8/18/2025

PRECISION MASS MEASUREMENTS WITH THE CPT FOR NUCLEAR ASTROPHYSICS

ADRIAN A. VALVERDE

U.S. DEPARTMENT of ENERGY

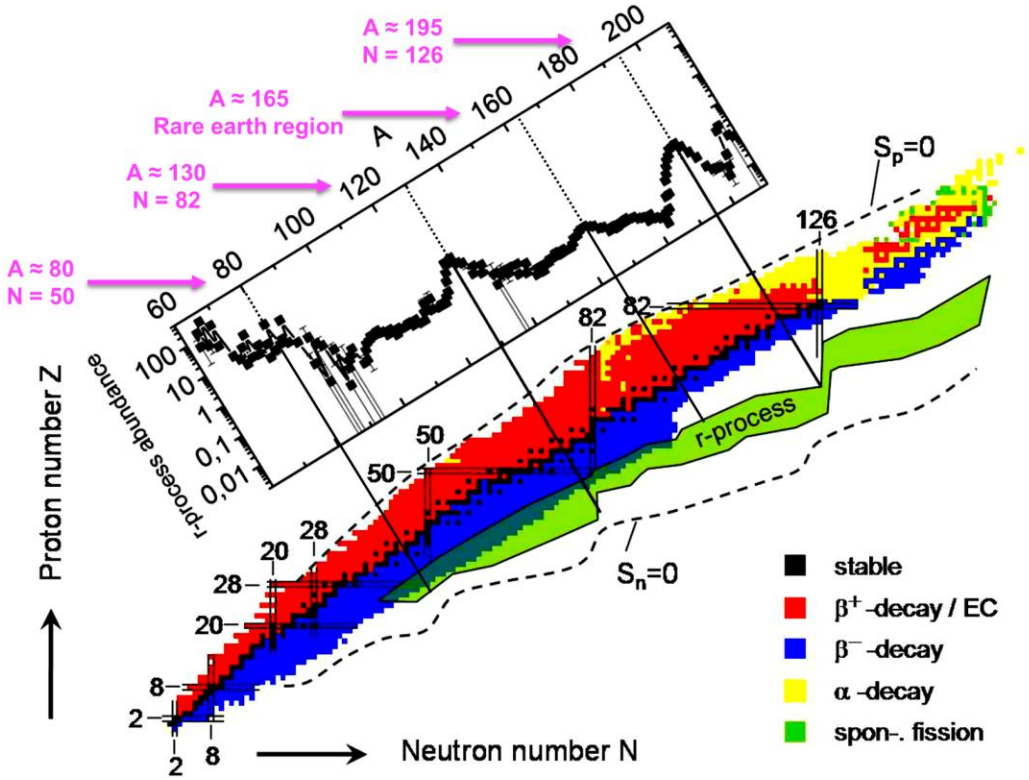
Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.

Argonne NATIONAL LABORATORY

OUTLINE

- R-Process
- CARIBU
- CPT/PI-ICR
- CPT Mass Measurements:
  - Rare Earth Peak
  - Astromers

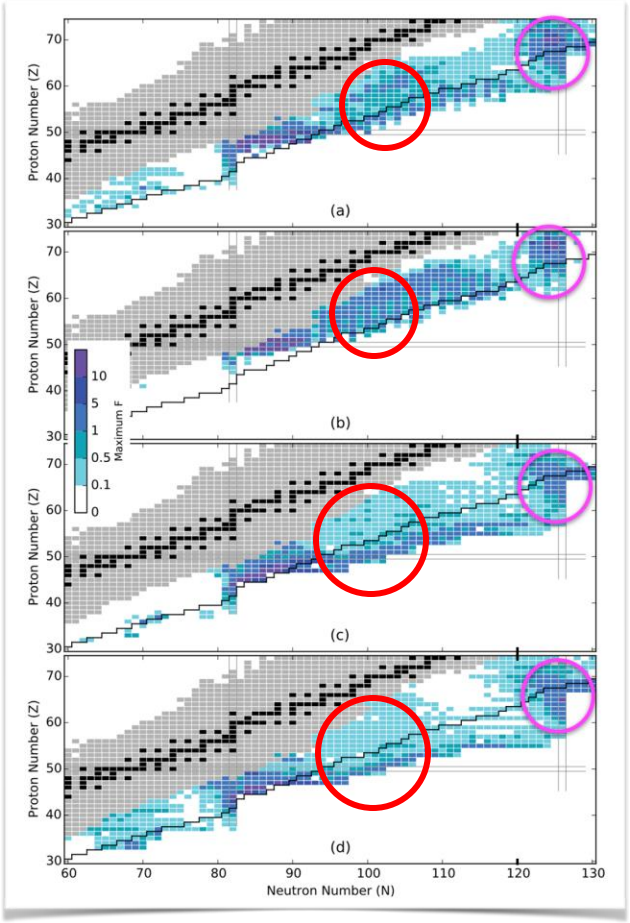
R PROCESS



R. Kruecken, arXiv:1006.2520 (2010)

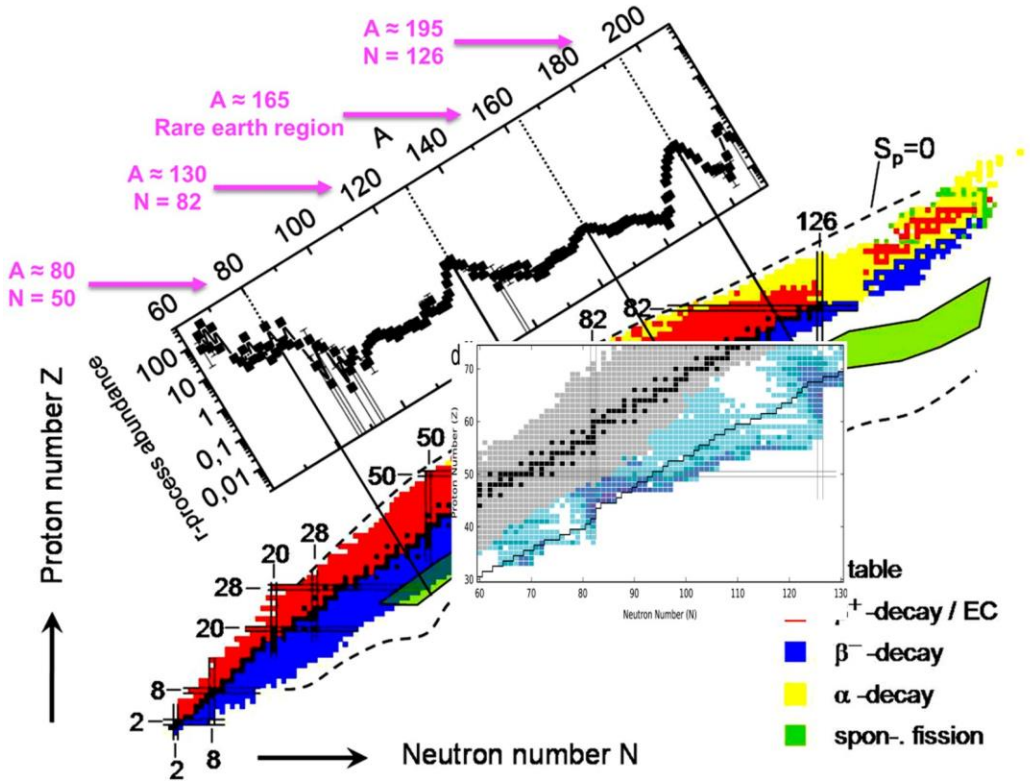
SENSITIVITY STUDIES

- Dynamical *r*-process simulations, each varying one piece of nuclear data
- Found masses (especially around closed shells) had greatest impact on final isotopic abundances
- Two areas of interest to the CPT: Rare-Earth Peak and A~195 Peak



M. Mumpower, R. Surman, G.C. McLaughlin, A. Aprahamian, PPNP, 86 (2016)

R PROCESS STUDIES AT ANL

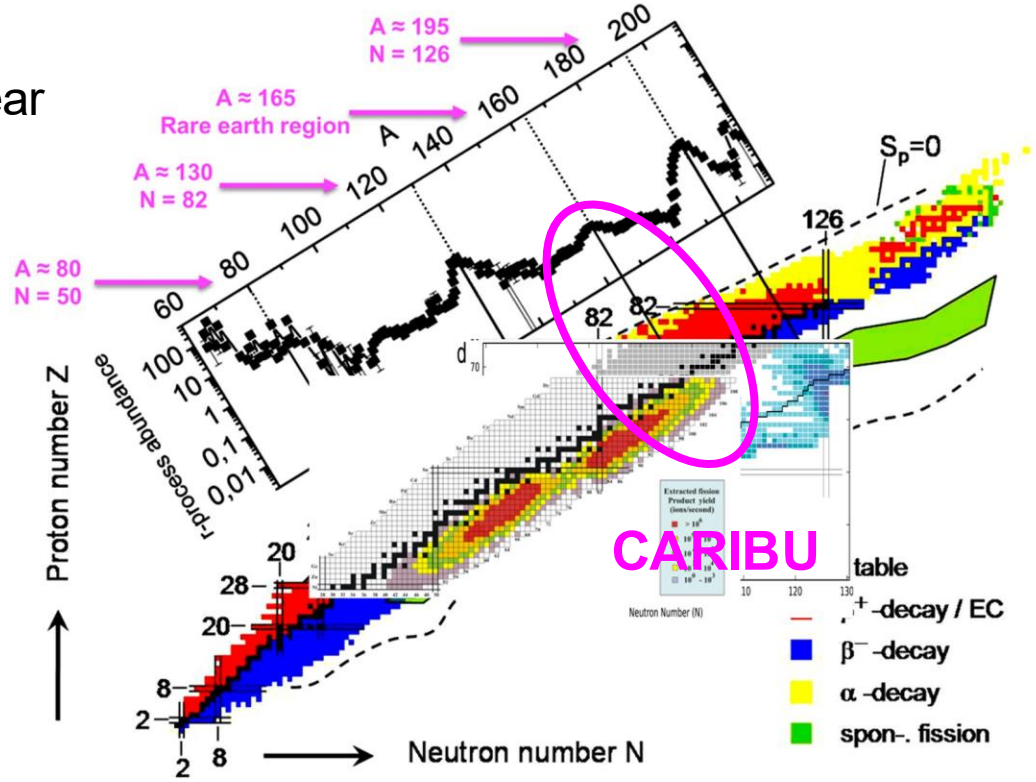


R. Kruecken, arXiv:1006.2520 (2010),

M.R. Mumpower et al., PPNP, 86 (2016)

