Hirschegg 2017 Jan. 18
Neutron star mergers: From gravitational waves to nucleosynthesis

Experimental beta-decay rates of r-process nuclei

Shunji NISHIMURA
RIKEN Nishina Center

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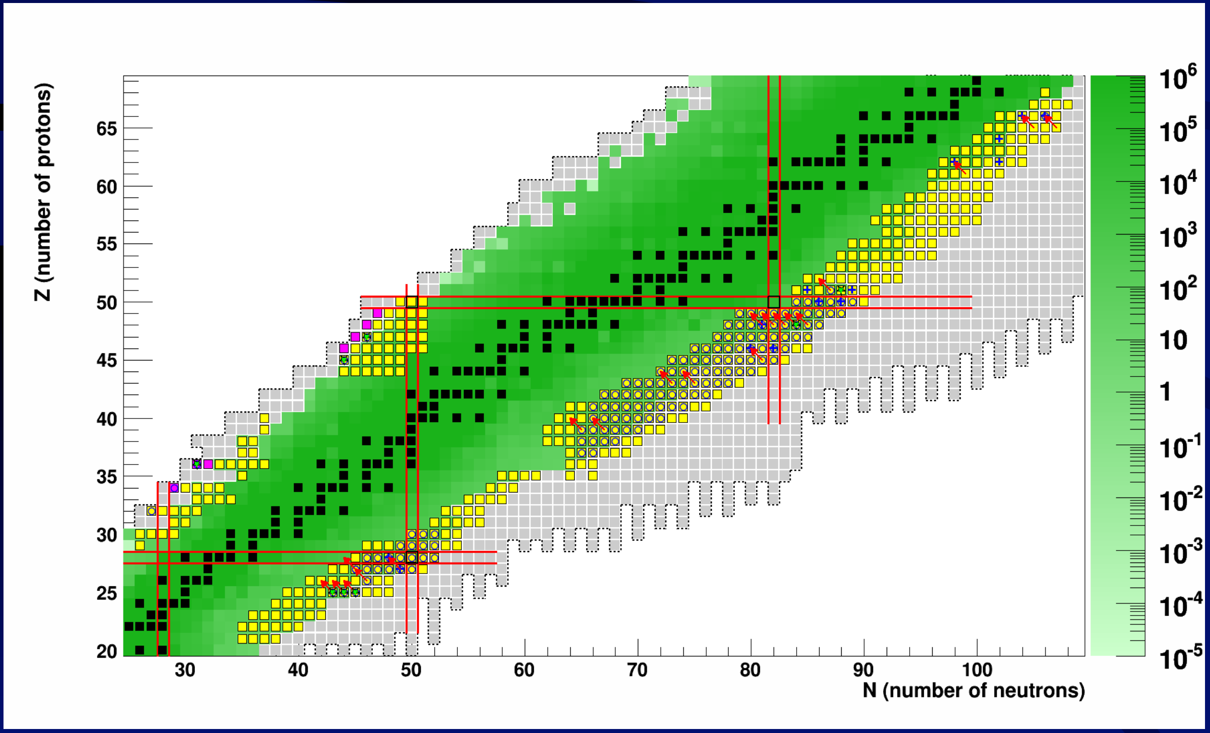


- **171 $T_{1/2}$ (66 new half-lives !)**
- **118 $T_{1/2}$ (70 new half-lives !)**

Impact on formation of rare-earth peak at freeze-out time

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

NASA/JPL-Caltech/O.Krause
(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

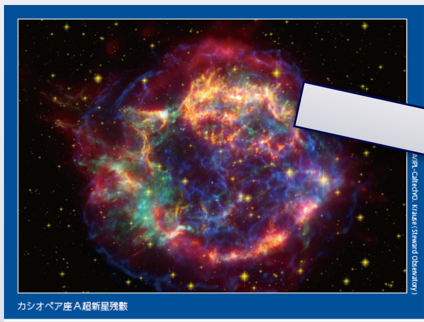
r-process conditions:
Y_e, S, τ, EOS, …

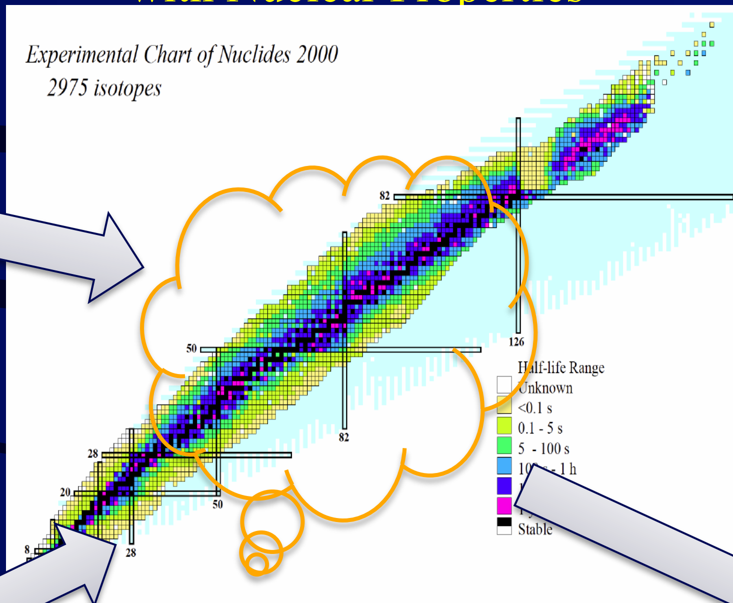
Network calculation
with Nuclear Properties

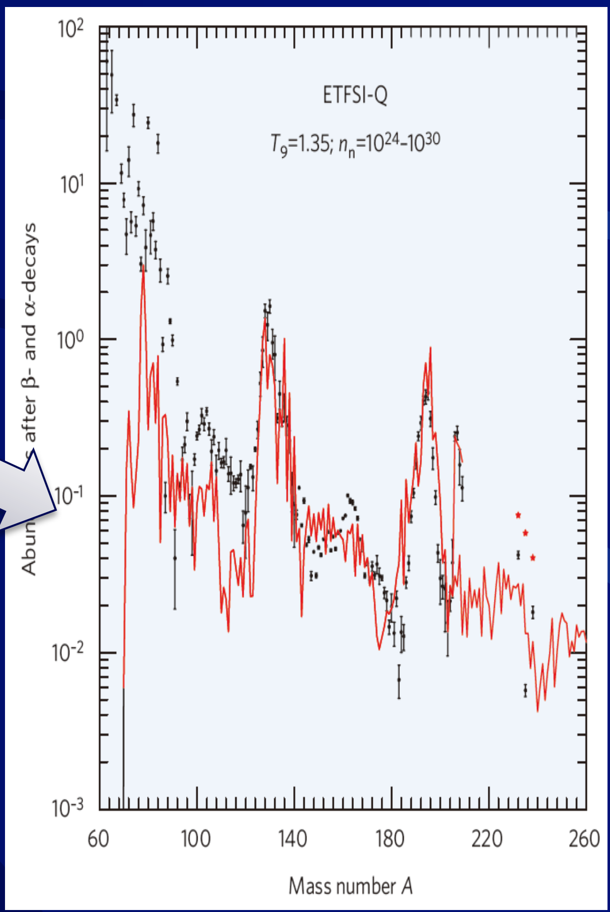
r-process abundance Z, A

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

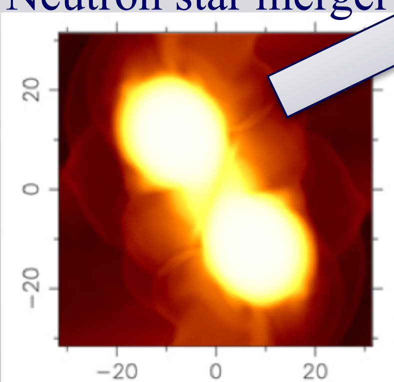
Supernovae explosion?







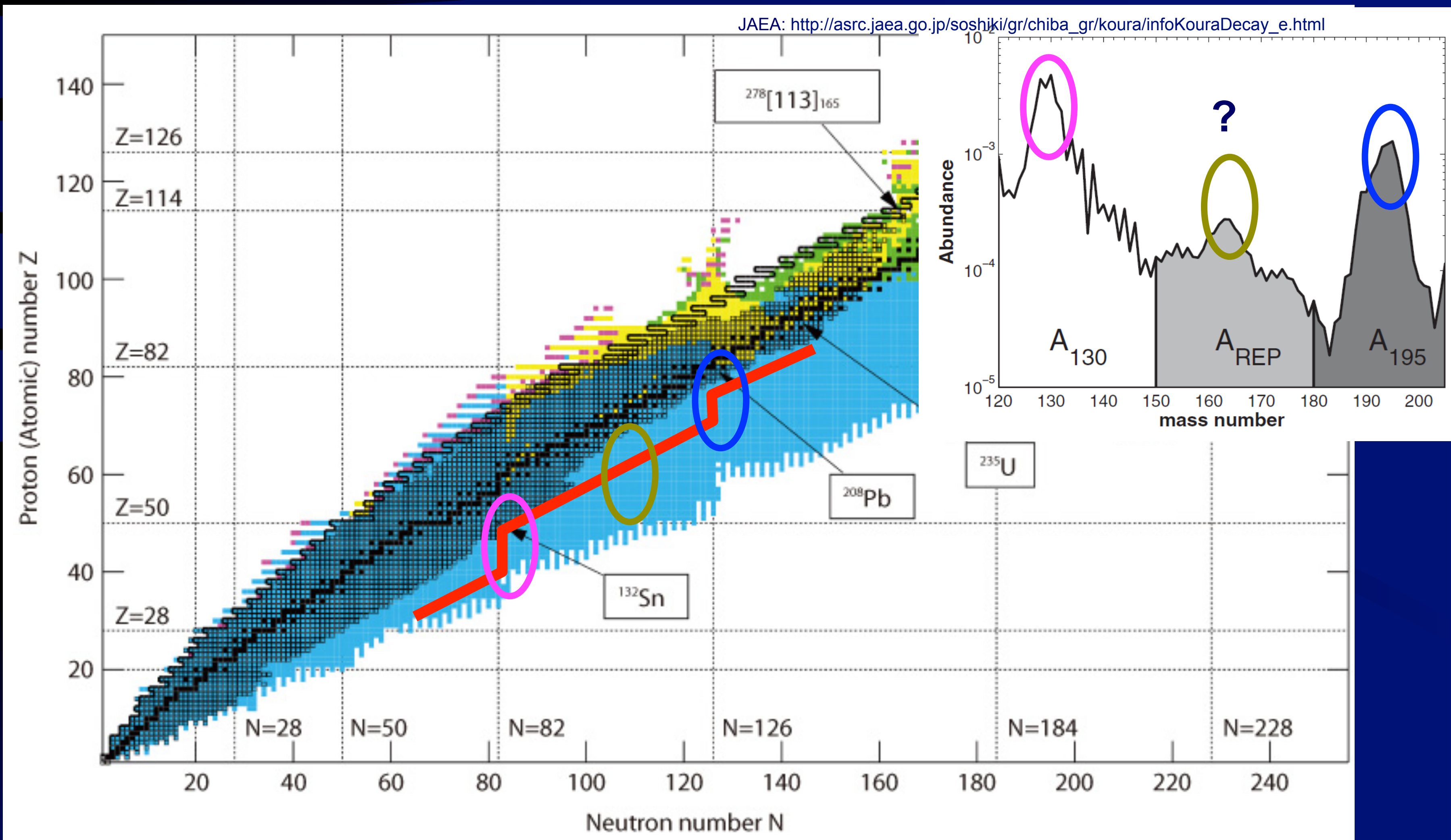
Neutron star merger?



