



JYVÄSKYLÄN YLIOPISTO  
UNIVERSITY OF JYVÄSKYLÄ

# Probing exotic silver and palladium isotopes beyond the N=50 shell closure near tin-100

15th Nordic Meeting 2026 Visby, Sweden

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Research Council  
of Finland

# Outline

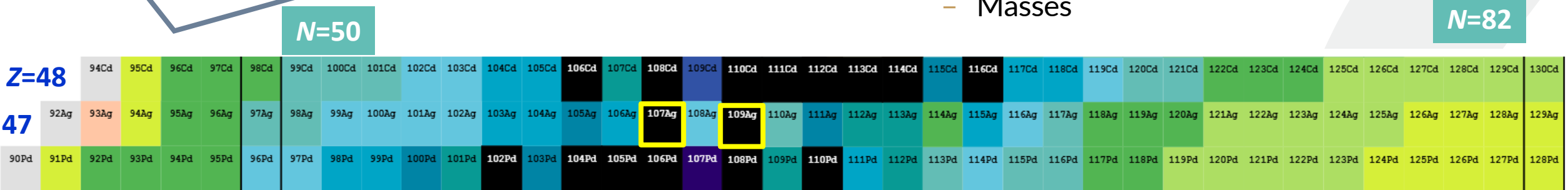
- Motivation
- Hot cavity catcher laser ion source
  - Evolution of charge radii and masses across  $N = 50$  in silver
  - Energetics of the two-proton decay of  $^{94}\text{Ag}$
  - View over the  $N=Z$  line from  $^{92}\text{Pd}$
  - Laser spectroscopy of a proton emitter
- Outlook

# Region of interest



				Z=50						
		In 96	In 97	In 98 37 ms	In 99 3.1 s	In 100 5.83 s	In 101 15.1 s	In 102 23.3 s	In 103 60 s	In 104 1.80 m
	Cd 94	Cd 95 32 ms	Cd 96 880 ms	Cd 97 1.10 s	Cd 98 9.2 s	Cd 99 16 s	Cd 100 49.1 s	Cd 101 1.36 m	Cd 102 5.5 m	Cd 103 7.3 m
Ag 92	Ag 93	Ag 94 26 ms	Ag 95 1.76 s	Ag 96 4.44 s	Ag 97 25.5 s	Ag 98 47.5 s	Ag 99 2.07 m	Ag 100 2.01 m	Ag 101 11.1 m	Ag 102 12.9 m
Pd 91 30 ms	Pd 92 1.0 s	Pd 93 1.15 s	Pd 94 9.0 s	Pd 95 7.5 s	Pd 96 122 s	Pd 97 3.10 m	Pd 98 17.7 m	Pd 99 21.4 m	Pd 100 3.63 d	Pd 101 8.47 h
Rh 90 29 ms	Rh 91 1.5 s	Rh 92 4.7 s	Rh 93 12.2 s	Rh 94 70.6 s	Rh 95 5.02 min	Rh 96 9.9 m	Rh 97 30.7 m	Rh 98 8.72 m	Rh 99 16.1 d	Rh 100 20.5 h
N=50										

- N=50
  - Charge radii, moments
    - Pd and Rh accessible in high-resolution
- N=Z
  - Masses
    - Tin-100 accessible with Penning trap.
  - Charge radii, moments
    - $^{94}\text{Ag}$ ,  $^{100}\text{Sn}$
- Beyond N=Z
  - Masses



