

08 June, 2018

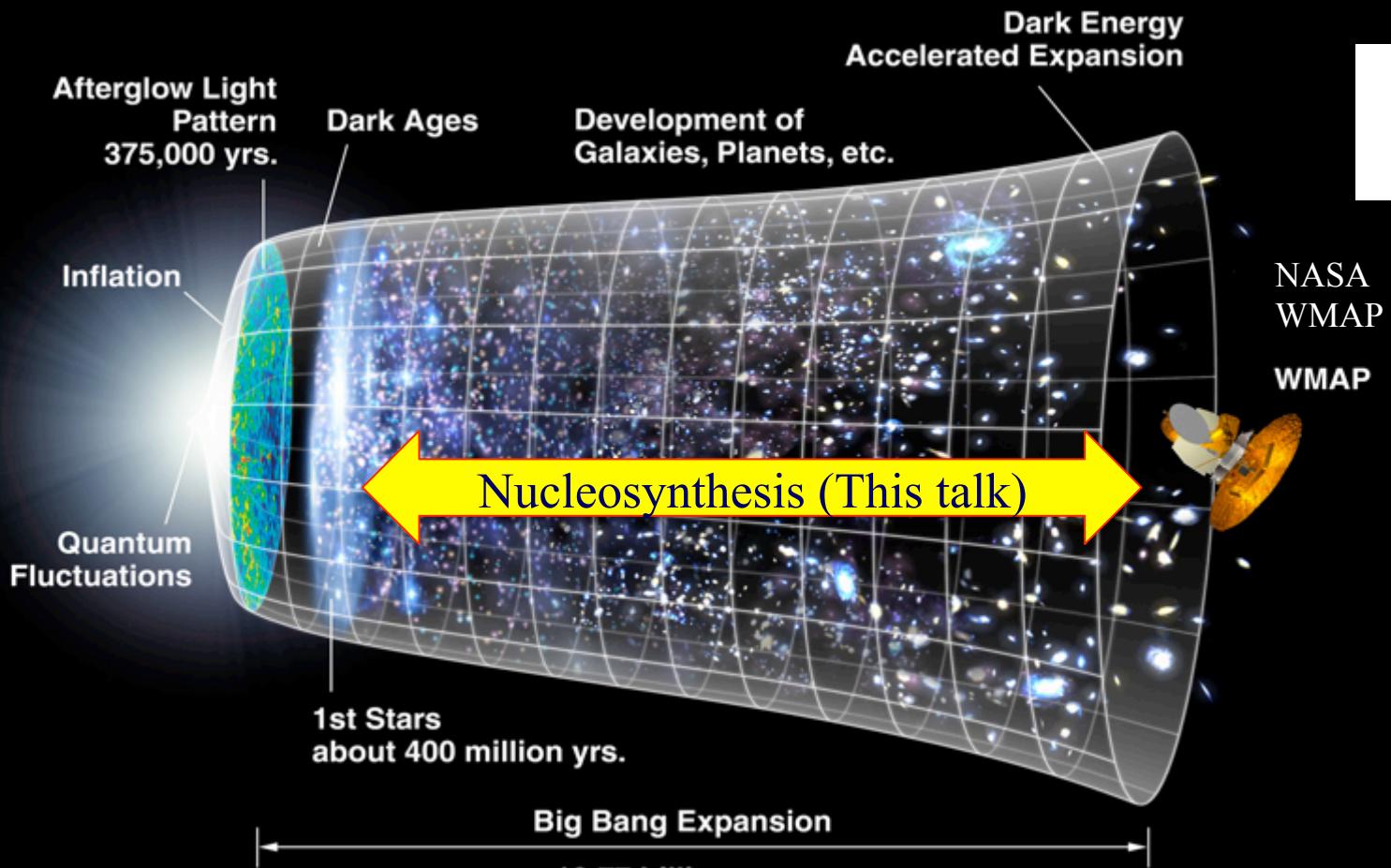


EMMI Rapid Reaction Task Force: The physics of neutron  
star mergers at GSI/FAIR

# Experimental challenges relevant to the r-process

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*RIKEN Nishina Center*

# History of Universe



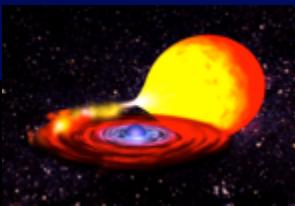
Extreme Conditions (Stars, Neutron-star, Black-hole)

Explosion: Big Bang, Supernova, X-ray bursts,  $\gamma$ -ray bursts, Collisions of Stars

Matters & Reactions: Equation of State (EOS), Nucleosynthesis

# Nucleosynthesis in Universe

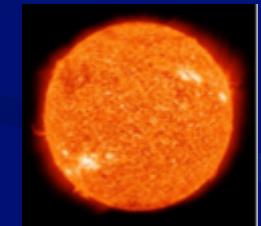
Big Bang



Interstellar  
Material

Get Together

Gravitational Force



Star



Scatter  
Ashes

Supernovae

Nucleosynthesis  
heavier than iron

Black hole  
Neutron Star



Nucleosynthesis  
up to iron

What kinds of Elements  
in “Our Solar System” ?

# Periodic Table of Elements

**元素周期表**

Big Bang Nucleosynthesis

Nucleosynthesis in Star

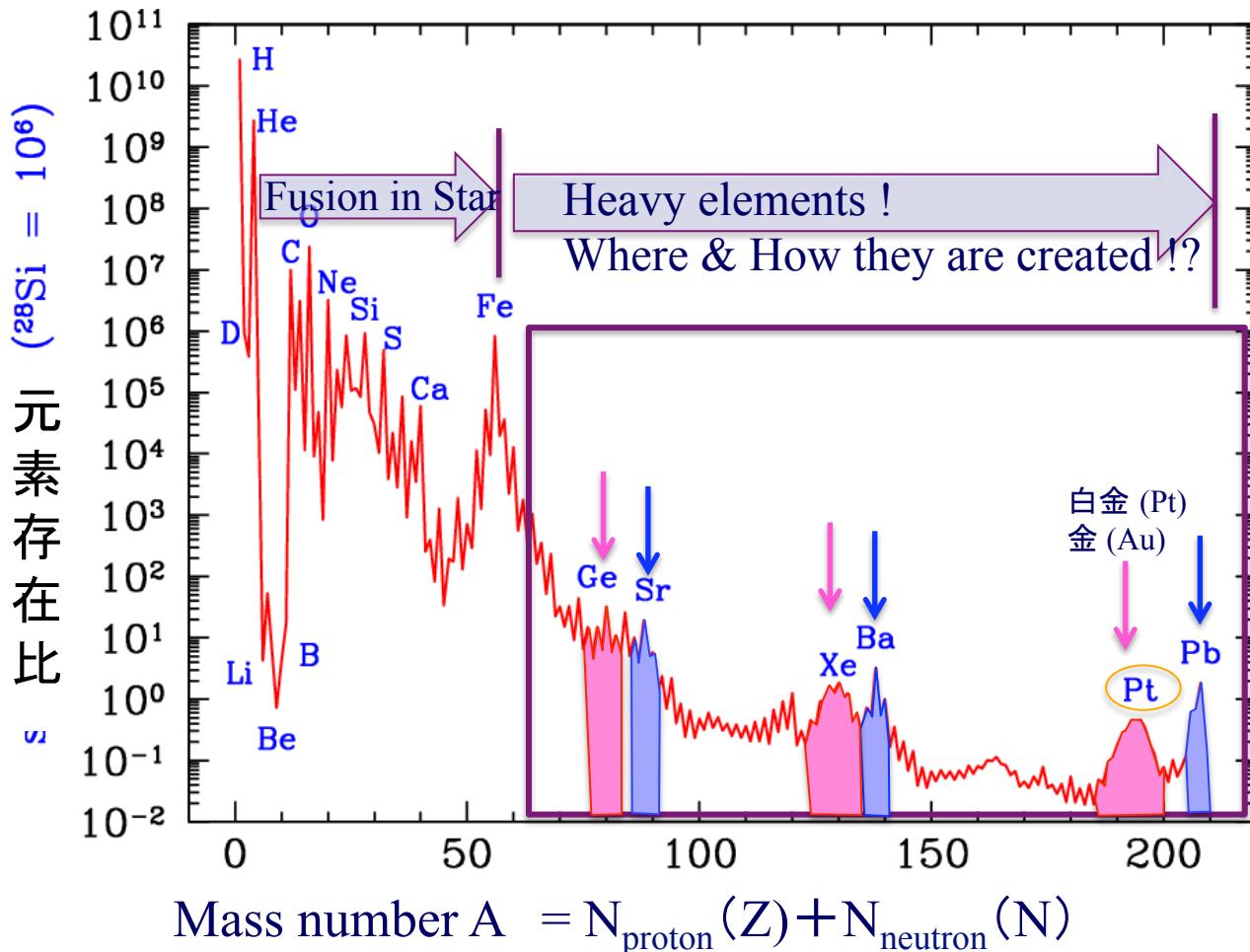
Nucleosynthesis of Heavy Elements

This image shows a Japanese periodic table with several highlighted regions:

- Big Bang Nucleosynthesis:** Elements H, He, Li, Be, B, C, N, O, F, Ne.
- Nucleosynthesis in Star:** Elements Na, Mg, Al, Si, P, S, Cl, Ar.
- Nucleosynthesis of Heavy Elements:** Elements Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe; Cs, Ba, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn; Fr, Ra, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Fl, Lv, Ho, Er, Tm, Yb, Lu; Ac, Th, Pa, U, Np, Pu, Am, Cm, Bk, Cf, Es, Fm, Md, No, Lr.
- Other highlighted elements:** H, He, Li, Be, B, C, N, O, F, Ne, Al, Si, P, S, Cl, Ar, Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe, Cs, Ba, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn, Fr, Ra, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Fl, Lv, Ho, Er, Tm, Yb, Lu.

The table includes Japanese names for most elements and their atomic numbers. A yellow box highlights the first two elements (Hydrogen and Helium). A green box highlights the second-period elements (Li, Be, B, C, N, O, F, Ne). A pink box highlights the third-period elements (Na, Mg, Al, Si, P, S, Cl, Ar). A purple box highlights the fourth-period elements (K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Kr). A blue box highlights the fifth-period elements (Rb, Sr, Y, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, I, Xe). A red box highlights the sixth-period elements (Cs, Ba, Hf, Ta, W, Re, Os, Ir, Pt, Au, Hg, Tl, Pb, Bi, Po, At, Rn). A black box highlights the seventh-period elements (Fr, Ra, Rf, Db, Sg, Bh, Hs, Mt, Ds, Rg, Cn, Fl, Lv, Ho, Er, Tm, Yb, Lu). A dashed-line box highlights the lanthanide and actinide series (Ce-Lu and Th-Lr).

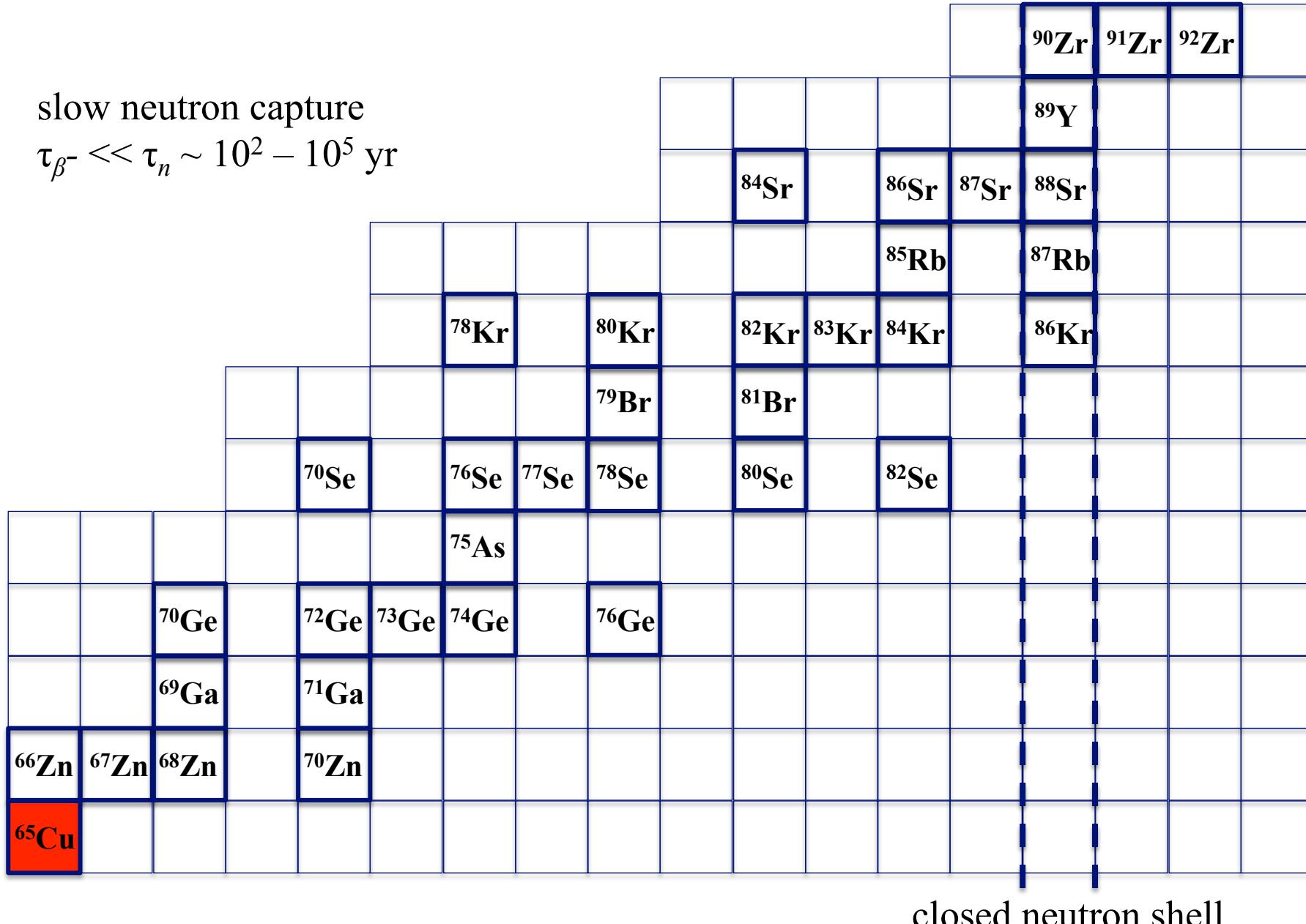
# Solar System: Abundance Pattern



(from wikipedia)

## The s-process

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



# The s-process

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

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

closed neutron shell

## The s-process

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

A periodic table diagram illustrating the s-process path. The elements are arranged in rows and columns, with the following specific elements highlighted:

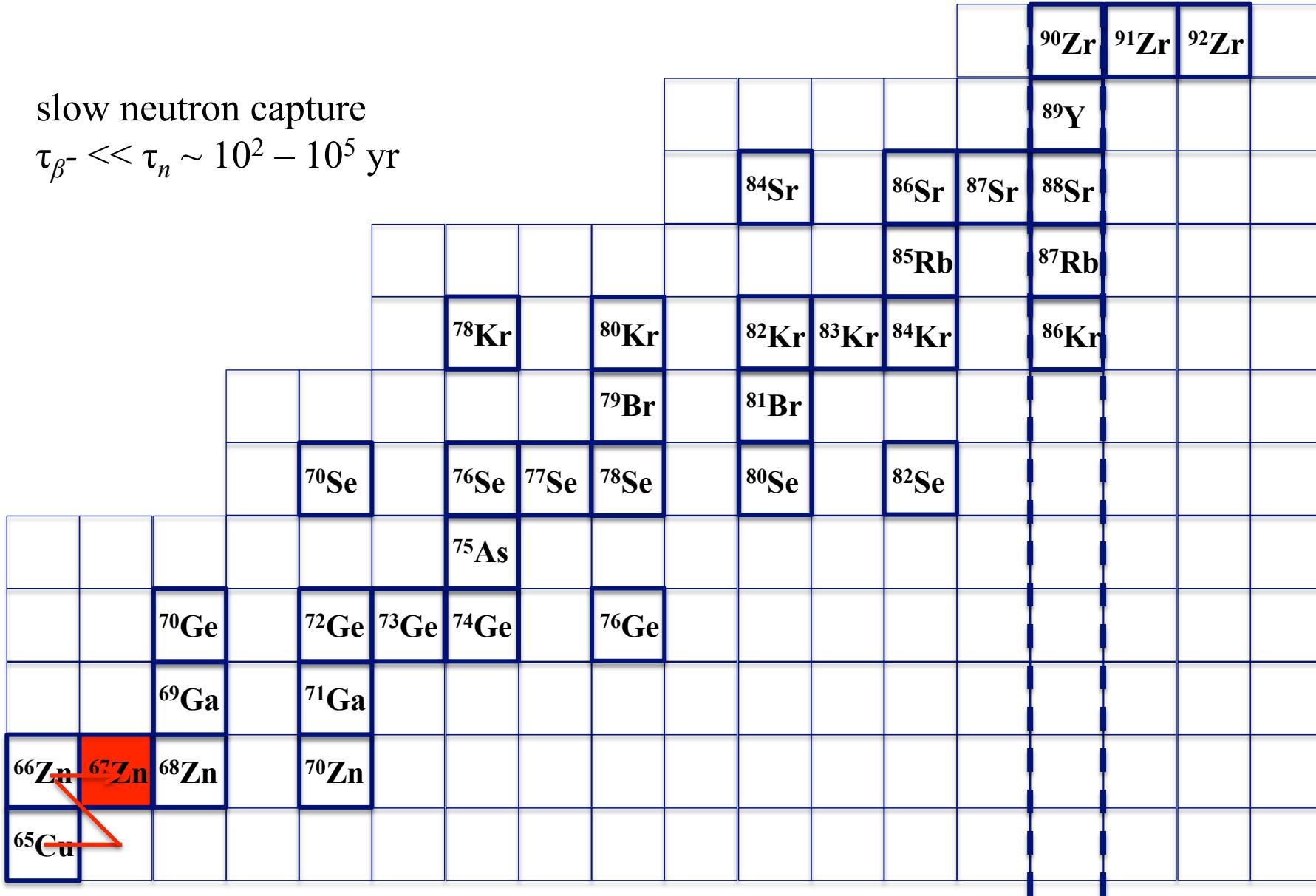
- Zinc:**  $^{66}\text{Zn}$  (red box),  $^{67}\text{Zn}$ ,  $^{68}\text{Zn}$ ,  $^{70}\text{Zn}$
- Gallium:**  $^{69}\text{Ga}$
- Germanium:**  $^{70}\text{Ge}$ ,  $^{72}\text{Ge}$ ,  $^{73}\text{Ge}$ ,  $^{74}\text{Ge}$ ,  $^{76}\text{Ge}$
- Selenium:**  $^{70}\text{Se}$ ,  $^{76}\text{Se}$ ,  $^{77}\text{Se}$ ,  $^{78}\text{Se}$ ,  $^{80}\text{Se}$ ,  $^{82}\text{Se}$
- Bromine:**  $^{79}\text{Br}$ ,  $^{81}\text{Br}$
- Krypton:**  $^{78}\text{Kr}$ ,  $^{80}\text{Kr}$ ,  $^{82}\text{Kr}$ ,  $^{83}\text{Kr}$ ,  $^{84}\text{Kr}$ ,  $^{86}\text{Kr}$
- Rubidium:**  $^{85}\text{Rb}$ ,  $^{87}\text{Rb}$
- Sr/Yttrium:**  $^{84}\text{Sr}$ ,  $^{86}\text{Sr}$ ,  $^{87}\text{Sr}$ ,  $^{88}\text{Sr}$ ,  $^{89}\text{Y}$
- Zirconium:**  $^{90}\text{Zr}$ ,  $^{91}\text{Zr}$ ,  $^{92}\text{Zr}$

A red arrow points from the  $^{65}\text{Cu}$  box down to the  $^{66}\text{Zn}$  box, indicating the start of the s-process chain.

closed neutron shell

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



closed neutron shell

## The s-process

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

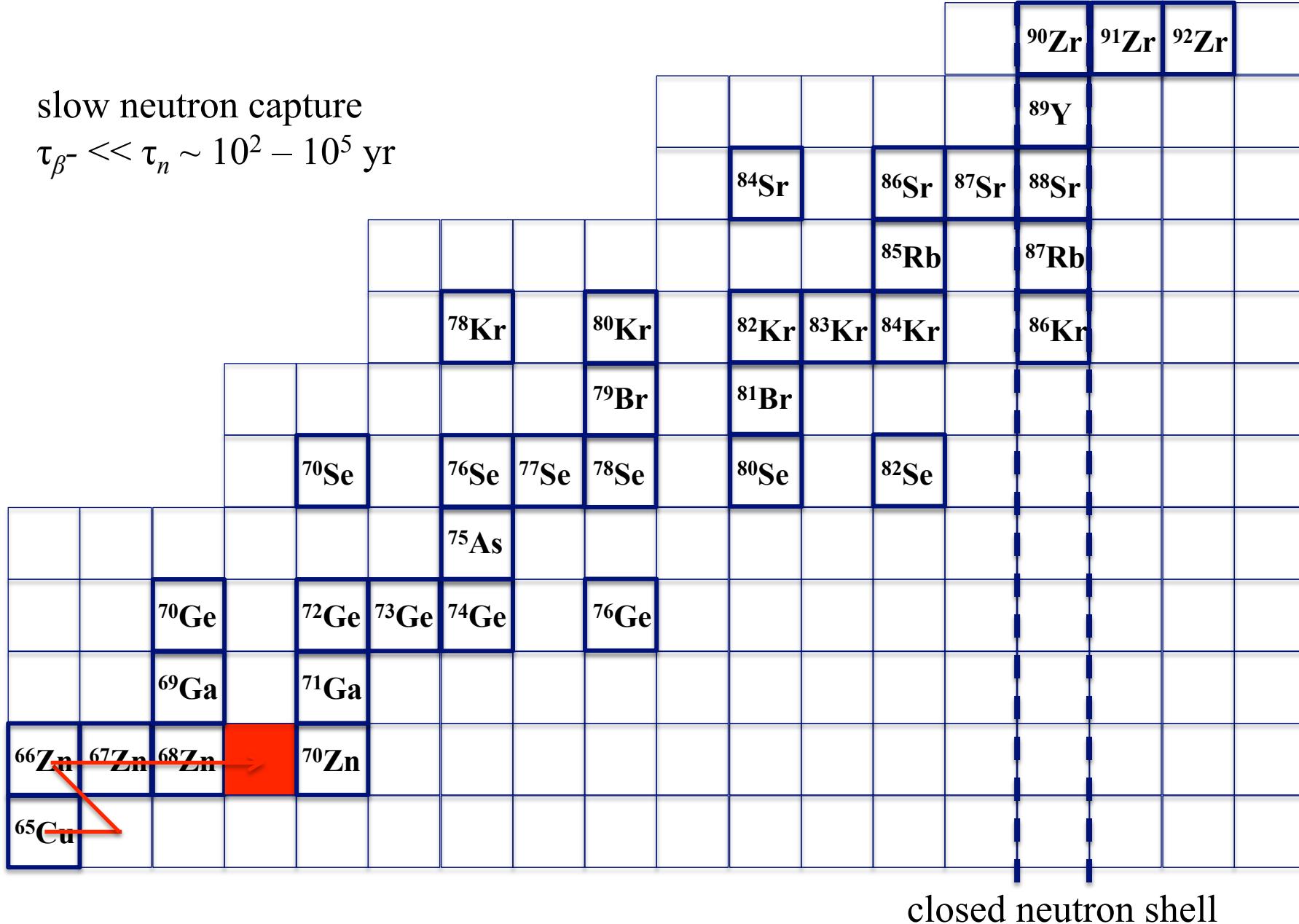
A periodic table diagram illustrating the s-process path. The elements shown are Zinc (Zn), Gallium (Ga), Germanium (Ge), Selenium (Se), Bromine (Br), Krypton (Kr), Strontium (Sr), Rubidium (Rb), and Yttrium (Y). The path starts at  $^{66}\text{Zn}$ , moves up to  $^{67}\text{Zn}$  (highlighted in red), then to  $^{68}\text{Zn}$  (also highlighted in red), then to  $^{70}\text{Zn}$ . From there, it moves up to  $^{69}\text{Ga}$ , then to  $^{70}\text{Ge}$ ,  $^{72}\text{Ge}$ ,  $^{73}\text{Ge}$ ,  $^{74}\text{Ge}$ ,  $^{75}\text{As}$ ,  $^{76}\text{Se}$ ,  $^{77}\text{Se}$ ,  $^{78}\text{Se}$ ,  $^{79}\text{Br}$ ,  $^{80}\text{Kr}$ ,  $^{82}\text{Kr}$ ,  $^{83}\text{Kr}$ ,  $^{84}\text{Kr}$ ,  $^{85}\text{Rb}$ ,  $^{86}\text{Sr}$ ,  $^{87}\text{Sr}$ ,  $^{88}\text{Sr}$ ,  $^{89}\text{Y}$ , and finally to  $^{90}\text{Zr}$ ,  $^{91}\text{Zr}$ , and  $^{92}\text{Zr}$ . A red arrow points from  $^{66}\text{Zn}$  to  $^{68}\text{Zn}$ . Another red arrow points from  $^{65}\text{Cu}$  towards the path.

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

closed neutron shell

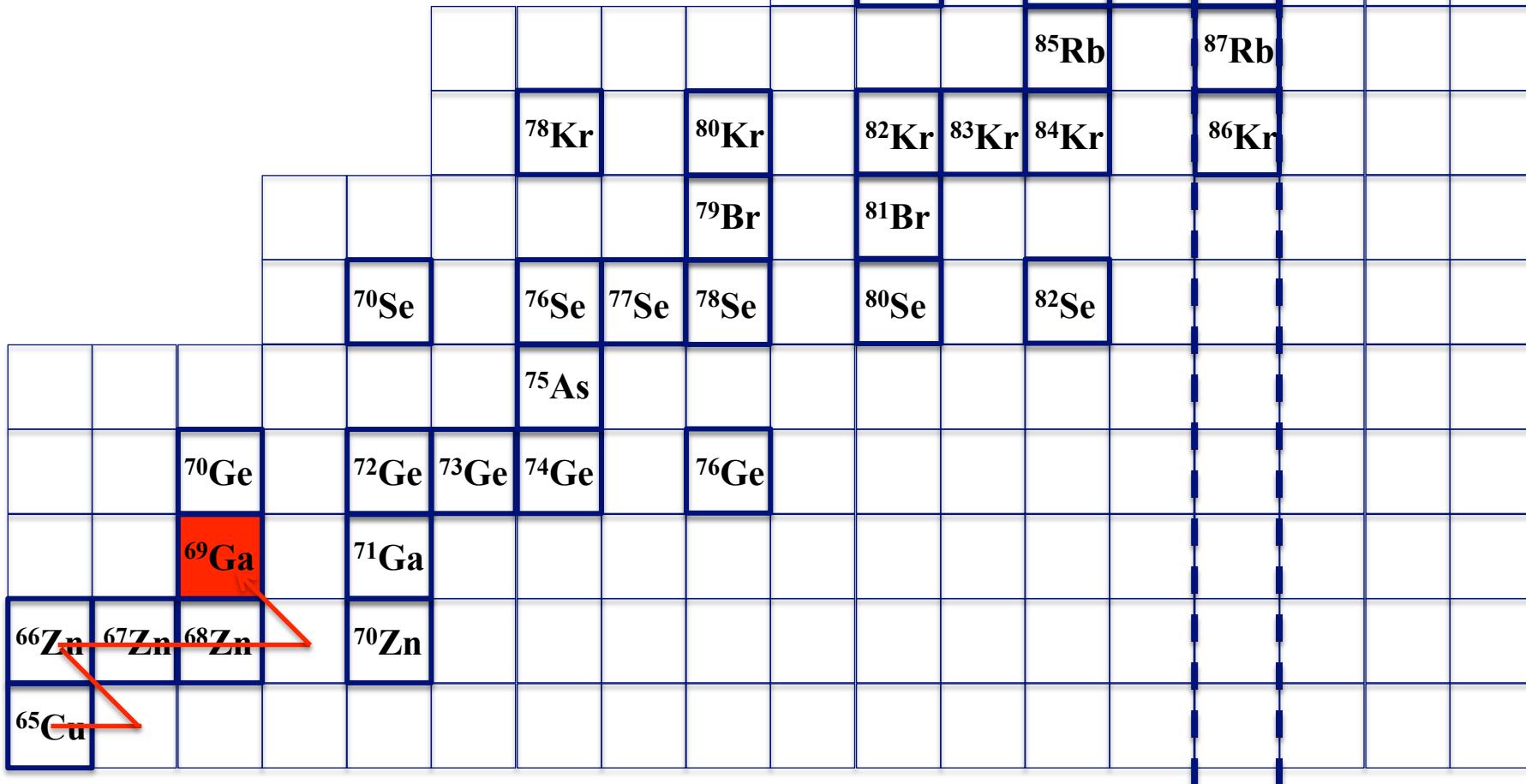
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slow neutron capture  
 $\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$  yr



# The s-process

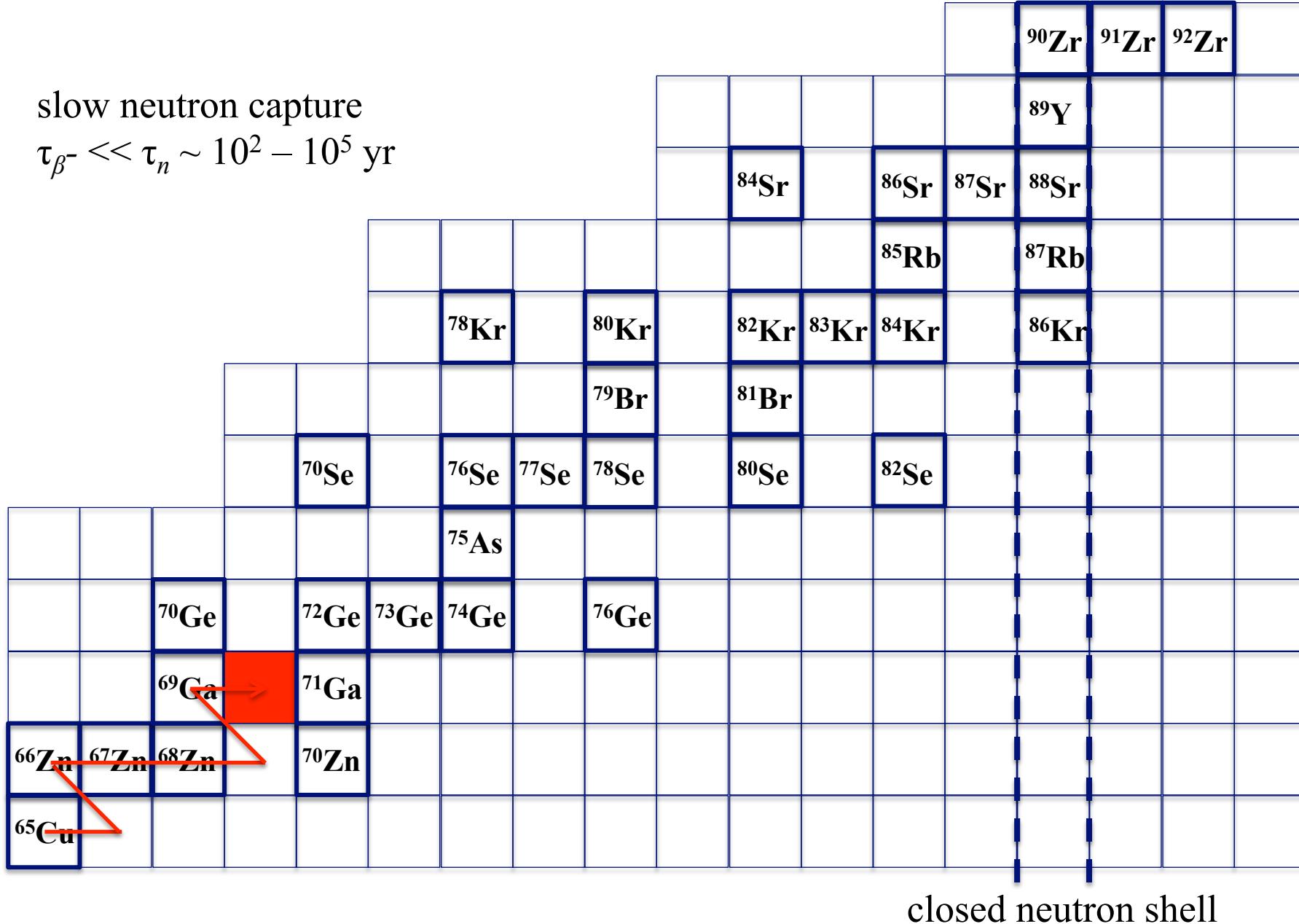
slow neutron capture  
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closed neutron shell

