Nuclear Structure and Reactions at NSCL and FRIB through the Lens of Astrophysics: Lecture 5

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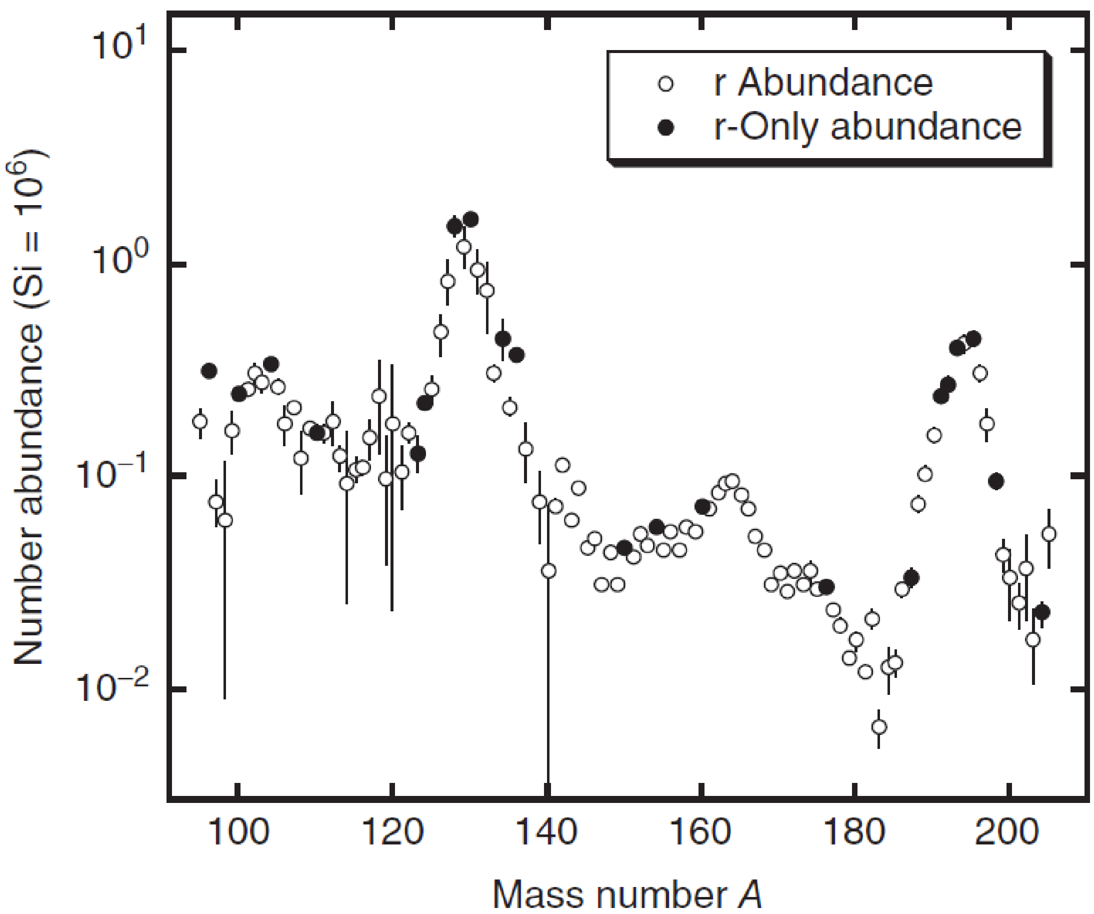
HUGS @ JLab

May 31st, 2019

Outline

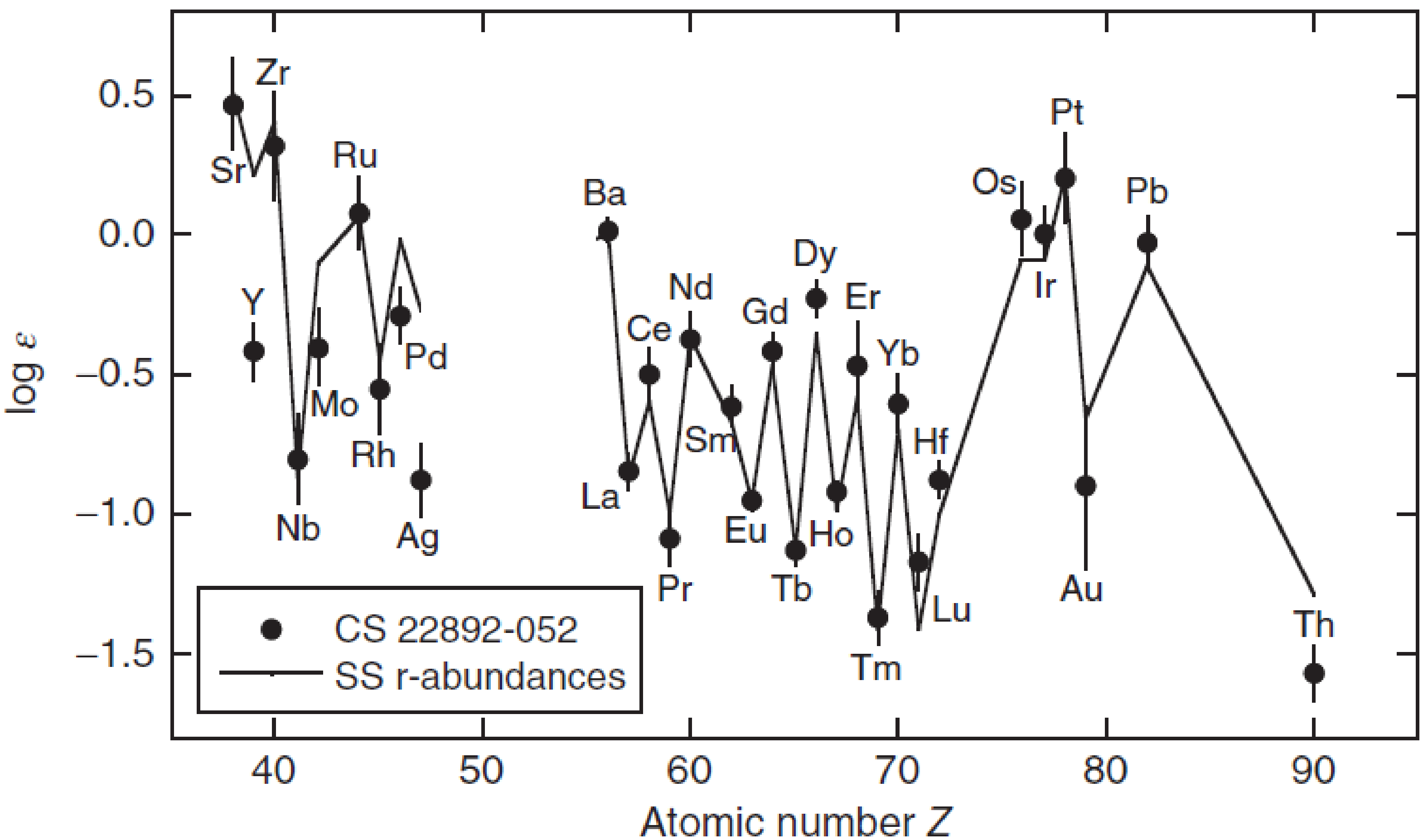
- Lecture 1: History, stellar evolution & thermonuclear rates
- Lecture 2: Charged-particle reactions: direct measurements
- Lecture 3: Charged-particle reactions: indirect measurements
- Lecture 4: Slow neutron capture process: direct measurements
- **Lecture 5: Rapid neutron capture process: indirect measurements**

Solar System r-process abundances



Obtained by subtracting s-process abundances

r process in metal-poor stars



Robust main r-process pattern (for $Z > 55$) identical over billions of years! What is the site?

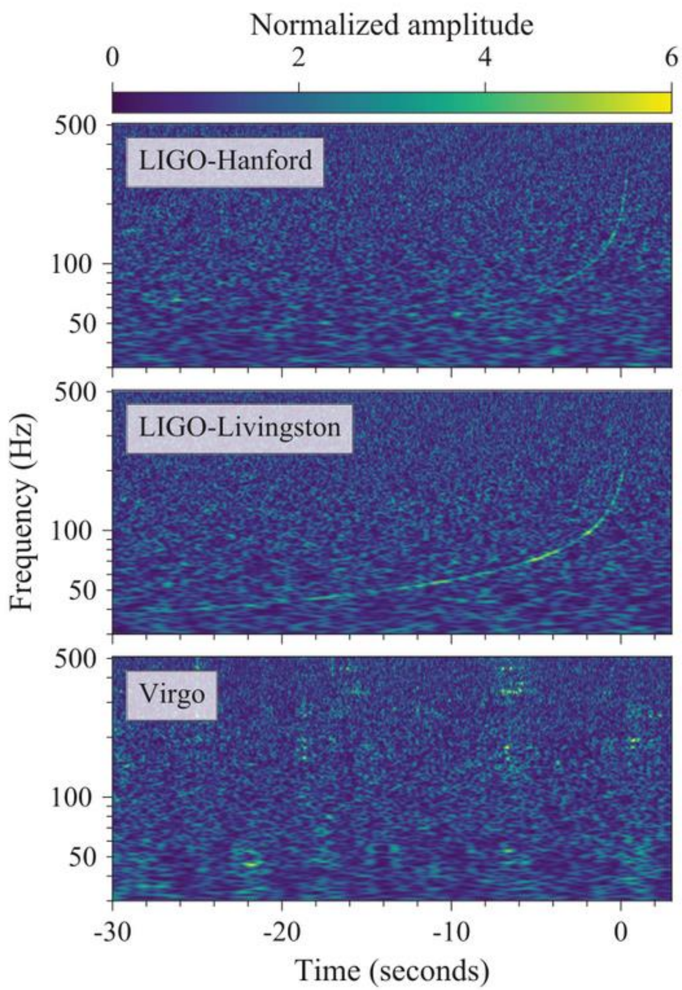
Nuclear Physics of Stars, Iliadis, 2nd Ed.

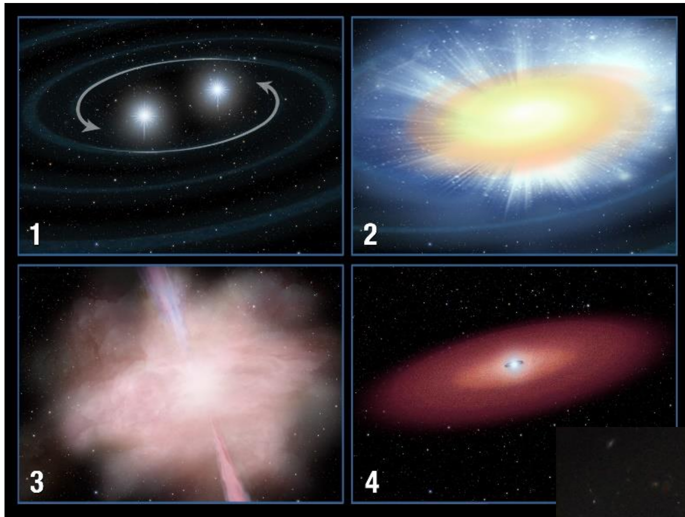
r-process site(s):

Neutron-star mergers!

Type II supernovae?

LIGO GW170817



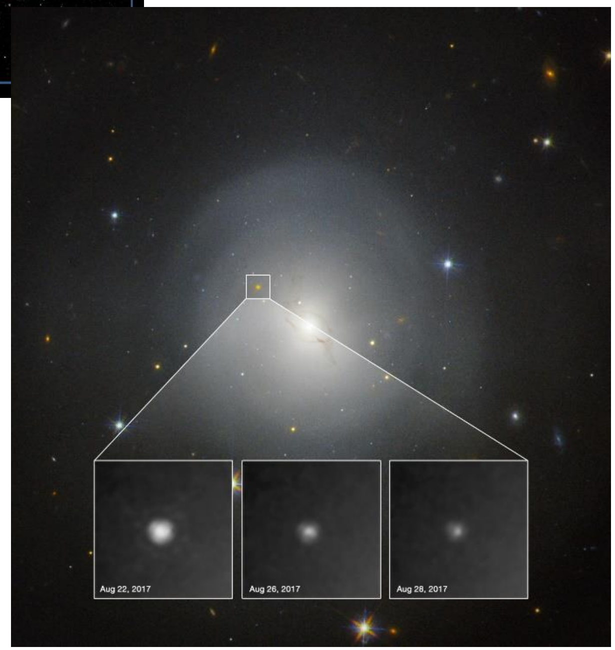


Model: merging neutron stars

→ r-process

→ Kilonova

Kilonova observed!



