JYVÄSKYLÄN YLIOPISTO
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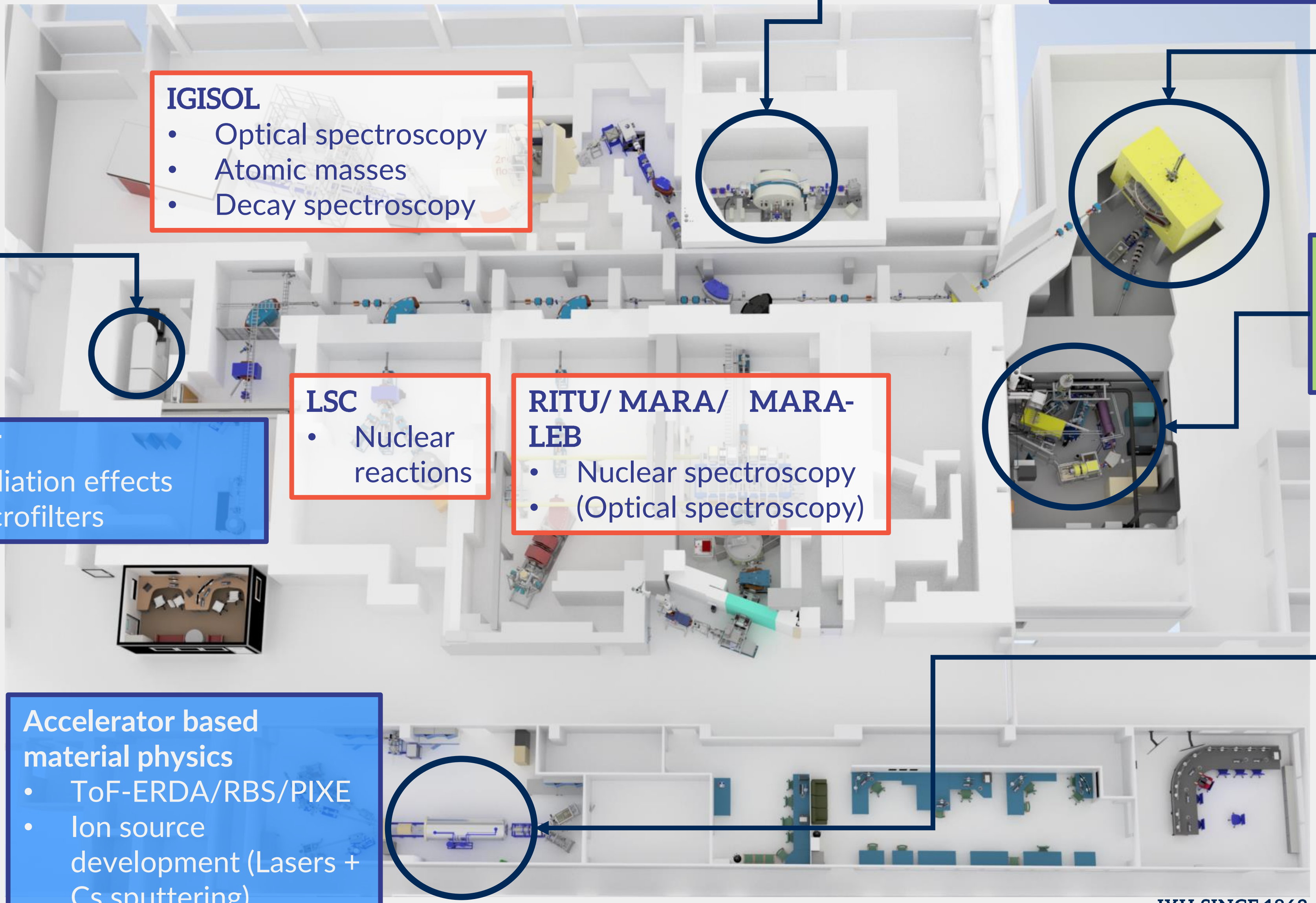
Laser and mass spectroscopy of exotic silver isotopes around N=50 shell-closure

