Experimental nuclear physics for the r-process

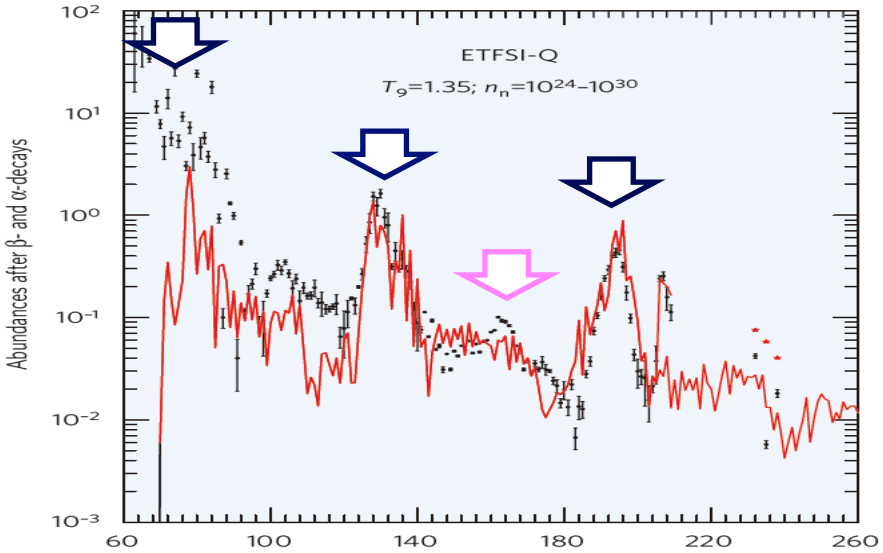
Shunji NISHIMURA

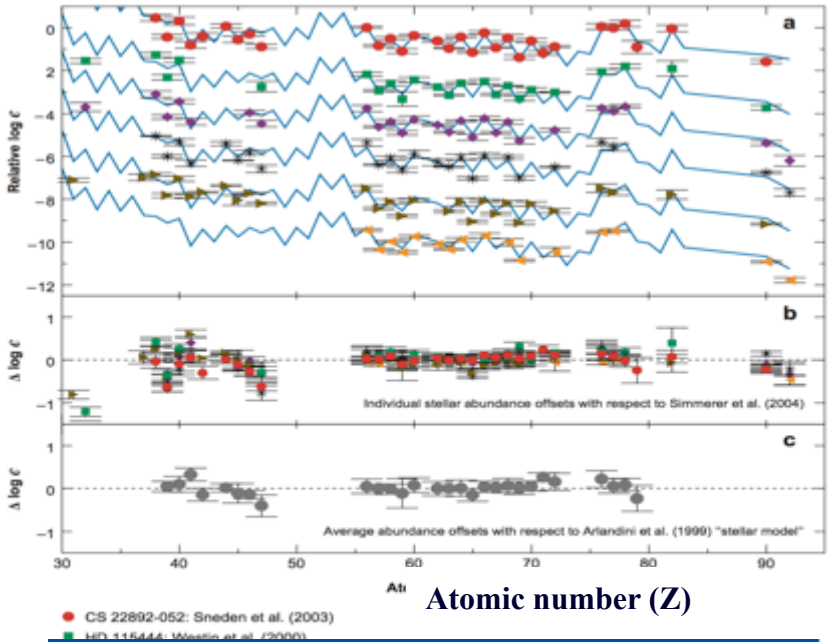
RIKEN Nishina Center

Present & Future

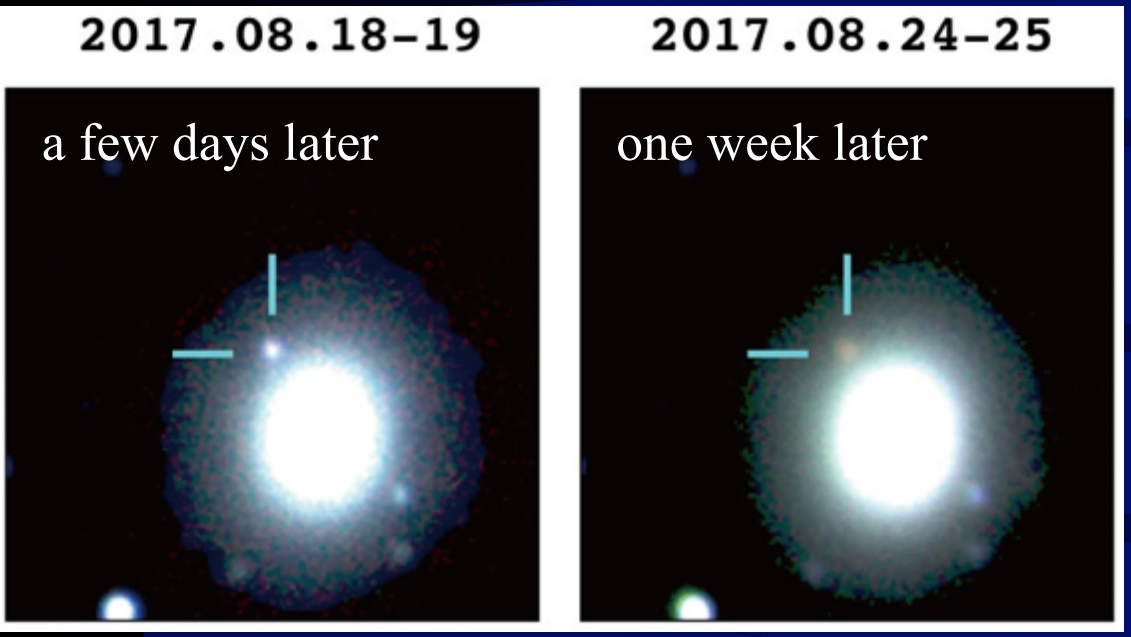
Nucleosynthesis of Heavy Elements (r-Process)

J.J.Cowan C.Sneden, Nature 440 (2006)

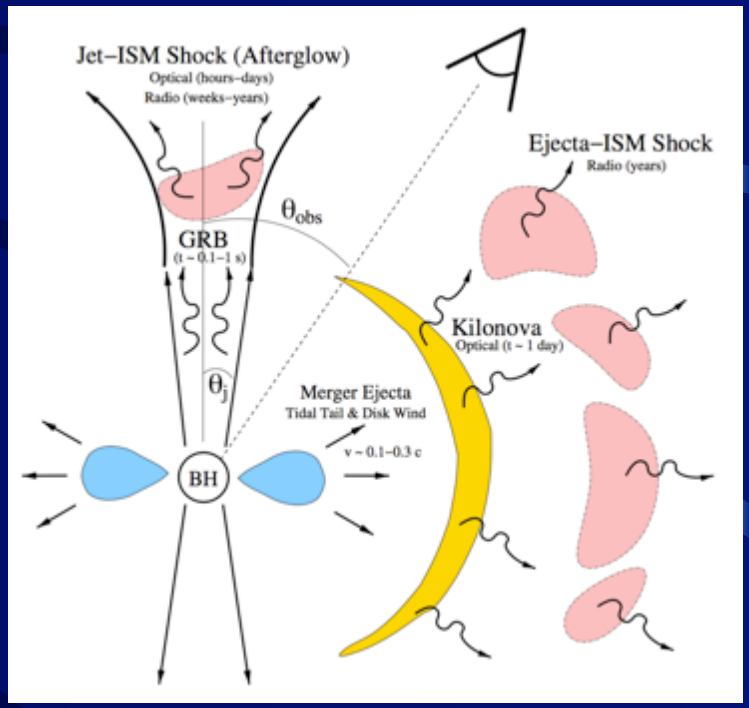




kilonova after Neutron Star Merger

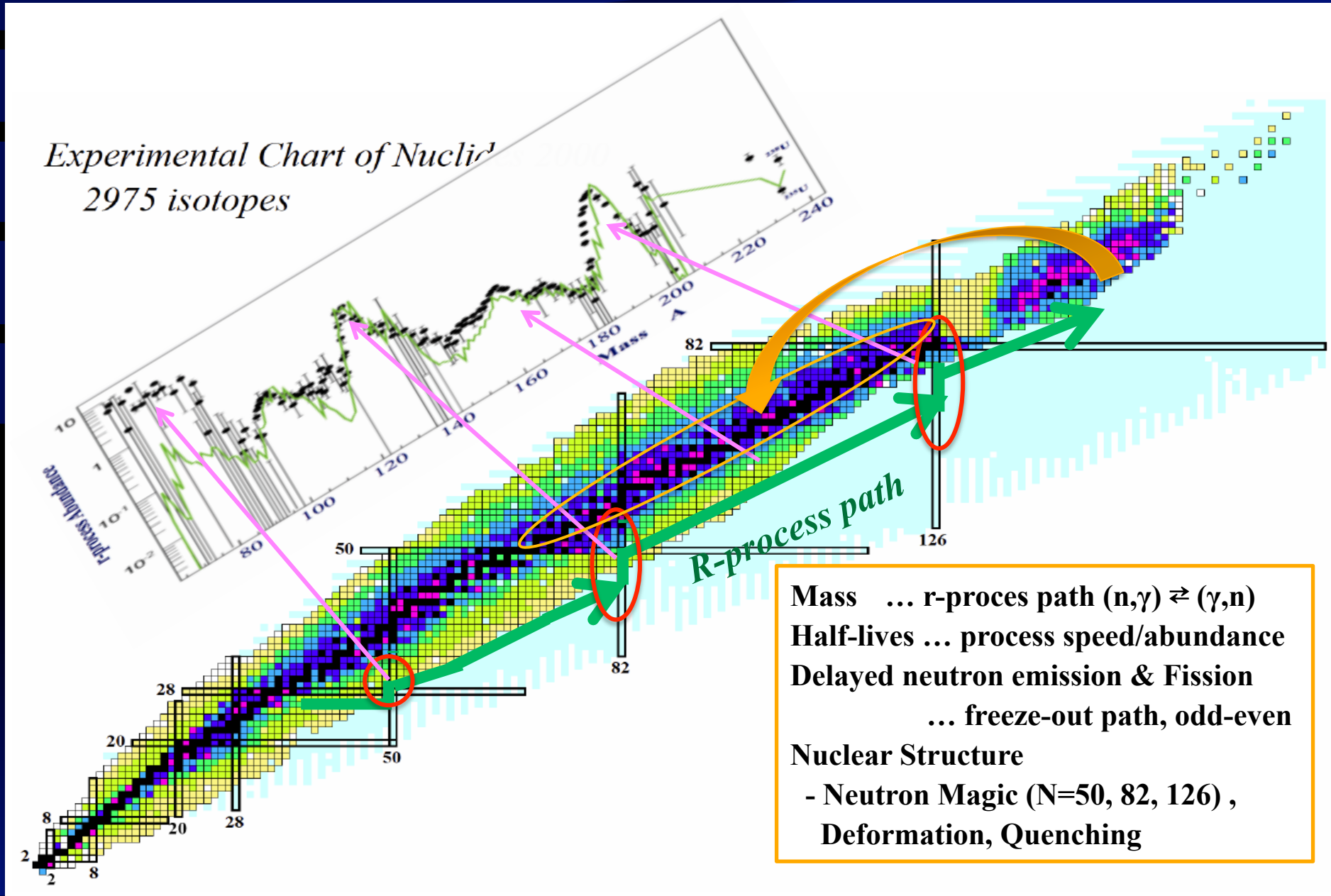


Credit: NAOJ/Nagoya Univ.



