RIKEN

# 中性子捕獲反応と元素合成：

# 鍵を握る原子核データの収集と研究戦略

西村俊二 （理研）

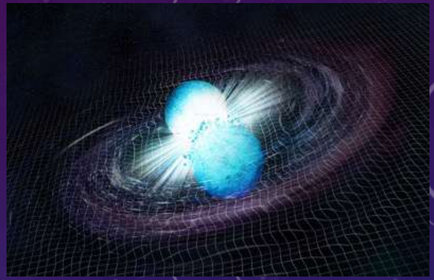
グローバルなr過程の理解　←→　r過程の局所的な元素成分の構造の理解

「r過程・フリーズアウト時の元素合成が重要」

β崩壊の崩壊レートに加え、遅発中性子、質量、中性子捕獲反応が重要な鍵を握る。

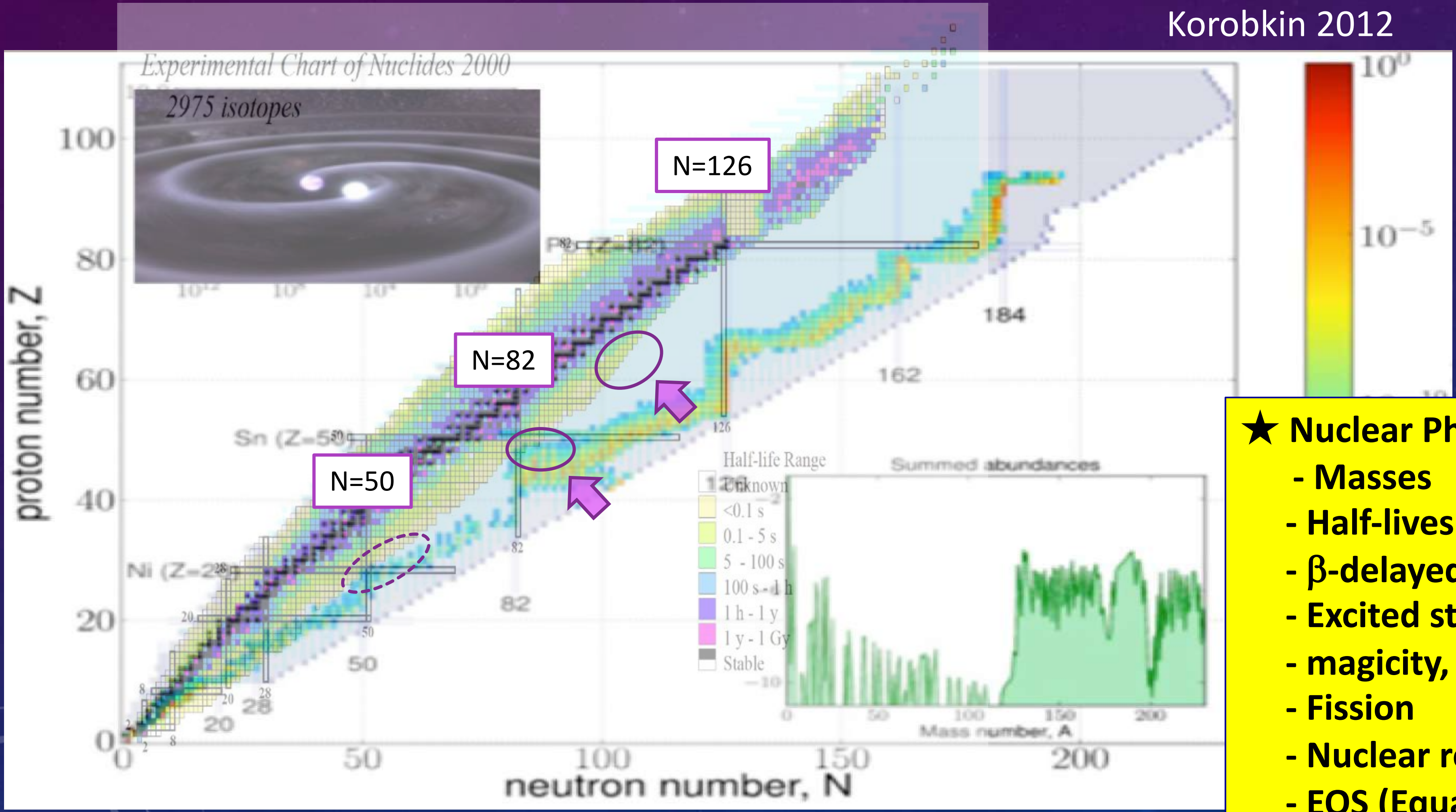
# r-過程の環境と中性子過剰な原子核

連星中性子星の合体



超新星爆発

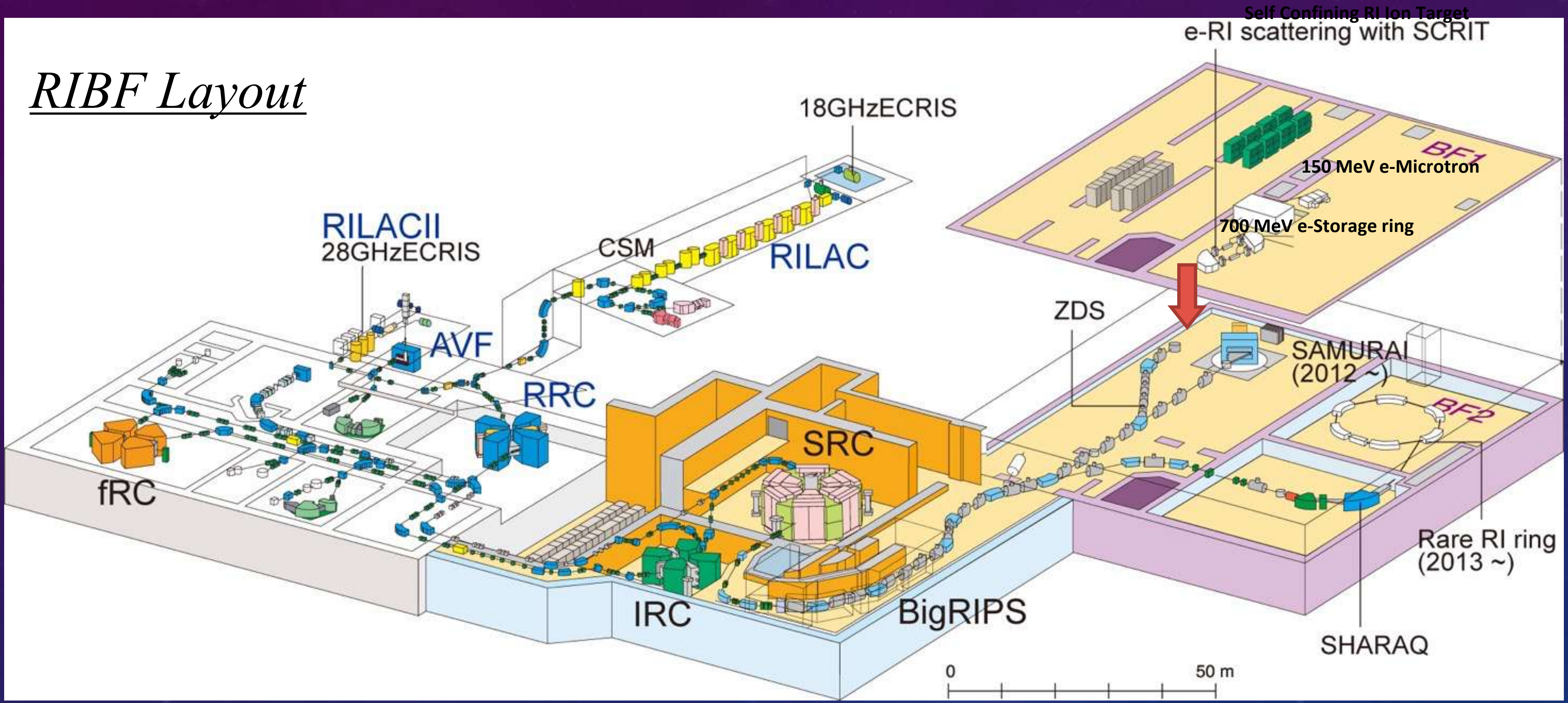
Korobkin 2012

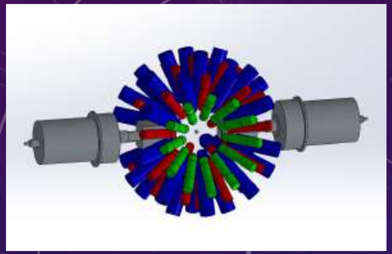


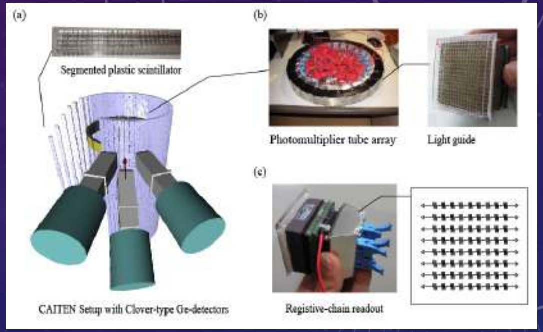

★ **Nuclear Physics Inputs (exp. / theory, astro)**

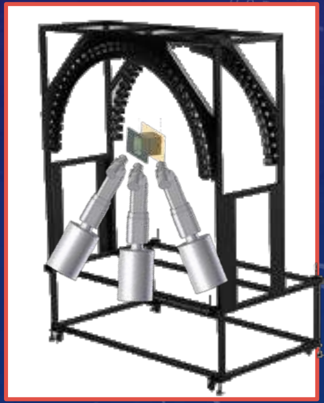
- **Masses**
- **Half-lives**
- **β-delayed neutron emission probabilities**
- **Excited states**
- **magicity, deformation**
- **Fission**
- **Nuclear reactions (n,γ), (α,n), (α,p), ….**
- **EOS (Equation of State)**

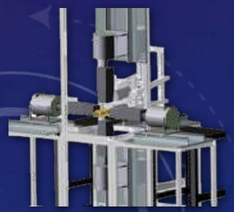
# Experimental Projects at Zero-Degree Spectrometer
# Decay & Mass

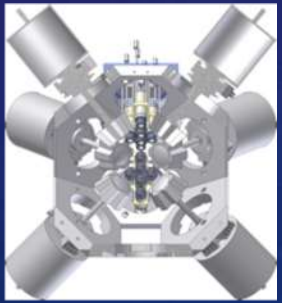


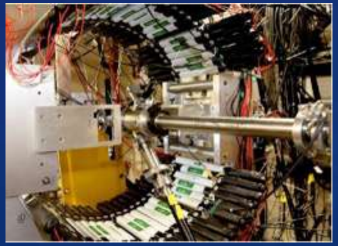



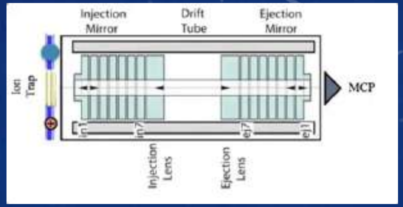








# Gross properties: Half-lives ($T_{1/2}$) and neutron branching ratio $P_{xn}$

**Beta-decay process**

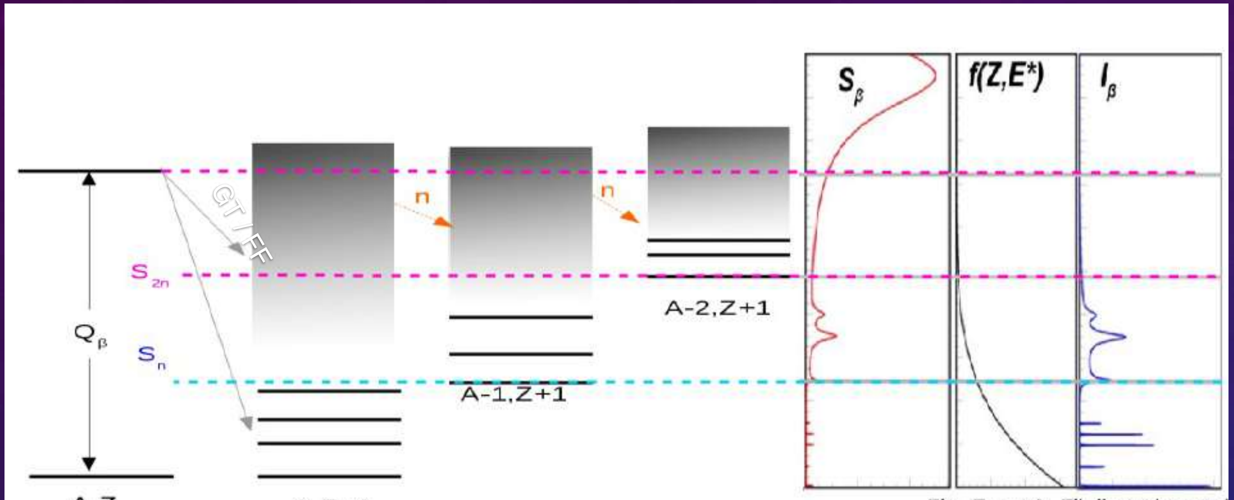
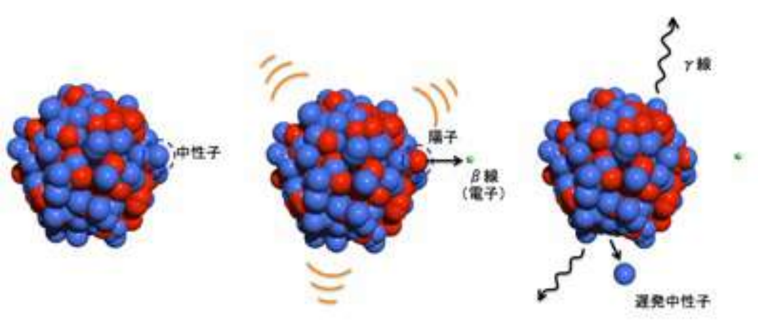


Fig. From A. Fijalkowska et.al




- $\beta$-delayed neutron branching ($P_{xn}$)
- Neutron-TOF

*BRIKEN/VANDLE/ToFU*

- $\beta$-delayed $\gamma$ spectroscopy (and $T_{1/2}$)

*EURICA/DTAS*

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

Half-lives (isotope)

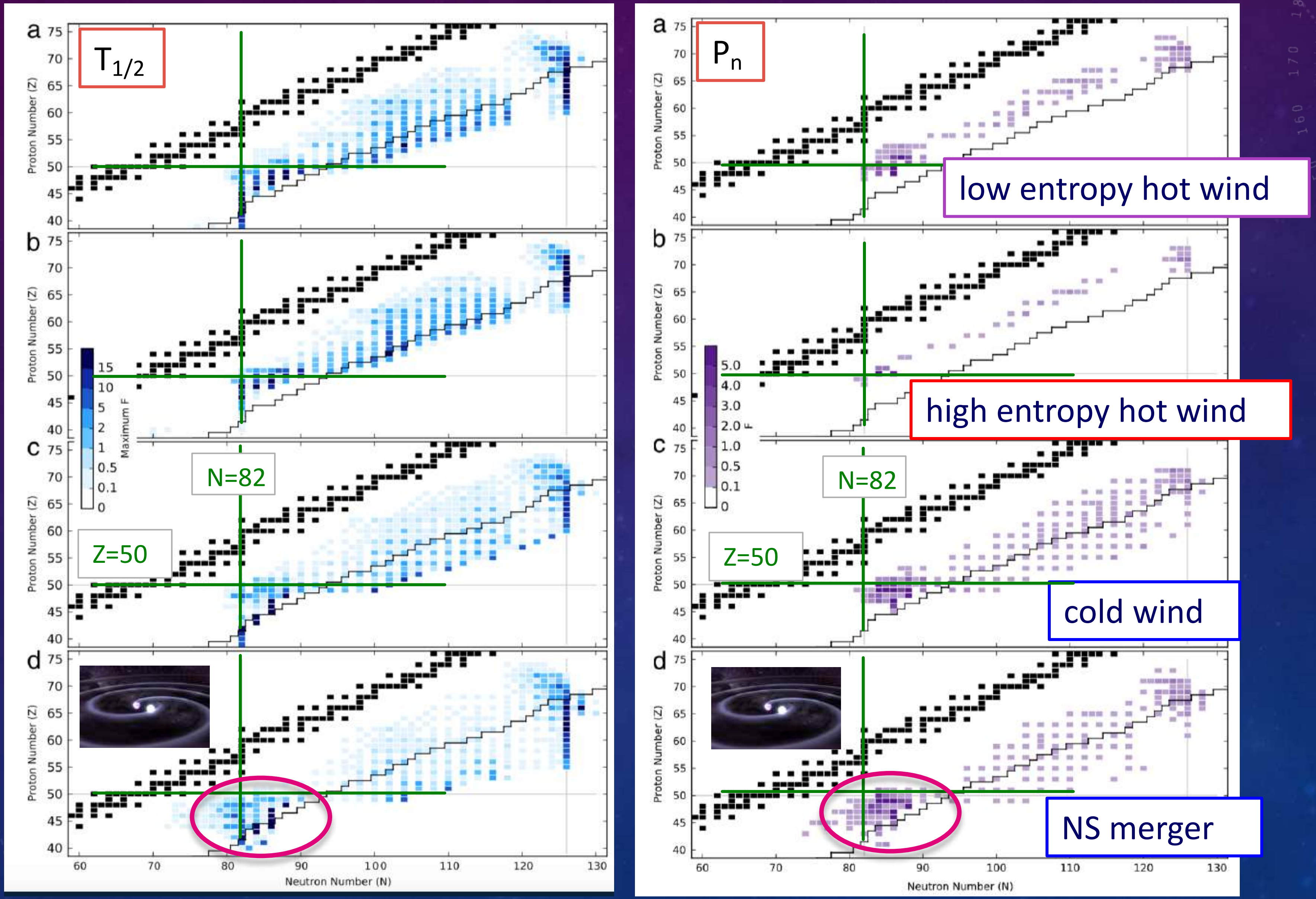
β-strength function

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

# r-Process Nucleosynthesis

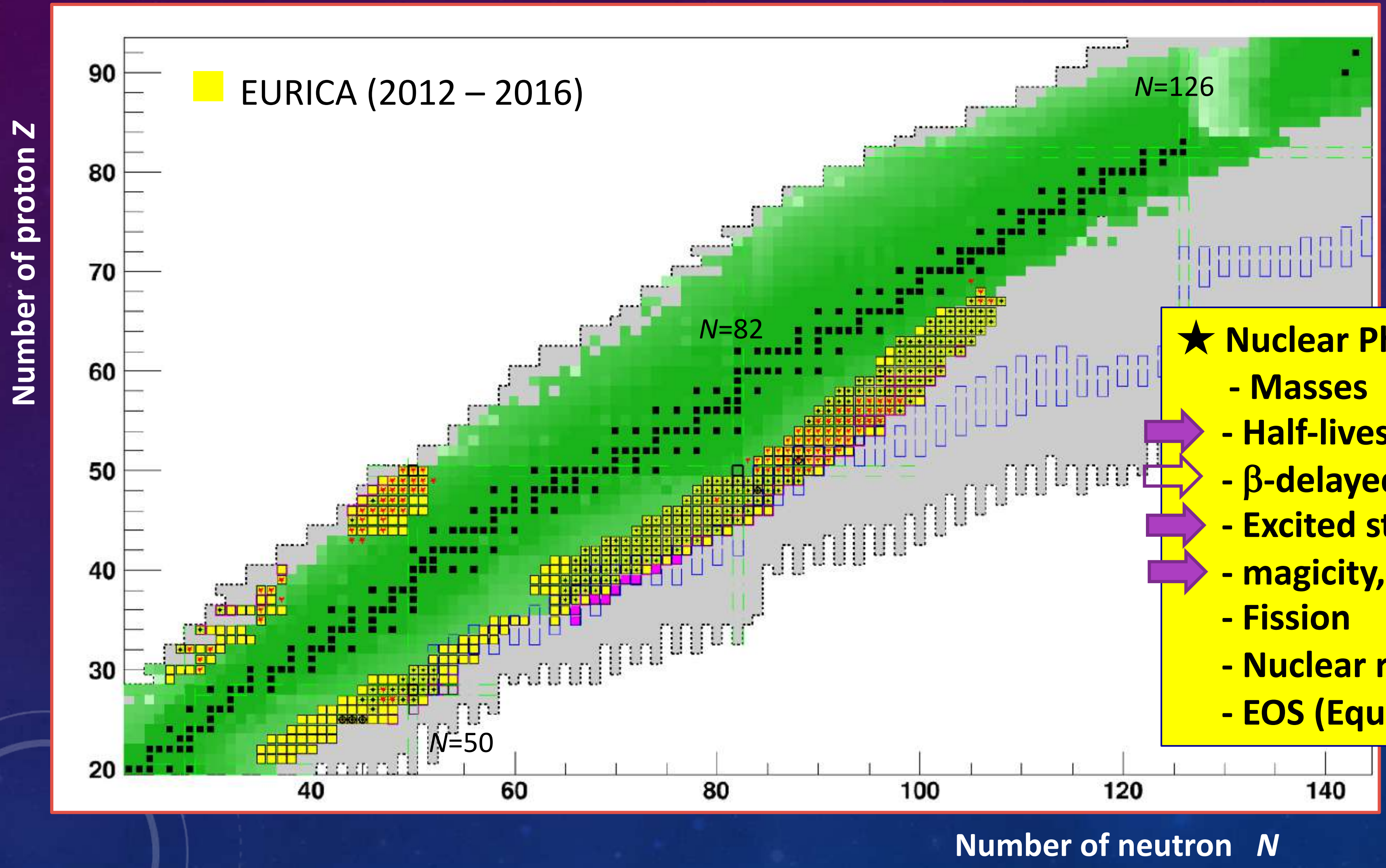
## 2nd Peak (Mass $A \sim 130$)

# Sensitivity Study of Decay Properties in r-Process




M.R. Mumpower et al.(2016)

# Critical Nuclear Properties in r-Process Nucleosynthesis
## （EURICA Project:2012 – 2016）

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- **Half-lives**
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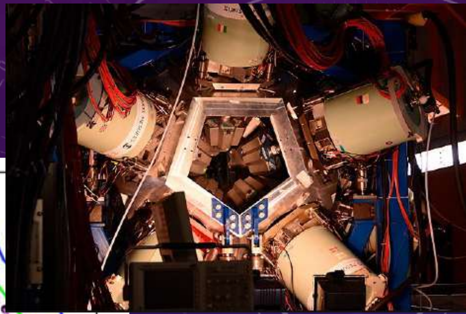
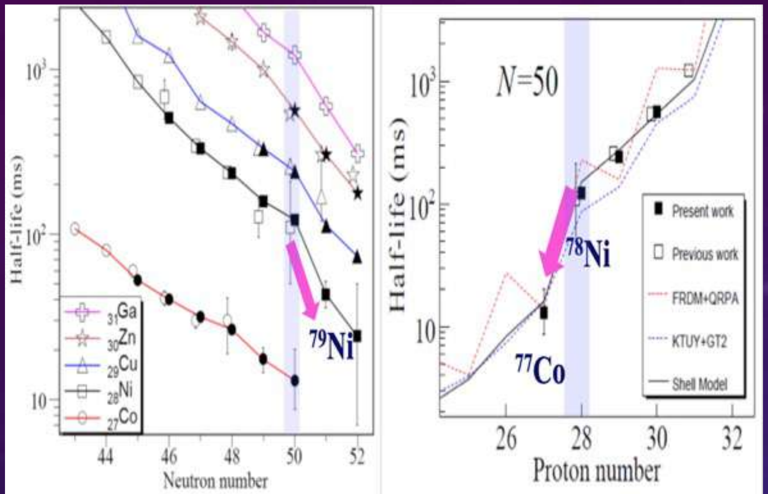
- **Nuclear reactions (n,γ), (α,n), (α,p), ….**
- **EOS (Equation of State)**

