Improved sensitivity of the Canadian Penning Trap mass spectrometer through PI-ICR

Rodney Orford

Sept. 18, 2018

PI-ICR: Canada/USA edition

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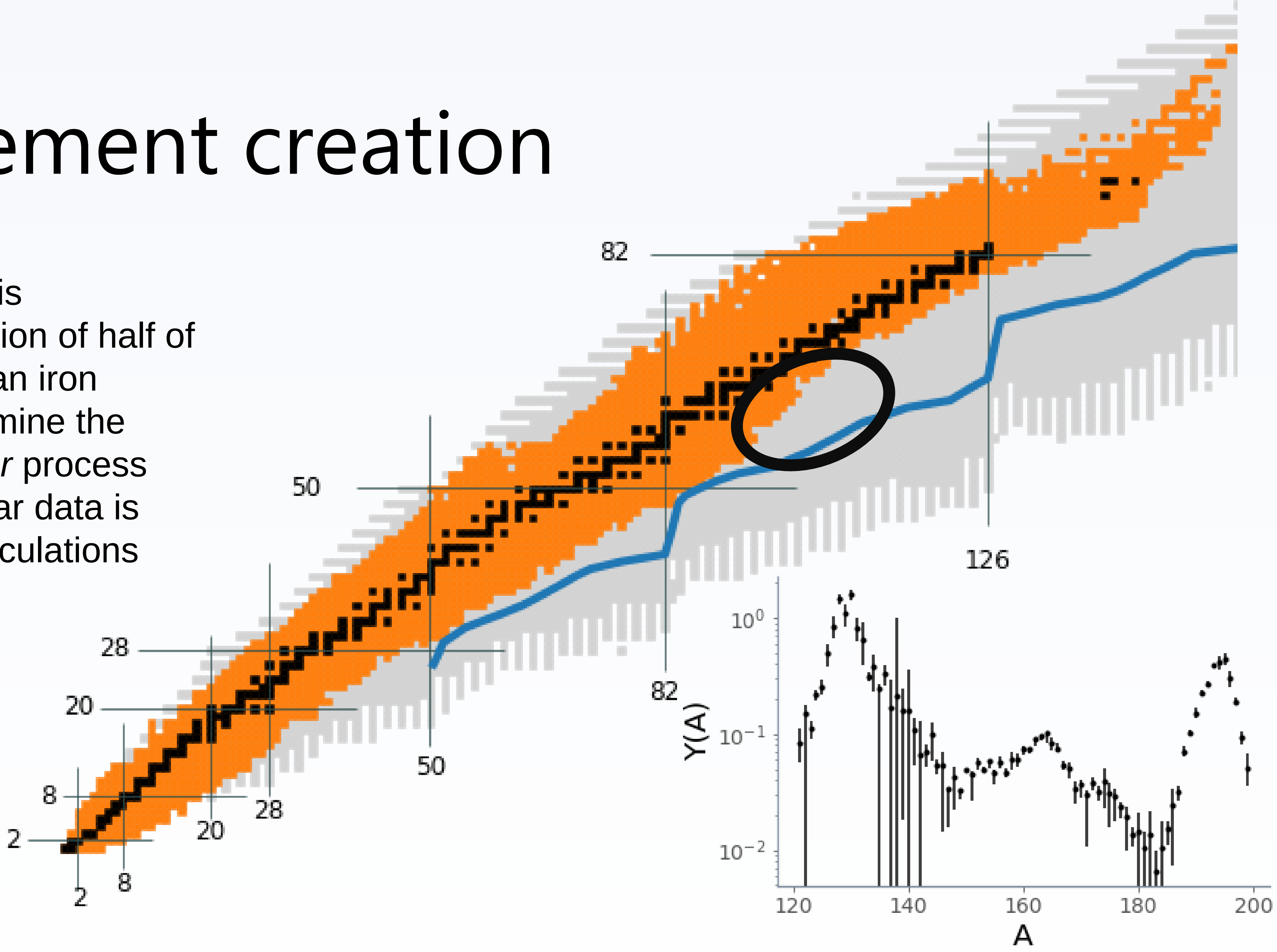
Outline

- Astrophysics motivation
- The CARIBU facility
- PI-ICR at the CPT
- Results

Heavy element creation

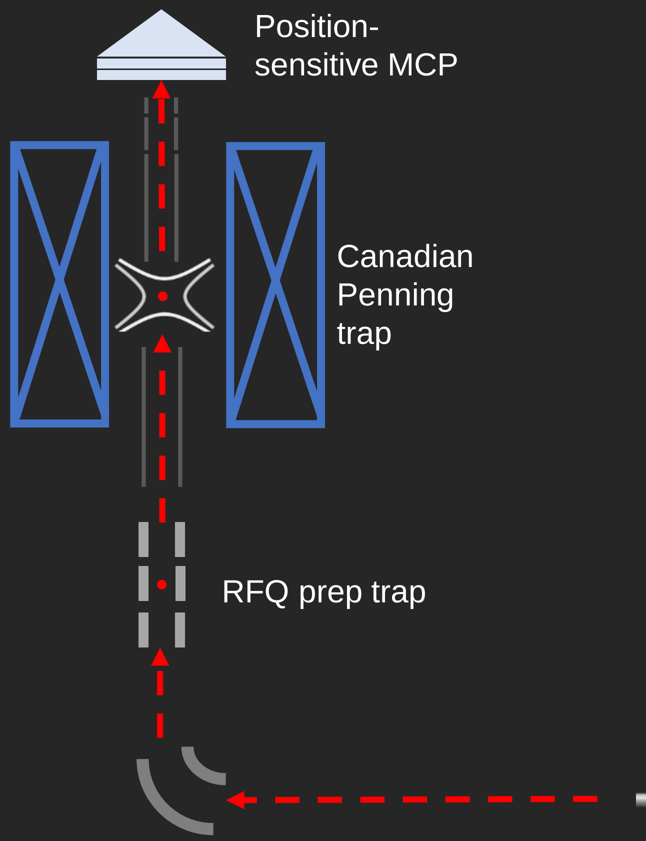
- Astrophysical *r* process is responsible for the creation of half of the elements heavier than iron
- General goal is to determine the astrophysical site of the *r* process
- More neutron rich nuclear data is required to constrain calculations

