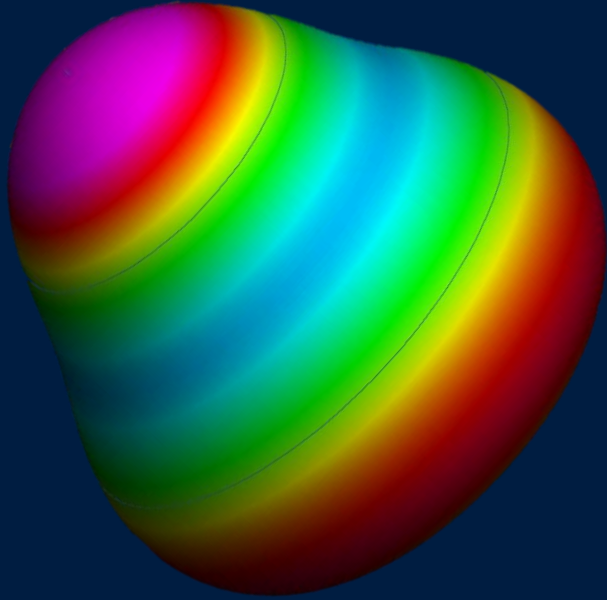




Getting NSHAPE

Combining laser spectroscopy with muonic atoms of exotic nuclei to reveal exciting features of the nuclear landscape

fwo

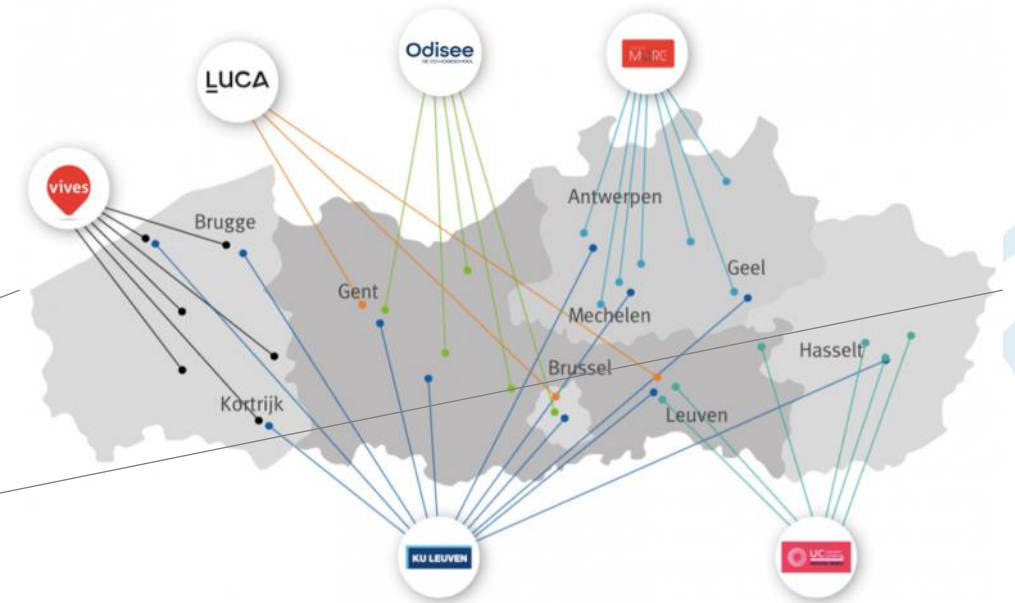


KU LEUVEN



KU Leuven

- Founded in 1425
- 23 campuses across Flanders
- >60,000 students across 15 Faculties
- >20,000 staff
- 3 main Groups:
 - Humanities & Social Sciences
 - Science & Technology
 - Biomedical Sciences
- #1 European university for innovation!



KU Leuven

ANNO ★ 1366



Outline

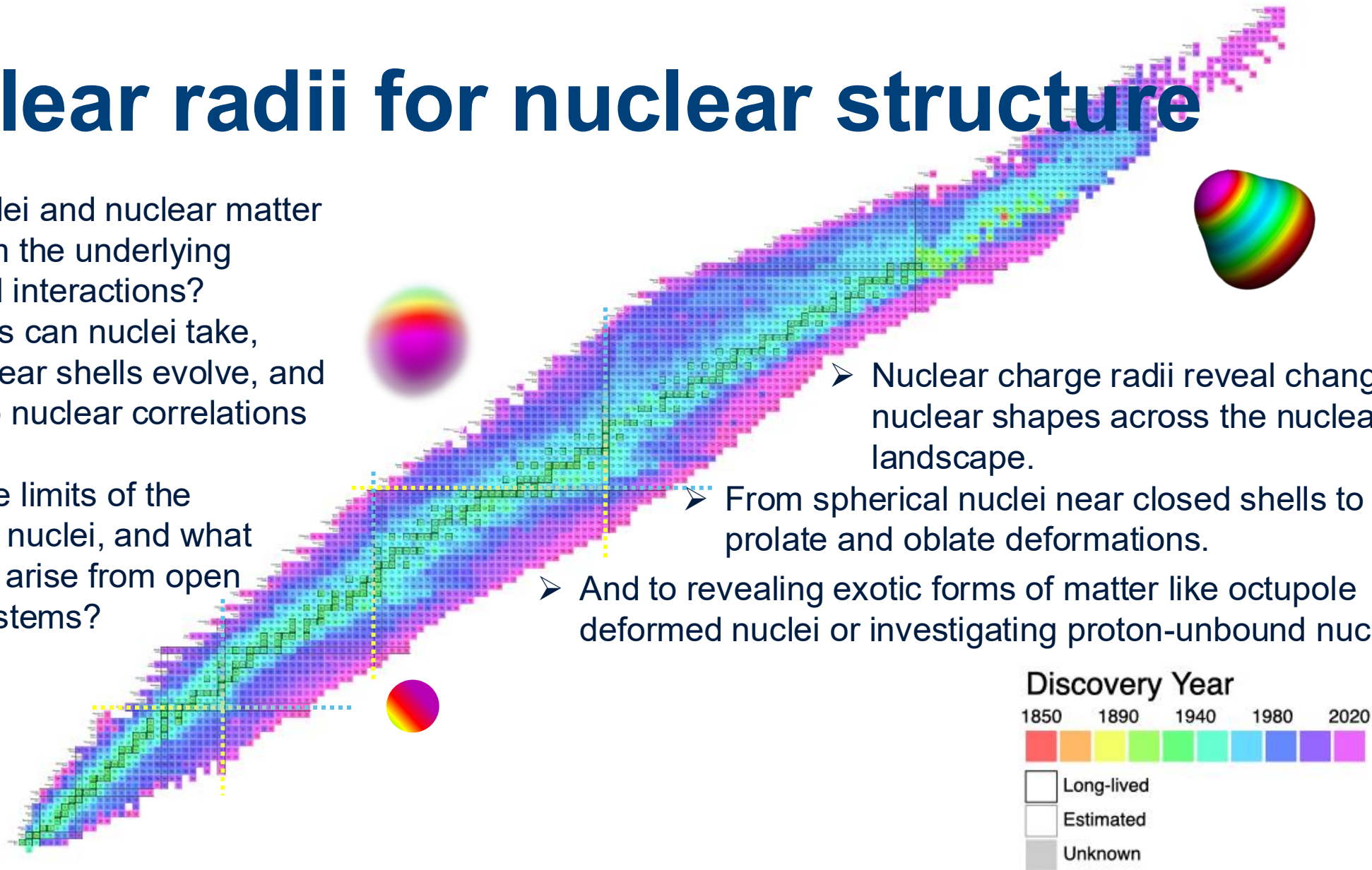
- Nuclear charge radii as probes of nuclear structure
- Accuracy limit in extracting charge radii
- muX and ReferenceRadii: absolute charge radii with microscopic samples of (radio)isotopes



Nuclear charge radii as probes of nuclear structure

Nuclear radii for nuclear structure

- How do nuclei and nuclear matter emerge from the underlying fundamental interactions?
- What shapes can nuclei take, how do nuclear shells evolve, and what role do nuclear correlations play?
- What are the limits of the existence of nuclei, and what phenomena arise from open quantum systems?
- Nuclear charge radii reveal changes in nuclear shapes across the nuclear landscape.
- From spherical nuclei near closed shells to prolate and oblate deformations.
- And to revealing exotic forms of matter like octupole deformed nuclei or investigating proton-unbound nuclei.

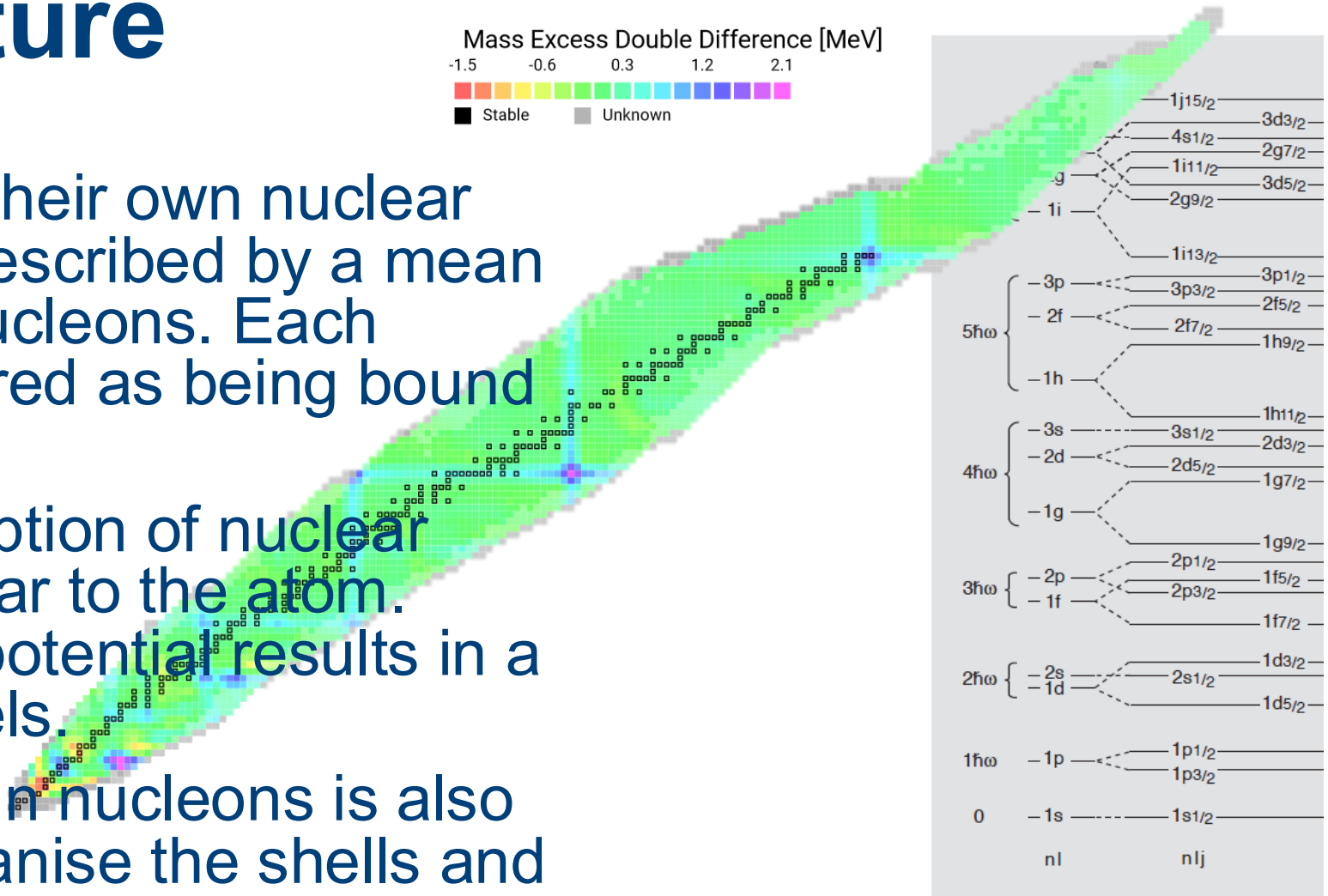


Nuclear structure

The nucleons produce their own nuclear potential. This is best described by a mean field generated by all nucleons. Each particle can be considered as being bound in this mean field.

This leads to the description of nuclear structure in shells, similar to the atom. However, the different potential results in a difference series of levels.

The spin-orbit strength in nucleons is also strong enough to reorganise the shells and results in the known *magic number*.

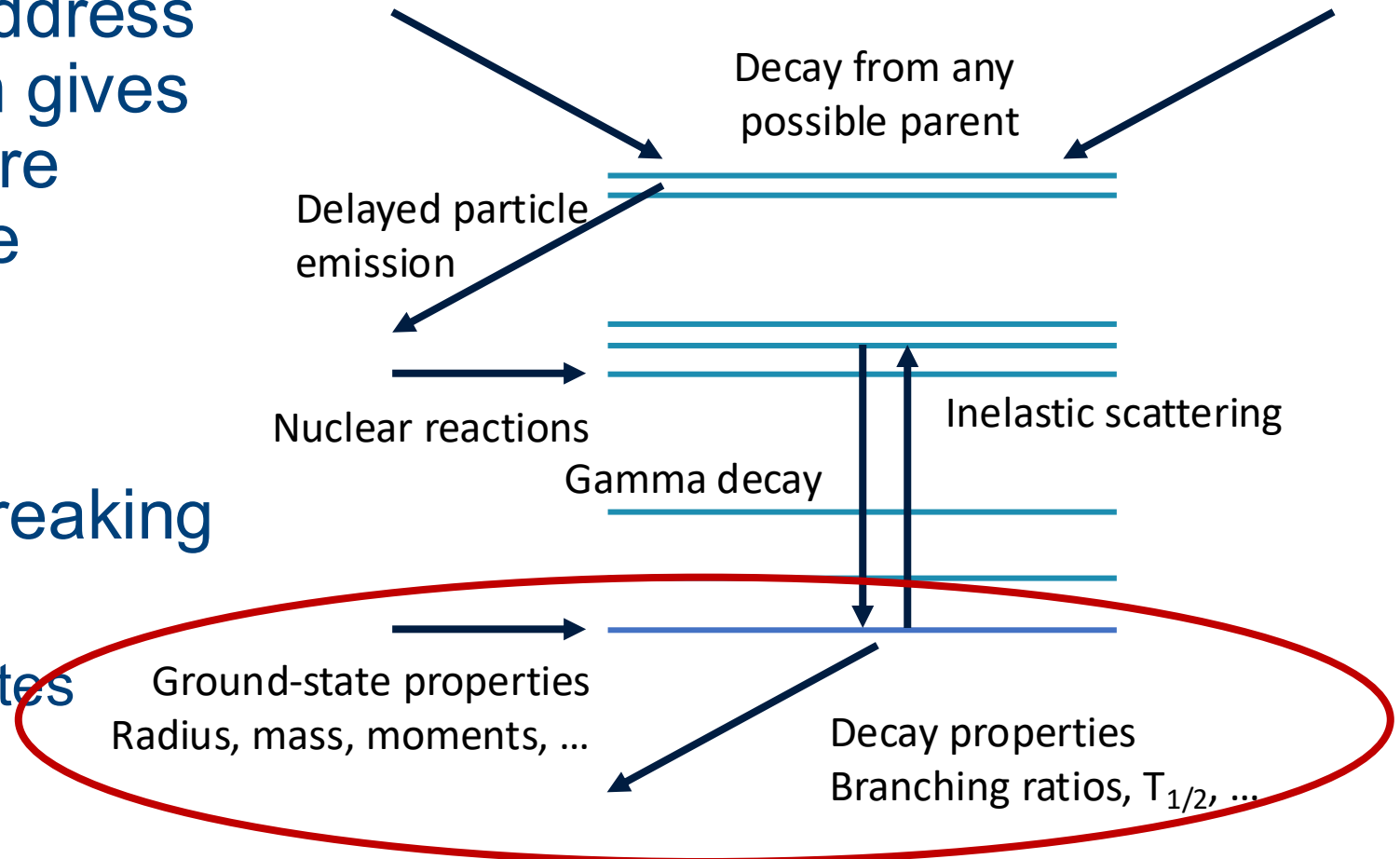


The multifaceted puzzle of experiments

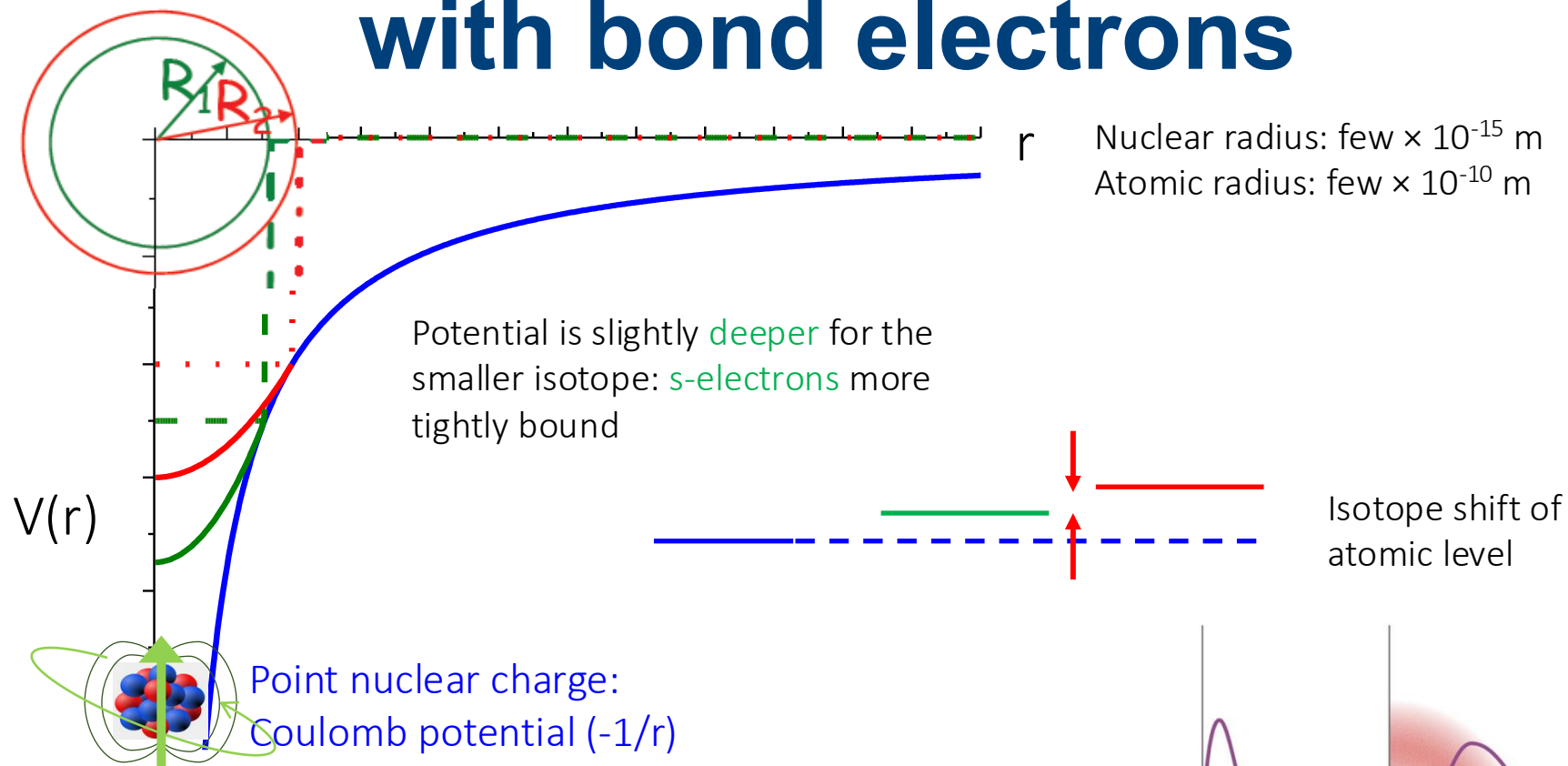
There are many ways to address the nucleus, none of which gives a full picture, all of which are needed to shed light on the nuclear puzzle.

There are many ways of breaking it down:

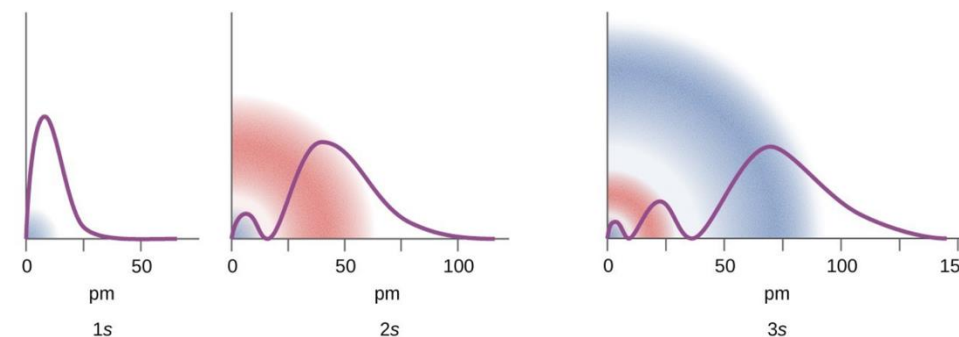
- Ground-state vs excited states
- Low-energy vs fast beams



Laser spectroscopy: probing the nucleus with bond electrons



$$\delta\nu^{AA'} = \frac{A' - A}{AA'} \left(m_e \nu + M_{SMS} \right) + F \delta \langle r^2 \rangle^{AA'}$$

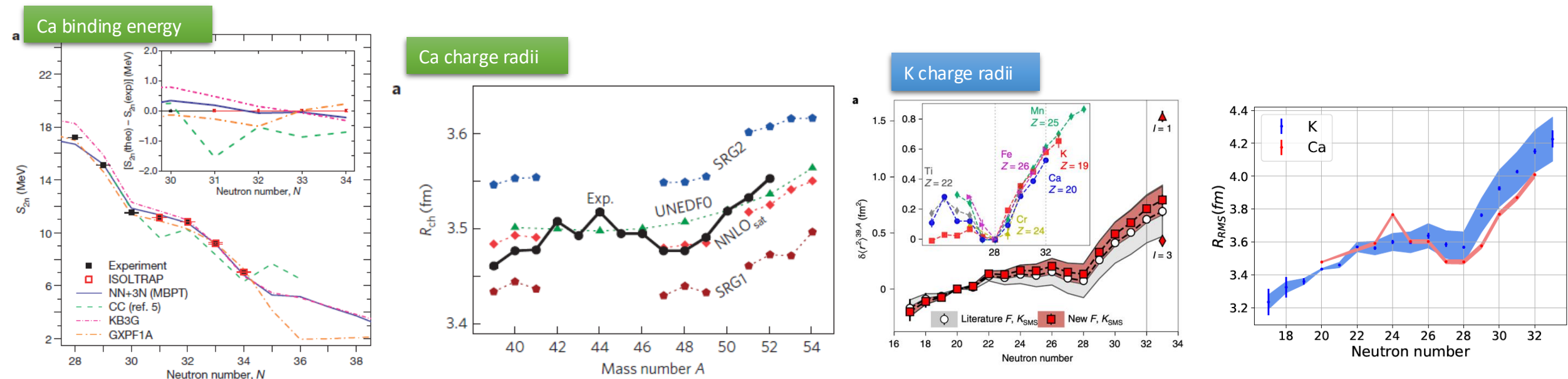


Medium-mass nuclei: $_{19}\text{K}$ vs $_{20}\text{Ca}$

The binding energies suggest there might be a new magic number at $N=32$ and 34 .

Charge radii show a large kink at $N=28$ but nothing at $N=20$ or $32,34$.

The radii of $_{19}\text{K}$ are plagued by large systematic uncertainties.