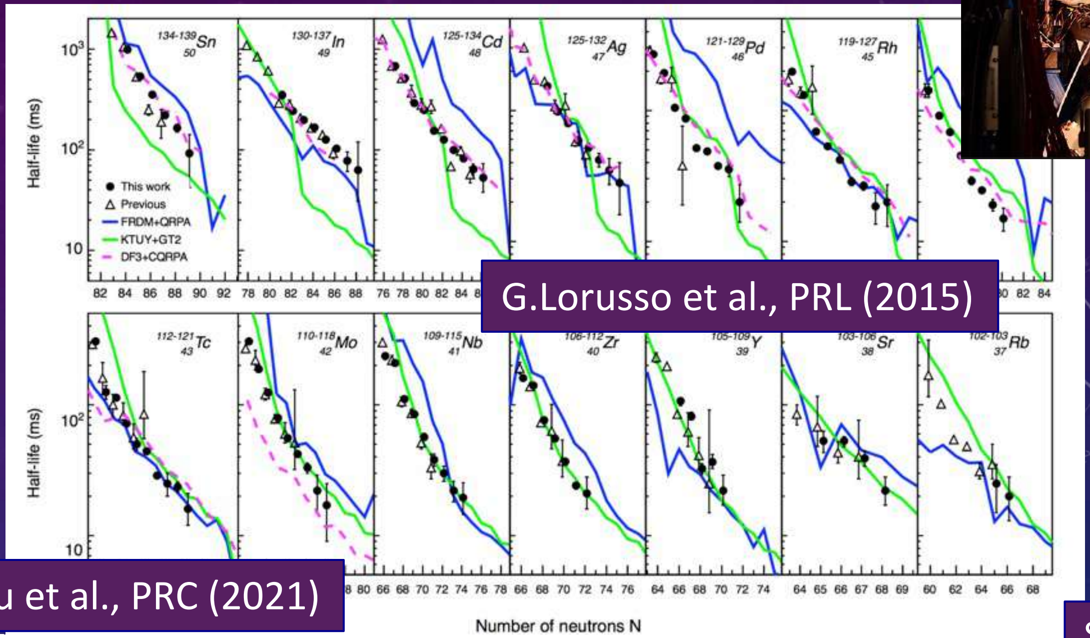
# ~ 284 β-Decay Half-lives (New T1/2 ~ 125) Measured at RIBF



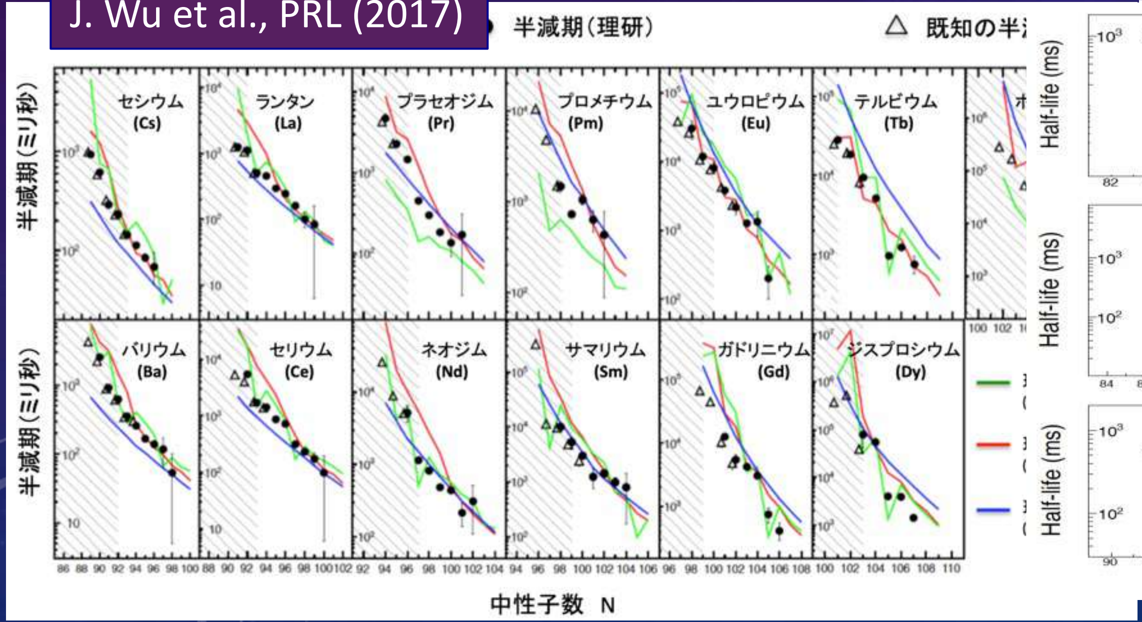
Z.Xu et al, PRL (2014)



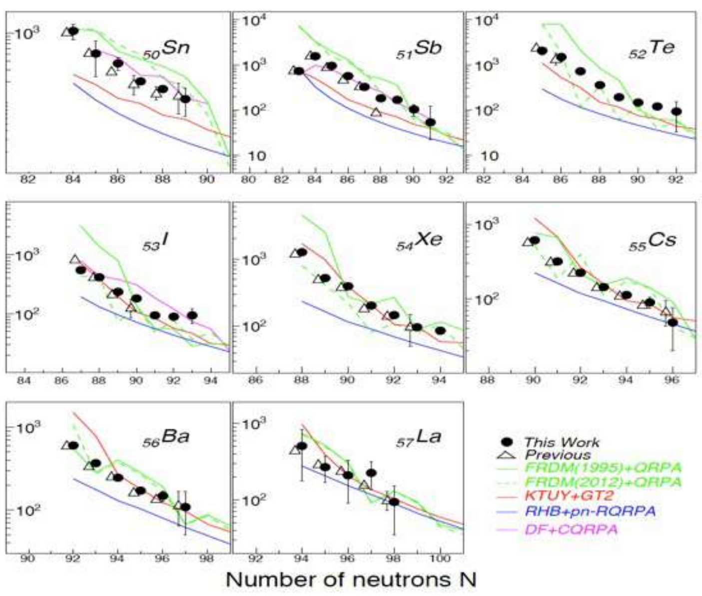

G.Lorusso et al., PRL (2015)



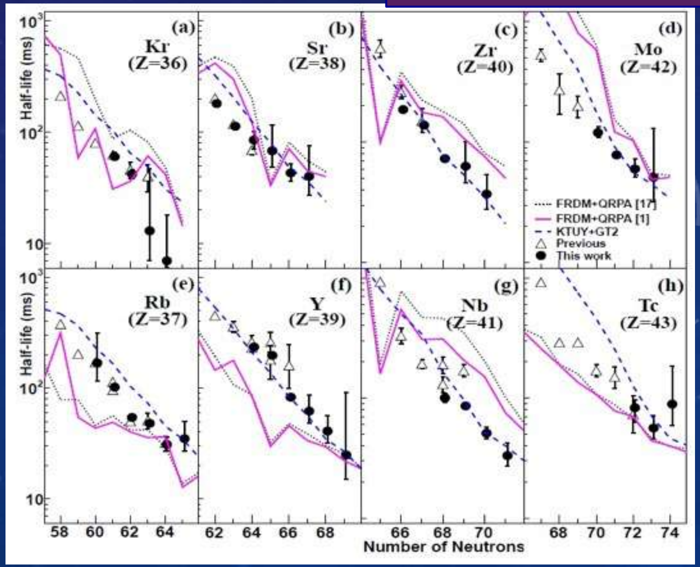

J. Wu et al., PRL (2017)




J. Wu et al., PRC (2021)

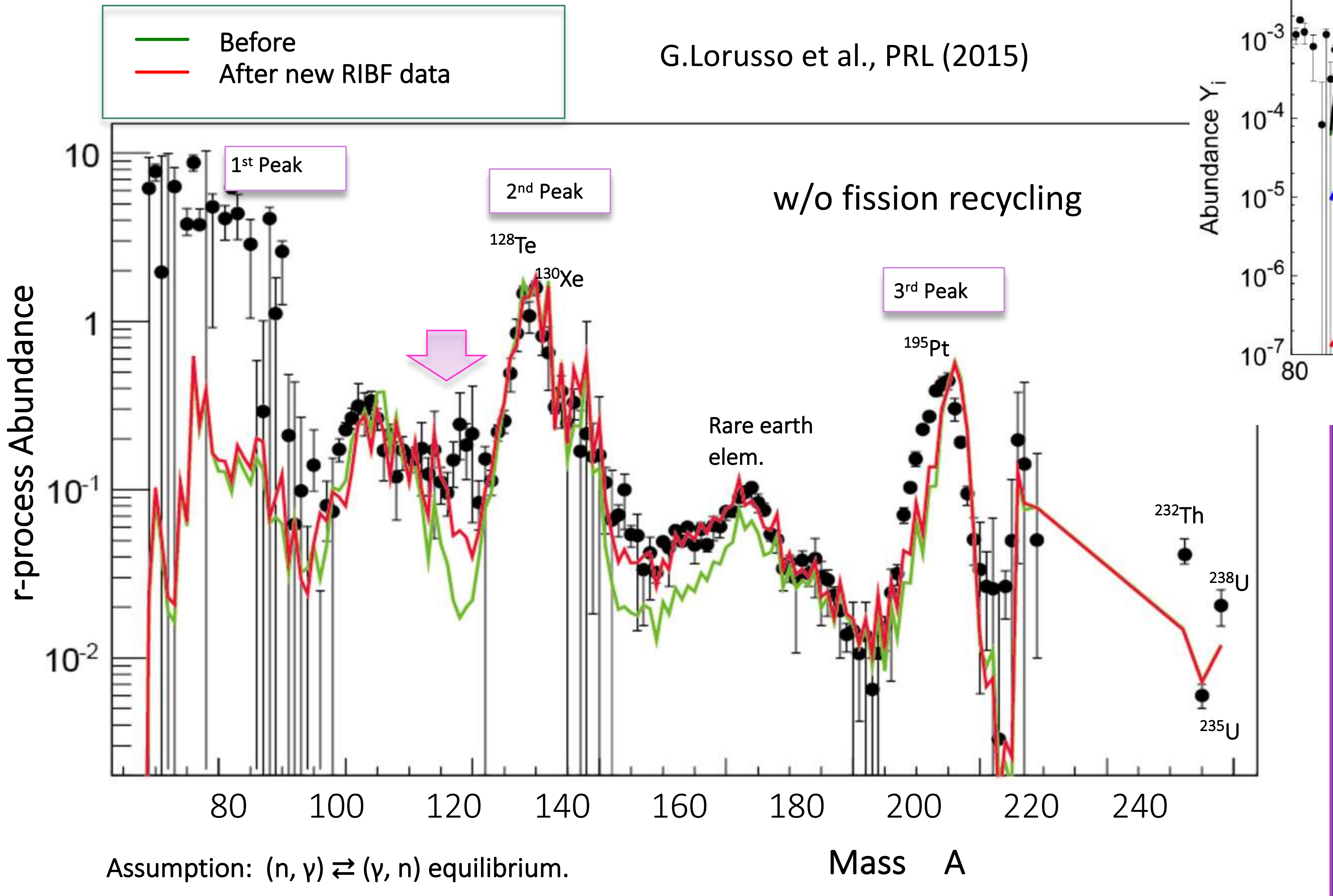


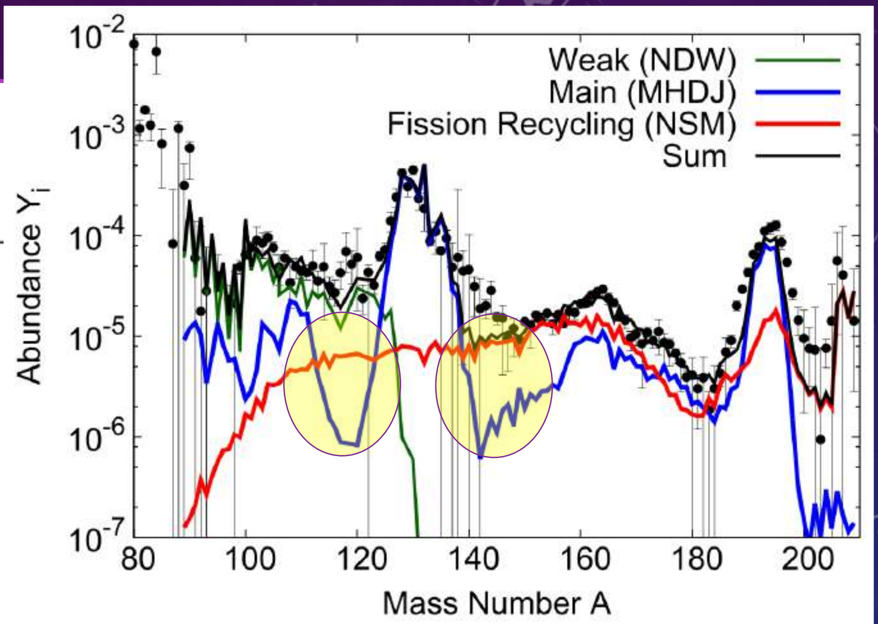

SN et al., PRL (2011)



# Impact on r-process nucleosynthesis

S. Shibagaki, T. Kajino et al. Astro. Phys. Jour. (2016)




Main (MHDJ)
Fission (NSM）

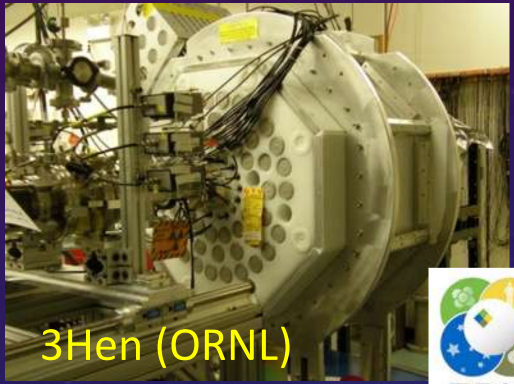
r過程の元素合成
フリーズアウト時の微細構造
の形成、議論

BRIKEN has started producing new data！

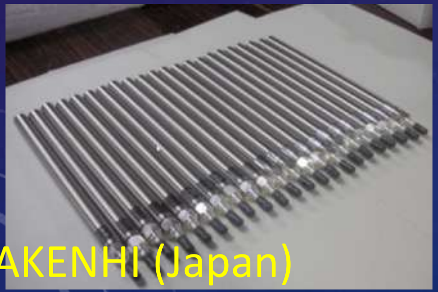
# BRIKEN : Highest neutron detection efficiency

FAIR


BELEN (Spain)


3Hen (ORNL)

FRIB

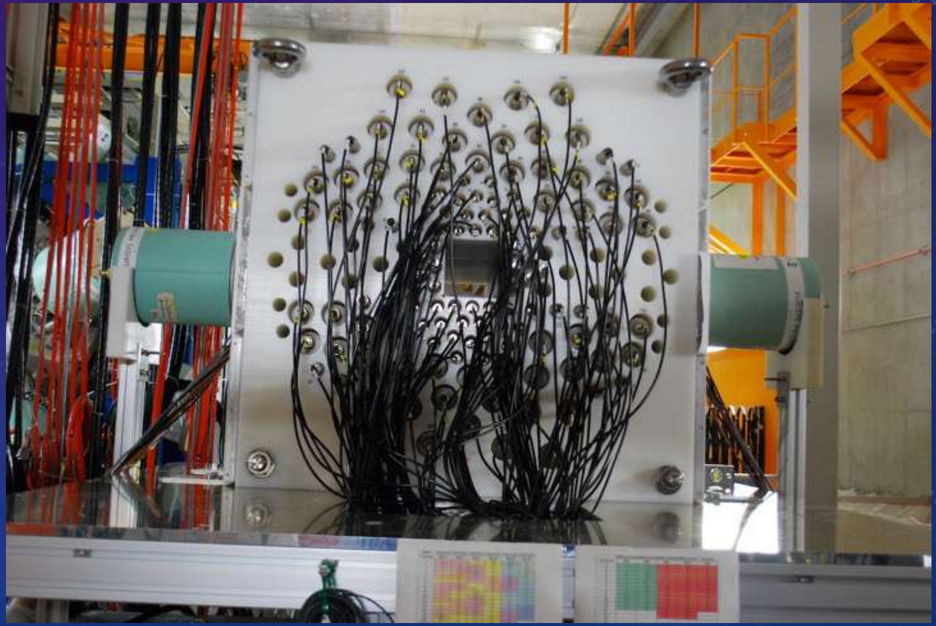

KAKENHI (Japan)

RIKEN NiSHiNA CENTER

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

Thermalization time τ 〜100 μs

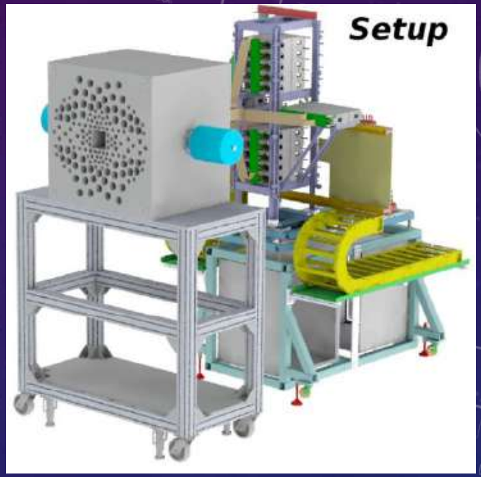

BRIKEN @ RIBF

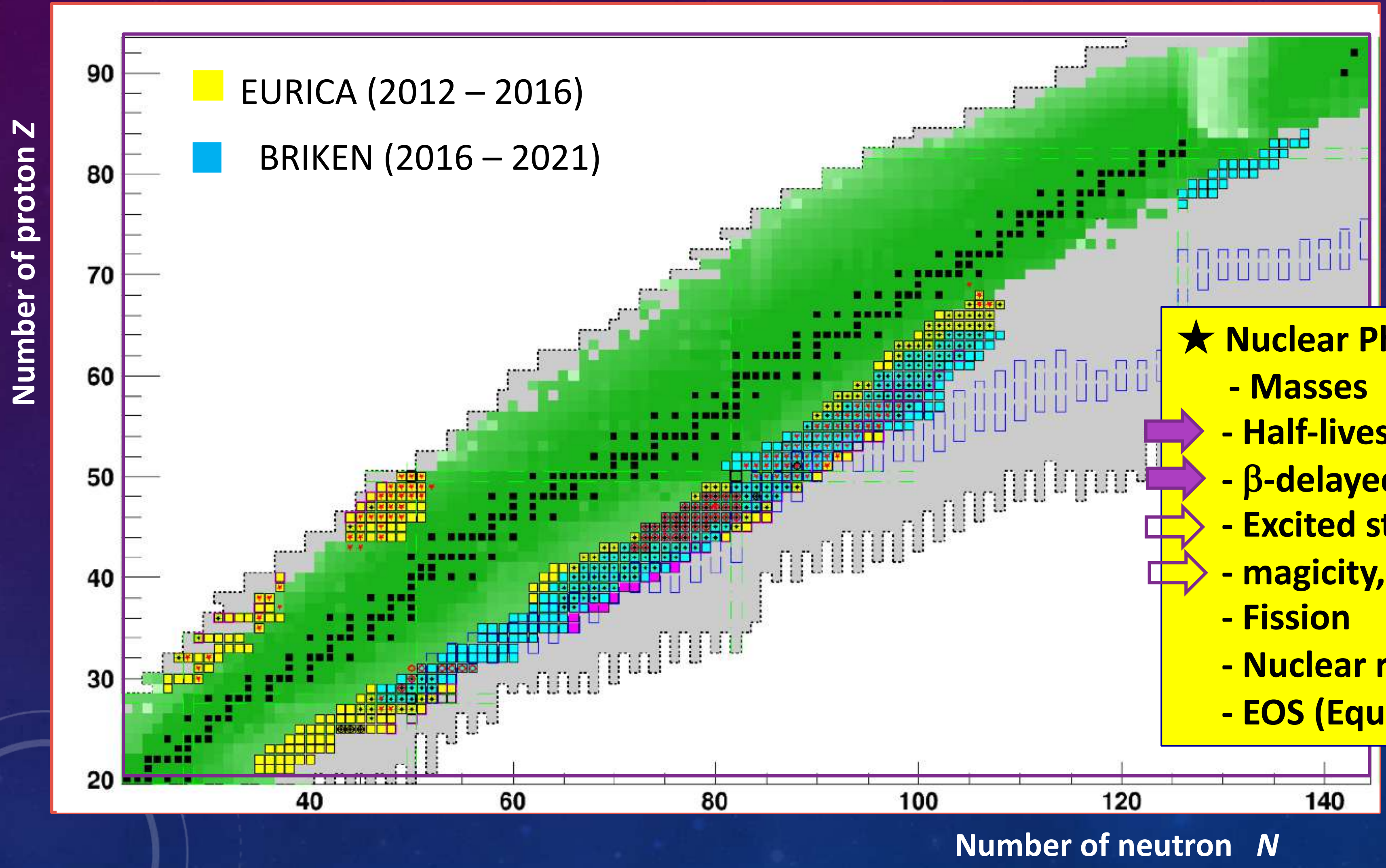


A.Tarifeno-Saldivia et al.
BRIKEN design, simulation
Jour. Instrum. 12, P04006 (2017)

# Critical Nuclear Properties in r-Process Nucleosynthesis （ BRIKEN Project ）

140 3He detector (RIKEN, ORNL, UPC)
beta-counting system
- AIDA or WAS3ABi

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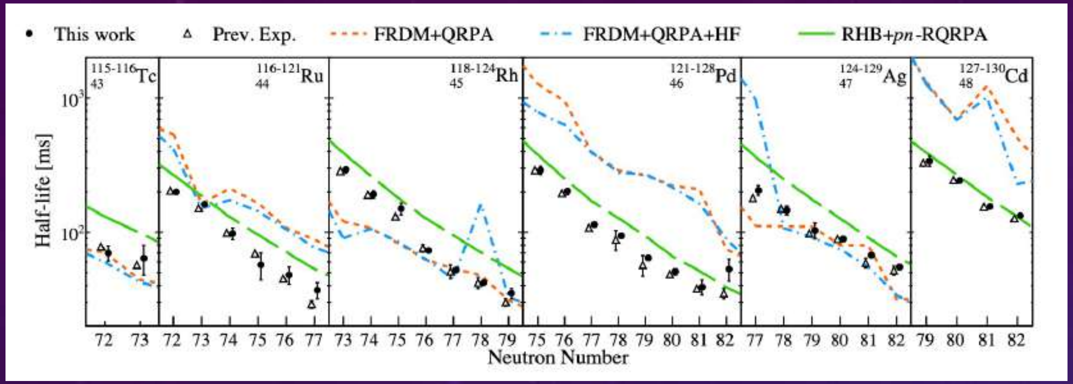
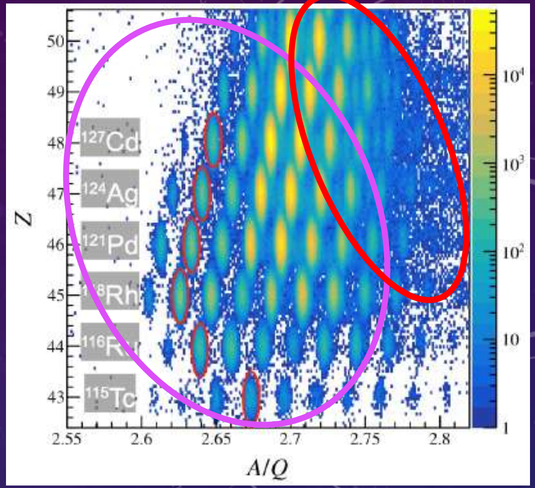
# β-Delayed Neutron Emission Probabilities ($N \leq 82$)

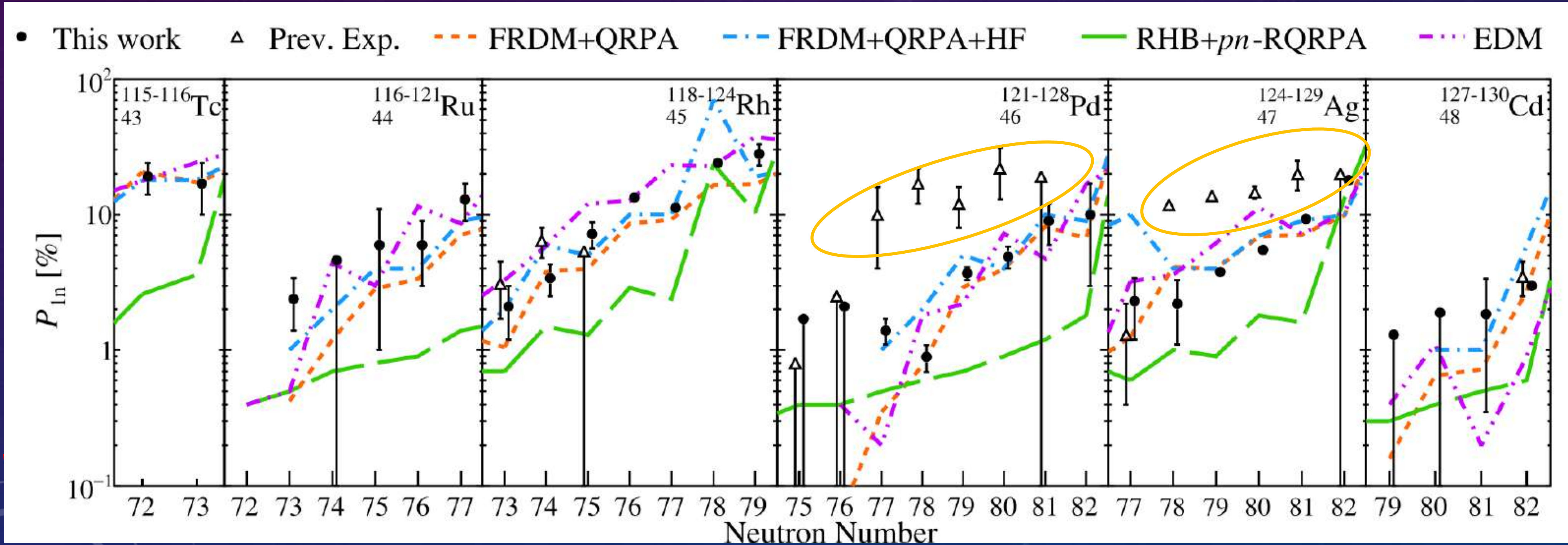
Spokespersons: A. Estrade, G. Lorusso, F. Montes