R PROCESS STUDIES AT ANL

CARIBU :
Masses, etc. near rare-earth peak

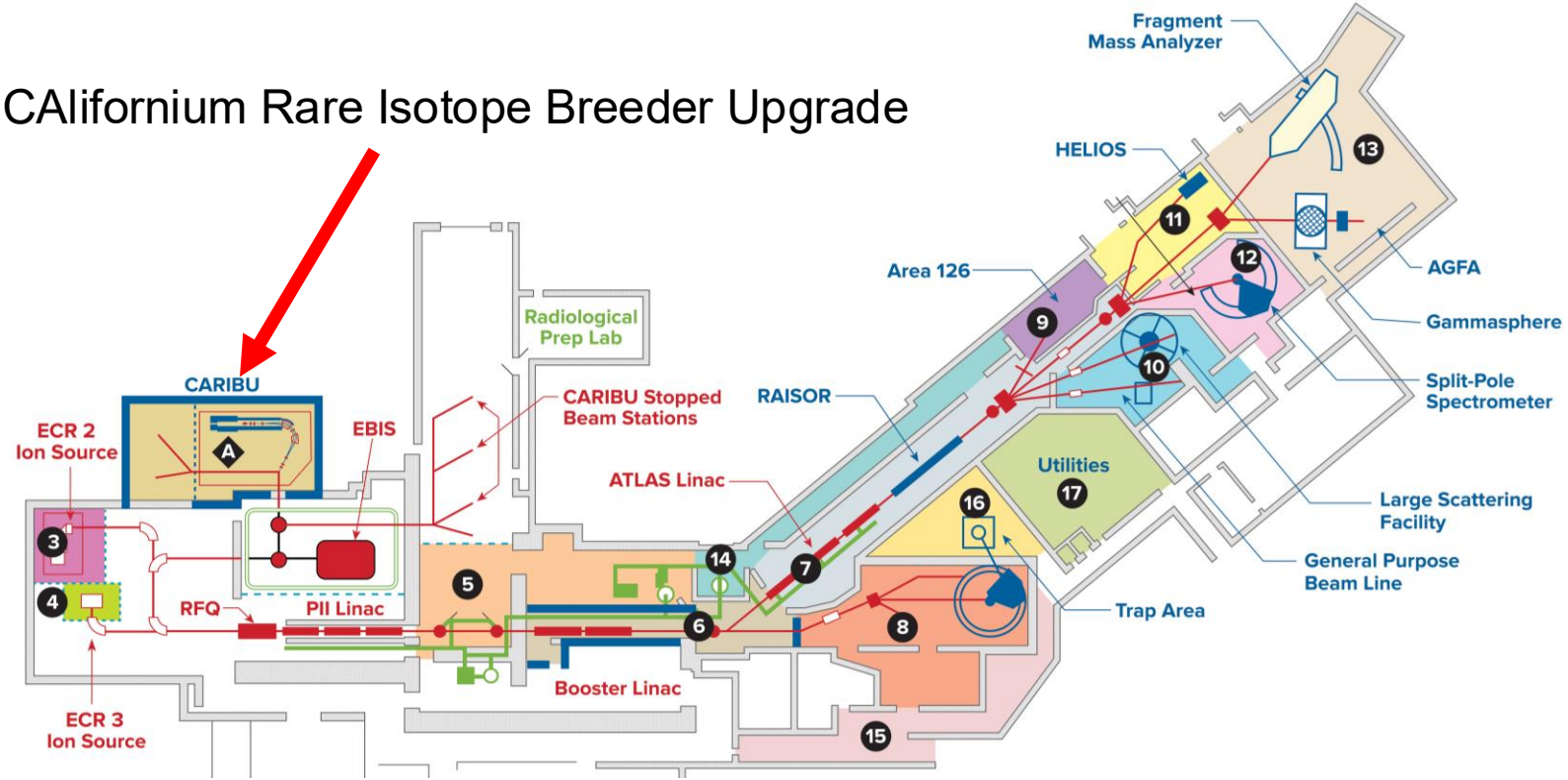


R. Kruecken, arXiv:1006.2520 (2010),

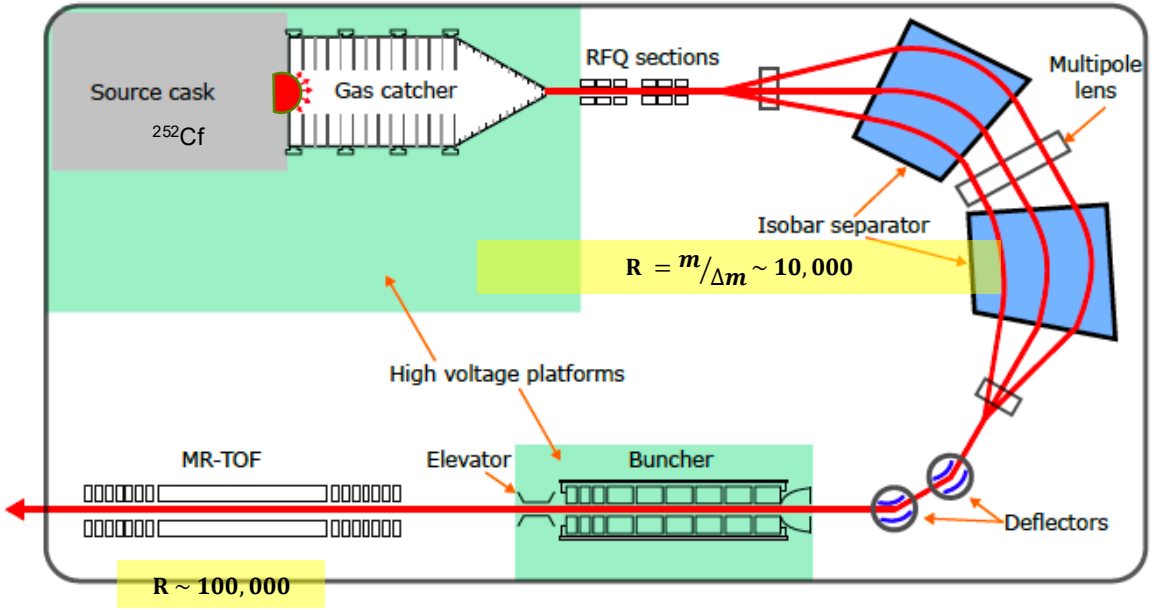
M.R. Mumpower et al., PPNP, 86 (2016)