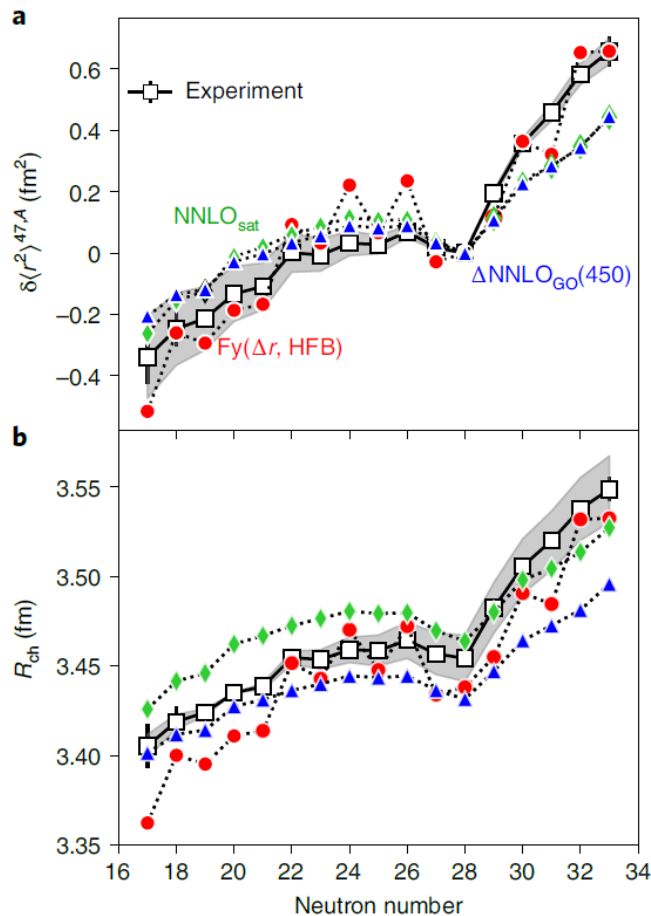


F. Wienholtz et al., *Masses of exotic calcium isotopes pin down nuclear forces*, *Nature* **498** (2013) 346-349.

10 R.F. Garcia Ruiz et al., *Unexpectedly large charge radii of neutron-rich calcium isotopes*, *Nature Physics* **12** (2016) 594-598.

Á. Koszorús et al, *Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of $N = 32$* , *Nature Physics* **17** (2021) 439-443.

Medium-mass nuclei: $_{19}\text{K}$ vs $_{20}\text{Ca}$

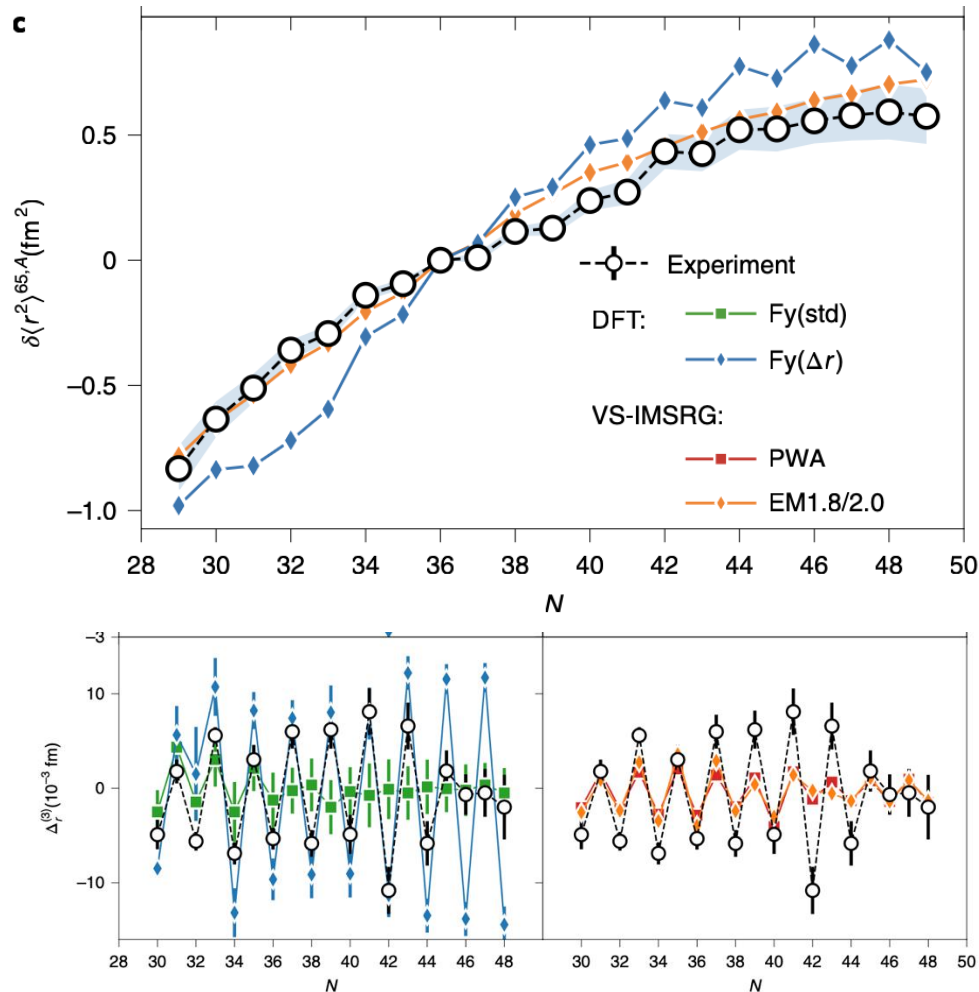


Radii measured up to N=33 probing the N=28 shell closure and N=32 subshell.

Ab initio models reproduce small variations well while DFT captures the global trend much better.

Limited precision on extracted radii induced by systematic uncertainties from the radii extraction from isotope shift, especially when evaluating absolute radii with respect to $^{39,41}\text{K}$.

^{29}Cu : jumping up & down



The same observations held at the next magic number: while the Fayans functionals perform well at describing the global scale, they do poorly with the finer details, which are well captured by ab initio models.

A flatening is found approaching $N=50$.

Odd-even staggering is another observable that is challenging for the models to reproduce.

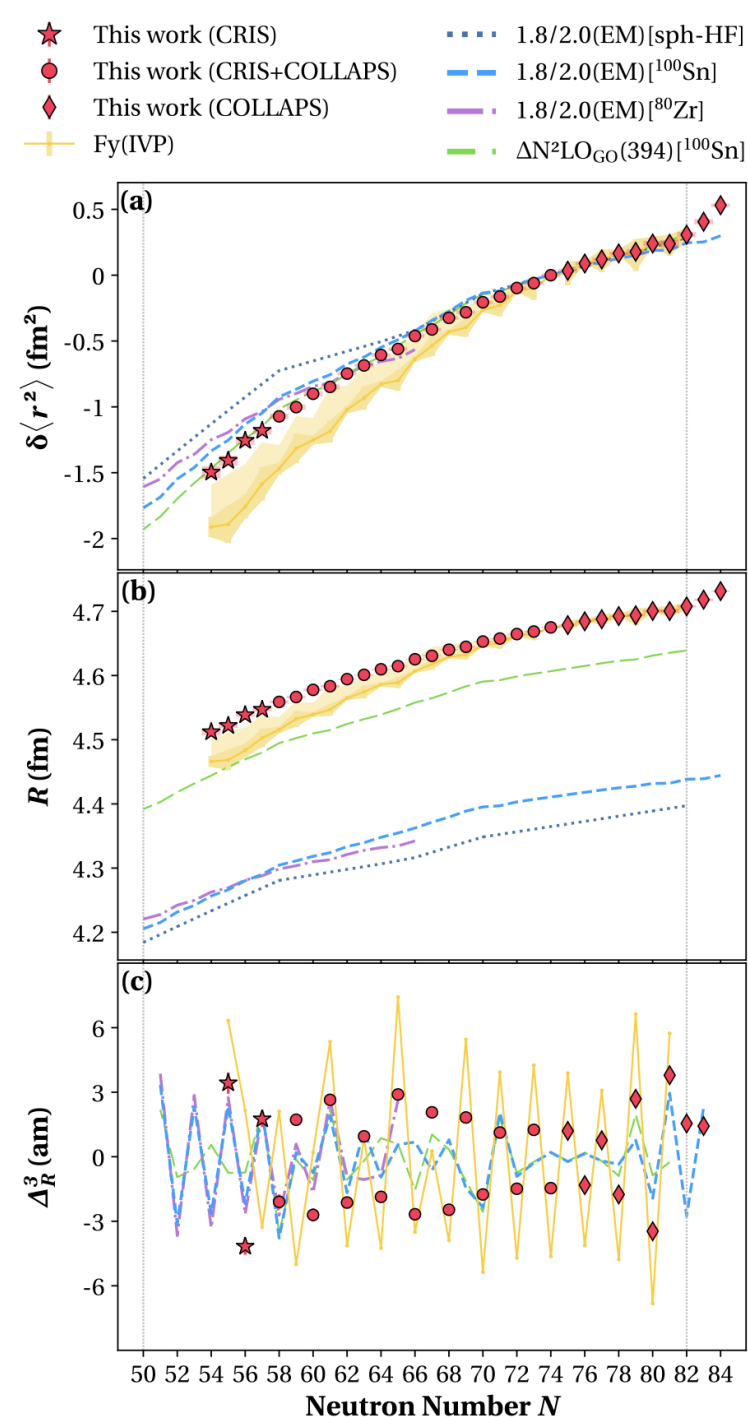
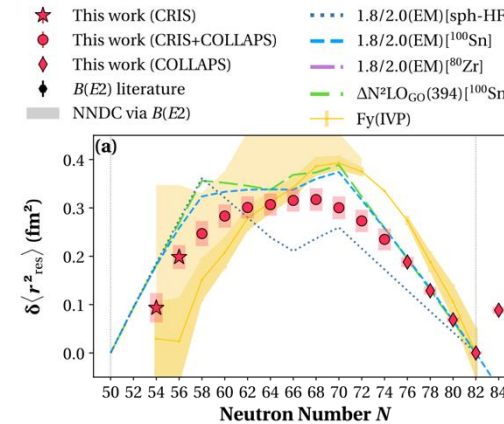
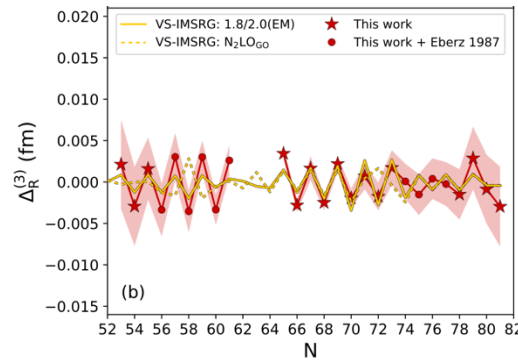
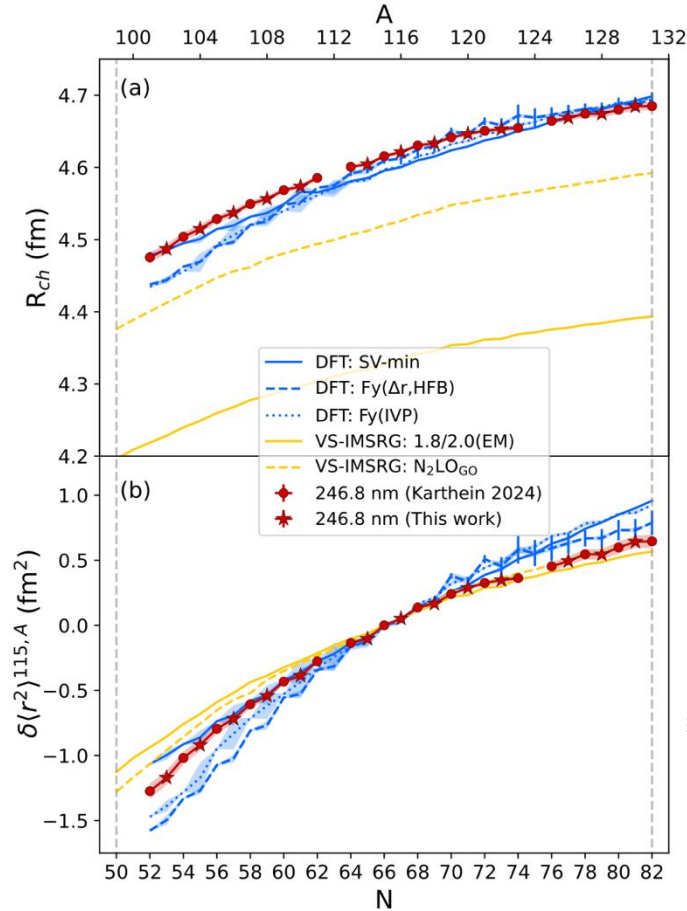
$_{49}\text{In}$ & $_{50}\text{Sn}$

Extensive work has been performed from $N=50$ to $N=82$ and beyond.

Known parabolic behaviour but hard to capture for the models.

$N=50, 82$ magic numbers are far from stability but seem to be strong in their magicity.

Other nearby chains are under strong scrutiny: $_{46}\text{Pd}$, $_{47}\text{Ag}$, $_{51}\text{Sb}$



A.R. Vernon et al., Variations in the charge radii of indium isotopes between $N=52$ and 82 , *Physical Review C* **111**

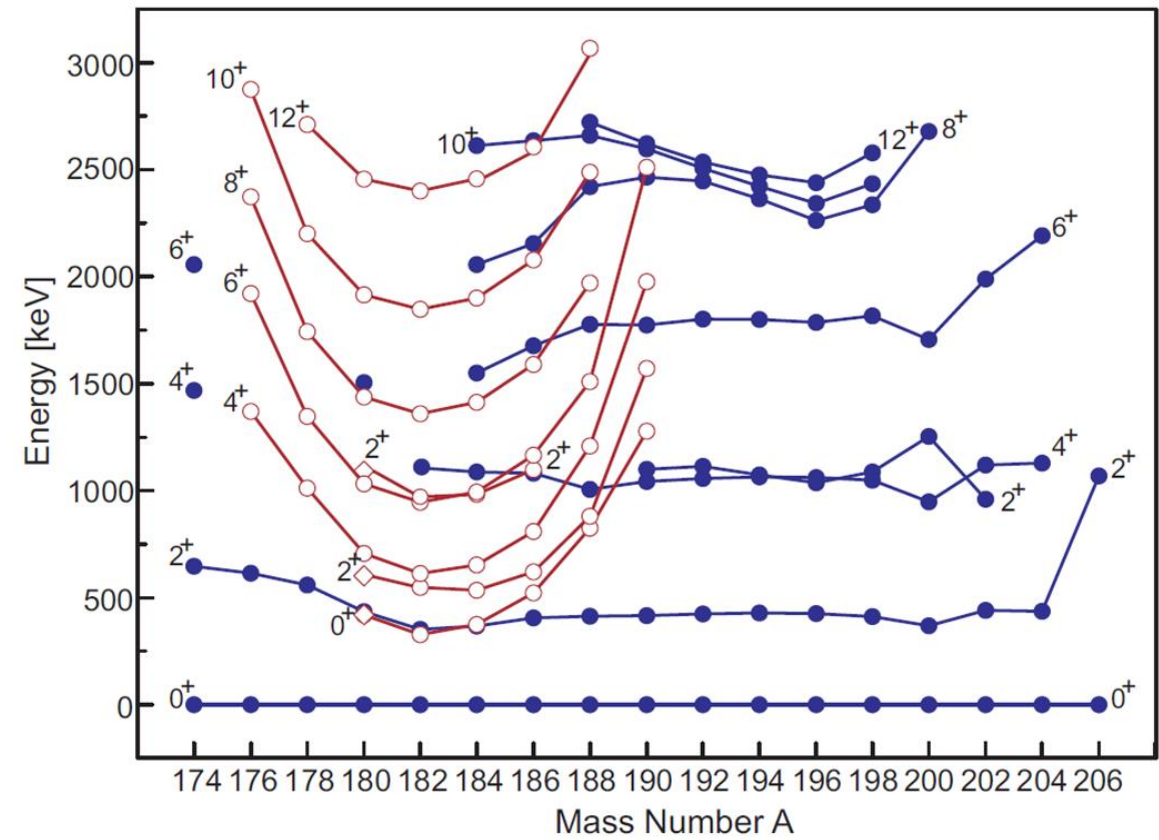
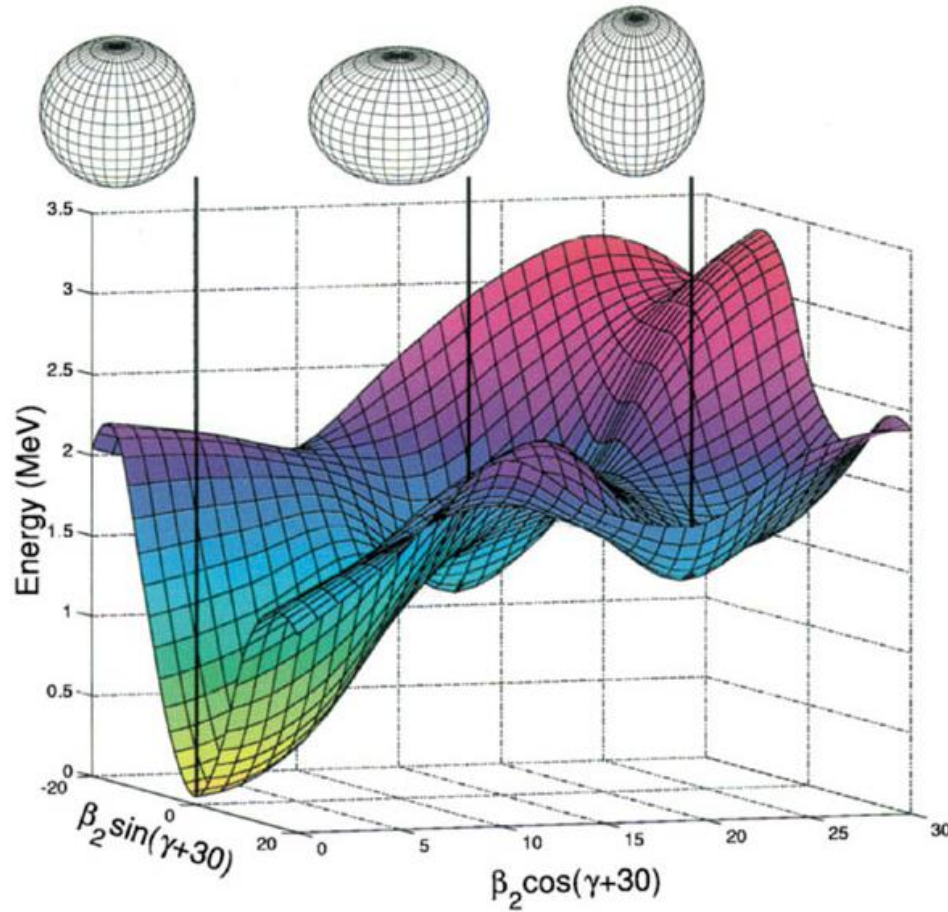
(2025) 054325.

F.P. Gustafsson et al., Charge radii measurements of exotic tin isotopes in the

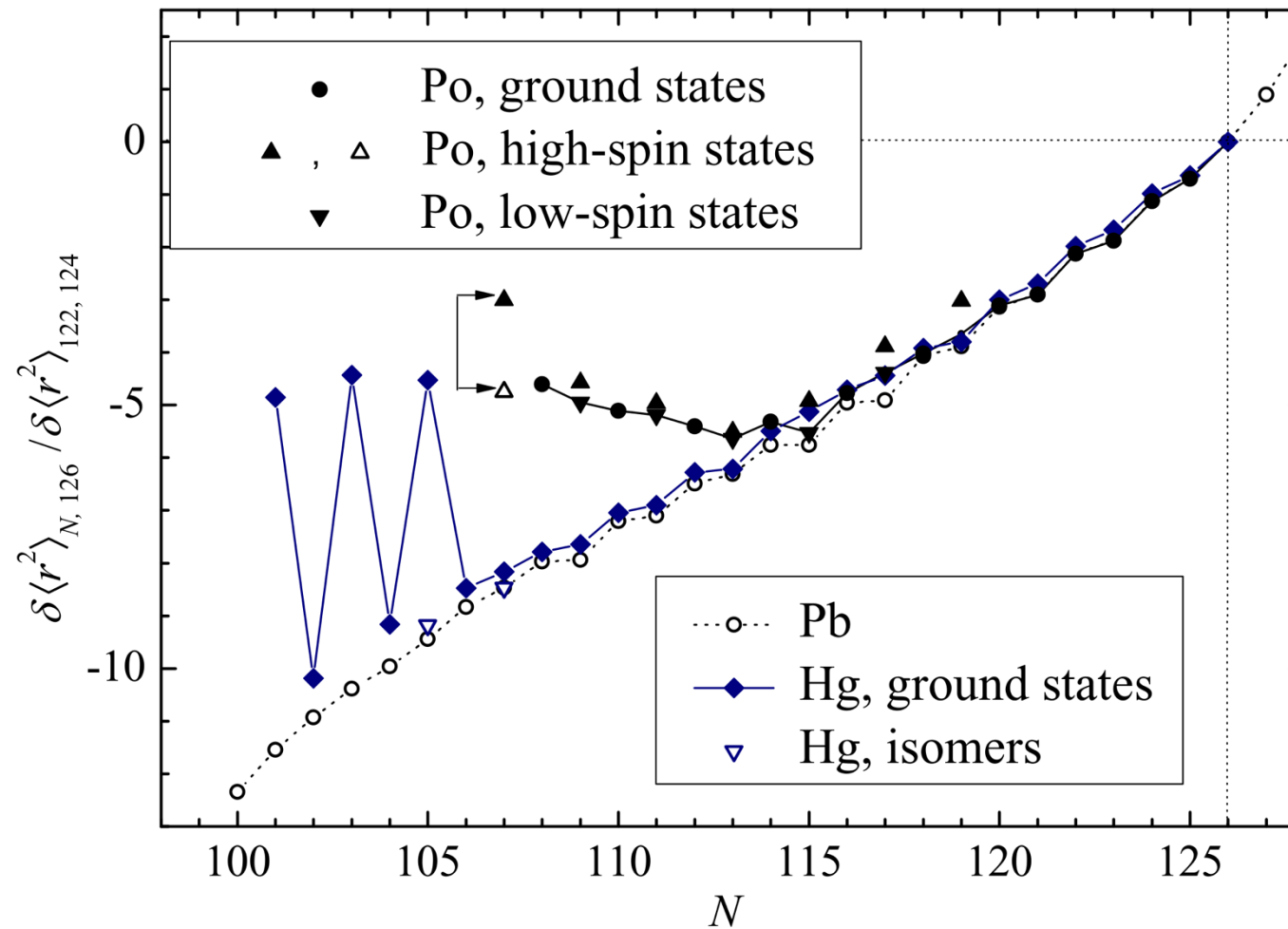
proximity of $N=50$ and $N=82$, *Physical Review Letters* **135** (2025) 222501.



Shape coexistence around ^{82}Pb



$_{80}\text{Hg}$ - $_{82}\text{Pb}$ - $_{84}\text{Po}$: this is not all the same!

