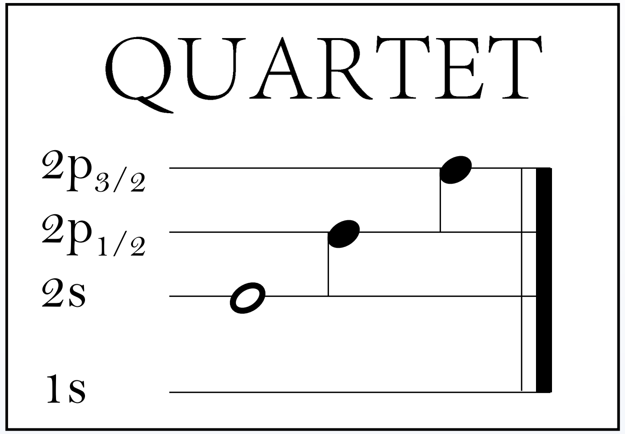
Spectroscopy of light muonic atoms with metallic magnetic calorimeters



Ben Ohayon

Technion IIT

For the QUARTET collaboration

Open CHRISP Users Meeting BVR54, 24.1.2023

Who we are:

Universität Heidelberg

Loredana Gastaldo
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Johannes Gutenberg Universität Mainz

Frederik Wauters
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T. Cocolios
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MuX, CREMA, HyperMu, MuMASS

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Who we are:

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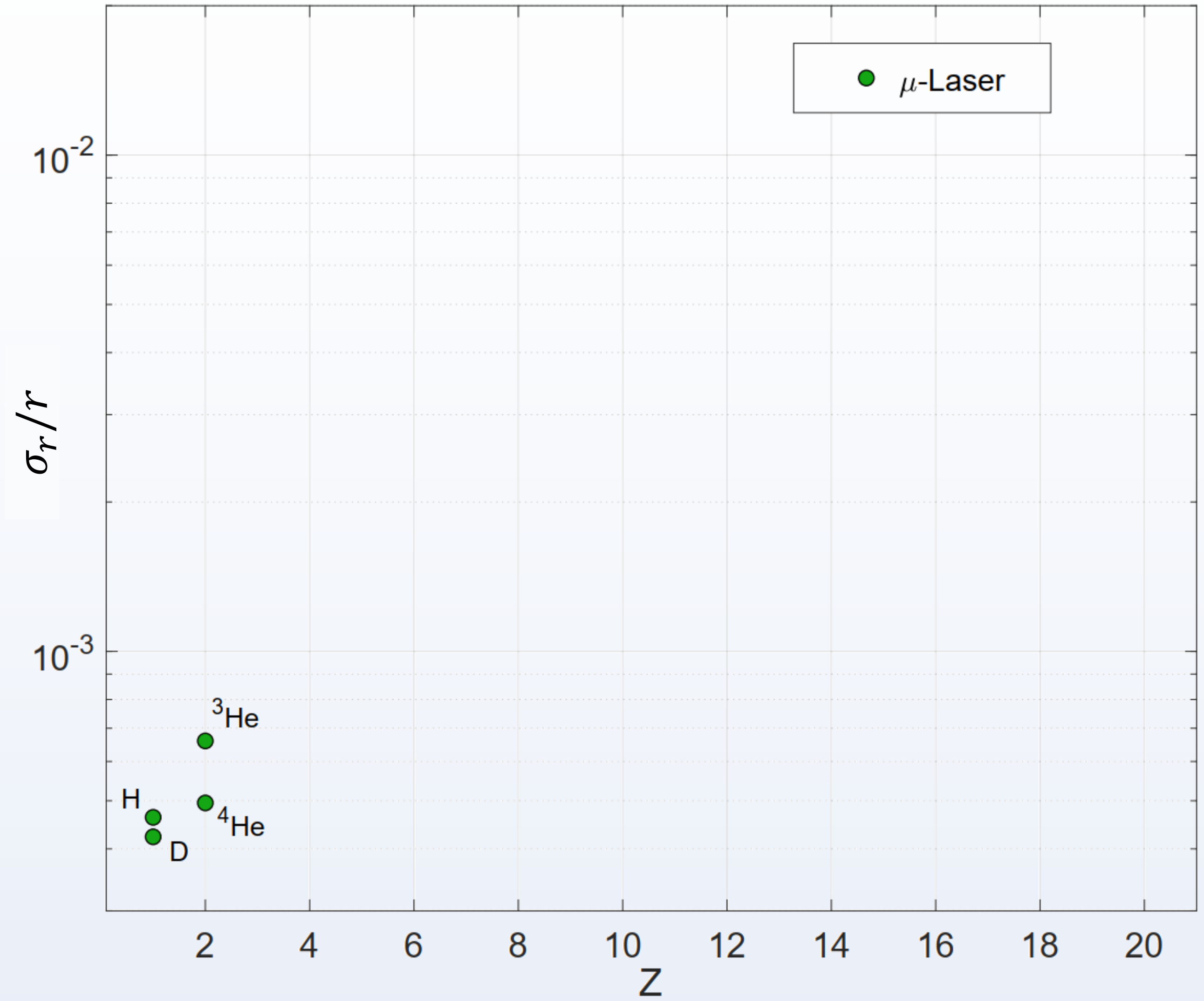
The radius gap

- **For $Z < 3$:**
  Laser spectroscopy of muonic atoms, limited by nuclear theory



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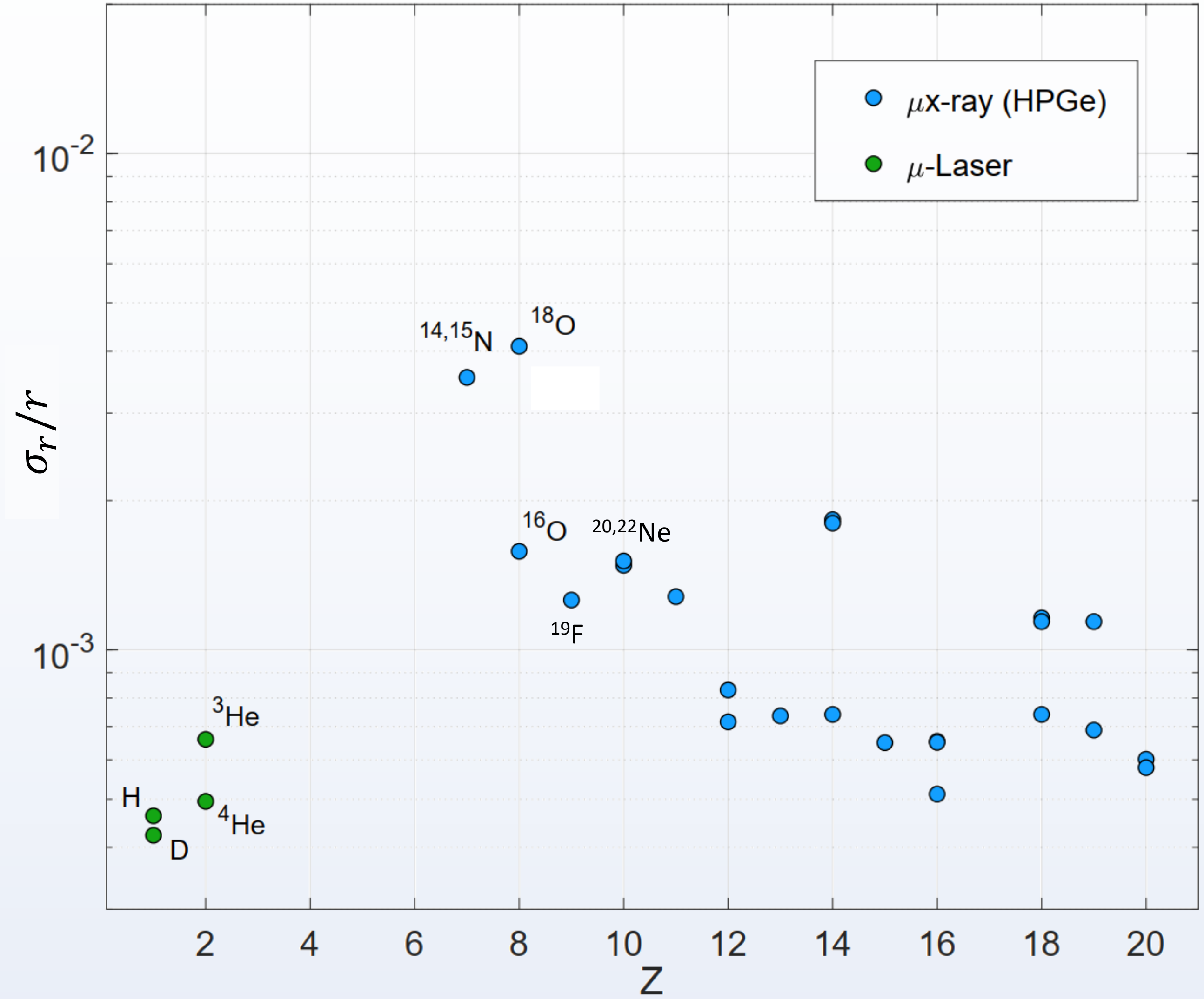

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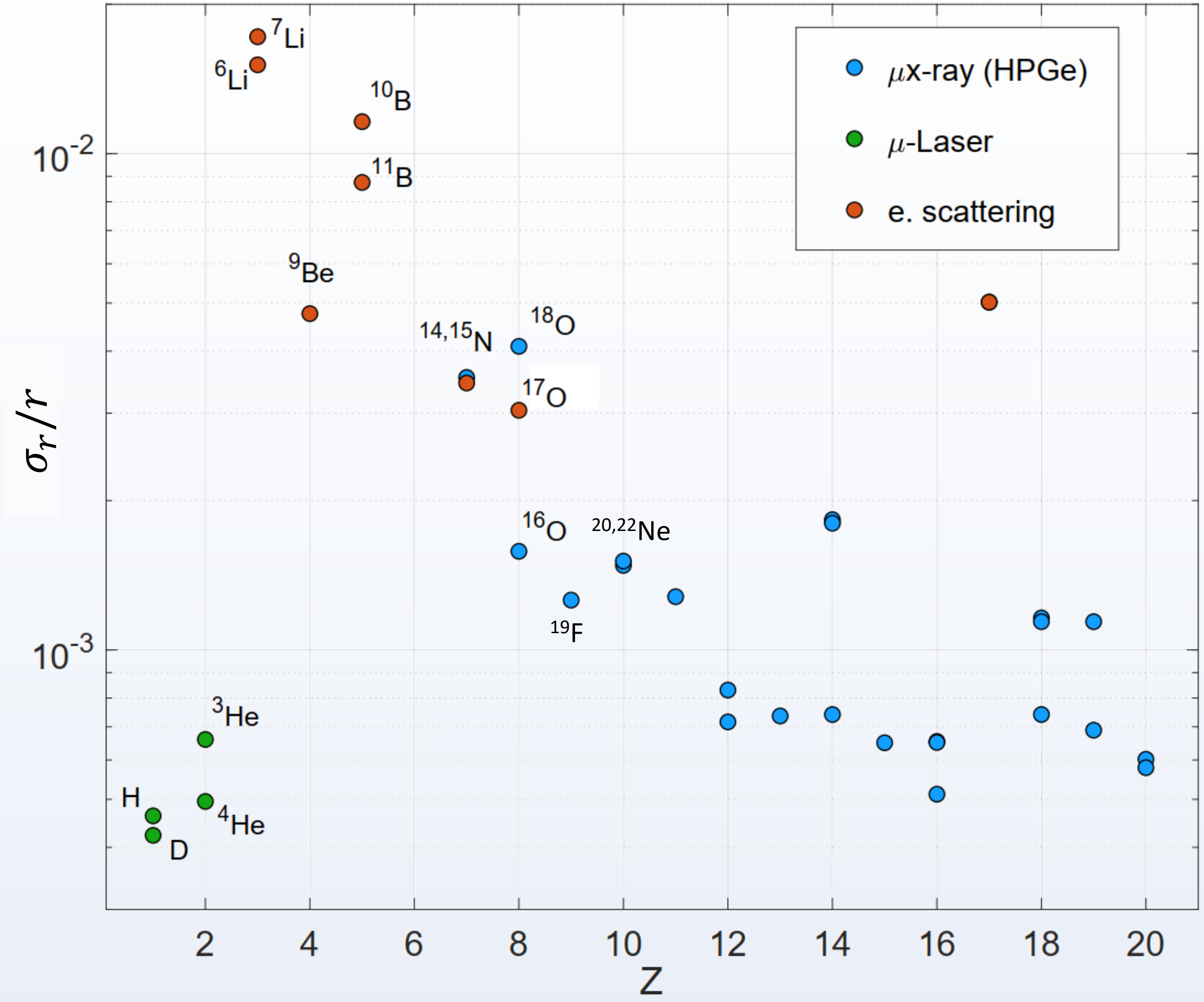

