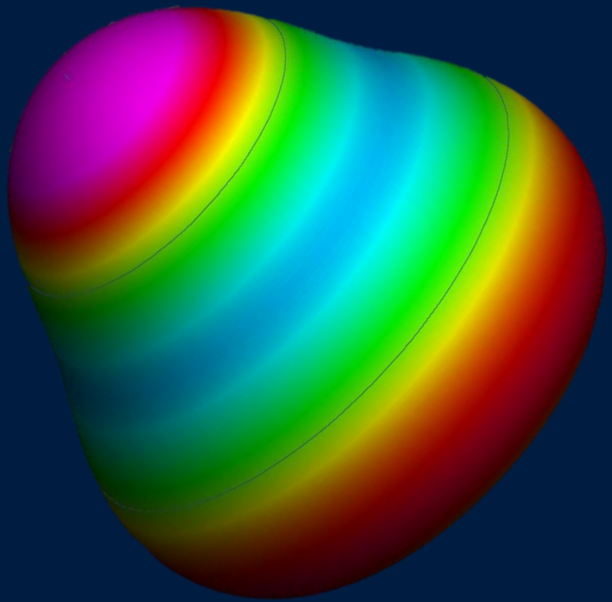
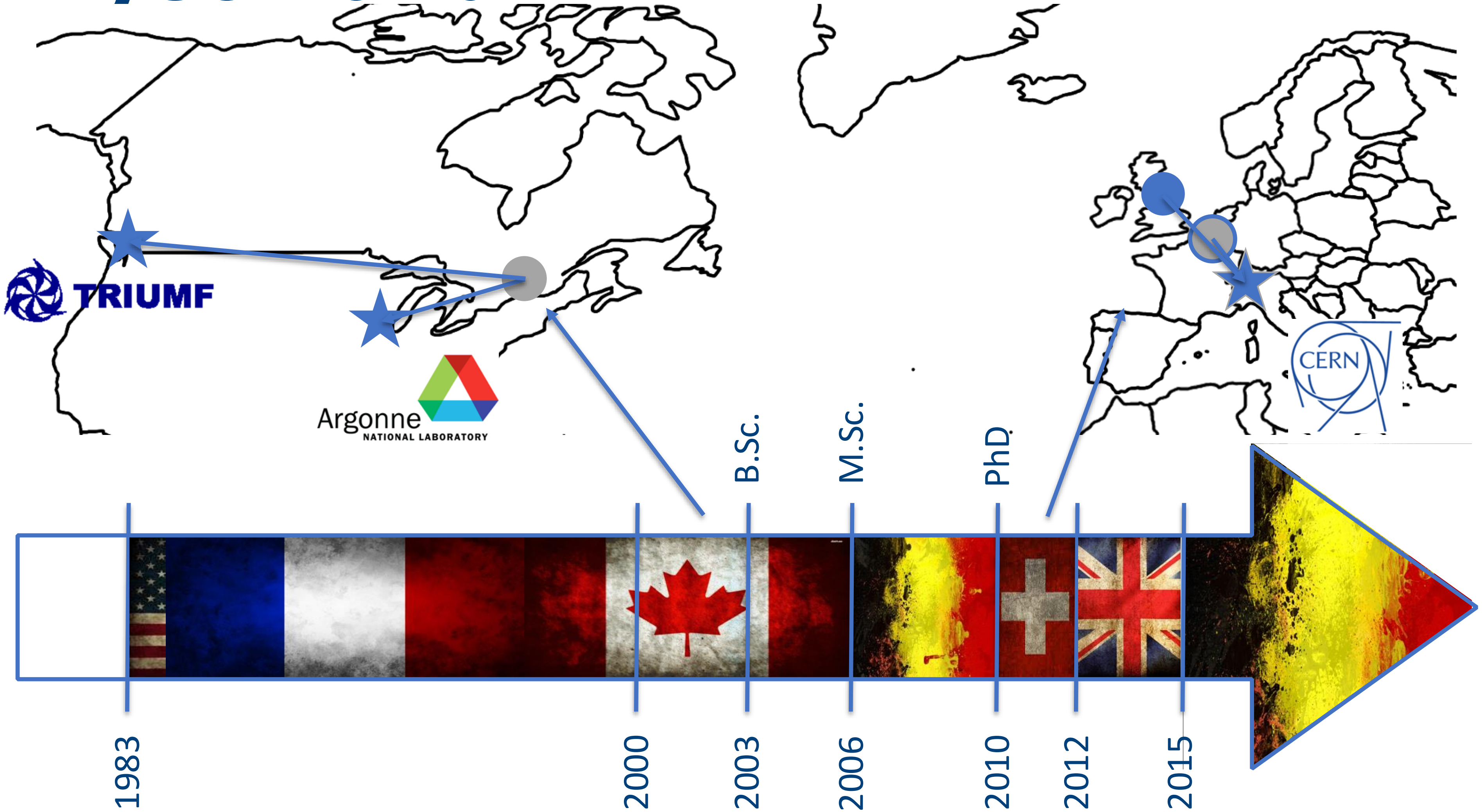


Getting NSHAPE

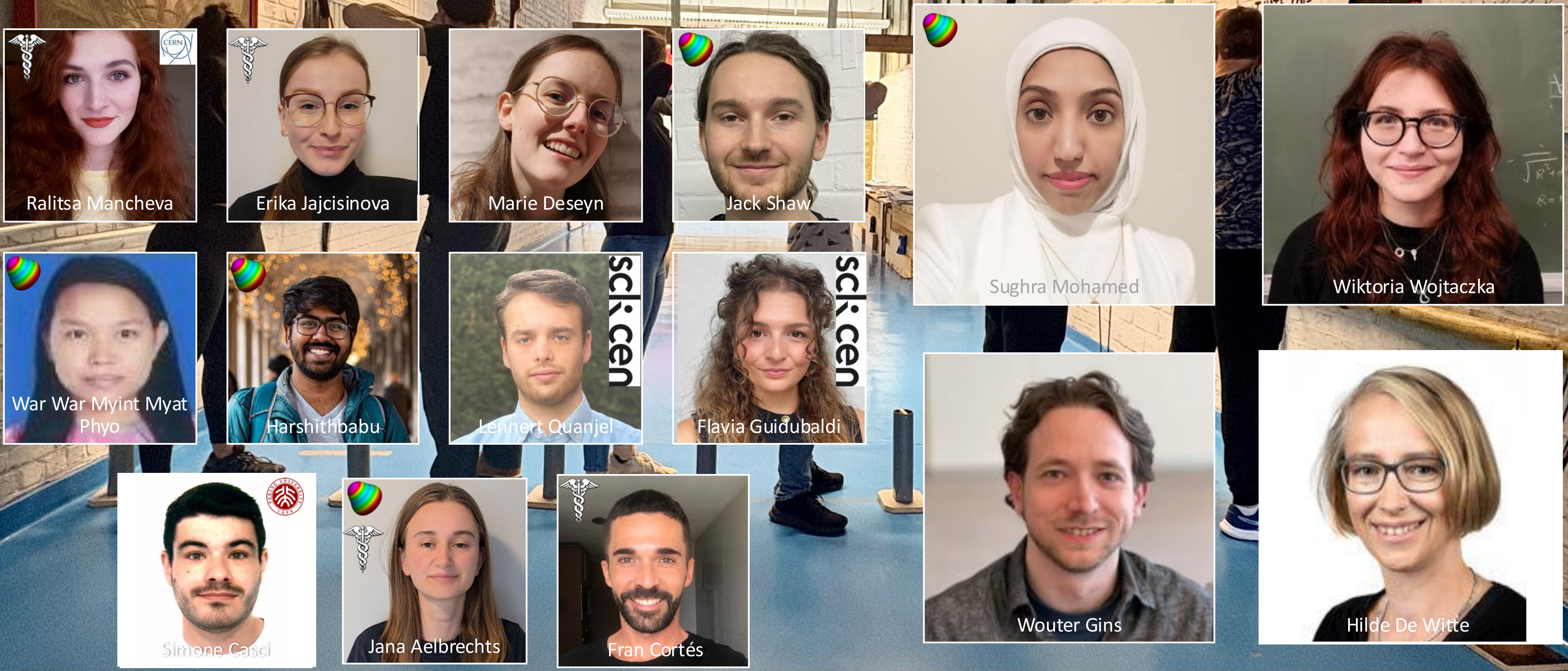
Combining laser spectroscopy with muonic atoms of exotic nuclei to reveal exciting features of the nuclear landscape

fwo erc KU LEUVEN 600

Me, myself and I



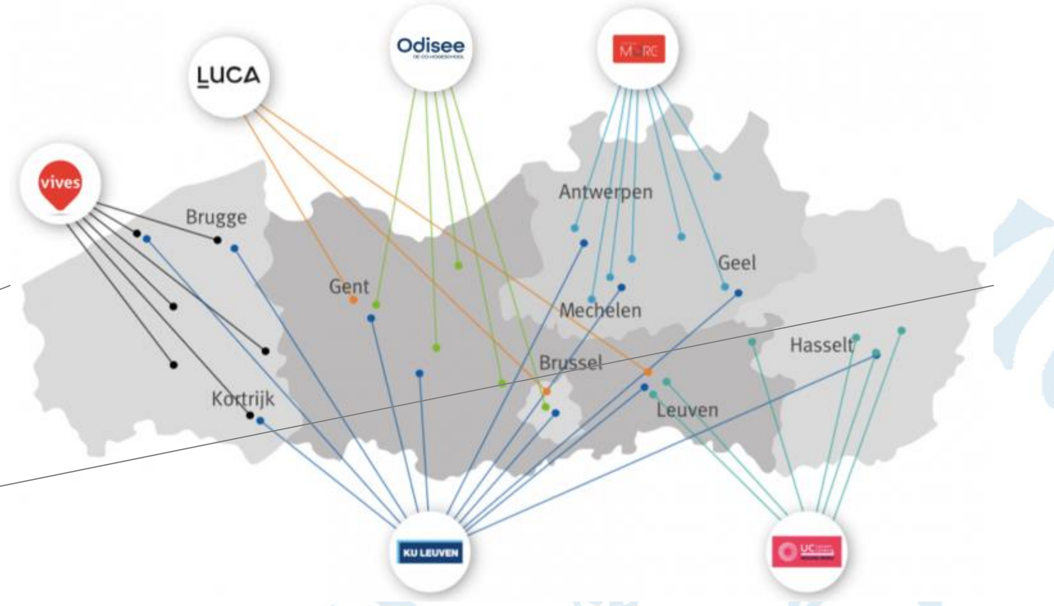
Team work!



https://fys.kuleuven.be/iks/interdisciplinary-research
thomas.cocolios@kuleuven.be

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!



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Outline

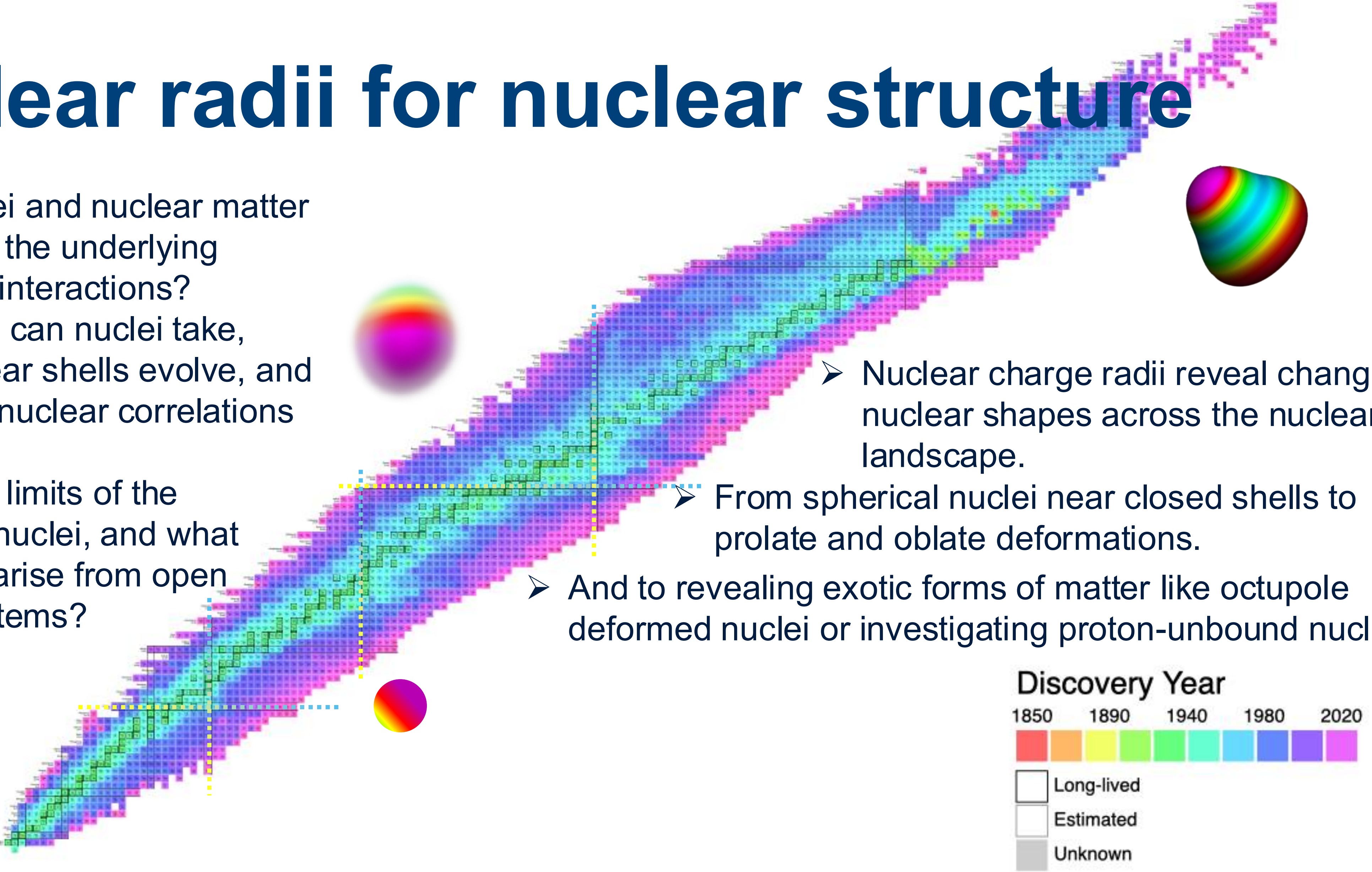
- Nuclear charge radii as probes of nuclear structure
- Accuracy limit in extracting charge radii
- muX and ReferenceRadii: absolute charge radii with microscopic samples of (radio)isotopes

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.



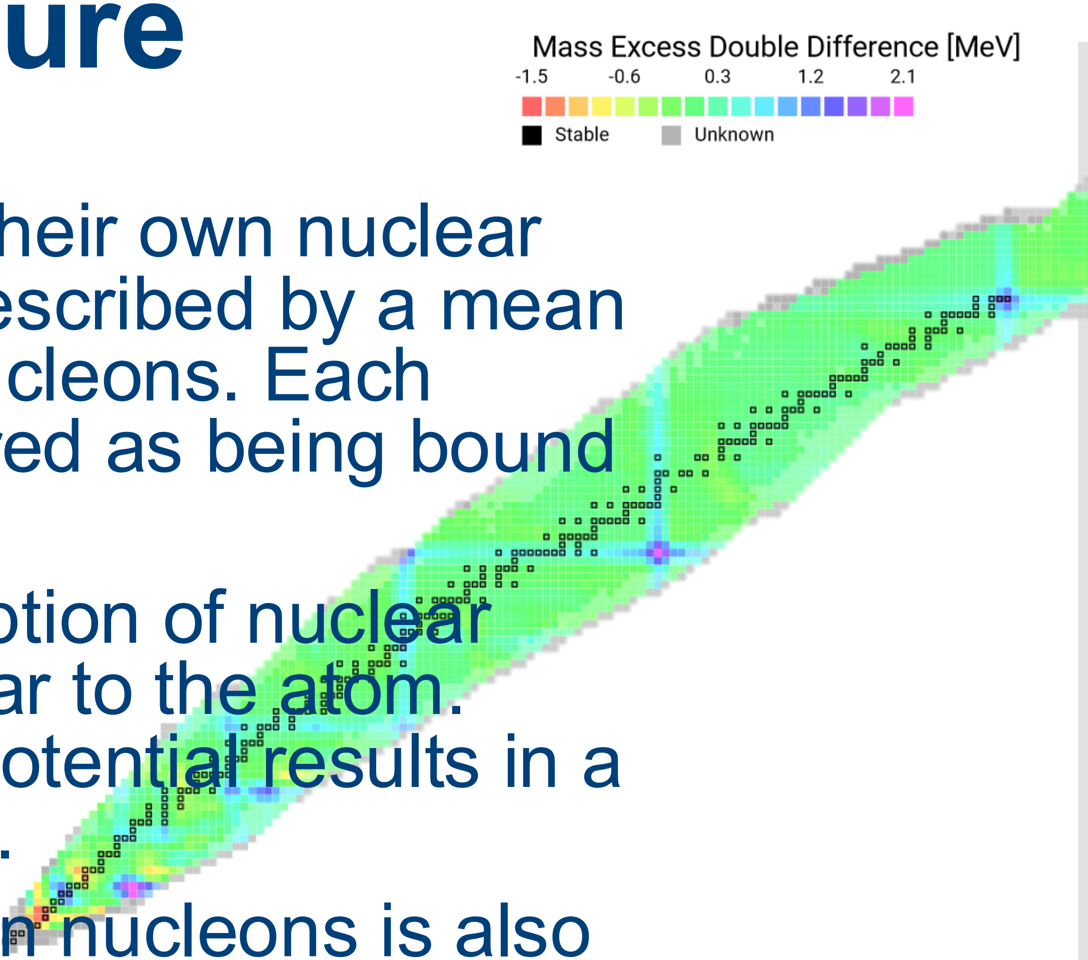
NuPECC Long Range Plan 2024, https://nupecc.org/lrp2024/Documents/nupecc_lrp2024.pdf
The Colourful Nuclear Chart, https://people.physics.anu.edu.au/~ecs103/chart/

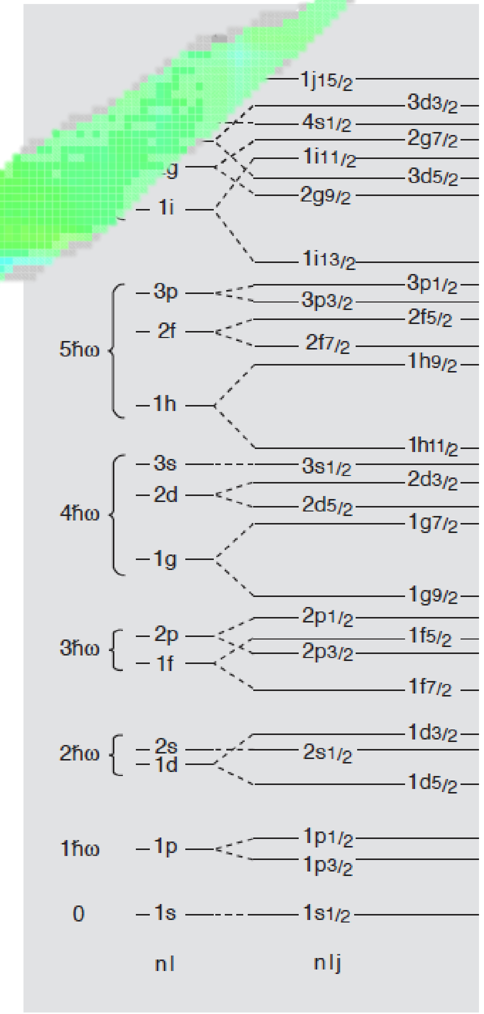
Nuclear structure

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 different series of levels.

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





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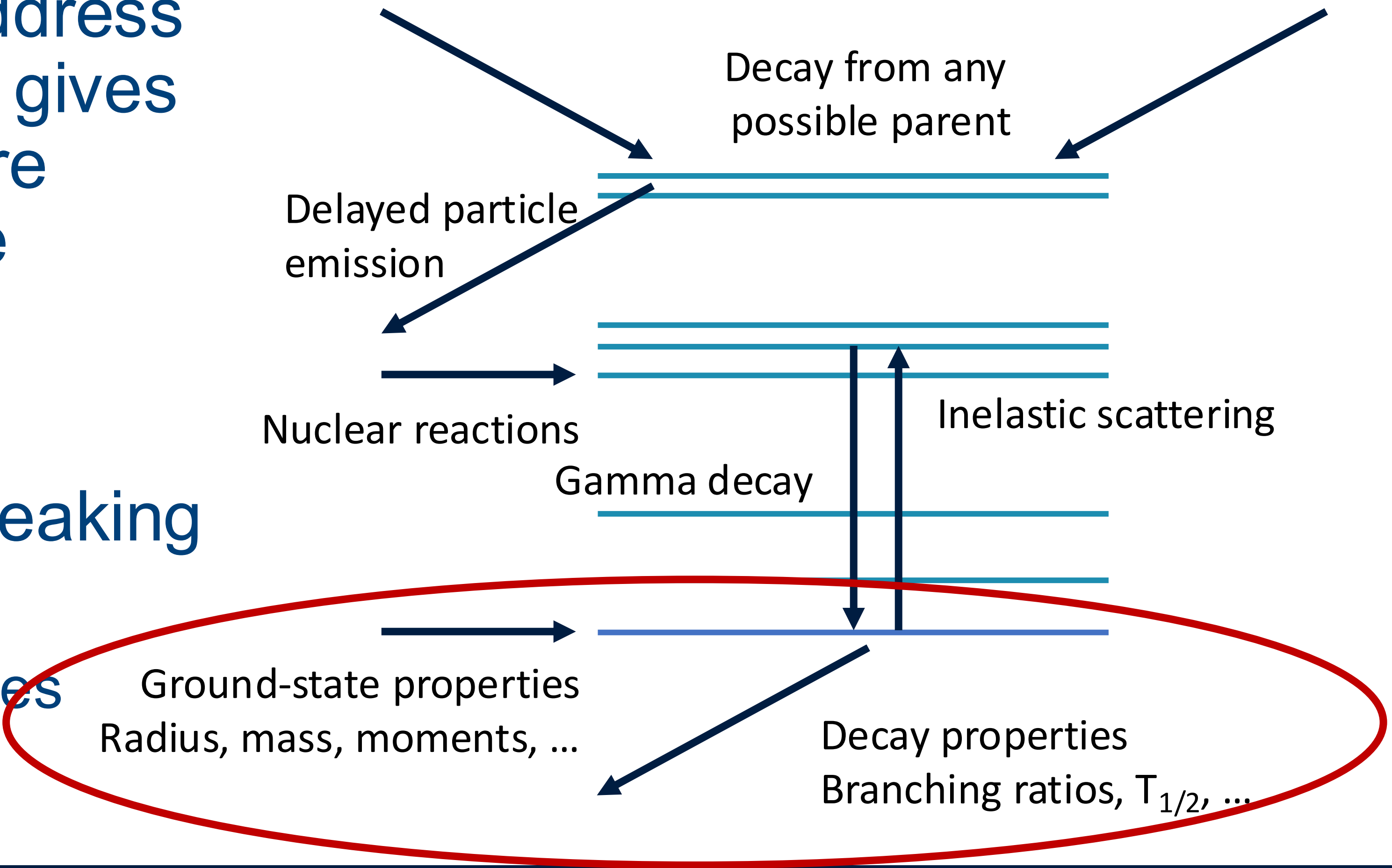
The multifaceted puzzle of experiments

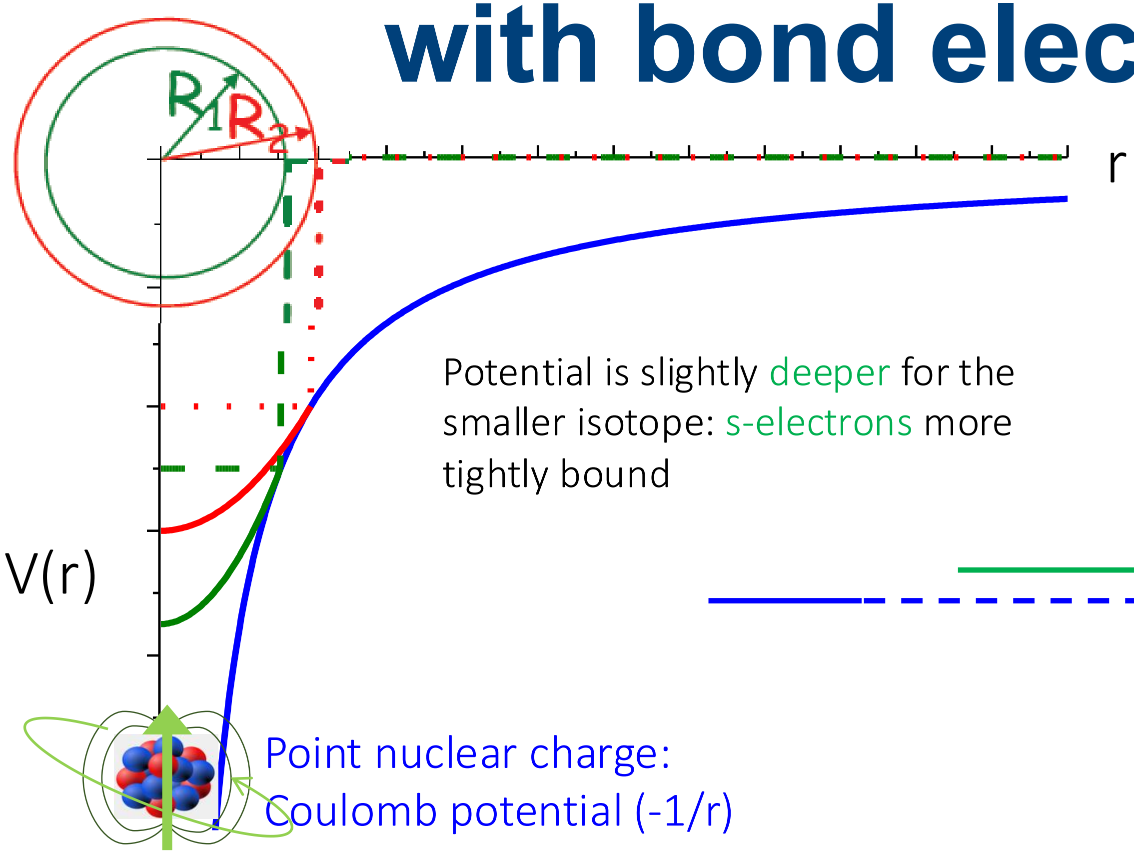
There are many ways to address the nucleus, none of which gives a full picture, all of which are needed to shed light on the nuclear puzzle.

