Experimental studies of the β-decay properties among other important nuclear data inputs for the r-process nucleosynthesis at the RIKEN RIBF

Vi Ho Phong[1,2], S. Nishimura[1]

1. RI Physics Laboratory, RIKEN Nishina Center, Japan

2. University of Science, Vietnam National University, Hanoi, Vietnam

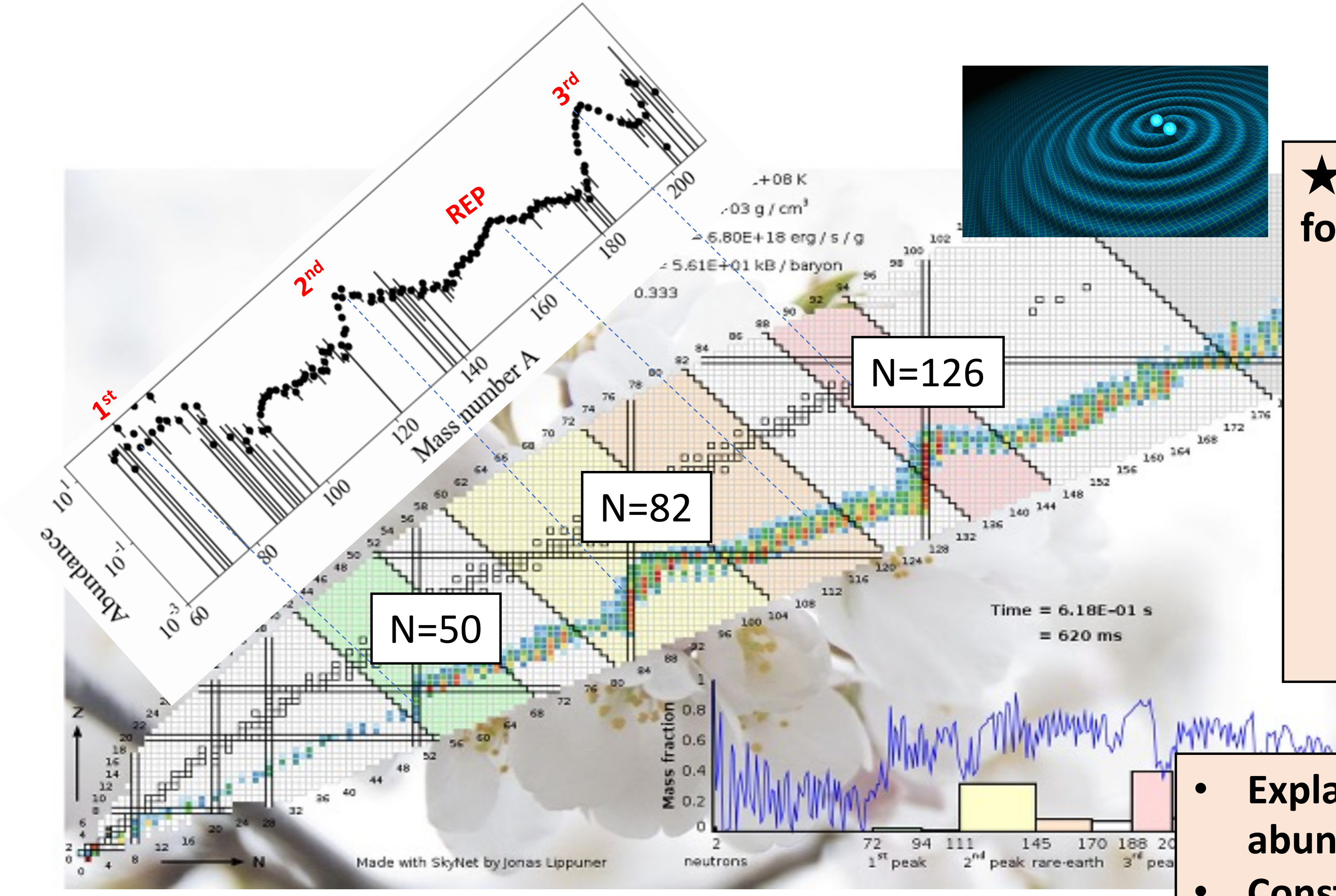
For the BRIKEN, EURICA and ZDMRTOF collaborations

OMEG16 l October 27th, 2022

Outline

- Past experimental programs at RIBF harvesting the nuclear properties for the r-process nucleosynthesis: **the EURICA and BRIKEN project**
- Latest results from the BRIKEN project relevant to the **second r-process peak**
- **Past** results and **future** experimental program focusing on the neutron-rich nuclei relevant to the **first**, **rare earth** and **third** r-process peaks.

Origin of the elements heavier than iron: the r-process

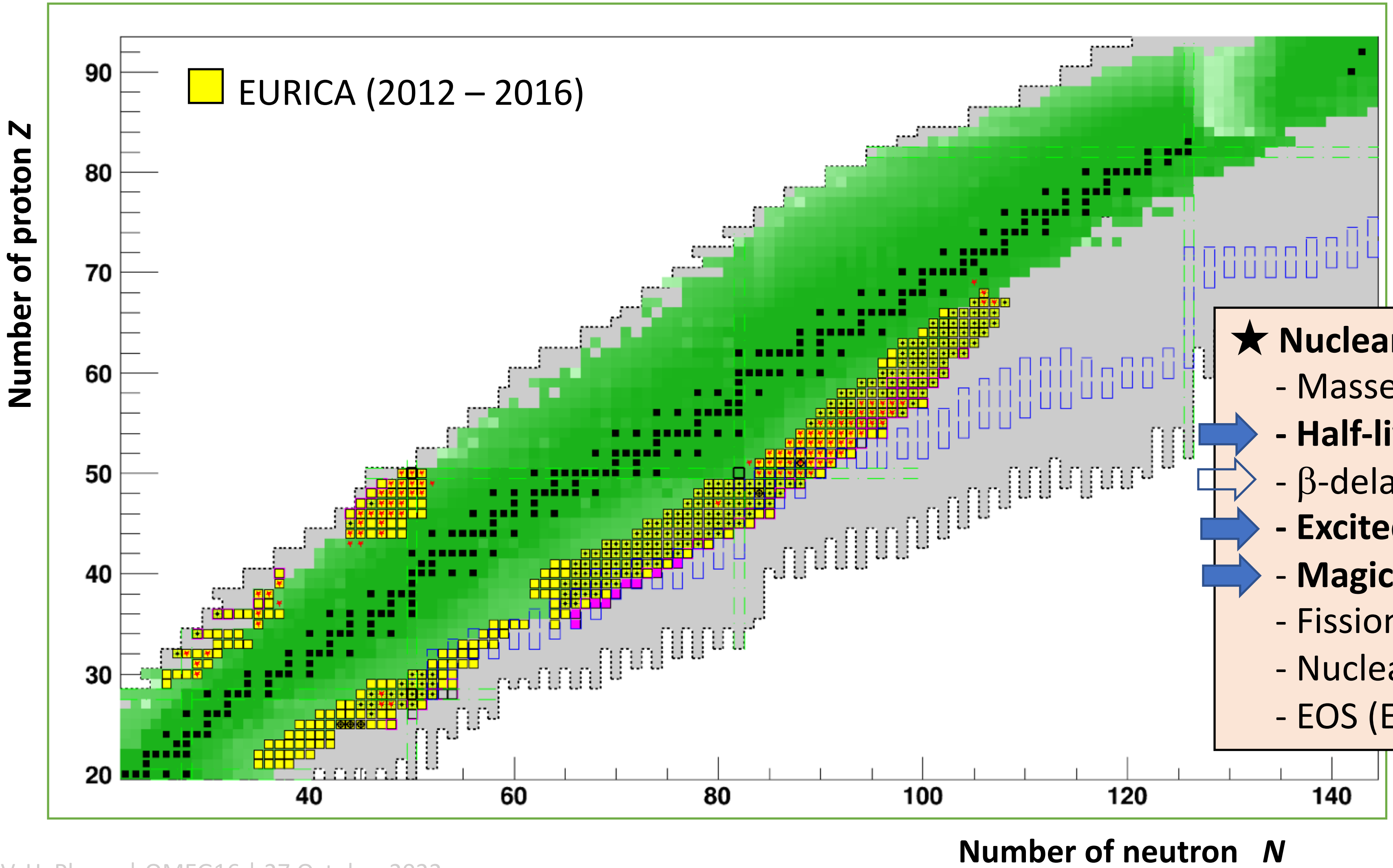


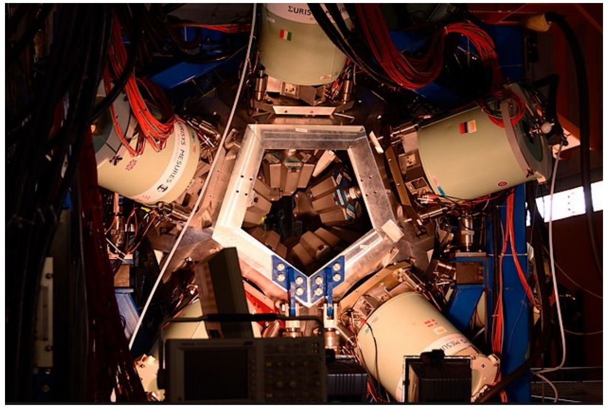
★ **Nuclear Physics Inputs (exp. / theory, astro) focusing on the r-process peaks:**

- **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)

- **Explain** the **observed elemental and isotopic abundances** in solar-system and metal-poor stars
- **Constraint** the **astrophysical environments** responsible for producing the observed abundance pattern.

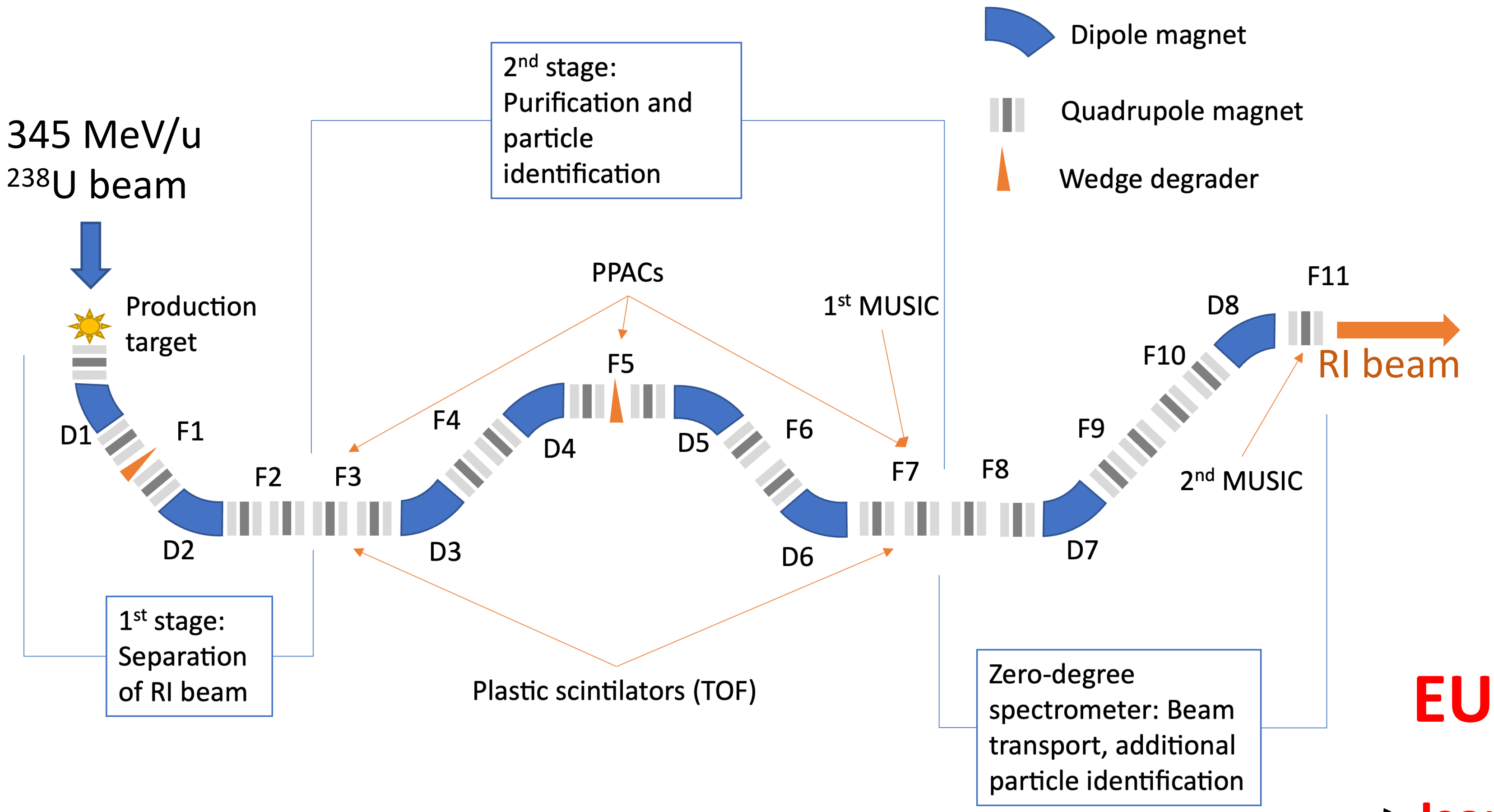
EURICA project (2012-2016): Harvesting beta-decay half-lives

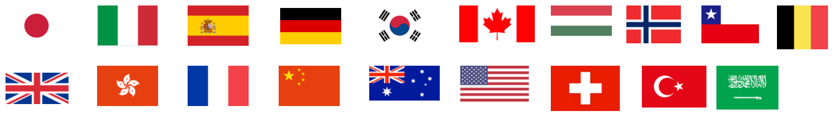


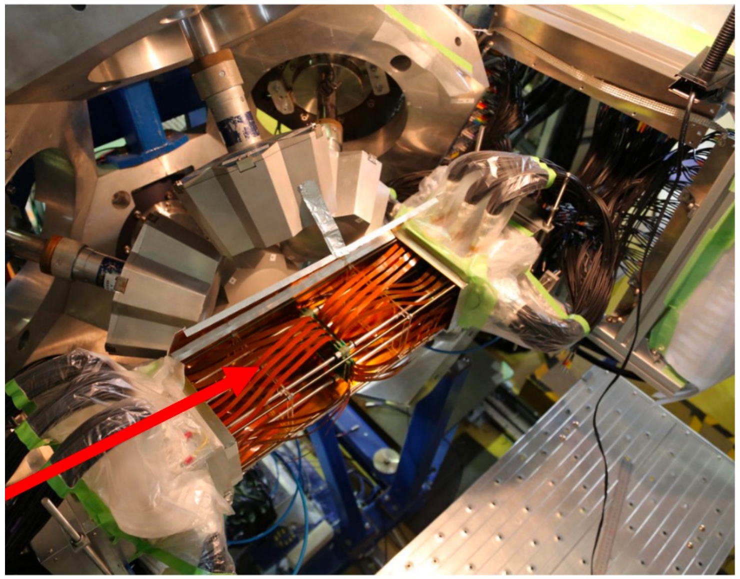


★ **Nuclear Physics Inputs (exp. / theory, astro)**
- Masses
- **Half-lives**
- β-delayed neutron emission probabilities
- **Excited states**
- **Magicity, deformation**
- Fission
- Nuclear reactions (n,γ), (α,n), (α,p), ….
- EOS (Equation of State)

Experimental setup: EURICA







EUroball RIken Cluster Array

=> Isomer and beta-decay spectroscopy!