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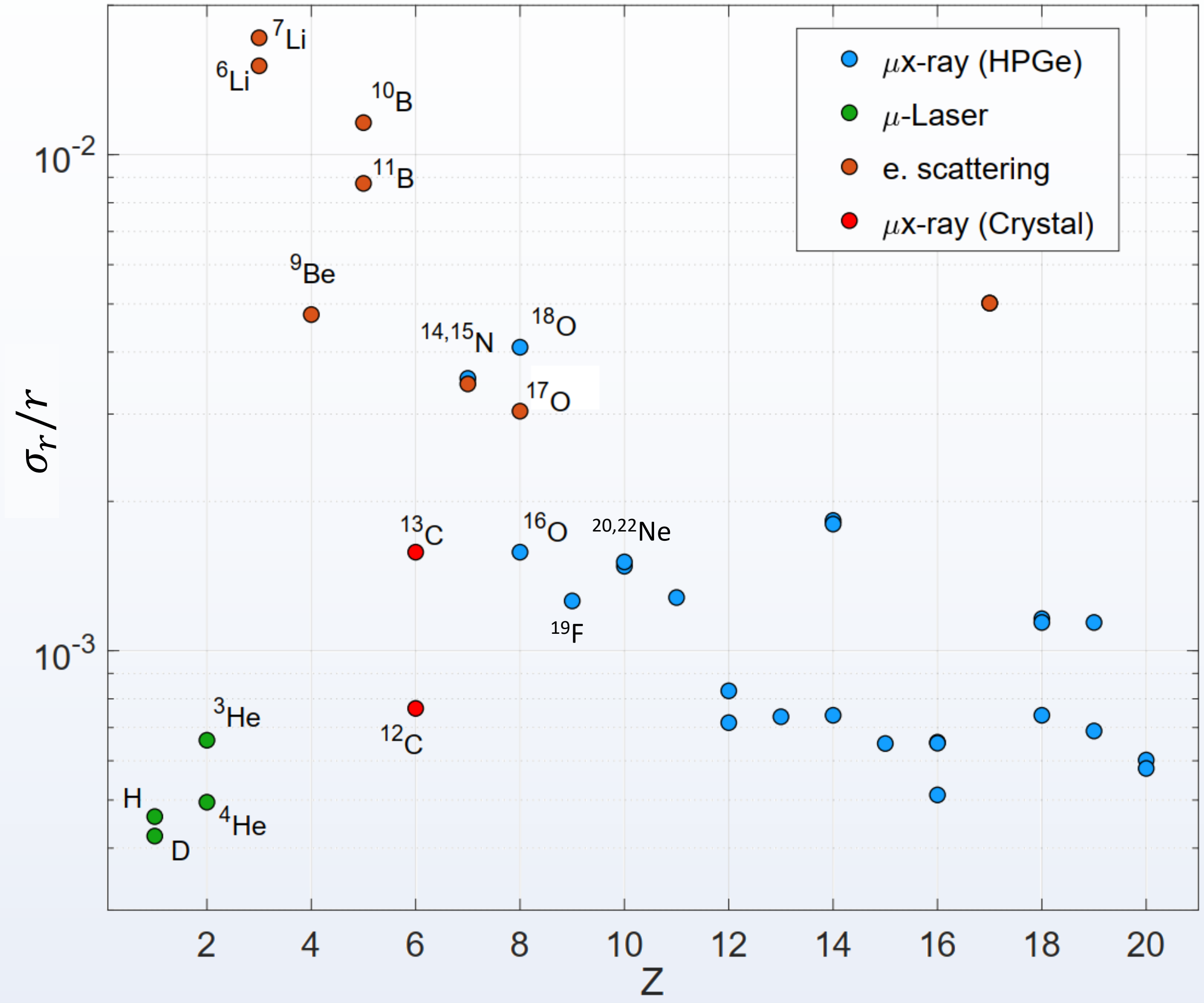

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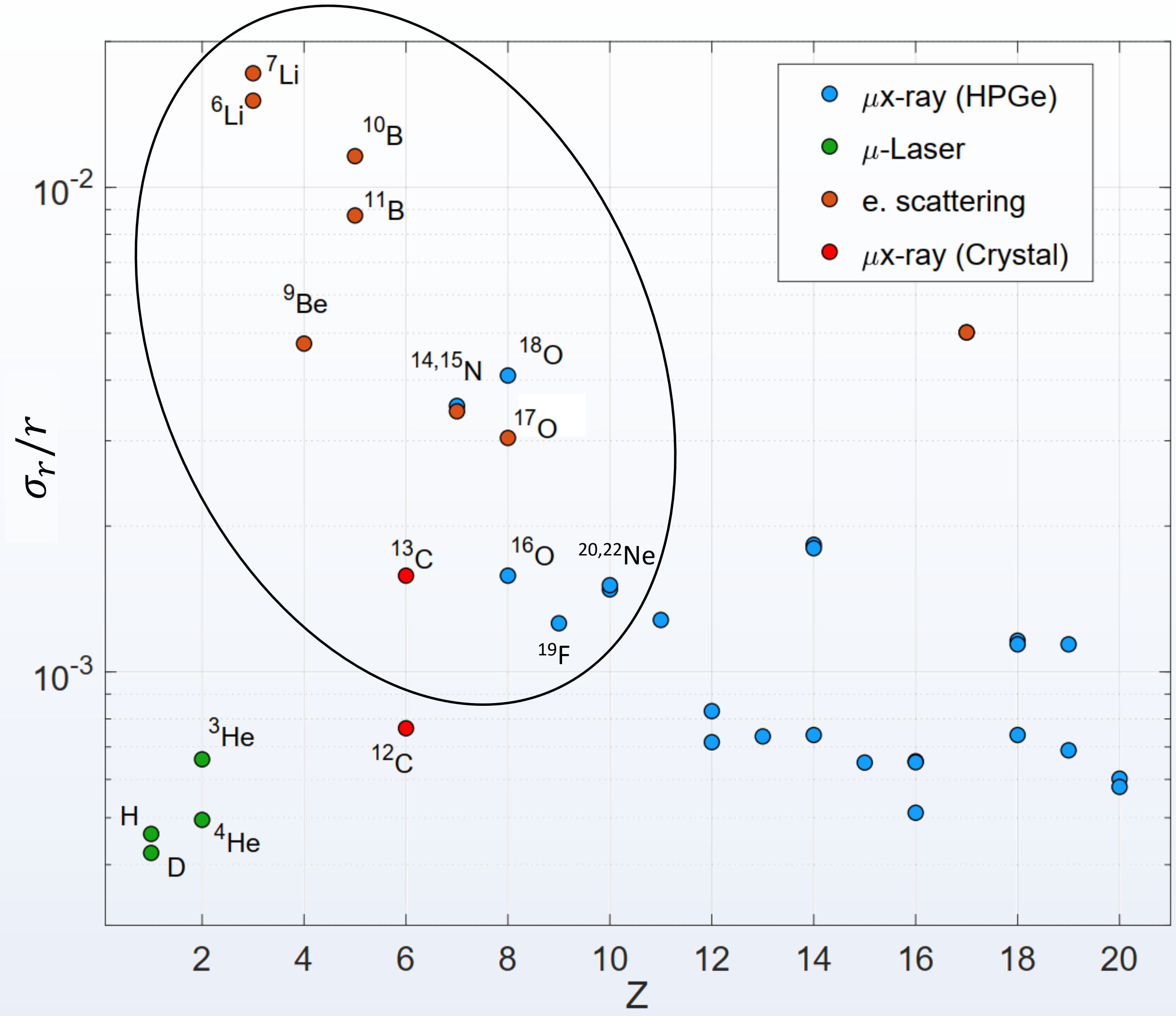

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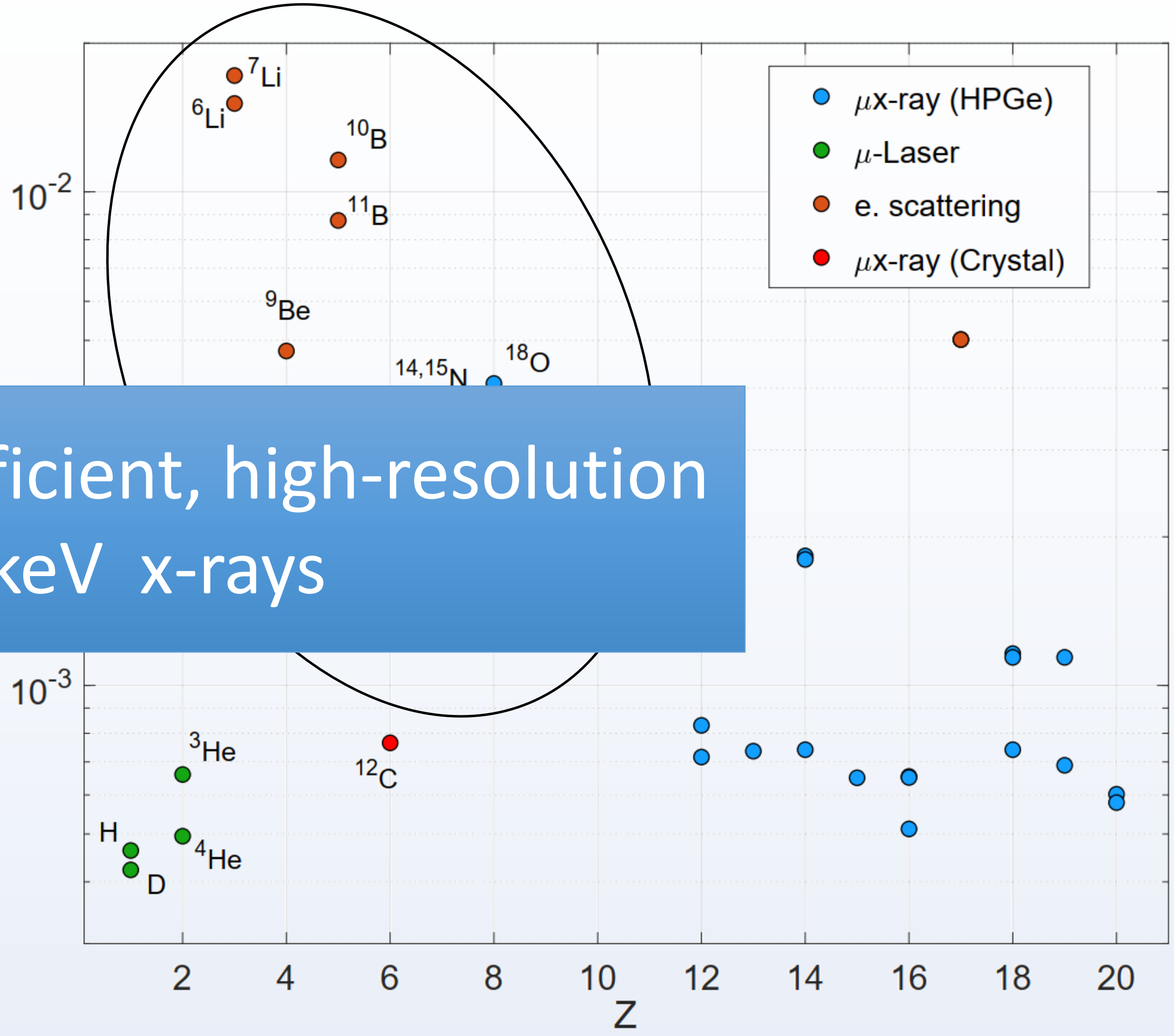
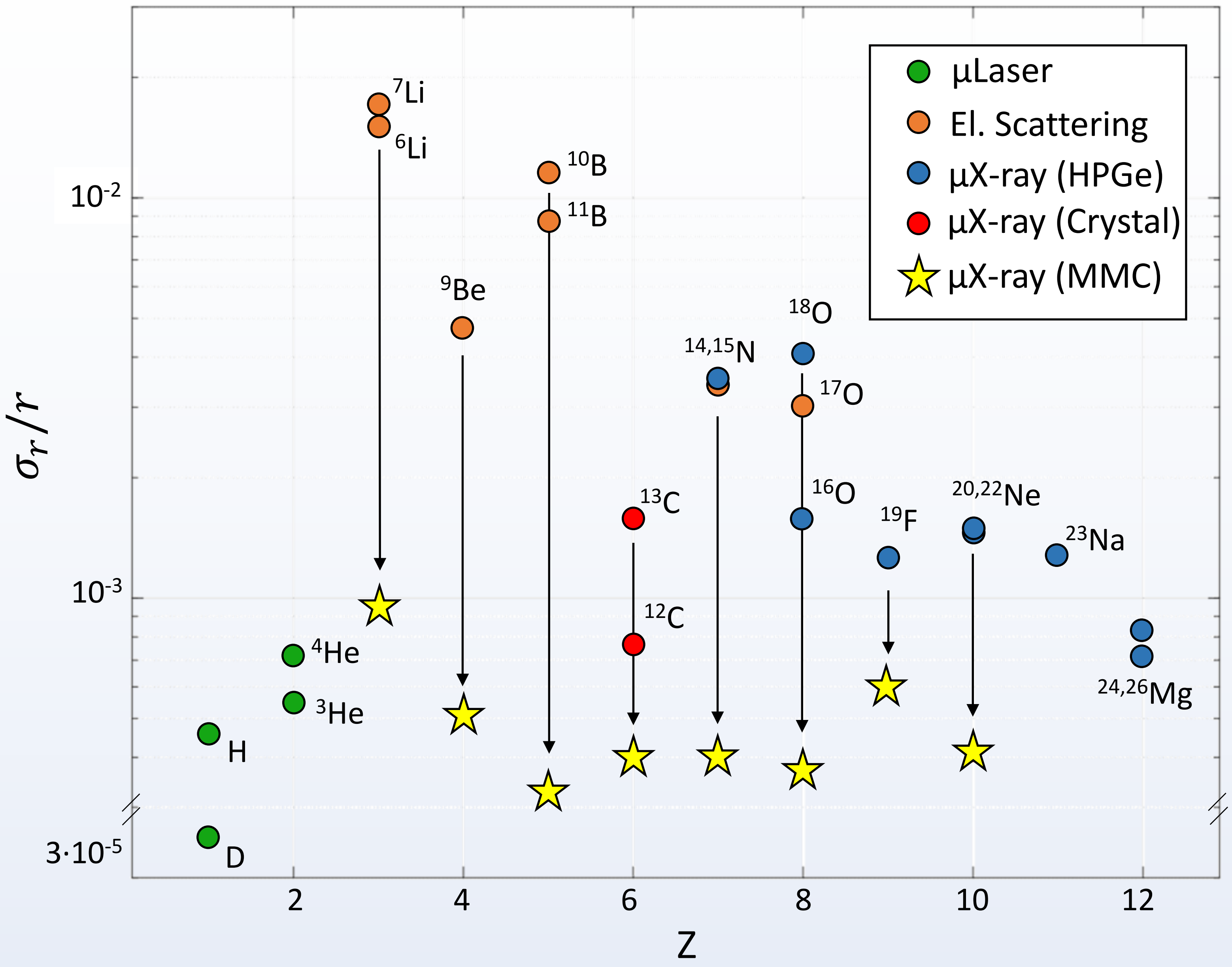


