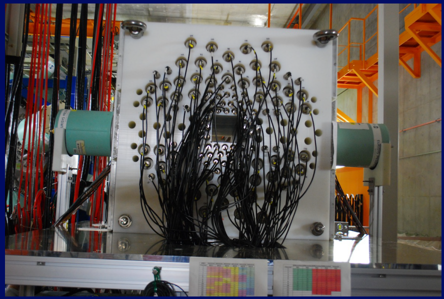
Experimental challenges relevant to r-process nucleosynthesis

Shunji NISHIMURA
RIKEN Nishina Center

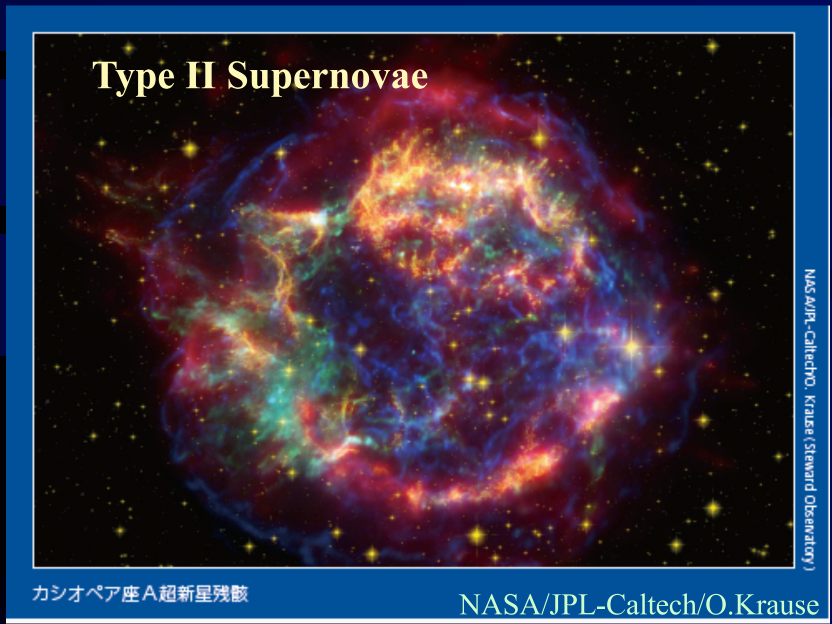


- **BRIKEN Project (2016 – 2018?)**
  - β–n–γ spectroscopy

- **Future Projects (2019 - …)**
  - CAITEN / NiGIRI

EURICA Project (2012 – 2016)
β–γ spectroscopy

Where is the site of heavy elements ?
(r-Process Nucleosynthesis)



(Steward observatory)

S. Wanajo

- Mechanism of Explosion.. ?
- Lack of Neutrino, Neutron ：
  Ye < 0.5?
- Strong magnetic field ?

N. Nishimura, T. Takiwaki, F.-K. Thielemann
Astrophys. J. 810 109 (2015)

- Extremely neutron-rich nuclei
- Very Rare to have two neutron stars close together.
- Not possible in 1st stars !?

Origin of Heavy Elements
Supernovae vs Neutron Star Merger

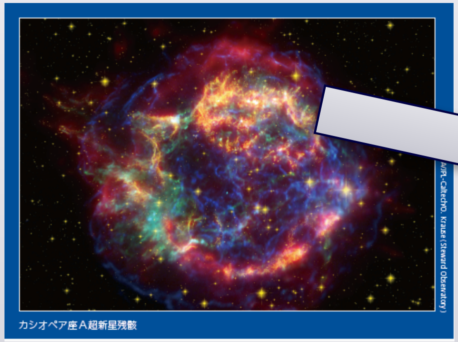
r-process conditions:
Y_e, S, τ, EOS, …

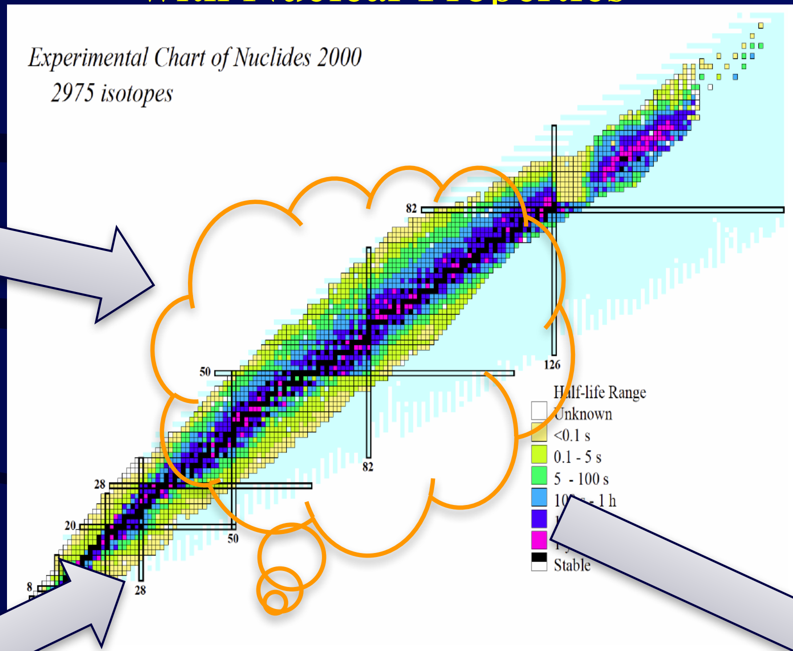
Network calculation
with Nuclear Properties

r-process abundance Z, A

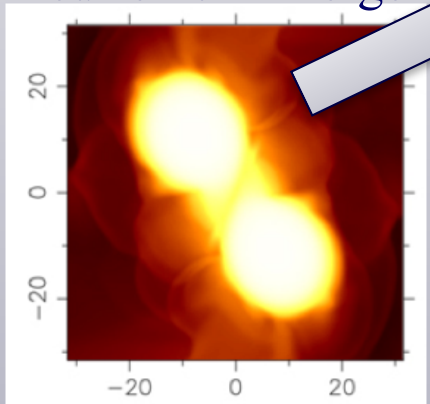
J.J.Cowan C.Sneden, Nature 440 (2006)

Supernovae explosion?

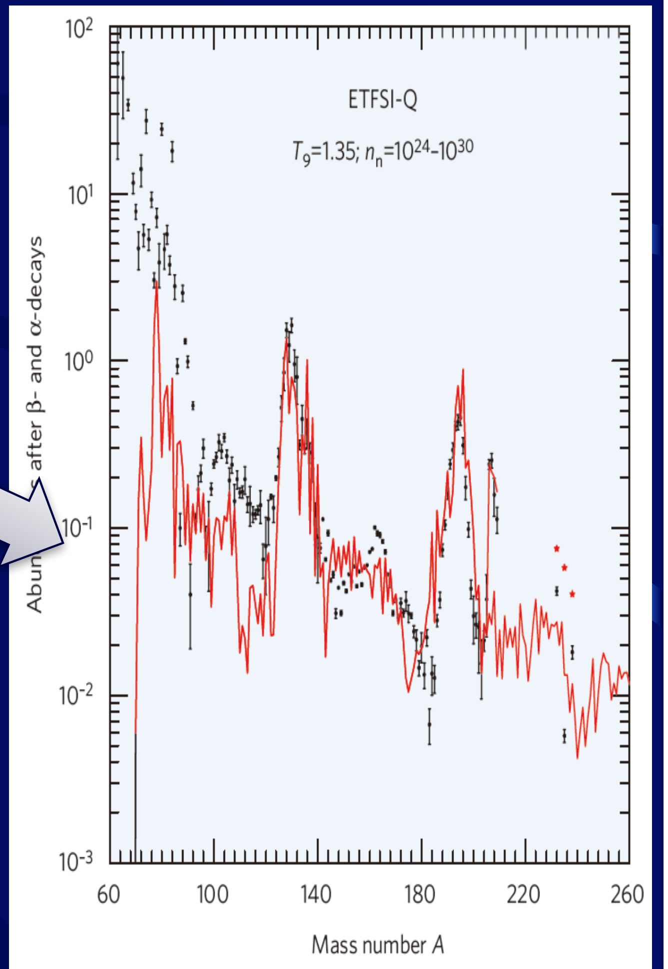




Neutron star merger?

