08 June, 2018

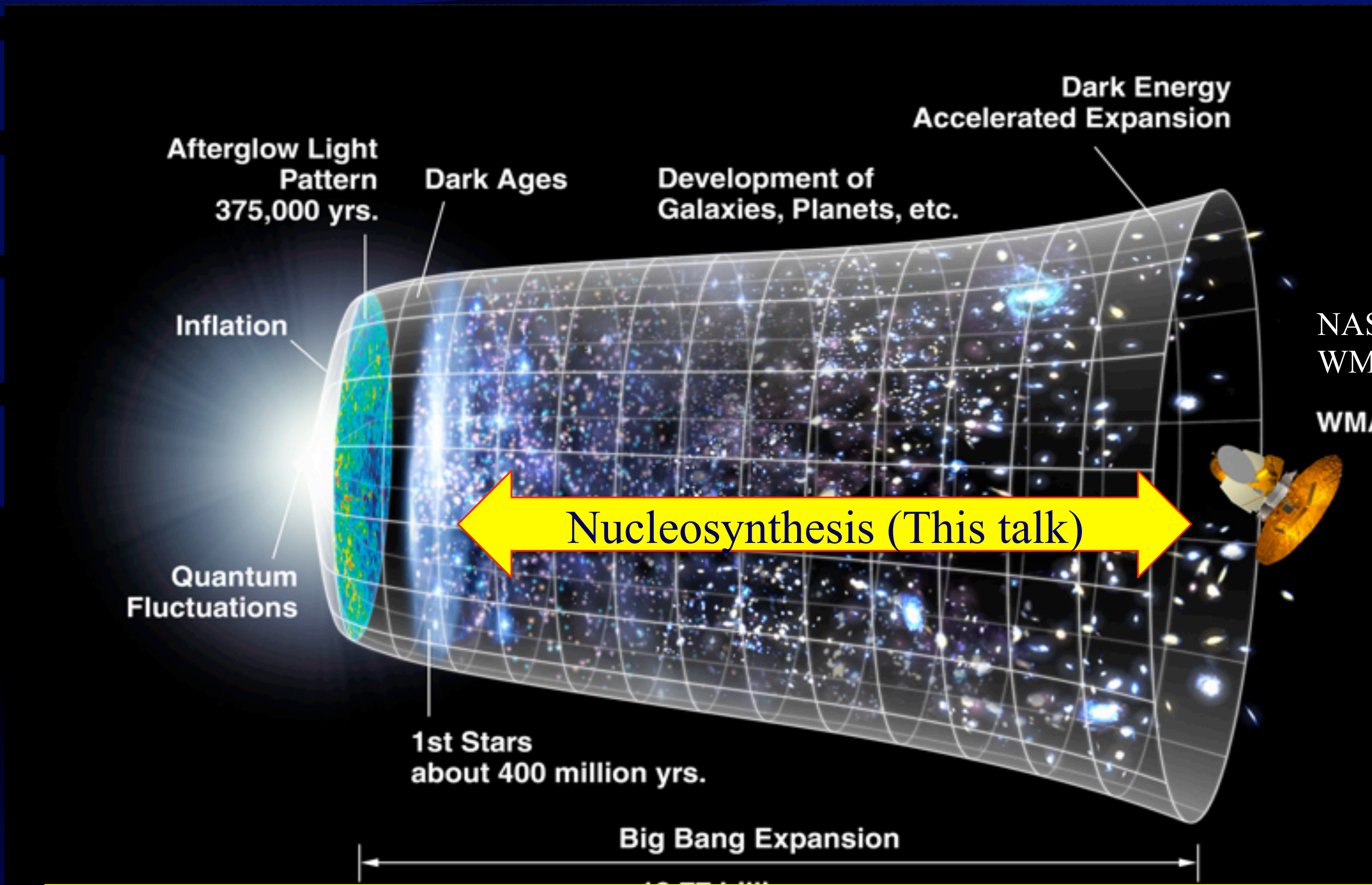
EMMI Rapid Reaction Task Force: The physics of neutron star mergers at GSI/FAIR

Experimental challenges relevant to the r-process

Shunji NISHIMURA

RIKEN Nishina Center

History of Universe



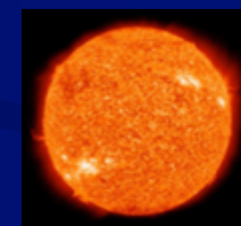
Extreme Conditions (Stars, Neutron-star, Black-hole)
Explosion: Big Bang, Supernova, X-ray bursts, γ-ray bursts, Collisions of Stars
Matters & Reactions: Equation of State (EOS), Nucleosynthesis

Nucleosynthesis in Universe

Big Bang

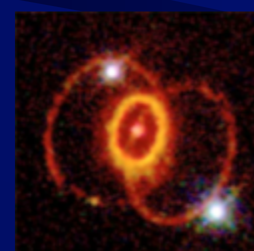
Get Together

Gravitational Force



Star

Nucleosynthesis up to iron

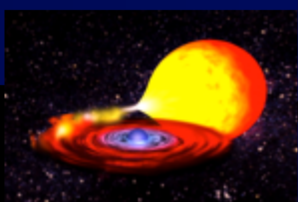


Supernovae

Nucleosynthesis heavier than iron

Scatter Ashes

Interstellar Material

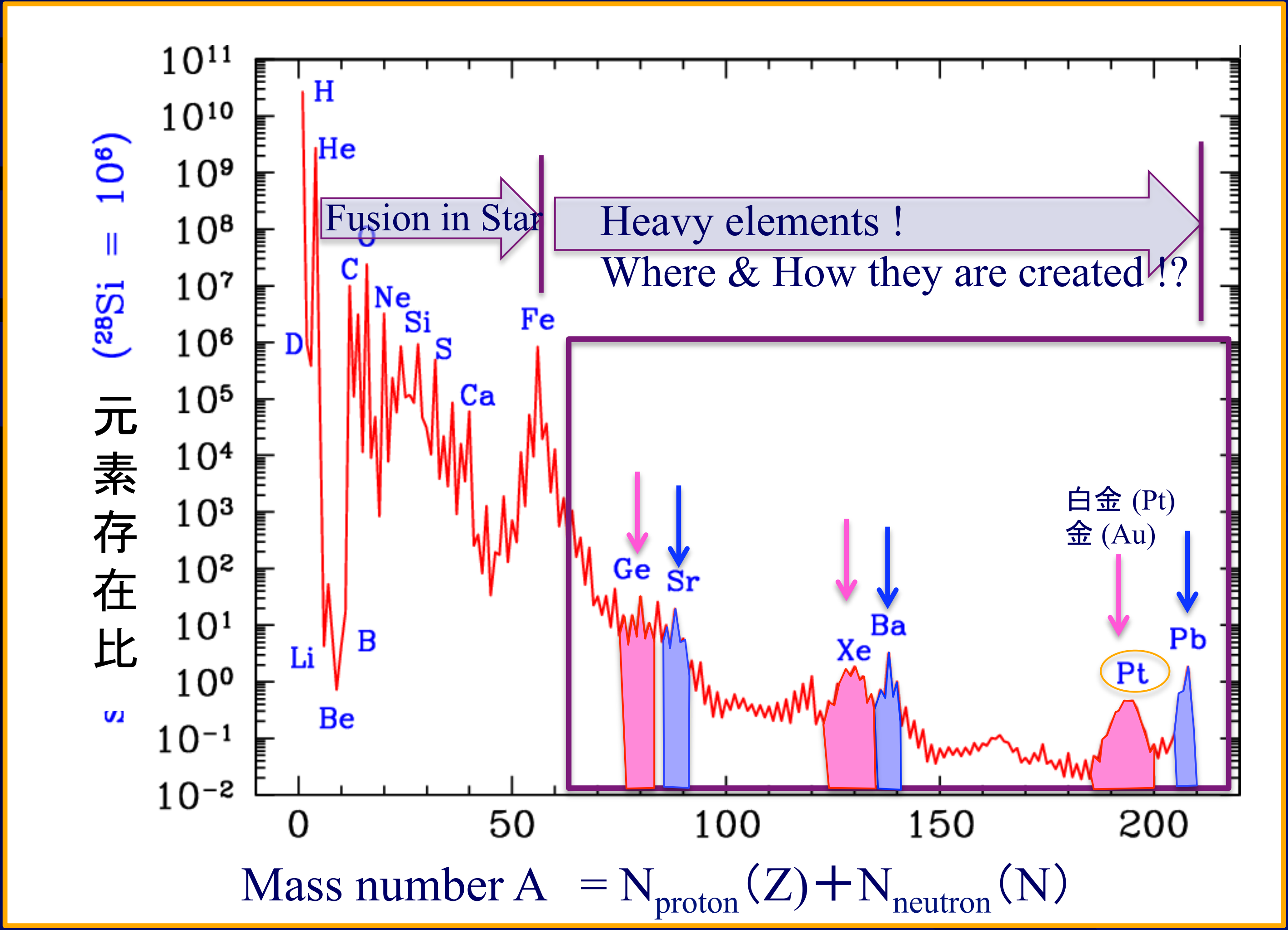


Black hole
Neutron Star

What kinds of Elements in "Our Solar System" ?

Periodic Table of Elements

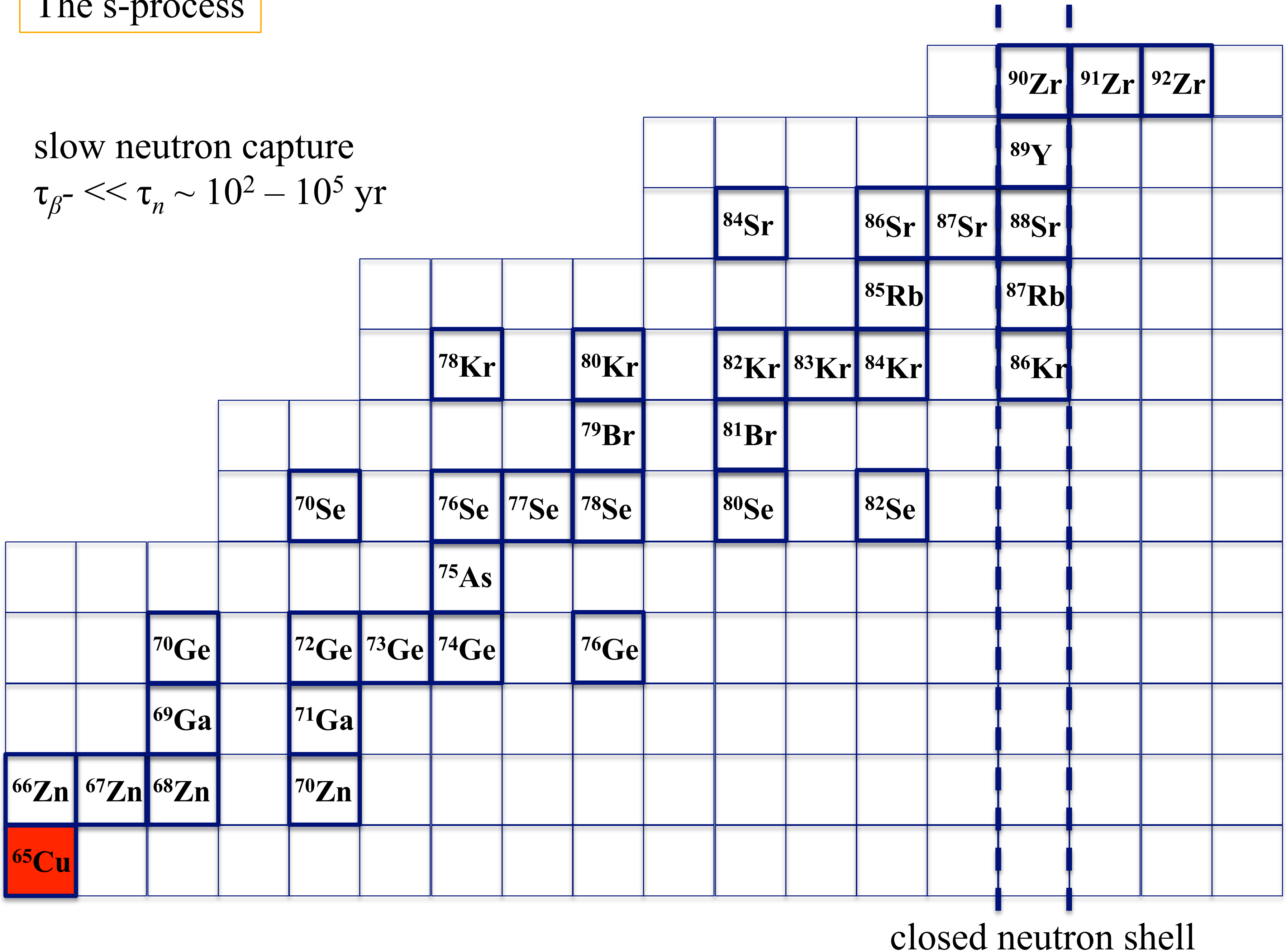
Solar System: Abundance Pattern



The s-process

slow neutron capture

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



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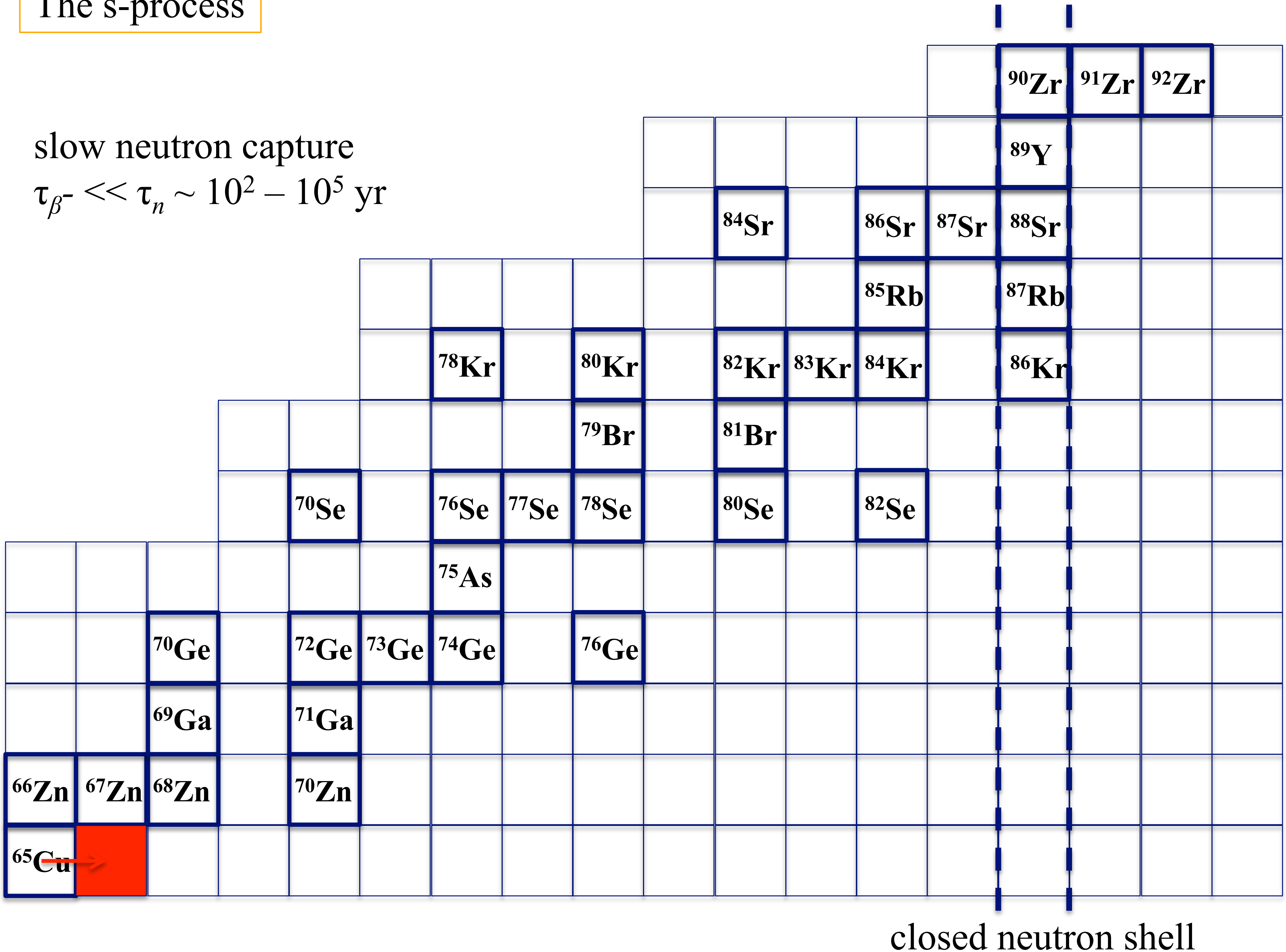

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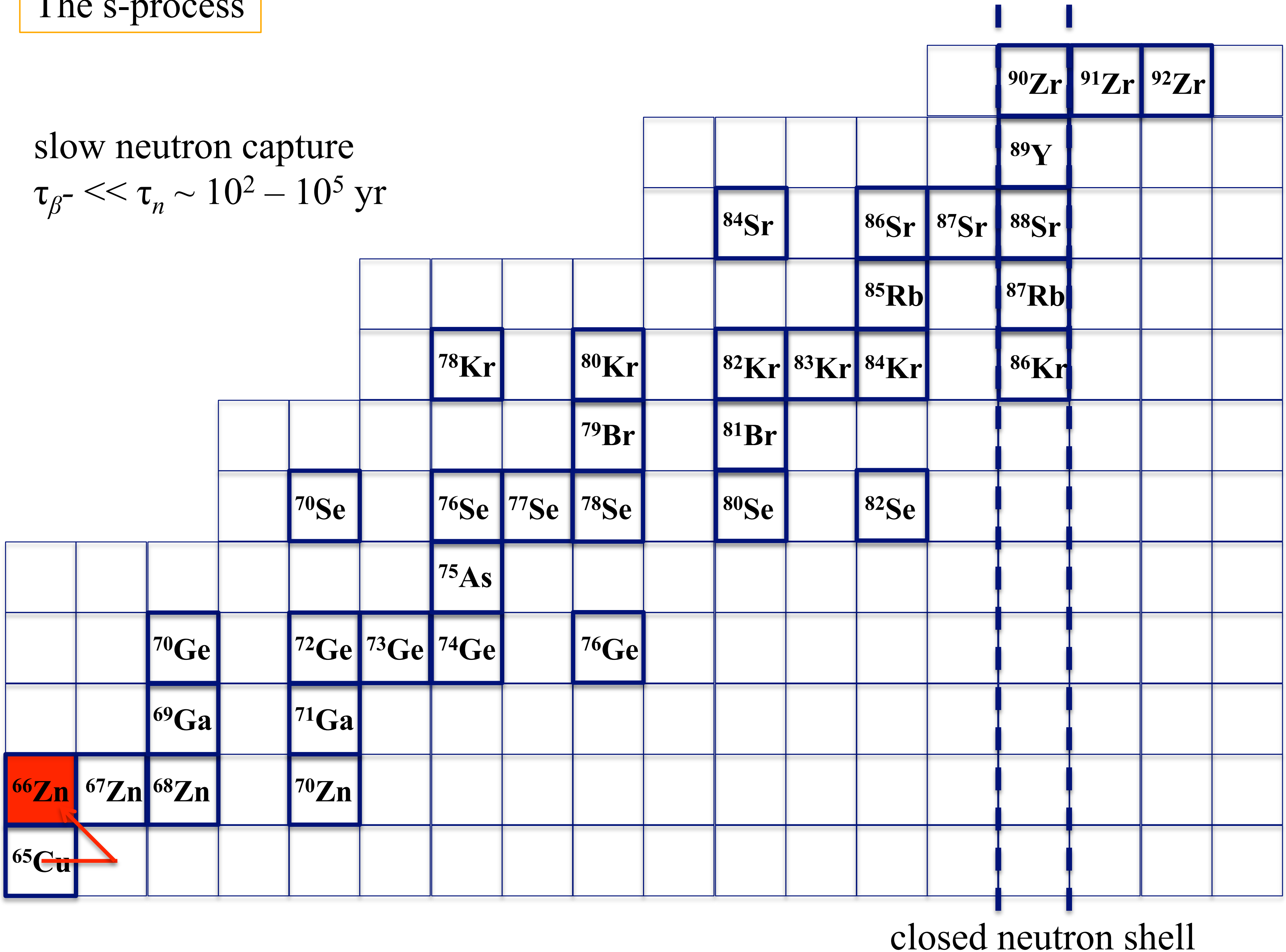

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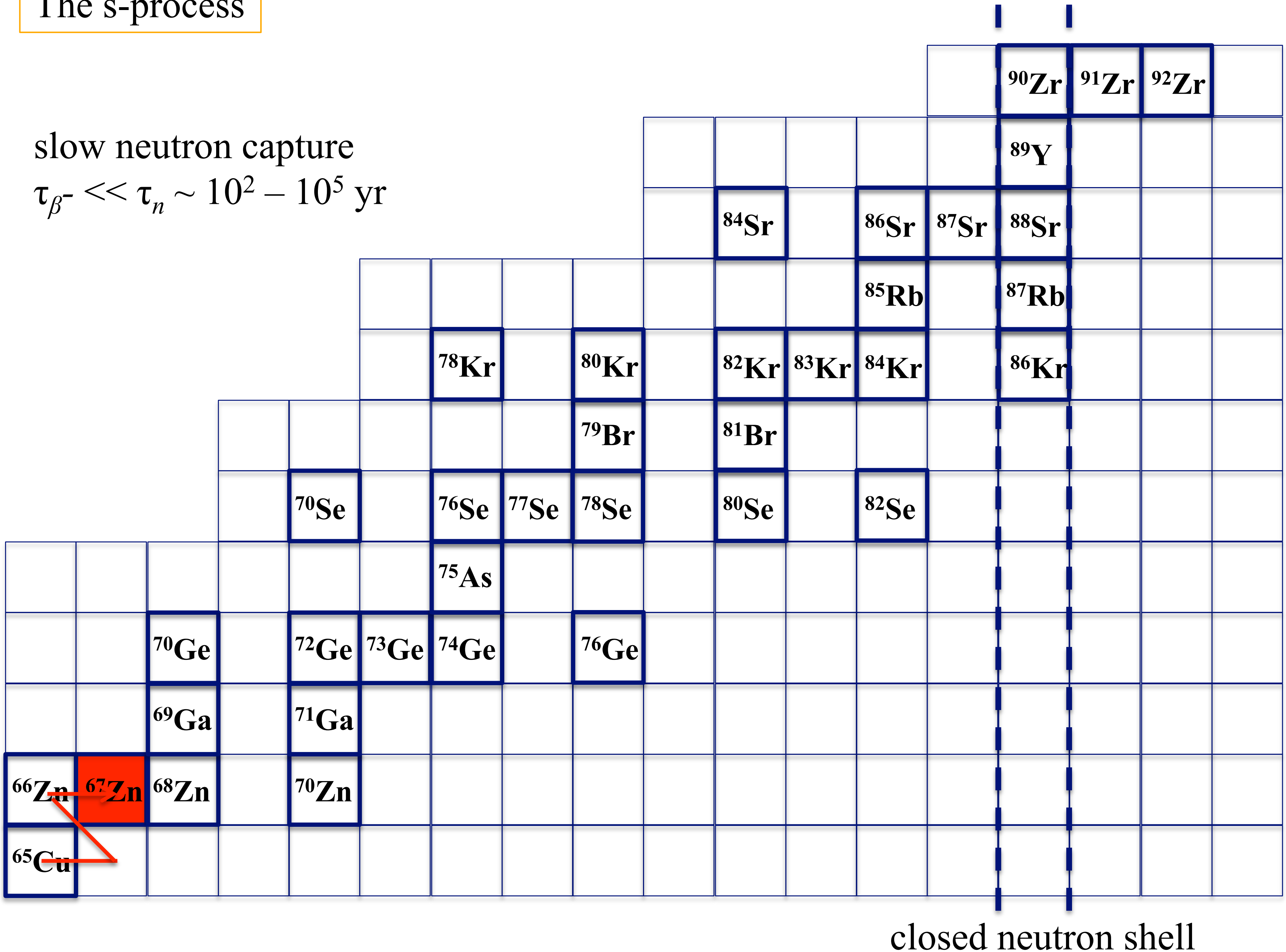

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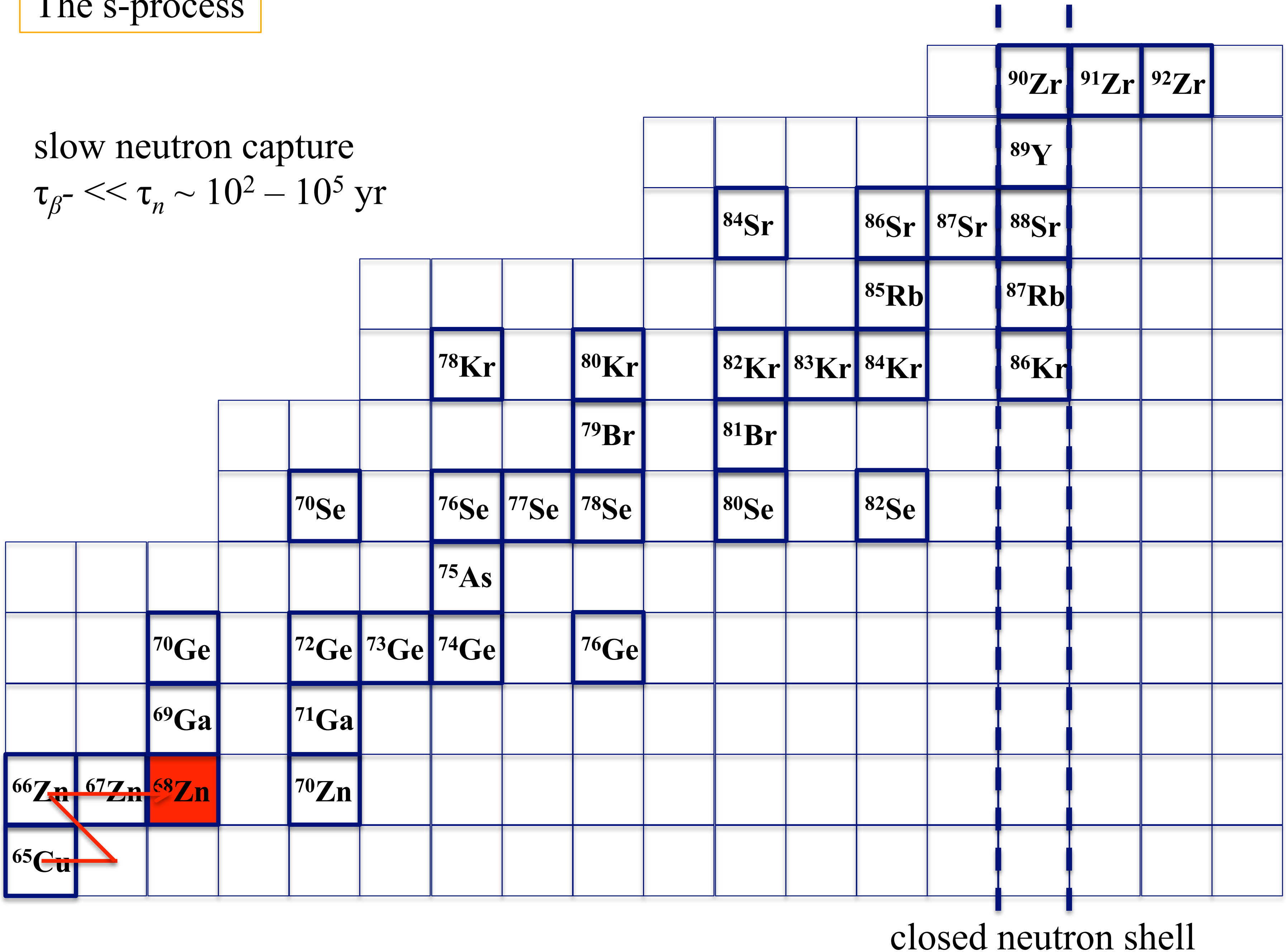

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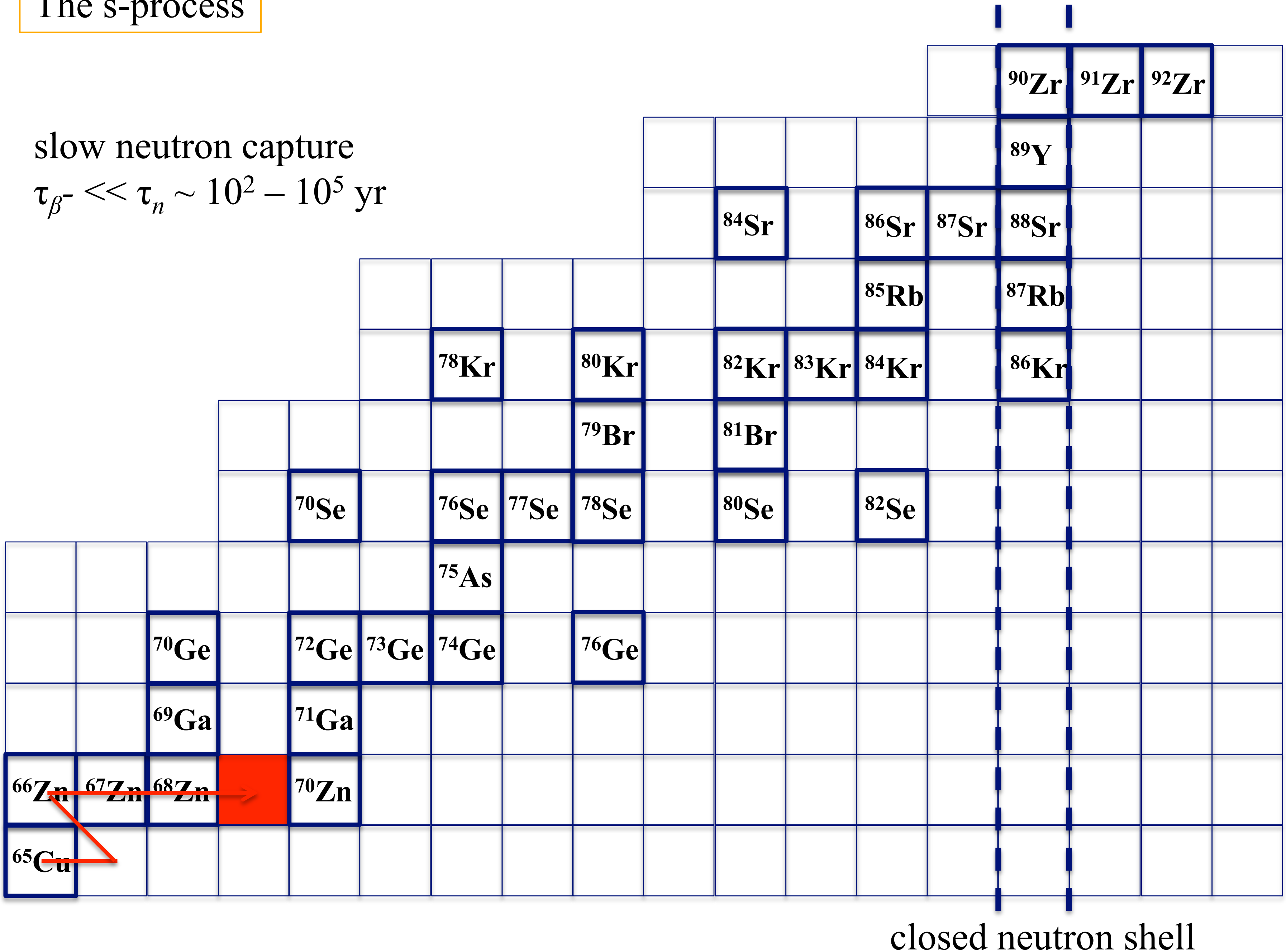

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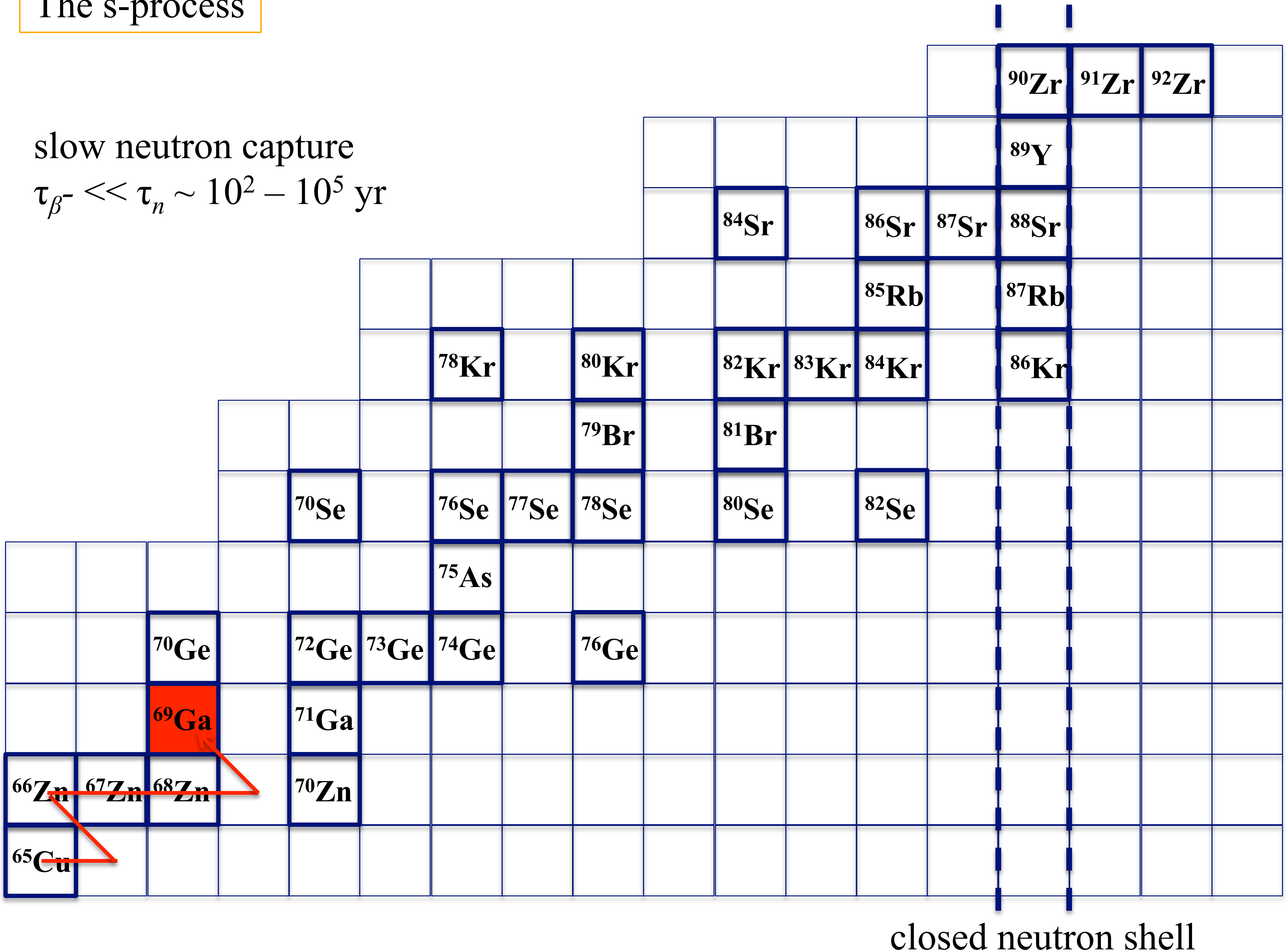

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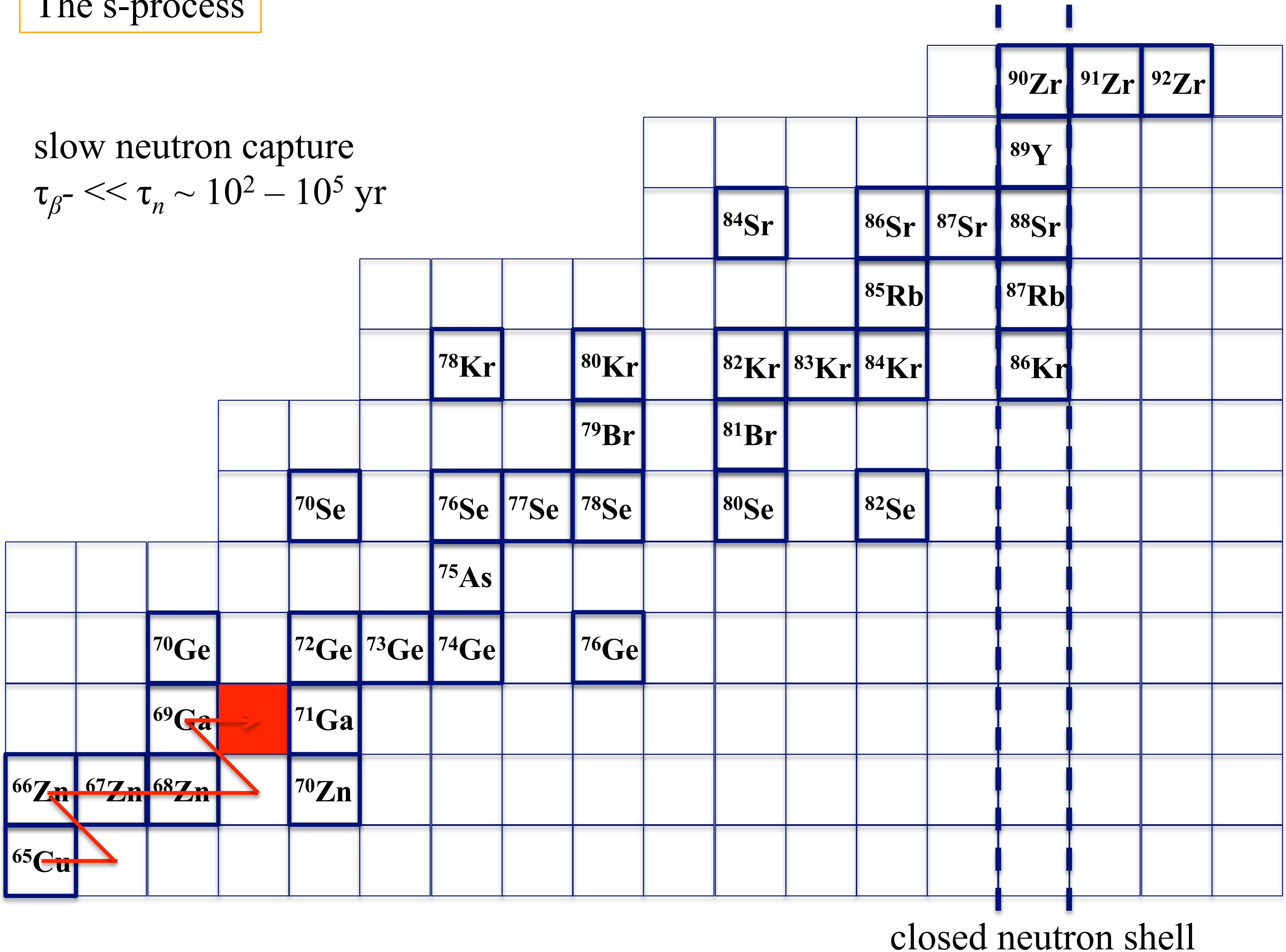

