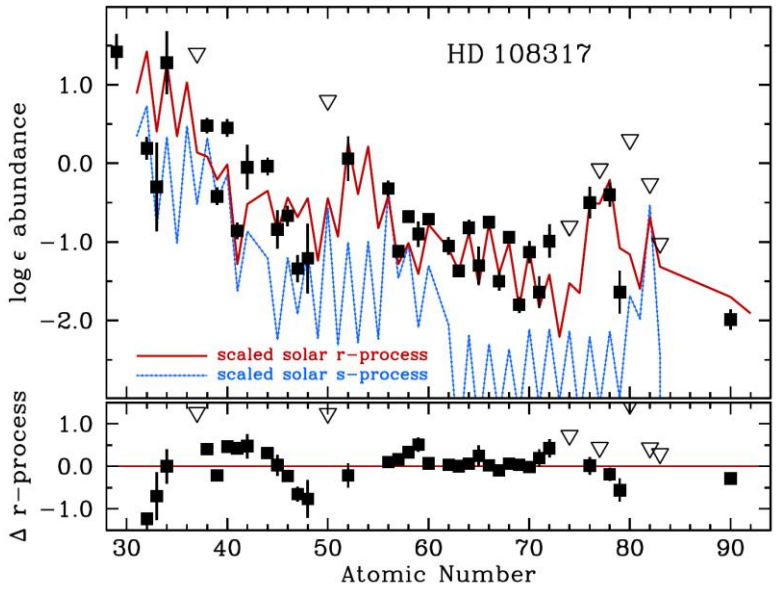
r-process experiments with unstable isotope beams

Alfredo Estrade
Central Michigan University

Conference on the Intersection of Particle and Nuclear Physics - 2018

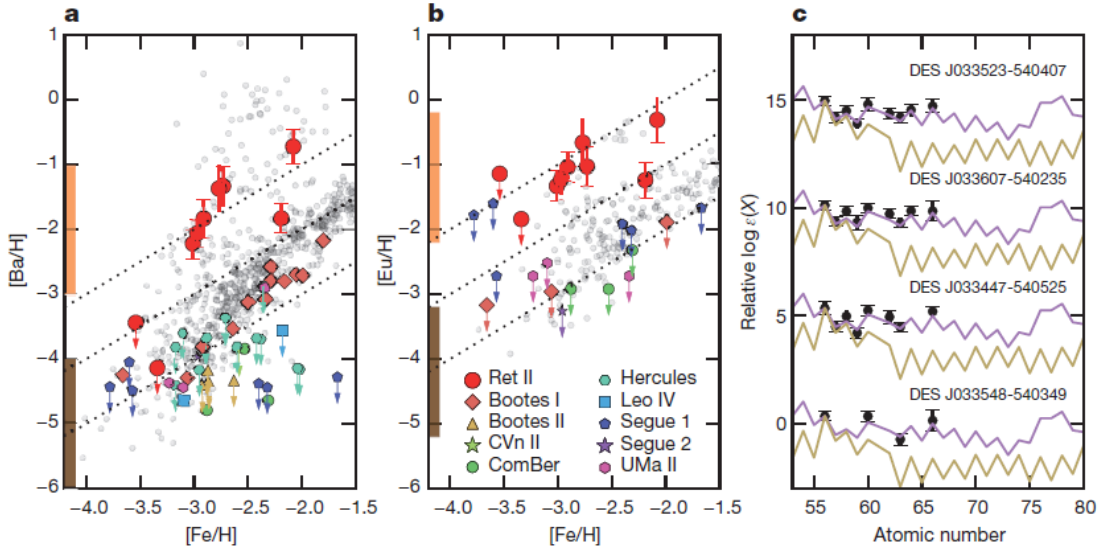
r-process observations

r-process elements in metal-poor stars



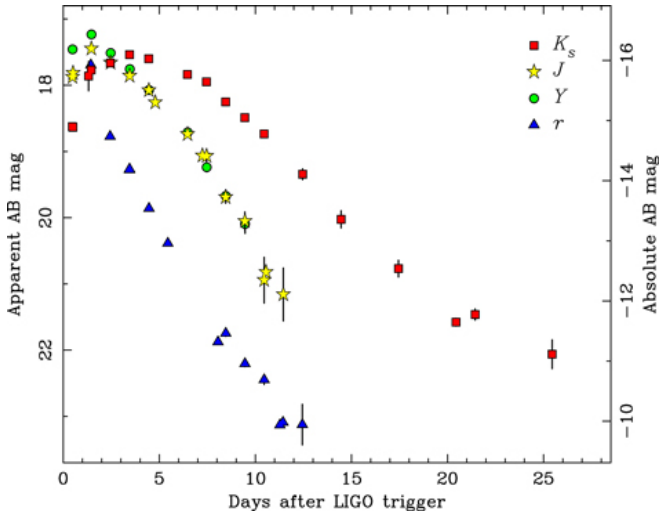
Roederer et al, ApJ (2014)

Ultra-faint Dwarf Galaxies (Reticulum II)



A. P. Ji et al, Nature (2016)

Kilonova from GW170817



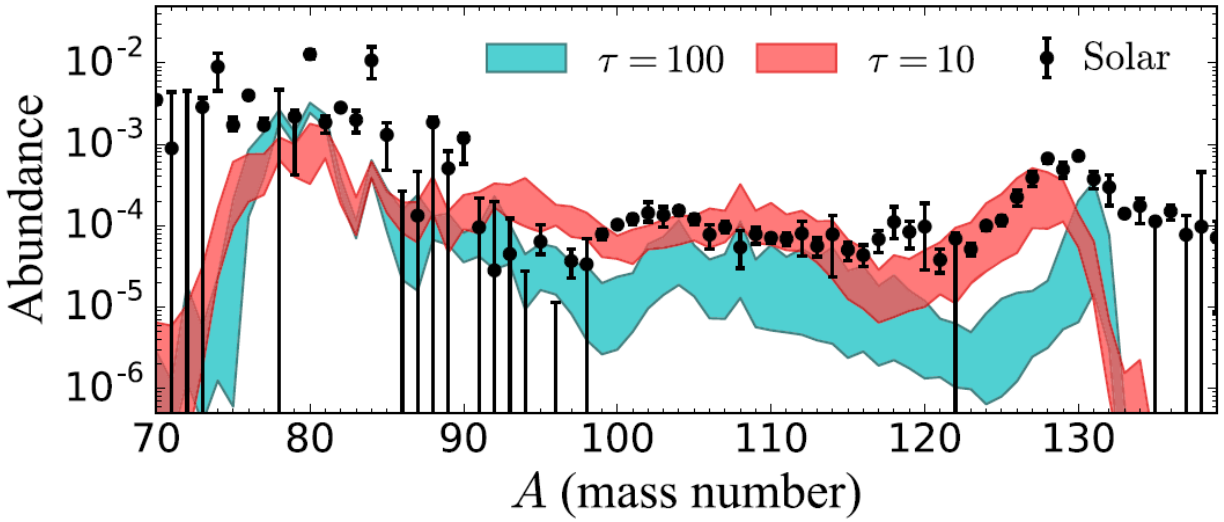
Tanvir et al, ApJ 848, L27 (2017)

Some outstanding questions:

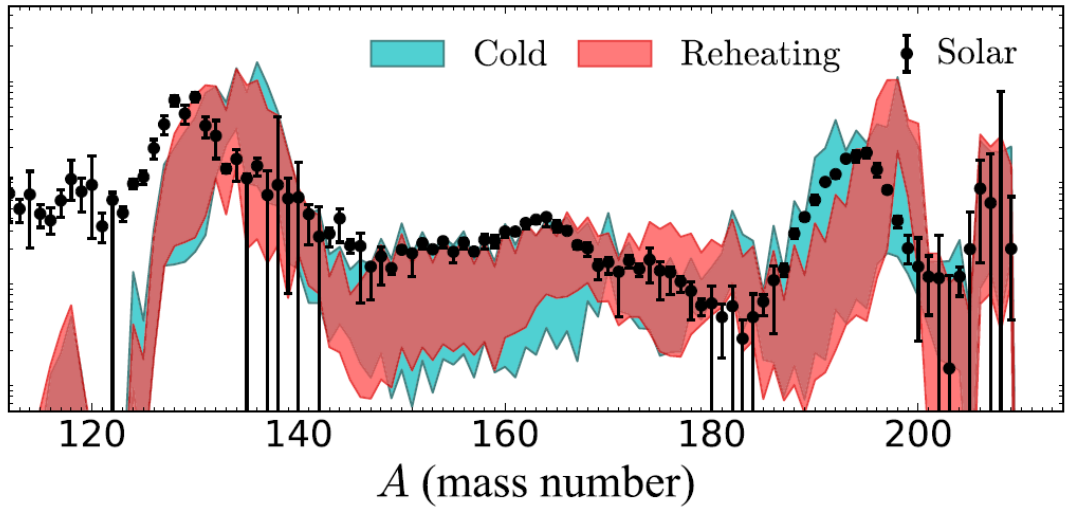
- Is there a weak r-process?
- What are the different sites?
- How does each site contribute to galactic chemical evolution?

Nuclear data uncertainties in r-process models

neutrino wind (*high* Y_e)



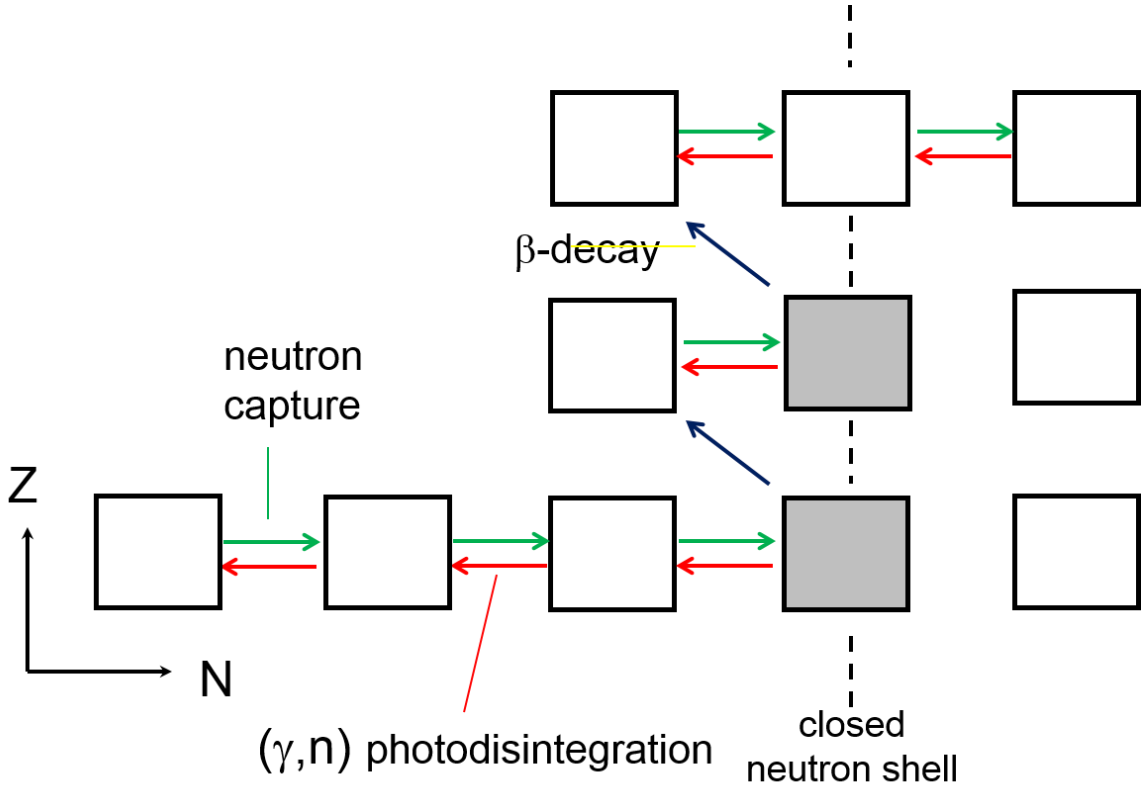
dynamical ejecta (*low* Y_e)



Cote et al, ApJ 855, 99 (2018)

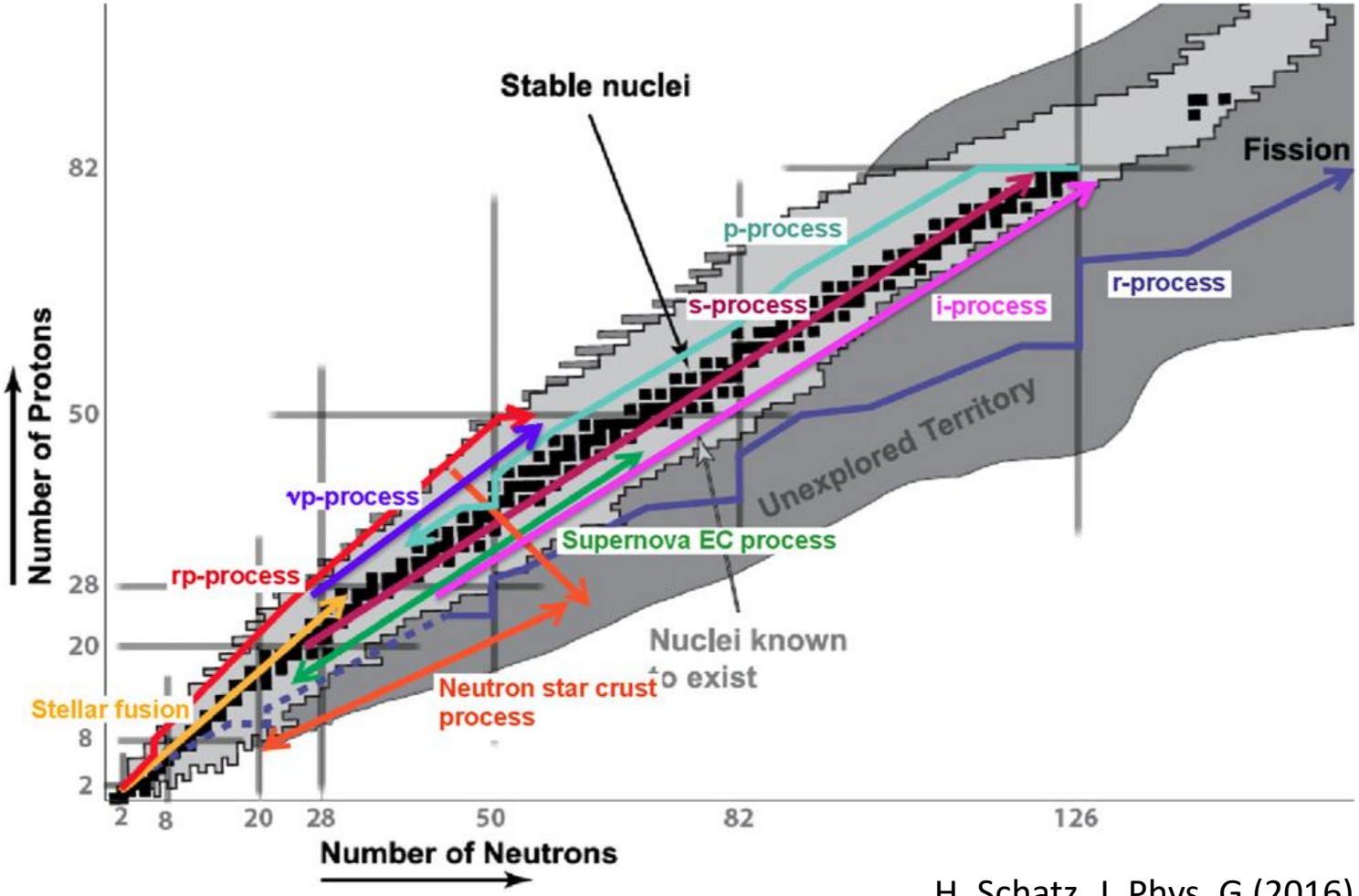
Uncertainty band: different theoretical models for nuclear mass