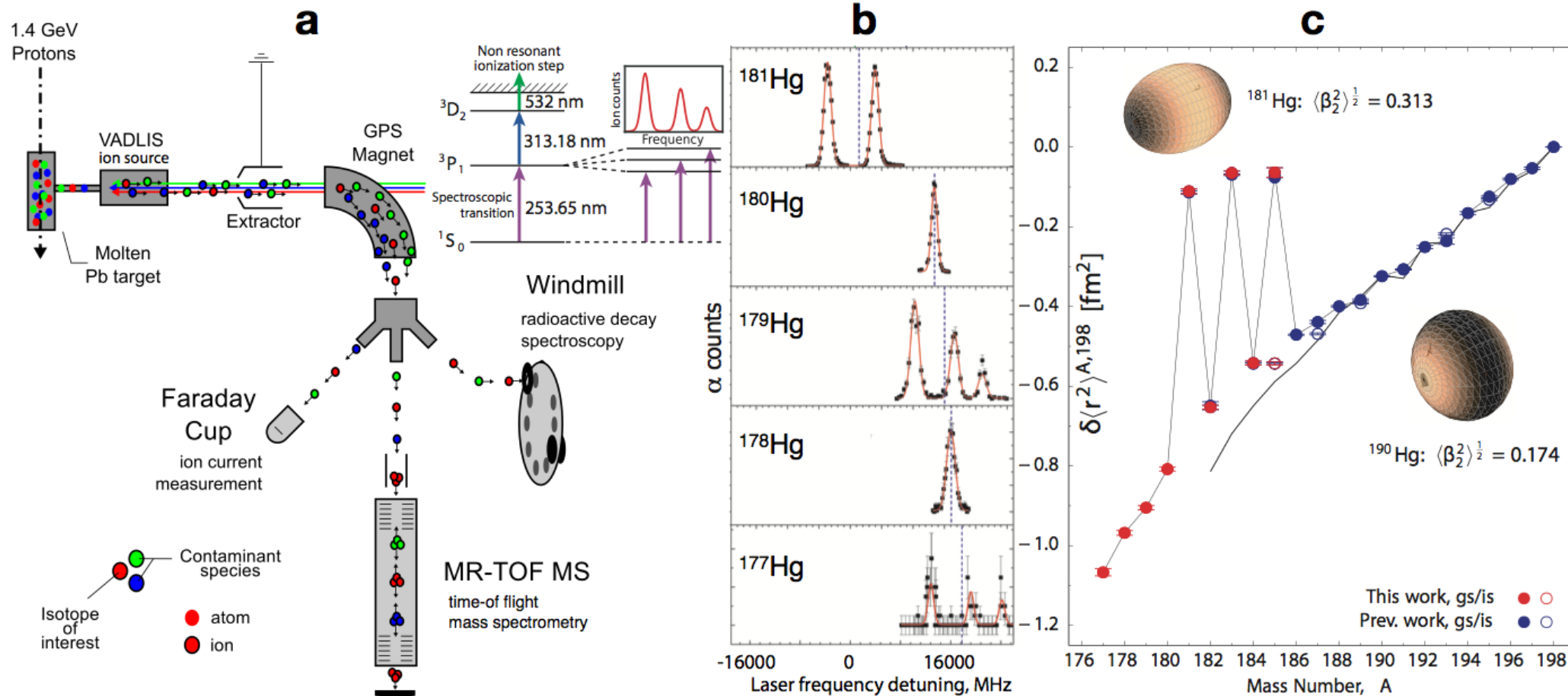


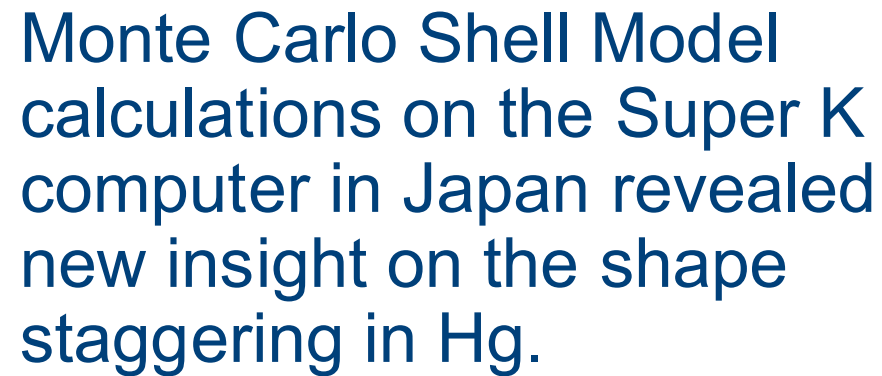
T.E. Cocolios et al. *PRL* **106** (2011) 052503.

M.D. Seliverstov et al. *PLB* **719** (2013) 362-366.

D.A. Fink et al., *PRX* **5** (2015) 011018.

In-source laser spectroscopy: $_{80}\text{Hg}$





Magnetic moments were used to guide the selection of the correct shell model states amidst the high degeneracy.

It takes many particle-hole pairs to create those shapes!





Octupole deformation

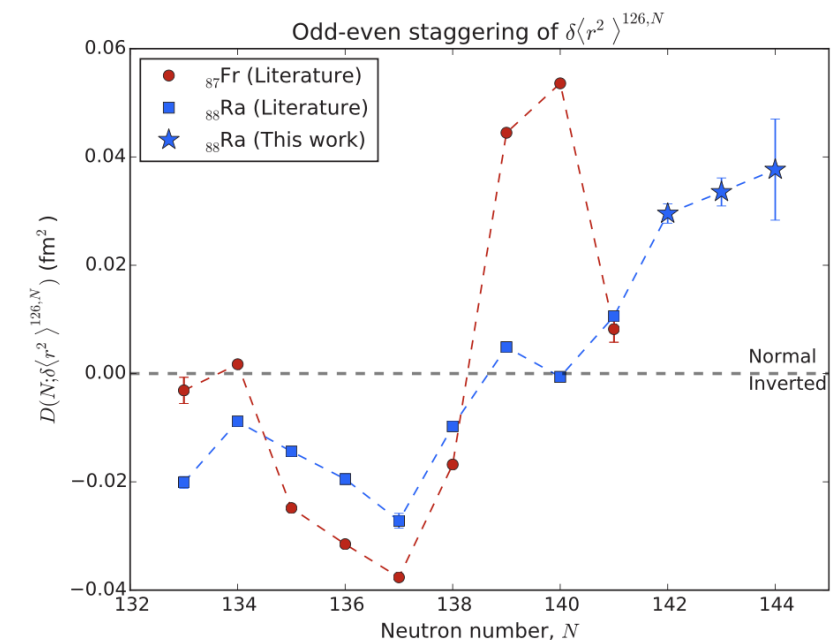
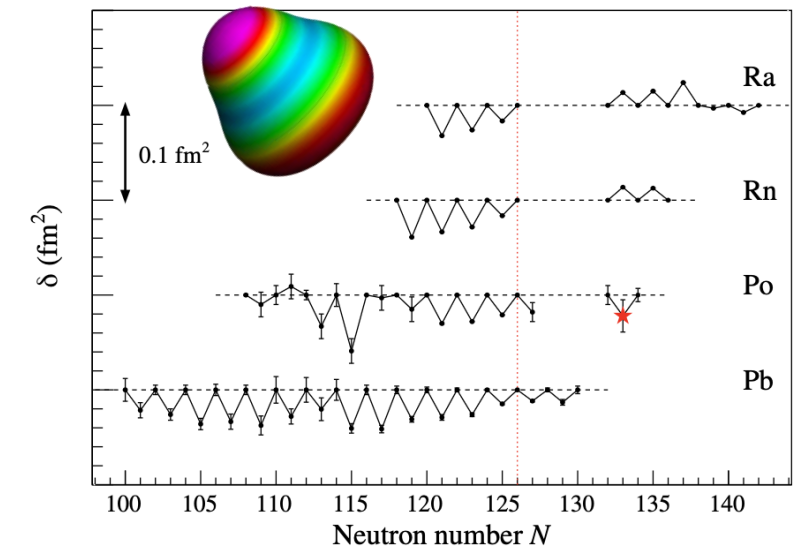
Nuclei are deformed by default, spherical being the 3rd most found in nuclear ground states. Prolate is #1, oblate is #2.

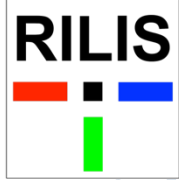
Other identified shapes are triaxial nuclei and **octupole deformed** nuclei.

Their assymmetric profile provides orientation to the nucleus, and thus is ideal when exploring parity violating effects in atoms.

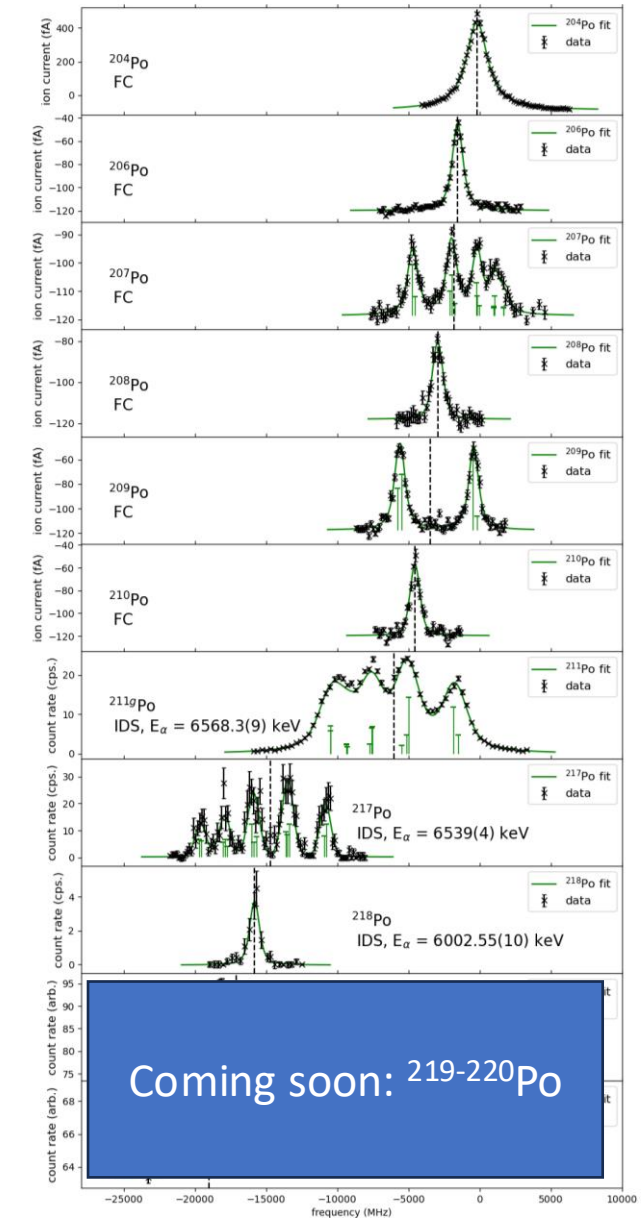
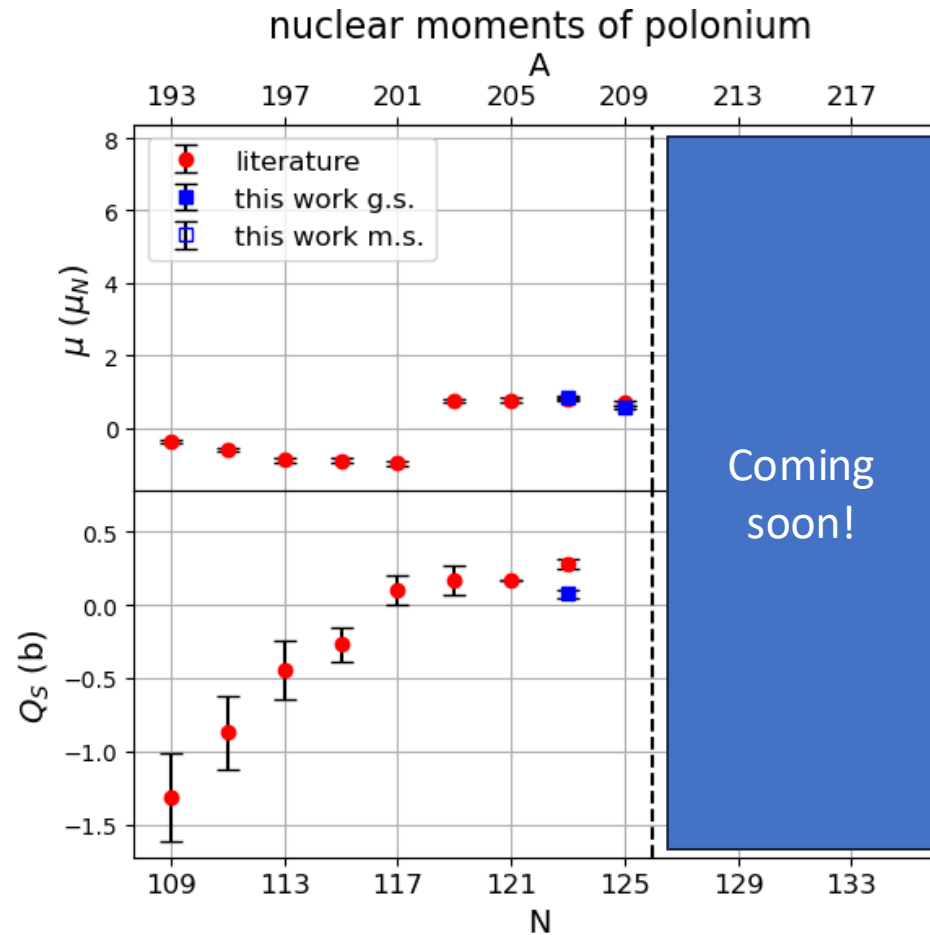
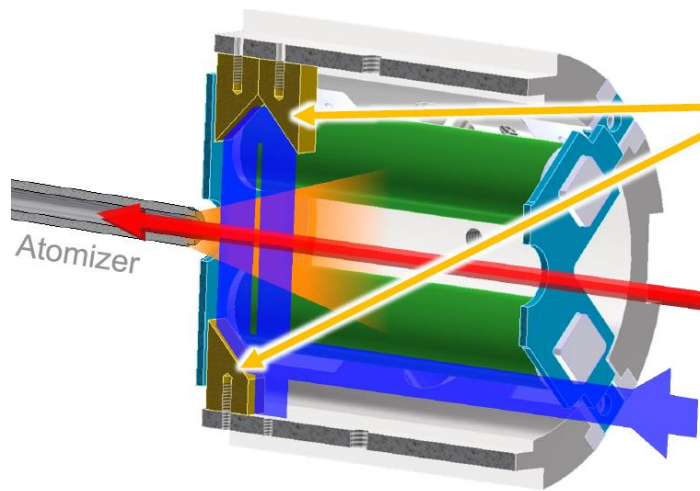
This effect is most prominent near $N=136$ – where nothing is stable! And knowing the radius is crucial.

Octupole-deformed nuclei show a peculiar reversal of the odd-even staggering, that can be used to reveal whether or not their belong to that family.





^{84}Po : plain old quadrupole





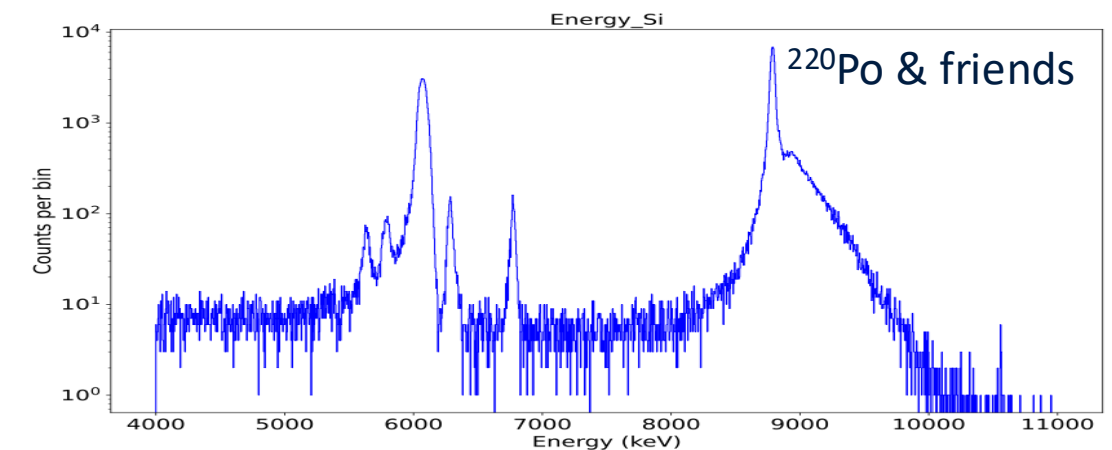
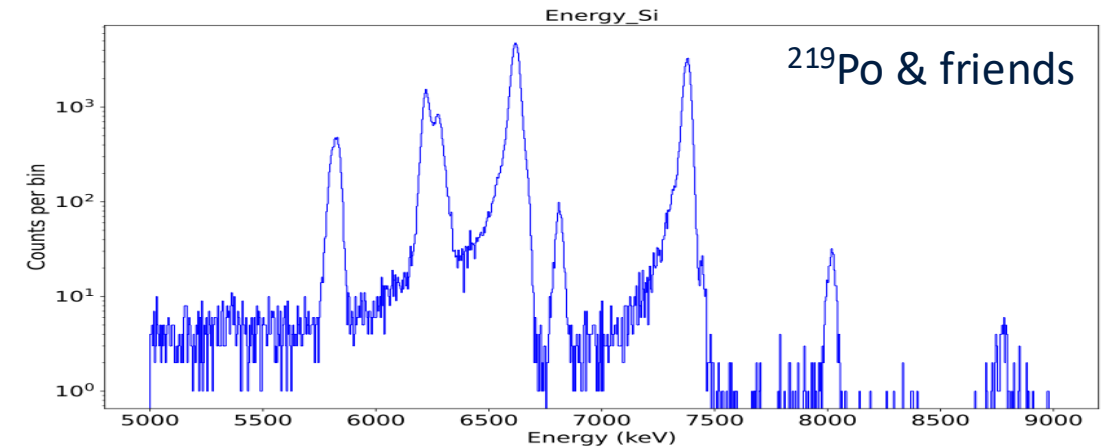
^{84}Po : Decay spectroscopy



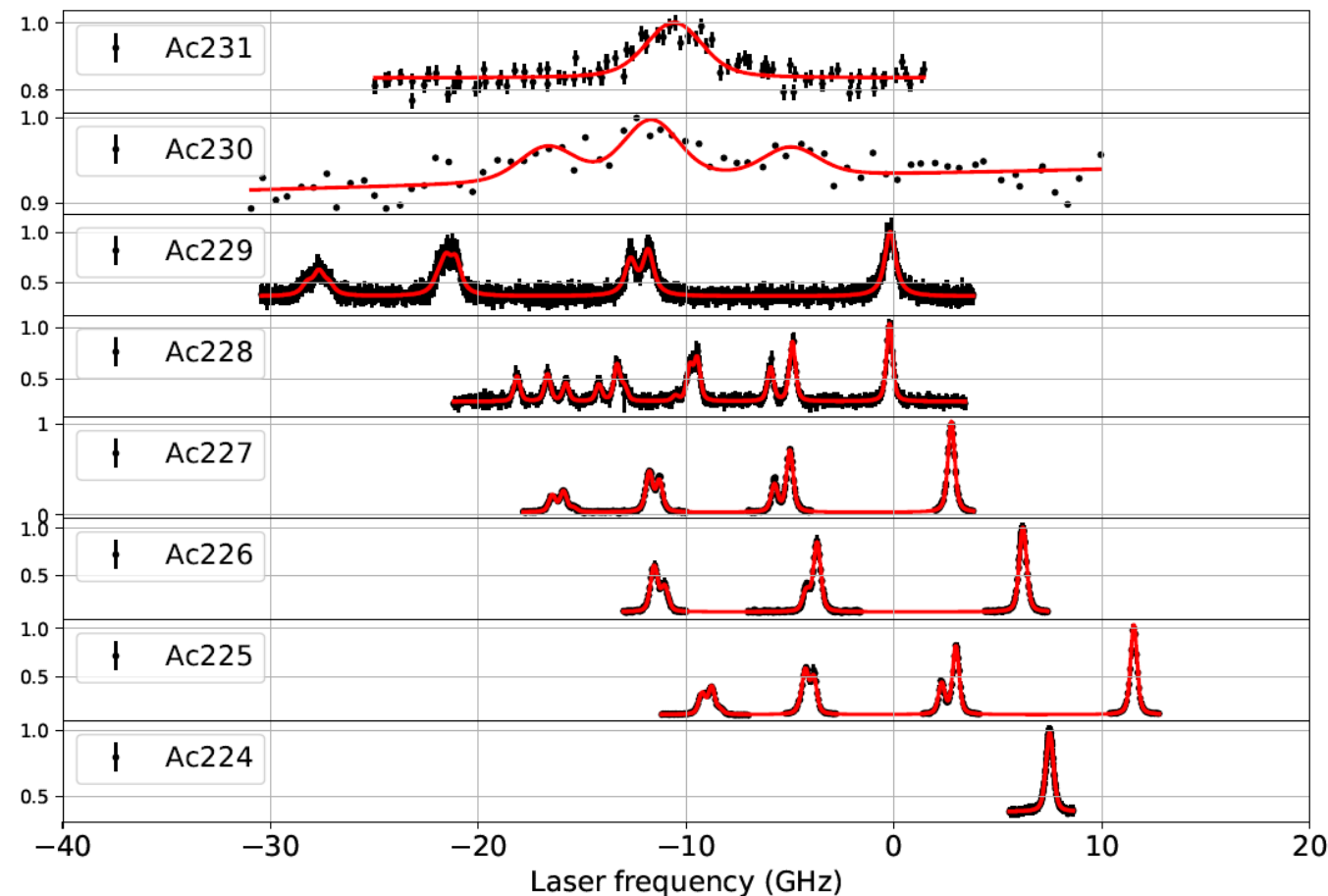
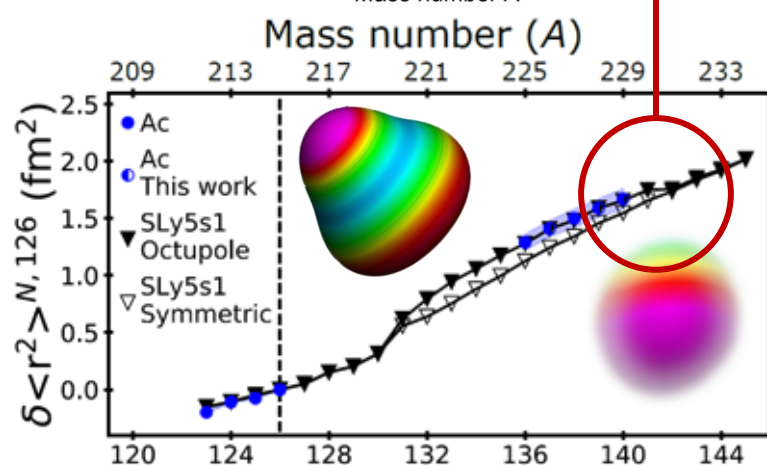
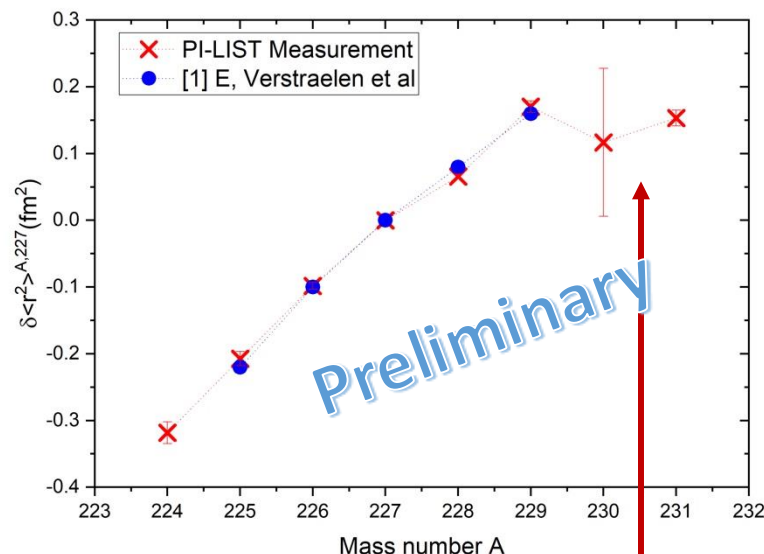
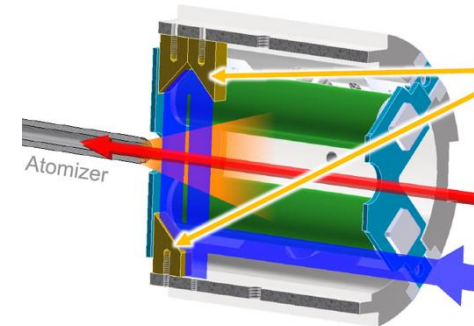
This study enabled the first investigation of ^{220}Po and a detailed look at ^{219}Po .

With $N=136$, ^{220}Po is at the heart of the octupole region. Yet, its radii and decay pattern suggest that it is not behaving in any exceptional way.

A detailed study of the beta decay to $^{219,220}\text{At}$ is on the way to explore the properties of those isotopes.