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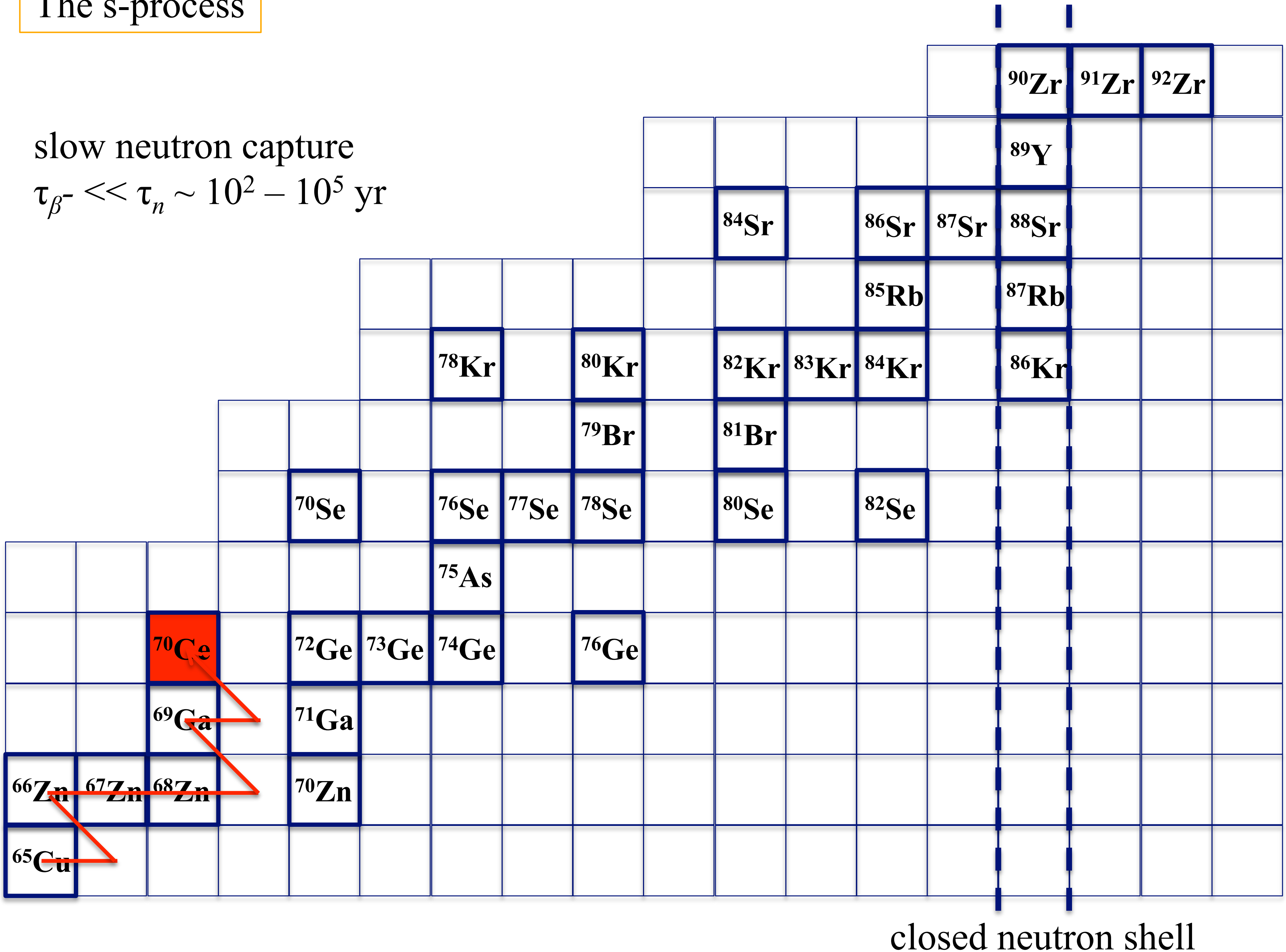

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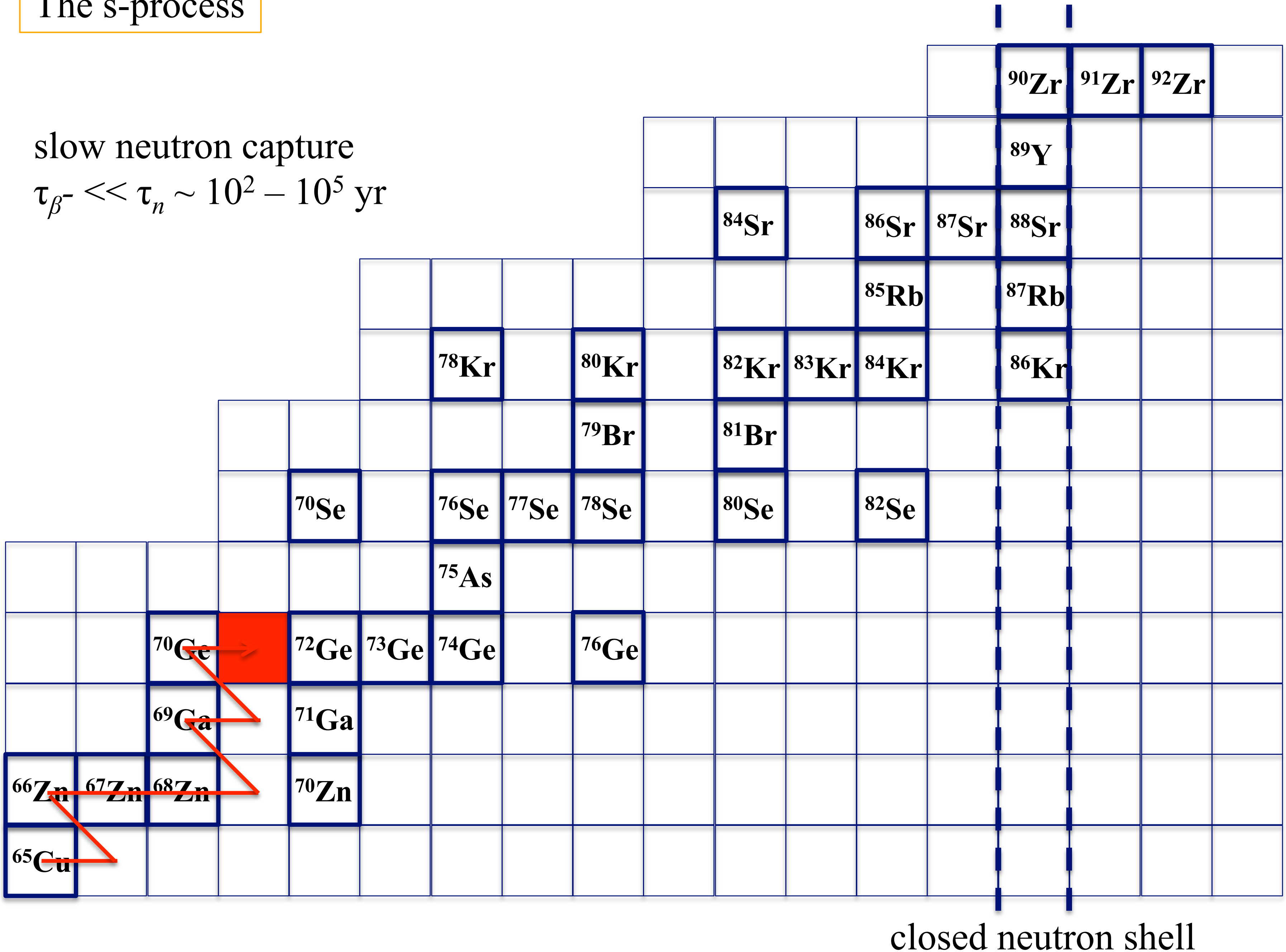

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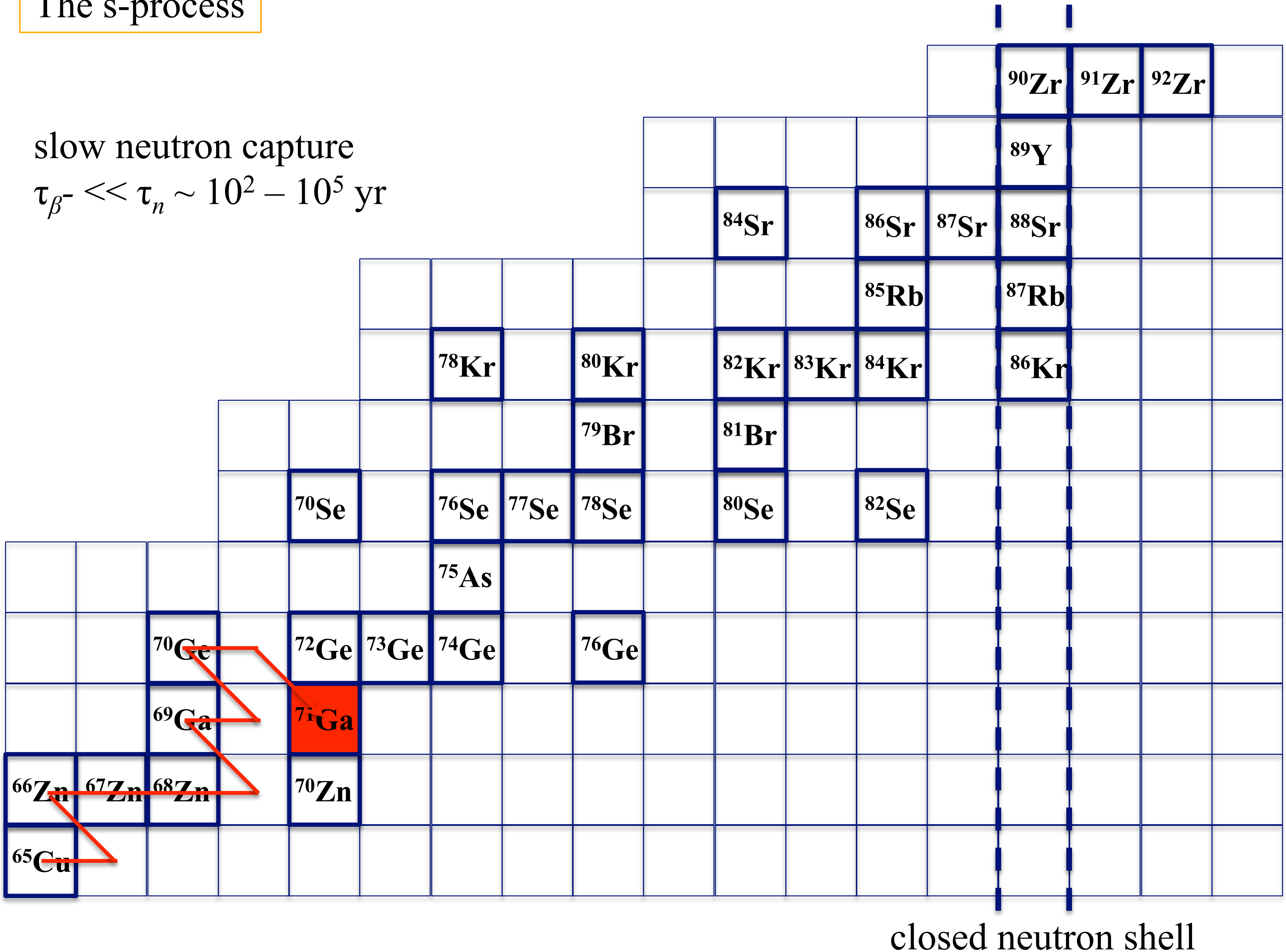

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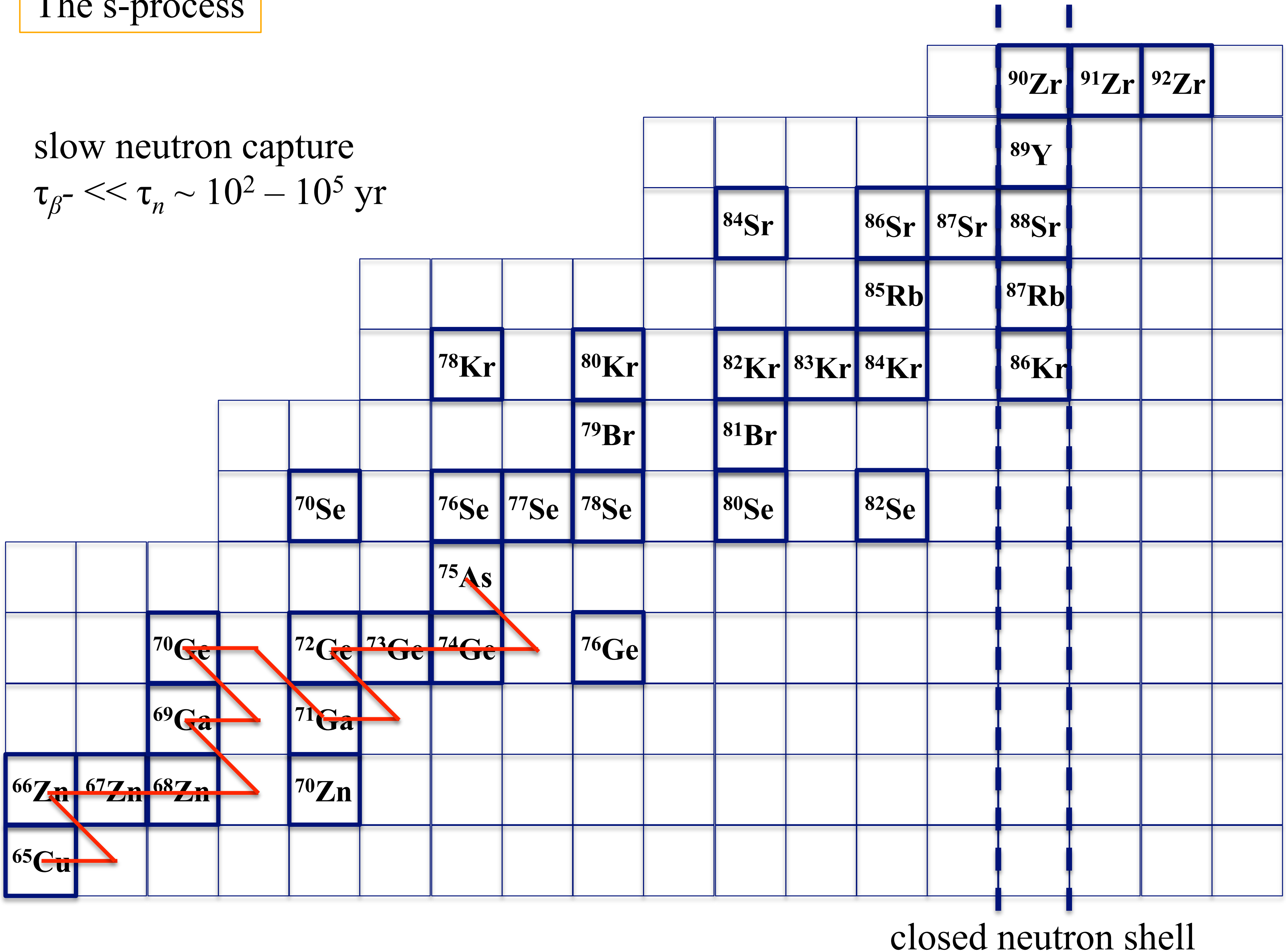

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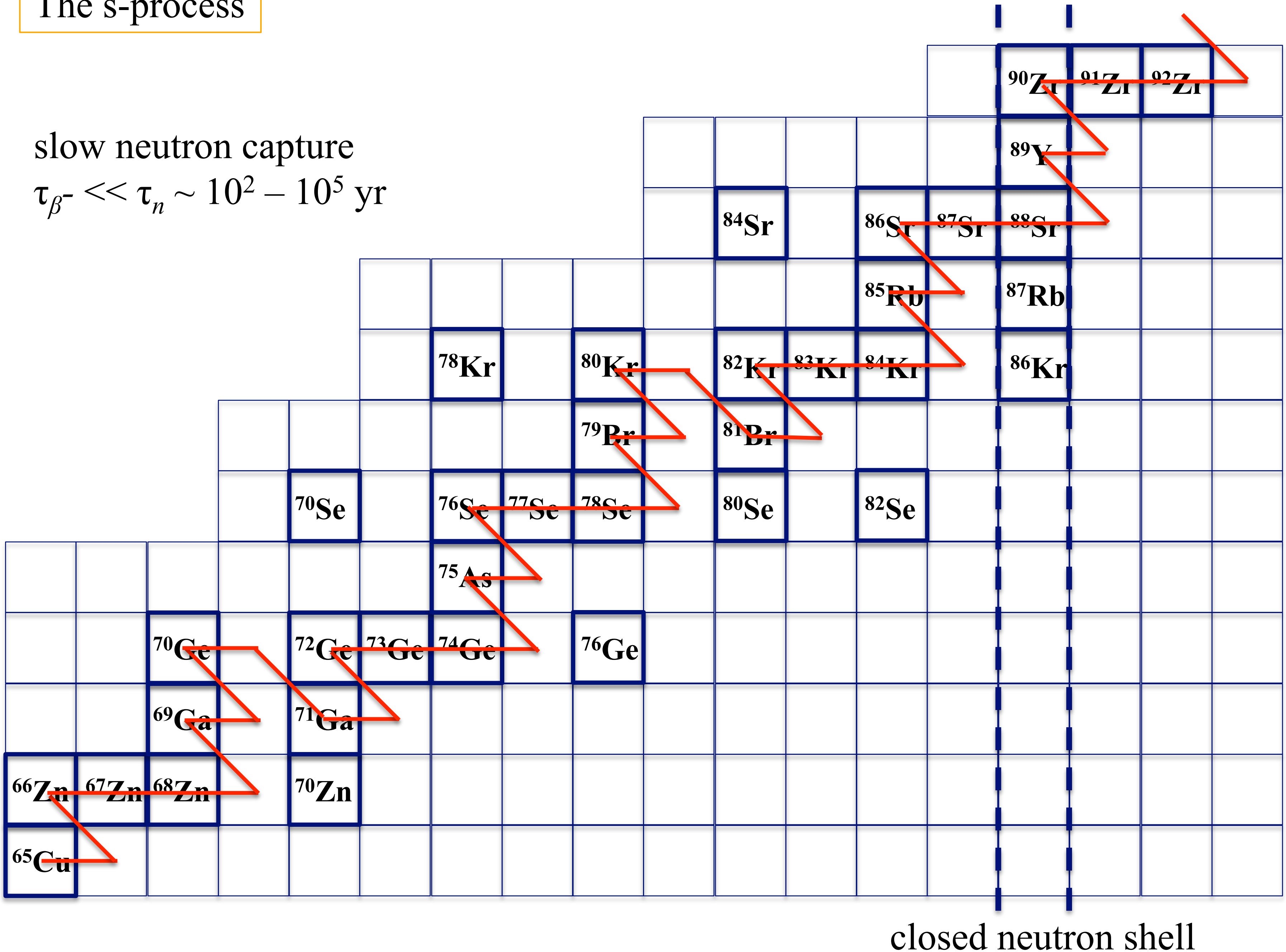

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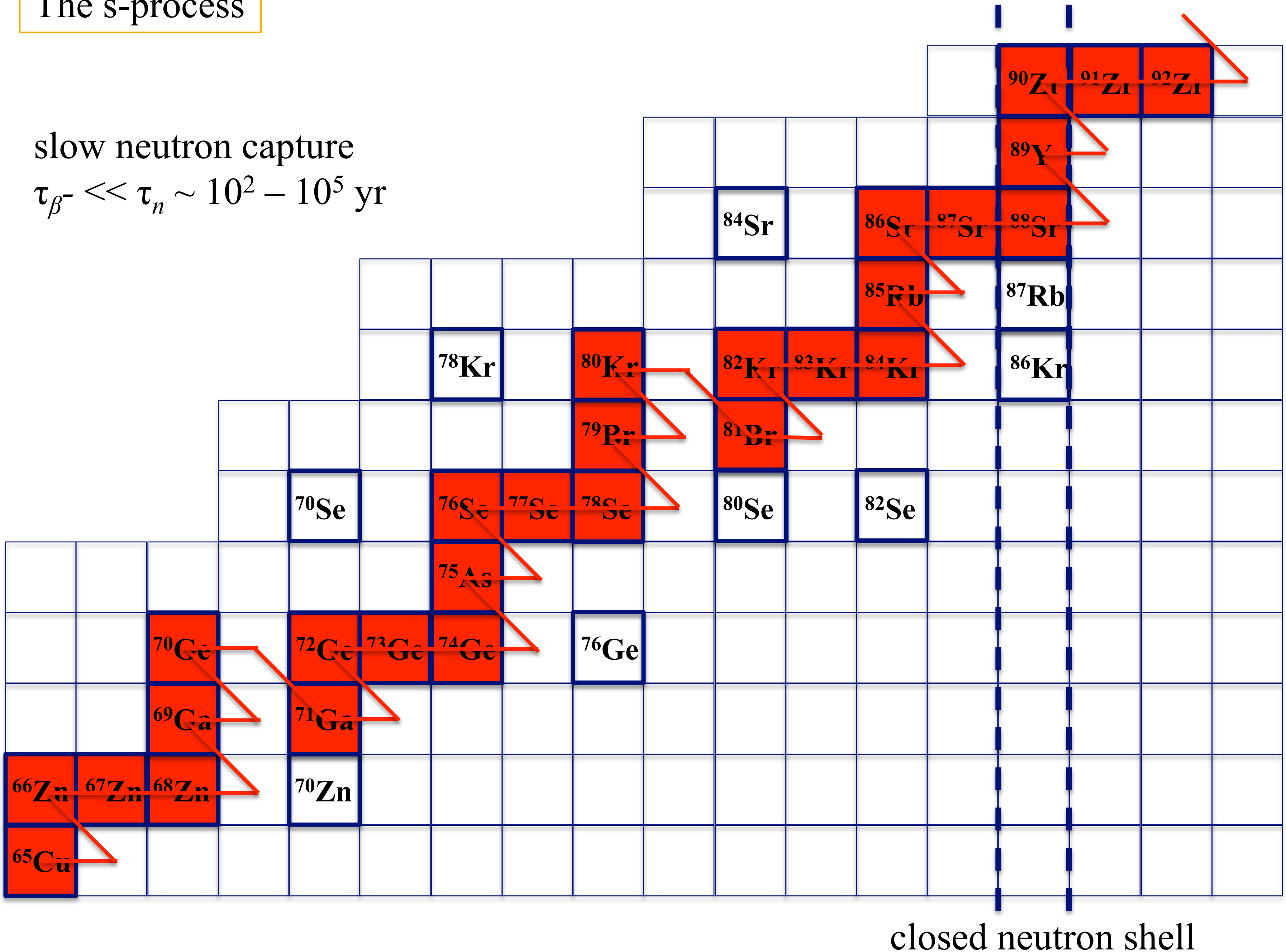
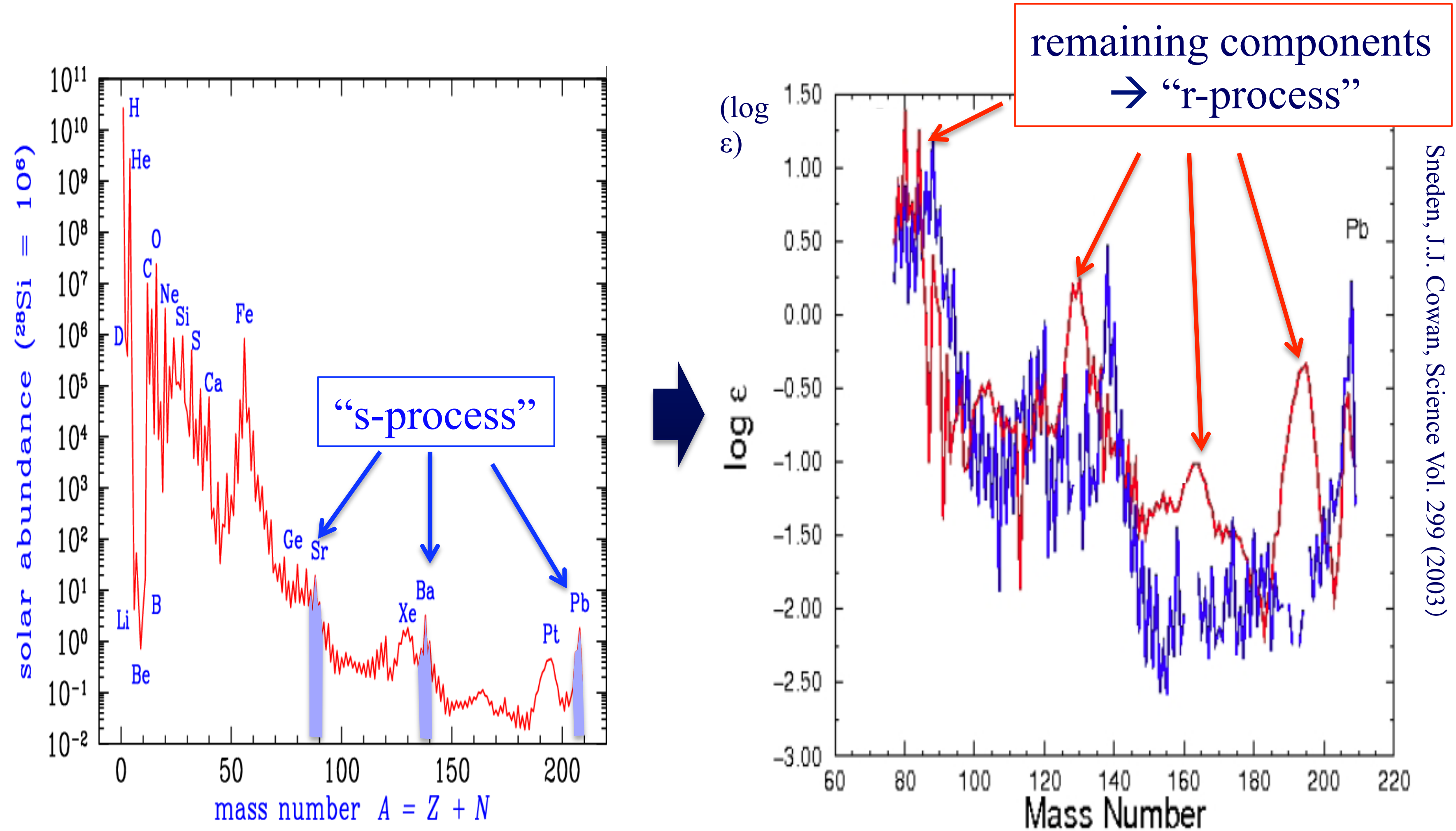


Solar System: Abundance Pattern



r-process peaks (A~80, 130, 195) are also associated to neutron magic number N = 50, 82, 126 !

The r-process

rapid neutron capture

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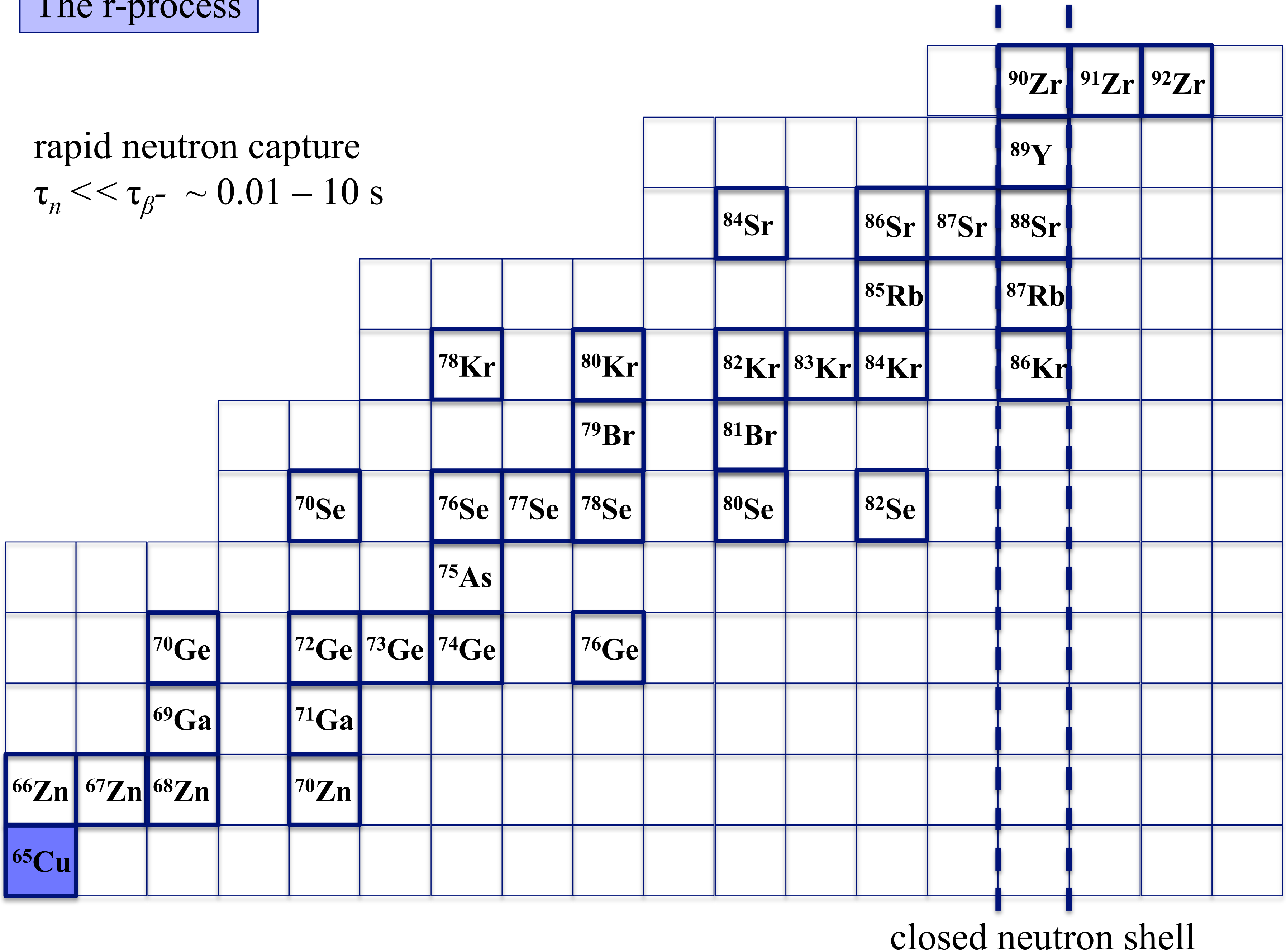

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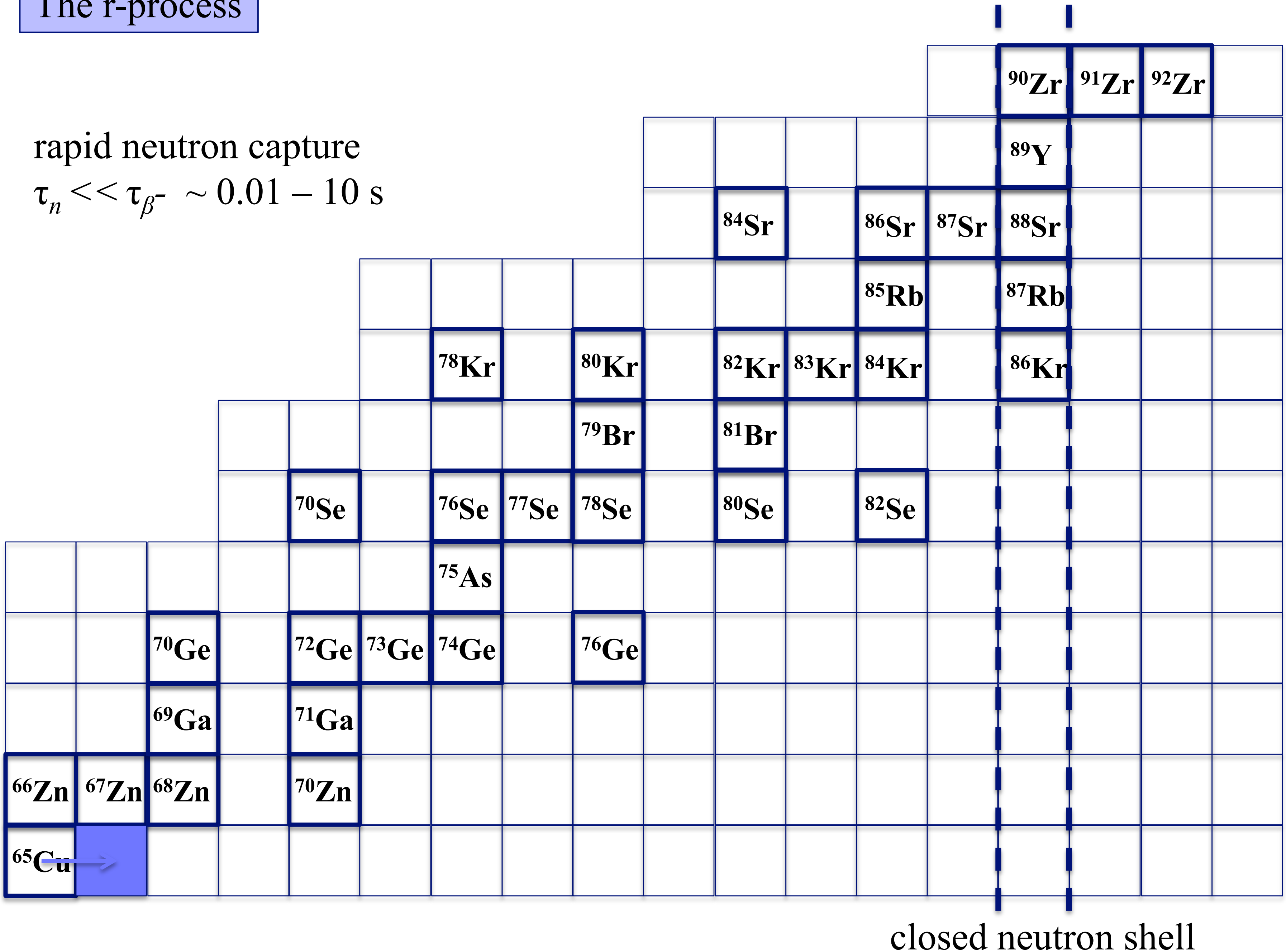

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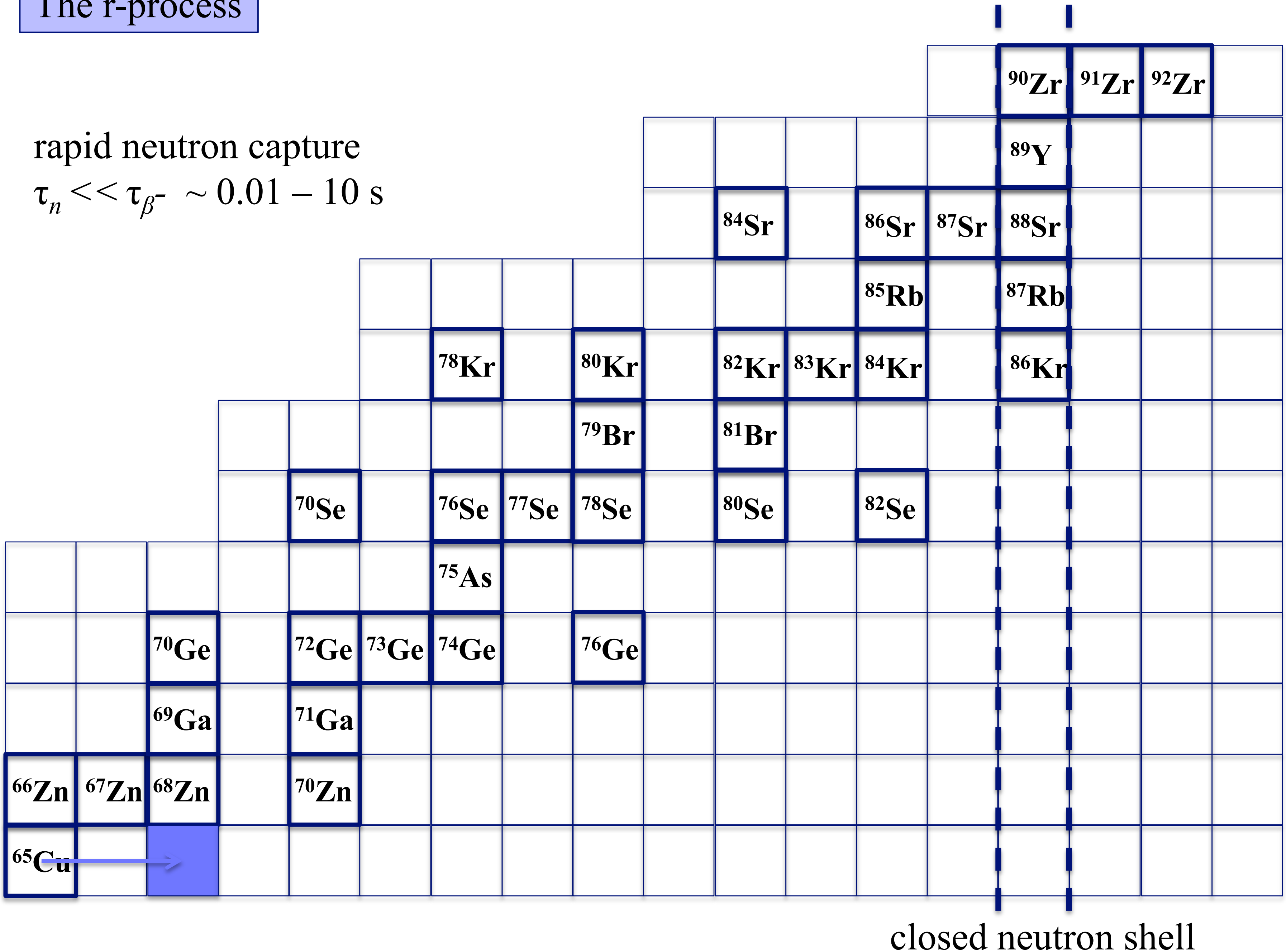