Relevant nuclear physics properties



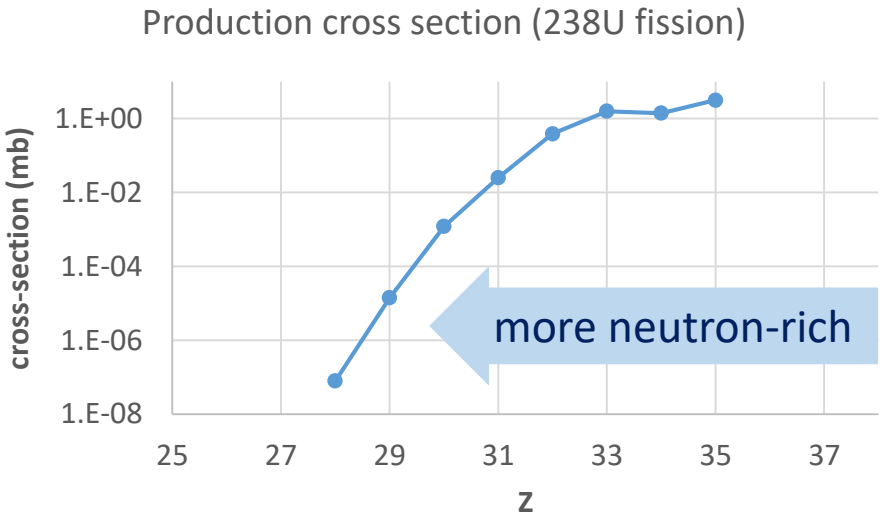
- **masses**
- β-decay half-lives and **modes**
- **(n,γ)** and (α,n) reactions
- fission properties

Terra-incognita



H. Schatz, J. Phys. G (2016)

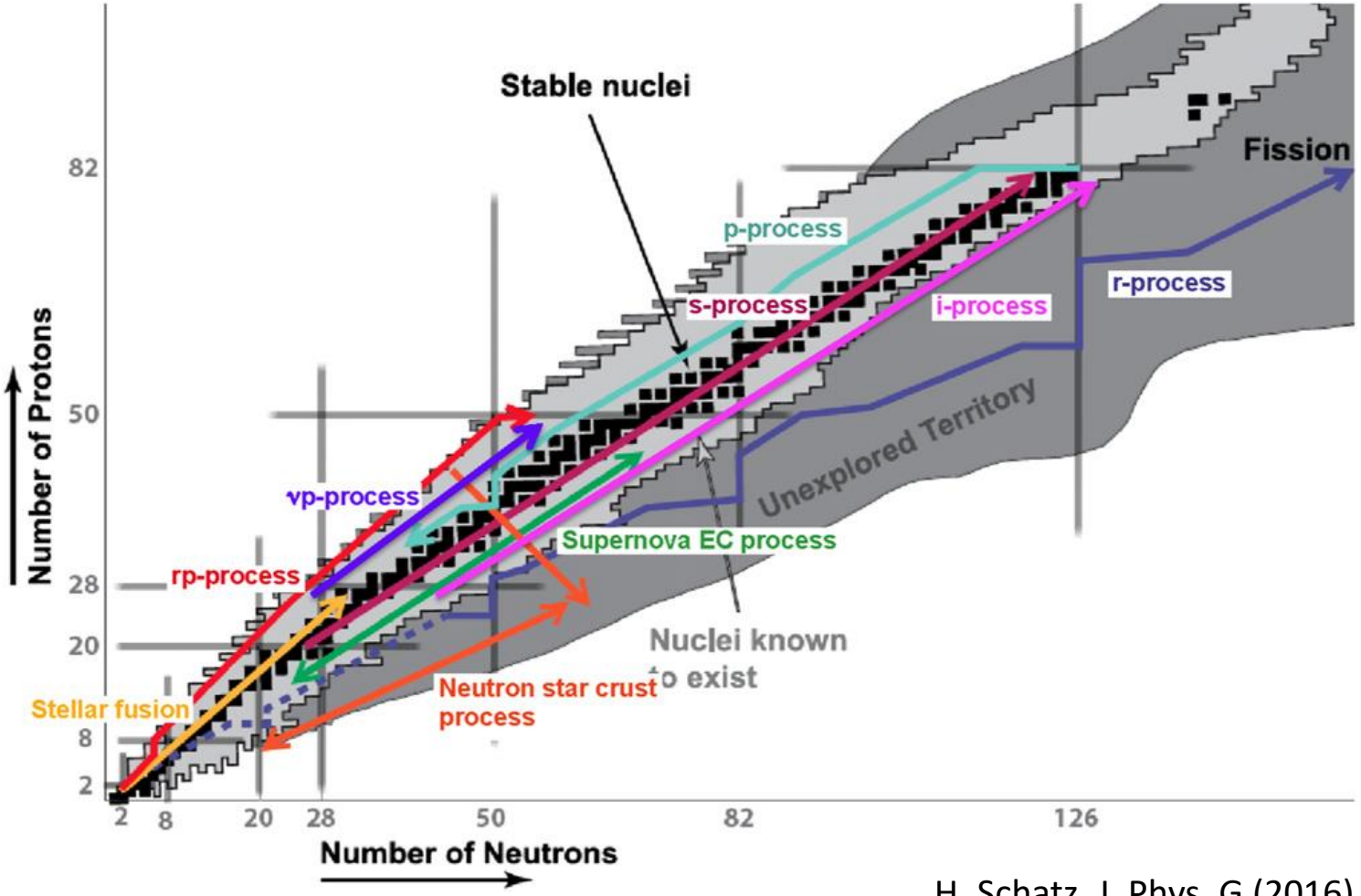
N=50 isotones



Facility for Rare Isotope Beams

@ Michigan State University

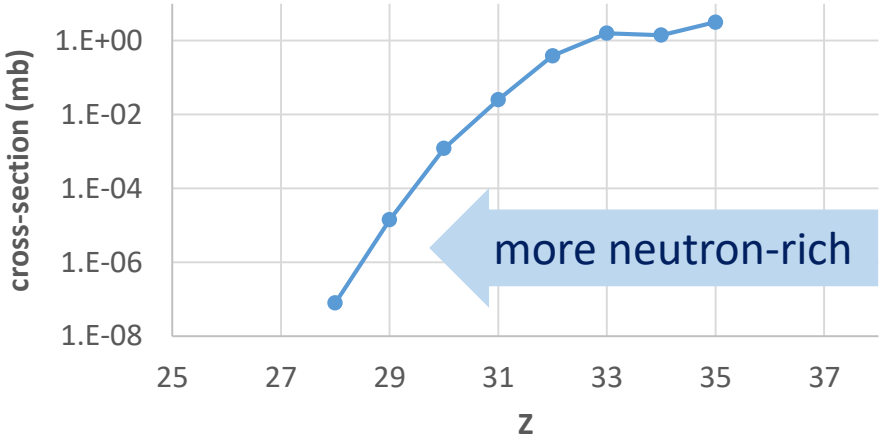
Terra-incognita



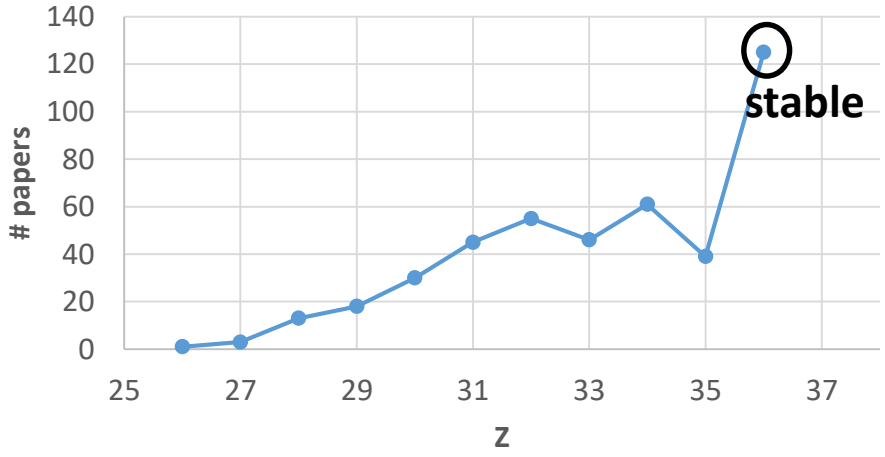
H. Schatz, J. Phys. G (2016)

N=50 isotones

Production cross section (238U fission)



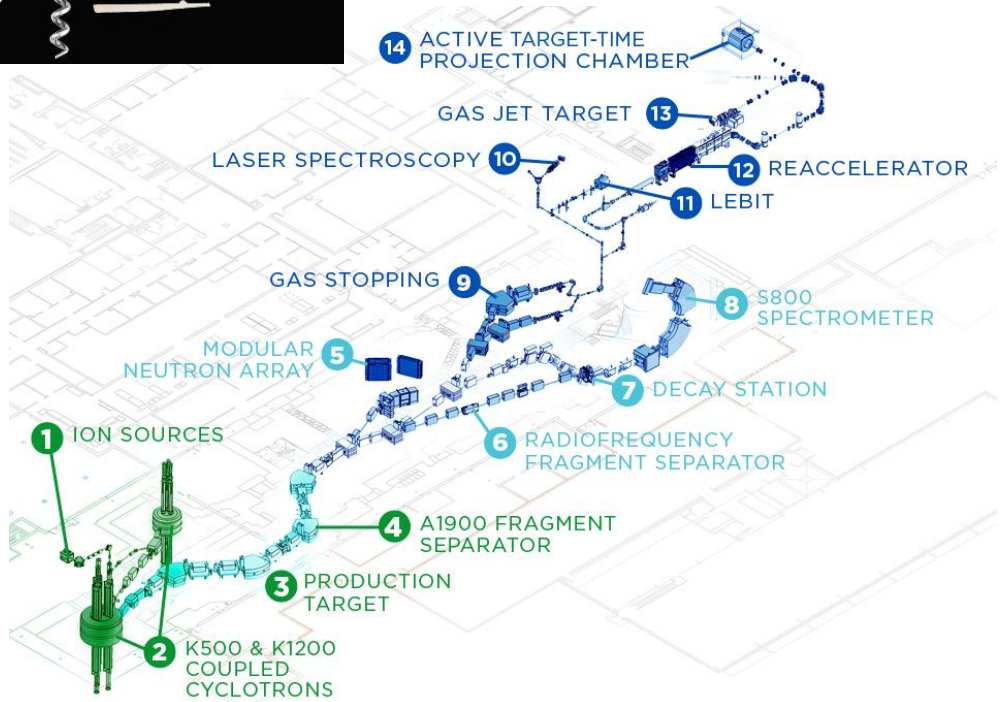
Experimental papers in NSR database



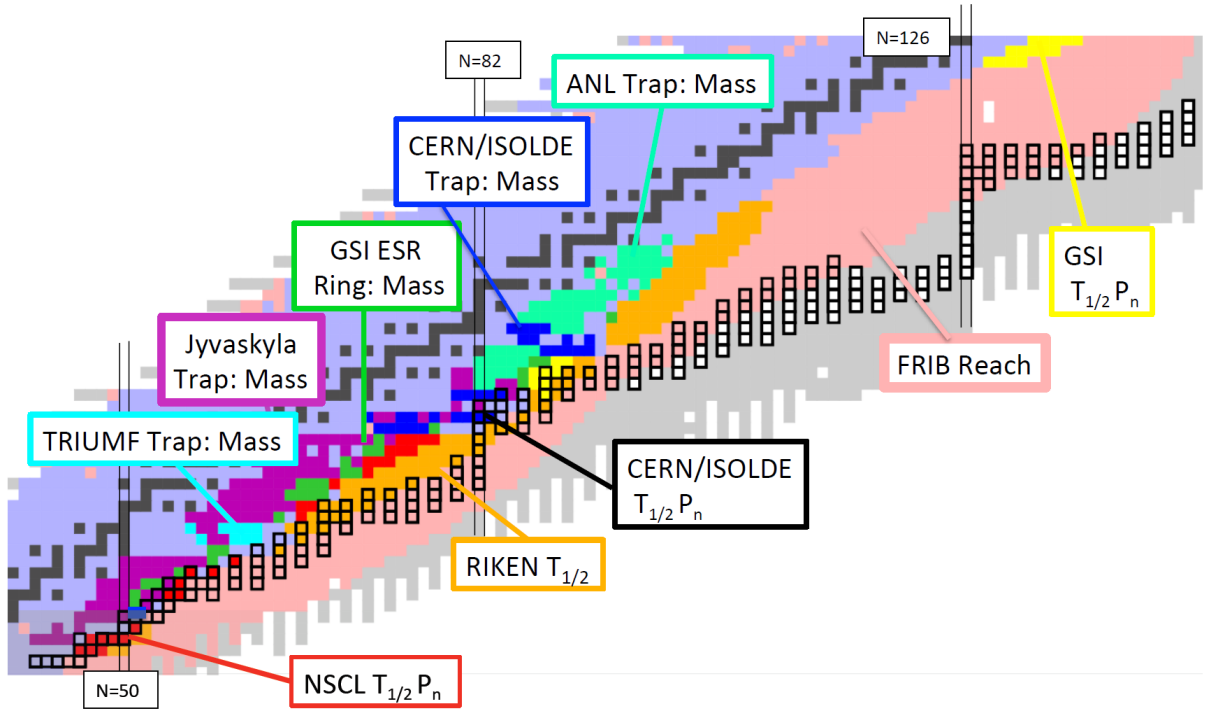
Experimental tools

National Superconducting Cyclotron Laboratory

@ Michigan State University



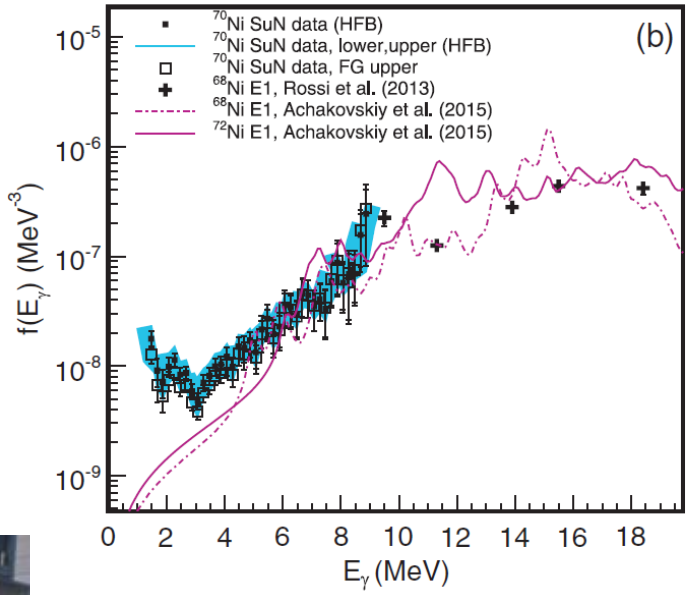
Recent experiments relevant to r-process models