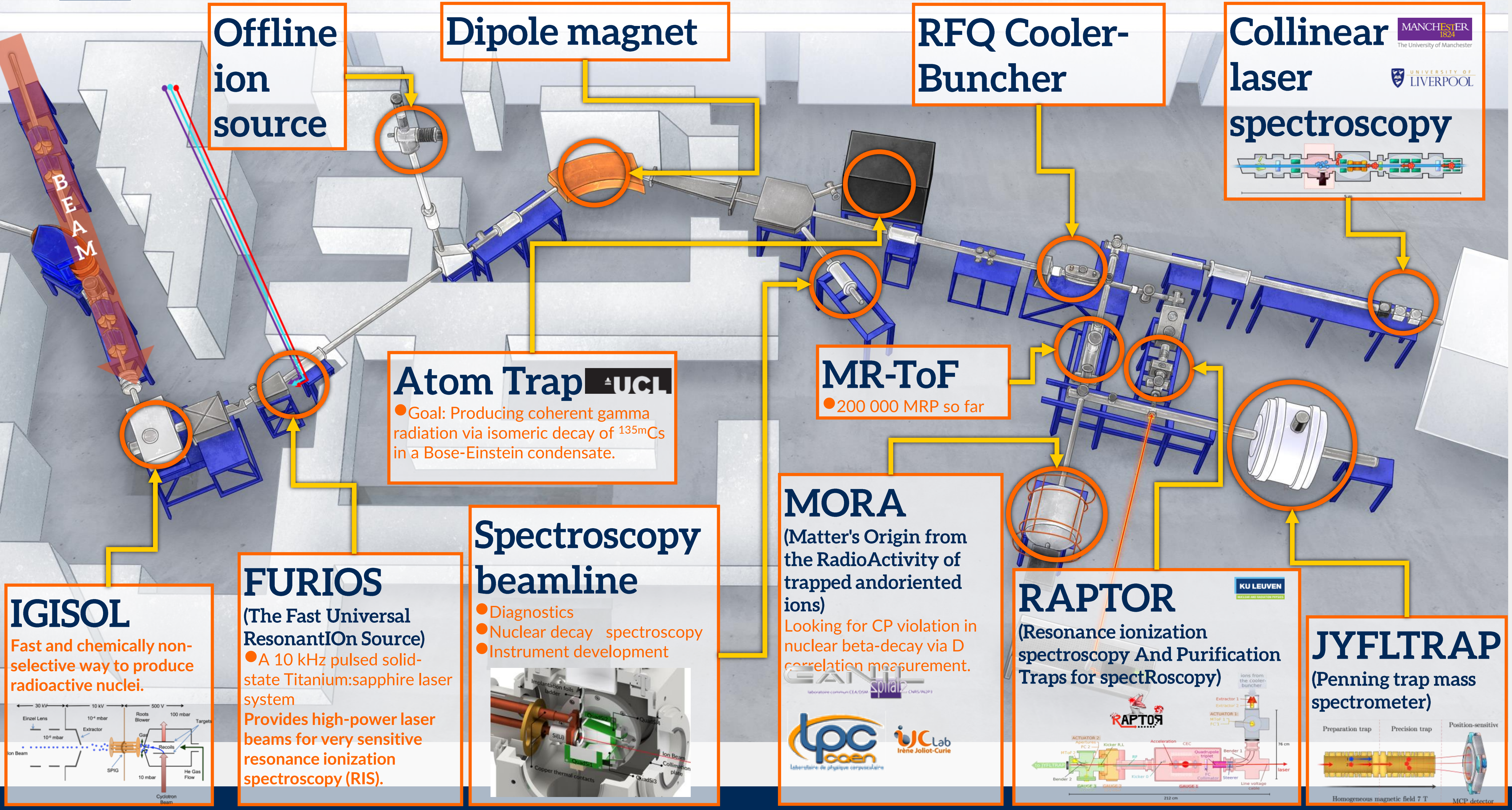
Mikael Reponen

NUSTAR Week – 13.10.2023

IFIN-HH / ELI-NP Bucharest - Magurele

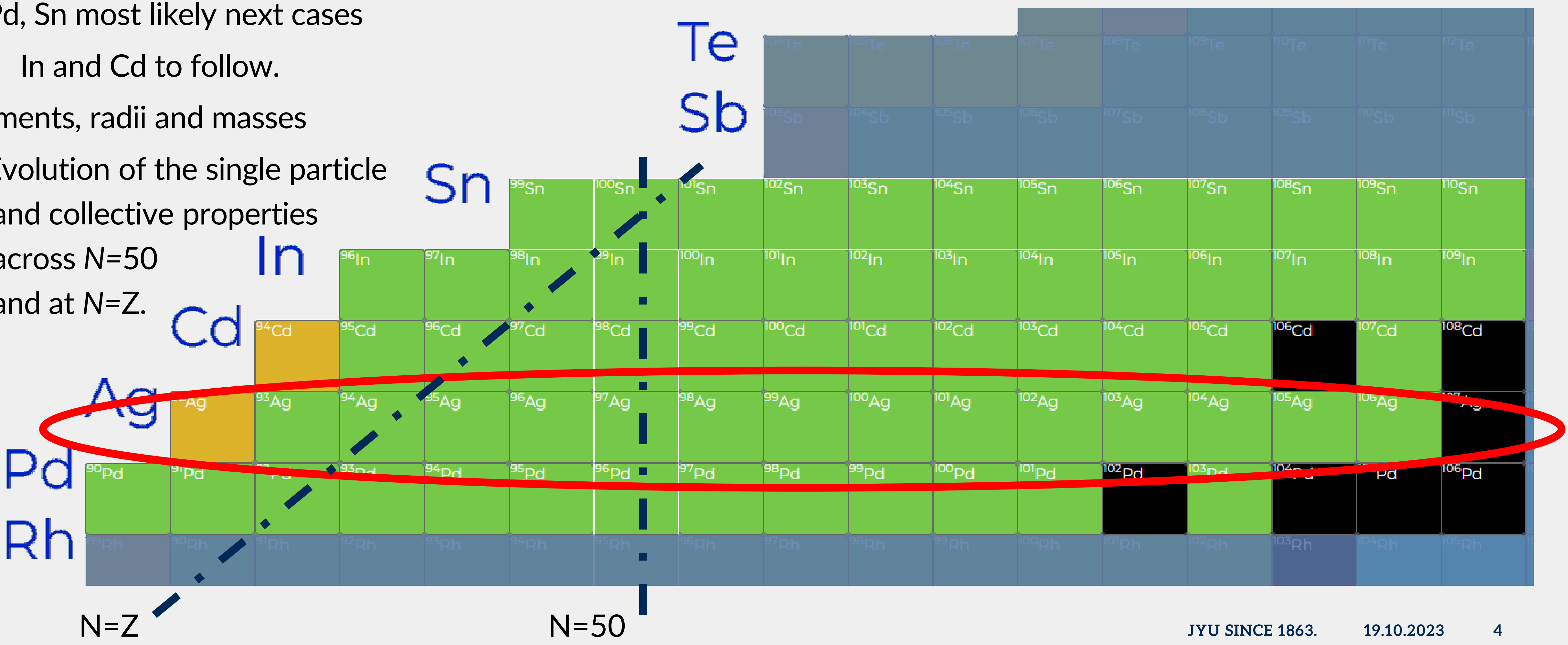
JYFL-ACCLAB


MCC30
Emax=30 MeV
K130:
Emax= 130 (q^2/A) MeV
Beams from p to Au
Annual use: 6500-7000 h/year
C-Linac
IGISOL
• Optical spectroscopy
• Atomic masses
• Decay spectroscopy
Ion sources
ECR: (6.5 GHz, 14 GHz, 18 GHz)
Multicusp: (H-,D-)
RADEF
• Radiation effects
• Microfilters
LSC
• Nuclear reactions
RITU/ MARA/ MARA-LEB
• Nuclear spectroscopy
• (Optical spectroscopy)
Pelletron
EMAX=1. 7 MeV
Accelerator based material physics
• ToF-ERDA/RBS/PIXE
• Ion source development (Lasers + Cs sputtering)


BEAM
Offline ion source
Dipole magnet
RFQ Cooler-Buncher
Collinear laser spectroscopy
MANCHESTER 1824
The University of Manchester
UNIVERSITY OF LIVERPOOL
Atom Trap
UCL
Goal: Producing coherent gamma radiation via isomeric decay of ^{135m}Cs in a Bose-Einstein condensate.
MR-ToF
200 000 MRP so far
IGISOL
Fast and chemically non-selective way to produce radioactive nuclei.
FURIOS
(The Fast Universal ResonantIOn Source)
A 10 kHz pulsed solid-state Titanium:sapphire laser system
Provides high-power laser beams for very sensitive resonance ionization spectroscopy (RIS).
Spectroscopy beamline
Diagnostics
Nuclear decay spectroscopy
Instrument development
MORA
(Matter's Origin from the RadioActivity of trapped andoriented ions)
Looking for CP violation in nuclear beta-decay via D correlation measurement.
GANIL
lpc caen
IJCLab Irène Joliot-Curie
RAPTOR
KU LEUVEN
(Resonance ionization spectroscopy And Purification Traps for spectRoscopy)
JYFLTRAP
(Penning trap mass spectrometer)
Preparation trap
Precision trap
Position-sensitive
Homogeneous magnetic field 7 T
MCP detector

Region of interest:
The immediate area below tin-100

- Silver the first chain studied in this work
  - Pd, Sn most likely next cases
    - In and Cd to follow.
- Moments, radii and masses
  - Evolution of the single particle and collective properties across *N*=50 and at *N*=Z.



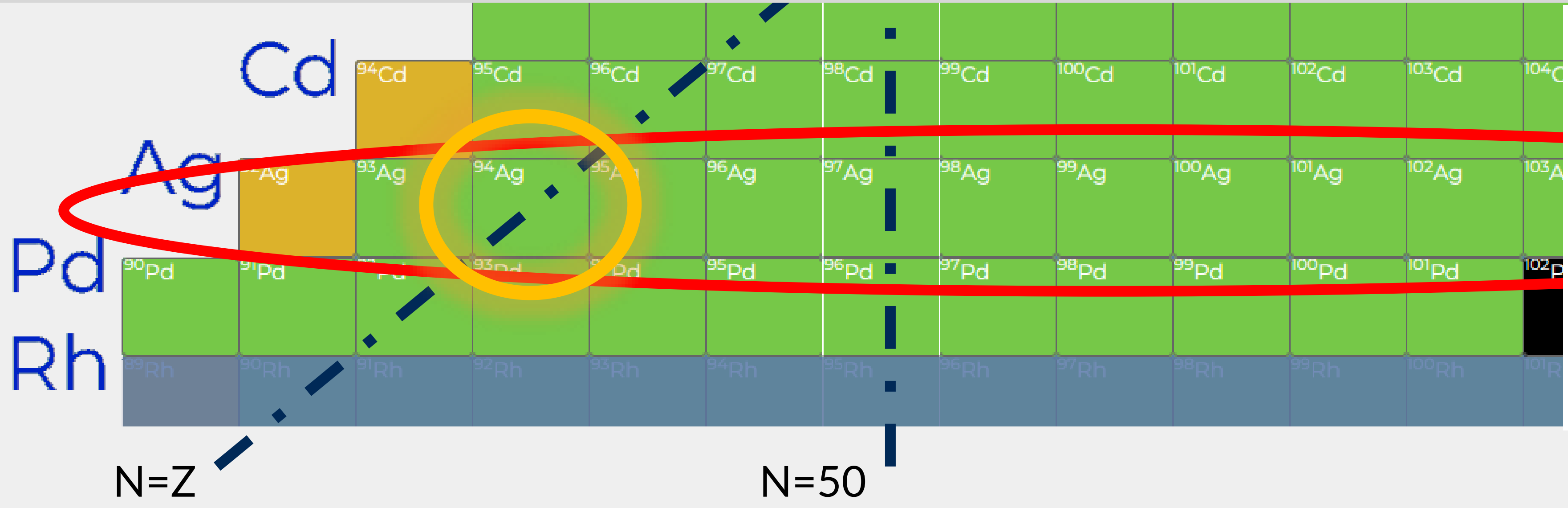
Region of interest:
The immediate area below tin-100

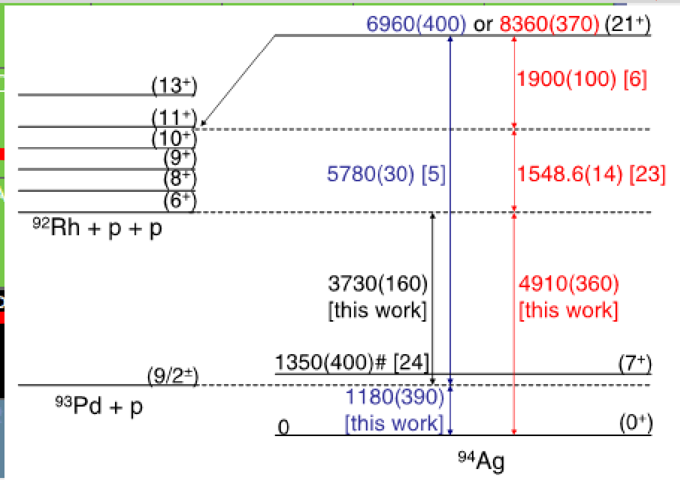
- High-spin isomer (21+) in ^{94}Ag , T1/2 = 0.4 s :
  - β decay (highest spin), β-delayed proton emission, 1-proton decay
  - **2-proton decay** (Mukha *et al.*, Nature (2006))

Schmidt *et al.*, Z. Phys A (1994), Commara et al., NPA (2002) , Mukha *et al.*, PRC (2004), PRL (2005), Nature (2006), Plettner et al., NPA (2004)

__The conundrum:__

- Non-observation of states in ^{92}Rh
  Pechenya et al., PRC (2007)
- Contradiction from masses
  A. Kankainen et al., Phys. Rev. Lett. 101 (2008) 142503
- No observation of 2-proton decay
  Cerny et al., PRL (2009)
- Large-scale SM calculations do not accept large deformation picture
  Kaneko et al., PRC (2008)



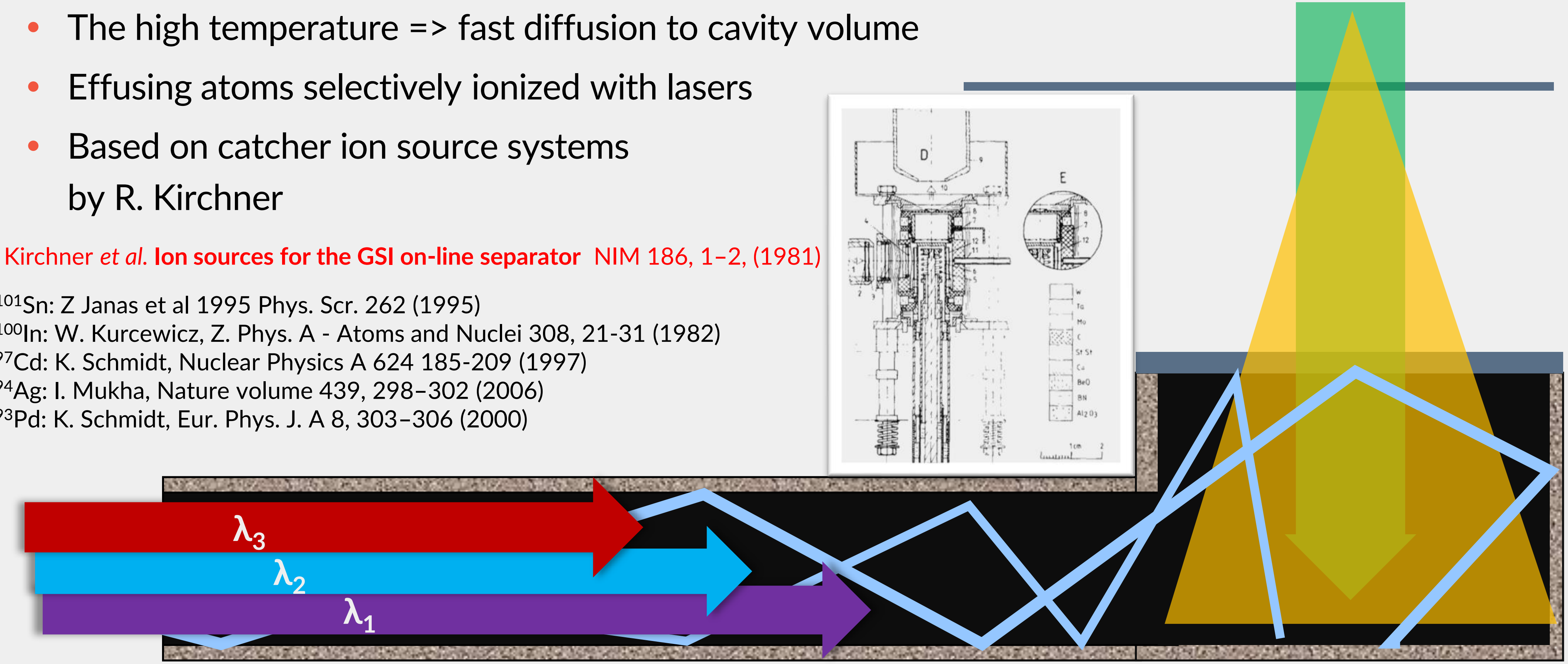


Inductively Heated Hot Cavity Cather Laser Ion Source

- Implantation of reaction products to as solid material
- The high temperature => fast diffusion to cavity volume
- Effusing atoms selectively ionized with lasers
- Based on catcher ion source systems
  by R. Kirchner

