JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Mass Measurements of Exotic Neutron-Deficient Nuclides at IGISOL

Zhuang Ge

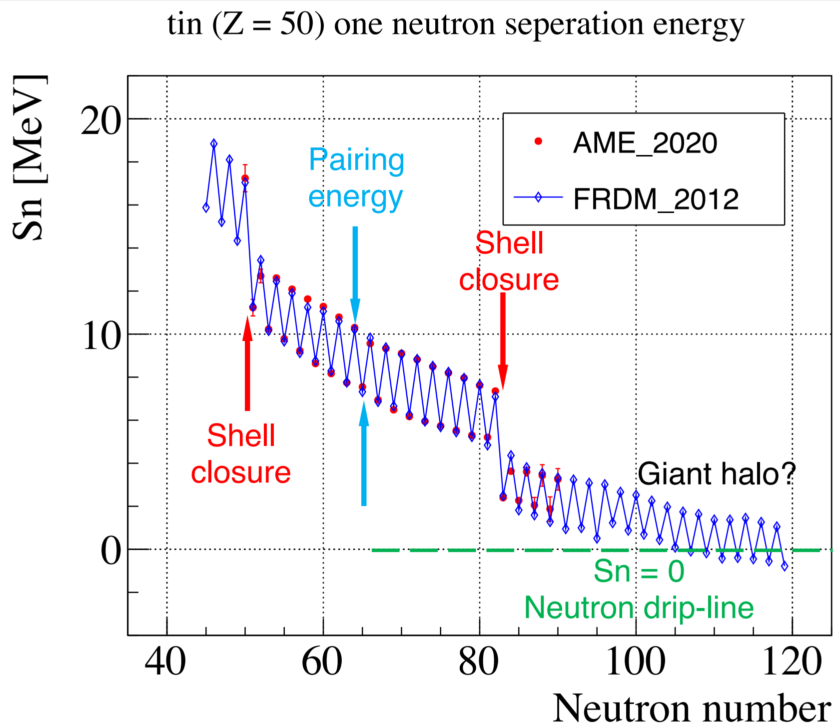
University of Jyväskylä

Motivation for mass measurements of neutron-deficient nuclei

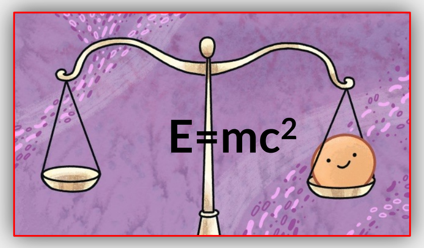
Nuclear mass ↔ nuclear binding energy:

$$M(N,Z) = Z \cdot m_p + N \cdot m_n - B(N,Z)/c^2$$

Nuclear structure



$$S_n(N,Z) = M(N-1,Z) + m_n - M(N,Z)$$
$$= B(N,Z)/c^2 - B(N-1,Z)/c^2$$



Nuclear astrophysics

Example:
rp process
X-ray burst

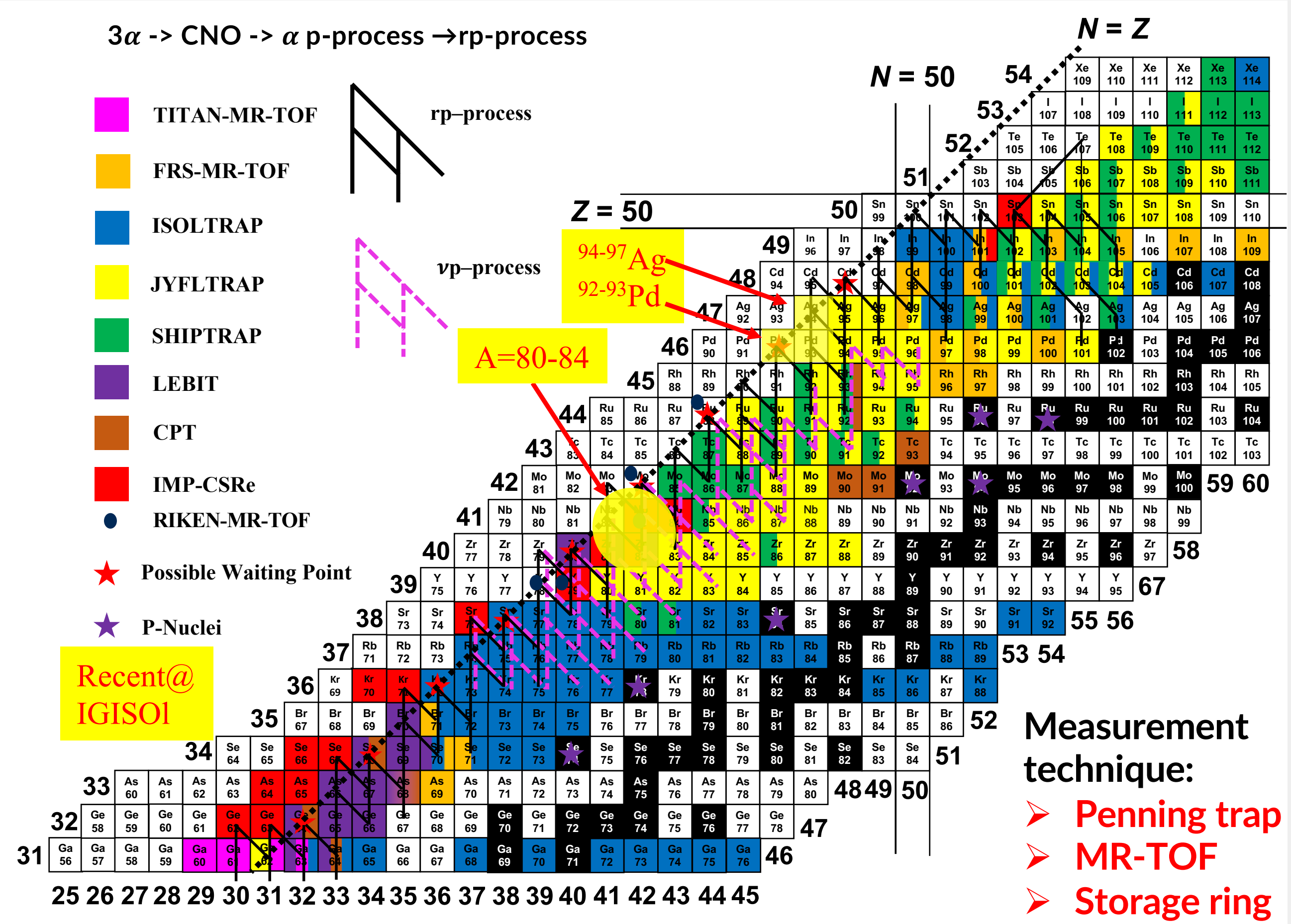
J. Grindlay et al., Astrophys. J. 205 (1976) L127.

time−scale $\propto e^{(Q/kT)} / A(Q)$
isotope production $\propto A(Q) \cdot e^{(Q/kT)}$
energy production $\propto A(Q) \cdot Q \cdot e^{(Q/kT)}$
Common parameter: Q (mass difference)

Status of mass measureements of neutron-deficient nuclei along N~Z line

Nuclear mass ↔ nuclear binding energy:

$$M(N,Z) = Z \cdot m_p + N \cdot m_n - B(N,Z)/c^2$$



Measurement technique:

- Penning trap
- MR-TOF
- Storage ring

C. Weber et al., Phys. Rev. C 78, 054310 (2008)
A. Kankainen et al., Phys. Rev. Lett. 101, 142503 (2008)
V.-V. Elomaa et al., Phys. Rev. Lett. 102, 252501 (2011)
E. Haettner et al., Phys. Rev. Lett. 106, 122501 (2011)
F. Herfurth et al., Eur. Phys. J. A, 47,75 (2011)
X. Tu et al., Phys. Rev. Lett. 106, 112501 (2011)
Y.M. Xing, et al., Phys. Lett. B 781 358–363 (2018)
C. Hornung et al., Physics Letters B 802, 135200 (2020)
M. Mougeot et al., Nature Physics 17, 1099 (2021)
Hamaker, et al., Nat. Phys. 17, 1408–1412 (2021).
A. Mollaebrahimi et al., Phys. Lett. B 839, 137833 (2023)
L. Nies et al., Phys. Rev. Lett. 131, 022502 (2023)
X. Zhou et al., Nature Physics 19, 1091–1097 (2023)
Z. Ge, M. Reponen, et al., Phys. Rev. Lett. 133, 132503 (2024)
C. M. Ireland et al.,Phys. Rev. C 111, 014314 (2025)
L. Nies et al., Phys. Rev. C 111, 014315 (2025)
S. Kimura et al., arXiv:2504.12639v1 (PRL, accepted)
V. Virtanen, M. Reponen, et al. to be submitted

Mass Measurement Techniques of Exotic N~Z Nuclei

Storage Rings

Isochronous MS

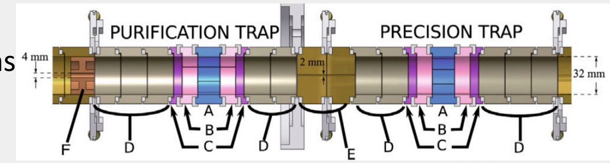
t_{meas} ~ 100 μs
$m/\Delta m = 2{\cdot}10^5$
$\delta m/m \sim 10^{-6}$
broadband
~ 10-200 keV