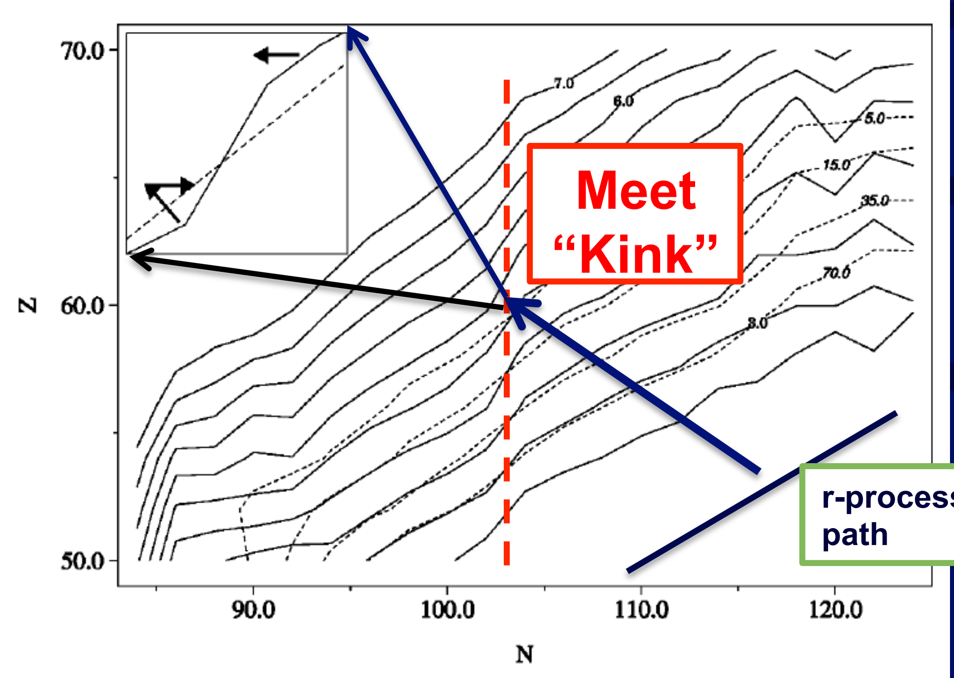
S. Wanajo

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

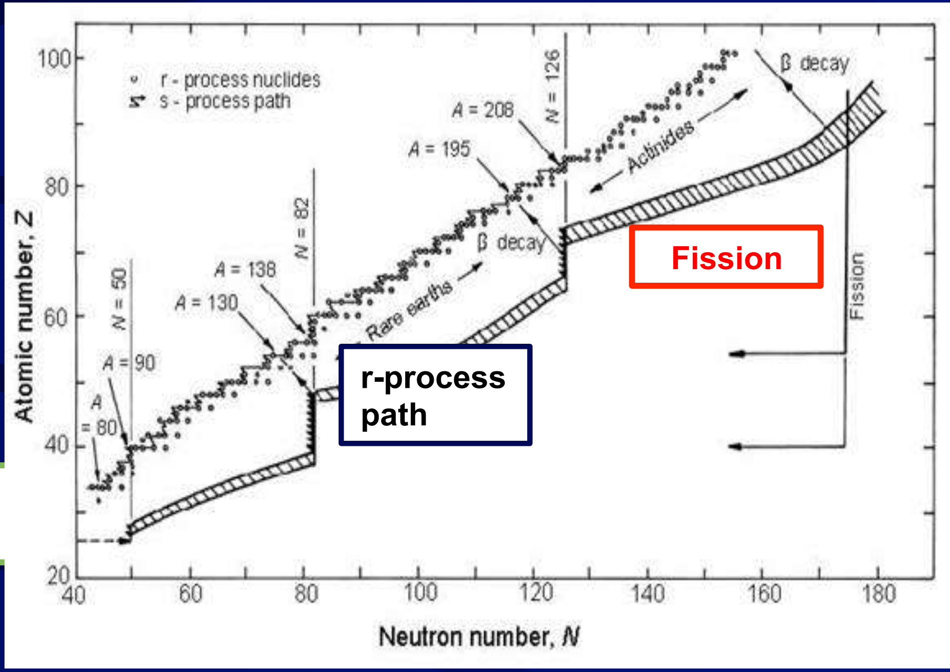
Introduction: Rapid neutron-capture (r-) process and the Rare-Earth Element (REE) peak



Introduction: The formation mechanism of rare-earth peak



R. Surman et al, PRL 79, 10 (1997)



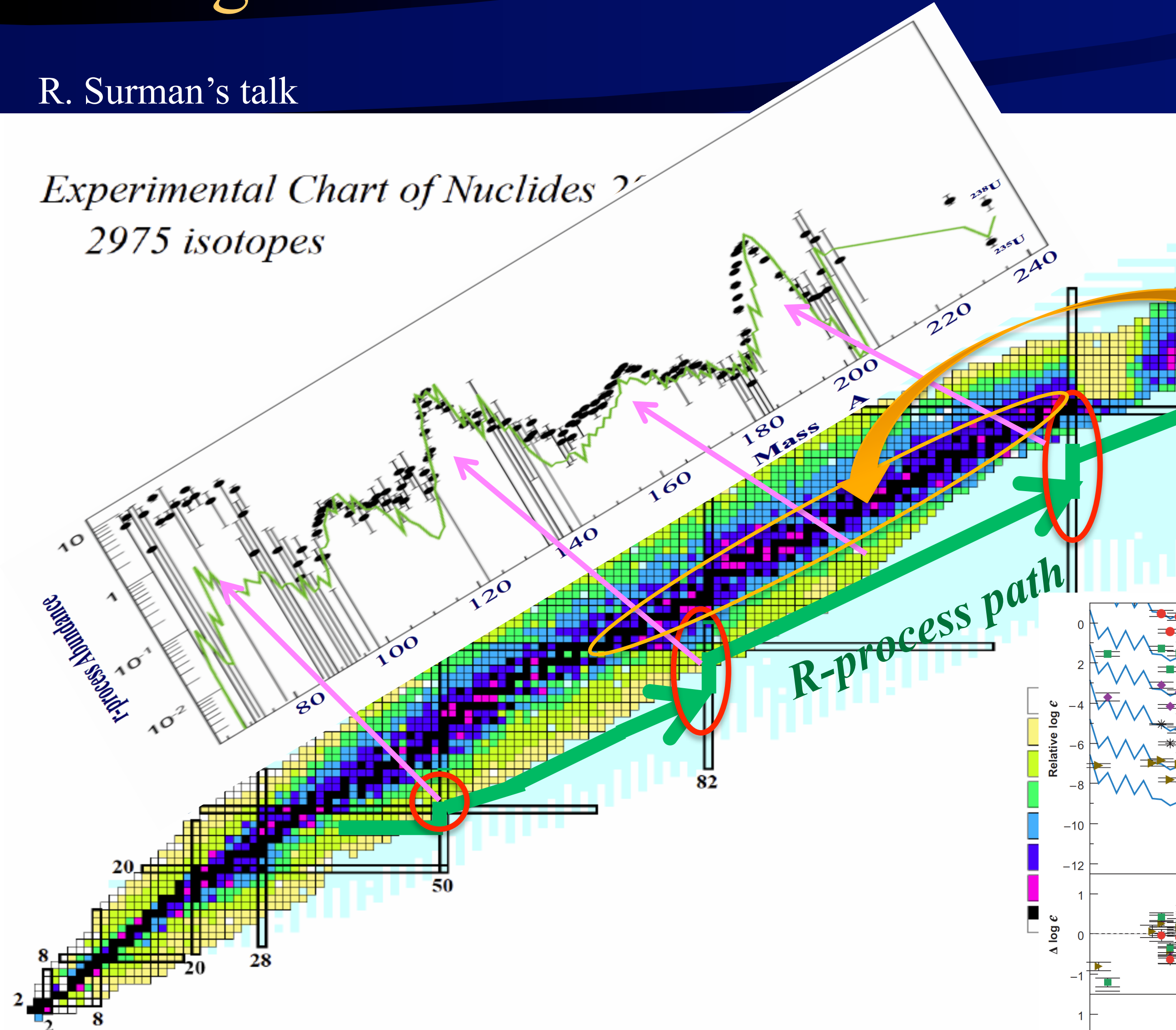
Solid line: constant S_n
Dashed line: constant $T_{1/2}$

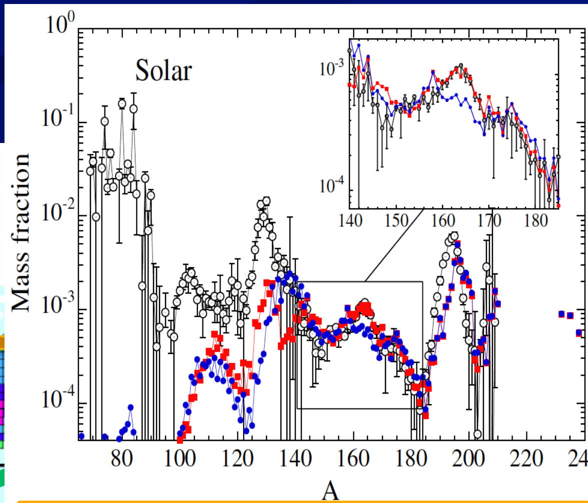
- Interplay of nuclear deformation and β decay
- Forms during freeze-out.

The spontaneous and β-delayed fission cycling takes place in the very heavy region, part of fission fragments locates in the region of rare-earth peak !?

Origin of Rare-Earth Elements

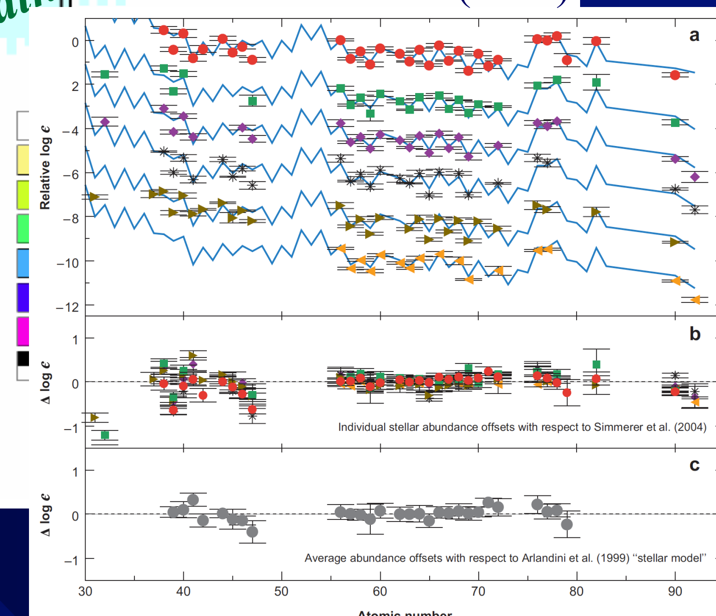
R. Surman's talk





S. Goriely et al PRL 111, (2013)

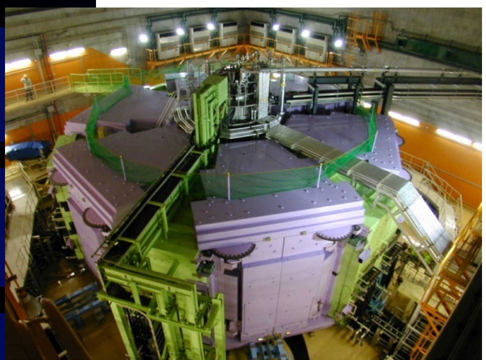
C. Sneden et al.(2008)

