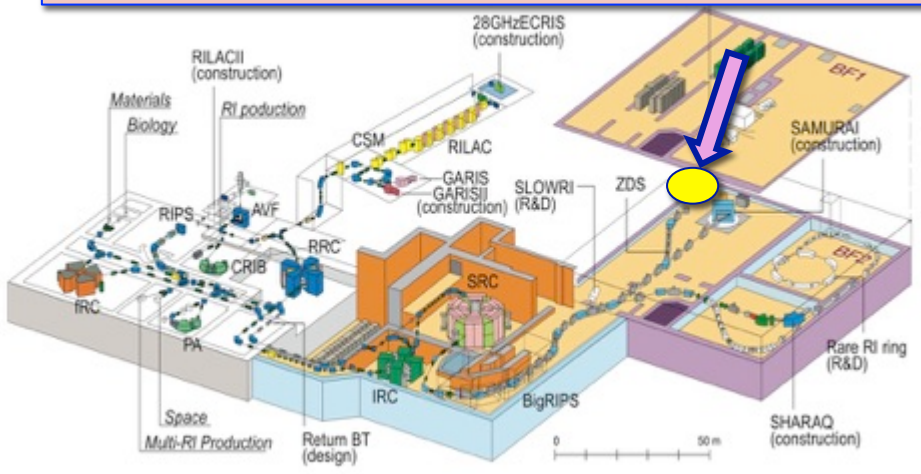
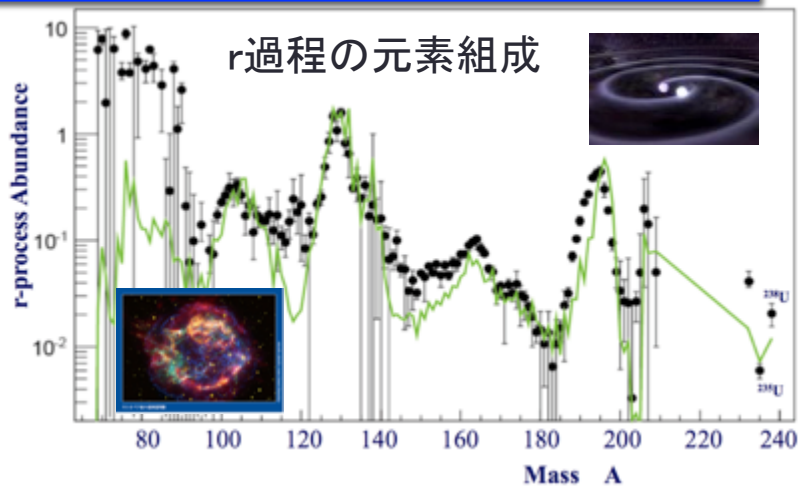
RIKEN NISHINA CENTER

Tomonaga Center for the History of the Universe

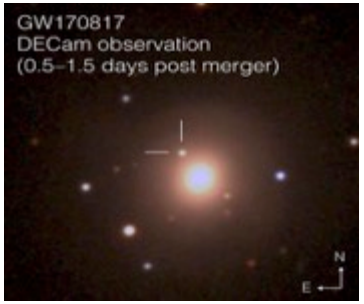
RIBFにおける宇宙元素合成

西村俊二 （理研）





LIGO-Virgo 重力波観測再開（4月～）

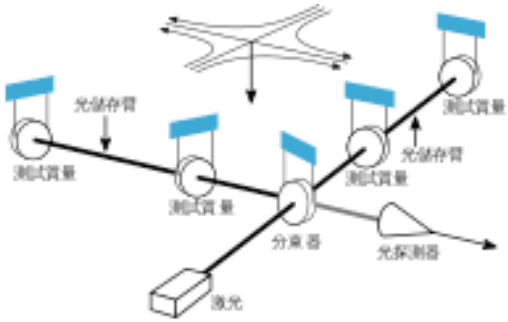


2017年
8月17日　連星中性子星合体

2019年　　https://gracedb.ligo.org/latest/
4月05日　？？
4月08日　？？
4月12日　連星ブラックホール合体（100%）

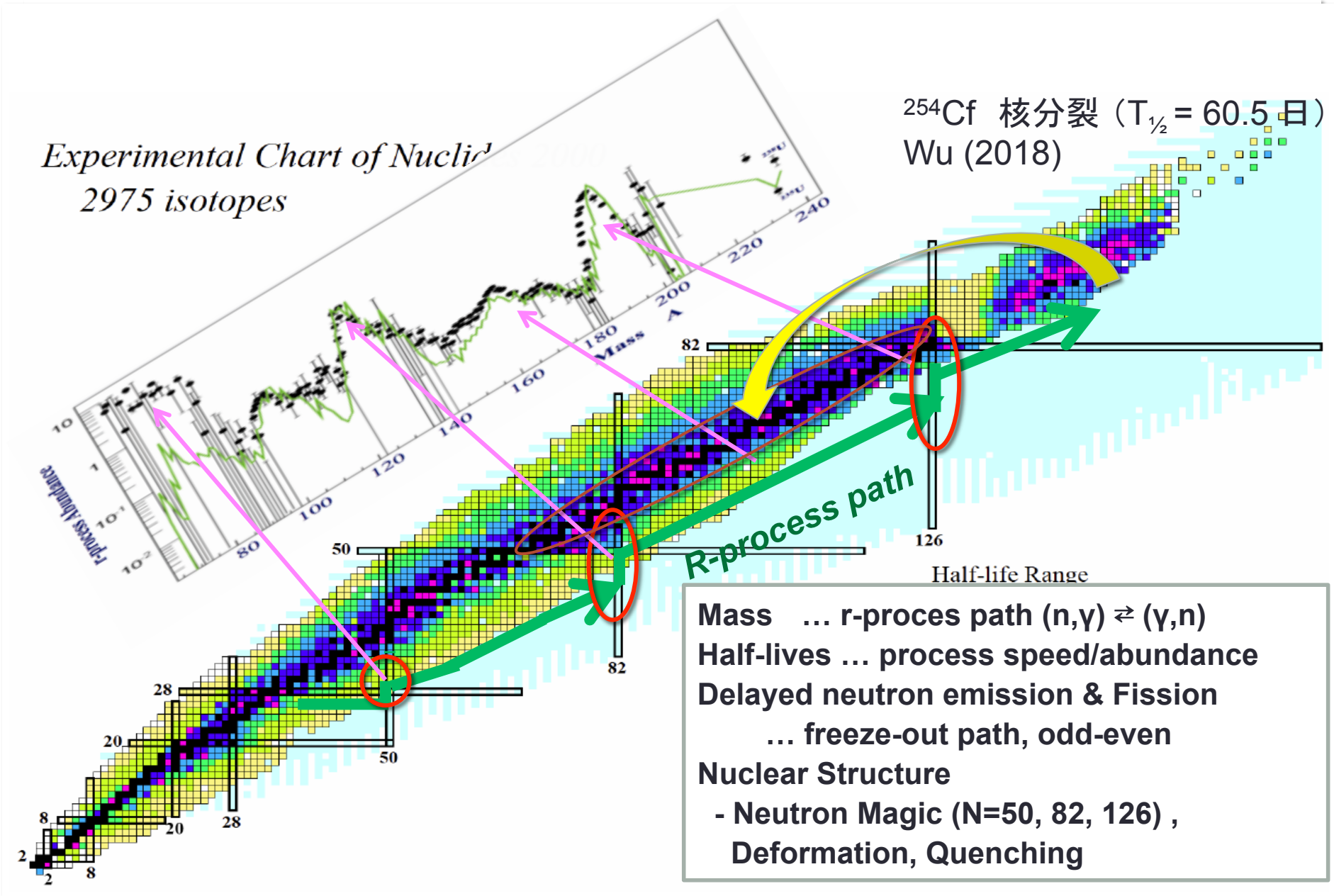
：：

5月13日　連星ブラックホール合体（94%）
5月17日　連星ブラックホール合体（98%）
➡ 5月18日　連星中性子星合体（75%）
5月19日　連星ブラックホール合体（96%）
5月21日　連星ブラックホール合体（97%）
5月21日　連星ブラックホール合体（99%）
➡ 5月24日　連星中性子星合体（29%）
6月　2日　連星ブラックホール合体（99%）



中性子星+ブラックホール合体は?

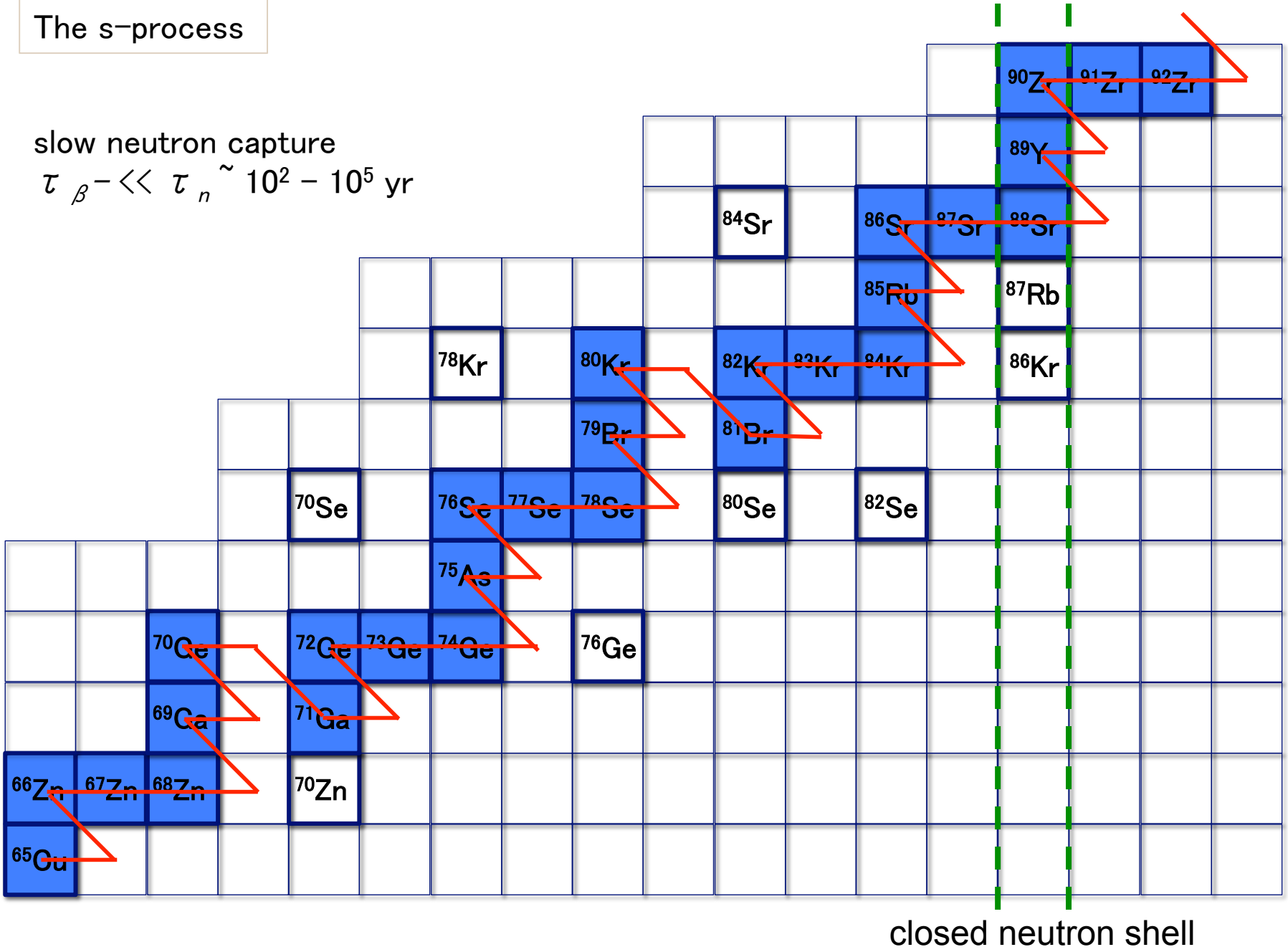
Nucleosynthesis of Heavy Elements (r-Process)



The s-process

slow neutron capture

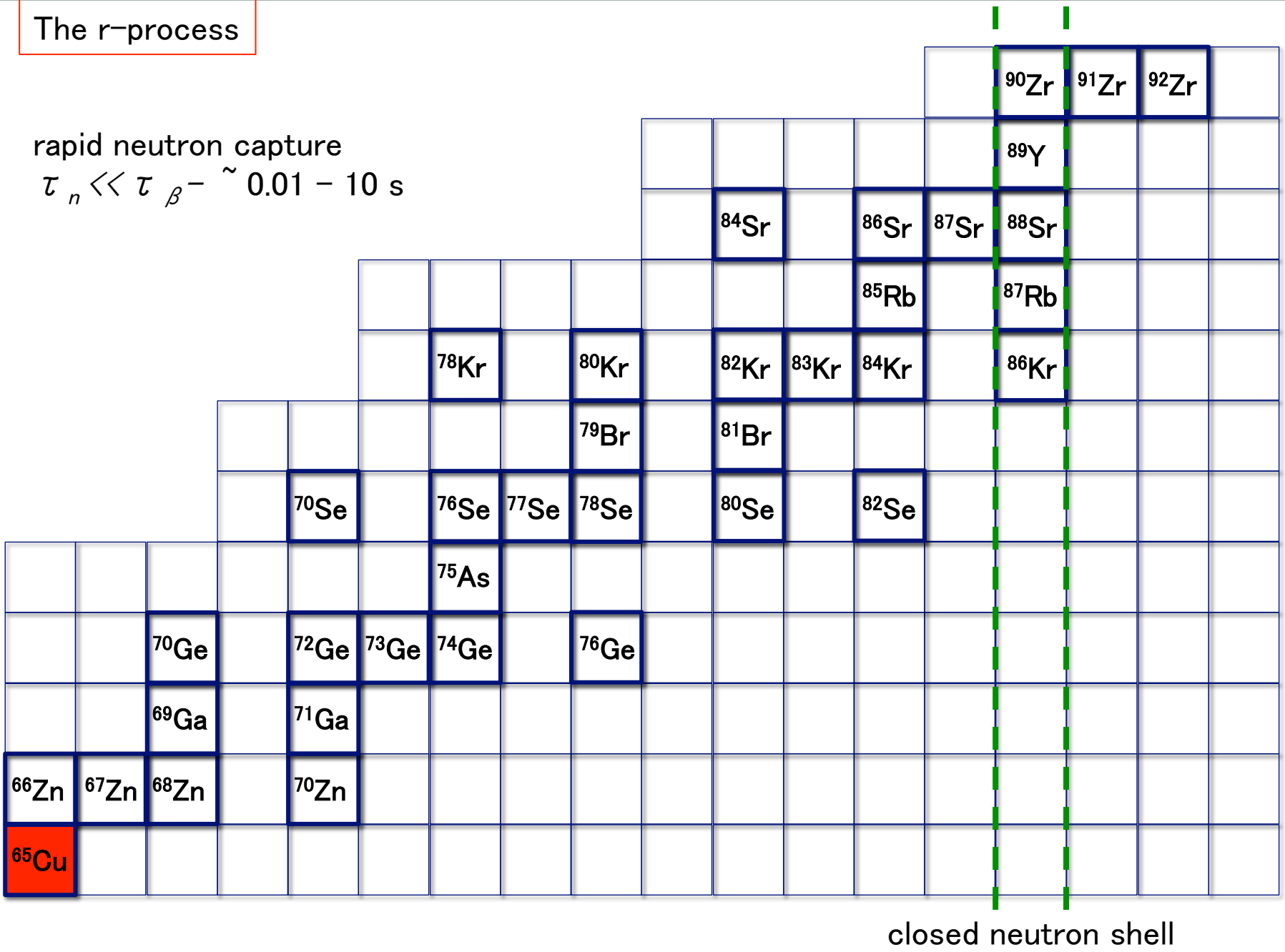
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