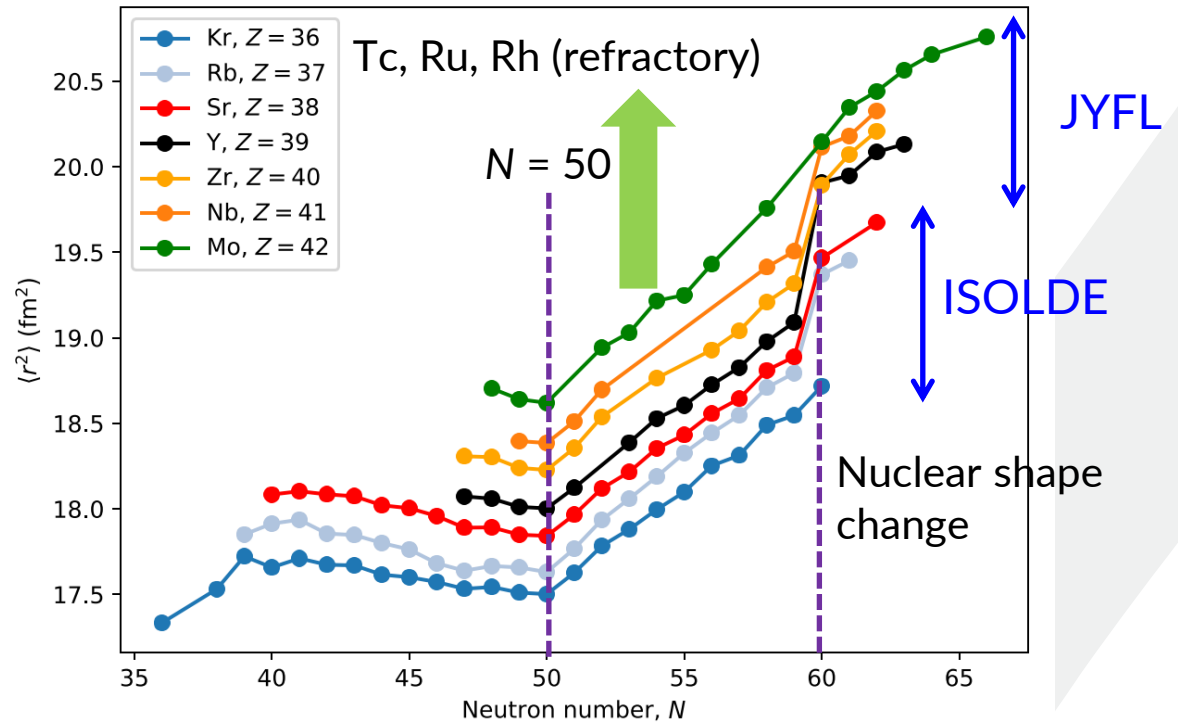
Heavy-ion fusion-evaporation reactions



# Motivation: Nuclear structure trends

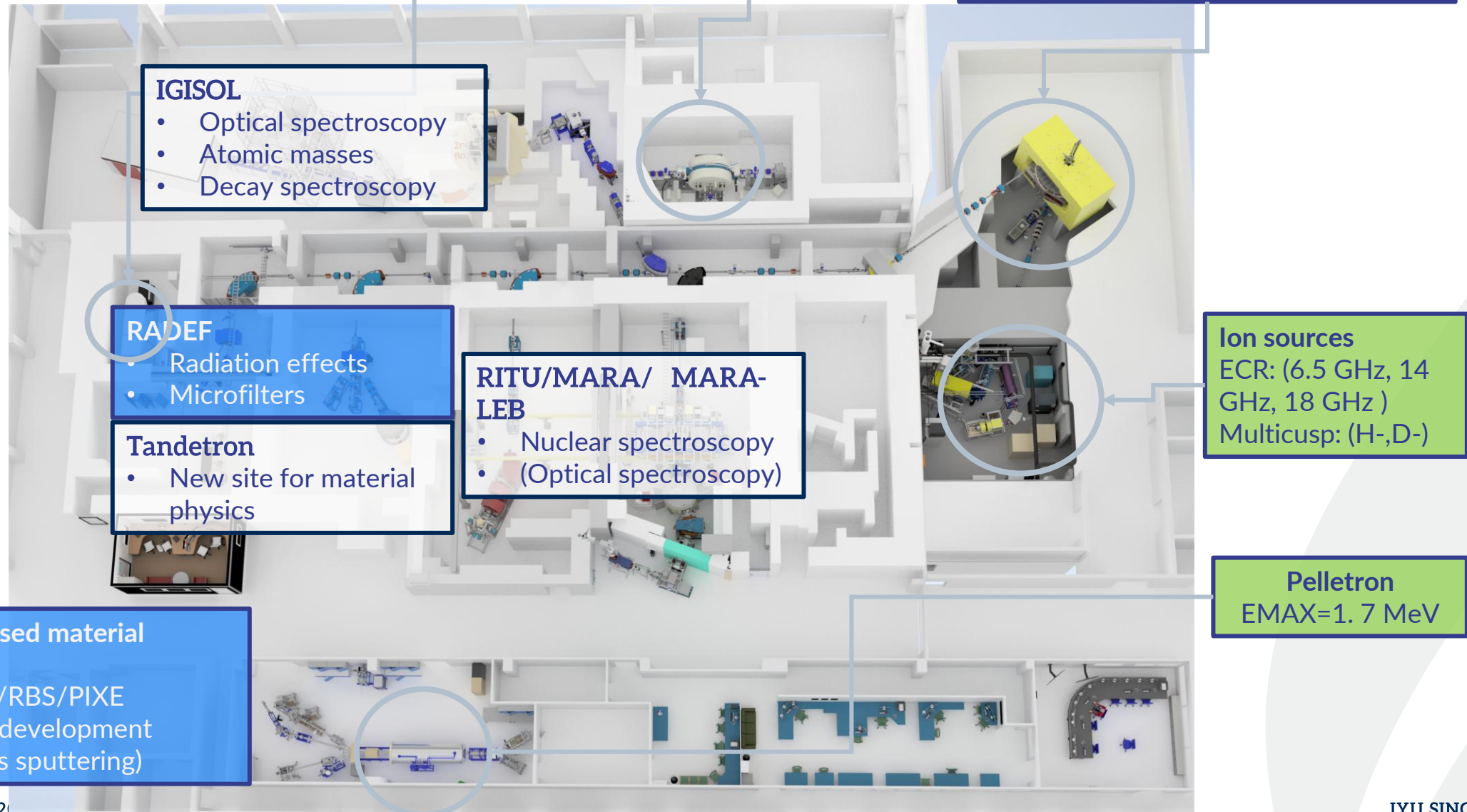


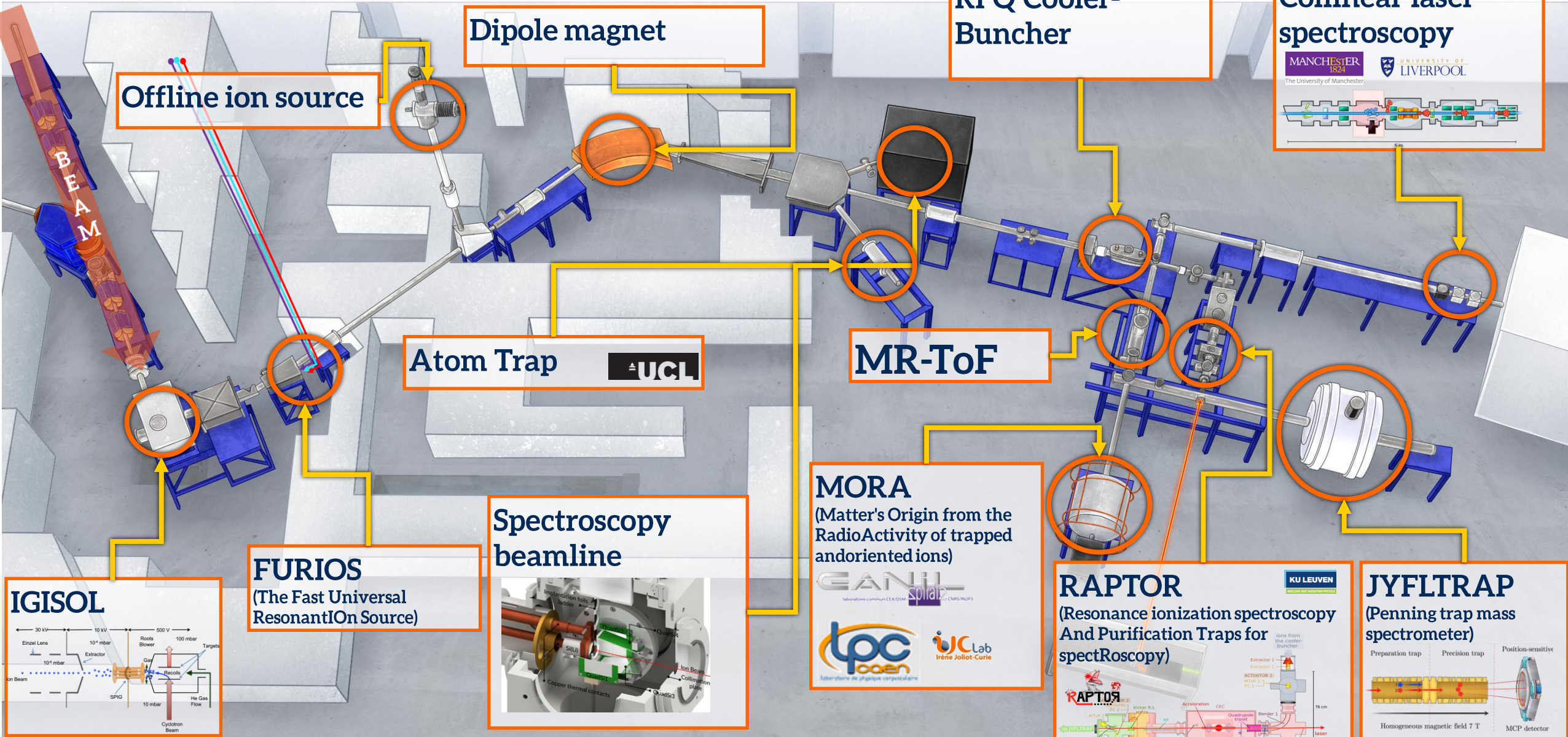
- Electromagnetic moments, charge radii and binding energies are essential benchmarks of theory
- Region below Sn ( $Z = 50$ ) is of high interest Data on neutron-rich odd-odd Ag isotopes is absent or incomplete
- Spin assignments are often tentative and in conflict due to experiments lacking isomeric or isobaric purification
- High precision mass and laser spectroscopy measurements can be combined with decay spectroscopy data



Overview figure: Nörtershäuser & Moore, Handbook of Nuclear Physics (2023)

# JYFL-ACCLAB



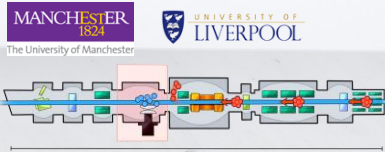


Offline ion source

Dipole magnet

RFQ Cooler-Buncher

Collinear laser spectroscopy



Atom Trap

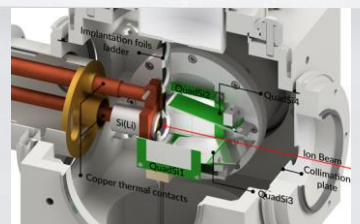


MR-ToF

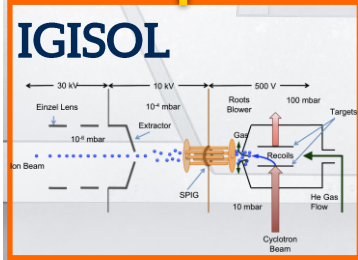
MORA  
(Matter's Origin from the RadioActivity of trapped and oriented ions)



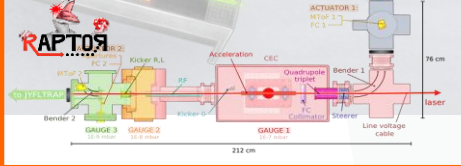
Spectroscopy beamline



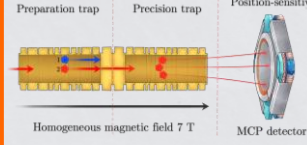
FURIOS  
(The Fast Universal Resonant Ion Source)



RAPTOR  
(Resonance ionization spectroscopy And Purification Traps for spectRoscropy)



JYFLTRAP  
(Penning trap mass spectrometer)



# Inductively Heated Hot Cavity Cather Laser Ion Source



- Implantation of reaction products to as solid material (graphite)
- The high temperature => fast diffusion to cavity volume
- Effusing atoms selectively ionized with lasers
- Based on GSI catcher ion source systems

R. Kirchner et al/NIM 186, 1-2, (1981)

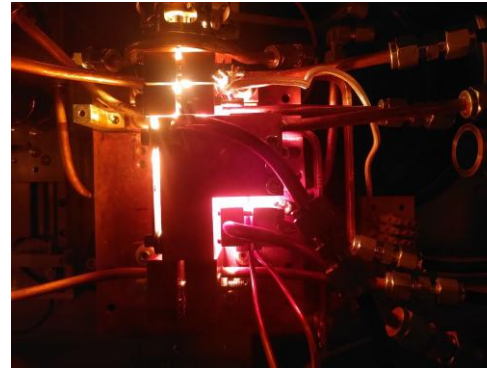
$^{101}\text{Sn}$ : Z Janas et al 1995 Phys. Scr. **262** (1995)

$^{100}\text{In}$ : W. Kurcewicz, Z. Phys. A - Atoms and Nuclei **308**, 21-31 (1982)