CARIBU

CAlifornium Rare Isotope Breeder Upgrade

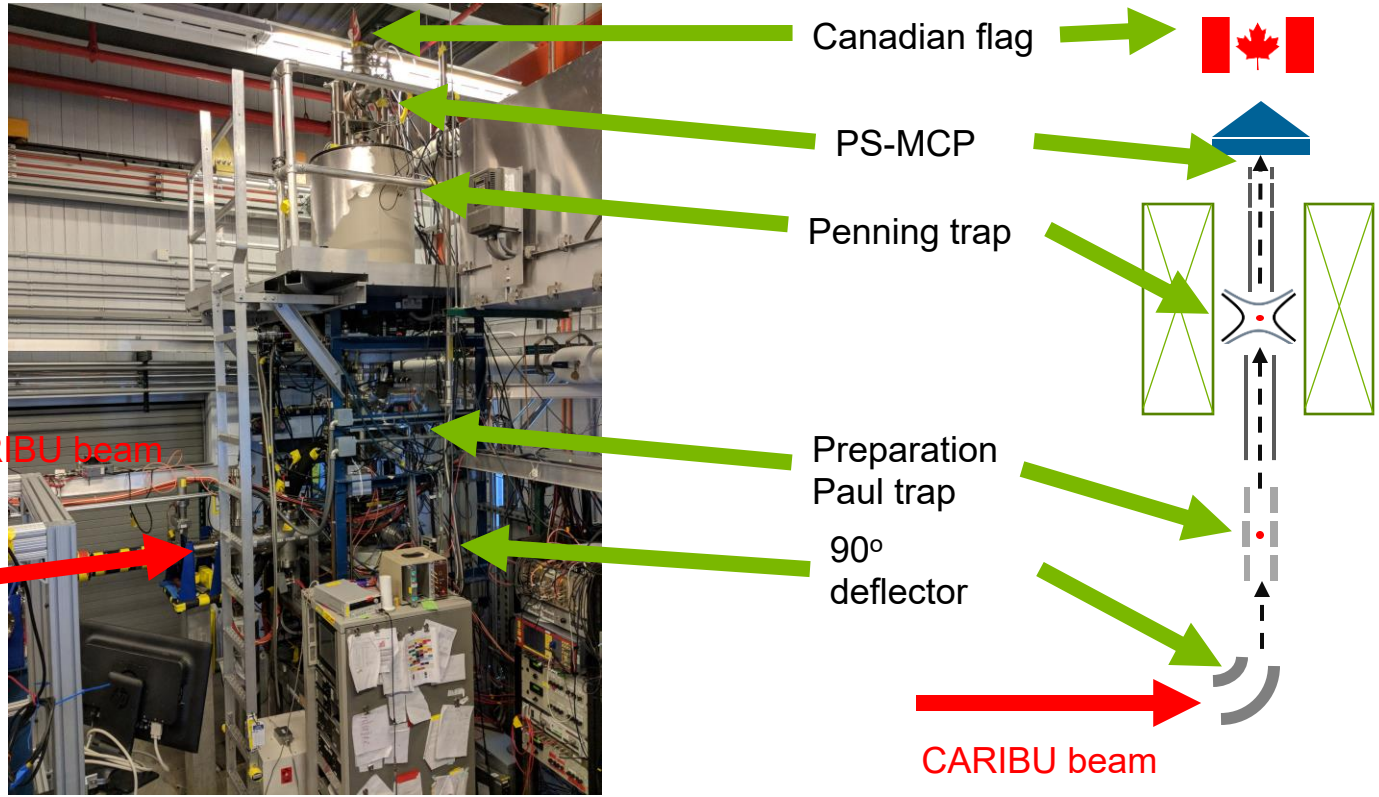


CARIBU

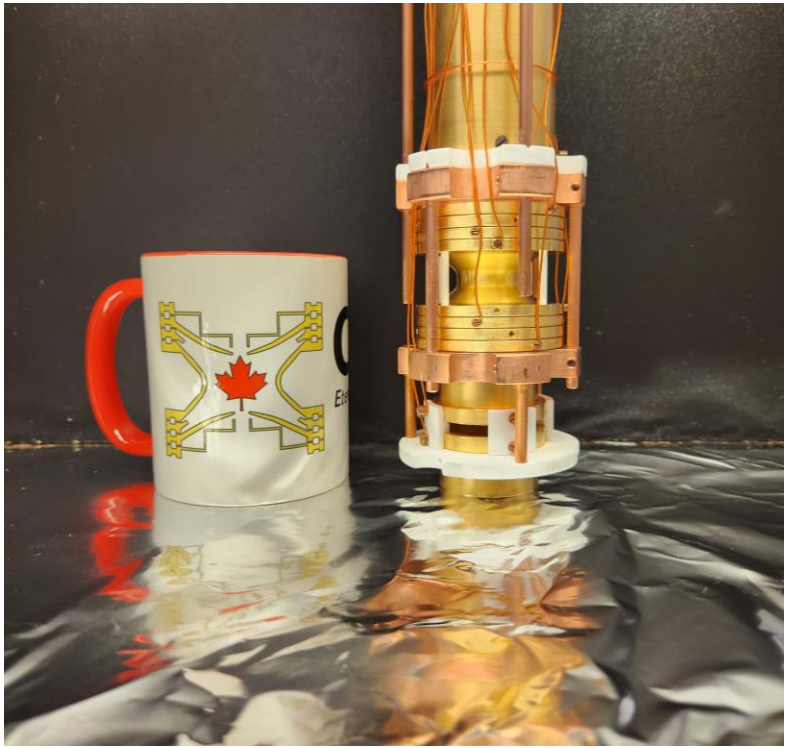


CARIBU

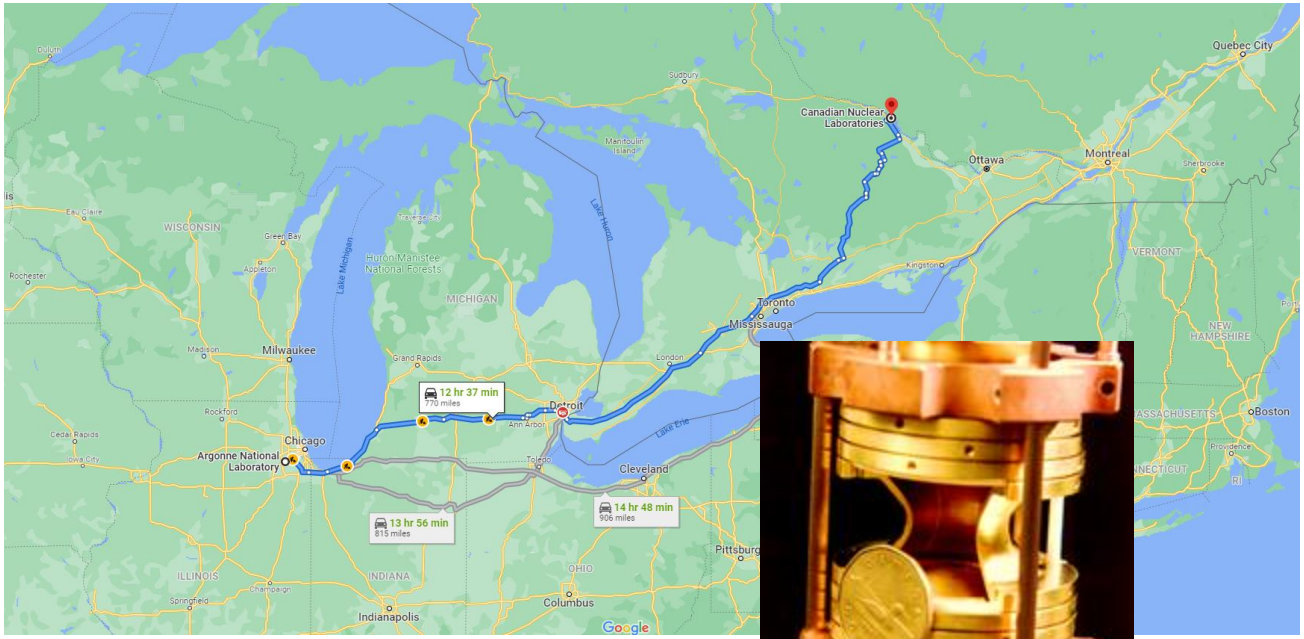
CANADIAN PENNING TRAP



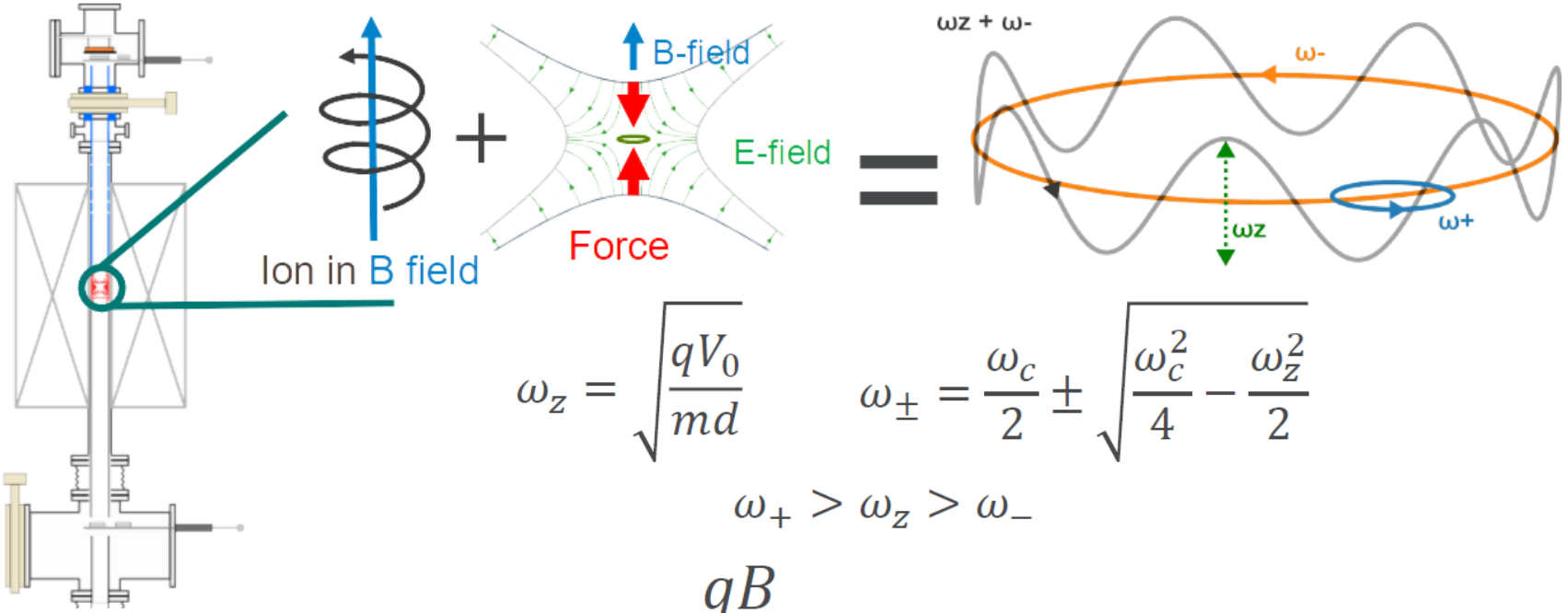
CANADIAN PENNING TRAP



CANADIAN PENNING TRAP



PENNING TRAP MASS SPECTROMETRY



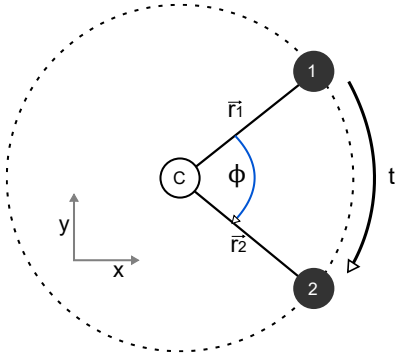
$$\omega_z = \sqrt{\frac{qV_0}{md}} \qquad \omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$$

$$\omega_+ > \omega_z > \omega_-$$

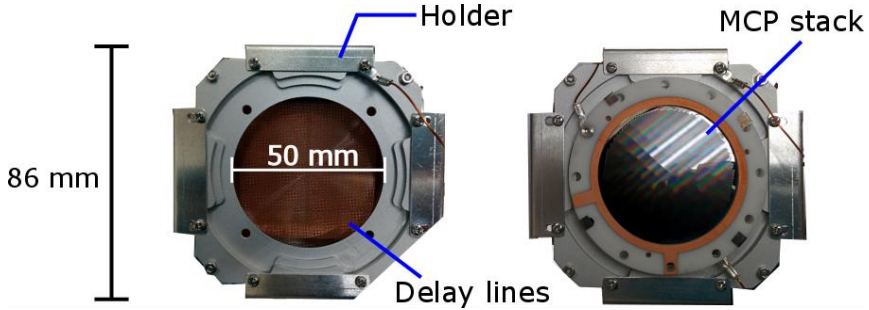
$$\omega_c = \frac{qB}{m_{\text{ion}}} = \omega_- + \omega_+$$

PI-ICR

- 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 period of time to determine the frequency of orbital motion

