Towards precision determination of the charge radii of light muonic ions

Ben Ohayon

Technion IIT

For the QUARTET collaboration

FFK, Vienna, 26 May 2023

Who we are:

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Experimenters in exotic atoms

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Ab. Initio. Nuclear theory

QED in exotic atoms

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Quantum Sensors group

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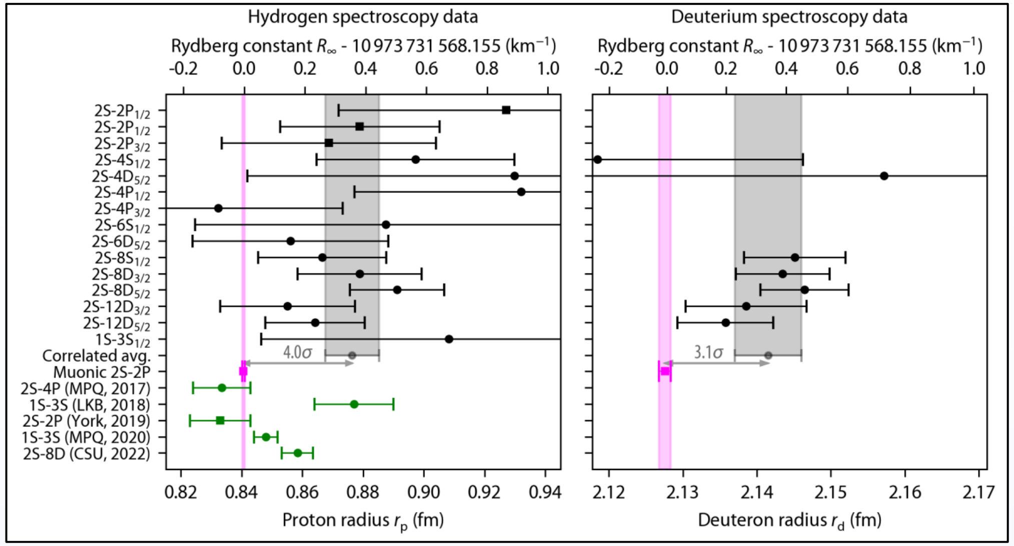
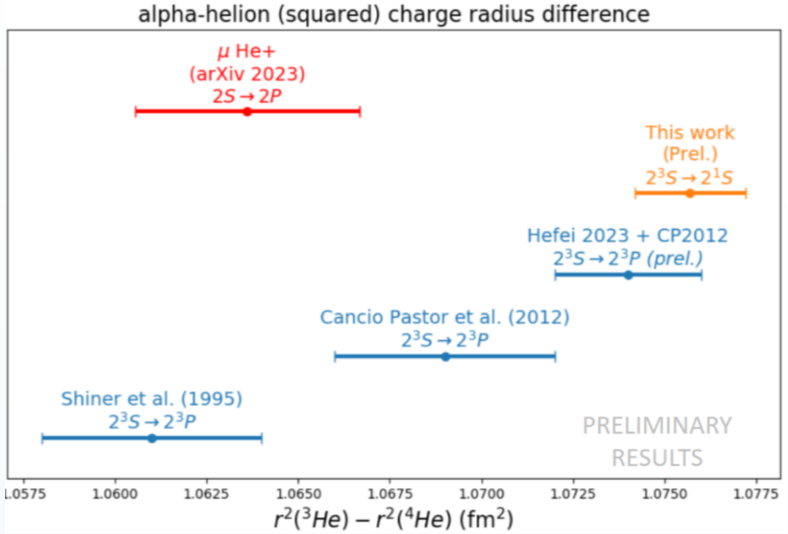
Radii and FFK

Hydrogenic, Z = 1



Vitaly Wirthl

Helium, Z = 2



Yuri van der Werf

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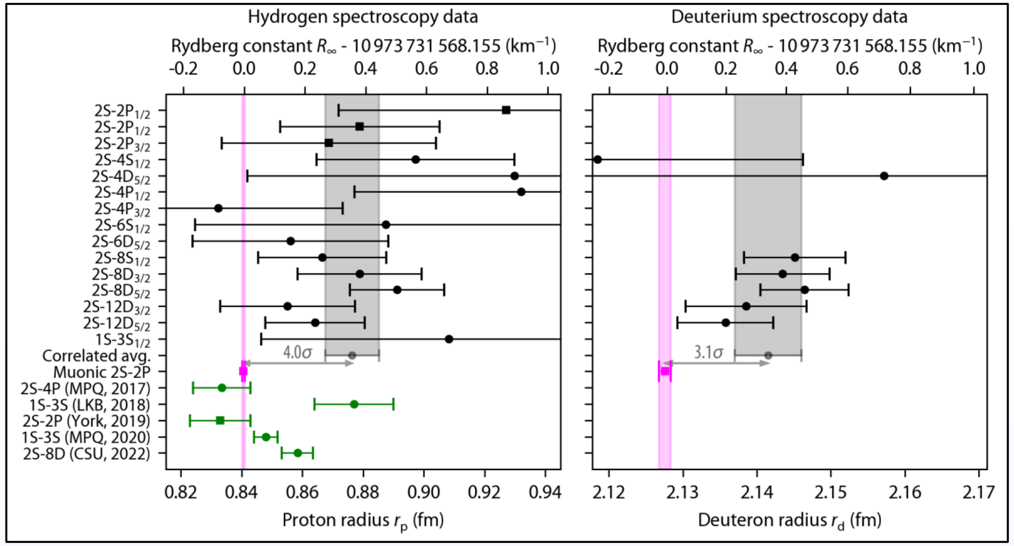

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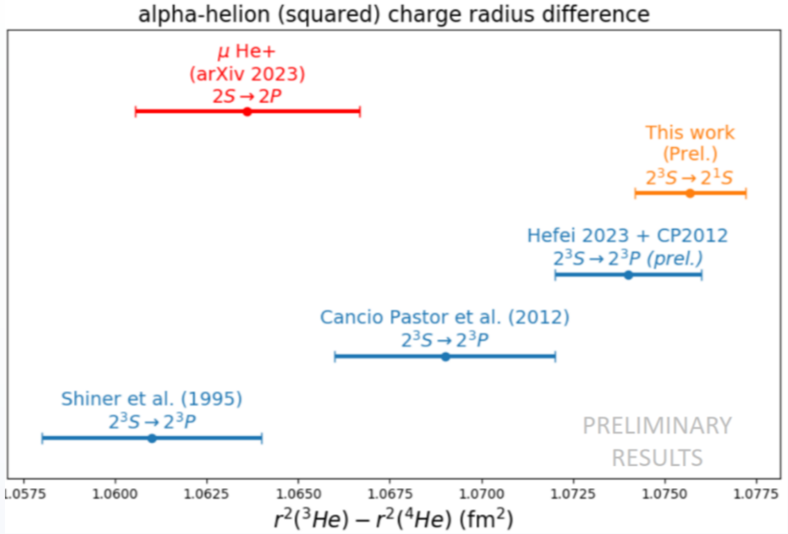

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Helium-like ions: Z = 3-7, ...

TABLE VI. The higher-order QED and finite nuclear size (FNS) contributions for the ground and the nonmixing $n = 2$ states. Units are $m\alpha^2(Z\alpha)^5$.

Z	$1/Z^0$	$1/Z^1$	$1/Z^{2+}$	FNS	Total
2^3S					
6	−7.967	2.041	−0.122	1.090	−4.958 (41)
8	−9.182	1.757	−0.078	1.075	−6.428 (34)
10	−10.246	1.565	−0.055	1.137	−7.601 (31)
14	−12.119	1.321	−0.033	0.963	−9.868 (18)
18	−13.831	1.179	−0.022	0.978	−11.696 (14)
20	−14.670	1.131	−0.019	0.943	−12.615 (13)
24	−16.380	1.064	−0.014	0.938	−14.391 (12)
28	−18.197	1.028	−0.011	0.943	−16.237 (12)
30	−19.170	1.019	−0.010	0.998	−17.163 (11)

Vojtech Patkos

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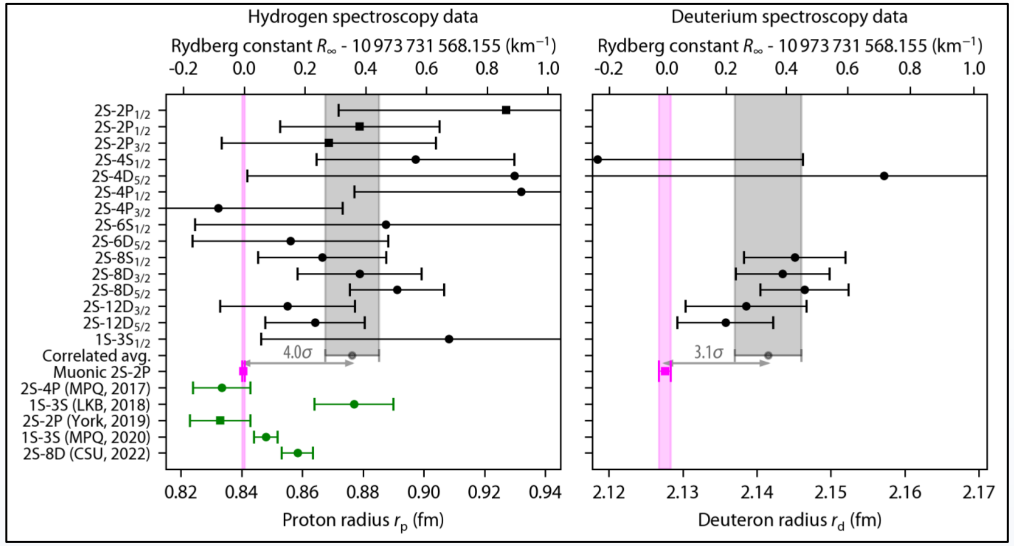

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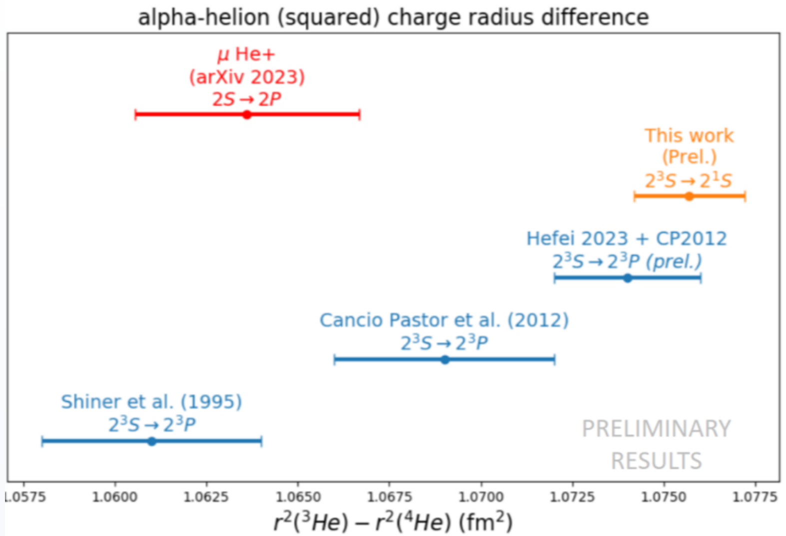

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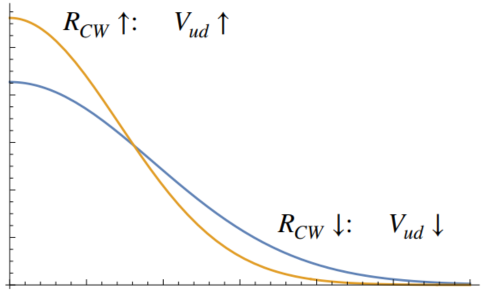
Beta Decay: Z = 4, … , 38

Charge radii + isospin symmetry —> nuclear recoil

Total decay rate $\sim ft|V_{ud}|^2 \sim |V_{ud}|^2 \int_0^{Q^2_{EC}} dQ^2 F_{CW}(Q^2)$



Misha Gorshteyn

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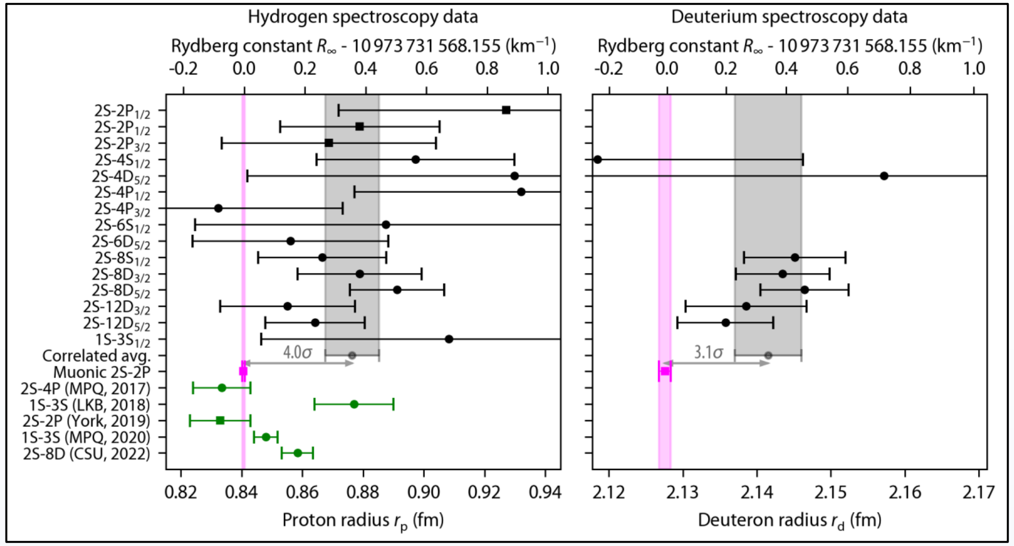

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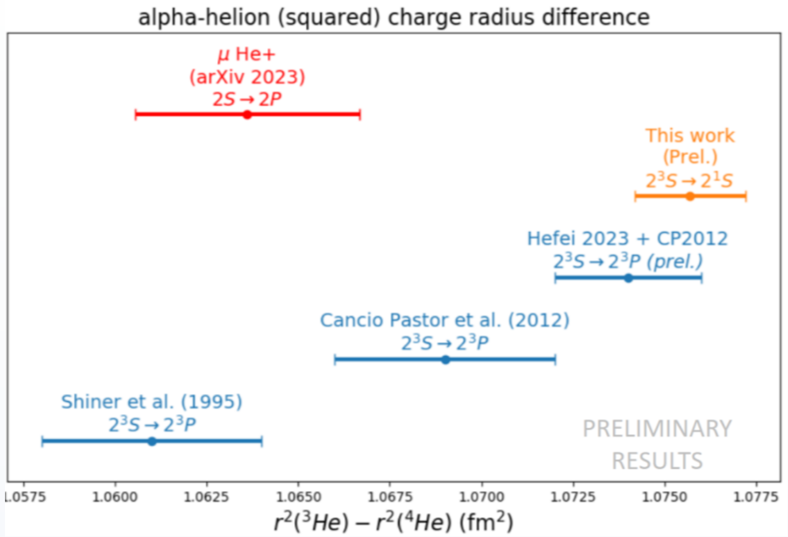

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+ g_e , HCI , …

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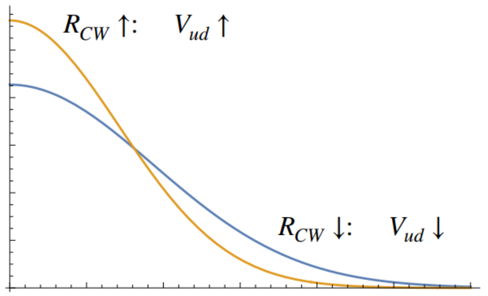

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The radius gap

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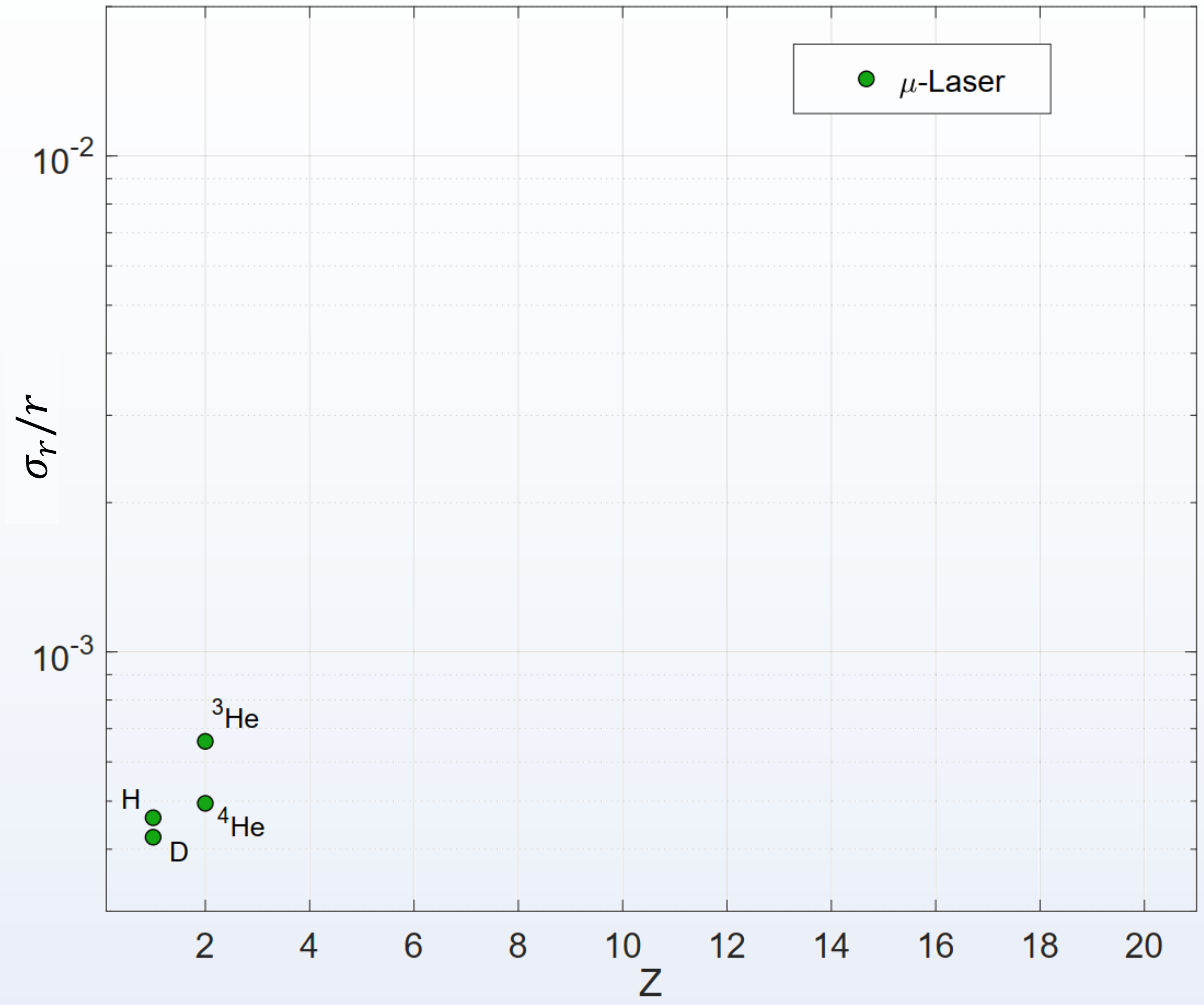
  Laser spectroscopy of muonic atoms, limited by nuclear theory