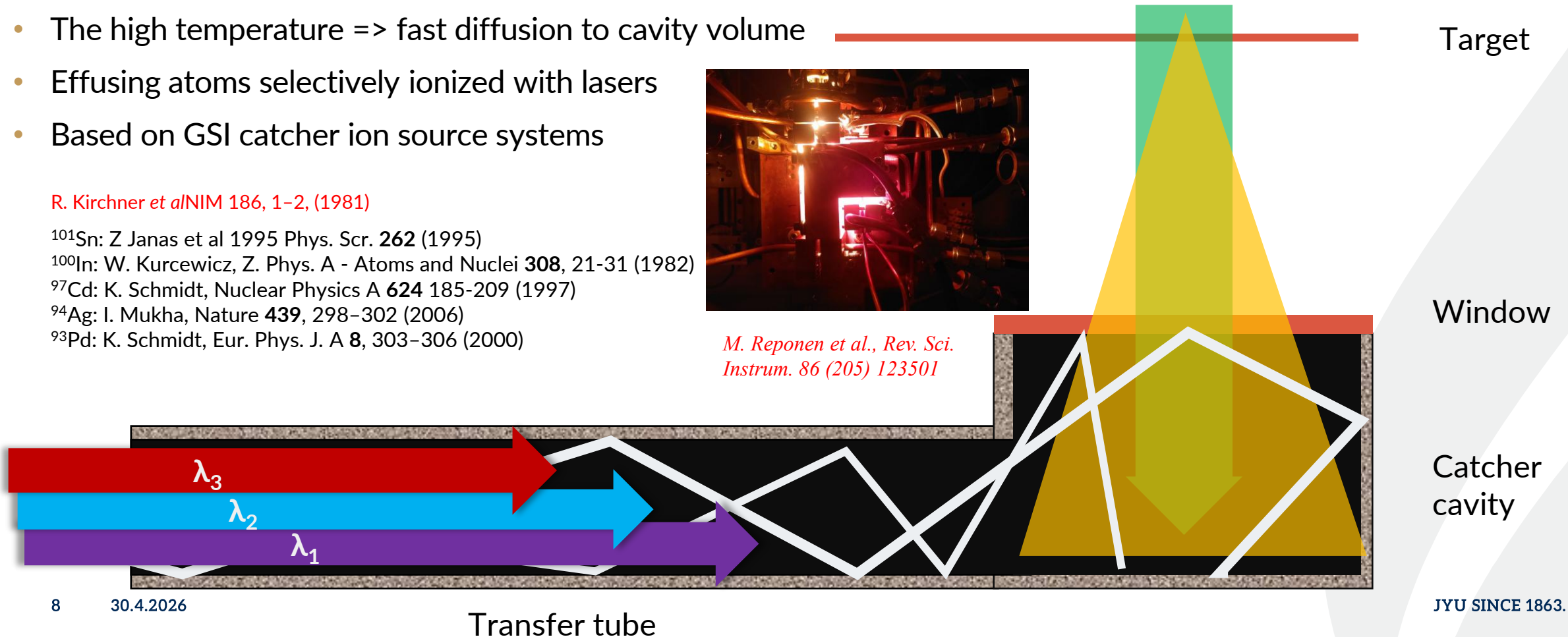
$^{97}\text{Cd}$ : K. Schmidt, Nuclear Physics A **624** 185-209 (1997)

$^{94}\text{Ag}$ : I. Mukha, Nature **439**, 298-302 (2006)

$^{93}\text{Pd}$ : K. Schmidt, Eur. Phys. J. A **8**, 303-306 (2000)



*M. Reponen et al., Rev. Sci. Instrum. 86 (205) 123501*



# A nuclear fingerprint on the atomic levels

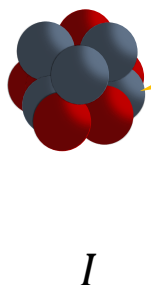
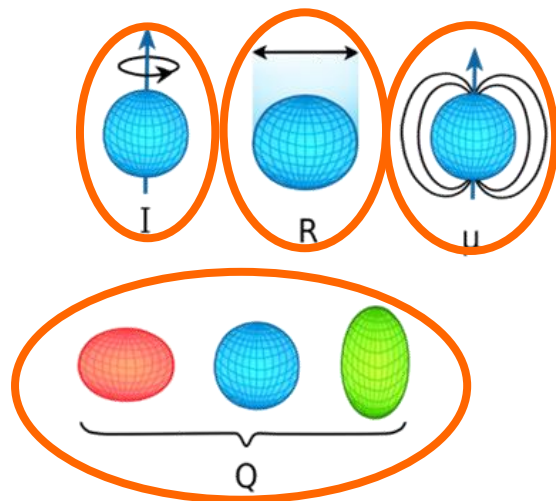


- Nuclear properties are mapped to the atomic structure.
  - Nuclear spin  $I$
  - Changes in the mean square charge radii  $\delta\langle r^2 \rangle$
  - Magnetic dipole moment  $\mu$
  - Electrical quadrupole moment  $Q$

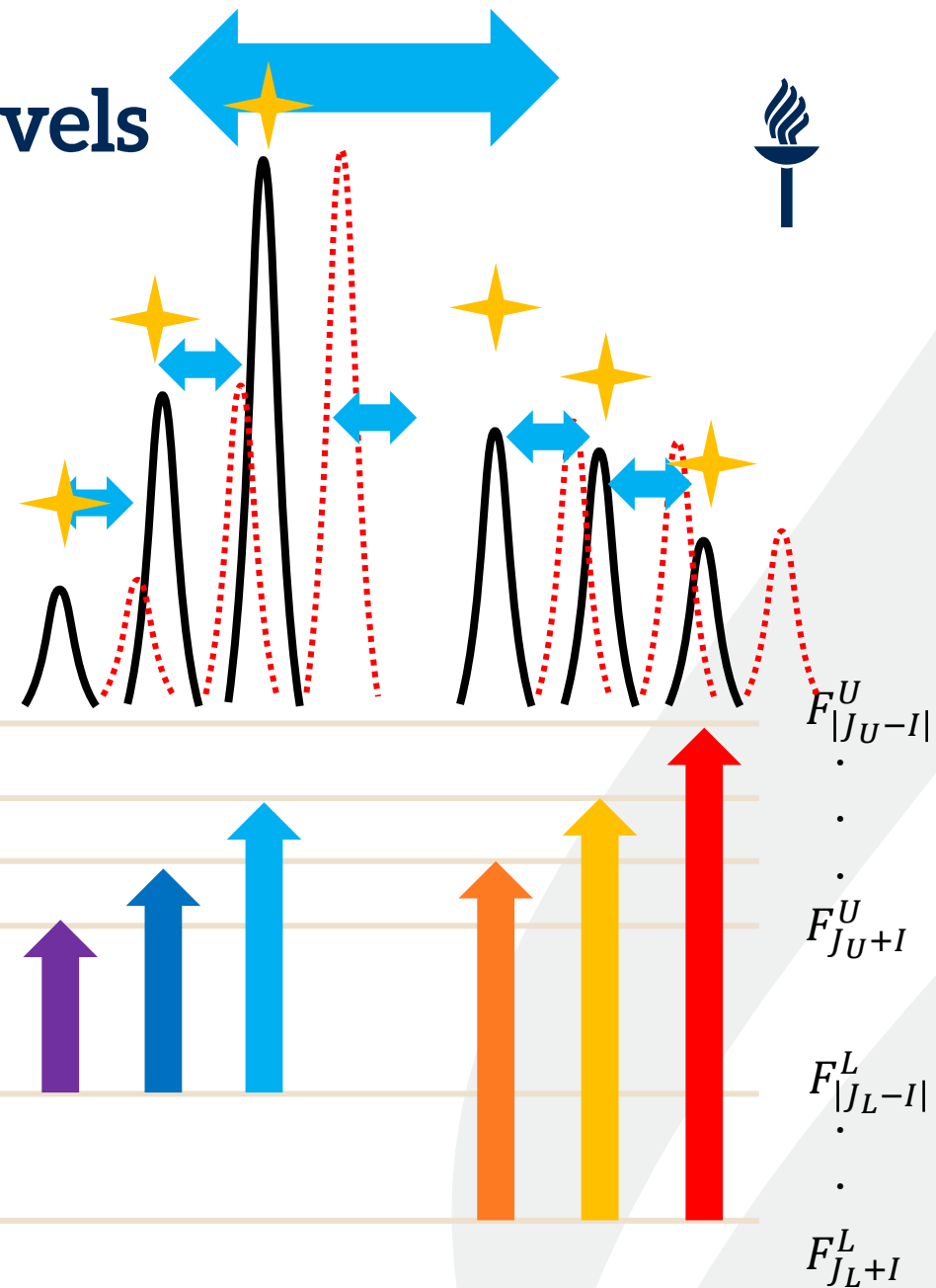
$$\delta\nu^{AA'} = M \frac{m_{A'} - m_A}{m_A m_{A'}} + F \delta\langle r^2 \rangle^{AA'}$$

$$g = \mu/I$$

Information on the configuration.



