Nishina School 2023, 2023/07/31（Monday）

# Nuclear Astrophysics

**Shunji Nishimura**
**RIKEN**

**Supernovae**


**Black Hole**

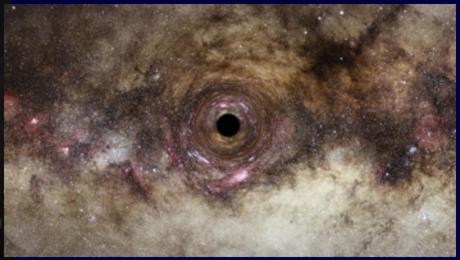
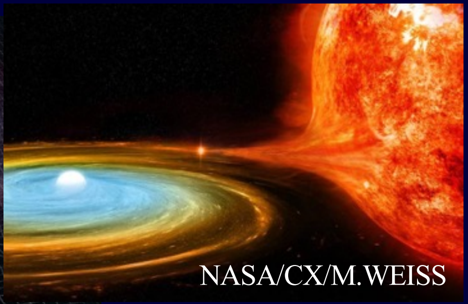


Photo / Ho/ESA-HUBBLE


**Keywords: Nucleosynthesis & Neutron**

# We Are Made of ”Star Stuff”

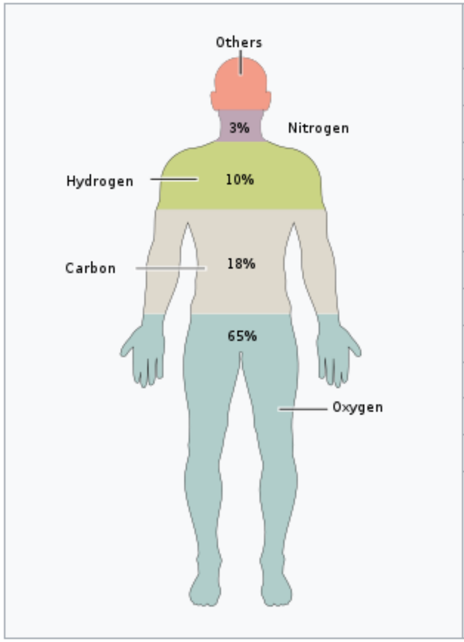
Carl Sagan

A scientist, cosmologist, astrophysicist, astrobiologist, author, and science communicator from the United States.

# We are Made of "Star Staff"

## [ Elements ]

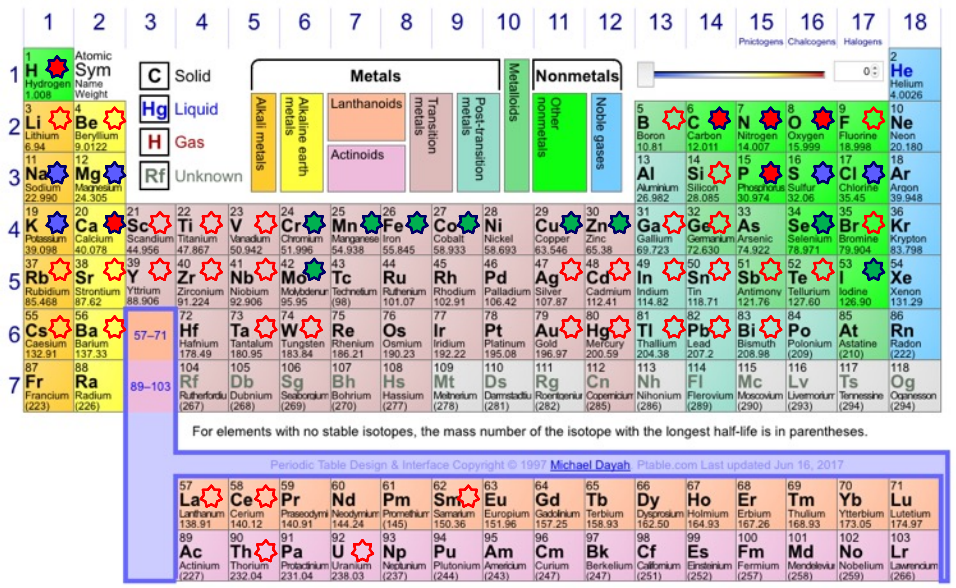
Wikipedia




| Element | Symbol | percent mass | percent atoms |
|---|---|---|---|
| Oxygen | O | 65.0 | 24.0 |
| Carbon | C | 18.5 | 12.0 |
| Hydrogen | H | 10 | 62.0 |
| Nitrogen | N | 3.2 | 1.1 |
| Calcium | Ca | 1.5 | 0.22 |
| Phosphorus | P | 1.0 | 0.22 |
| Potassium | K | 0.4 | 0.03 |
| Sulfur | S | 0.3 | 0.038 |
| Sodium | Na | 0.2 | 0.037 |
| Chlorine | Cl | 0.2 | 0.024 |
| Magnesium | Mg | 0.1 | 0.015 |
| All others | | < 0.1 | < 0.3 |

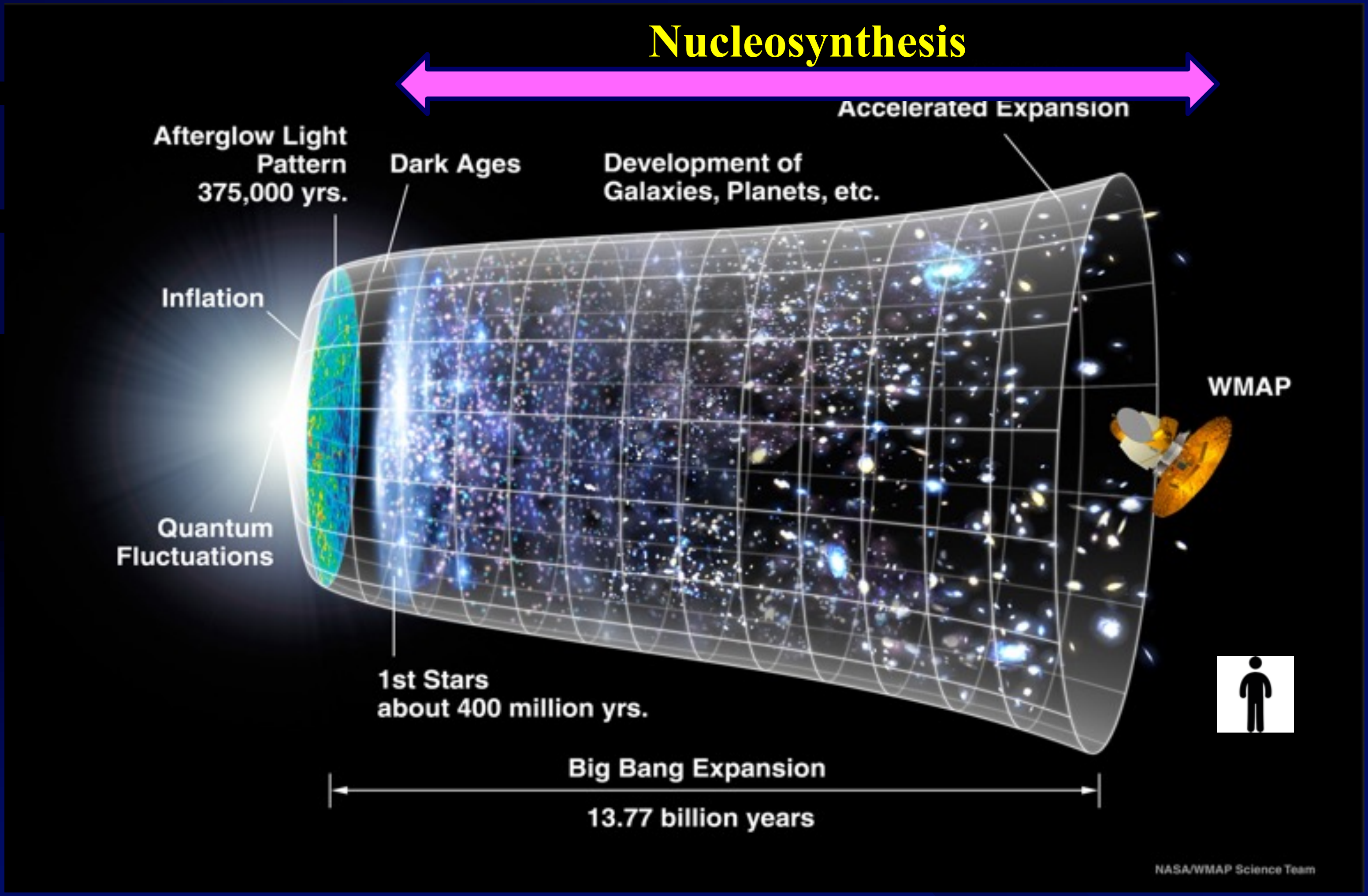
Periodic Table of Elements

Wikipedia




**Where and How are the elements made in the universe ..?**

# Where & How the Elements are Made in the Universe !?



# Nucleosynthesis in Universe

**Big Bang**

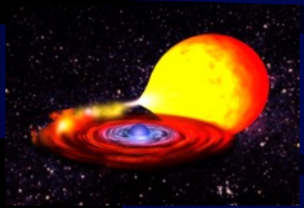
***Get Together***

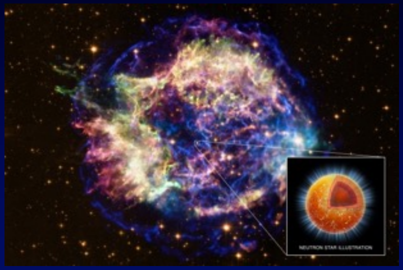
Gravitational Force

**Interstellar Material**

**Star**

Nucleosynthesis up to iron





*Scatter Ashes*

***Supernovae***

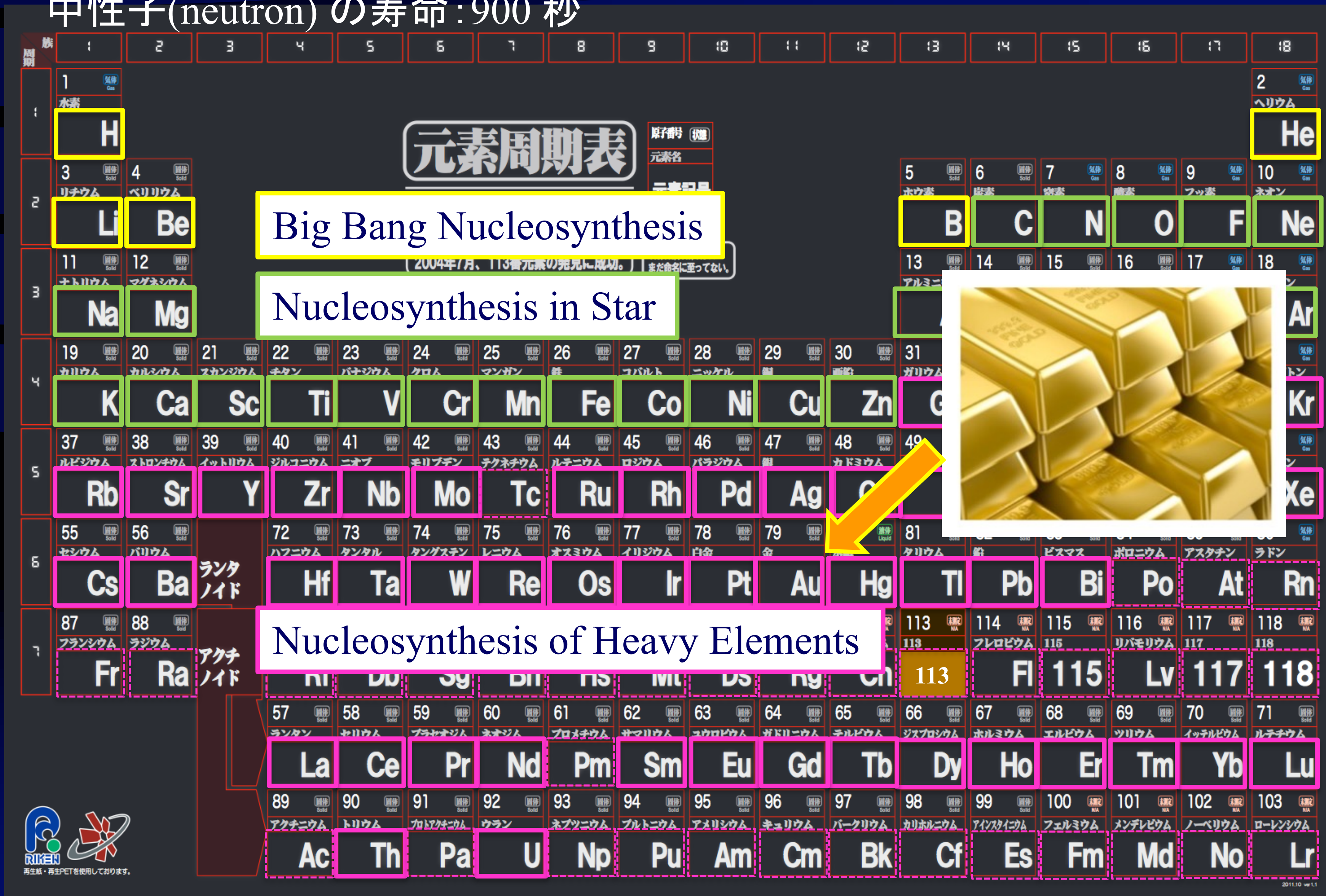
Nucleosynthesis heavier than iron

**Black hole**
**Neutron Star**

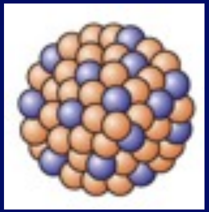
**What kinds of Elements in "Our Solar System" ?**

# Periodic Table of Elements

中性子(neutron) の寿命 : 900 秒



# For example.. “Gold”



**Gold (Stable) ...**

- **Symbol of Element ... Au**
- **Number of Proton (*Z*) = 79**
- **Number of Neutron (*N*) = 118**
- **Mass Number (*A*) = 197**

$$A = Z + N$$

**Symbol of Element**
**Number of Proton**

$$^{197}\text{Au}$$

**Mass Number *A***

Credit: Pirates of the Caribbean

# We are making Golds (Au) in the Laboratory

Joseph Wright

Alchemy (鍊金術)

**Gold (Stable) ...**

- **Symbol of Element ... Au**
- **Number of Proton ($Z$) = 79**
- **Number of Neutron ($N$) = 118**
- **Mass Number ($A$) = 197**

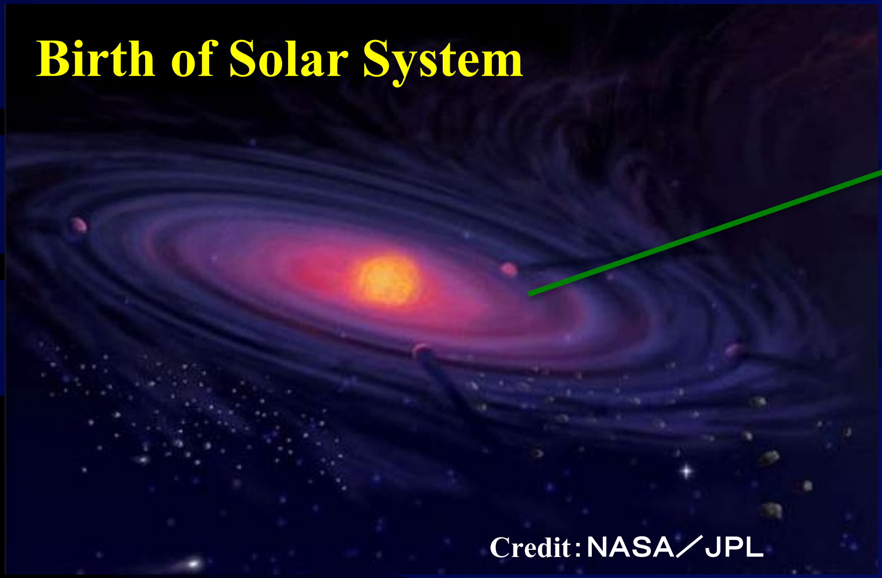
$$A = Z + N$$


Less neutrons (Neutron-deficient)

More neutrons (Neutron-rich)


$N = 91$ *Light gold* $N = 118$ *Heavy gold* $N = 131$

# Nucleosynthesis of Heavy Elements




Gold

Uranium

１）Heavy elements have been created before the solar system

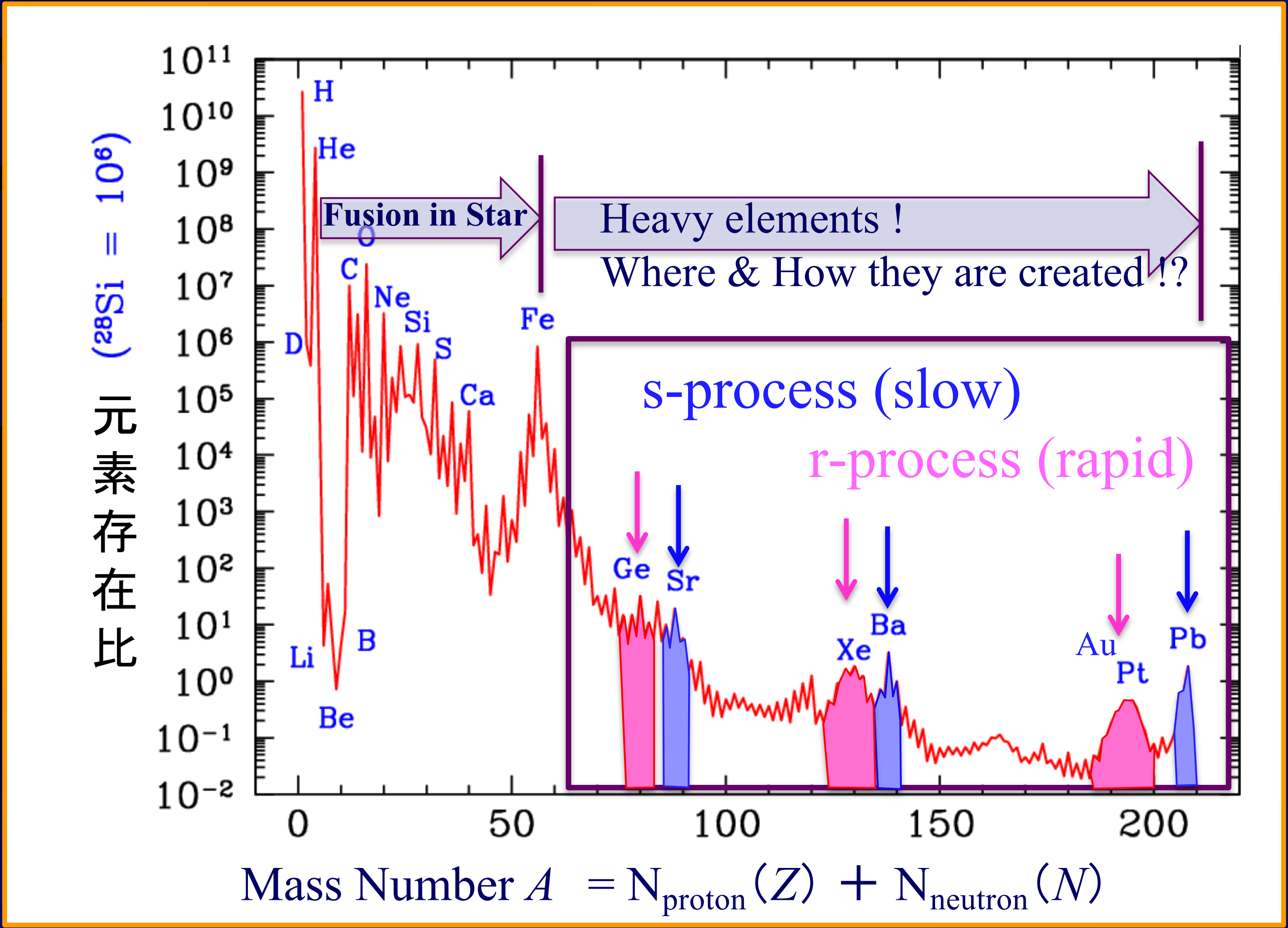
２）About half of those heavy elements must be created in short time (~sec).

３）Where and when are heavy elements created ?

**Still Open question in Astrophysics and Nuclear Physics**

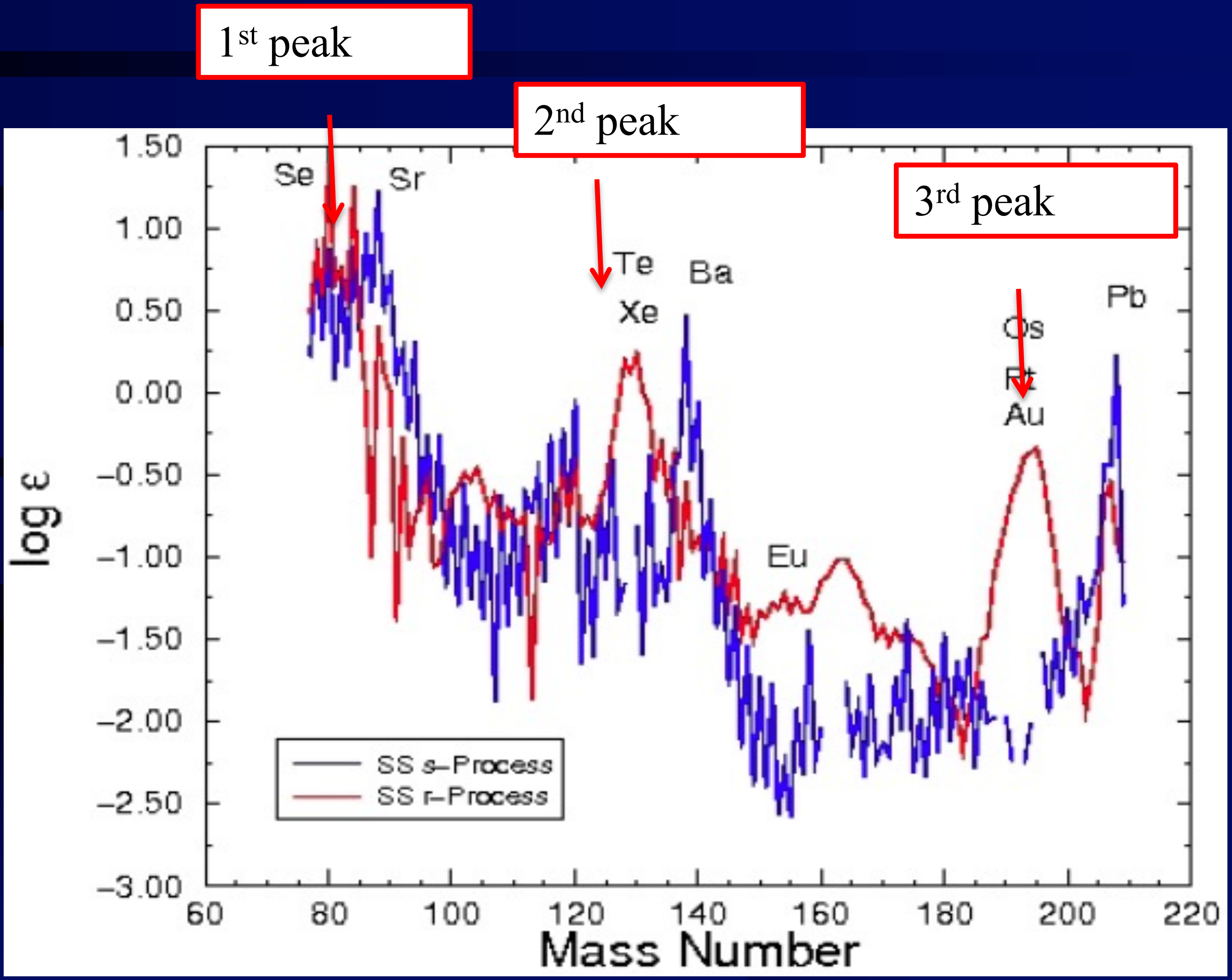
Hints are in the Elemental Abundance in Solar System.

# Solar System: Abundance Pattern




# Nucleosynthesis of Heavy Elements

## s-process (slow) and r-process (rapid)



# s-過程

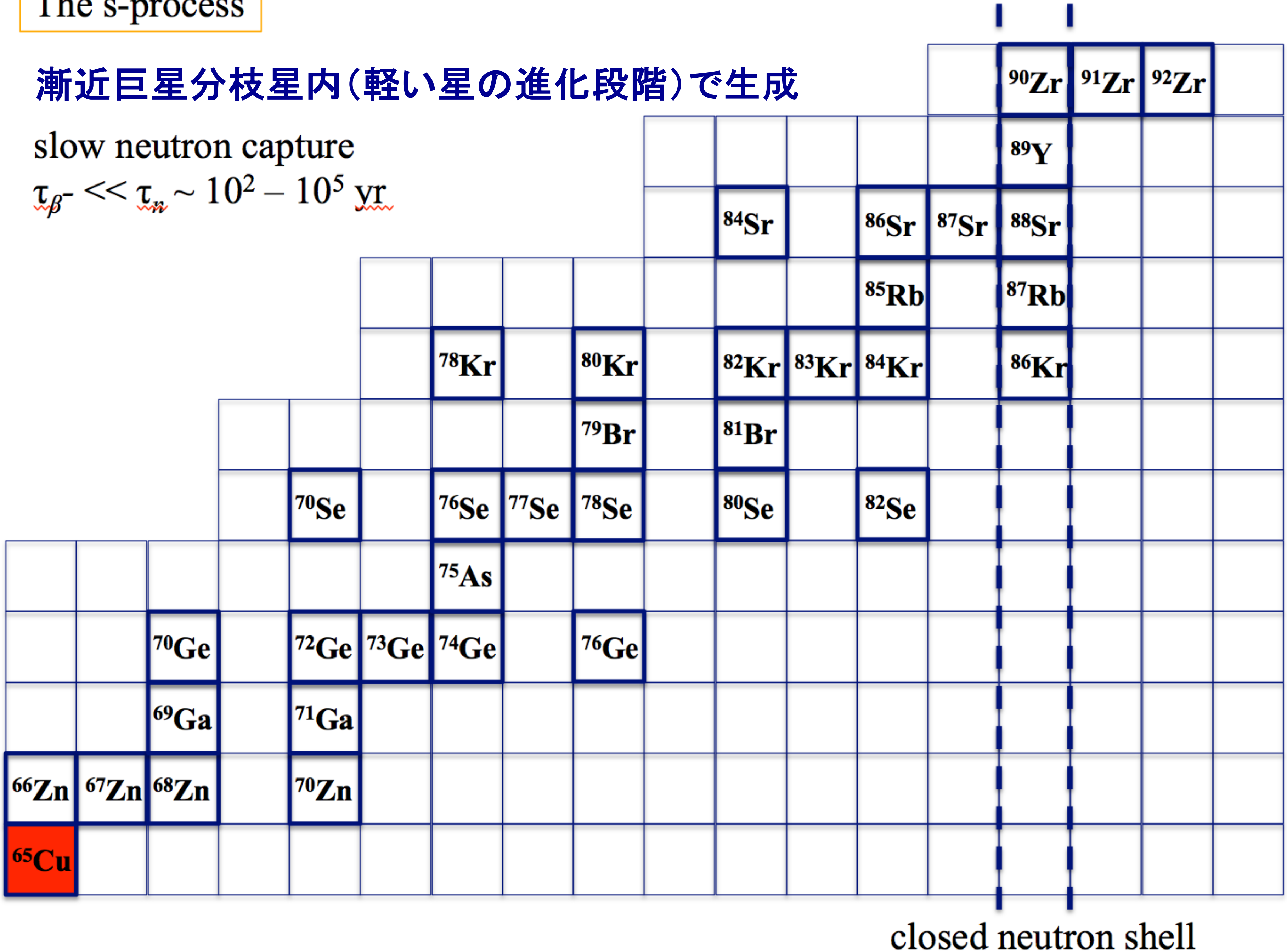
slow neutron capture process
(s-process)

The s-process

## 漸近巨星分枝星内(軽い星の進化段階)で生成

slow neutron capture

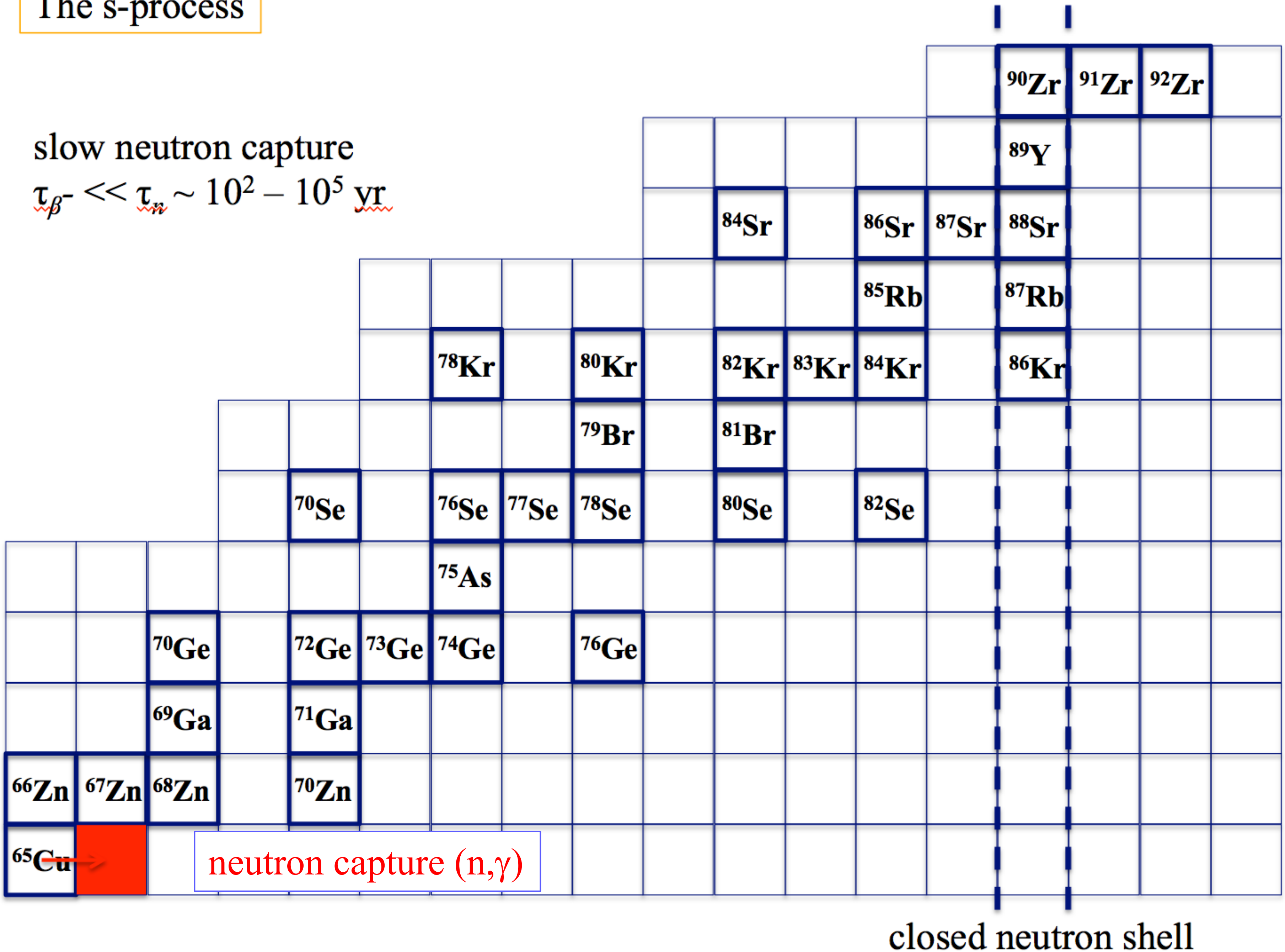
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