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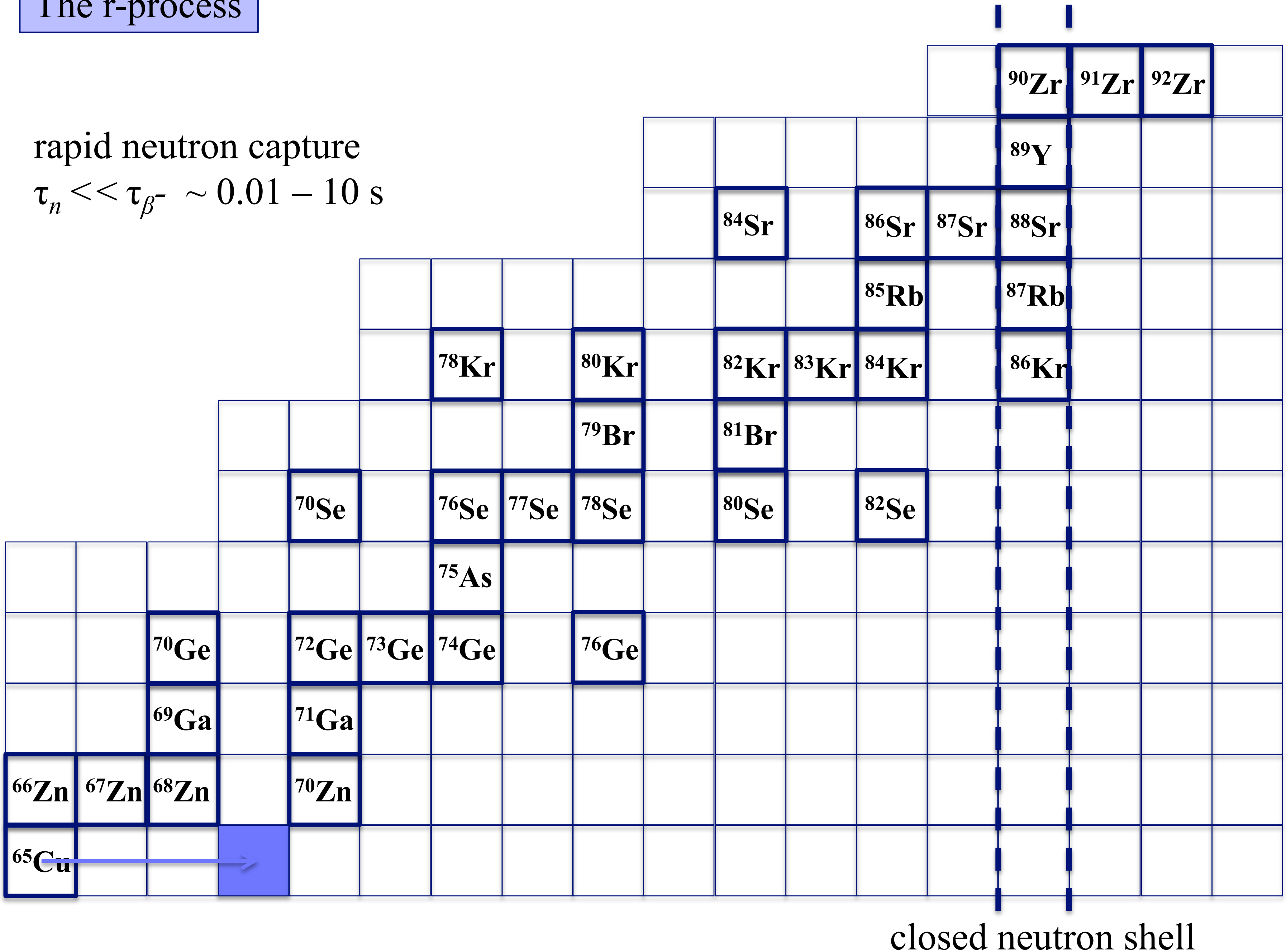

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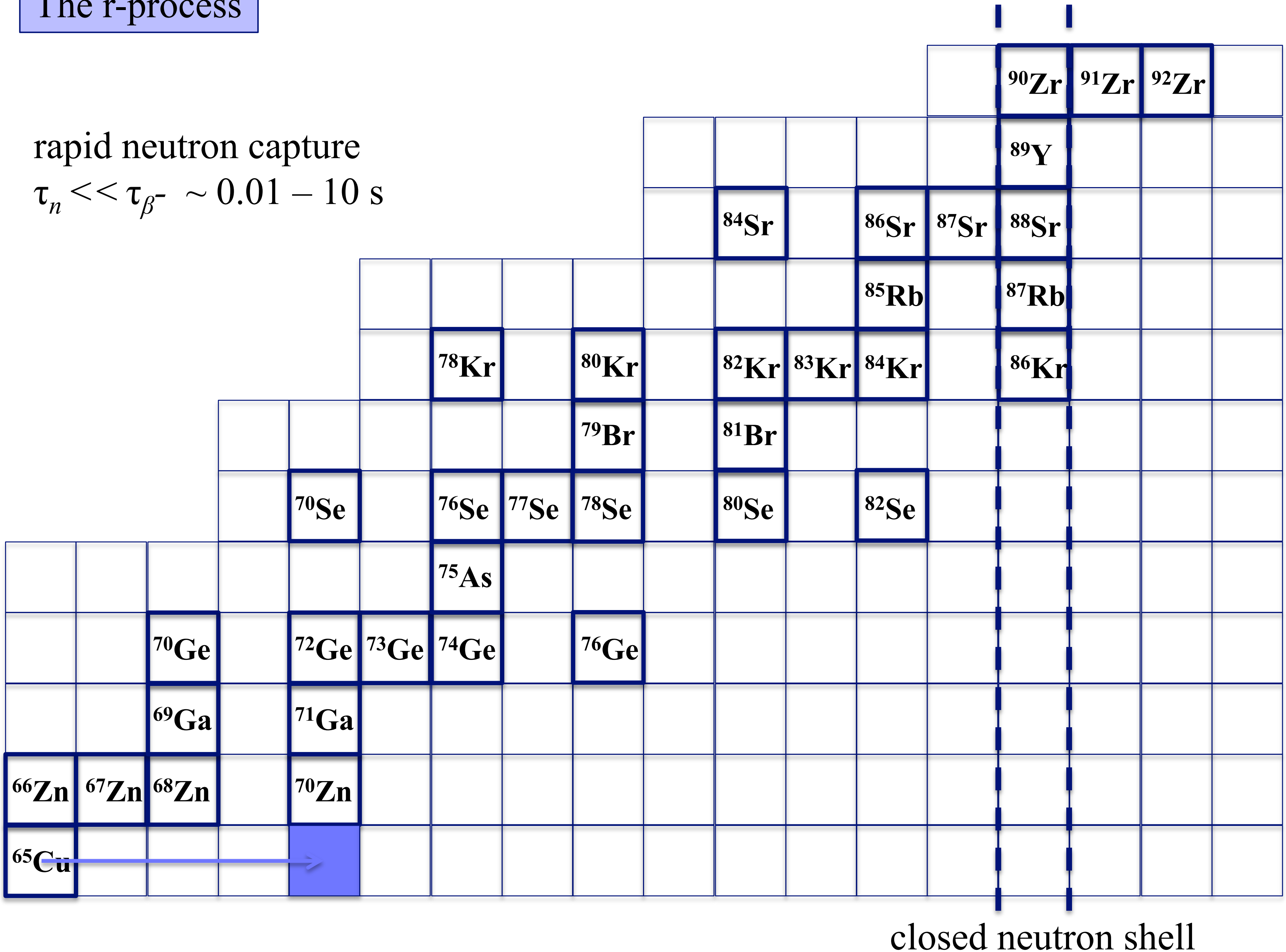

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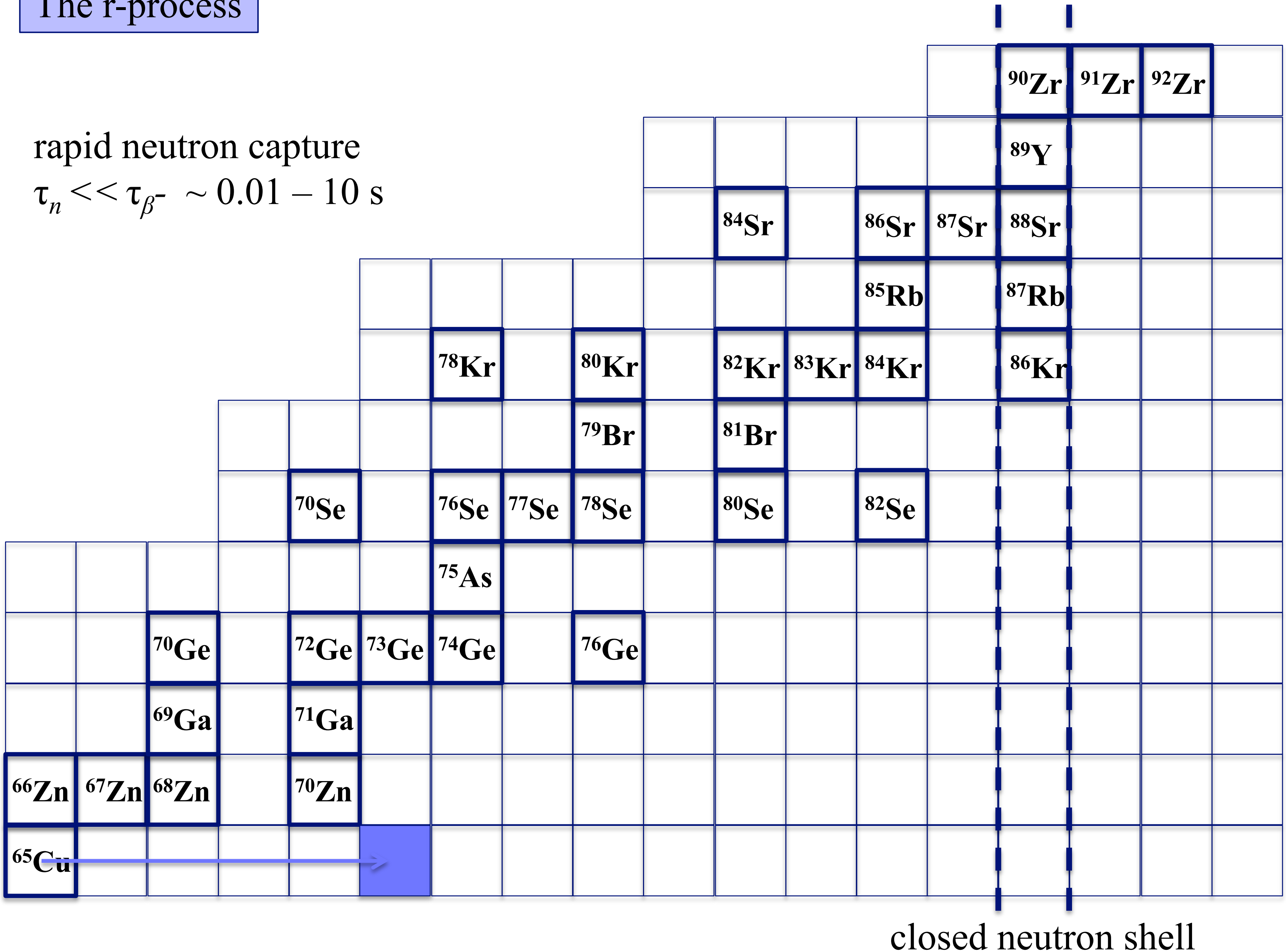

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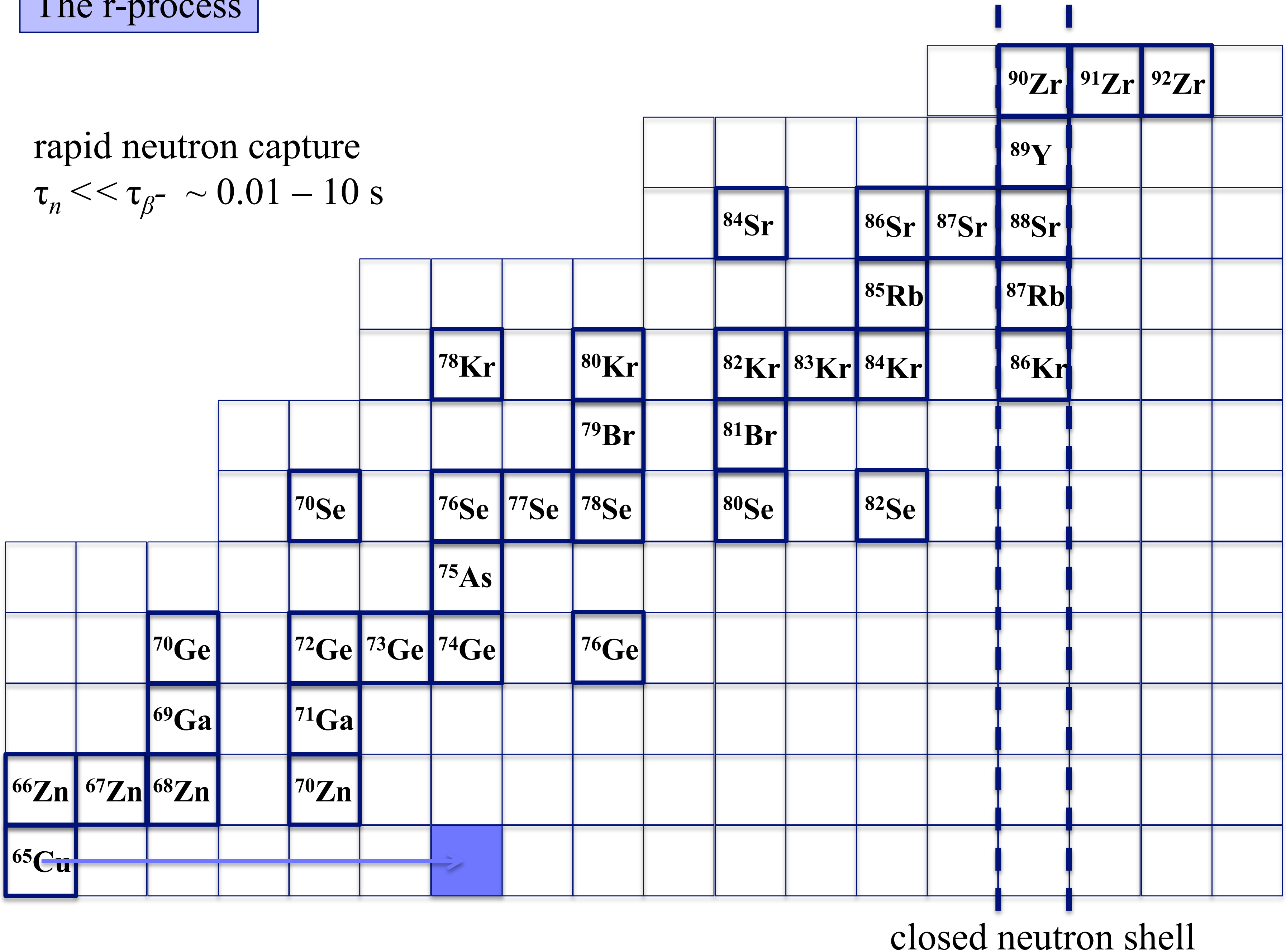

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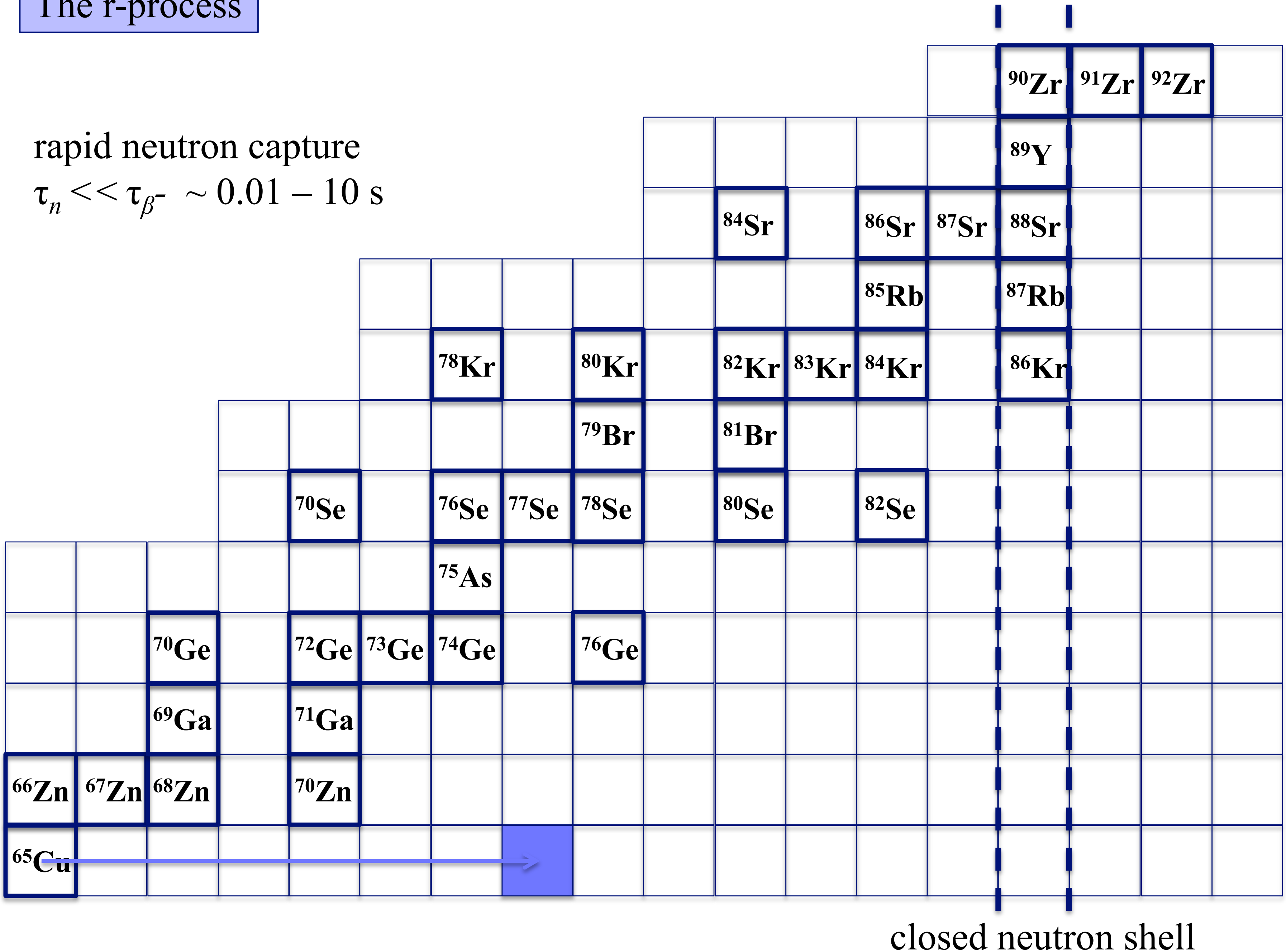

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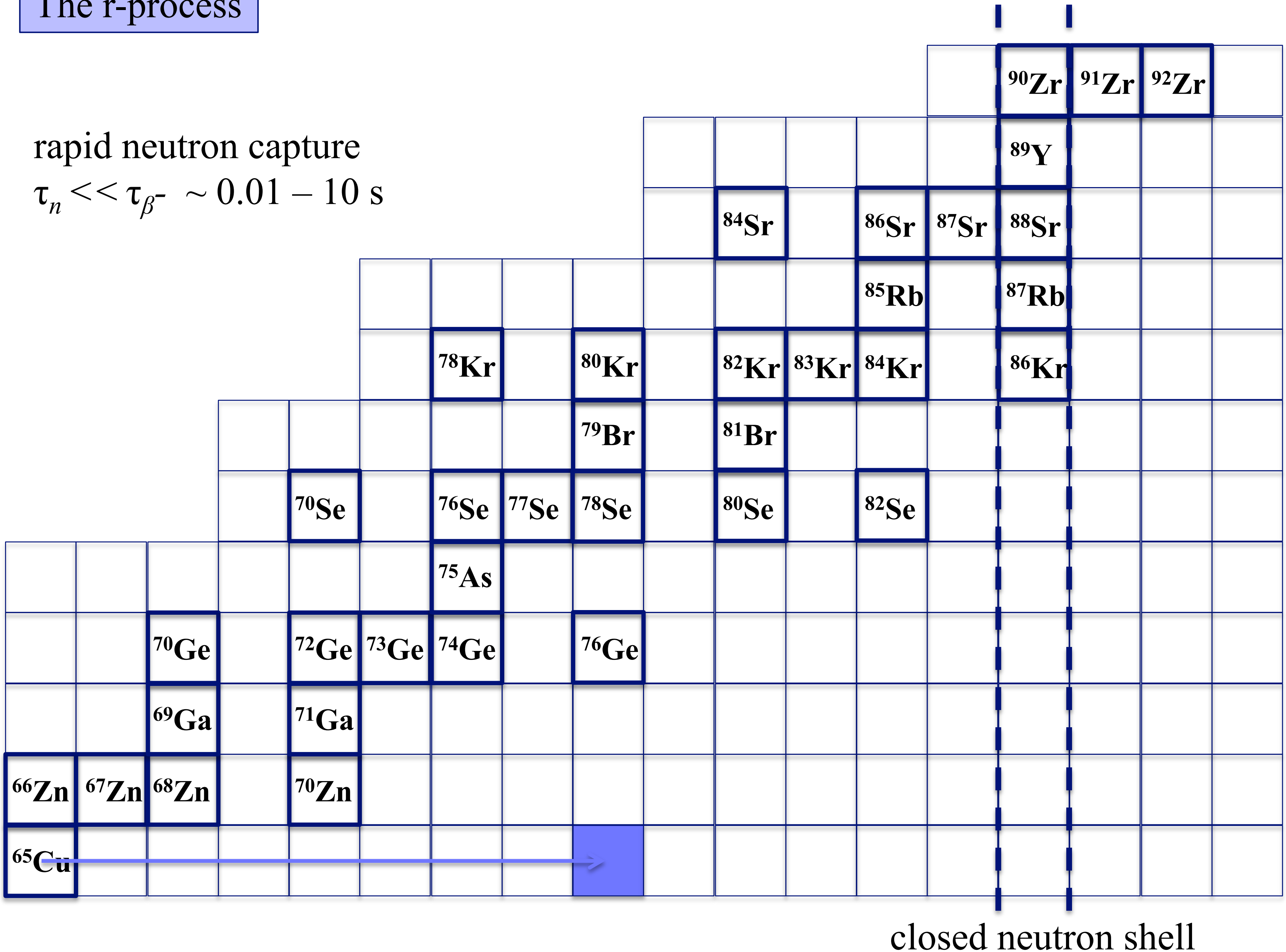

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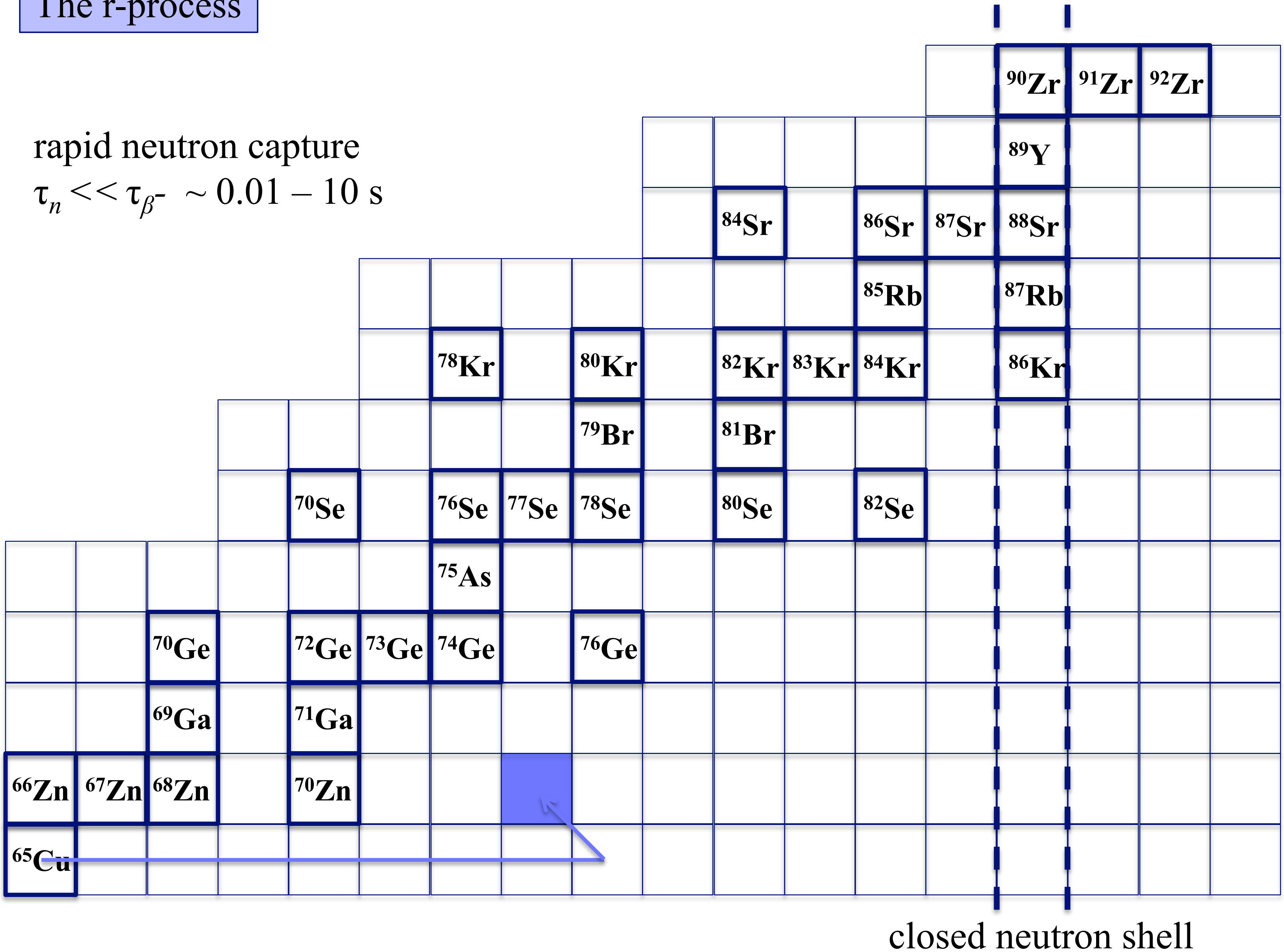

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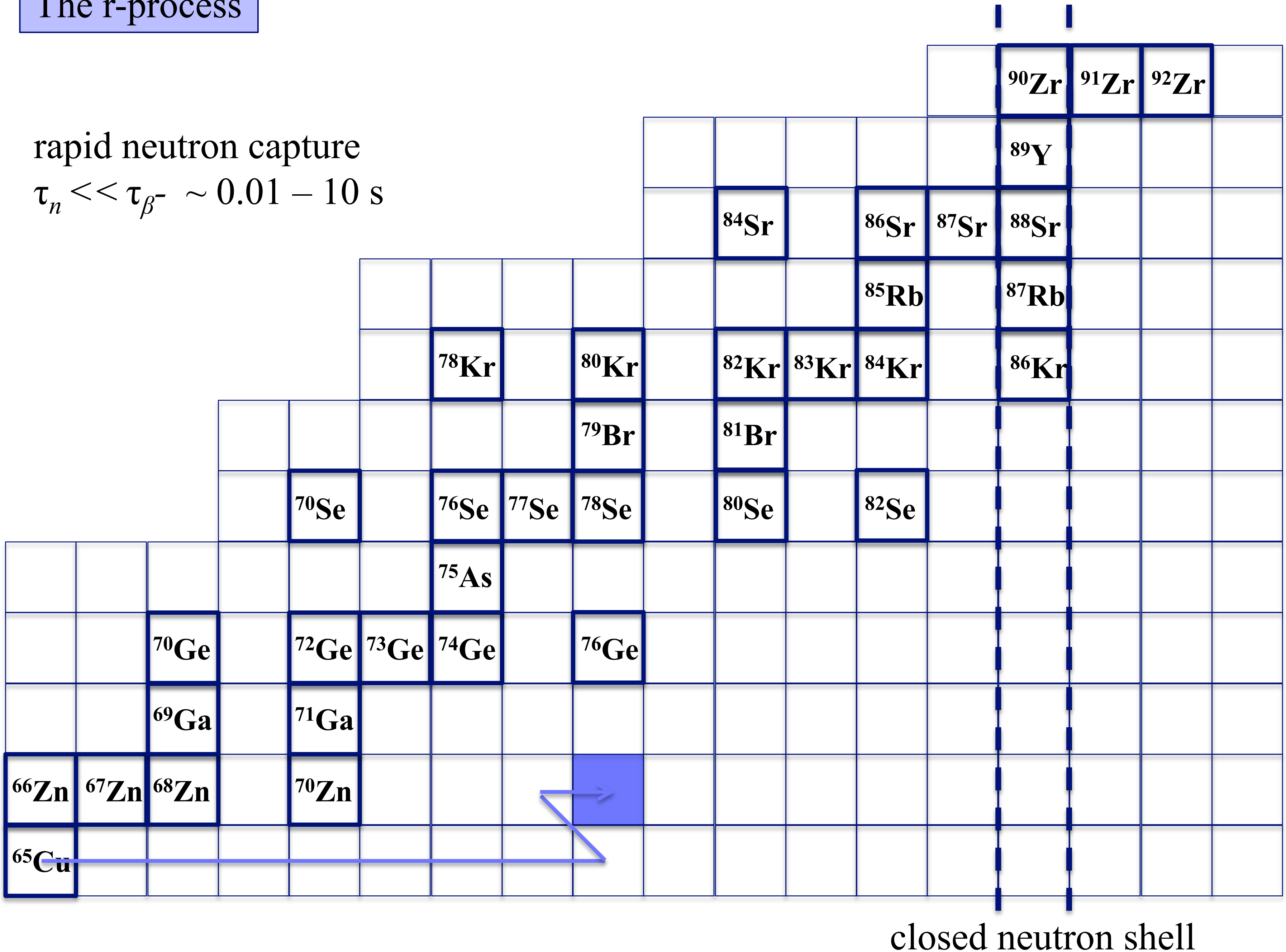

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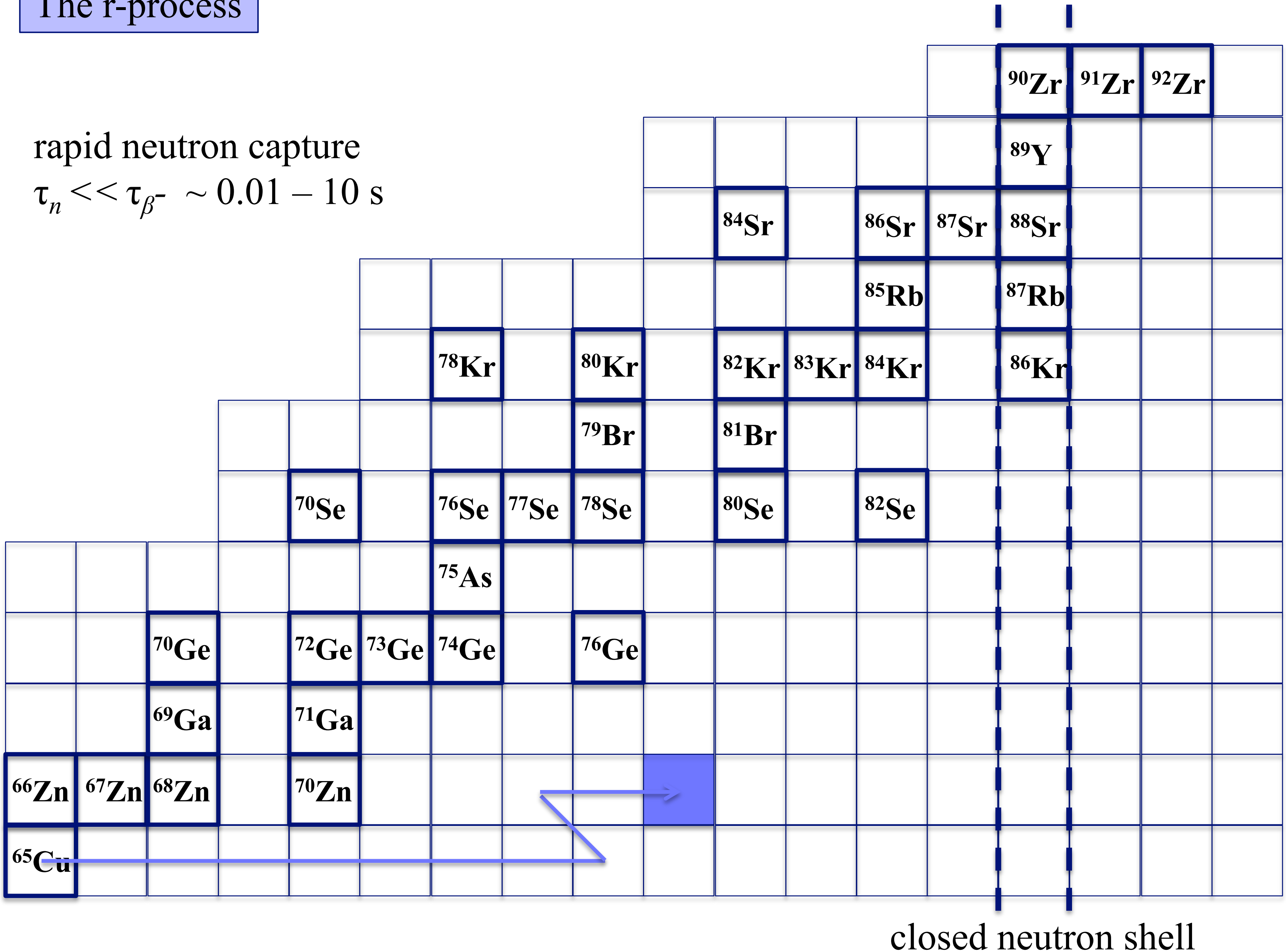

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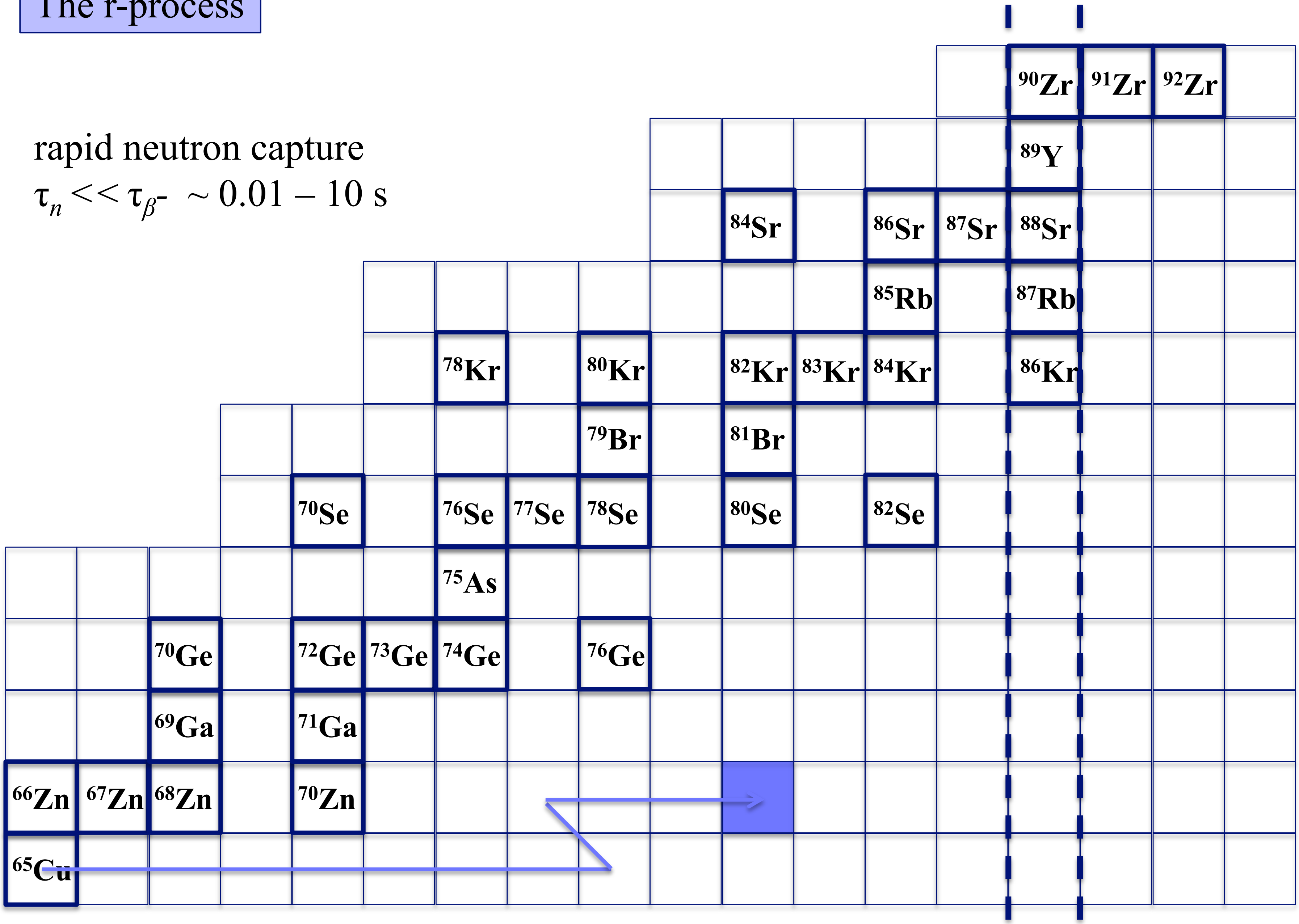

