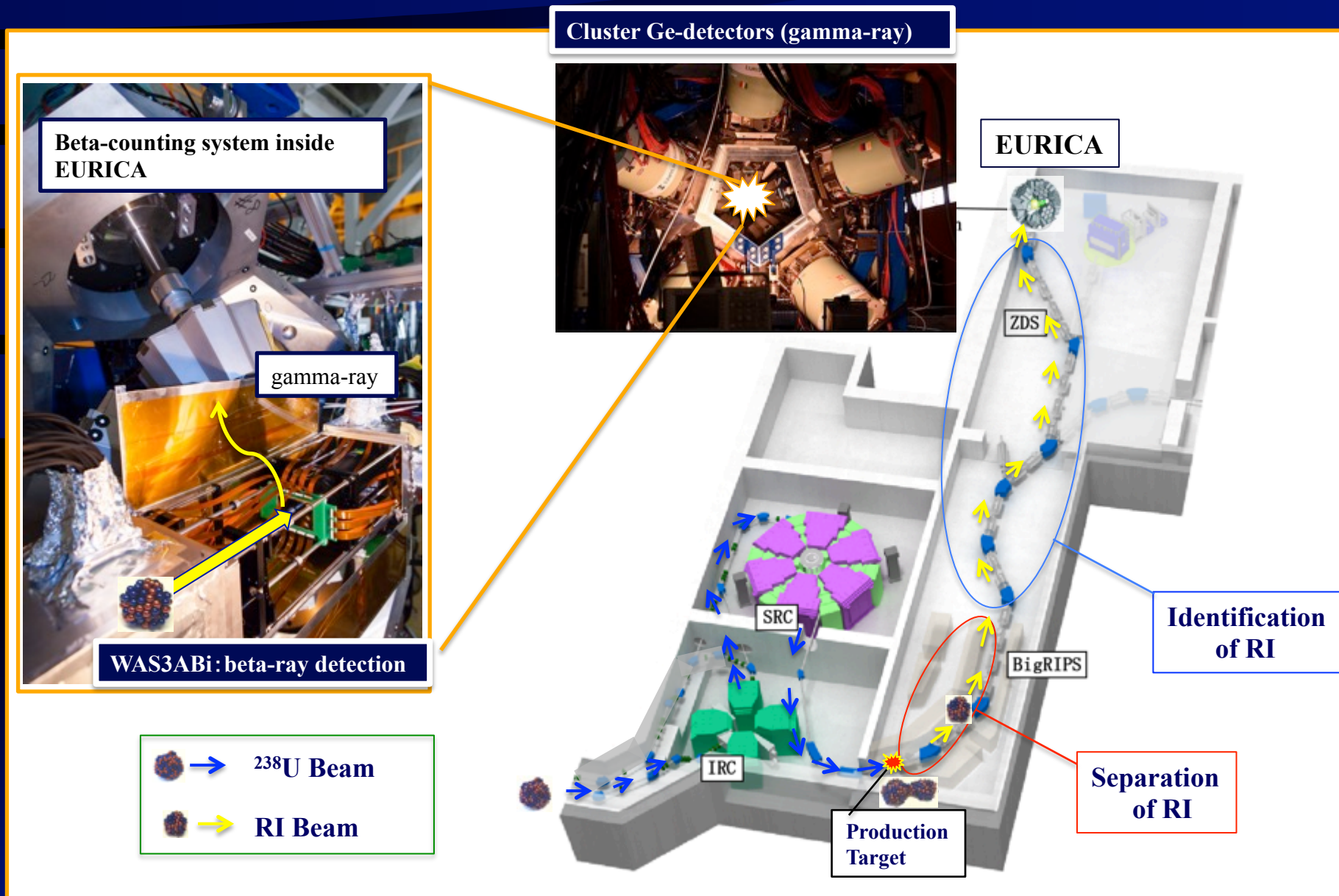




Recent Results and Perspectives of Experimental Nuclear Astrophysics

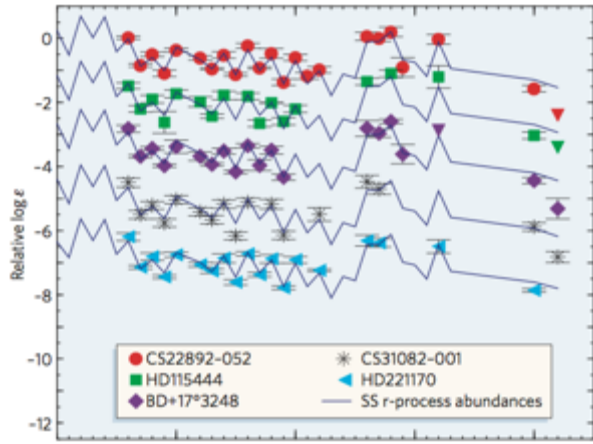
Shunji NISHIMURA
RIKEN Nishina Center

EURICA Spectrometer at RIBF

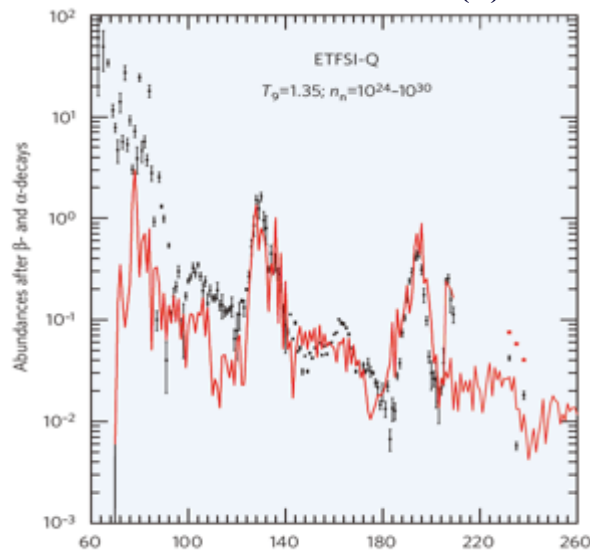


Origin of Elements Heavier than Fe

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

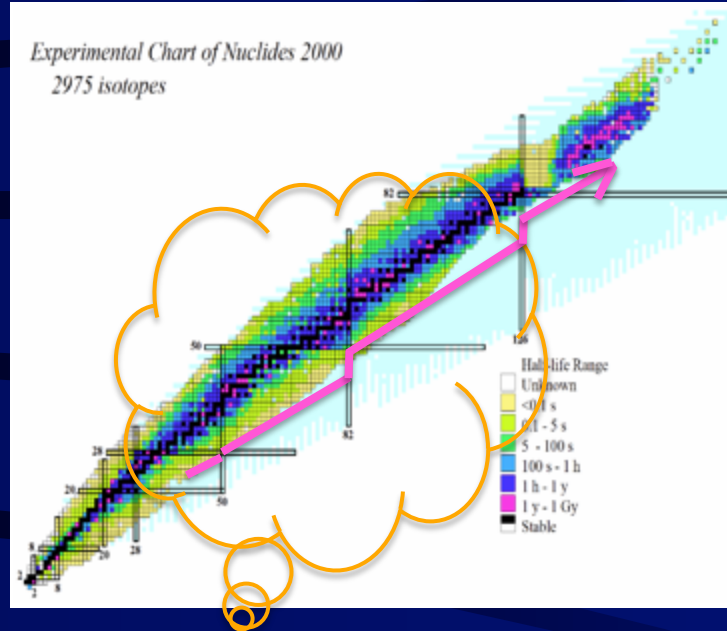


Atomic number (Z)



Mass number (A)

Experimental Chart of Nuclides 2000
2975 isotopes

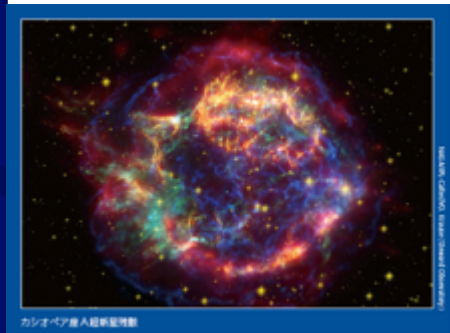


Nuclear Structure

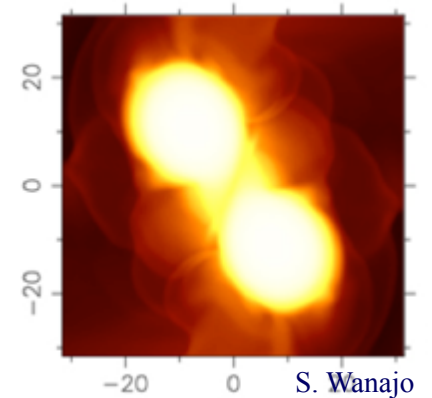
- Neutron Magic (N=50, 82, 126), Deformation, Quenching
- Mass ... r-process path $(n, \gamma) \rightleftharpoons (\gamma, n)$
- Half-lives ... process speed
→ abundance & shape
- Delayed neutron emission
... freeze-out path, odd-even
- Fission recycling

r-process conditions:
 Y_e, S, τ, EOS, \dots

Supernovae explosion?