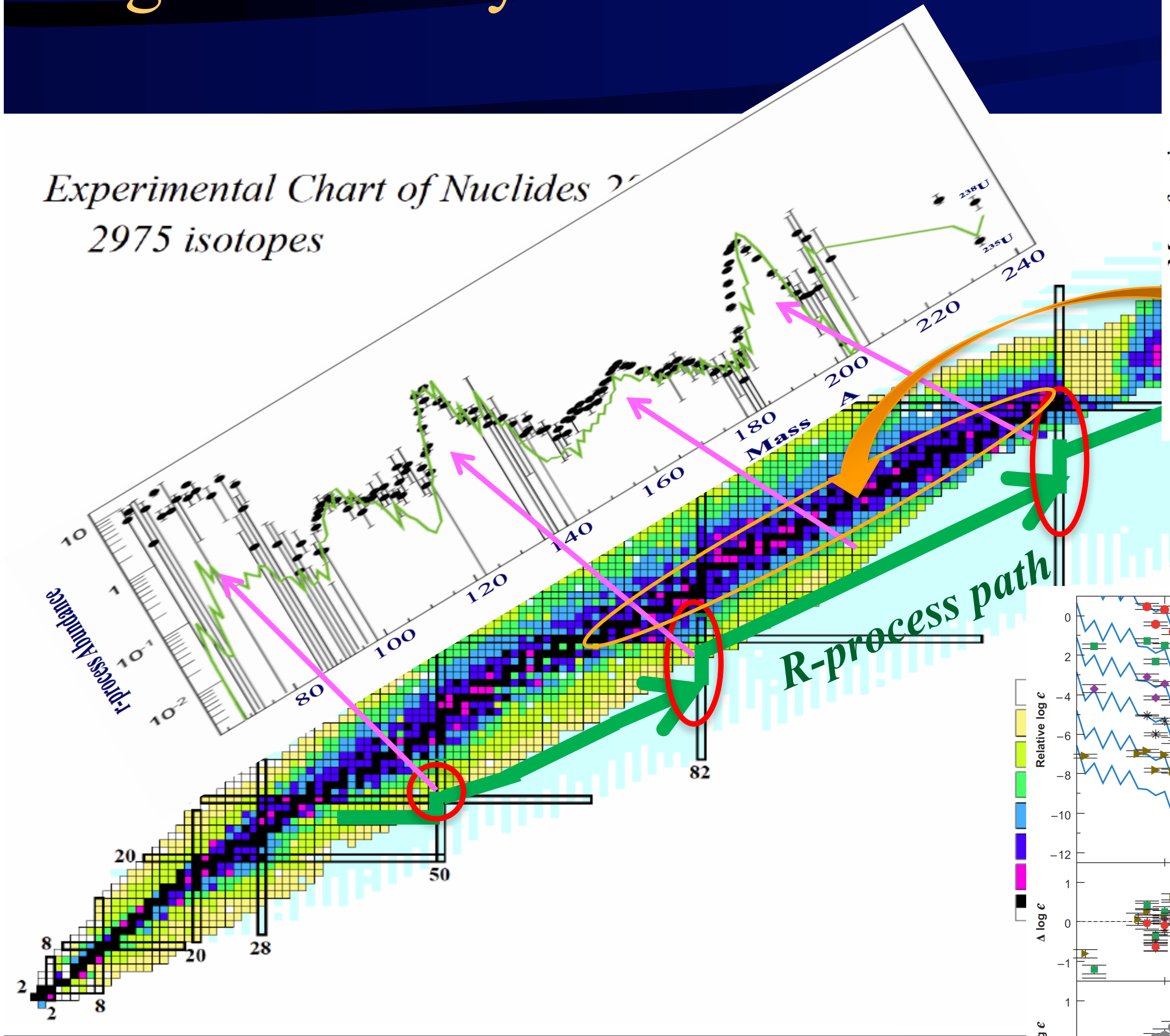


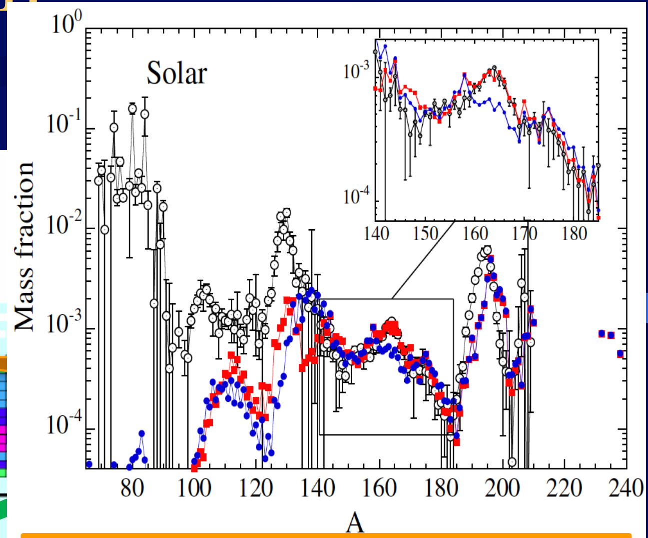
S. Wanajo



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

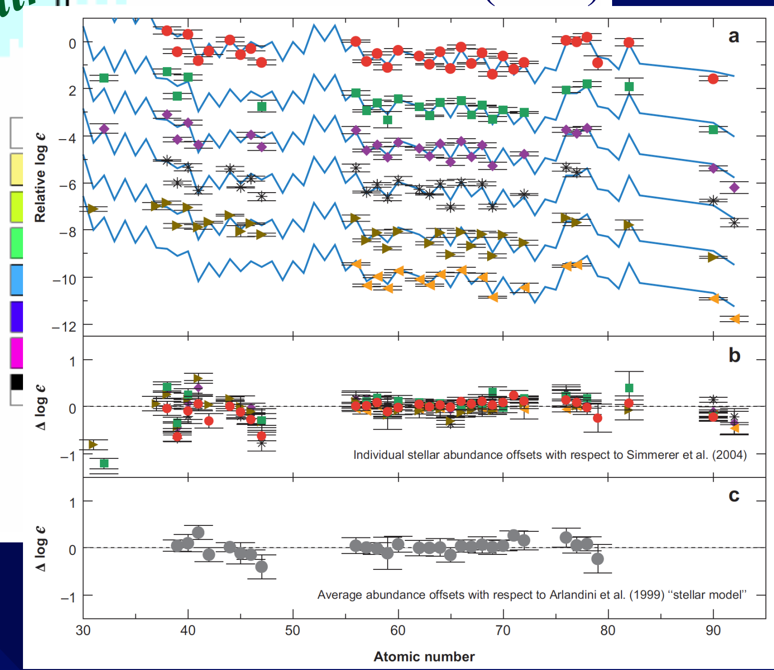
Origin of Heavy Elements: Rare-earth





S. Goriely et al PRL 111, (2013)

C. Sneden et al.(2008)

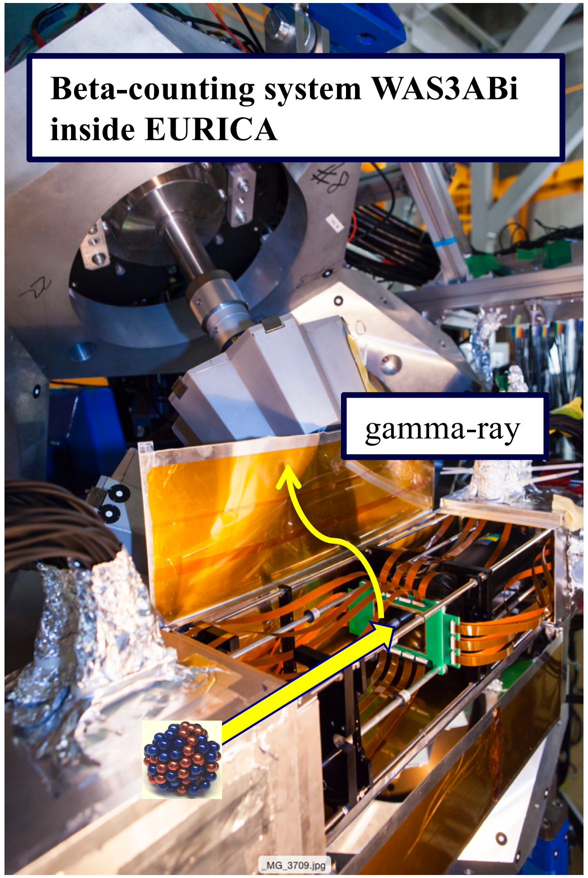


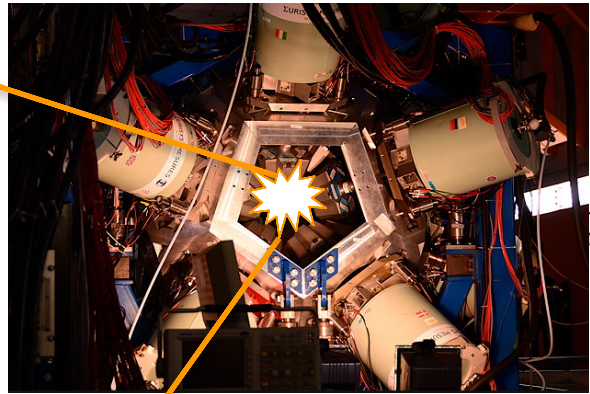
decay rates, masses, fission, b-delayed neutron
← → magic, deformation

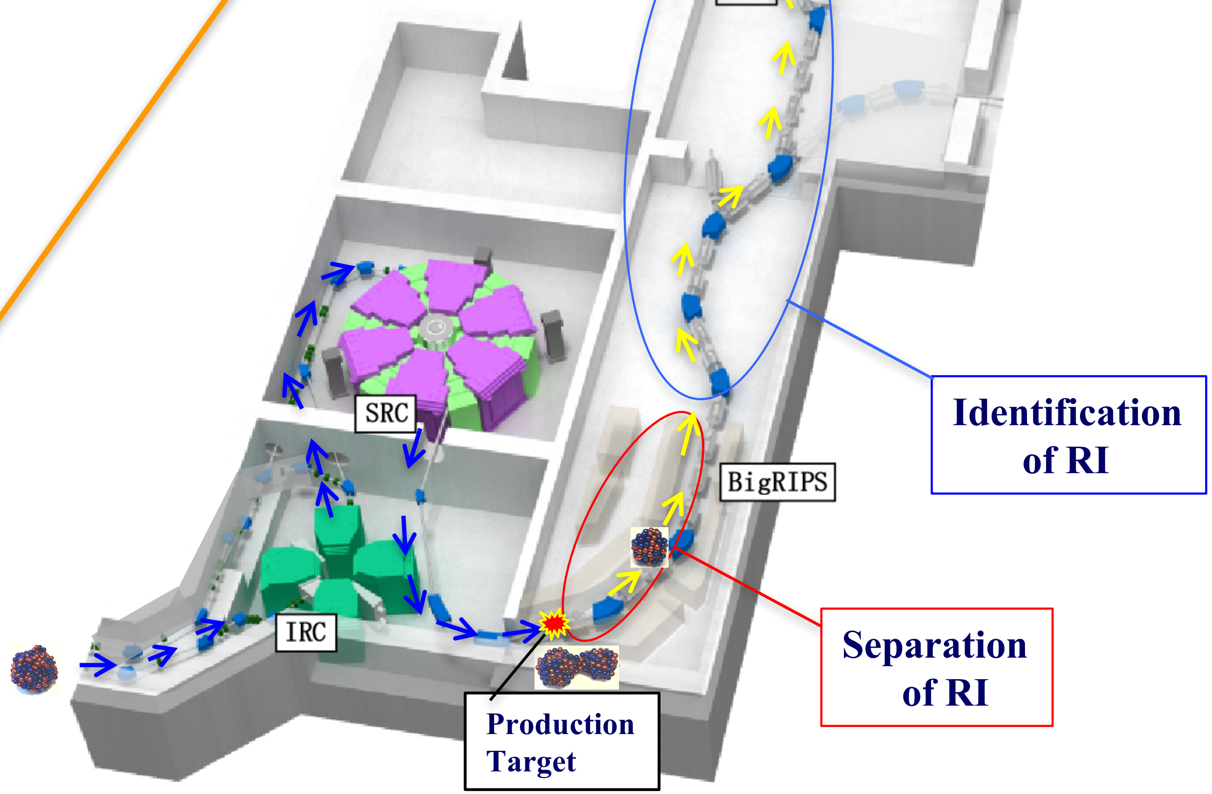
Decay Spectroscopy at RIBF

EURICA Spectrometer at RIBF

^{238}U … 345 MeV/u; int. 5 – 12 pnA (now 50 pnA)



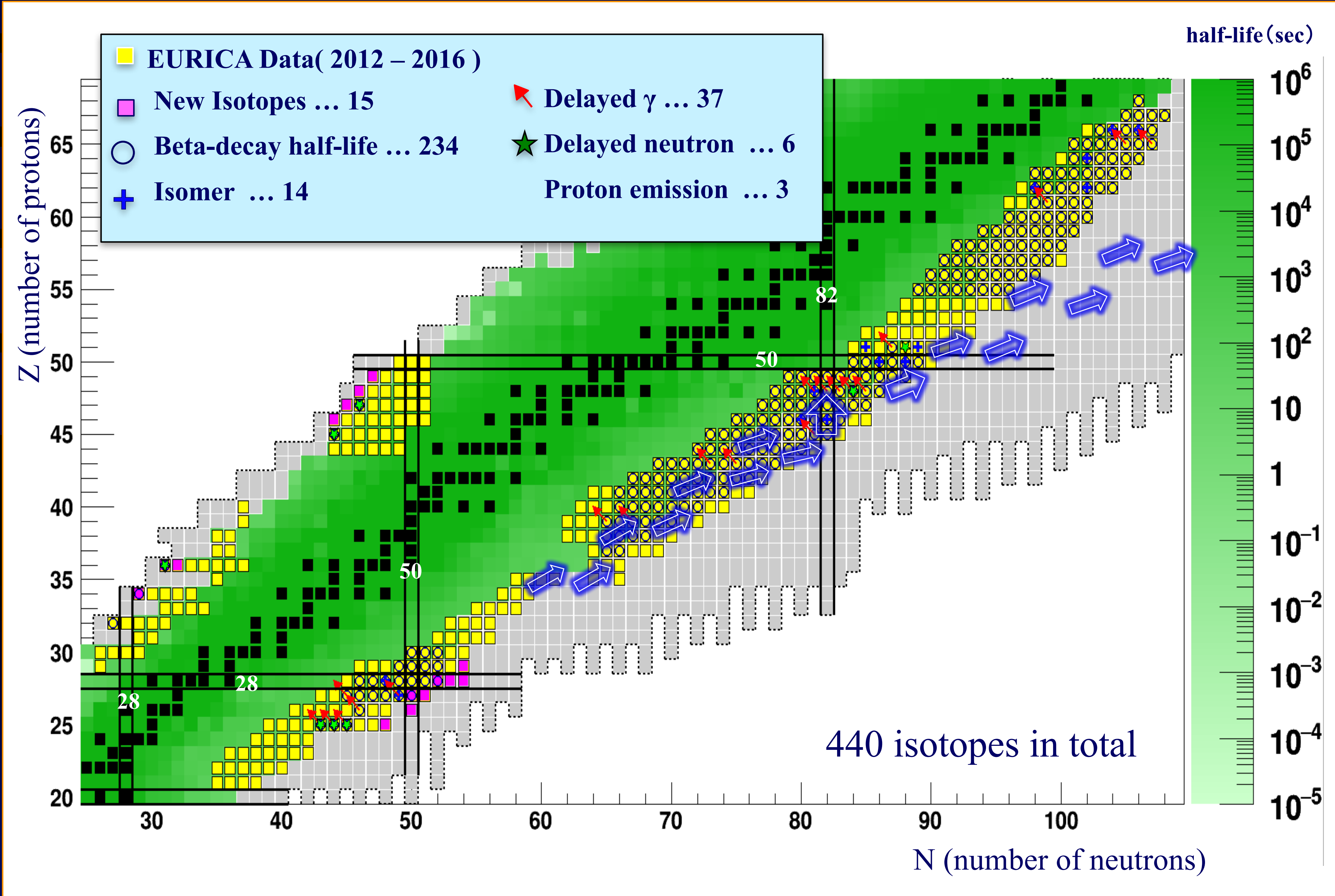




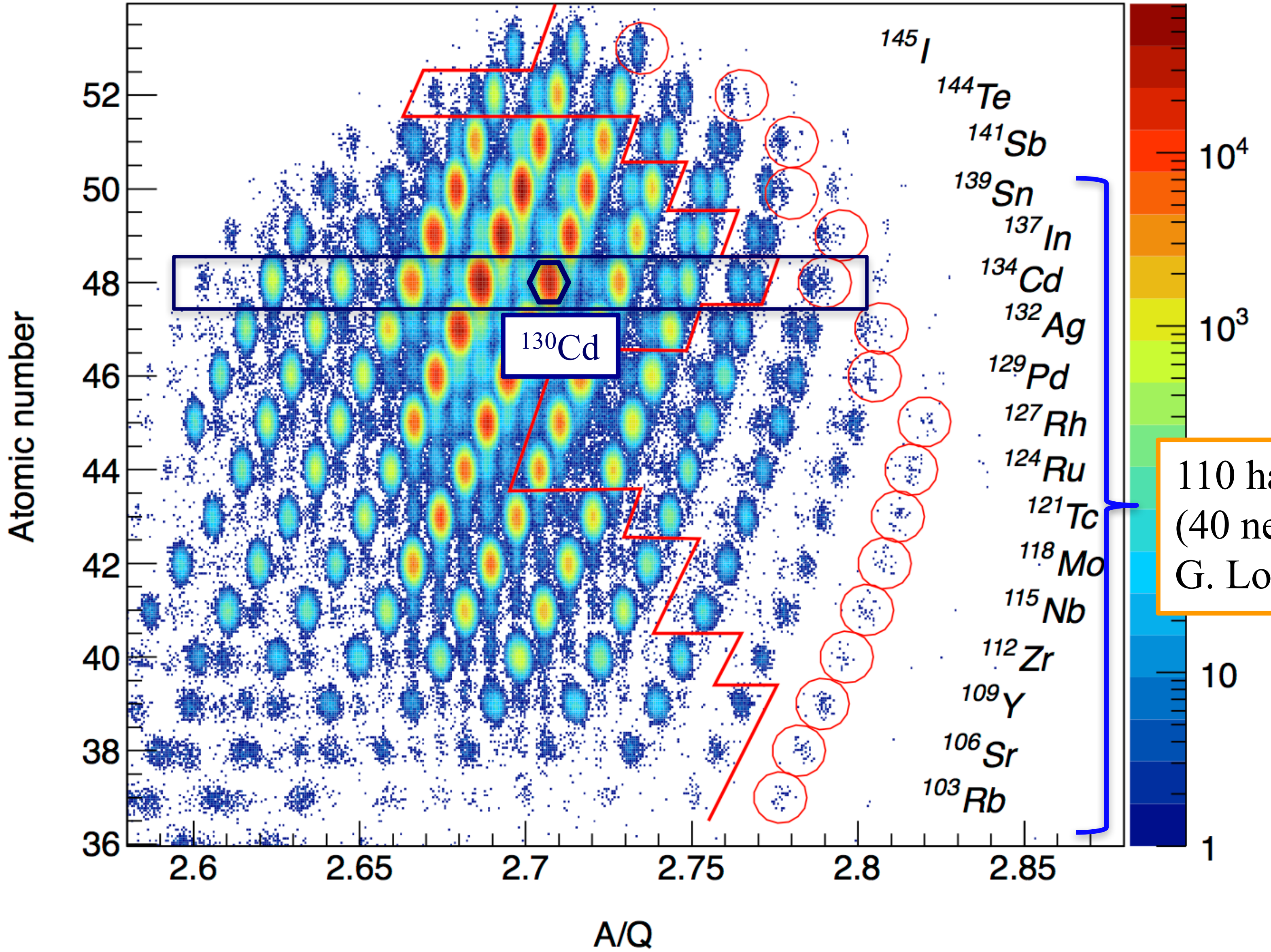
Primary Beam (^{238}U / ^{124}Xe / ^{78}Kr)