$T_{1/2}$ … consistent with EURICA

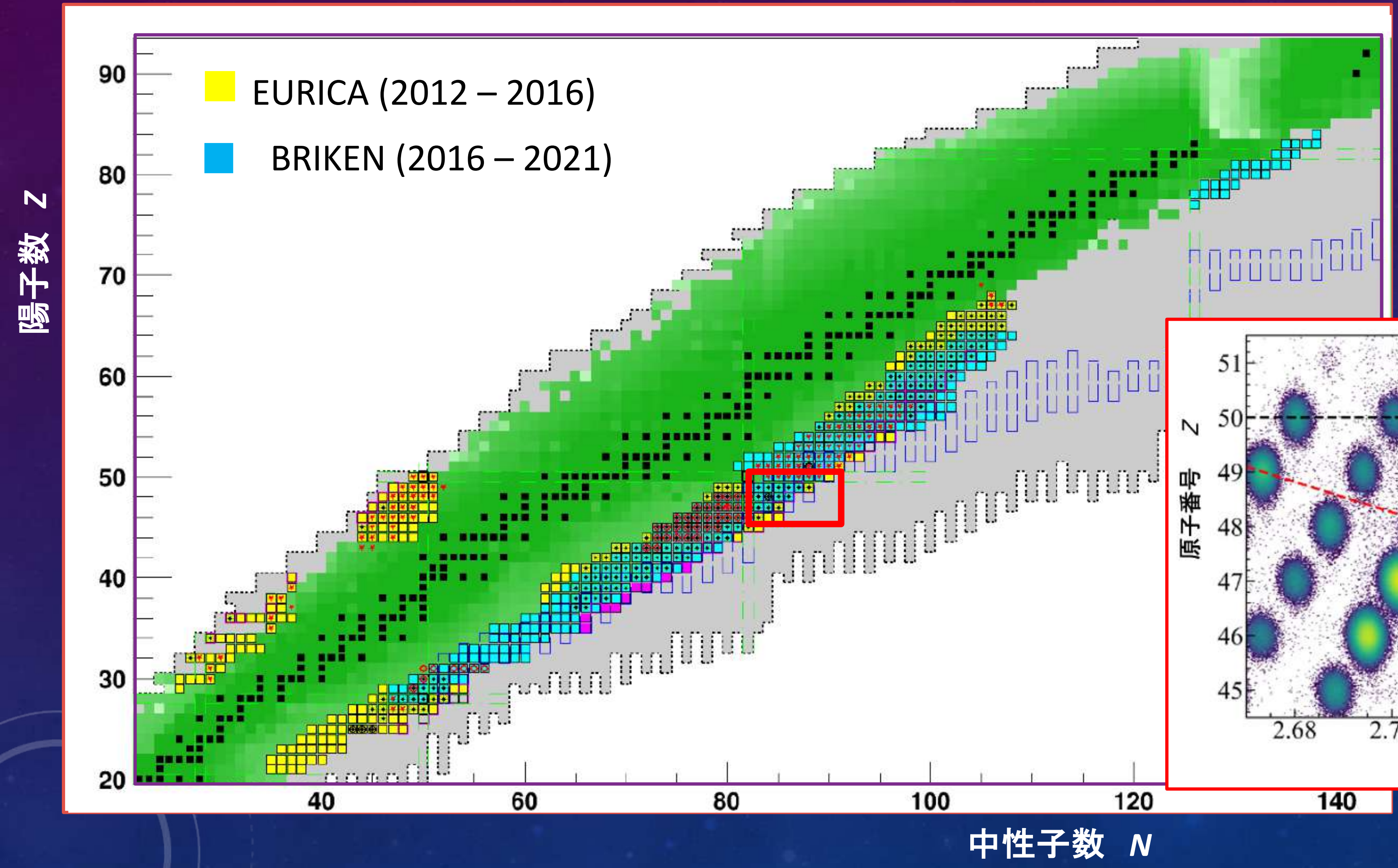
O. Hall. et al. PLB 816, 136266 (2021)

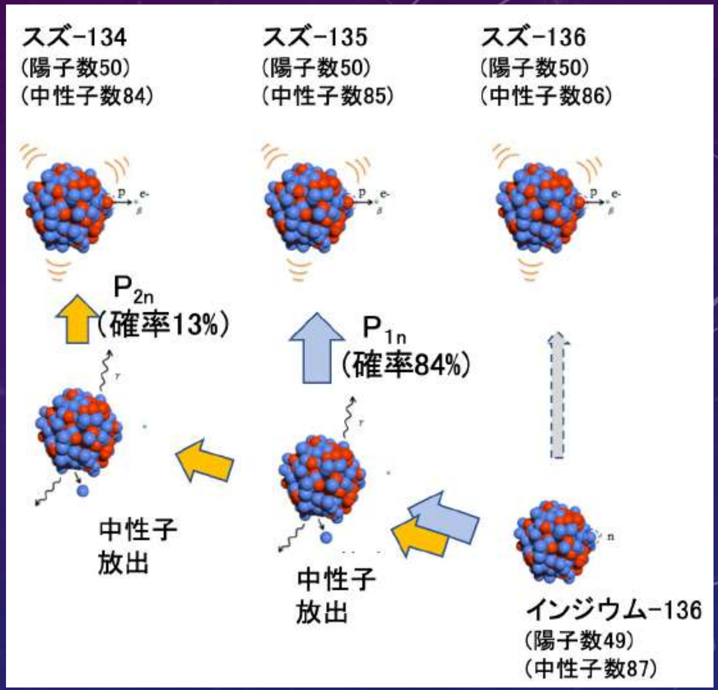


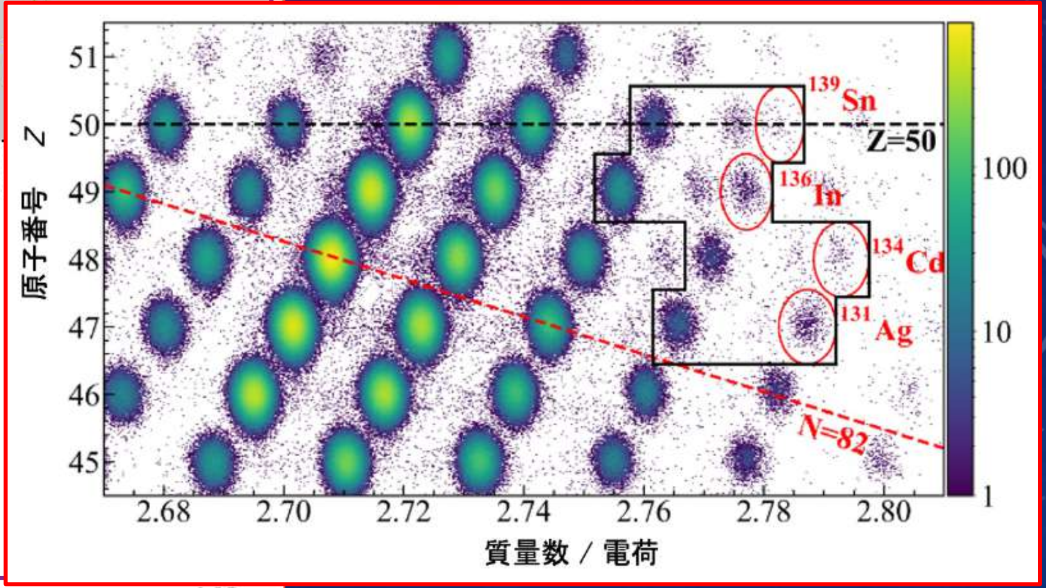

PhD thesis from GSI

Machine learning.. → Di. Wu, C.L. Bai, H. Sagawa et al., PRC 104, 054303 (2021)

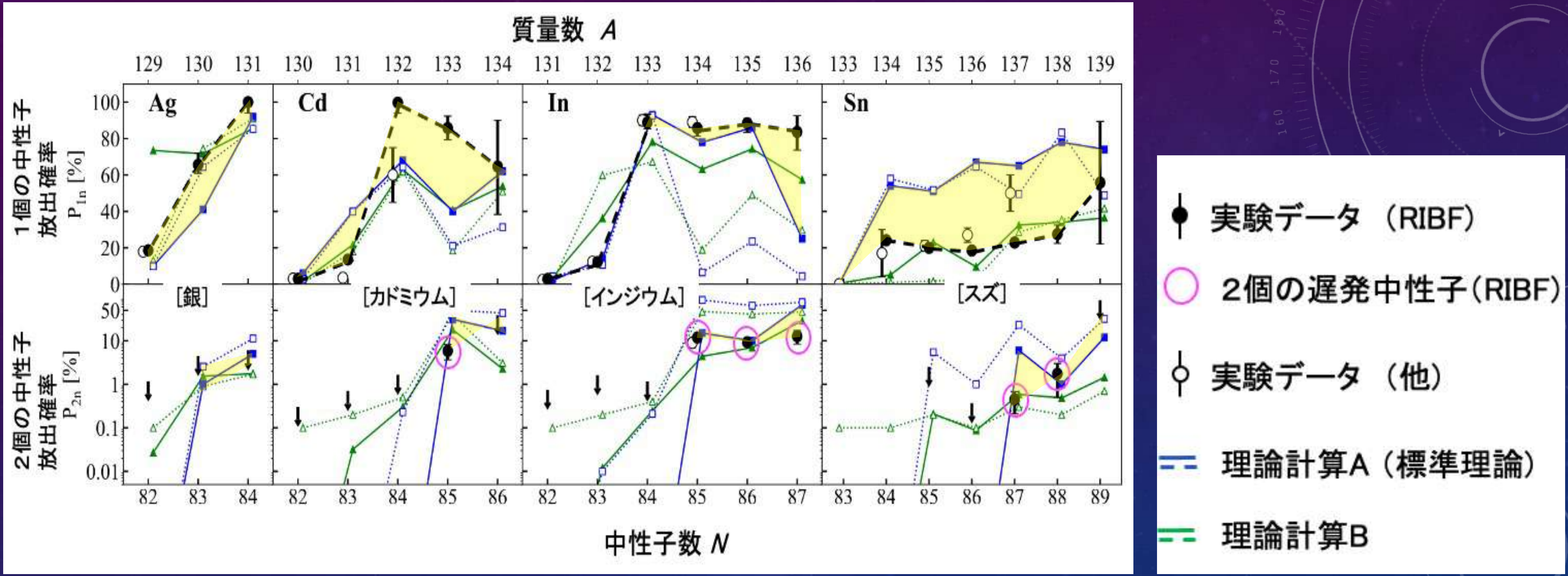
# BRIKENで収集した実験データ



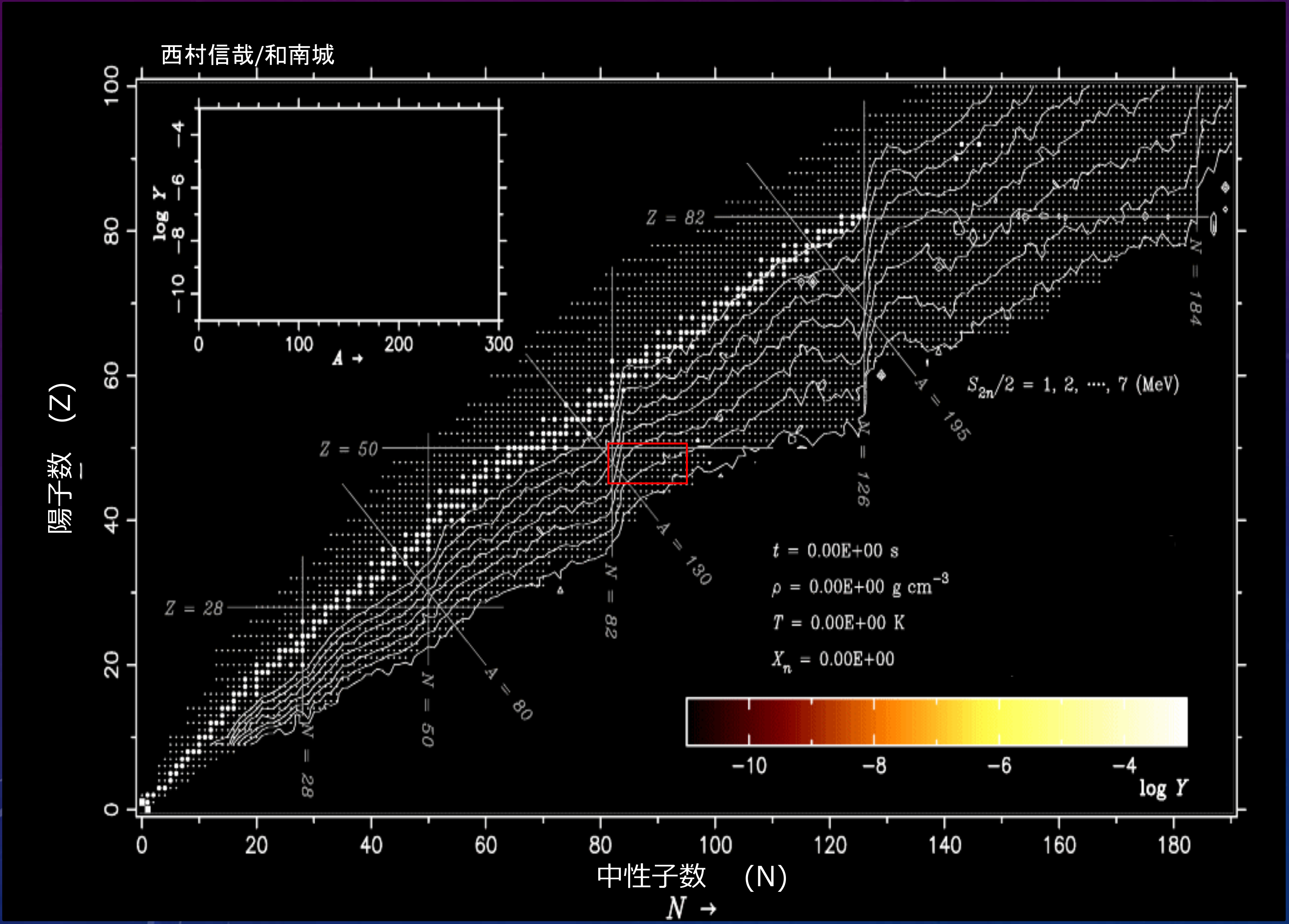
# 中性子魔法数N > 82の遅発中性子放出確率の測定に成功




これら中性子過剰な原子核はベータ崩壊することにより、
安定な原子核（テルル、セシウム、キセノン、バリウムなど）に変換される

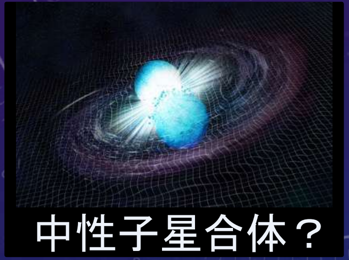
ベータ崩壊に伴い中性子を放出すると、質量が減る。

# 速い中性子捕獲過程（r過程）

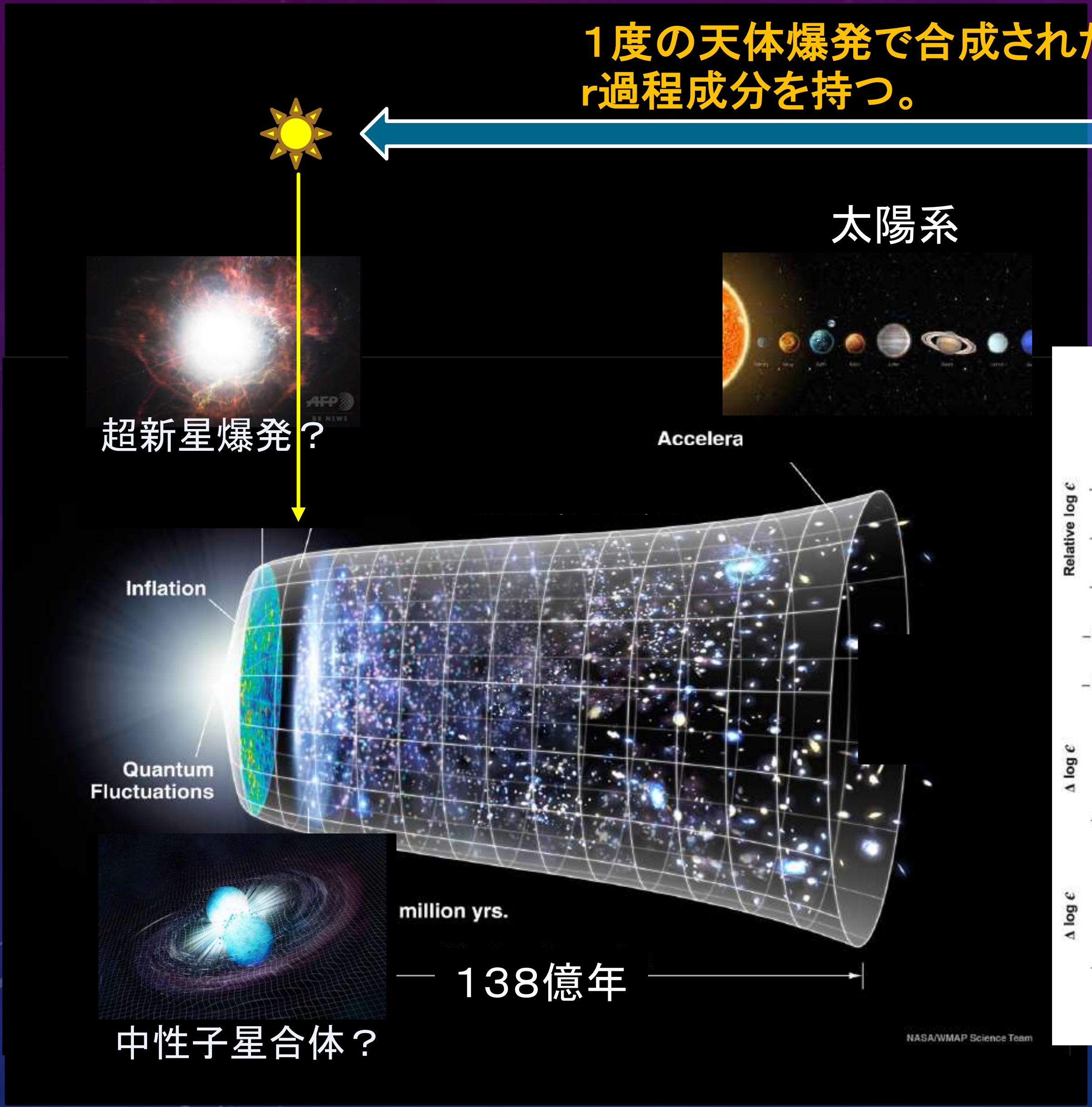



金、ウランなど重元素の起源

→ 大量の中性子が存在する環境


# 宇宙初期の古い金属欠乏星の探索

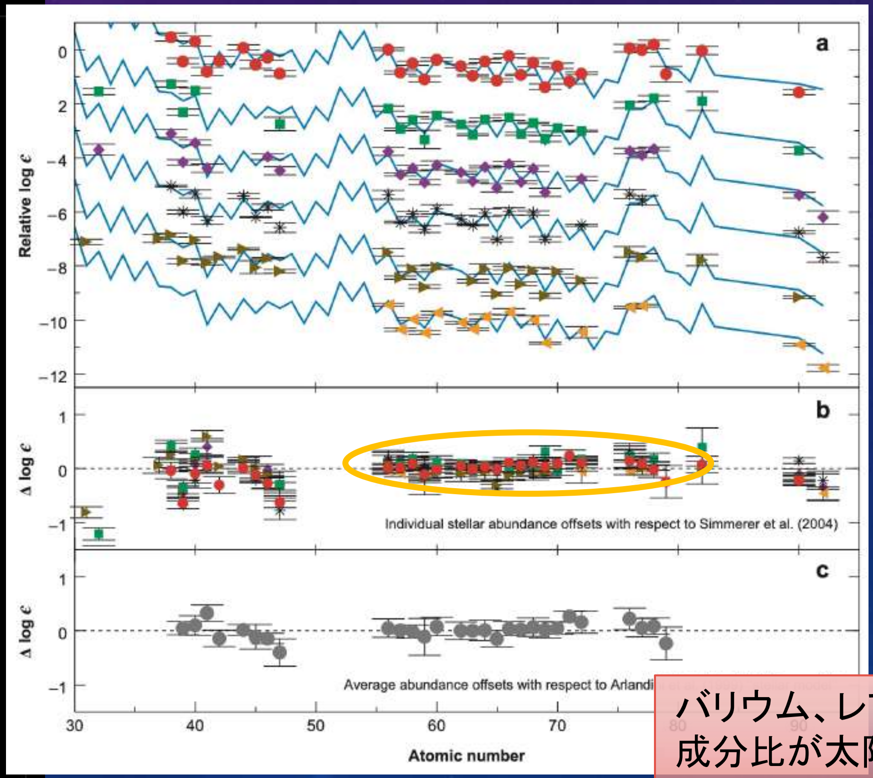



ハッブル宇宙望遠鏡

すばる望遠鏡


SkyMapper

Sneden (2008)

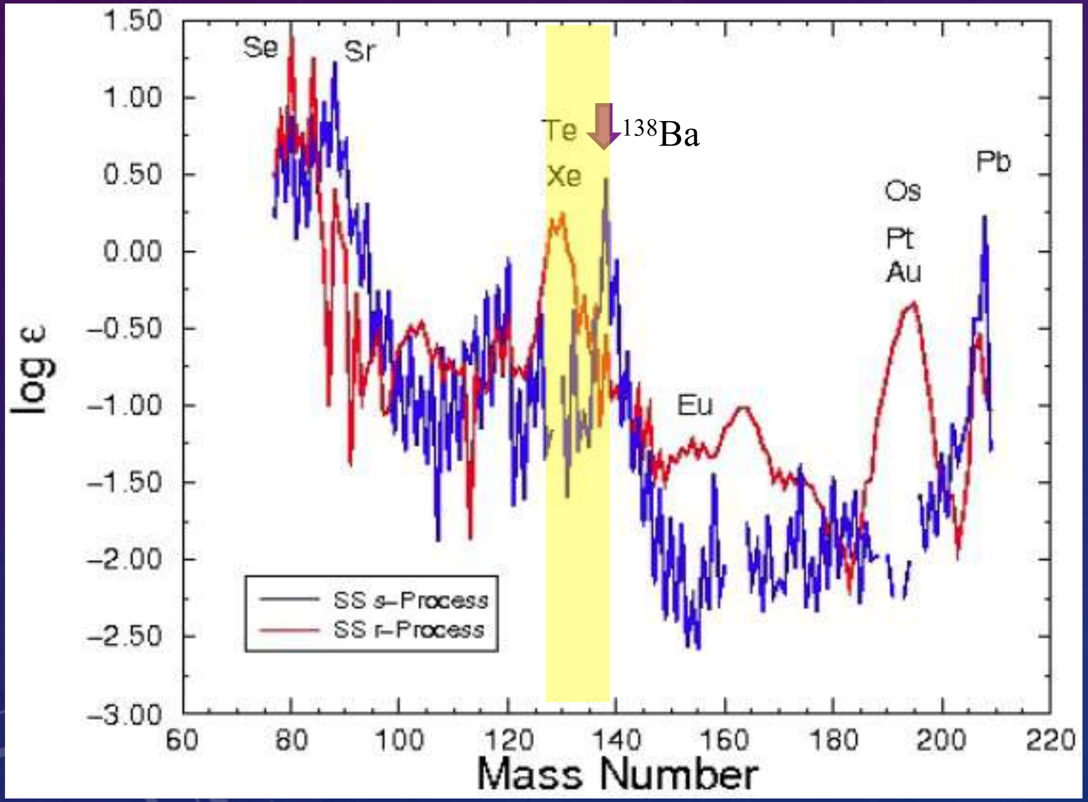



バリウム、レアアース、金、白金、トリウムの
成分比が太陽系のものと酷似

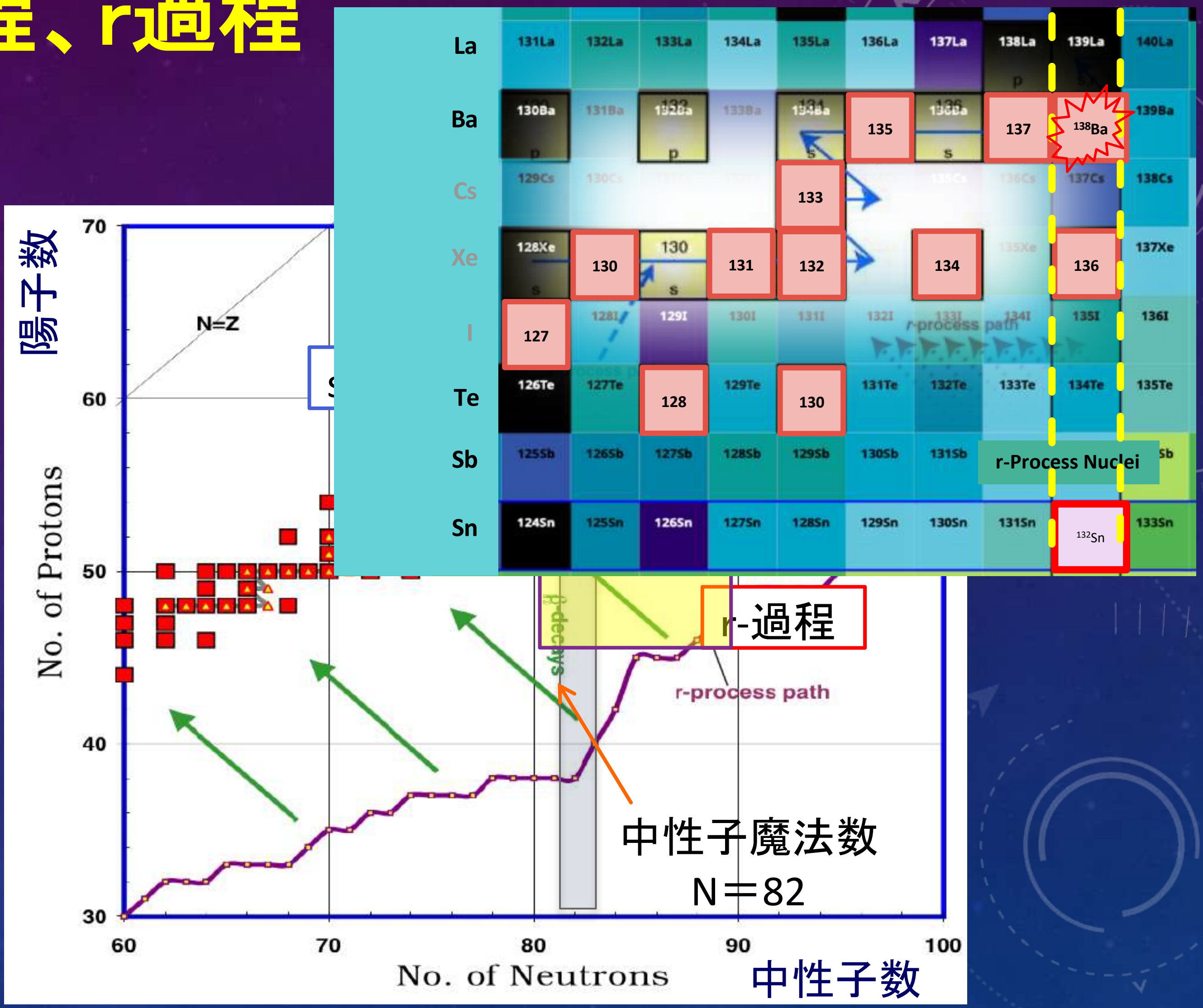
# 太陽系の元素の起源：s過程、r過程

s過程とr過程が混在。
$^{138}$Ba などが大量につくられる。

Sneden, Cowan, (2003)