1. RIKEN/Rare RI Ring

Penning Trap MS (TOF-ICR and PI-ICR-MS)

TOF-ICR MS

t_{meas} ~ 100-1000 ms
$m/\Delta m = 10^6$-10^7
$\delta m/m < 10^{-7}$
scanning



PI-ICR MS

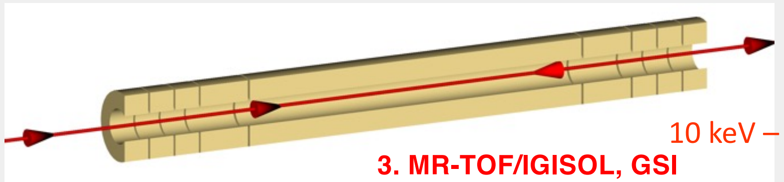
t_{meas} ~ 100-1000 ms
$m/\Delta m \sim 10^7$
$\delta m/m < 10^{-8}$
broadband

10s eV – 10 keV

2. IGISOL/JYFLTRAP

Multiple-Reflection Time-of-Flight MS (MR-TOF-MS)

t_{meas} ~ 10 ms
$m/\Delta m$ >10^5
$\delta m/m < 10^{-6}$
Broadband

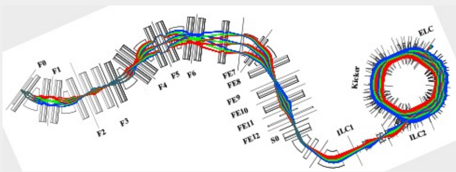


10 keV – 100 keV

3. MR-TOF/IGISOL, GSI

Magnetic-rigidity Time-of-Flight MS

t_{meas} < 1 us
$m/\Delta m \sim 10^4$
$\delta m/m > 10^{-6}$
Broadband



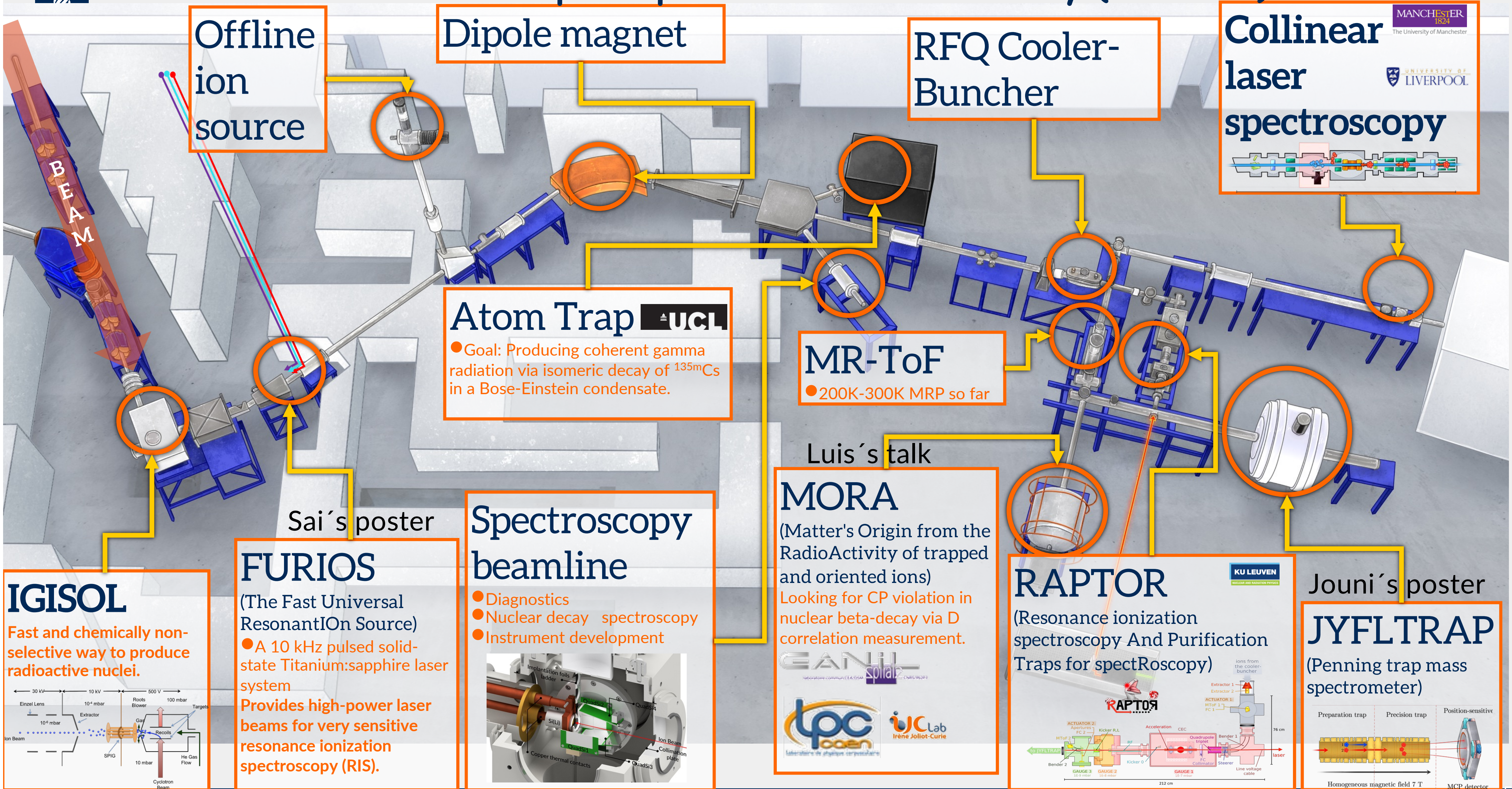
100 keV – 1000 keV

1. RIKEN/BigRIPS-OEDO-SHARAQ

SUOMEN AKATEMIA

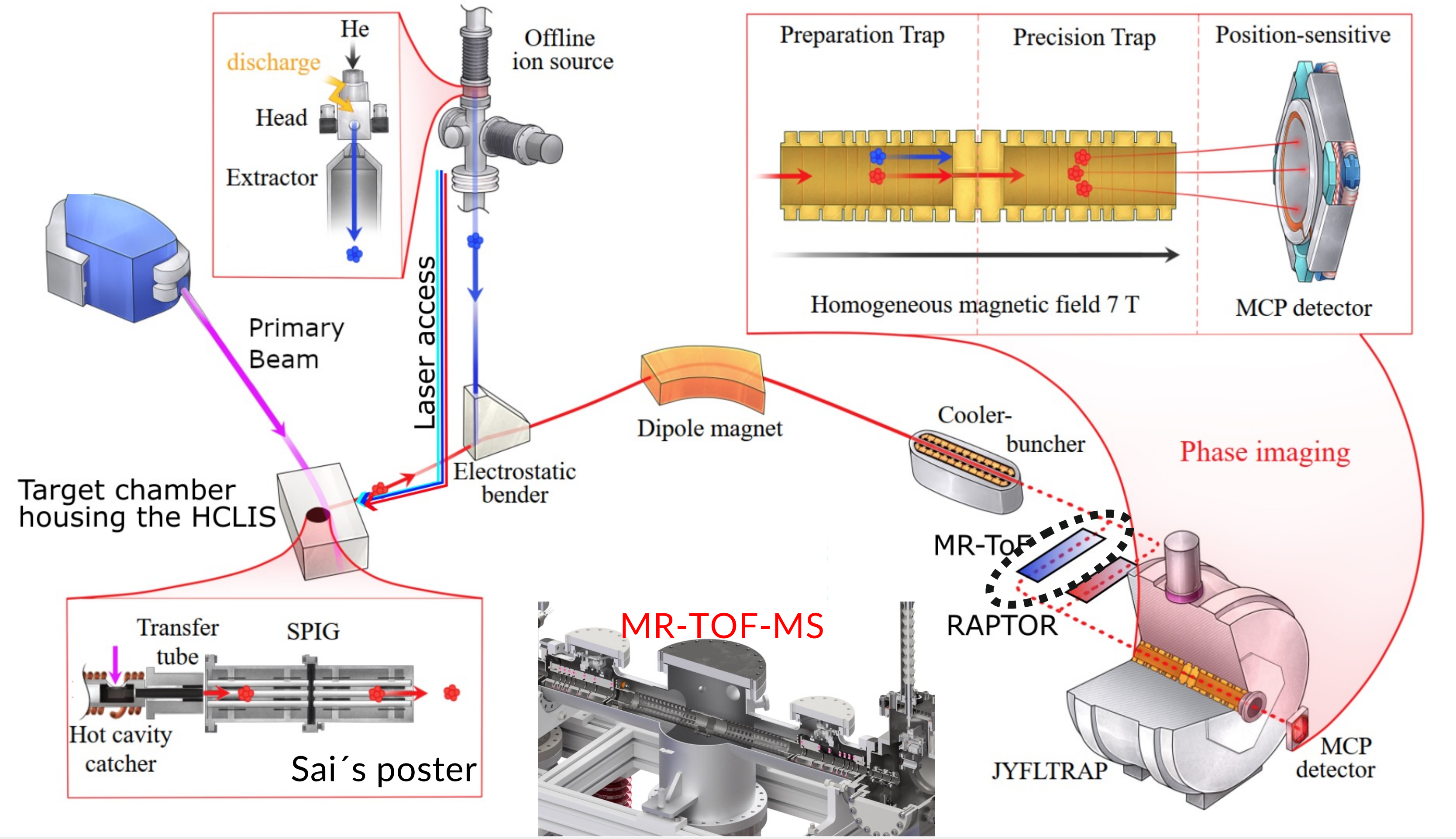
Recently Research Council of Finland **budget support (354589)**:
Using all these facilities and devices for the **Exotic N~Z Nuclei**