RI Beam

440 Exotic Isotopes Surveyed by EURICA Spectrometer

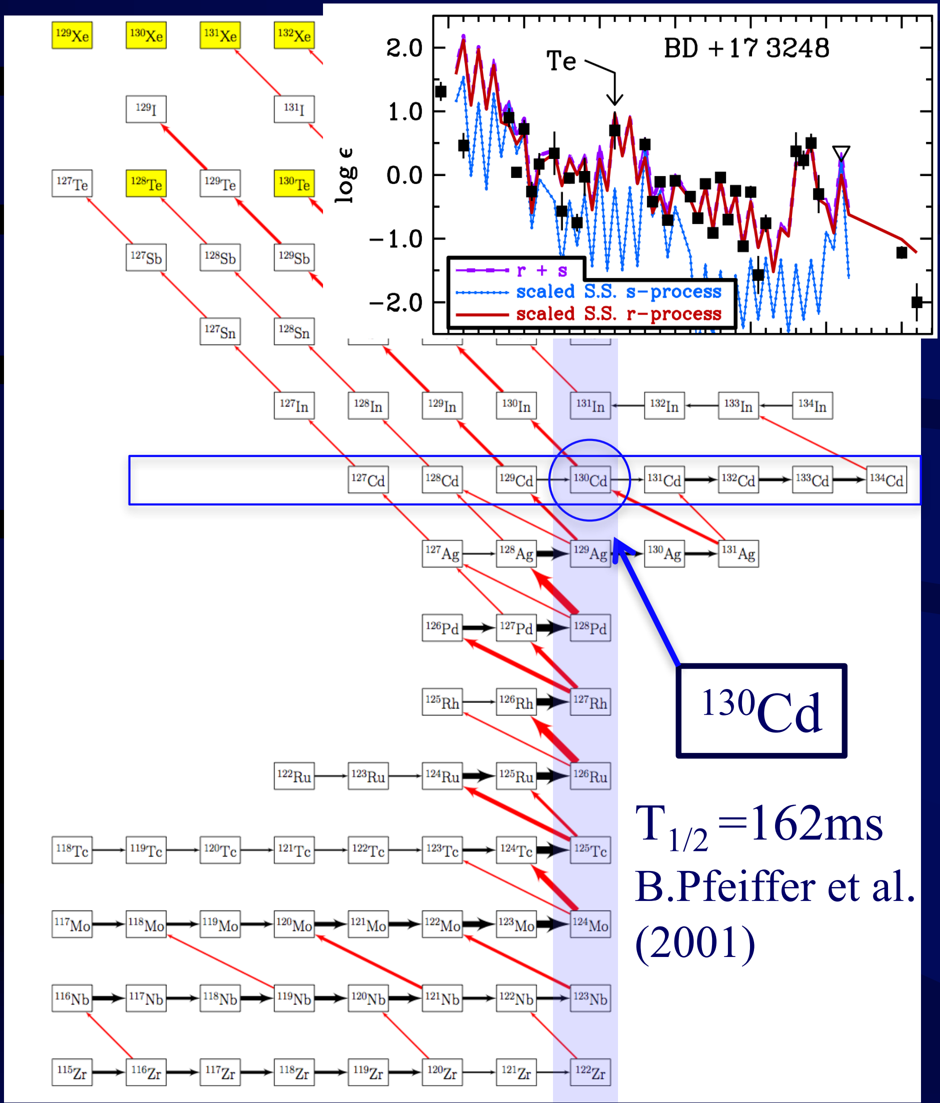


β-decay half-lives on r-process path

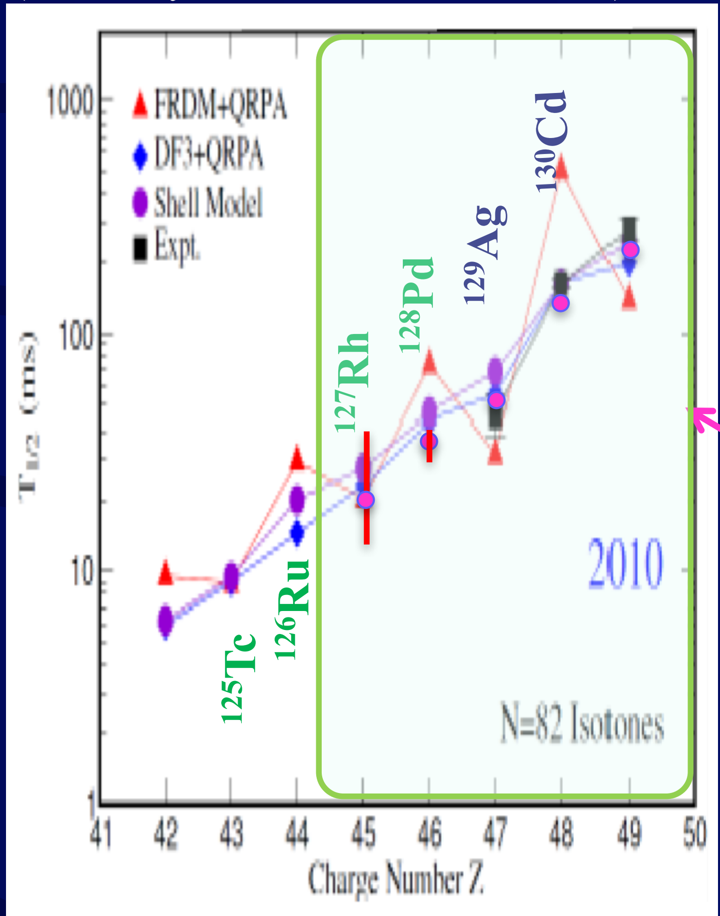


110 half-lives (40 new $T_{1/2}$)
G. Lorusso

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



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



RIBF EURICA

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

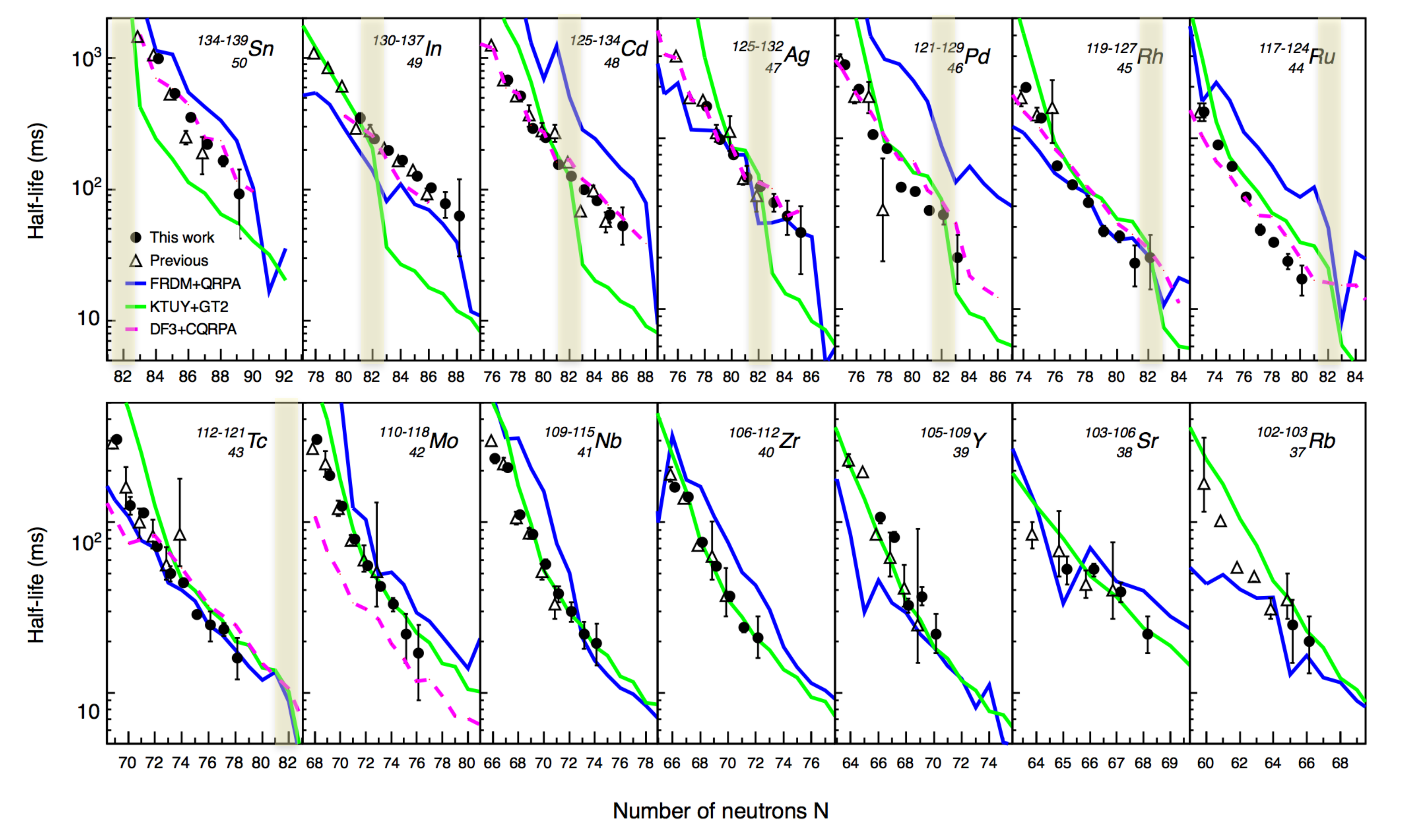
Shell model ← ~ 25% shorter $T_{1/2}$

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

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

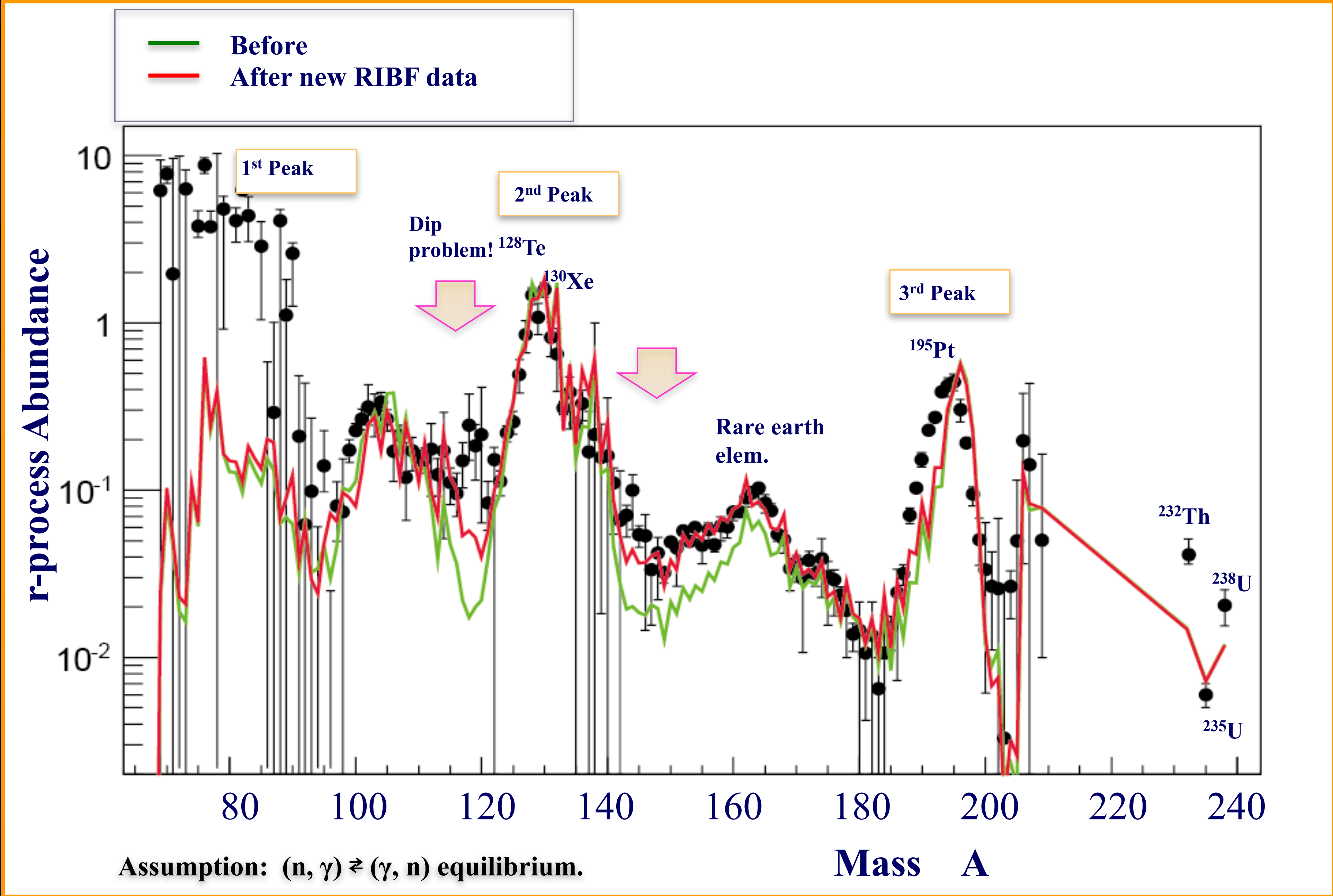
40 new half-lives ! G.Lorusso et al., PRL 114, 192501 (2015)

