June 09, 2022, 5th week of MCD2022

Experiments related to r-process nucleosynthesis

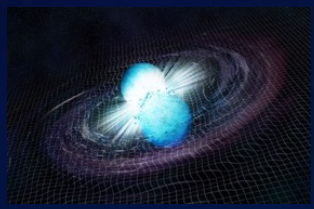
【 Harvesting the Nuclear Properties at RIBF 】

Shunji Nishimura (RIKEN)

https://ribf.riken.jp/~nishimu/

Supernovae

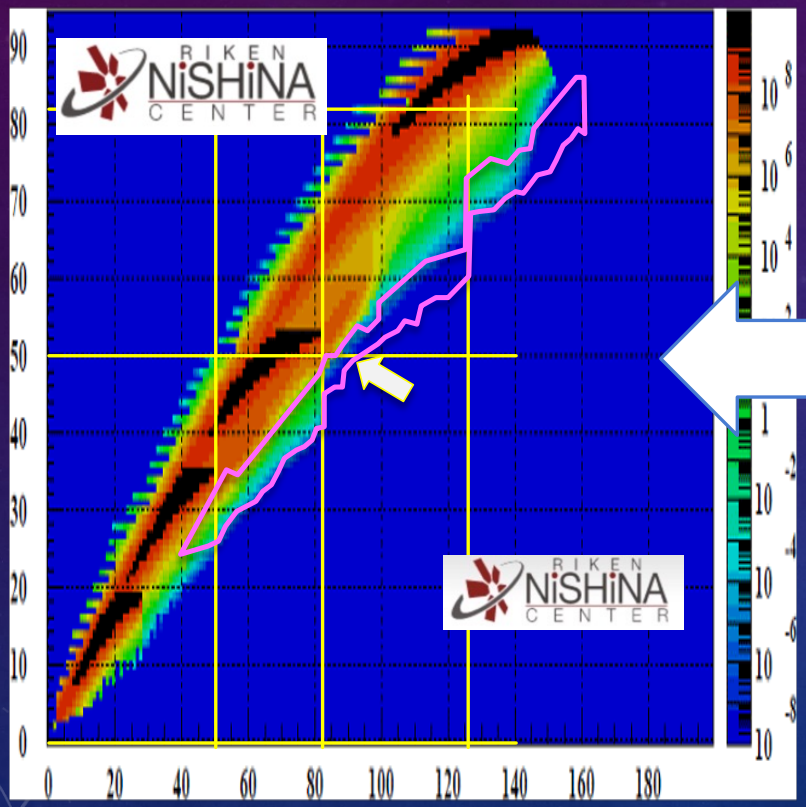
Neutron Star Merger

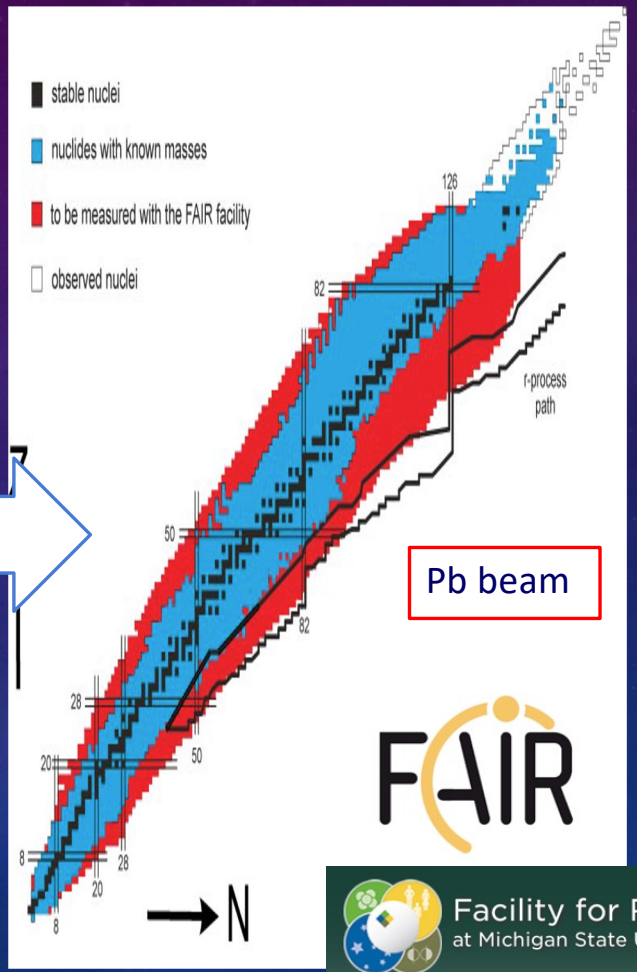


Production of Neutron-Rich Nuclei

RIBF & Other Fragmentation Facilities

RIBF goal = 2,000 pnA (current int. = 70 pnA)





Facility for Rare Isotope Beams
at Michigan State University

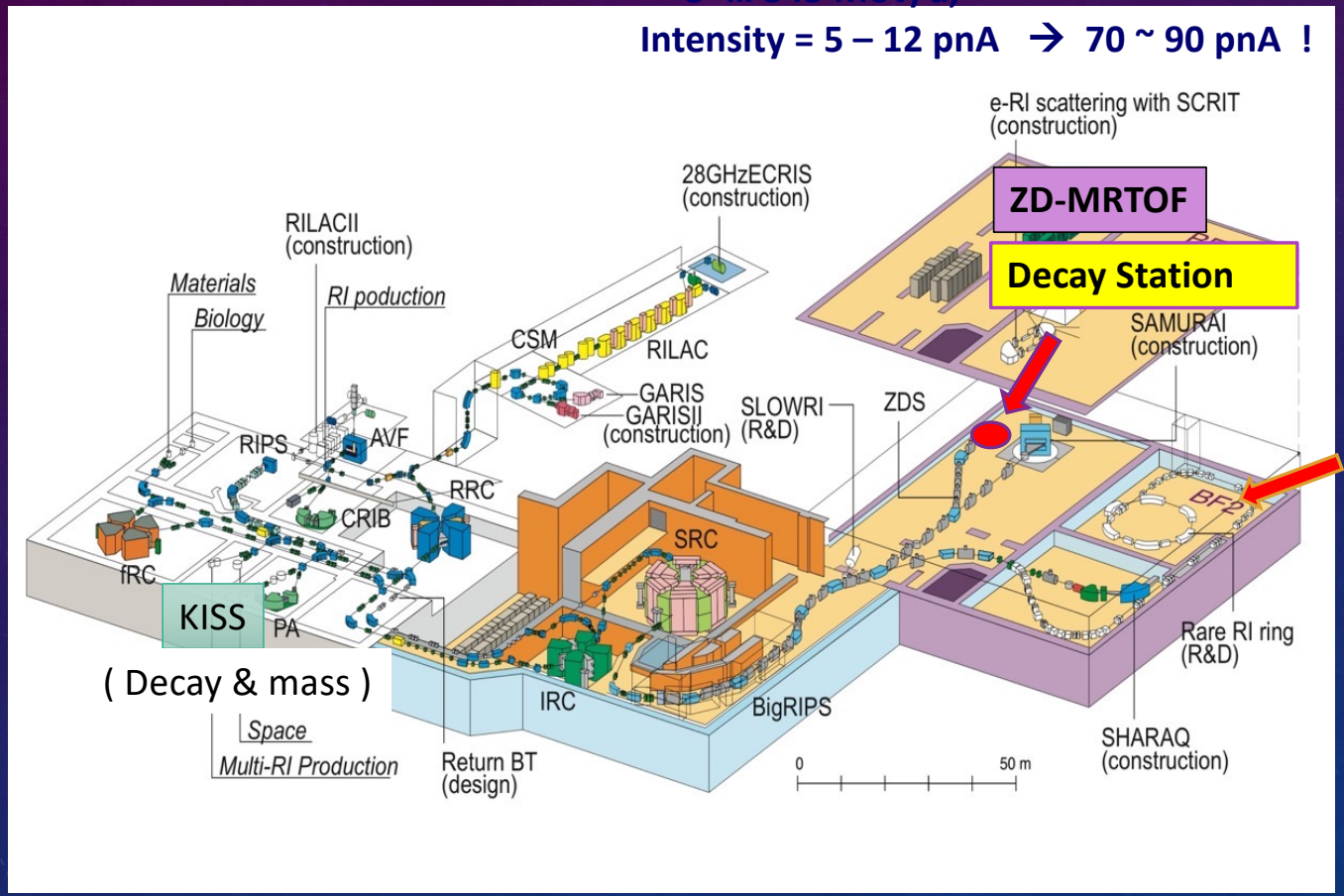
FRIB has started experiments !

Experiments at RIBF

Experiments related to r-process at RIBF

^{238}U … 345 MeV/u,

Intensity = 5 – 12 pnA → 70 ~ 90 pnA !



Rare-RI Ring (R3)

H.F. Li, S. Naimi et al., Phys. Rev. Lett. 128, 152701 (2022)
^{123}Pd mass was determined

OEDO / SHARAQ

(d,p) reactions

Experimental Programs

at ZeroDegree Spectrometer

Experiments for harvesting properties of exotic nuclei

ACTA-TPC (GANIL)
YSO (Tennessee)

2019 2020 2021 2022

EURICA

① 

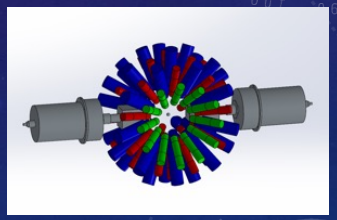
Beta-gamma Campaign

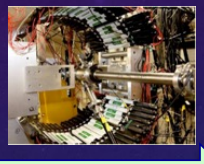
⑦ Ge-detector array

BRIKEN

② β delayed neutron emission probabilities (Pn)

⑥ Fast timing
IDATEN





③

VANDLE/HAGRID

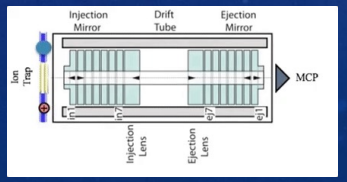
LaBr3(Ce)

β delayed neutron: energy spectra (E_n)
& neutron TOF

④ Total absorption: γ energy spectra (E_γ)

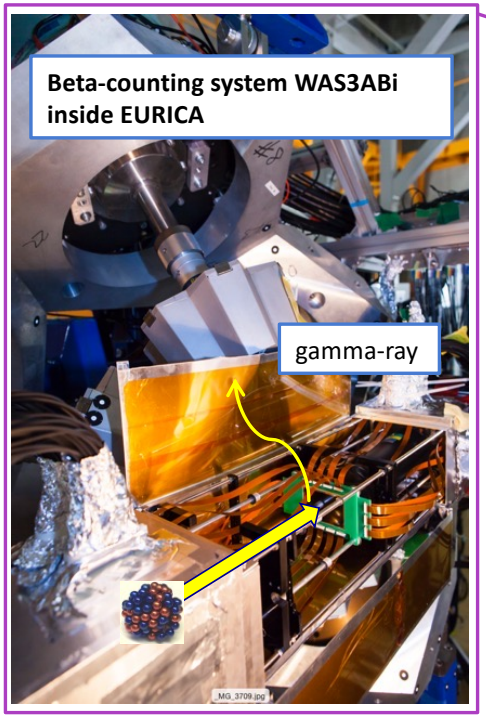
DTAS

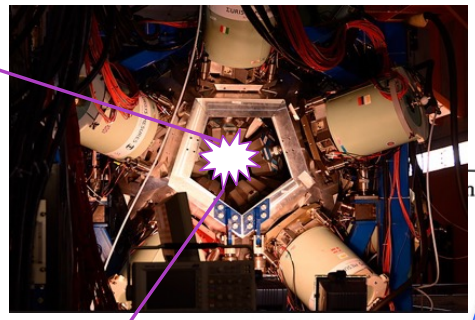
⑤ MRTOF



EURICA

^{238}U … 345 MeV/u; int. 5 – 12 pnA (now 70 - 90 pnA)