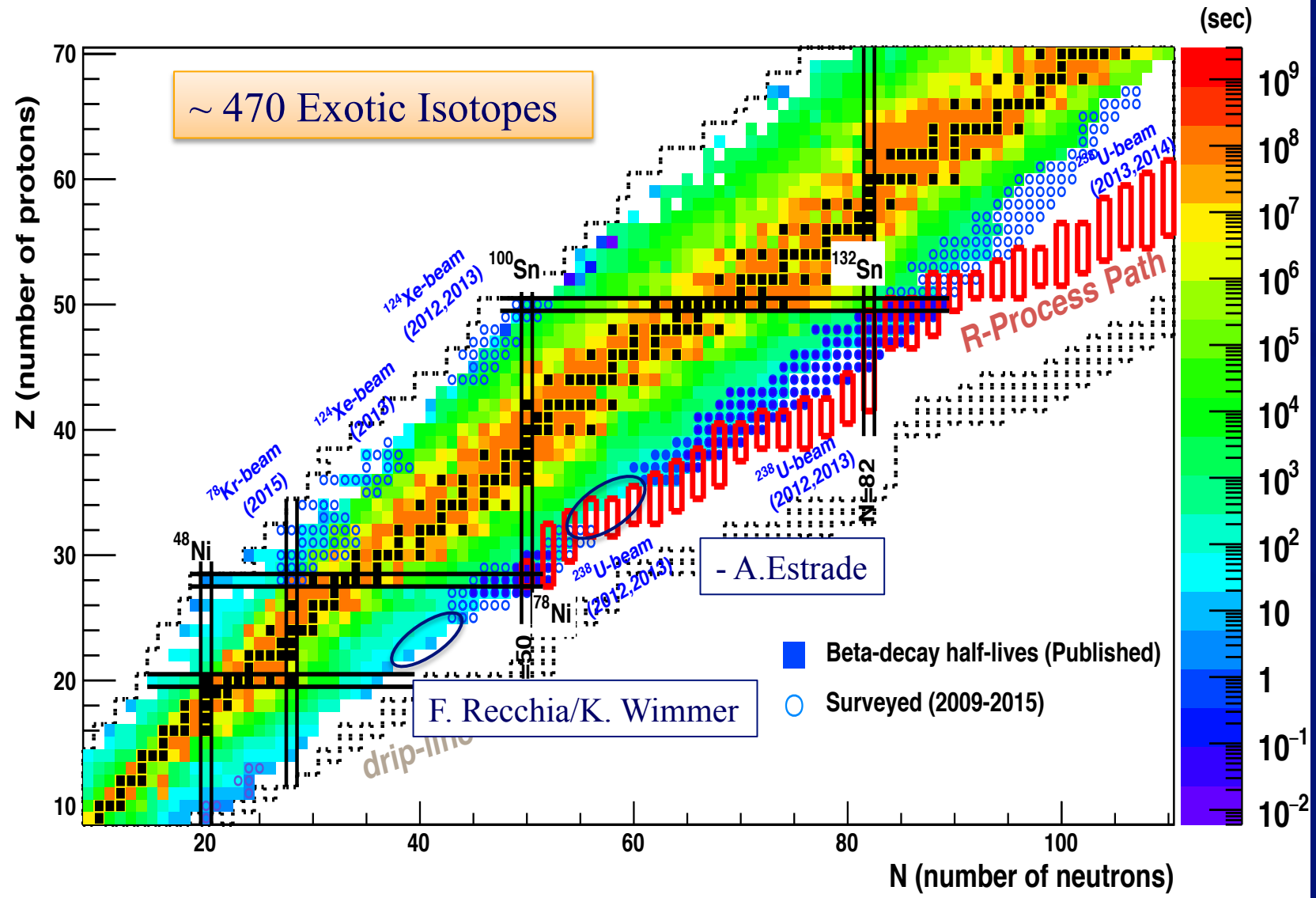


Neutron star merger?



→ Nuclear properties play important role in r-process nucleosynthesis

Harvesting the Decay Properties of Exotic Nuclei



EURICA Programs (2012-16)



2011

From GSI to RIKEN & Construction

MT (S.Nishimura/P.Doornenbal)

2012

RIBF-85 (P.Boutachkov)

RIBF-10 (S.Nishimura), RIBF-90 (M.Niikura) ... ~78Ni

RIBF-60/62 (H.Watanabe, G.Lorusso) ... ~ 128Pd

RIBF-85 (G.Simpson/A.Jungclaus) ... ~ 136,138Sn

2013

RIBF-87 (A.Odahara/C.B.Moon/R.Lozeva) ... A~140

RIBF-26 (T.Sumikama) ... ~ 110Zr

RIBF-85 (E.Ideguchi/G.Simpson) ... Z ~ 60

RIBF-80 (G. Benzoni) N=40-50

RIBF-97 (G.Lorusso)

2014

RIBF-10 (M.Lewitowicz/R.Kruecken/R.Gernhäuser/S/Nishimura) ... 100Sn

RIBF-88 (H.Watanabe/P-A Söderström/P.Regan/P.Walker) ... ~170Dy

2015

RIBF-04 (B.Blank) ... 59Ge ~ 67Kr

RIBF-82 (B.Rubio/Y.Fujita/W.Gelletly) ... ~ 70Kr

RIBF-93 (A.Algora/F.Recchia/G.deAngelis/B.Rubio) ... ~72Kr

2016

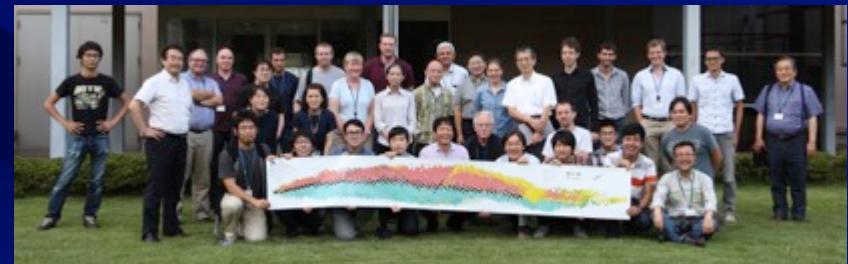
RIBF-106 (A.Estrade) ... N~56

RIBF-140 (F.Recchia/K.Wimmer) ... N~40

Dismantled ! Back to GSI

*About ~100 days
of Beam Time*

230 Collaborators
19 countries



EURICA: Publications



From GSI to RIKEN & Construction

2011
2012
2013
2014
2015
2016
2017

MT (S.Nishimura/P.Doornenbal)

RIBF-85 (P.Boutachkov)

RIBF-10 (S.Nishimura), RIBF-90 (M.Niikura) ... ~78Ni

RIBF-60/62 (H.Watanabe, G.Lorusso) ... ~ 128Pd

RIBF-85 (G.Simpson/A.Jungclaus) ... ~ 136,138Sn

RIBF-87 (A.Odahara/C.B.Moon/R.Lozeva) ... A~140

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RIBF-88 (H.Watanabe/P-A Söderström/P.Regan/P.Walker) ... ~170Dy

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RIBF-106 (A.Estrade) ... N~56

