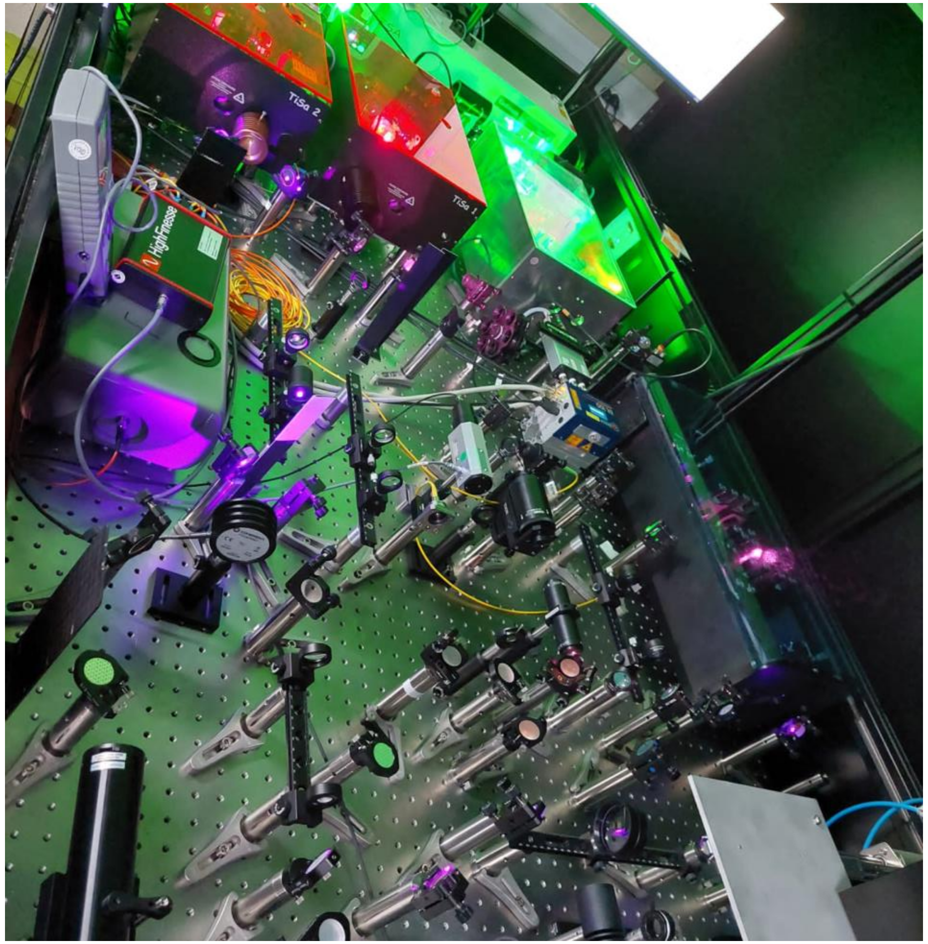
# Coupled laser spectroscopy and mass spectrometry

Antoine de Roubin



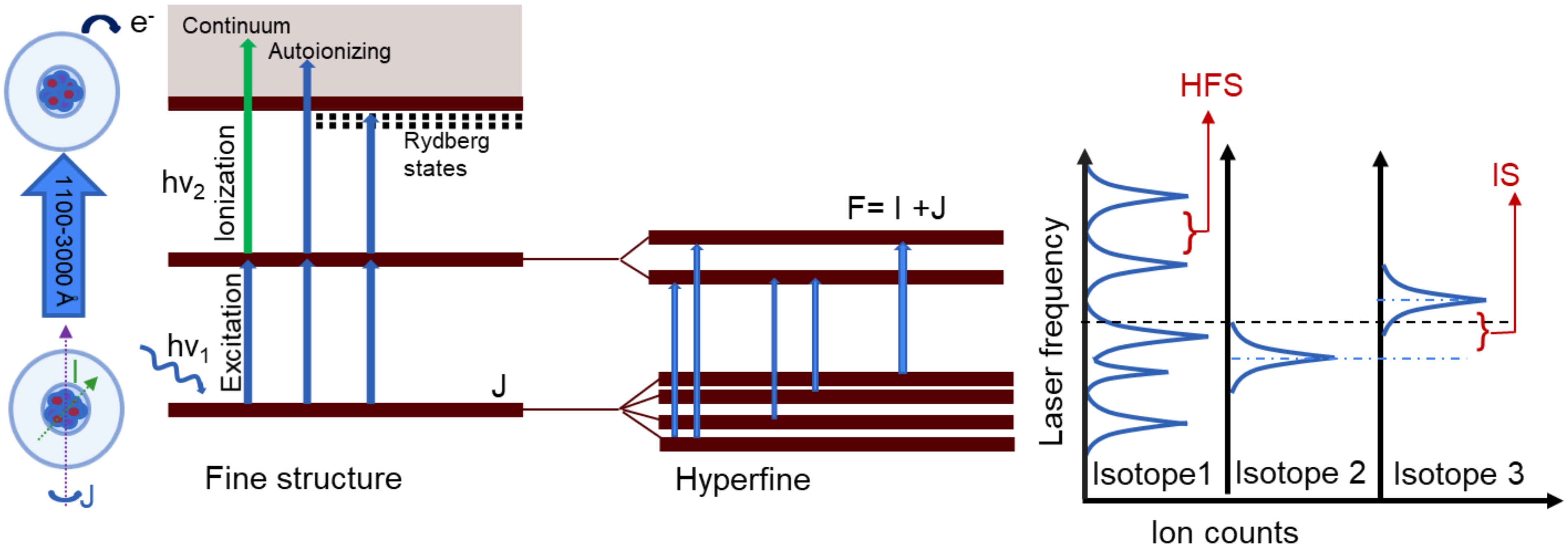
# Outline

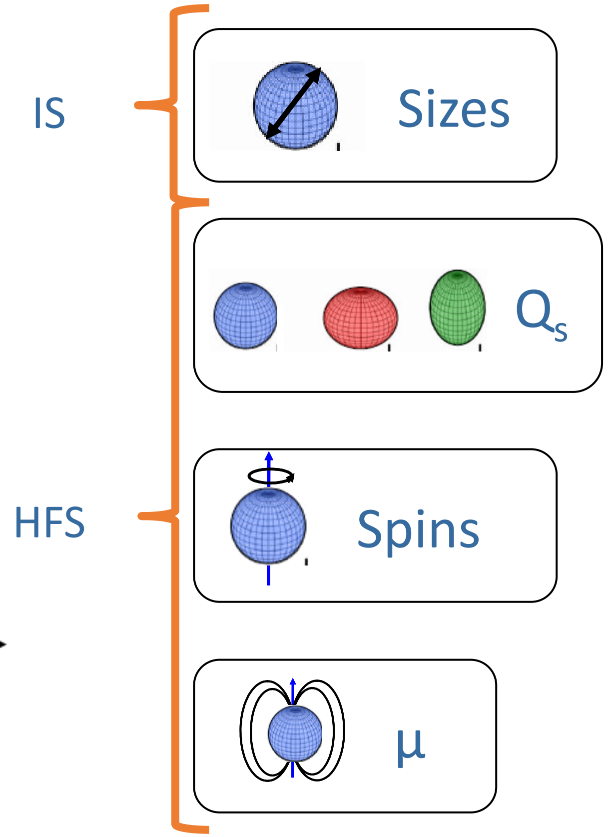
- **Introduction to the techniques:**
  - Laser spectroscopy
  - Mass spectrometry

- **Recent results from coupled laser spectroscopy and mass spectrometry techniques**
  - Ag campaign
  - Hg and In

- **Future perspectives**
  - $S^3$-LEB
  - RADRID & JetRIS
  - PI-LIST
  - RAPTOR

# Resonant laser ionization spectroscopy



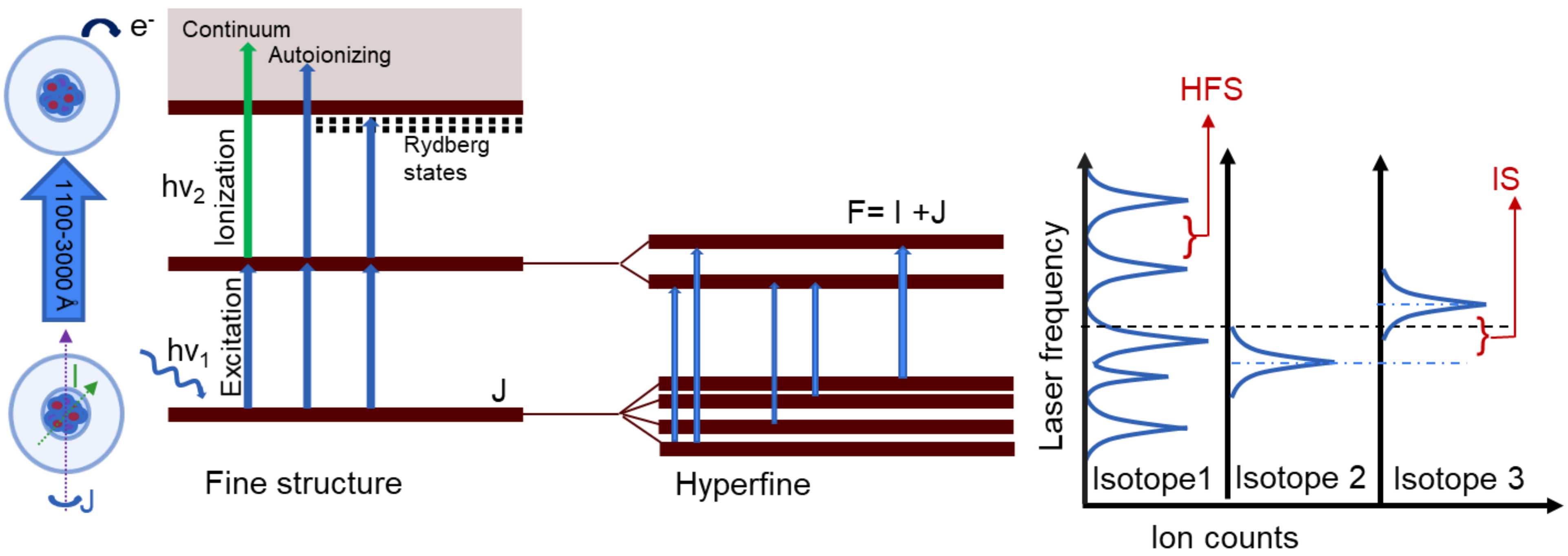



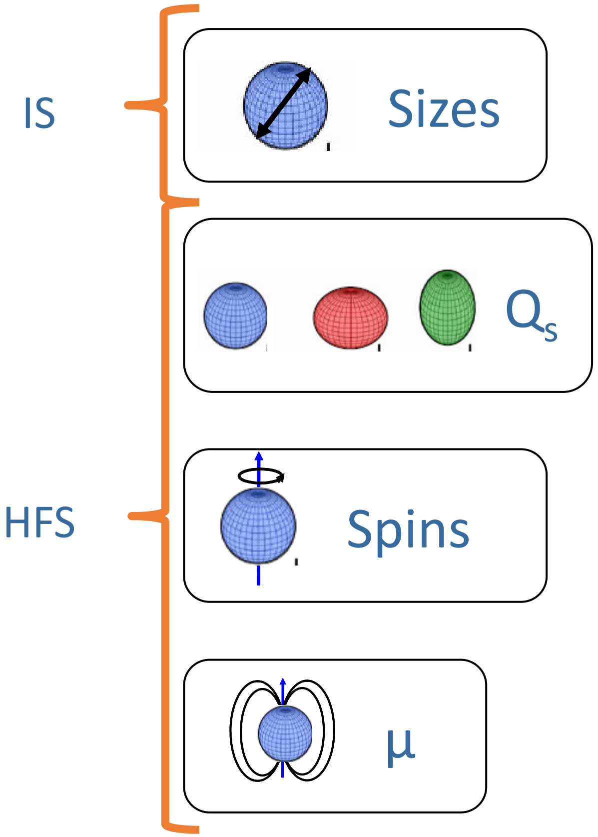

**Resonant Laser Ionization method:**

- Gives an extra selection in Z to the ions of interest
  - Only one given element (isomer) is ionised with the chosen combination of photons.