The r-process

rapid neutron capture

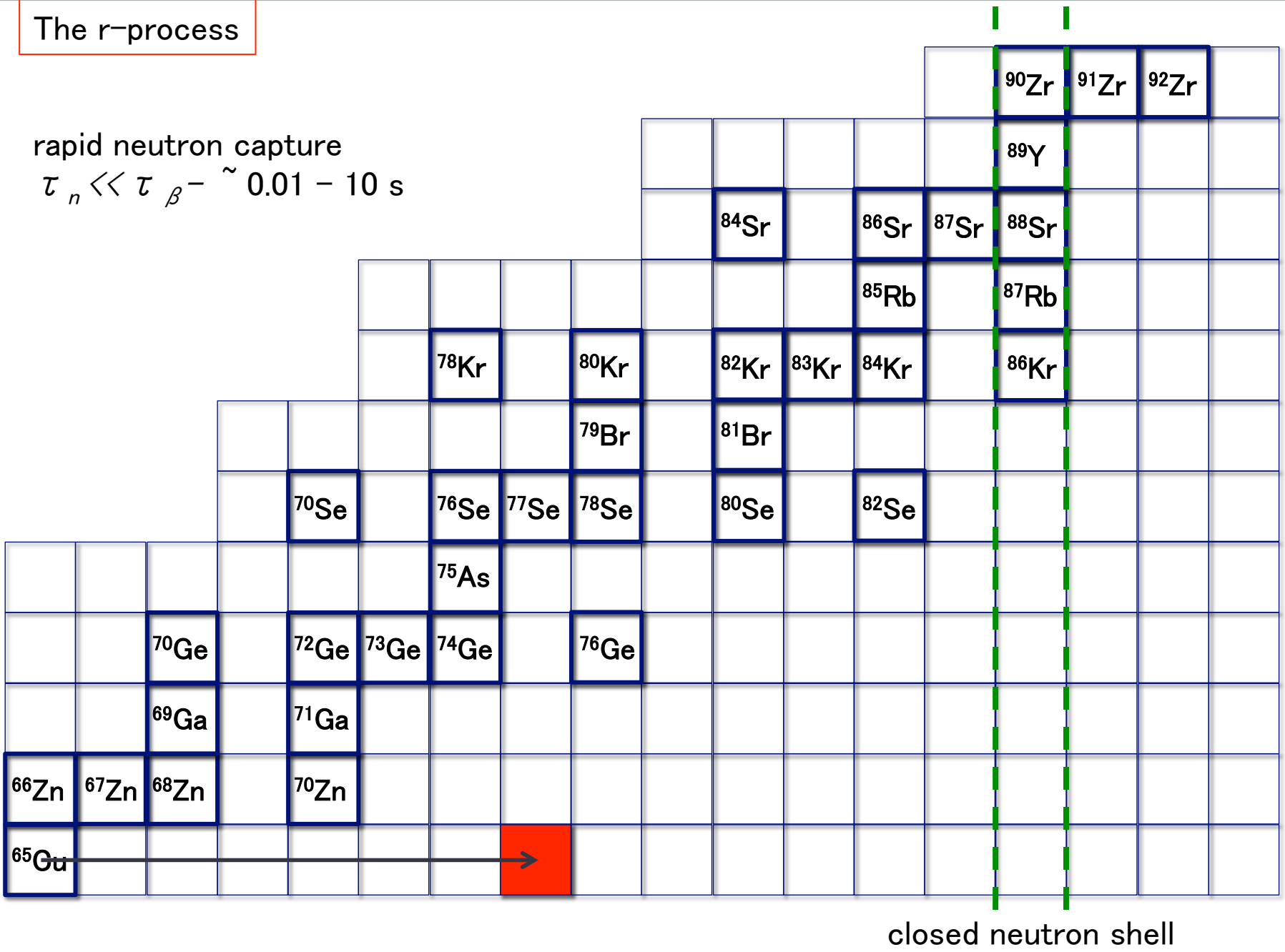
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process

rapid neutron capture

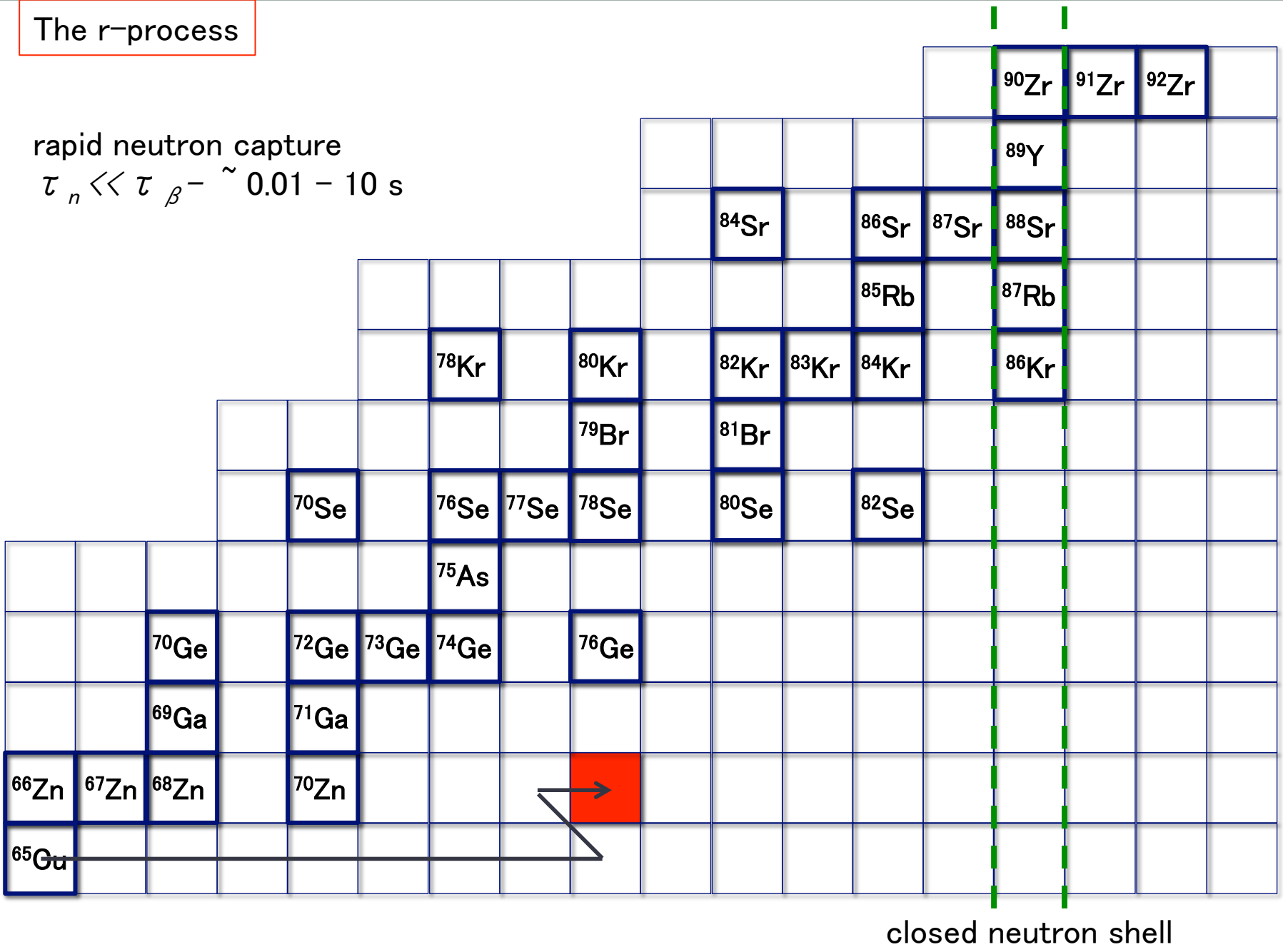
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process

rapid neutron capture

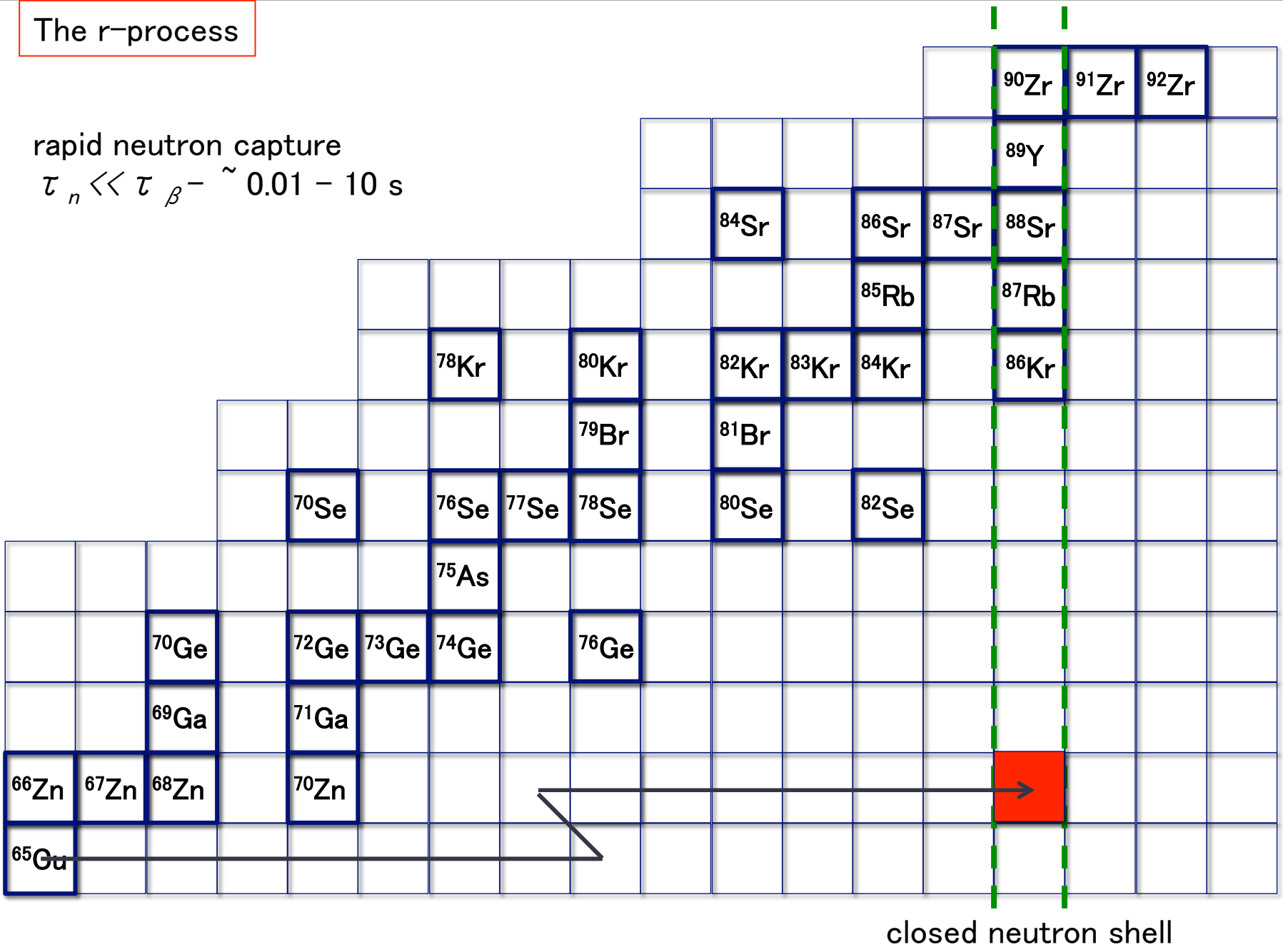
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r–process

rapid neutron capture

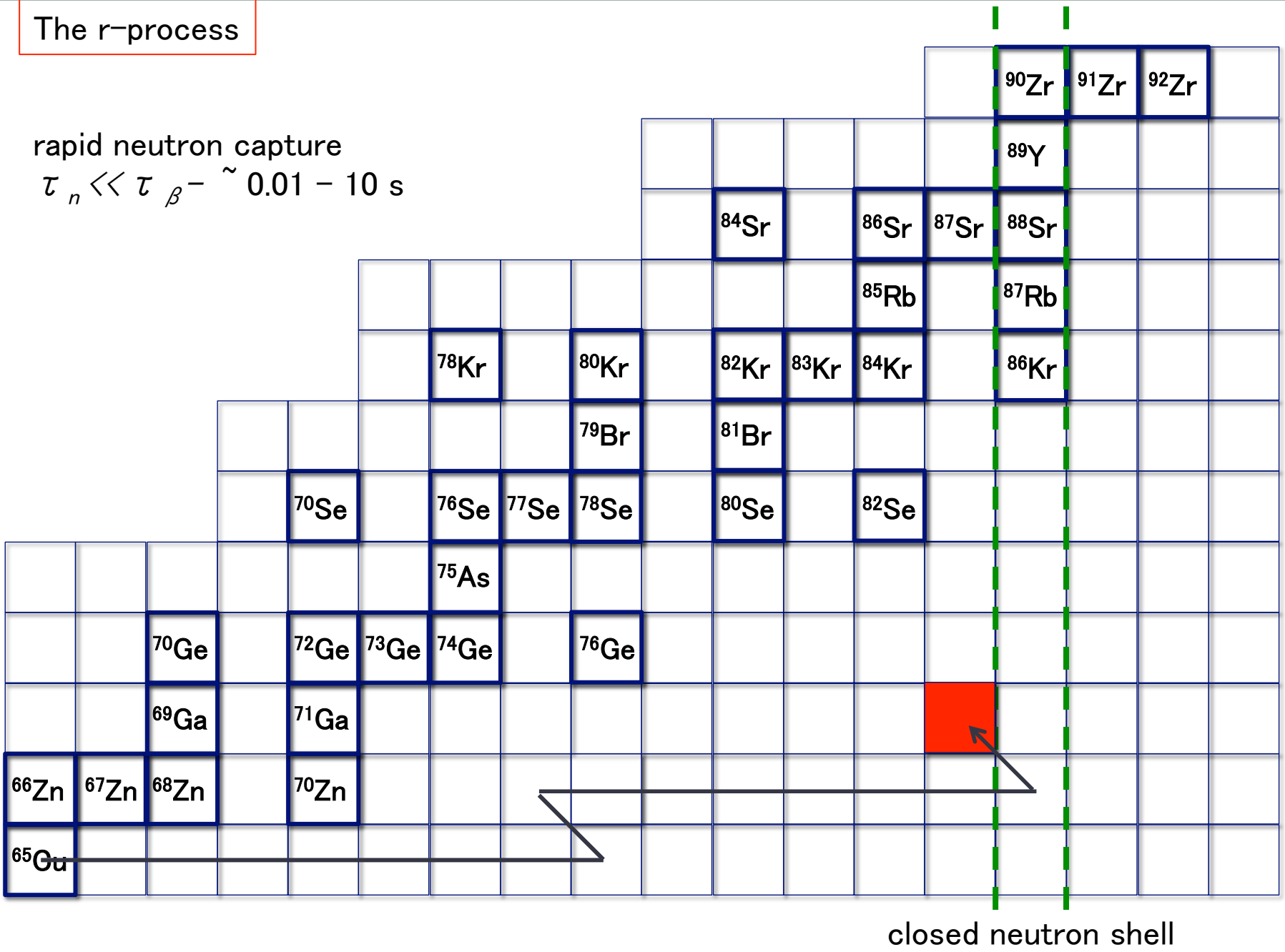
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process

rapid neutron capture

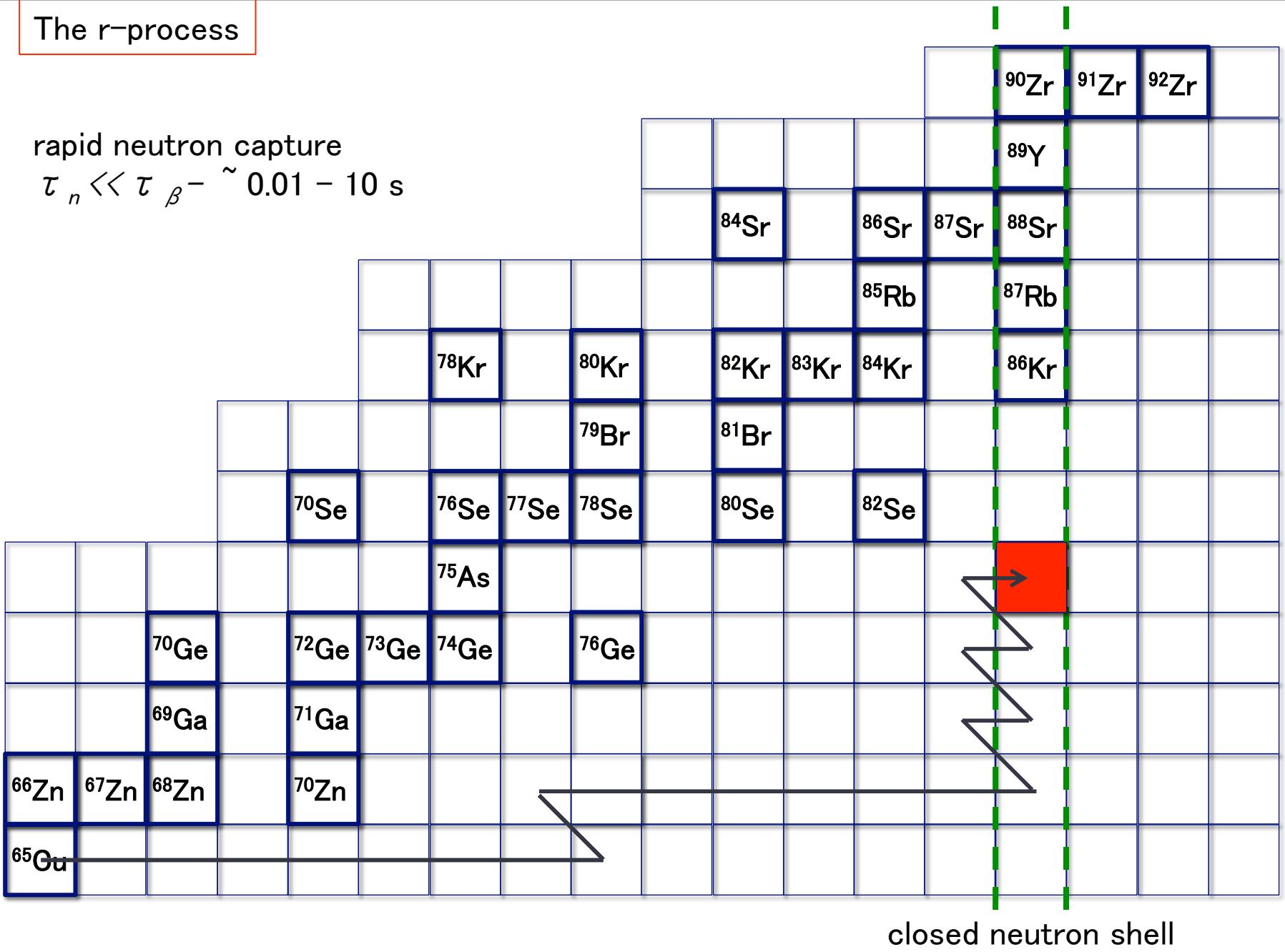
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process