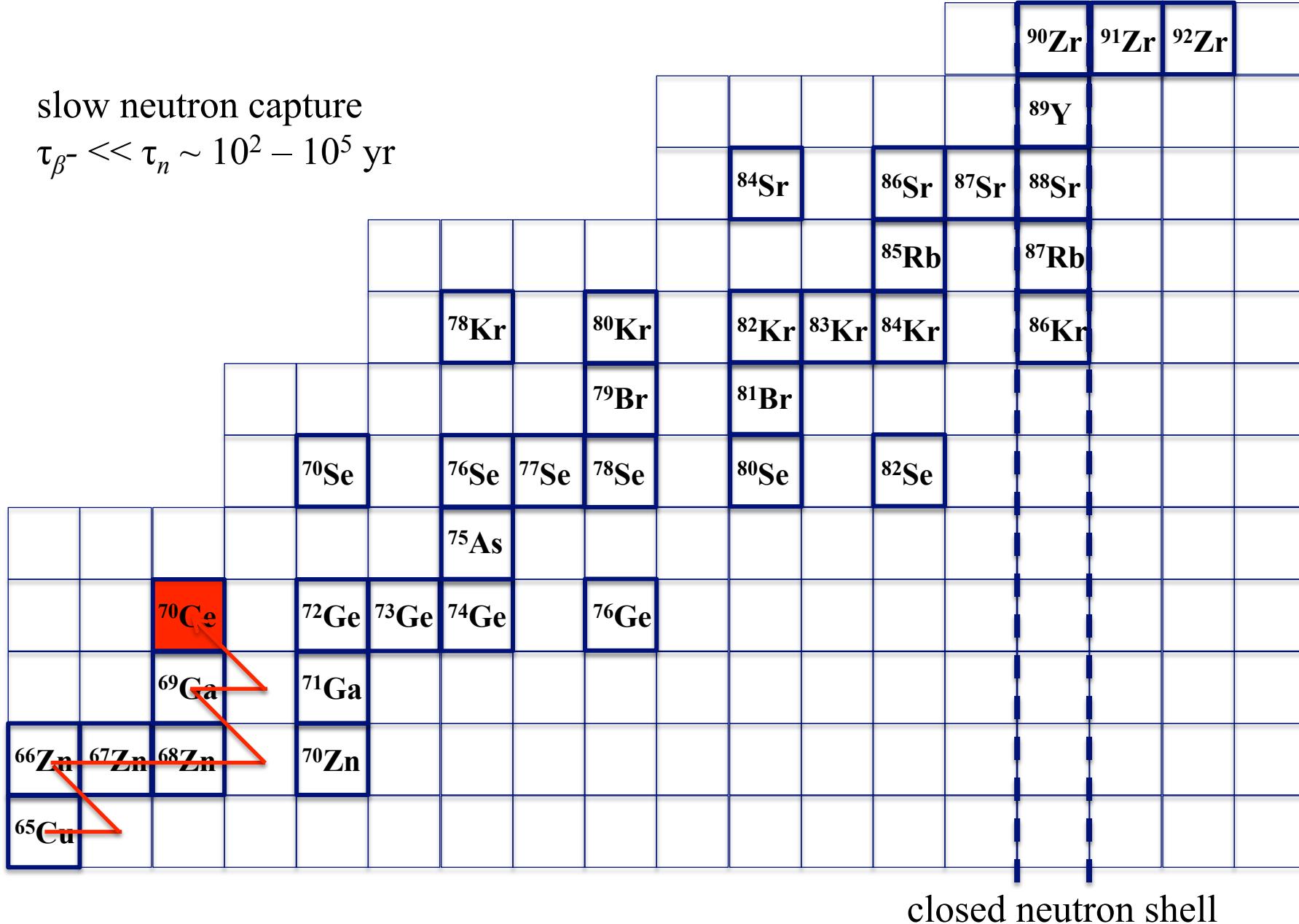
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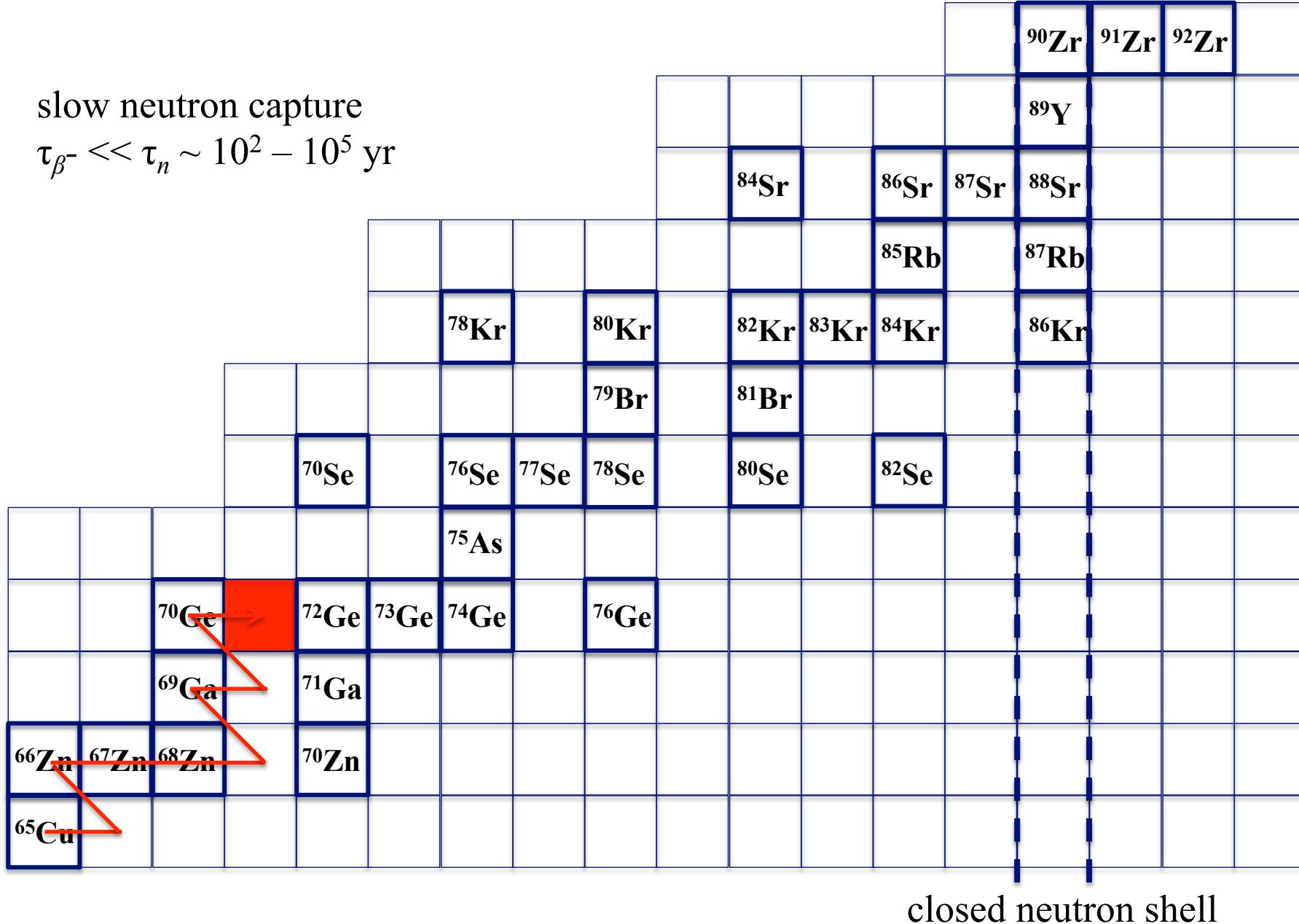
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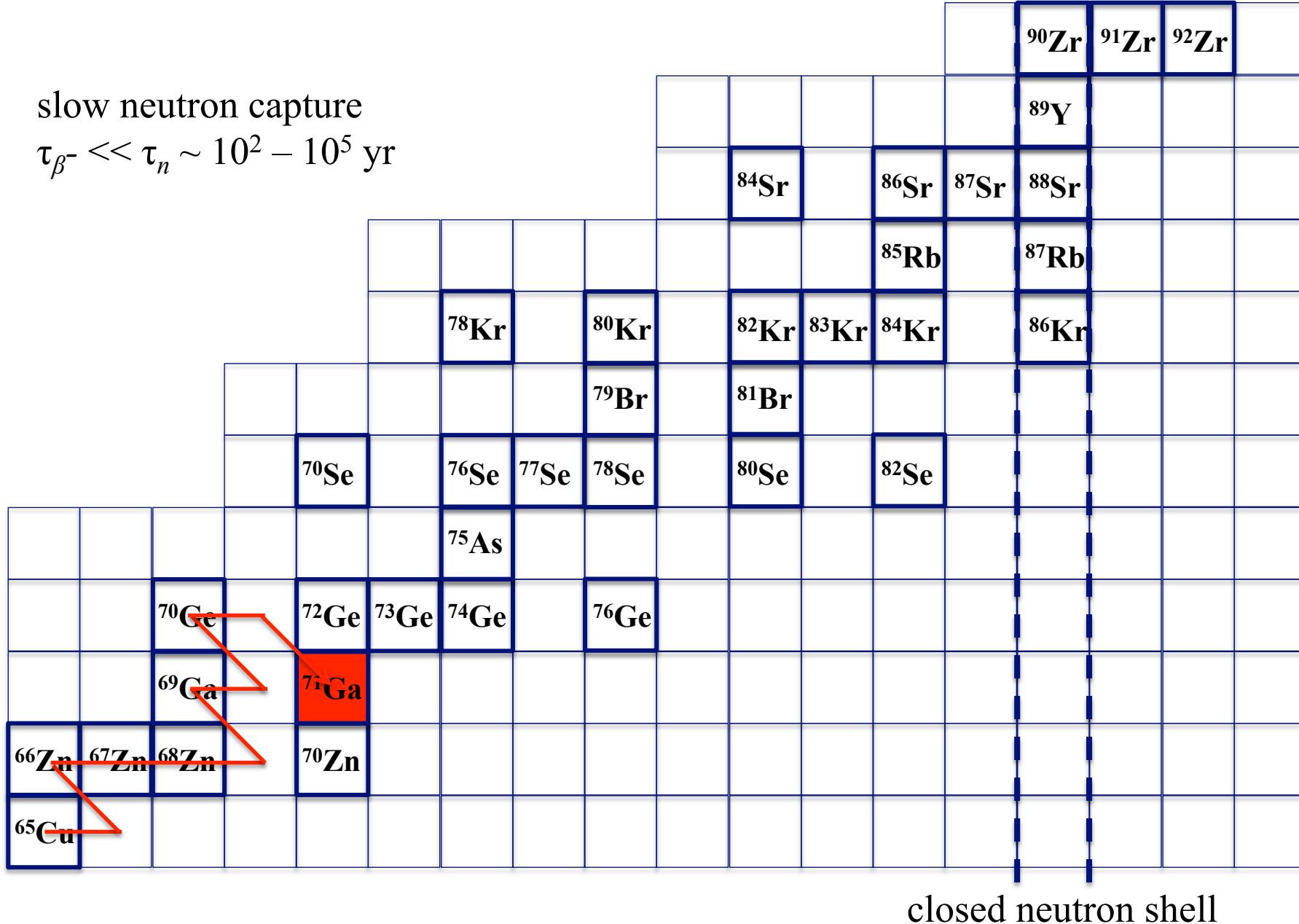
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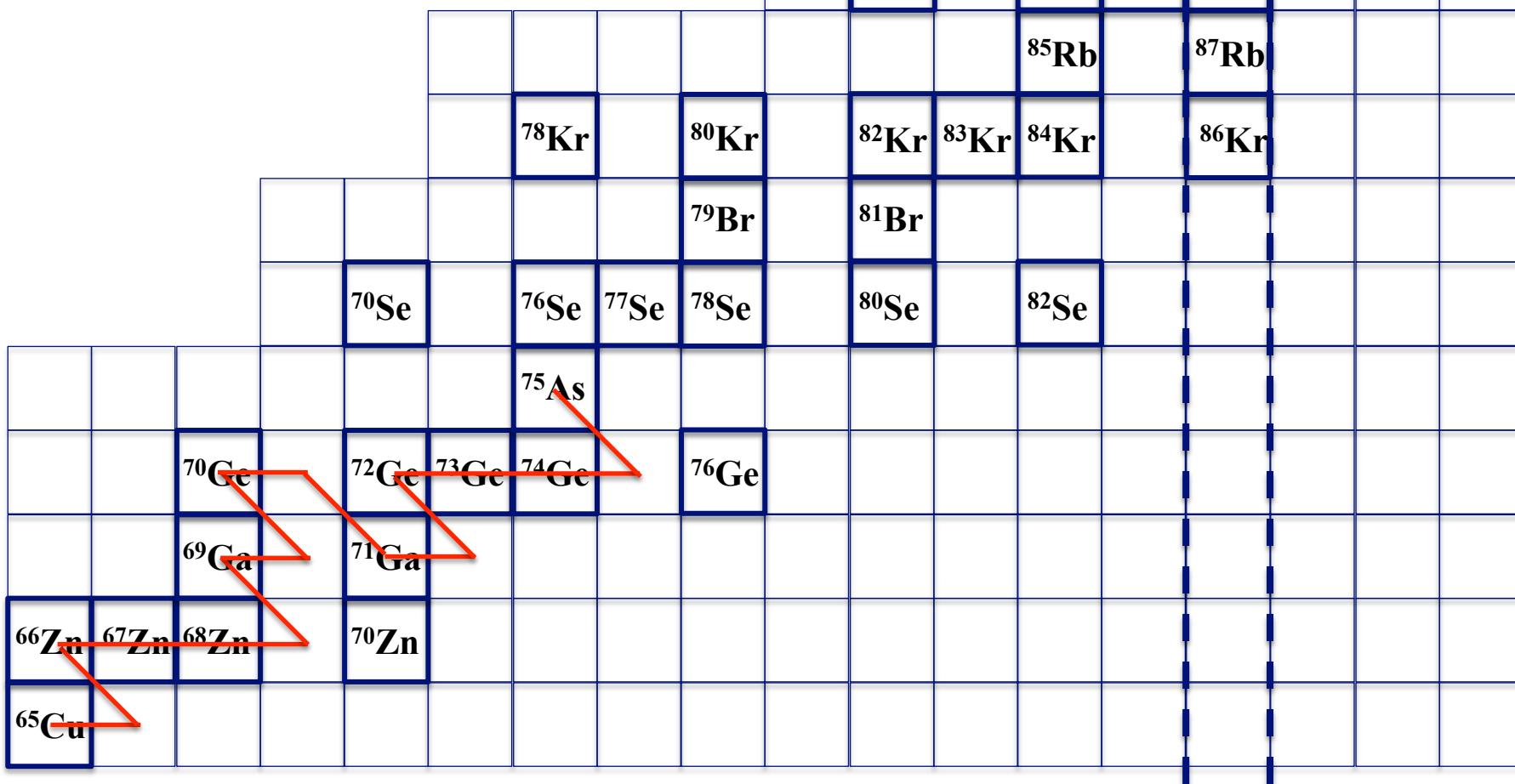
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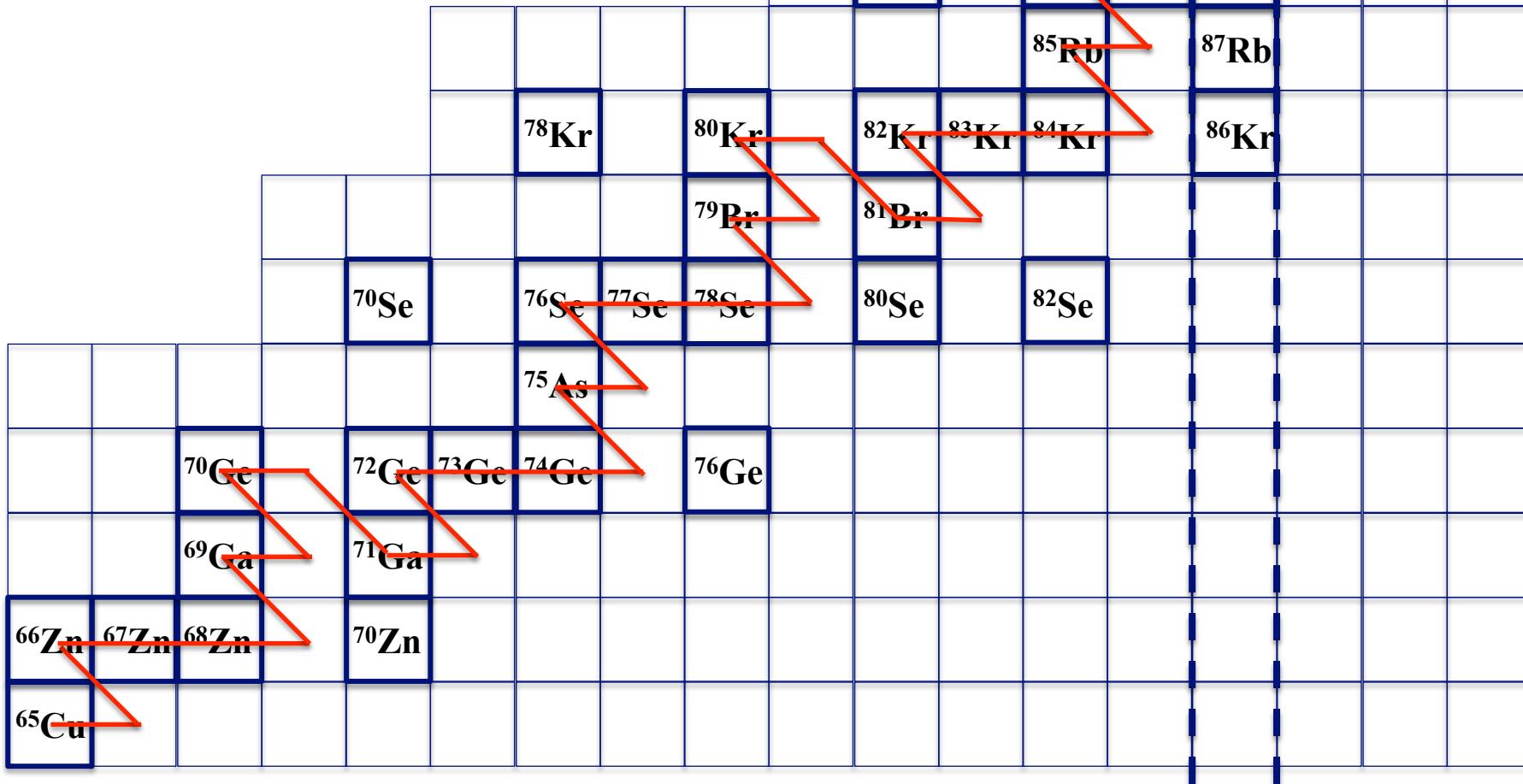
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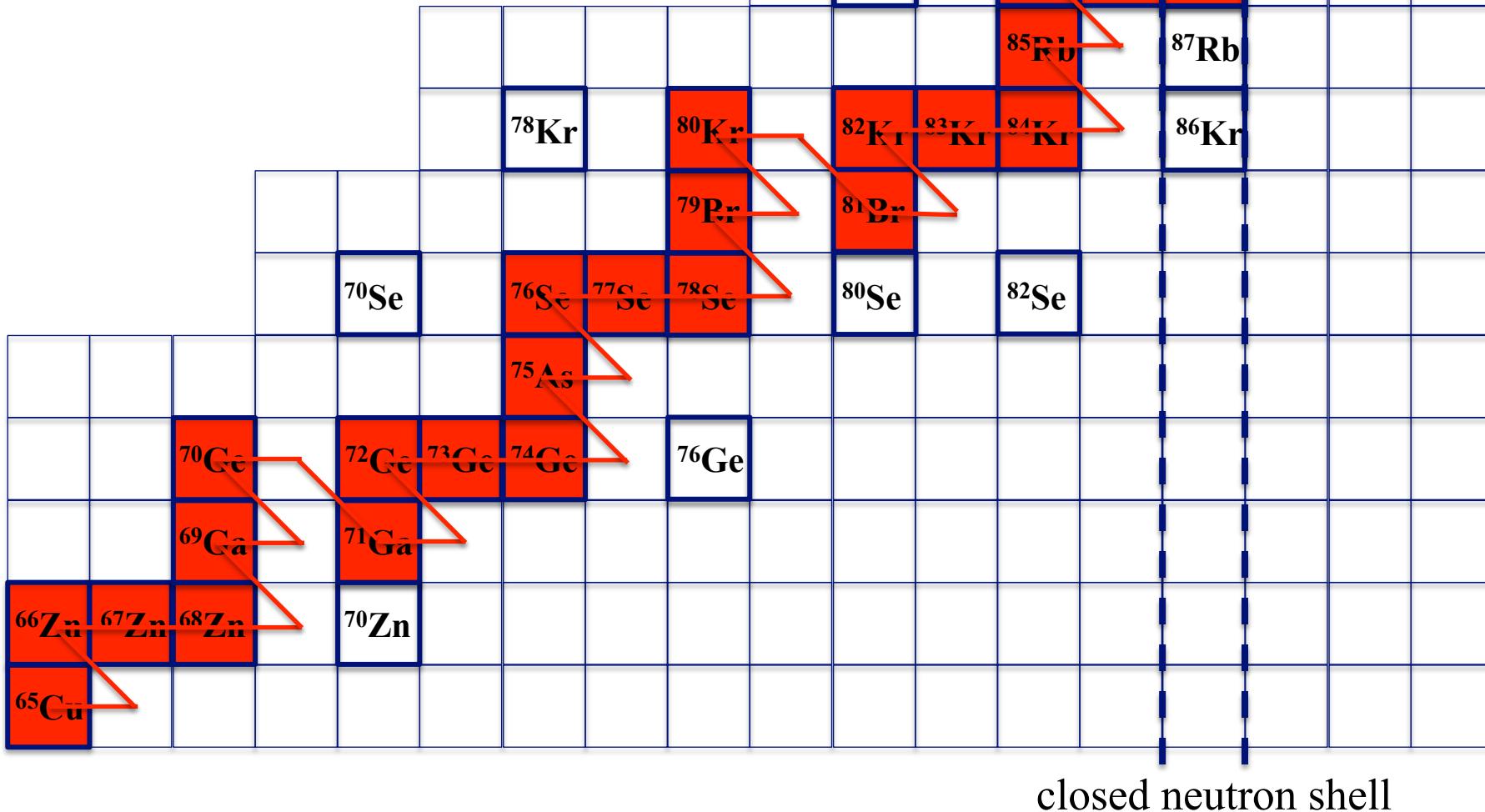
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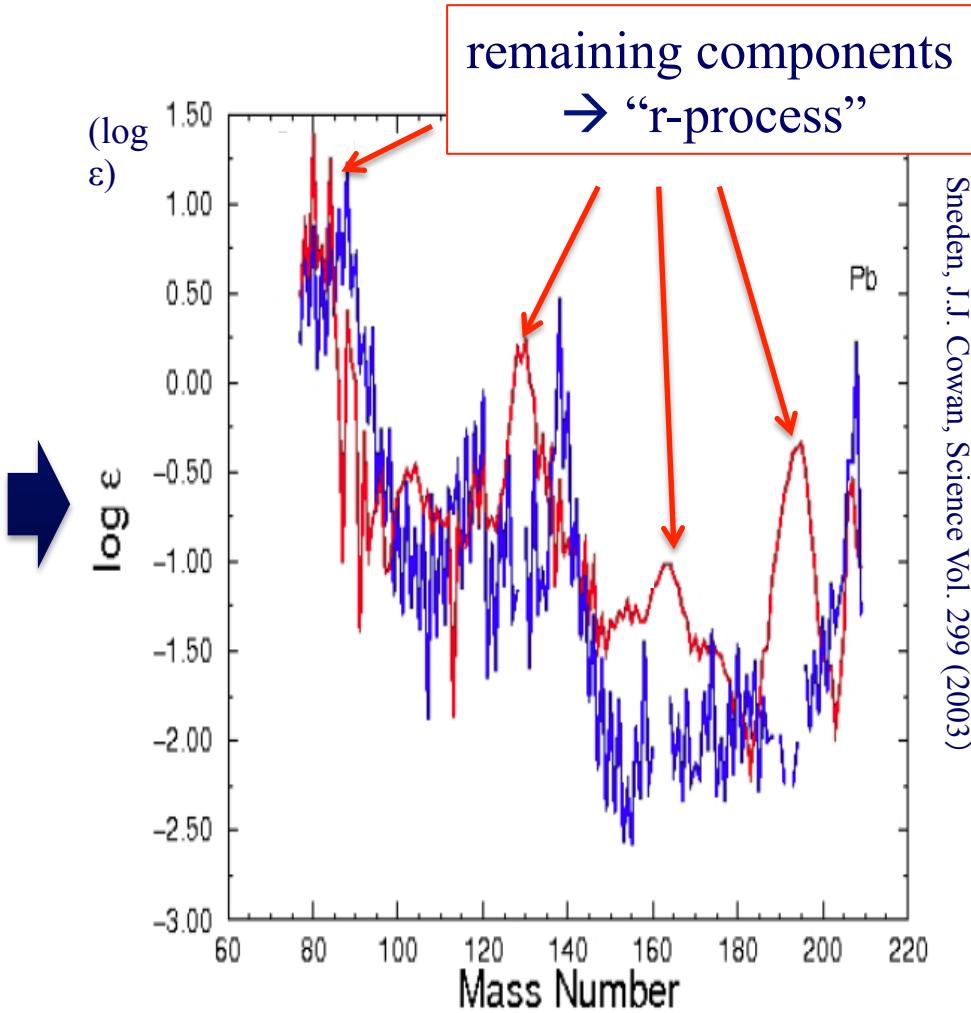
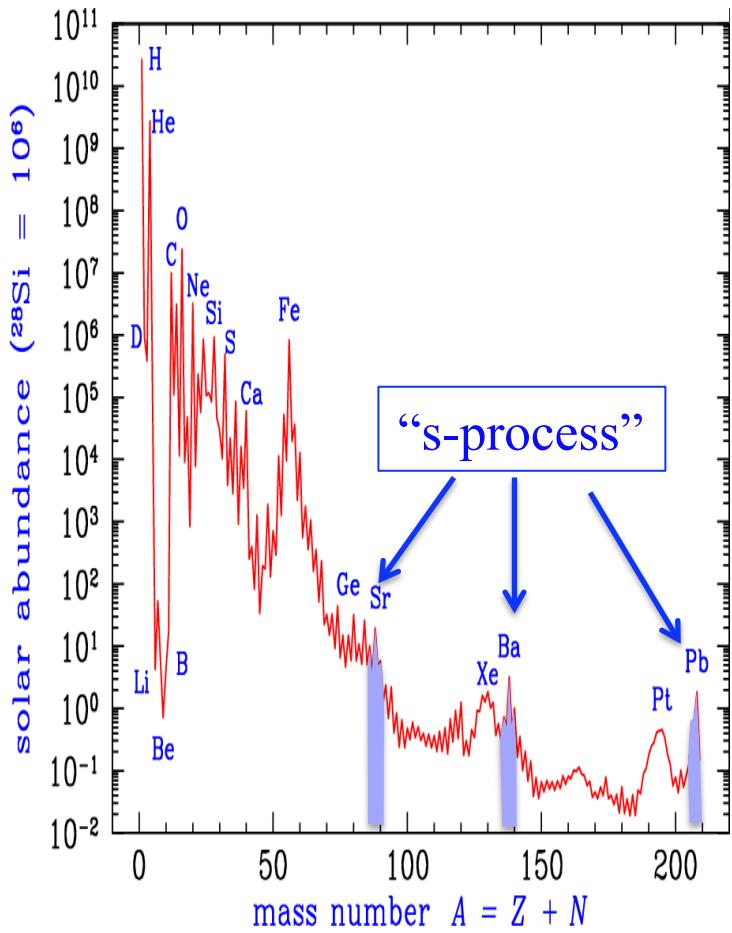


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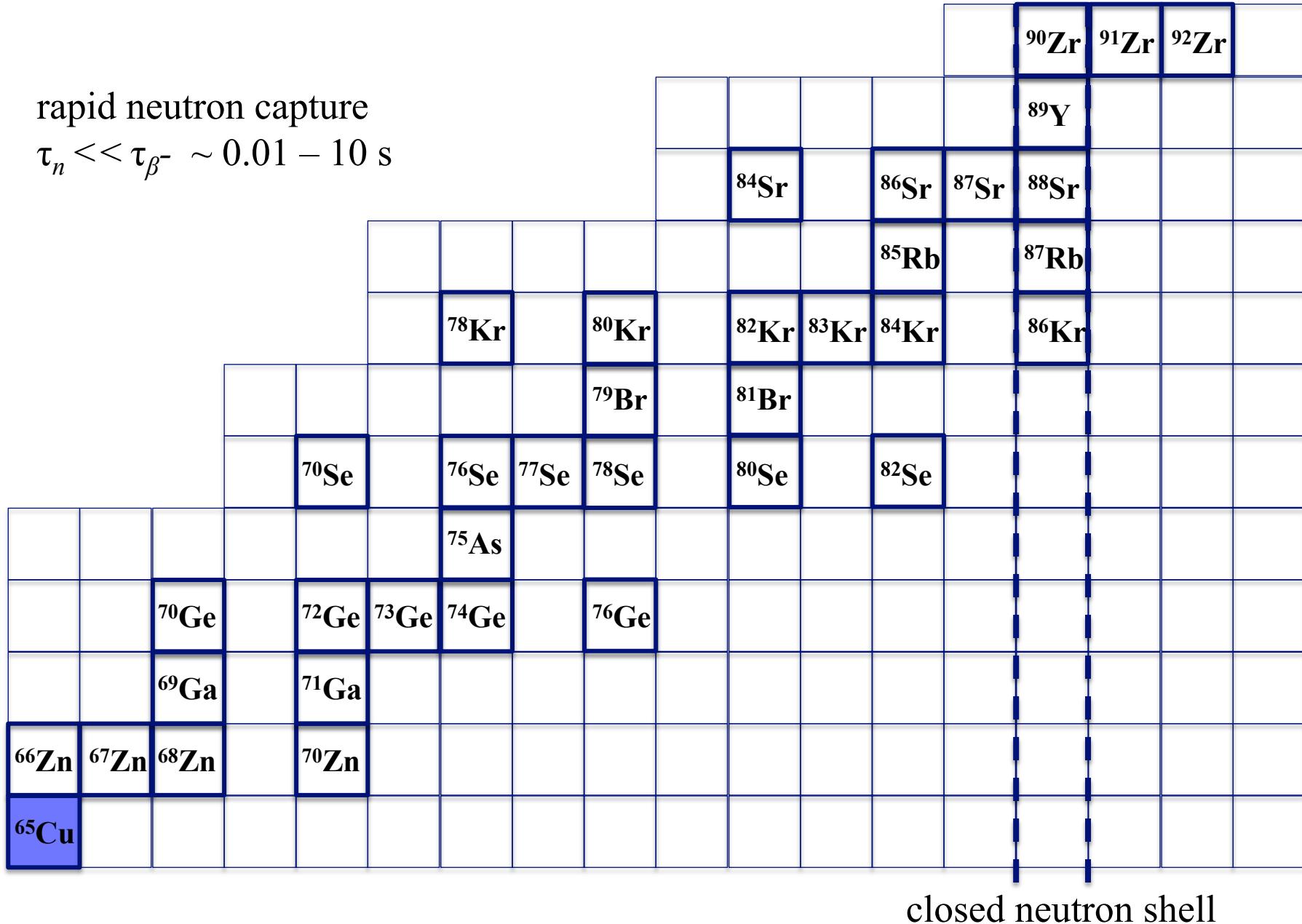
# Solar System: Abundance Pattern