The Ion Guide Isotope Separator On-Line facility (IGISOL)



Penning trap and MR-TOF mass spectrometer at IGISOL

T. Eronen et al., EPJA 48 (2012) 46
A. Kankainen et al., Hyperfine Interactions (2020) 241:43



- Production of N=Z nuclei and the vicinity:
  - Heavy ion induced fusion-evaporation
  - MNT
- Extraction technique:
  - HIGISOL gas cell
  - MNT gas cell
  - Hot cavity

- Production of reference nucleus:
  - Co-produced in Target chamber
  - Sparking ion source
  - Surface ion source
  - Laser ablation ion source

Schematic of PI-ICR for ^{95}Ag mass measurements

Z. Ge, M. Reponen, T. Eronen et al., Phys. Rev. LETT. 133, 132503 (2024)
M. Reponen et al., Nat Commun 12, 4596 (2021).

Sensitivity of 1 count/10 min

Hot cavity& in source Laser ionization
Identification/measurement with PI-ICR

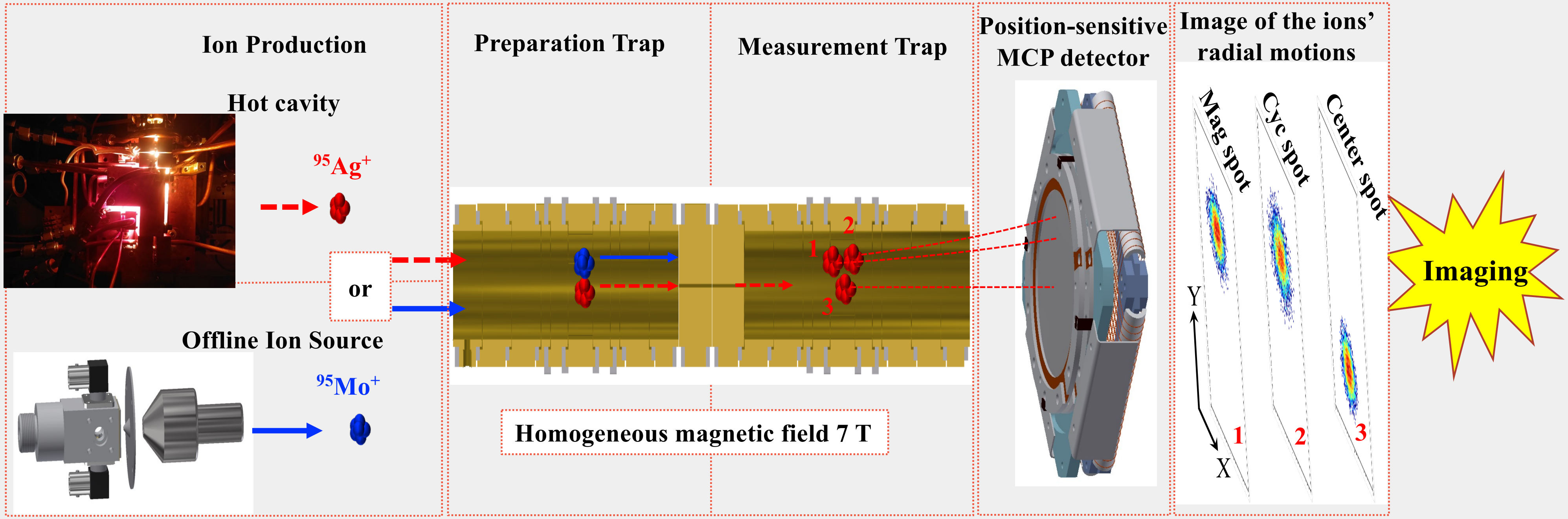
Traps ❤️ Lasers

Angle difference between cyclotron and magnetron motion phases:

$$\alpha_c = \alpha_- + \alpha_+$$

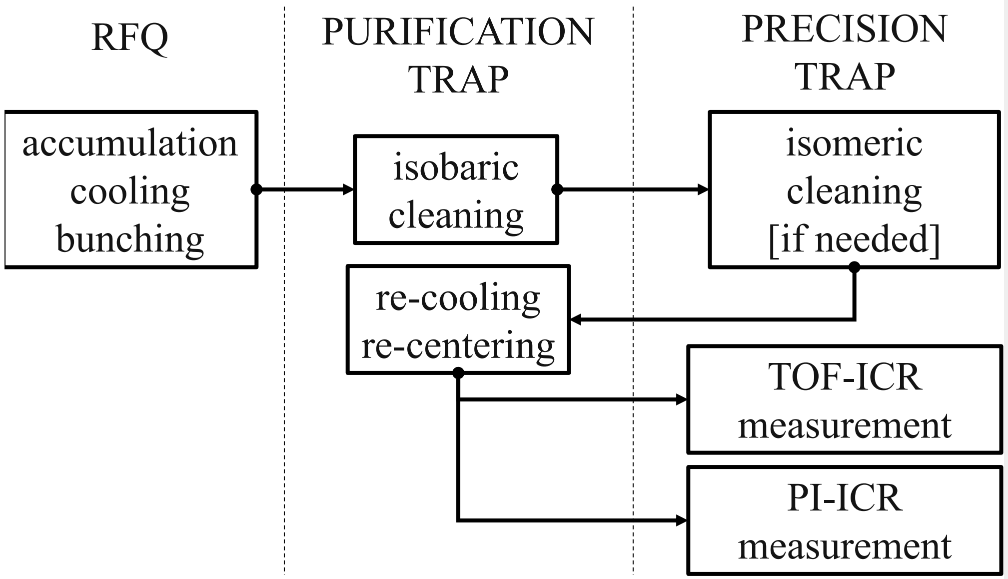
cyclotron frequency:

$$\nu_c = \nu_+ + \nu_- = \frac{\alpha_c + 2\pi n}{2\pi t}$$

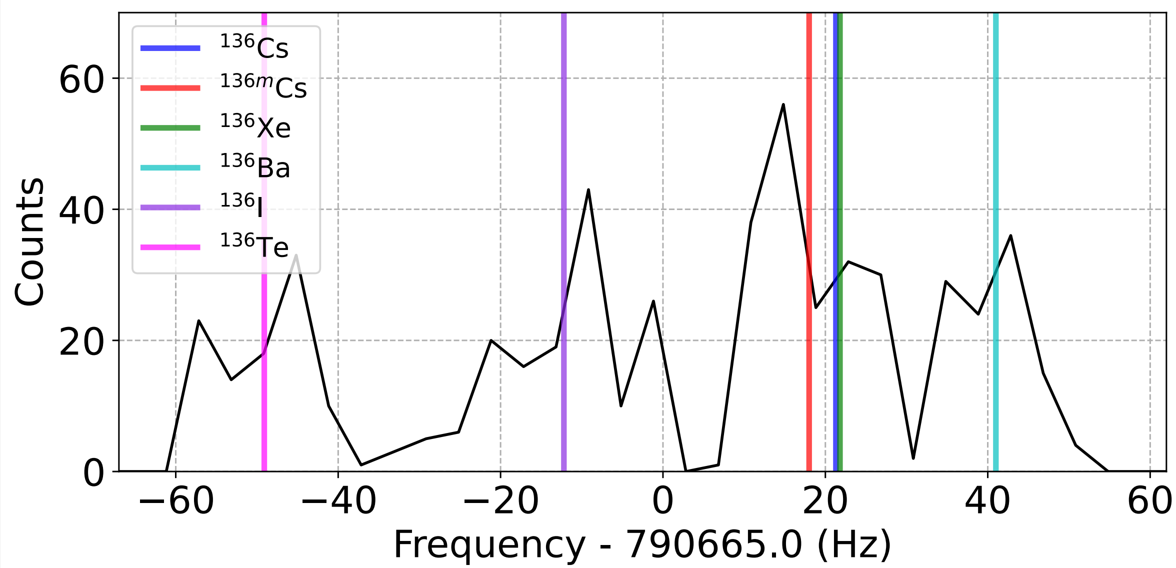


State-of-the-art trap method for purfication of isomers

T. Eronen et al., EPJA 48 (2012) 46
Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C 108, 045502 (2023)
Z. Ge, M. Reponen, T. Eronen et al., Phys. Rev. LETT. 133, 132503 (2024)



Buffer gas cleaning with purifiction trap



Conatminant-free ion sample preparation (especially isomers)

?