# The s-process

slow neutron capture

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

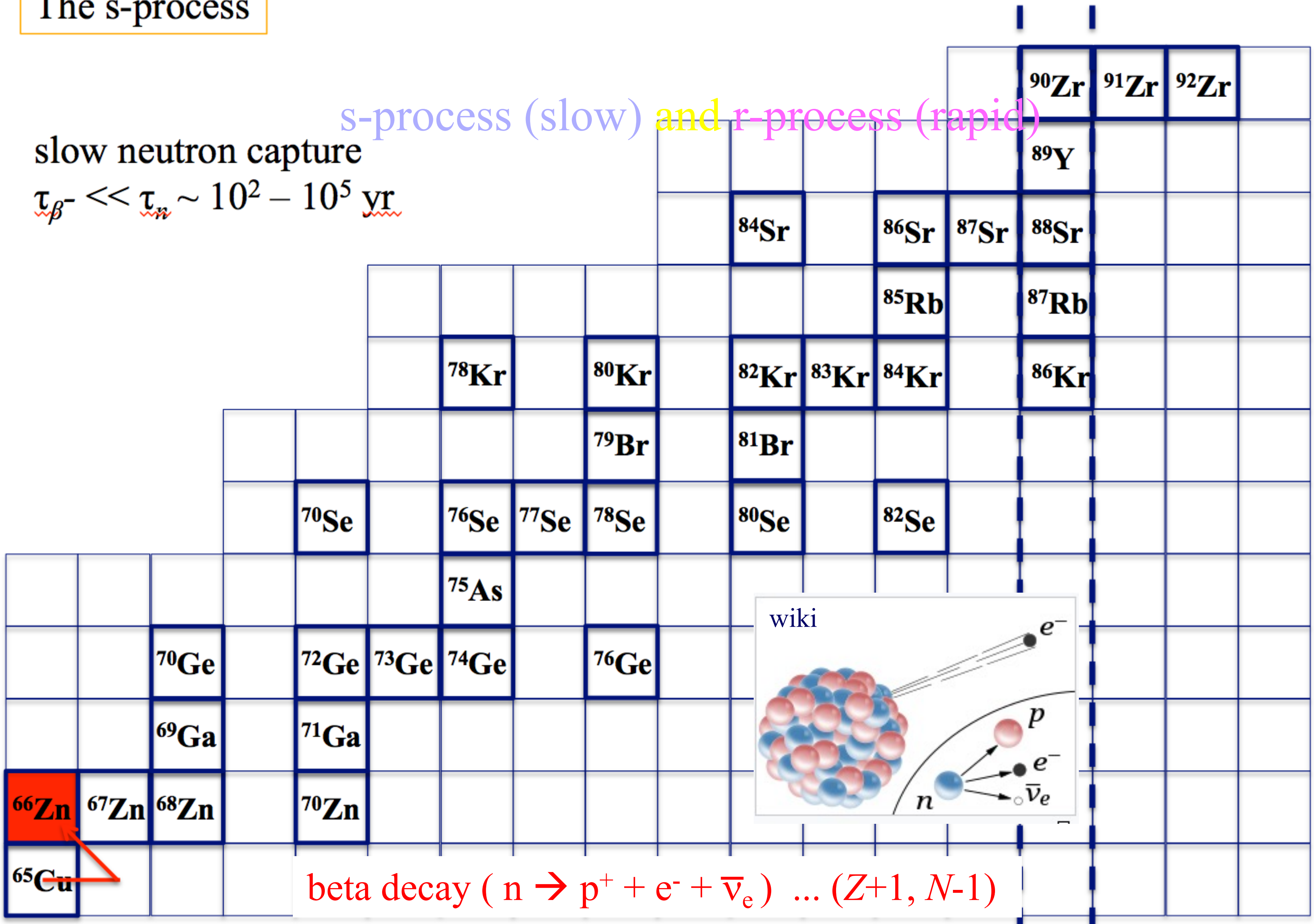


# The s-process

s-process (slow) and r-process (rapid)

slow neutron capture

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



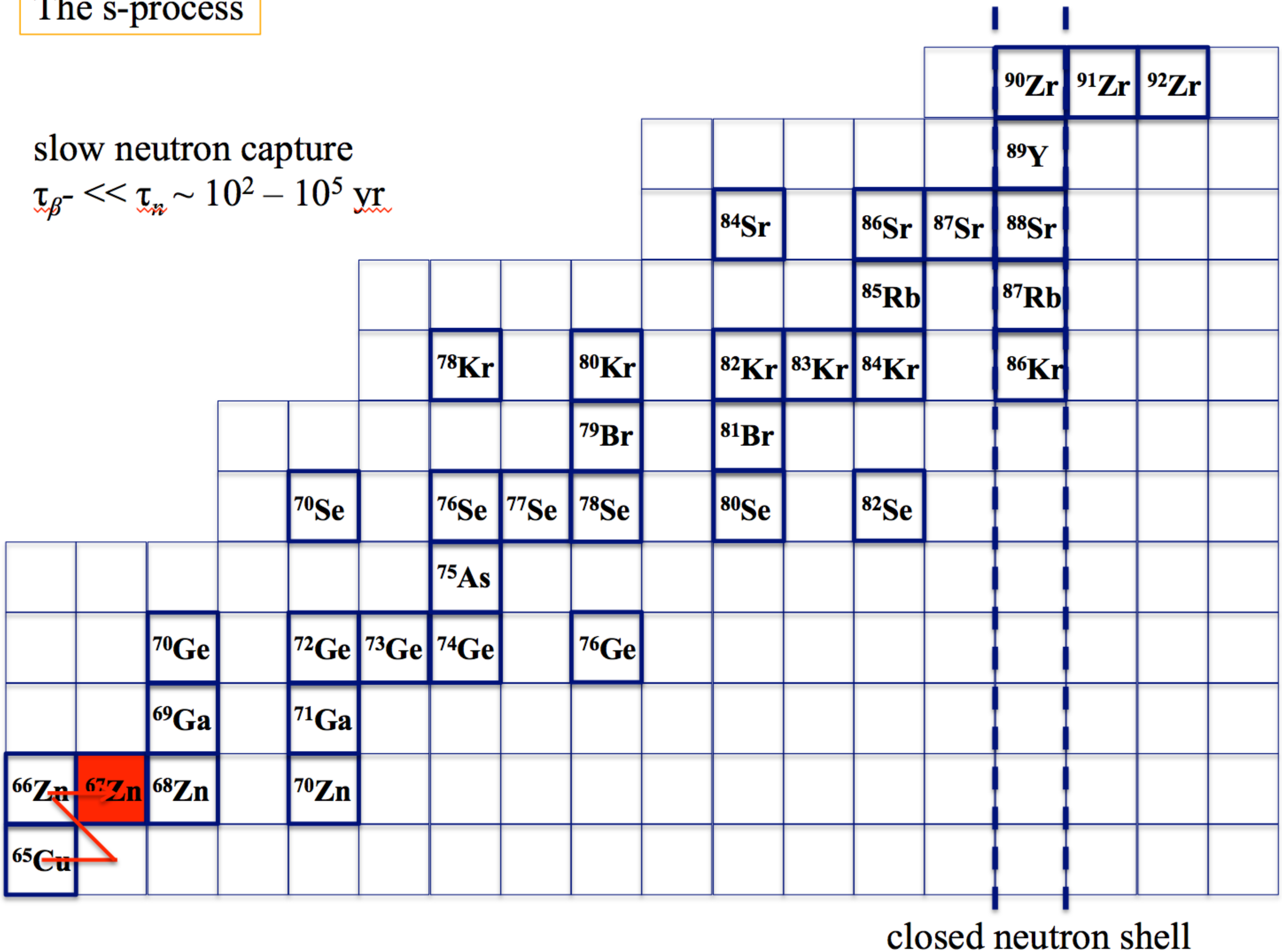

beta decay ( n → $p^+ + e^- + \bar{\nu}_e$ ) ... ($Z$+1, $N$-1)

closed neutron shell

The s-process

slow neutron capture

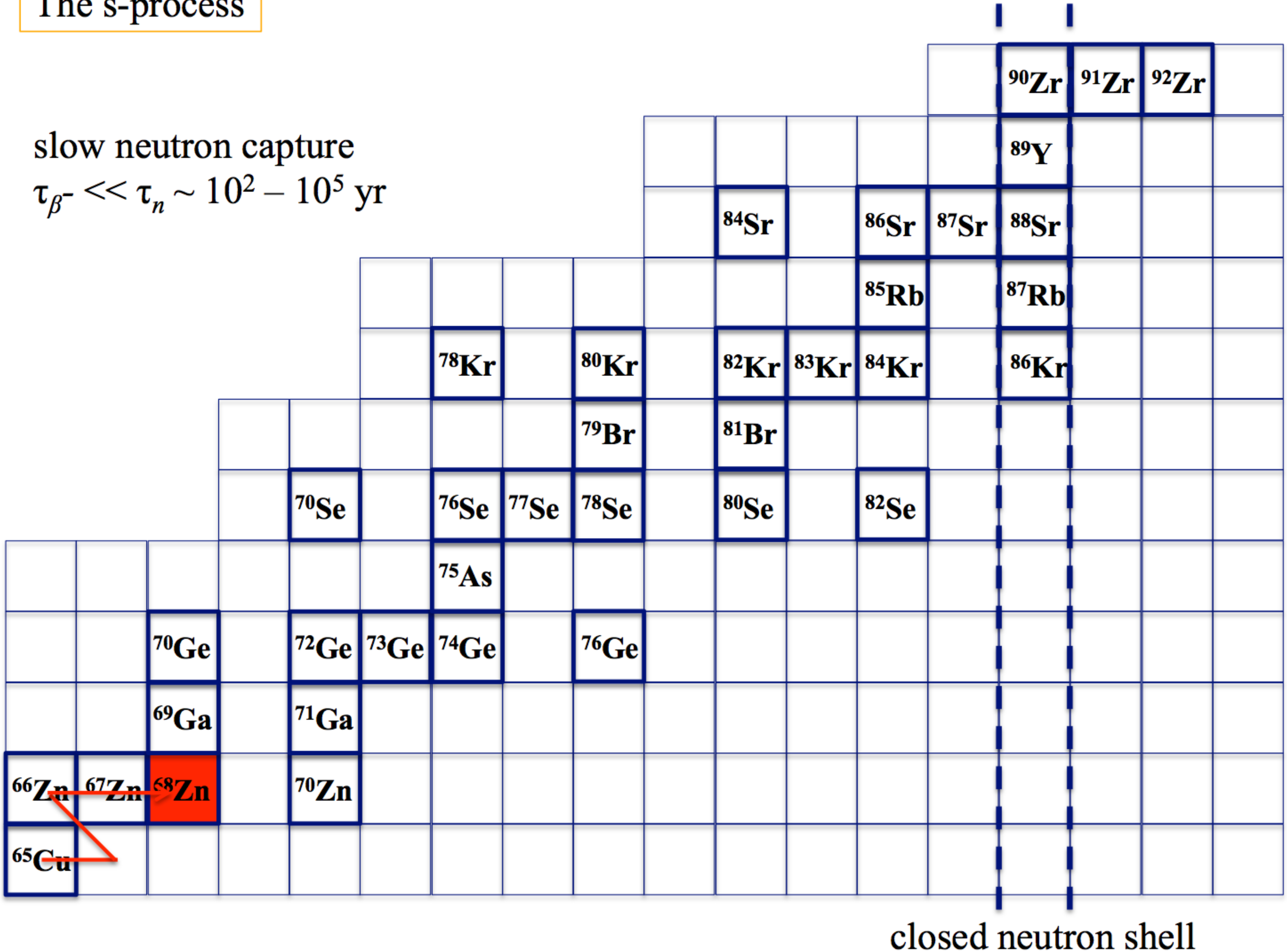
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



The s-process

slow neutron capture

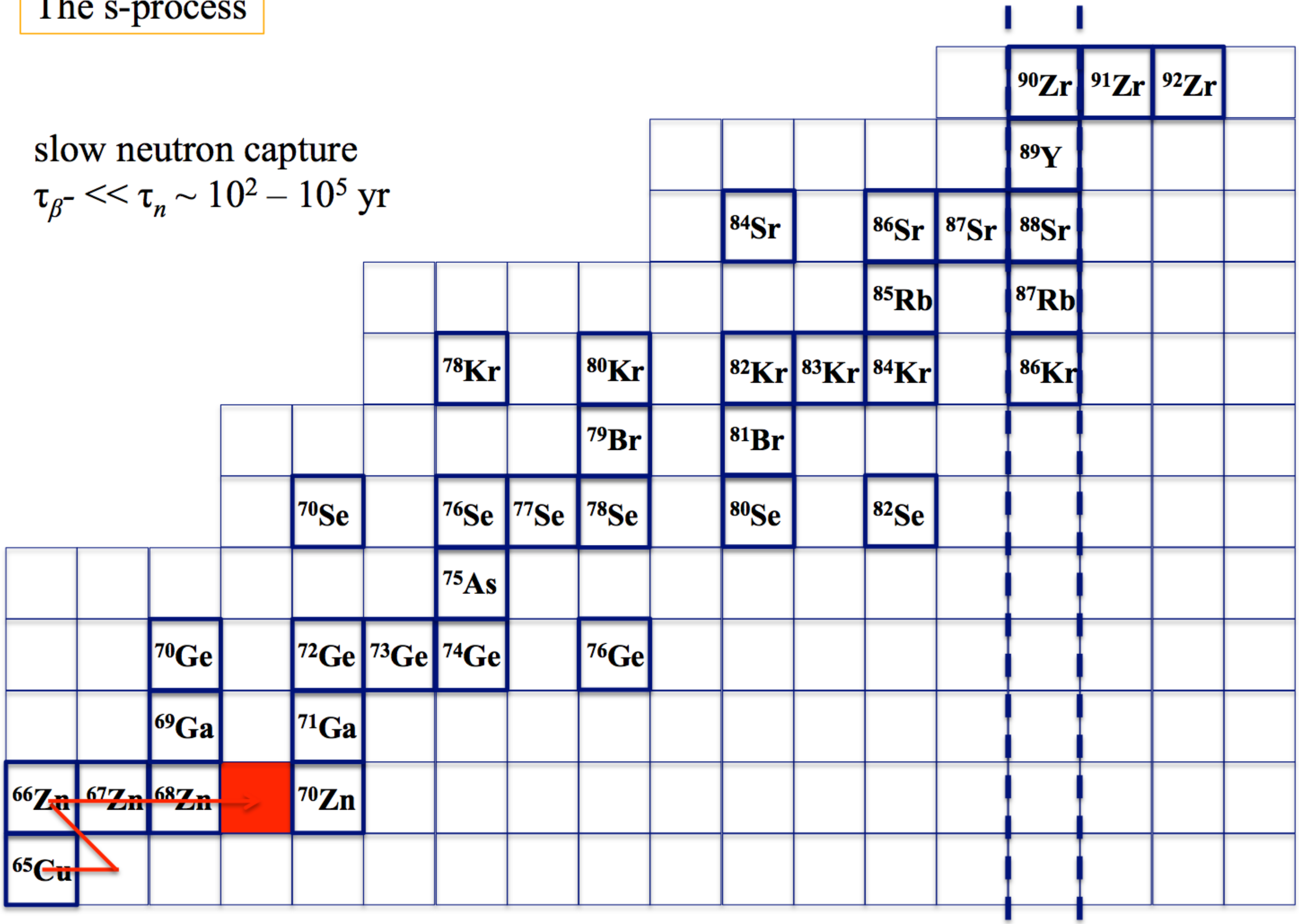
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



# The s-process

slow neutron capture

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

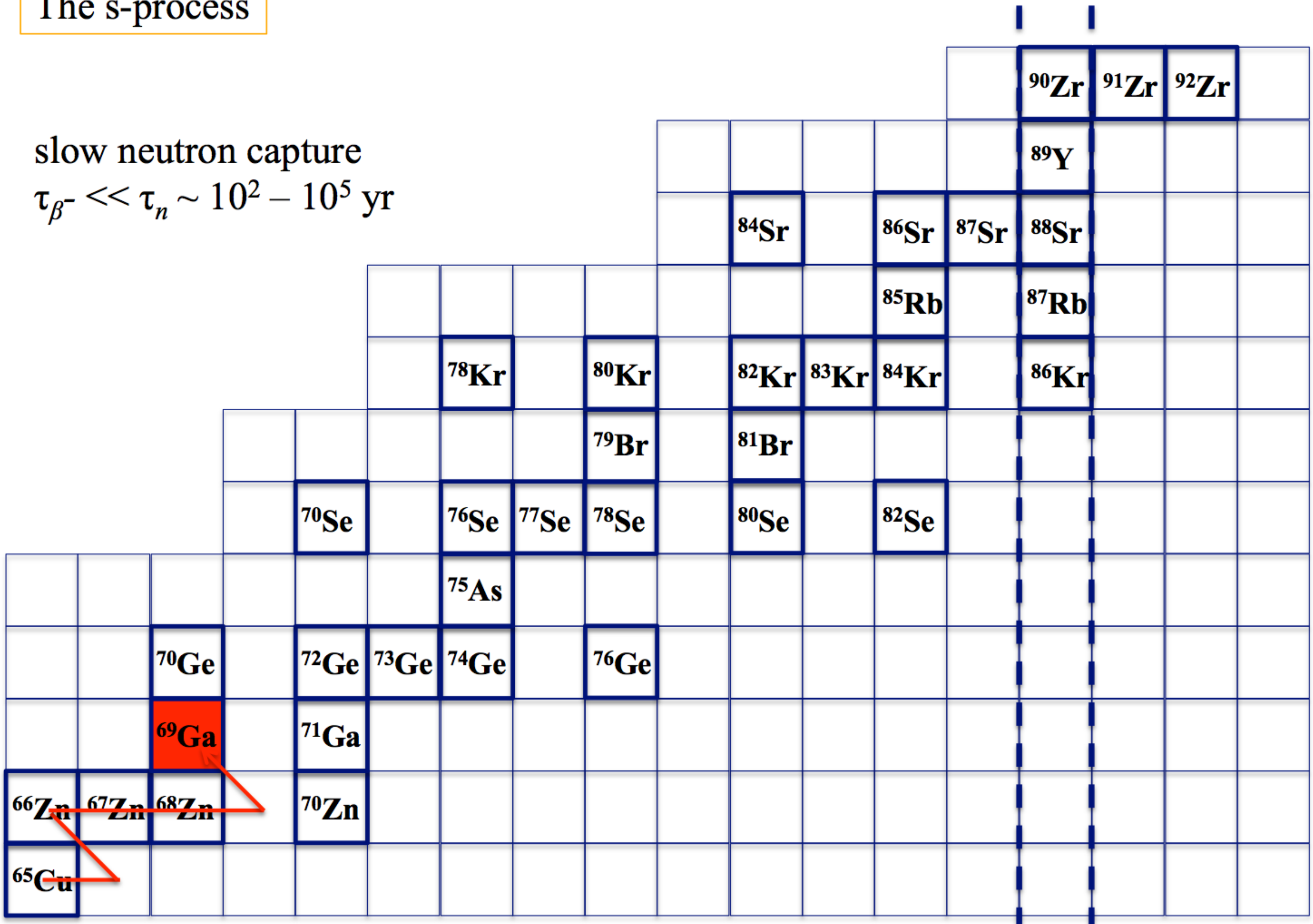



closed neutron shell

The s-process

slow neutron capture

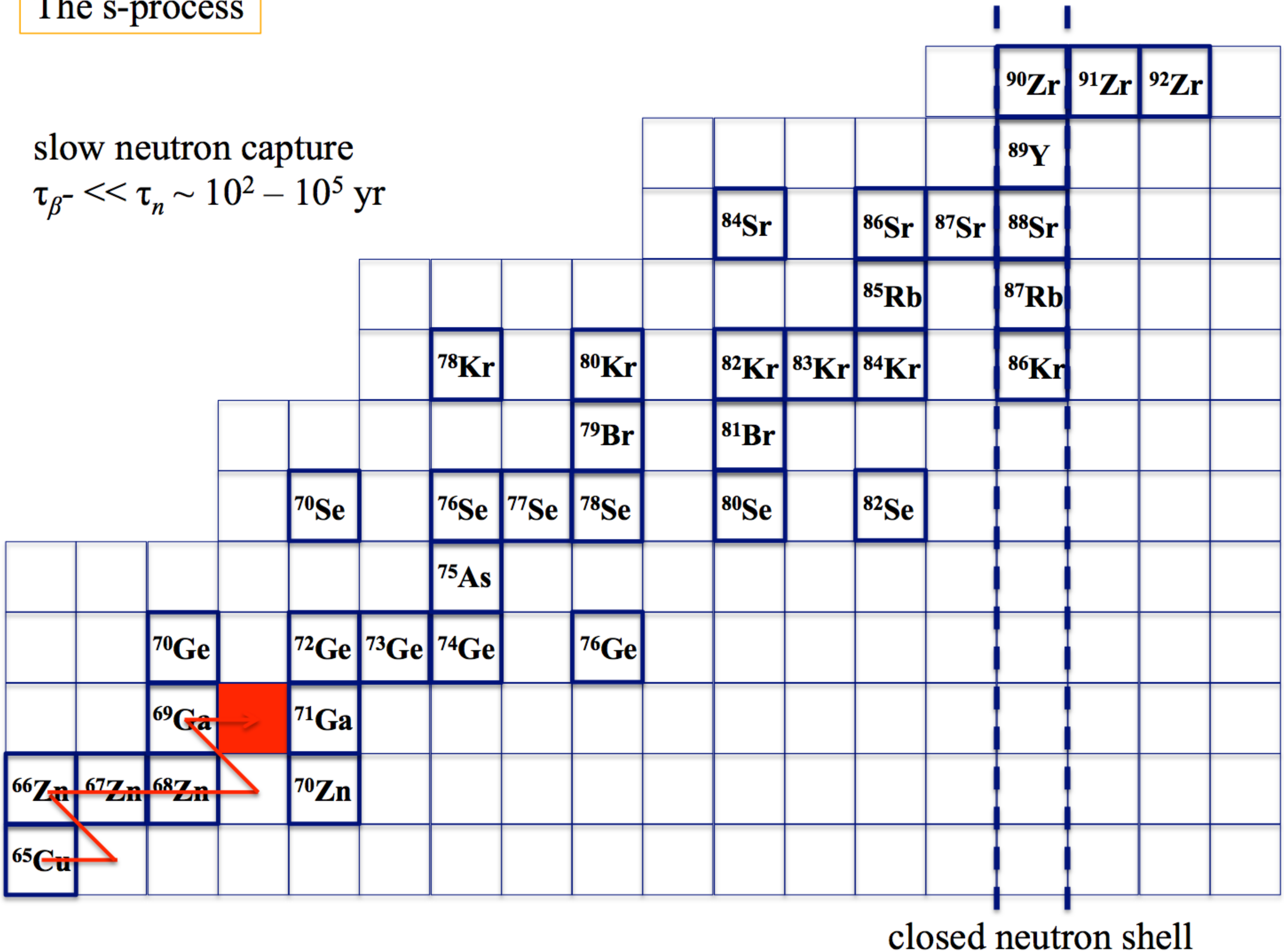
$\tau_{\beta^-} << \tau_n \sim 10^2 - 10^5$ yr



# The s-process

slow neutron capture

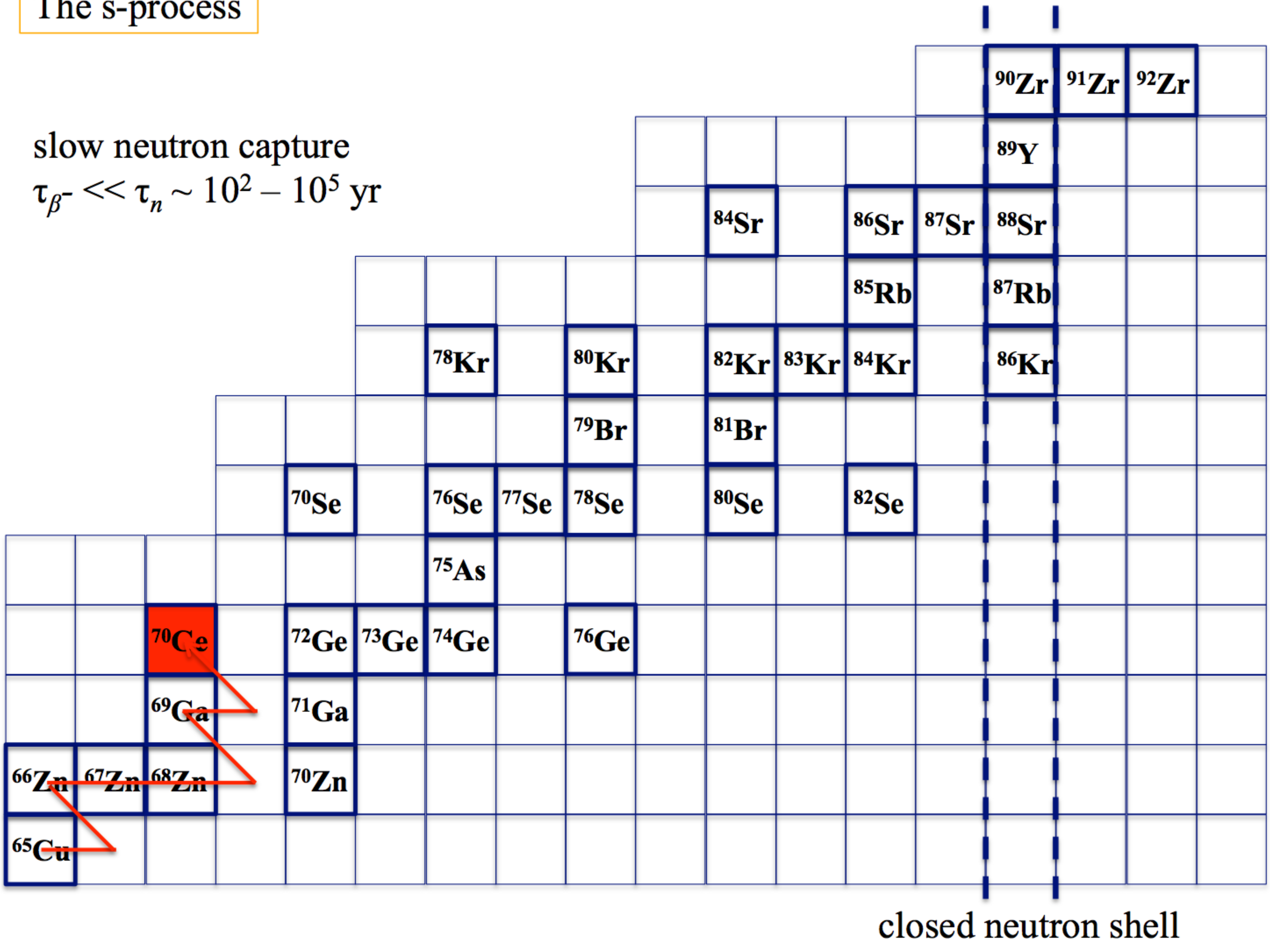
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



The s-process

slow neutron capture

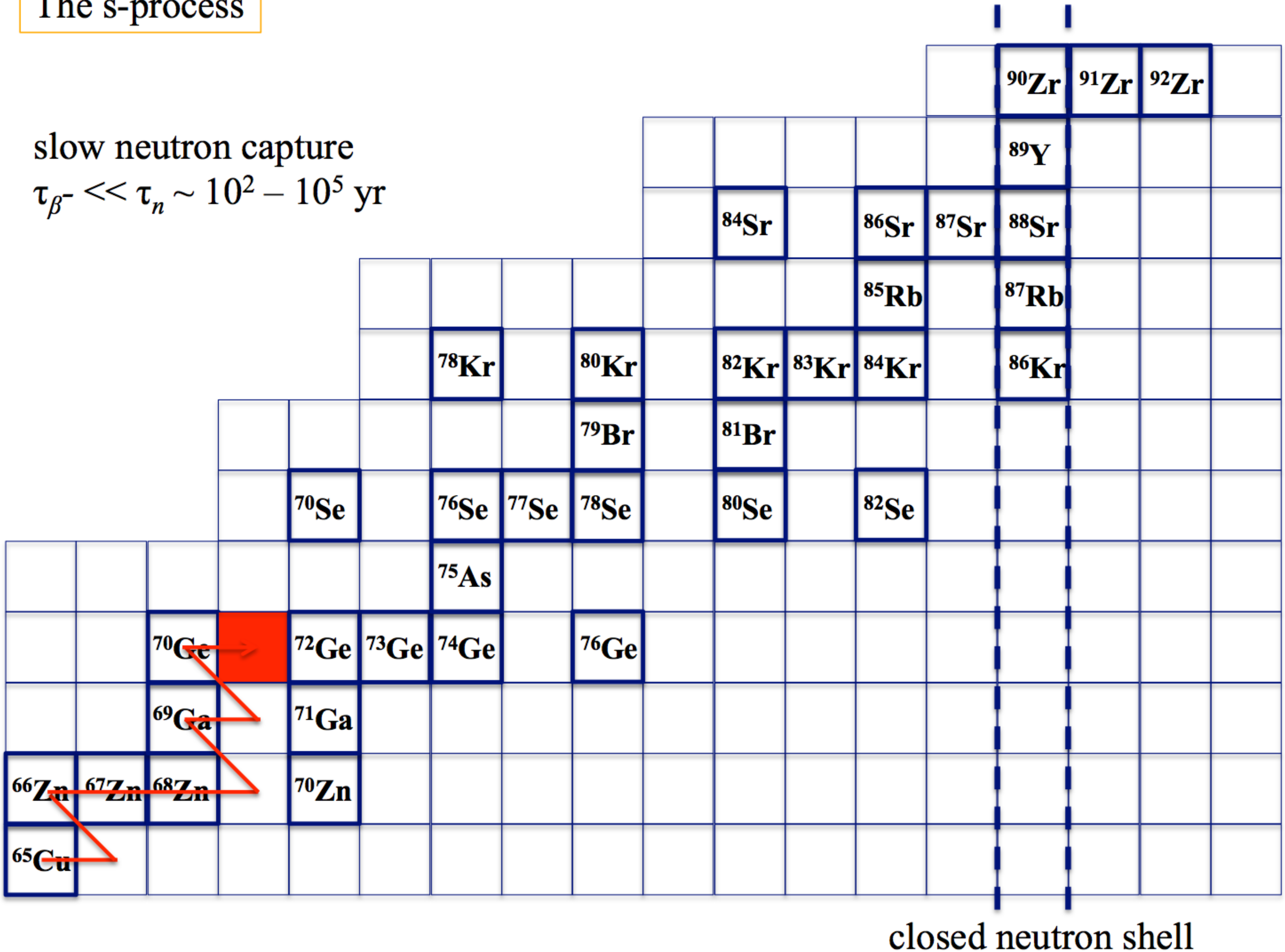
$\tau_{\beta^-} << \tau_n \sim 10^2 - 10^5$ yr