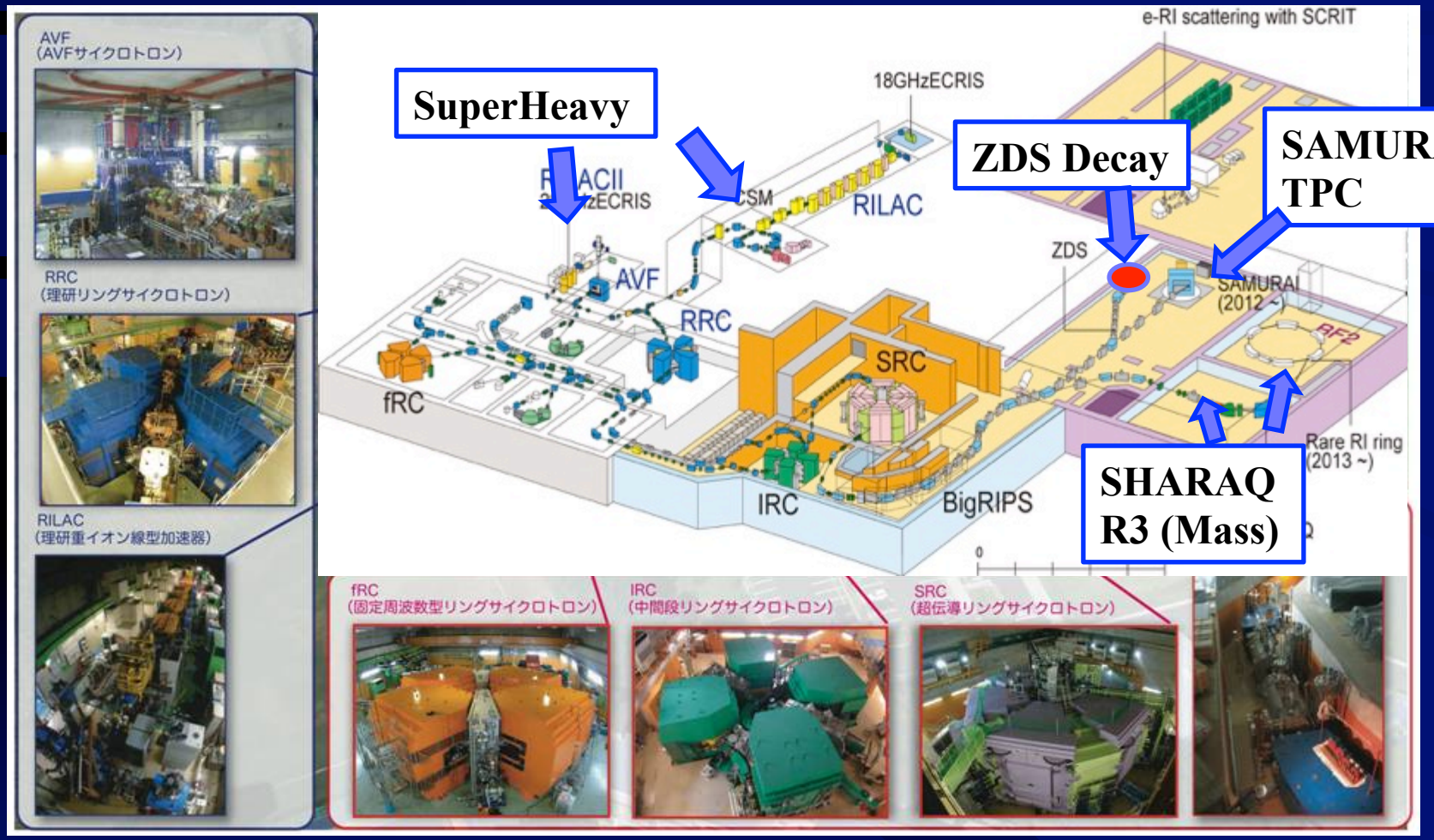
What kinds of RI created ?
How those RI are created ?

Nuclear Properties are Key Inputs



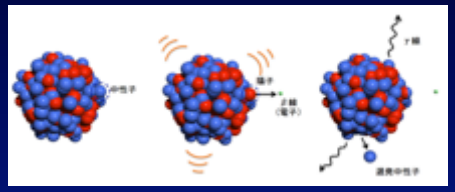
Mass … r-proces path (n,γ) ⇄ (γ,n)
Half-lives … process speed/abundance
Delayed neutron emission & Fission
… freeze-out path, odd-even
Nuclear Structure
- Neutron Magic (N=50, 82, 126) ,
Deformation, Quenching

RI Beam Factory (RIBF)

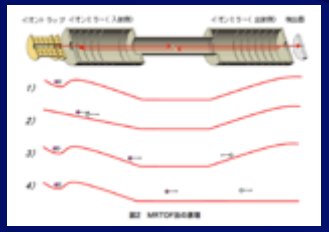


Evaluation from Nuclear Physics

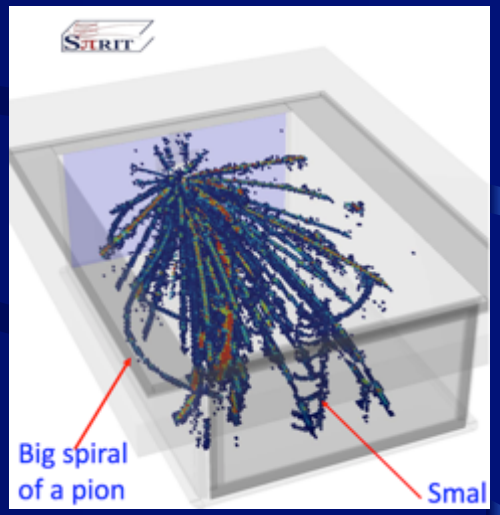
β-decay half-lives,
delayed neutron emission
（process speed,
abundance pattern）

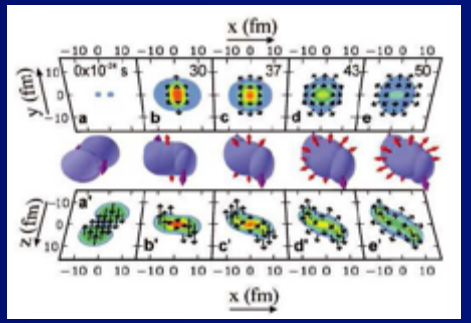


Mass measurement
（path of r-process）



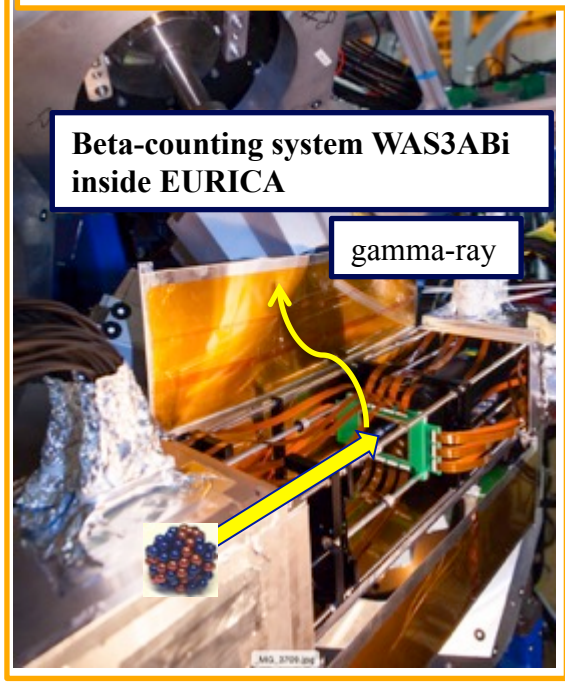
Equation of State (EOS)
in high density matter
(explosive condition)