R. Kirchner *et al.* **Ion sources for the GSI on-line separator** NIM 186, 1–2, (1981)

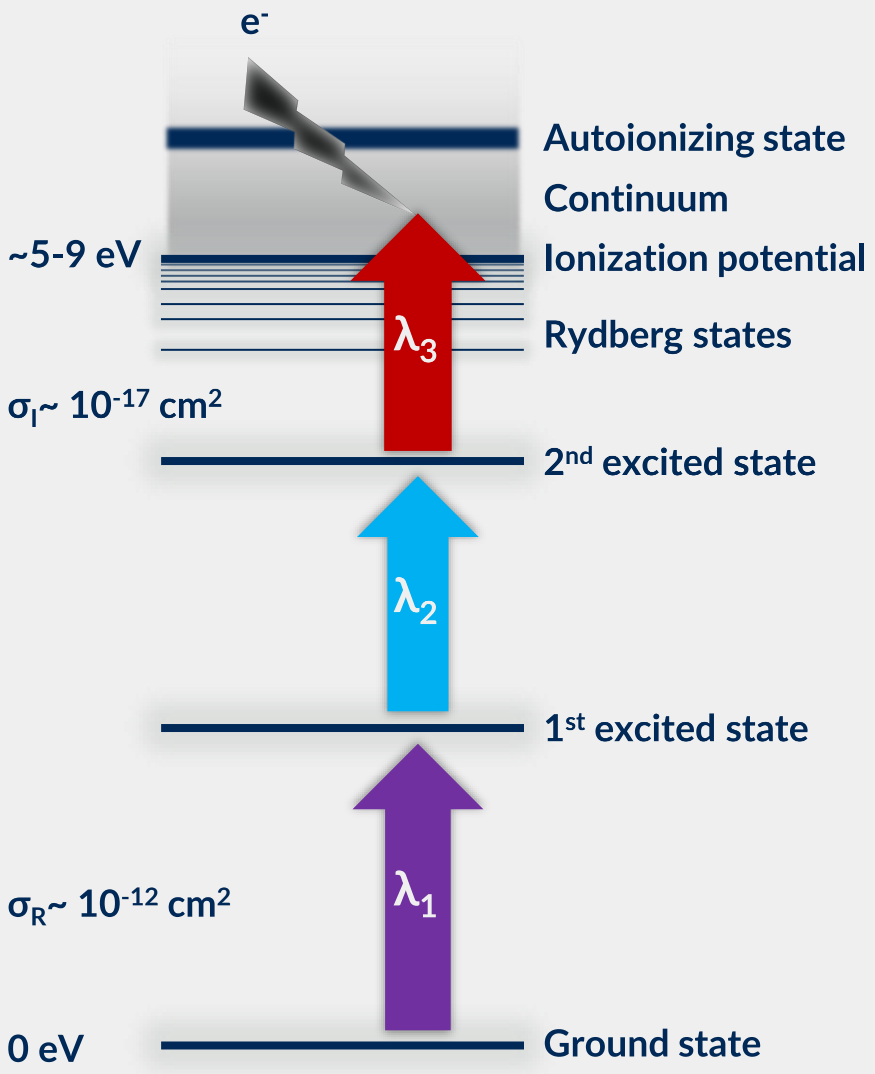
^{101}Sn: Z Janas et al 1995 Phys. Scr. 262 (1995)
^{100}In: W. Kurcewicz, Z. Phys. A - Atoms and Nuclei 308, 21-31 (1982)
^{97}Cd: K. Schmidt, Nuclear Physics A 624 185-209 (1997)
^{94}Ag: I. Mukha, Nature volume 439, 298–302 (2006)
^{93}Pd: K. Schmidt, Eur. Phys. J. A 8, 303–306 (2000)



Ionization method: Laser resonance ionization

- Each element have their unique atomic structure - “fingerprint”.
- Multiple laser beams overlapped with atoms to stepwise excite and ionize
  - Efficient! As high as >50%, typically a few %
- A great method for sensitive laser spectroscopy
  - Resolution highly environment dependent.

We chose resonance ionization to gain a huge improvement in selectivity!

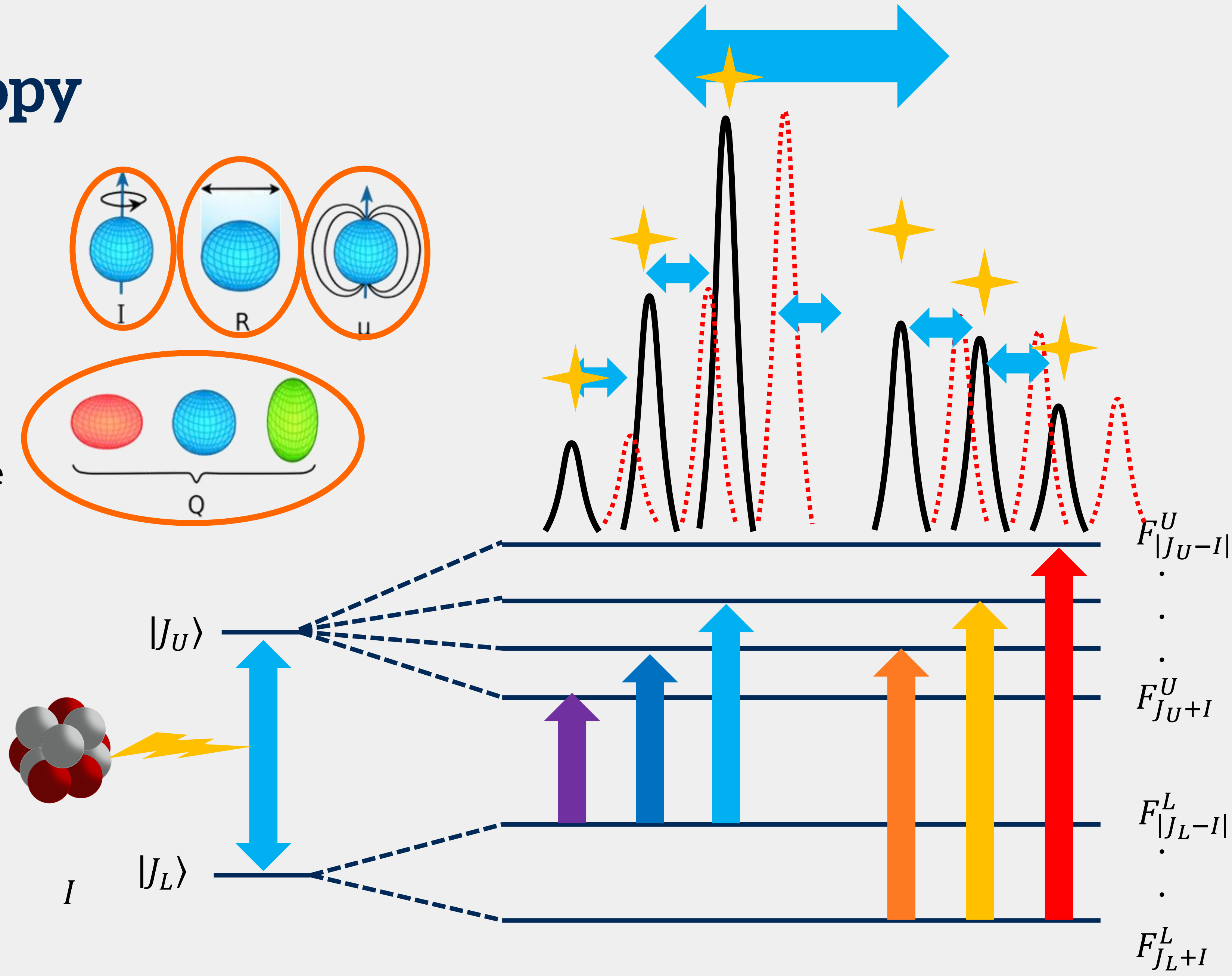


Laser spectroscopy

- 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 μ
  - Electrical quadrupole moment Q

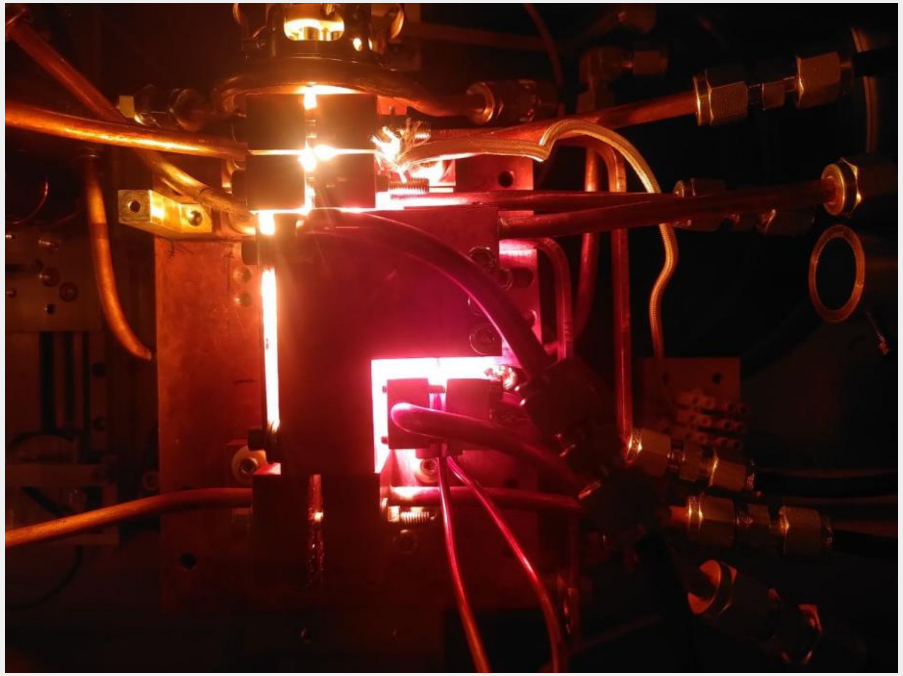
$$\delta\nu^{AA'} = M\frac{m_{A'} - m_A}{m_A m_{A'}} + F\,\delta\langle r^2\rangle^{AA'}$$