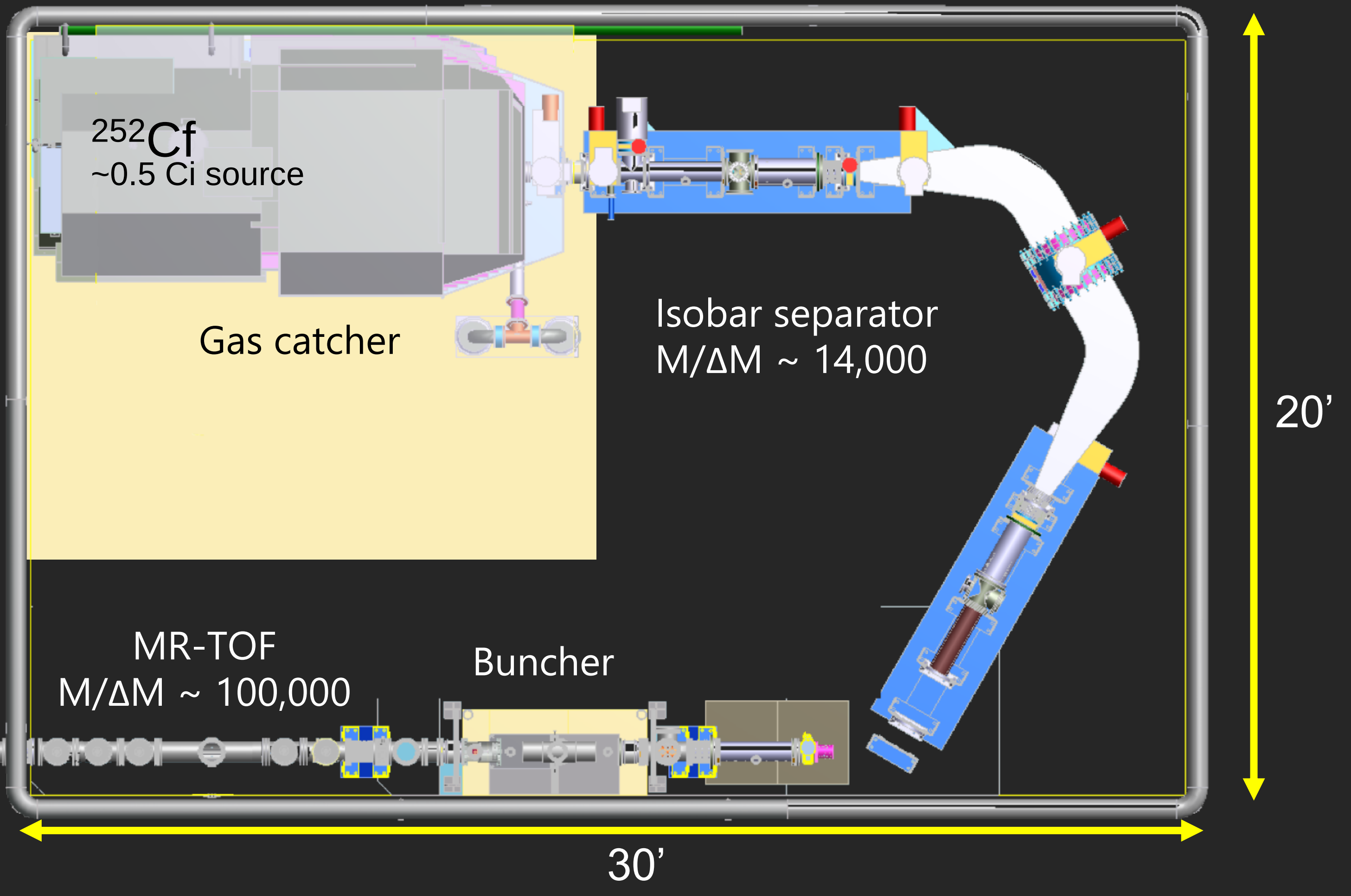


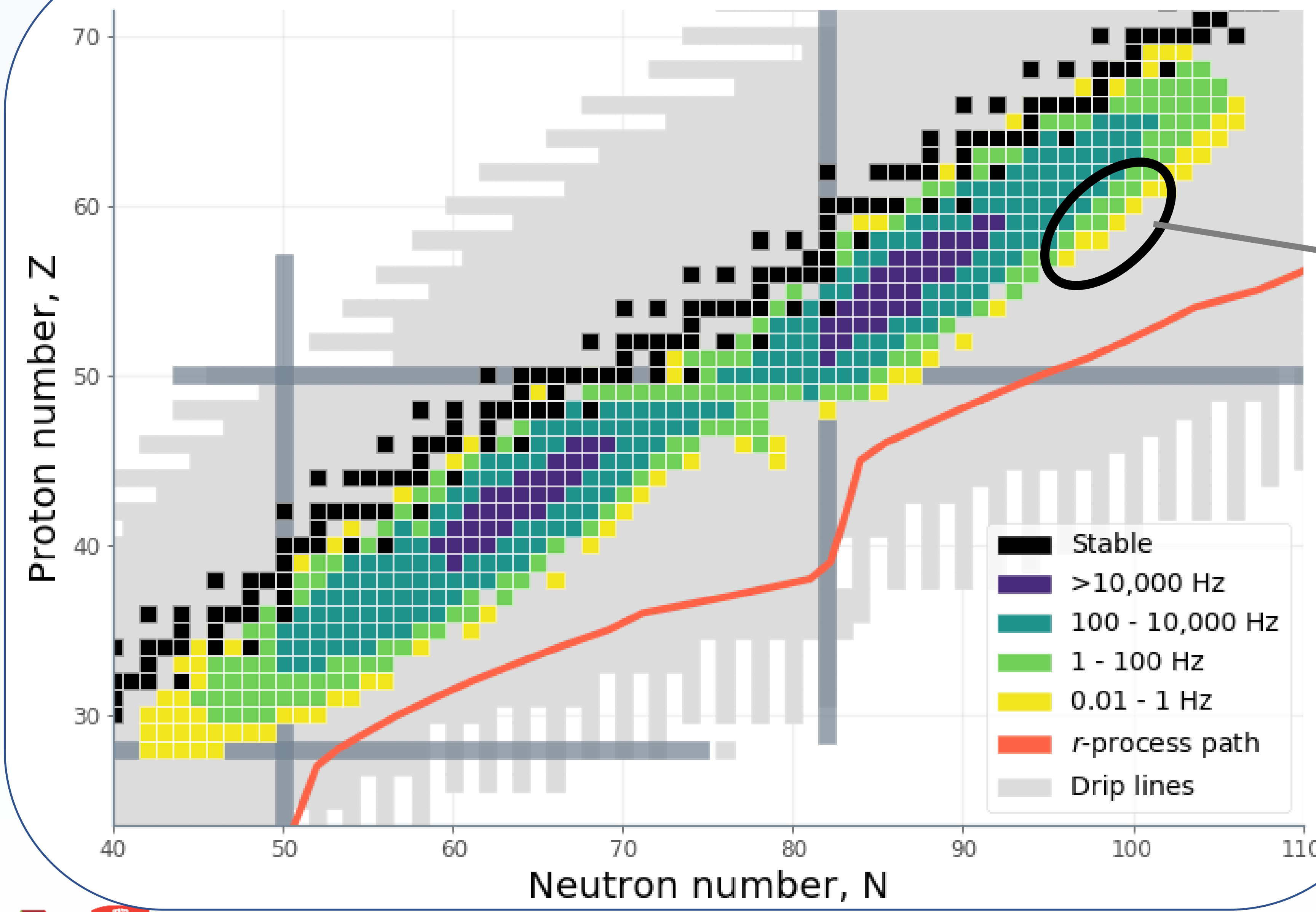
- Rare-earth peak likely formed late in the *r* process
- Material pile-up due to nuclear structure effect near N = 100.

CARIBU

Californium rare isotope breeder upgrade



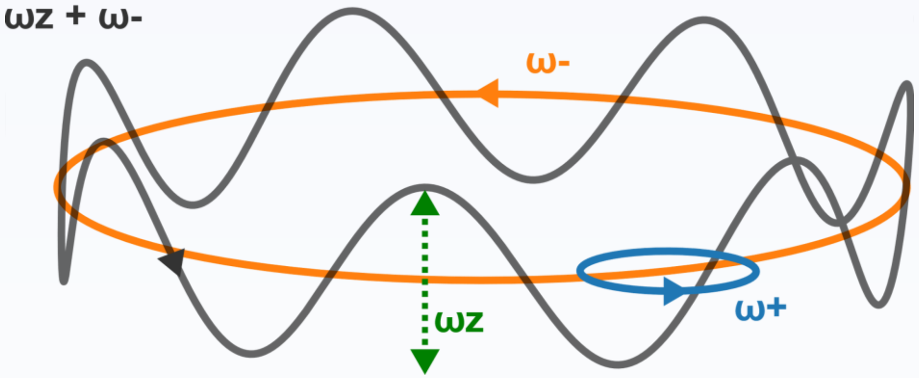




Factor of ~2 higher yield than FRIB year 2 predicted rates are available today at CARIBU! [1]