Need broadband, efficient, high-resolution detector for 10-200 keV x-rays

What we will do:

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



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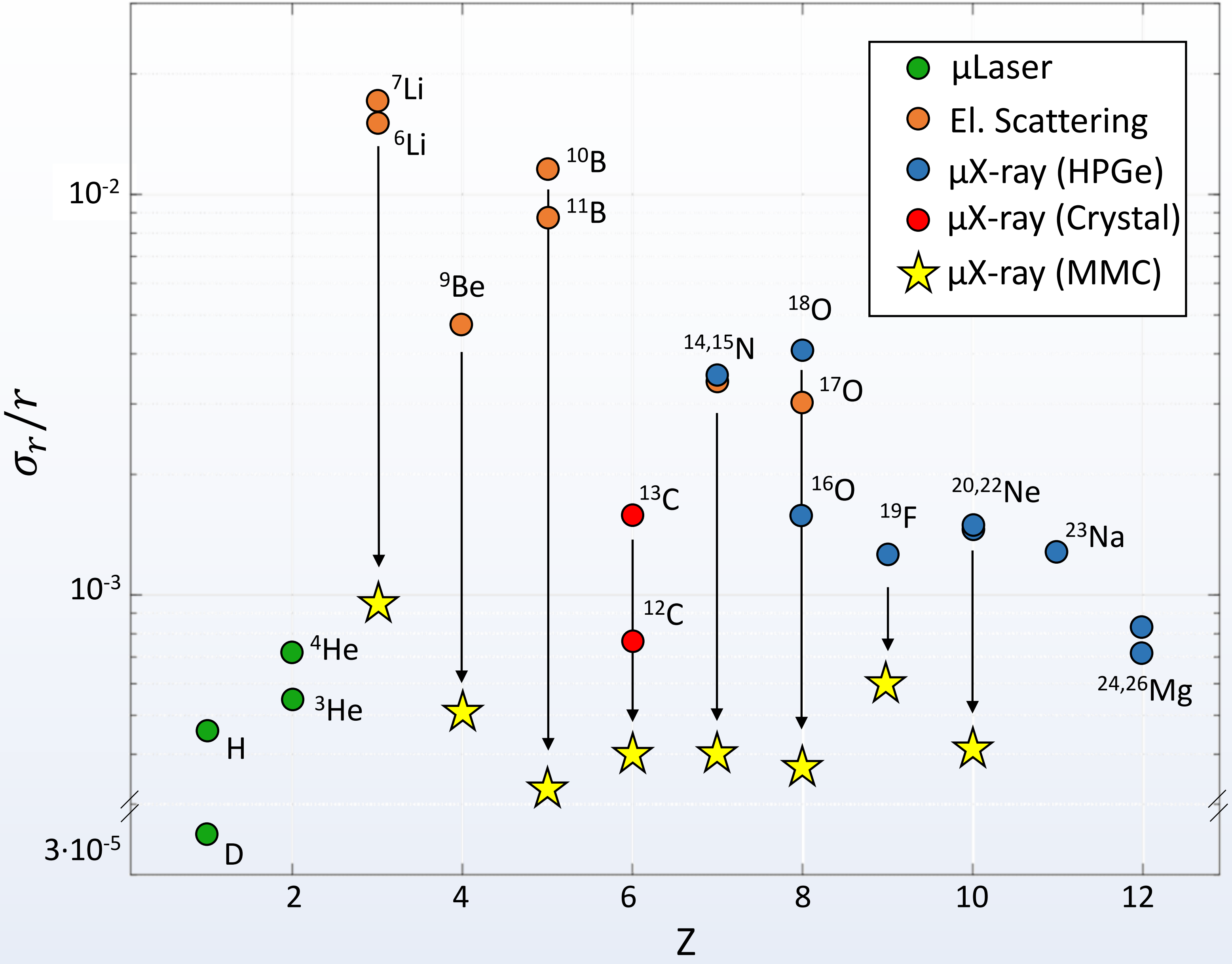

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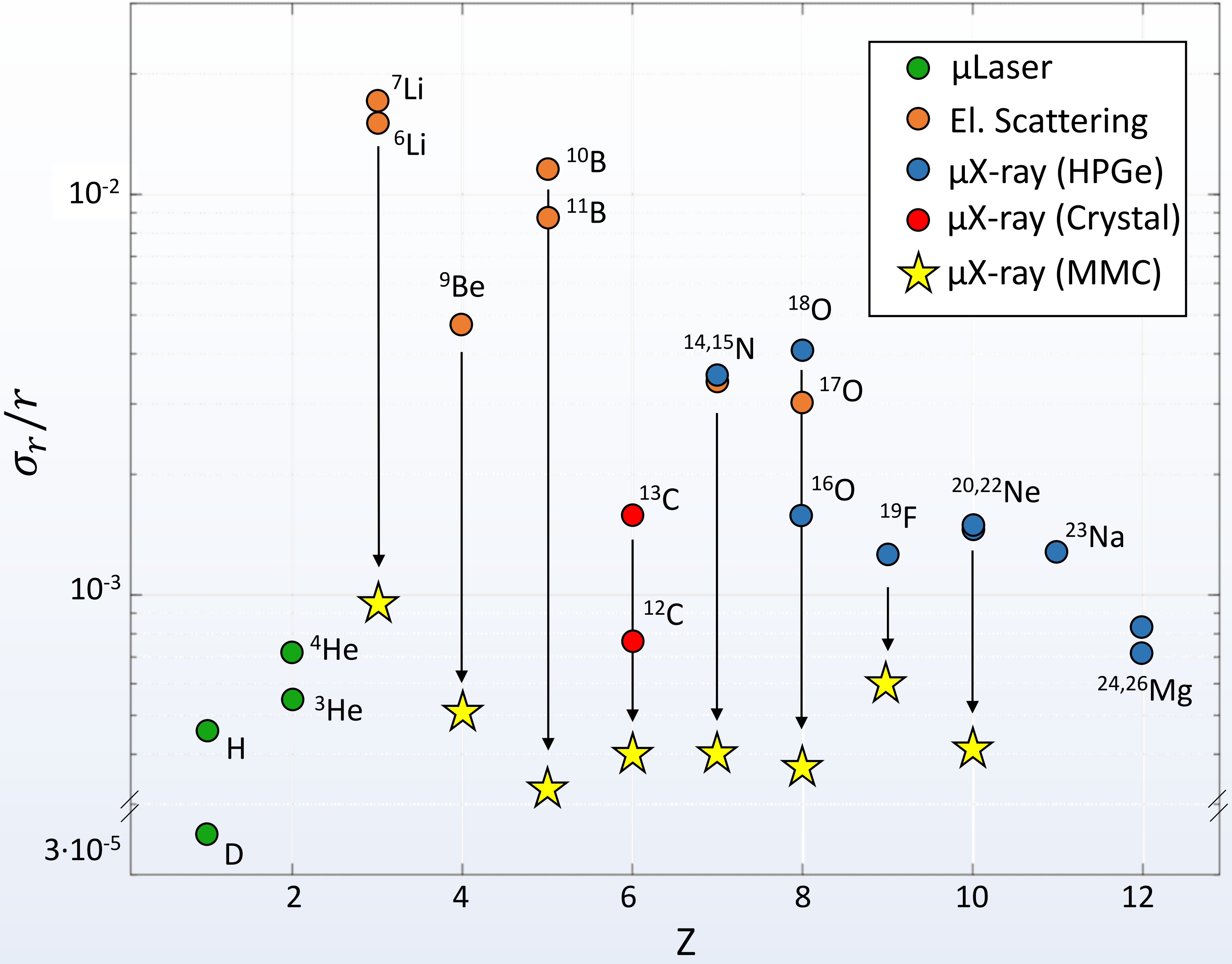
- Enable the next generation of laser spectroscopy of light muonic atoms



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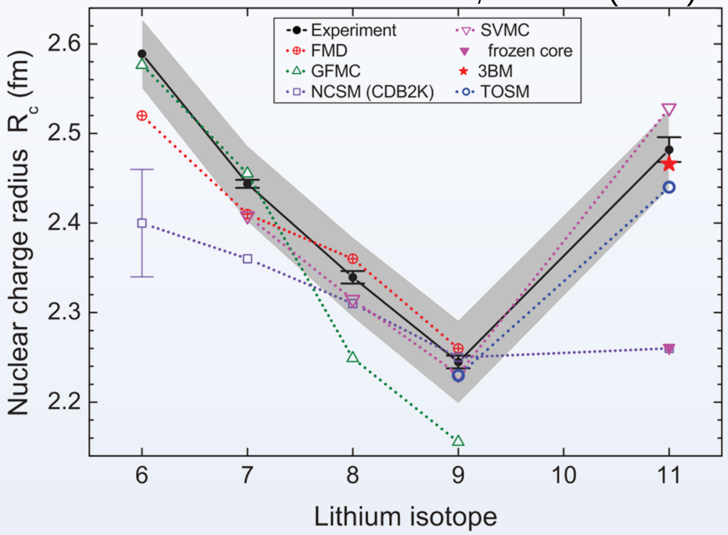
$^{6\text{-}9,11}$Li:

PRC 84, 024307 (2011)



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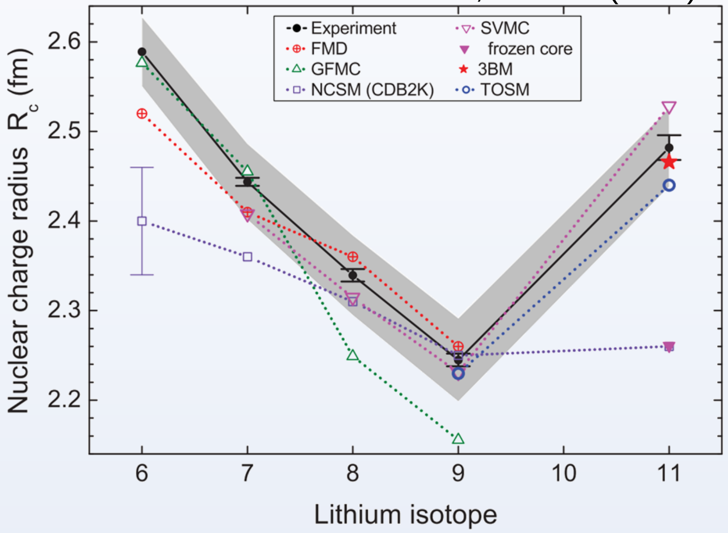