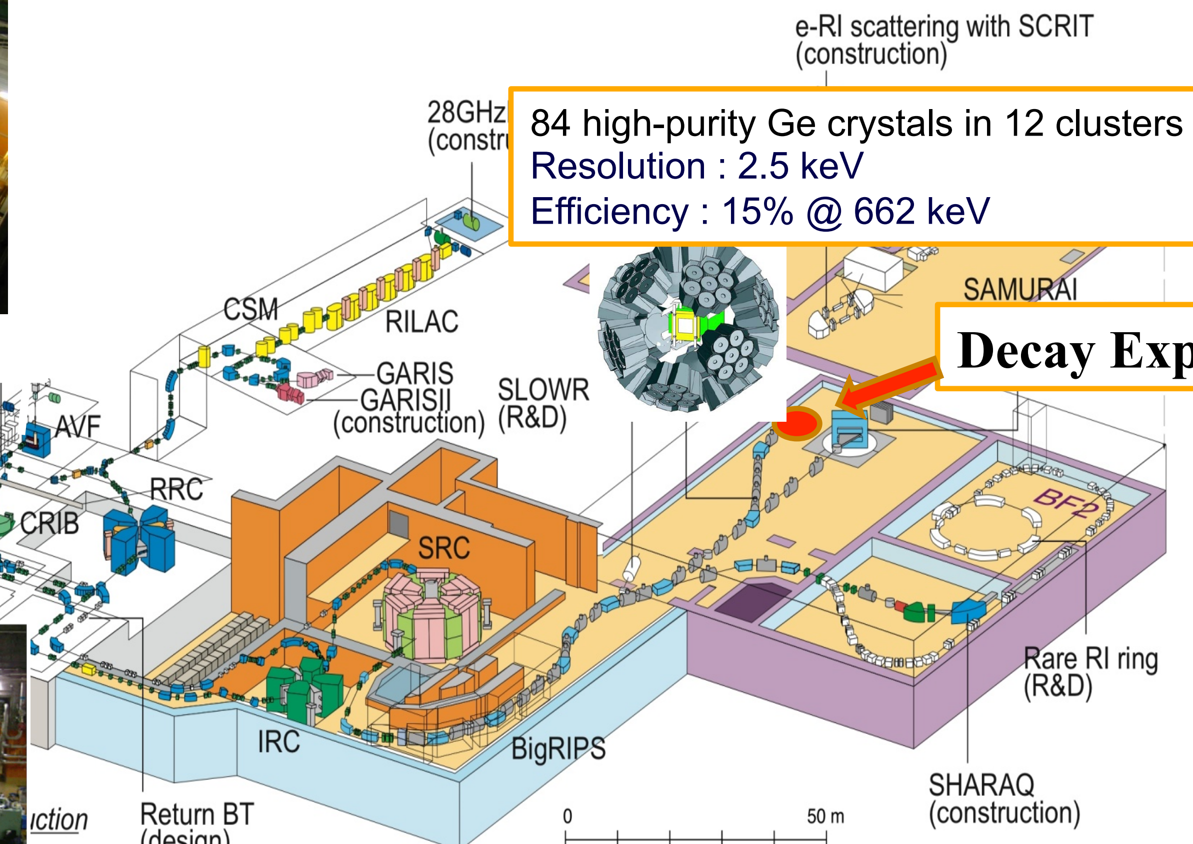


decay rates, masses, fission, b-delayed neutron
← → magic, deformation

Decay Spectroscopy at RIBF

Location of Decay Station at RIBF



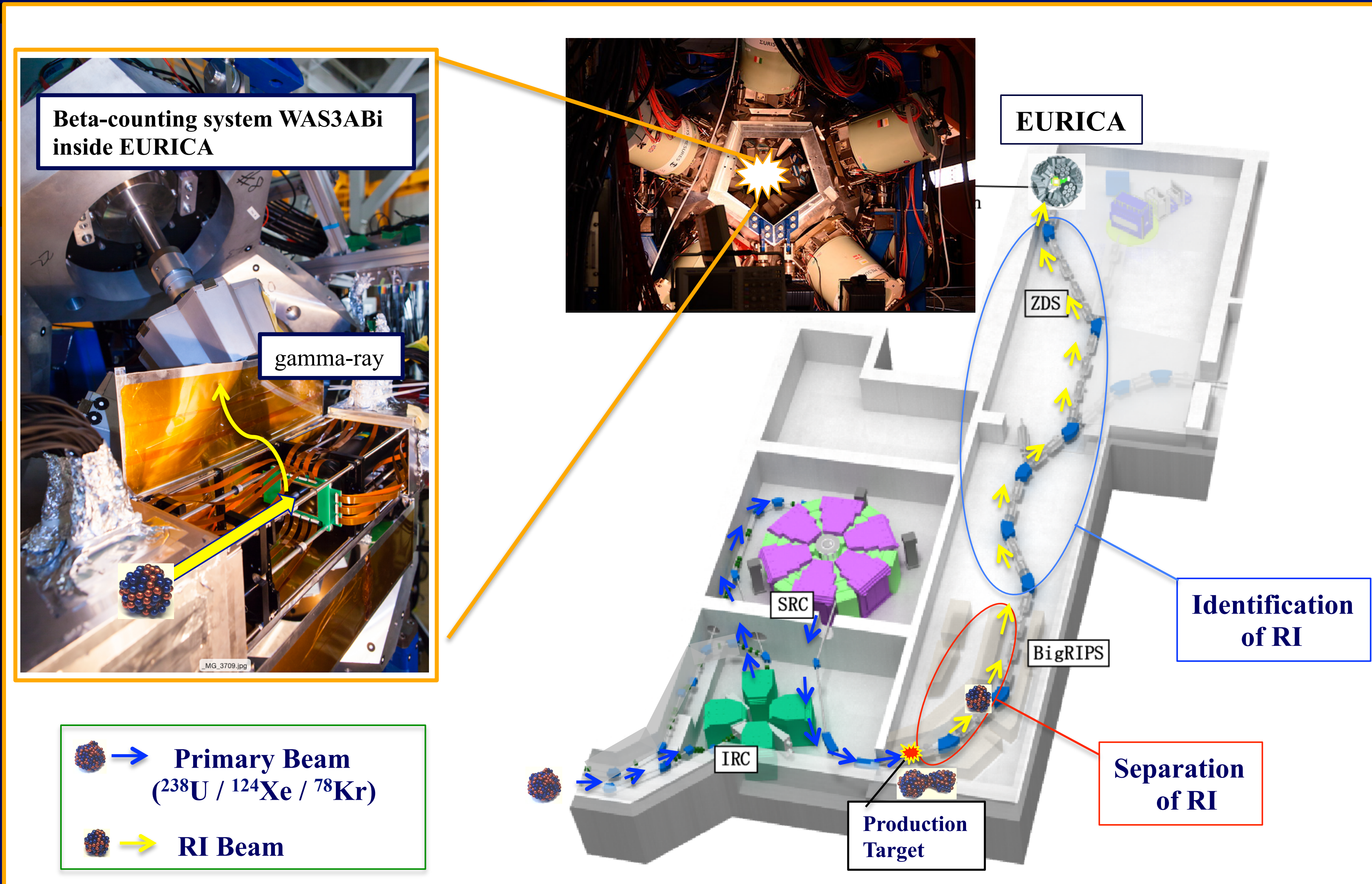


84 high-purity Ge crystals in 12 clusters
Resolution : 2.5 keV
Efficiency : 15% @ 662 keV

Decay Exp.

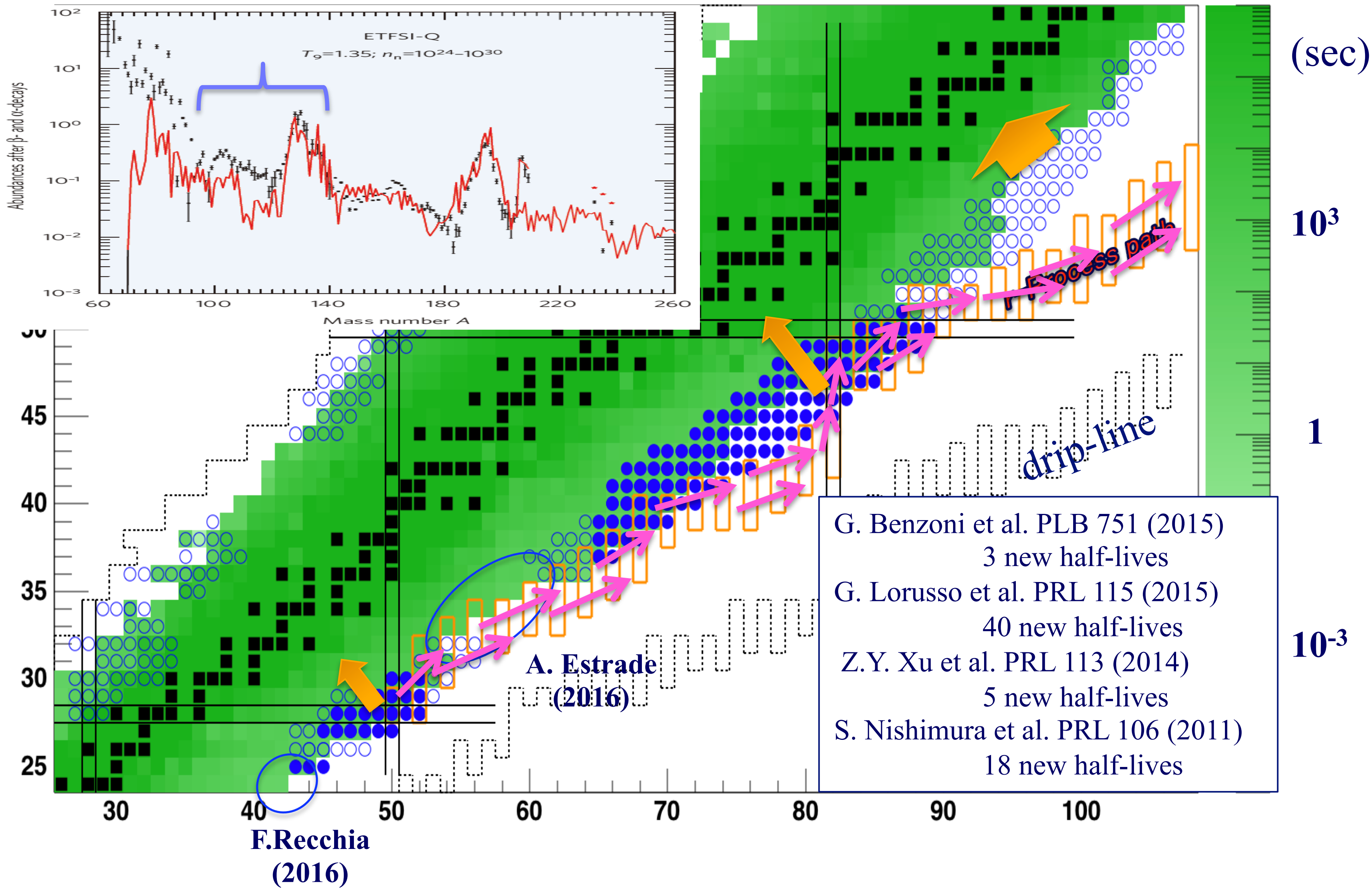
^{238}U … 345 MeV/u,
… Intensity = 5 – 12 pnA (now 30-50pnA)

EURICA Spectrometer at RIBF

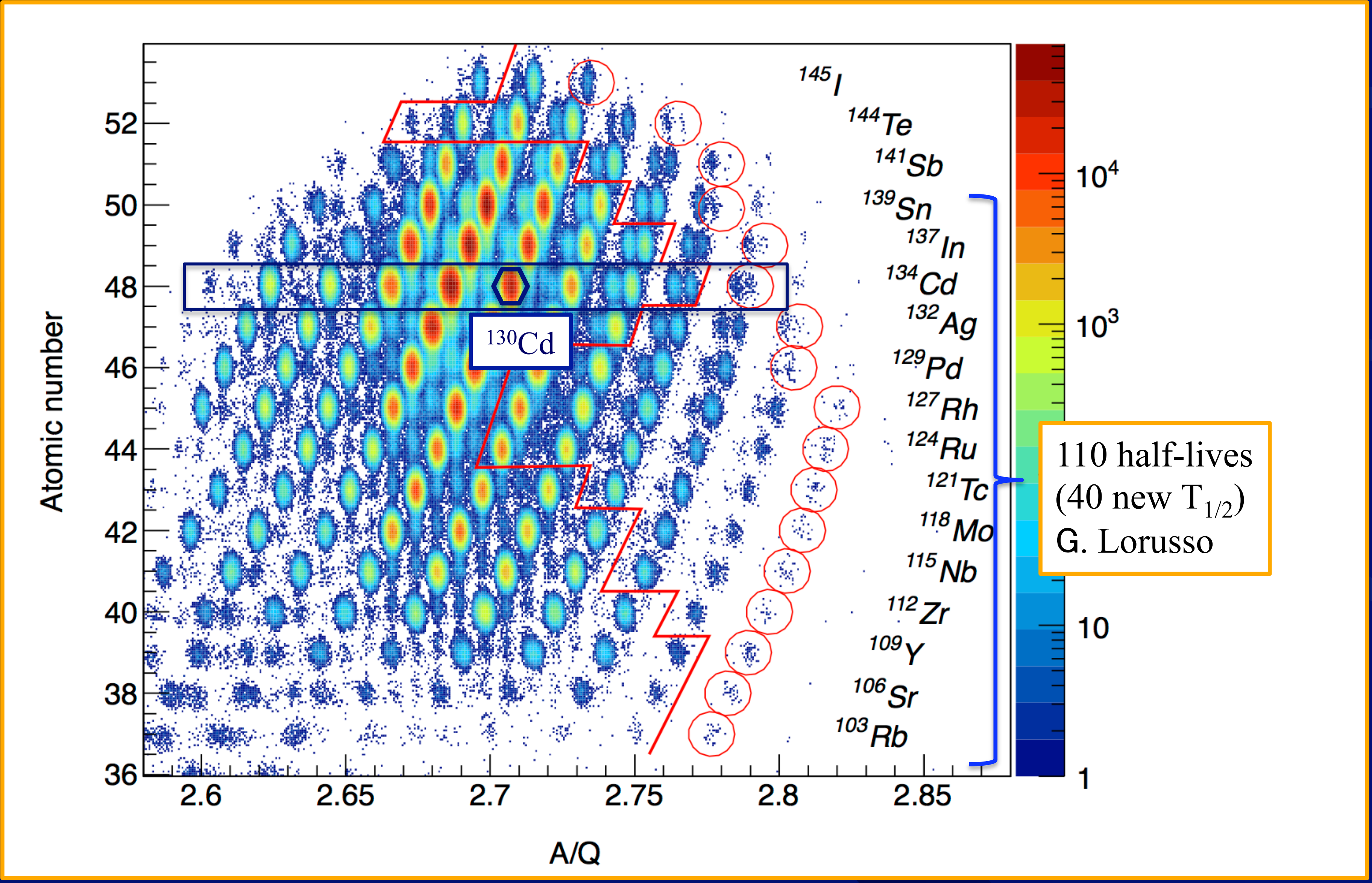


β-decay half-lives of neutron-rich nuclei

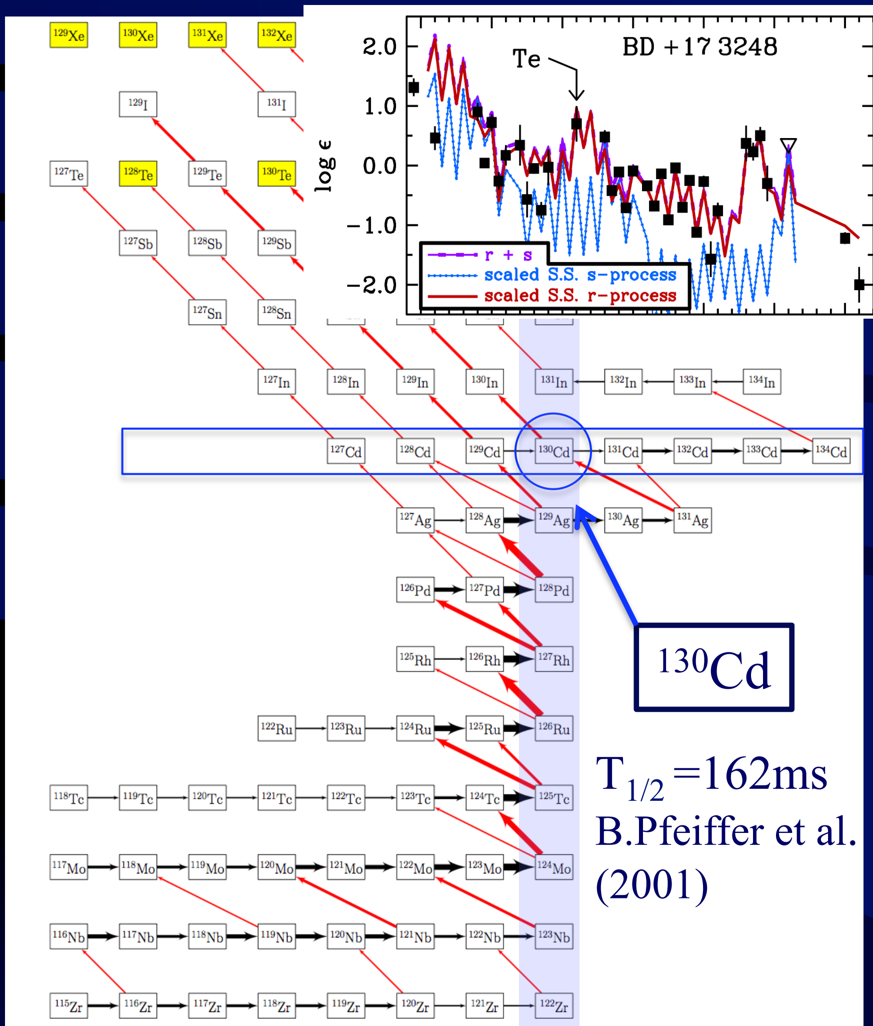
Decay experiments (2009, 2012 ~ 2016)