State-of-the-art trap method for purfication of isomers

T. Eronen et al., EPJA 48 (2012) 46
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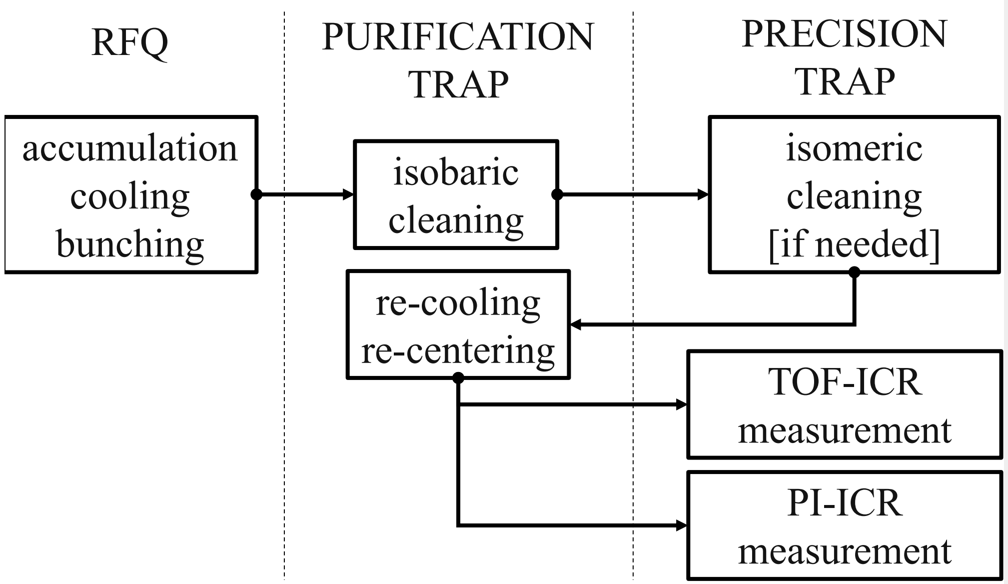
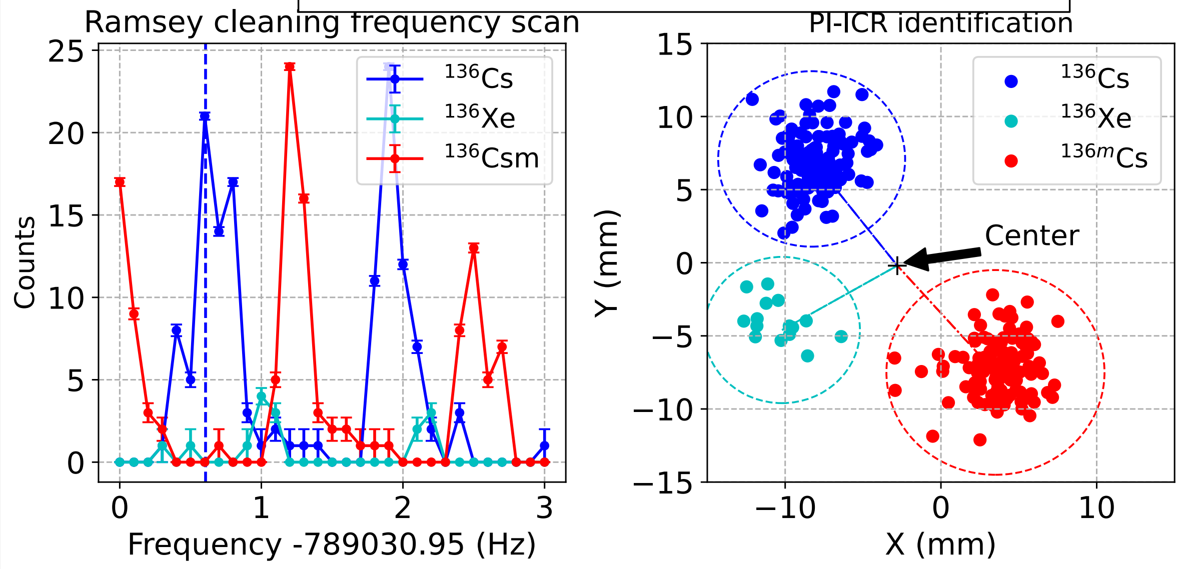


Ramsey cleaning with precision trap



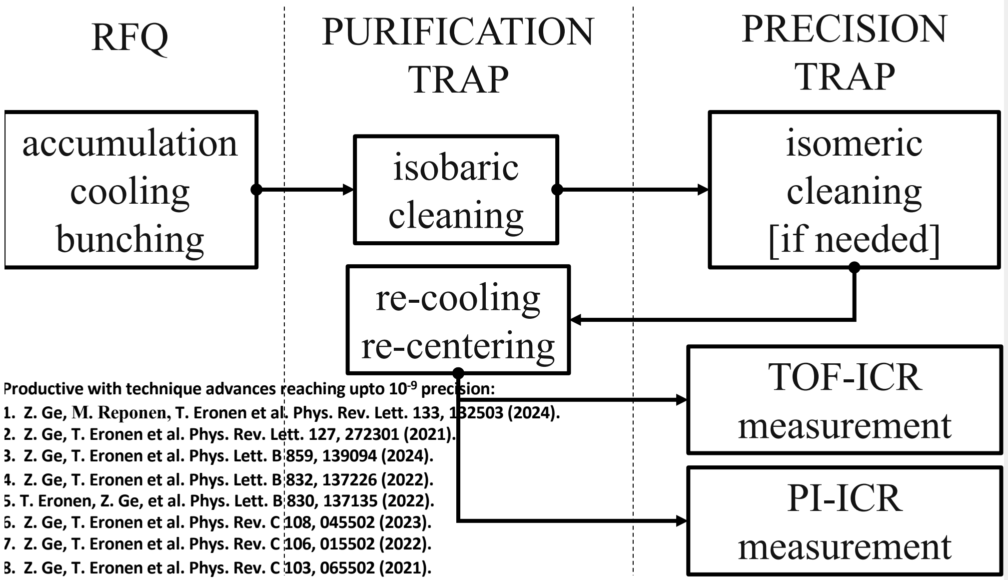
Conatminant-free ion sample preparation (especially isomers):

Coupling of Ramsey cleaning & PI-ICR method for unambiguous cleaning (to reach 10^{-9} precision for exotic cases)

contaminants of 90 keV (A =136) away from ion of interest easy to clean, more than 10^6 resolving power to clean 2 or more closely lying contaminants

State-of-the-art trap method for purfication of isomers

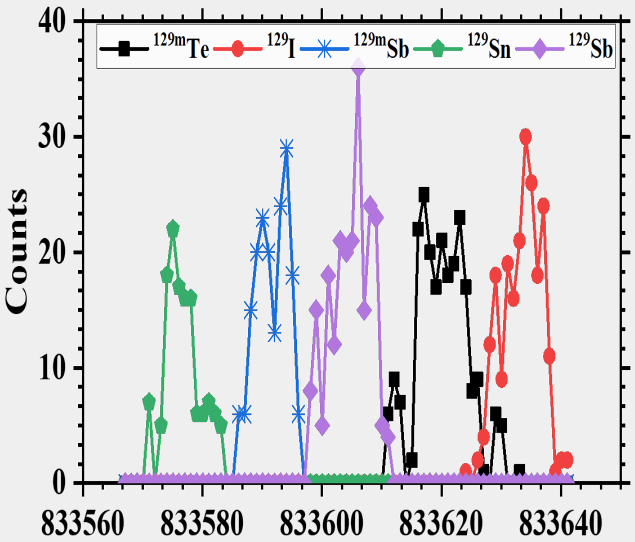
T. Eronen et al., EPJA 48 (2012) 46
Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C 108, 045502 (2023)
Z. Ge, M. Reponen, T. Eronen et al., Phys. Rev. LETTERS 133, 132503 (2024)

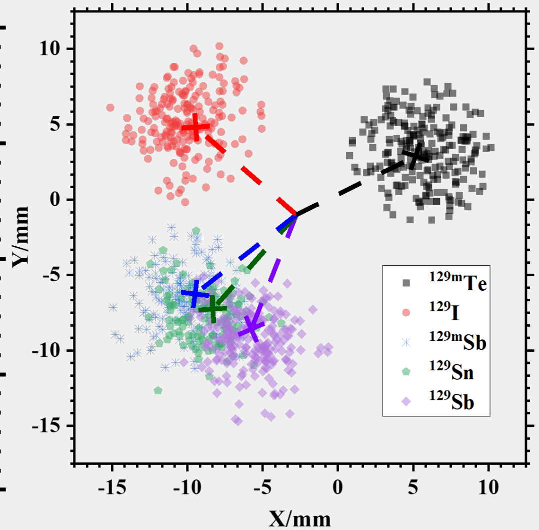


Productive with technique advances reaching upto 10^{-9} precision:

1. Z. Ge, M. Reponen, T. Eronen et al. Phys. Rev. Lett. 133, 132503 (2024).
2. Z. Ge, T. Eronen et al. Phys. Rev. Lett. 127, 272301 (2021).
3. Z. Ge, T. Eronen et al. Phys. Lett. B 859, 139094 (2024).
4. Z. Ge, T. Eronen et al. Phys. Lett. B 832, 137226 (2022).
5. T. Eronen, Z. Ge, et al. Phys. Lett. B 830, 137135 (2022).
6. Z. Ge, T. Eronen et al. Phys. Rev. C 108, 045502 (2023).
7. Z. Ge, T. Eronen et al. Phys. Rev. C 106, 015502 (2022).
8. Z. Ge, T. Eronen et al. Phys. Rev. C 103, 065502 (2021).
9. Z. Ge, T. Eronen et al. Eur. Phys. J. A 60, 104 (2024).
10. Z. Ge, T. Eronen et al. Eur. Phys. J. A 60, 147 (2024).
11. M. Ramalho, Z. Ge, T. Eronen et al. Phys. Rev. C 106, 015501 (2022).
12. Z. Ge, T. Eronen et al. Phys. Rev. C 112, 035501 (2025).