⁸⁹Ac: where theory led



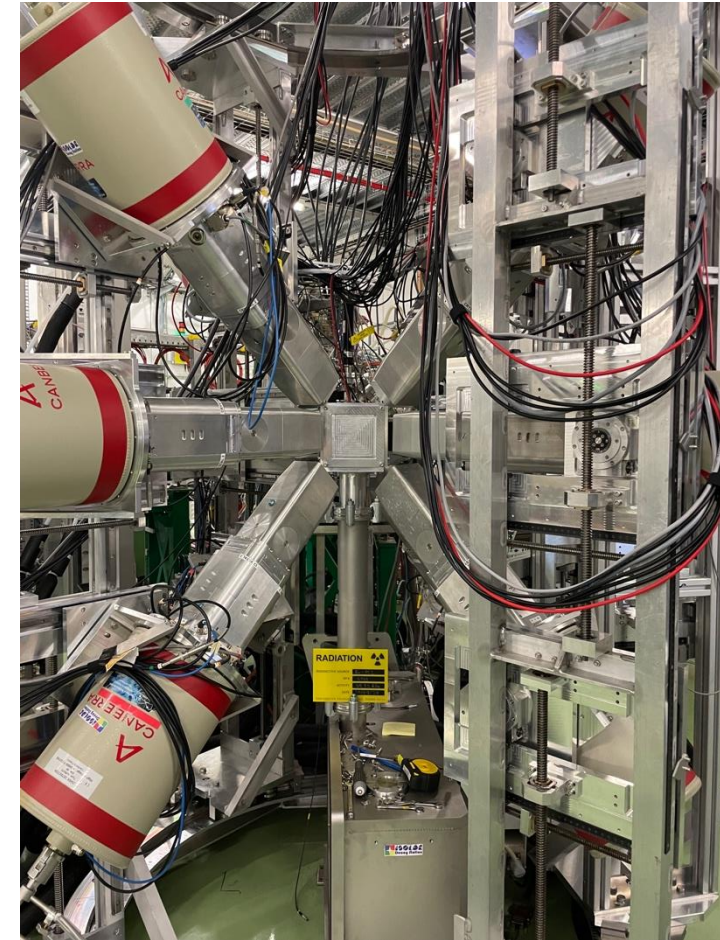
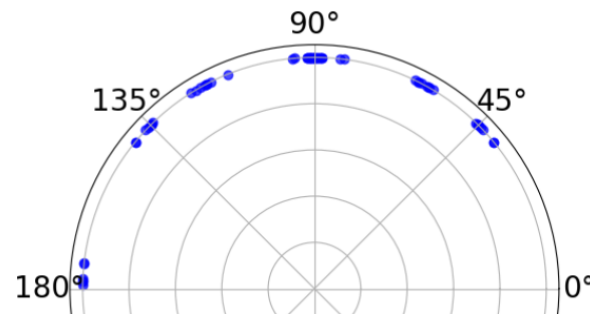
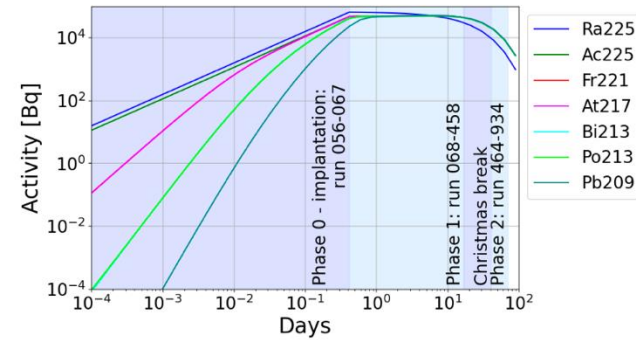


Decay spectroscopy of ^{225}Ac



The LIST technology enables the production of very clean beams, and in particular ^{225}Ac , a promising radionuclide for medical application.

At ISOLDE, we are investigating for the first time the decay of ^{225}Ac , ^{221}Fr , ^{213}Bi , and ^{209}Tl as pure beams using plastic scintillators, Si PIN diodes and HPGe clover detectors to resolve discrepancies in the decay scheme that have recently been uncovered.

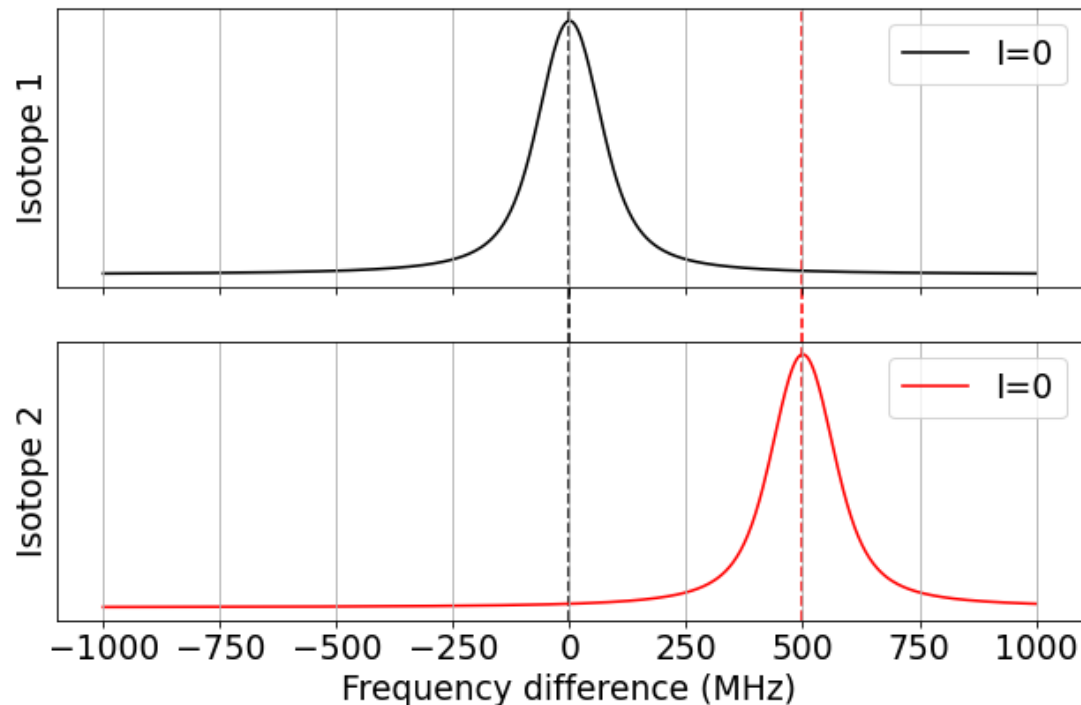




Accuracy limit in extracting charge radii

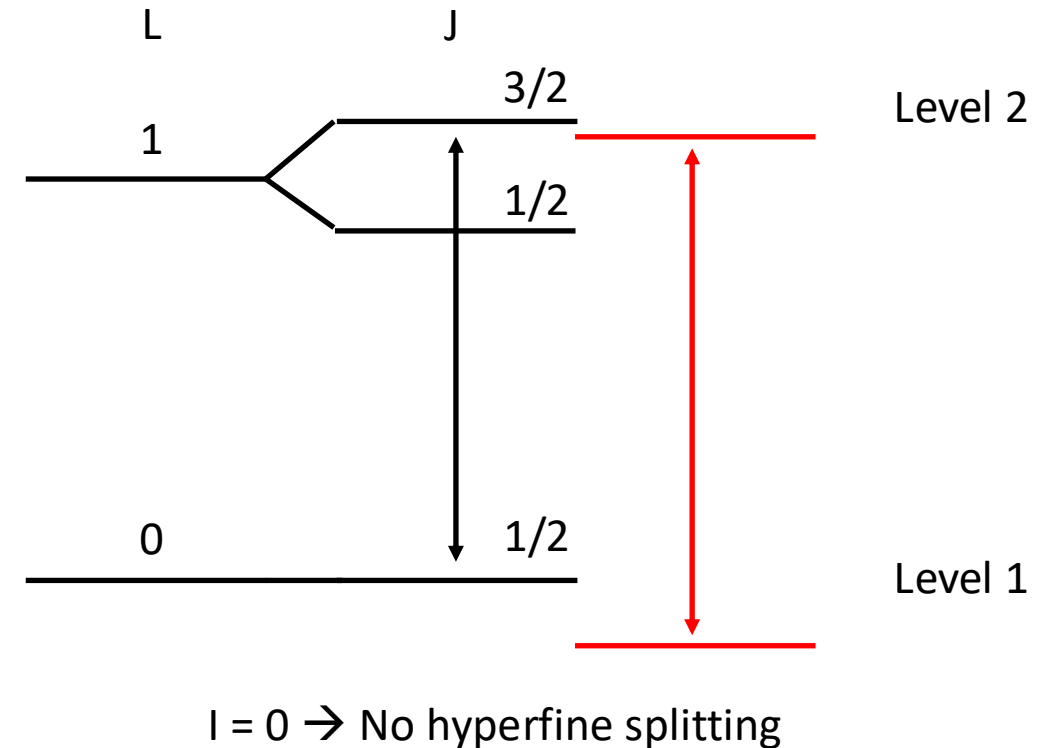
Probing the nucleus through its electrons

Use lasers to scan for transition energies



Extract isotope shifts $\delta\nu^{A,A'} \rightarrow$ Infer $\delta \langle r^2 \rangle^{A,A'}$

$$\delta \langle r^2 \rangle^{A,A'} = \frac{1}{F} \left(\delta\nu^{A,A'} - M \frac{m_{A'} - m_A}{m_A m_{A'}} \right)$$



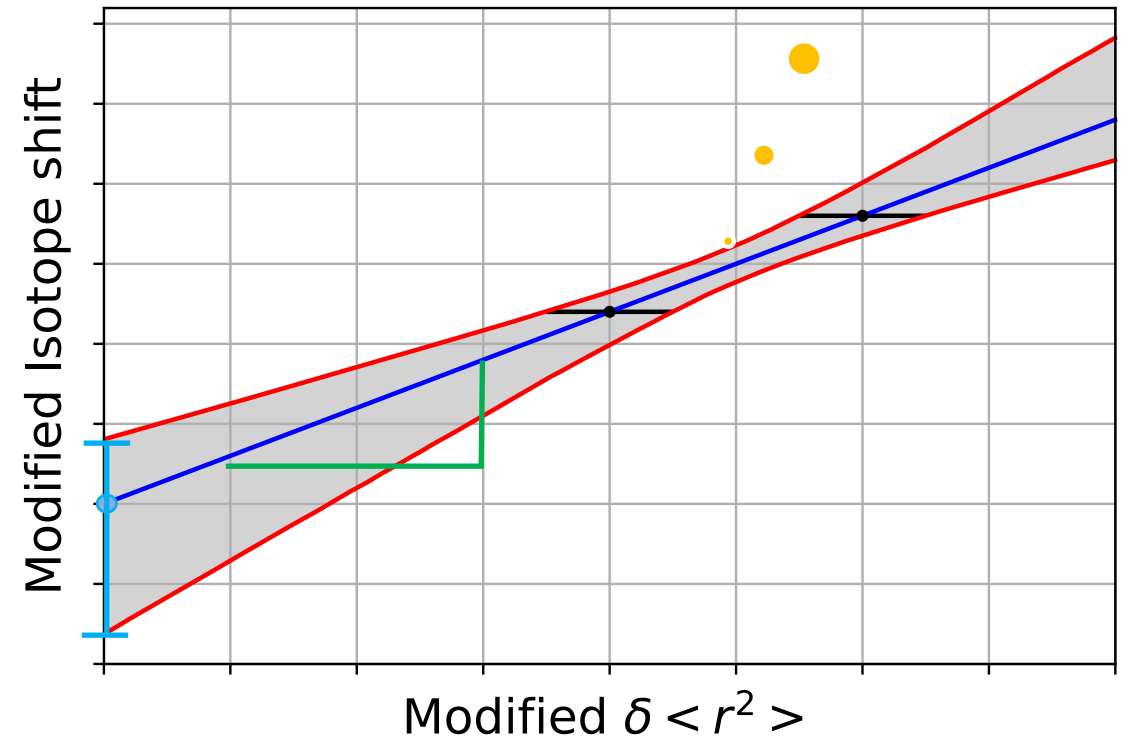
King plot against absolute radii

It takes 3 absolute radii to produce 2 $\delta \langle r^2 \rangle$

$$\delta \langle r^2 \rangle^{A,A'} = \frac{1}{F_i} \left(\delta \nu_i^{A,A'} - \frac{A - A'}{A A'} M_i \right)$$

- M_i : Mass shift factor
- F_i : Field shift factor

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

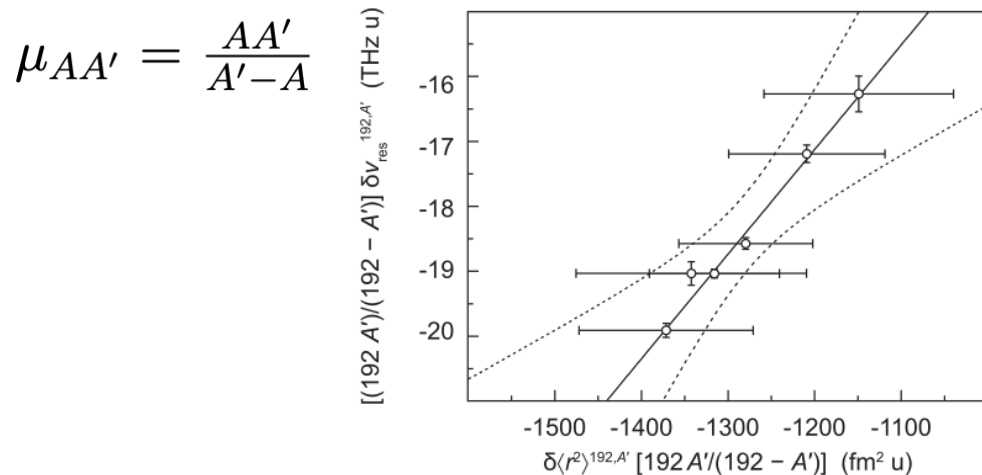


From isotope shift to charge radii

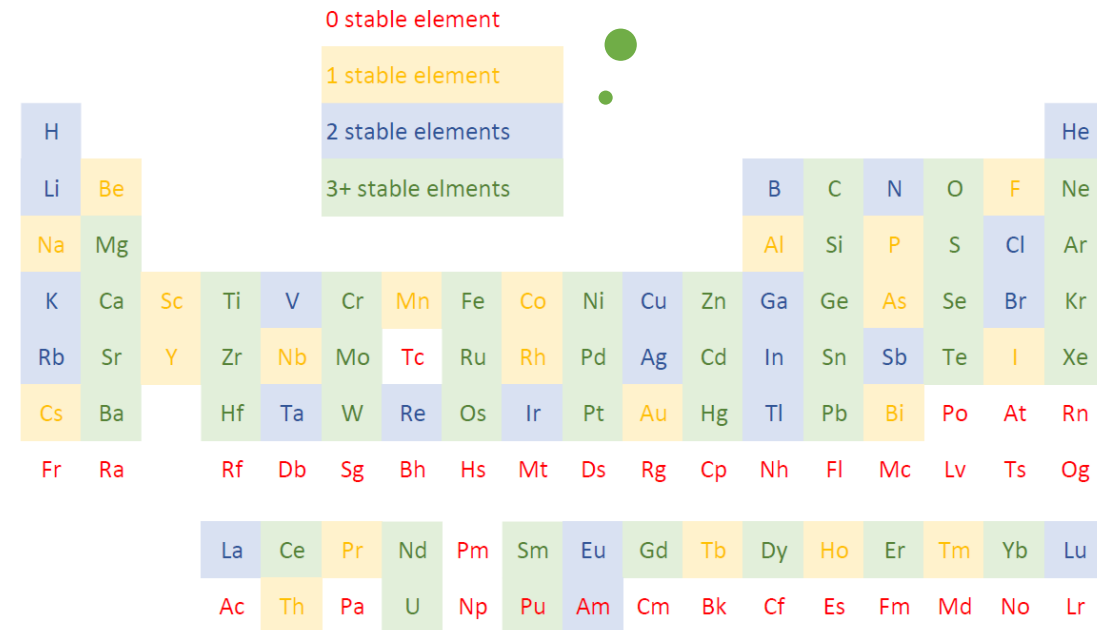
$$\delta\nu^{AA'} = \frac{A' - A}{AA'} \left(m_e \nu + M_{SMS} \right) + F \delta \langle r^2 \rangle^{AA'}$$

The atomic parameters are essential to extract $\delta \langle r^2 \rangle$
There are atomic theorists who can calculate them.
Experimental extraction or validation is still needed

$$\mu_{AA'} \delta\nu^{AA'} = M + F \mu_{AA'} \delta \langle r^2 \rangle^{AA'}$$



Many elements – all odd-Z & heavy elements – do not possess 3 stable isotopes to work with!



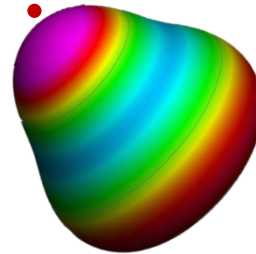
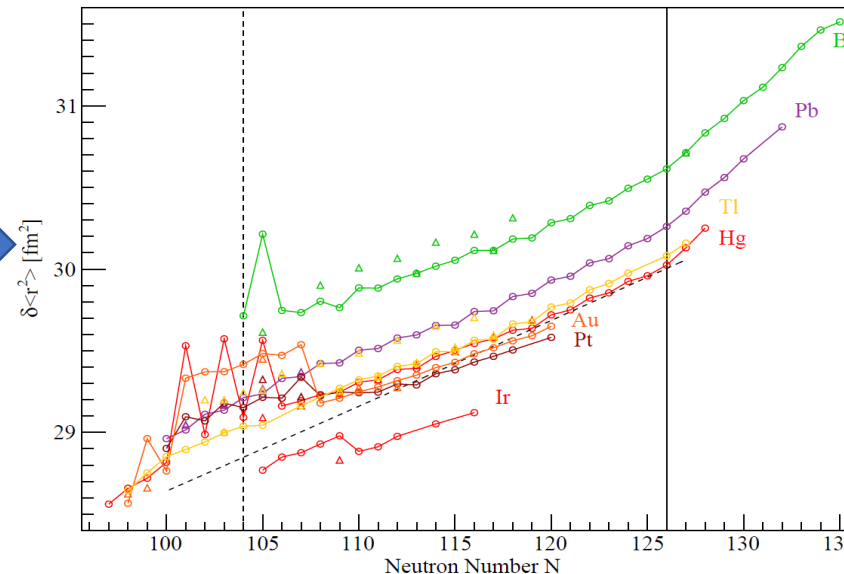
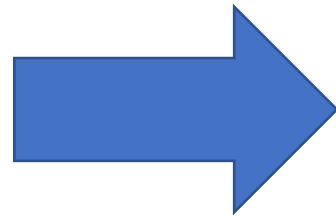
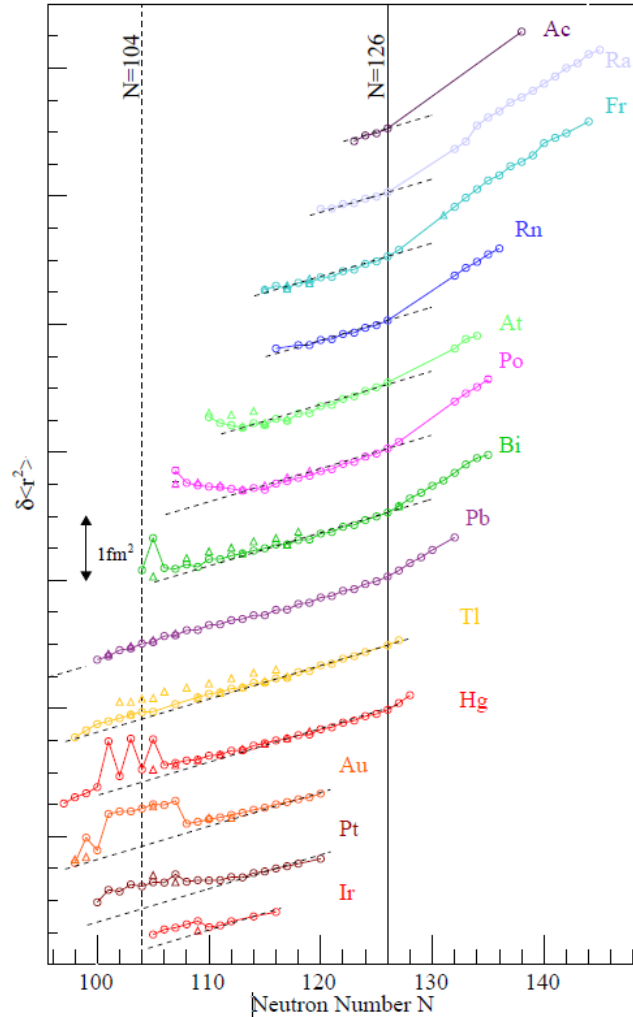
Absolute size of the heavy elements

Key measurements of absolute charge radii could easily complete this picture

Exploring isotonic chains across $Z=82$

- Last known magic proton number
- No anchor point between $_{83}\text{Bi}$ and $_{90}\text{Th}$ prevents to investigate these isotopes extensively
- Input needed to support other fields that use the