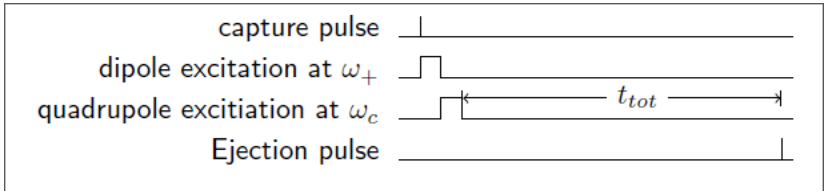


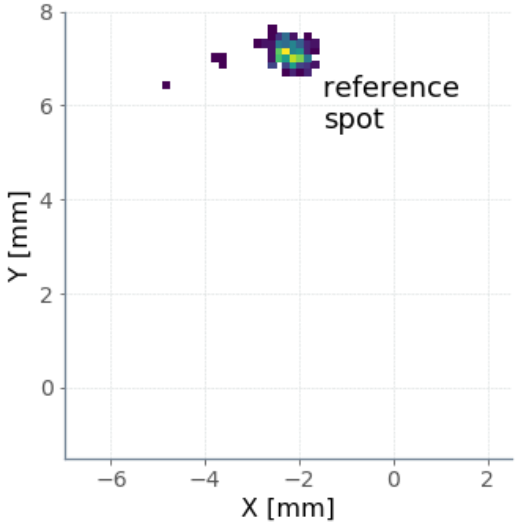
$$\nu = \frac{\phi_2 - \phi_1}{2\pi t}$$



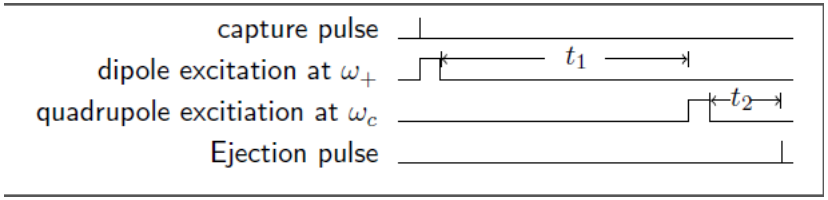
[1] Eliseev et al. PRL 110 082501 (2013)

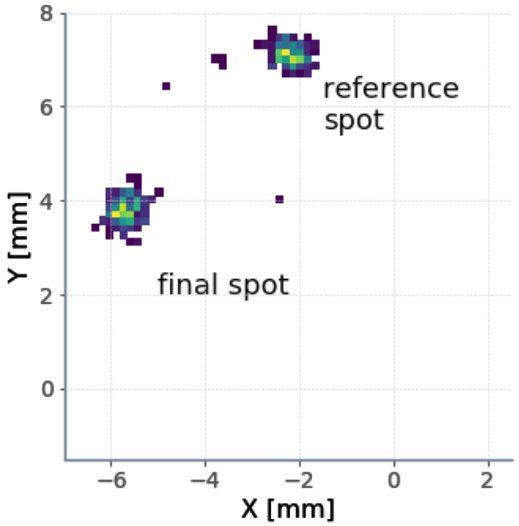
PI-ICR



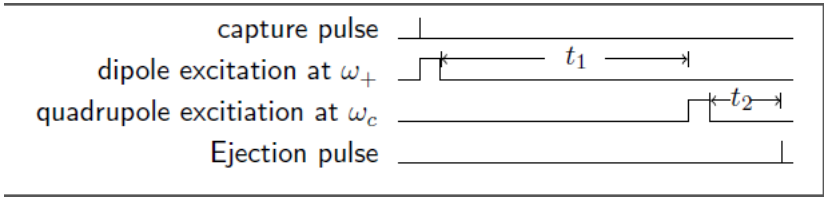


PI-ICR

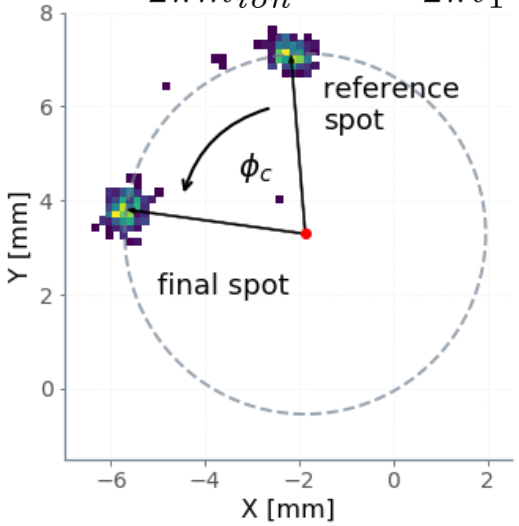




PI-ICR

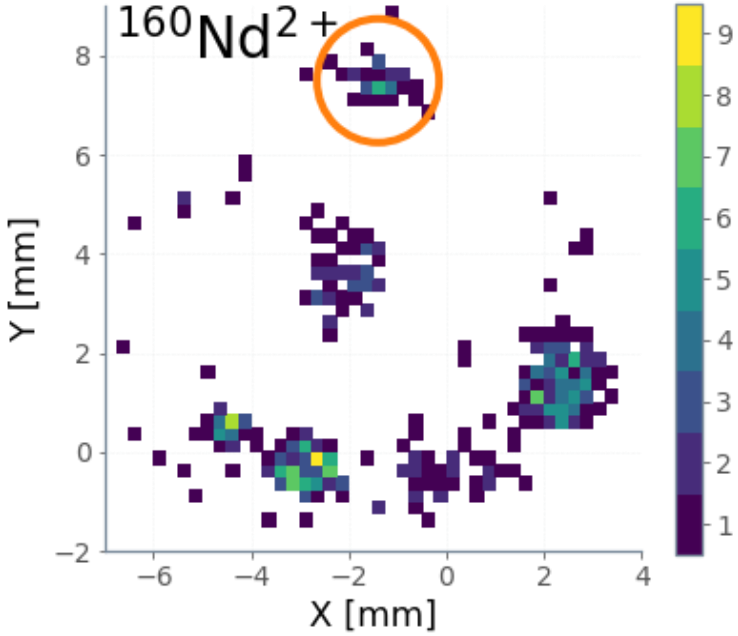


$$\nu_c = \frac{qB}{2\pi m_{ion}} = \frac{\phi_c + 2\pi N}{2\pi t_1}$$

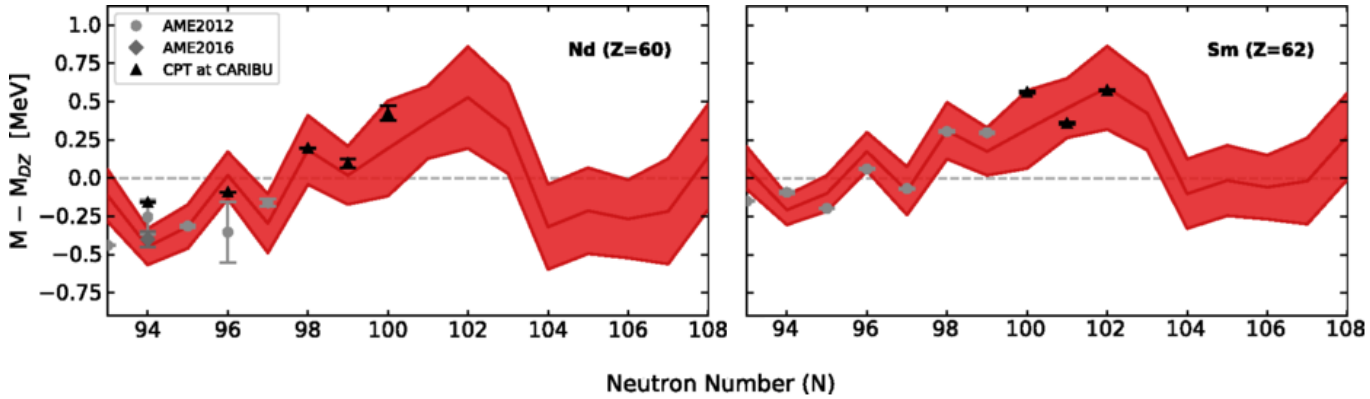


BENEFITS OF PI-ICR

- Spatial Resolution of Contaminants
  → Can do measurements of highly contaminated beams
- Low rate threshold: here 0.004 ions per second
  → Every detected ion contributes to measurement
- Higher-precision measurements
  → Order of magnitude improvement over TOF-ICR
- Faster measurements
  → Nuclei with shorter half-lives



CARIBU *R*-PROCESS RESULTS



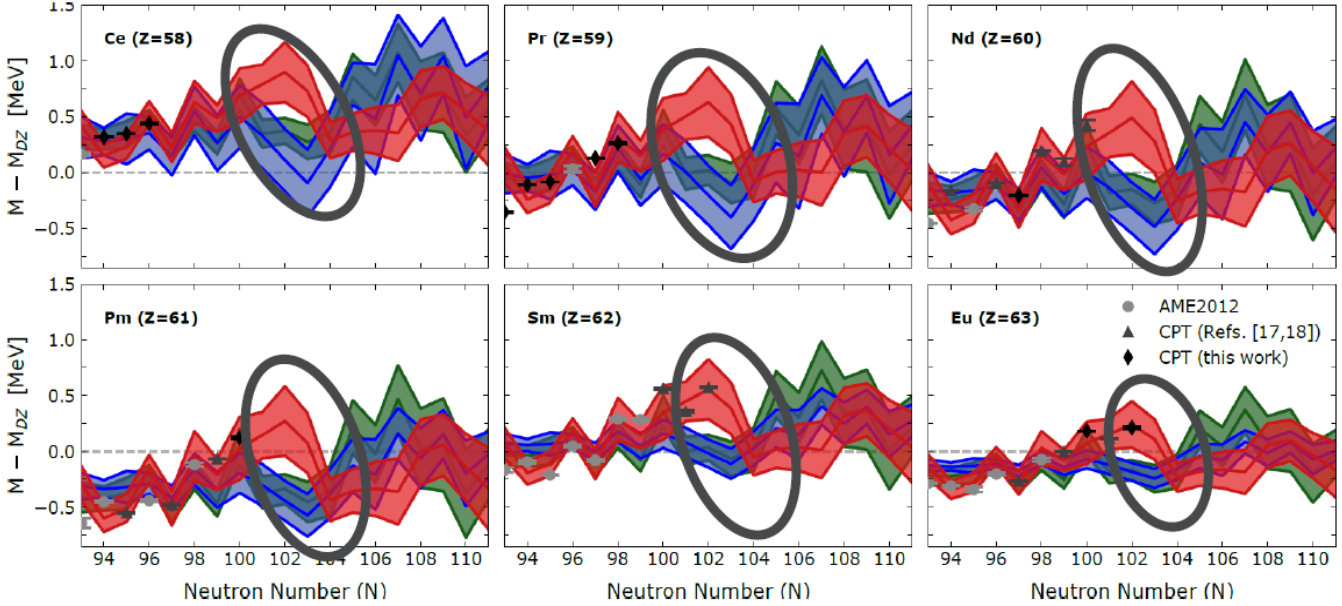
Reverse engineering framework : Pioneered by M. Mumpower (Los Alamos Nat. Lab.) and R. Surman (Notre Dame) and most recently carried out by N. Vassh (TRIUMF).