Buffer gas cleaning coupled with PI-IR method





Conatminant-free ion sample preparation (especially isomers):

Coupling of Buffer gas cleaning & PI-ICR method for unambiguous cleaning (to reach 10^{-9} precision for exotic cases)

State-of-the-art trap method for purfication of isomers

T. Eronen et al., EPJA 48 (2012) 46
Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C 108, 045502 (2023)
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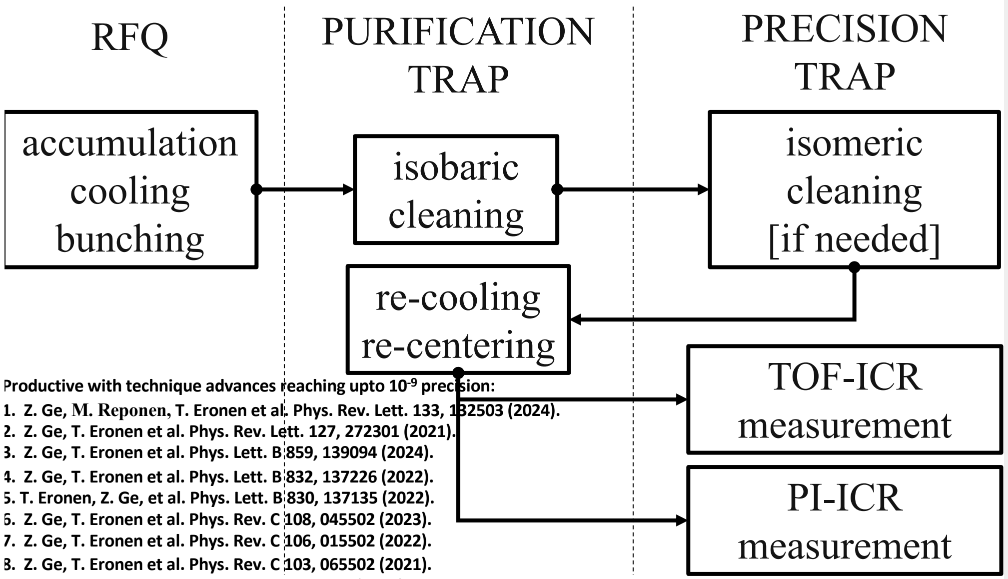

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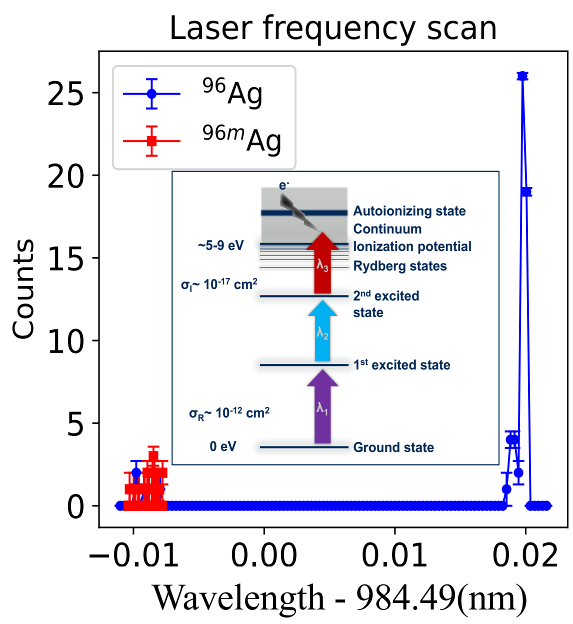
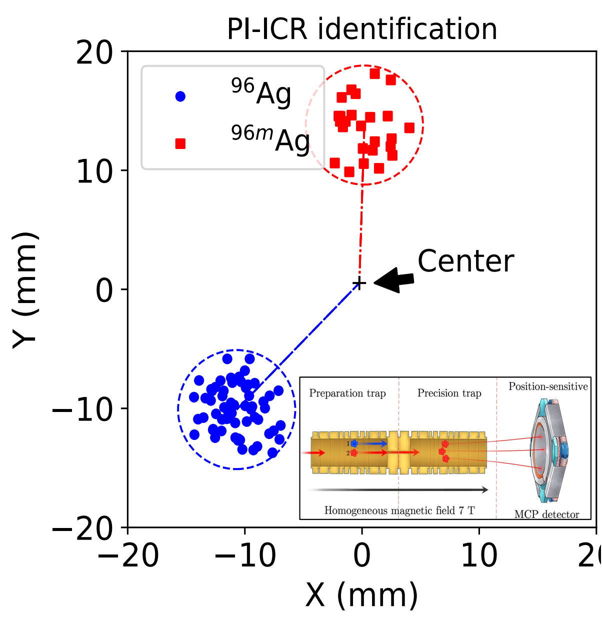


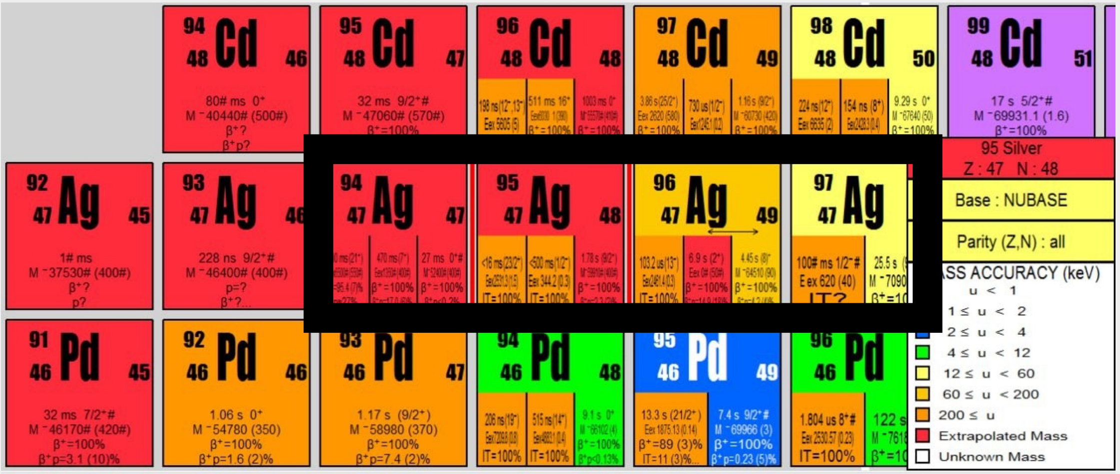


Conatminant-free ion sample preparation (especially isomers):

Coupling of laser frequency scan & PI-ICR method for unambiguous cleaning
And extremely high sensitivity: 1 counts/ 10 min for 95Ag

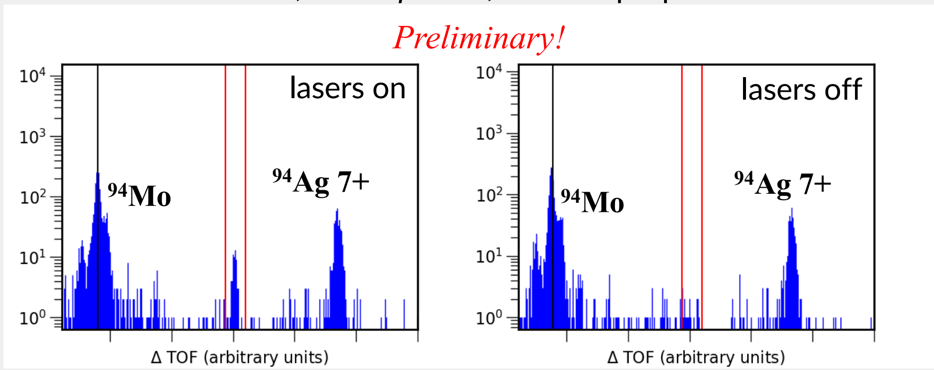
$^{94\text{-}97}$Ag mass measurements at IGISOL