中性子魔法数
*N* = 82



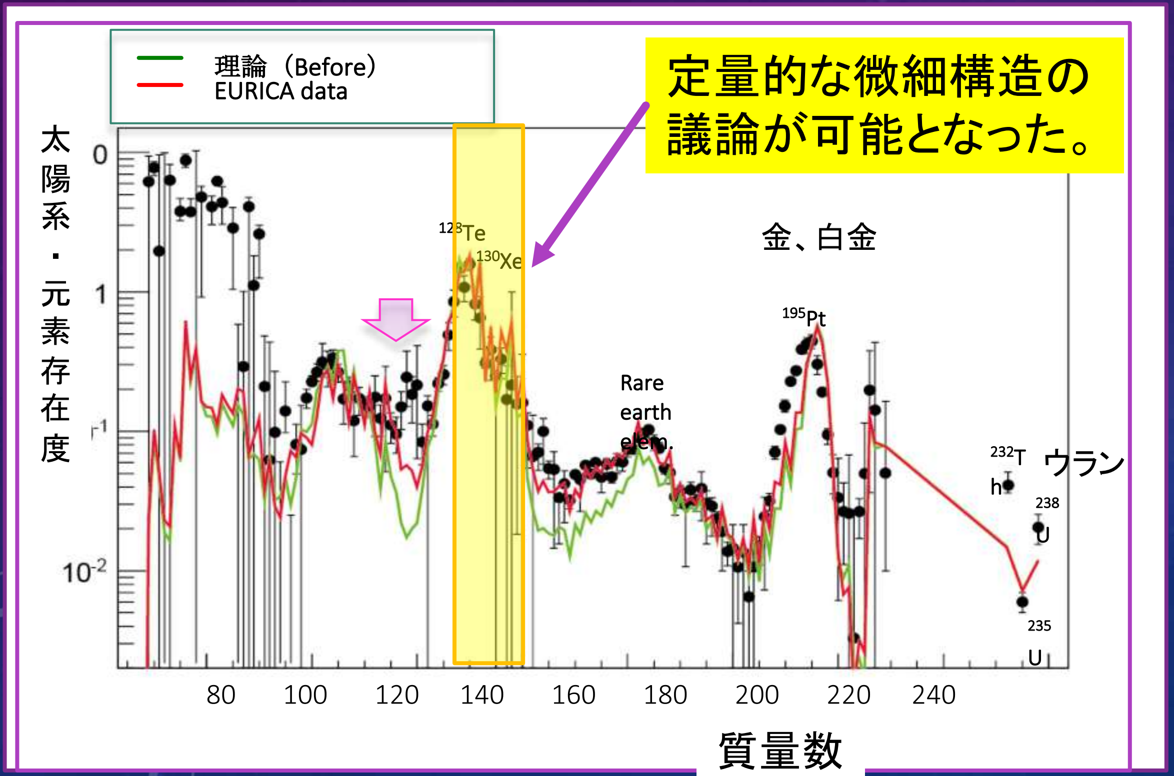

①元素には質量の異なる同位体が存在する。
②宇宙初期のBa同位体が観測可能となった。

# RIBFのデータを取り込んだr過程の計算

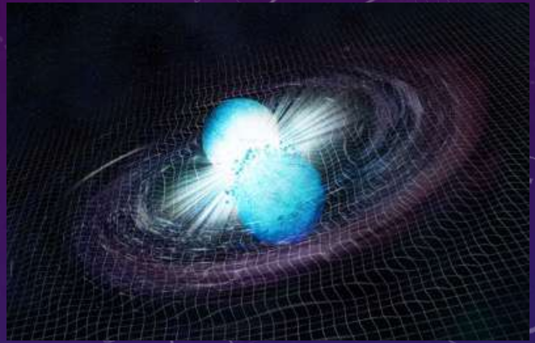


- ○ 半減期を測定（EURICA)
- ○ 遅発中性子放出確率（理論）→ 実験データ（BRIKEN)

G.Lorusso et al., PRL (2015)

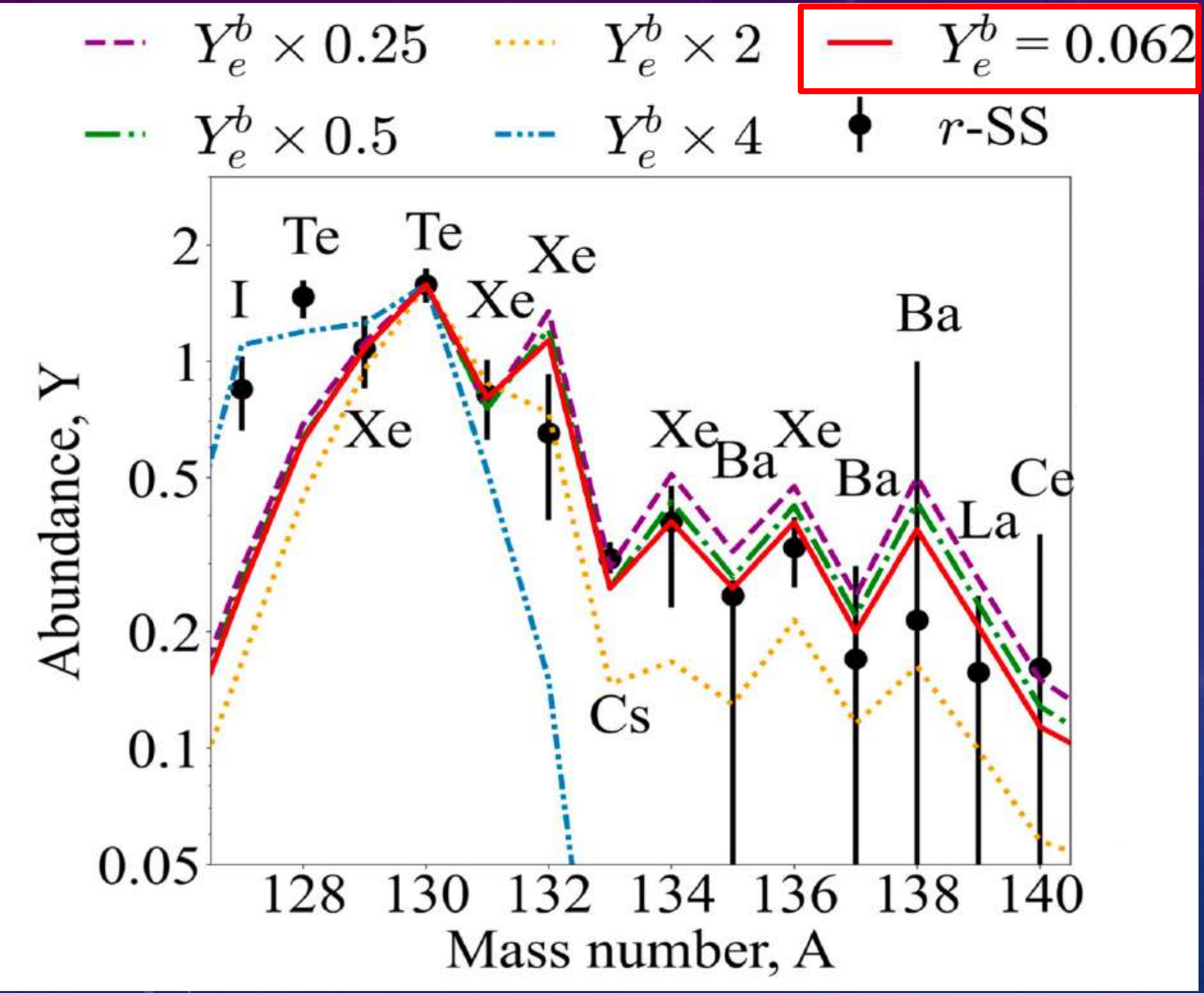



# Ye Dependence of r-process abundance (A~135)



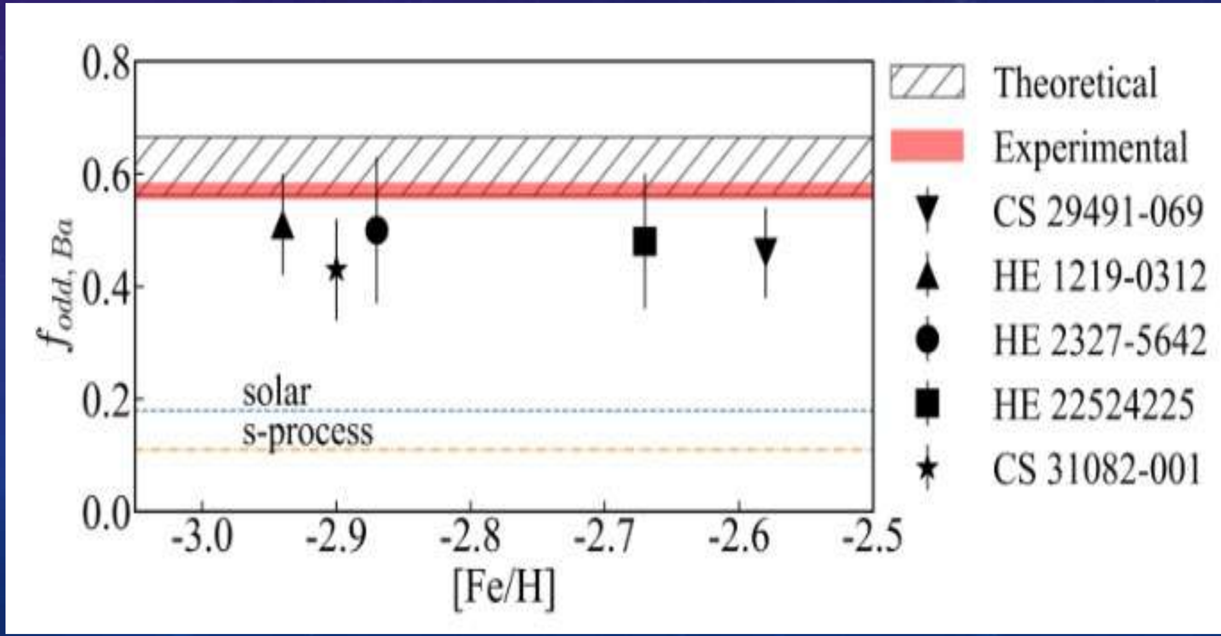
*V.H Phong et al.*

Ye dependence of odd-even systematics



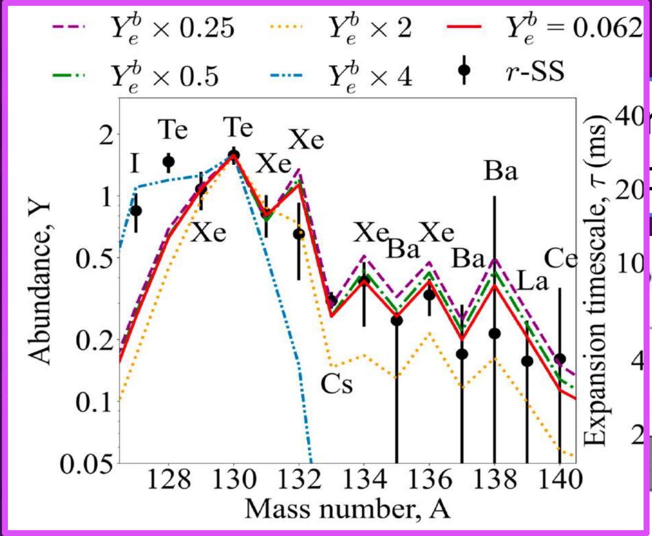

$$f_{odd,Ba} = \frac{n(^{135}Ba) + n(^{137}Ba)}{n(Ba)}$$

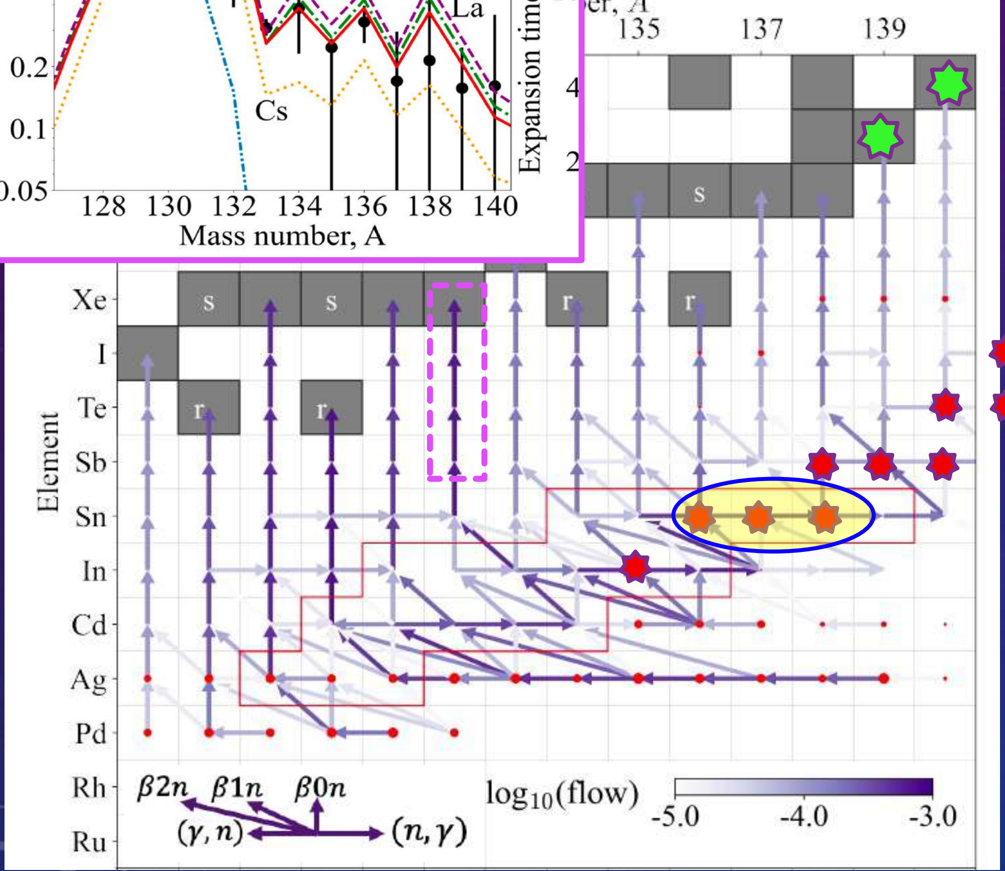
C. Wenyuan et al., Astrophys. J. 854, 131 (2018)



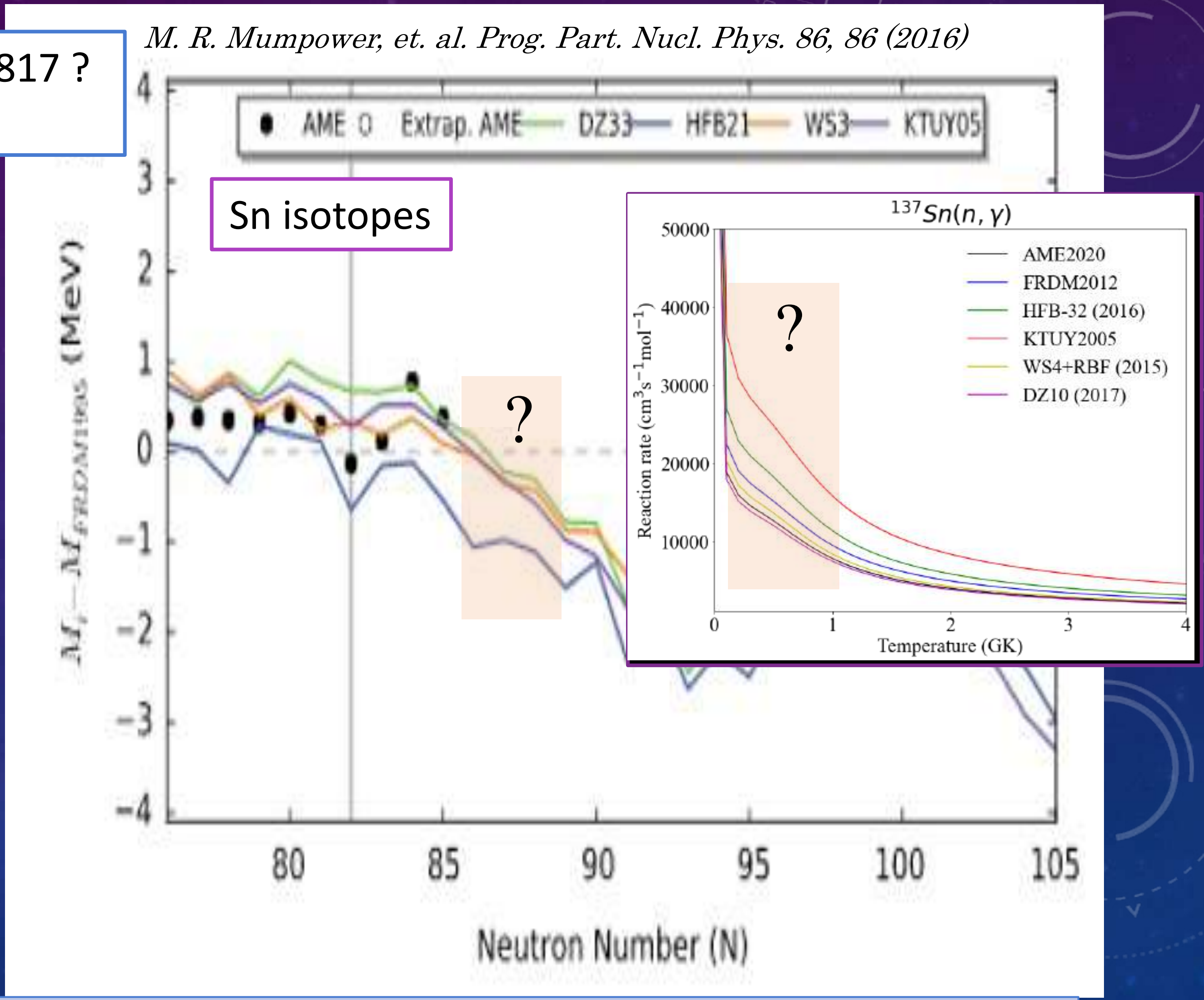
# 2ND R-PROCESS PEAK FORMATION DURING FREEZE-OUT TIME OF R-PROCESS

roduction observed GW170817 ?
oto et al. ApJ 939 (2022)




ReacLib2 (FRDM 1995)




masses of $^{137}$Sn and $^{138}$Sn ←→ expected (n,γ) reaction rate
( Large uncertainties )

# 関連した研究

東北大学 TOHOKU UNIVERSITY
大学共同利用機関法人 自然科学研究機構 核融合科学研究所 National Institute for Fusion Science
東京大学 大学院 理学系研究科・理学部 SCHOOL OF SCIENCE THE UNIVERSITY OF TOKYO
国立天文台 NAOJ National Astronomical Observatory of Japan

**Press Release**

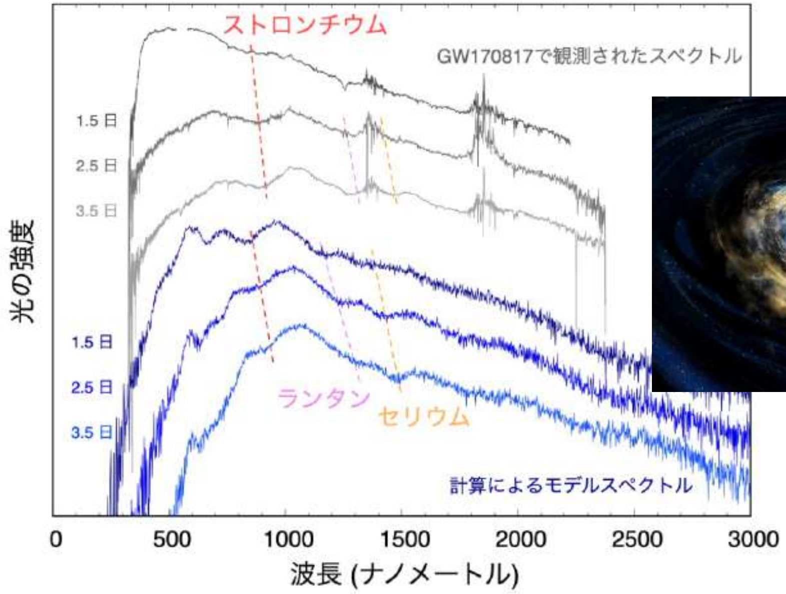
2022 年 10 月 27 日

報道機関　各位

配信先：宮城県政記者会、文部科学記者会、科学記者会、名古屋教育記者会、岐阜県政記者クラブ、多治見市政記者クラブ、国立天文台登録メディア
解禁日：なし

東北大学大学院理学研究科
大学共同利用機関法人自然科学研究機構 核融合科学研究所
東京大学大学院理学系研究科
大学共同利用機関法人 自然科学研究機構 国立天文台

**中性子星の合体で合成されたレアアースを初めて特定**




狭山隕石は１９８６年（昭和６１年）４月２９日頃、埼玉県狭山市の民家に落下した隕石である。２０００年５月に当館に依頼があり、隕石であることを確認した。落下そのものは目撃されておらず、朝に玄関横に落ちているのを発見したとのことである。ちょうどチェルノブイリ原子力発電所の事故が大きく報道された時で、放射能を持った破片ではないかとしばらく放置されていたそうである。数日後の雨で隣家の屋根の瓦が割れているのが発見され、まずここに当たって跳ね返ったと考えられる。球粒隕石でも珍しい炭素質（CMグループ）の隕石で、約２％の炭素を含んでいる。内部まで黒くて非常にもろく、母天体で水質変形を大きく受けたことが分かっている貴重な標本である。


H.Hidaka, S. Yoneda,
Scientific Report, 1330 (2013)

