Research Opportunities with the Canadian Penning Trap

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Workshop on Nuclear Astrophysics Opportunities at ATLAS 2019

7/13/2019

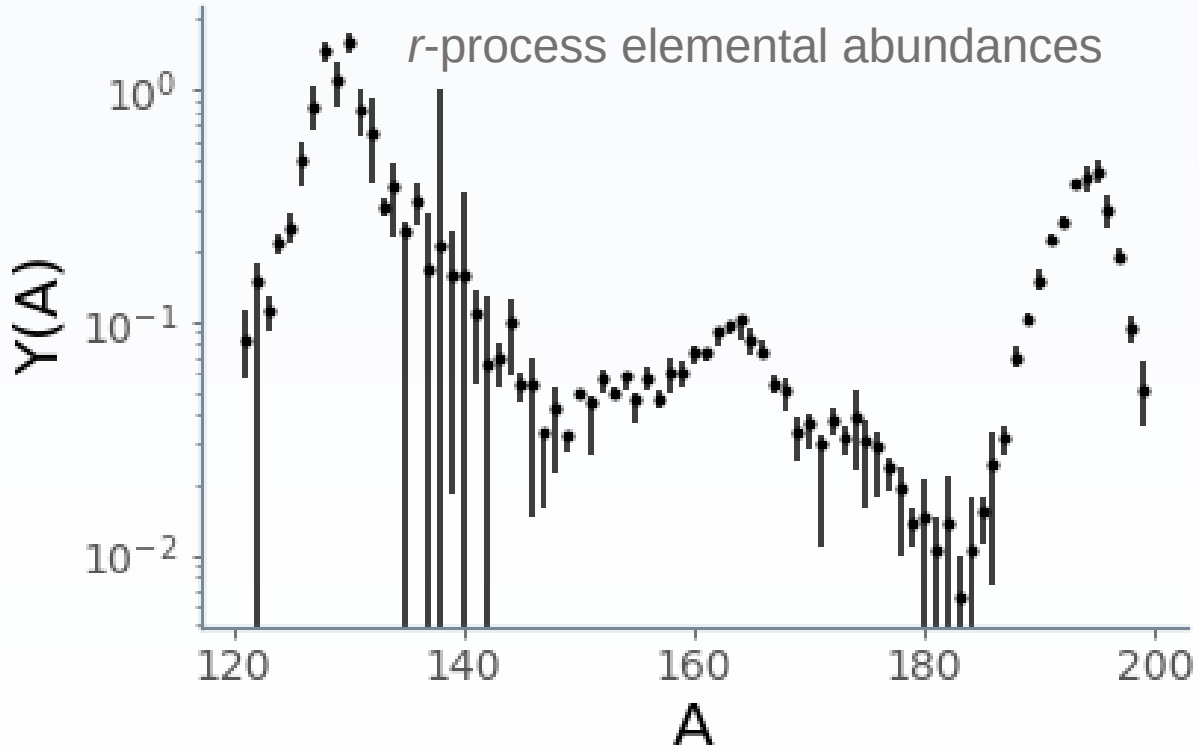
OUTLINE

- Why measure masses?
- Which masses should we measure?
- How do we measure masses?

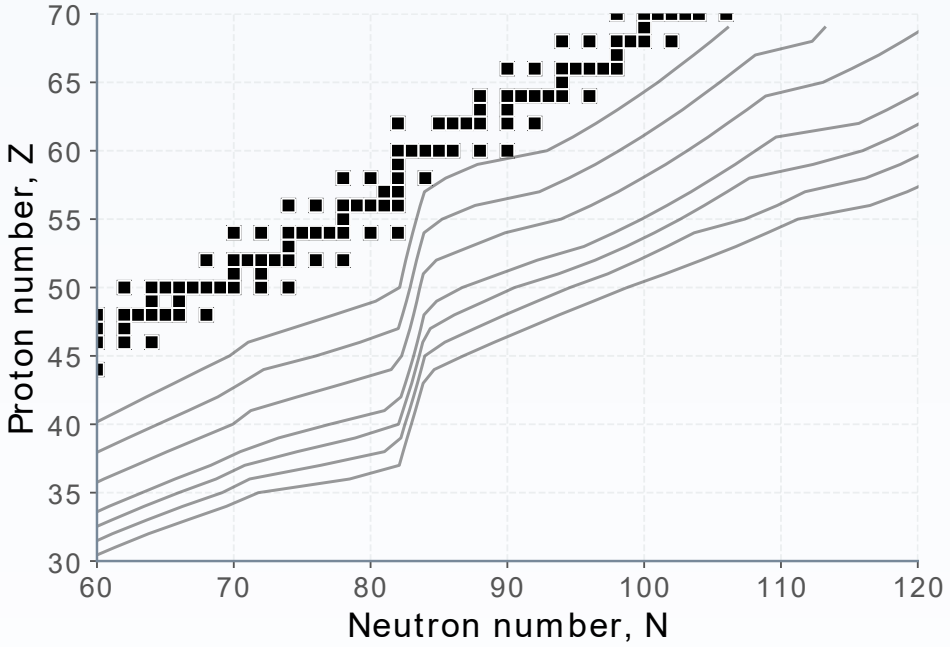
The rare-earth abundance peak

Two proposed methods to form the rare-earth abundance peak:

1. Dynamical formation during freeze-out
2. Fission cycling

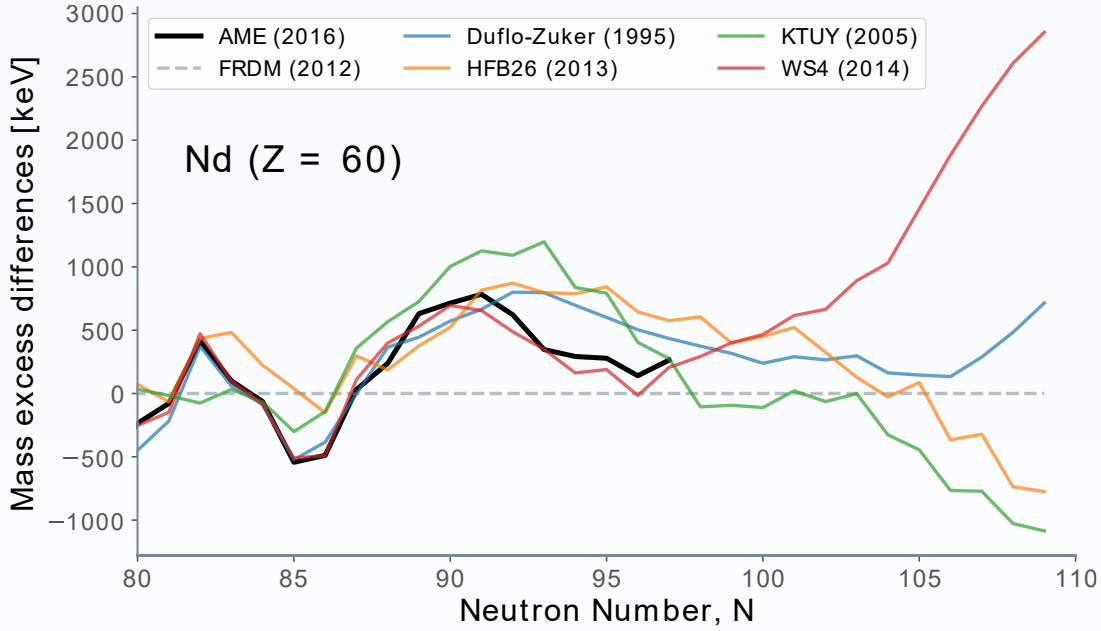


$$S_n(Z,N) = M(Z,N-1) - M(Z,N) + M_n$$

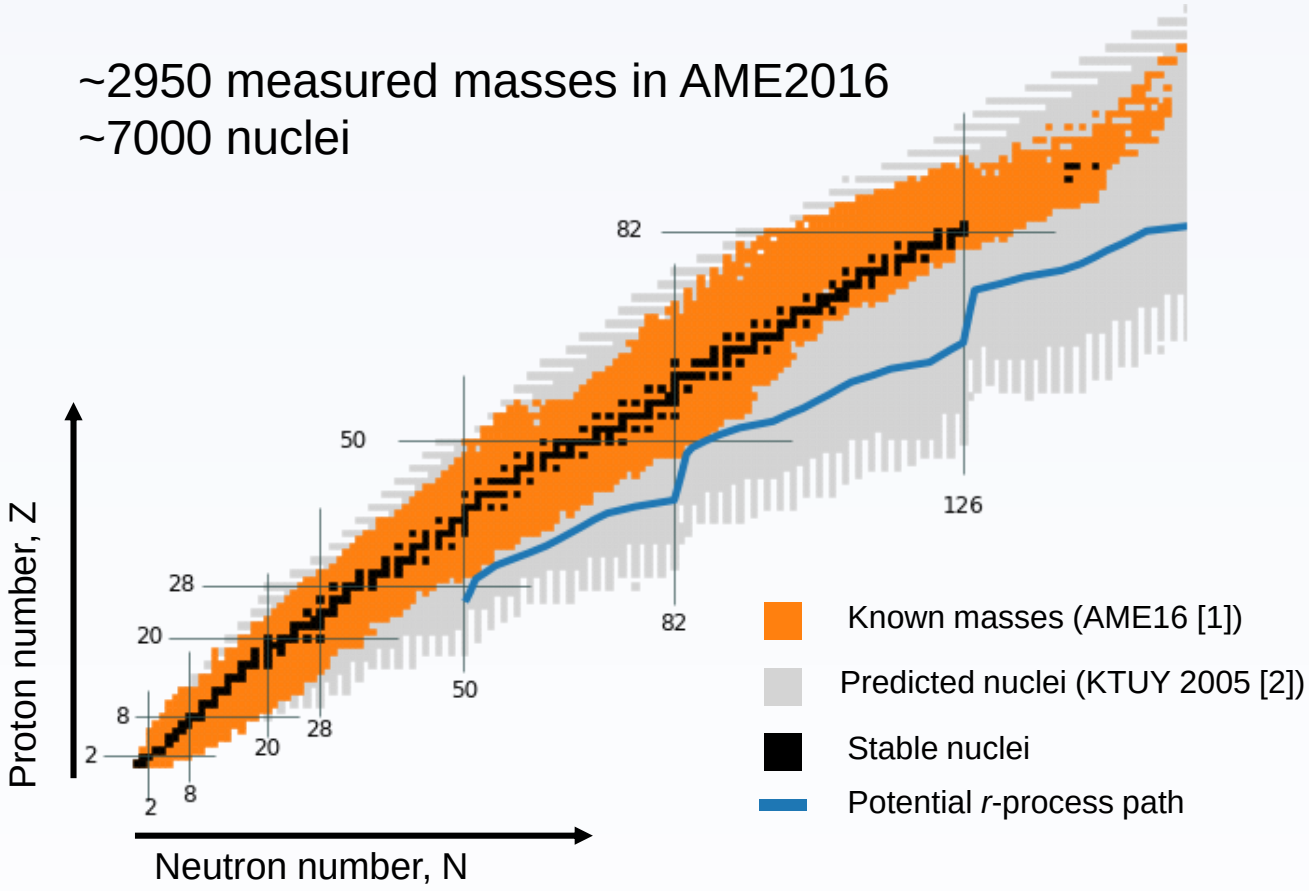


- Nuclear structure effect near N = 100 causes material to “pile up” and funnel into the A~165 peak.
- Feature is not predicted by mass models

Known masses



~2950 measured masses in AME2016
~7000 nuclei



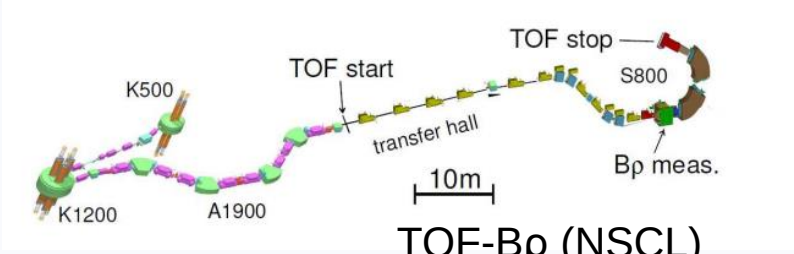
Techniques:

- TOF (very fast, low precision)
- Storage rings (fast, many measurements at once)
- MR-TOFs (fast, low resolution)
- Penning traps ("slow", high resolution, high precision)

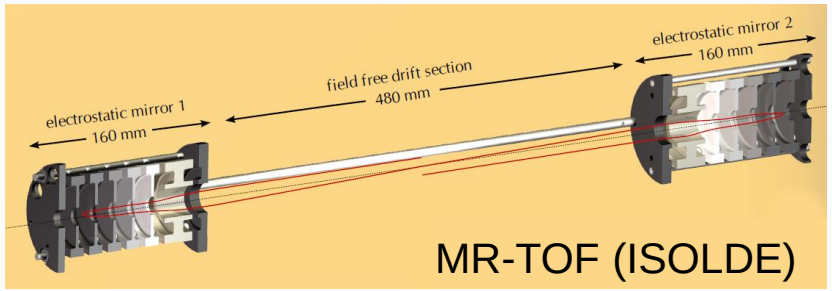
- ❑ Little experimental data in the N = 100 region
- ❑ Need more nuclear physics input including masses, half-lives, neutron-capture rates, and β-delayed neutron emission probabilities to help guide theory.