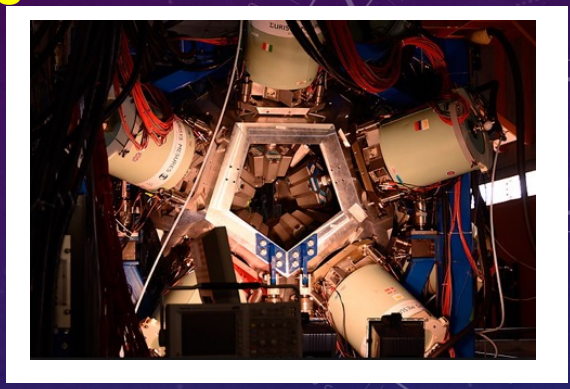


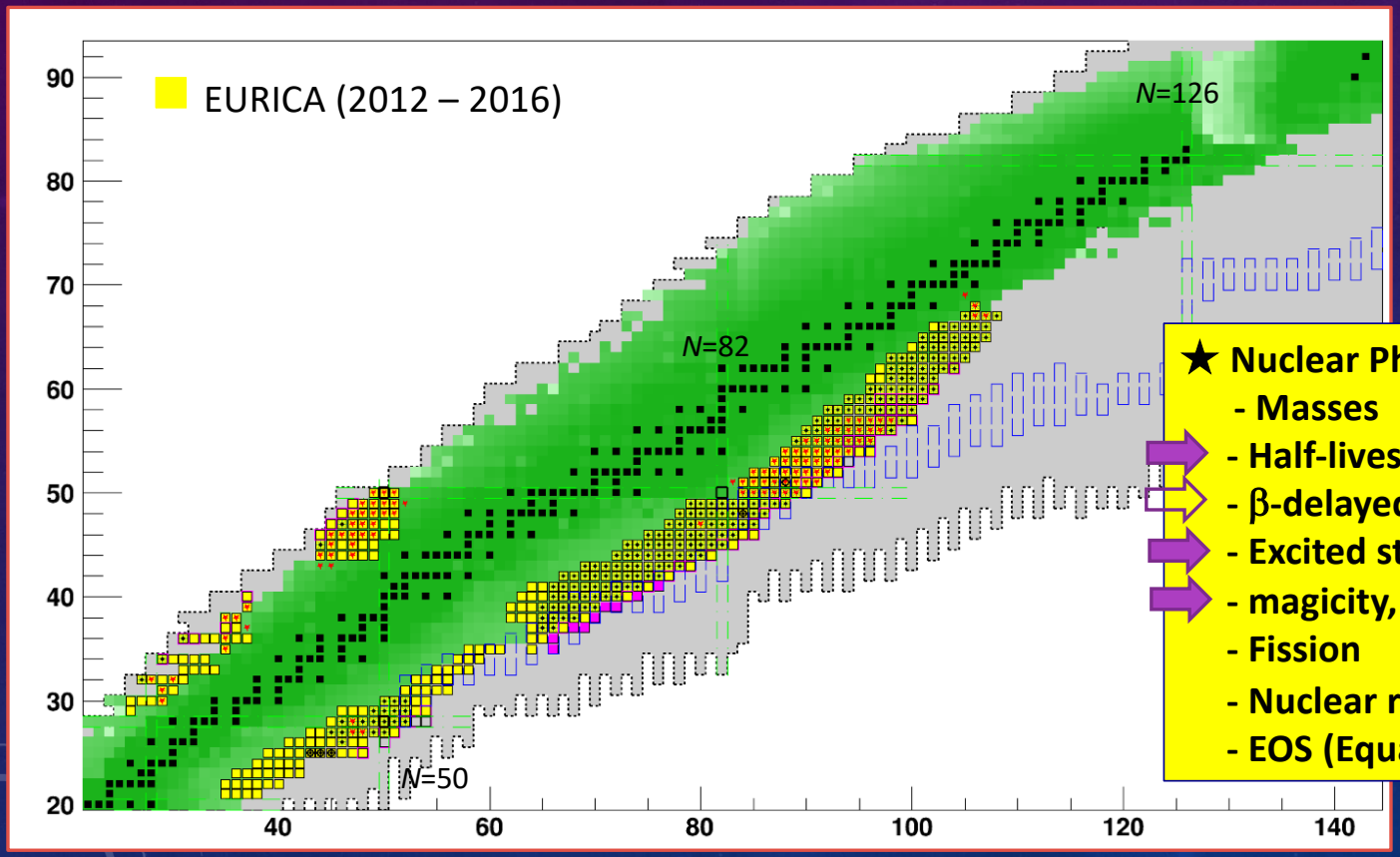


Primary Beam (^{238}U / ^{124}Xe / ^{78}Kr)

RI Beam

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



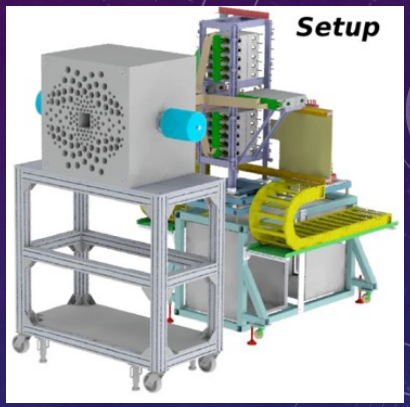


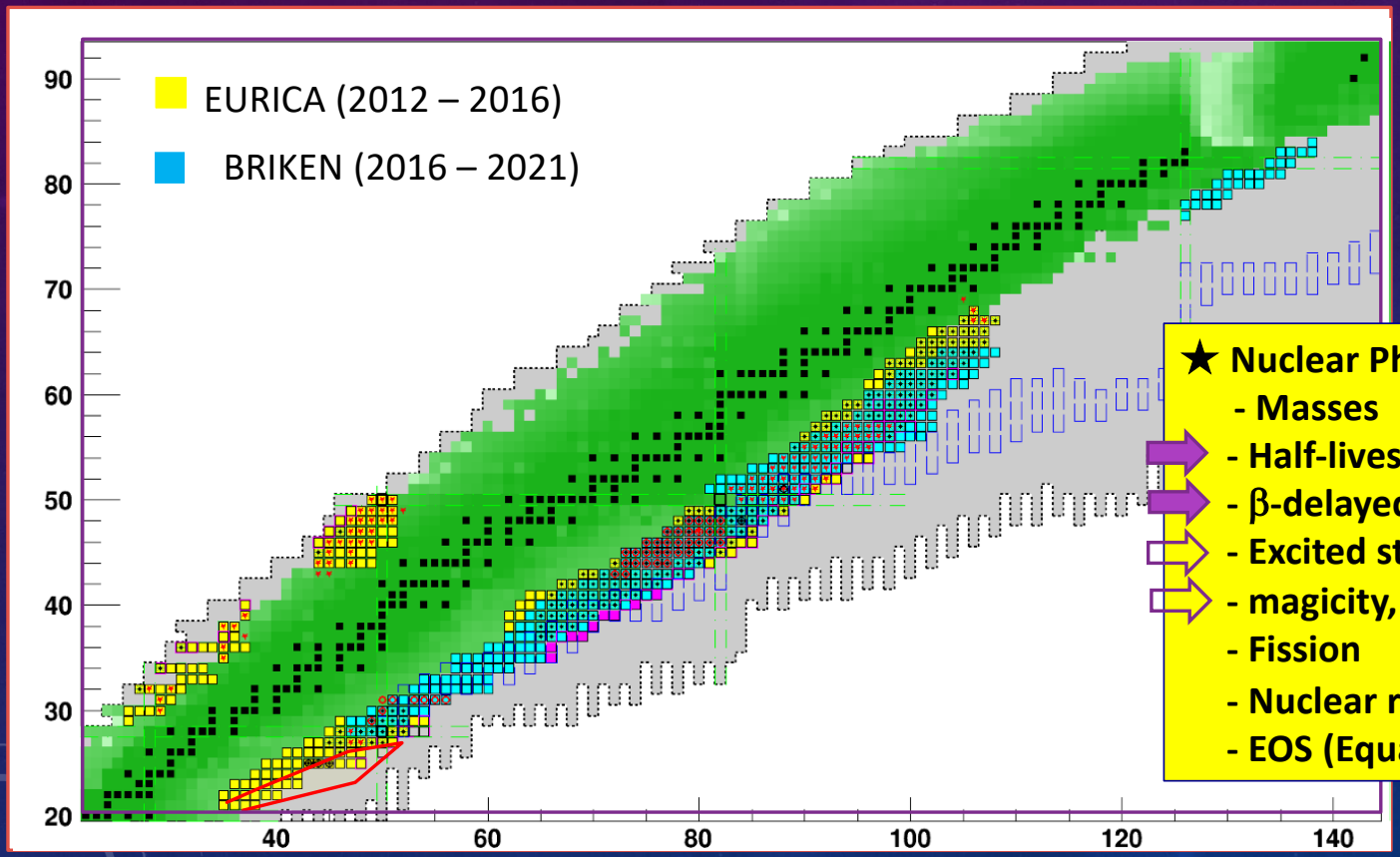
★ **Nuclear Physics Inputs (exp. / theory, astro)**

- **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)**

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

3He detector (RIKEN, ORNL, UPC) x 140 tubes





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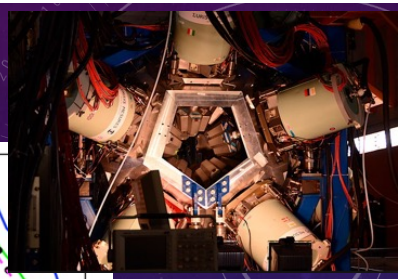
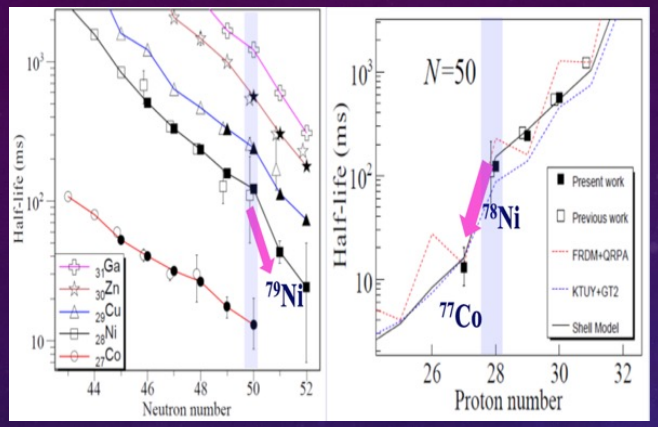
- Nuclear reactions (n,γ), (α,n), (α,p), ….
- EOS (Equation of State)

β-Decay Half-lives

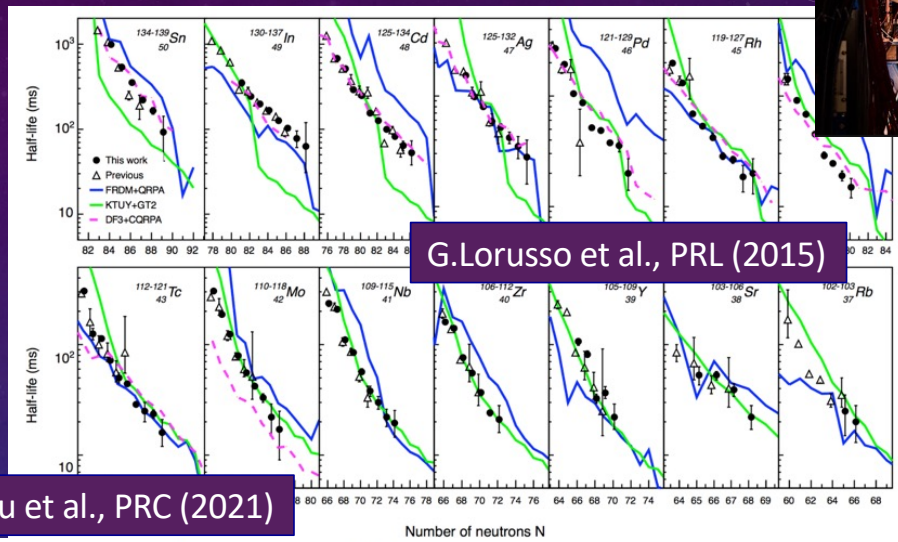
~ 284 β-Decay Half-lives (New T1/2 ~ 125) Measured at RIBF