https://www.aldebaran.cz/bulletin/2017_36/kilonova.jpg
Metzger, 2010
Wikipedia

r process: nuclear data needed

Bold: can measure directly

***Q* values for (n,γ) reactions**

β^- decay half lives

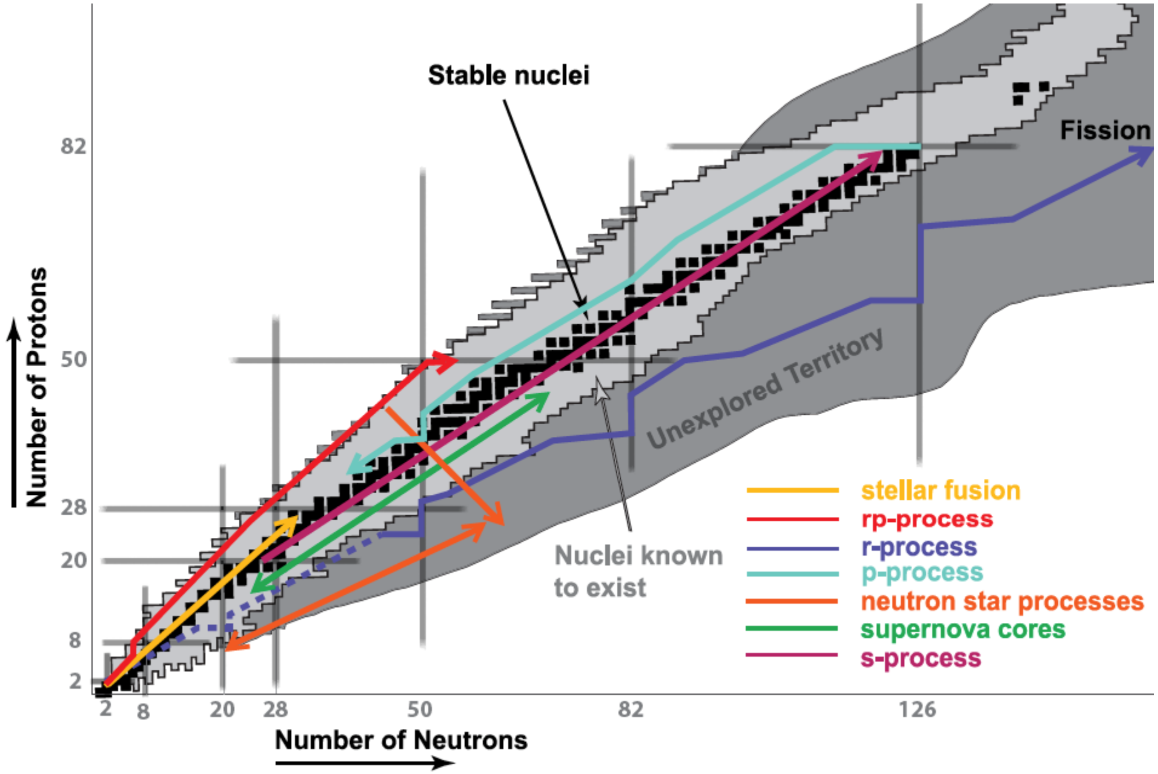
β^- delayed neutron decay

Partition functions

Fission probabilities

α-decay half lives

(n,γ) reaction rates



Generally, these properties are not known experimentally: need RIBs (eg. FRIB)

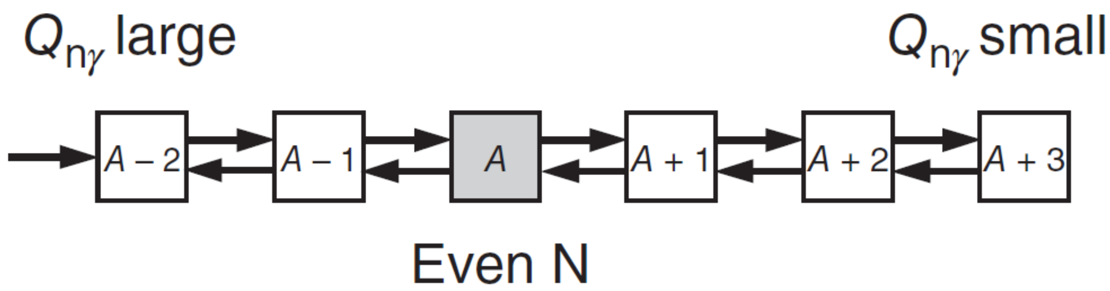
Nuclear masses: importance

Nuclear masses play a fundamental role in calculating most of nuclear properties needed to model the r process.

Most directly: if in (n,γ)-(γ,n) equilibrium then successive application of the Saha equation along isotopic chain yields general expression for number density of isotope x_m, which is m neutron captures away from isotope x_0:

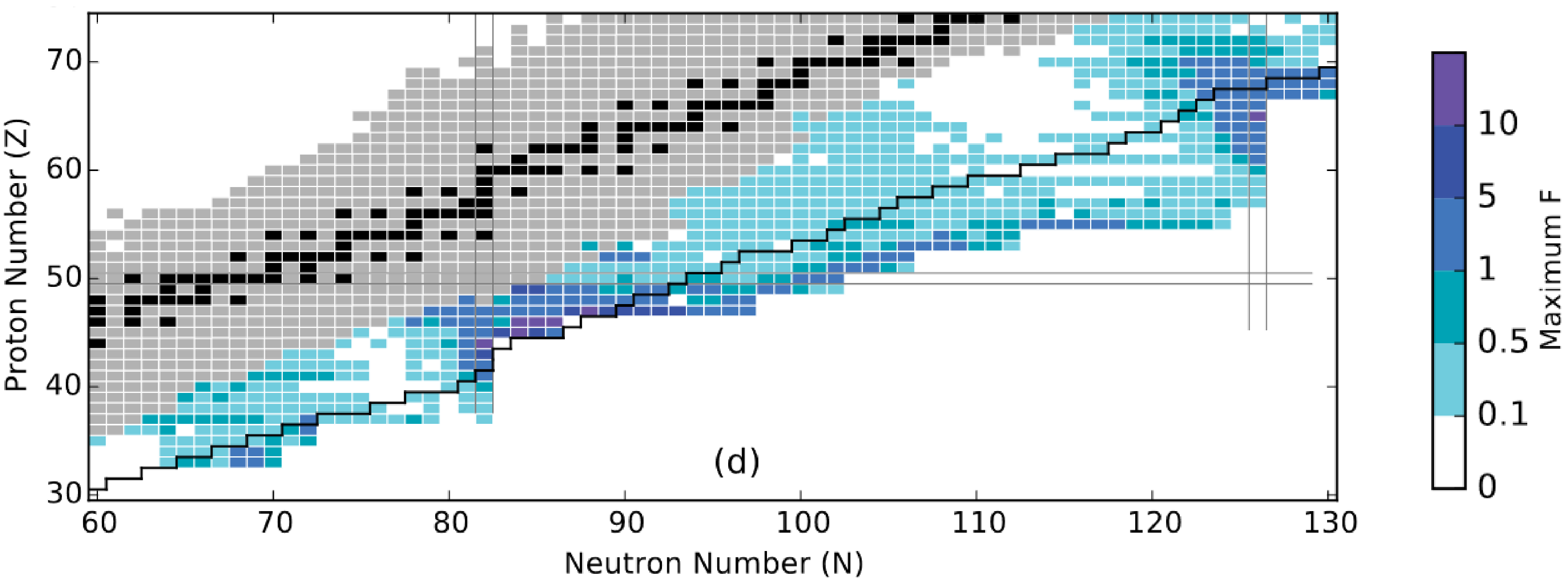
$$N_{x_m} \approx N_{x_0} \left(\frac{N_n}{1.188 \times 10^{34} T_9^{3/2}} \right)^m \exp\left[\frac{11.605}{T_9} \sum_{j=0}^{m-1} Q_{x_j(n,\gamma)} \right]$$

Due to decrease of $Q_{n\gamma}$ as neutron drip line is approached and odd-even-N staggering, maximum abundance occurs at a particular even-N isotope with optimal $Q_{n\gamma}$ (given T, N_n).



Nuclear Physics of Stars, Iliadis, 2nd Ed.

r-process mass sensitivity

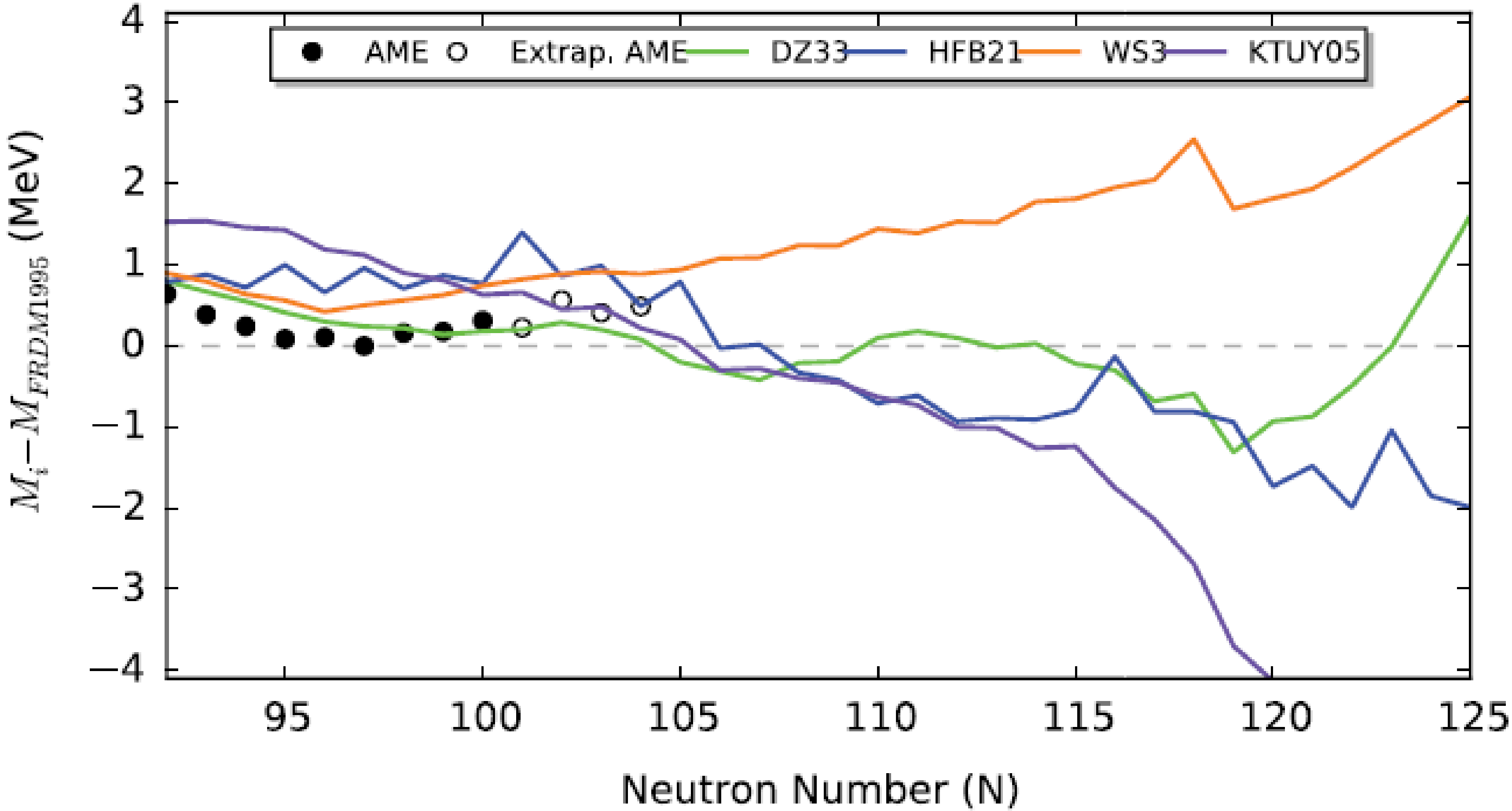


Black squares: stable nuclides

Grey squares: nuclides with measured masses in 2013 Atomic Mass Evaluation

Colored squares: nuclides with unmeasured masses affecting r-process abundances

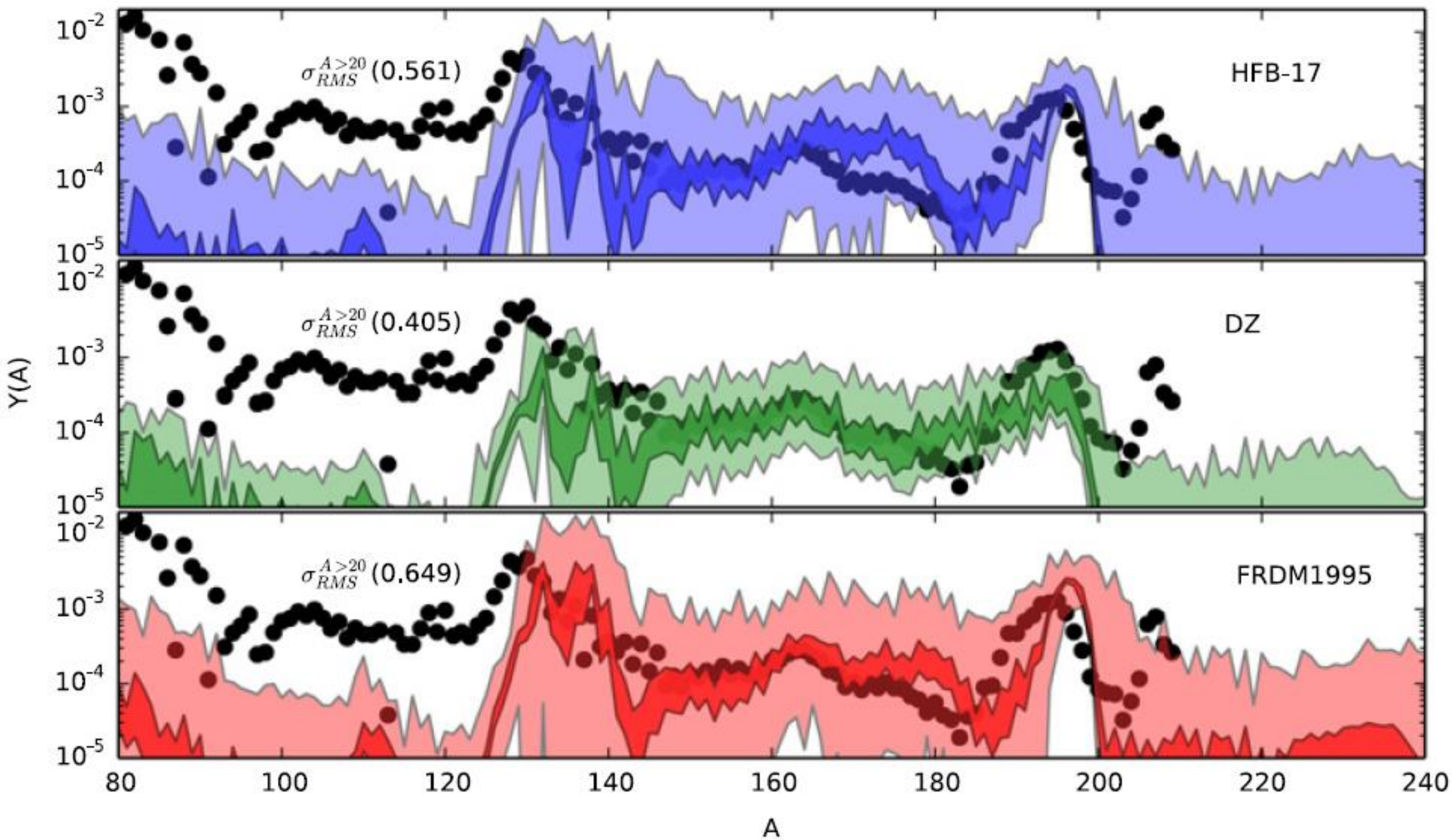
Europium isotope masses



Nuclear theories don't predict consistent masses: need to measure them!