RIBF-140 (F.Recchia/K.Wimmer) ... N~40

23 publications

PRL x 9, PLB x 5, PRC(R) x 3, PRC x 7

P.-A.Soederstroem et al. PRC88 (2013) ●

H.Watanabe et al. PRL 113 (2013) ●●

Z.Y.Xu PRL 113 (2014) ●

H.Watanabe PRL 113 (2014) ●●●

J. Taprogge et al. PRL 113 (2014) ●●●

G.Simpson et al. PRL 113 (2014) ●

J. Taprogge et al. PLB 738 (2014) ●

Z. Patel et al. PRL 113 (2014) ●

P.-A.Soederstroem et al. PRC 92 (2015) ●●

G. Lorusso et al. PRL114 (2015) ●

J. Taprogge et al. PRC91 (2015) ●

R. Lozeva et al. PRC 92 (2015) ●

P. Lee et al. PRC 92 (2015) ●●

F. Browne et al. PLB750 (2015) ●●

G.Benzoni et al. PLB 751 (2015) ●●●

A.Jungclaus et al. PRC 93 (2016) ●●●

A.Jungclaus et al. PRC 94 (2016) ●

R. Lozeva et al. PRC 93 (2016) ●

Z. Patel et al. PLB 753 (2016) ●

A.I. Morales et al. PRC 93 (2016) ●●

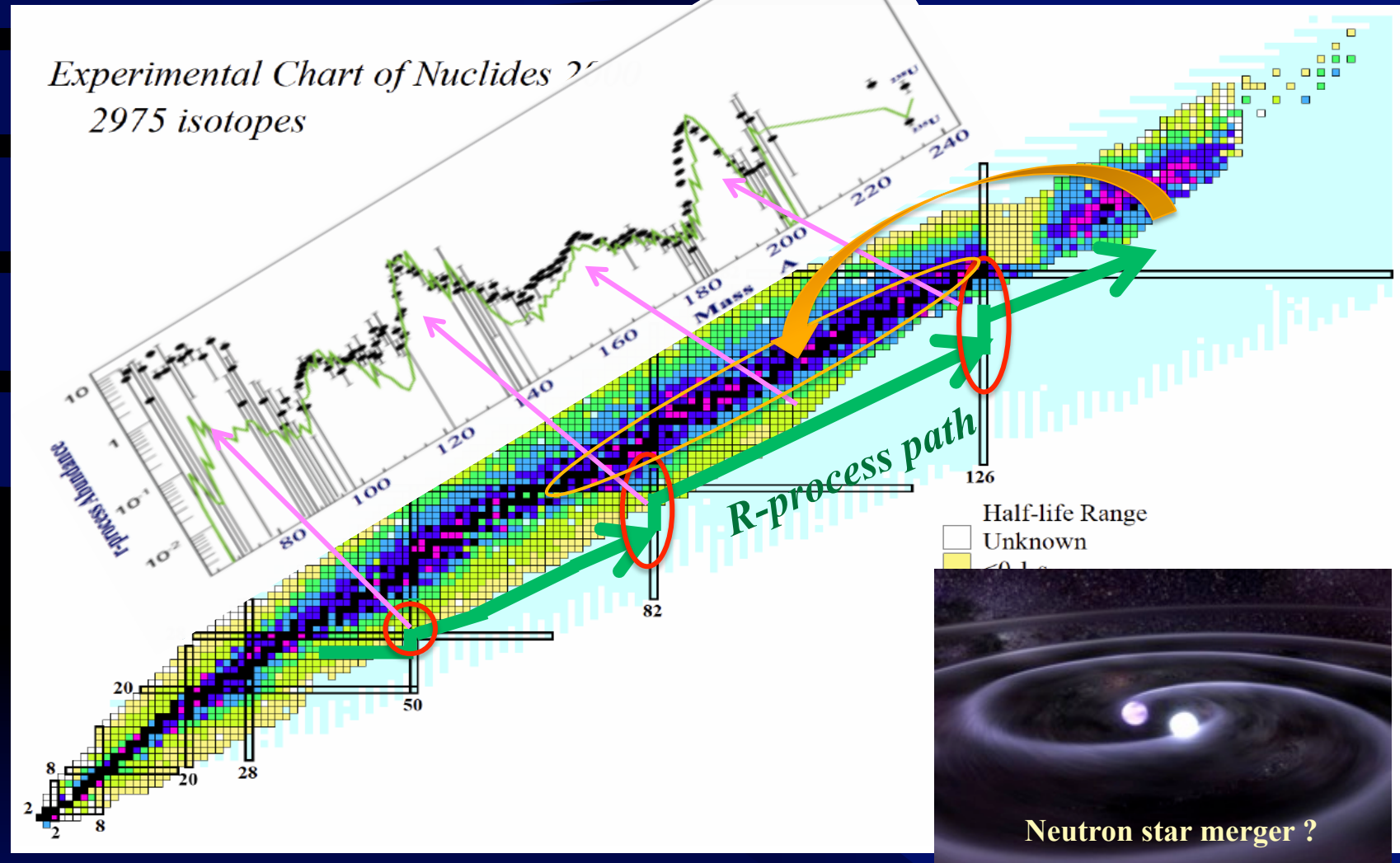
I. Celikovic et al. PRL 116 (2016) ●●

H. Watanabe et al. PLB641 (2016) ●●●

B. Blank et al. PRC 93 (2016) ●●

T. Goigoux et al. PRL 117 (2016) ●●

Nuclear Properties

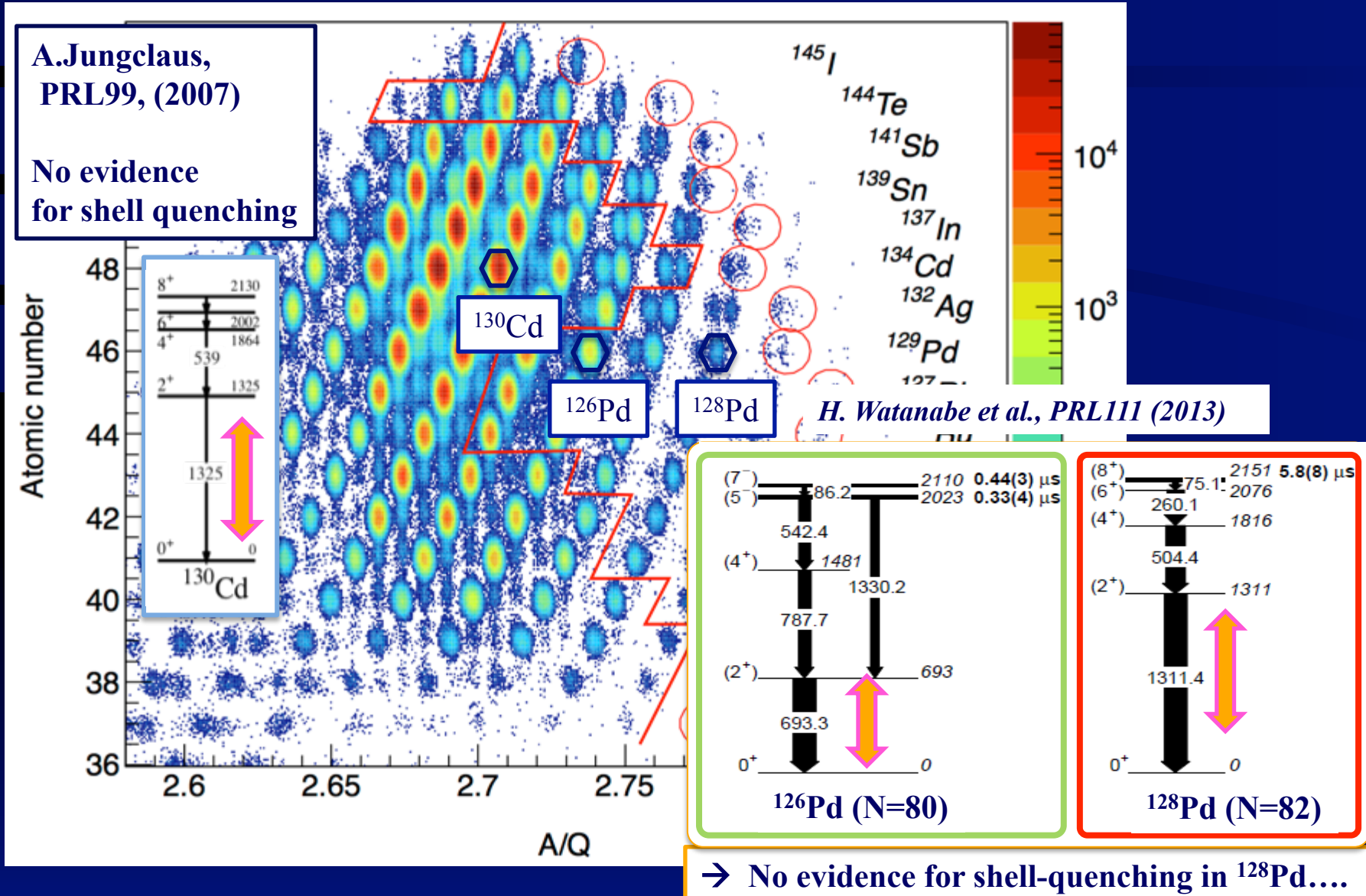


A lots of nuclear properties for very neutron-rich nuclei are required !

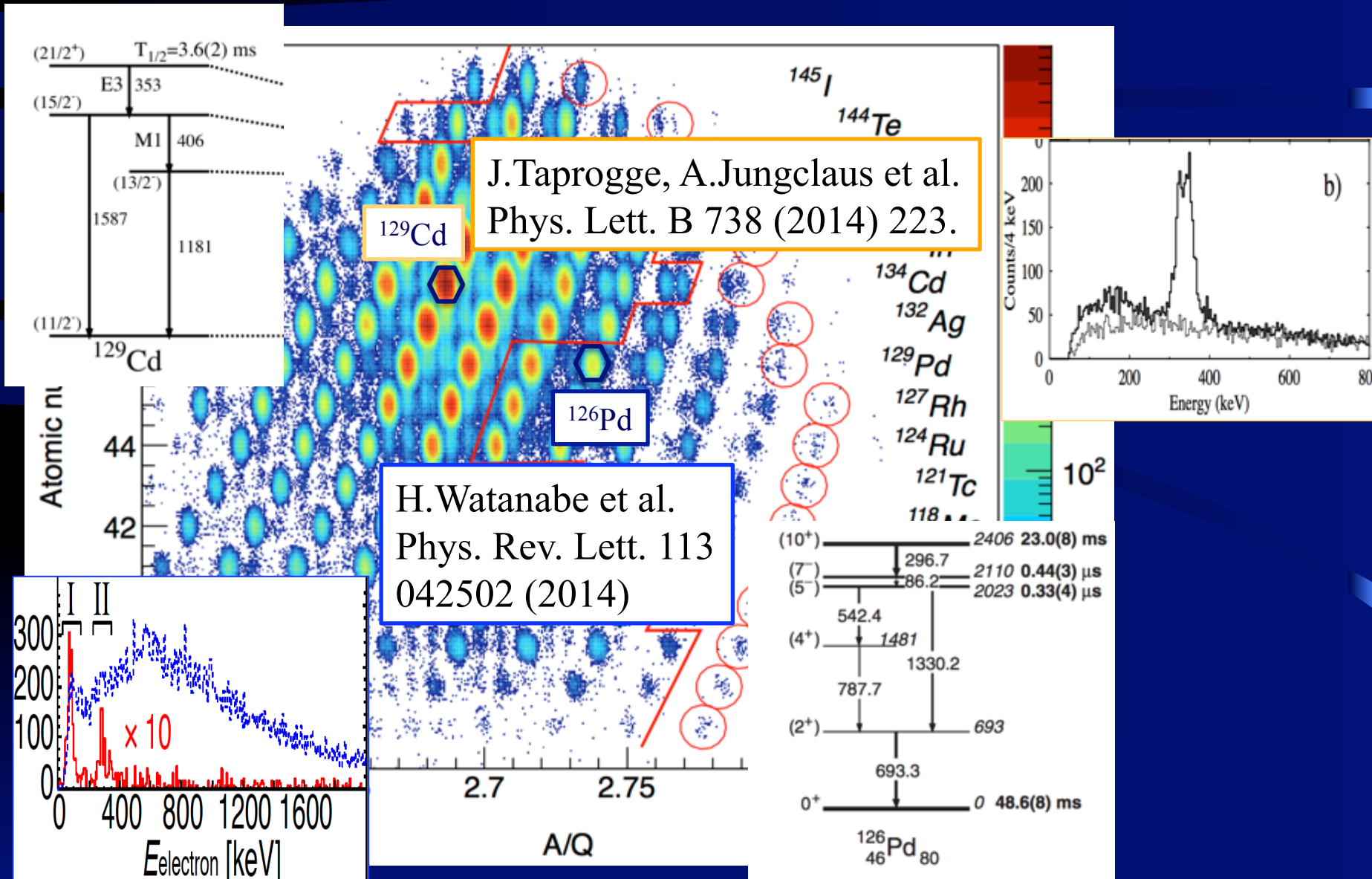
Decay Spectroscopy around $A = 100 \sim 145$

U-beam: 8 – 10 pnA
 ~ Two weeks

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



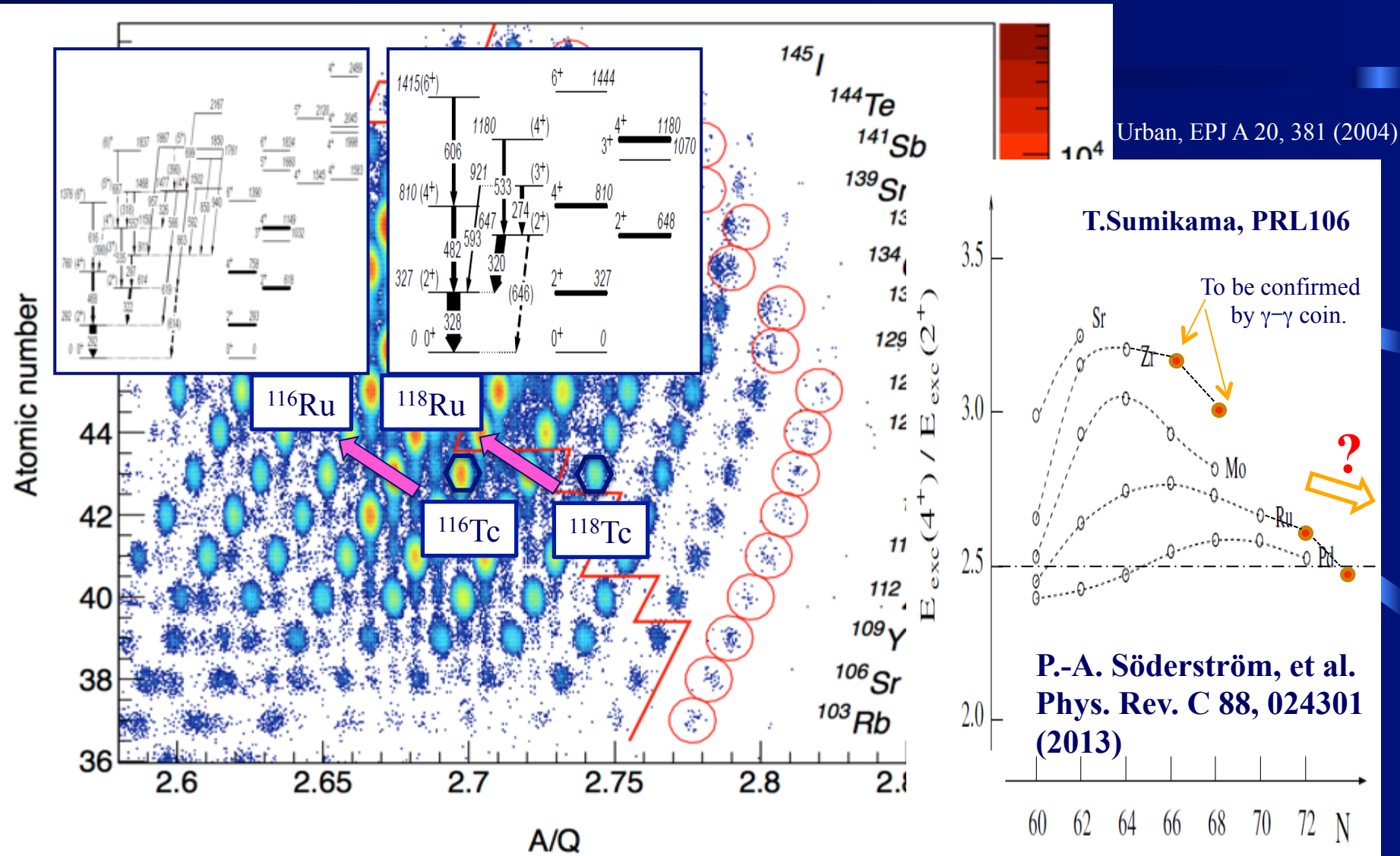
Identification of milisecond isomeric states via detection of conversion electrons



