R-process experiments with fast ion beams at the NSCL and FRIB

Alfredo Estrade

Central Michigan University

JINA-CEE
NSF Physics Frontiers Center

Outline

- Time-of-flight mass measurements at the National Superconducting Cyclotron Laboratory (NSCL)

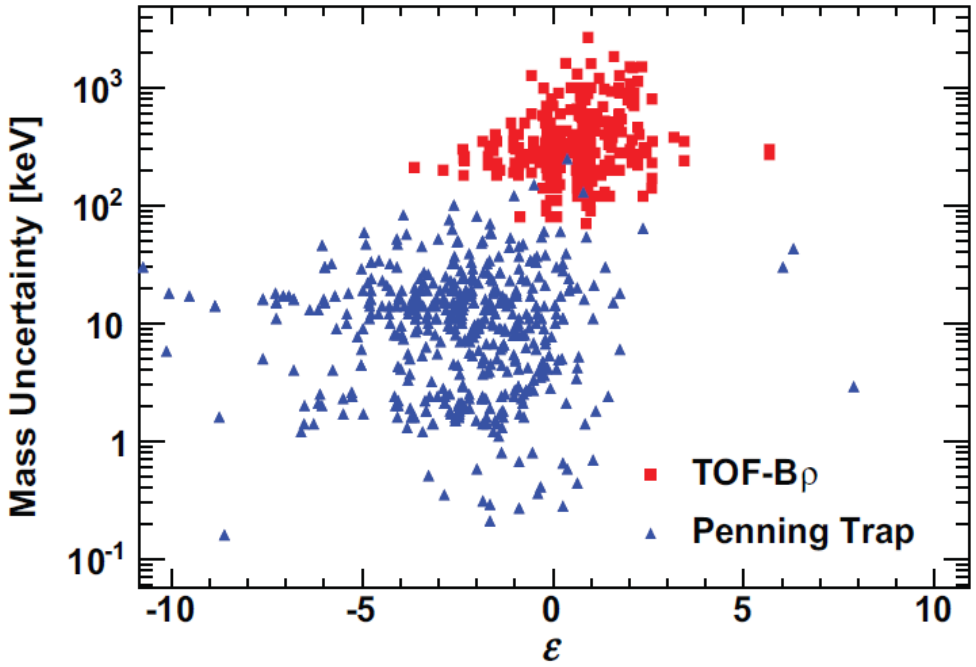
- Nuclear mass and heavy neutron-rich beams at the Facility for Rare Isotope Beams (FRIB):
  - High Rigidity Spectrometer (HRS)
  - Isochronous Separator with Large Acceptance (ISLA)

Motivation

“Maybe the most important piece of nuclear data are the masses.”

Rebecca Surman, ECT* workshop, Trento 2019

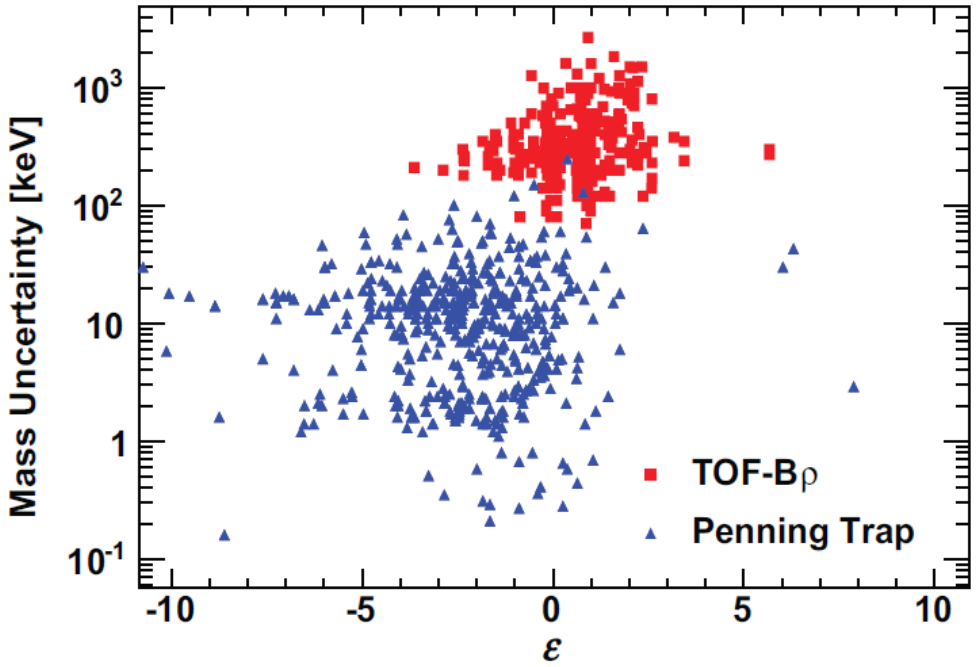
Mass measurement techniques



$$\epsilon = \log_{10} \left| \frac{dN_{stab}}{T_\beta * (dN_{drip} + 1)} \right|$$

Meisel and George, IJMS 2013

Mass measurement techniques: TOF-Brho



$$\epsilon = \log_{10}\left|\frac{dN_{stab}}{T_\beta * (dN_{drip}+1)}\right|$$

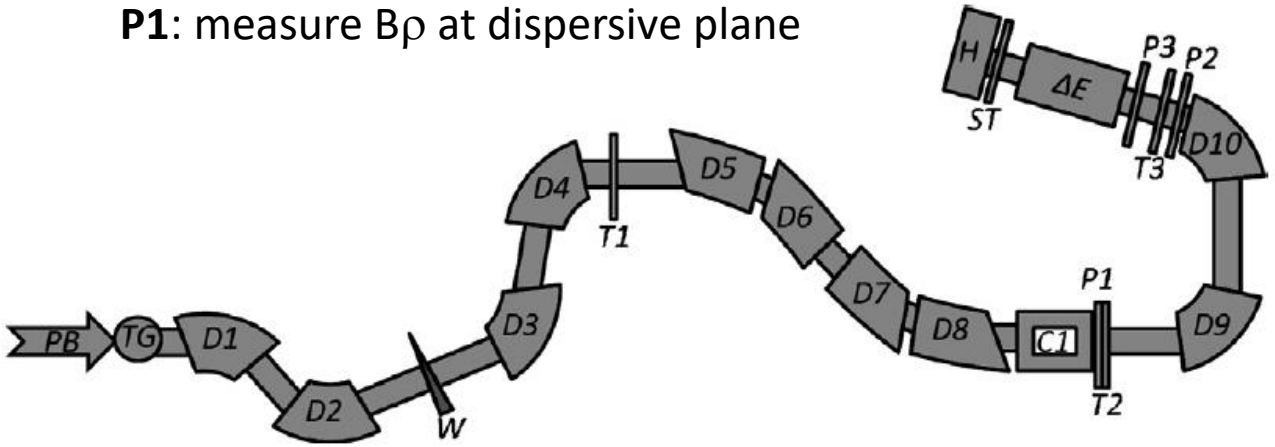
Meisel and George, IJMS 2013

Obtain mass from equation of motion of ions through beamline:

$$B\rho = \frac{\gamma v m}{q} = \gamma \frac{TOF}{L}\frac{m}{q}$$

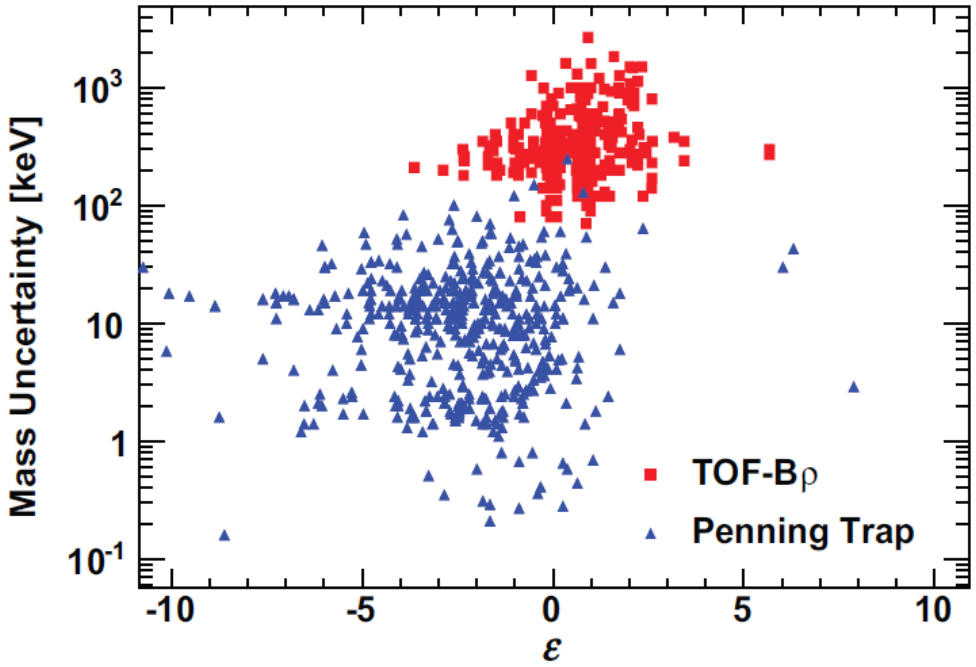
T1 – T2: measure TOF

P1: measure Bρ at dispersive plane



≈100 m

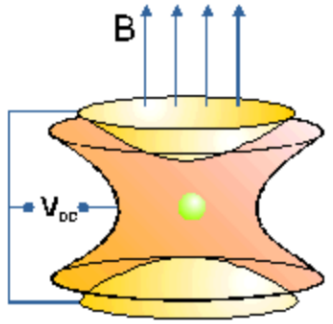
Mass measurement techniques: high resolution