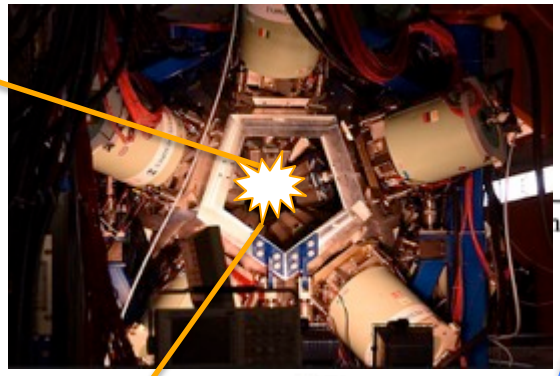




Decay Spectroscopy: EURICA

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



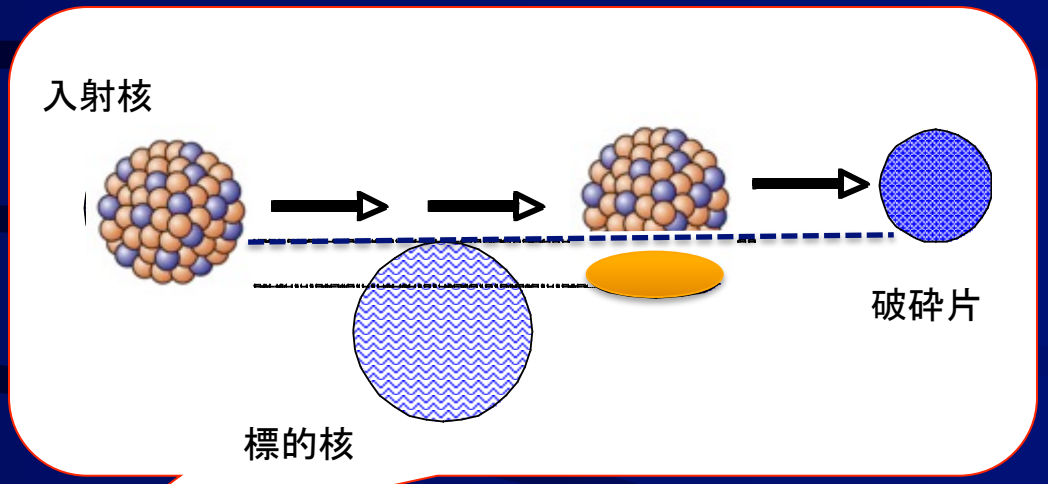


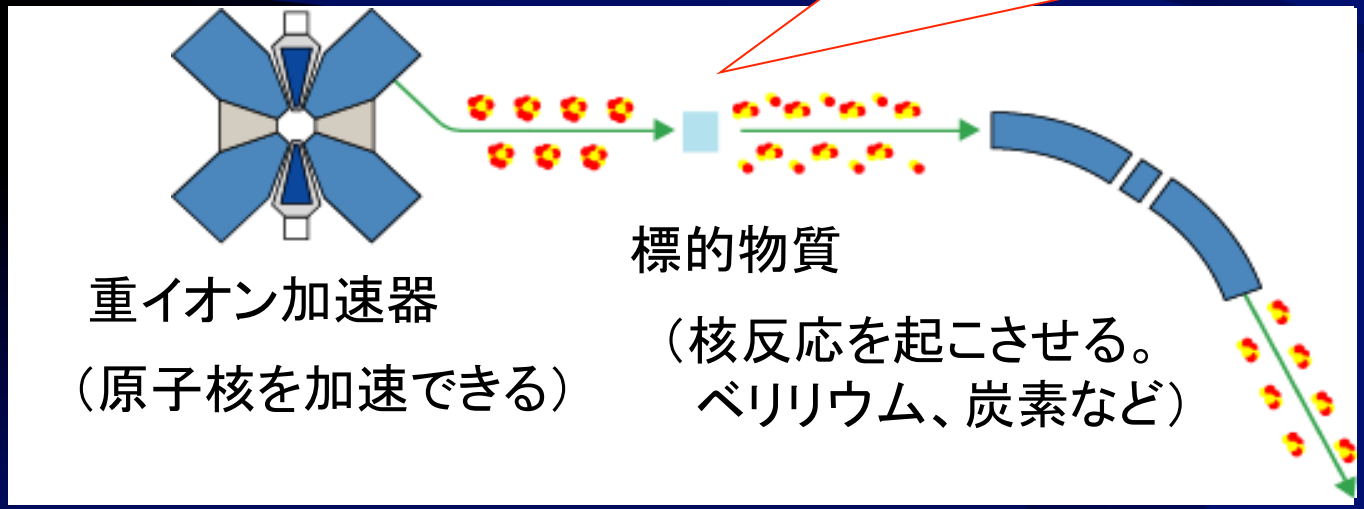
Primary Beam
(^{238}U / ^{124}Xe / ^{78}Kr)

RI Beam

Make Radioisotopes (RI Beam)