[1] Huang et al. Chin Phys. C **41** 03002 (2017)
[2] Koura et al. Prog. Theor. Phys. **113** 305 (2005)

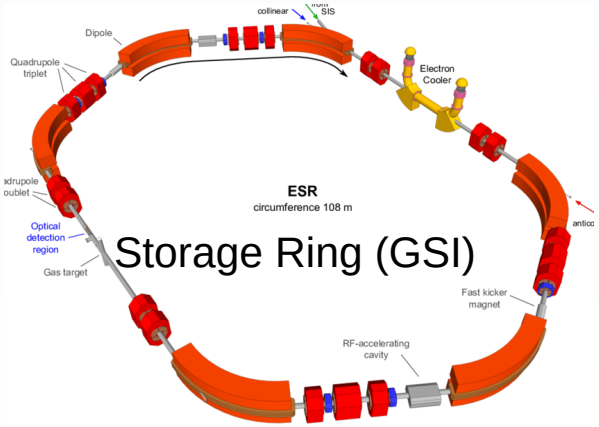
Masses by technique



TOF-Bρ (NSCL)

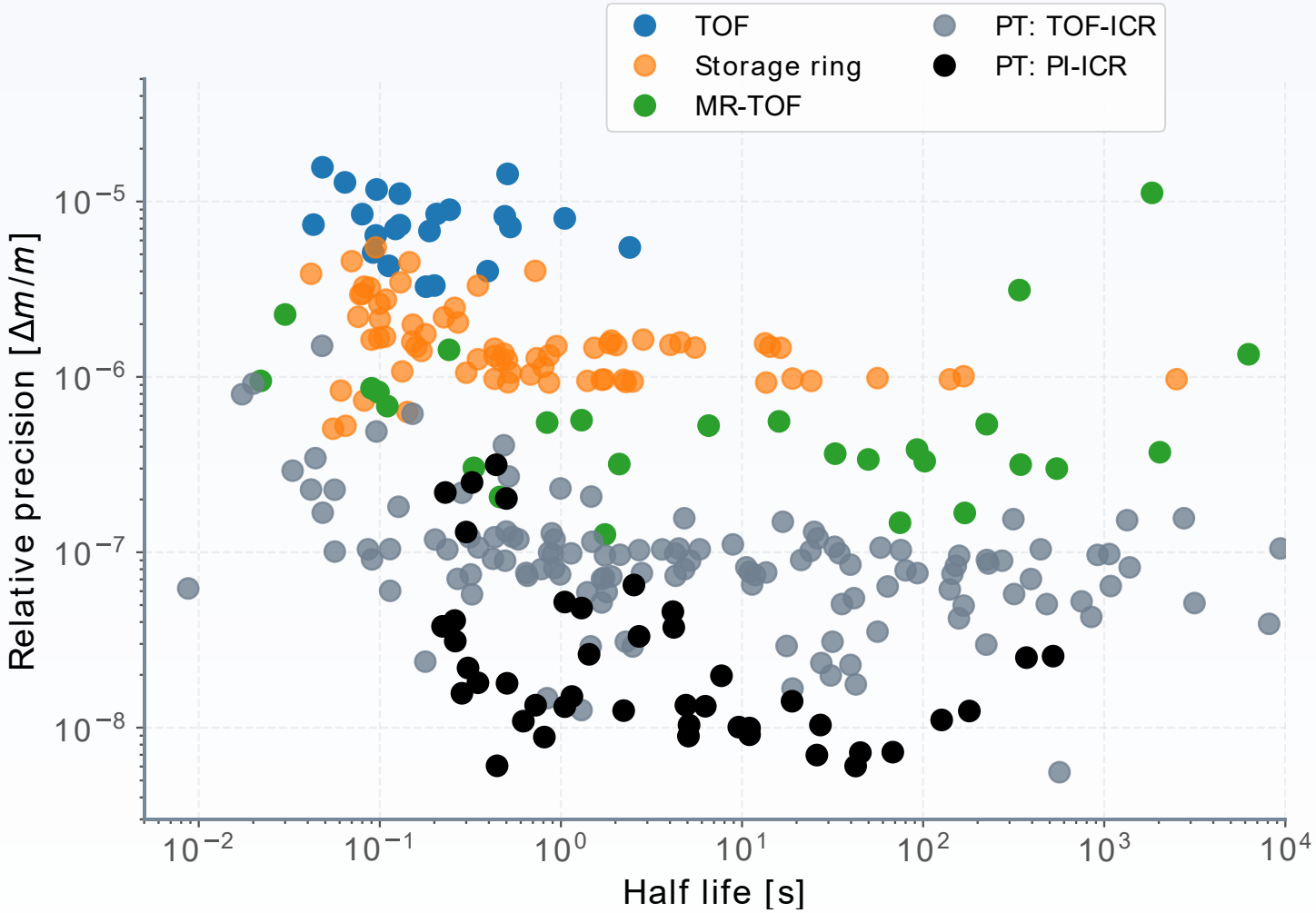


MR-TOF (ISOLDE)



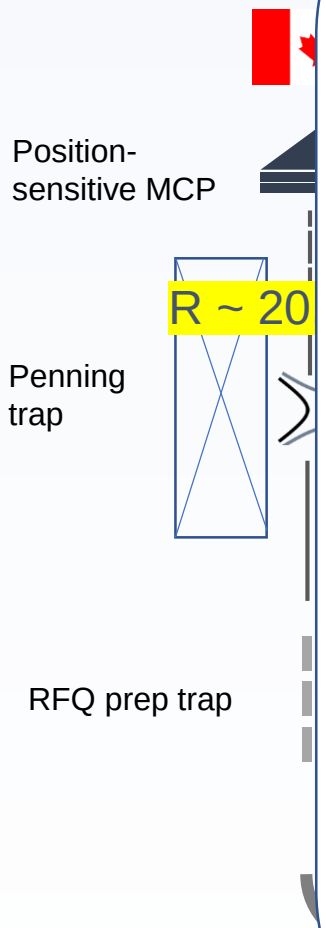
Storage Ring (GSI)

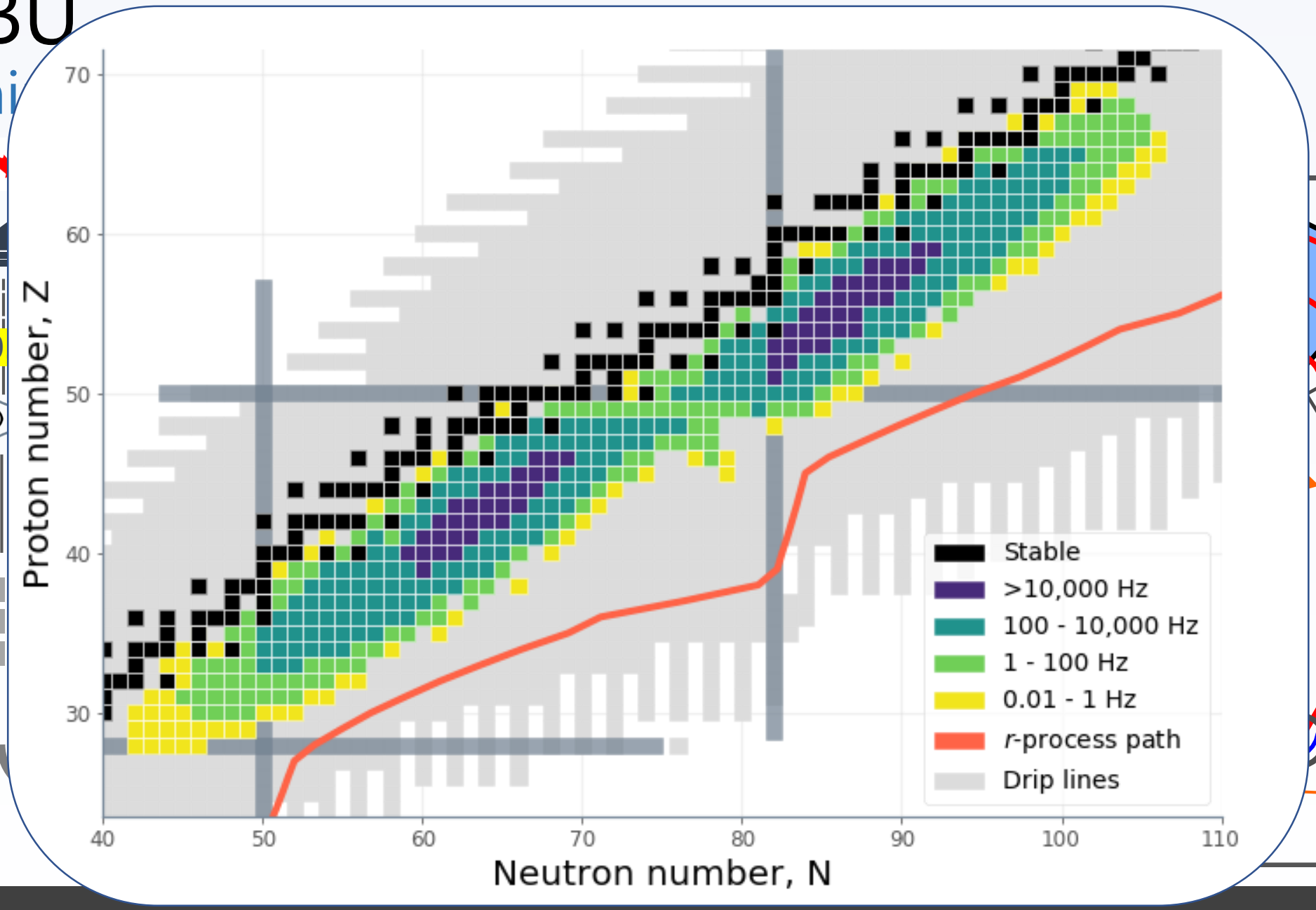
Penning trap (CPT at Argonne)