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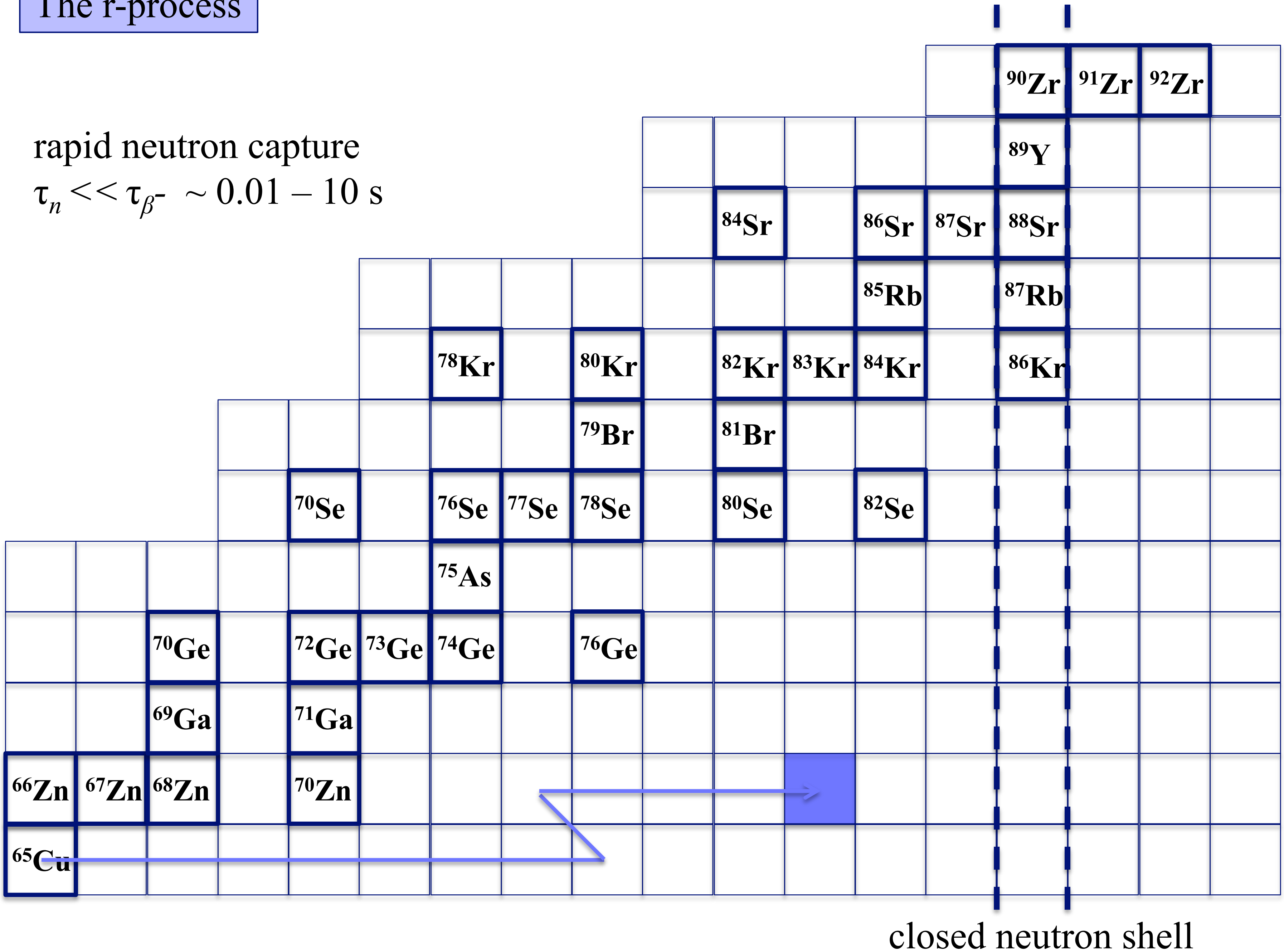

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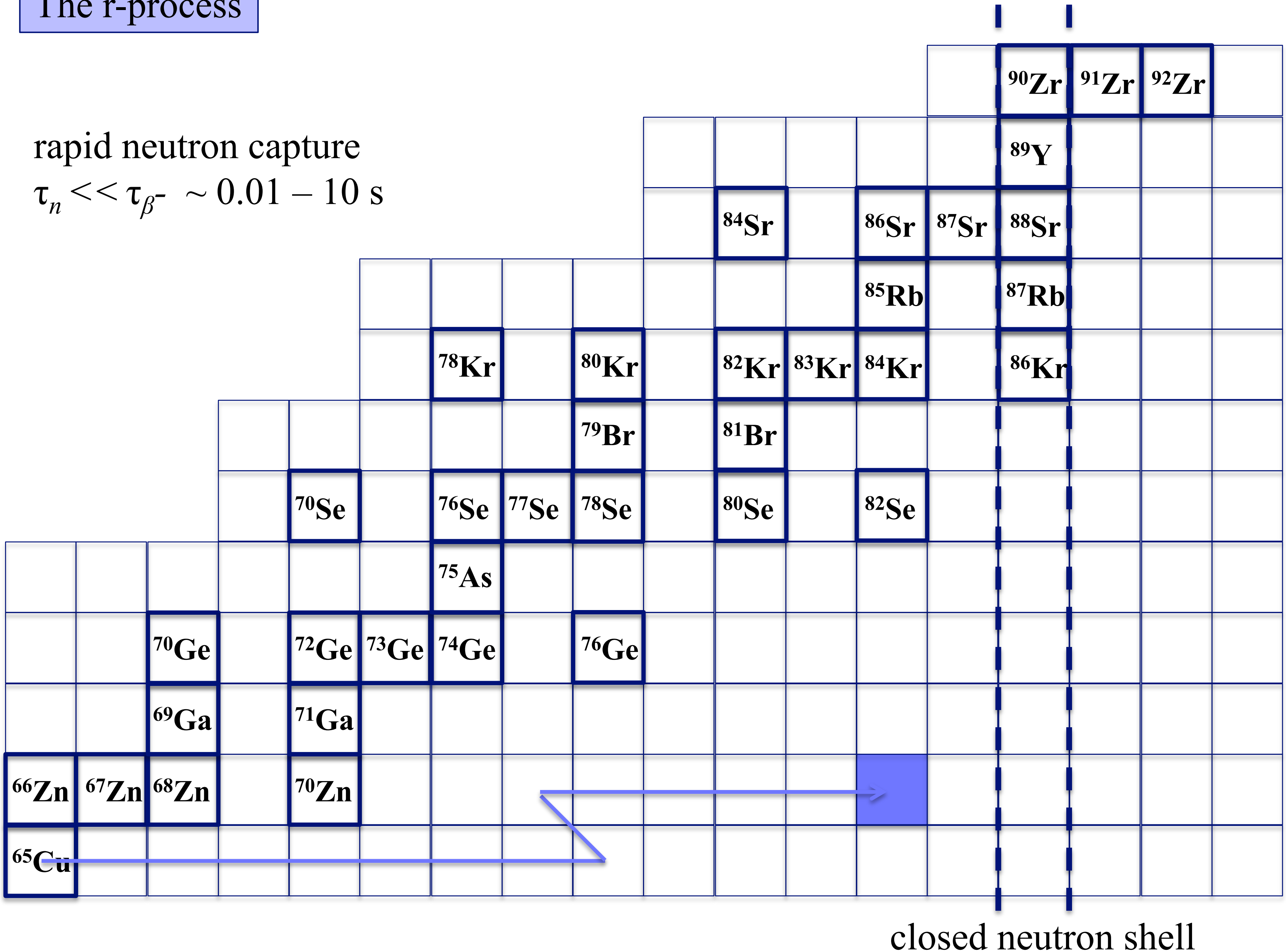

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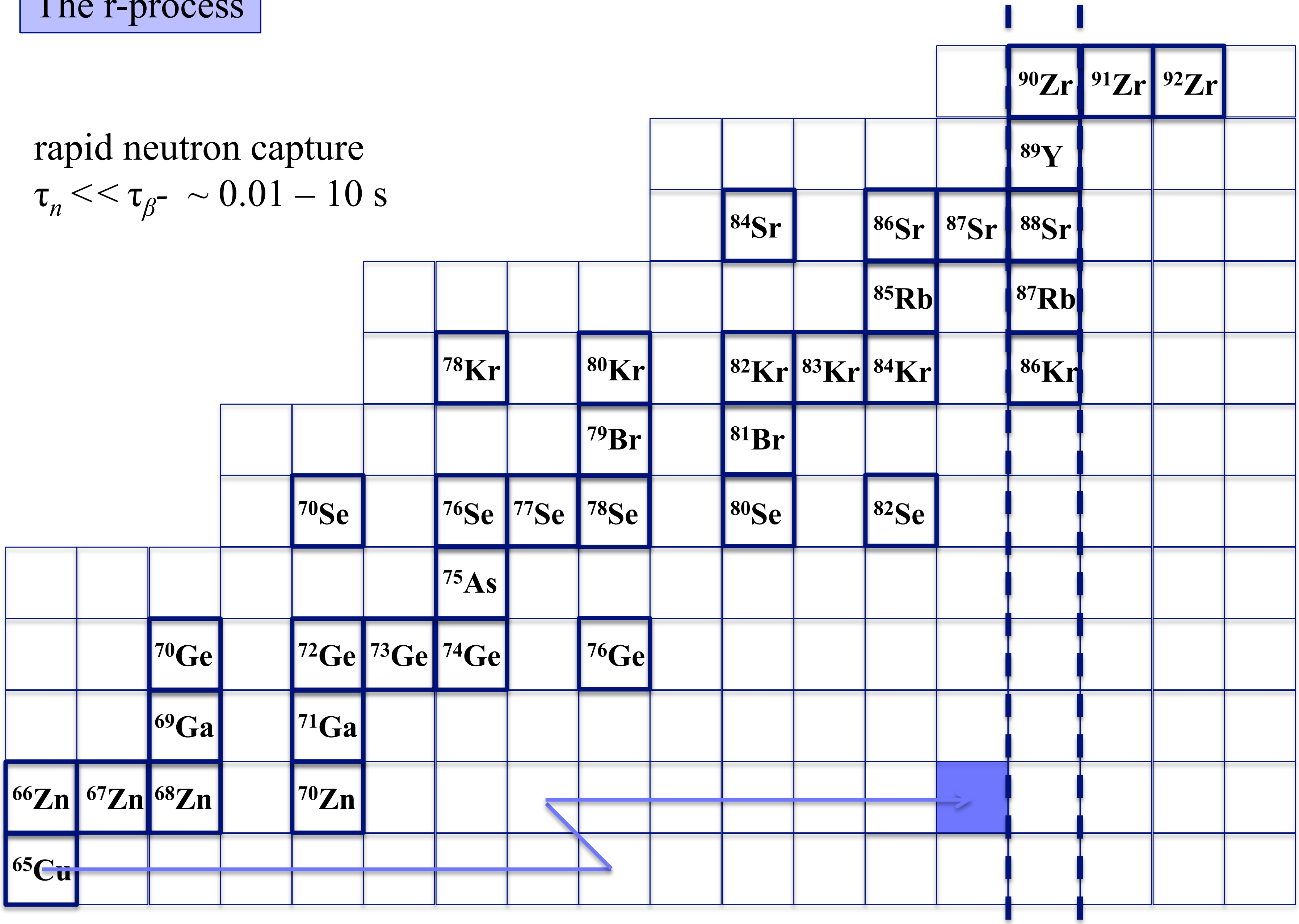

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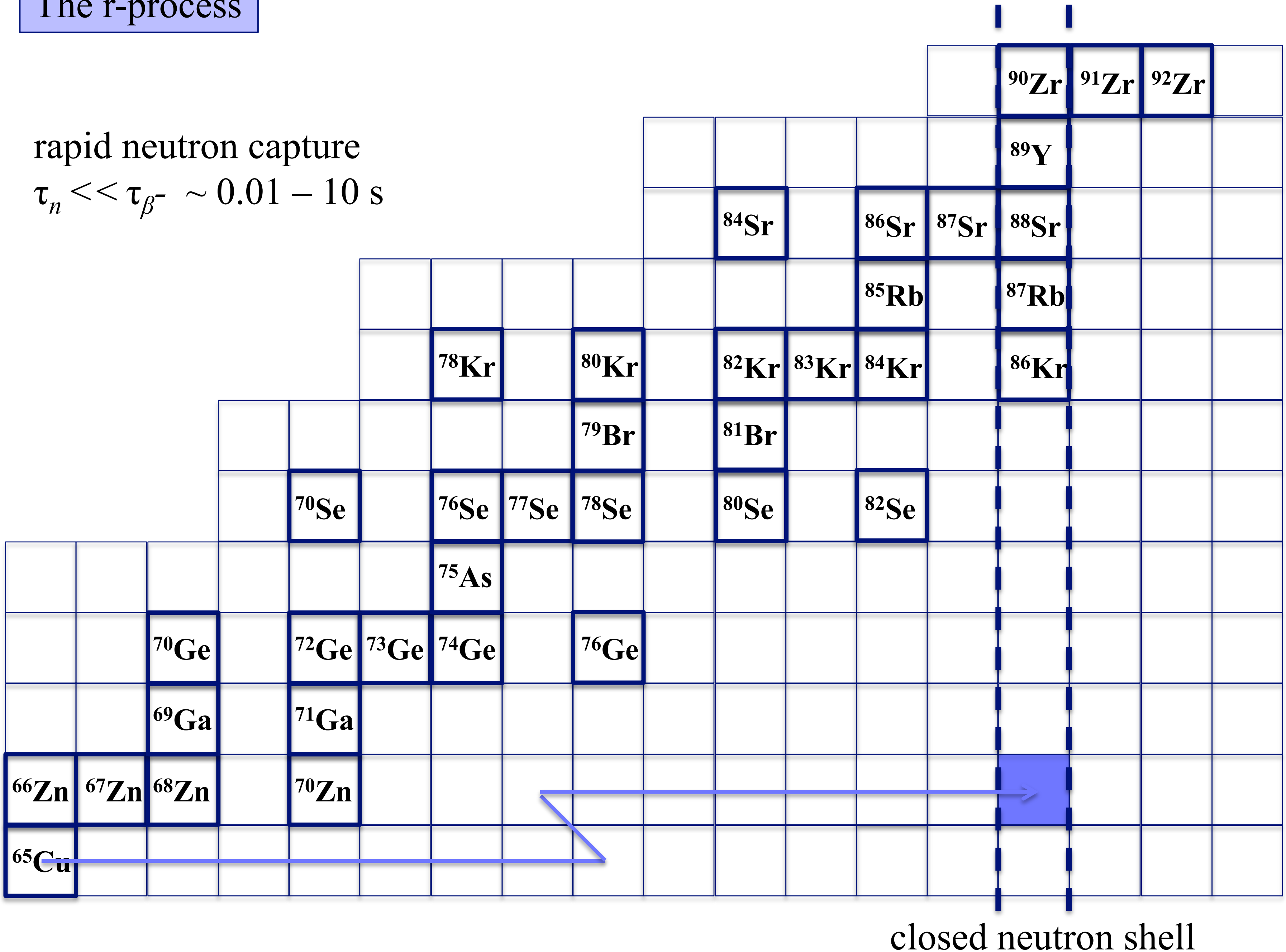

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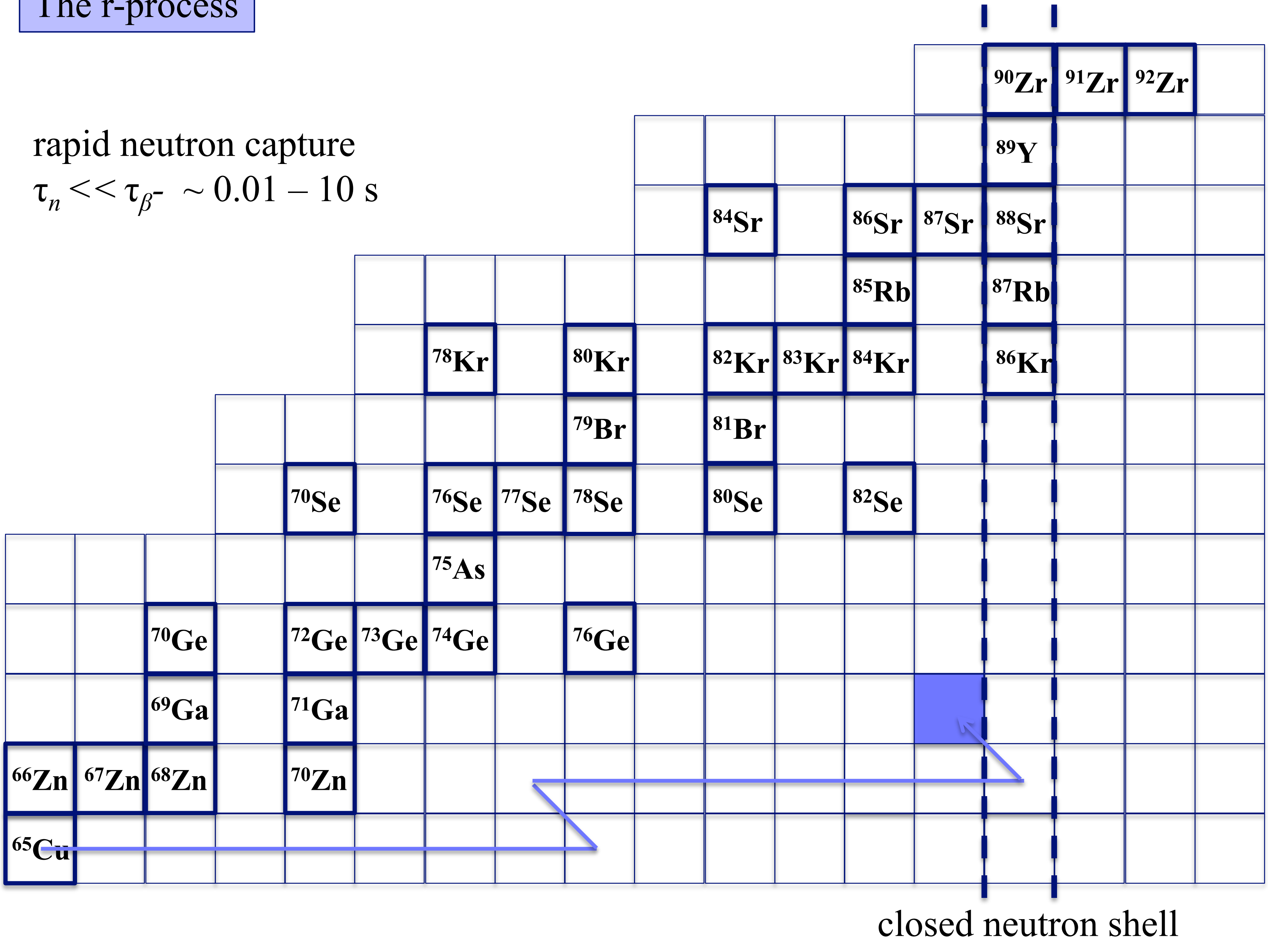

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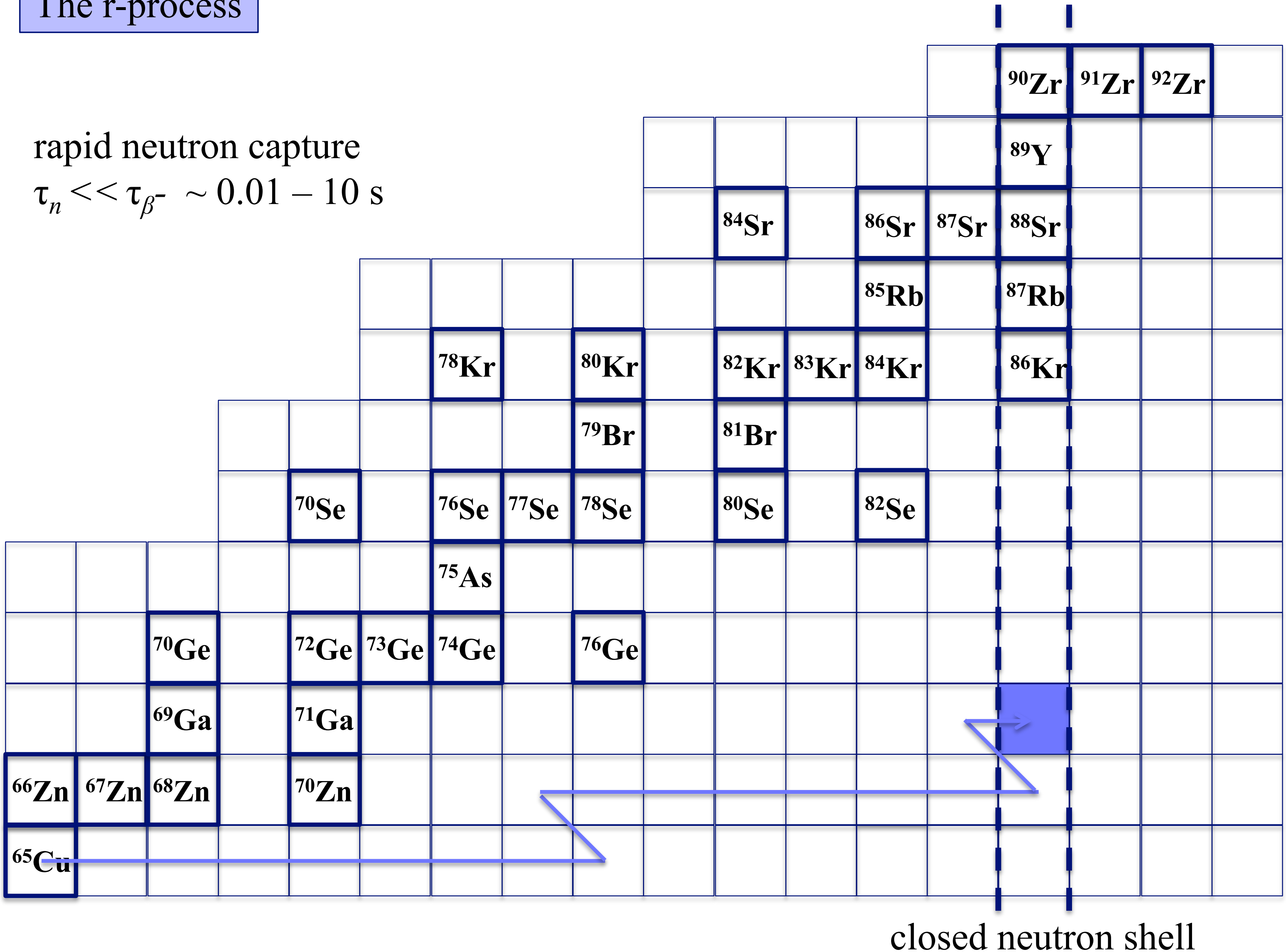

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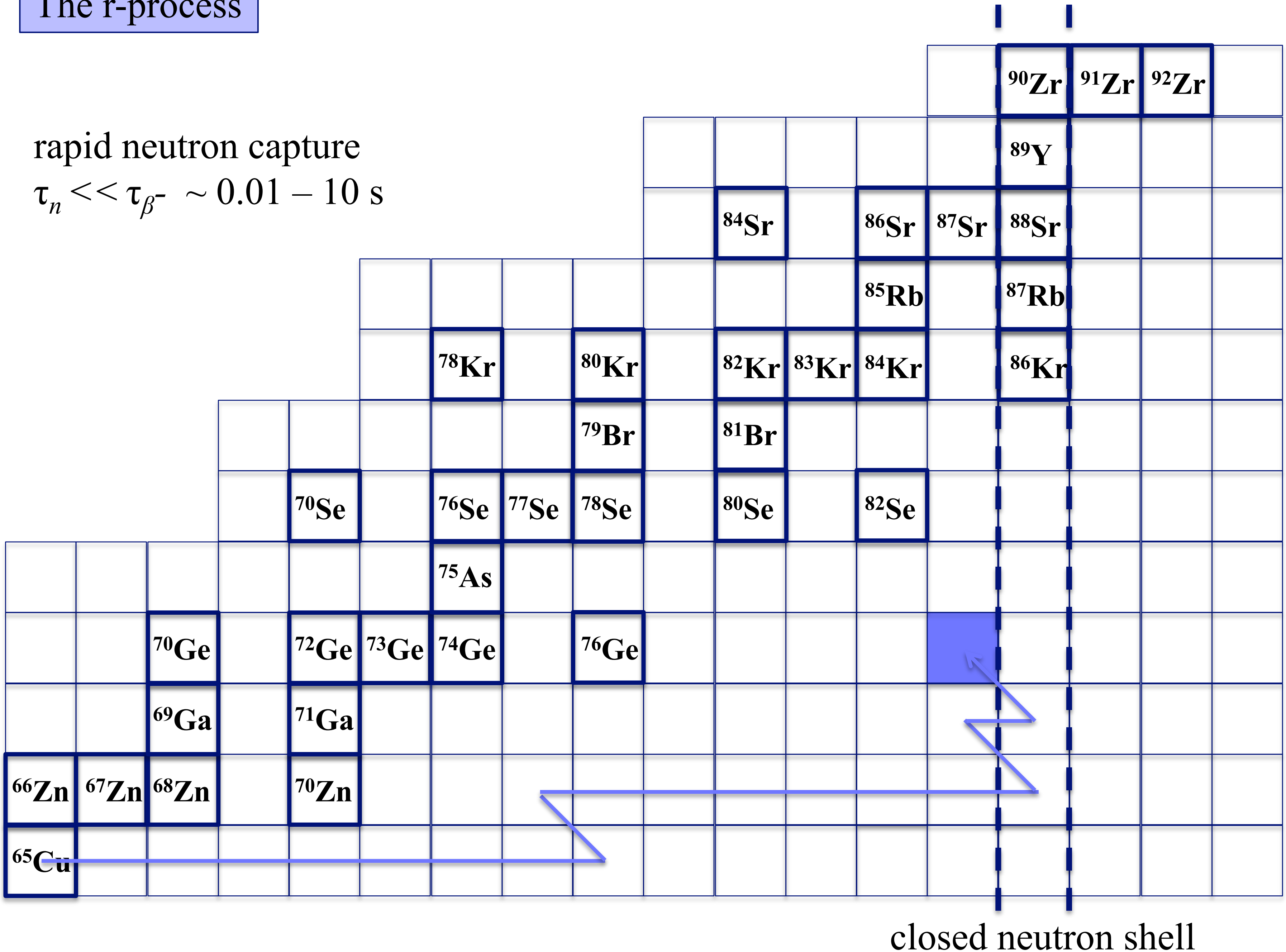

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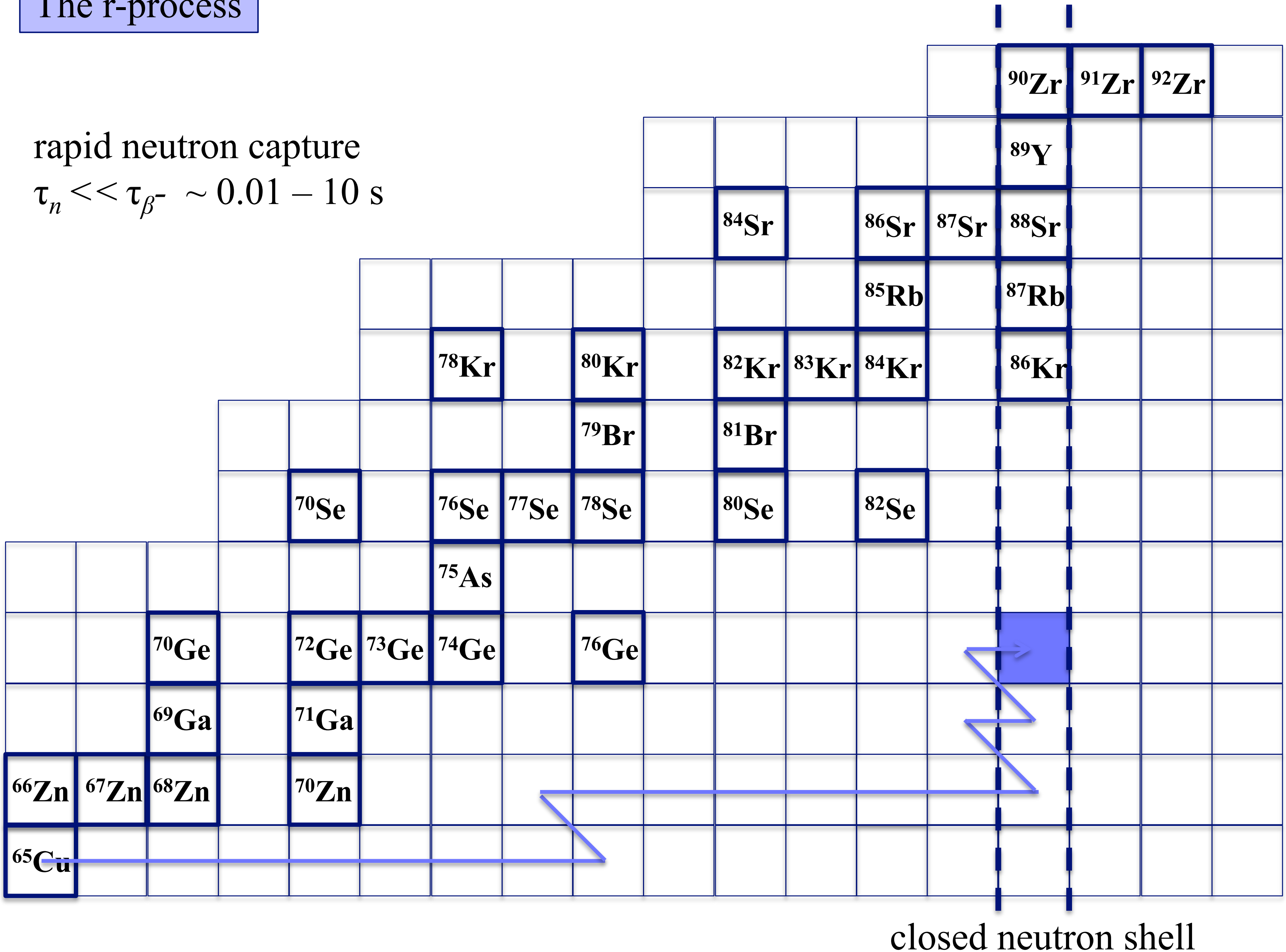

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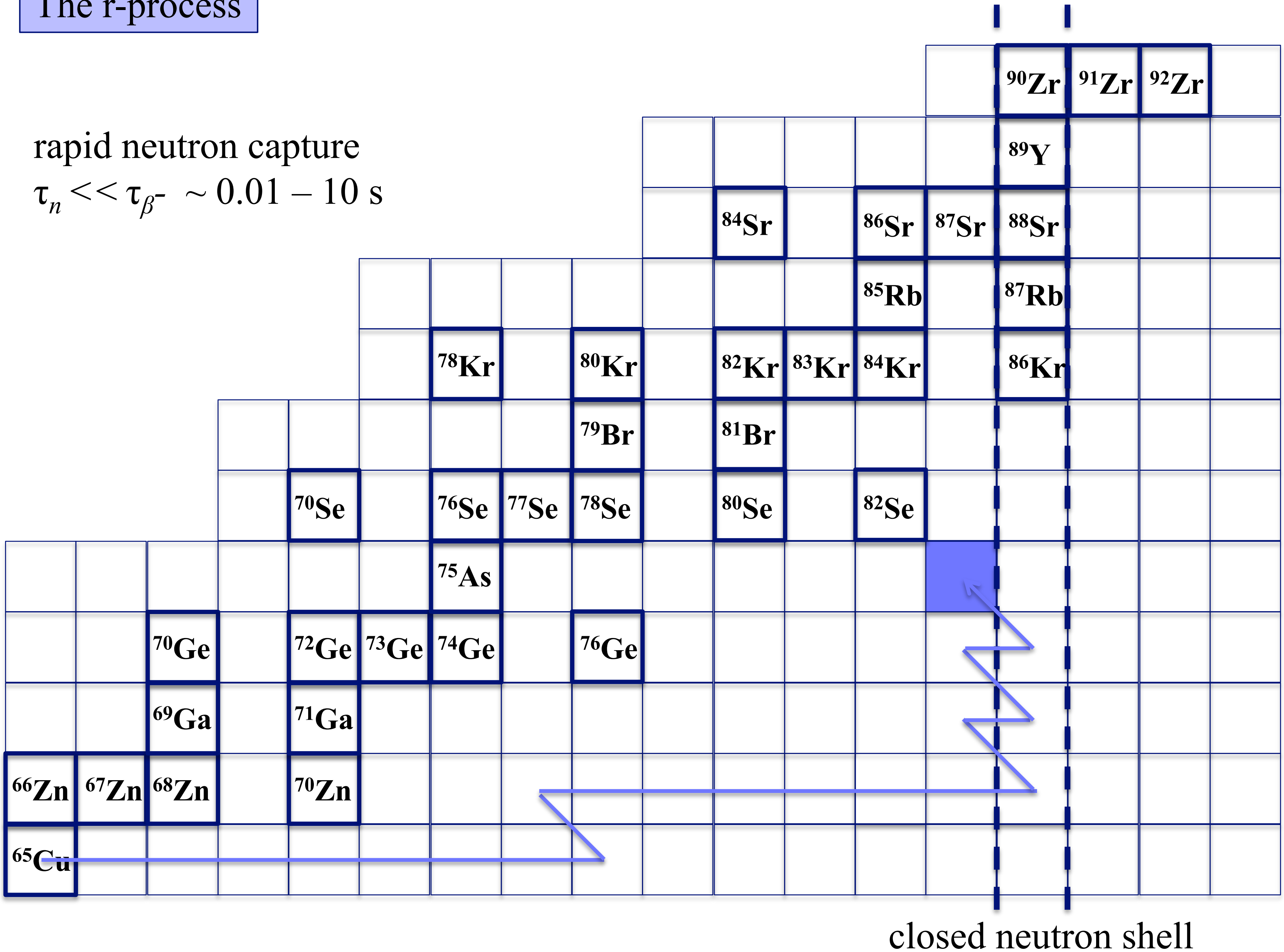

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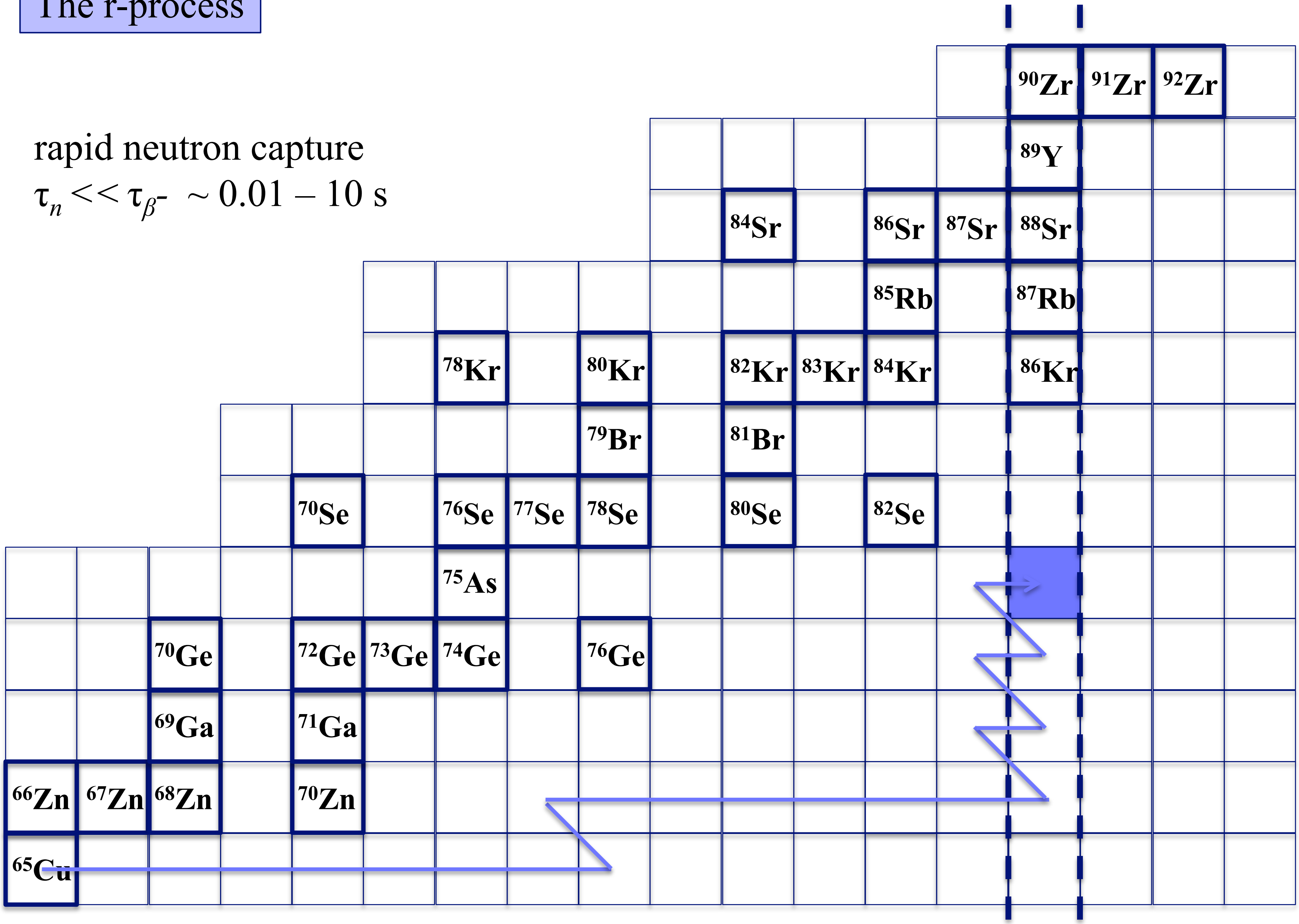