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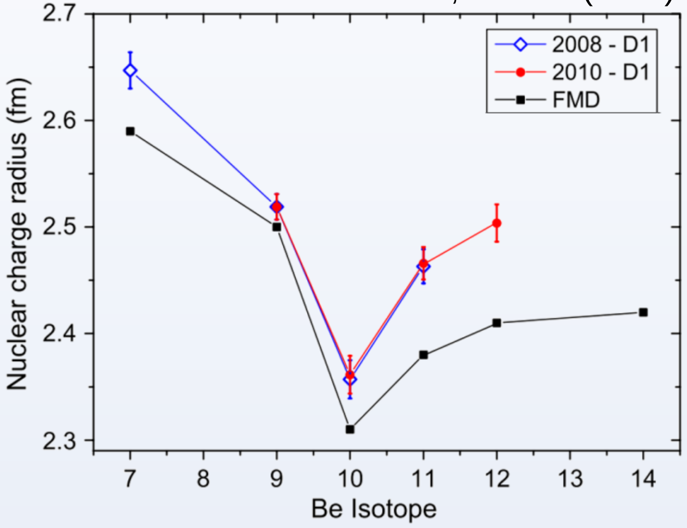

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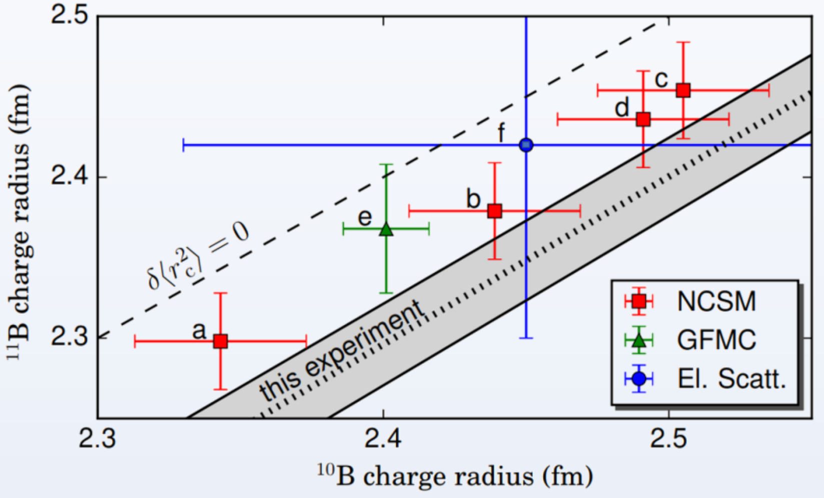

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- Needed fractional accuracy $\sim 5 \times 10^{-3}$ for one stable isotope of Li, Be, and B

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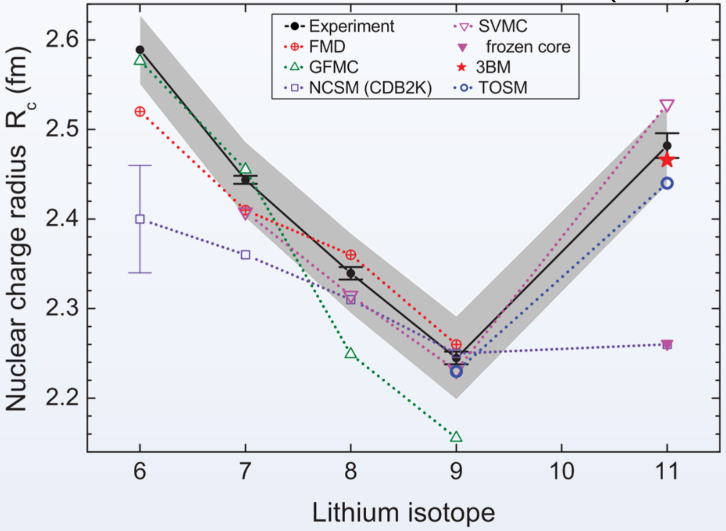

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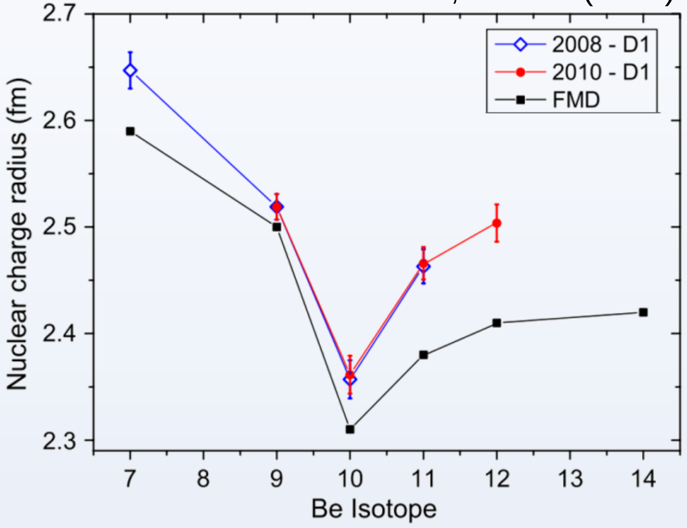

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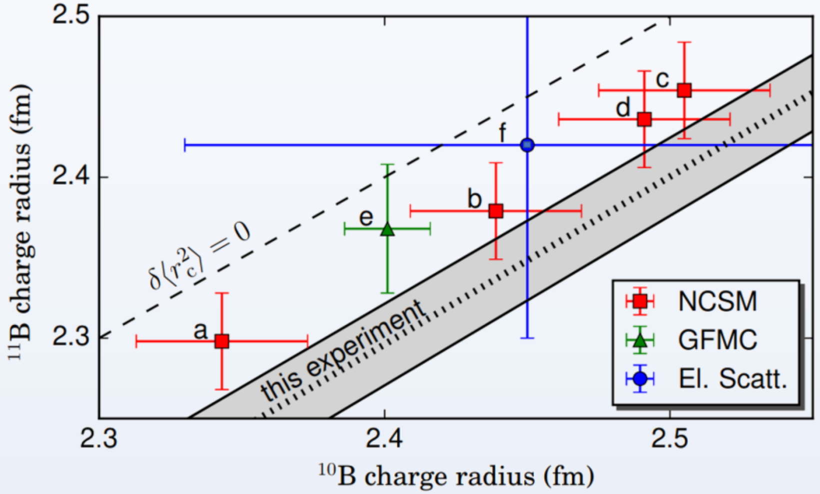

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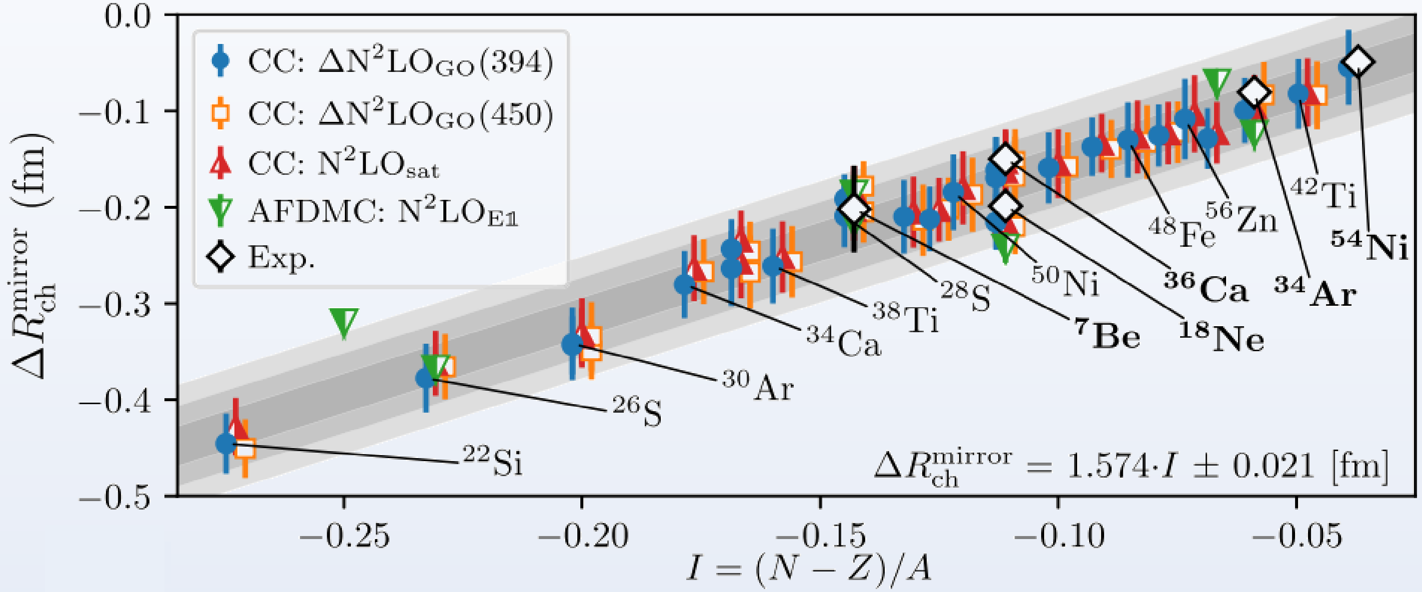
- Vigorous nuclear theory activity, but **scarce measurements,** especially in **light nuclei** with large isospin asymmetry: $I = (N - Z)/A$.

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



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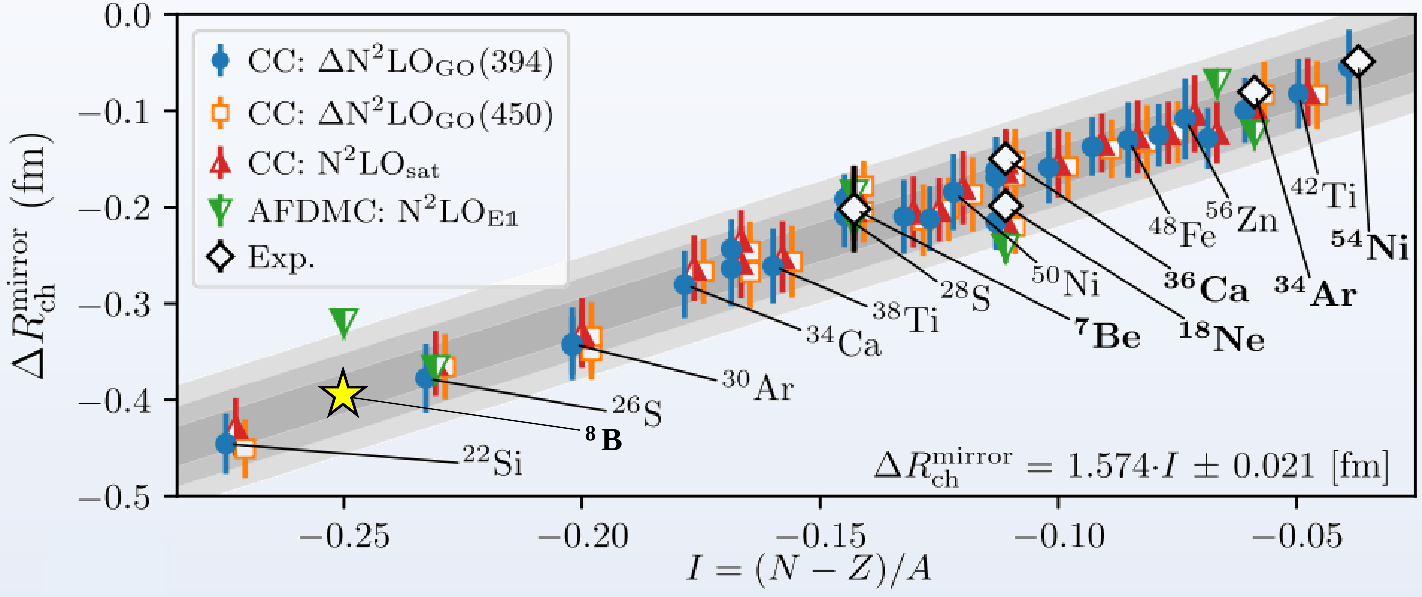
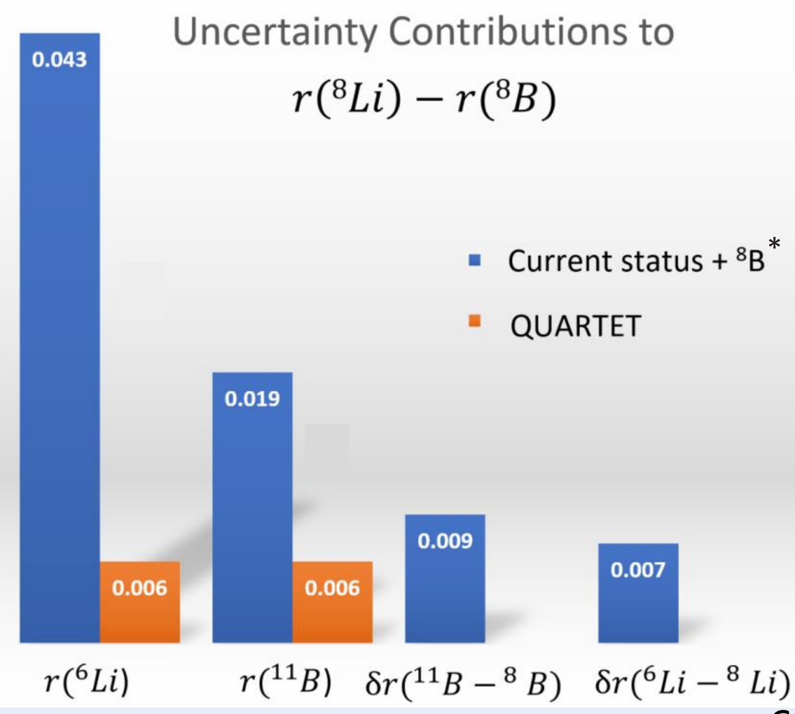