J. Taprogge, A. Jungclaus et al.
 Phys. Lett. B 738 (2014) 223.

H. Watanabe et al.
 Phys. Rev. Lett. 113
 042502 (2014)

Decay Spectroscopy around $A = 100 \sim 145$



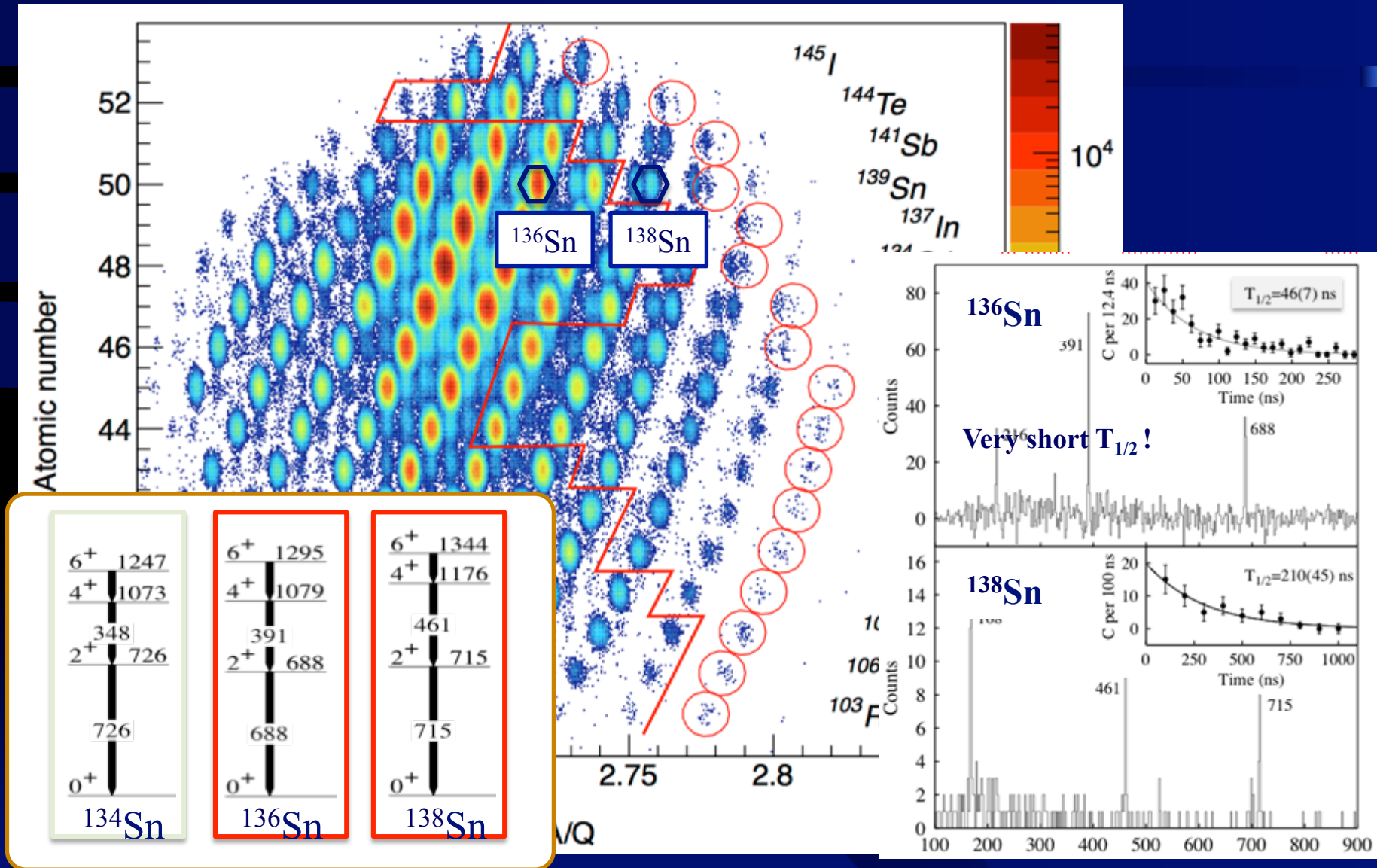
Urban, EPJ A 20, 381 (2004)

T.Sumikama, PRL106

P.-A. Söderström, et al.
Phys. Rev. C 88, 024301
(2013)

Decay Spectroscopy around $A = 100 \sim 145$

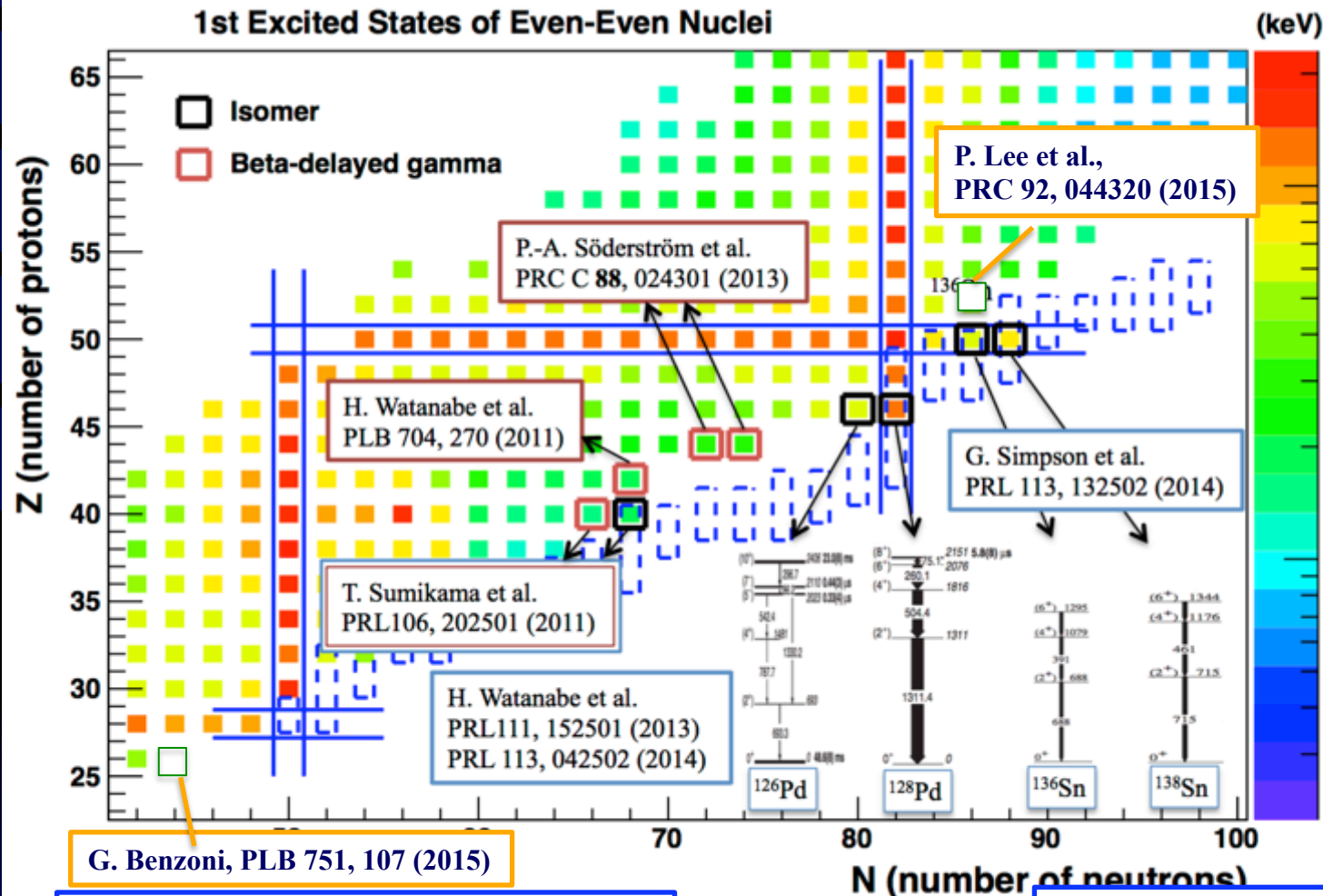
G. Simpson, G. Gey, A. Jungclaus ..
Phys. Rev. Lett. 113, 132502 (2014)



Results Related to Nuclear Structure

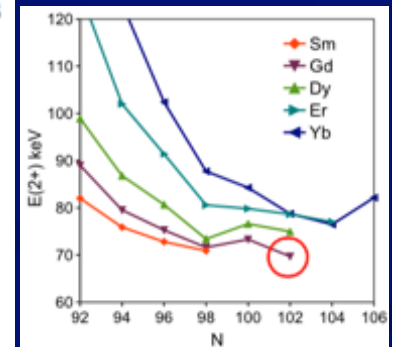
First Excited State: E(2+)