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

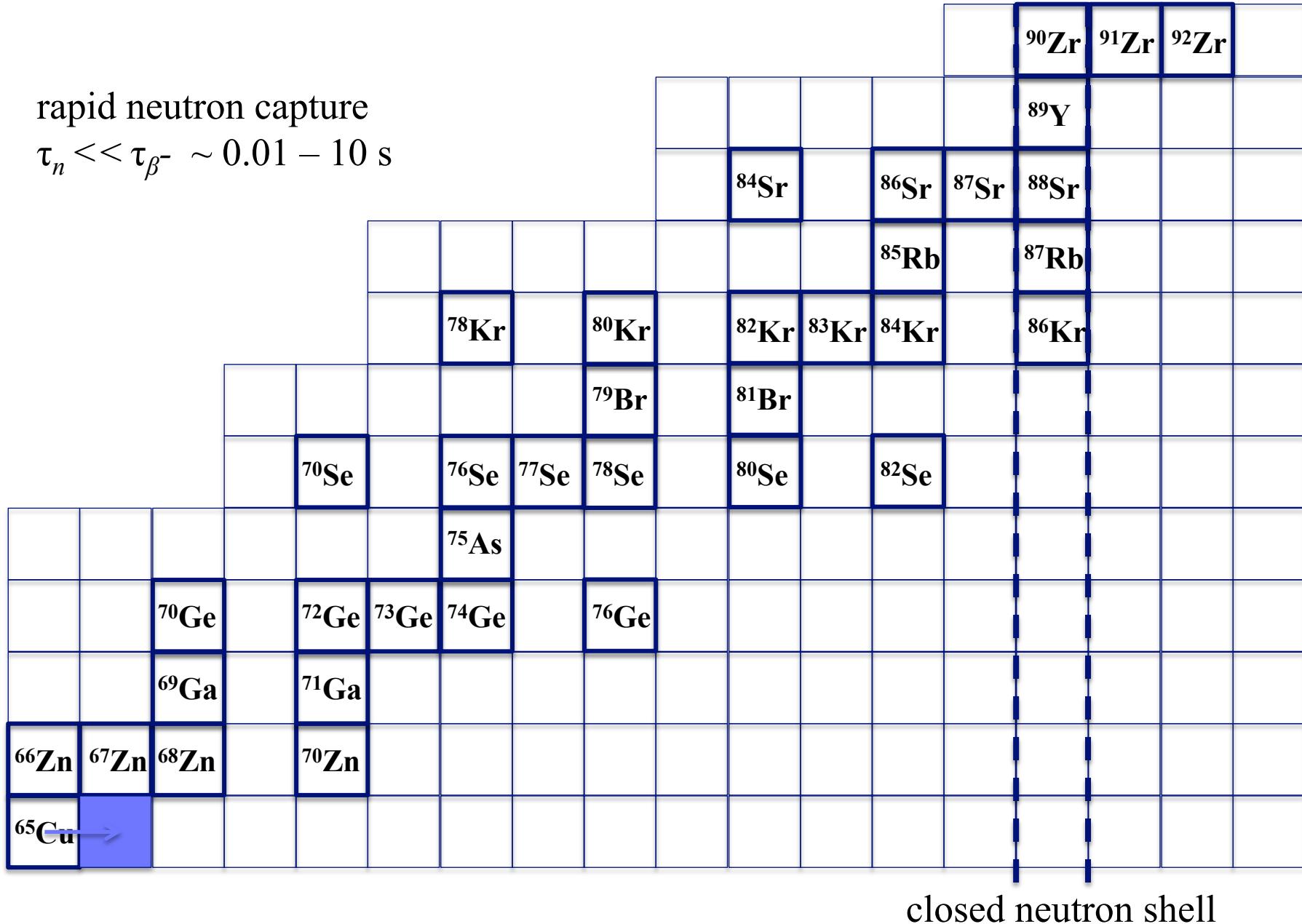
## The r-process

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



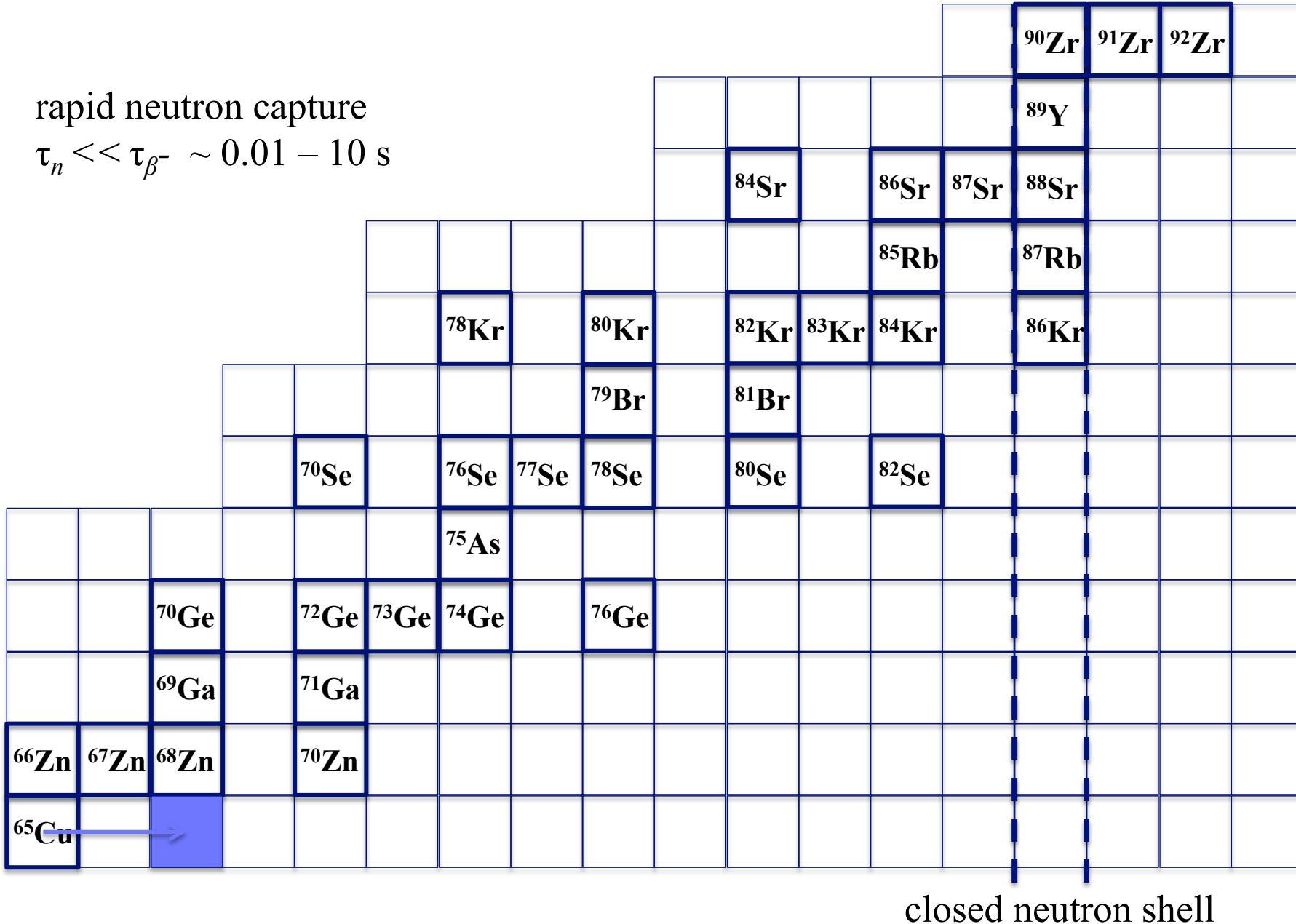
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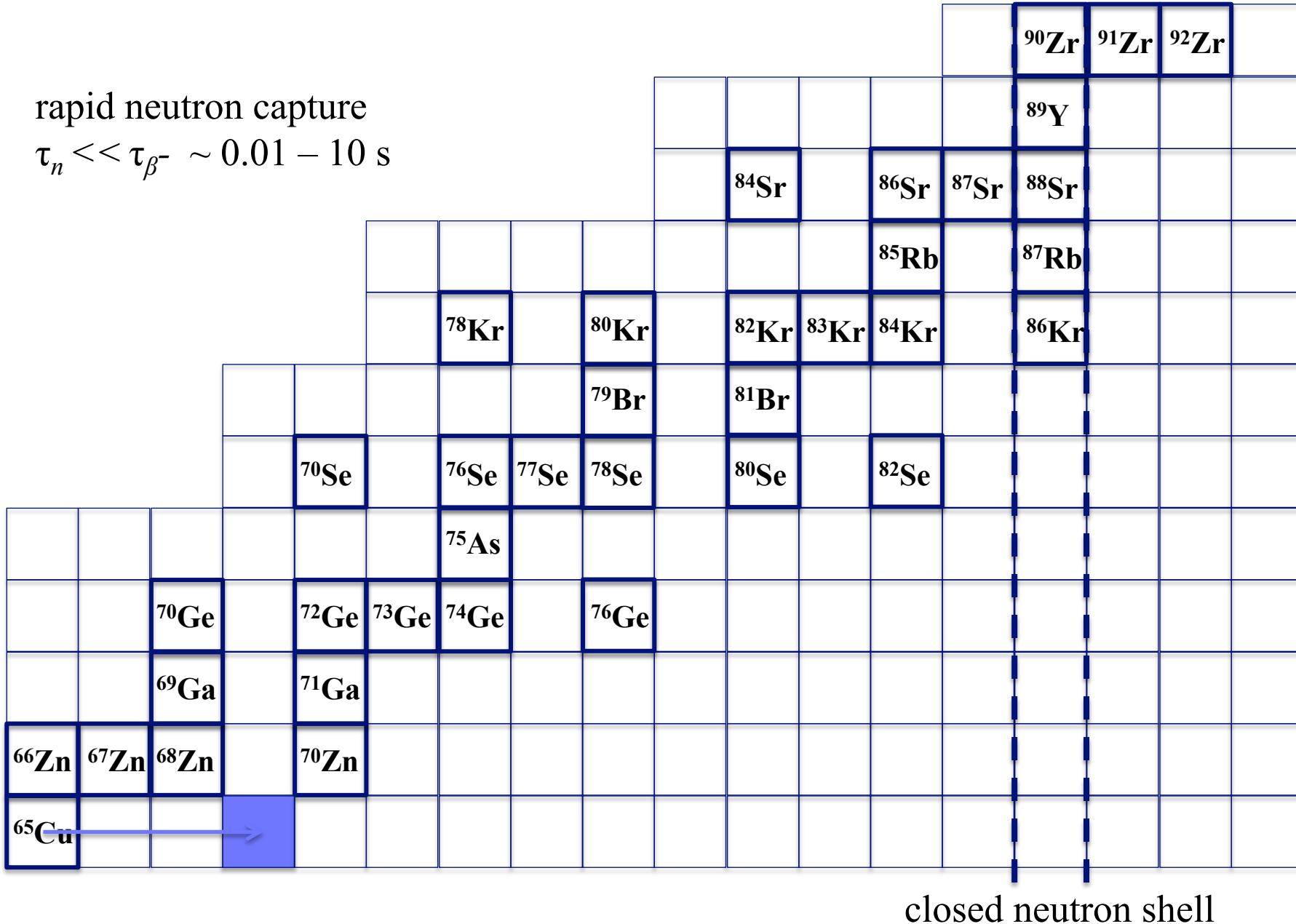
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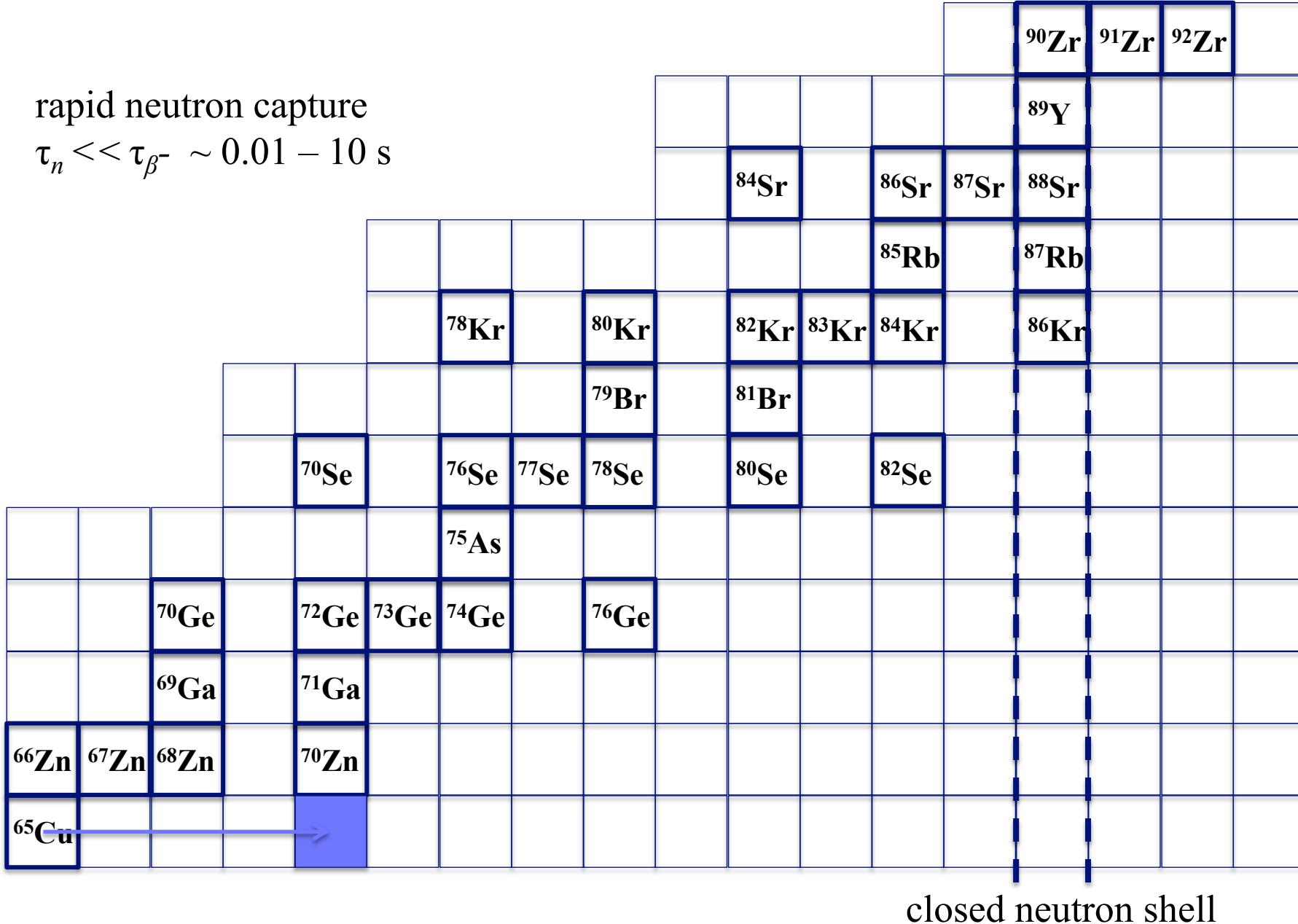
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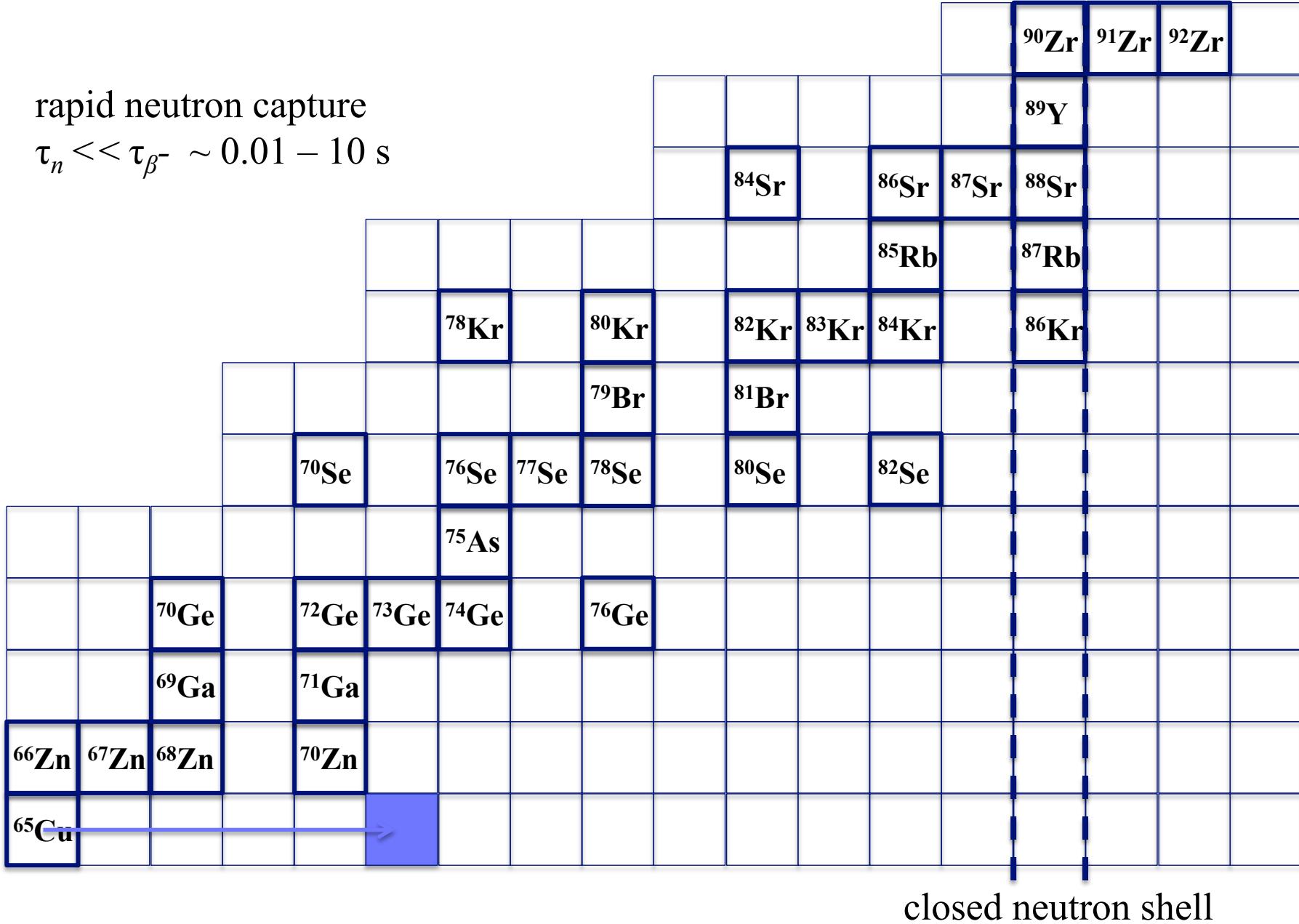
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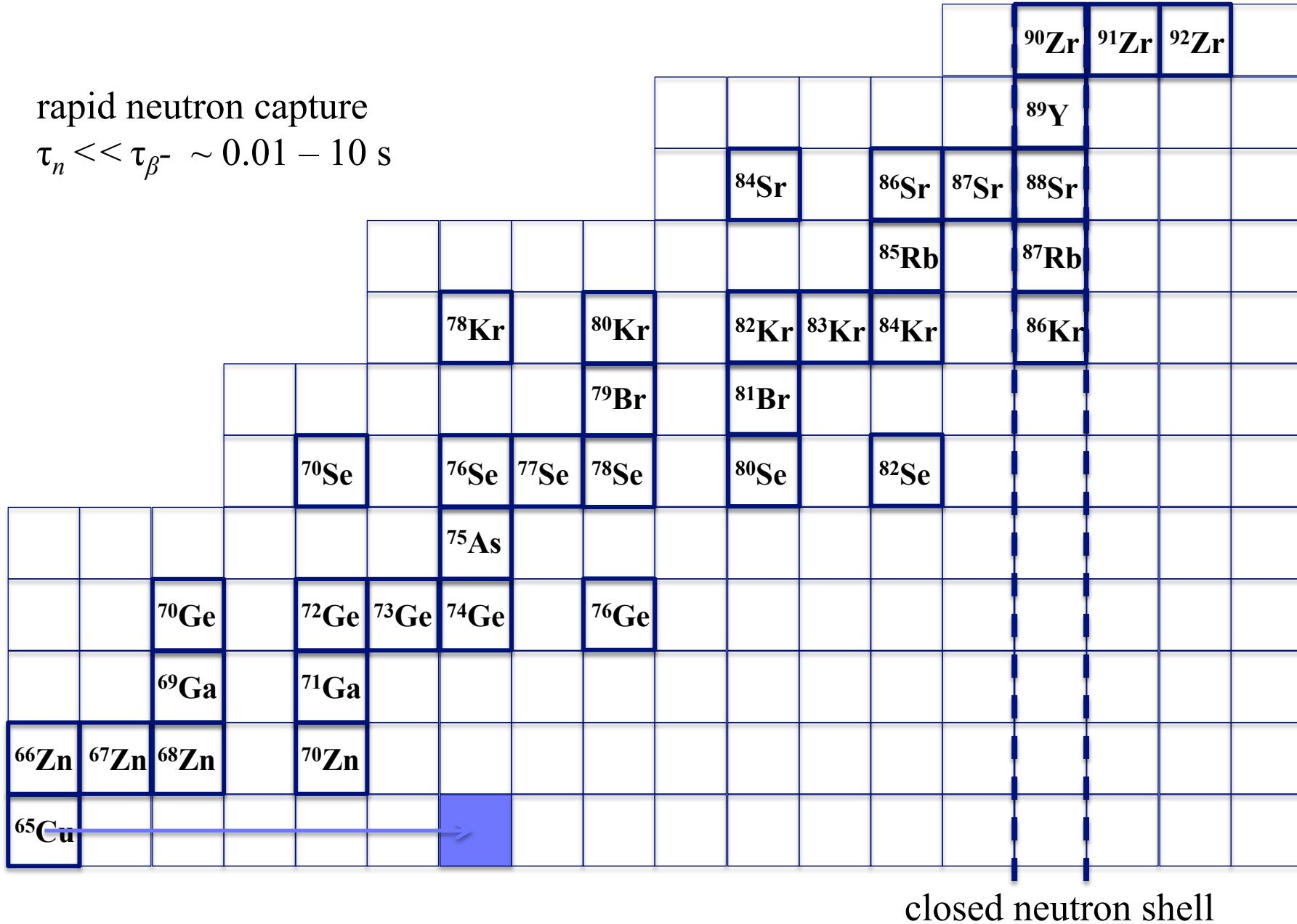
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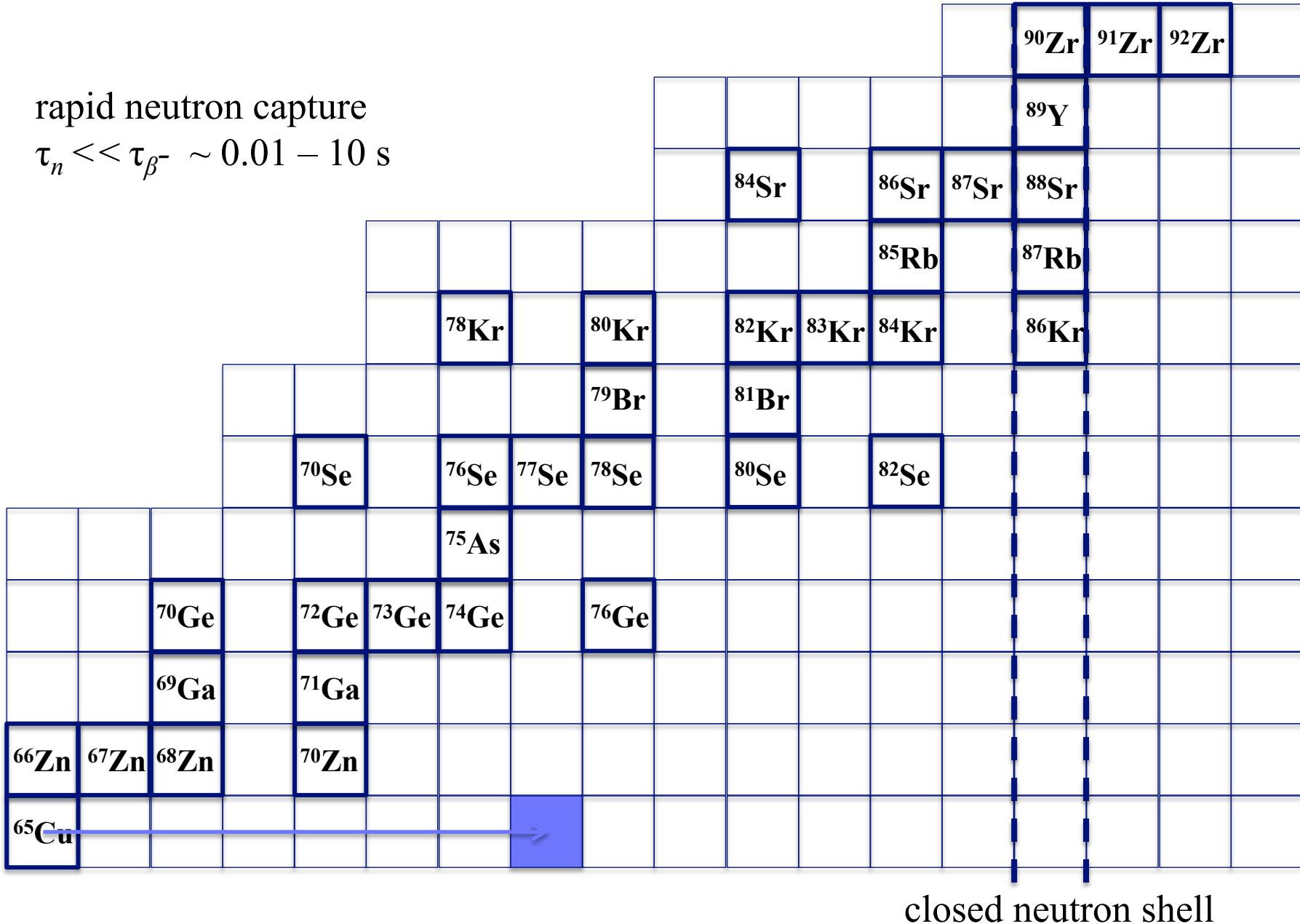
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# The r-process

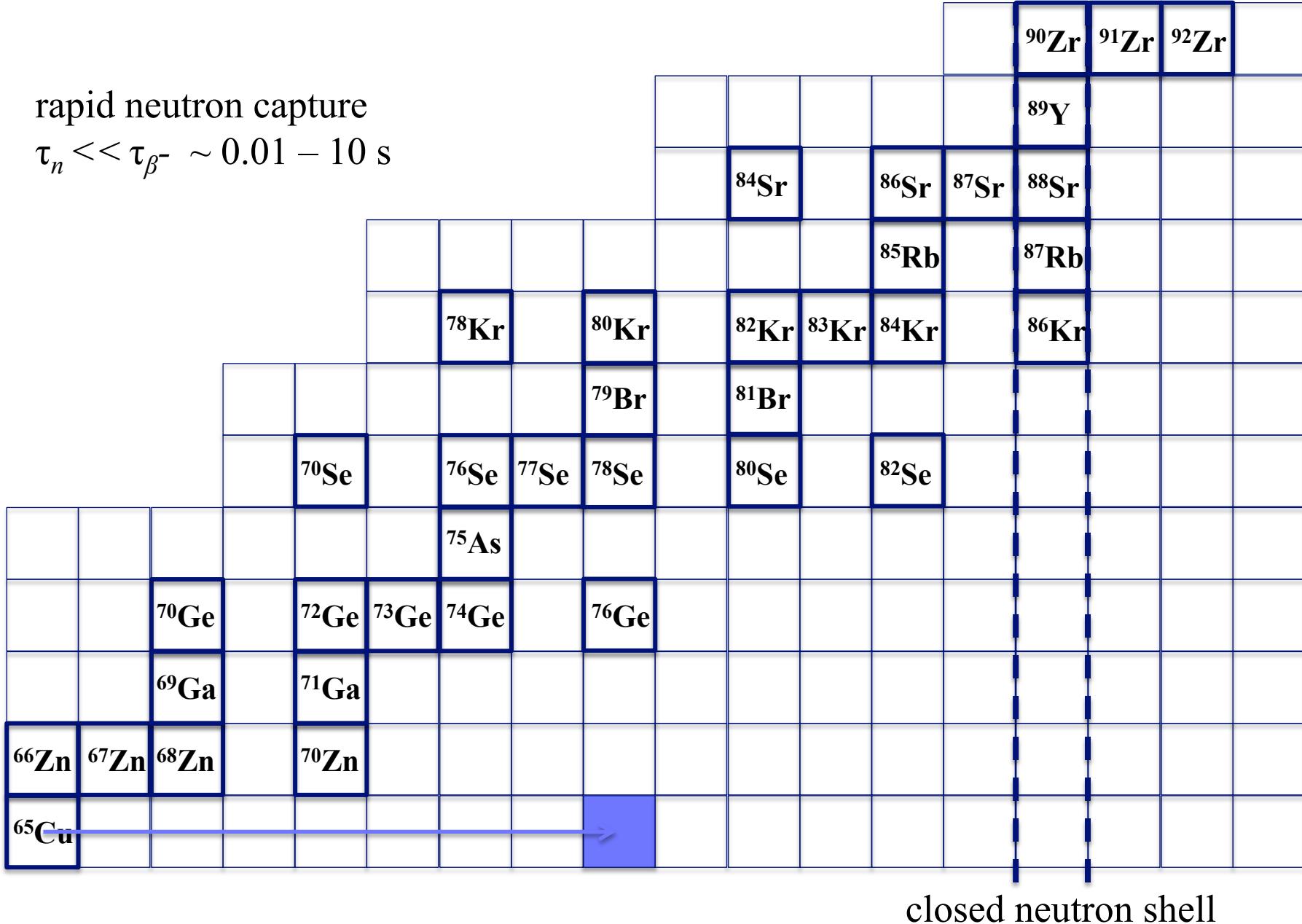
rapid neutron capture  
 $\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$  s