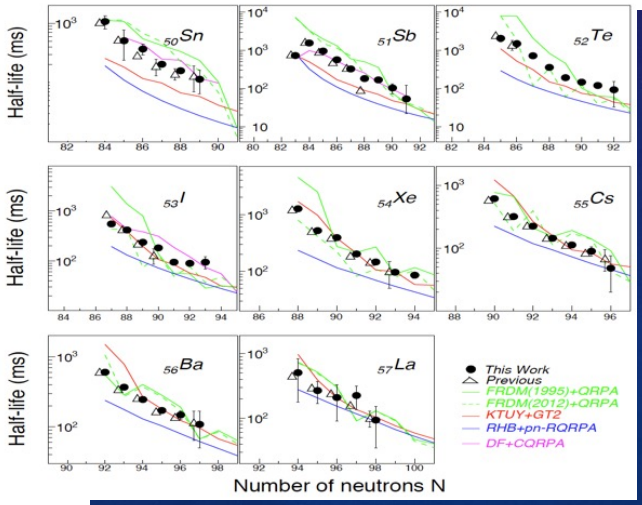
Z.Xu et al, PRL (2014)



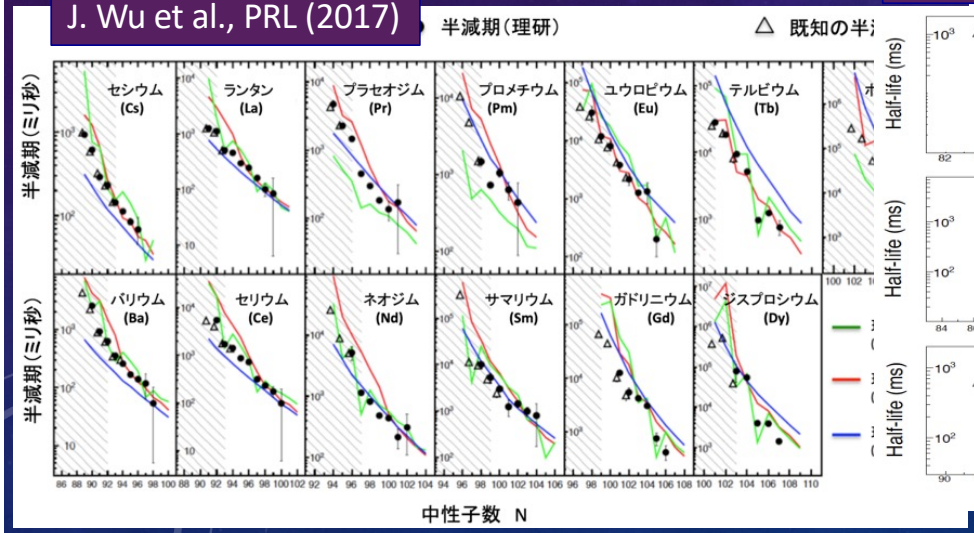
G.Lorusso et al., PRL (2015)



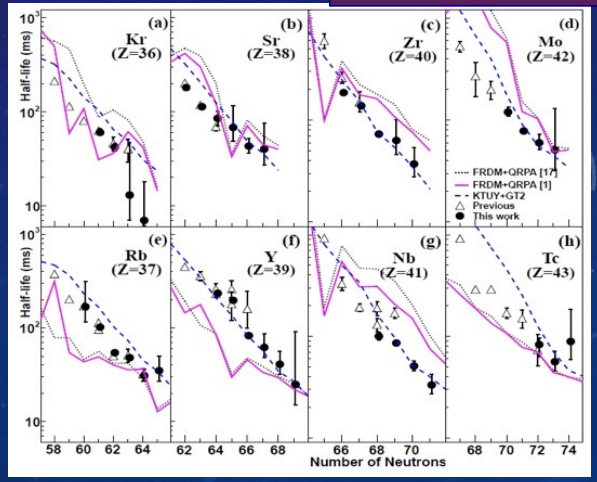
J. Wu et al., PRC (2021)



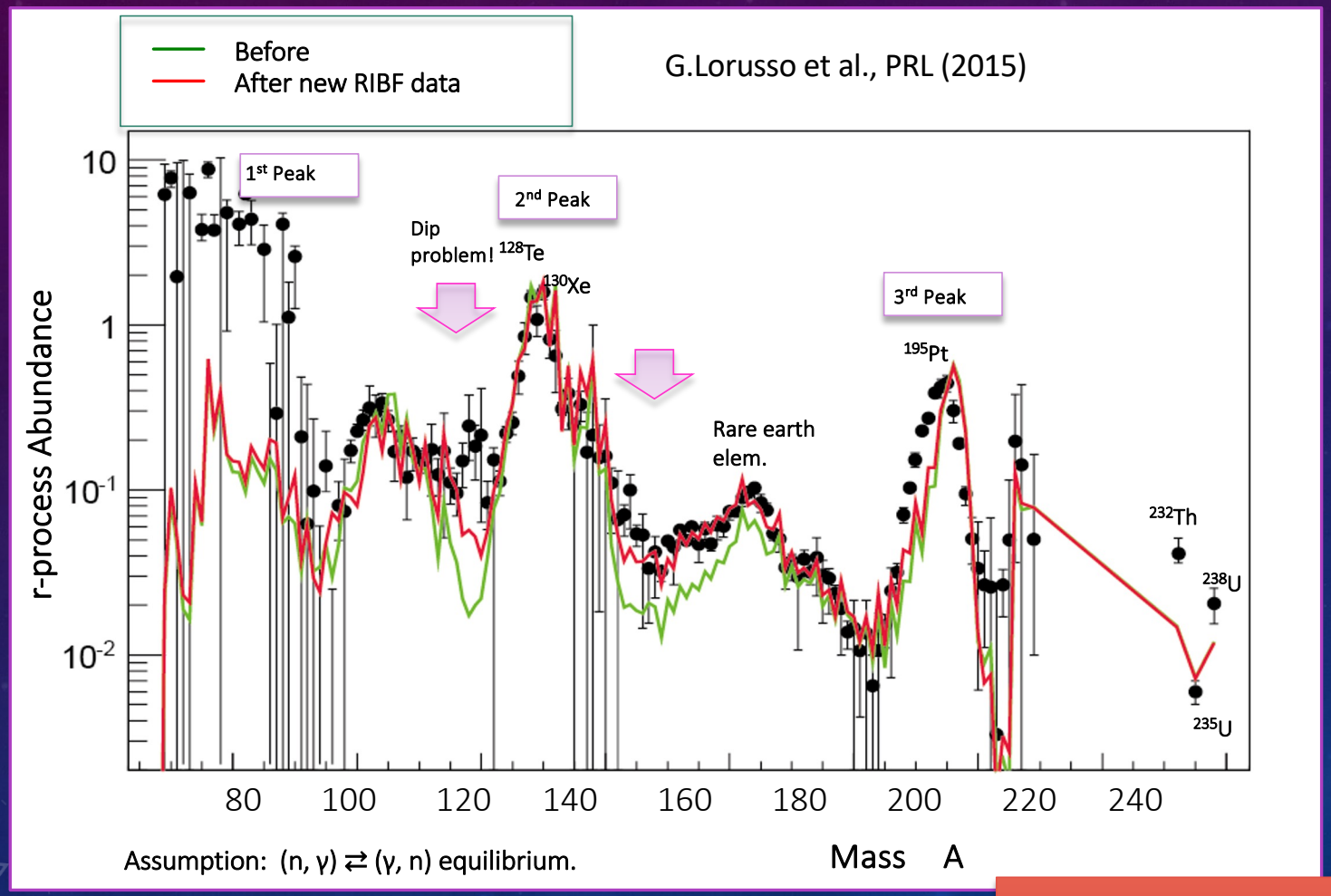
J. Wu et al., PRL (2017)



SN et al., PRL (2011)

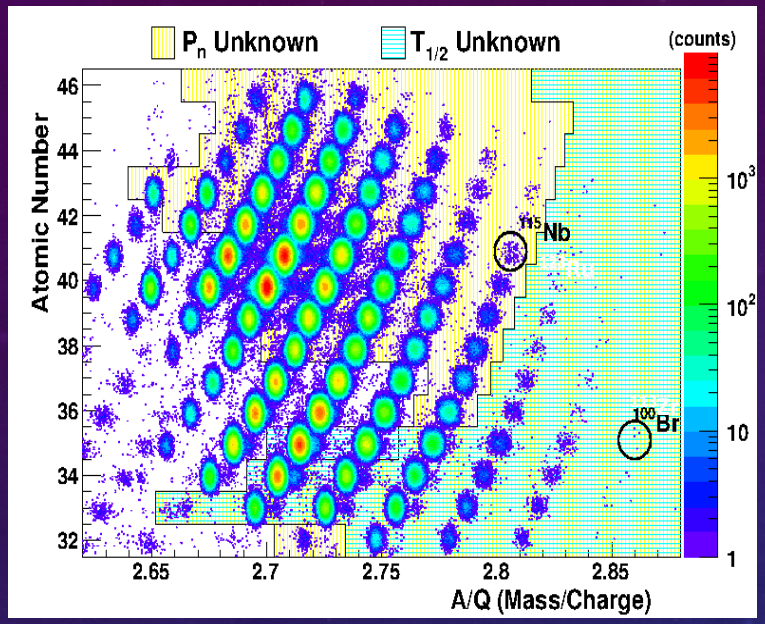


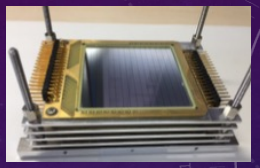
Impact on r-process nucleosynthesis



BRIKEN has started producing new data !

More β-Decay Half-lives around mass *A* = 100





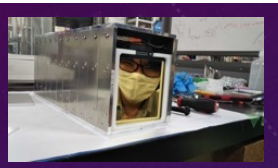
WAS3ABi (Si)

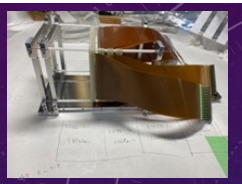
N. Nepal et al. to be submitted to PRC

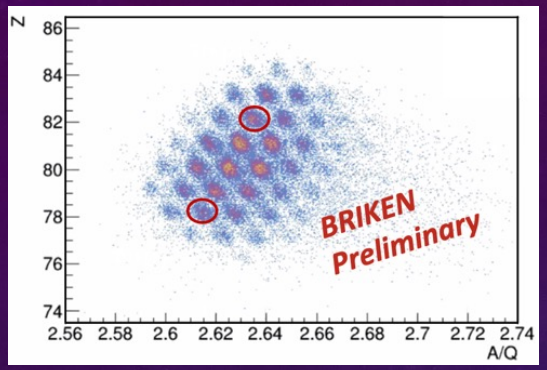
Spokespersons: S.N (RIKEN), A. Algora (IFIC-CSIC)
5.5 days

More $T_{1/2}$ values expected
… analysis in progress by V. Phong (RIKEN)
To be discussed with you.