Red band : A mass prediction which reproduces the observed REP in the abundance pattern from *r*-process simulations, carried out for a hot, low entropy neutron star merger wind scenario.

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

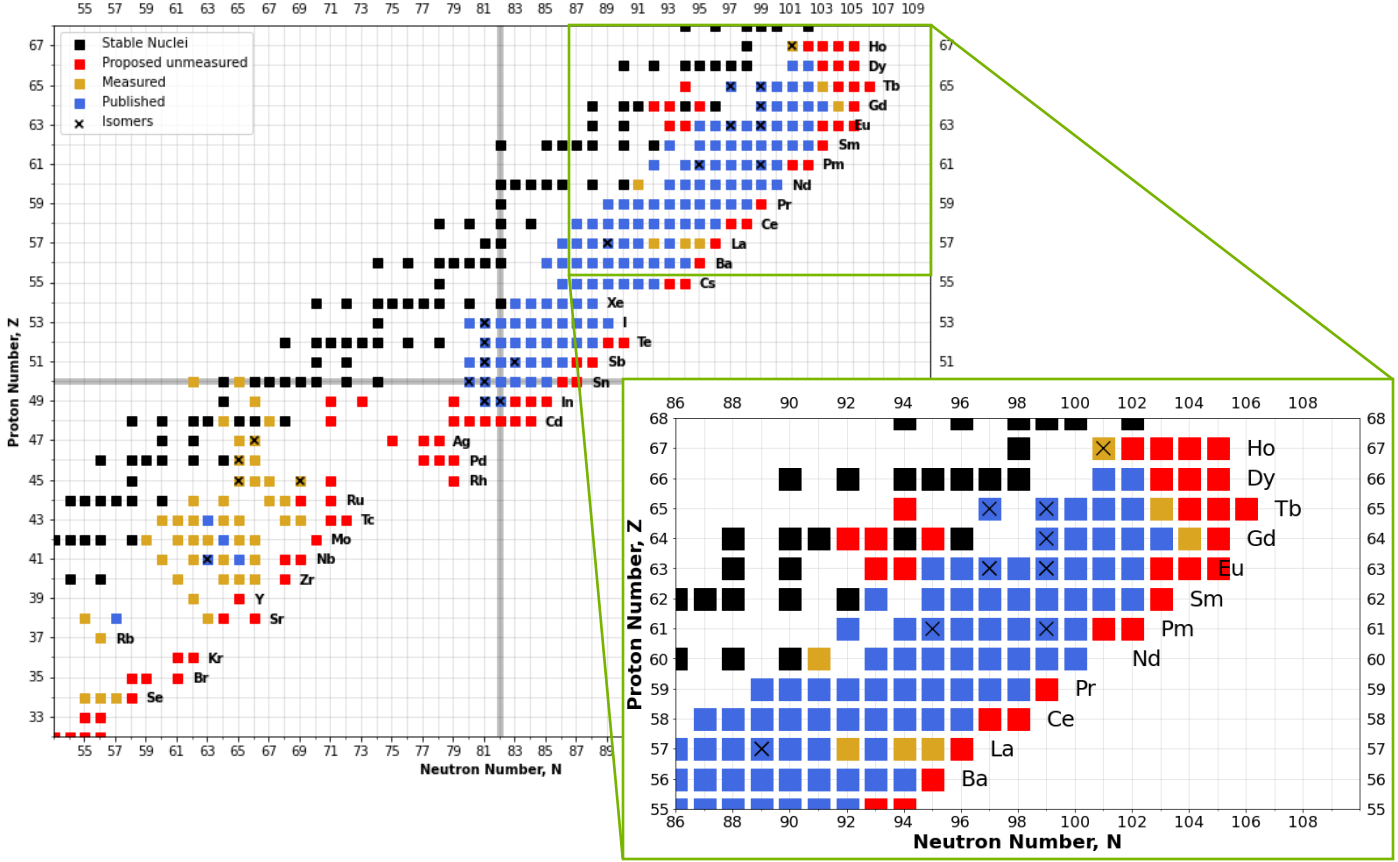
R PROCESS MEASUREMENTS

- Can see differentiation between hot accretion disk and cool accretion disk r-processes