β-decay half-lives on r-process path



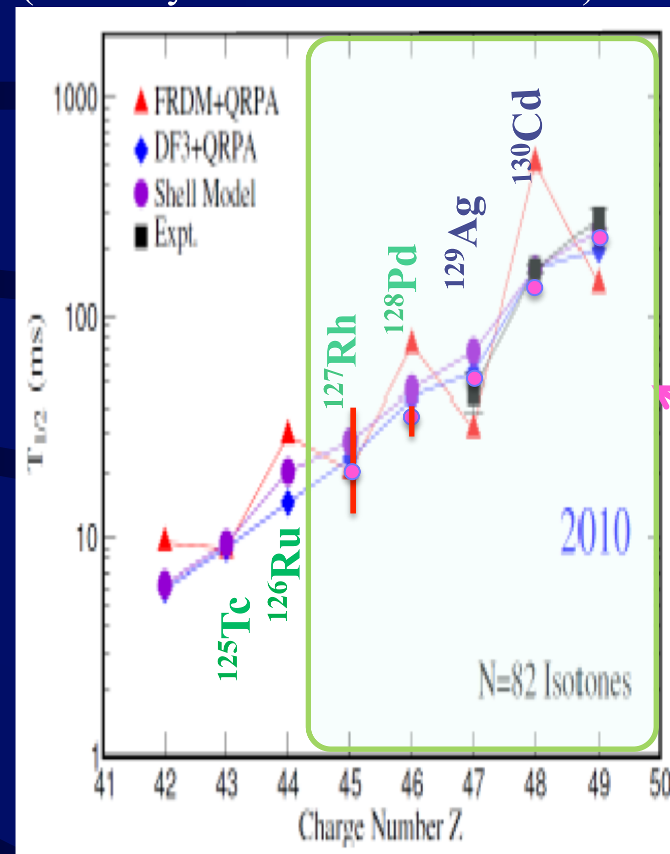
Beta-decay Half-lives N = 82 → Feedback to the Theory



^{130}Cd

$T_{1/2}$ =162ms
B.Pfeiffer et al.
(2001)

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

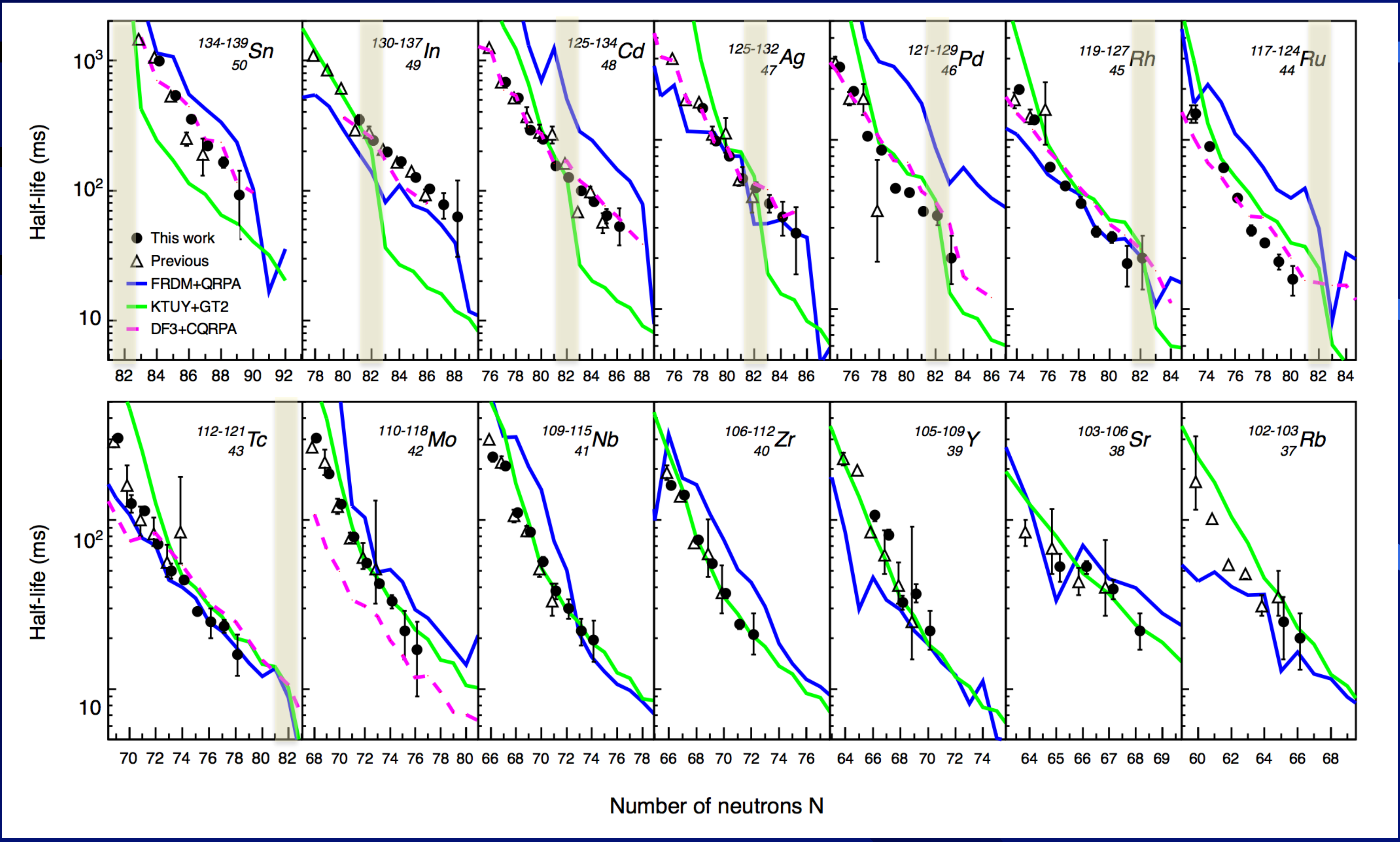
Shell model ← ~ 25% shorter $T_{1/2}$

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

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

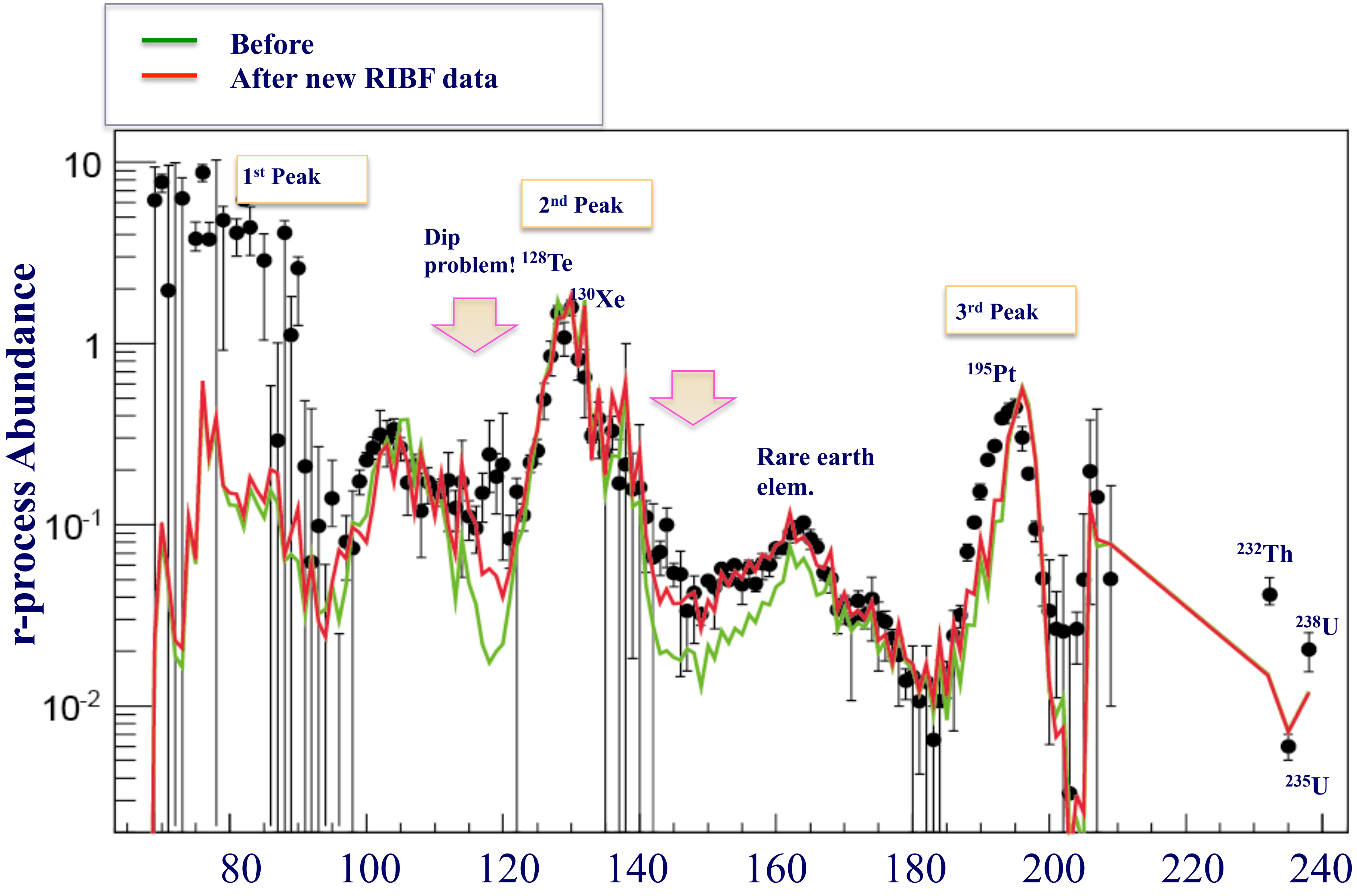
40 new half-lives ! G.Lorusso et al., PRL 114, 192501 (2015)