closed neutron shell

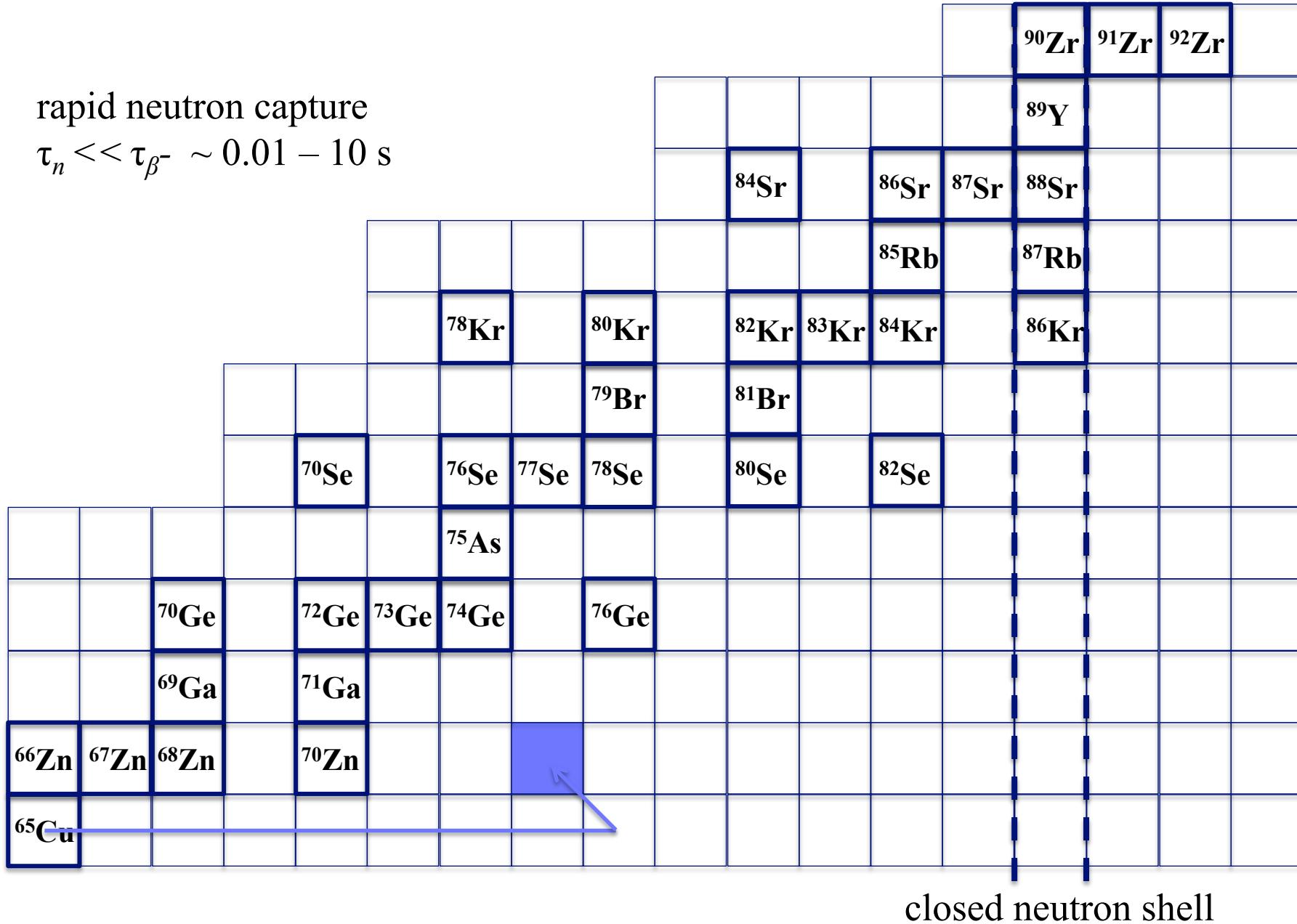
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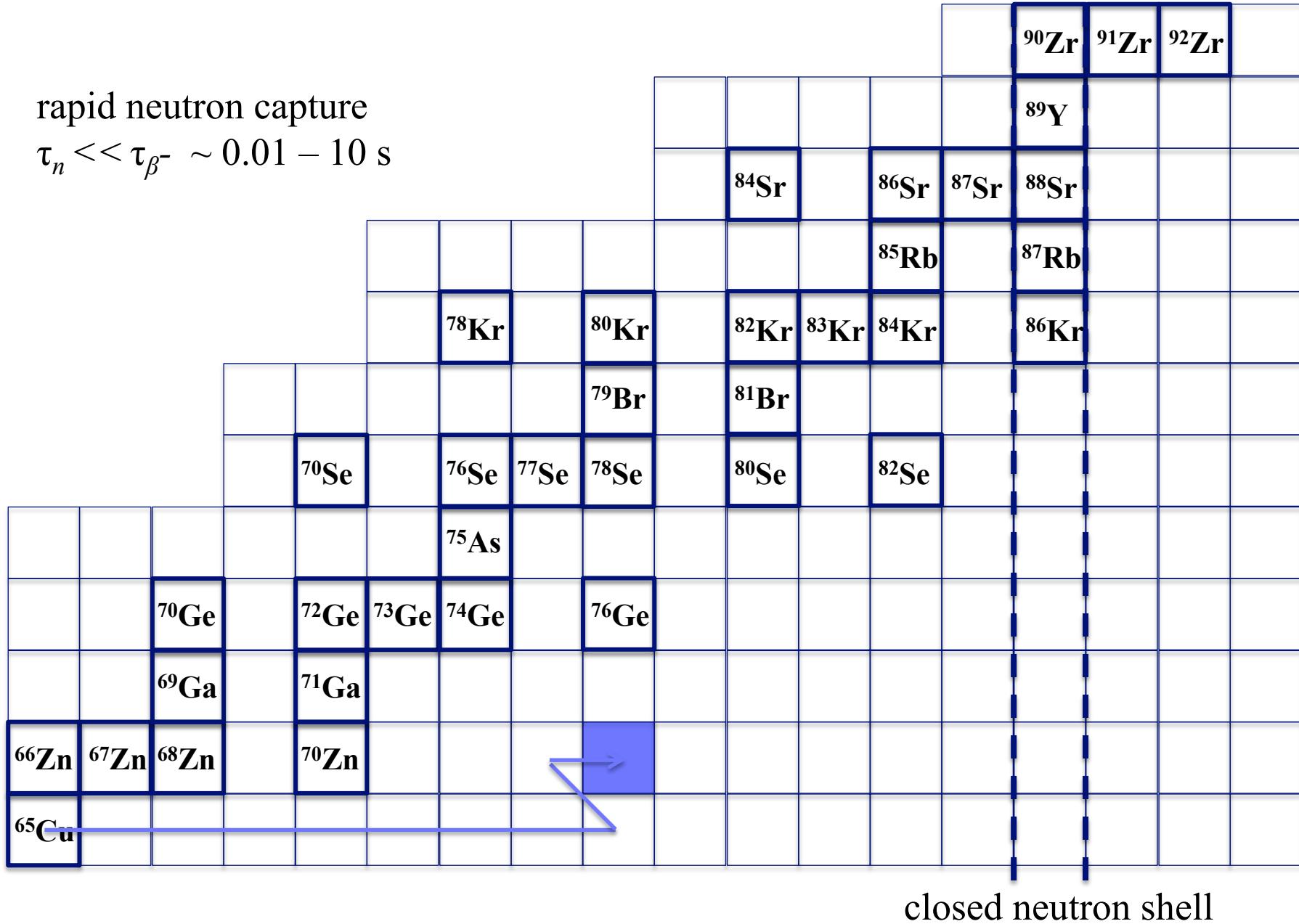
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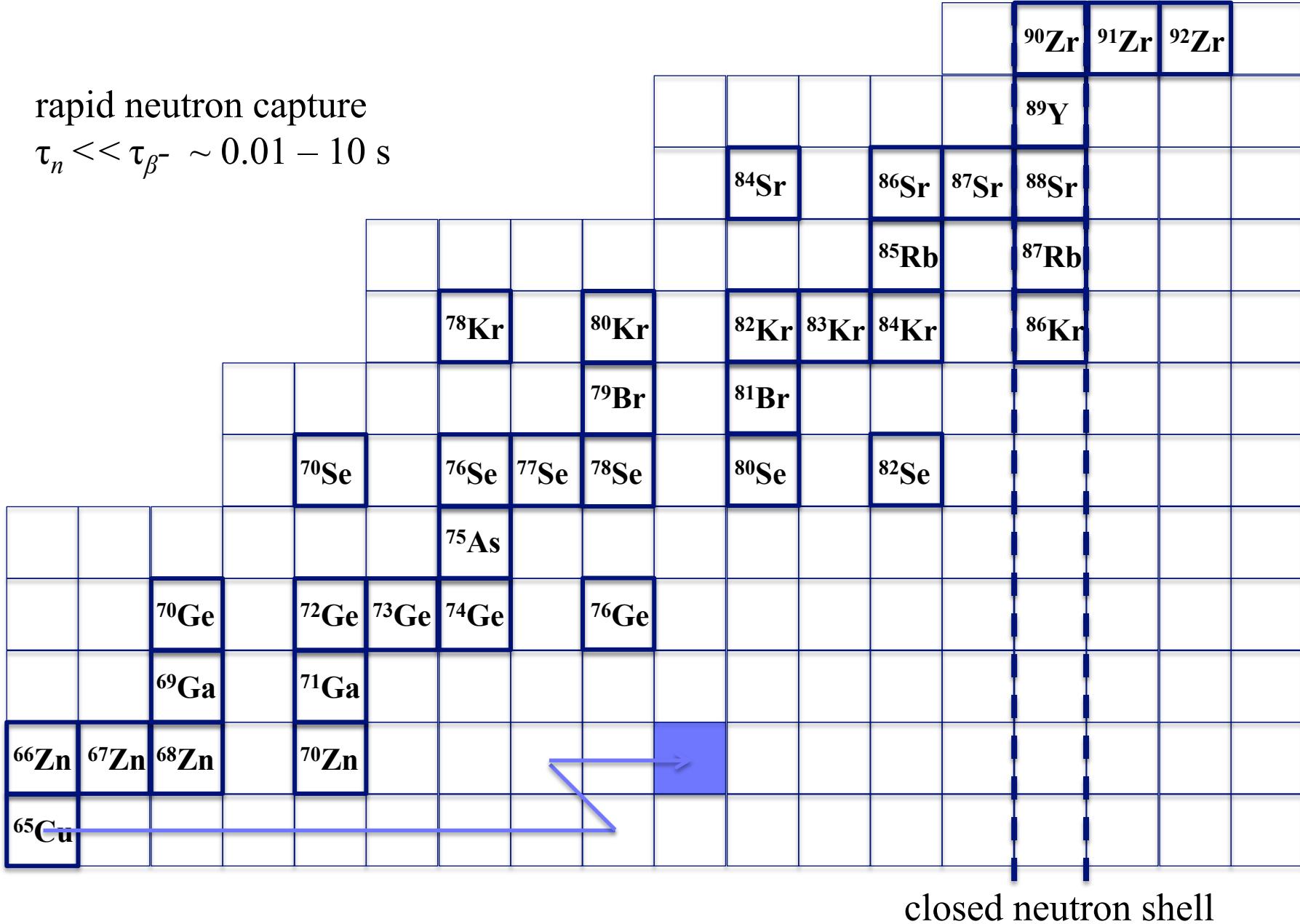
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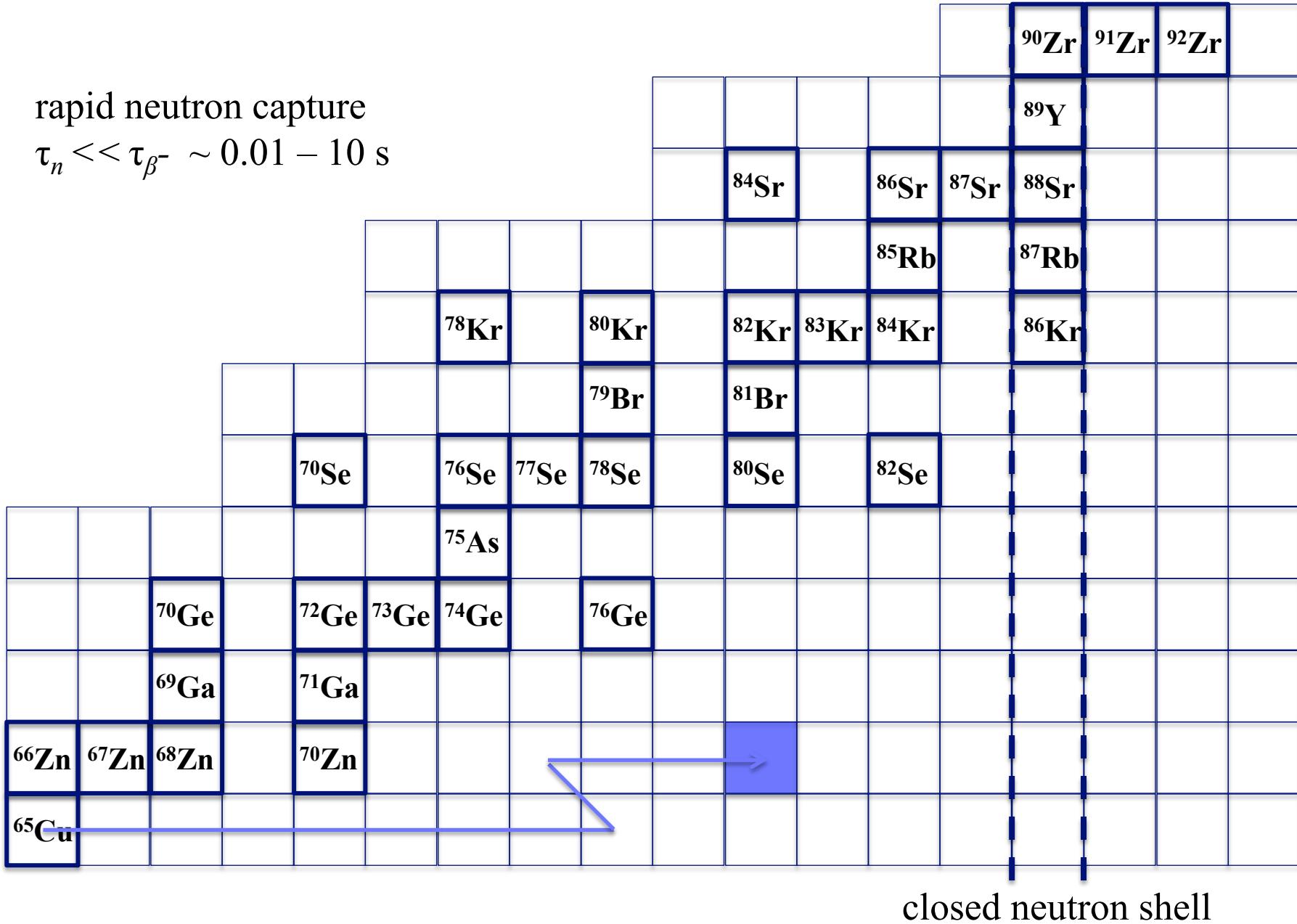
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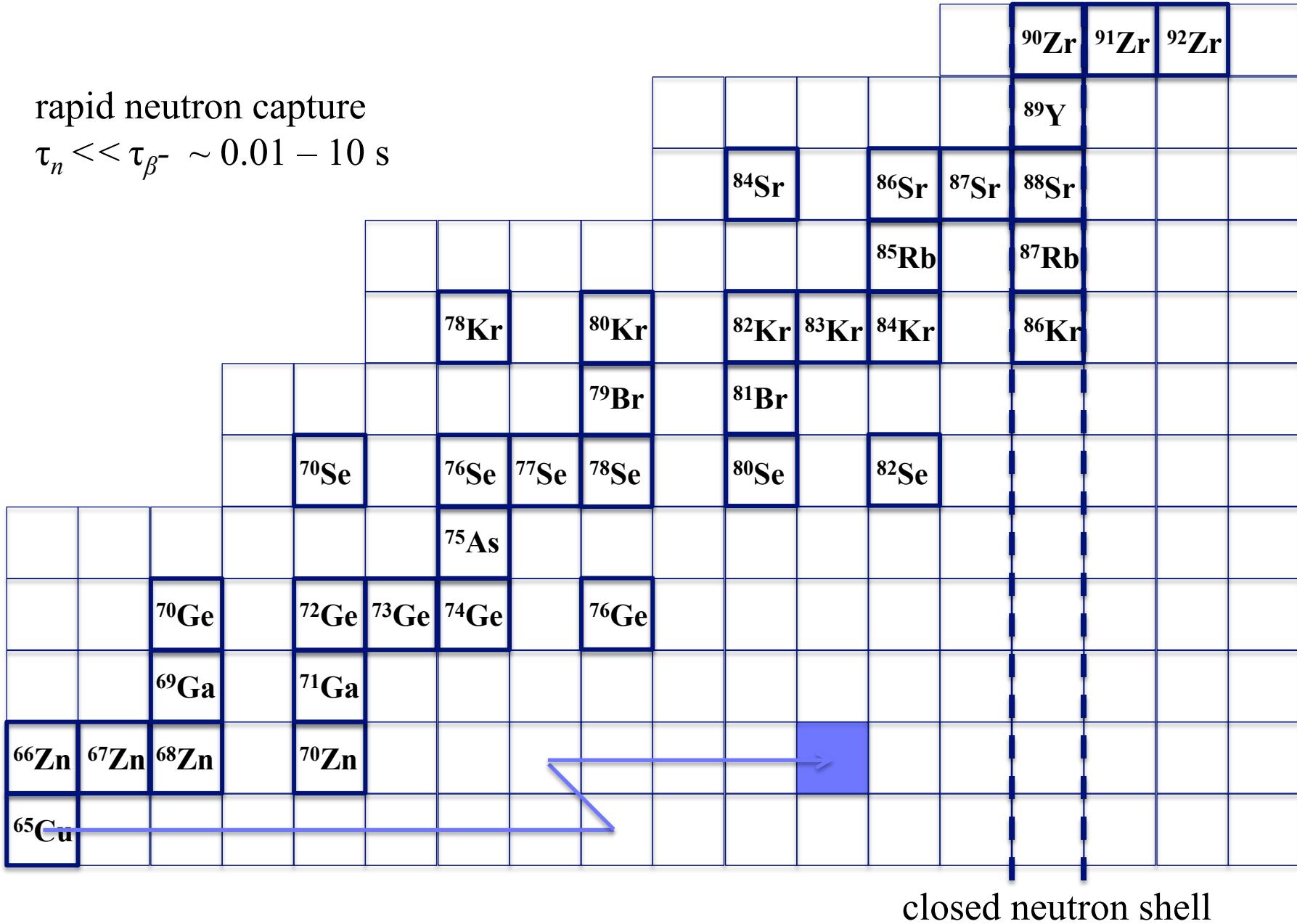
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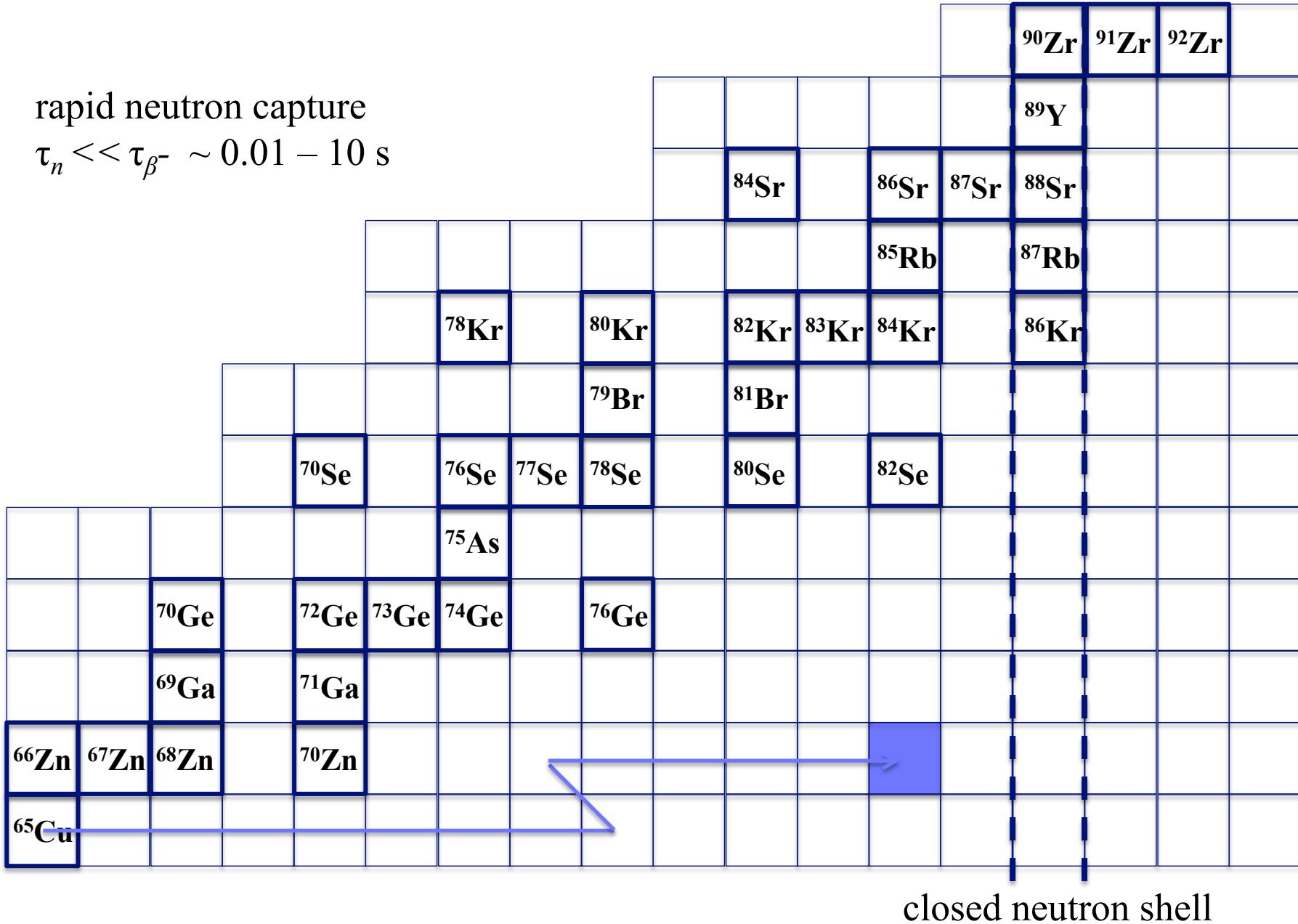
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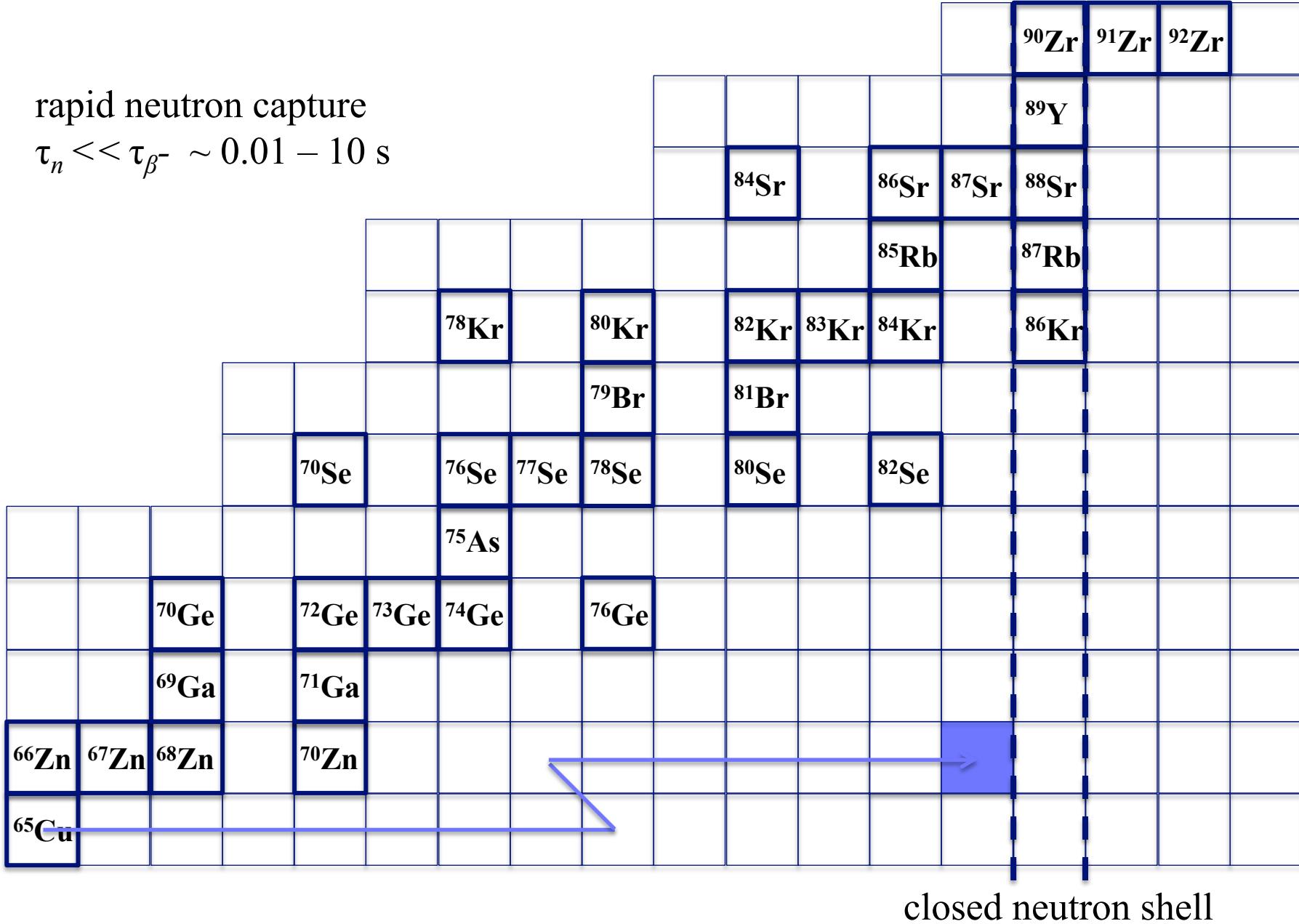
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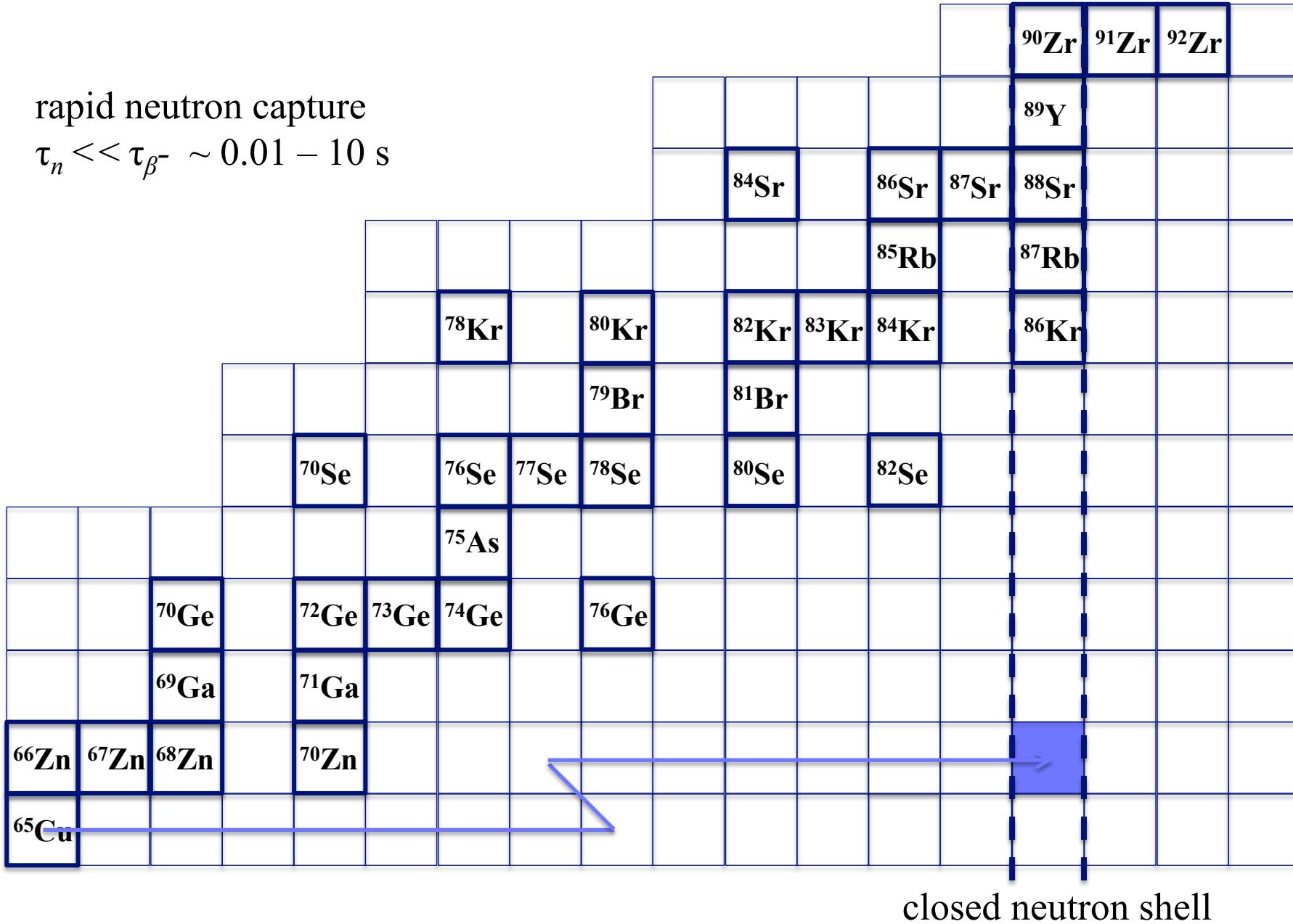
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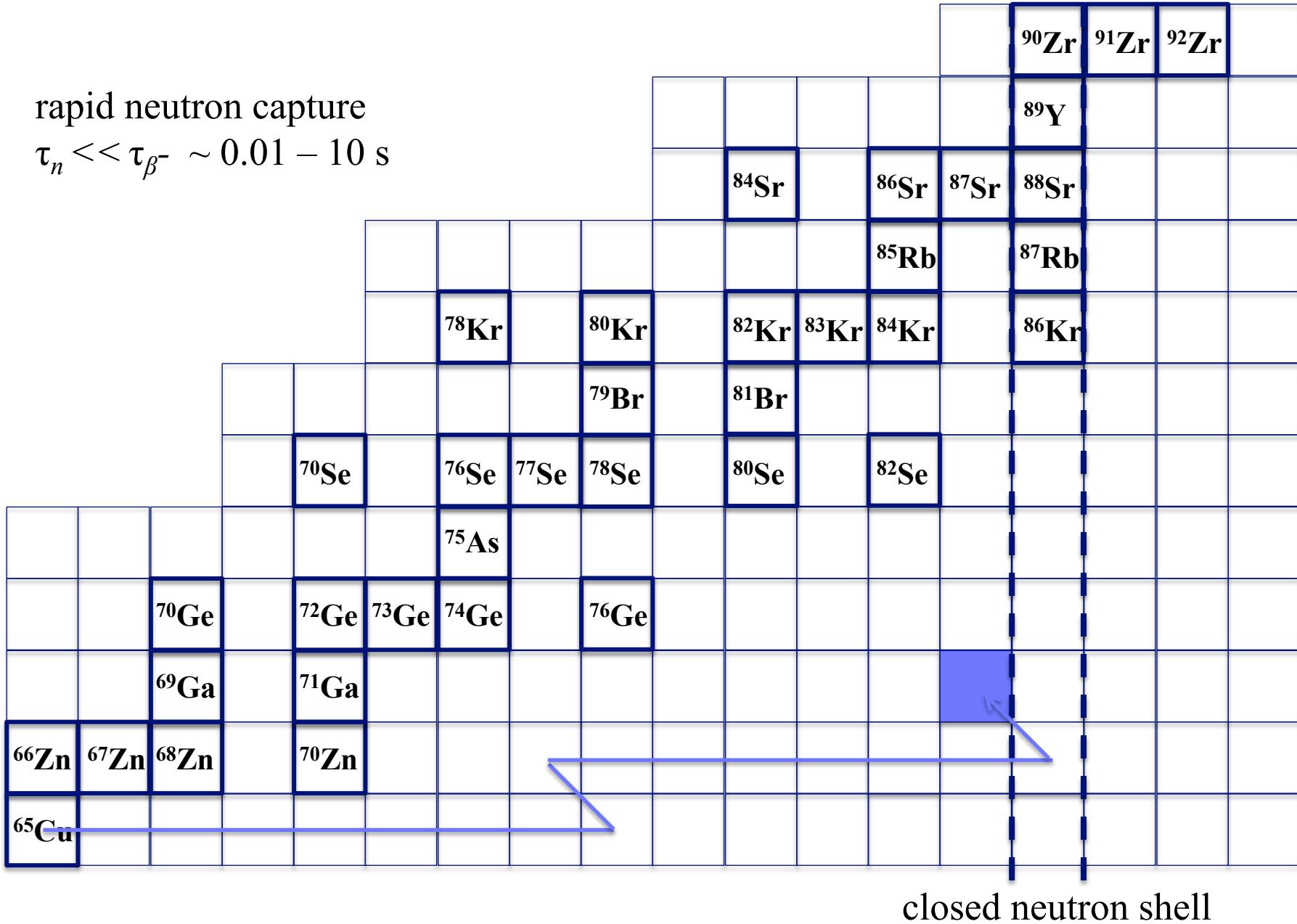
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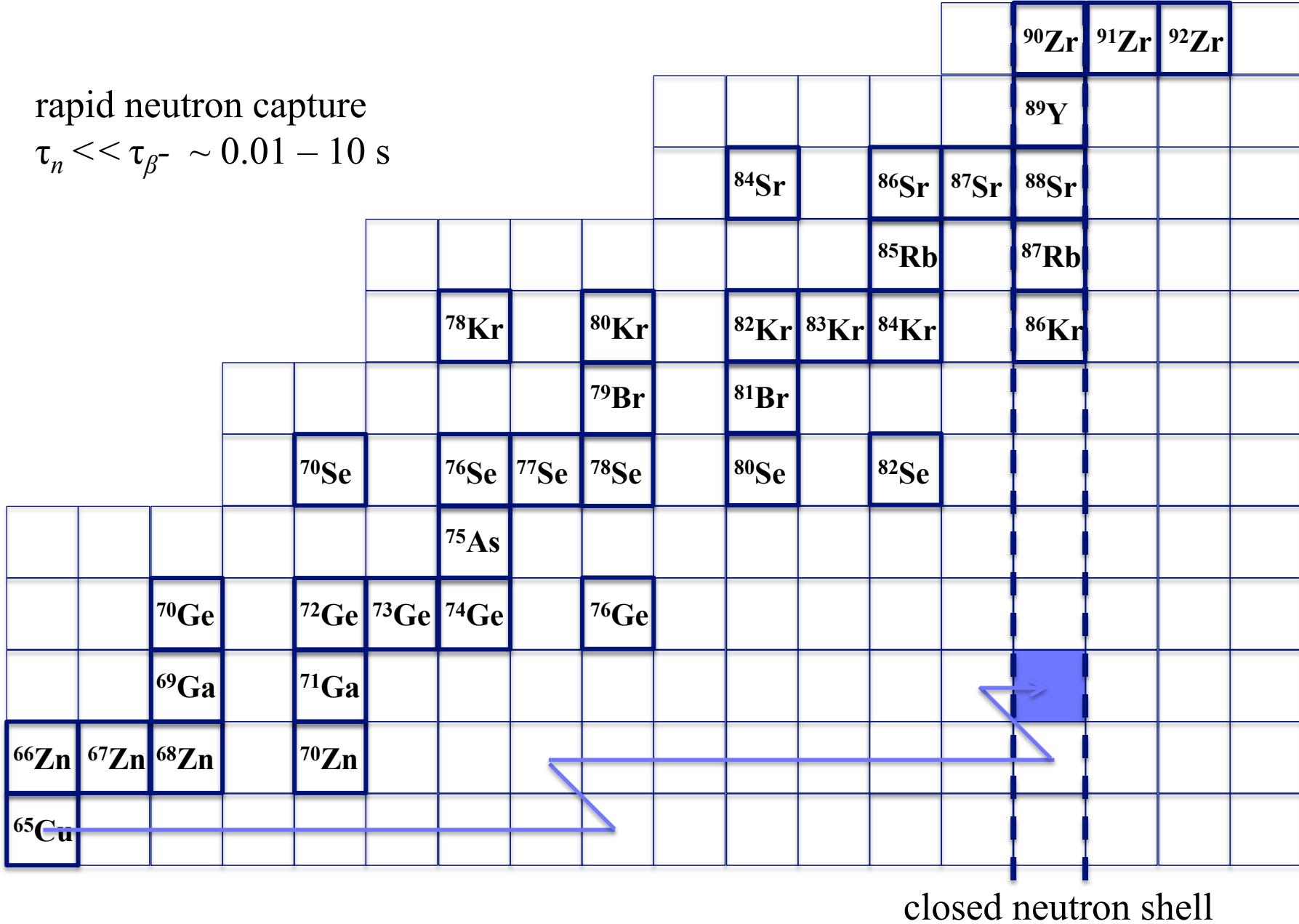
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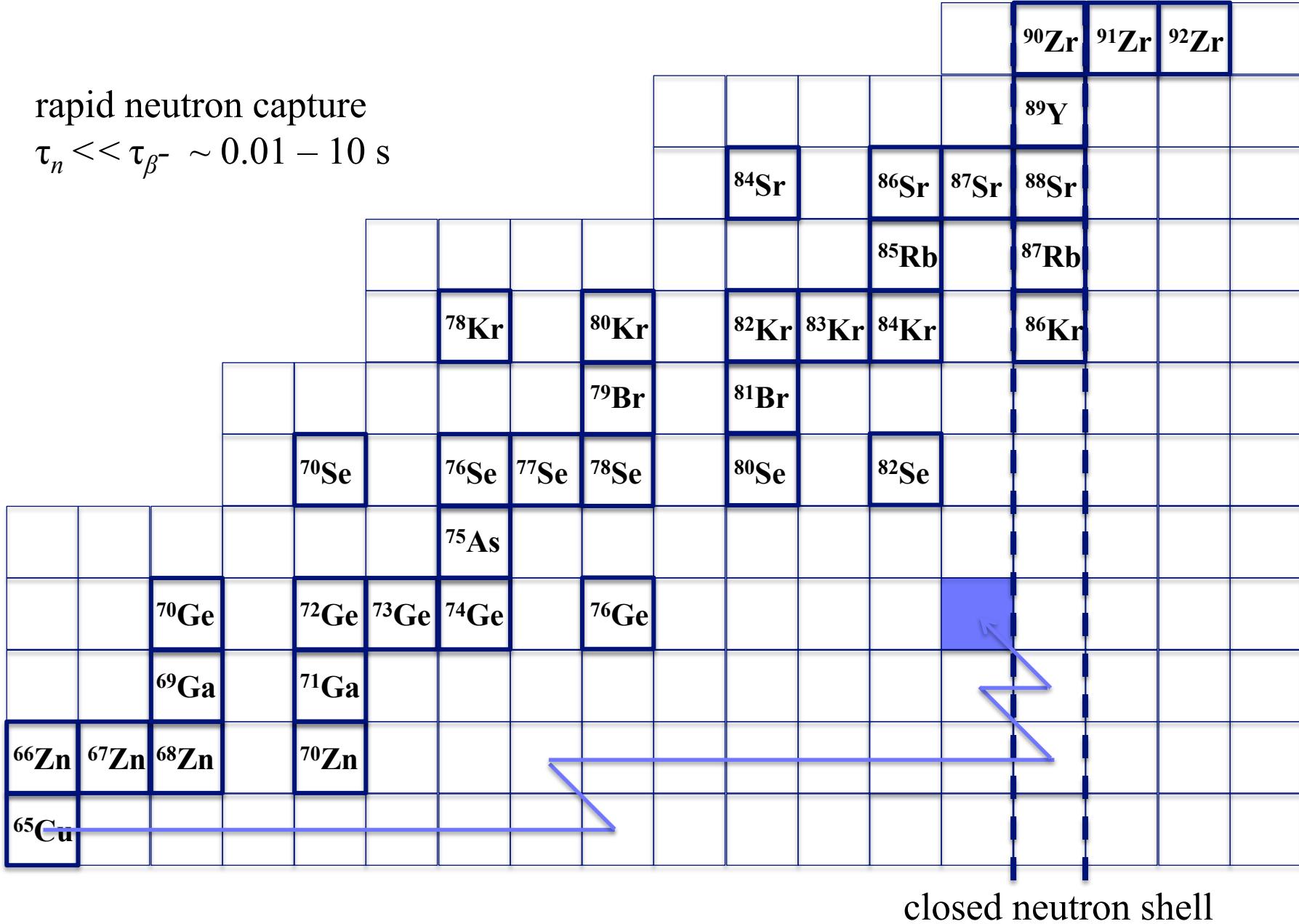
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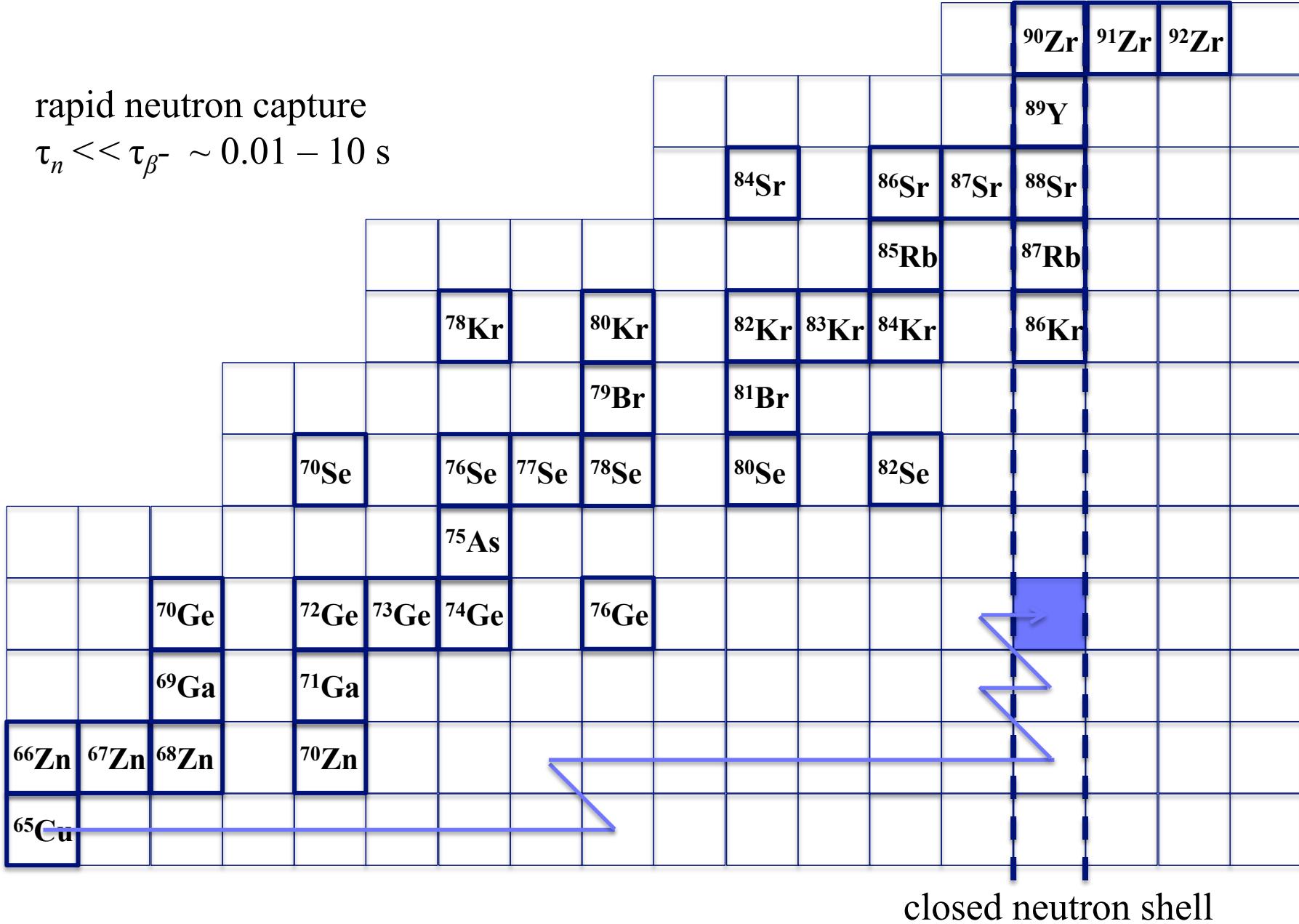
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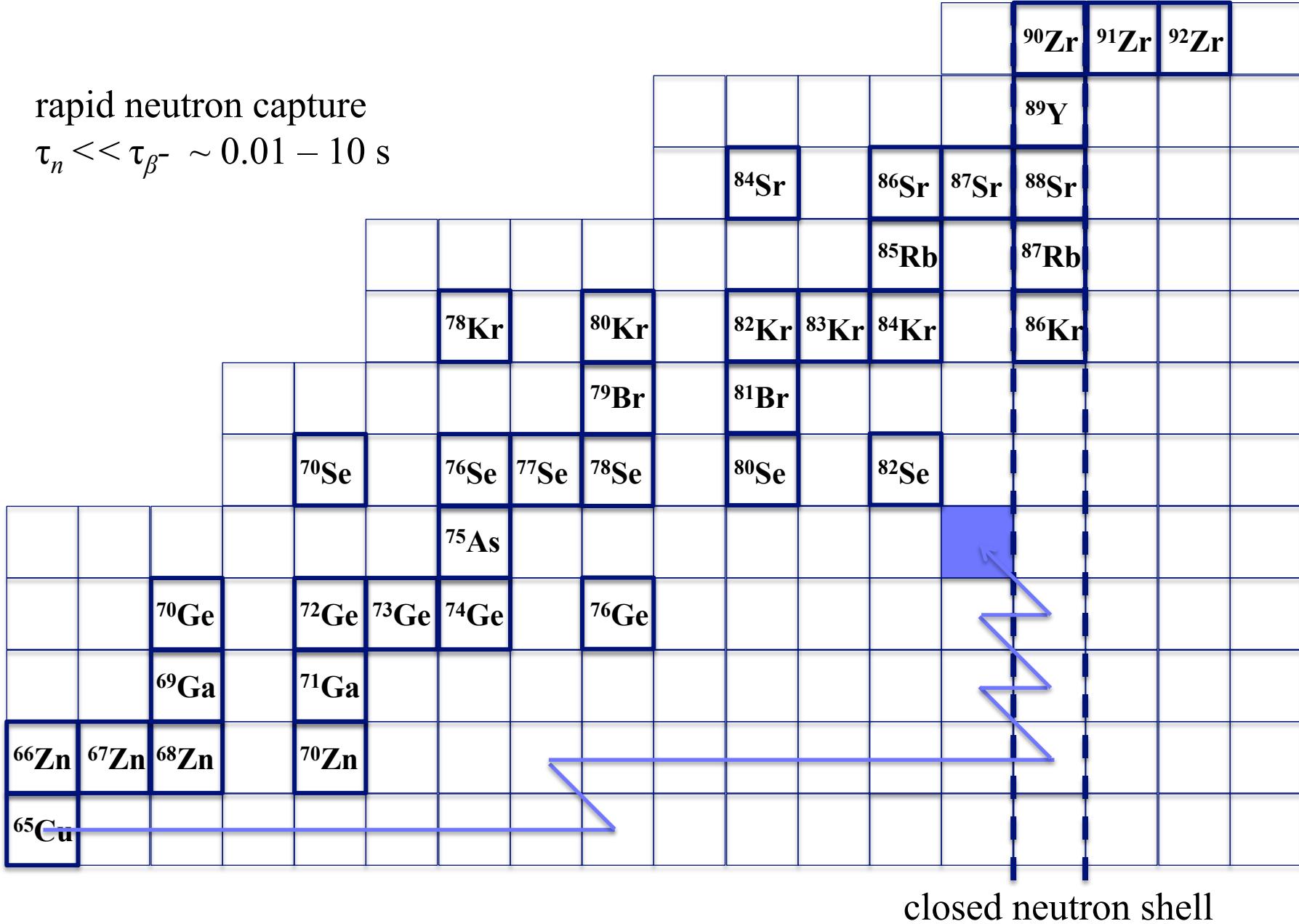
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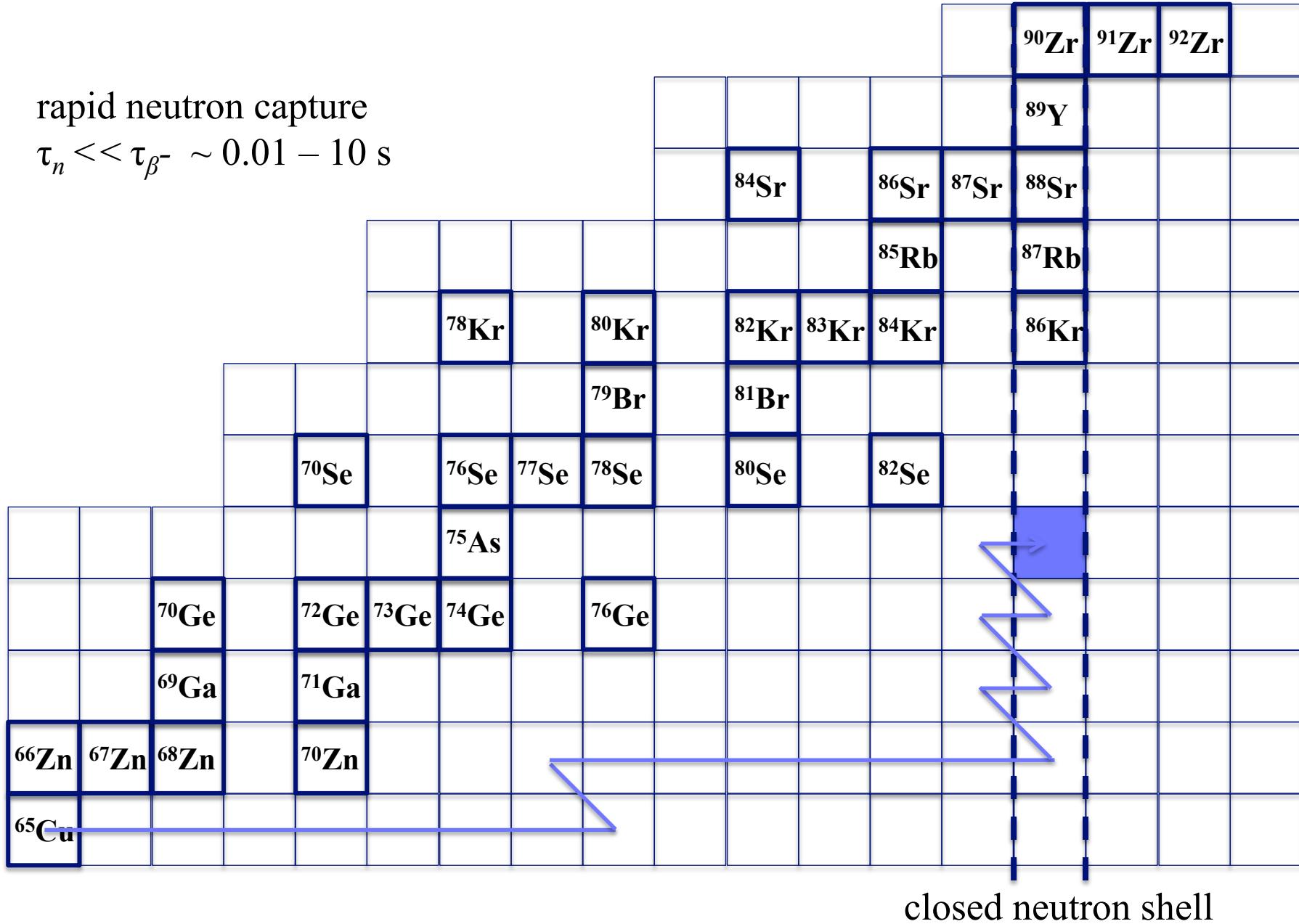
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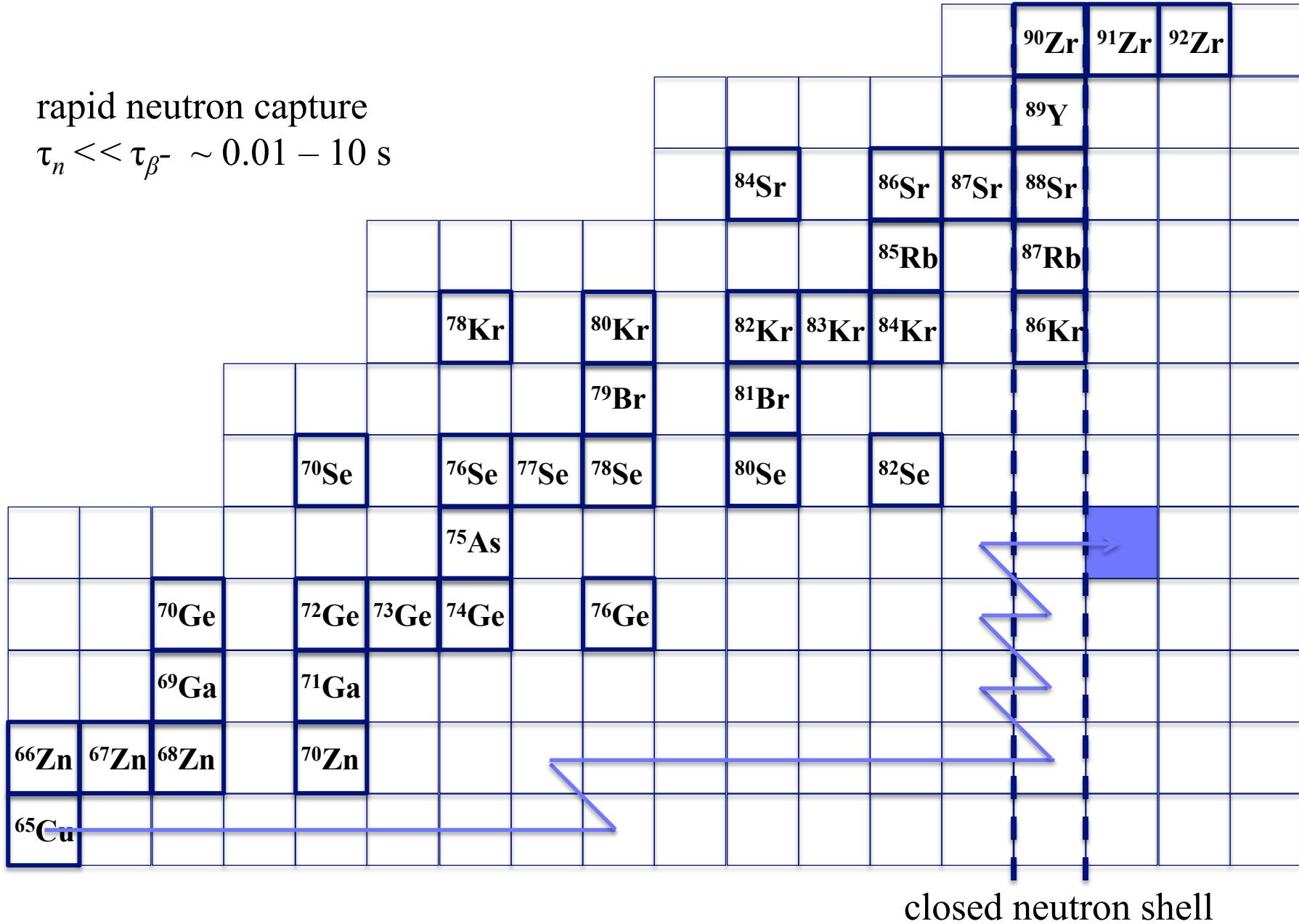
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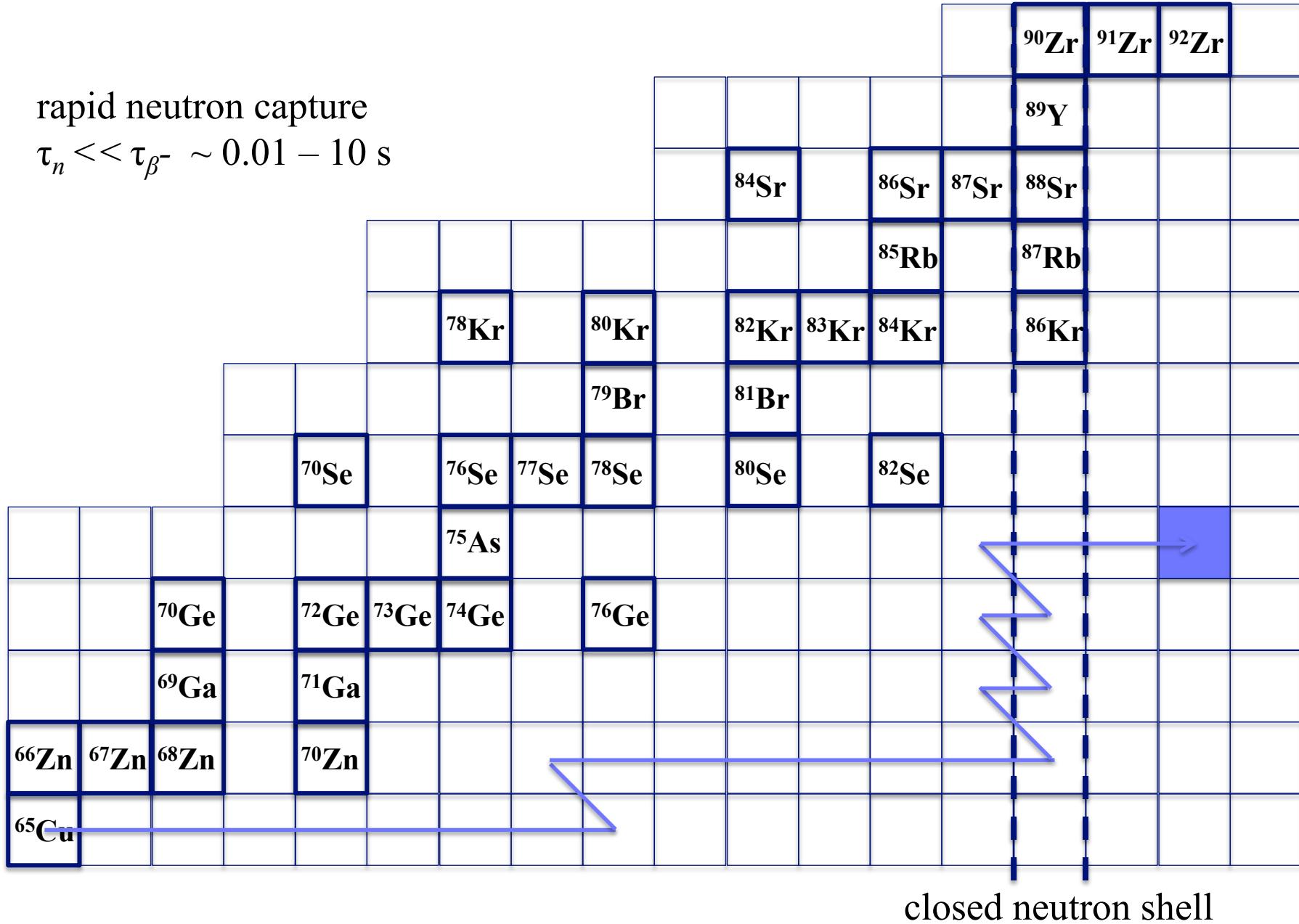
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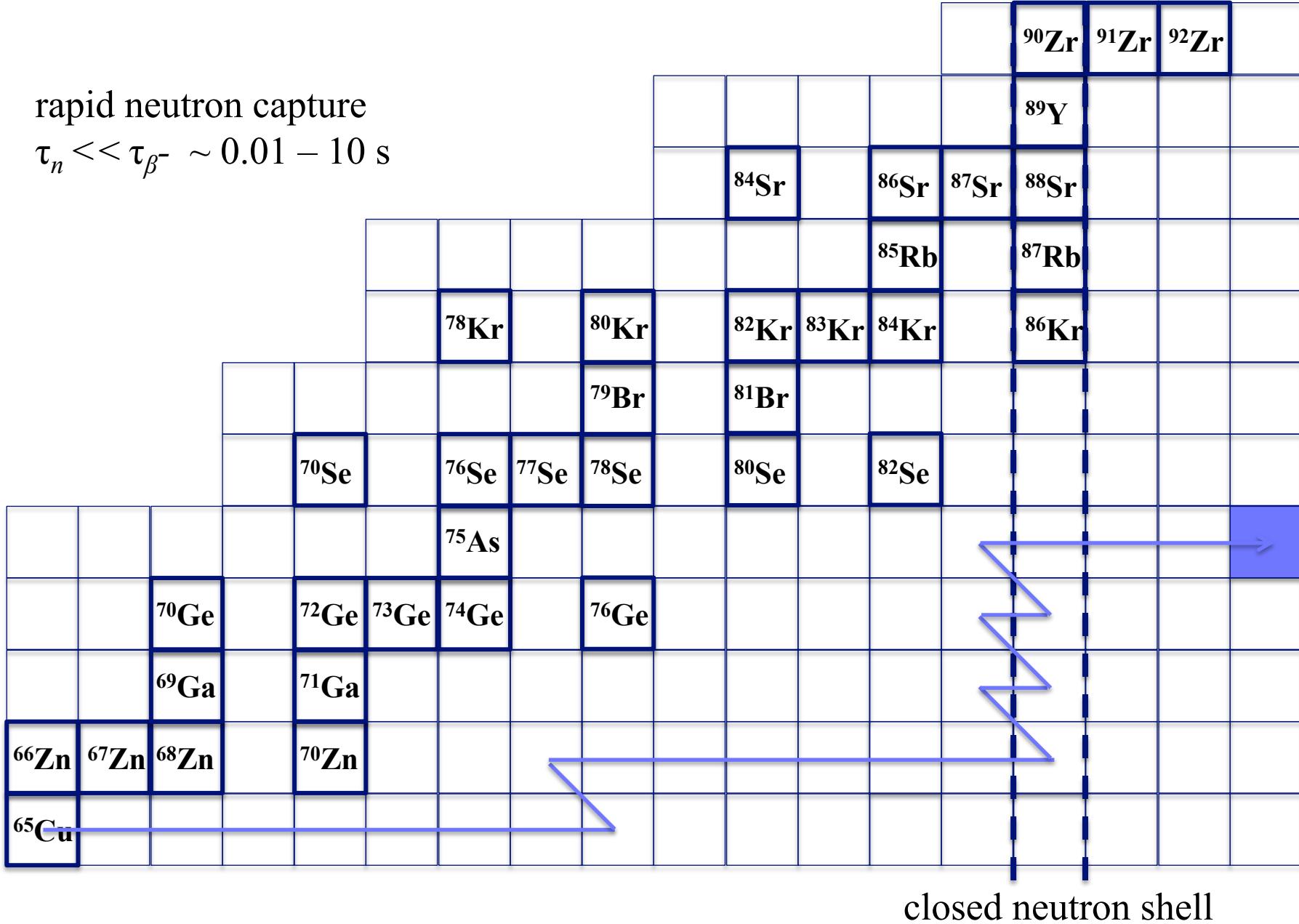
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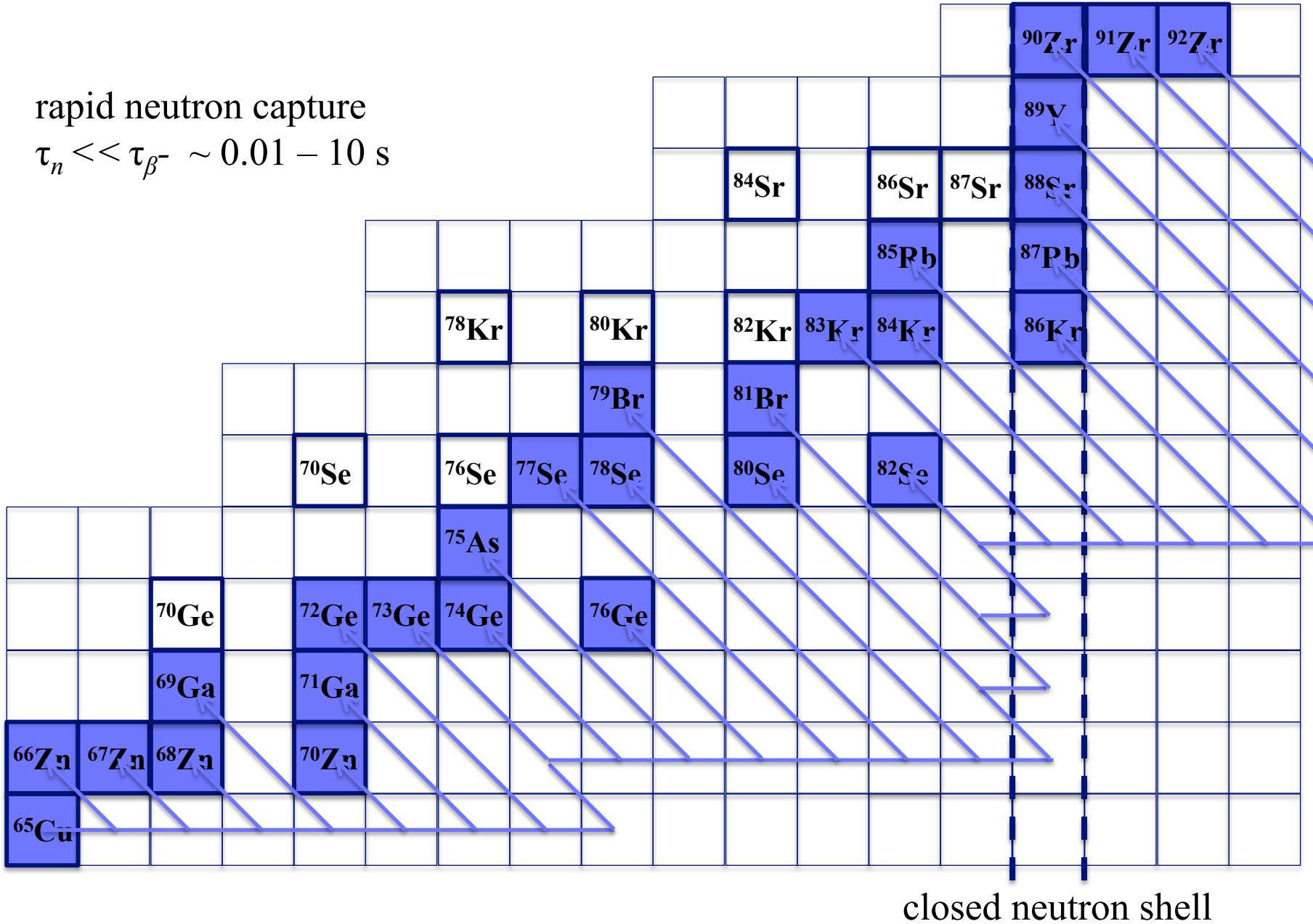
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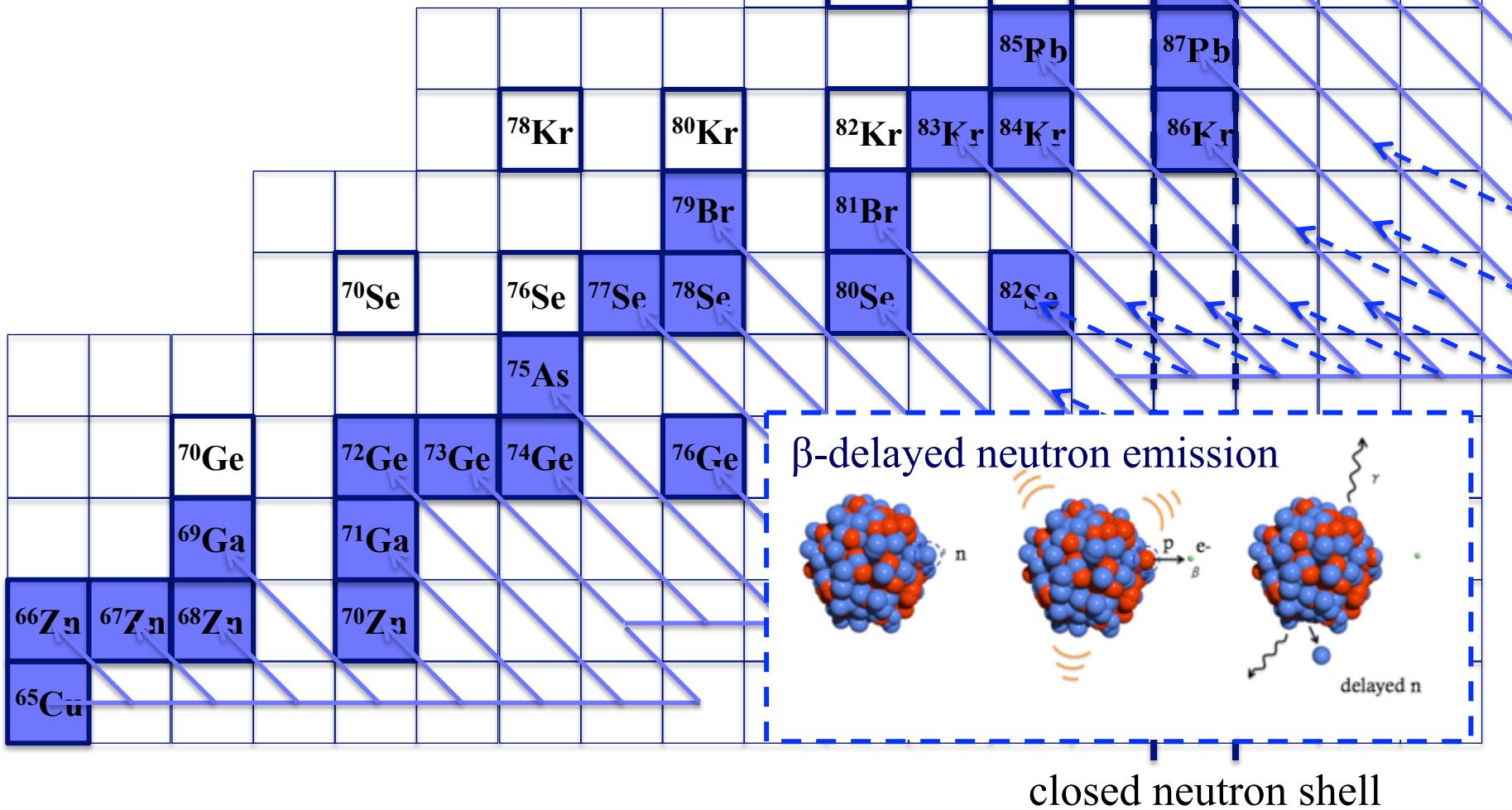
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rapid neutron capture  
 $\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$  s



