JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Mass Measurements of Exotic Neutron-Deficient Nuclides Below ^{100}Sn at IGISOL and Their Astrophysical Implications

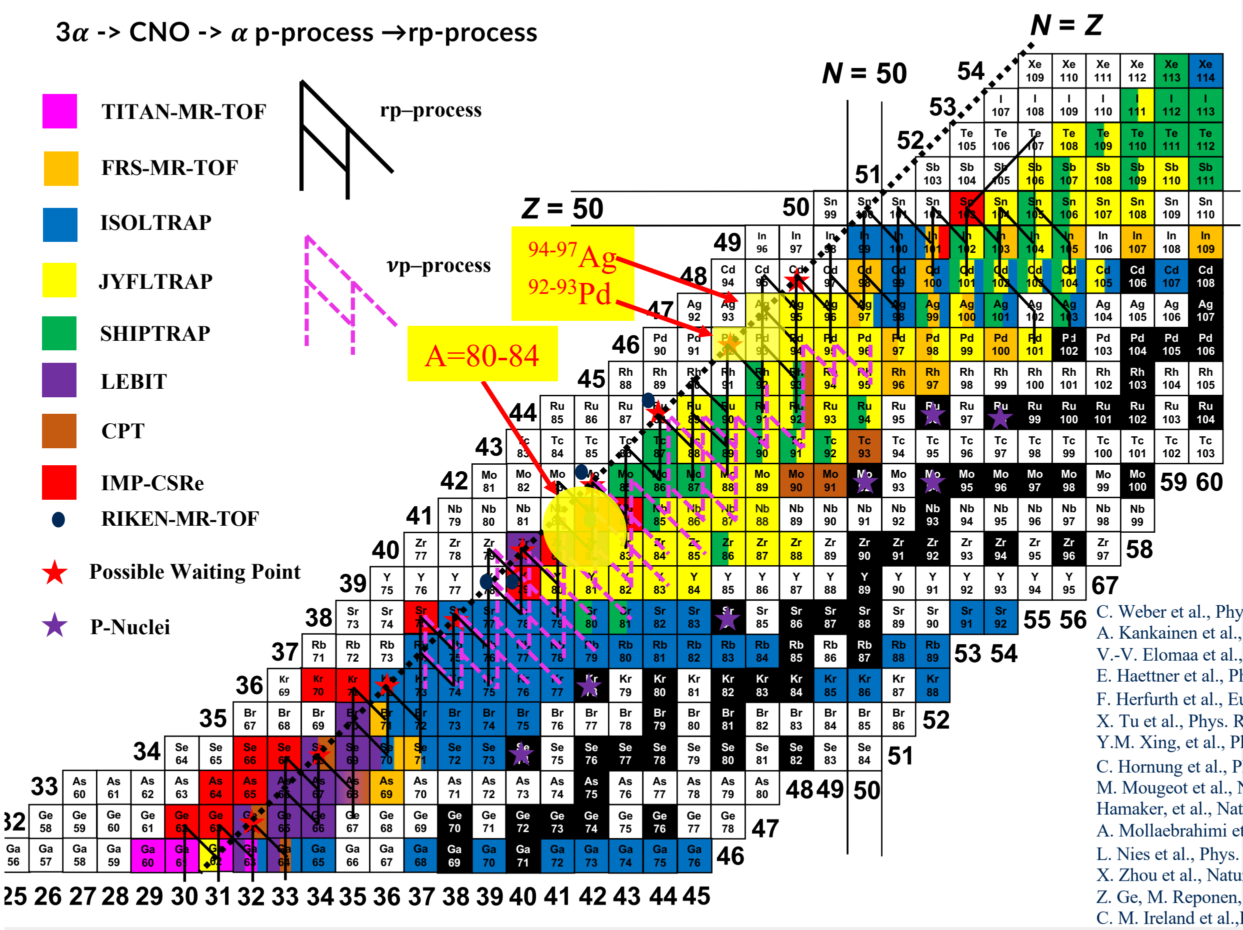
Zhuang Ge

University of Jyväskylä

Motivation

Nuclear mass ↔ nuclear binding energy:

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



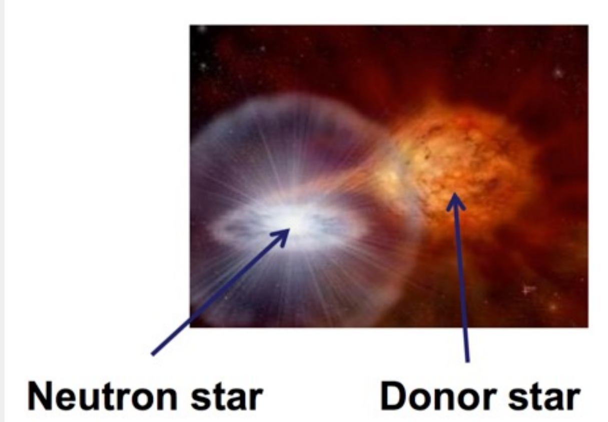
Nuclear Astrophysics

vp-, rp-process
(waiting point, Zr-Nr cycle)
abundance of P-nuclei
($^{92;94}$Mo and $^{96;98}$Ru,^{84}Sr isotopes)

H. Schatz, International Journal of Mass Spectrometry, 251(2–3), 293–299 (2006).

Measurement techniques:

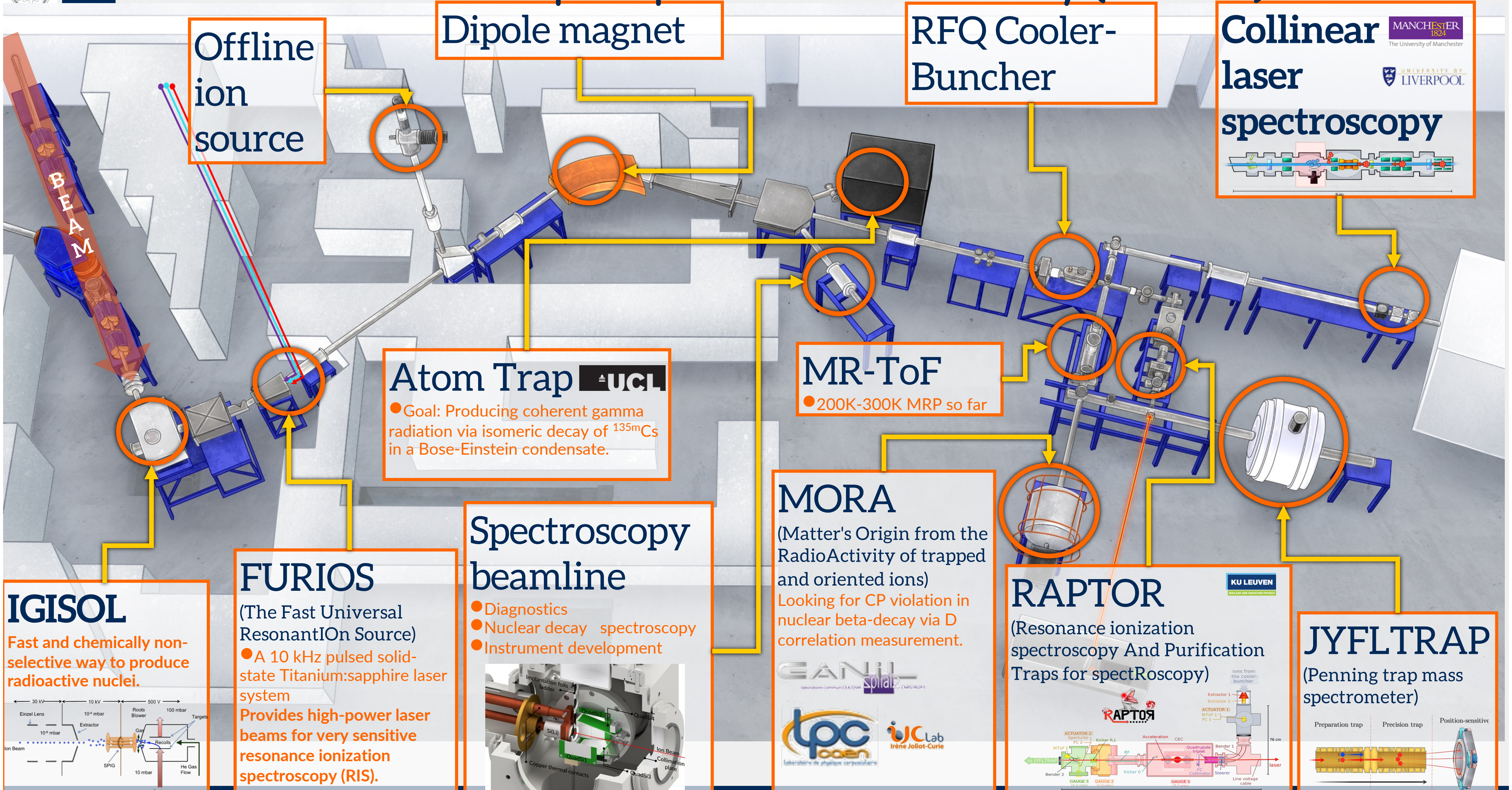
Penning trap
MR-TOF
Storage ring



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., Physics Letters 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., Physics Letters 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

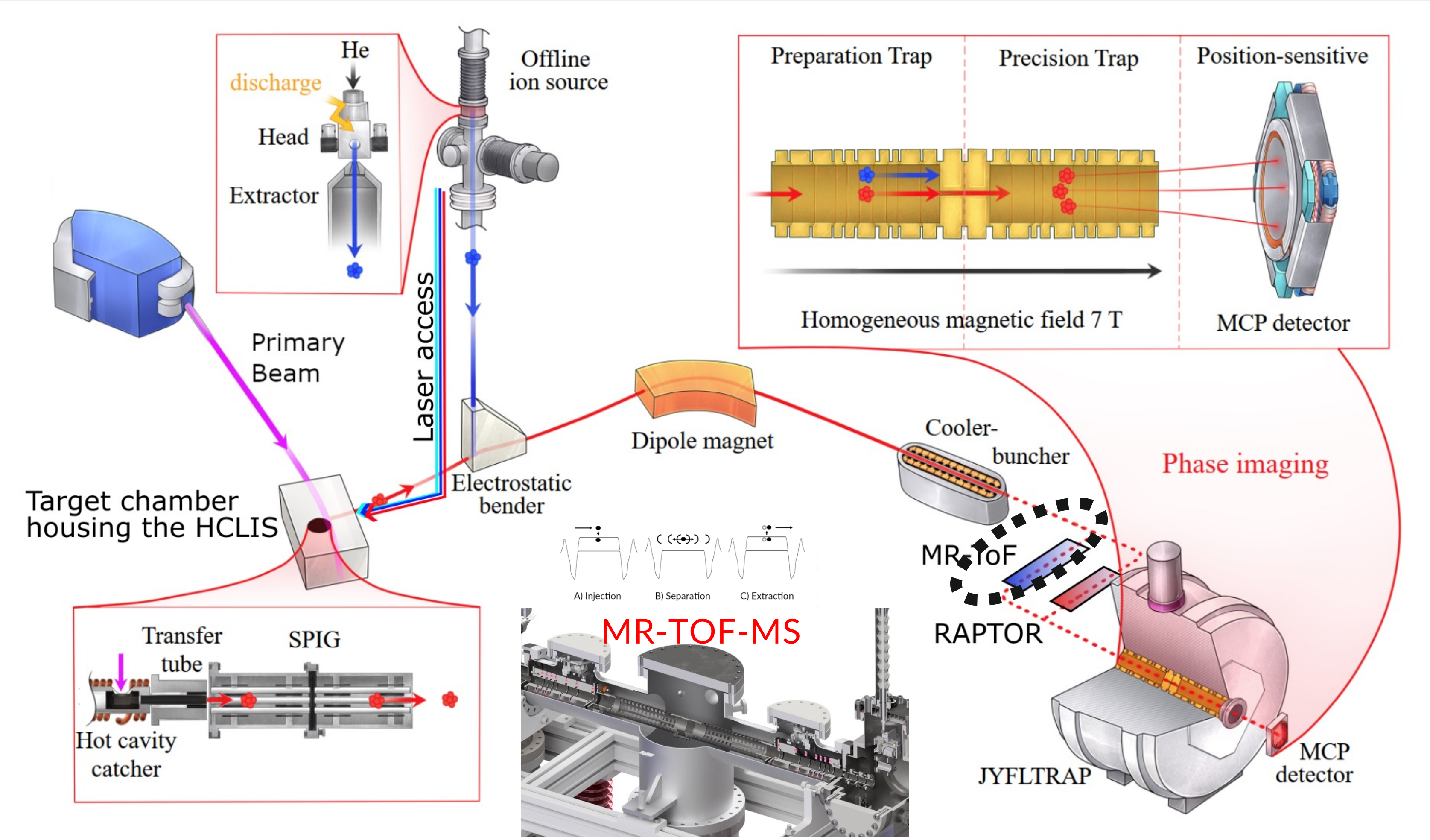
time−scale $\propto e^{(Q/kT)}$ / $A(Q)$
isotope production$\propto A(Q) \cdot e^{(Q/kT)}$
energy production $\propto A(Q) \cdot Q \cdot e^{(Q/kT)}$
Common parameter: Q (mass difference)