# The s-process

slow neutron capture

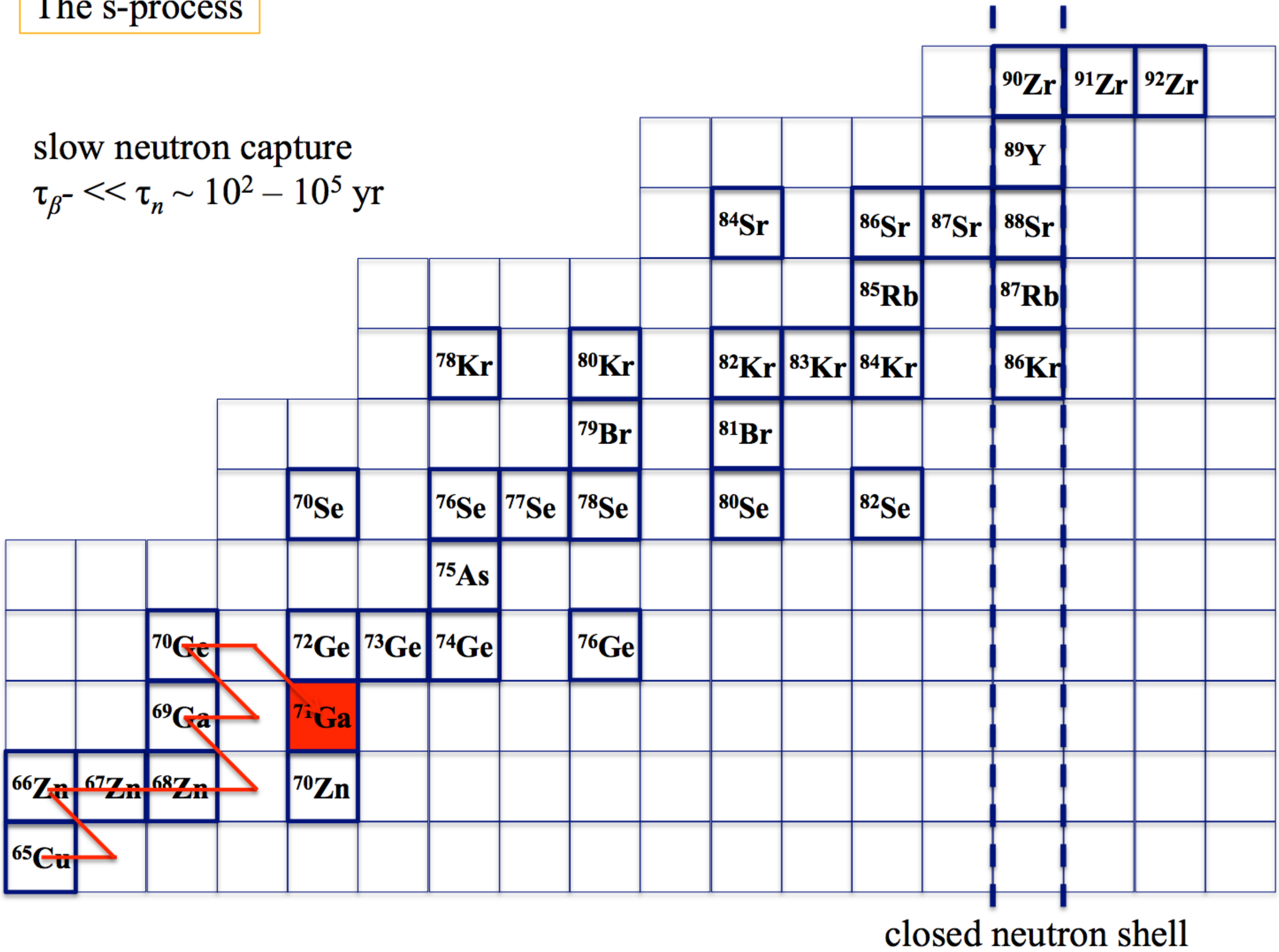
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



# The s-process

slow neutron capture

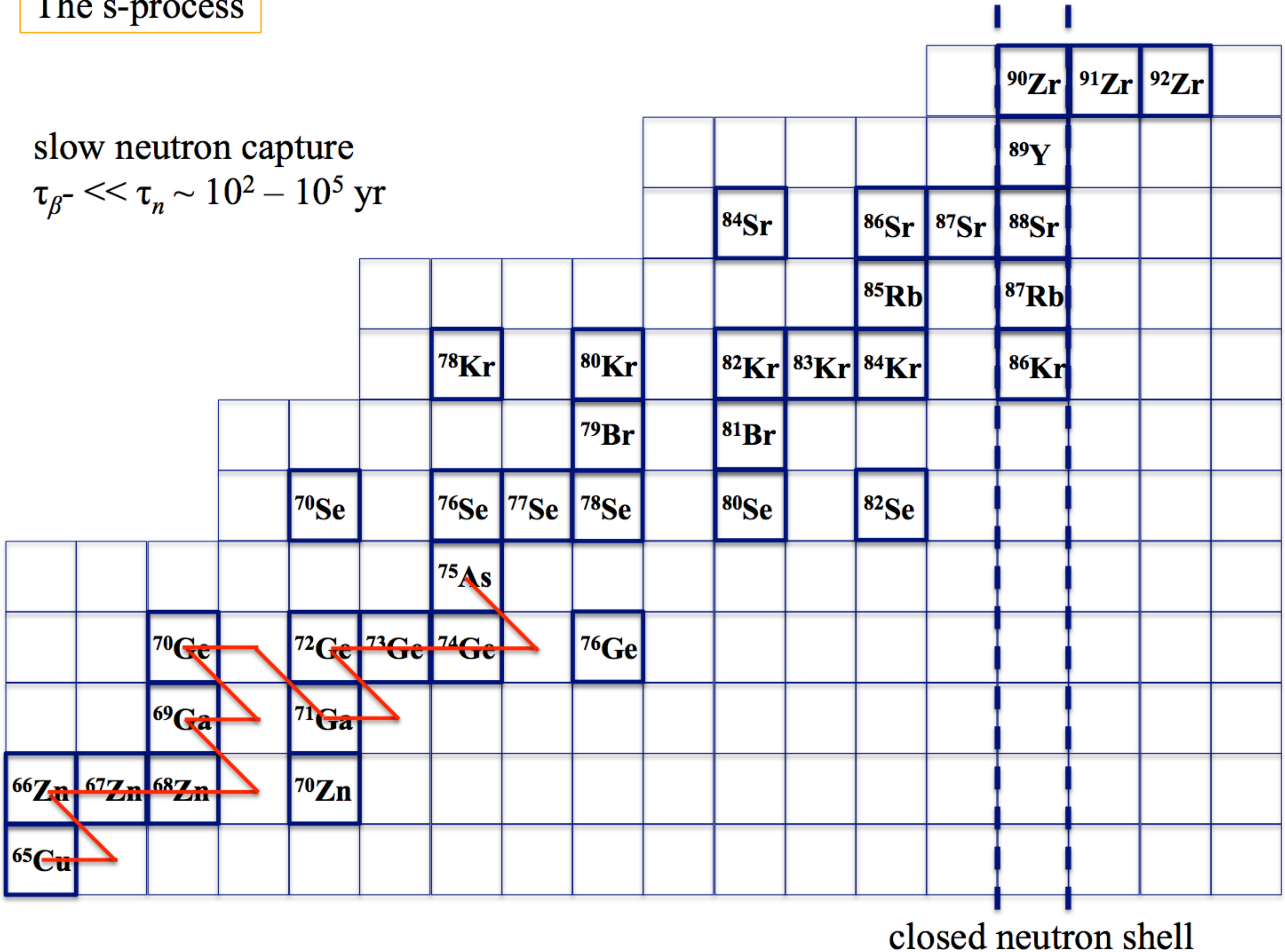
$\tau_{\beta^-} << \tau_n \sim 10^2 - 10^5$ yr



## The s-process

slow neutron capture

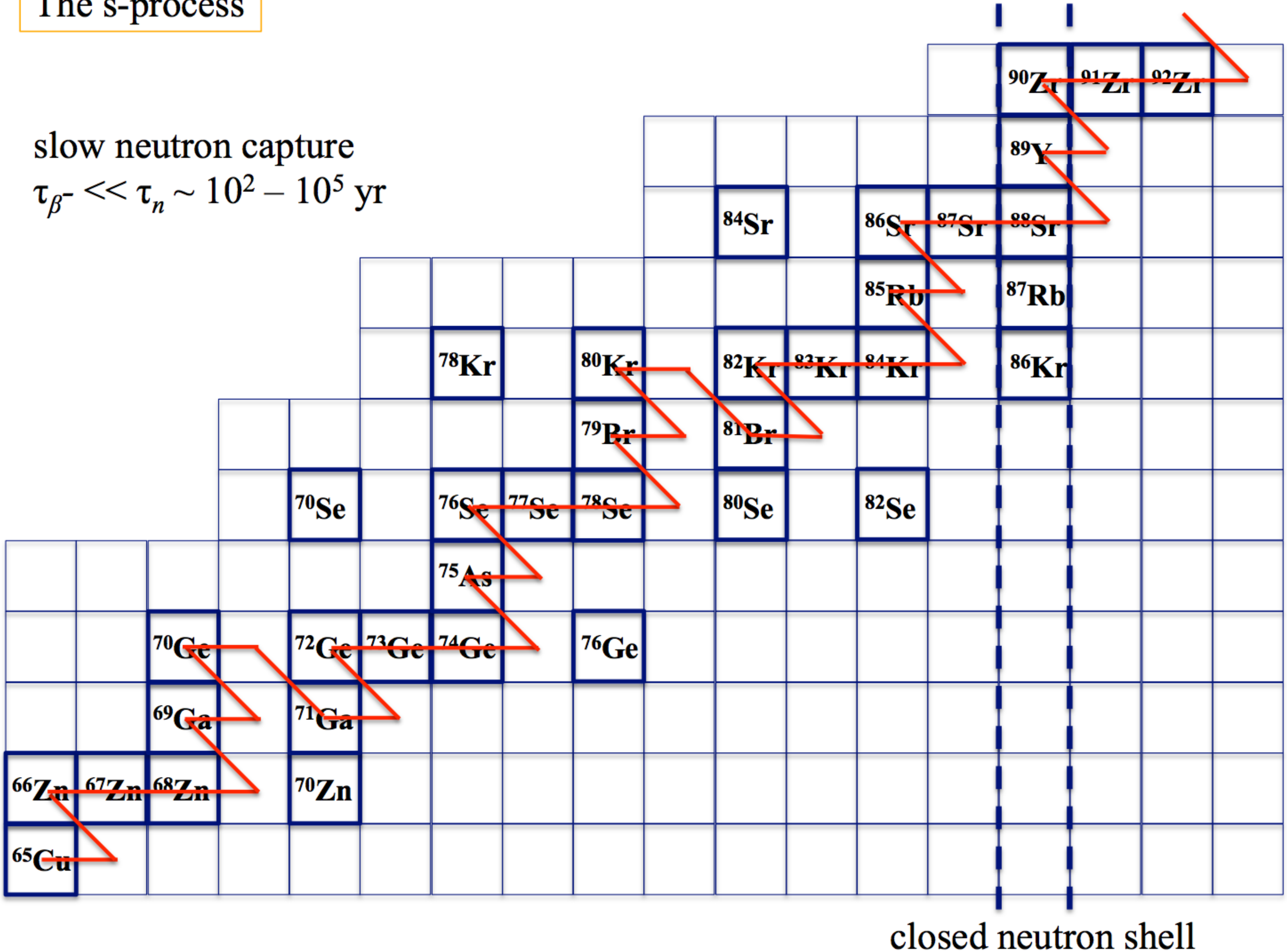
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



The s-process

slow neutron capture

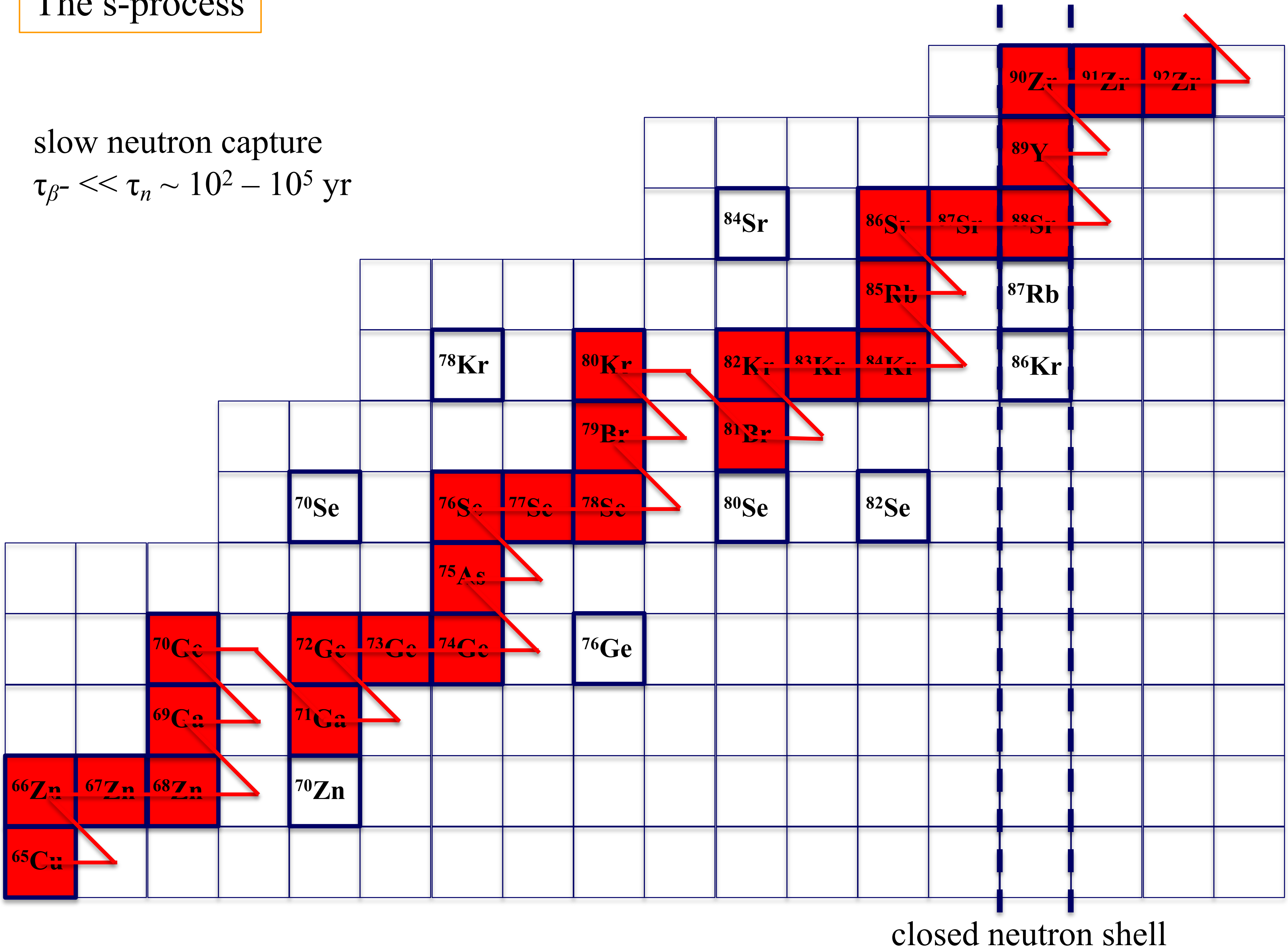
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



# The s-process

slow neutron capture

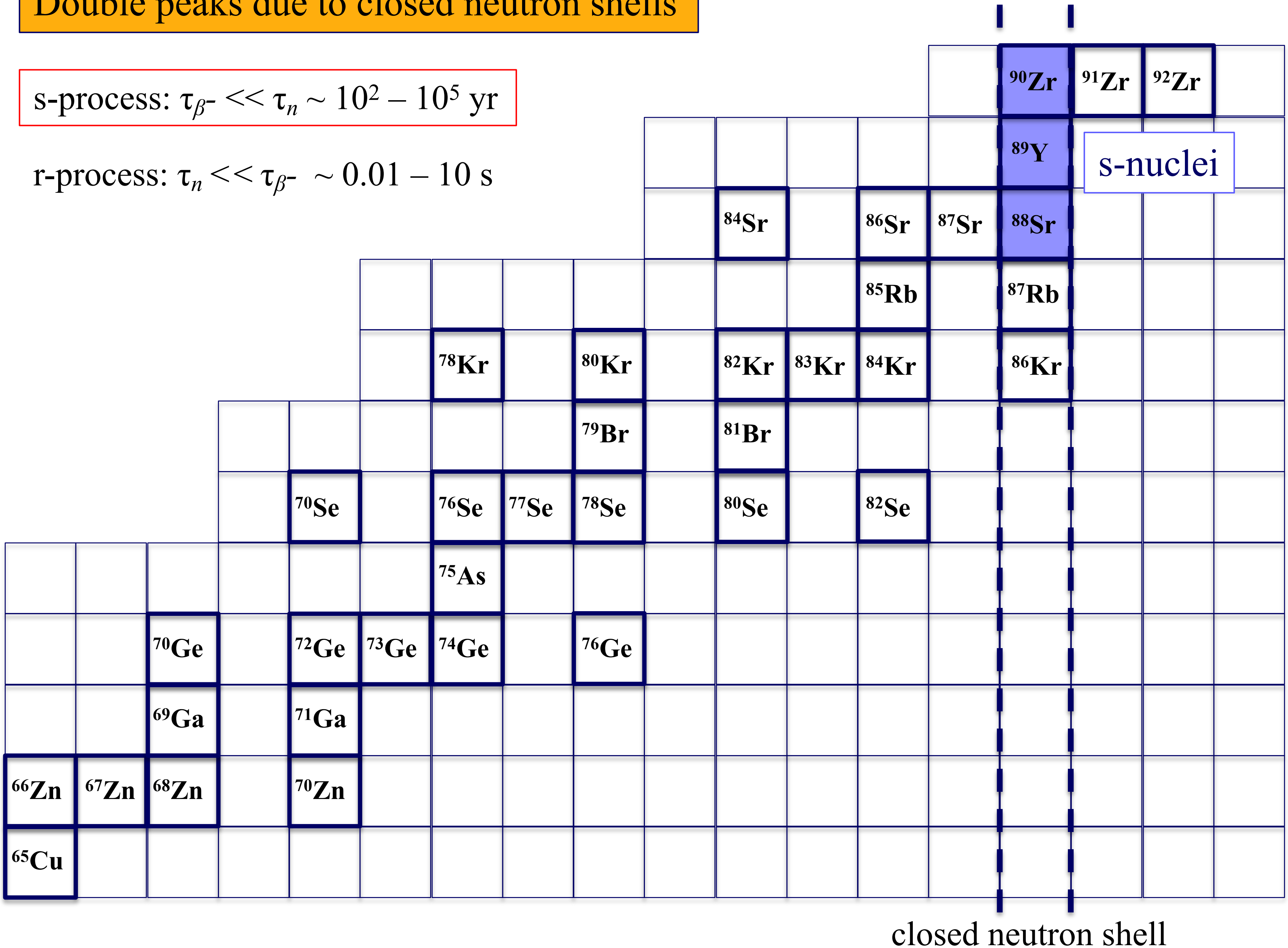
$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



# 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



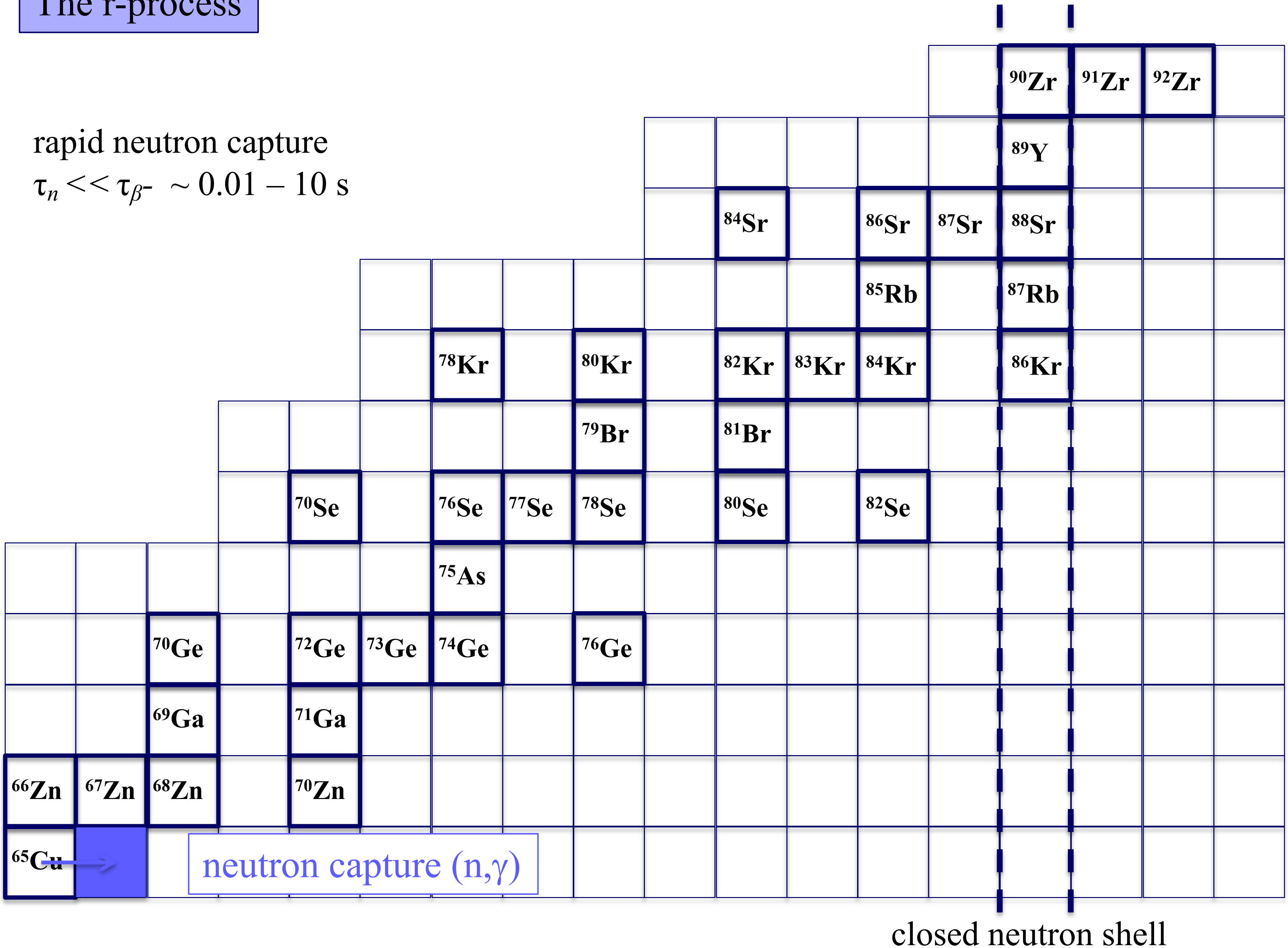
# r-過程

rapid neutron capture process
(r-process)

# The r-process

rapid neutron capture

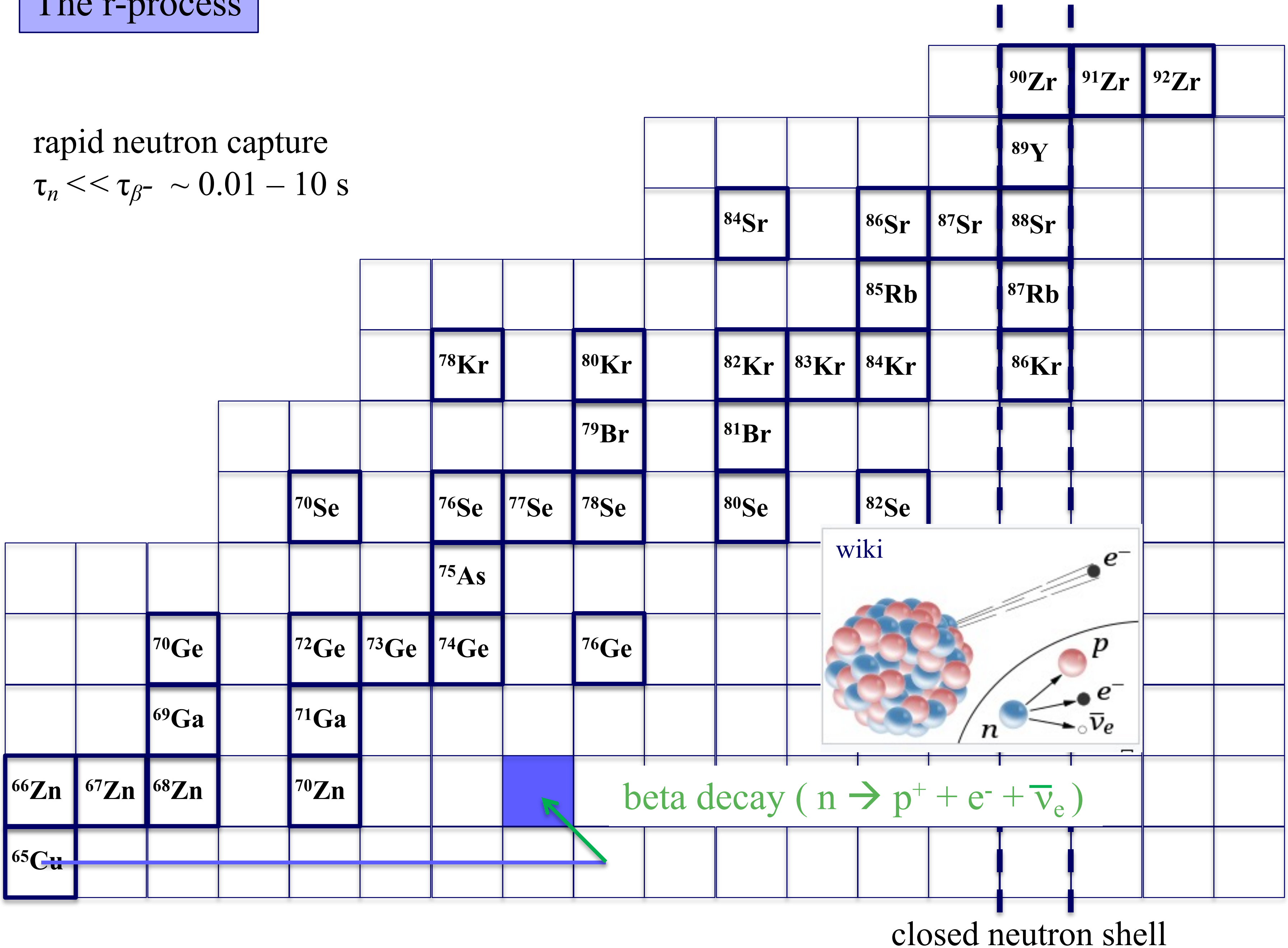
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



# The r-process

rapid neutron capture

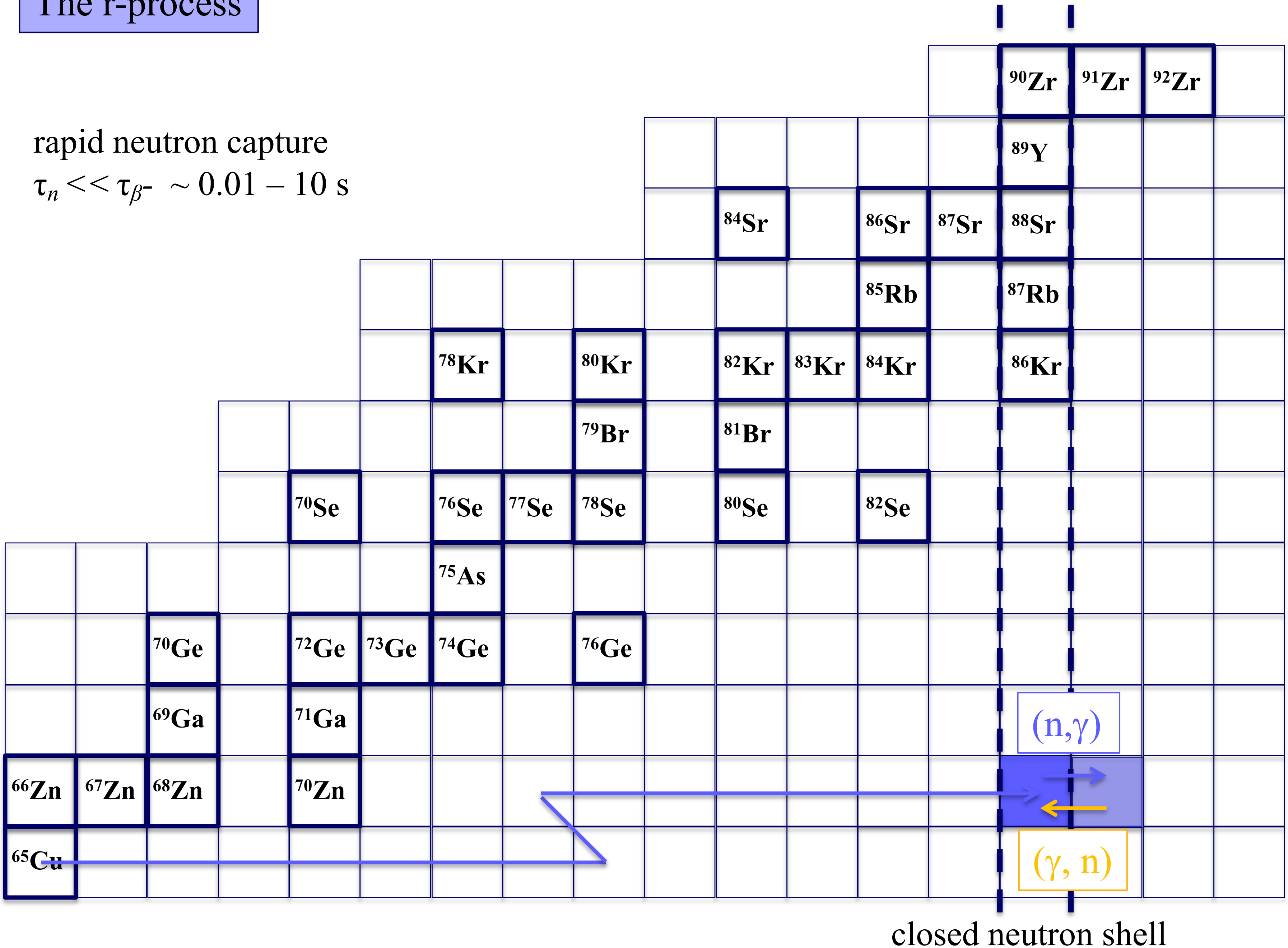
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