- Increasing the resolution of the system can give access to the hyperfine structure
  - Due to the coupling of the nucleus with the electronic orbital

# Resonant laser ionization spectroscopy

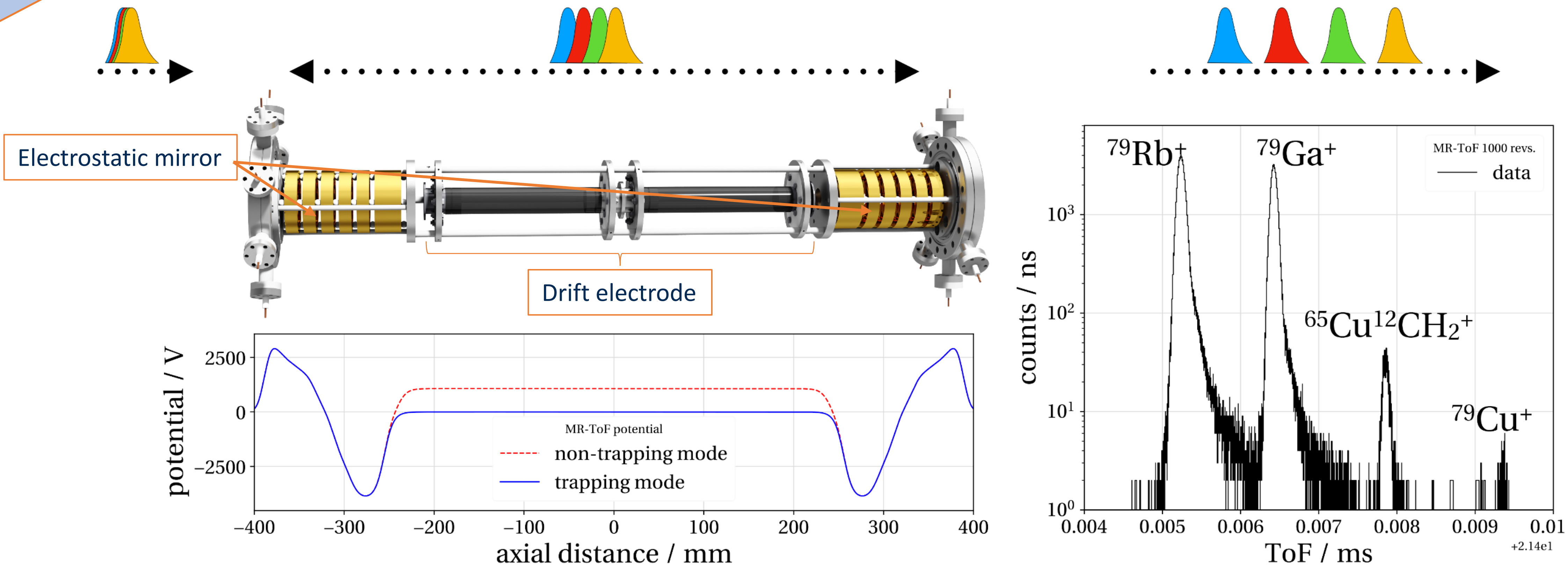



**Resonant Laser Ionization method:**

- Scan the laser frequency of the transition to measure isotope shifts
  - Information on charge radii
- Hyperfine splitting
  - Give access to deformation, spins and magnetic moments.

# Multi-reflection time-of-flight mass spectrometer (MR-ToF MS)



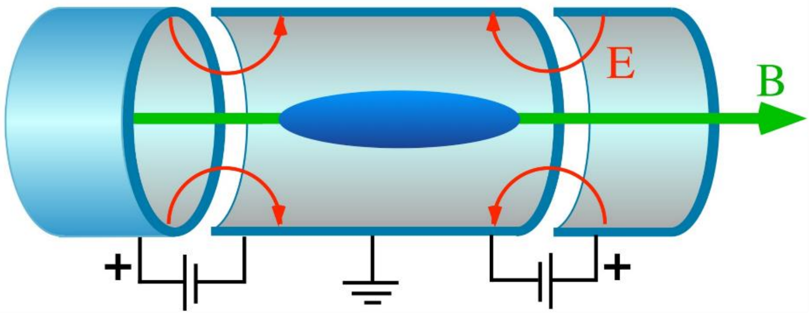

**Tool for mass separation and/or mass measurement**

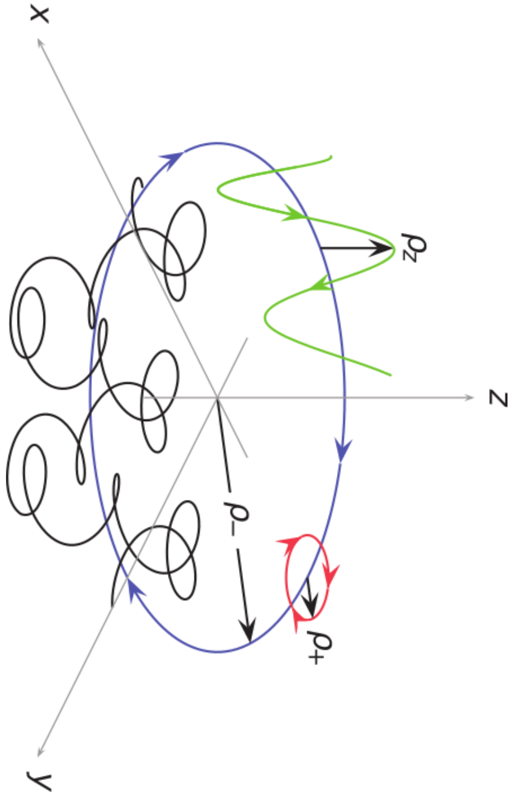
- Extension of the ion species flight path to obtain a mass separation
  - Constituted with 2 electrostatic mirrors and a drift electrode
- Inside a device of ≈ 1 m ions can travel ≈ 1 km
- The potential on the mirror electrodes has to be very precisely defined

# Penning trap

**Radial confinement:**
- strong homogeneous magnetic field

**Axial confinement:**
- electric field




3 ion motions ⟷ 3 ion frequencies

- Axial $\nu_z$
- Magnetron $\nu_-$
- Reduced cyclotron $\nu_+$

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{U_0}{d^2}\frac{q}{m}}$$

$$\nu_\pm = \frac{1}{2}\left(\nu_c \pm \sqrt{\nu_c^2 - 2\nu_z^2}\right)$$

Invariance theorem

$$\nu_c^2 = \nu_-^2 + \nu_+^2 + \nu_z^2$$

Cyclotron frequency

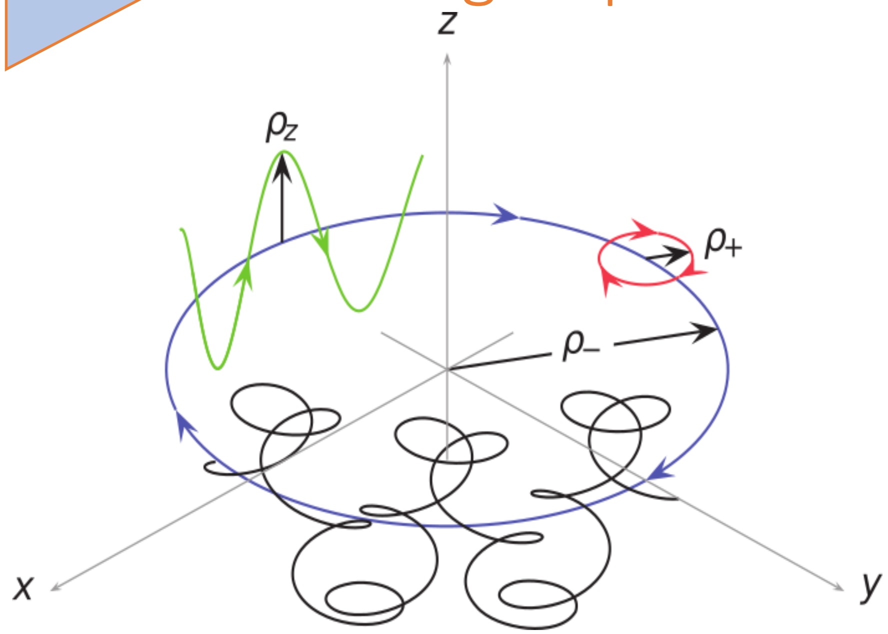
$$\nu_c = \nu_- + \nu_+$$

Cyclotron frequency

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

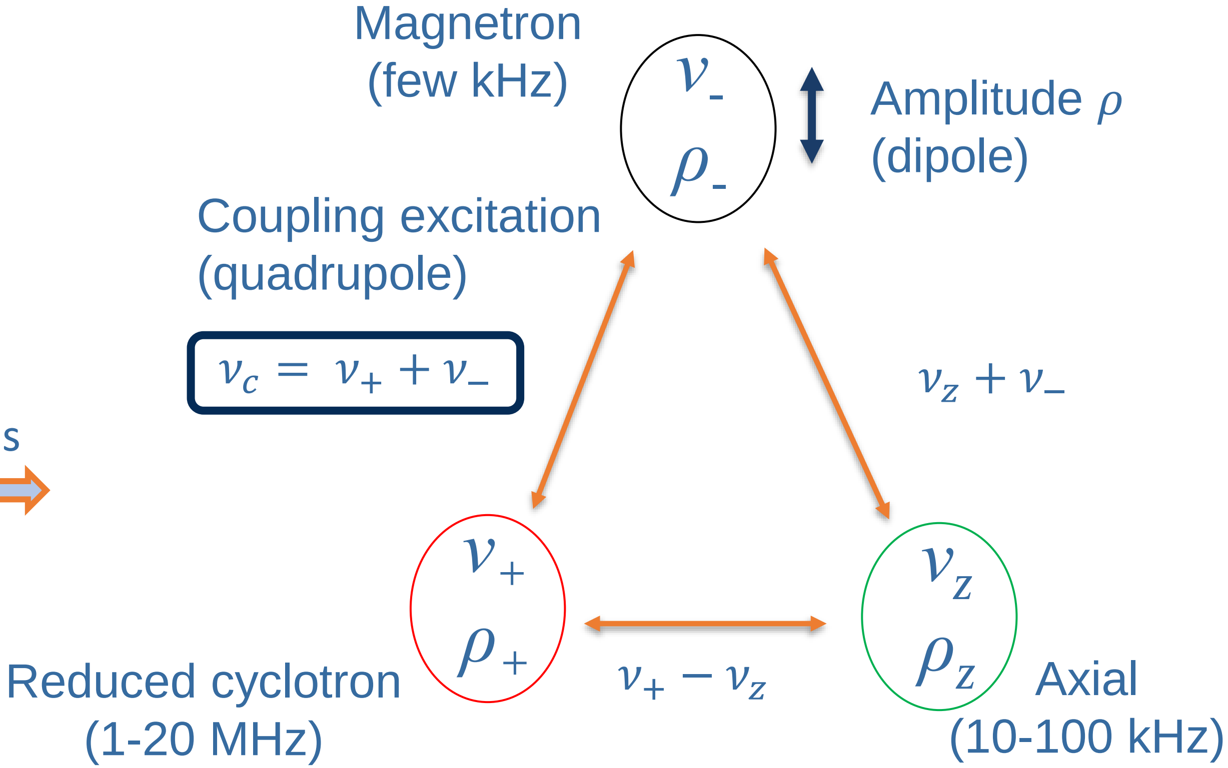
q : electric charge
B : magnetic field
m : mass

# Penning trap




Control amplitudes

Convert motions

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Cyclotron frequency

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q : electric charge
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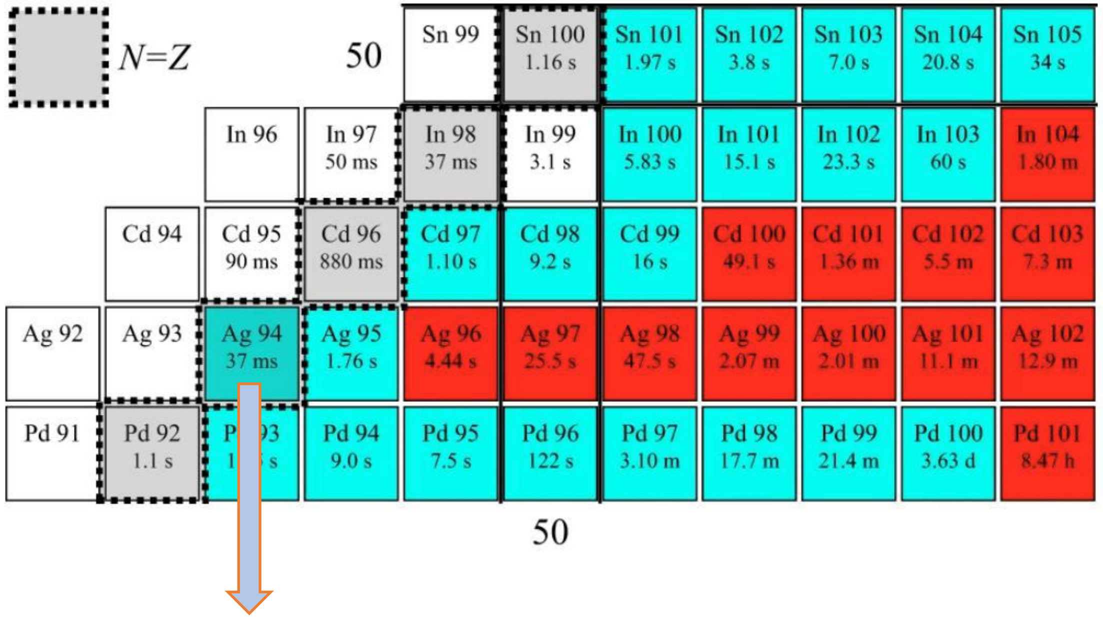
# Penning-trap assisted RIS of silver isotopes

Courtesy of M. Reponen and R.P. de Groote




**Production mechanism :**

- $^{14}\mathrm{N}(^{nat,92}\mathrm{Mo}, 2pxn)\mathrm{Ag}$
- Silver isotopes: dip well below pps
- Other isotopes: much greater quantities
- $^{nat}\mathrm{Mo}$ get knocked out of target ⇒ more contamination
- Cross section for $^{96\text{-}98}$Ag lower compare to other reactions
  - Development of production and detection techniques made it possible!

