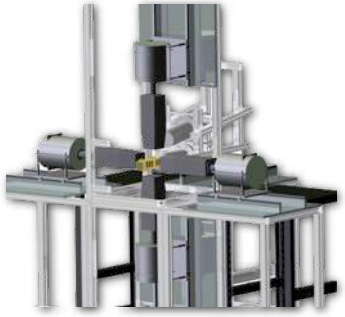
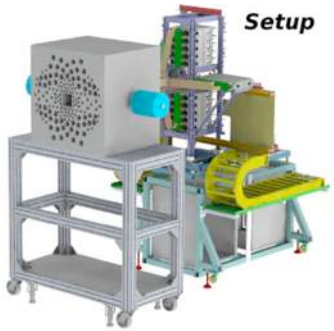
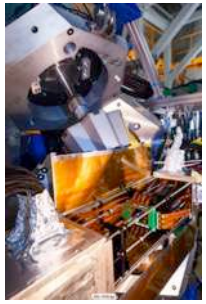
Rプロセスの研究：実験的検証と挑戦

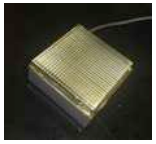
[現状と今後の戦略]

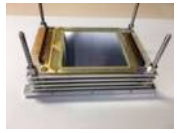
西村俊二 （理研）

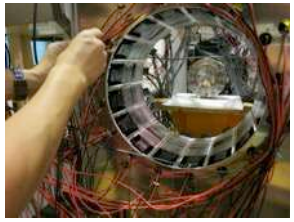


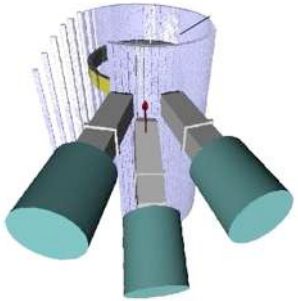




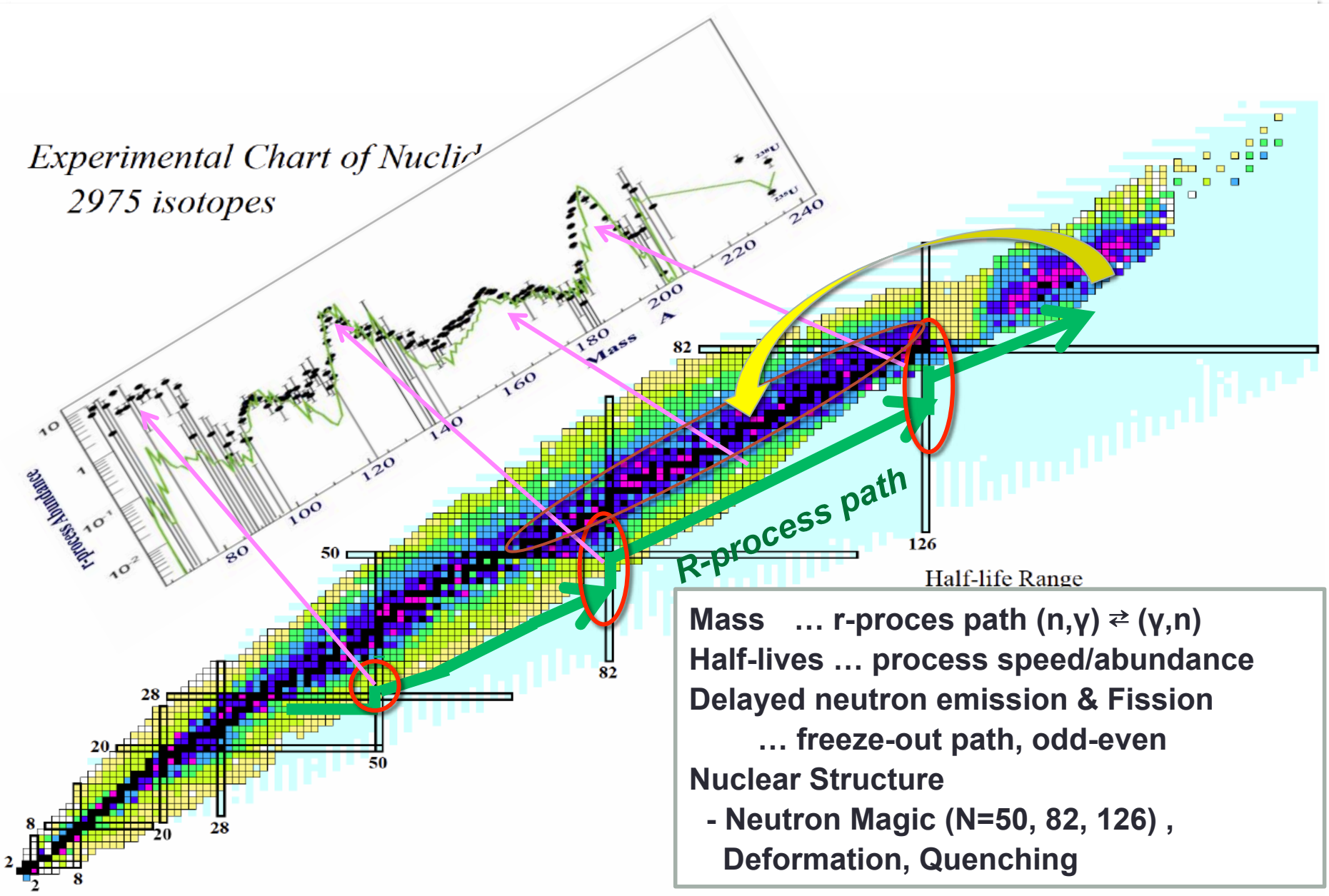








Nucleosynthesis of Heavy Elements (r-Process)



Mass … r-proces path (n,γ) ⇄ (γ,n)
Half-lives … process speed/abundance
Delayed neutron emission & Fission
… freeze-out path, odd-even
Nuclear Structure
- Neutron Magic (N=50, 82, 126) ,
Deformation, Quenching

Contents

1. Experiments for r-process nucleosynthesis at RIBF (ZDS)

2. Decay Spectroscopy at RIBF
    1. EURICA
    2. BRIKEN
    3. VANDLE / CAITEN
    4. DTAS
    5. Future Plan

3. Other Activities
    1. Heavy-ion Collisions (EOS)

4. Summary

Experiments ➡ Nuclear Theory

[Feedback to Theory]

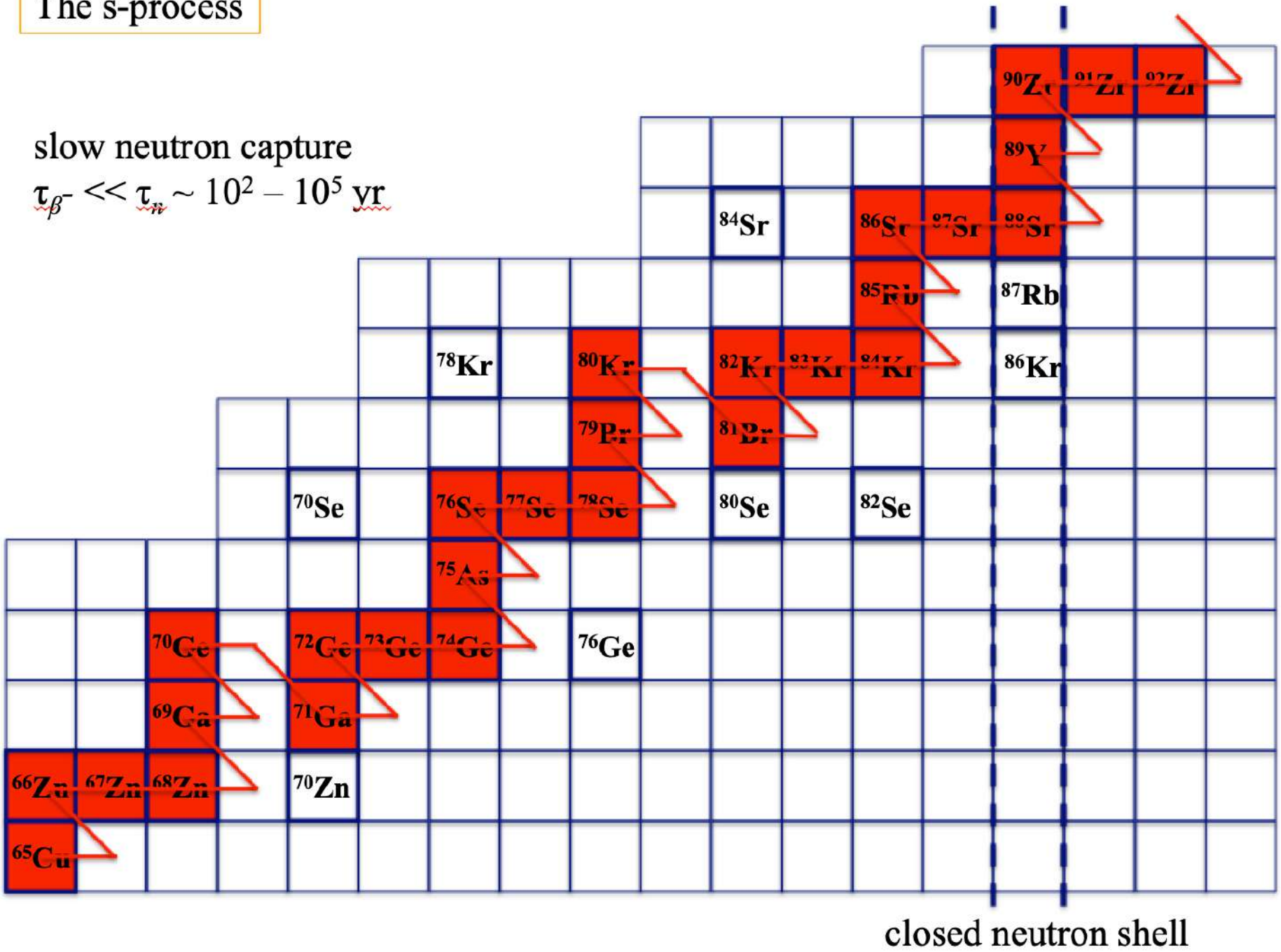
Experiments ⬅ Nuclear Theory

[Feedback from Theory]

The s-process

slow neutron capture

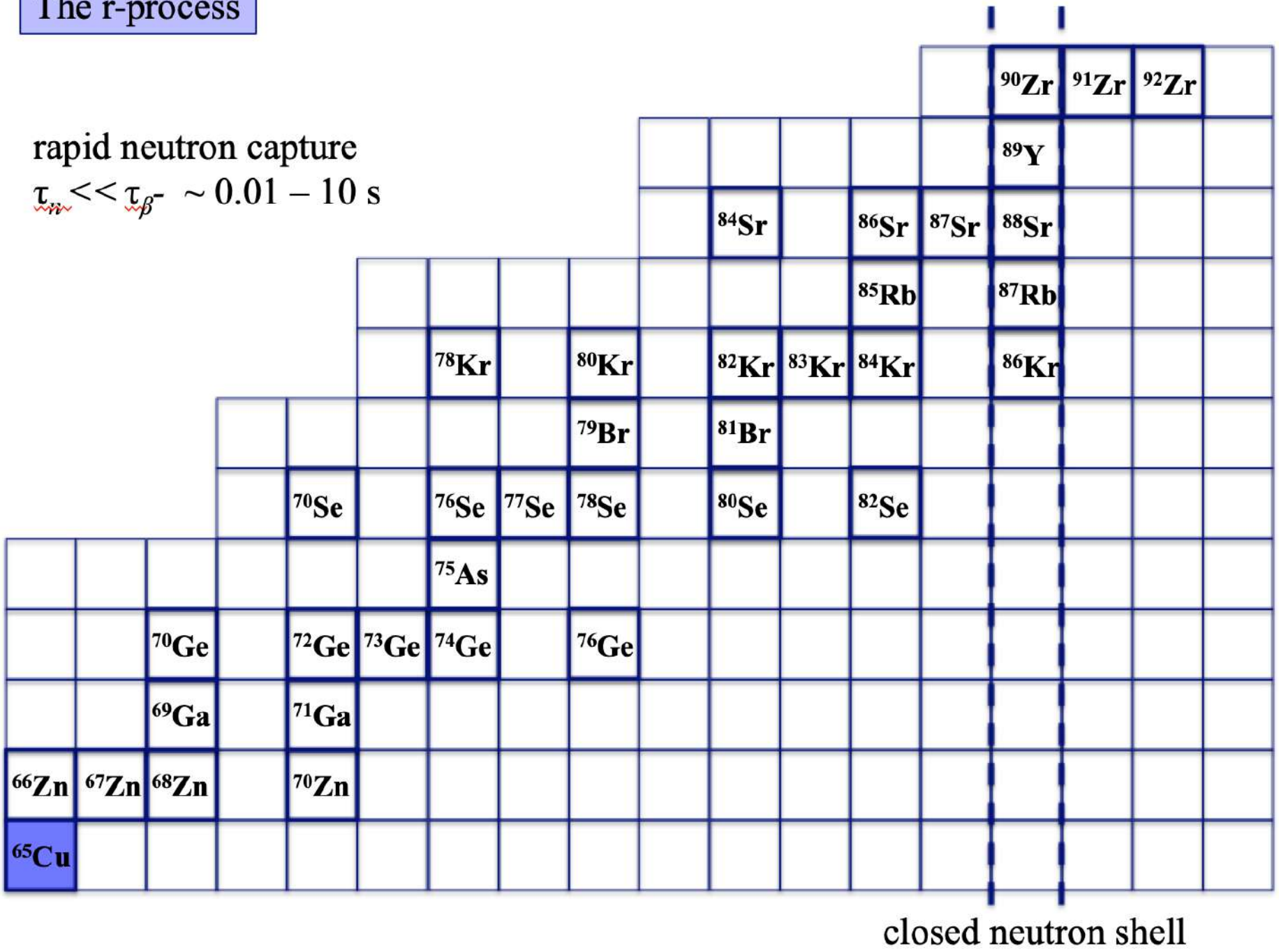
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



The r-process

rapid neutron capture

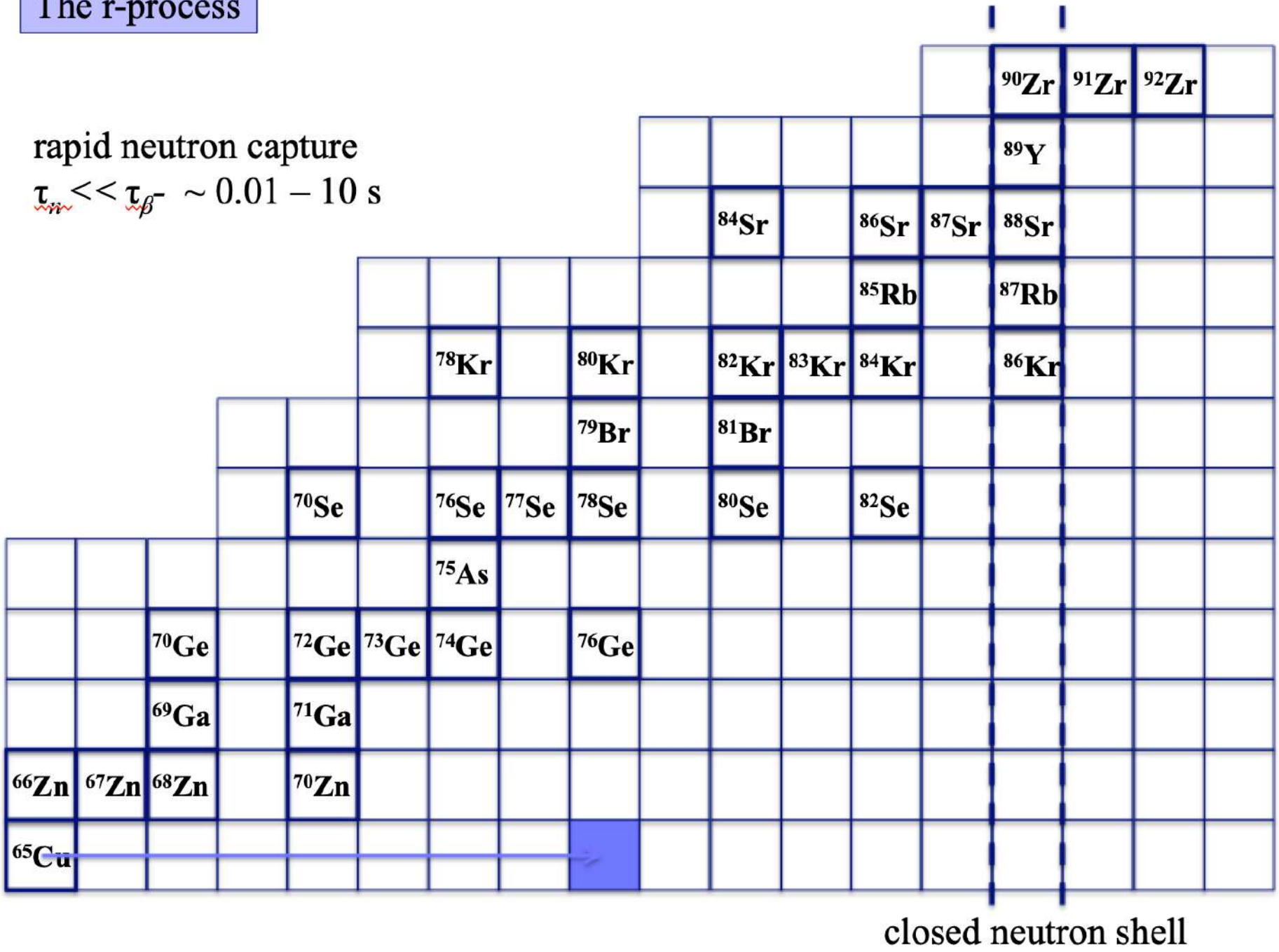
$\tau_n << \tau_{\beta^-}$ ~ 0.01 – 10 s



