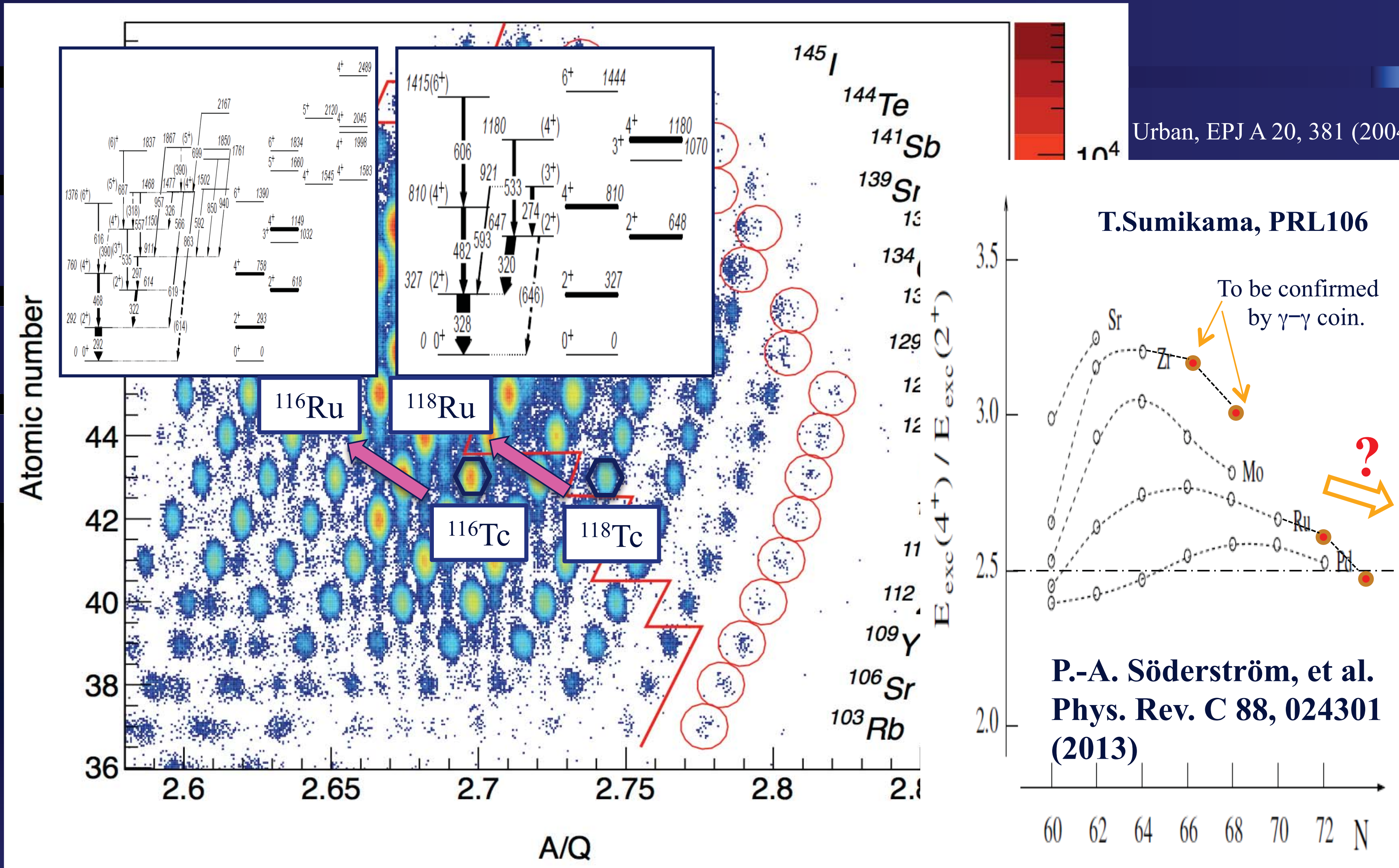


Decay Spectroscopy around A = 100 ~ 145



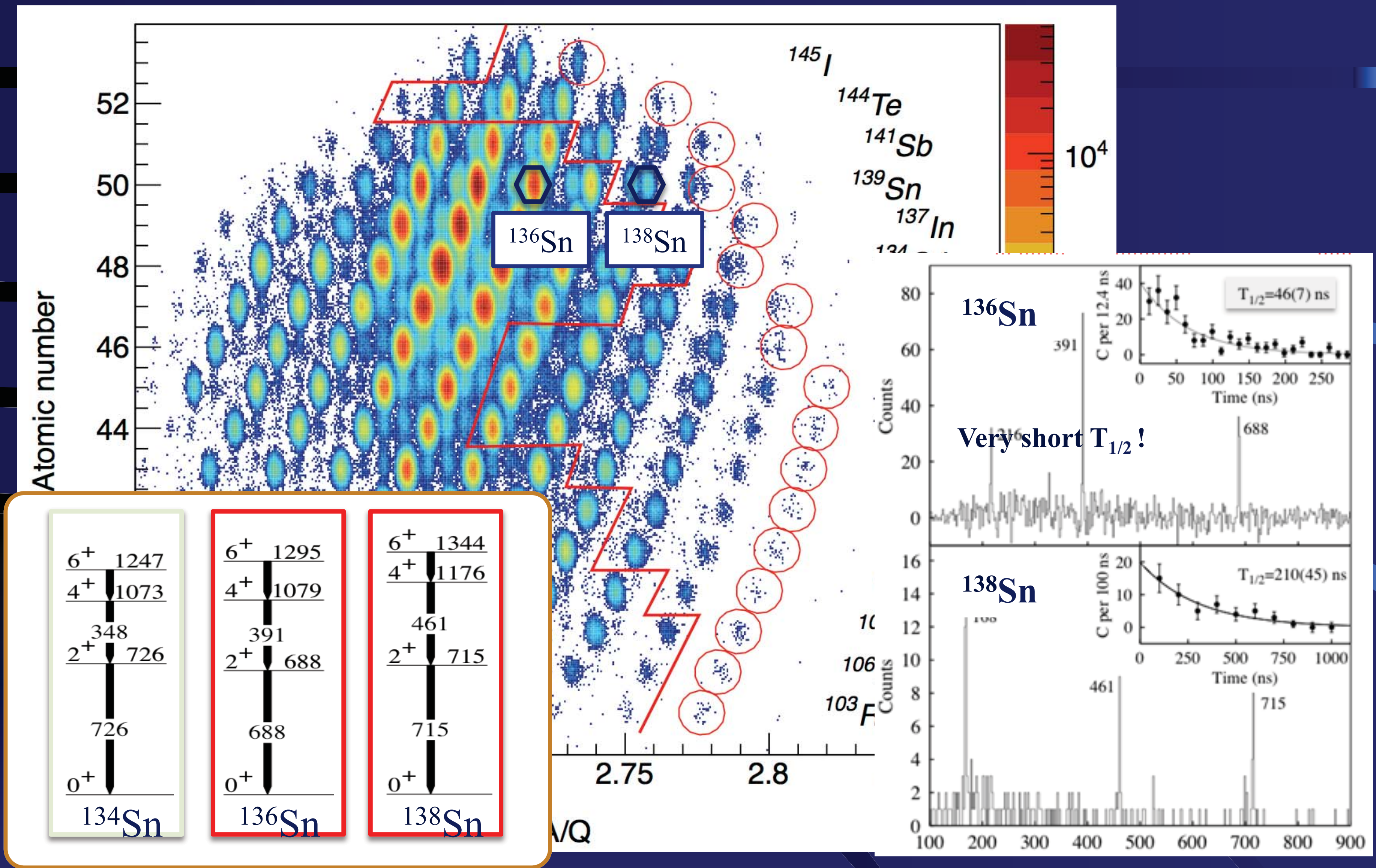
→ No evidence for shell-quenching in ^{128}Pd….