Mumpower *et al.*, PNPP 86, 86 (2016)

r-abundances from theoretical masses

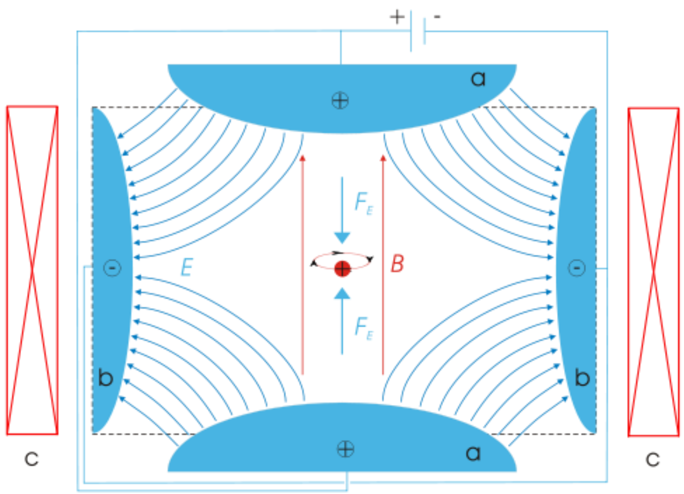


Need to measure masses to about 100 keV uncertainty (darker-shaded bands)

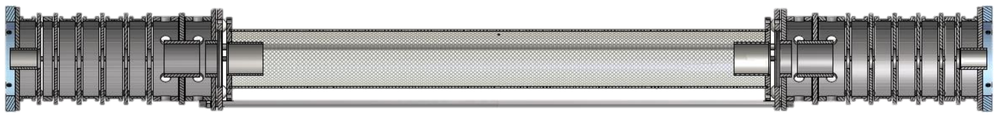
Mumpower *et al.*, PNPP 86, 86 (2016)

Nuclear masses: experimental approaches

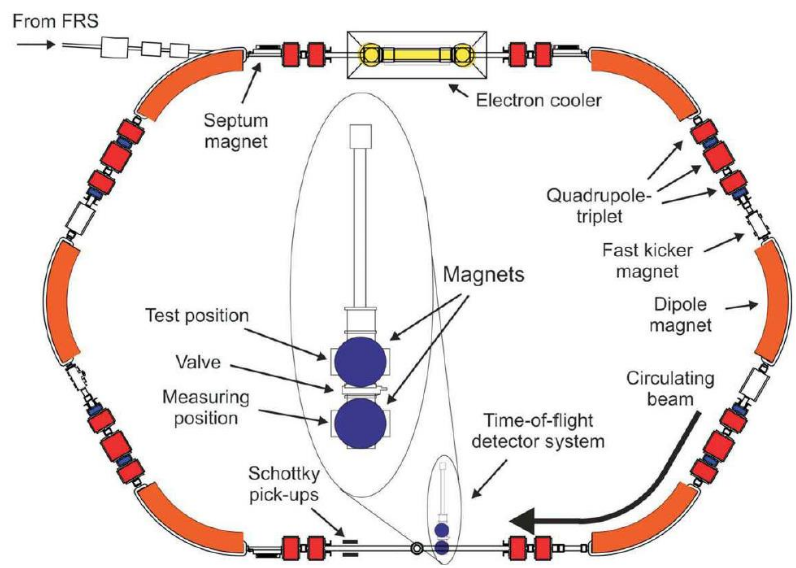
Penning trap



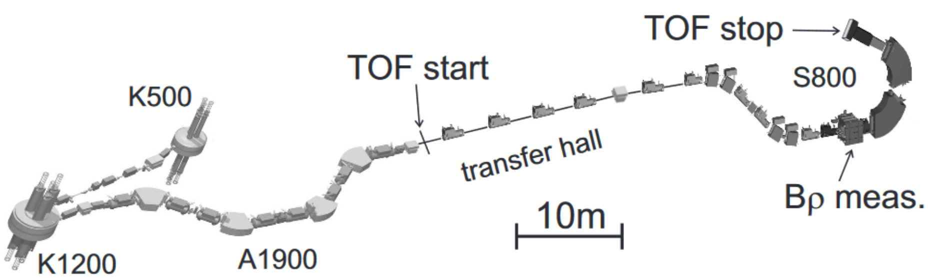
MR-ToF



Storage ring



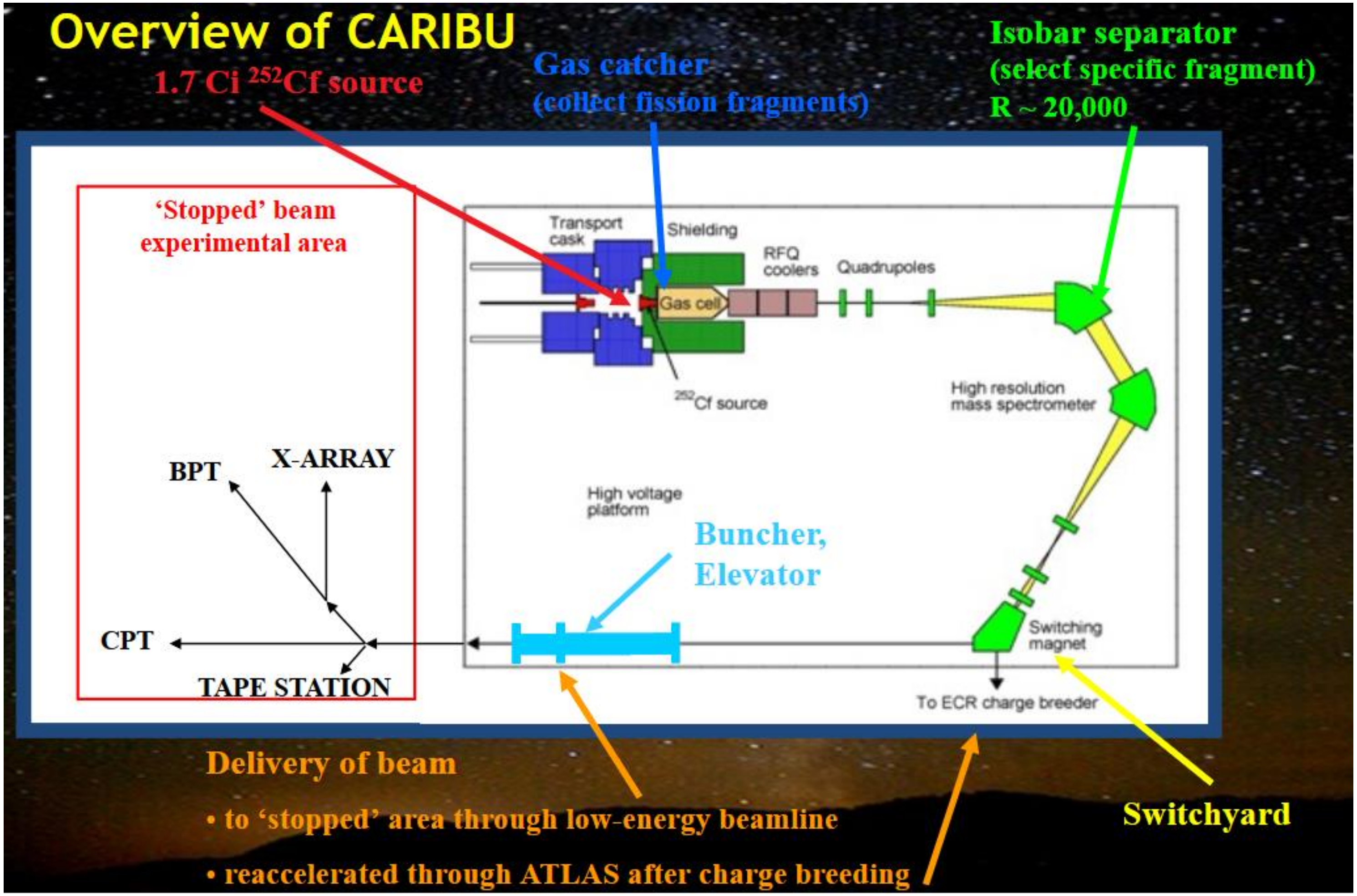
ToF-Bρ



FRIB researchers will employ most (potentially all) of the approaches above

Example: CARIBU + CPT at ANL

CPT: Canadian Penning Trap

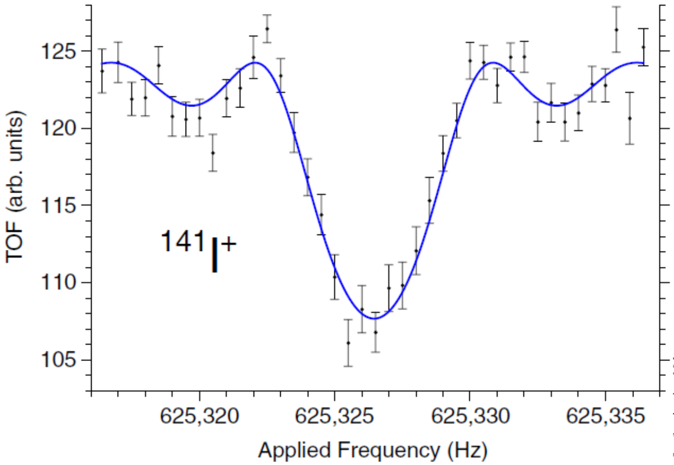


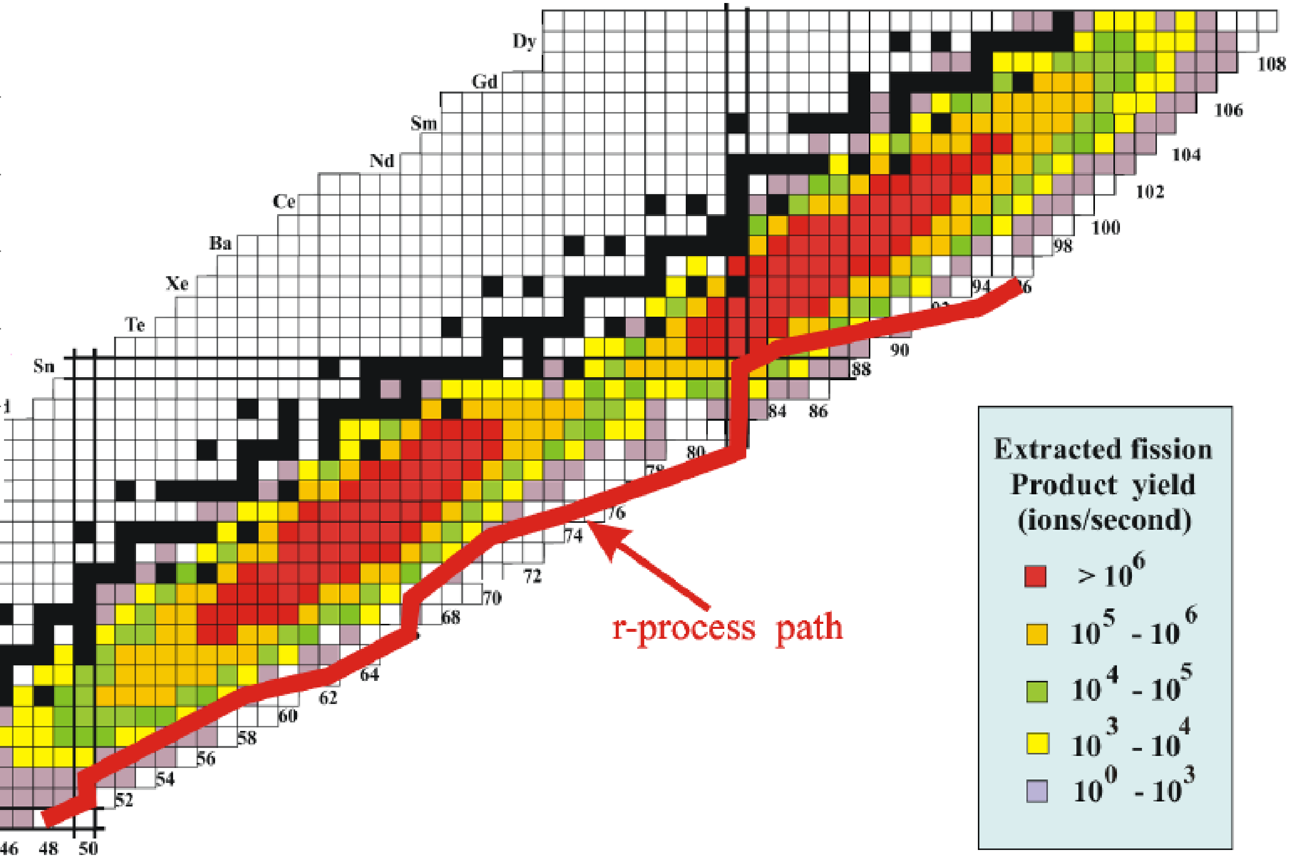
Fission of 1 Ci ^{252}Cf source at Argonne National Lab's ATLAS facility is projected to produce 500 neutron-rich species at a rate of >1/s.