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



^{166}Gd

^{164}Sm



G. Benzoni, PLB 751, 107 (2015)

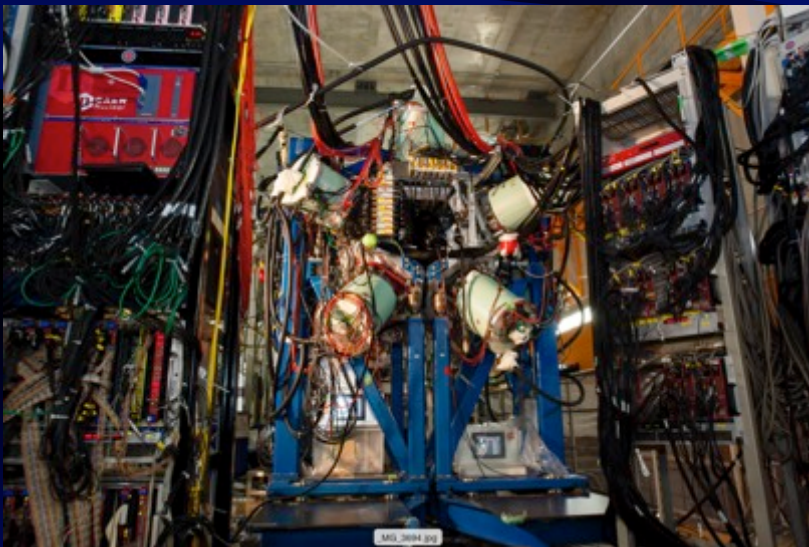
J. Taprogge et al, PRL 112, 132501 (2014)
 J. Taprogge et al, PRC 91, 054324 (2015)
 R. Lozeva et al., PRC 92, 024304(2015)
 F. Browne et al., PLB 750, 448 (2015)
 P.-A. Soderstrom, PRC 92, 051305 (2015)

R. Lozeva et al. PRC 93, 014316 (2016)
 A.I. Morales et al. PRC 93, 034328 (2016)
 A. Jungclaus et al., PRC 93, 041301(R) (2016)
 I. Celikovic et al. PRL 116, 162501 (2016)
 B. Blank et al. PRC 93, 061301 (2016)

EURICA: Half-life measurement

EURICA:

Harvesting the decay properties of
exotic nuclei (2012 ~ 2016)

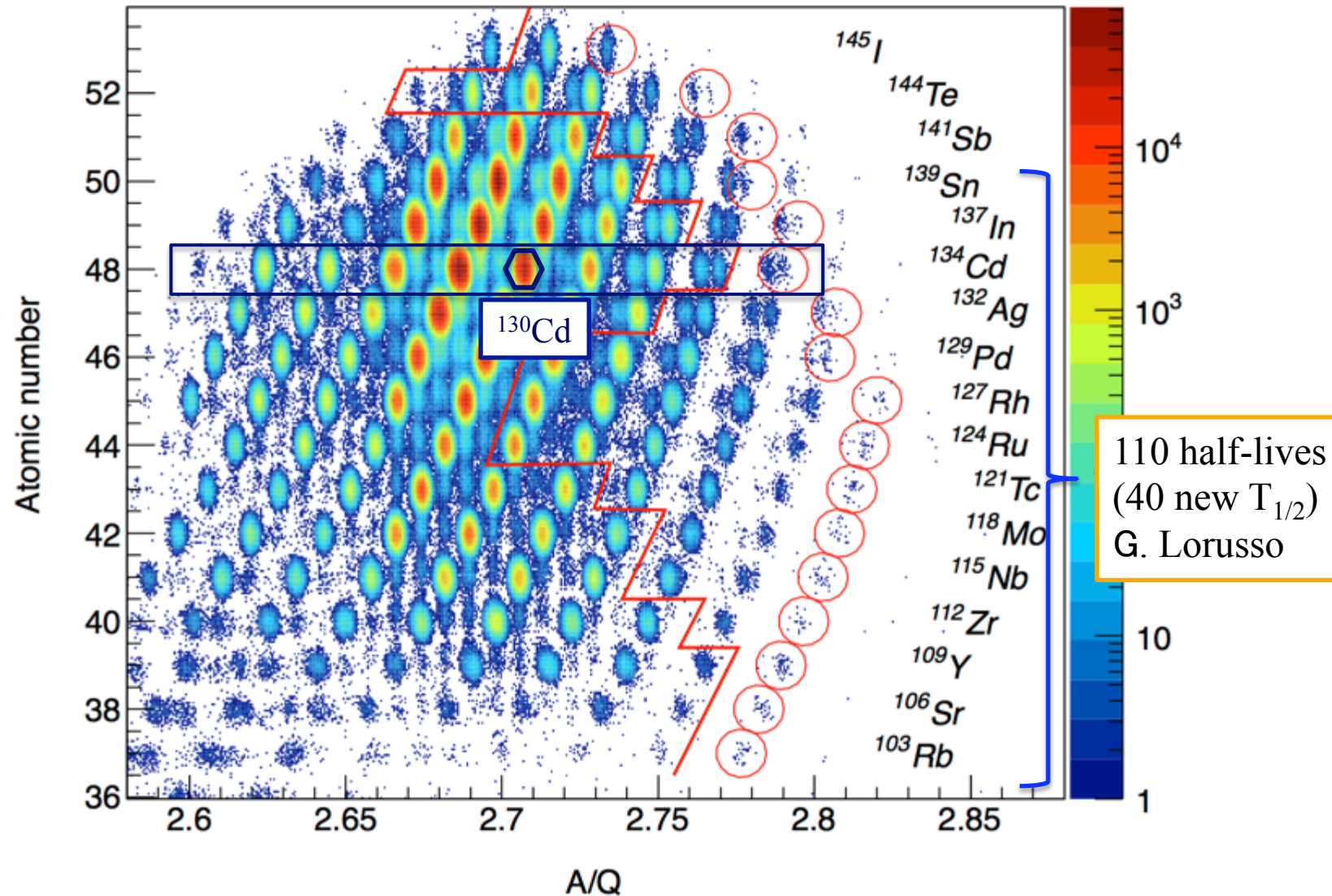


- Decay experiments in 2009, 2012
1st Peak (N=50) , 2nd Peak (N=82)
 $T_{1/2}$: 38 (18) + 20 (5) + 110 (40) + 3 (3)
→ 171 $T_{1/2}$ (66 new half-lives !)
- Decay experiments in 2013, 2014
Rare Earth Peak (A = 140 ~ 170)
 $T_{1/2}$: 92 (57) + 26 (13)
→ 118 $T_{1/2}$ (70 new half-lives !)



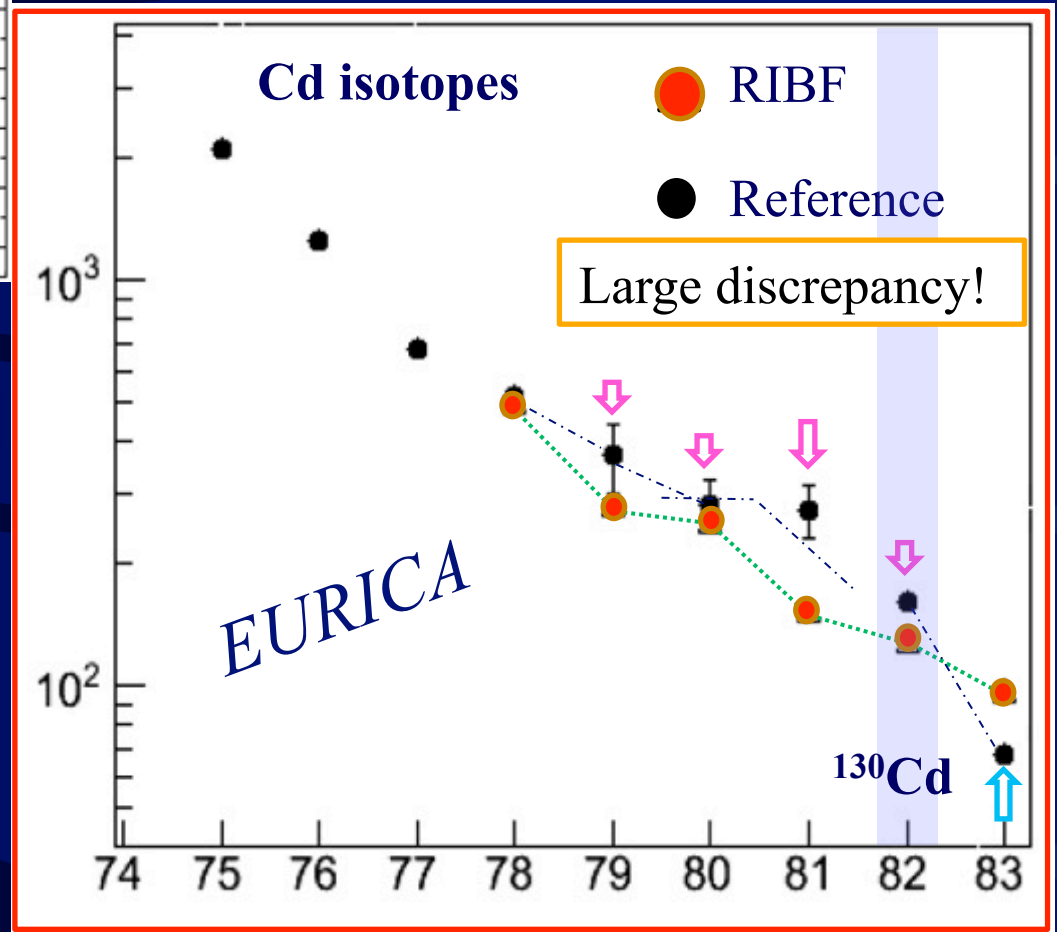
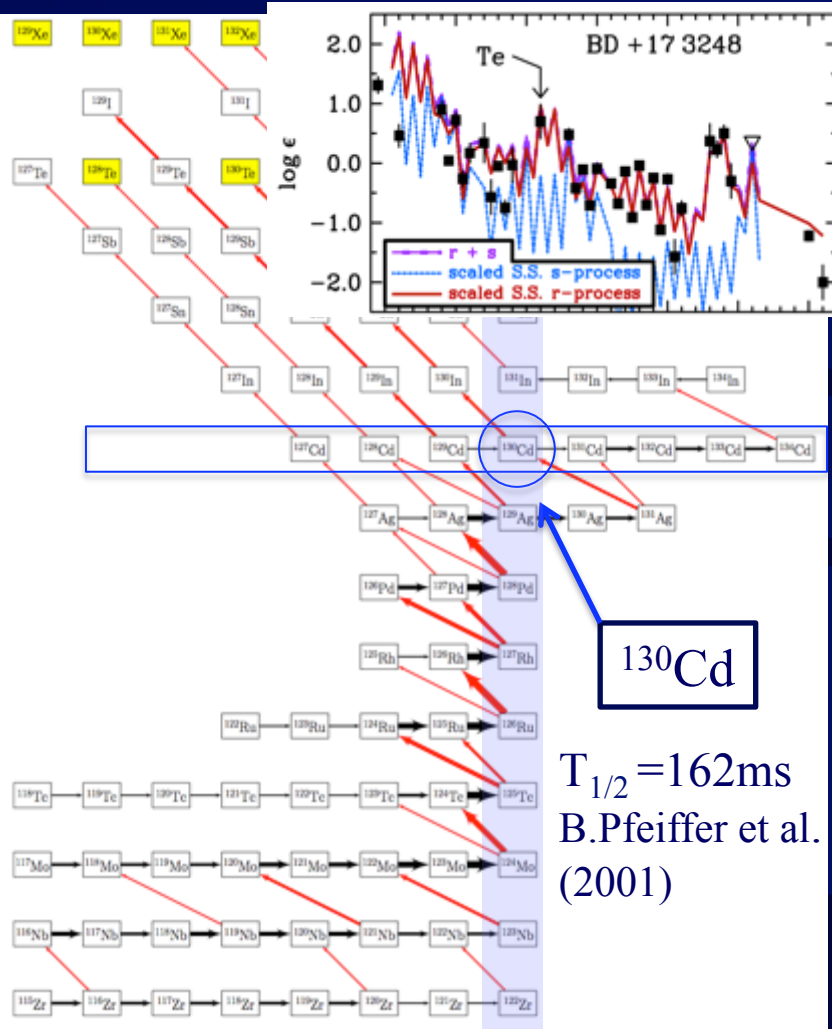
*Impact on 2nd r-process peak and
rare-earth elements !?*