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



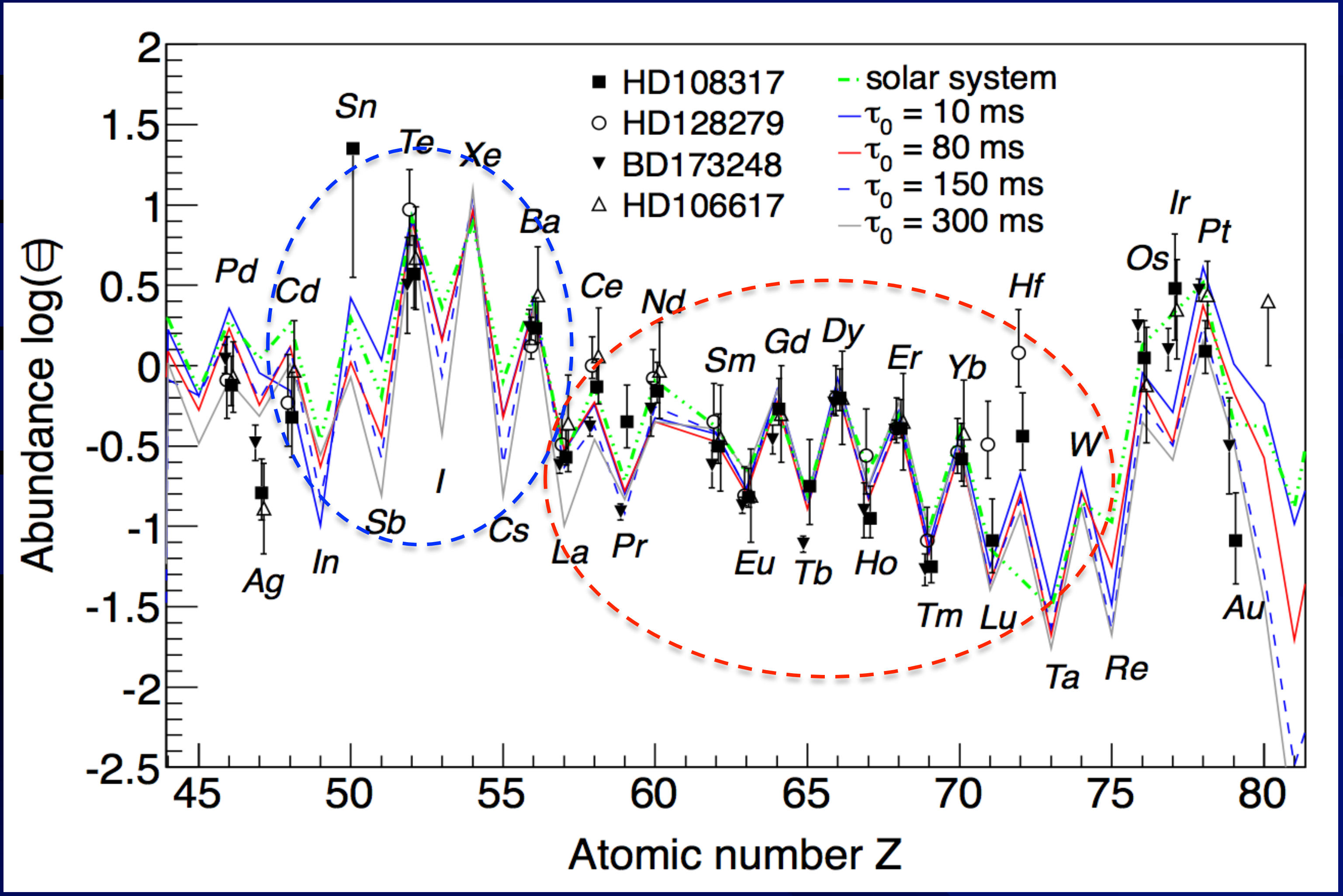
r-process Abundance with New $T_{1/2}$ (RIBF)

G.Lorusso et al., PRL (2015)



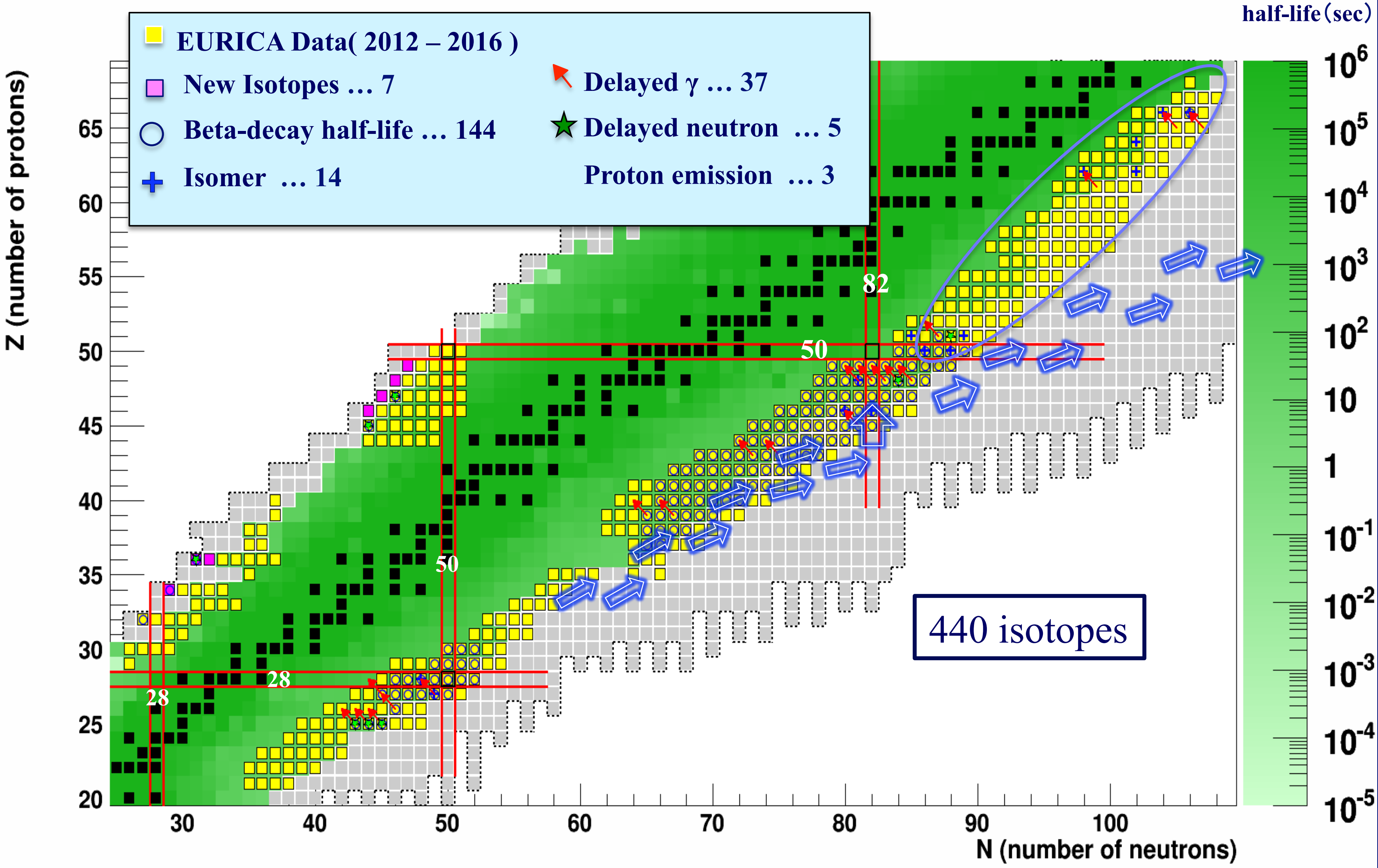
Assumption: (n, γ) ⇄ (γ, n) equilibrium.

Universality of r-process elements (Z ≥ 56)



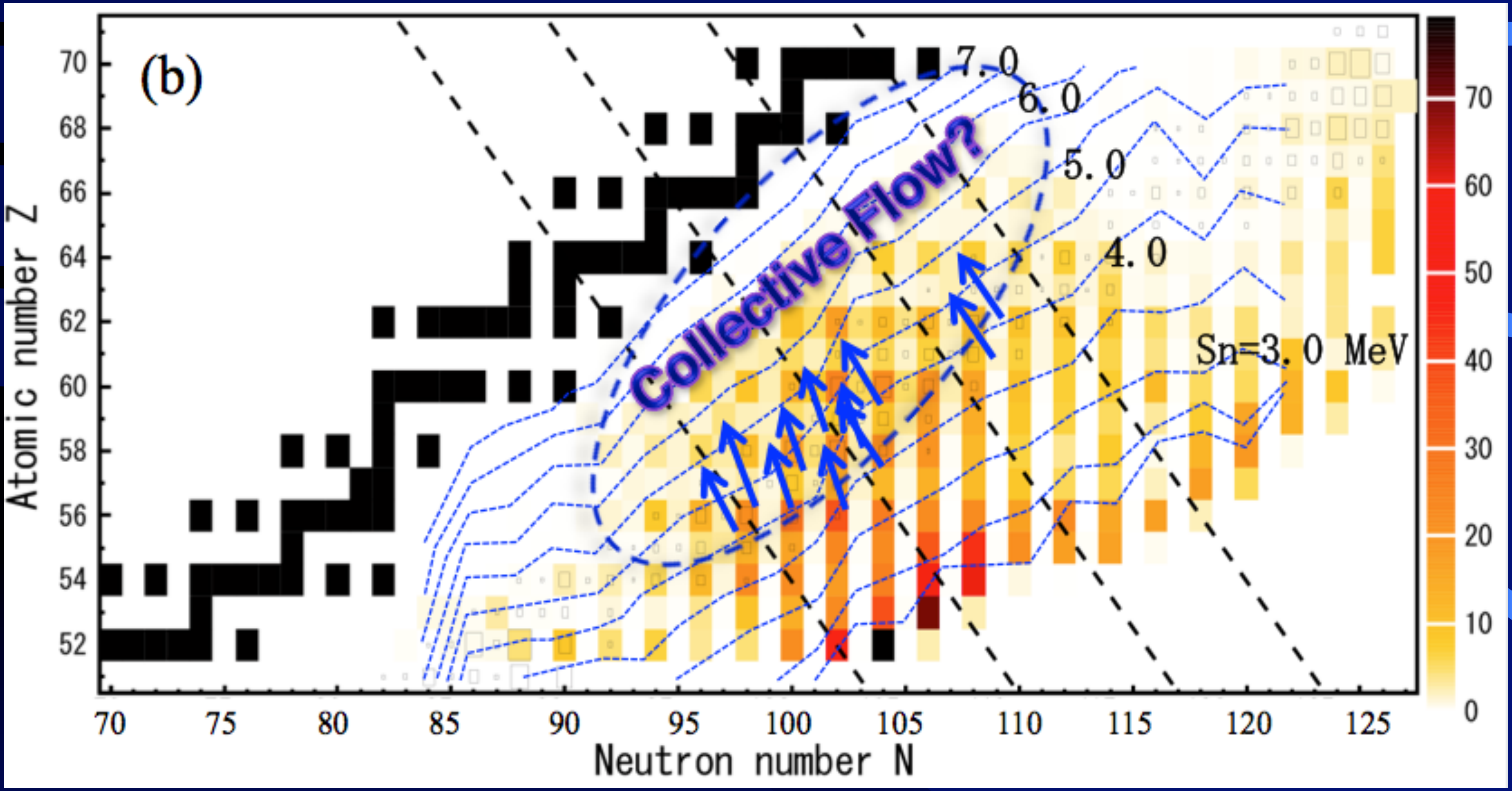
Decay Spectroscopy around mass A =160 was performed !

Survey of Decay Properties at RIBF (EURICA)



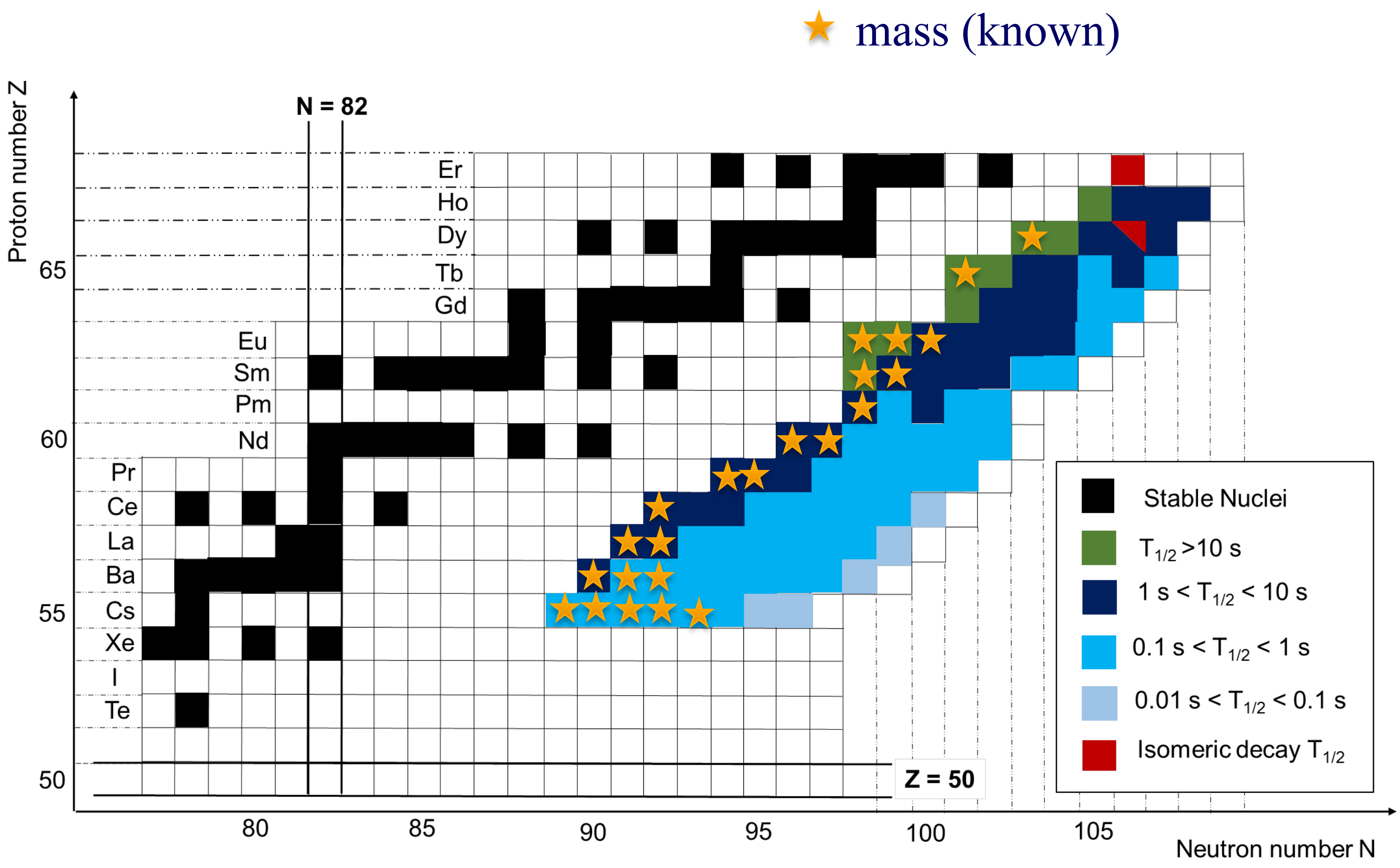
Rare-Earth Peak Formation at Freeze-Out Time