J. A. Clark

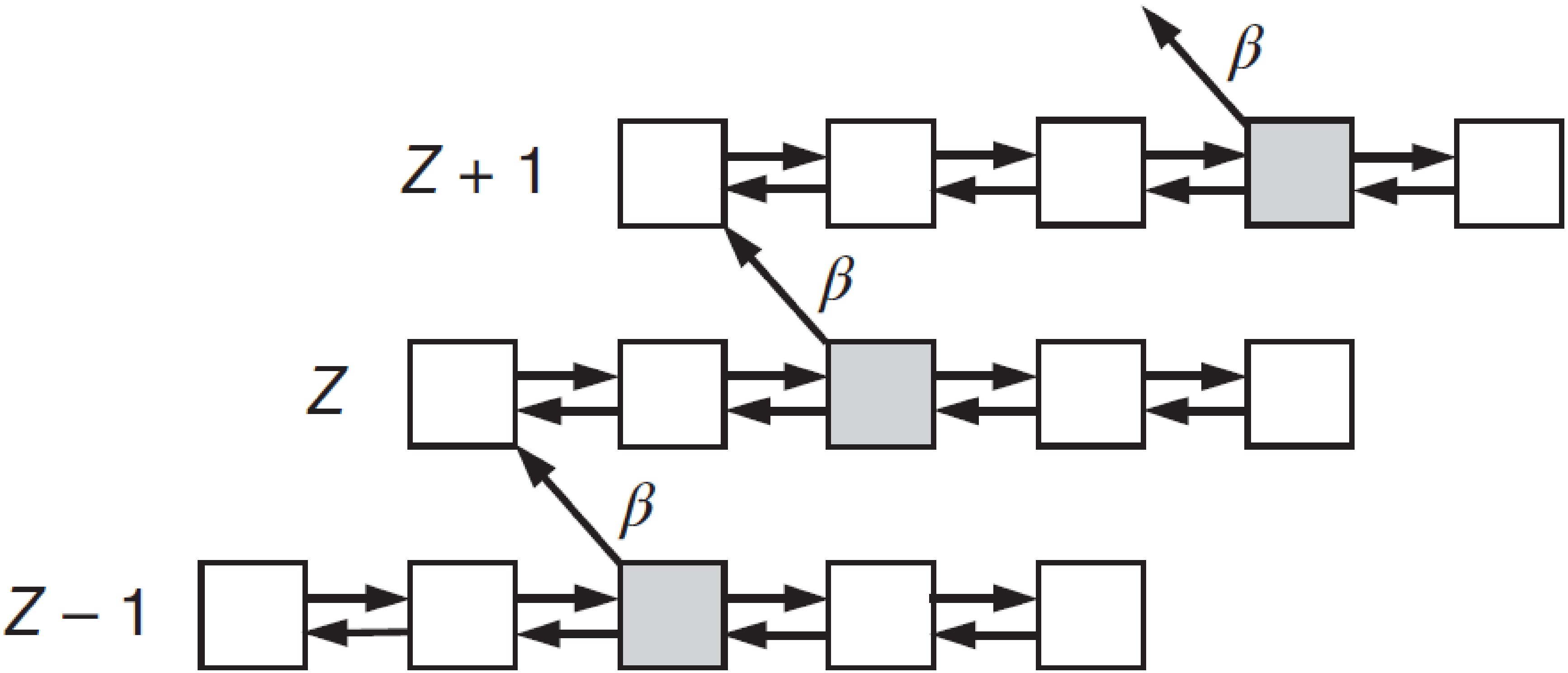
Canadian Penning Trap

One ion per second is sufficient for r-process mass measurements with the Canadian Penning Trap at ANL, for example.



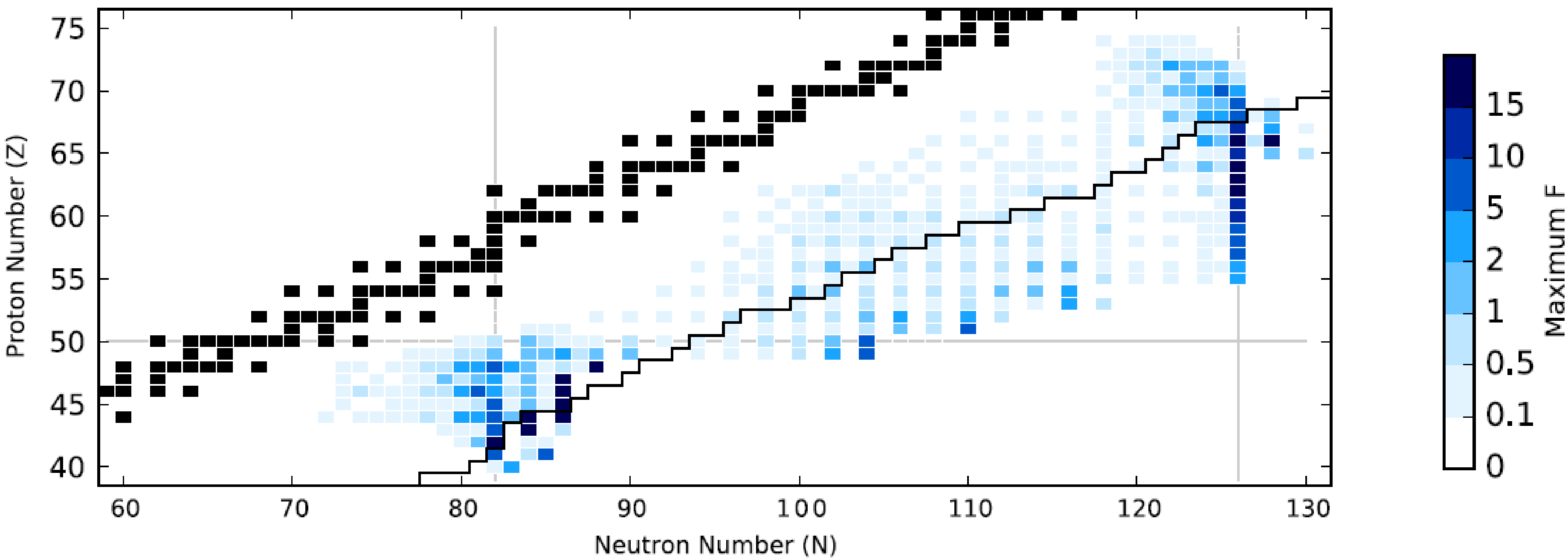


Beta decay half lives: importance



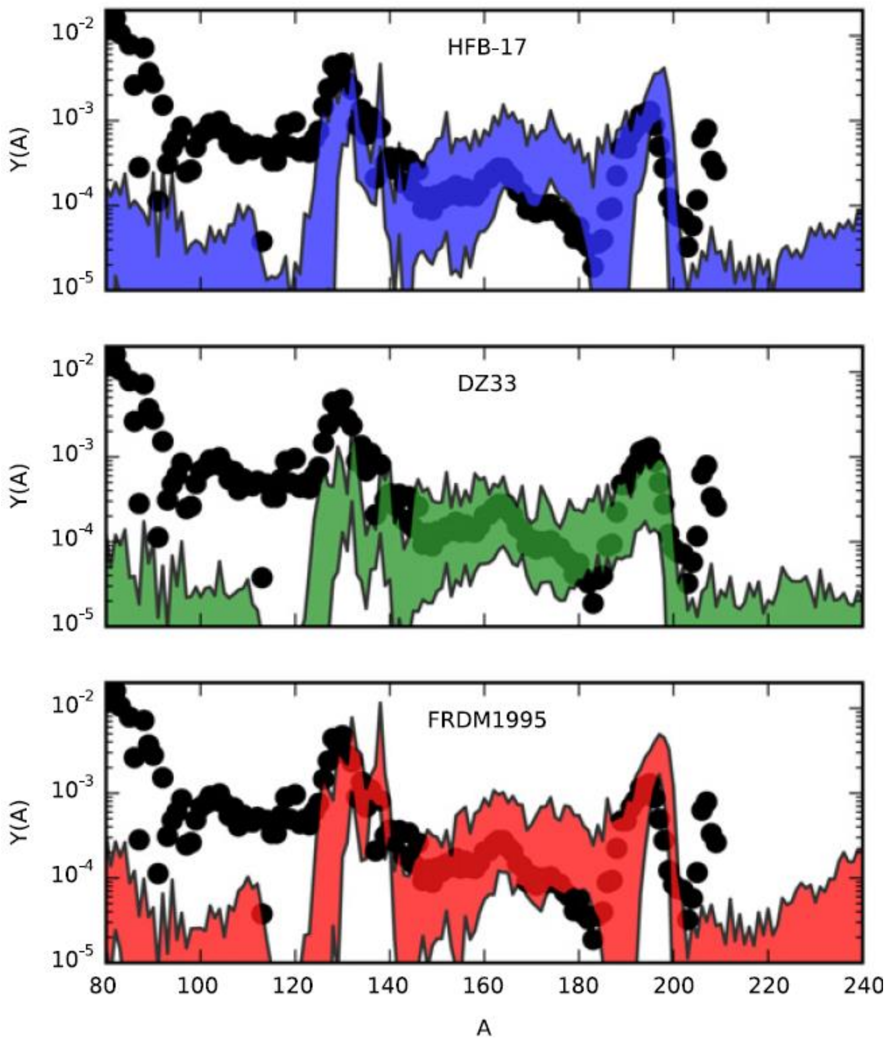
Beta decay transfers material to isotopic chains of higher-Z chemical elements, where equilibrium is established again. Gives rise to r process path.

r-process $T_{1/2}$ sensitivity



Mumpower *et al.*, PNPP 86, 86 (2016)

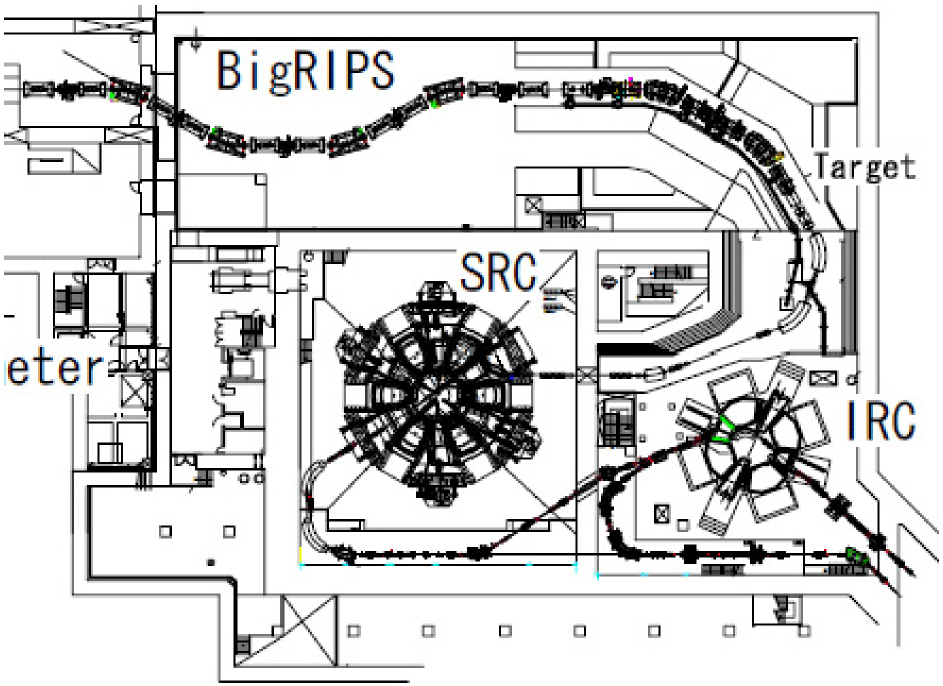
r-abundances from theoretical $T_{1/2}$

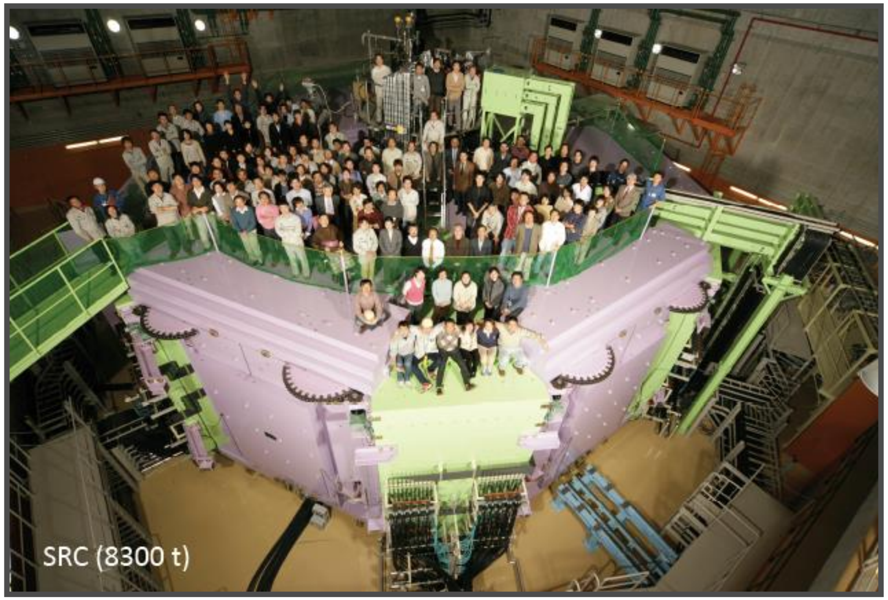


Need to measure half lives, too!