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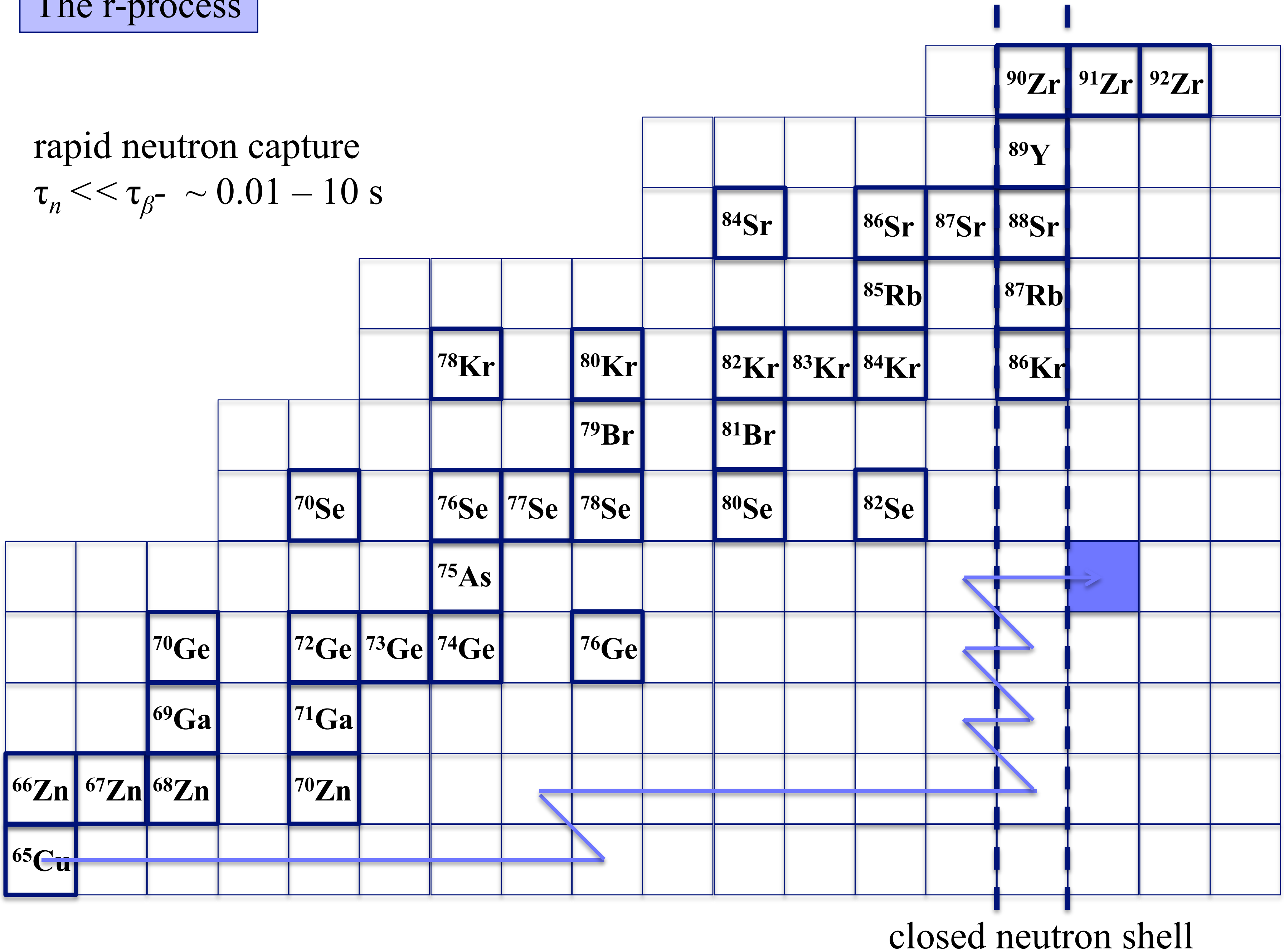

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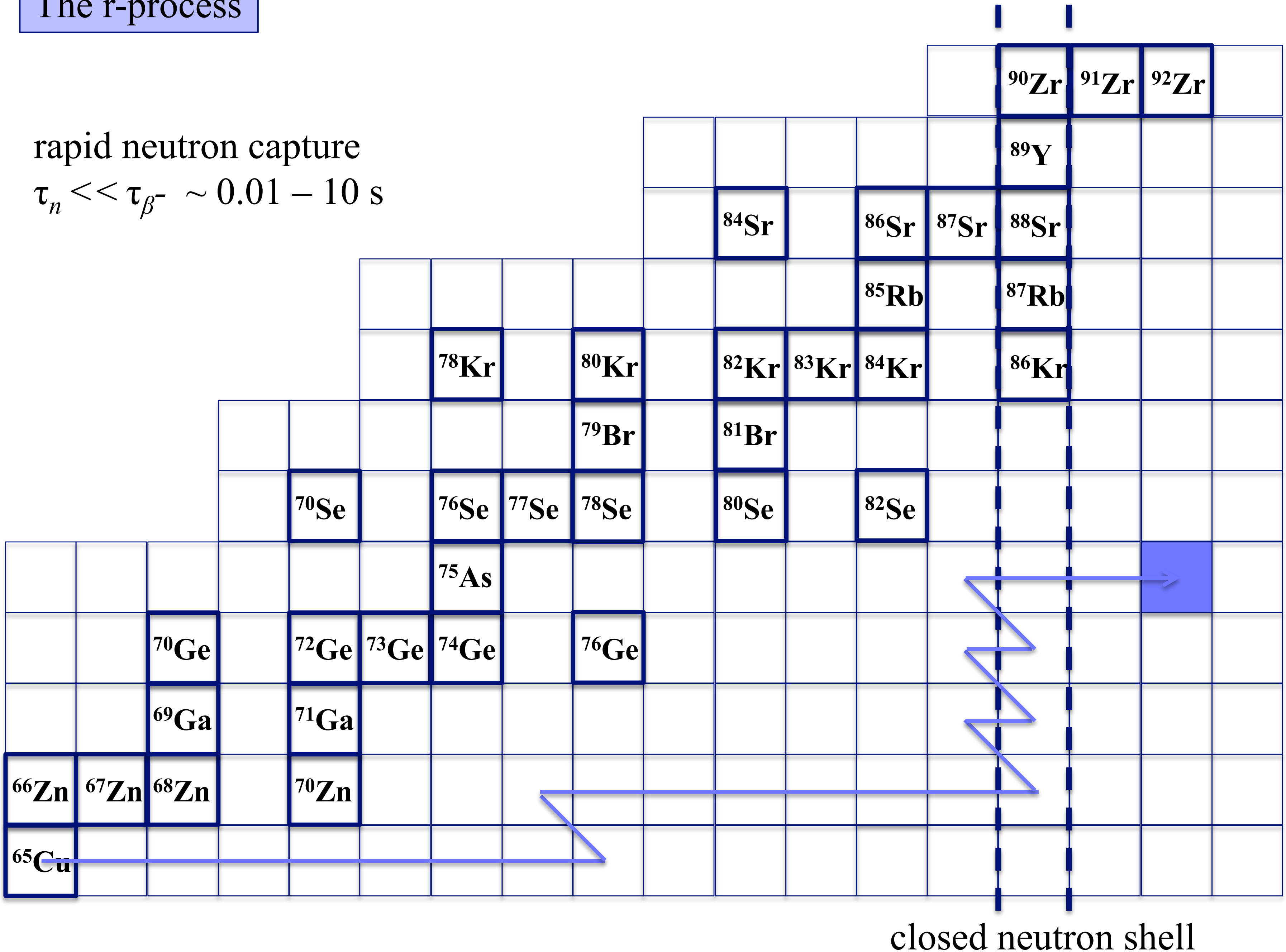

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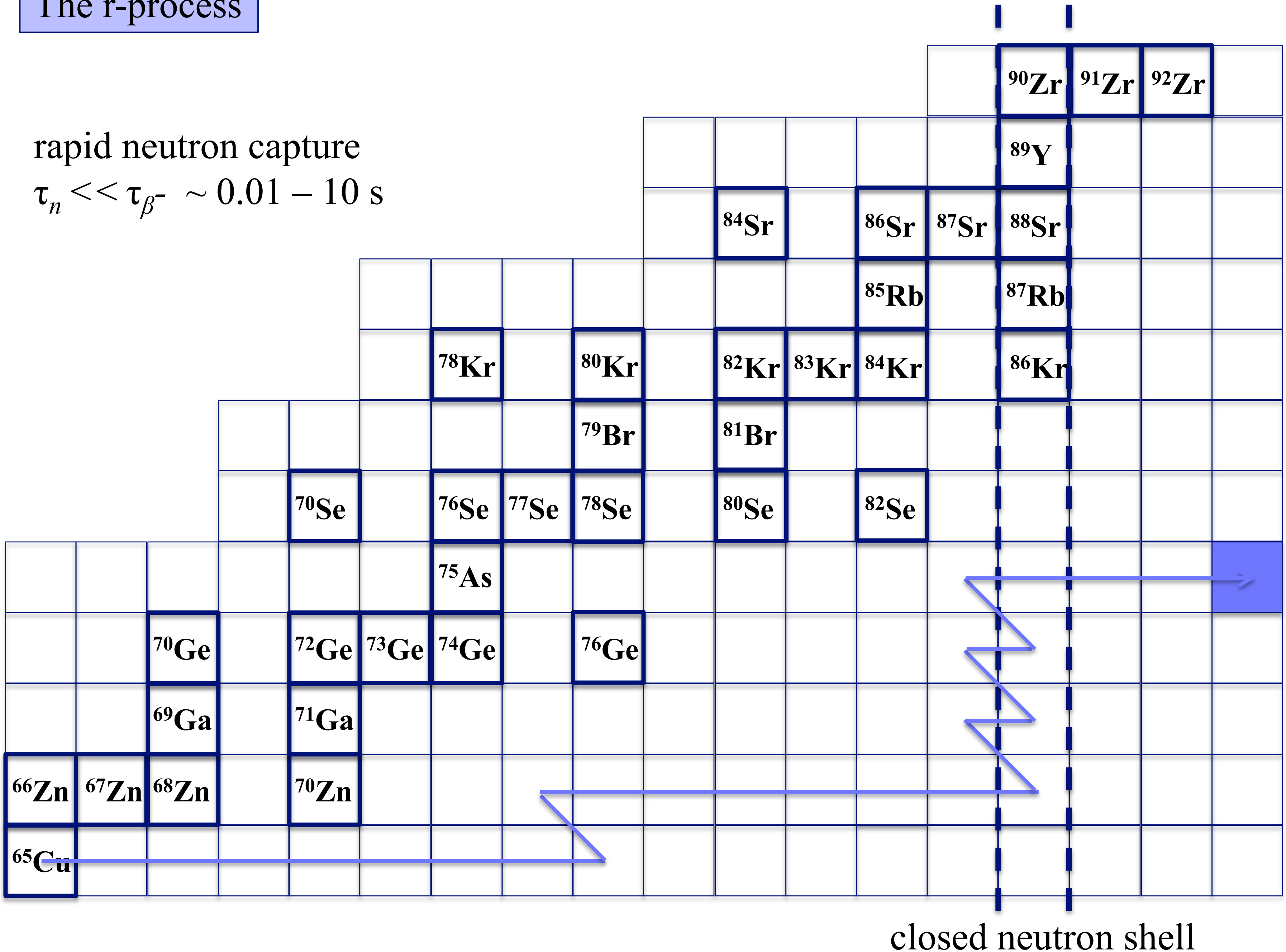

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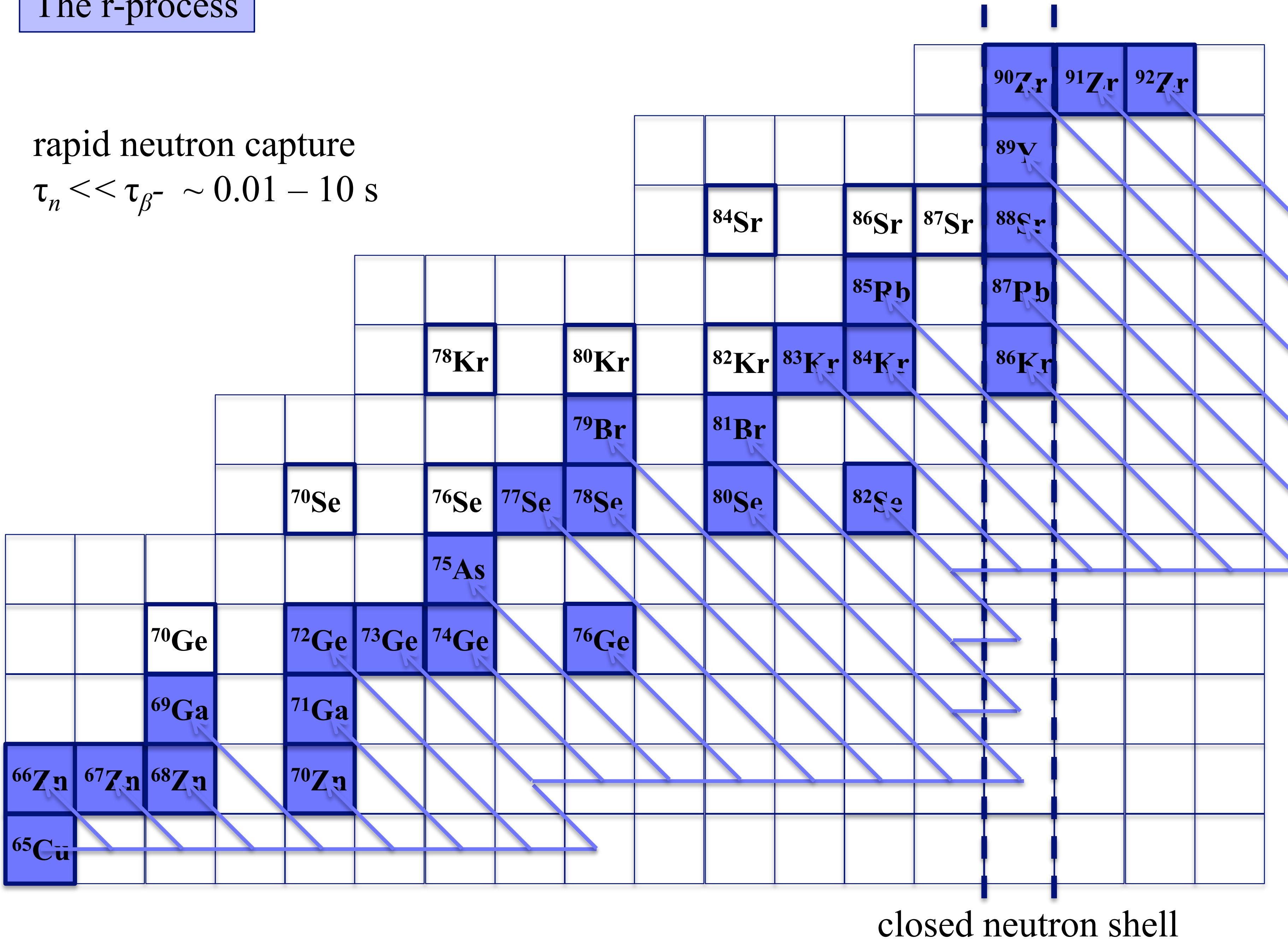

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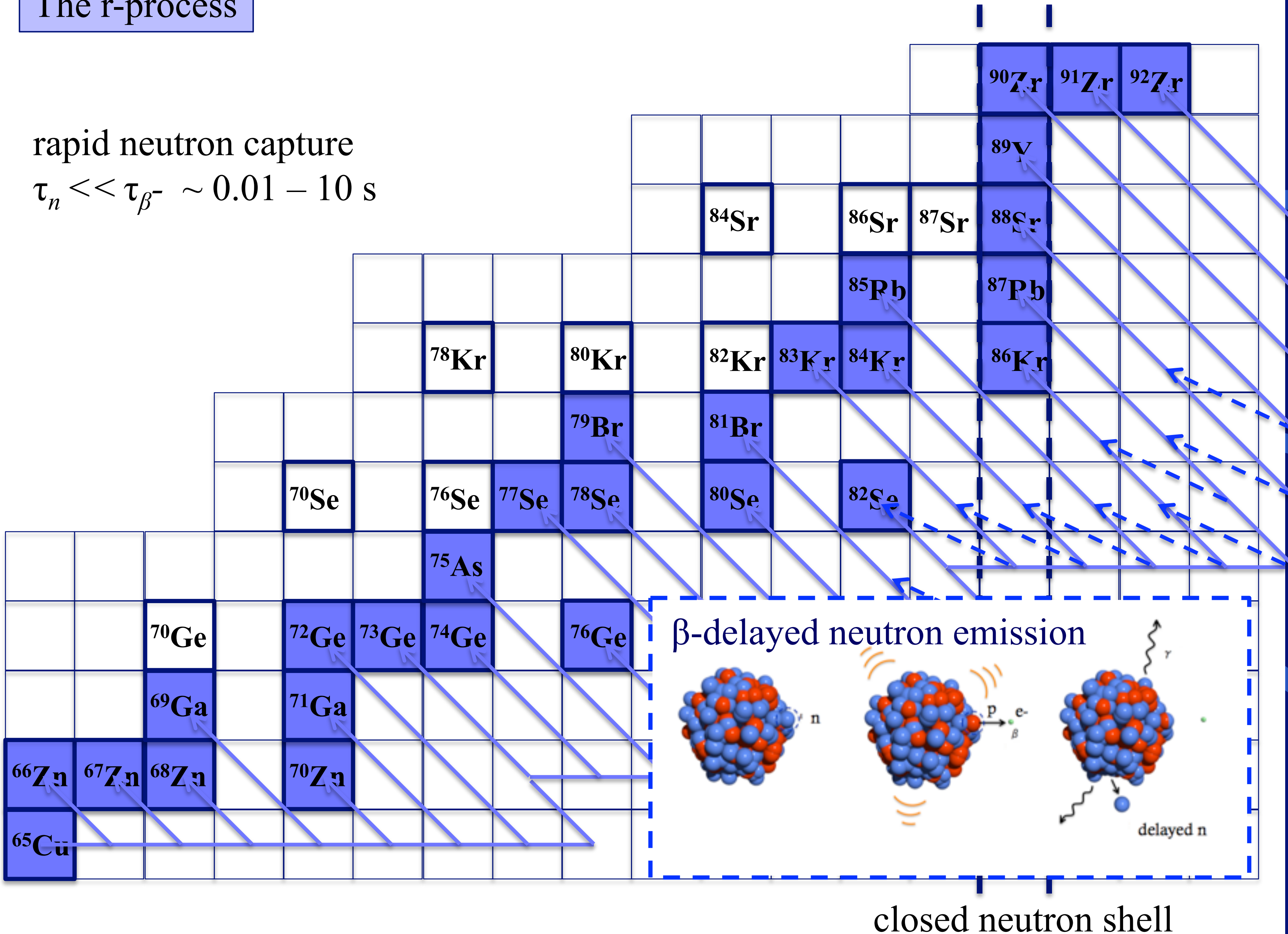

Double peaks due to closed neutron shells

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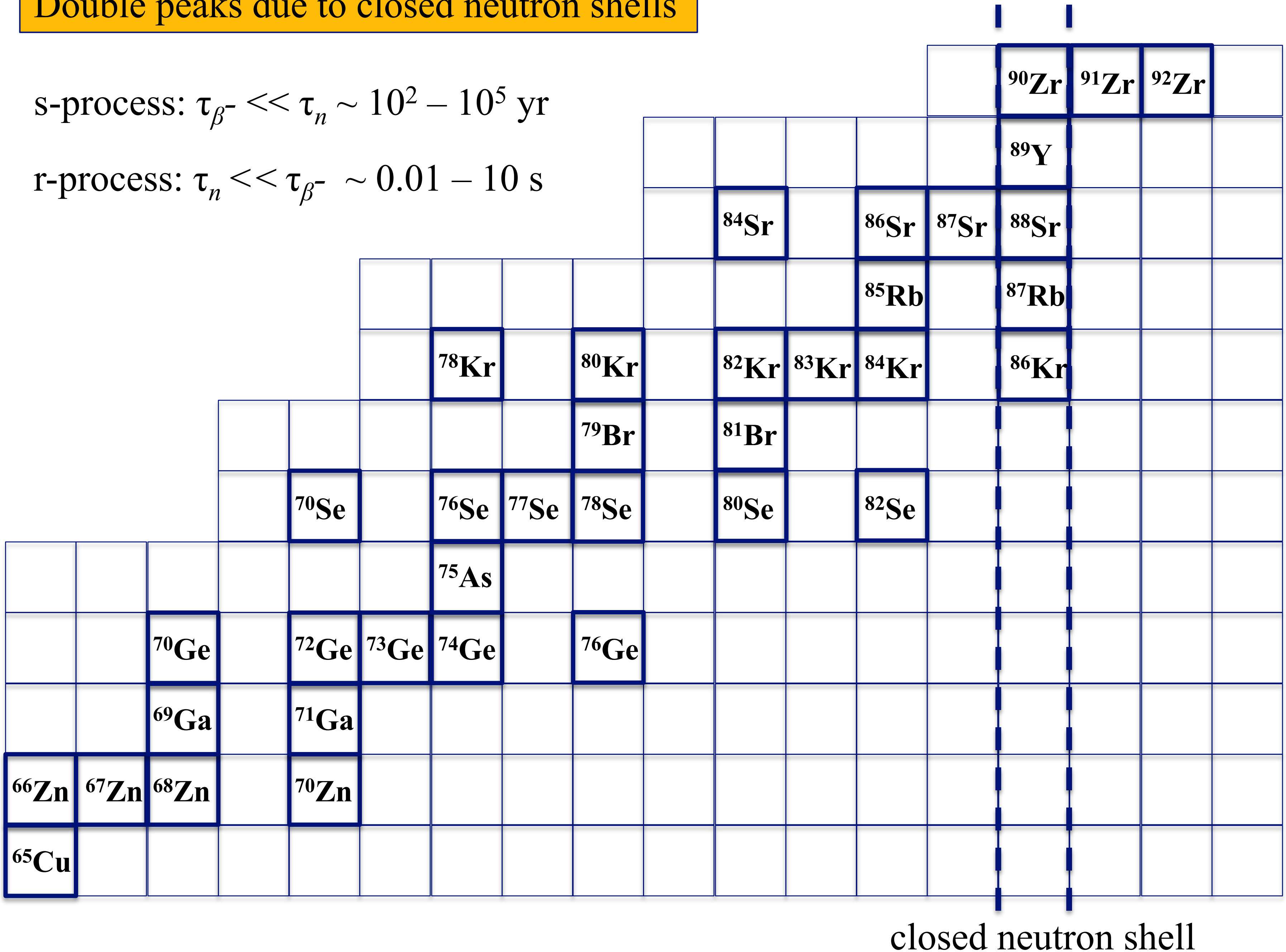

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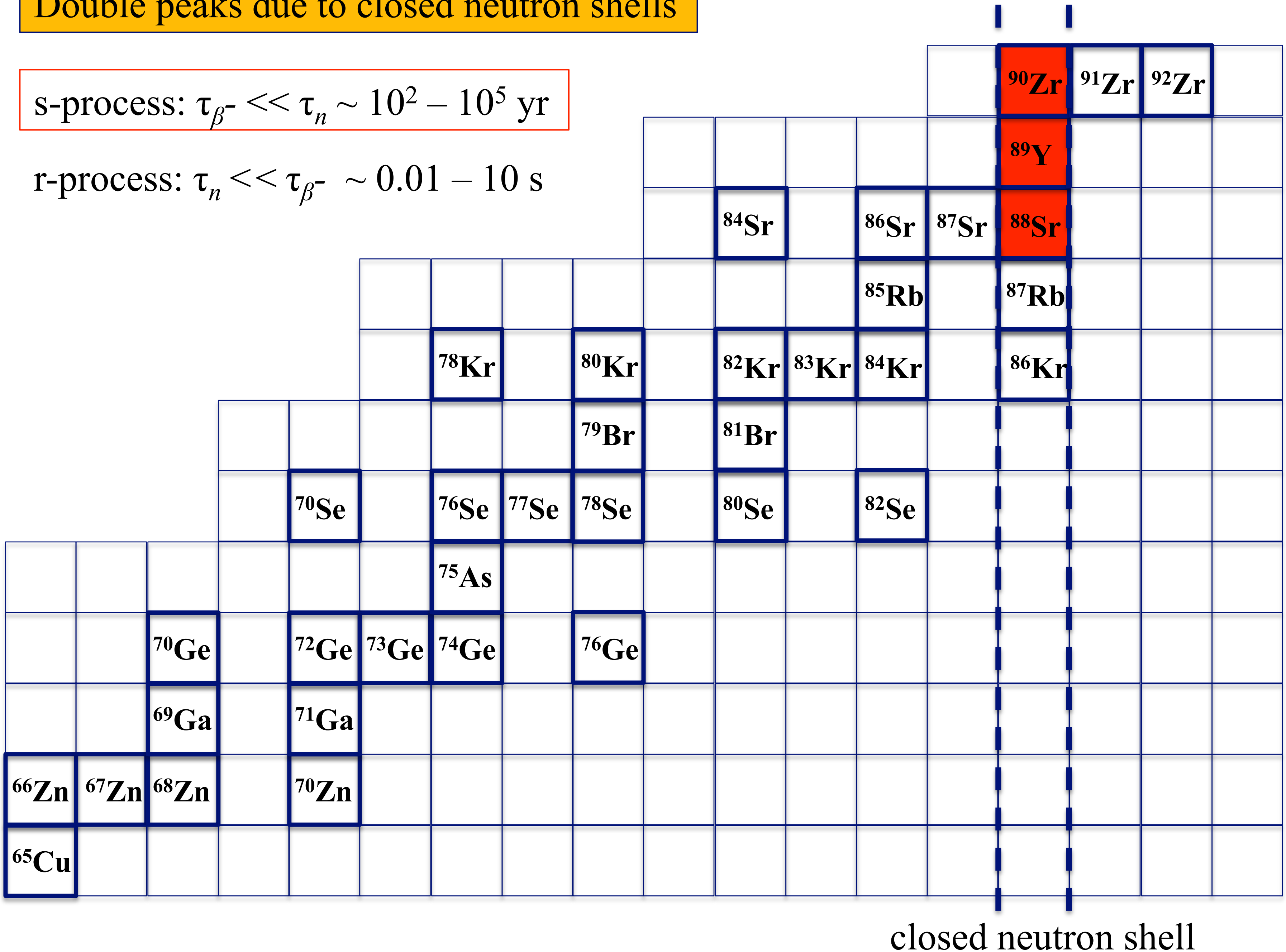

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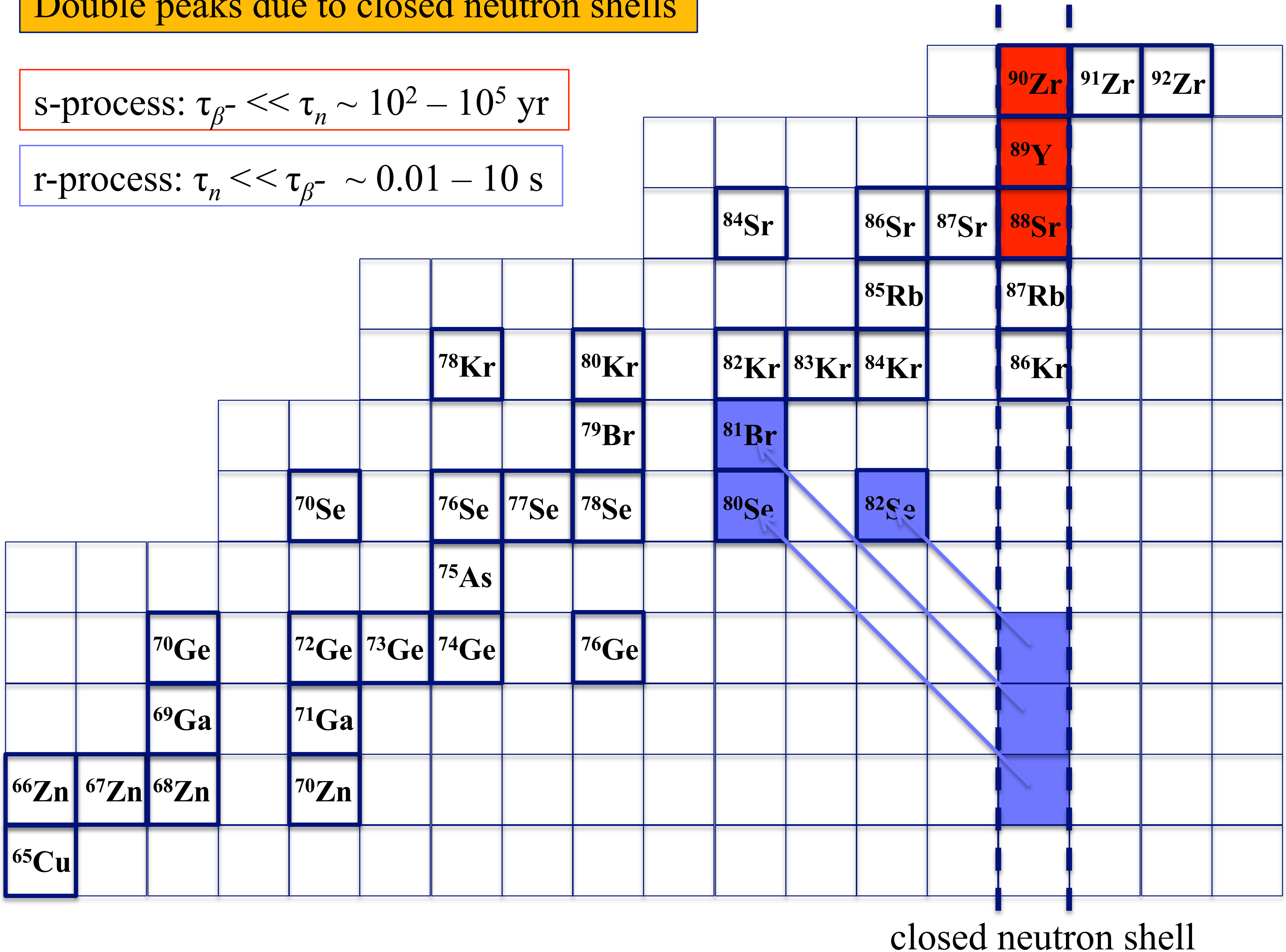
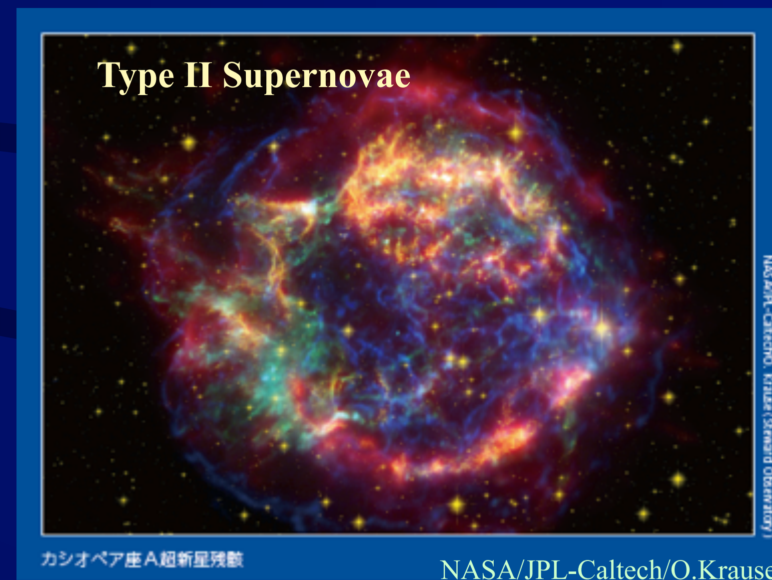


Where is the site of heavy elements ? (r-Process Nucleosynthesis)

S. Wanajo

- Extremely neutron-rich nuclei
- Very Rare to have two neutron stars close together.
- Not possible in 1st stars !?
  NS-BH ?



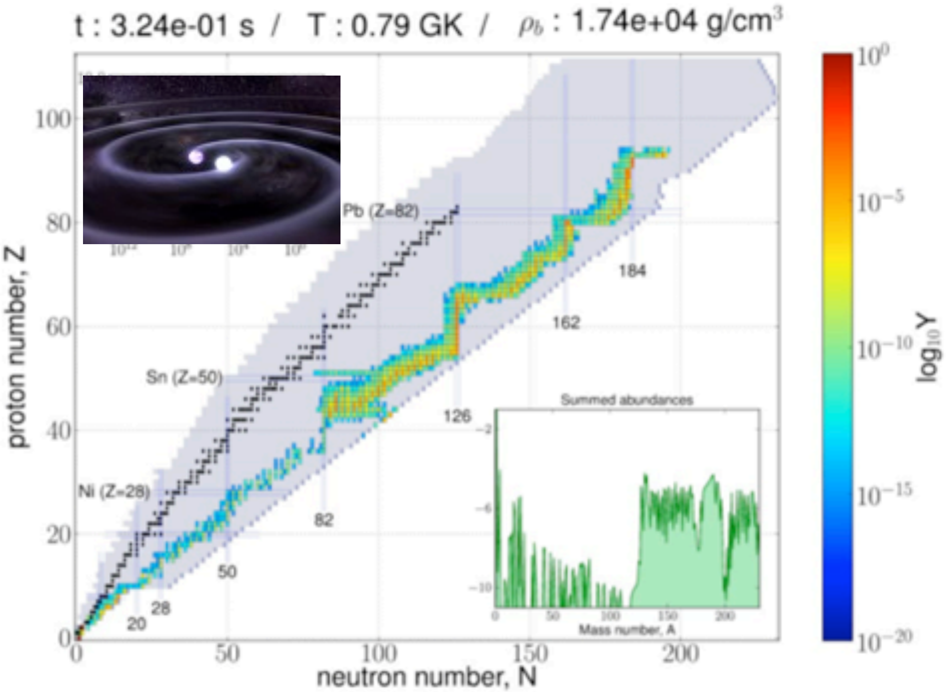
NASA/JPL-Caltech/O.Krause (Steward observatory)

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

N. Nishimura, T. Takiwaki, F.-K. Thielemann Astrophys. J. 810 109 (2015)

Nucleosynthesis for dynamic ejecta

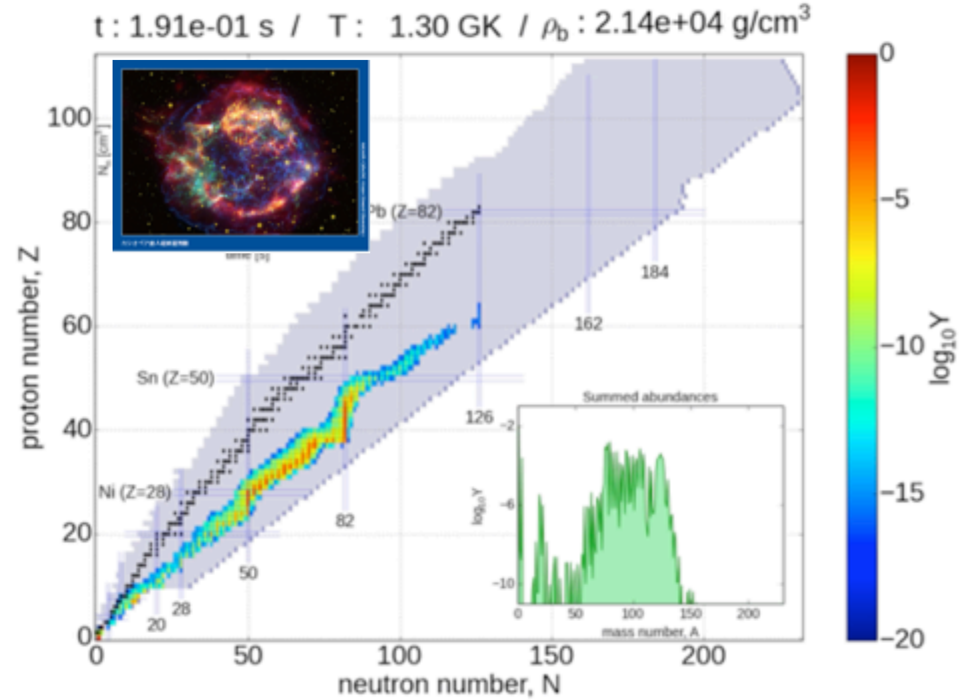
(snapshot; Korobkin et al. 2012)



- extremely neutron-rich (Ye ≈ 0.04)
- close to neutron drip-line
- extending to very large neutron (N≈ 200) and proton numbers (Z≈ 90)
- forging the heaviest elements (A>130) in the Universe (e.g. gold and platinum)

Nucleosynthesis for neutrino-driven winds

(snapshot; Martin et al. 2015)



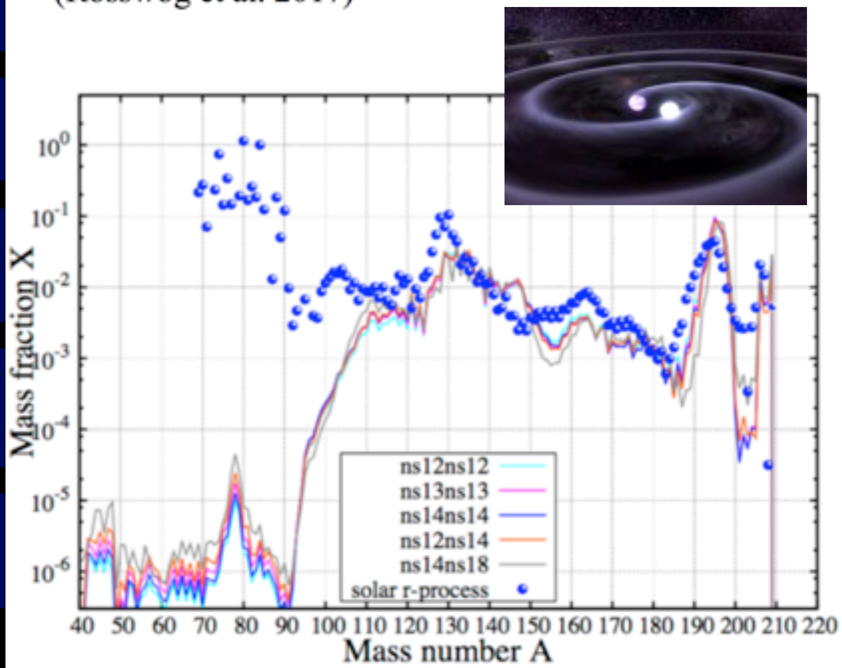
- neutron-rich, broad distribution (0.2< Ye < 0.4)
- further away from neutron drip-line
- extending to moderately large neutron and proton number
- forging heavy elements, but usually with nucleon numbers A < 130

http://compact-merger.astro.su.se/Macronovae_04_2017.html

S. Rosswog, U. Feindt, O. Korobkin et al. arXiv:1611.09822

Nucleosynthesis for dynamic ejecta

(Rosswog et al. 2017)