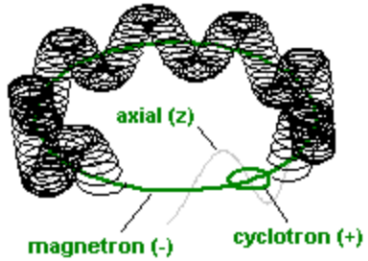


$$\epsilon = \log_{10}\left|\frac{dN_{stab}}{T_\beta * (dN_{drip}+1)}\right|$$

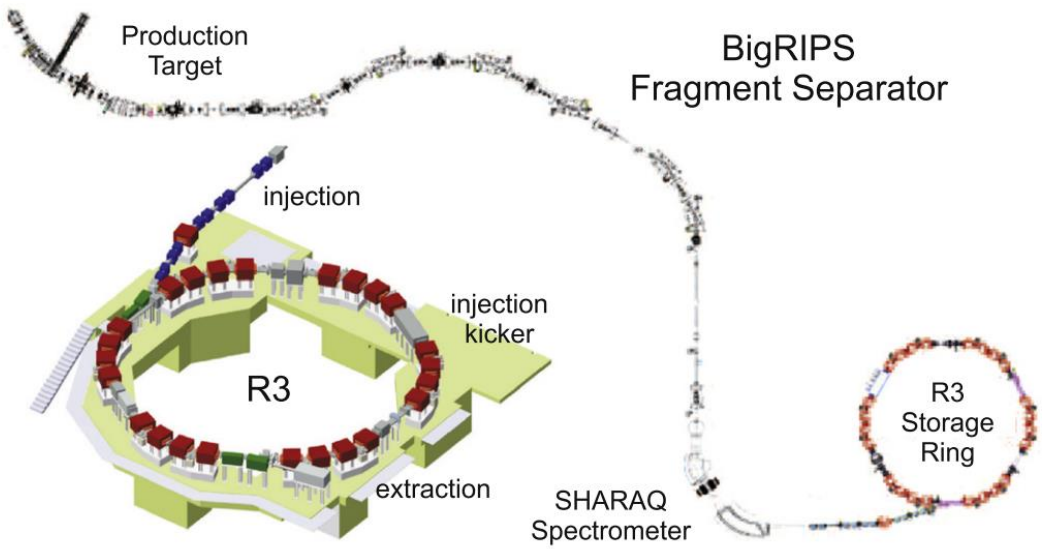
Meisel and George, IJMS 2013

Penning traps (L. Canete talk**):**

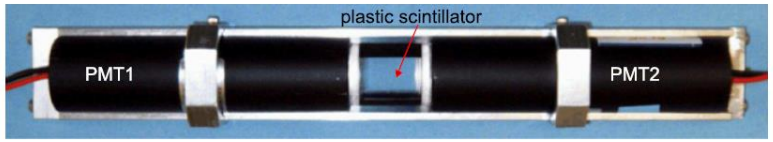


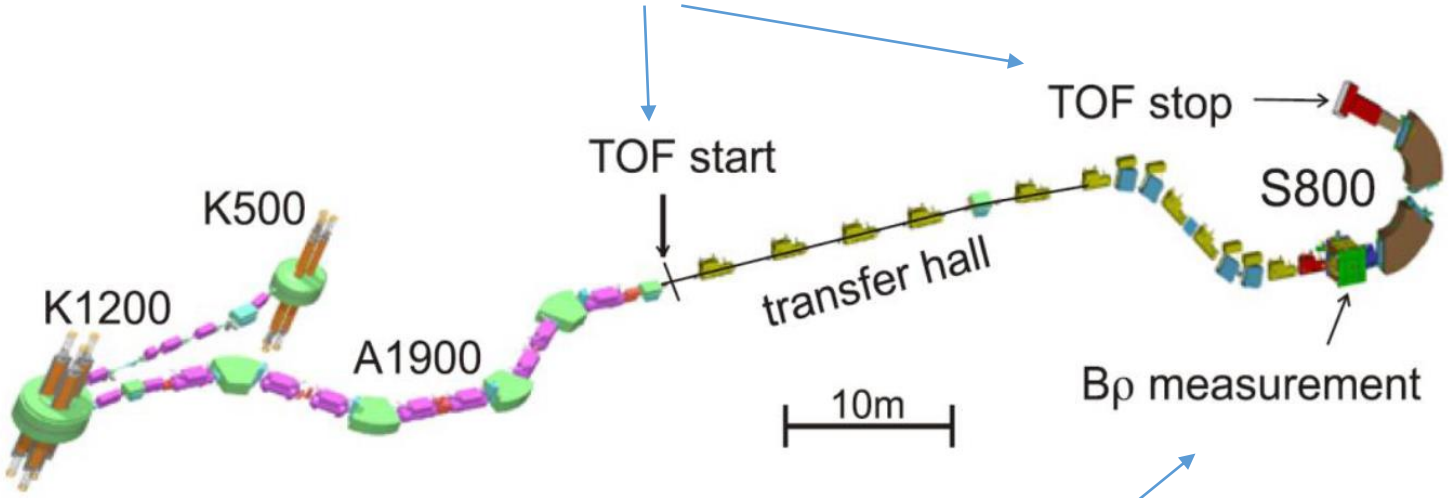


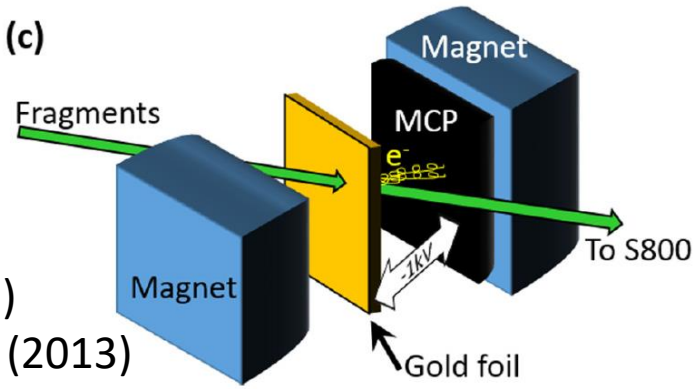
Storage rings:

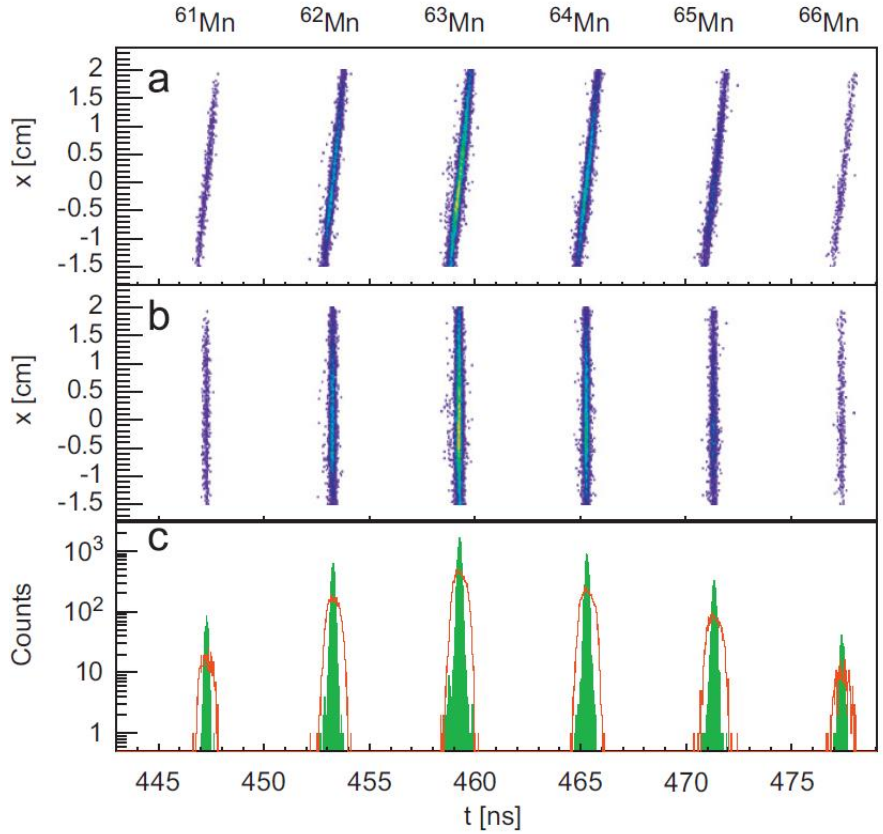


TOF-Bρ experiments at NSCL







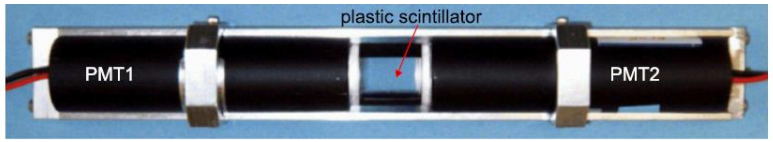


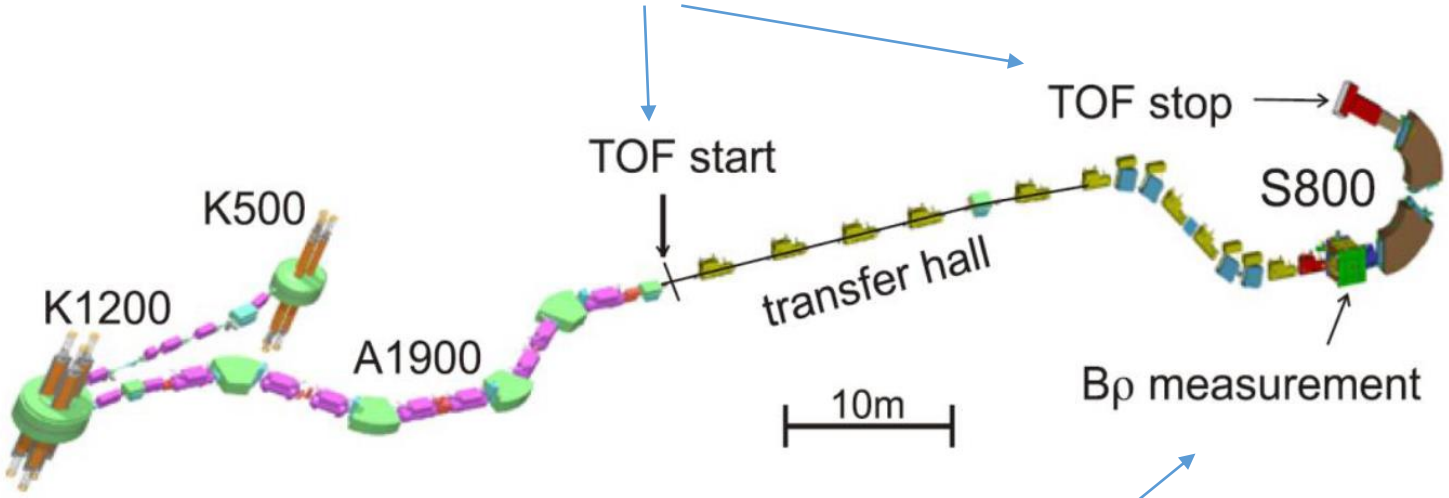
$$\frac{\delta m}{m} \approx 2 \times 10^{-4}$$