Mumpower *et al.*, PNPP 86, 86 (2016)

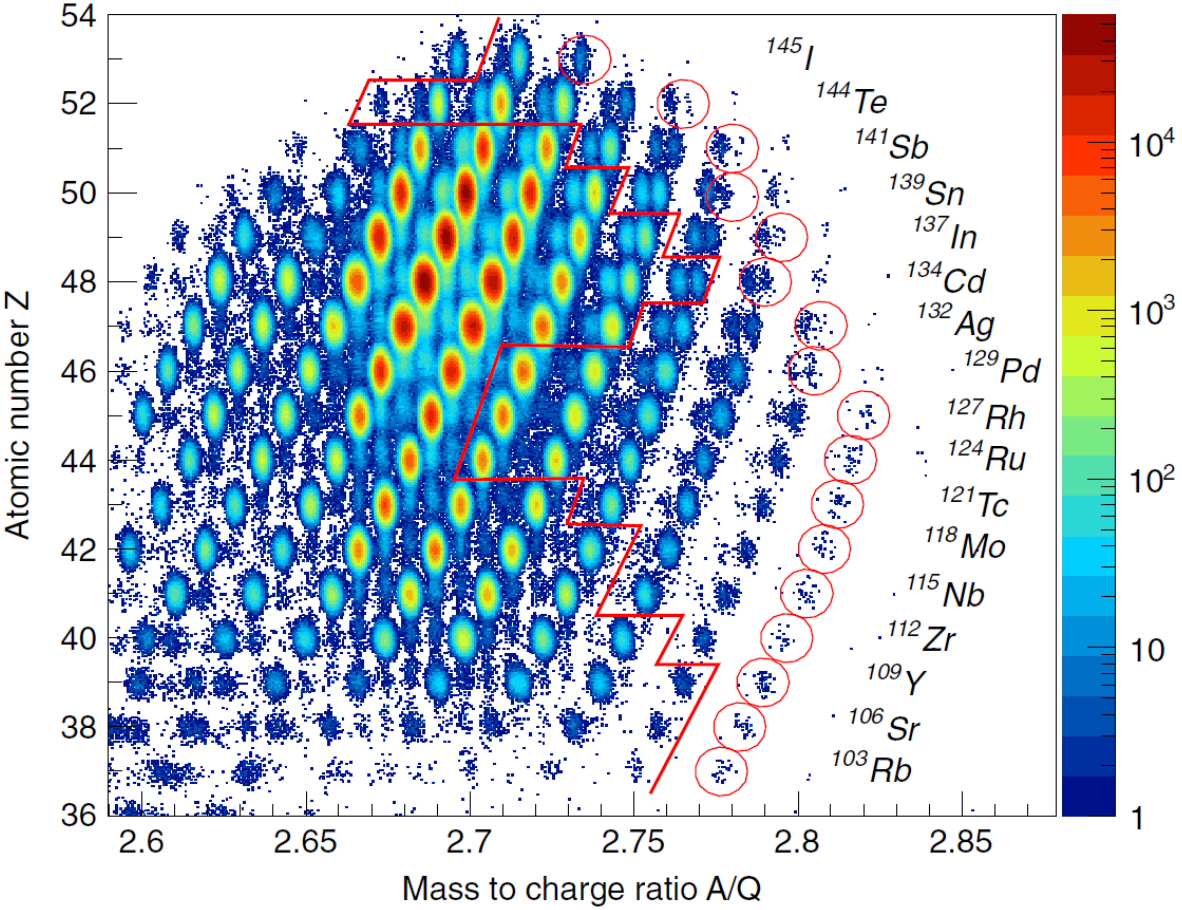
RIBF at RIKEN (Japan)





RIBF at RIKEN is currently the world leading in-flight RIB facility: it has primary beam powers exceeding 10 kW and can produce very neutron-rich nuclides.

Beta decay half lives: experiments



Example: fast beams produced by in-flight fission of ^{238}U at RIBF.

Species to the right of the red line are newly-measured half lives.

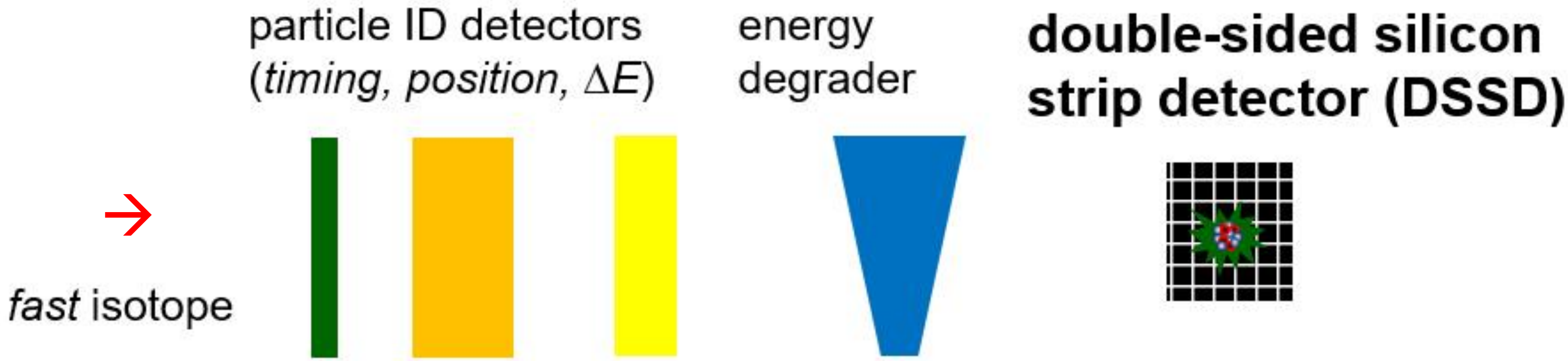
Circled species are most neutron-rich isotopes measured of each element.

Half lives can be measured in bulk given RIB rates of a few per day.

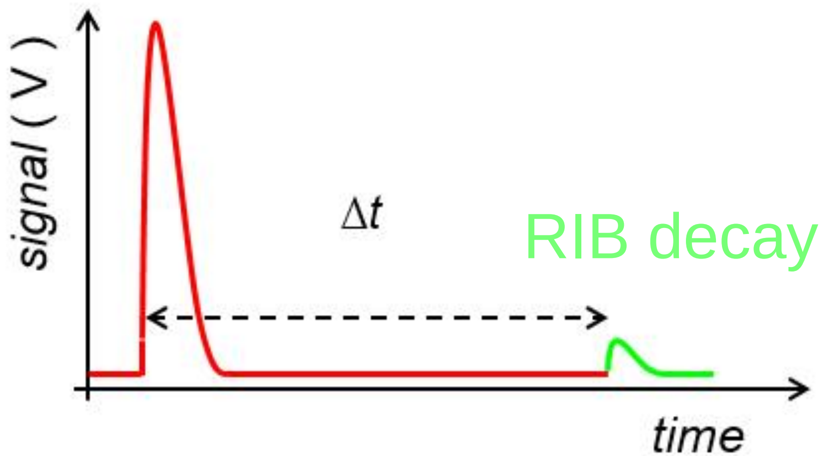
Particle ID plot obtained by combining time-of-flight with energy loss

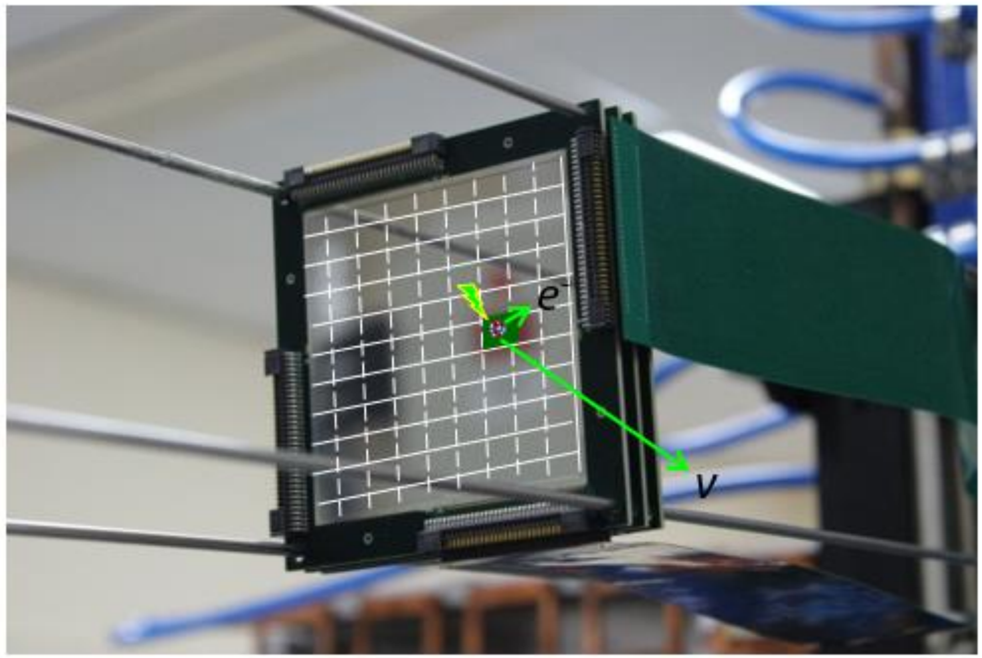
G. Lorusso *et al.*, Phys. Rev. Lett.114, 192501 (2015)