## 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

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

closed neutron shell

## Double peaks due to closed neutron shells

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

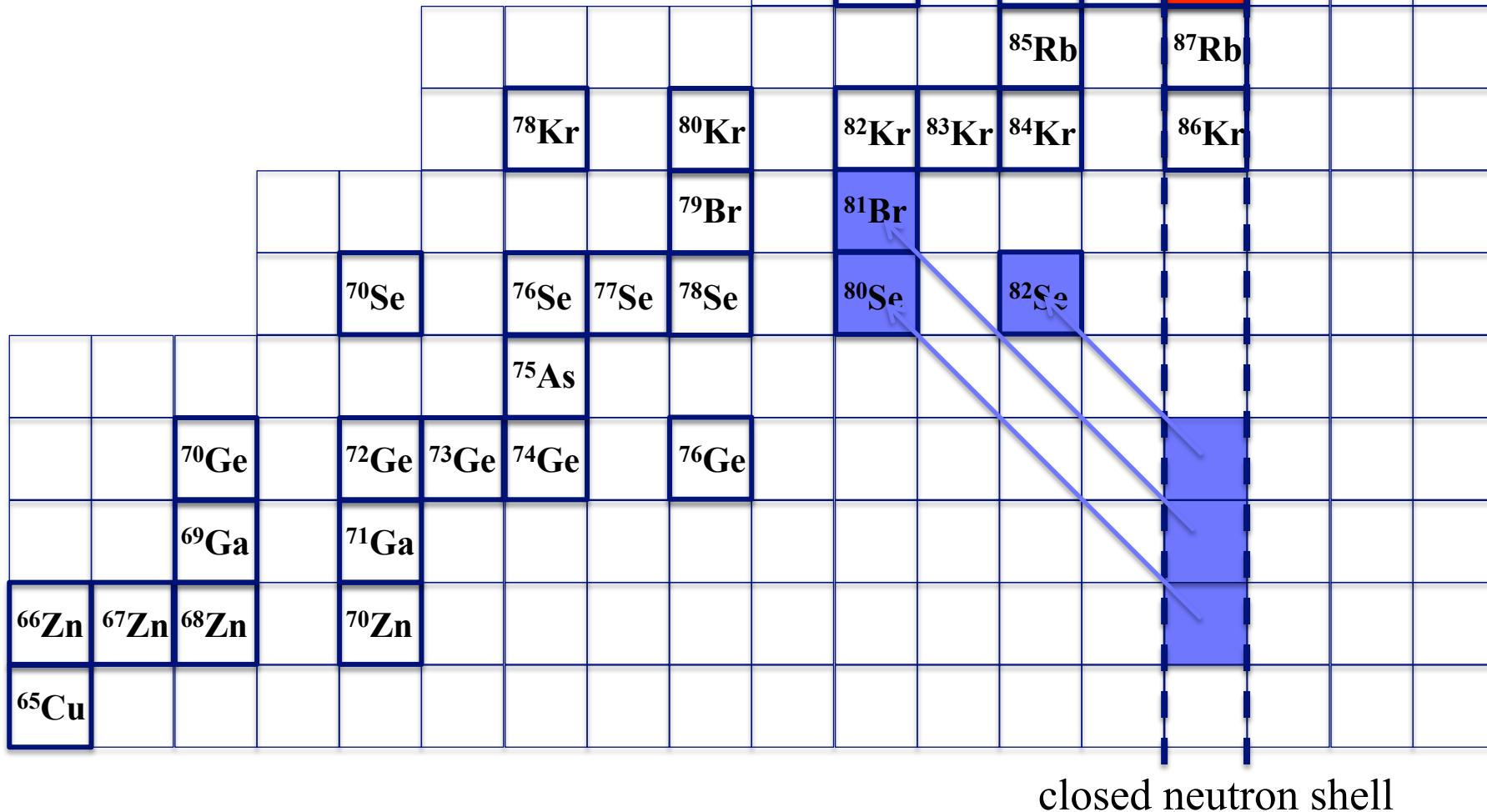
r-process:  $\tau_n \ll \tau_{\beta^-} \sim 0.01 - 10$  s

## closed neutron shell

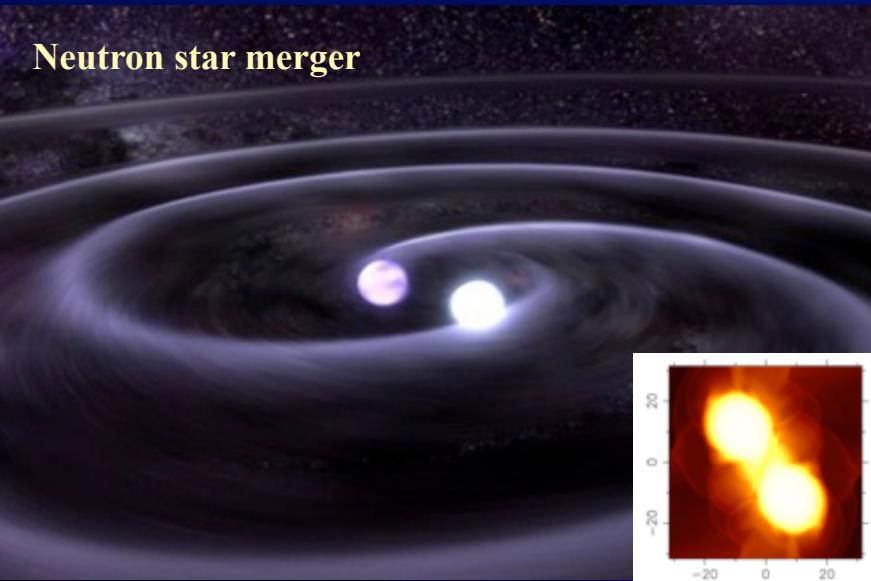
# Double peaks due to closed neutron shells

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



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



S. Wanajo

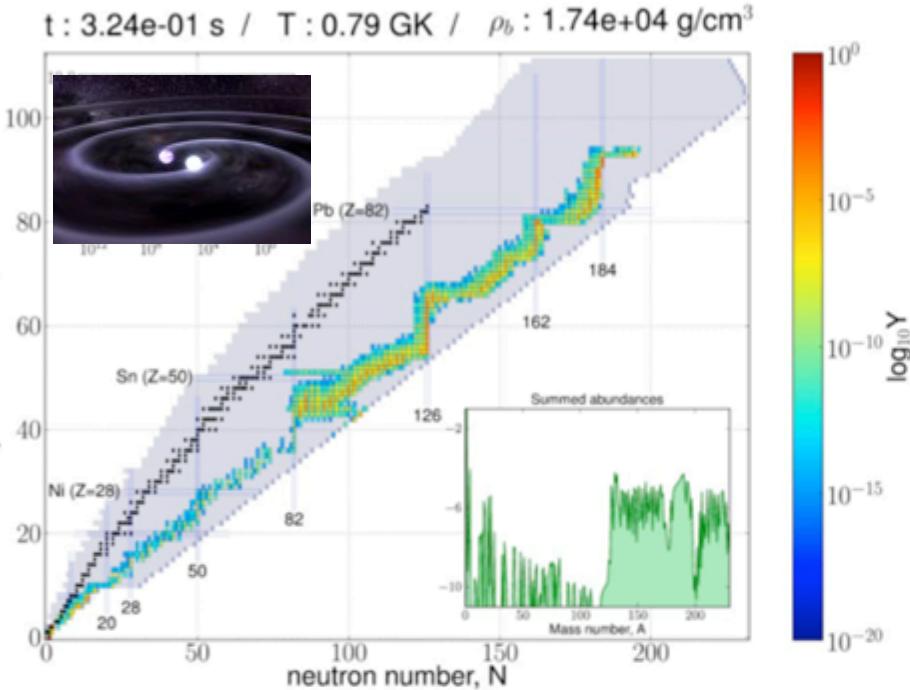
- Extremely neutron-rich nuclei
- Very Rare to have two neutron stars close together.
- Not possible in 1<sup>st</sup> stars !?  
NS-BH ?



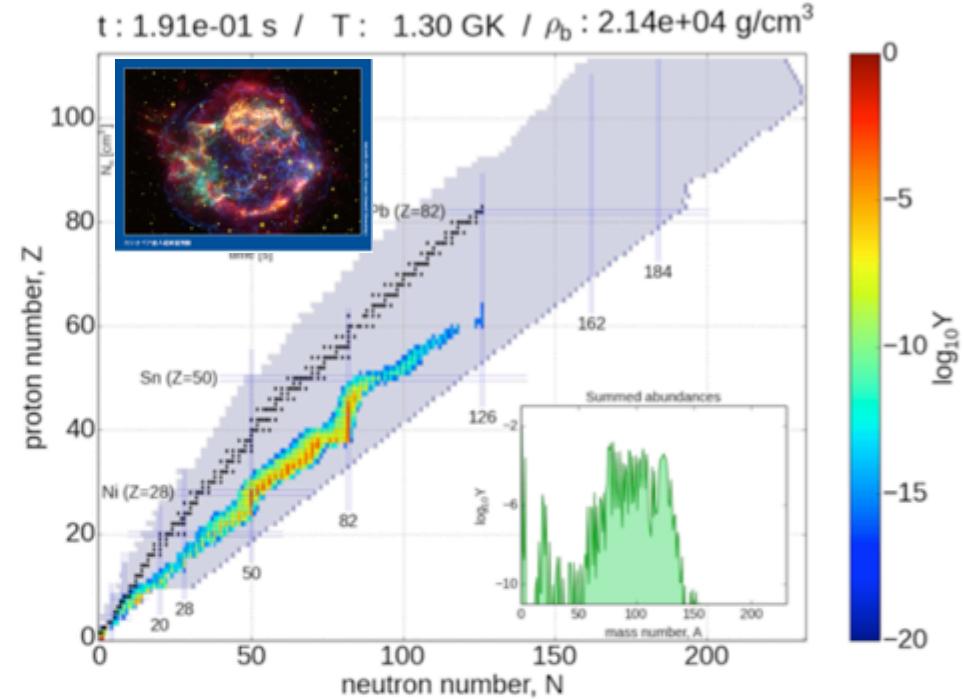
- Mechanism of Explosion.. ?
- Lack of Neutrino, Neutron :  
 $Y_e < 0.5$ ?
- Strong magnetic field ?

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

## Nucleosynthesis for dynamic ejecta (snapshot; Korobkin et al. 2012)



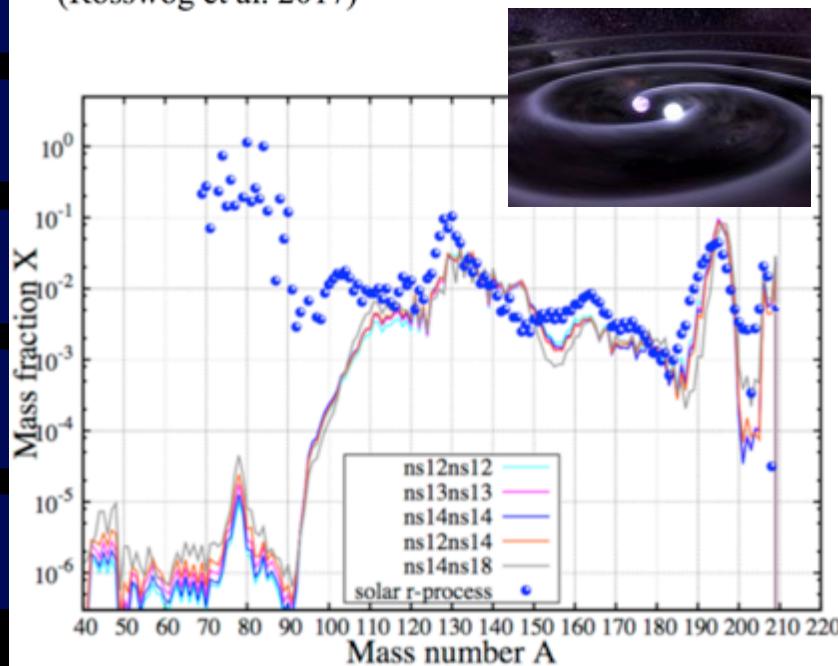
## Nucleosynthesis for neutrino-driven winds (snapshot; Martin et al. 2015)



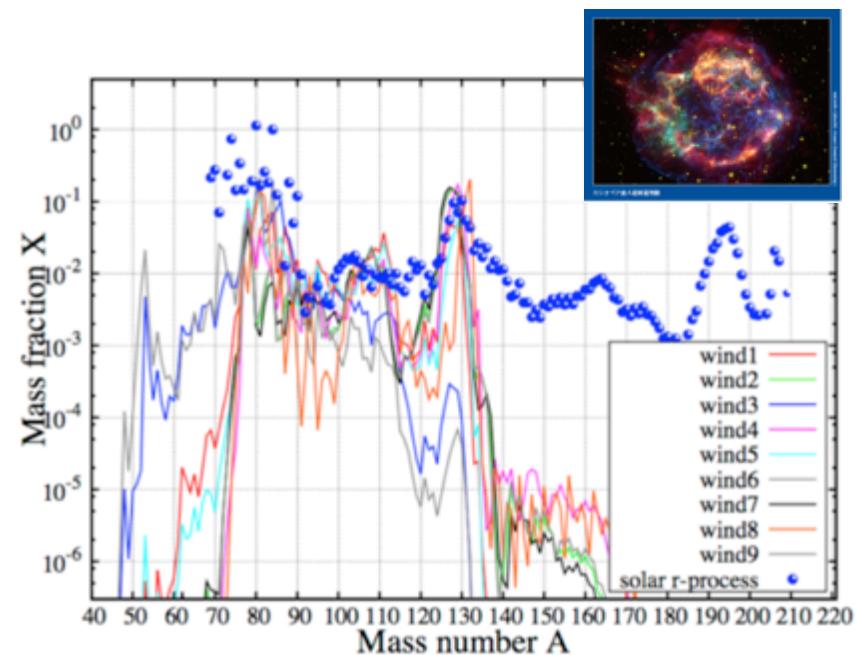
- extremely neutron-rich ( $Y_e \approx 0.04$ )
- close to neutron drip-line
- extending to very large neutron ( $N \approx 200$ ) and proton numbers ( $Z \approx 90$ )
- forging the heaviest elements ( $A > 130$ ) in the Universe (e.g. gold and platinum)

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

## Nucleosynthesis for dynamic ejecta (Rosswog et al. 2017)



## Nucleosynthesis for neutrino-driven winds (Rosswog et al. 2017)



- 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.