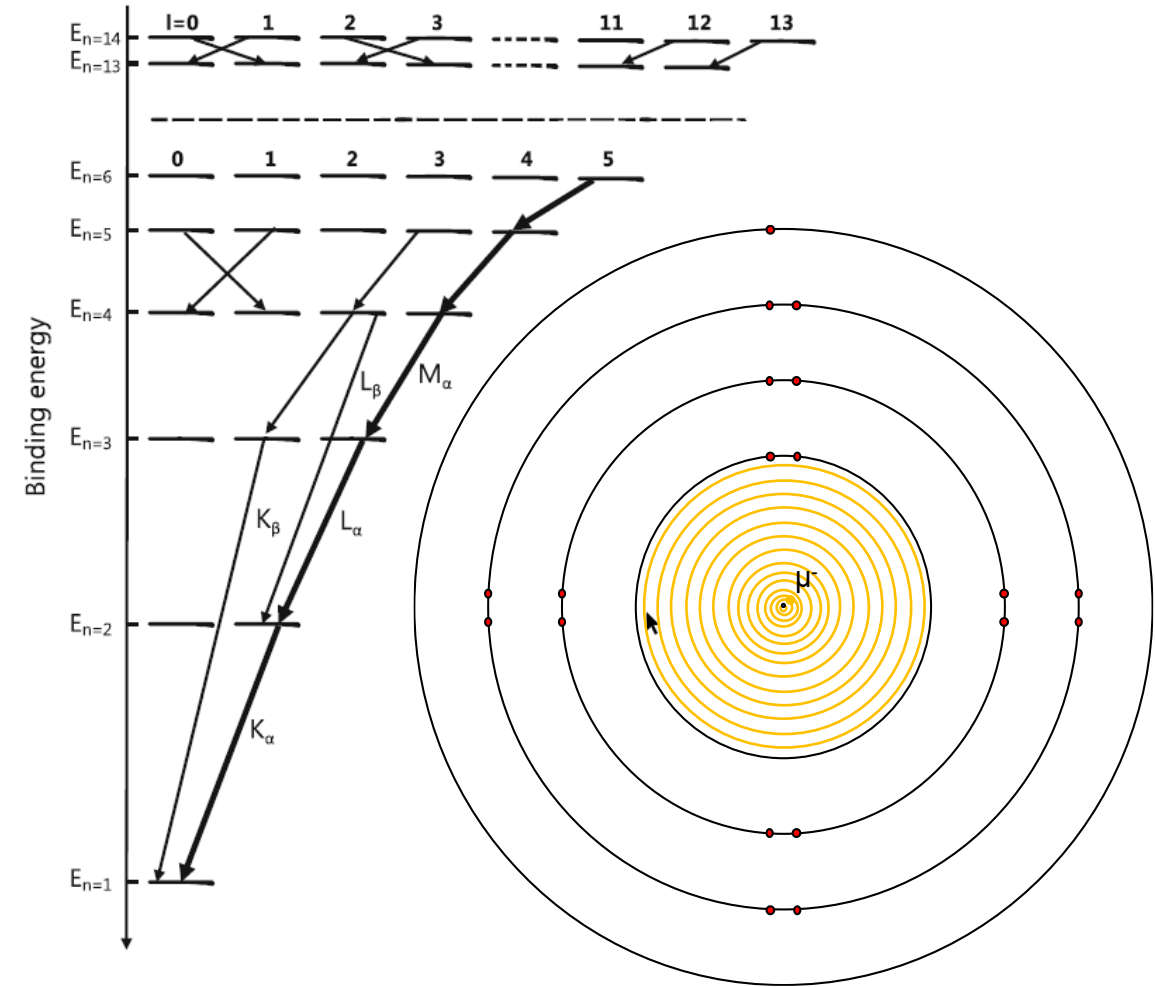
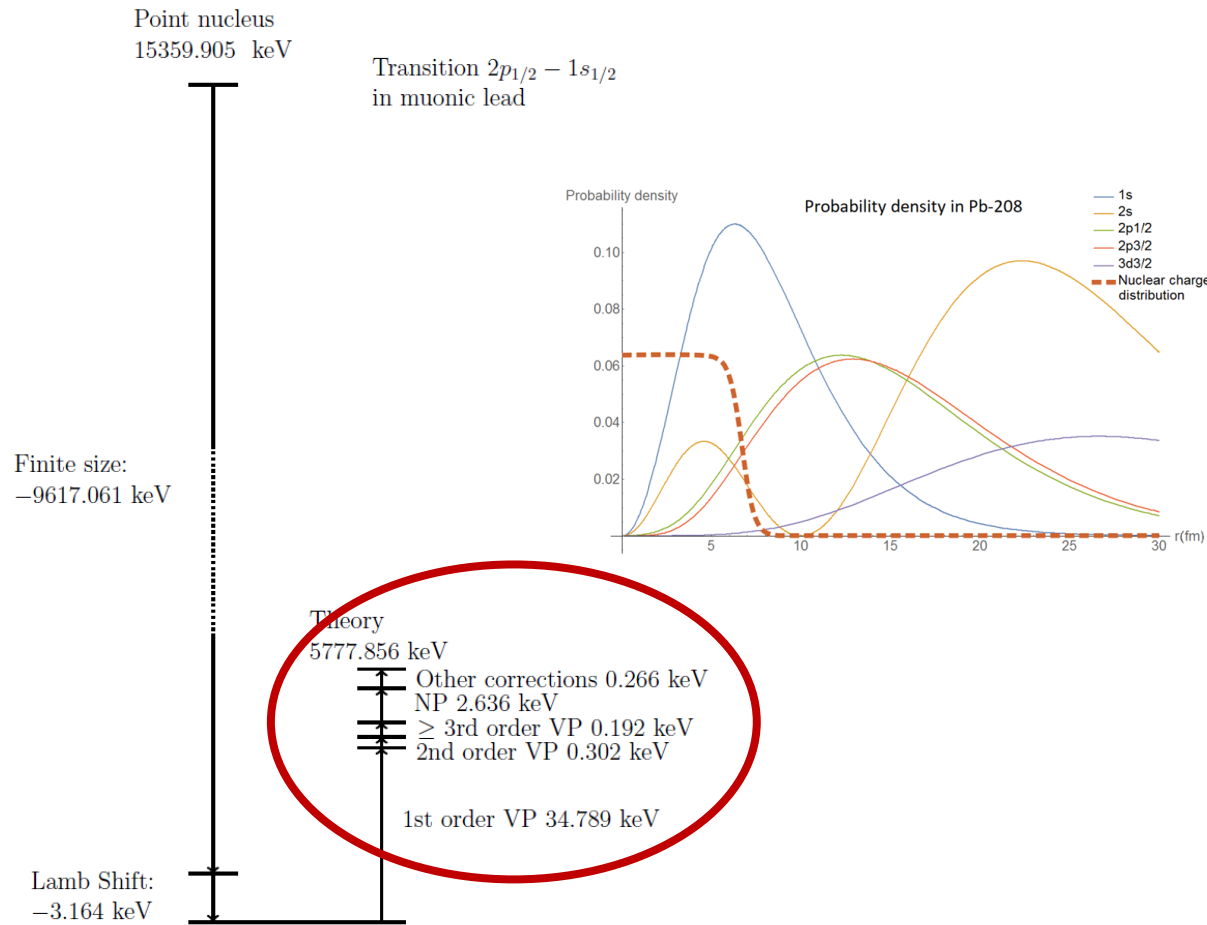
Absolute charge radii are needed for the searches of physics beyond the standard model



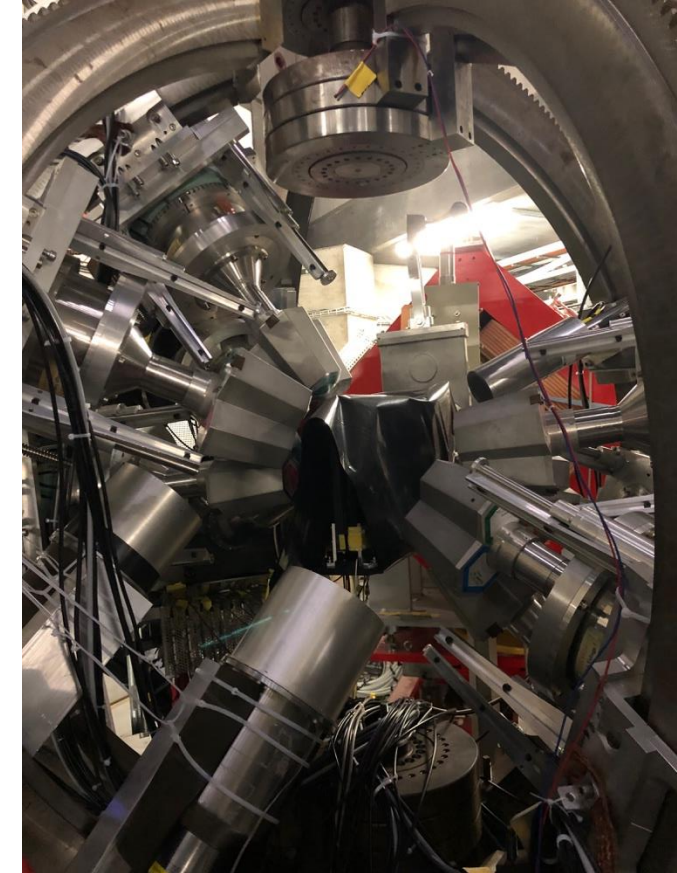
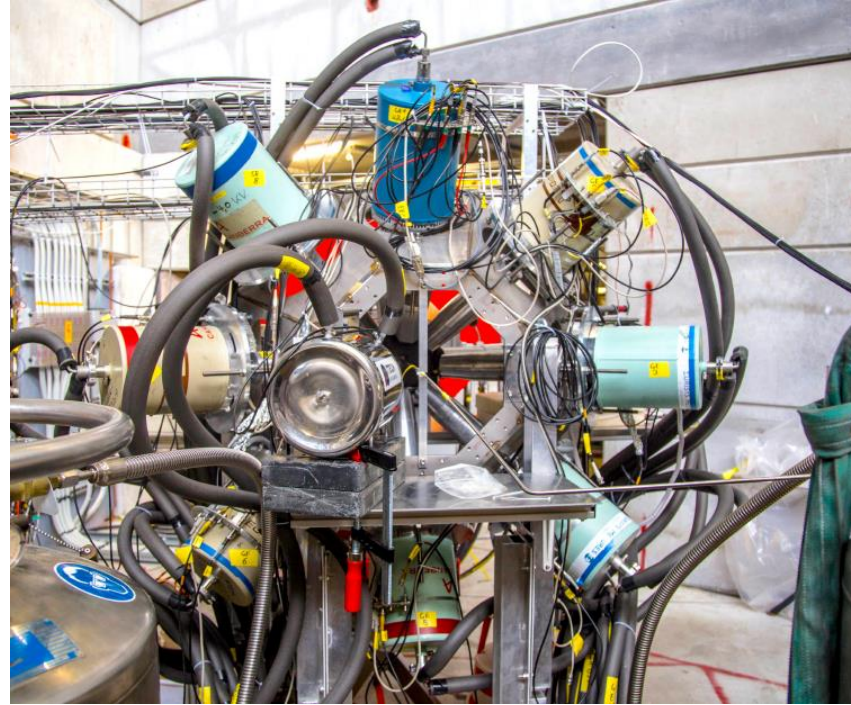
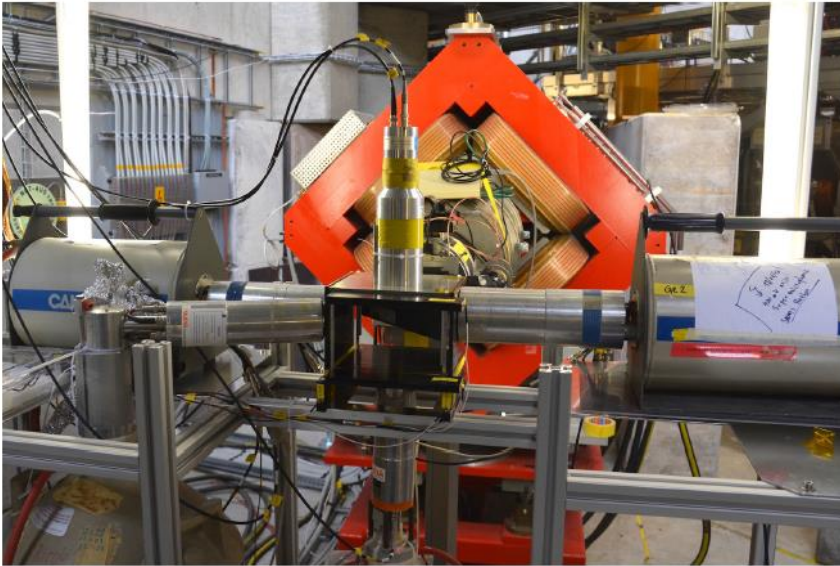
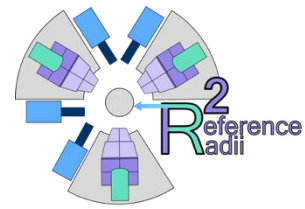


muX and ReferenceRadii

Muonic x-rays as probe

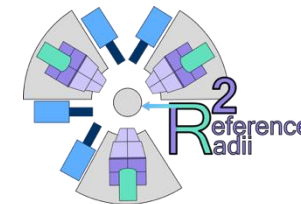


μ -atomic spectroscopy with muX at PSI



- 2016: 2 HPGe from Leuven
- 2017/18: the Death Star Array
MiniBall Cluster + detectors from PSI & IPNO
- 2019: MiniBall @ PSI campaign
- 2020+: GIANT Array with MIXE, muX and muon capture

μ -atomic spectroscopy with muX at PSI



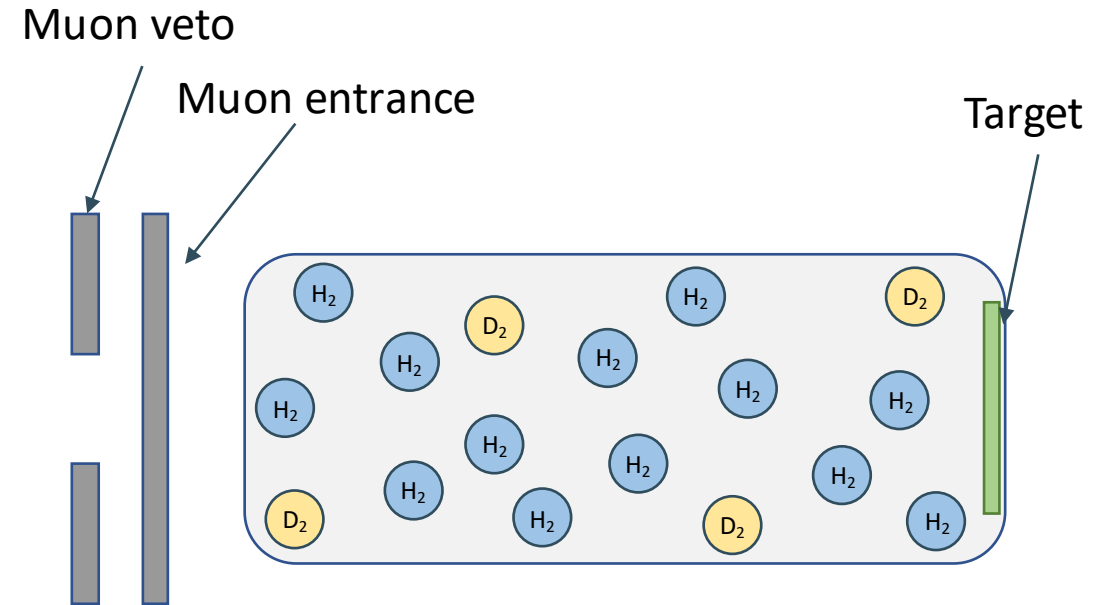
- 2020+: GIANT Array with MIXE, muX and muon capture

Measuring microgram materials

Traditionally: Limited to target mass $O(10-100 \text{ mg})$

Hydrogen gas cell (100 bars; 0.25% deuterium)

- Limited to $O(5 \text{ } \mu\text{g})$
- Down to 20 year half-life (radioprotection)

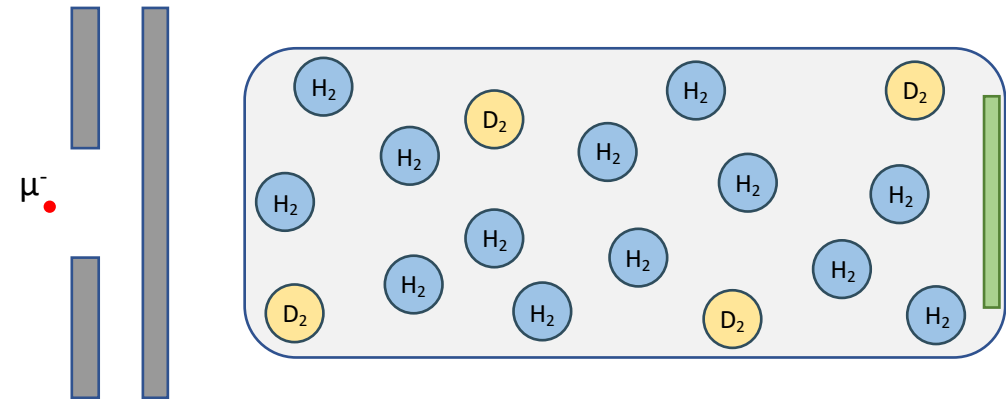


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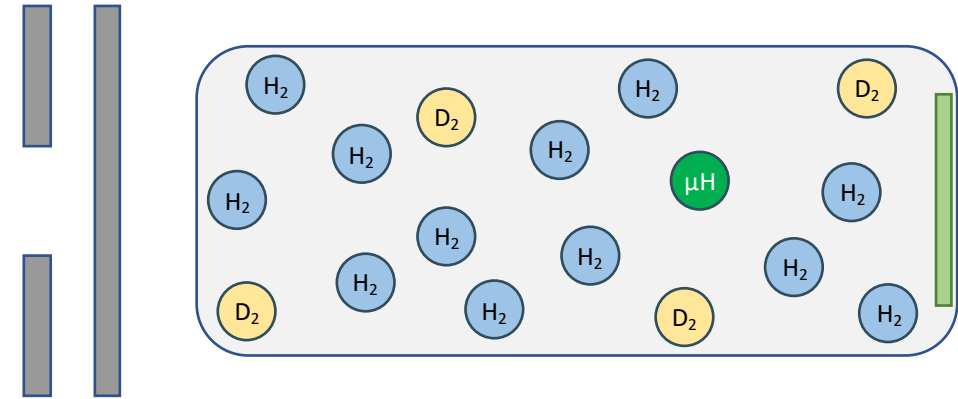


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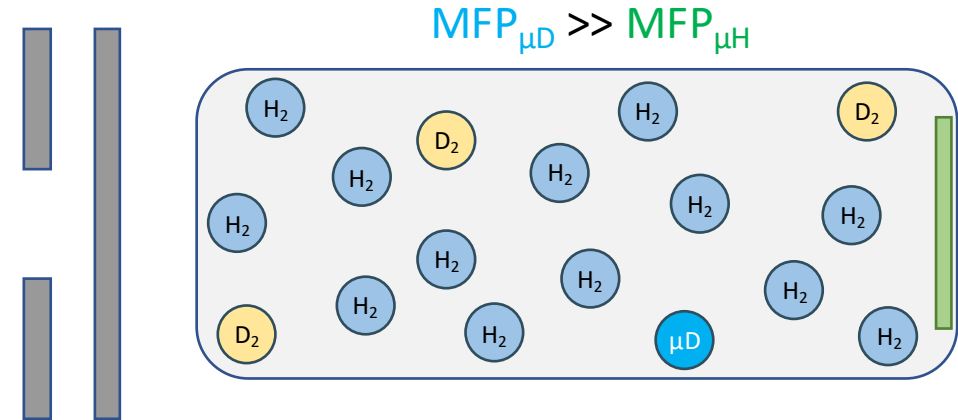
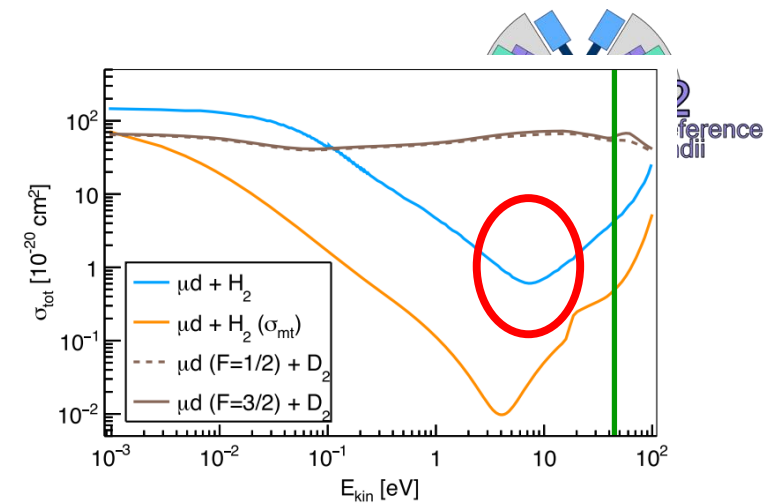


Measuring microgram materi

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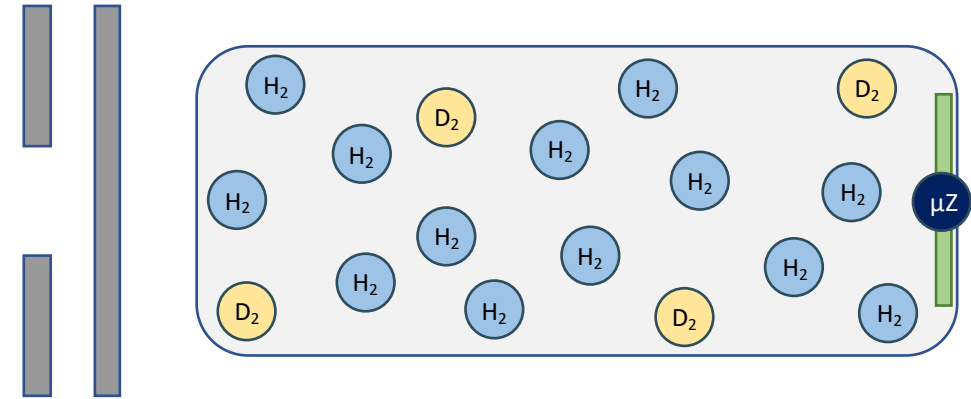


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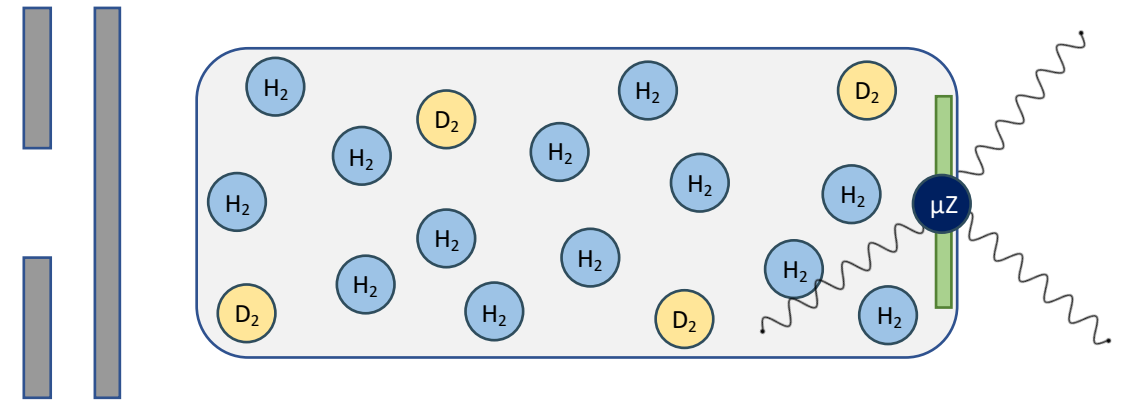