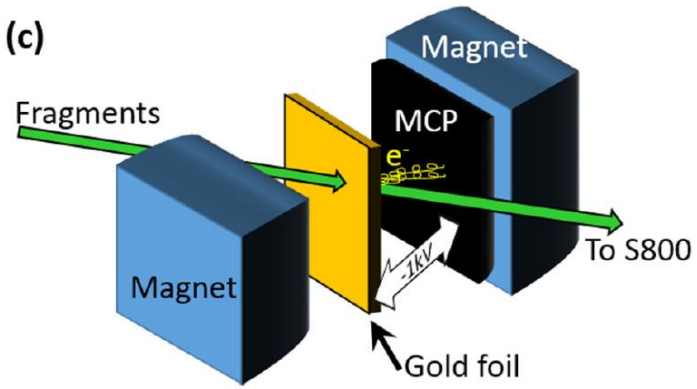
Matos et al , NIMA (2012)
Meisel and George, IJMS (2013)

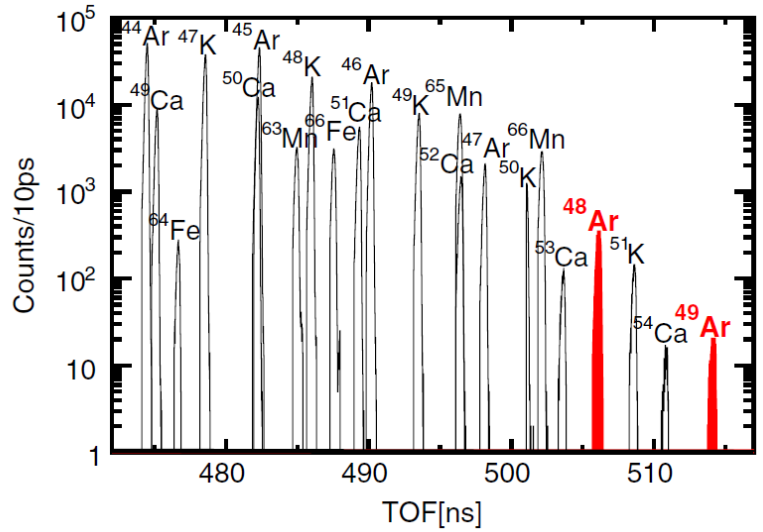
Note: technique pioneered at GANIL (SPEG), currently also an active program at RIKEN (e.g. Michimasa et al, PRL 2018)

TOF-Bρ experiments at NSCL: mass calibration

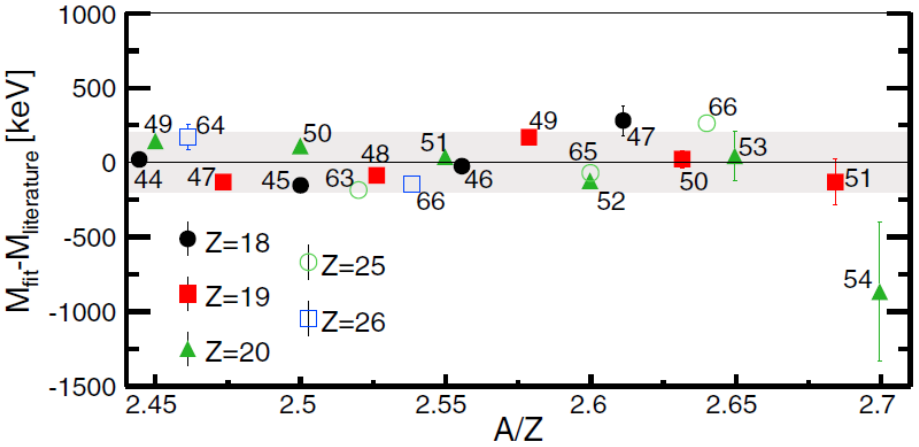




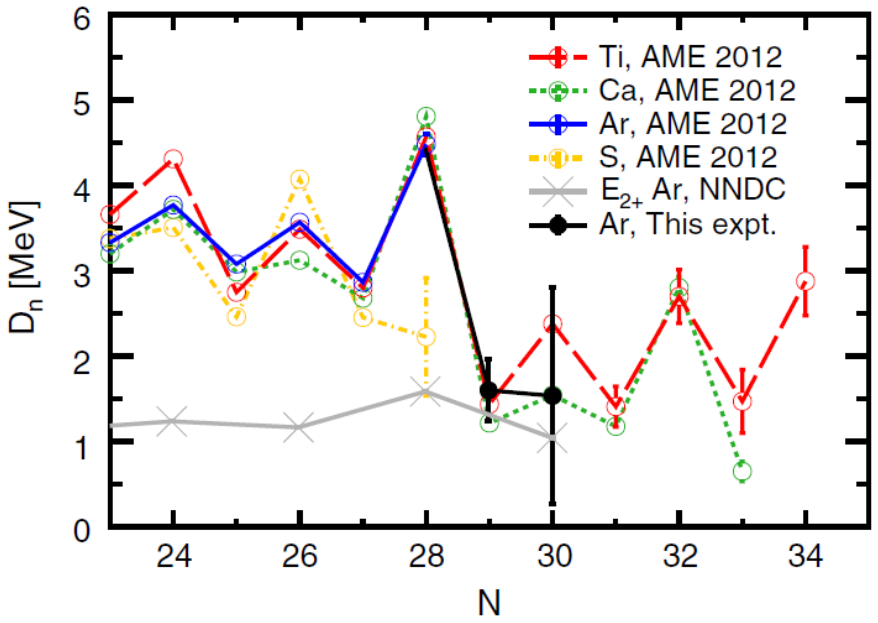


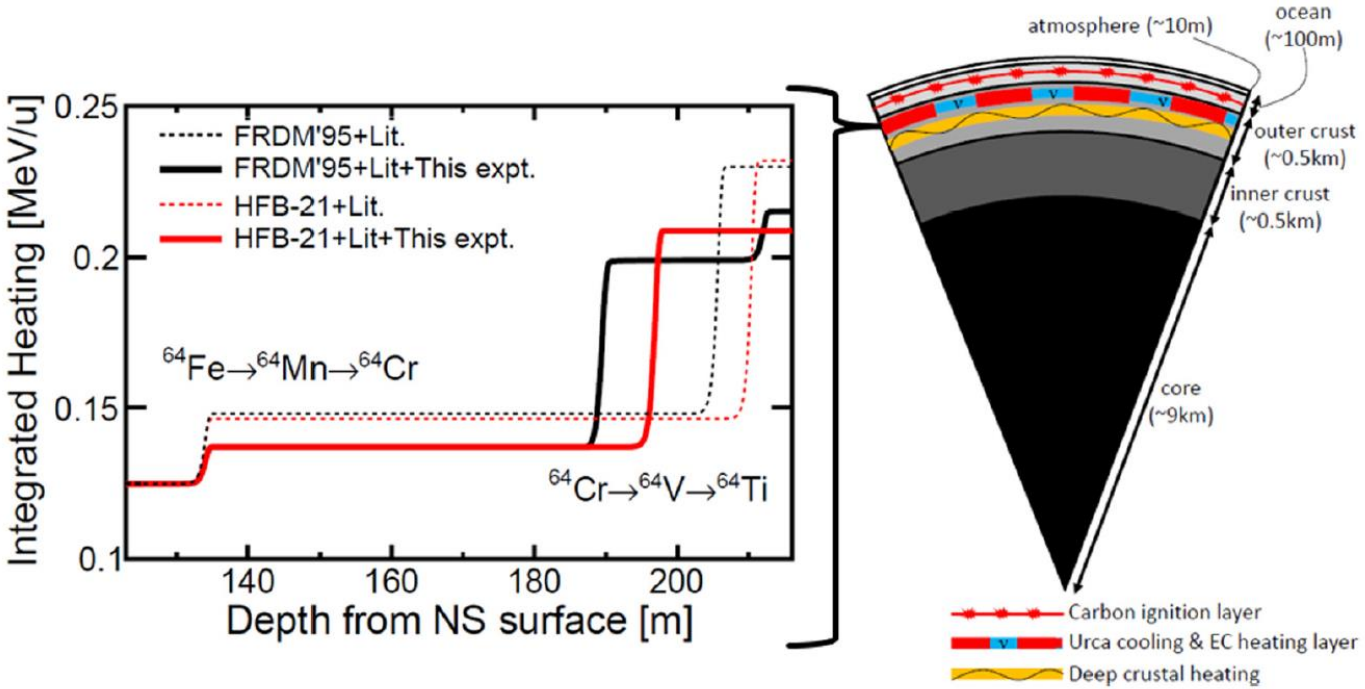


$$\frac{m}{q} = f(TOF_{B\rho}, Z)$$



TOF-Bρ experiments at NSCL: results



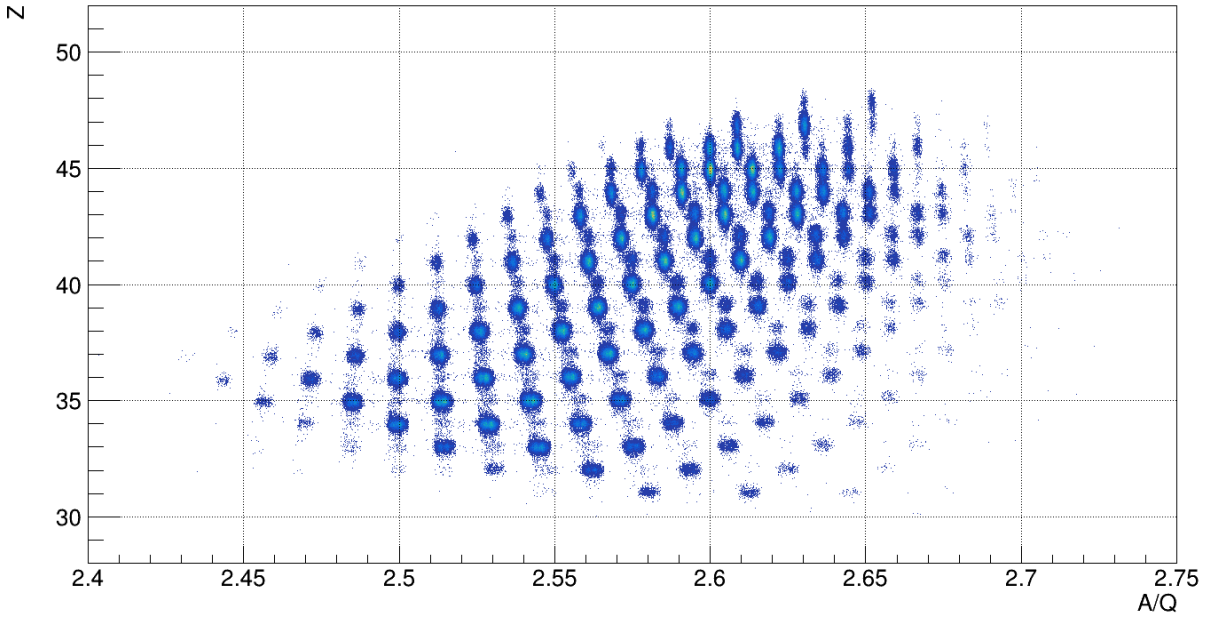


A. Estrade et al, PRL 2011
Z. Meisel et al, PRL 2015a
Z. Meisel et al, PRL 2015b

Experiment E12022: mass measurement for neutron-rich nuclei near 65<N<75

Mike Famiano (WMU)
Hendrik Schatz (NSCL)
Kailong Wang (CMU)

Particle Identification Histogram



August 2018: First TOF-Bρ experiment at NSCL relevant to r-process!