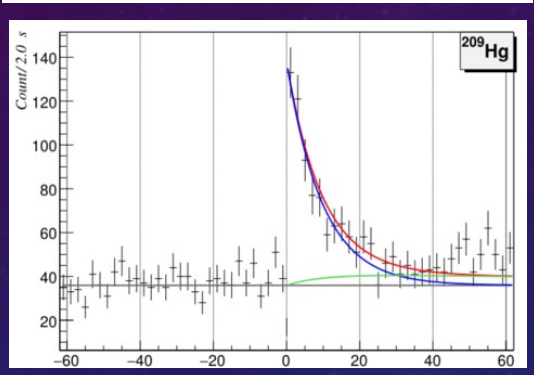
β-Decay Half-lives around *N* = 126







Analysis in progress by T.T. Yeung (U. Tokyo) Master Student



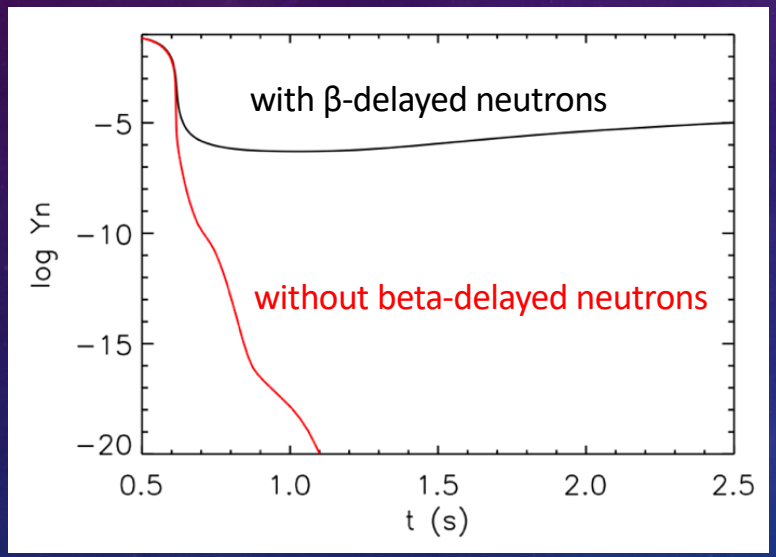
$T_{1/2}$ analysis in progress by
T.T. Yeung @U. Tokyo / RIKEN
L. Sexton @ Edinburgh U.

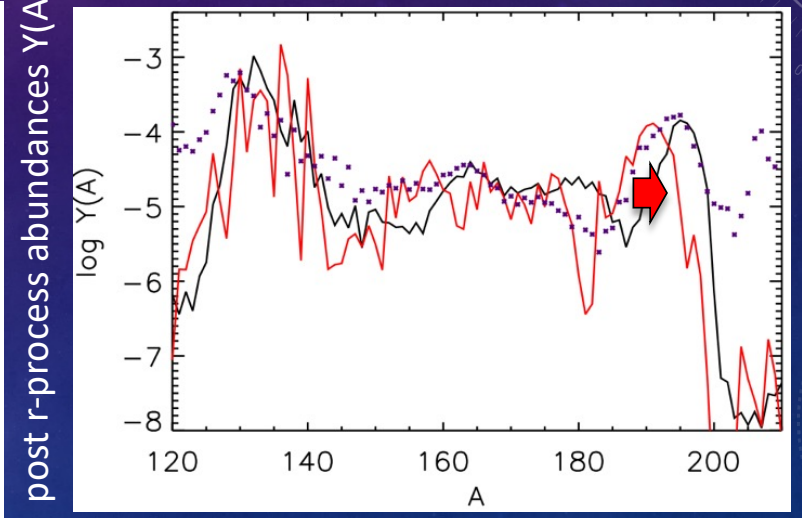
Beta-delayed Neutron Emission Probabilities

(BRIKEN)

Impact of β-delayed neutrons in r-Process

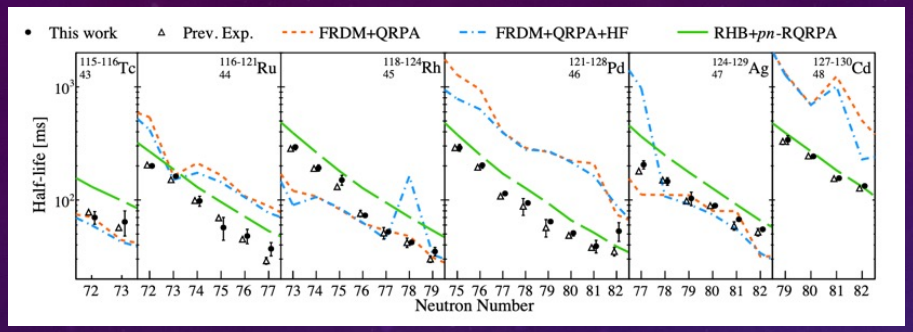
R. Surman et al. at Gordon conf., June 2013, at ARIS conf., June 2014



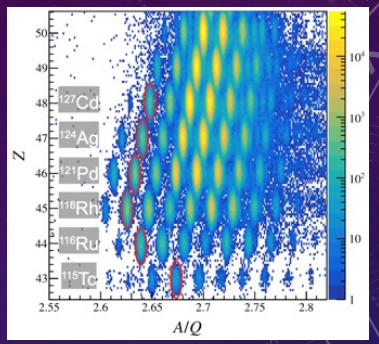


β-delayed neutron → (n, γ) reactions at freeze-out time

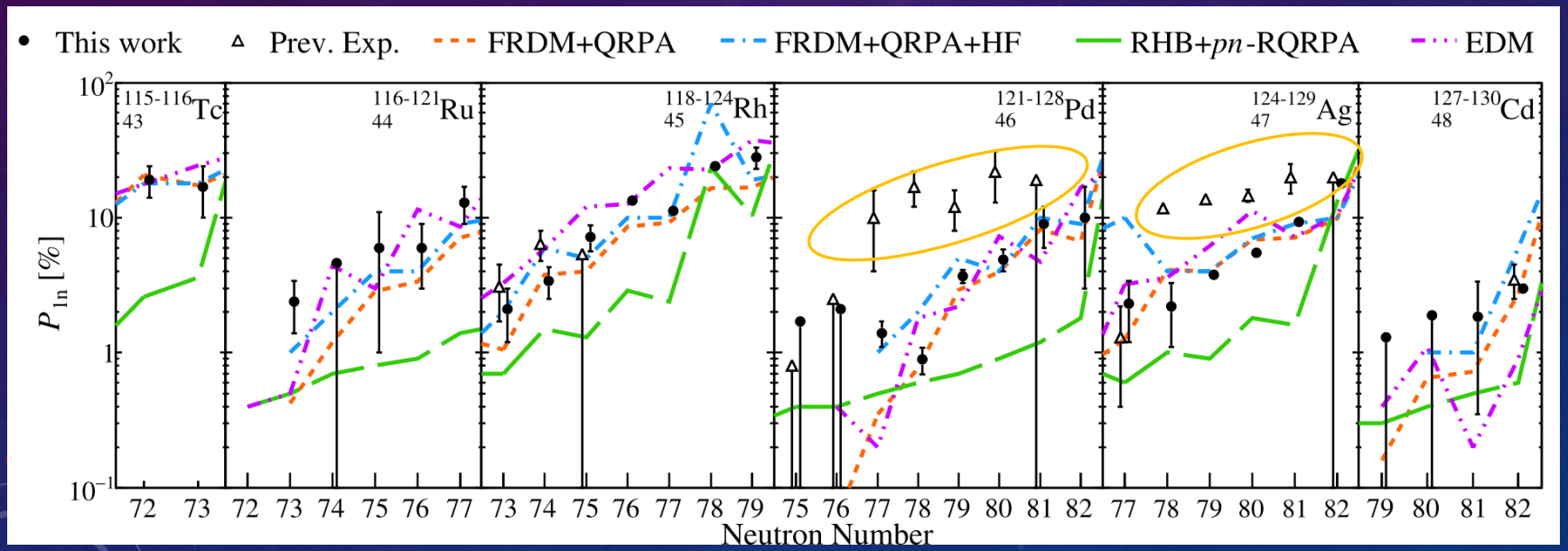
β-Delayed Neutron Emission Probabilities ($N \leq 82$)



$T_{1/2}$ … consistent with EURICA



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

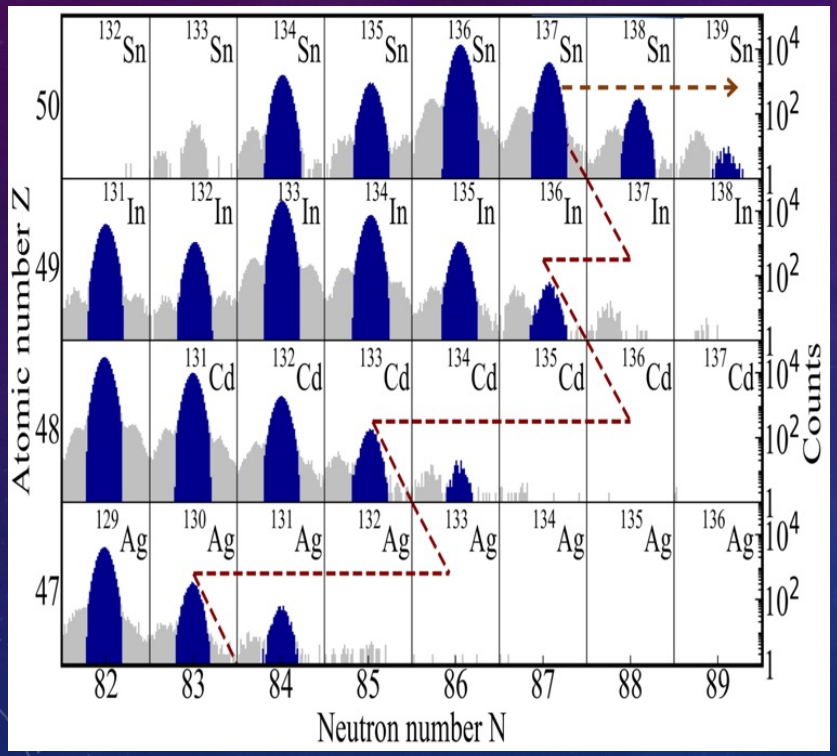


PhD thesis from GSI

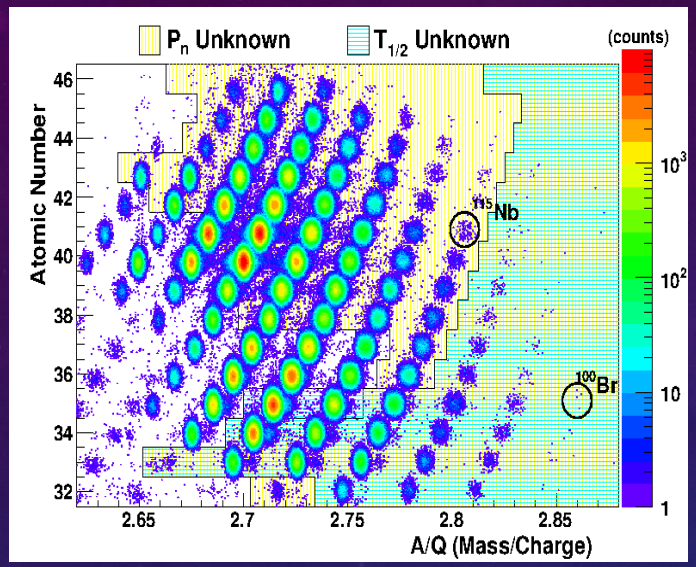
Di. Wu, C.L. Bai, H. Sagawa et al., PRC 104, 054303 (2021)

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

V.H Phong, SN, G.L. et al. (BRIKEN), just submitted.



β-Delayed Neutron Emission Probabilities (*A ~ 100*)



N. Nepal et al., part of data to be submitted soon.

FRDM+QRPA
FRDM+QRPA+HF
RHB+pn-QRPA
RHB+pn-QRPA+HF

More P_{1n} & P_{2n} values from ^{90}Ge ~ ^{125}Rh expected by V. Phong (RIKEN); To be discussed with you.