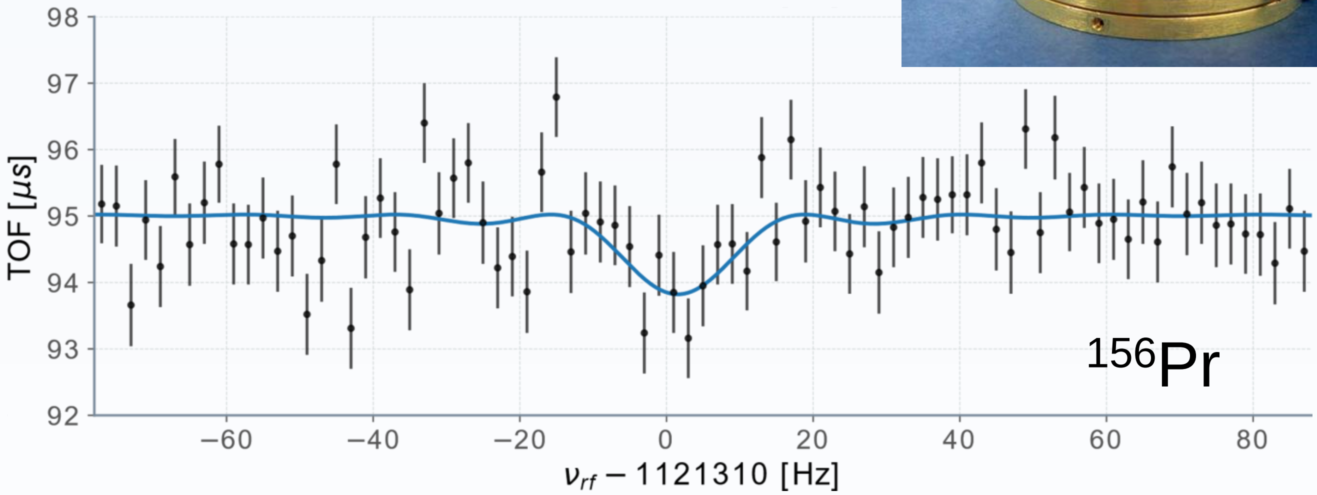
[1] https://groups.nscl.msu.edu/frib/rates/fribrates.html

Penning trap mass measurements



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

- ω_+ ~ 1 MHz and is mass-dependent
- ω_- ~ 1 kHz and is mass-independent

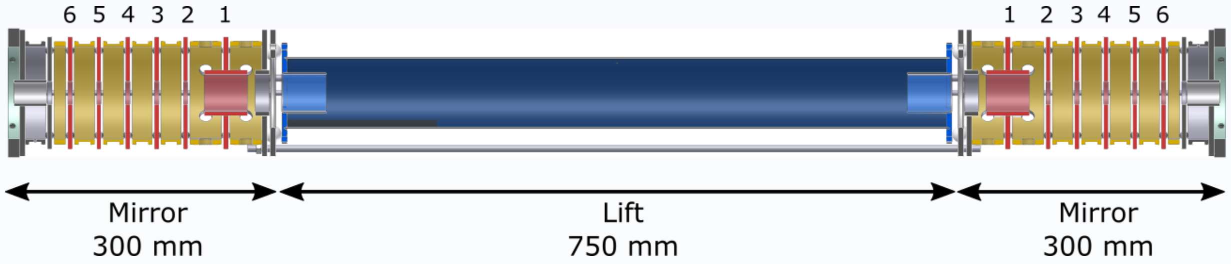


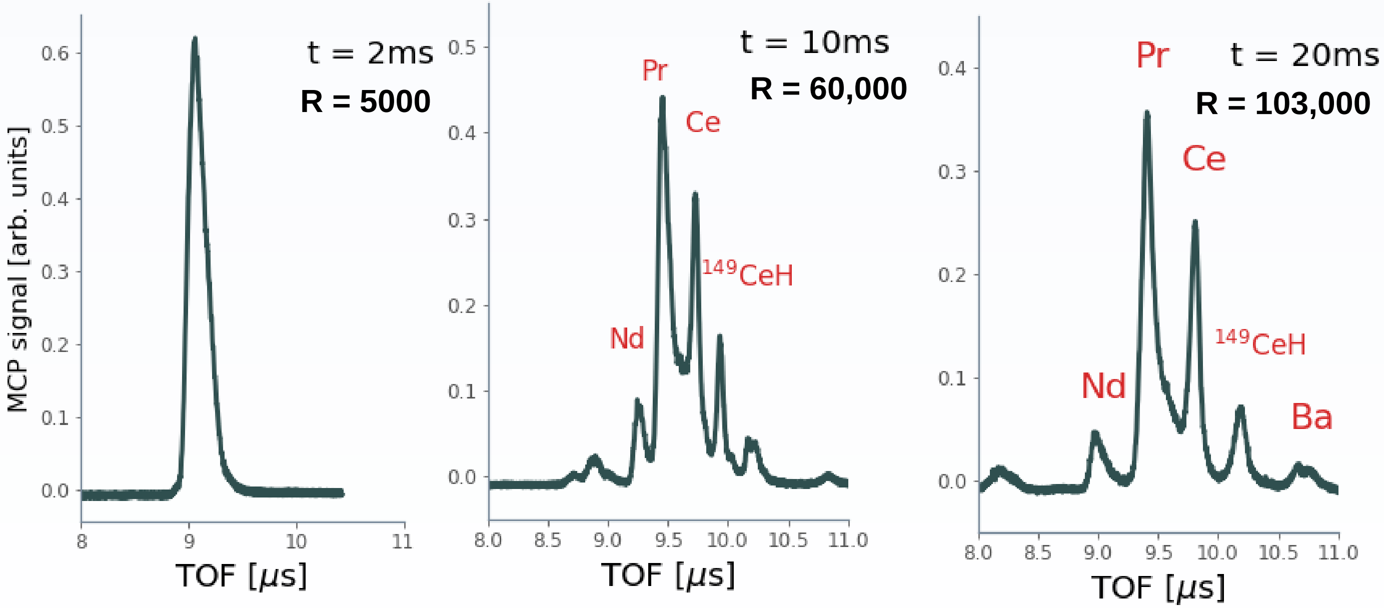
Need:
- Cleaner beams
- Sensitivity to weak beams

Limitations of TOF-ICR:
- Inefficient use of desired ions
- Fourier-limited resolution
- Signal is diluted by beam contamination