BRIKEN project (2017-2021): Beta-delayed neutron emission probability

★ **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)

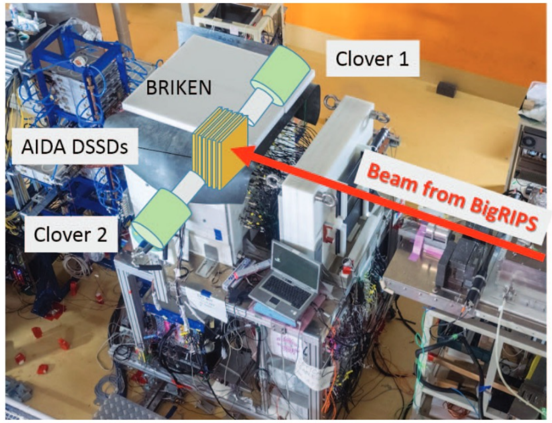
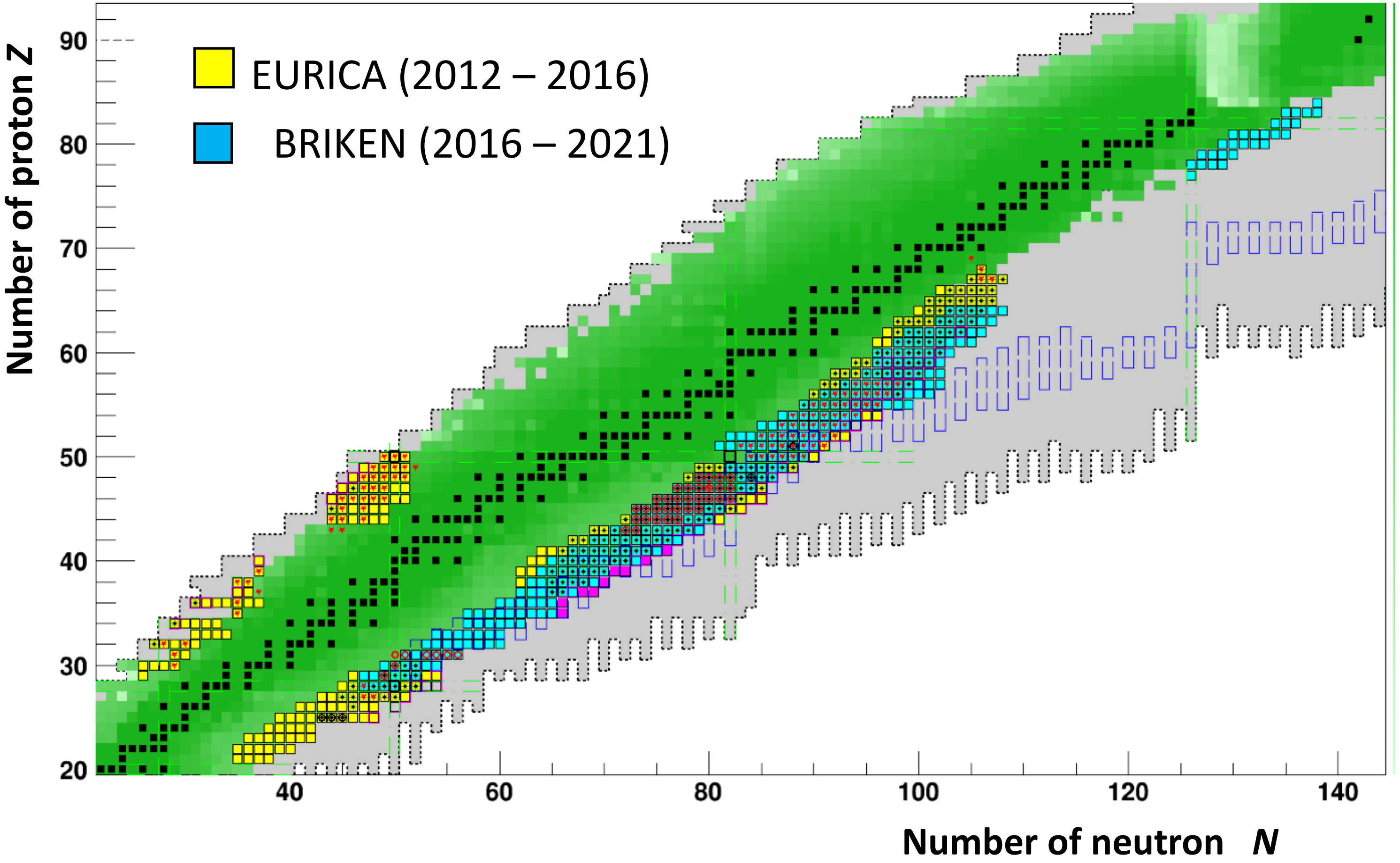
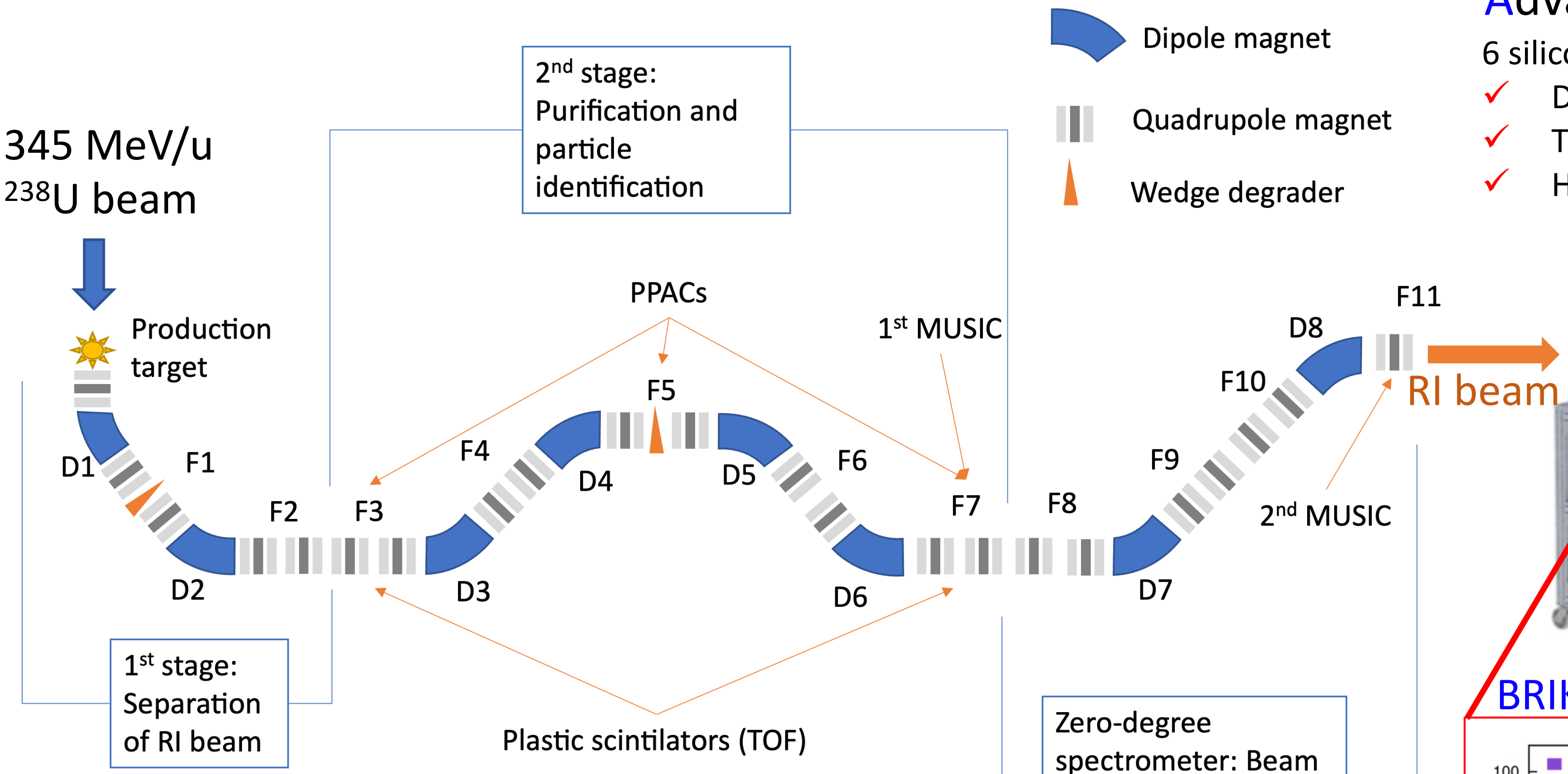


Figure 4. *BRIKEN hybrid setup with schematic positions of the AIDA detectors and the two HPGe clovers.*

30 *Nuclear Physics News*, Vol. 28, No. 1, 2018



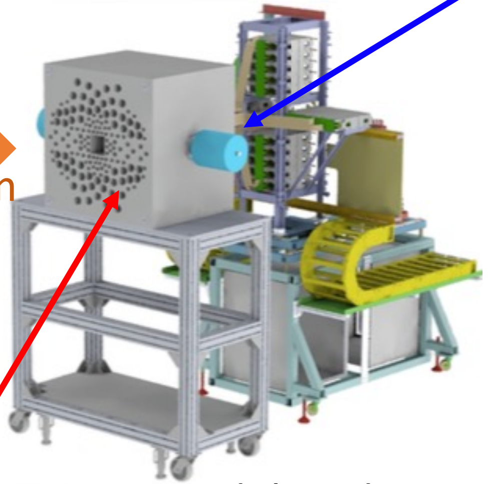
Experimental setup: BRIKEN



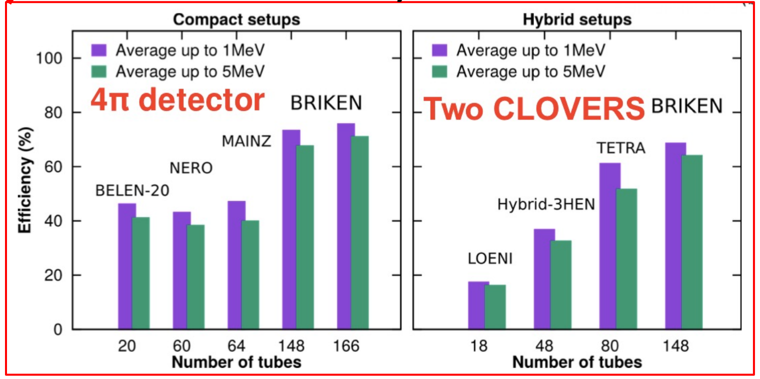
Advance Implantation Detector Array AIDA

6 silicon DSSDs with 128x128 pixels

- ✓ Detect implant+beta decay
- ✓ Triggerless DAQ
- ✓ High counting rate



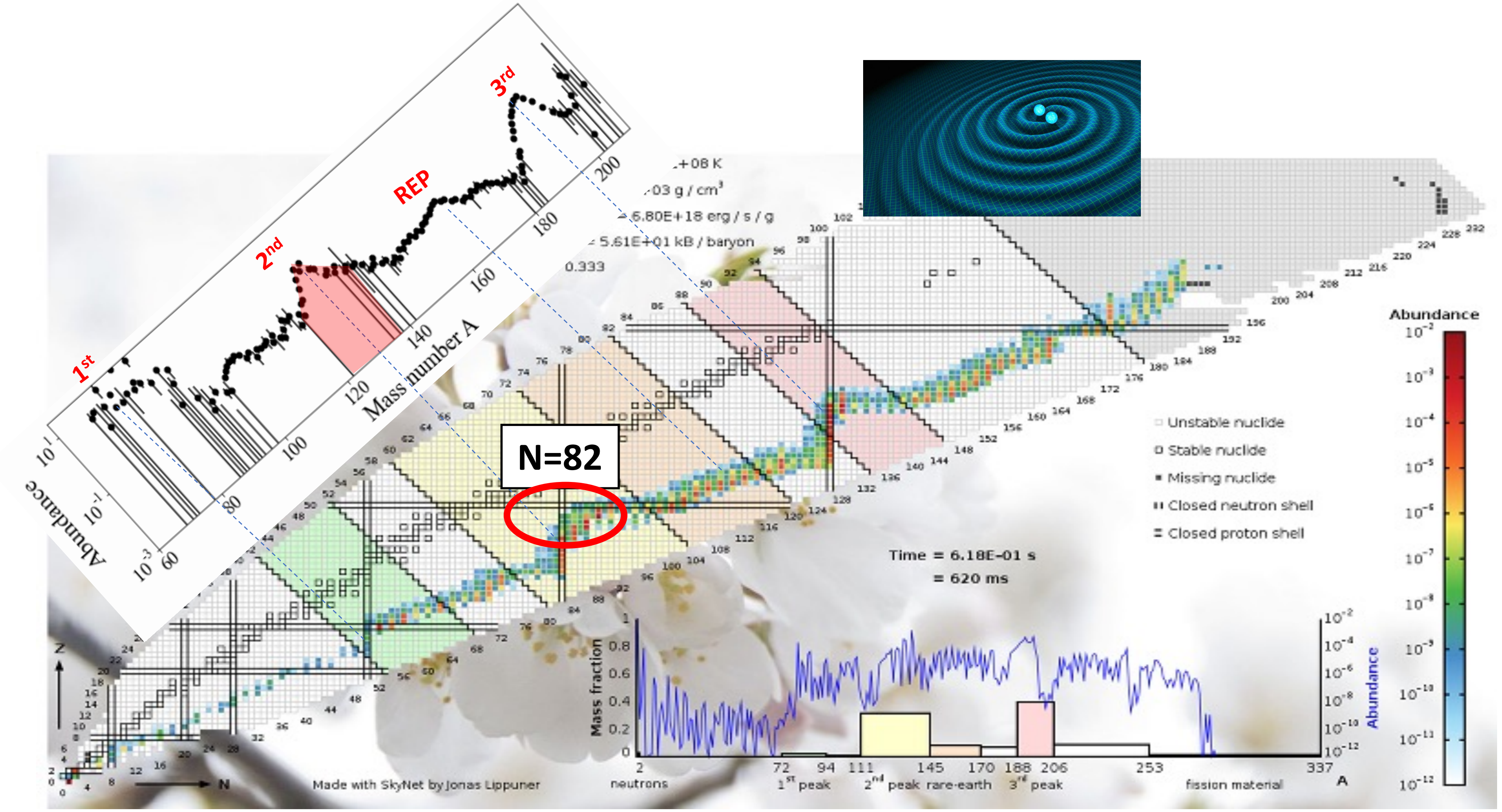
BRIKEN: Beta-delayed neutrons at RIKEN



✓ World's most efficient β-delayed neutron detector

A. Tarifeño-Saldivia et al.

Experimental β-decay properties relevant to the **second r-process peak**

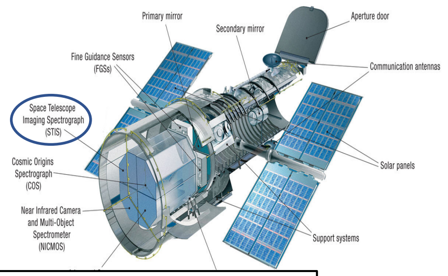


EURICA: G. Lorusso et al., **PRL** (2015); J. Wu et al., **PRC** (2021)
BRIKEN: O. Hall et al. **PLB** 816, 136266 (2021); VHP, G. Lorusso et al., **PRC** 100, 011302(R) (2019);
VHP, S. Nishimura, G. Lorusso et al., **PRL** 129, 172701 (2022)