$^{135}$Ba, $^{137}$Ba, $^{138}$Ba & $^{135}$Cs

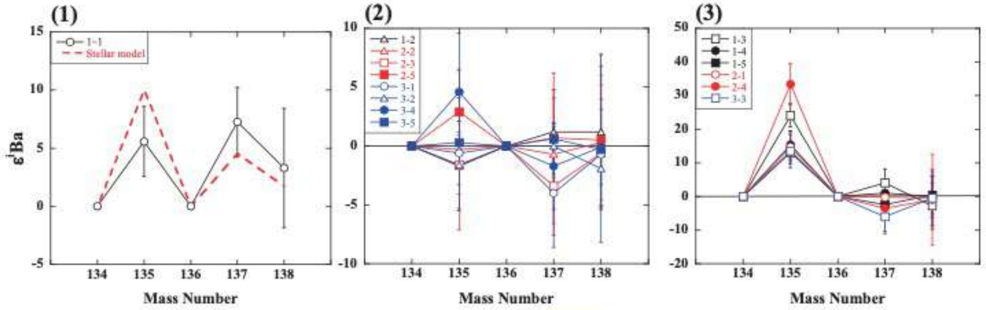


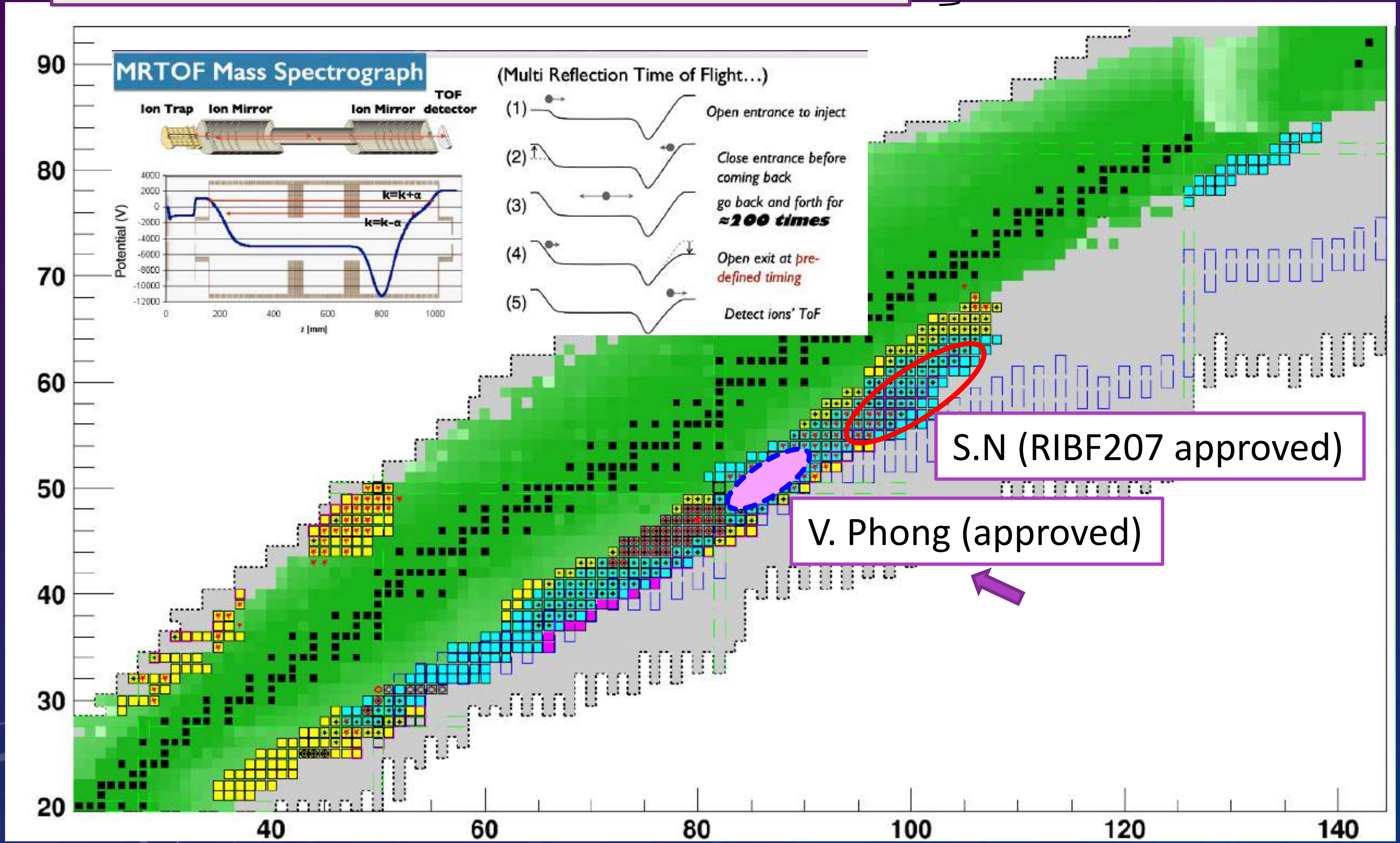

**Figure 1 | Isotopic deviation patterns of Ba found in the chemical leachates of the Sayama chondrules.** (1) type 1 with positive $^{135}$Ba and $^{137}$Ba isotopic anomalies due to depletion of s-process isotopic components; (2) type 2 having no significant isotopic anomalies; (3) type 3 with isotopic excess of $^{135}$Ba only. For reference, the pattern calculated from the stellar model[24] is also given in (1).

# SURVEY PROGRAMS RELEVANT TO R-PROCESS NUCLEOSYNTHESIS (DECAY & MASS)

Fast timing decay experiment : CAITEN (2010 - )

Mass measurement : ZD-MRTOF (2019 - )

Project Combined.




SN, PTEP 2012, 03C006 (2012)

CAITEN ( 2009 - )

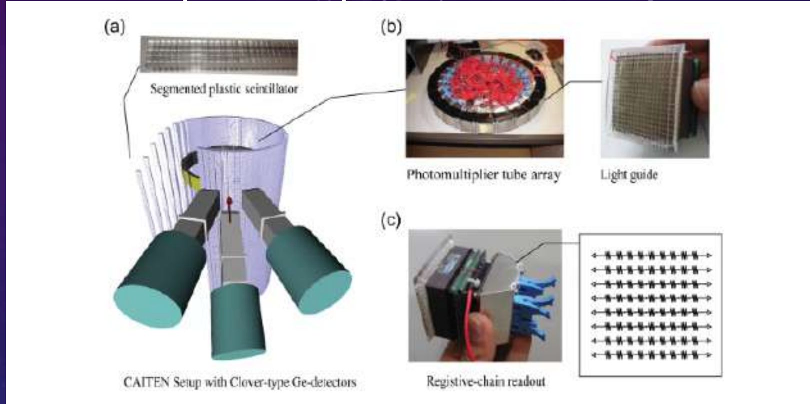
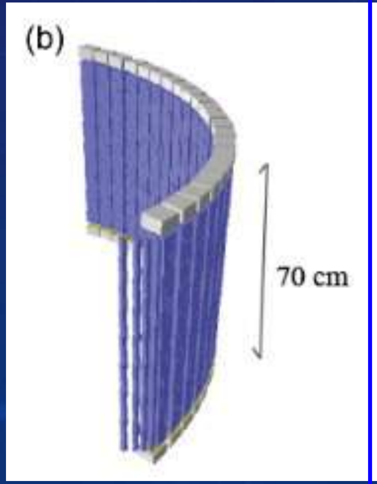



**Fig. 7.** (a) Segmented plastic scintillators. (b) Position-sensitive photomultiplier tube array. (c) Resistive channel readout of the PSPMTs.

K. Steiger et al., EPJ A (2015) 51

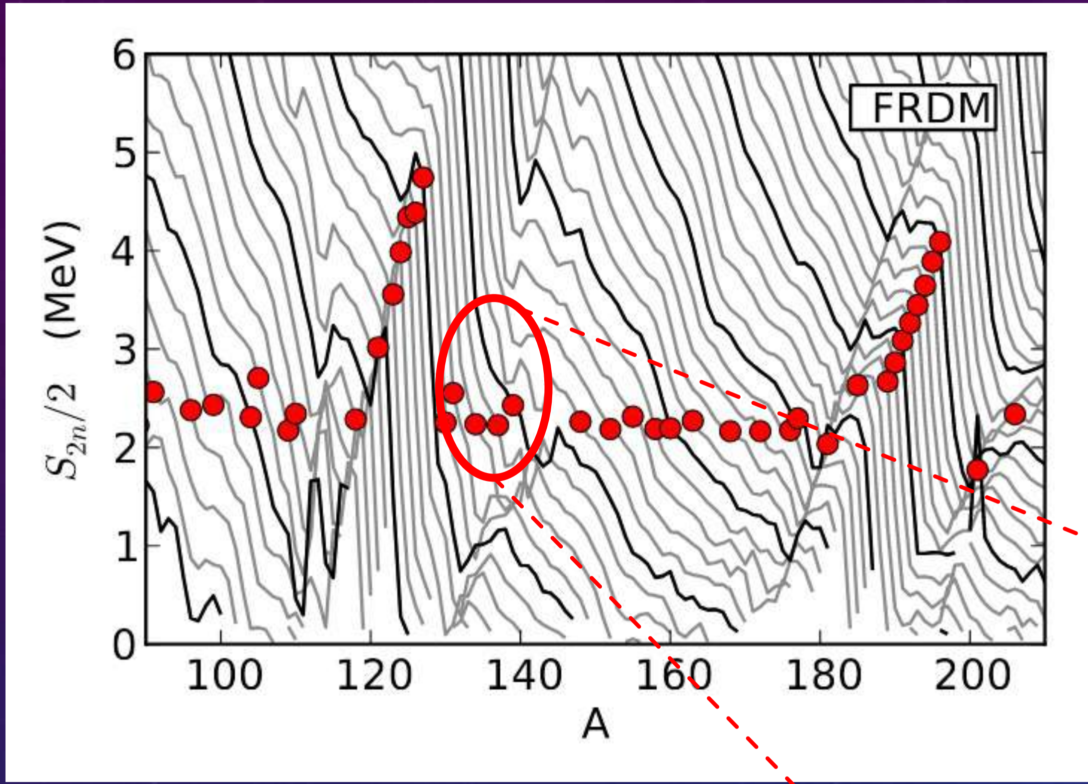
LaB3(Ce)

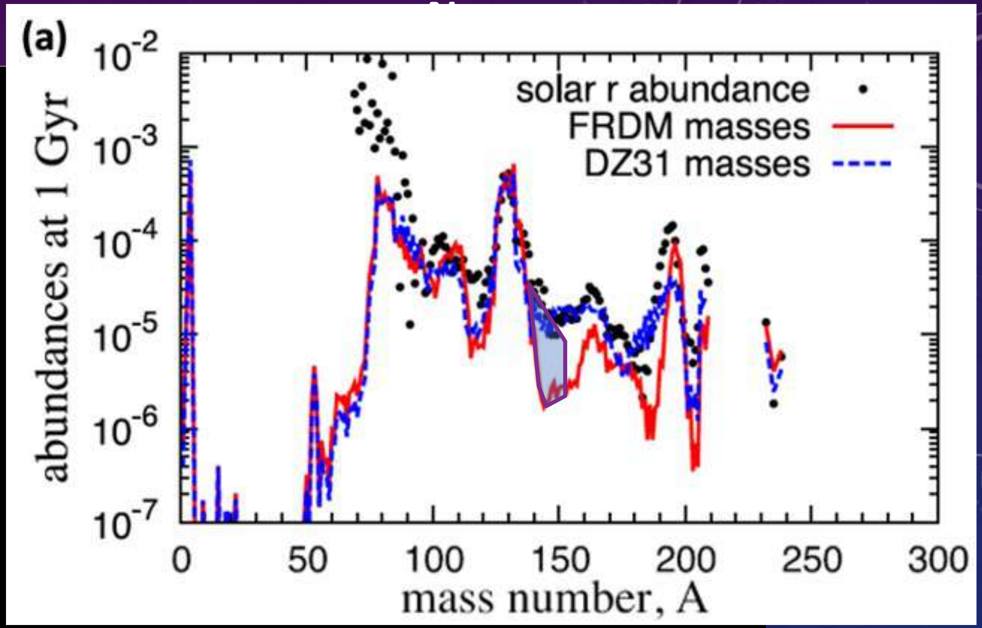


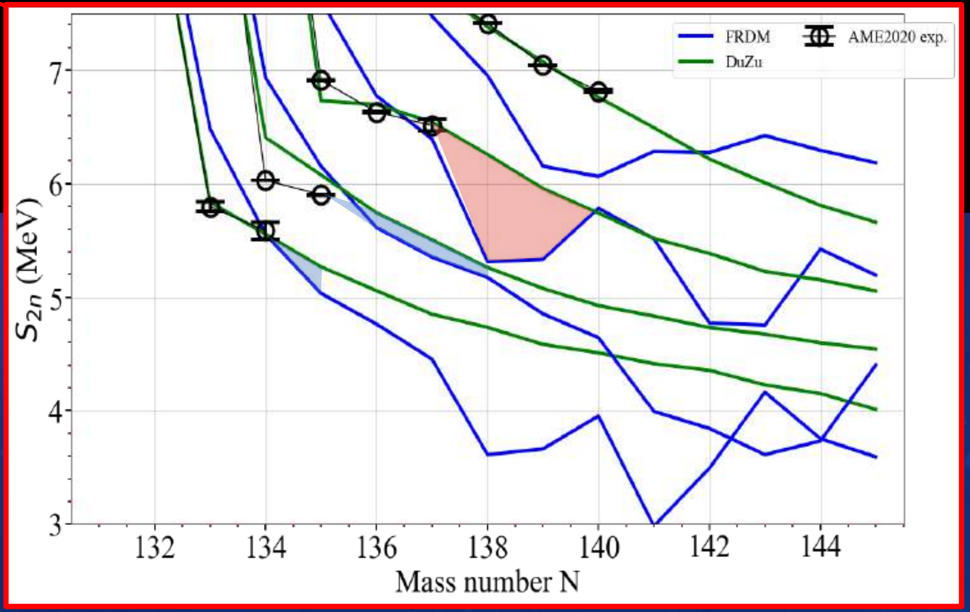

Neutron time of flight

# MASSES AND R-PROCESS ABUNDANCE

M. Wu et al., *MNRAS* 463 (2016) 2323



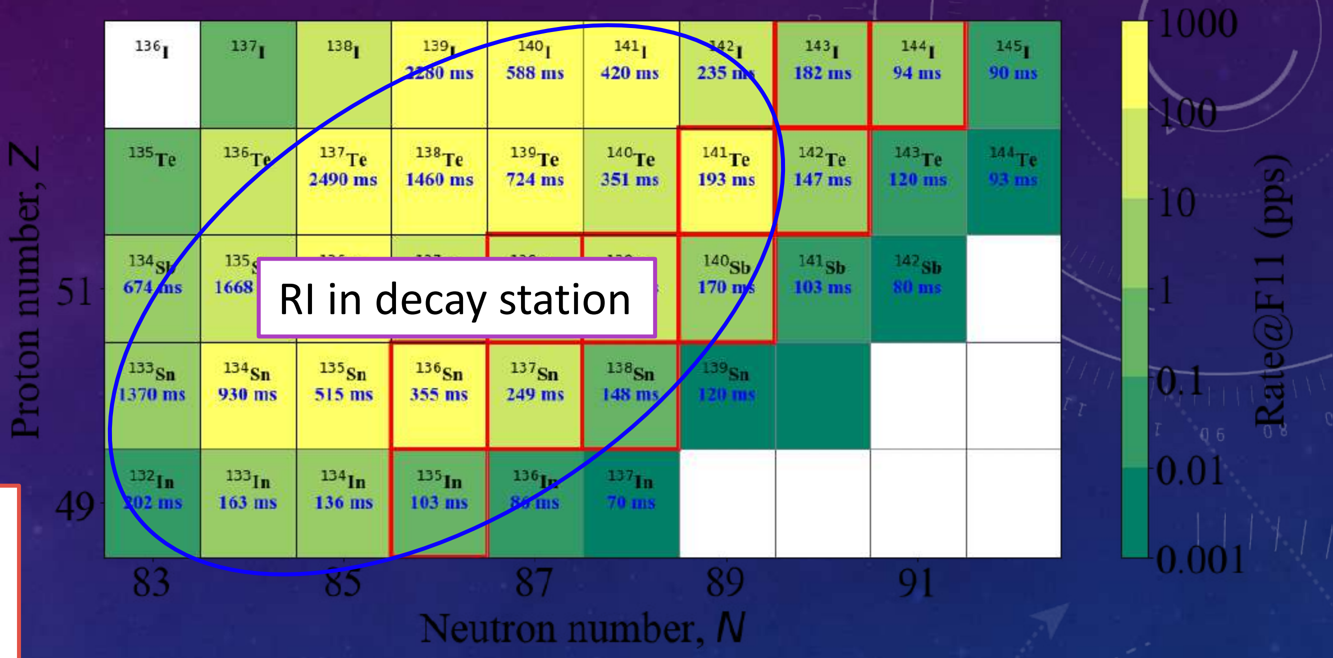




Masses beyond beyond N = 82 are sensitive to the r-process mass distribution around A > 135.

→ Experimental values are desired.

# EXPERIMENTAL SETUP AND REGION OF INTERESTS

Primary beam : $^{238}$U, Target: Be, BigRIPS for RI production

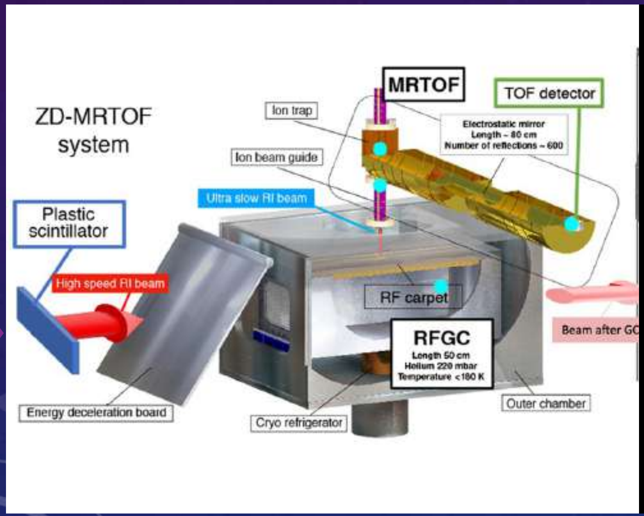



***Devices***

## ① ZD-MRTOF in ZeroDegree Spectrometer

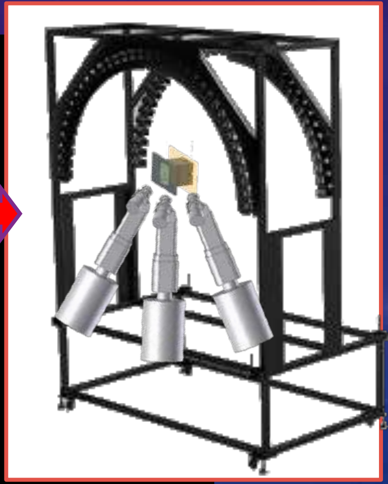
- **Mass measurements** of **12** neutron-rich nuclei: $^{135}$In, $^{136-138}$Sn, $^{138-141}$Sb, $^{141-142}$Te and $^{143,144}$I
- **Search for possible long-lived isomers**

RI




ZD-MRTOF

RI



β-decay station

## ② Decay

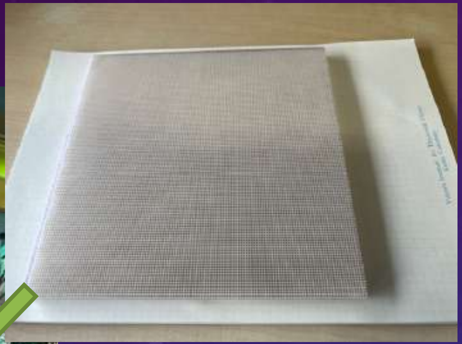
- **β-γ-n spectroscopy**
  - **Fast timing pixel scintillation detector (GARi)**
  - **Neutron time-of-flight (TOFU)**
  - **3 – 4 clover Ge detectors**
  - **15 LaBr3(Ce) detectors**

# Status: Fast timing Decay Experiment after ZD-MRTOF

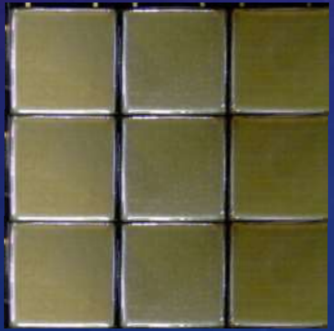
Fast beta-counting system (GARi)

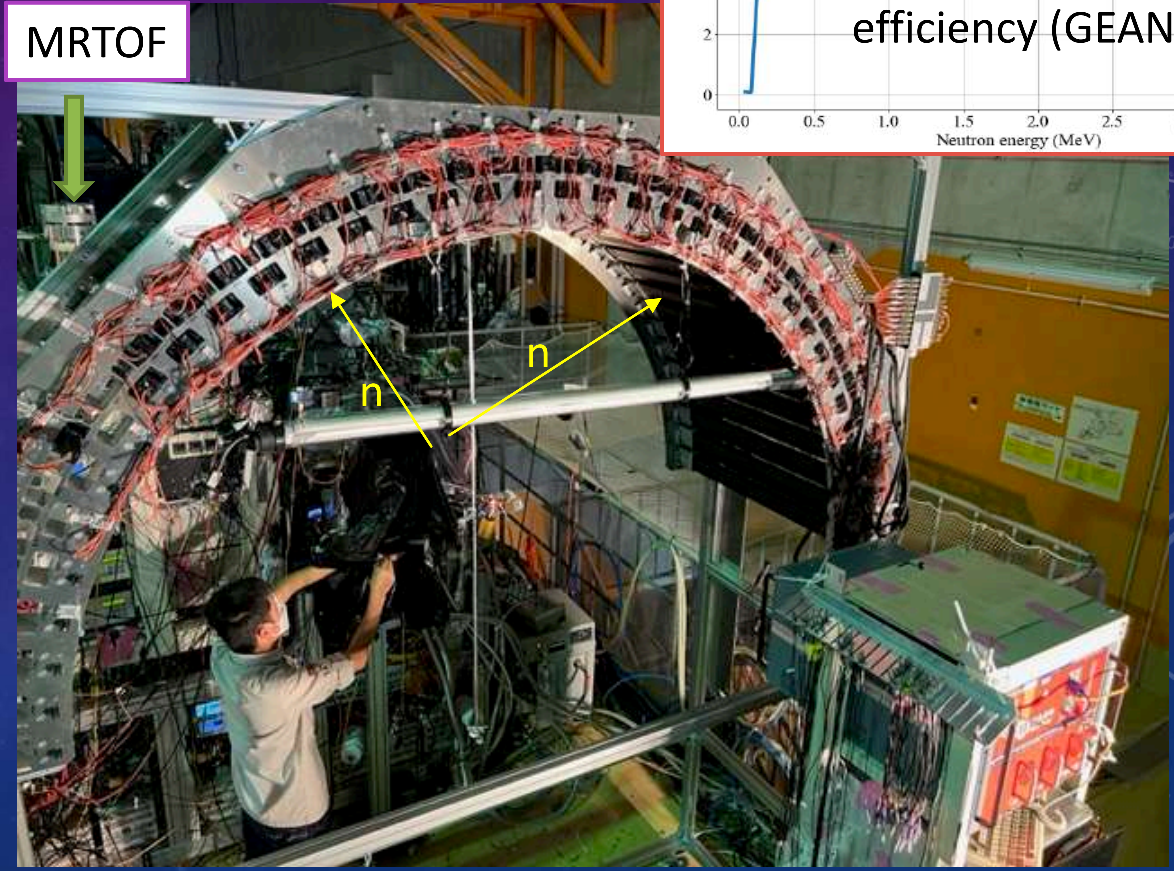
H12700A/B : 3 x 3
→ CAEN Digitizer

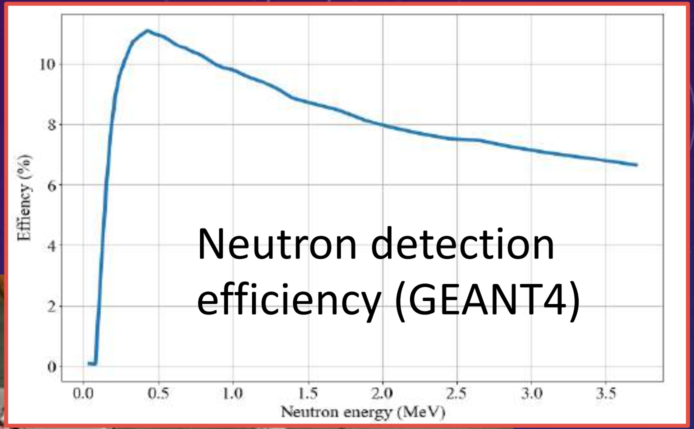
Pixel scintillator



Position sensitive PMT






Time-of-Flight detectors (TOFU) for beta-delayed neutrons
→ CAEN Digitizer

Ready to perform experiments.