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

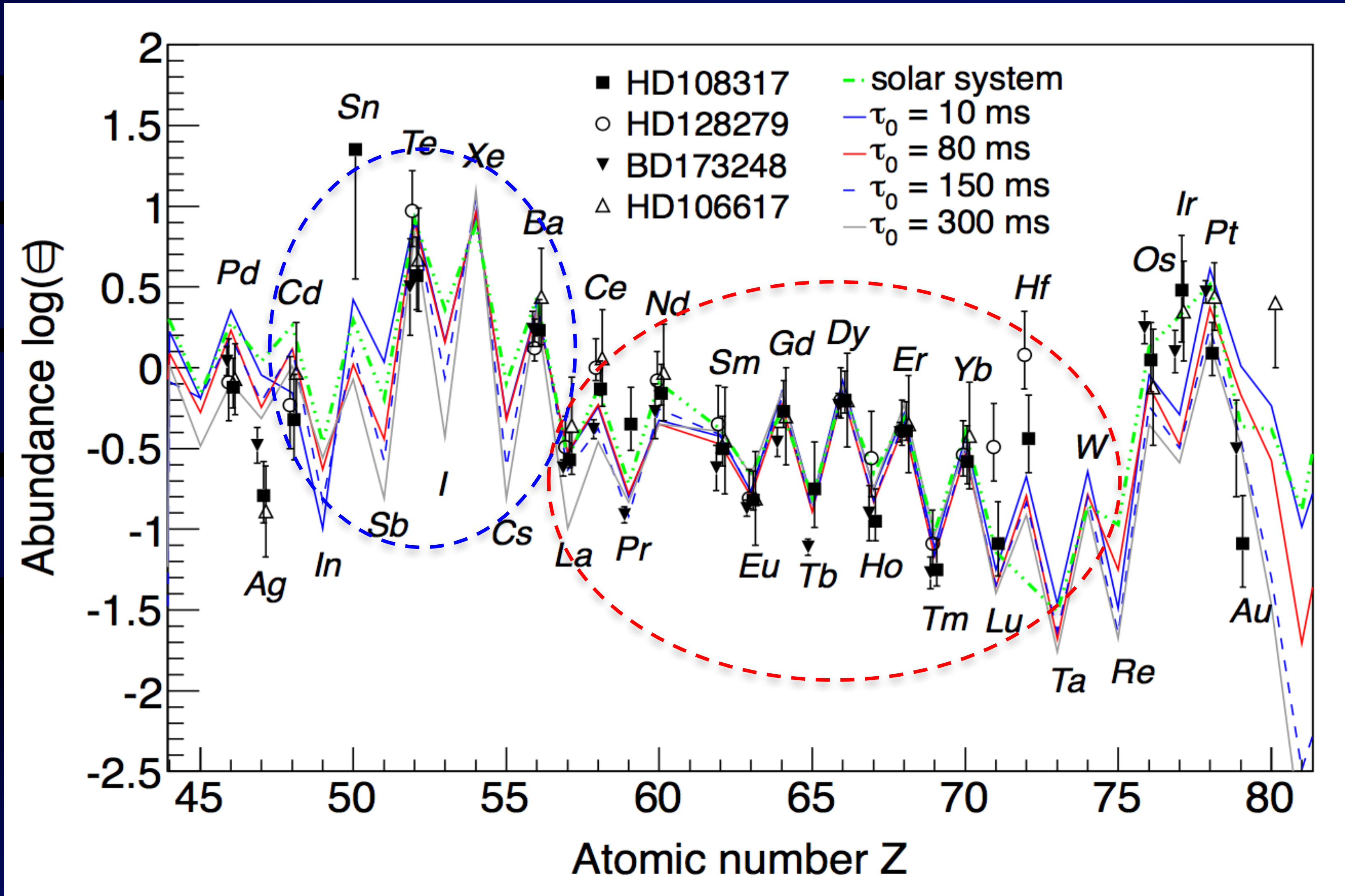


r-process Abundance with New $T_{1/2}$ (RIBF)

G.Lorusso et al., PRL (2015)



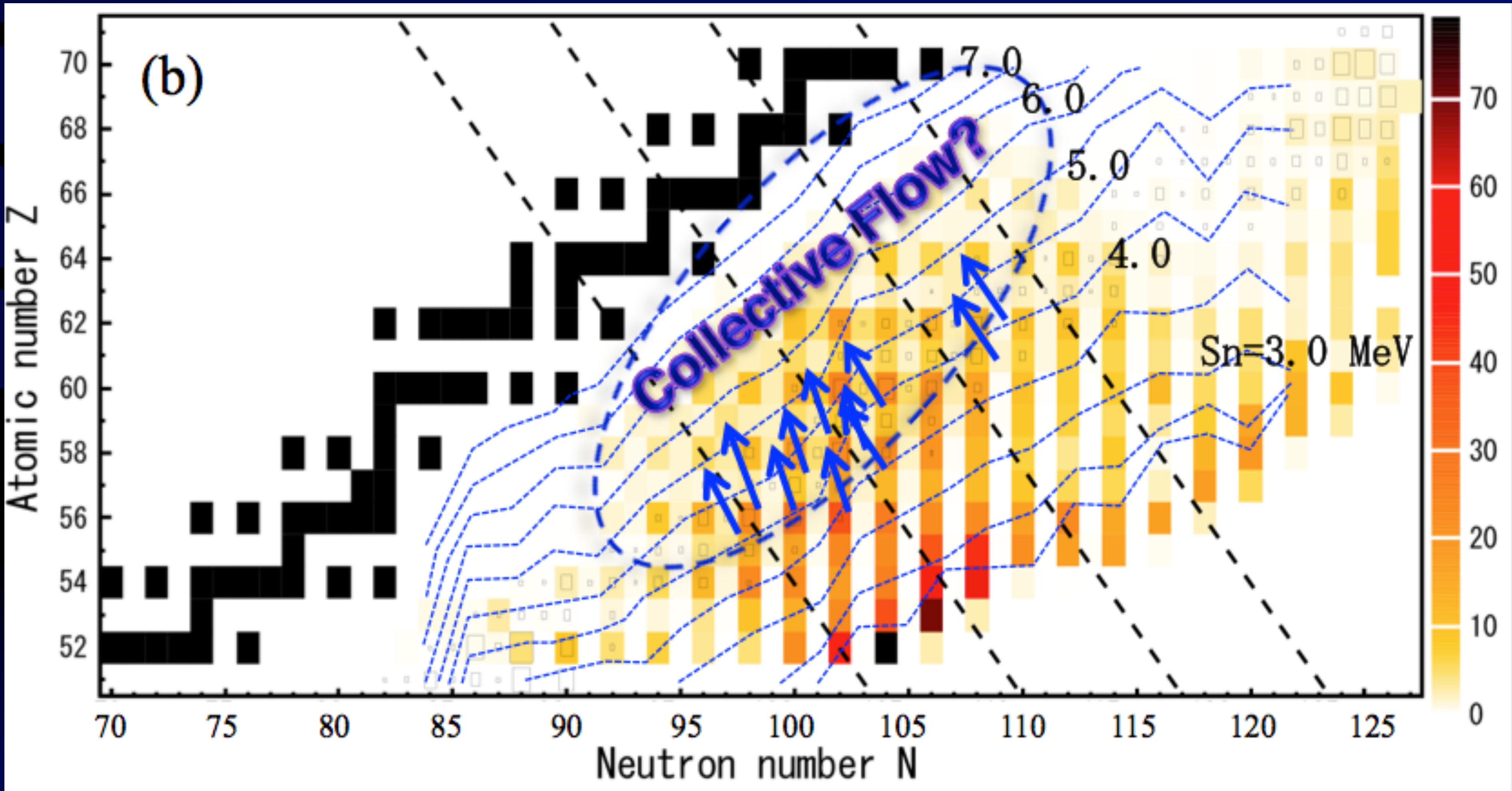
Universality of r-process elements (Z ≥ 56)



Decay Spectroscopy around mass A =160 was performed !

Rare-Earth Peak Formation at Freeze-Out Time

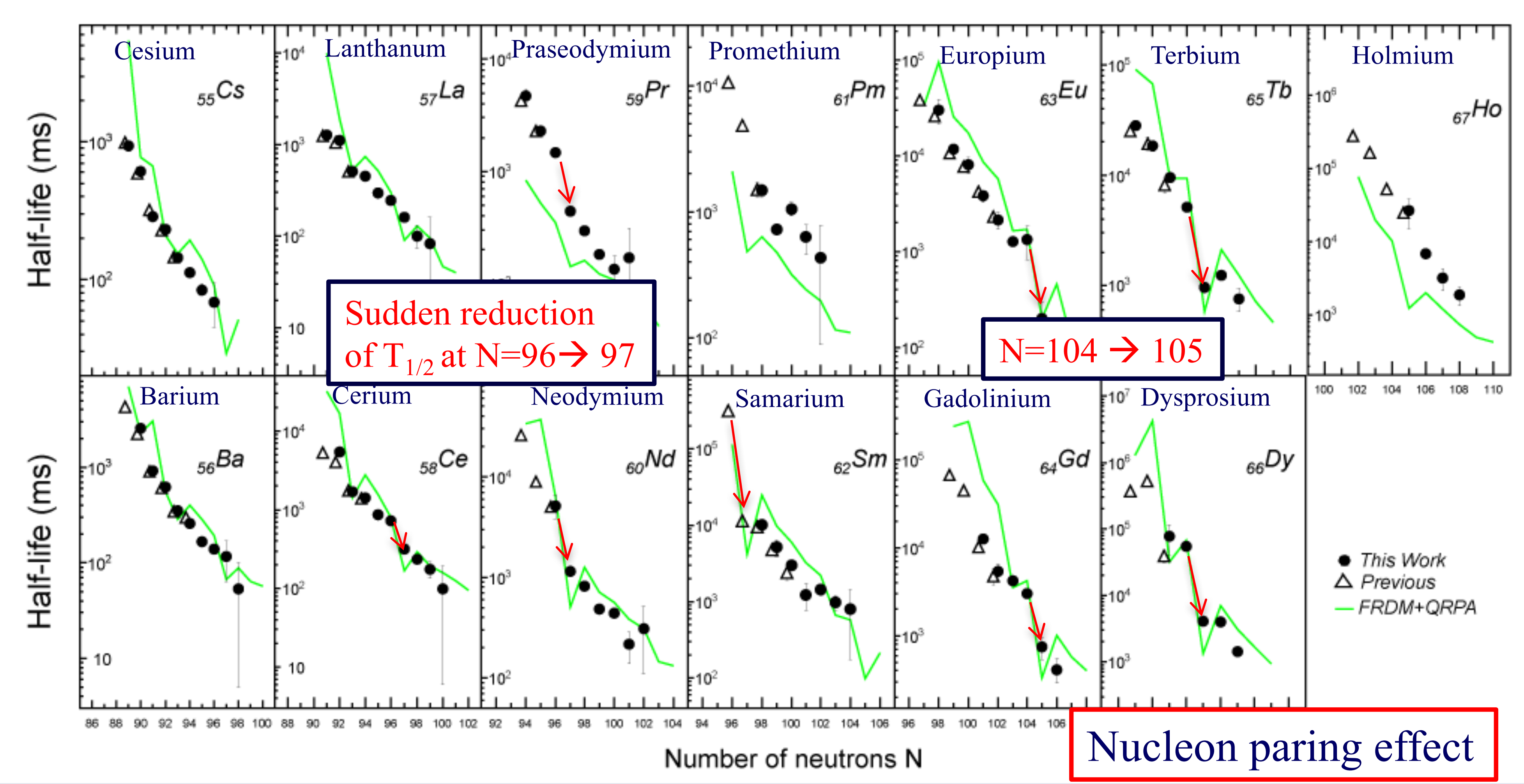
R. Surman et al. PRL 79 (1997)