Astrophysical observations related to the second r-process peak

Metal-poor stars: elemental abundances

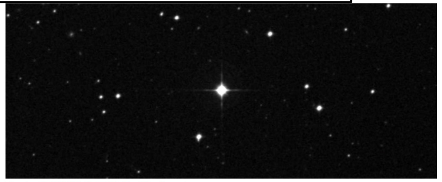
Hubble Space Telescope

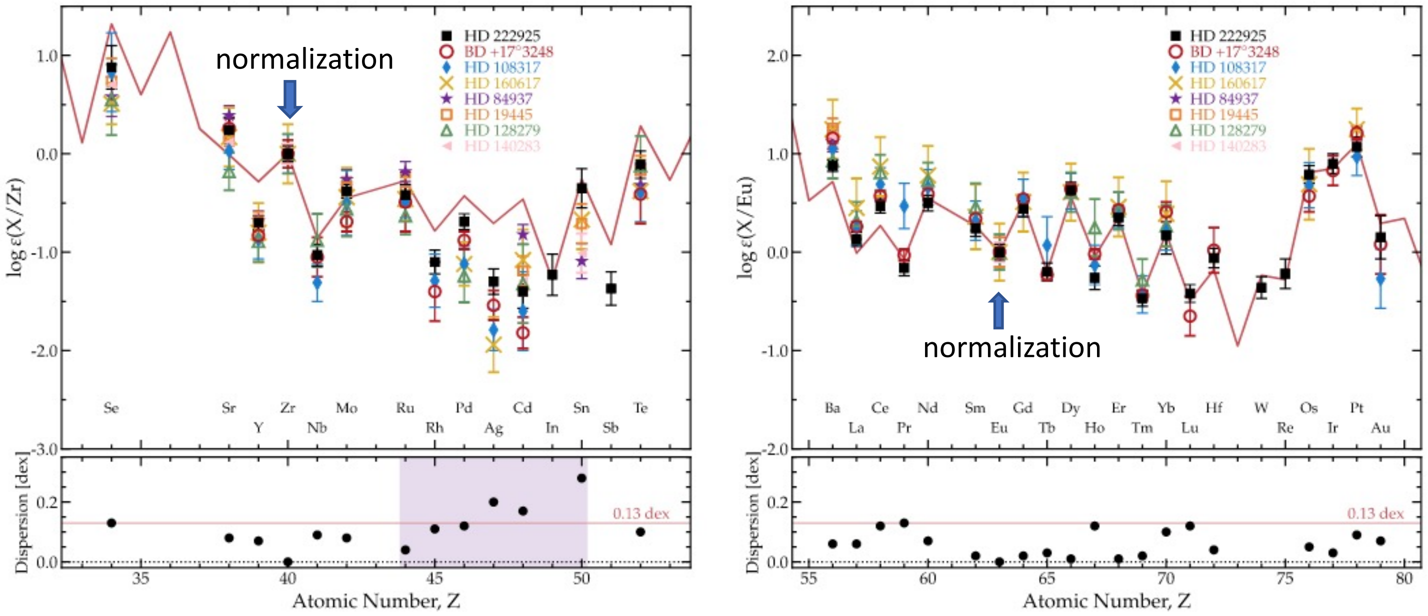



sciencealert

This Record-Breaking 'Gold Standard' Star Is Unlike Any We've Seen Before

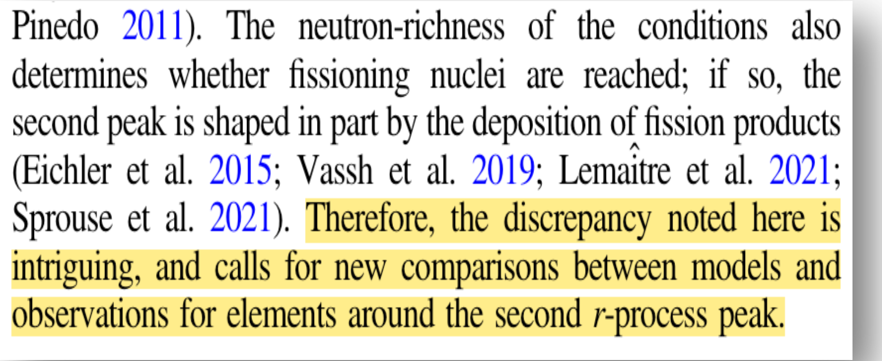
SPACE 13 May 2022 By MICHELLE STARR


The star HD 222925. (STScI Digitized Sky Survey)

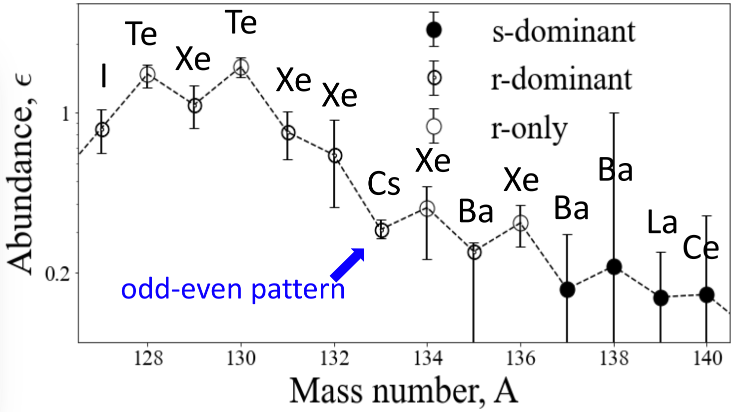


*I. U. Roederer et al., **ApJ** Suppl. 260, 27 (2022).*
*I. U. Roederer et al., **ApJ** 936, 84 (2022)*

- Star-to-**star** dispersions are generally small => "universality" for light – heavy elements.
- Star-to-**solar** discrepancies are large for Rh-Cd and **second r-process peak elements Sb, Te and Ba.**

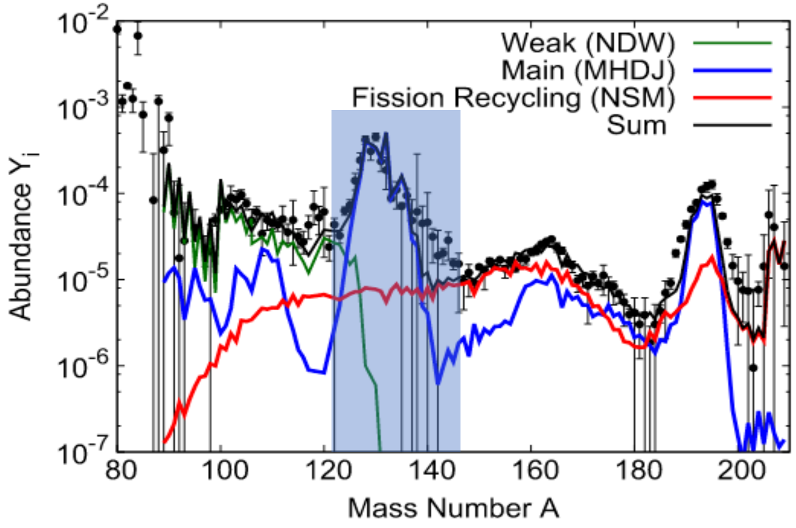

Pinedo 2011). The neutron-richness of the conditions also determines whether fissioning nuclei are reached; if so, the second peak is shaped in part by the deposition of fission products (Eichler et al. 2015; Vassh et al. 2019; Lemaître et al. 2021; Sprouse et al. 2021). Therefore, the discrepancy noted here is intriguing, and calls for new comparisons between models and observations for elements around the second *r*-process peak.

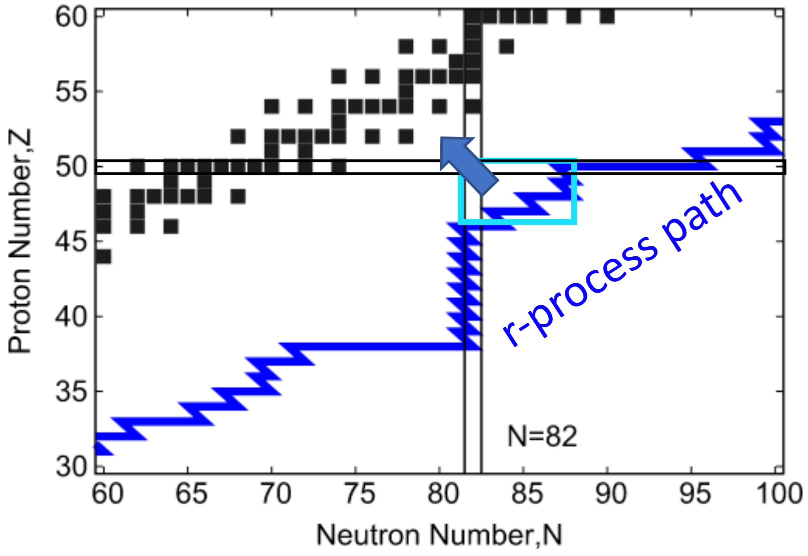
Solar-system r-process abundances



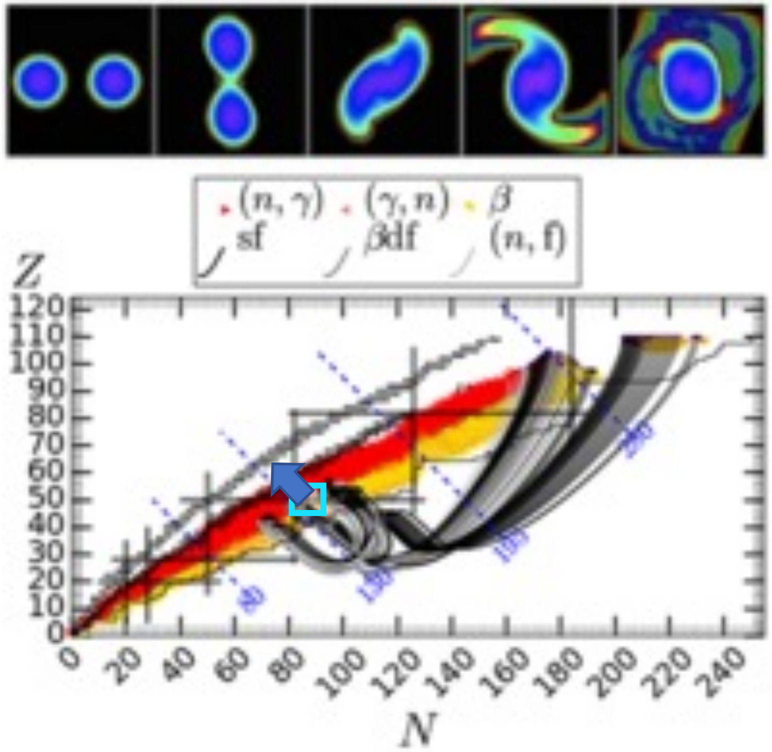
S. Goriely, A&A 342, 881 (1999).

Nucleosynthesis models for the second r-process peak

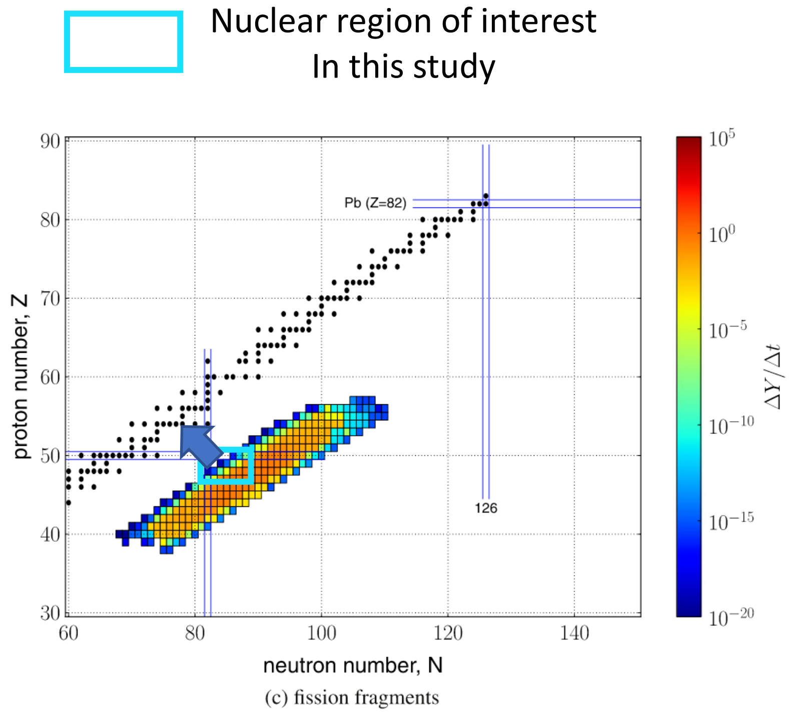




S. Shibagaki et al., **ApJ** 816:79 (2016): MHDJ model



S. Lemaître et al., **PRC** 103, 025806 (2021) : NSM model



(c) fission fragments

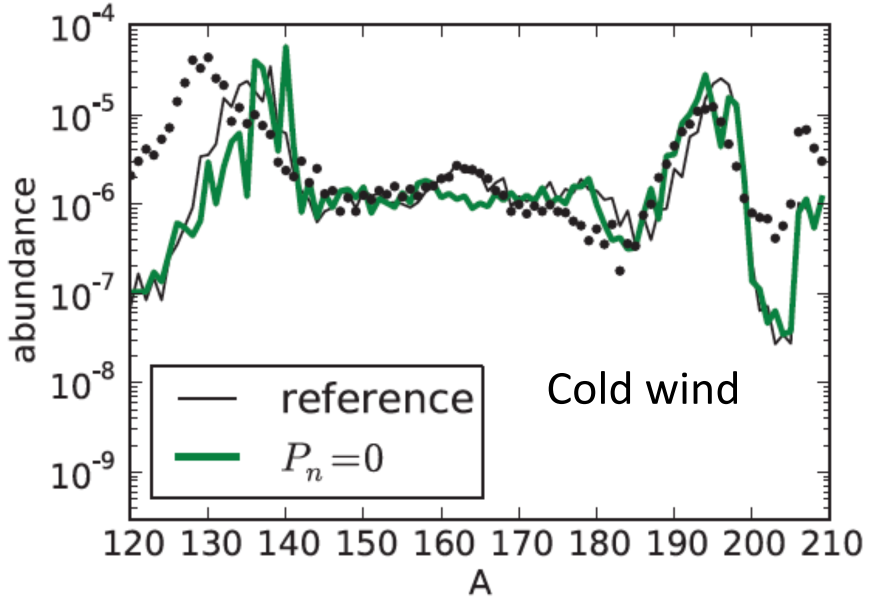
E. Eicher et al., ApJ 808:30 (2015)