The r-process

rapid neutron capture

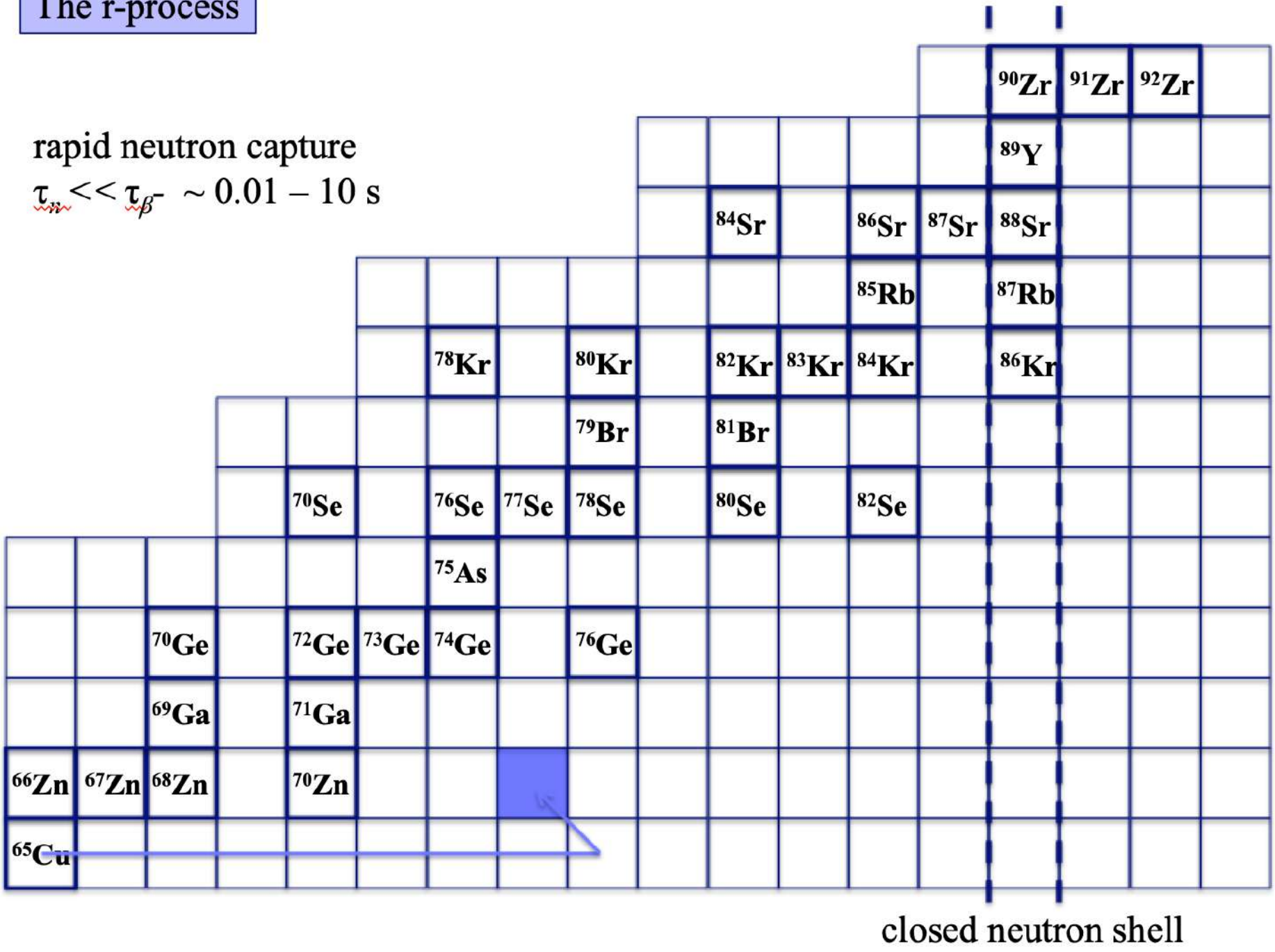
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



The r-process

rapid neutron capture

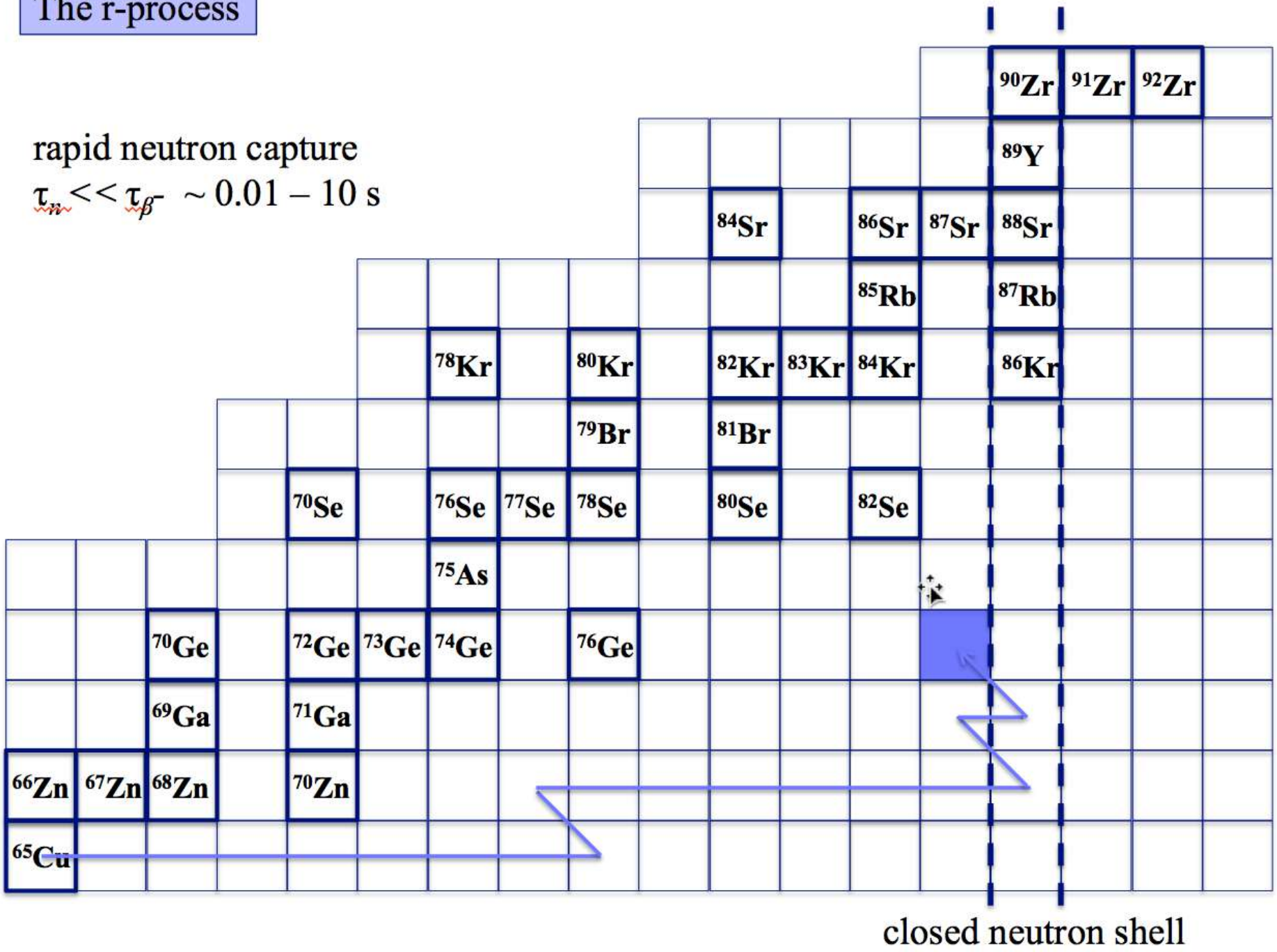
$\tau_{n} << \tau_{\beta^-}$ ~ 0.01 – 10 s



The r-process

rapid neutron capture

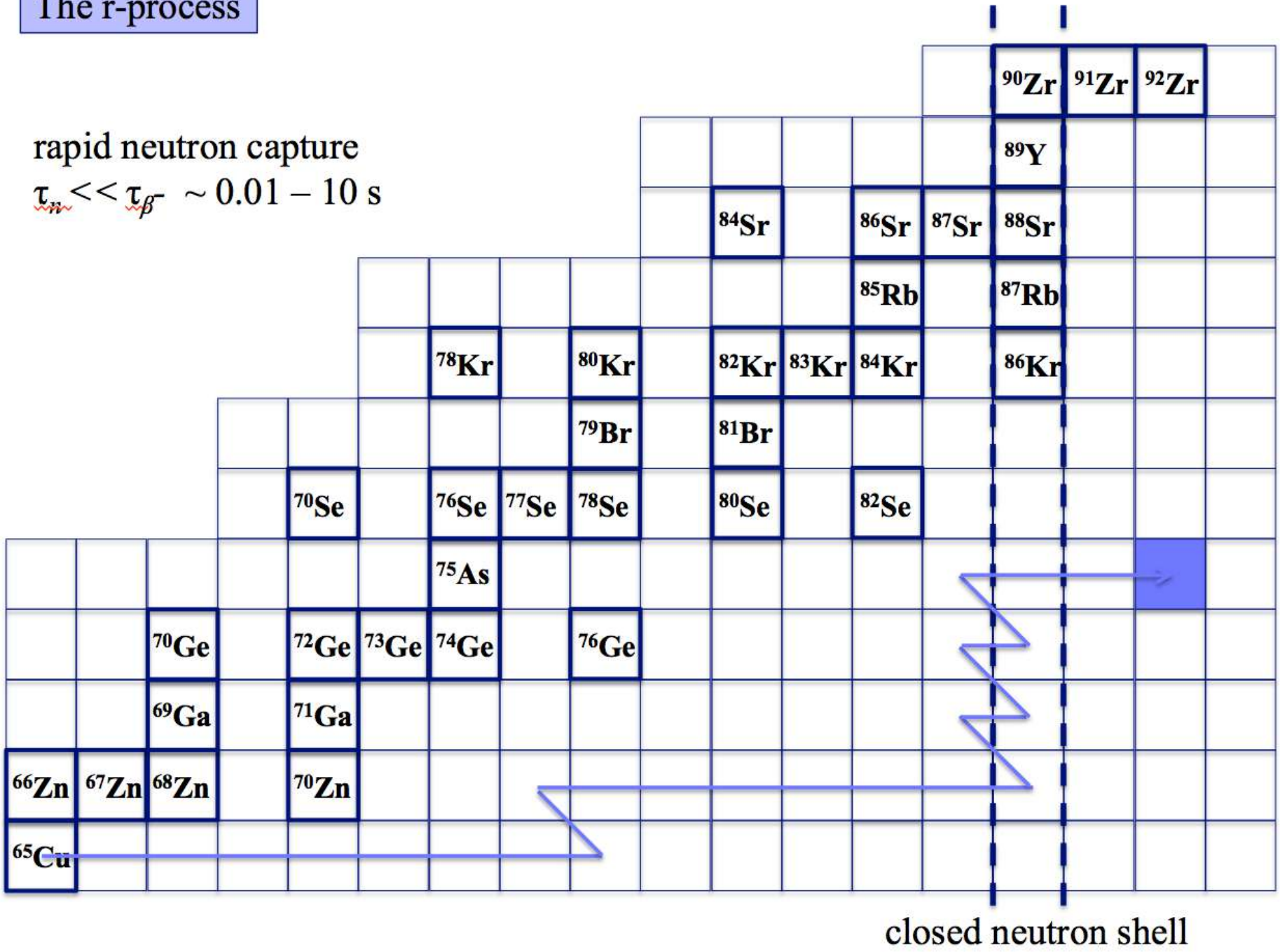
$\tau_n << \tau_{\beta^-}$ ~ 0.01 – 10 s



The r-process

rapid neutron capture

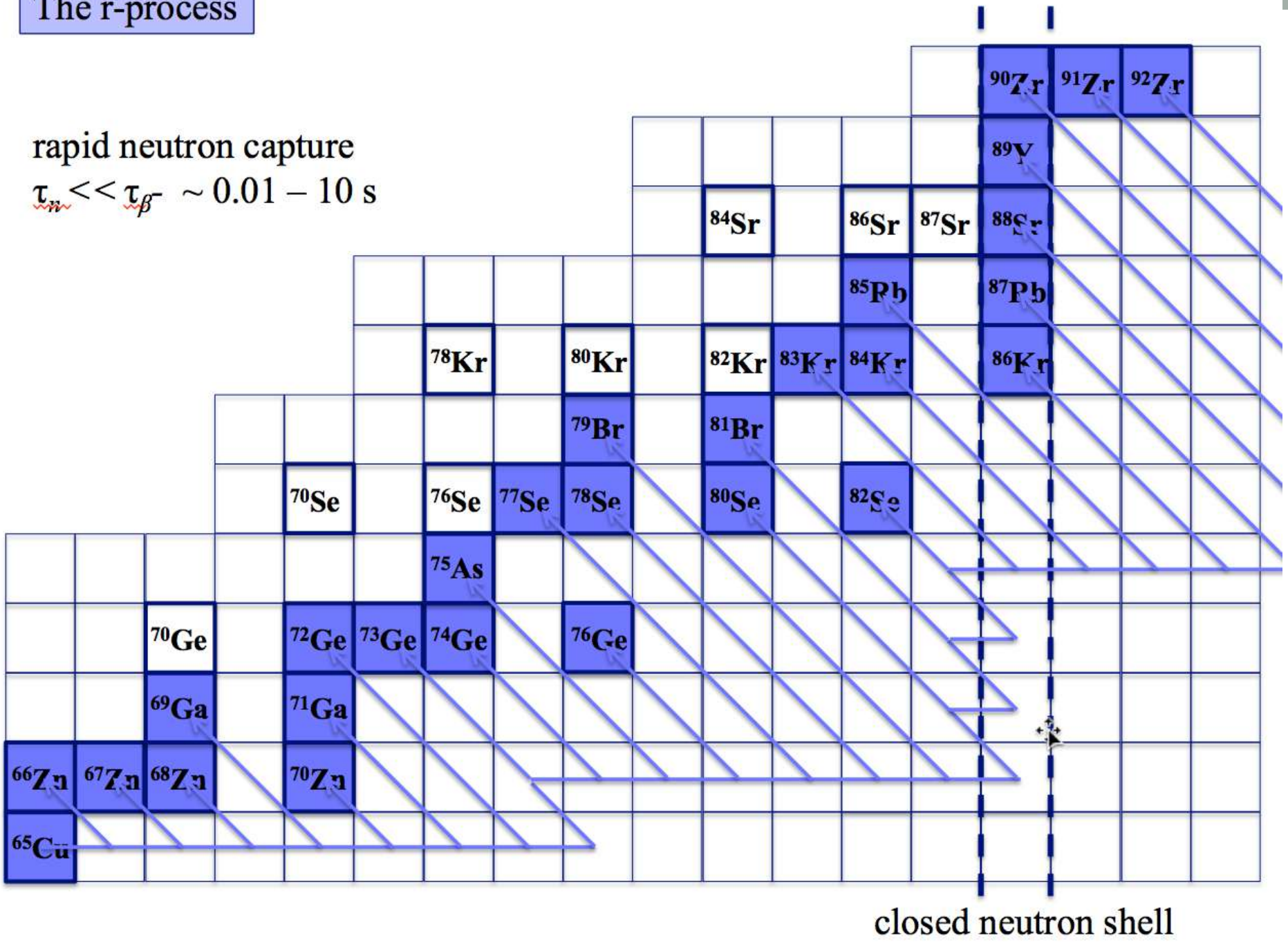
$\tau_n << \tau_{\beta^-}$ ~ 0.01 – 10 s