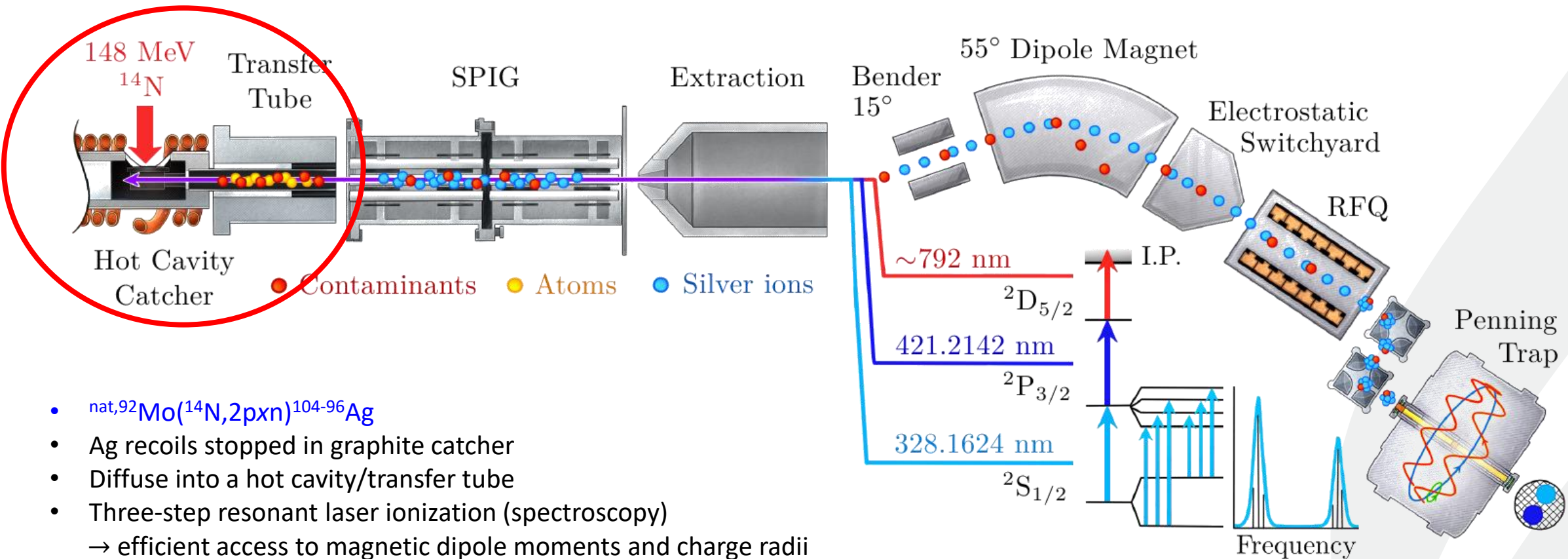
$|J_U\rangle$   
 $|J_L\rangle$



# PI-ICR assisted in-source spectroscopy



Recent efforts to combining methods from ion manipulation and trapping techniques with laser resonance ionization have enabled almost a complete suppression of background, opening a window to the most exotic nuclei.



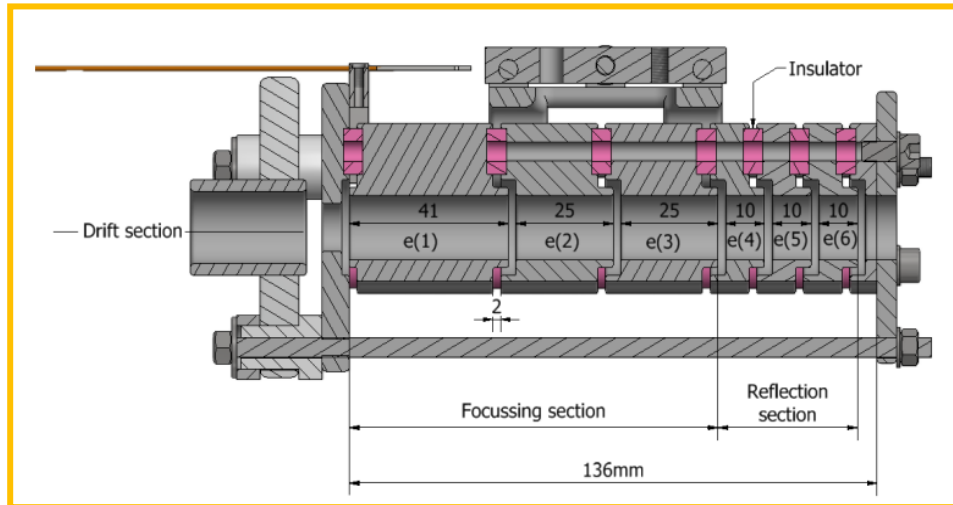
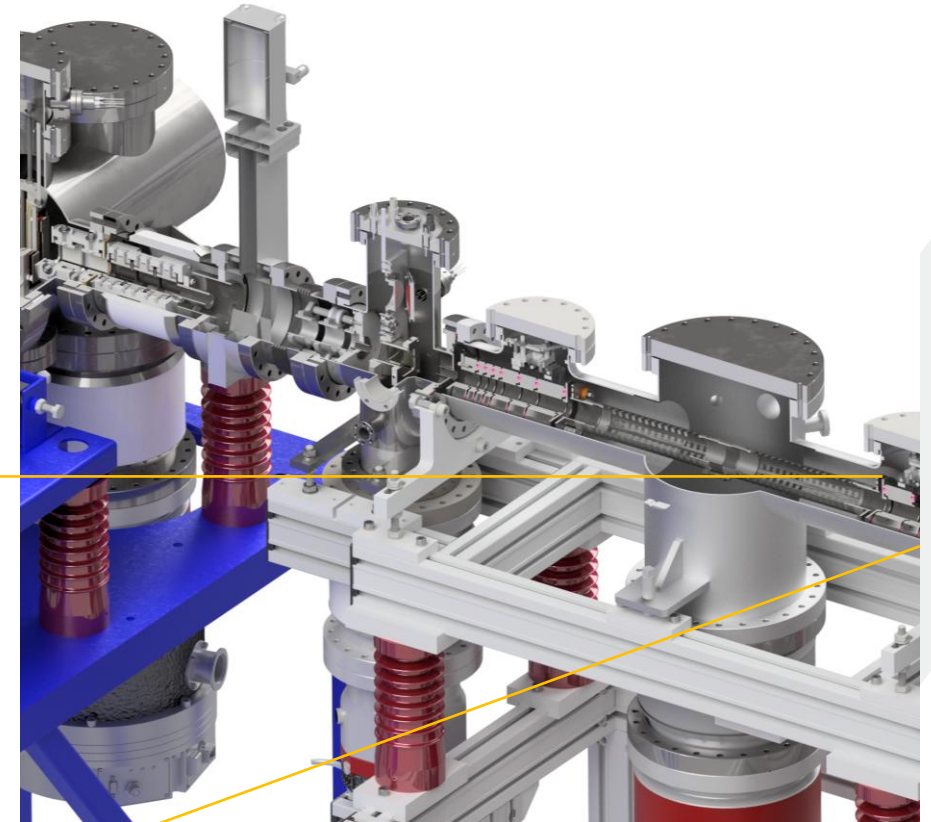
- $^{nat,92}\text{Mo}(^{14}\text{N}, 2\text{pxn})^{104-96}\text{Ag}$
- Ag recoils stopped in graphite catcher
- Diffuse into a hot cavity/transfer tube
- Three-step resonant laser ionization (spectroscopy)  
→ efficient access to magnetic dipole moments and charge radii

*T. Eronen et al., Eur. Phys. J. A 48 (2012) 46*  
*S. Eliseev et al., Appl. Phys. B 114 (2014) 107*  
*D.A. Nesterenko et al., Eur. Phys. J. A 54 (2018) 154*