Decay Spectroscopy around A = 100 ~ 145

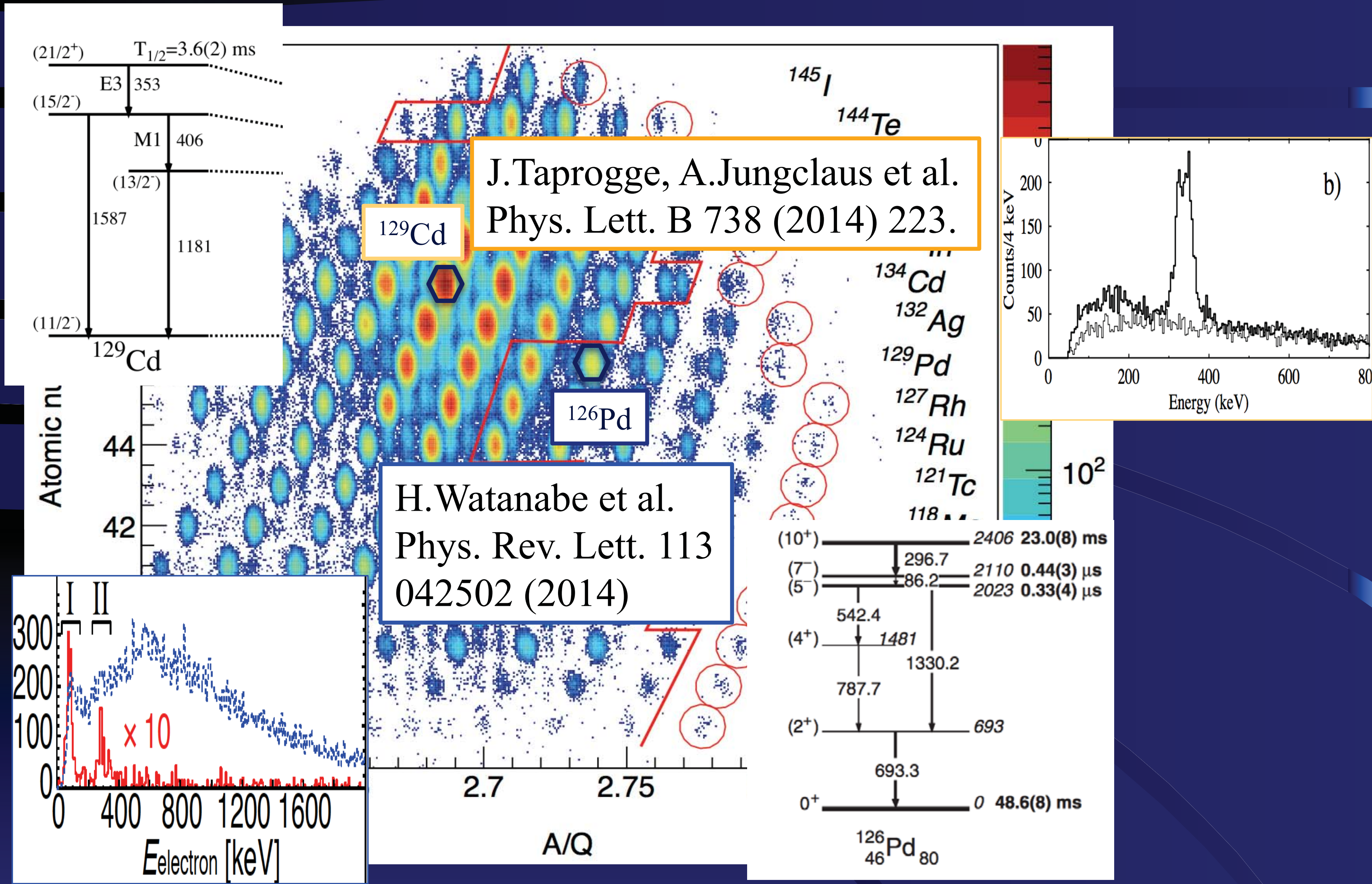


Decay Spectroscopy around A = 100 ~ 145

G. Simpson, G.Gey, A.Jungclaus ..
Phys. Rev. Lett. 113, 132502 (2014)

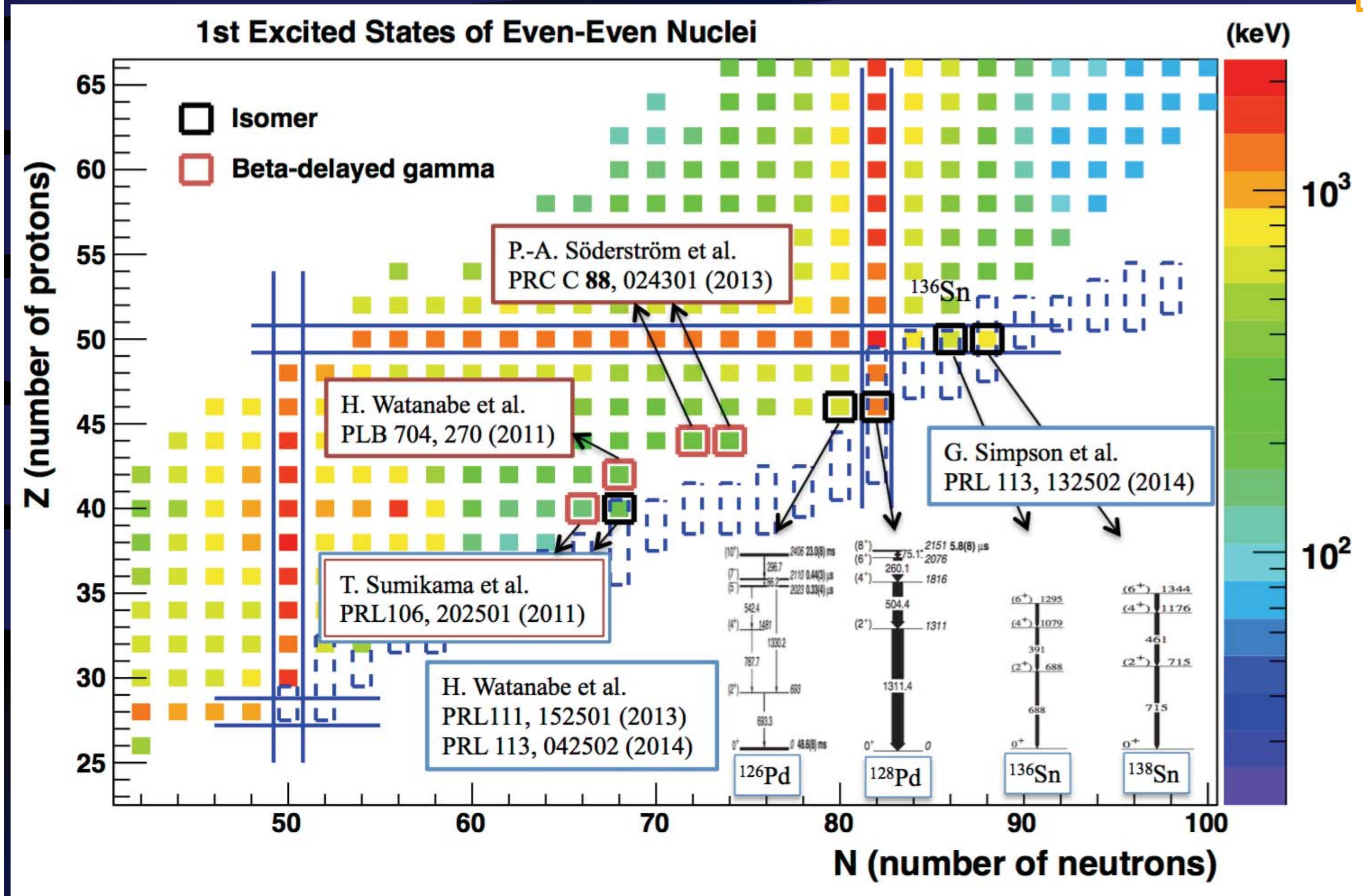


Identification of milisecond isomeric states via detection of conversion electrons



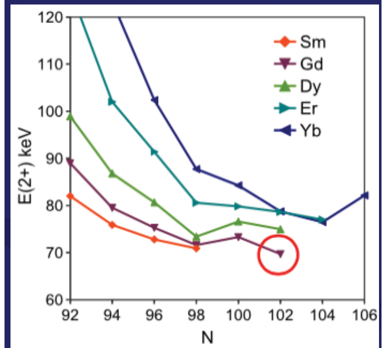
First Excited State: E(2+)

Z.Patel et al.
PRL 113, 0262502 (2014)