**One of the most fasinating nuclei:**

- $N = Z$
  - Fertile ground for testing Shell Model predictions
  - Improving our understanding of the p-n interactions
- High-spin isomerism
- Double proton decay ?

# Penning-trap assisted RIS of silver isotopes

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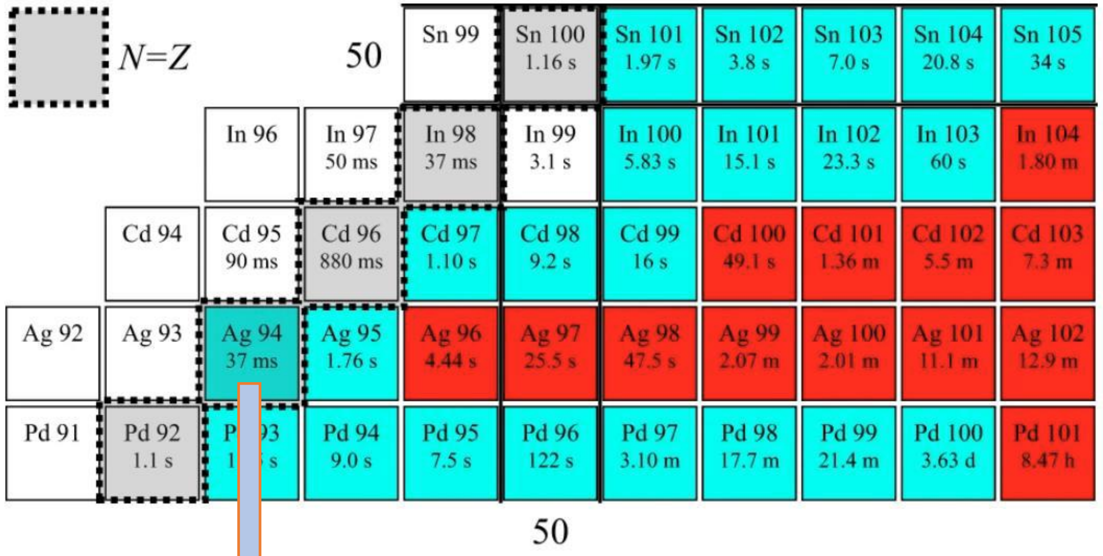
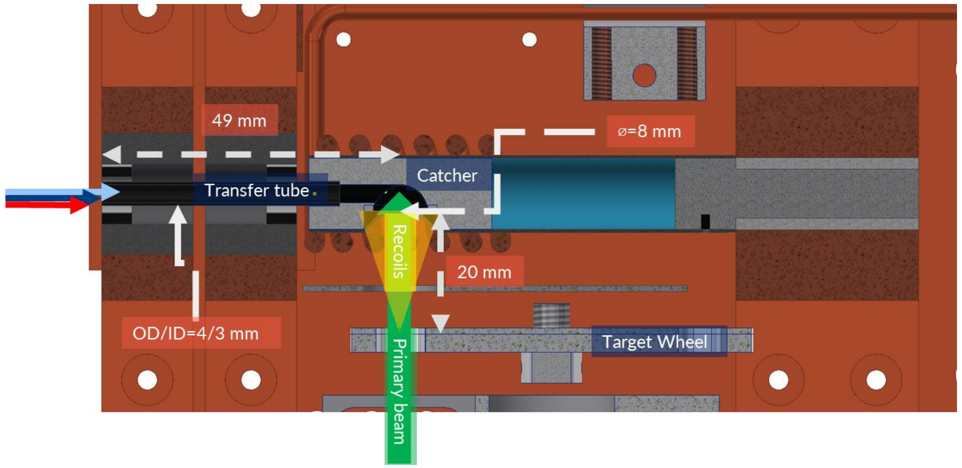



## Hot cavity catcher laser ion source

- Fast
- High efficiency stopping and extraction of neutral reaction products
- Selective laser ionization

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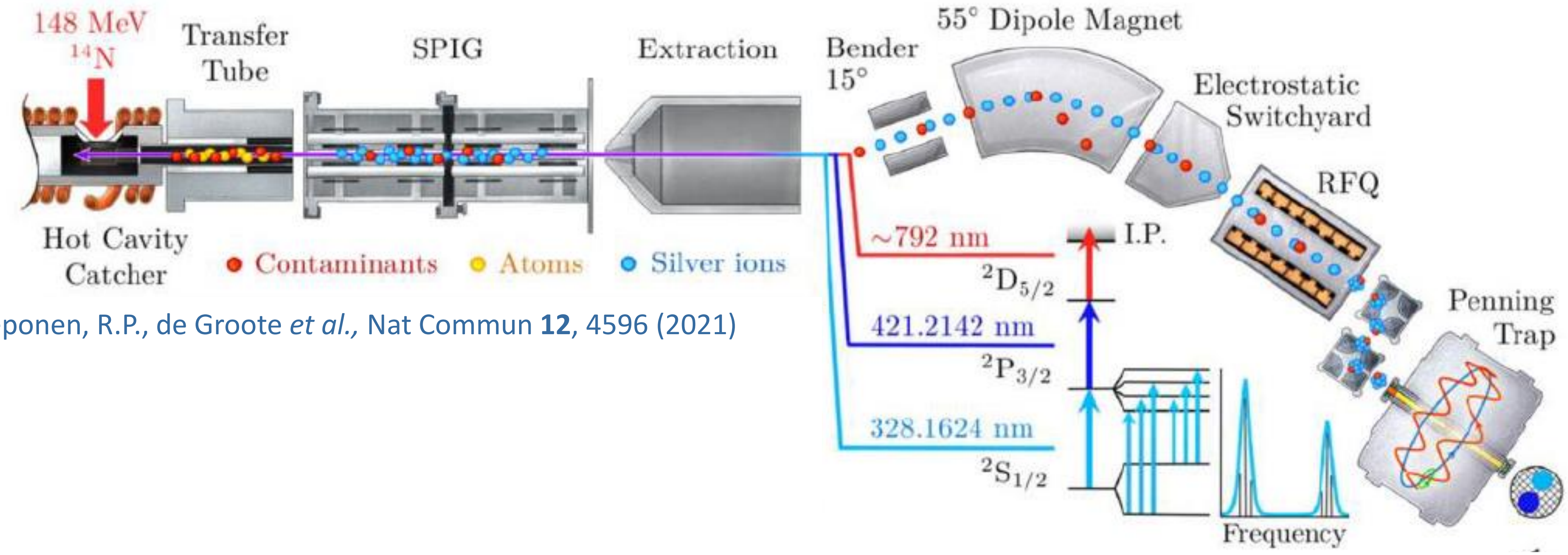
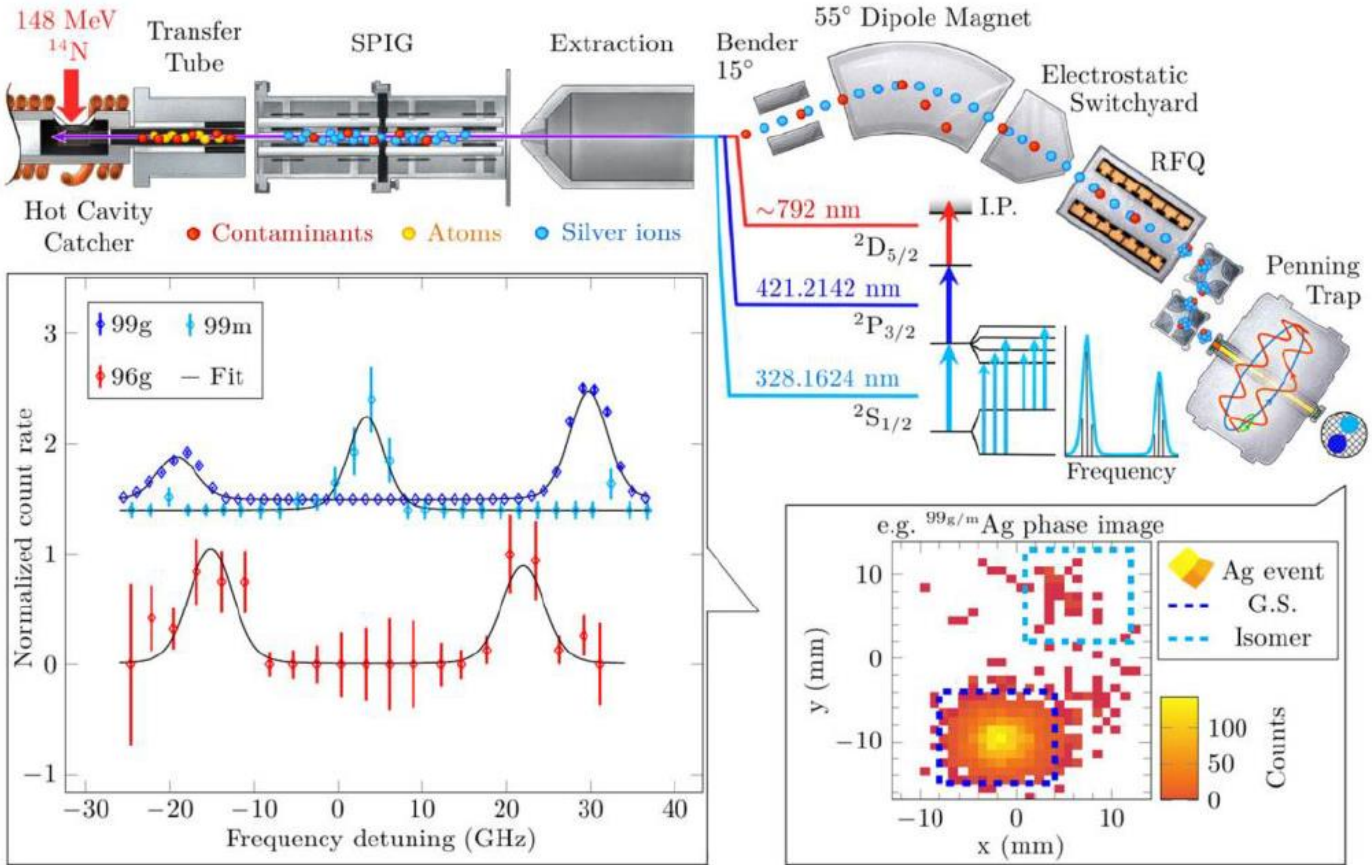



M. Reponen, R.P., de Groote *et al.*, Nat Commun **12**, 4596 (2021)

- Ion are separated with PI-ICR and tagged with the frequency of the first resonance step
- PI-ICR enables simultaneous measurements of the hyperfine structure of nulcear stats with a mass differences as low as $\sim 10$ keV
- RIS of $^{96}$Ag on resonance signal
  - 0.005 cps $\rightarrow \sim \mu$barn
  - Required a low background