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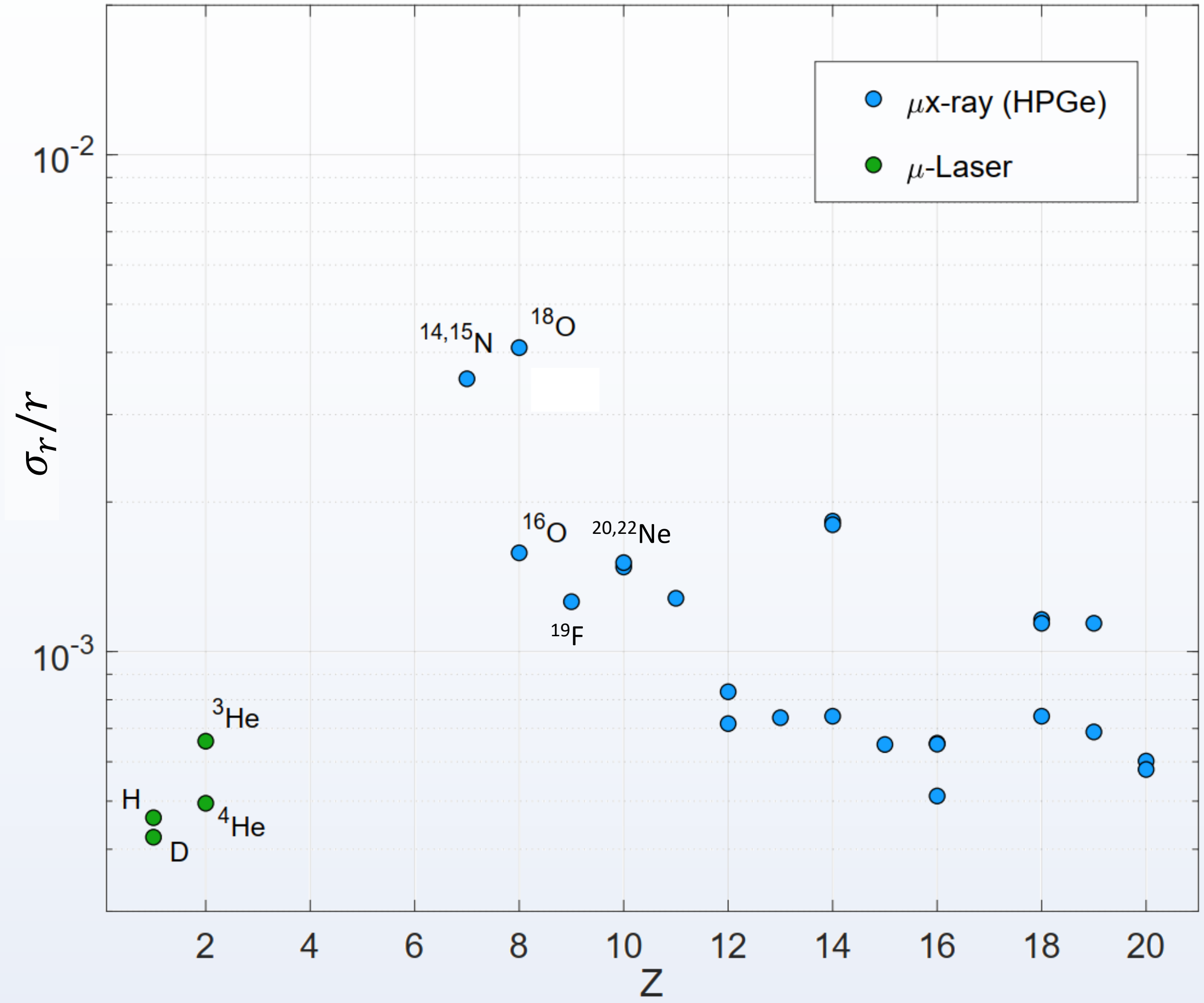

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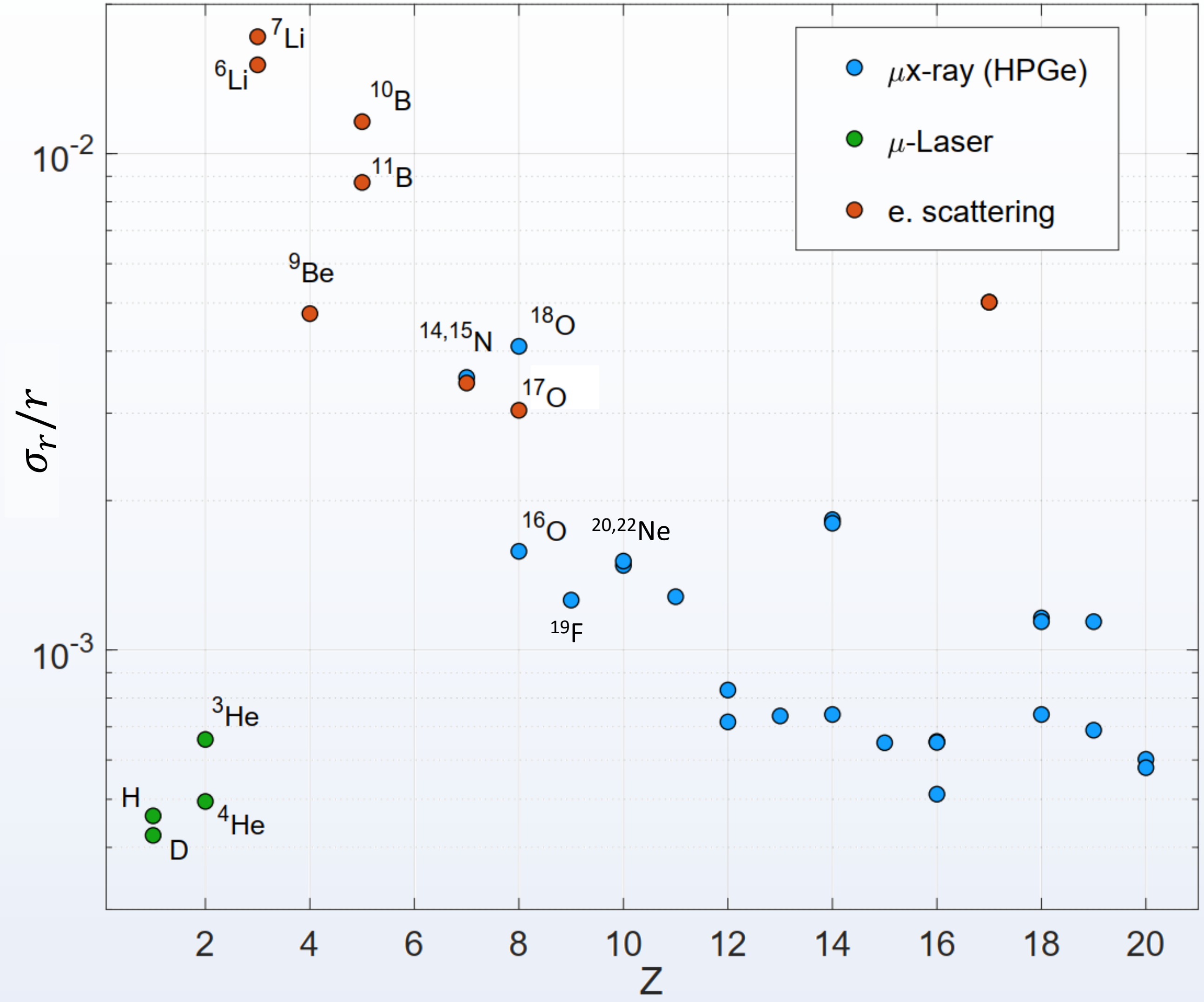

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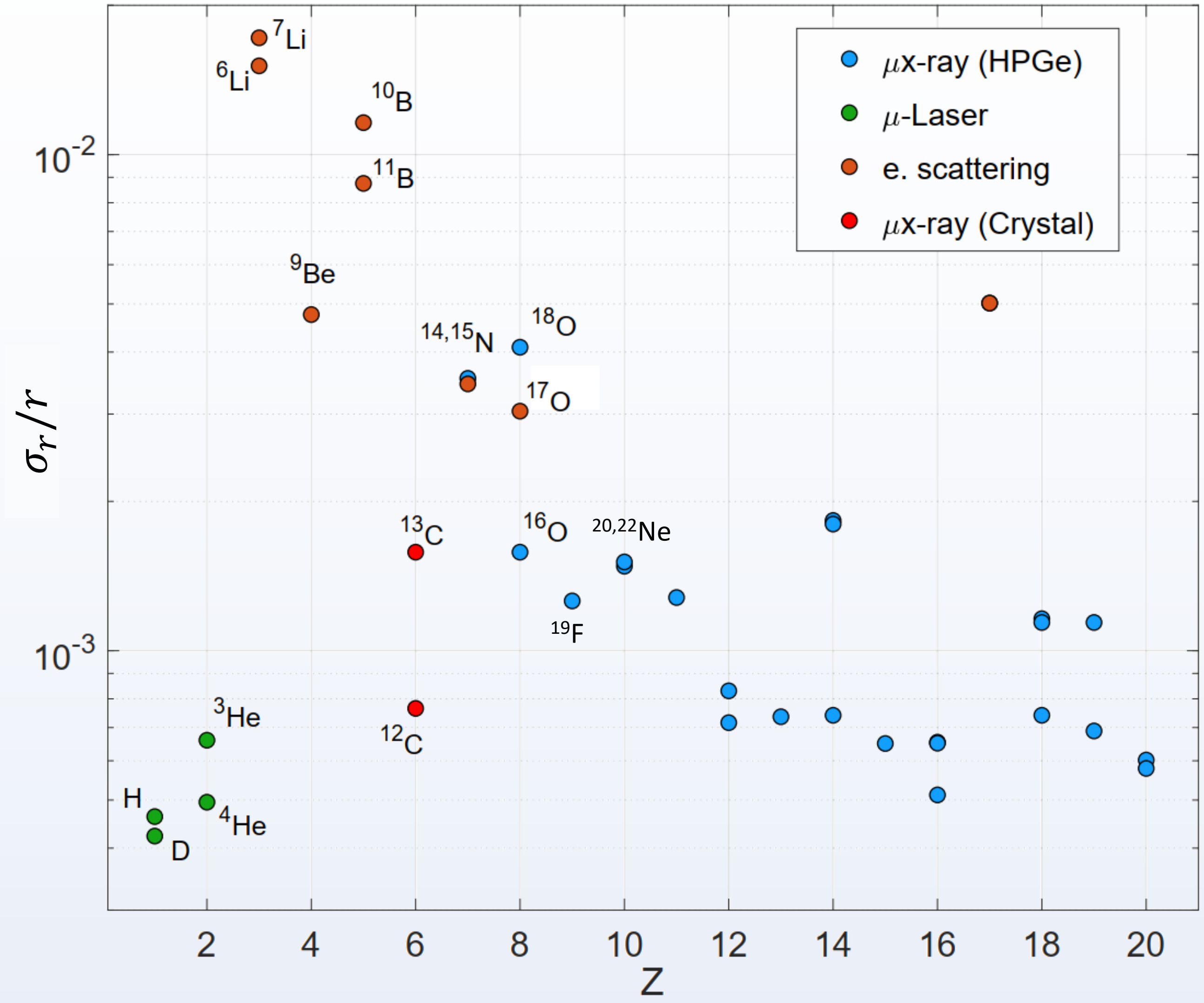

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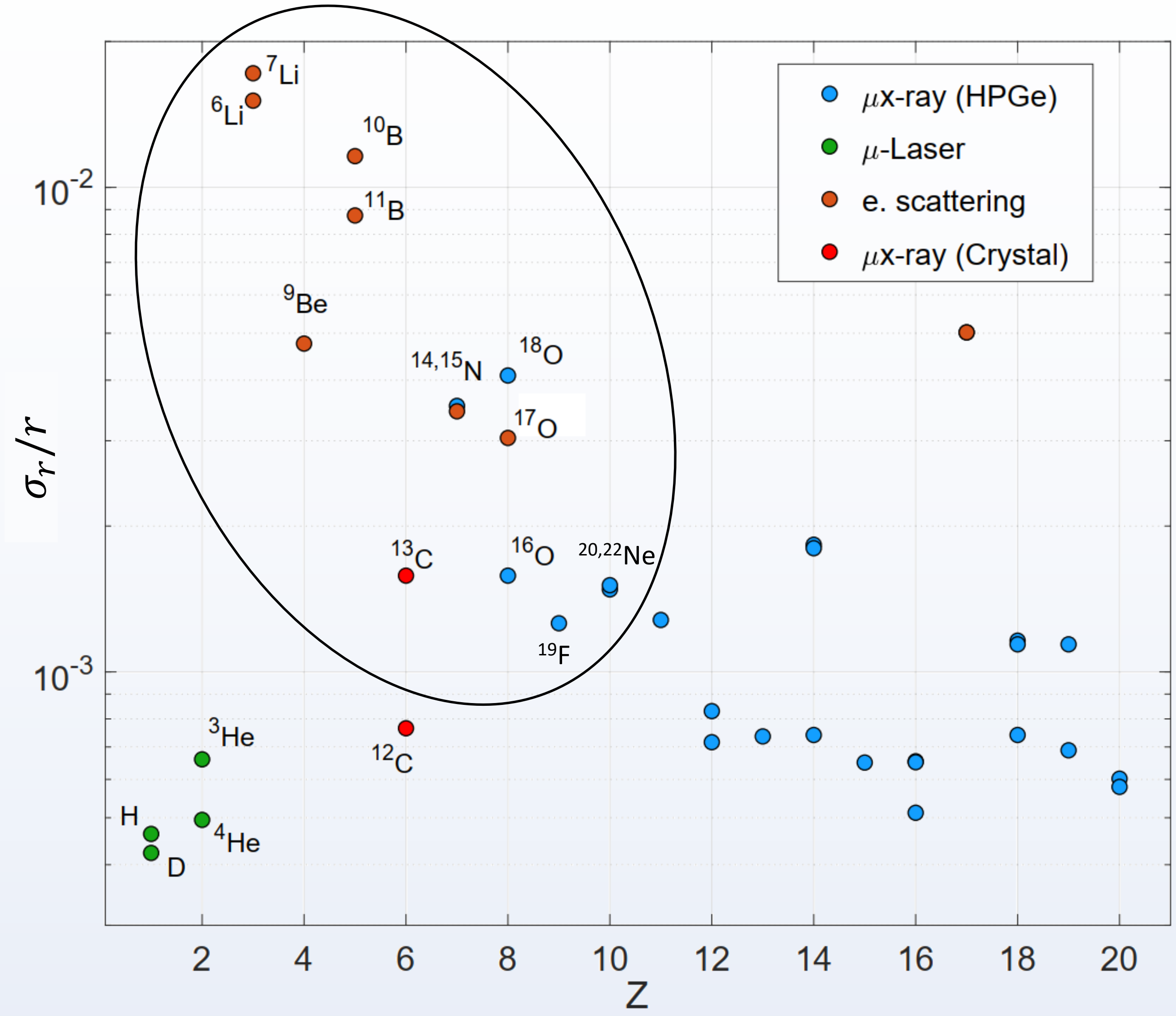

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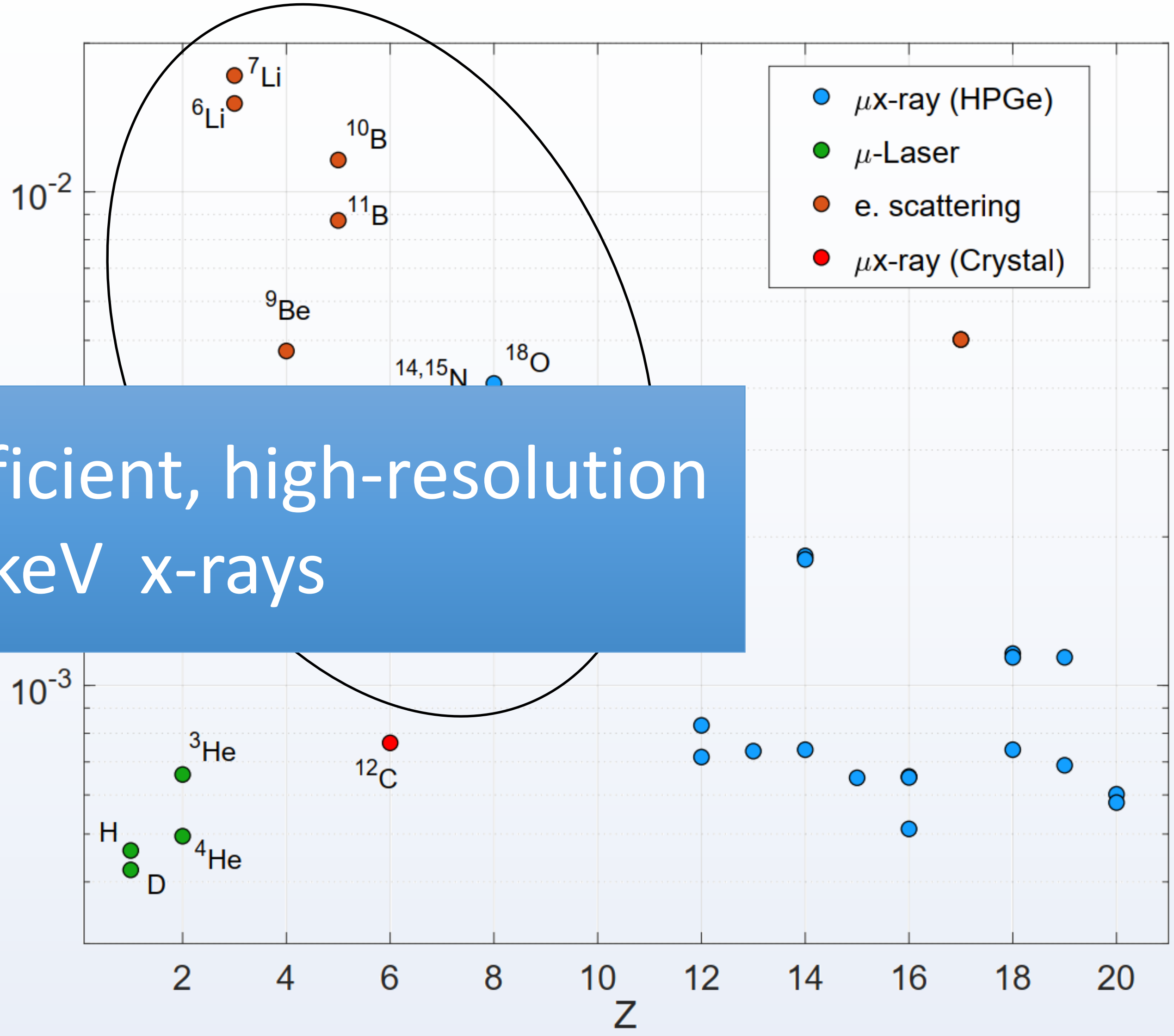
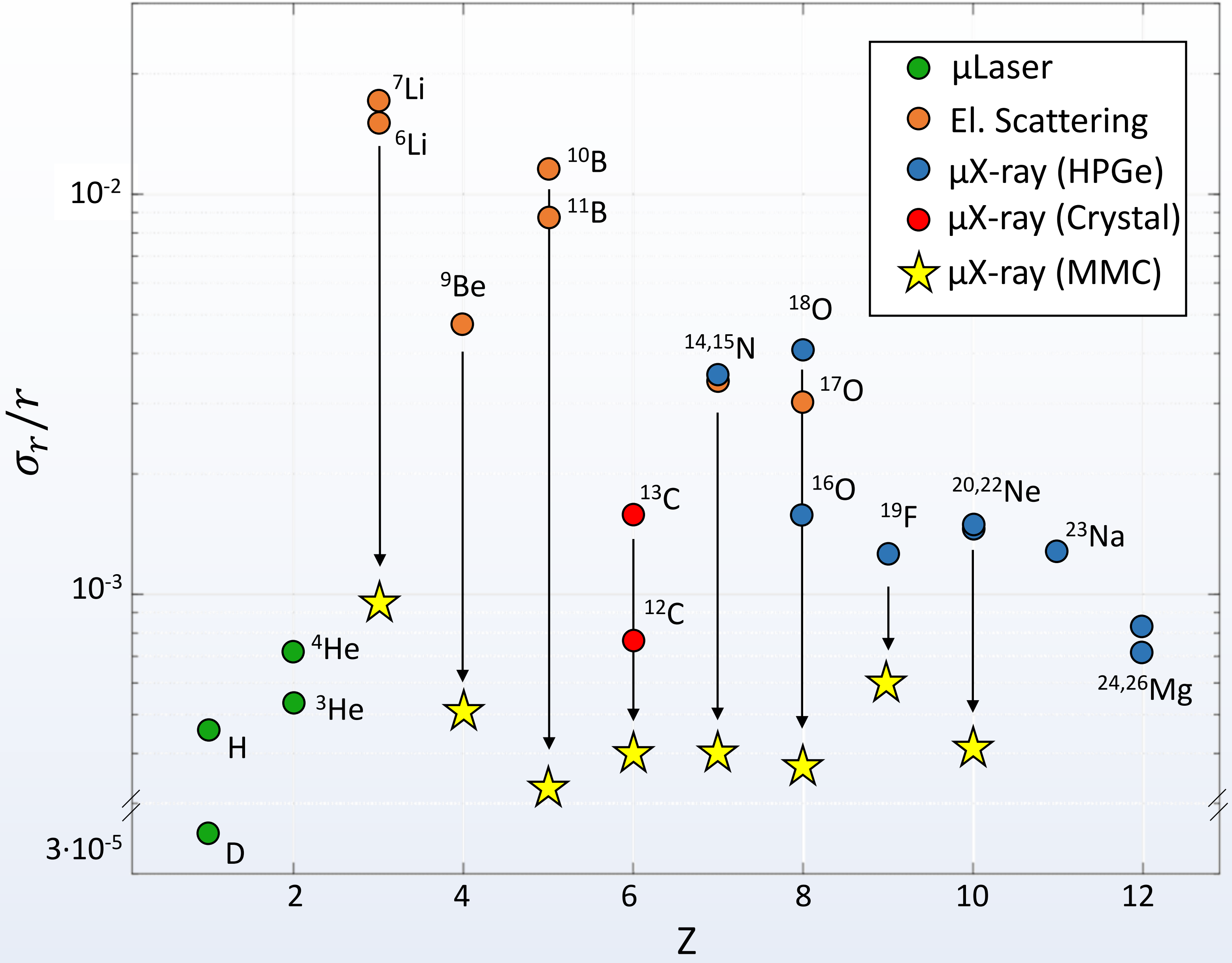