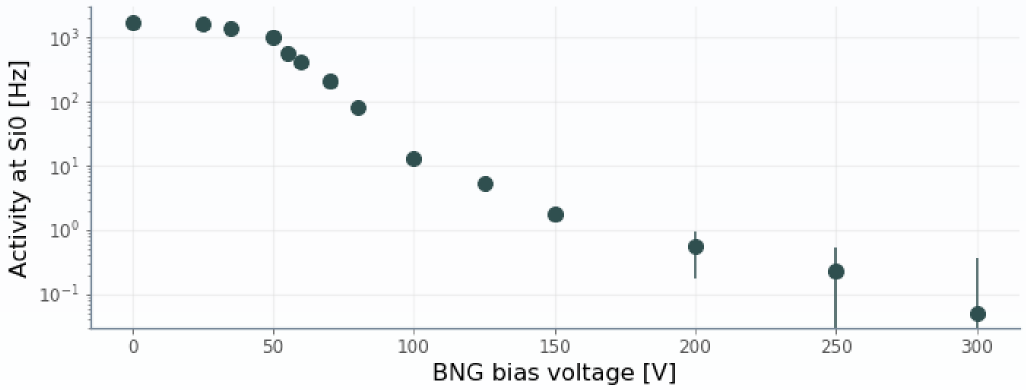
1. Clean beams
MR-TOF + BNG

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



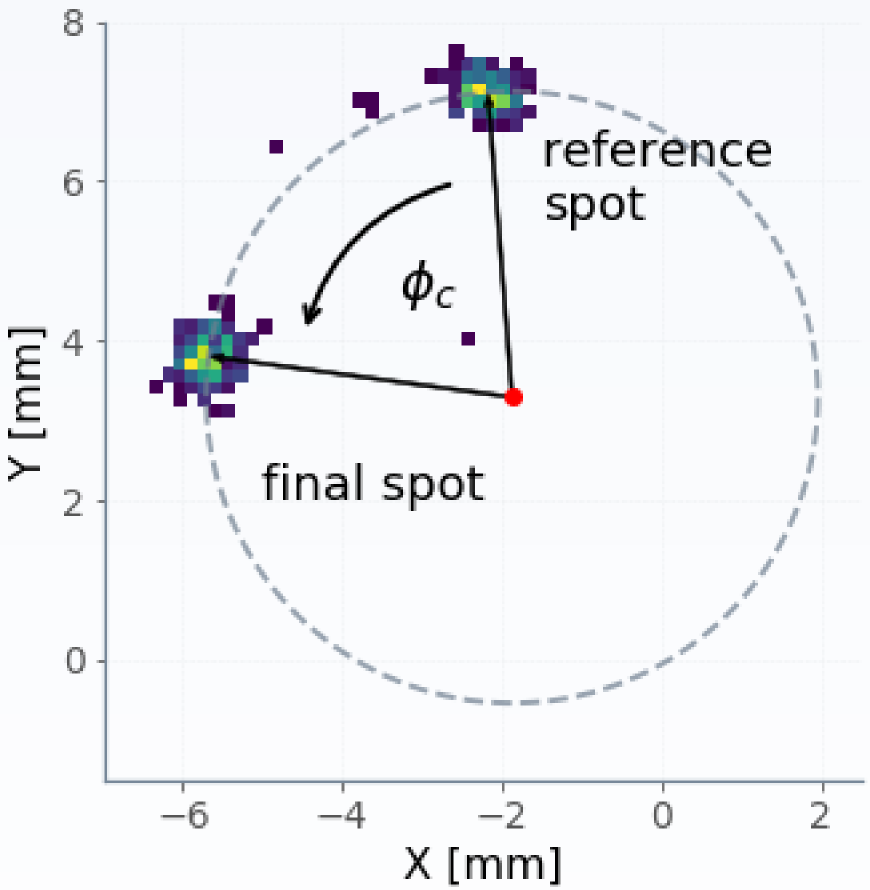


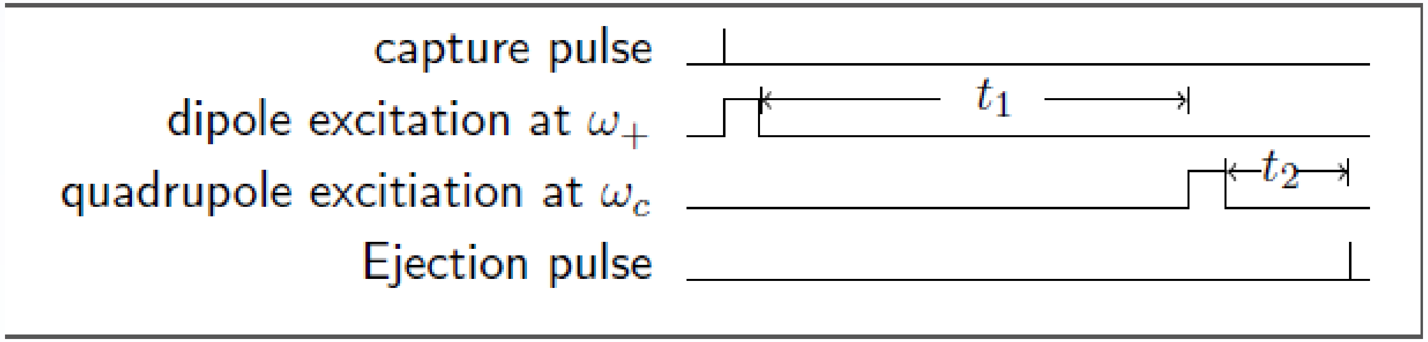
- CARIBU MR-TOF is a fast (10-30 ms), high resolution isobar separator
- Typically run at R = 70,000 with ~30-40% transmission
- BNG located at the focal plane is used to select ions of interest.
- Capable of 4 orders of magnitude suppression



2. Higher sensitivity:
PI-ICR

- Use a position-sensitive MCP to measure the phase advance of trapped ions during a period of excitation-free accumulation time
- Reference spot contains only magnetron motion (ie. no mass separation)
- Phase of final spot is cyclotron frequency dependent