There are many ways of breaking it down:

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



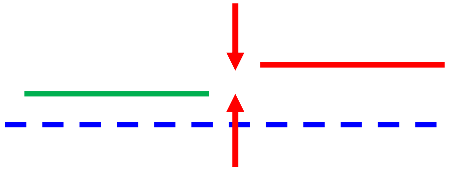
Laser spectroscopy: probing the nucleus with bond electrons



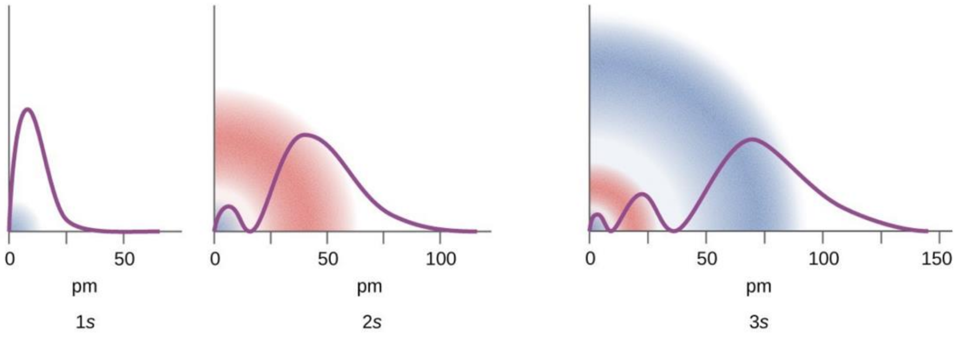
Nuclear radius: few × 10^{-15} m
Atomic radius: few × 10^{-10} m

Potential is slightly deeper for the smaller isotope: s-electrons more tightly bound

Point nuclear charge: Coulomb potential (-1/r)



Isotope shift of atomic level



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

Slide courtesy from R.P. de Groote

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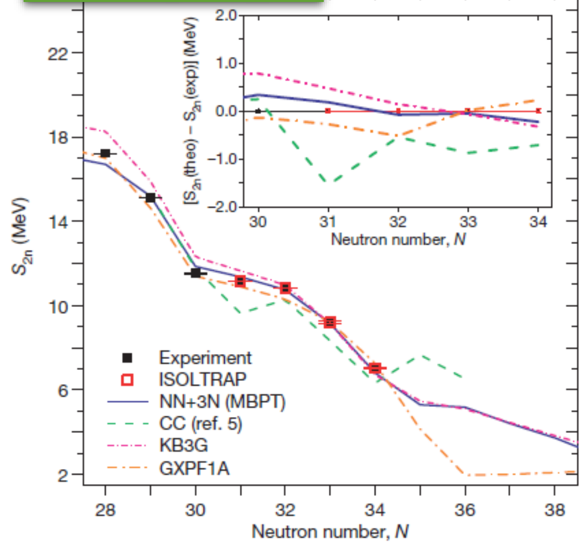
Medium-mass nuclei: $_{19}$K vs $_{20}$Ca

The binding energies and first 2^+ excited state suggest there might be new magic numbers at N=32 and 34.

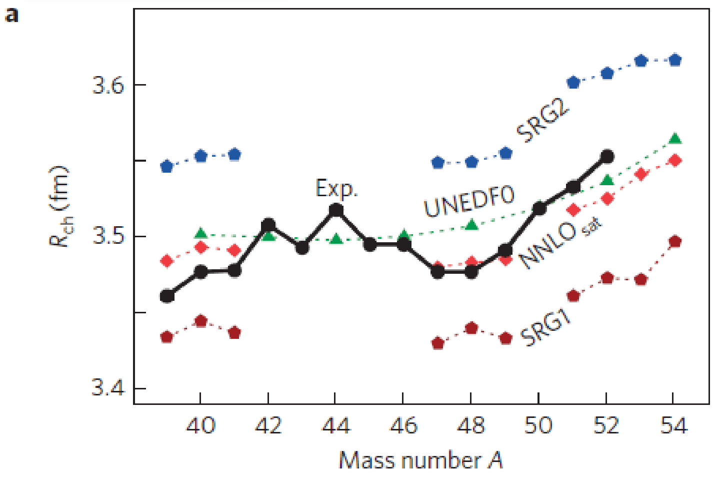
Charge radii show a large kink at N=28 but nothing at N=20 or 32,34.

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

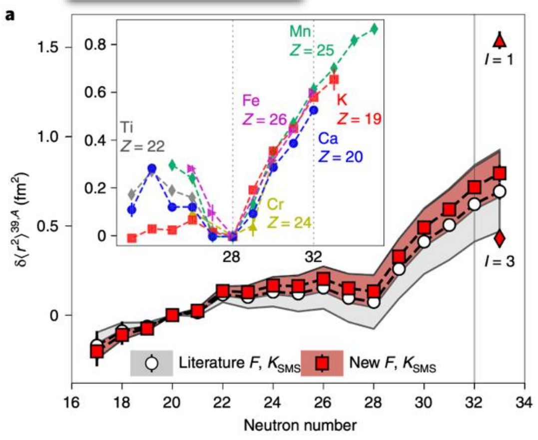
Ca binding energy

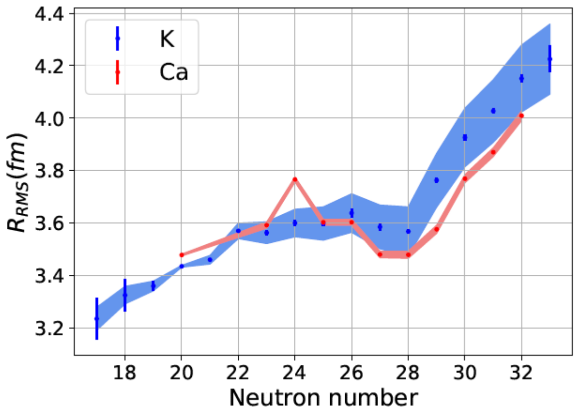


Ca charge radii



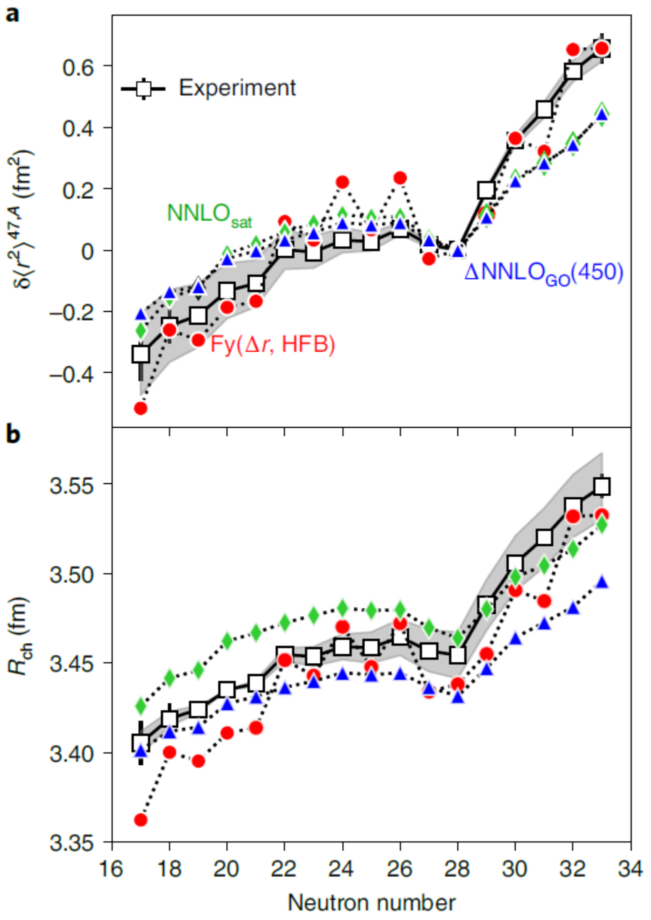
K charge radii





*F. Wienholtz et al., Masses of exotic calcium isotopes pin down nuclear forces, Nature **498** (2013) 346-349.*
*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: $_{19}$K vs $_{20}$Ca



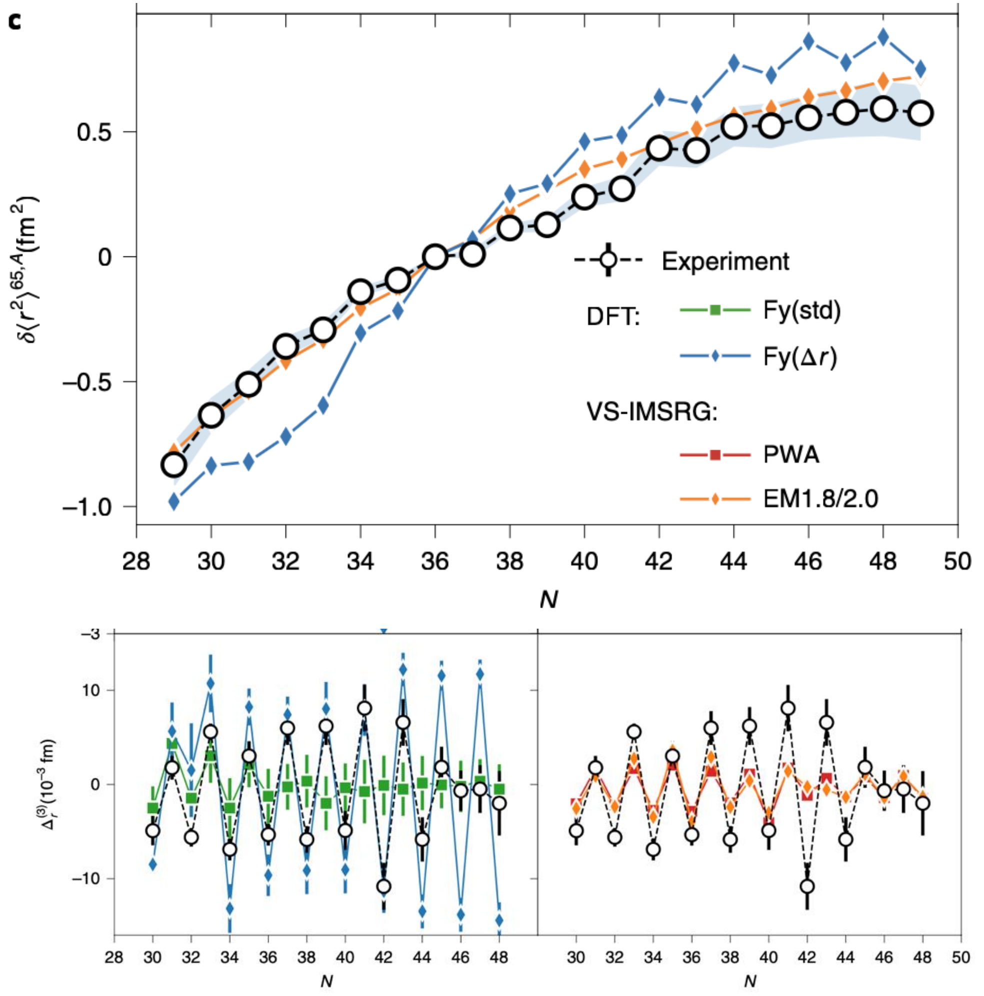
Radii measured up to N=33 probing the N=28 shell closure and N=32 subshell.

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}K.

 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*

$_{29}$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.

R.P. de Groote et al., *Measurement and microscopic description of odd-even staggering of charge radii of exotic copper isotopes, Nature Physics* ***16*** *(2020) 620-624.*

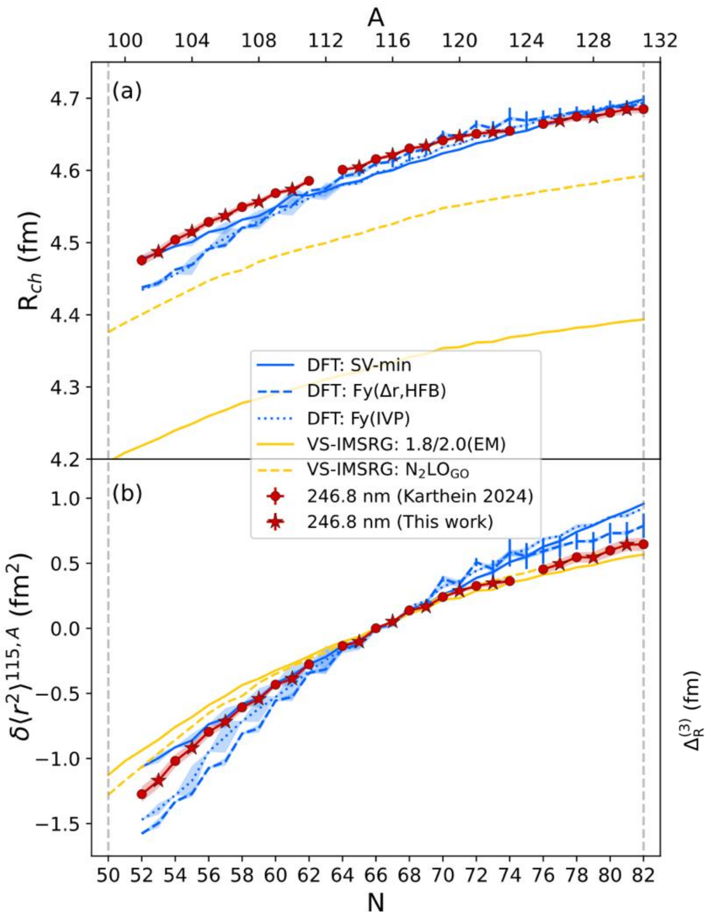
$_{49}$In & $_{50}$Sn

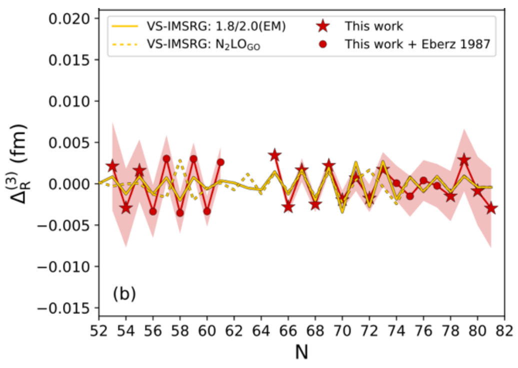
Extensive work has been performed from N=50 to N=82 and beyond.

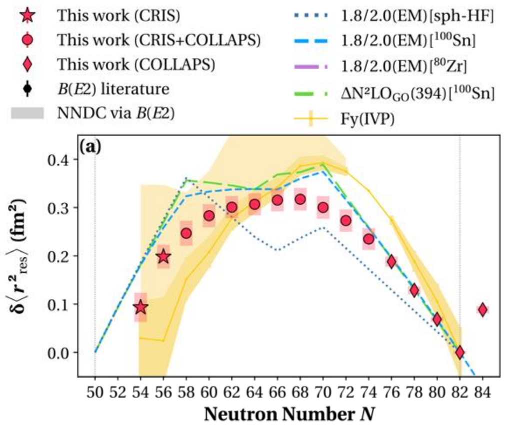
Known parabolic behaviour but hard to capture for the models.

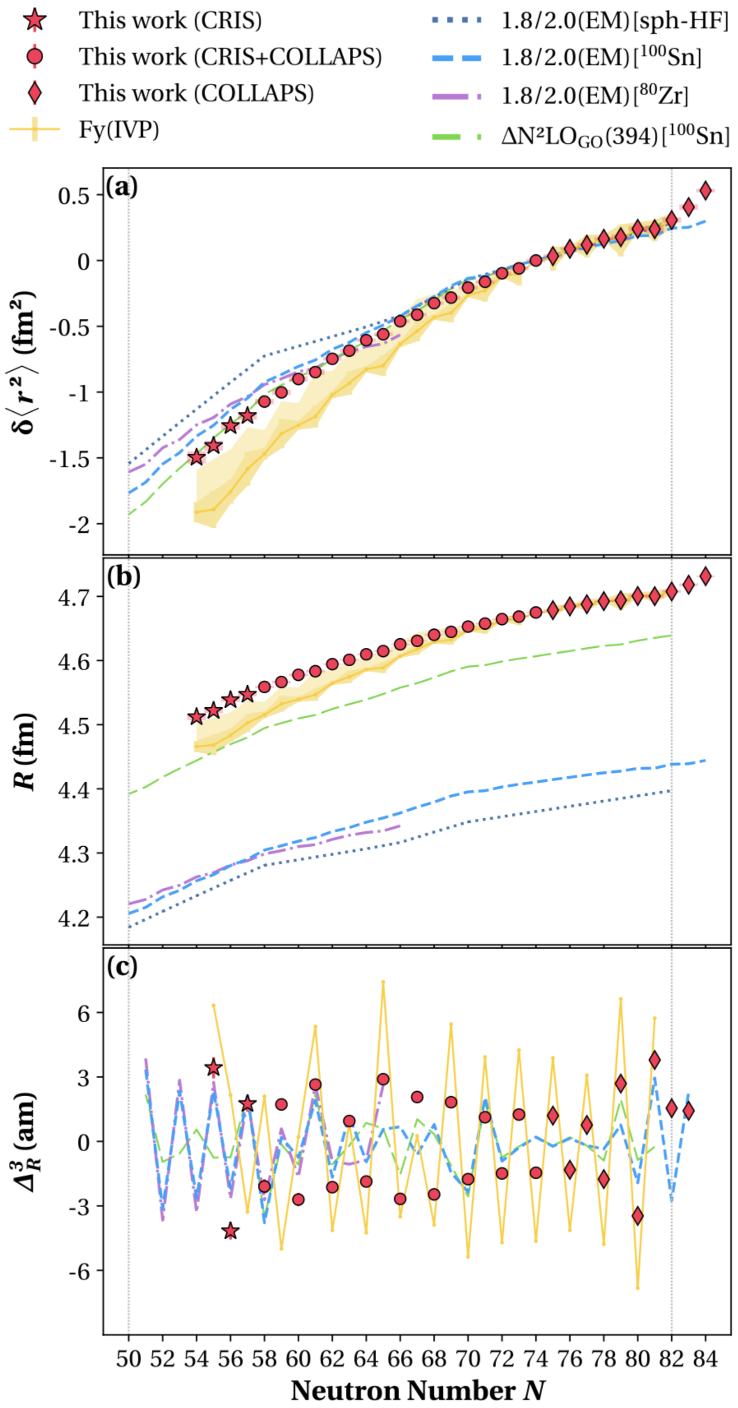
N=50, 82 magic numbers are far from stability but seem to be strong in their magicity.

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



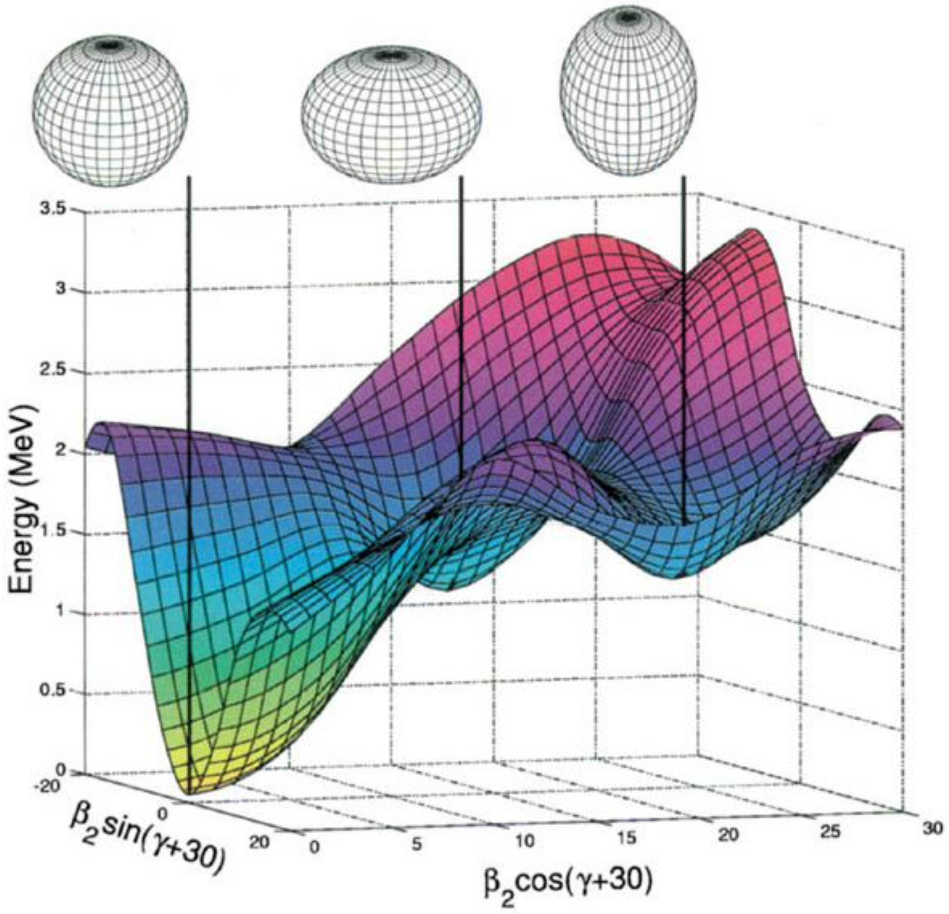


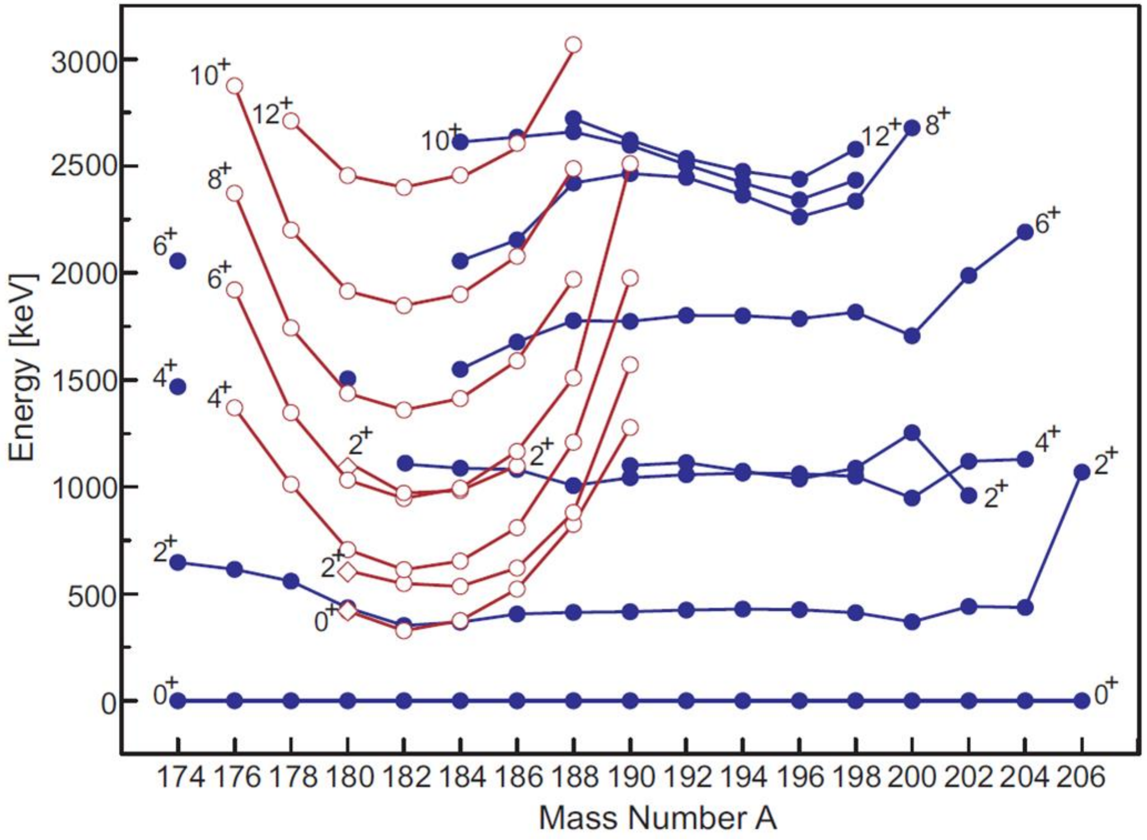




A.R. Vernon et al., Variations in the charge radii of indium isotopes between N=52 and 82, Physical Review C ***111*** *(2025) 054325.* *F.P. Gustafsson et al., Charge radii measurements of exotic tin isotopes in the proximity of N=50 and N=82, Physical Review Letters* ***135*** *(2025) 222501.*