Measuring microgram materials

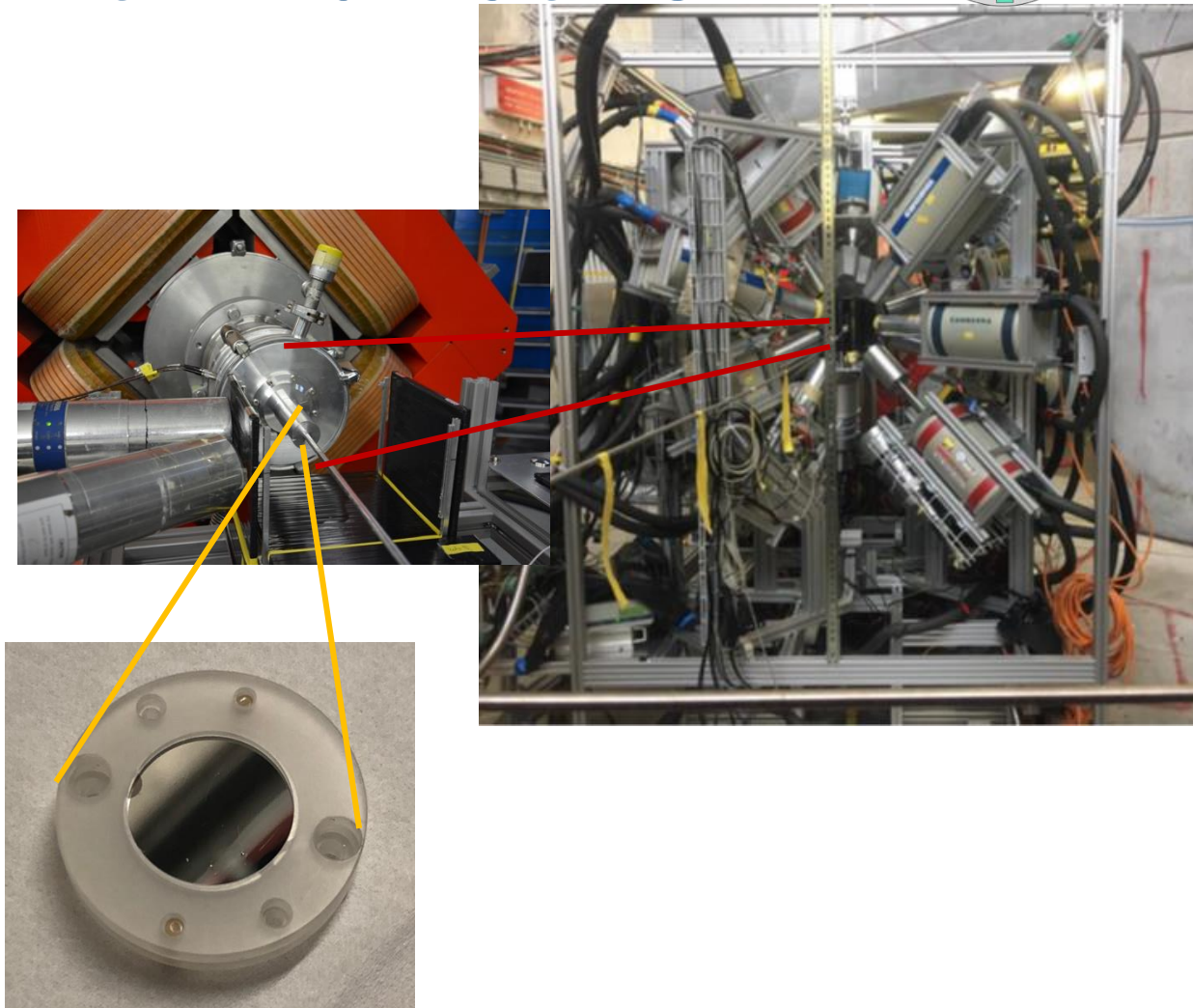
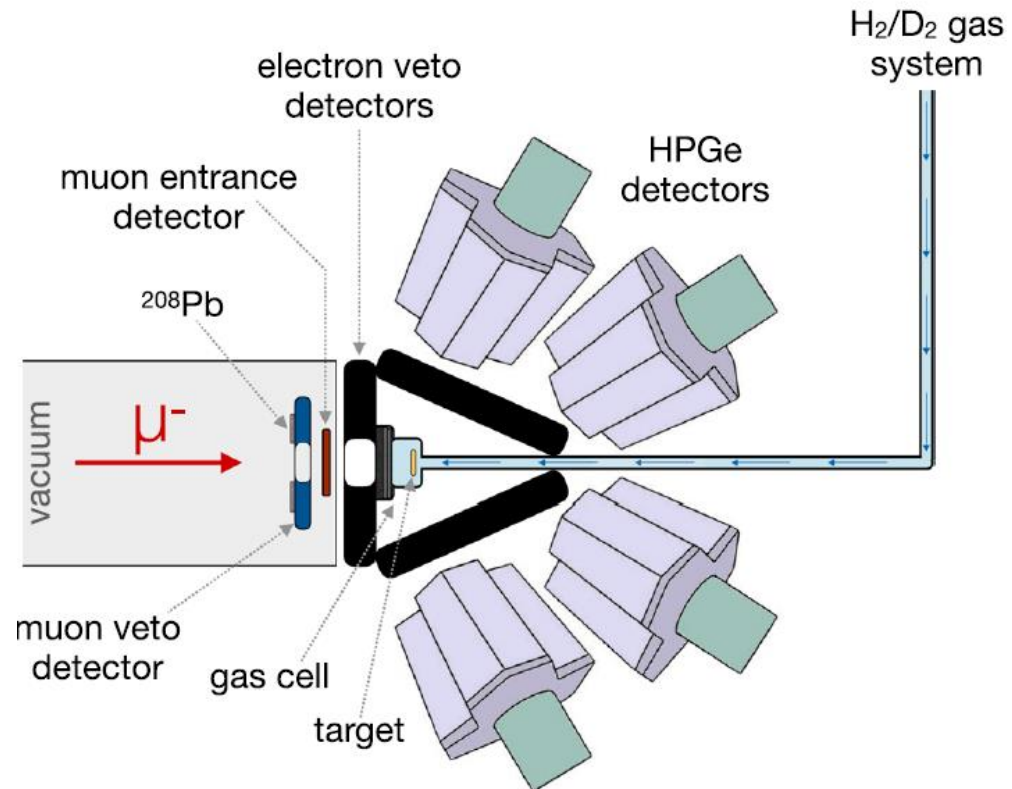
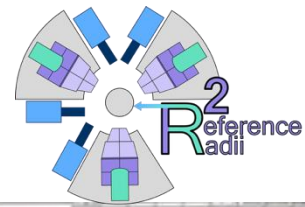
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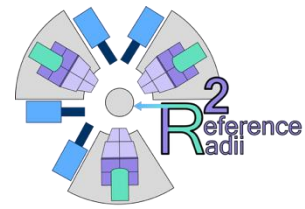
- Limited to O(5 μg)
- Down to 20 year half-life (radioprotection)



μ -atomic spectroscopy with muX at PSI



^{17}Cl and ^{19}K : probing near $Z=20$

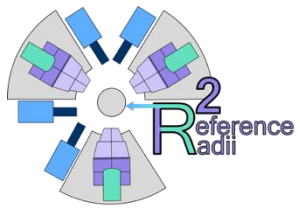


2023

- Used enriched targets of ^{35}Cl , ^{37}Cl , ^{39}K , ^{40}K , ^{41}K .
- ^{40}K required mass separation to obtain a pure sample.
- First measurement with pure Cl isotopes and first measurement of ^{40}K for a full triplet.



^{17}Cl and ^{19}K : probing near $Z=20$

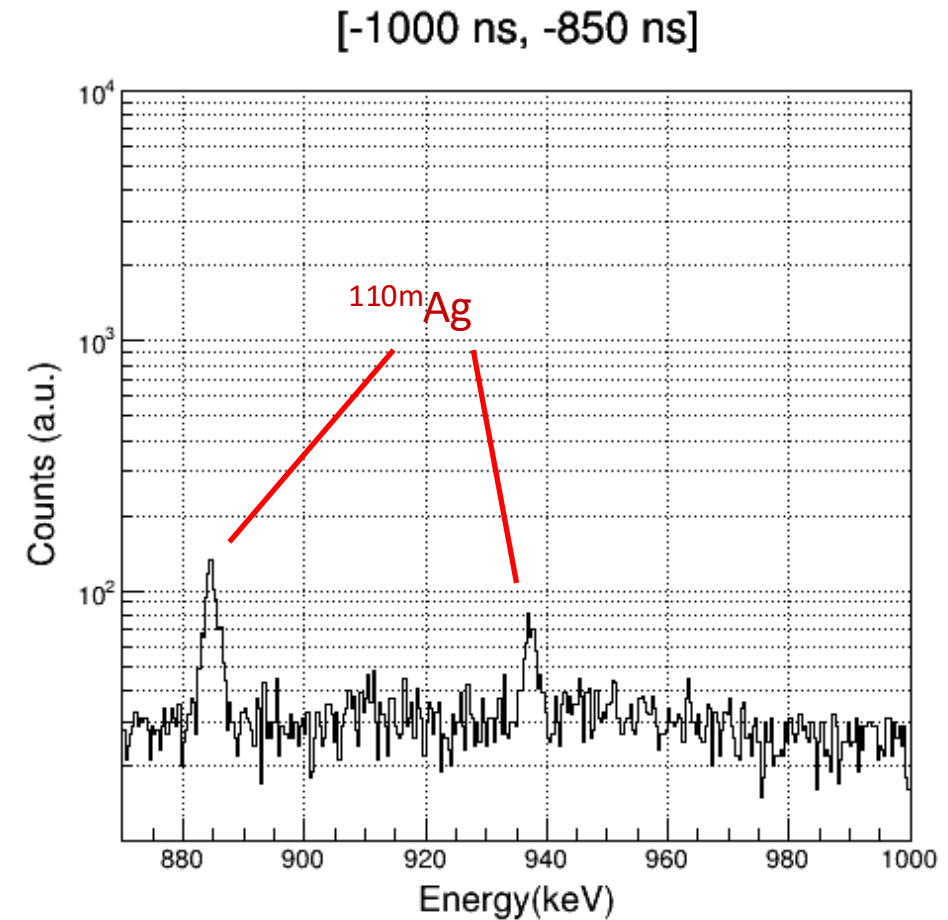
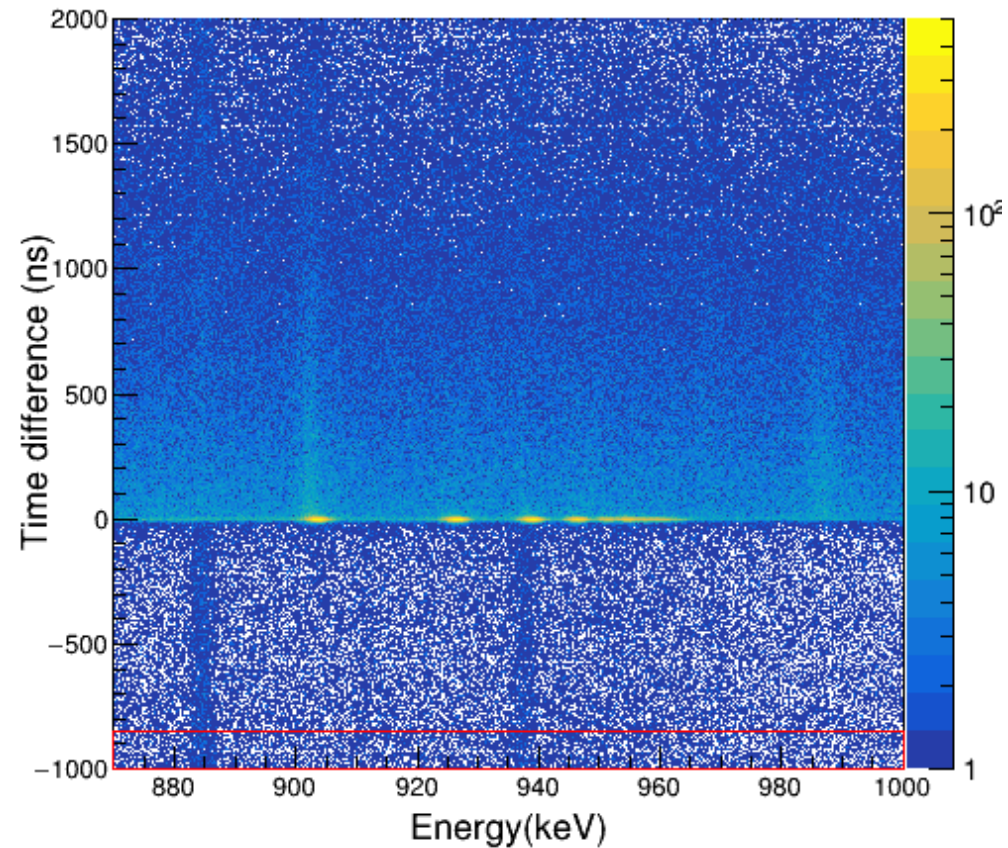


2023

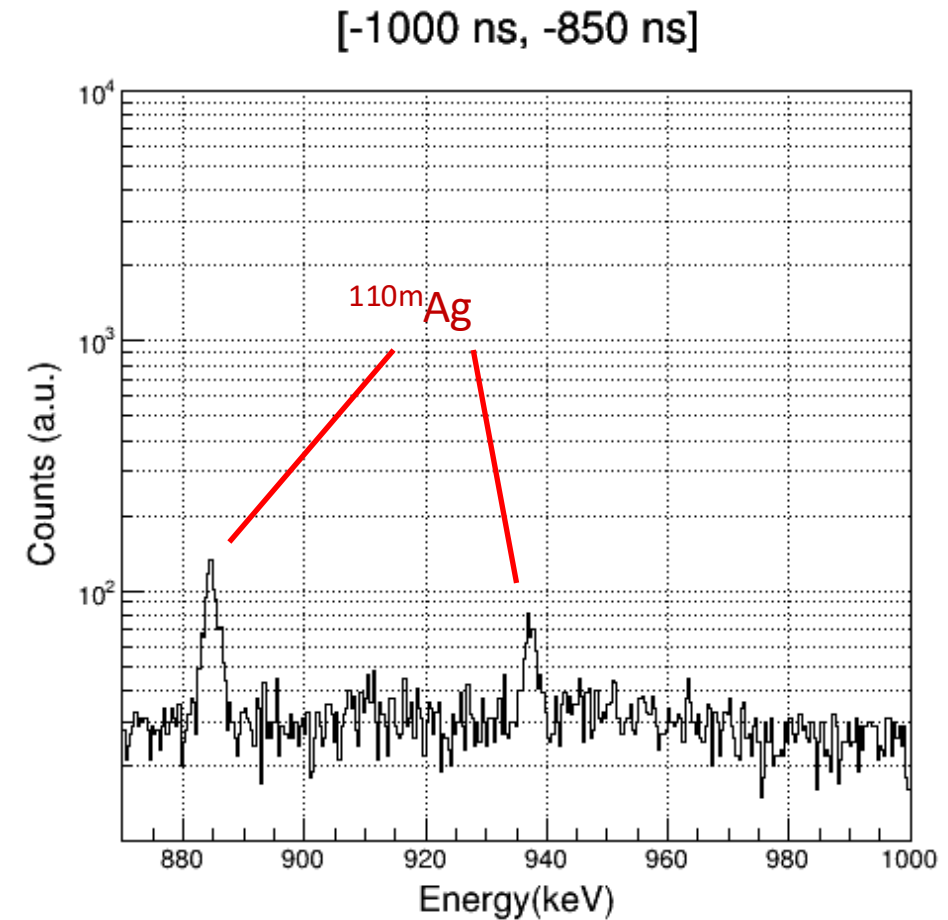
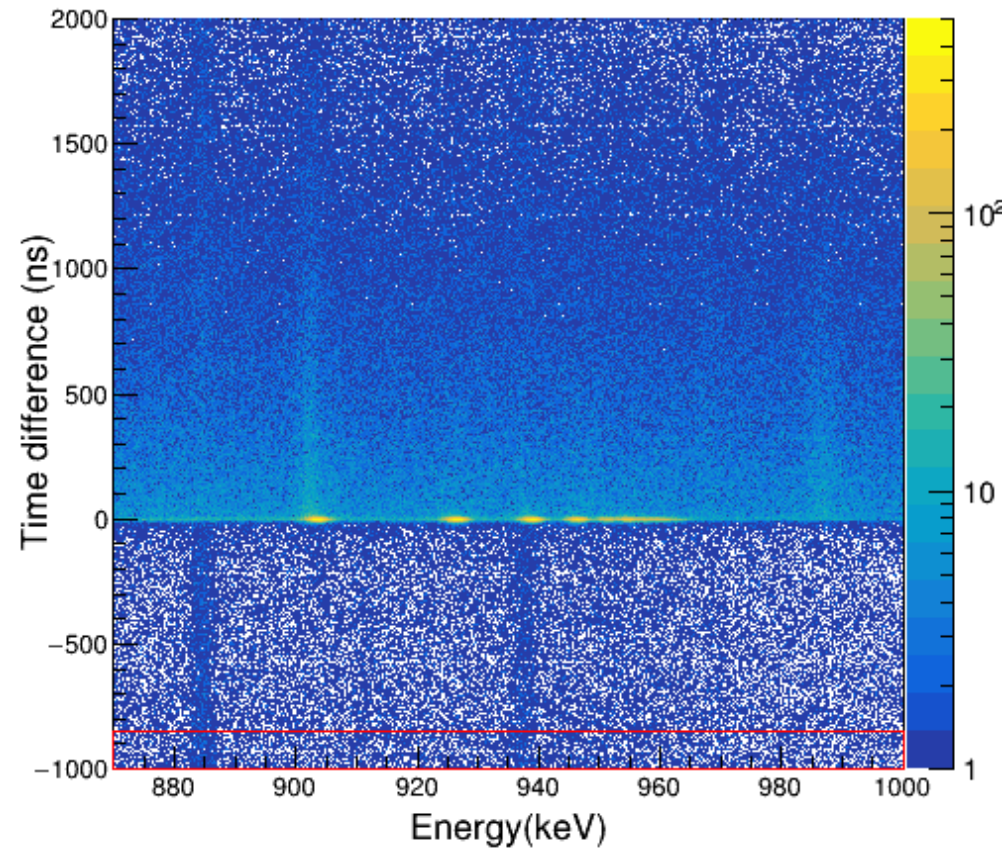
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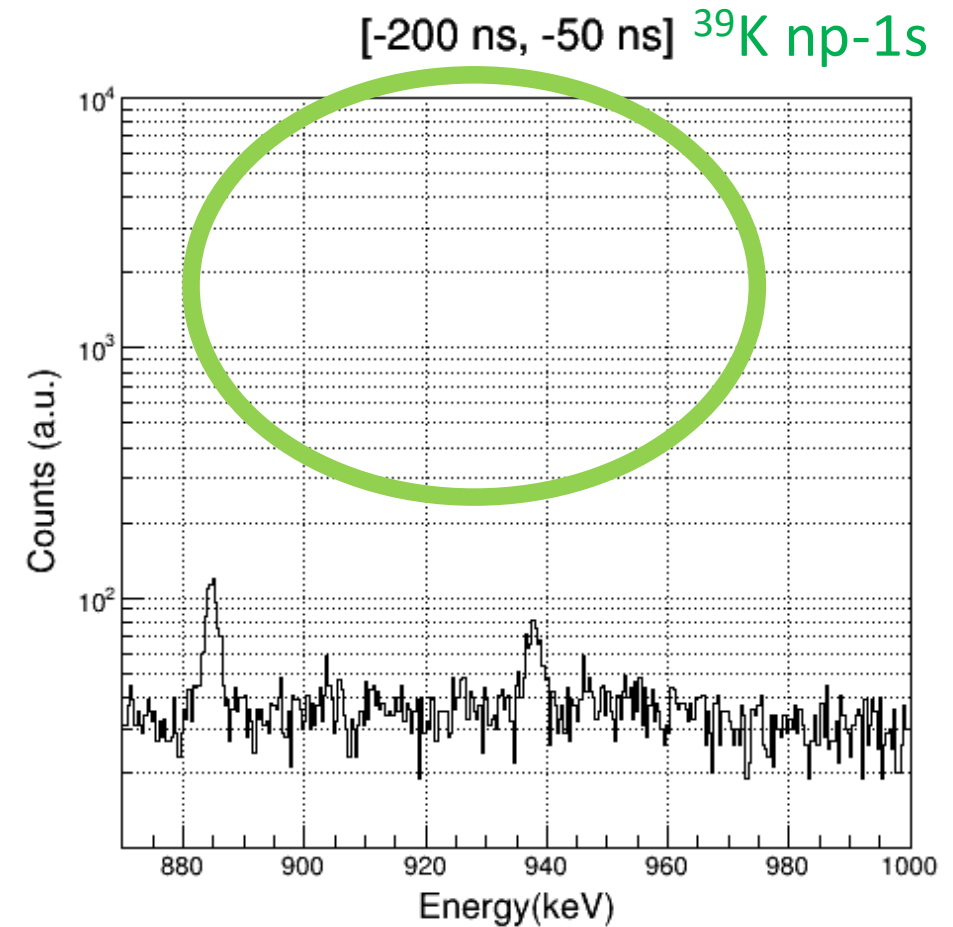
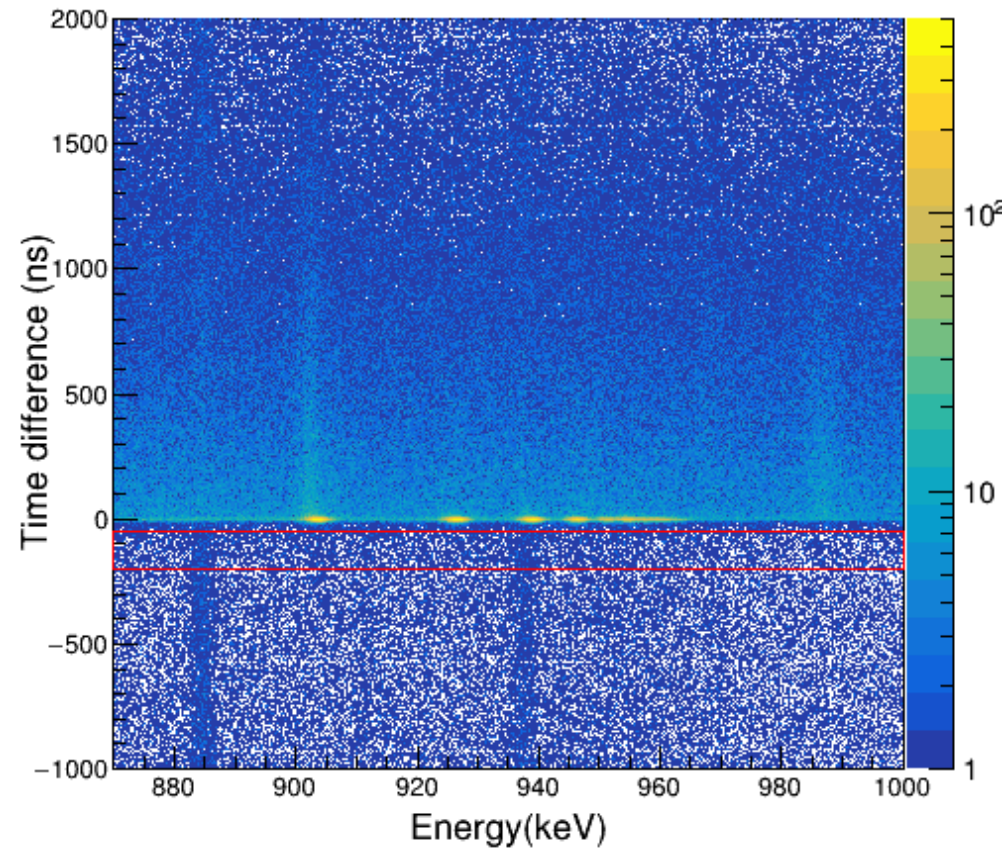
Interpreting energy Vs time plots



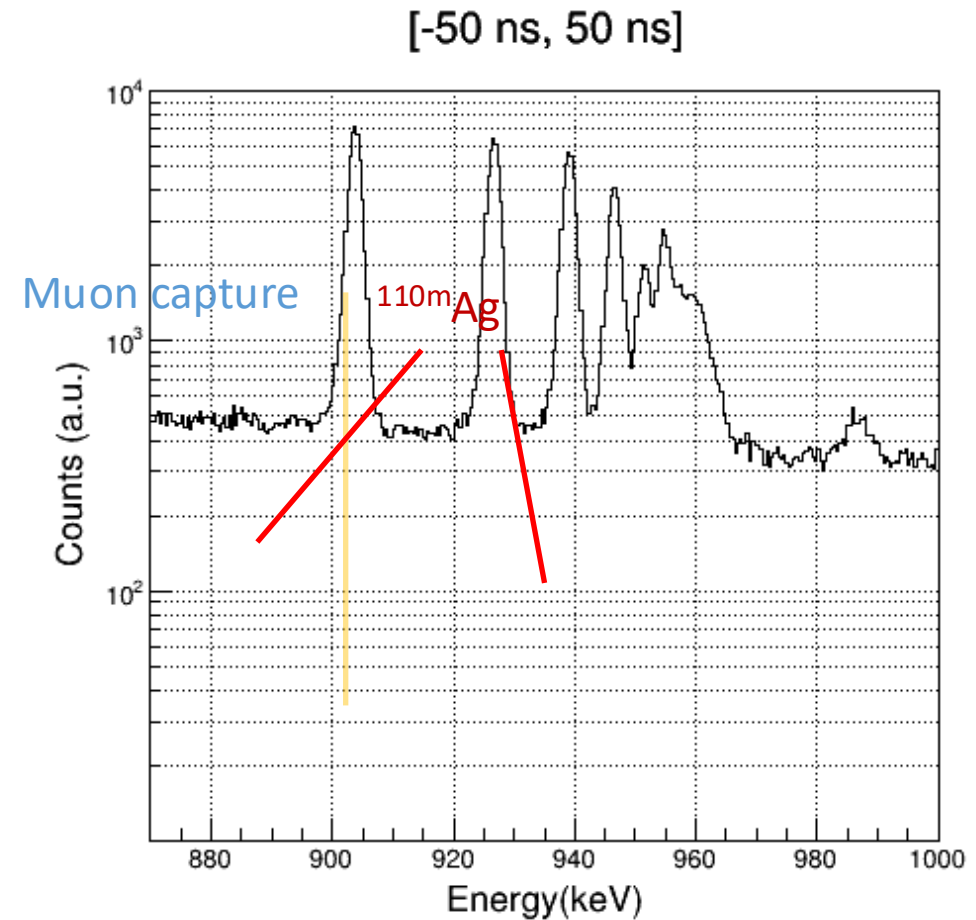
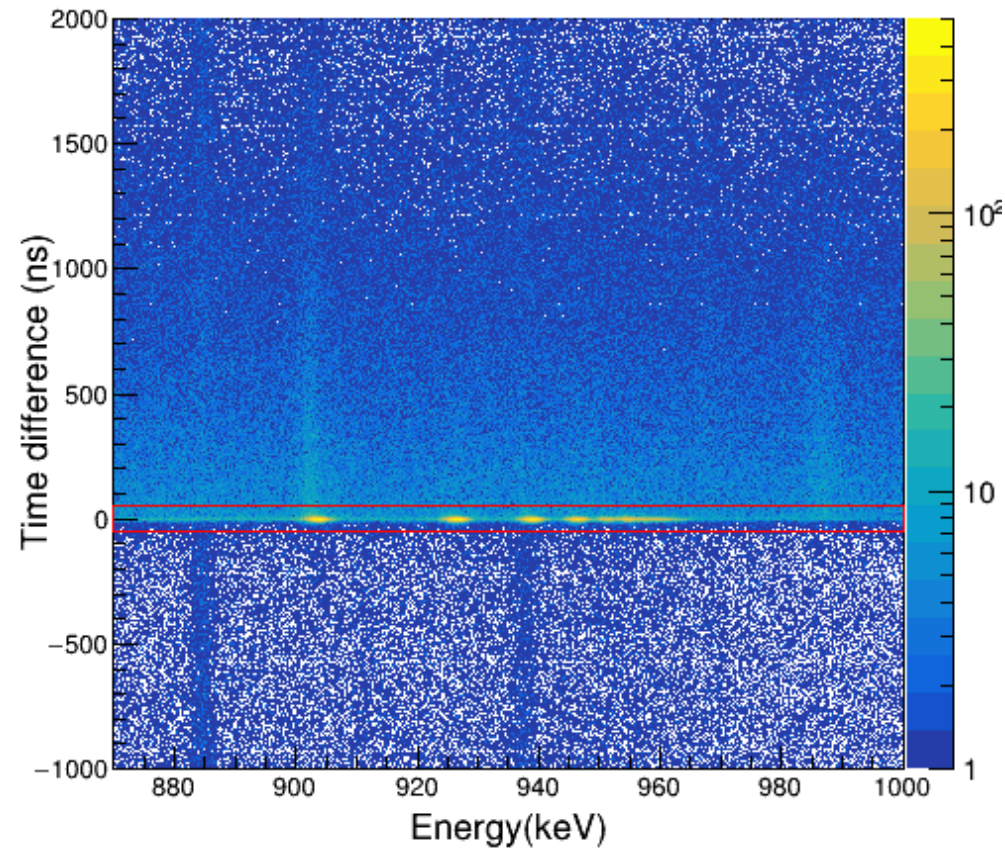
Interpreting energy Vs time plots