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

Inductively Heated Hot Cavity Cather Laser Ion Source

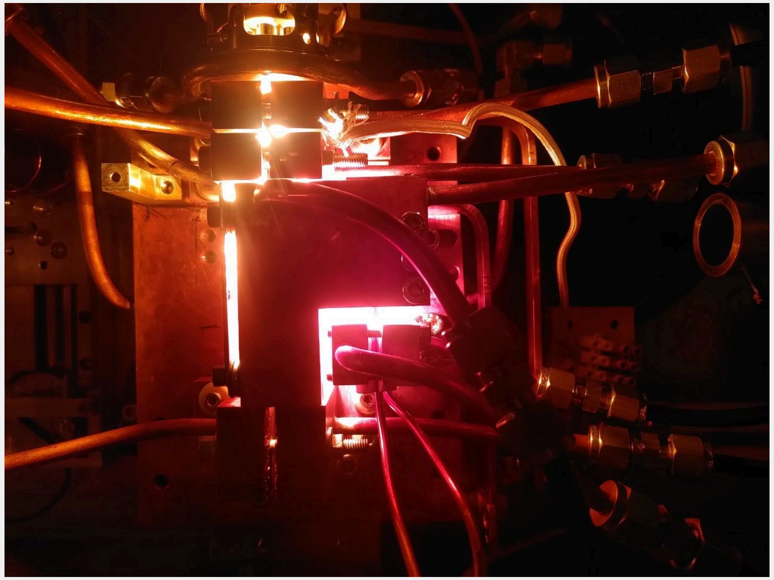
Novel technique advance

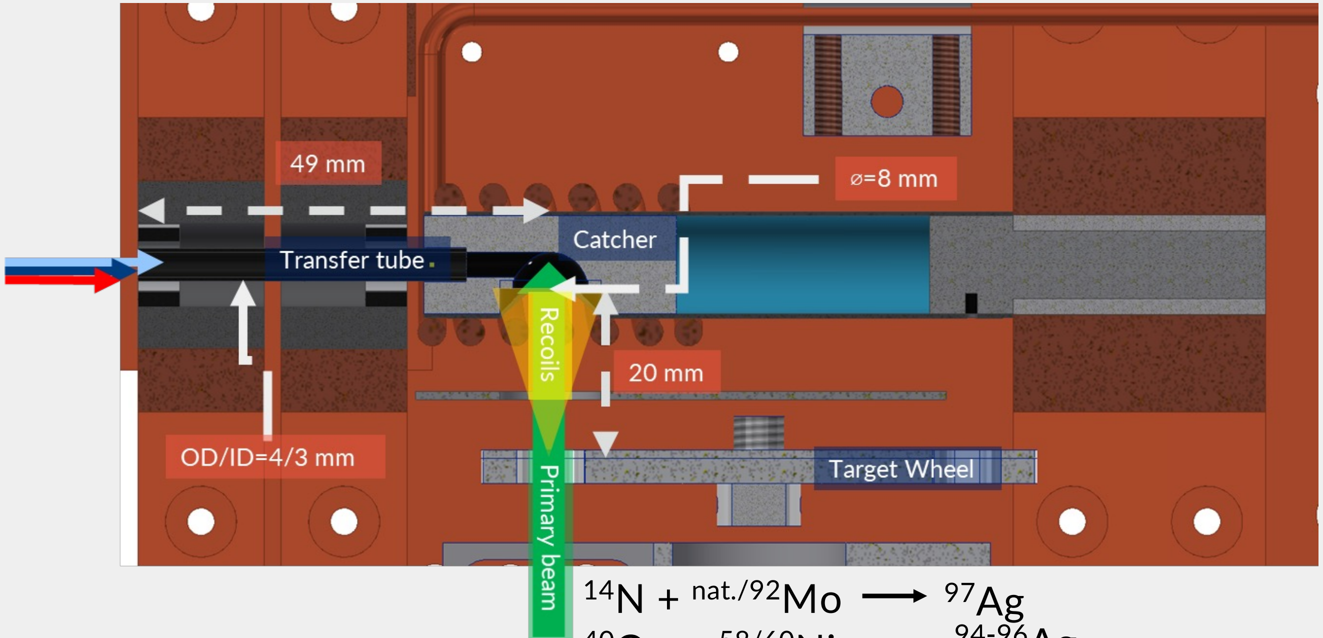
- The hot cavity project (Ver 1.) at IGISOL started in 2007.
  - First iterations were primary-beam heated catchers

M. Reponen et al., Eur. Phys. J. A 42, 509–515 (2009)
M. Reponen et al., Rev. Sci. Instrum 86 (2015) 123501
M. Reponen *et al.*, Nat. Comm. 12 (2021)
Z. Ge, M. Reponenet al., Phys. Rev. Lett. 133, 132503 (2024)

- A target ion source system for fusion-evaporation products
  - Efficient: 10 % for Ag (most recent test)
  - Fast: <20 ms for Ag, less than 90 ms for Pd
  - High Sensitivity: ^{95}Ag at a rate of ~1/10 minutes
  - Selectivity: provides high elemental and isotopic selectivity from contaminants.

Version 6.