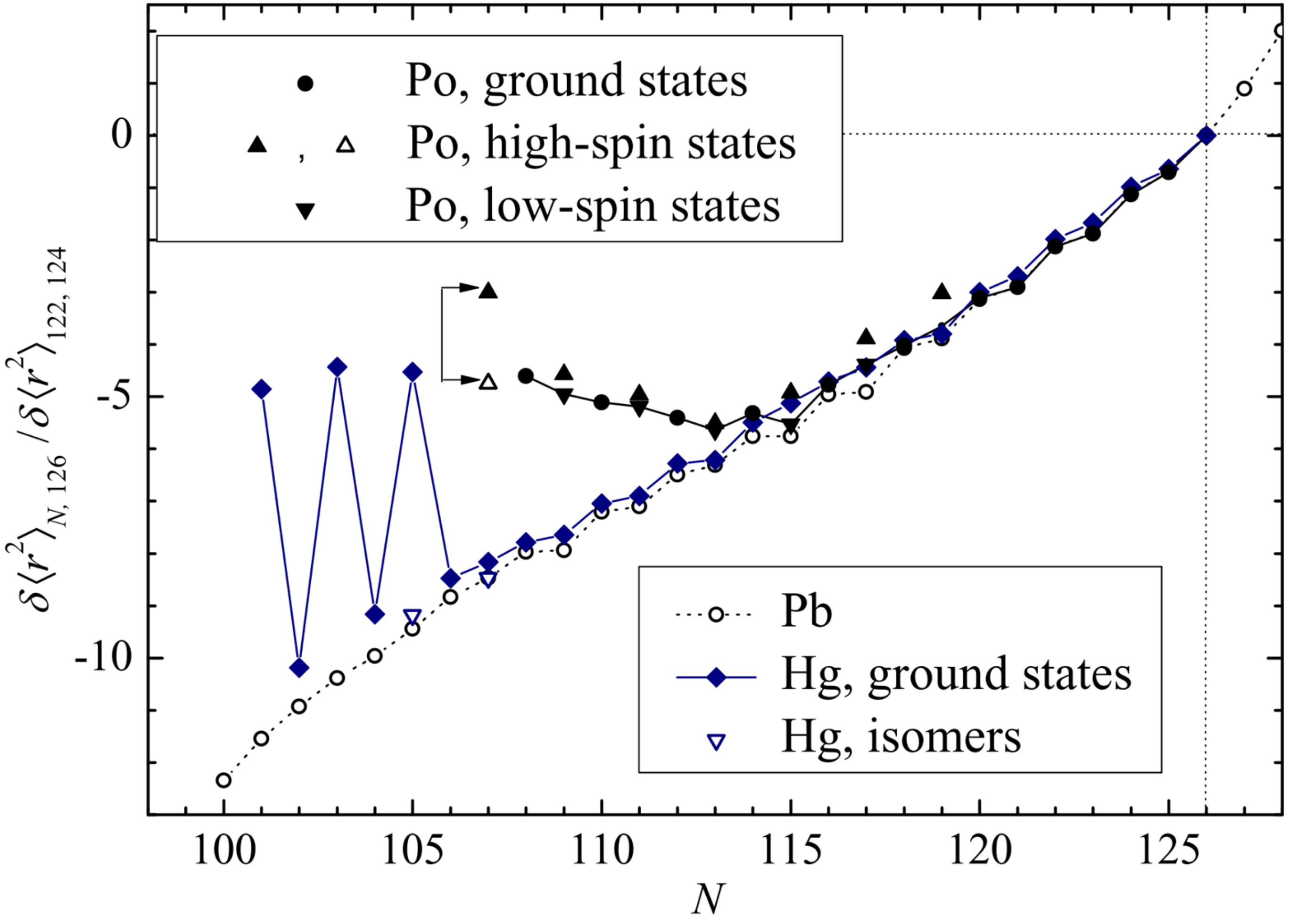
Shape coexistence around $_{82}$Pb

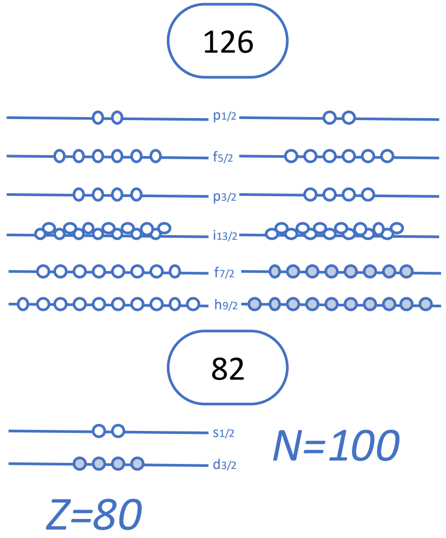




*A.N. Andreyev et al. Nature **405** (2000) 430-433.*
*J. Elseviers et al. PRC **84** (2011) 034307.*

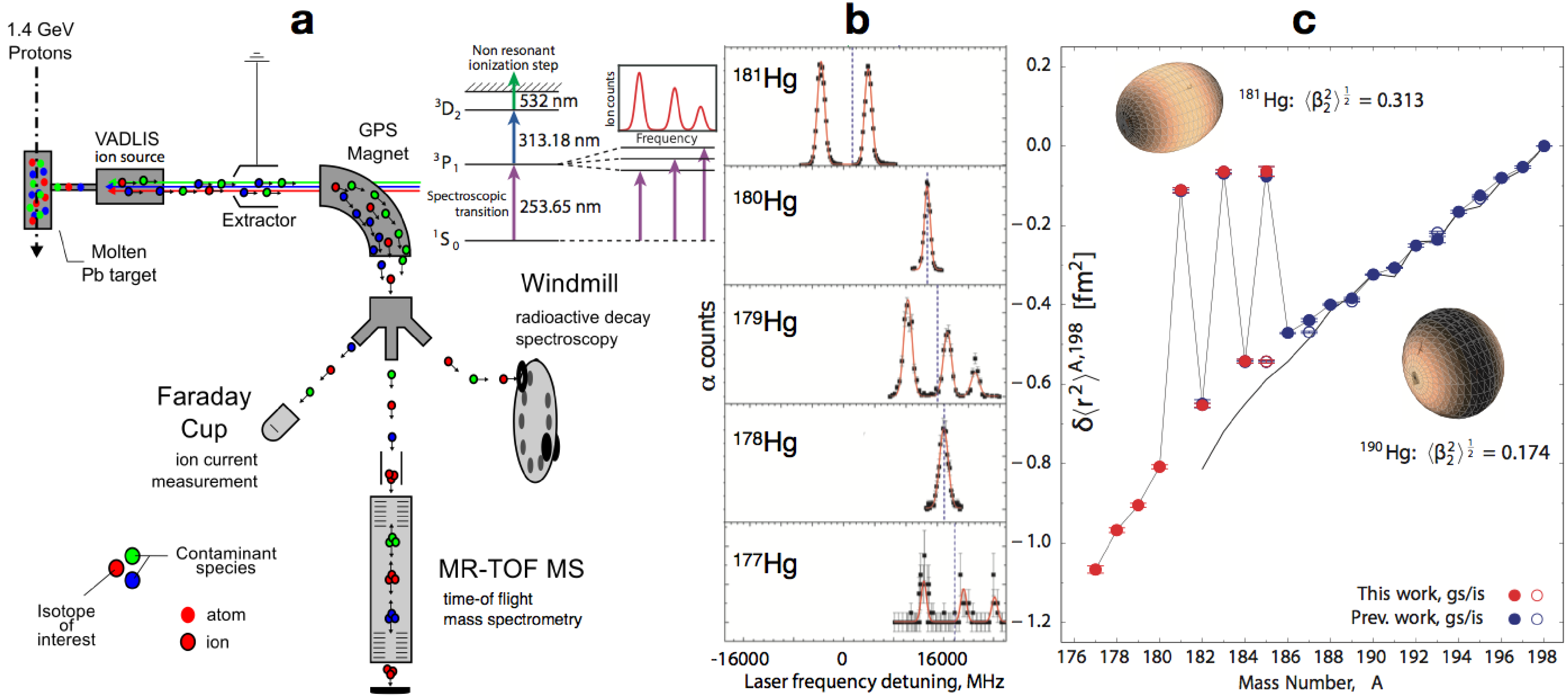
$_{80}$Hg-$_{82}$Pb-$_{84}$Po: this is not all the same!





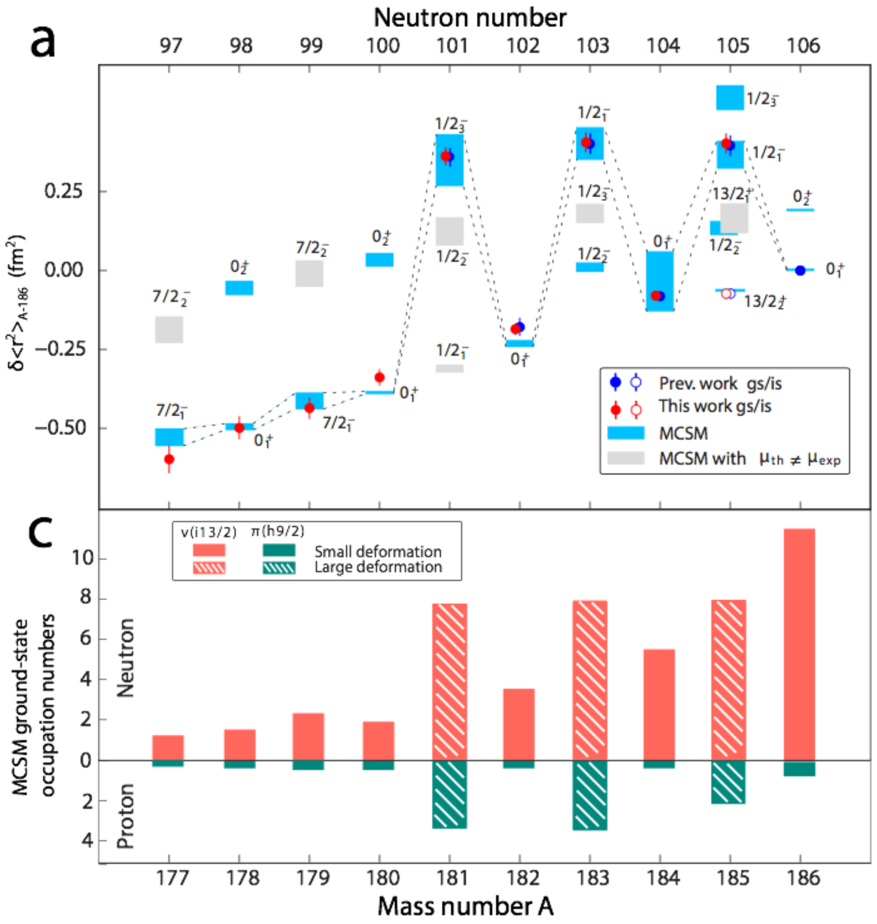
T.E. Cocolios et al. PRL **106** (2011) 052503.
M.D. Seliverstov et al. PLB **719** (2013) 362-366.
D.A. Fink et al., PRX **5** (2015) 011018.

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



B.A. Marsh et al. Nature Physics **14** (2018) 1163.

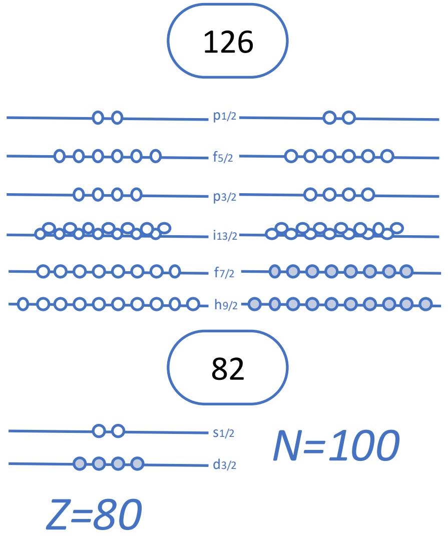
In-source laser spectroscopy: $_{80}$Hg



Monte Carlo Shell Model calculations on the Super K computer in Japan revealed new insight on the shape staggering in 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!



 B.A. Marsh et al. Nature Physics ***14*** *(2018) 1163.*

RILIS

Octupole deformation

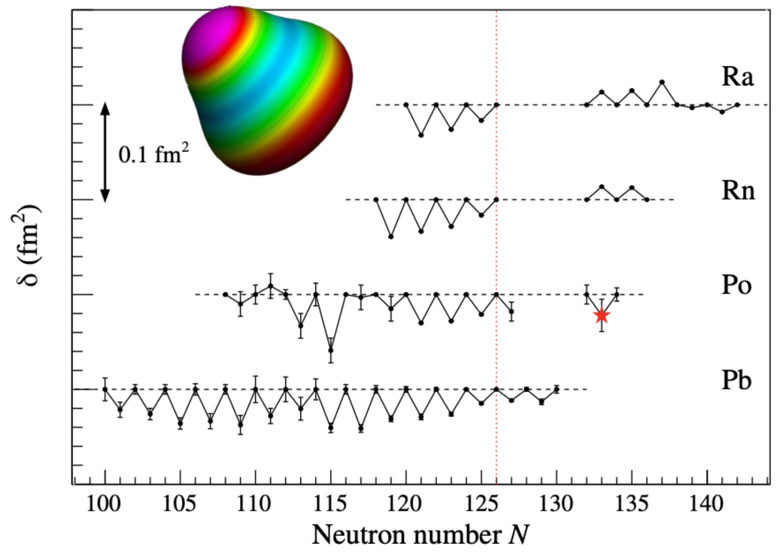
Nuclei are deformed by default, spherical being the 3rd most found in nuclear ground states. Prolate is #1, oblate is #2.

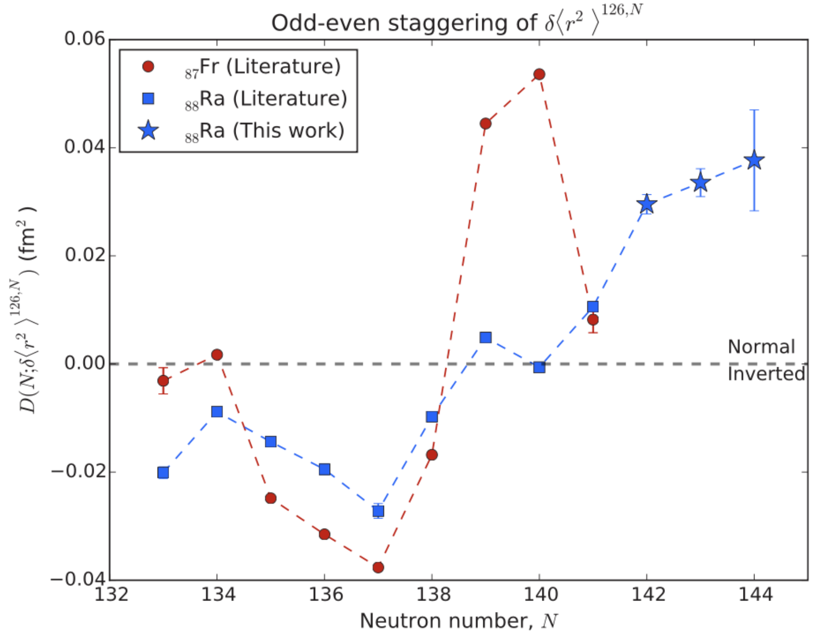
Other identified shapes are triaxial nuclei and **octupole deformed** nuclei.

Their assymetric 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.





*D.A. Fink et al., In-source laser spectroscopy with the LIST: first direct study of the ground-state properties of ^{217,219}Po, Physical Review X **5** (2015) 011018.*
*K.M. Lynch et al., Laser-spectroscopy studies of the nuclear structure of neutron-rich radium, Physical Review C **97** (2018) 024309.*

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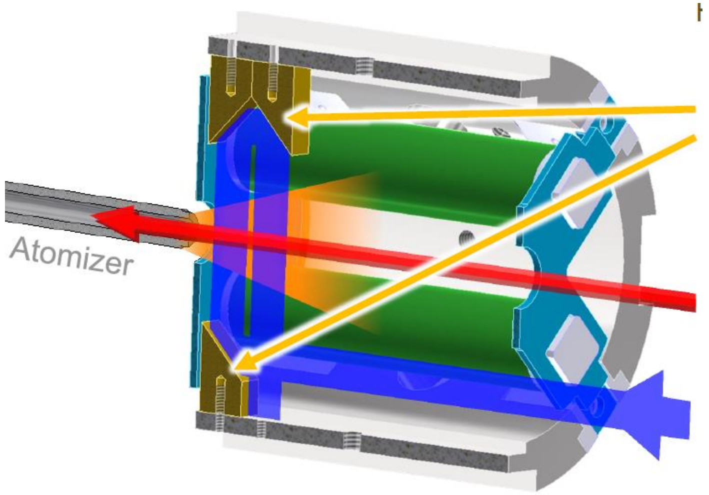
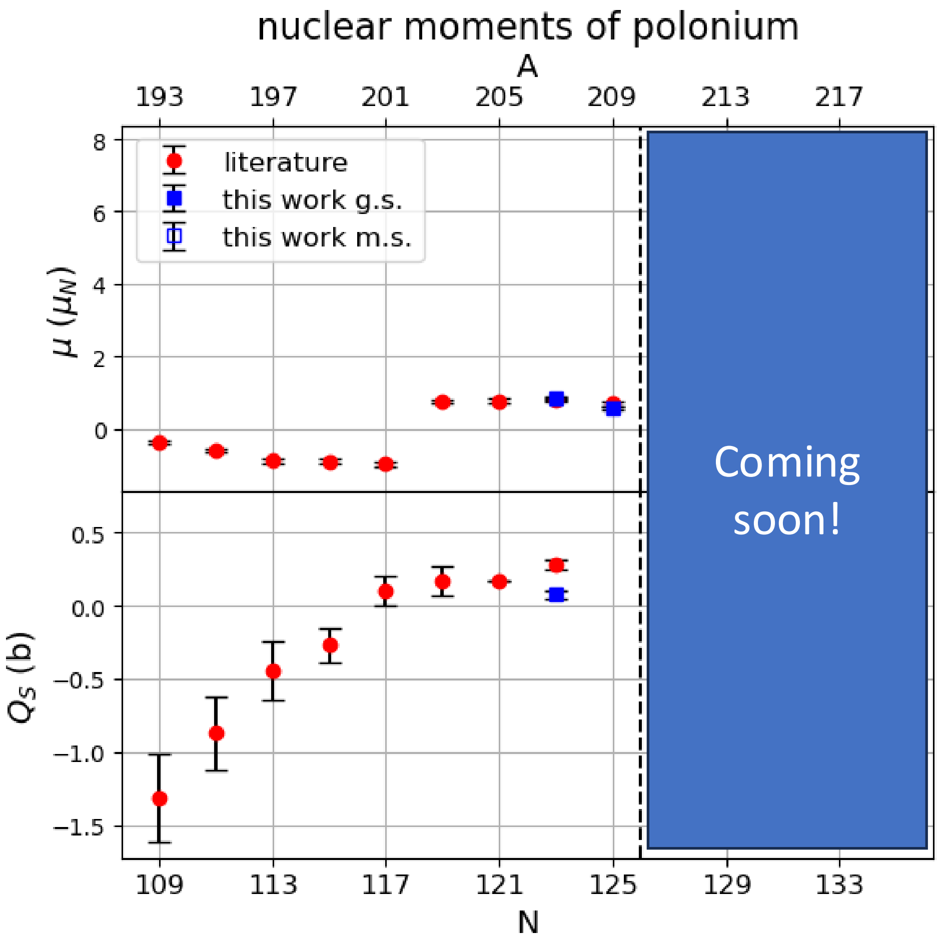
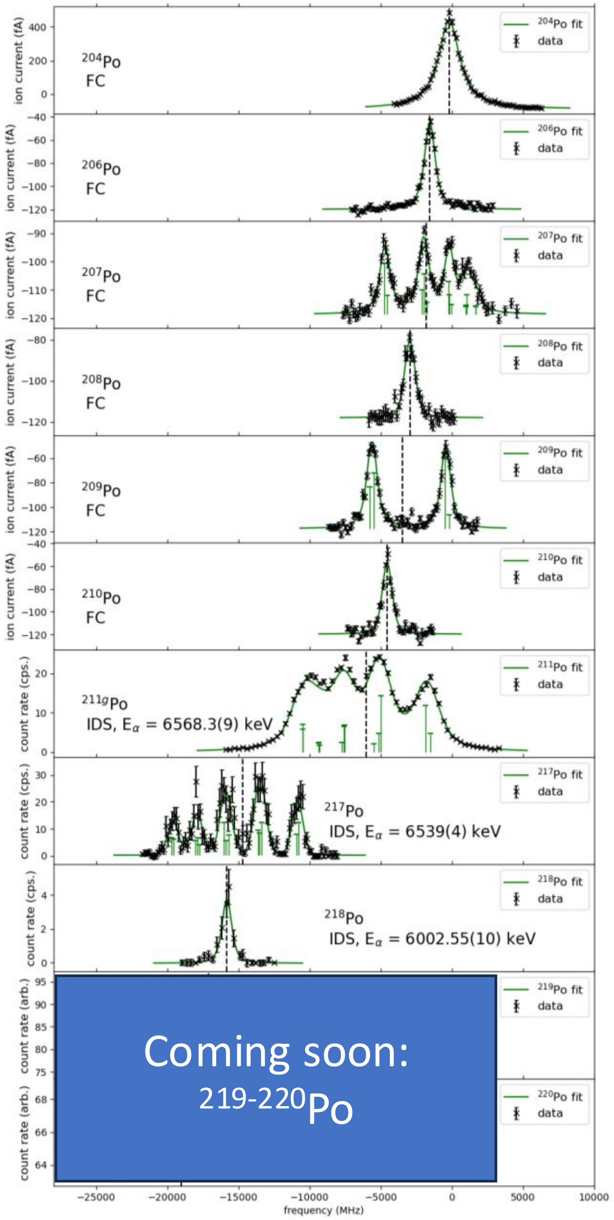
$_{84}$Po: plain old quadrupole







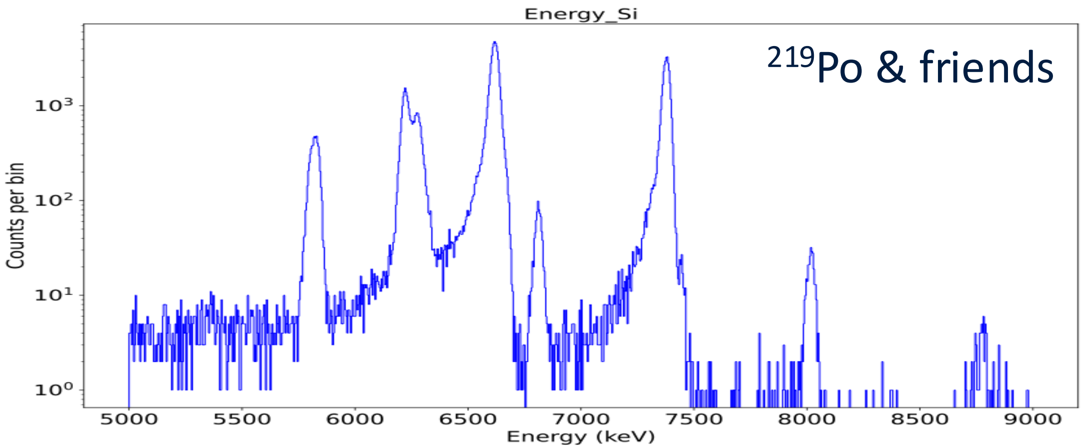
 PhD work Julius Wessolek (CERN/The University of Manchester).

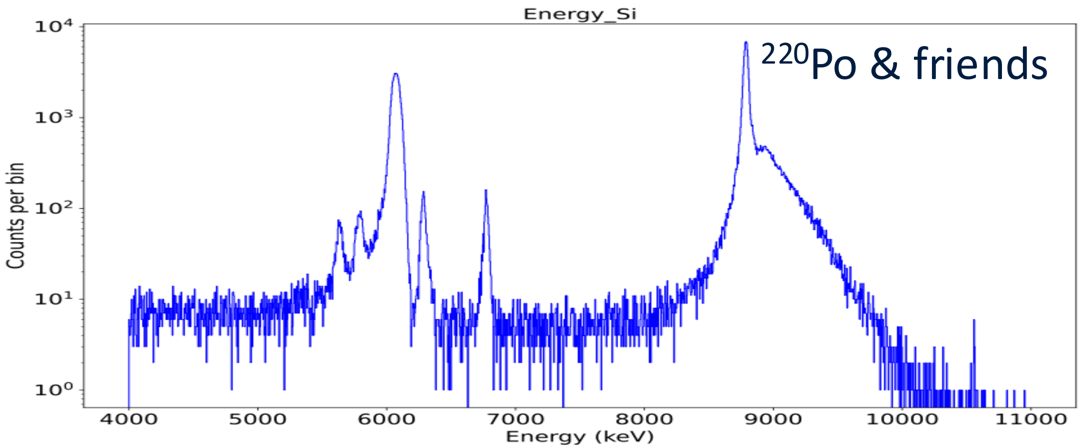
$_{84}$Po: Decay spectroscopy

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.

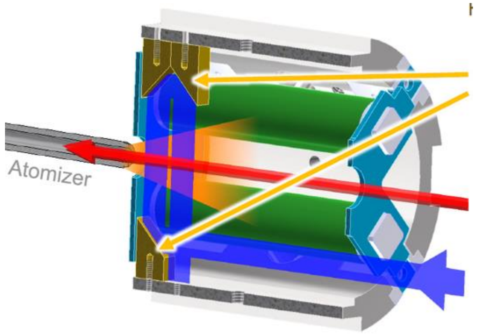
A detailed study of the beta decay to ^{219,220}At is on the way to explore the properties of those isotopes.