Need broadband, efficient, high-resolution detector for 10-200 keV x-rays

What we will do:

- Significantly improve nuclear charge radii of light stable isotopes by measuring $^nP - 1S$ x-rays in muonic atoms



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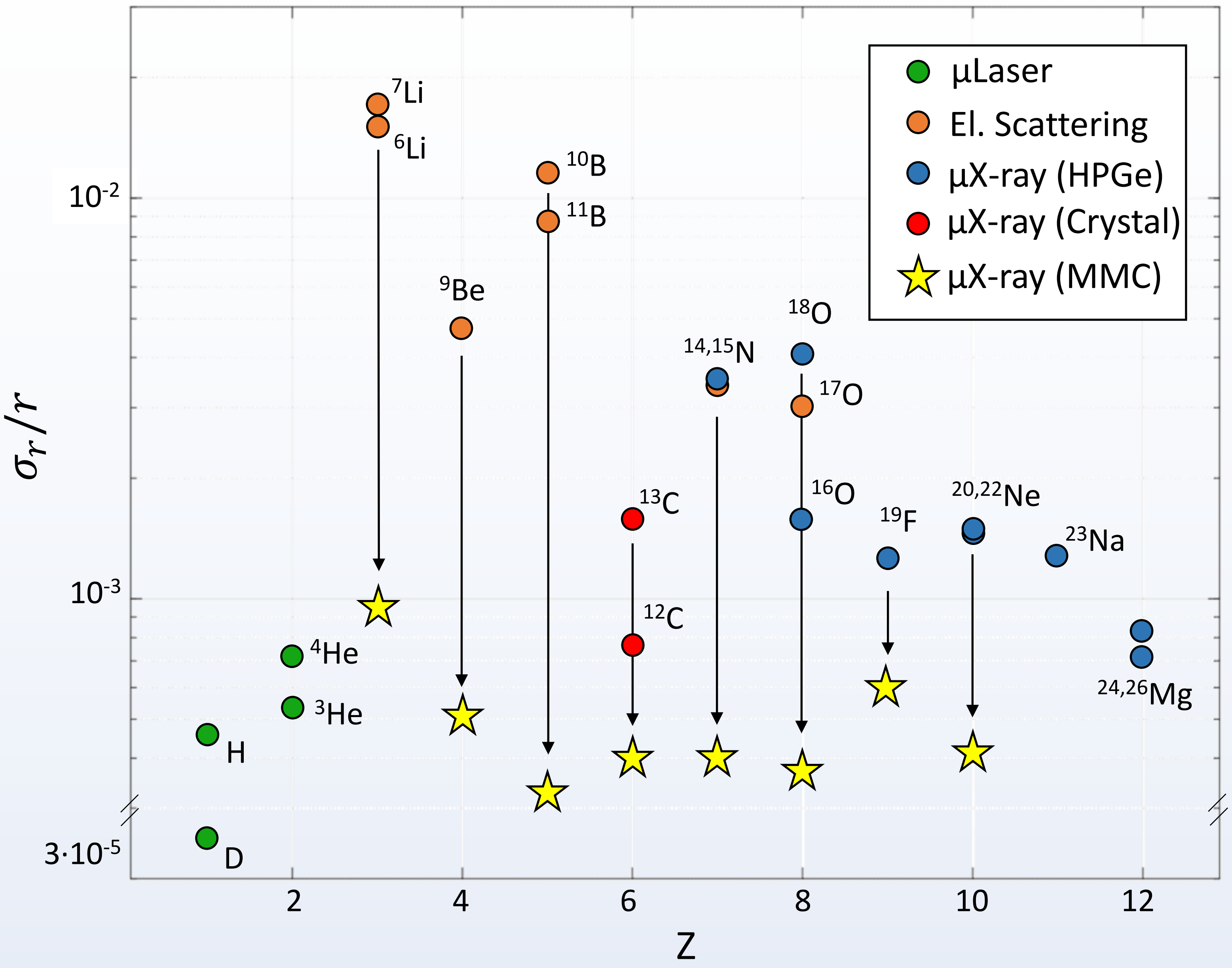

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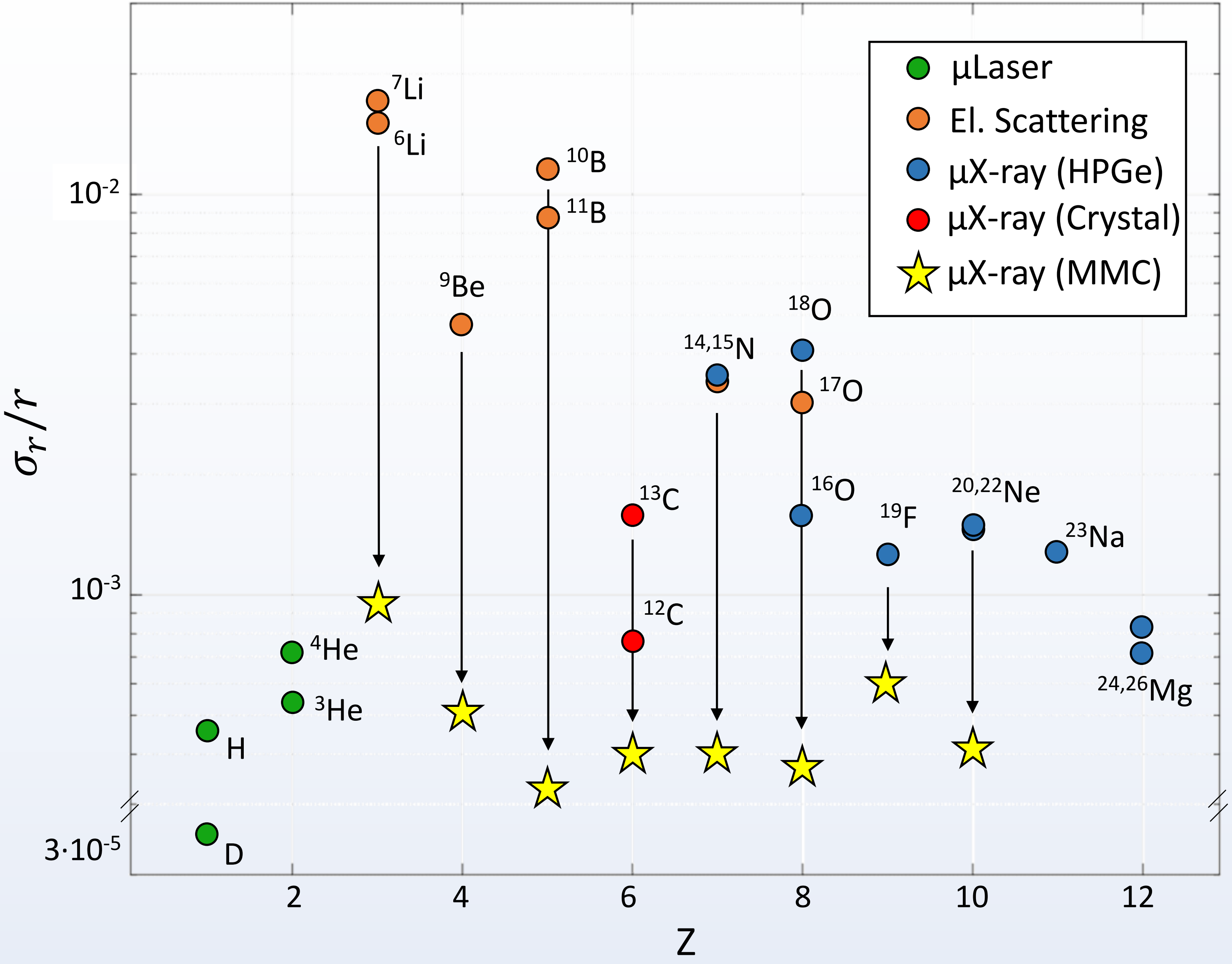
- Commission a dedicated x-ray detector array based on Metallic Magnetic Microcalorimeter (MMC) at the PiE1 beamline.
- Enable the next generation of laser spectroscopy of light muonic atoms (e.g. measure ^{6,7}Li Zemach radius)



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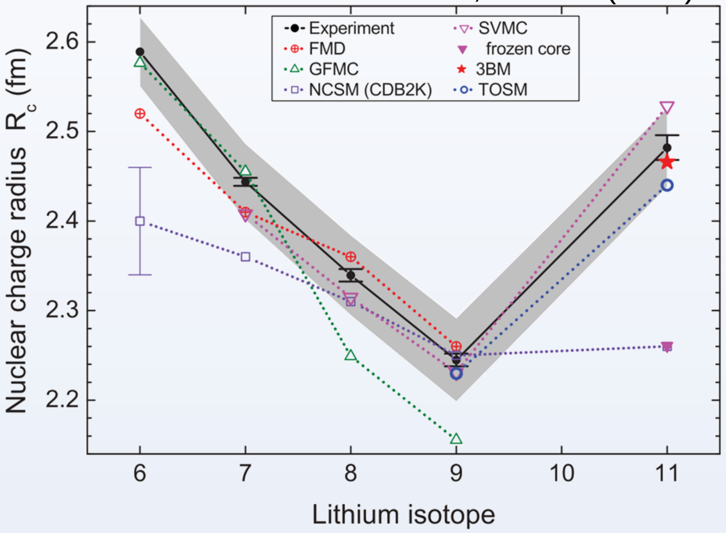
$^{6\text{-}9,11}$Li:

PRC 84, 024307 (2011)



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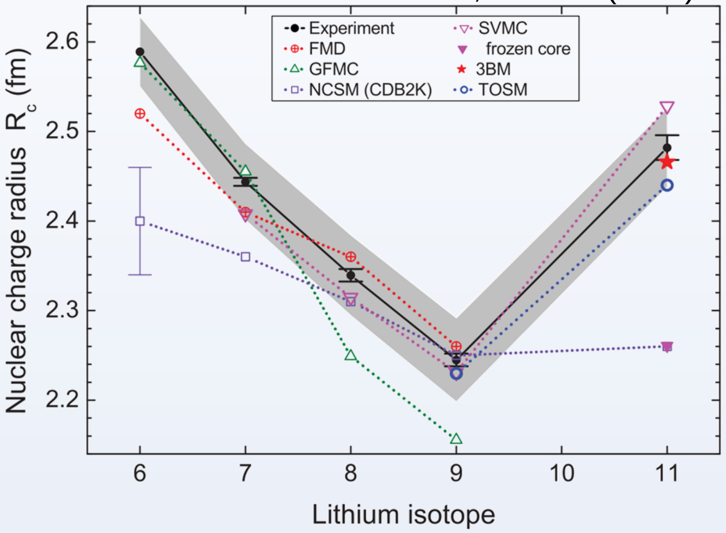

$^{7-12}$Be:

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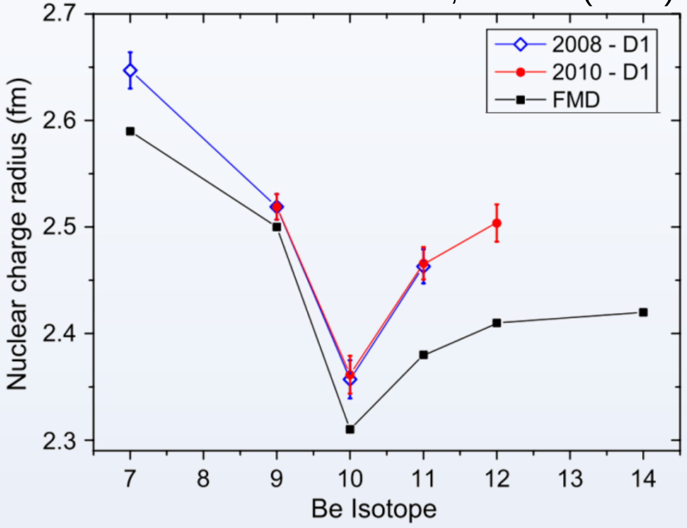

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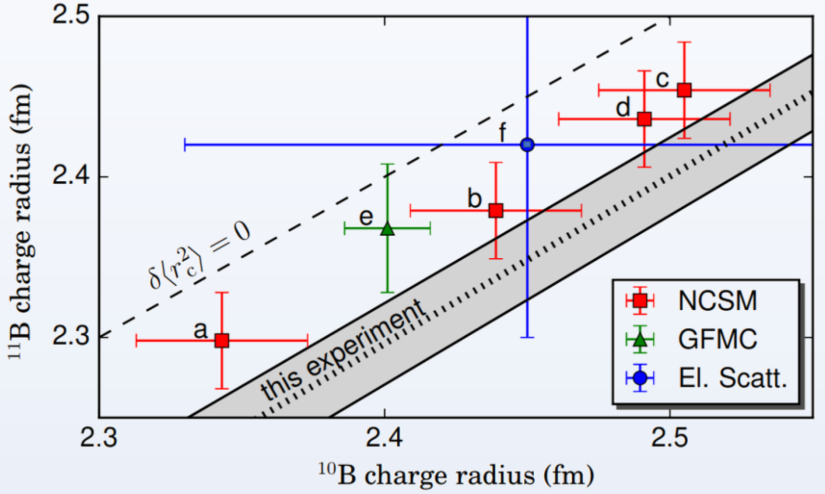

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- Systematically improve χEFT parameters through comparisons with measurements
- Needed fractional accuracy $\sim 5 \times 10^{-3}$ for one stable isotope of Li, Be, and B

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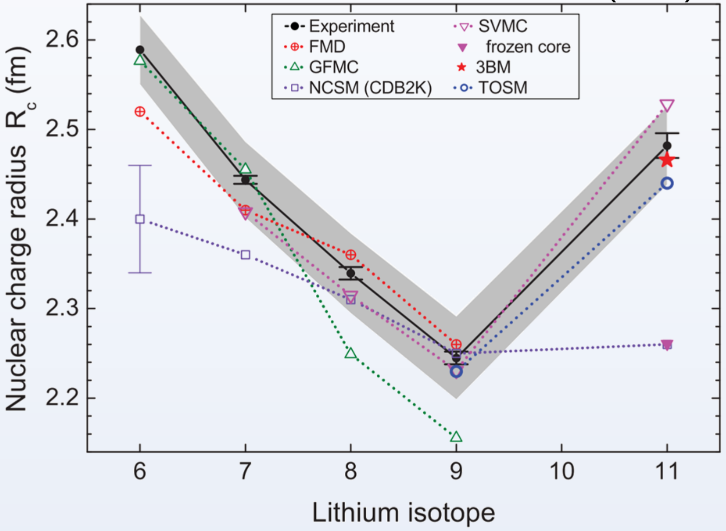

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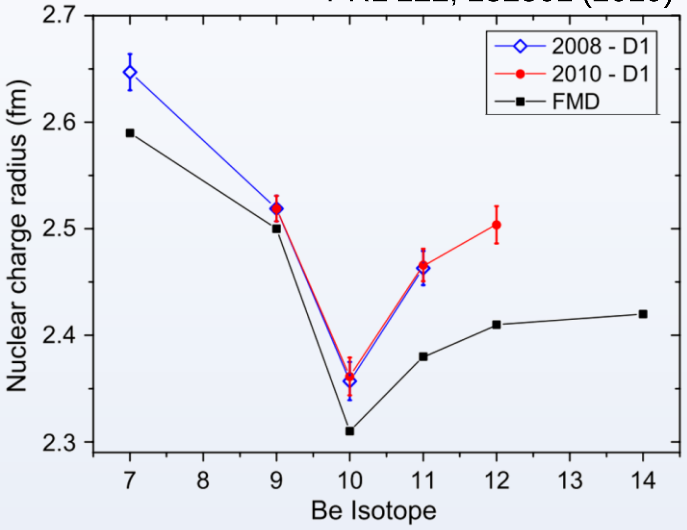

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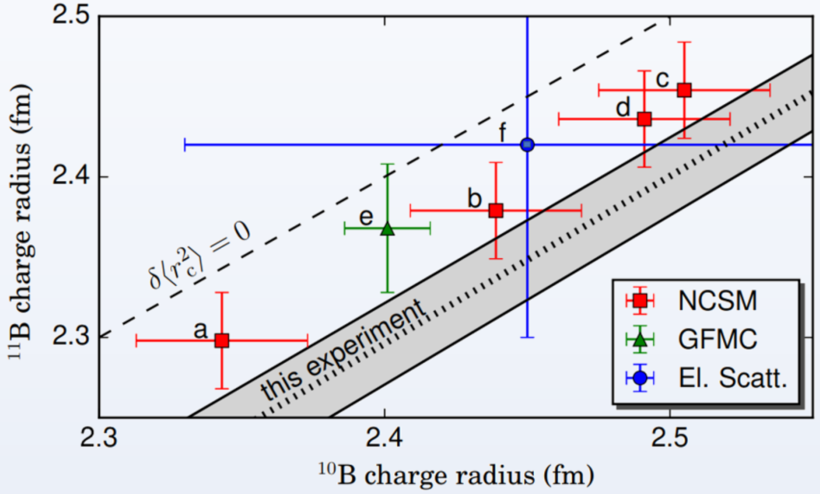

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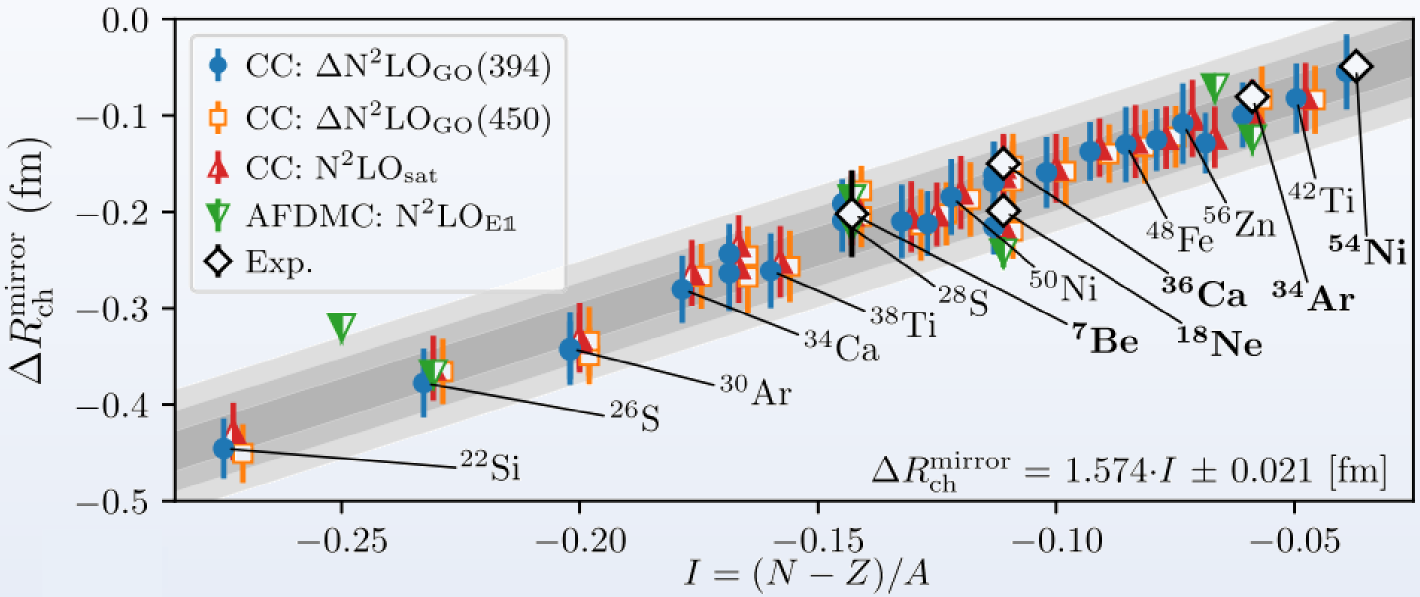
S. J. Novario, *et. al.,* PRL 130, 032501 (2023)