$^{14}N + {}^{nat./92}Mo \longrightarrow {}^{97}Ag$

$^{40}Ca + {}^{58/60}Ni \longrightarrow {}^{94\text{-}96}Ag$

Schematic of PI-ICR for 95Ag mass measurements

Coupling of cleaning methods with PI-ICR method for cleaning
Z. Ge, T. Eronen, A. de Roubin et al., Phys. Rev. C **108**, 045502 (2023)

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

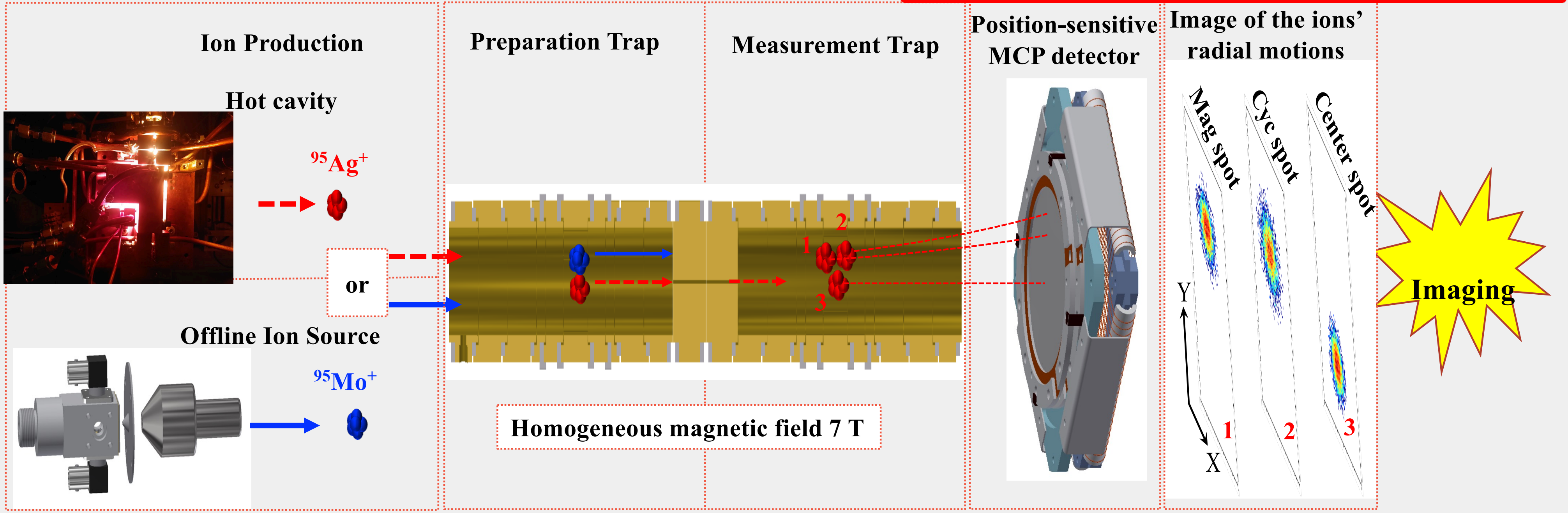
Traps ❤️ Lasers

Angle between cyclotron and magnetron motion phases with respect to the center spot:

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

cyclotron frequency:

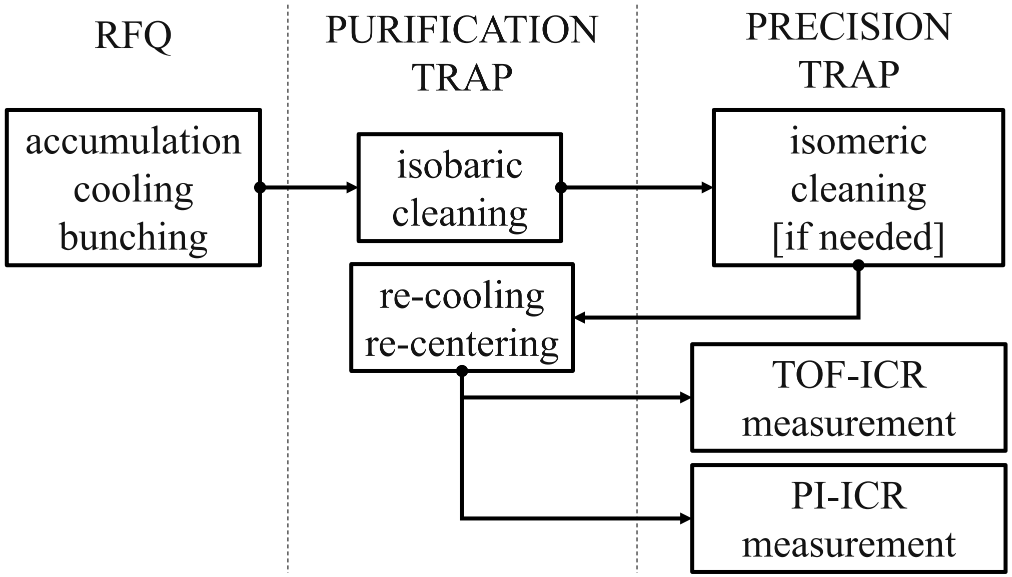
$$\nu_c = \nu_+ + \nu_- = \frac{\alpha_c + 2\pi n}{2\pi t}$$



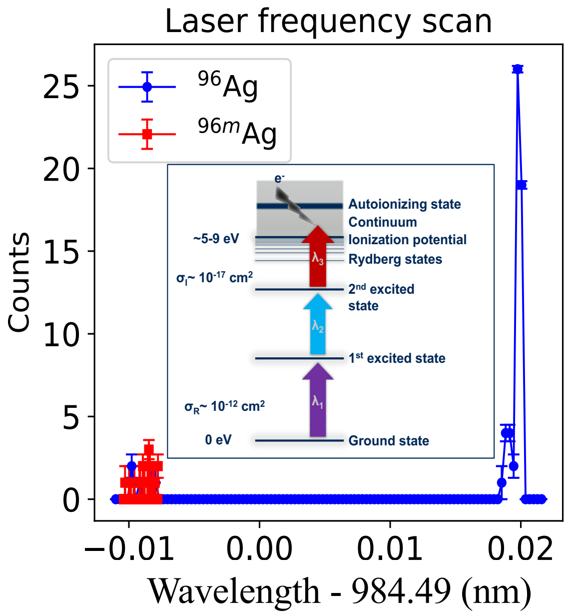
State-of-the-art laser&trap method for purfication of isomers