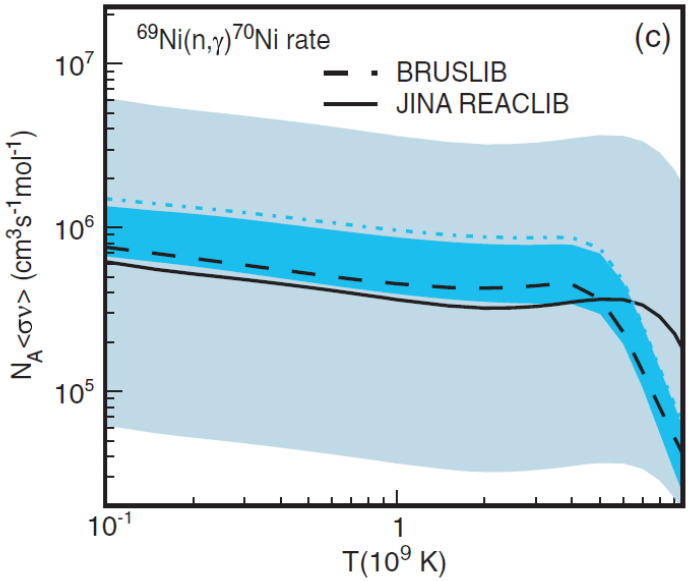


Review paper: C Horowitz et al, arXiv 1805.04637

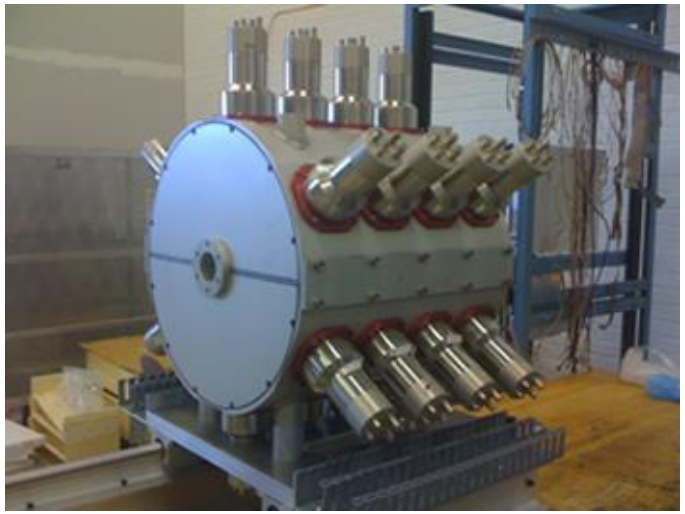
Neutron capture rates through β-Oslo method

Experimental constrains on nuclear level densities and gamma strength function for statistical-model calculations of neutron capture rates.



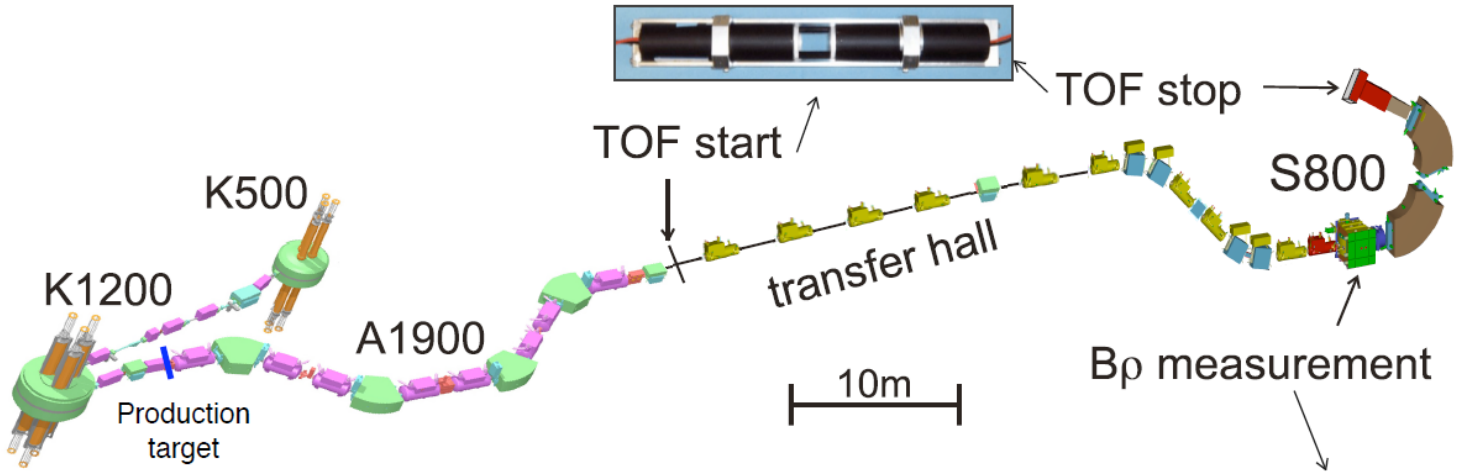


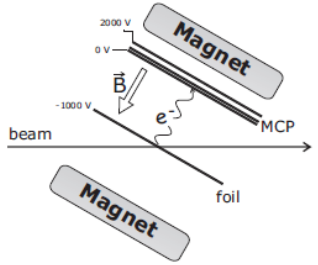
SuN: Summing NaI detector



S. Liddick et al, PRL 116, 242502 (2016)
A. Spyrou et al, PRL 117, 142701 (2016)

TOF mass measurements

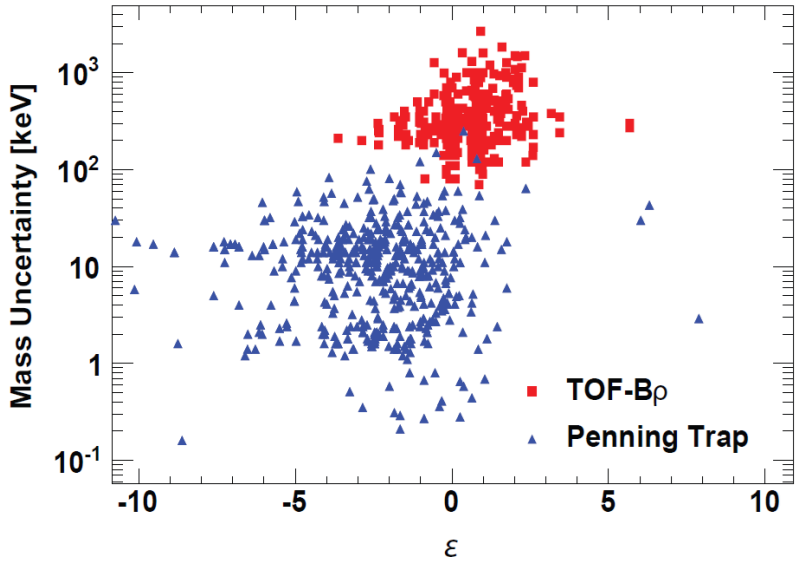




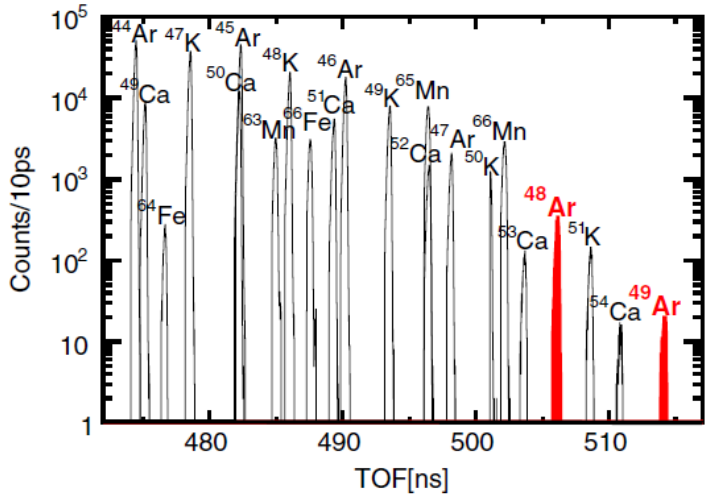
Mass derived from equation of motion of ions in beamline:

$$B\rho = \frac{\gamma p}{q} = \frac{\gamma m_0}{q}\left(\frac{L}{TOF}\right)$$

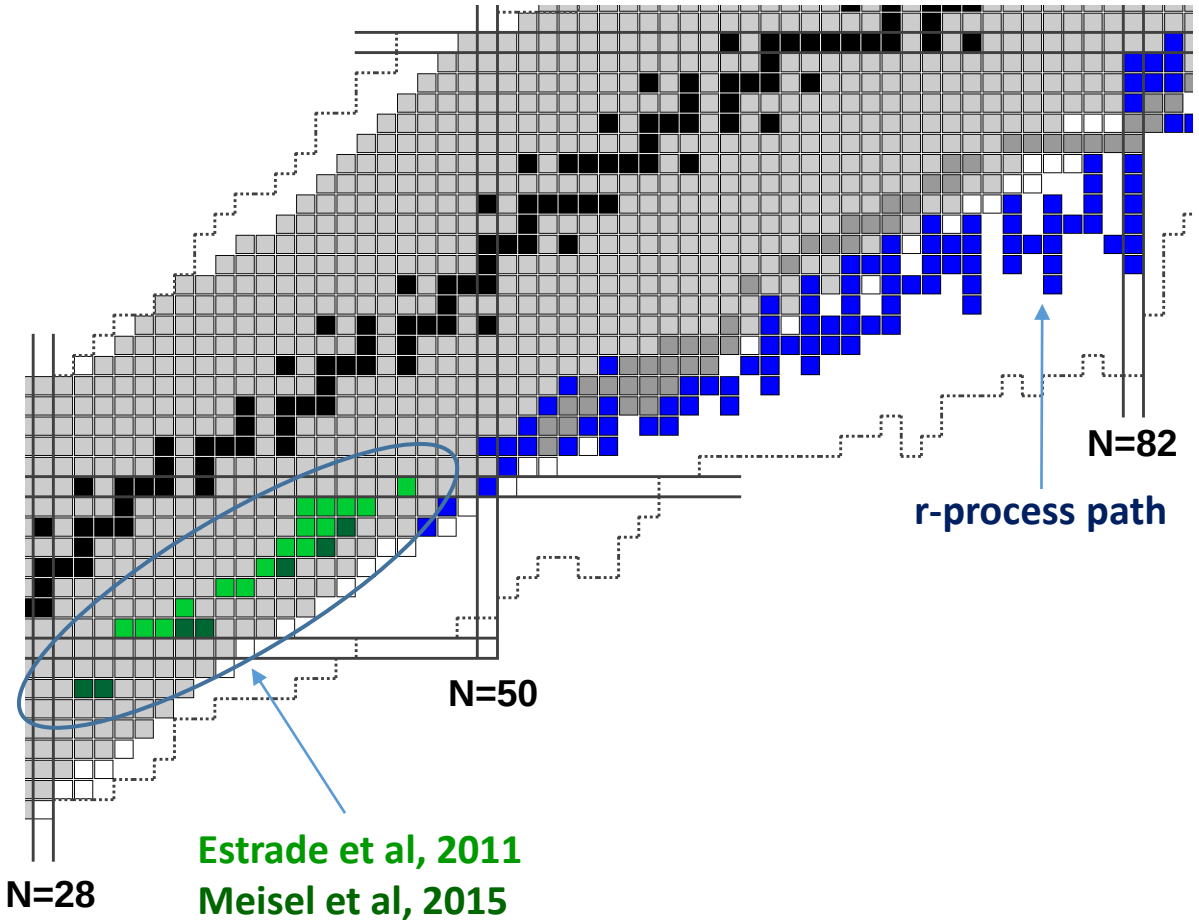
M. Matos, A. Estrade et al, NIMA 696 (2012) 171