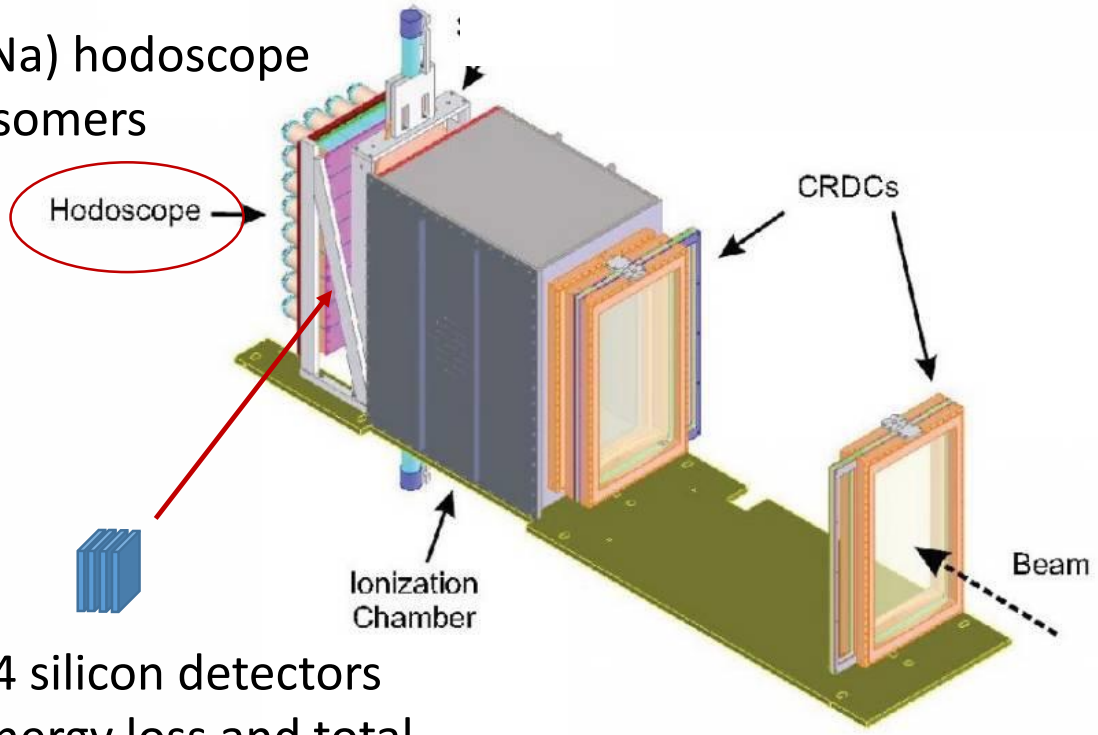
Limitations of NSCL setup

- Beam intensity
- Mass resolution
- Particle identification for heavy beams (charged-states)
- Unresolved micro-second isomers
- Mass calibration function

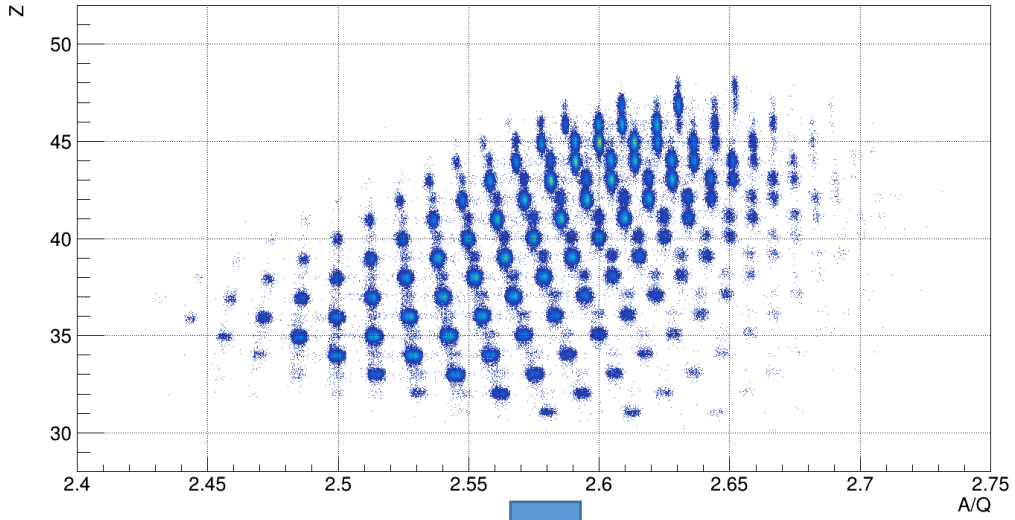
Adjustments to NSCL setup: charge-states

S800 detector box at end of beamline

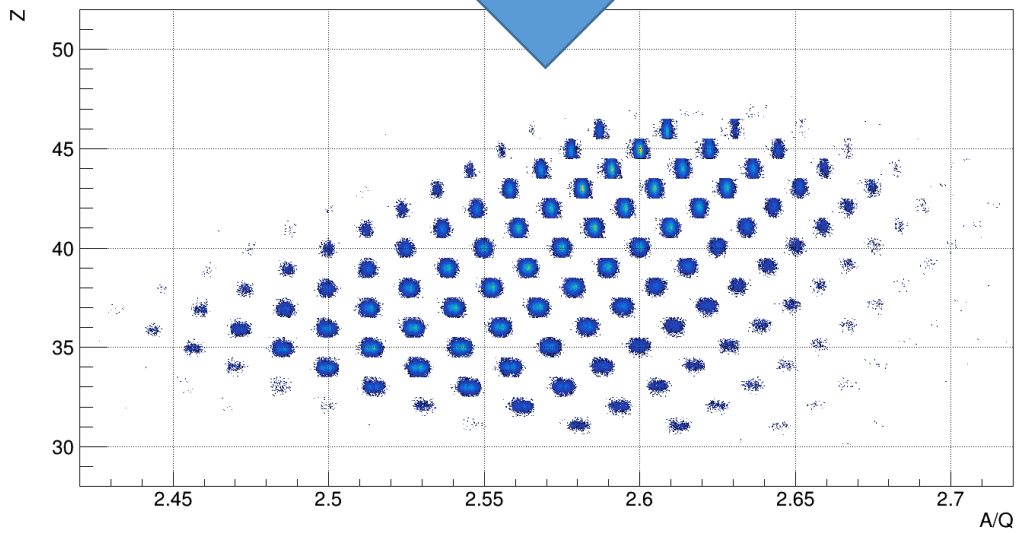
CsI(Na) hodoscope for isomers



Add 4 silicon detectors for energy loss and total kinetic energy measurement

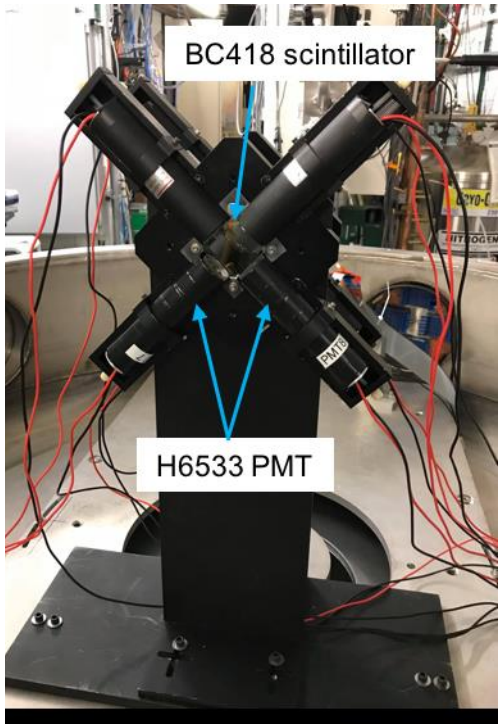


Charge-state removal with TKE measurement



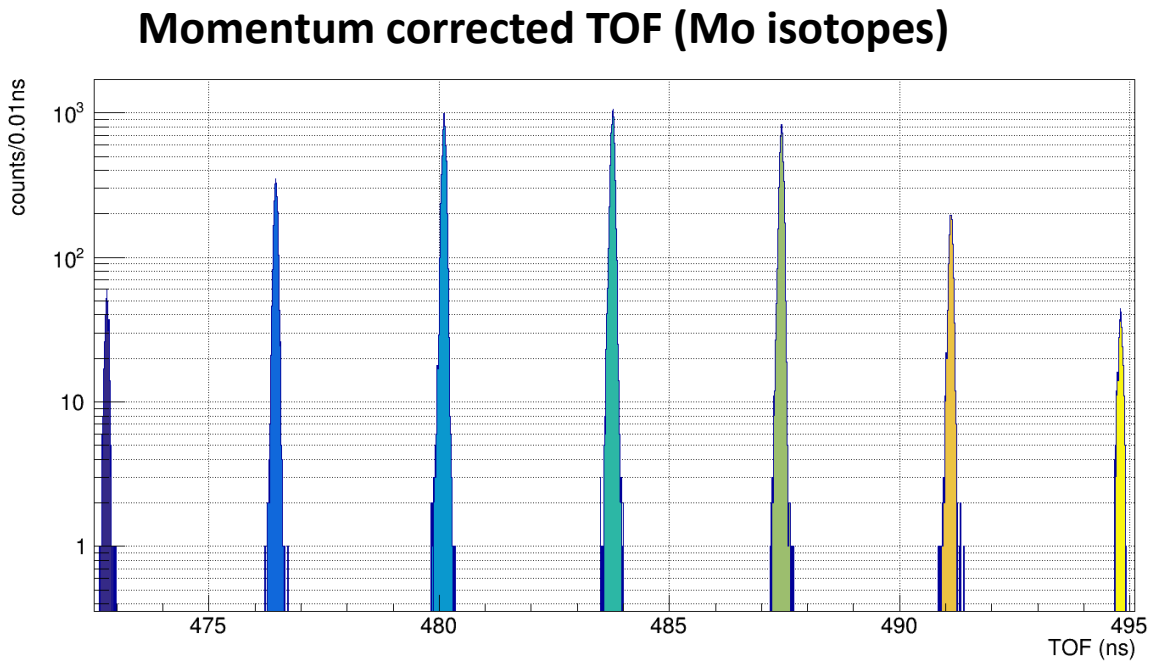
Adjustment to NSCL setup: resolution

New timing detectors
(double number of PMTs)