Make
Various Nuclei（Z, N）
確率的に生成！





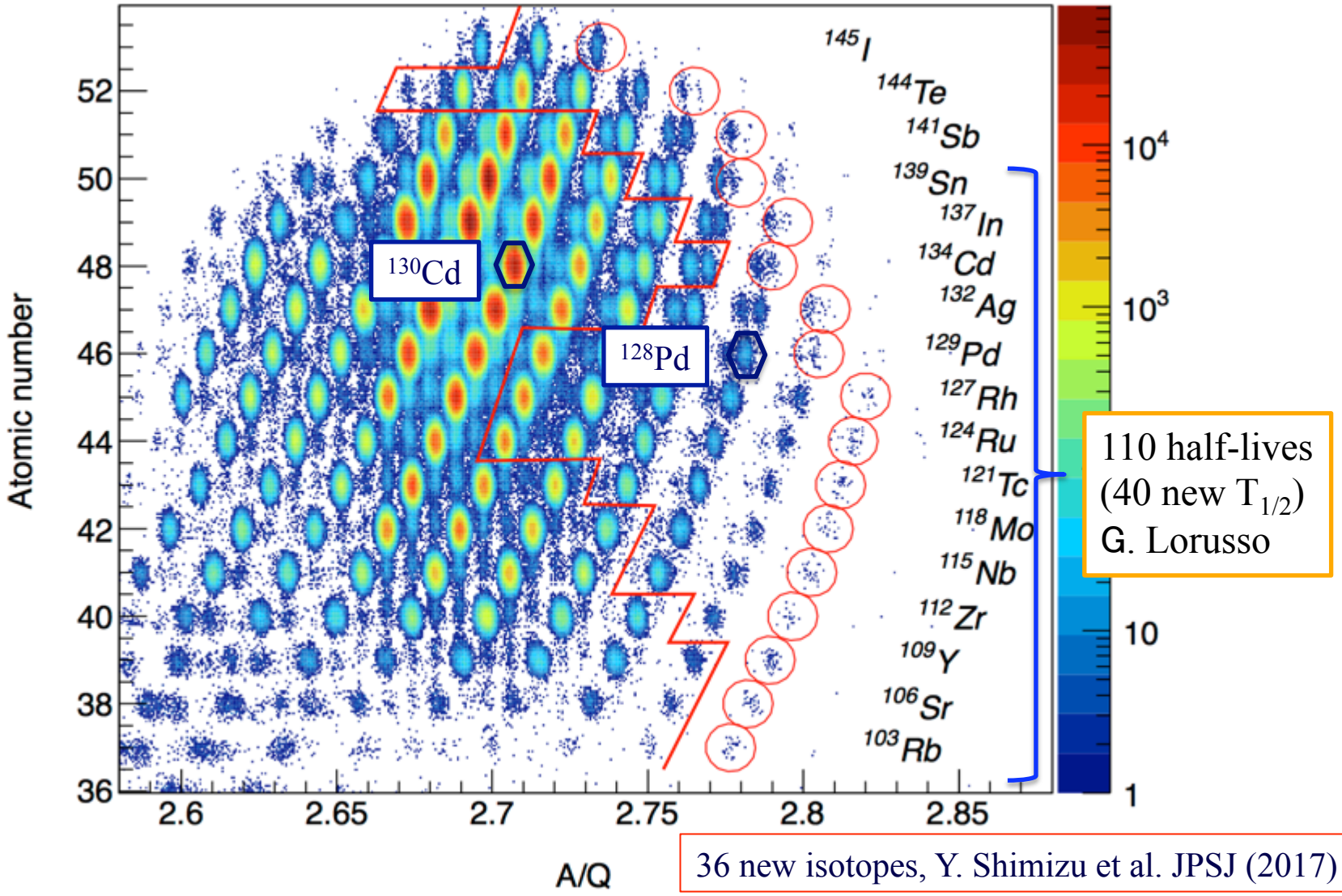
重イオン加速器
（原子核を加速できる）

標的物質
（核反応を起こさせる。
ベリリウム、炭素など）

（分析電磁石で生成されたRIを分離）

RIビーム

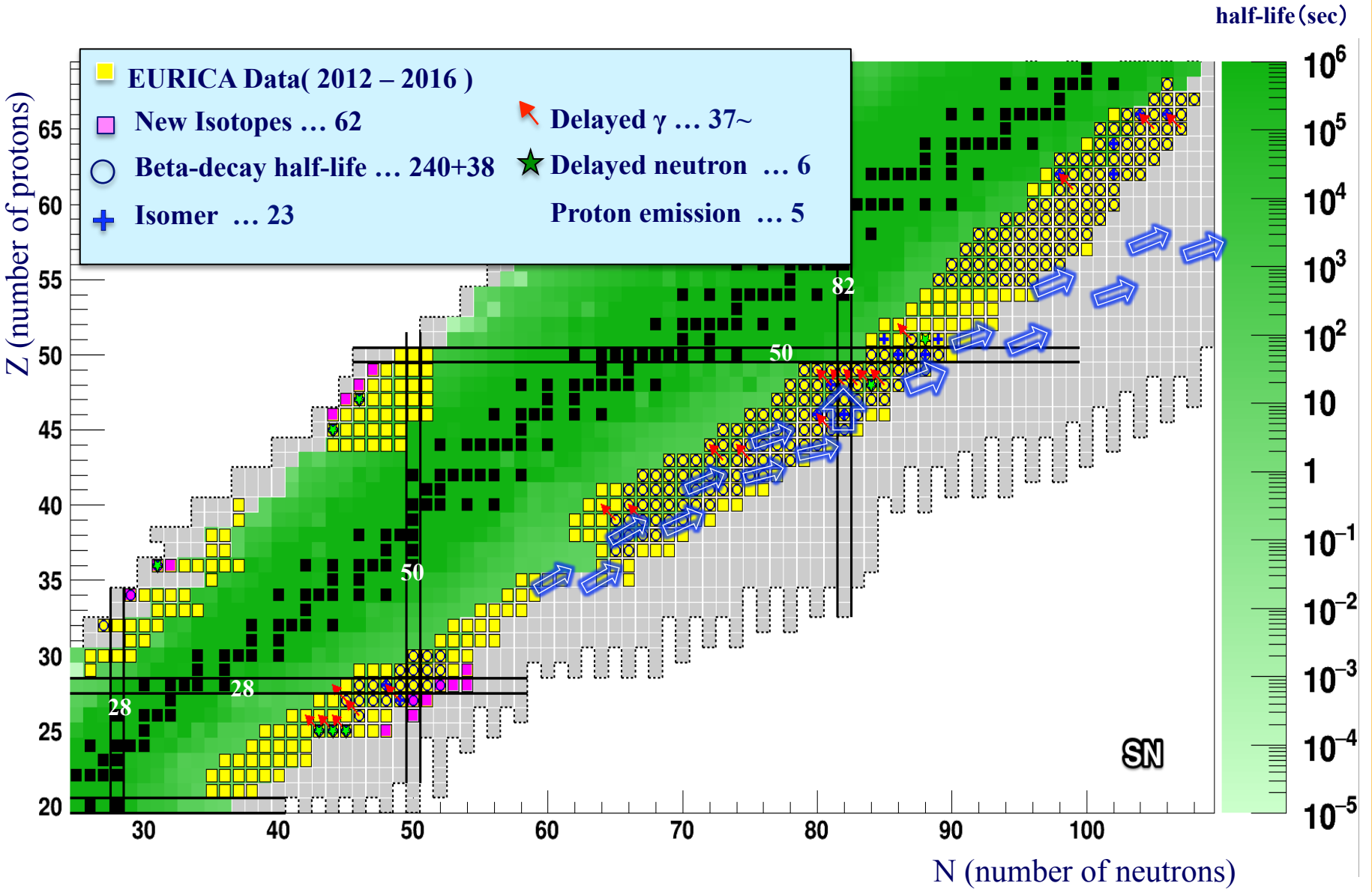
β-decay half-lives on r-process path



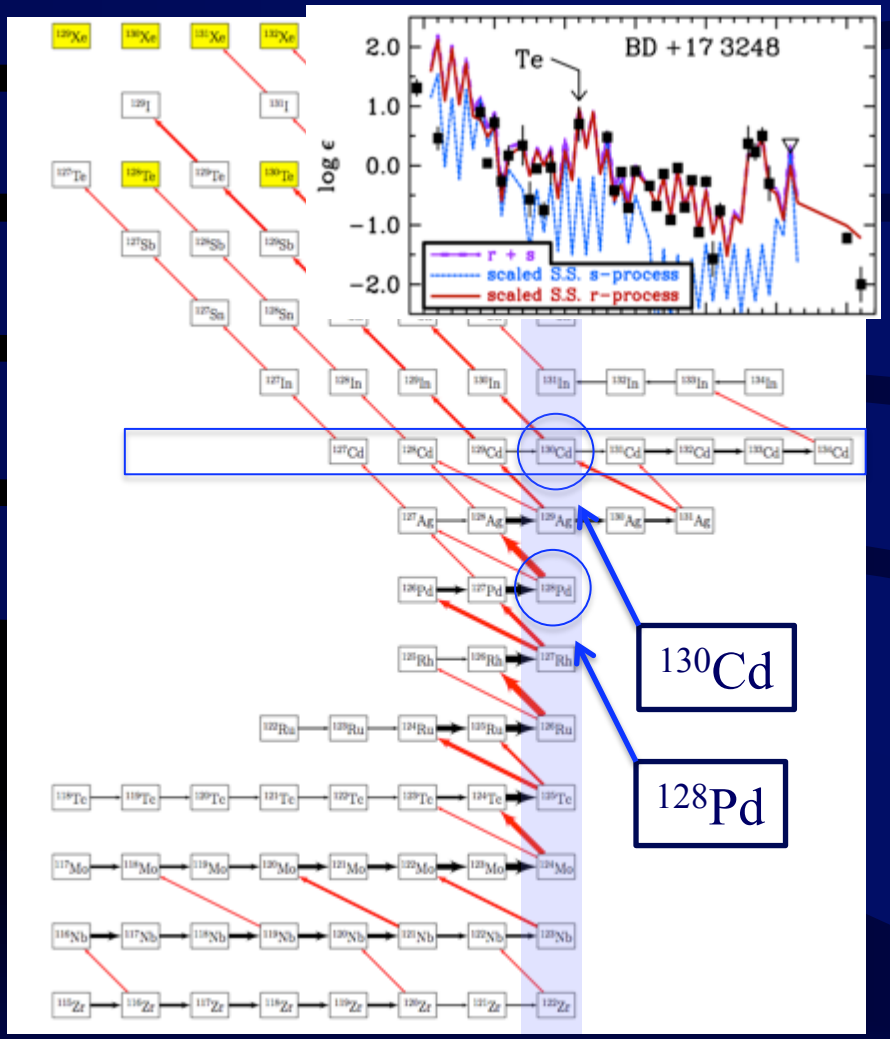
110 half-lives
(40 new $T_{1/2}$)
G. Lorusso

36 new isotopes, Y. Shimizu et al. JPSJ (2017)

440 Exotic Isotopes Surveyed by EURICA Spectrometer

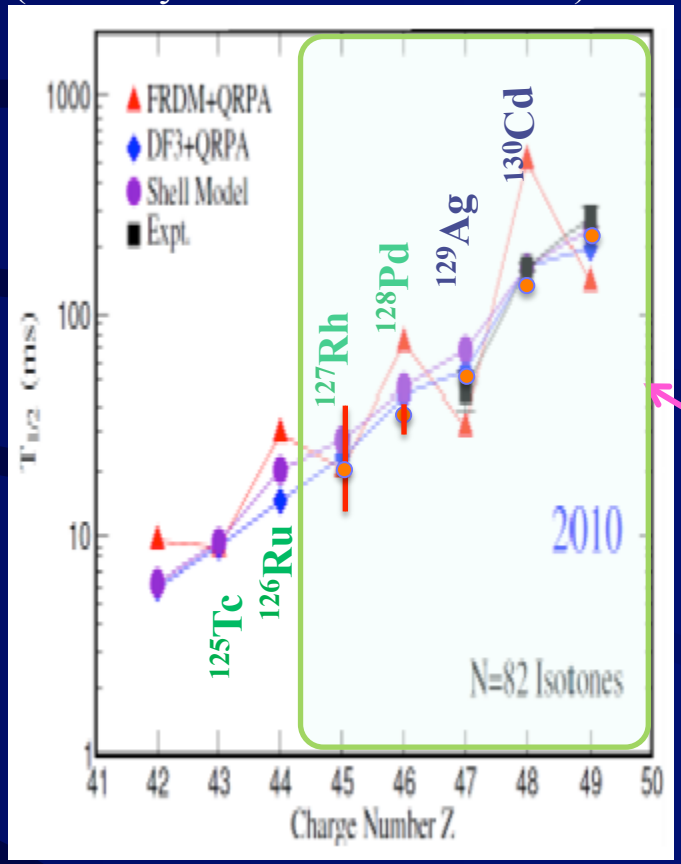


Beta-decay Half-lives N = 82 → Feedback to the Theory



So call r-process waiting point nuclei (N=82)
- r-process path
- residual r-matter flow in freeze-out

K.Langanke Phys. Scr. T152 (2013) 014011
(Courtesy of G. Martines-Pinedo)