Z. Ge, M. Reponen, et al., Phys. Rev. Lett. 133, 132503 (2024), T. Eronen et al., EPJA 48 (2012) 46



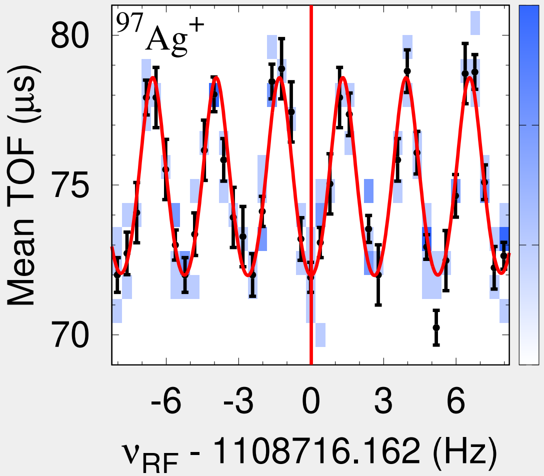
Uncertainty of 10s keV with MR-TOF

V. Virtanen, M. Reponen, et al. in preparation

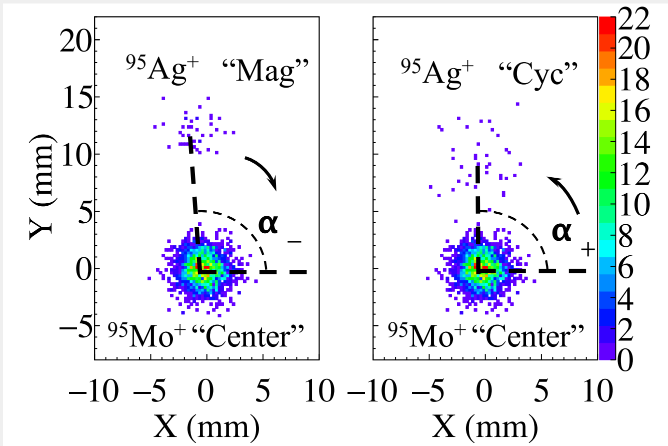


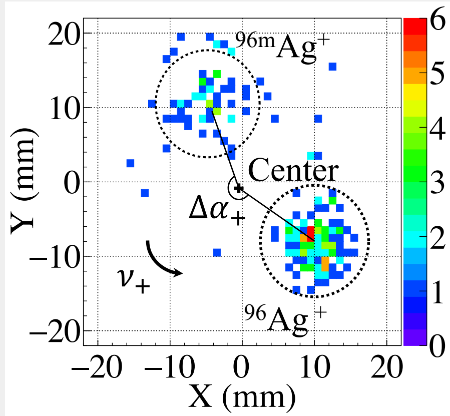
Uncertainty of around 1 keV with Penning Trap

Time-of-Flight Ion-Cyclotron-Resonance (TOF-ICR)



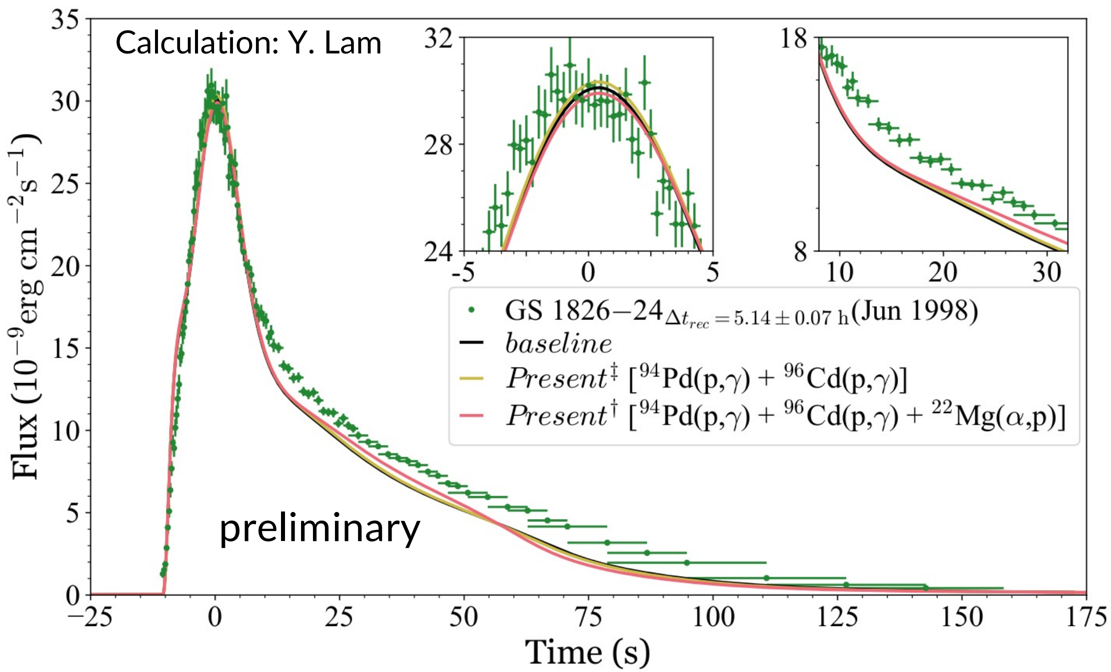
Phase-imaging Ion-Cyclotron-Resonance (PI-ICR)