# r-Process Nucleosynthesis

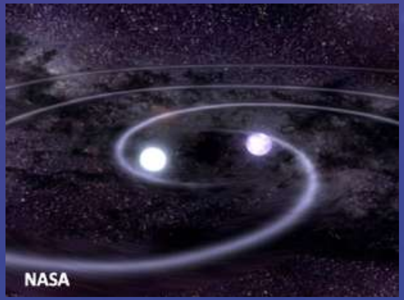
## Rare-Earth Peak

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

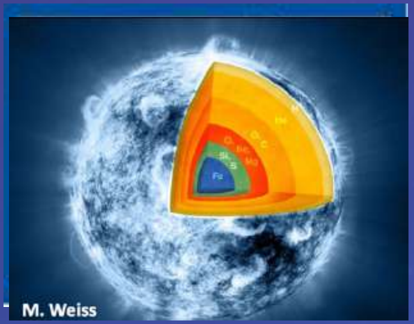
## [ Astrophysics Observation ]

- **Site of r-process** High neutron density environment

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

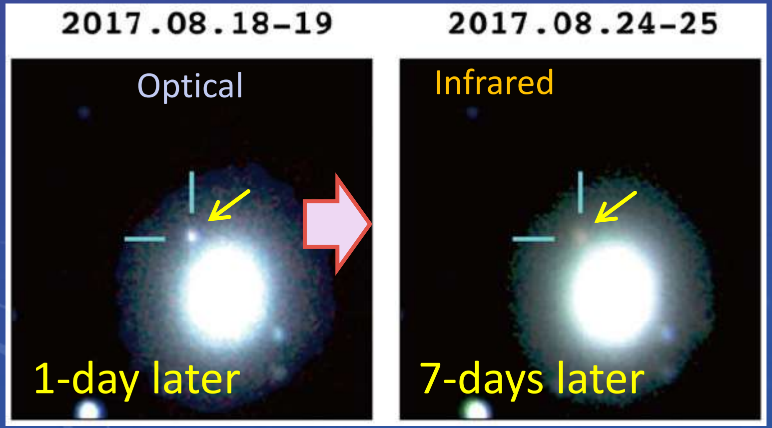



Supernovae



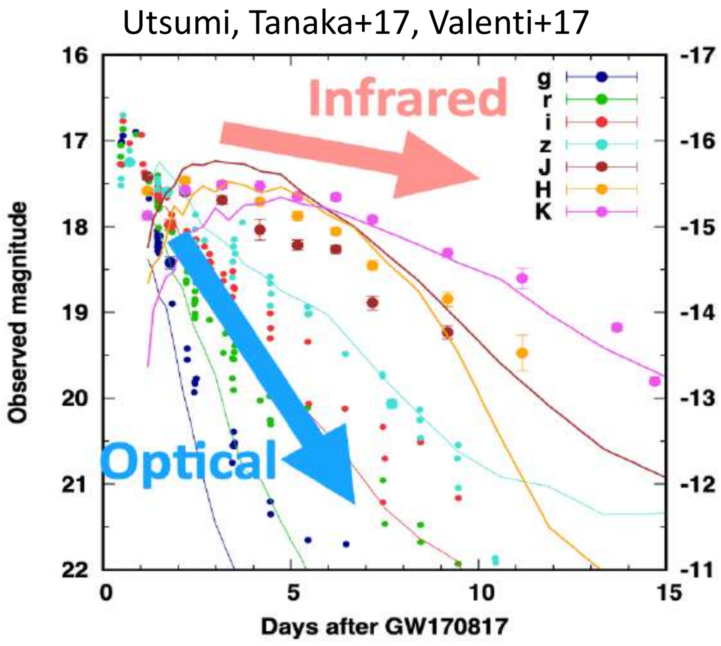

- **Observation of electromagnetic wave**

Site of GW170817

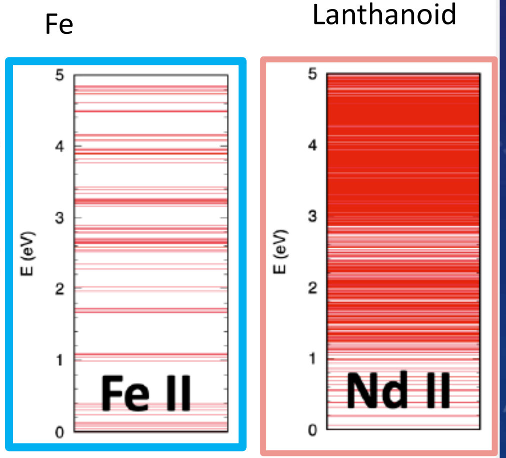



nuclear decay heat

Kilonova is expected & observed !




$$\lambda = \frac{hc}{\Delta E}$$

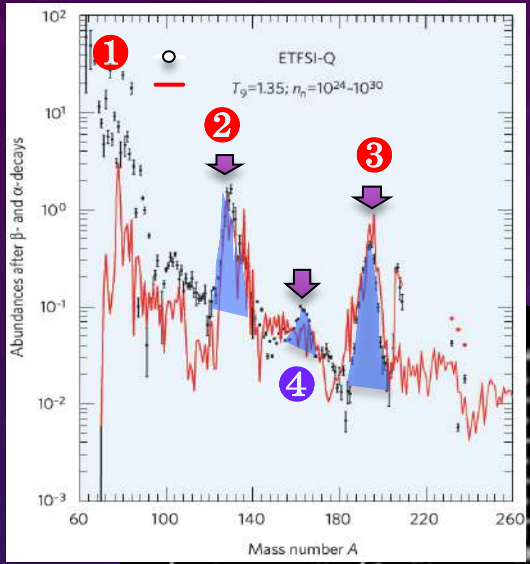



Infrared indicates the synthesis of lanthanoid elements in NS-NS collisions

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

## [ Nuclear Physics ]

C.Sneden et al. (2008)

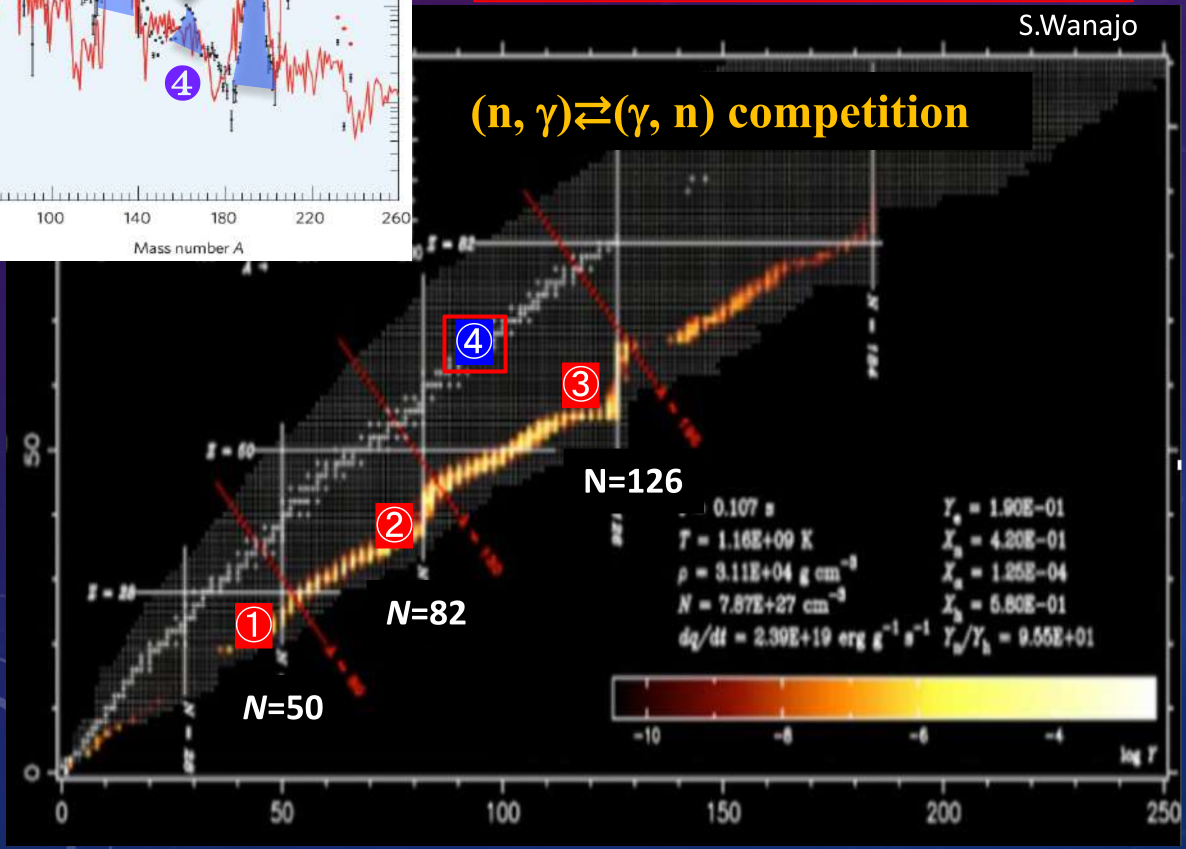



① Neutron shell closure *N*=50

② Neutron shell closure *N*=82

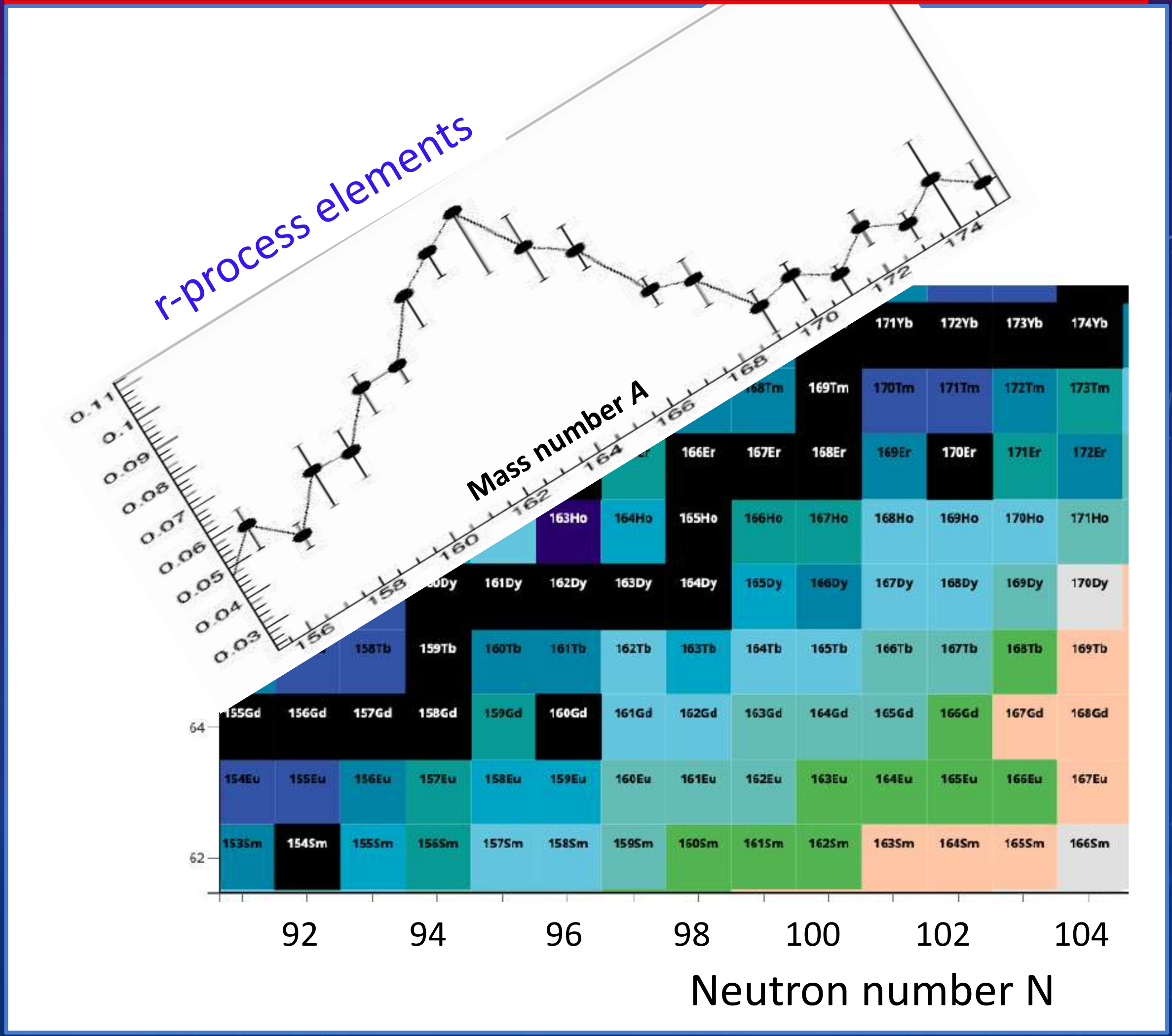
③ Neutron shell closure *N*=126

S.Wanajo




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

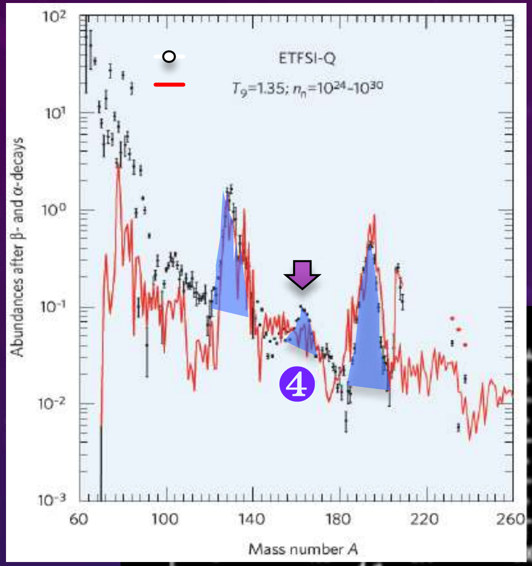
There is no shell closure expected around A ~ 165..




(3)

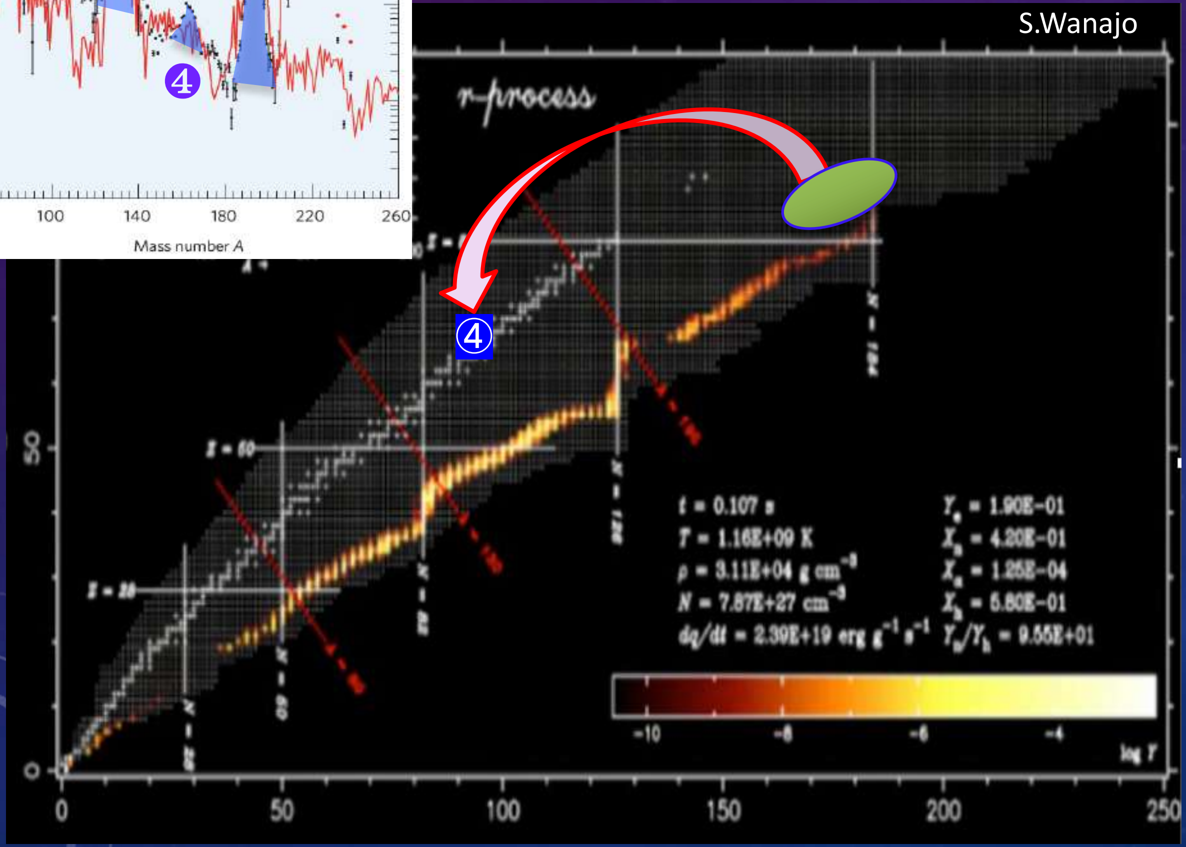
# Where & How the Rare-Earth Elements are Synthesized !?

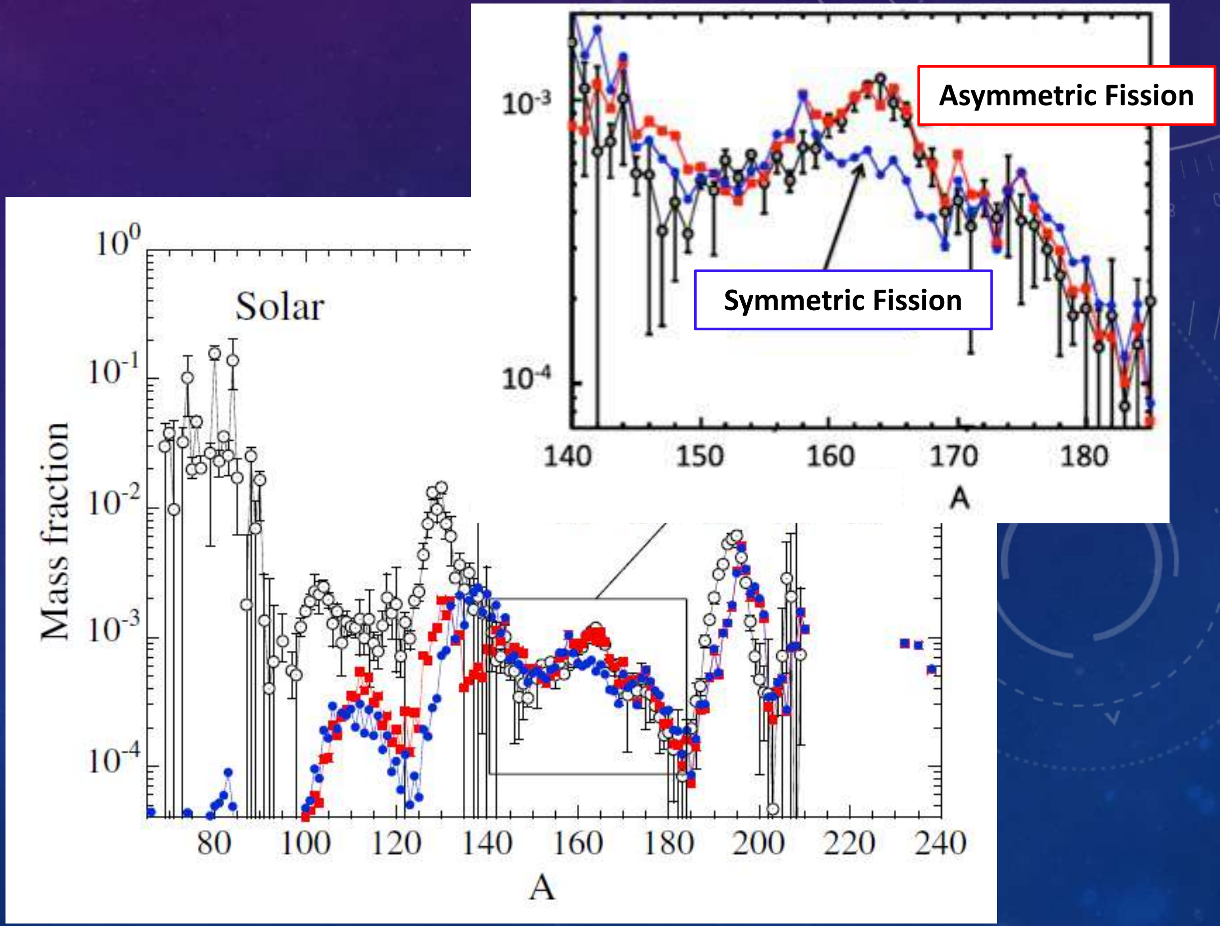
C.Sneden et al. (2008)




Asymmetric fission of neutron-rich heavy nuclei
（S. Goriely et al.)

S. Goriely et al, PRL 111, 242502 (2013)

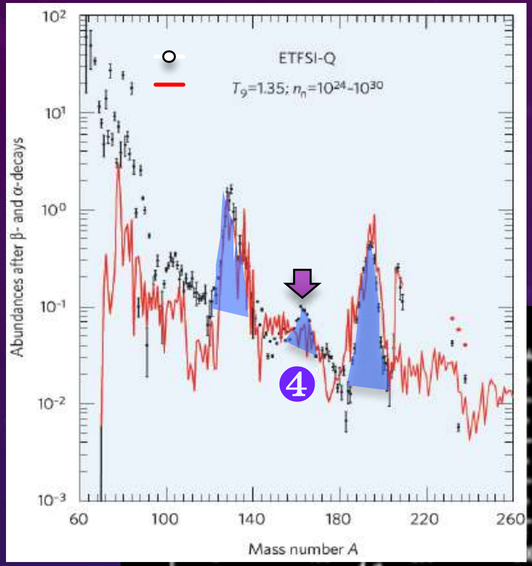



(4)

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

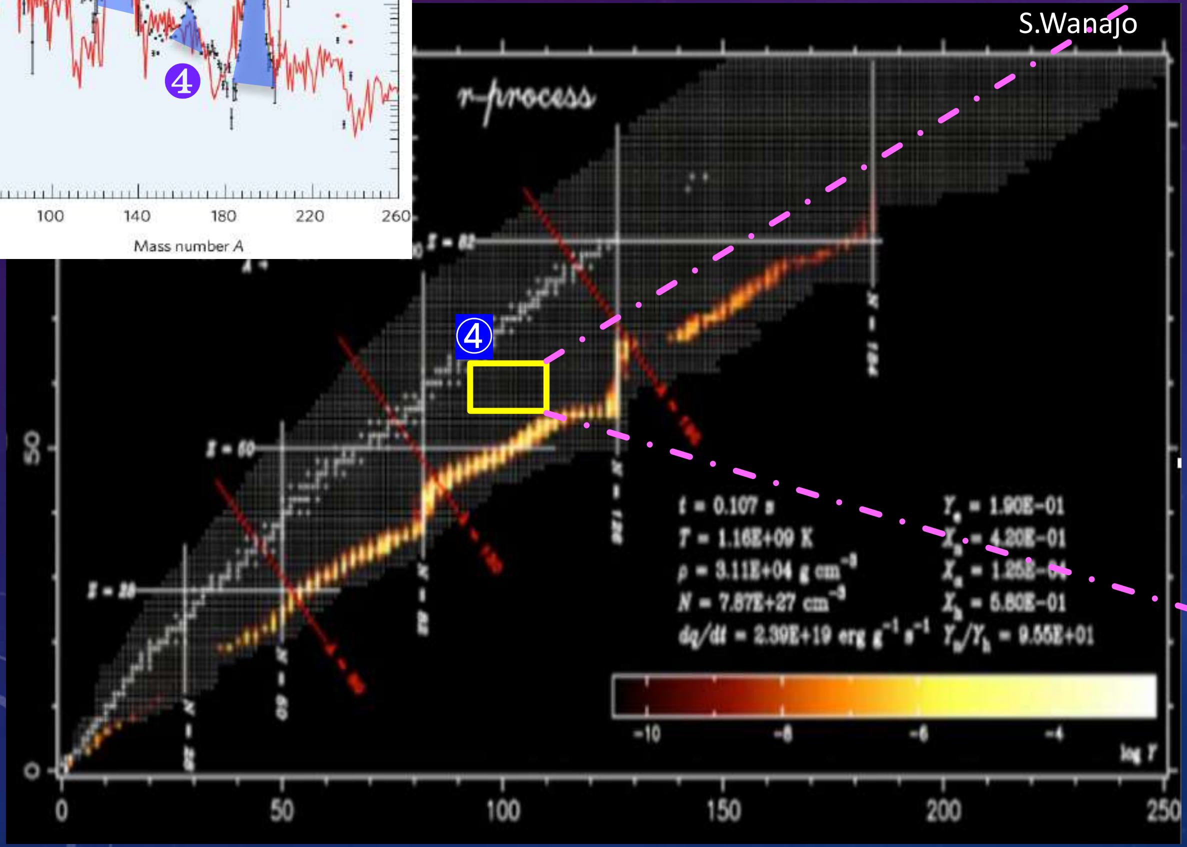
C.Sneden et al. (2008)



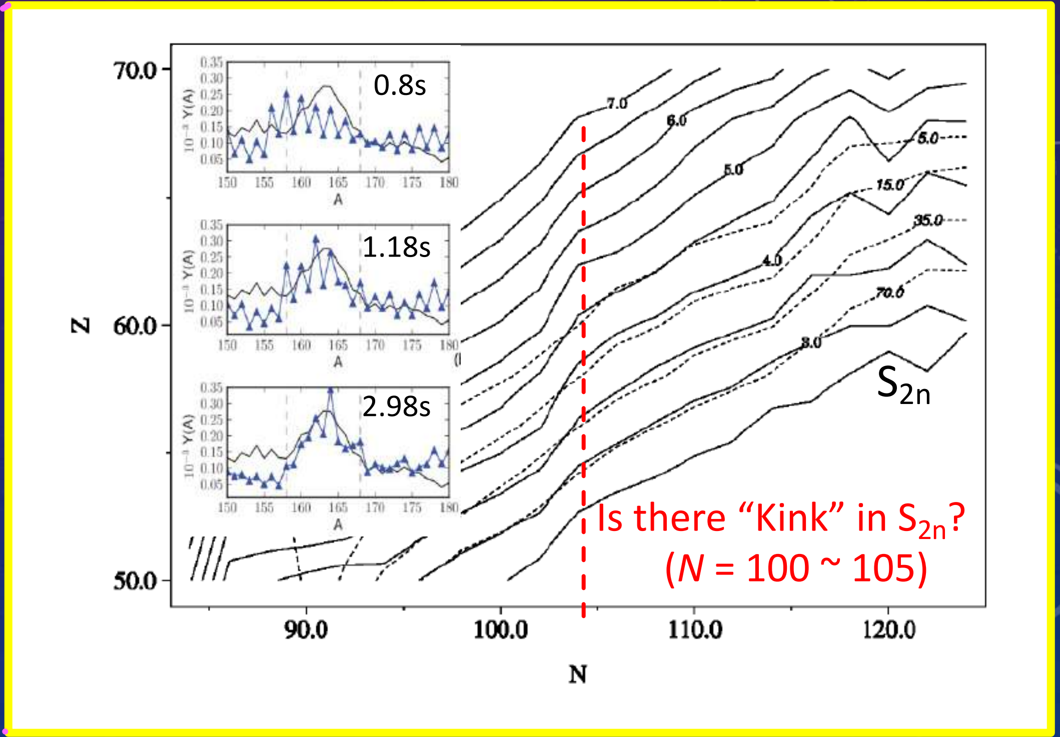

Nuclear deformation（R.Surman et al.)