# The r-process

rapid neutron capture

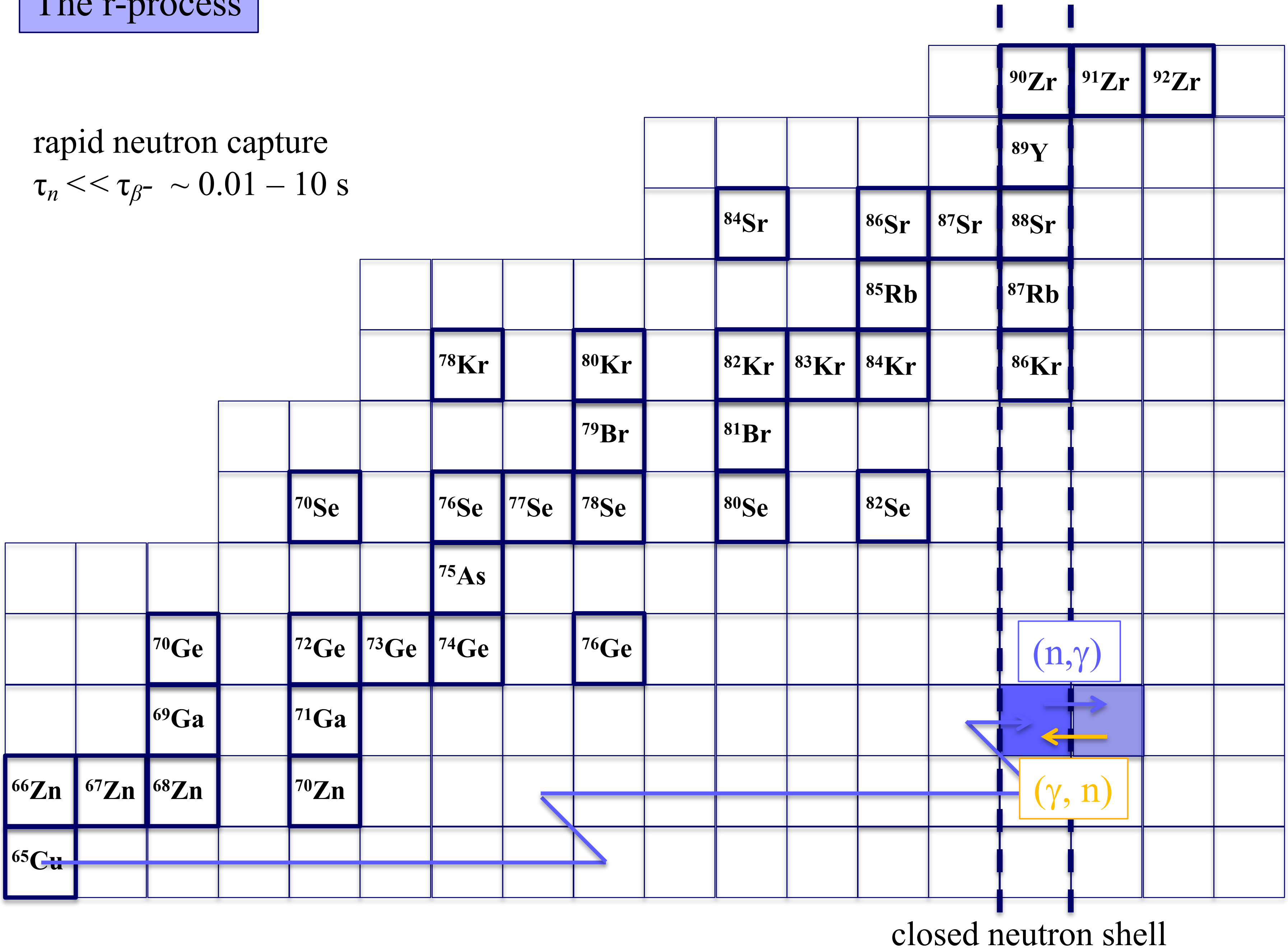
$\tau_n << \tau_{\beta^-}$ ~ 0.01 – 10 s



# The r-process

rapid neutron capture

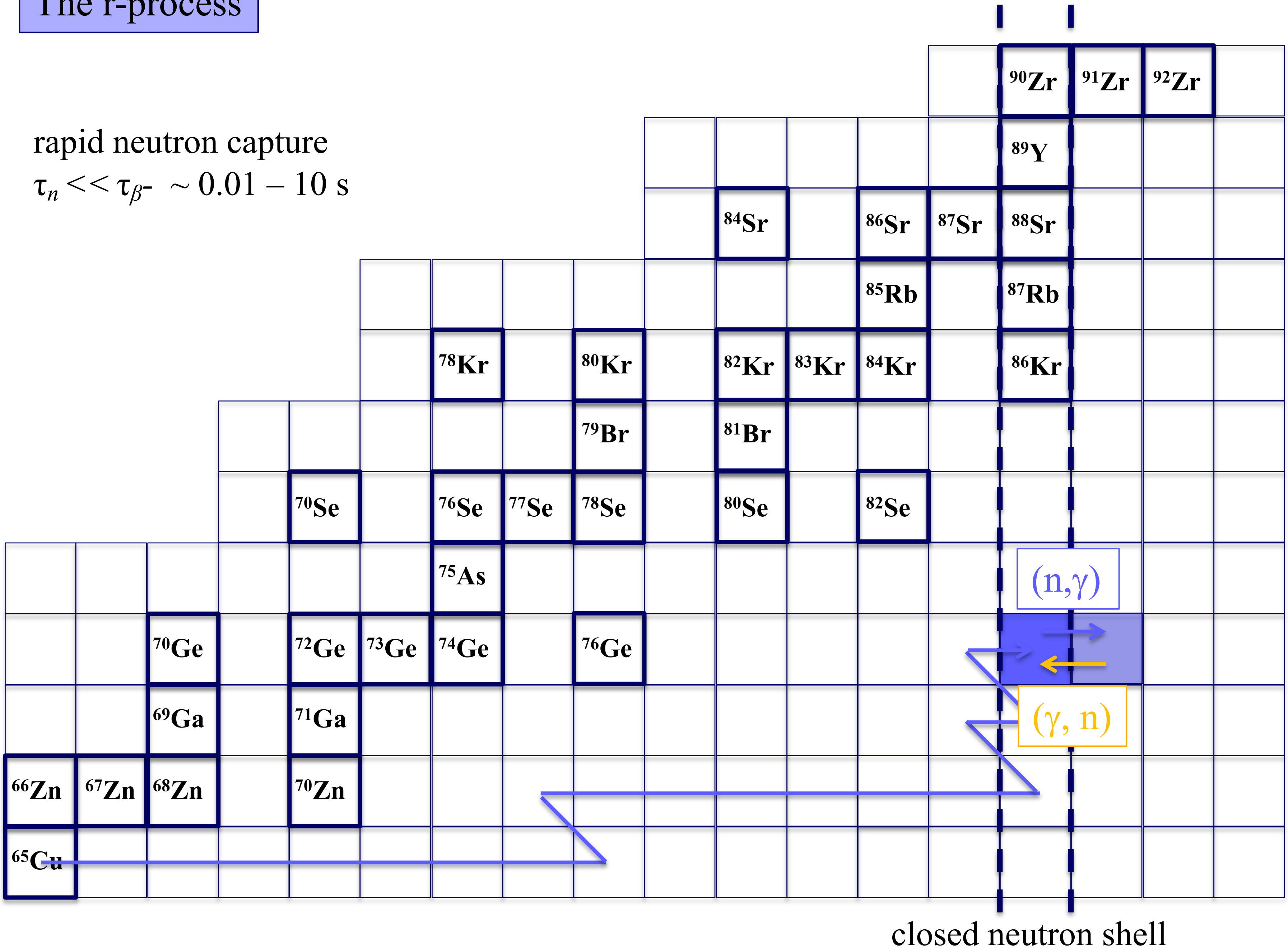
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



# The r-process

rapid neutron capture

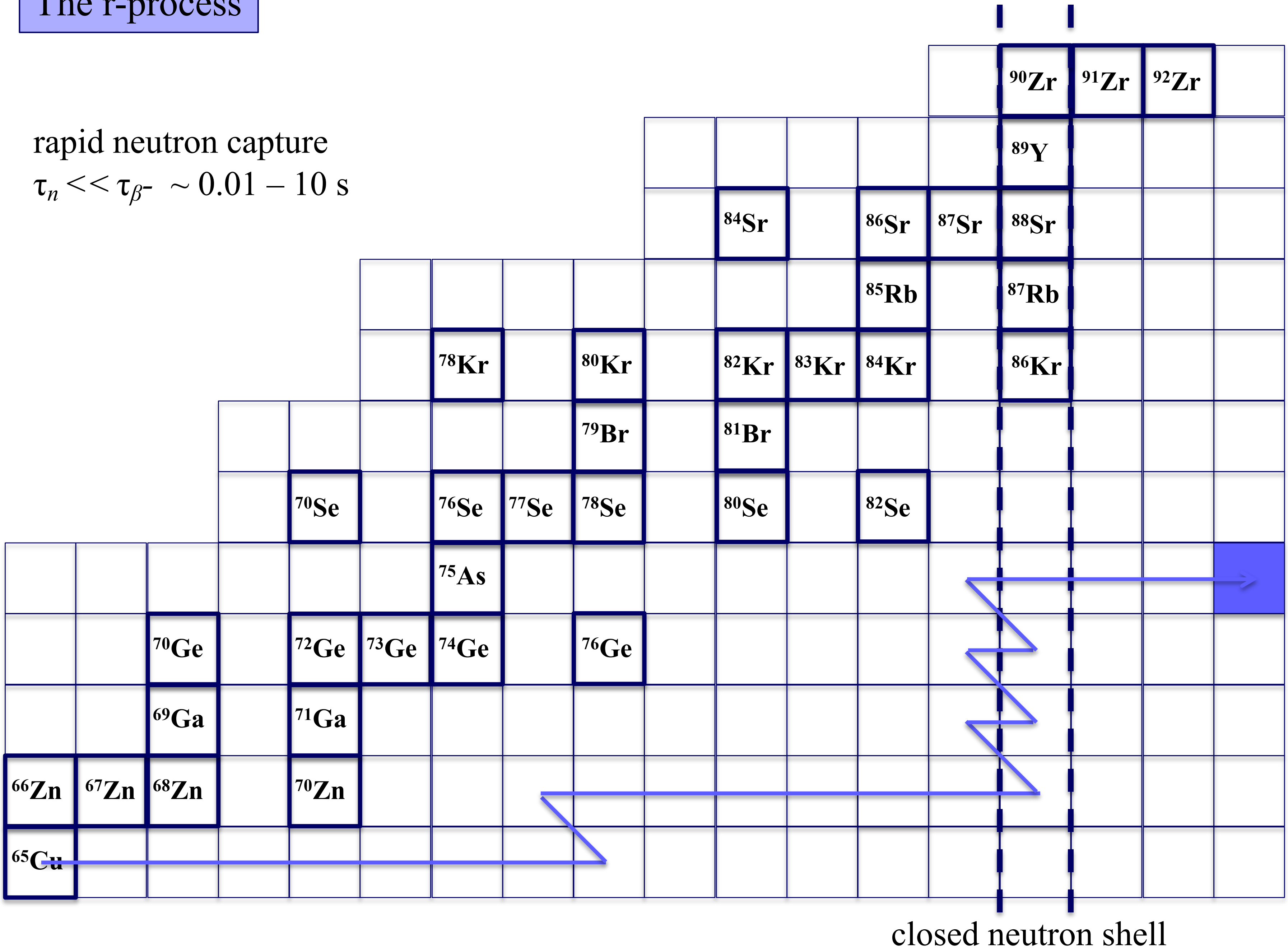
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



# The r-process

rapid neutron capture

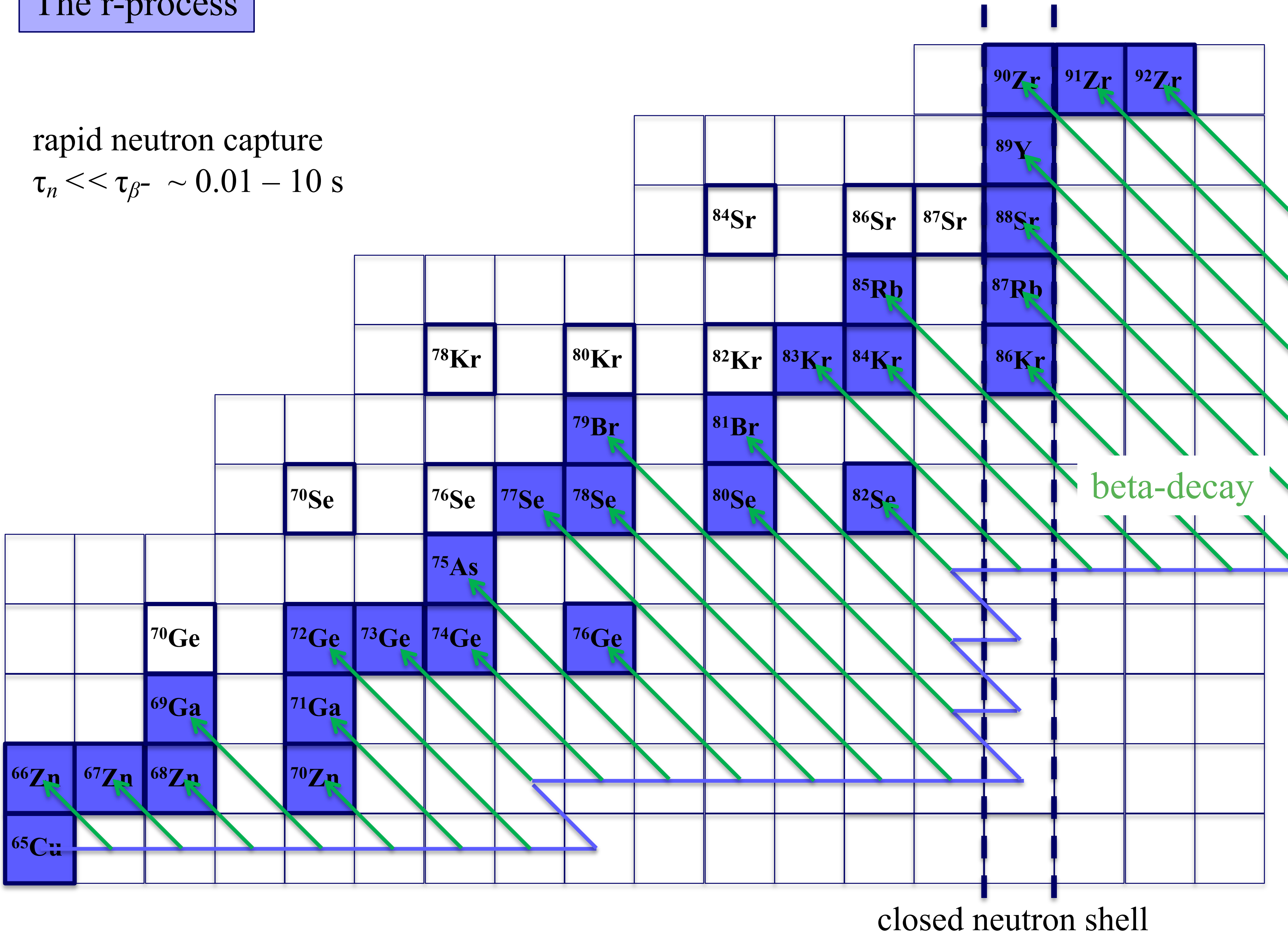
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



# The r-process

rapid neutron capture

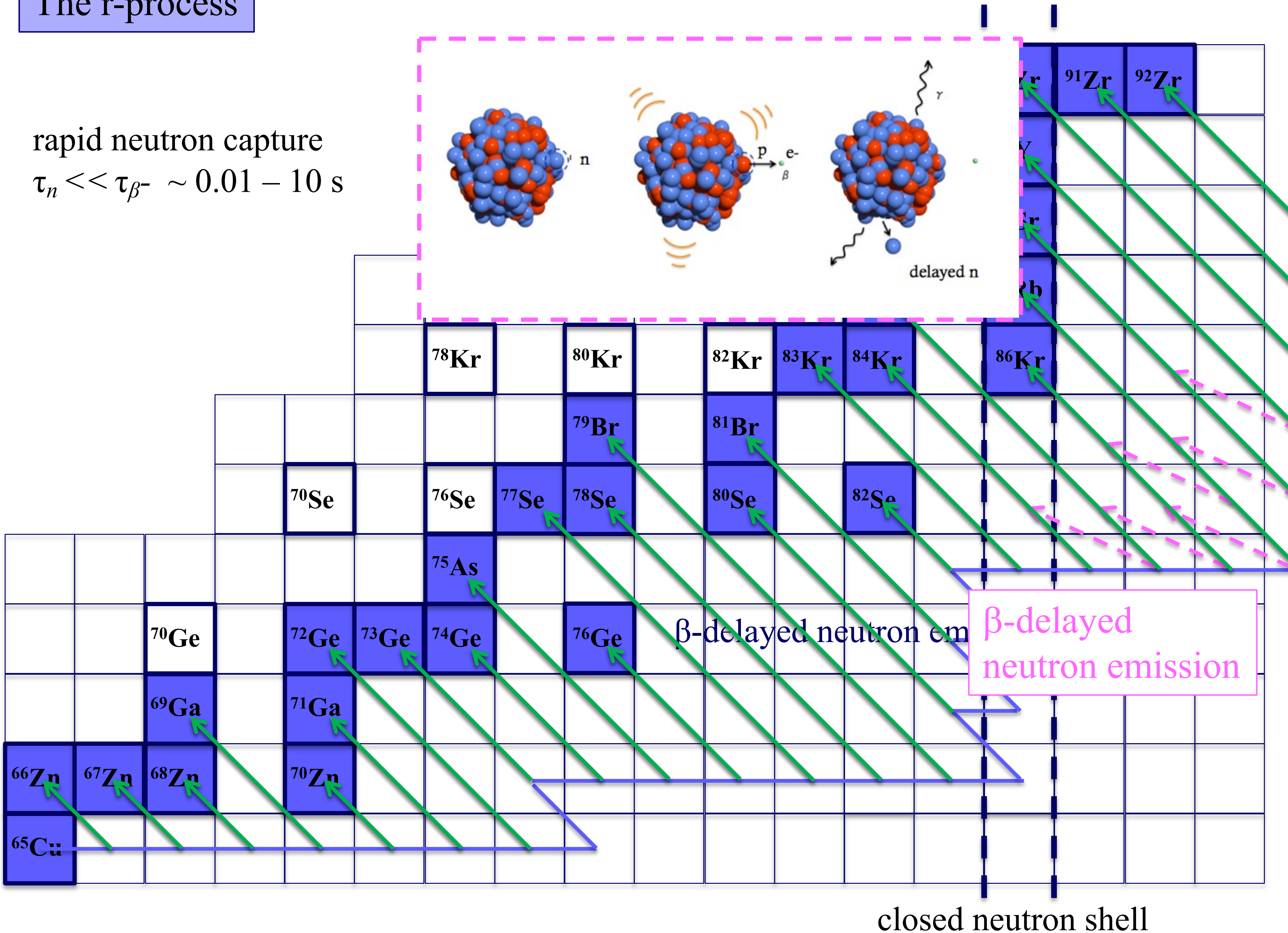
$\tau_n << \tau_{\beta^-} \sim 0.01 - 10$ s



# The r-process

rapid neutron capture

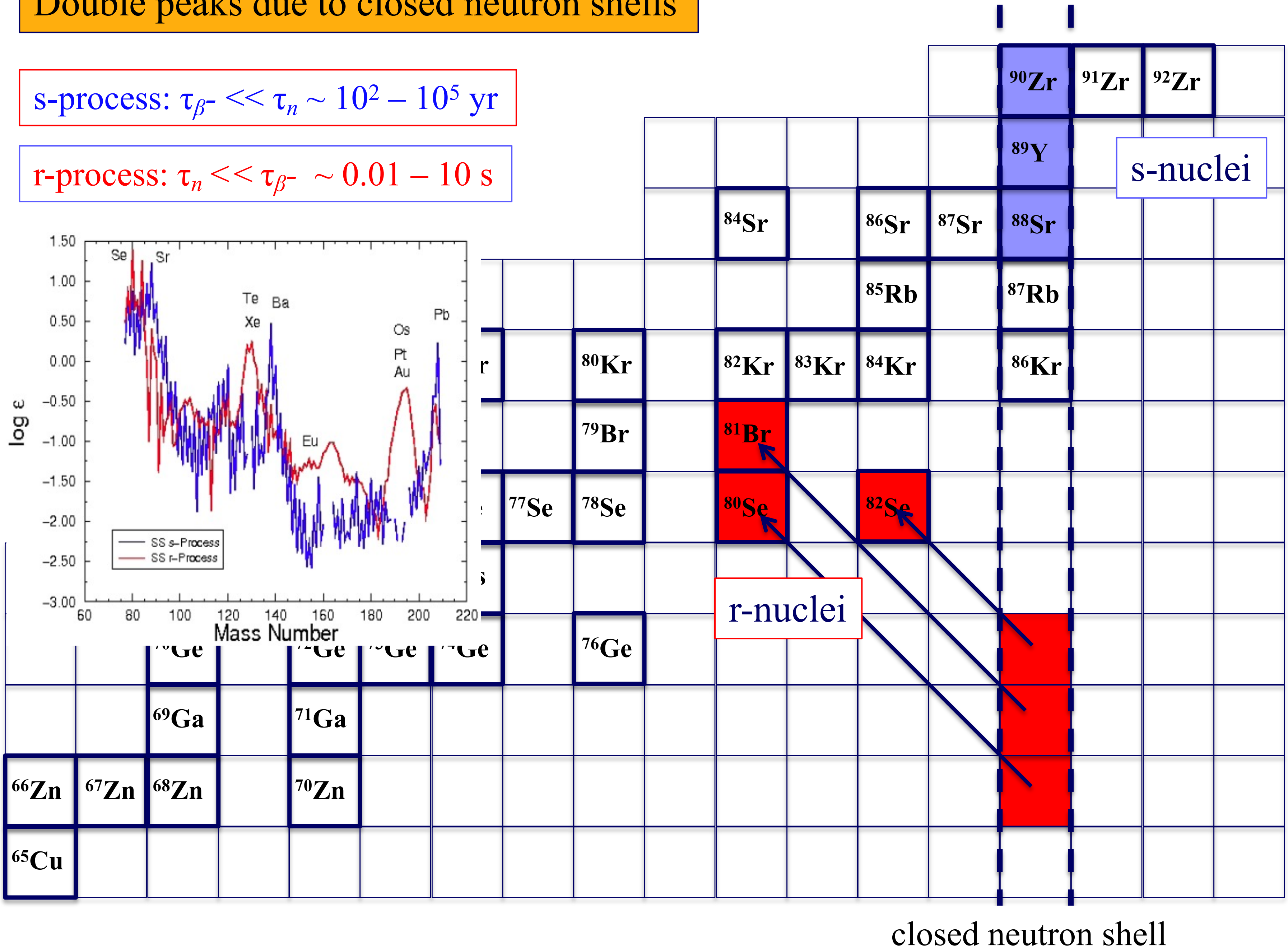
$\tau_n << \tau_{\beta\text{-}} \sim 0.01 - 10$ s



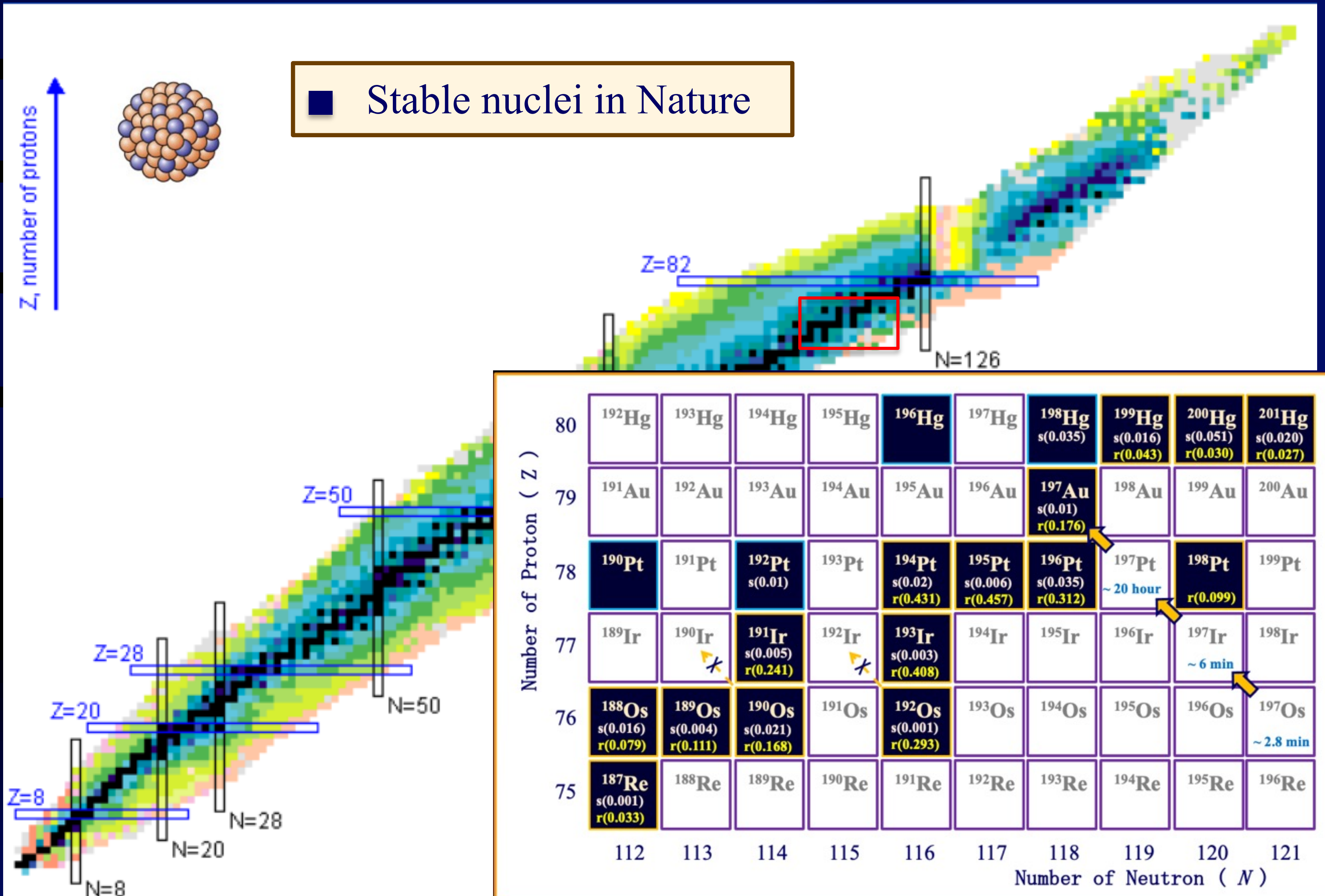
# Double peaks due to closed neutron shells

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

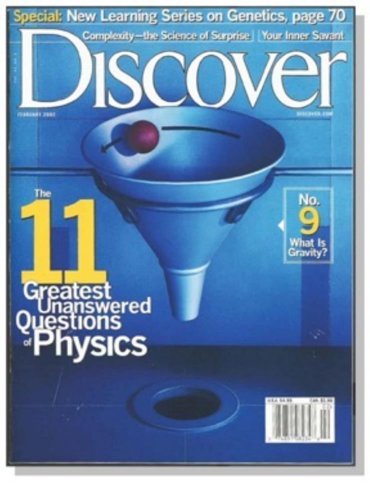


# Production of Gold in r-Process




**Production of Gold via beta-decay: * → * → $^{197}$Os → $^{197}$Ir → $^{197}$Pt → $^{197}$Au**

# 11 Greatest Unanswered Questions in Physics




1. What is dark matter ?
2. What is dark energy ?
3. How were the heavy elements from iron to uranium made?
4. Do neutrinos have mass ?
5. What do ultra-energy particles come from ?
6. Is a new theory of light and matter needed to explain what happen at very high energies and temperatures ?
7. Are there new states of matter at ultrahigh temperatures and densities ?
8. Are protons unstable ?
9. What is gravity ?
10. Are there additional dimensions ?
11. How did the Universe begin ?

Physics in
Extreme Environments

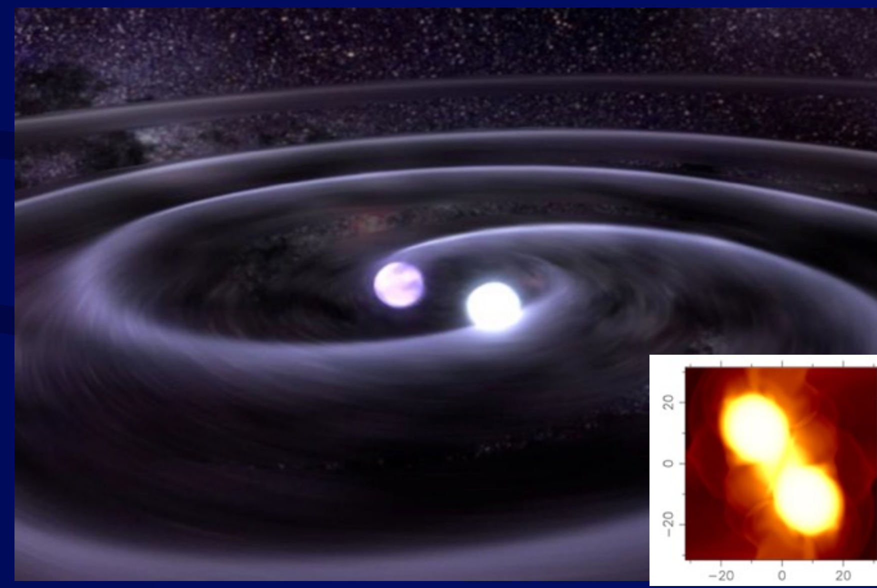
# Sites of r-Process Candidates

**Supernova（Mass > 8 x Mass (Sun) ）**


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

- Frequent events
- Issue in Explosion of Supernovae
- Lack of Neutrons
- Special supernovae with strong magnetic field ?

**Binary Neutron Star Merger (Neutron Star + Black Hole)**

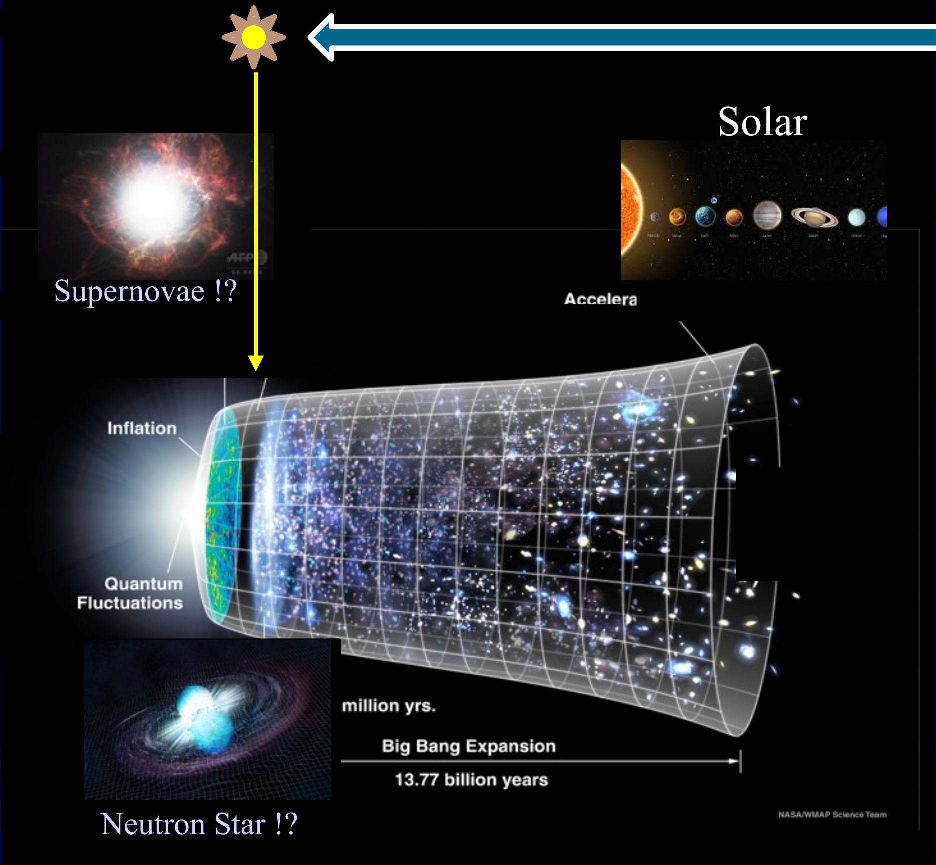



S. Wanajo

- A lots of neutrons
- Rare events
- It takes time to make collisions

# Finding Old Star in Early Universe

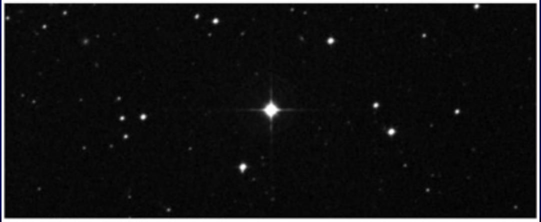
Single r-Process Event !?