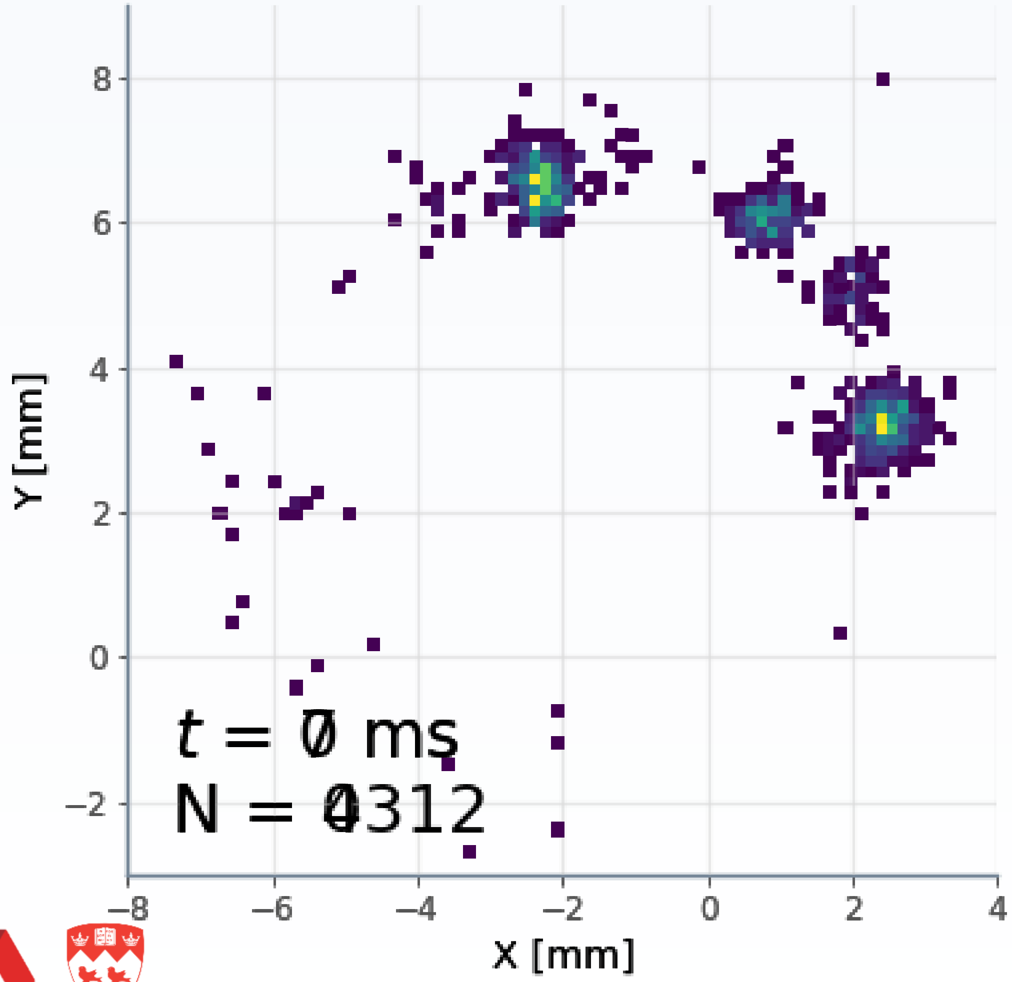


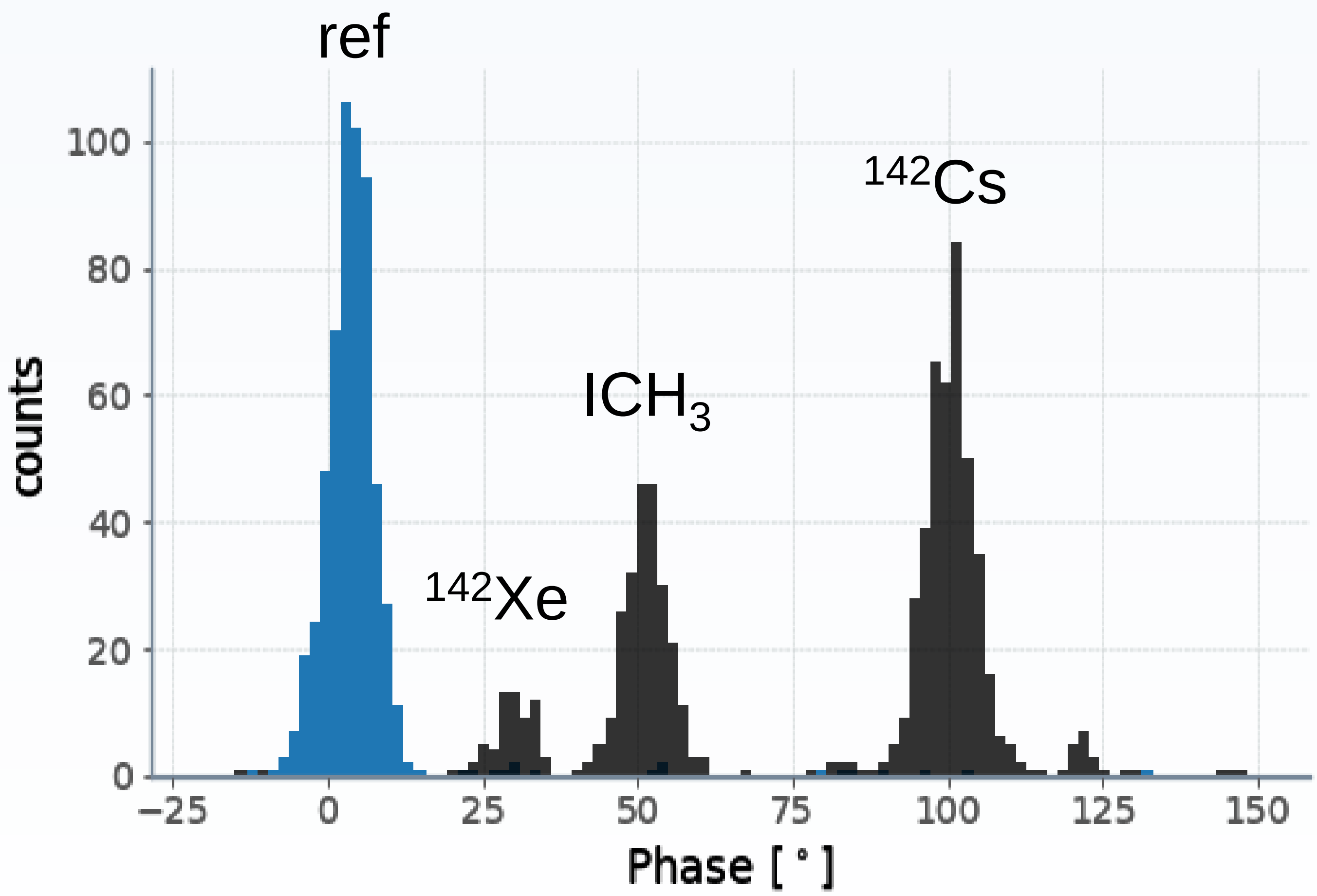


$$\nu_c = \frac{\phi_{tot}}{2\pi t_1} = \frac{\phi_c + 2\pi N}{2\pi t_1}$$

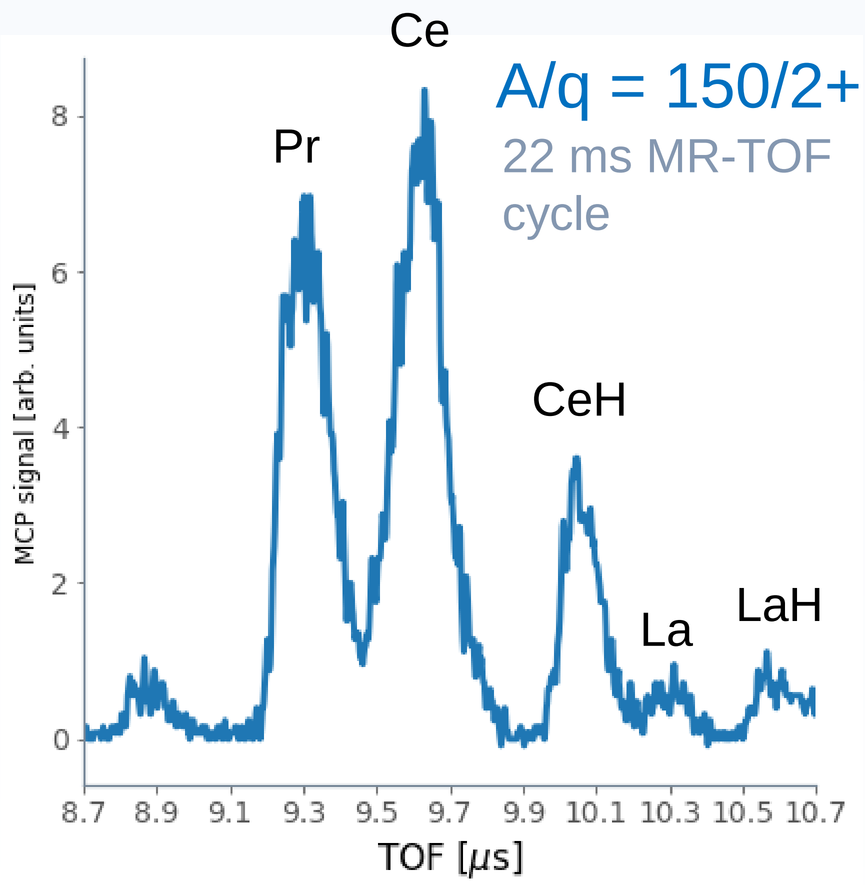
PI-ICR mass separation

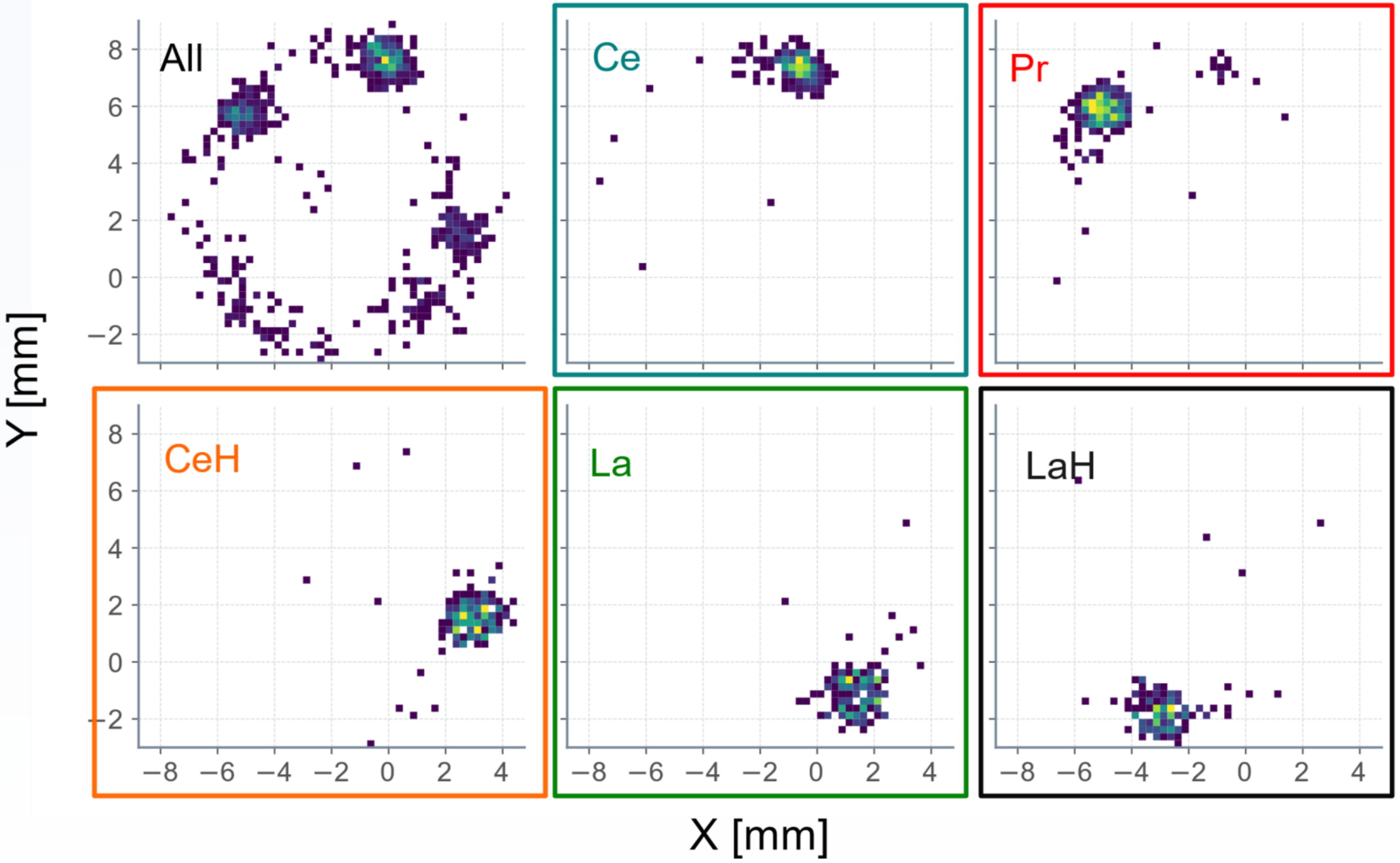