β -decay half-lives on r-process path



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

G. Lorusso

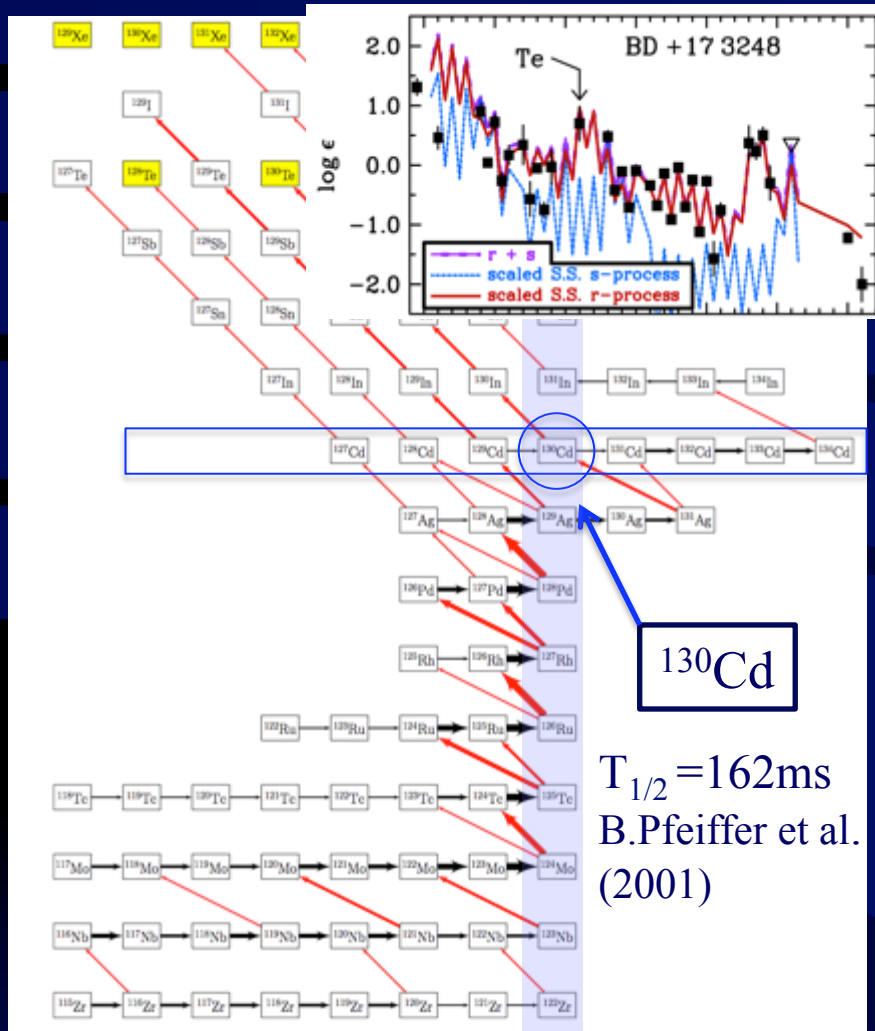


Significant impact to SM calc. & r-process simulation !

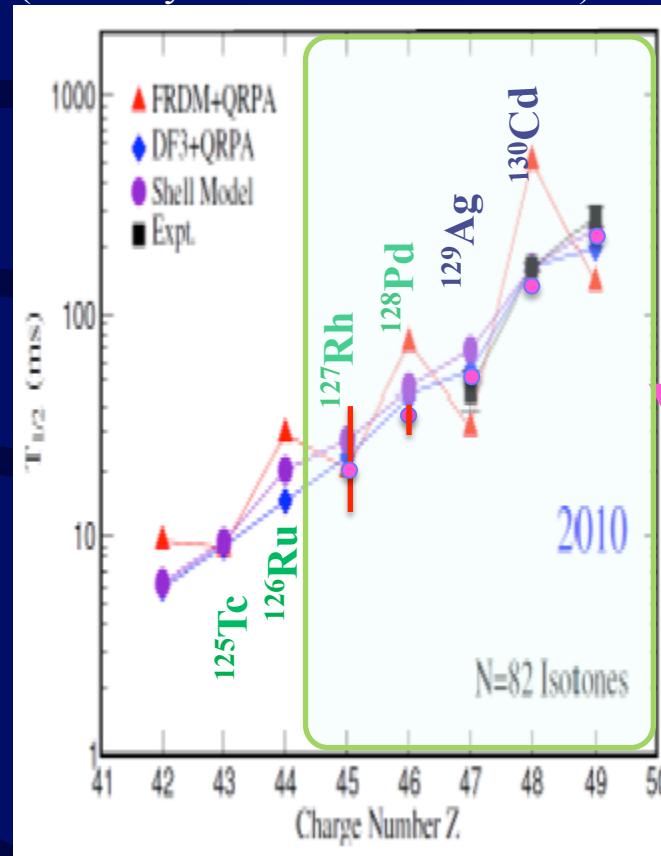
R. Dunlop et al., PRC 93, 062801 (2016)

$^{130}\text{Cd} \dots T_{1/2} = 126(4) \text{ ms}$ (TRIUMF)

Beta-decay Half-lives $N = 82 \rightarrow$ Feedback to the Theory



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



So call r-process waiting point nuclei ($N=82$)

- r-process path
- residual r-matter flow in freeze-out

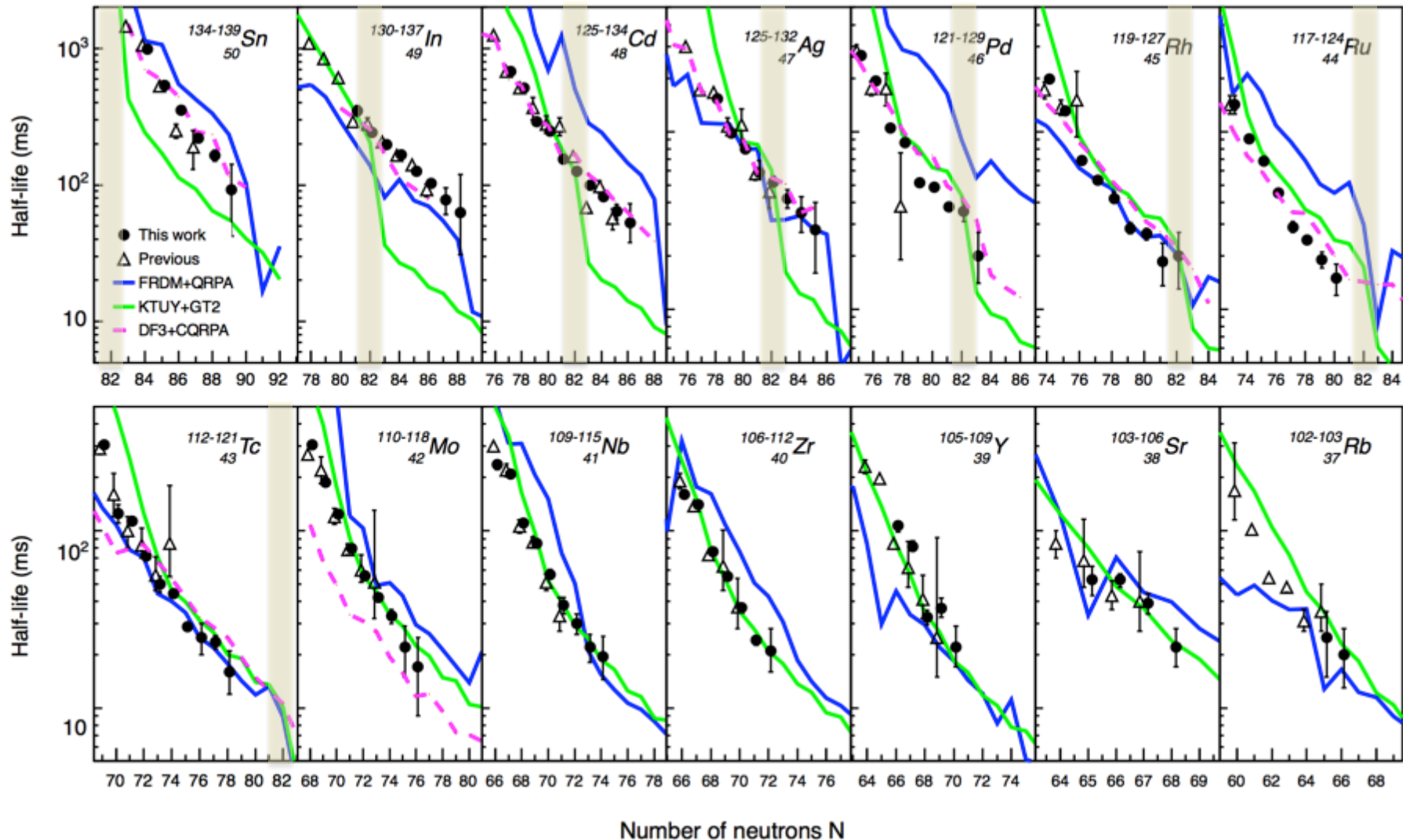
Shell model $\leftarrow \sim 25\%$ shorter $T_{1/2}$

Confirmed by R. Dunlop (2016, TRIUMF)
 $^{130}\text{Cd} \dots T_{1/2} = 126(4)\text{ms}$