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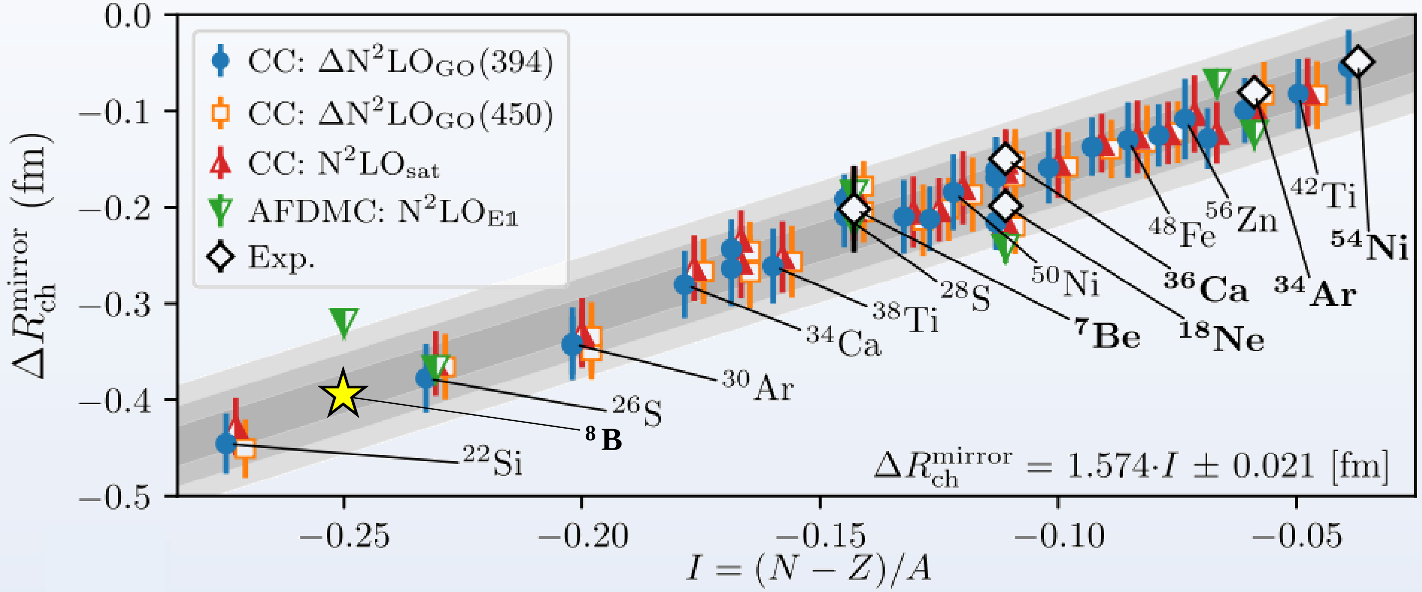
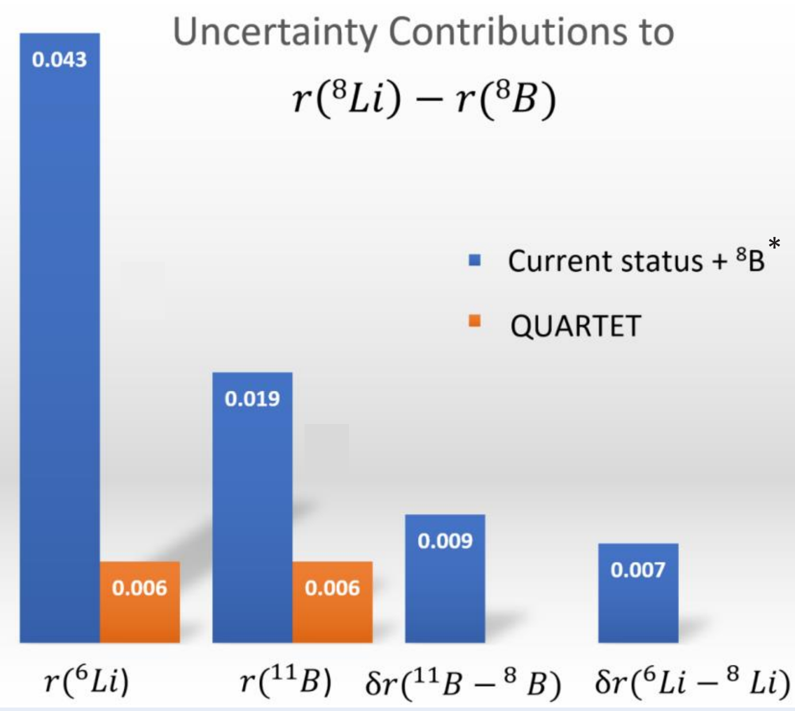


☆ Golden case $I = 0.25$:

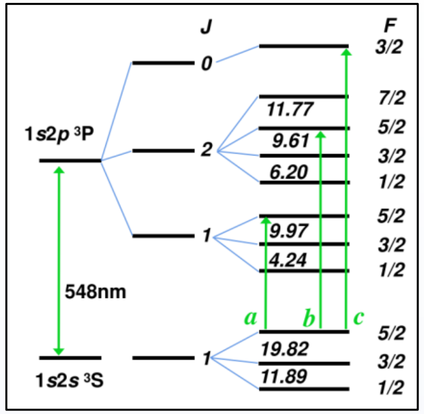


*Priv. Com. With W. Nörtershäuser

Physics case 3: QED with Helium like ions

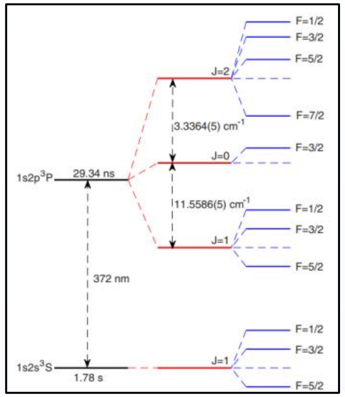
1. Next generation experiments in precision laser spectroscopy under way:

$^{7}Li^{+}$



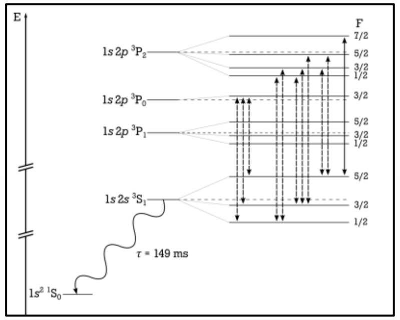
PHYSICAL REVIEW A **102**, 030801(R) (2020)

$^{9}Be^{2+}$



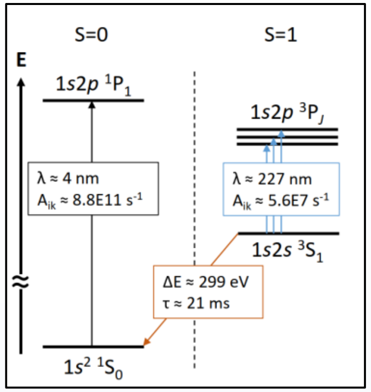
PHYSICAL REVIEW A **107**, L010802 (2023)

$^{11}B^{3+}$



Atoms **2023**, *11*, 11

$^{12}C^{4+}$



P. Ingram Thesis 2023

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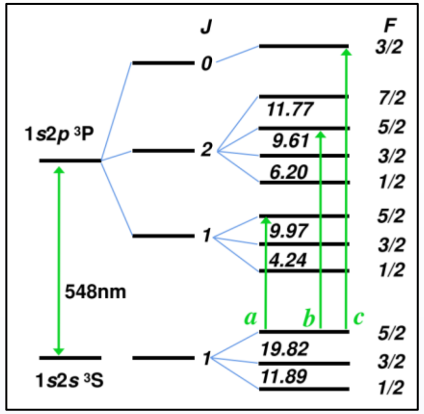

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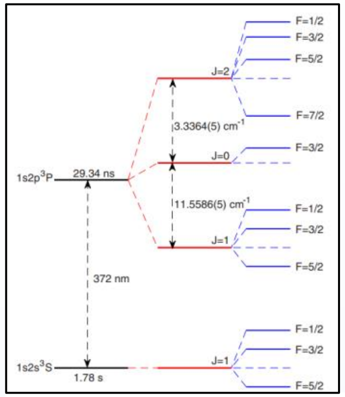

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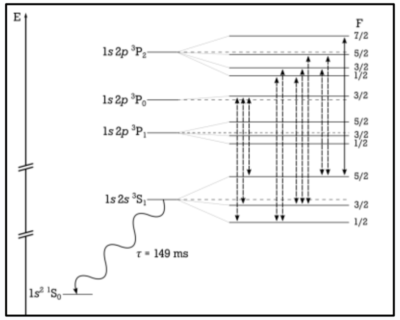
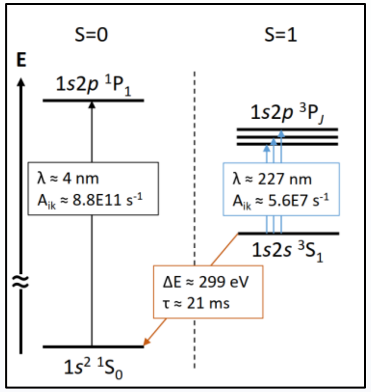


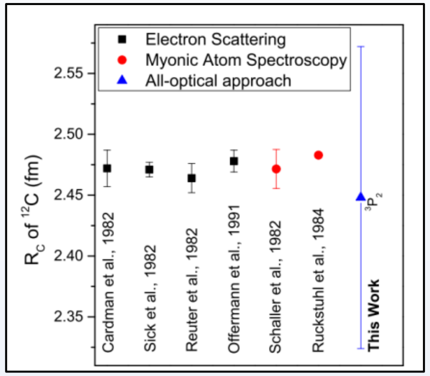
Atoms **2023**, *11*, 11

$^{12}C^{4+}$



P. Ingram Thesis 2023

2. Optical radii from $^{12}C^{4+}$ limited by QED calc / has determined the high order NRQED correction



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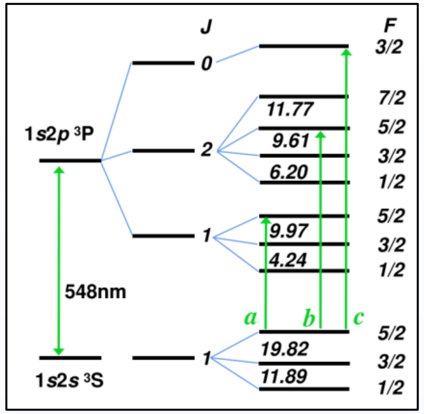
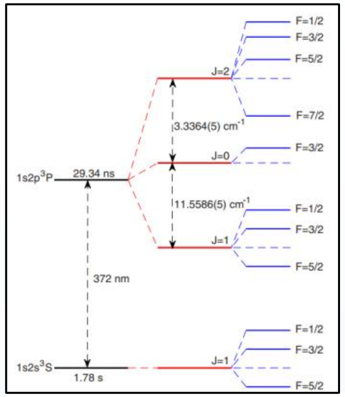
Physics case 3: QED with Helium like ions

$^{7}Li^{+}$



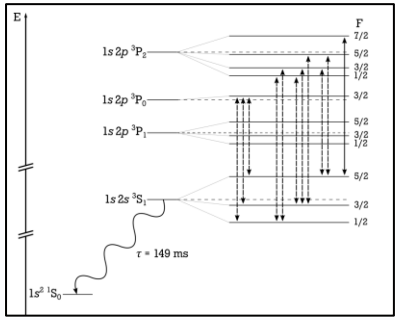
PHYSICAL REVIEW A **102**, 030801(R) (2020)

$^{9}Be^{2+}$



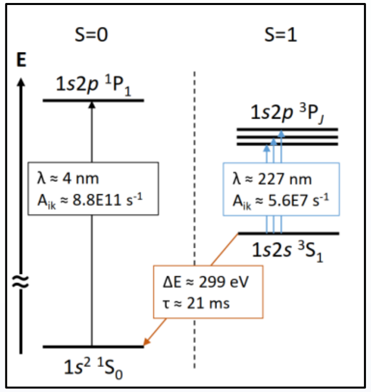
PHYSICAL REVIEW A **107**, L010802 (2023)

$^{11}B^{3+}$



Atoms **2023**, *11*, 11

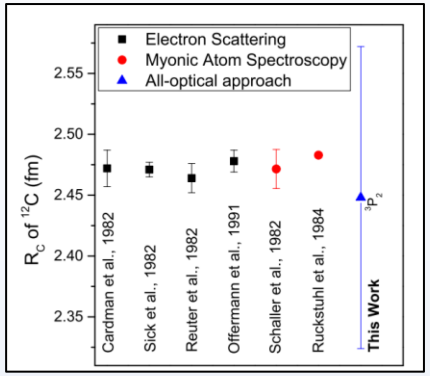
$^{12}C^{4+}$



P. Ingram Thesis 2023

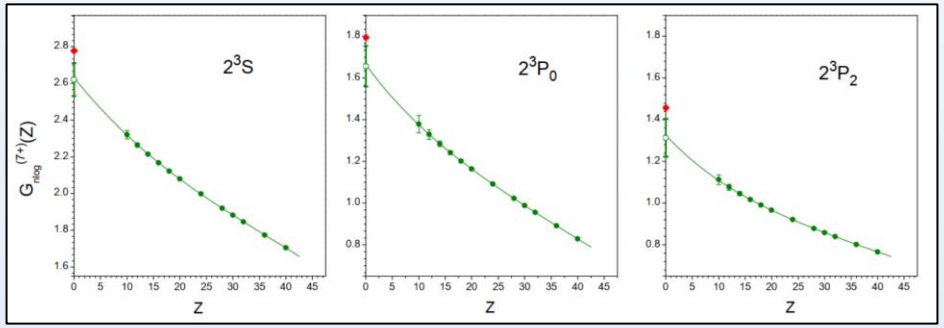
1. Next generation experiments in precision laser spectroscopy under way:

2. Optical radii from $^{12}C^{4+}$ limited by QED calc / has determined the high order NRQED correction



P. Ingram Thesis 2023

3. What is the unc. goal in radii to be able to study missing QED effects / having determined missing correction, where can we push lighter nuclei?

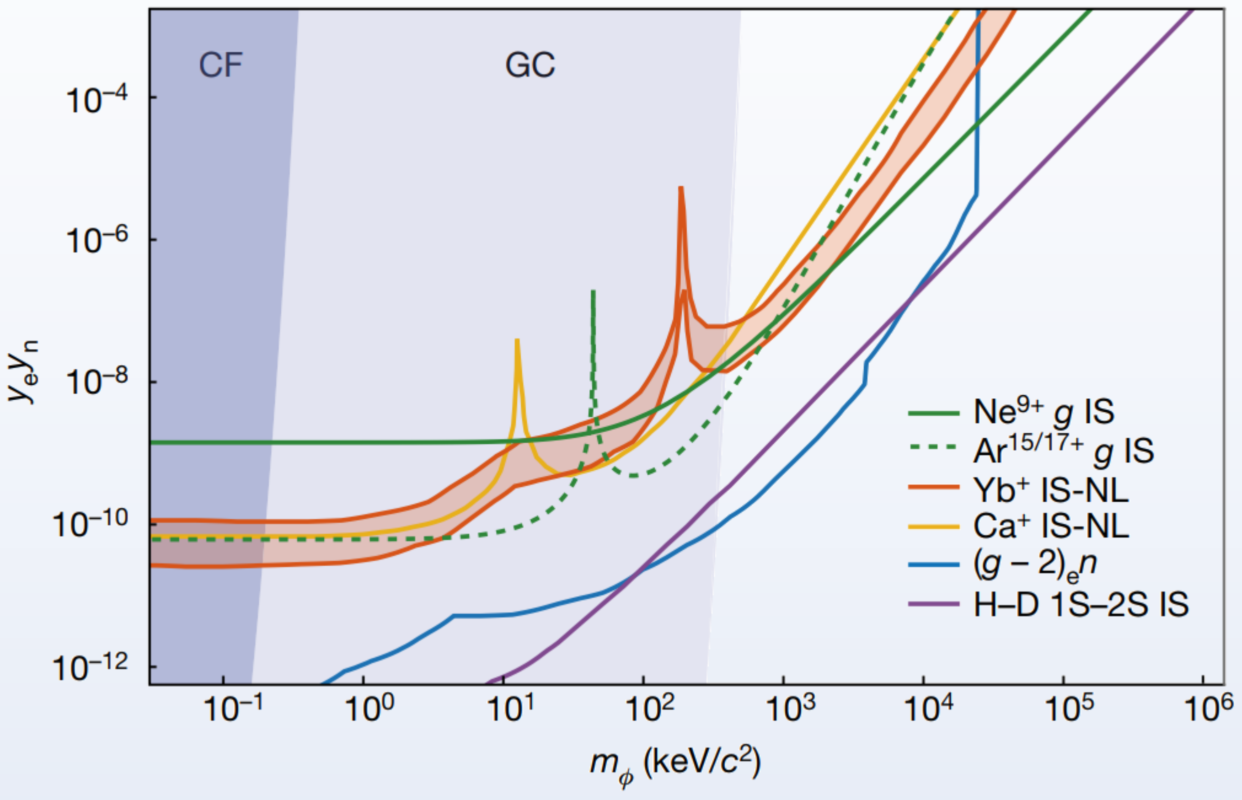


A. Yerokhin, V. Patkóš, K. Pachucki, Phys. Rev. A 107, 012810 (2023).

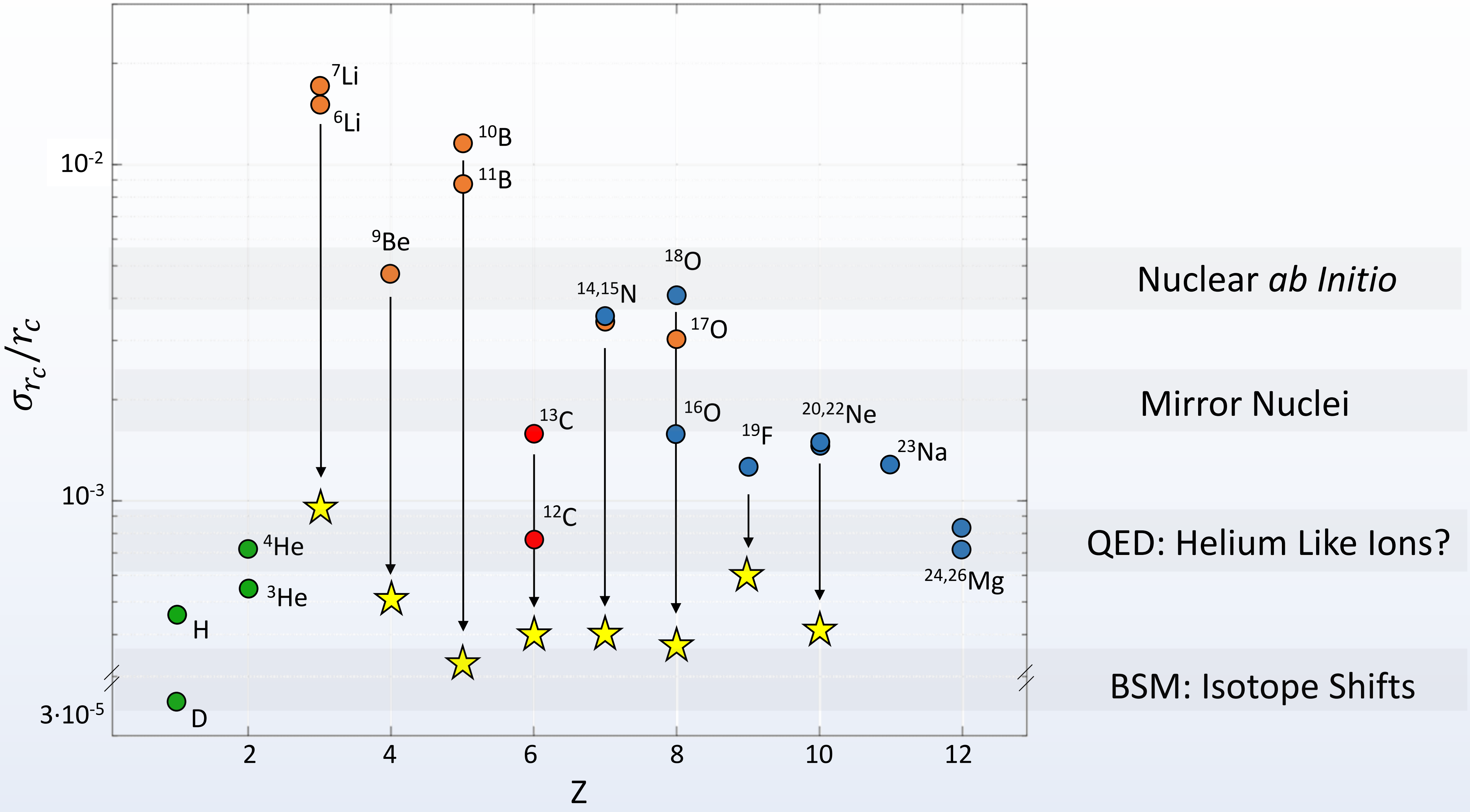
Physics case 4: Beyond Standard Model

- combining isotope shifts between electronic and muonic atoms to search for new lepton-neutron interactions
- Best limits come from Hydrogen-Deuterium pair. Z enhancement favors heavier pairs.
- Novel measurements of bound electron g-factors in H-like ions **limited by muonic isotope shifts**