Test r-Process calculation with new RIBF data

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

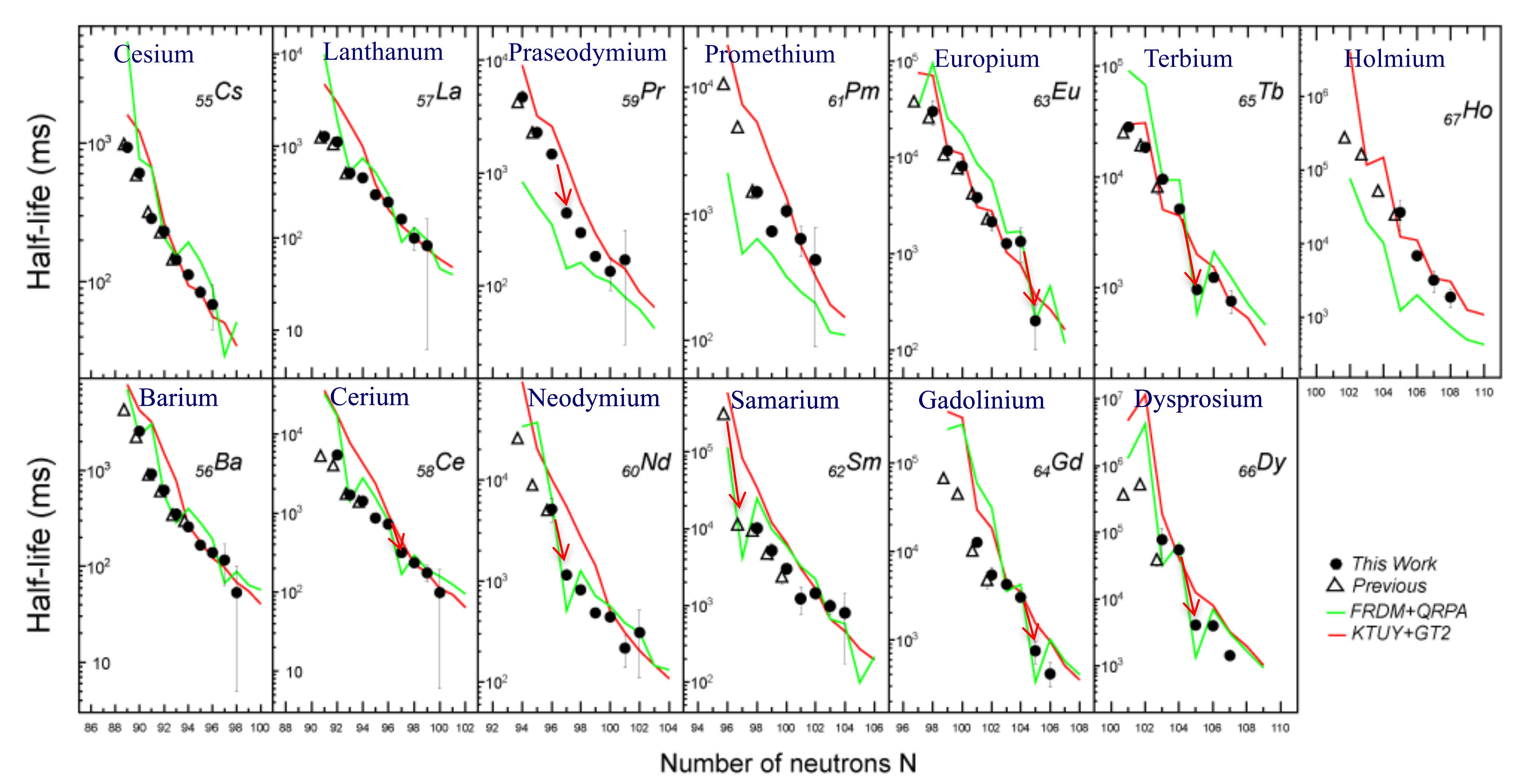
J. Wu, PRL (2017)



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).

92 β-Decay Half-lives (Mass A = 144 – 175) vs KTUY+GT2

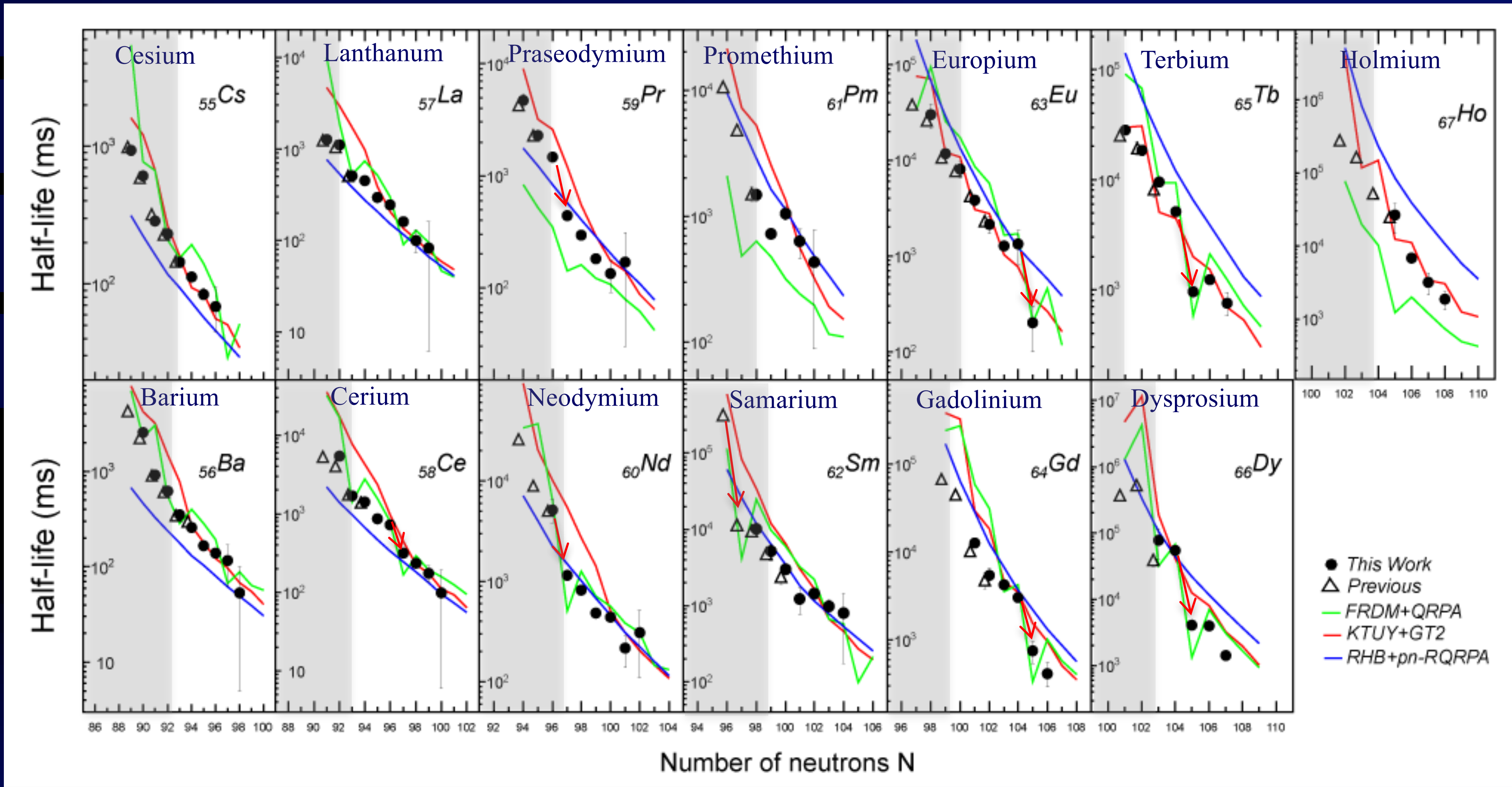
J. Wu, PRL (2017)



KTUY+GT2 shows systematic trends similar with exp. values in mid-shell. However, it can not reproduce even-odd effects.

92 β-Decay Half-lives (Mass A = 144 – 175)
vs RHB+pn-RQRPA

J. Wu, PRL (2017)

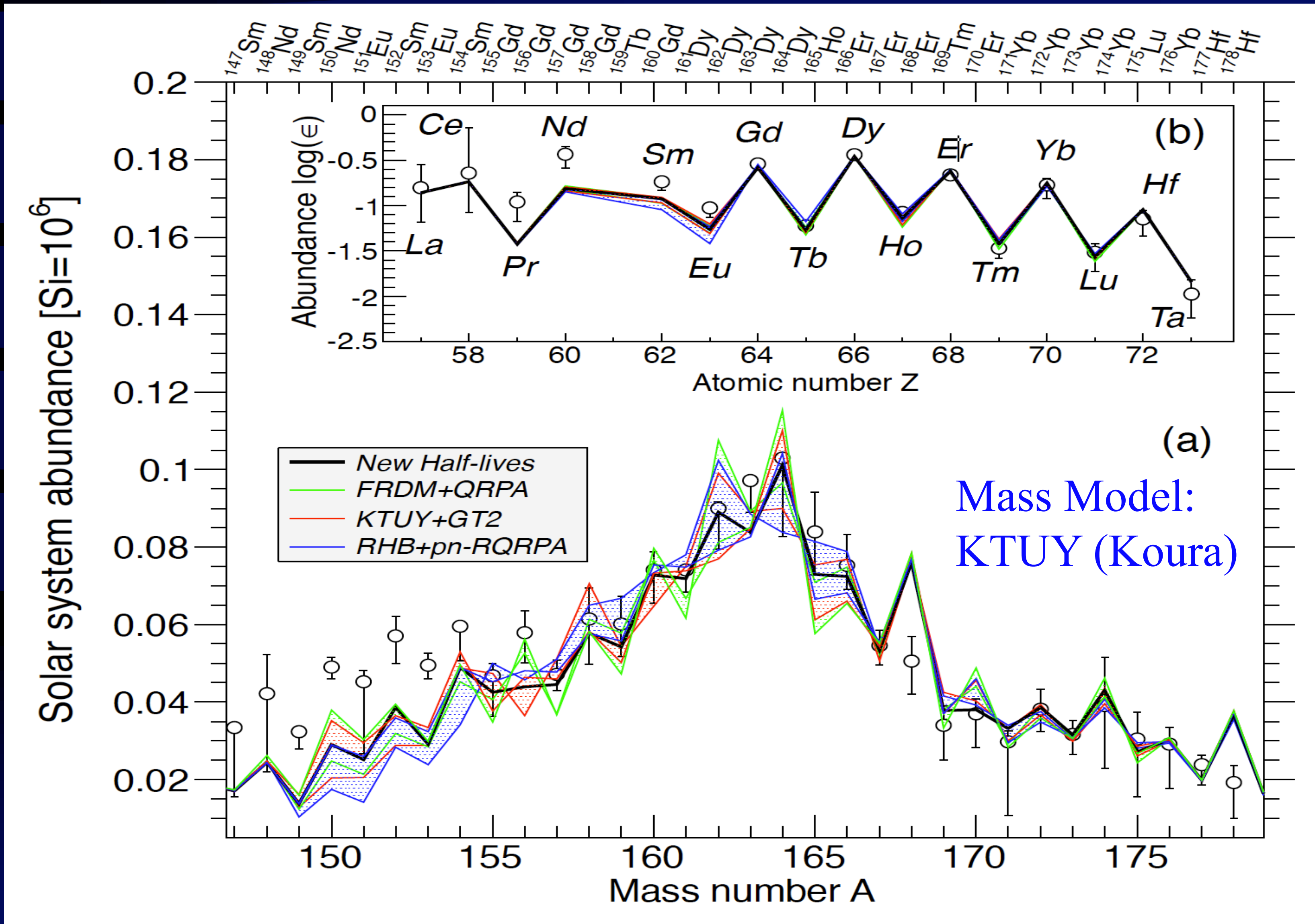


RHB+pn-RQRPA underestimates the T1/2 for Z=55-56 (Cs, Ba) and overestimates the $T_{1/2}$ for Z =63-67 (Eu, Gd, Tb, Dy, Ho).
No reproduce of even-odd effects.

r-Process Elemental Abundance (A = 150-179)