The r-process

rapid neutron capture

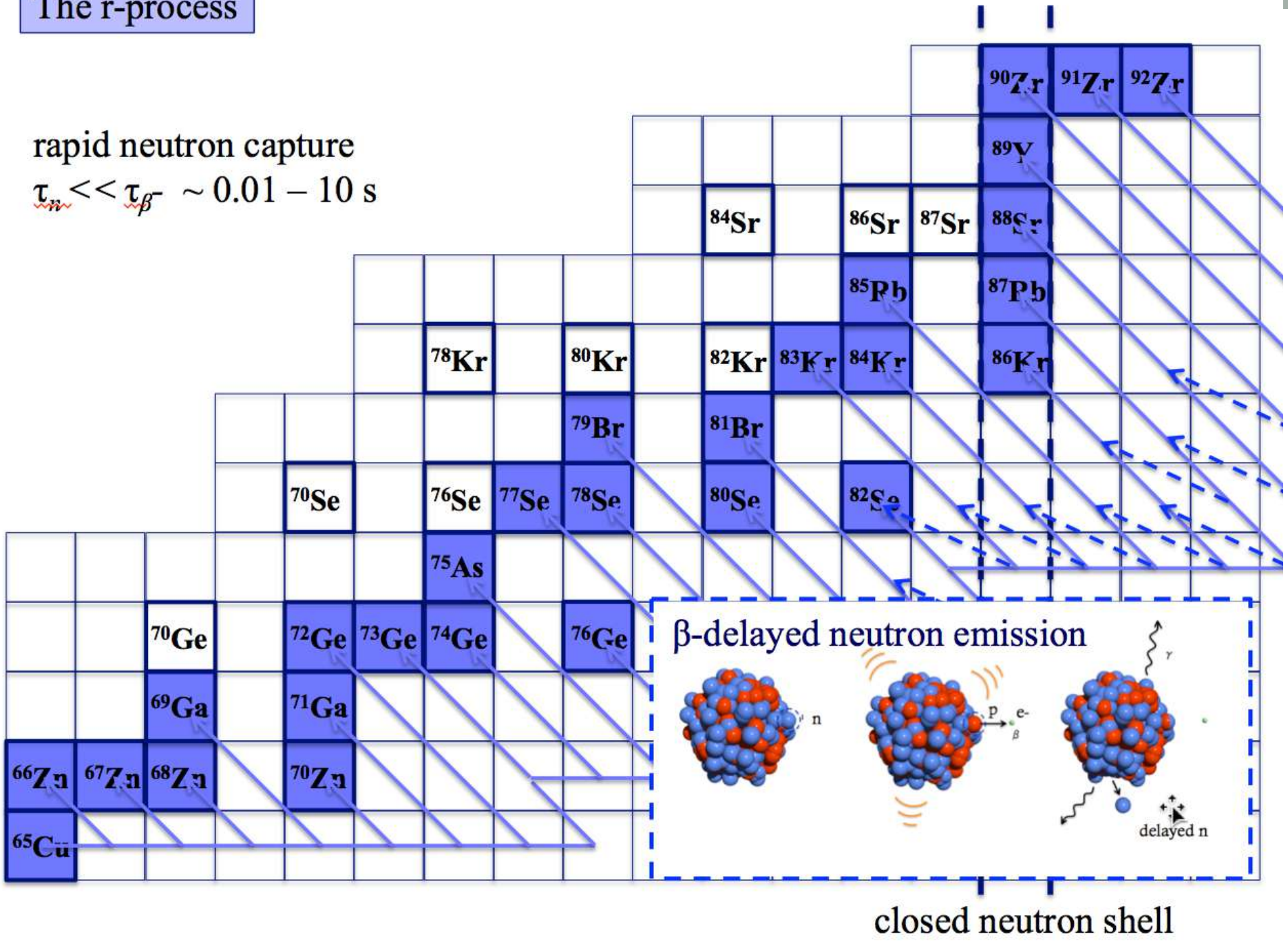
$\tau_n << \tau_{\beta^-}$ ~ 0.01 – 10 s



The r-process

rapid neutron capture

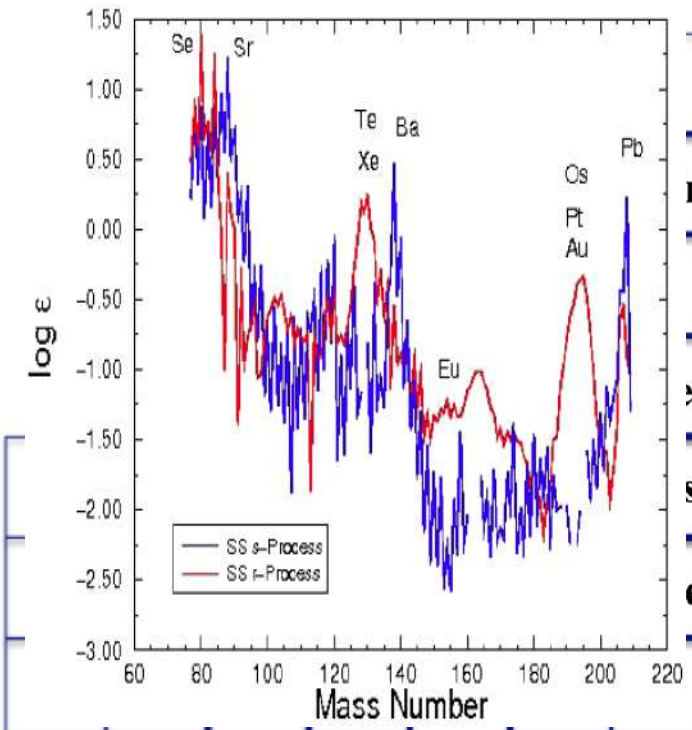
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



Double peaks due to closed neutron shells

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

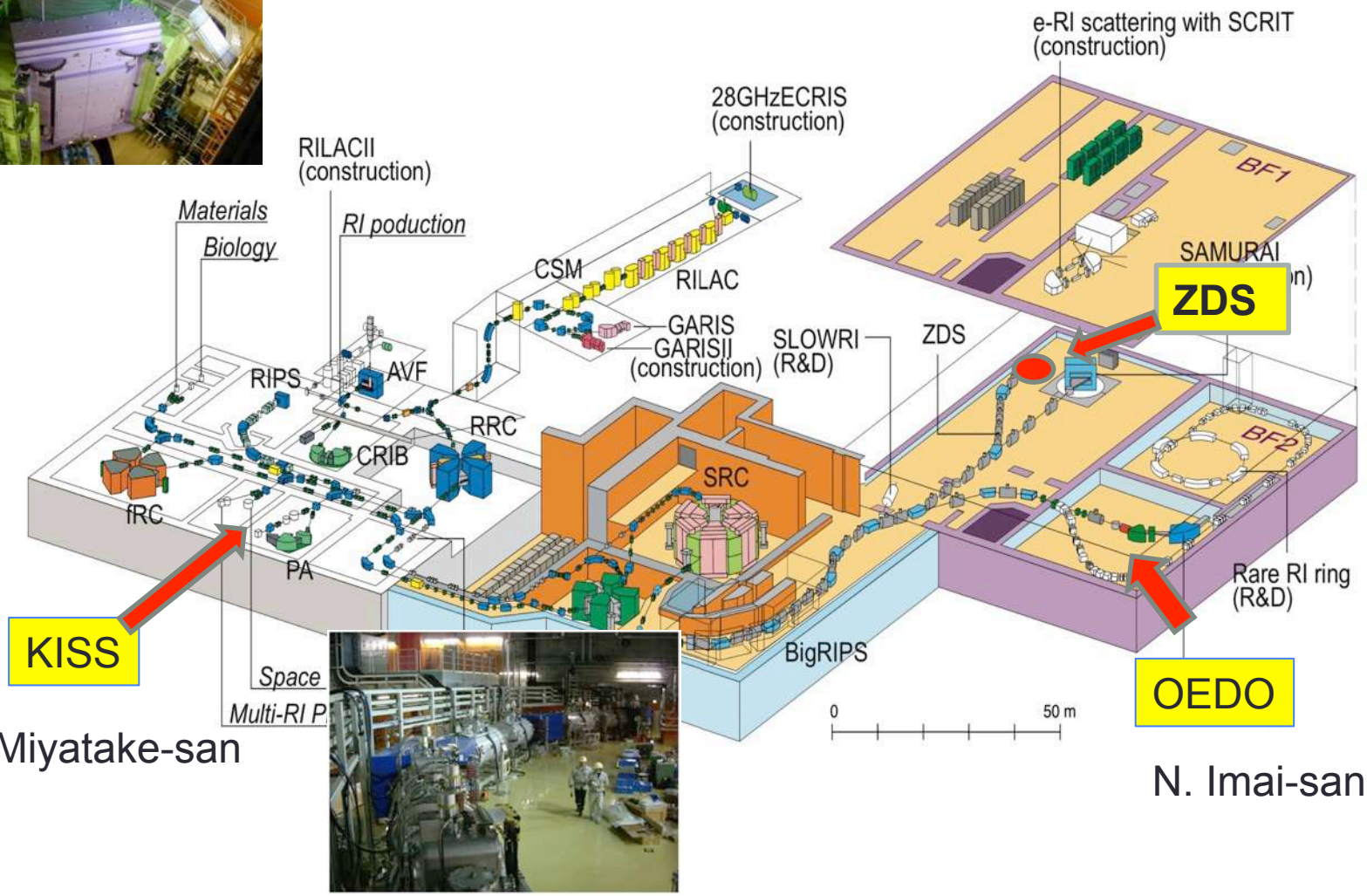
r-process: $\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