# Penning-trap assisted RIS of silver isotopes

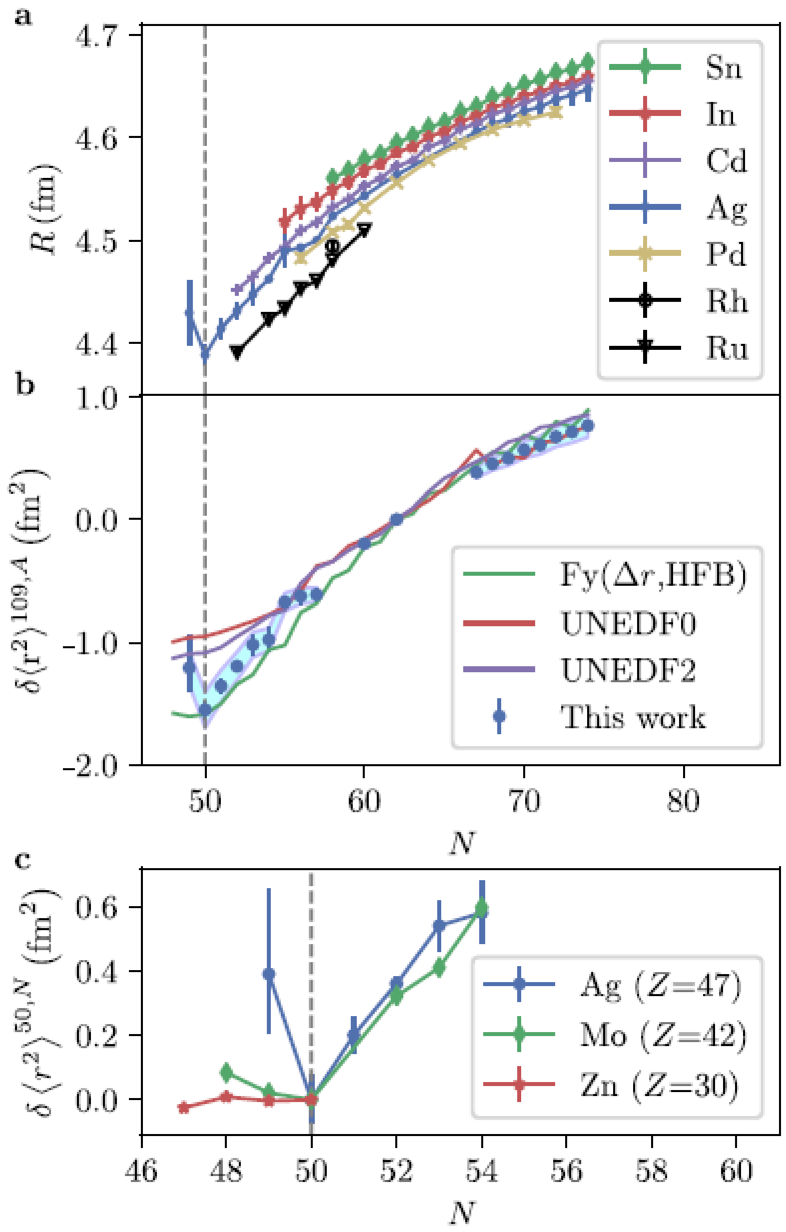



M. Reponen, R.P., de Groote et al., Nat Commun 12, 4596 (2021)

# Penning-trap assisted RIS of silver isotopes

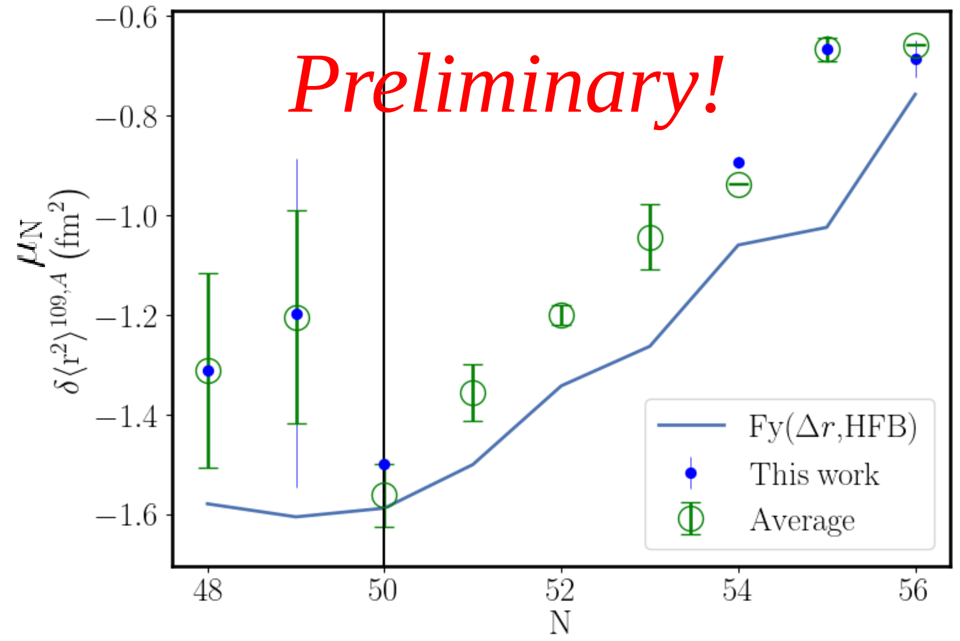
**Kink at $N = 50$**

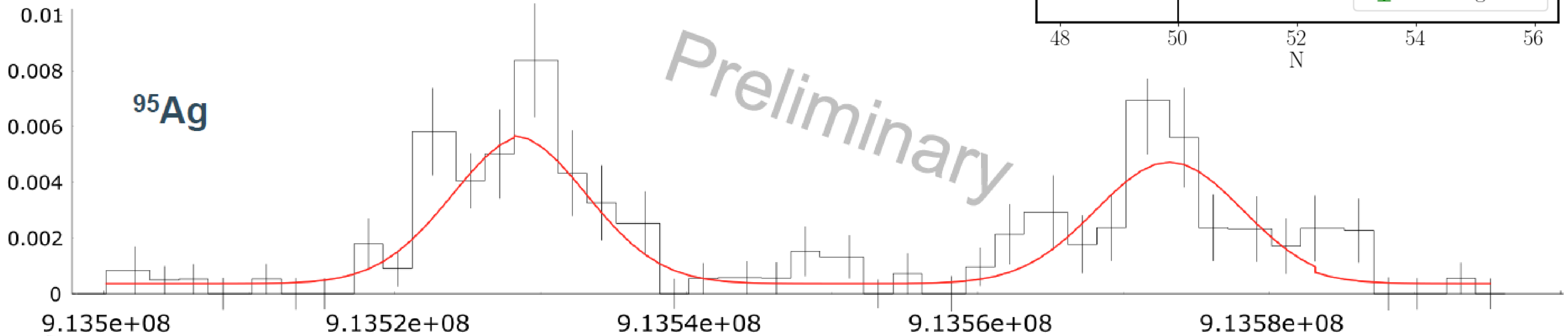
- Also observed for other magic nuclei: $N = 28, N = 82$
- Provides support for $N = 50$ as a magic number
- Larger increase in charge radius in the Ag chain
  - Perhaps indicating an increasing trend in magnitude towards doubly-magic $^{100}$Sn?
- The charge radii of $^{94,95}$Ag are required to understand the trend across N = 50



# Penning-trap assisted RIS of silver isotopes

- New charge radii confirms the kink at $N = 50$.
- Magnetic moments of even-$N$ isotope indicate a different mixing on the two sides of $N = 50$.
- MR-ToF measurement performed on $^{94}$Ag.
- Analysis under way
- **Indicate the feasibility of RIS of the 21+ isomer!**



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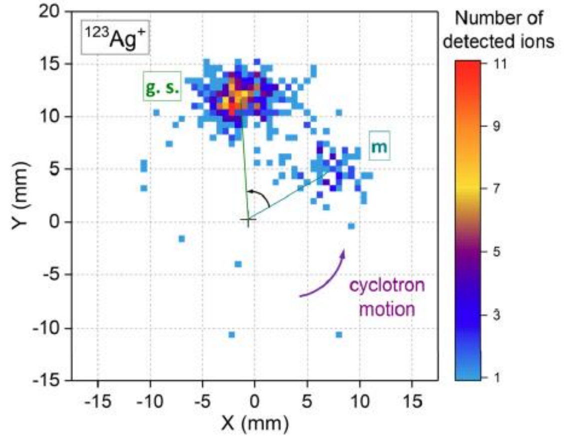
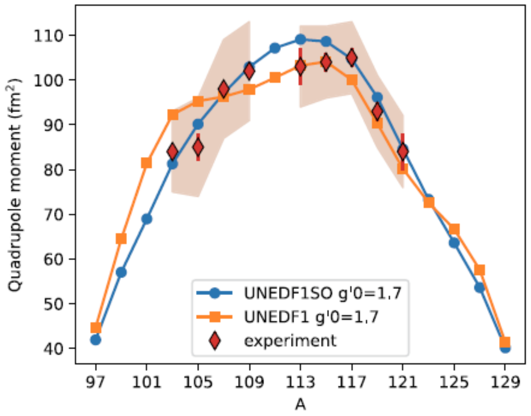


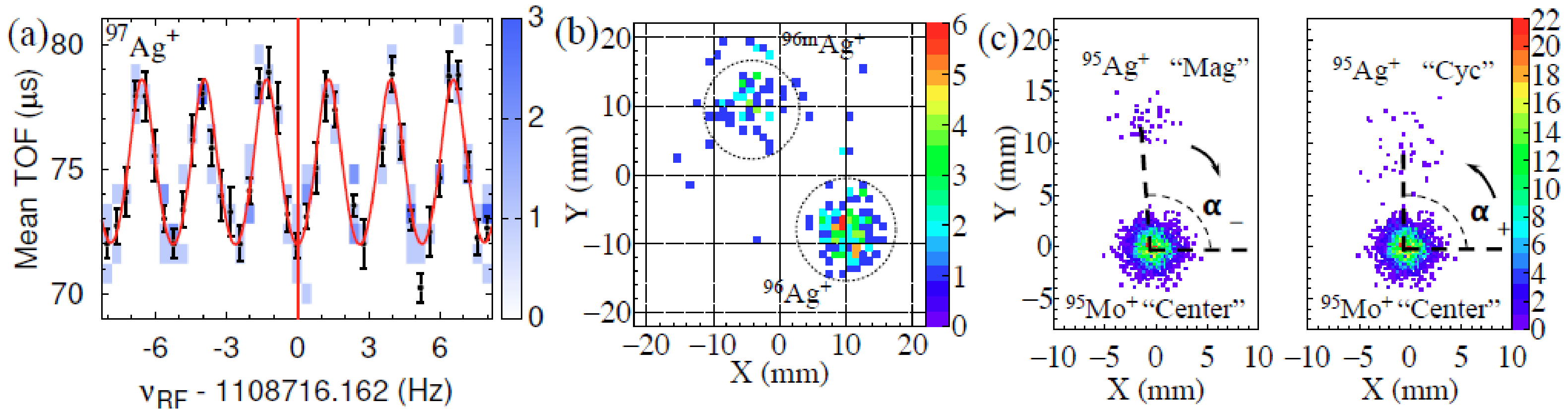




**High-precision measurements of:**

- nuclear binding and excitation energies
- nuclear spins
- magnetic dipole
- electric quadrupole moments

of neutron-rich silver isotopes $^{113-123}$Ag

- High-precision mass measurements of $^{95-97}$Ag isotopes
- The precise determination of the isomeric excitation energy of $^{96m}$Ag serves as a benchmark for ab initio predictions of nuclear properties beyond the ground state




R.P., de Groote *et al.*, PLB **848**, 138352 (2024) & Z. Ge *et al.*, arXiv:2401.07976v1 (2024)

# Shape staggering in Hg

**Production:**
- Proton induced reaction in molten Pd target
- Vapor effuses into the anode of the VADLIS ion source

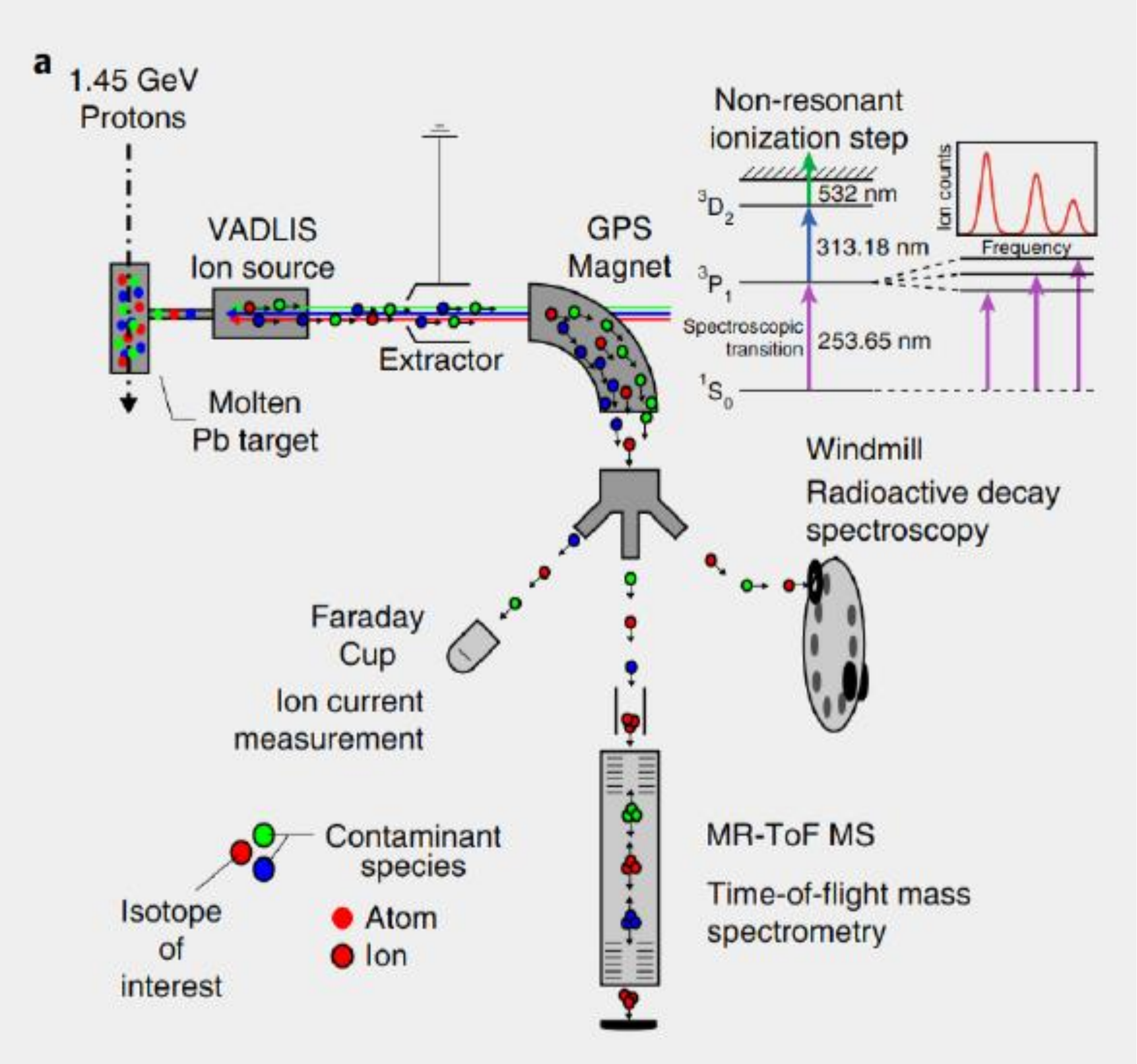
**RILIS mode:** no electron impact ionization, $Hg^{+}$ beam purity maximised