Mass Measurement

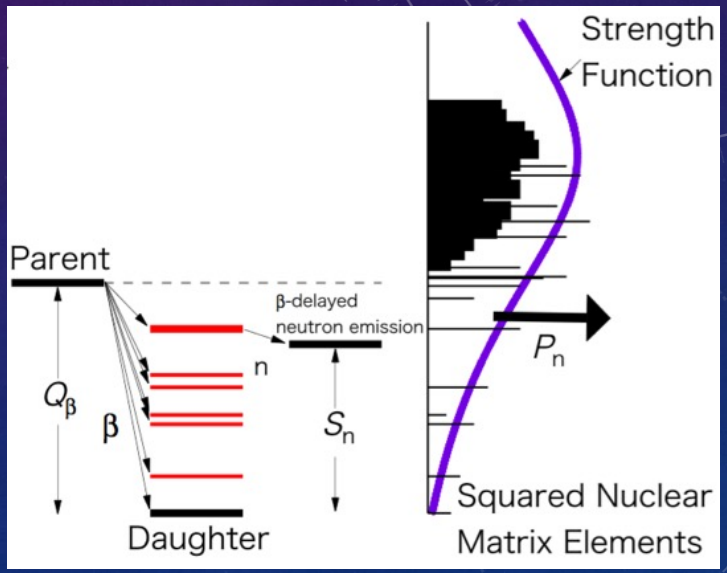
ZD-MRTOF

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

Half-lives (isotope)

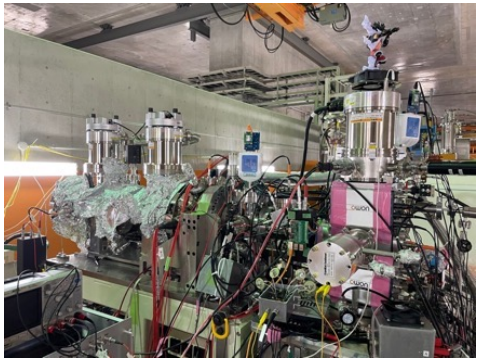
β-strength function

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



and Decay Spectroscopy

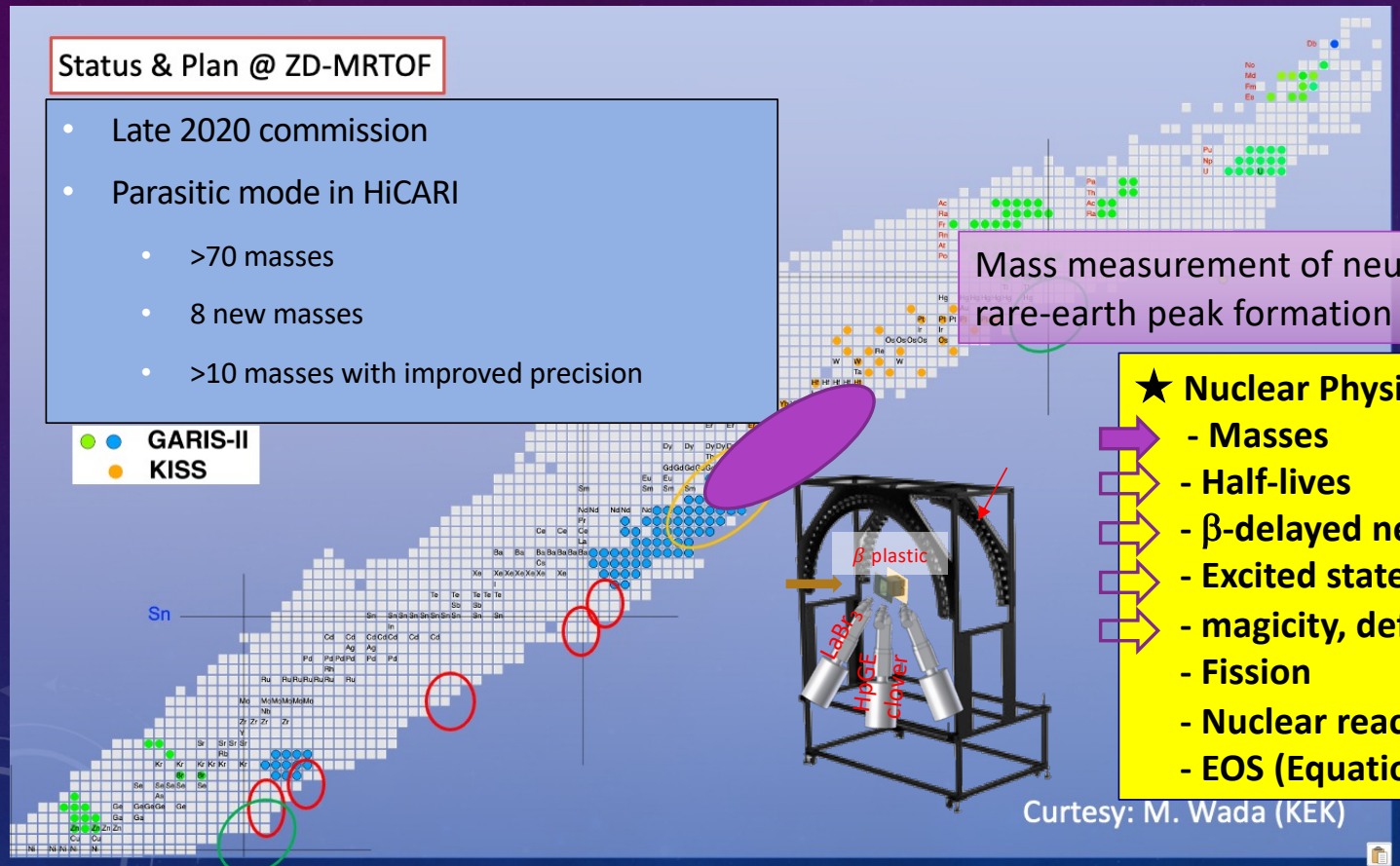
Critical Nuclear Properties in r-Process Nucleosynthesis
（ZD-MRTOF Project : 2020 - ）



Status & Plan @ ZD-MRTOF

- Late 2020 commission
- Parasitic mode in HiCARI
  - >70 masses
  - 8 new masses
  - >10 masses with improved precision

Mass measurement of neutron-rich nuclei relevant to rare-earth peak formation (SN, Wada) ... 9-days



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

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

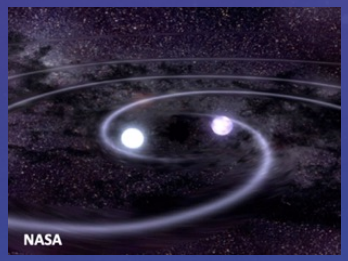
Curtesy: M. Wada (KEK)

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

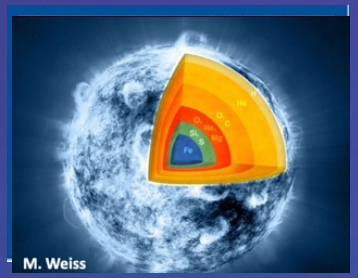
[Astrophysics Observation]

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

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

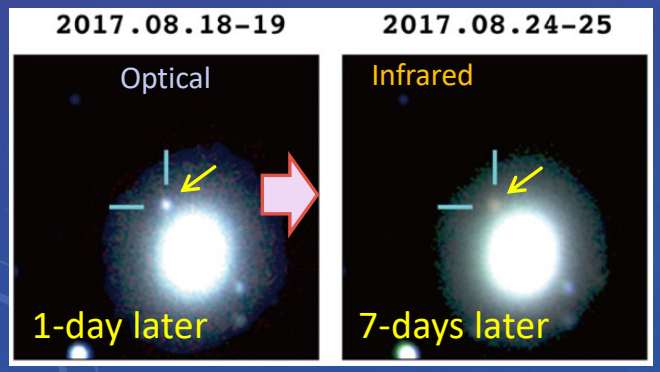


Supernovae



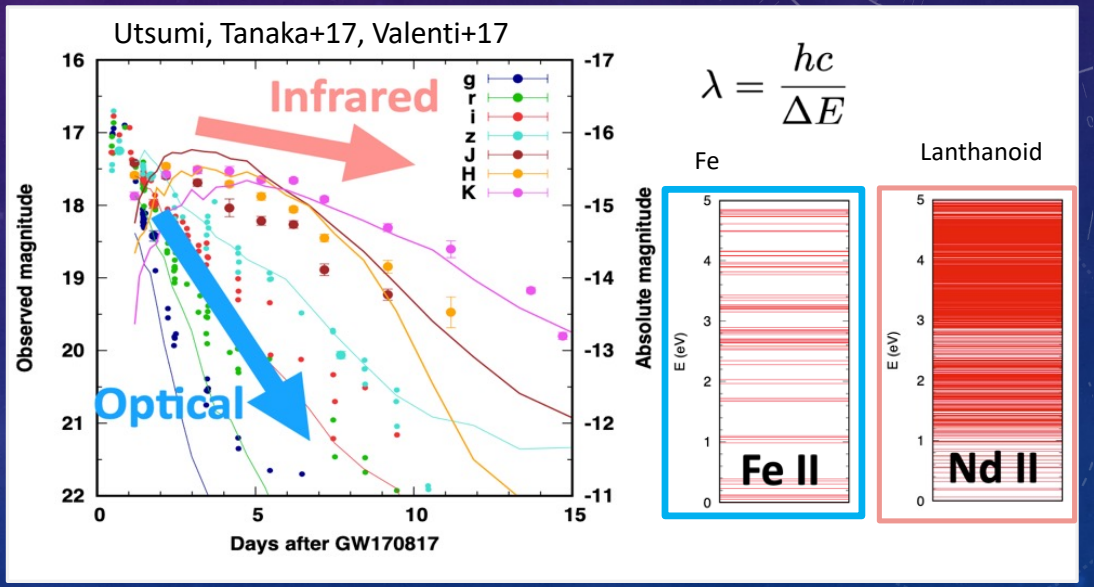
● **Observation of electromagnetic wave**

Site of GW170817



nuclear decay heat

Kilonova is expected & observed !

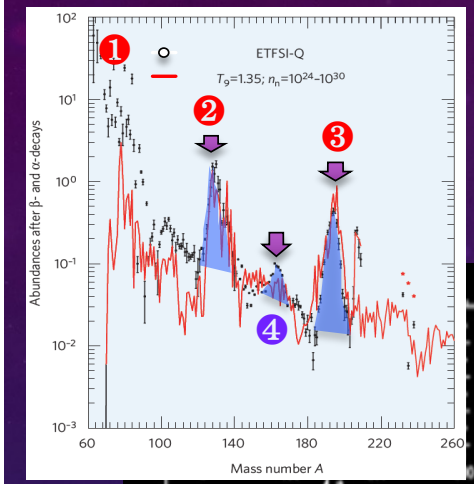


Infrared indicates the synthesis of lanthanoid elements in NS-NS collisions

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

[Nuclear Physics]

C.Sneden et al. (2008)