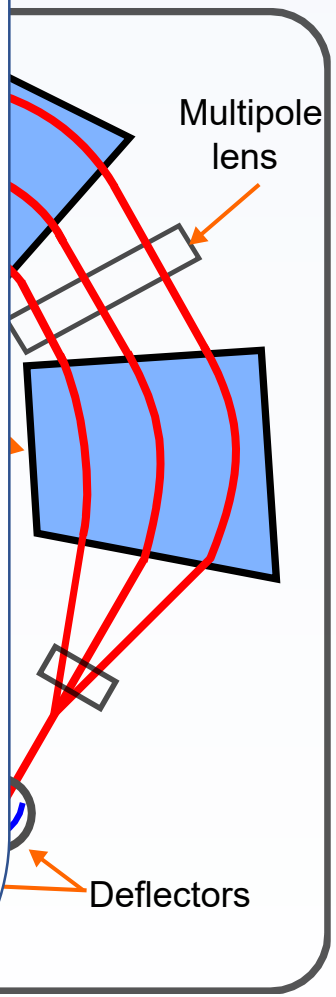


CARIBU

Californi



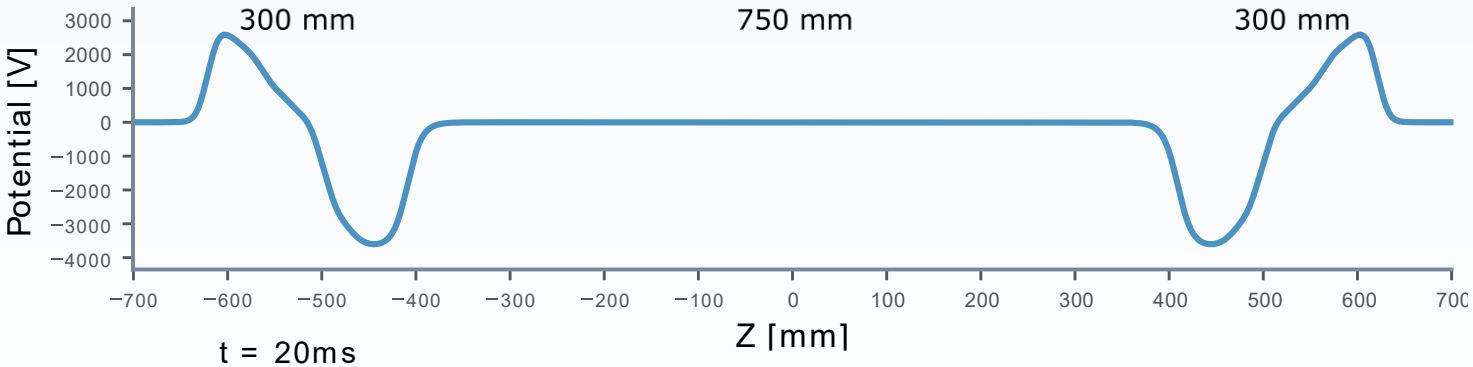


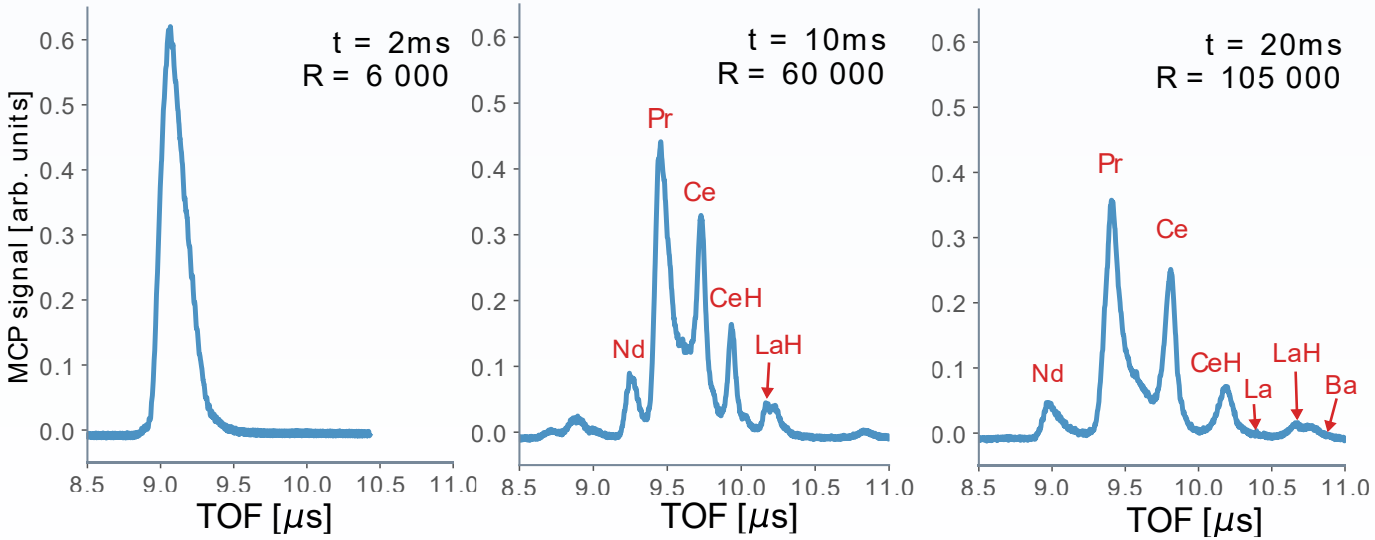


MR-TOF

Multireflection time-of-flight mass separator

- Fast (~10s ms), simple, high resolution (R ~ 100,000) isobar separator.
- Trapped ions bounce between the mirrors, picking up a time separation described by: $t \propto \sqrt{m/q}$.

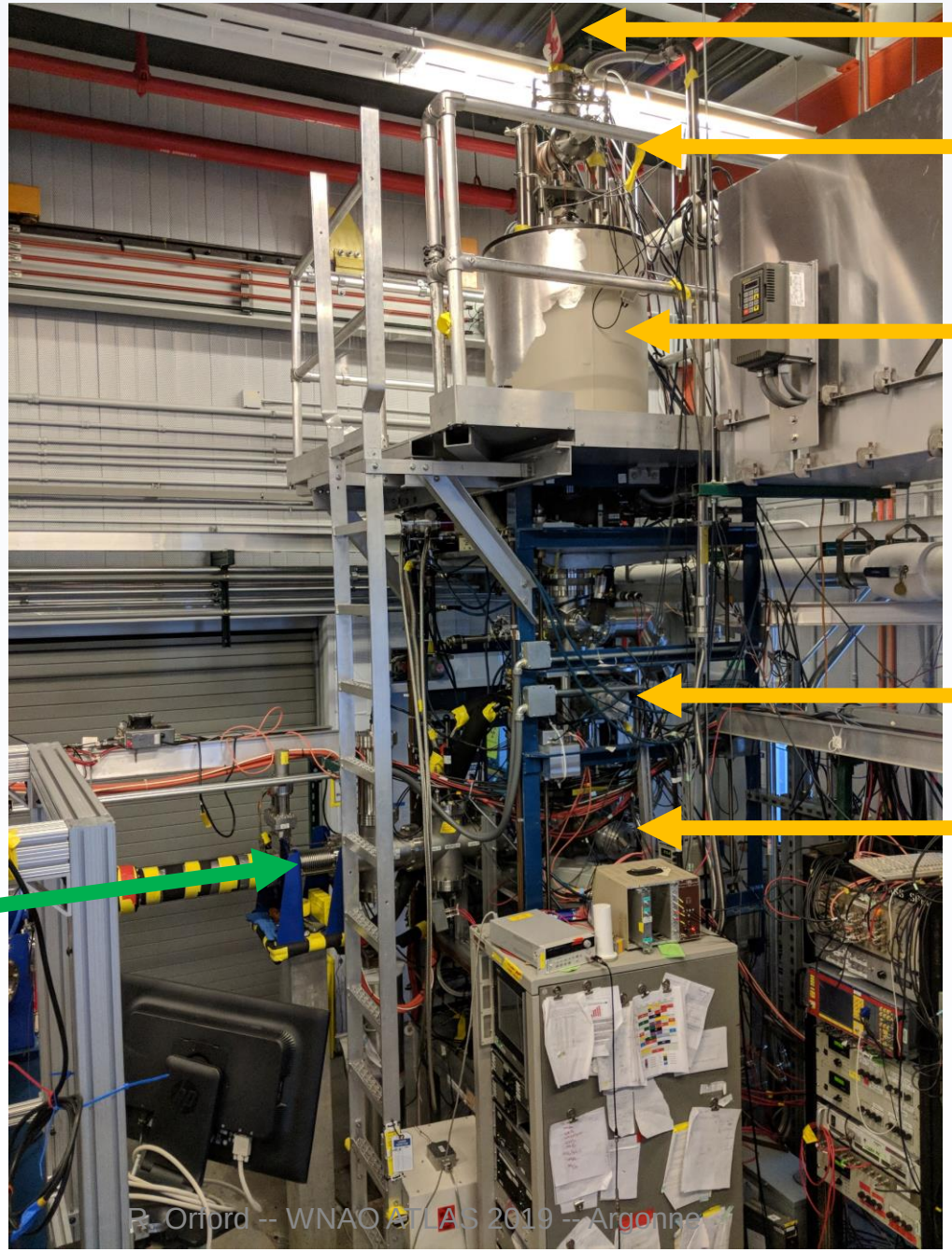




$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t}$$

- Transmission of 50% at 10ms
- Bradbury-Nielsen Gate (BNG) is used to precisely select the isobar of interest