Correlating exotic ions with their β decays



RIB implantation



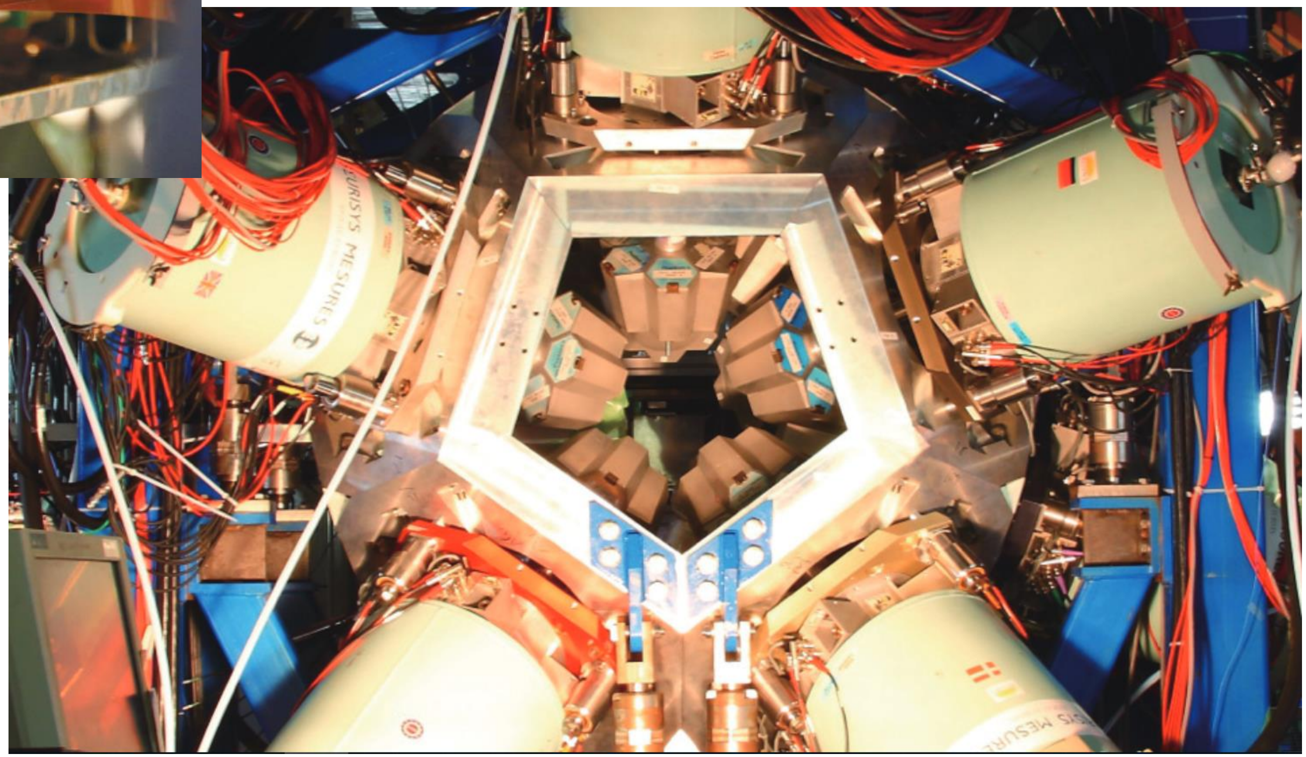


A. Estrade

RIKEN RIBF $T_{1/2}$ measurements

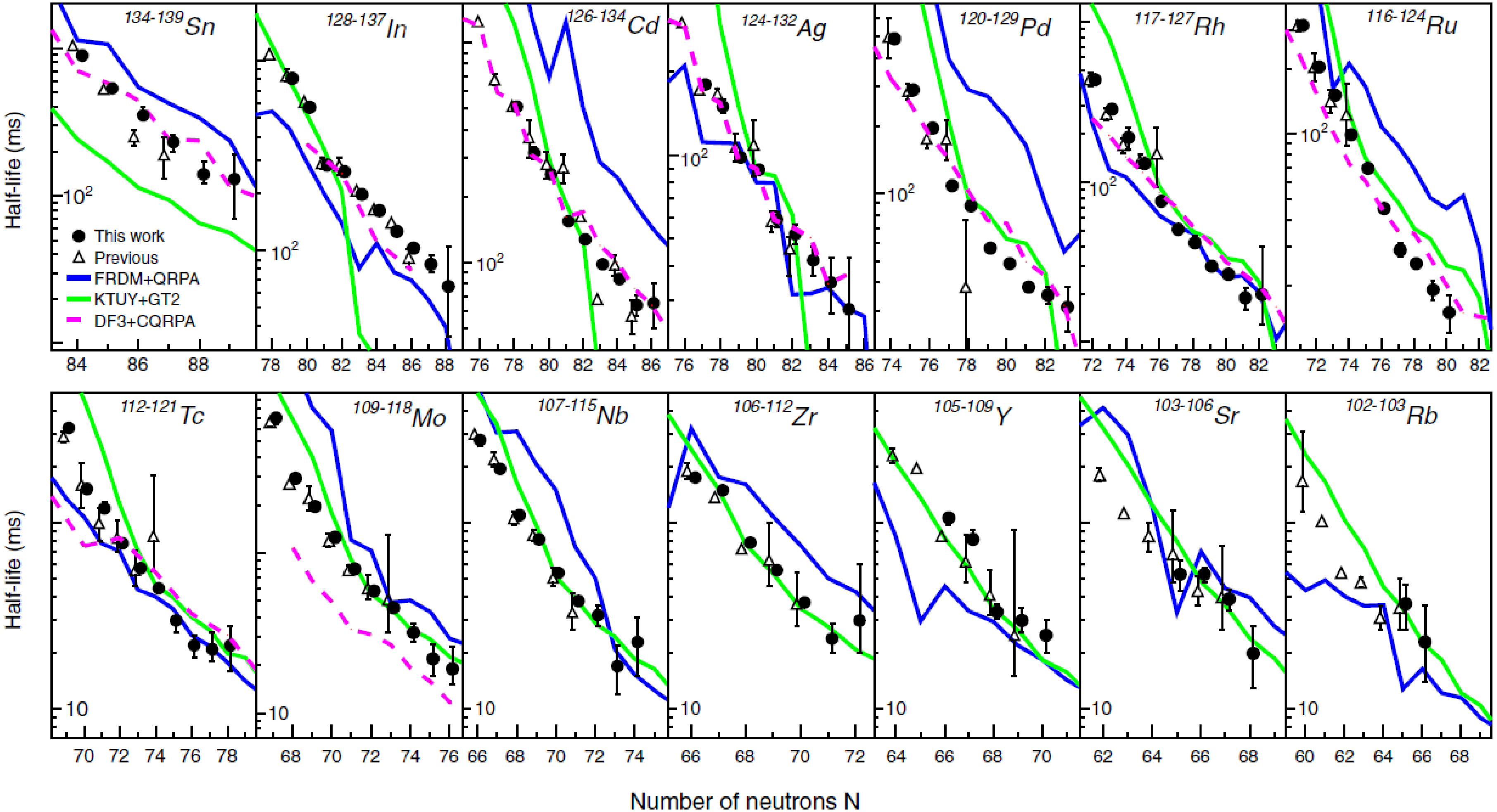
WASA3Bi Si stack detects RIB implantations and subsequent β decays.

EURICA Ge array detects γ rays emitted following β decay



G. Lorusso *et al.*, Phys. Rev. Lett.114, 192501 (2015)

RIKEN RIBF $T_{1/2}$ measurements

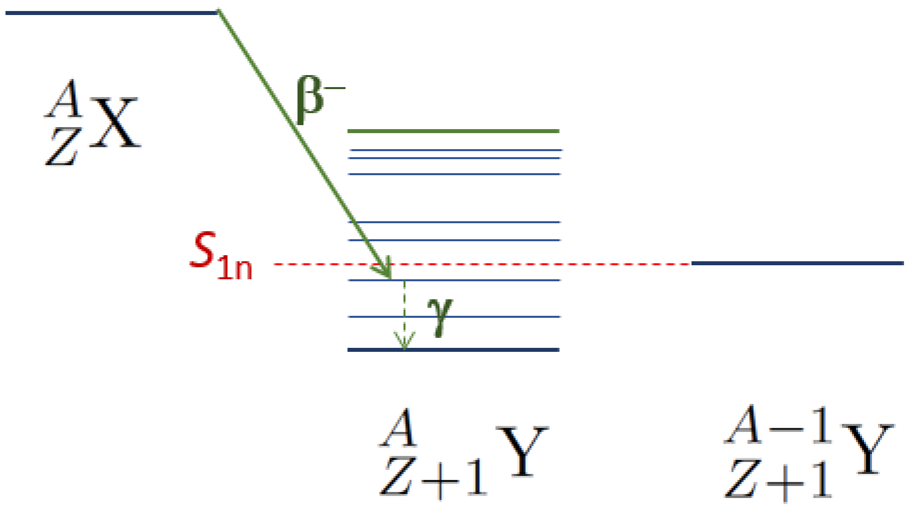


$T_{1/2}$ of 110 neutron-rich nuclides were measured including 40 new ones in the vicinity of *N* = 82 r-process waiting point. Sensitivity to nuclides with $T_{1/2}$ as low as 15 ms.

G. Lorusso *et al.*, Phys. Rev. Lett.114, 192501 (2015)

Beta delayed gamma decay

β-decay: $${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + \mathrm{e}^{-} + \bar{\nu}_e$$



A. Estrade

Beta delayed neutron decay

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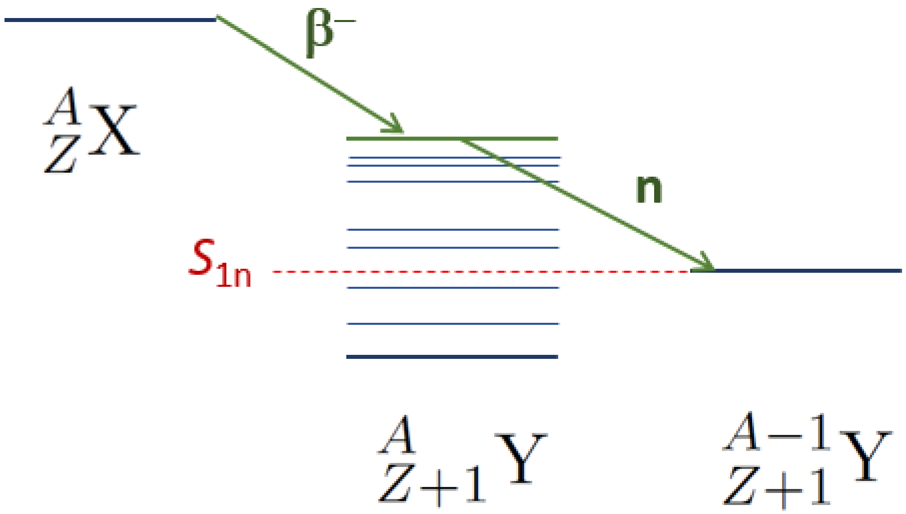
β-delayed neutron decay:

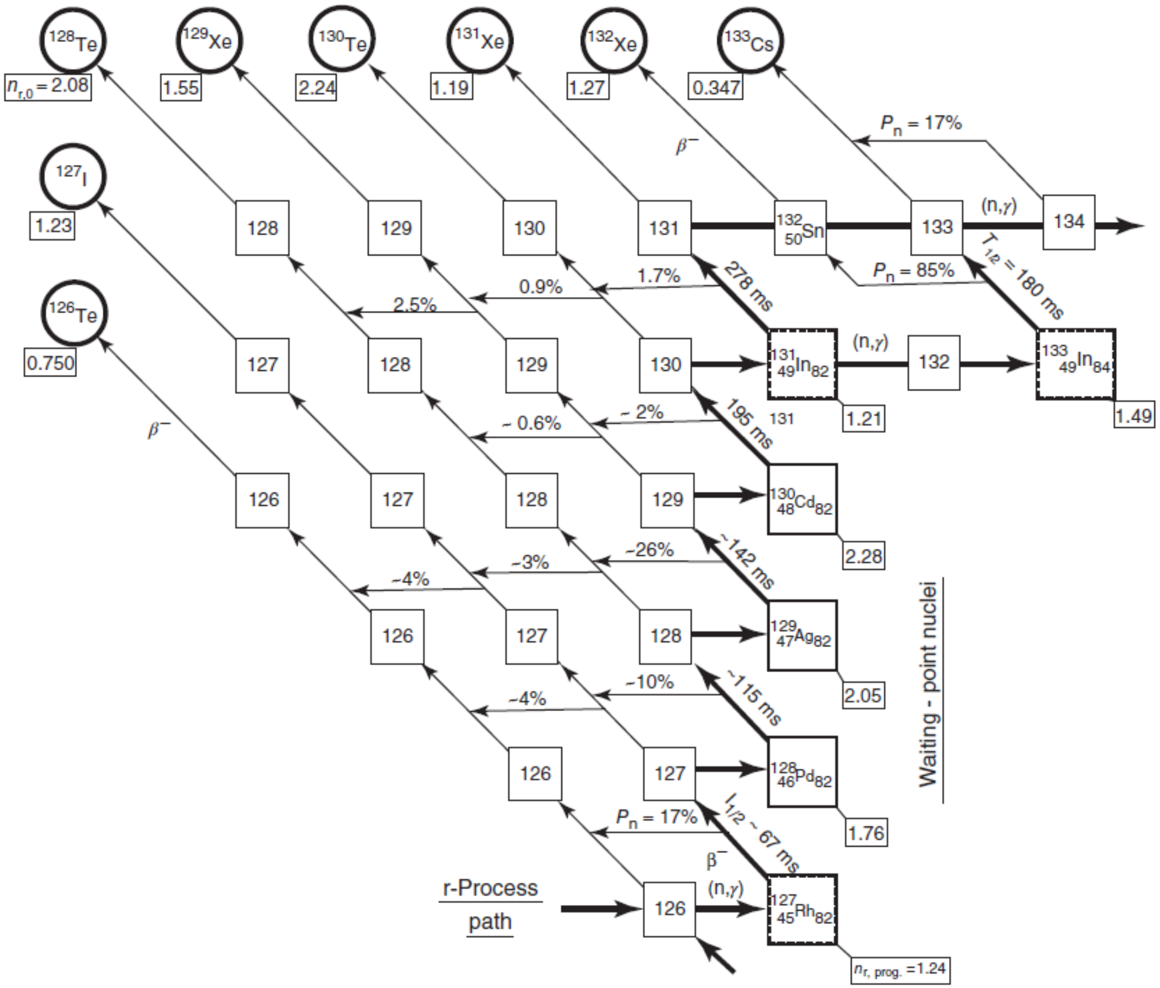
$${}^{A}_{Z}\mathrm{X} \rightarrow {}^{A-1}_{Z+1}\mathrm{Y} + \mathrm{n} + \mathrm{e}^{-} + \bar{\nu}_e$$



Probability for beta delayed neutron emission is called P_n.

A. Estrade

Beta delayed neutron decay: importance



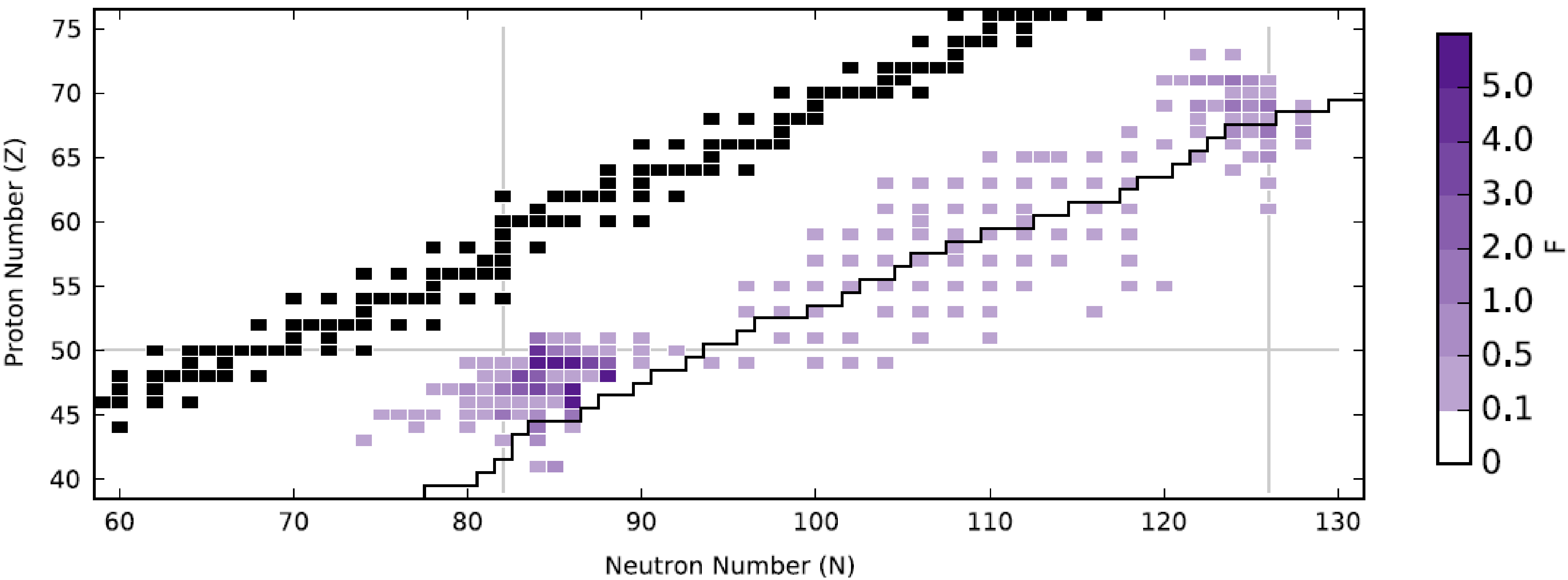
When r process ends, material β decays back to stability to form the r-process abundance pattern.

β decays can't be assumed to proceed along an isobaric chain because β-delayed neutron emission branch can be significant.

Example: interpretation of *A* = 130 abundance peak is influenced by probabilities of β delayed neutron emission, P_n.