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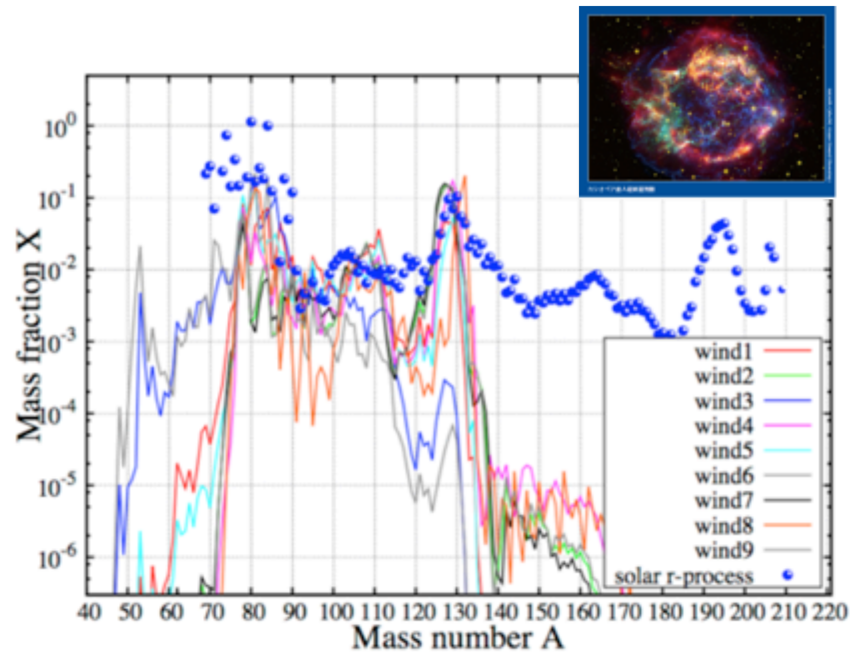


- the heaviest elements, A>130
- robustly producing the "platinum peak" at A= 195
- very little variation between different mergers

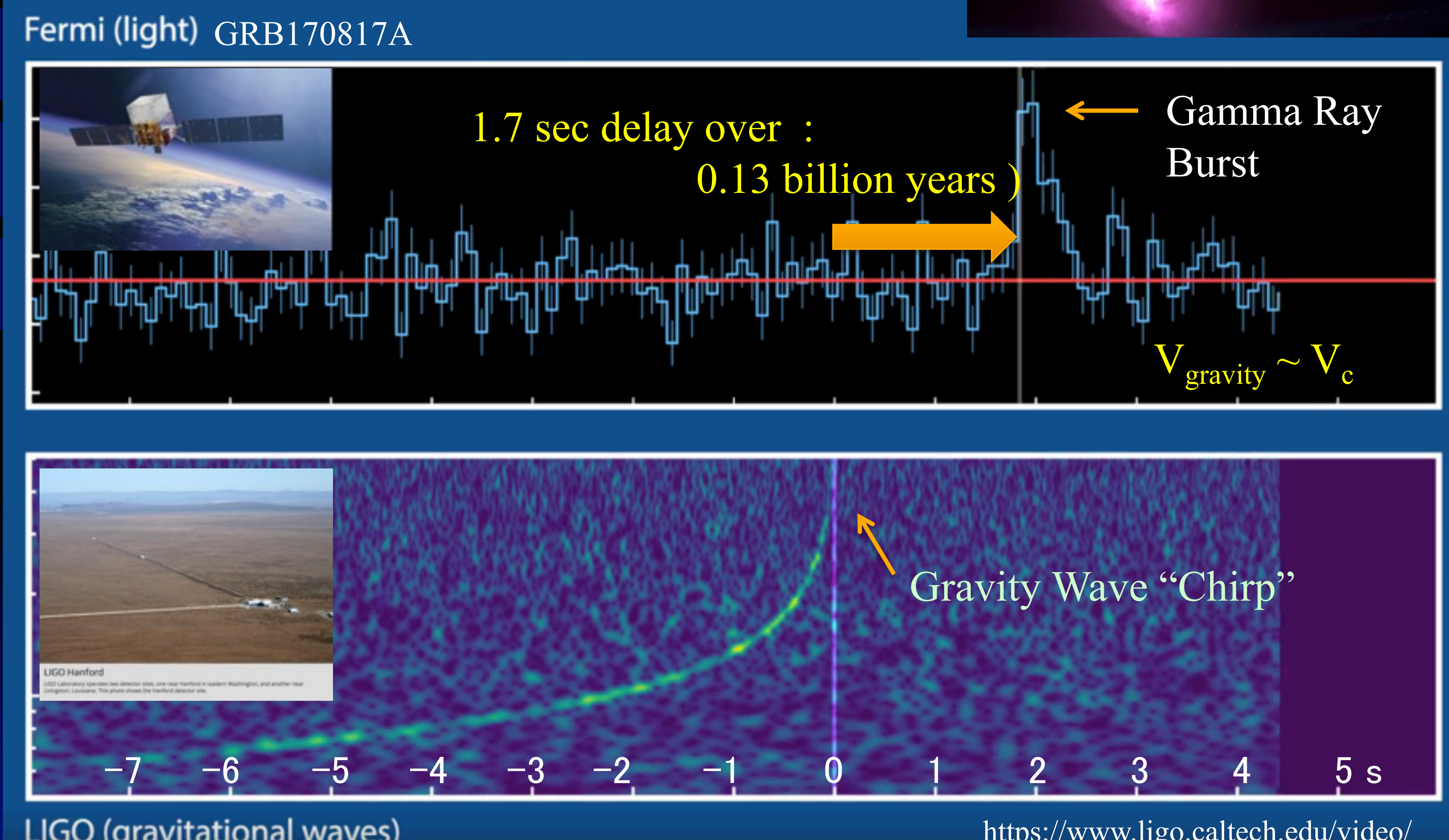
- lighter r-process elements, A <130
- large variation between different astrophysical events expected

⇒ together, they add up to the solar abundance pattern (blue dots)

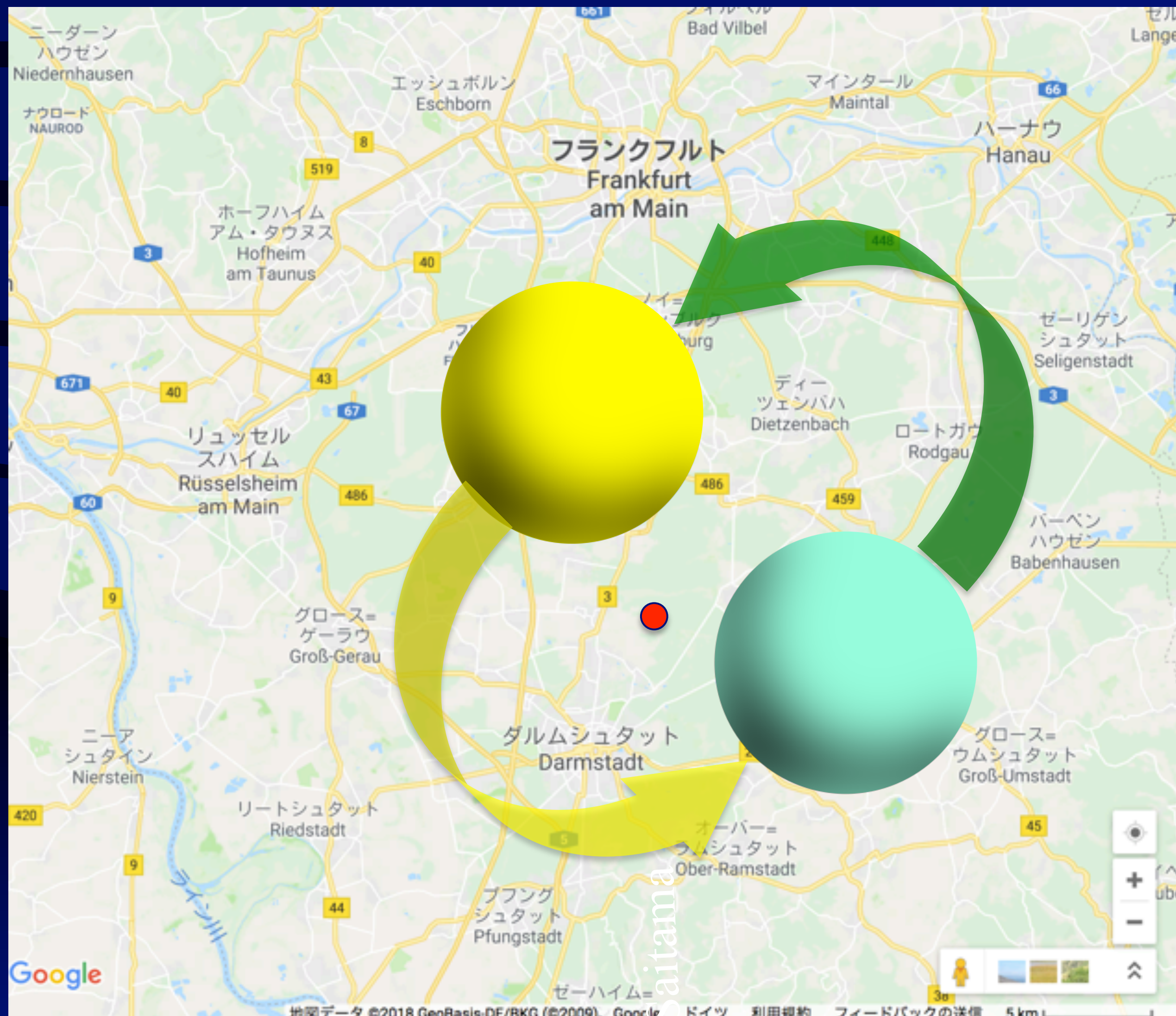
Key: We need properties of very neutron-rich nuclei.

GW170817
Neutron Stars Merger !

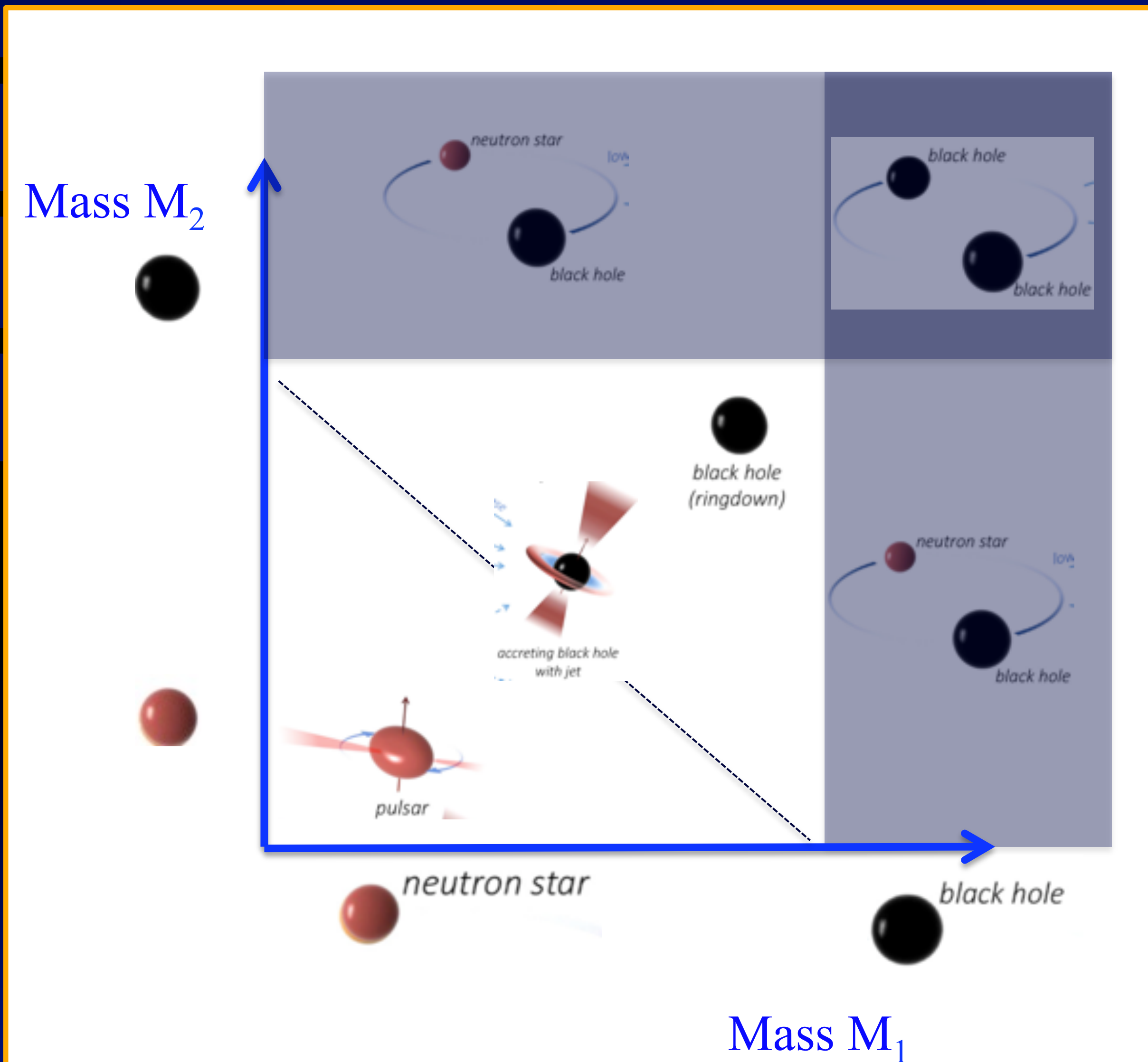
Aug. 17, 2017



Neutron Star Merger : Scale



Mapping “NS-NS”, “NS-BH” Merger Events



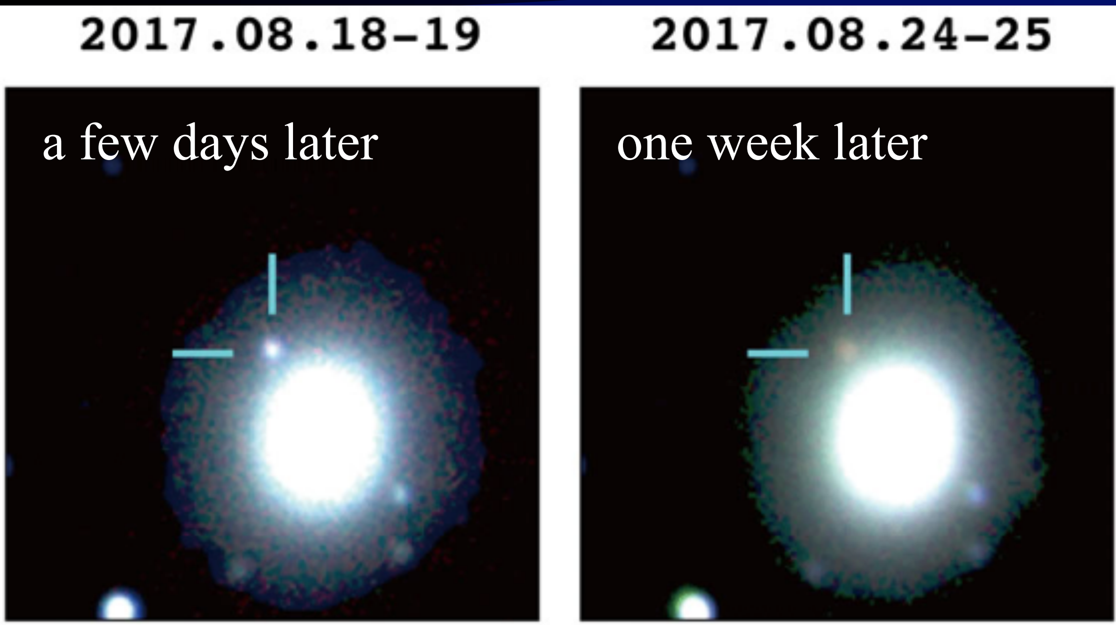
Observation

(as func. of time)

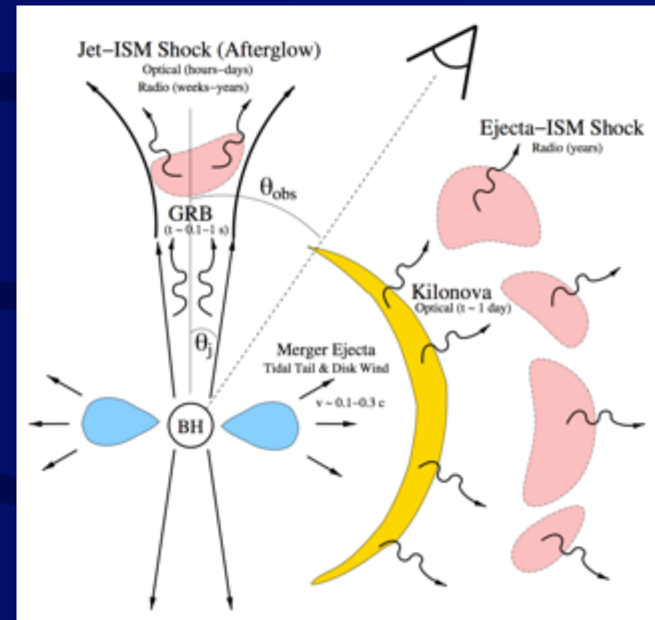
GW
Kilonova
GRB
: :

Nuclear Physics
EOS, Reactions,
Mass, Decay, …

kilonova after Neutron Star Merger



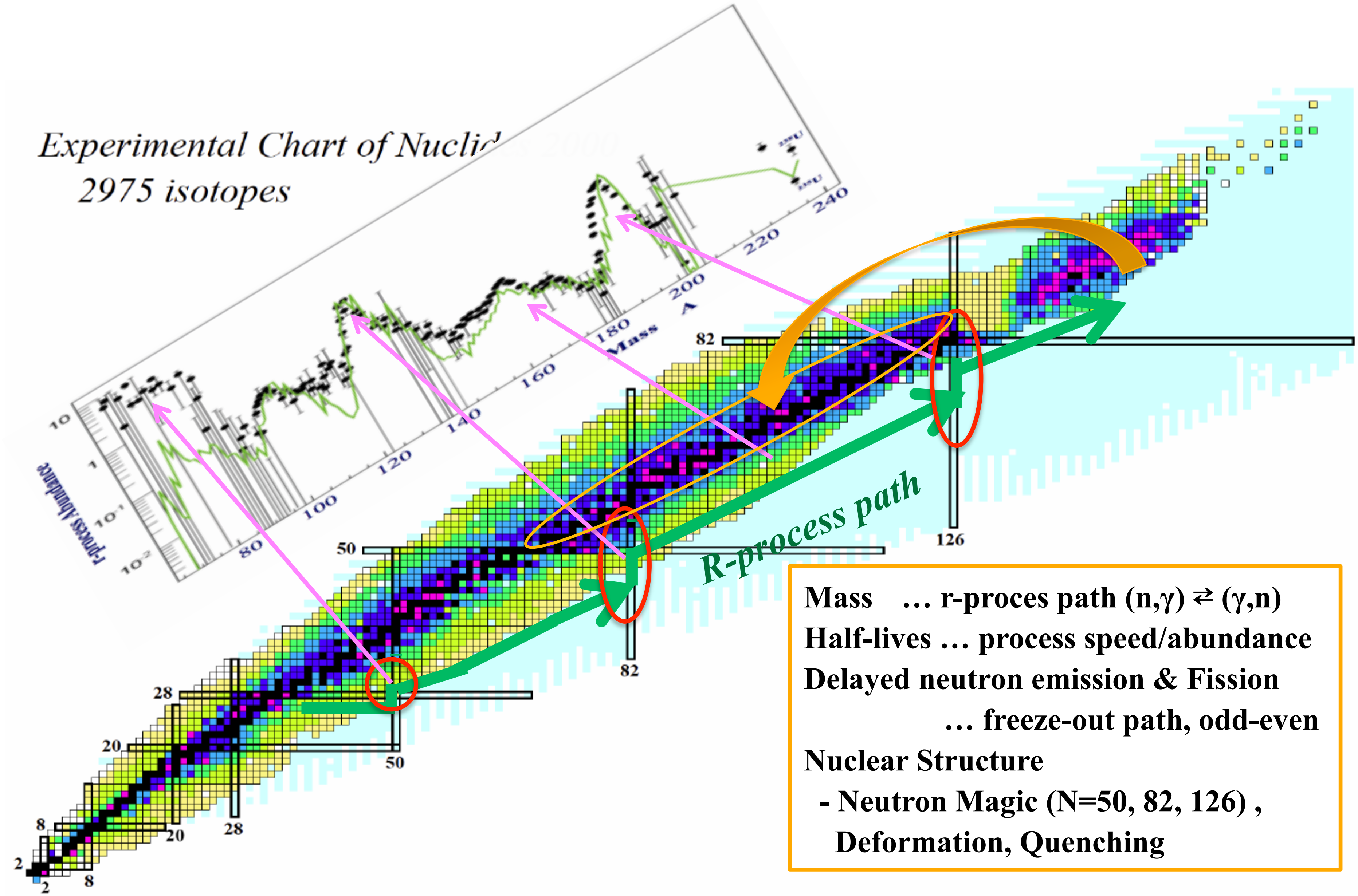
Credit: NAOJ/Nagoya Univ.



Radiation from radioactive isotopes (RI).

Is there any evidence of fission recycling? → Au, Pt, U

Nuclear Properties are Key Inputs



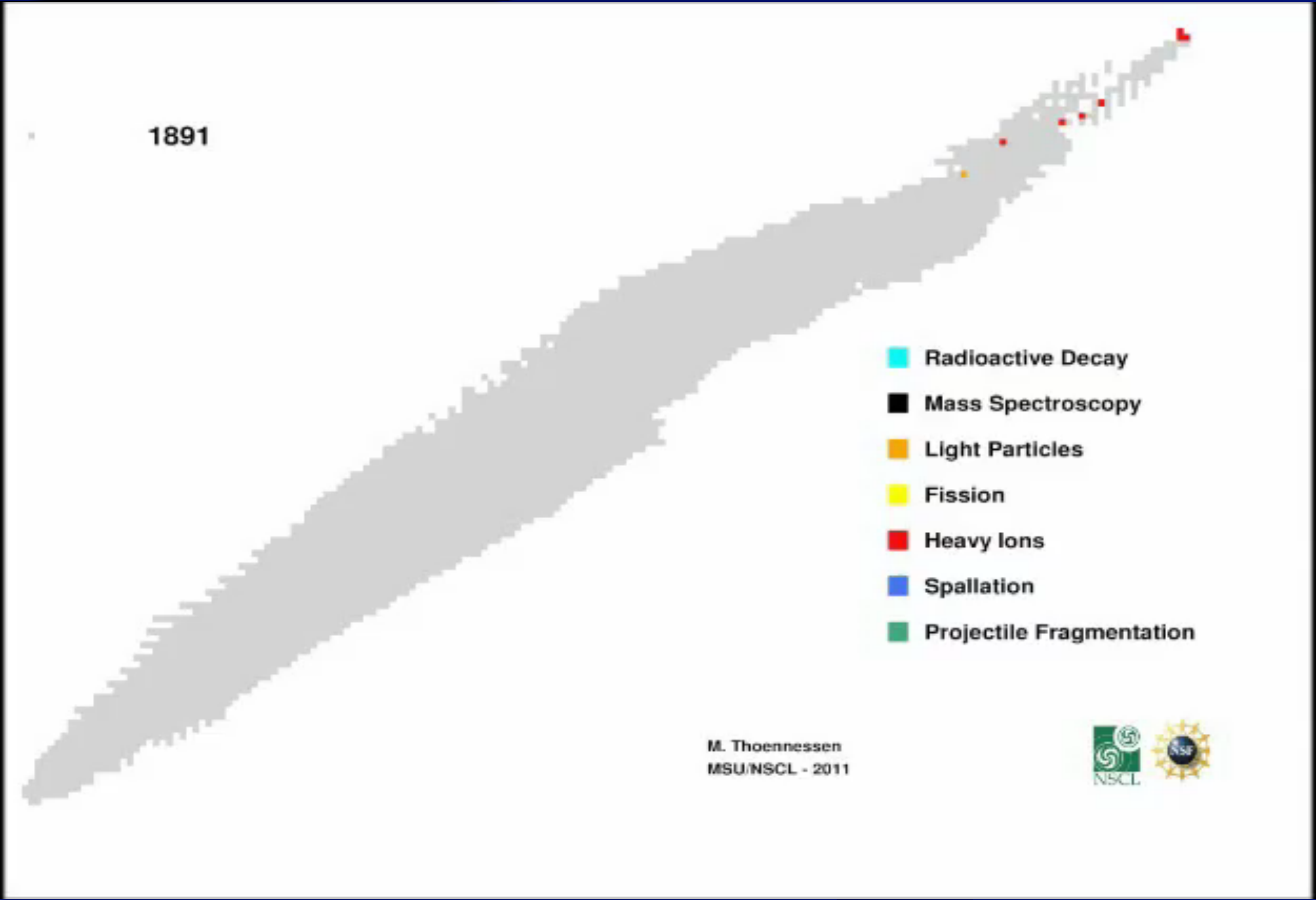
Mass … r-proces path (n,γ) ⇄ (γ,n)
Half-lives … process speed/abundance
Delayed neutron emission & Fission
… freeze-out path, odd-even
Nuclear Structure
- Neutron Magic (N=50, 82, 126) ,
Deformation, Quenching

r-Process Nucleosynthesis

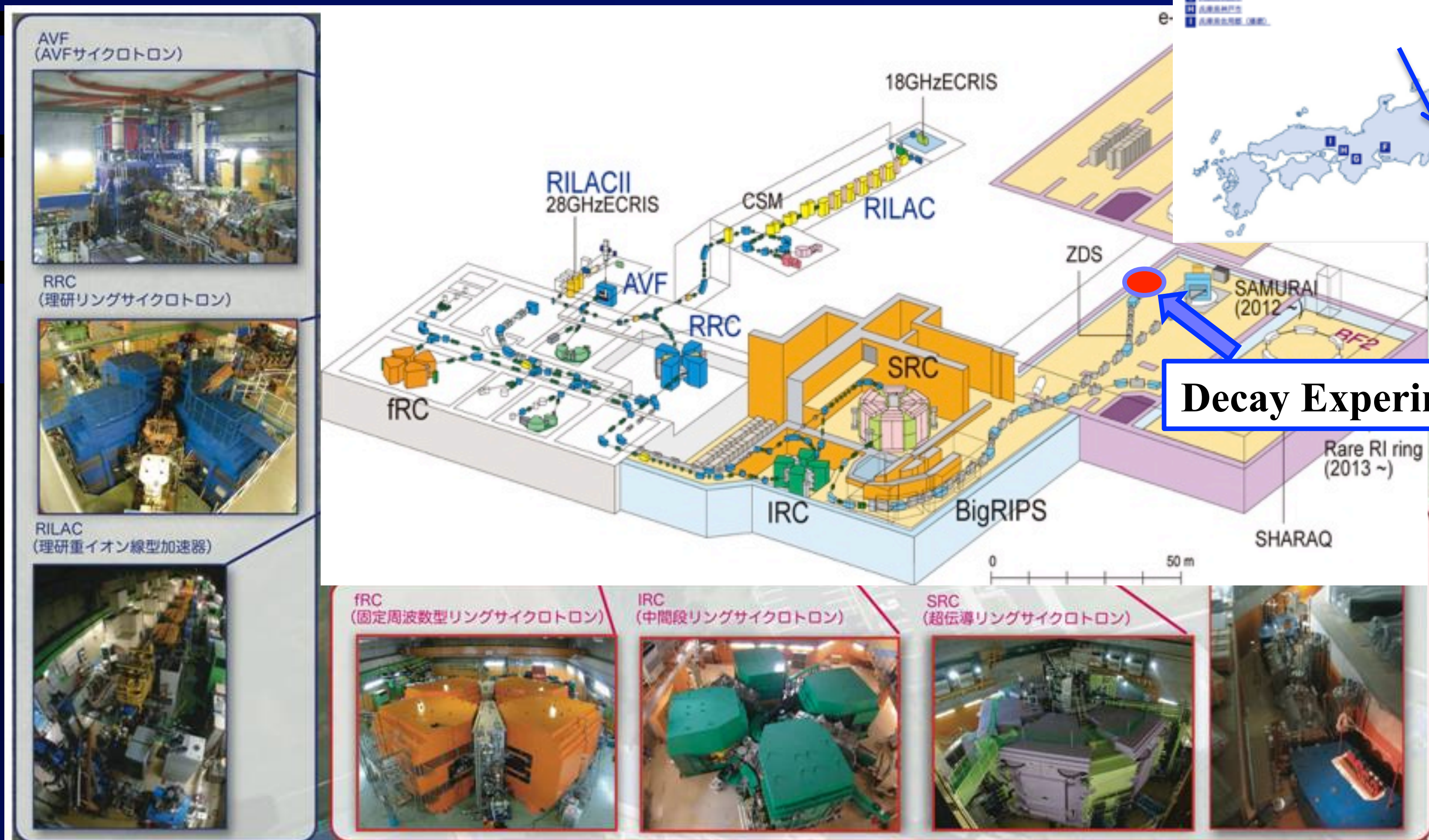
Reproduction of r-Process Nuclei in the Experiment

Oh ! it is not easy at all .

New Isotope Search (History)

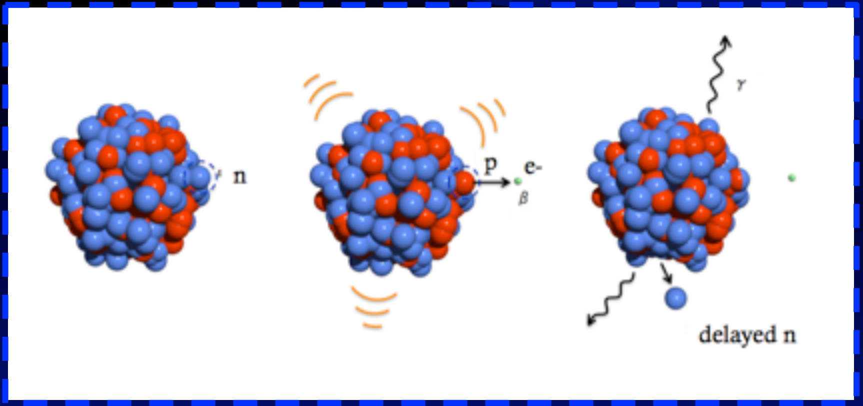


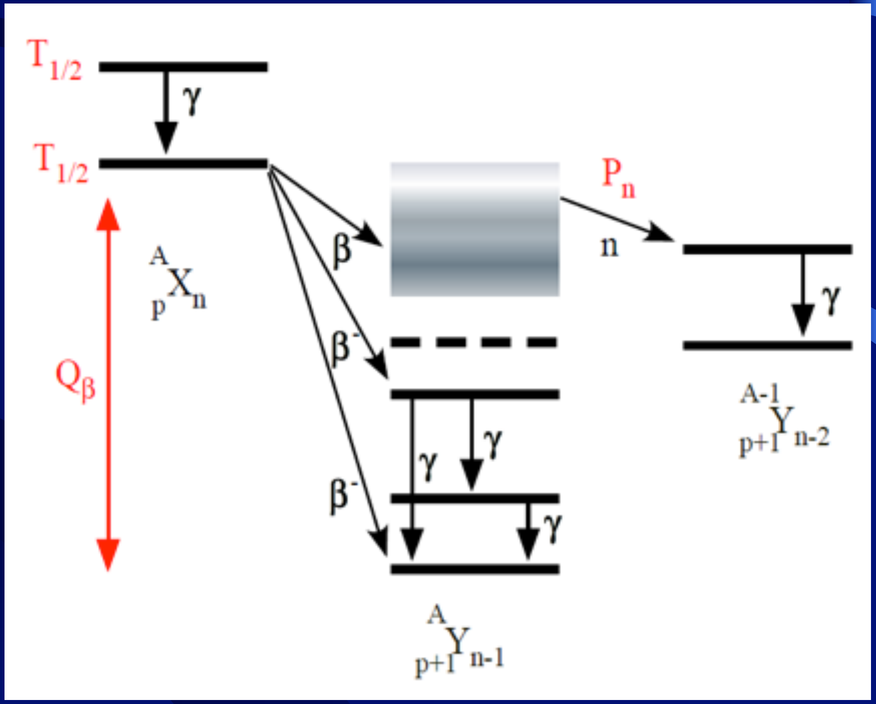
RI Beam Factory (RIBF)



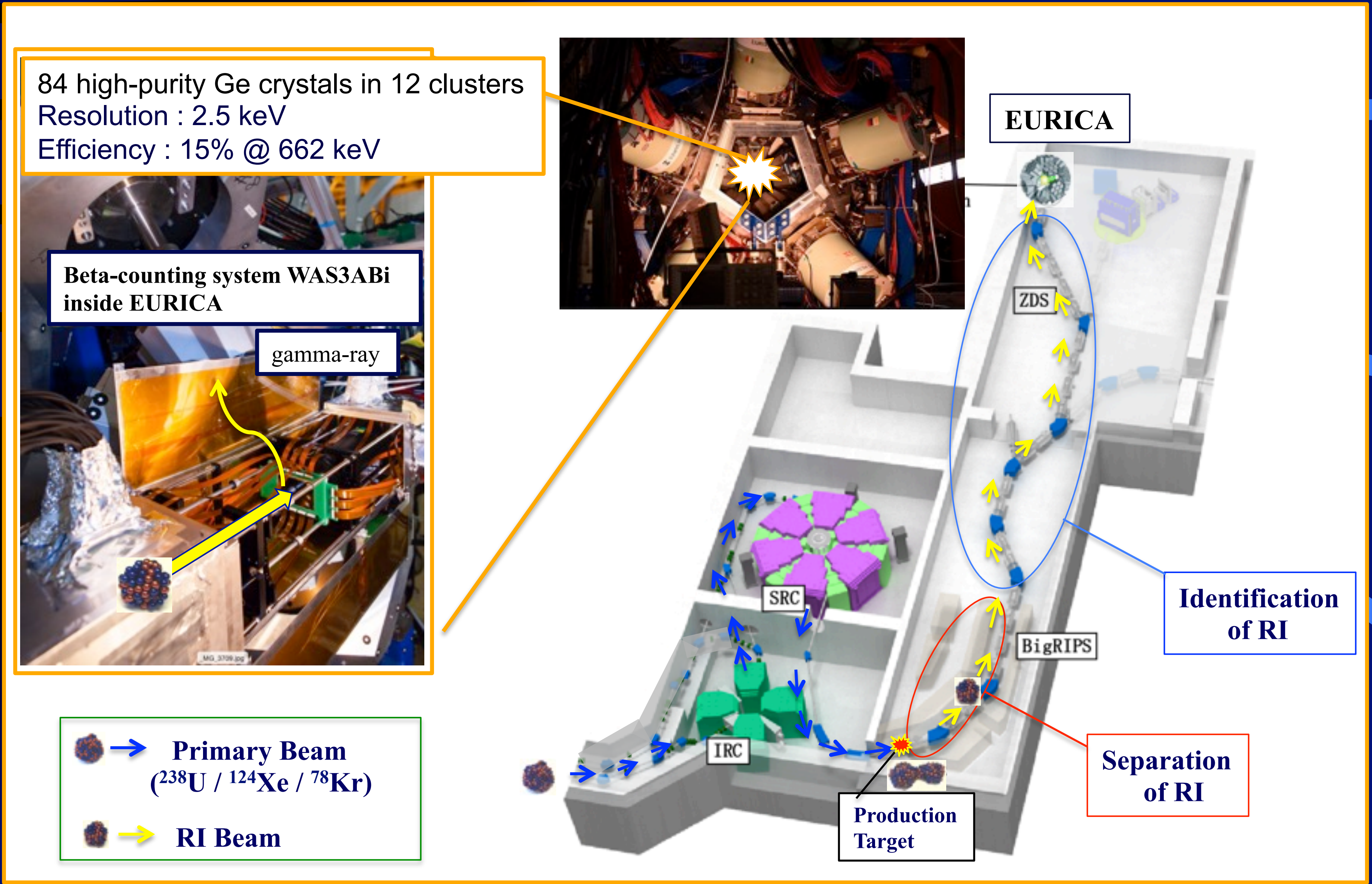
※All accelerators and experimental facilities are underground.