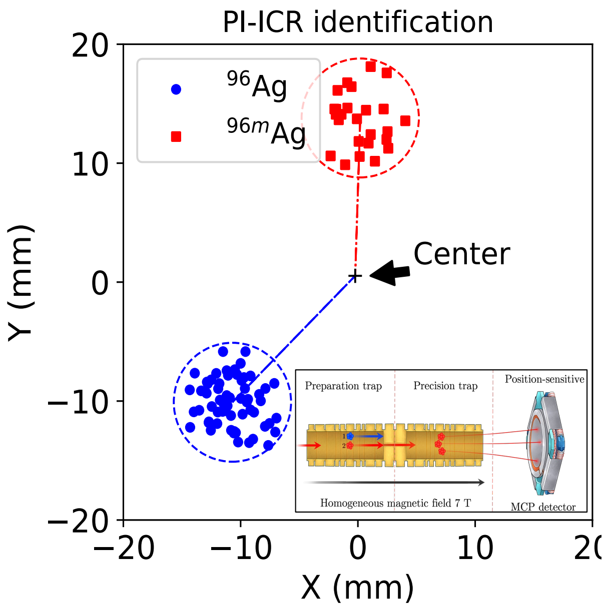
Purification trap resolving power M/dM: 10^5 ; Precision Trap M /dM : > 10^6

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



Novel technique advances





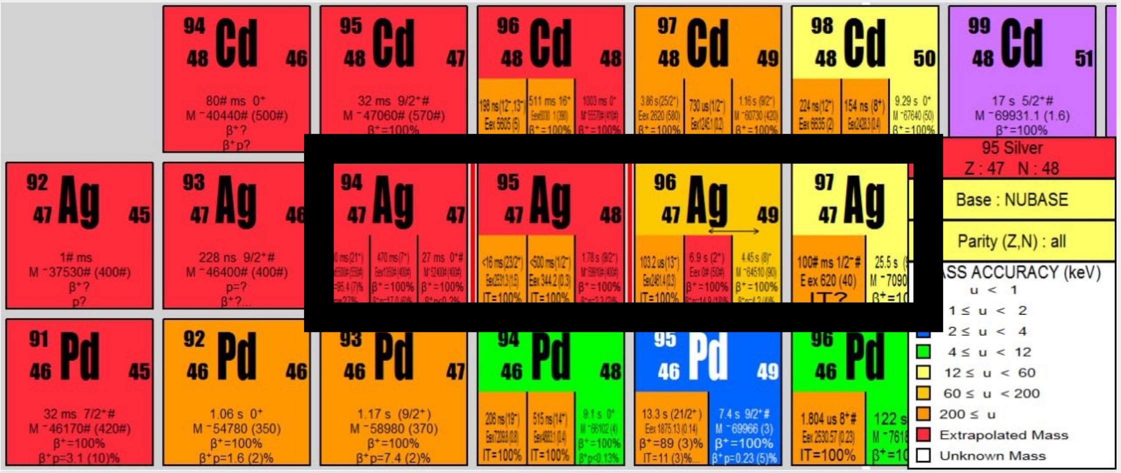
Conatminant-free ion sample preparation (especially pure isomeric ion species, half-life of 10s ms with E*=10 keV):
Coupling of
Ramsey cleaning&Buffer gas cleaning&laser ionisation frequency scan
and PI-ICR method
for unambiguous cleaning and identification

2025/7/17

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

Uncertainty of around 1 keV with Penning Trap, unprecedented precision (10^{-8})

^{94}Ag:
with MR-TOF



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

Penning trap Cyclotron frequency:

$$\nu_c = \nu_+ + \nu_- = \frac{qB}{2\pi m}$$

Frequency ratio r:

$$r = \frac{\nu_1}{\nu_2}$$

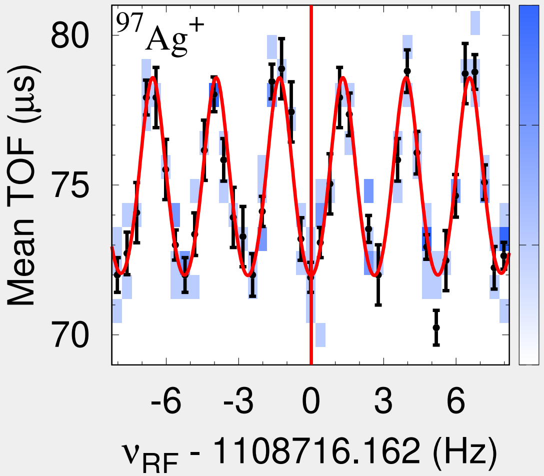
Q-value:

$$Q = M_2 - M_1 = (r-1)(M_1 - m_e) + m_e$$

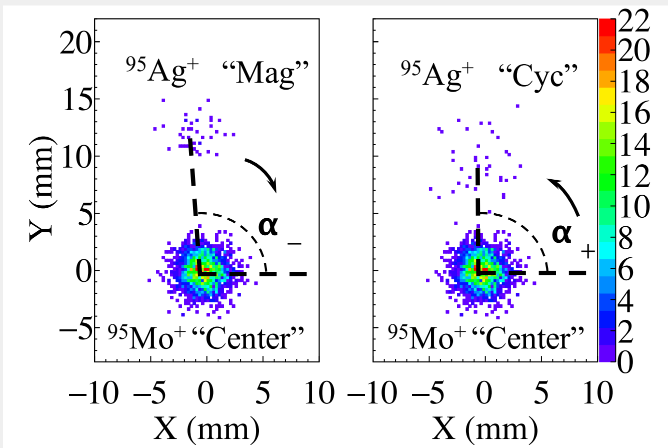
Mass:

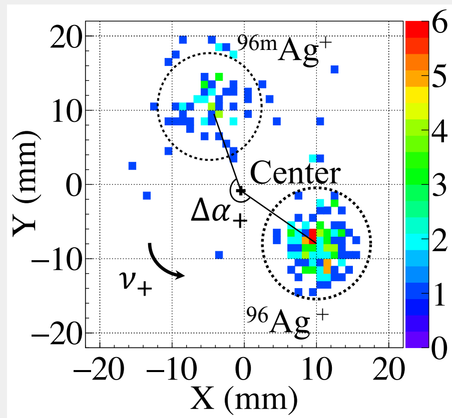
$$M_2 = r(M_1 - m_e) + m_e$$

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



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



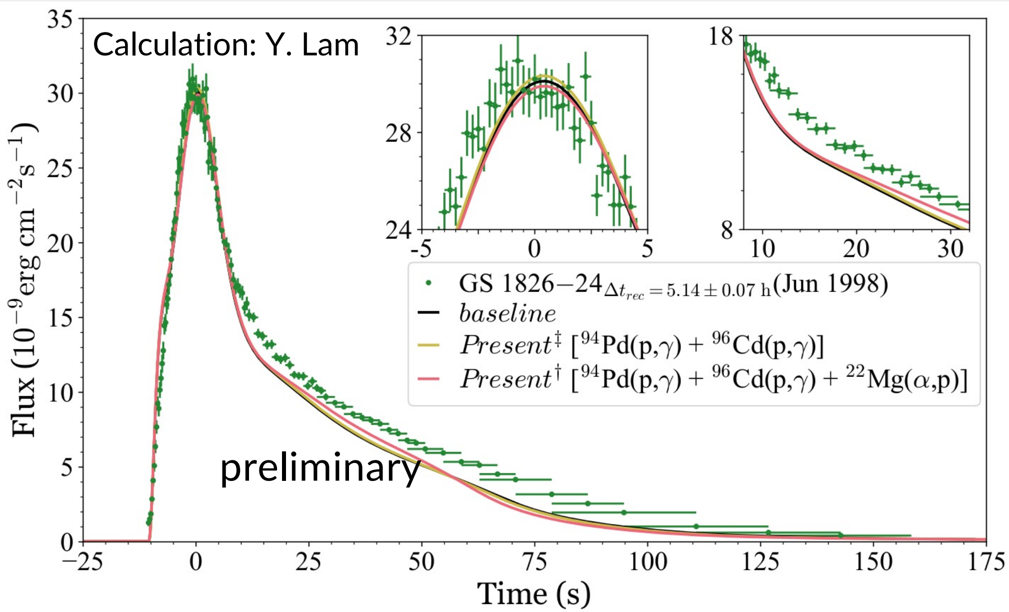


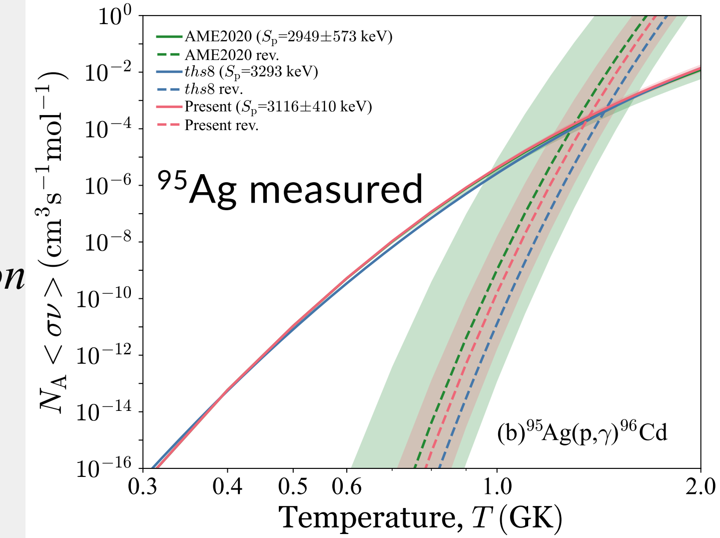
Impacts on the X-ray burst

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

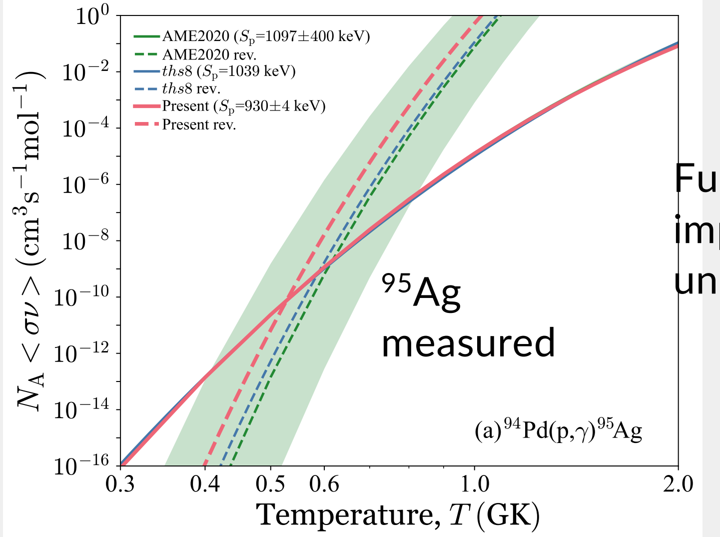
- Refined the reaction rate of rp-process
- *Reproducing burst light curves*
- *Influence on the final abundance of the burst ash composition*
- *Impact on neutron star crusts*

$$\frac{Y_{\mathbf{n+1}}}{Y_{\mathbf{n}}} = \rho_{\mathrm{n}} \frac{G_{n+1}}{2G_n} \left(\frac{A_{n+1}}{A_n} \frac{2\pi\hbar^2}{m_u kT}\right)^{3/2} exp\left(\frac{S_{n+1}}{kT}\right)$$