$$\nu_c = \frac{\phi_{tot}}{2\pi t_1} = \frac{\phi_c + 2\pi N}{2\pi t_1}$$





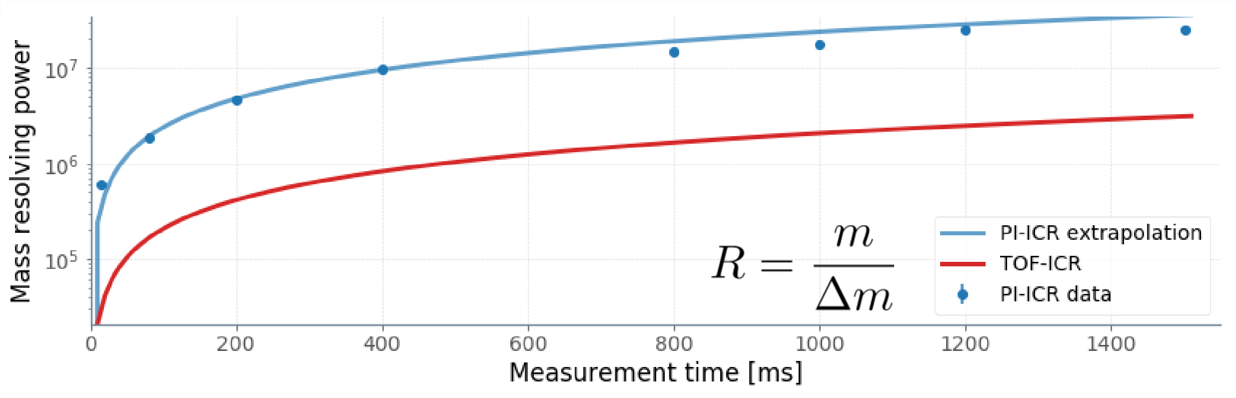
PI-ICR + MR-TOF

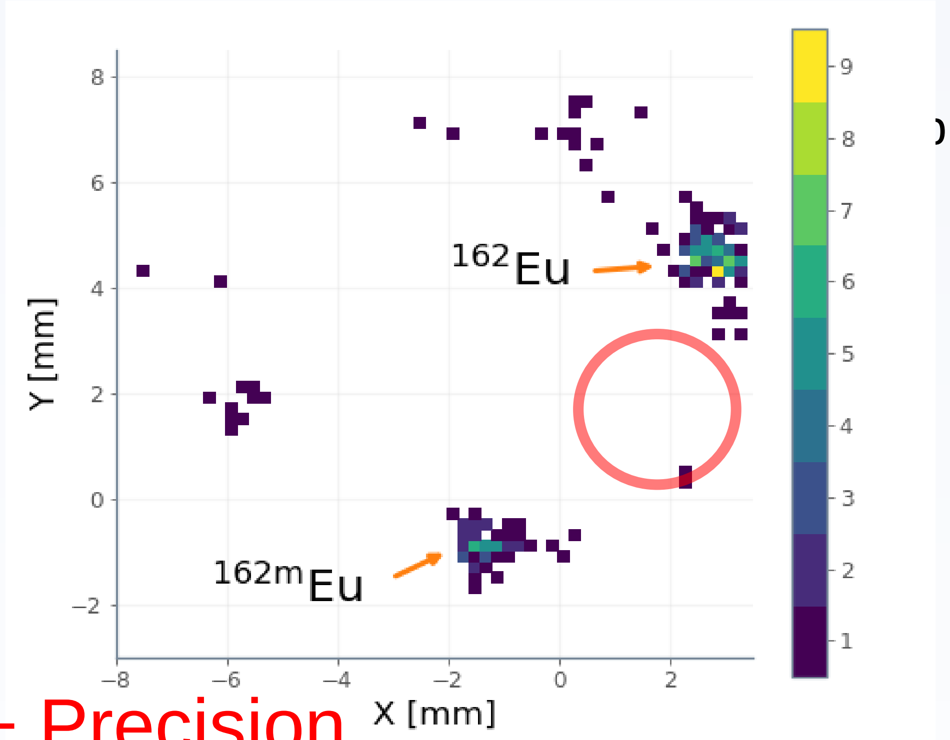

Ce
Pr
CeH
La
LaH
A/q = 150/2+
22 ms MR-TOF cycle
MCP signal [arb. units]
TOF [μs]
0
2
4
6
8
8.7
8.9
9.1
9.3
9.5
9.7
9.9
10.1
10.3
10.5
10.7