Decay Spectroscopy

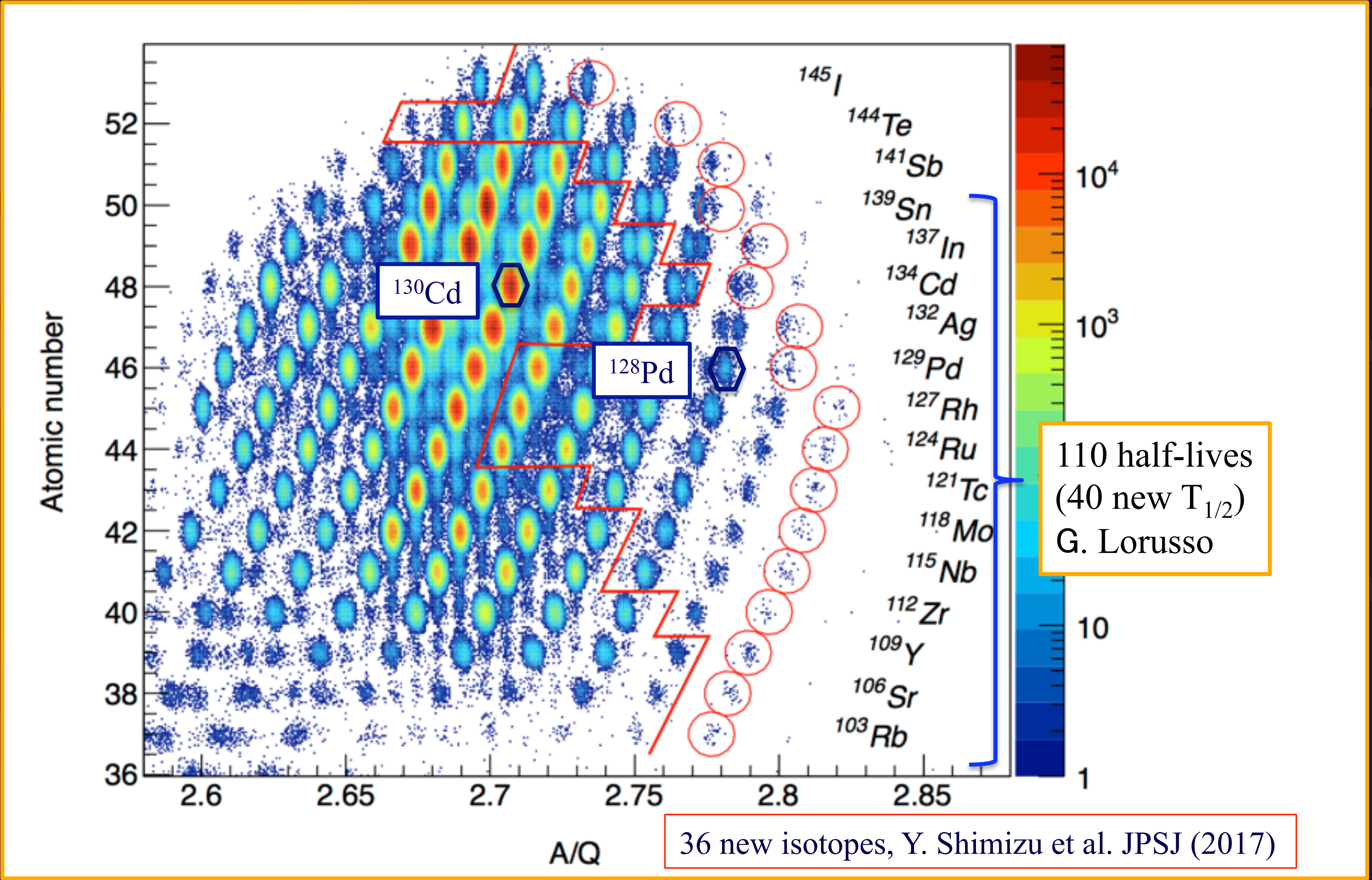




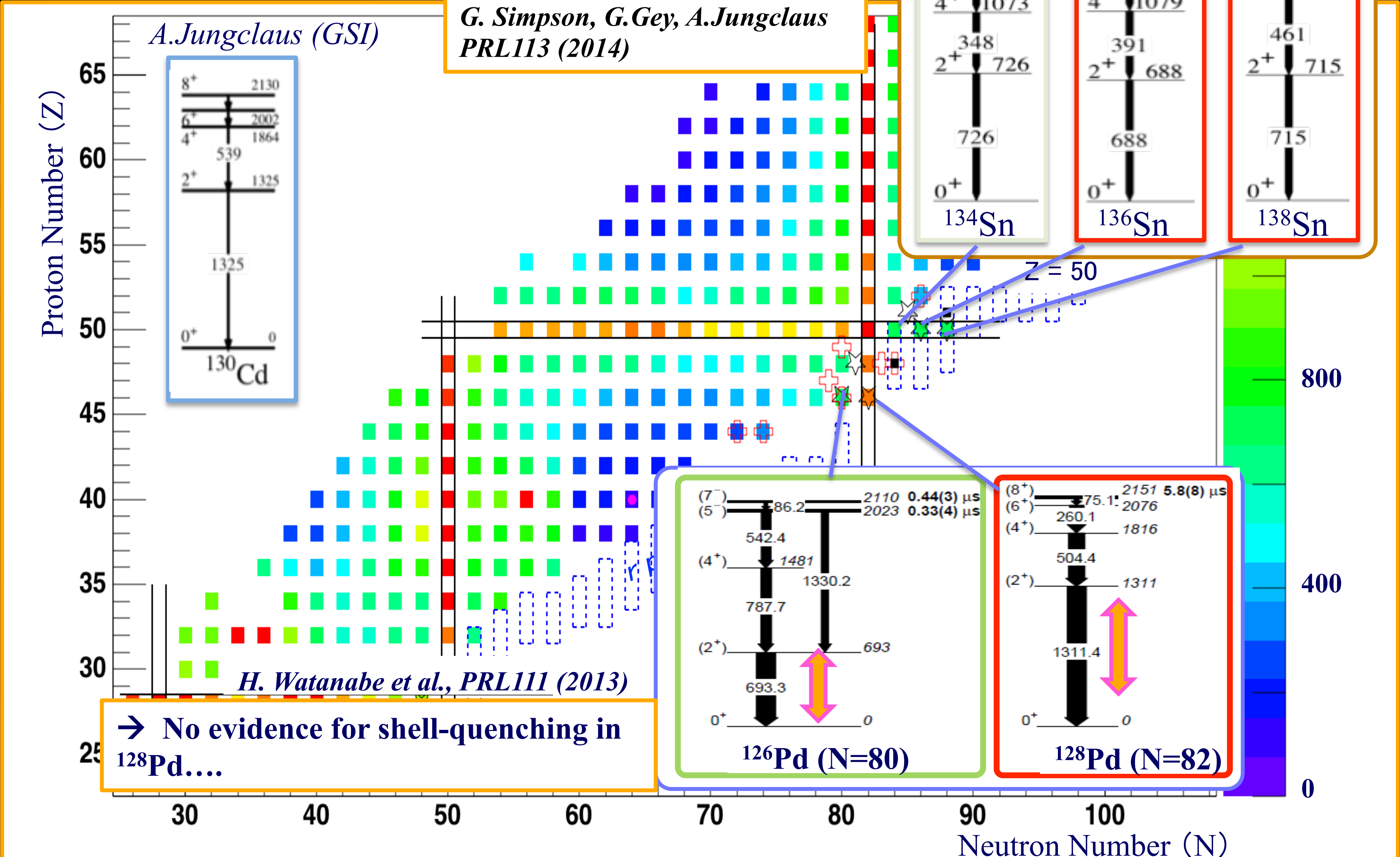
Decay Spectroscopy: EURICA



β-decay half-lives on r-process path

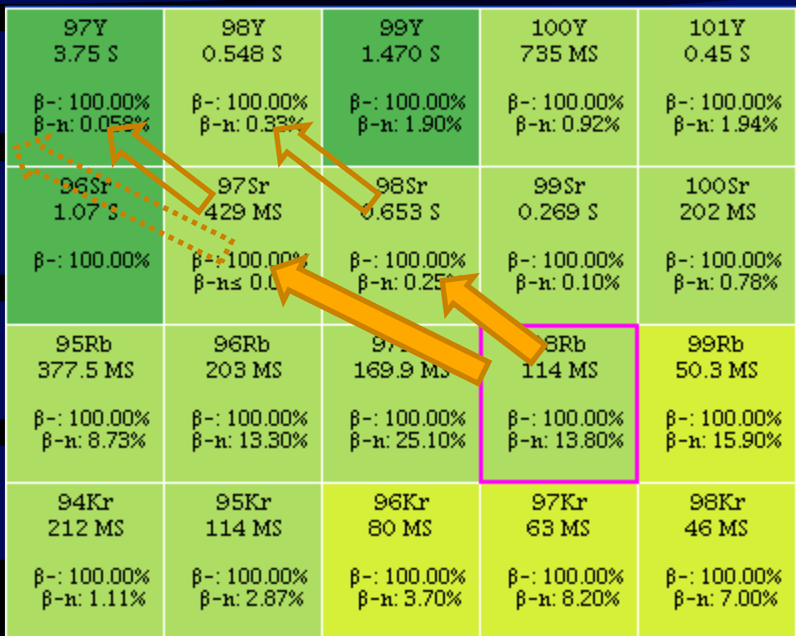


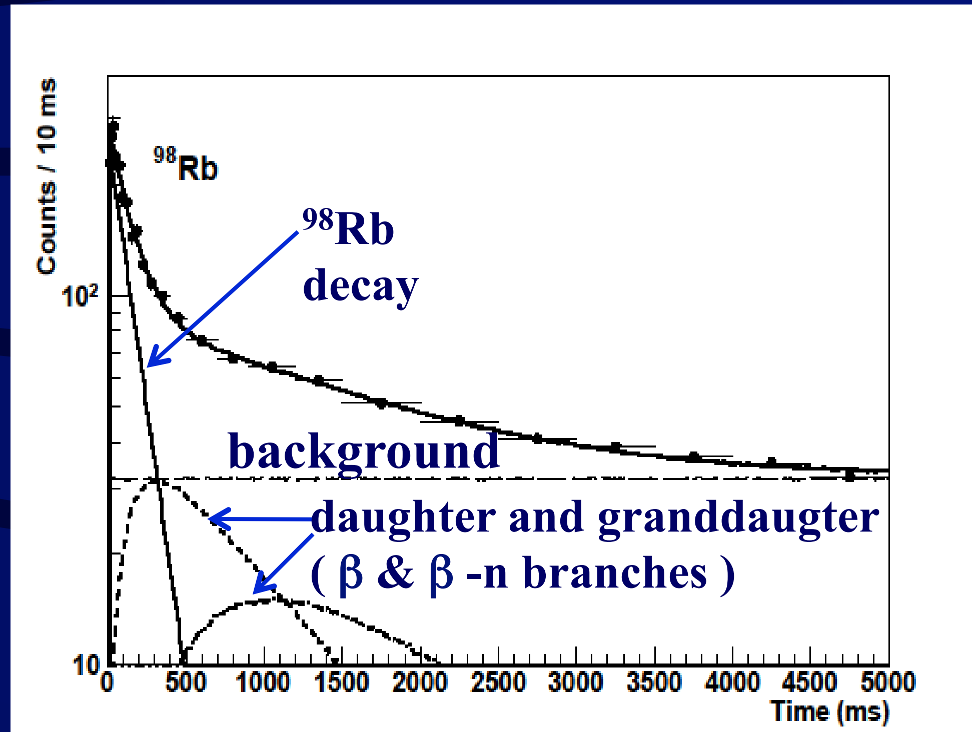
First Excited States E (2+)



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

Beta Decay Half-lives





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

Free parameters for fitting

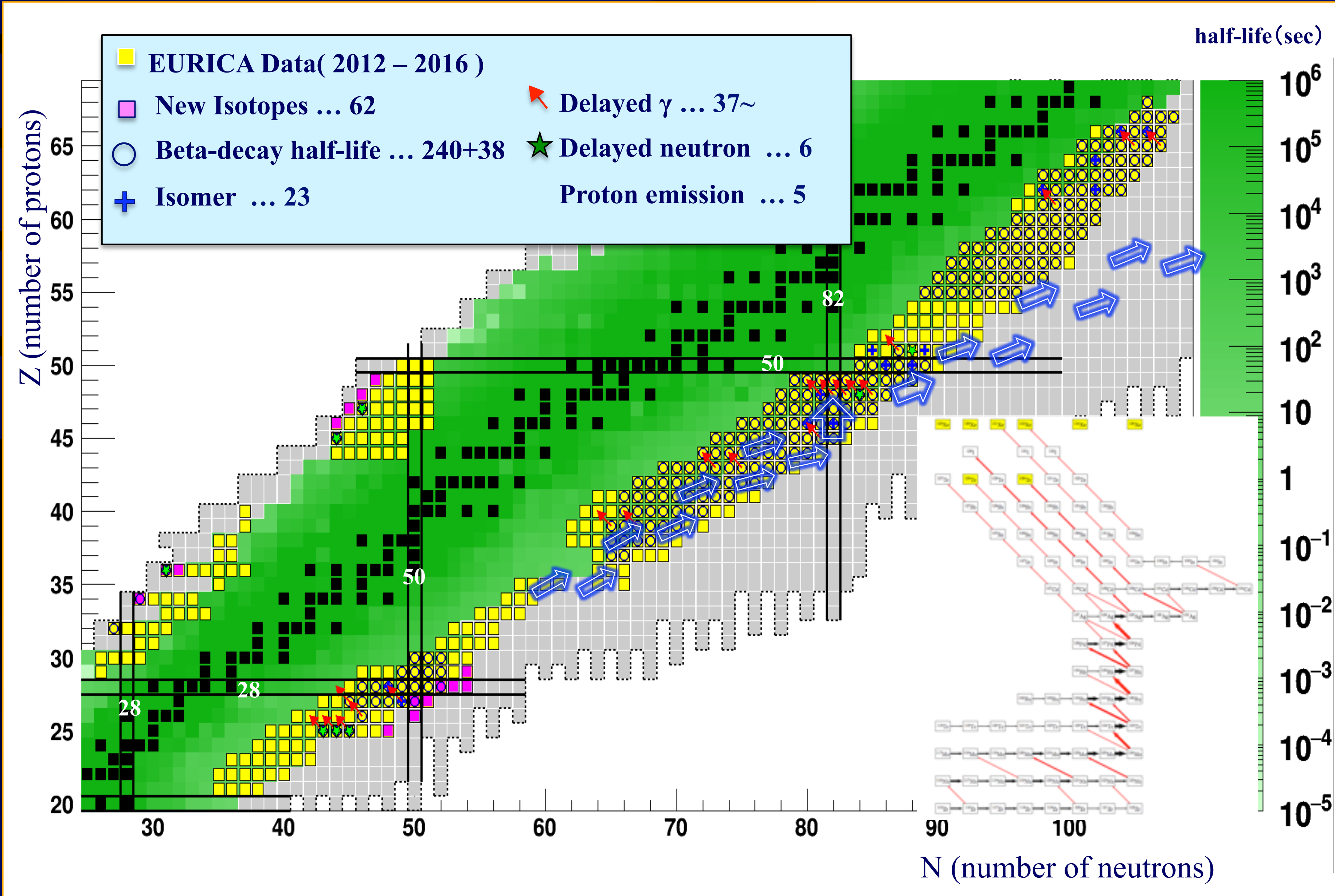
- Background … ~ 0.5 cps
- Neutron emission Probability (P_n)
- Detection efficiency (ε) … 40% - 80%

Consistency check

- Monte Carlo Simulation

$\Rightarrow$ $T_{1/2}$

440 Exotic Isotopes Surveyed by EURICA Spectrometer



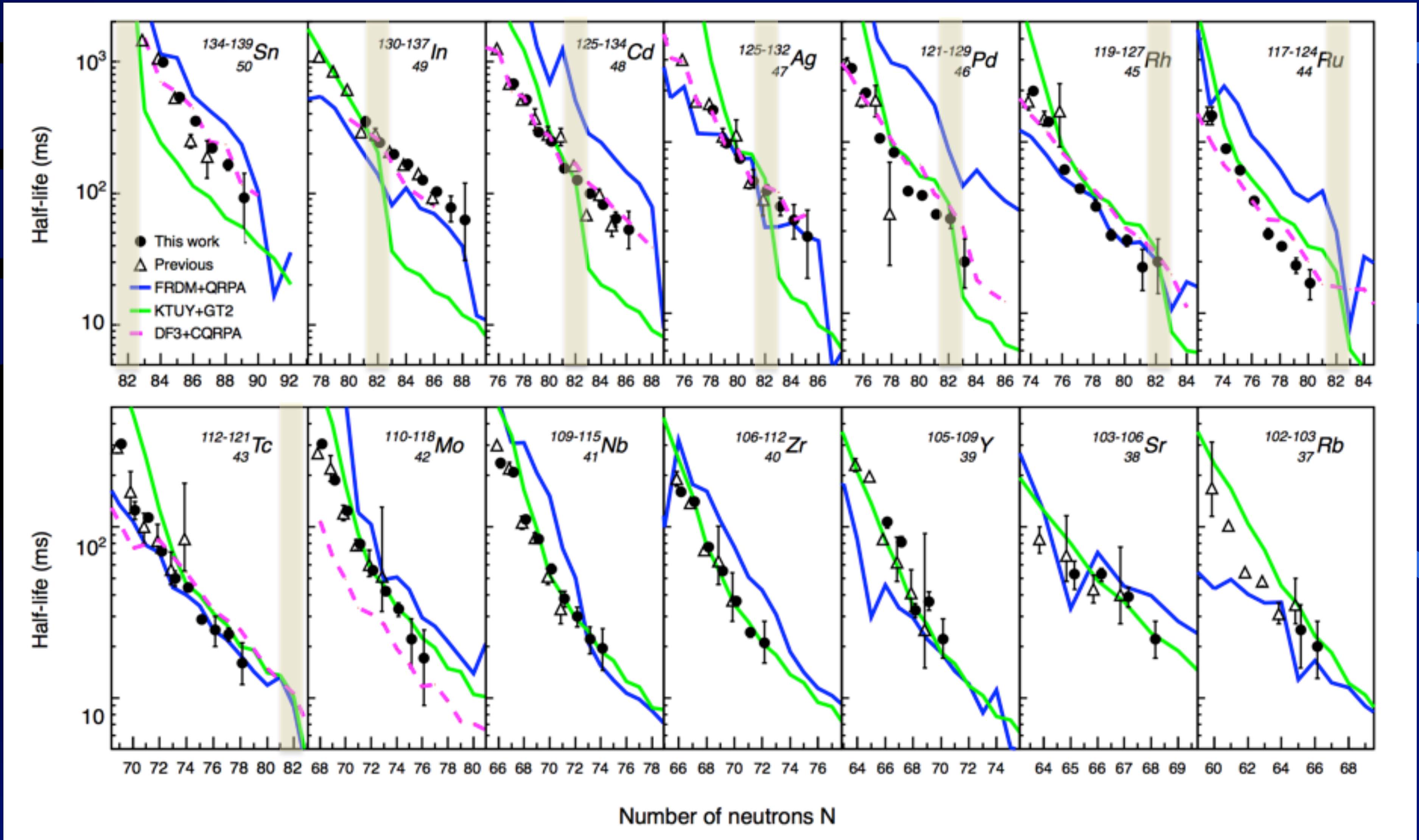
110 Half-lives of Very Neutron-Rich Rb to Sn Around N = 82

40 new half-lives !

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

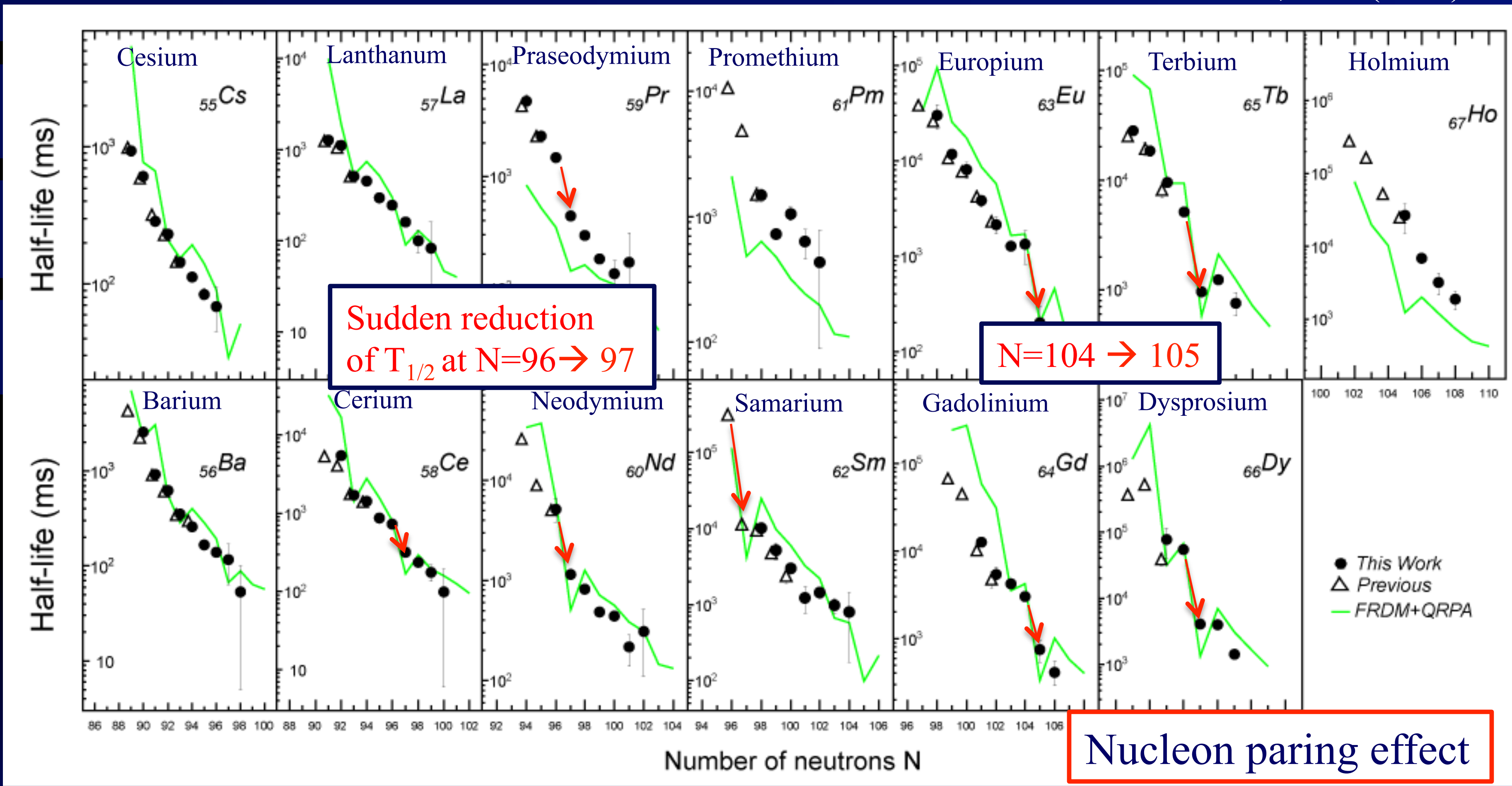
18 new half-lives !

S.Nishimura PRL 106, 052502 (2011)



92 β-Decay Half-lives (Mass A = 144 – 175) vs FRDM+QRPA

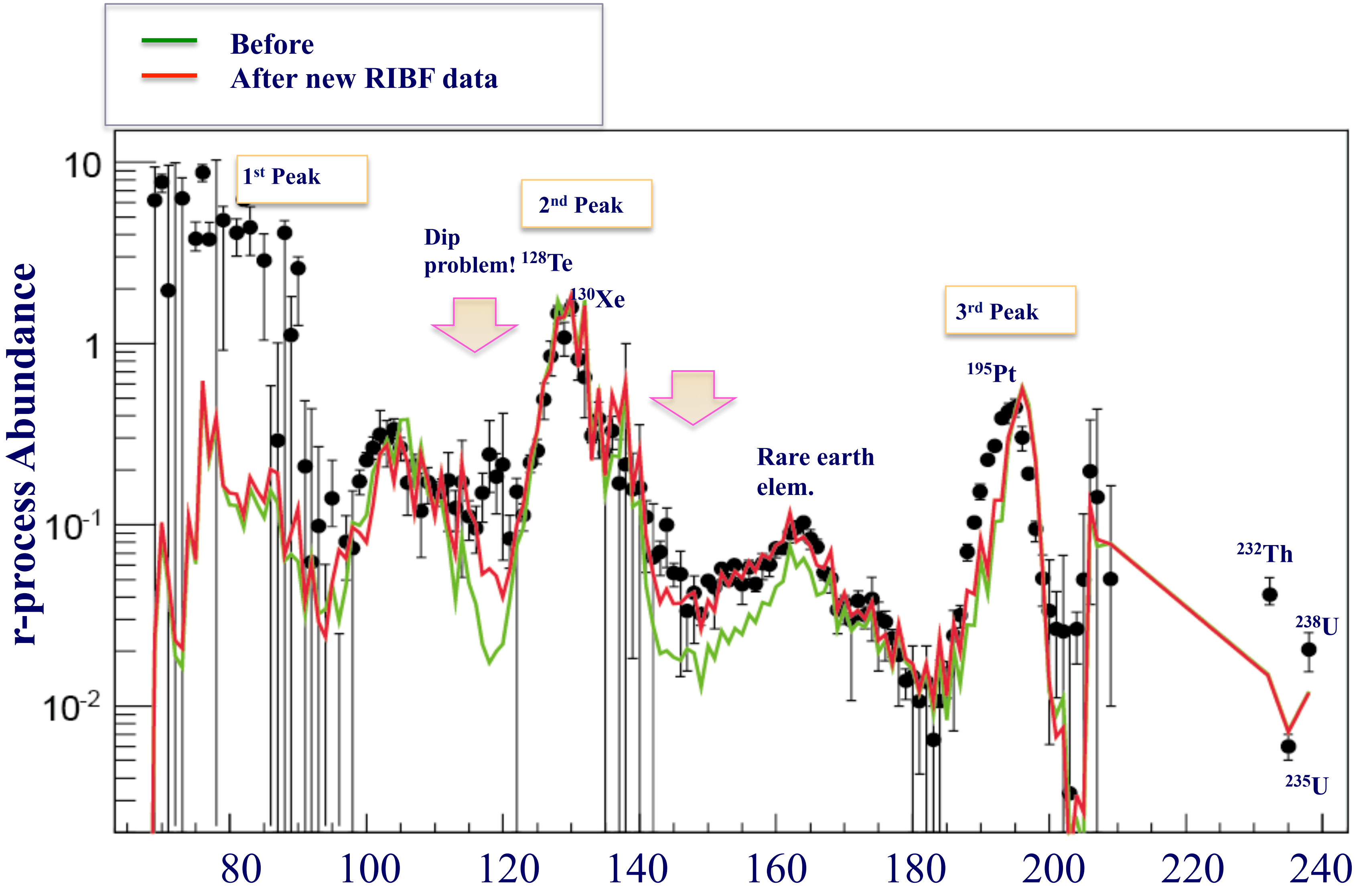
J. Wu, PRL (2017)



The β-decay half-lives of 92 neutron-rich $^{144-151}$Cs, $^{146-154}$Ba, $^{148-156}$La, $^{150-158}$Ce, $^{153-160}$Pr, $^{156-162}$Nd, $^{159-163}$Pm, $^{160-166}$Sm, $^{161-168}$Eu, $^{165-170}$Gd, $^{166-172}$Tb, $^{169-173}$Dy, and $^{172-175}$Ho were measured at the Radioactive Isotope Beam Factory (RIBF).

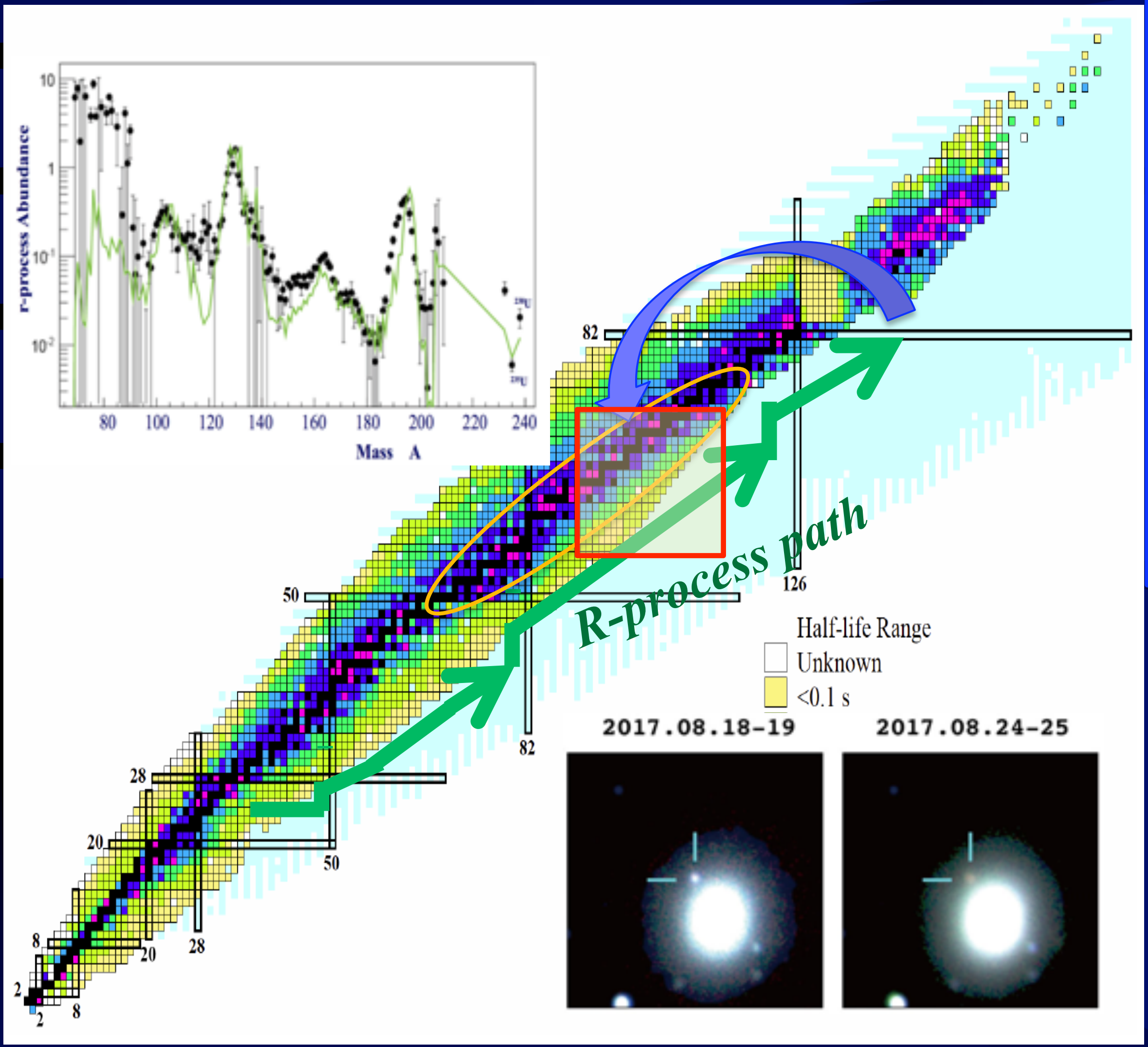
r-process Abundance with New $T_{1/2}$ (RIBF)

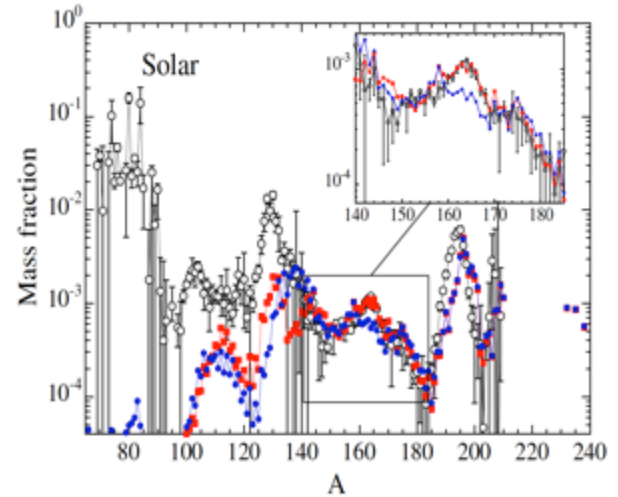
G.Lorusso et al., PRL (2015)



Assumption: (n, γ) ⇄ (γ, n) equilibrium.

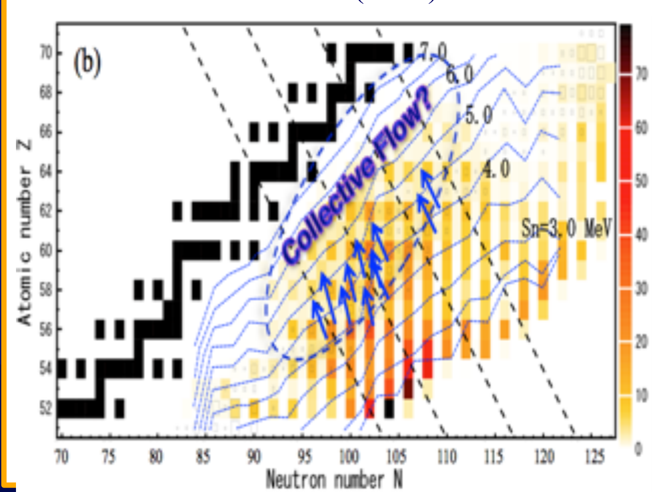
Origin of Rare-Earth Elements



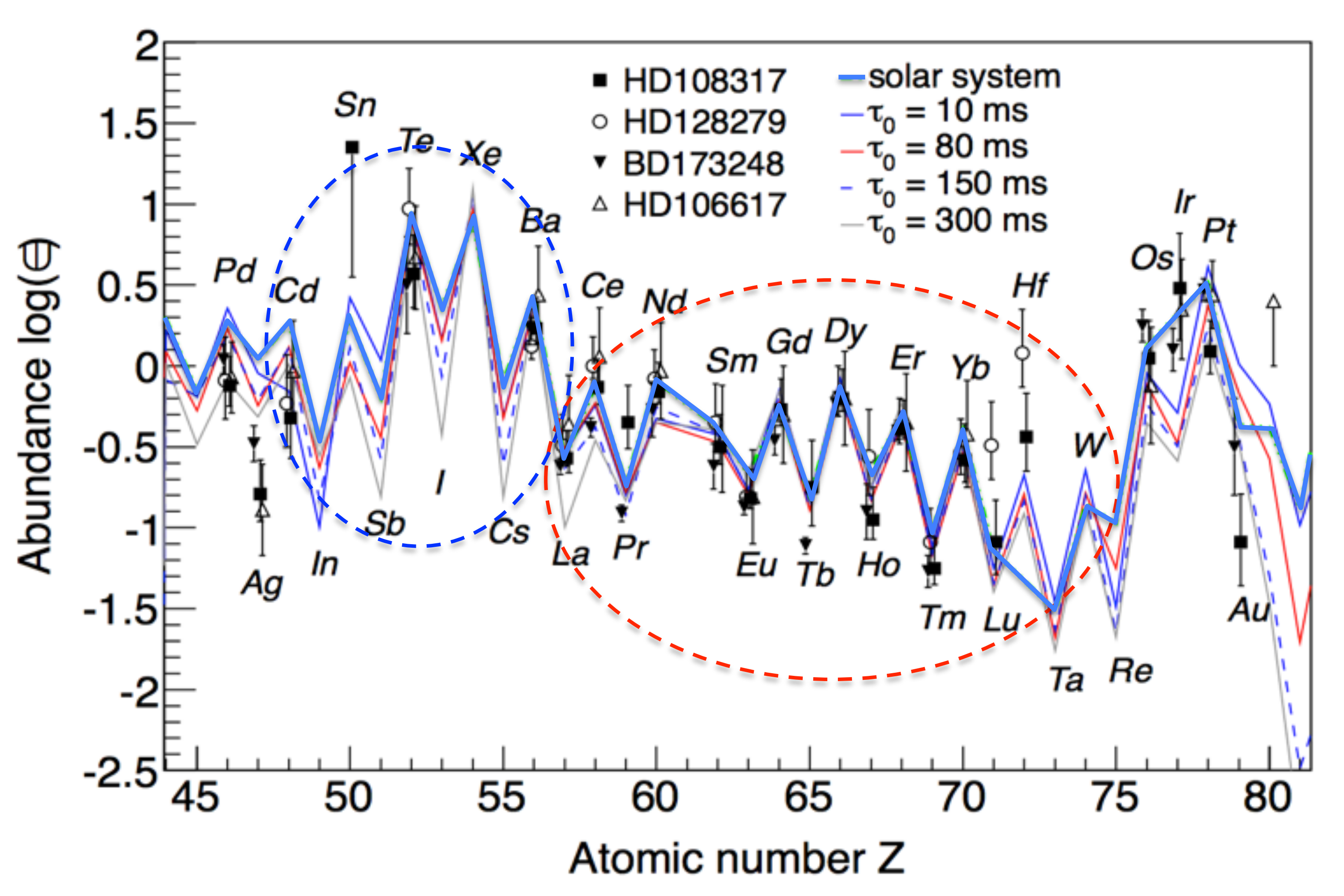


S. Goriely et al PRL 111, (2013)

R. Surman et al. PRL 79 (1997)

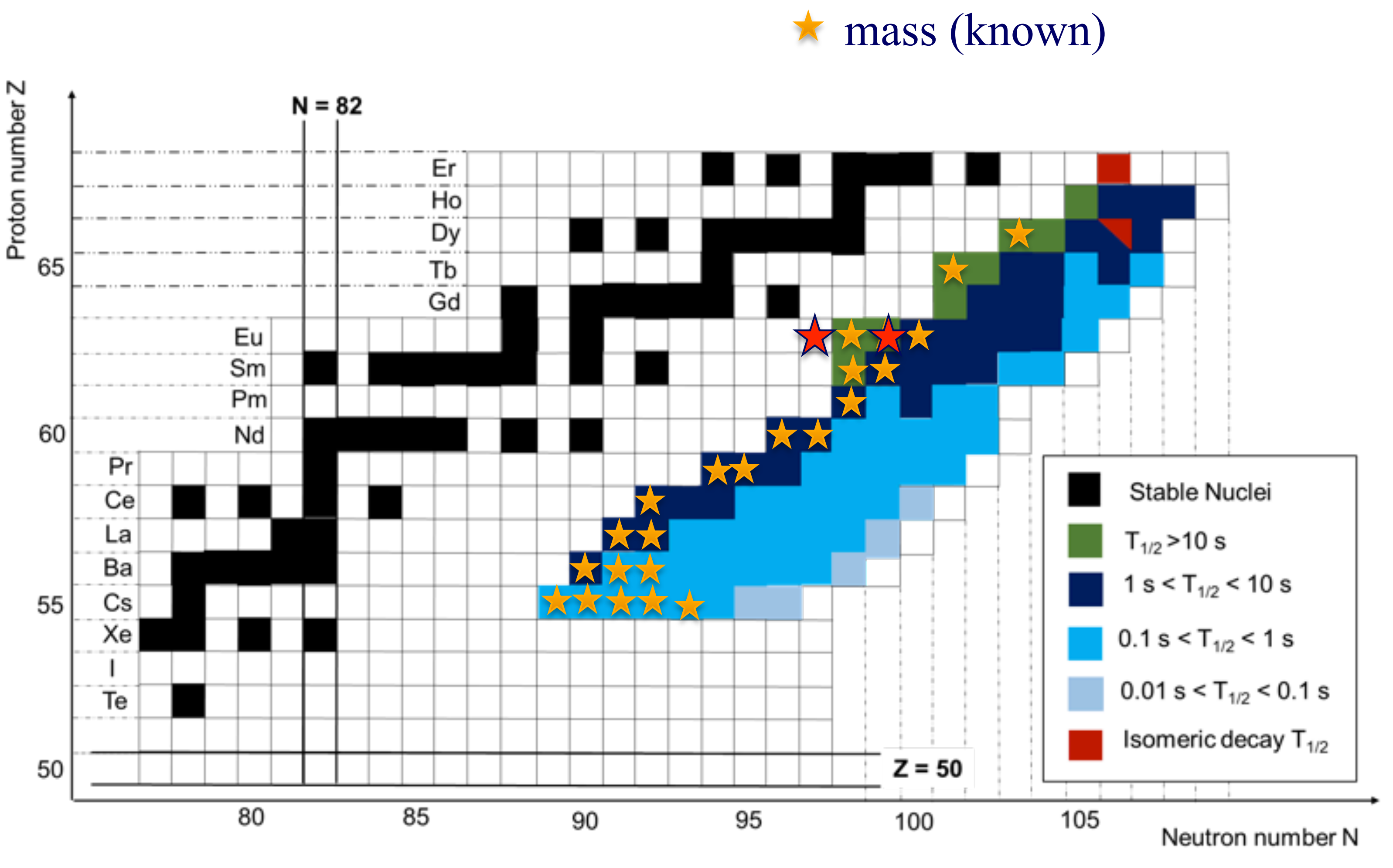


Universality of r-process elements (Z ≥ 56)



Decay Spectroscopy around mass A =160 was performed !