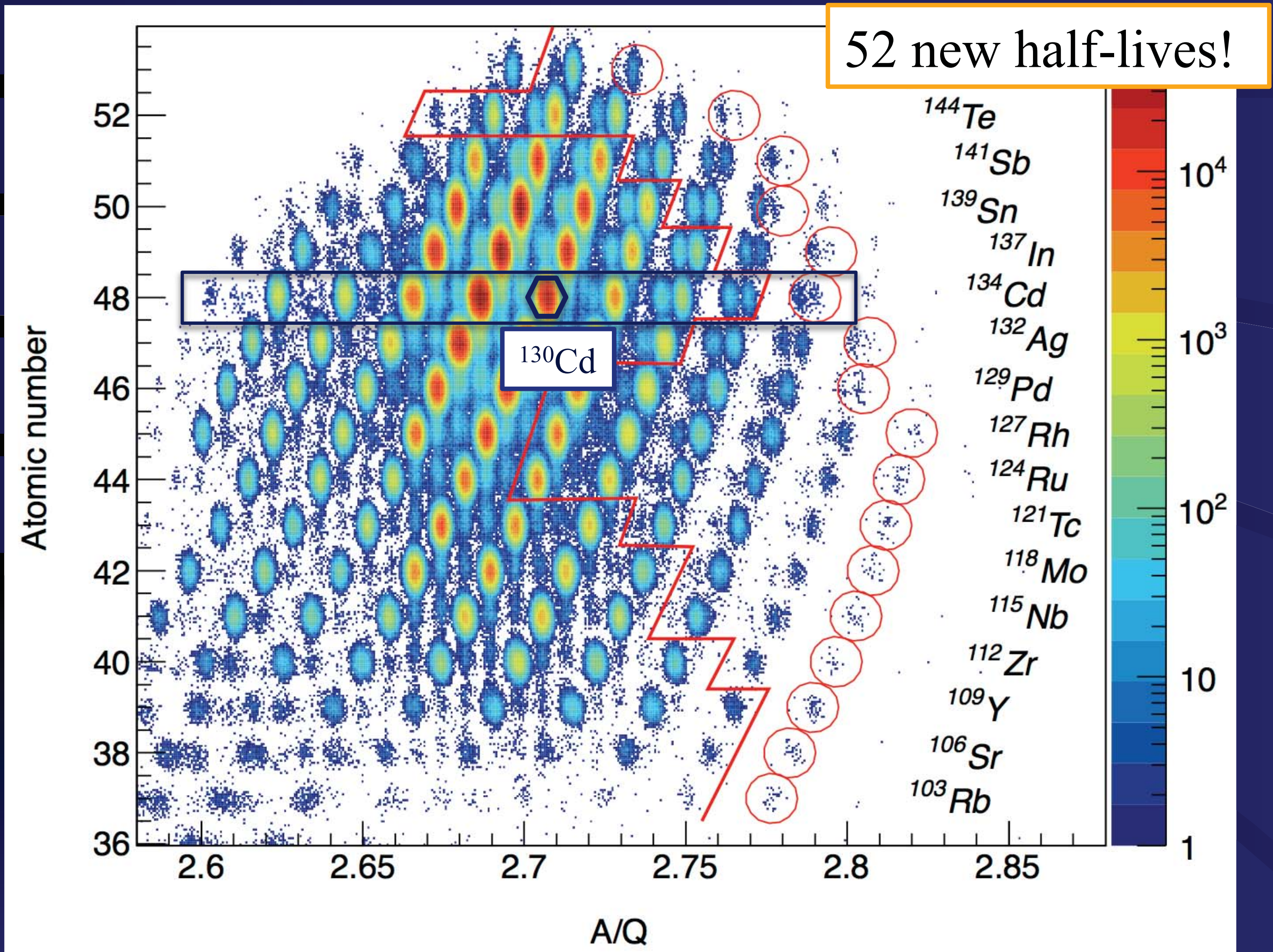
166Gd

164Sm



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

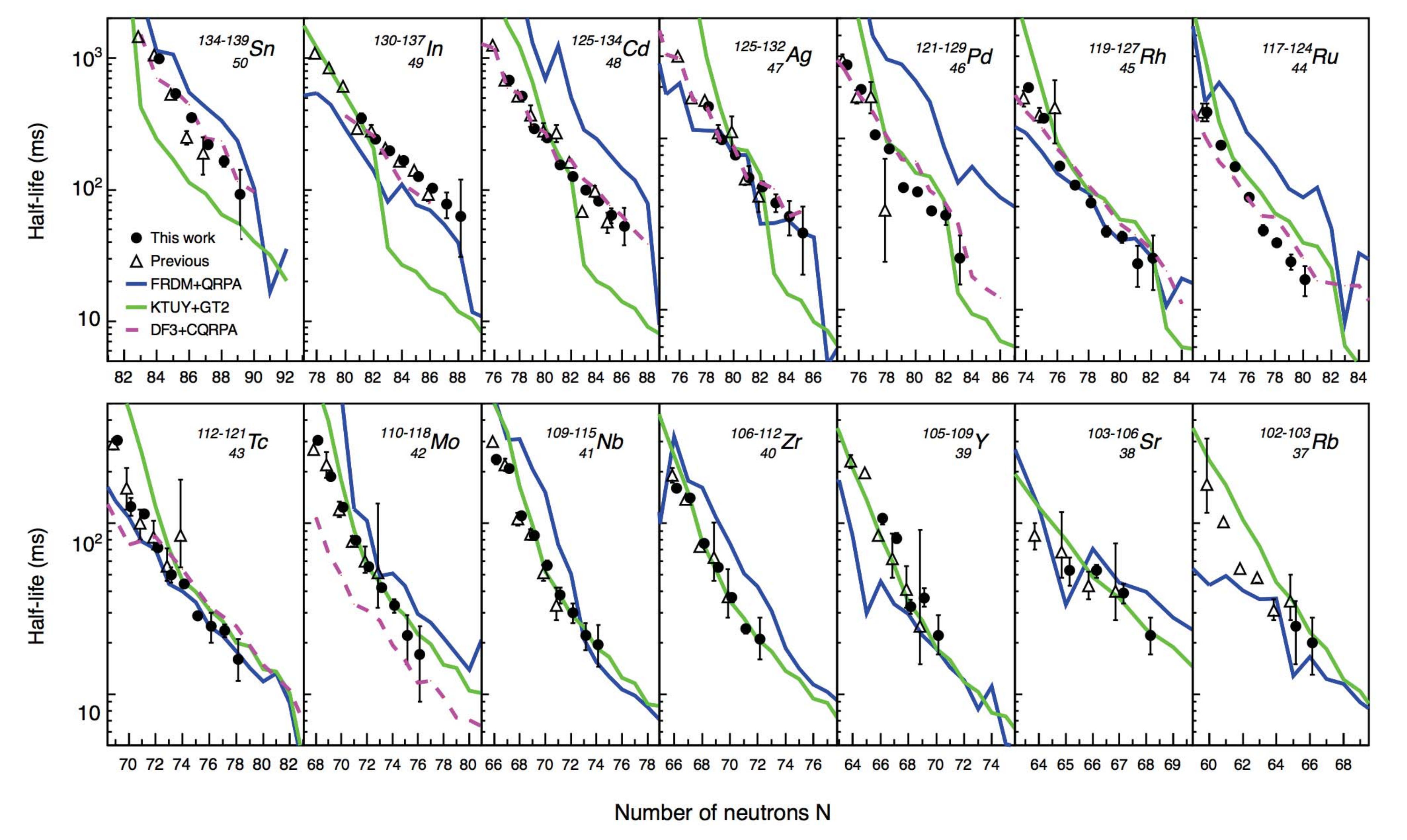