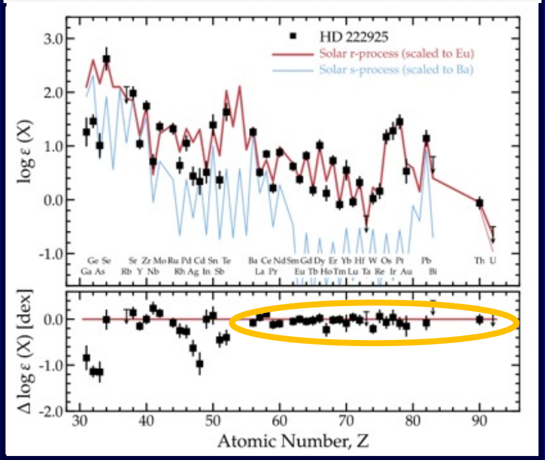

Hubble Space Telescope

Subaru Telescope

"gold standard" Metal Poor Star




I. Roederer, et al. (2022)



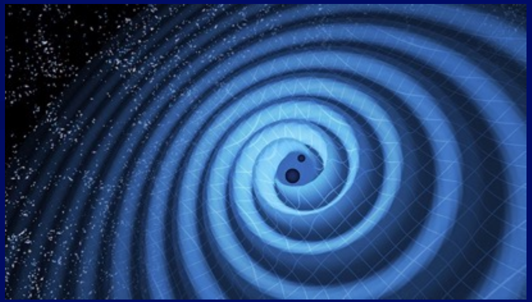

Paranal Observatory

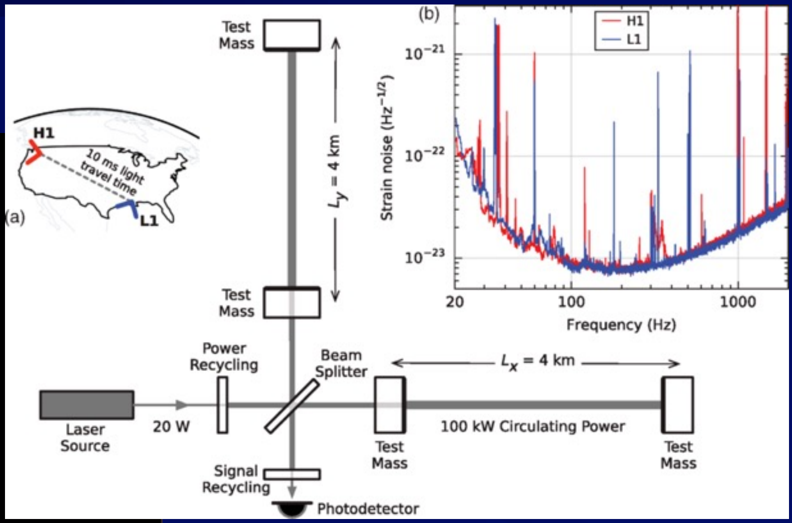
SkyMapper

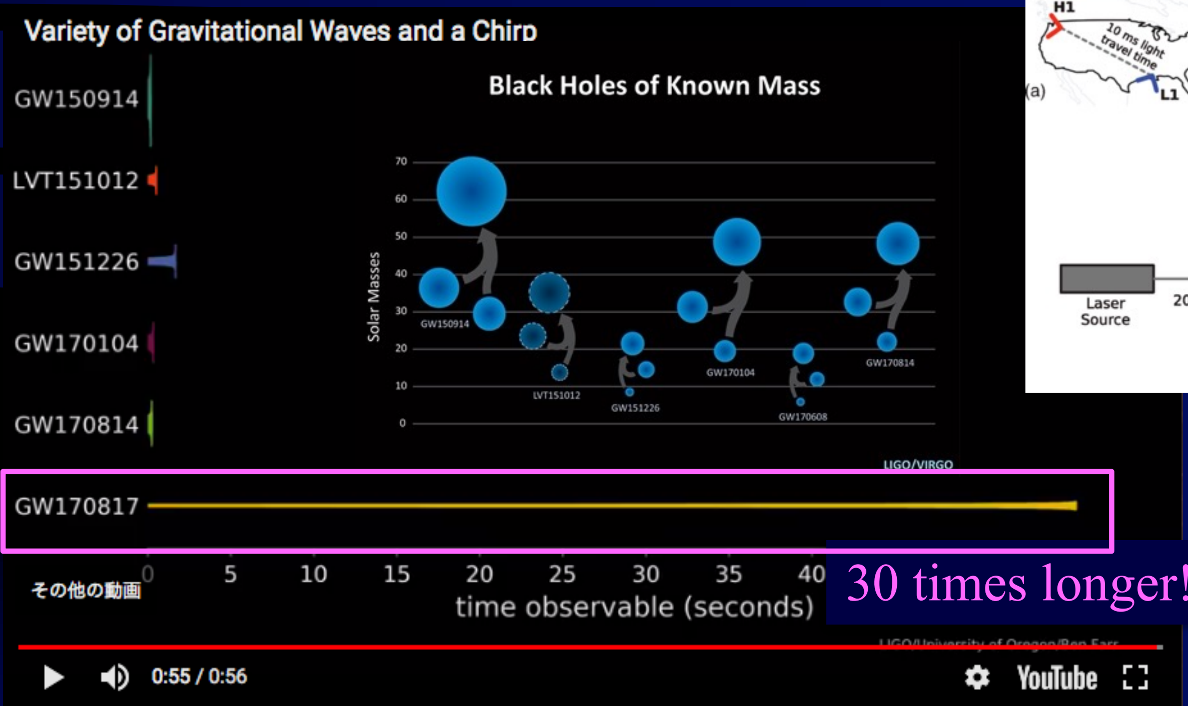
**Very Similar Elemental Abundance Pattern**

**Determined by Nuclear Properties!?**

# Violent Site in Universe
# 【 Binary Star Merger 】





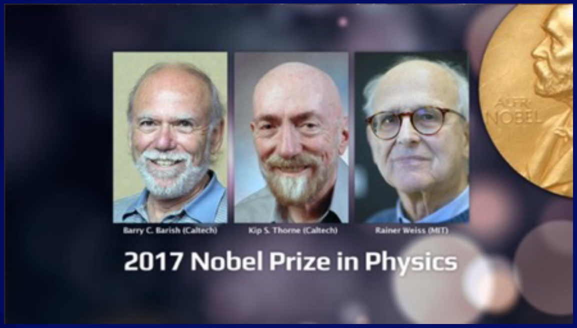




30 times longer!

## Variety of Gravitational Waves

The signal measured by LIGO and Virgo from the neutron star merger GW170817 is compared here to previously detected binary black hole mergers. All signals are shown starting at 30 Hertz, and the progression of GW170817 is shown in real time, accompanied by its conversion to audio heard at the end of the movie. GW170817 was observable for more than 30 times longer than any previous gravitational-wave signal.

Credit: LIGO/University of Oregon/Ben Farr

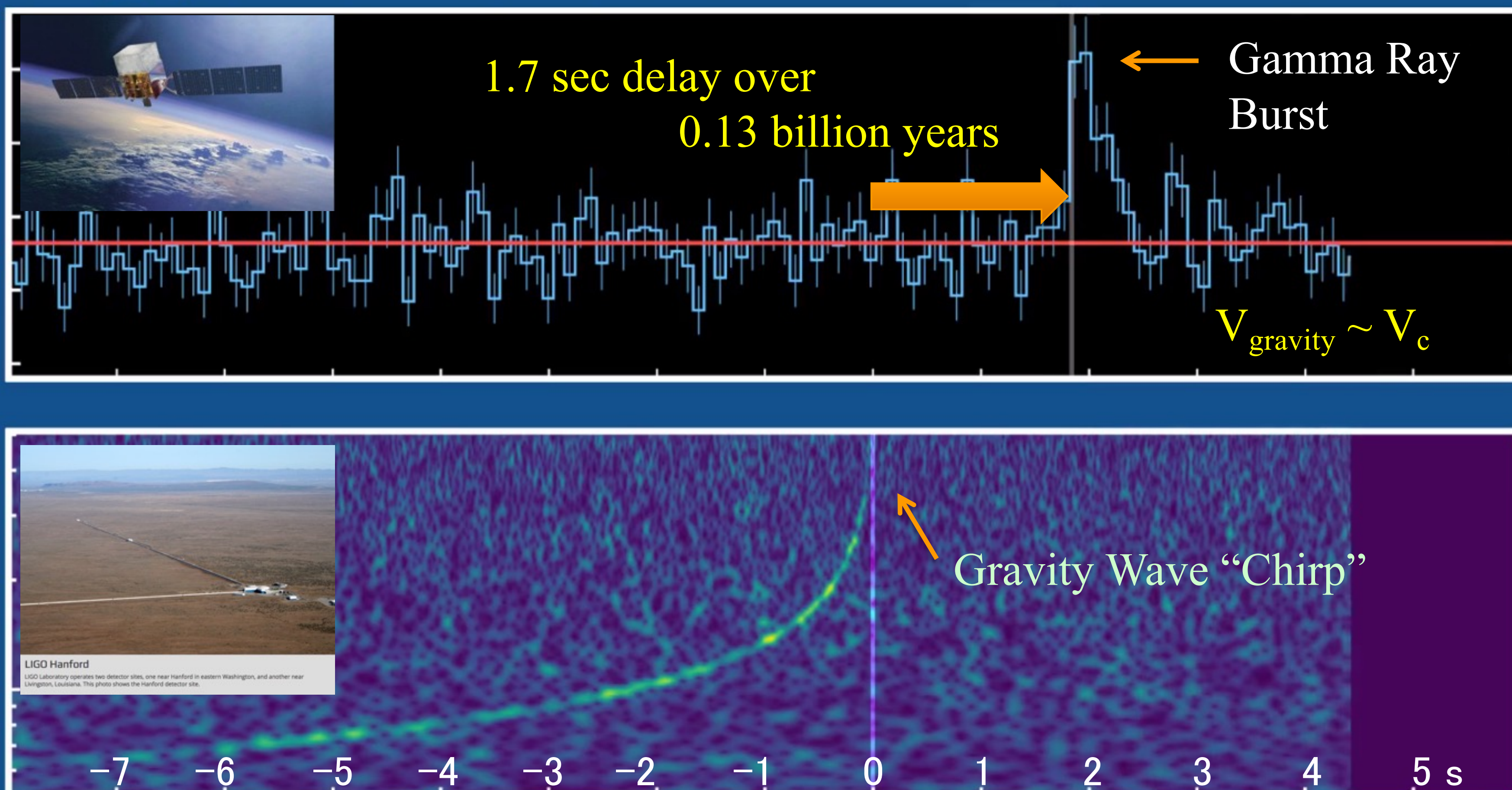



Merger of Two Black Holes: GW150914

# Discovery of Neutron Star Merger !　(GW170817)

Aug. 17, 2017

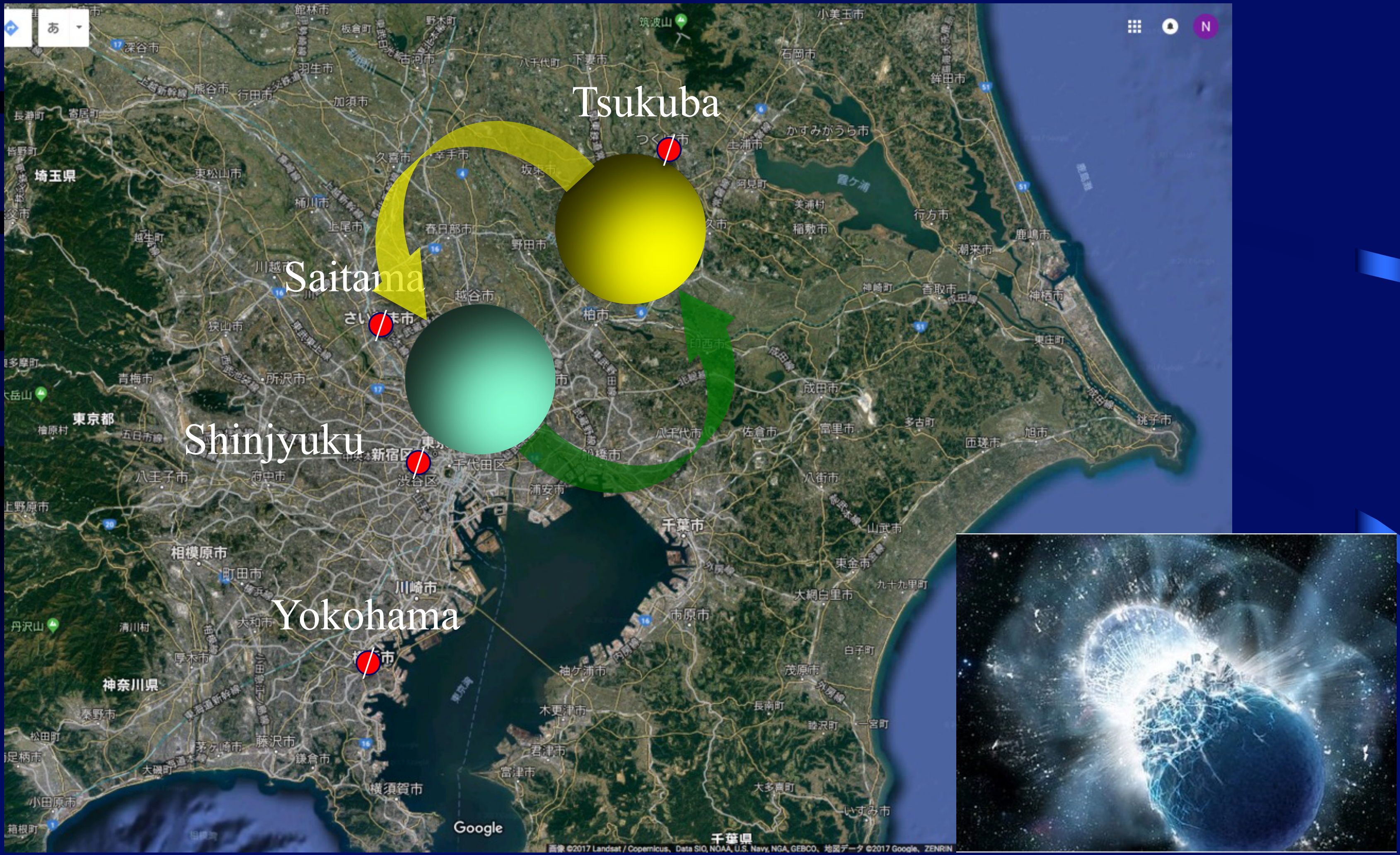
Fermi (light) GRB170817A




LIGO (gravitational waves)

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

# Neutron Star Merger : Scale



# Where & How the Rare-Earth Elements are Synthesized !?

nuclear decay heat

## [ Astrophysics Observation ]

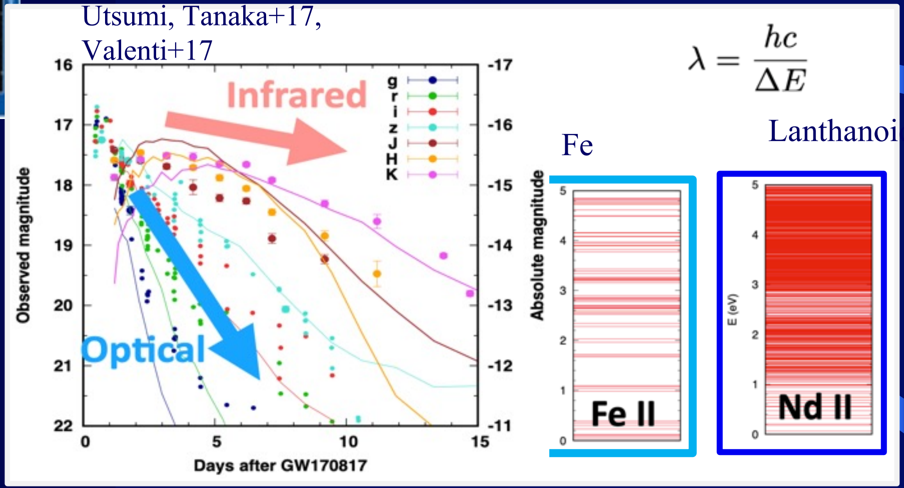
High neutron density environment

- **Site of r-process**

Neutron Star Merger (NS-NS, NS-BH)

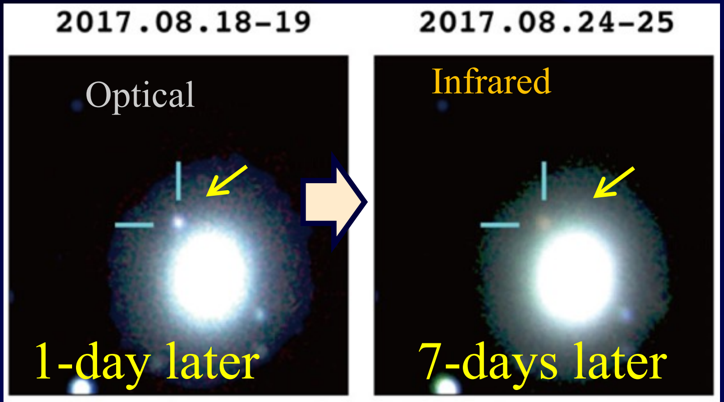

Supernovae

Kilonova is expected & observed !




- **Observation of electromagnetic wave**

Site of GW170817




Infrared indicates the synthesis of lanthanoid elements in NS-NS collisions

# Coffee Break

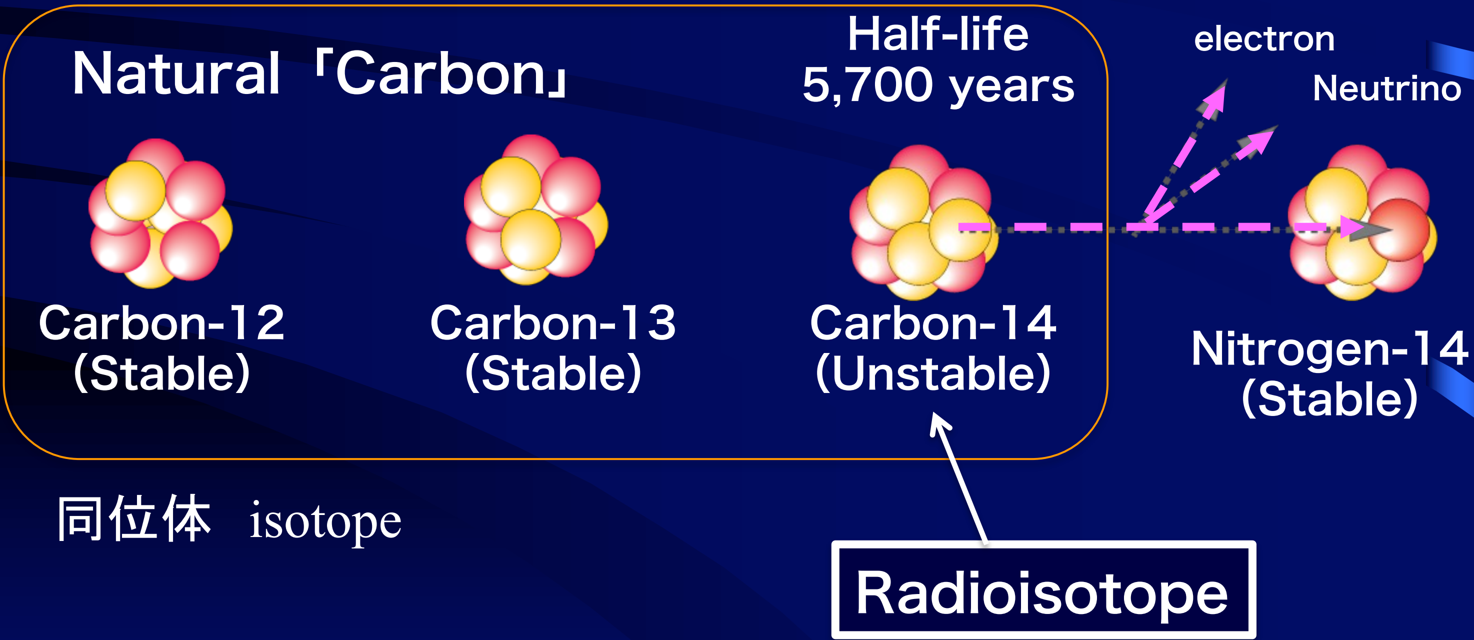
# Dating using Radioisotopes

| | | | | |
|---|---|---|---|---|
| Number of proton | 6 | 6 | 6 | 7 |
| Number of neutron | 6 | 7 | 8 | 7 |

Photo by S. Yamashita, National Geog.

西暦774-775年

$^{14}$C … 1.2 % 増加



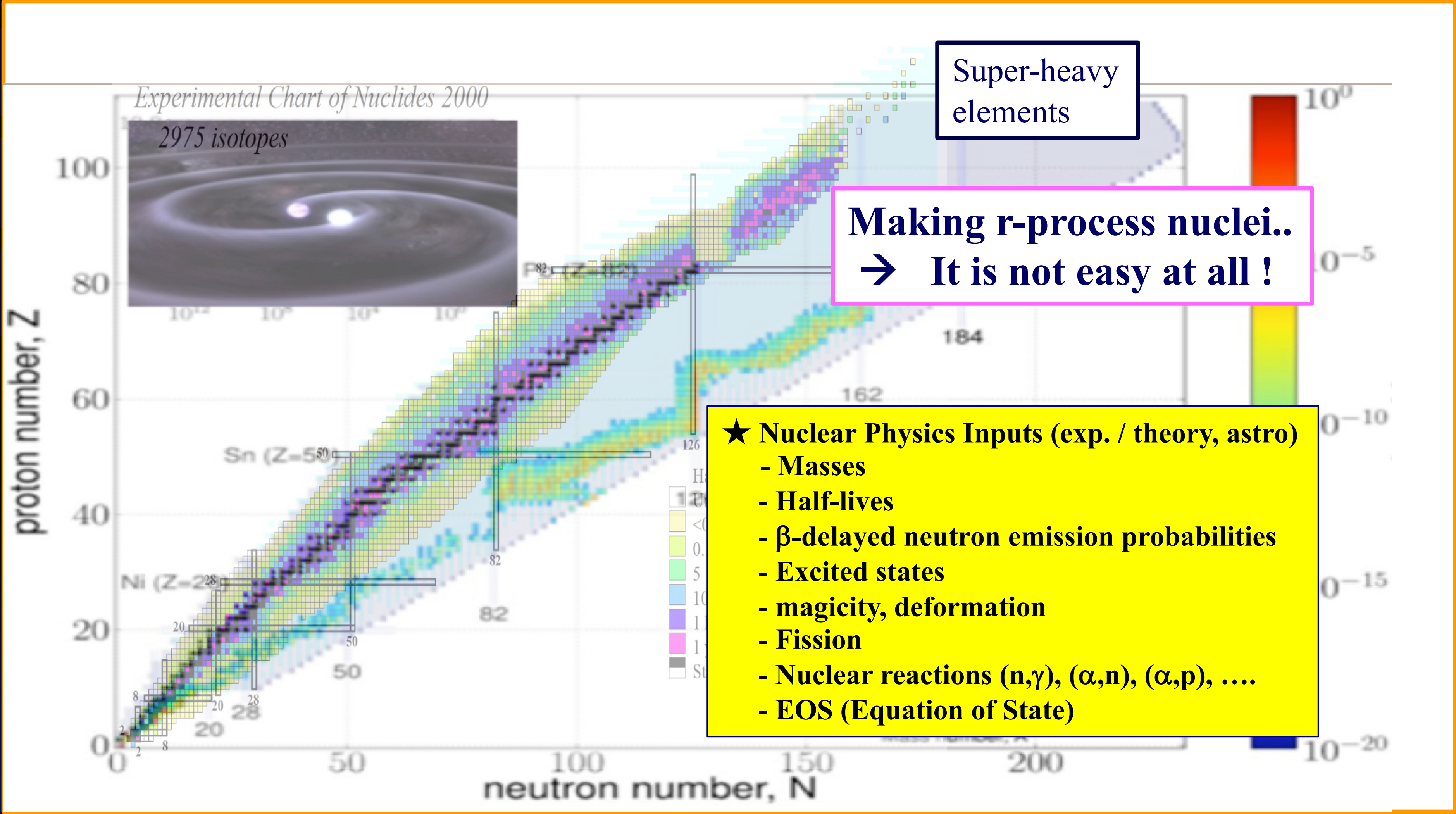

同位体　isotope

# r-過程
# r-Process Nucleosynthesis

Reproduction of r-process Nuclei
(検証実験：  Experiment)

# Nuclei Produced in r-Process
# (Depending on Environment..)

Korobkin 2012



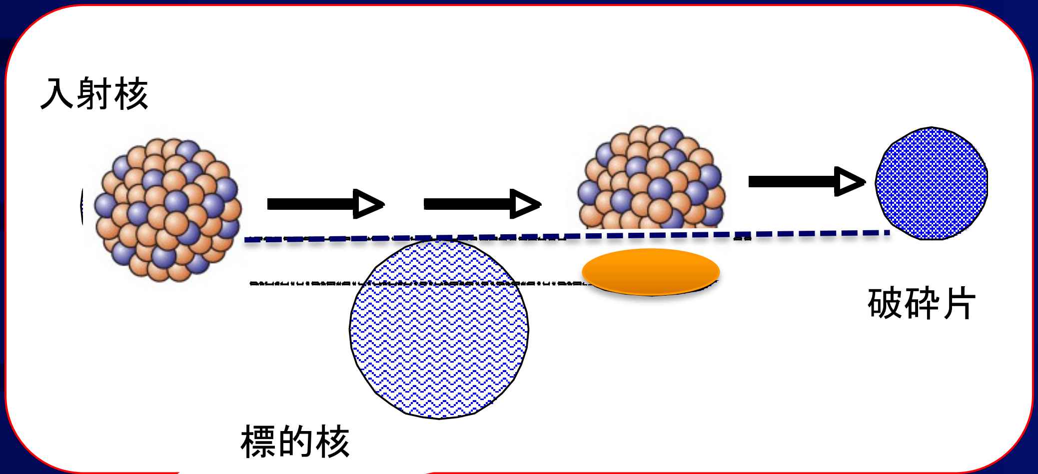

**Making r-process nuclei..**
**→ It is not easy at all !**

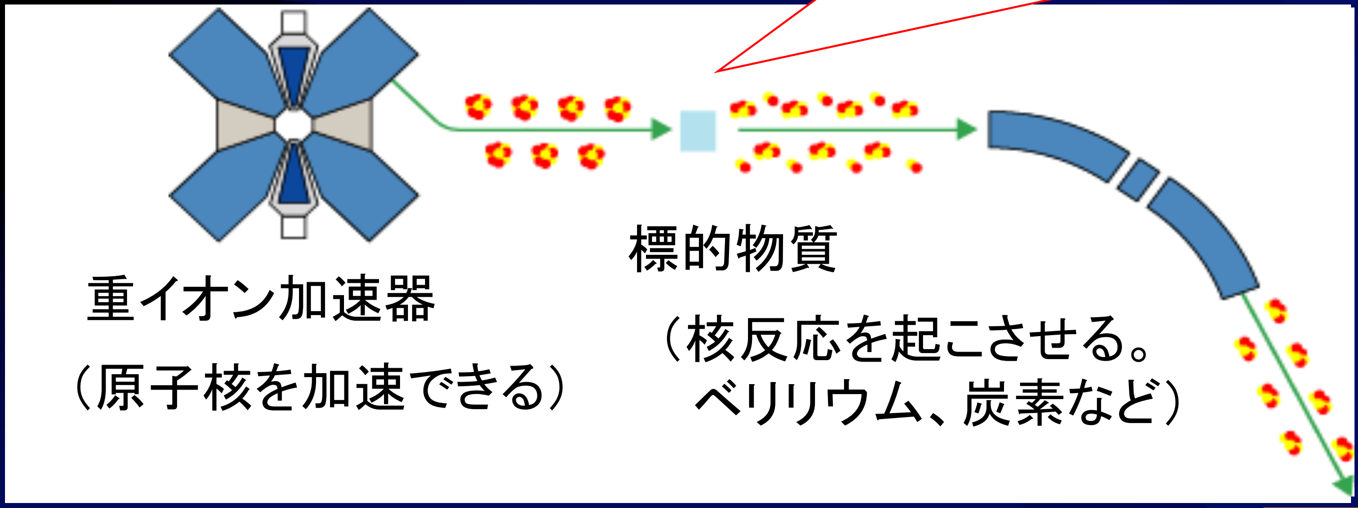
**★ Nuclear Physics Inputs (exp. / theory, astro)**

- **Masses**
- **Half-lives**
- **β-delayed neutron emission probabilities**
- **Excited states**
- **magicity, deformation**
- **Fission**
- **Nuclear reactions (n,γ), (α,n), (α,p), ….**
- **EOS (Equation of State)**

# Make Radioisotopes (RI Beam)

**Make**
**Various Nuclei（Z，N）**

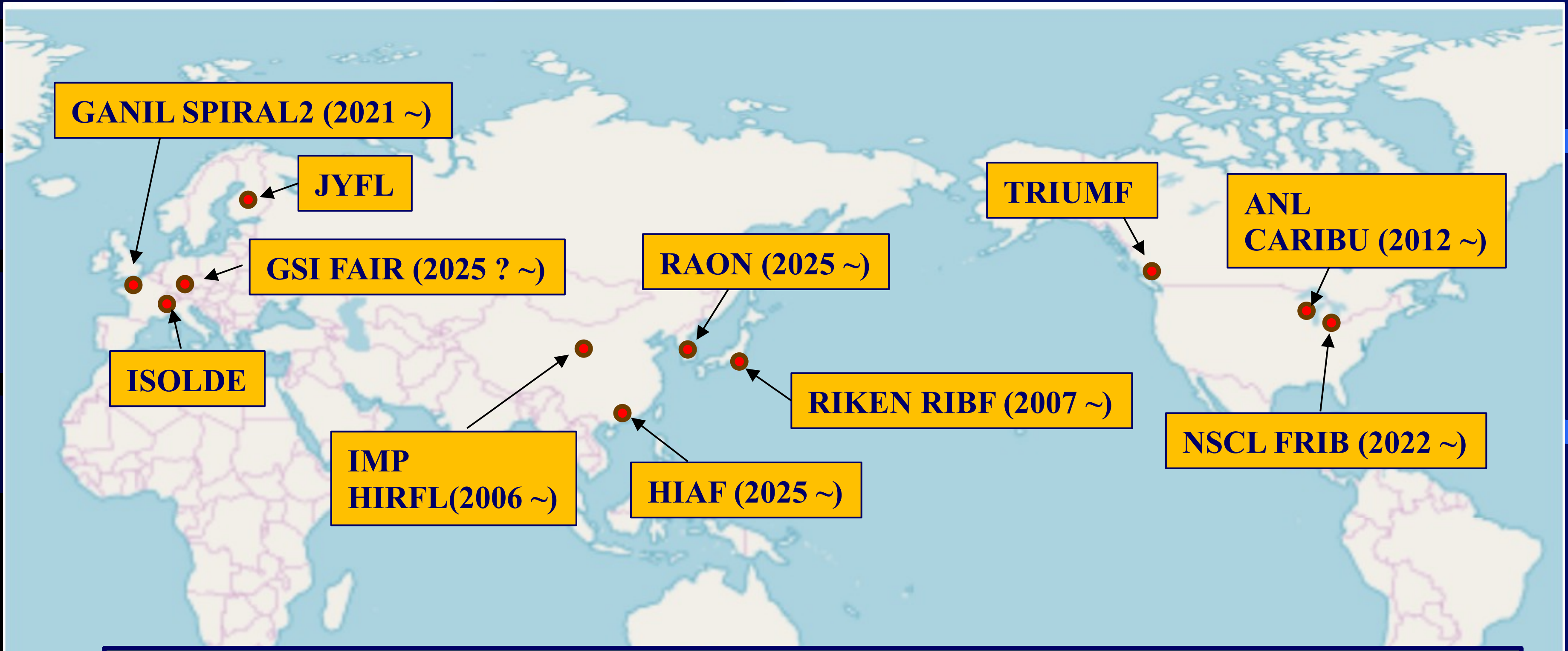



Selection of Isotopes by magnets

Radioactive Isotopes

# Radioactive Isotope Beam Facilities in the World




1980s: First generation RI beam facilities
Early 2000s: Plans for new generation facilities
2007 - : Radioactive Isotope Beam Factory (RIBF) @ RIKEN (Japan)
2022 - : FRIB @ MSU (USA)
~ 2025 - : HIAF (China), FAIR (Germany), RAON (Korea)

# Radioactive Isotope Beam Facility in Your Country !?

Nature

The world this week

**News in focus**

# LONG-AWAITED ACCELERATOR READY TO EXPLORE ORIGINS OF ELEMENTS

**The Facility for Rare Isotope Beams will be the first to produce and analyse hundreds of isotopes crucial to physics.**

**By Davide Castelvecchi**

One of nuclear physicists' top wishes is about to come true. After a decades-long wait, a US$942-million accelerator in Michigan officially opened on 2 May. Its experiments will chart unexplored regions of the landscape of exotic atomic nuclei and shed light on how stars and supernova explosions create most of the elements in the Universe.