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

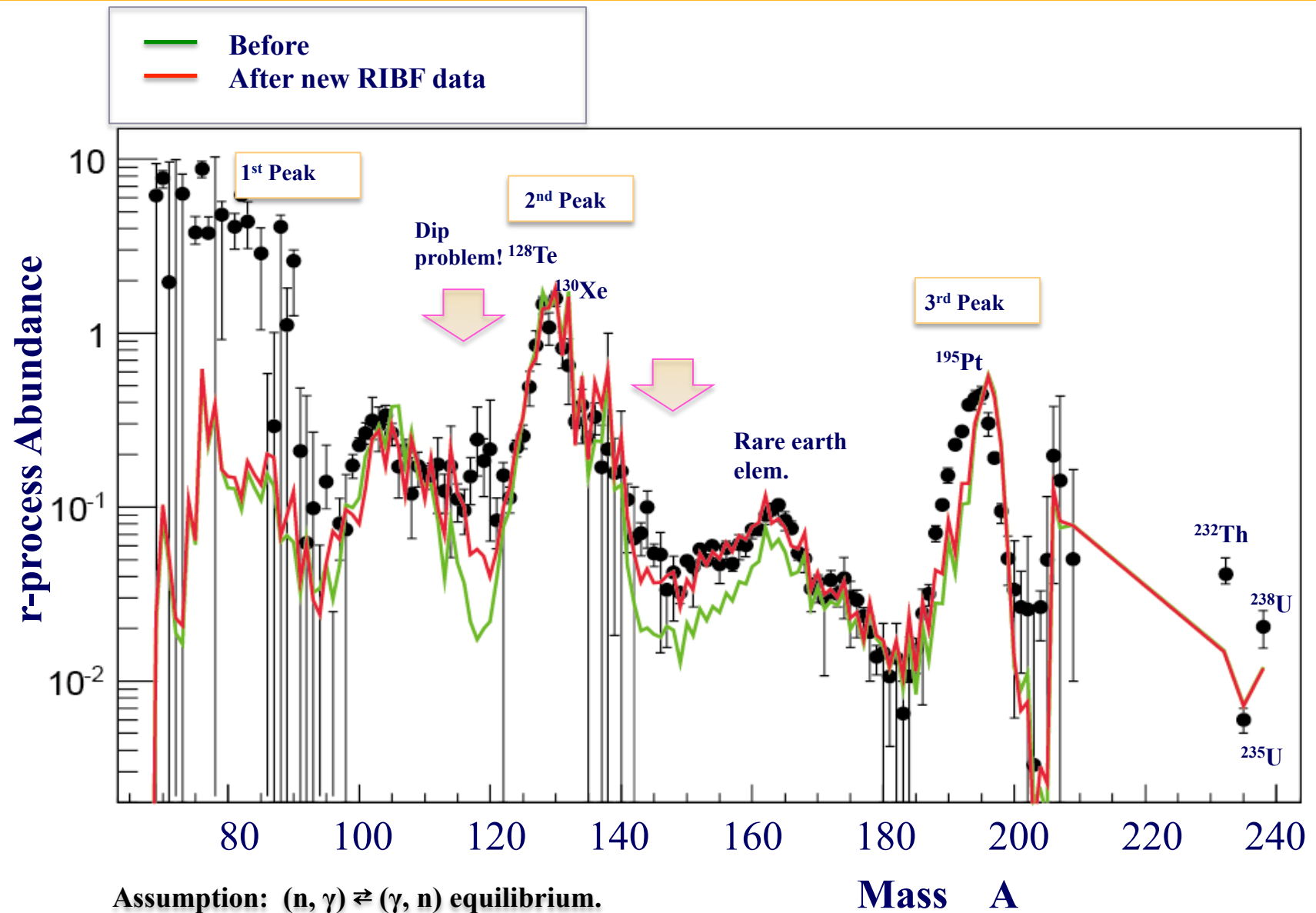
40 new half-lives ! G.Lorusso et al.,
PRL 114, 192501 (2015)

18 new half-lives ! SN
PRL 106, 052502 (2011)

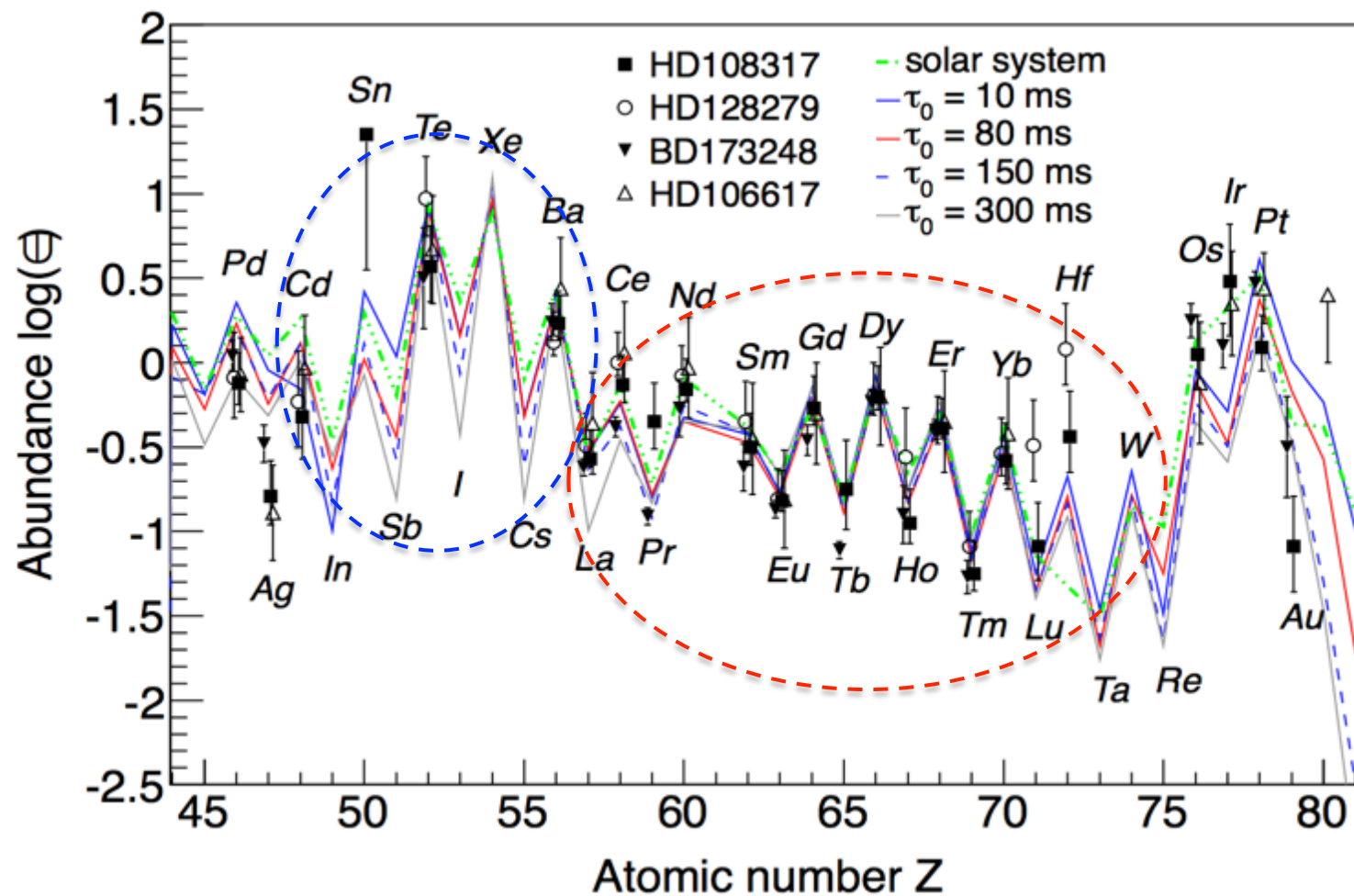


r-process Abundance with New $T_{1/2}$ (RIBF)

G.Lorusso et al., (2015)



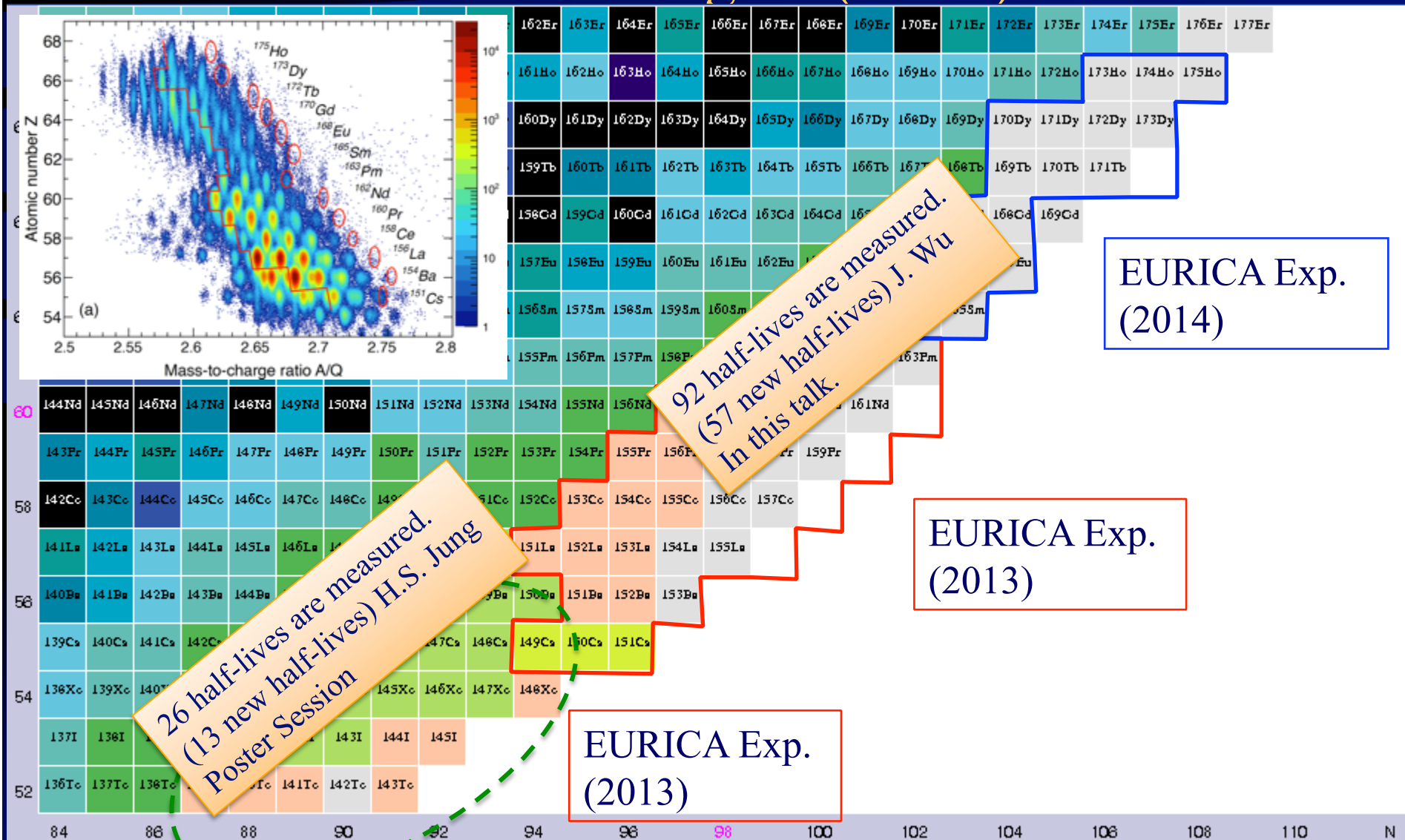
Universality of r-Process Elements ($Z \geq 56$)