# Multi-Reflection Time-of-Flight Mass Spectrometer



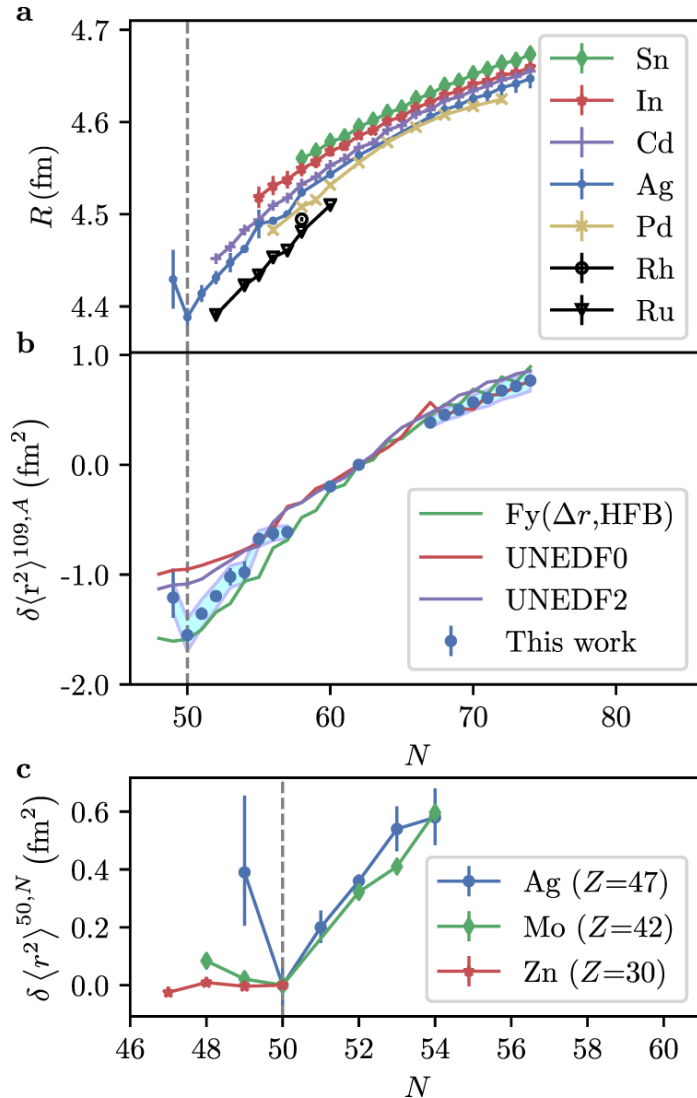
- Works as a separator and as a spectrometer
- Non-scanning – measures full mass spectrum simultaneously
- Fast -> exotic radioactive nuclei
- Ions trapped with the same energy ->  $t = a \sqrt{\frac{m}{q}} + b$



$$R = \frac{m}{\Delta m} = \frac{t}{2\Delta t} \sim 200\,000$$



# Evolution of charge radii across $N = 50$



*M. Reponen et al., Nature Comm. 12 (2021) 4596*

- Measurements cross  $N=50$  shell closure in the region of  $^{100}\text{Sn}$  for the first time.
- UNEDF functionals predict a rather smooth behaviour; Fayans EDF better reproduces local variations
- None of the models reproduces the remarkably sharp increase in crossing  $N=50$

$$\delta \nu_i^{A,A'} = M_i \frac{A' - A}{AA'} + F_i \delta \langle r^2 \rangle^{A,A'}$$

Atomic factors  $F$  and  $M$  from empirical estimation:  
 $F = -4300(300)$  MHz fm<sup>-2</sup>,  $M = 1956(360)$  GHz u

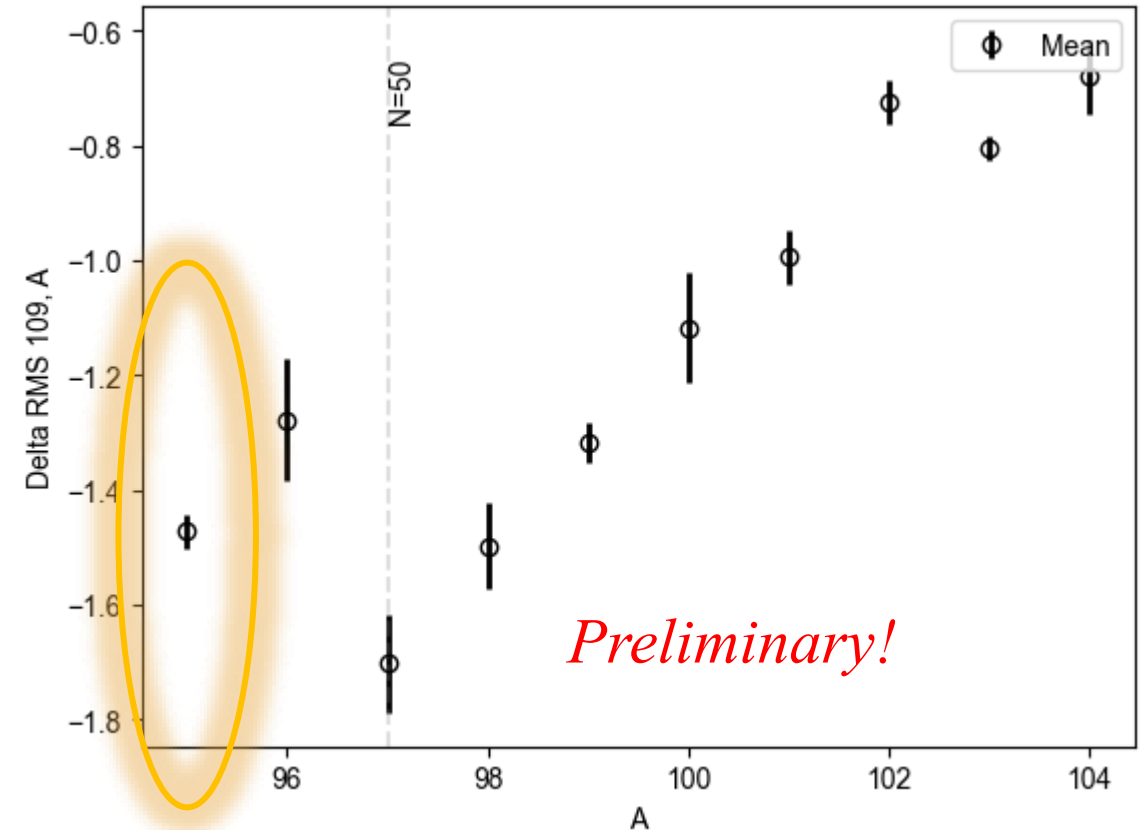
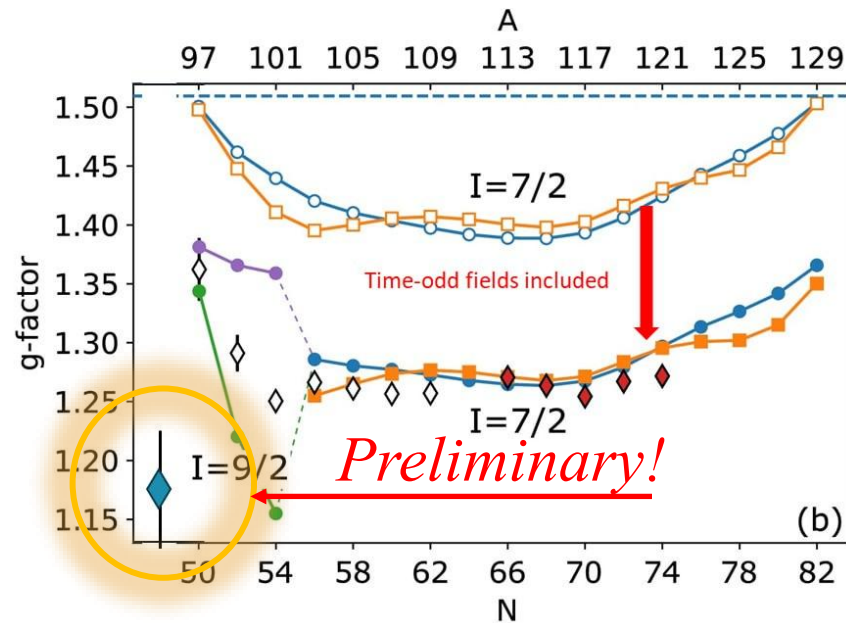
More recent *ab initio* calculations:  
 $F = -3557(49)$  MHz fm<sup>-2</sup>,  $M = 1479(14)$  GHz u

*B. Ohayon et al., Phys. Rev. Res. 6 (2024) 033040*

# Towards the $N=Z$ line

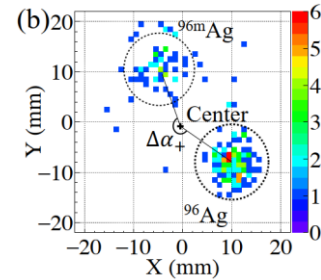
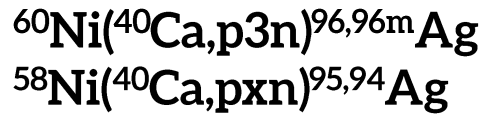


- New data for  $^{97,96,95}\text{Ag}$  using  $^{40}\text{Ca}(^{58/60}\text{Ni}, \text{pxn})$ 
  - confirms the large kink at  $N=50$ .
- The  $g$ -factor of  $^{95}\text{Ag}$  exhibits possibly a large jump after  $N=50$  (**Natalia will speak more about these later!**)