"This project has been the realization of a dream of the whole community in nuclear physics," says Ani Aprahamian, an experimental nuclear physicist at the University of Notre Dame in Indiana. Kate Jones, who studies nuclear physics at the University of Tennessee in Knoxville, agrees. "This is the long-awaited facility for us," she says.

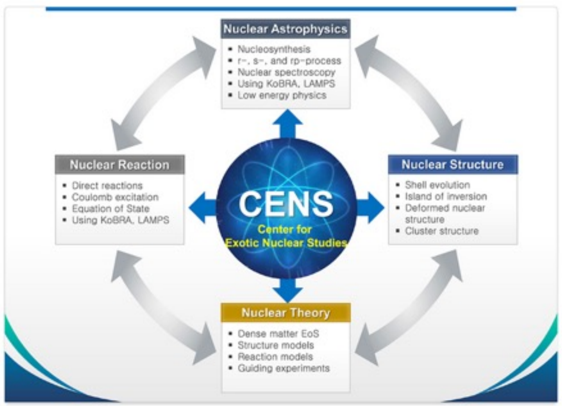
The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) in East Lansing had a budget of $730 million, most of it funded by the US Department of Energy, with a $94.5-million contribution from the state of Michigan. MSU contributed another $212 million in various ways, including the land. The facility replaces an earlier National Science Foundation accelerator, called the National Superconducting Cyclotron Laboratory (NSCL), at the same site. Construction of FRIB started in 2014 and was completed late last year, "five months early and on budget", says nuclear physicist Bradley Sherrill, who is FRIB's science director.

For decades, nuclear physicists had been pushing for a facility of its power – one that could produce rare isotopes orders of magnitude faster than is possible with the NSCL and similar accelerators worldwide. The first



CENS Home page

A panorama of the branch of the Institute of Modern Physics, located about 5 kilometers away from the downtown of the Huizhou City.




기초과학연구원의 희귀 핵 연구단은 자연에서 발견되지 않은 방사성 원자핵 연구를 통해 천체물리학과 핵물리학의 근본적인 질문들에 답하기 위하여 세워졌습니다.

화학 원소들의 기원, 특히 철보다 더 무거운 원소들인 금, 납, 혹은 우라늄 등의 생성 환경과 과정 규명은 핵천체물리학의 핵심 주제중 하나입니다. 몇가지 가설이 제안되었는데, 그중 하나는 초신성 혹은 중성자별 충돌과 같은 폭발적 천체현상에서 일어나는 빠른 중성자 포획 과정(r-process) 입니다. 해당하는 핵종 생성 과정에 관여된 불안정한 핵종들의 지식이 보완되어야 제시된 가설들을 더 면밀히 검증할수 있고, 더 정확한 실험 데이터에 기반한 이론들을 천문학에서 측정한 원소 존재량 분수에 대입하여 평가할수 있게 됩니다.

또한 불안정한 희귀 핵종들은 일반 원자핵에 비해 중성자/양성자 대비 수가 현저히 다르며, 그로 인해 신기한 구조와 반응 현상을 보입니다. 해당하는 희귀핵 연구를 통해 입자들의 근본적인 상호작용을 섬세하게 조사할수 있게 되는 가능성이 열립니다. 그리고 지금까지 알려진 모든 원자핵의 구조와 반응을 설명하는 통합된 이론을 설립하기 위해 약 100년이 흘렀습니다. 현재 기술력으로는 약 3000가지의 희귀 핵종을 생산할수 있으며, 이론상으로는 7000가지의 핵종이 존재한다고 합니다. 실험으로 도달할수 있는 희귀 핵종 수를 늘리기 위해 전 세계 여러 곳에서 새로운 시설들을 구축하고 있으며, 그 중에 대한민국의 라온 중이온가속기 (RAON)도 포함되어 있습니다. 지금이 매우 고무적이면서도 경쟁적인 시기입니다.

본 연구단은 국내외로 각광받는 희귀 핵 물리학 연구 그룹이 되는 것을 목표로 하고 있으며, 목적 달성을 위해 불안정한 원자핵 빔을 이용한 획기적이고 독창적인 실험들을 수행하는 동시에 탄탄한 이론 개발로 핵 구조와 핵천체물리학 분야에서 가장 중요한 질문들의 해답을 제시할 것입니다.

HIAF Home Page

The Institute of Modern Physics is establishing the High Intensity Heavy-ion Accelerator Facility (HIAF) as a scientific user facility sponsored by the National Development and Reform Commission of China. HIAF will enable scientists to perform a large variety of modern nuclear physics experiments with outstanding potential of scientific discoveries, and the primary physics goa[…]

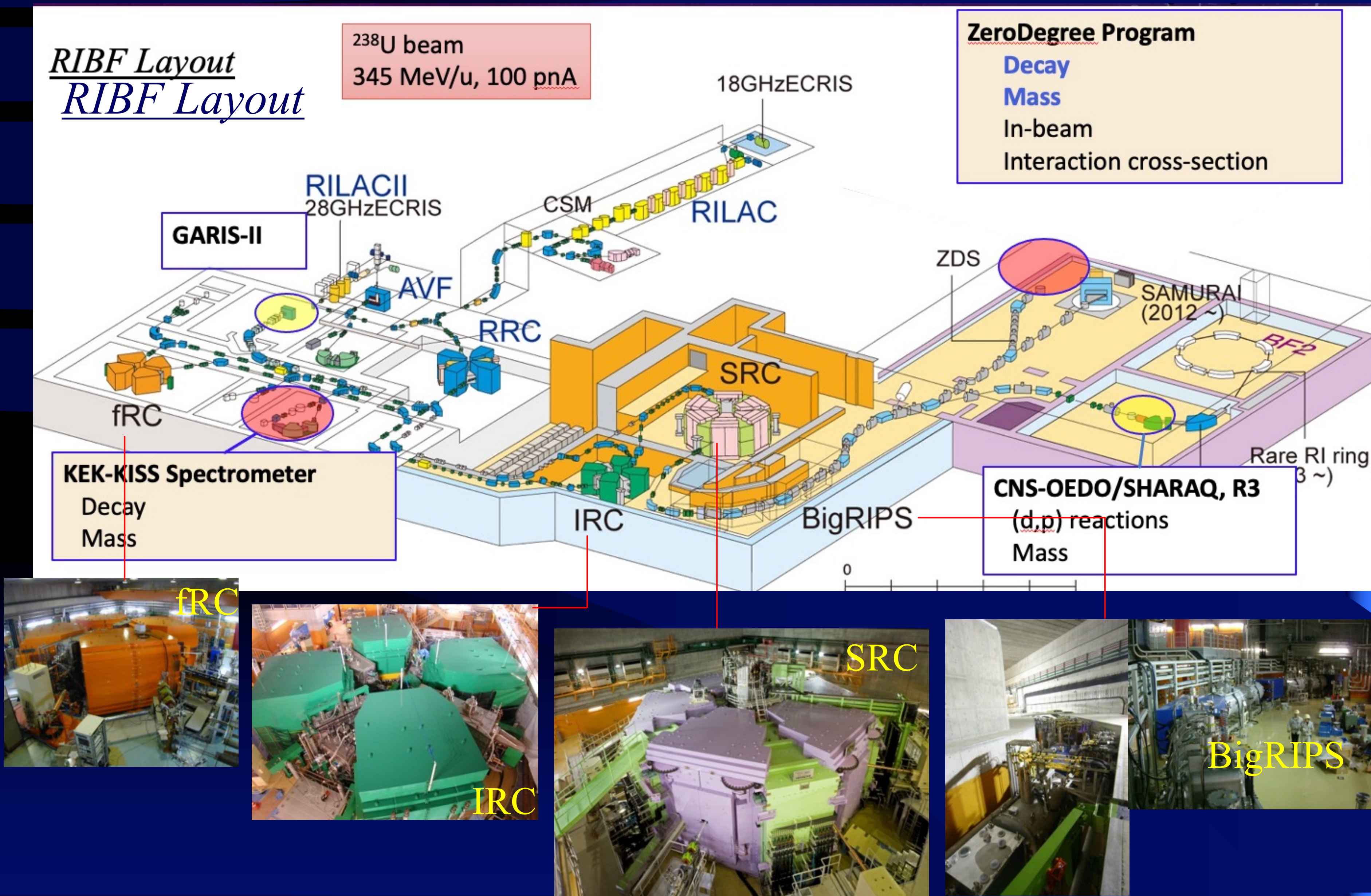

· To explore the limit to the existence of nuclei in terms of proton and mass numbers

· To find exotic nuclear properties and recognize the physics behind

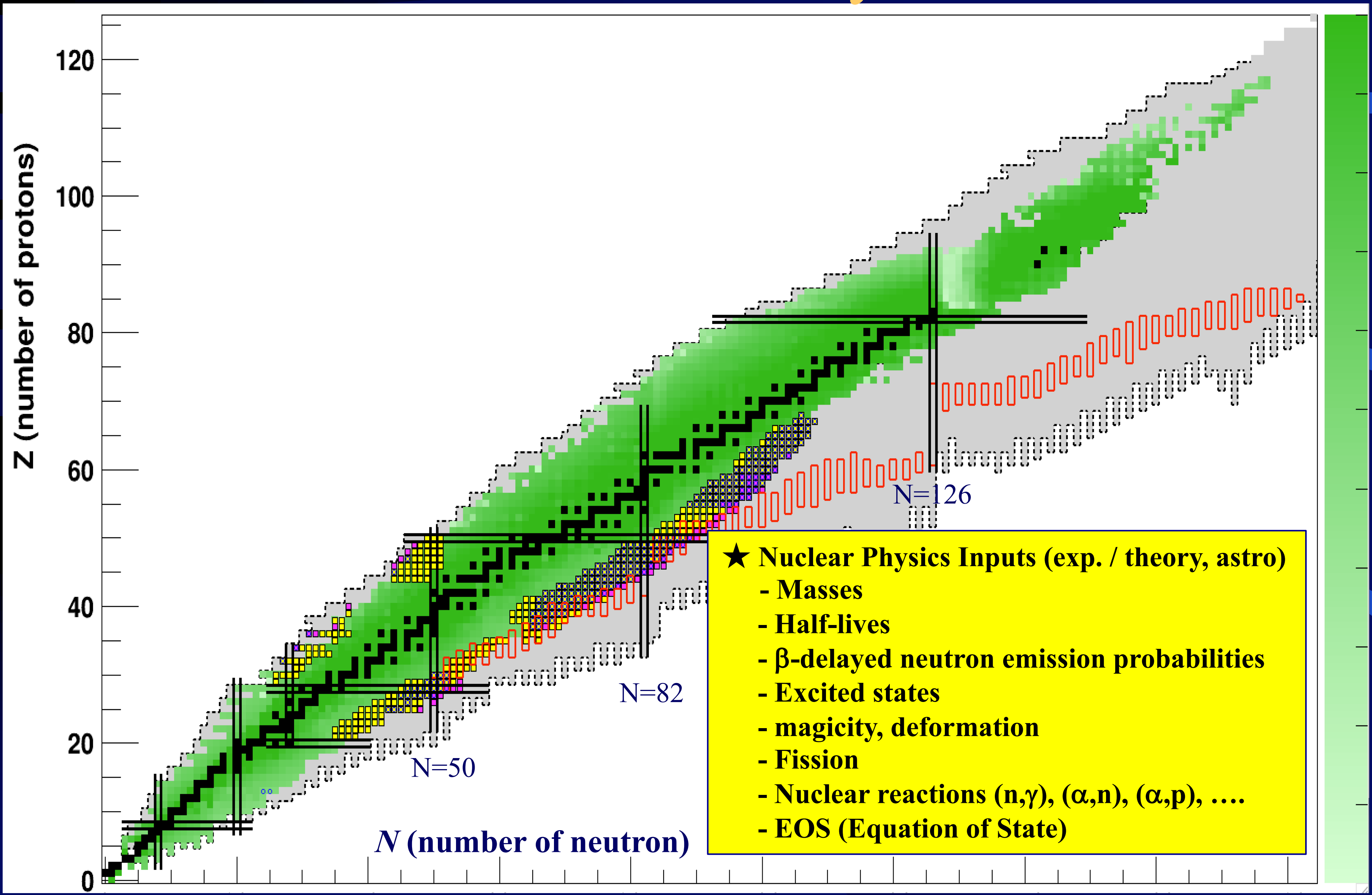
· To understand the origin of chemical elements in the Universe, and

· to depict the Quantum Chromodynamics phase diagram of nuclear matter

# Radioactive Isotope Beam Facility (RIBF) in Japan



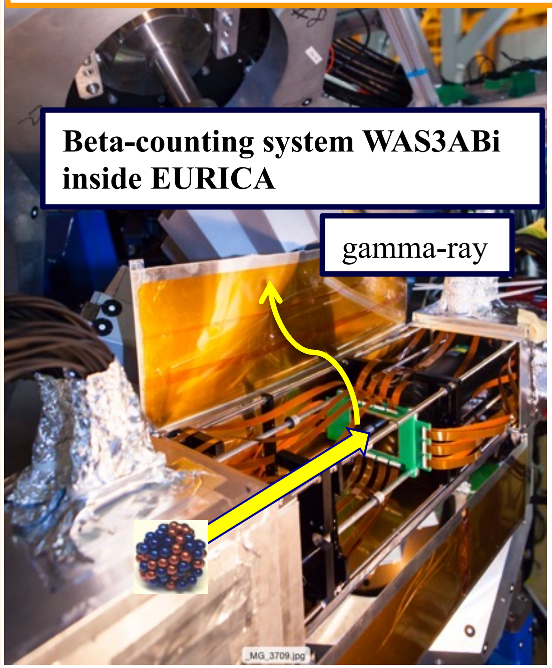
# Critical Nuclear Properties in r-Process Nucleosynthesis

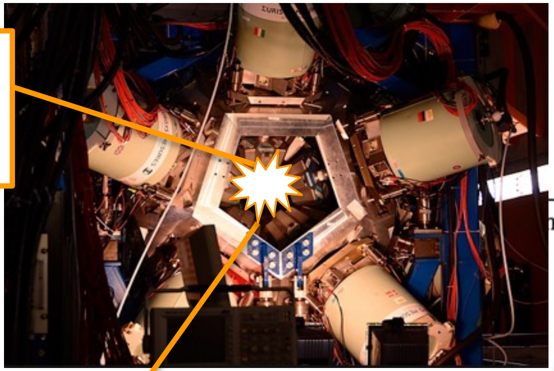


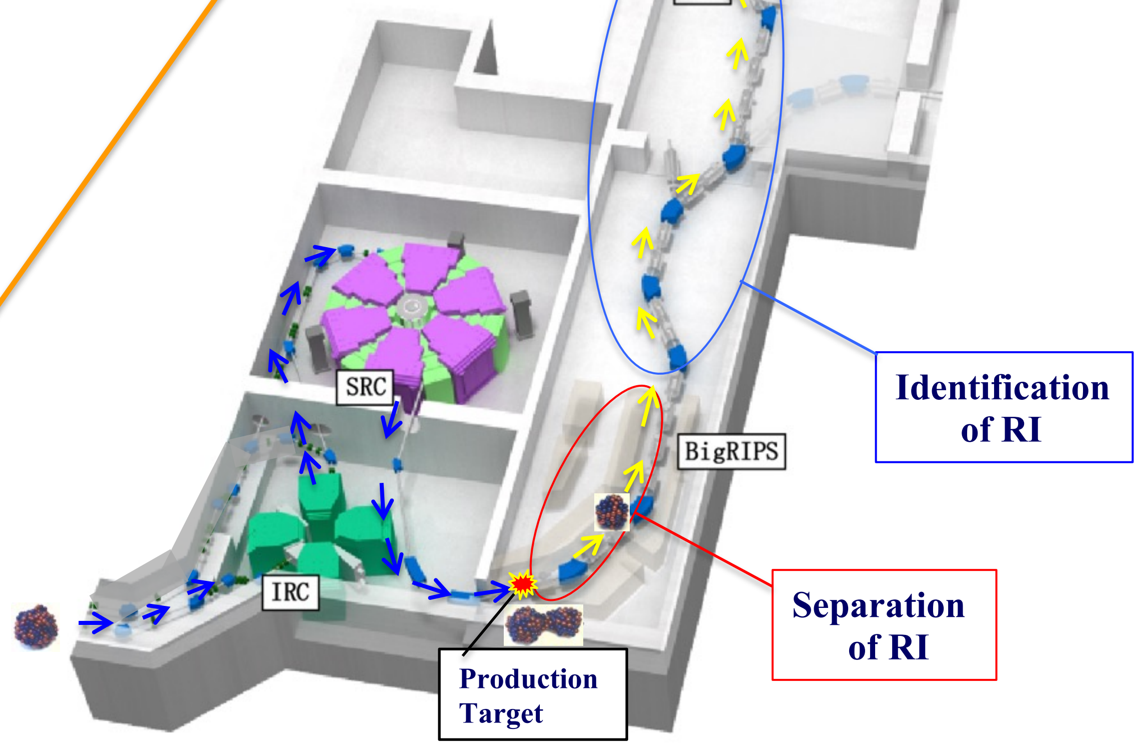
# Decay Experiments
# EURICA Project

19 countries : 237 collaborators

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



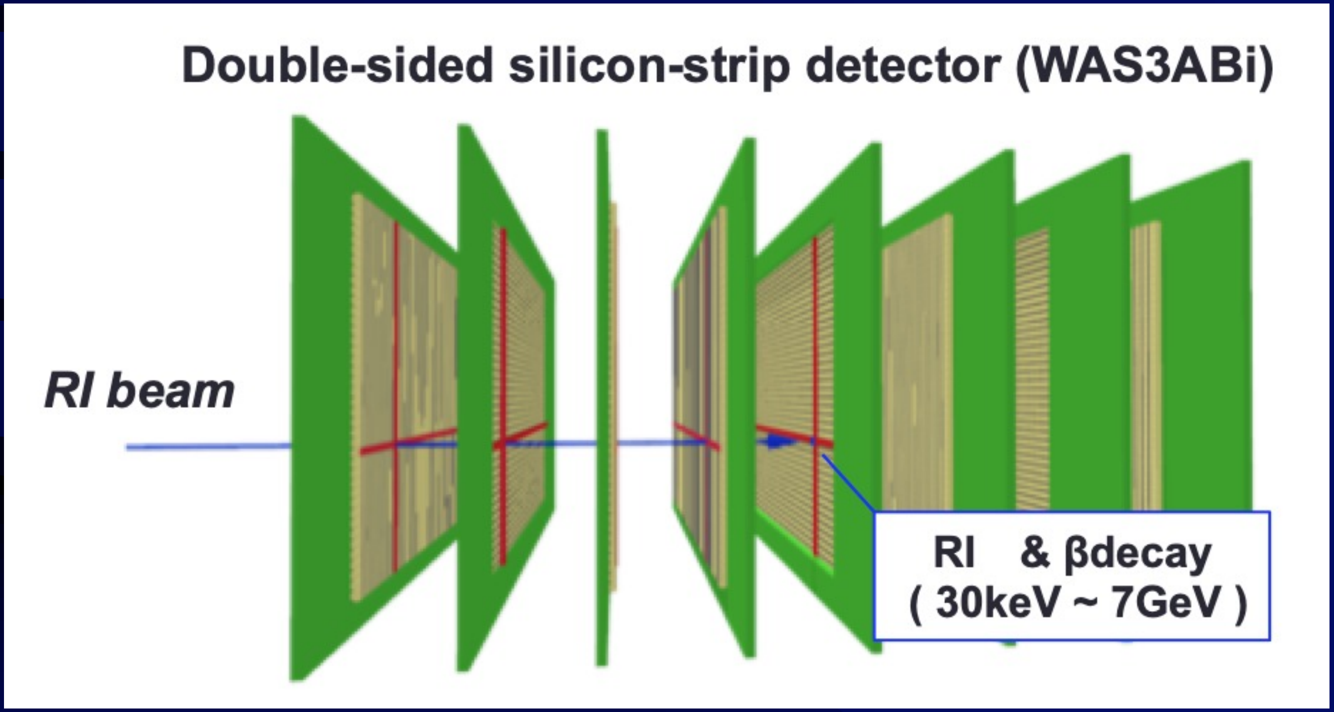





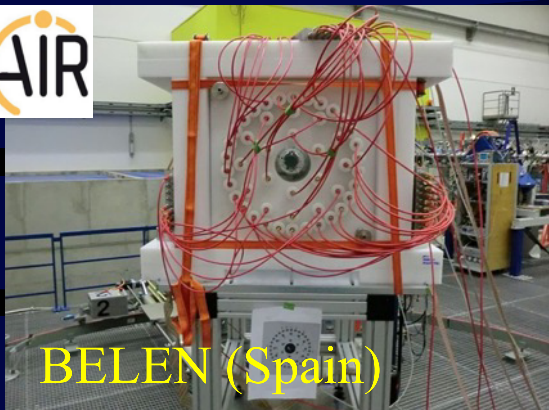

Primary Beam ($^{238}$U / $^{124}$Xe / $^{78}$Kr)

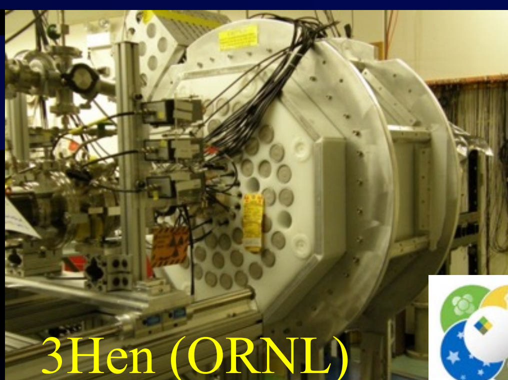
RI Beam

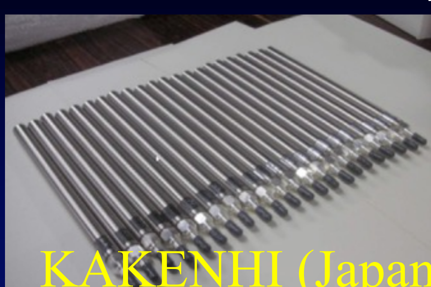
# beta counting system



# Decay Experiment at RIBF

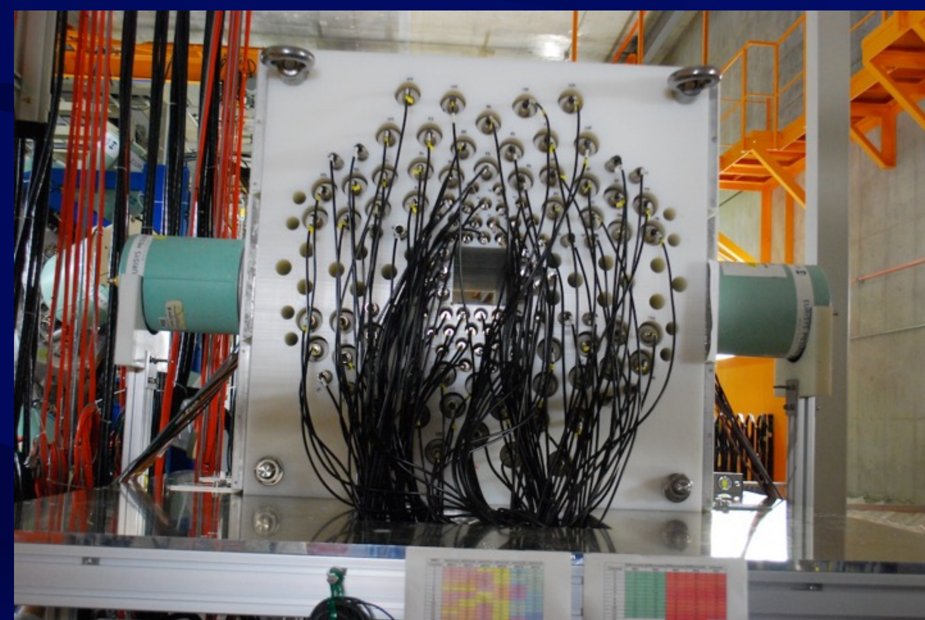


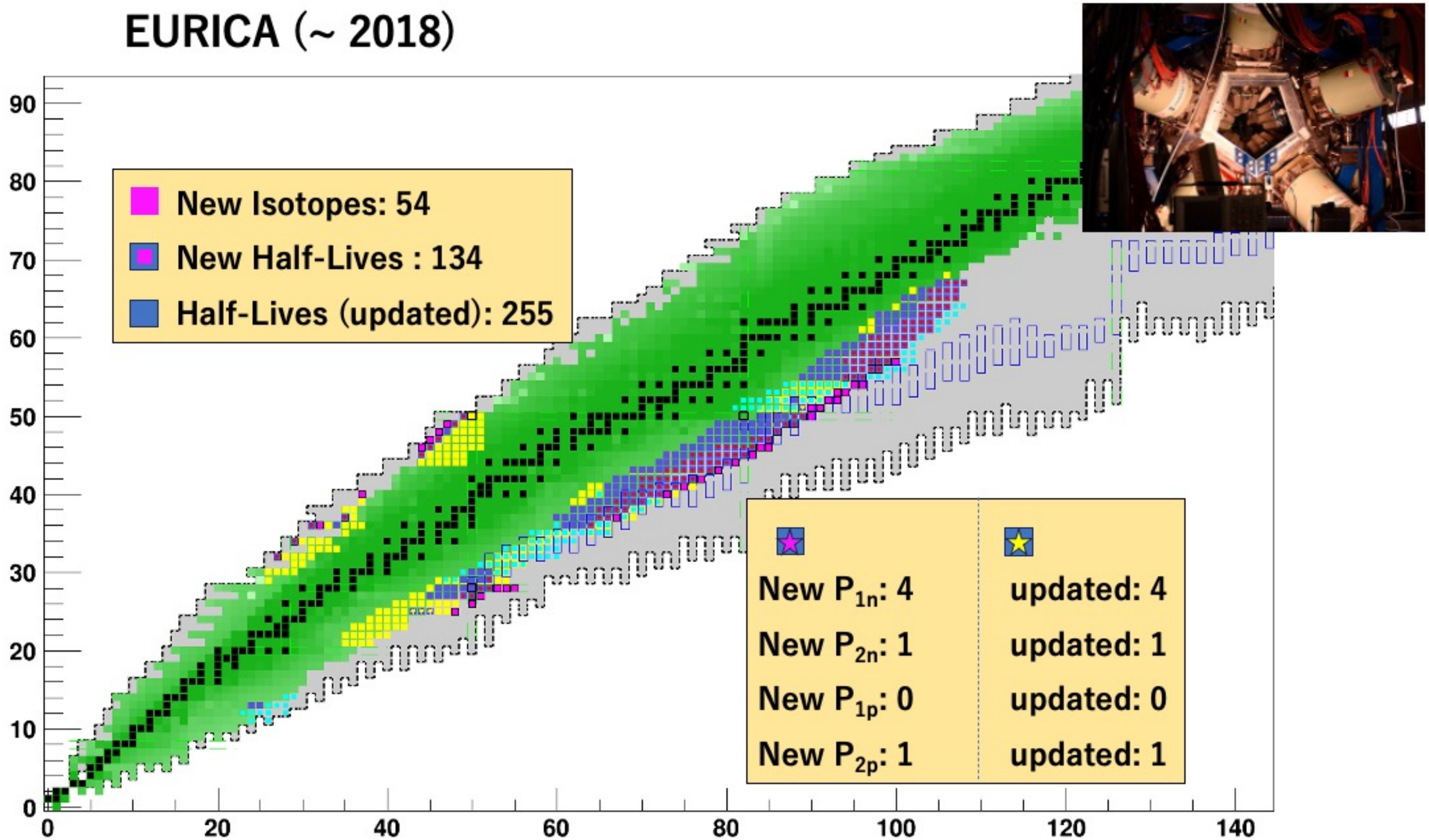




$^{3}\mathrm{He} + n \rightarrow {}^{3}\mathrm{H} + p + 780$ keV

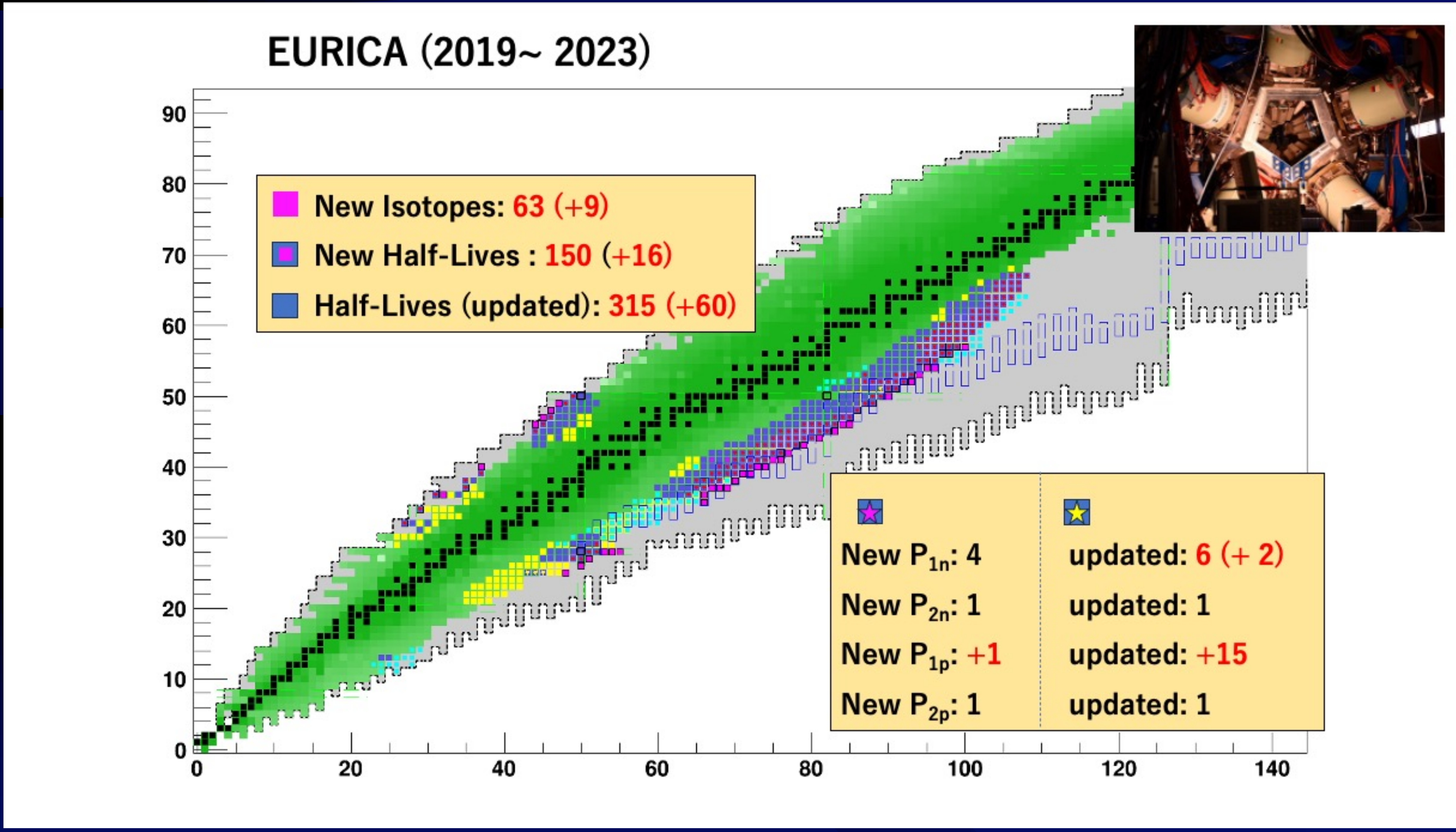
Thermalization time $\tau \sim 100\ \mu s$