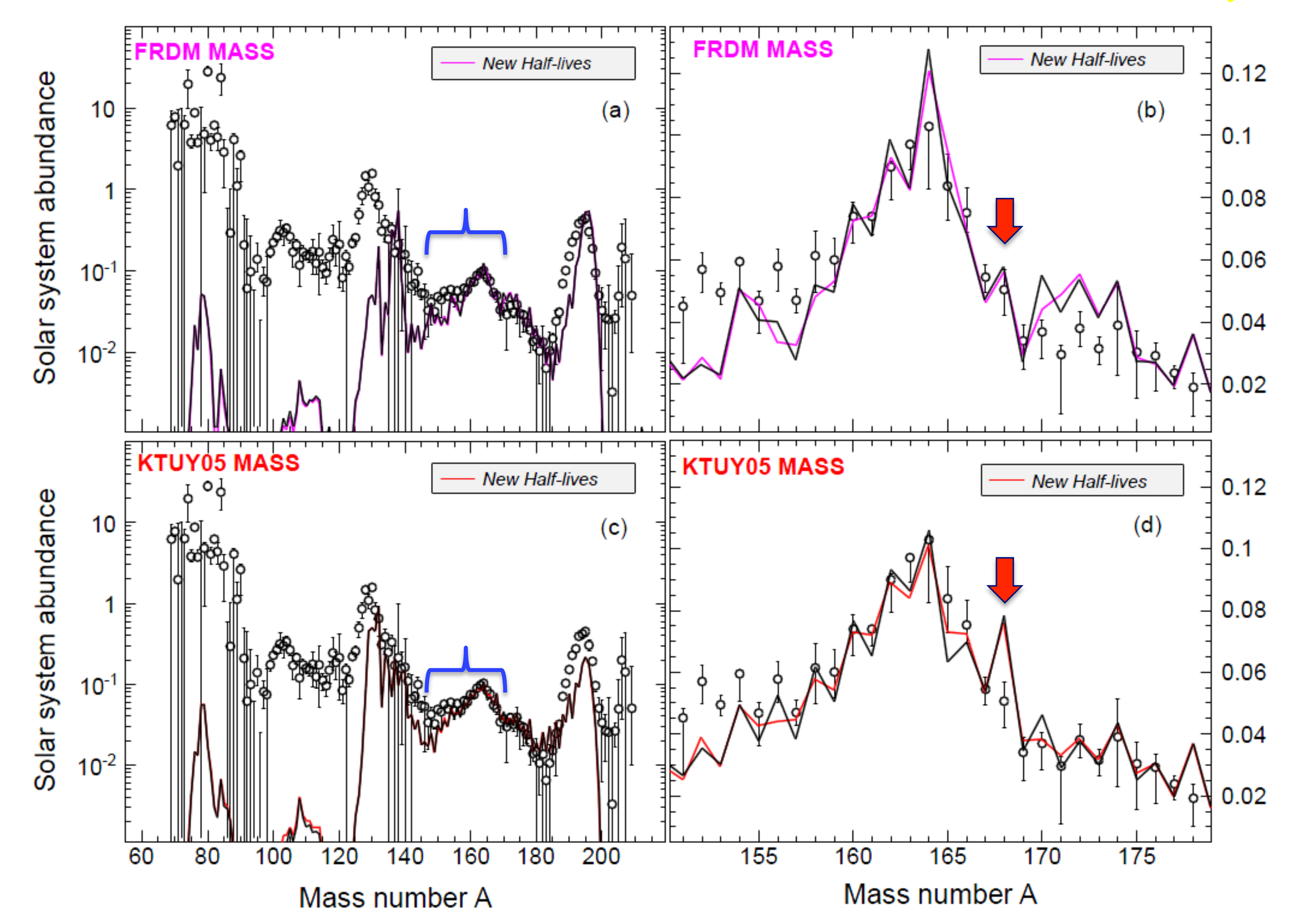
How About Mass Measurement ?



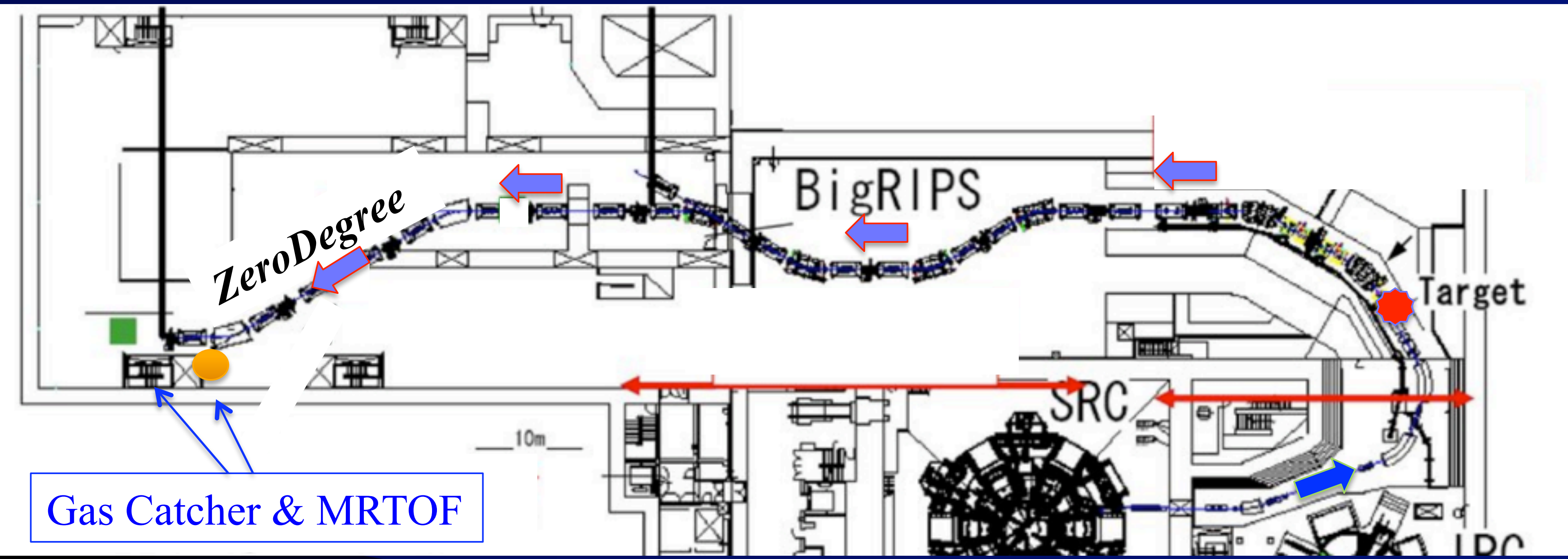
Rare-Earth Peak with Different Mass Models

Half-lives: FRDM and new half-lives.   Mass: FRDM and KTUY.

by J. Wu



MRTOF & Decay in ZeroDegree (2019 ? ~)

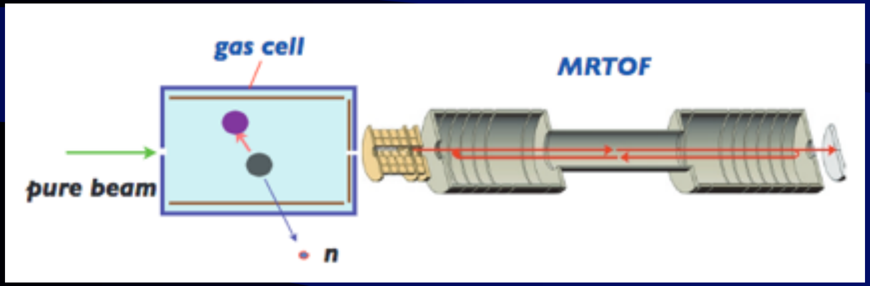


Yakitori Mode

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

ZD-MRTOF Workshop (3-4, September, 2018) … to be announced.

ZD-MRTOF → Decay



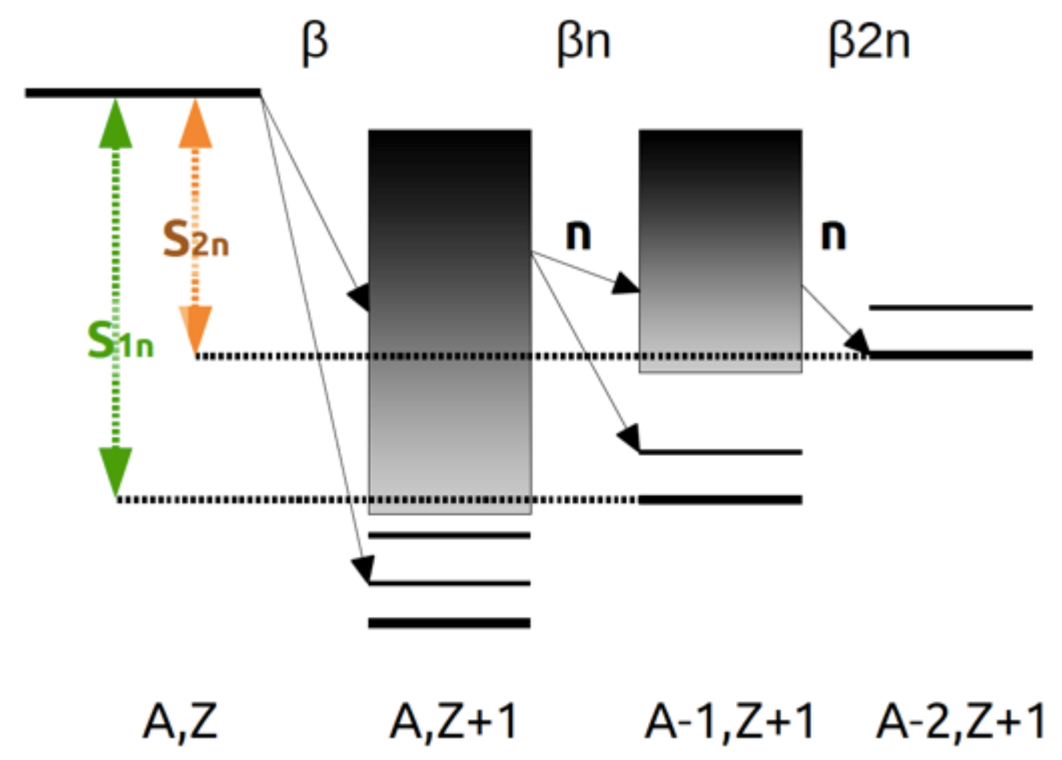
RI Identification by MRTOF

AGARI
(Active mass Gated stopper for RI spectroscopy)

Development has been started..

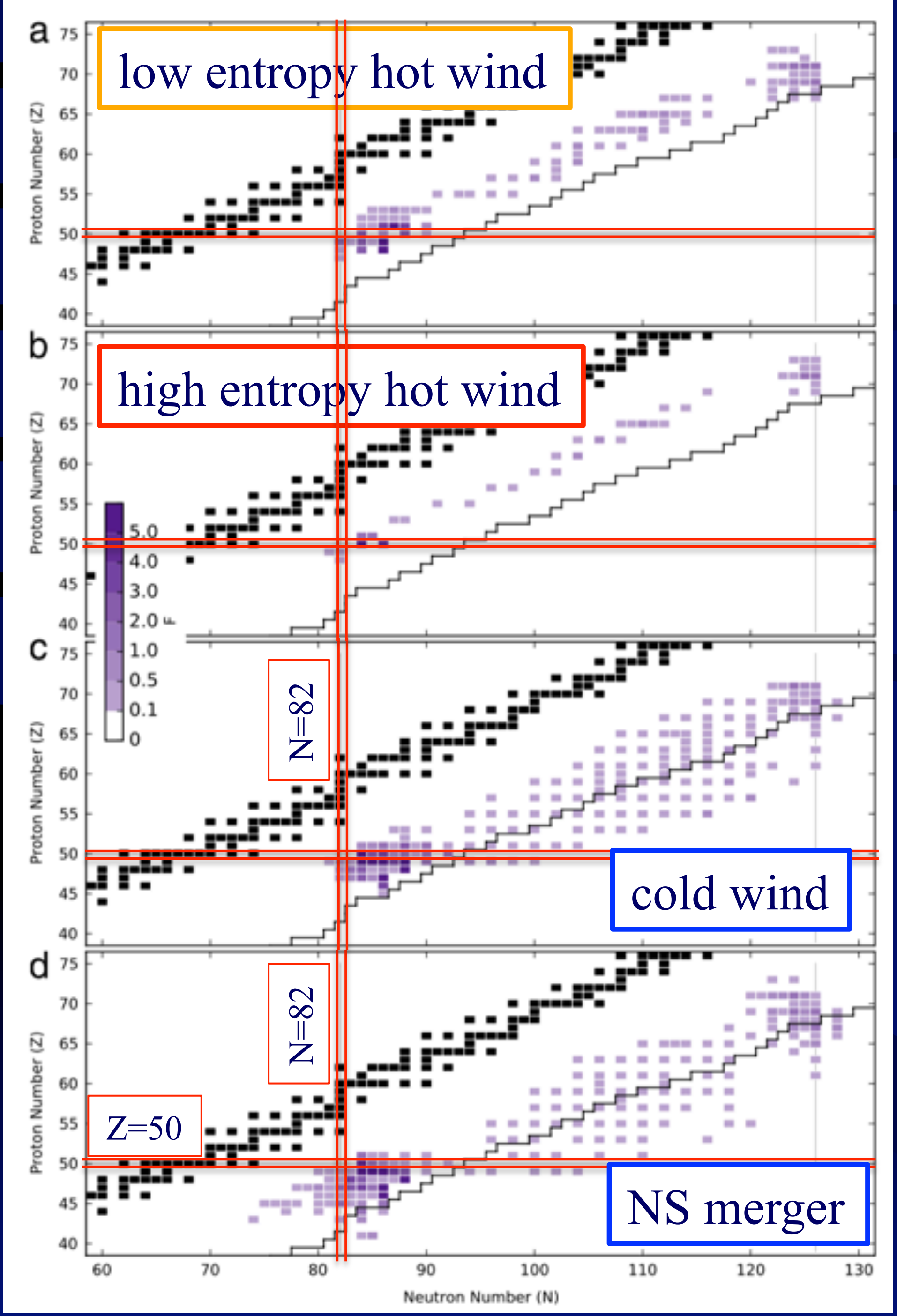
Beta-delayed neutron emission probabilities Pn

- **Beta decay of neutron-rich nuclei**
- **Far enough $S_{xn} < Q_{\beta}$: multiple neutron emission**



BRIKEN (2016 ~)

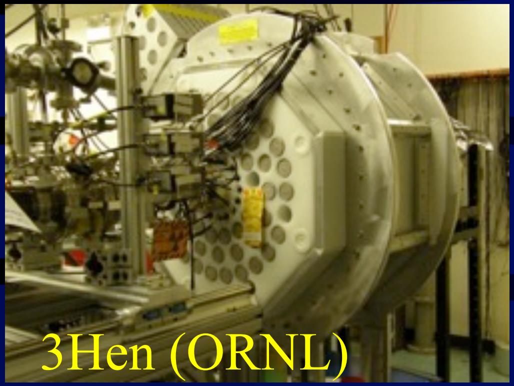
Pn values: How Sensitive in r-Process Calc.?

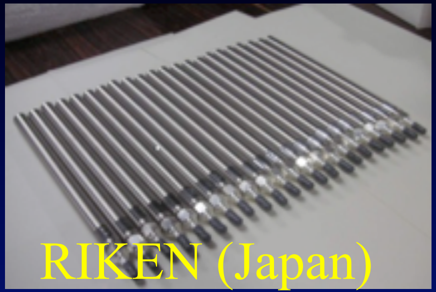


beta-delayed neutron emitters

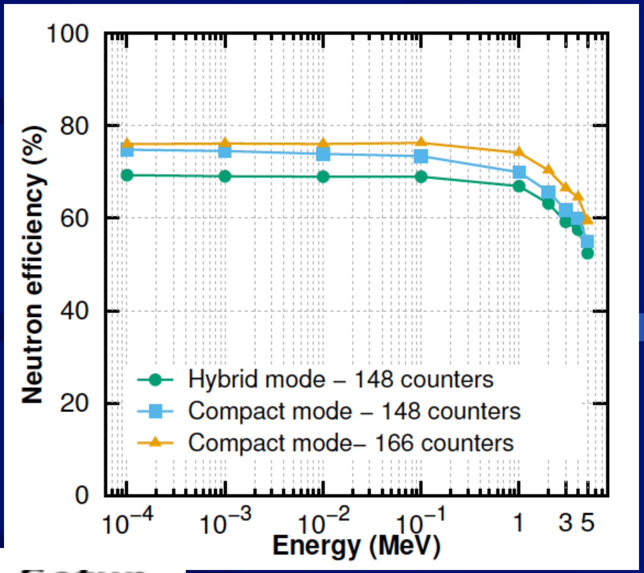
M.R. Mumpower et al.
Prog. in Part. and Nucl. Phys
86 (2016) 86-126

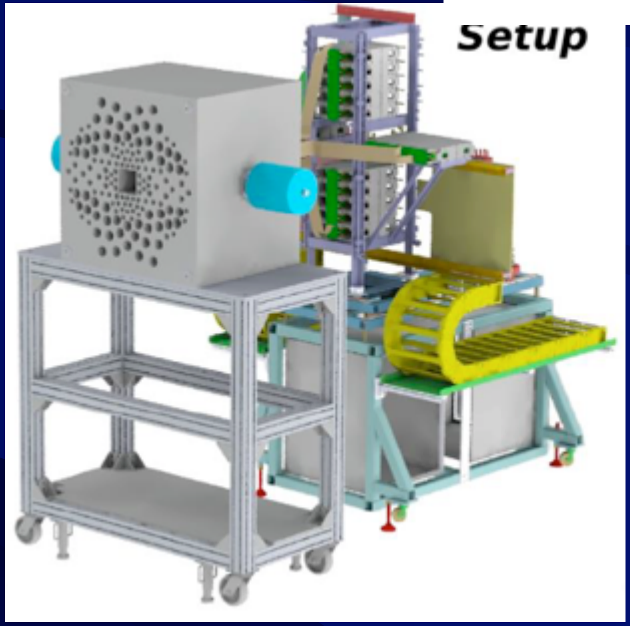
^{3}He gas detectors





BRIKEN @ RIBF





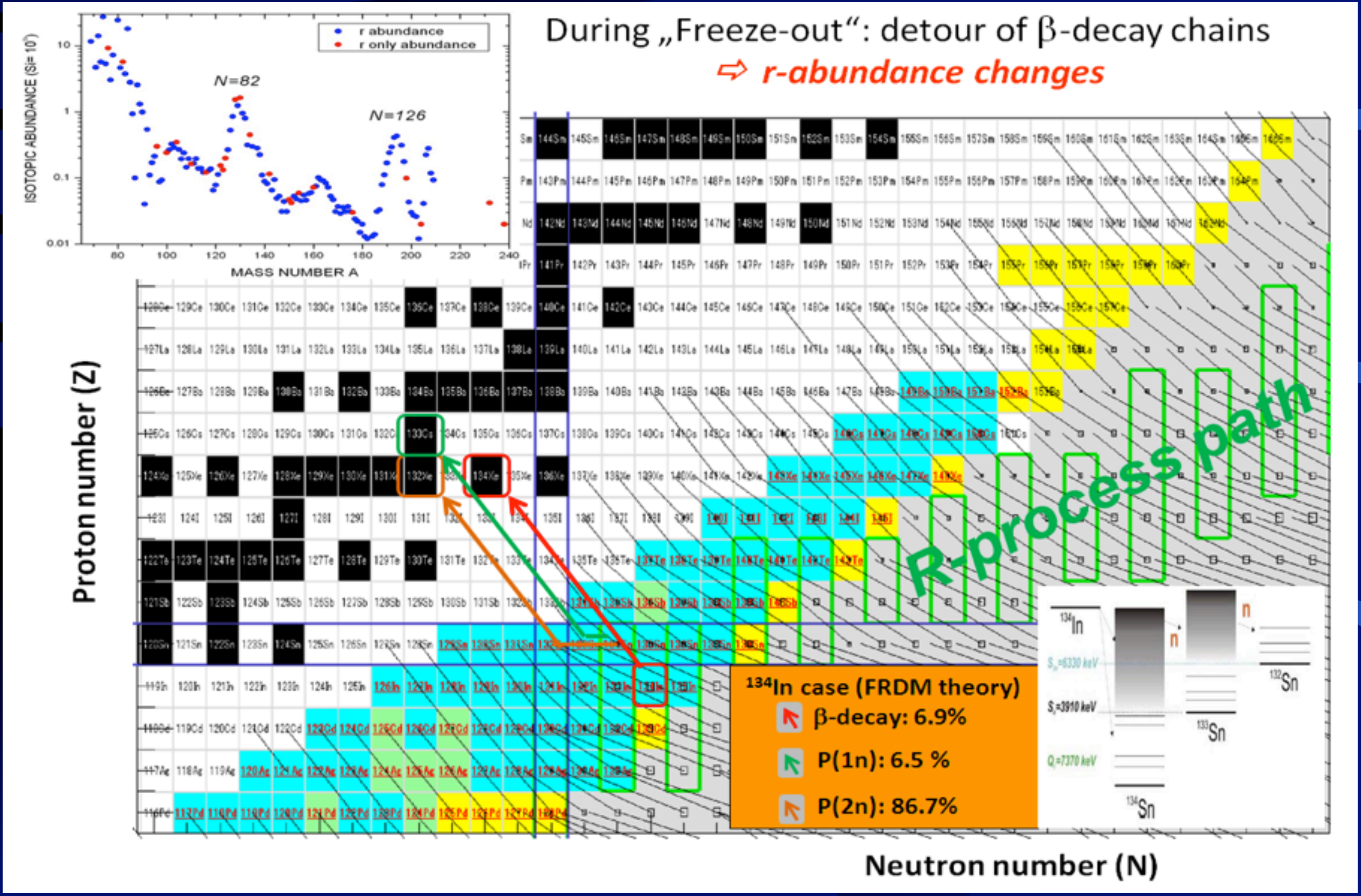
$^{3}He + n \rightarrow {}^{3}H + p + 780$ keV

No info. about initial E_n, but large efficiency

Thermalization time $\tau \sim 100$ μs

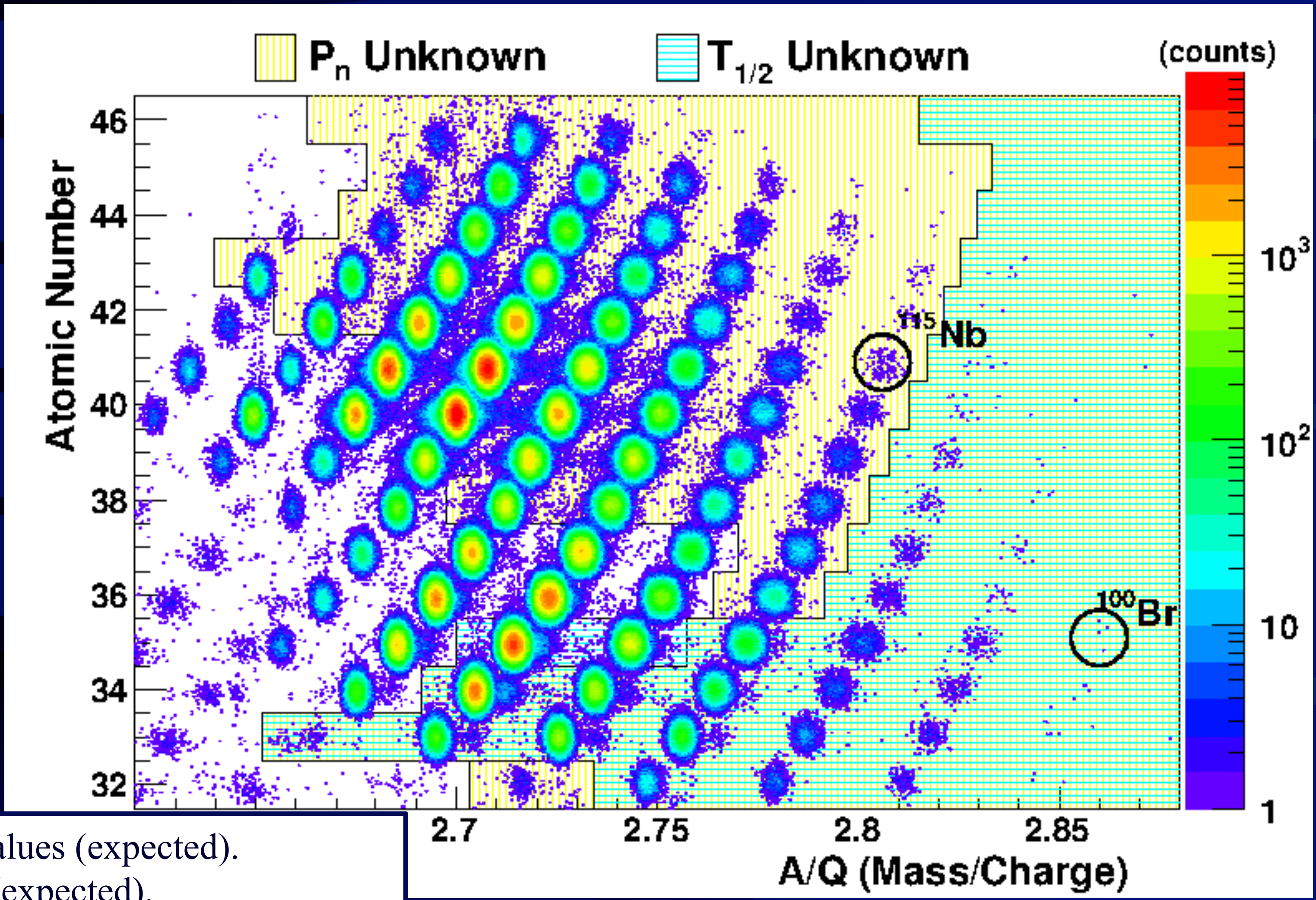
r-Process Elements : Freeze-out Time

A. Estrade, G. Lorusso, F. Montes



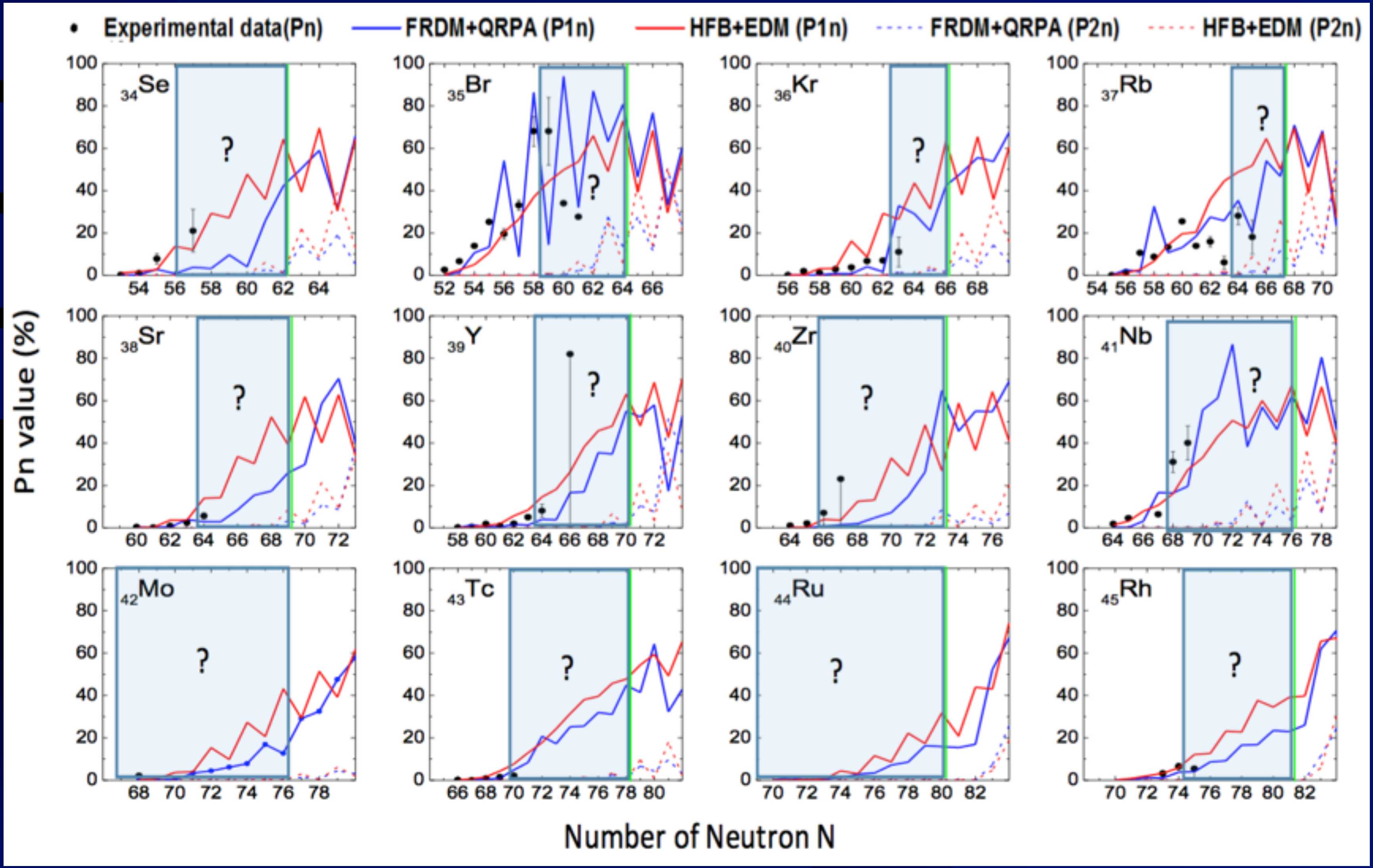
BRIKEN Campaign (2017 Nov.)

Spokesperson: SN, A. Algora



* 50 ~ new P_n values (expected).
* ~ 20 new $T_{1/2}$ (expected).
* Isomers
* Beta-delayed gamma with neutron-gate
* U-beam int. ~ 65 pnA

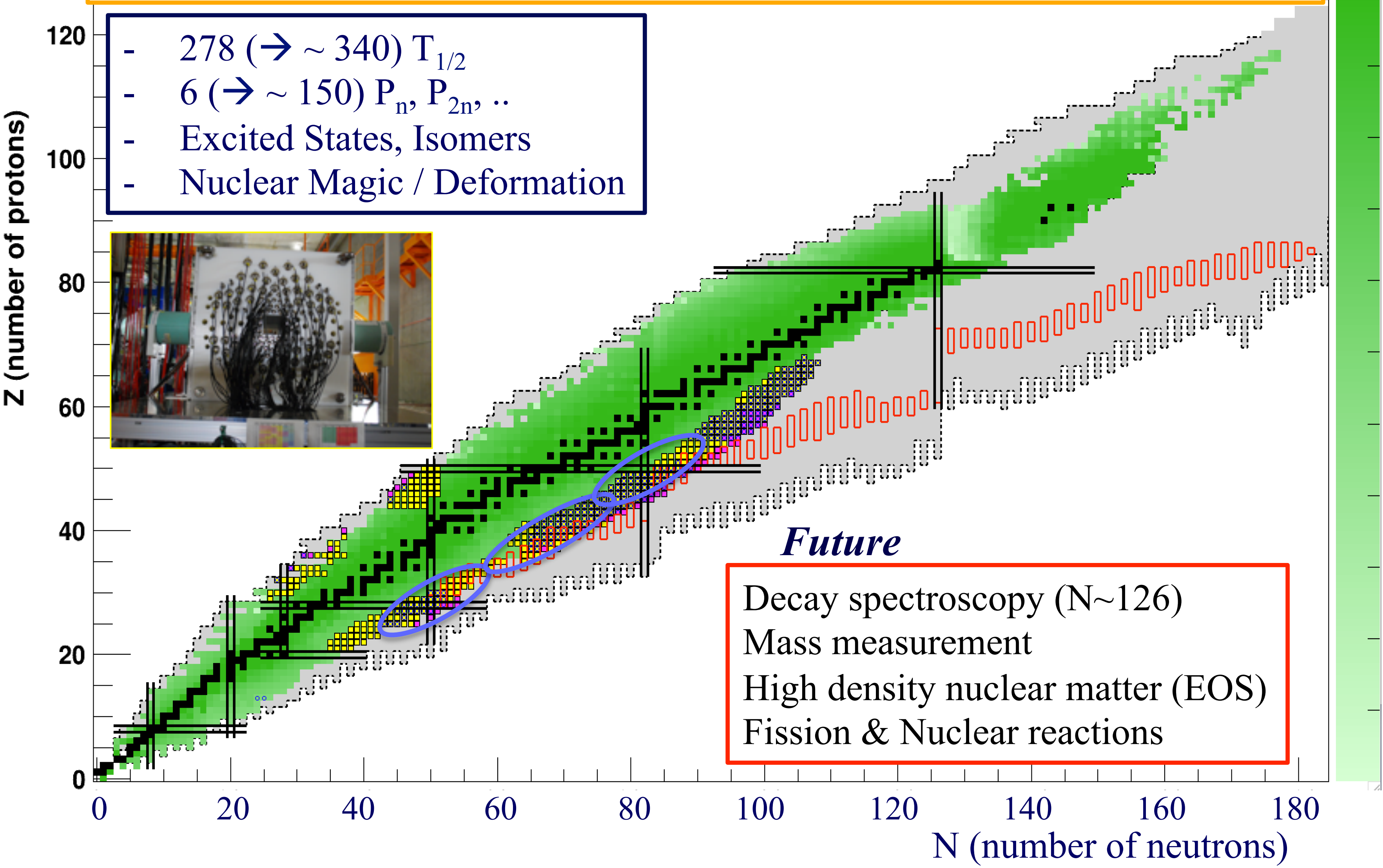
Delayed neutrons in mass A = 100 region



Summary

Survey of decay properties EURICA/BRIKEN (CAITEN) in progress.

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



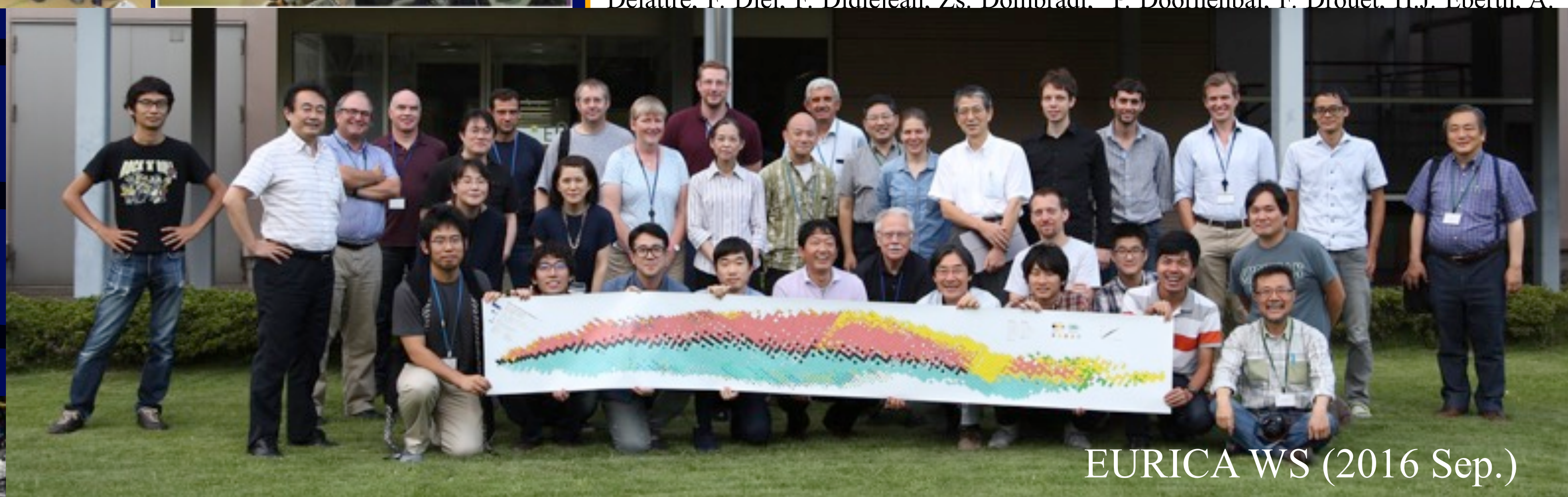
Future

Decay spectroscopy (N~126)
Mass measurement
High density nuclear matter (EOS)
Fission & Nuclear reactions

EURICA Collaboration

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. Didierjean, Zs. Dombradi, P. Doornenbal, F. Drouet, H.J. Eberth, A.



Napoli, I, Naqvi, M. Niikura, H. Nishibata, S. Nishimura, I. Nishizuka, C. Nita, 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

MTA Atomki Debrecen

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

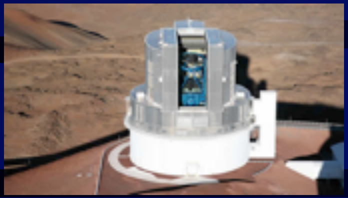
University of Guelph

University of Surrey

Michigan State University

University of Warsaw

Nucleosynthesis under Extreme Matter & Conditions



SUBARU/Hubble & TMT Telescopes