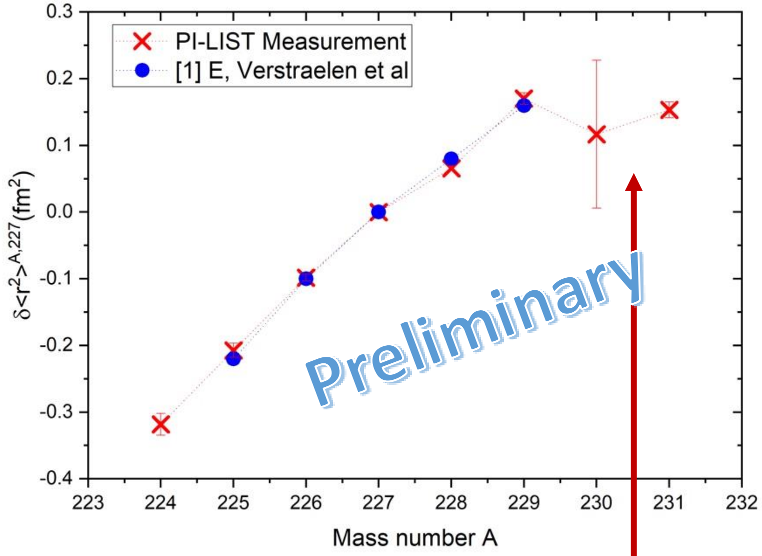


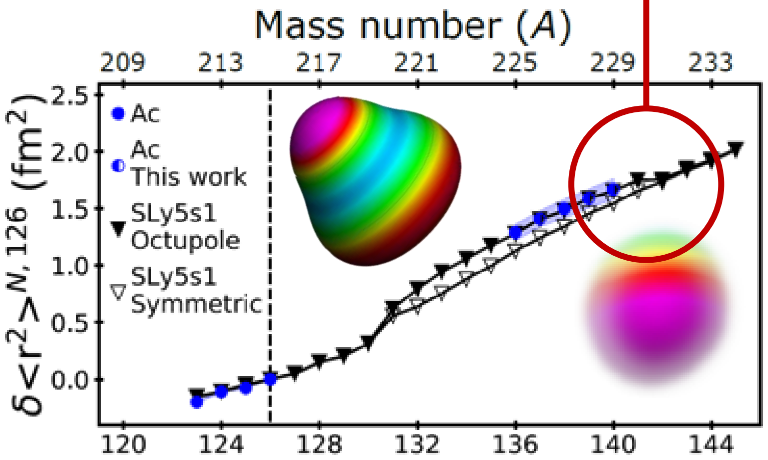


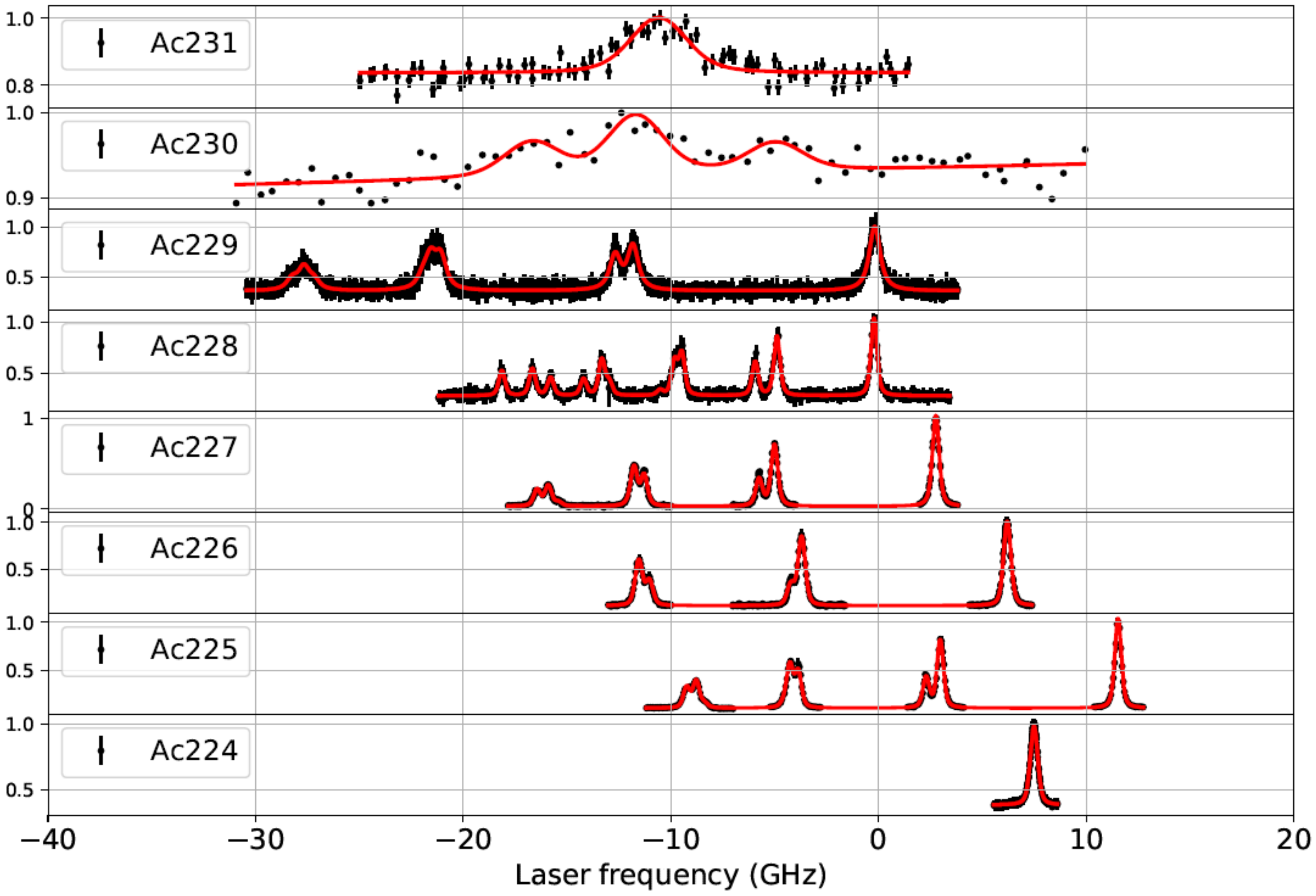
 PhD work Jack Shaw (KU Leuven).

$_{89}$Ac: where theory led









E. Verstraelen et al., Search for octupole-deformed actinium isotopes using resonance ionization spectroscopy, Physical Review C ***100*** *(2019) 044321.*

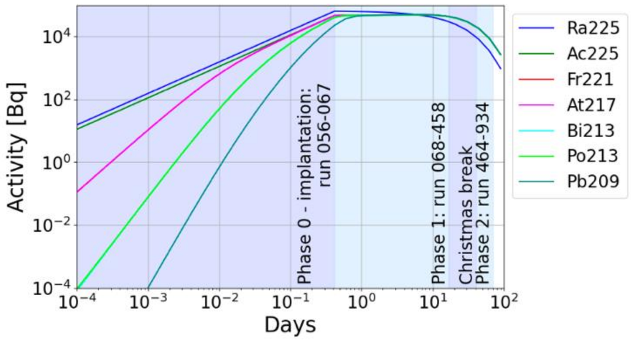
PhD work Asar Jaradat (CERN/The University of Manchester).

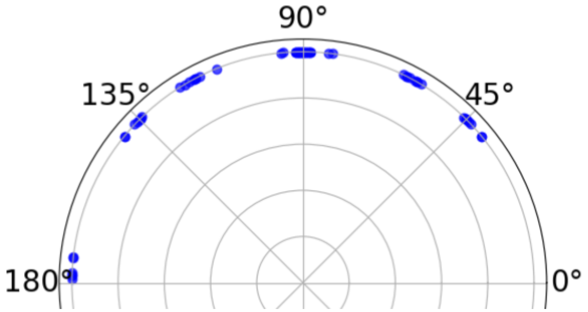
LISA KU LEUVEN

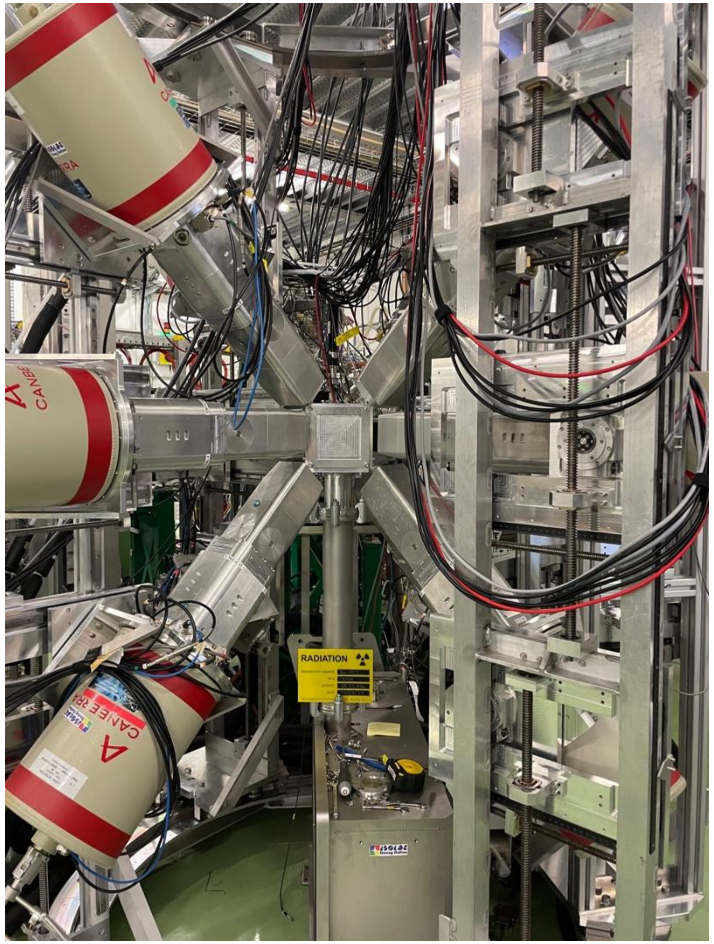
Decay spectroscopy of ^{225}Ac

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.





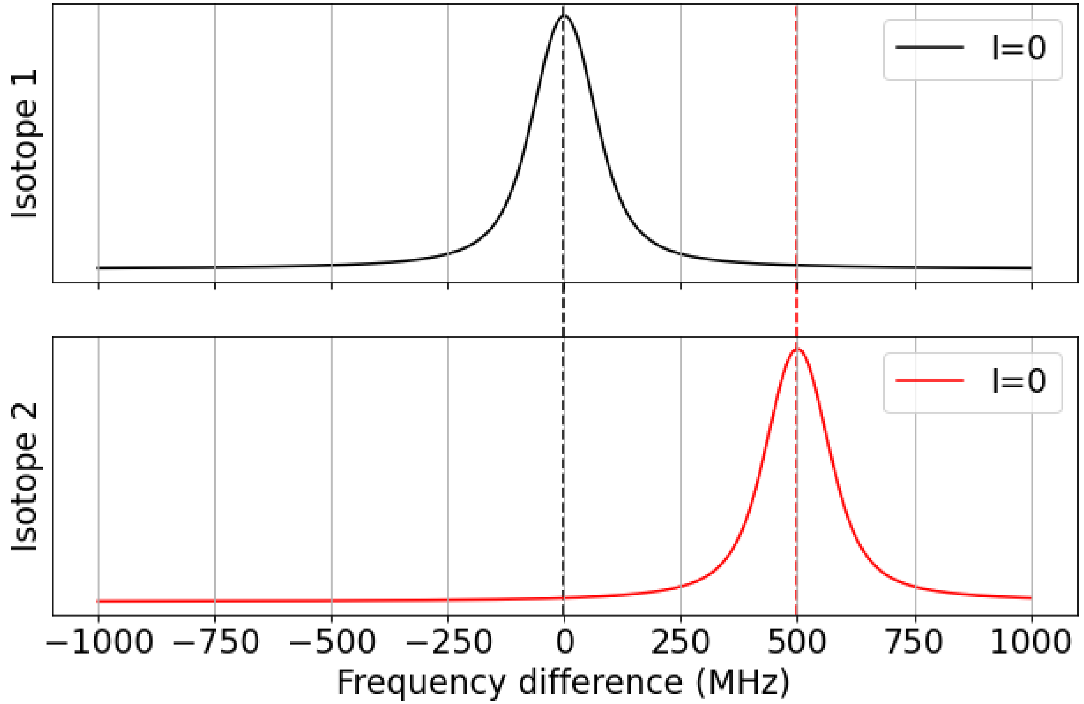


J. Aelbrechts, MSc KU Leuven (2025).
PhD work Jana Aelbrechts (KU Leuven).

Accuracy limit in extracting charge radii

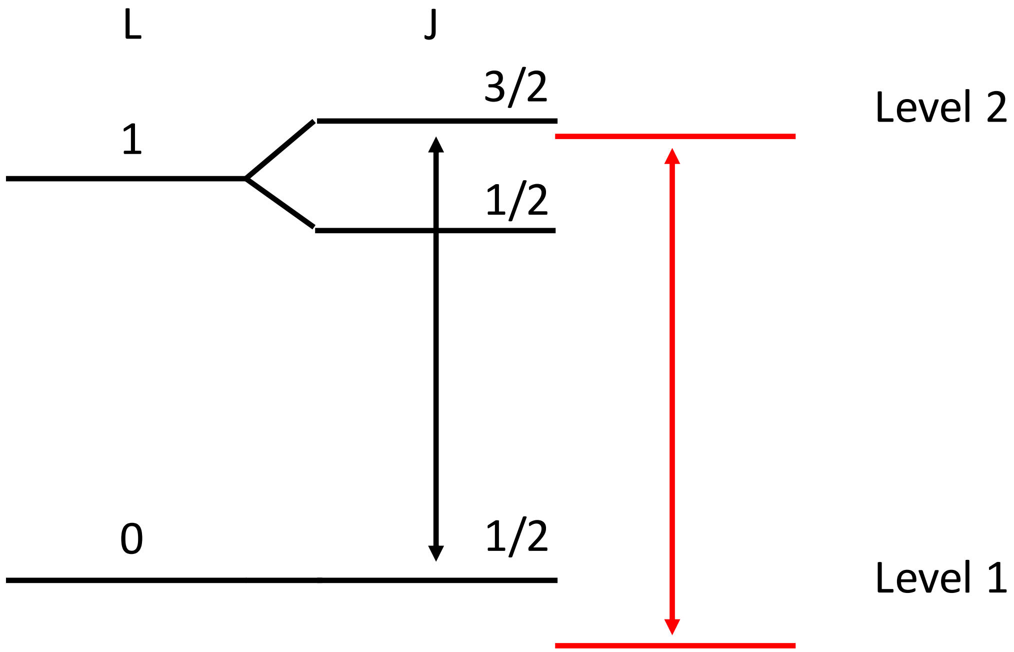
Probing the nucleus through its electrons

Use lasers to scan for transition energies



Extract isotope shifts $\delta\nu^{A,A'}$ → Infer $\delta < r^2 >^{A,A'}$

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



I = 0 → No hyperfine splitting

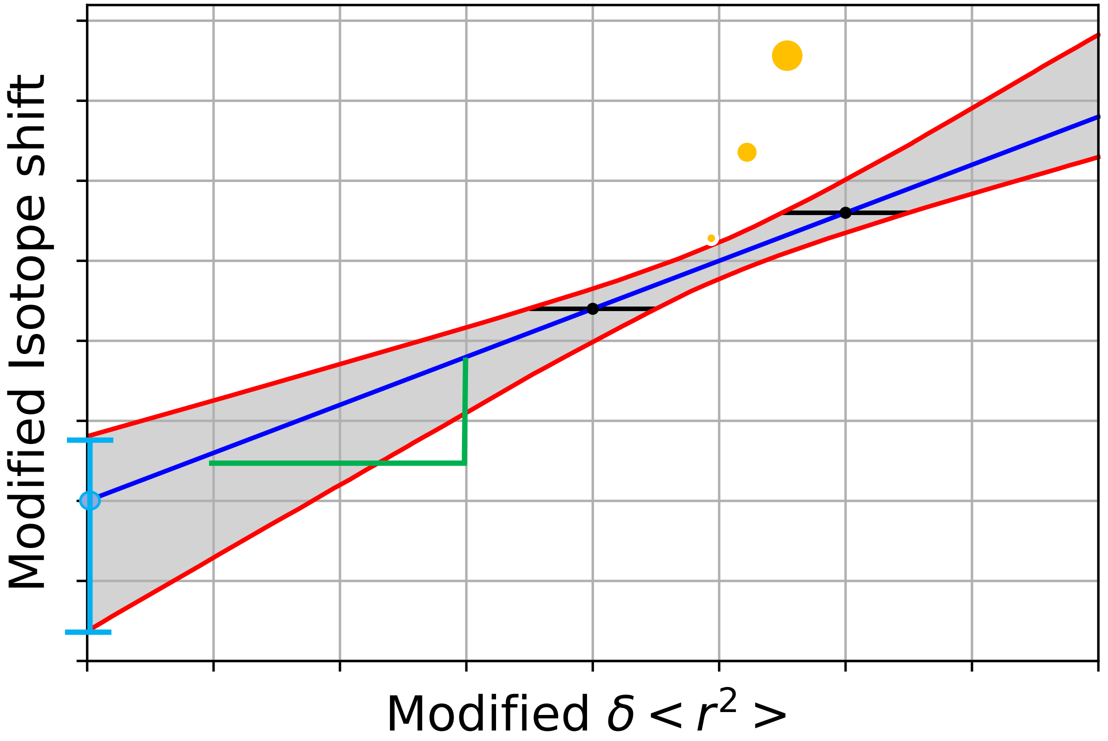
King plot against absolute radii

It takes 3 absolute radii to produce 2 ∂<r^2>

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

- 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

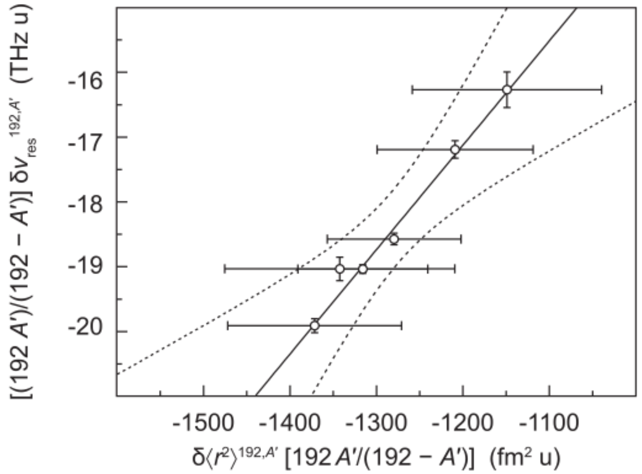
$$\delta\nu^{AA'} = \frac{A' - A}{AA'}\left(m_e\nu + M_{SMS}\right) + F\delta\langle r^2\rangle^{AA'}$$

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

The atomic parameters are essential to extract ∂<r²>
There are atomic theorists who can calculate them.
Experimental extraction or validation is still needed

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

$$\mu_{AA'} = \frac{AA'}{A' - A}$$



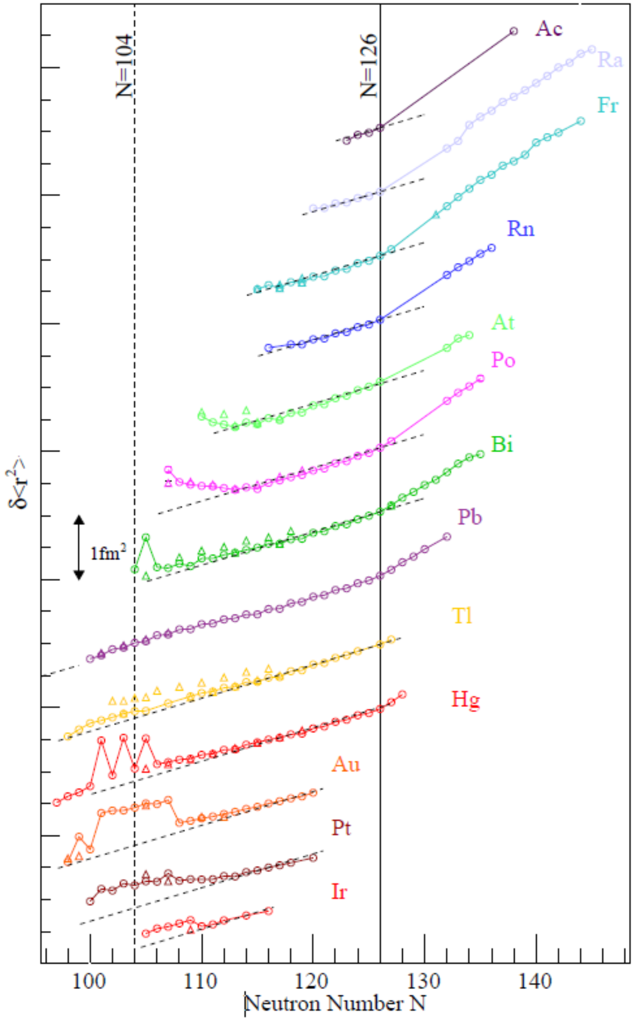
0 stable element
1 stable element
2 stable elements
3+ stable elments

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cp	Nh	Fl	Mc	Lv	Ts	Og
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

A. Kellerbauer et al., Isotope shift of the electric-dipole transition in Os⁻, Physical Review A ***84*** *(2011) 062510.*
T.E. Cocolios, A new perspective on charge radii around Z = 82, Hyperfine Interactions ***238*** *(2017) 16.*

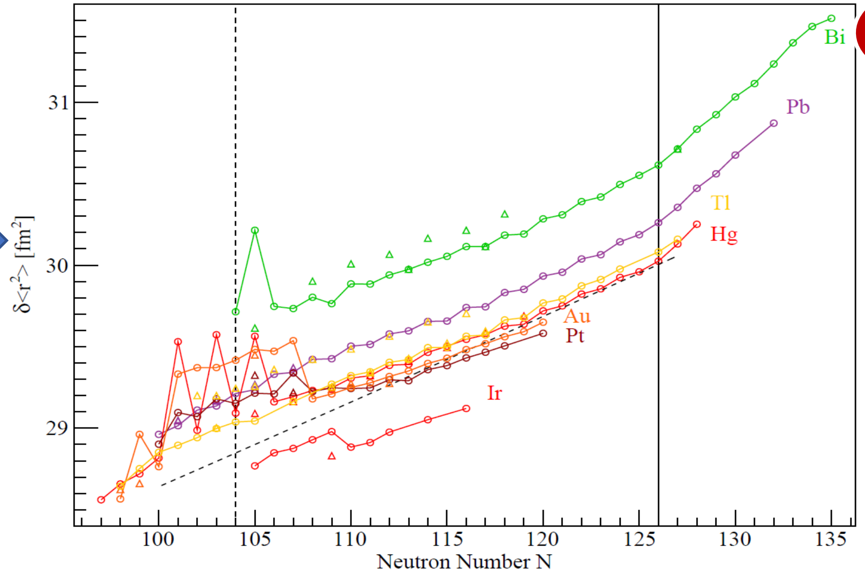
Absolute size of the heavy elem

Key measurements of absolute charge radii could easily complete this picture

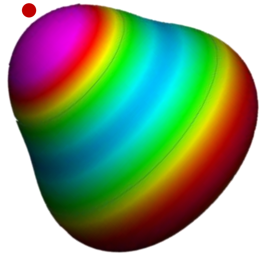


Exploring isotonic chains across Z=82

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



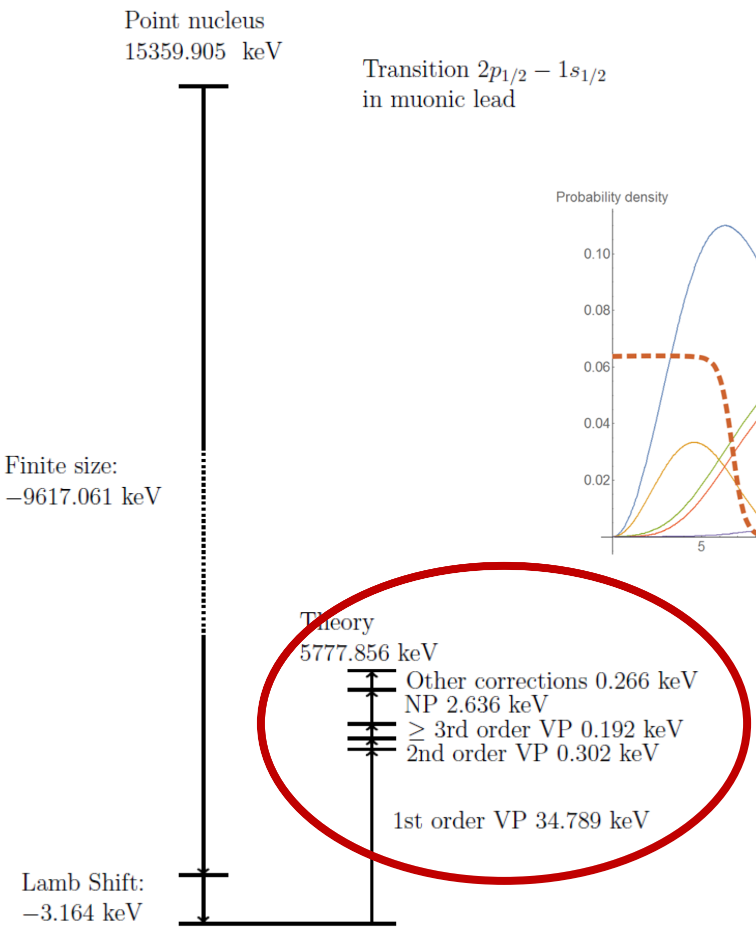
Absolute charge radii are needed for the searches of physics beyond the standard model