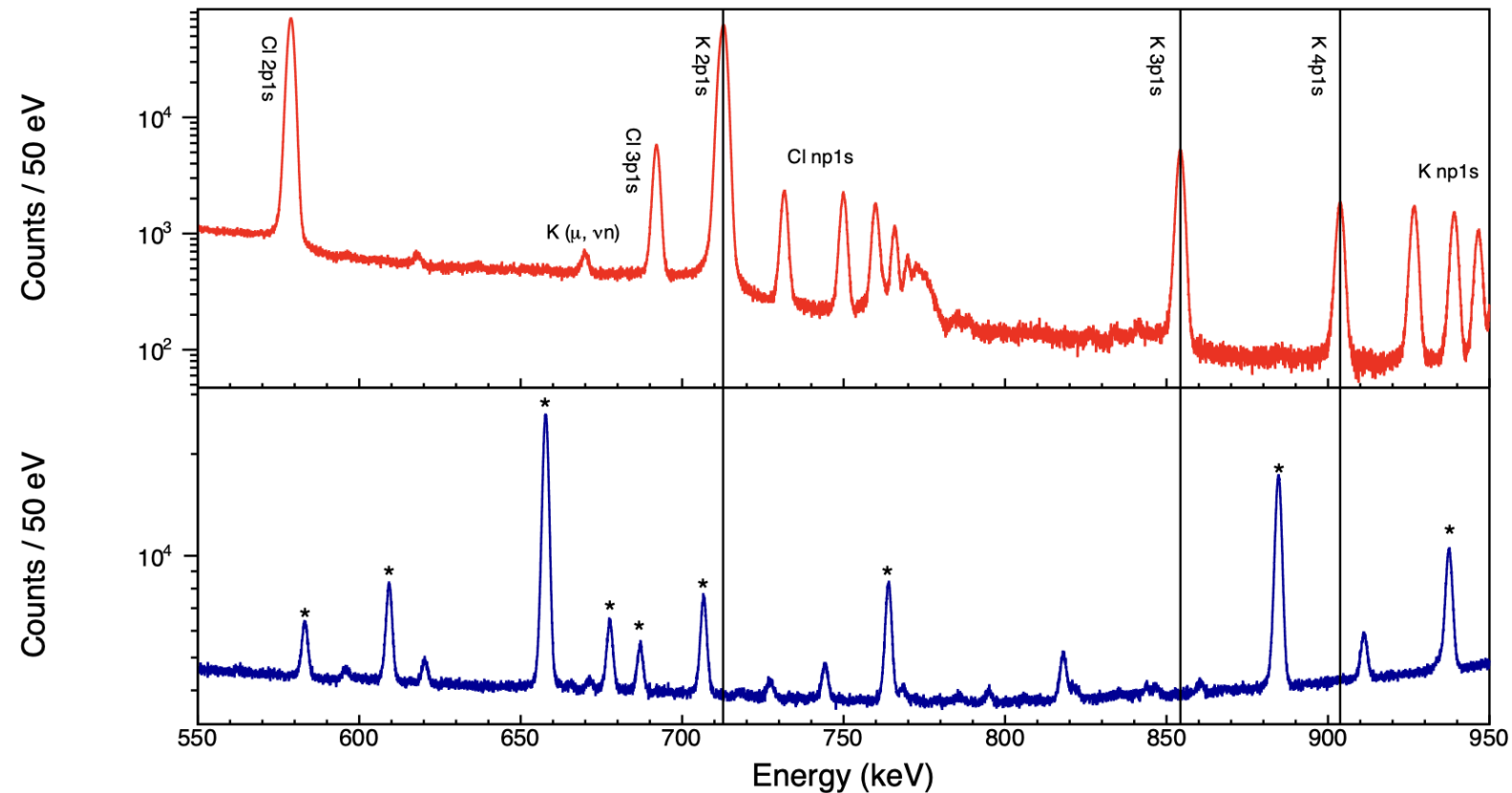
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Interpreting energy Vs time plots



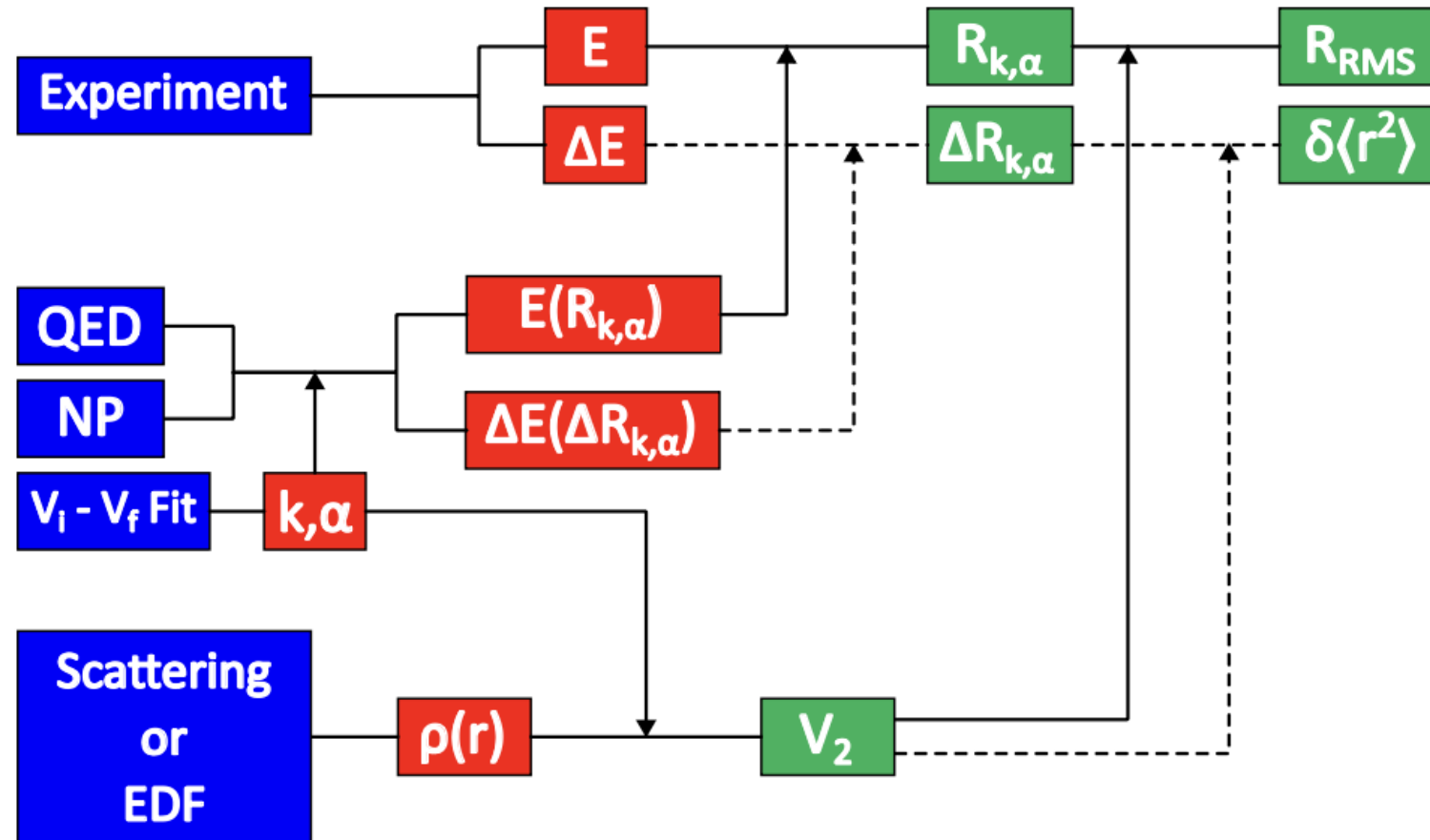
$_{17}\text{Cl}$ and $_{19}\text{K}$: probing near $Z=20$



$^{39}\text{K}^{\text{nat}}\text{Cl}$ np1s

PhD work Michael Heines (KU Leuven).

$_{17}\text{Cl}$ and $_{19}\text{K}$: probing near $Z=20$

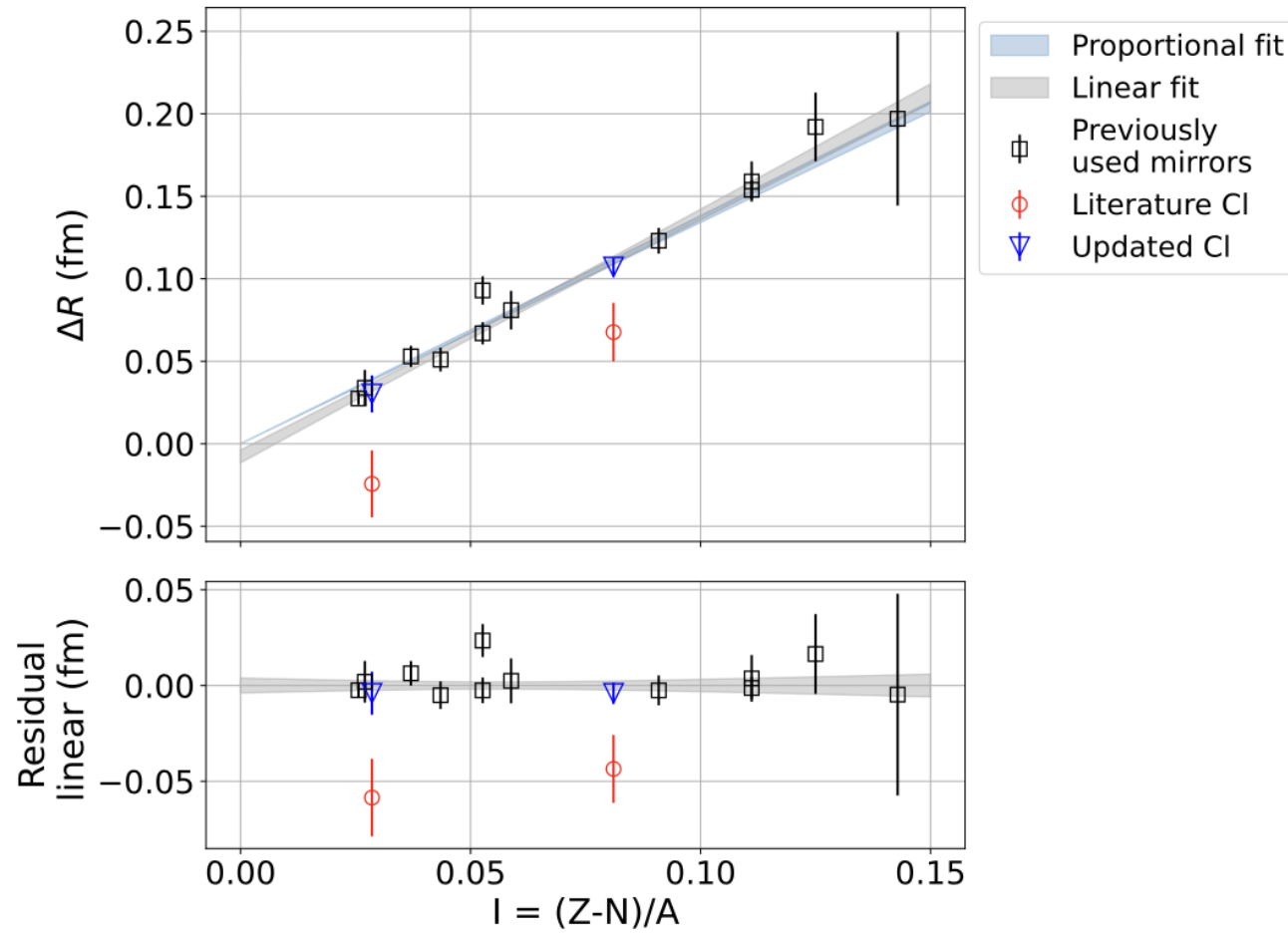


$_{17}\text{Cl}$ and $_{19}\text{K}$: probing near $Z=20$

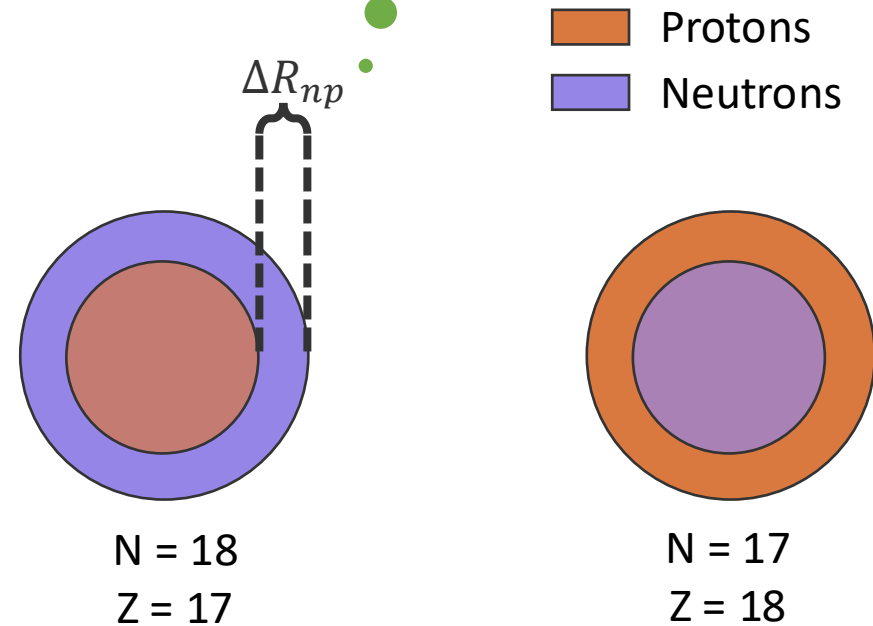
- Large targets for $^{39,41}\text{K}$ and $^{35,37}\text{Cl}$
→ Direct stopping with high statistics
Uncertainty dominated by calibration error.
→ 2p1s, 3p1s, and 4p1s energies extracted with $\sim 15\text{-}25$ eV precision
- Small target for ^{40}K (~ 10 μg)
→ muX transfer mechanism with limited statistics
Uncertainty dominated by statistical error.
→ 2p1s energy extracted with ~ 35 eV precision



Mirror nuclei



Links with the symmetry energy L in the nuclear matter equation of state.



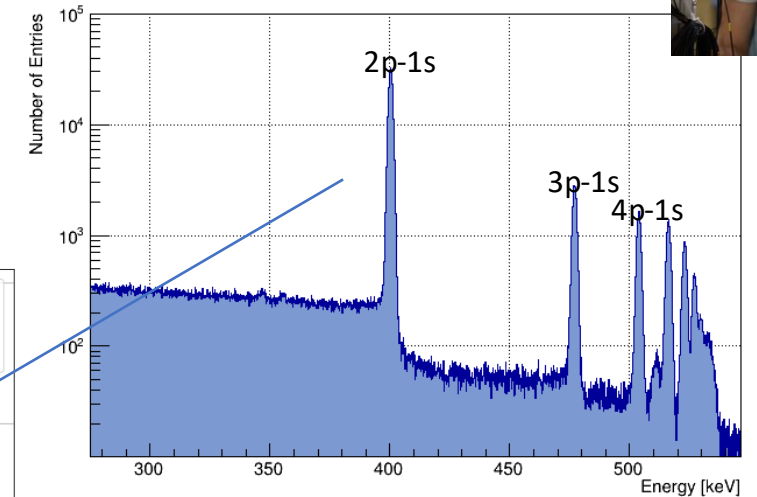
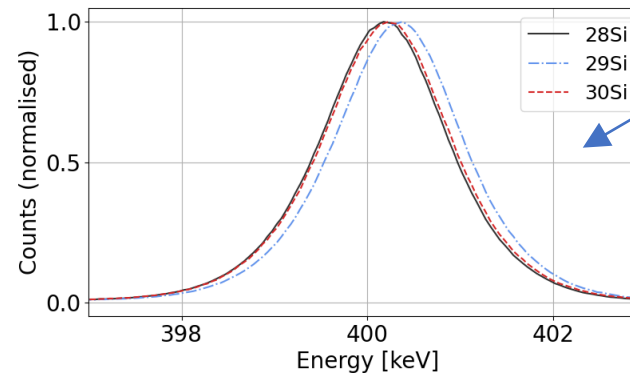
^{14}Si to probe the nuclear EOS

Mirror nuclei provide insight into the slope of the symmetry energy L of the nuclear equation of state.

The pair ^{32}Si - ^{32}Ar has been identified as a particularly sensitive case.

Neither Si nor Ar is properly established in spite of earlier measurements.

→ A dedicated remeasurement has been performed on $^{28,29,30}\text{Si}$, combined with a full re-analysis of the $^{36,38,40}\text{Ar}$ historical data.



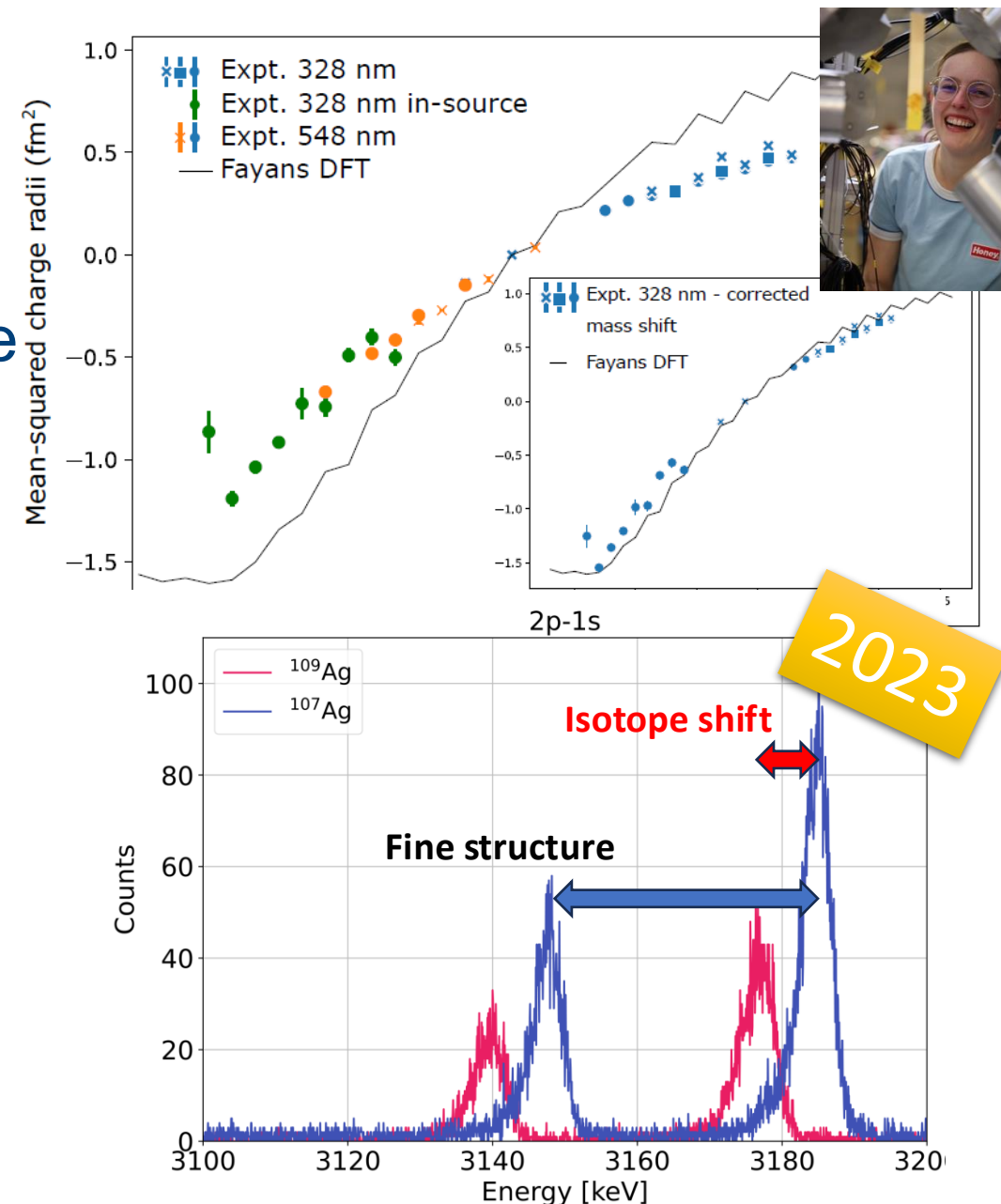
^{47}Ag

Extensive new laser spectroscopy data have recently been collected on Ag, from ^{95}Ag to ^{129}Ag , at Jyväskylä and ISOLDE.

The N=Z isotope ^{94}Ag remains a major interest to elucidate the infamous 2-proton emission and measure the shape of that emitting state.

However, all the current data are in mutual disagreements and also with nuclear theory. Atomic theory is the one to blame!

Experimental benchmark requires $^{107}, ^{108\text{m}}, ^{109}\text{Ag}$ – and input for radii extraction (data taking scheduled in Oct 2026).