❖ In various scenarios, abundance pattern of the second r-process peak is effectively shaped by the **β-decay path** to stability during freezeout, which mostly determined by the **β-delayed neutrons**

P_{xn} as important inputs for r-process calculations

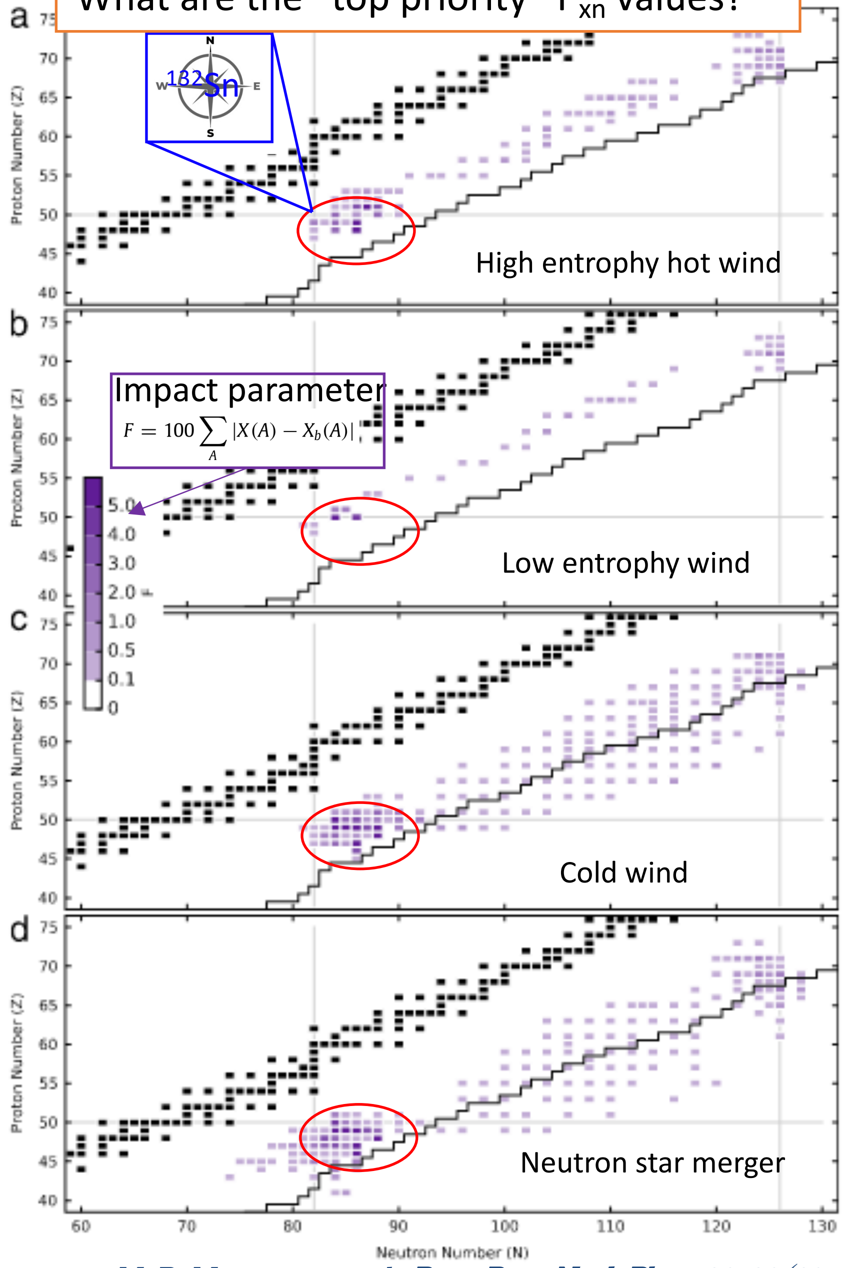
- **β-delayed x neutron branching ratios – emission probabilities (P_{xn})**
  - Altering the decay path to stability during freezeout

  => Modifying the odd-even staggering pattern
  - Additional source of neutrons for late-time neutron-captures



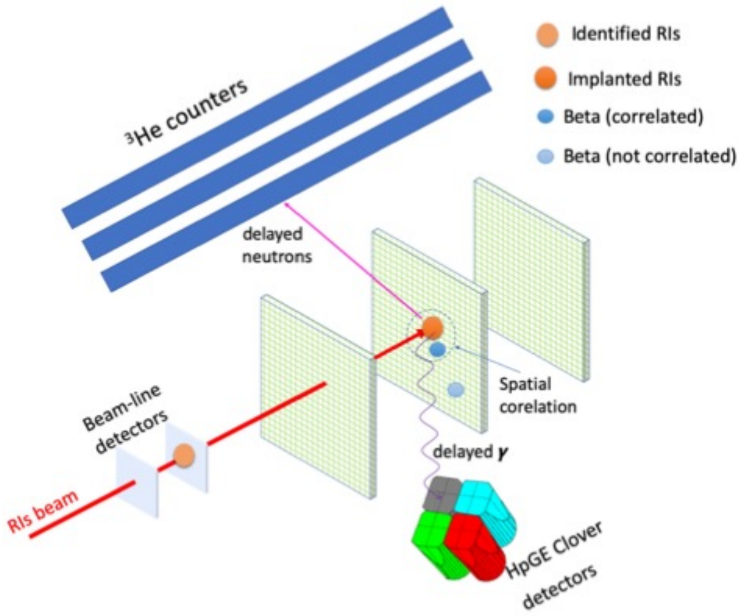
*Arcones, A., and G. Martínez-Pinedo., **PRC** 83 045809 (2011)*

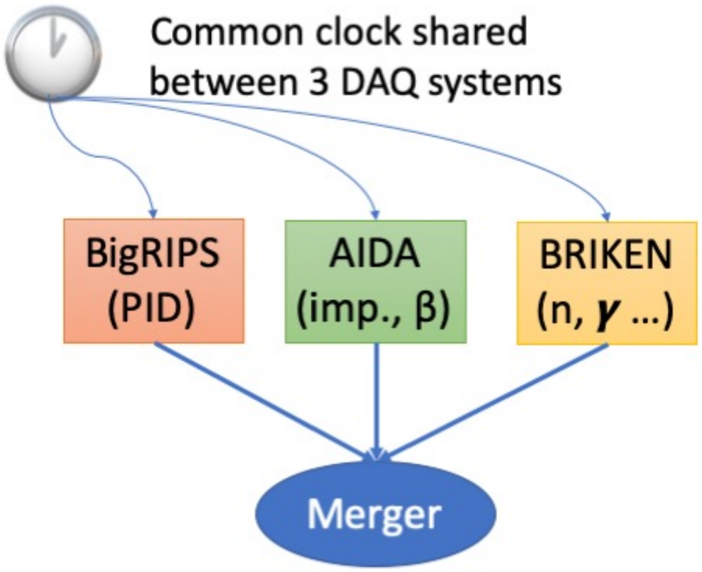
What are the "top priority" P_{xn} values?

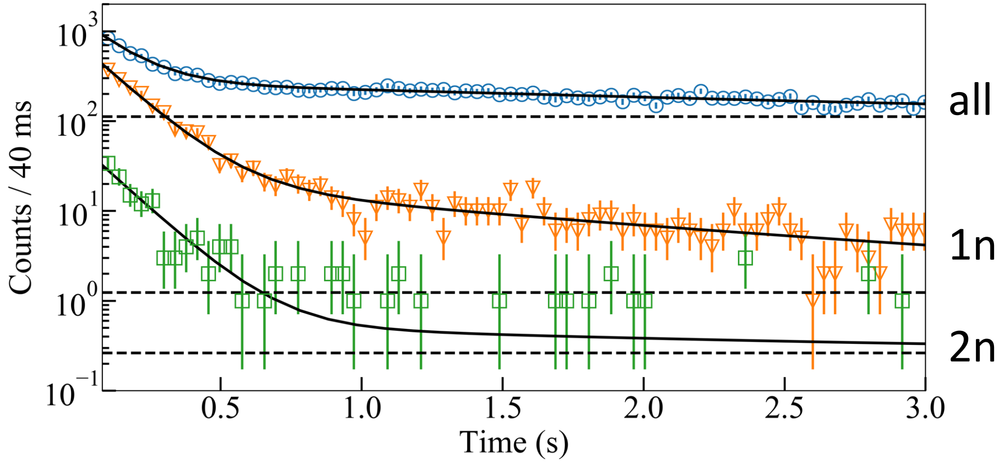


*M. R. Mumpower et al., **Prog. Part. Nucl. Phys.** 86, 86 (2016).]*

Data analysis: data merging and fits to extract P_{1n}, P_{2n} and $T_{1/2}$





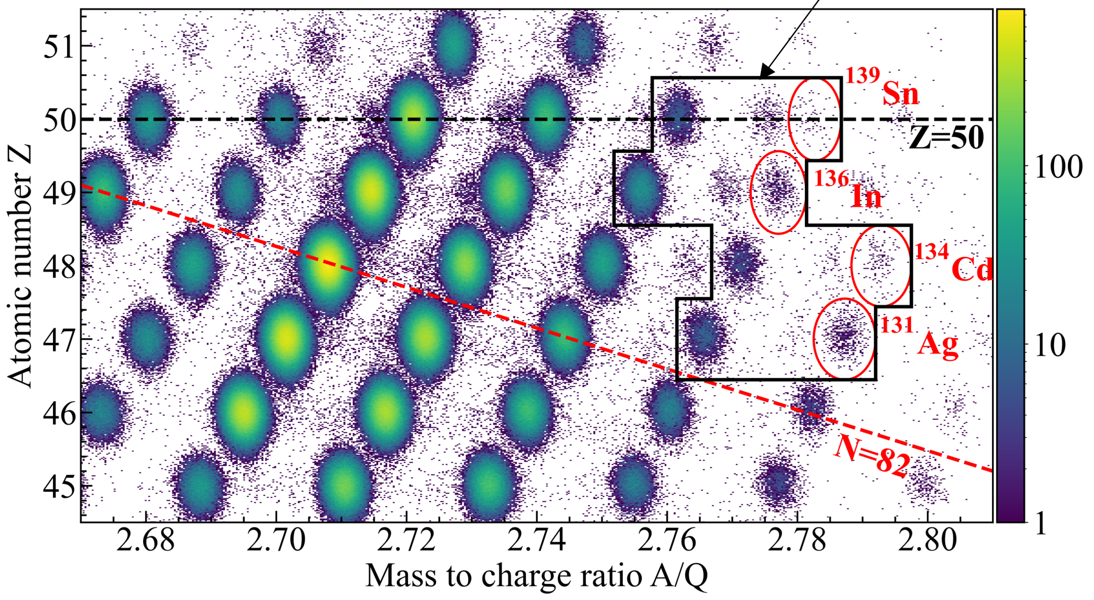


- Sorting the data produced from 3 independent DAQs
- Merging the data from 3 DAQs based on time-stamp
- Time and position correlation → β decay curves: $T_{\beta} - T_{implant}$ with/without neutron gates
- Fits to Bateman functions that include corrections for random coincidences to extract $T_{1/2}$, P_{1n} and P_{2n}

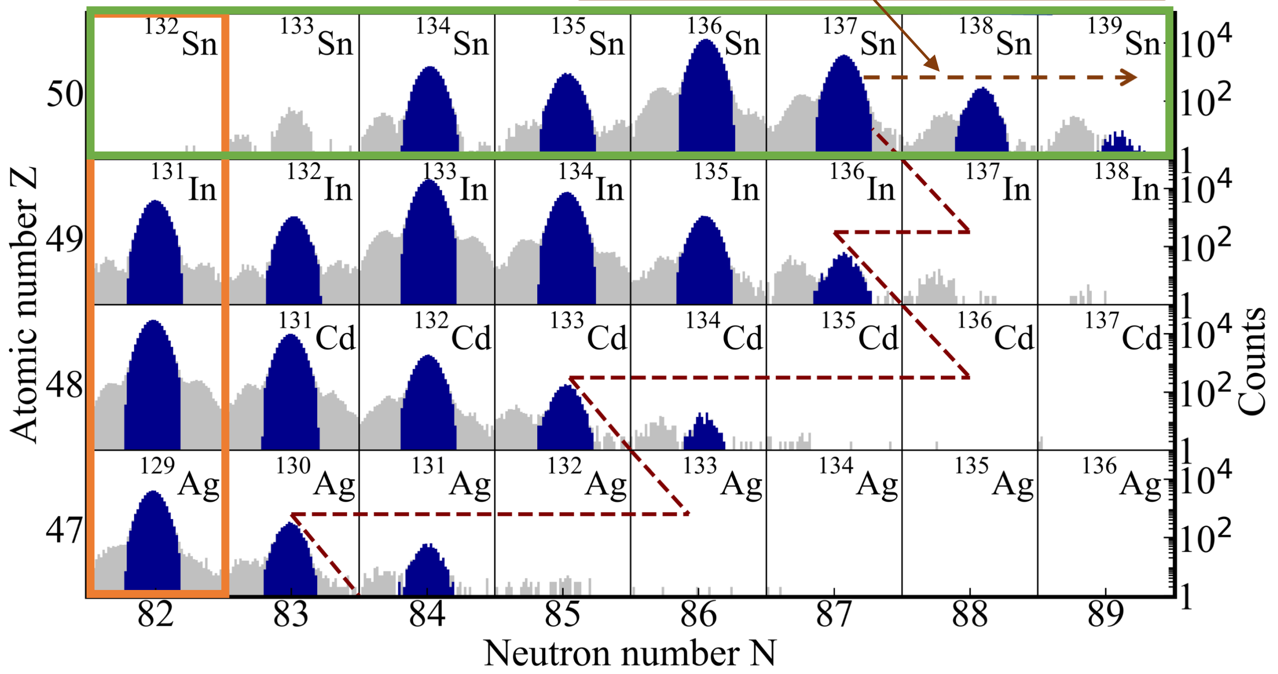
(VHP et al., **CIP** 28, 311 (2018), A. Tolosa-Delgado et al., **NIMA** 925, 133 (2019))