All
Ce
Pr
CeH
La
LaH
Y [mm]
X [mm]
−8
−6
−4
−2
0
2
4
6
8

PI-ICR advantages

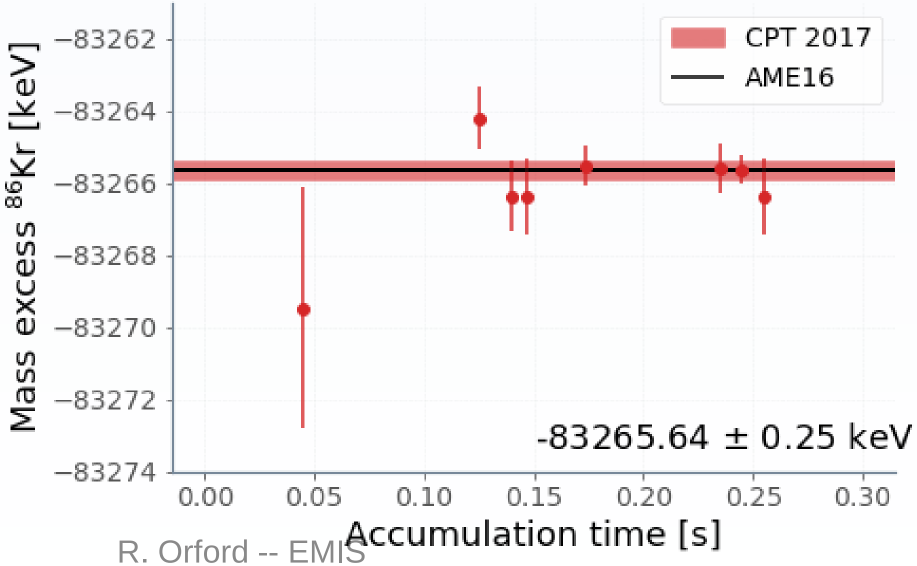
1. Resolution





- Factor of ~30 improvement in resolution
  - Separate contaminants faster
  - Discover long-lived isomers

2. Accuracy + Precision

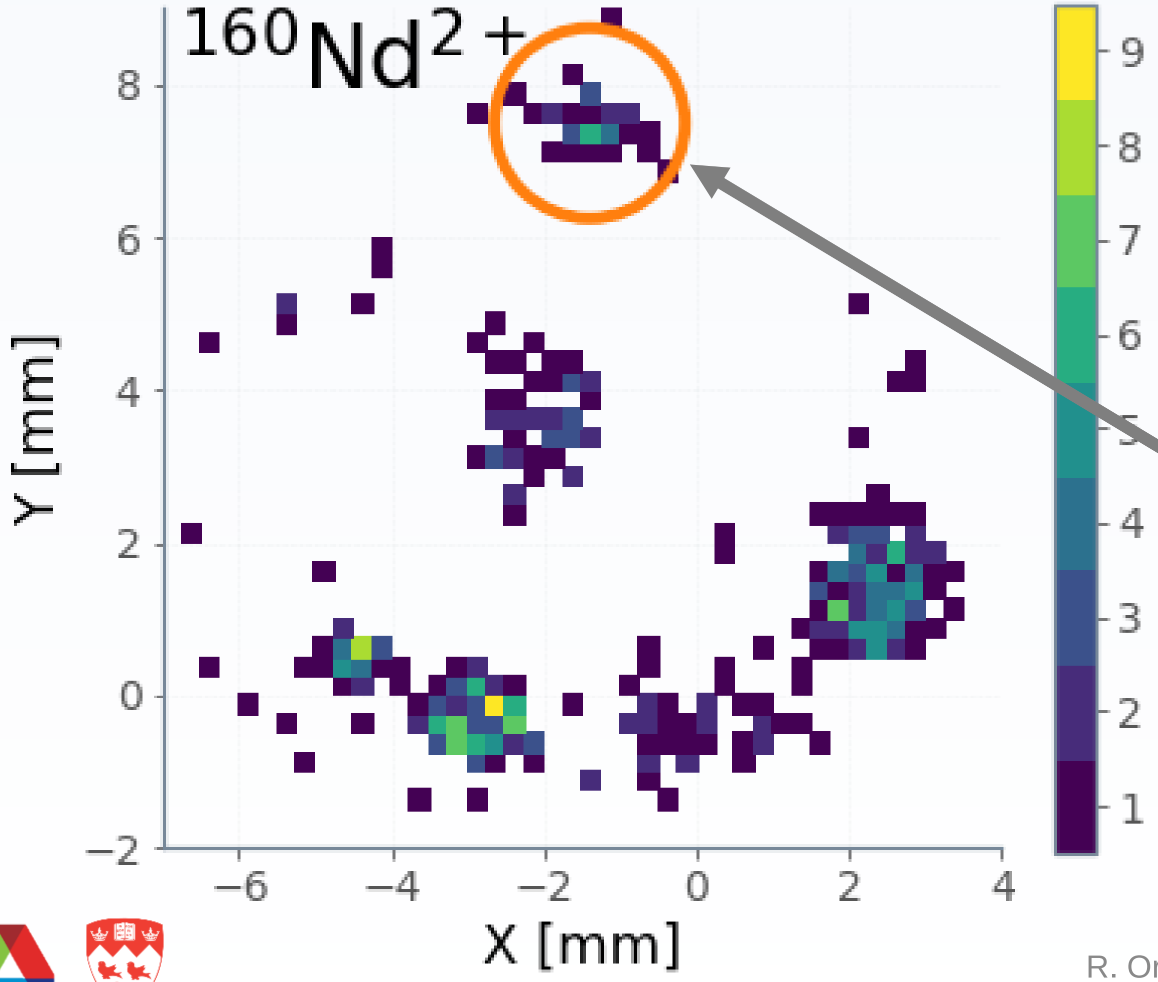


- Order of magnitude gain in precision
- Sub-keV precision with ~200 ms accumulation time

[1] D. Hartley et al. **PRL 120** (2018)

PI-ICR advantages

3. Low rate capability



- ^{160}Nd is the most weakly produced fission fragment measured so far with the CPT (10^{-5} %)
- Counted 1 count every ~10 minutes
- Current limitation is ~ 1 ct/hr