β-decay half-lives on r-Process path



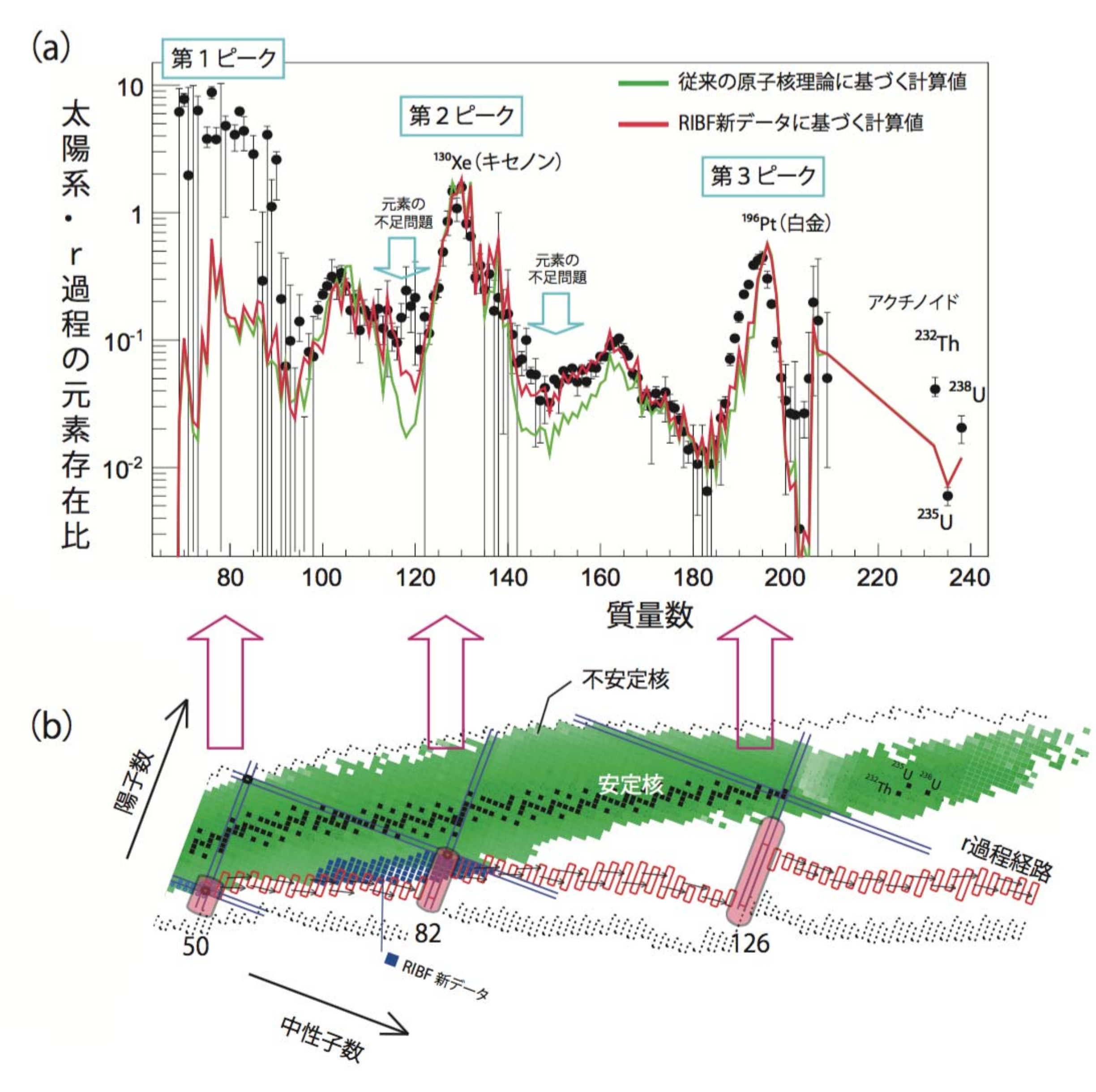
110 Half-lives from Very Neutron-Rich Rb to Sn

40 new half-lives !