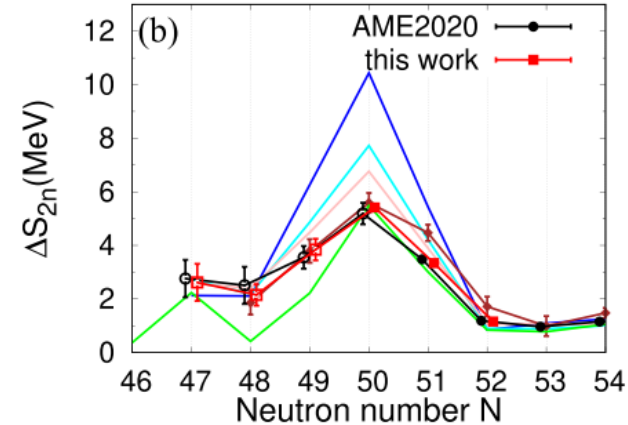


R.P. de Groote et al., Phys. Lett. B 848 (2024) 138352

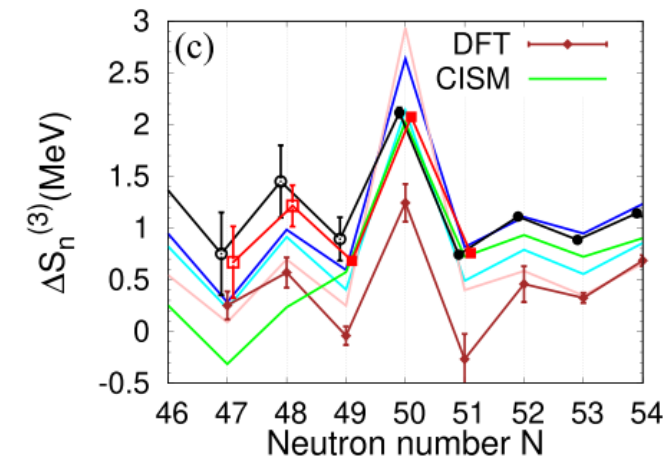
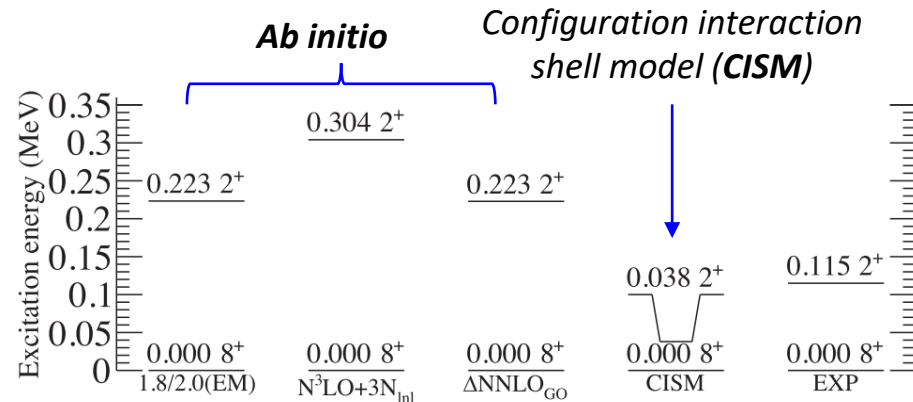
# Mass measurement of $^{95}\text{Ag}$



- Probing the robustness of the  $N = 50$  shell closure
- Atomic masses of  $\beta$ -decaying  $2^+$  and  $8^+$  states identified in  $^{96}\text{Ag}$  and measured for the first time
- Excitation energy of  $^{96m}\text{Ag}(2^+) = 115.0(17)$  keV
- Atomic mass of  $^{95}\text{Ag}$  measured for the first time (precision of 1.4 keV)



$$\Delta S_{2n}(Z, N) = S_{2n}(Z, N) - S_{2n}(Z, N + 2)$$



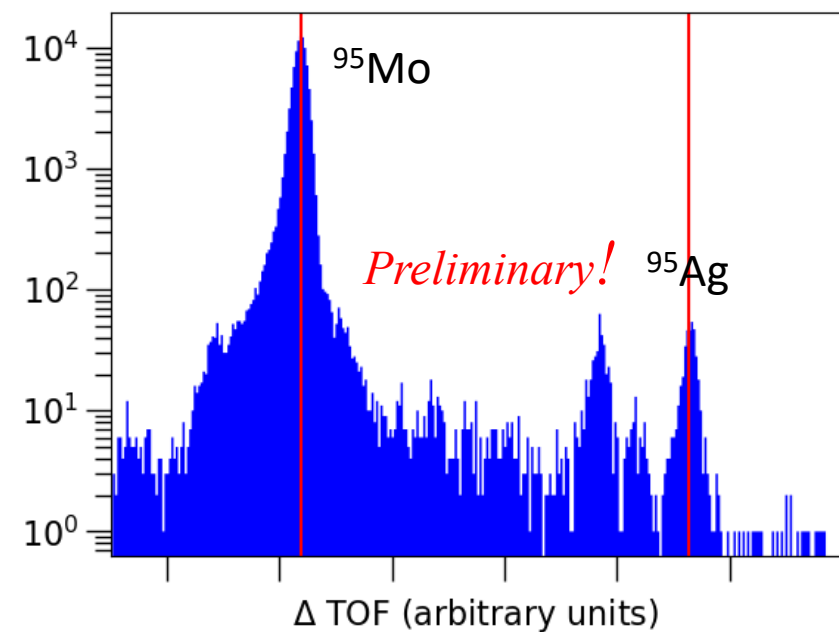
$$\Delta S_n^{(3)} = (-1)^N [S_n(Z, N) - S_n(Z, N + 1)] / 2$$

*Z. Ge, M. Reponen et al., Phys. Rev. Lett. 133 (2024) 132503*

# MR-TOF Mass Spectrometry of $N = Z$ $^{94}\text{Ag}$

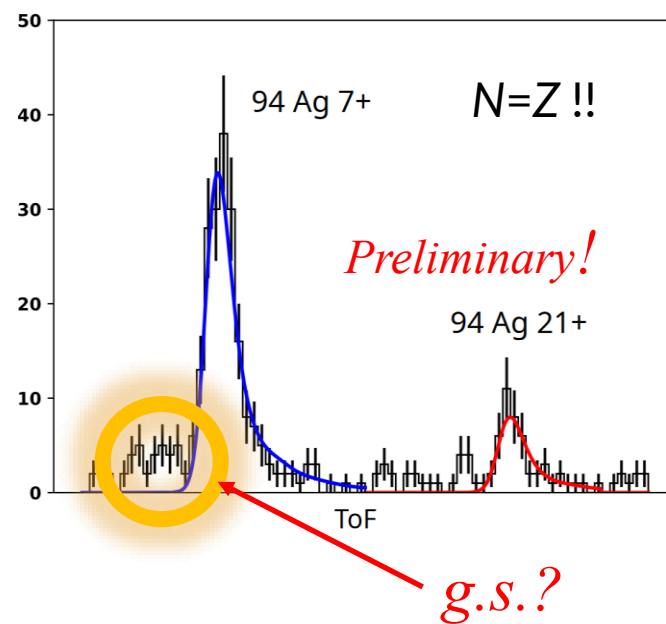


- The reliability of the MR-TOF method was verified with  $^{94}\text{Zr}$  and  $^{95}\text{Ag}$  (the latter measured at JYFLTRAP to 1.4 keV)
- $^{58}\text{Ni}(^{40}\text{Ca}, \text{xpxn})^{95,94}\text{Ag}/^{93,92}\text{Pd}$



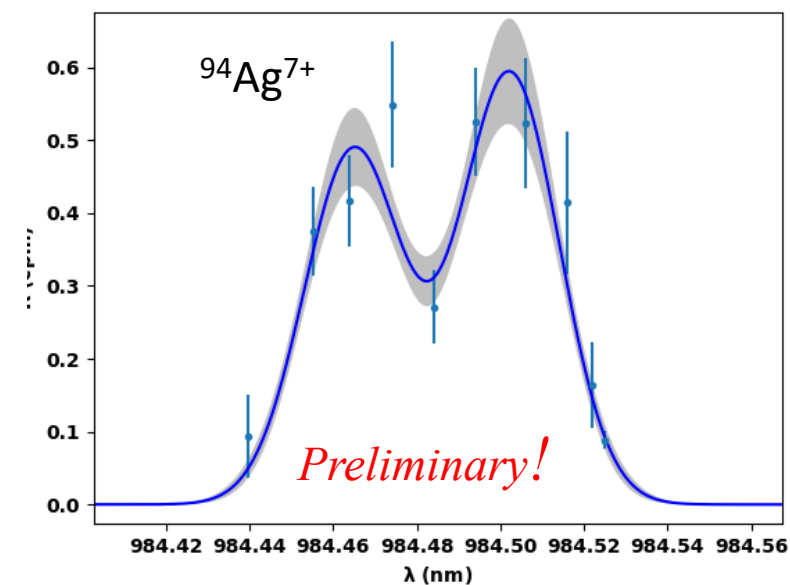
Mass precision of  $^{95}\text{Ag}$   $\sim 10$  keV