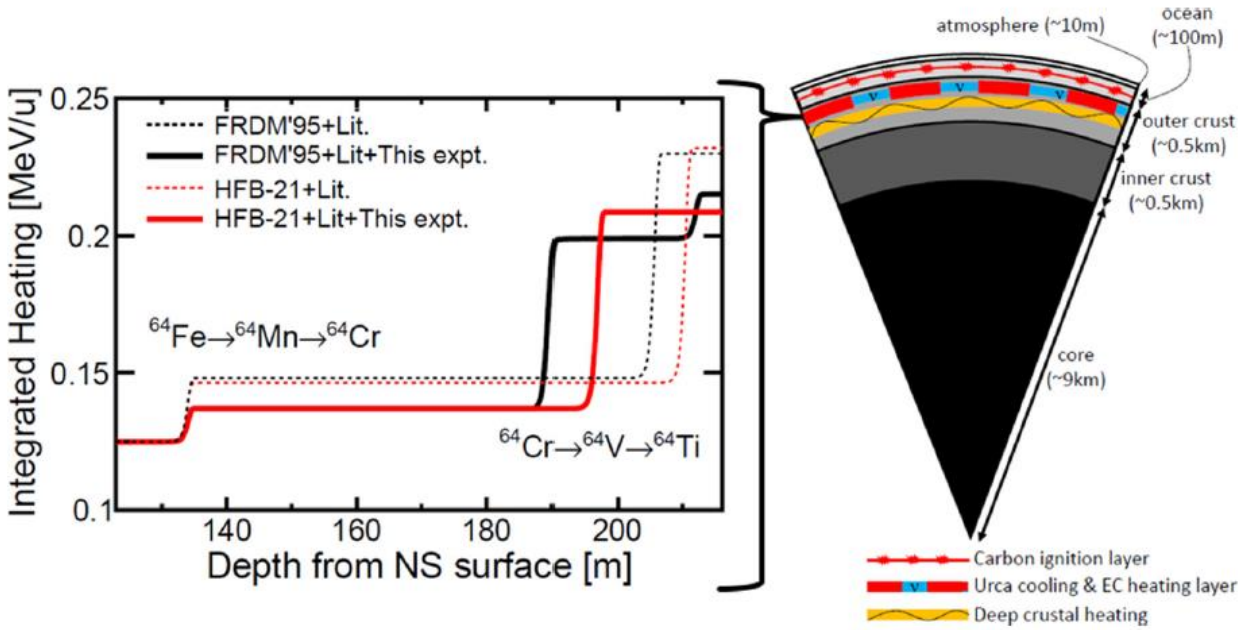
Z Meisel and S George, IJMS (2013)



Past TOF experiments at the NSCL

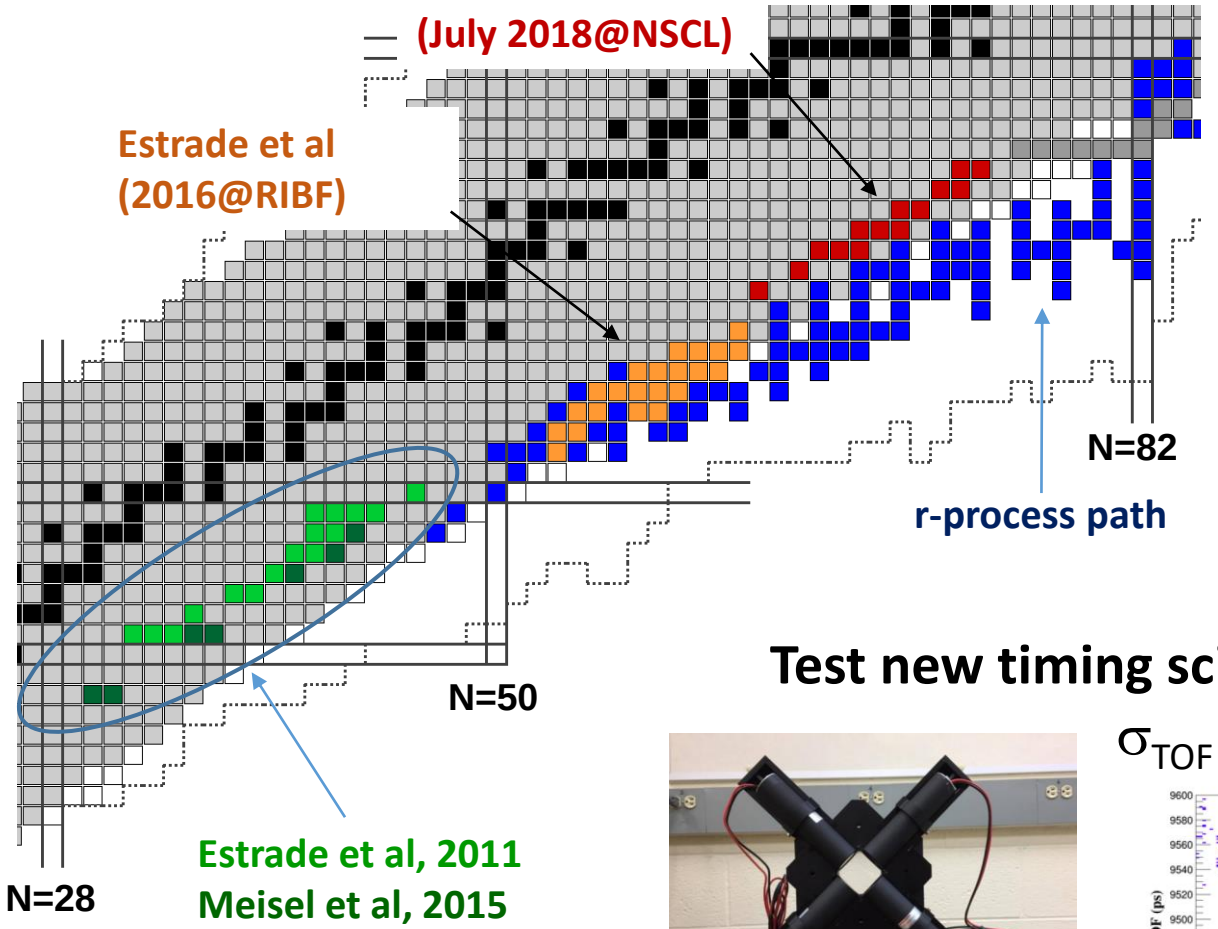


Electron capture processes in the crust of accreting neutron stars

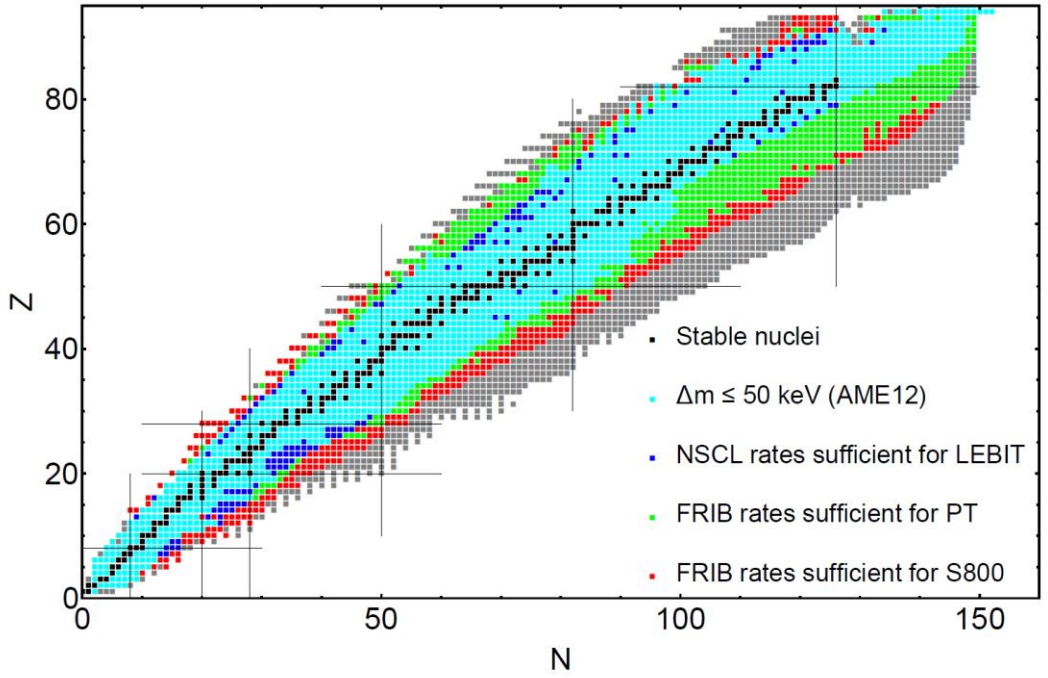


Z Meisel et al, PRC 93, 035805 (2016)
Z Meisel et al, PRL 115, 162501 (2015)
A Estrade et al, PRL 107, 172503 (2011)

r-process motivated TOF experiments

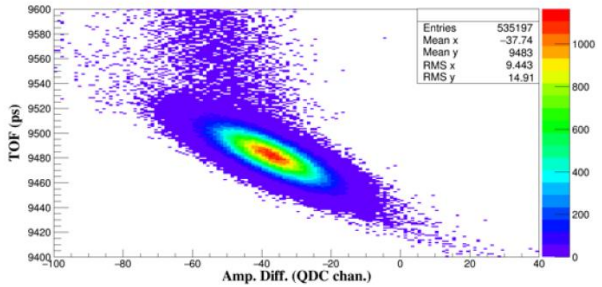


Expected reach of mass measurements at FRIB



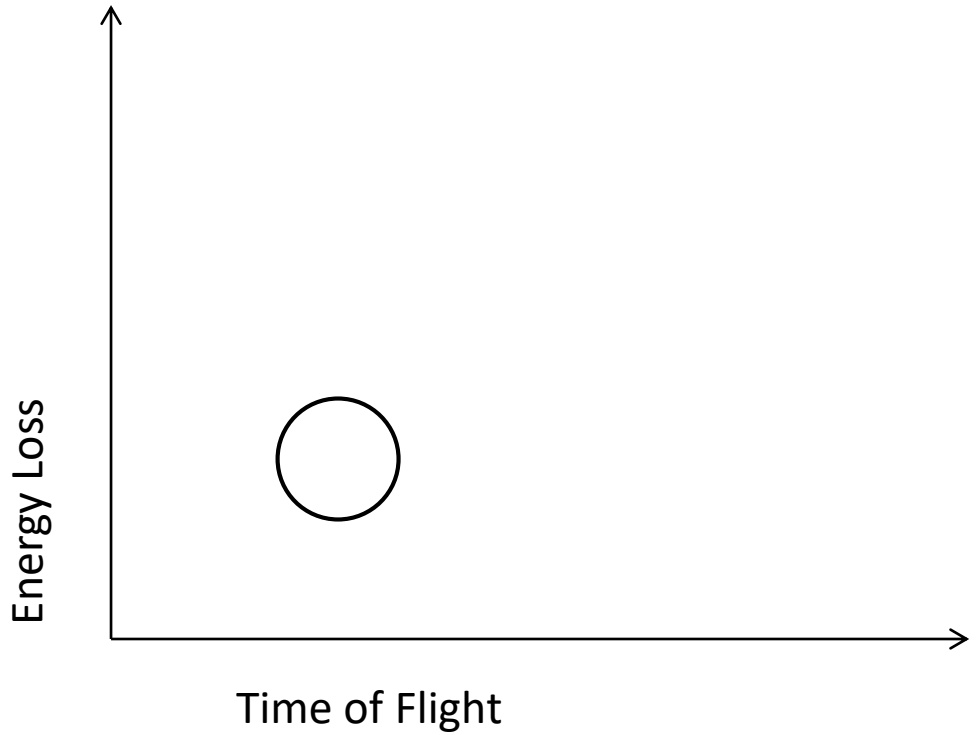
Test new timing scintillators

σ_{TOF} = 8 ps



A new generation of RIBs: the story of ^{78}Ni

Half-life measurement at the NSCL



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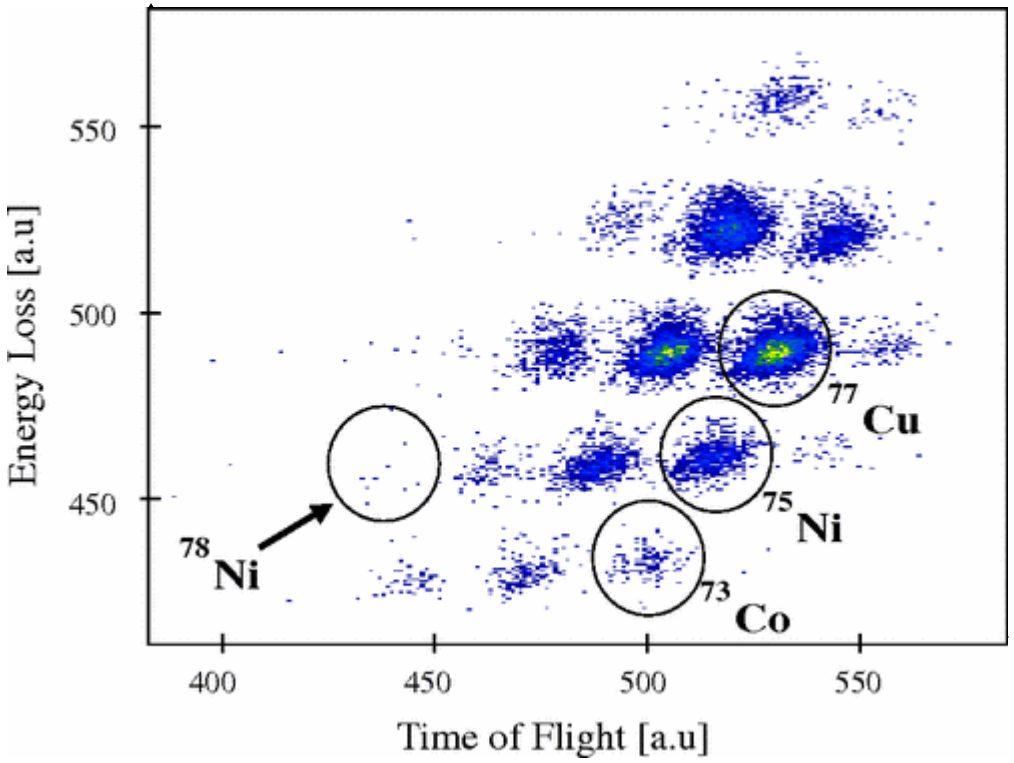