CPT tower



Canadian flag

Detector

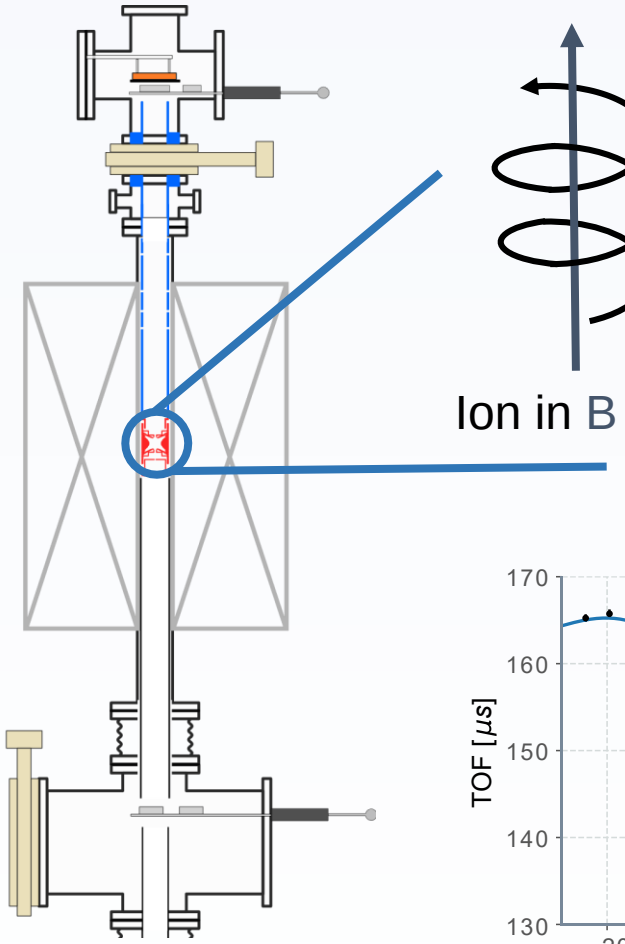
Penning trap

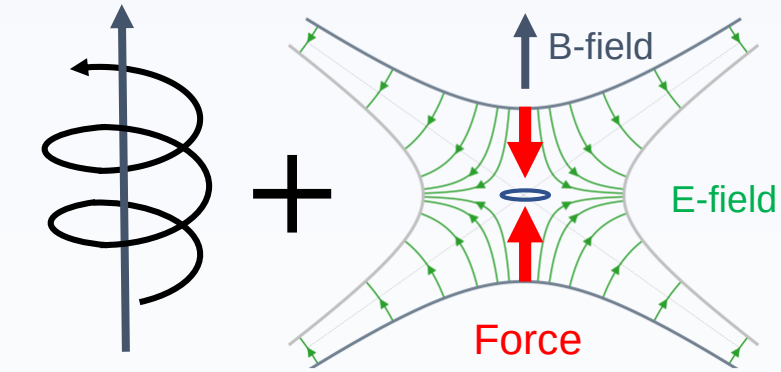
Preparation Paul trap

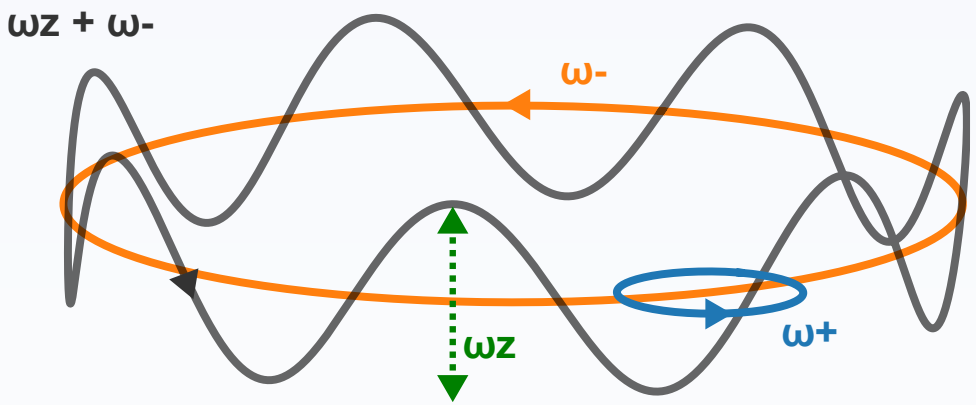
90º deflector

CARIBU beam

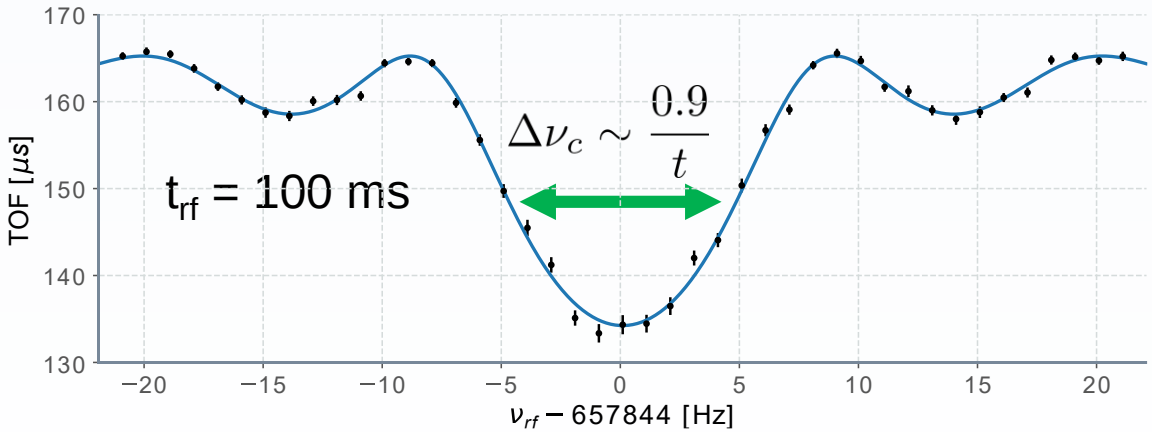
Penning trap mass measurements





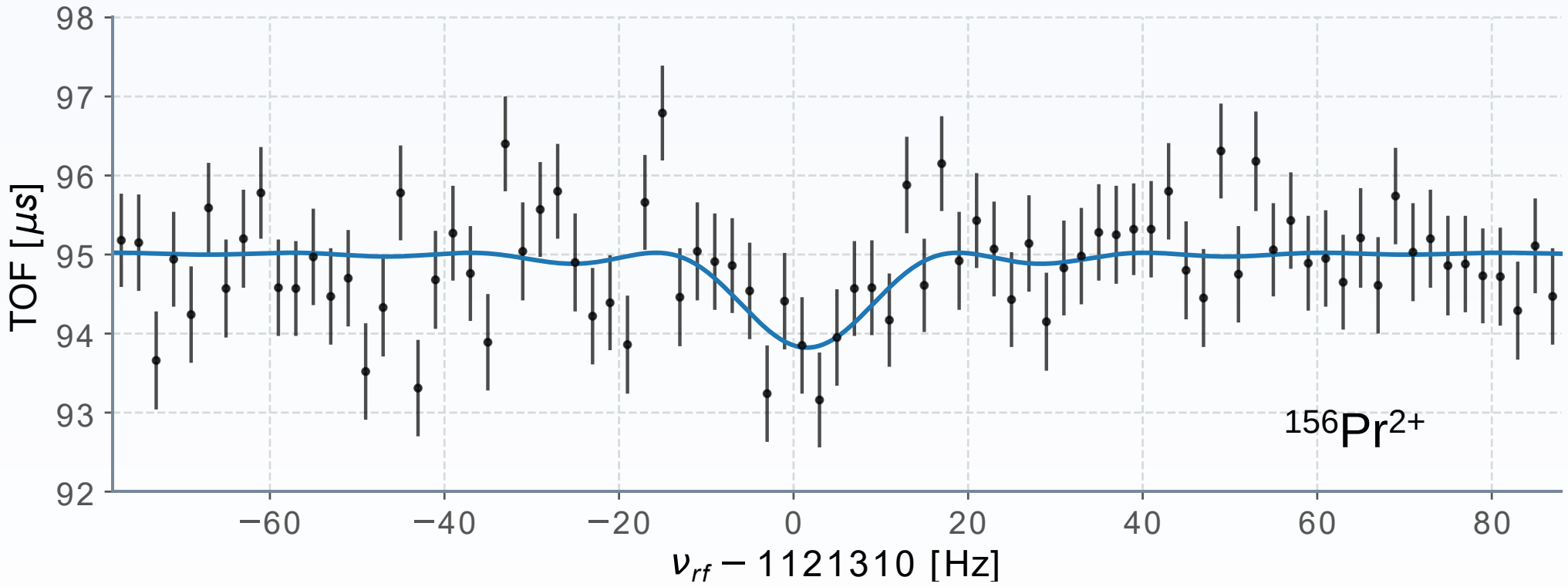


$$\omega_c = \frac{qB}{m_{\text{ion}}} = \omega_- + \omega_+$$



- Time-of-flight ion-cyclotron-resonance (TOF-ICR)
- Standard technique since the 1980s

TOF-ICR

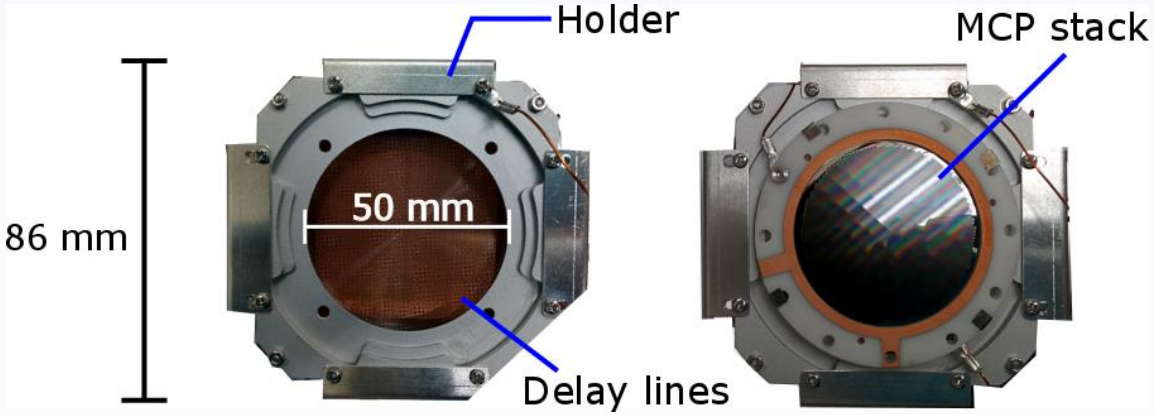


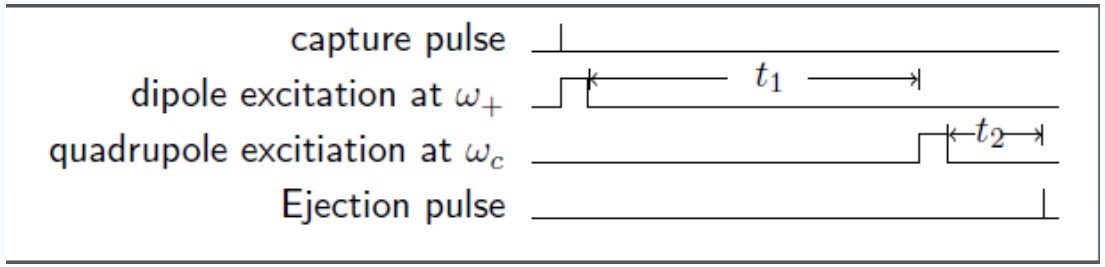
- For more exotic nuclei we need higher sensitivity

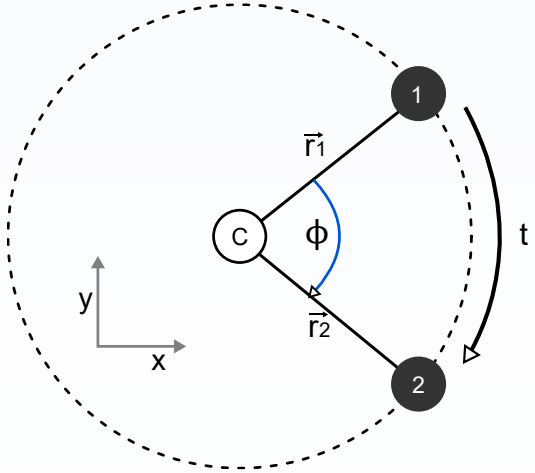
PI-ICR

Phase-imaging ion-cyclotron resonance

$$\nu_c = \frac{qB}{2\pi m_{ion}} = \frac{\phi_c + 2\pi N}{2\pi t_1}$$



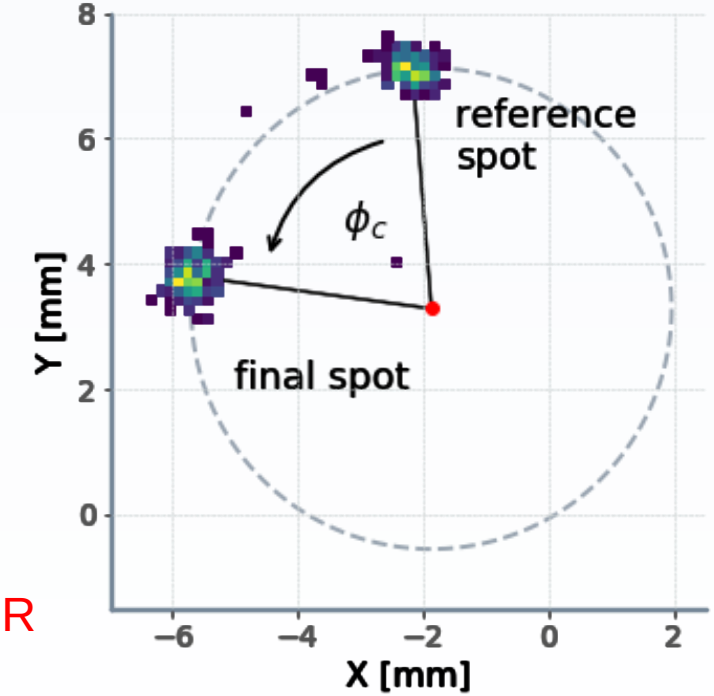




- Developed by SHIPTRAP group [1], now being adopted by other Penning trap mass spectrometers
- Use a position-sensitive MCP to infer the instantaneous phase of the orbital motion of an ion ejected from the Penning trap
- Measure the phase advance over some a period of time to determine the frequency of orbital motion

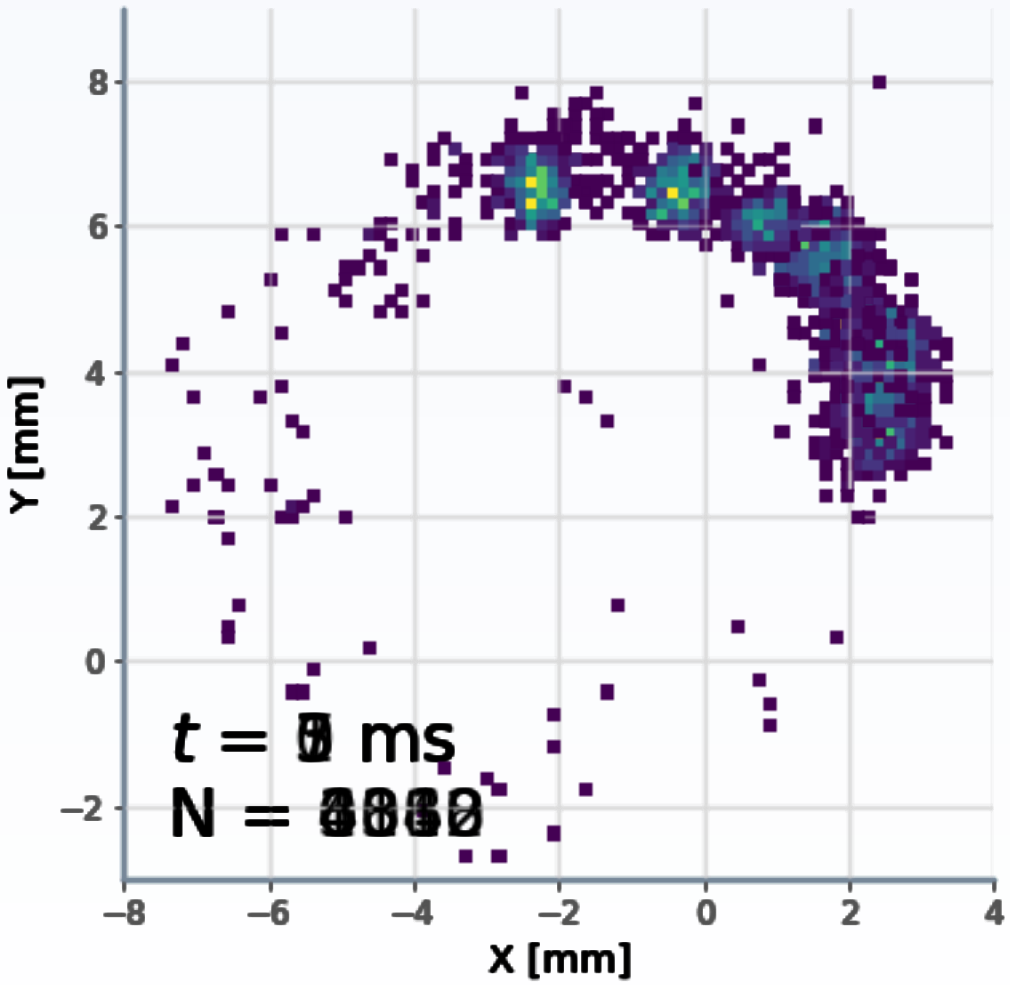
$$\nu = \frac{\phi_2 - \phi_1}{2\pi t}$$