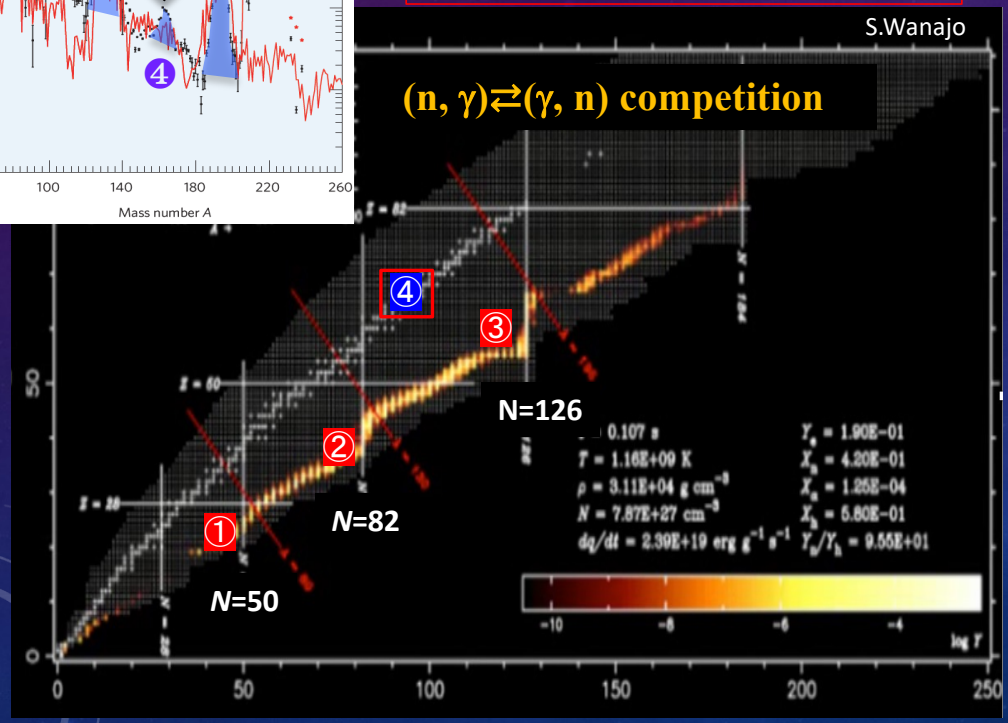


① Neutron shell closure N=50

② Neutron shell closure N=82

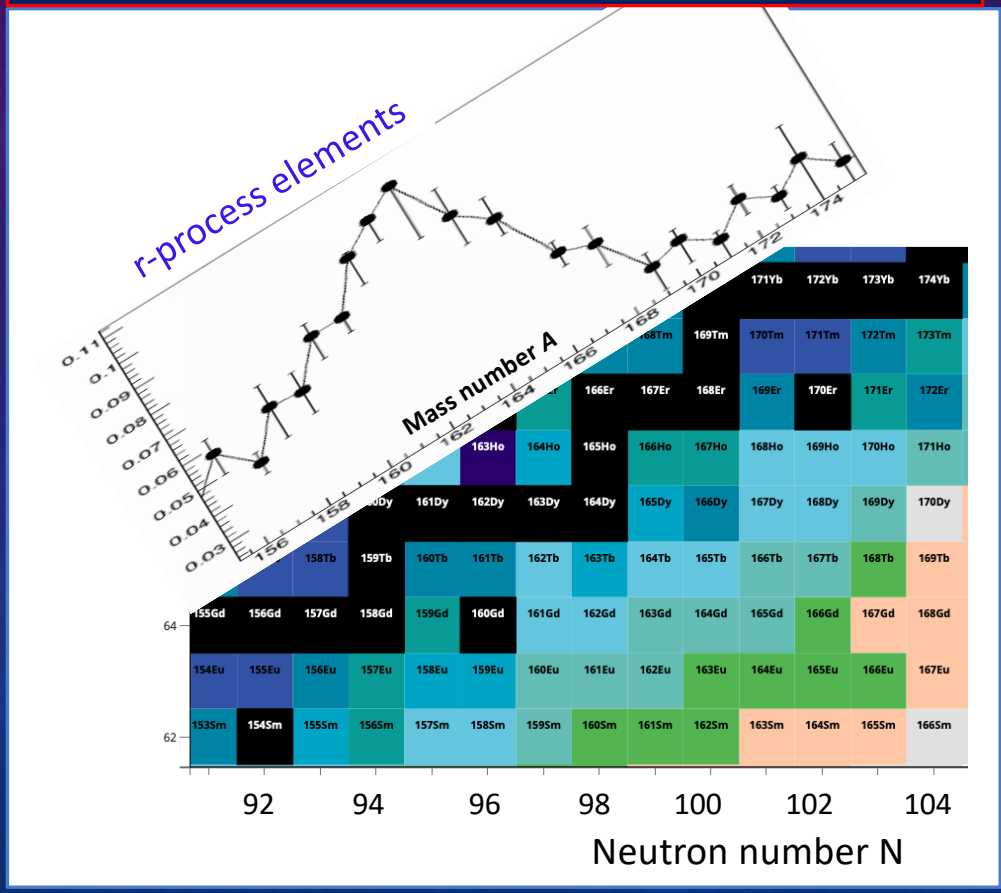
③ Neutron shell closure N=126

S.Wanajo



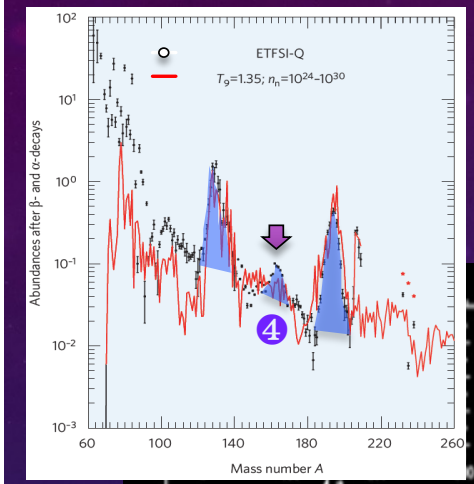
④ Lanthanide peak (Z = 64 ~ 70, A = 158 ~ 170)

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



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

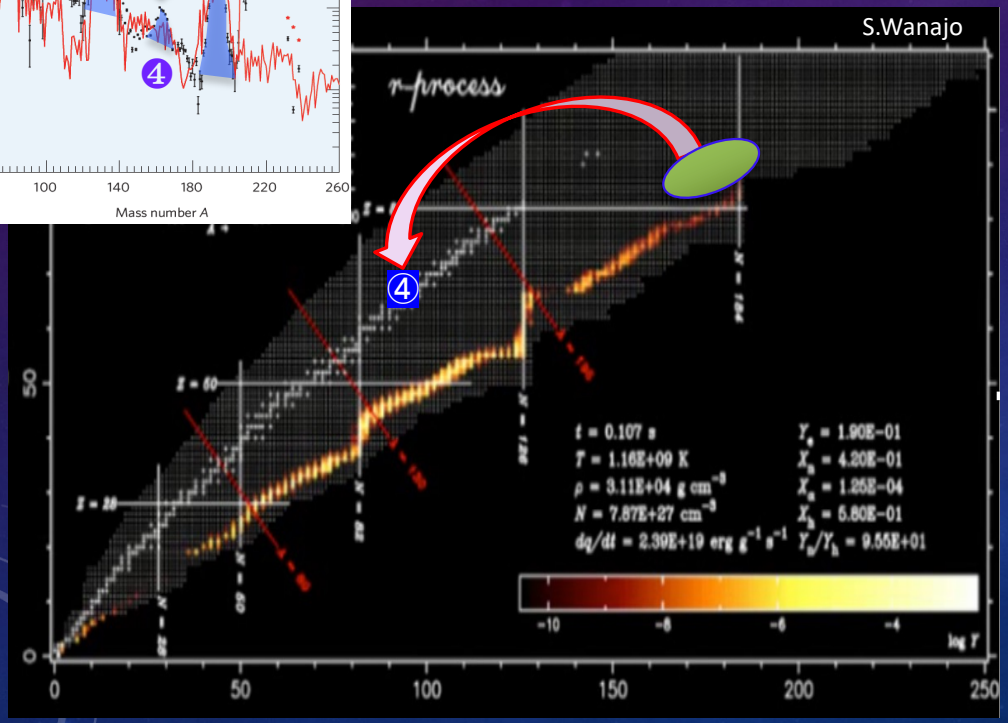
C.Sneden et al. (2008)

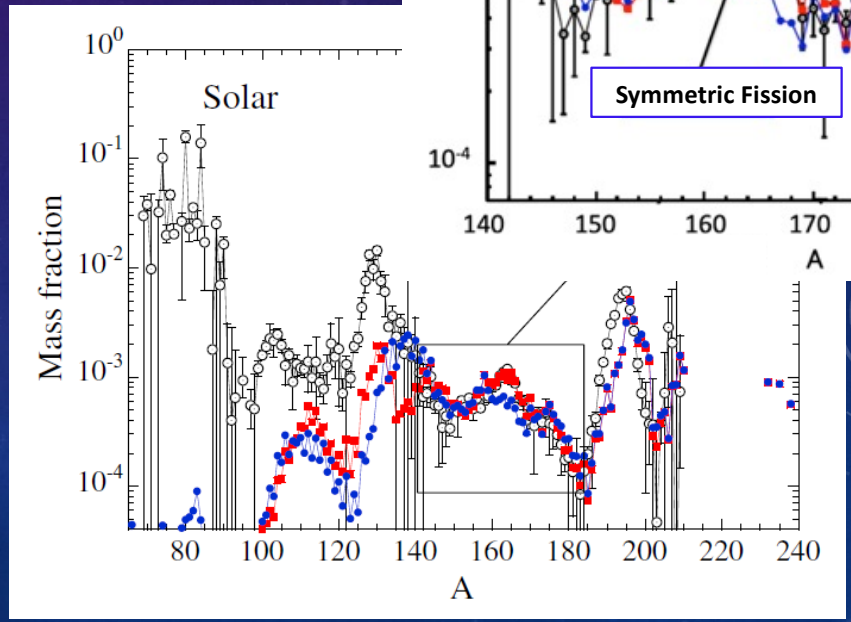


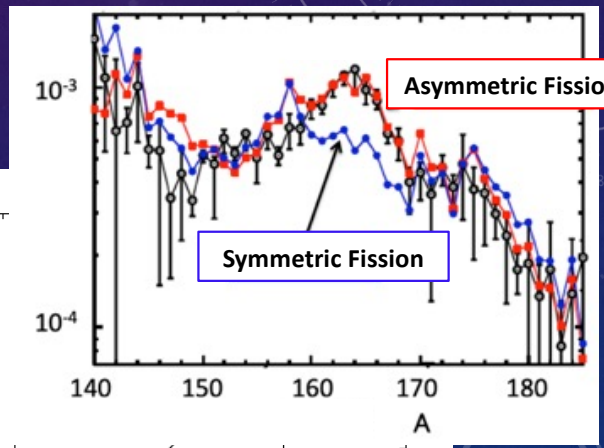
Asymmetric fission of neutron-rich heavy nuclei (S. Goriely et al.)

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

S.Wanajo

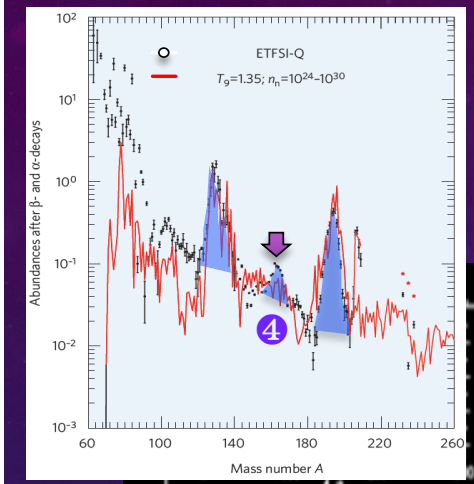






Where & How the Rare-Earth Elements are Synthesized !?

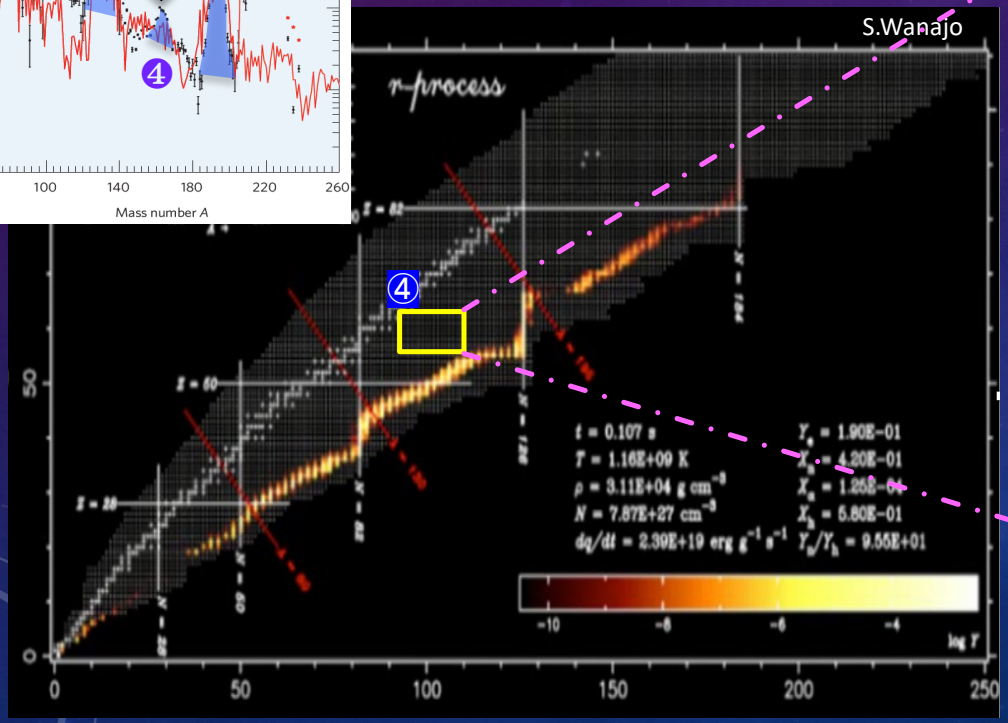
C.Sneden et al. (2008)