RI Production

Location of Decay Station at RIBF

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

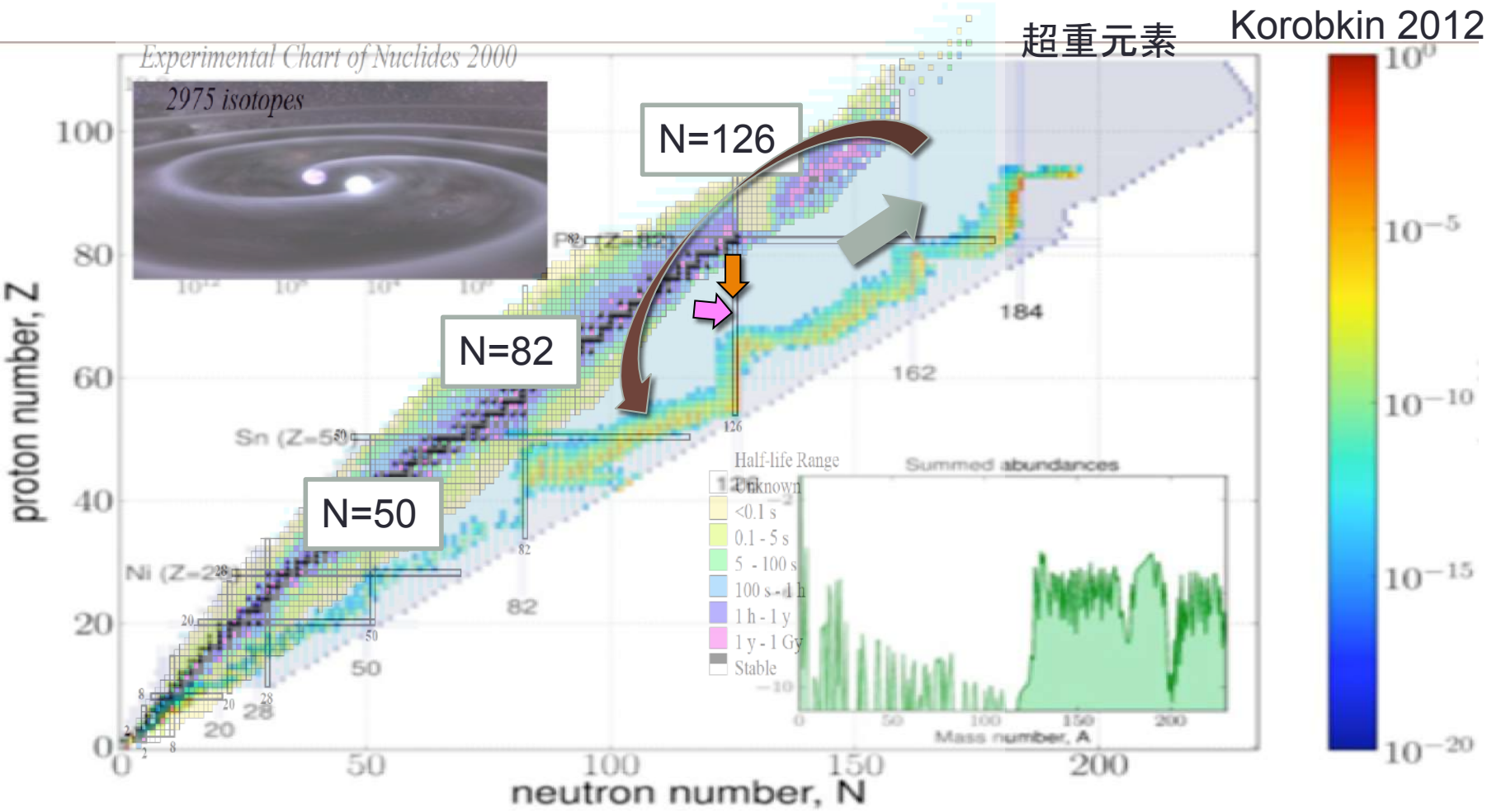


H. Miyatake-san

N. Imai-san

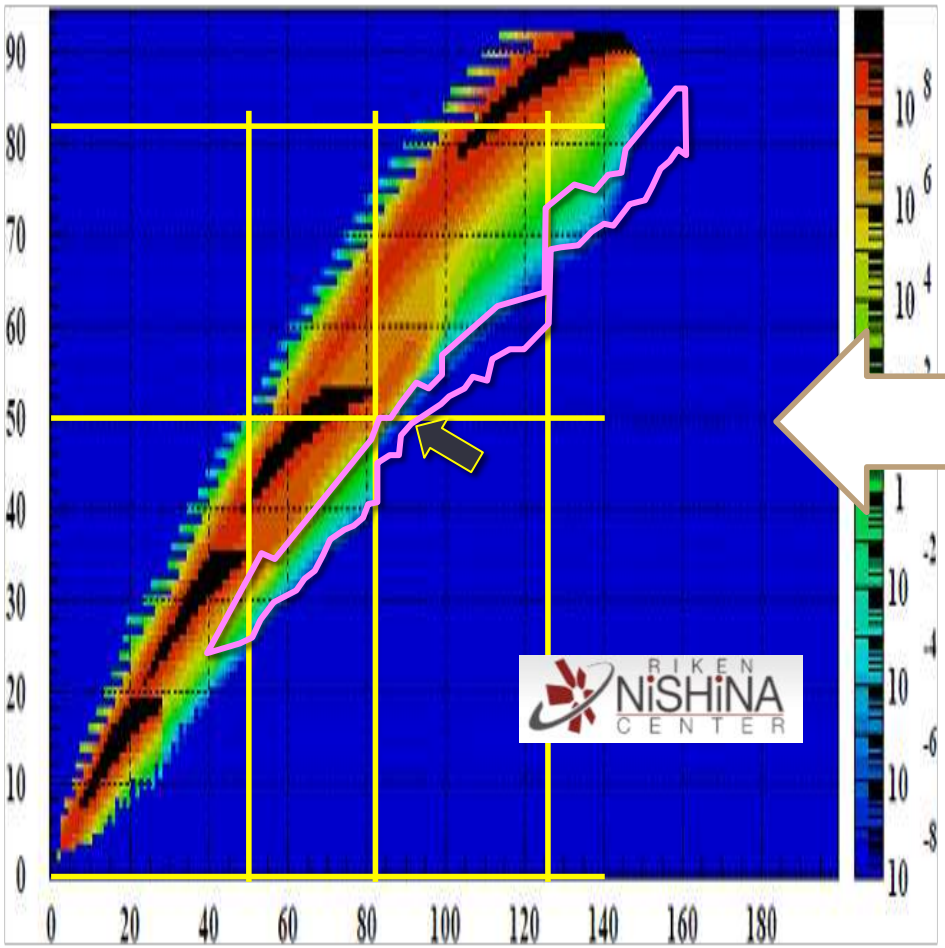
Question: Accessible r-nuclei

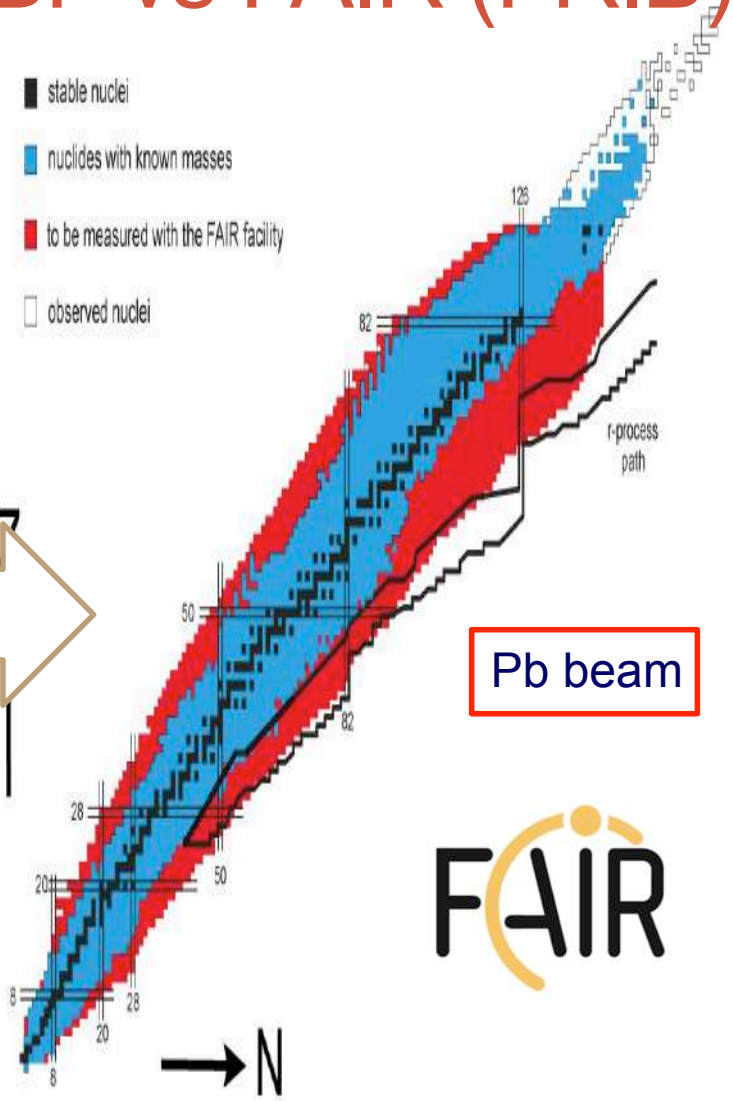
Which part of that nuclear physics data is already known, which part remains yet unmeasured, and which part will be accessible in the new RIB-facilities?



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

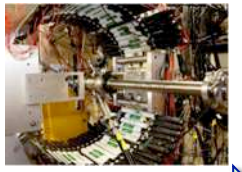
① 

Beta-gamma Campaign

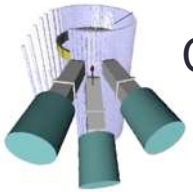
⑤ Ge-detector array from Lanzhou Gr. (IBS + Other Institutes?)

BRIKEN

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



VANDLE/HAGRID



CAITEN/NiGIRI/LaBr3(Ce) array

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

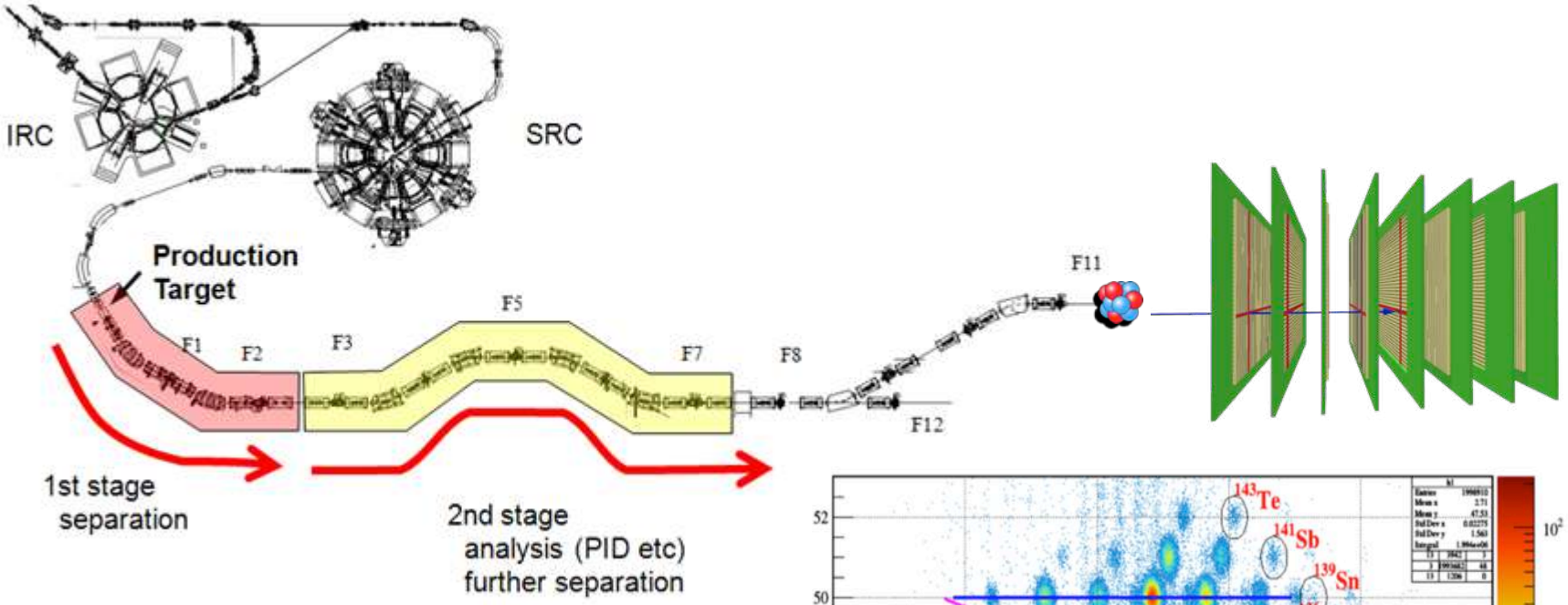
④ **Total absorption: γ energy spectra (E_γ)**

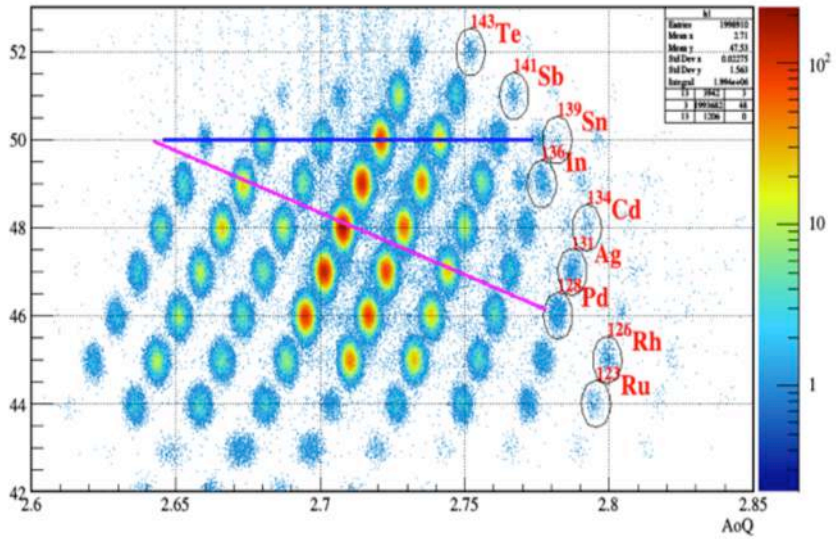
DTAS

⑥ Heavier RI N=126 and beyond!

MRTOF & β-TOF (Mass & Decay : R&D)

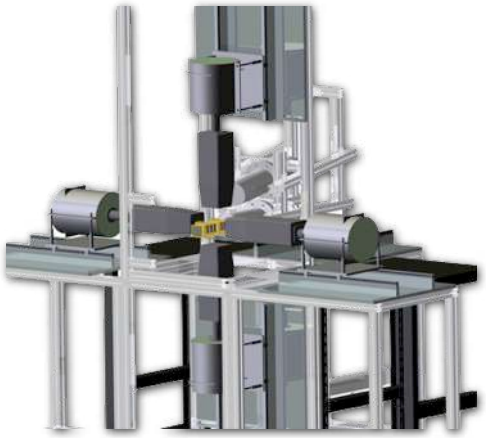
Beam Production & Decay Station

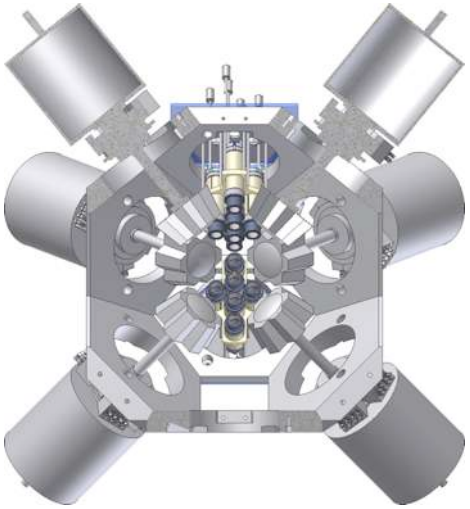




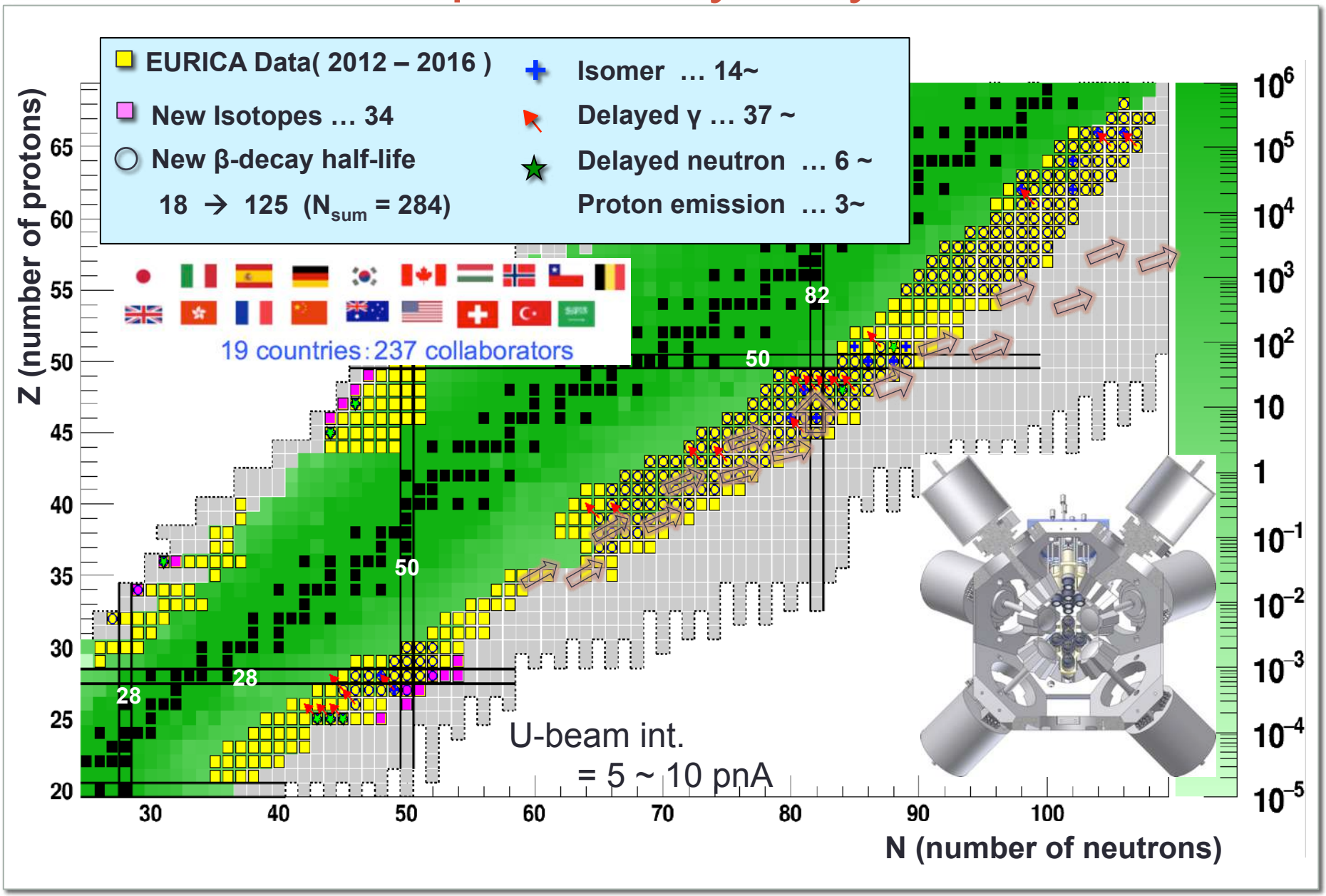
- The implantation of an identified RI is associated with the following β-decay events that are detected in the same silicon pixel (DSSSD).