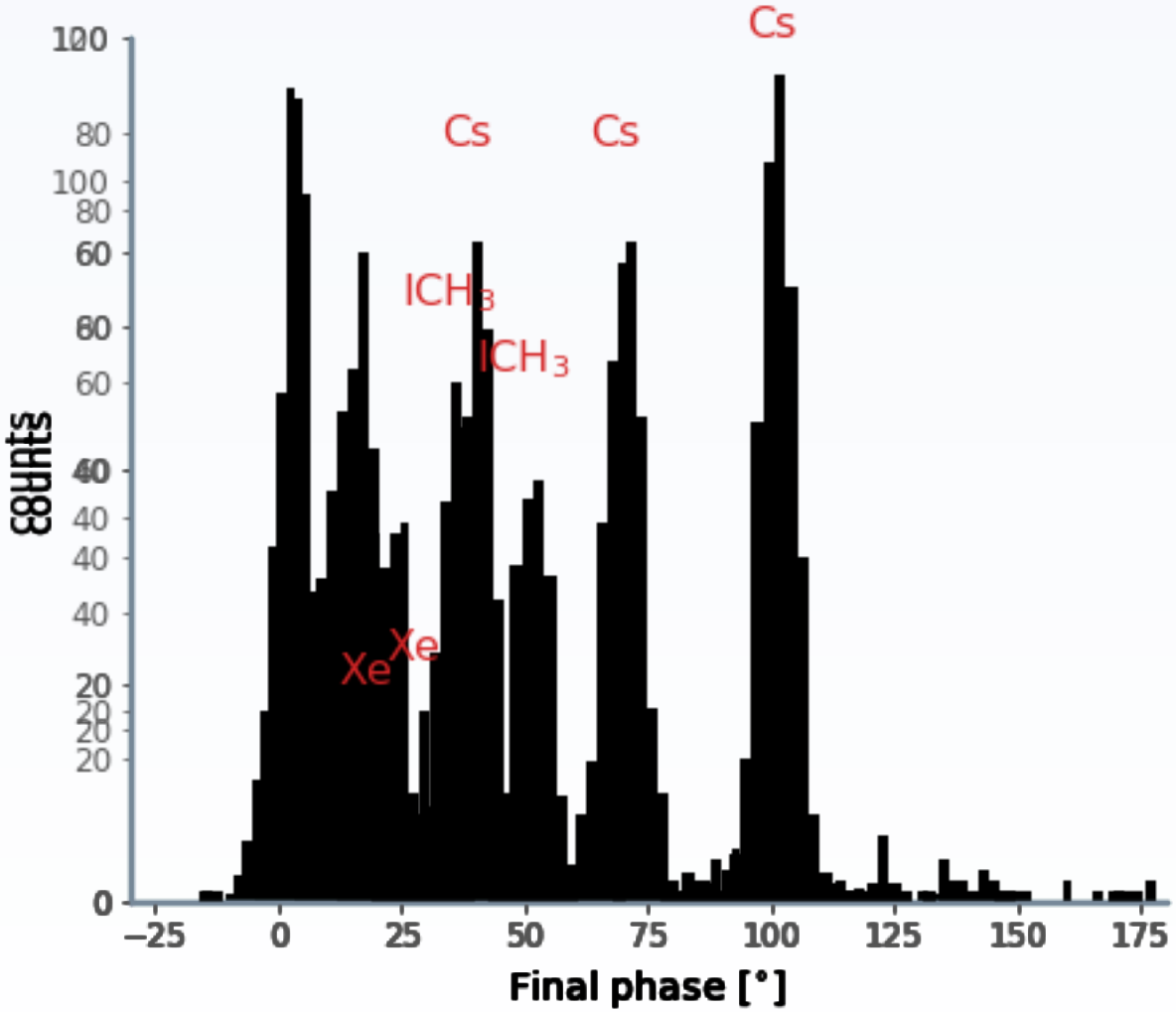
- Several advantages over TOF-ICR



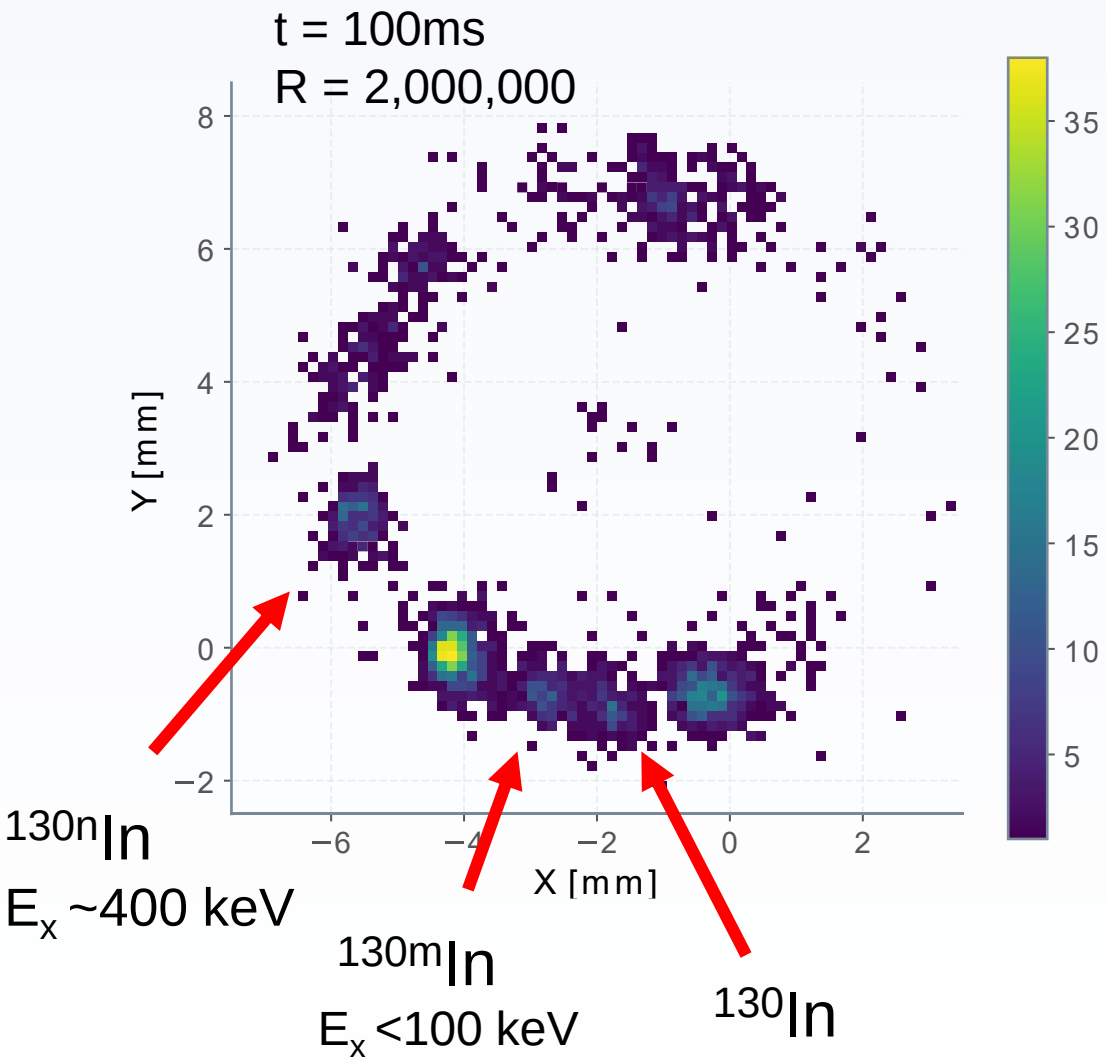
PI-ICR mass separation

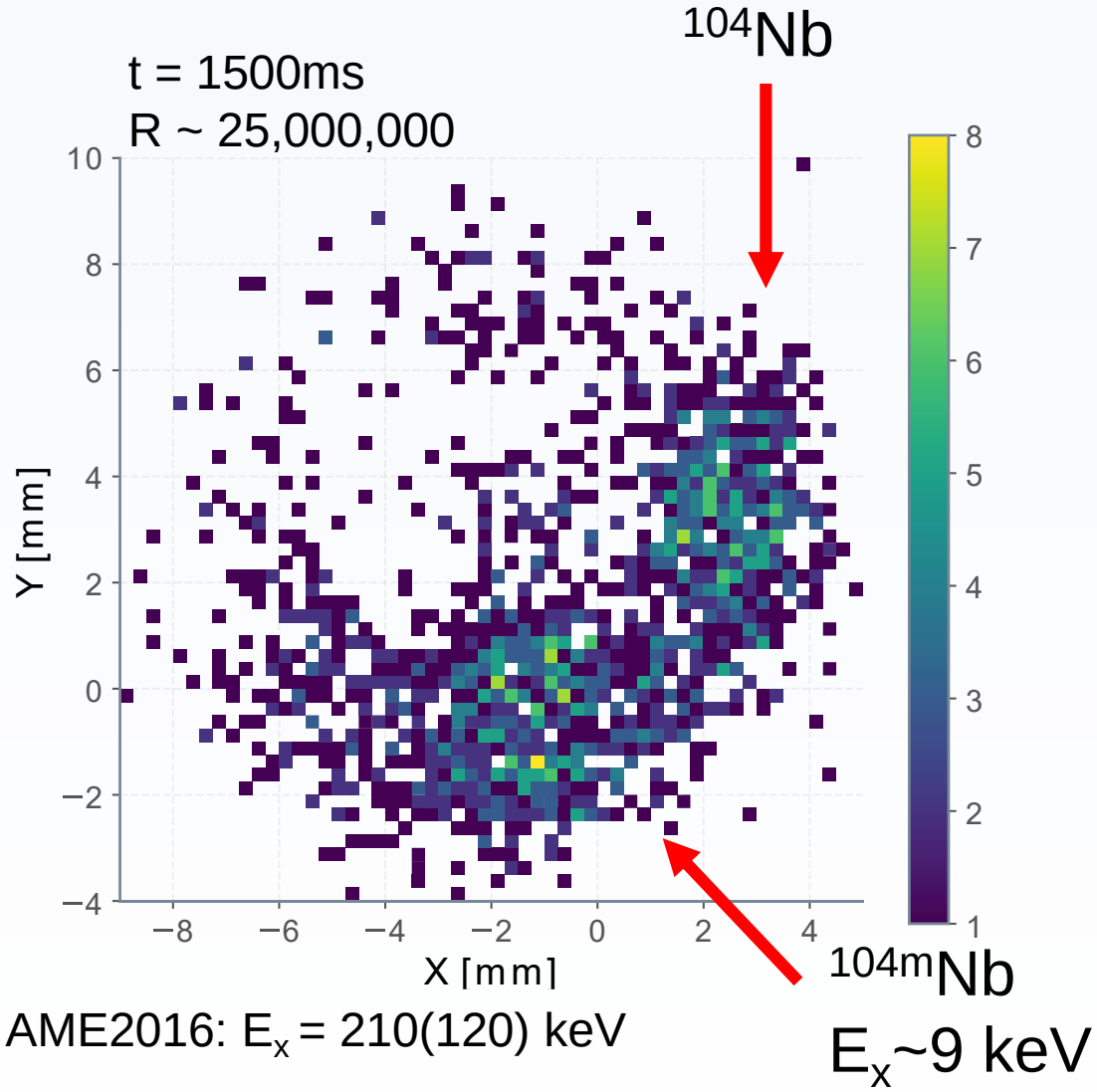
$$\nu_c = \frac{\phi_{tot}}{2\pi t} = \frac{\phi_c + 2\pi N}{2\pi t}$$





Resolution extremes

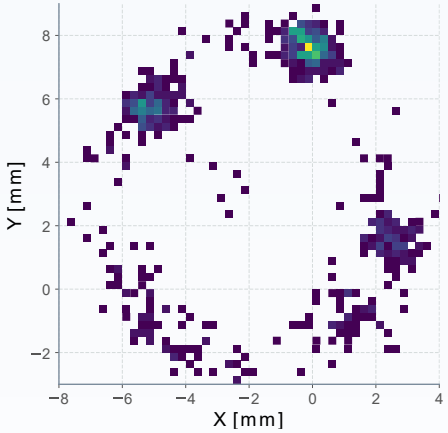


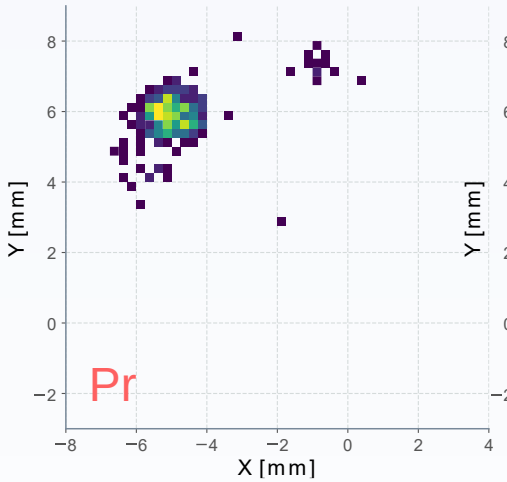


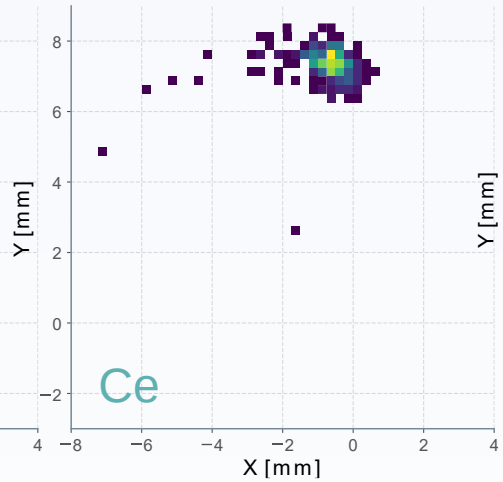
MR-TOF + PI-ICR

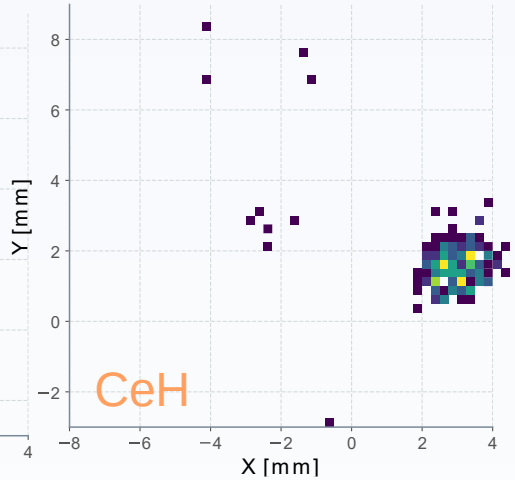
Beam of A/q = 150/2+

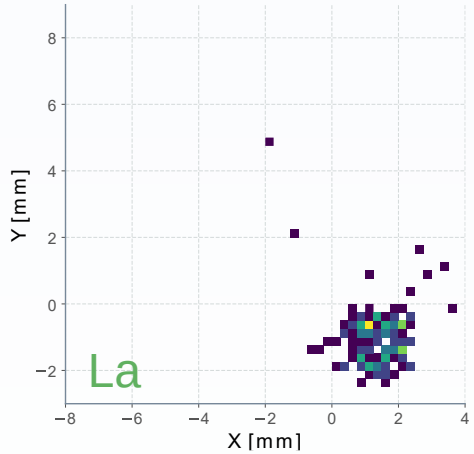
- MR-TOF is a crucial device for the CPT
- What does R = 100,000 really mean?
- Moving 300ns BNG window around allows us to select a single isobar and suppress others