*V. Virtanen, M. Reponen et al., to be submitted*



Mass precision of  $^{94}\text{Ag}^{21+}$   $\sim 90$  keV

## Laser frequency scan



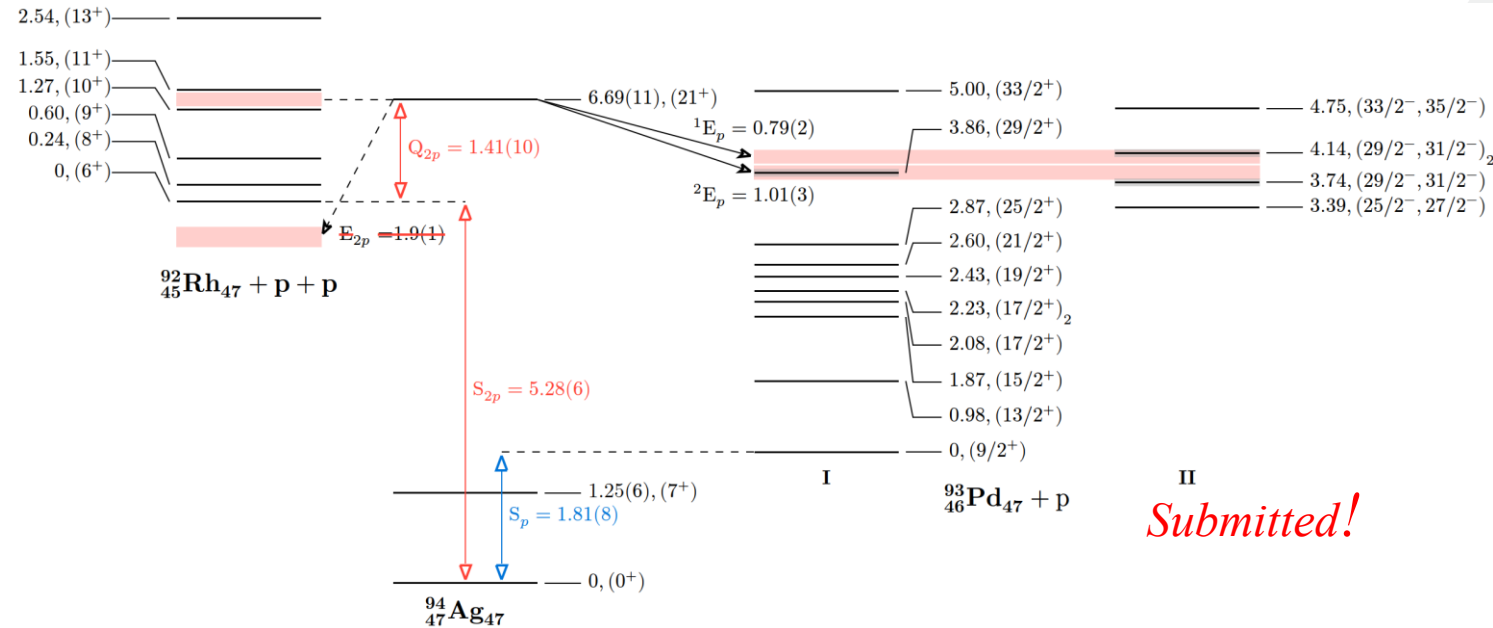
## Ion rates

- ( $7^+$ ) = 0.55 ions/min
- ( $21^+$ ) = 0.15 ions/min

# Energetics of the (21+) isomer in $^{94}\text{Ag}$



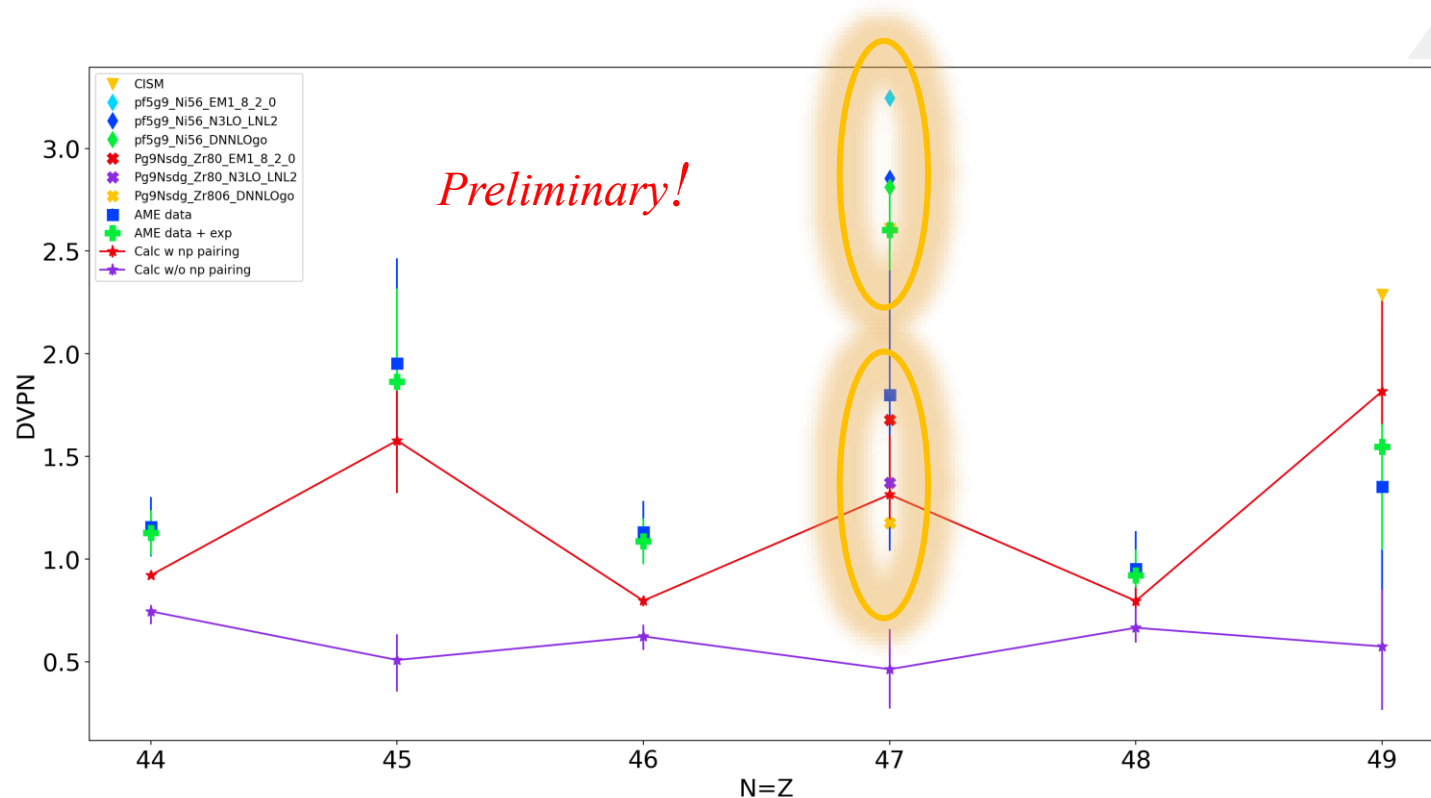
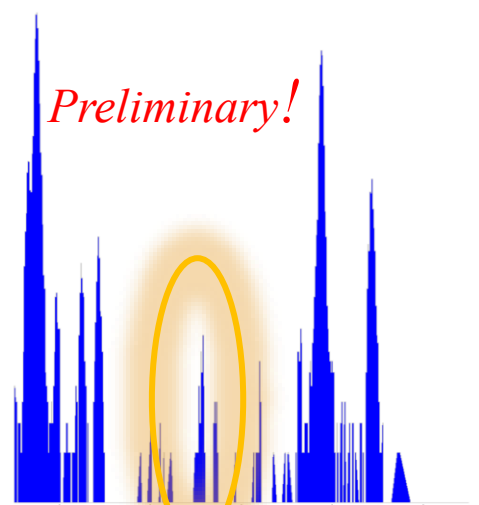
- ME of the (21<sup>+</sup>) state measured with ~90 keV uncertainty
- Combined with the  $^{92}\text{Rh}$  ground state ME (JYFLTRAP) =>,  $Q_{2p} \sim 1.4$  MeV (to the ground state),
  - Enforces an angular momentum difference >10.
  - 1.9 MeV 2-proton emission not possible



# MR-TOF Mass Spectrometry of $N = Z$ $^{92}\text{Pd}$



- $^{58}\text{Ni}(^{40}\text{Ca}, 4p2n) ^{92}\text{Pd}$ 
  - Yield comparable to  $^{94}\text{Ag}(7^+)$
- $^{92}\text{Pd}$  ME close to the AME2020 extrapolation
- Extends silver masses beyond the  $N=Z$  line,
  - when combined with  $^{93}\text{Ag} S_p$  value\* and  $^{94}\text{Ag}(0^+)$  ME.