rapid neutron capture

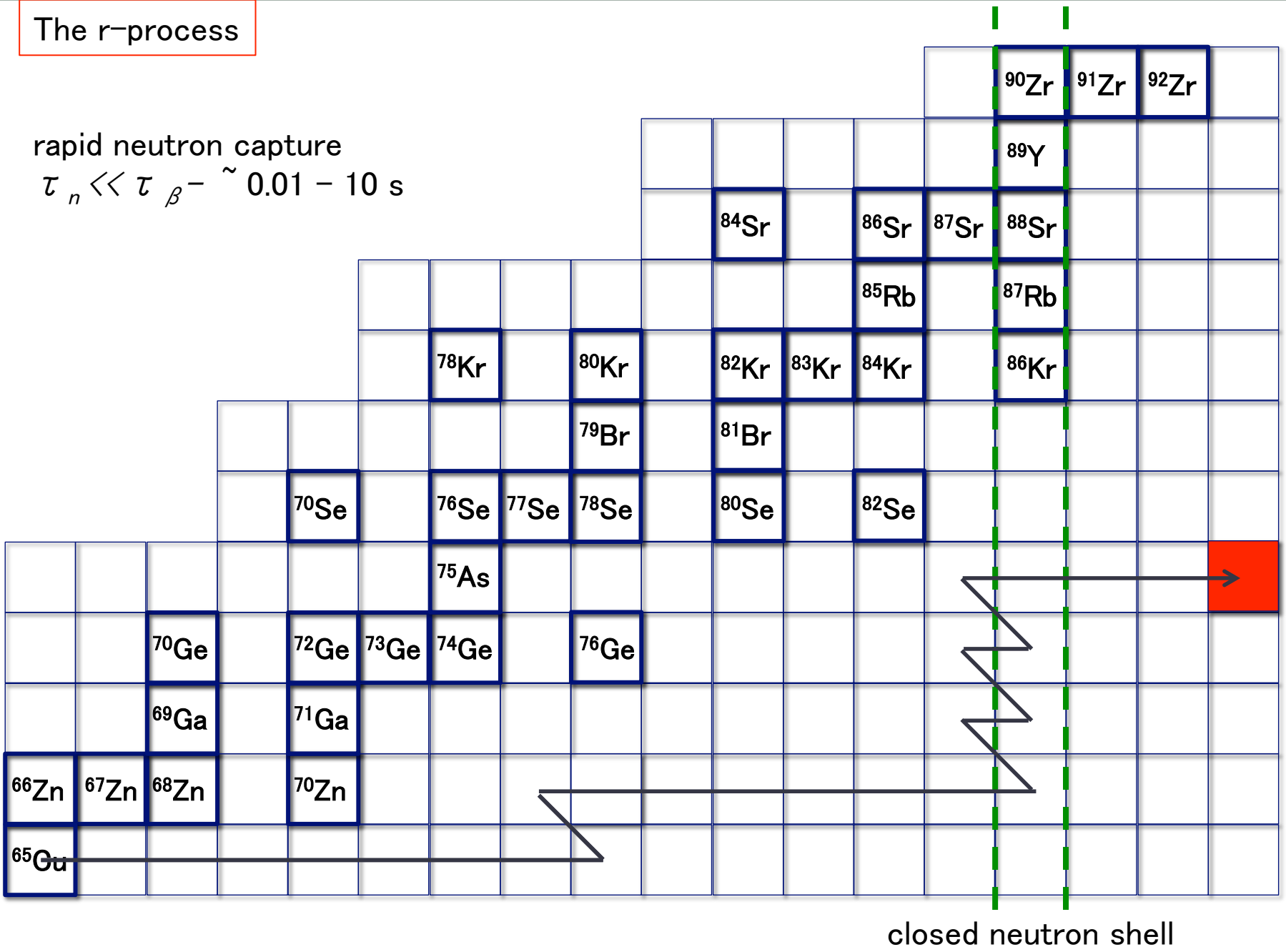
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process

rapid neutron capture

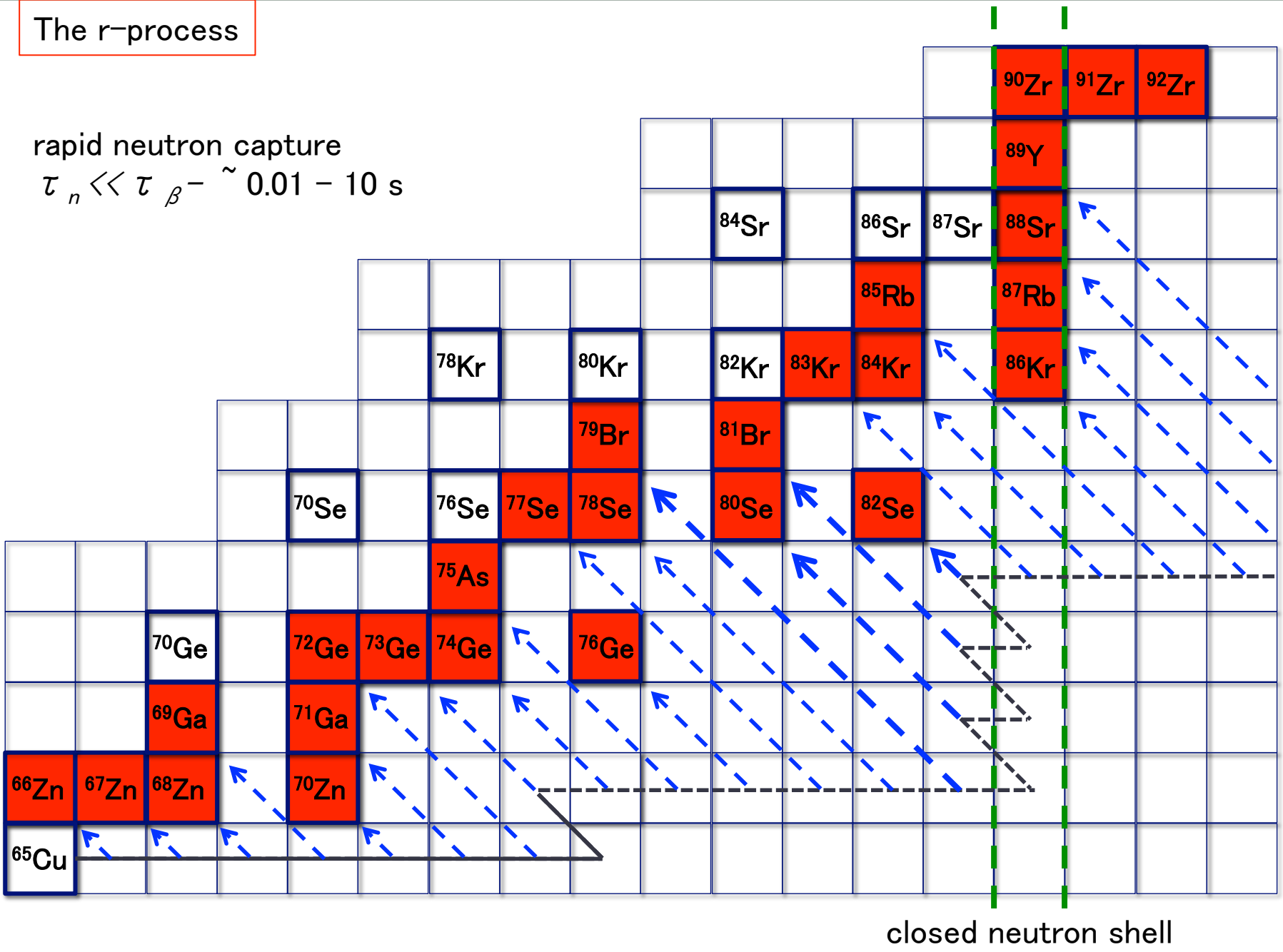
$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



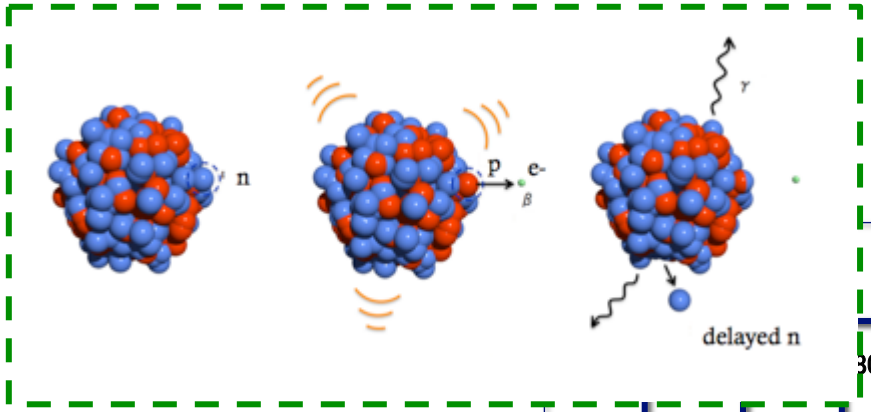
The r–process

rapid neutron capture

$\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process



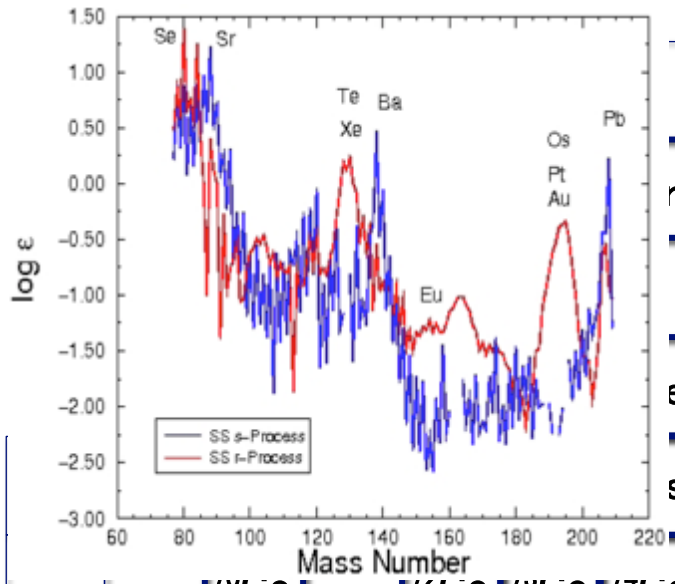
^{90}Zr ^{91}Zr ^{92}Zr
^{89}Y
^{84}Sr ^{86}Sr ^{87}Sr ^{88}Sr
^{85}Rb ^{87}Rb
^{80}Kr ^{82}Kr ^{83}Kr ^{84}Kr ^{86}Kr
^{79}Br ^{81}Br
^{70}Se ^{76}Se ^{77}Se ^{78}Se ^{80}Se ^{82}Se
^{75}As
^{70}Ge ^{72}Ge ^{73}Ge ^{74}Ge ^{76}Ge
^{69}Ga ^{71}Ga
^{66}Zn ^{67}Zn ^{68}Zn ^{70}Zn
^{65}Cu

closed neutron shell

Double peaks due to closed neutron shells

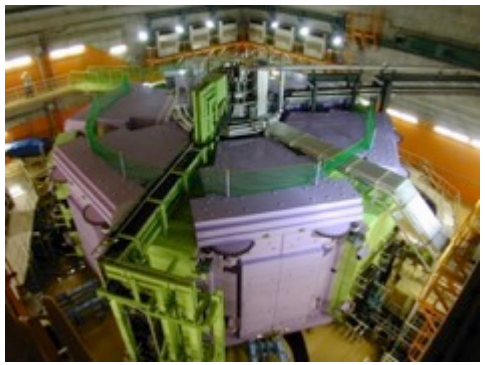
s-process: $\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr

r-process: $\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$ s

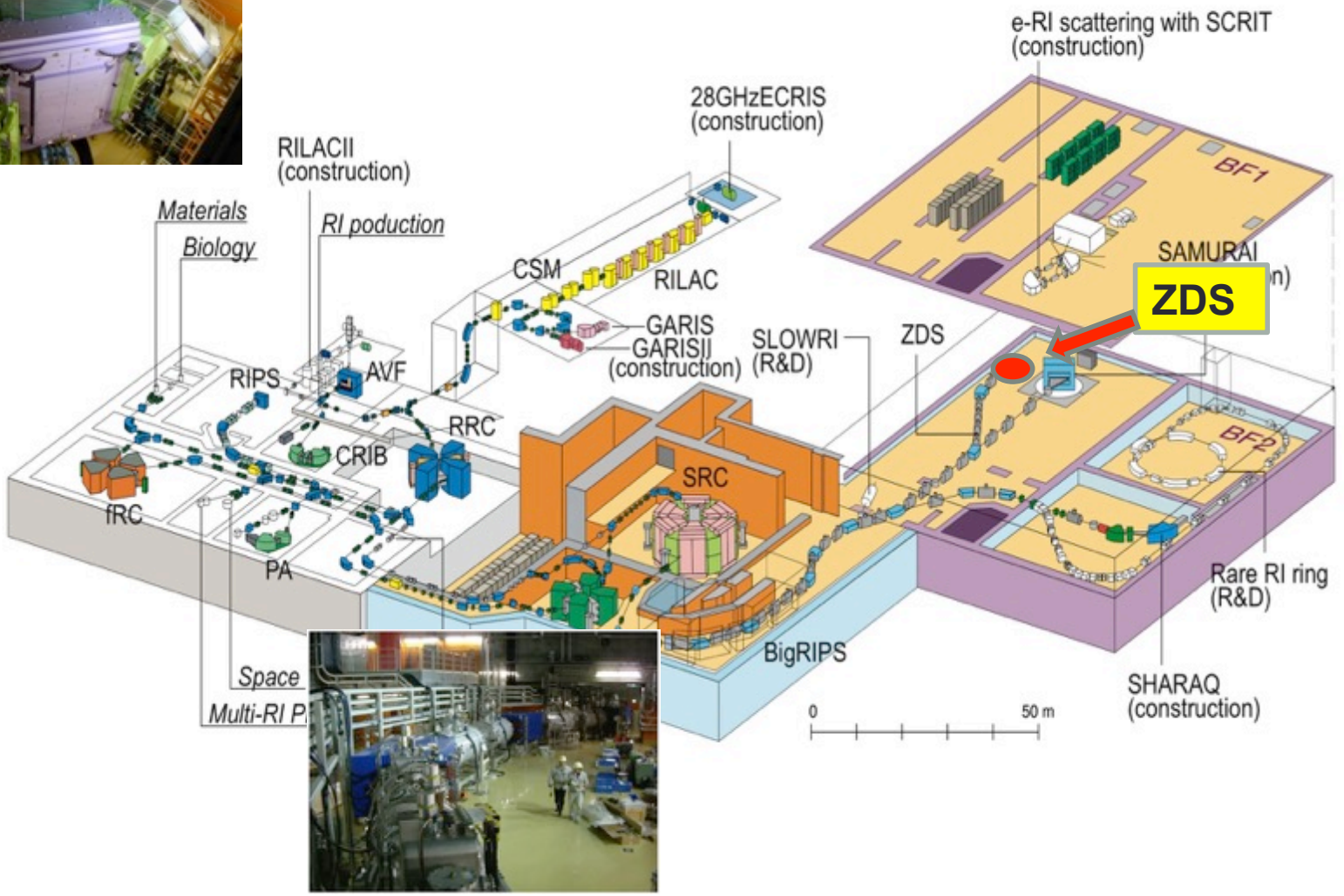


RI Production

Location of Decay Station at RIBF

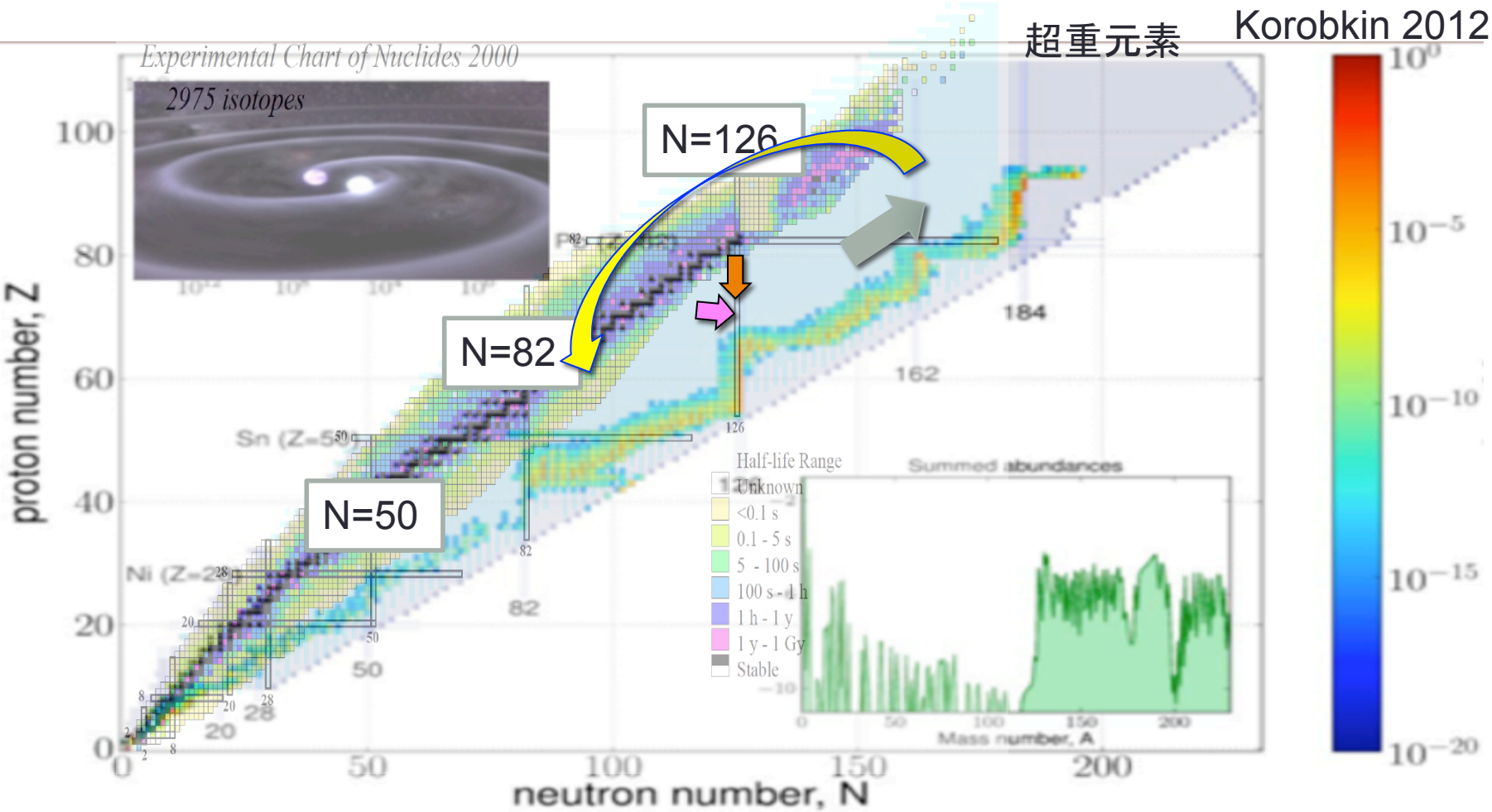


^{238}U … 345 MeV/u,
Intensity = 5 – 12 pnA → 70pnA !