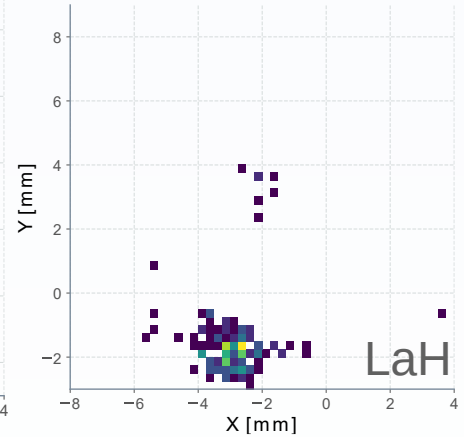


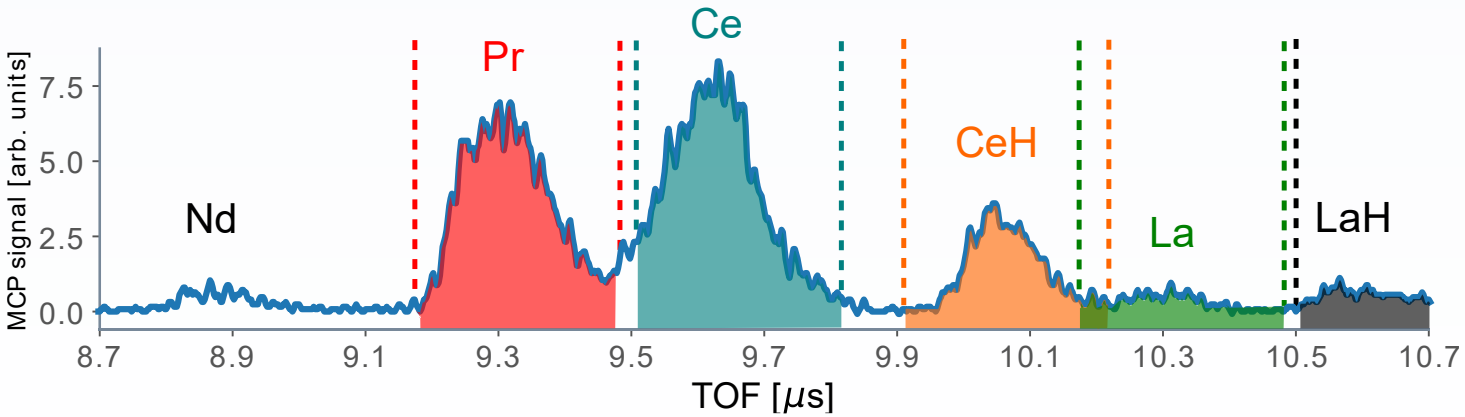




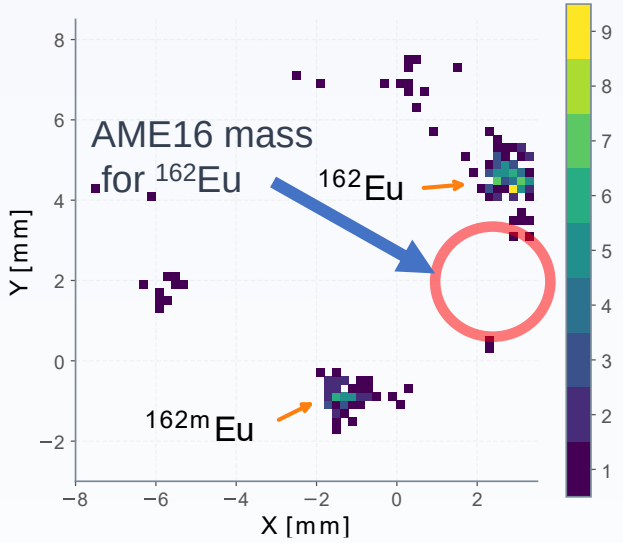






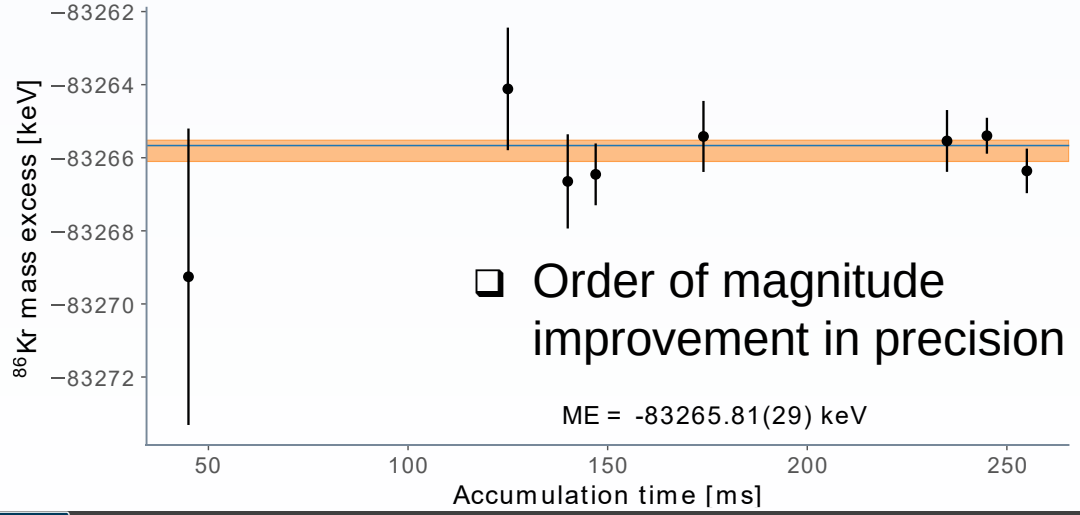


Benefits of PI-ICR

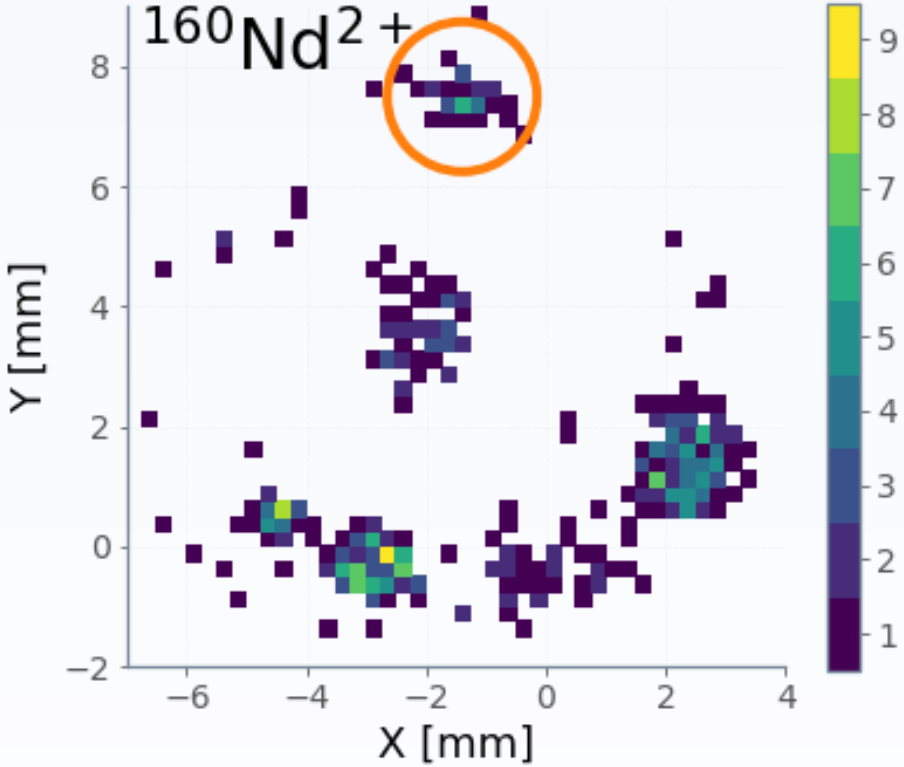


Improved resolution enables:

- ❑ Faster measurements
  - → Nuclei with shorter half-lives
- ❑ Improved accuracy
  - → Isomer discoveries (eg. Ref. [1])