T. Sailer *et. al.*, Nature 606 (2022)



Accuracy goals of physics cases:

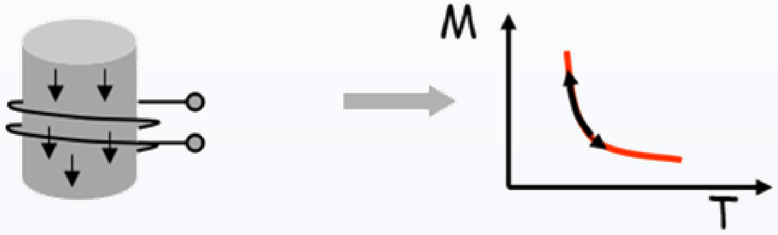


Metallic Magnetic Calorimeters (MMCs)

Temperature change

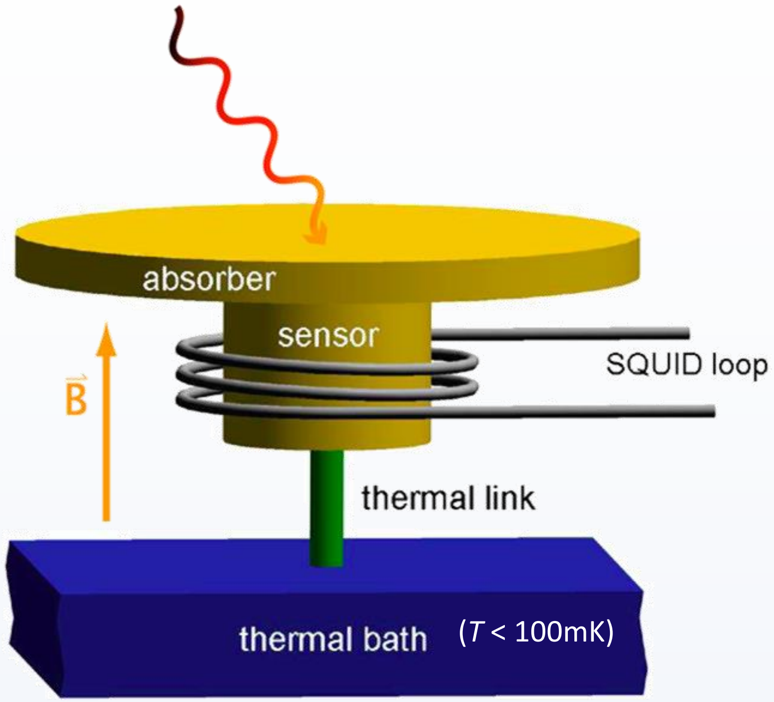
$$\delta T = \frac{E}{C_{\mathrm{tot}}}$$

Magnetization of paramagnetic material:



Signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$



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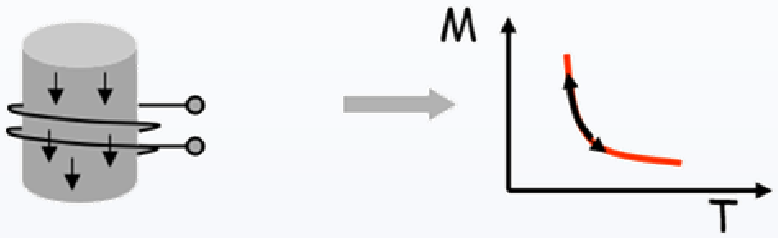
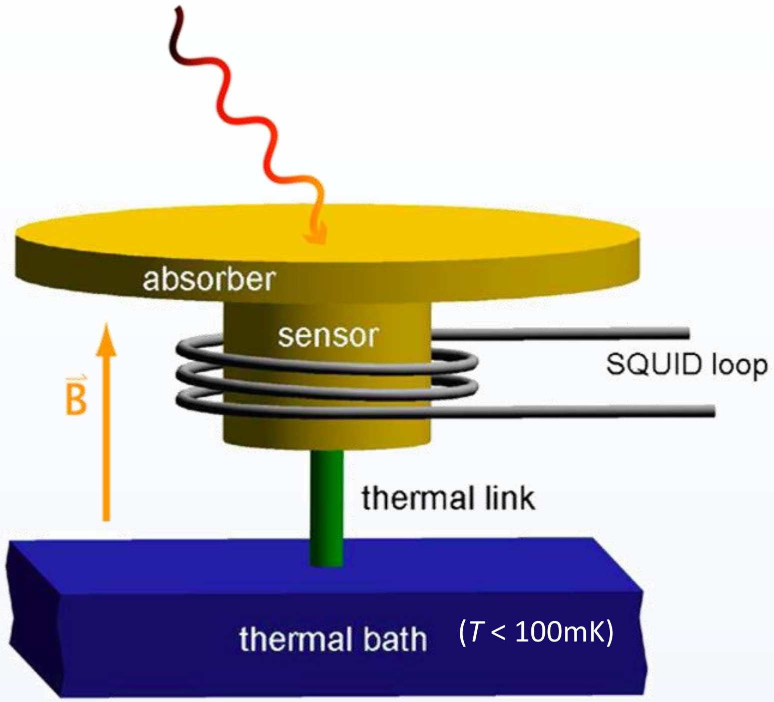


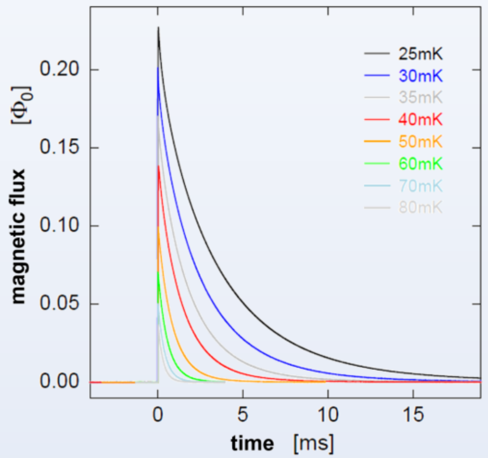


Signal size:

$$\delta M = \frac{\partial M}{\partial T}\delta T = \frac{\partial M}{\partial T}\frac{E_\gamma}{C_{\mathrm{tot}}}$$

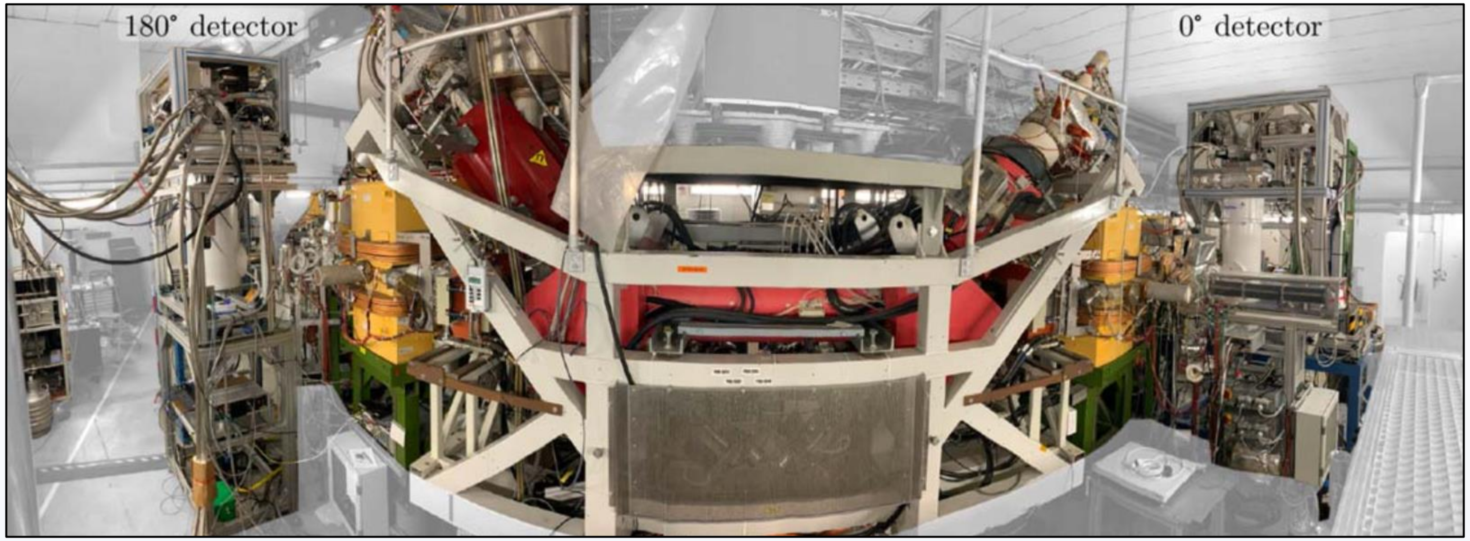
Relaxation to bath temperature

$$\tau = \frac{C_{\mathrm{tot}}}{G}$$



Frontier applications of MMCs:

X-ray spectroscopy of highly charged ions @ storage rings



A. Fleischmann, *et. al.,* Phys. Scr. 97 (2022). A. Fleischmann, P. Indelicato *et. al.,* Atoms 11, 13 (2023), …

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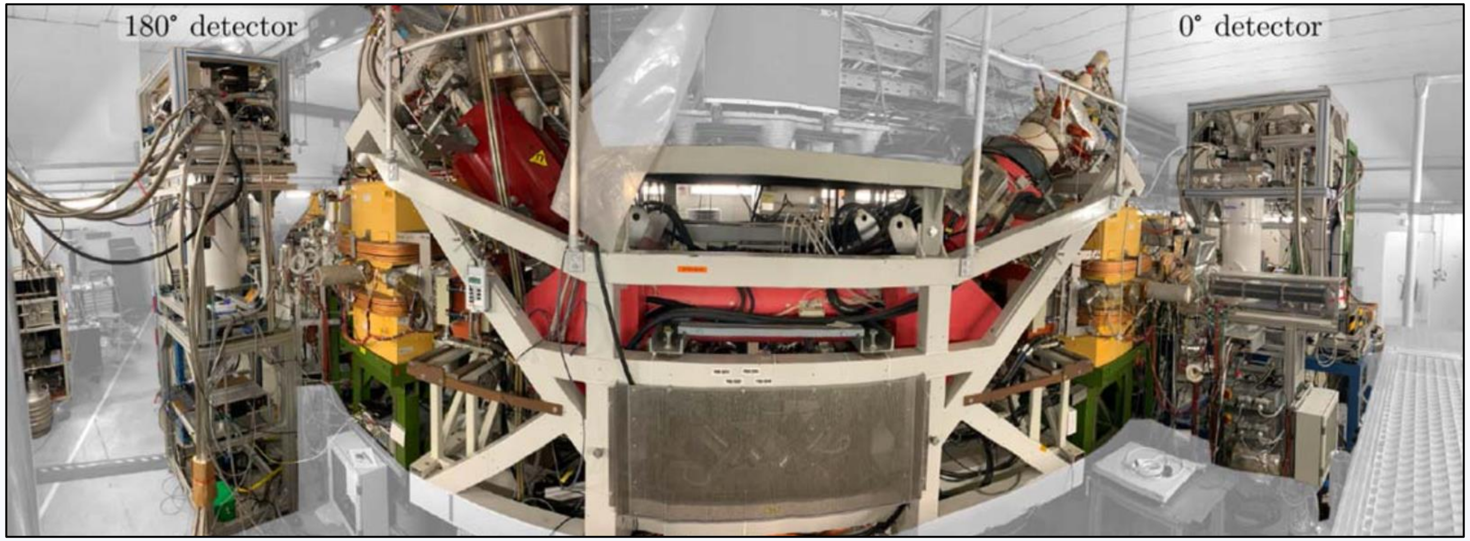
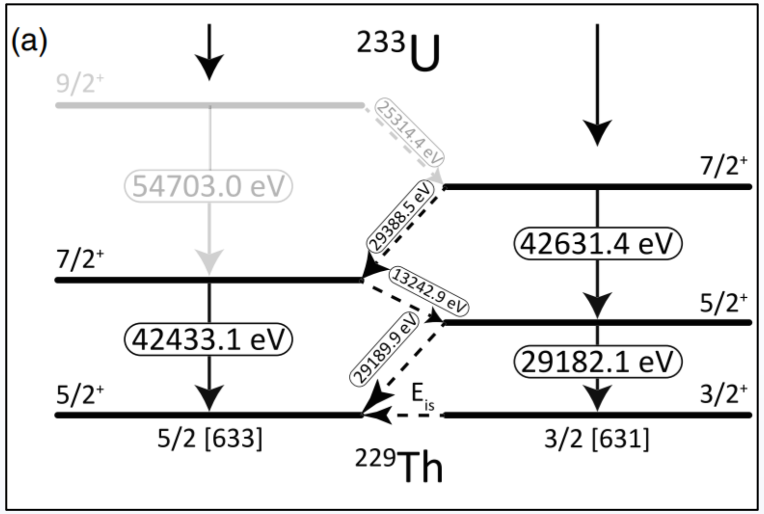


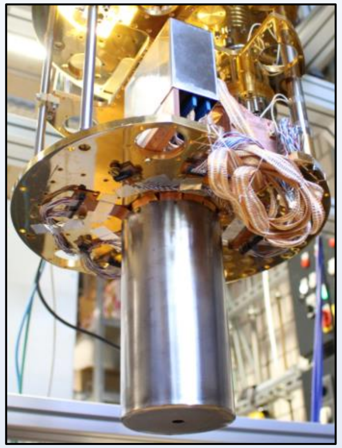
A. Fleischmann, *et. al.,* Phys. Scr. 97 (2022). A. Fleischmann, P. Indelicato *et. al.,* Atoms 11, 13 (2023), …

^{229m}Th optical excitation energy $8.1(2)$ eV:



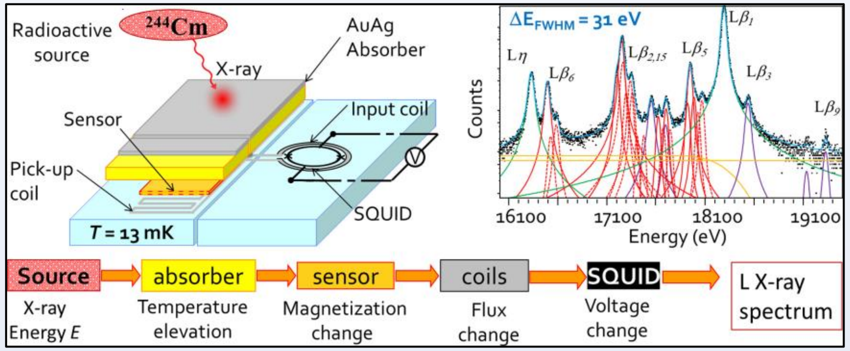
L. Gastaldo, A. Fleischmann, *et. al.,* PRL 125, 142503 (2020)

Search for Axion-like particles:



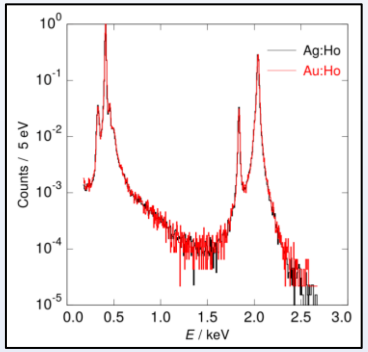
L. Gastaldo, A. Fleischmann, *et. al.,* JINST 16 (2021)

Determination X-ray absolute emission intensities:



R Mariam, *et. al.,* Spectrochimica Acta B 187 (2022)

Electron capture in ^{163}Ho:



L. Gastaldo, A. Fleischmann, *et. al.,*
Journal of Low Temperature Physics 209 (2022)

Frontier applications of MMCs:

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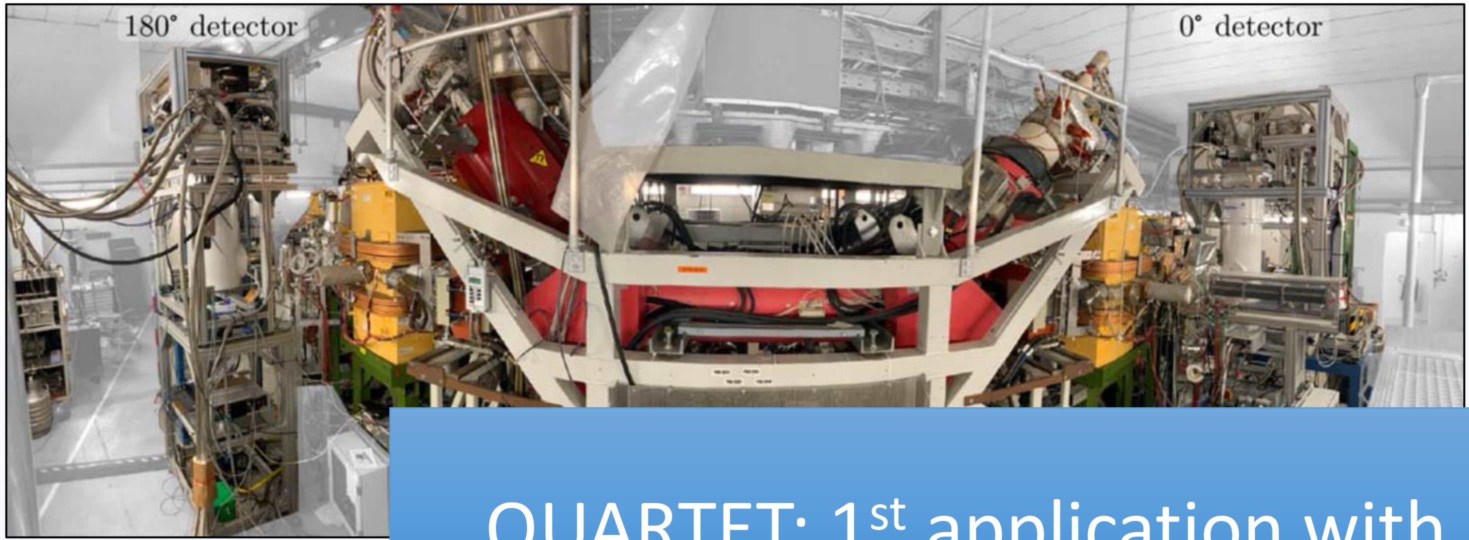
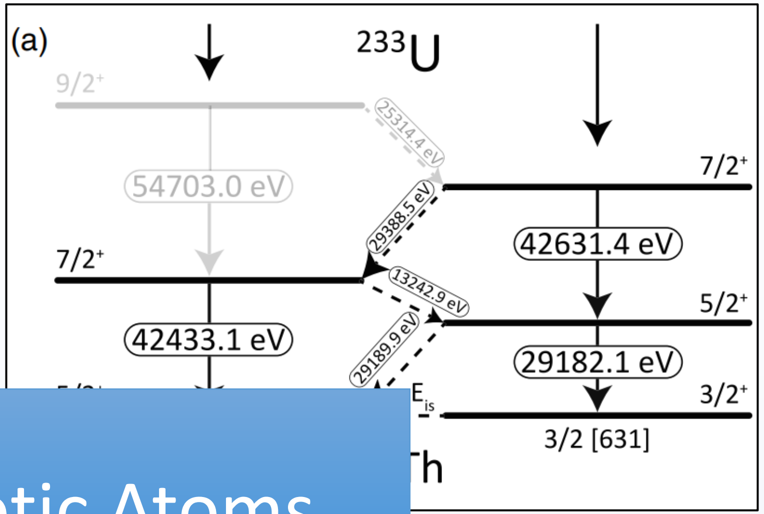