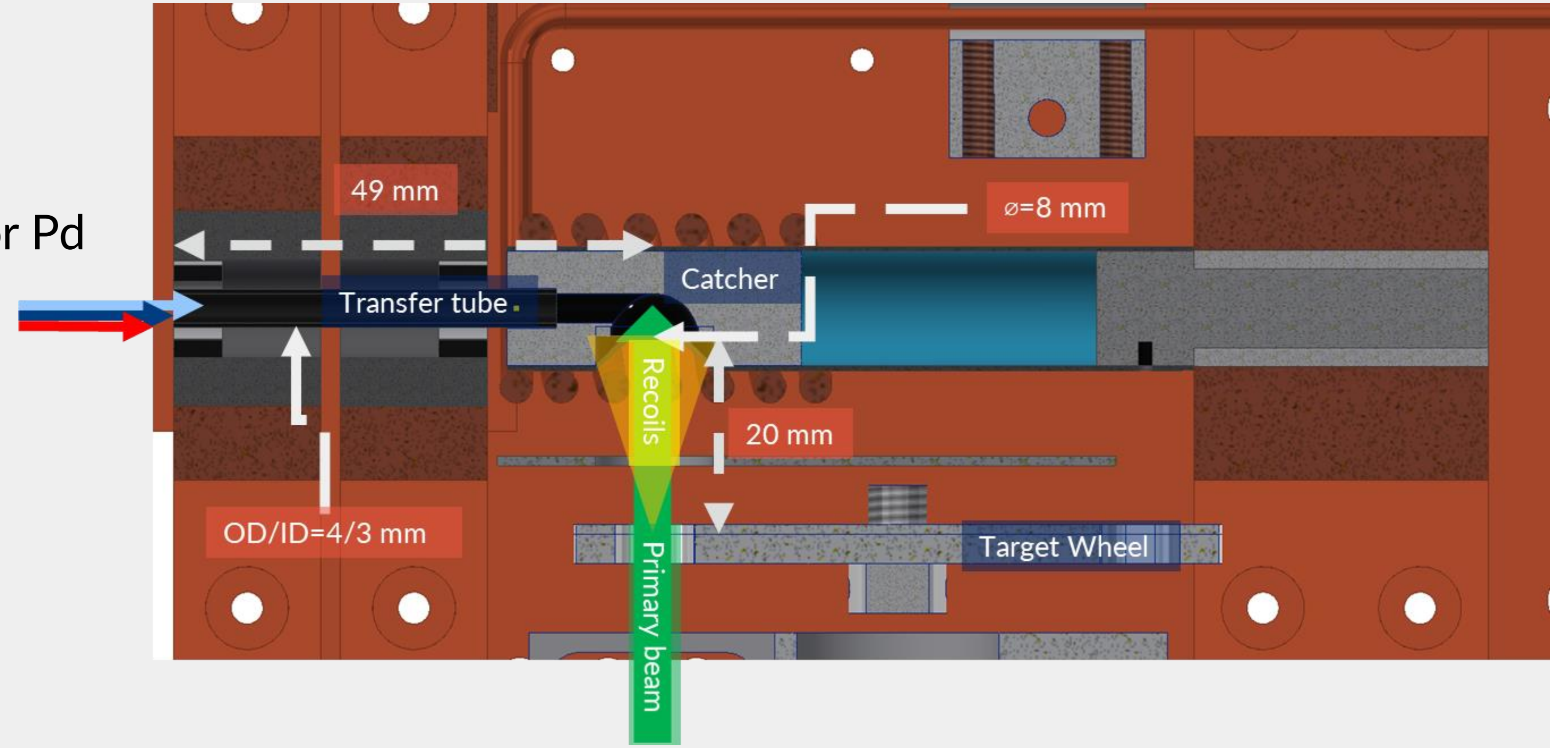
$\mathbf{g} = \mu/\mathrm{I}$ Information on the configuration.



Inductively Heated Hot Cavity Cather Laser Ion Source
ver 6.

- A target ion source system for fusion-evaporation products
  - Efficient: 1 % for Ag and Pd
  - Fast: <20 ms for Ag, less than 90 ms for Pd



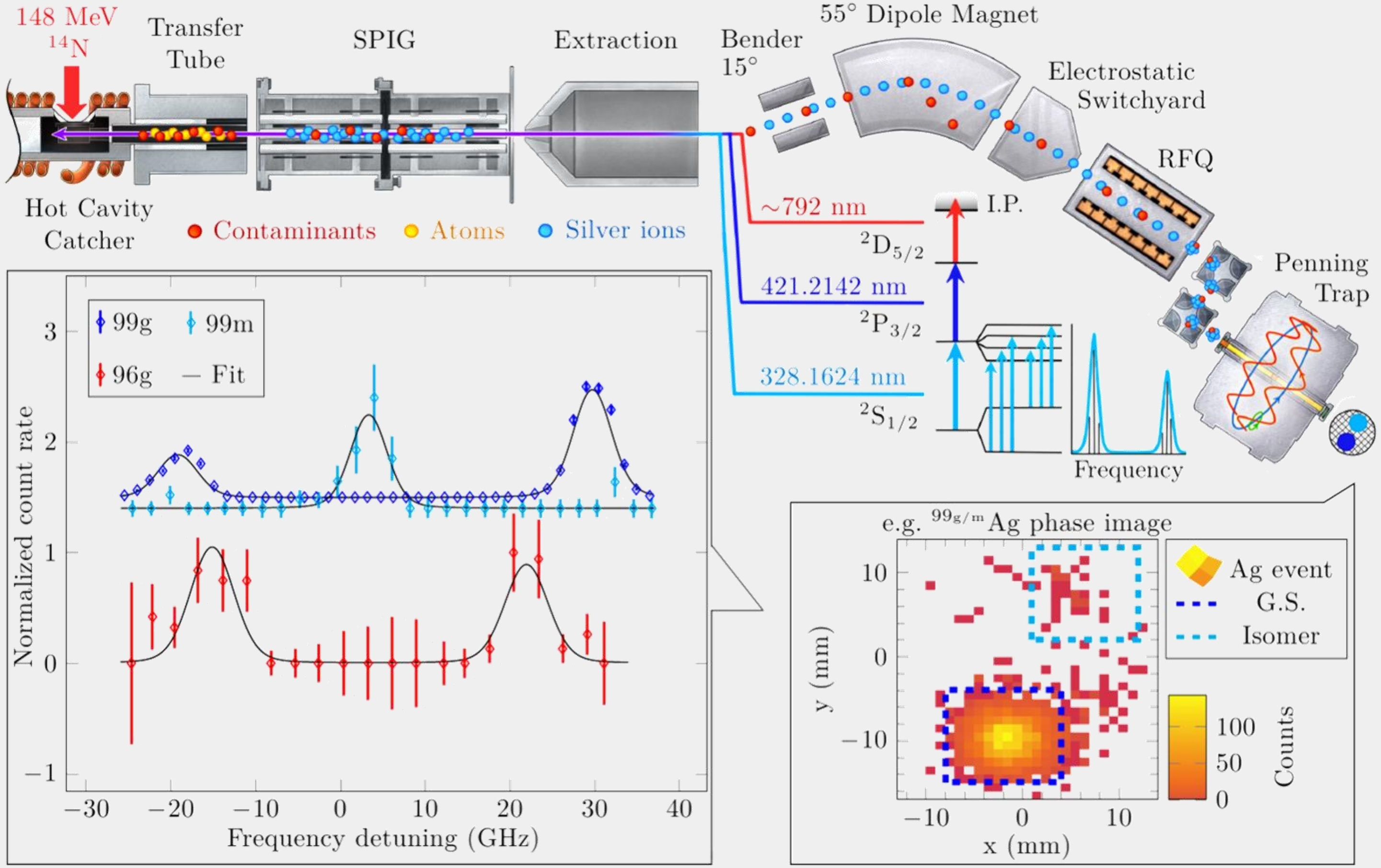


$^{14}N + ^{nat./92}Mo$
$^{40}Ca + ^{58/60}Ni$

Challenging nuclear theory

The first crossing of *N*=50 with optical methods in the tin-100 region

- In-source laser spectroscopy in the immediate vicinity of ^{100}Sn
  - PI-ICR assisted RIS
  - Dual etalon ~5 GHz linewidth.
- *Virtually* a background-free measurements
  - Signal rates of 1 per 5 minutes



Evidence of a sudden increase in the nuclear size of proton-rich silver-96

M. Reponen, R. P. de Groote, L. Al Ayoubi, O. Beliuskina, M. L. Bissell, P. Campbell, L. Cañete, B. Cheal, K. Chrysalidis, C. Delafosse, A. de Roubin, C. S. Devlin, T. Eronen, R. F. Garcia Ruiz, S. Geldhof, W. Gins, M. Hukkanen, P. Imgram, A. Kankainen, M. Kortelainen, Á. Koszorús, S. Kujanpää, R. Mathieson, D. A. Nesterenko, I. Pohjalainen, M. Vilén, A. Zadvornaya & I. D. Moore — Show fewer authors