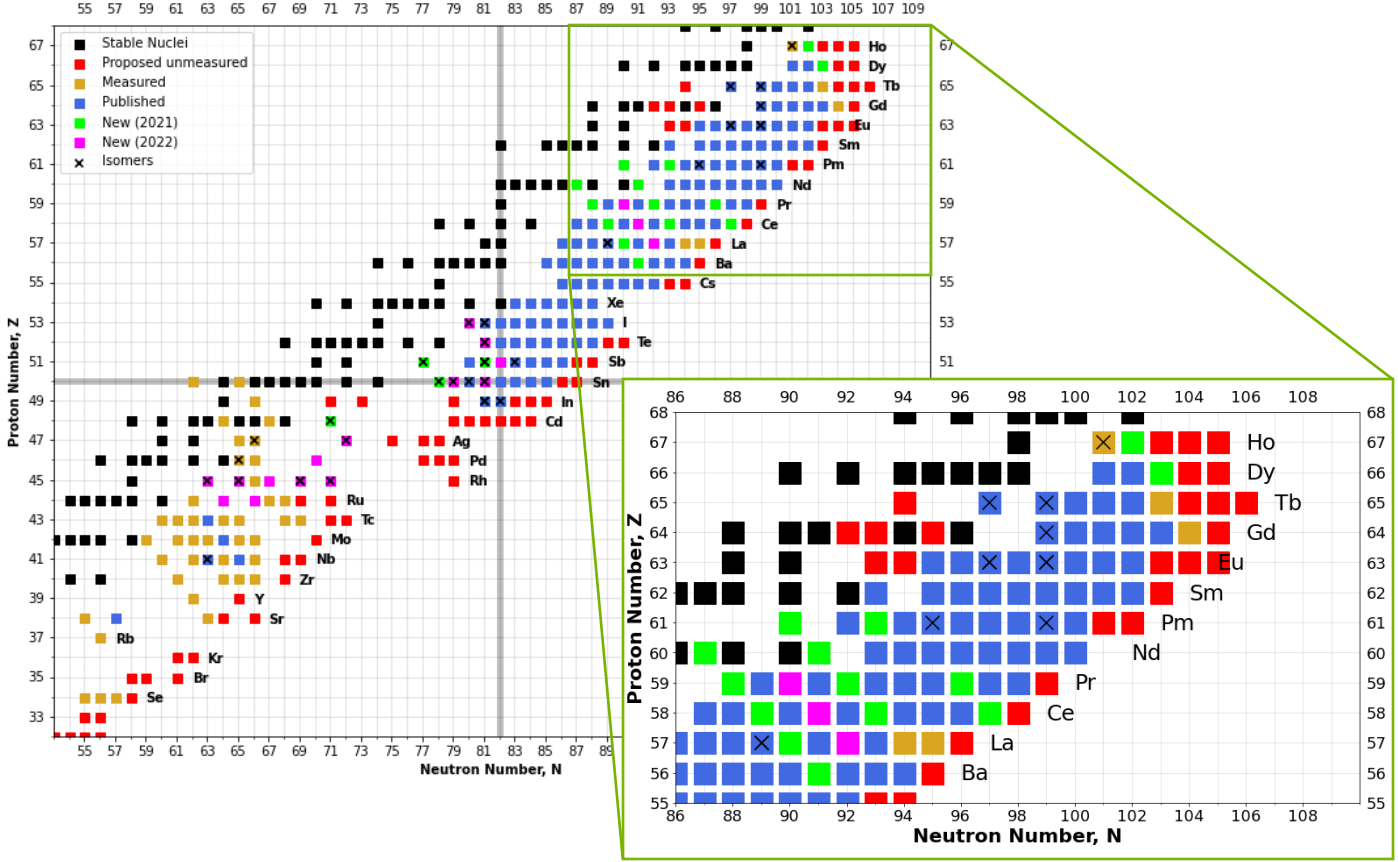


R. Orford, N. Vassh, et al., PRC 105, L052802 (2022)

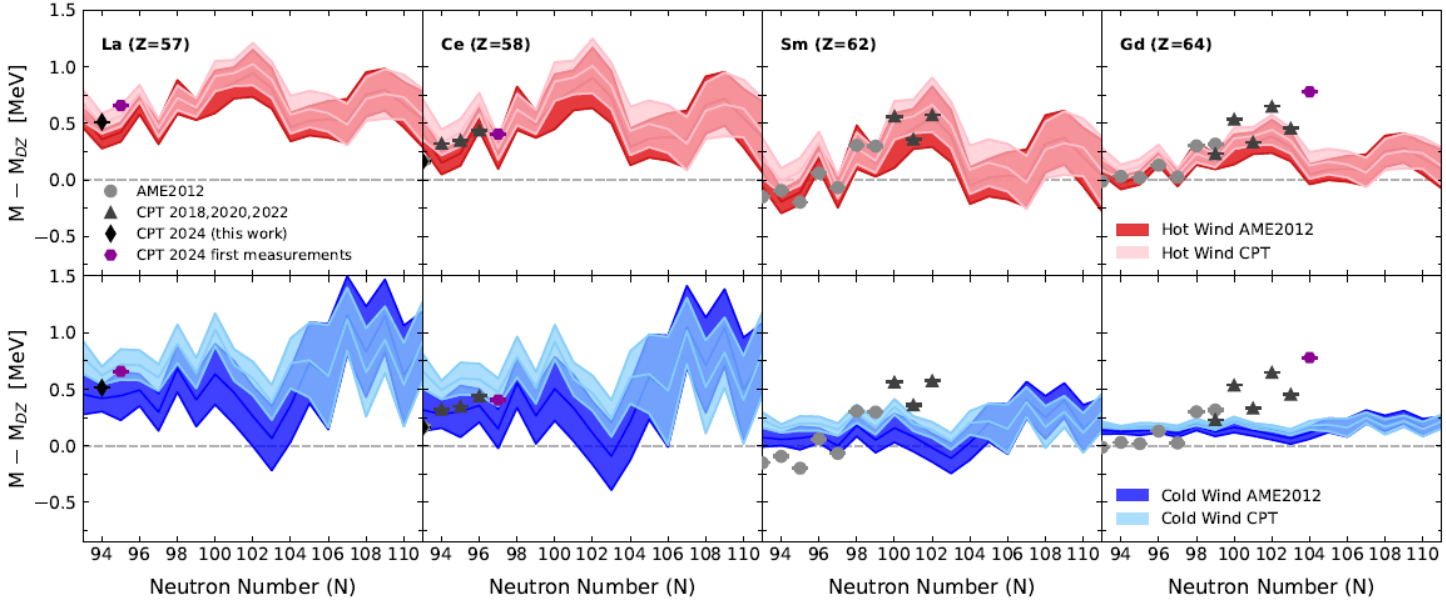
MASS MEASUREMENTS AT CARIBU



MASS MEASUREMENTS AT CARIBU

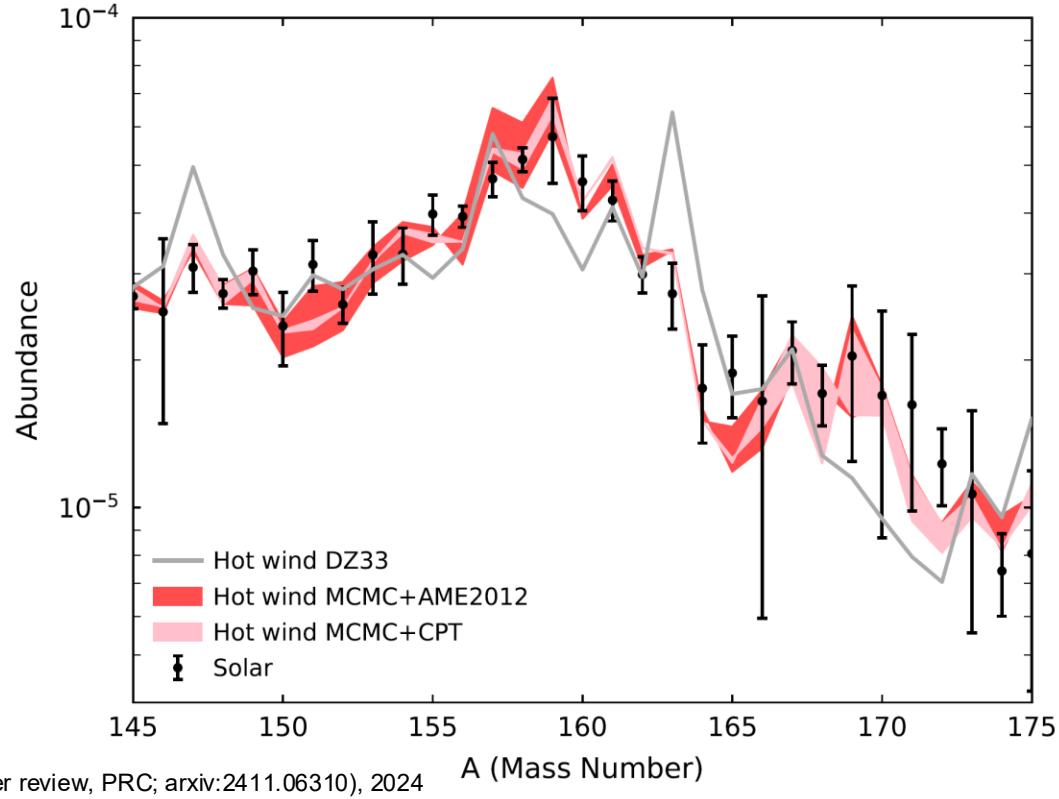


CARIBU *R*-PROCESS RESULTS



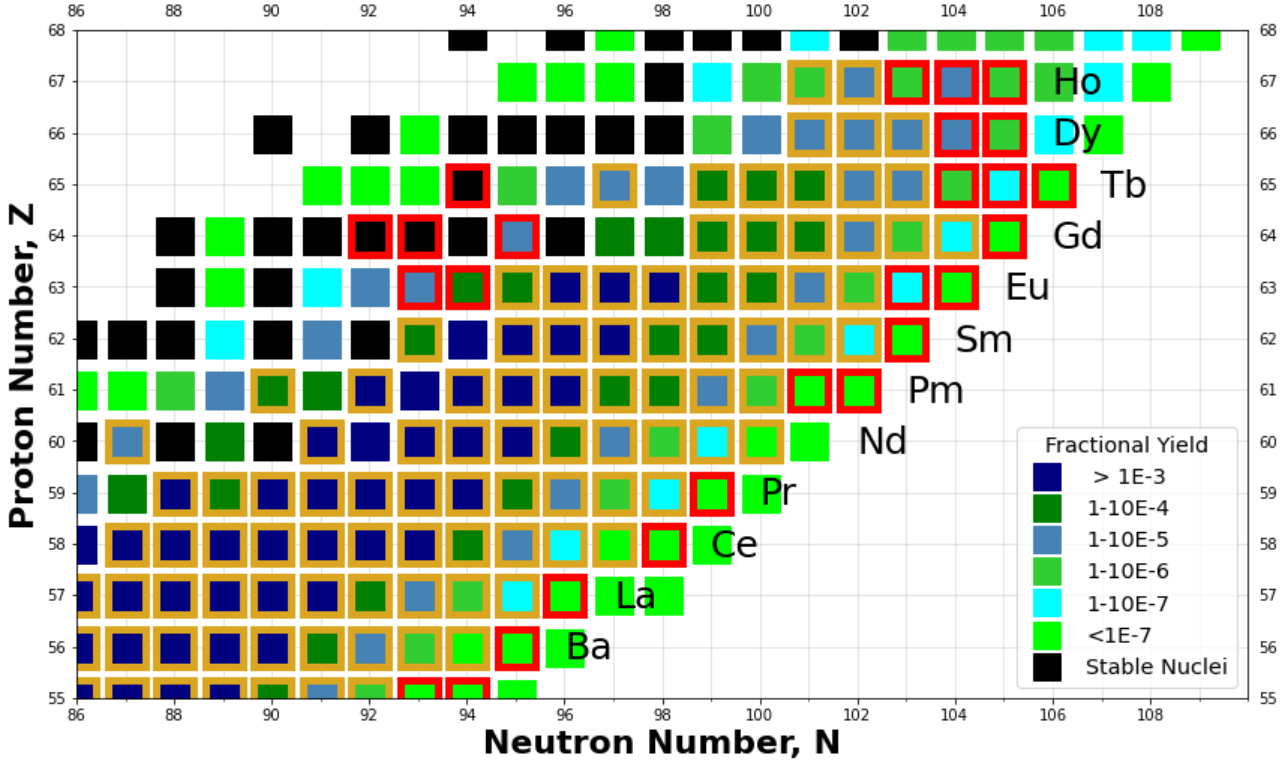
D. Ray, N. Vassh, *et al.*, (under review, PRC; arxiv:2411.06310), 2024

CARIBU *R*-PROCESS RESULTS



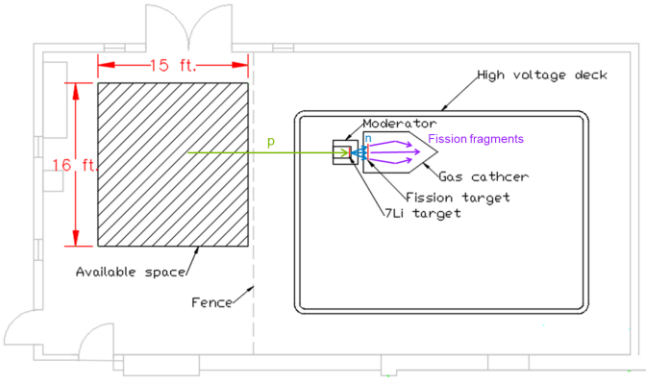
D. Ray, N. Vassh, *et al.*, (under review, PRC; arxiv:2411.06310), 2024