Uncertainty of β-decay half-lives → r-Process Rare-Earth Peak

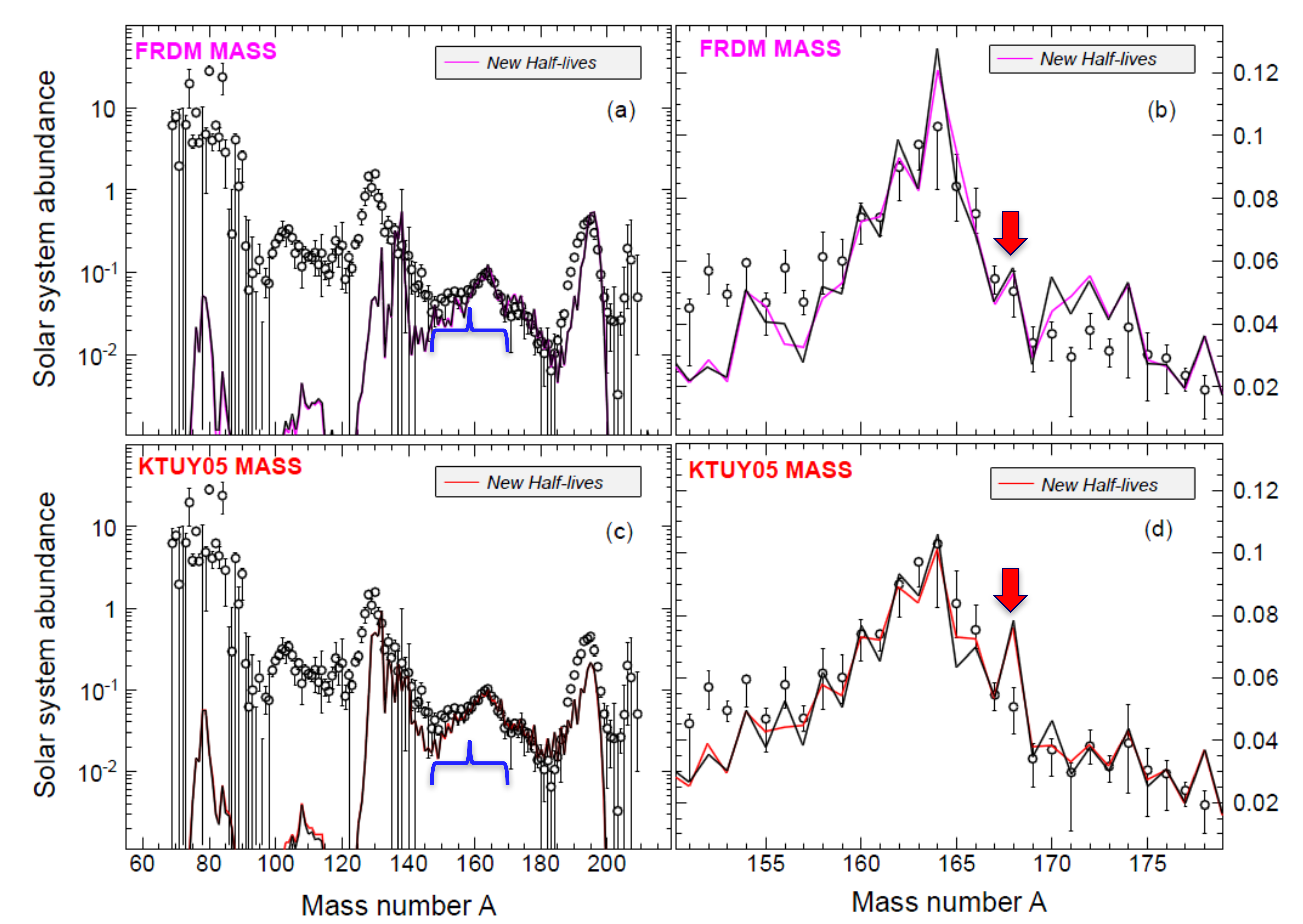
J. Wu et al. PRL (2017)



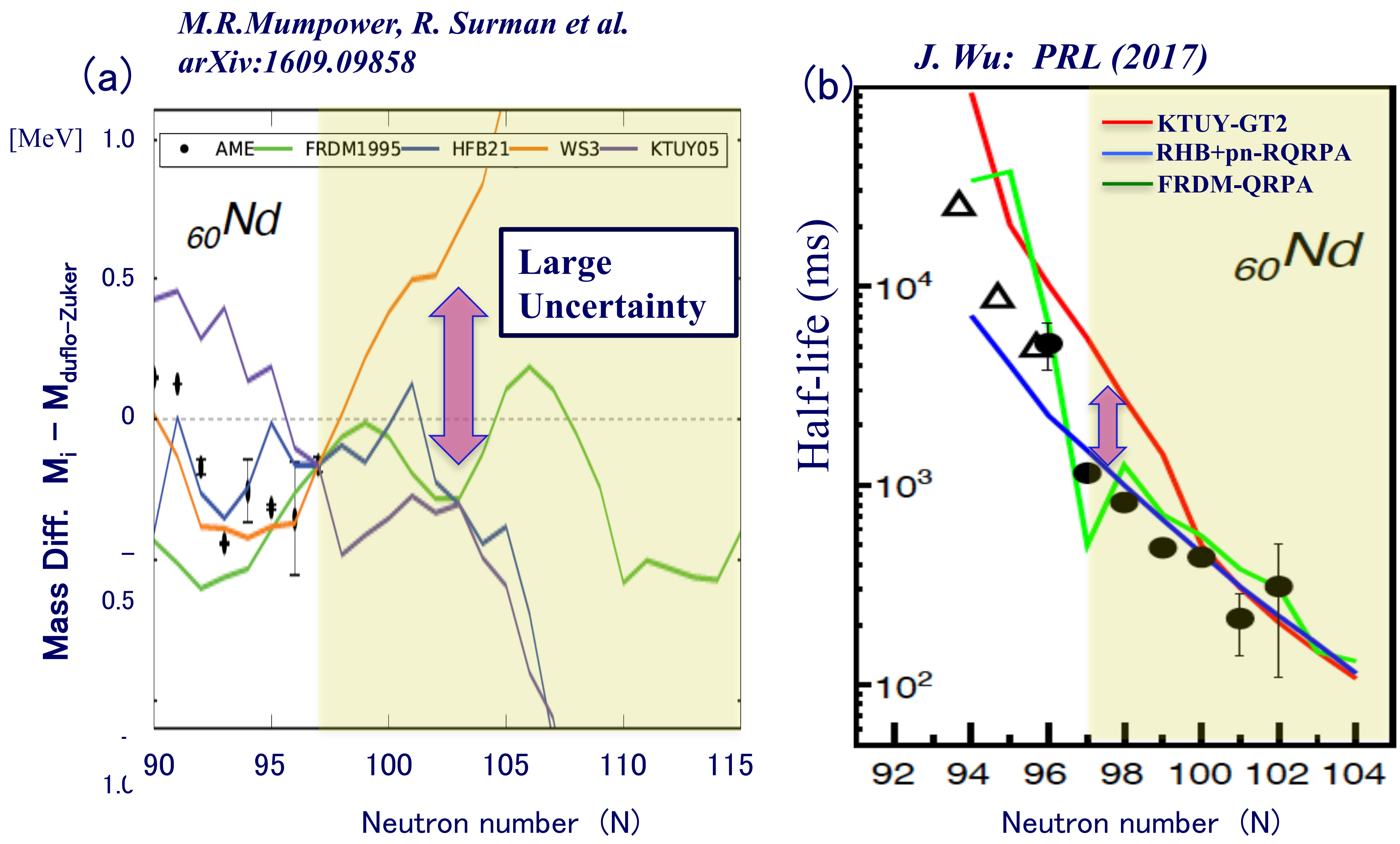
Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation

Rare-Earth Peak with Different Mass Models

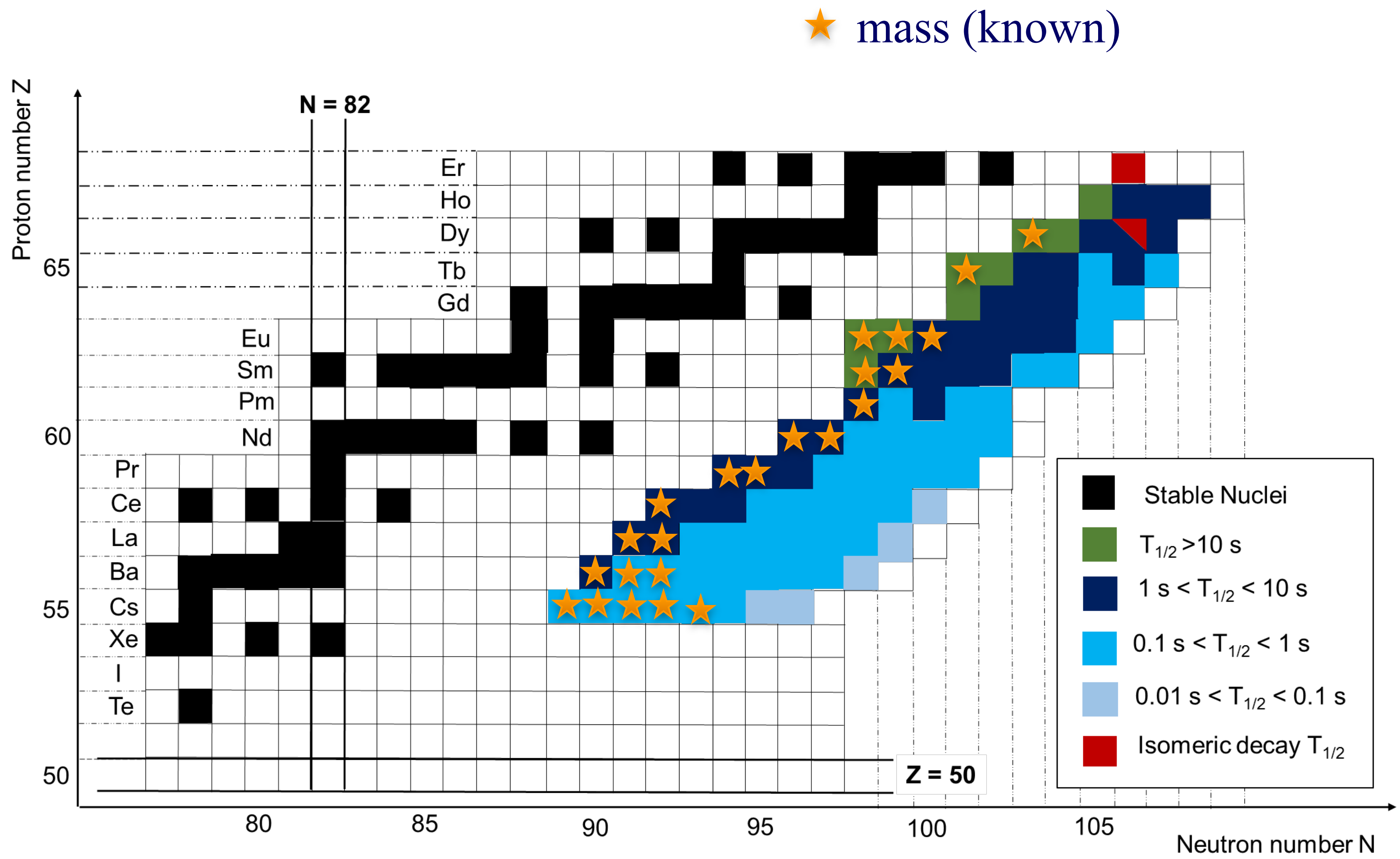
J. Wu



Mass & beta-decay half-lives

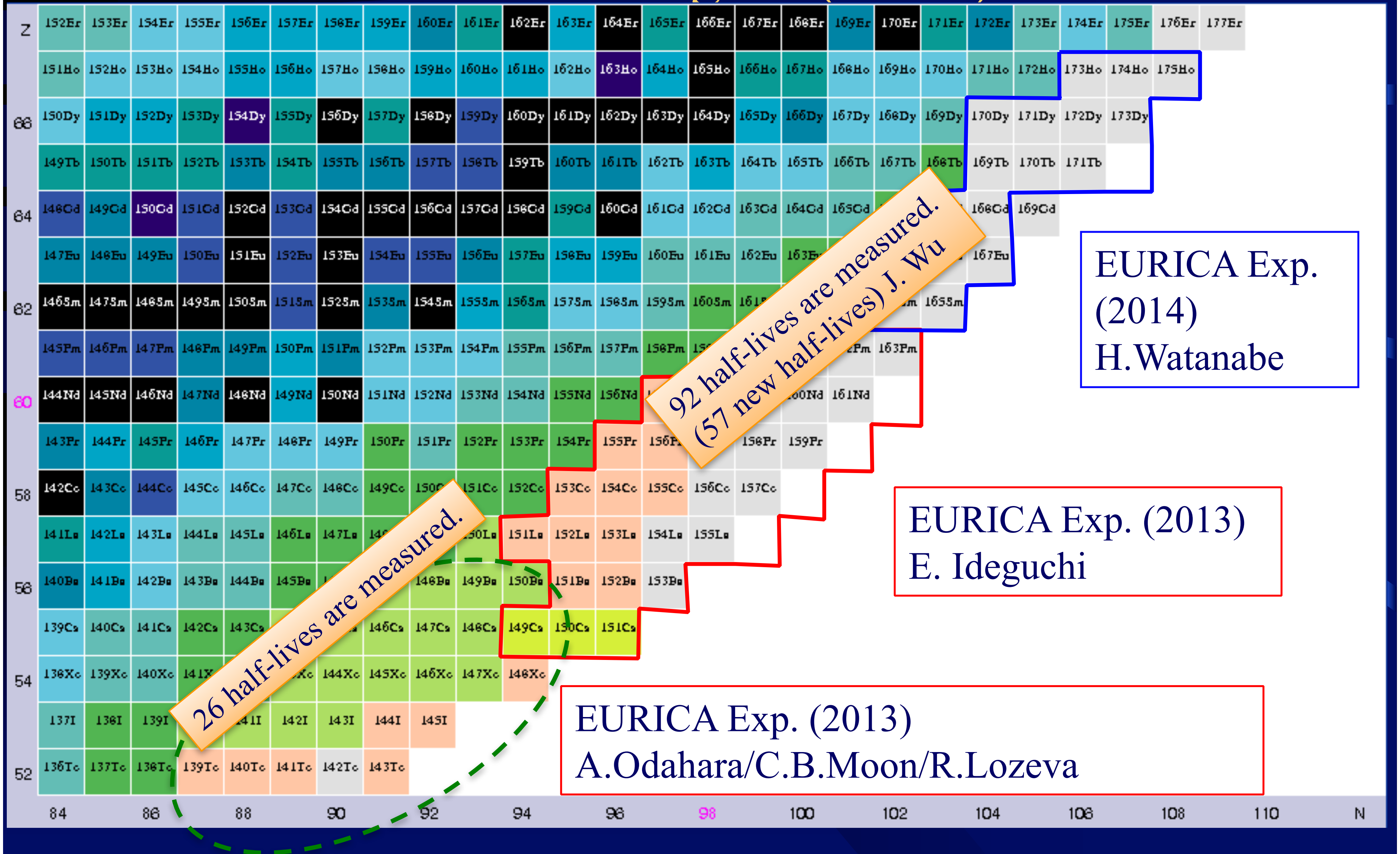


Half-lives and Mass Measurement



Half-lives

Heavier region (Z>50)