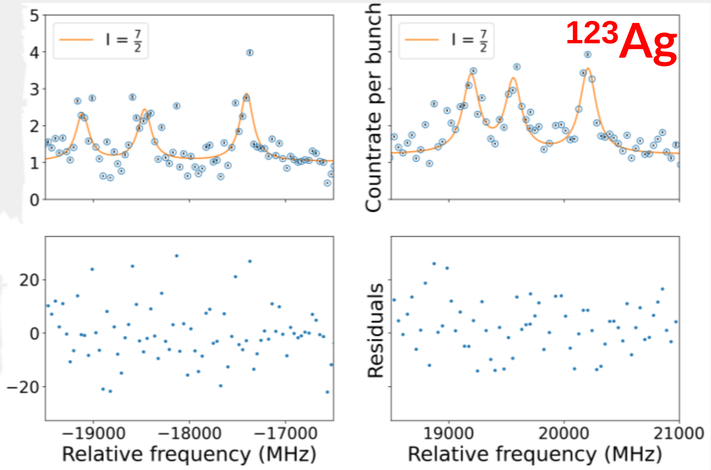
Nature Communications **12**, Article number: 4596 (2021) | Cite this article

Slide contributions: S. Kujanpää

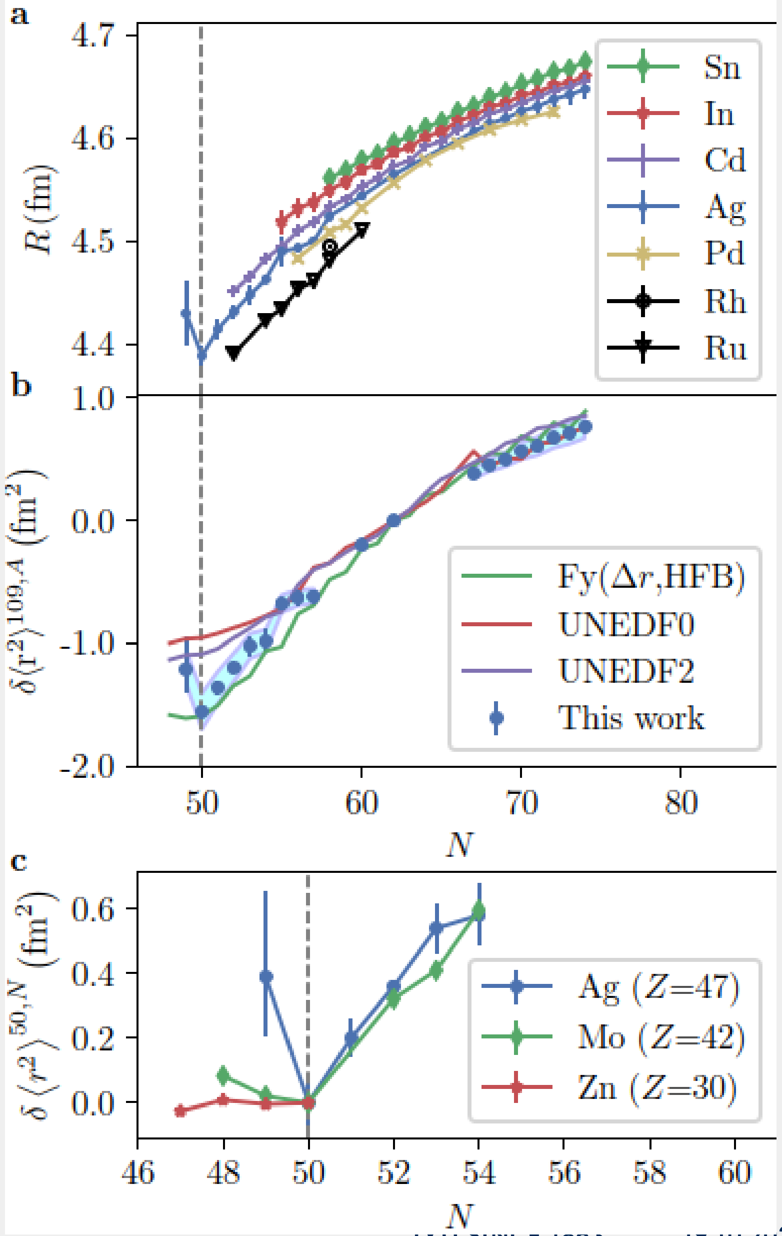
Charge-radii of silver-96

A challenge to nuclear DFT

- Spectra for $^{104-96}$Ag obtained using ^{14}N(^{92}Mo, 2pxn) Ag
- Very sharp kink observed at *N*=50 – beyond current DFT models. More data needed to refine error bar.
  - Points towards a need for symmetry-restored multi-reference EDF
- Complemented by laser spectroscopy of neutron-rich silver in ISOLDE.



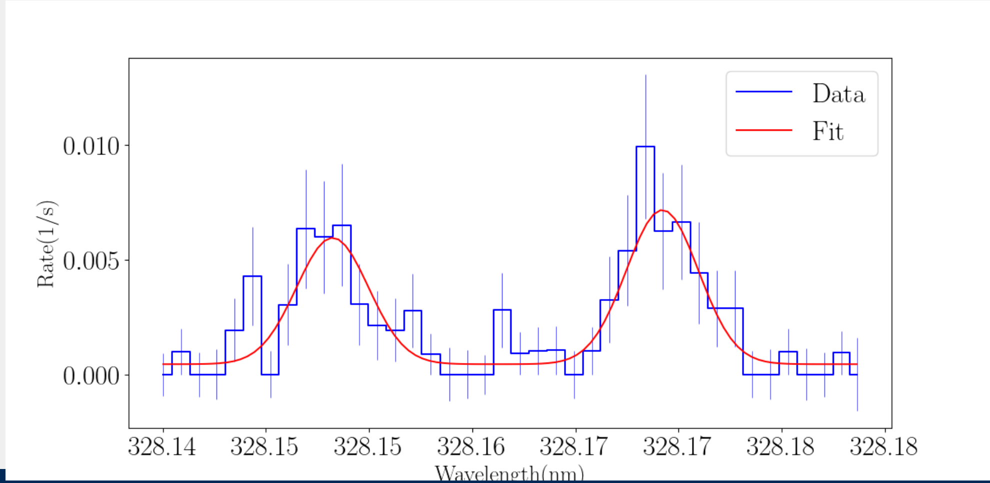
*M. Reponen et al., Nat Comm, **12**, (2021), 4596*

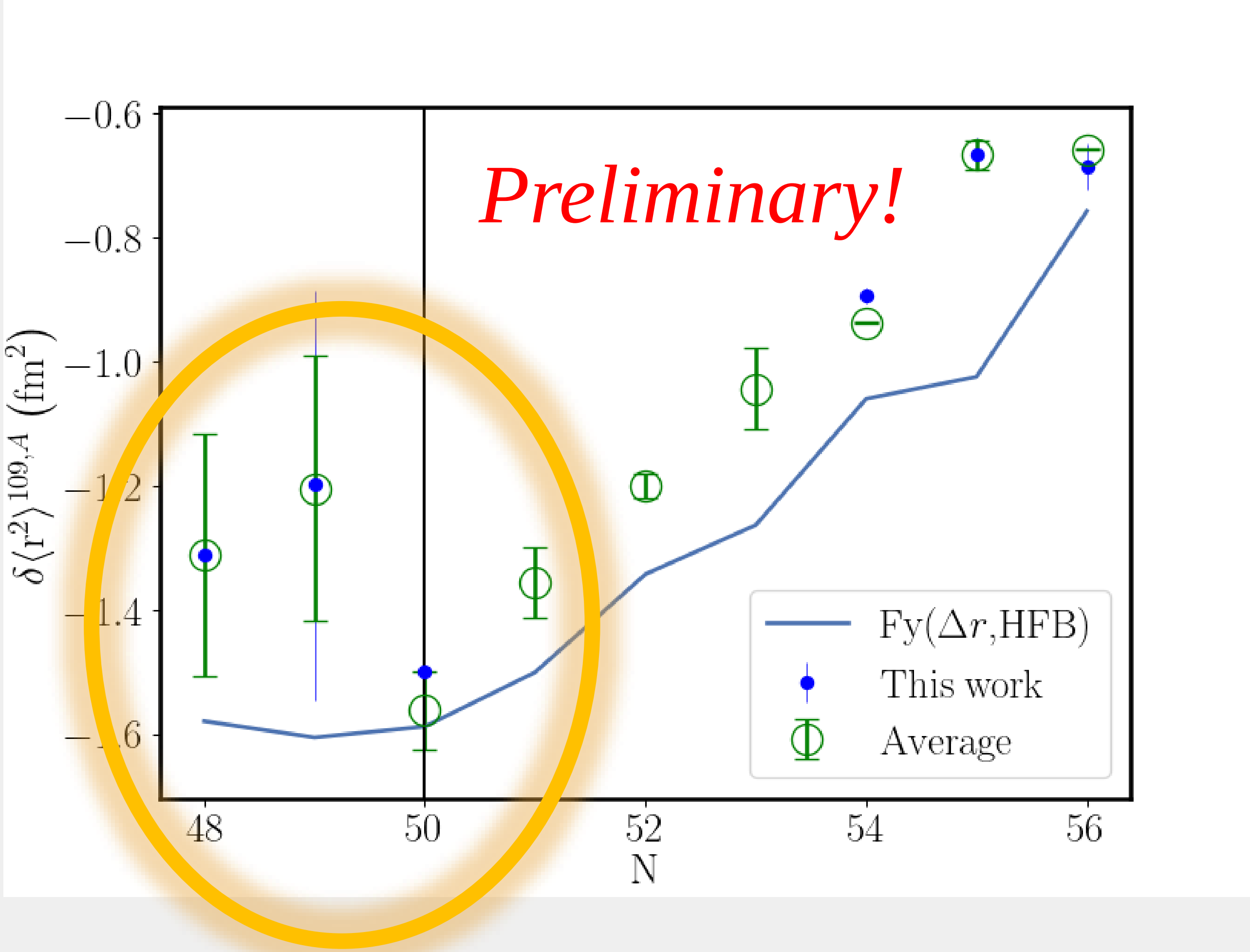


Slide contributions: B. van den Borne, R P. de Groote

Towards the N=Z line
radii of ^{95}Ag

- New data for ^{97,96,95}Ag using ^{40}Ca($^{58/60}$Ni, pxn) Ag
- New charge radii confirms the large kink at N=50.
  - Change in ^{95}Ag radii follows a decreasing trend
    - Low stats => high errors
- Theory development needed to reproduce the feature
  - E.g. Multi-reference EDF.