96Cd needed

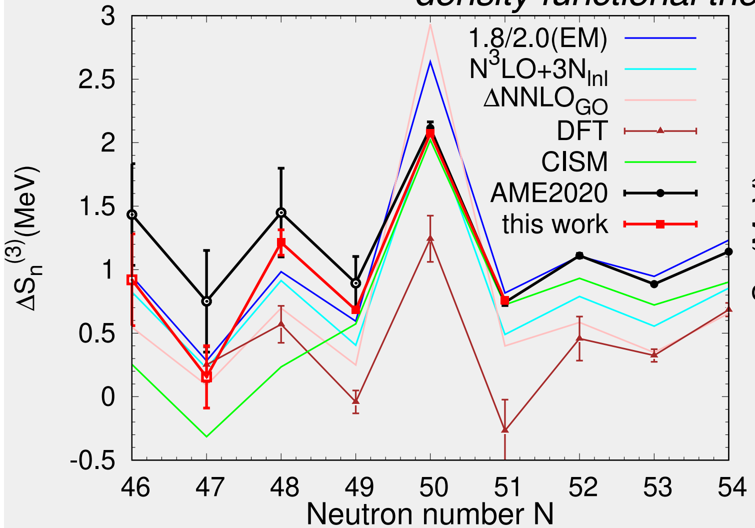


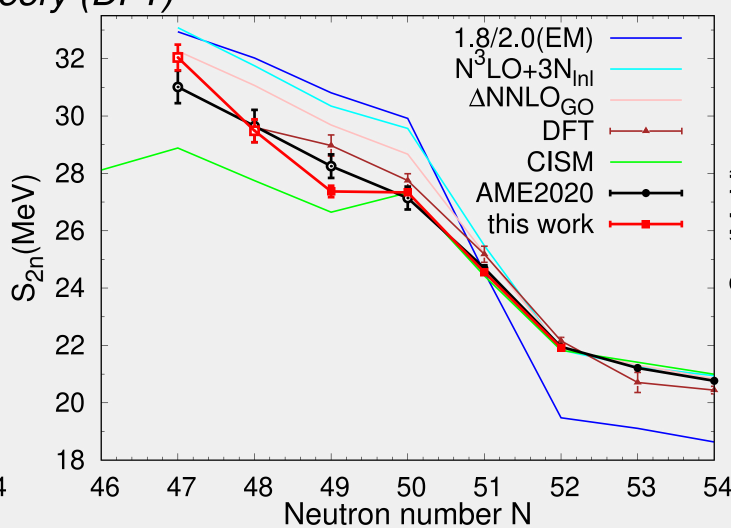
Fully rull out the impact from mass uncertainties

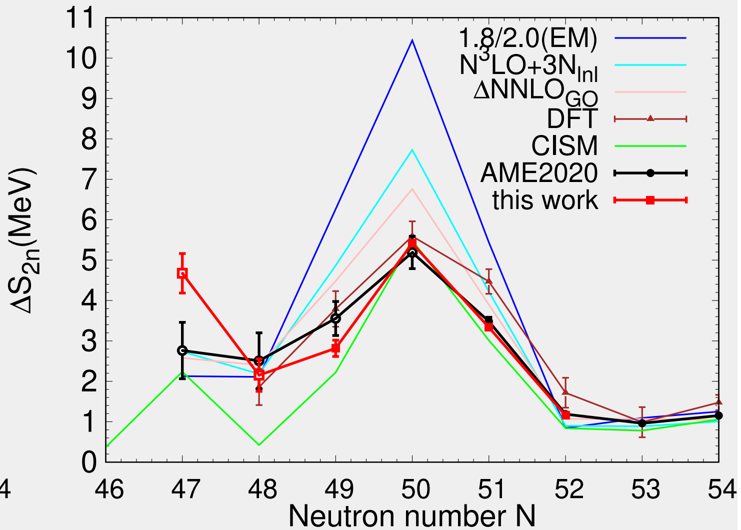
Benchmark theoretical models and isomer as *"astromer"*

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).

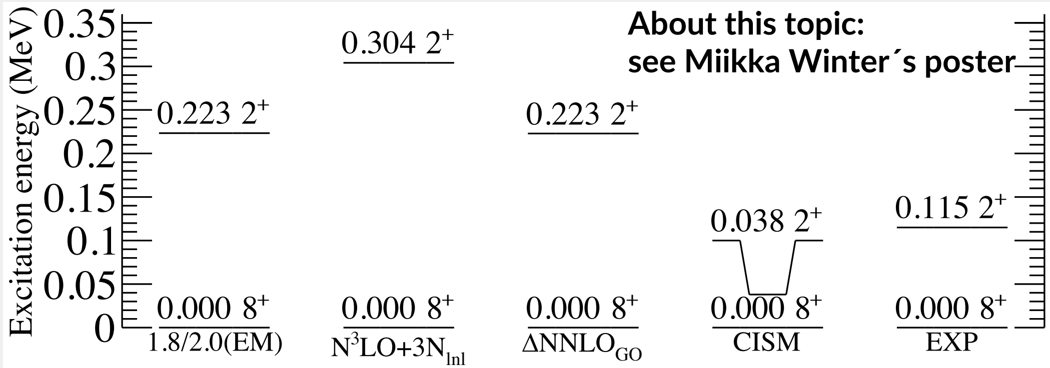






- Identification of **nuclear isomer of ^{96m}Ag,** *"astromer"*
- understanding of the **nuclear structure at N=50 shell**
- **Benchmark** nuclear models and shell models
  - ✓ improve effectiveness in astrophysical processes
- ^{94}Ag(21^+) 2p/p decay puzzle----in process (V. Virtanen, M. Reponen et al.)
- **Wigner energy, np-pairing--- other N=Z masses**

Possible, astrophysical nuclear isomer, "astromer"



energy level of ^{96}Ag isomeric state

N~Z mass measurements outlook

with hot cavity/HIGISOL/MNT gas cells + Penning Trap & MR-TOF

- Mass measurements with **hot cavity + MR-TOF**
  - ✓ Mass measurements of ground states and isomers of other N=Z nuclei by fusion evaporation reactions at IGISOL with MR-TOF
  - ✓ Mass measurements of ^{93}**Pd**: : p-decay daughter of ^{94}Ag (Measured also at FRS ion catcher @ GSI/Germany within our collaboration)
  - ✓ Mass measurements of ^{94}**Ag 21^{+} and 7^{+}** isomeric states
  - ✓ Mass of ^{92}**Pd** (N=Z=46)
- Mass measurements **with HIGISOL gas cell + MR-TOF**
  - ✓ **Masses of N~Z A=80-84** Area