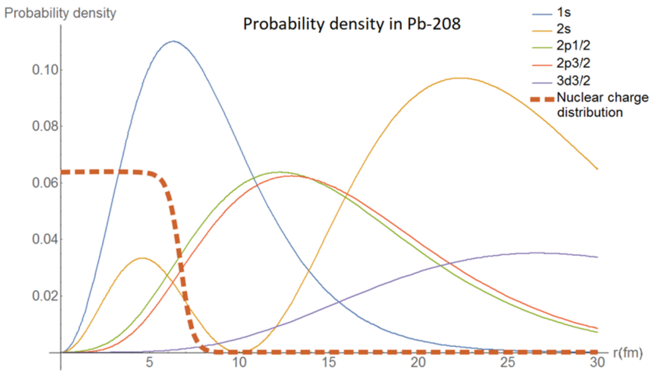


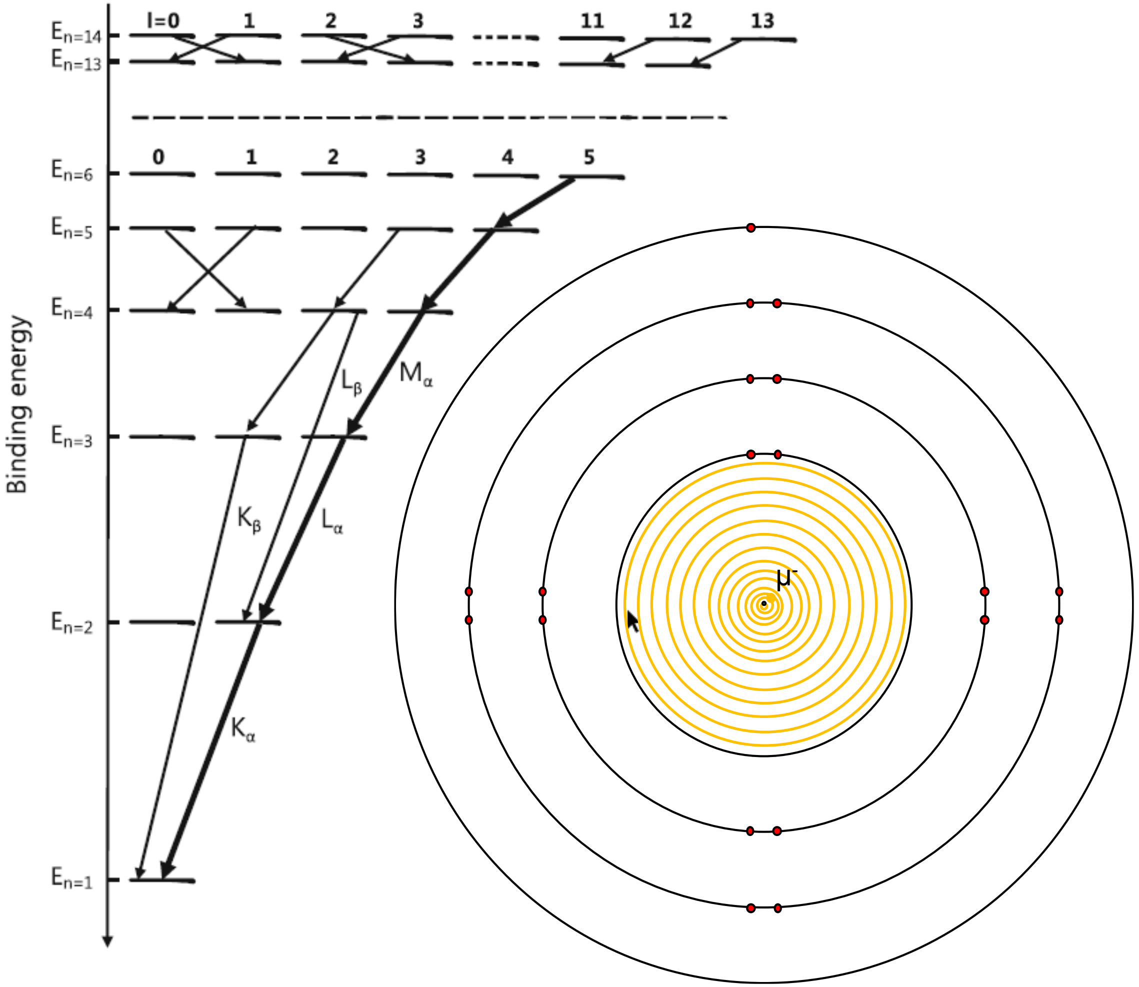
*Pictures adapted from T.E. Cocolios, A new perspective on charge radii around Z = 82, Hyperfine Interactions **238** (2017) 16.*

muX and ReferenceRadii

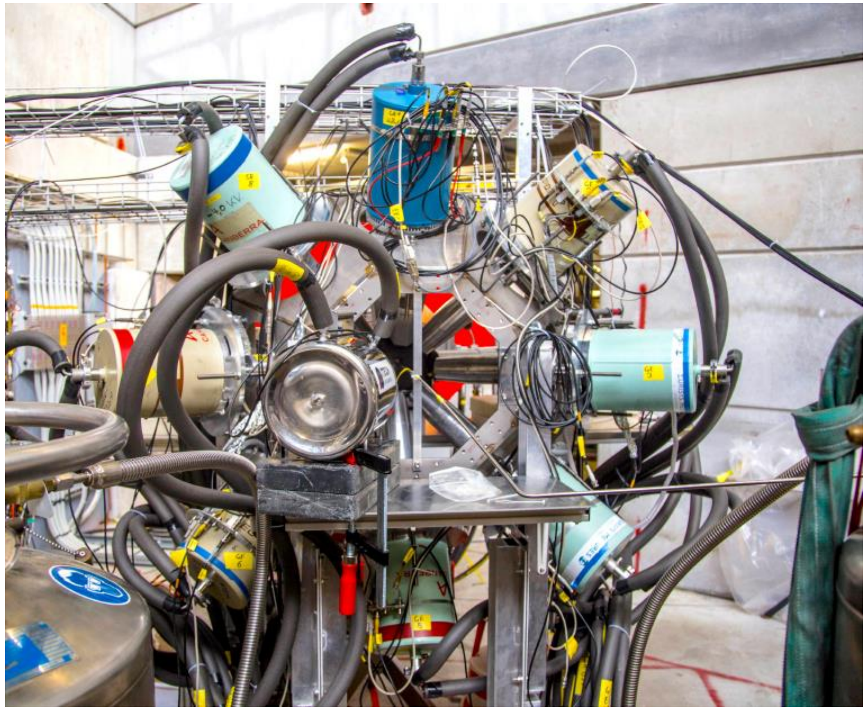
Muonic x-rays as probe

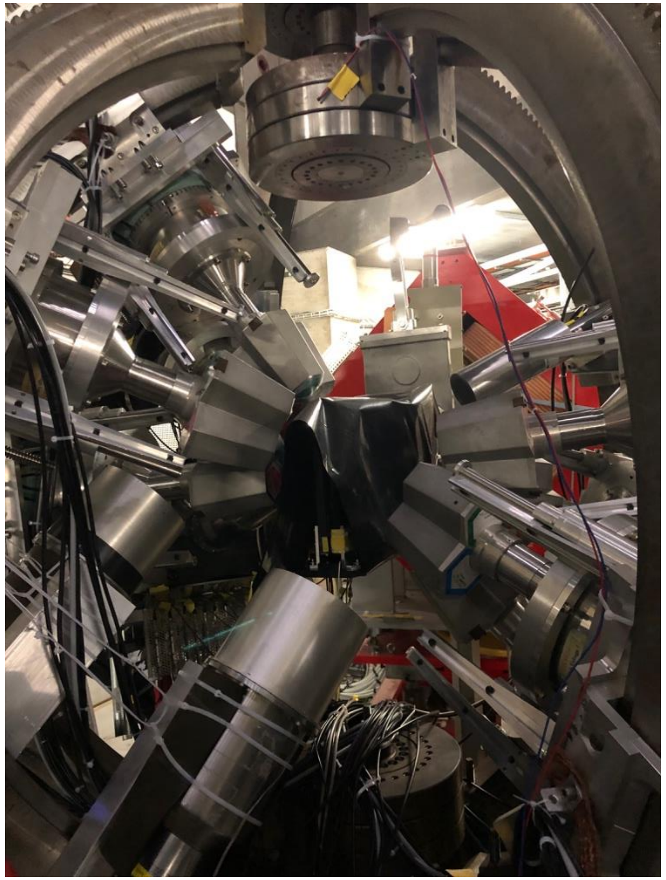






μ-atomic spectroscopy with muX at PSI





- 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

A. Adamczak et al, Nuclear structure with radioactive muonic atoms, EPJ WC ***193*** *(2018) 04014.*
A. Skawran et al, Towards nuclear structure with radioactive muonic atoms, Il Nuovo Cimento ***42 C*** *(2019) 125.*

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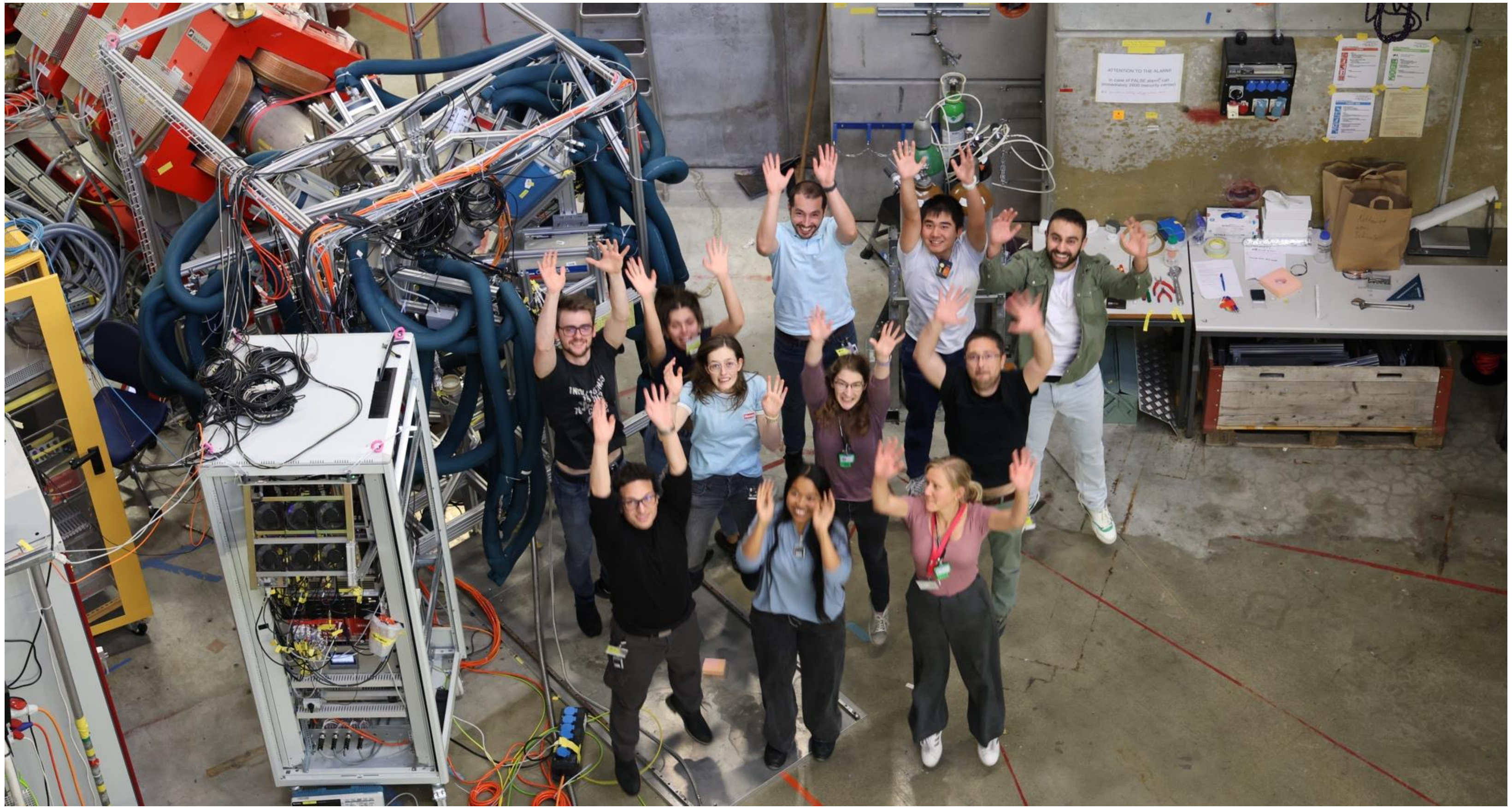


- 2020+: GIANT Array with MIXE, muX and muon capture

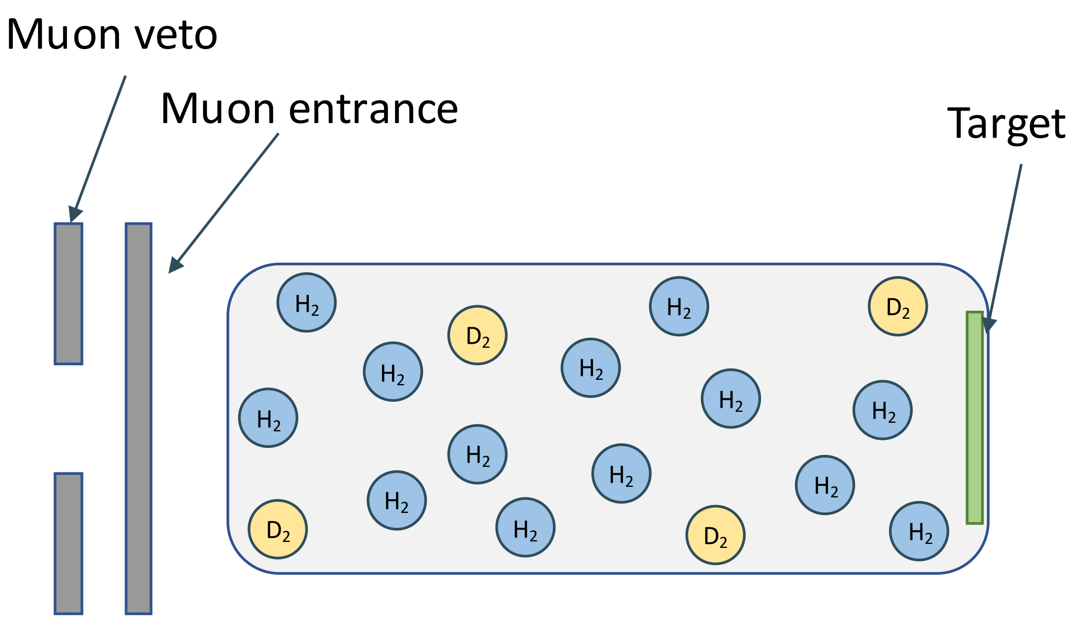
*L. Gerchow et al., GermanIum Array for Non-destructive Testing (GIANT) setup, Review of Scientific Instruments **94** (2023) 045106.*

Measuring microgram materials

Traditionally: Limited to target mass O(10-100 mg)

Hydrogen gas cell (100 bars; 0.25% deuterium)

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



Bubak, M., & Fajman, M. P. (1987). *Cross sections for hydrogen muonic atomic processes in two-level approximation of the adiabatic framework* (No. JINR-E--4-87-464). Joint Inst. for Nuclear Research.
Adamczak, Andrzej, et al. "Muonic atom spectroscopy with microgram target material." *The European Physical Journal A* **59** (2023): 15.

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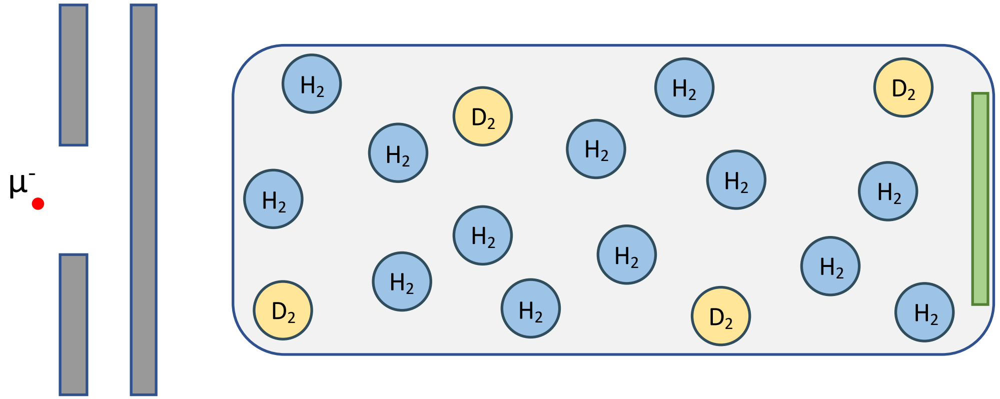

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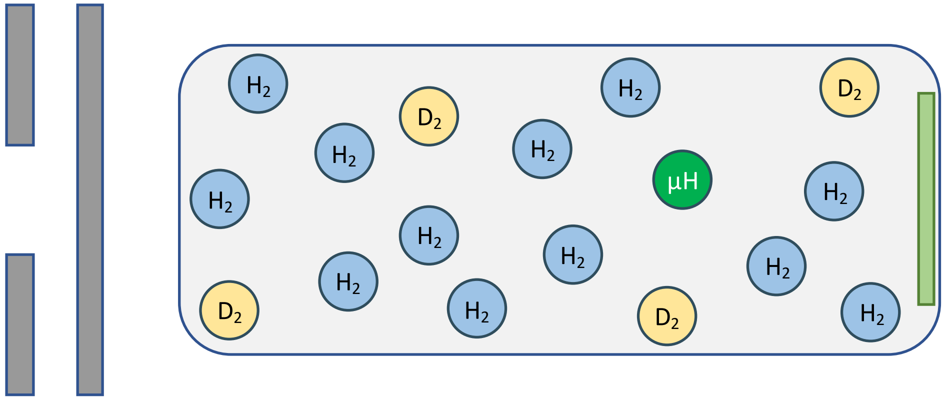

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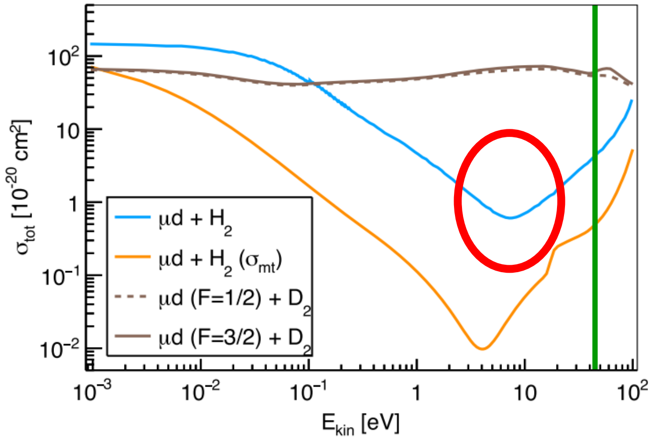

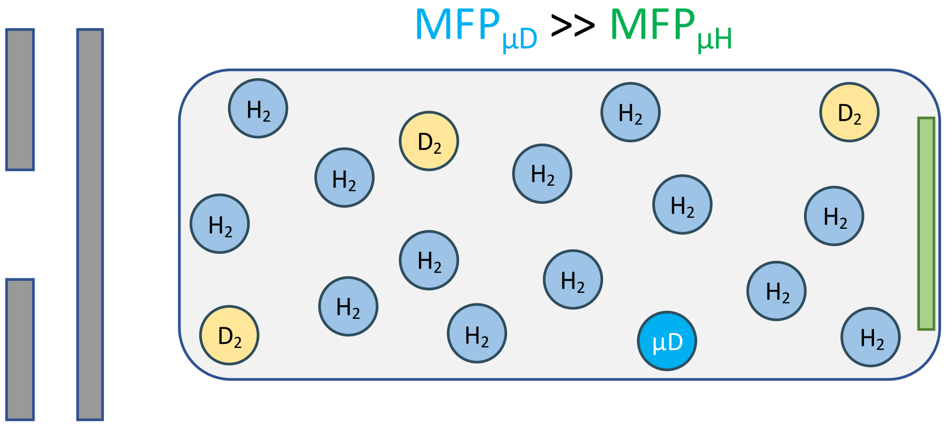

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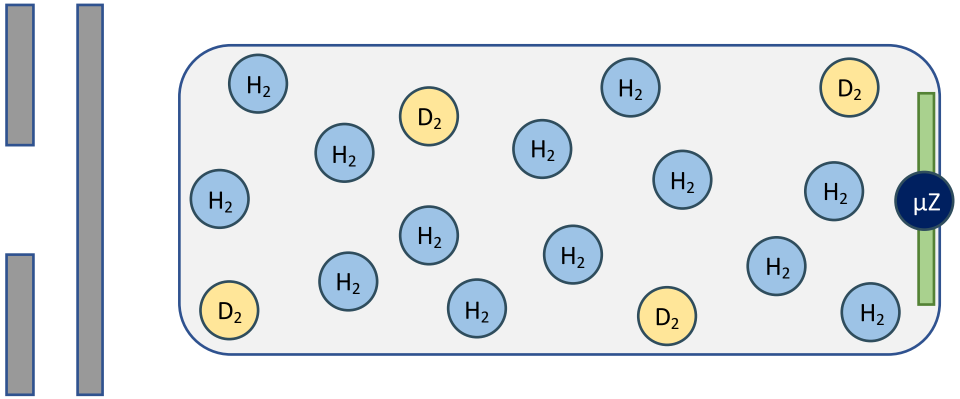

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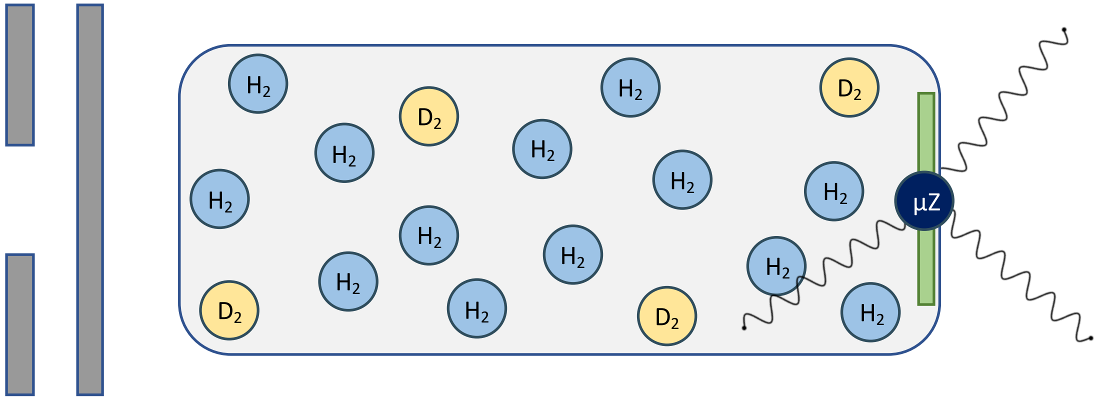

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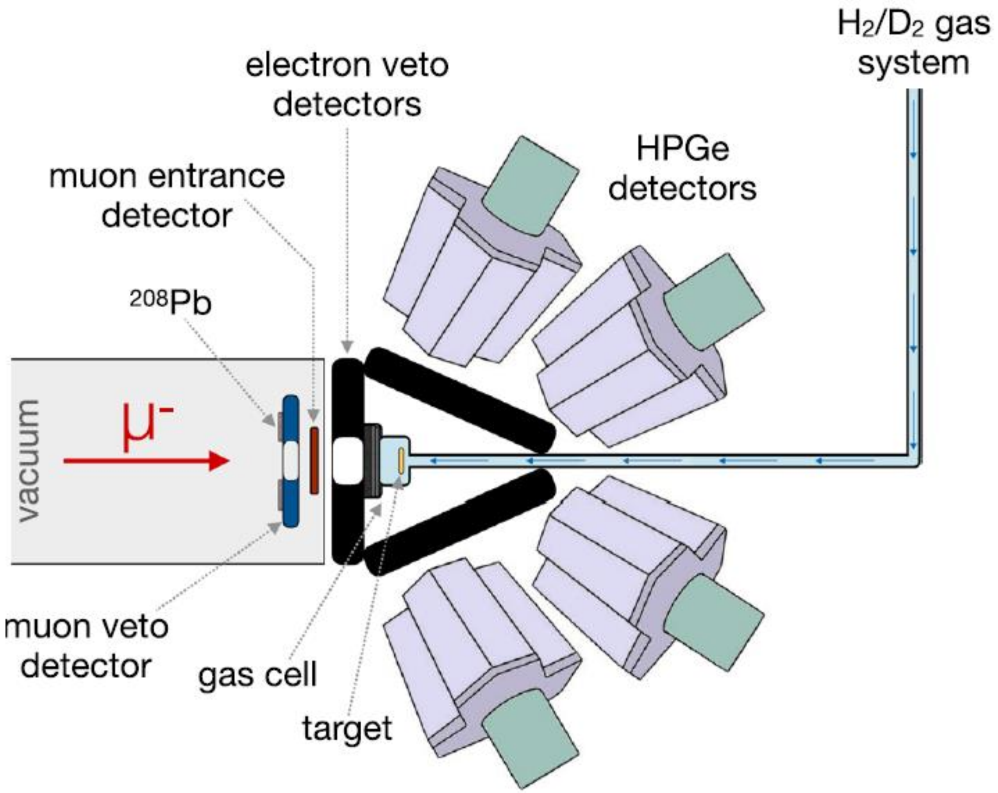

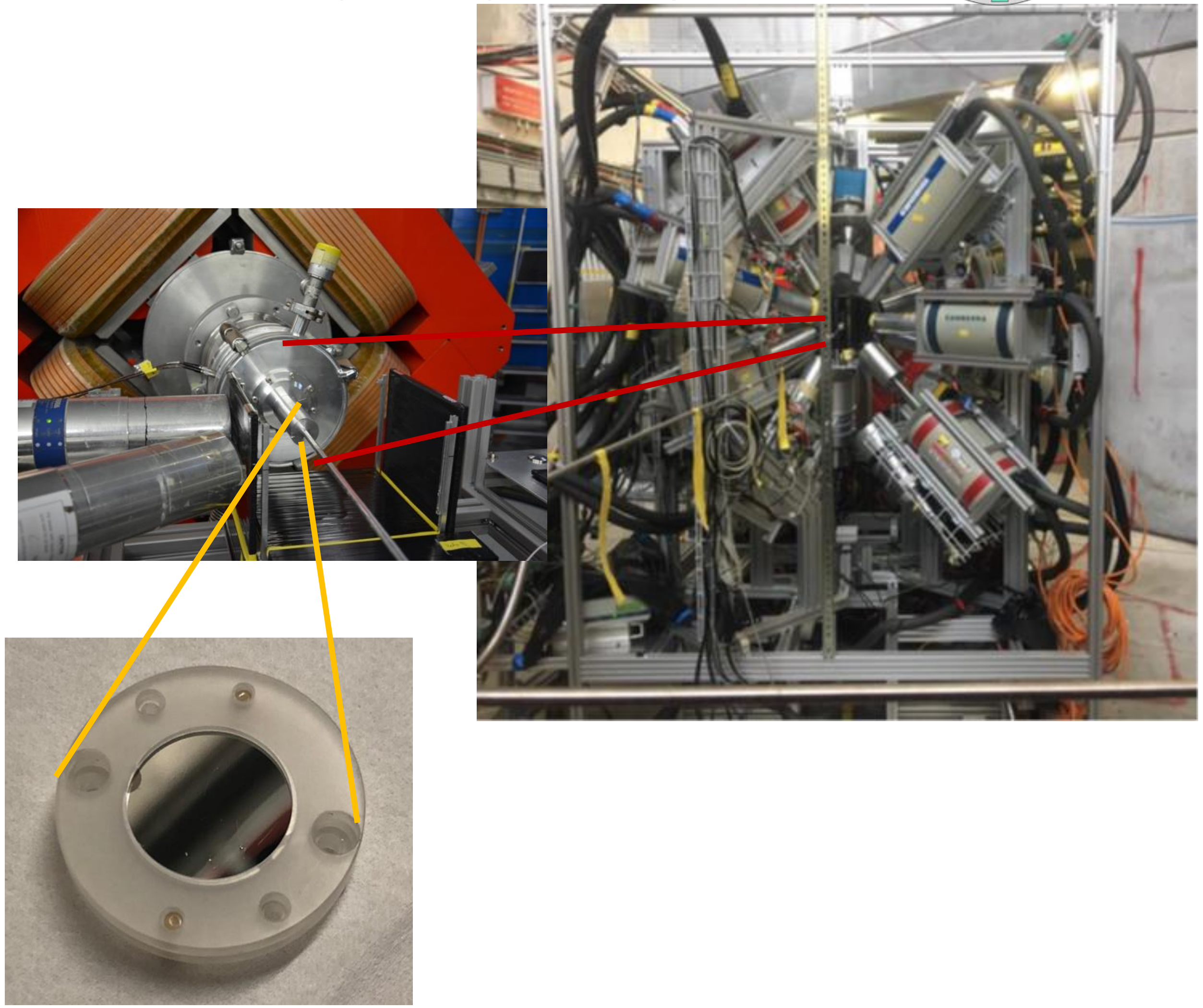

A. Adamczak et al., Muonic atom spectroscopy with microgram target material, Eur. Phys. A ***59*** *(2023) 15.*

${}_{17}$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.