**Ions transported to one of several possible detection stations:**
- Decay spectroscopy: tag on characteristic radiation
- Mass spectrometry: single out one isotope from isobar using its mass

**Yields:** ~ 1 ion per minute

**Flexibility:** Tailor the detection to the isotope and beam at hand

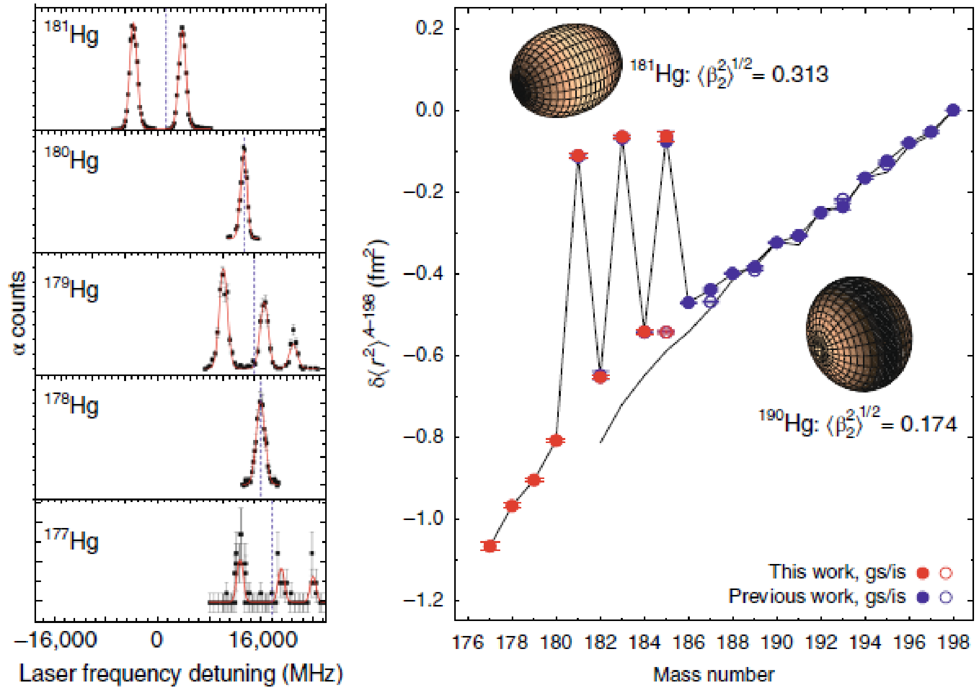
B.A. March *et al.*, Nature Phys **14**, 1163-1167 (2018)

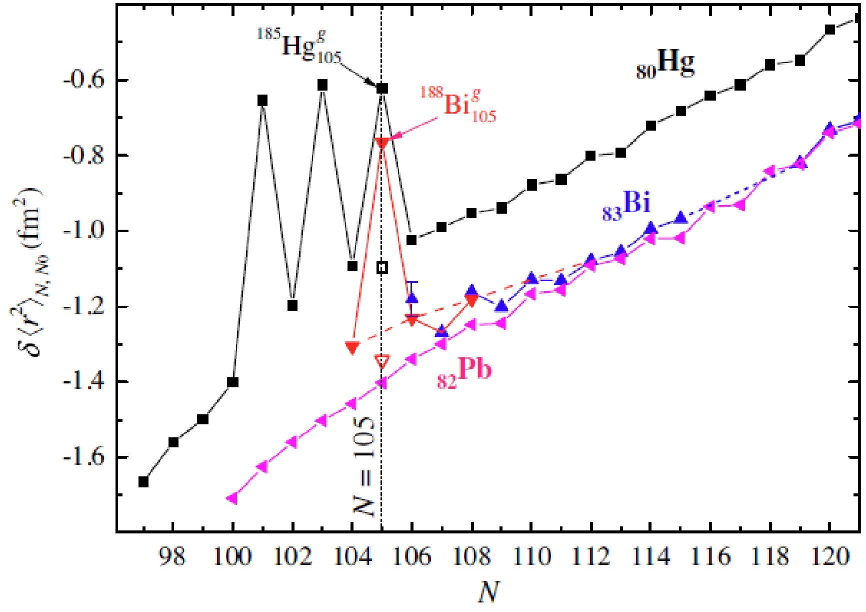


# Shape staggering in Hg

**Shape staggering in Hg and Bi:**

- Odd Hg isotopes → large charge radii
  - Origin?
  - Interplay between monopole and quadrupole interaction driving a quantum phase transition
- Significant challenge for nuclear theory
- Magnetic moments are key to pin down nuclear configuration to aid the interpretation!



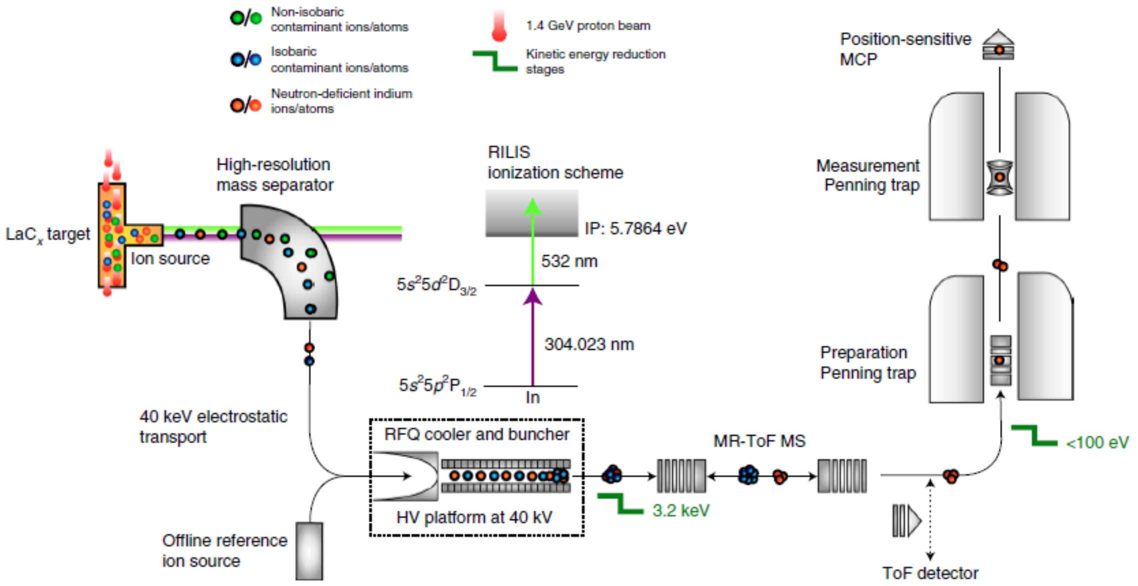

B.A. March *et al.*, Nature Phys **14**, 1163-1167 (2018)
A. Barzakh *et al.*, PRL **127**, 192501 (2021)

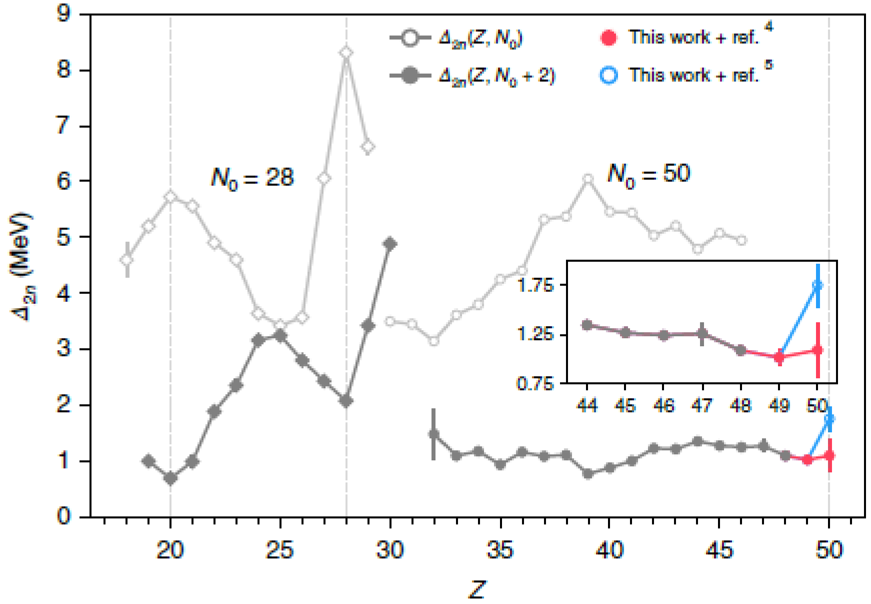
# Mass measurements of $^{99-101}$In

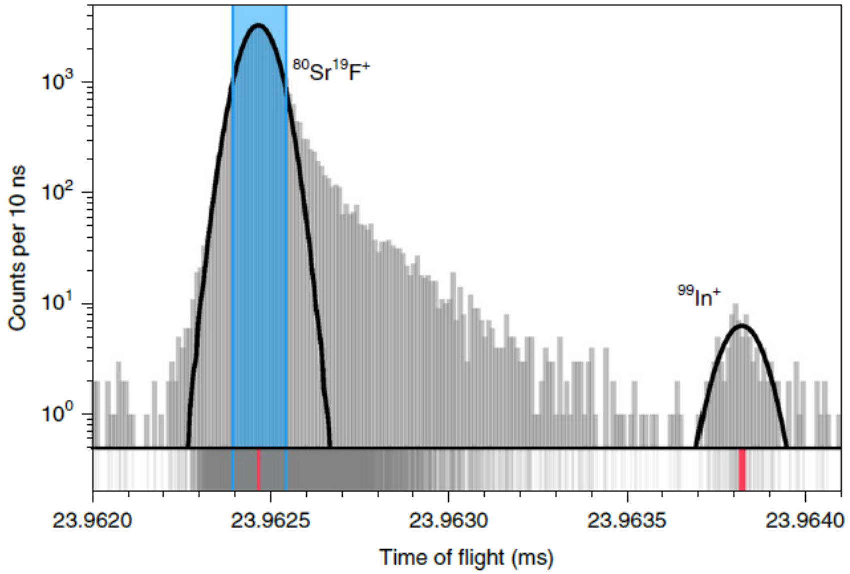
The production of medium mass neutron-deficient nuclides is usually prohibitively difficult at ISOL facilities

Experimental challenge overcome in this work was the production and separation of the $^{99,100,101g,101m}$In

- In atoms of interest selectively ionized via RILIS
- First mass separation through the HRS
- Molecular ions $^{80-82}Sr^{19}F^{+}$ predominant in the beam
- MR-ToF MS revolving power $\frac{m}{\Delta m} = 10^5$