Beta-gamma spectroscopy



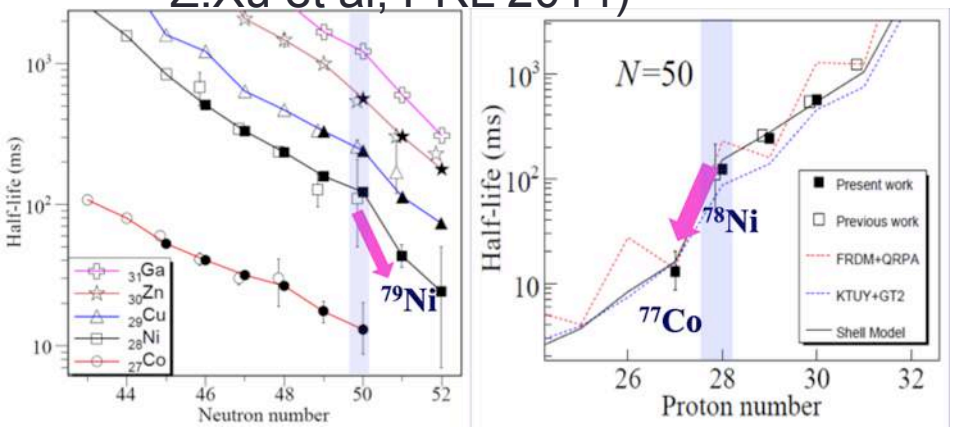


440 Exotic Isotopes Surveyed by EURICA

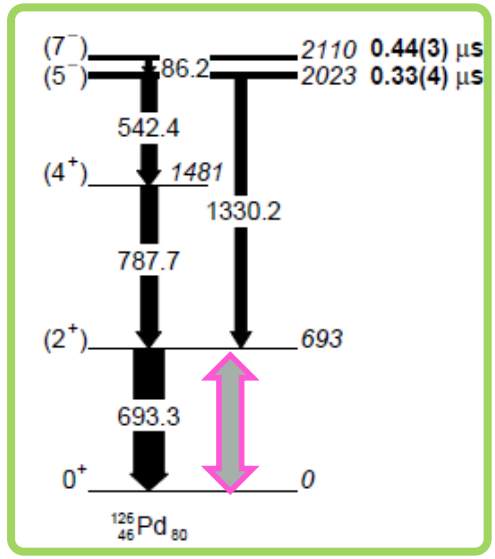


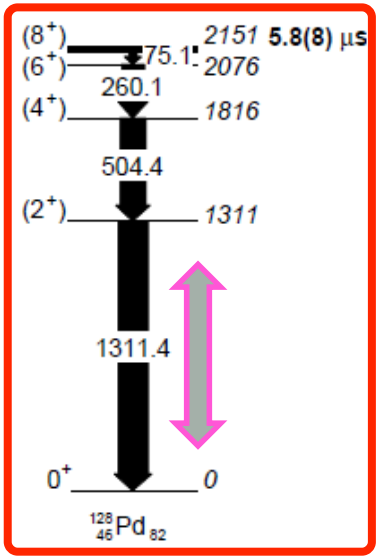
First Excited States of RI (Even-Z, Even-N)

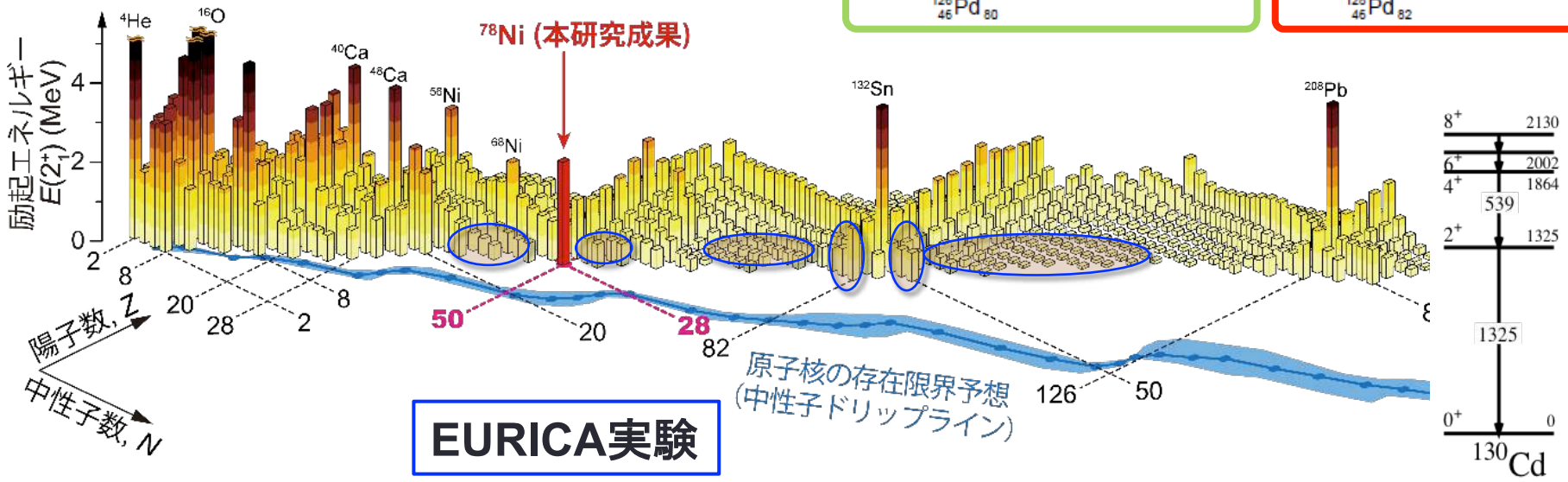
Z.Xu et al, PRL 2014)



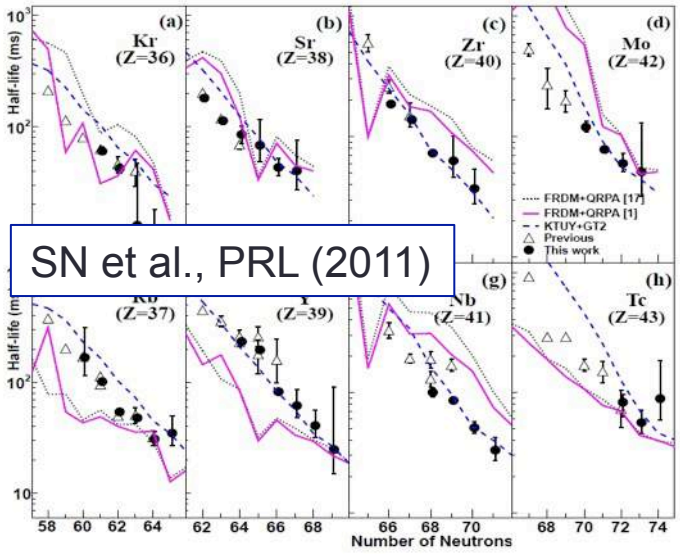
R. Taniuchi et al., Nature (2019)
In-beam gamma exp.



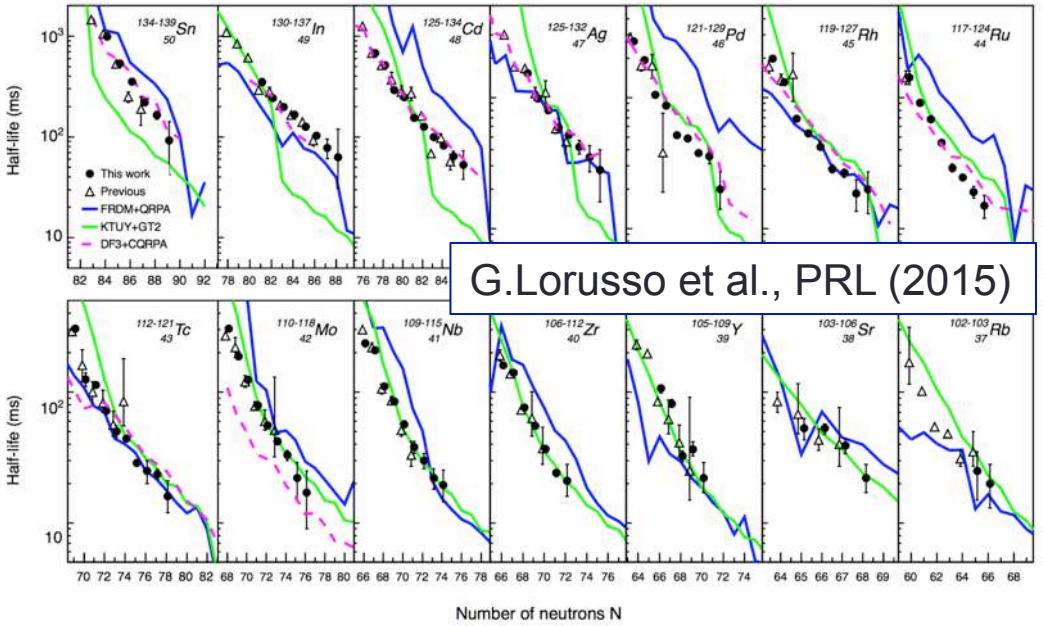




~284 Half-lives (New $T_{1/2}$ ~125) Measured at RIBF

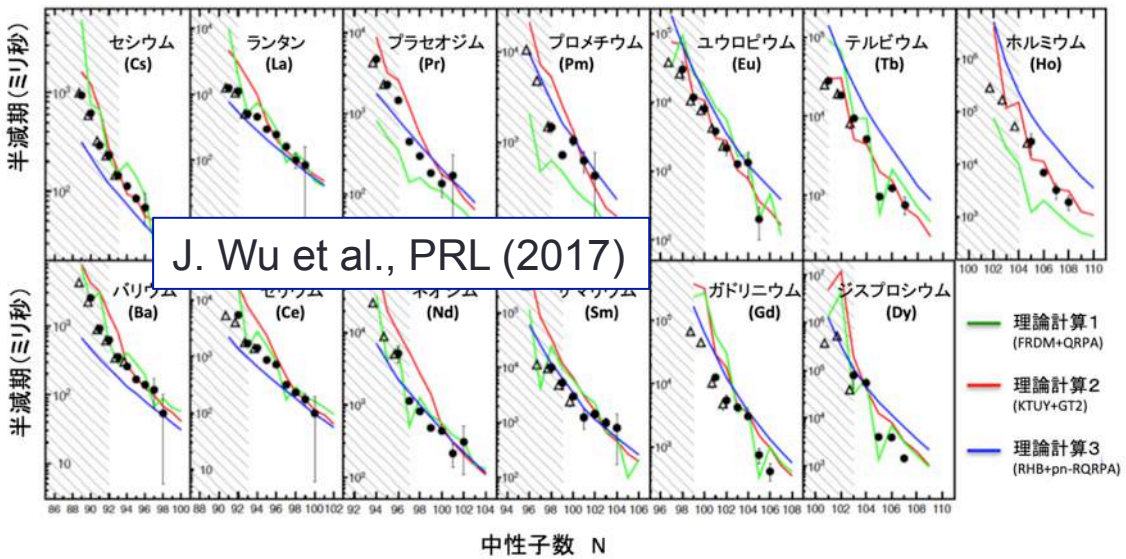


SN et al., PRL (2011)



G.Lorusso et al., PRL (2015)

半減期の中性子過剰度依存性　● 半減期（理研）　△ 既知の半減期



J. Wu et al., PRL (2017)

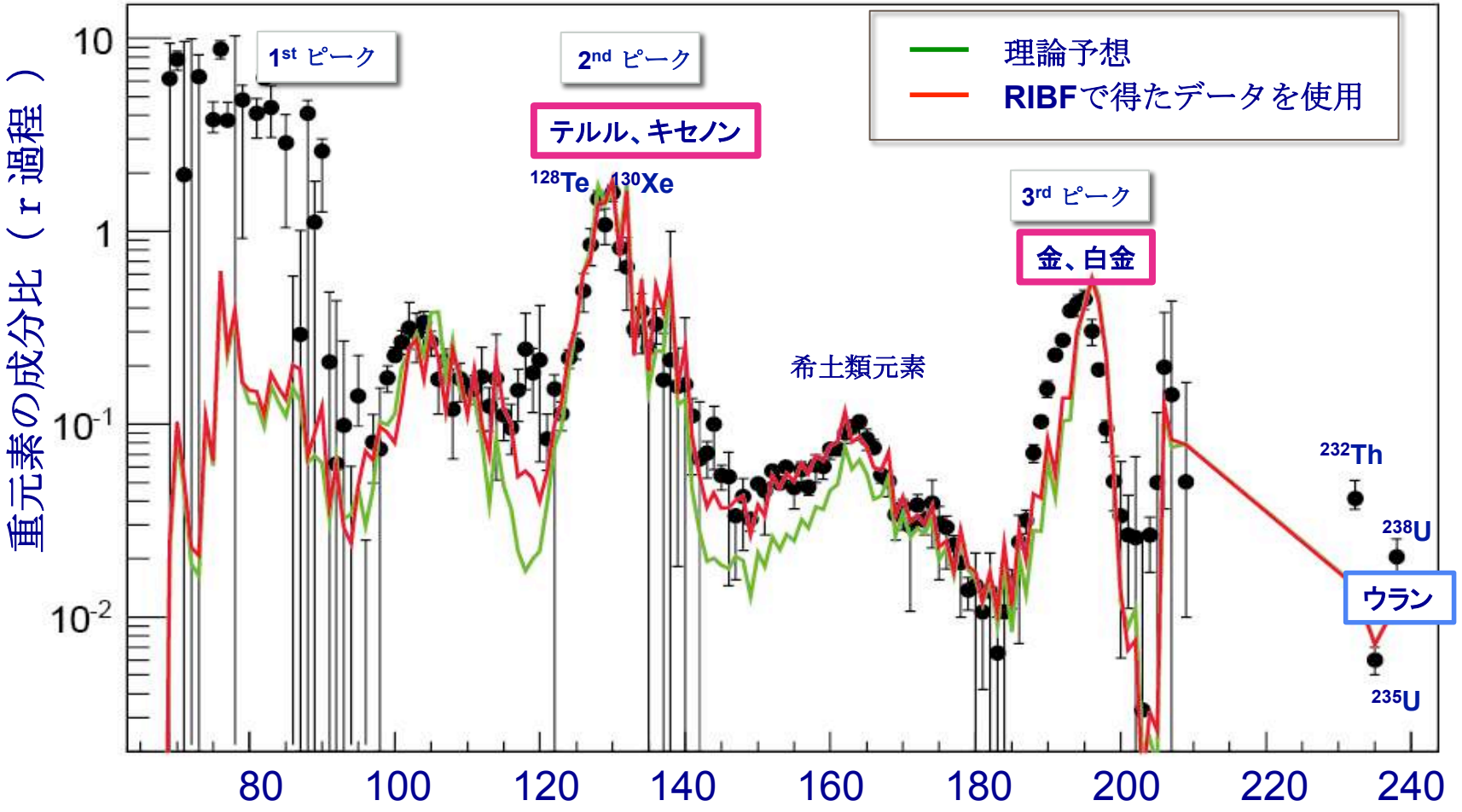
$$\frac{1}{T_{1/2}} = \sum_{0 \le E_i \le Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i),$$

lives (isotope)　β-strength function

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

Feedback to Network Calculation

G.Lorusso et al., PRL (2015)



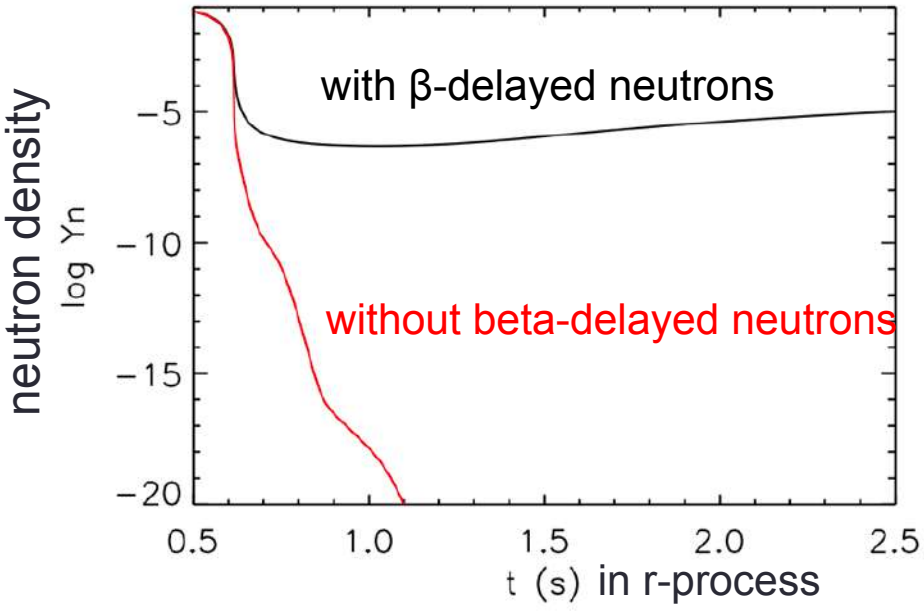
Assumption: Hot r-process
(n, γ) ⇄ (γ, n) equilibrium.