☆ Golden case $I = 0.25$:



*Priv. Com. With W. Nörtershäuser

Physics case 3: QED with Helium like ions

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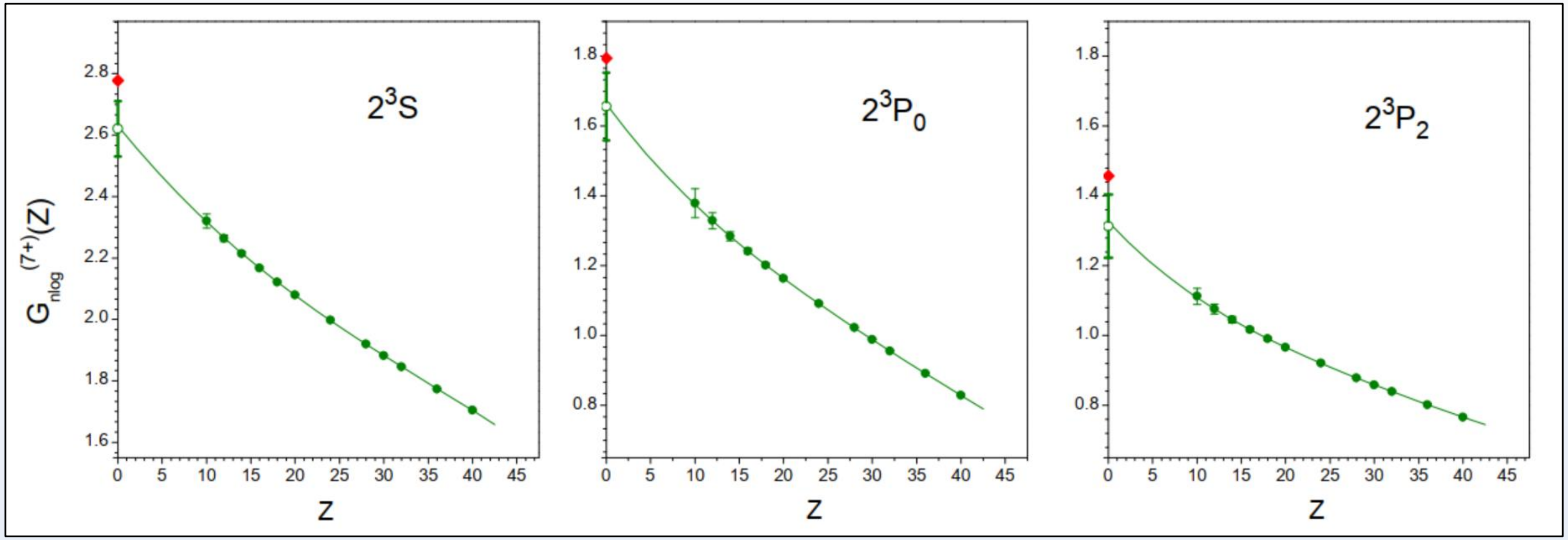
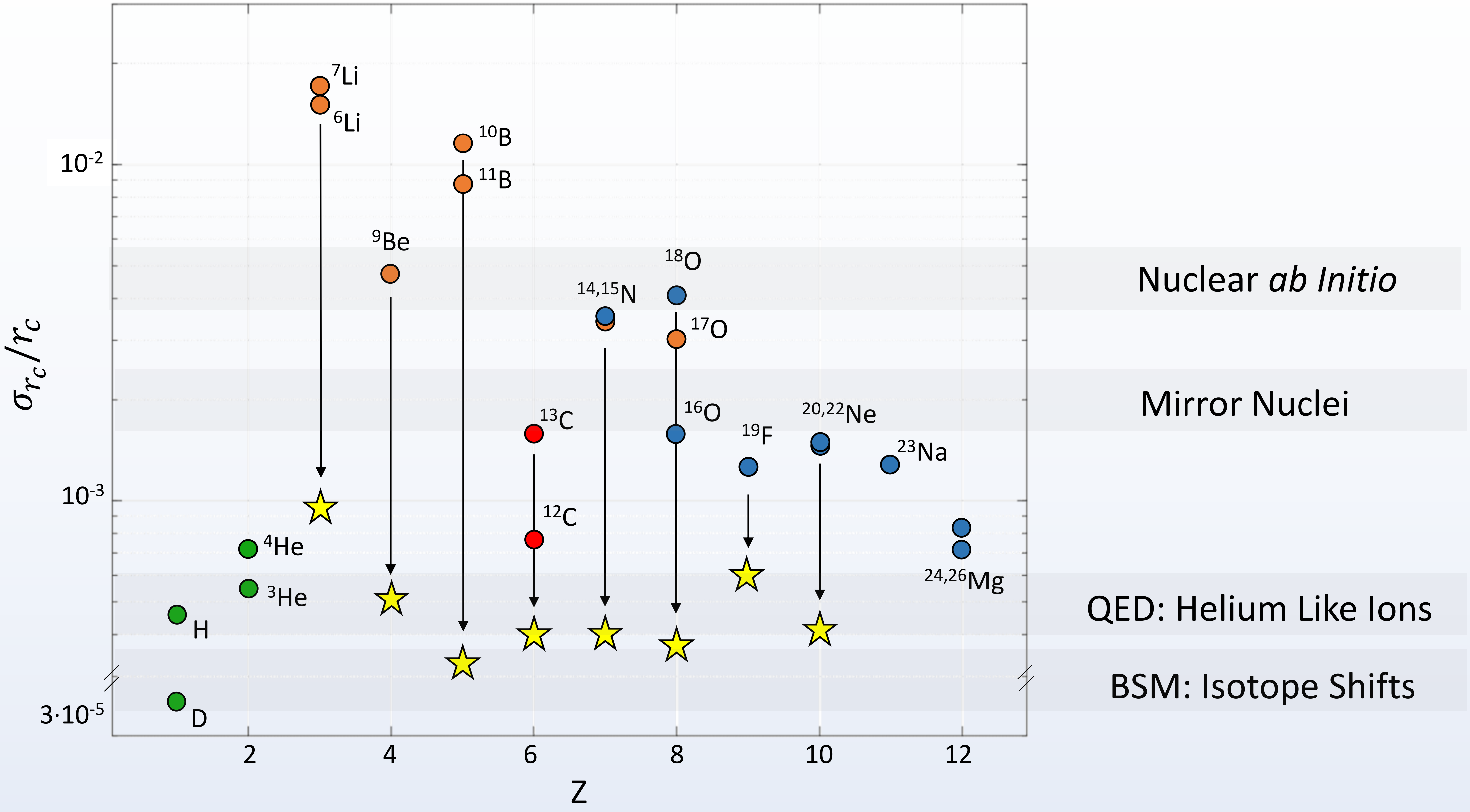
- Shed light on the deviation in the high-order QED contribution between all order-methods (green) and NRQED (red)



A. Yerokhin, V. Patkóš, K. Pachucki, arXiv:2211.17062 (Nov 2022)

Accuracy goals of physics cases:



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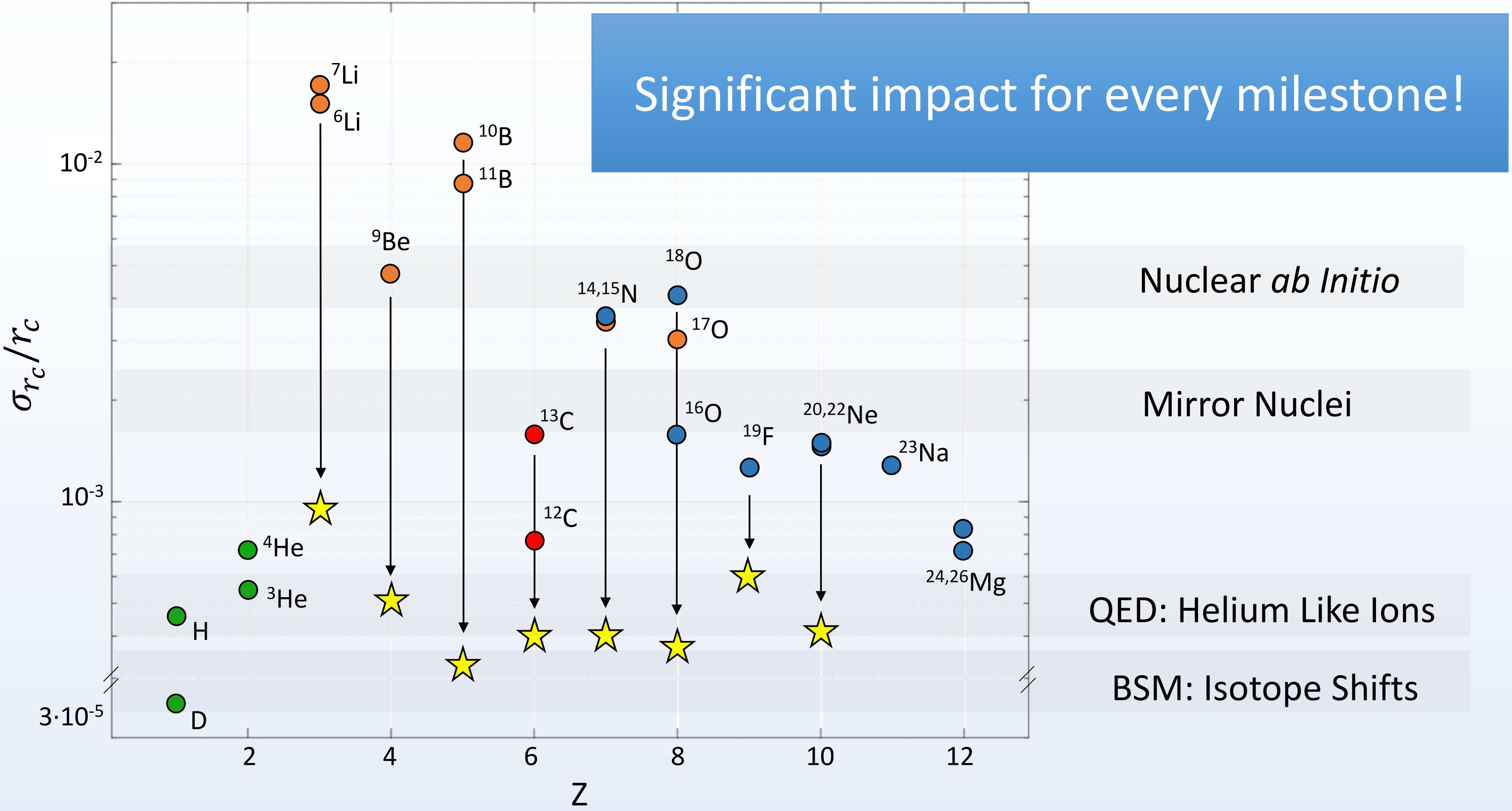
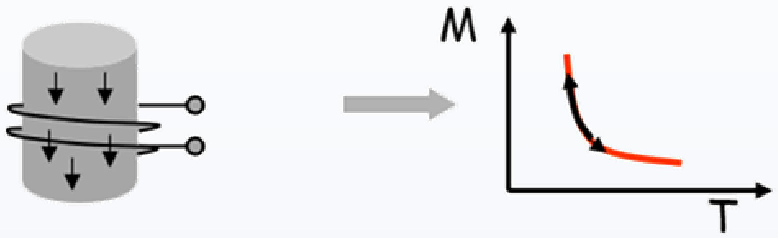