Detector beam test at NSCL
(timing resolution up to 8ps)

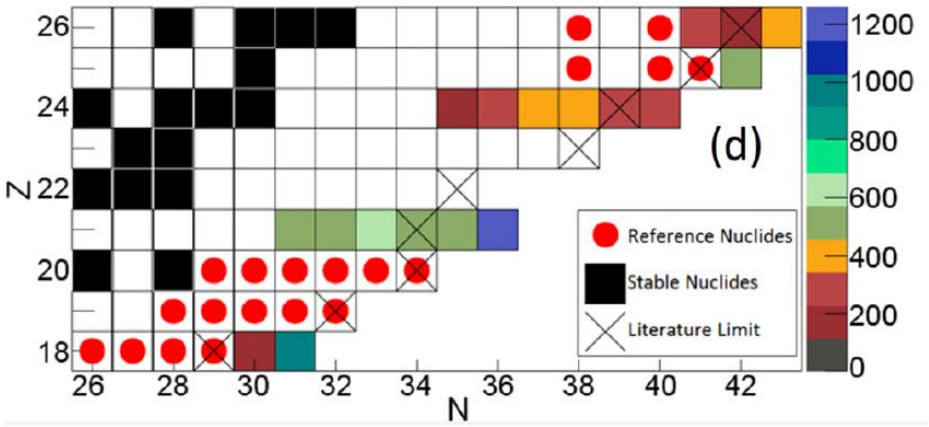
New TOF resolution: 50 ps
Previous TOF resolution: 80 ps



Adjustments to NSCL setup: mass calibration fit

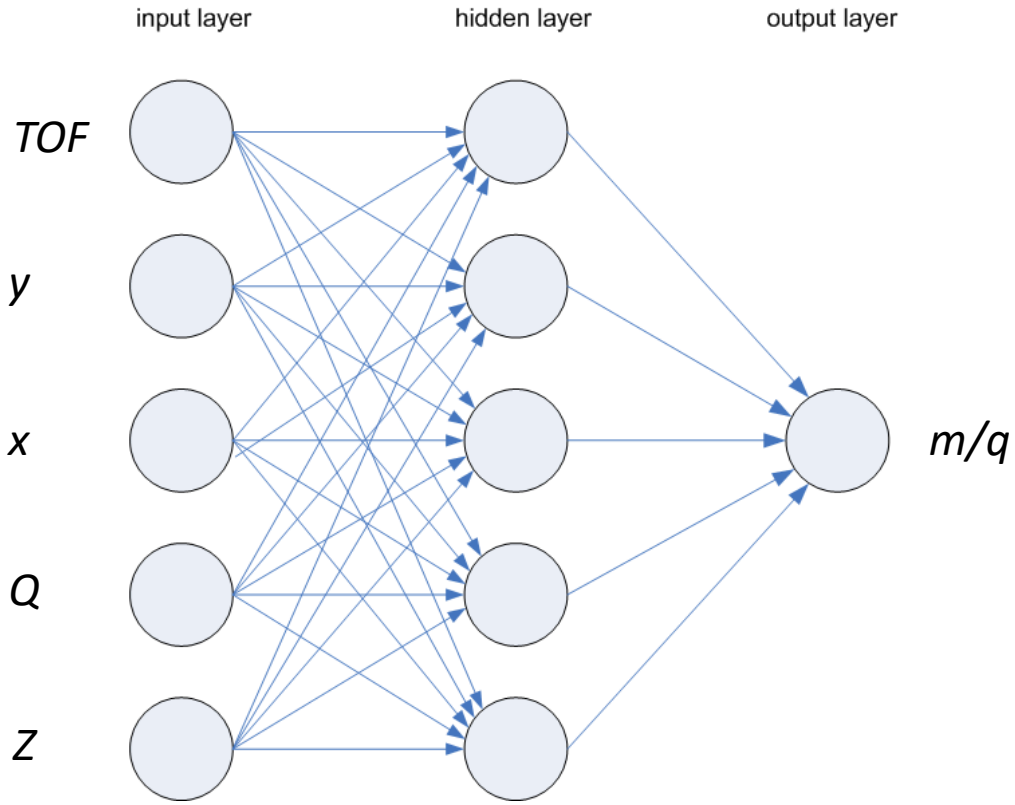
In last experiment there was significant uncertainty from choice of calibration function:

$$\frac{m}{q} = f(TOF_{\mathrm{B}\rho}, Z)$$



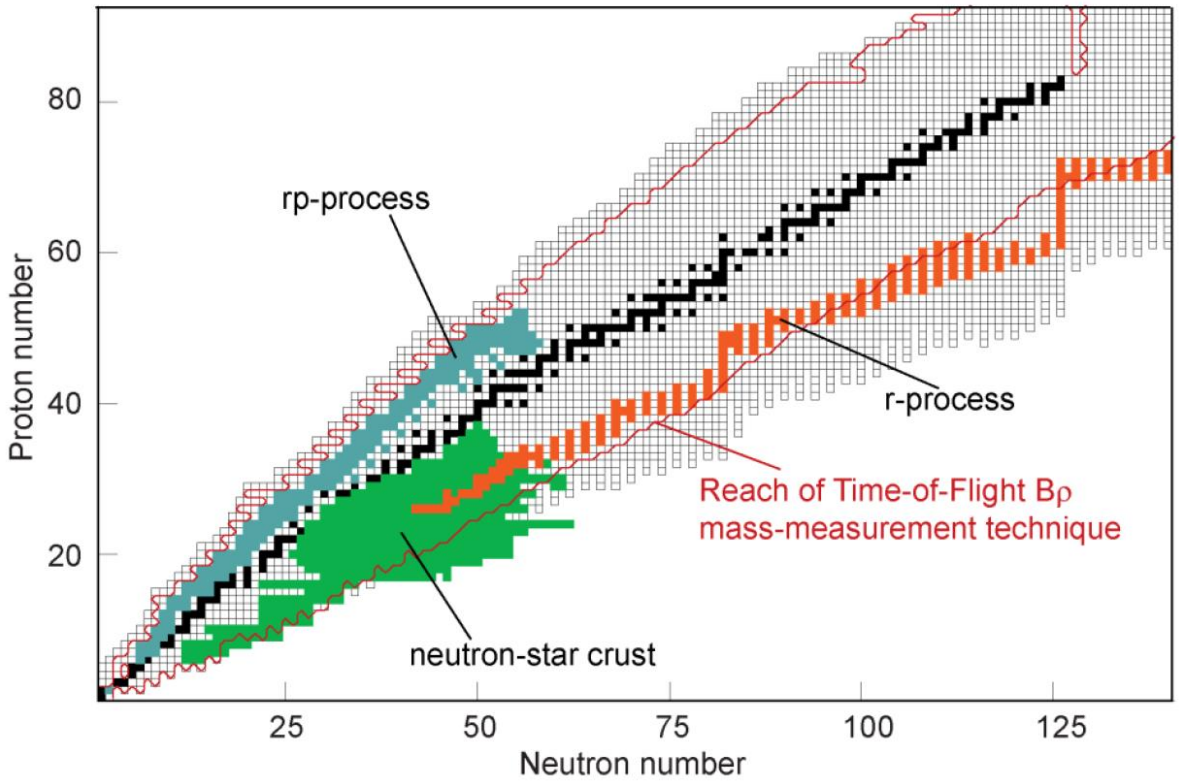
Z. Meisel et al, PRC (2016)

Machine learning approach to fit data? Fit could be done event-by-event.



Facility for Rare Isotope Beams: improved statistics!

TOF-Brho reach at FRIB: 1000 events per week



HRS: High Rigidity Spectrometer

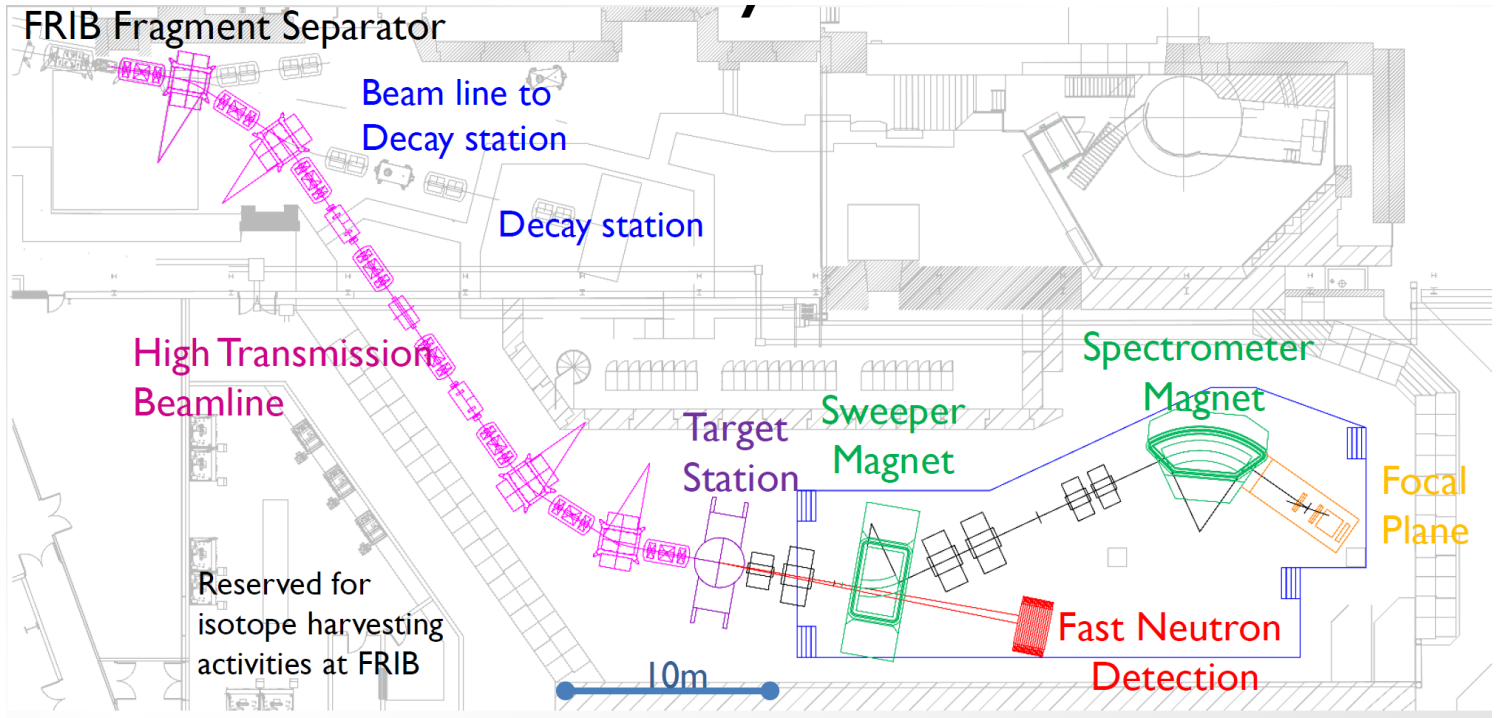
http://hrs.lbl.gov/

Remco Zegers (NSCL)
Shumpei Noji (NSCL)
Georg Berg (ND)