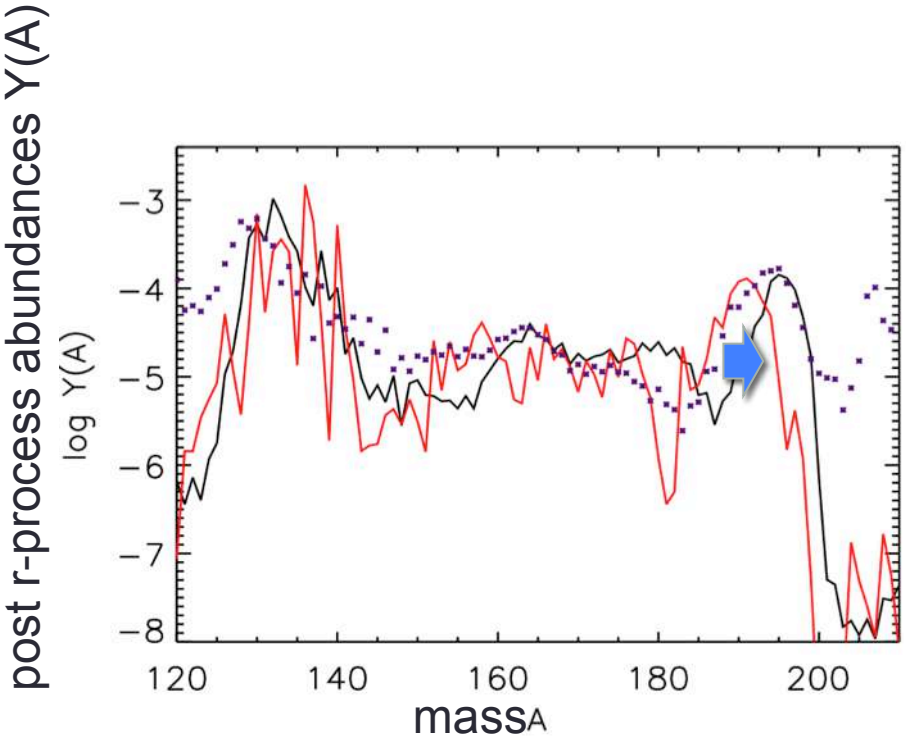
BRIKEN (2016 – 2021)

Beta-delayed neutron emission probabilities

Impact of β-delayed neutrons in R-Process

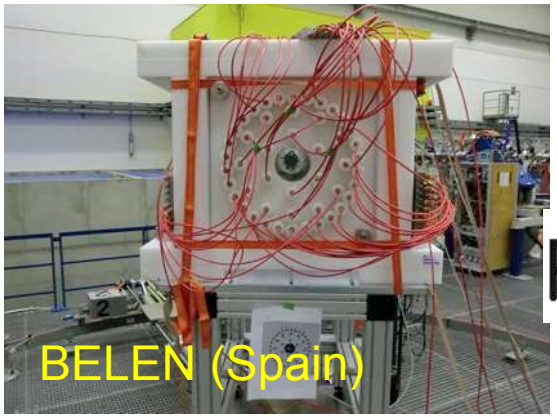
R. Surman, at Gordon conf., June 2013, at ARIS conf., June 2014





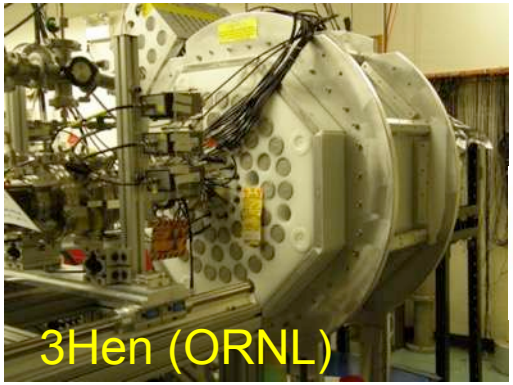
β-delayed neutron → (n, γ) reactions at freeze-out time

BRIKEN: Highest neutron detection eff.

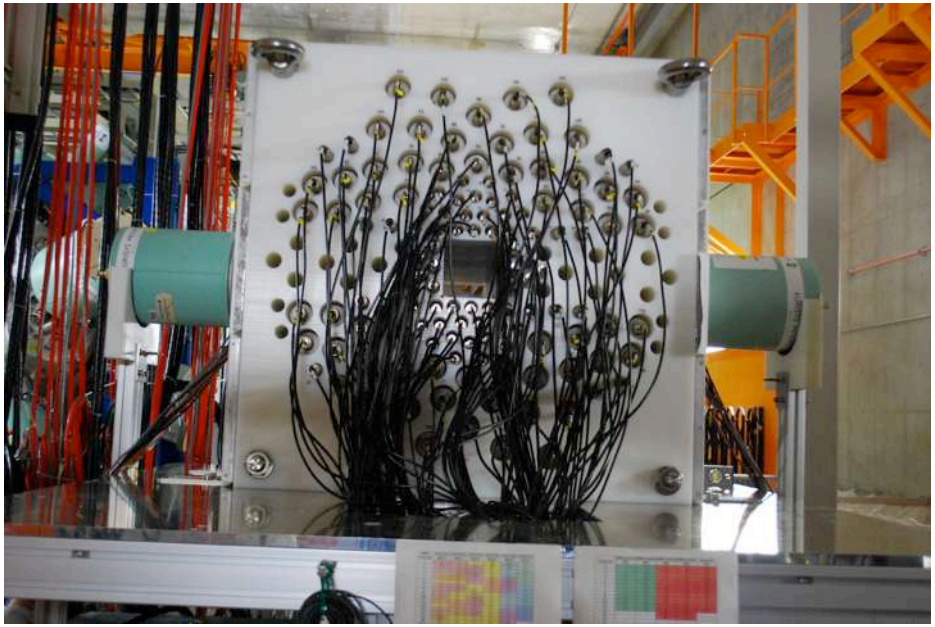


FAIR

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

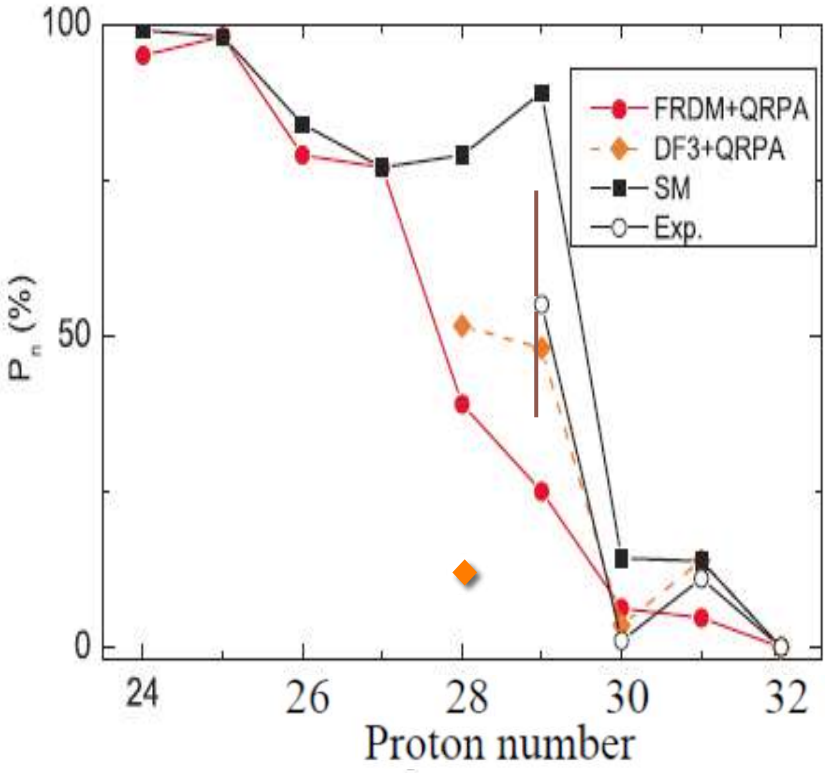
RIBF148 (Kiss) ... 6 days (+2 days..)

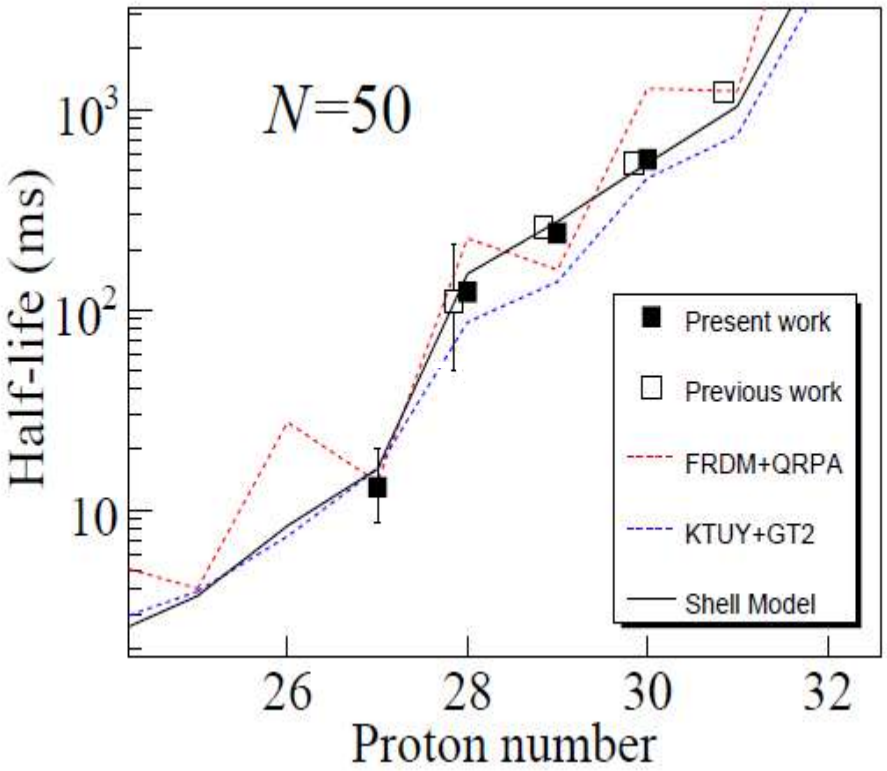
Total : ~ 34.5 days

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

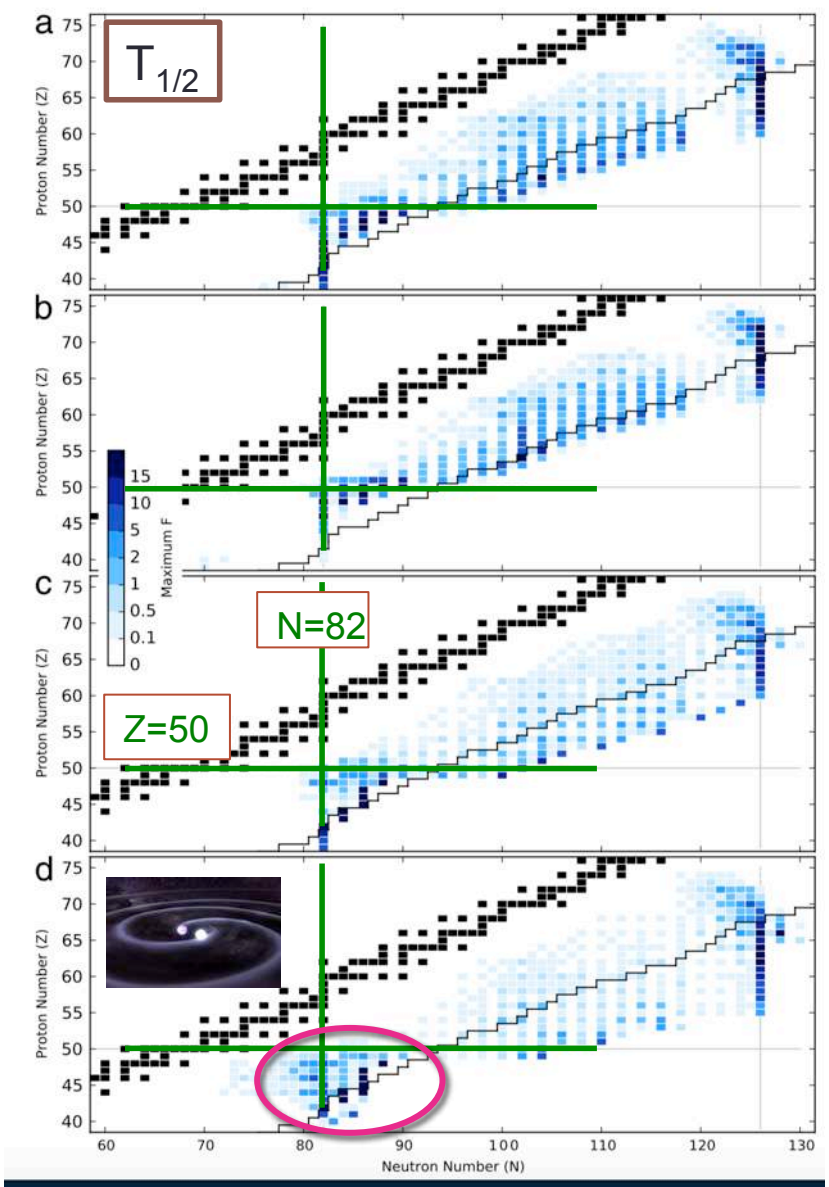
(Experiment ←→ Theory)

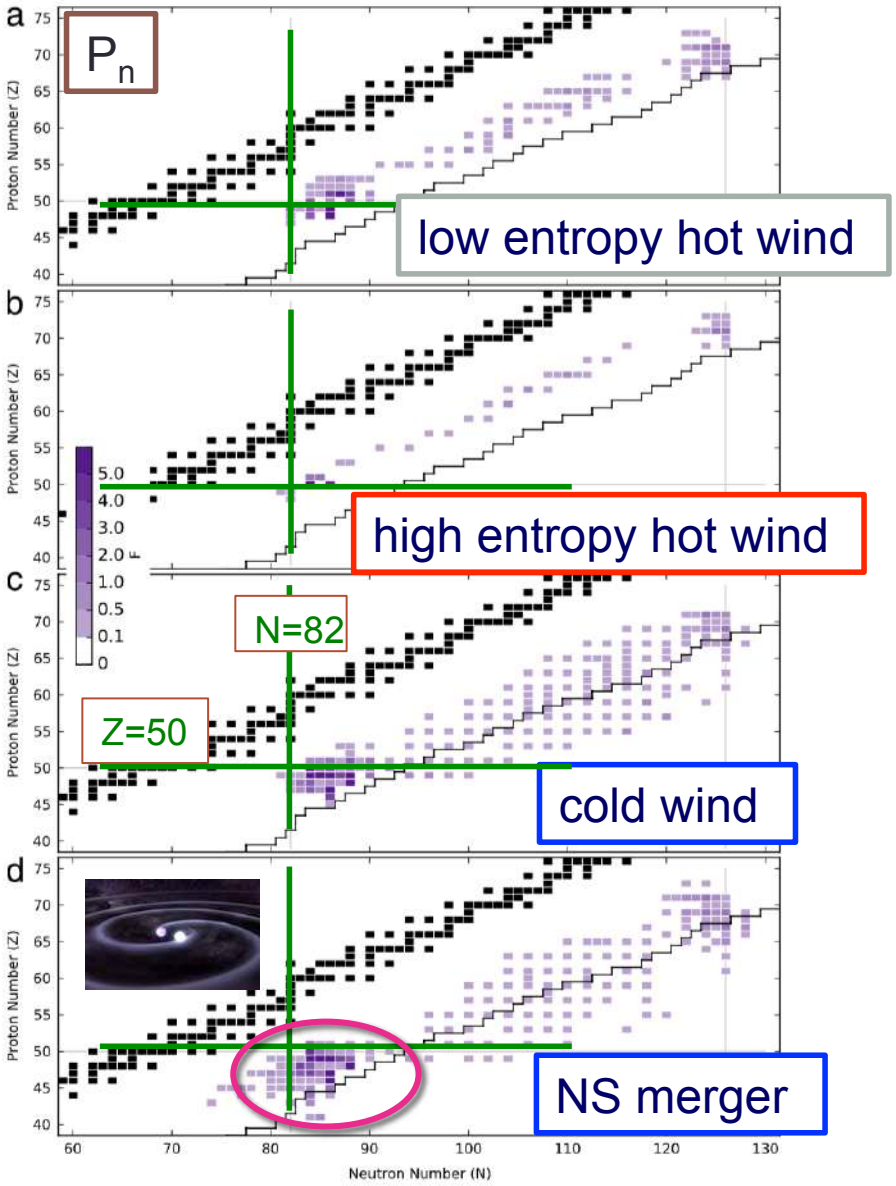
Z.Xu PhD thesis (2014)