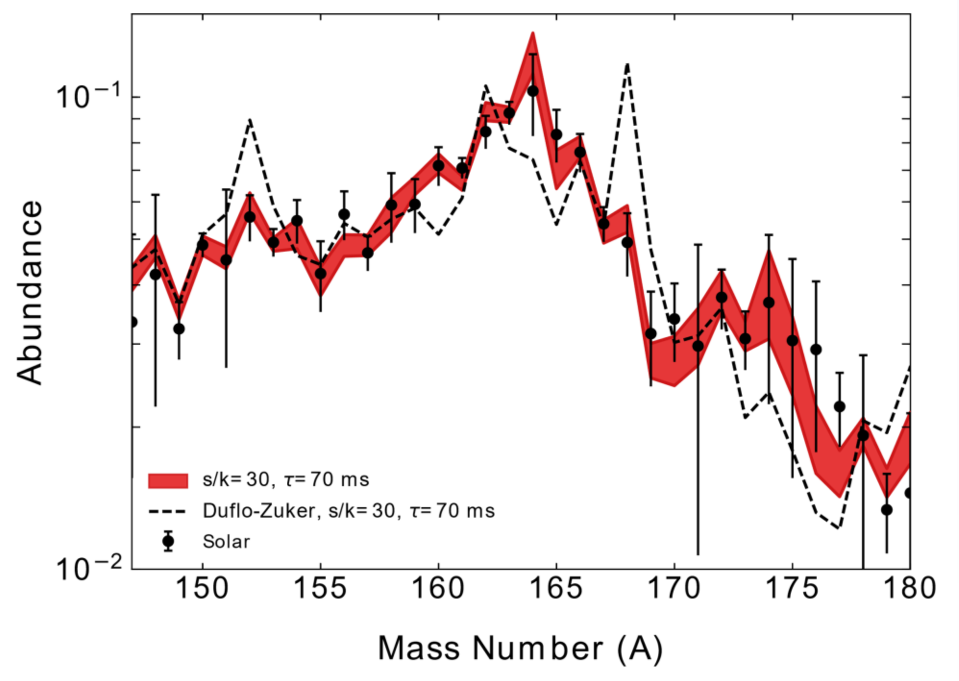
4. Every ion counts

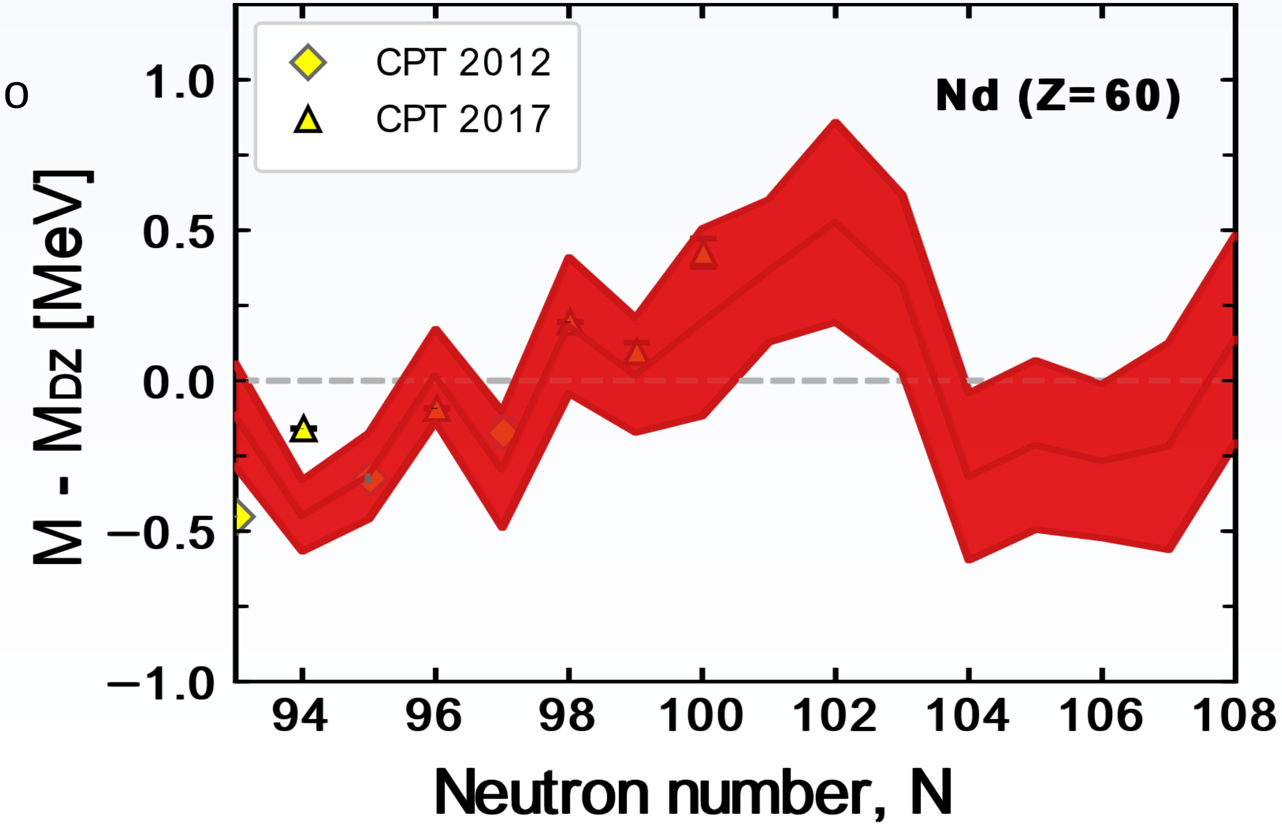
- Every ion contributes to the frequency measurement
- Fewer ions needed
- ~50 keV uncertainty using 40 Nd ions

Reverse-engineering mass predictions

- Calculations by Matthew Mumpower (Los Alamos) and Nicole Vassh (Notre Dame)
- Obtain mass predictions, which under a particular set of astrophysical conditions reproduce the observed rare-earth peak of the abundance pattern.

- Hot *r* process in a neutron star merger scenario





Summary

- MR-TOF at CARIBU is currently operational – R ~70,000 with transmission of ~30-40%
- PI-ICR has been implemented at the CPT providing several improvements over other Penning trap mass measurement techniques
- Combination of the two upgrades has improved our experimental sensitivity by a couple orders of magnitude
- ~50 nuclei have been measured in the past year using the technique
- With more mass measurements and further reverse-engineering calculations we may be able to make a more definitive statement about potential sites of the *r* process

Collaboration

Students
Post-docs

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A. Nystrom (ND)
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D. A. Gorelov (UofMB)
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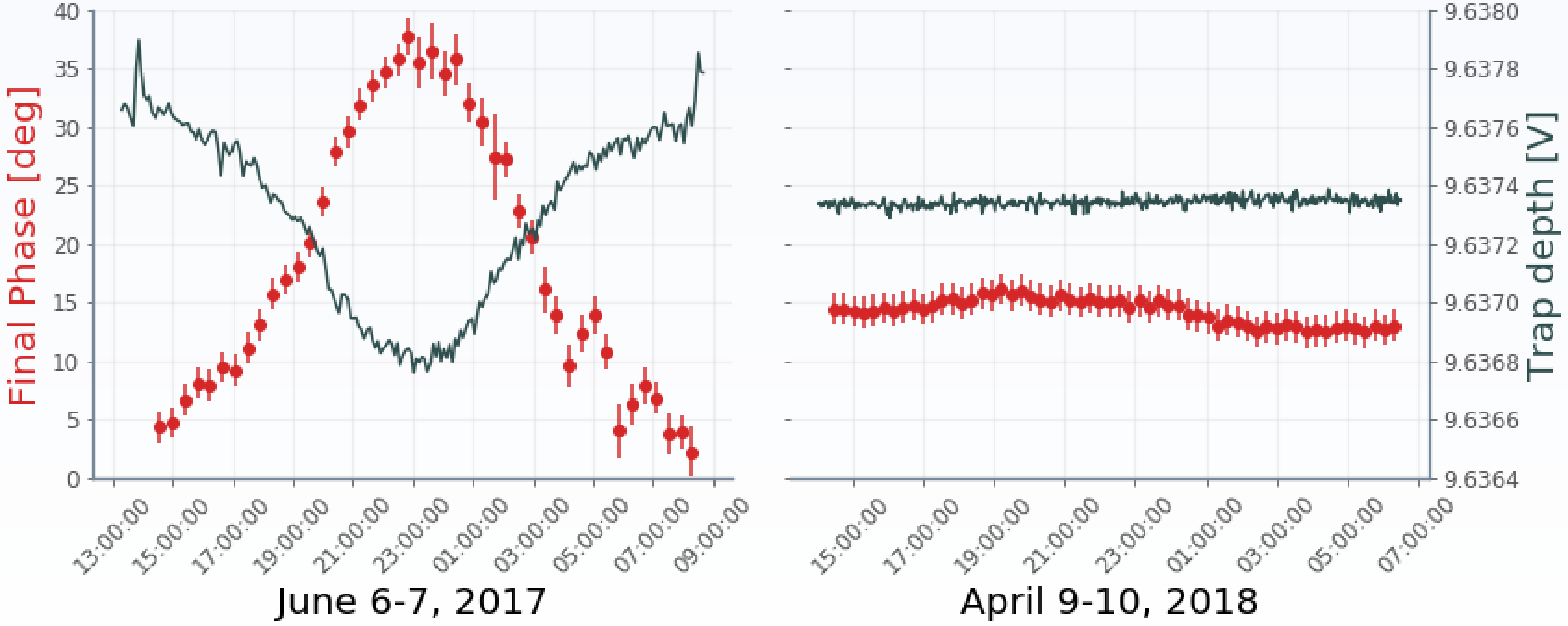
New Penning trap power supply



MR-TOF resolution
What really matters…