P. T. Hosmer et al, PRL 94 112501 (2005)

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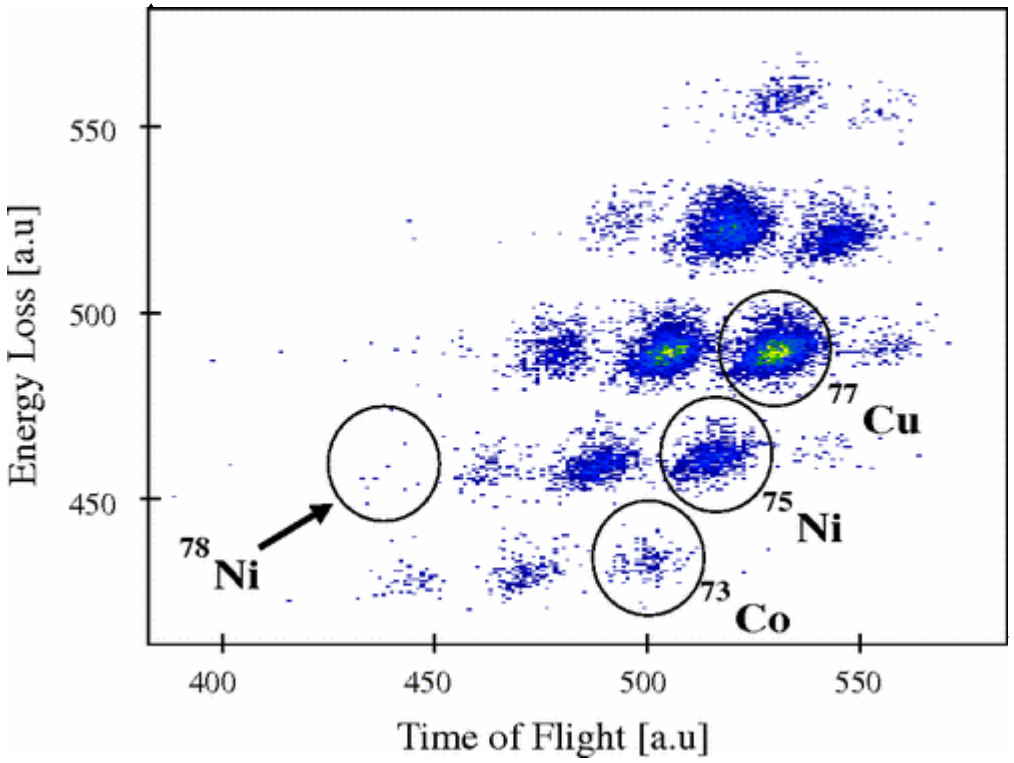
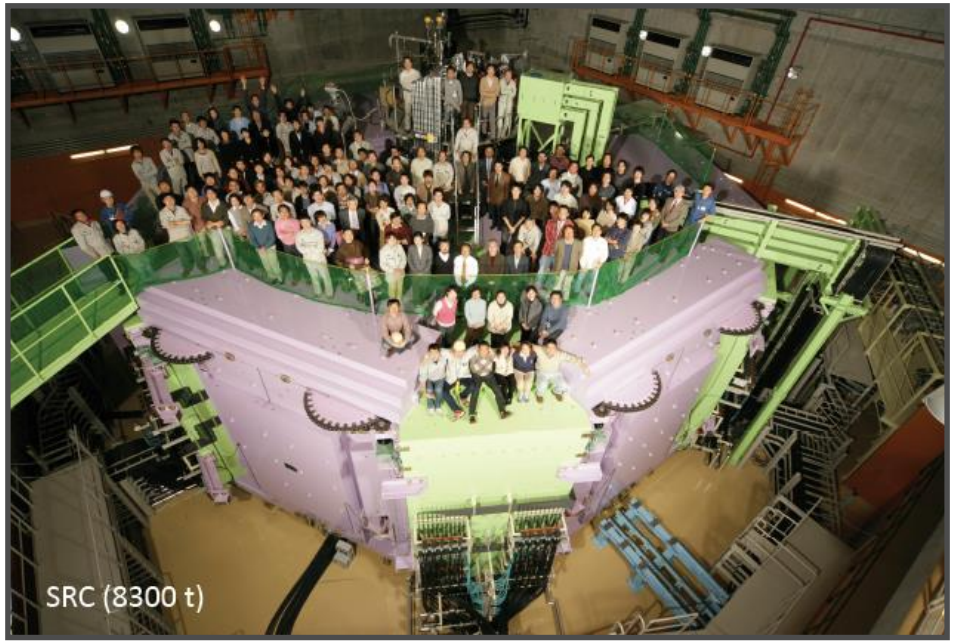


P. T. Hosmer et al, PRL 94 112501 (2005)

Radioactive Ion Beam Factory (RIBF)
@RIKEN, Japan



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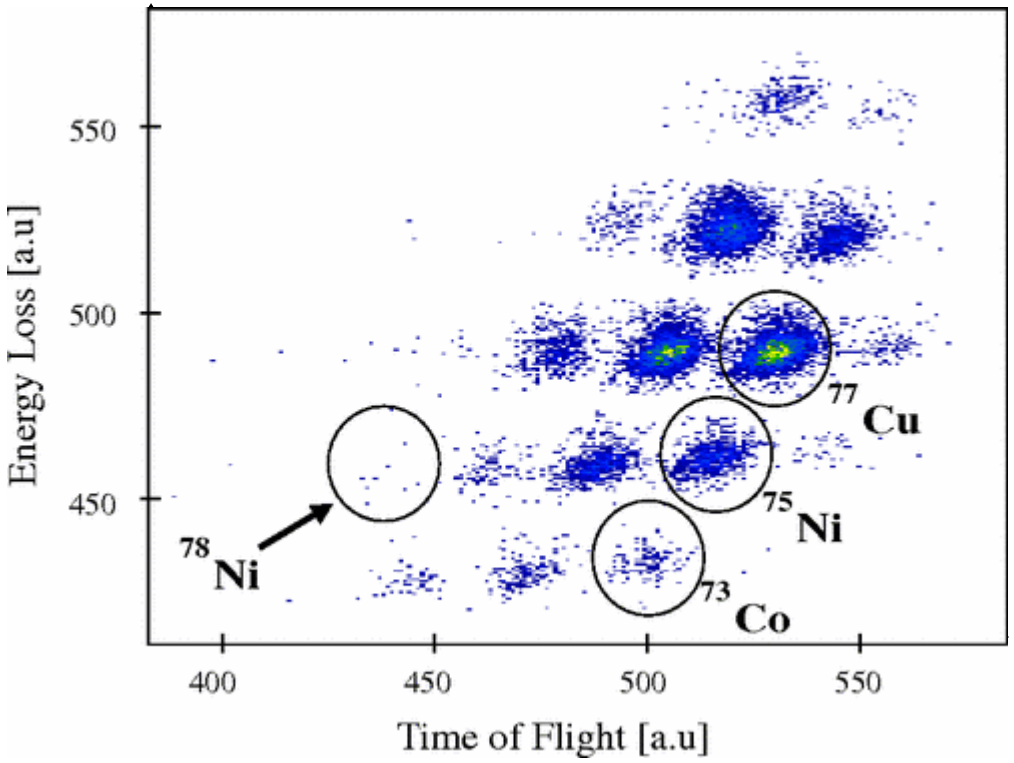
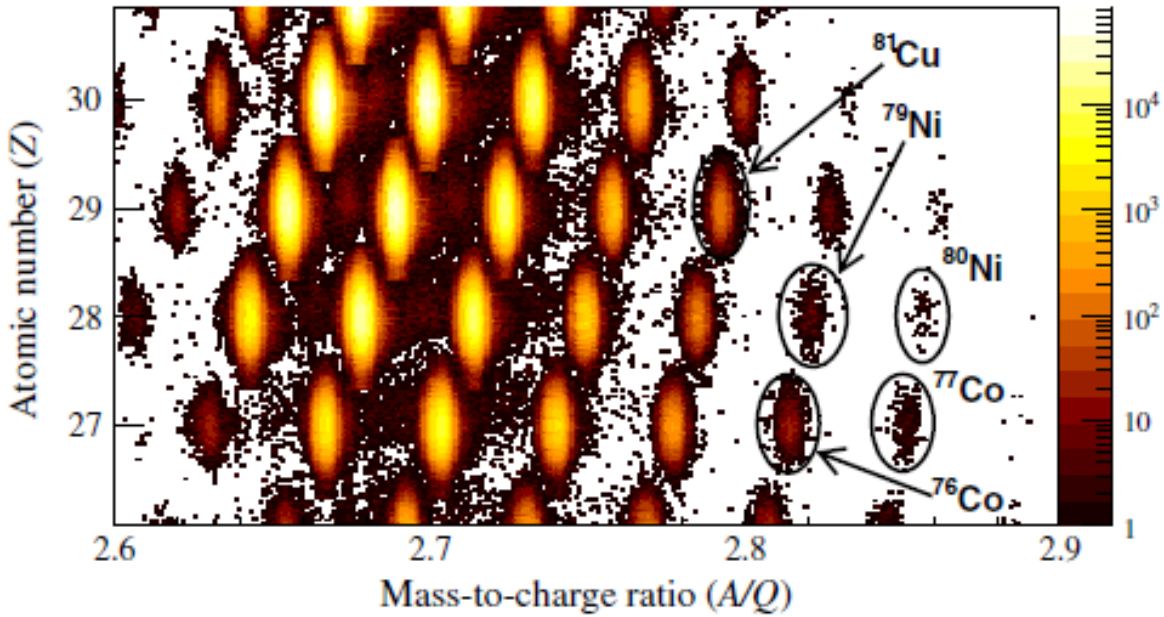
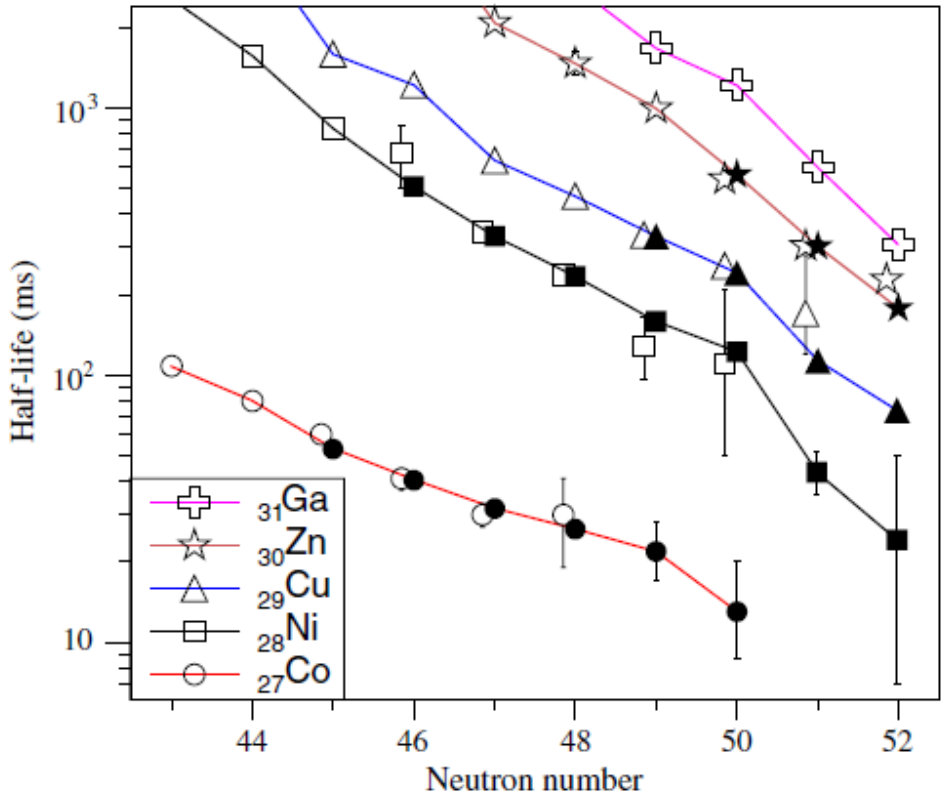


Half-life measurement at RIBF



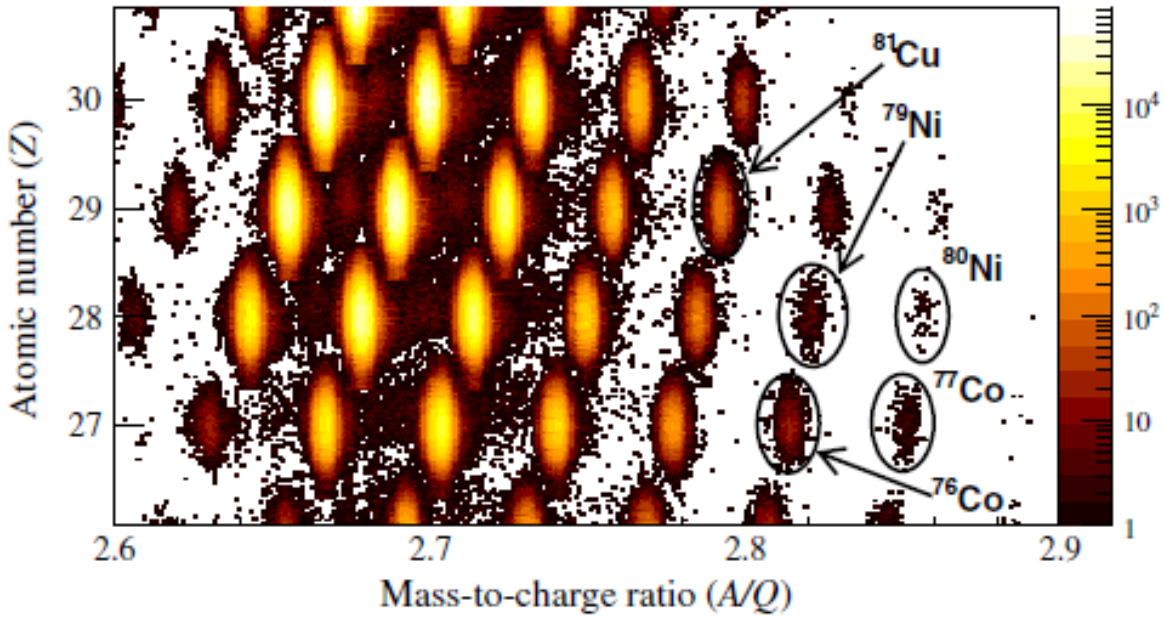
P. T. Hosmer et al, PRL 94 112501 (2005)