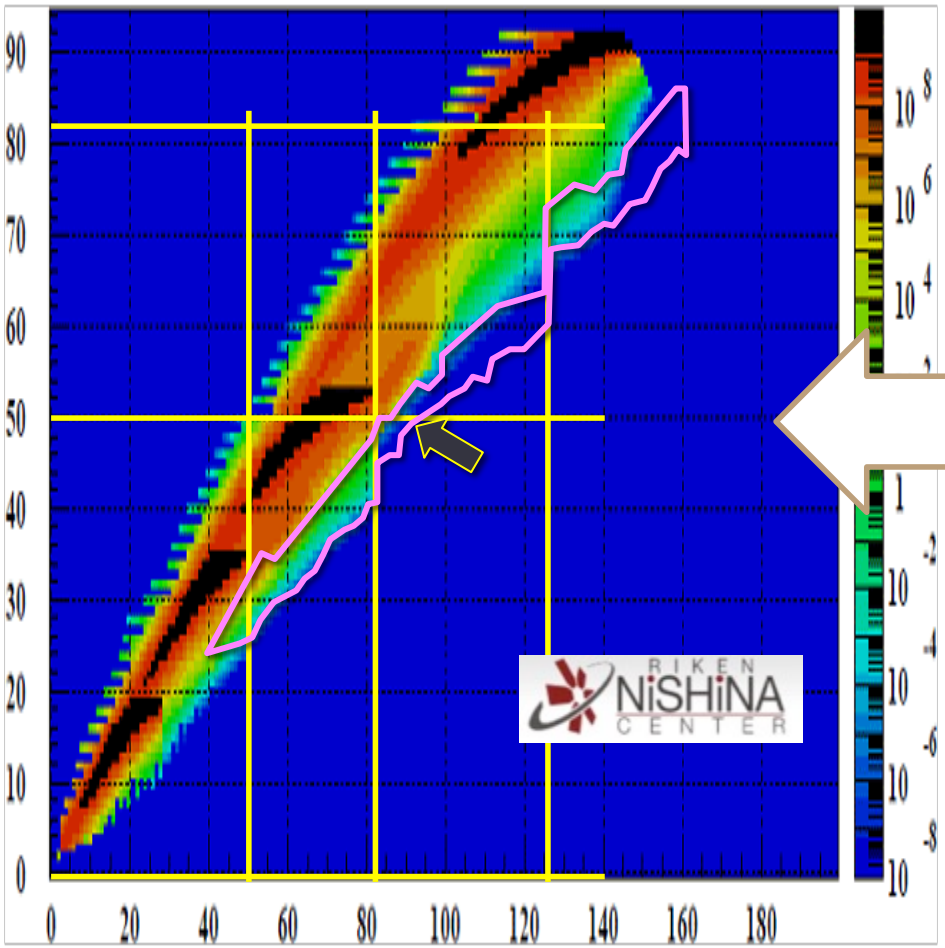
Question: Accessible r-nuclei

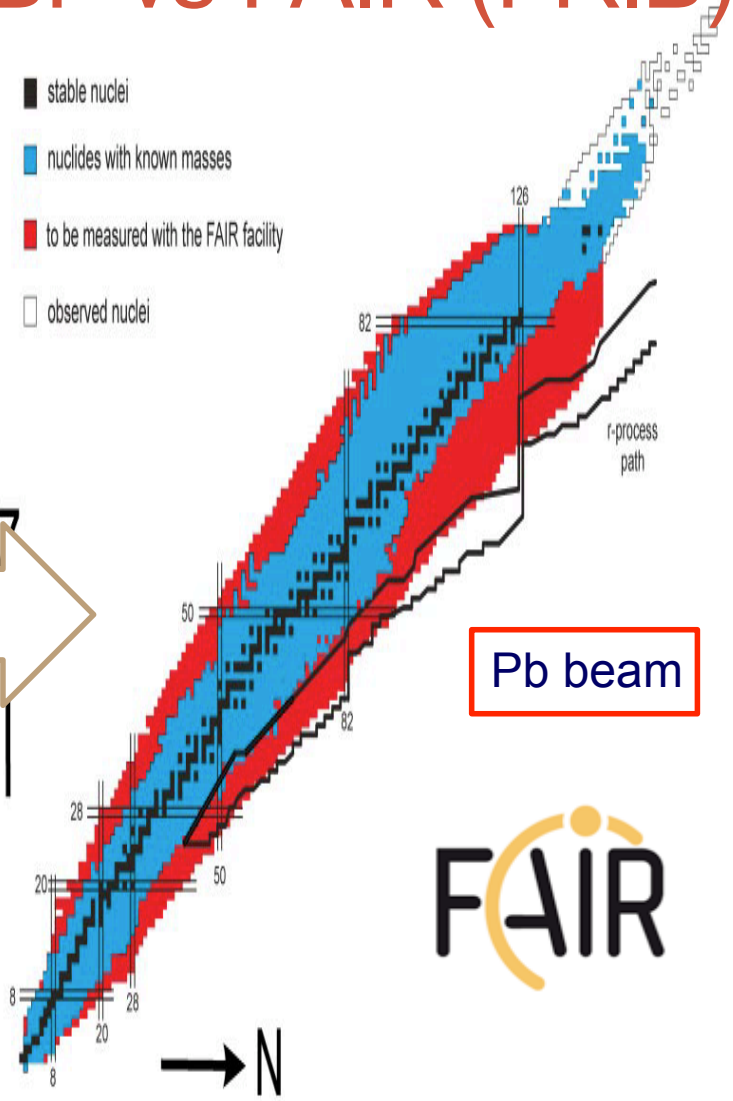
Which part of that nuclear physics data is already known, which part remains yet unmeasured, and which part will be accessible in the new RIB-facilities?



RI Beam Production : RIBF vs FAIR (FRIB)

RIBF goal = 1000 pnA (current int. = 70 pnA)





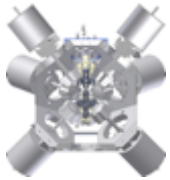
Beam line transport should be taken into account

Decay Spectroscopy Experiment

Decay Exp. Programs at ZDS (Past, Present, Future)

EURICA

2019 2020 2021 2022

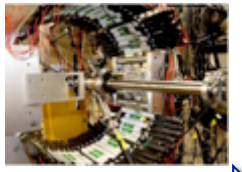
① 

Beta-gamma Campaign

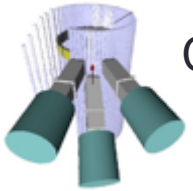
⑤ Ge-detector array from Lanzhou Gr. (Other Institutes?)

BRIKEN

② **β delayed neutron emission probabilities (Pn)**



VANDLE/HAGRID



CAITEN/NiGIRI/LaBr3(Ce) array

③ **β delayed neutron: energy spectra (E_n)**

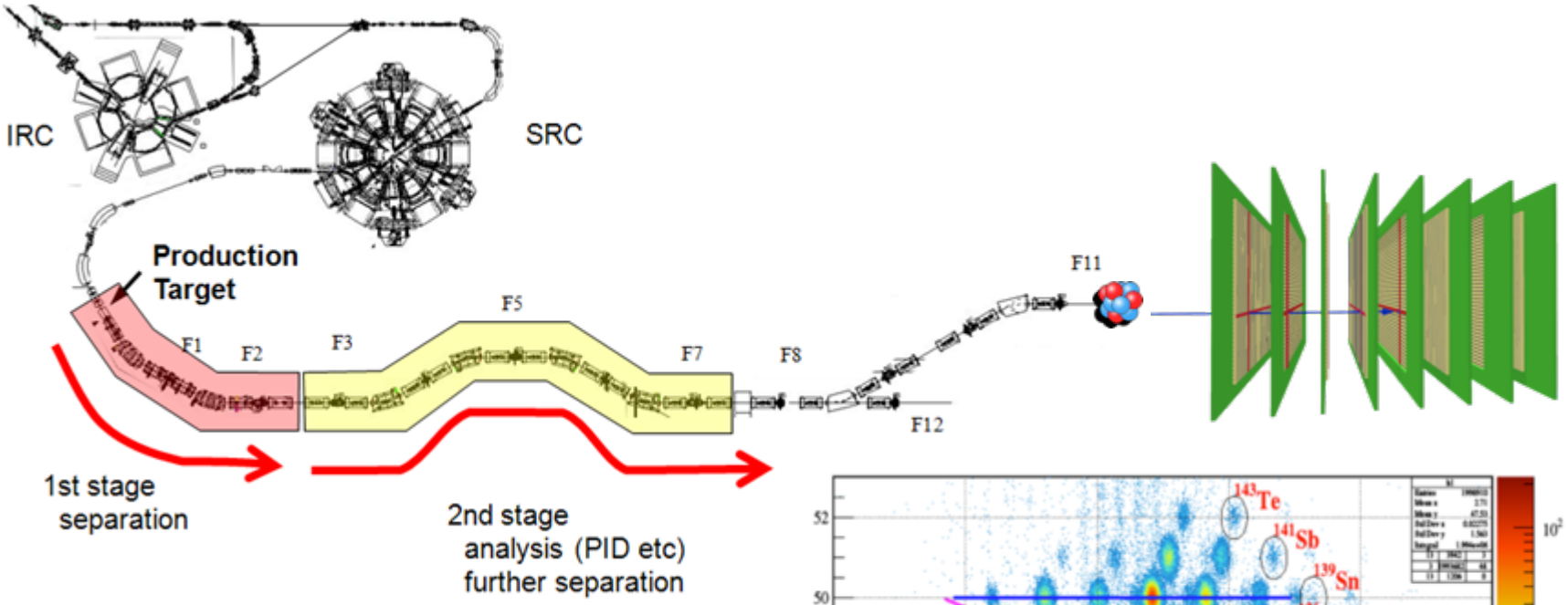
DTAS

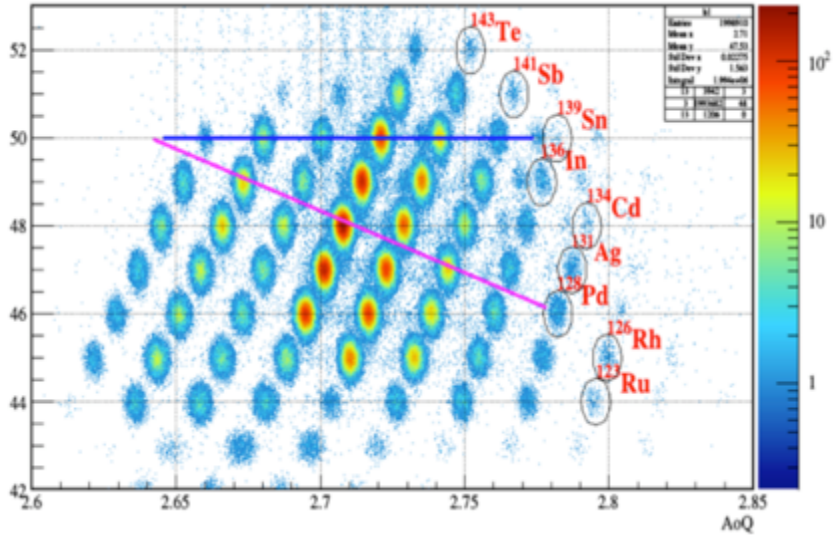
④ **Total absorption: γ energy spectra (E_γ)**

⑥ Heavier RI N=126 and beyond!

MRTOF & β-TOF (Mass & Decay : R&D)

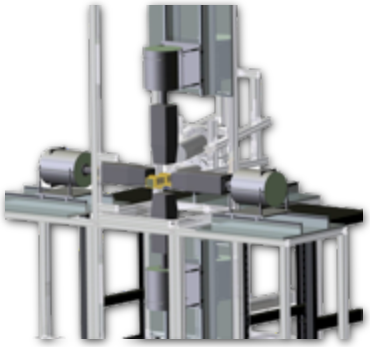
Beam Production & Decay Station

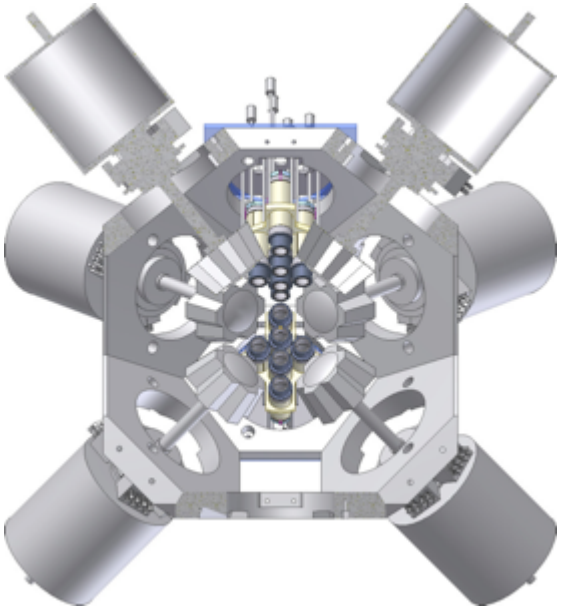




- The implantation of an identified RI is associated with the following β-decay events that are detected in the same silicon pixel (DSSSD).

Beta-gamma spectroscopy





EURICA「ユーリカ」
プロジェクト

19 countries : 237 collaborators

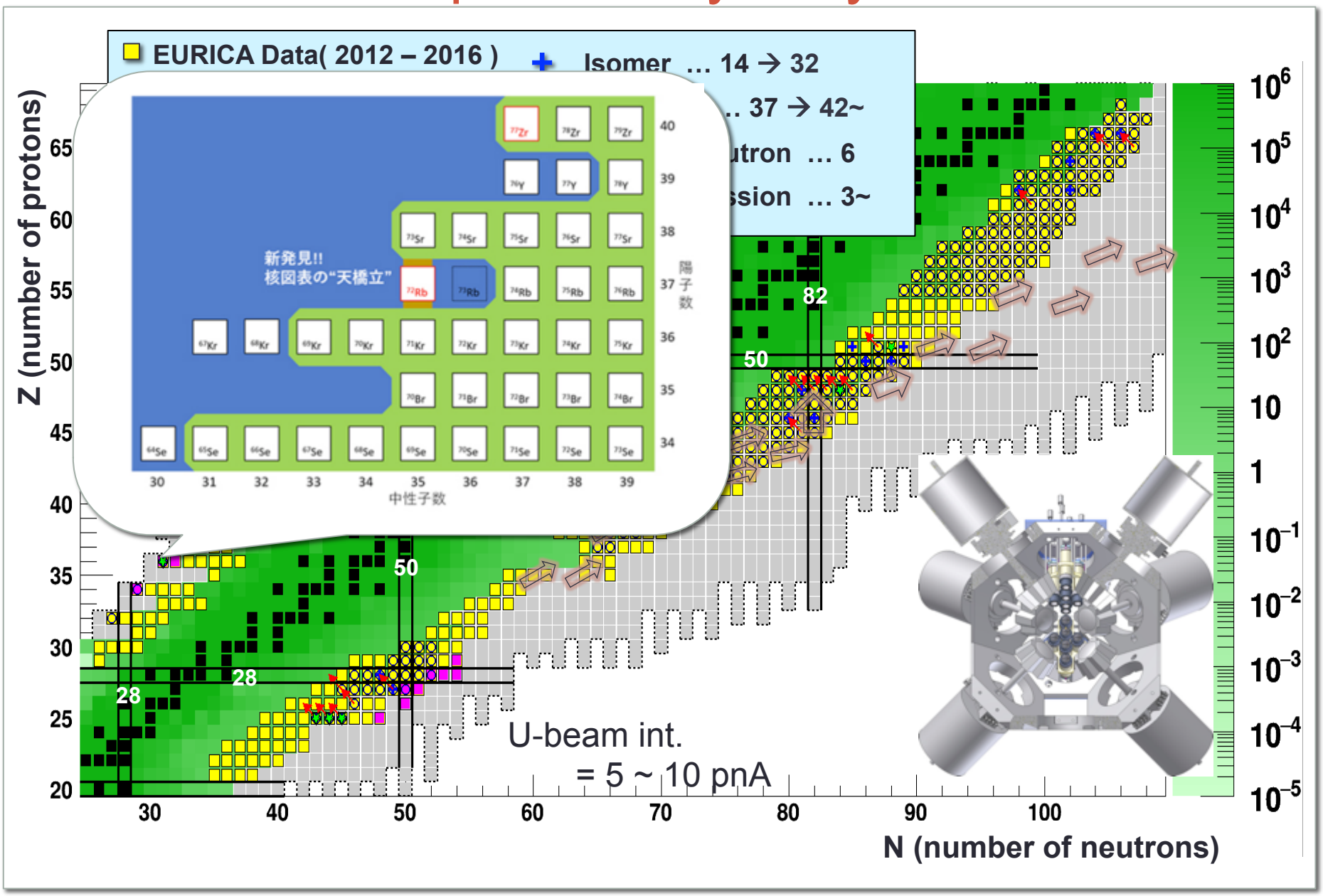
「博士論文」
英国（4名）、
ドイツ（3名）、
日本（2名）、韓国（2名）、フランス（2名）、カナダ（1名）
中国（1名）、スペイン（1名）

計 16名

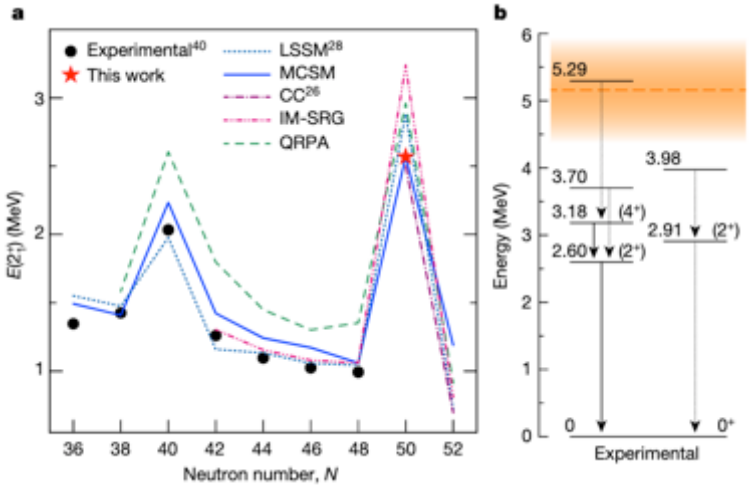
PRL x 16,
PLB x 13,
PRC(R)x5,
PRC x15,
EPJA x2,
PTEPx2,
JSPSJx1