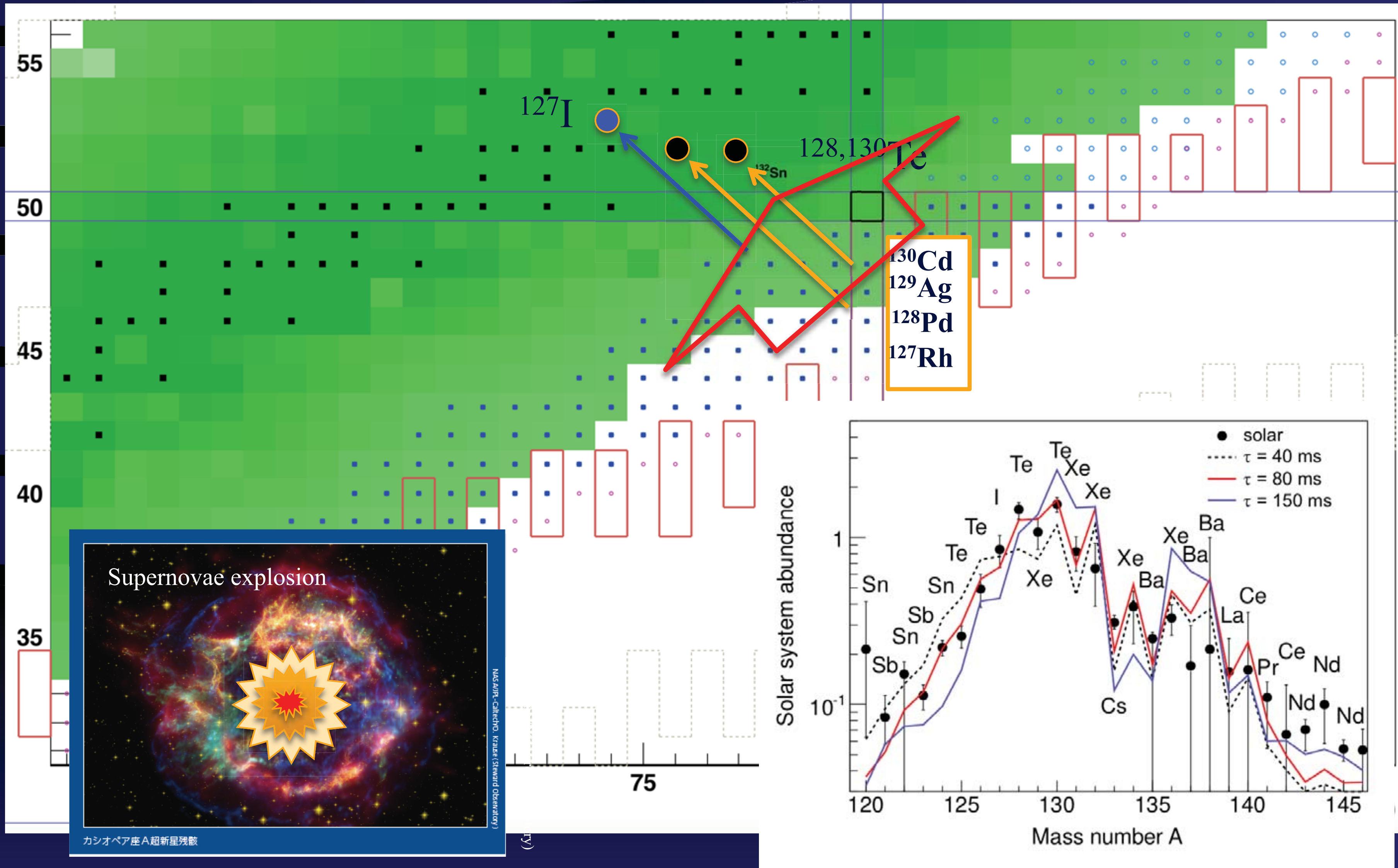
G.Lorusso et al.,
PRL 114, 192501 (2015)



r-process abundance with new $T_{1/2}$ (RIBF)