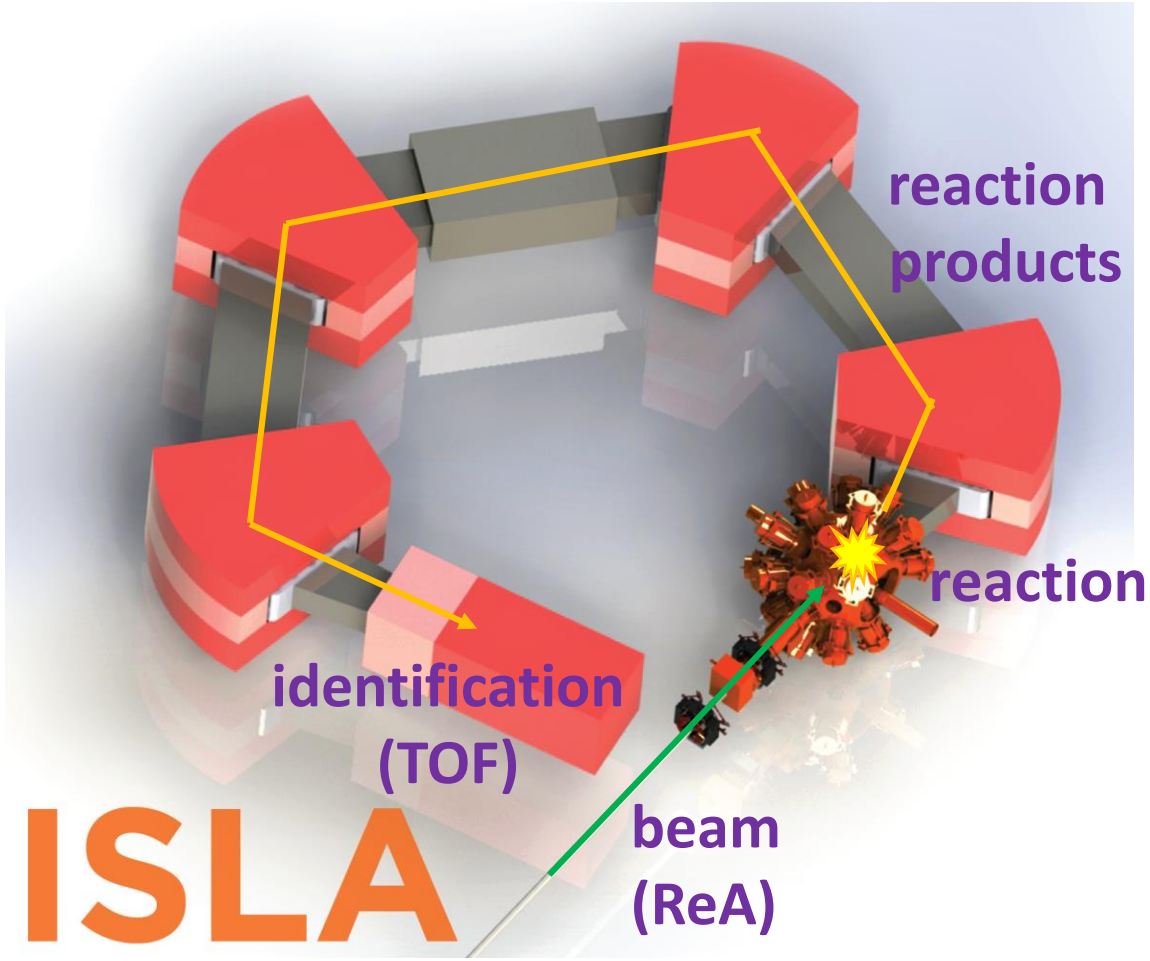
Mass measurement mode:

- High rigidity (8 Tm): neutron-rich beams
- Long flight path (includes ARIS): improve resolution
- Increased acceptance

Plus a flexible toolkit of ancillary detectors for a diverse science program: in-beam gamma spectroscopy, a variety of nuclear reaction techniques.



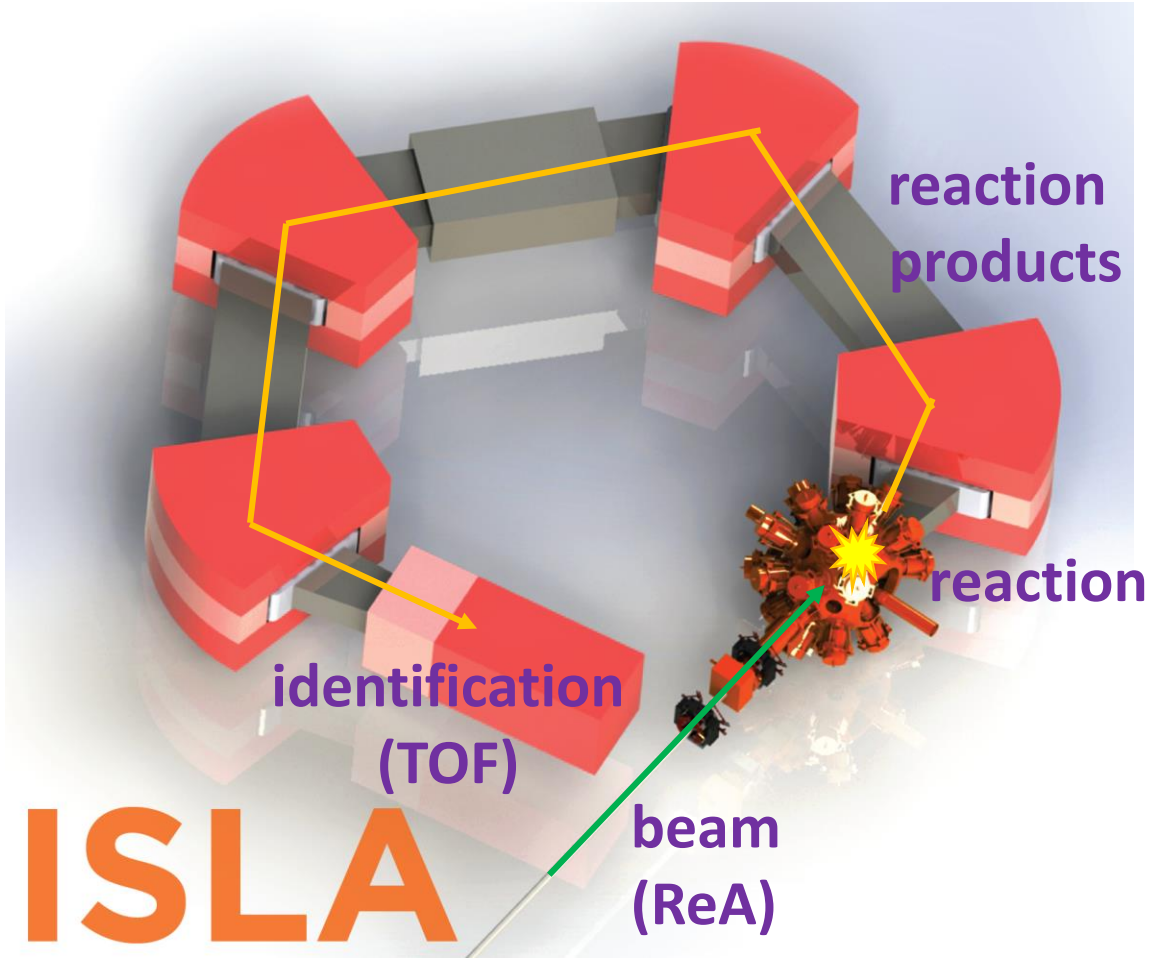
Isochronous Separator with Large Acceptances at FRIB



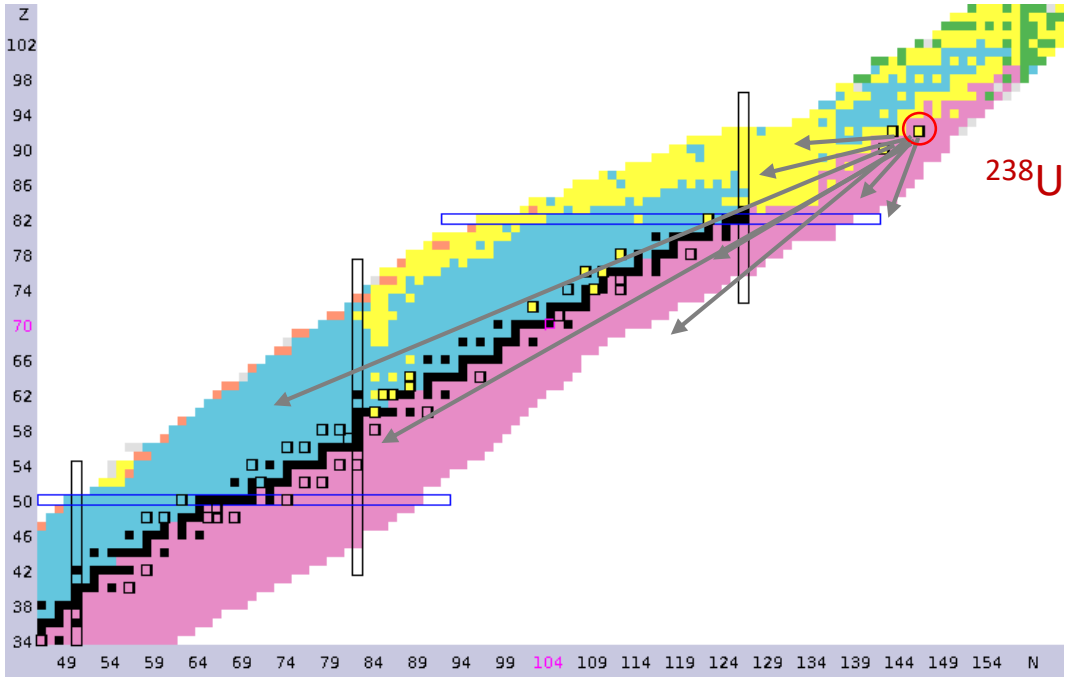
https://fribusers.org/workingGroups/isla.html

Matt Amthor (Bucknell), Daniel Bazin (NSCL) et al.