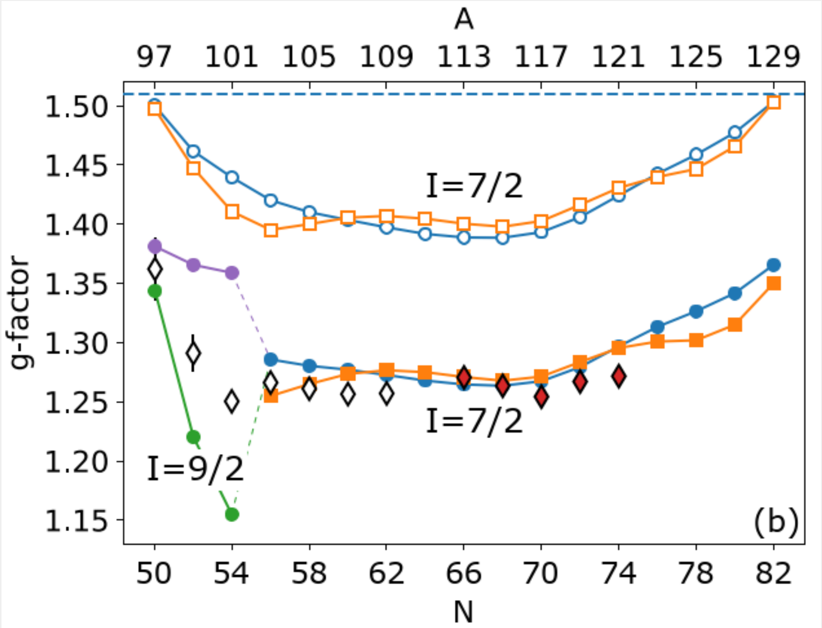


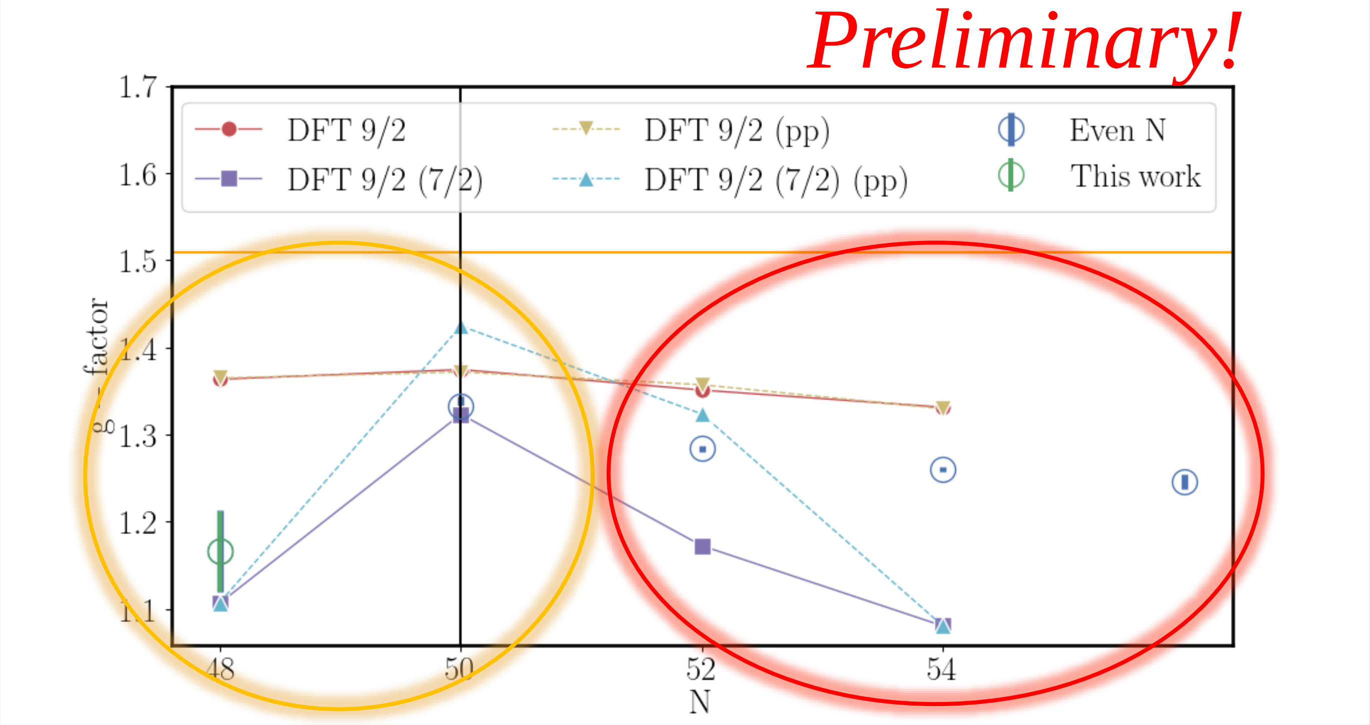


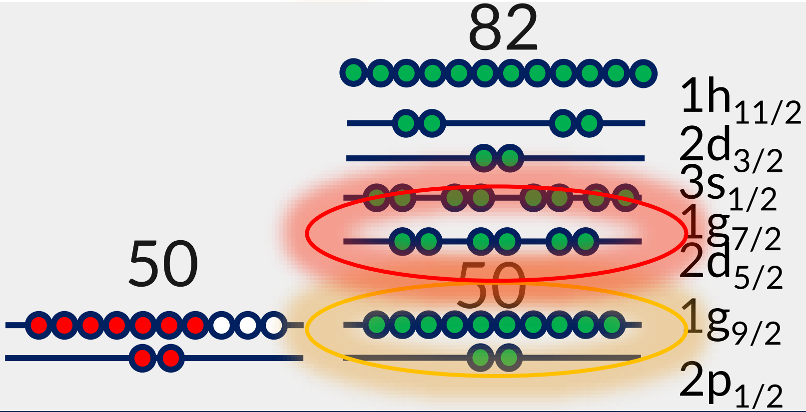
Towards the *N*=*Z* line

magentic dipole moment of ^{95}Ag

- UNEDEF calculationsfor even-N
  - Calculations by Jacek Dobaczewski
  - Following work done for neutron-rich nuclei (R. P. de Groote et al., submitted to Phys. Lett. B)
- Mixing of the two configurations on two sides of *N*=50 seems be different.