計 54 報

440 Exotic Isotopes Surveyed by EURICA

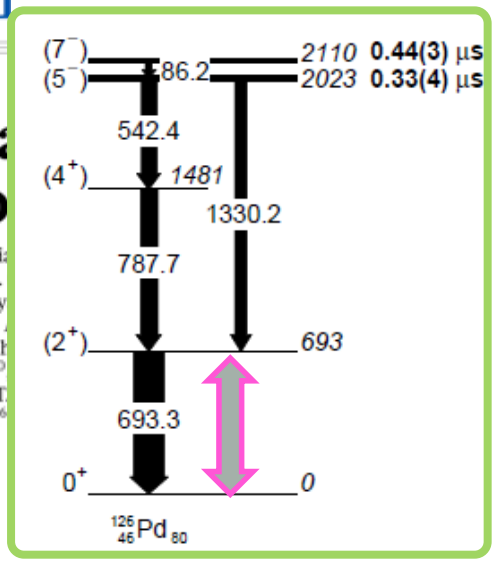


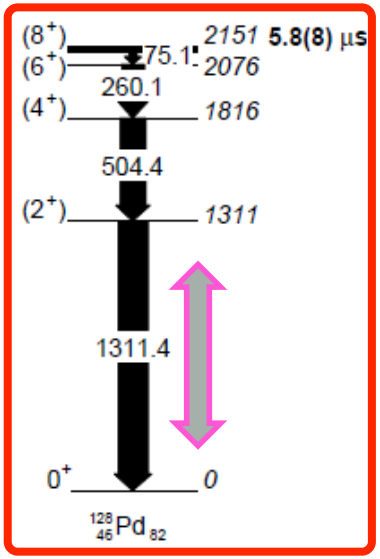
First Excited States of RI (Even-Z, Even-N)

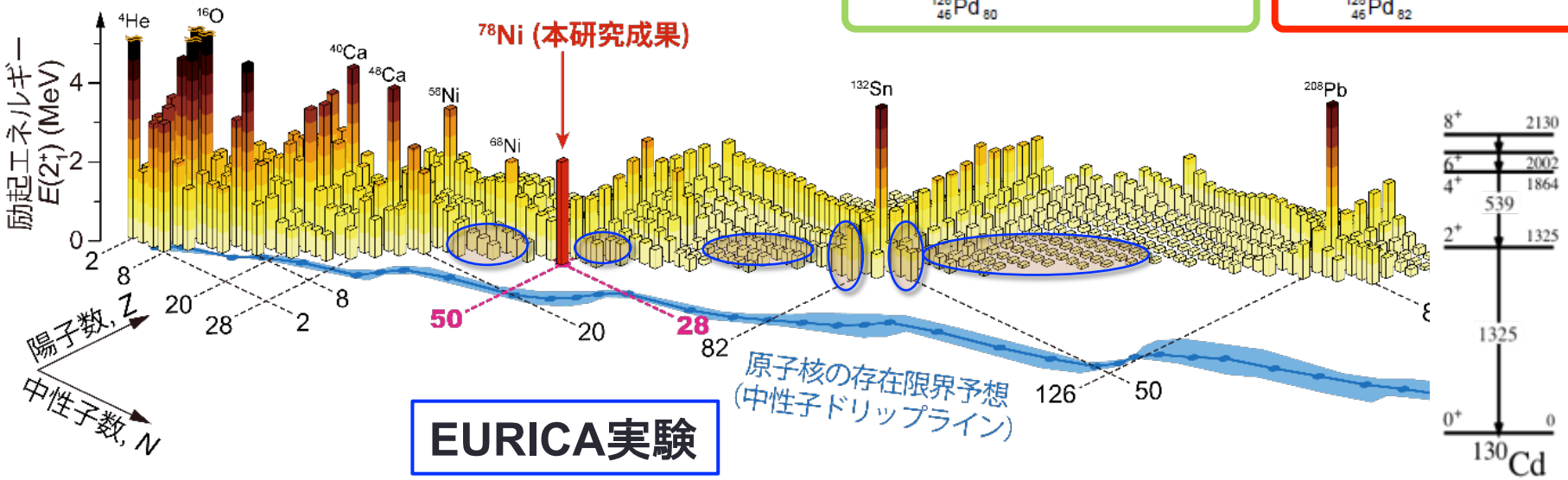


R. Taniuchi et al., Nature (2019)
In-beam gamma exp.

ARTICLE

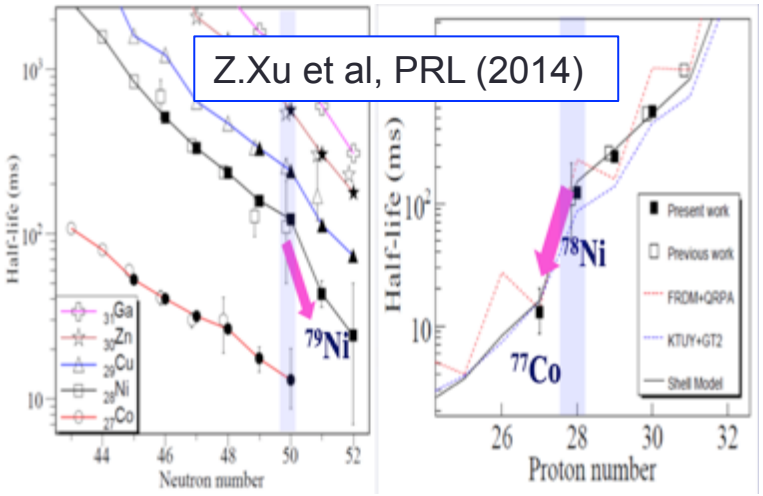


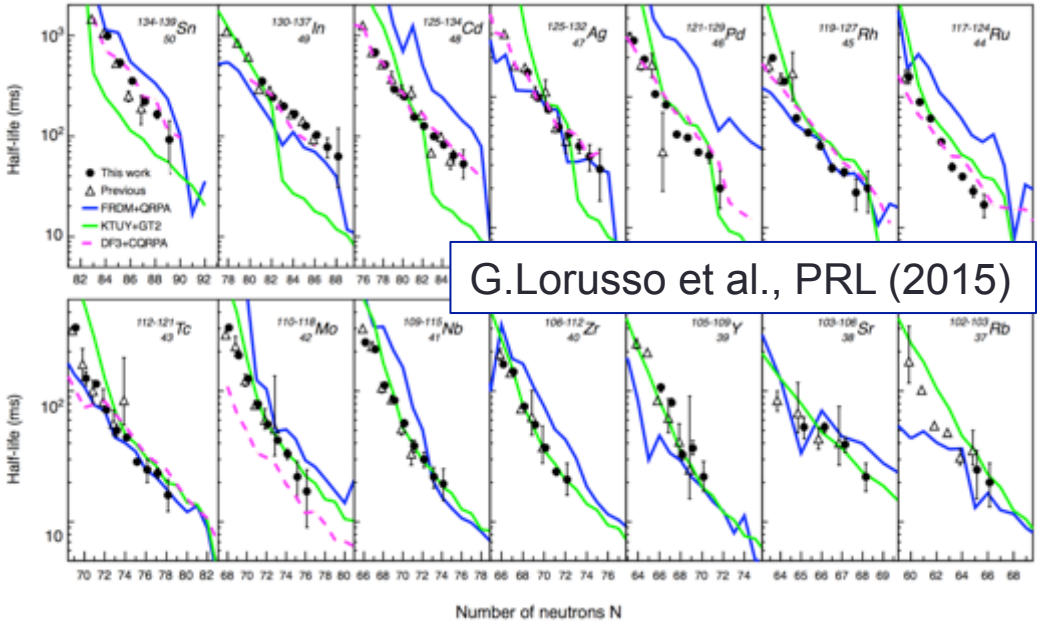


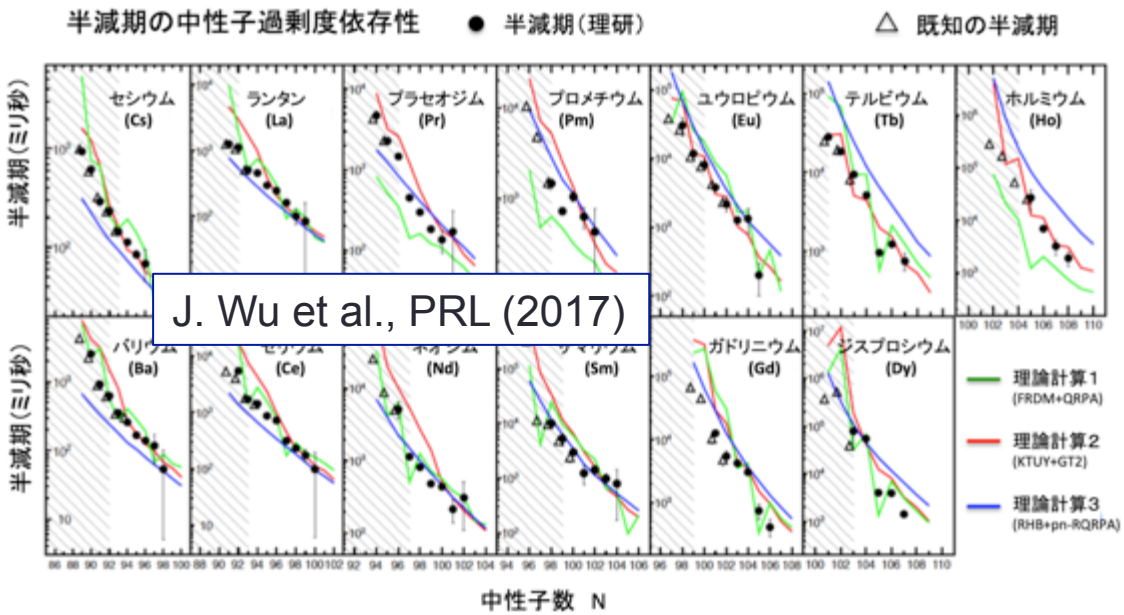


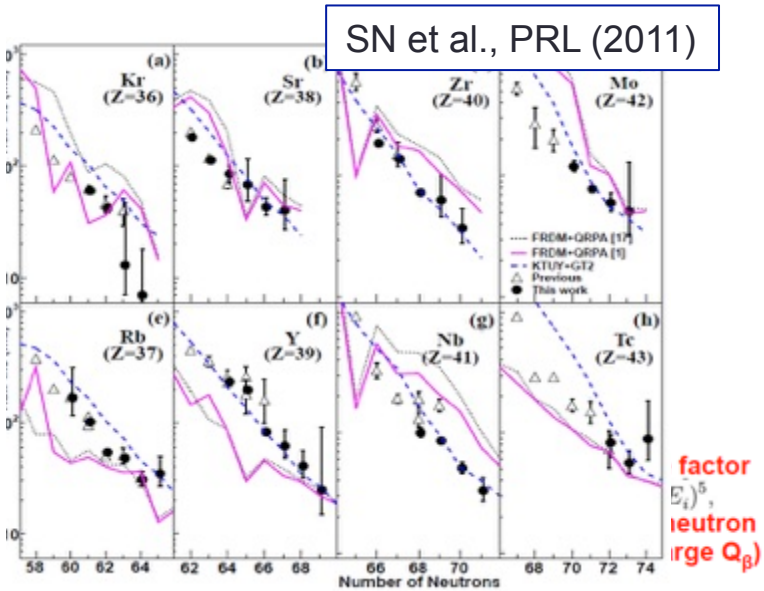
EURICA実験

~284 Half-lives (New $T_{1/2}$ ~125) Measured at RIBF



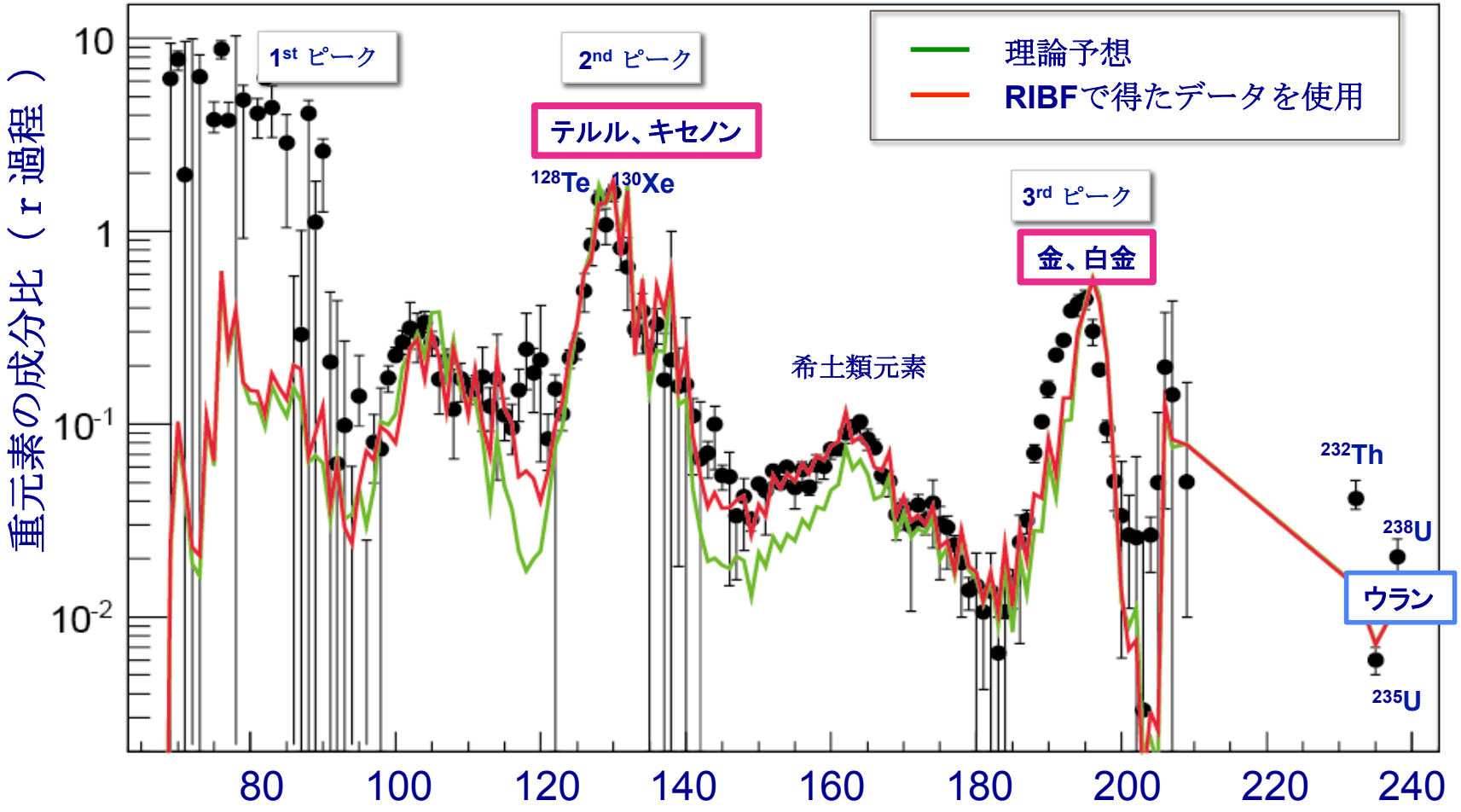






Feedback to Network Calculation

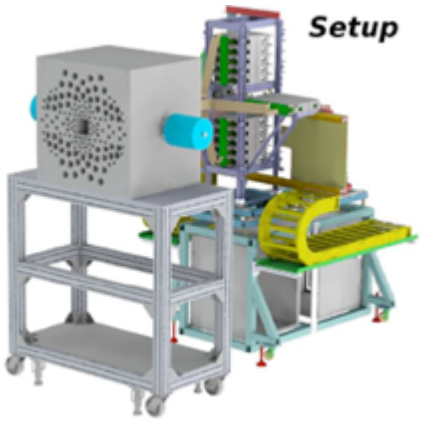
G.Lorusso et al., PRL (2015)



Assumption: Hot r-process
(n, γ) ⇄ (γ, n) equilibrium.