NRF National Research Foundation | iThemba LABS Laboratory for Accelerator Based Sciences

- First measurement with pure Cl isotopes and first measurement of ^{40}K for a full triplet.

L. Antwiss et al., *A comparative study of target fabrication strategies for microgram muonic atom spectroscopy, Scientific Reports* **15** (2025) 6939.

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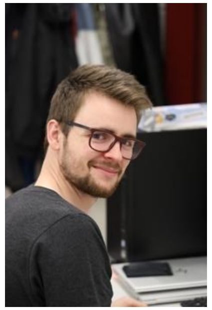
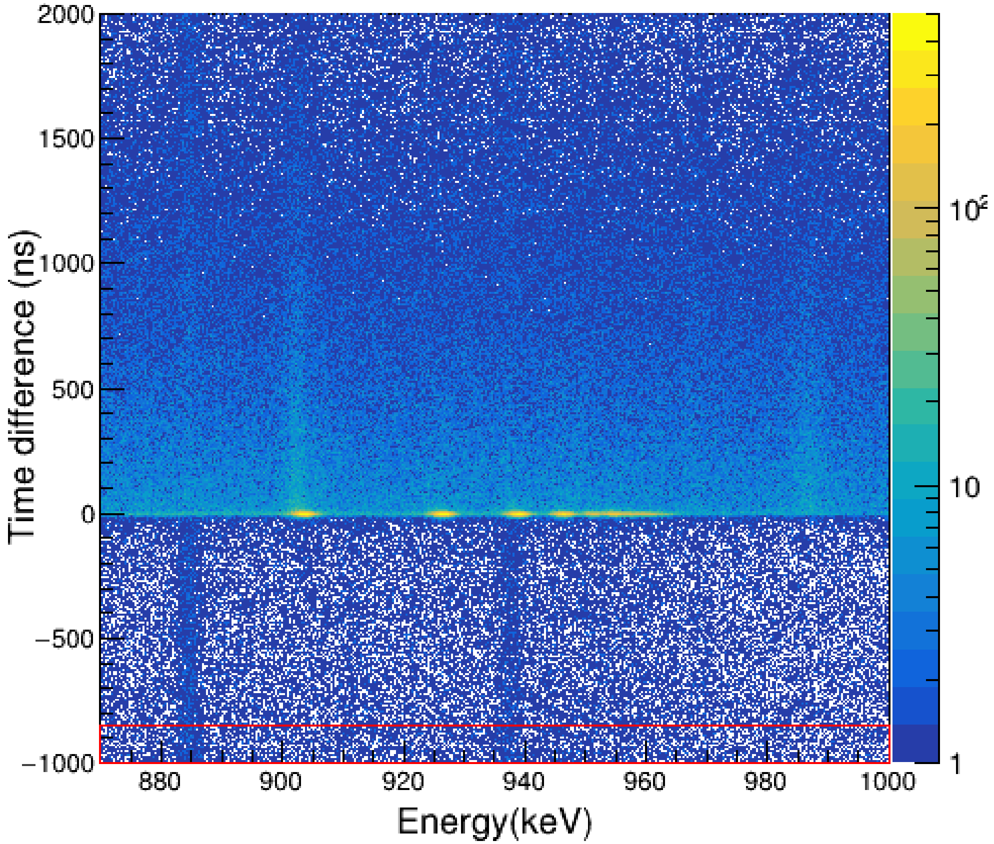
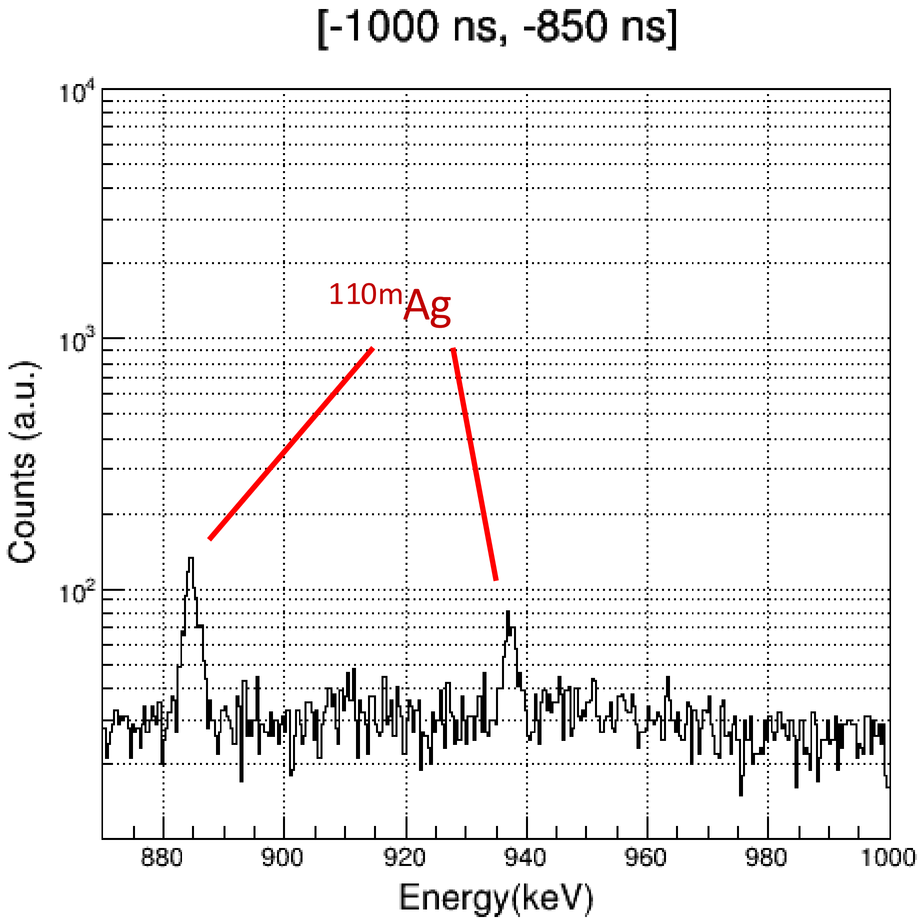
Interpreting energy Vs time plots







 PhD work Michael Heines (KU Leuven).

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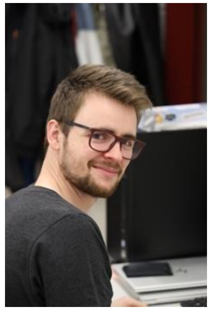

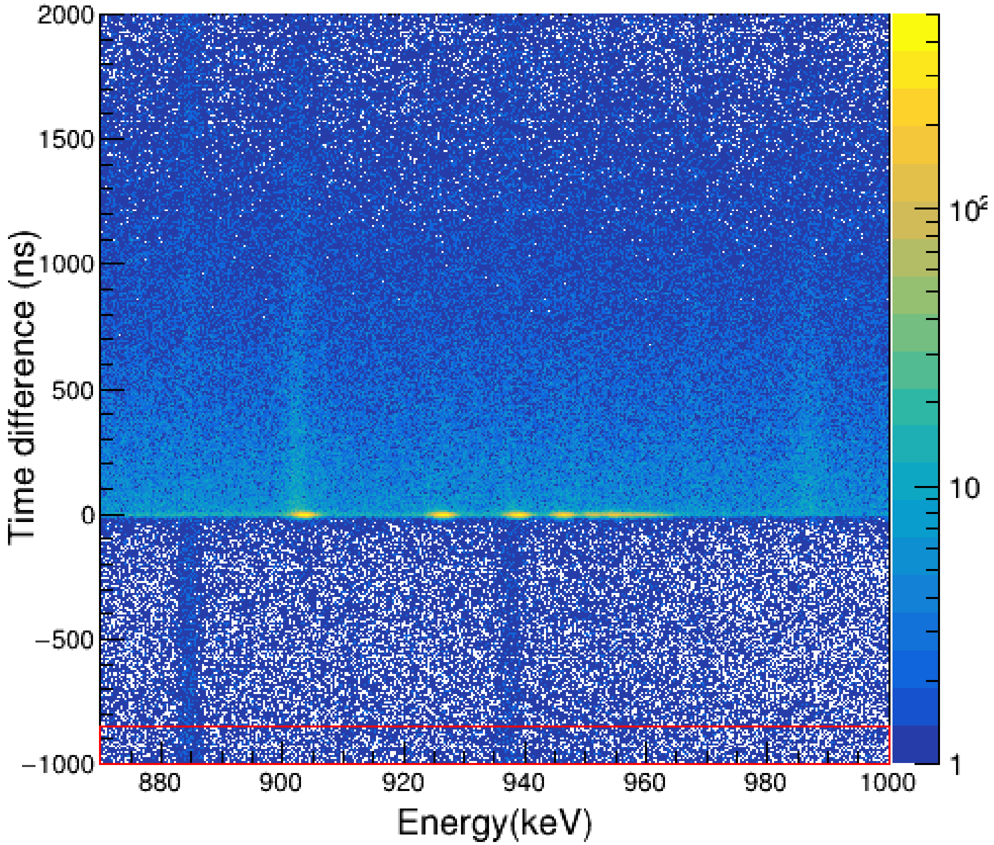

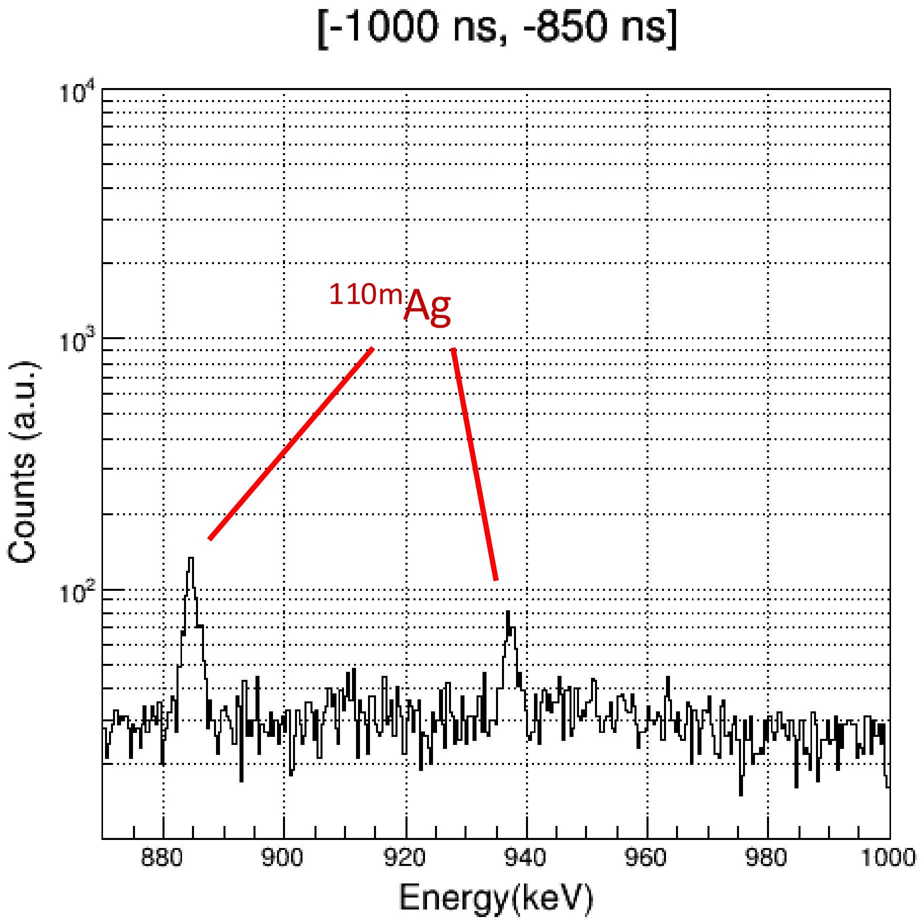

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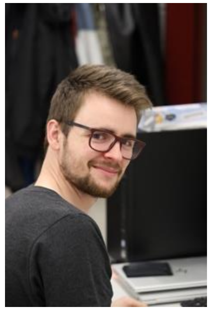

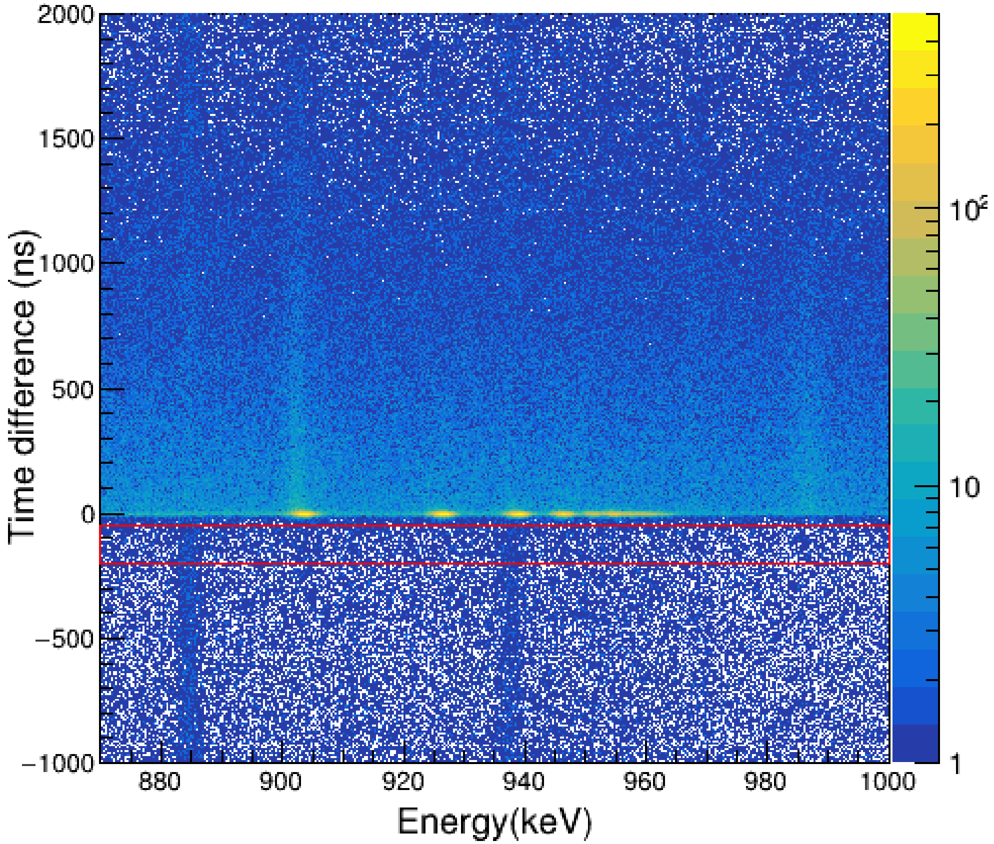

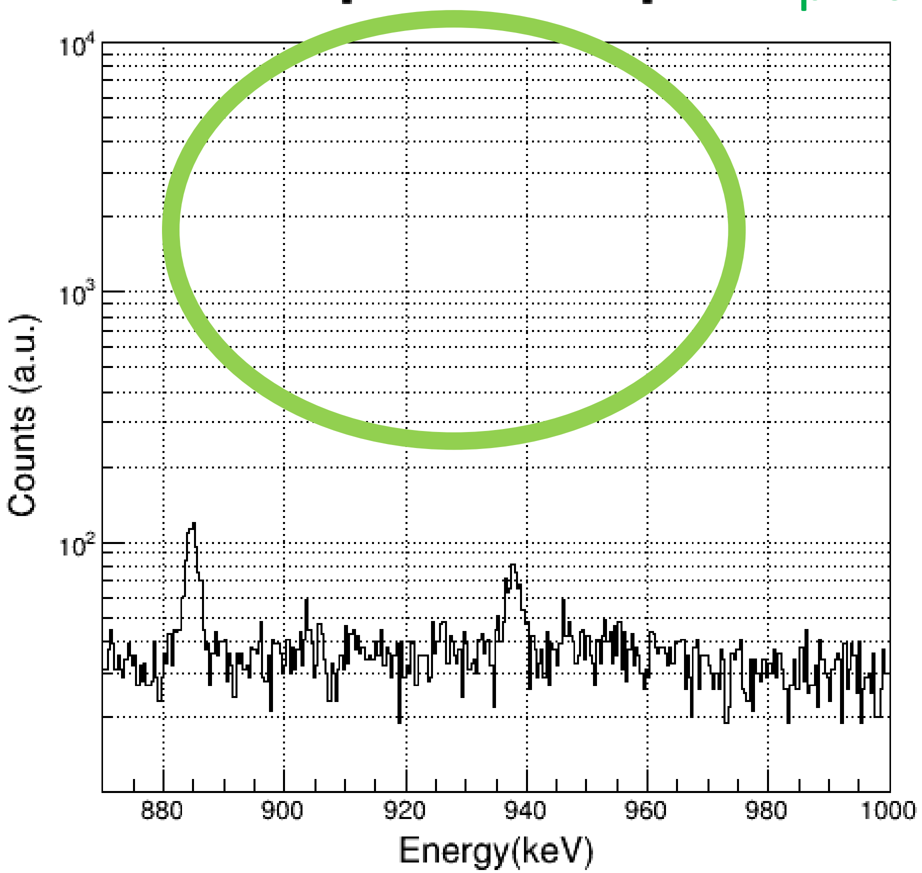

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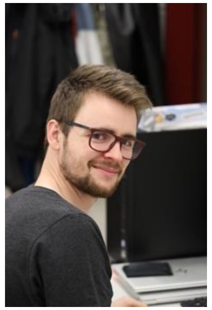

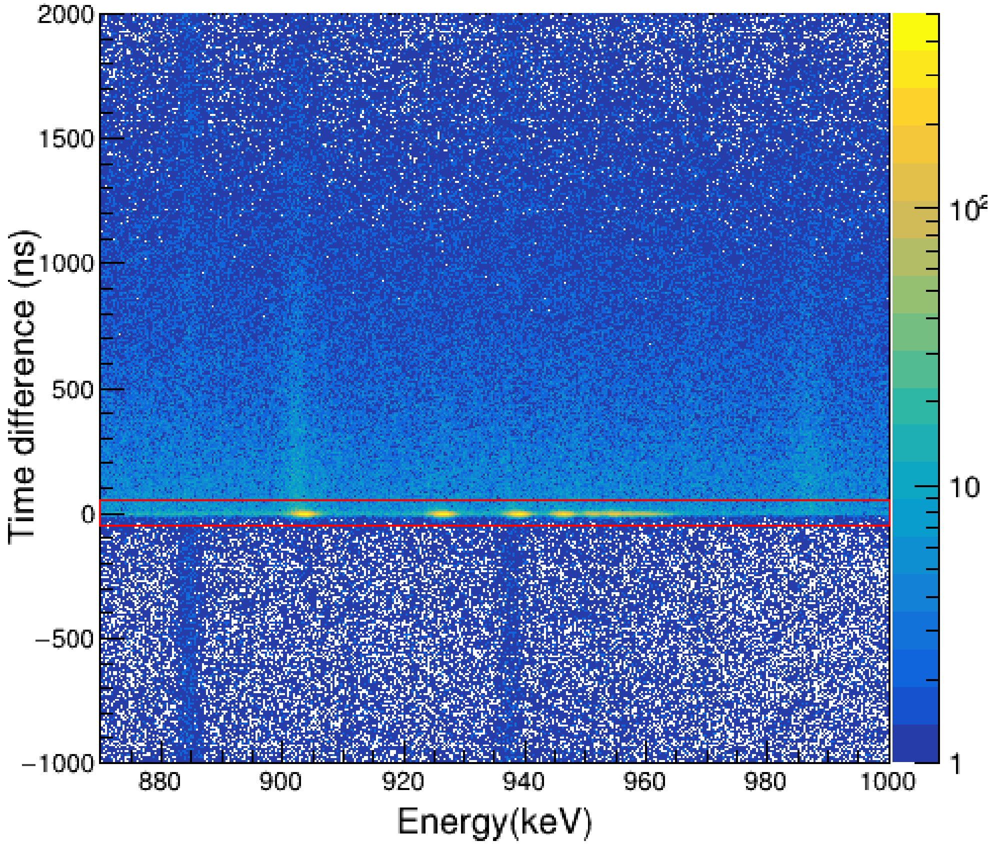

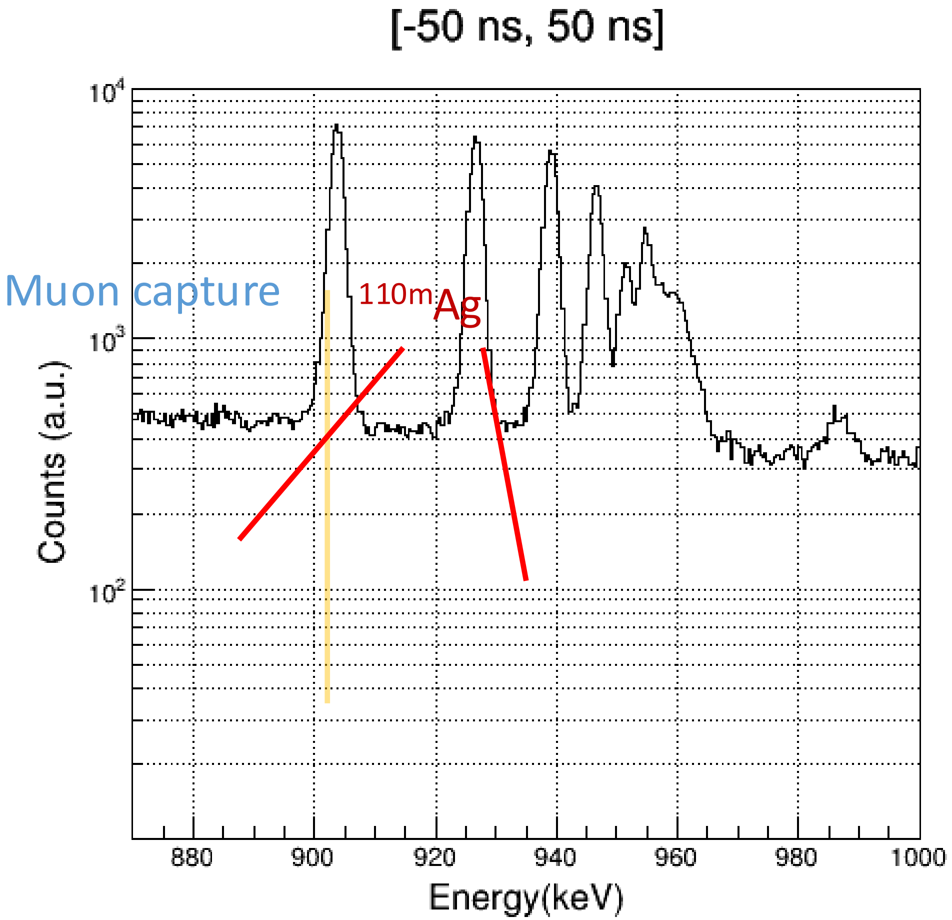

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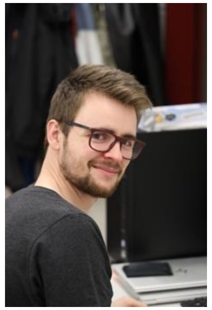
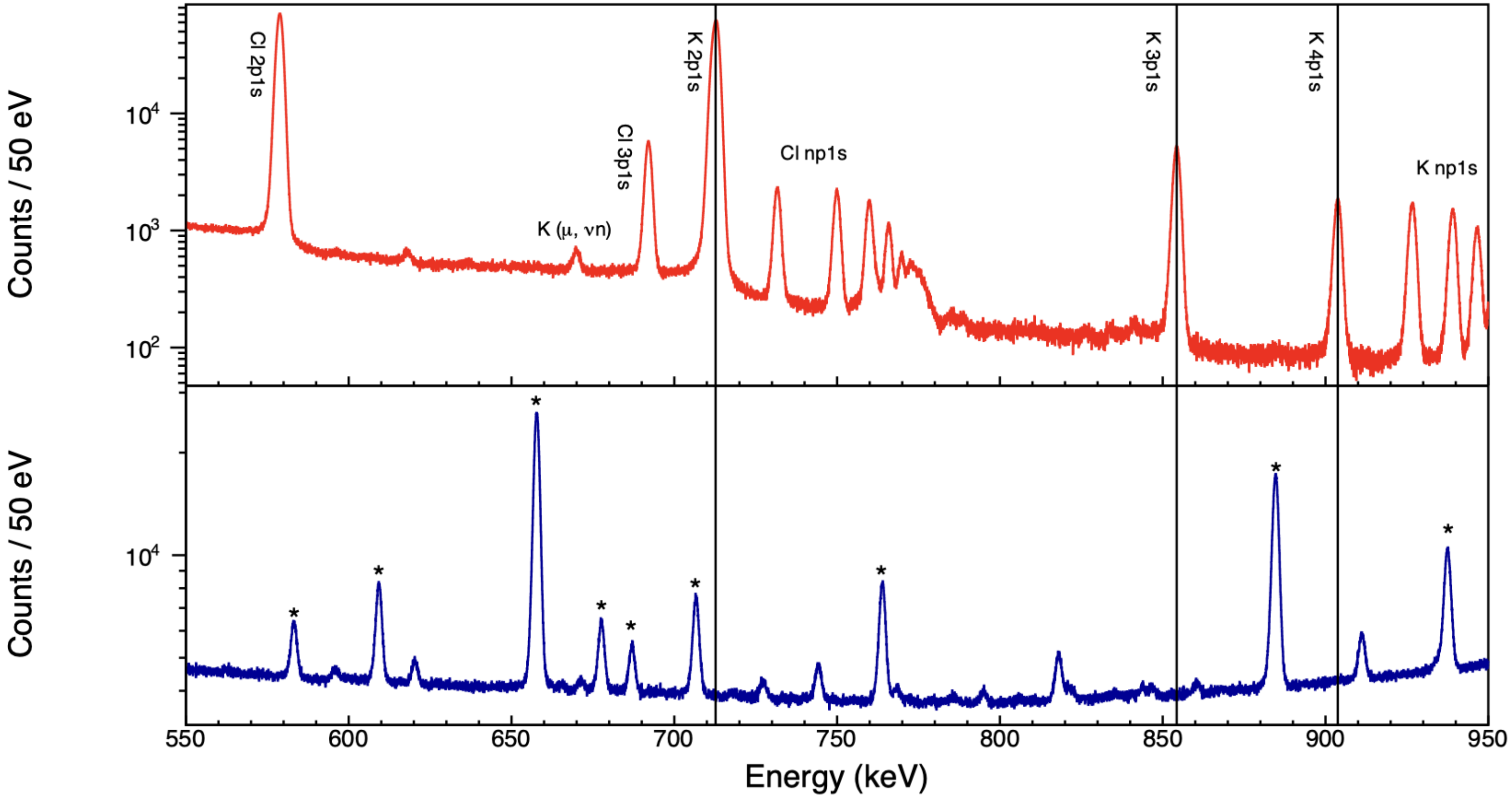
$_{17}$Cl and $_{19}$K: probing near Z=20





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

PhD work Michael Heines (KU Leuven).