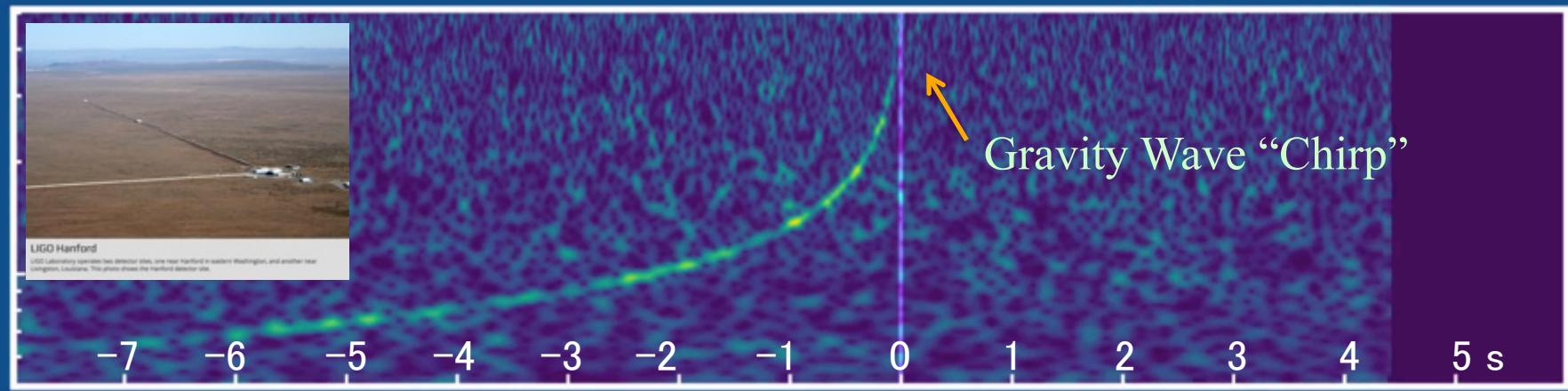
# GW170817

## Neutron Stars Merger !

Aug. 17, 2017



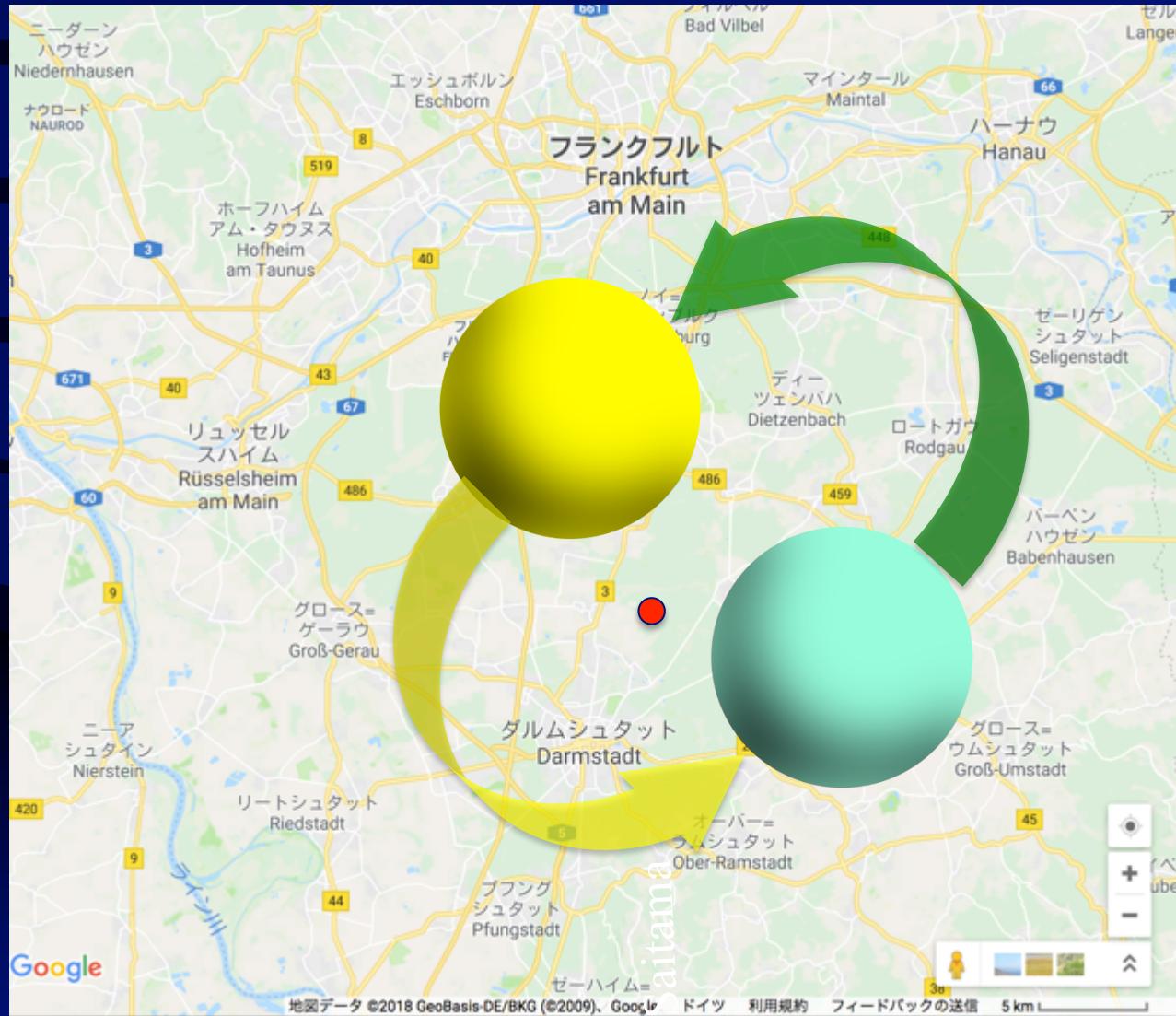
Fermi (light) GRB170817A



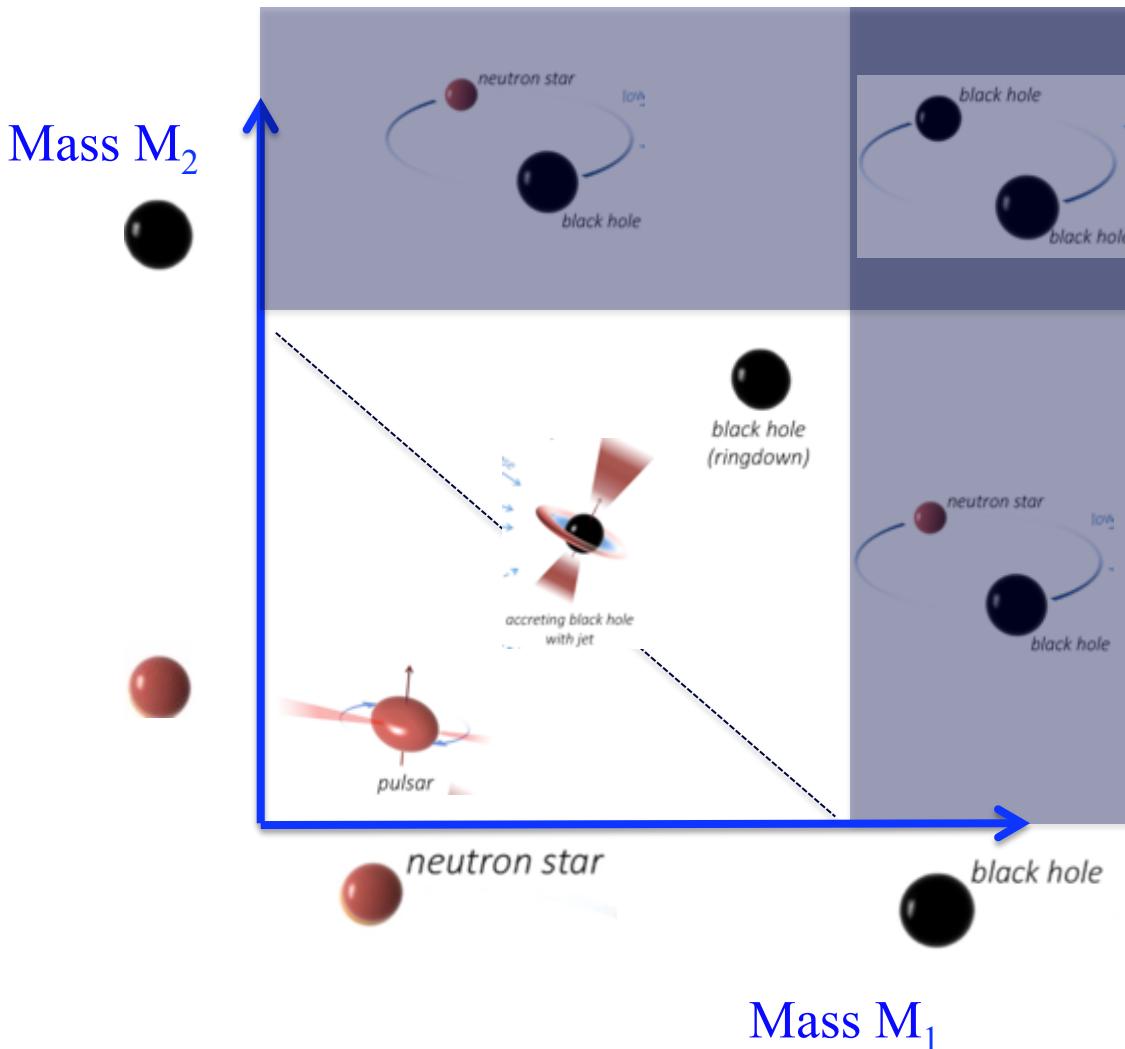
LIGO (gravitational waves)

<https://www.ligo.caltech.edu/video/>

# Neutron Star Merger : Scale



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

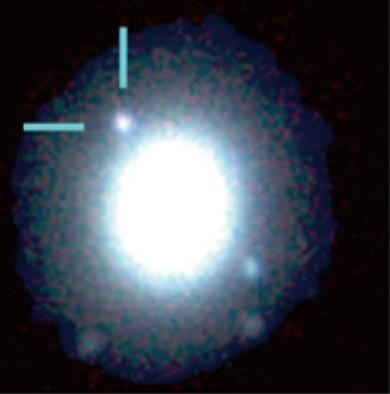


**Nuclear Physics**  
EOS, Reactions,  
Mass, Decay, ...

# kilonova after Neutron Star Merger

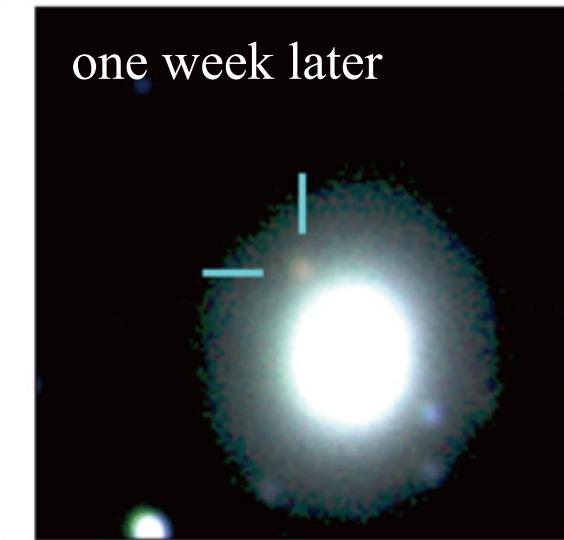
2017.08.18-19

a few days later

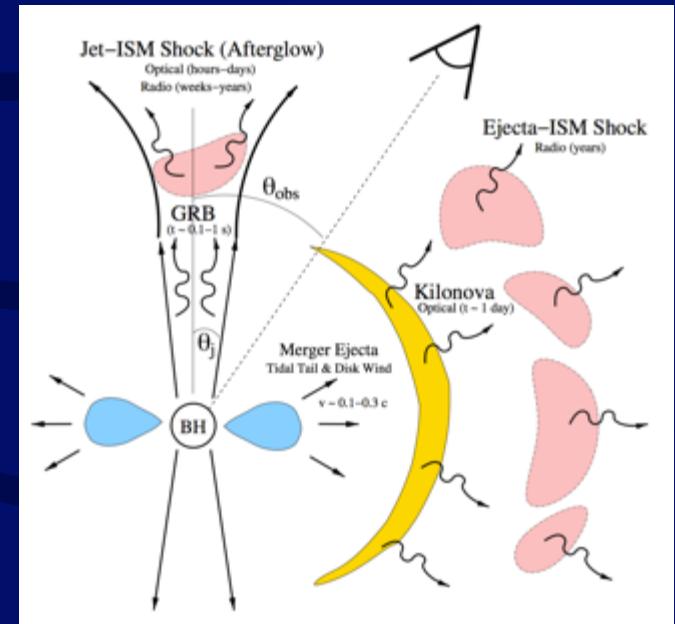


2017.08.24-25

one week later



Credit: NAOJ/Nagoya Univ.

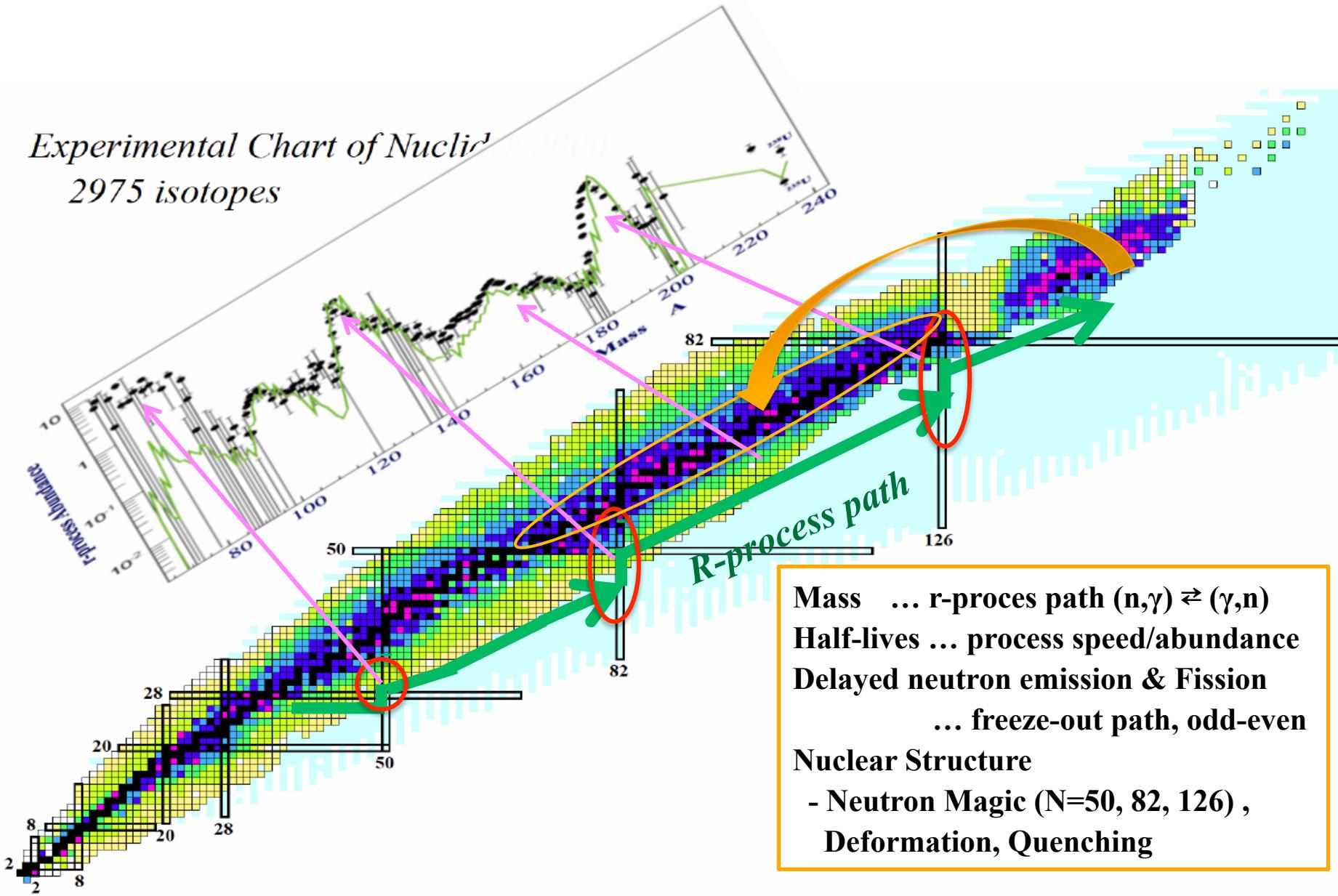


Radiation from radioactive isotopes (RI).

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

# Nuclear Properties are Key Inputs

Experimental Chart of Nuclides  
2975 isotopes



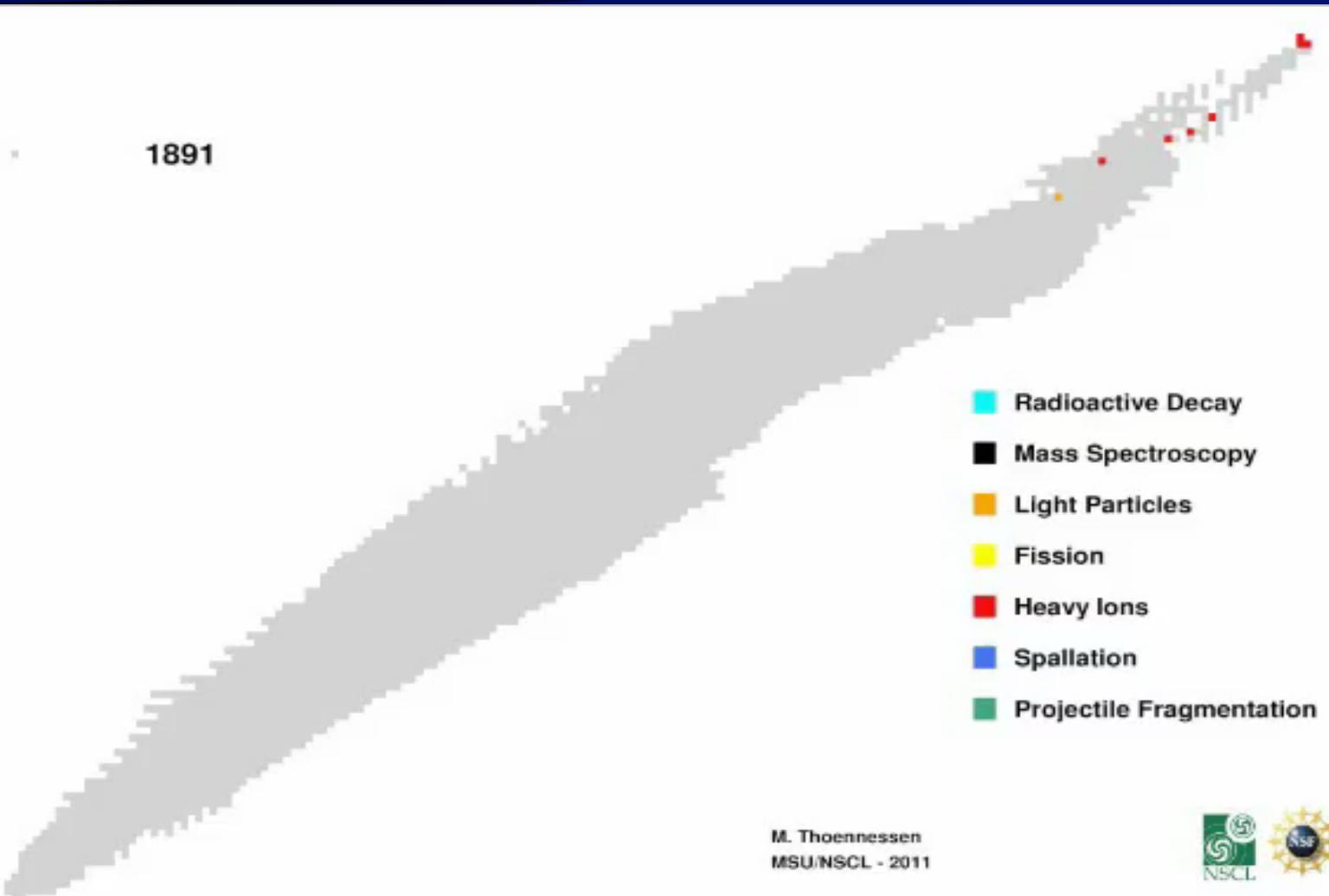
# r-Process Nucleosynthesis

Reproduction of r-Process Nuclei  
in the Experiment

Oh ! it is not easy at all .

# New Isotope Search (History)

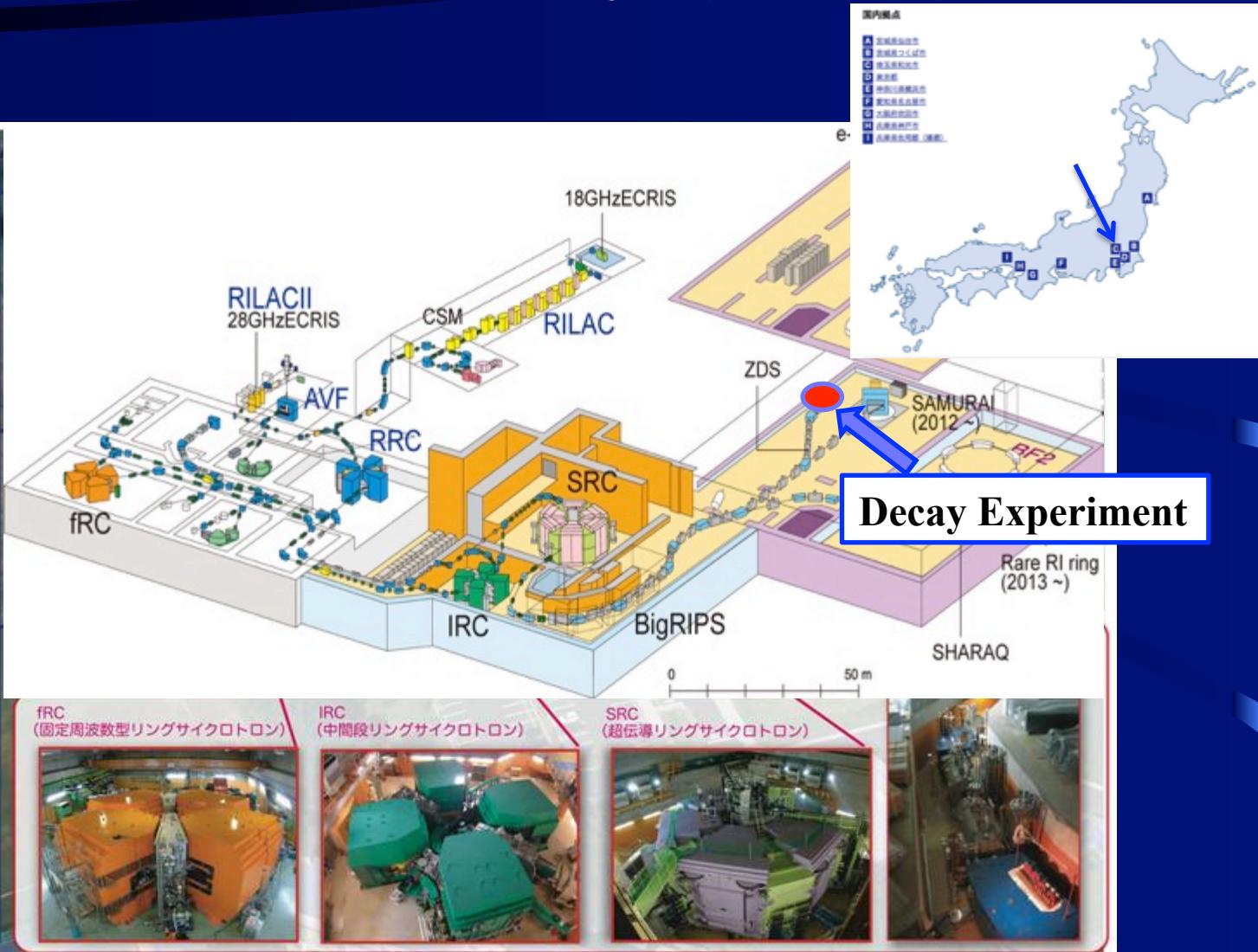
1891

- 
- Radioactive Decay
  - Mass Spectroscopy
  - Light Particles
  - Fission
  - Heavy Ions
  - Spallation
  - Projectile Fragmentation

M. Thoennessen  
MSU/NSCL - 2011

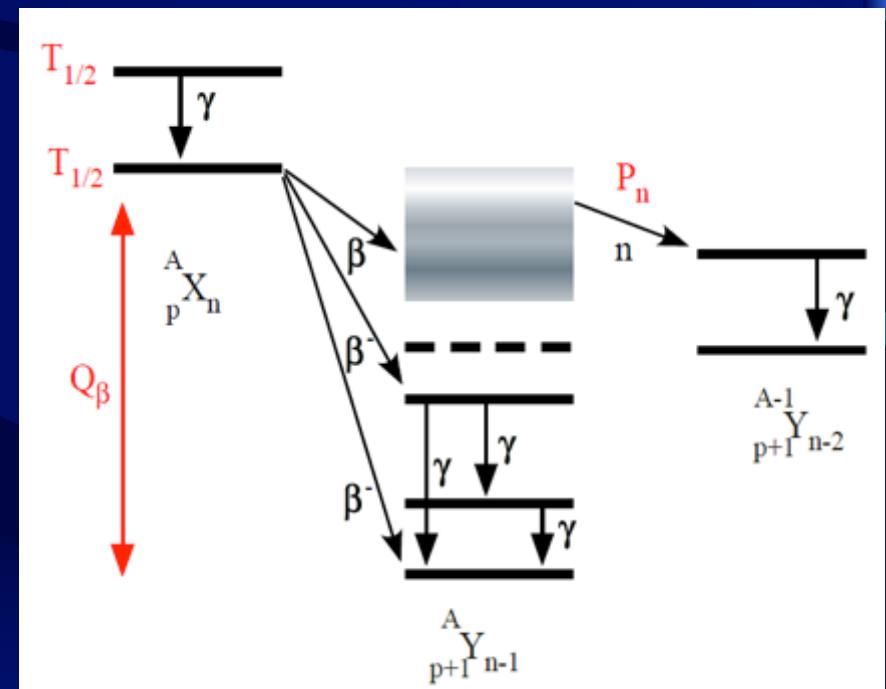
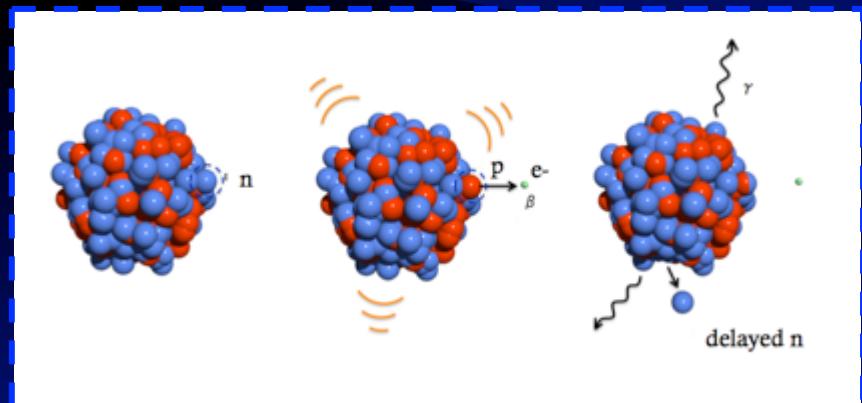


# RI Beam Factory (RIBF)



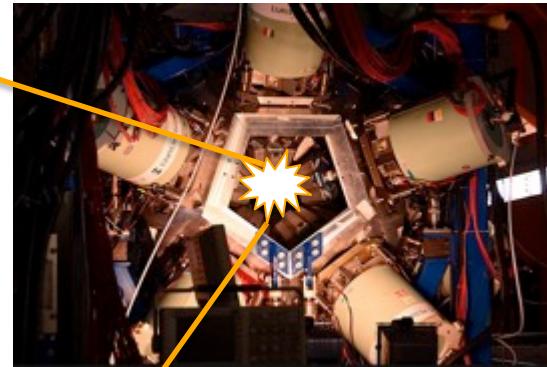
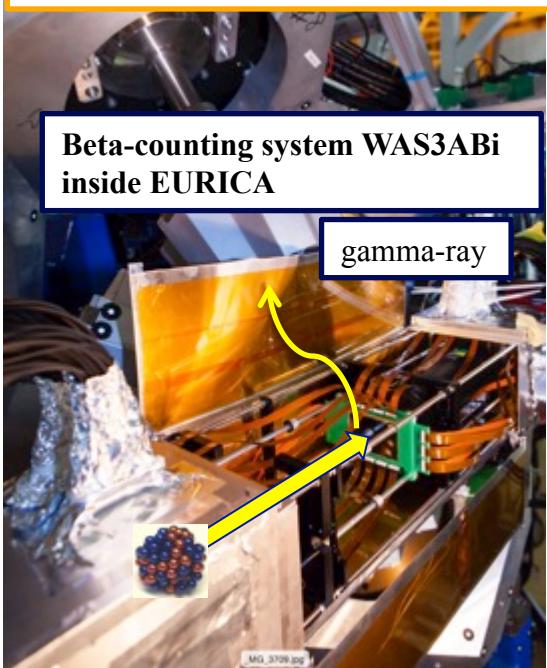
※All accelerators and experimental facilities are underground.

# Decay Spectroscopy

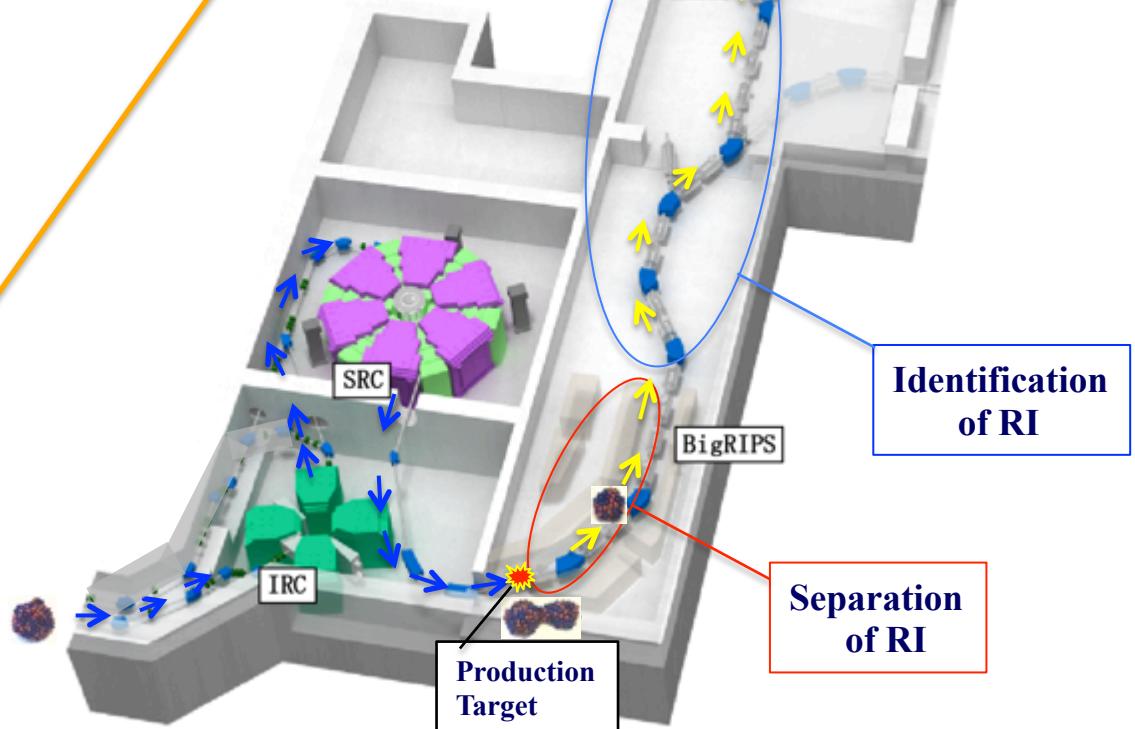


# Decay Spectroscopy: EURICA

84 high-purity Ge crystals in 12 clusters  
Resolution : 2.5 keV  
Efficiency : 15% @ 662 keV

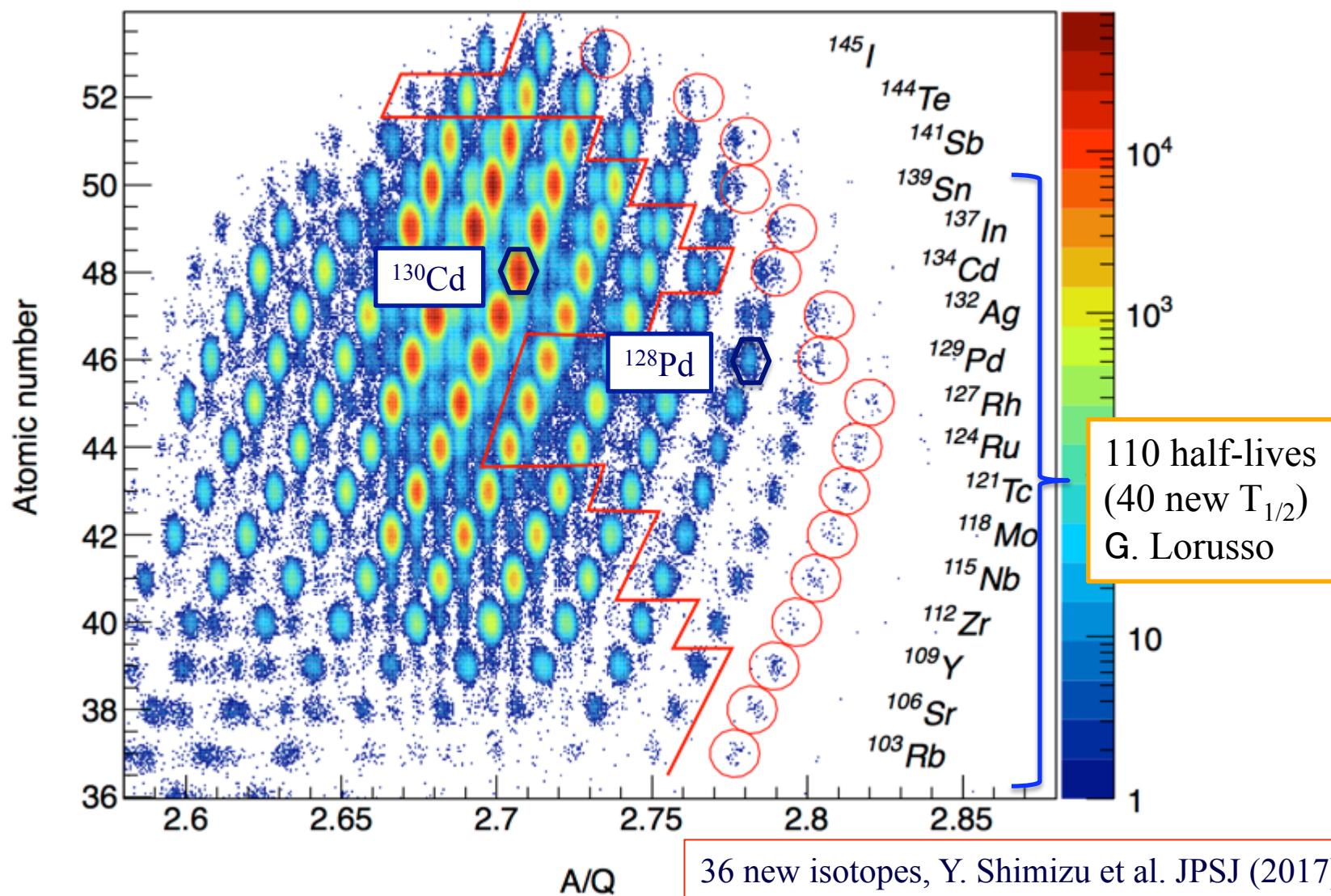


EURICA

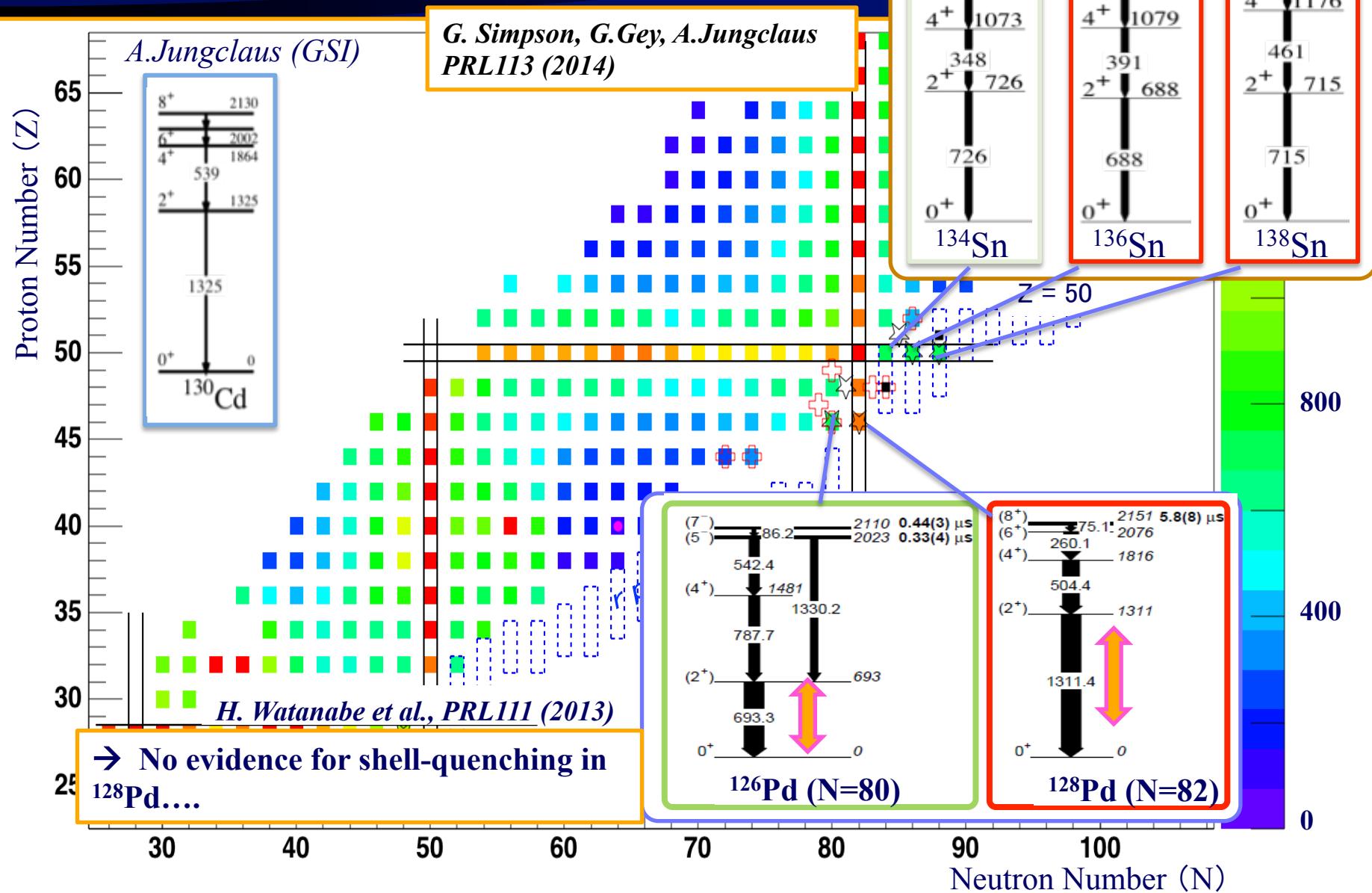


→ Primary Beam ( $^{238}\text{U}$  /  $^{124}\text{Xe}$  /  $^{78}\text{Kr}$ )  
→ RI Beam