R. Surman et al, PRL 79, 10 (1997)
M. Mumpower al., PRC 85, 045801 (2012)

S.Wanajo




Formation of rare-earth peak at freeze-out time of r-process



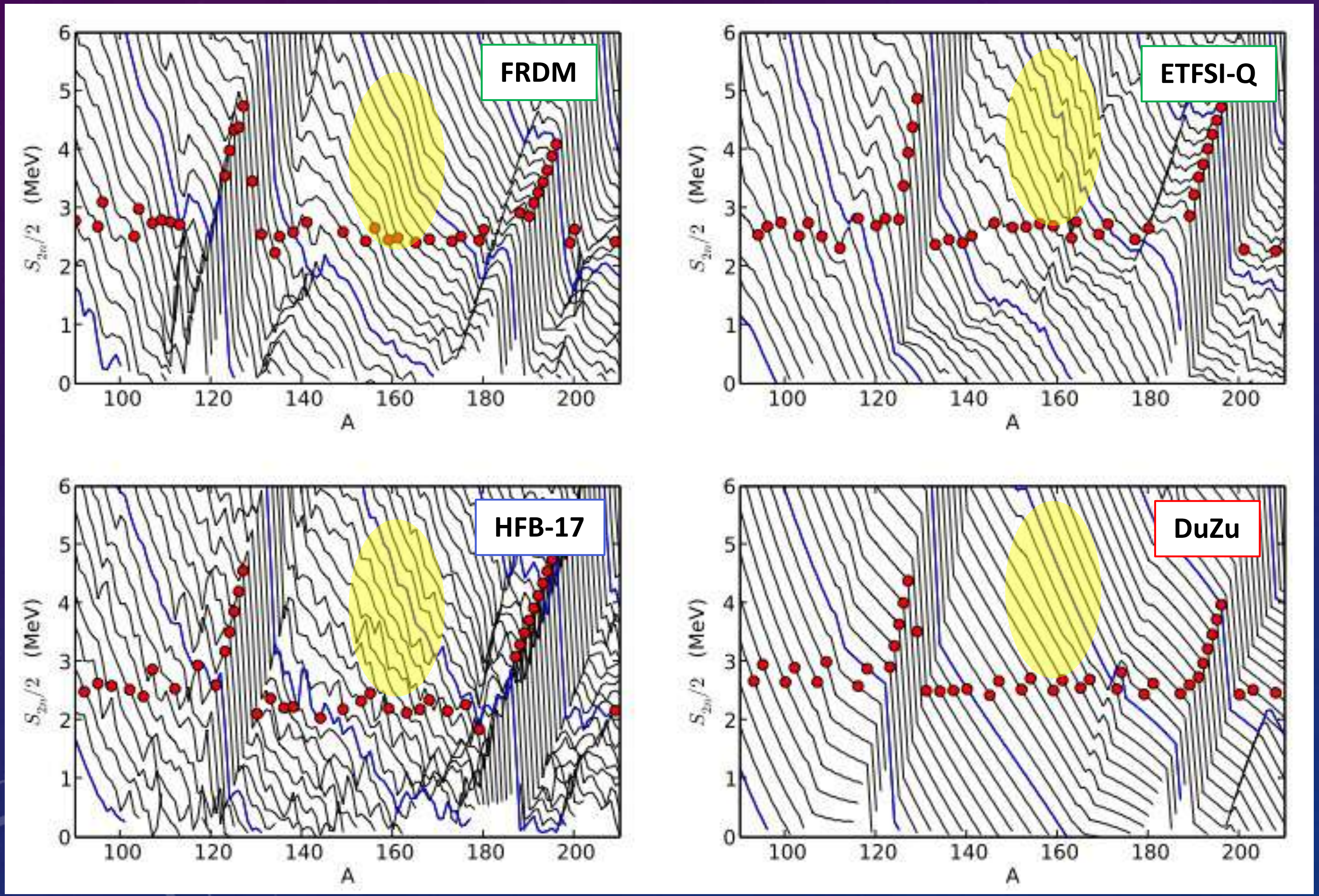

$S_{2n}(Z,N)$ = E ($Z$, $N$ - 2) – E ($Z$, $N$)
... Suitable to study on shell gaps, test of magicity

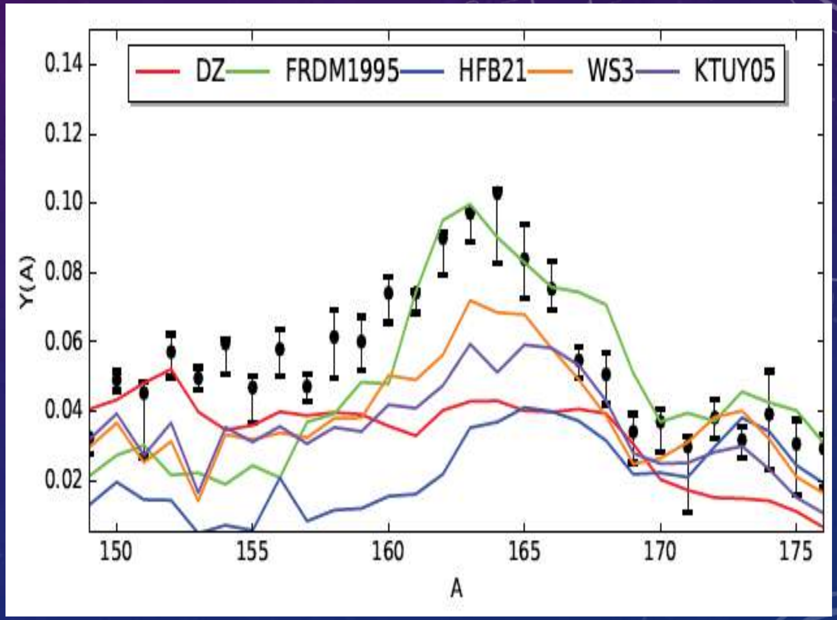
# Rare-Earth Peak Formation with Various Mass Models

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

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

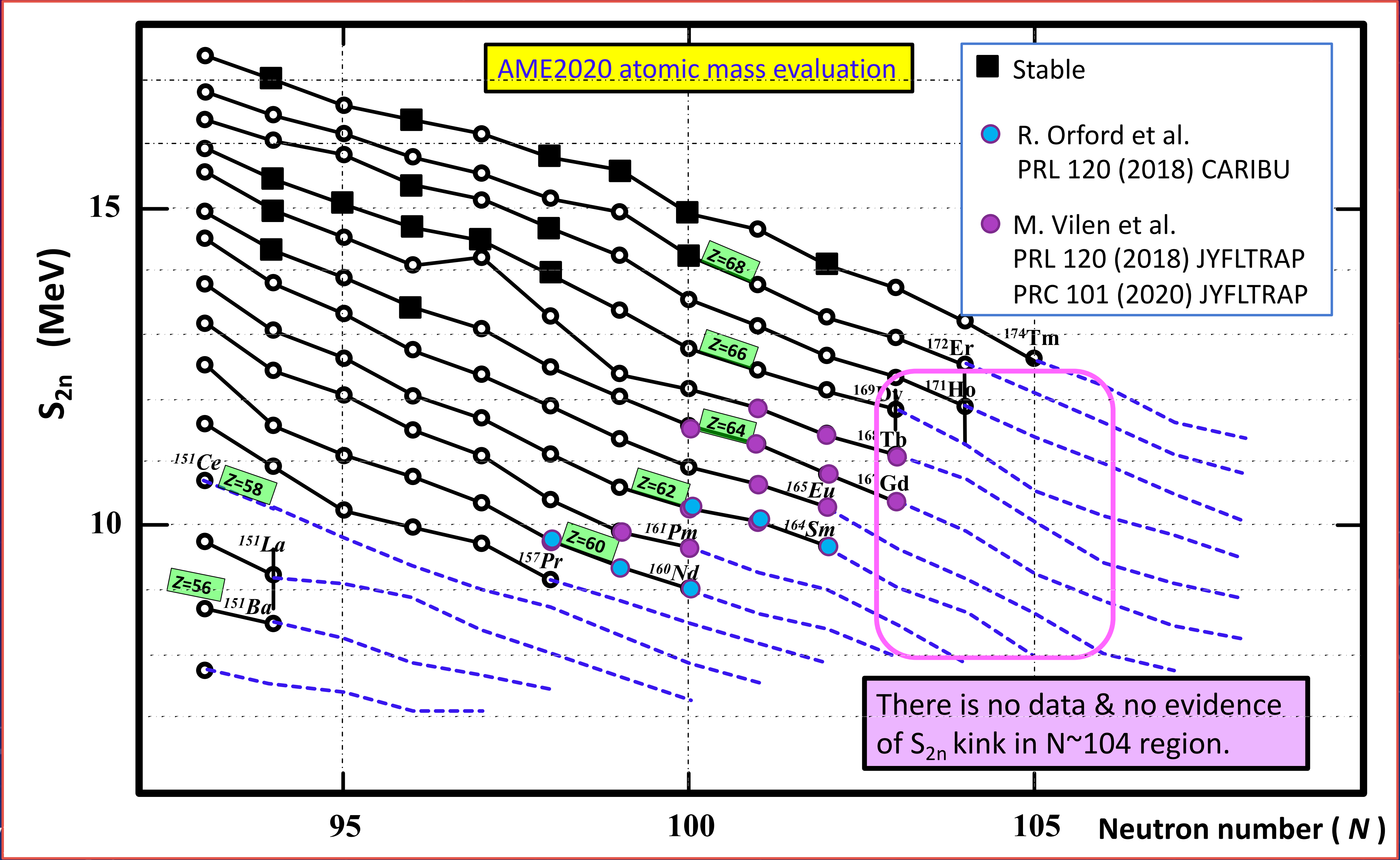
A. Arcones, G.Marinez-Pinedo (2007, 2012)



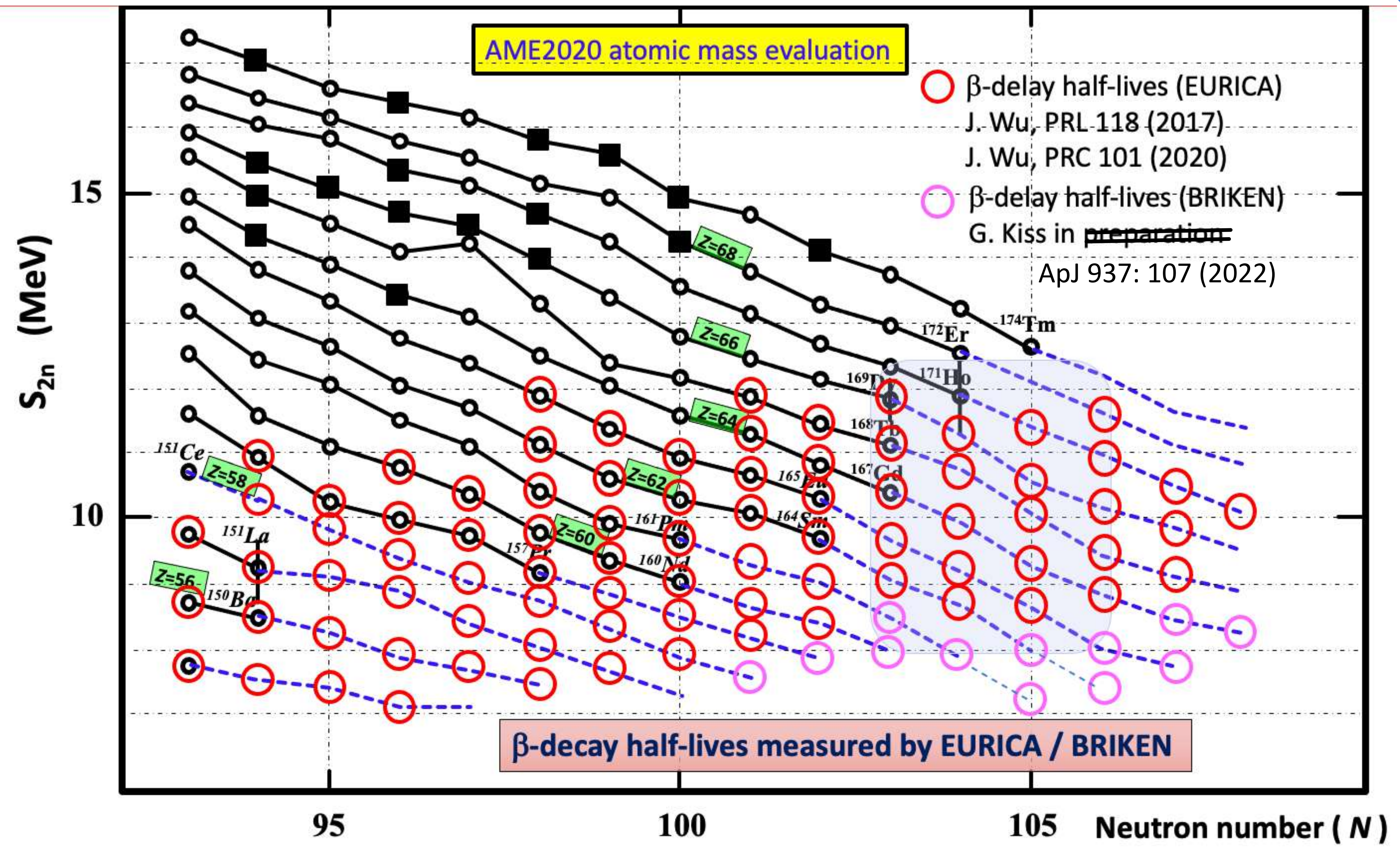




Rare-earth peak formation depends on mass models.
→ Uncertainties of mass models are critical issue !

We need experimental data !



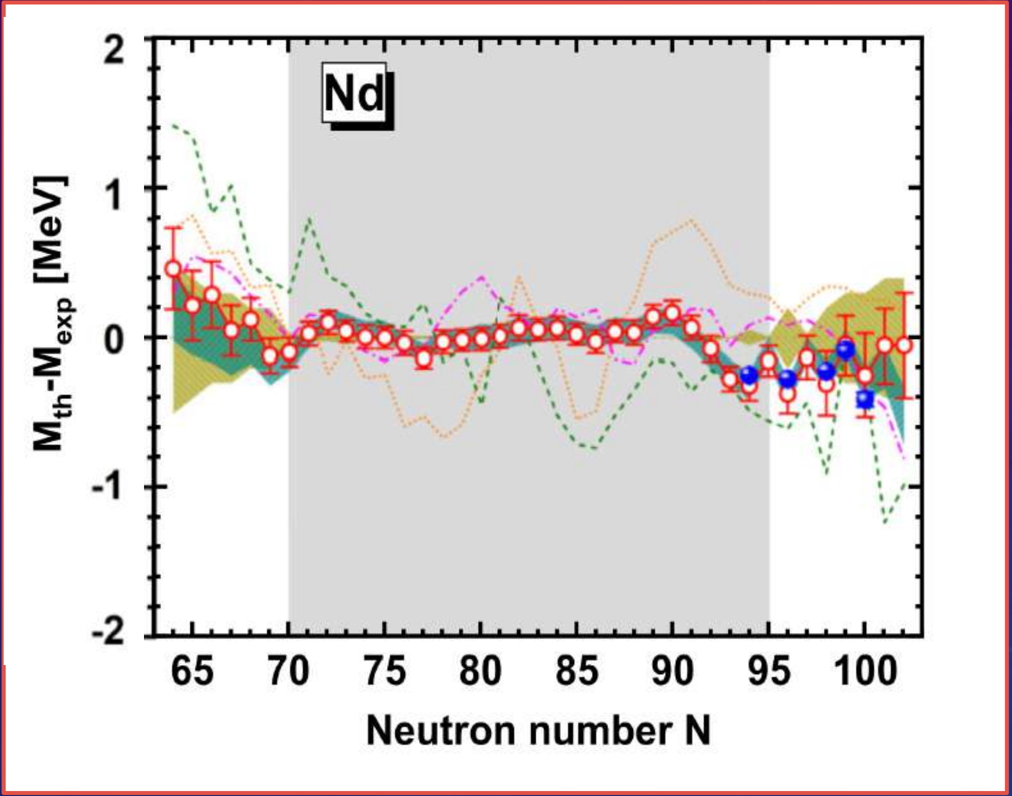
AME2020 atomic mass evaluation
Stable
R. Orford et al.
PRL 120 (2018) CARIBU
M. Vilen et al.
PRL 120 (2018) JYFLTRAP
PRC 101 (2020) JYFLTRAP
S2n (MeV)
15
10
95
100
105
Neutron number ( N )
Z=68
Z=66
Z=64
Z=62
Z=60
Z=58
Z=56
174Tm
172Er
171Ho
Tb
Gd
165Eu
164Sm
161Pm
160Nd
157Pr
151Ce
151La
151Ba
There is no data & no evidence of S2n kink in N~104 region.

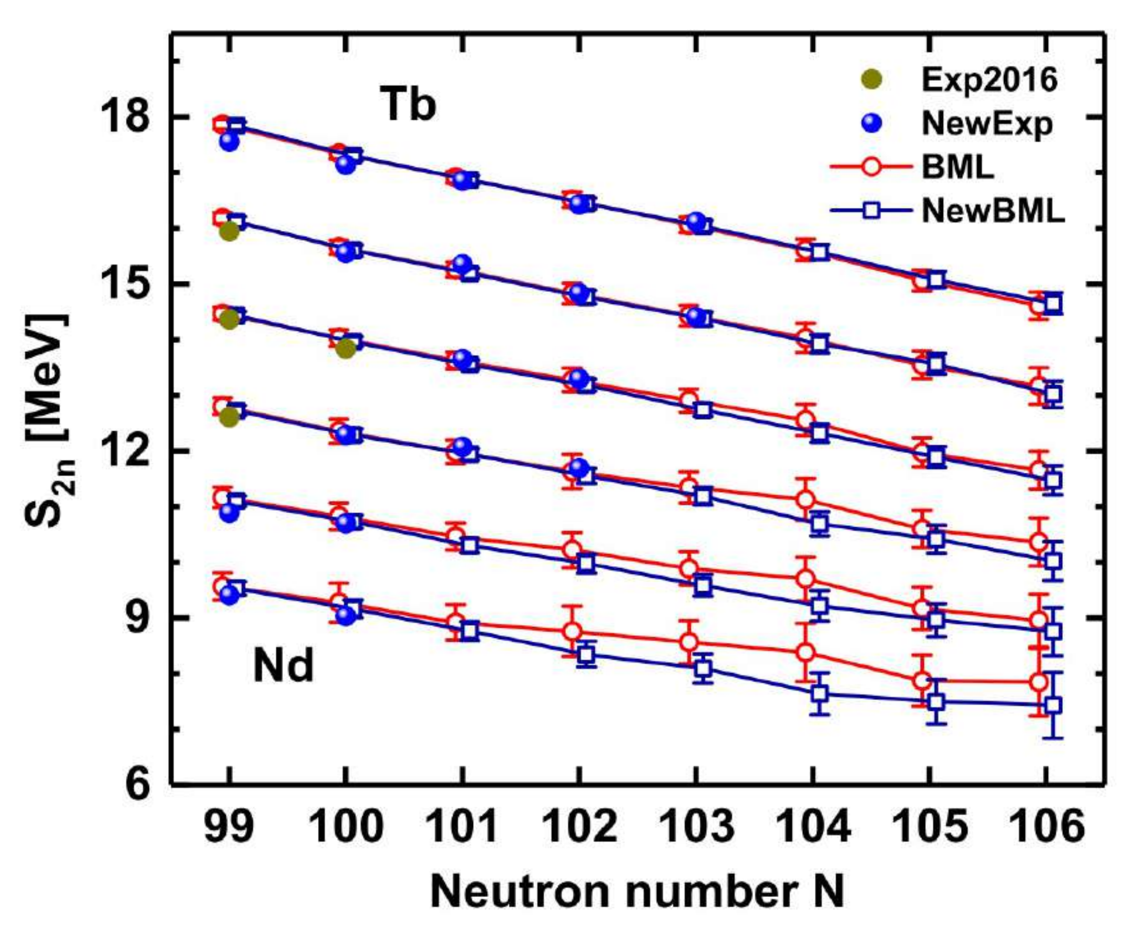


AME2020 atomic mass evaluation
β-delay half-lives (EURICA)
J. Wu, PRL 118 (2017)
J. Wu, PRC 101 (2020)
β-delay half-lives (BRIKEN)
G. Kiss in preparation
ApJ 937: 107 (2022)
β-decay half-lives measured by EURICA / BRIKEN
S2n (MeV)
15
10
95
100
105
Neutron number ( N )
Z=56
Z=58
Z=60
Z=62
Z=64
Z=66
Z=68
151Ce
151La
150Ba
157Pr
160Nd
161Pm
164Sm
165Eu
167Gd
168Tb
169Dy
171Ho
172Er
174Tm

# Nuclear Mass (theoretical prediction with machine learning)

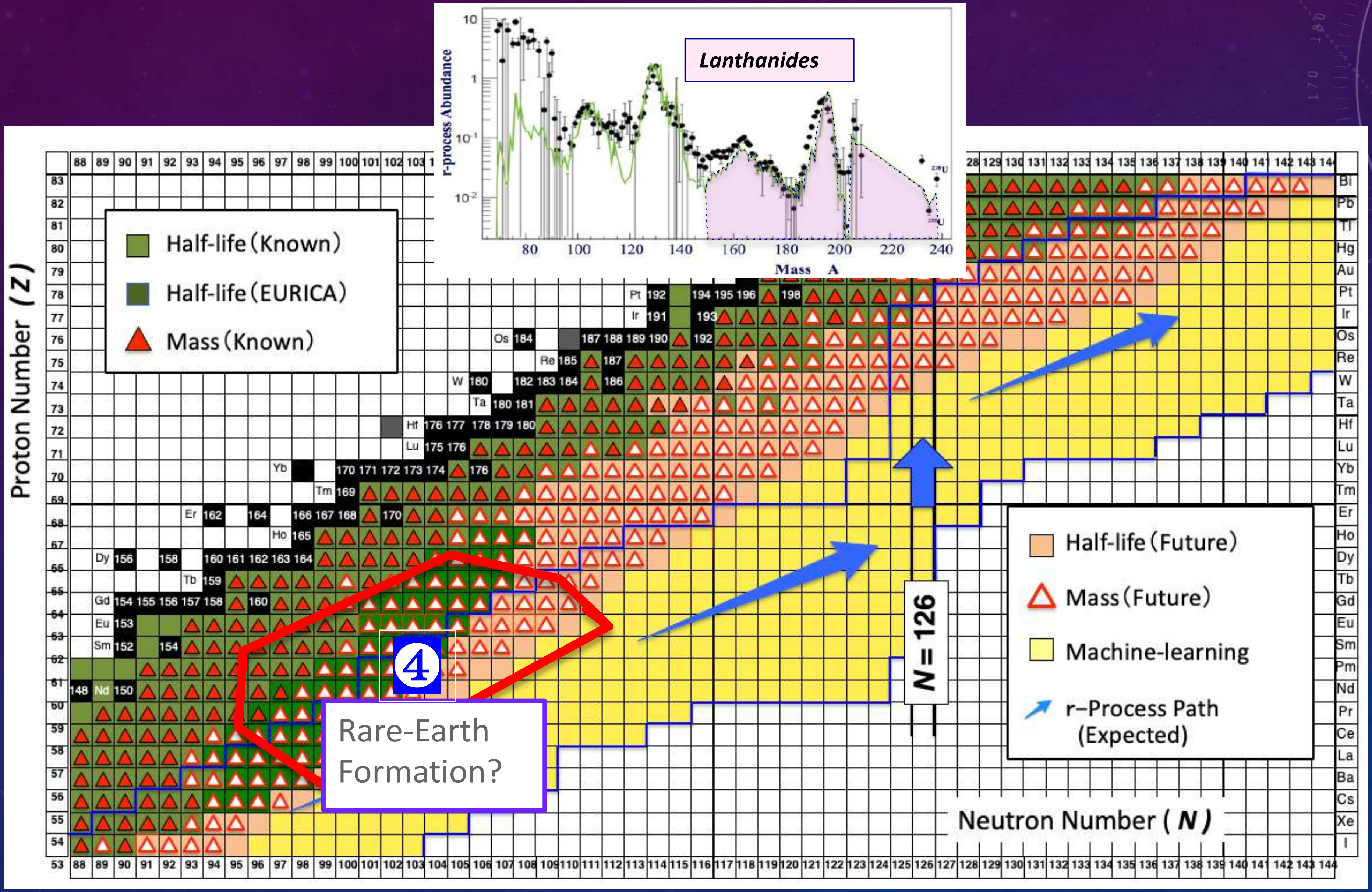
Z.M. Niu and H.Z Liang, Phys. Rev. C 106, L201303 (2022)




New BML with lexperimental results –> Sn2 “kink” around N = 104 is suppressed.