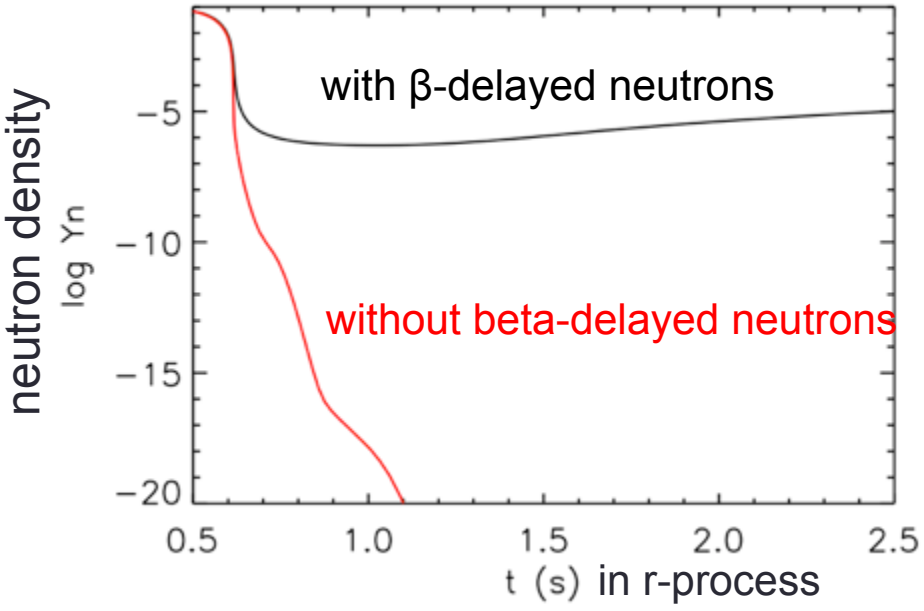
BRIKEN (2016 – 2021)

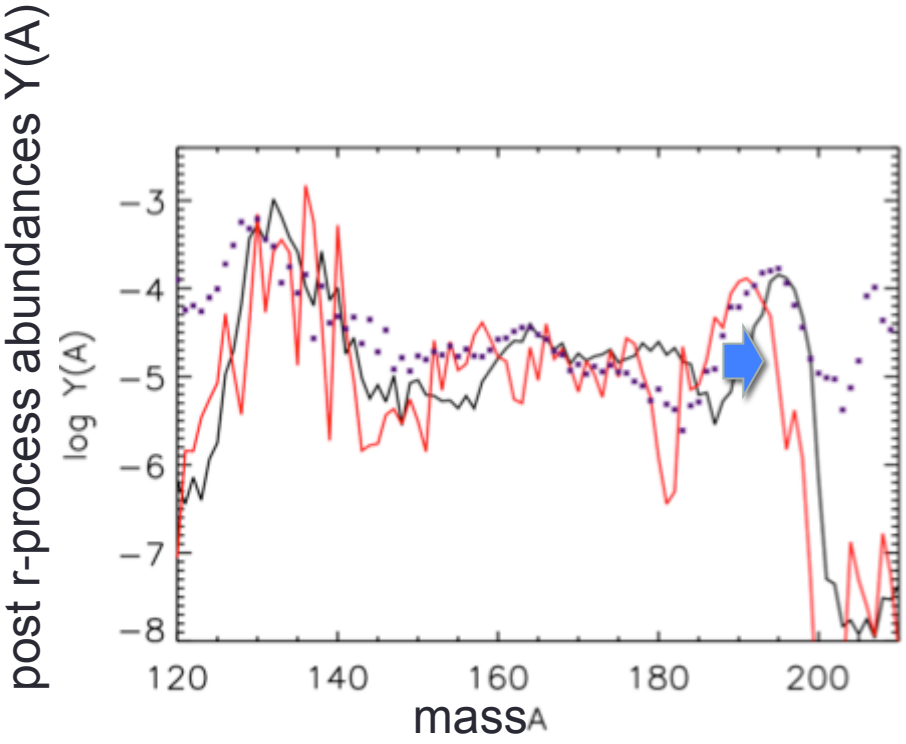
Beta-delayed neutron emission probabilities



Impact of β-delayed neutrons in R-Process

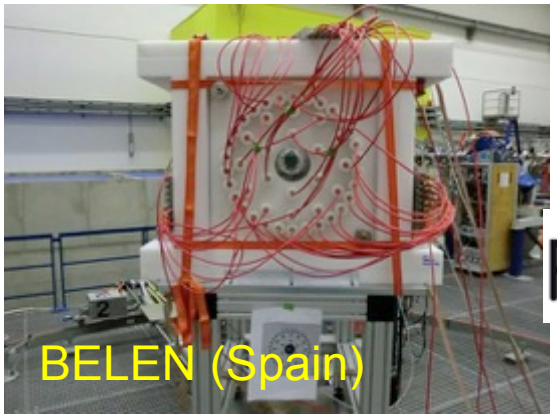
R. Surman, at Gordon conf., June 2013, at ARIS conf., June 2014





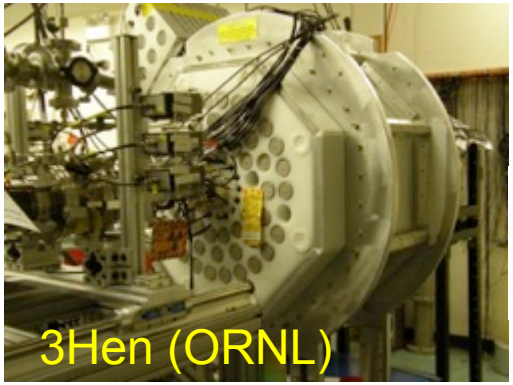
β-delayed neutron → (n, γ) reactions at freeze-out time

BRIKEN: Highest neutron detection eff.

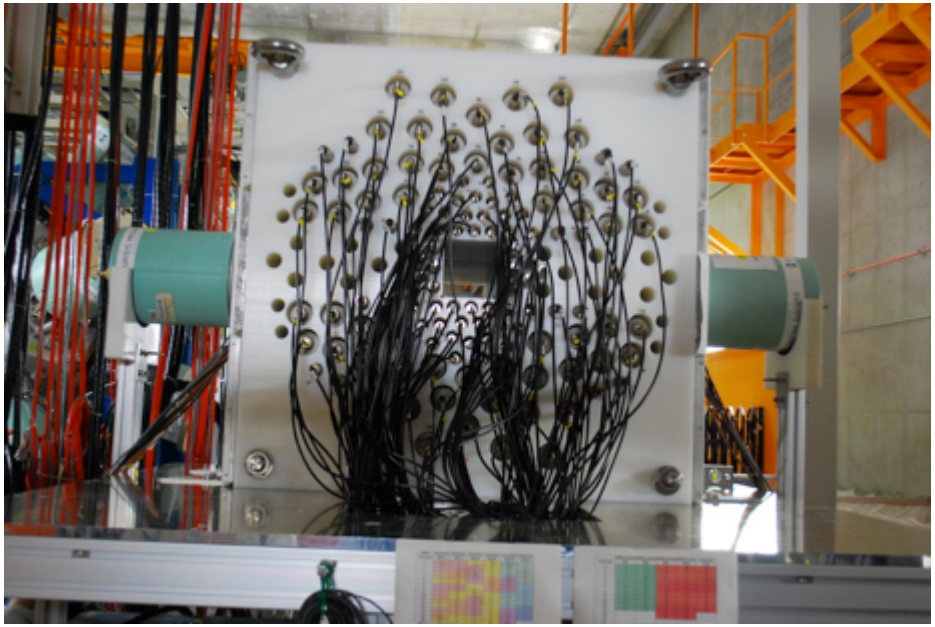


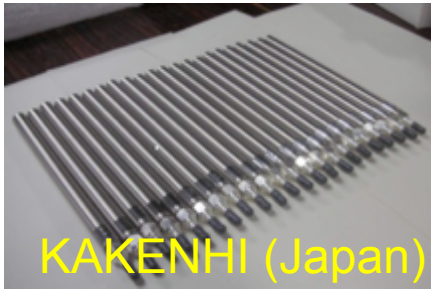
FAIR

BRIKEN @ RIBF



FRIB





RIKEN NISHINA CENTER

A.Tarifeno-Saldivia et al.
BRIKEN design, simulation
Jour. Instrum. 12, P04006 (2017)

BRIKEN Experiments (2016 - 2018)

Commissioning & Experiments (Parasitic Mode)

(1) 2016 Oct.
RIBF123R1 (Takechi Exp.) … 2 days — ^{77}Ni → A.Tolosa-Delgado et al. NIMA 925 (2019) 133 (^{81,82}Ga, ^{80}Zn)

(2) 2016 Nov.
RIBF03R1 (Fallon Exp.) ... 6.5 days — ^{40}Mg

(3) 2017 Mar.
DA16-01 (Ahn Exp.) ... 3 days — ^{40}Mg

11.5 days

2017 May-June BRIKEN Campaign-1

(4) RIBF127R1 (Rykaczewski) ... 4.5 days — ^{78}Ni (N ~ 50)

(5) RIBF128 (Estrade) ... 6.5 days — ^{128}Pd (N~82)

(6) RIBF148 (Kiss) ... 2 days/11 days — Rare earth (A ~ 150-160)

2017 Oct.-Nov. BRIKEN Campaign-2

(7) DA17-02 (Rykaczewski) ... 10 days — ^{82}Cu

(8) RIBF139 (Nishimura) ... 5.5 days — Mid-shell (A ~ 90-125)

B.C.Rasco et al. (^{77}Cu) NIM A 911 (2018) 79

R.Yokoyama et al. (^{86,87}Ga) (submitted)

2018 Nov. BRIKEN Campaign-3

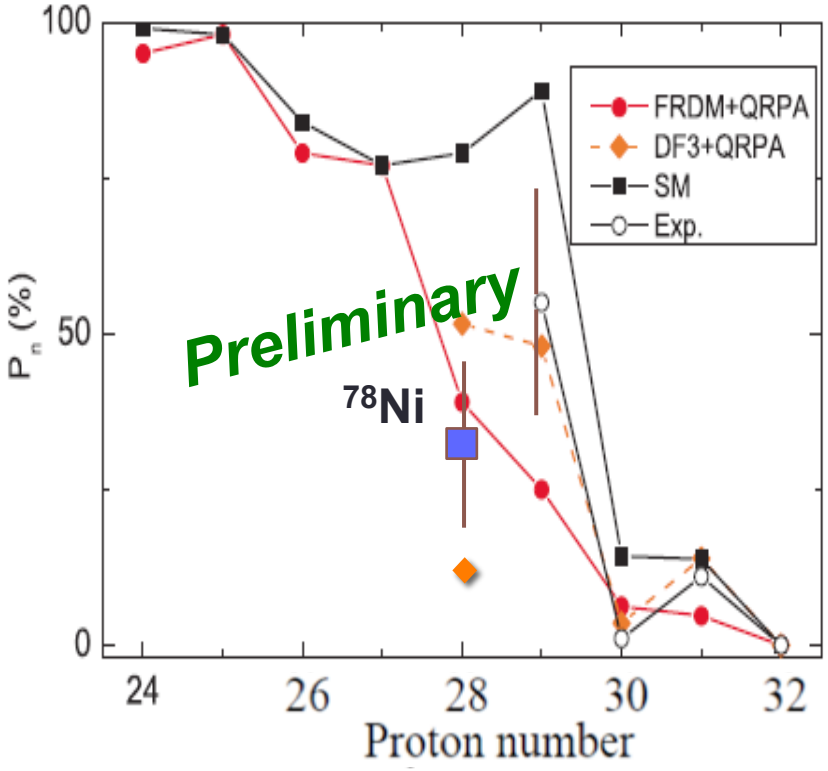
RIBF148 (Kiss) ... 6 days (+2 days..)

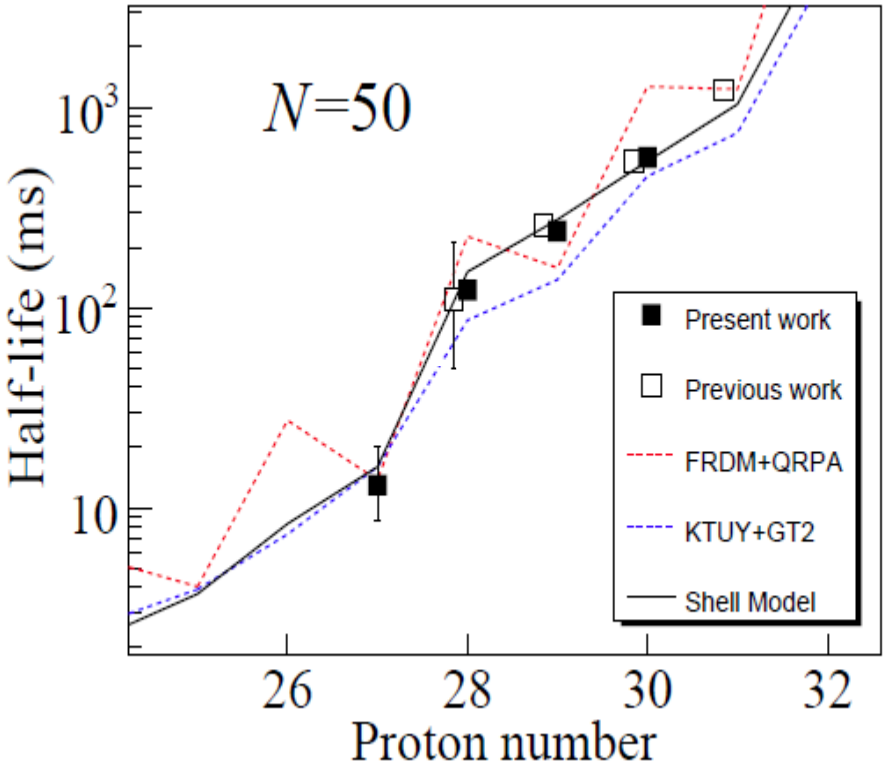
Total : ~ 34.5 days

Delayed neutron of ^{78}Ni on N = 50

(Experiment ←→ Theory)

Z.Xu PhD thesis (2014)

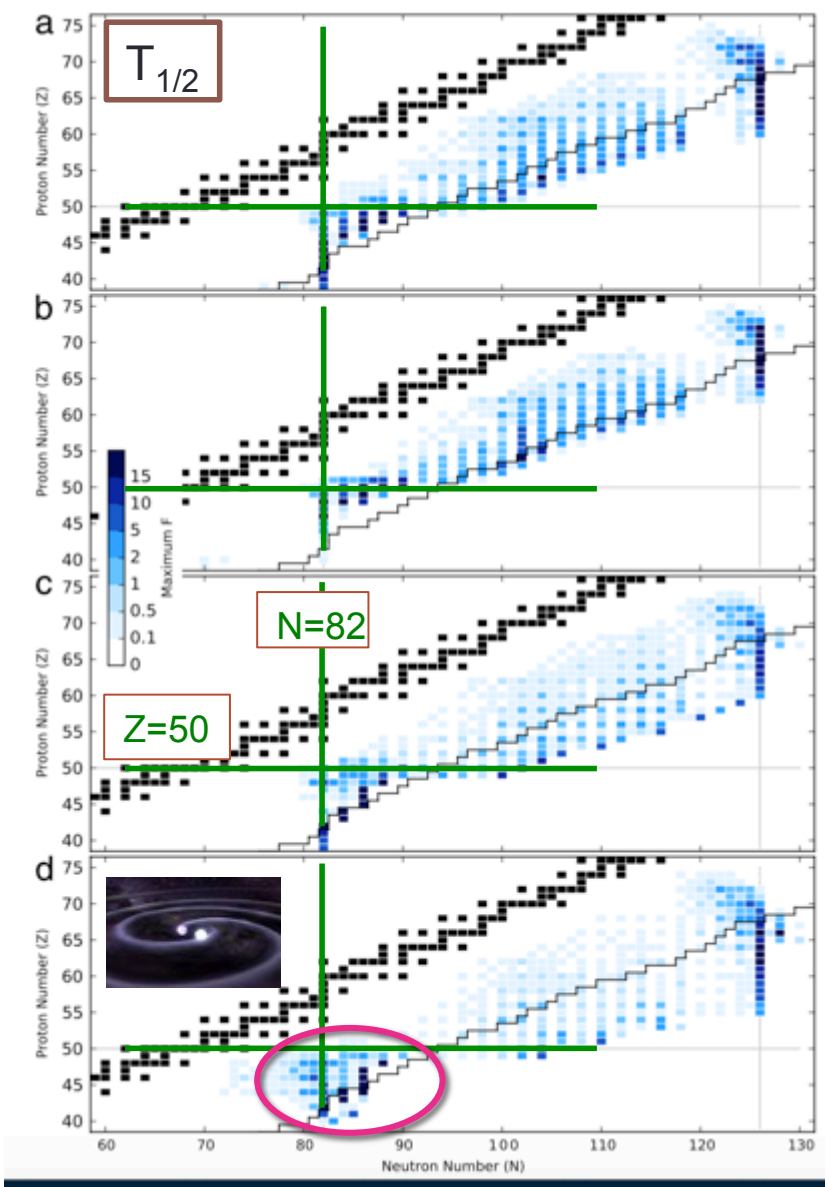


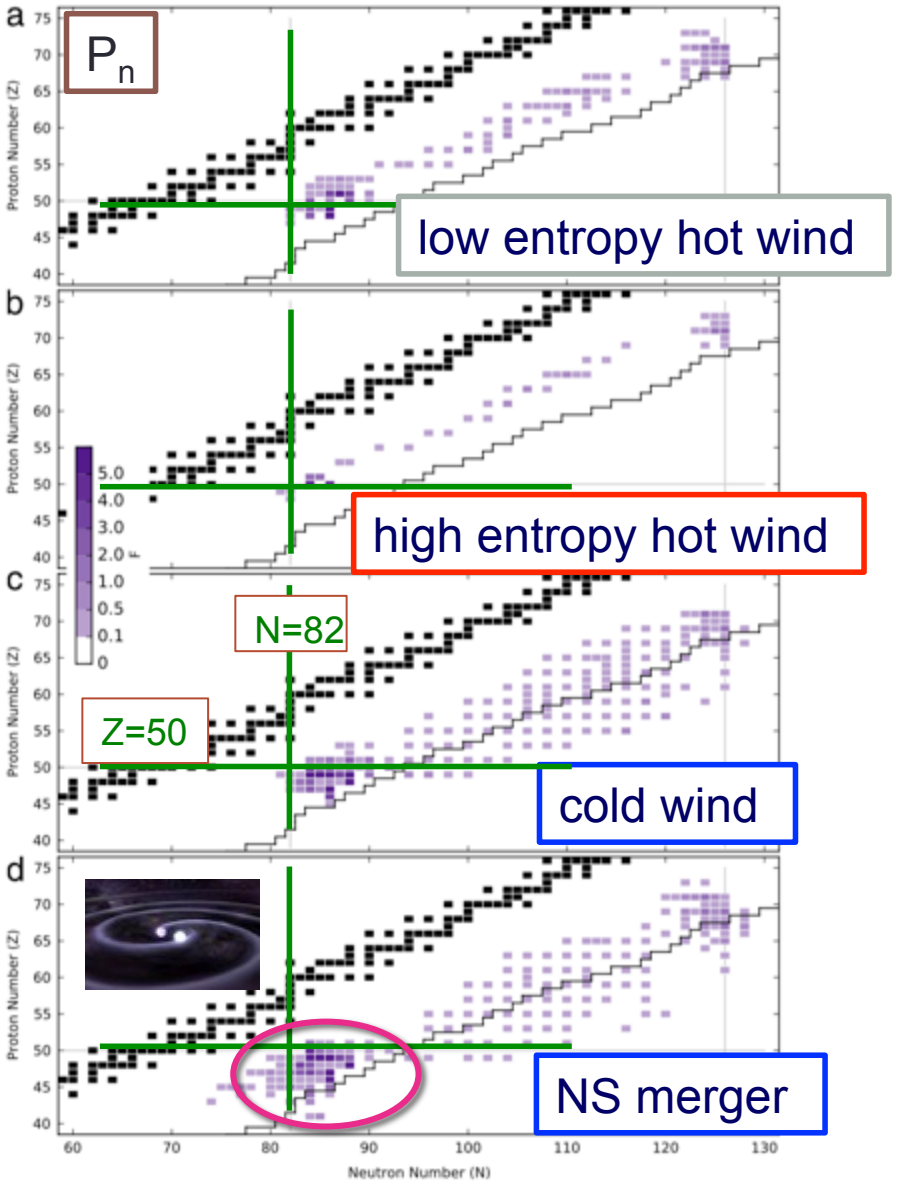


Pn value of 78Ni :