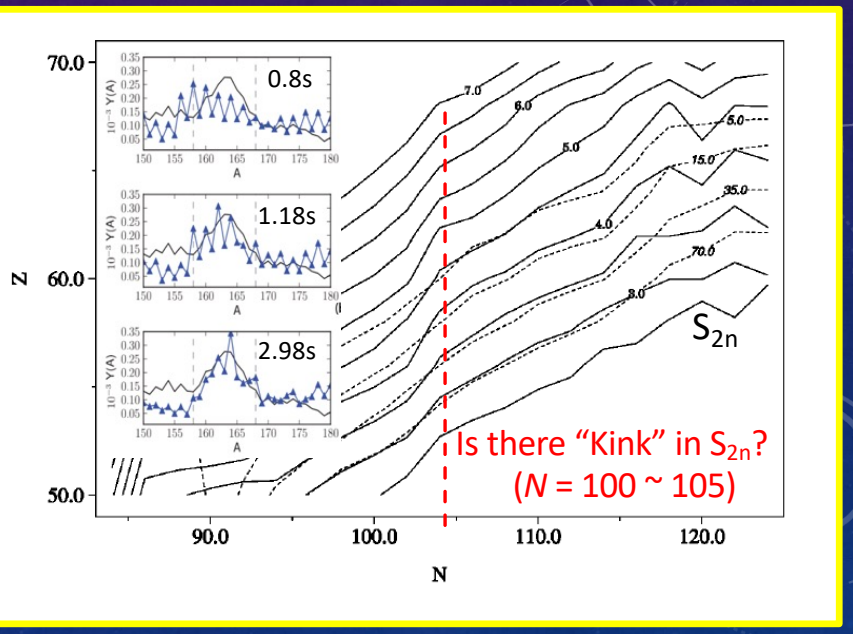
Nuclear deformation（R.Surman et al.)

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

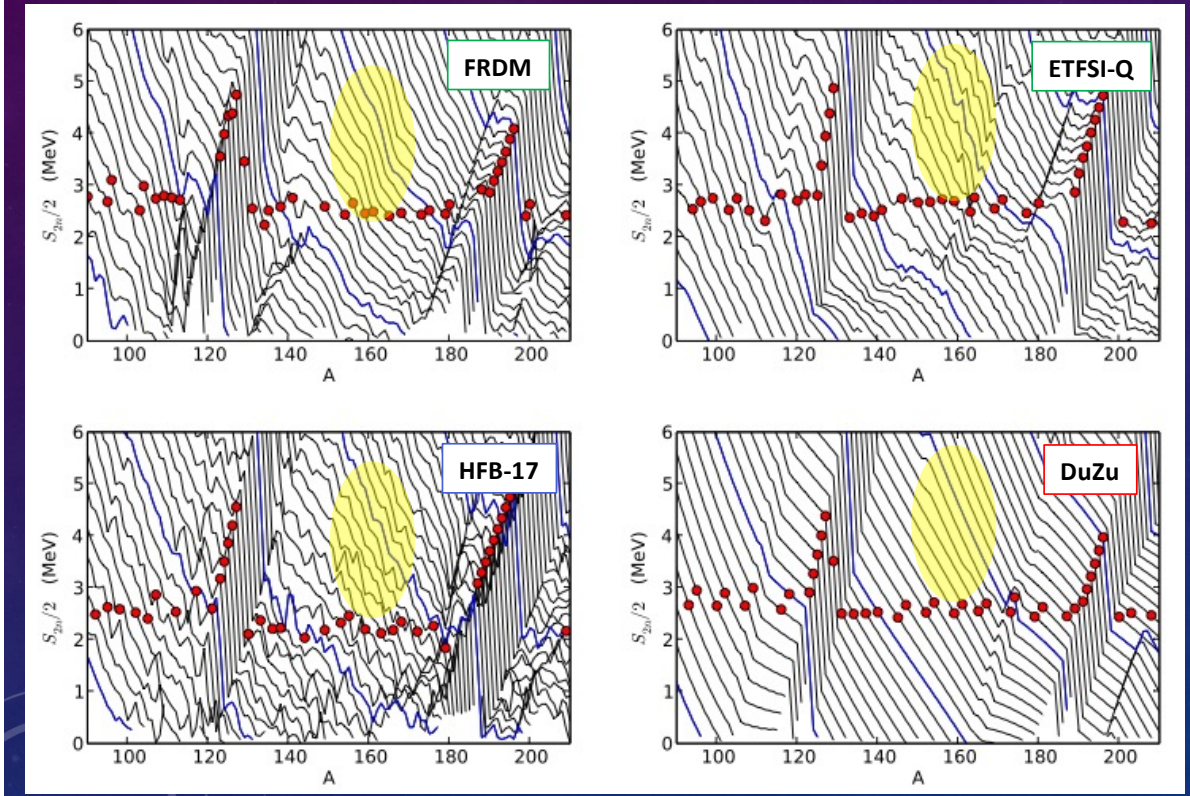


$S_{2n}(Z,N)$ = E (Z, N - 2) – E (Z, N)
... Suitable to study on shell gaps, test of magicity

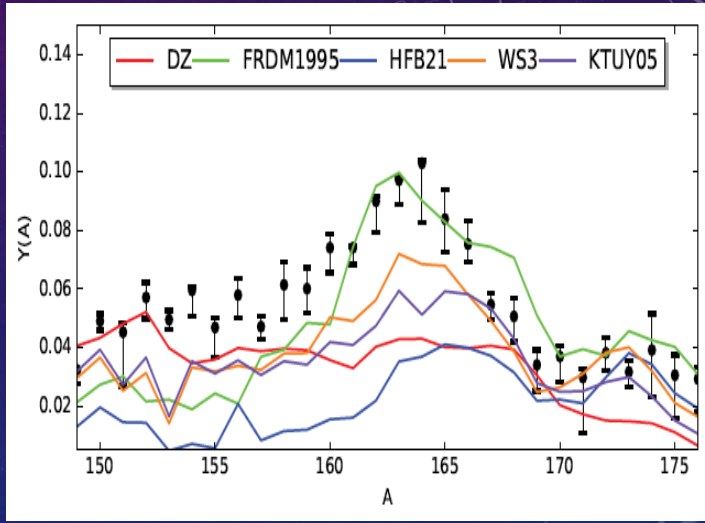
Rare-Earth Peak Formation with Various Mass Models

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

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



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

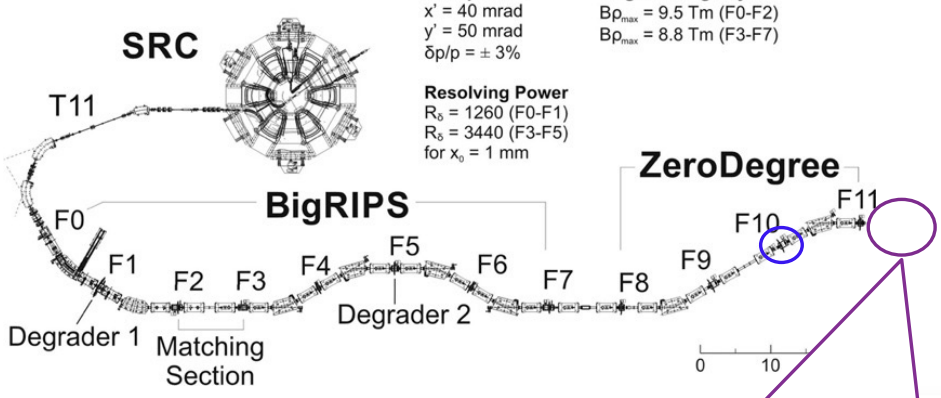


Rare-earth peak formation depends on mass models.

→ Uncertainties of mass models are critical issue !

We need experimental data !

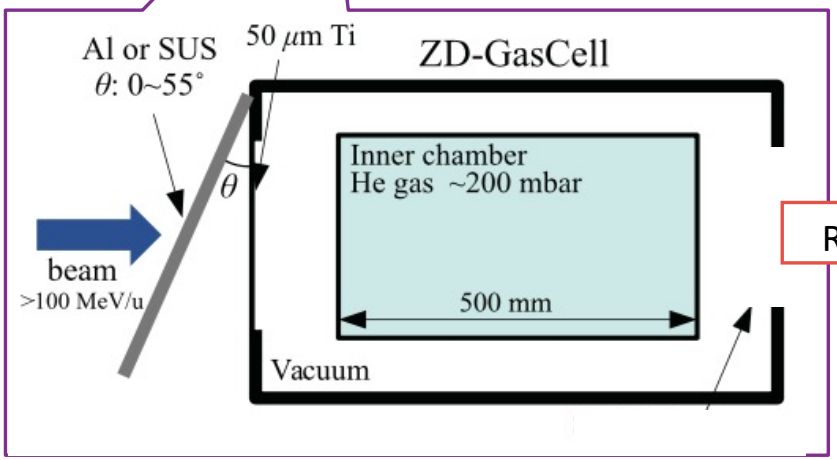
Mass Measurement by ZD-MRTOF + Decay Spectroscopy



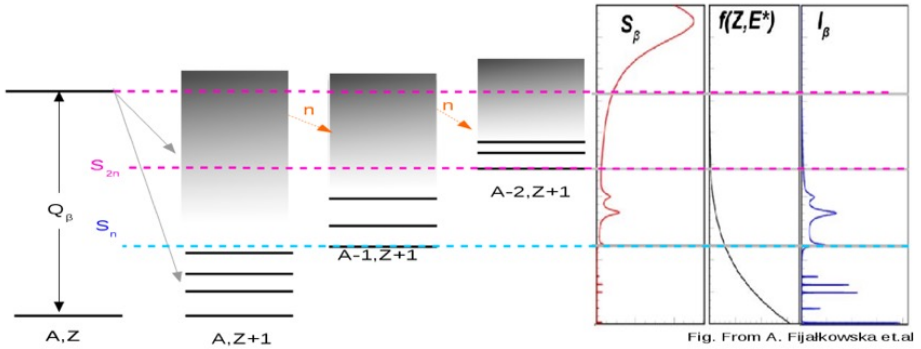
Acceptance
x' = 40 mrad
y' = 50 mrad
δp/p = ± 3%

Magnetic Rigidity
$B\rho_{max}$ = 9.5 Tm (F0-F2)
$B\rho_{max}$ = 8.8 Tm (F3-F7)

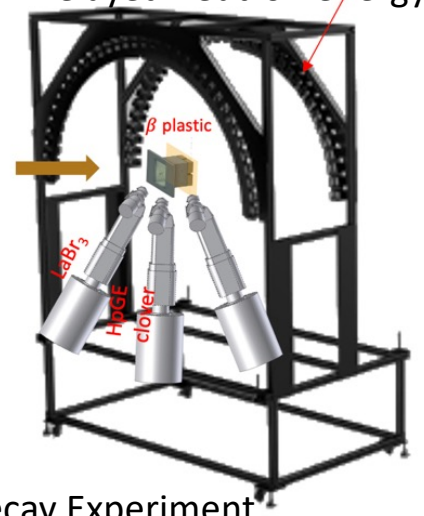
Resolving Power
R_δ = 1260 (F0-F1)
R_δ = 3440 (F3-F5)
for x_0 = 1 mm