K.A. Beyer et al., *Modern approach to muonic x-ray spectroscopy demonstrated through the measurement of stable Cl radii, submitted to Physical Review X,* https://arxiv.org/abs/2506.08804

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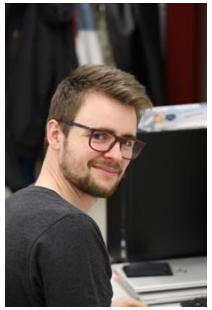

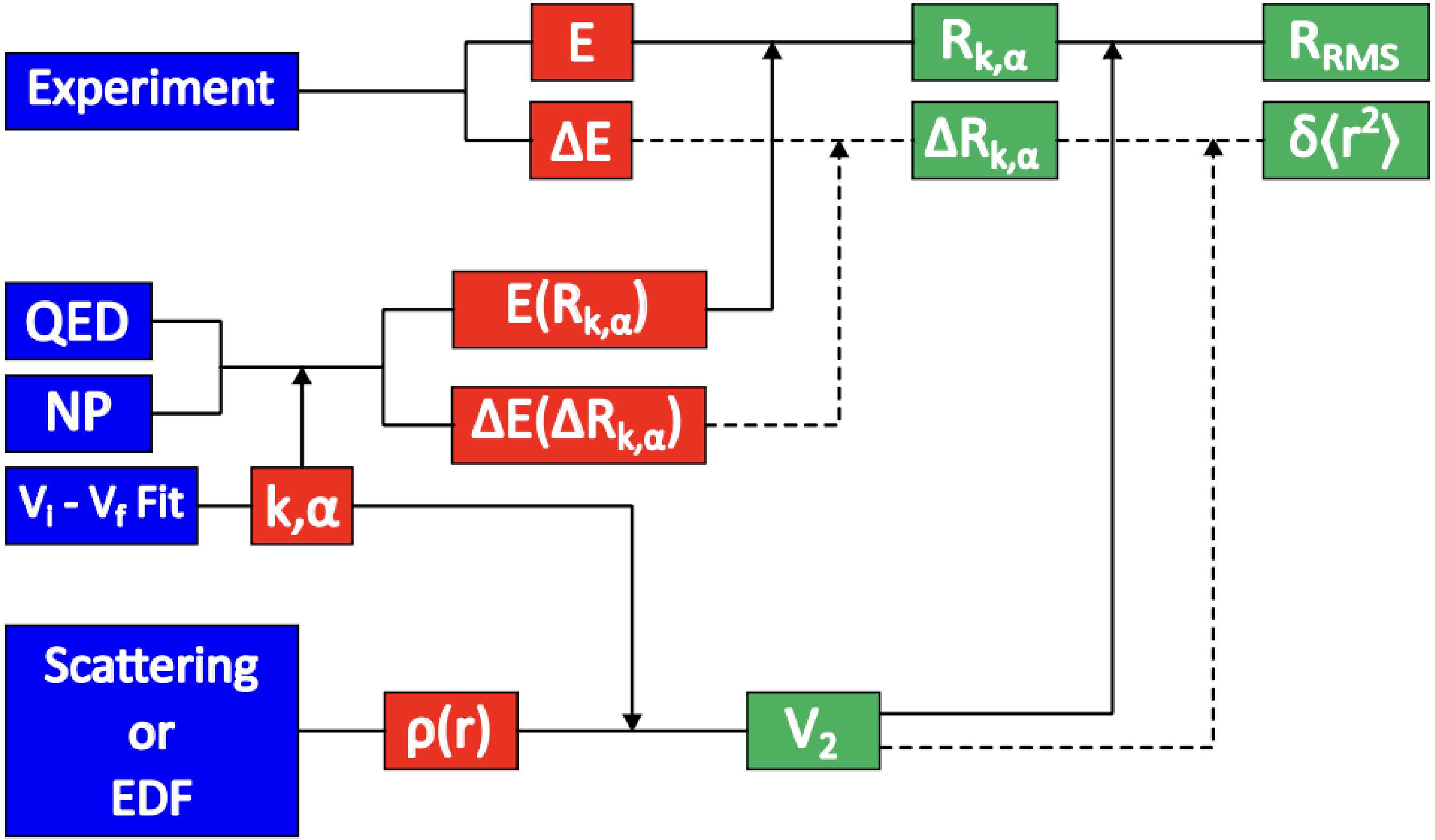

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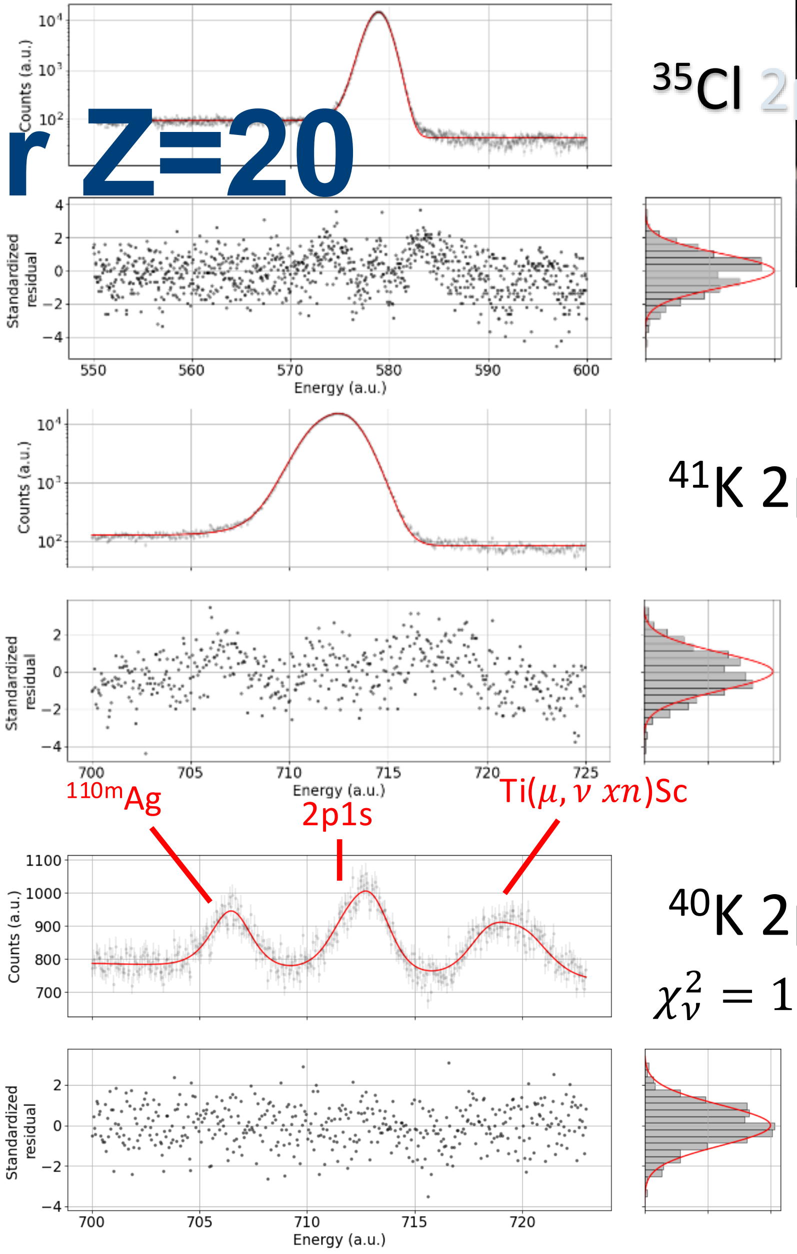
KU LEUVEN

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

- Large targets for ^{39,41}K and ^{35,37}Cl
  → Direct stopping with high statistics
  Uncertainty dominated by calibration error.
  ➔ 2p1s, 3p1s, and 4p1s energies extracted with ~15-25 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



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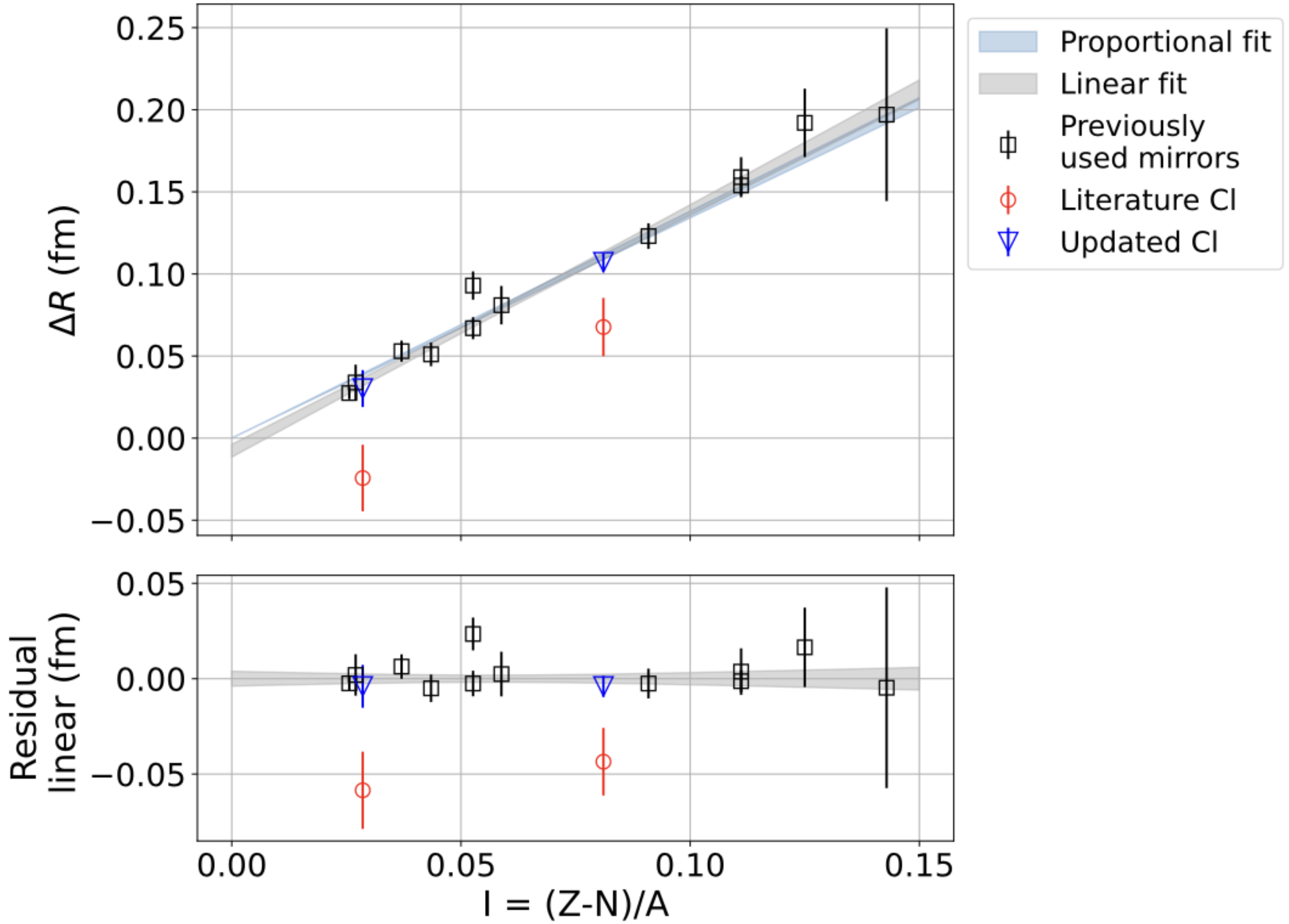
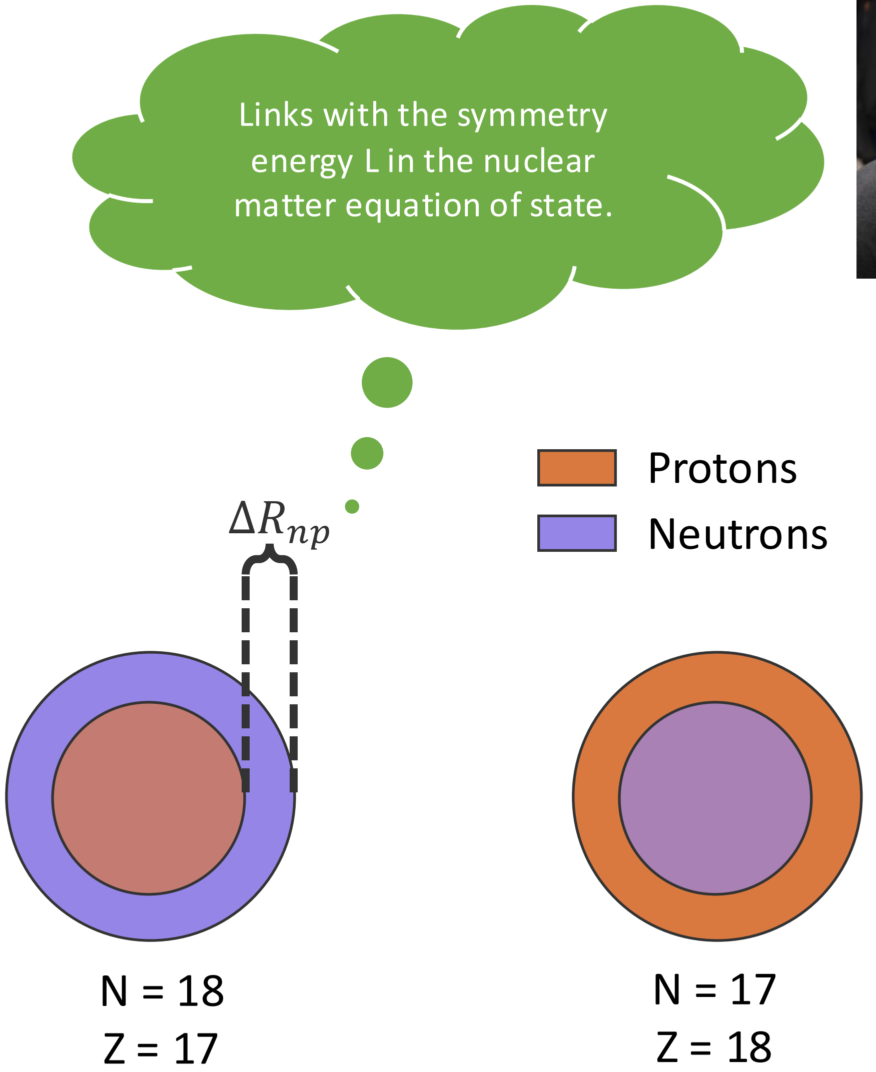
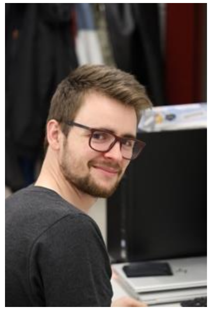
KU LEUVEN 600

Mirror nuclei

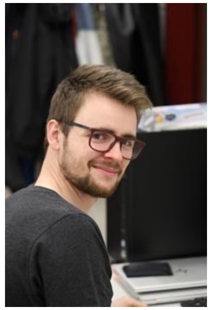




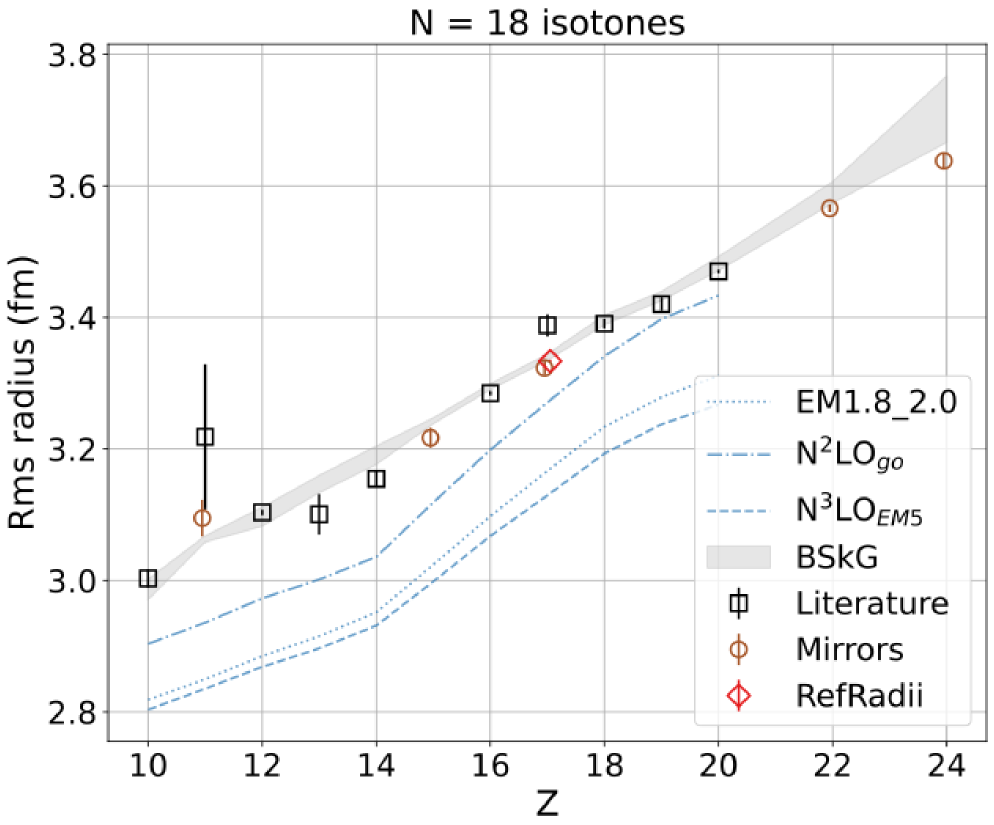


*B. Ohayon, […] charge radii and applications in mirror nuclei, ADNDT **165** (2025) 101732.*
PhD work Michael Heines (KU Leuven).

Nuclear structure along isotonic chain



- Absolute radii allow to anchor all the isotopic chains measured with laser spectroscopy and to compare them to one another.
- Similar to isotopic chains, the EDF models capture the global scale much better than the ab initio models.
- However, the ab initio models do better in capturing the details.



 PhD work Michael Heines (KU Leuven).

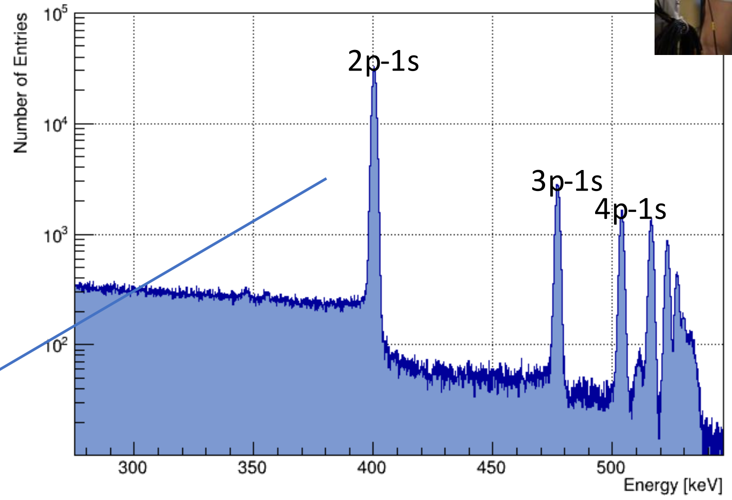
$_{14}$Si to probe the nuclear EOS

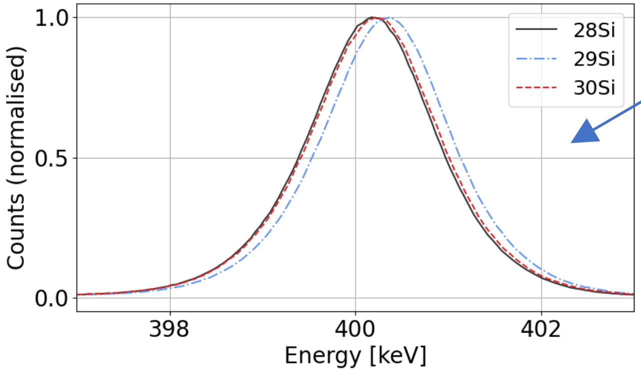
Mirror nuclei provide insight into the slope of the symmetry energy L of the nuclear equation of state.

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}Si, combined with a full re-analysis of the ^{36,38,40}Ar historical data.





PhD work Marie Deseyn (KU Leuven).

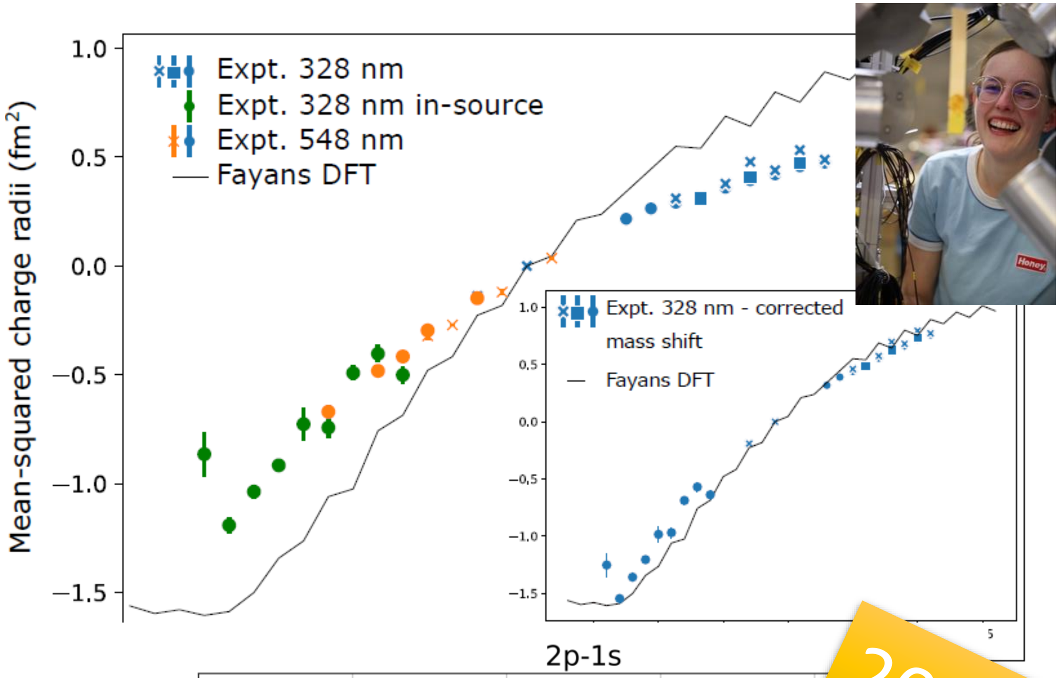
$_{47}$Ag

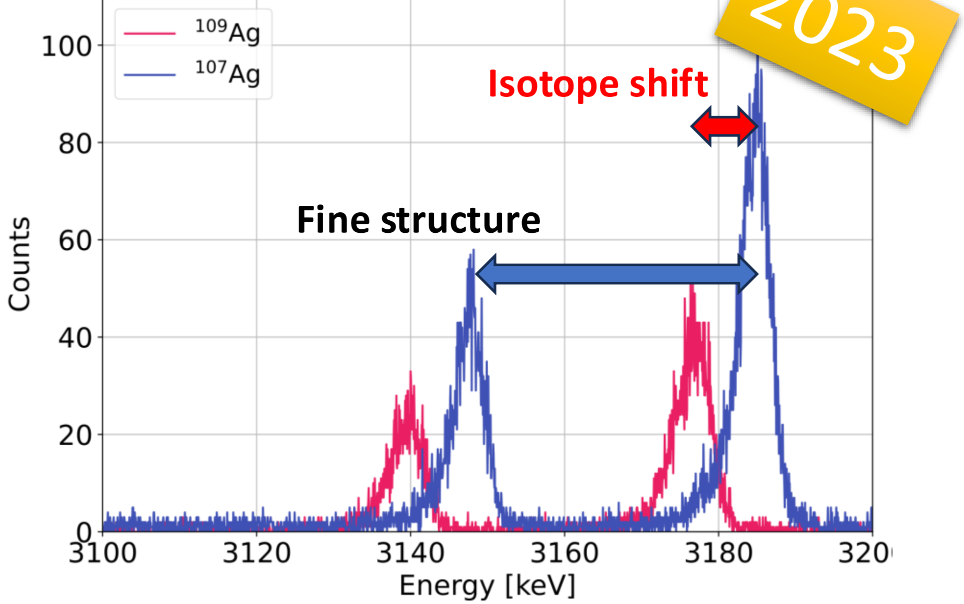
Extensive new laser spectroscopy data have recently been collected on Ag, from ^{95}Ag to ^{129}Ag, at Jyväskylä and ISOLDE.

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





PhD work Marie Deseyn (KU Leuven).
Ag laser spectroscopy data courtesy B. van den Borne & R.P. de Groote.