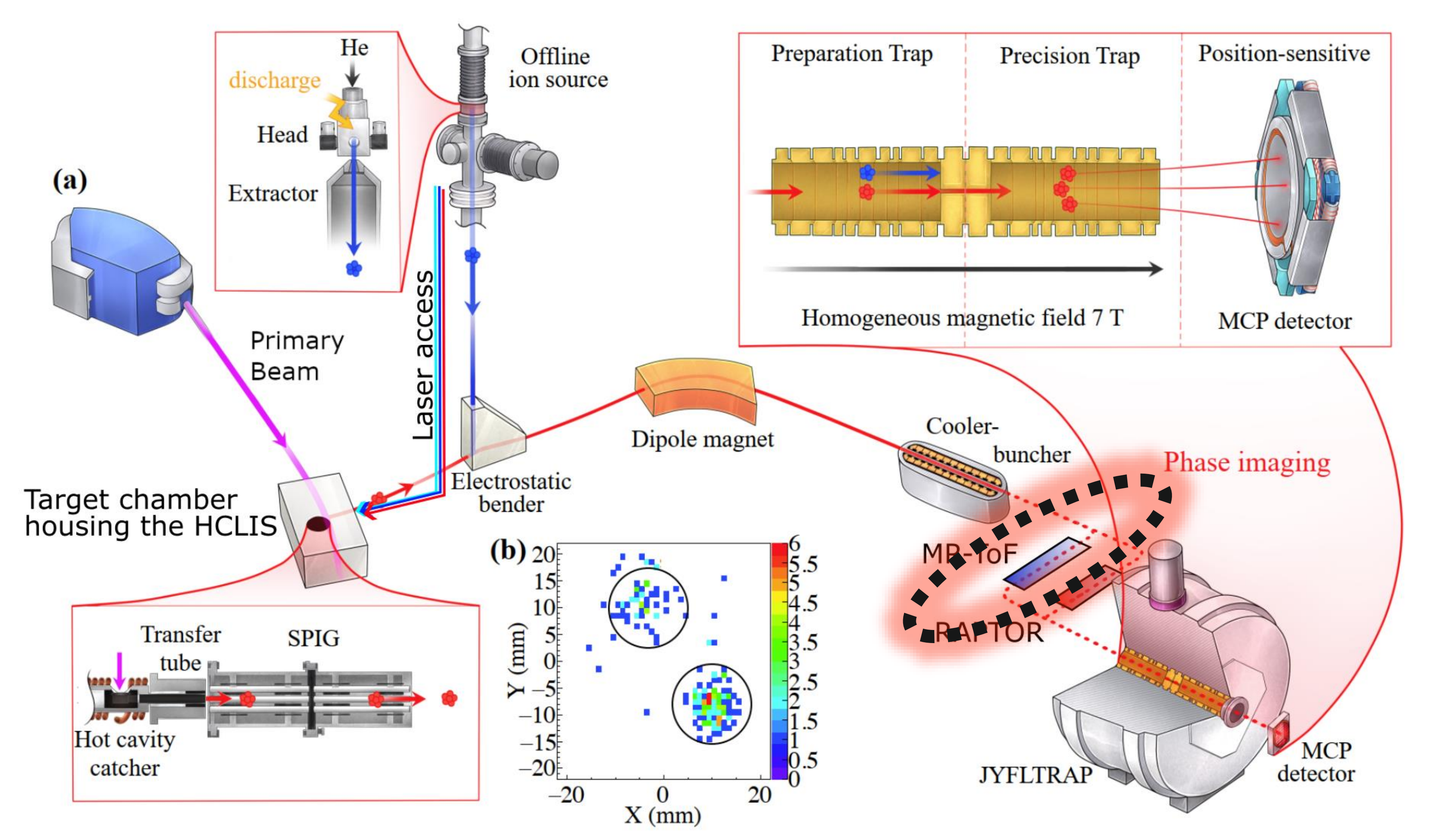






Towards the *N*=*Z* line

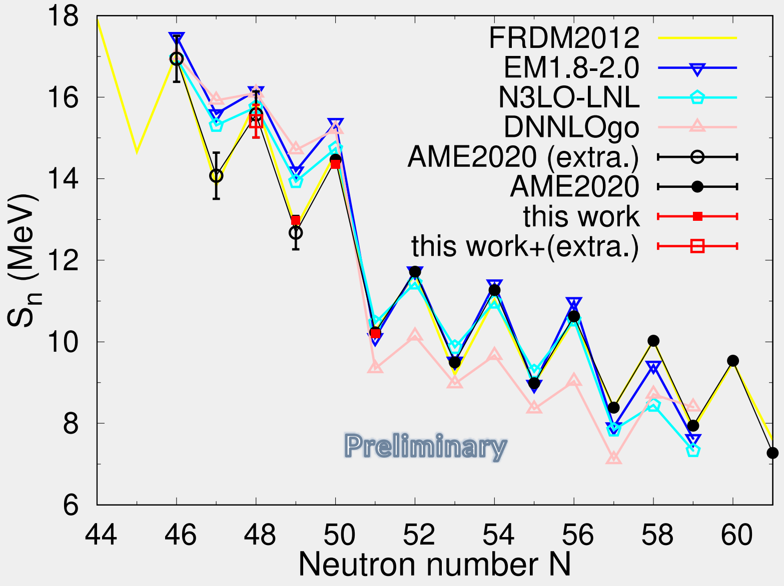
Probing the masses of $^{96-94}$Ag

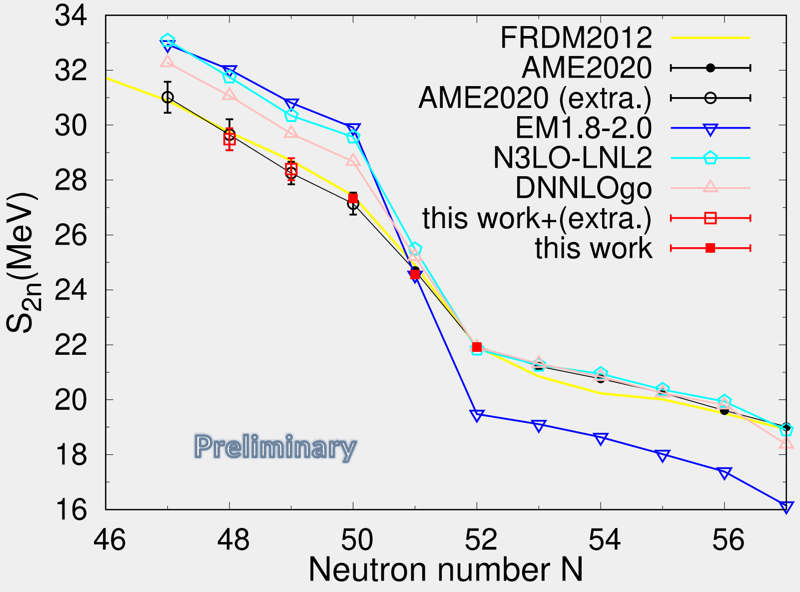


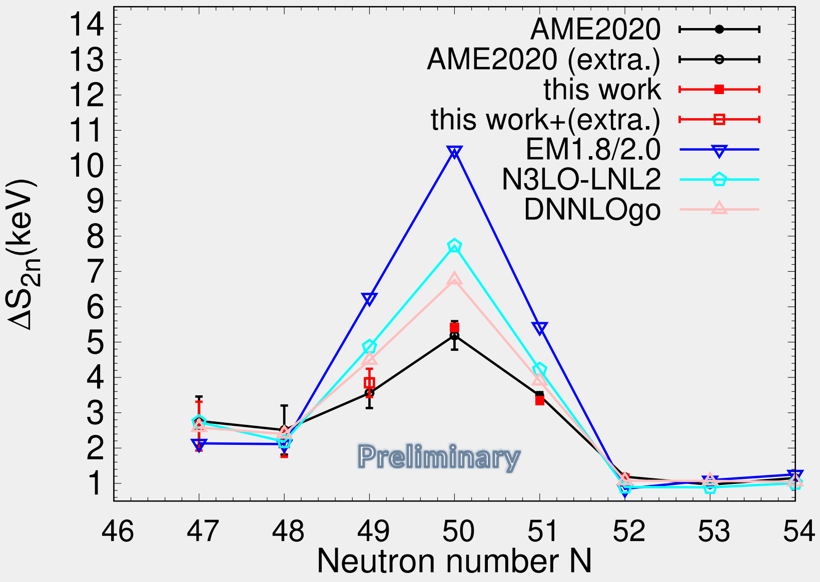
Slide contributions: S. Kujanpää

$^{95-96}$Ag mass: Testing nuclear theories

ab-initio calcluation across the *N*=50 shell B. Hu, J. D. Holt et al.







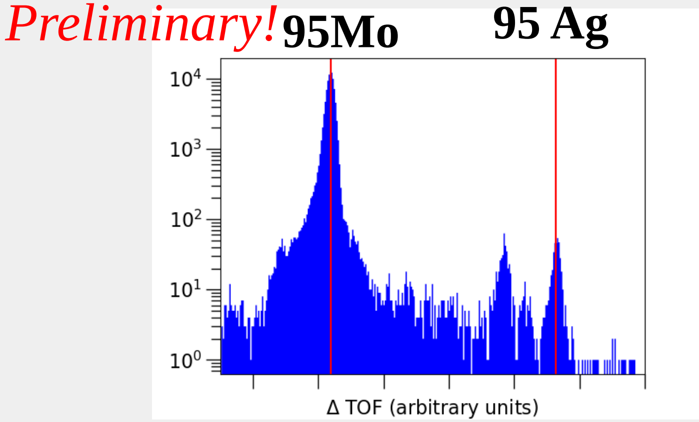
Z. Ge, M. Reponen, T. Eronen et al. in preparation

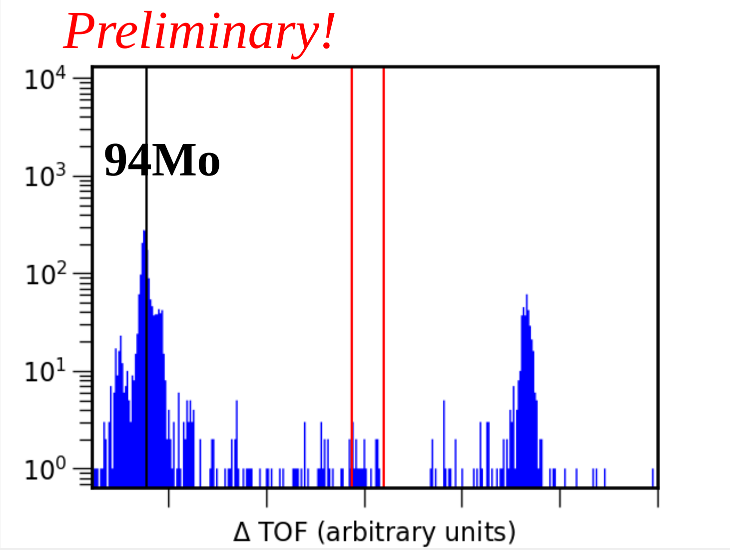
- understanding of the **nuclear structure at *N*=50 shell**
- **Benchmark** nuclear models and shell model calculations

Slide contributions: Z. Ge

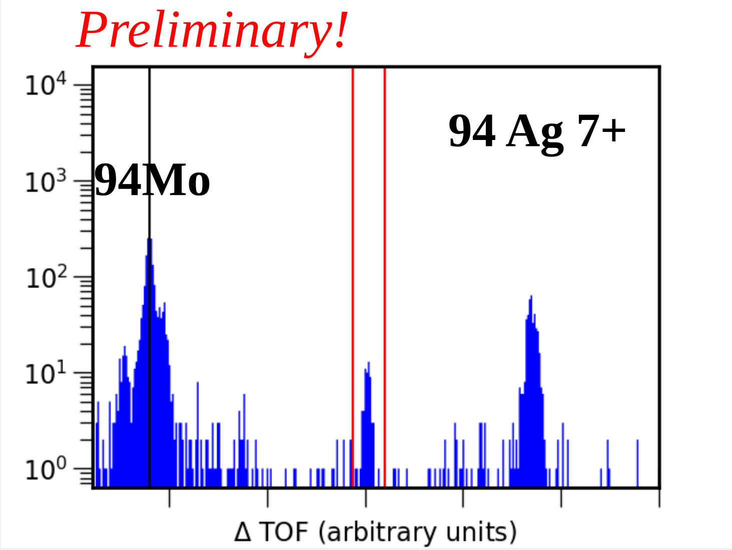
Latest results- mass spectrometry of ^{94}Ag

- Experiment:
  - 2.2 mg/cm^2 ^{58}Ni rotating target, 205 MeV ^{40}Ca beam
    - **^{40}Ca(^{58}Ni,1p3n)^{94}Ag**
  - **1**, 2, 3, 4 µm Mo degrader set
- ^{95}Ag clearly seen with MR-ToF
  - **^{95}Ag measured to compare against Penning trap data.**
- **7+ clearly observed at mass 94 with lasers near at expected centroid.**