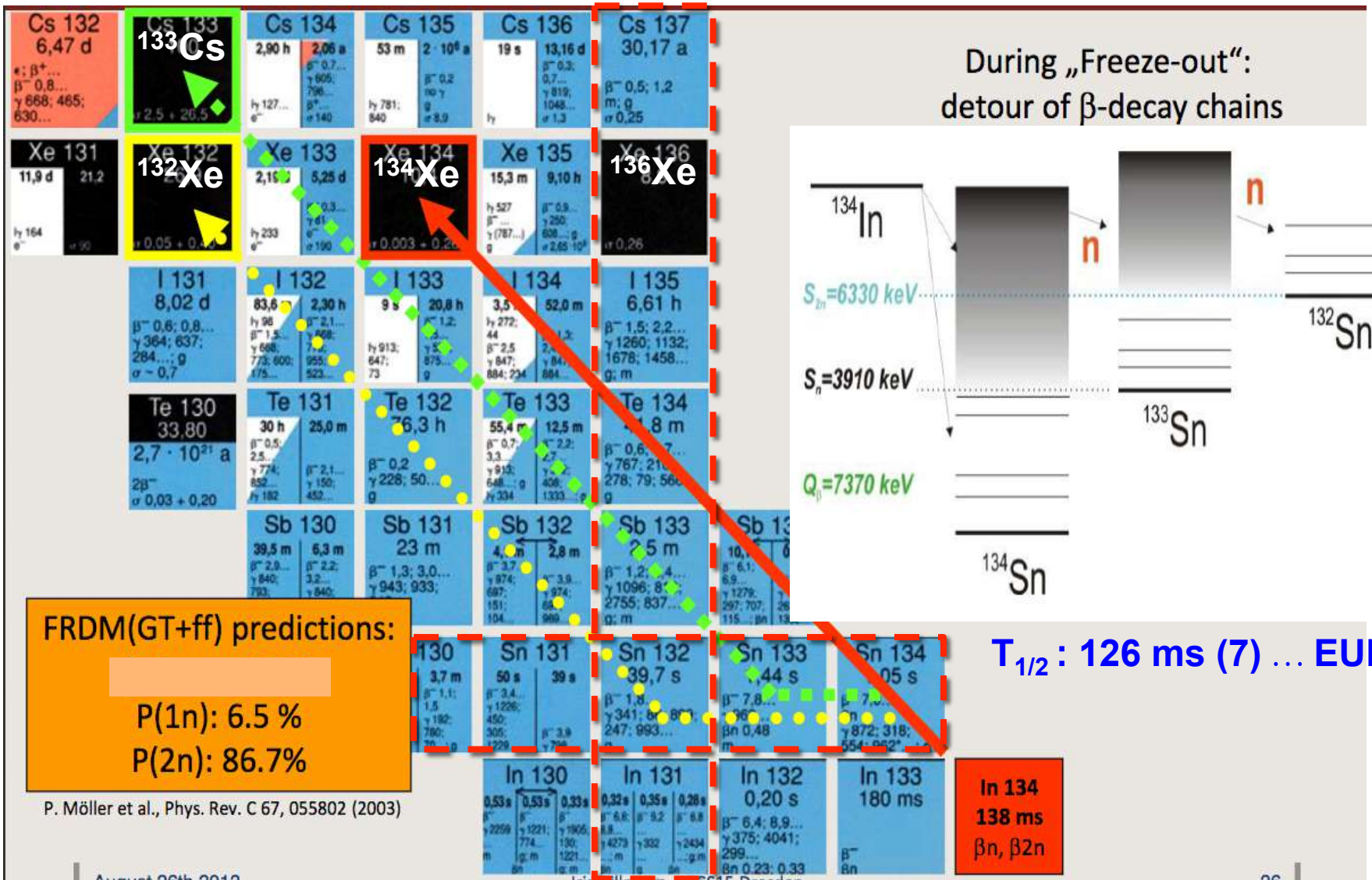


Sensitivity Study of Decay Properties in r-Process



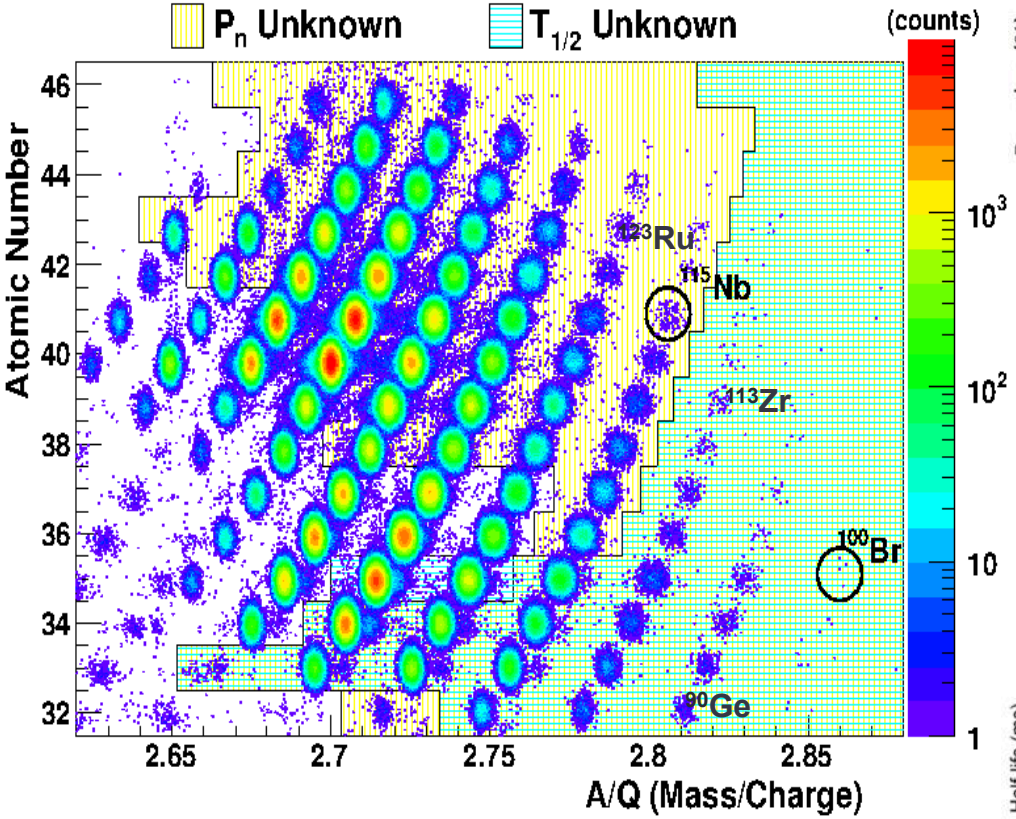


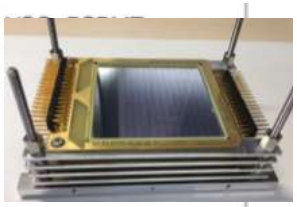
M.R. Mumpower et al.(2016)


During „Freeze-out“:
detour of β-decay chains
^{134}In
S_{2n}=6330 keV
S_n=3910 keV
Q_β=7370 keV
^{134}Sn
^{133}Sn
^{132}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

BRIKEN 2017 Nov.

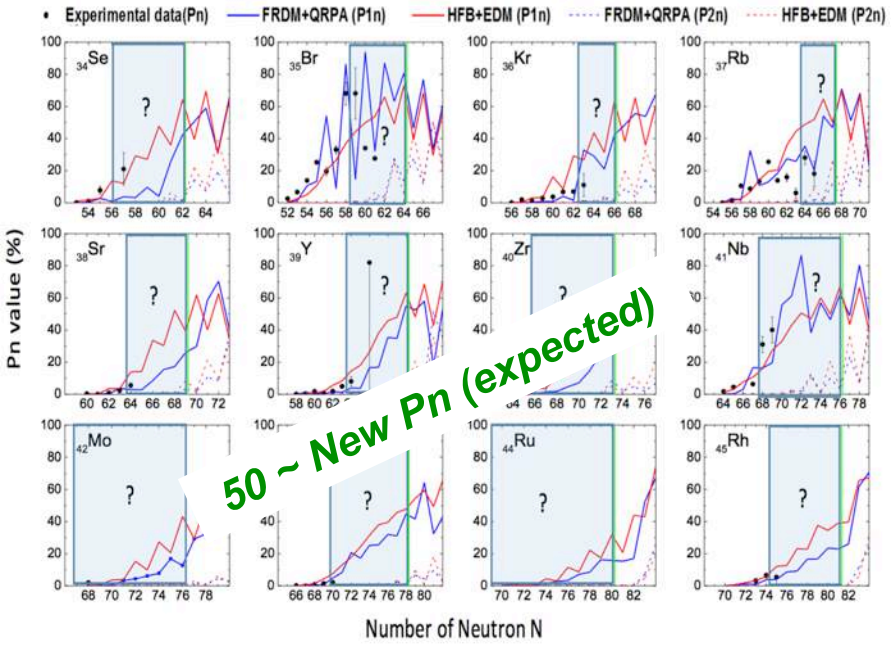
Spokespersons: S. Nishimura (RIKEN), A. Algora (IFIC-CSIC) 5.5 days

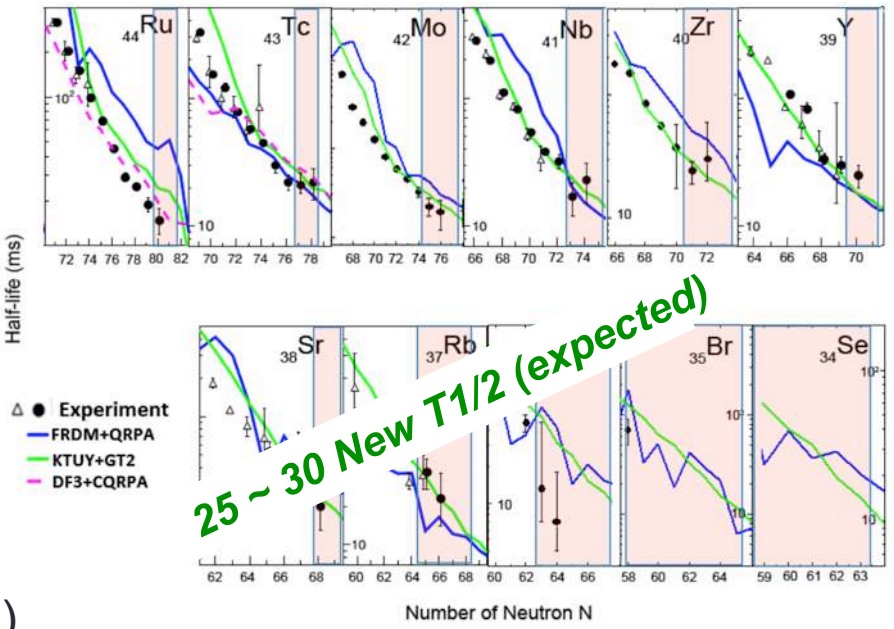




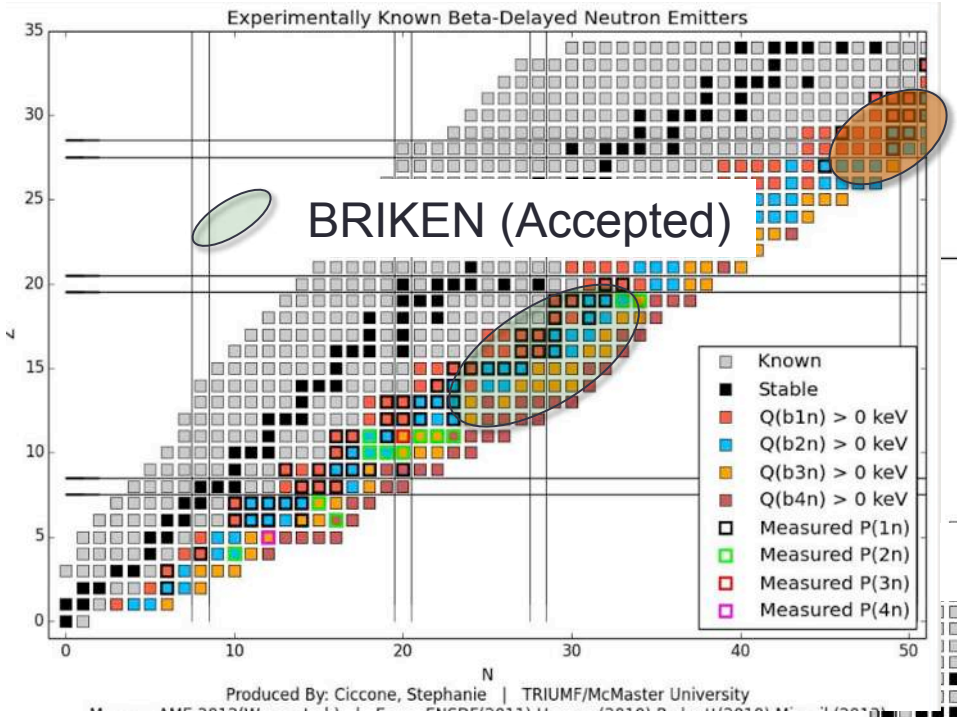
WAS3ABi (Si)
YSO (U.Tennessee)

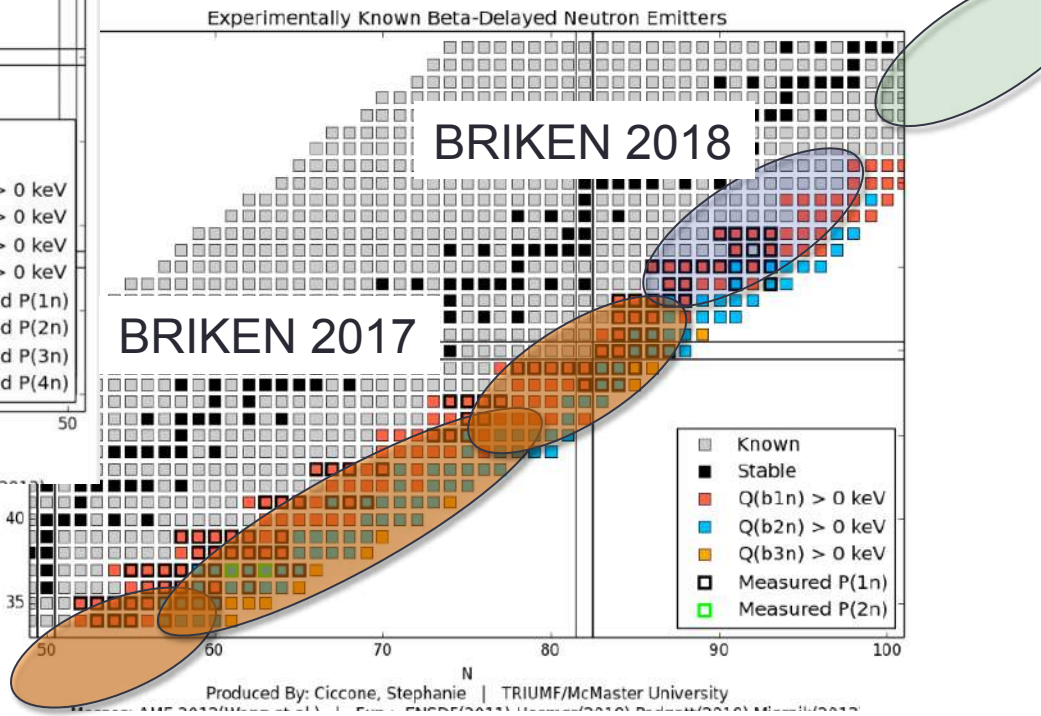
7 isomers (known)
6 isomers (unknown)