A new generation of RIBs: the story of ^{78}Ni

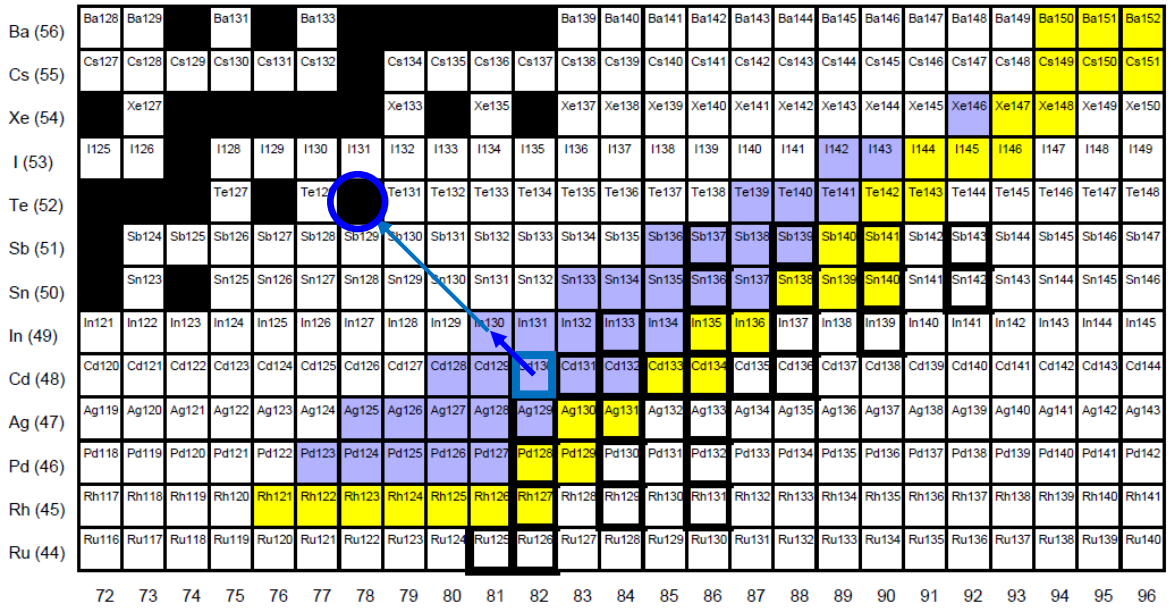


Z.Y. Xu et al, PRL 113, 032505 (2014)

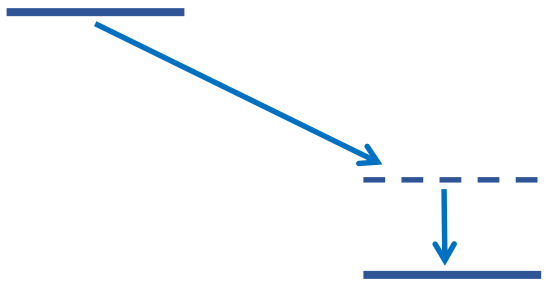
Half-life measurement at RIBF



β-delayed neutrons and the r-process



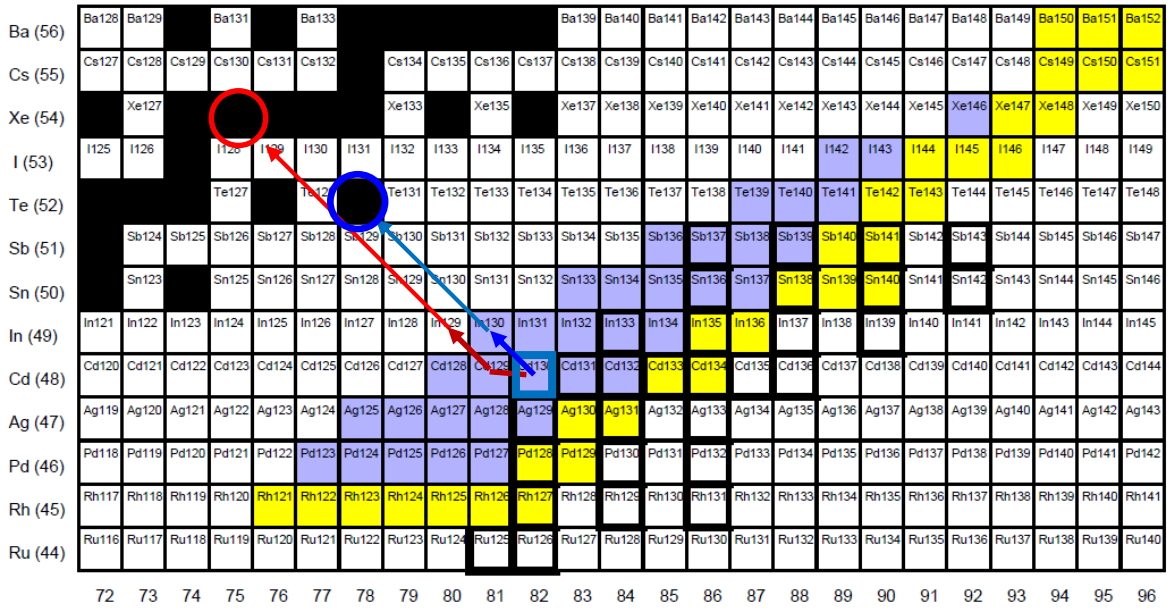
β-decay: $^{A}Z \rightarrow {}^{A}Z\text{-}1 + e^{-} + \nu$



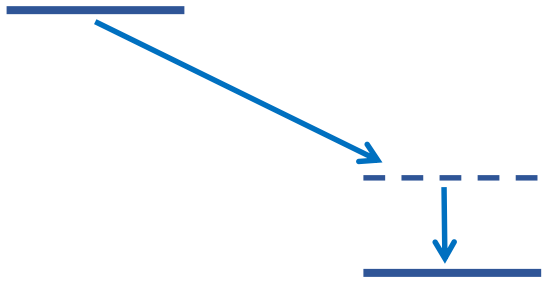
^{A}Z (parent)

$^{A}Z\text{-}1$ (daughter)

β-delayed neutrons and the r-process



β-decay: $^{A}Z \rightarrow {}^{A}Z\text{-}1 + e^{-} + \nu$

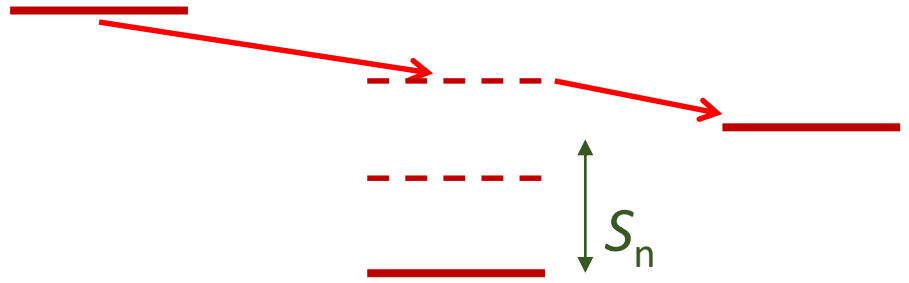


^{A}Z (parent)

$^{A}Z\text{-}1$ (daughter)

β-delayed neutron decay:

$^{A}Z \rightarrow {}^{A-1}Z\text{-}1 + e^{-} + \nu + \mathbf{n}$



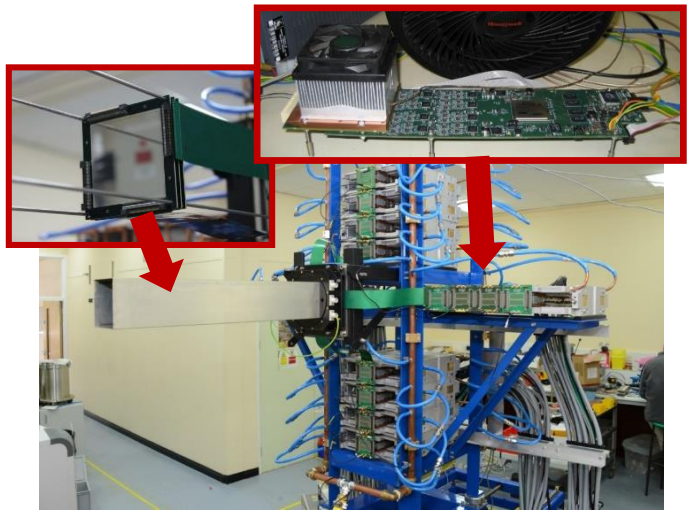
^{A}Z (parent)

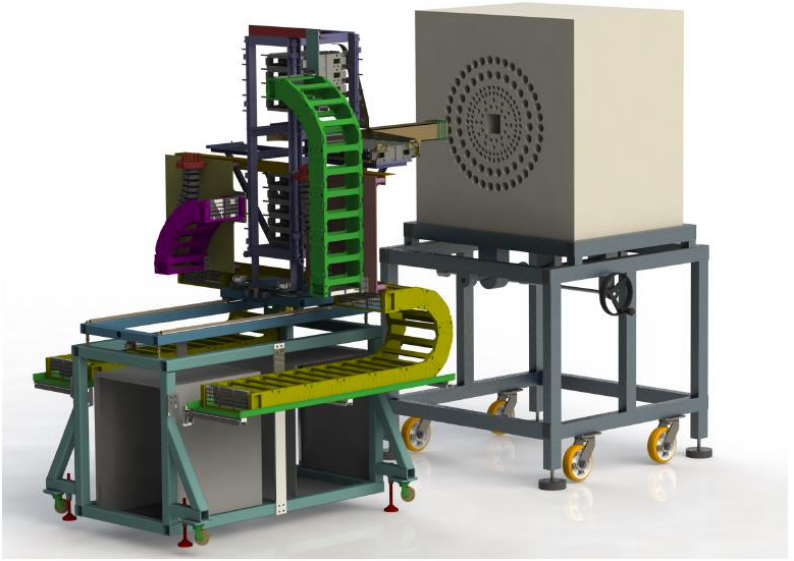
$^{A}Z\text{-}1$

$^{A-1}Z\text{-}1 + n$ (daughter)

BRIKEN: β-delayed neutrons at RIKEN

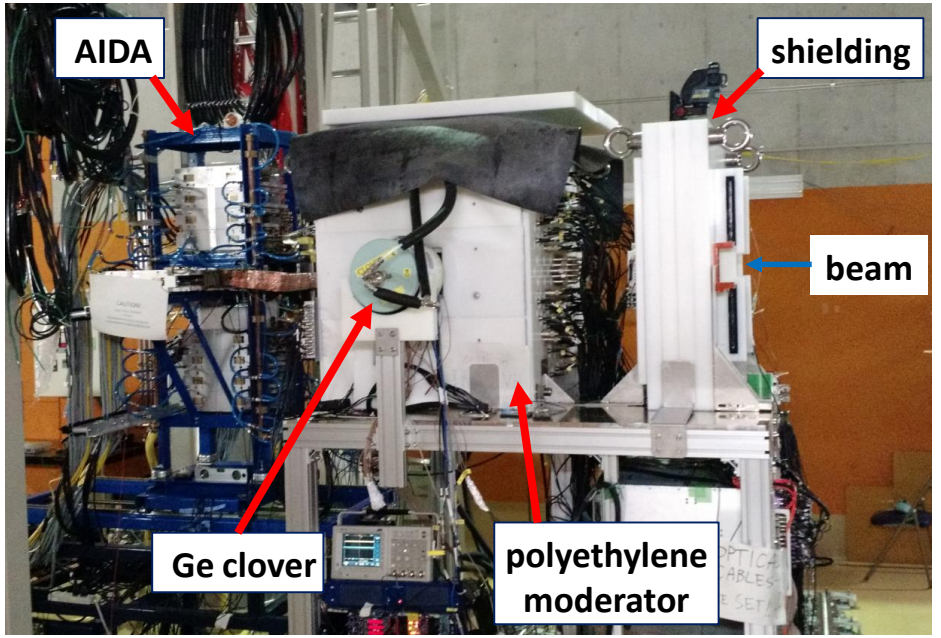
- β-decay in AIDA: Advanced Implantation Detector Array (DSSSD):





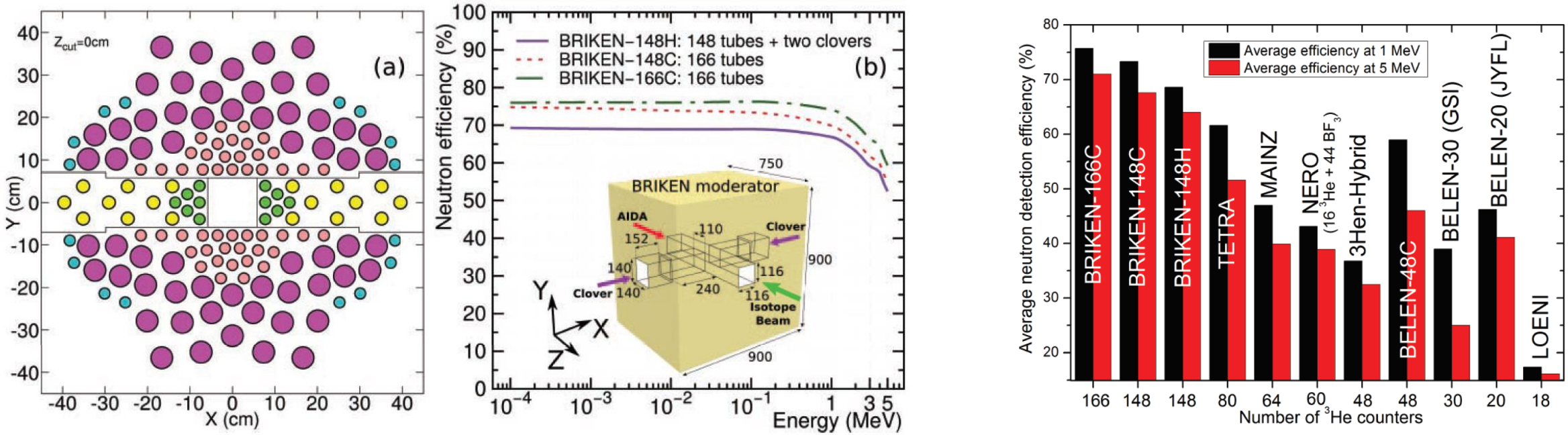
- BRIKEN neutron detector:

$$^{3}He + n \longrightarrow {}^{3}H + p$$



GOAL: measure P_{xn}-value, the probability for emission of *x* beta-delayed neutrons