Identified isotopes

New P_{1n}/P_{2n} values



r-process path:
Shibagaki et al., **APJ** 816, 79 (2016)

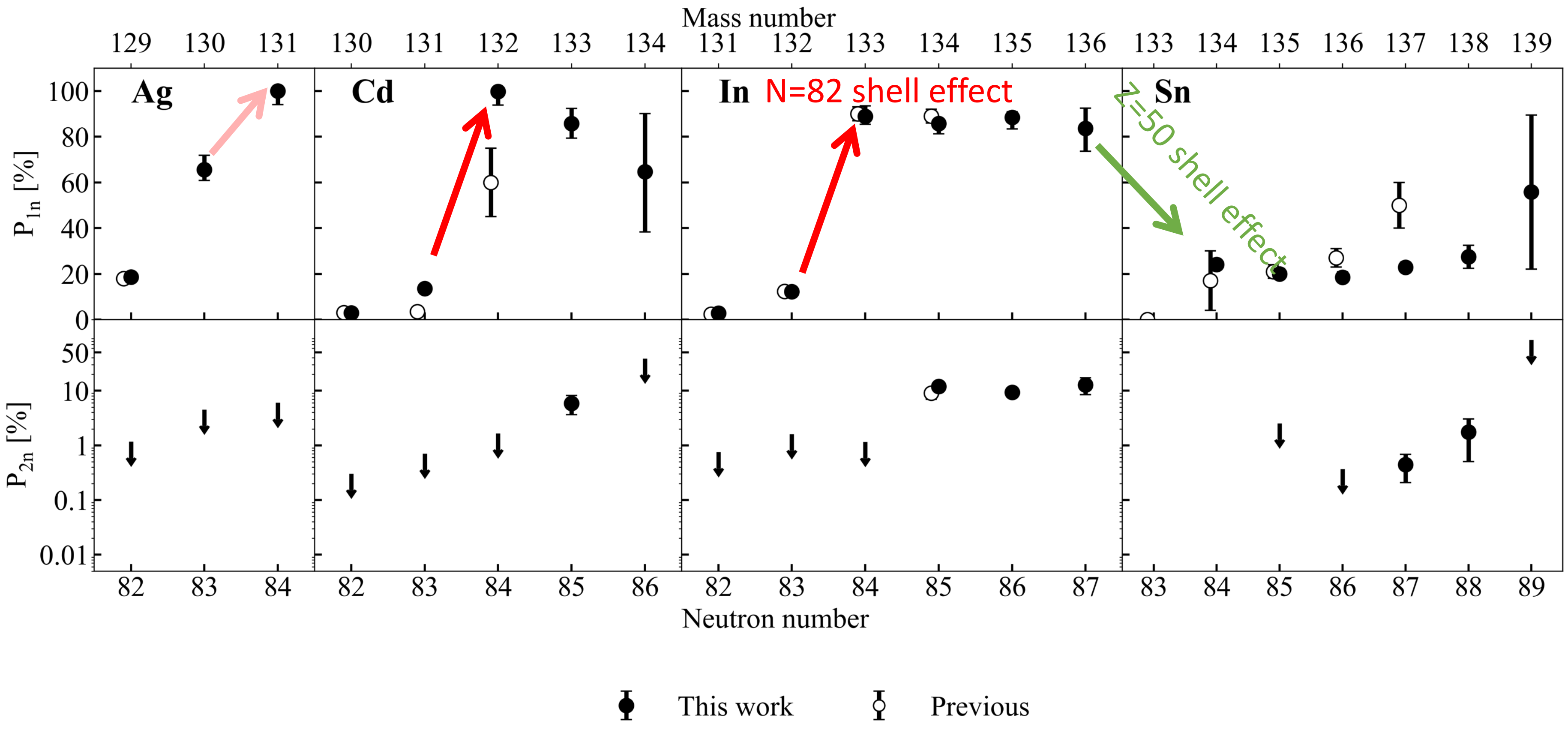


$P_{1n/2n}$ values of 20 neutron-rich nuclei across the Z=50 and N=82 shell closures:

- 8 new P_{1n} values in ^{130,131}Ag, ^{133,134}Cd, ^{135,136}In and ^{138,139}Sn
- 3 new P_{2n} values in ^{133}Cd and ^{135,136}In, and upper limits for all cases.

VHP, S. Nishimura, G. Lorusso et al., **PRL** 129, 172701 (2022)

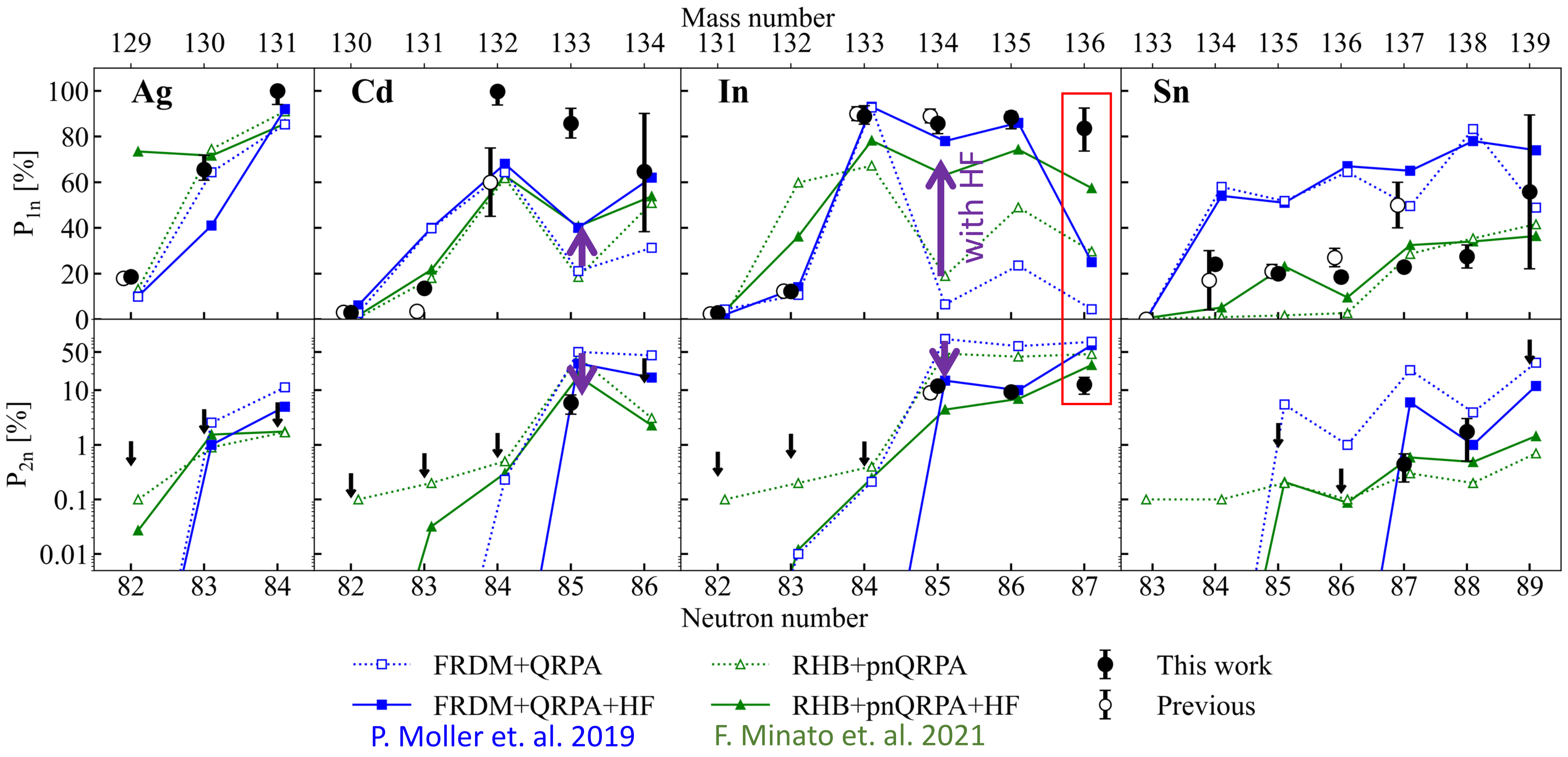
Experimental results: feedback to theoretical β decay models



- Nuclear shell effect on the P_n value due to the sudden changes in the S_n and/or Q_β values when crossing N=82 and Z=50 shell closure
- Important benchmarks for the theoretical models predicting P_{xn}:
  - Statistical Hauser-Feshbach (HF) models of competition between neutron emission channels
  - Large disagreements between the experimental data and theoretical calculations are observed for ^{136}In, $^{133\text{-}134}$Cd, Sn…

VHP, S. Nishimura, G. Lorusso et al., **PRL** 129, 172701 (2022)

Experimental results: feedback to theoretical β decay models

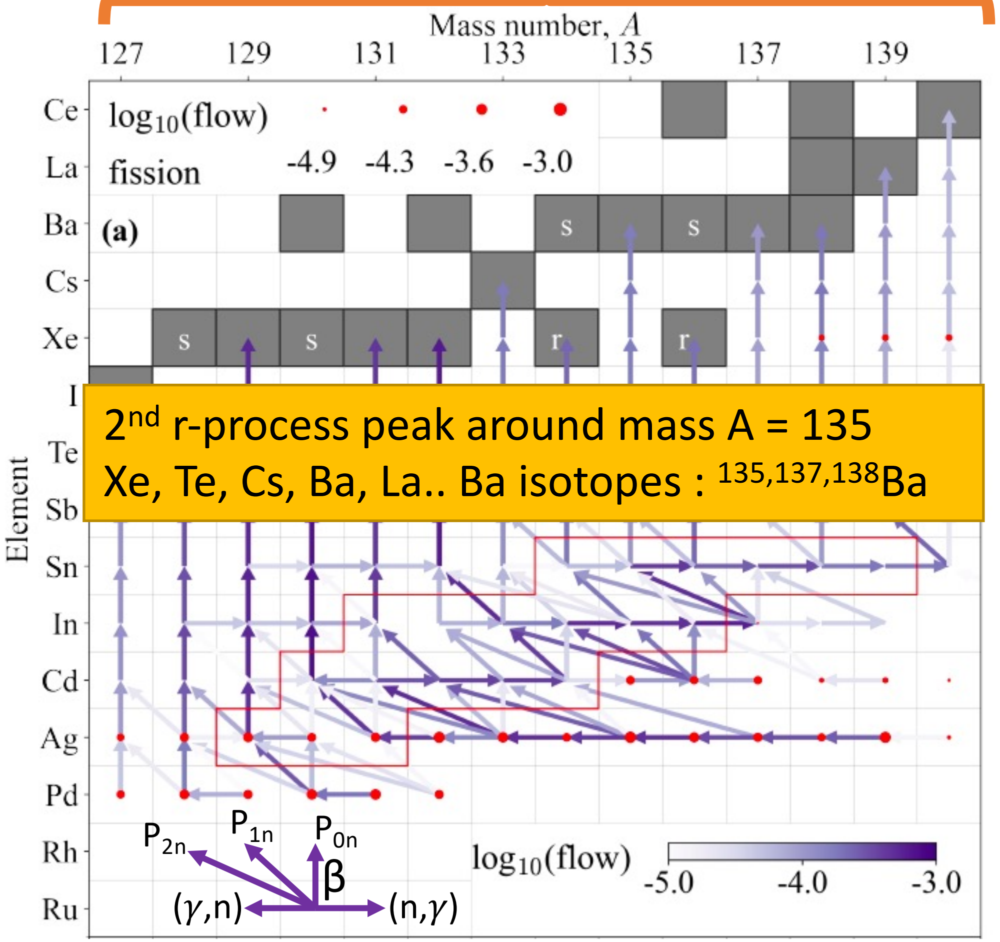


- Nuclear shell effect on the P_n value due to the sudden changes in the S_n and/or Q_β values when crossing N=82 and Z=50 shell closure
- Important benchmarks for the theoretical models predicting P_{xn}:
  - Statistical Hauser-Feshbach (HF) models of competition between neutron emission channels
  - Large disagreements between the experimental data and theoretical calculations are observed for ^{136}In, $^{133\text{-}134}$Cd, Sn…

VHP, S. Nishimura, G. Lorusso et al., **PRL** 129, 172701 (2022)

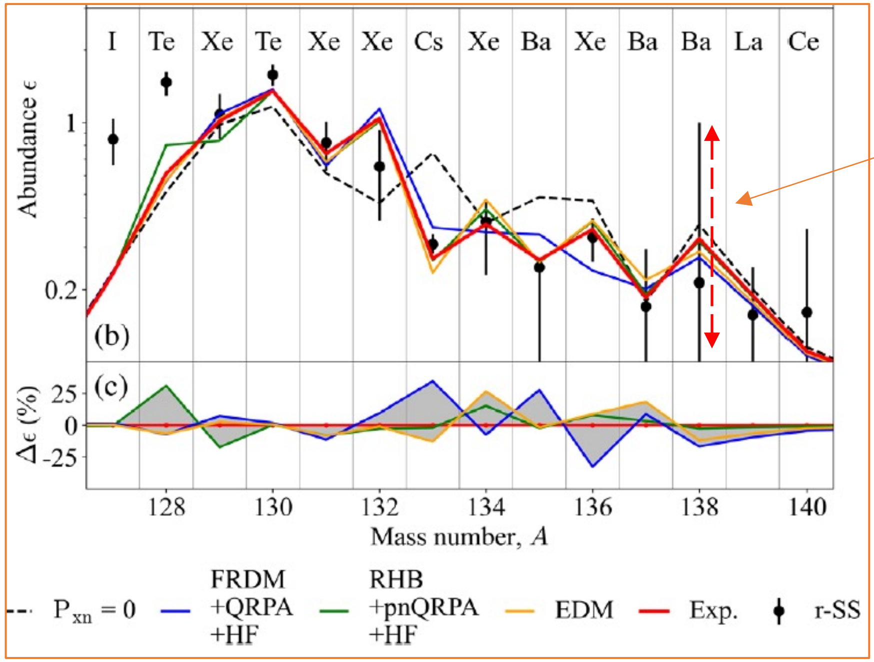
Impact on the odd-even pattern of the second r-process peak

Reaction flows after freezeout…



2nd r-process peak around mass A = 135
Xe, Te, Cs, Ba, La.. Ba isotopes : ^{135,137,138}Ba