RIBF
EURICA

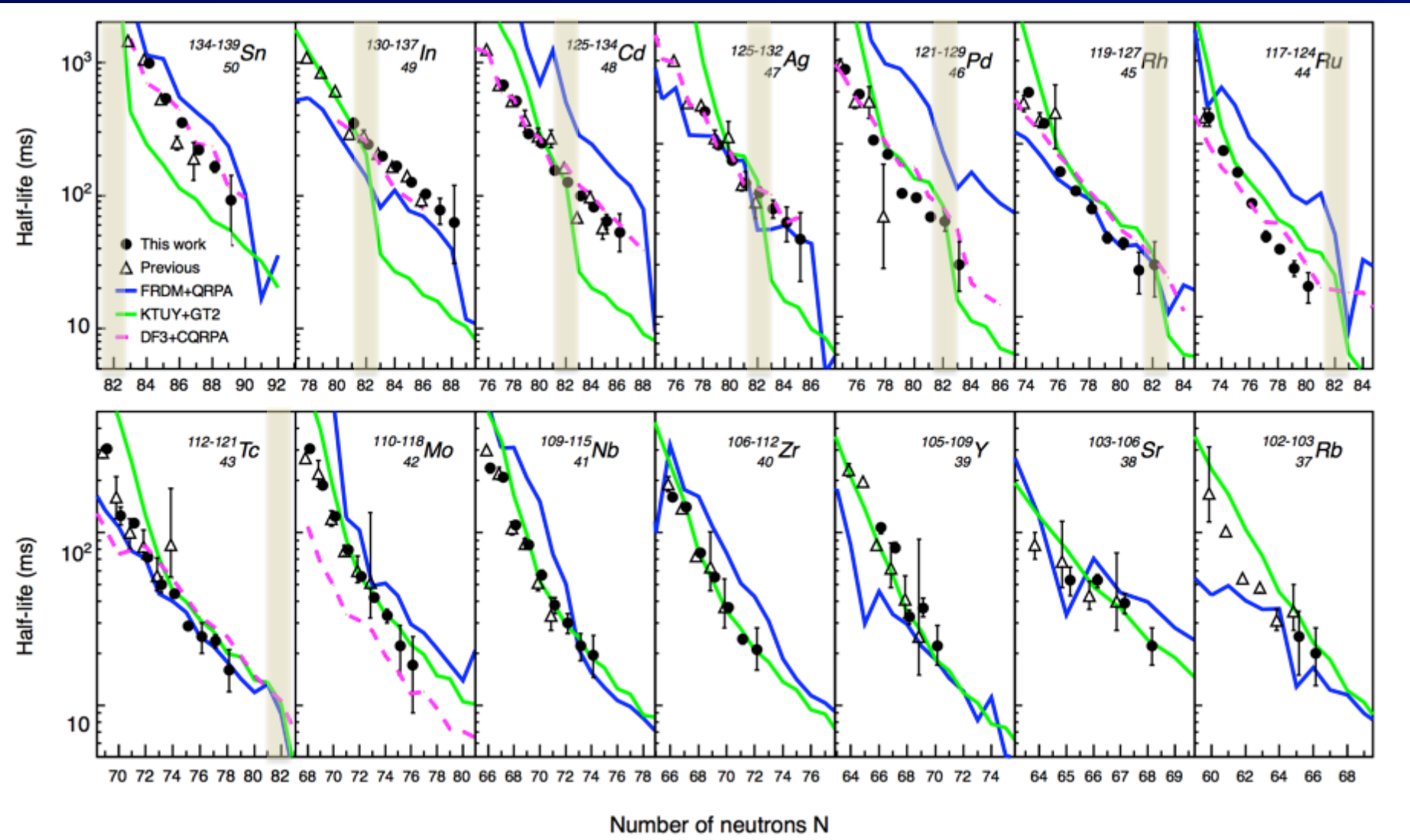
~ 25% shorter $T_{1/2}$

Confirmed by R. Dunlop (2016, TRIUMF)
^{130}Cd … $T_{1/2}$ = 126 (4) ms

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

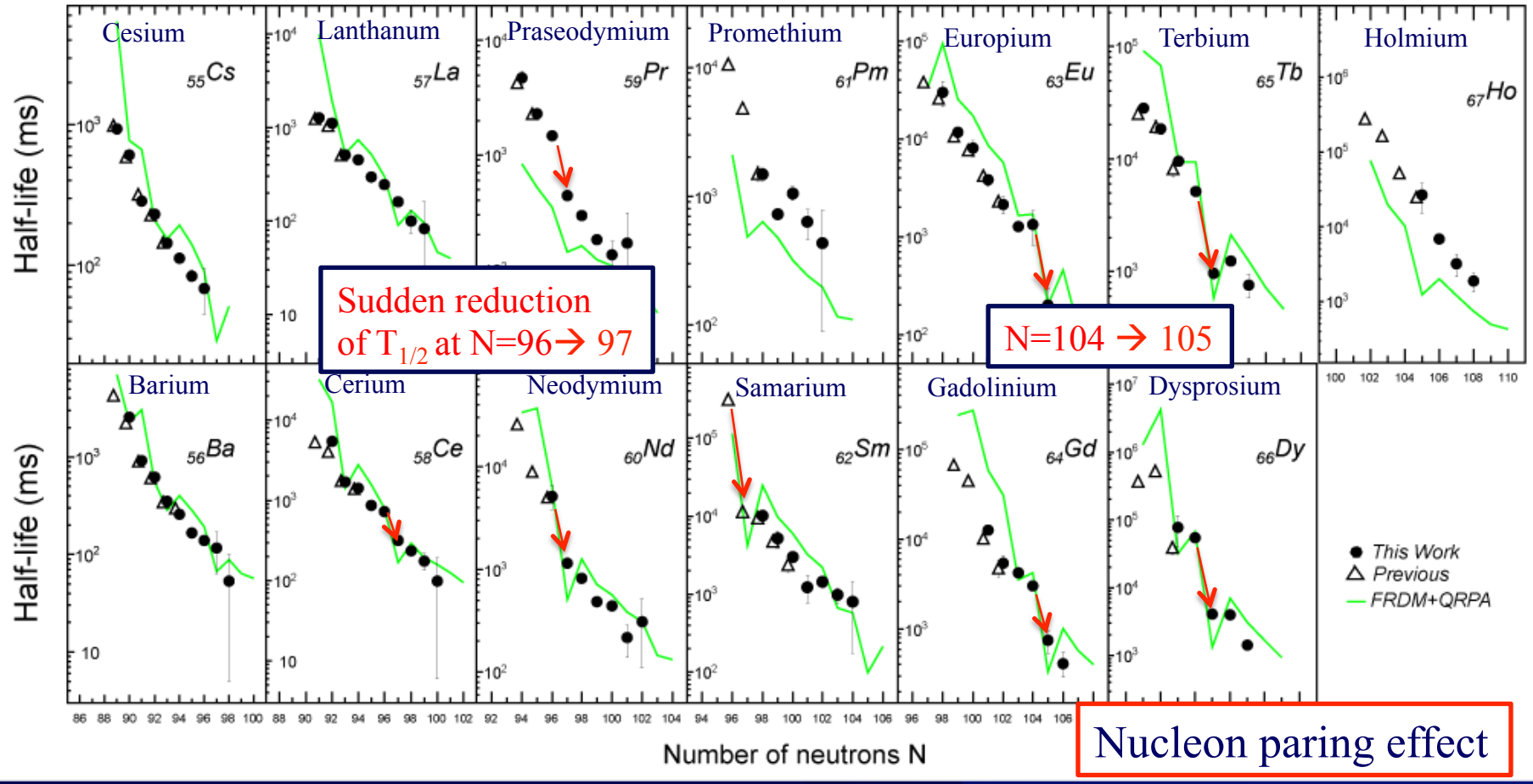
40 new half-lives ! G.Lorusso et al., PRL 114, 192501 (2015)

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



92 β-Decay Half-lives (Mass A = 144 – 175) vs FRDM+QRPA

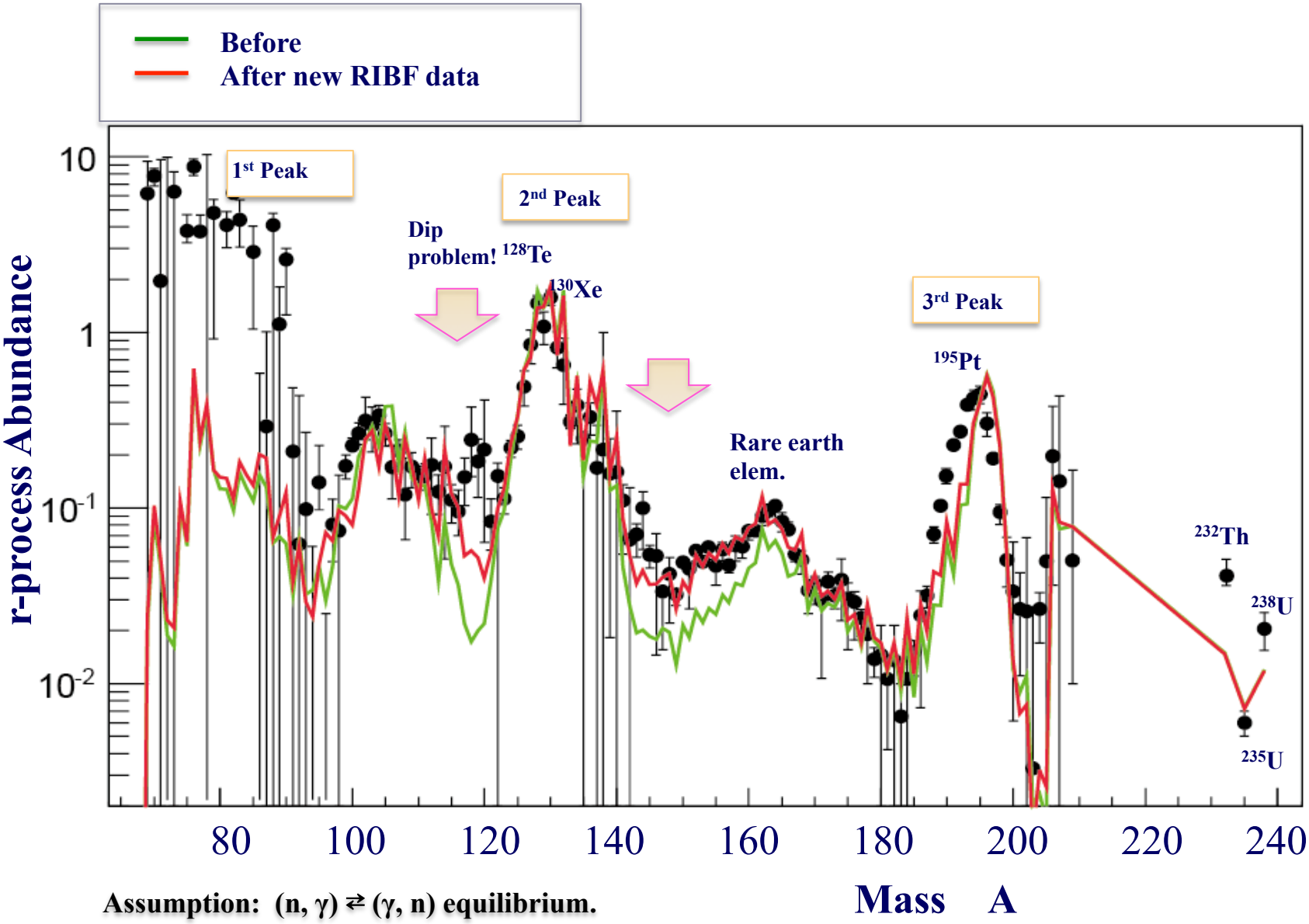
J. Wu, PRL (2017)



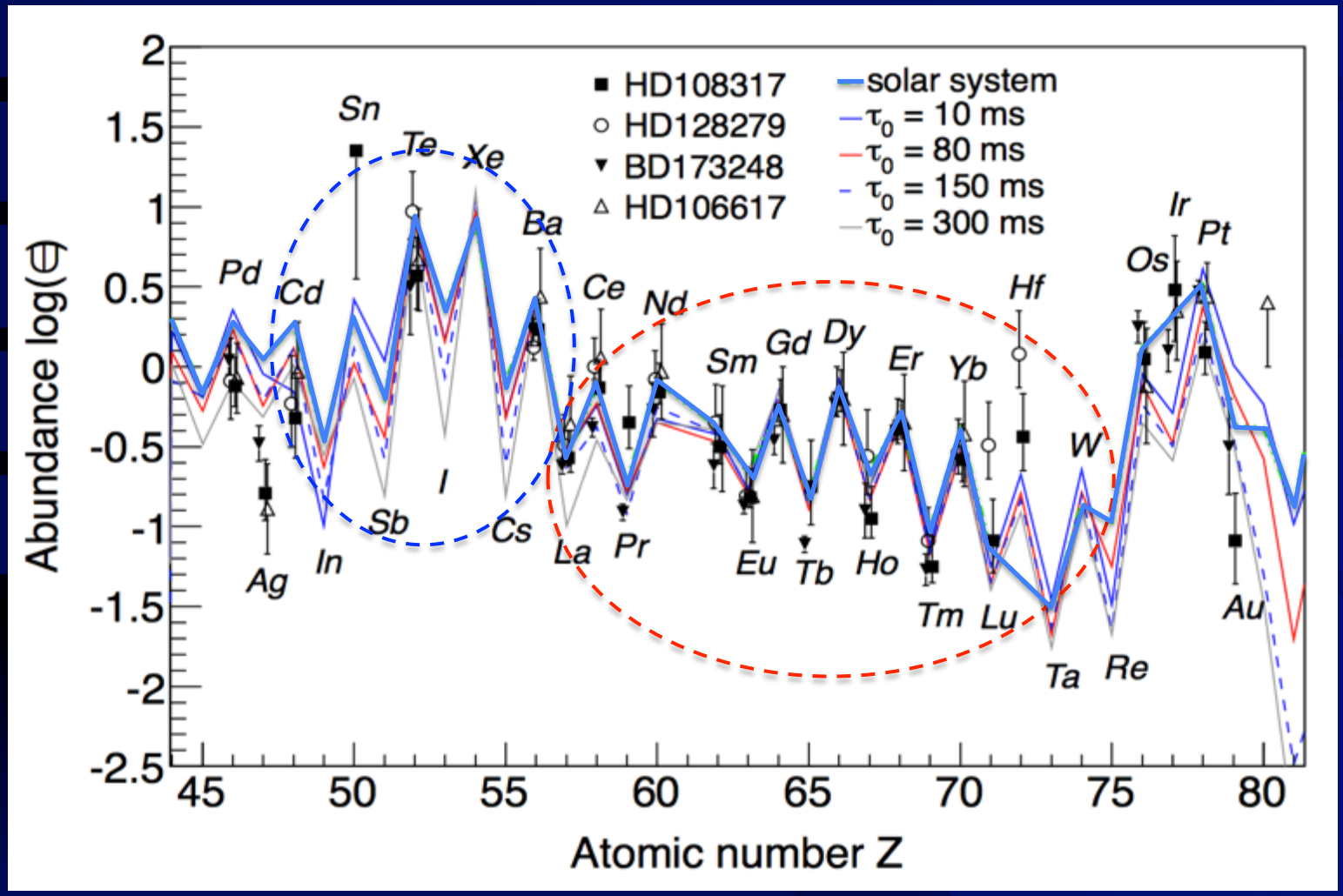
The β-decay half-lives of 92 neutron-rich $^{144-151}$Cs, $^{146-154}$Ba, $^{148-156}$La, $^{150-158}$Ce, $^{153-160}$Pr, $^{156-162}$Nd, $^{159-163}$Pm, $^{160-166}$Sm, $^{161-168}$Eu, $^{165-170}$Gd, $^{166-172}$Tb, $^{169-173}$Dy, and $^{172-175}$Ho were measured at the Radioactive Isotope Beam Factory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

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

G.Lorusso et al., PRL (2015)