R. Surman et al. PRL 79 (1997)

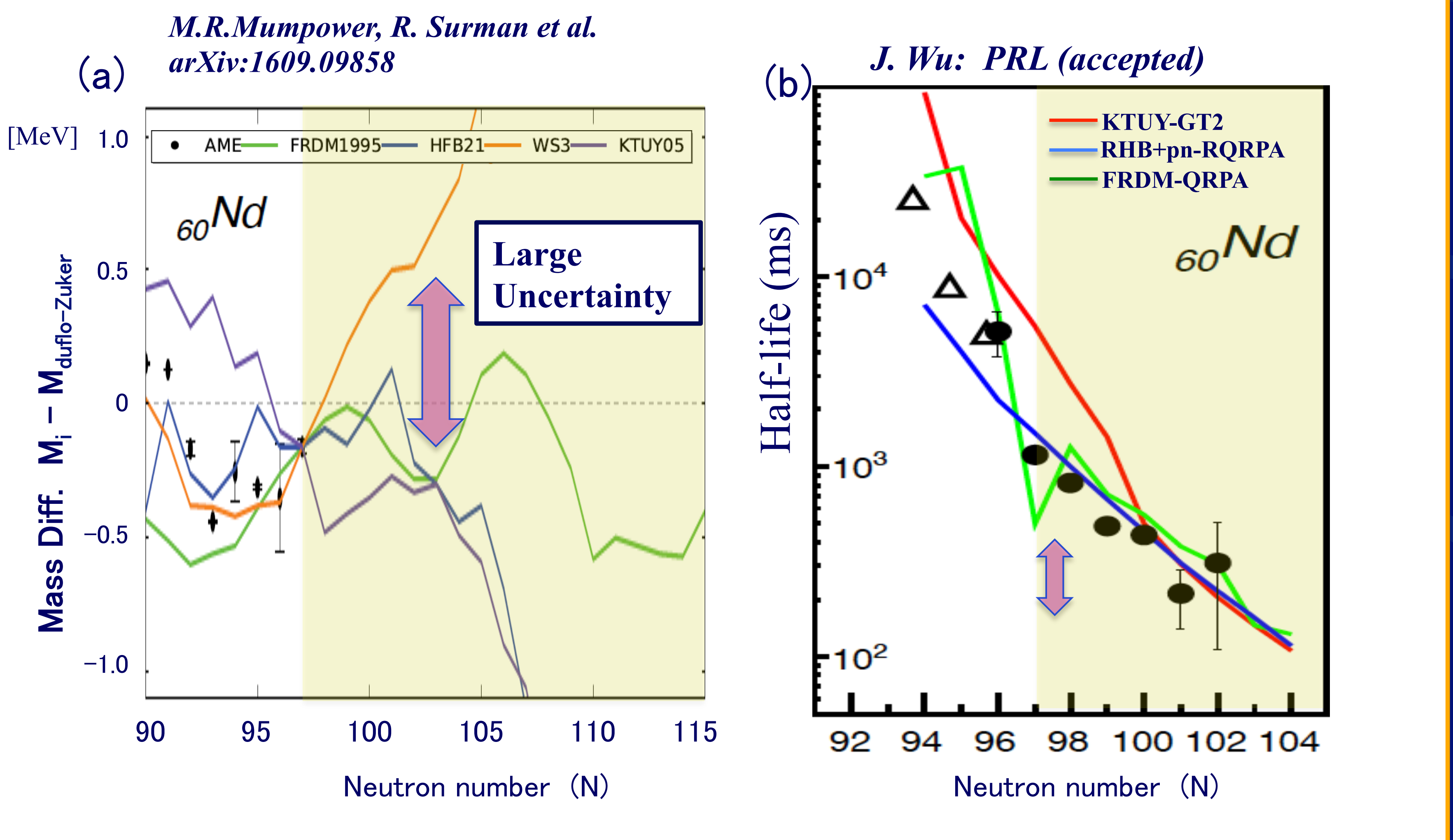


Test r-Process calculation with new RIBF data

Half-lives and Mass Measurement

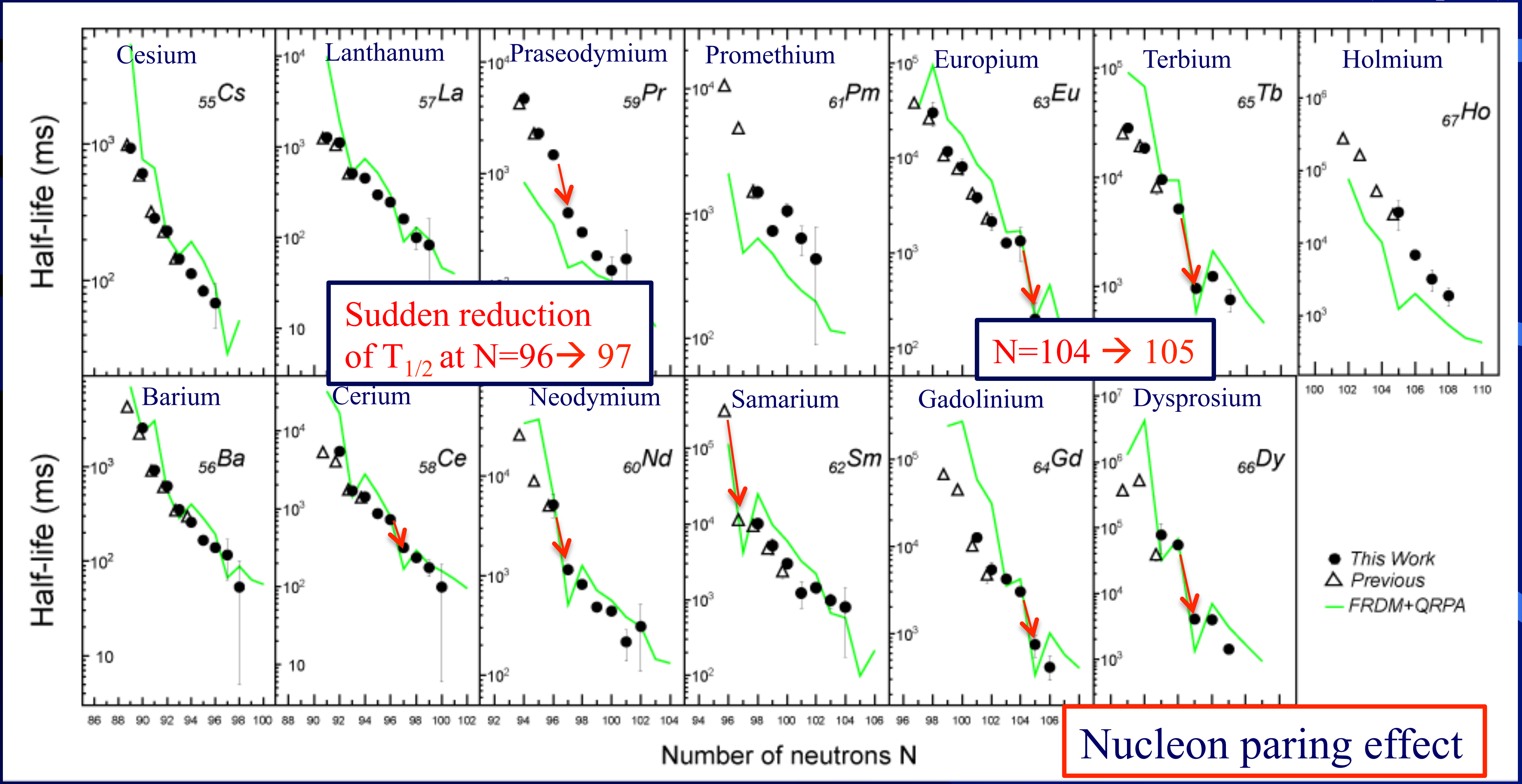


Mass & beta-decay half-lives



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

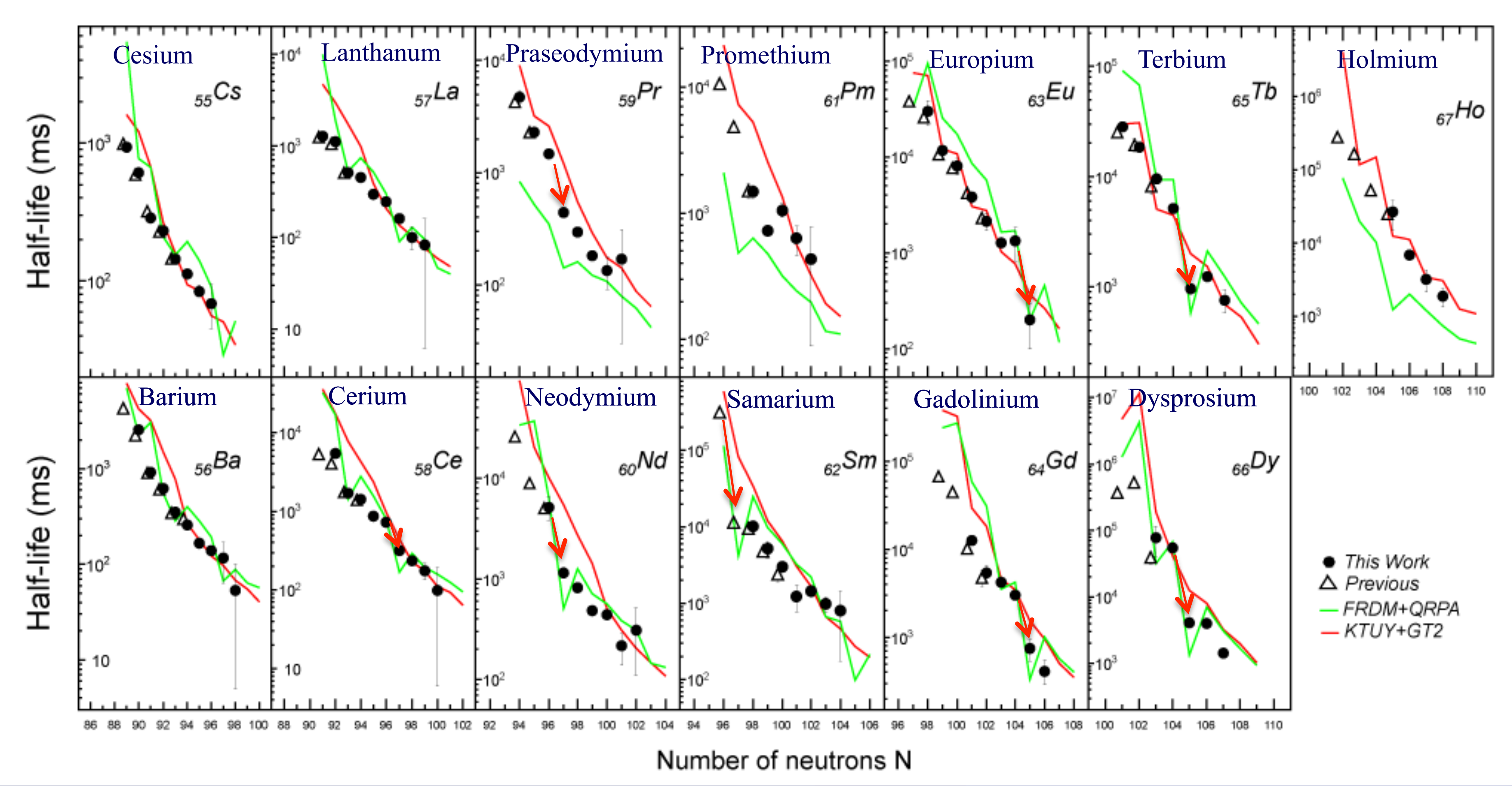
J. Wu, PRL (accepted)