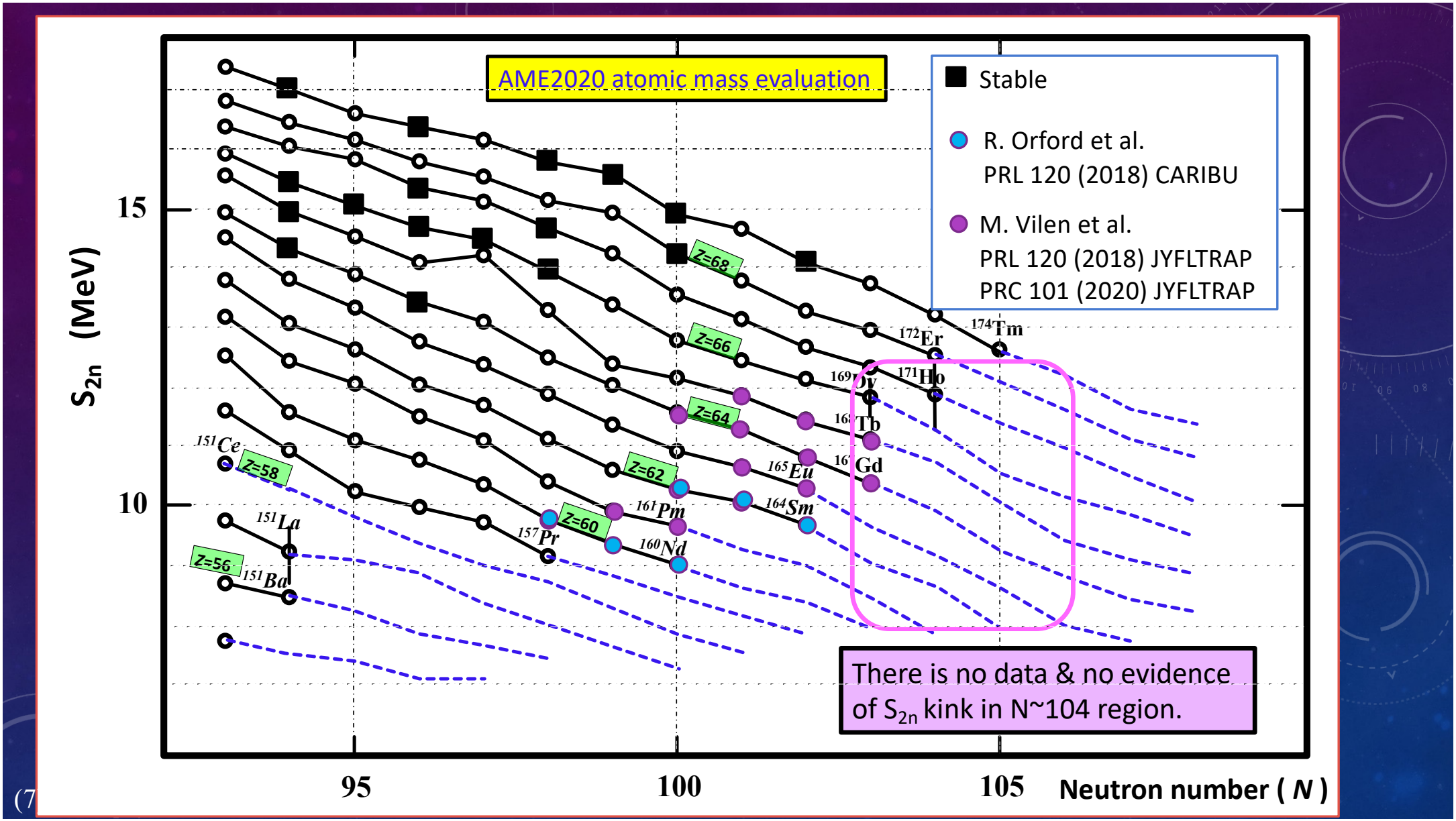
RI



Delayed gamma
Delayed neutron energy



Decay Experiment


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
There is no data & no evidence of S_{2n} kink in N~104 region.
S_{2n} (MeV)
Neutron number (N)
15
10
95
100
105
Z=68
Z=66
Z=64
Z=62
Z=60
Z=58
Z=56
^{174}Tm
^{172}Er
^{171}Ho
^{165}Eu
^{164}Sm
^{161}Pm
^{160}Nd
^{157}Pr
^{151}Ce
^{151}La
^{151}Ba

Summary

◎ Decay properties are measured at RIBF (EURICA, BRIKEN)

- 284 β-Decay Half-lives (125 New $T_{1/2}$) were reported from EURICA
- More β-Decay Half-lives will be provided from BRIKEN
- 37 β-Delayed Neutron Emission Probabilities (17 New P_n) were reported from BRIKEN
- More results of β-Delayed Neutron Emission Probabilities (P_{1n}, P_{2n}) will be provided from BRIKEN

◎ Mass measurement has been started at RIBF (ZD-MRTOF)

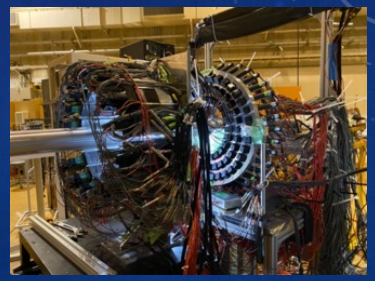
- Commissioning of ZD-MRTOF was performed successfully. Papers in preparation
- Mass measurement in rare-earth region will be performed.

◎ Various Decay Programs are also in progress

- Total gamma-ray absorption measurement (DTAS)
- Fast gamma-decay measurement (IDATEN)
- β-delayed neutron energy (TOFU, NiGIRI) with delayed gamma (Ge, LaBr3(Ce)) with ZD-MRTOF

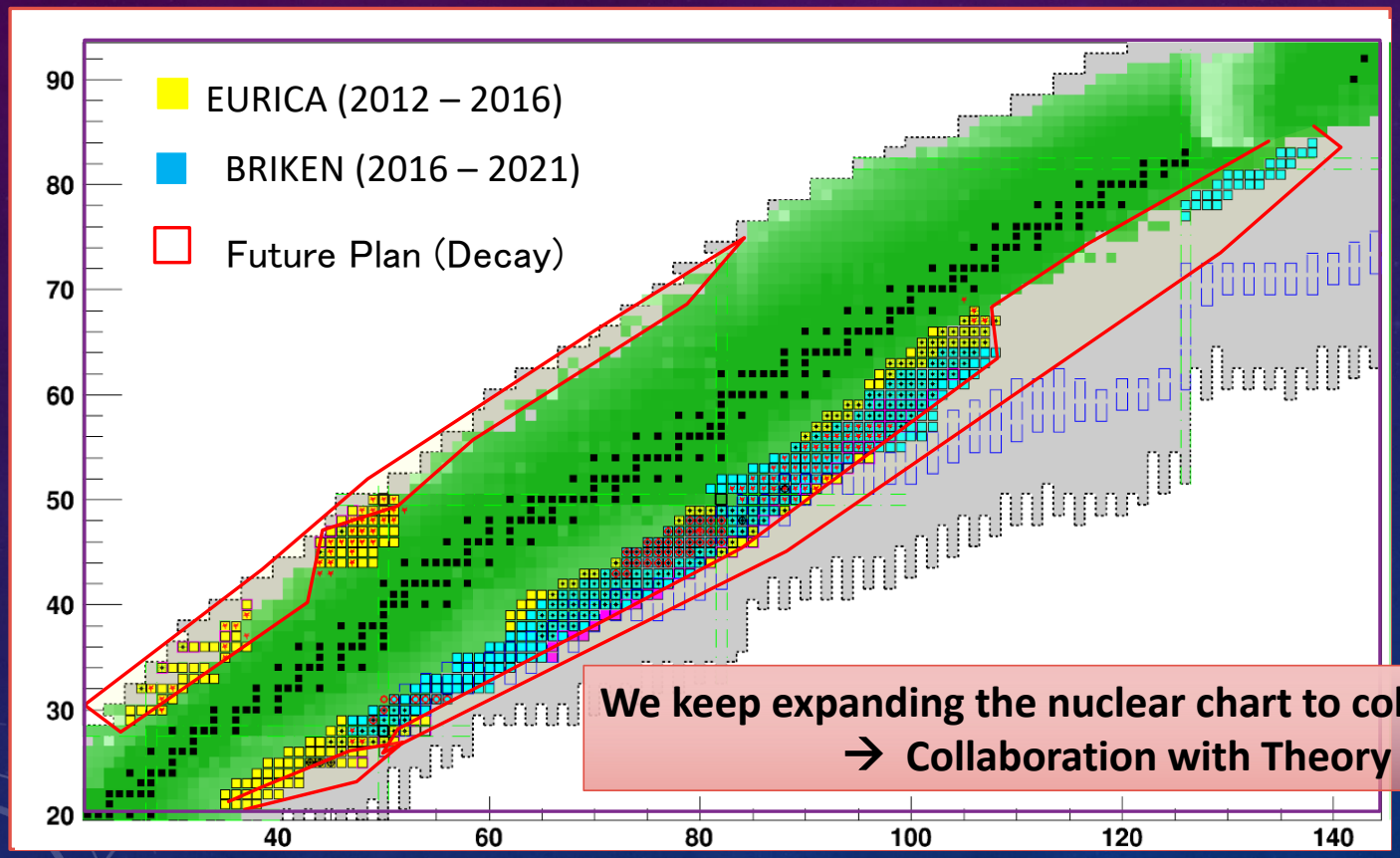
◎ Equation of state (EOS) for high density neutron-rich matter

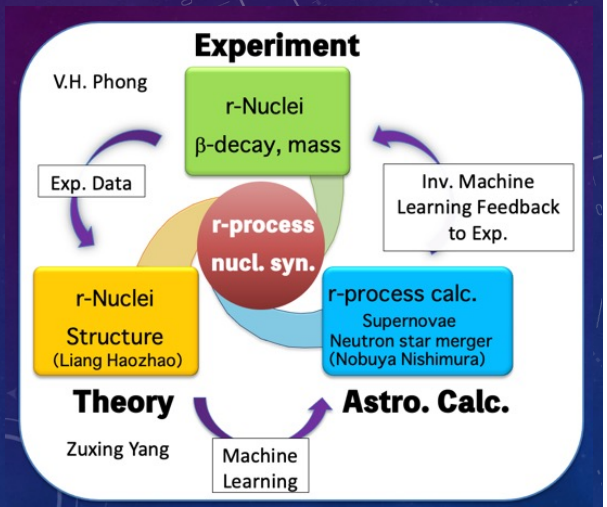
- Pilot experiments conducted at HIMAC (H355, H447)
  → Collective flow of proton and neuron in Xe+CsI collisions



Experiments related to r-process nucleosynthesis

【 Survey of nuclear properties at RIBF 】

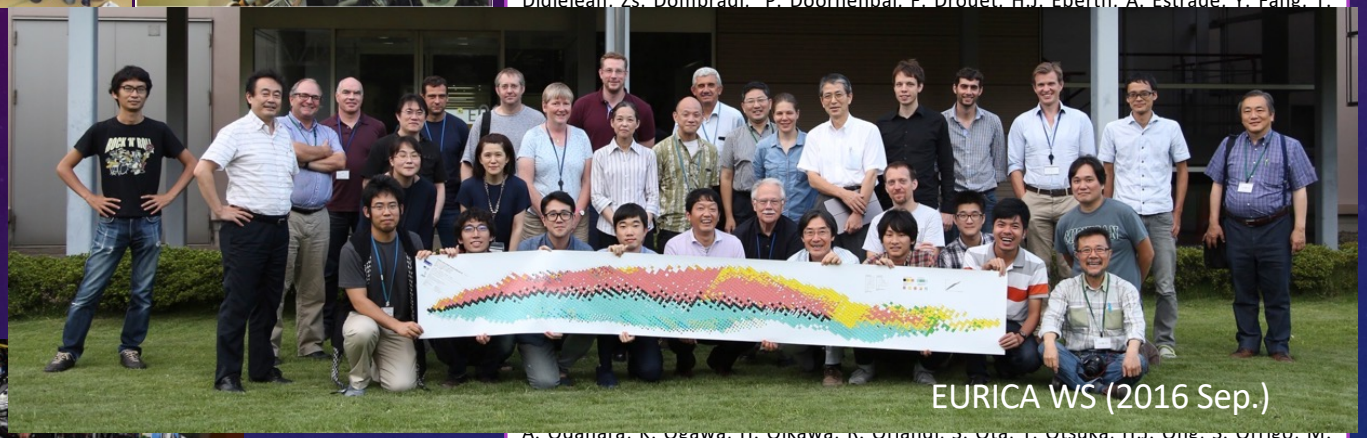




We keep expanding the nuclear chart to collect the nuclear properties.
→ Collaboration with Theory groups are very appreciated !

EURICA Collaboration



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