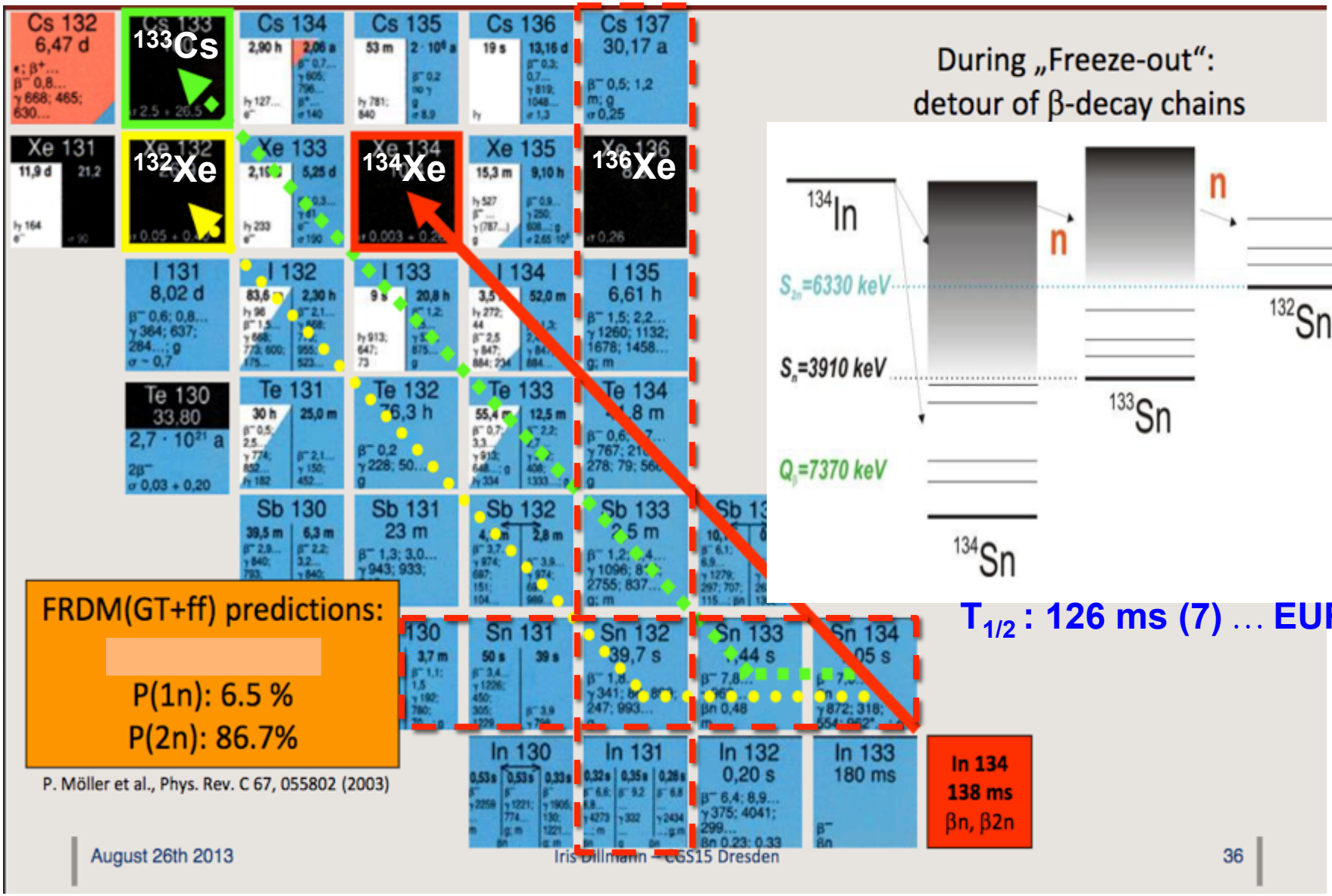
- SM overestimates the Pn value (x 2).
- Consistent value with FRDM+QRPA

Sensitivity Study of Decay Properties in r-Process



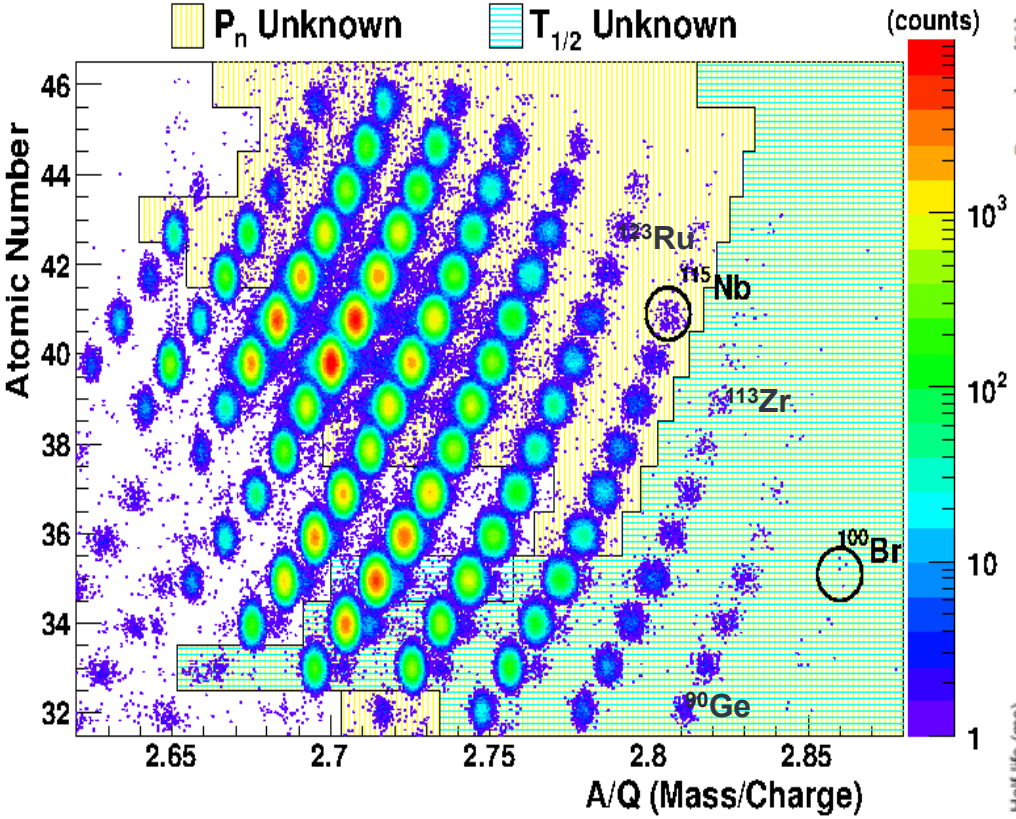


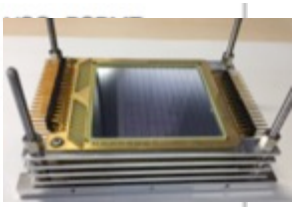
M.R. Mumpower et al.(2016)


During „Freeze-out“:
detour of β-decay chains
^{134}In
S_{2n}=6330 keV
S_n=3910 keV
Q_β=7370 keV
^{132}Sn
^{133}Sn
^{134}Sn
n
n
^{133}Cs
^{132}Xe
^{134}Xe
^{136}Xe
FRDM(GT+ff) predictions:
P(1n): 6.5 %
P(2n): 86.7%
P. Möller et al., Phys. Rev. C 67, 055802 (2003)
$T_{1/2}$: 126 ms (7) … EURICA
In 134
138 ms
βn, β2n
August 26th 2013
Iris Dillmann – CGS15 Dresden
36

BRIKEN 2017 Nov.

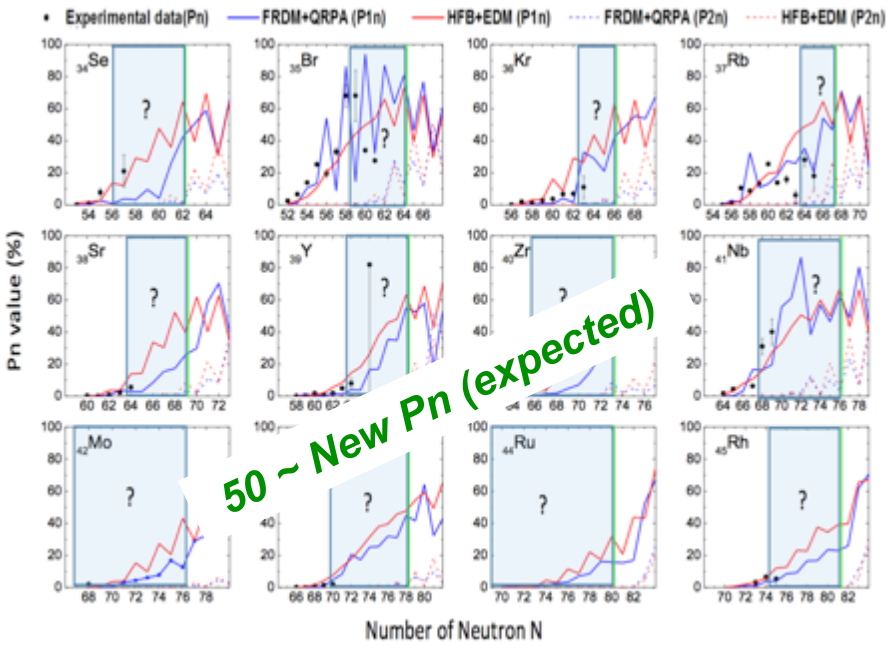
Spokespersons: S. Nishimura (RIKEN), A. Algora (IFIC-CSIC) 5.5 days

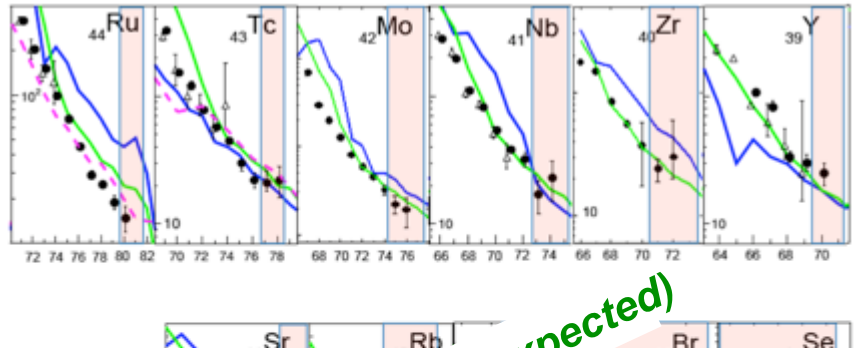


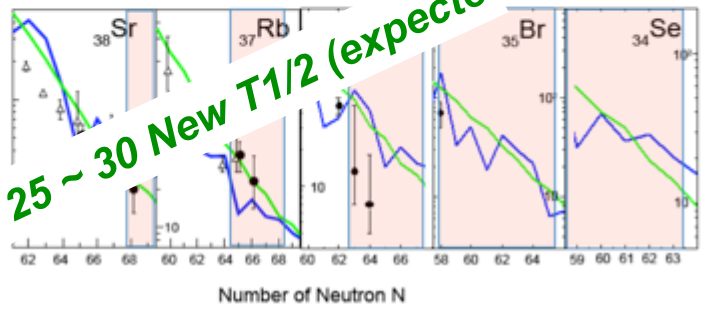


WAS3ABi (Si)
YSO (U.Tenneessee)

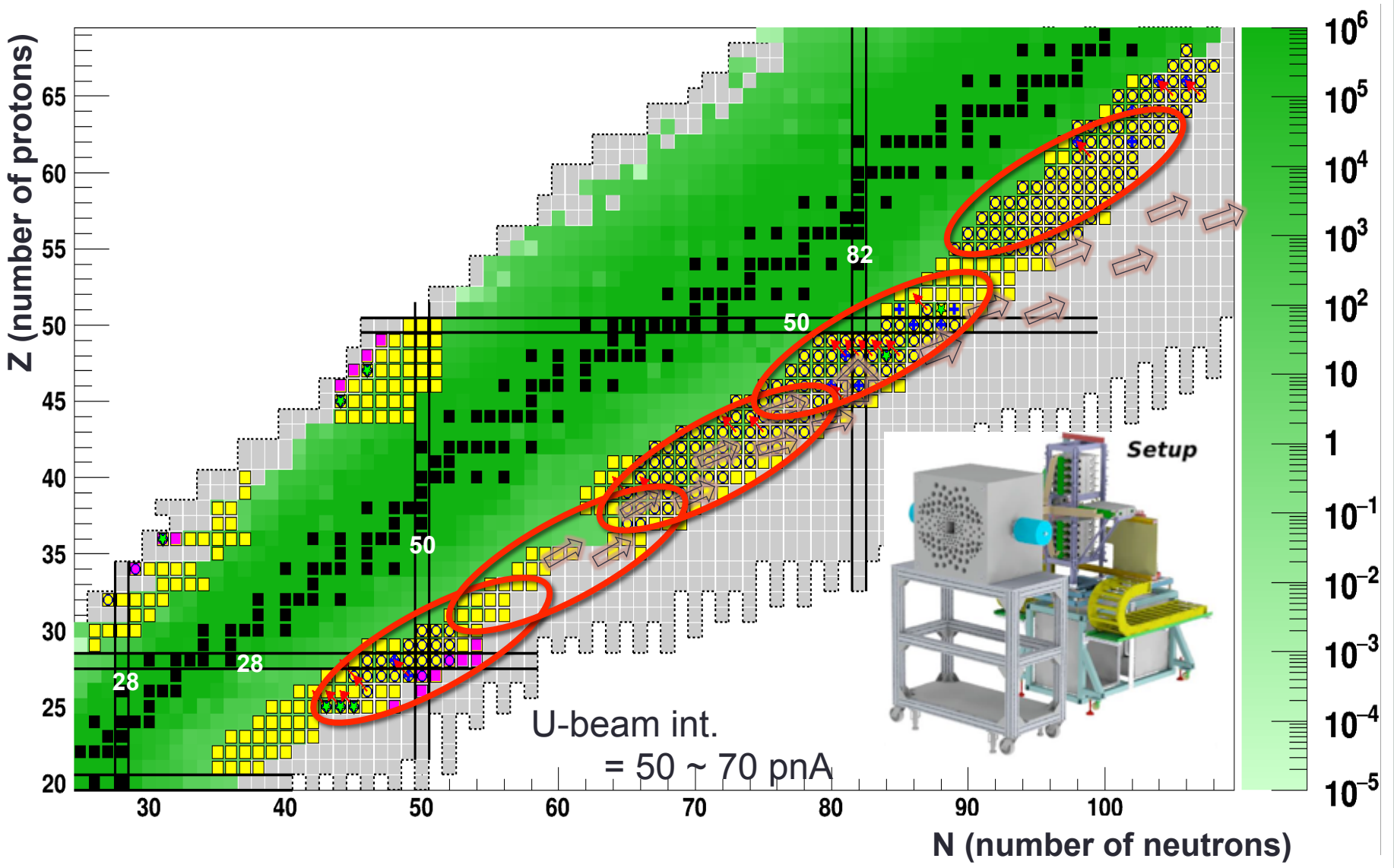
7 isomers (known)
6 isomers (unknown)







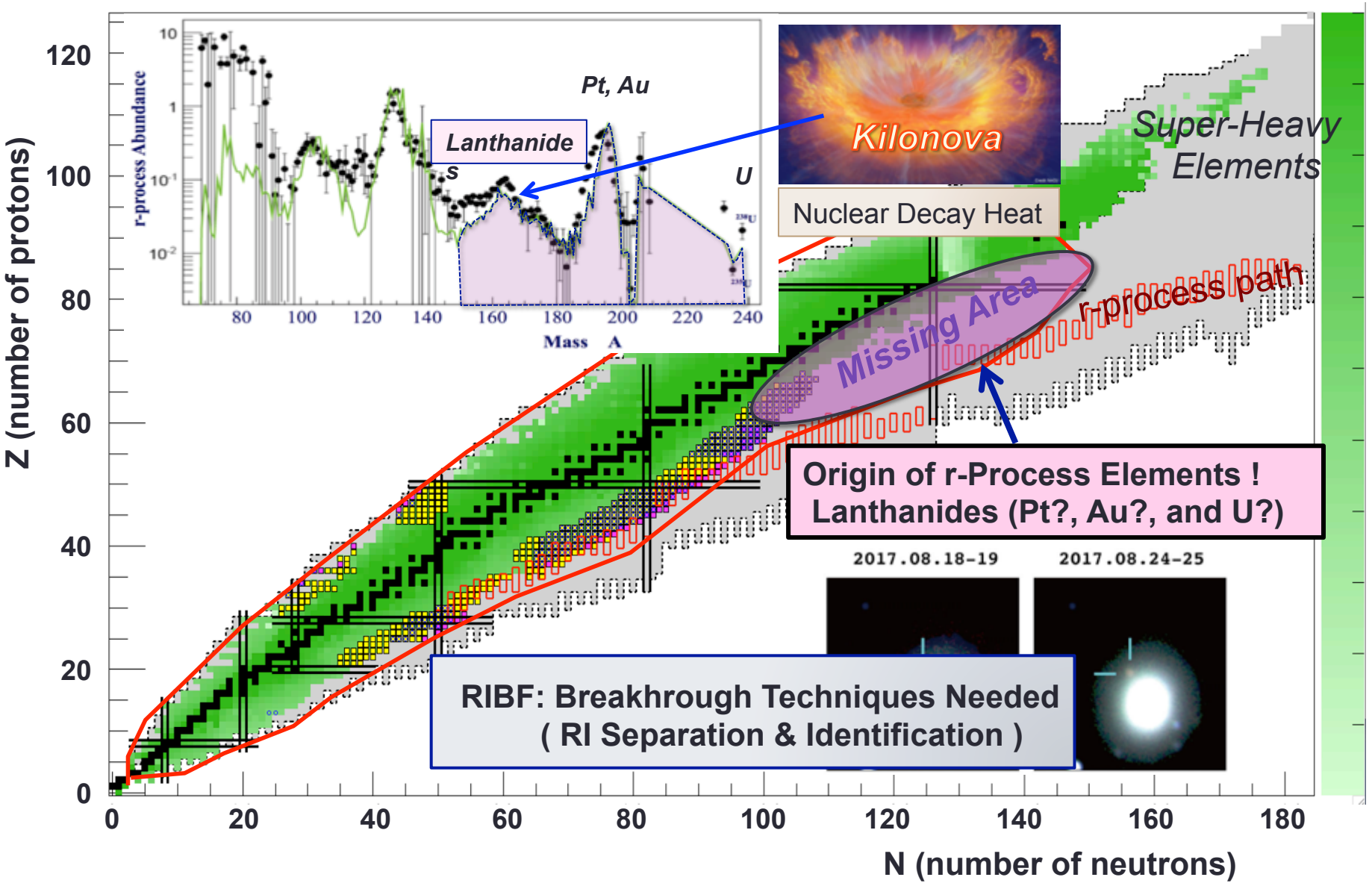
Exotic Isotopes Surveyed by BRIKEN



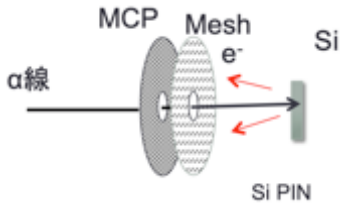
BRIKEN (N ~ 126) will be performed in near future (2019 fall?).