A. Fleischmann, *et. al.,*

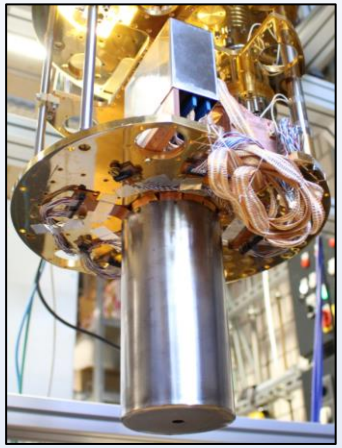
^{229m}Th optical excitation energy 8.1(2) eV:



al., PRL 125, 142503 (2020)

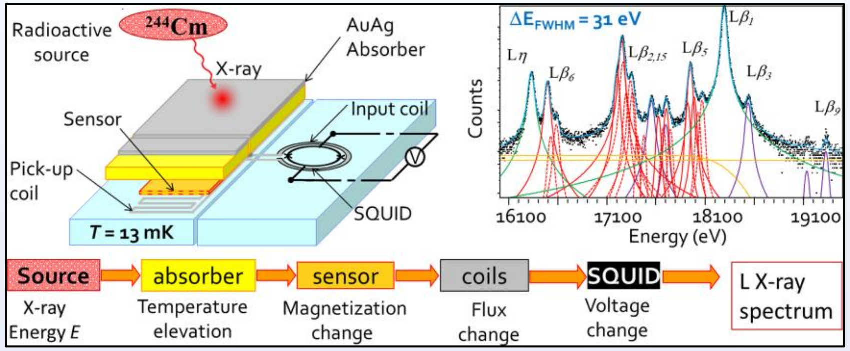
QUARTET: 1st application with Exotic Atoms

Search for Axion-like pa



L. Gastaldo, A. Fleischmann, *et. al.,* JINST 16 (2021)

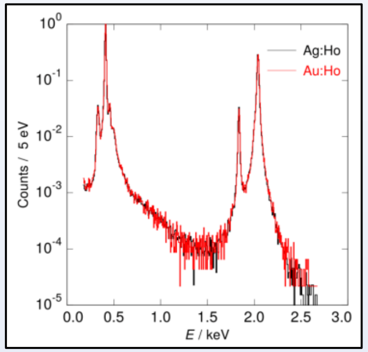
Determination X-ray absolute emission intensities:



R Mariam, *et. al.,* Spectrochimica Acta B 187 (2022)

Electron capture in ^{163}Ho:

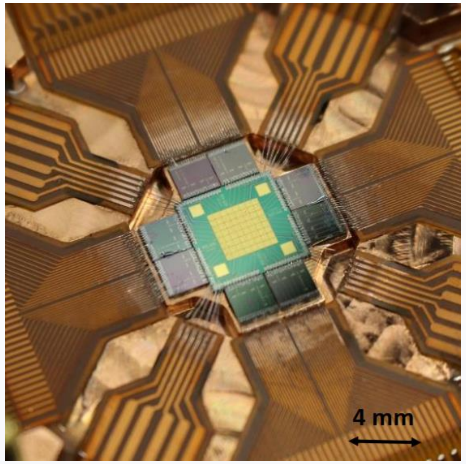
ECHo



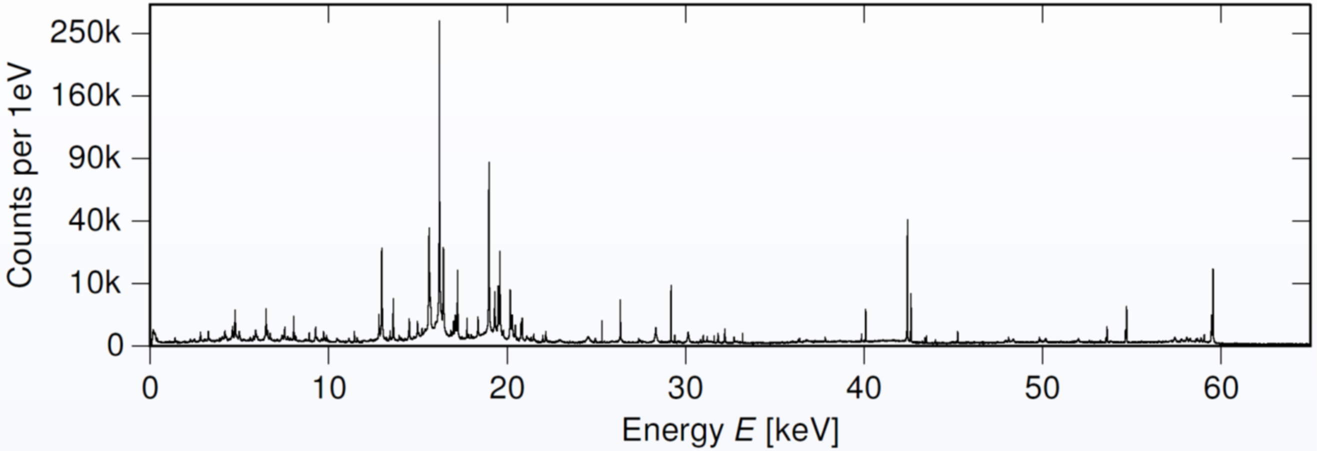
L. Gastaldo, A. Fleischmann, *et. al.,*
Journal of Low Temperature Physics 209 (2022)

For test beamtime: maXs-30 (One of) The Heidelberg MMC arrays

8×8 pixel array, area $16mm^2$



High efficiency (>90%) for photons 10-60 keV



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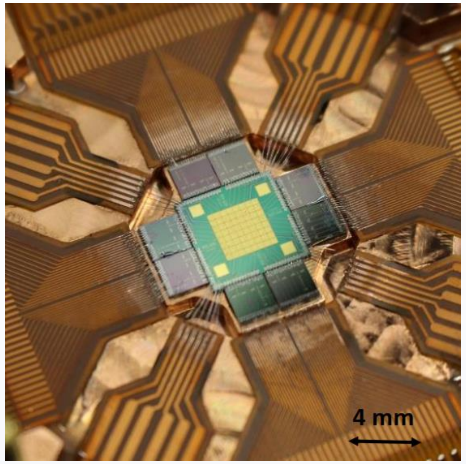

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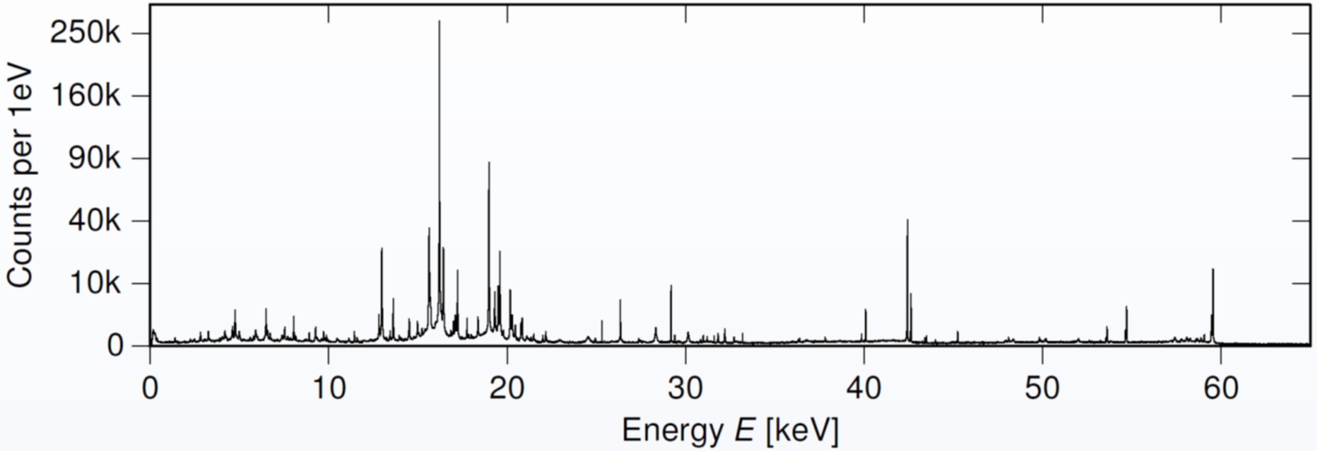
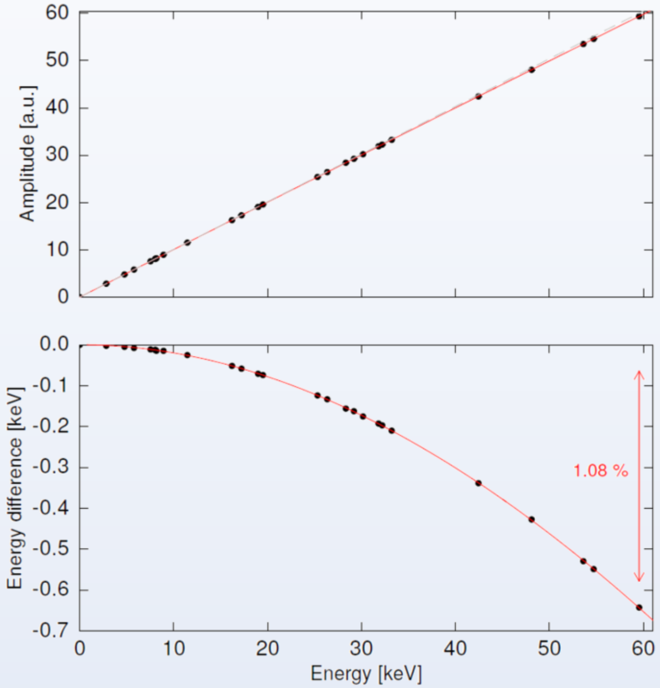
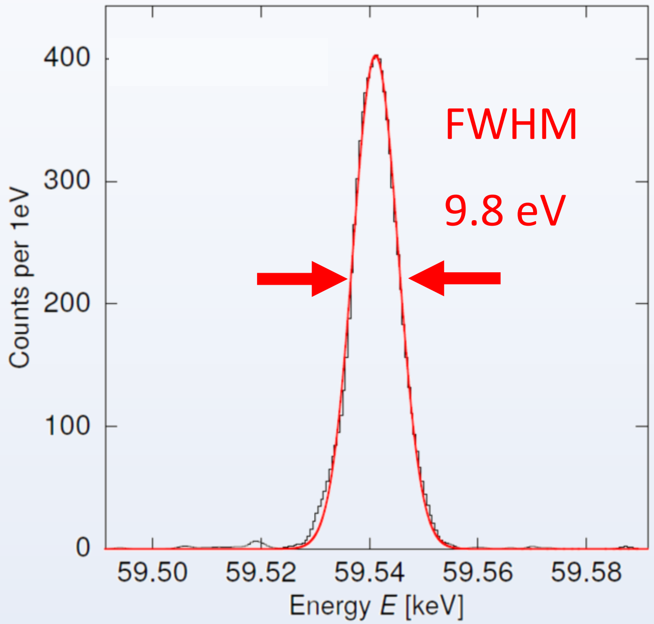


Non-linearity well-understood



World record

resolving power: 6000



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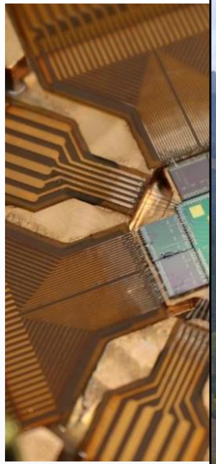

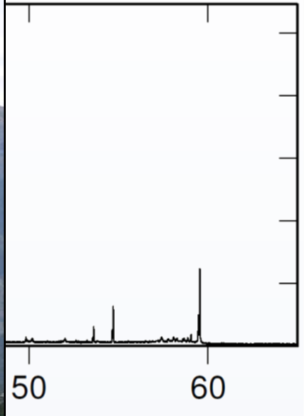

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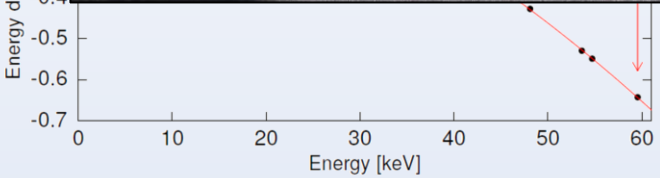
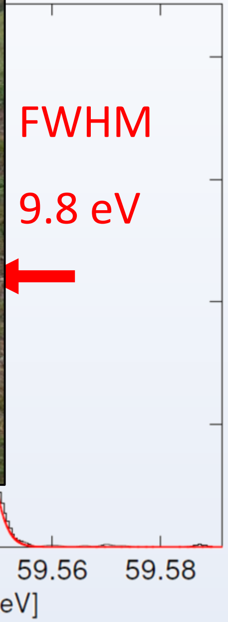
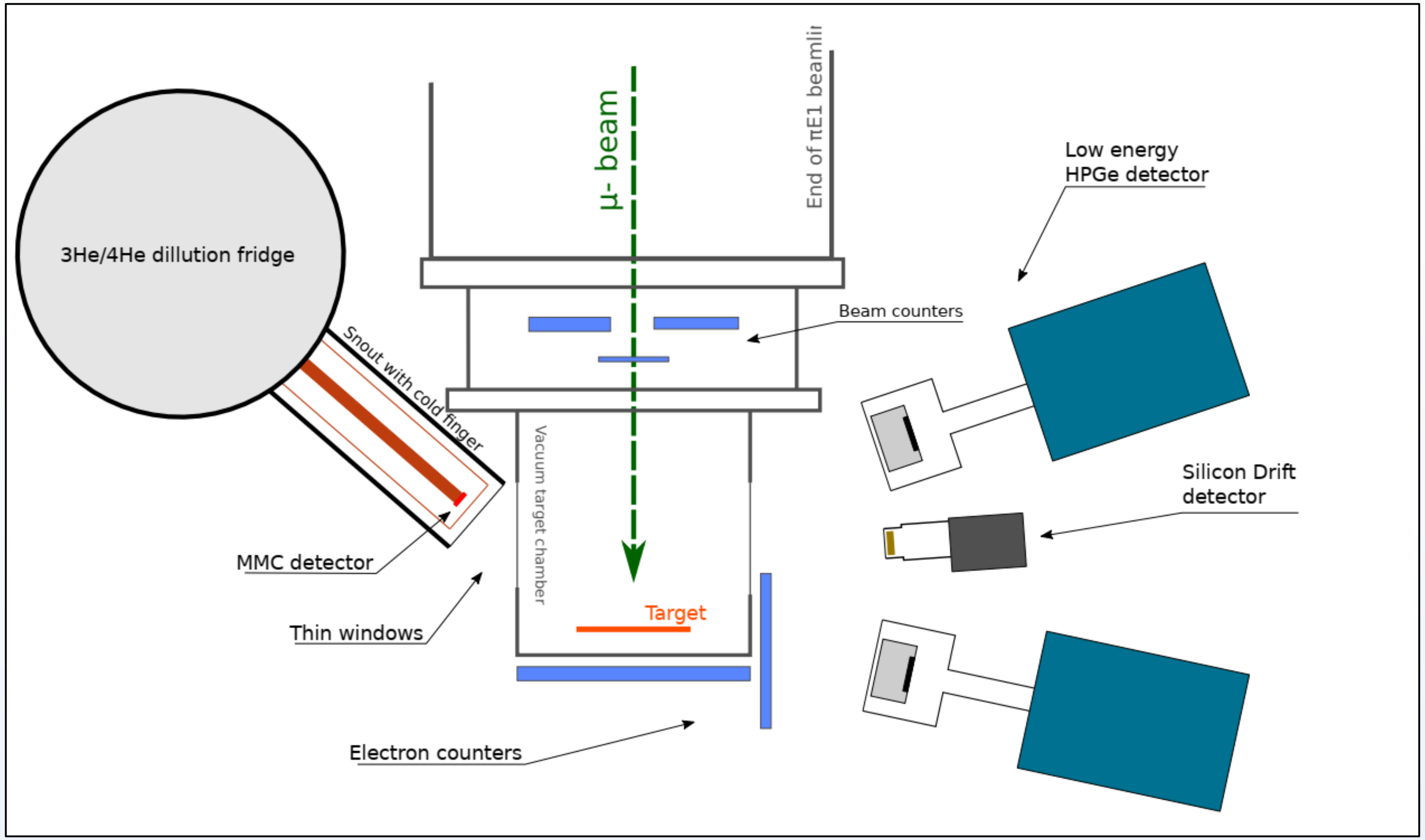




Sketch of test experiment and rates:



Sketch of test experiment and rates:

Expected rates:

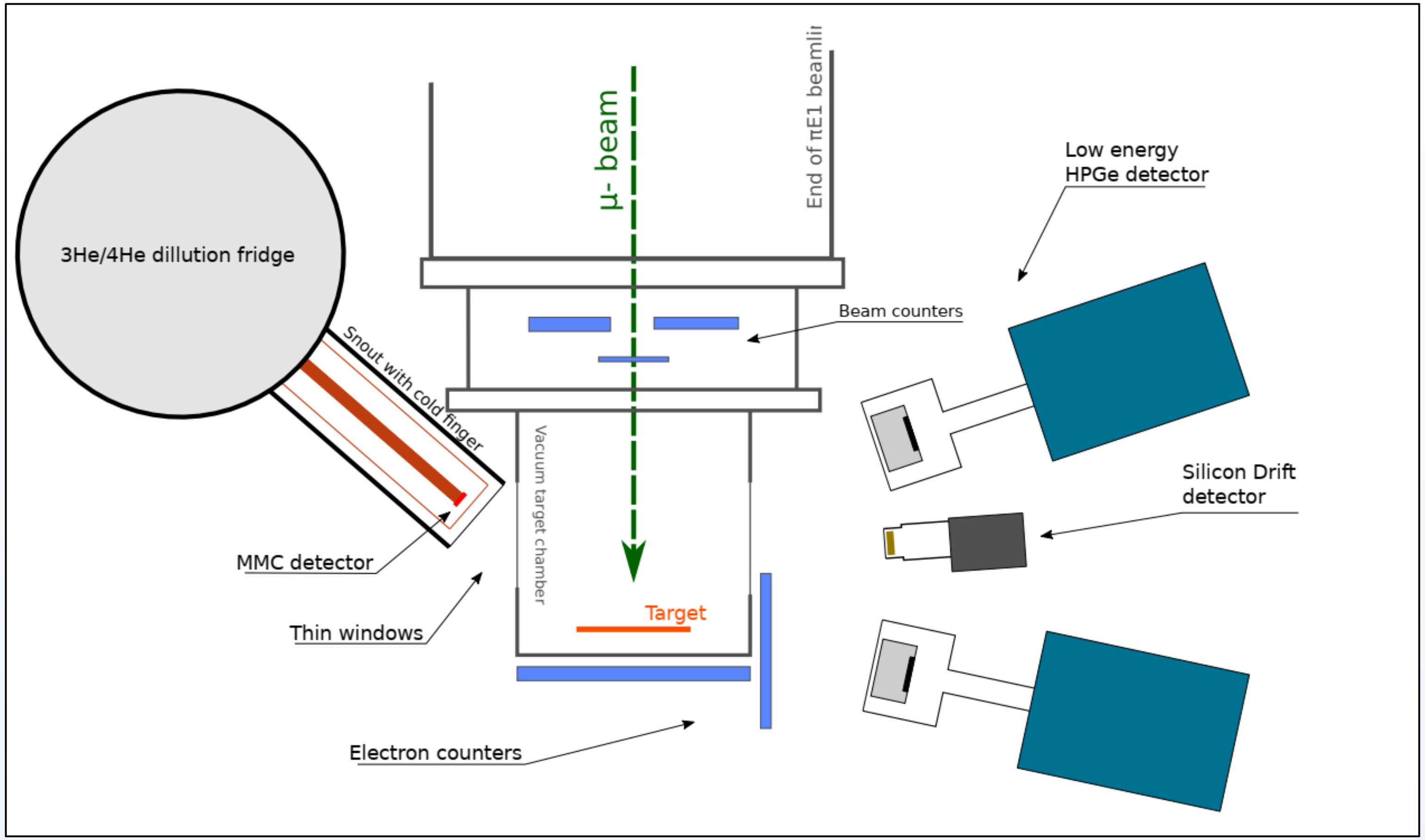
$$0.8 \times 10^{-4} \times \frac{10^3}{s} = 0.1\ event/s$$