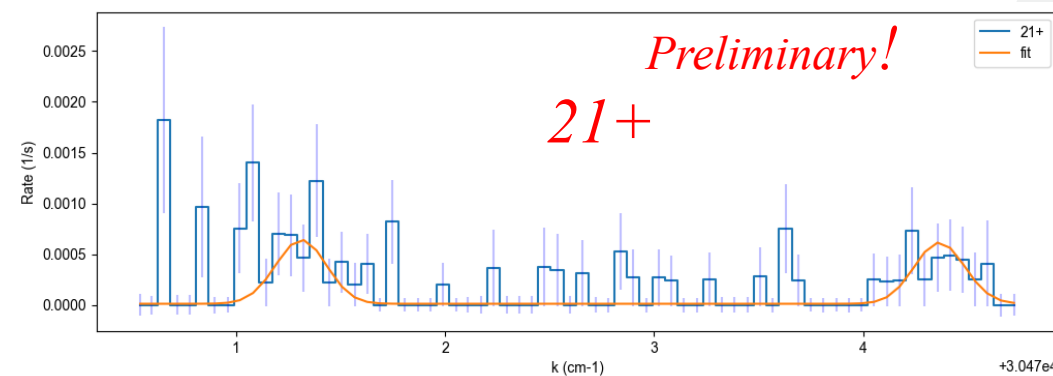
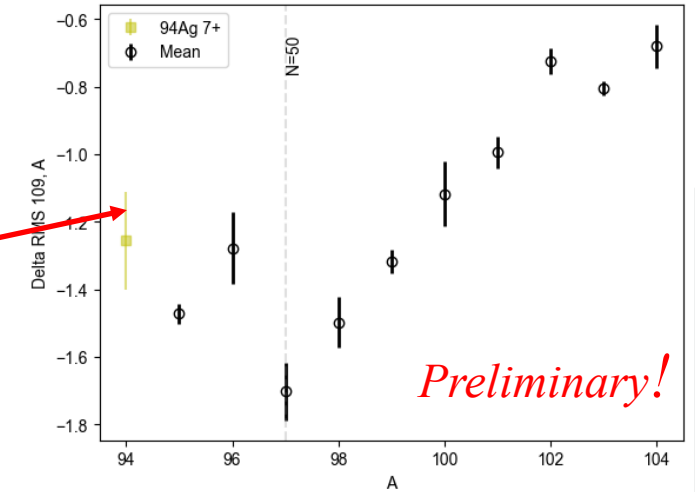
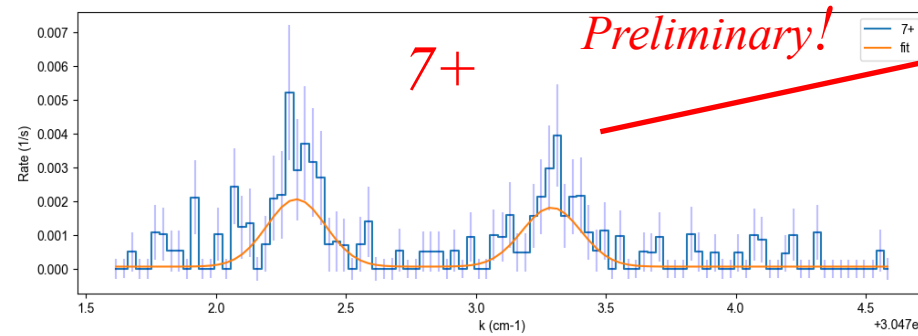
CISM: B. Cai  
 NP calc: P. Zhao  
 VS-IMSRG: B. Hu, J. Holt

\*I. Čeliković, PRL 116 162501 (2016)

# Laser spectroscopy at the $N=Z$ line



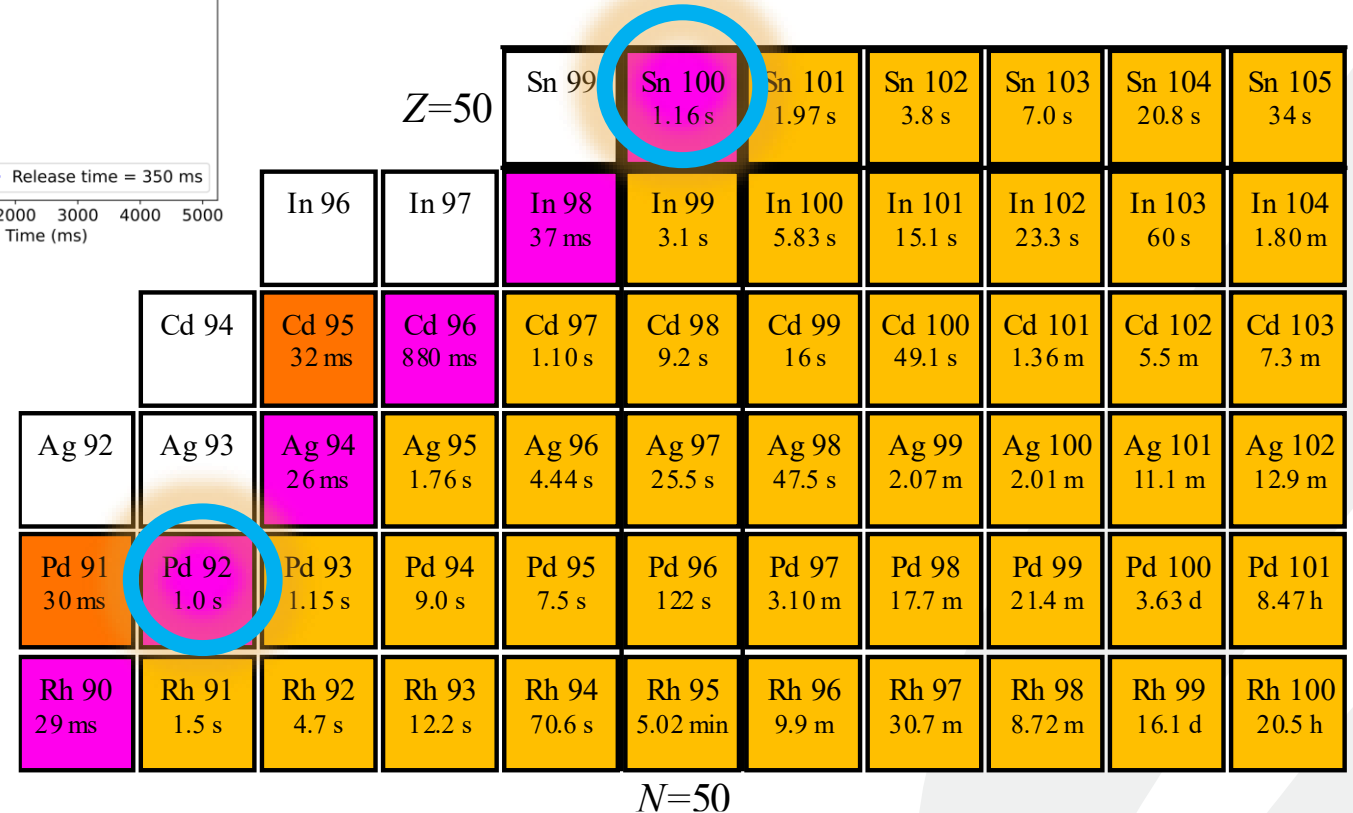
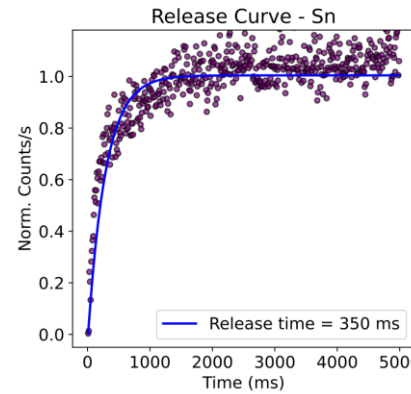
- MR-ToF assisted in-source RIS of  $^{94}\text{Ag}$ .
  - $7+$  and  $21+$  states observed
- Analysis under way
  - Charge radii
  - Magnetic moment
- Statistics to be improved in near future
  - **However, this already marks the first laser spectroscopy of a proton emitter!**



# Outlook - $N=Z$ line:



- Pd: In principle feasible
  - RIS scheme insensitive\*.
- Sn: Release time enough for tin-100\*\*, estimated yield comparable to  $^{94}\text{Ag}^{(21+)}$ .
  - JYFLTRAP measurement feasible.
  - RIS sensitivity for even cases.
- Release test for indium done
  - Targeting  $^{98}\text{In}$ , but more development needed!
- Feasibility to go beyond  $N=Z$  investigated!



\*\* S. Chinthakayala thesis work

\*A. Ortiz Cortes, JYU Dissertations 2023

# Acknowledgements

## The NUANZ team:

- Mikael Reponen (PI)
- Natalia Ambrosio
- Markus Kortelainen (Co-PI)
- Samuli Tähtelä

## The IGISOL team:

Particularly:

- Ville Virtanen (MR-TOF)
- Zhuang Ge (PI-ICR)
- Saikumar Chinthakayala(Lasers)