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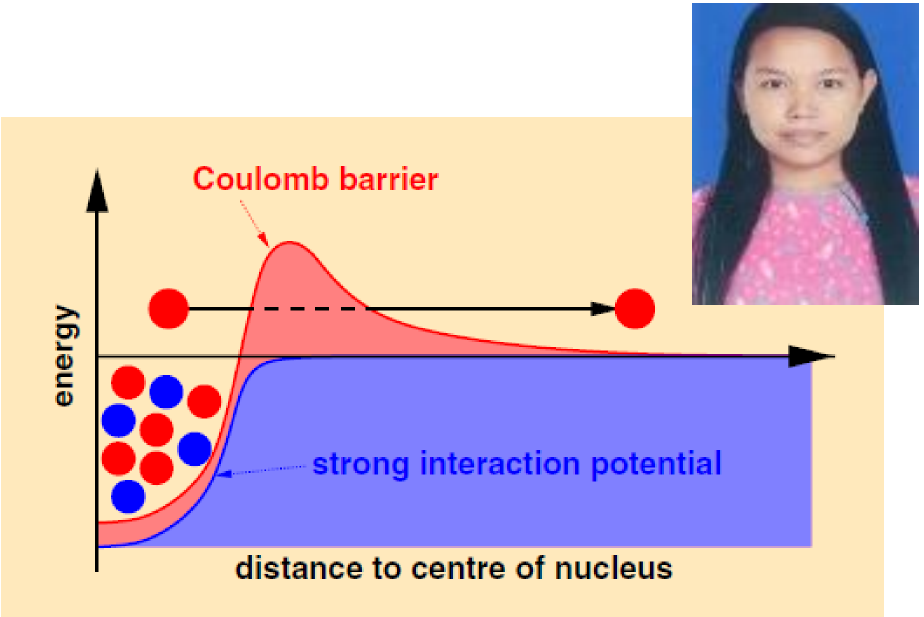
$_{71}Lu$



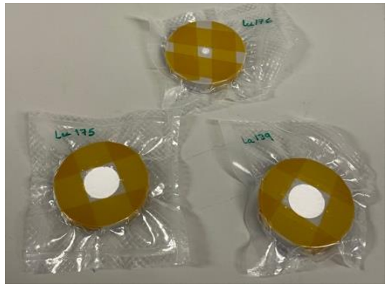
Across the rare earth elements, there is a big effort to reach out to proton emitters with laser spectroscopy: $_{57}La$, $_{65}Tb$, $_{67}Ho$, $_{69}Tm$, $_{71}Lu$ all seem within reach of the upcoming facilities (FRIB, MARA, S3).

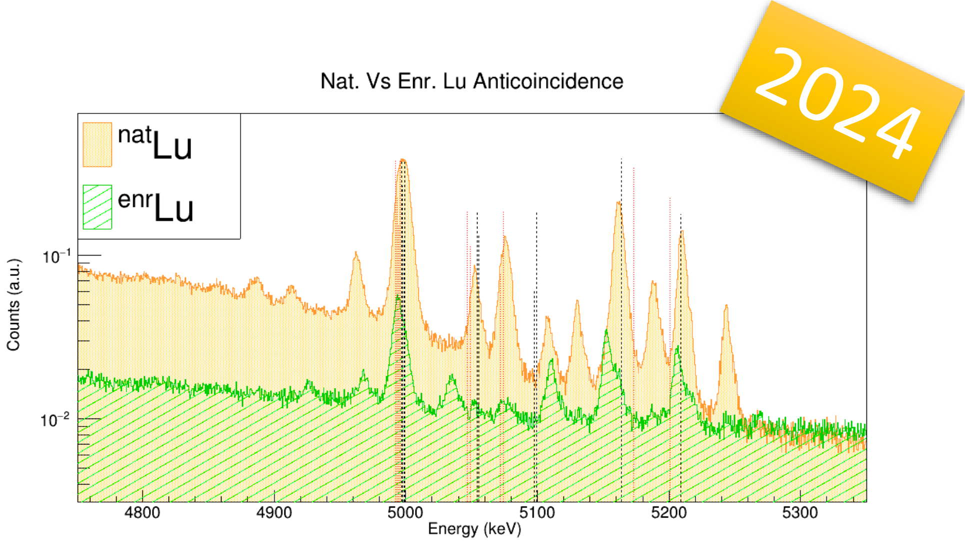
The question being: 'where' is the proton? Is it still confined? Already spread beyond the nucleus?

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

Amazing data from 2024!

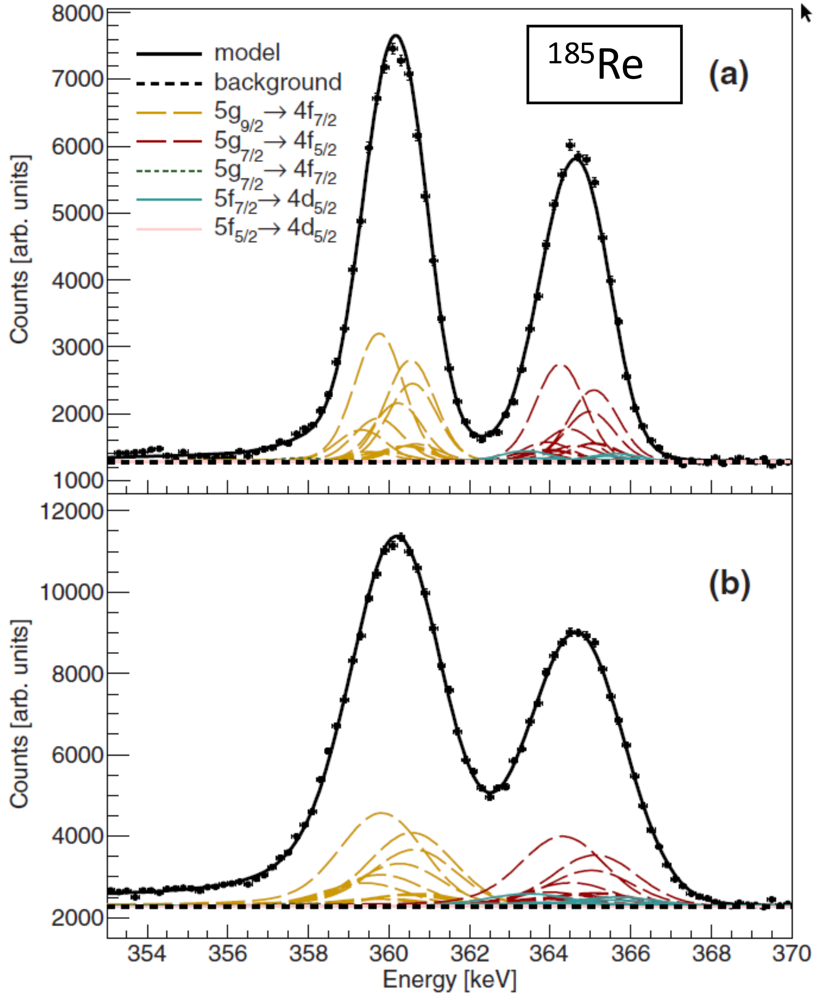
- ^{nat}Lu (97.4% ^{175}Lu vs 2.6% ^{176}Lu)
- ^{enr}Lu (25% ^{175}Lu vs 75% ^{176}Lu)

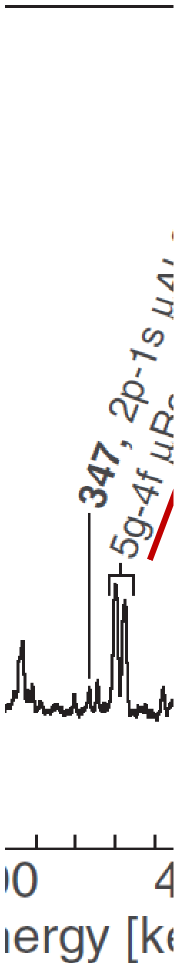


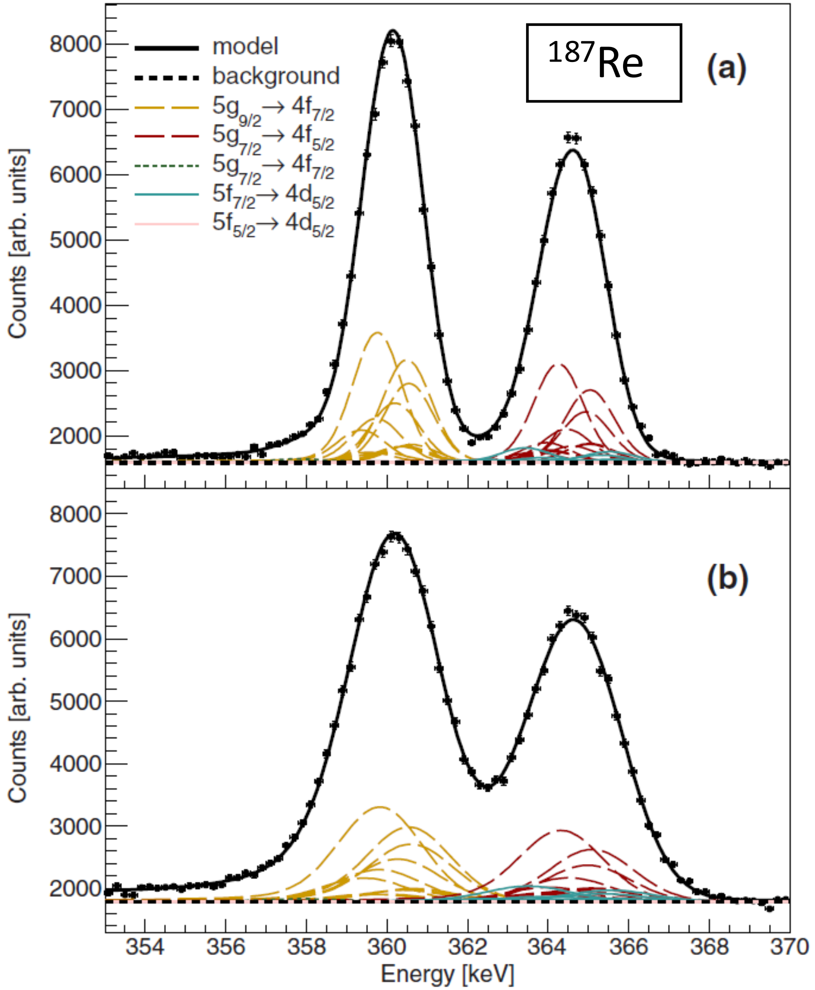


PhD work War War Myint Myat Phyo (KU Leuven).
*B. Blank & M Płoszajczak, Two-proton radioactivity, Report on Progress in Physics **71** (2008) 046301.*

Quadrupole moment of ^{185,187}Re







:

test on macroscopic

les of ^{185,187}Re

Those two peaks contain 76 different components fitted simultaneously!

A. Antognini et al, Measurement of the quadrupole moment of ^{185}Re and ^{187}Re from the hyperfine structure of muonic X rays, Physical Review C ***101*** *(2020) 054313.*

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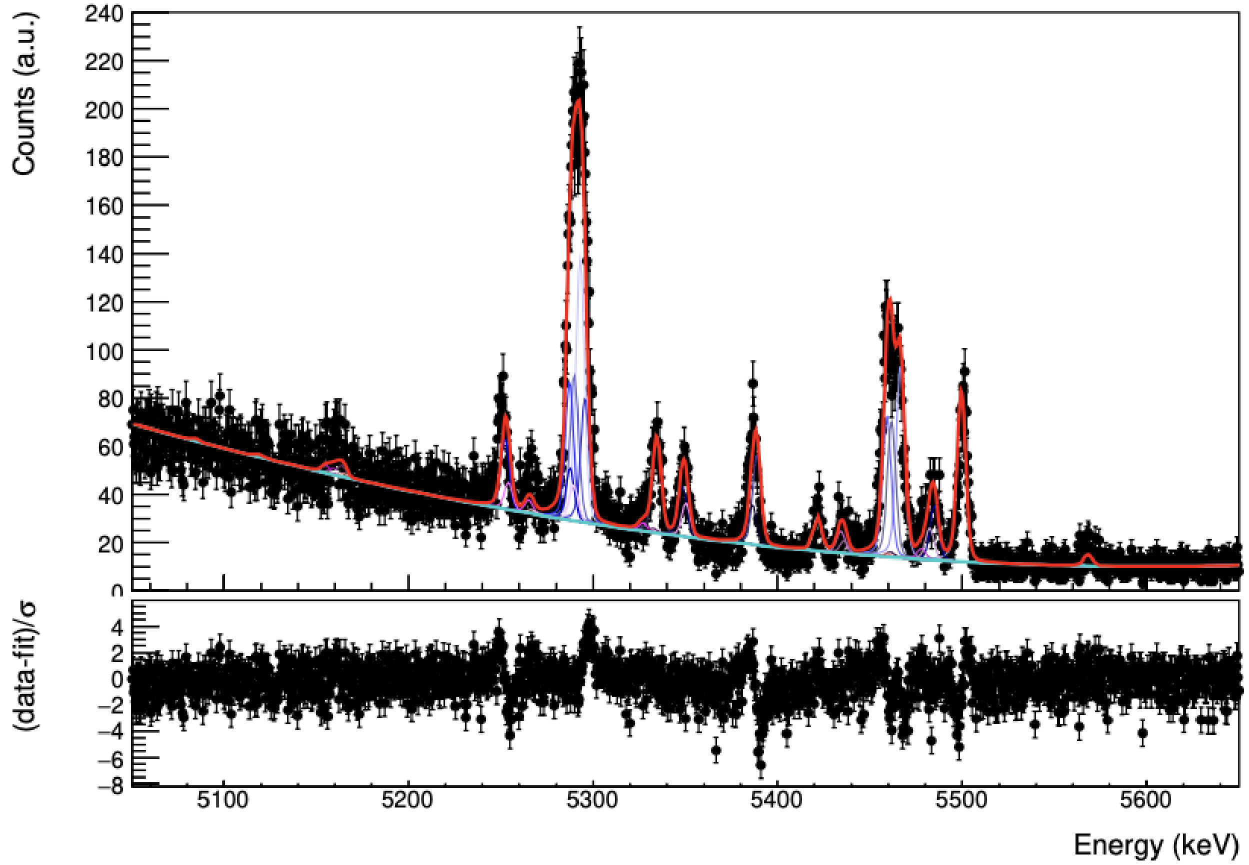
Absolute charge radius of ^{185,187}Re



(b) ^{187}Re

2016:

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

Today:

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

 PhD thesis Stella Vogiatzi, ETH Zurich (2023).

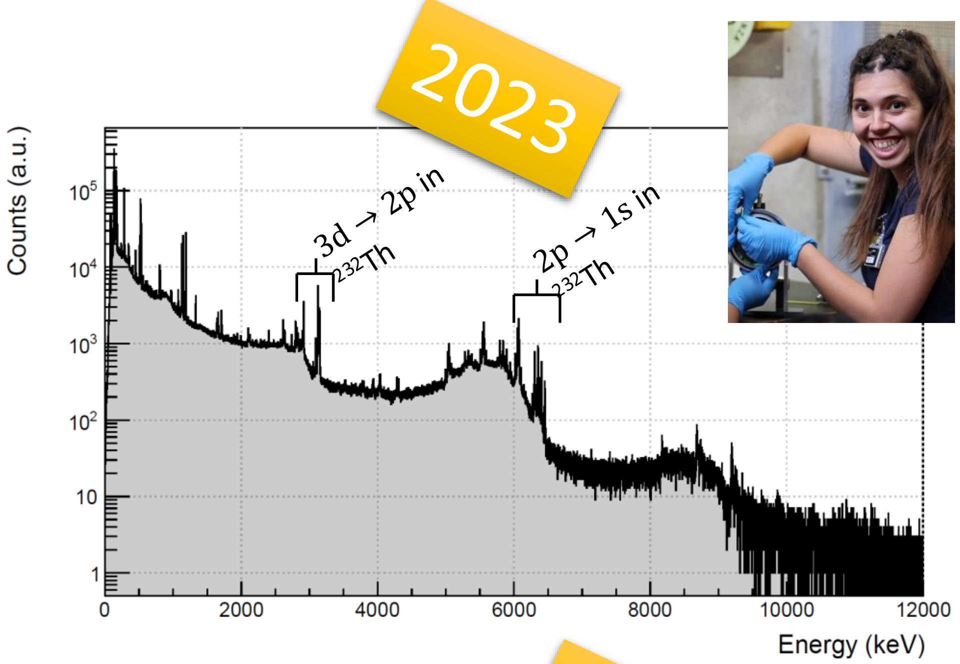
Beyond Pb

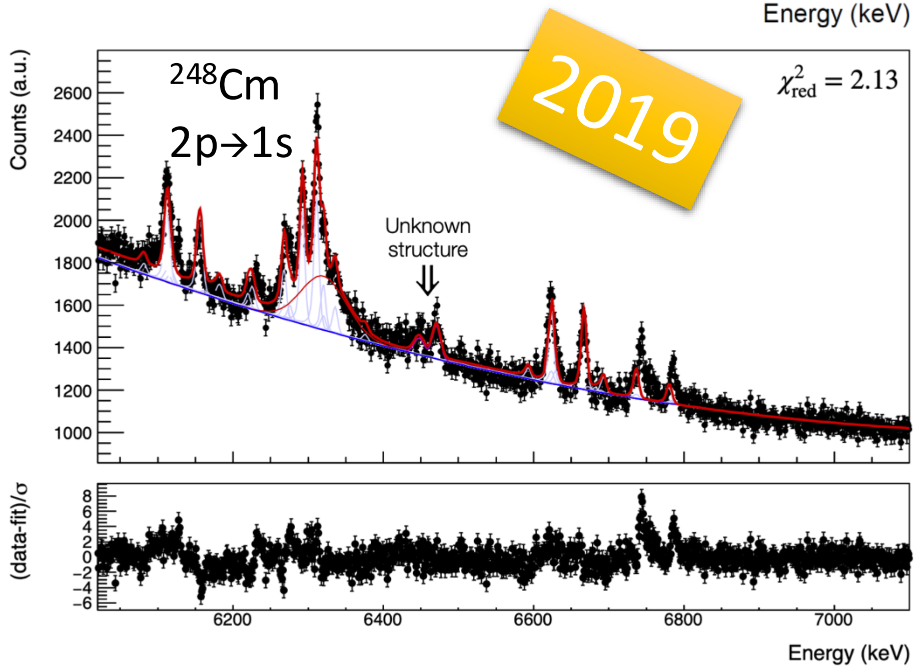
While getting a triplet measured beyond Pb is as good as impossible, having a single absolute charge radius for any isotopic chain would already be a huge accomplishment.

^{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}Th and ^{235}U.

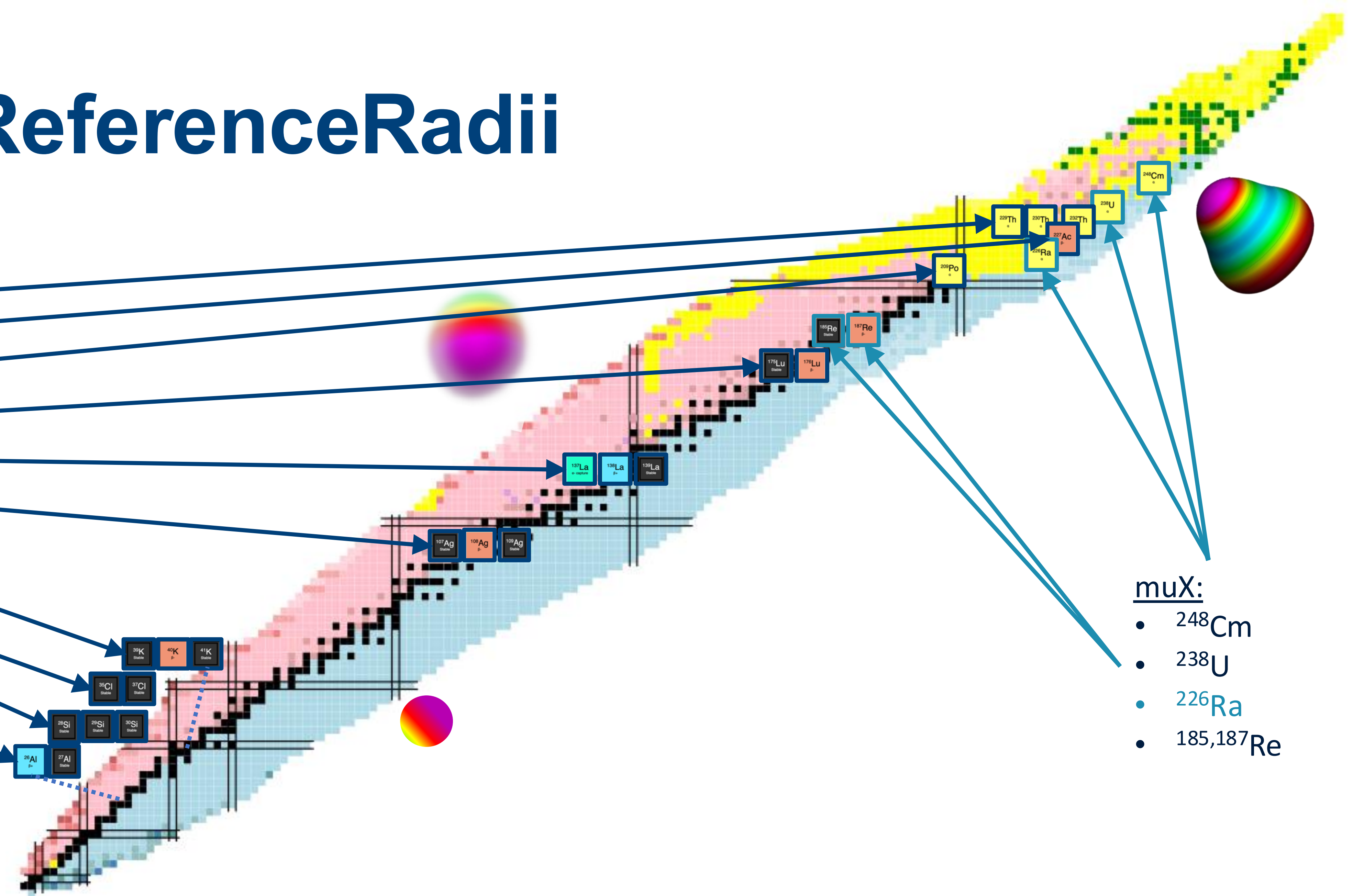
Beautiful spectra of ^{248}Cm but challenging extraction of the charge radius from the dynamic hyperfine spectra.





PhD thesis Stella Vogiatzi, ETH Zurich (2023).
PhD work Anastiasia Doinaki (PSI & ETH Zurich).

muX & ReferenceRadii



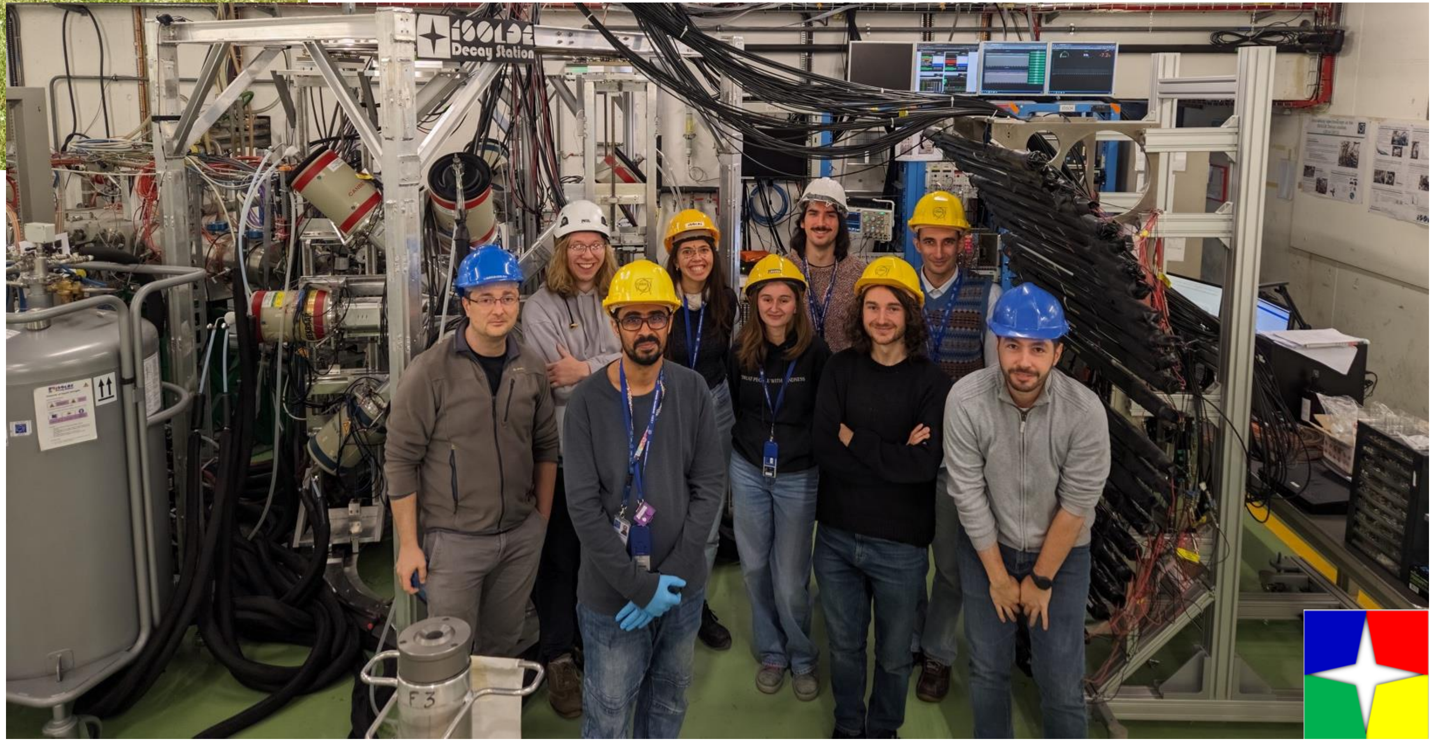
ReferenceRadii:

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

muX:

- ^{248}Cm
- ^{238}U
- ^{226}Ra
- ^{185,187}Re

- 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 $_{13}Al$ to $_{96}Cm$.
- Challenges include target production, background suppression, data analysis, atomic & nuclear corrections, …
- Our first results are out (quadrupole moments of $^{185,187}Re$, absolute radii of $^{35,37}Cl$) and more is coming!
- We are bringing the IDS detector array to PSI in 2026 for an exciting campaign!



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Kennis kent geen einde

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Knowledge knows no end

*This project has received support from KU Leuven BOF, grant C14/22/104,
from the FWO, grants G0G3121N & I001323N and fellowship 11P6V24N, and
from the European Commission, ERC Consolidator Grant 101088504 (NSHAPE) and MSCA
Innovative Training Network 861198 (LISA).*