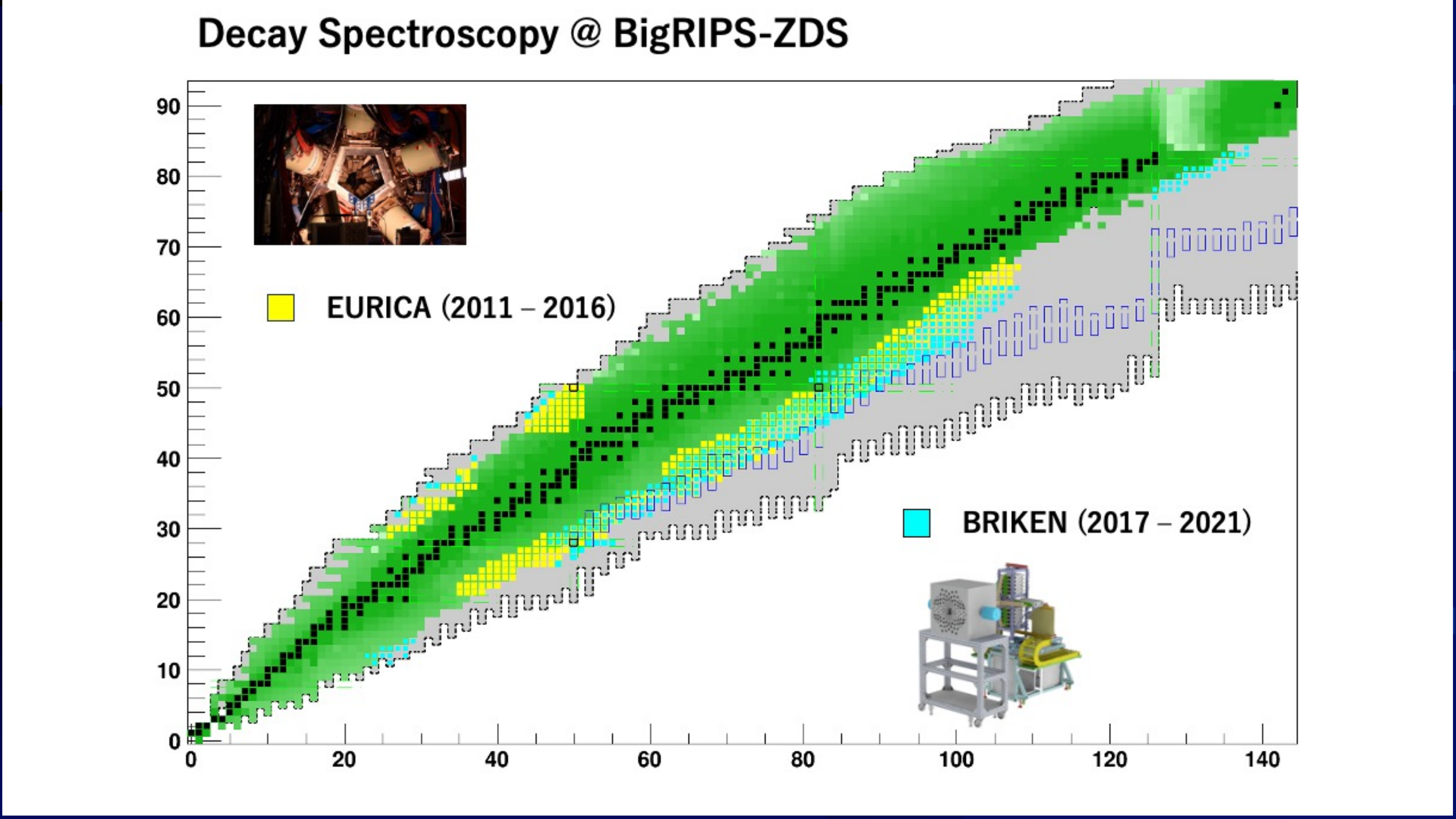
# Harvesting Decay Properties for r-Process Nucleosynthesis



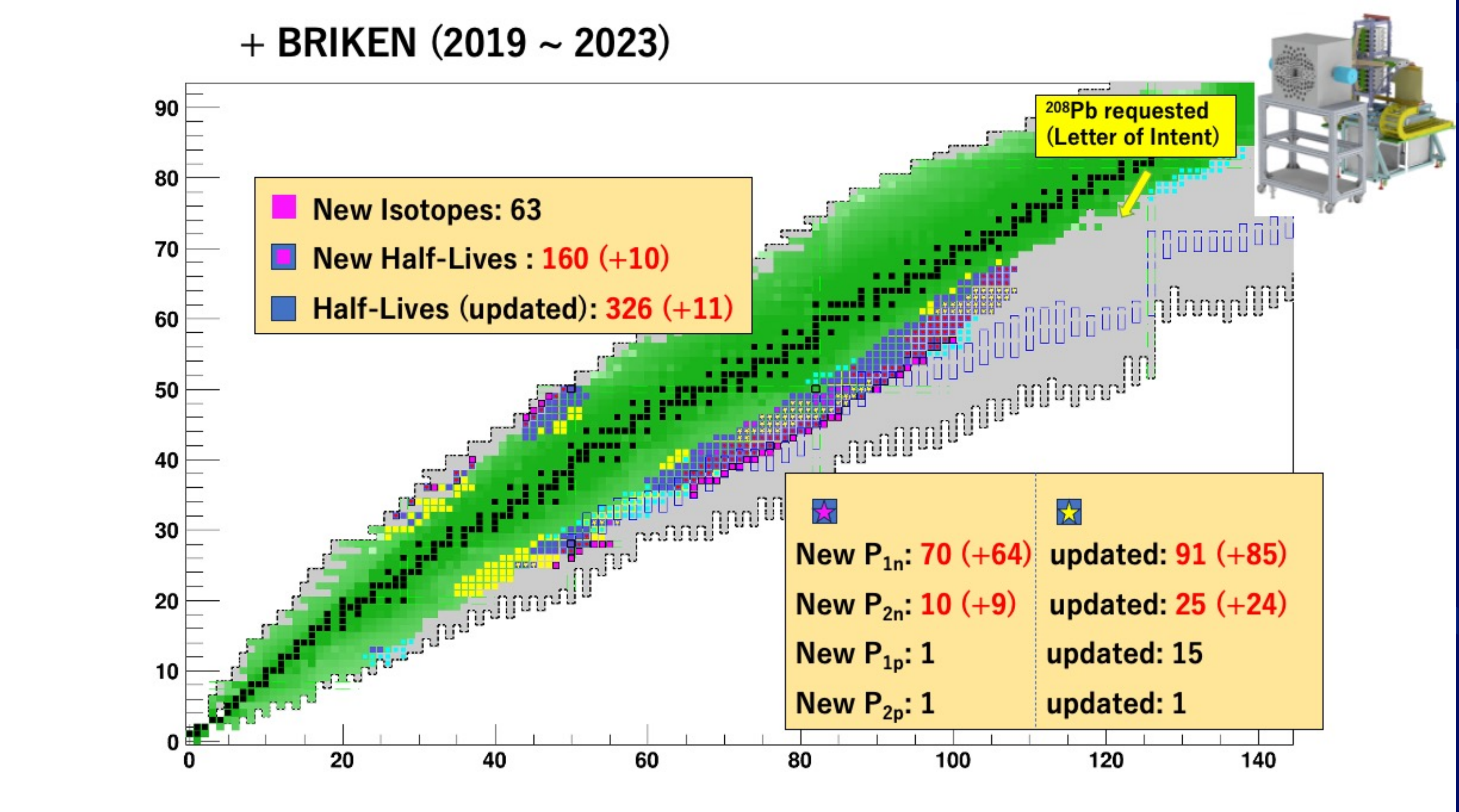
# Harvesting Decay Properties for r-Process Nucleosynthesis



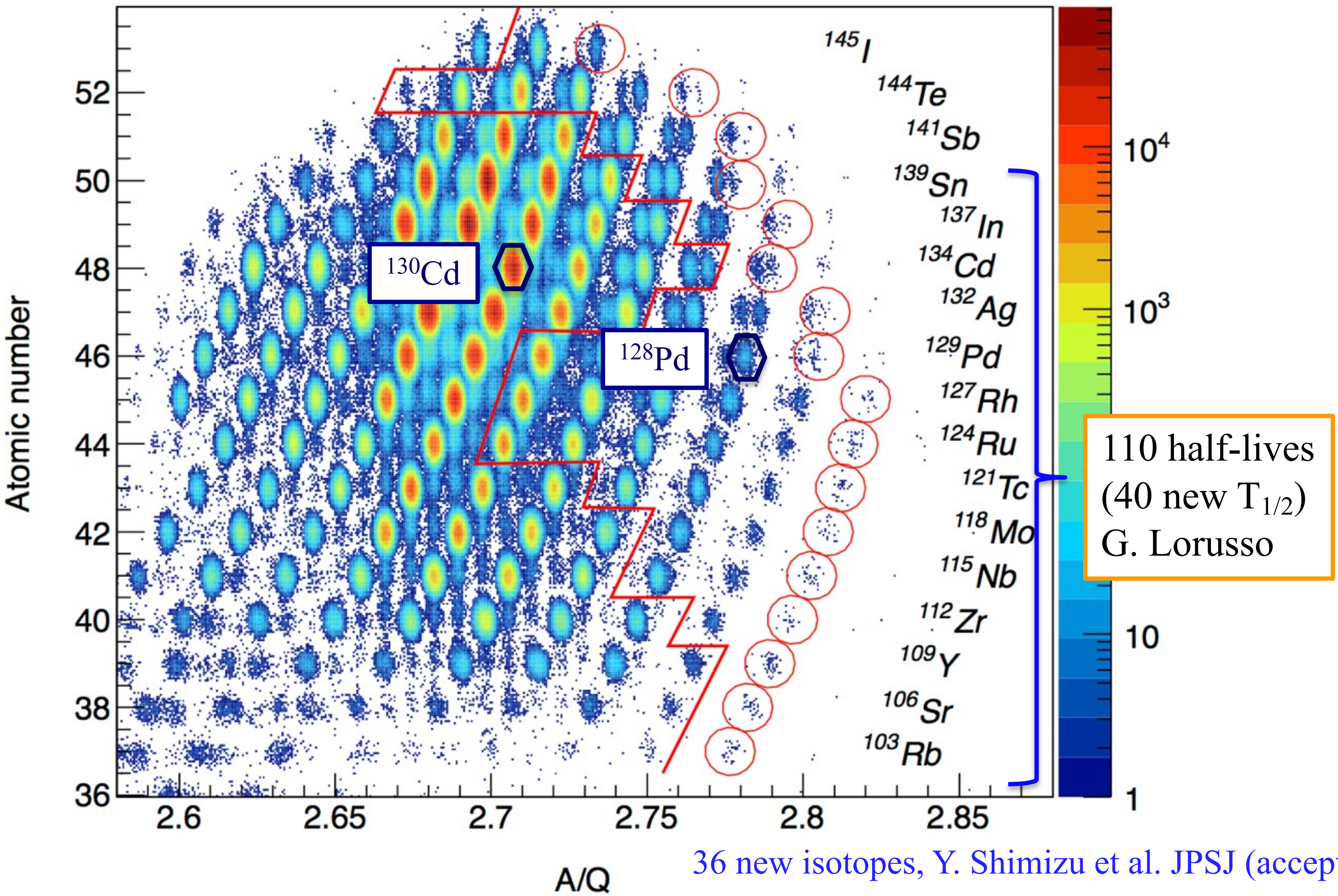
# Harvesting Decay Properties for r-Process Nucleosynthesis



# Harvesting Decay Properties for r-Process Nucleosynthesis



# β-decay half-lives on r-process path

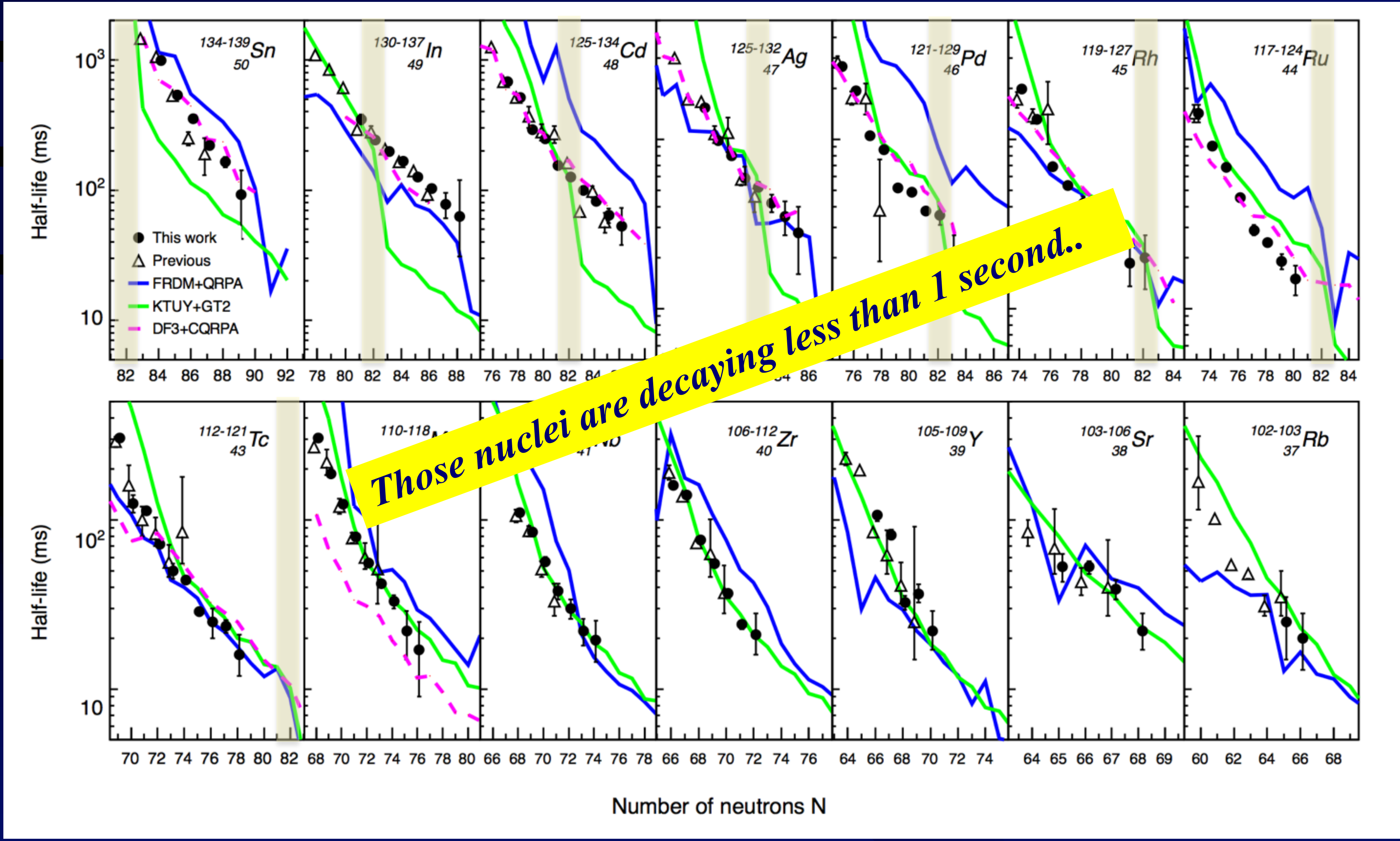



36 new isotopes, Y. Shimizu et al. JPSJ (accepted)

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

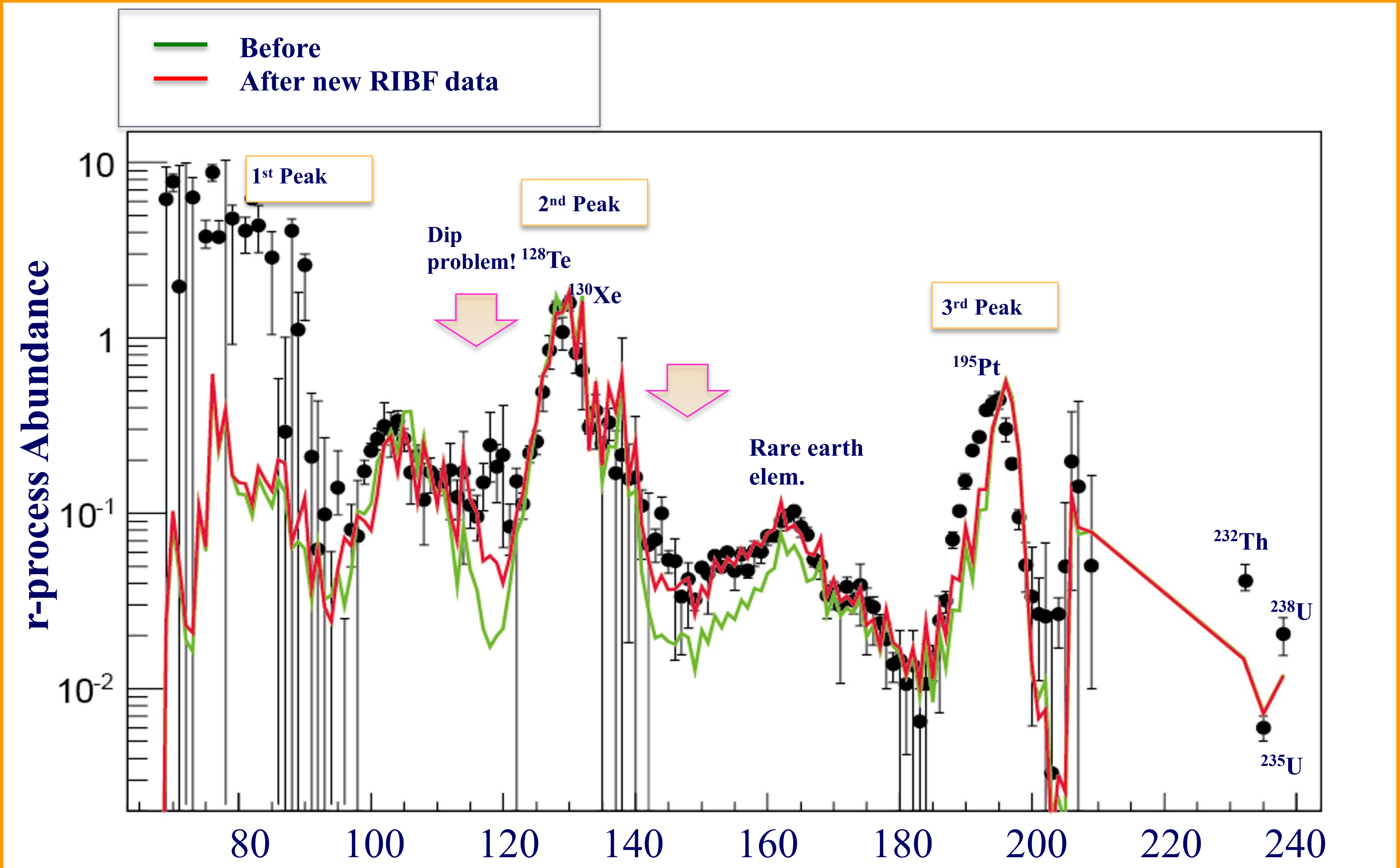
40 new decay rates ! G.Lorusso et al., PRL 114, 192501 (2015)

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



# r-process Abundance with New Decay Rates

G.Lorusso et al., PRL (2015)

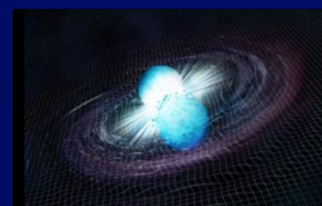



Assumption: (n, γ) ⇄ (γ, n) equilibrium.

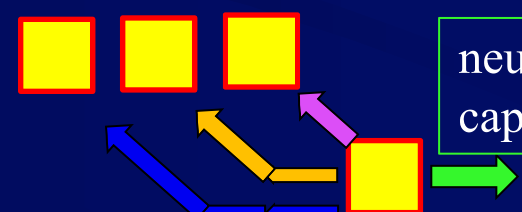
# Beta-Delayed Neutron in r-Process


Possible Candidates

Supernova



Neutron Star Merger



neutron capture

Beta-decay

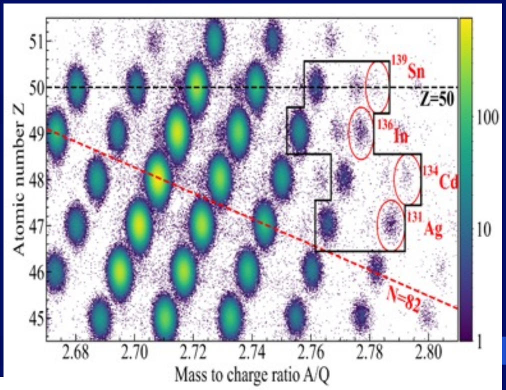
Beta-delayed one neutron

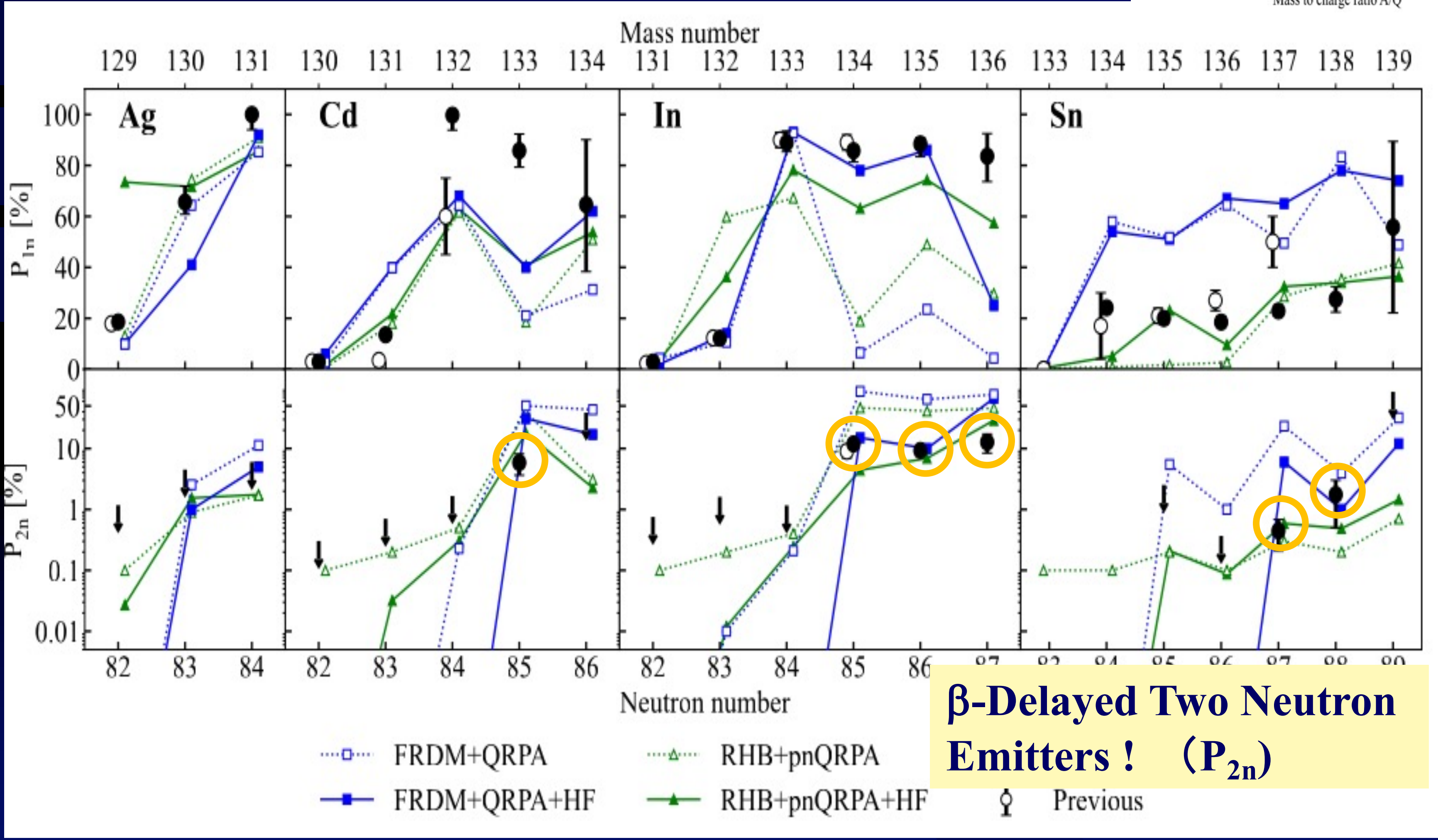
Beta-delayed two neutrons

Mass Number A is reduced.

# β-Delayed Neutron Emission Probabilities ($N \geq 82$ )

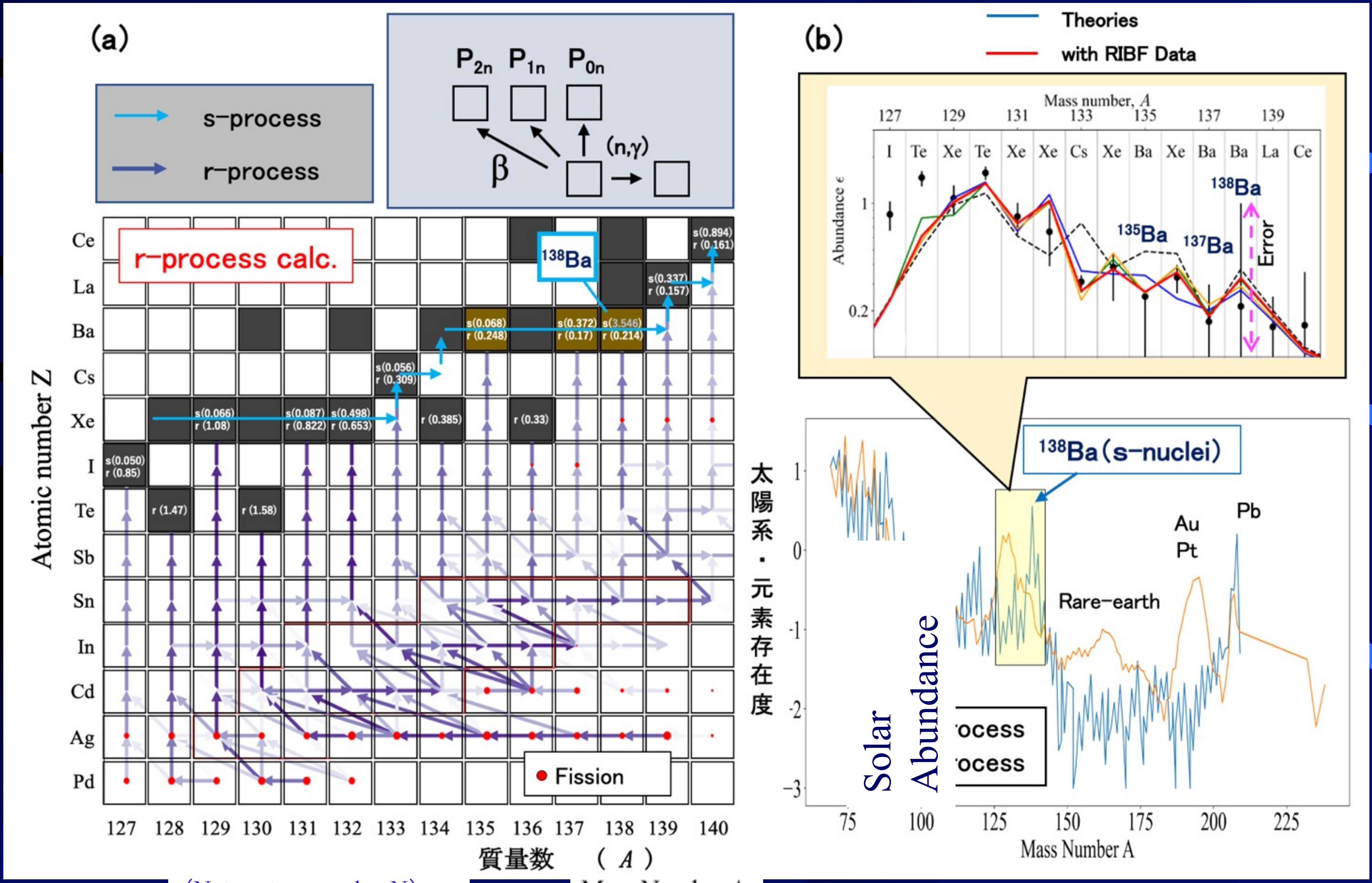
*V.H Phong, SN, G.L. et al., PRL 129, 172701 (2022)*




**β-Delayed Two Neutron Emitters !　($P_{2n}$)**

V.H Phong et al.