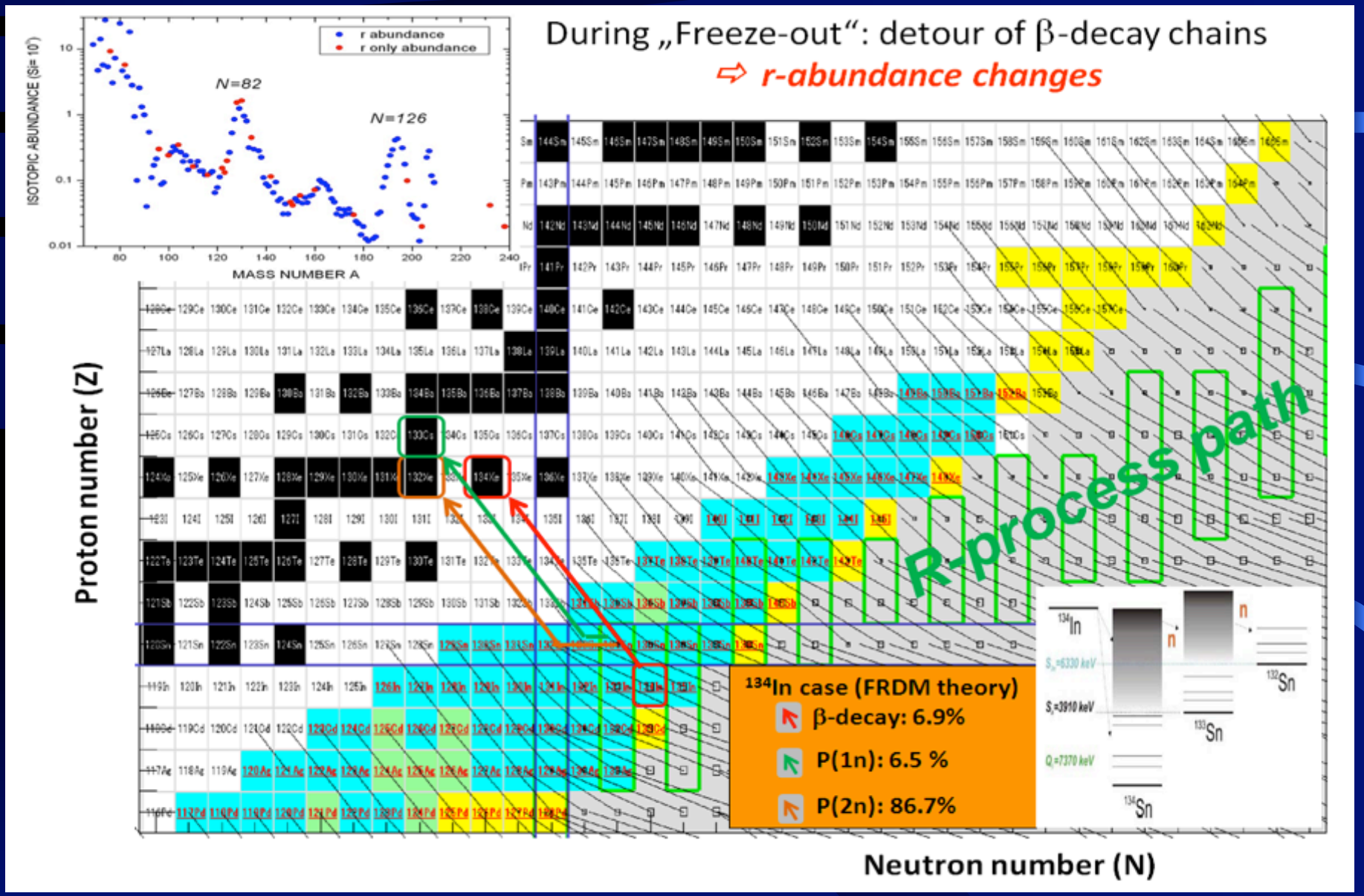


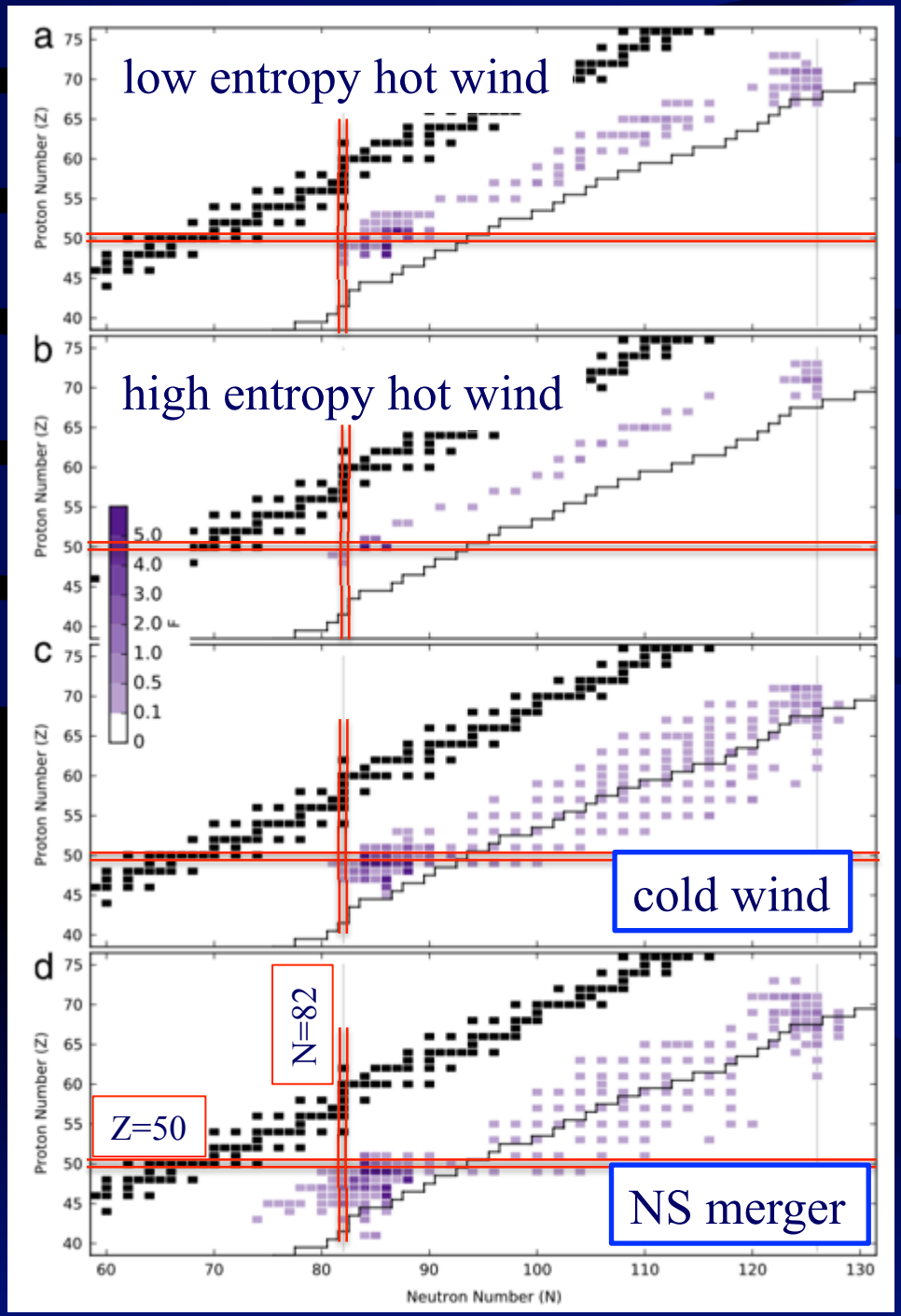
Universality of r-process elements ($Z \geq 56$)



Decay Spectroscopy around mass A =160 was performed !

r-Process Elements : Freeze-out Time



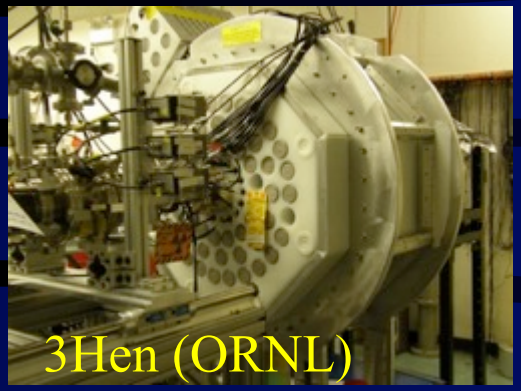


Pn values: How Sensitive in r-Process Calc.?

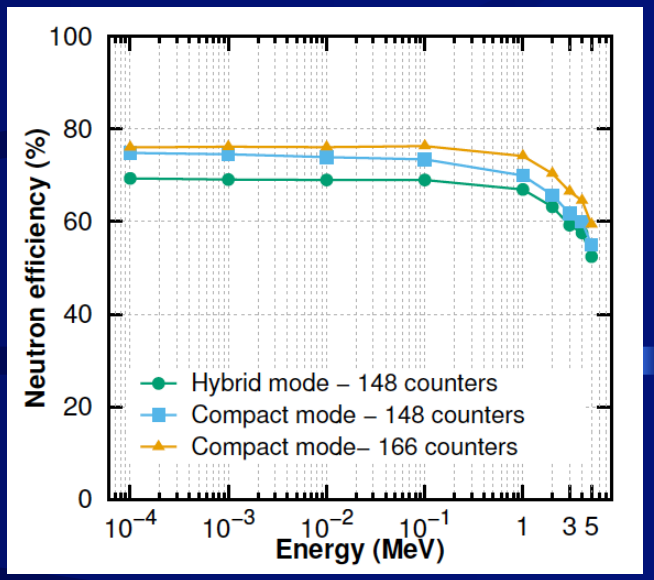
beta-delayed neutron emitters

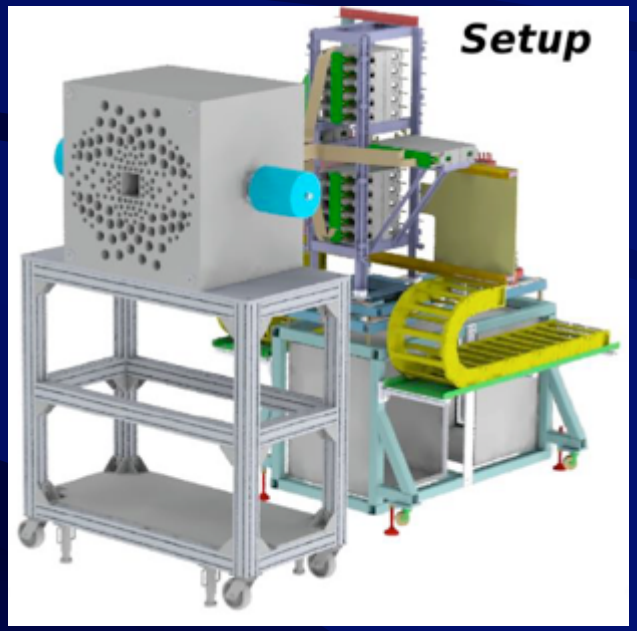
M.R. Mumpower et al.
Prog. in Part. and Nucl. Phys
86 (2016) 86-126