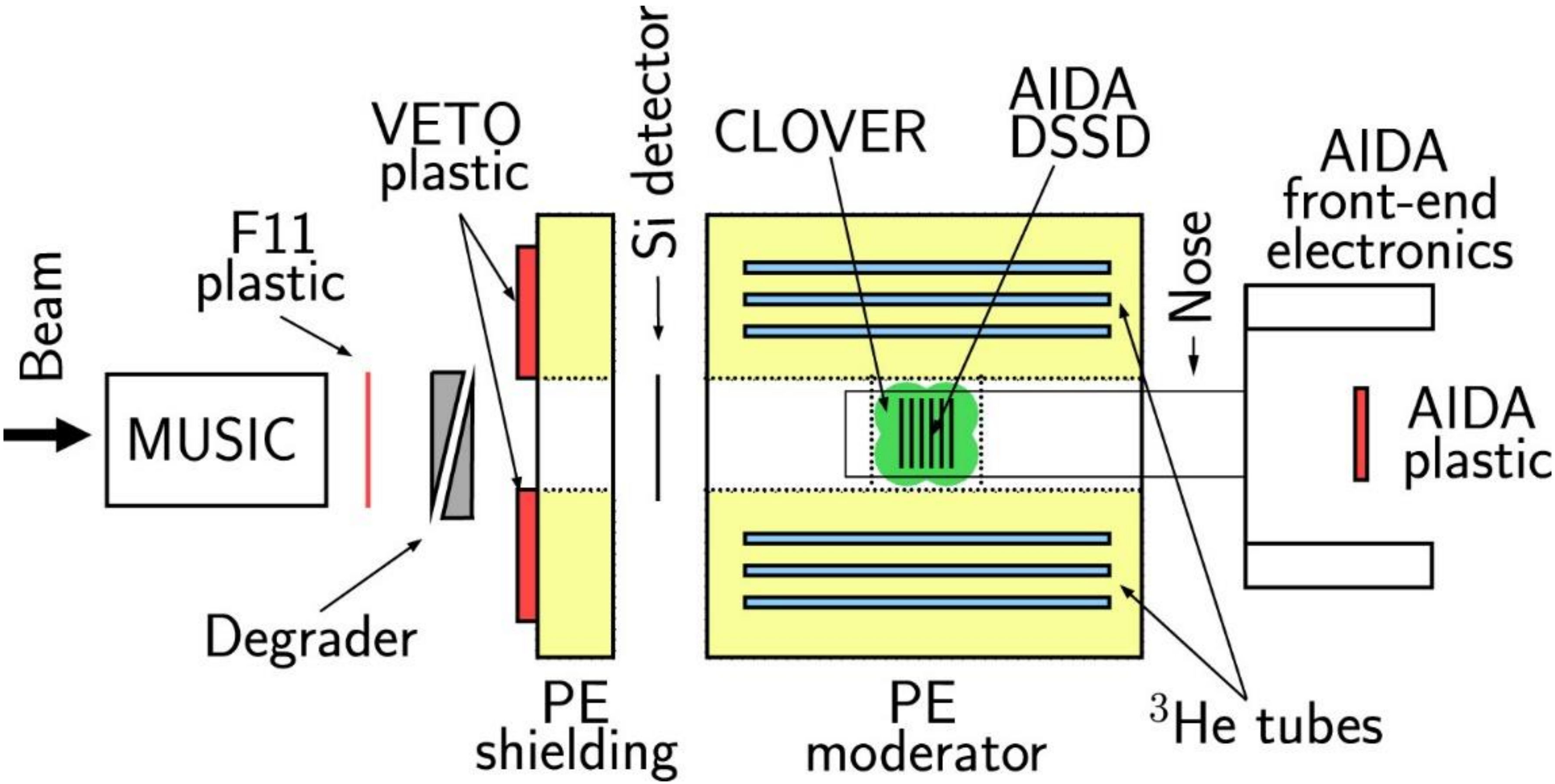
Nuclear Physics of Stars, Iliadis, 2nd Ed.

r-process P_n sensitivity



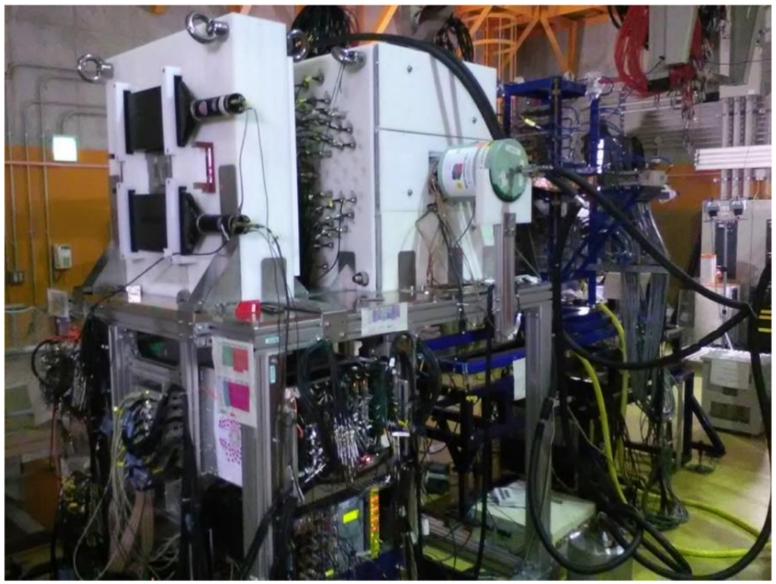
Mumpower *et al.*, PNPP 86, 86 (2016)

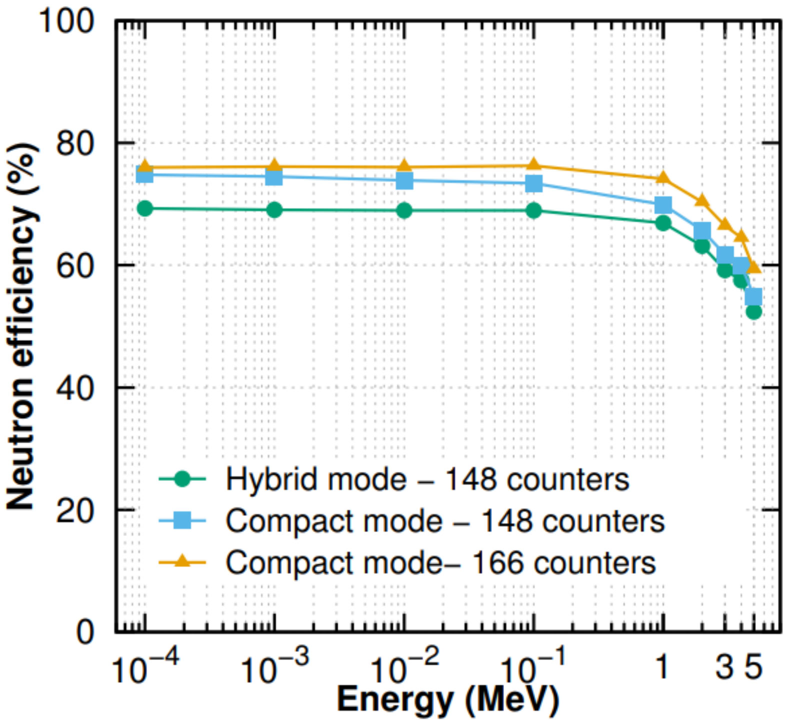
P_n experiment example: BRIKEN @ RIBF



A. Estrade
B. C. Rasco et al, NIM A 911, 79 (2018)
A. Tolosa-Delgado et al, *NIM A 925, 133 (2019)*

BRIKEN setup

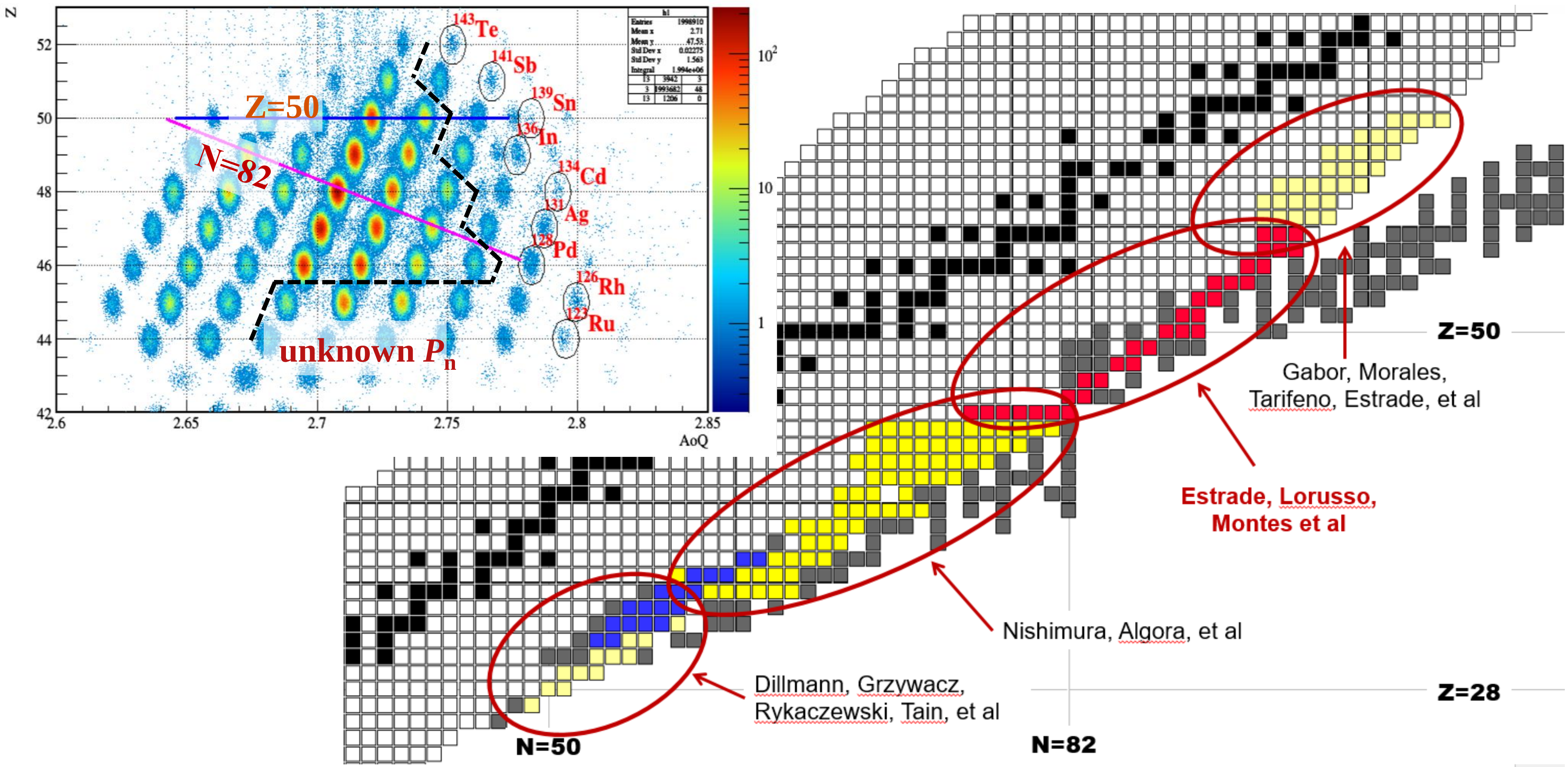




High neutron detection efficiency:
64% up to 1 MeV

A. Estrade
A. Tarifeño-Saldivia et al, JINST 12 P04006 (2017)
B. C. Rasco et al, NIM A 911, 79 (2018)
A. Tolosa-Delgado et al, *NIM A 925, 133 (2019)*

BRIKEN experimental campaigns



BRIKEN collaboration has recently acquired data to measure over 100 P_n values on or near the r-process path (also P_{2n} and P_{3n}).

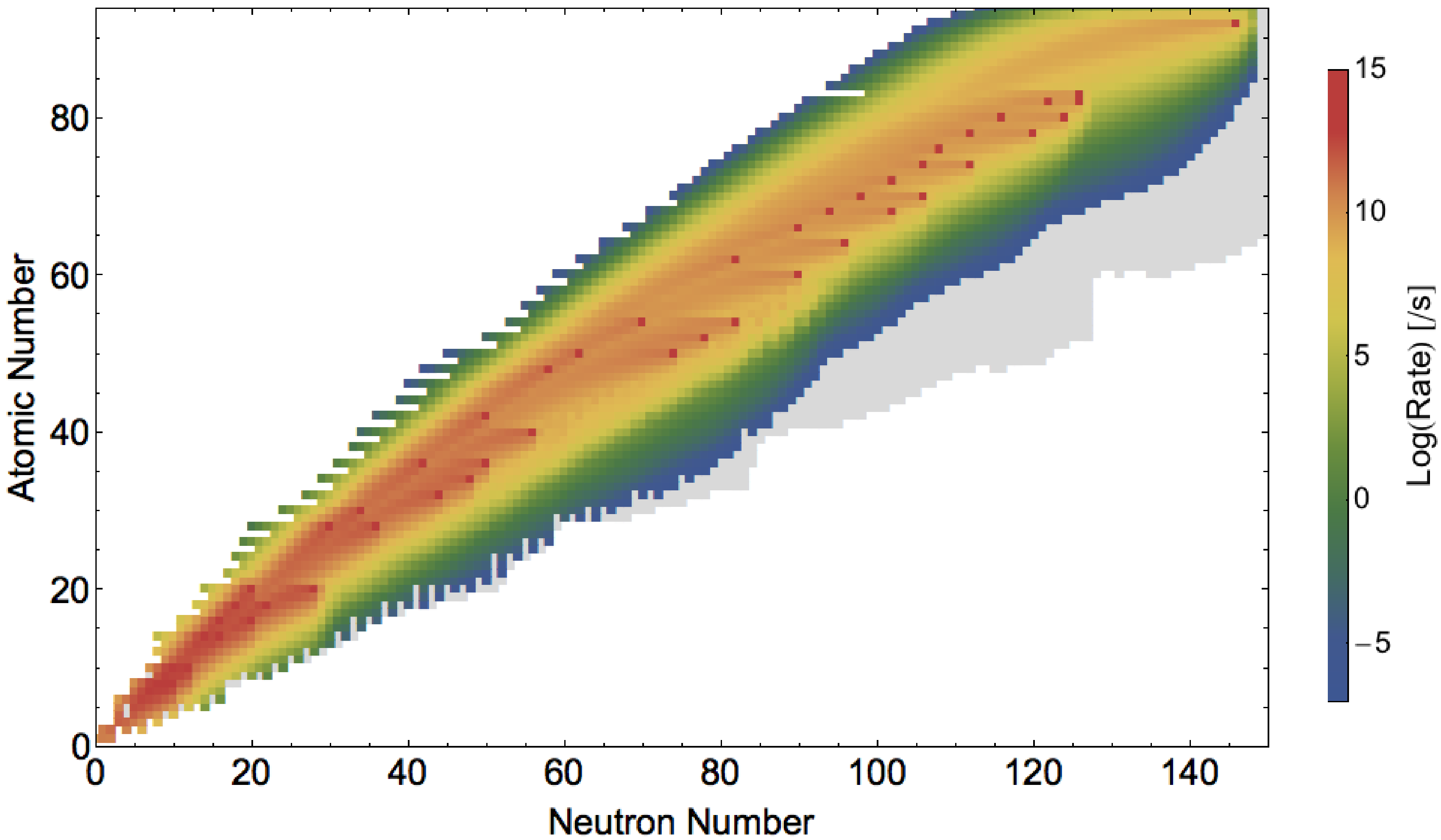
Things experimentalists won't be able to measure in detail/bulk anytime soon

Partition functions: Needed to augment ground-state decay constants with thermal excitations. Requires complete spectroscopy of the low-lying excited states of nuclides on the r-process path.