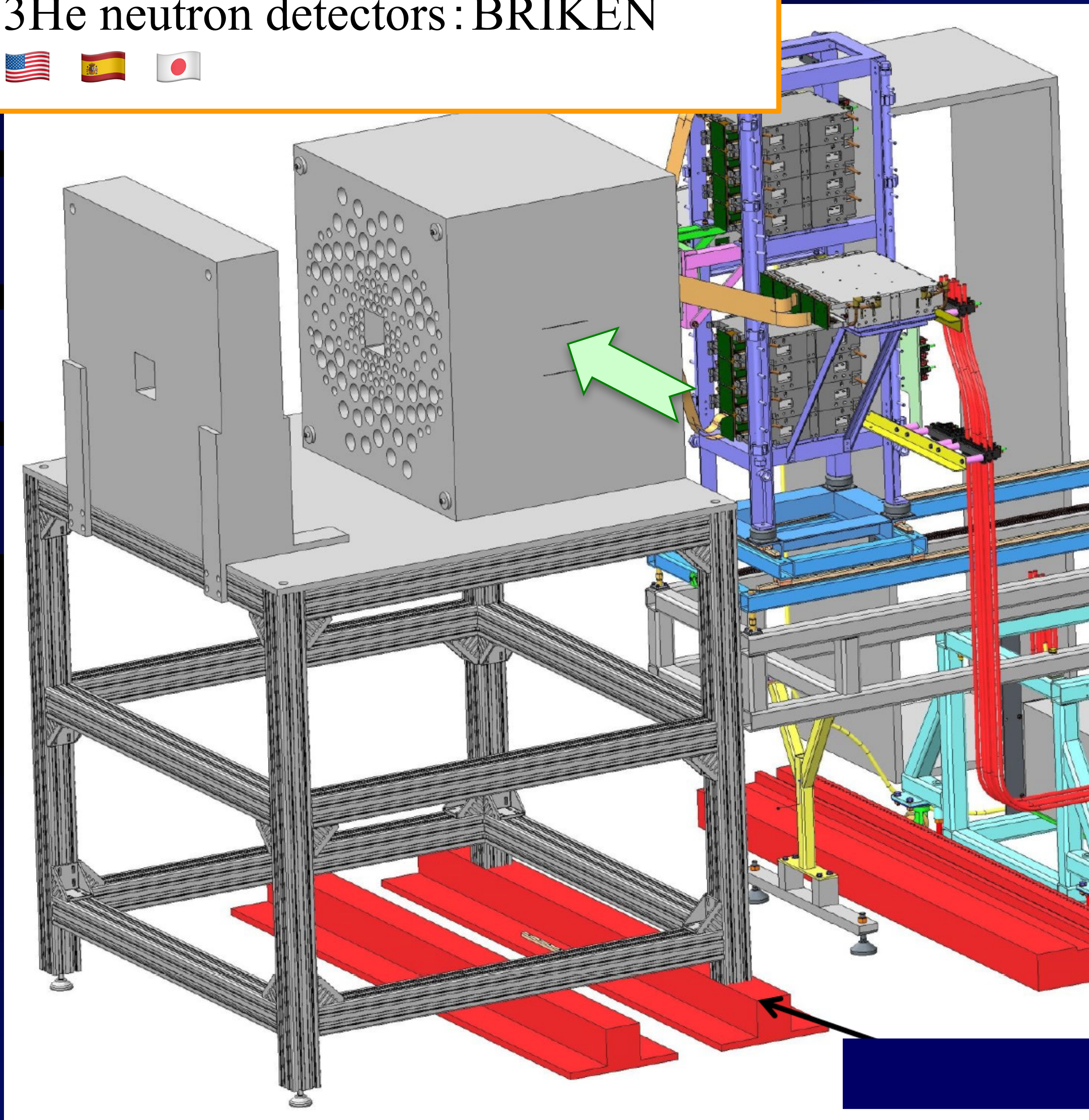
From Now:
beta-delayed neutron emission probabilities Pn

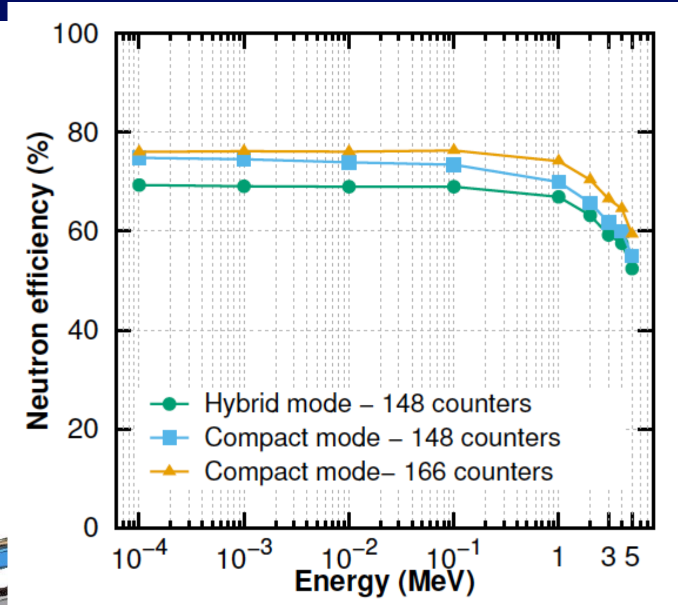
BRIKEN (2017 ~)

BRIKEN Setup

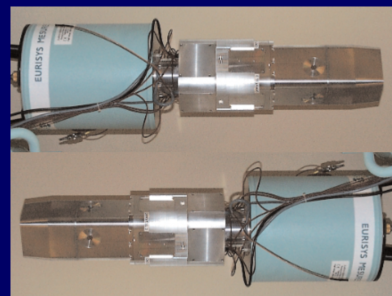
beta counting system: AIDA
←→ WAS3ABi

3He neutron detectors : BRIKEN



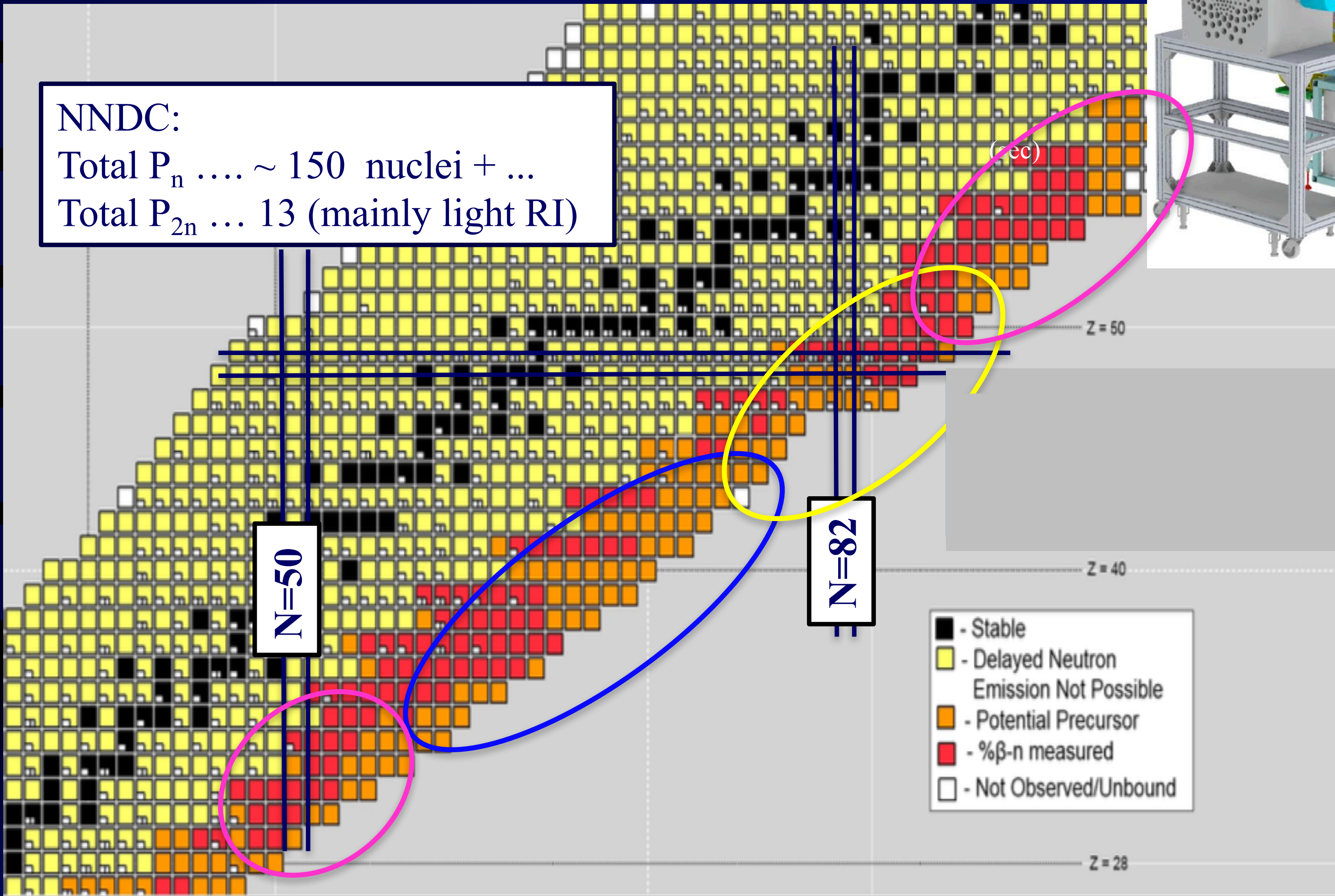


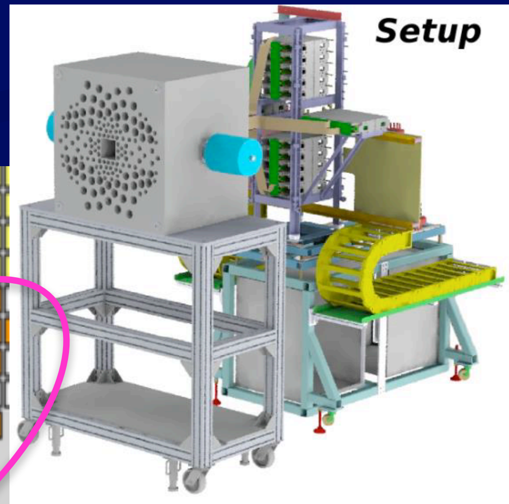
γ-ray:
Two clover Ge detectors



BRIKEN Project (2016 ~)

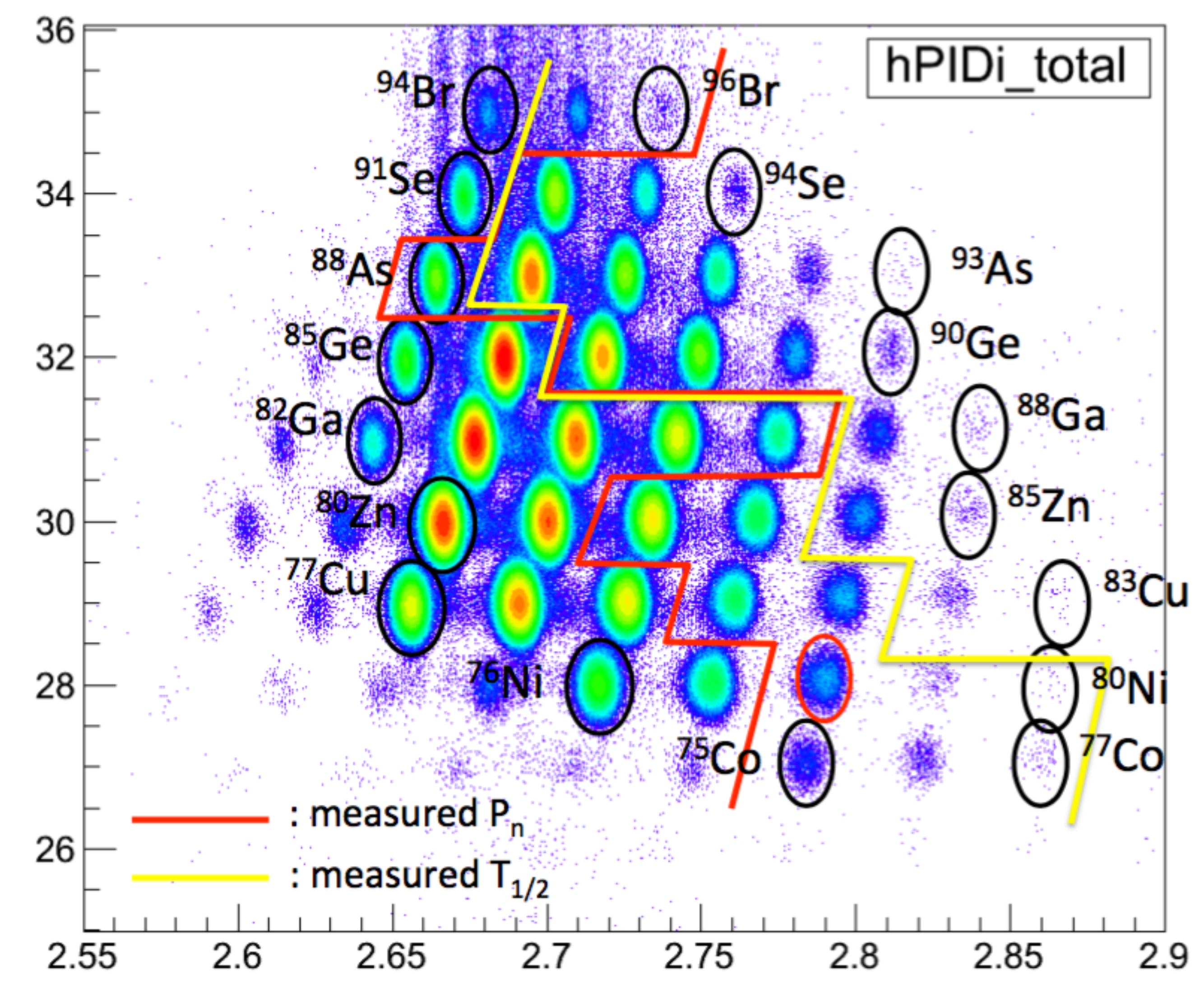
NNDC:
Total P_n …. ~ 150 nuclei + …
Total P_{2n} … 13 (mainly light RI)