… and final abundances



Large error due to dominant s-process component

- Significant contribution of **β1n** and **β2n** flows affects the **odd-even** pattern in the right-wing of the second r-process peak
- Effect on shaping final odd-even pattern is prominent **with and without β-delayed neutrons**
- Removing up to **30 % uncertainties** deriving from theoretical models

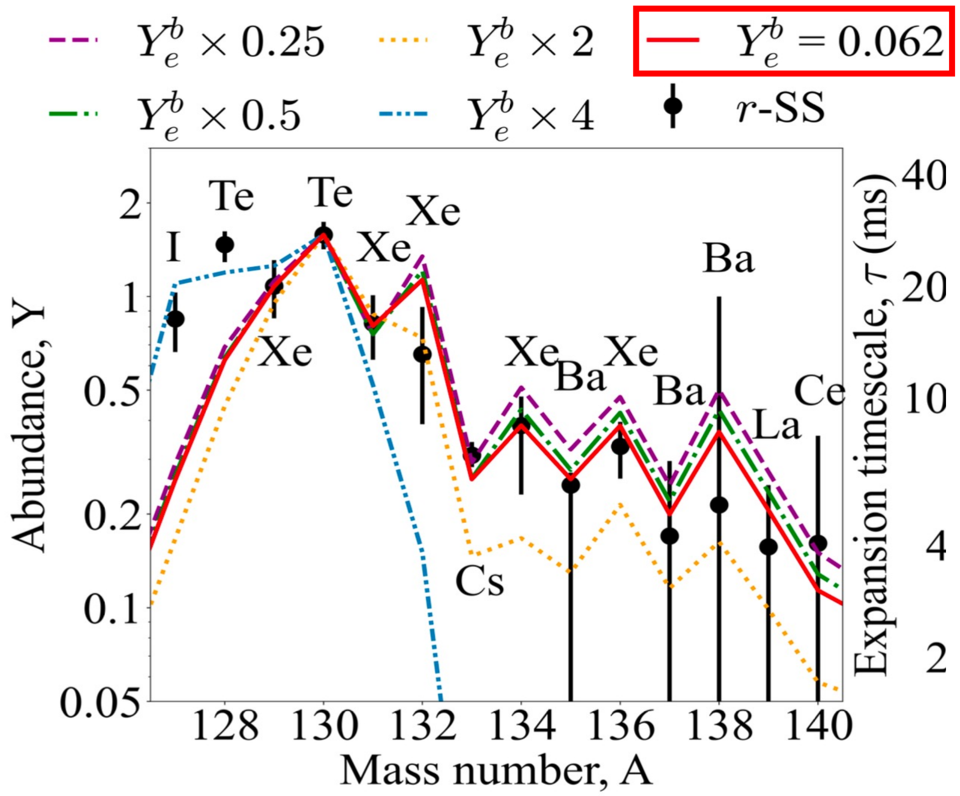
Skynet + Nucnet codes [J. Lippuner 2015, B. S. Mayer 2007]

Baseline simulation: Y_e = 0.062, **S** = 12 kb/b and **τ** = 66 ms: reproduce abundance mass range A=129-139

VHP, S. Nishimura, G. Lorusso et al., **PRL** 129, 172701 (2022)

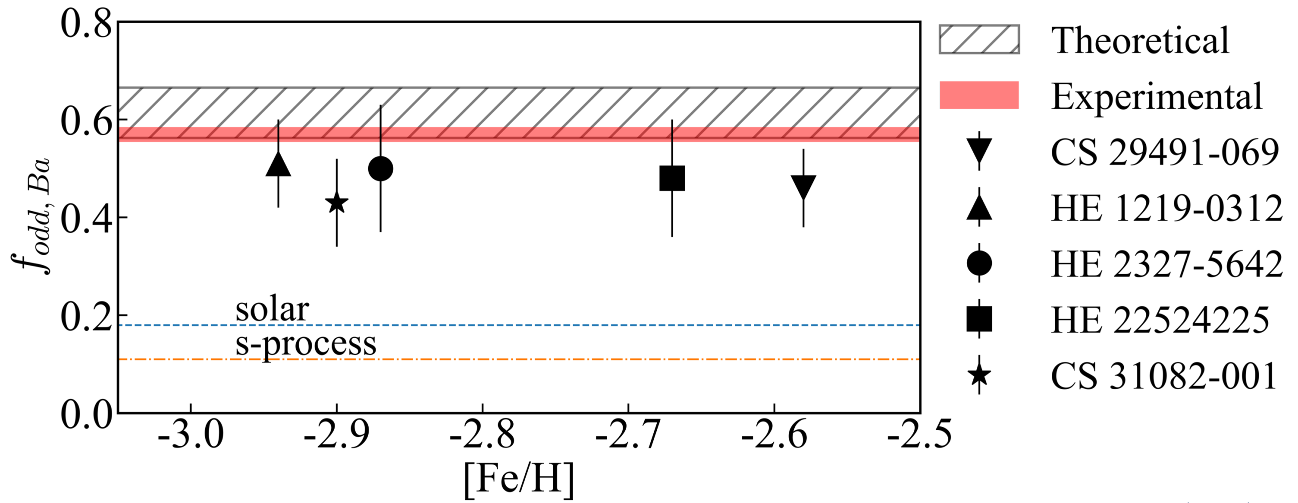
Constrains on the odd-mass isotopic fraction of Ba

❖ Ye dependance of odd-even systematic



❖ Improvement of Ba isotopic fraction abundances using the current experimental results

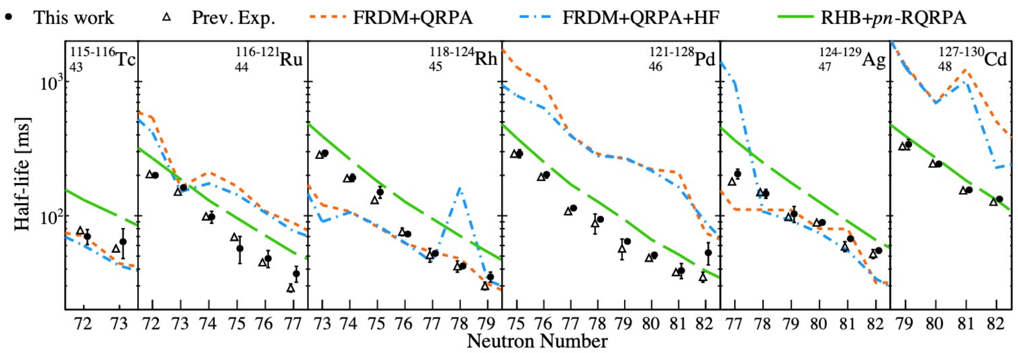
Odd-mass isotopic fraction of Ba: $f_{odd,Ba} = (Y_{135Ba} + Y_{137Ba})/Y_{Ba}$



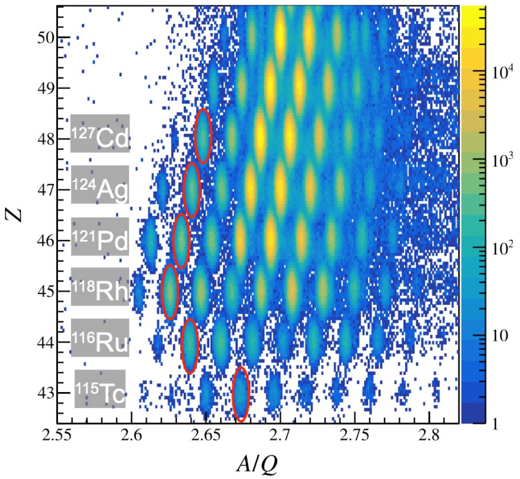
X. Y. Meng et al., Astron. Astrophys. 593, A62 (2016).
C. Wenyuan et al., Astrophys. J. 854, 131 (2018).

VHP, S. Nishimura, G. Lorusso et al., **PRL** 129, 172701 (2022)

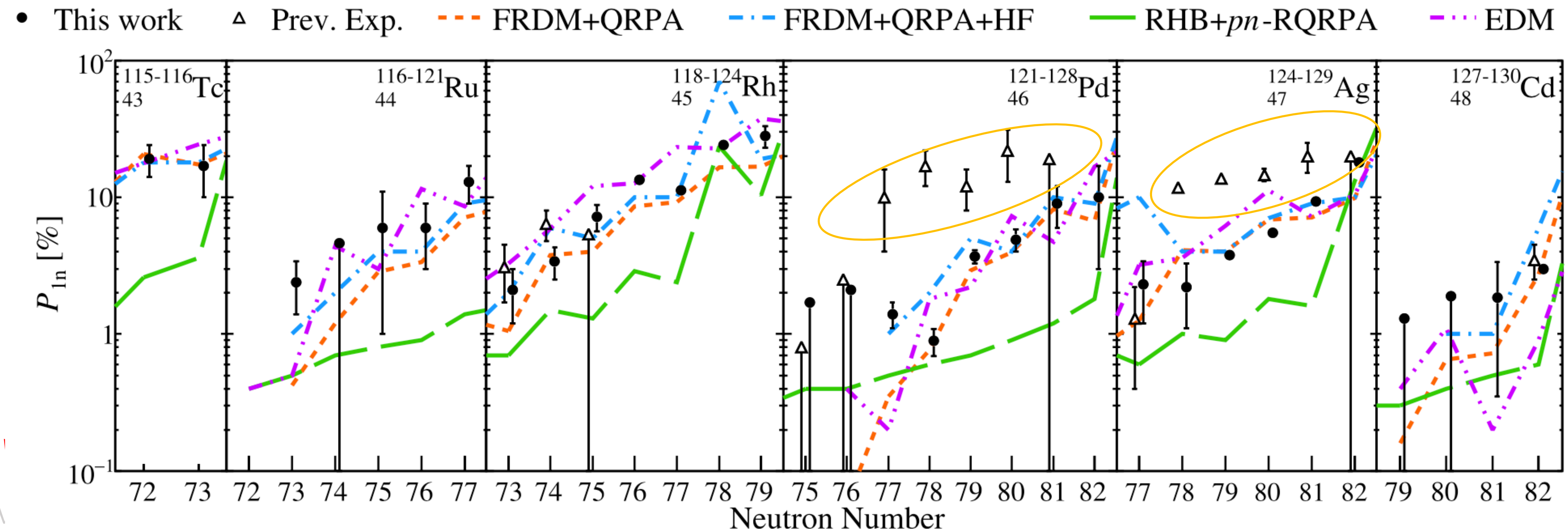
BRIKEN data reaching N=82 ("southwest" of ^{132}Sn)