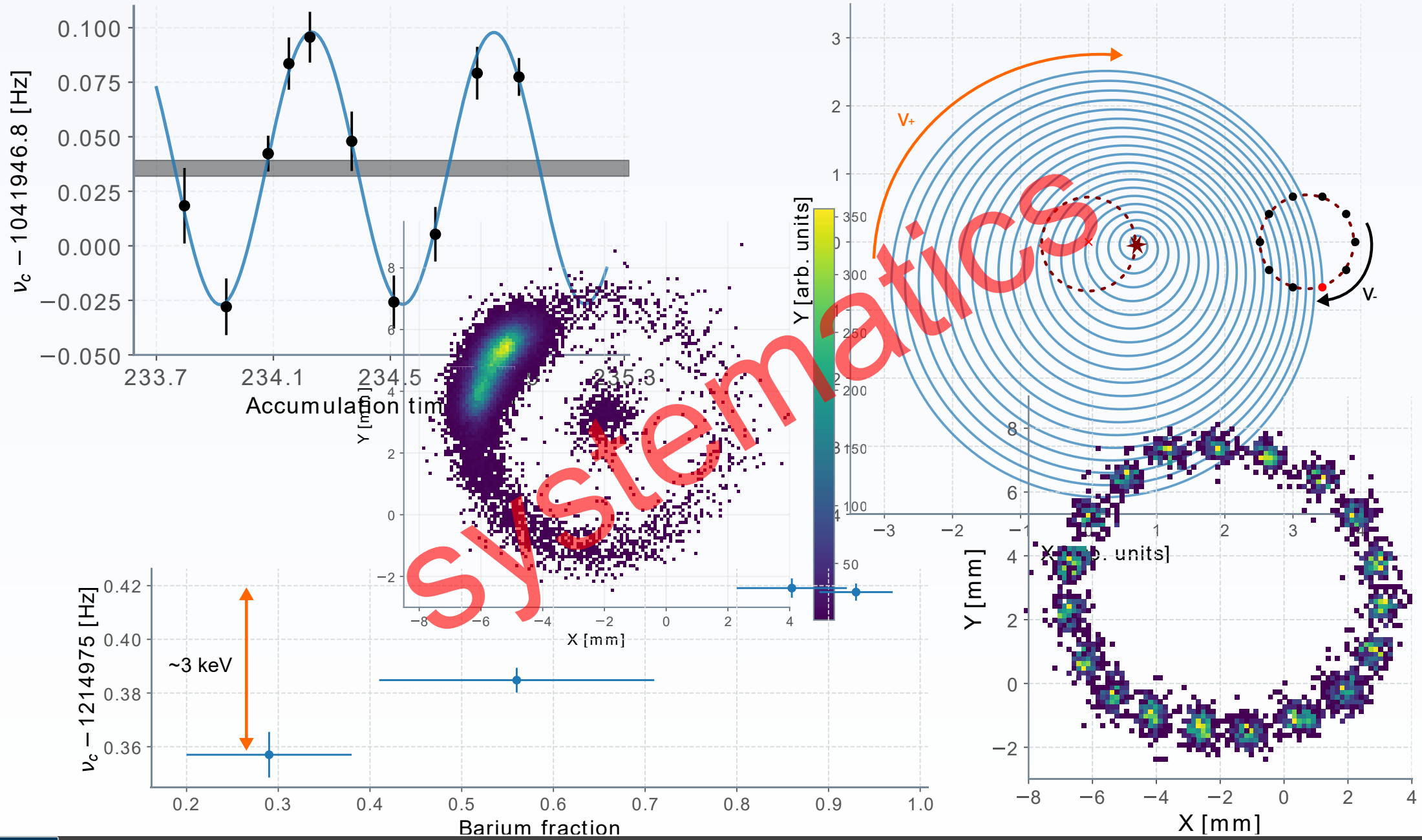


- ❑ Order of magnitude improvement in precision



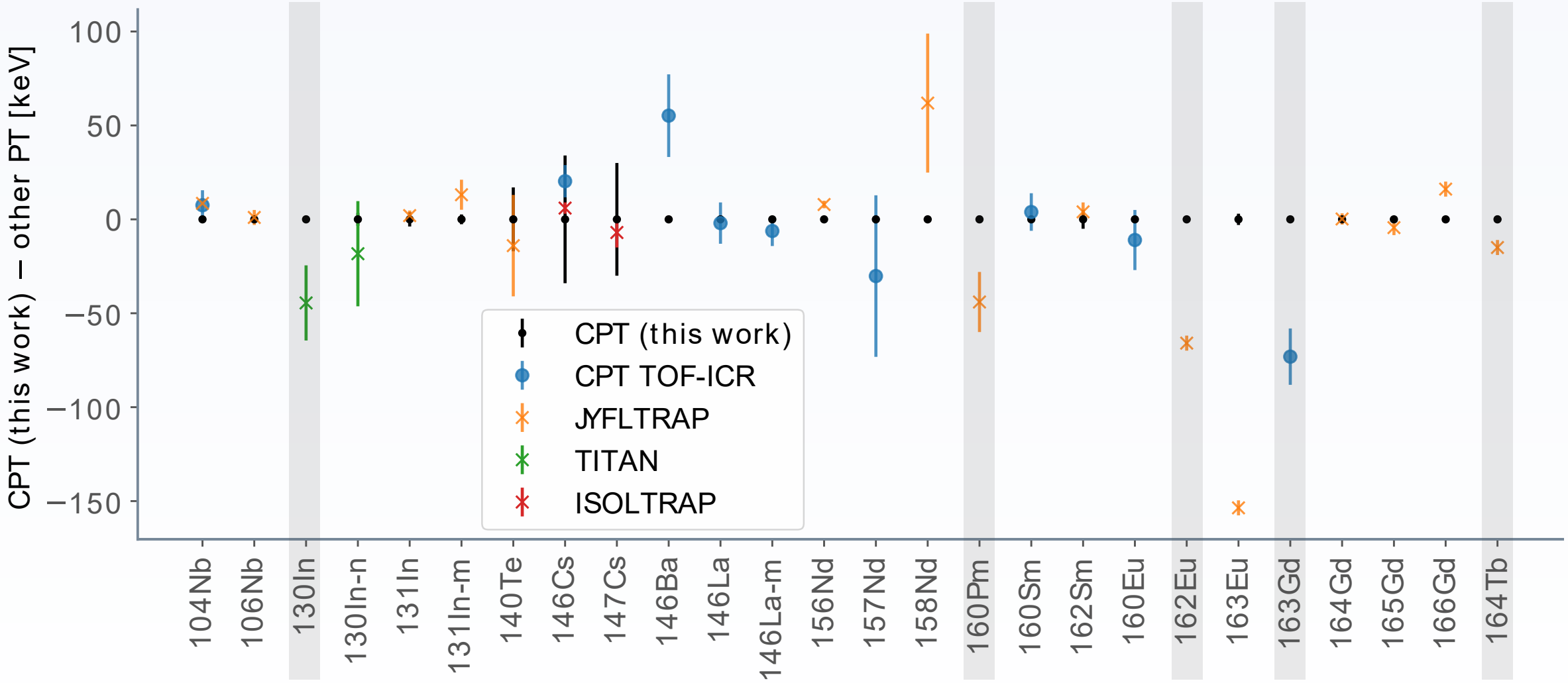
- ❑ Low rate threshold: here 0.004 Hz
- ❑ Every detected ion contributes to measurement
  - → Accessibility to more neutron-rich nuclei at CARIBU
- ❑ Smallest fission branch measured thus far is ~1x10^{-5}%

[1] Hartley, Kondev, et al. PRL **120** 182502 (2018)

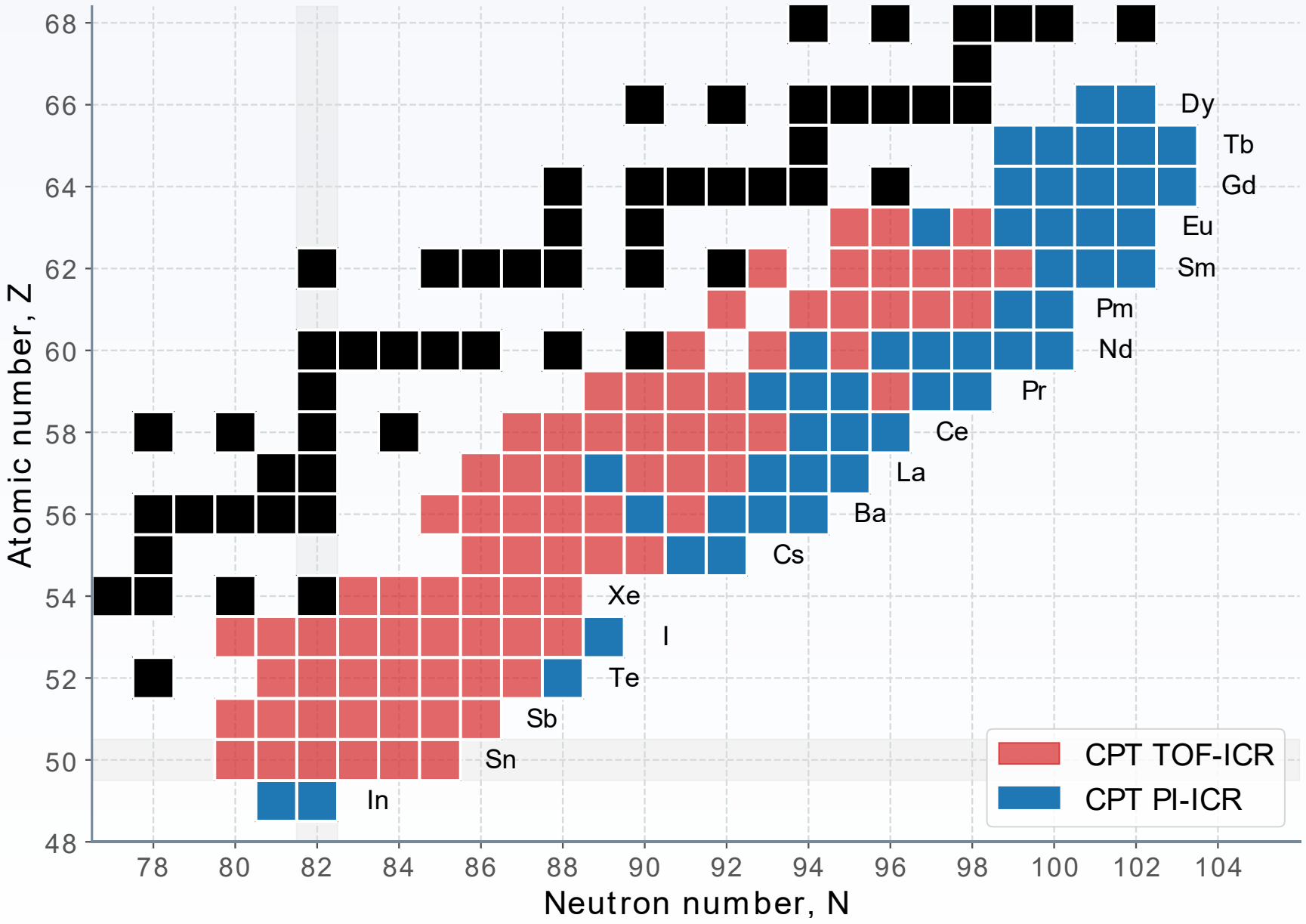

systematics
$\nu_c - 1041946.8$ [Hz]
Accumulation time
Y [mm]
X [mm]
Y [arb. units]
V+
V-
$\nu_c - 1214975$ [Hz]
~3 keV
Barium fraction
Y [mm]
X [mm]

Accuracy

Comparison with TOF-ICR



progress so far



- Currently have 26 priority 1 and 23 priority 2 days of approved beam time by the ATLAS PAC.

Astrophysical impact

Step 1: Measure masses

Step 2: Find some theorist friends

Nicole Vassh
Notre Dame

Rebecca Surman
Notre Dame

Matthew Mumpower
Los Alamos Nat'l Lab.

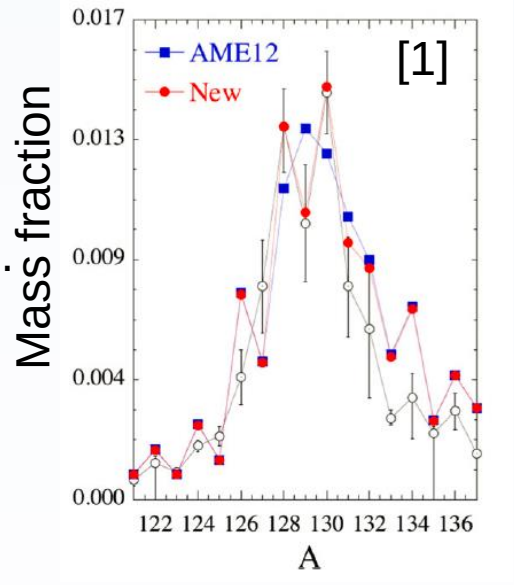
Gail McLaughlin
NC State

Step 3: Find a big computer

LCRC Argonne

Step 4: Compute the *r* process

- Simulate an *r* process under some astrophysical conditions and obtain elemental abundance pattern
- Add new masses to the simulation and repeat
- Compare both results to the observed abundance pattern.

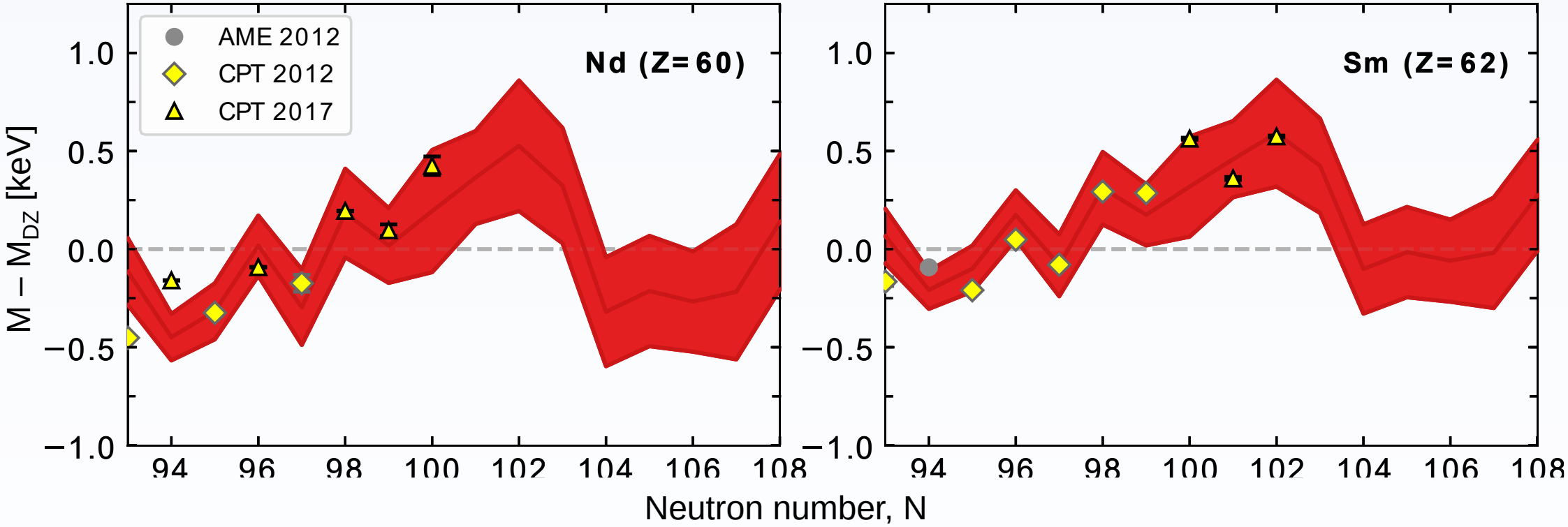


New approach:

- "reverse-engineer" the observed abundances under specific conditions
- Compare predicted masses to measured ones.

[1] D. Atanasov et al. PRL. **115**, (2015).