^{3}He gas detectors



BRIKEN @ RIBF





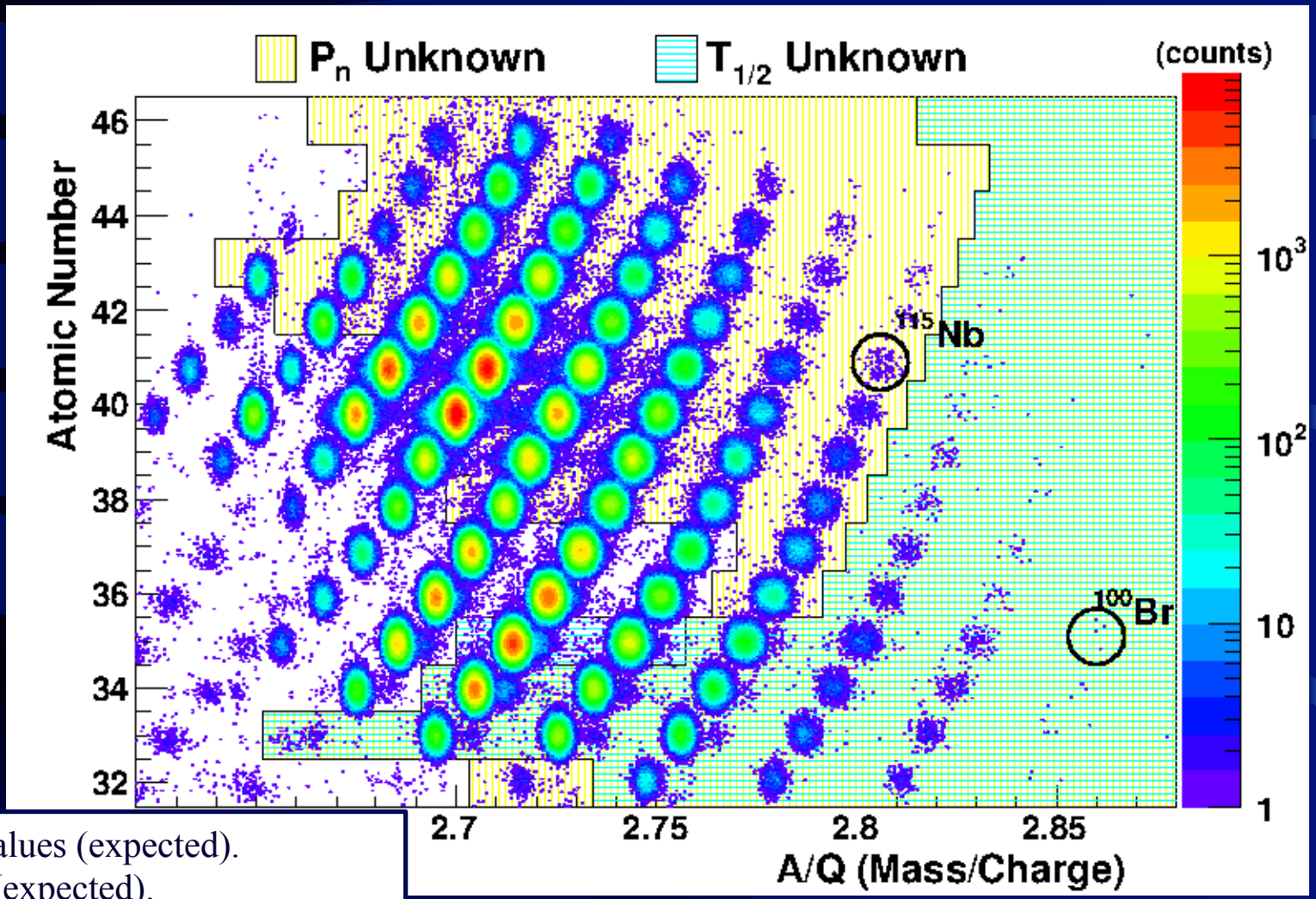
^{3}He + n → ^{3}H + p + 780 keV

No info. about initial E_n, but large efficiency

Thermalization time τ ~100 μs

BRIKEN Campaign (2017 Nov.)

Spokesperson: SN, A. Algora



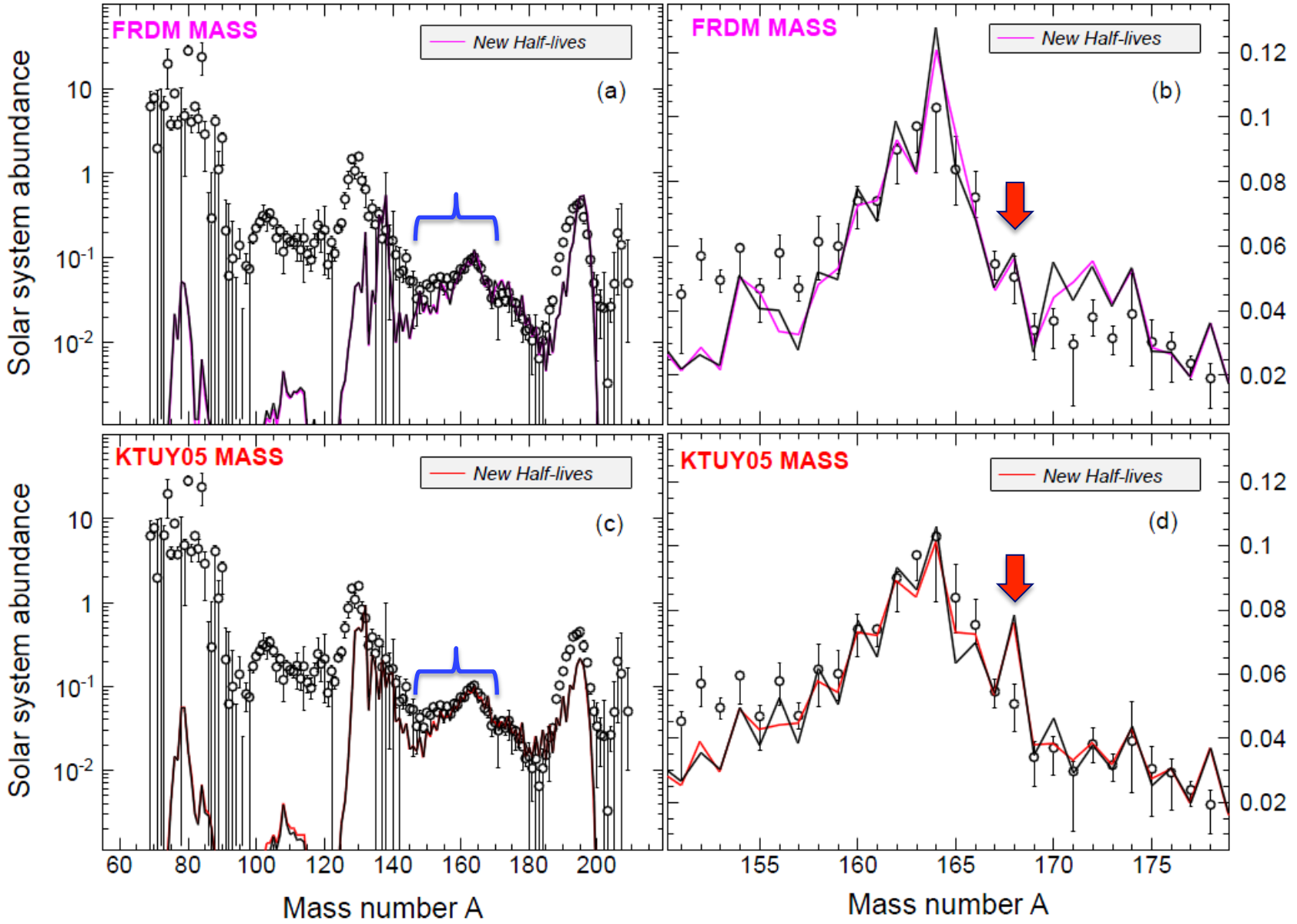
* 50 ~ new P_n values (expected).
* ~ 20 new $T_{1/2}$ (expected).
* Isomers
* Beta-delayed gamma with neutron-gate
* U-beam int. ~ 65 pnA

Mass & Decay Spectroscopy

Rare-Earth Peak with Different Mass Models

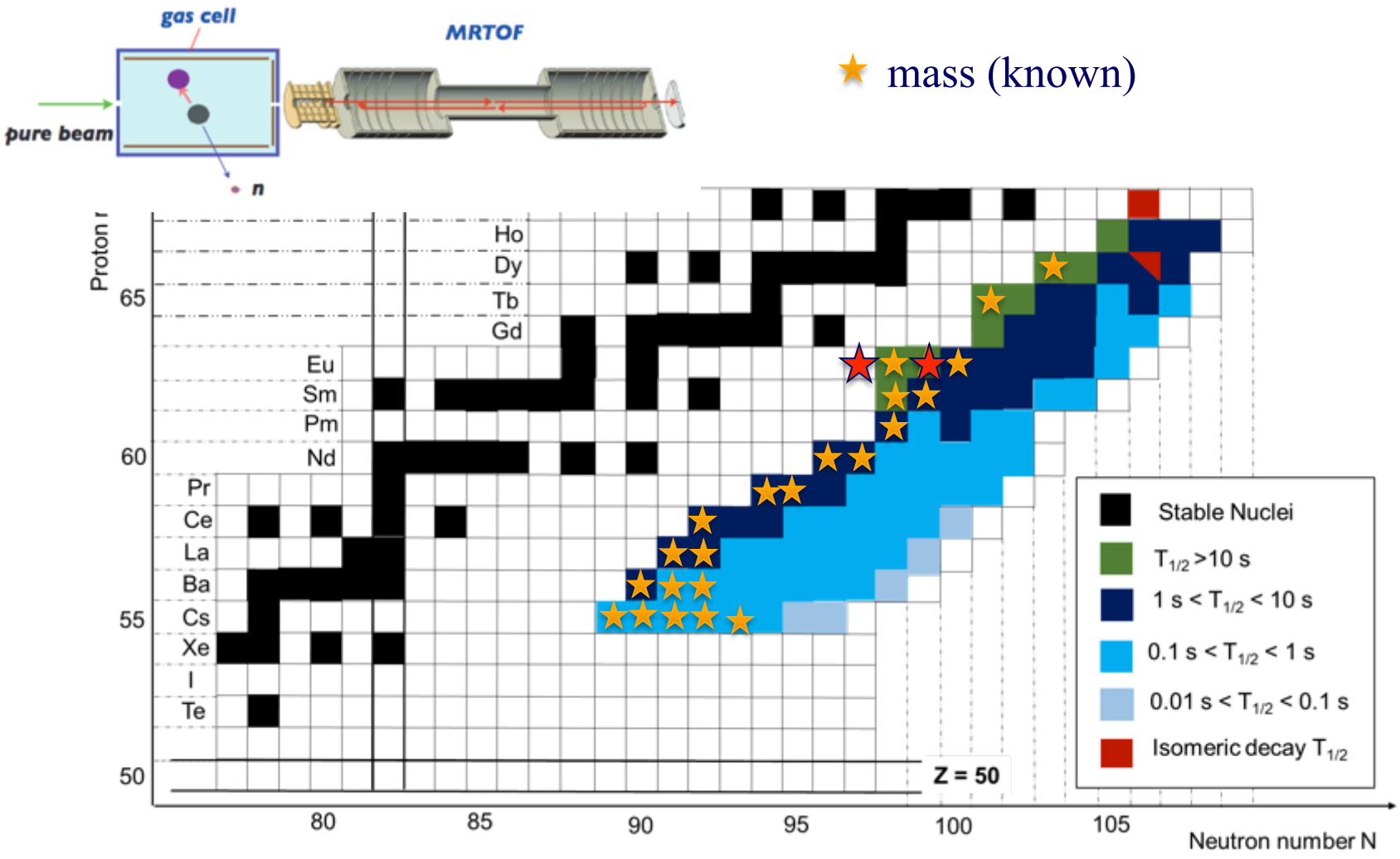
Half-lives: FRDM and new half-lives. Mass: FRDM and KTUY.