✓ Recent campaigns

- Mass measurements with HIGISOL/MNT gas cell + Penning Trap, approved proposals
- Other collaboration efforts: FRS ion catcher @ GSI and Rare RI Ring @ RIKEN/Japan

Plans

- **Further combine the measurements to study the Influence of masses on rp-process and νp-process**

Collaboration

IGISOL Group

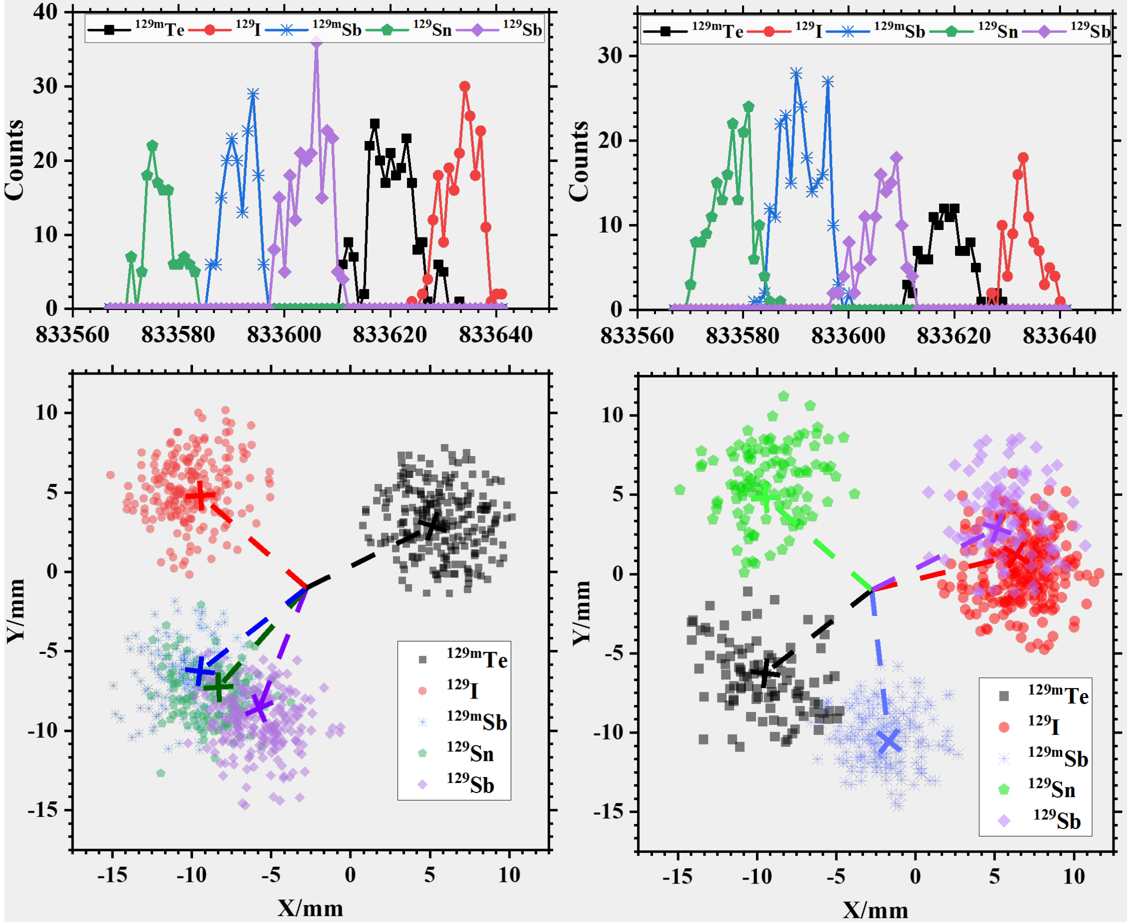
Z. Ge,[1,2,*] Mikael Reponen,[1,†] T. Eronen,[1] Y. H. Lam,[3,4] B. S. Hu,[5] S. Nikas,[1] D. A. Nesterenko,[1] A. Kankainen,[1] O. Beliuskina,[1] L. Cañete,[1,6] R. de Groote,[1,7] C. Delafosse,[1,8] P. Delahaye,[9] T. Dickel,[2,10] A. de Roubin,[7] S. Geldhof,[1,7] W. Gins,[1] A. Heger,[11,12,13,14] 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]

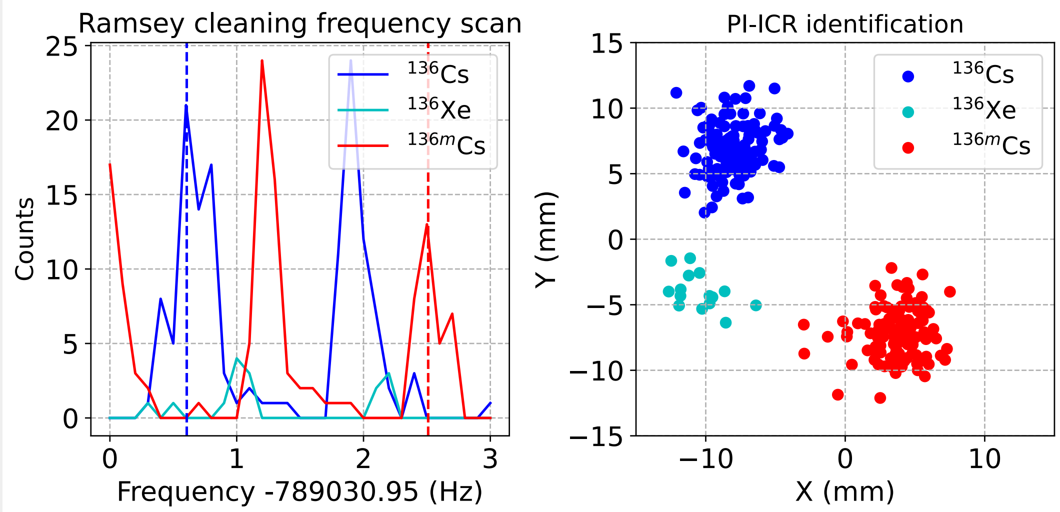
Miikka Winter[1]

[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


^{129m}Te
^{129}I
^{129m}Sb
^{129}Sn
^{129}Sb
Counts
X/mm
Y/mm


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