# $\beta$ -decay half-lives on r-process path

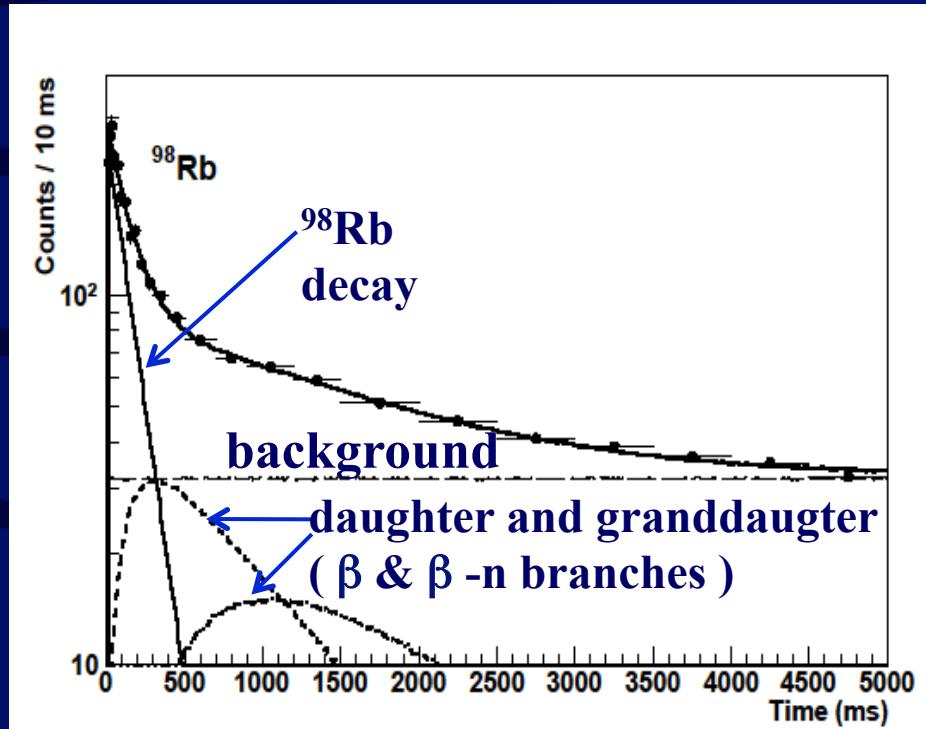


# First Excited States E (2+)



# Beta Decay Half-lives

97Y 3.75 S $\beta^-$ : 100.00% $\beta^-n$ : 0.05%	98Y 0.548 S $\beta^-$ : 100.00% $\beta^-n$ : 0.3%	99Y 1.470 S $\beta^-$ : 100.00% $\beta^-n$ : 1.90%	100Y 735 MS $\beta^-$ : 100.00% $\beta^-n$ : 0.92%	101Y 0.45 S $\beta^-$ : 100.00% $\beta^-n$ : 1.94%
96Sr 1.07 S $\beta^-$ : 100.00% $\beta^-n \leq 0$	97Sr 429 MS $\beta^-$ : 100.00% $\beta^-n \leq 0$	98Sr 0.653 S $\beta^-$ : 100.00% $\beta^-n$ : 0.25%	99Sr 0.269 S $\beta^-$ : 100.00% $\beta^-n$ : 0.10%	100Sr 202 MS $\beta^-$ : 100.00% $\beta^-n$ : 0.78%
95Rb 377.5 MS $\beta^-$ : 100.00% $\beta^-n$ : 8.73%	96Rb 203 MS $\beta^-$ : 100.00% $\beta^-n$ : 13.30%	97Rb 169.9 MS $\beta^-$ : 100.00% $\beta^-n$ : 25.10%	98Rb 114 MS $\beta^-$ : 100.00% $\beta^-n$ : 13.80%	99Rb 50.3 MS $\beta^-$ : 100.00% $\beta^-n$ : 15.90%
94Kr 212 MS $\beta^-$ : 100.00% $\beta^-n$ : 1.11%	95Kr 114 MS $\beta^-$ : 100.00% $\beta^-n$ : 2.87%	96Kr 80 MS $\beta^-$ : 100.00% $\beta^-n$ : 3.70%	97Kr 63 MS $\beta^-$ : 100.00% $\beta^-n$ : 8.20%	98Kr 46 MS $\beta^-$ : 100.00% $\beta^-n$ : 7.00%



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

Free parameters for fitting

- Background ...  $\sim 0.5$  cps
- Neutron emission Probability ( $P_n$ )
- Detection efficiency ( $\epsilon$ ) ... 40% - 80%

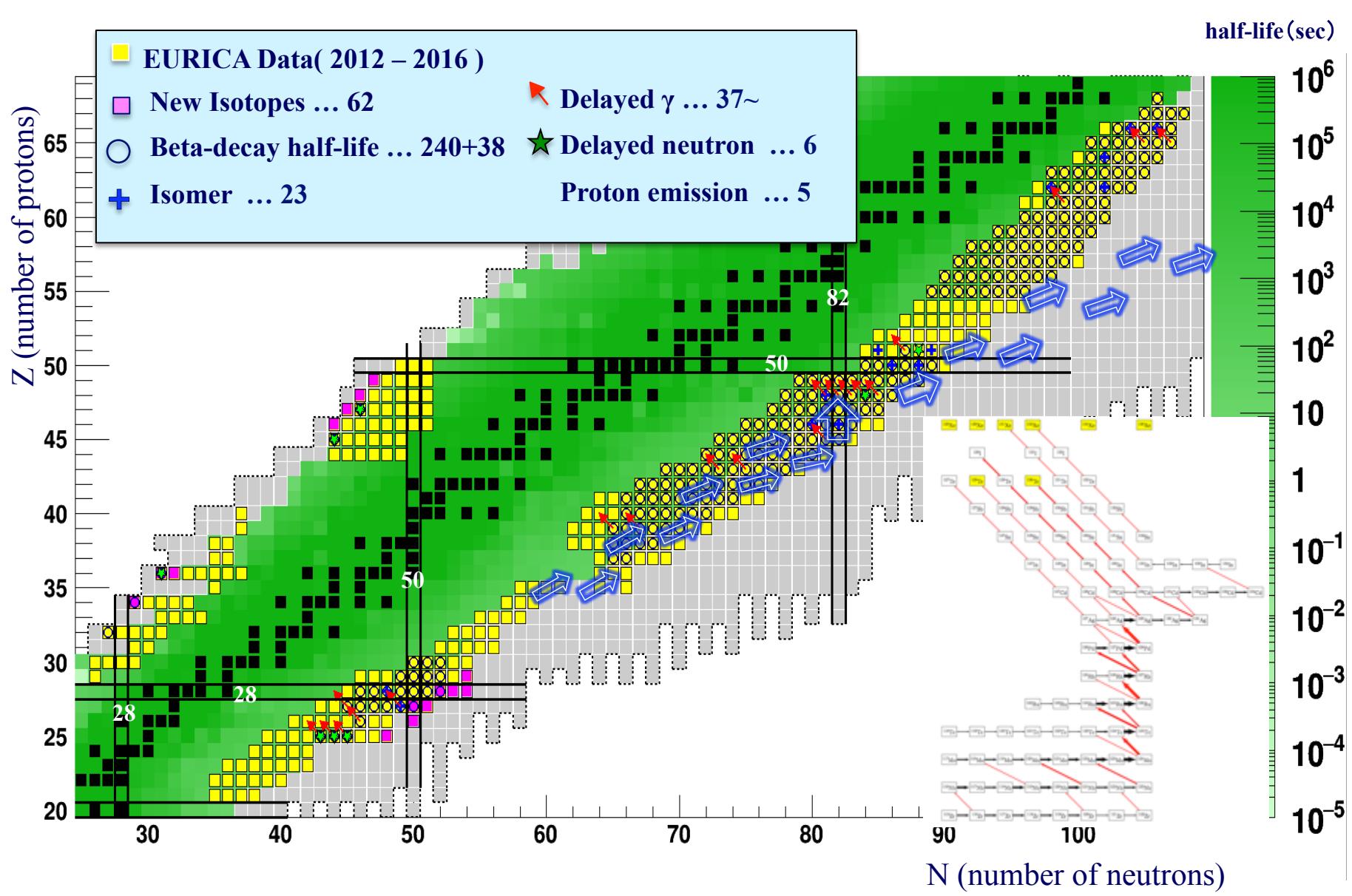
Consistency check

- Monte Carlo Simulation



$$T_{1/2}$$

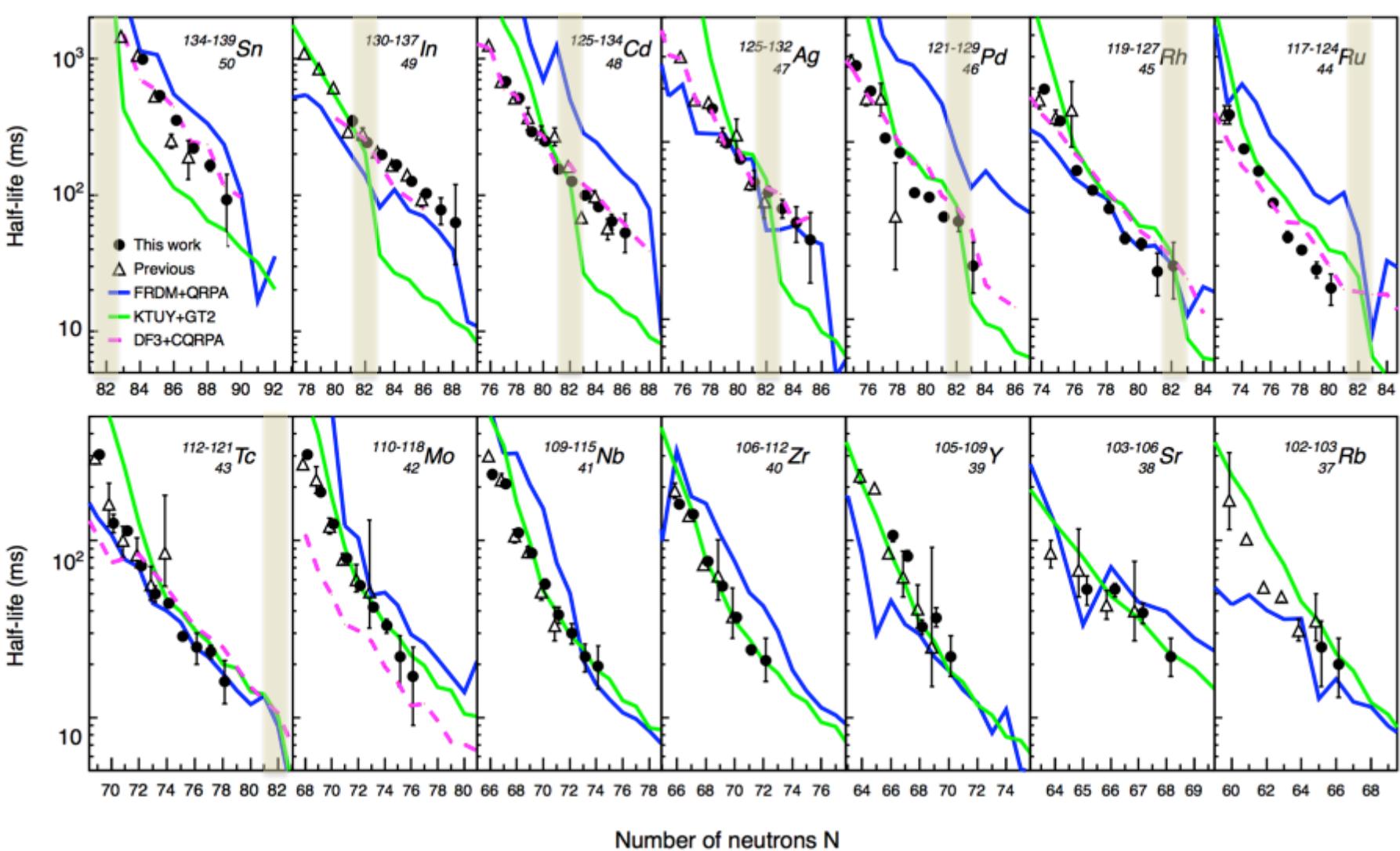
# 440 Exotic Isotopes Surveyed by EURICA Spectrometer



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

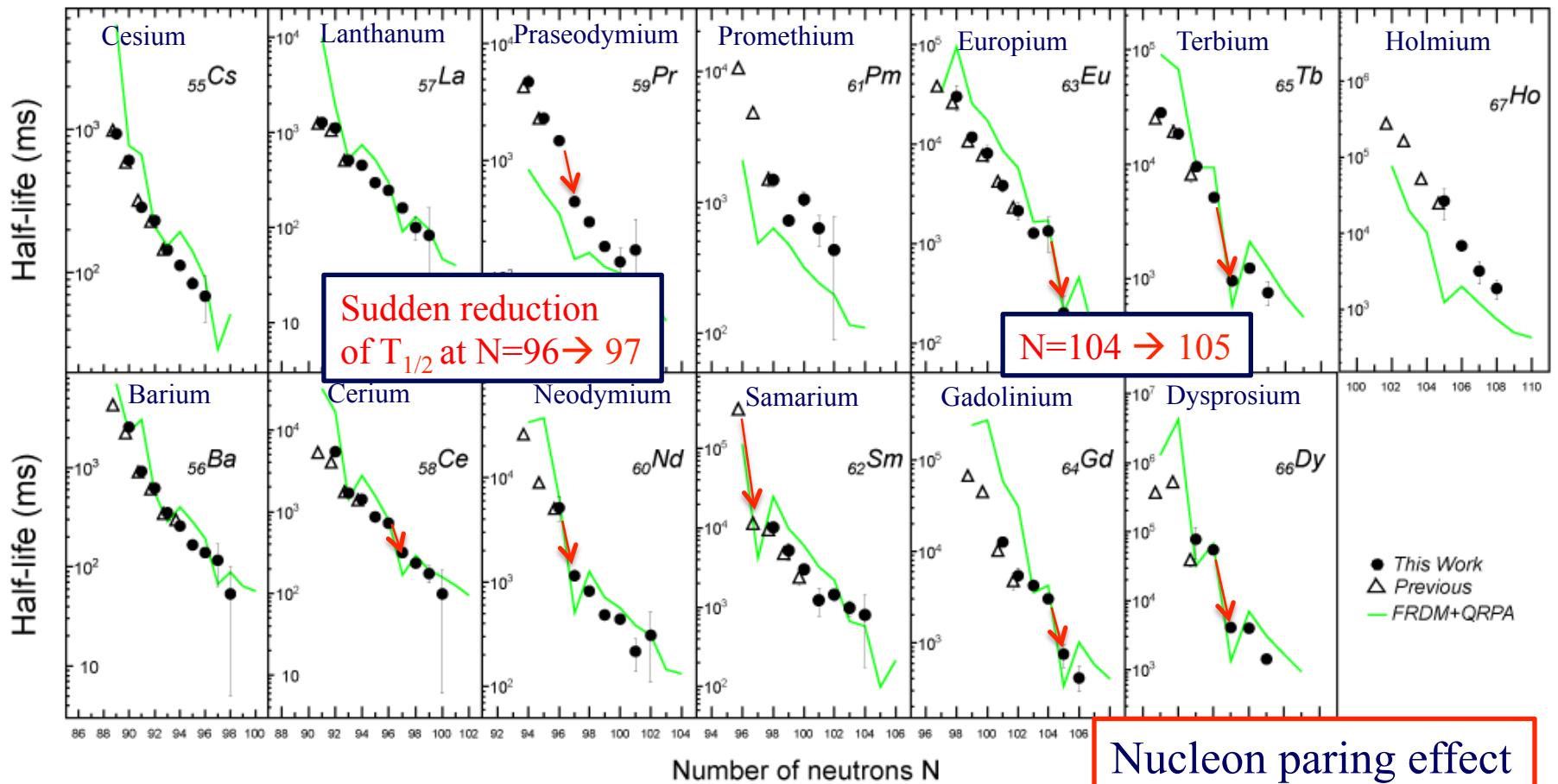
G.Lorusso et al.,  
40 new half-lives ! PRL 114, 192501 (2015)

S.Nishimura  
18 new half-lives ! PRL 106, 052502 (2011)



# 92 $\beta$ -Decay Half-lives (Mass A = 144 – 175) vs FRDM+QRPA

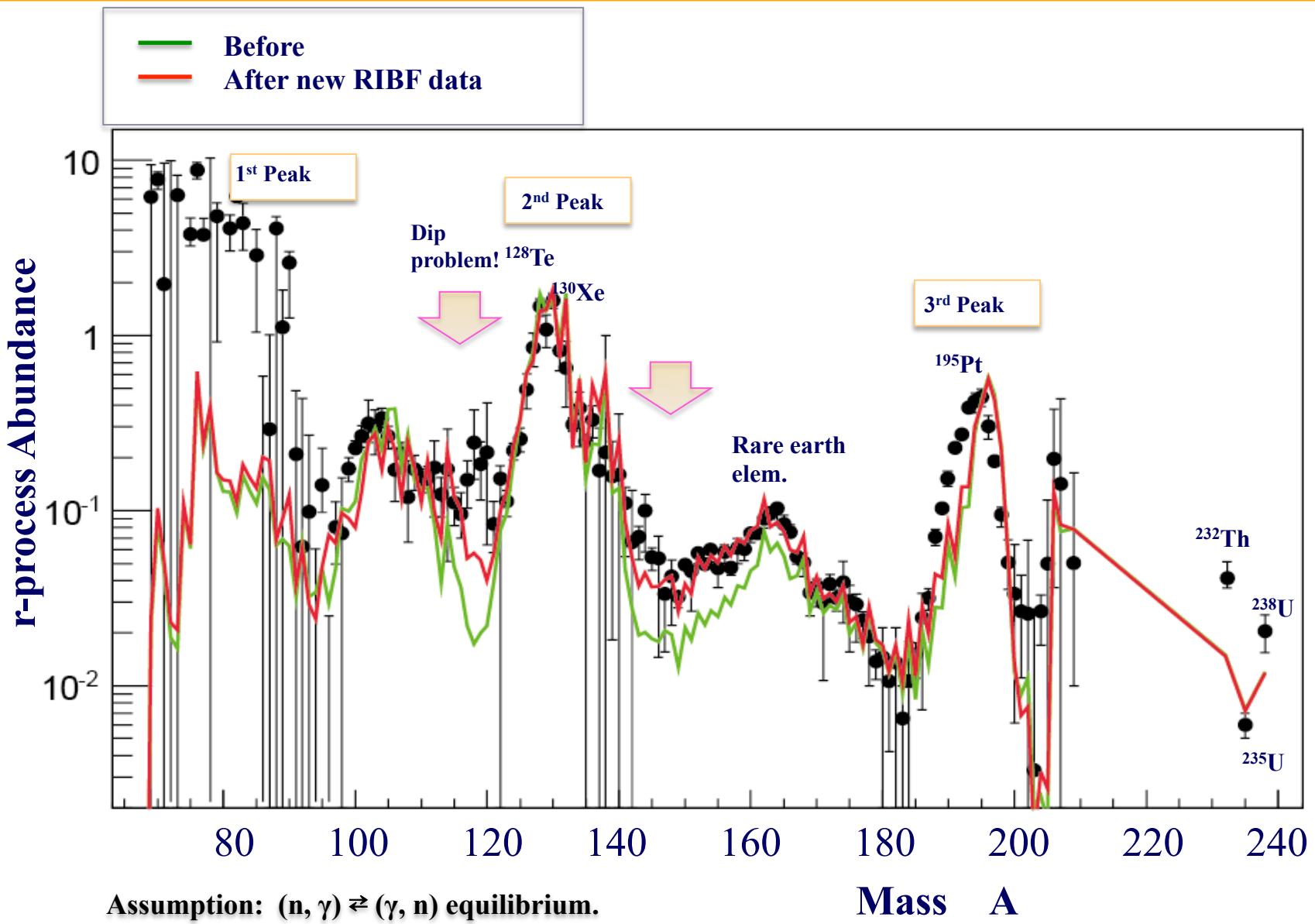
J. Wu, PRL (2017)



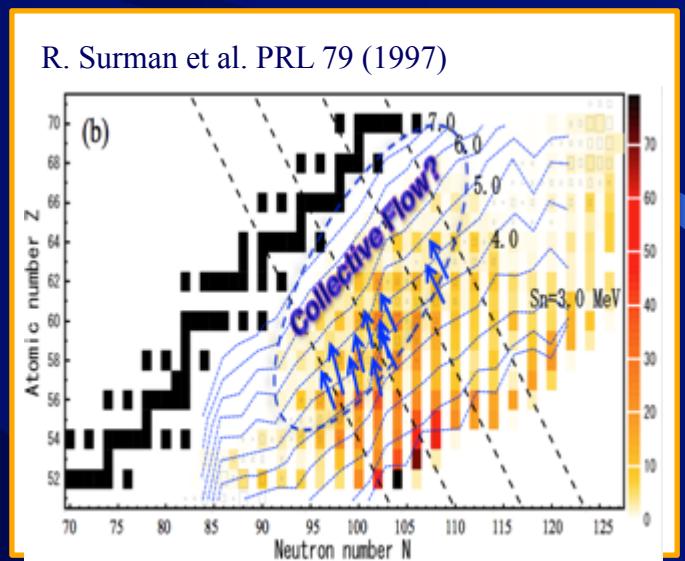
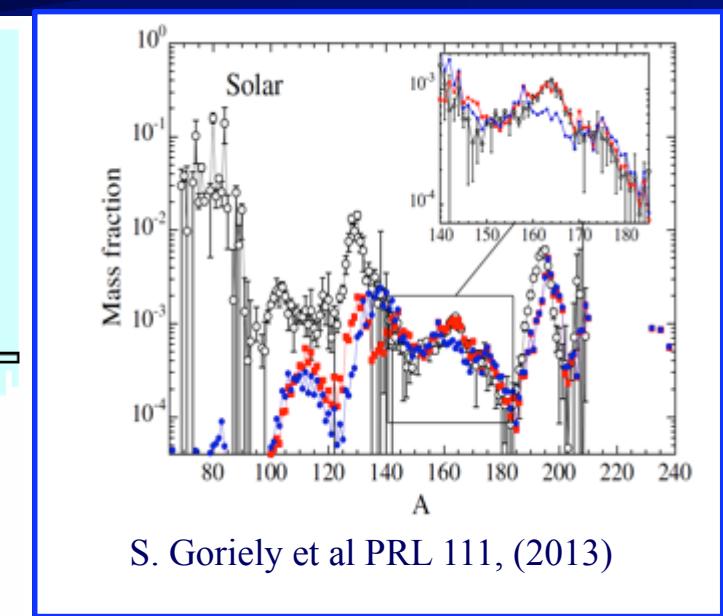
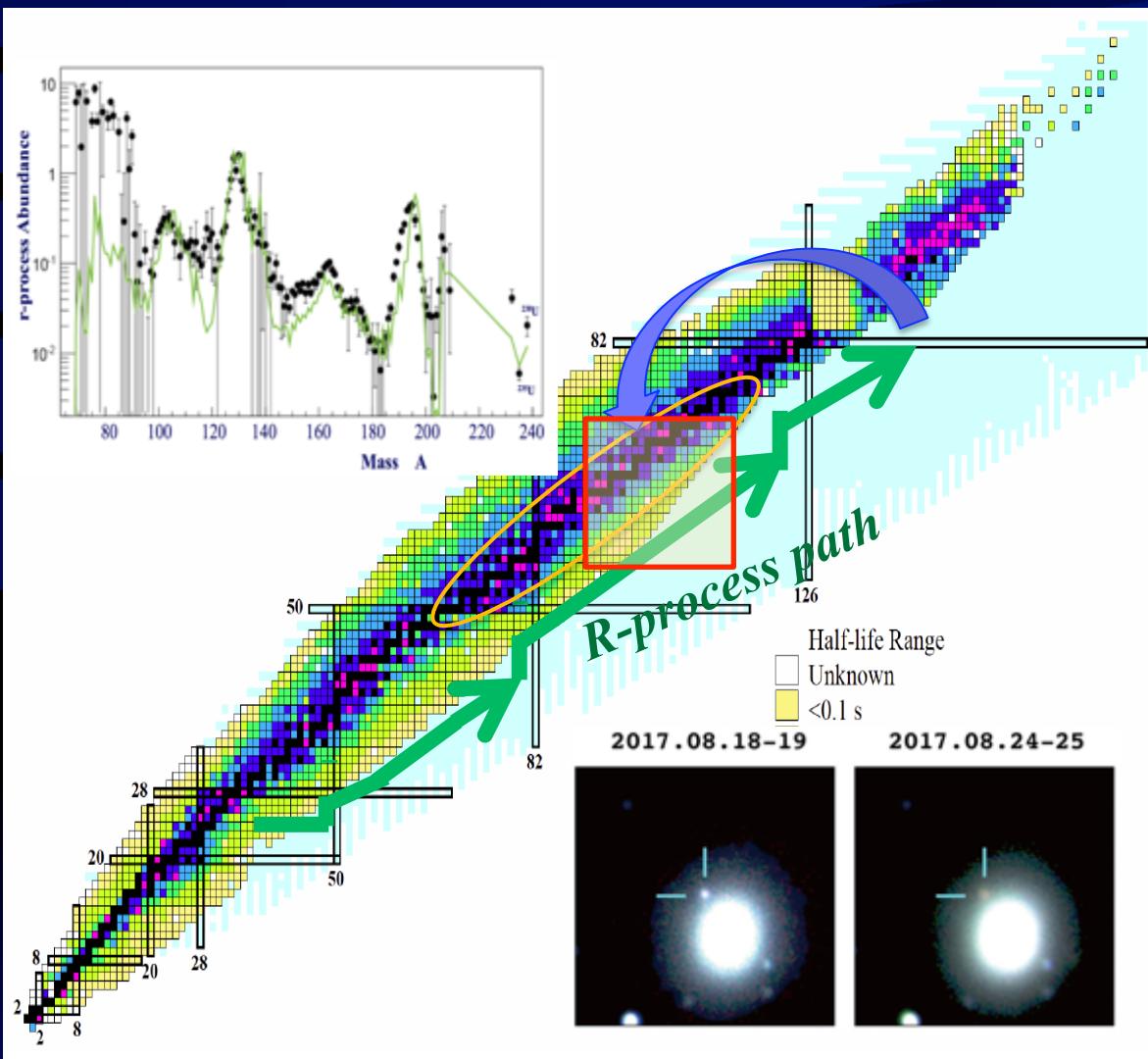
The  $\beta$ -decay half-lives of 92 neutron-rich  $^{144-151}\text{Cs}$ ,  $^{146-154}\text{Ba}$ ,  $^{148-156}\text{La}$ ,  $^{150-158}\text{Ce}$ ,  $^{153-160}\text{Pr}$ ,  $^{156-162}\text{Nd}$ ,  $^{159-163}\text{Pm}$ ,  $^{160-166}\text{Sm}$ ,  $^{161-168}\text{Eu}$ ,  $^{165-170}\text{Gd}$ , 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

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

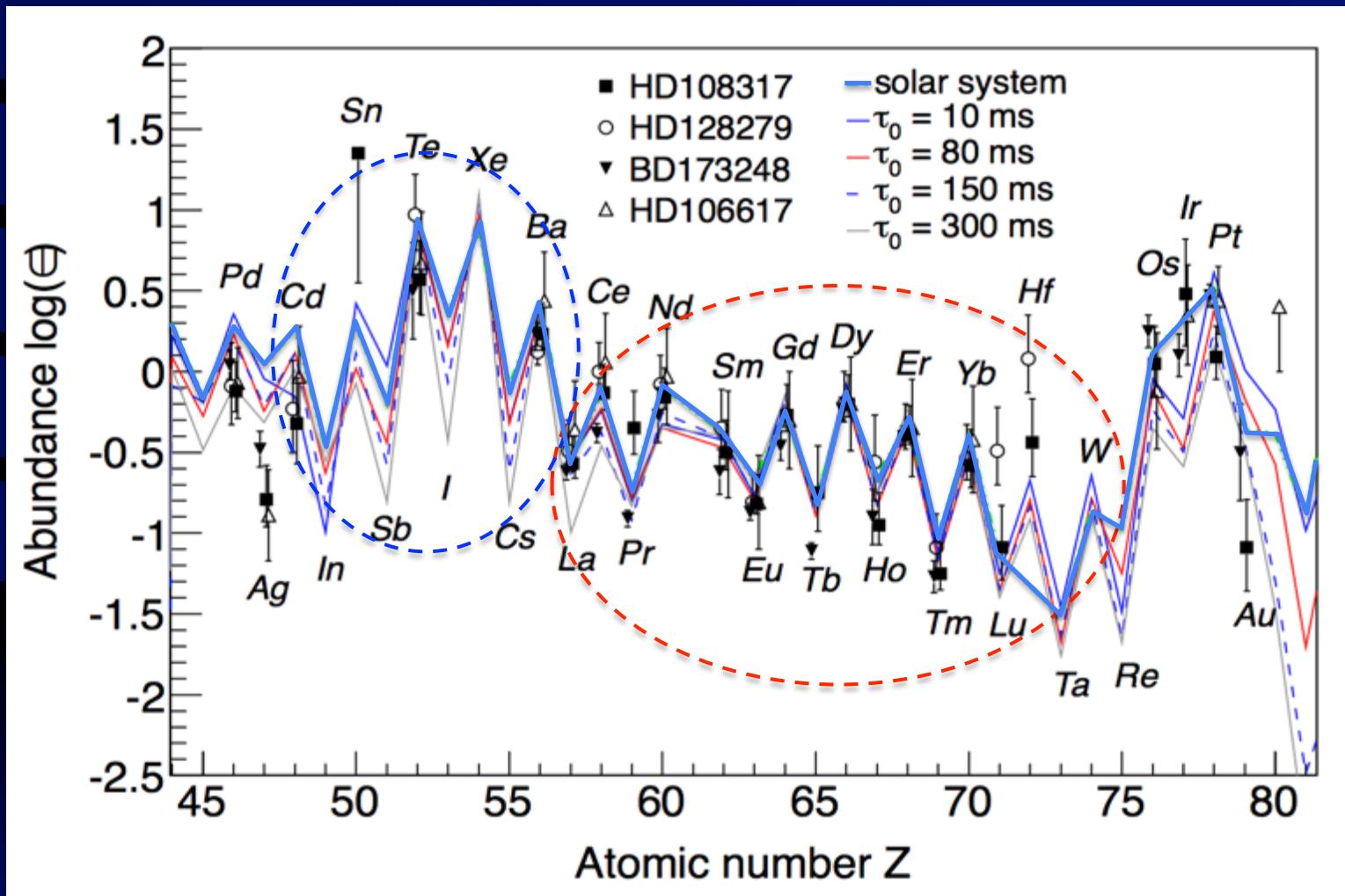
G.Lorusso et al., PRL (2015)



# Origin of Rare-Earth Elements

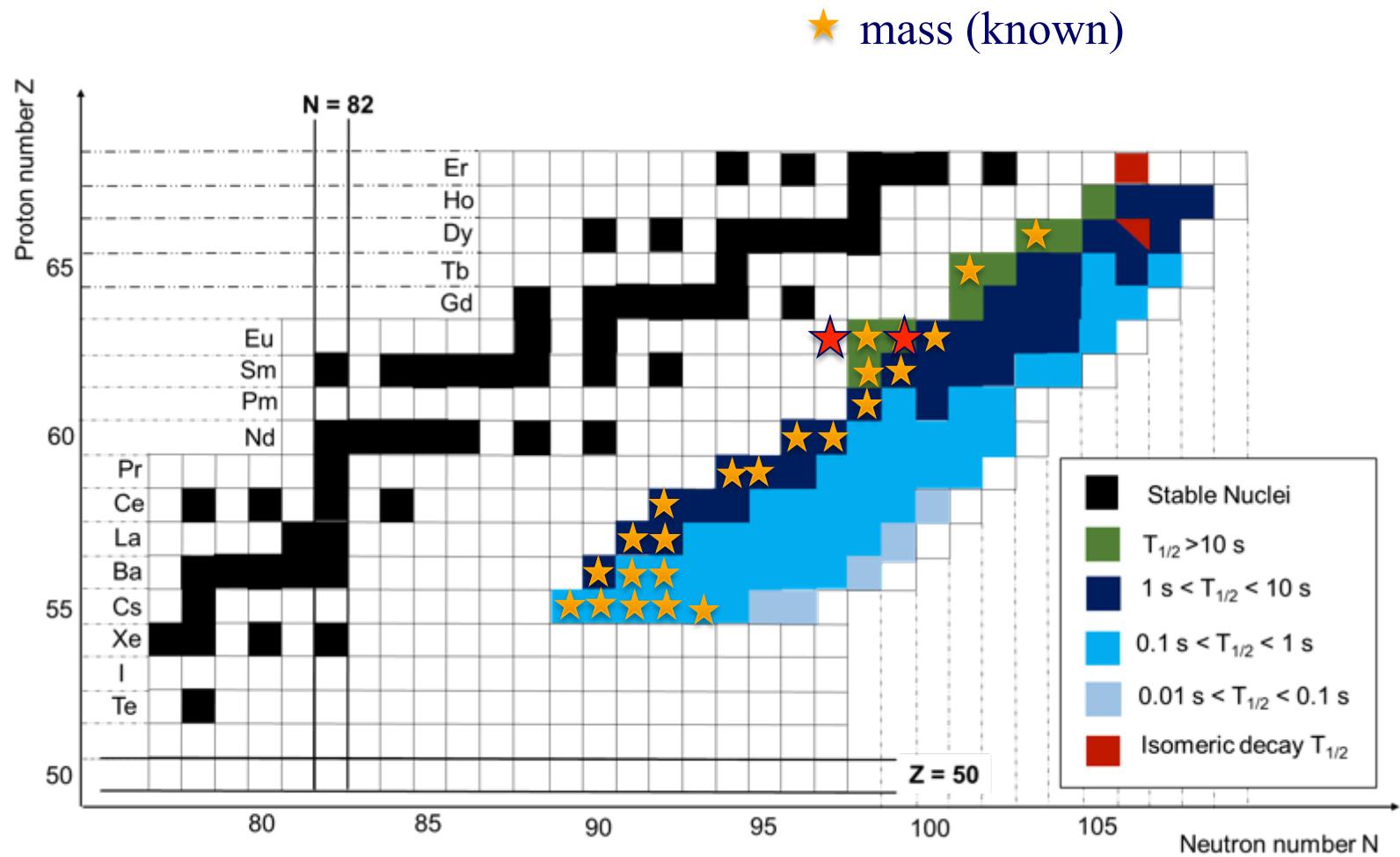


# Universality of r-process elements ( $Z \geq 56$ )



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

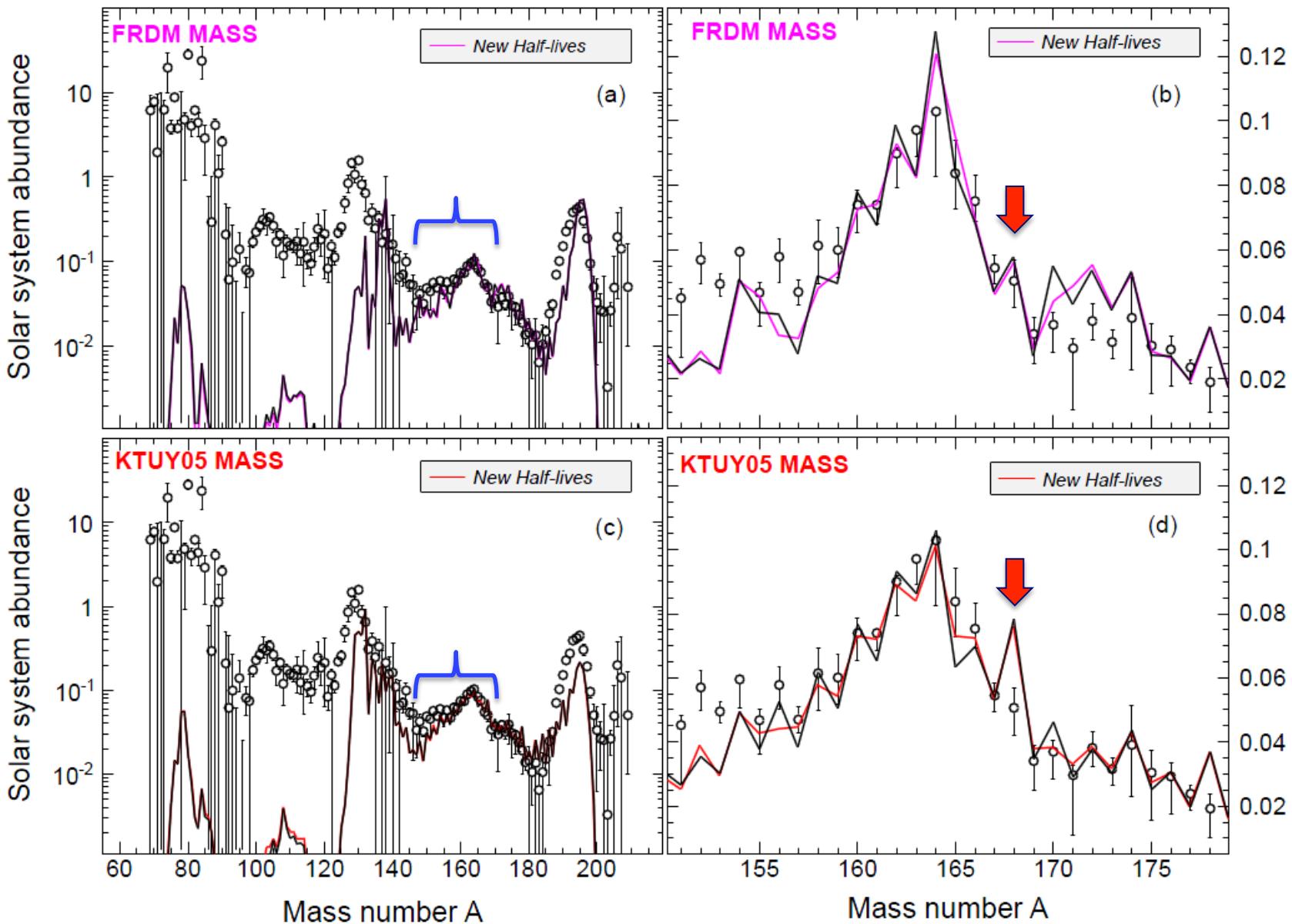
# How About Mass Measurement ?