by J. Wu

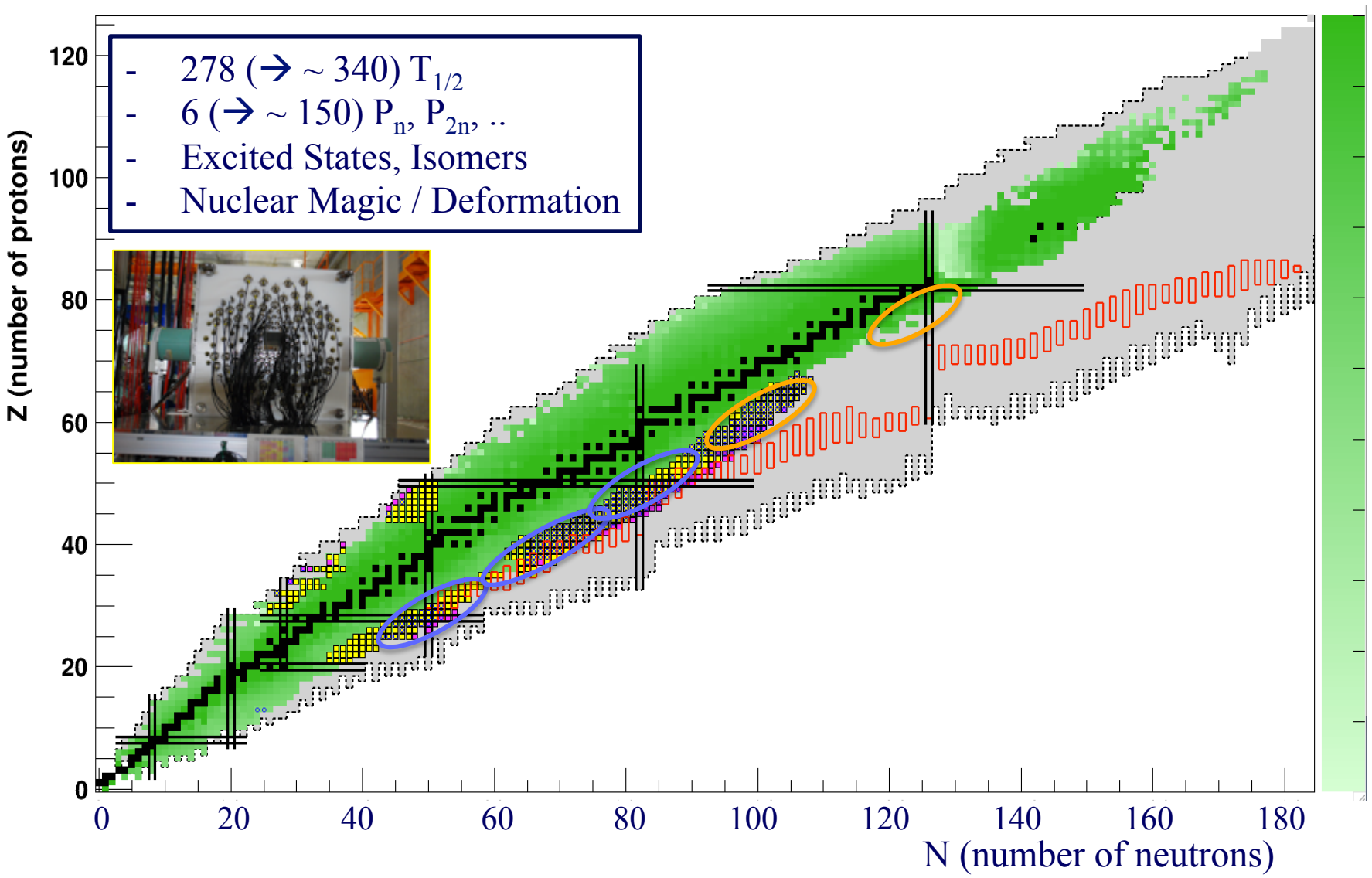


Half-lives and Mass Measurement

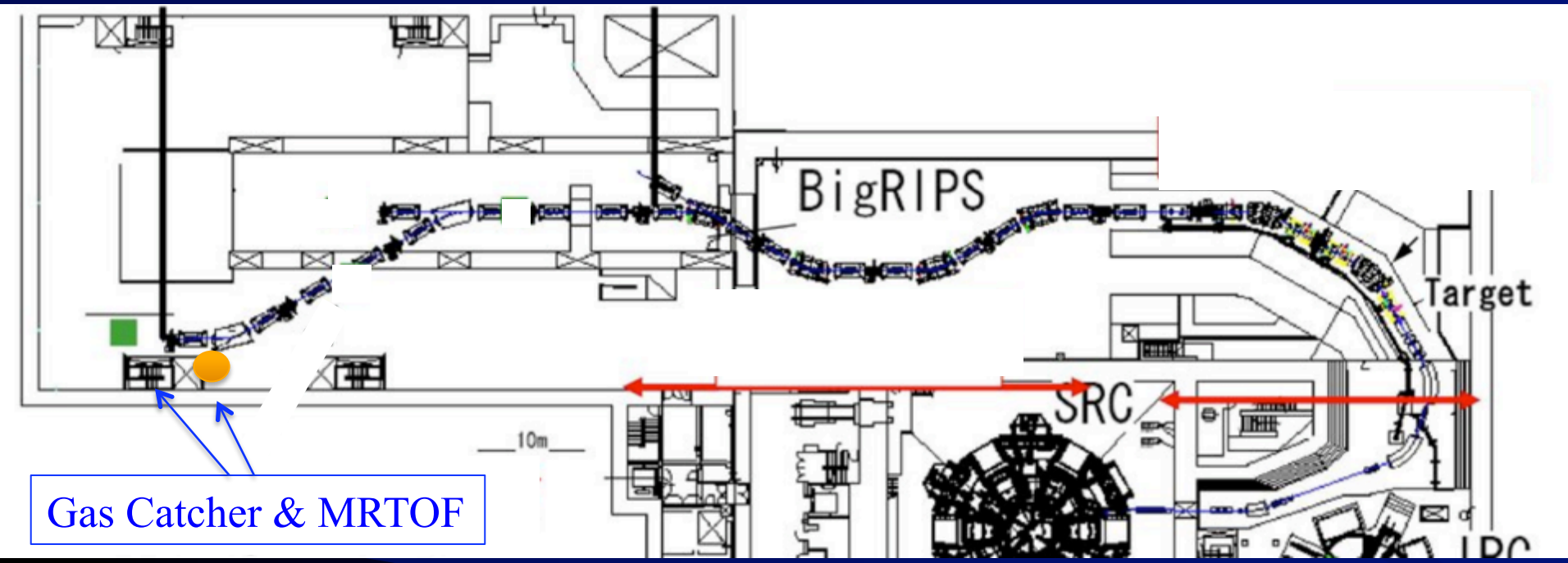
RIKEN Acc. Prog. Rep. 48 (2015) 213



Heavy RI (N = 126)



MRTOF Project in ZeroDegree spectrometer

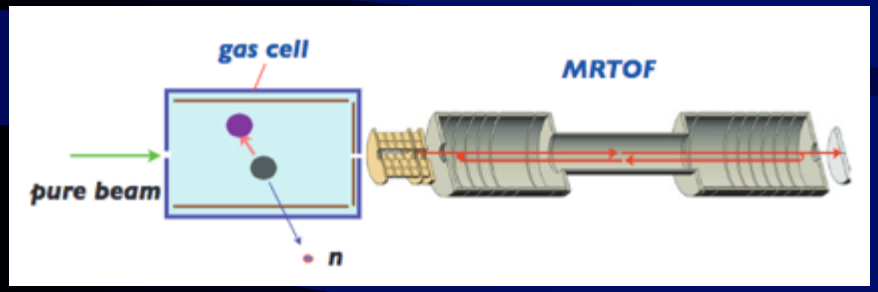


Yakitori Mode

- BigRIPS/ZDS Experiments → MRTOF (Symbiotic Collaboration)
  - In-beam, New isotopes, Interaction cross-section, Decay
- ZD-MRTOF & Decay for heavy RI (N = 126)

ZD-MRTOF Workshop (3-4, September, 2018) … to be announced.

ZD-MRTOF → Decay



RI Identification by MRTOF

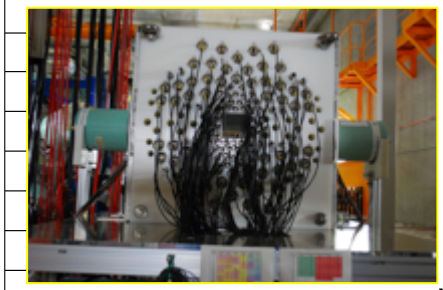
AGARI
(Active mass GAted stopper of RI)

Development has been started.
Can be applicable for superheavy elements.

Delayed neutron emission P_{1n}, P_{2n},..

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

- 278 (→ ~ 340) $T_{1/2}$
- 6 (→ ~ 150) P_n, P_{2n}, ..
- Excited States, Isomers
- Nuclear Magic / Deformation



Decay spectroscopy (N~126)
Mass measurement
High density nuclear matter (EOS)
Fission & Nuclear reactions

Z (number of protons)

N (number of neutrons)