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

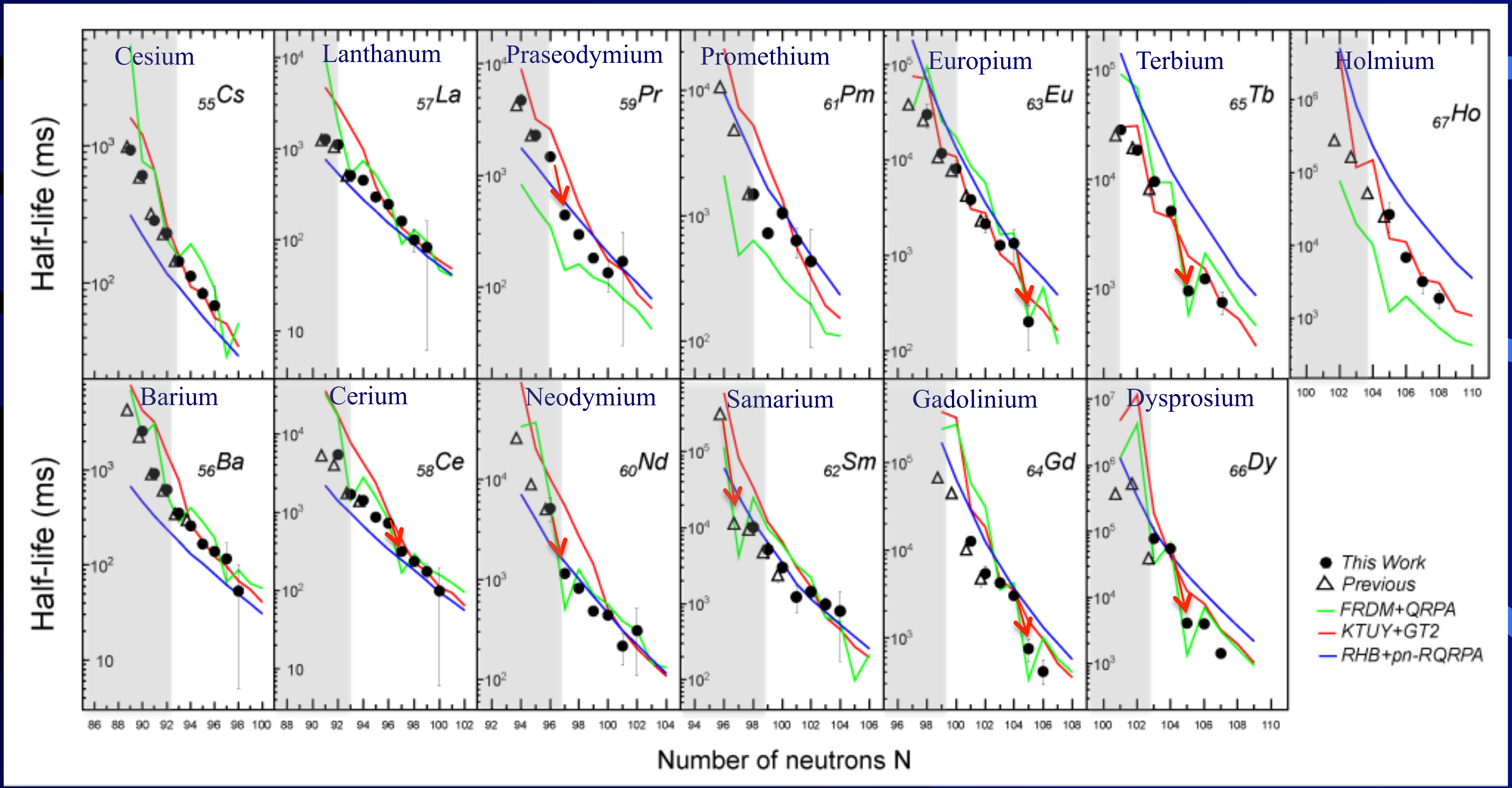
J. Wu, PRL (accepted)



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

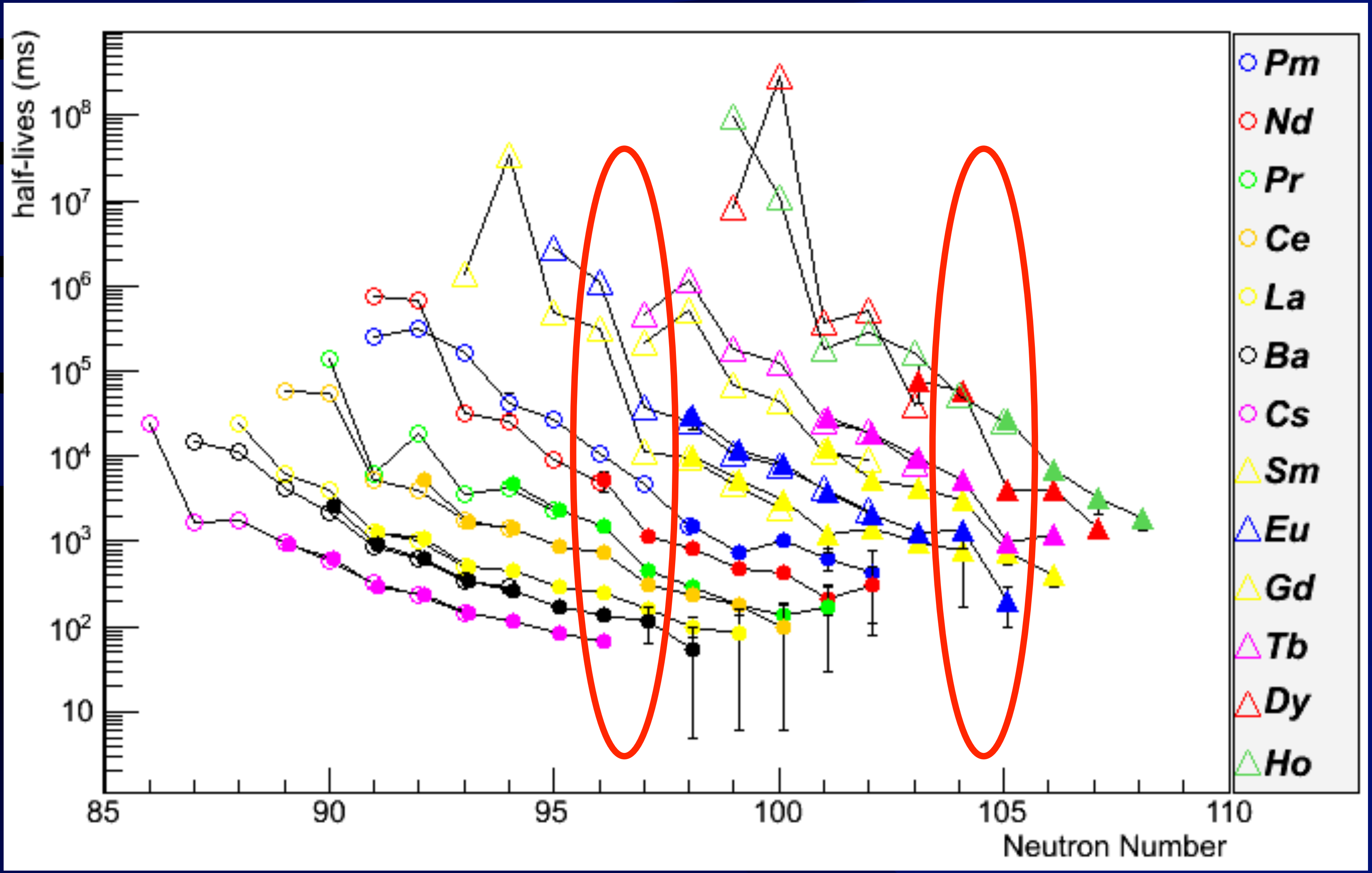
J. Wu, PRL (accepted)



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).

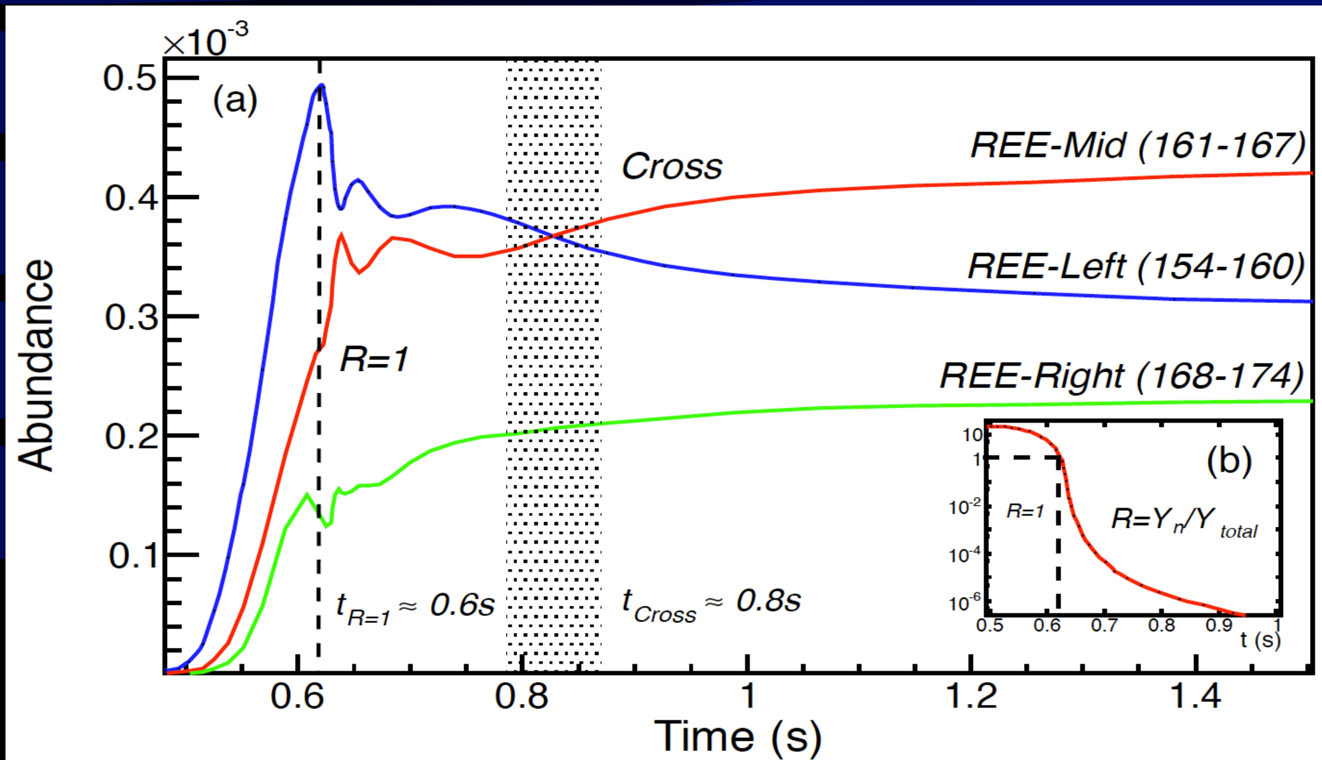
No reproduce of even-odd effects.

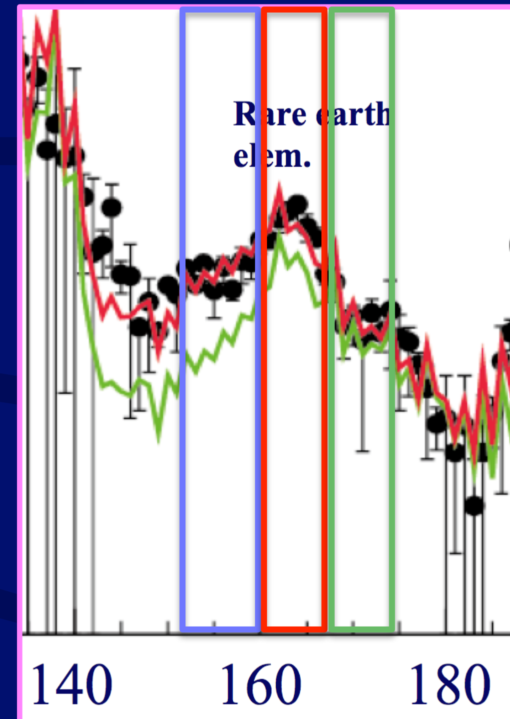
Discussion: Two significant features



A sudden drop of feature at neutron number N=97 and N=105.
(N = 100 : deformed sub-shell gap?)