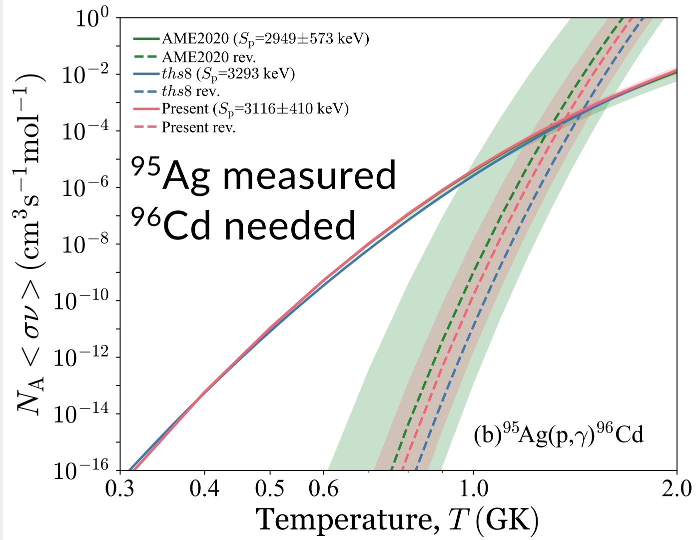


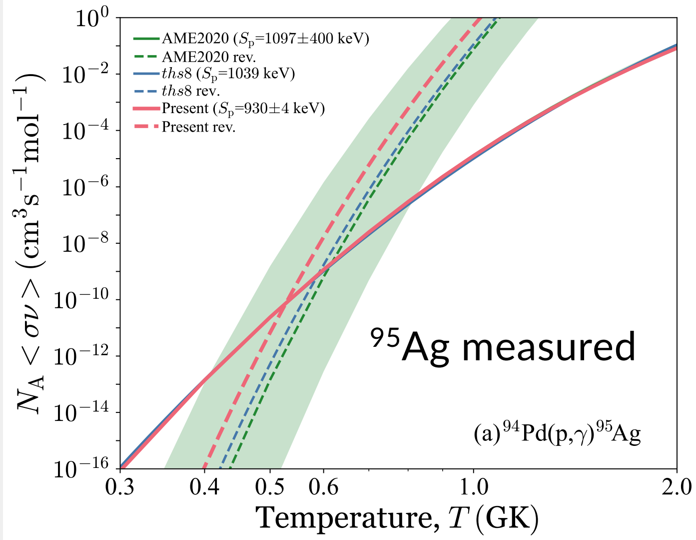


Impacts on the X-ray burst

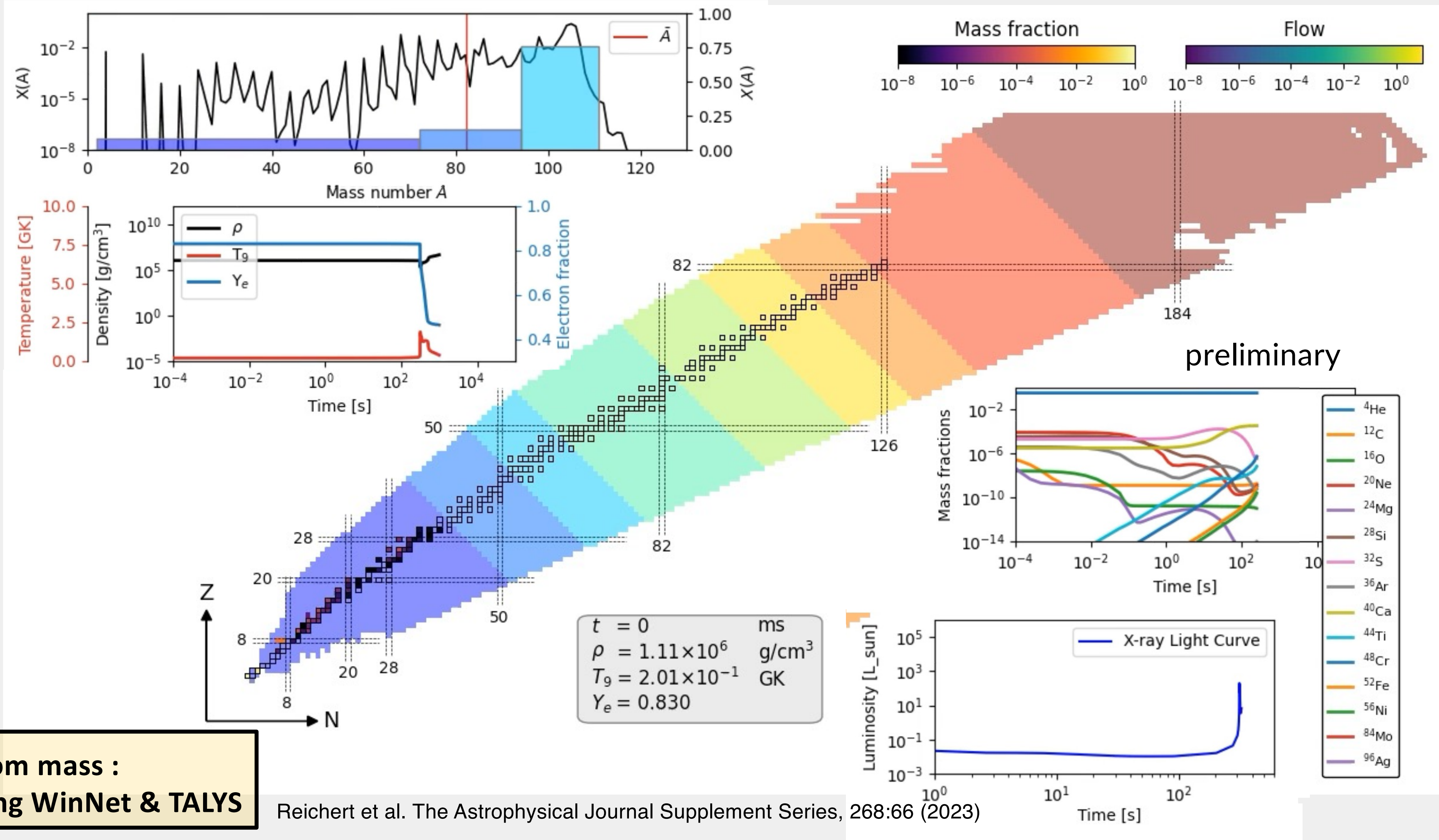
Timescale, isotope&energy production:
Exponential dependence on masses!







rp-process network calculations



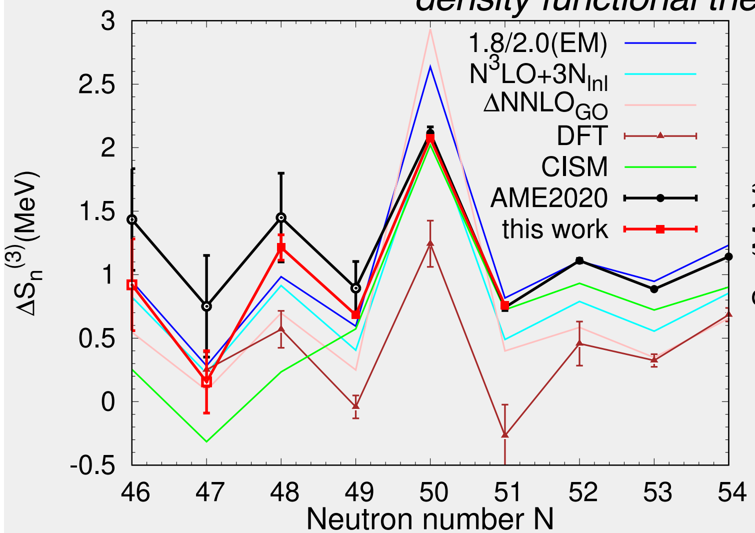
Impact study from mass :
Calculations using WinNet & TALYS

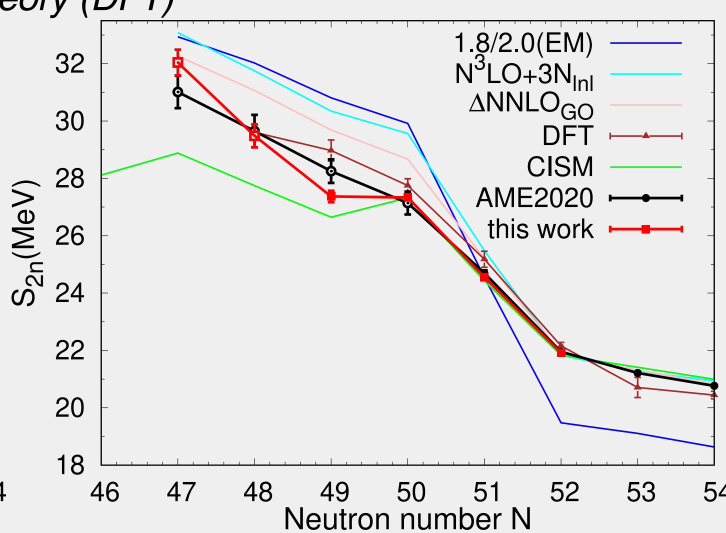
Reichert et al. The Astrophysical Journal Supplement Series, 268:66 (2023)

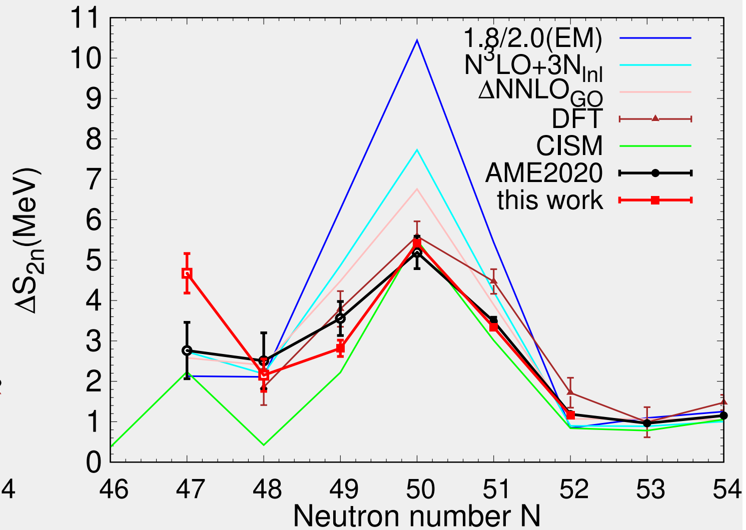
Benchmark theoretical models and isomer as “astromer”

Theory: *ab initio,*
configuration-interaction shell-model (CISM)
density functional theory (DFT)

Z. Ge, M. Reponen, T. Eronen et al., PRL 133, 132503 (2024)
G.W. Misch et al., Eur. Phys. J. Spec. Top. 233, 1075 (2024).

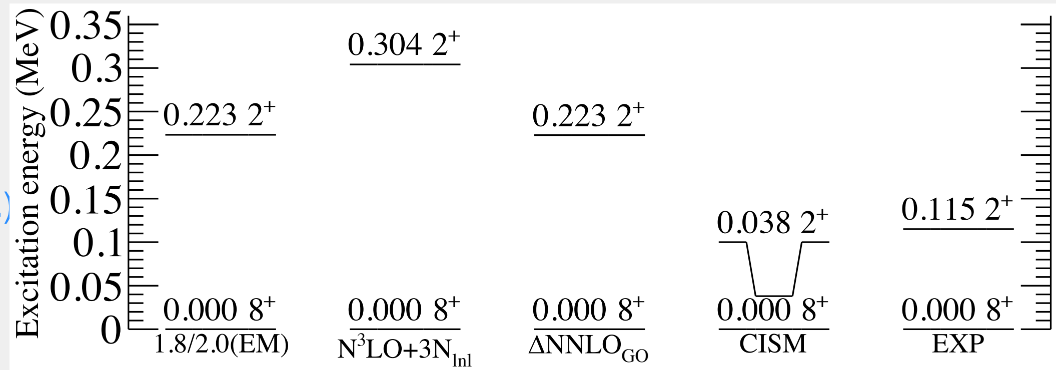






Possible, astrophysical nuclear isomer, “astromer”

- Identification of **nuclear isomer of ^{96m}Ag,** ***“astromer”***
- understanding of the **nuclear structure at N=50 shell**
- **Benchmark** nuclear models and shell model calculations
- **Solve the ^{94}Ag(21^+) 2p/p decay puzzle----in process** (Ville, Mikael et al.)
- **Wigner energy, np-pairing--- other N=Z masses**



energy level of ^{96}Ag isomeric state

Neutron-deficient nuclei mass measurements outlook

- Mass measurements with **hot cavity + MR-TOF/Penning trap (published)**
  - ✓ Mass measurements of ground states and isomers of other N~Z nuclei: $^{95-97}$Ag, ^{96m}Ag
- Mass measurements with **hot cavity + MR-TOF/Penning trap**
  - ✓ Mass measurements of ground states and isomers of other N=Z nuclei by fusion evaporation reactions at IGISOL with MR-TOF:
    - ^{94}**Ag 21^{+} and 7^{+}** isomeric states, $^{92-93}$**Pd**
- Mass measurements with HIGISOL gas cell + MR-TOF: **A=80-84** Area (measured by RIKEN)
  - ✓ **N~Z A=80-84** Area (try again with Penning Trap later)
- Mass measurements with HIGISOL/MNT gas cell + Penning Trap, approved proposals
- Mass measurements with Rare RI Ring and BigRISP-OEDO-SHARAQ ($B\rho$-TOF-MS) @ RIKEN (8 years pending, 2 times approved 9 days of beam time, wish for next 10 years´ plan)
- Other collaboration efforts: FRS ion catcher @ GSI
- **Further combine the measurements to study the Influence of masses on rp-process and vp-process**