$T_{1/2}$ … consistent with EURICA

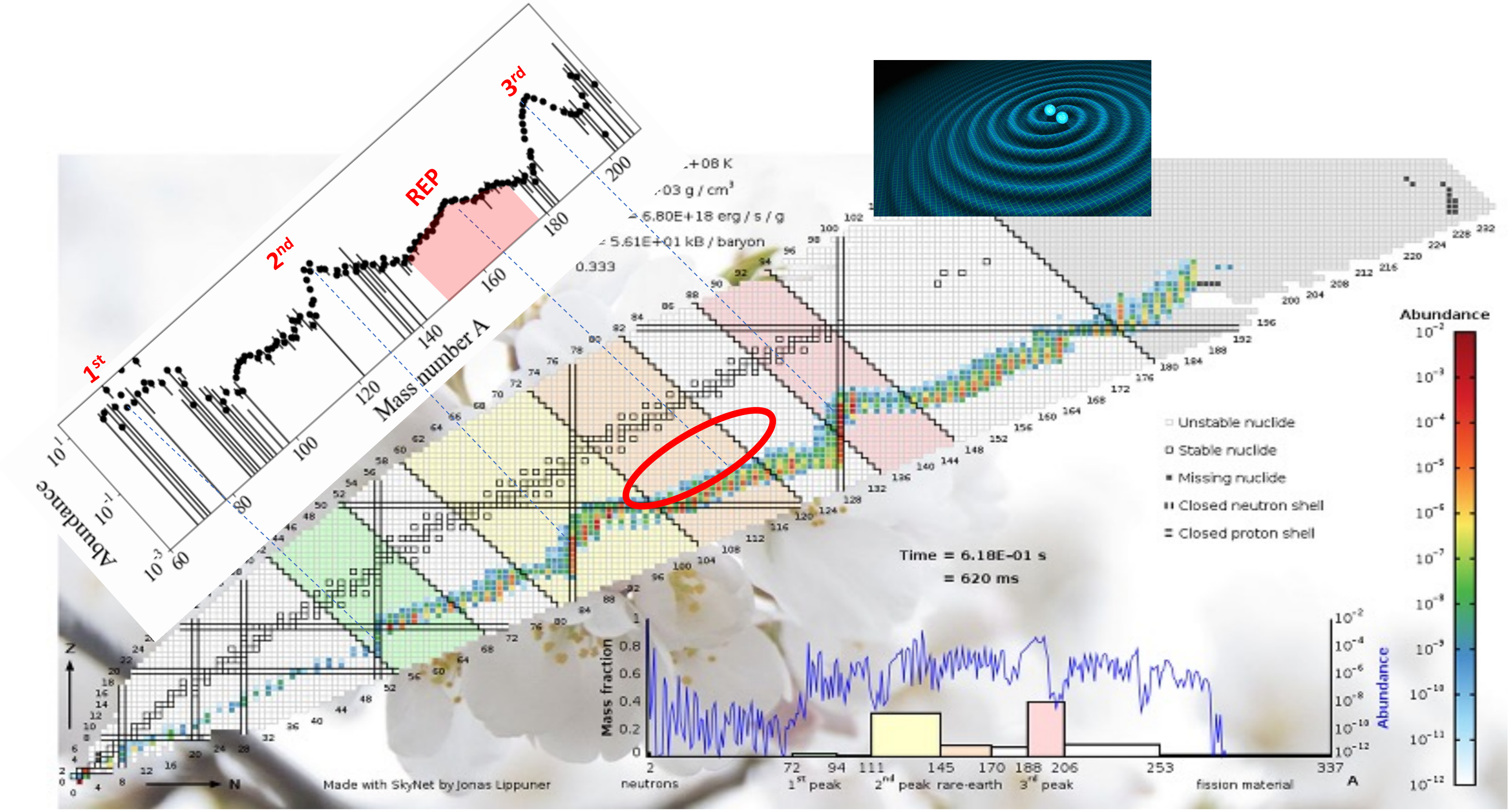


O. Hall. et al. **PLB** 816, 136266 (2021)



PhD thesis from GSI

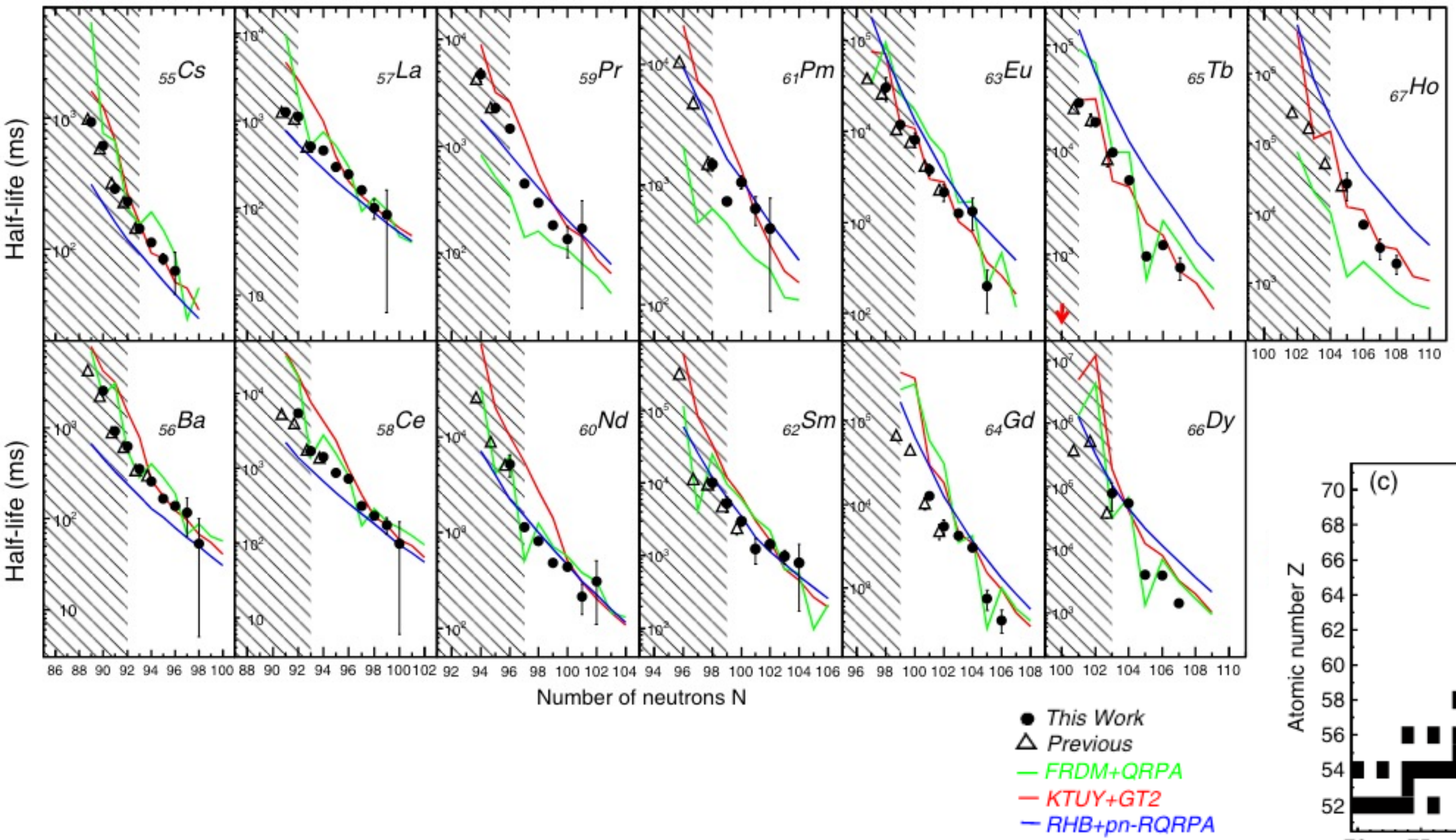
Masses and β -decay properties relevant to the Rare earth peak

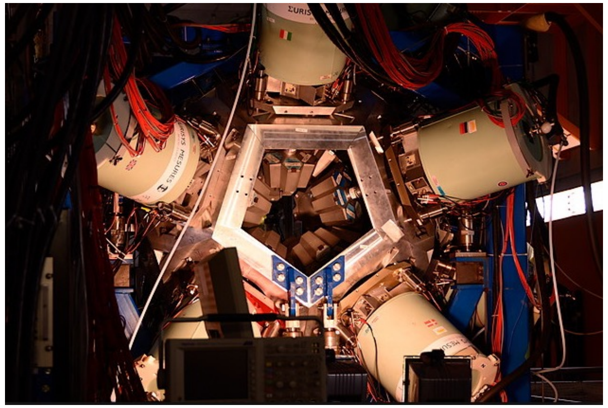


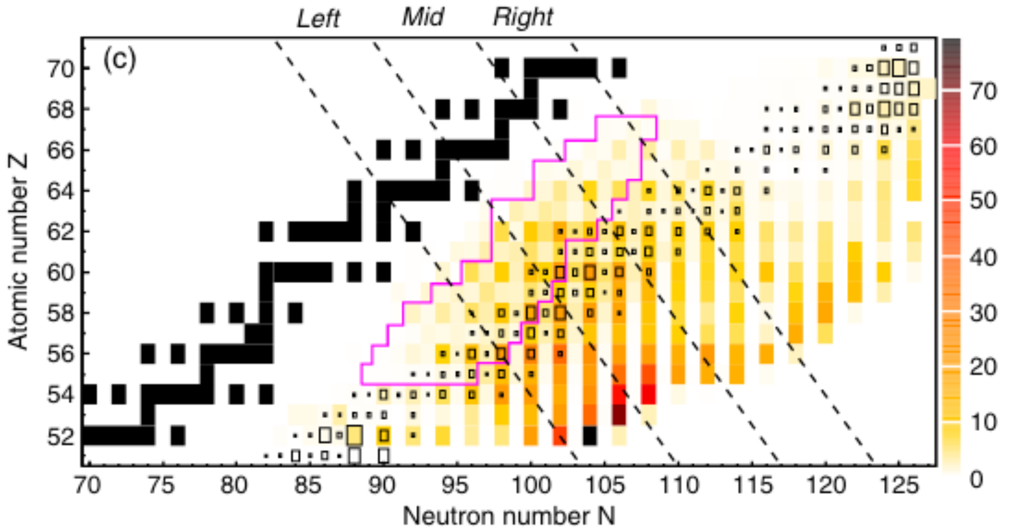
EURICA: J. Wu et al., **PRL** 118, 072701 (2017).
BRIKEN: G. Kiss et al., **ApJ** 936:107 2022 (2022).

β-decay half-lives relevant to the Rare earth peak

J. Wu et al., **PRL** 118, 072701 (2017)



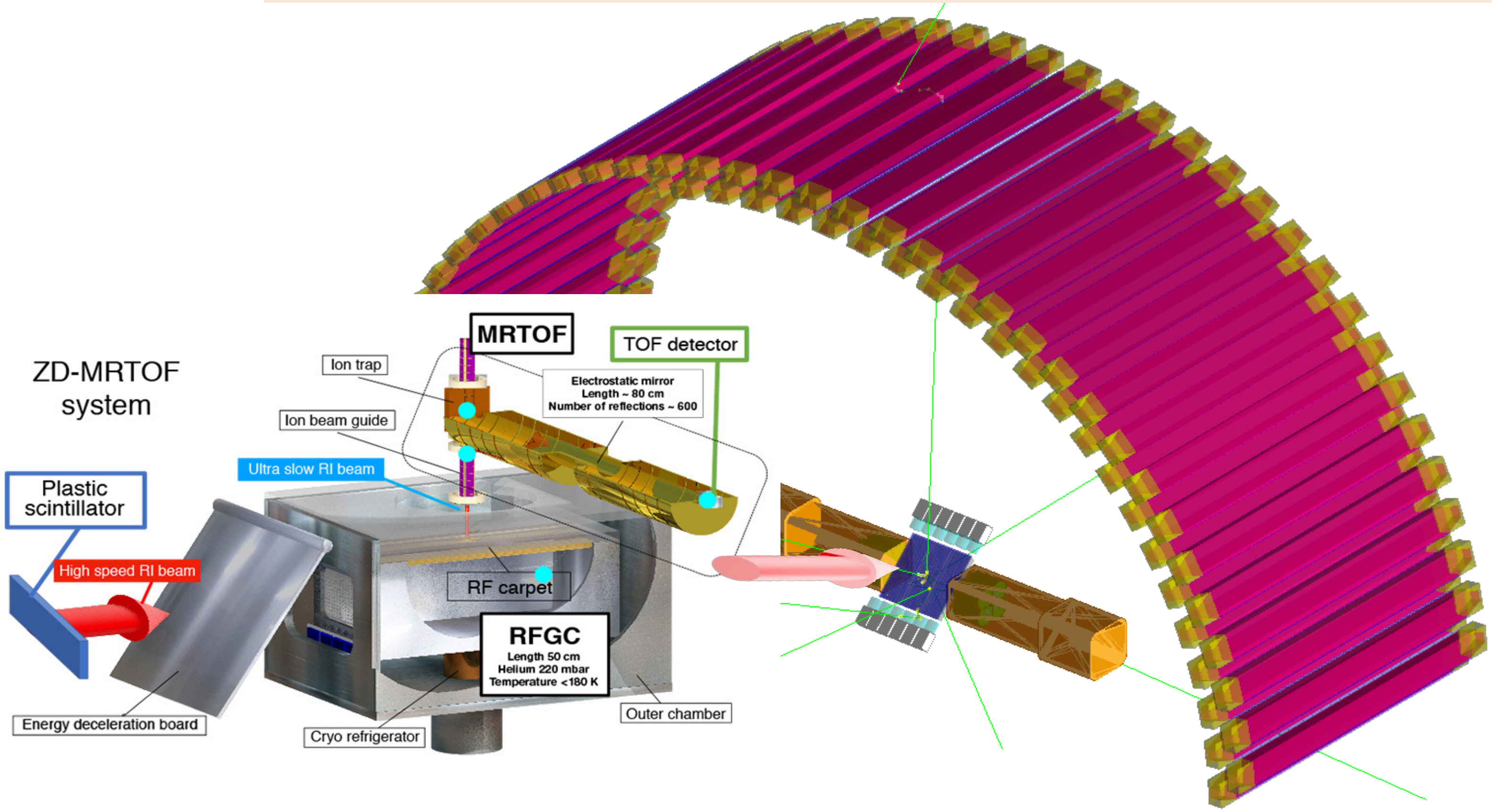




Proposed experiment: Masses and β-decay properties relevant to REP

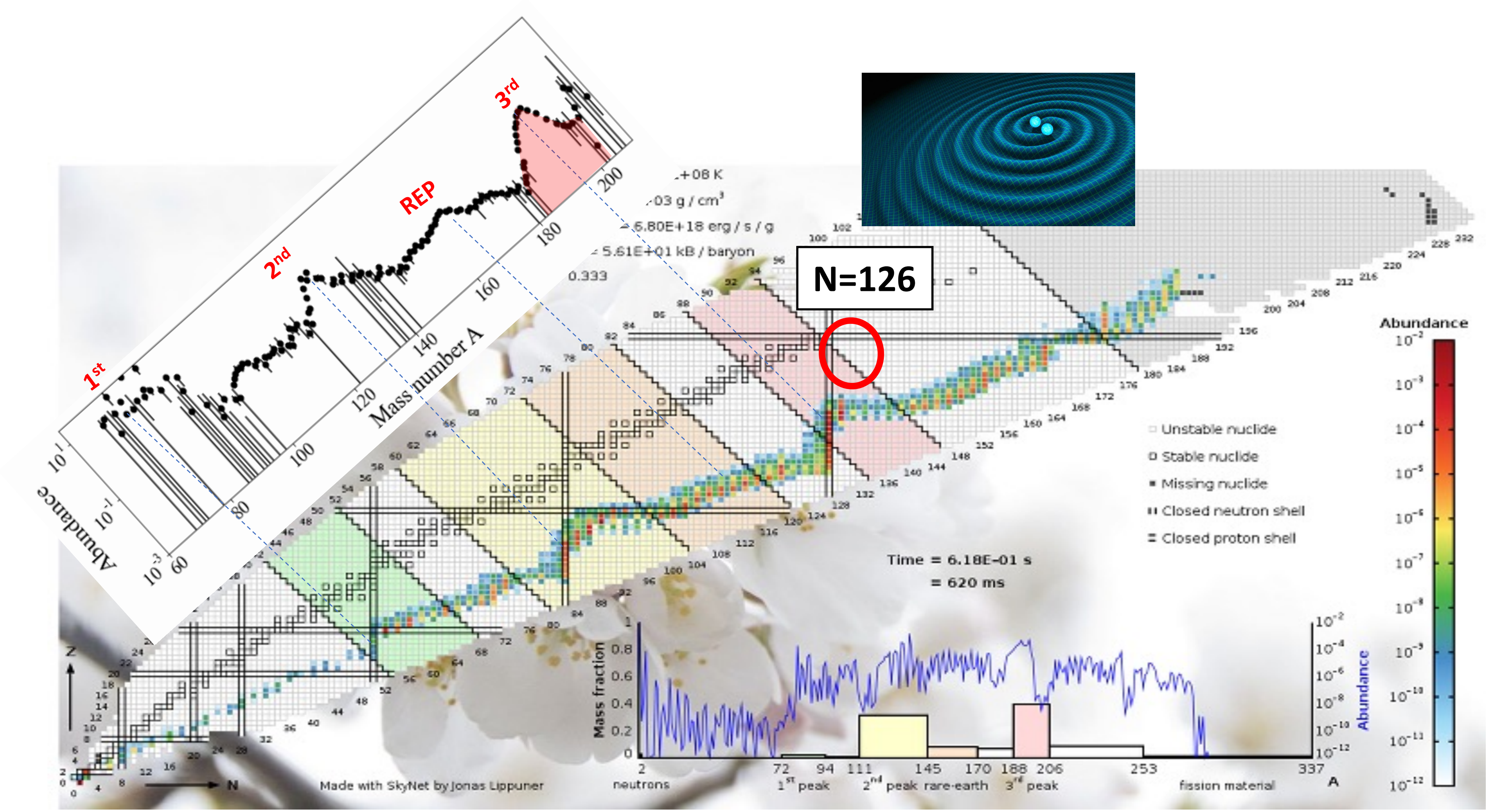
Spokespersons: S. Nishimura , M. Wada

Simultanous measurement of nuclear mass and β decay properties!