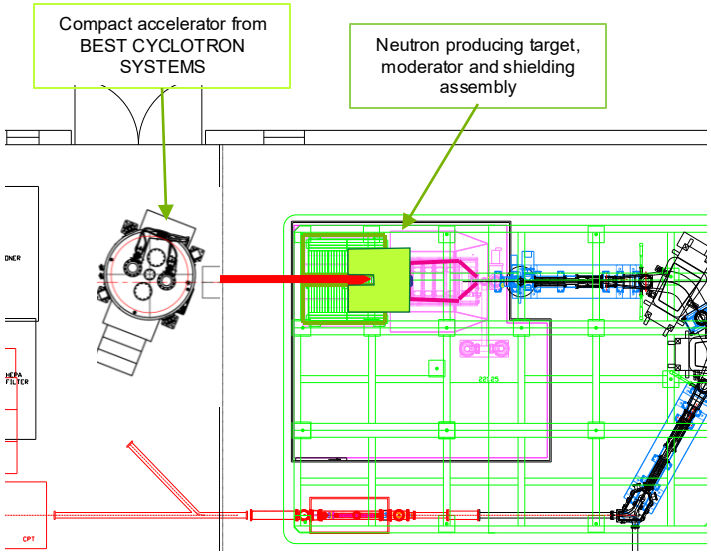
MASS MEASUREMENTS AT CARIBU



NUCARIBU

- p,^{7}Li reaction will be used to produce neutrons





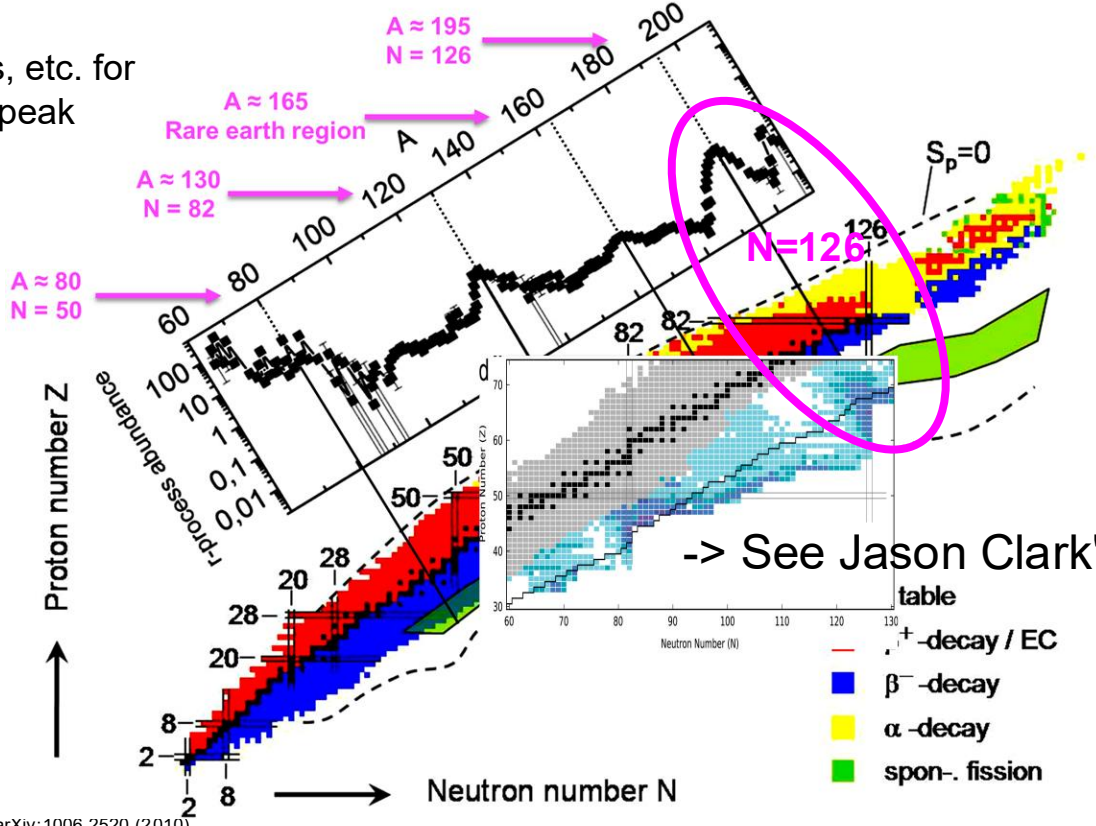
END OF CPT AT CARIBU

- CARIBU Mass measurement campaign finished
- Disassembled from CARIBU room in Spring 2023 to make room for nuCARIBU

NUCARIBU

R-PROCESS STUDIES AT ANL

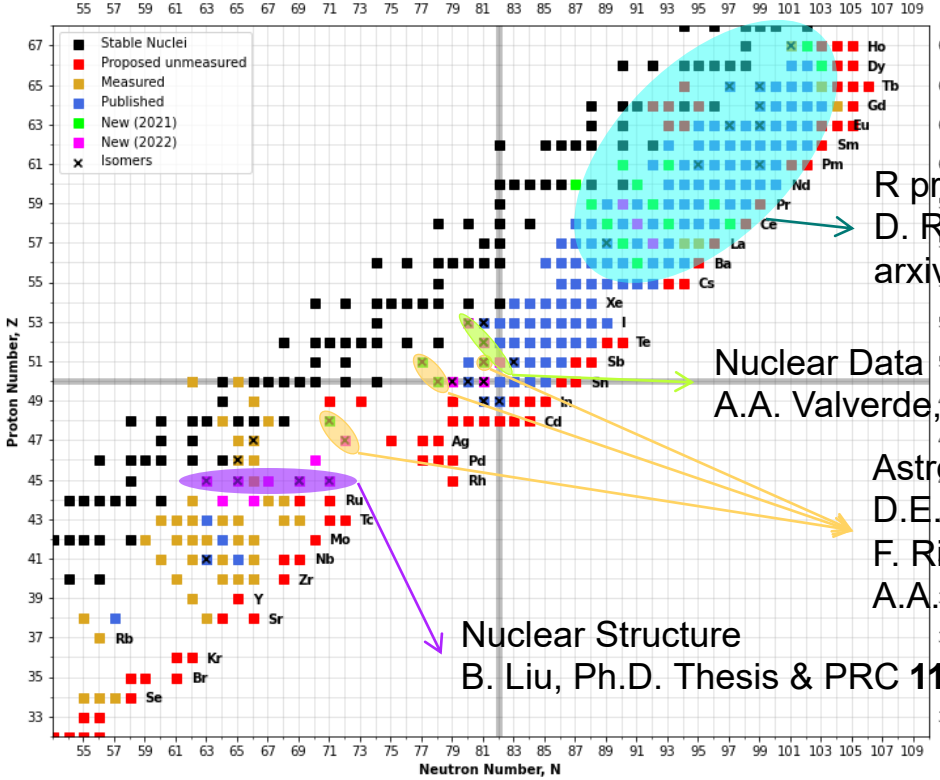
N=126:
Masses, etc. for
A~195 peak



R. Kruecken, arXiv:1006.2520 (2010);

M.R. Mumpower et al., PPNP, 86 (2016)

MASS MEASUREMENTS AT CARIBU



+ Isotope & Isomer fission yield ratio measurements

R process
D. Ray, Ph.D. Thesis &
arxiv:2411.06310 (under review PRC)

Nuclear Data
A.A. Valverde, PLB **858** 139037 (2024)

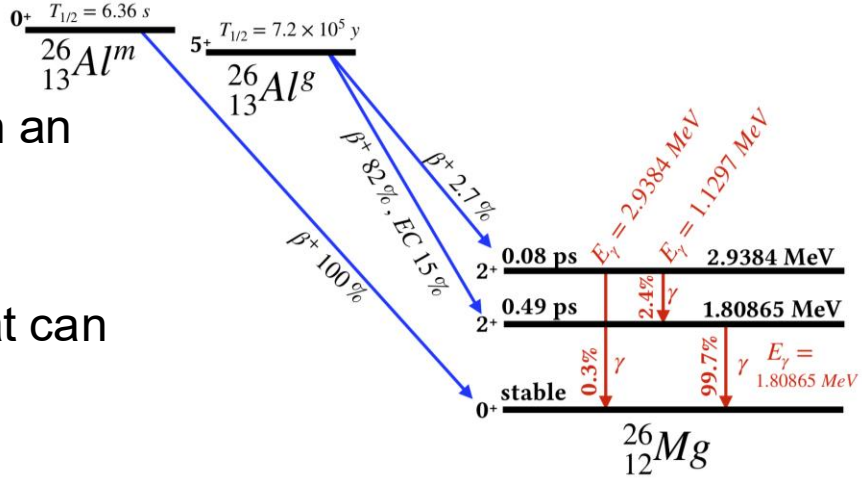
Astromers
D.E.M. Hoff, PRL **131** 262701 (2023)
F. Rivero, arxiv:250403944 (accepted PRC)
A.A. Valverde, in prep.

Nuclear Structure
B. Liu, Ph.D. Thesis & PRC **111** 034308 (2025)

-> See Max Brodeur's Talk

ASTROMERS

- Astromers [1] are nuclear isomers with an impact on astrophysical processes
- Generally, these are isomers with significantly different half-lives that can be populated during nucleosynthesis
- A notable case is 26mAl



[1]: G.W. Misch et al., Astrophys. J. Lett. **913**, L2 (2021)

ASTROMERS

- Recently, interest has grown in the effect of astromers on the r-, i-, and s-processes
- Here, isomers can be populated in various methods, including directly in decays, thermally in the astrophysical medium, or during neutron capture
- These astromers can impact nuceosynthesis by deferring or accelerating heating and produce identifiable electromagnetic signals
- With the identification of several interesting potential astromers, a campaign of mass measurements were embarked on using the CPT at CARIBU

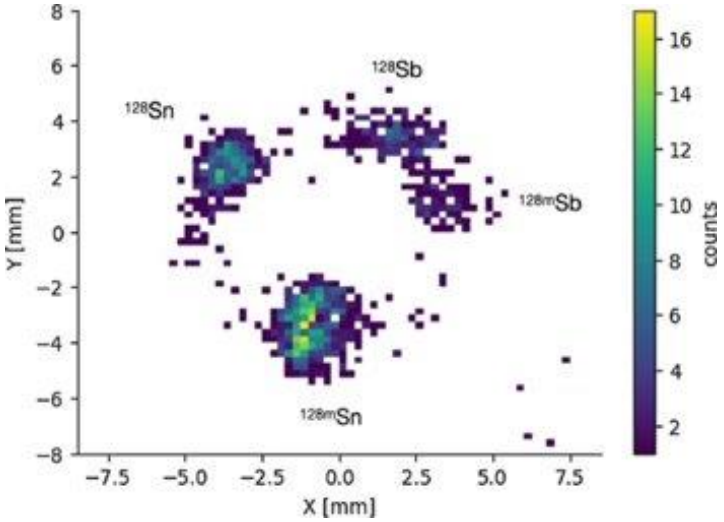
Fujimoto *et al.,* Astronom. Soc. Lett. **493**, L103 (2020); Misch & Mumpower, Eur. Phys. J. Spec. Top. **233** 1075 (2024); Tannous et al., Astrophys. J. **986** 107 (2025)

128M-SB

- Sensitivity studies indicated that ^{128m}Sb was potentially a high-impact astromer in the r process
- ^{128}Sb has a half-life of ~9 hrs and boosts heating in the r-process for several hours, affecting the light curve
- ^{128m}Sb has a half-life of only ~10 minutes, and should be preferentially populated in ^{128}Sn decay
- Impact is determined by level structure and excitation energy of this isomer