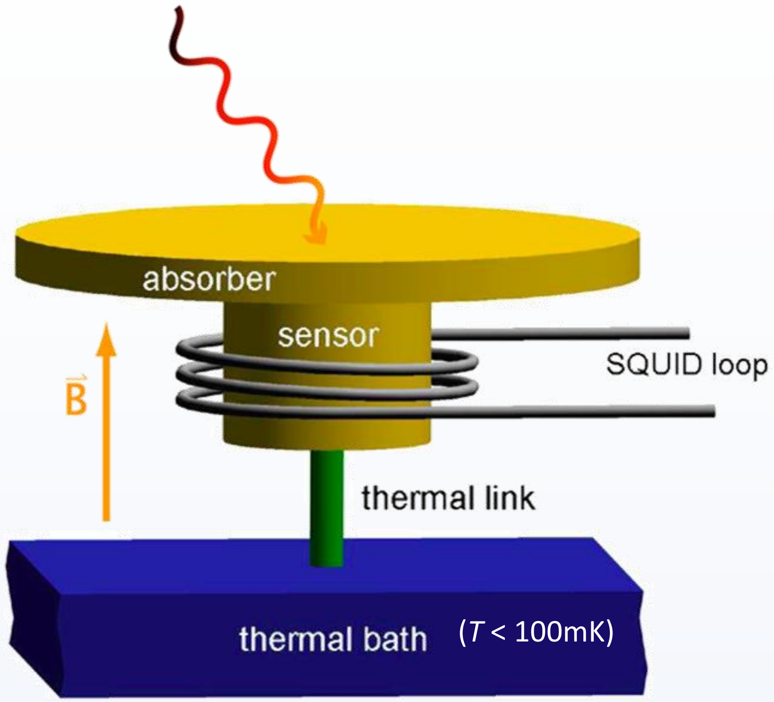
Metallic Magnetic Calorimeters (MMCs)

Temperature change

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

Magnetization of paramagnetic material:





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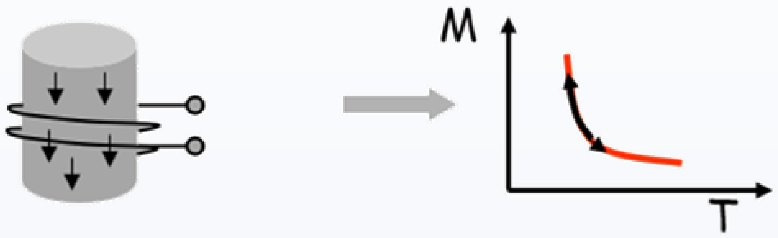

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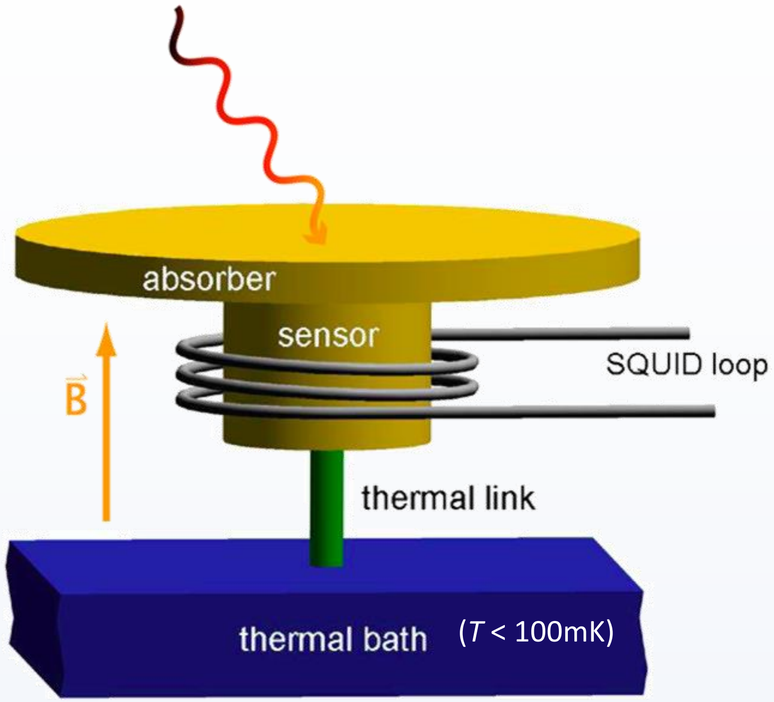
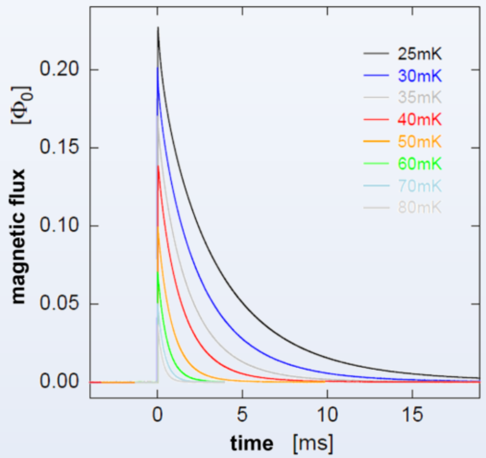
Relaxation to bath temperature

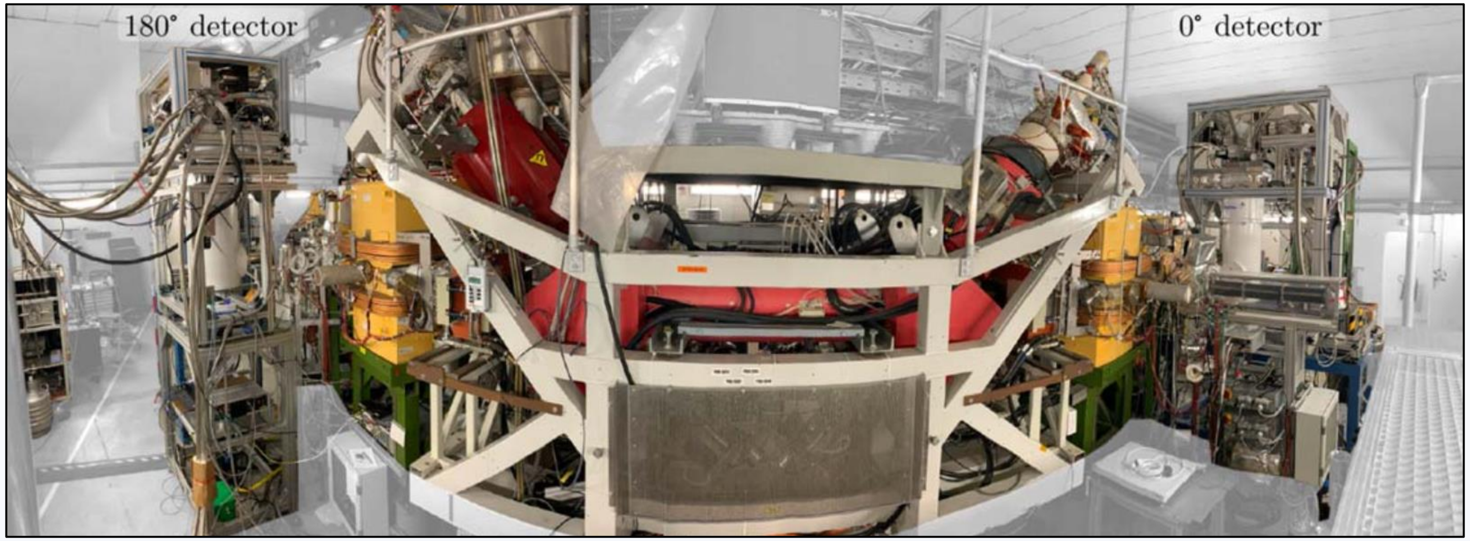
$$\tau = \frac{C_{\mathrm{tot}}}{G}$$





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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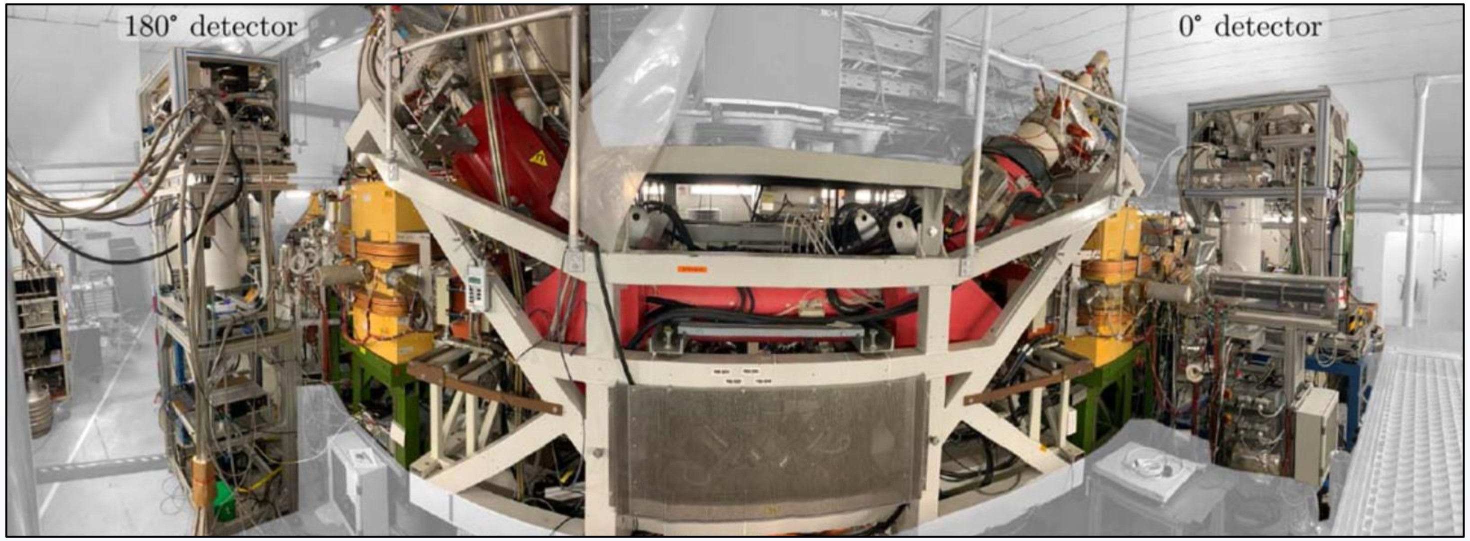

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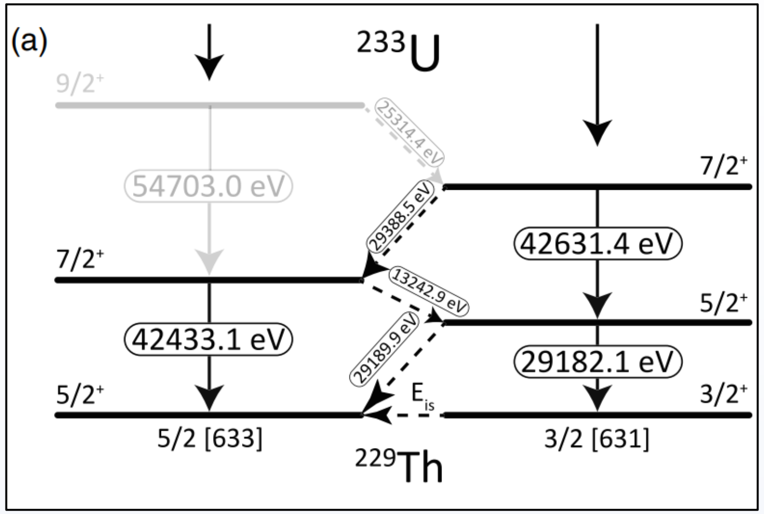
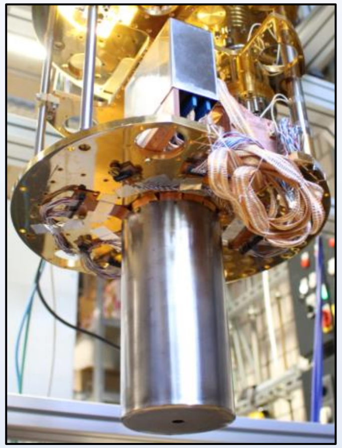
^{229m}Th optical excitation energy 8.1(2) eV:



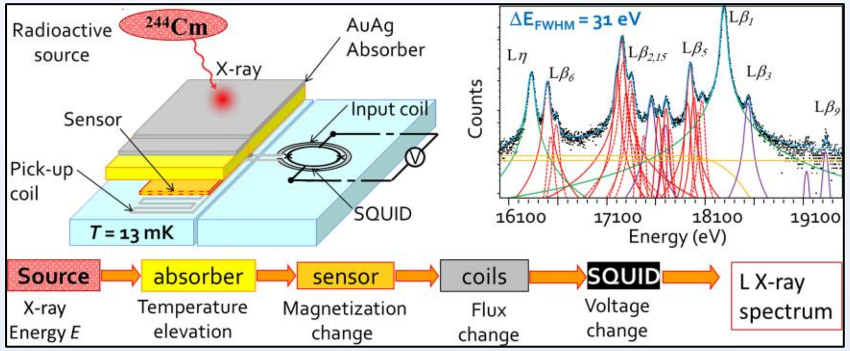
L. Gastaldo, A. Fleischmann, *et. al.,* PRL 125, 142503 (2020)

Search for Axion-like particles:



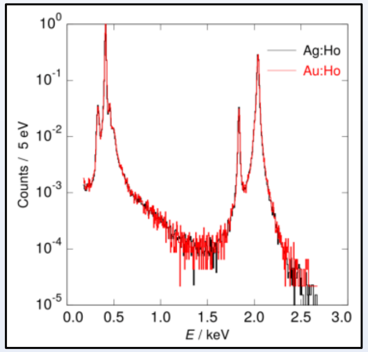
L. Gastaldo, A. Fleischmann, *et. al.,* JINST 16 (2021)

Determination X-ray absolute emission intensities:



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

Electron capture in ^{163}Ho:



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Journal of Low Temperature Physics 209 (2022)

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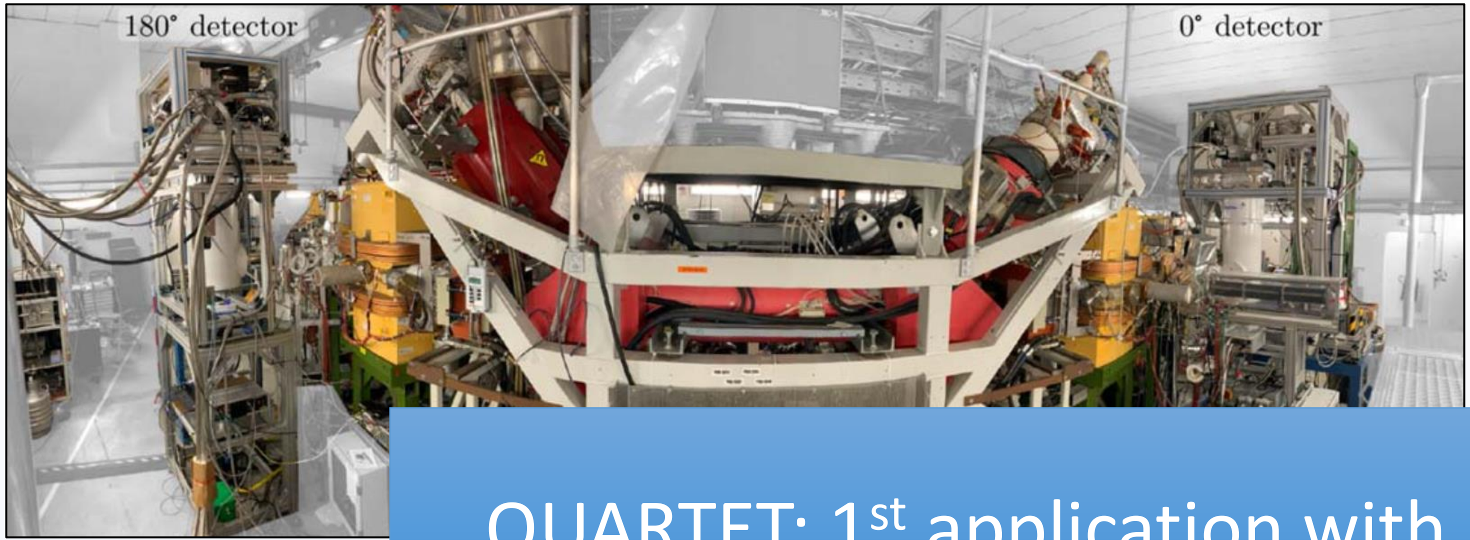

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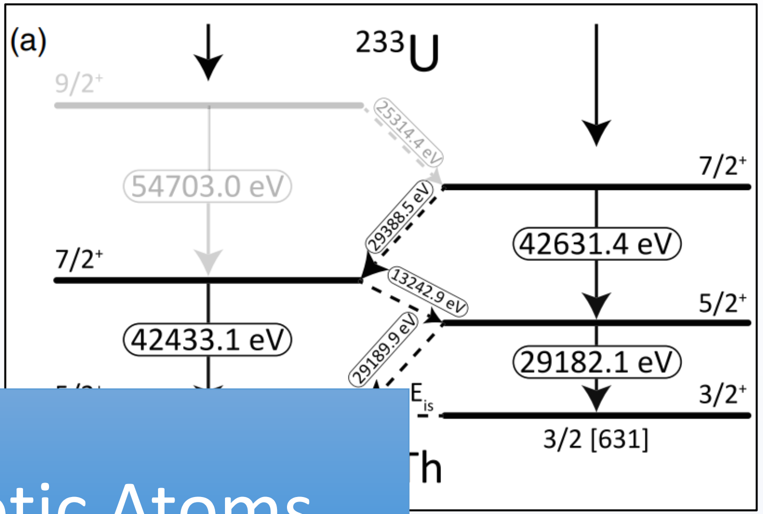

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QUARTET: 1st application with Exotic Atoms

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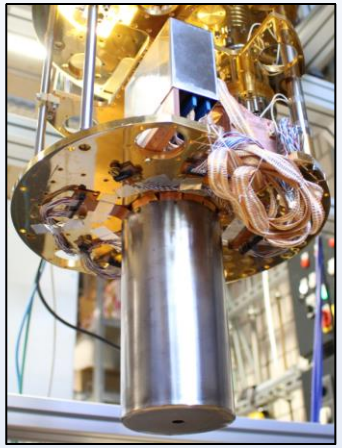

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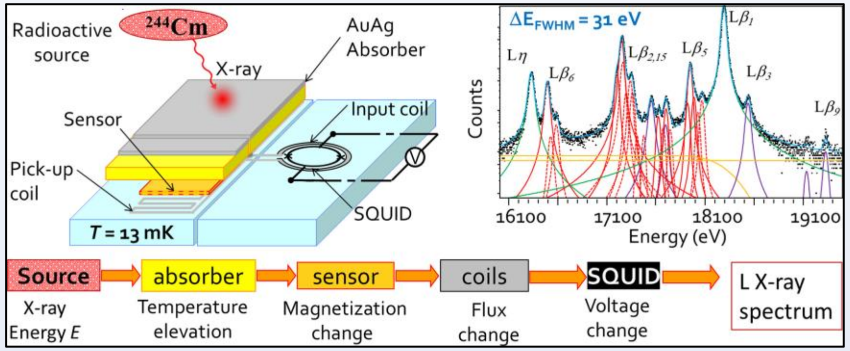

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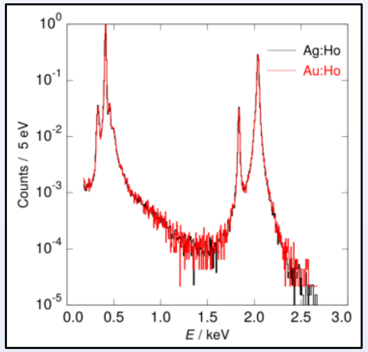
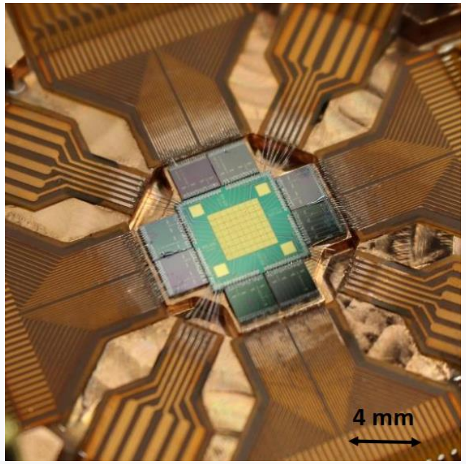


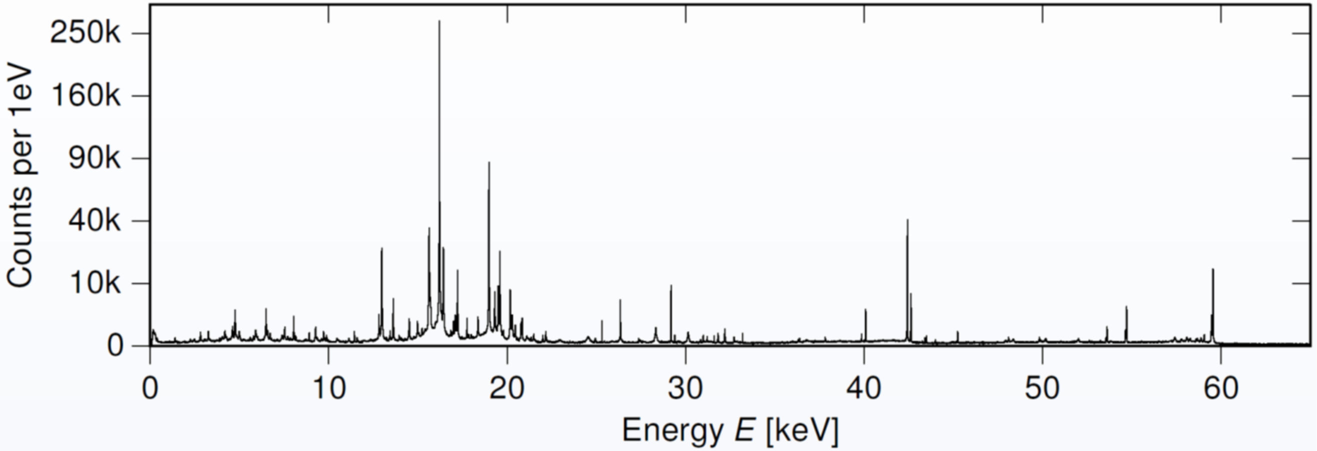
L. Gastaldo, A. Fleischmann, *et. al.*,
Journal of Low Temperature Physics 209 (2022)

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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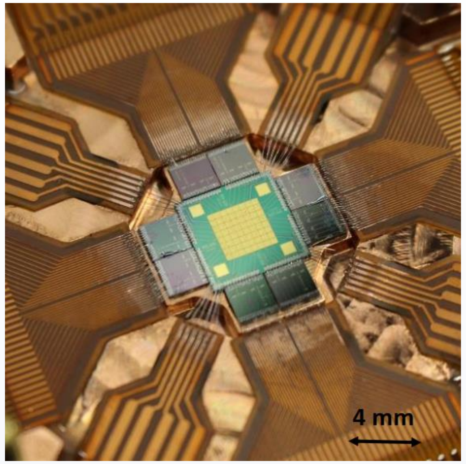