ZDMRTOF setup: Wada-san talk on Tuesday

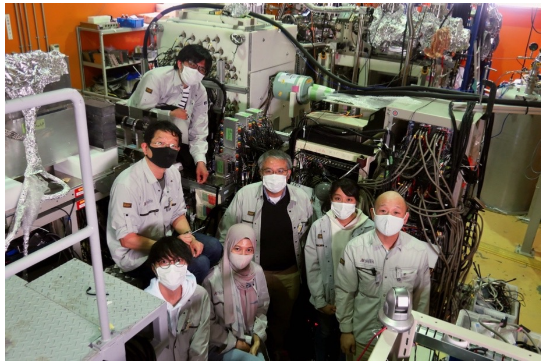
Experimental β-decay properties relevant to the **third r-process peak**

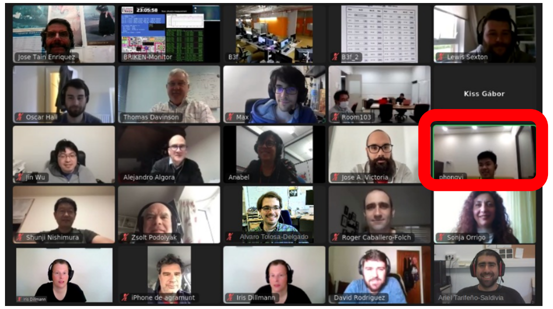


BRIKEN: J.Wu, S. Nishimura ,T.Davinson, J.L.Tain (experiment finished)
DTAS: A. Morales, VHP, Z. Podolyák, A. Tolosa-Delgado (accepted experimental proposal)

BRIKEN experiment in the vicinity of N=126

Spokespersons: J.Wu, S. Nishimura ,T.Davinson, J.L.Tain



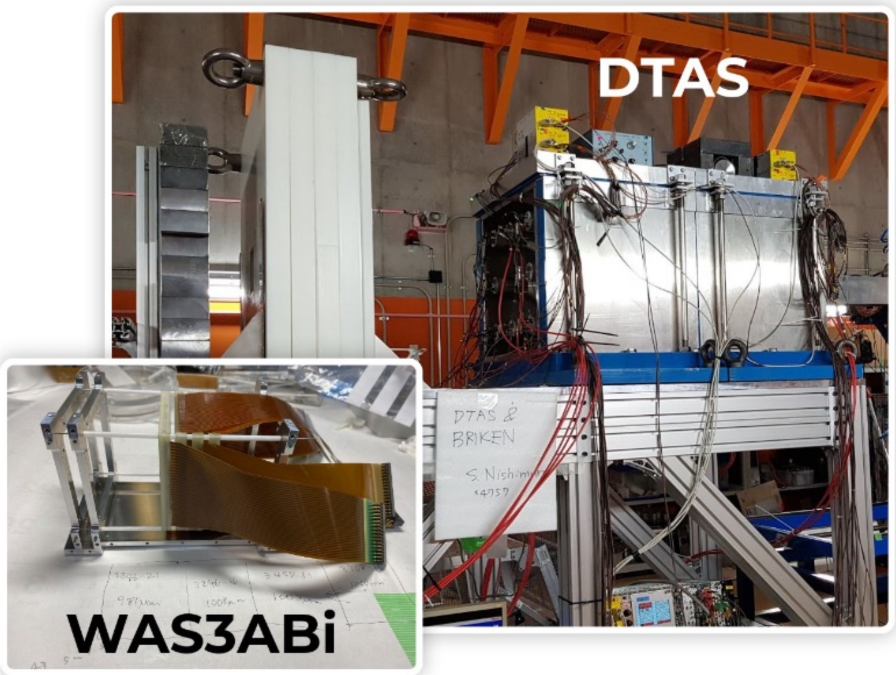


❖ Analysis undergoing!

Shell evolution beyond ^{208}Pb

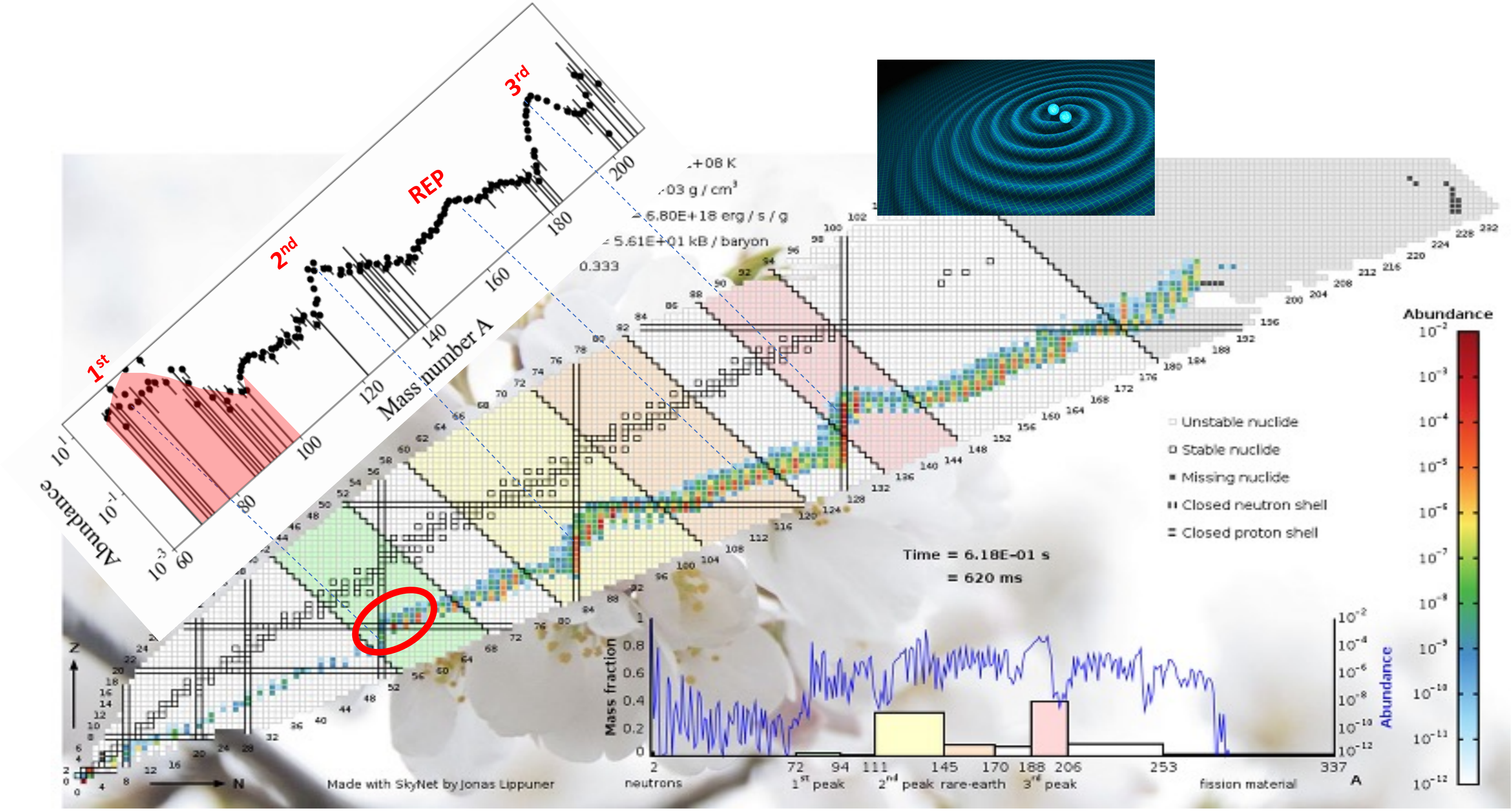
TATAKI-Pro* setup
Total **A**bsorption spectroscopy
Technique **A**ppliced to **K**ey **I**sotopes
in r-**Pro**cess nucleosynthesis

Spokespersons: A. Morales, VHP, Z. Podolyák, A. Tolosa-Delgado



❖ To be performed

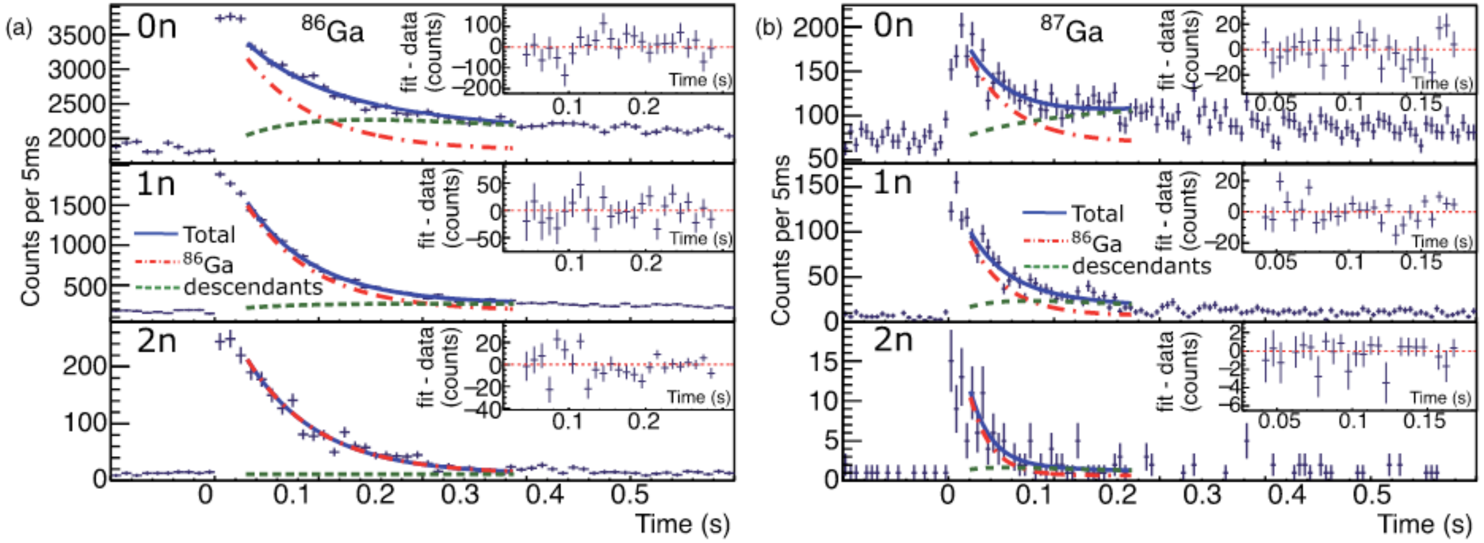
Experimental β-decay properties relevant to the **first r-process peak**

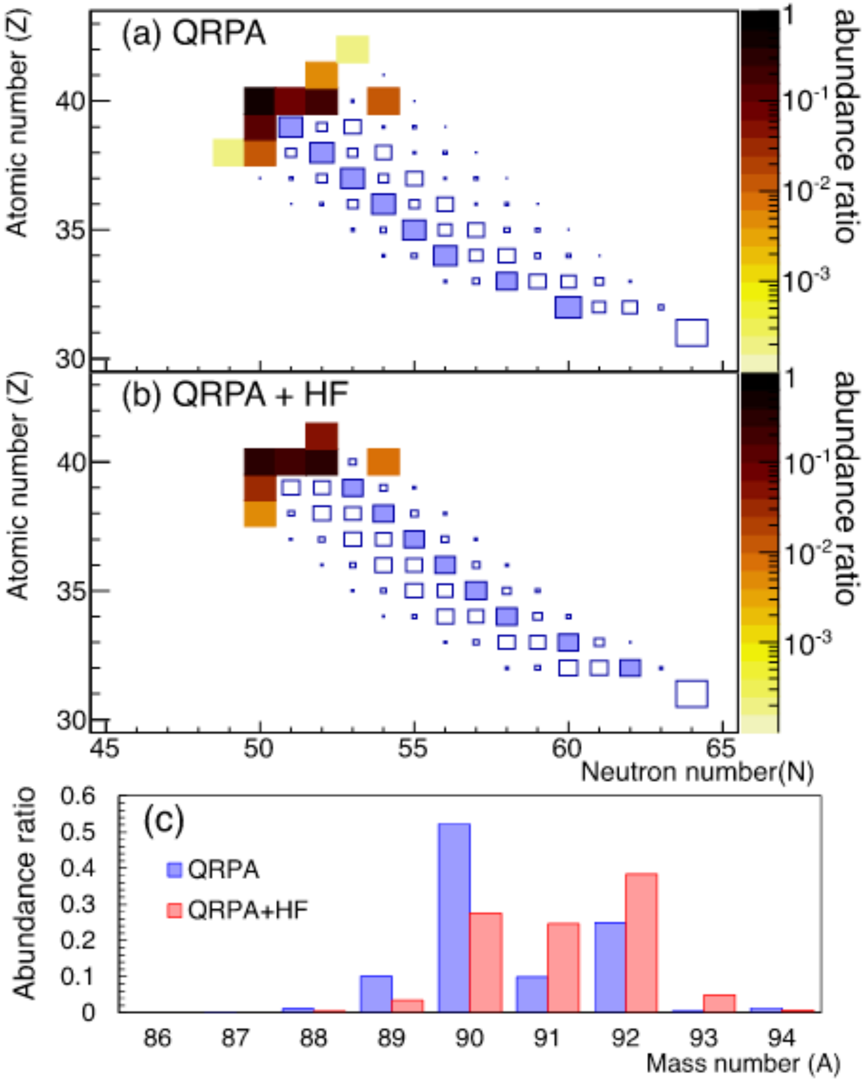


EURICA: Z.Xu et al, **PRL** 113, 032505 (2014)
BRIKEN: R. Yokoyama, **PRC** 100, 031302(R) (2019)

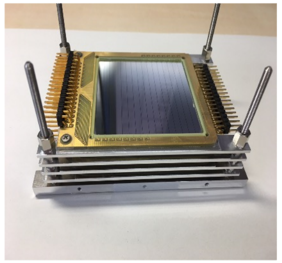
New BRIKEN data around N=50 magic number

R. Yokoyama et al., **PRC** 100, 031302(R) (2019)

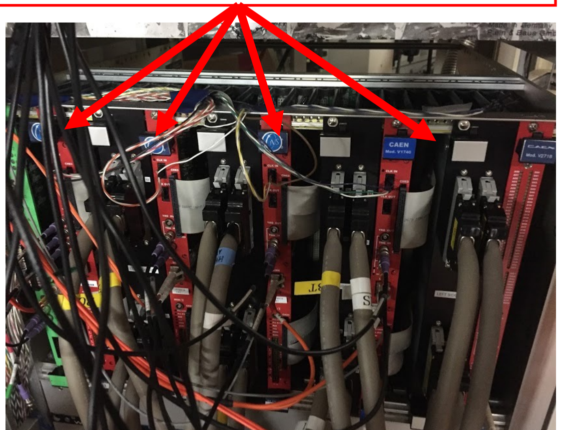




WAS3ABi (Wide- range Active Silicon-Strip Stopper Array for Beta and ion detection



CAEN V1740 flash-ADC (Digitizer)



Summary

Harvesting the **β-decay properties** is in progress at RIBF focusing on the **major r-process peaks**

- EURICA (2012 – 2016)
- BRIKEN (2016 - 2021)
- DTAS, IDATEN in progress and ZD-MRTOF & TOFU (fast timing) in future

2^{nd} r-process peak

- ❖ New astrophysical observations of the elements of the second r-process peak **calls for new comparison between models and observation.**
- ❖ New experimental data provide benchmarks for development of **theoretical β-decay models** and directly **impacts on the odd-even pattern** of the second r-process peak, **improving** the calculation of **odd Ba fractions** matching the metal-poor star observations.

Thank you for your attention!