Detection efficiency — Solid angle — 2P-1S rate

Stat. accuracy per nominal week:

$$\frac{10\ eV}{2.4} / \sqrt{10^5} \sim 0.02\ \text{eV}$$

Resolution — Events



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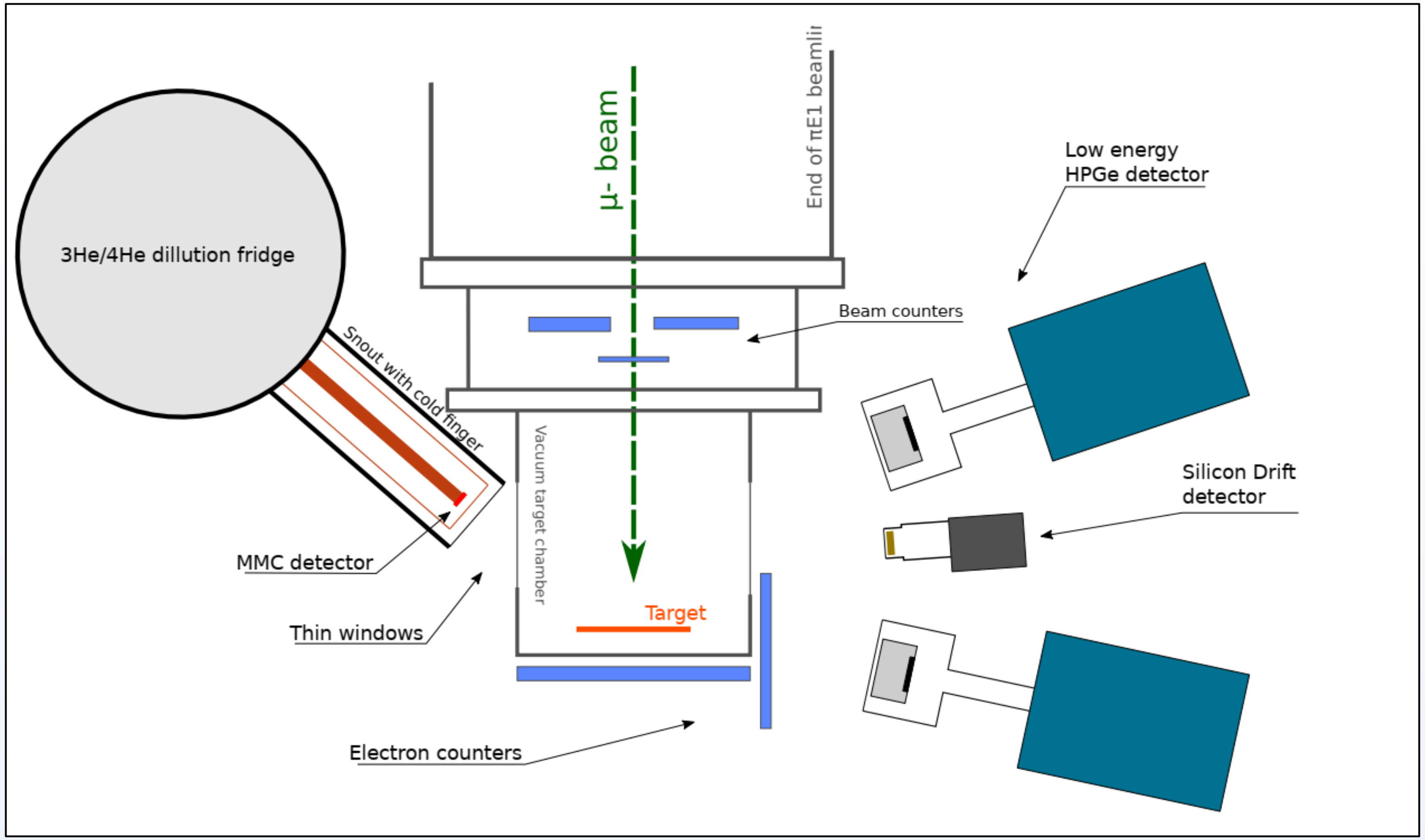
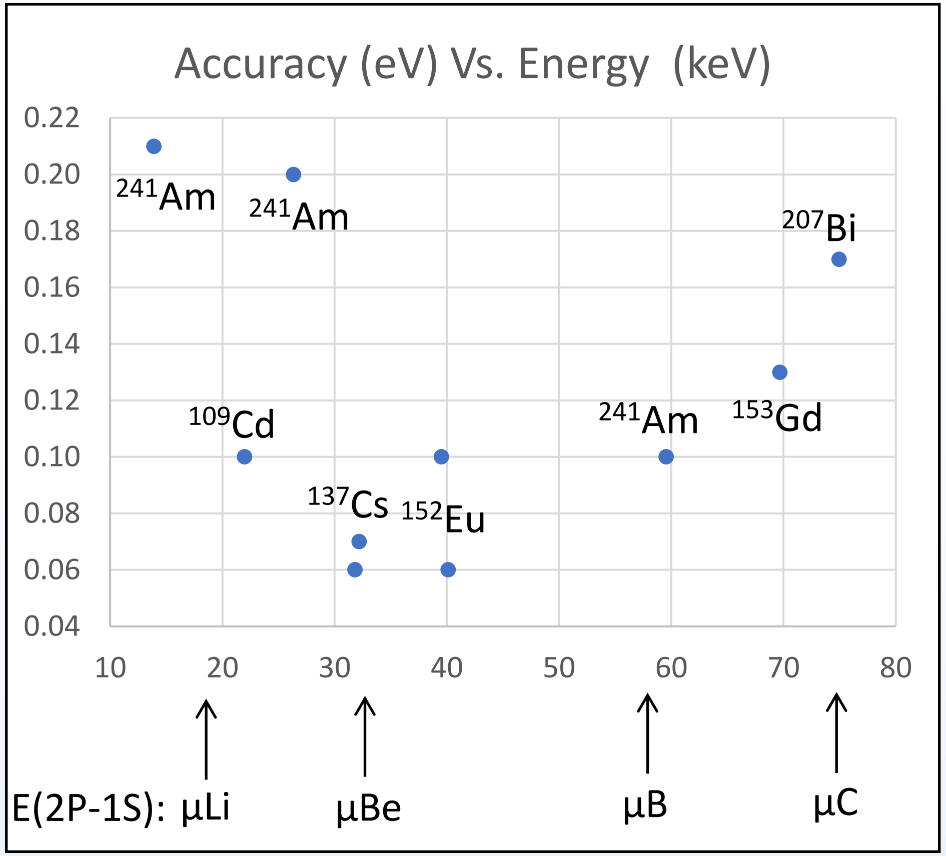


Pileup negligible, statistics more than sufficient.
Energy determination **expected to be limited by calibration**

Calibration Strategies:

1. Commercial radioactive sources:



- Calibration studies with ^{241}Am ongoing @ KIP
- Metrology with LKB crystal spectrometer

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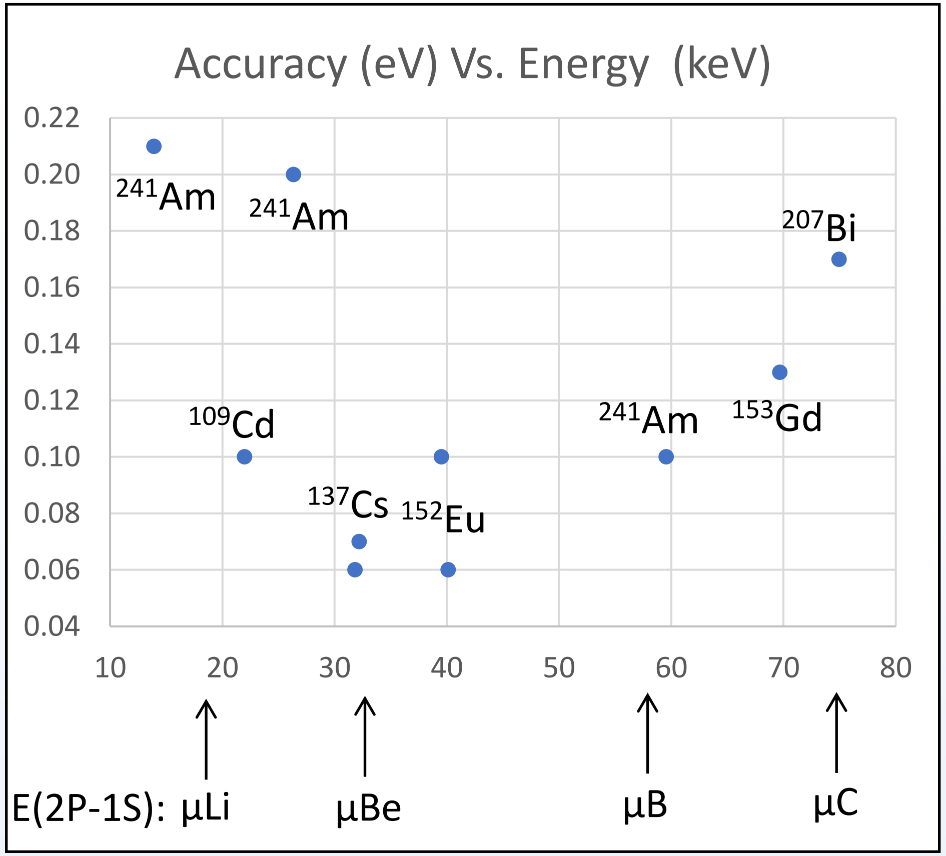

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2. Online x-ray generator

- Some x-ray transitions very well known:

  P. Indelicato, *et. al.*, Rev. Mod. Phys. 75 (2003)

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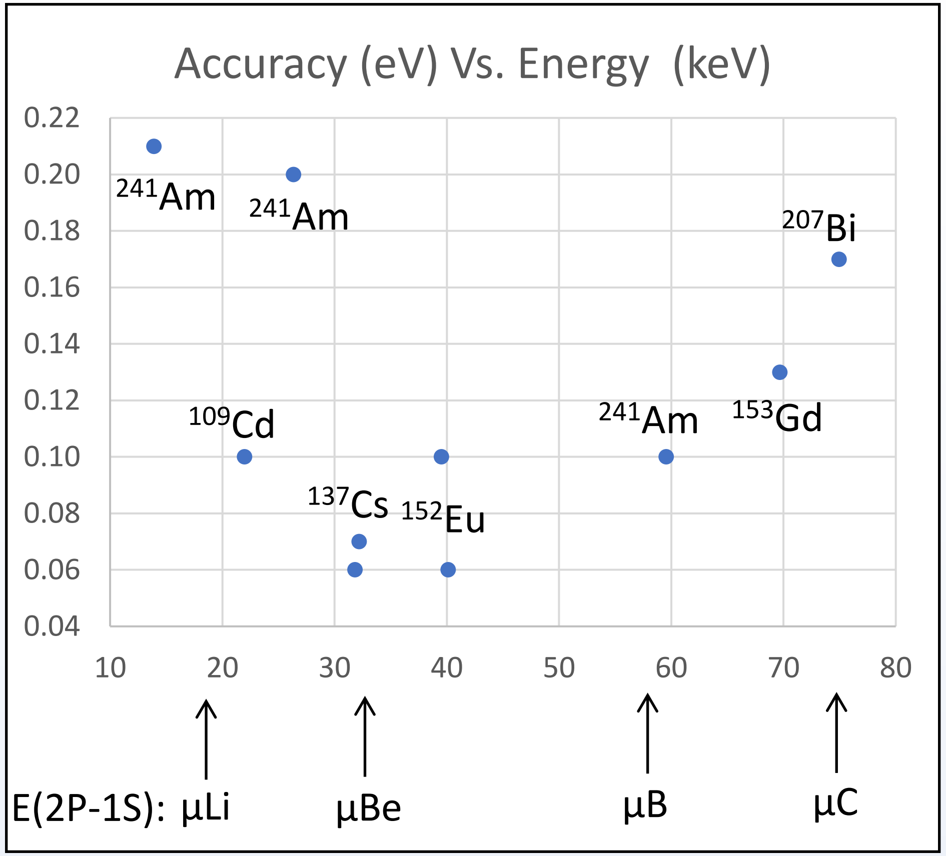

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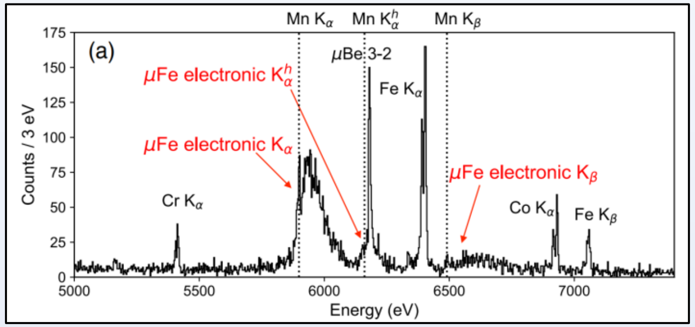
- Employ x-ray generator *online* to monitor detector response continuously
- Successfully implemented at JPARC:



P. Indelicato, N. Paul, *et. al.*, PRL 127 (2021)

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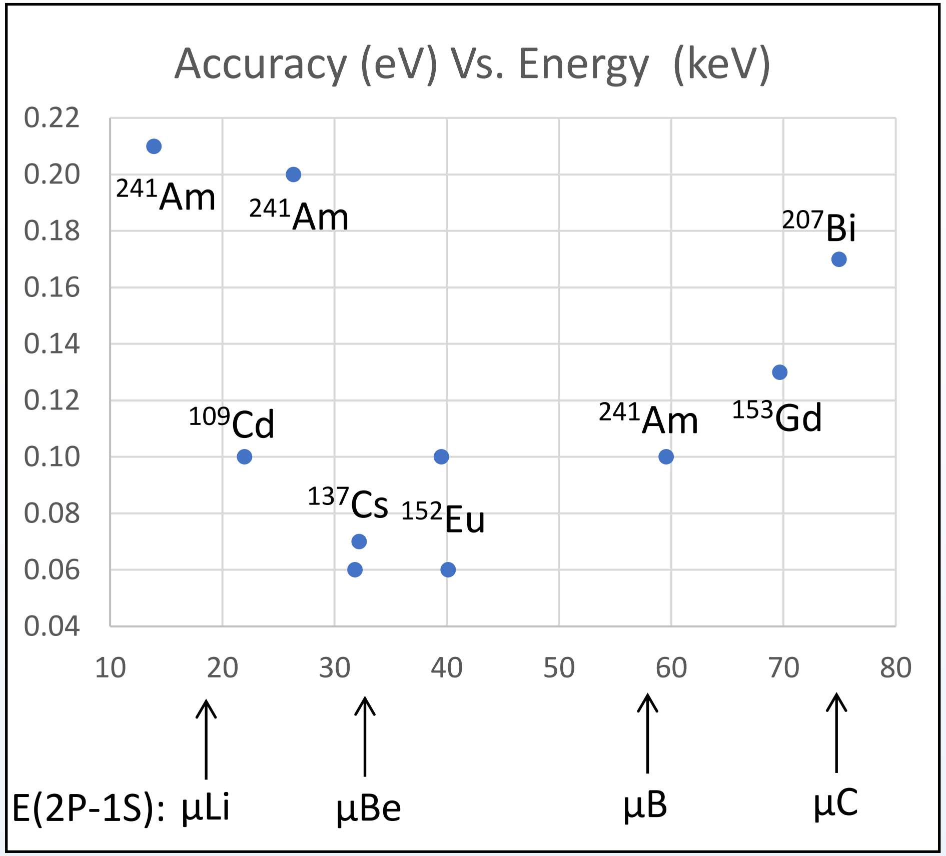

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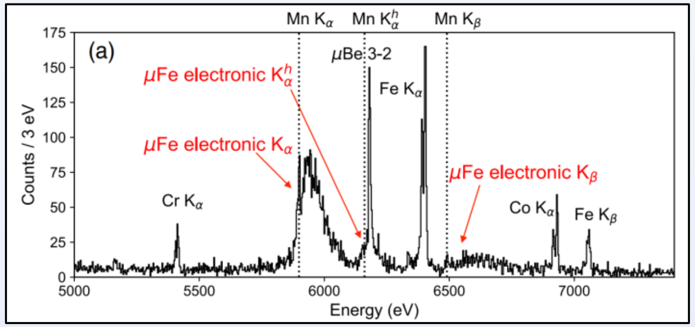
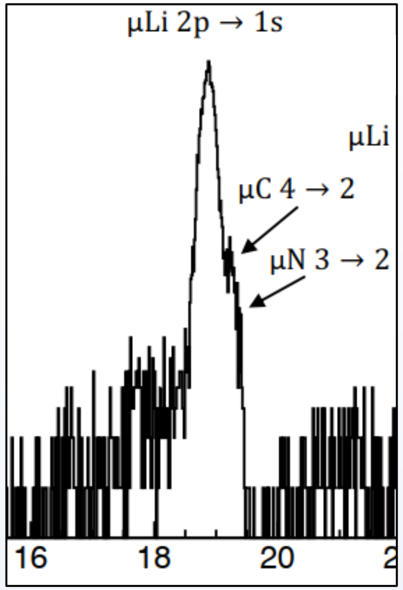


P. Indelicato, N. Paul, *et. al.*, PRL 127 (2021)

3. Transitions in muonic atoms:

^{6}Li spectrum measured by MuX with silicon drift detector (245eV FWHM):

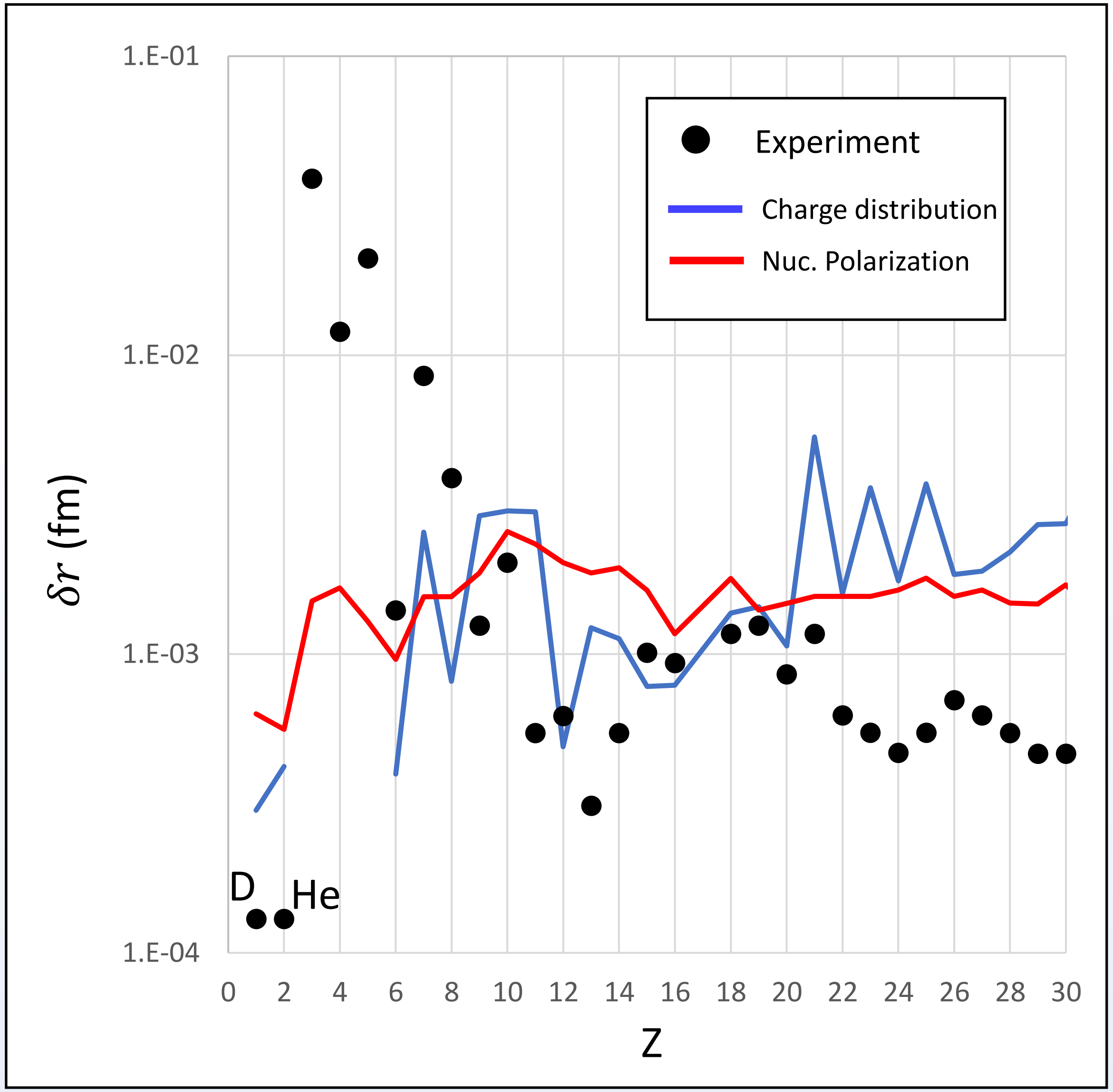


- "contamination" peaks well-resolved with MMC
- Negligible uncertainty ~meV for transitions between levels that do not overlap with the nucleus.