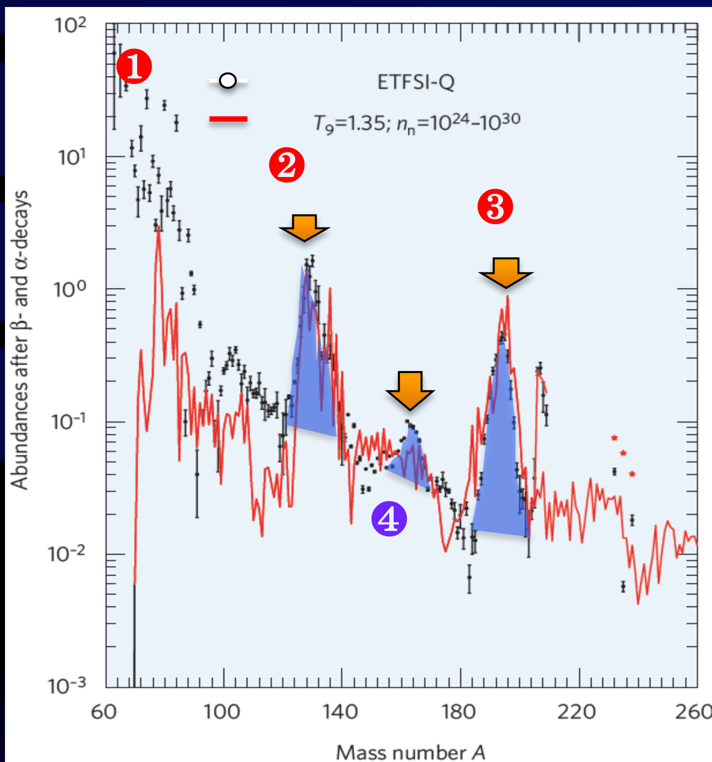

(Not neutron number N)

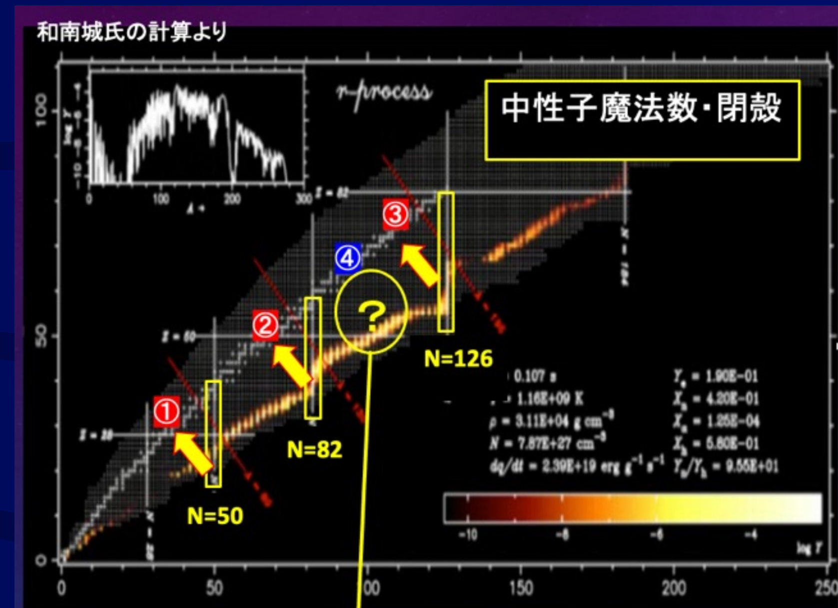
Mass Number A

# One of Open Questions related to r-Process

# Origin of Rare-Earth Elements

C.Sneden et al. (2008)




① Neutron shell closure $N$=50

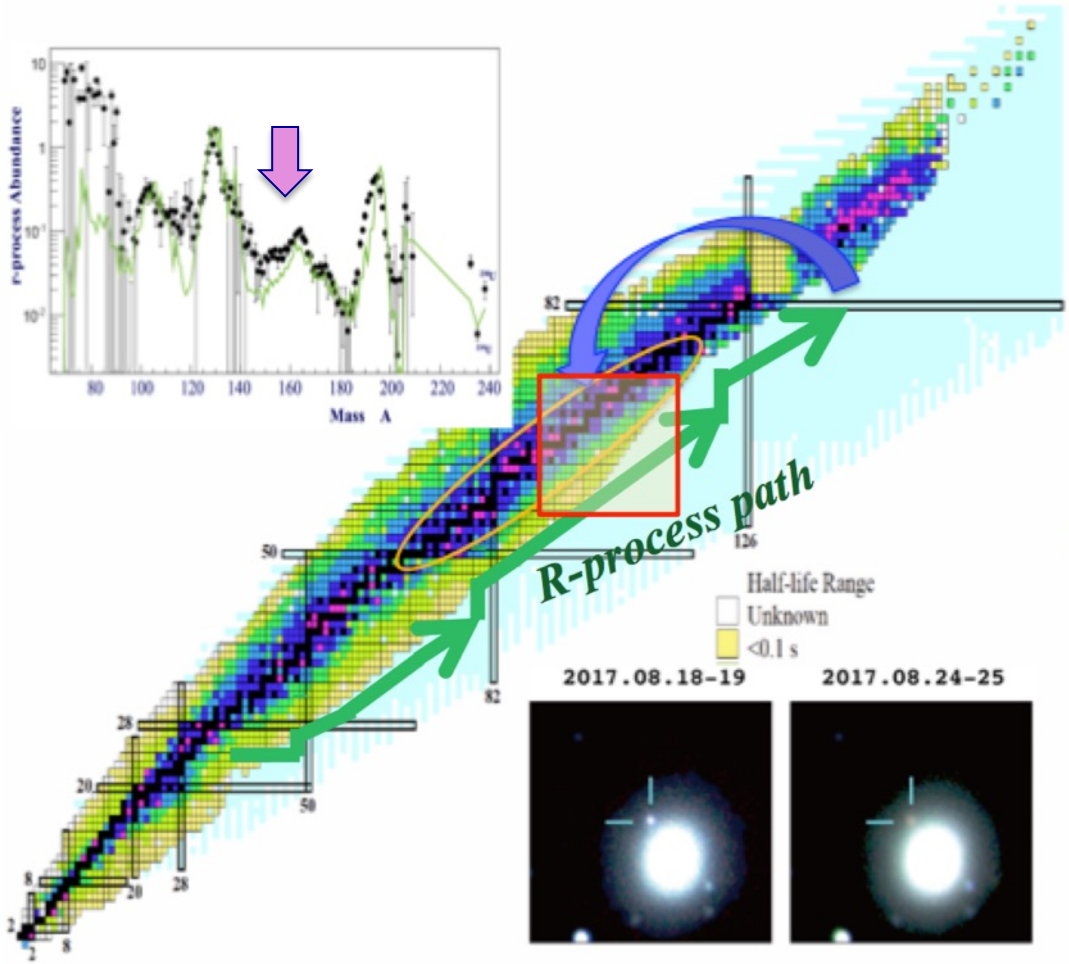
② Neutron shell closure $N$=82

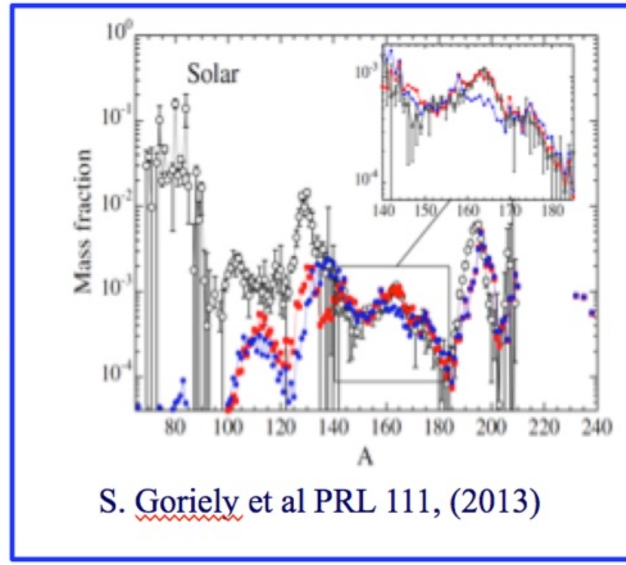
③ Neutron shell closure $N$=126

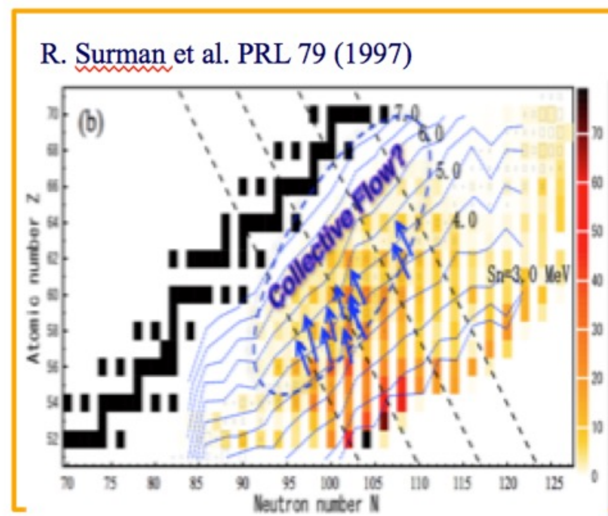
④ Lanthanide peak ($Z$ = 64 ~ 70, $A$ = 158 ~ 170)

There is no shell closure expected around A ~ 165..

# Origin of Rare-Earth Elements



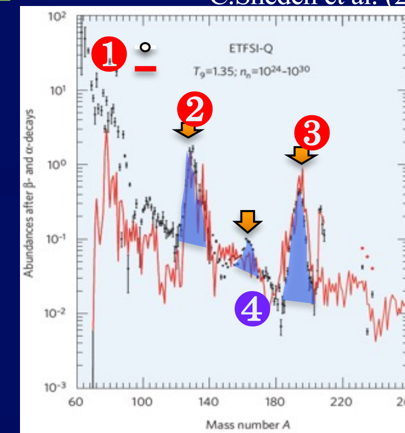



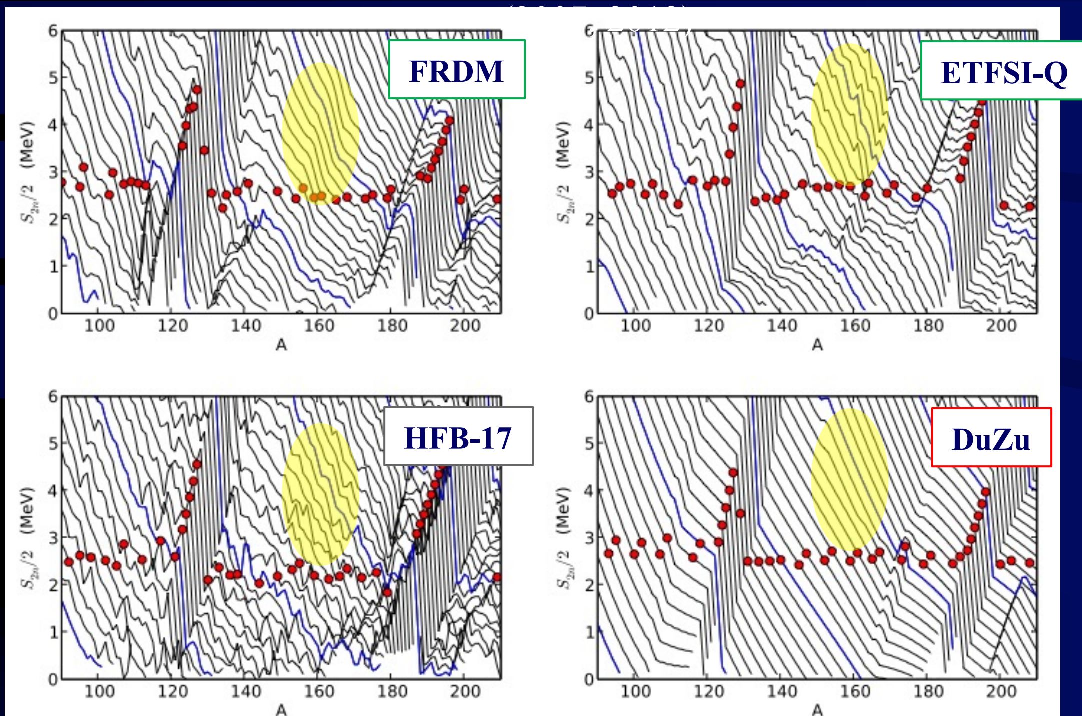
# Rare-Earth Peak Formation with Various Mass Models

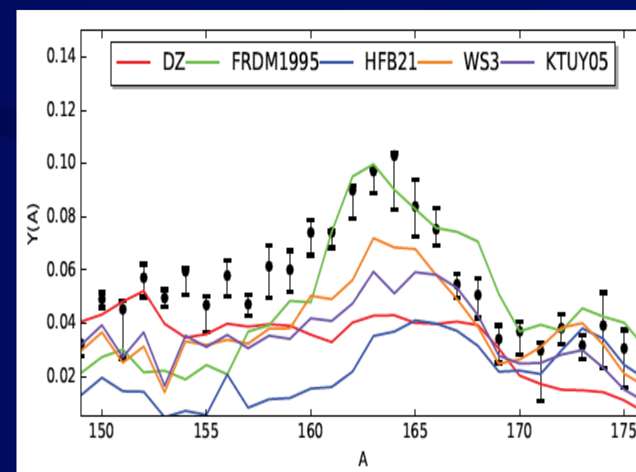
## 【 Uncertainties of Masses in Neutron-Rich Rare-Earth Elements 】

C.Sneden et al. (2008)




A. Arcones, G.Marinez-Pinedo



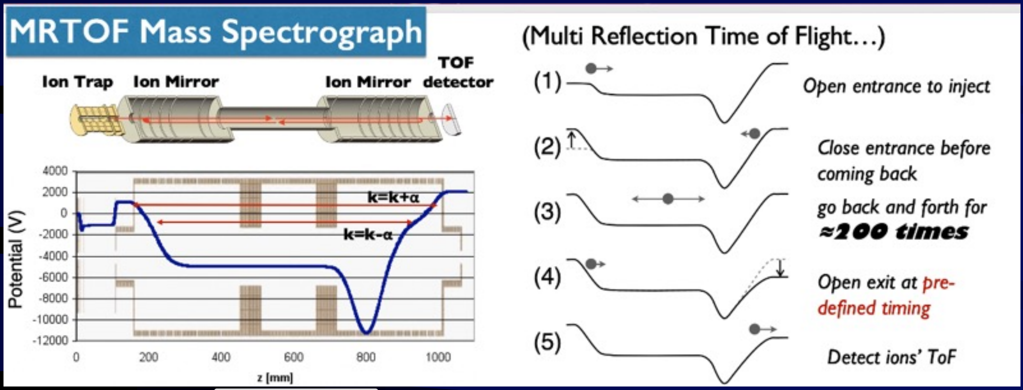



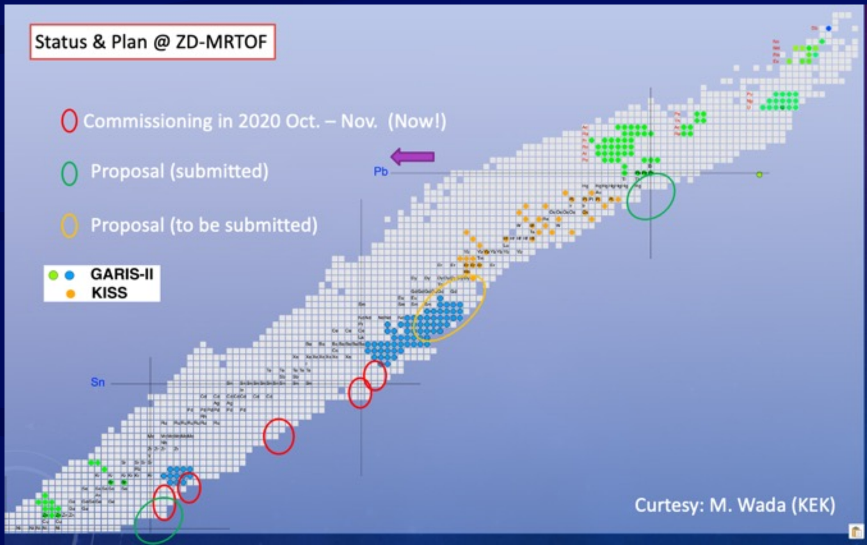

M. Mummpower et al.,
J. Phys. G. Nucl. Part. Phys. (2017)

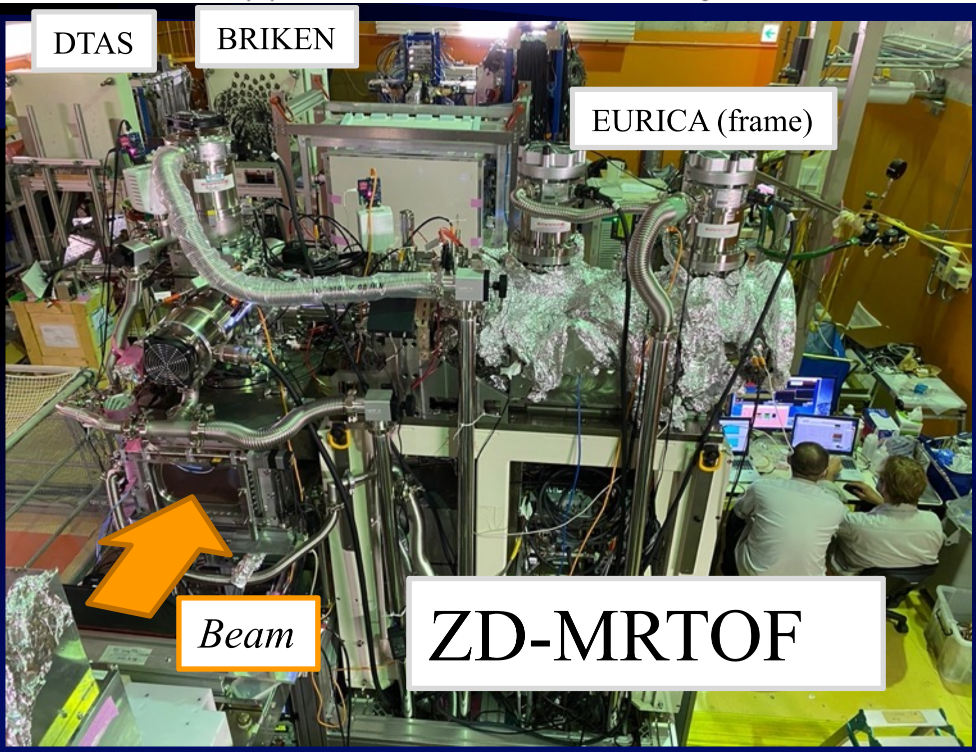
Rare-earth peak formation depends on mass models.
→ Uncertainties of mass models are critical issue !

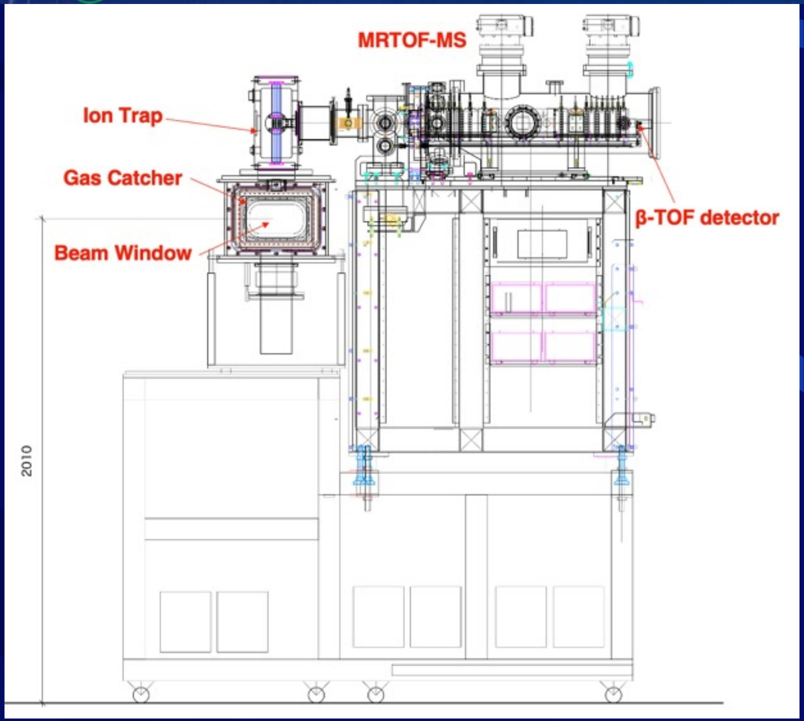
**We need experimental data !**

# ZD-MRTOF Project for Mass Measurement

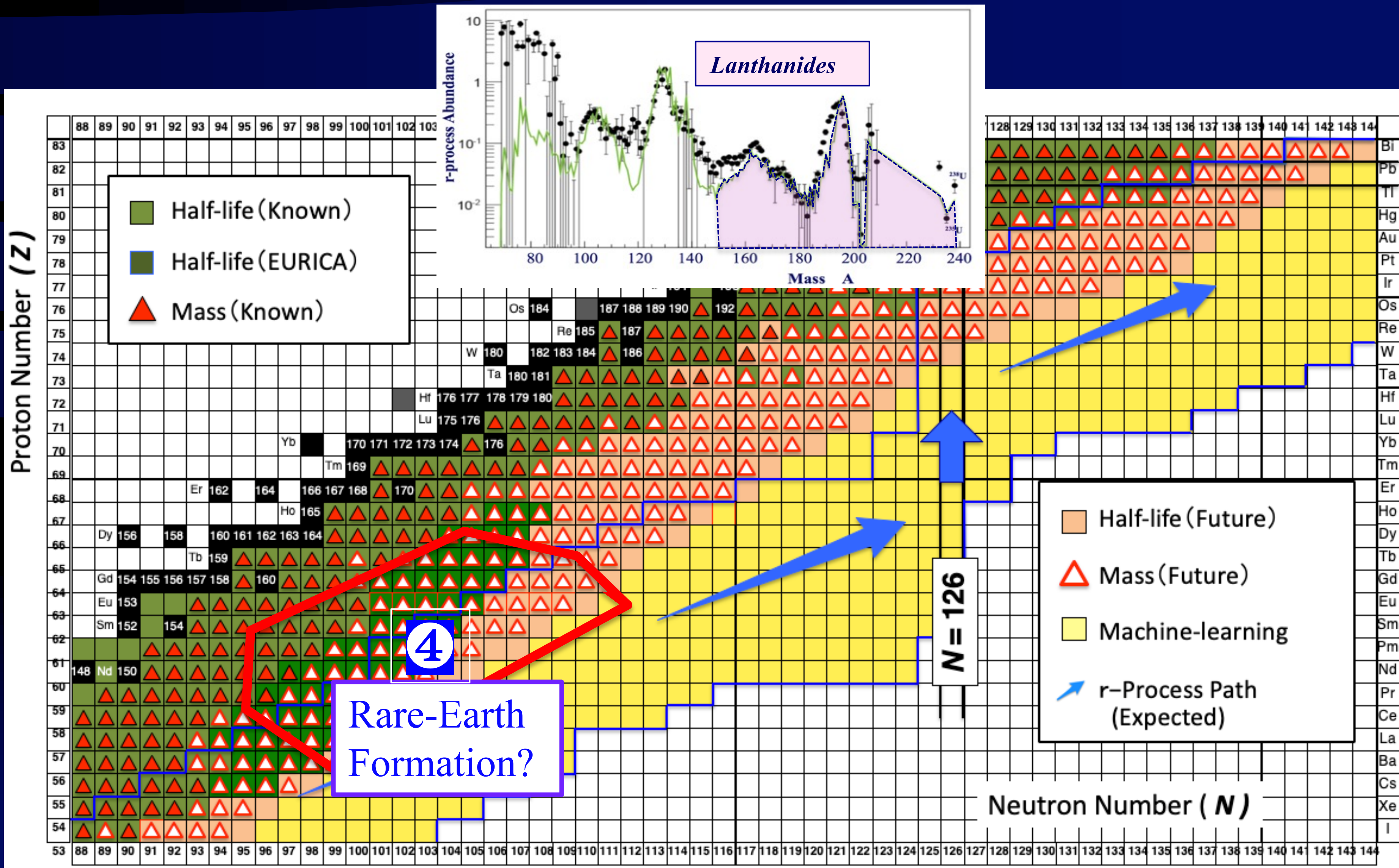


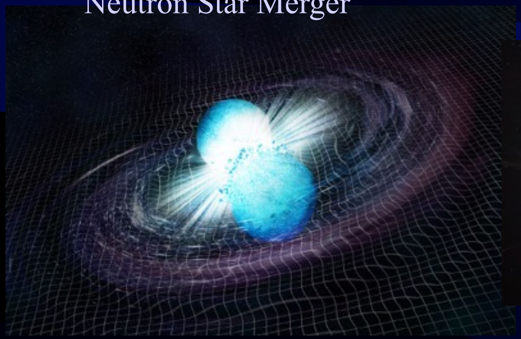
# Future Plan at RIBF-ZDS



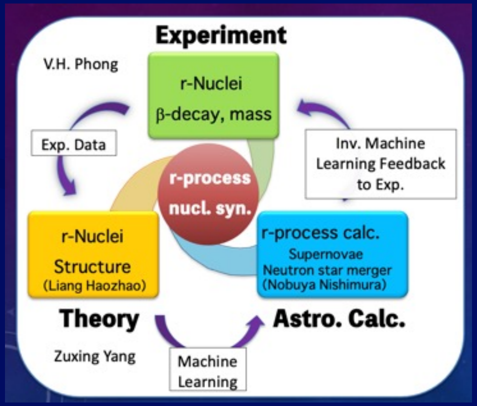
# Summary
## 【Nucleosynthesis】

- There is still an open question about site of r-process nucleosynthesis.

Neutron Star Merger



Supernovae

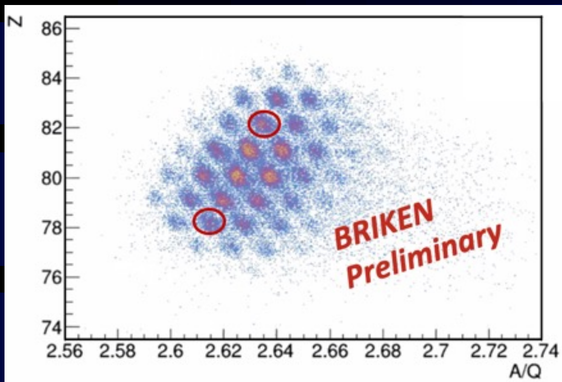


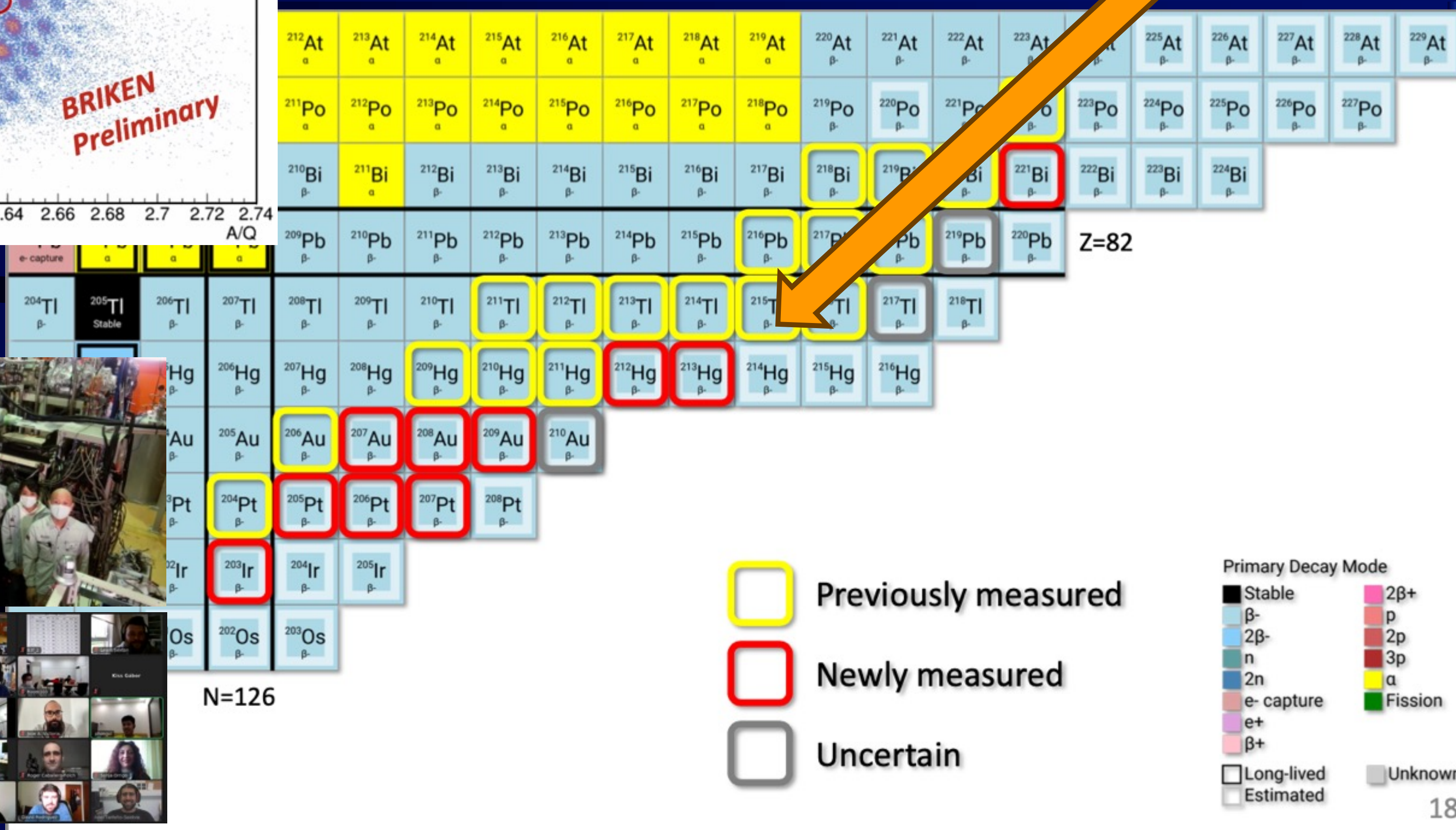

Nuclear Properties play critical role to form heavy elements.

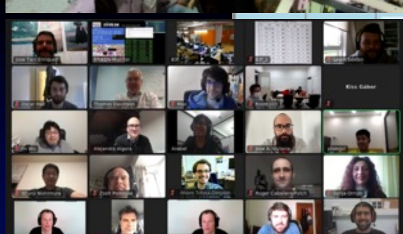
→ There are still a lots of isotopes to be studied to understand how the elements are created in the Universe.

# Do You Like “Gold”?

# We are Producing "Heavy" Gold at RIBF

**Enjoy Nishina School at RIKEN !**