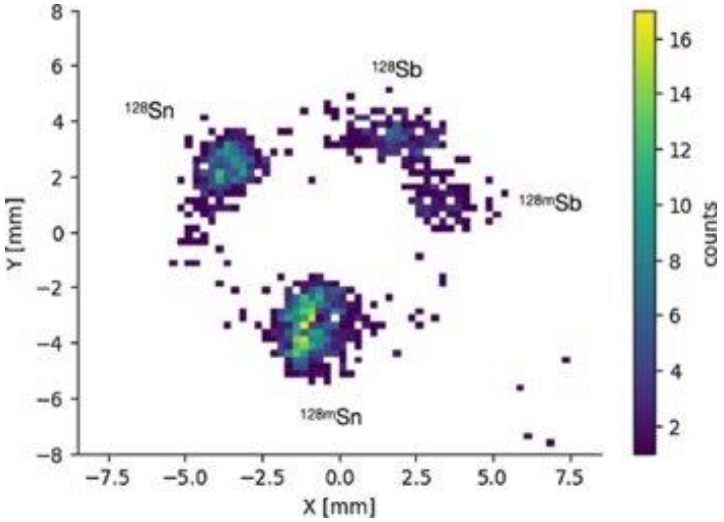
128M-SB

- Masses of ^{128}Sb and ^{128m}Sb measured using CPT @ CARIBU
- Excitation energy found to be 43.9(3.3) keV, much higher than the ~10 keV energy from previous evaluations
- Alongside shell model calculations of ^{128}Sb, this indicates the thermalization temperature of ^{128m}Sb between 1 and 9 keV



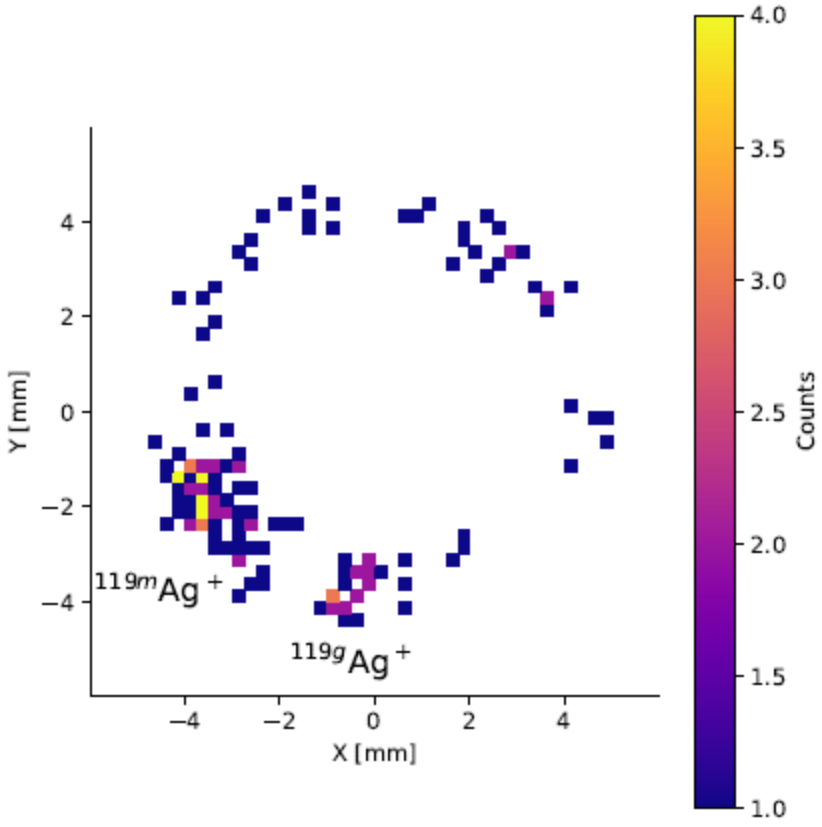
128M-SB

- Given the 10-15 minute timescale at which ^{128}Sb is believed to be populated in the r process, the temperature of the environment will be <1 keV
- Thus, ^{128m}Sb is an r process astromer
- D.E.M. Hoff *et al.*, PRL **131** 262701 (2023)



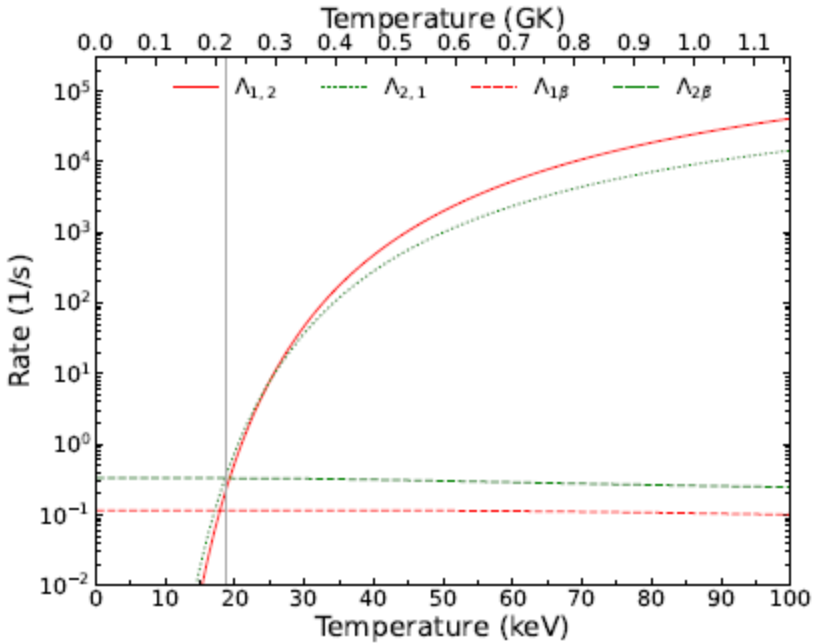
119M-AG

- Mass measurement of ^{119}Ag and ^{119m}Ag
- Excitation energy measured to be 34.3(53) keV, higher than the 20# keV from the AME (and consistent with contemporaneous measurements)



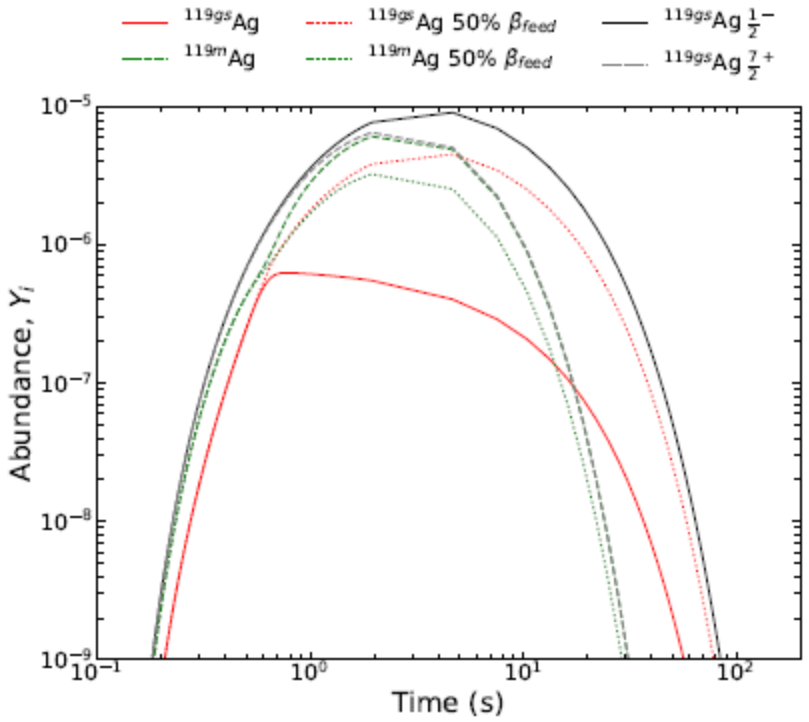
119M-AG

- This improved resolution of these states allowed the estimate of beta-decay thermalization temperature
- Thermal equilibrium determined to break at 18.7 keV; below this temperature, ^{119m}Ag must be treated separately and is an astromer



119M-AG

- From r-process simulation, this temperature should be crossed at ~0.6 s, and ^{119m}Ag be an astromer
- F. Rivero *et al.*, accepted PRC (2025)
- ArXiv:2504.03944



NEAR 132SN

- Several candidate astromers identified near ^{132}Sn, where shell closure has significant impact both on i-process path and on r-process decay back to stability
- Mass measurements of several isotopes in this region completed and impact as astromers simulated
- Results in preparation

CONCLUSIONS

- CARIBU was a facility that used a large ^{252}Cf source to produce rare isotope beams
- The CPT at CARIBU used the PI-ICR technique to conduct Penning trap mass spectrometry
- The final CPT @ CARIBU program focused on two areas of interest to nuclear astrophysics:
  - Mass measurements aimed at understanding the origin of the rare earth peak
  - Mass measurements exploring 'astromers'
- CARIBU is being replaced by nuCARIBU, but the CPT is moving to the N=126 Factory

ACKNOWLEDGEMENTS

Argonne NATIONAL LABORATORY

J.A. Clark,
A. Jacobs,
R. Knaack
O.S. Kubiniec,
A. LaLiberte,
M.S. Martin,
G. Savard,
A.A. Valverde

UNIVERSITY OF NOTRE DAME

M. Brodeur,
A.M. Houff,
B. Liu,
A. Mitra,
W.S. Porter,
E. Ribeiro,
R. Surman

TRIUMF

D. Ray,
N. Vassh

Los Alamos NATIONAL LABORATORY EST. 1943

M. Mumpower

BERKELEY LAB

R. Orford

NC STATE

G.C. McLaughlin

ACKNOWLEDGEMENTS

CPT
Eternal Beamtime
2021-??

M. Brodeur,
D.P. Burdette,
N. Callahan,
A. Cannon,
J.A. Clark,
D.E.M. Hoff,
A. Gallant,
K. Kolos,
F.G. Kondev,
B. Liu,
G.W. Misch,
G.E. Morgan,
M. Mumpower,
A. Gallant,
R. Orford,
W.S. Porter,
D. Ray,
F. Rivero,
D. Santiago-Gonzalez,
G. Savard,
N. Scielzo,
A.A. Valverde,
L. Varriano,
C.M. Weber,
G. Wilson

CONCLUSIONS

- CARIBU was a facility that used a large ^{252}Cf source to produce rare isotope beams
- The CPT at CARIBU used the PI-ICR technique to conduct Penning trap mass spectrometry
- The final CPT @ CARIBU program focused on two areas of interest to nuclear astrophysics:
  - Mass measurements aimed at understanding the origin of the rare earth peak
  - Mass measurements exploring 'astromers'
- CARIBU is being replaced by nuCARIBU, but the CPT is moving to the N=126 Factory

THANK YOU


Argonne
NATIONAL LABORATORY