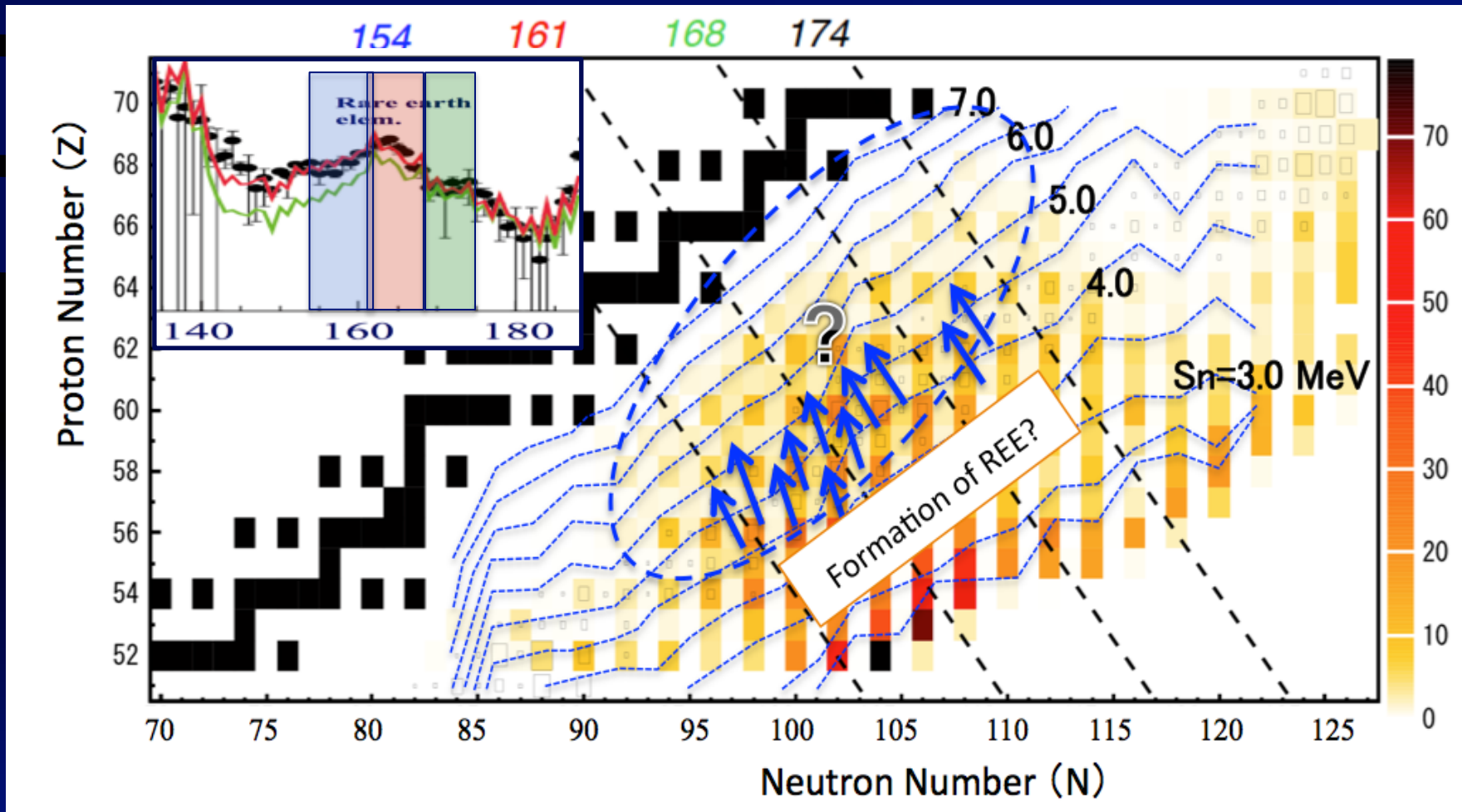
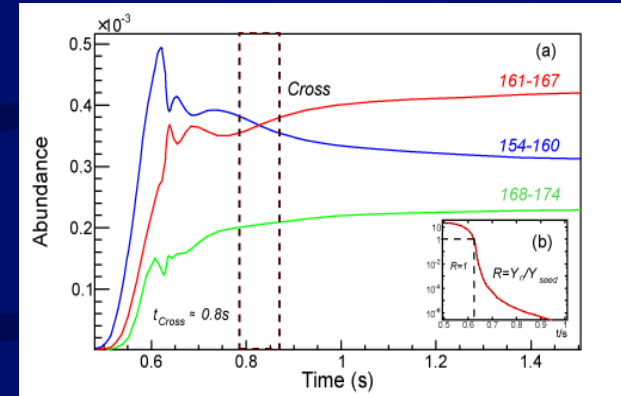
Decay Spectroscopy around mass $A=160$ was performed !

Half-lives

Heavier region ($Z > 50$)



Rare-Earth Peak Formation at Freeze-Out Time



Up to Now...

- Neutron Shell N=82

- Decay spectroscopy project has been started at RIBF.

Survey of decay properties using EURICA & WAS3ABi detectors

38 Half-lives (18 new half-lives) : ^{100}Kr , $^{103-105}\text{Sr}$, $^{106-108}\text{Y}$, $^{108-110}\text{Zr}$, $^{111,112}\text{Nb}$, $^{112-115}\text{Mo}$, $^{116-117}\text{Tc}$.. S. Nishimura (2011)

20 Half-lives (5 new half-lives) : $^{72-77}\text{Co}$, $^{74-80}\text{Ni}$, $^{78-81}\text{Cu}$, $^{80-82}\text{Zn}$... Z.Y. Xu (2014)

110 Half-lives (40 new half-lives) : $^{102-103}\text{Rb}$, $^{103-106}\text{Sr}$, $^{104-109}\text{Y}$, $^{106-112}\text{Zr}$, $^{107-115}\text{Nb}$, $^{109-118}\text{Mo}$, $^{112-121}\text{Tc}$, $^{116-124}\text{Ru}$,
 $^{118-127}\text{Rh}$, $^{121-129}\text{Pd}$, $^{124-132}\text{Ag}$, $^{126-134}\text{Cd}$, $^{128-137}\text{In}$, $^{134-139}\text{Sn}$... G. Lorusso (2015)

92 Half-lives (57 new half-lives!) : $^{144-151}\text{Cs}$, $^{146-154}\text{Ba}$, $^{148-156}\text{La}$, $^{150-158}\text{Ce}$, $^{153-160}\text{Pr}$, $^{156-162}\text{Nd}$, $^{159-163}\text{Pm}$, $^{160-166}\text{Sm}$,
 $^{161-168}\text{Eu}$, $^{165-170}\text{Gd}$, $^{166-172}\text{Tb}$, $^{169-173}\text{Dy}$, $^{172-175}\text{Ho}$... J. Wu submitted to PRL

26 Half-lives (13 new half-lives): $^{137-141}\text{Sb}$, $^{139-145}\text{Te}$, $^{140-146}\text{I}$, $^{142-148}\text{Xe}$... H.S. Jung (in preparation)

- r-Process : Still very challenging topics !

- The 2nd Peak ($A \approx 130$)

- Consistent results for “Universality of r-process elements ($Z \geq 56$)”

- Rare-earth-element ($A \approx 160$) : First experimental investigation the rare-earth peak !

In total.. $T_{1/2} = 286$ (133 New) half-lives

- Too much ^{168}Er (Erbium).

Future Perspective

Coming five years and



r-process: 1st, 2nd, rare-earth peaks

$\beta\gamma$ Spectroscopy (EURICA/BRIKEN/CAITEN)

(Production of heavy isotopes & PID issue)
Competition with FRIB, FAIR

Design of new spectrometer toward
N = 126 & beyond

(3rd peak,
Fission)

quasi-fission of U+U (Cm)

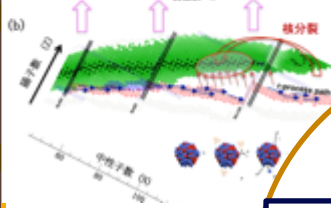
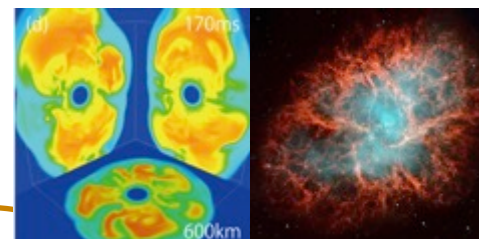
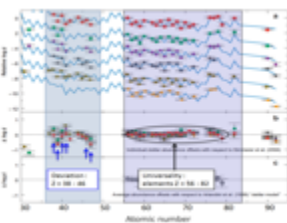
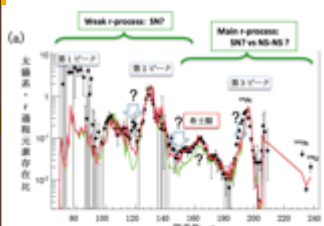
r-process dynamics (NS merger vs SN), inside of NS (mass vs radius)

Heavy-ion collisions (EOS) Collective flow, high density matter

$\beta\gamma$ 実験

rp-process

Study of rp-process in γ -ray burst
proton capture process and mass measurement



Nucleosynthesis

r-Process
SN
Explosion
NS-NS
merger

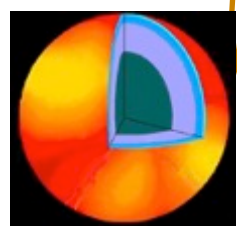
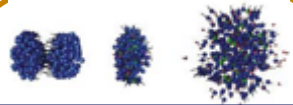
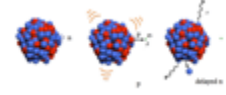
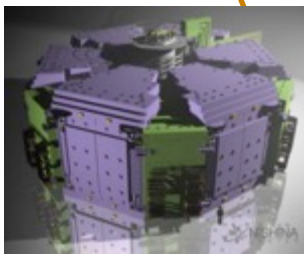
Explosive Conditions

EoS

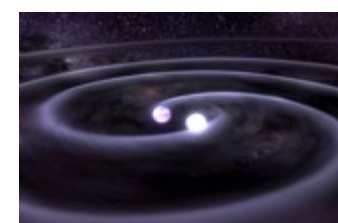
rp-process
X/gamma-ray burst
Neutron Star

High Density Matter

Gravitational Wave
NS-NS merger



neutron star



NS-NS, NS-BH, BH-BH