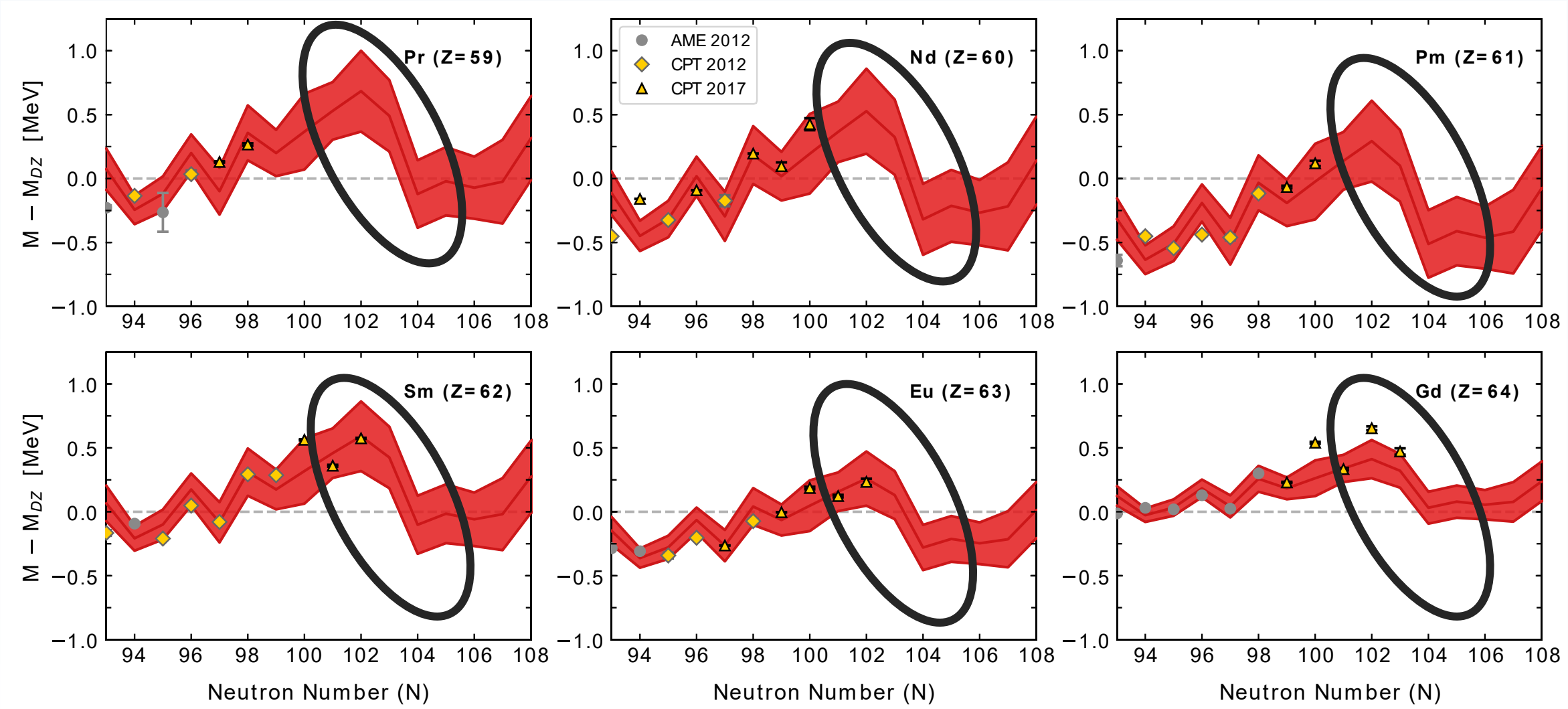
Reverse-engineering mass predictions



- Hot, neutron-star merger wind scenario
- CPT masses are consistent with the predictions given this scenario!
- Next step is to examine other astrophysical scenarios and make further neutron-rich mass measurements

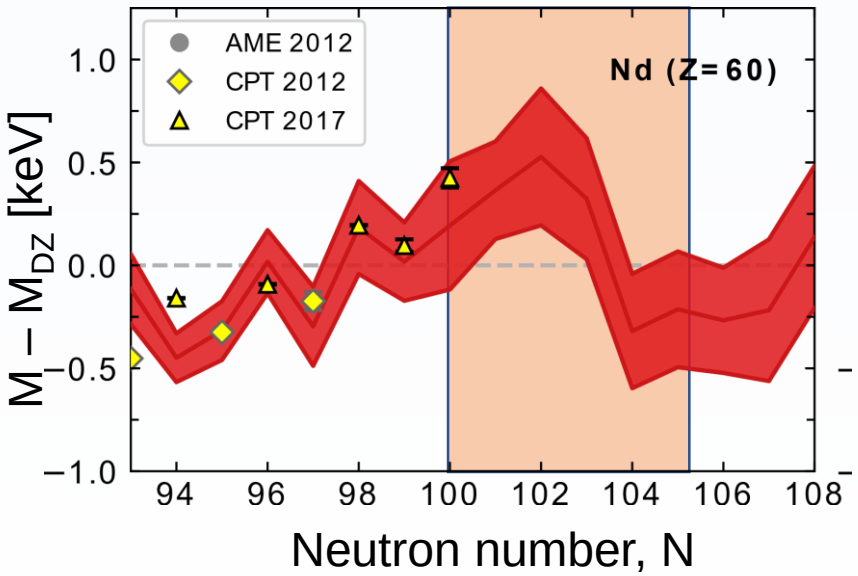
[1] R. Orford, N. Vassh et al. PRL **120** 262702 (2018)

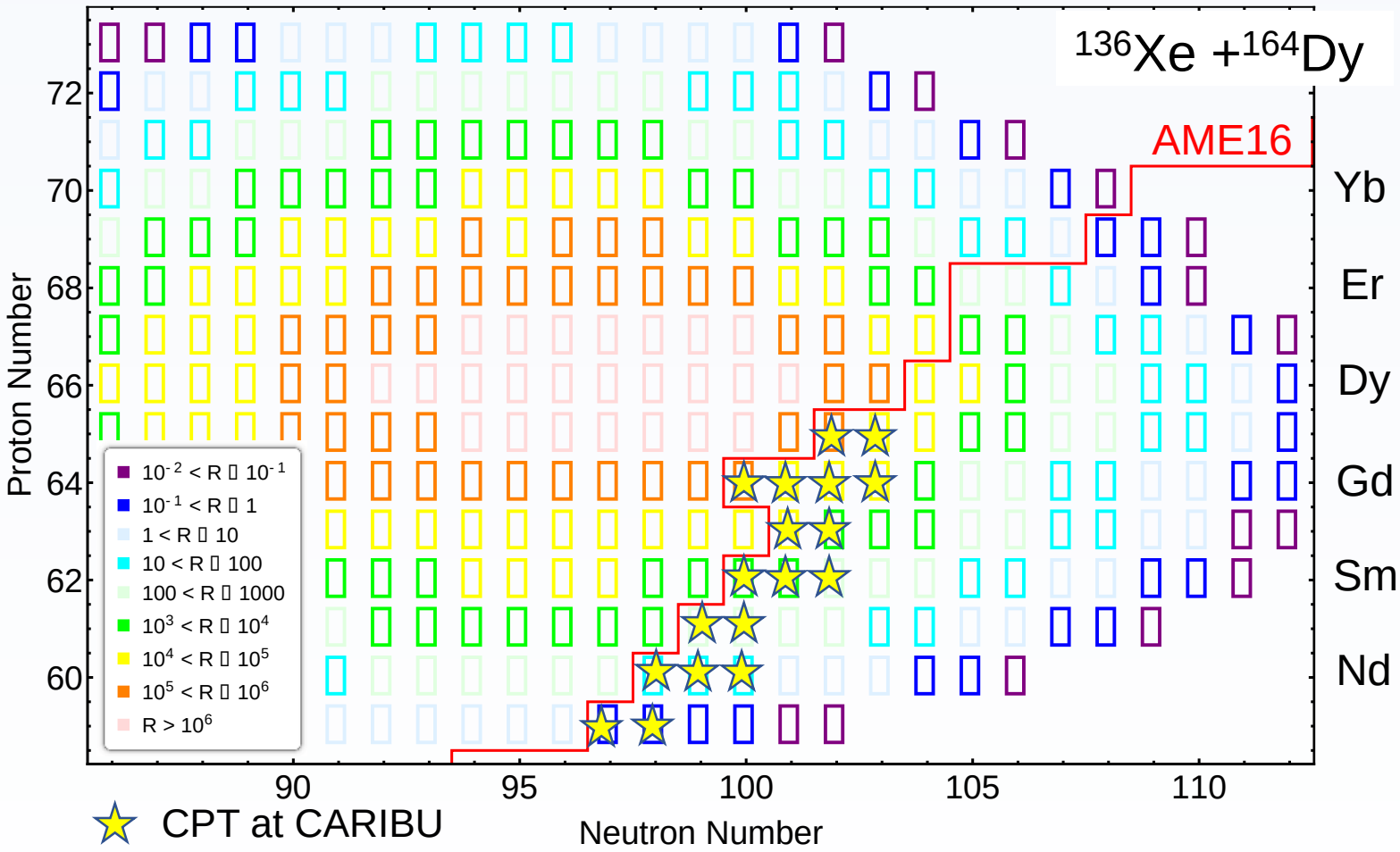
Other isotopic chains



The *rare-earth* factory

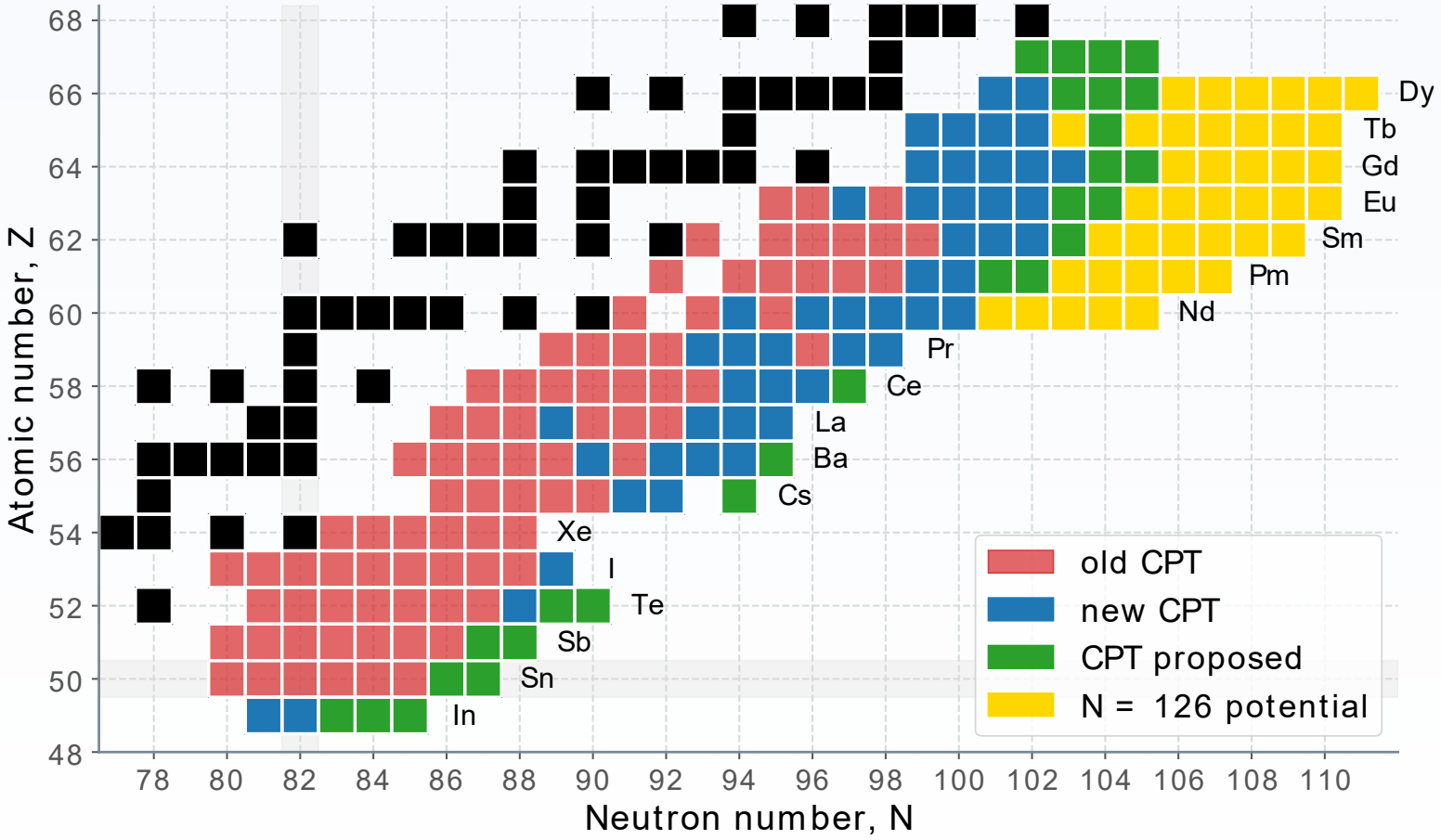
- N = 126 factory coming soon
- Will also be a versatile rare isotope beam facility
- Using rare-earth target can produce beams of extremely neutron rich nuclei in the region





SUMMARY

- More neutron-rich mass measurements are needed for the *r* process
- With PI-ICR the CPT will be busy over the next several years at CARIBU and at the N = 126 factory



Collaboration

Students
Post-docs

McGill — F. Buchinger

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University of Manitoba — K.S. Sharma, A. Valverde, D. Ray, S. Geddes

The University of Chicago — G. Savard, L. Varriano

University of Notre Dame — A. Aprahamian, R. Surman, M. Brodeur, N. Vassh, D. Burdette

Los Alamos National Laboratory — M. Mumpower

NC State — G.C. McLaughlin

CPT Veterans:

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N. Paul (ND)
T.Y. Hirsh (UofMB)
G.E. Morgan (UofMB)
A. Nystrom (ND)
T. Kuta (ND)
D. A. Gorelov (UofMB)
A. Sacchetti (Guelph)
D. Lascar (ANL)
J.W. Klimes (ANL)
R. Orford (McGill)
J. Pierce (UofC)
M.T. Burkey (UofC)


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