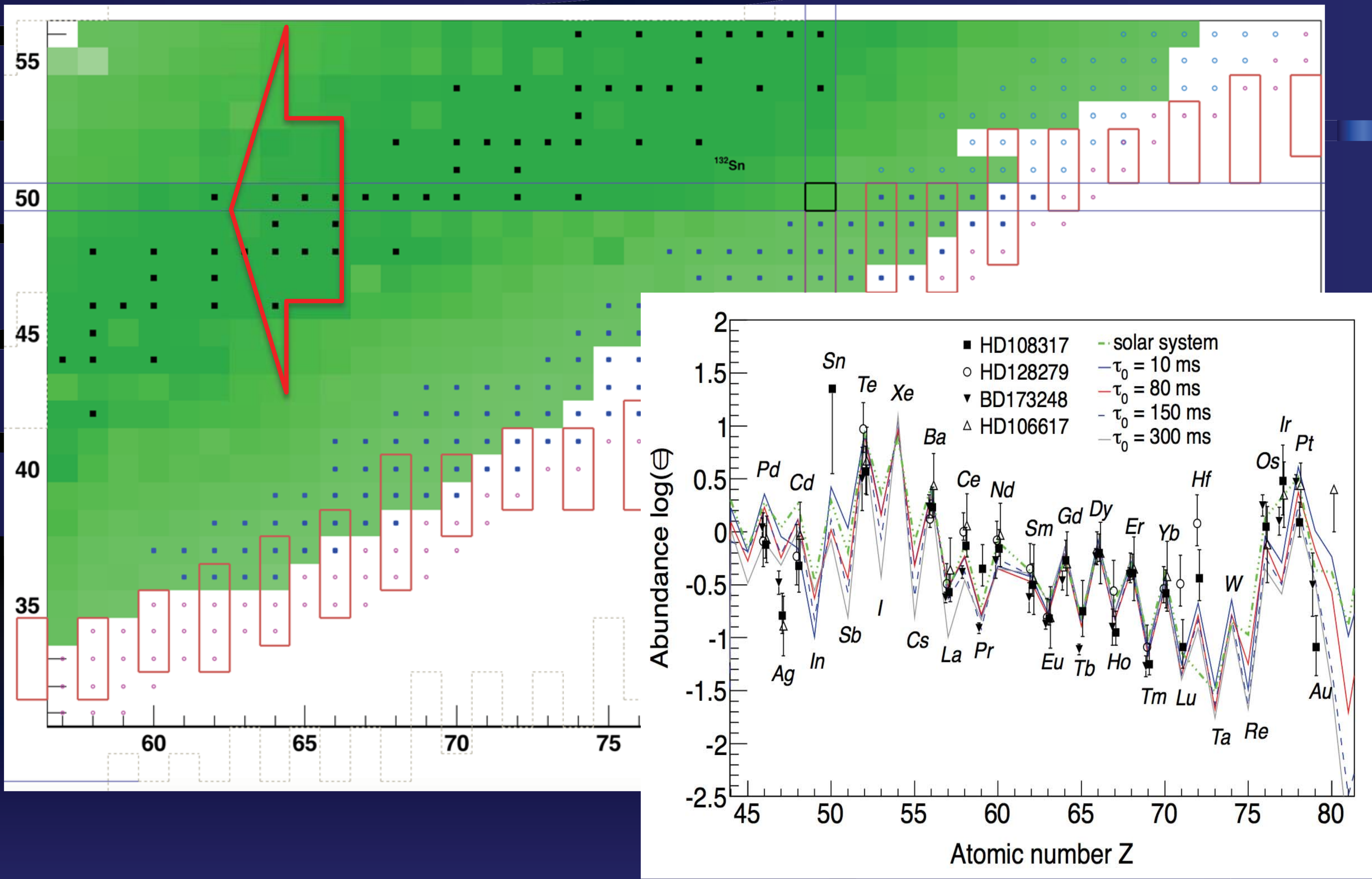


r-process universality and duration of r-process

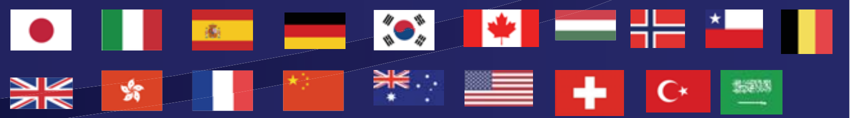


Duration of r-process

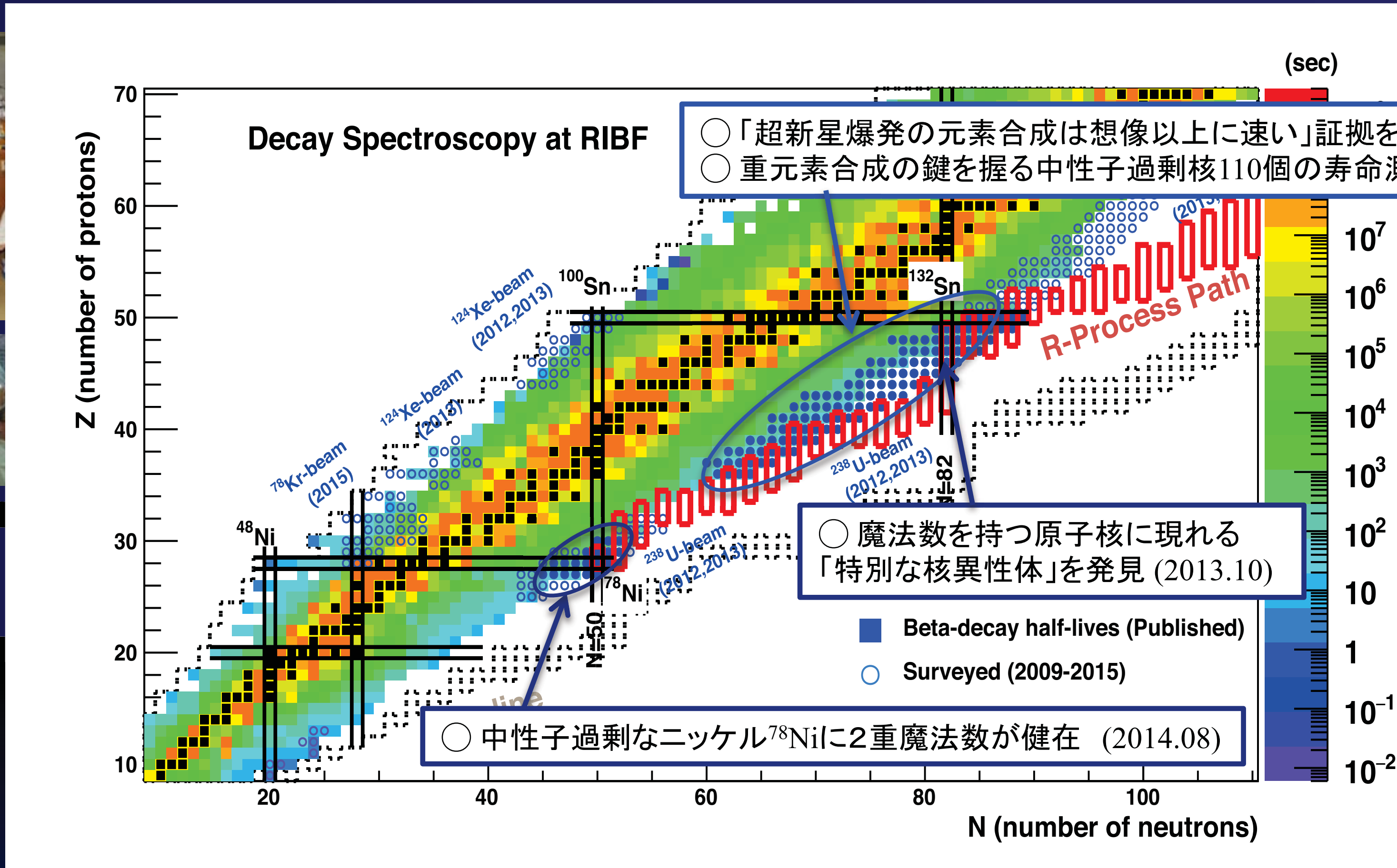
Universality of r-process elements (Z ≥ 56)