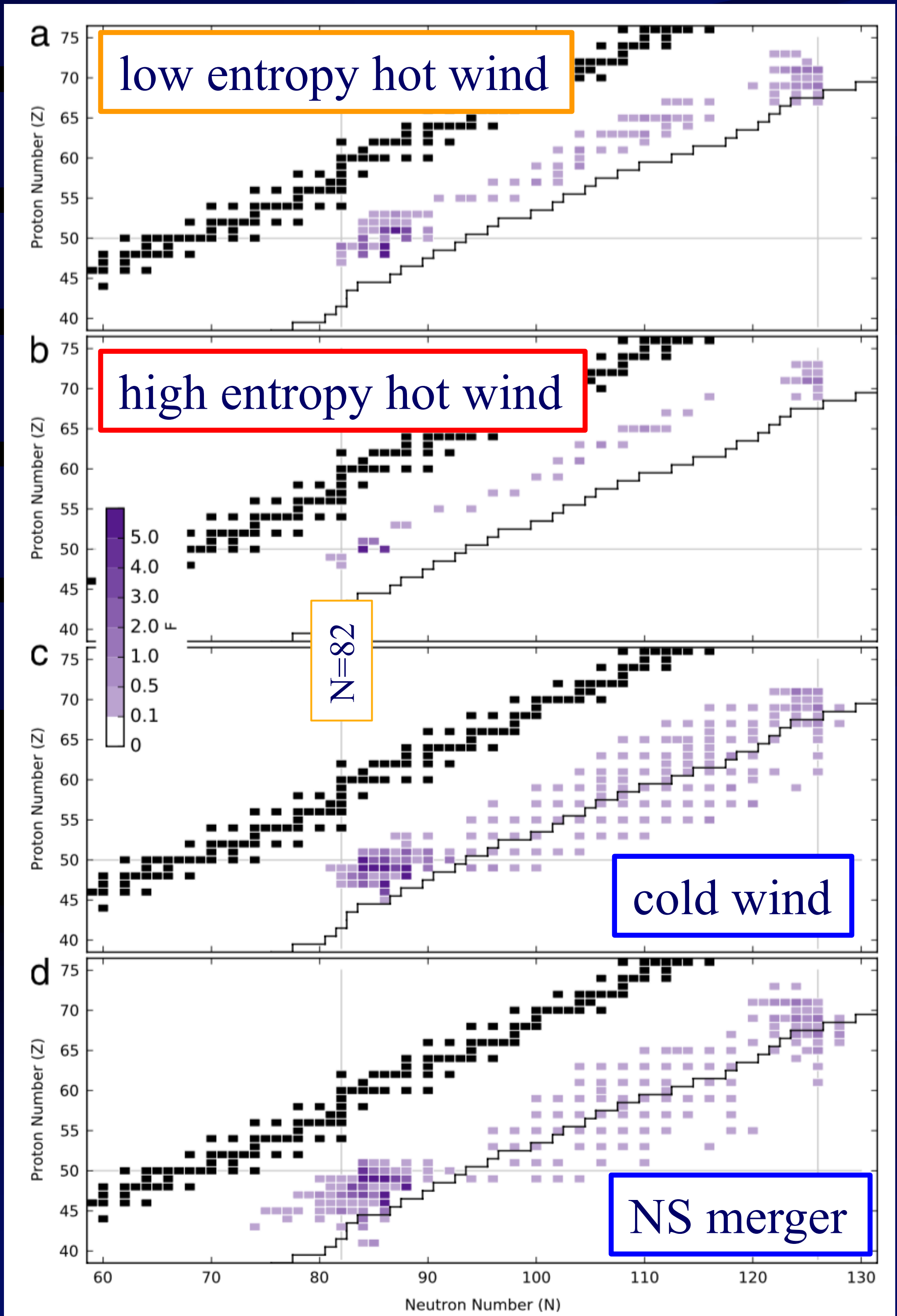




Several hundreads of beta-delayed neutron emission P_n (n) together with $T_{1/2}$ (β) & level scheme (γ)

BRIKEN: β-delayed neutron emissions



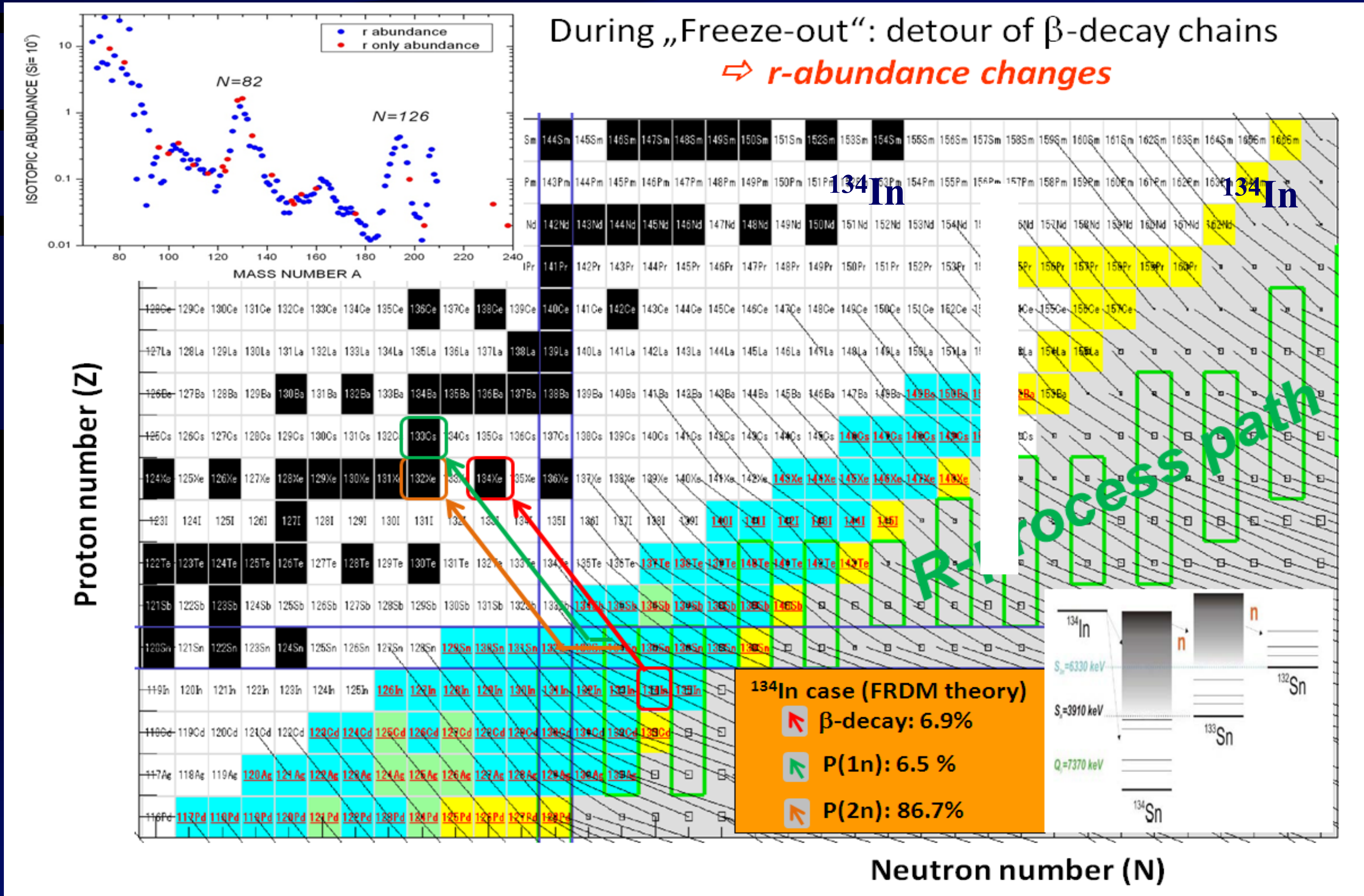


Pn values: How Sensitive in r-Process Calc.?

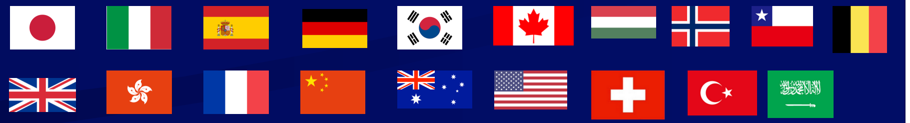
beta-delayed neutron emitters

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

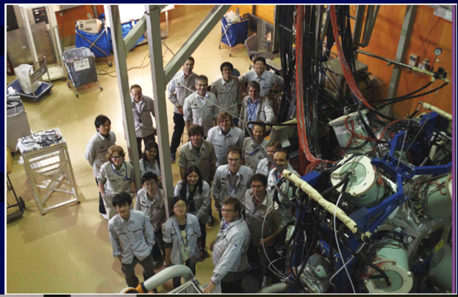
r-Process Elements : Freeze-out Time



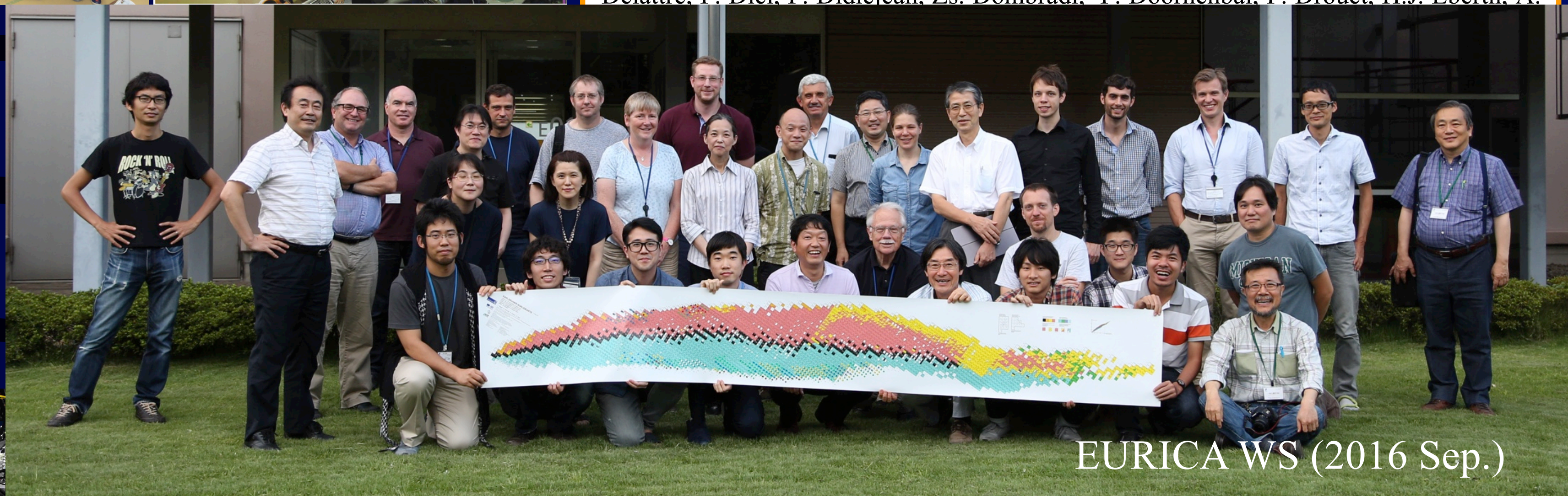
EURICA Collaboration



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. Didierjean, Zs. Dombradi, P. Doornenbal, F. Drouet, H.J. Eberth, A.



EURICA WS (2016 Sep.)

D.R. Napoli, F. Naqvi, M. Niikura, H. Nishibata, S. Nishimura, T. Nishizuka, C. Nita, F. Nowacki, A. Odahara, K. Ogawa, H. Oikawa, R. Orlandi, S. Ota, T. Otsuka, H.J. Ong, S. Orrigo, M. 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

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PreSPEC, GSI, IBS-RISP

Acknowledgement: Gammapool, Preepc, IBS

BRIKEN Collaboration

Summary & Future