Summary of BRIKEN @ RIBF



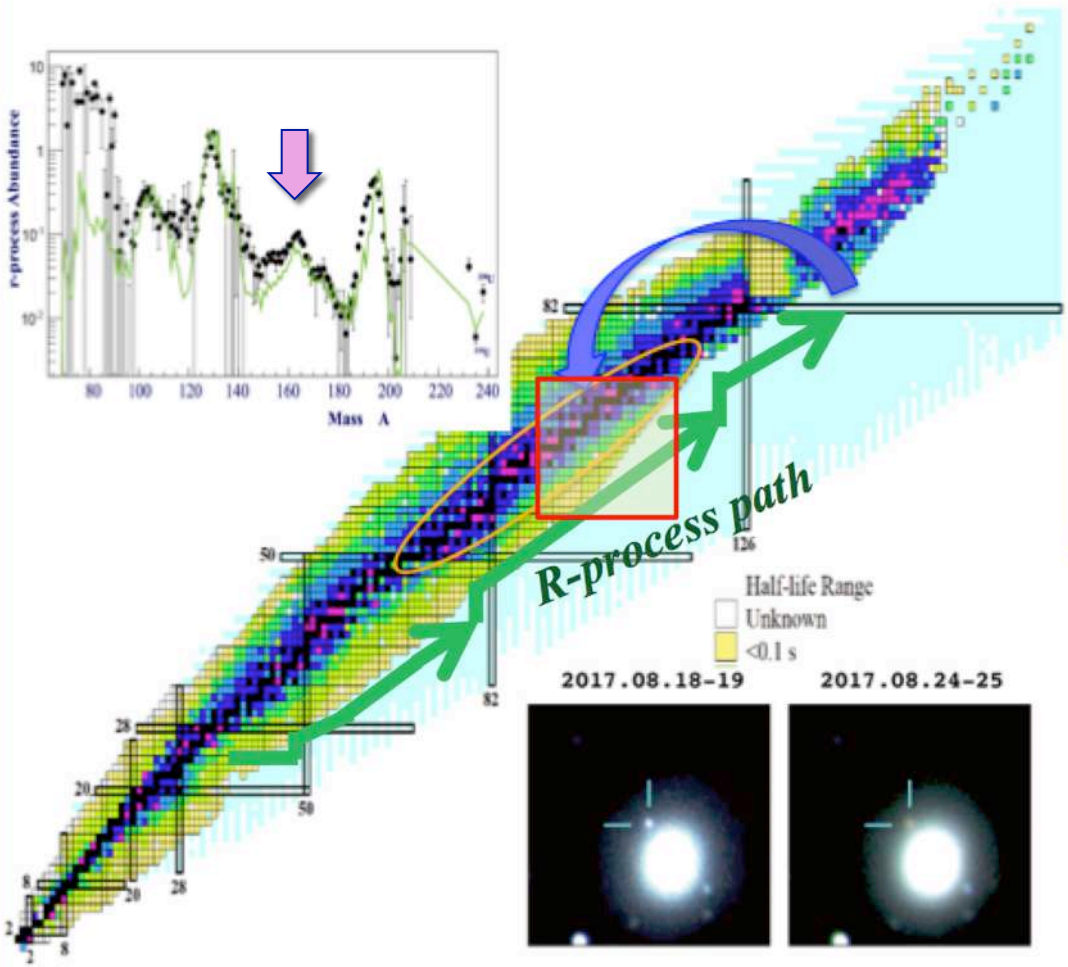


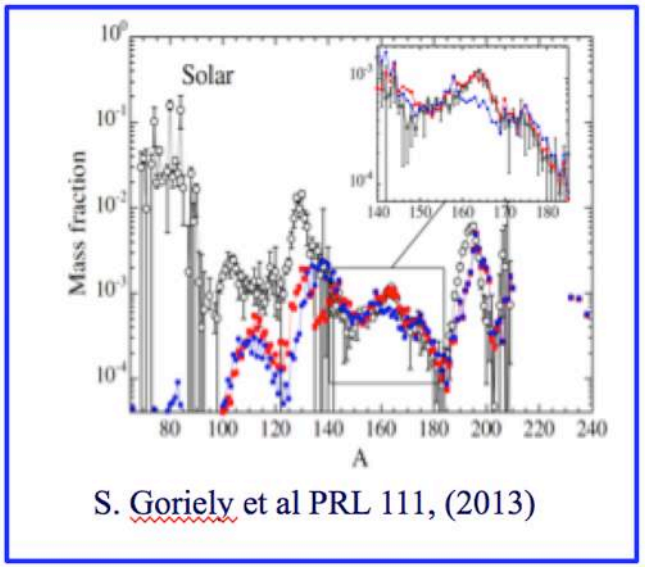
- 284 (→ ~ 340) $T_{1/2}$
- 6 (→ ~ 150) P_n, P_{2n}, ..
- Excited States, Isomers
- Magic / Deformation

Survey of decay properties is in progress.

Decay Spectroscopy toward Heavier RI

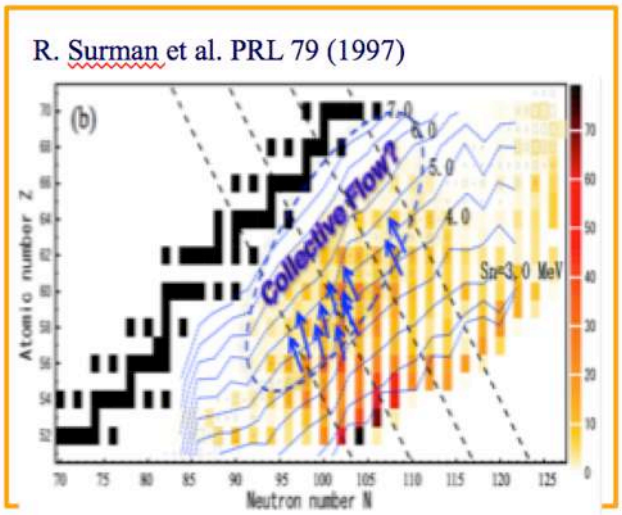
Origin of Rare-Earth Elements



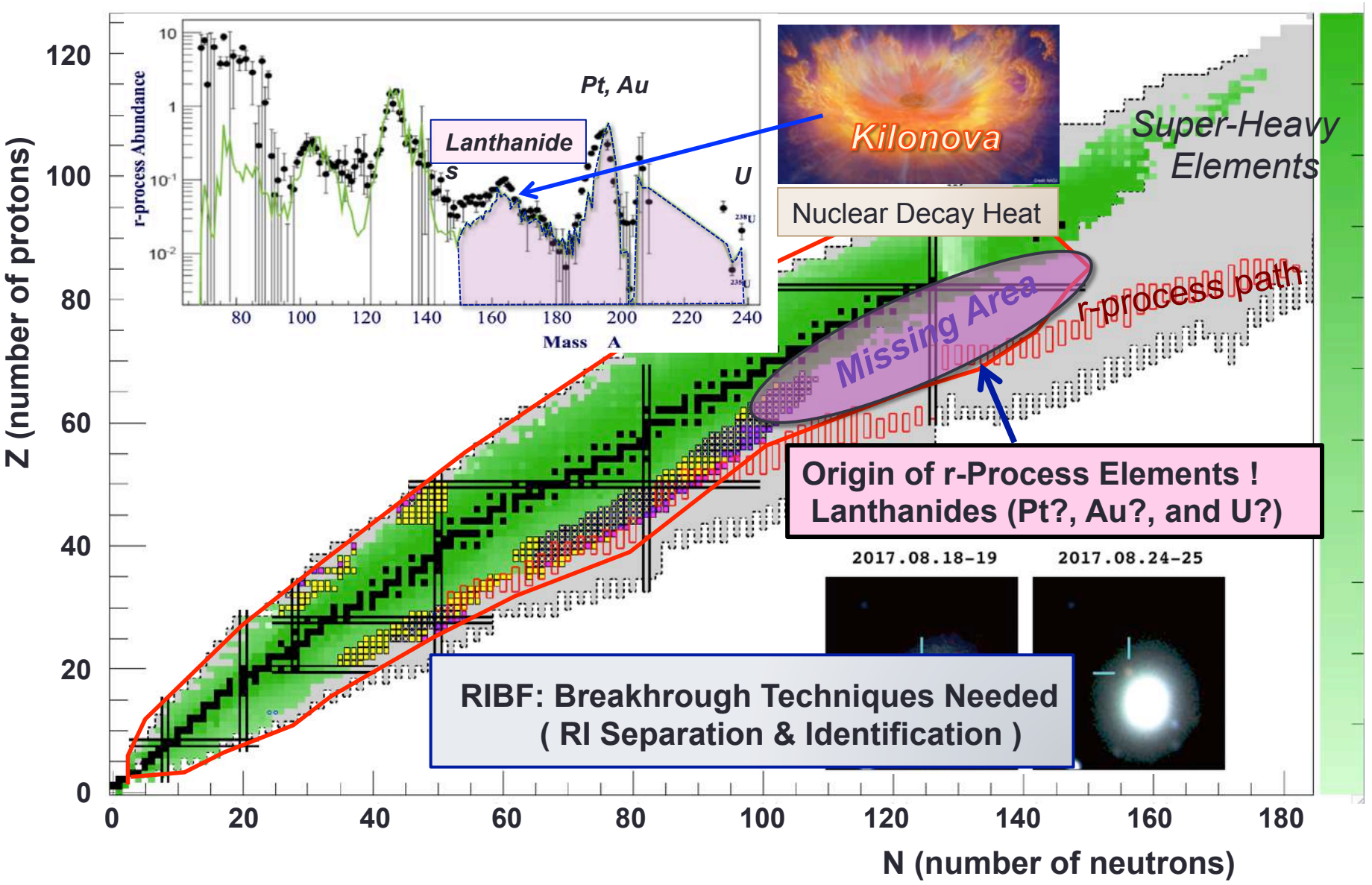


S. Goriely et al PRL 111, (2013)

R. Surman et al. PRL 79 (1997)

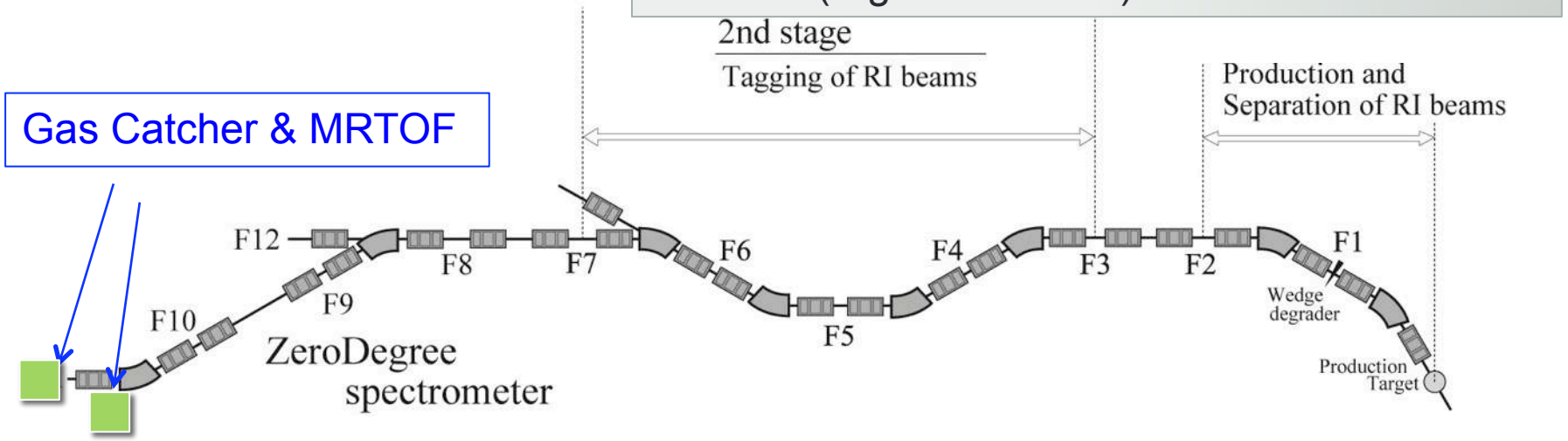


3rd r-Process Peak (N = 126 Region)



Decay Program with ZD-MRTOF

N~126 …. Upgrade of detectors & Better Optics
(BigRIPS – ZDS)



- BigRIPS/ZDS Experiments → MRTOF (Symbiotic Collaboration)
  - In-beam, New isotopes, Interaction cross-section, Decay & Mass

Workshop 2018 Sep. for Gas-Cell & MRTOF development with exotic nuclei

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

Summary

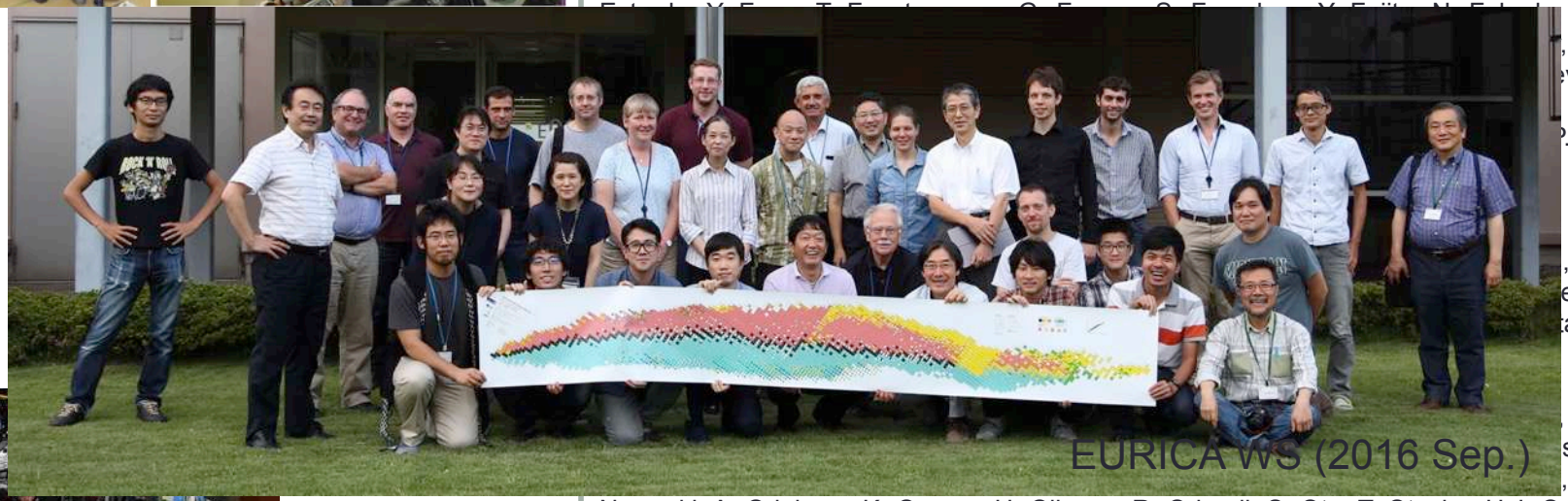
- ✓ **Beta-gamma spectroscopy 2009, 2012-2016,**
  - ✓ **Successful Campaigns with EURICA (~ 100 days)**
    Cluster Detectors are shipped back to GSI

  - ✓ **Beta-Neutron & gamma spectroscopy in progress**
    - ✓ **Successful Campaigns with BRIKEN (~35 days)**

    → 284 (EURICA) → ~ 340 $T_{1/2}$, 6 (EURICA) → ~150 P_{xn}

  - ✓ **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

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PreSPEC, GSI, IBS-RISP

Acknowledgement: Gammapool, Preepc, IBS

BRIKEN collaboration (November 2017)

~ 60 collaborators in total