International collaboration



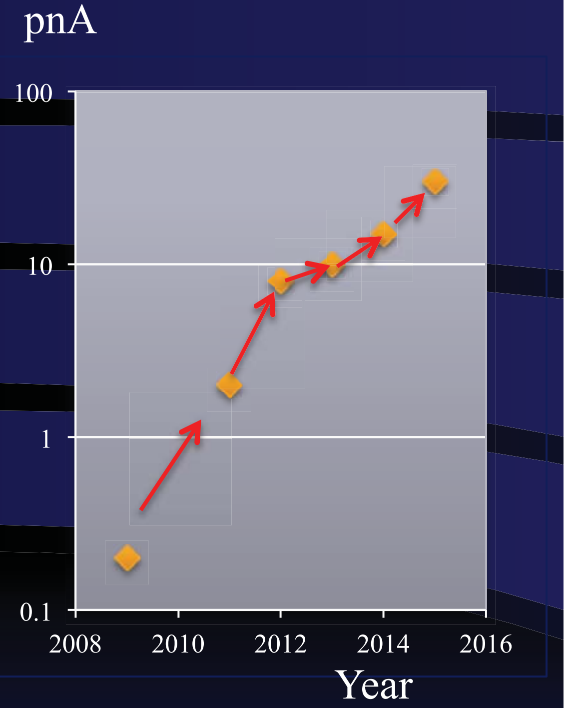
19 countries：237 collaborators！

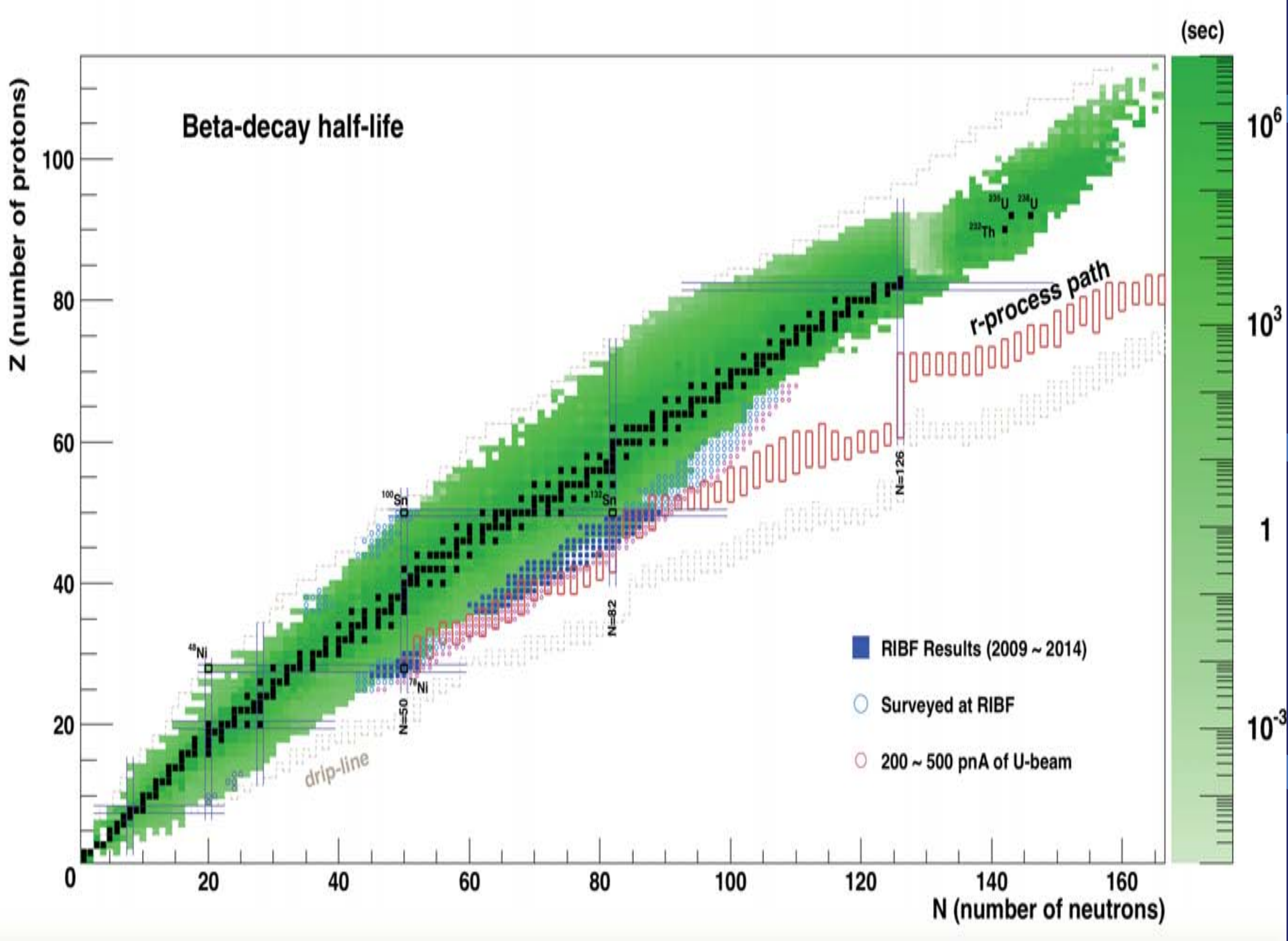


, N. Aoi, P. Ascher, R. Avigo,
L.Bello Garrote, G. Benzoni,
oo, Y. Fujita, N. Fukuda, A.
x, R. Gernhauser, G. Gey, J.
Gottardo, H. Grawe, S. Grevy,
J. Henderson, C. Hinke, N.
obe, Y. Ito, D.G. Jenkins, P.R.
anaoka, Y. Kanke, Y. Kawada,
obayashi, M. Kobayashi, N.
F.G. Kondev, Z. Korkulu, Y.
ubono, M. Kurata-Nishimura,
ne, S. Lalkovski, G. Lane, E.
, T. Lokotko, G. Lorusso, G.
a, K. Matsui, M. Matsushita,
aki, V. Modamio Hoybjor, S.
. Morfouace, S. Morimoto, K.
Nakao, T. Nakatsukasa, D.R.
ura, I. Nishizuka, C. Nita, F.
. Ota, T. Otsuka, H.J. Ong, S.
chia, V. Phong, Zs. Podolyak,
nin, H. Sakurai, K. Sato, H.
aki, T. Shimoda, Y. Shimizu,
ohler, I.G. Stefan, K. Steiger,
H. Suzuki, T. Tachibana, K. Tajiri, S. Takano, A. Tashima, H. Takeda, Man. Tanaka, Mas. Tanaka, Y. Takei, R. Taniuchi, J. Taprogge, K. Tajiri, T. Teranishi, S. Terashima, G. Thiamova, K. Tshoo, Zs. Vajta, J. Valiente Dobon, Y. Wakabayashi, P.M. Walker, H. Watanabe, A. Wendt, V. Werner, O. Wieland, K. Wimmer, J. Wu, Q. Wu, F.R. Xu, Z.Y. Xu, A. Yagi, S. Yagi, H. Yamaguchi, K. Yamaguchi, T. Yamamoto, M. Yalcinkaya, R. Yokoyama, S. Yoshida, K. Yoshinaga, G. Zhang

謝辞：欧州ガンマ線検出器委員会

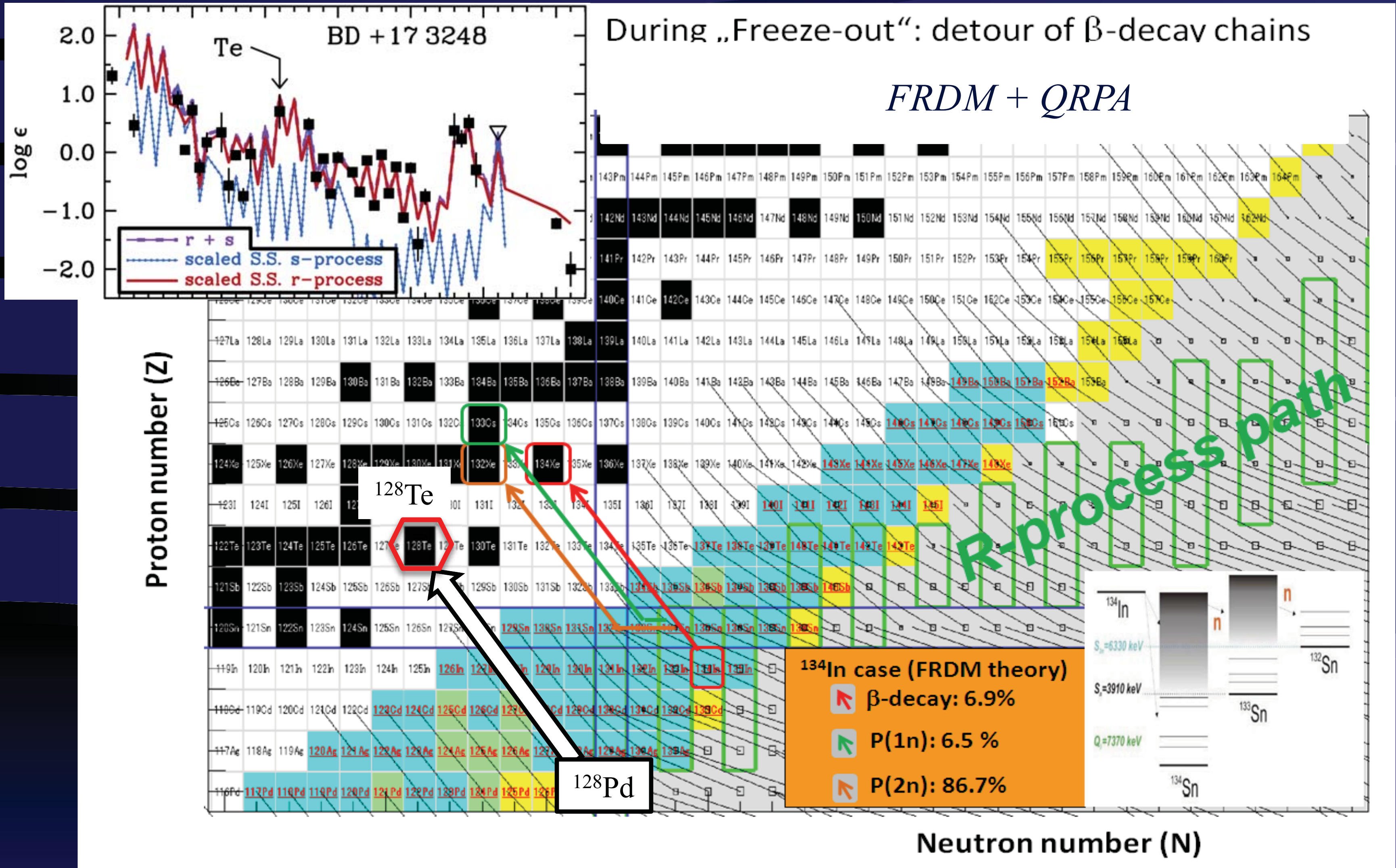
In four years…
(U-beam int. ≥ 100 pnA!?)