Rare-Earth Peak Formation

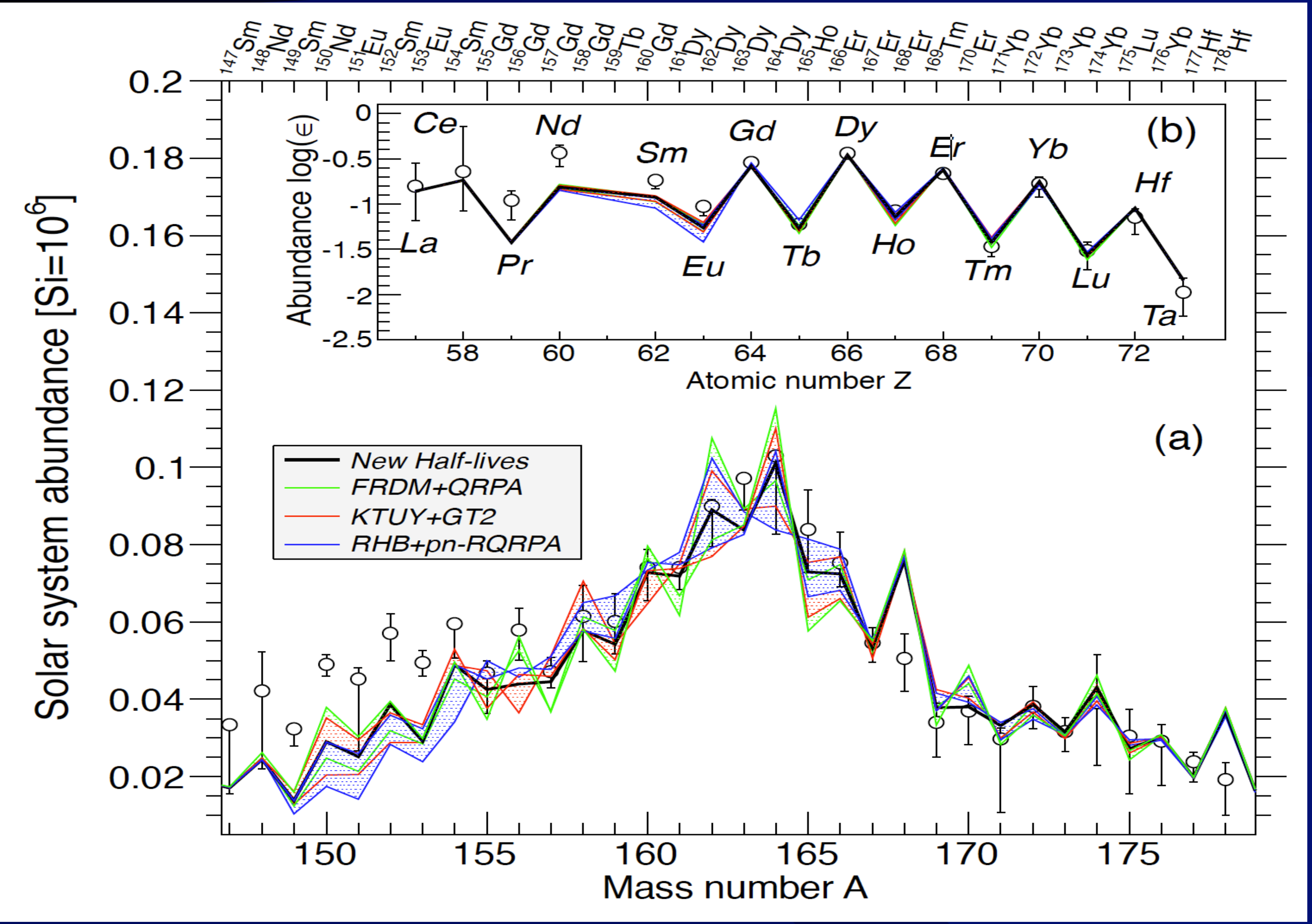




r-Process Elemental Abundance (A = 150-179)

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

J. Wu et al. PRL (accepted)

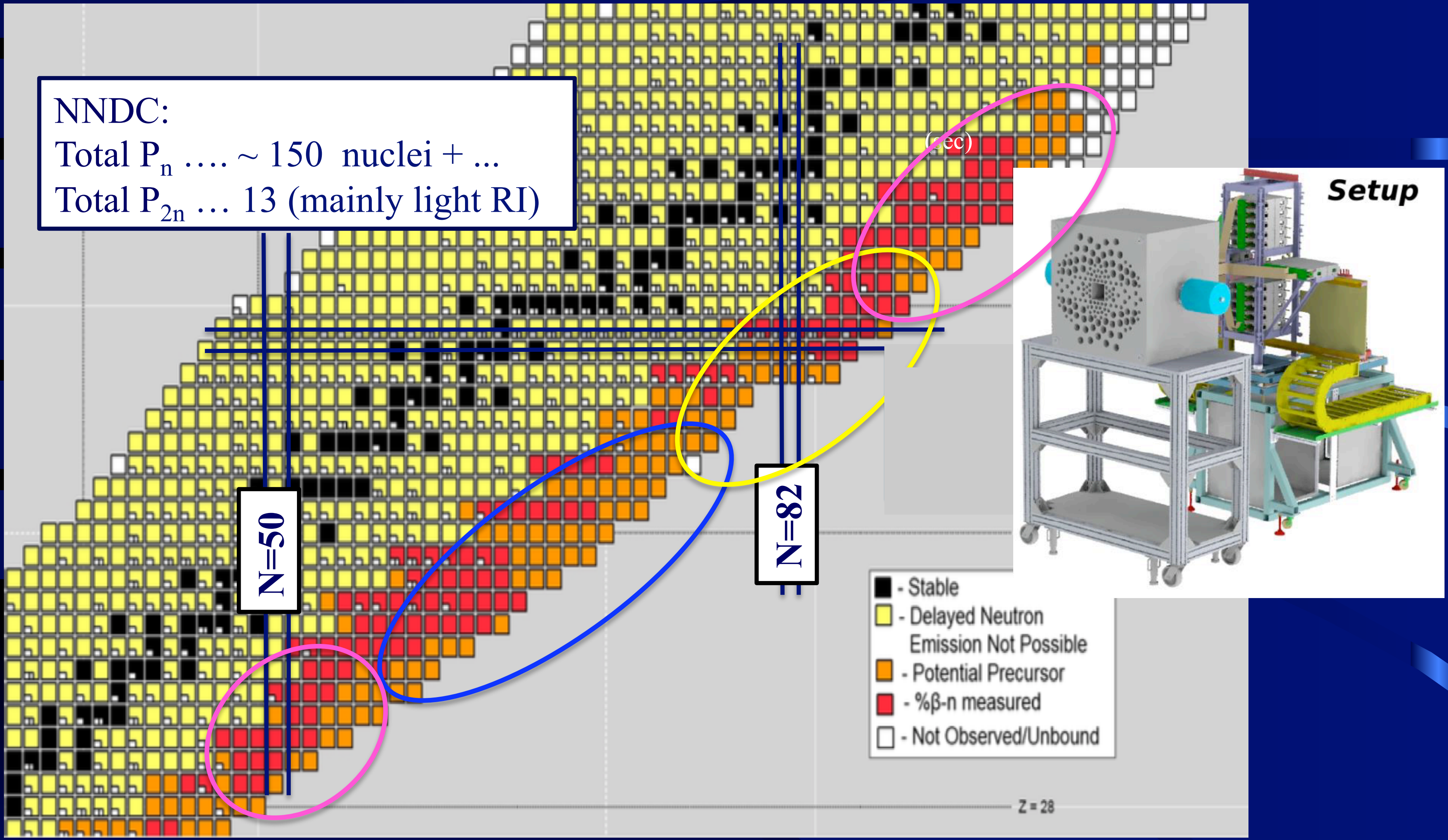


Experimental Feedback and Evaluation of the r-Process Rare-Earth Peak Formation

Perspective

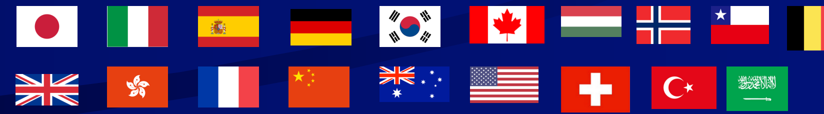
BRIKEN Project (2016 ~)

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



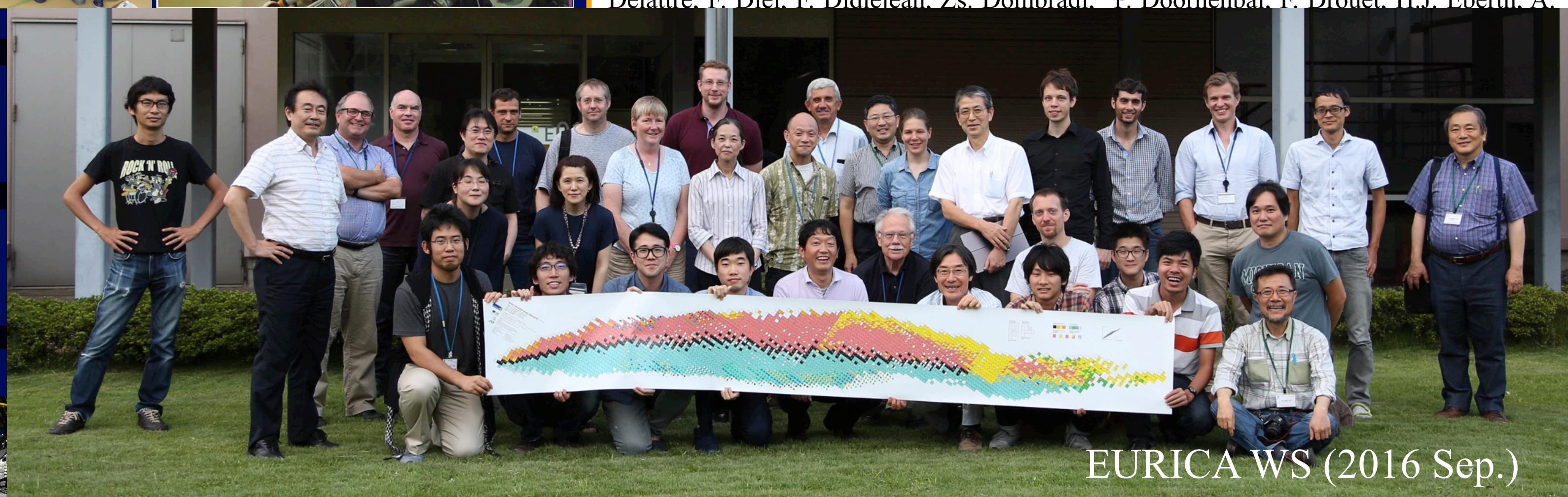
Several hundreads of beta-delayed neutron emission P_n (n) together with $T_{1/2}$ (β) & level scheme (γ)

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.



Napoli, F, Naqvi, M. Niikura, H. Nishibata, S. Nishimura, I. 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

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

Acknowledgement: Gammapool, Preepc, IBS

BRIKEN Collaboration

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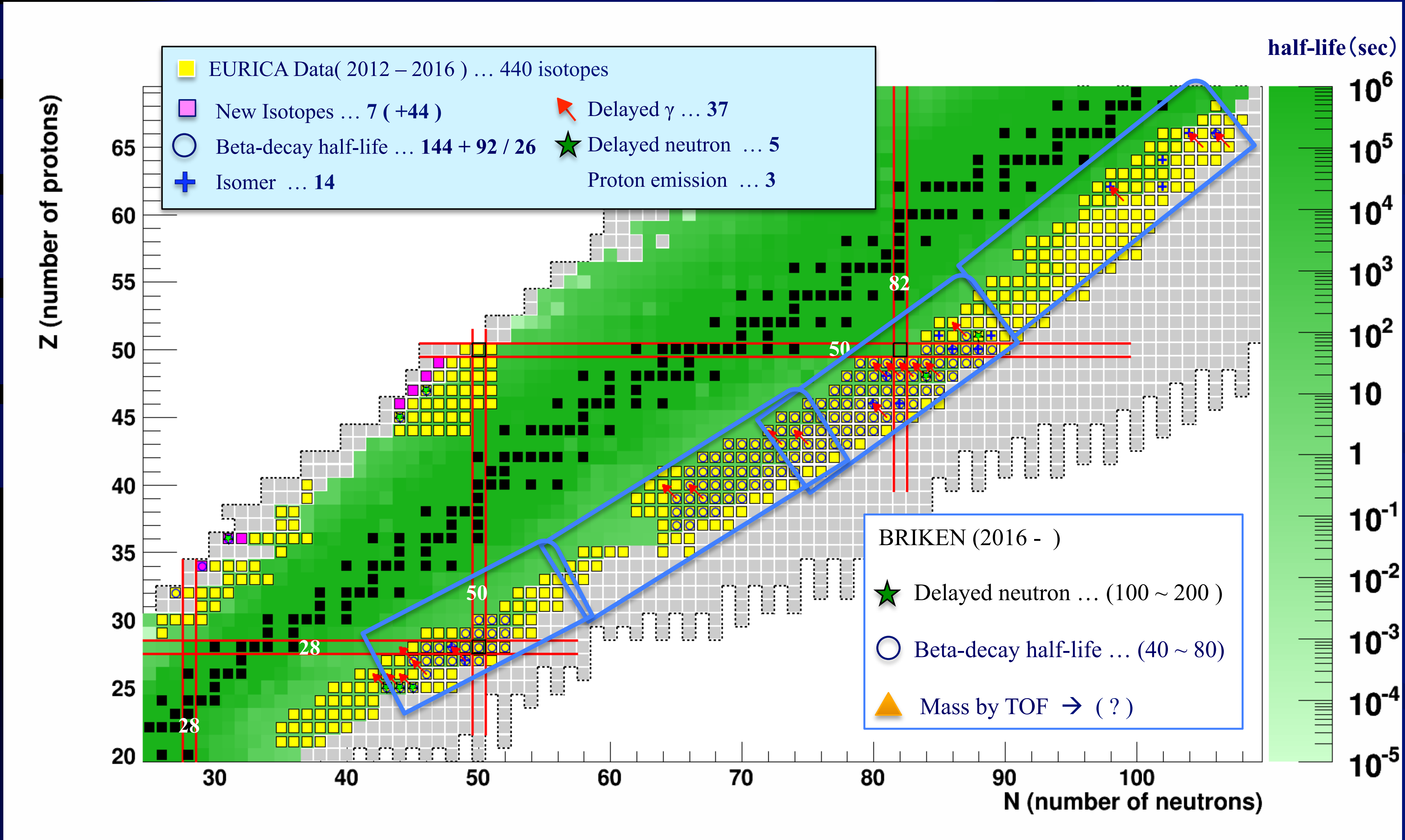
Peking Univ. :	Jin Wu, Z.H. Li

Summary



New beta-decay half-lives play important role in formation of 2^nd peak and rare-earth peak