Fission probabilities: When r-process path runs close to the drip line, fission cycling becomes important. Region of interest (A~260, Z~94) is far from anything RIB facilities can produce in the near future. Instead, experimentalists will measure fission where they can and use that information to constrain theoretical models, which can then be applied to the r process.

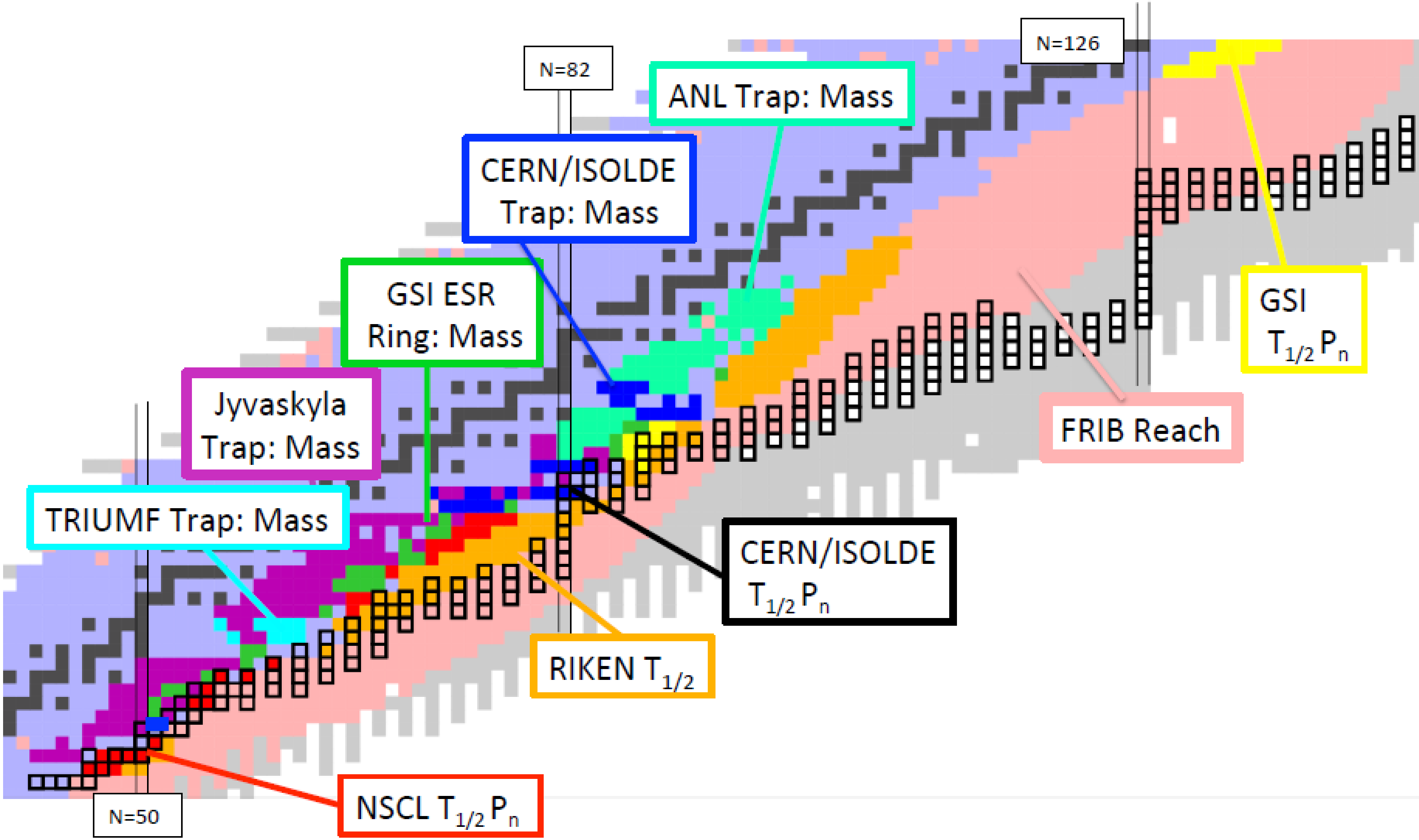
(n,γ) reaction rates: Important when there is no (n,γ)-(γ,n) equilibrium. Can't make a sufficiently dense neutron target for use with RIBs. Maybe one day our grandkids will be able to fill a bottle with Avogadro's number of ultra-cold neutrons. Until then, use indirect methods on selected reactions to constrain statistical-model calculations.

Near Future: FRIB



FRIB at MSU has been billed as the “r-process machine”: will facilitate measurements of all quantities discussed today for more exotic species.

Recent r-process measurements vs. FRIB



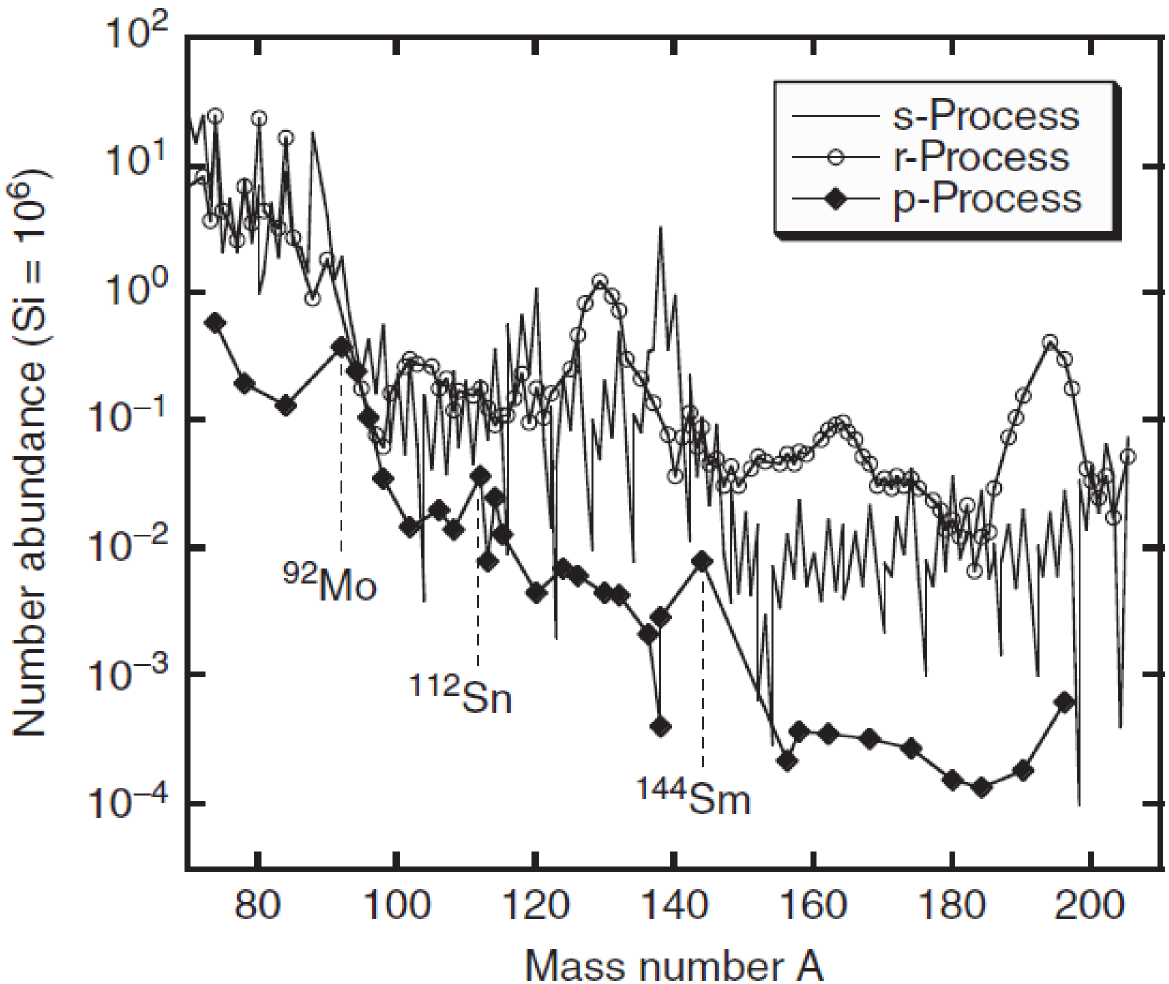
Horowitz *et al.*, arxiv:1805.04637

Summary

- Astrophysical r-process produces about half of the abundance of elements heavier than iron in the Universe
- Renewed interest in r-process due to the clear observation of one r-process site: neutron star mergers
- r-process yield depends on astrophysical conditions, and nuclear properties such as masses, half lives, and beta delayed neutron emission probabilities of very neutron-rich isotopes
- We can measure all of these quantities directly in the lab given sufficient RIB intensities; facilities worldwide are beginning to make measurements on the r-process path
- FRIB will take us further

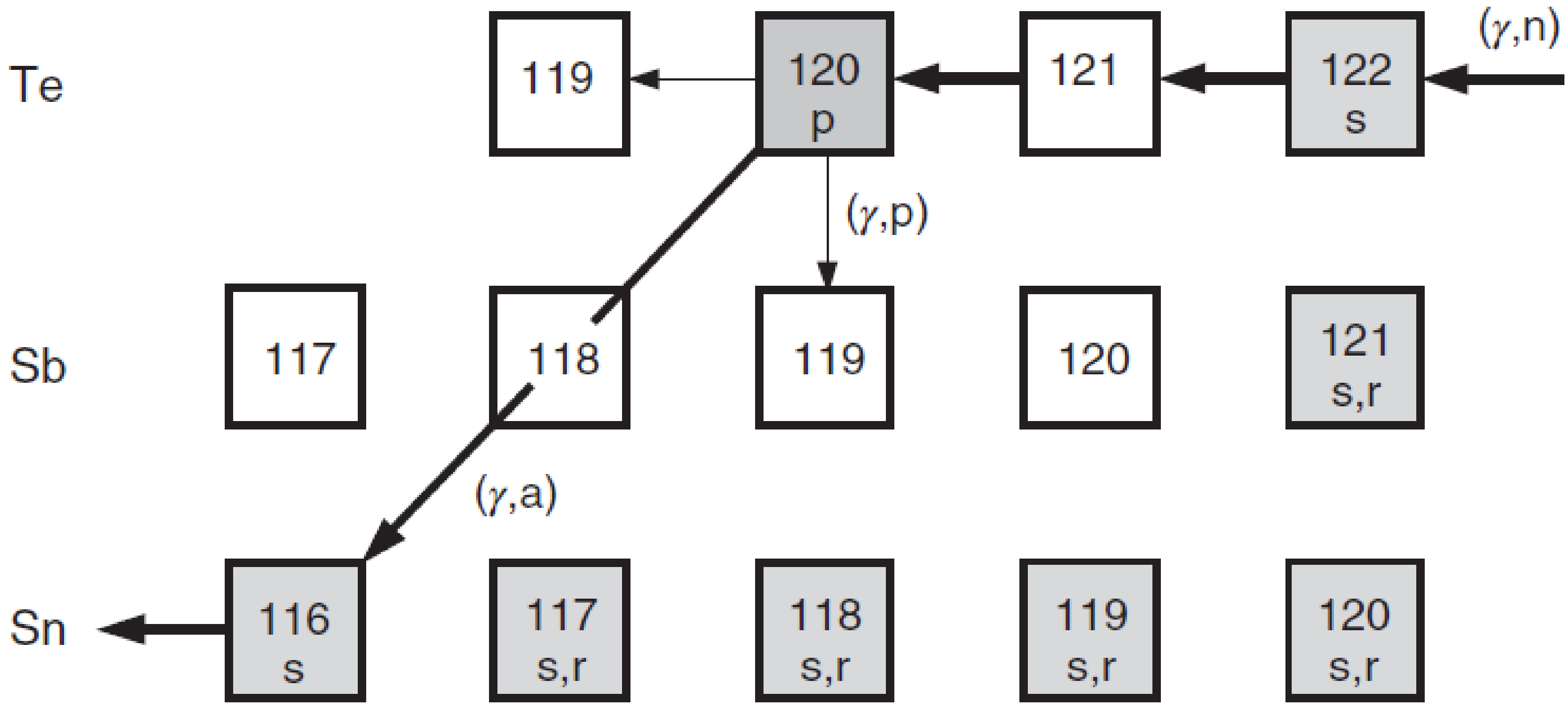
Thanks again for your attention!

p process



There are about 35 heavy nuclides that can't be produced by neutron capture processes: the p nuclides.

p process



"Gamma process" likely produces many p nuclides from s,r-process seeds in supernovae

Can measure (p,γ) and (α,γ) reactions to learn about photodisintegrations

Nuclear Physics of Stars, Iliadis, 2nd Ed.