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

Beta-decay flow back to stability



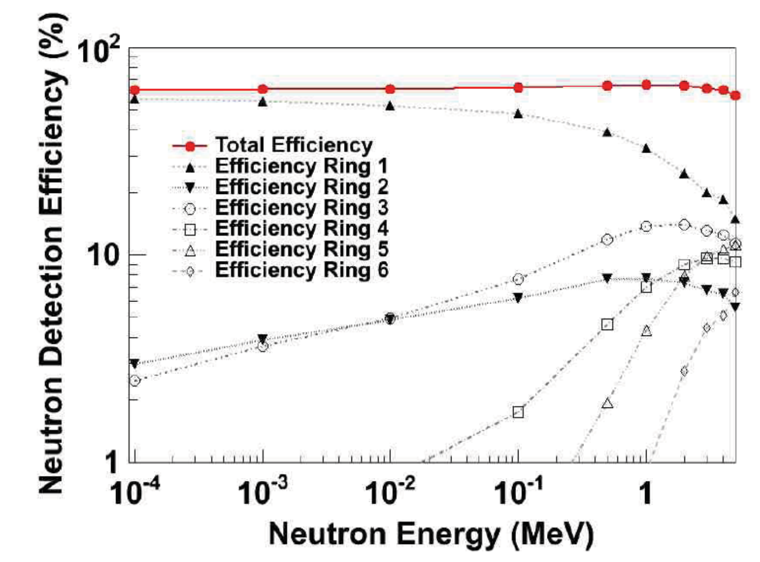
Beta-decay of isotopes : 127Rh, 128Pd, 129Ag, 130Cd (N=82) → Sn, Te

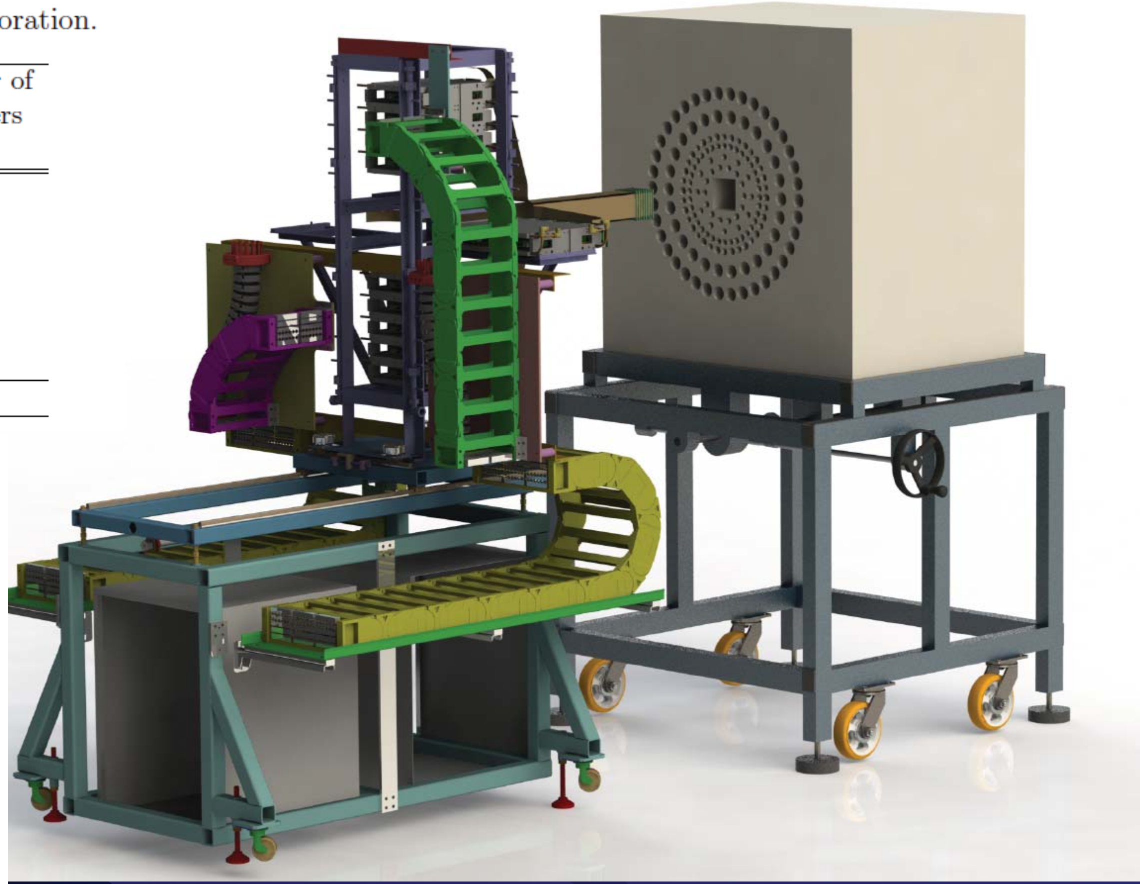
BRIKEN Project (RIBF)

Monster of 3He Detectors

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

Owner	Pressure (atm)	Size: Diameter (inch/cm)	Size: Eff. Length (inch/mm)	Number of Counters
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





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

r-Process path toward heavy region

RIKEN News 2015 Sep.