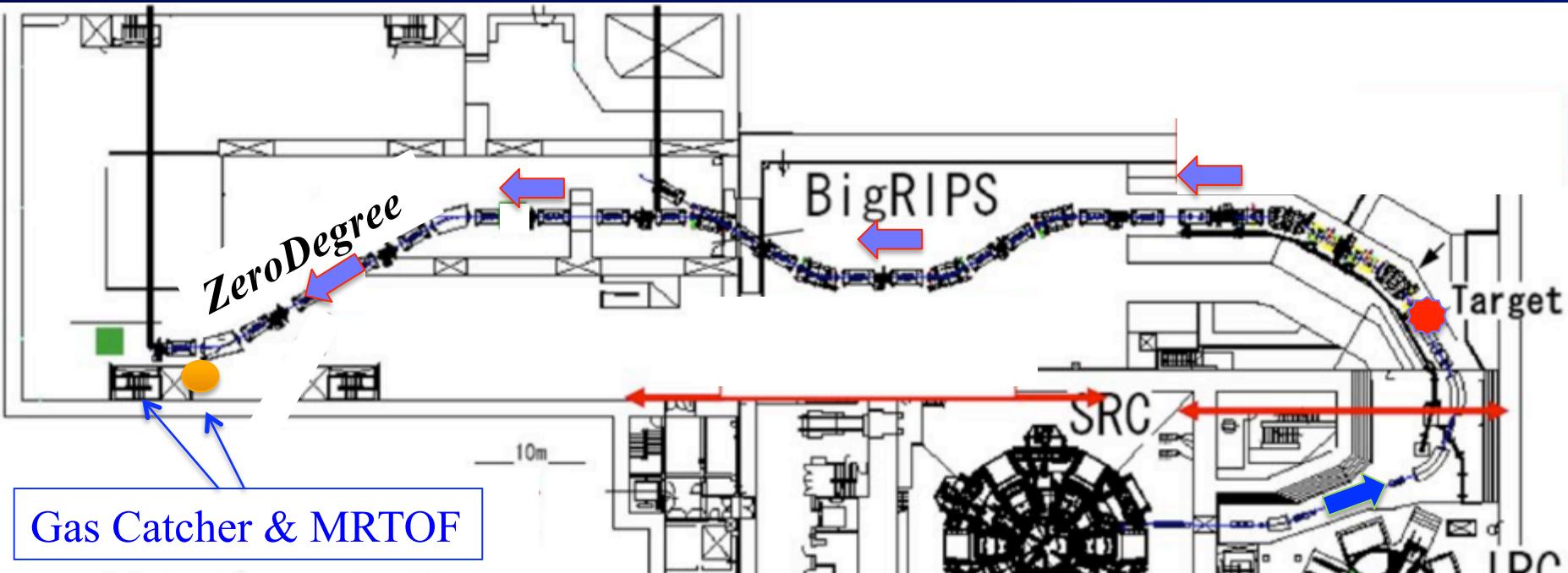
# Rare-Earth Peak with Different Mass Models

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

by J. Wu



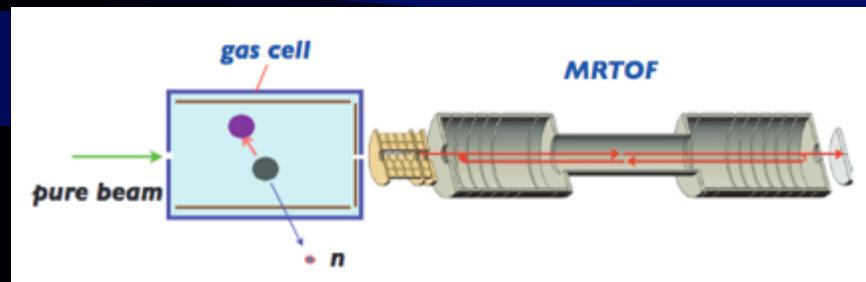
# MRTOF & Decay in ZeroDegree ( 2019 ? ~ )



- 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



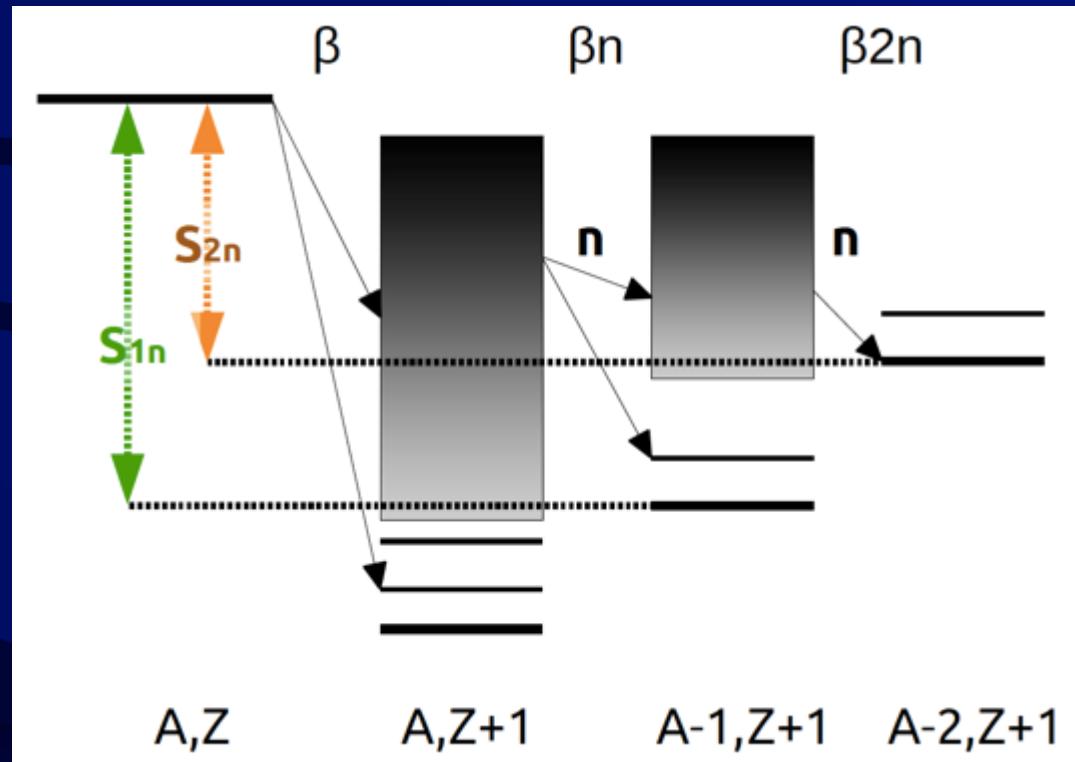
RI Identification by MRTOF

AGARI  
(Active mass Gated stopper  
for RI spectroscopy)

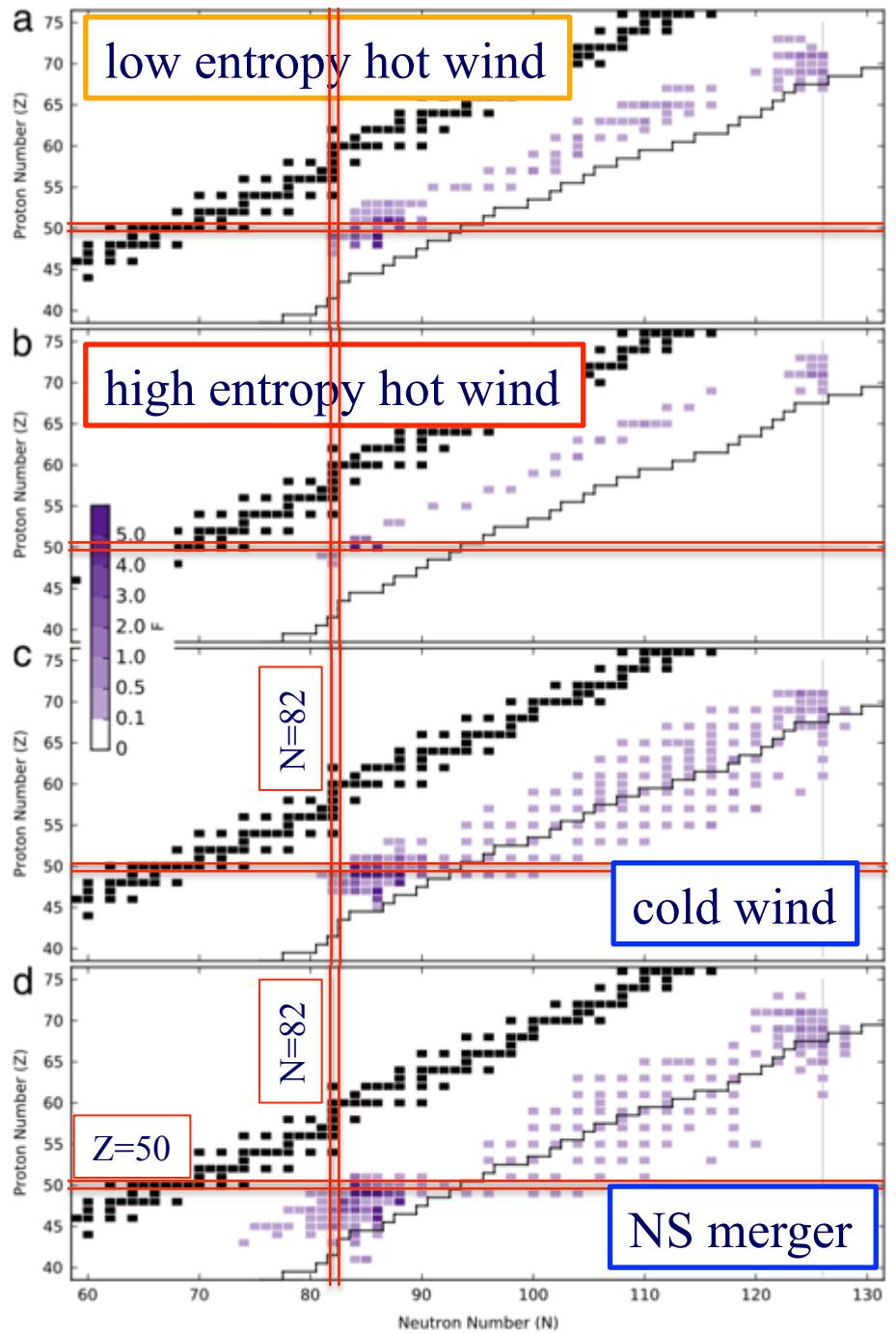
Development has been started..

# Beta-delayed neutron emission probabilities $P_n$

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



BRIKEN (2016 ~ )

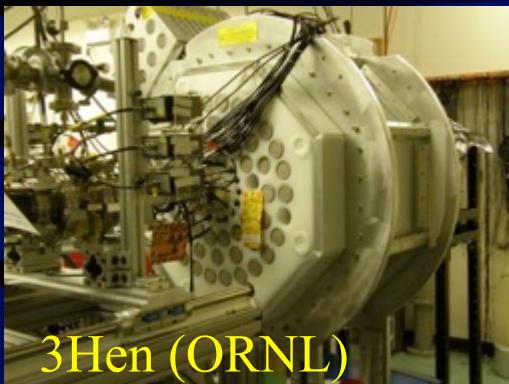


Pn values:  
How Sensitive in  
r-Process Calc.?

beta-delayed neutron emitters

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

# $^3\text{He}$ gas detectors



3Hen (ORNL)

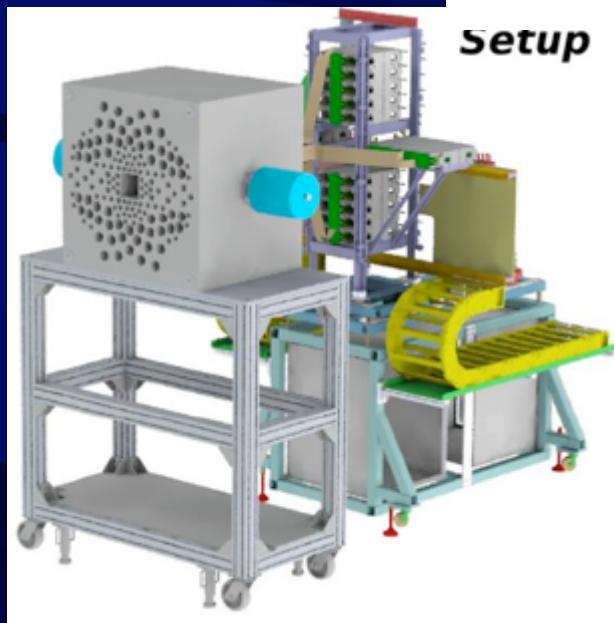
BRIKEN @ RIBF



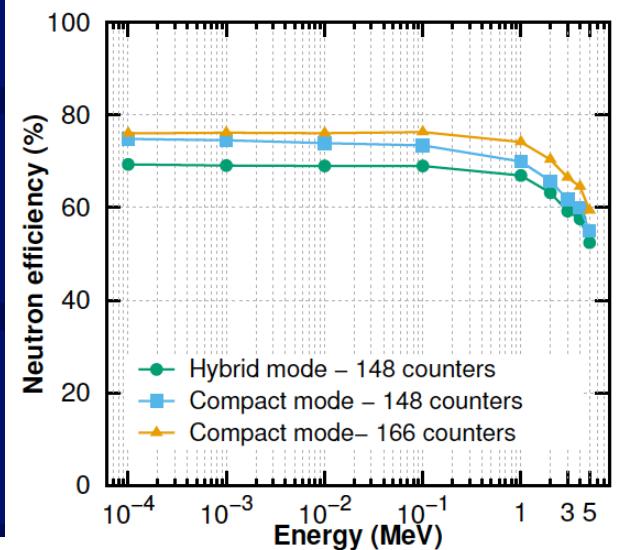
BELEN (Spain)



RIKEN (Japan)



Setup

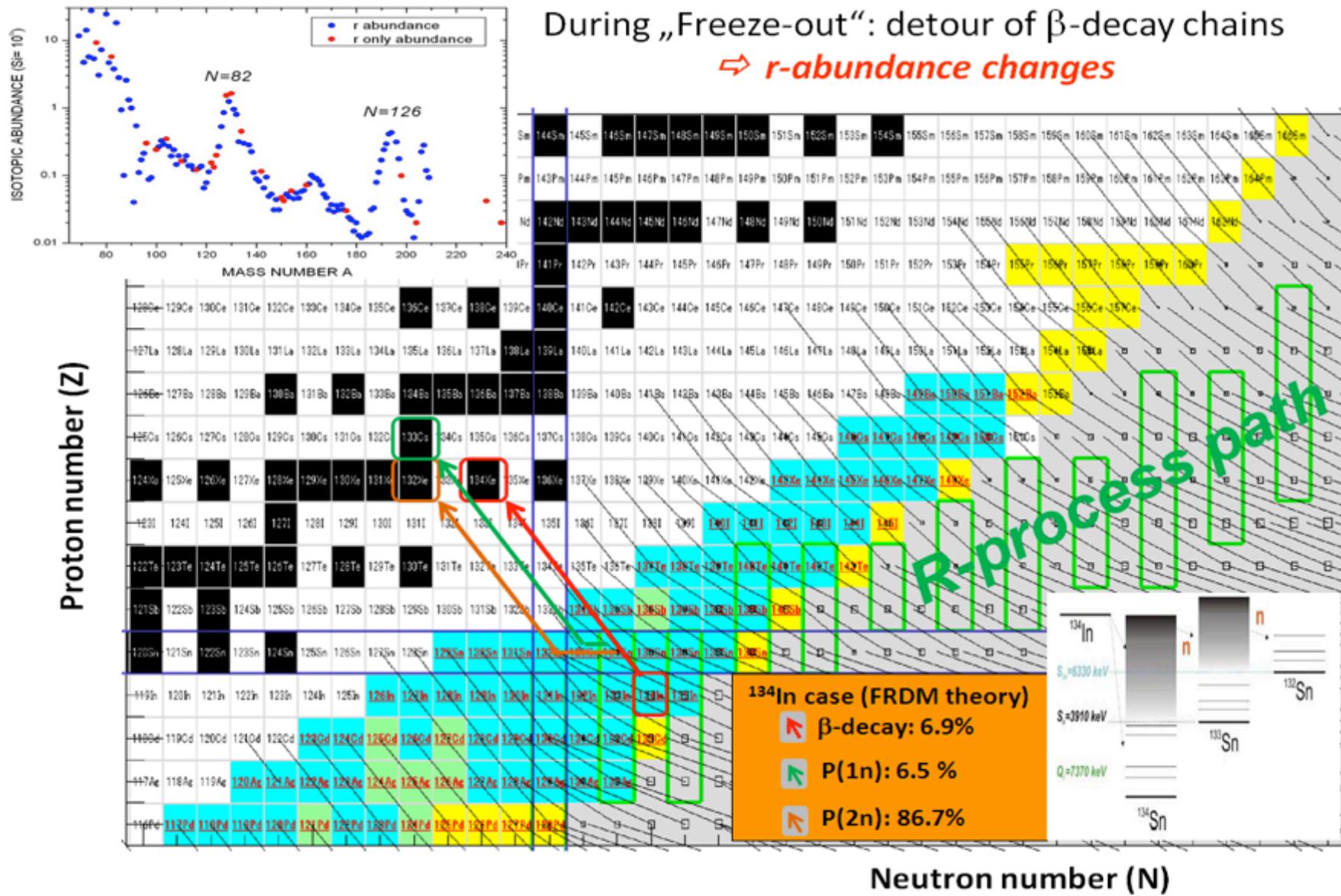


No info. about initial  $E_n$ , but large efficiency

Thermalization time  $\tau \sim 100 \mu\text{s}$

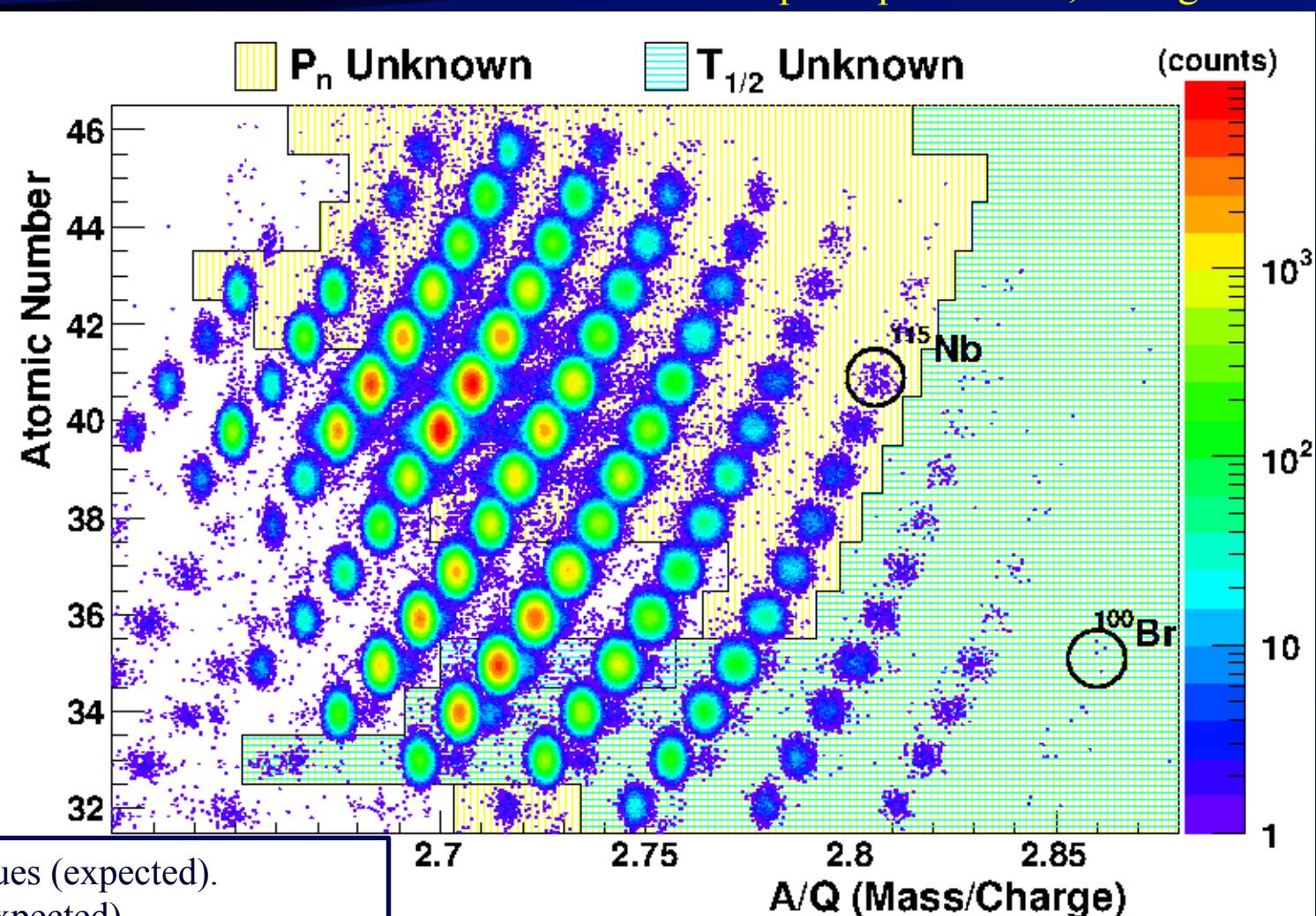
# r-Process Elements : Freeze-out Time

A. Estrade, G. Lorusso, F. Montes



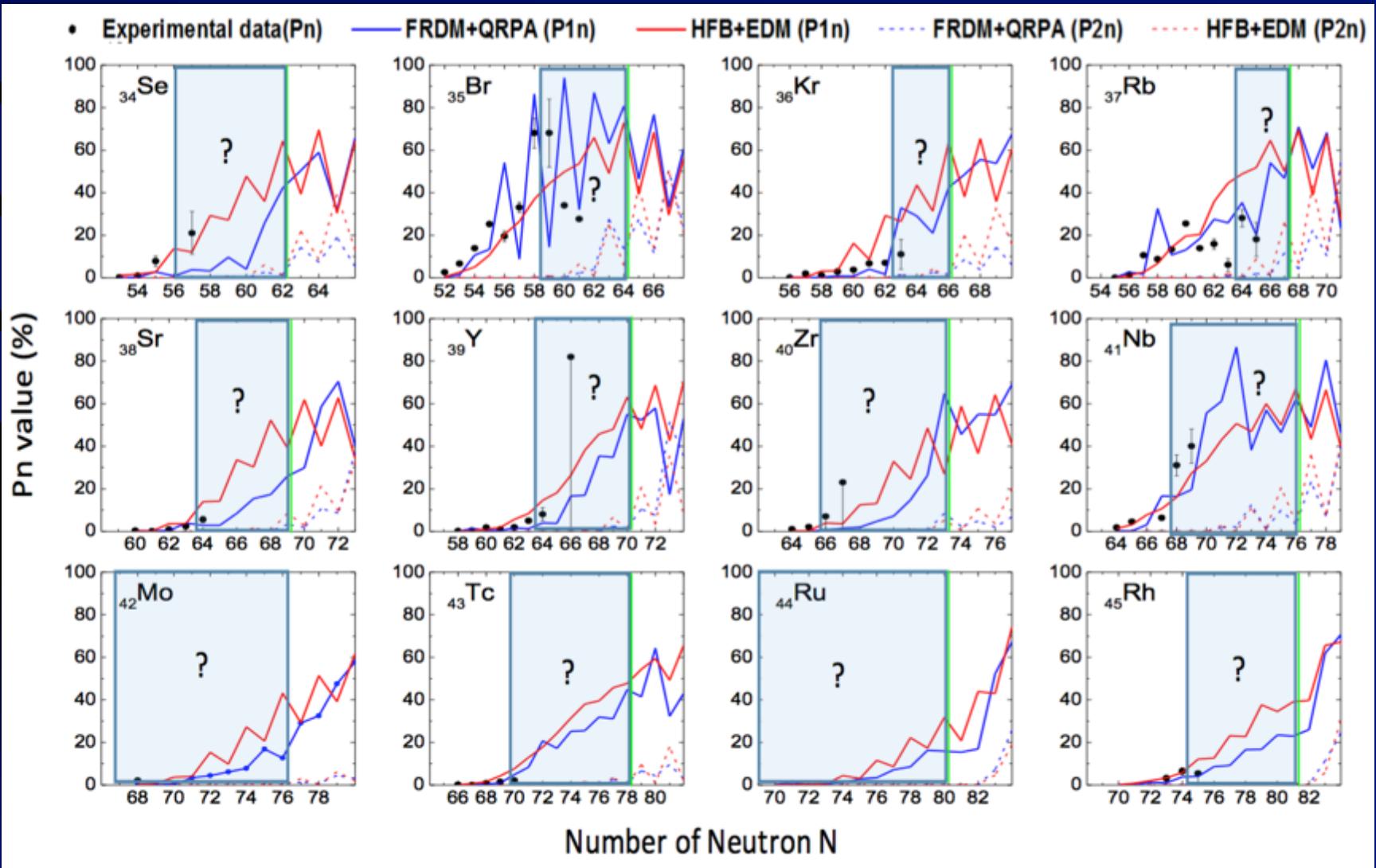
# BRIKEN Campaign (2017 Nov.)

Spokesperson: SN, A. Algora



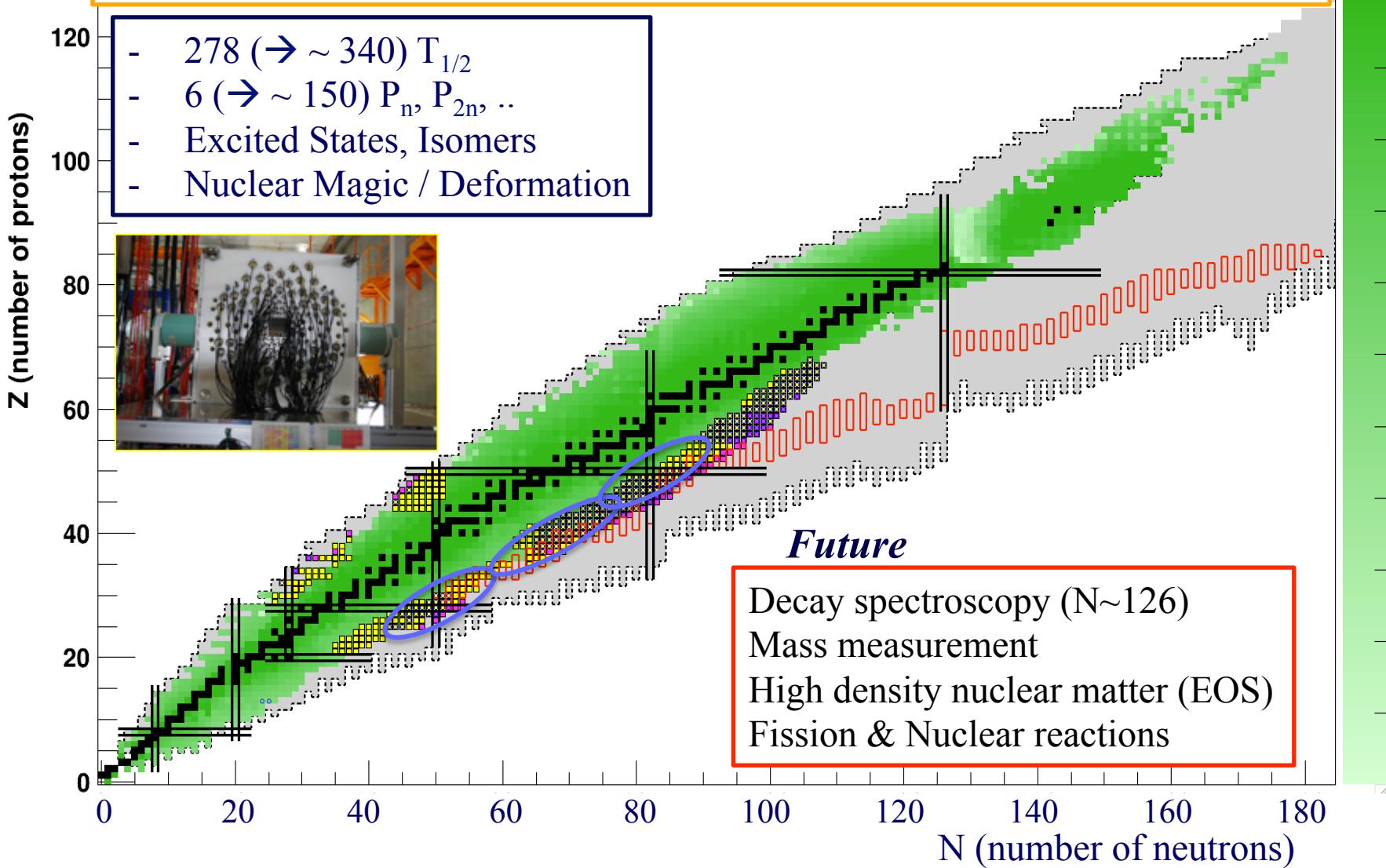
- \* 50 ~ new  $P_n$  values (expected).
- \* ~ 20 new  $T_{1/2}$  (expected).
- \* Isomers
- \* Beta-delayed gamma with neutron-gate
- \* U-beam int. ~ 65 pnA

# Delayed neutrons in mass A = 100 region



# Summary

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

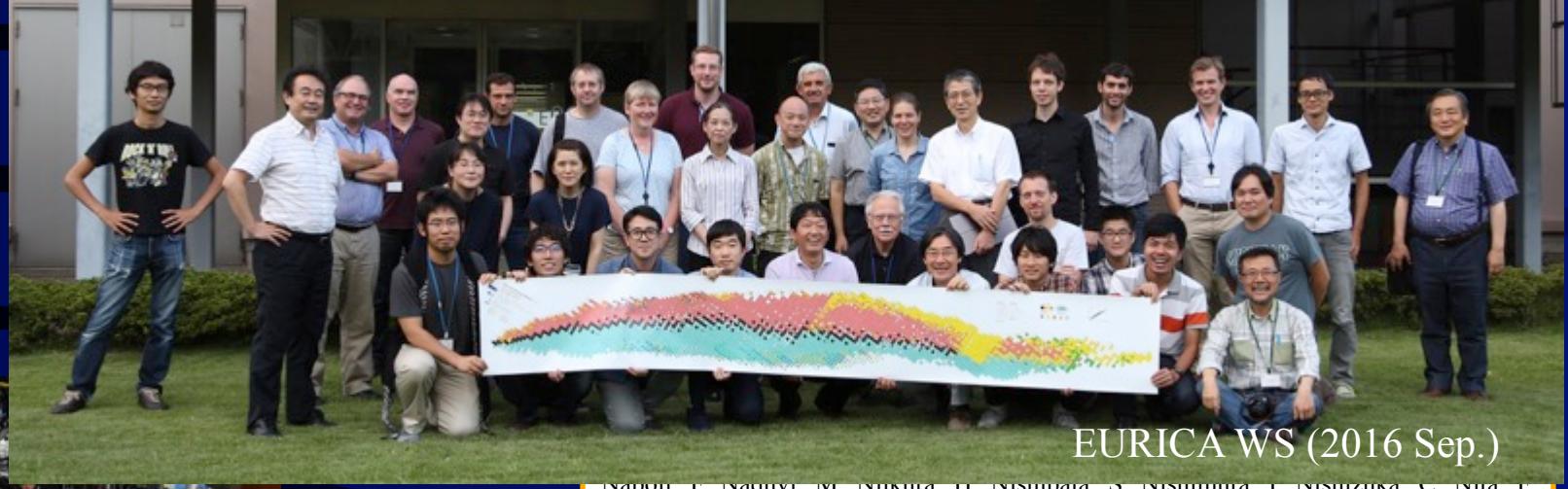


# EURICA Collaboration



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. Benzon, 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.



EURICA WS (2016 Sep.)



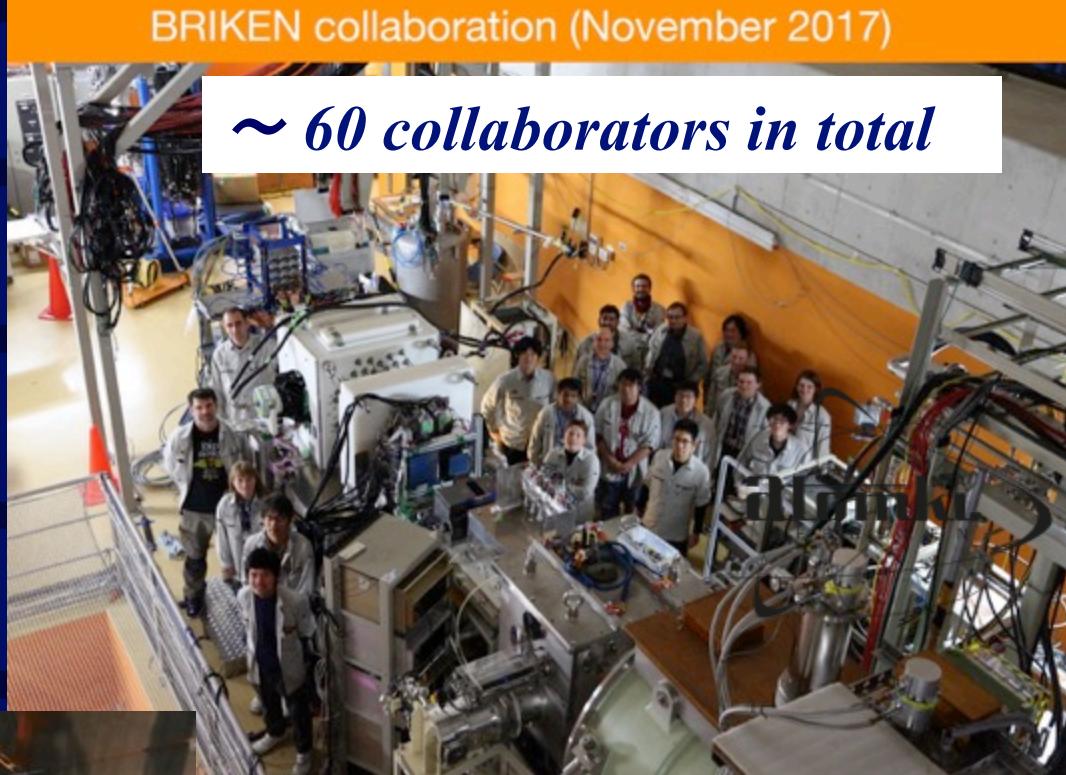
Acknowledgement:  
Euroball Owners Committee  
PreSPEC, GSI, IBS-RISP

Napon, T., Naquvi, M., Nakura, H., Nishimura, S., Nishimura, T., Nishizuka, C., Nita, T., 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: Gammapool, Prepc, IBS



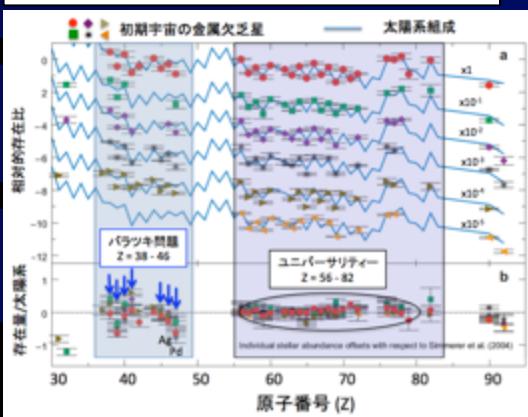
Science & Technology Facilities Council  
Daresbury Laboratory



# Nucleosynthesis under Extreme Matter & Conditions



SUBARU/Hubble & TMT Telescopes



Neutron stars have magnetic fields exceeding  $10^{12}$  Gauss.