P. Indelicato, *et. al.*, PLB 759 (2016)

Input needed from Nuclear Theory:

1. Point nucleus QED is under control
2. Charge distribution is a small effect for light systems
3. Main missing component is nuclear polarization
4. To be calculated by P. Navratil & Co. via NCSMC



From new compilation of radii Z=3-30…

Summary

1. Charge radii are central for confronting theory with experiment

2. Only for Z=1,2, they are both **precise** & **reliable**

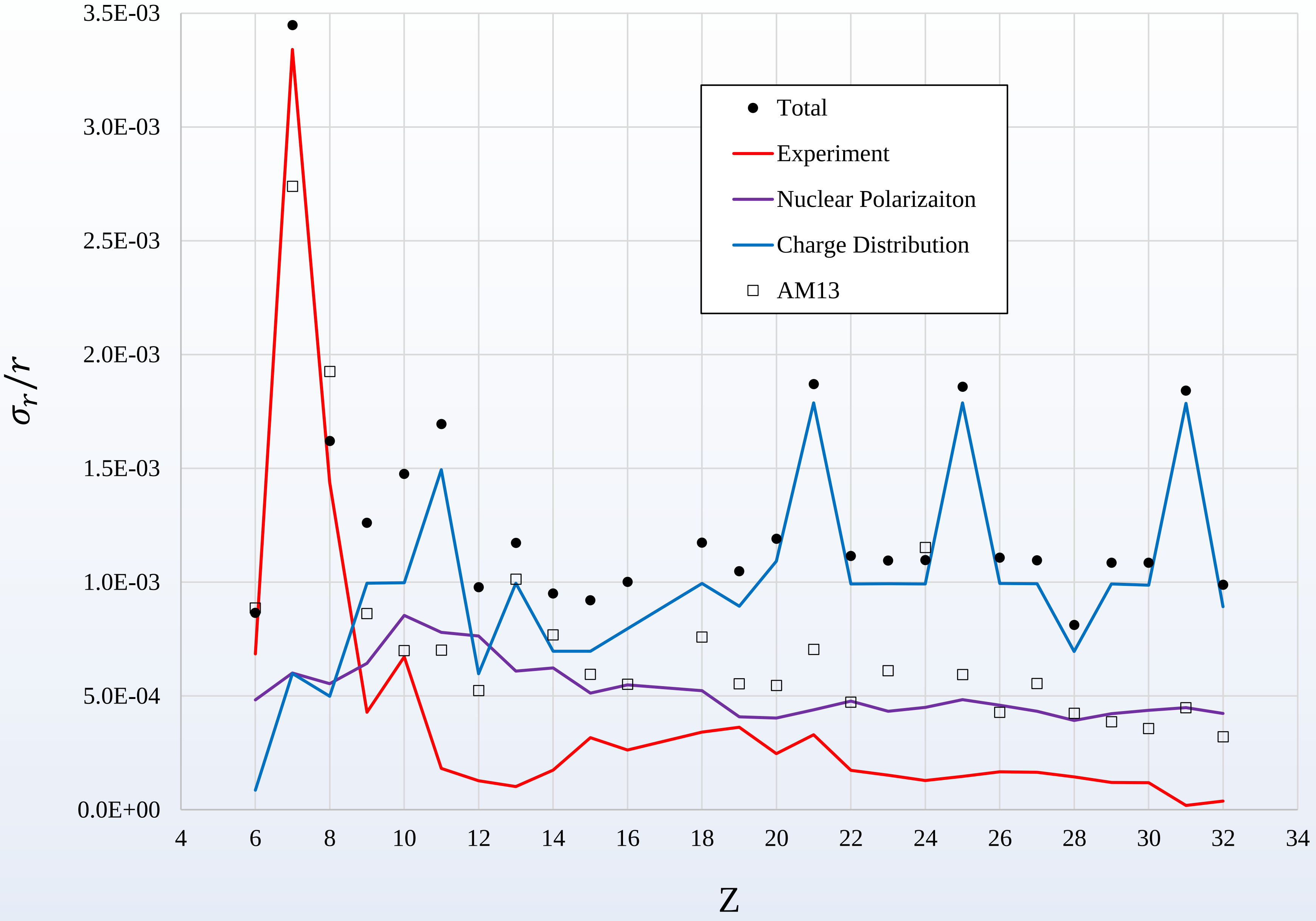
3. For Z>10, they are **precise** bot not **reliable** (opportunities for theory)

4. For Z=3-10, not **precise**. Limited by available **experimental** methods

5. New collaboration – QUARTET: Determine radii (and more) via x-ray spectroscopy of light muonic atoms using novel cryo-calorimeters

6. Test beamtime awarded @ PSI, winter 2023 – **Stay tuned**!

Aside: New compilation of radii from Z=3-30:



Test beamtime goals:

1. Deploy an existing MMC detector system (maXs-30) at the πE1 beamline (3-4 days).

2. Integrate with MuX detectors and DAQ (1 day)

3. Determine the respective background sources (e.g. beam and Michel electrons, and muon capture products) and study possible systematic effects (1 day, and parallel)

4. Test and establish different calibration strategies (online/offline) under accelerator conditions (drifts, noises, etc.) (in parallel)

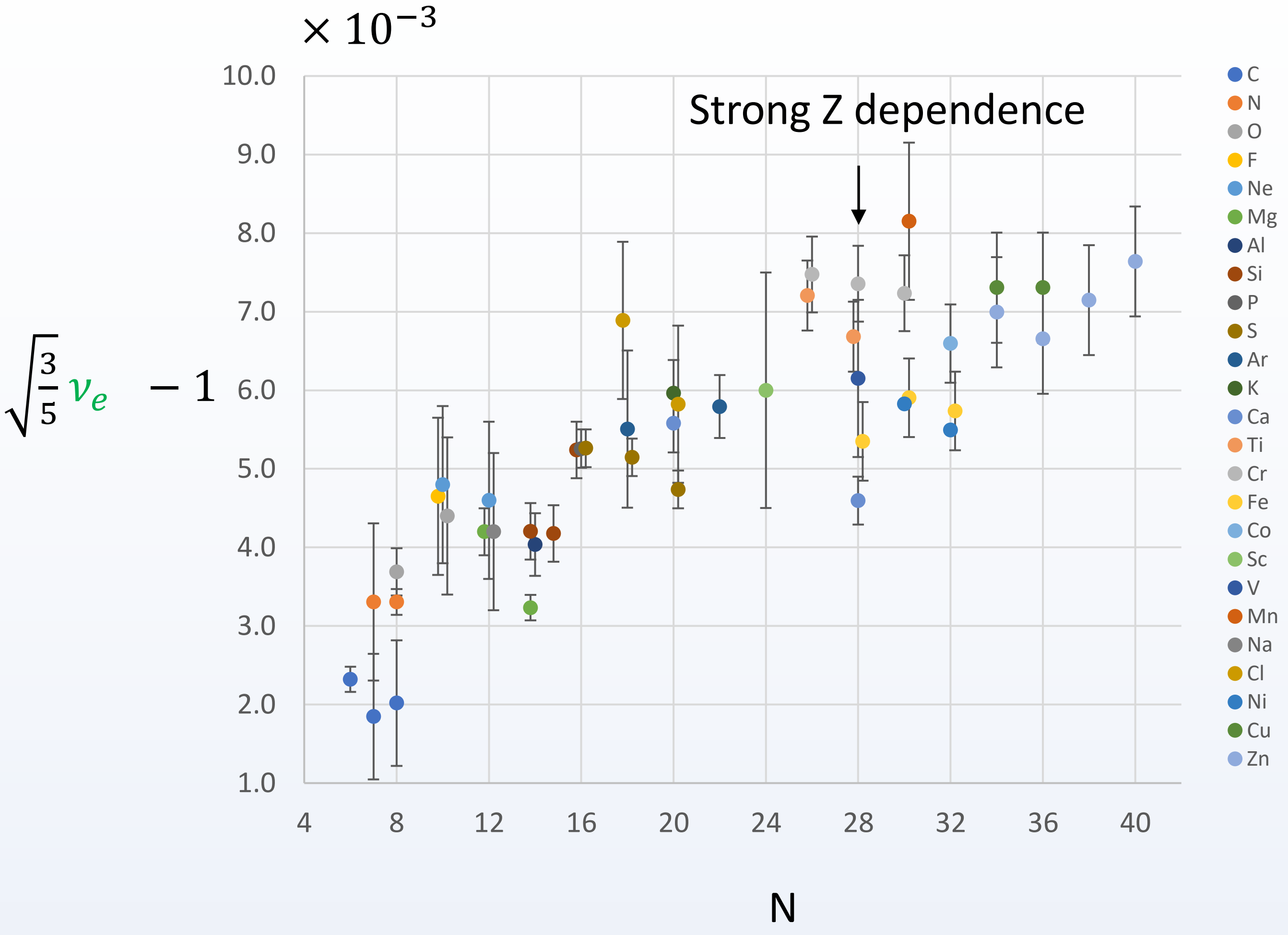
5. Target testing (^{6}Li, ^{7}Li, ^{9}Be, ^{10,11}B), study pileup and rates. 2 days per target.

TABLE 1 Targeted nuclei for radii determinations through x-ray spectroscopy of $2P-1S$ transitions, which energy is given the second column. The full width at half max (FWHM) resolution is calculated from the detector response, unresolved features, and Doppler broadening from coulomb explosion [40]. σ_{stat} is the predicted statistical accuracy for 10^5 detected events with this resolution. It corresponds to approximately one week of data taking, assuming $2\times10^3\ \mathrm{s}^{-1}$ relevant x-rays generated, 0.1 permill solid-angle coverage, and 80% detection efficiency. σ_{TPE} is our estimation of the achievable uncertainty in the two-photon-exchange correction within this project time-frame. σ_r is the corresponding uncertainty in the absolute charge radius, including a calibration uncertainty of 50 meV. $\sigma_{\delta r}$ is the uncertainty of isotope shifts. The comparison with the state of the art is portrayed in Fig. 1.

Isotopes	E_{2P-1S} [keV]	FWHM [eV]	σ_{stat} [eV]	σ_{TPE} [eV]	σ_r [am]	$\sigma_{\delta r}$ [am]
^{6,7}Li	19	4	0.01	0.02	2	0.6
^{9}Be	33	12	0.02	0.06	1	
^{10,11}B	52	18	0.02	0.1	1	0.5
^{12,13}C	75	36	0.05	0.3	1	0.7
^{14,15}N	102	39	0.05	0.6	1	0.7
^{16,18}O	134	45	0.06	1	1	0.5
^{19}F	169	50	0.07	2	2	
^{20,22}Ne	207	50	0.07	3	1	0.8

Input from electron scattering

$$r_{\mu e} = \frac{R_\mu}{\nu_e} = R_\mu \frac{r_e}{R_e}$$

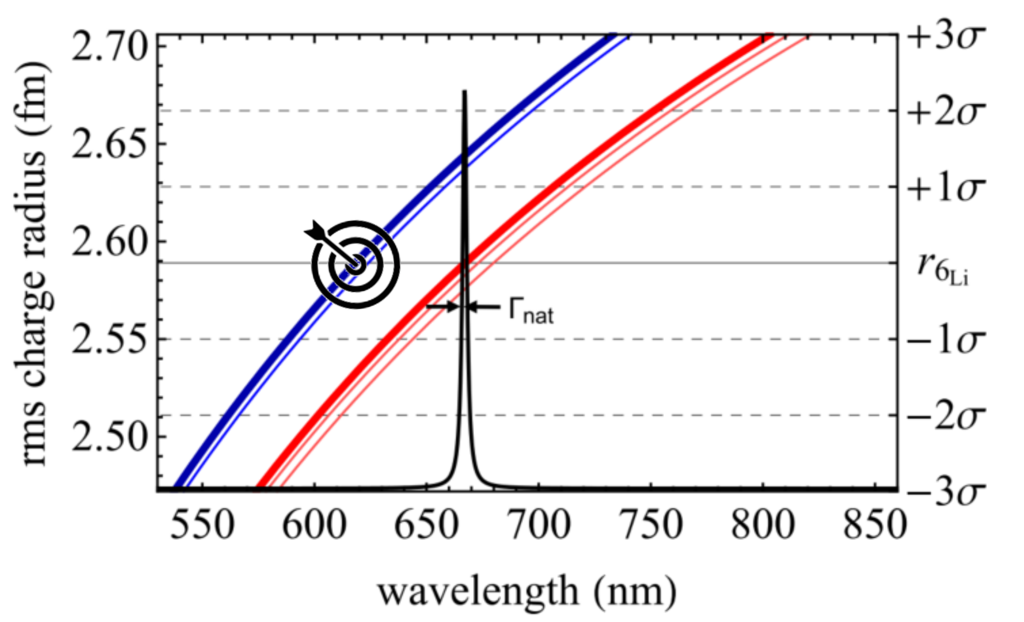


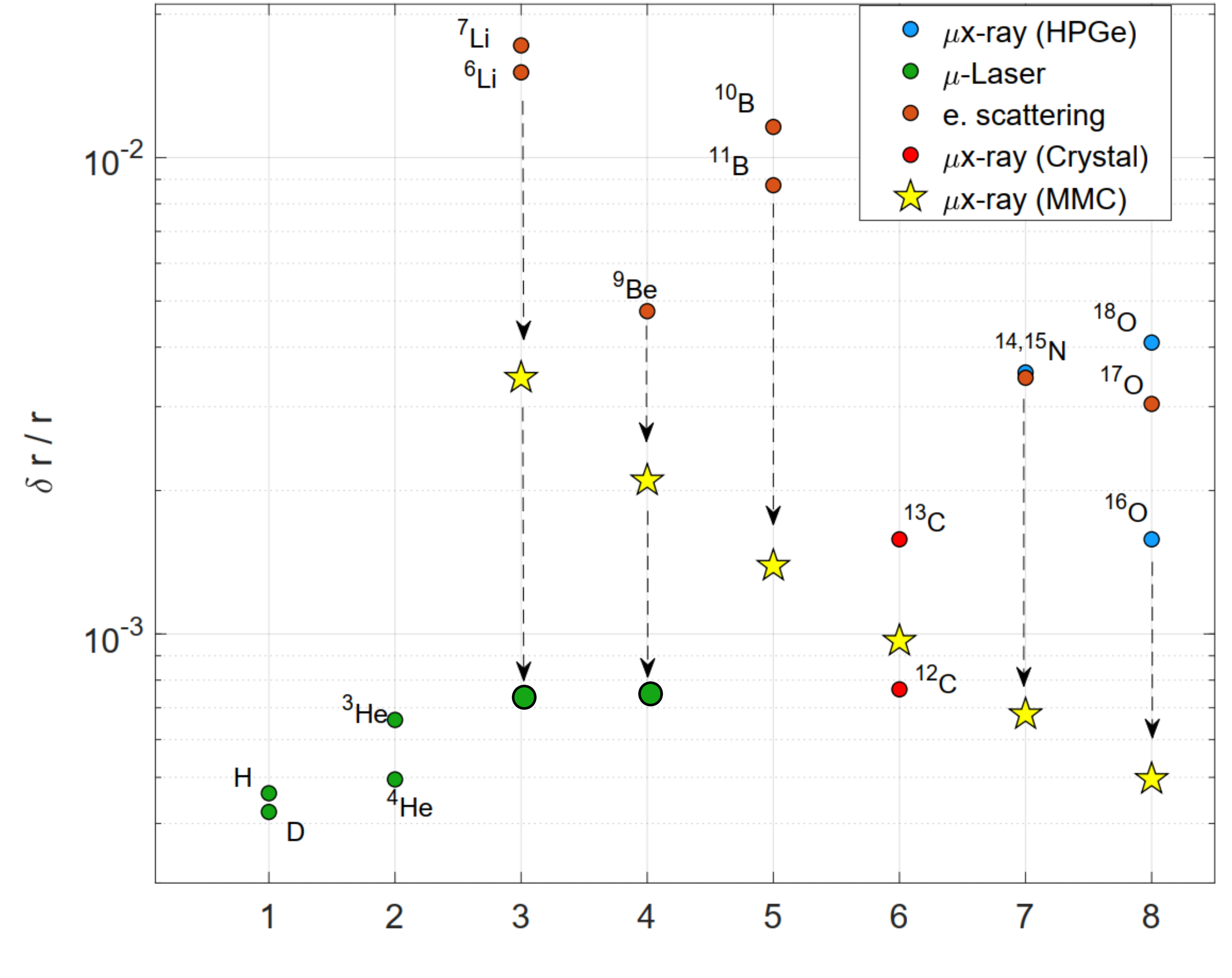
- Take Charge distribution from elec. Scat
- Calculate $\nu_e = \frac{r_e}{R_e} \to \sqrt{\frac{5}{3}}\,(\text{sphere})$
- Can be obtained with much smaller uncertainty than e.g. r_e
- Compare distributions, extrapolate and **estimate unc.**

Conclusions: Uncertainty is not negligible! Some nuclei much better known then the others

Enabling the laser spectroscopy of monic Li/Be(?):

- MMCs: Improve r_c of ^{6}Li by factor ~5.
- Narrow 2S-2P wavelength search from 200 nm to 20 nm
- Similarly for Be/B (more challenging)





Physics reach of muonic atom measurements

1. Test r_c calculations:
   - Experiment: Muonic: $r_c + TPE$
   - Theory: - TPE →
   - Combined: r_c
   - Comparison ↔ Theory: r_c

2. Test TPE calculations:
   - Experiment: Muonic: $r_c + TPE$; Electronic: $r_c + QED$
   - - r_c →
   - Combined: TPE
   - Comparison ↔ Theory: TPE

3. bsQED test
   - Experiment: Muonic: $r_c + TPE$; Electronic: $r_c + QED$
   - Theory: - TPE →
   - Combined: QED
   - Comparison ↔ Theory: QED

4. BSM search
   - Experiment: Muonic: $r_c + TPE + BSM$; Electronic: $r_c + QED + BSM$
   - Theory: - TPE - QED →
   - Combined: BSM
   - Comparison ↔ Theory: $BSM\ model$