^{71}Lu

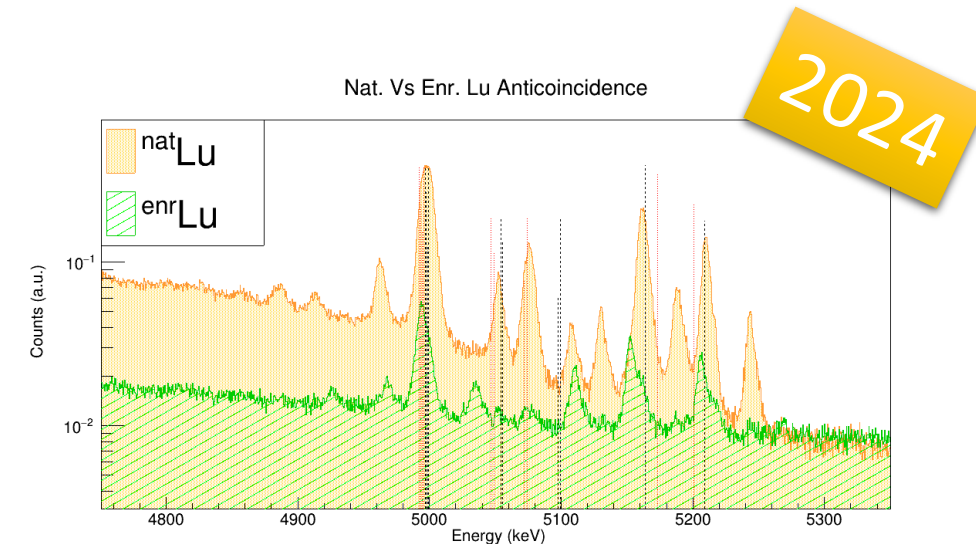
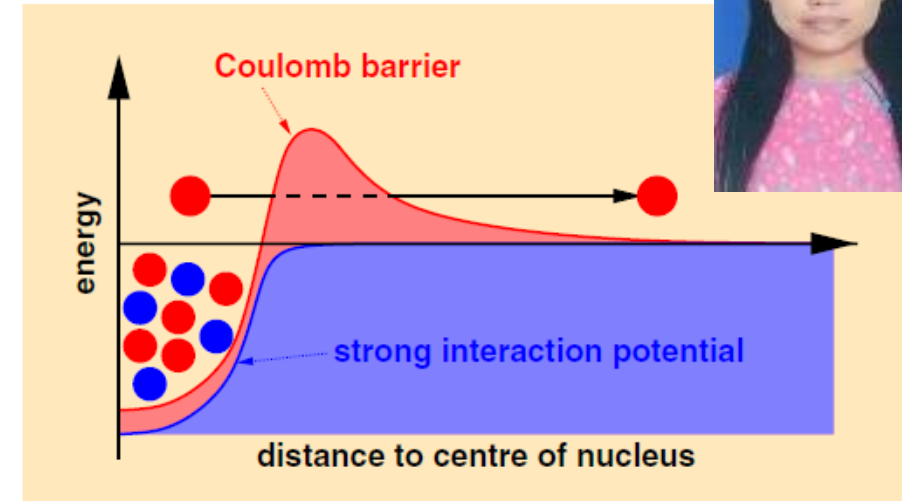
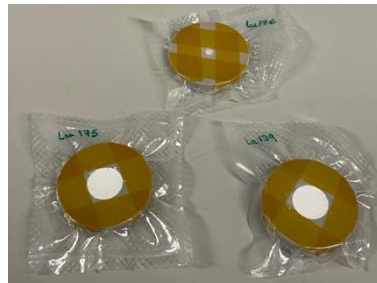
Across the rare earth elements, there is a big effort to reach out to proton emitters with laser spectroscopy: ^{57}La , ^{65}Tb , ^{67}Ho , ^{69}Tm , ^{71}Lu all seem within reach of the upcoming facilities (FRIB, MARA, S3).

The question being: 'where' is the proton? Is it still confined? Already spread beyond the nucleus?

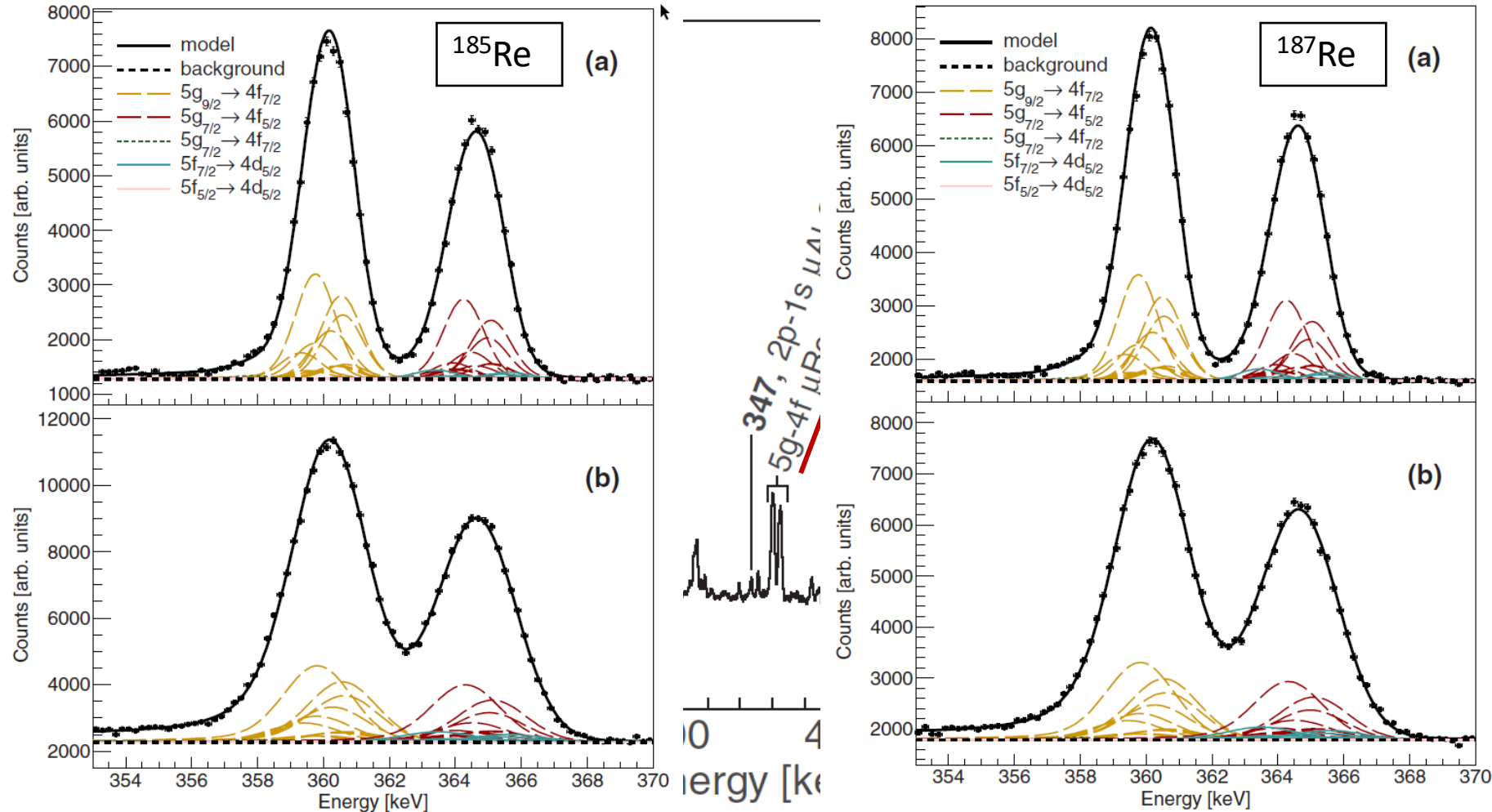
All those are, by default, odd-Z elements...

Amazing data from 2024!

- natLu (97.4% ^{175}Lu vs 2.6% ^{176}Lu)
- enrLu (25% ^{175}Lu vs 75% ^{176}Lu)



Quadrupole moment of $^{185,187}\text{Re}$



:
test on macroscopic
samples of $^{185,187}\text{Re}$

Those two peaks contain
76 different components
fitted simultaneously!

Absolute charge radius of $^{185,187}\text{Re}$

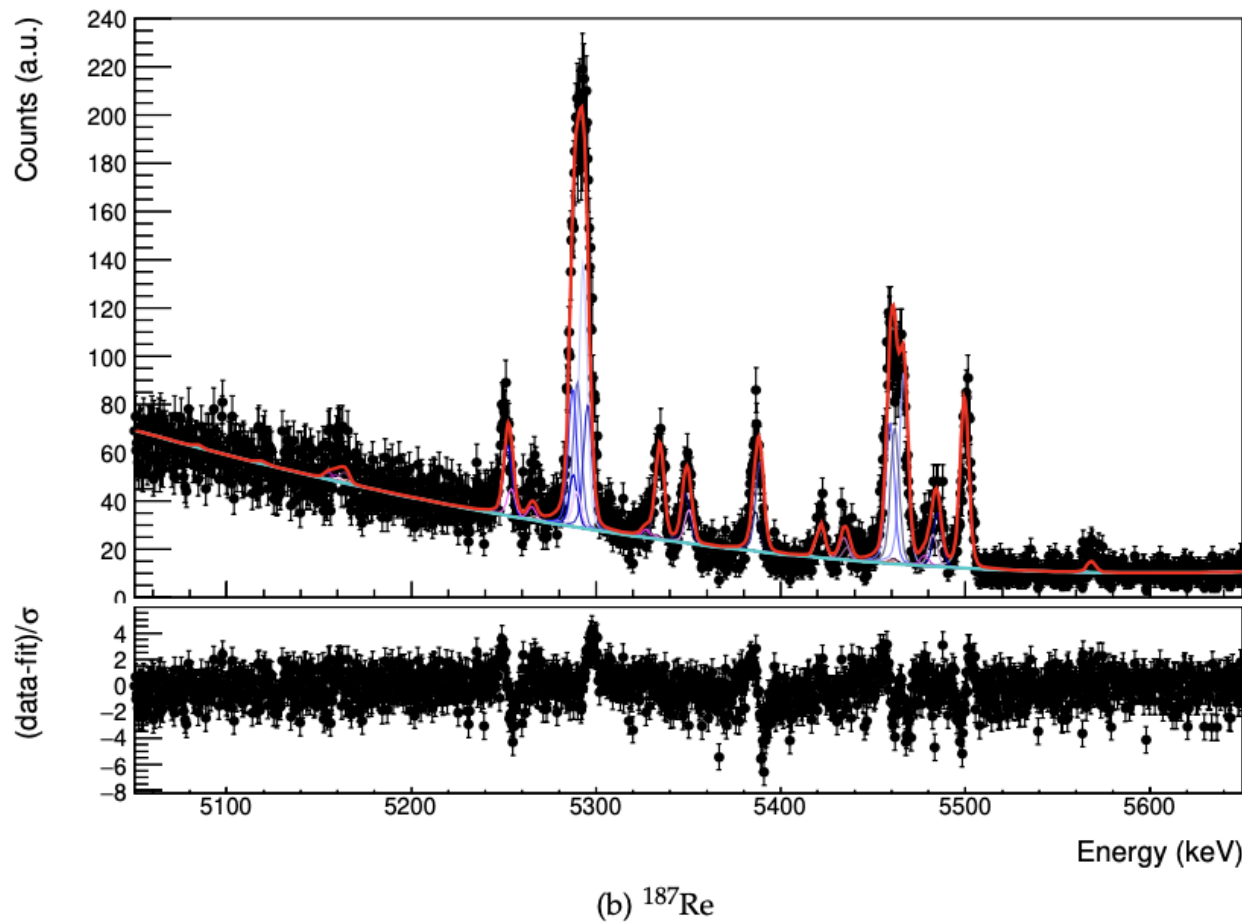


2016:

First test on macroscopic samples of $^{185,187}\text{Re}$

Today:

Still cannot extract charge radius from 2p1s transition because of missing nuclear polarization correction.



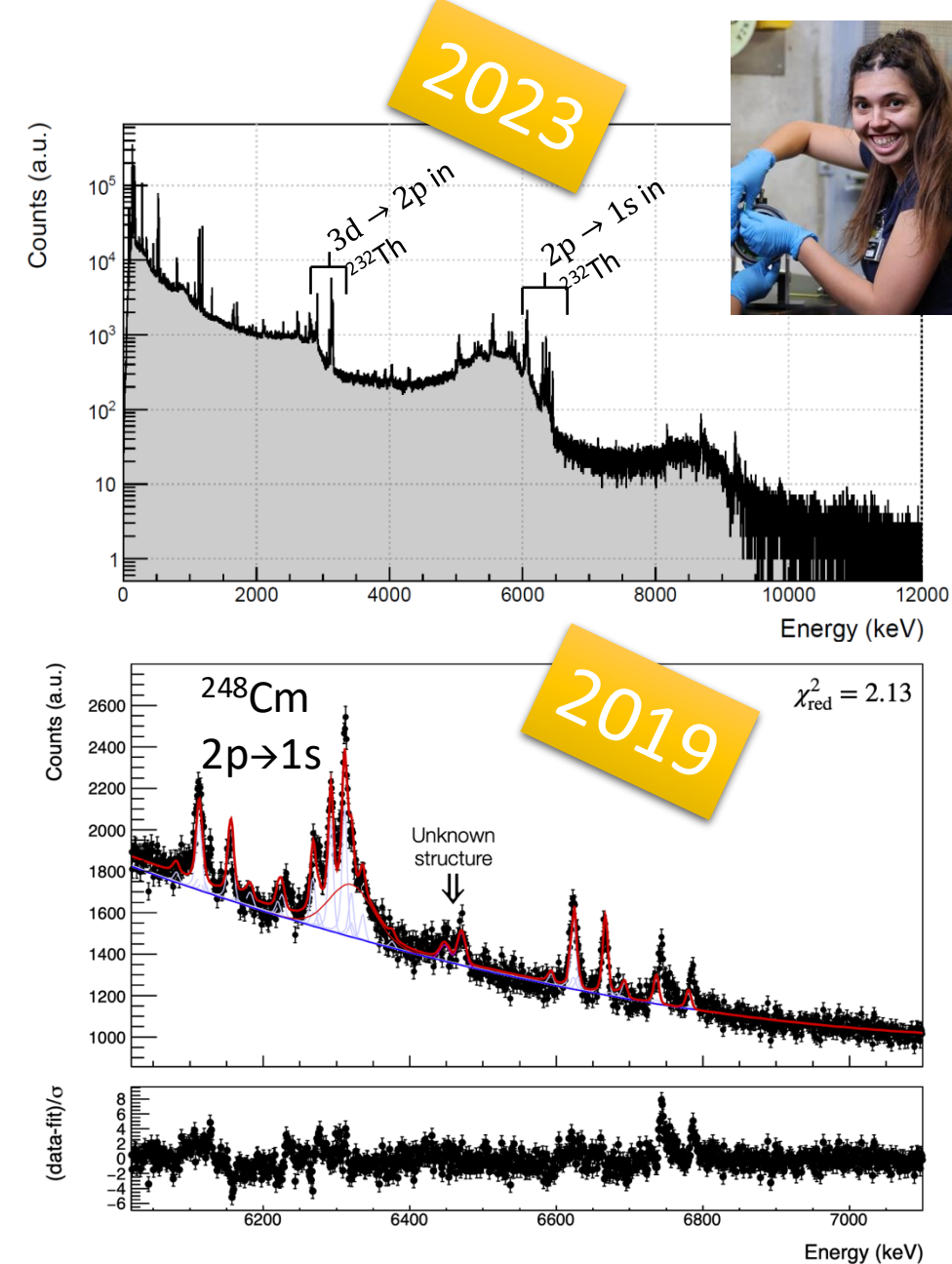
Beyond Pb

While getting a triplet measured beyond Pb is as good as impossible, having a single absolute charge radius for any isotopic chain would already be a huge accomplishment.

^{226}Ra has been attempted multiple times by muX, but the targets have always shown strange distributions and we do not have any muonic spectrum yet.

^{232}Th and ^{238}U have been investigated and we believe we could also measure $^{229,230}\text{Th}$ and ^{235}U .

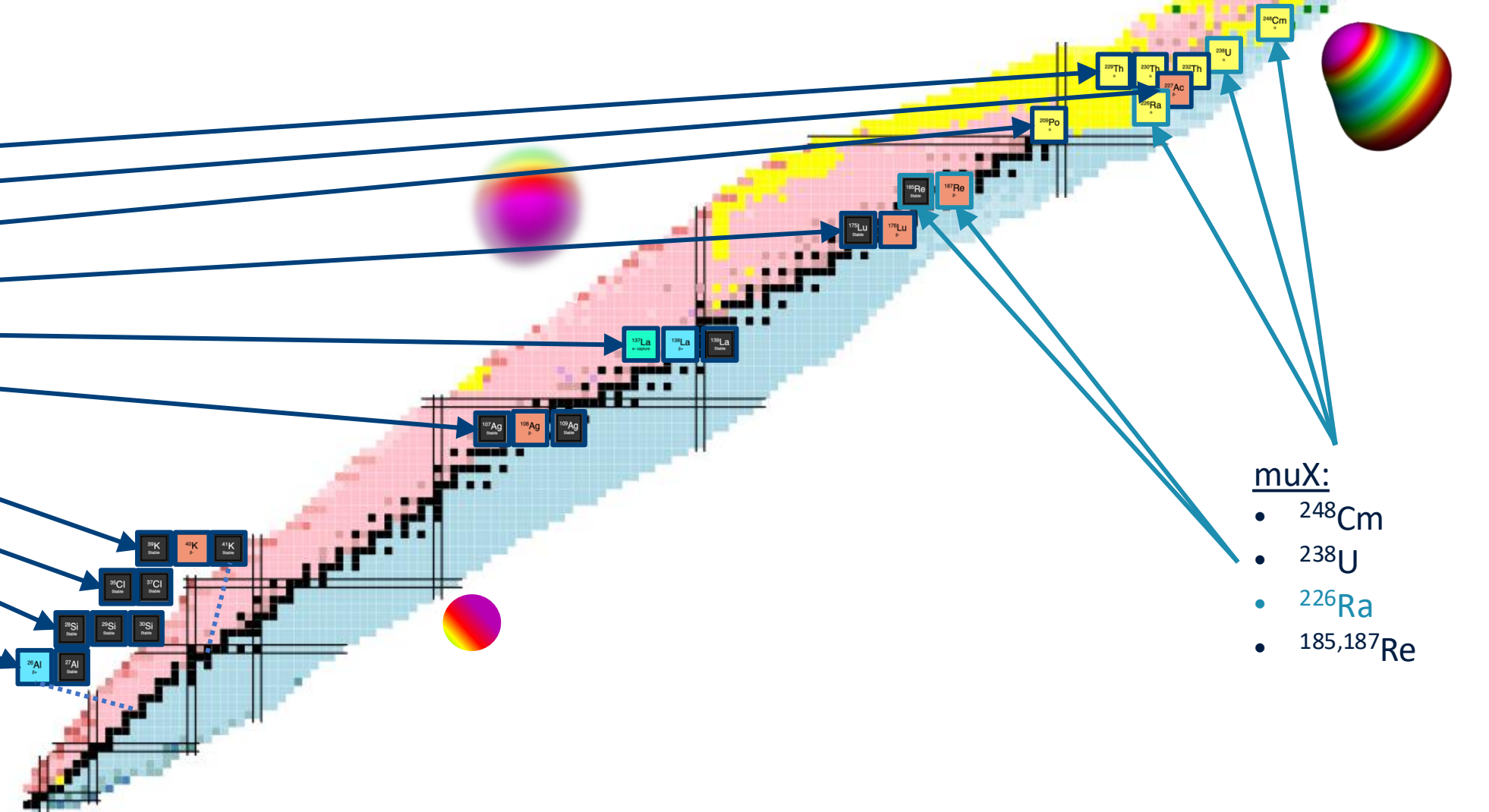
Beautiful spectra of ^{248}Cm but challenging extraction of the charge radius from the dynamic hyperfine spectra.



muX & ReferenceRadii

ReferenceRadii:

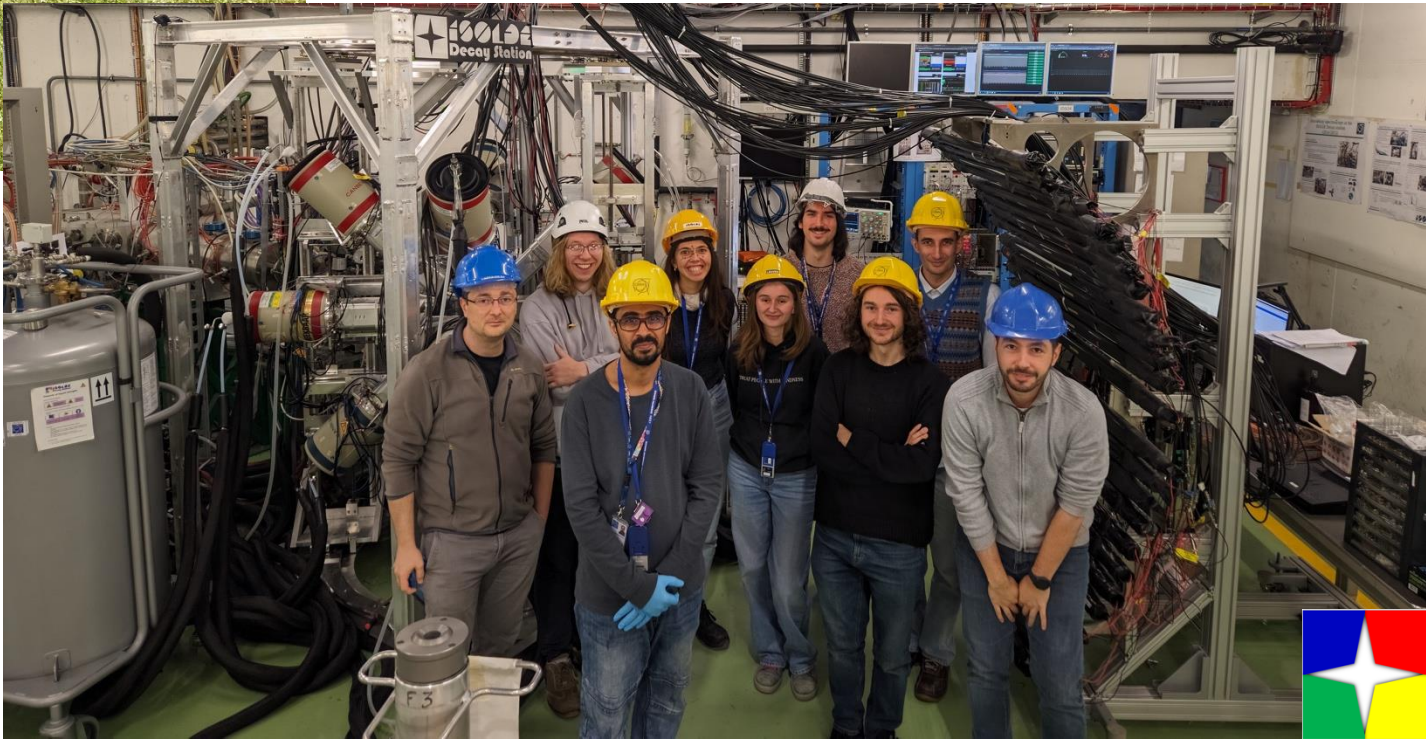
- 229,230,232Th
- 227Ac
- 209Po
- 175,176Lu
- 137,138,139La
- 107,108m,109Ag
- 39,40,41K
- 35,37Cl
- 28,29,30Si
- 26,27Al



muX:

- 248Cm
- 238U
- 226Ra
- 185,187Re

- Charge radii are used extensively to probe nuclear structure and challenge nuclear models.
- Long isotopic chains have been investigated thanks to laser spectroscopy, but accuracy is highly impacted by the shortage of absolute radii, especially for odd-Z and heavy elements.
- muX and ReferenceRadii have an intense program addressing this, from $_{13}\text{Al}$ to $_{96}\text{Cm}$.
- Challenges include target production, background suppression, data analysis, atomic & nuclear corrections, ...
- Our first results are out (quadrupole moments of $^{185,187}\text{Re}$, absolute radii of $^{35,37}\text{Cl}$) and more is coming!
- We are bringing the IDS detector array to PSI in 2026 for an exciting campaign!



fwo



Kennis kent
geen einde

KU LEUVEN



Knowledge
knows no end

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from the European Commission, ERC Consolidator Grant 101088504 (NSHAPE) and MSCA
Innovative Training Network 861198 (LISA).***