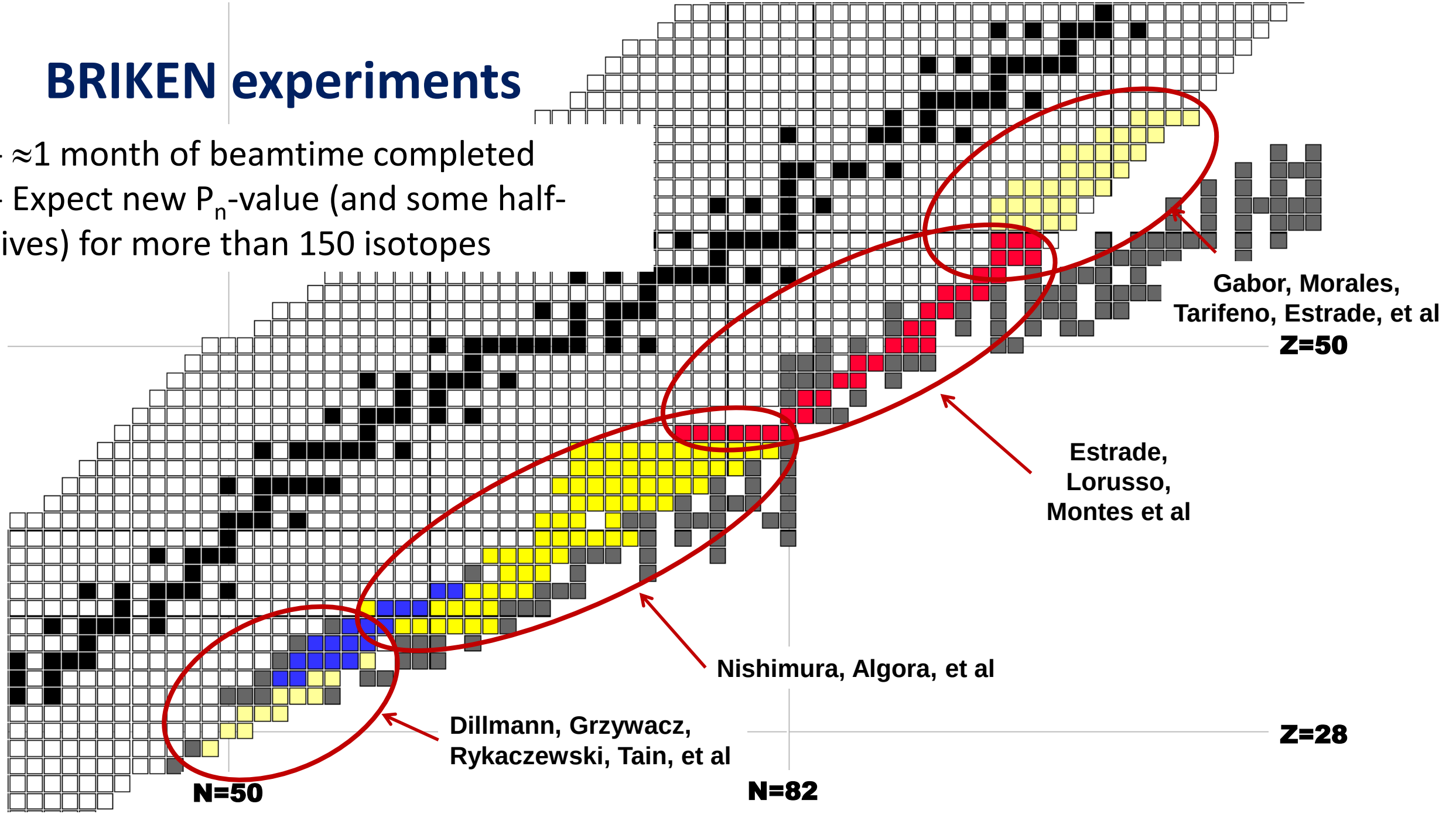
BRIKEN: β-delayed neutrons at RIKEN



I. Dillmann and A. Tarifeño-Saldivia, Nucl. Phys. News 28:1 (2018)
A. Tarifeño-Saldivia et al., J. of Instrum. 12 (2107) P04006

BRIKEN experiments

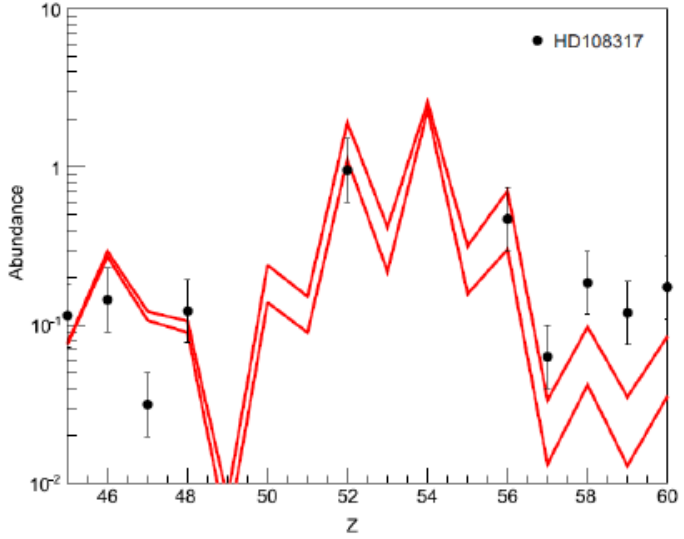
- ≈1 month of beamtime completed
- Expect new P_n-value (and some half-lives) for more than 150 isotopes



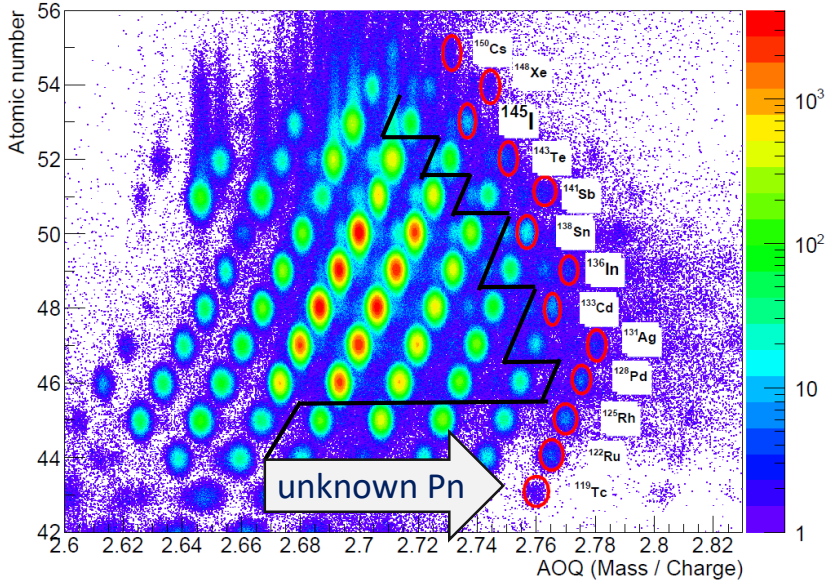
N=82 experiment

Sensitivity to β-delayed neutrons

Elemental distribution in HD108317



F. Montes priv. comm.



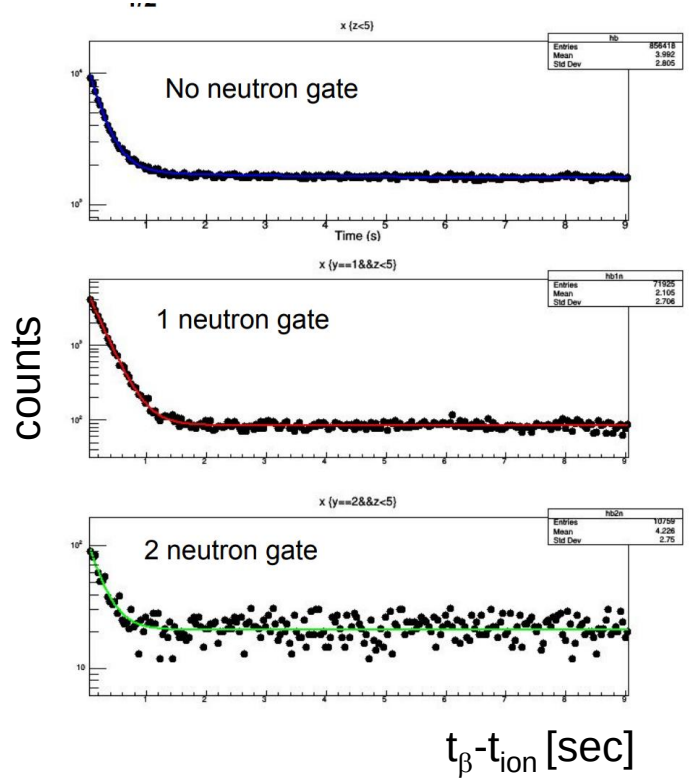
Particle identification

Decay curves (^{137}Sn)

PRELIMINARY

$\tau_{1/2}$= 232.9±3.8 ms (BRIKEN)

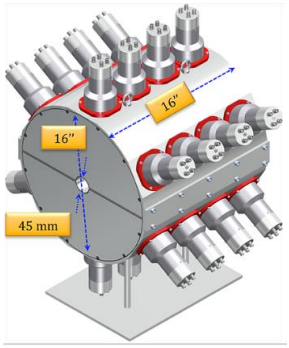
$\tau_{1/2}$= 230±30 ms (prev. exp)



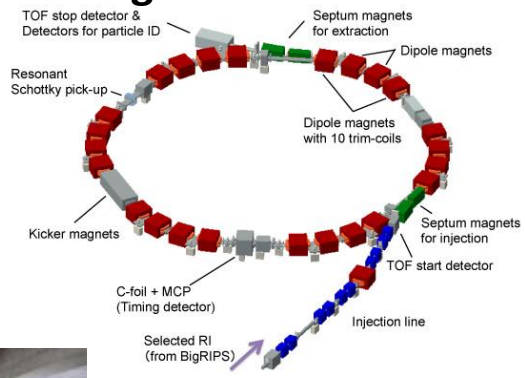
Stay tuned! Ph.D. work of V. Phong (VNU), J. Liu (HKU), O. Hall (U Edinburgh) R. Yokoyama, R. Grzywacz, et al., *in preparation* (Ge region)

Conclusion: we are entering an era of r-process experiments

SuN: (n,g)

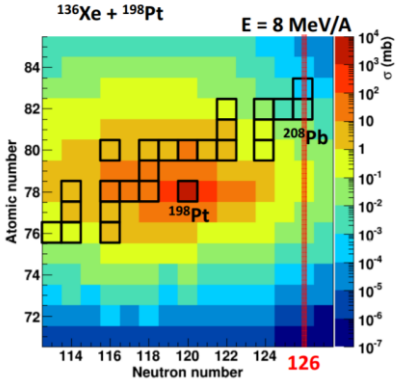


RI ring: mases



ARIEL@TRIUMF

KISS: N=126 isotopes

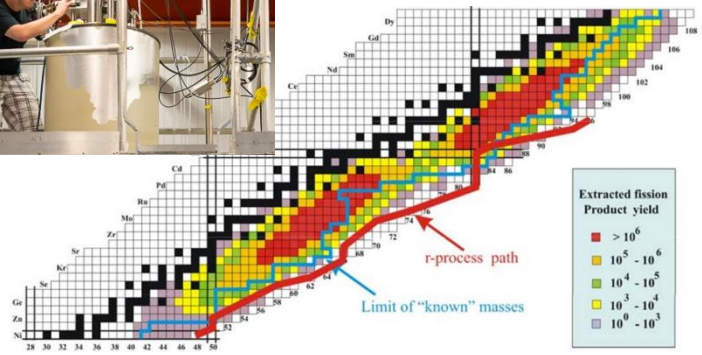


BRIKEN: decay

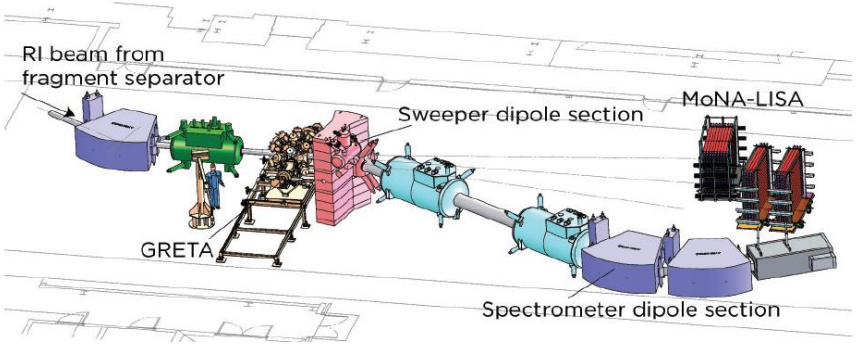
ESR: mases

SAMURAI: fission

CPT+CARIBU



HRS at FRIB: masses, reactions



Conclusions

- Progress in r-process astronomical data and theoretical models demands more precise nuclear physics data for r-process models.

- A new generation of radioactive ion beam facilities, like FRIB at Michigan State University, will make a large number of r-process isotopes accessible to experimental study.

- A variety of experimental techniques have been developed to meet the challenges of performing experiments with very neutron-rich isotopes relevant to r-process models (very low beam rates, need to use indirect techniques, etc).

    - We have extended the reach of TOF experiments to regions relevant to the weak r-process.
    - The BRIKEN setup at RIBF will measure a large number of new Pn-values of r-process isotopes (beamtime for first campaign of experiments already completed).

Thank you!