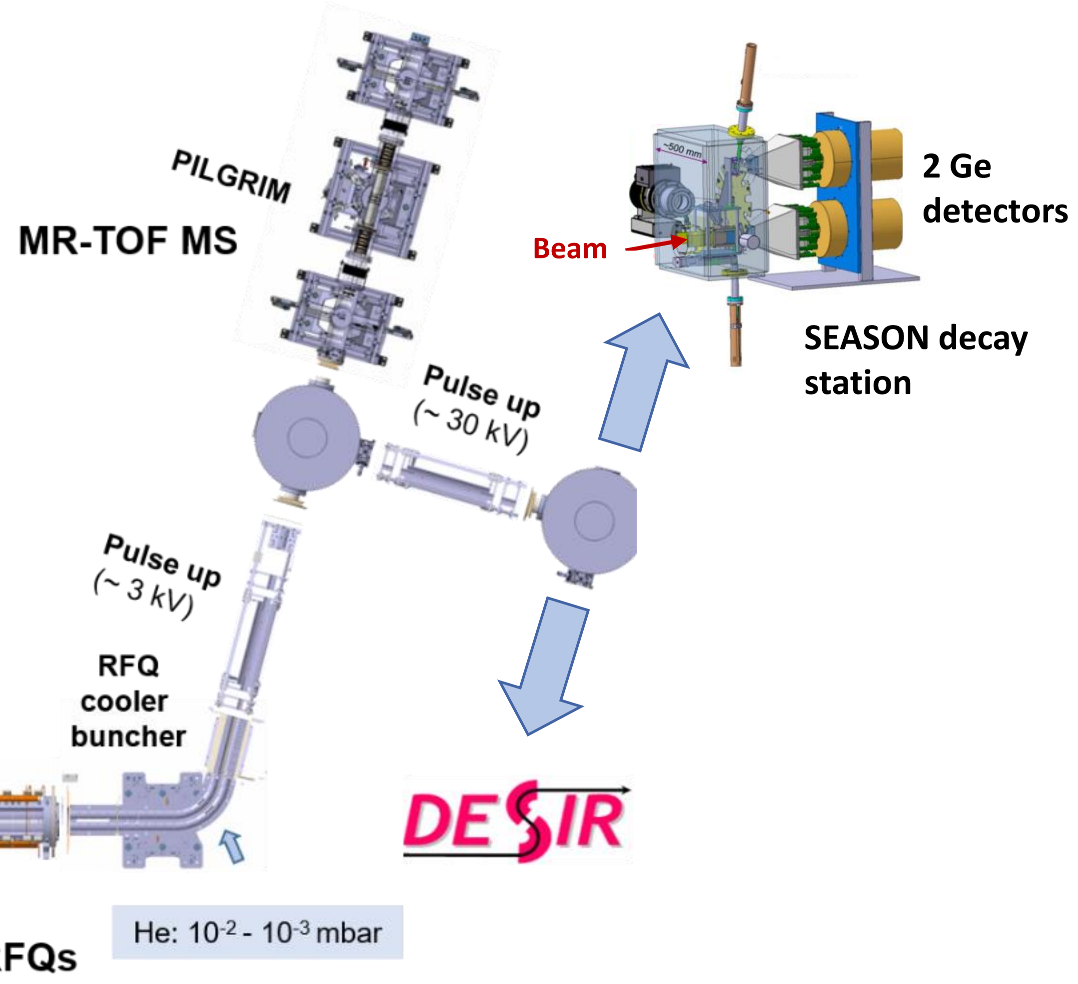



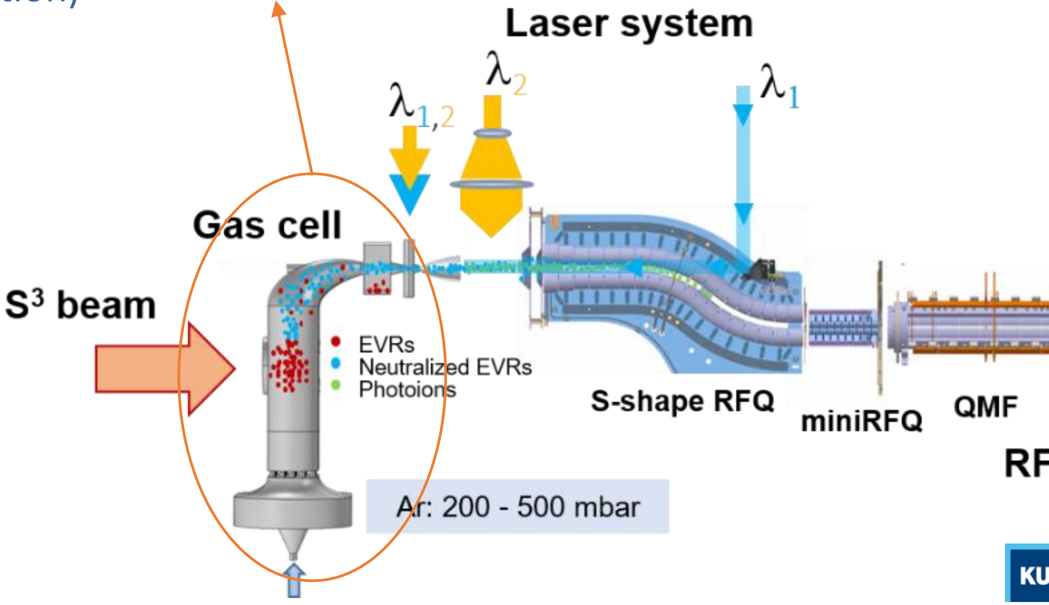

M. Mougeot *et al.*, Nature Phys. **17**, 1099-1103 (2021)

# $S^3$ Low Energy Branch ($S^3$-LEB)

**Laser system:**

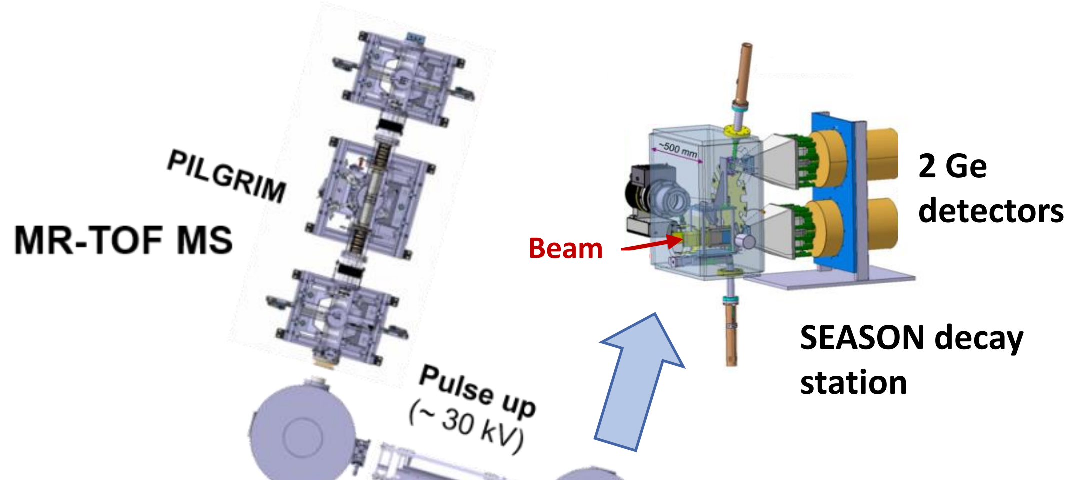
- Broad band lasers in the gas cell to look for atomic transitions
- Narrow band ionization in the gas jet
  - Low temperature
  - Low pressure
- High resolution spectroscopy (300 MHz resolution, isomer purification)

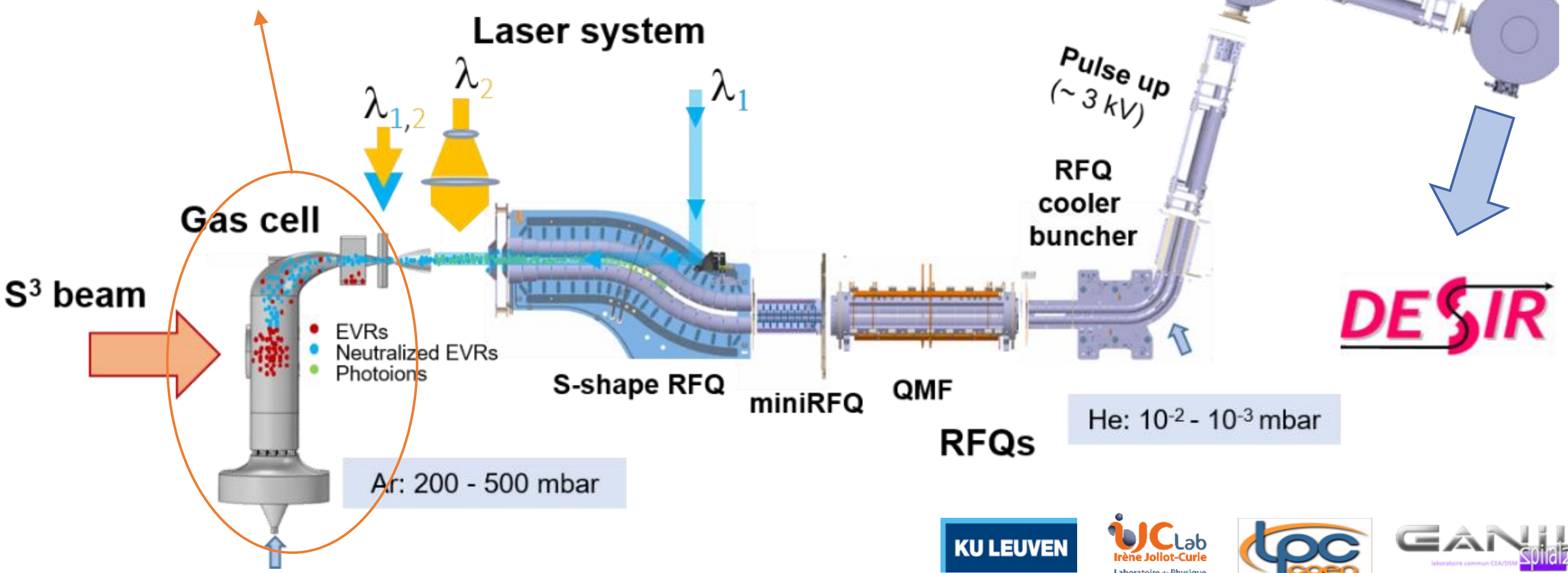


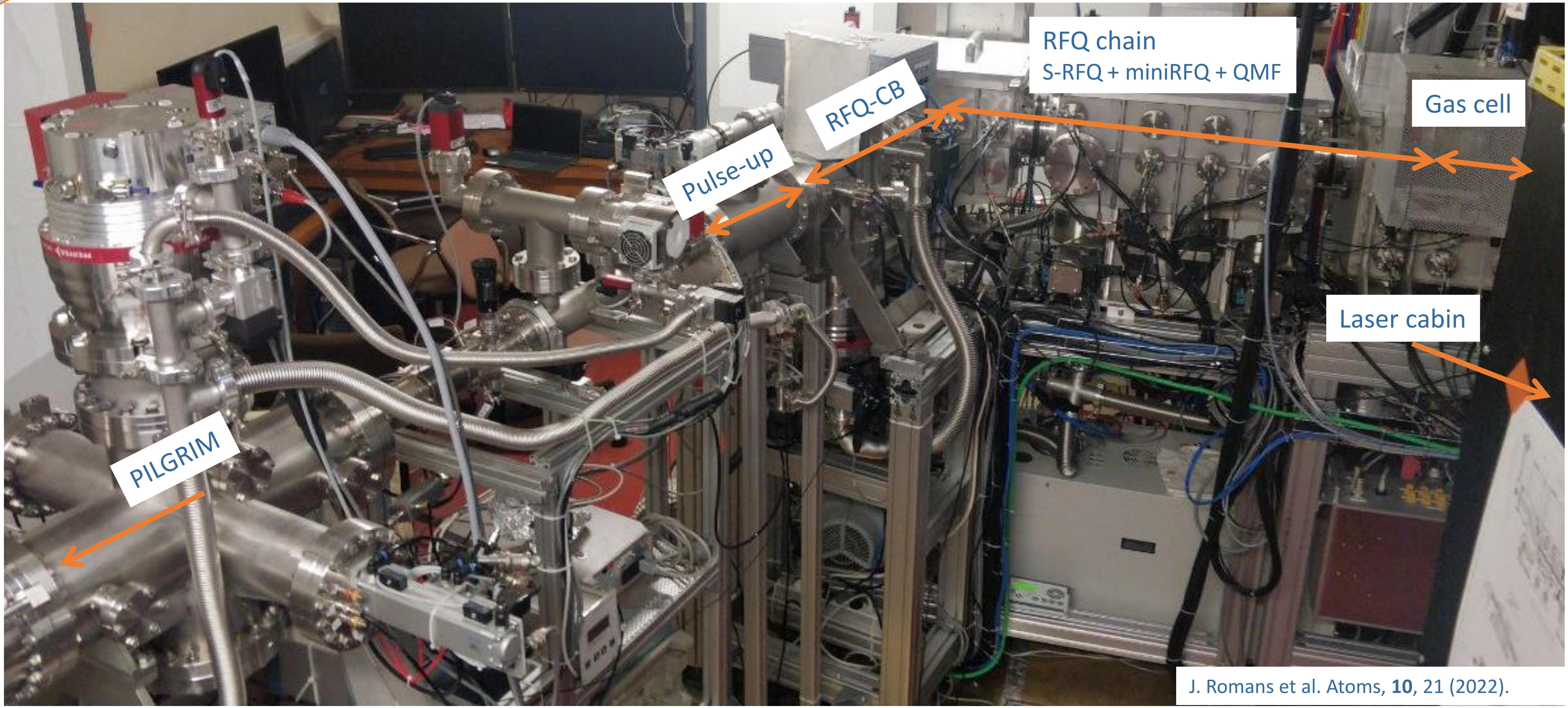
# $S^3$ Low Energy Branch ($S^3$-LEB)