✓ **Published**

✓ **Recent campaigns**

Plans

IGISOL Group

Collaboration

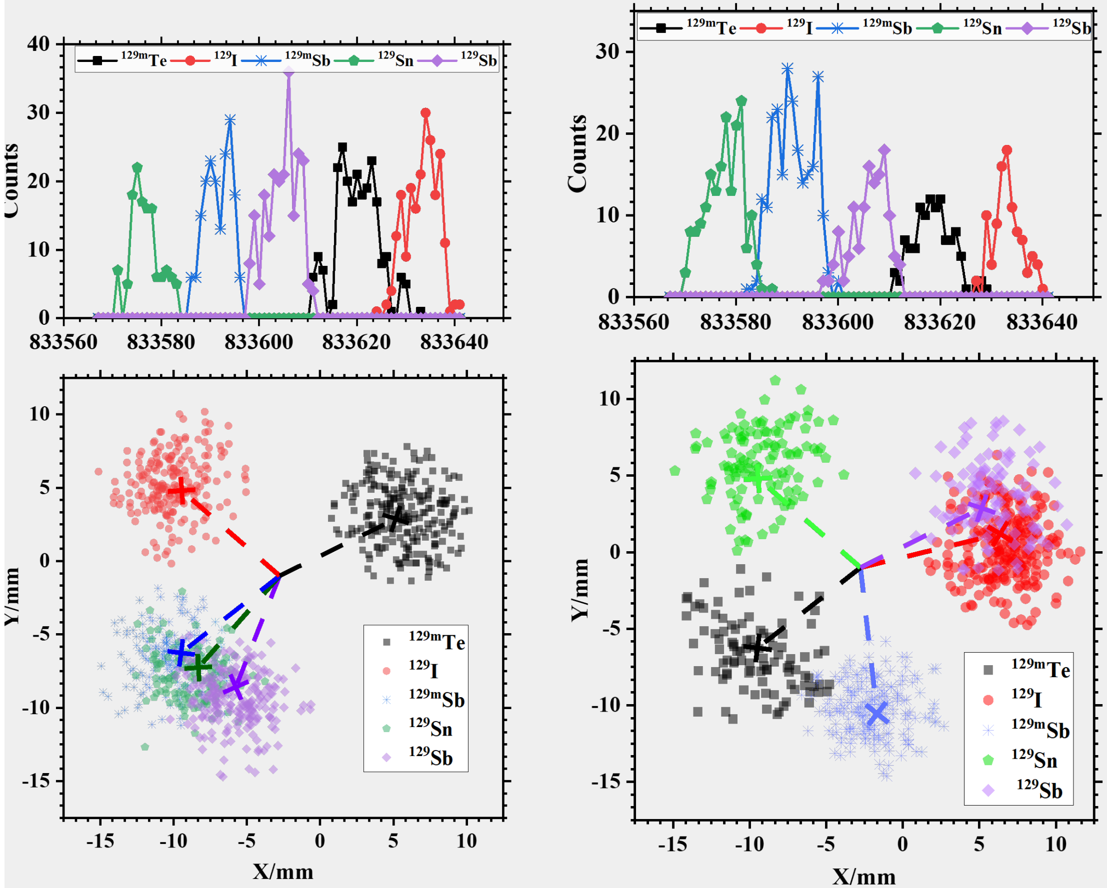
Z. Ge,[1,2,*] Mikael Reponen,[1,†] T. Eronen,[1] Y. H. Lam,[3,4] B. S. Hu,[5] S. Nikas,[1] D. A. Nesterenko,[1] A. Kankainen,[1]
O. Beliuskina,[1] L. Cañete,[1,6] R. de Groote,[1,7] C. Delafosse,[1,8] P. Delahaye,[9] T. Dickel,[2,10] A. de Roubin,[7] S. Geldhof,[1,7]
W. Gins,[1] A. Heger,[11,12,13,14] J. D. Holt,[5,15] M. Hukkanen,[1,8] A. Jaries,[1] A. Jokinen,[1] Á. Koszorús,[16,17] G. Kripko-Koncz,[10]
S. Kujanpää,[1] I. D. Moore,[1] A. Ortiz-Cortes,[1] H. Penttilä,[1] D. Pitman-Weymouth,[1] W. Plaß,[2,10] A. Raggio,[1]
S. Rinta-Antila,[1] J. Romero,[1] M. Stryjczyk,[1] M. Vilen,[1,17] V. Virtanen,[1] X. F. Yang,[18] C. X. Yuan,[19] and A. Zadvornaya[1]
M. Winter. J. Ruotsalainen, S. Chinthakayala, L. M. Motilla

[1] *Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014, Jyväskylä, Finland*
[2] *GSI Helmholtzzentrum für Schwerionenforschung GmbH, 64291 Darmstadt, Germany*
[3] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, People's Republic of China*
[4] *School of Nuclear Science and Technology, University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China*
[5] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[6] *University of Surrey, Department of Physics, Guildford GU2 7XH, United Kingdom*
[7] *KU Leuven, Instituut voor Kern- en Stralingsfysica, B-3001 Leuven, Belgium*
[8] *Centre d'Etudes Nucléaires de Bordeaux Gradignan, UMR 5797 CNRS/IN2P3 - Université de Bordeaux, 19 Chemin du Solarium, CS 10120, F-33175 Gradignan Cedex, France*
[9] *GANIL, CEA/DSM-CNRS/IN2P3, Bd Henri Becquerel, 14000 Caen, France*
[10] *II. Physikalisches Institut, Justus-Liebig-Universität Gießen, 35392 Gießen, Germany*
[11] *School of Physics and Astronomy, Monash University, Vic 3800, Australia*
[12] *OzGrav-Monash - Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Vic 3800, Australia*
[13] *Center of Excellence for Astrophysics in Three Dimensions (ASTRO-3D), School of Physics and Astronomy, Monash University, Vic 3800, Australia*
[14] *Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, MI 48824, USA*
[15] *Department of Physics, McGill University, Montréal, QC H3A 2T8, Canada*
[16] *Oliver Lodge Laboratory, Oxford Street, University of Liverpool, Liverpool, L69 7ZE, United Kingdom*
[17] *Experimental Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[18] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*
[19] *Sino-French Institute of Nuclear Engineering and Technology,*

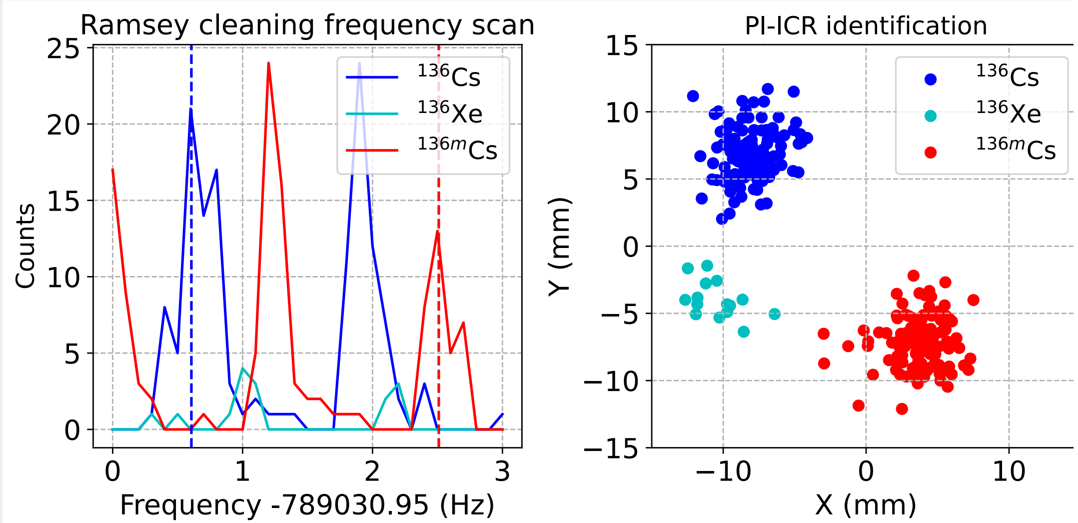
Thank you

for your attention

Thank you for your attention



129mTe
129I
129mSb
129Sn
129Sb
Counts
833560
833580
833600
833620
833640
Y/mm
X/mm



Ramsey cleaning frequency scan
136Cs
136Xe
136mCs
Counts
Frequency -789030.95 (Hz)
PI-ICR identification
Y (mm)
X (mm)