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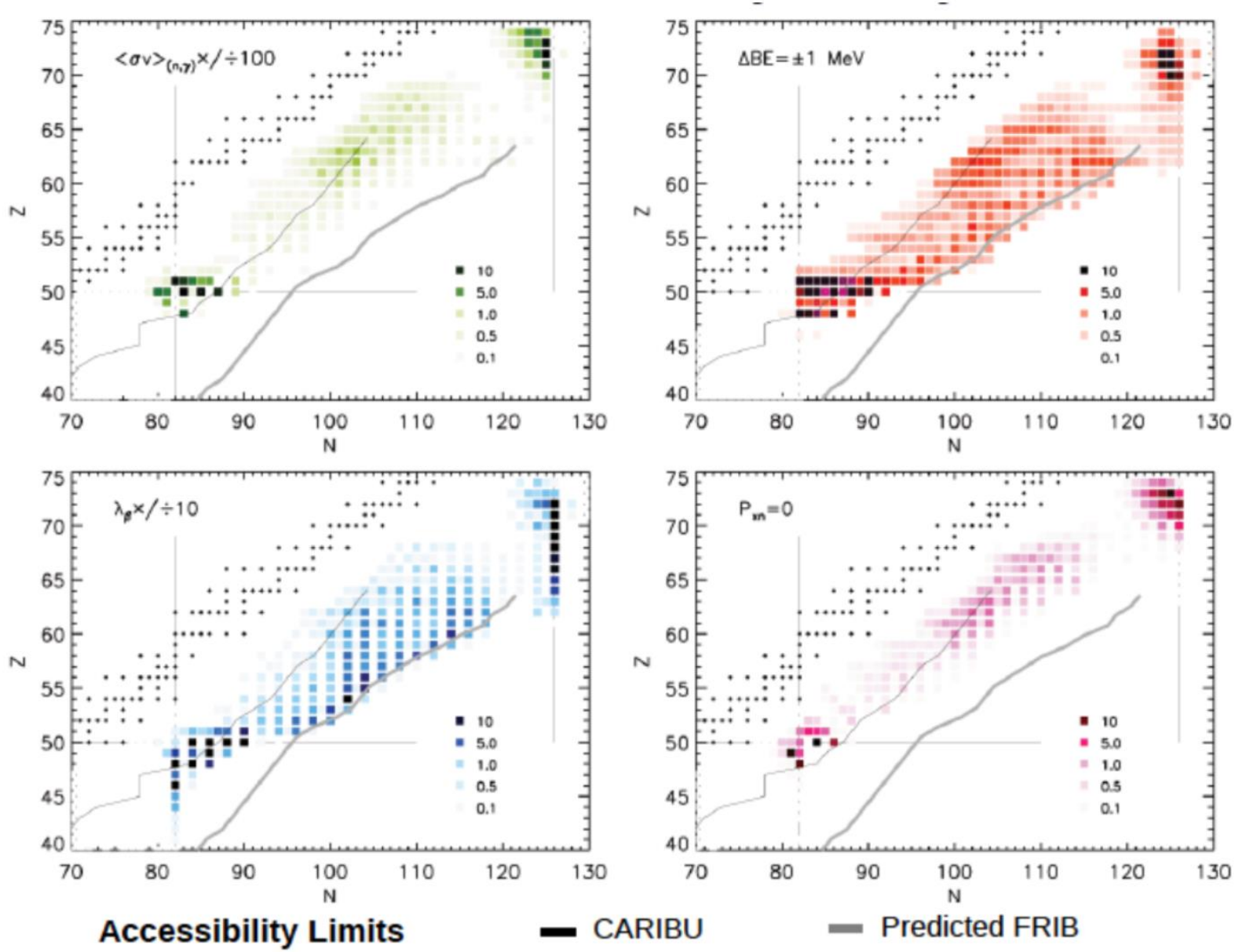
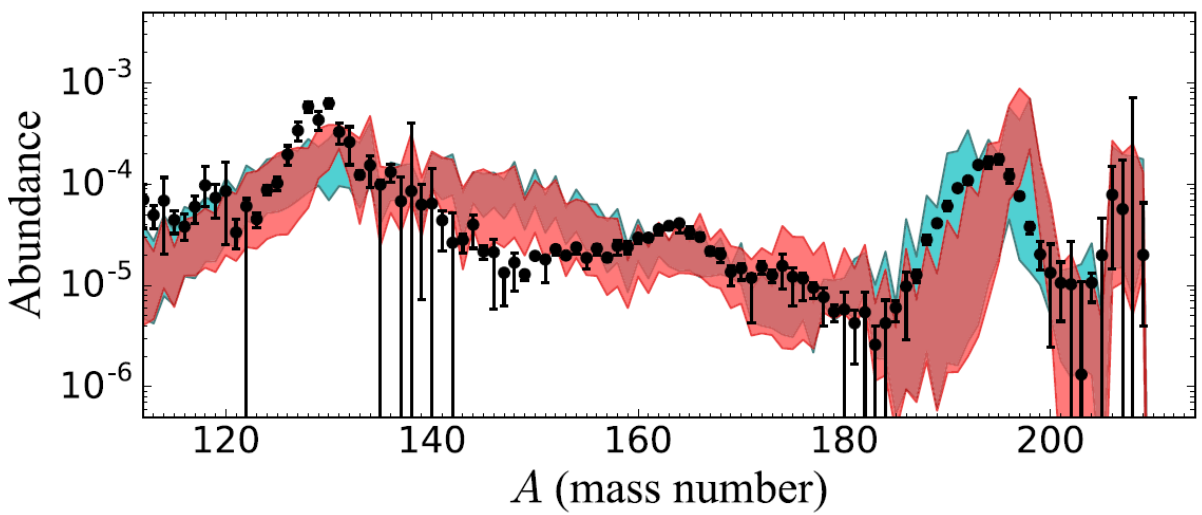
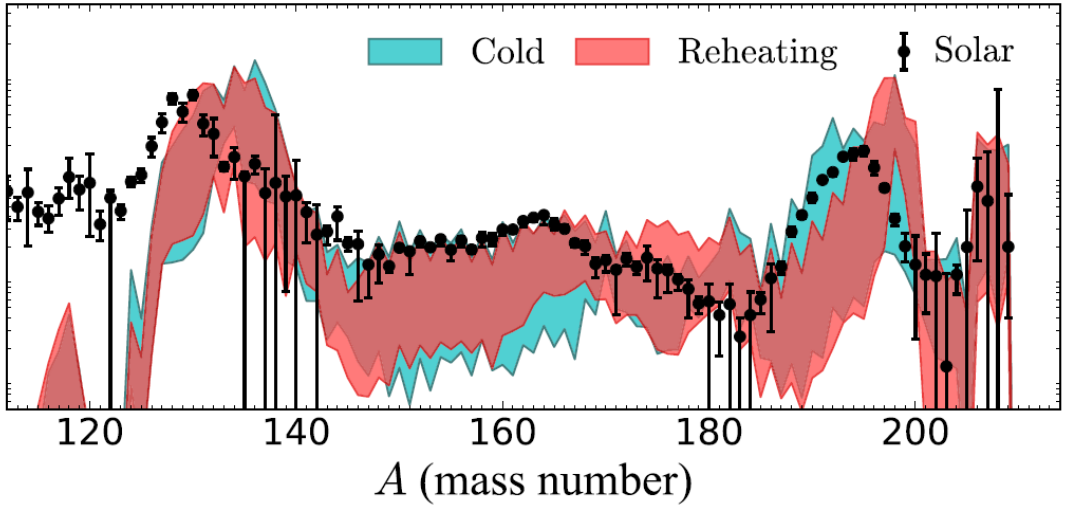
Extra

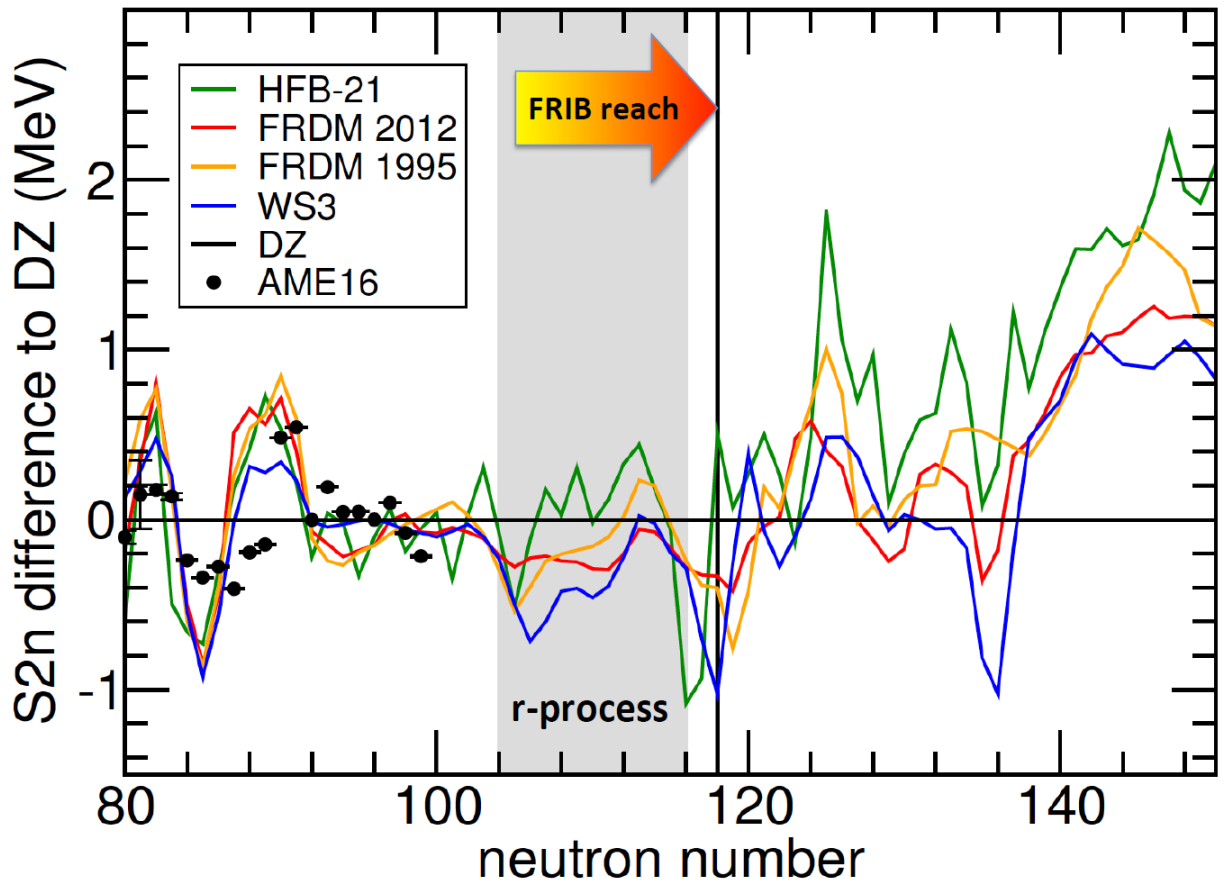

<σv>(n,γ)×/÷100
ΔBE=±1 MeV
λβ×/÷10
Psn=0
10
5.0
1.0
0.5
0.1
Z
N
Accessibility Limits
CARIBU
Predicted FRIB

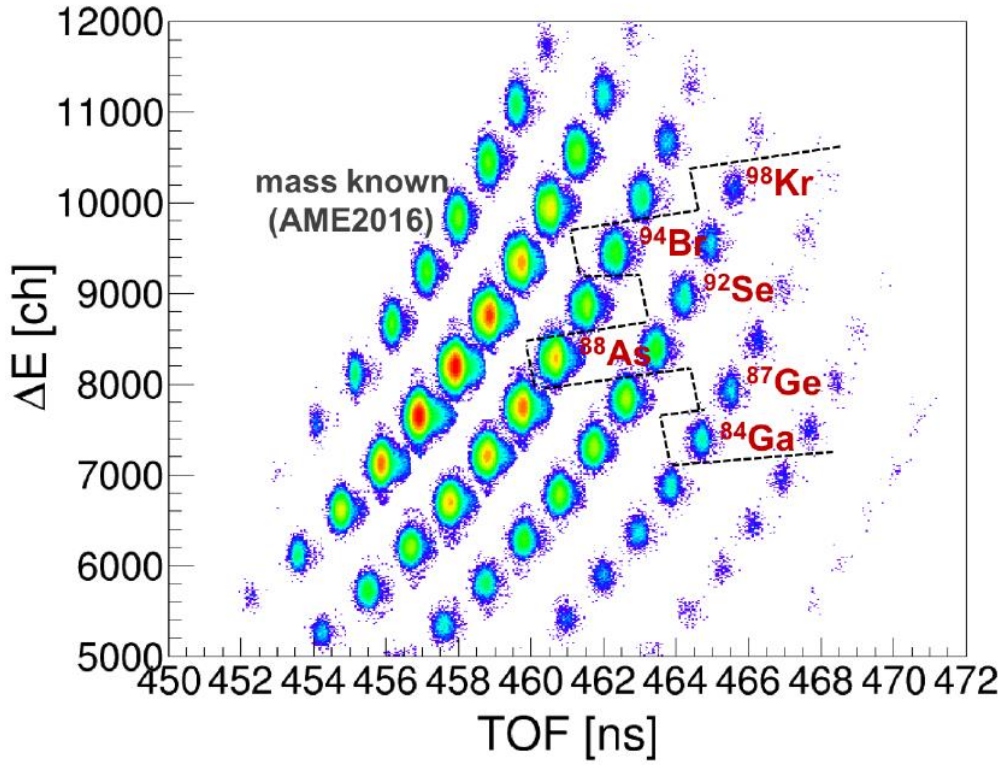
Nuclear data uncertainties in r-process models

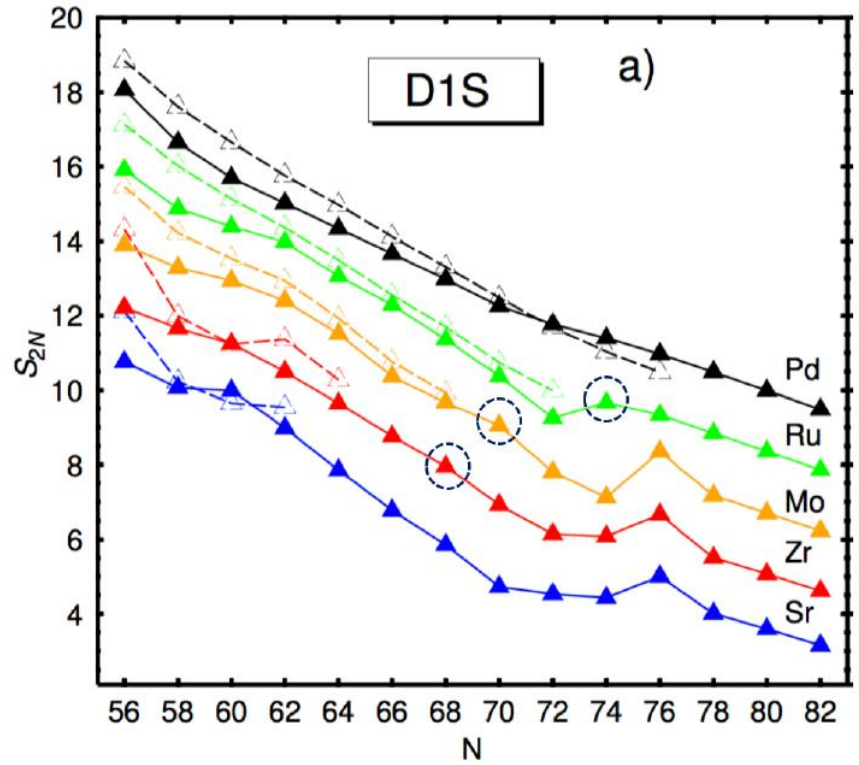




Cote et al, ApJ 855, 99 (2018)


HFB-21
FRDM 2012
FRDM 1995
WS3
DZ
AME16
FRIB reach
r-process
S2n difference to DZ (MeV)
neutron number
2
1
0
-1
80
100
120
140


mass known
(AME2016)
^{98}Kr
^{94}Br
^{92}Se
^{88}As
^{87}Ge
^{84}Ga
ΔE [ch]
TOF [ns]
12000
11000
10000
9000
8000
7000
6000
5000
450 452 454 456 458 460 462 464 466 468 470 472


D1S
a)
S_{2N}
N
Pd
Ru
Mo
Zr
Sr
20
18
16
14
12
10
8
6
4
56 58 60 62 64 66 68 70 72 74 76 78 80 82