With the laser timing delayed

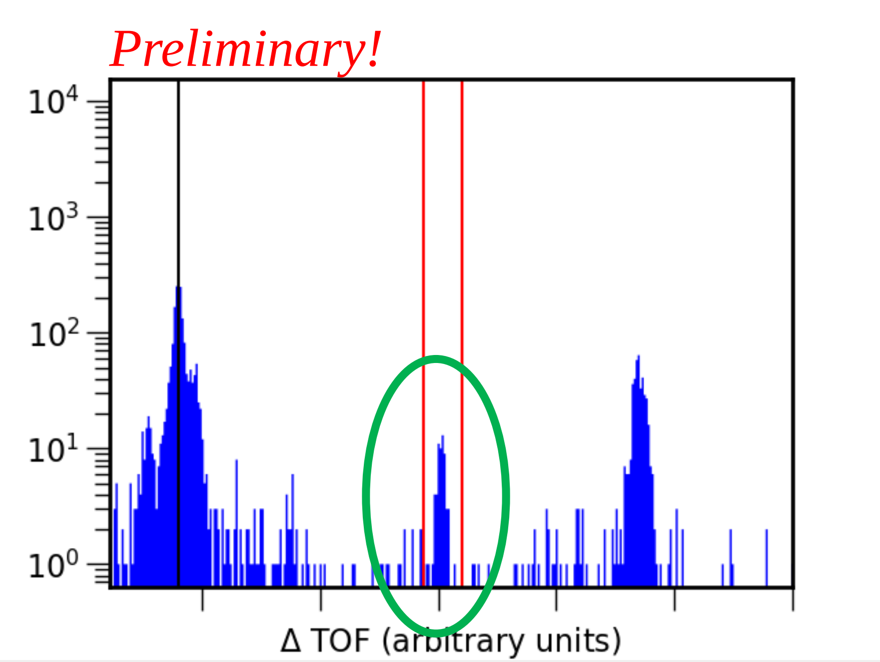


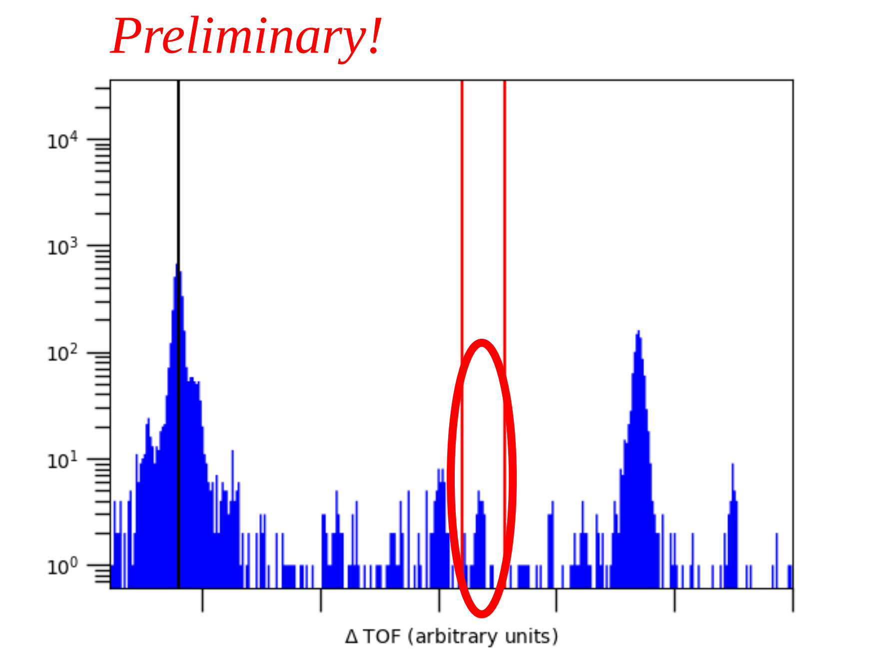
With the lasers on time

Slide contributions: V. Virtanen

Latest results - mass spectrometry of ^{94}Ag

Laser wavelength set to 984.494 nm (JUN45 based estimate for 7+!)





Laser wavelength set to 984.525 nm (JUN45 based estimate for **21+ !)**

Whether the 0+ is in the data will be known later.

^{94}Ag ground state band oberved at MARA (X. Pereira-López EPJA 59, 44 (2023))

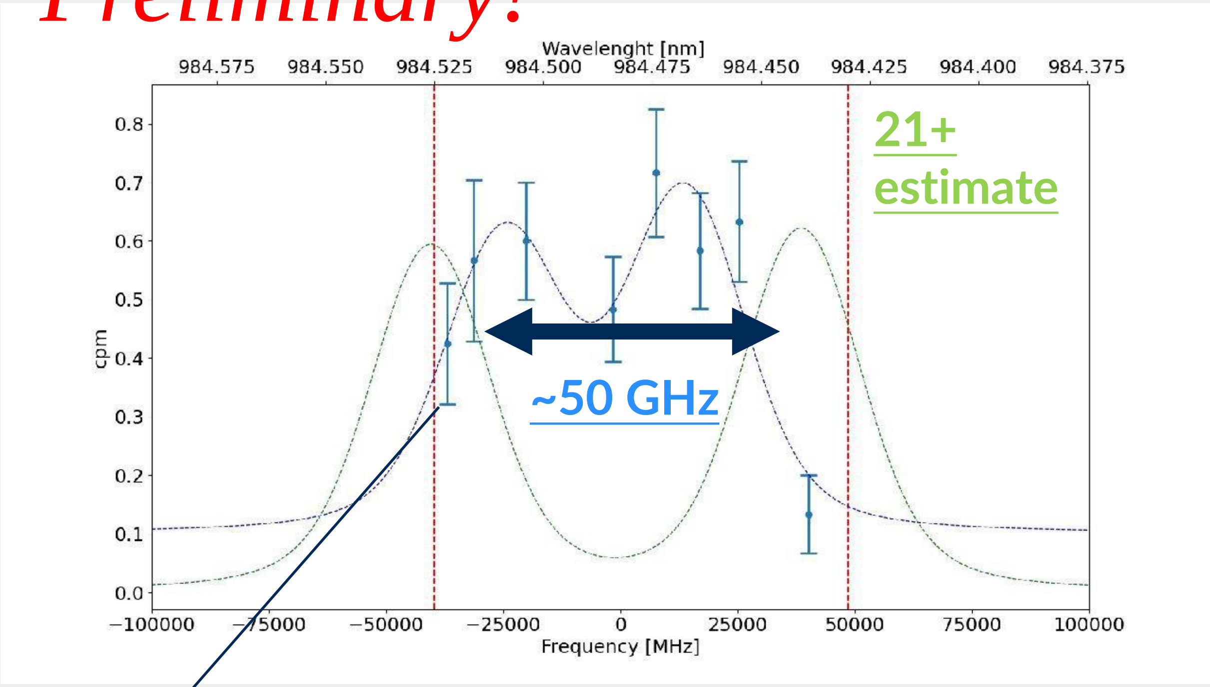
Slide contributions: V. Virtanen

Status and outlook

- **Hot cavity + lasers + mass filters =>Access to *N*=*Z* line!**
  - **Laser spectroscopy done down to ^{95}Ag**
  - **7+ and 21 + isomers mass excess measured in ^{94}Ag.**
- Near future research goals with the setup
  - Laser spectroscopy of proton emitting states
    - 21+ isomer in ^{94}Ag
    - Access to, for example, Tm at drip-line?
  - Decay spectroscopy with pure isomeric beams?
    - Hot cavity efficiency development required.
  - Further ground state studies towards the *N*=*Z*
    - 1 % HCLIS efficiency shown for Pd!

Preliminary!

7+ scan



Laser FWHM ~ 18 GHz = > HFS structure

Thank you for listening!

JYFL: L. Al Ayoubi, O. Beliuskina, L. Cañete, C. Delafosse, A. de Roubin T. Eronen, S. Geldhof, W. Gins, M. Hukkanen, A. Jaries, A. Kankainen, M. Kortelainen, S. Kujanpää, D. A. Nesterenko, I. D. Moore, S. Nikas, I. Pohjalainen, A. Raggio, J. Ruotsalainen, M. Stryjczyk, M. Vilén, V. Virtanen, A. Zadvornaya

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U Liverpool: B. Cheal, C. S. Devlin, A. Koszorus, R. Mathieson

TU Darmstad: P. Imgram

MIT: R. F. Garcia Ruiz

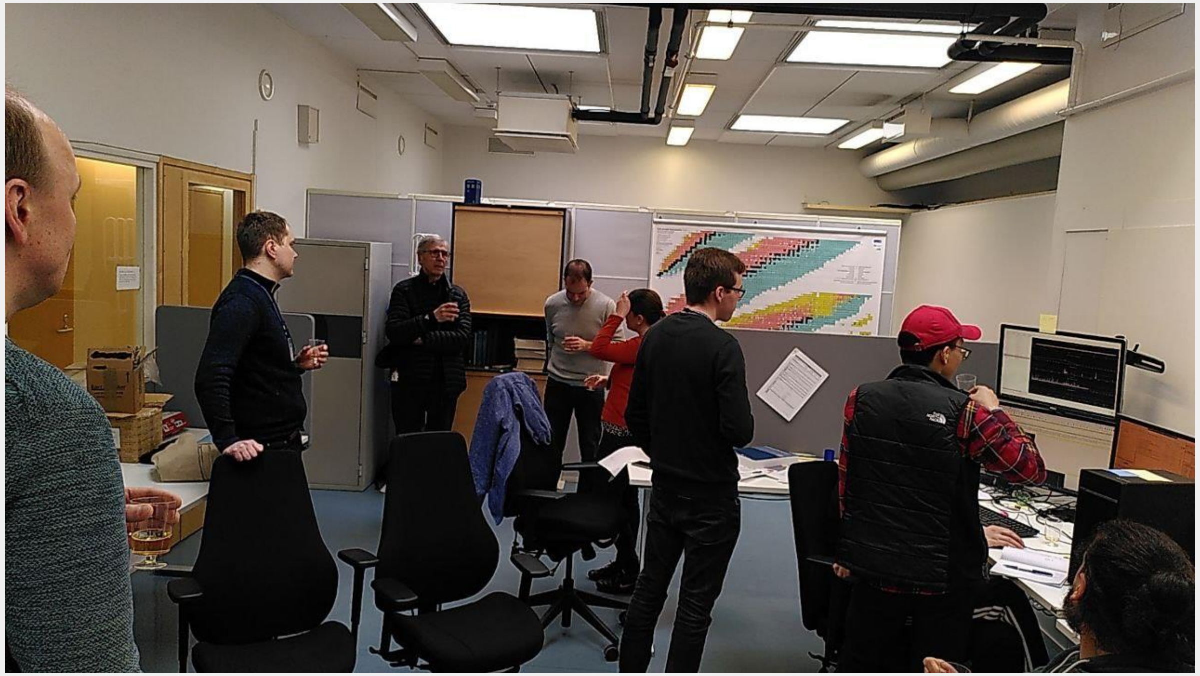
KU Leuven: R. P. de Groote

GSI: Z. Ge

Giessen: G. Kripko-Koncz

GANIL: L. Caceres

CERN: K. Chrysalidis



Affiliation at the time of contribution