Decay Spectroscopy toward Heavier RI

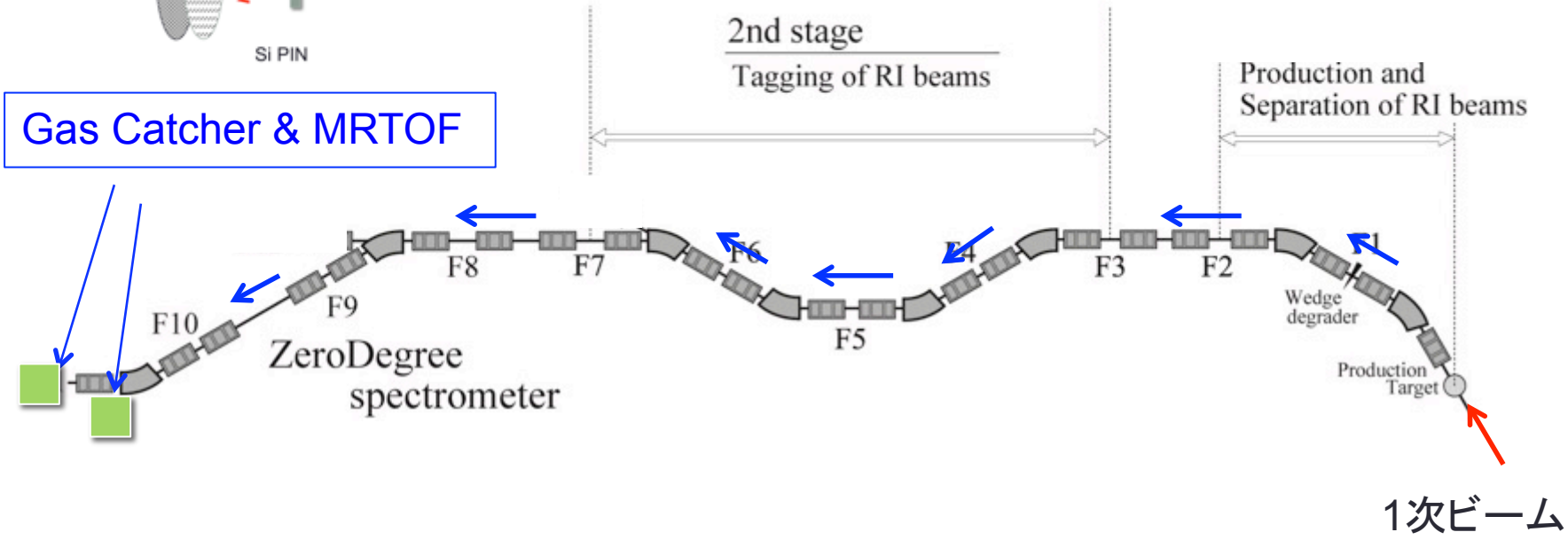
3rd r-Process Peak (N = 126 Region)



Decay Program & ZD-MRTOF



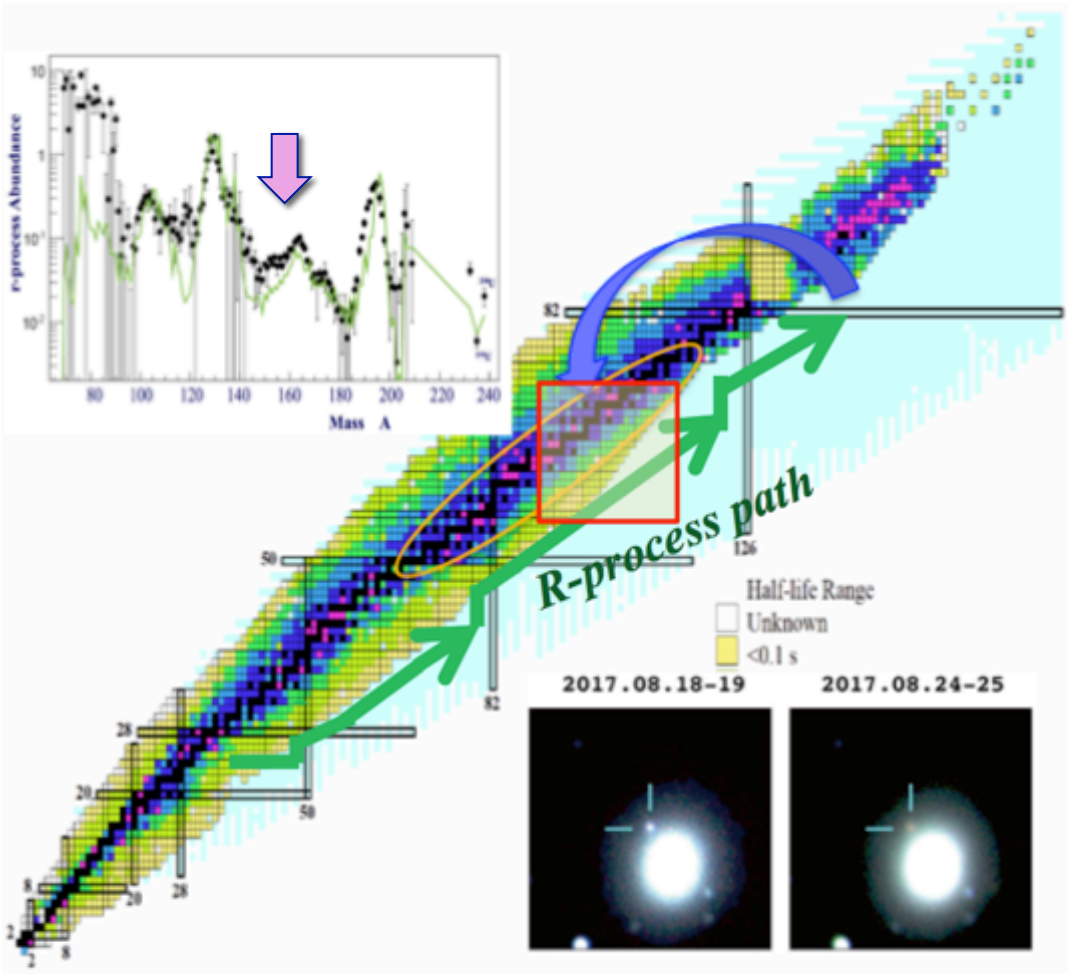
Gas Catcher & MRTOF

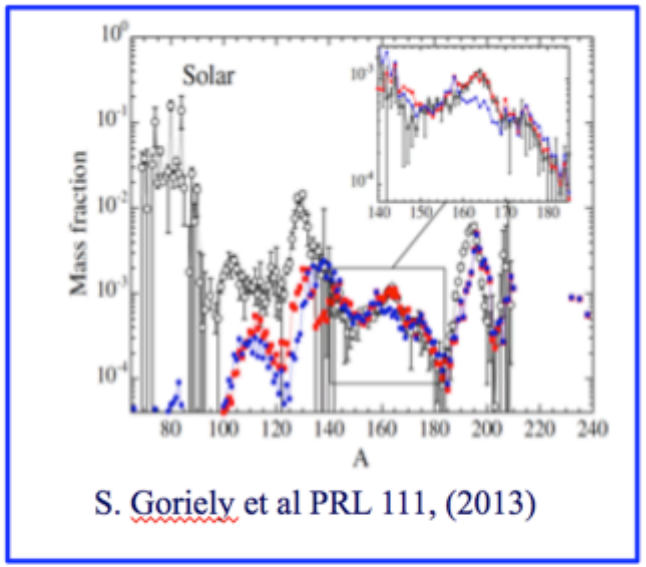


BRIKEN (N~126) using BigRIPS/ZDS in 2019 fall ?

ZD-MRTOF & Decay for heavy RI (N = 126)

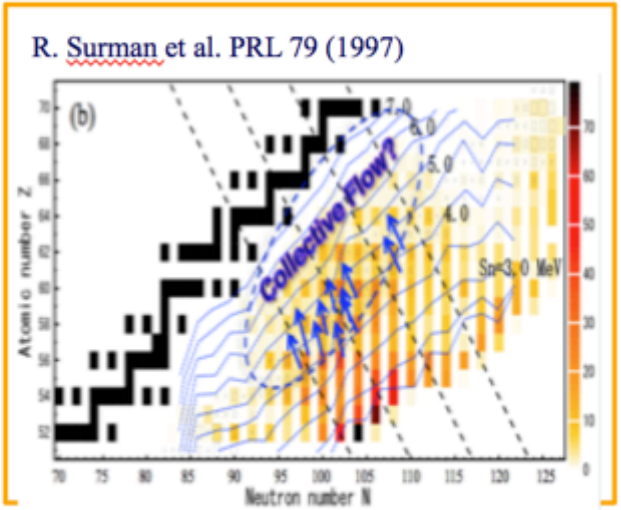
Origin of Rare-Earth Elements





S. Goriely et al PRL 111, (2013)

R. Surman et al. PRL 79 (1997)



Summary

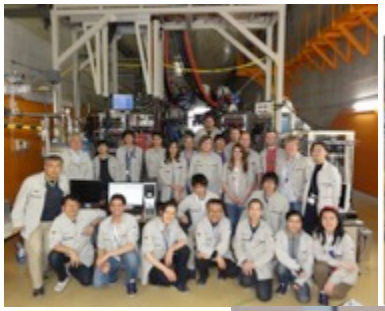
- ✓ **Beta-gamma spectroscopy 2009, 2012-2016,**
  - ✓ **Successful Campaigns with EURICA (~ 100 days)**
    Cluster Detectors are shipped back to GSI
  - ✓ **Beta-Neutron & gamma spectroscopy in progress**
    - ✓ **Successful Campaigns with BRIKEN (~35 days)**

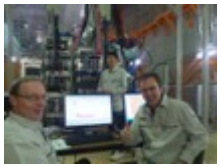
→ 284 → 307(EURICA) → ~ 370 $T_{1/2}$, 6 (EURICA) → ~150 P_{xn}

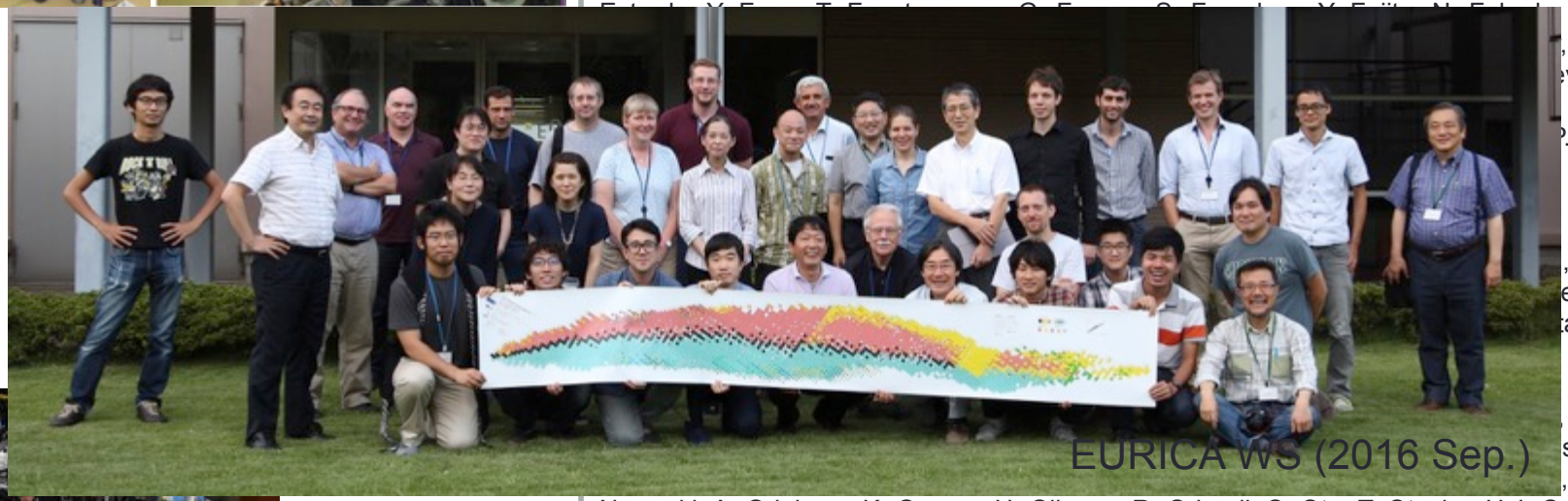
Emission type	Energetically allowed	Already measured	BRIKEN New P_n values expected
β1n	621	298	~250
β2n	300	25	~50
β3n	138	4	~10
β4n	58	1	~5

  - ✓ **Future Plan**
    - ✓ **Decay experiments around N = 126**
    - ✓ **2nd Beta-gamma campaign**
    - ✓ **Delayed neutron energy / Fast γ-decay**
    - ✓ **BigRIPS-ZDS → MR-TOF → Decay Station**

EURICA Collaboration







EURICA WS (2016 Sep.)

19 countries : 237 collaborators

J. Agramunt, P. Aguilera, T. Alharbi, A. Algora, G. Angelis, N. Aoi, P. Ascher, R. Avigo, H.Baba, C. Borcea, A. Boso, A.M. Bruce, R.B. Cakirli, F.L.Bello Garrote, G. Benzoni, J.S.Berryman, R. Berta, B. Blank, N. Blasi, A. Blazhev, P. Boutachkov, S. Bonig, A. Bracco, F. Browne, F. Camera, R.J. Carroll, S. Ceruti, I. Celikovic, K.Y. Chae, J. Chiba, L. Coraggio, A. Covello, F.C.L. Crespi, J.-M. Daugaus, R. Daido, P. Davis, M.C. Delattre, F. Diel, F. Didiejean, Zs. Dombradi, P. Doornenbal, F. Drouet, H.J. Eberth, A. A. , J. vy, N. .R. Y. N. Y. , T. ee, ay, B. S. K. sa, , F. Nowacki, A. Odahara, K. Ogawa, H. Oikawa, R. Orlandi, S. Ota, T. Otsuka, H.J. Ong, S. Orrigo, M. Rajabali, J. Park, Z. Patel, A. Petrovici, F. Recchia, V. Phong, Zs. Podolyak, O.J. Roverts, L. Prochniak, P.H. Regan, S. Rice, E. Sahin, H. Sakurai, K. Sato, H. Schaffner, H.Scheit, P. Schury, C. Shand, Y. Shi, S. Shibagaki, T. Shimoda, Y. Shimizu, K. Sieja, L. Sinclair, G.S. Simpson, P.-A. Soderstrom, D. Sohler, I.G. Stefan, K. Steiger, D. Steppenbeck, K. Sugimoto, T. Sumikama, D. Suzuki, 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

Acknowledgement:
Euroball Owners Committee
PreSPEC, GSI, IBS-RISP

Acknowledgement: Gammapool, Preepc, IBS

BRIKEN collaboration (November 2017)

~ 60 collaborators in total

OAK RIDGE National Laboratory

IFIC INSTITUT DE FÍSICA CORPUSCULAR

RIKEN NISHINA CENTER

Los Alamos NATIONAL LABORATORY EST. 1943

NPL National Physical Laboratory

Science & Technology Facilities Council Daresbury Laboratory

IMP

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THE UNIVERSITY OF EDINBURGH

TRIUMF

Argonne NATIONAL LABORATORY

CMU CENTRAL MICHIGAN UNIVERSITY

THE UNIVERSITY OF TENNESSEE KNOXVILLE

VNU

東京大学 THE UNIVERSITY OF TOKYO

UNIVERSITY OF GUELPH

UNIVERSITY OF SURREY

VERITAS LUX MEA

SAPIENTIA·ET·VIRTUS

MICHIGAN STATE UNIVERSITY

UNIVERSITY OF WARSAW