- Isomericaly pure RIBs at low energy (~ 3 keV)
- Refractory elements available (gas cell)
- High resolution laser spectroscopy (gas jet)
- Mass spectrometry (PILGRIM)
- Decay spectroscopy (SEASON)
- Beams available for DESIR



# $S^3$ Low Energy Branch ($S^3$-LEB) at LPC (before)



J. Romans et al. Atoms, **10**, 21 (2022).

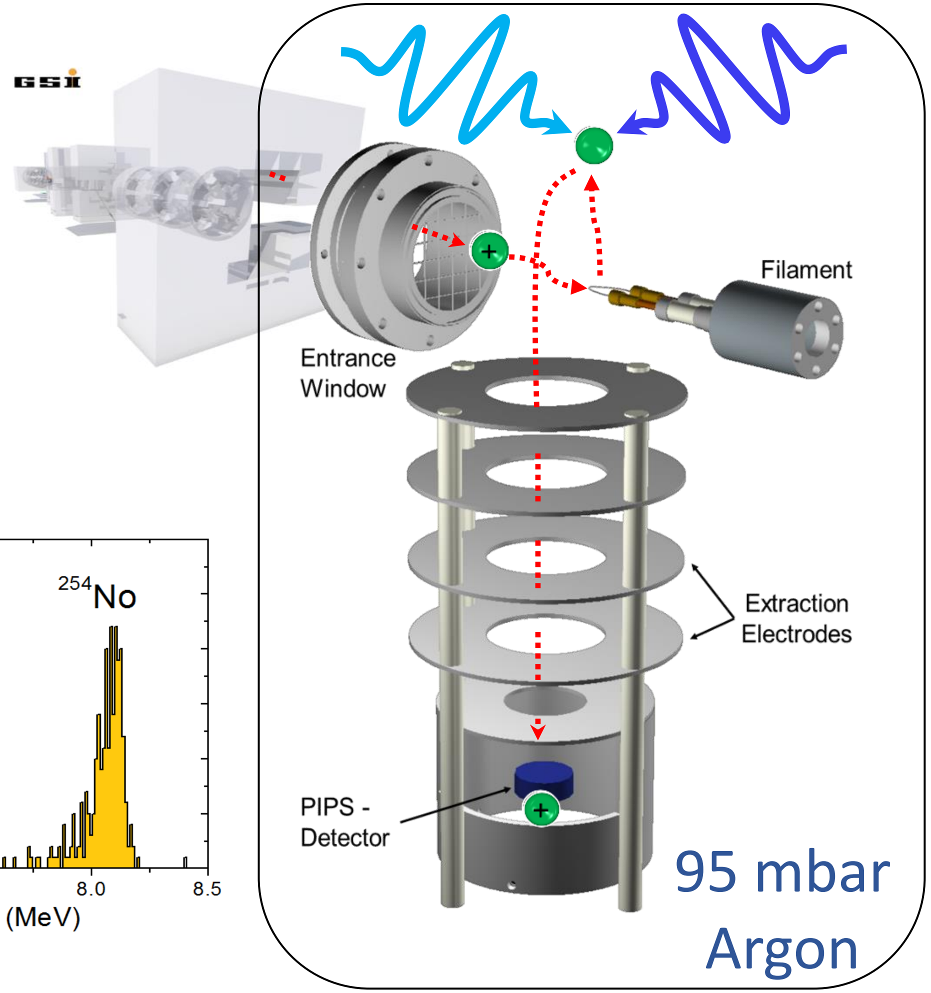
# $S^3$ Low Energy Branch ($S^3$-LEB) at LPC (now)

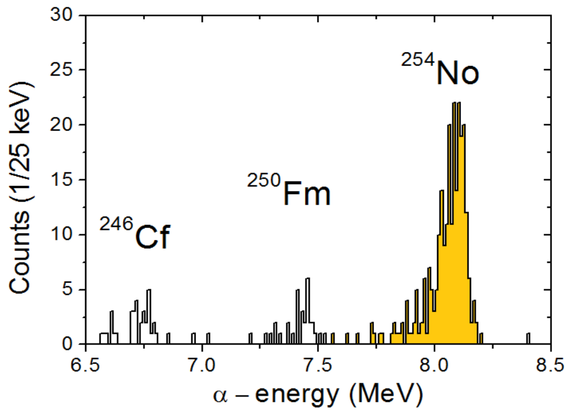
# Radiation Detected Resonance Ionization Spectroscopy

Courtesy of S. Reader

RADRIS method:

- Thermalizing of incoming fusion products
- Collectinf onto thin tantalum wire
- Evaporation and two-step photoionization process
- Transport to detector and detection of alpha decay
- High power 100 Hz Laser system

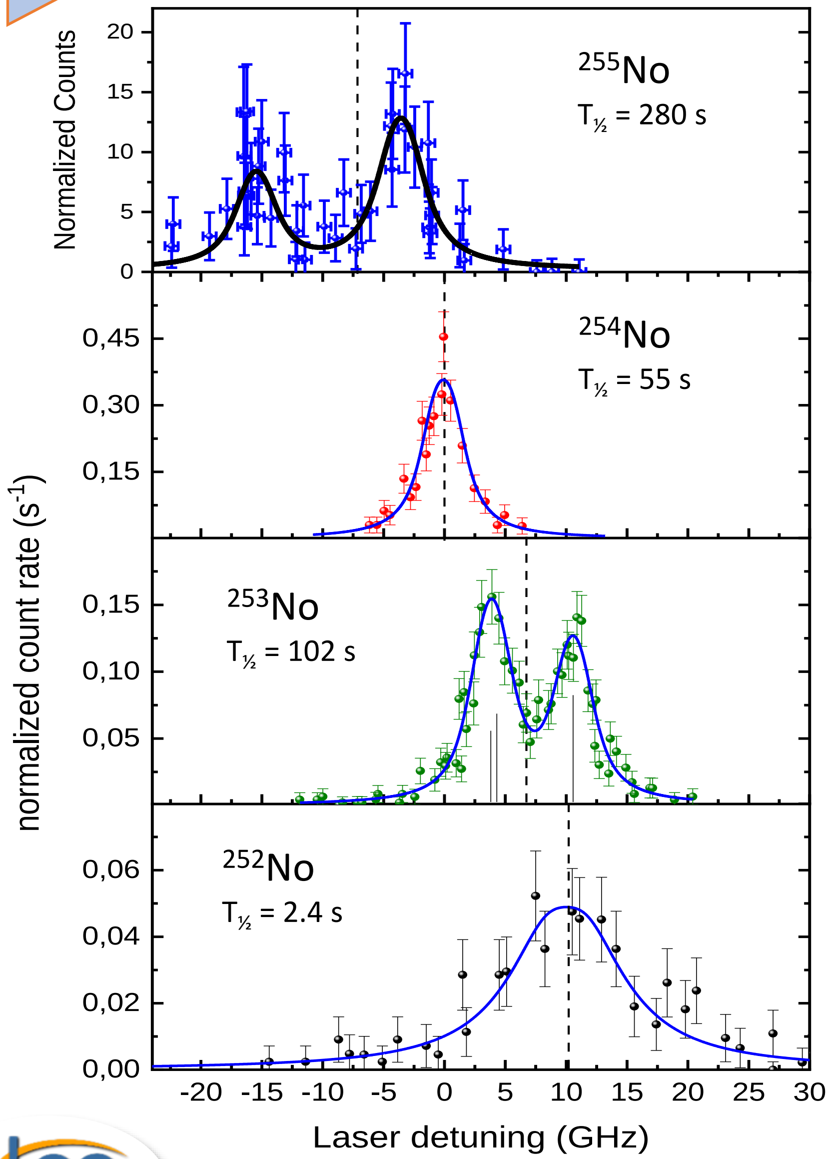



H. Backe *et al.*, Eur. Phys. J. D **45**, 99 (2007)
F. Lautenschläger *et al.*, NIMB **383**, 115 (2016)

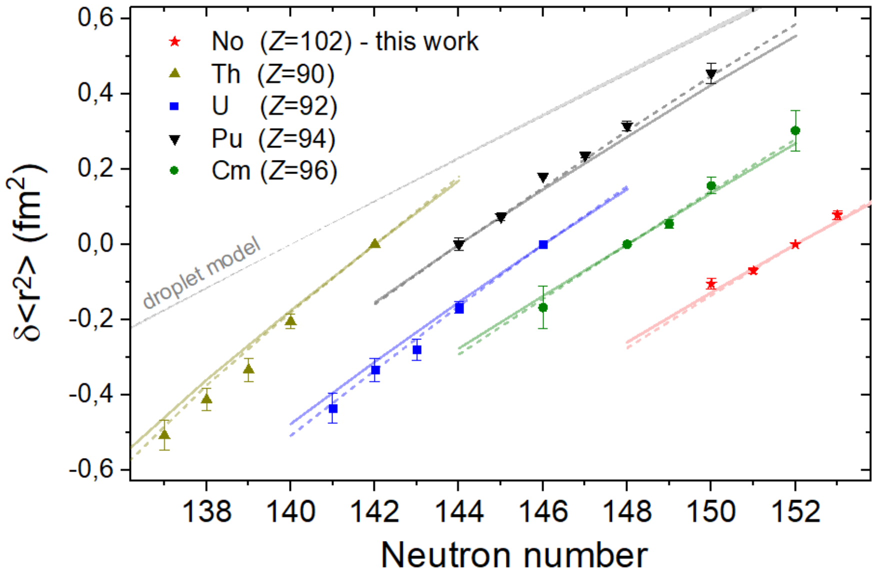
# Isotope Shift of $^{252\text{-}254}$No & HFS in $^{253,255}$No

Courtesy of S. Reader




- Isotope shift for 252-254No measured
- Change in charge radii: Input from atomic theory
  - Mass-shift constant: 1044 GHz u
  - Field-shift parameter: -95.8(7.0) GHz/fm

*(R. Beerwerth & S. Fritzsche (MCDF), V. Dzuba, M. Safranove (CI), A. Borschevsky (RCC))*