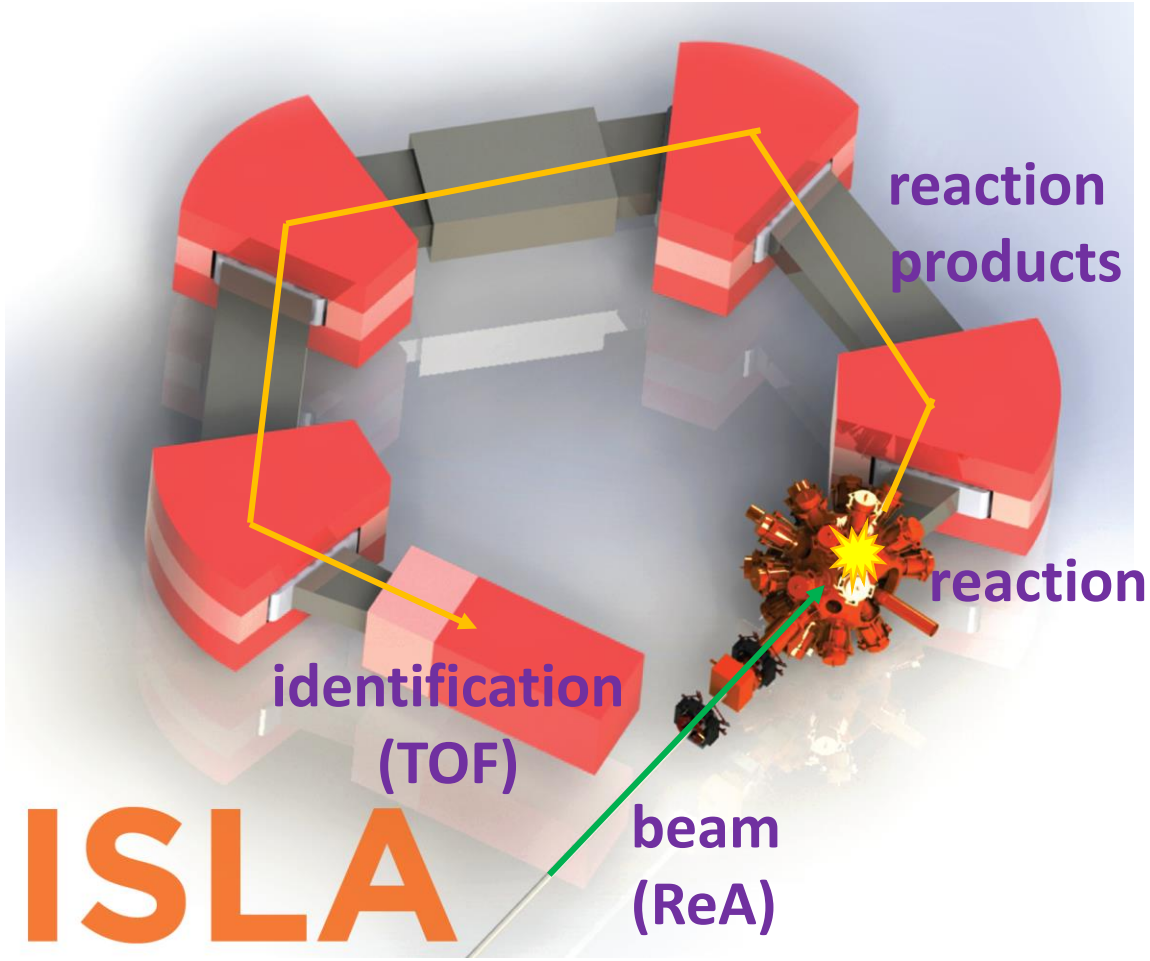
Isochronous Separator with Large Acceptances



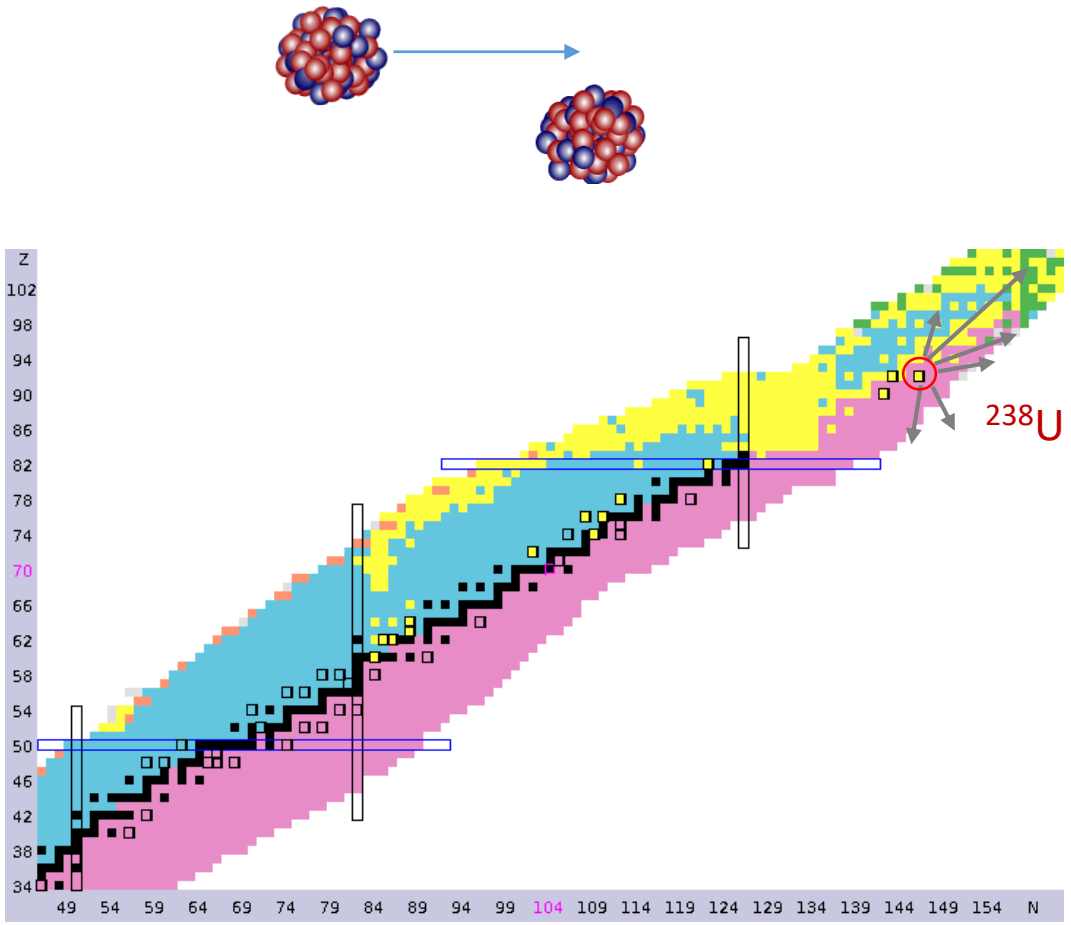
Fragmentation reactions: energy ≈100 A MeV