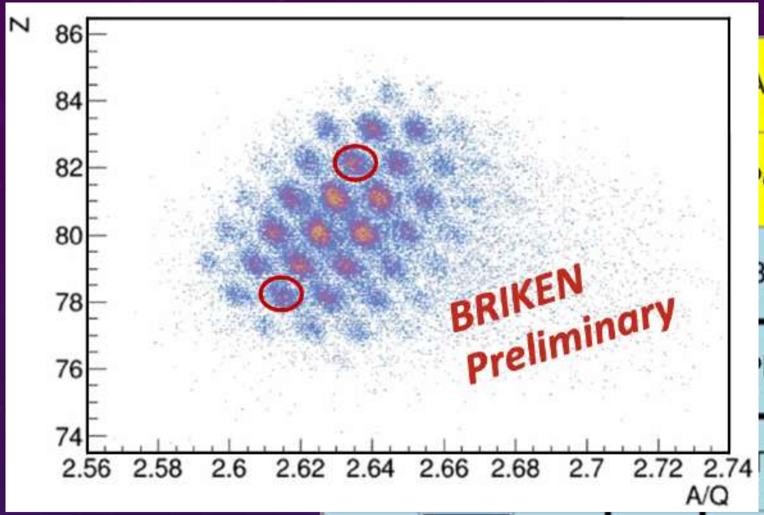
# Future Plan at RIBF-ZDS

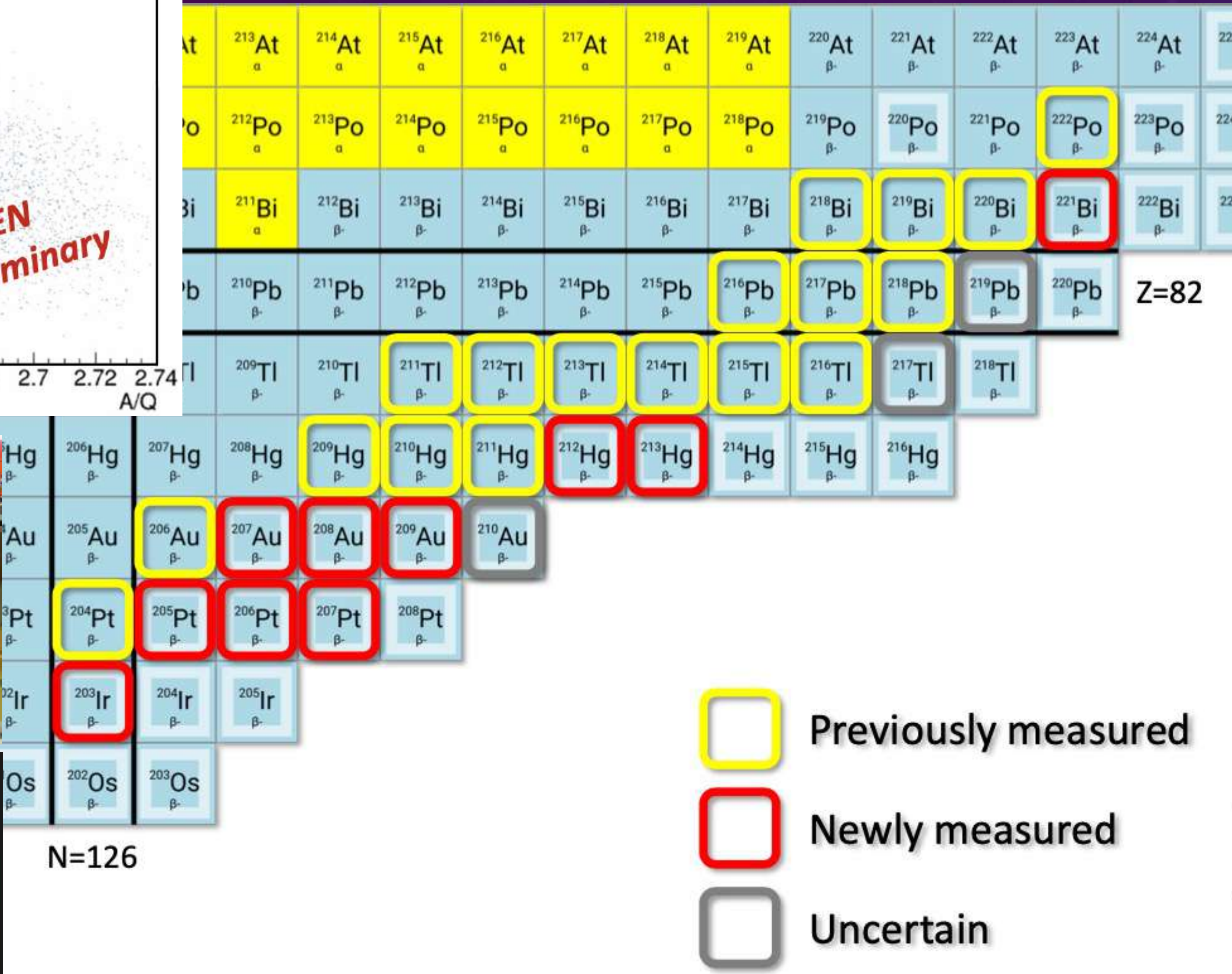


# BRIKEN Experiment in Vicinity of N = 126

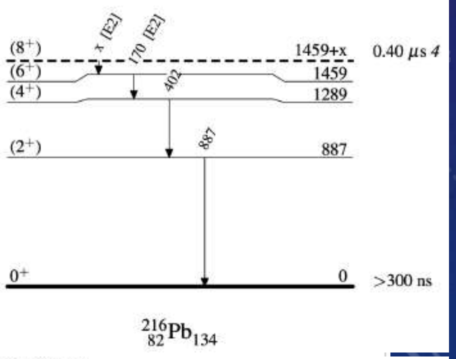
Spokespersons: J.Wu, SN,T.Davinson, J.L.Tain

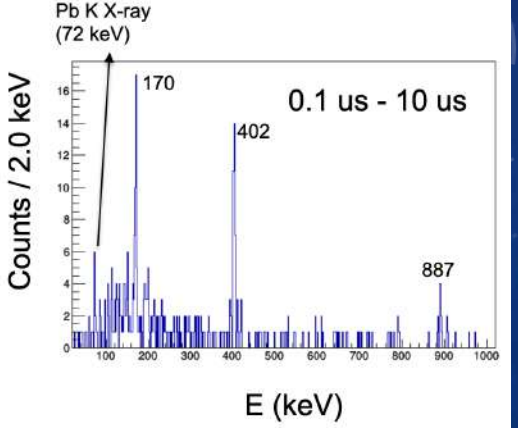
Isomer search in progress (J. Wu and A. Morales)




A. Gottardo et al, PRL **109**, 162502



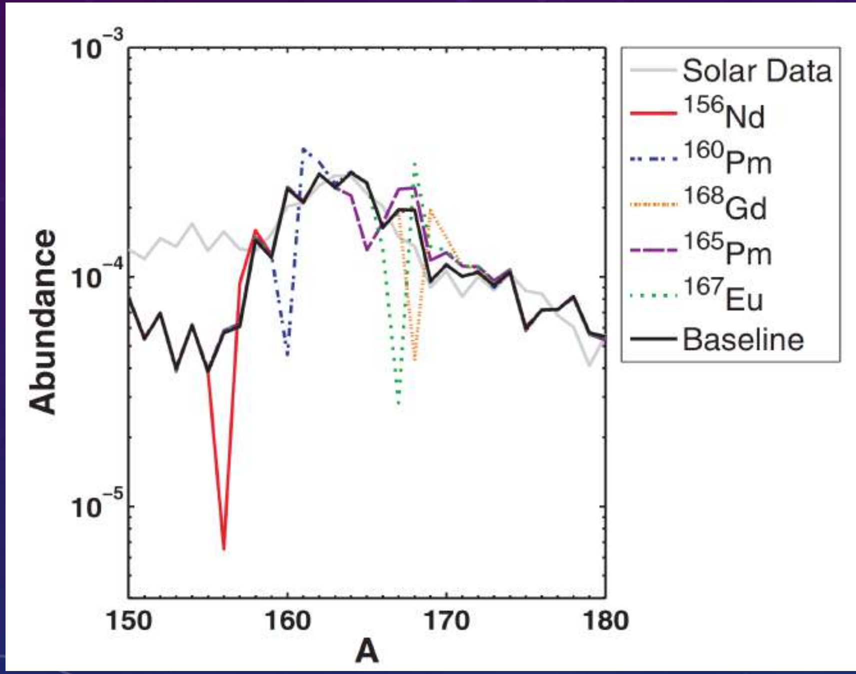



# 今後の予定 （DTAS: Tataki Project)

$$t_{1/2} = \frac{1}{\int_0^{Q_\beta} S_\beta(E_x) f(Q_\beta - E_x) dE_x} \quad (1.)$$

$$P_n = t_{1/2} \int_{S_n}^{Q_\beta} \frac{\Gamma^n}{\Gamma^n + \Gamma^\gamma} S_\beta(E_x) f(Q_\beta - E_x) dE_x \quad (2.)$$

M. R. Mumpower et al., PRC 86, 035803 (2012)




***single*** neutron capture rate was changed by factor of 10 ($Y_{K=10}$)

**Rare-Earth (4-days) ... G. Kiss**

**N>126 (7-days) ... A. Morales**

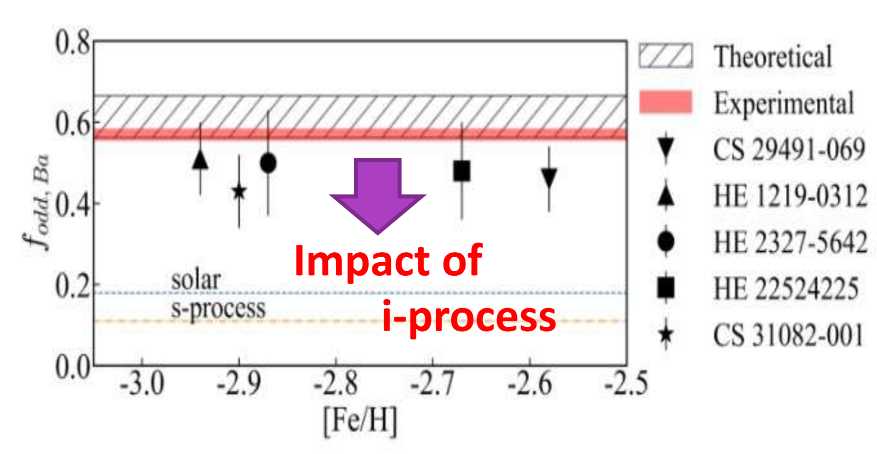
**Goal : to measure the γ-emission from neutron unbound states using the total absorption technique to constrain the Hauser-Feshbach model provided (n,γ) cross sections.**

$$S_\beta(E_x) = \frac{I_\beta(E_x)}{t_{1/2} f(Q_\beta - E_x)} \quad (3.)$$

# まとめ

$$f_{odd,Ba} = \frac{n(^{135}Ba) + n(^{137}Ba)}{n(Ba)}$$

- 中性子過剰な原子核の性質とr過程は密接な関係
  - EURICA (2012 – 2016)
  - BRIKEN (2016 - 2021)
  - DTAS (2019 - ), IDATEN (2023 - )
  - ZD-MRTOF (2019 - ) & TOFU (2023 - )



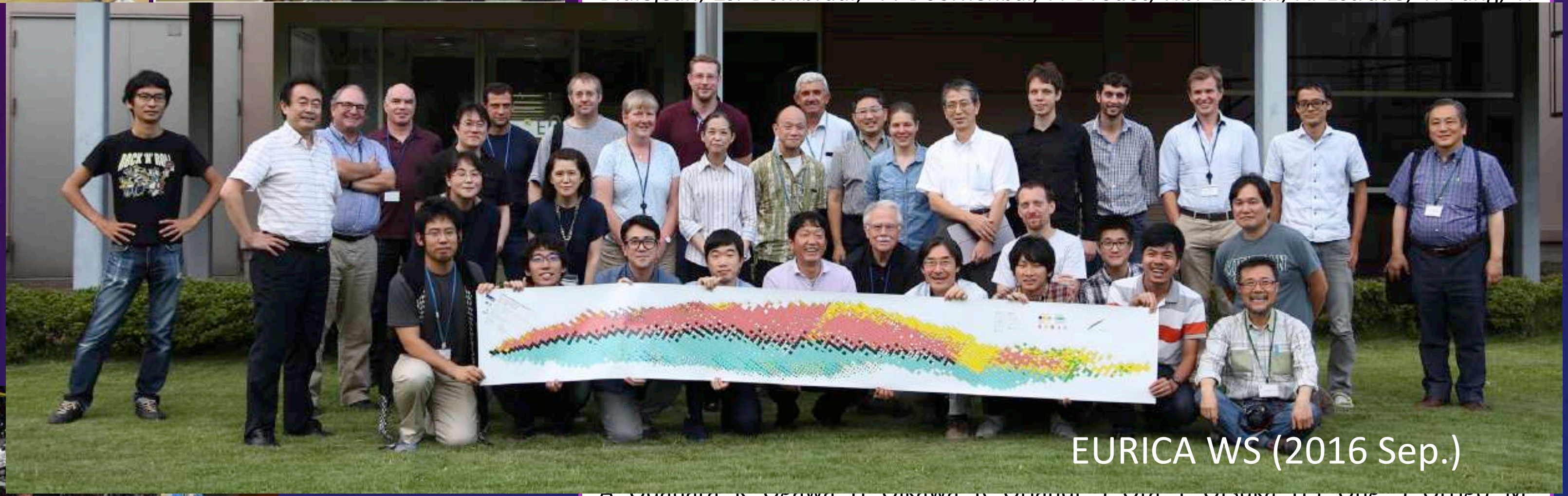

- 中性子捕獲反応の重要性
  - 第2ピーク領域の微細構造
    - ✔ 質量数 A = 132の不足 ($^{132}Xe$)
    - ✔ 質量数 A = 135, 137 vs 138の不確定性 ($^{135,137}Ba$ and $^{138}Ba$)
  - 希土類元素のピーク形成
    - ✔ 質量数 A ~ 165 （N~ 104)領域の中性子捕獲


r-process & i-process !?

# EURICA Collaboration

19 countries：237 collaborators

J. Agramunt, P. Aguilera, T. Alharbi, A. Algora, G. Angelis, N. Aoi, P. Ascher, R. Avigo, H.Baba, C. Borcea, A. Boso, A.M. Bruce, R.B. Cakirli, F.L.Bello Garrote, G. Benzoni, J.S.Berryman, R. Berta, B. Blank, N. Blasi, A. Blazhev, P. Boutachkov, S. Bonig, A. Bracco, F. Browne, F. Camera, R.J. Carroll, S. Ceruti, I. Celikovic, K.Y. Chae, J. Chiba, L. Coraggio, A. Covello, F.C.L. Crespi, J.-M. Daugaus, R. Daido, P. Davis, M.C. Delattre, F. Diel, F. Didiejean, Zs. Dombradi, P. Doornenbal, F. Drouet, H.J. Eberth, A. Estrade, Y. Fang, T.


EURICA WS (2016 Sep.)

Rajabali, J. Park, Z. Patel, A. Petrovici, F. Recchia, V. Phong, Zs. Podolyak, O.J. Roverts, L. Prochniak, P.H. Regan, S. Rice, E. Sahin, H. Sakurai, K. Sato, H. Schaffner, H.Scheit, P. Schury, C. Shand, Y. Shi, S. Shibagaki, T. Shimoda, Y. Shimizu, K. Sieja, L. Sinclair, G.S. Simpson, P.-A. Soderstrom, D. Sohler, I.G. Stefan, K. Steiger, D. Steppenbeck, K. Sugimoto, T. Sumikama, D. Suzuki, H. Suzuki, T. Tachibana, K. Tajiri, S. Takano, A. Tashima, H. Takeda, Man. Tanaka, Mas. Tanaka, Y. Takei, R. Taniuchi, J. Taprogge, K. Tajiri, T. Teranishi, S. Terashima, G. Thiamova, K. Tshoo, Zs. Vajta, J. Valiente Dobon, Y. Wakabayashi, P.M. Walker, H. Watanabe, A. Wendt, V. Werner, O. Wieland, K. Wimmer, J. Wu, Q. Wu, F.R. Xu, Z.Y. Xu, A. Yagi, S. Yagi, H. Yamaguchi, K. Yamaguchi, T. Yamamoto, M. Yalcinkaya, R. Yokoyama, S. Yoshida, K. Yoshinaga, G. Zhang

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

Acknowledgement: Gammapool, Preepc, IBS

# BRIKEN COLLABORATION

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C. Michigan: A. Estrade, Nepal
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TRUMF: I. Dillmann, R.Caballero-Folch
Daresbury Lab. : John Simpson
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ORNL: K.P. Rykaczewski,
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Univ. Guelph: P. Garrett
Univ. Surrey: P. Regan, Z. Podolyák, W. Gelletly
MTA ATOMKI: Z. Dombrádi, D. Sohler, Z. Fülöp
Peking Univ. : Jin Wu, Z.H. Li

# ZD-MRTOF Collaboration

* Spokespersons

RIKEN ... S. Nishimura*, A. Takamine, H. Ishiyama, V.H. Phong*, S. Kimura, T. Kojima, T. Sonoda, H. Sakurai, N. Fukuda, H. Suzuki, H. Takeda, Y. Shimizu, M. Mukai, S. Naimi

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U. Tokyo ... T.T. Tsun

IMP Lanzhou ... D.S. Hou, J. Liu, Z. Liu

JAEA ... Y. Ito

CNS ... S. Michimasa

GSI ... T. Dickel, D. Kumar

NPL ... G. Lorusso

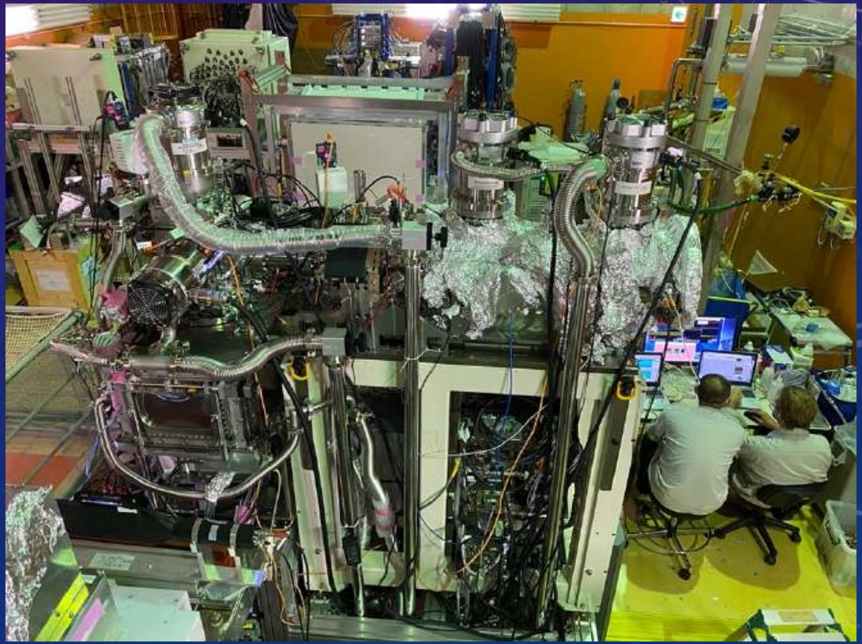
JYFL ... A. Kankainen

U. York ... S. Chen

CMU ... A. Estrade, I. Sultana

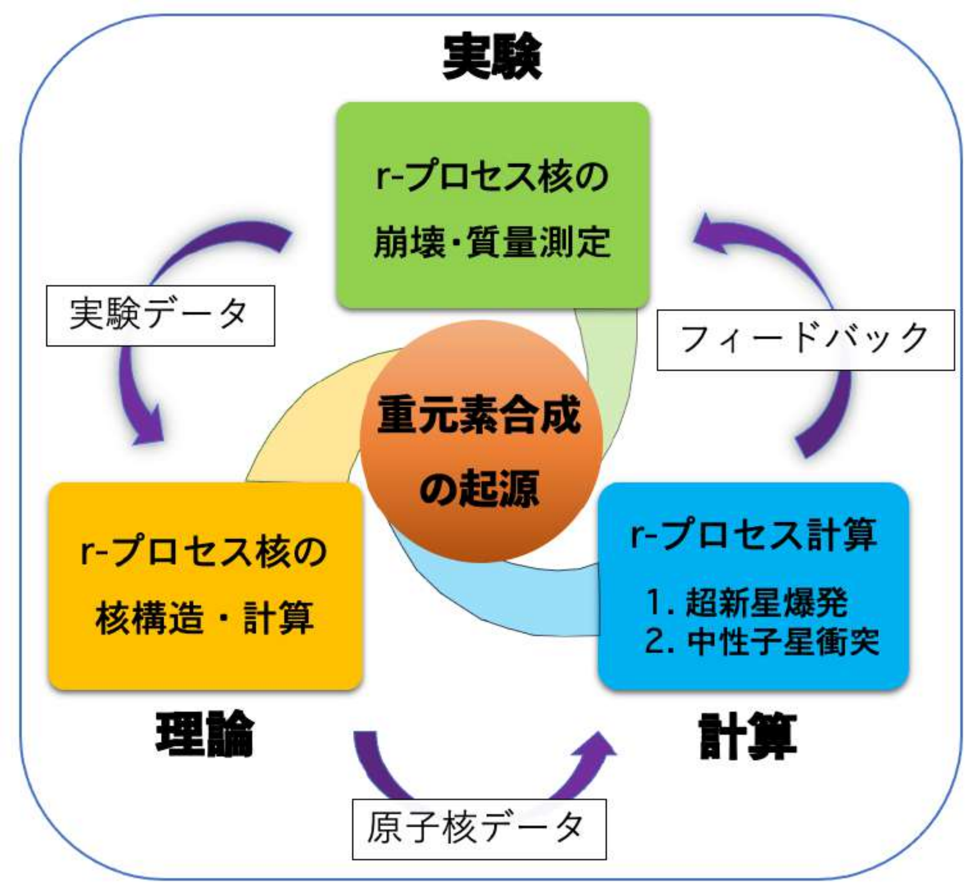
IFIC... A. Alogora

IOP... H.M. Bui



20H05648

科研費
KAKENHI

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