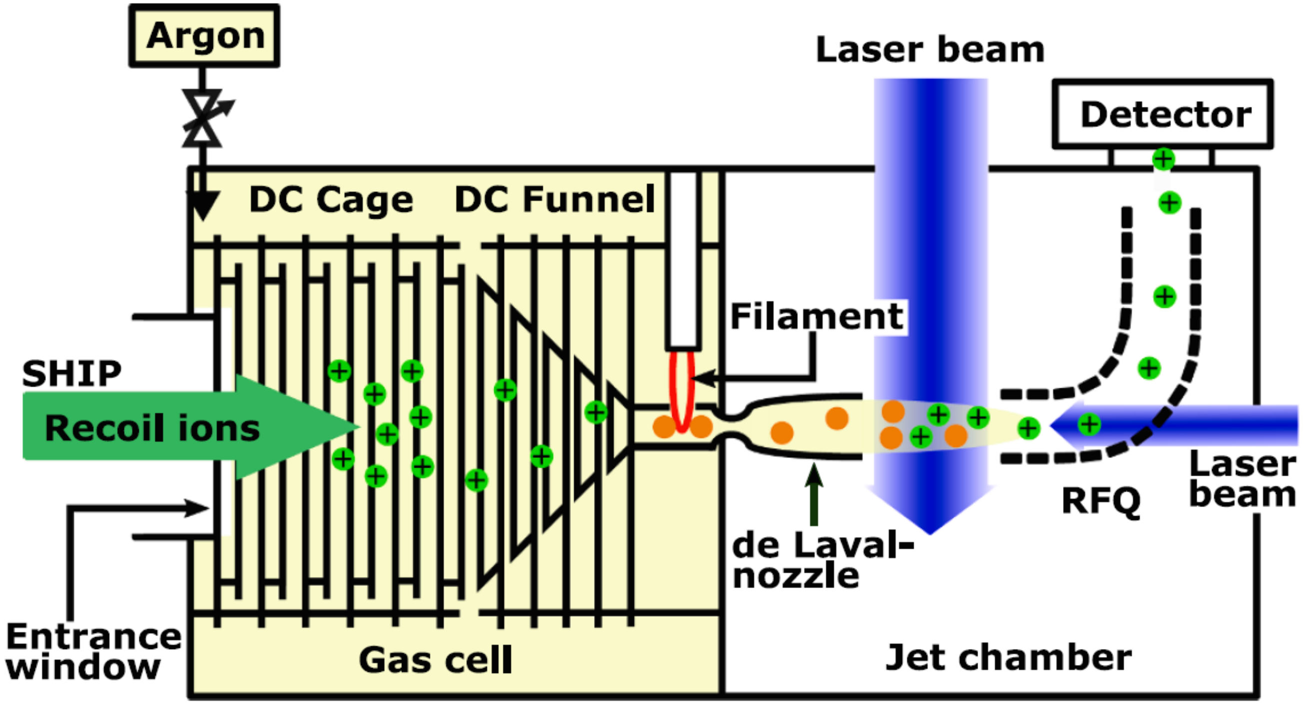


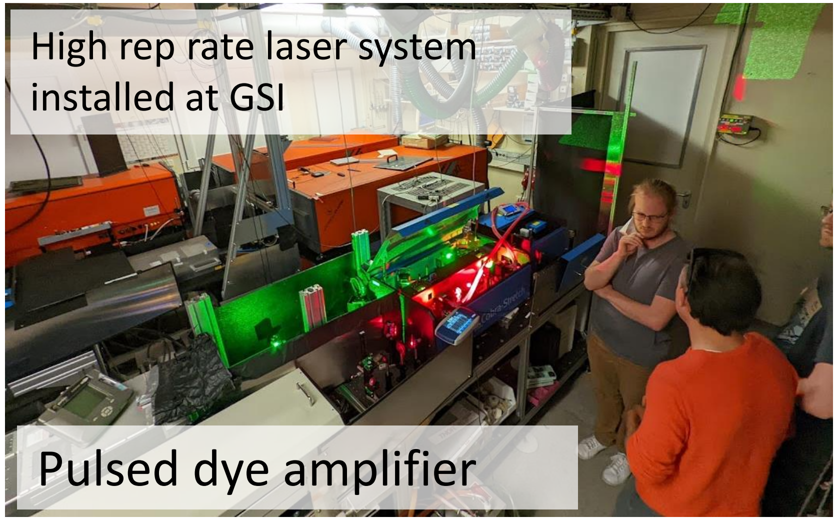

Agrees well with nuclear DFT calculations

# In-gas-jet laser spectroscopy on $^{254}$No at GSI

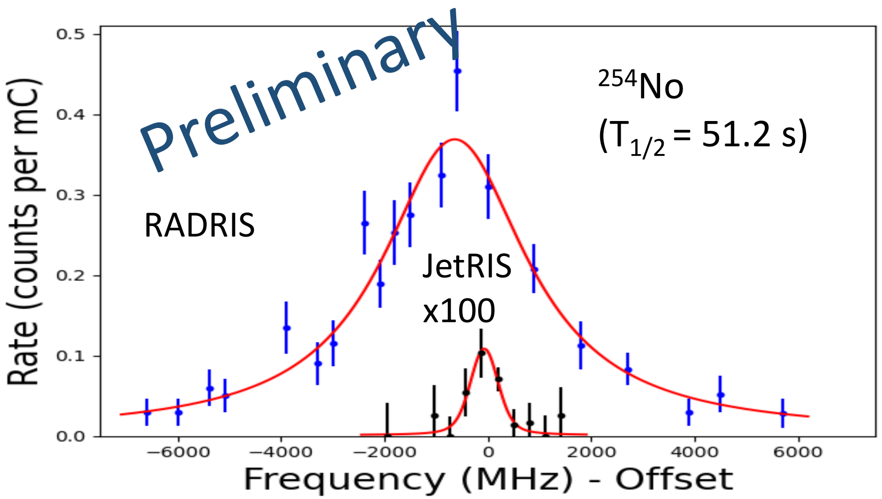
Courtesy of S. Reader

**Combination of high-efficiency RADRIS with high resolution in-jet methods**




**Beamtime 2022**




First in-gas-jet laser spectroscopy on 254No with improved resolution !

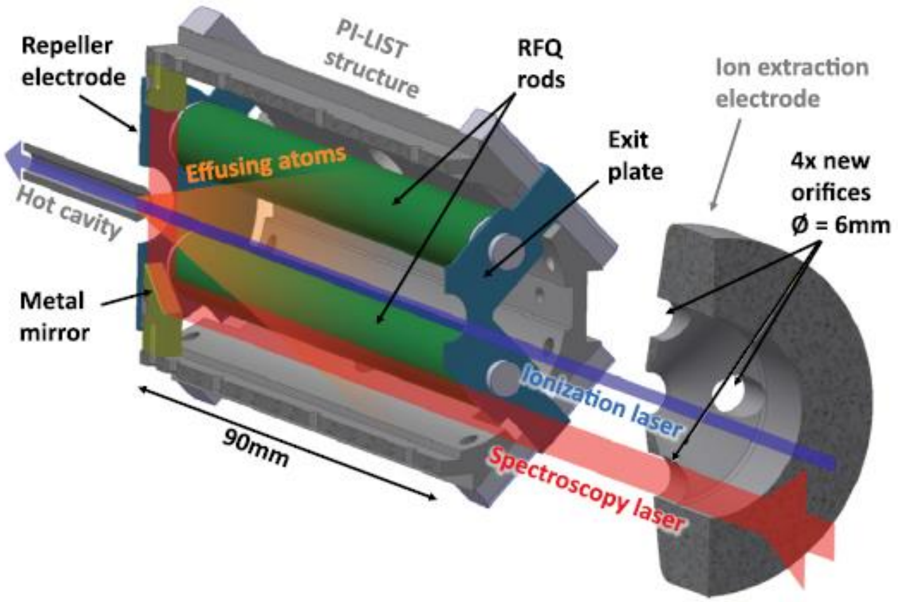
S. Raeder *et al.*, NIM B **463** (2020)(2019) 272 & M. Laatiaoui *et al.*, Nature (London) **538**, 495 (2016)

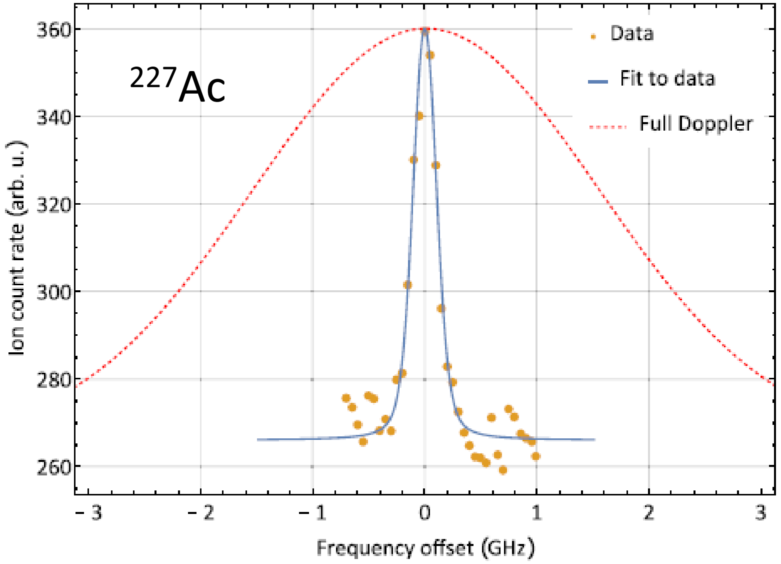
# The high-resolution spectroscopy laser ion source PI-LIST

The PI-LIST ion source:
- Perpendicular laser/atom beam interaction in a RFQ unit
- Spectral linewidth of ~ 250 MHz

Three opeartion modes:
- Ion guide mode: high efficiency, no contamination suppresion
- LIST mode: high beam purity, loss in efficiency
- PI-LIST mode: high-resolution spectroscopy

PI-LIST offers the possibility to perform HFS studies directly at the ion source and below the limits of hot cavity atomic vapor



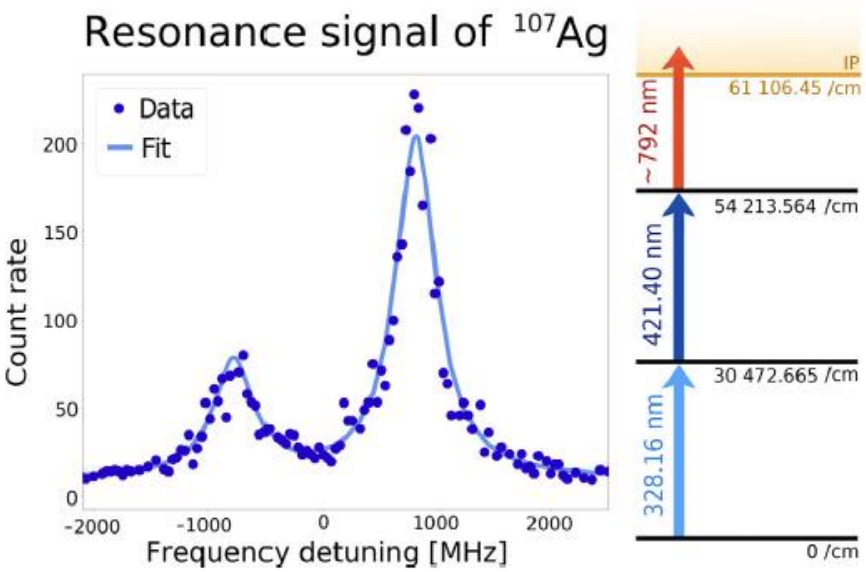



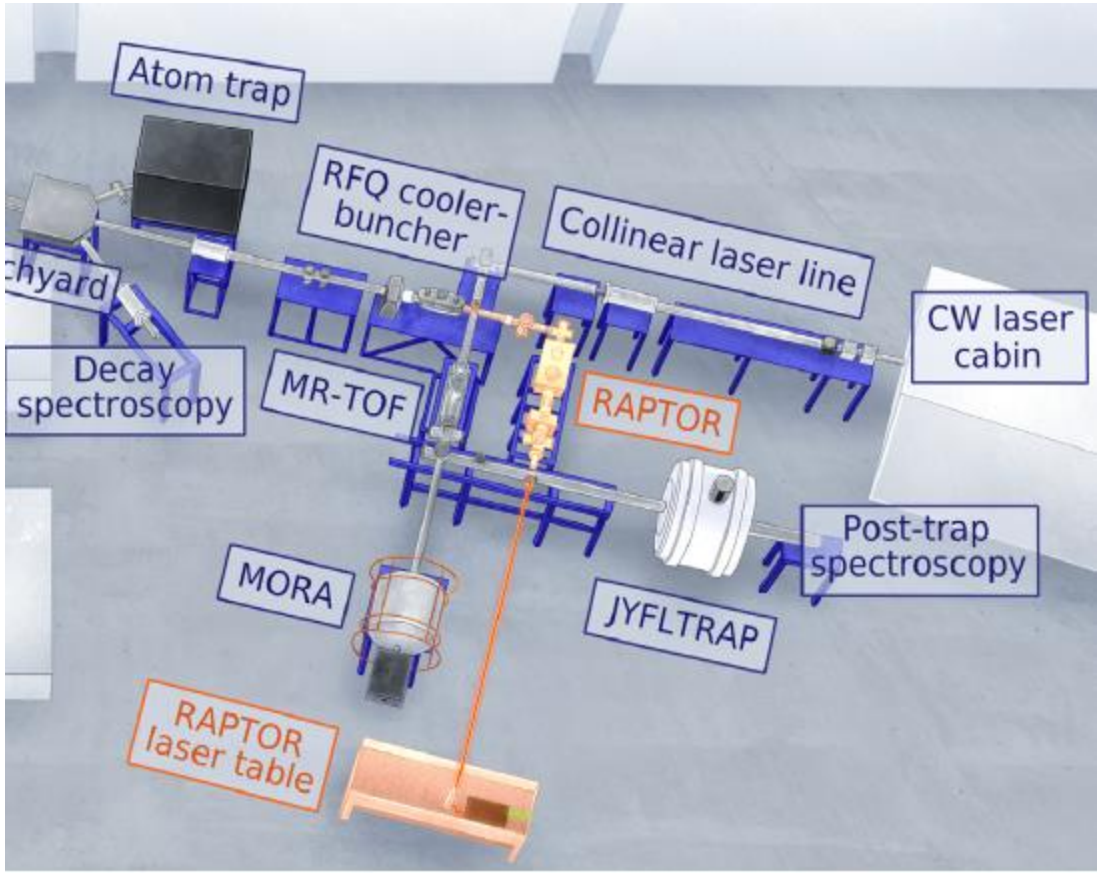

R. Heinke *et al.*, NIM B **541**, 8-12 (2023)

# RAPTOR: Resonance ionization spectroscopy And Purification Traps for Optimized spectRoscopy

Collinear resonance ionization spectroscopy device

- Beam energy < 10 keV
- Coupled to JYFLTRAP
  - laser-assisted nuclear-state selective purification
  - post-trap decay spectroscopy experiments
  - high-precision laser-radiofrequency double-resonance experiments




S. Kujanpää *et al.*, NIM B **541**, 388-391 (2023)

# Thank you for your attention !!!

And thanks to Ruben, Mikael and Sebastian for slides !