Isochronous Separator with Large Acceptances

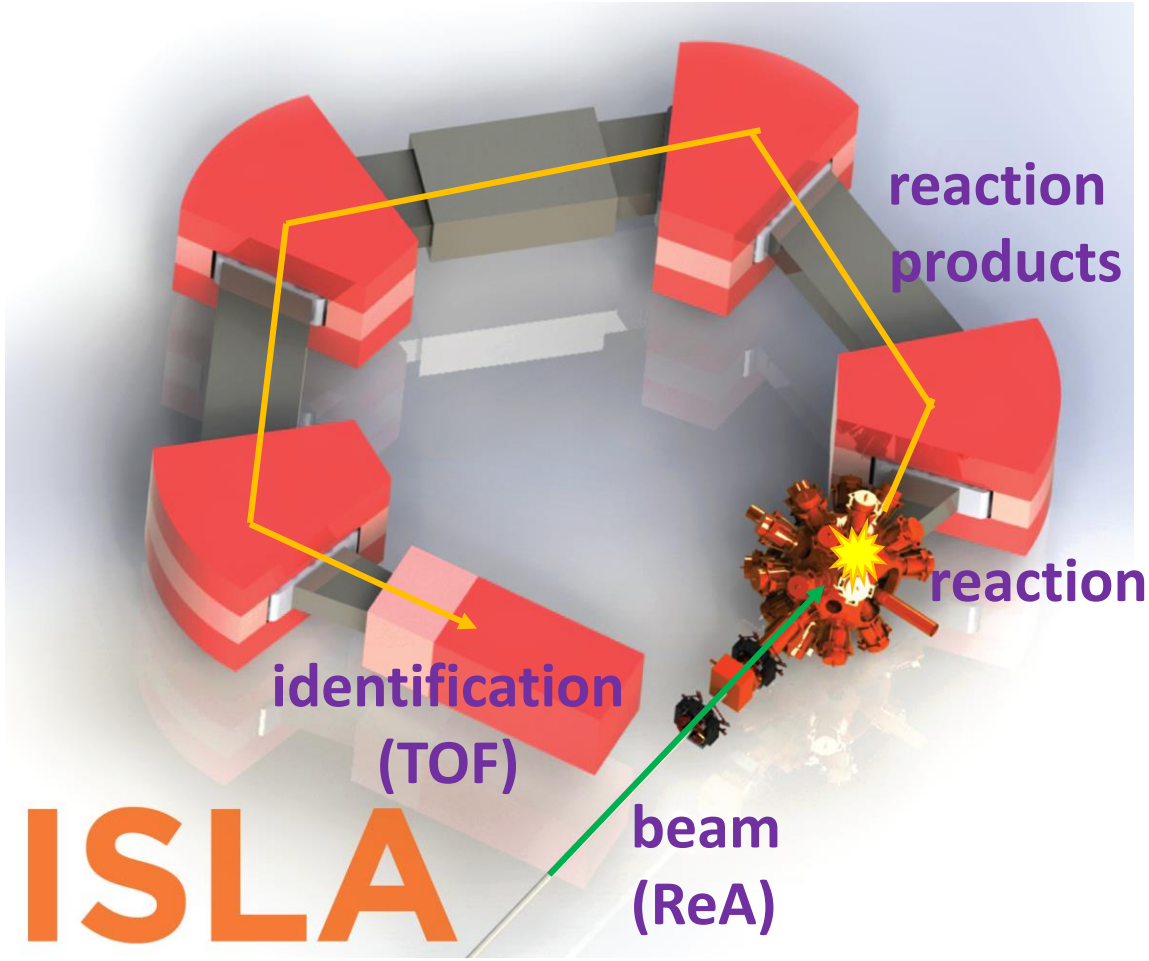


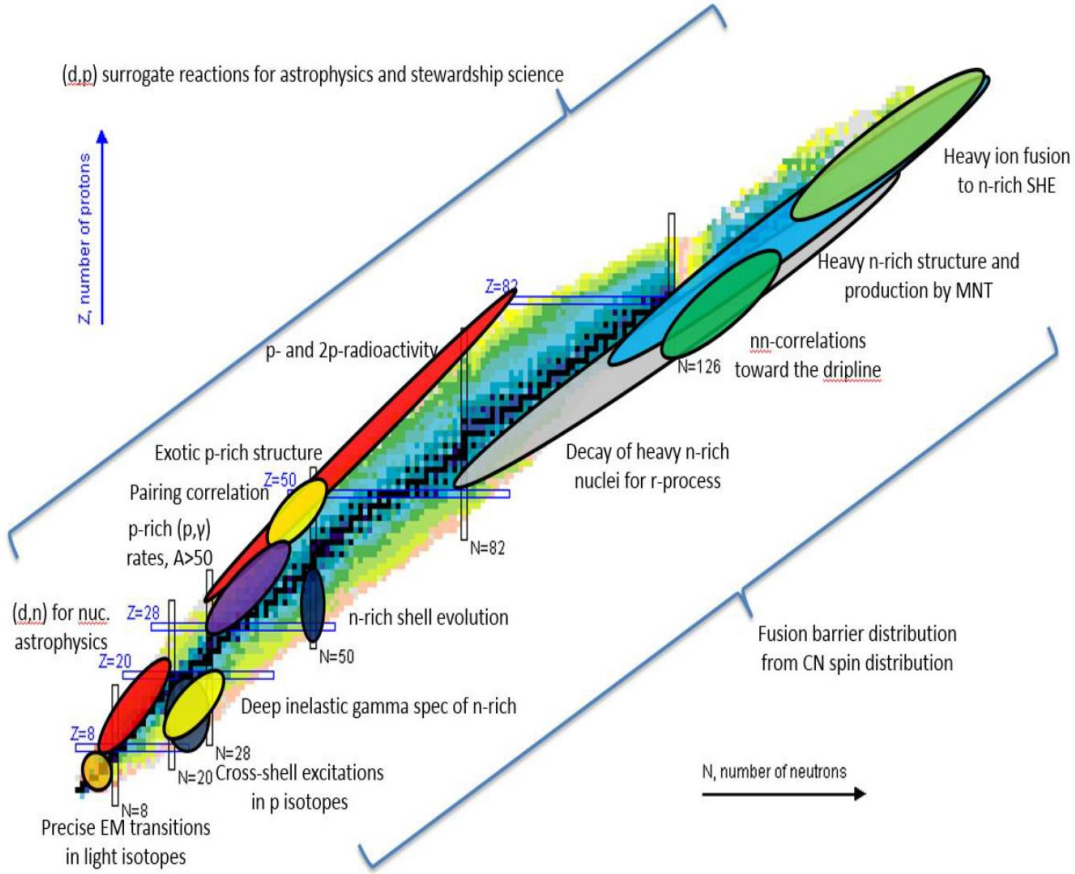
ISLA: multinucleon transfer, energy ≈10 A MeV



Corradi et al, NIMB (2013)
Welsh et al, PLB (2017)

Isochronous Separator with Large Acceptances



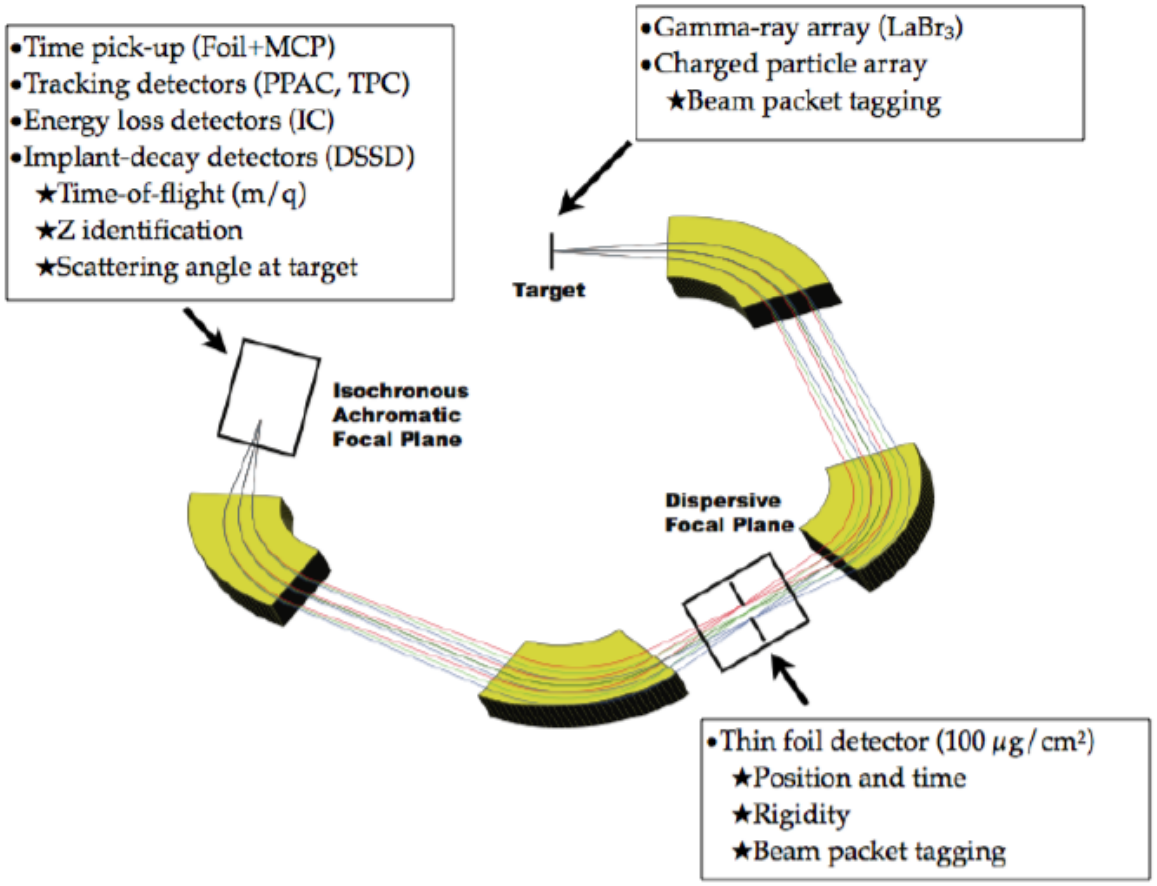


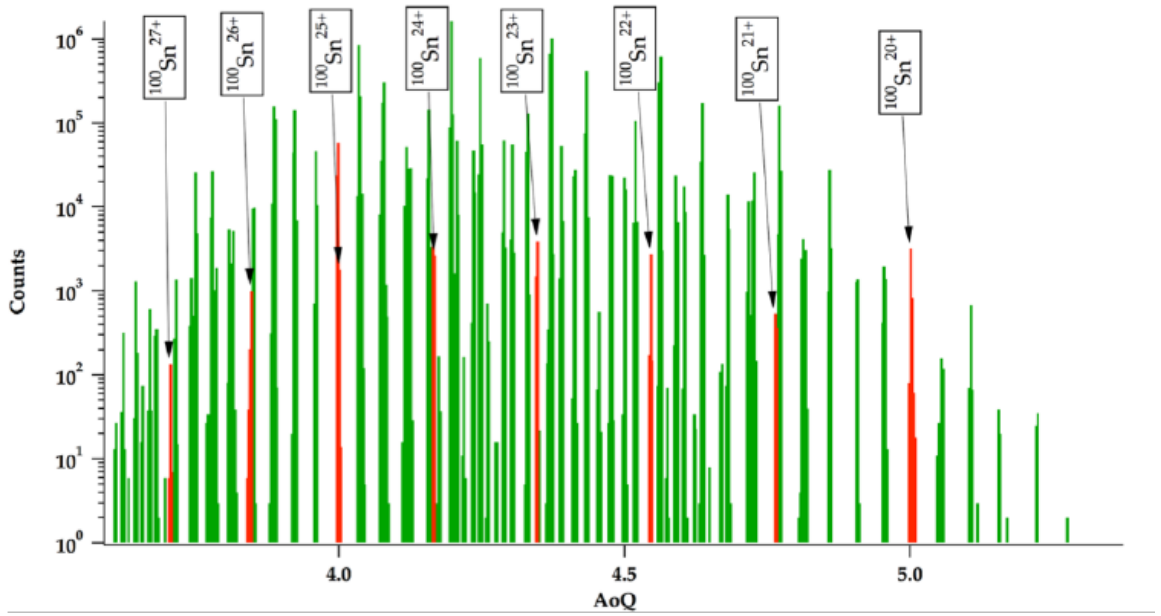
And other projects at advanced development stages around the world!

MNT+gas cell+ MR-TOF: N=126 Factory (ANL), KEK-KISS (RIKEN), ++ …

Spectrometers: AGFA (ANL), ++ …

Experiments with ISLA





Conclusions:

- TOF-Brho experiments offer access to very neutron-rich masses.
- Ongoing developments to extend technique to r-process isotopes and improve resolution of NSCL setup.
- Need statistical improvement of FRIB beams to reach r-process path.
- New devices in FRIB will also improve TOF-Brho setup, and open new exiting opportunities for experiments.

Collaborators:

K. Wang, N. Nepal, G. Zimba, T. Chapman, M. Barber (CMU), **M. Famiano**, J. Jenkins, L. Klan, K. Bhatt (WMU), M. Amthor (Bucknell Univ.), R. Zegers, S. Noji, F. Montes, S. Schatz, D. Bazin, W. Mittig, J. Pereira, O. Tarasov, T. Ginter, N. Rijal, S. Liddick (NSCL), Z. Meisel (Ohio), A. Rogers, J. Dopfler, M. Giles (UMass Lowell), S. George (MPI Heidelberg)