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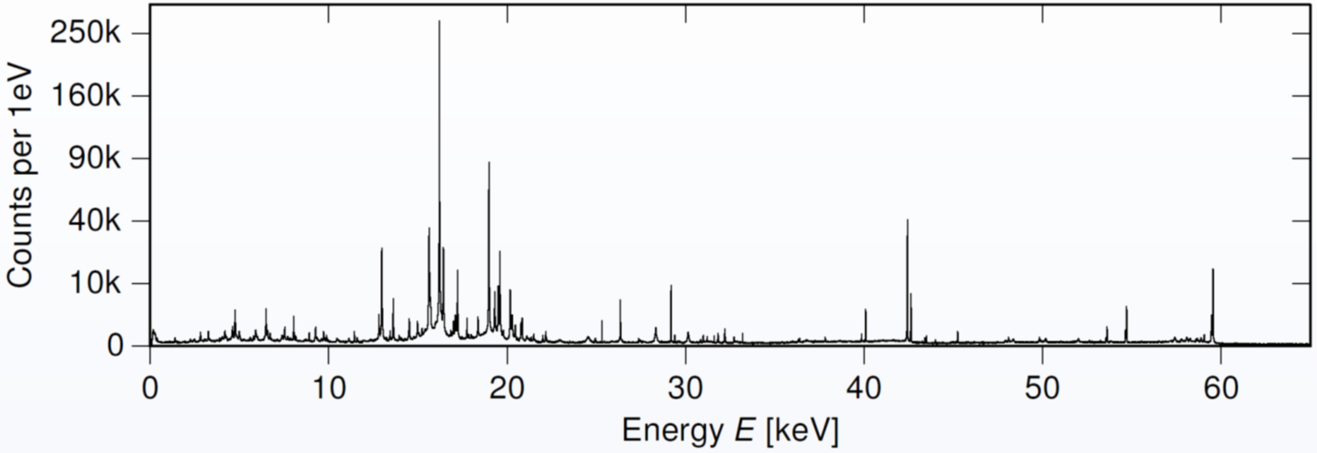
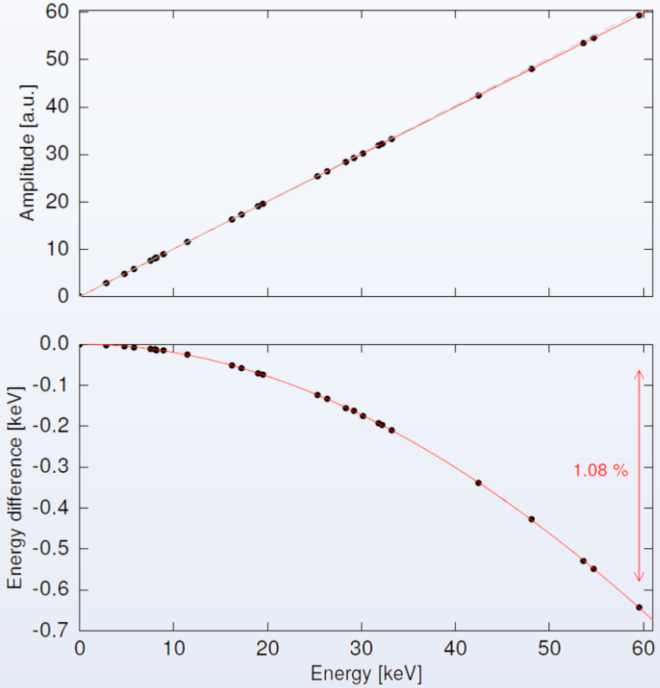
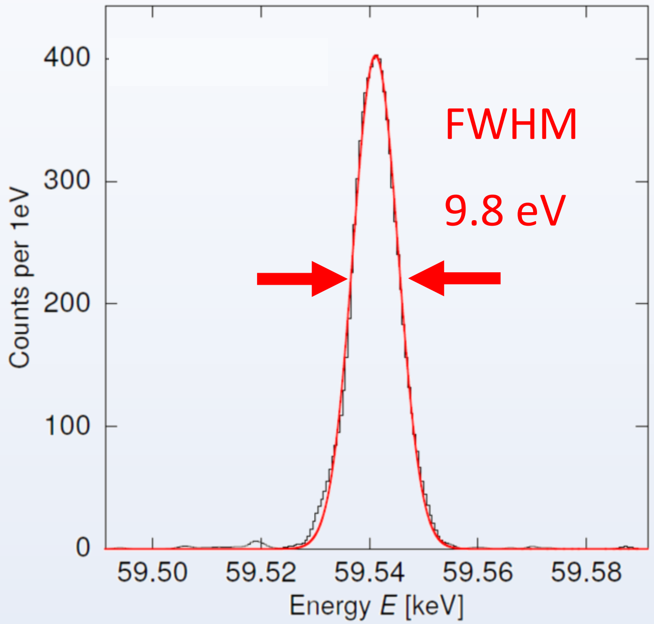


Non-linearity well-understood



World record

resolving power: 6000



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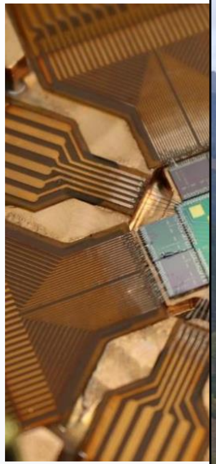

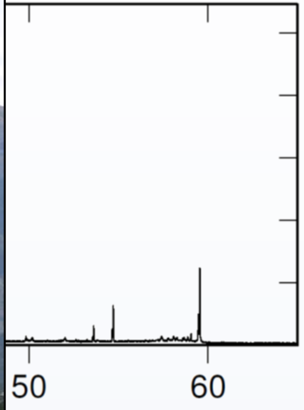

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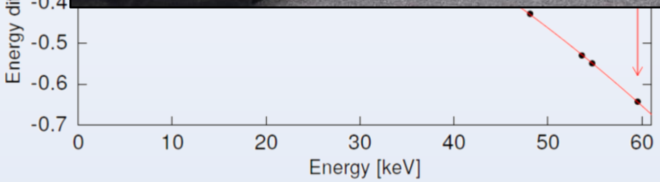
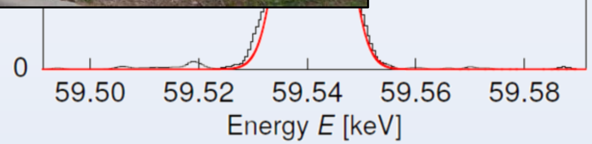
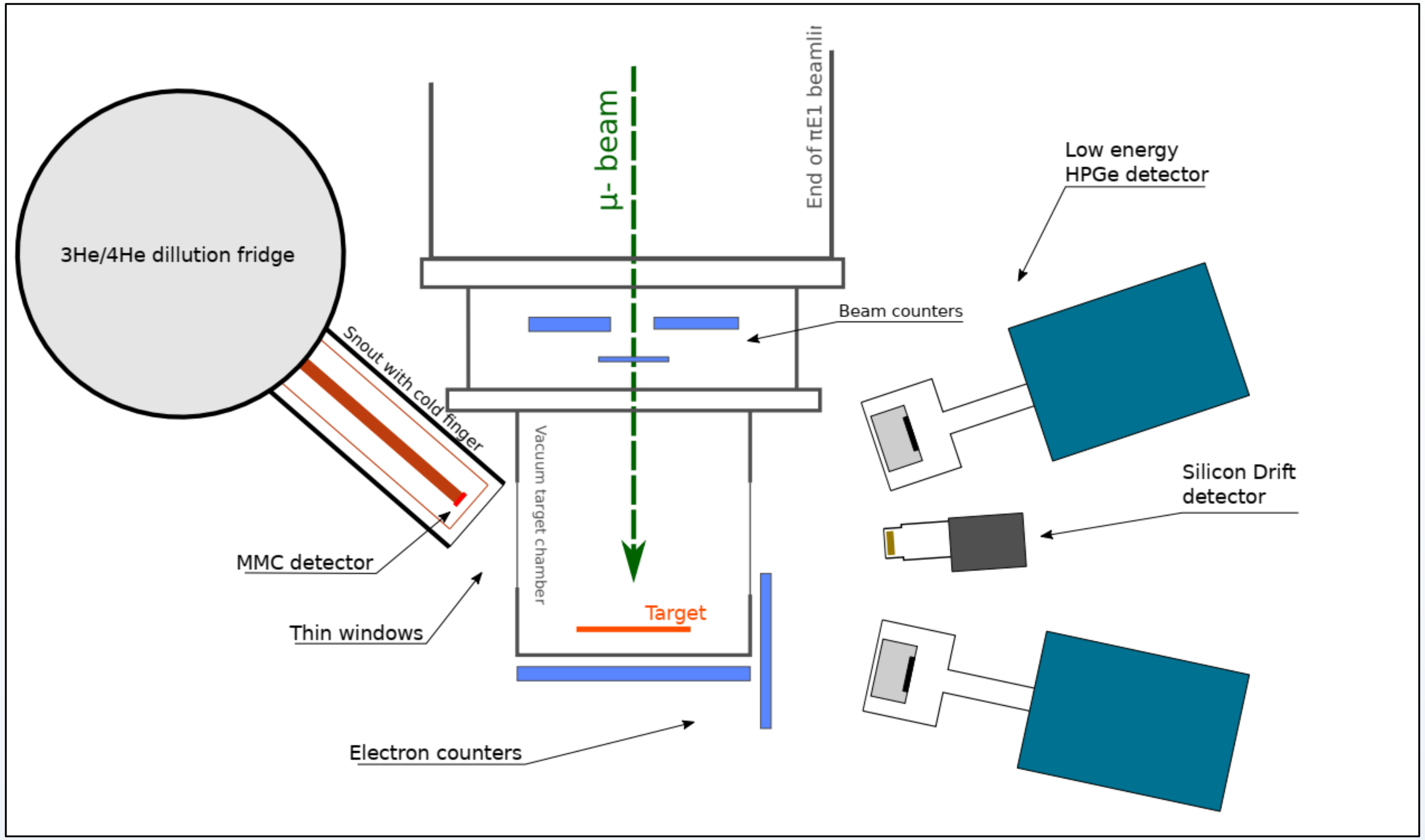




Sketch of test experiment and rates:



Sketch of test experiment and rates:

Expected rates:

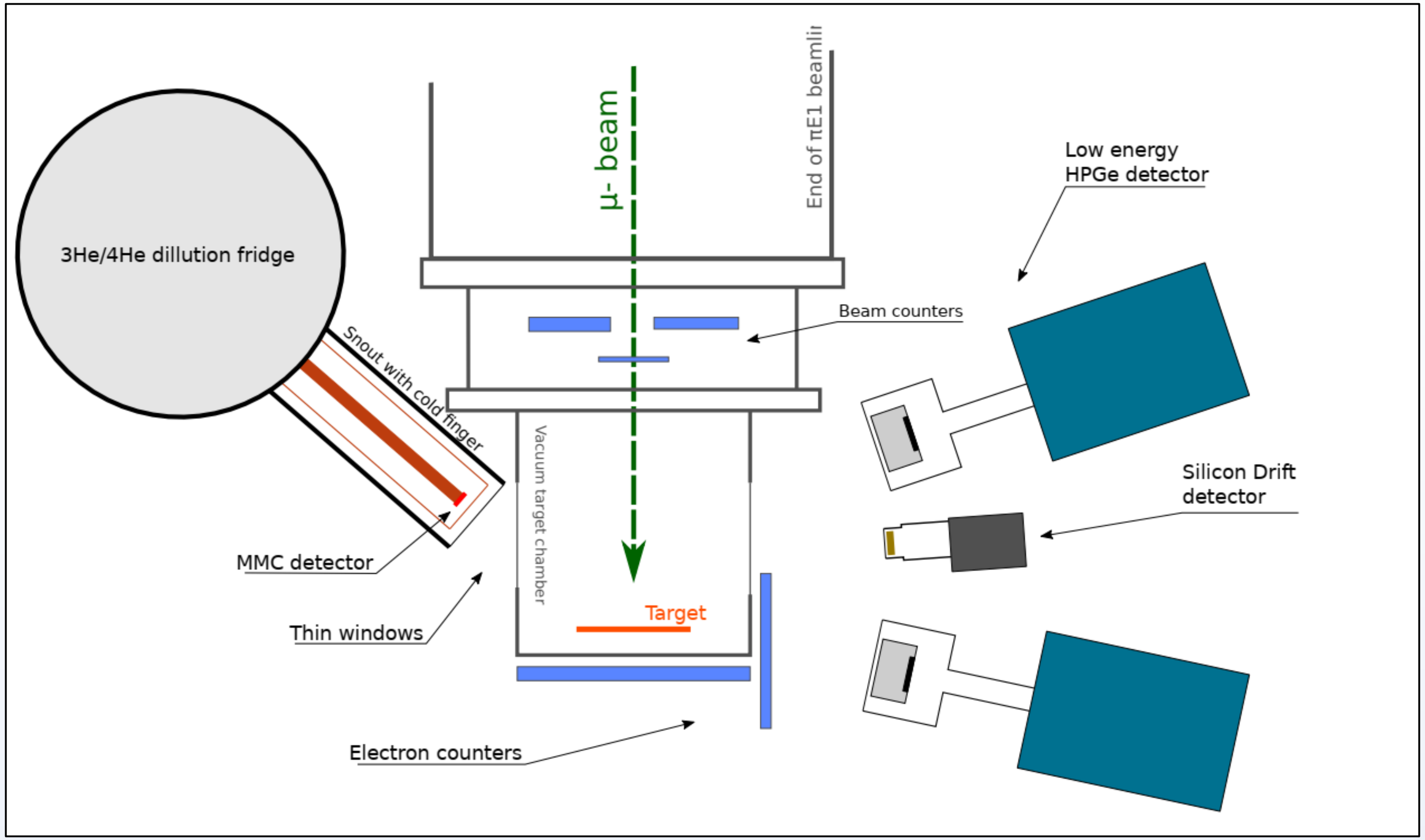
$$0.8 \times 10^{-4} \times \frac{10^3}{s} = 0.1\ event/s$$

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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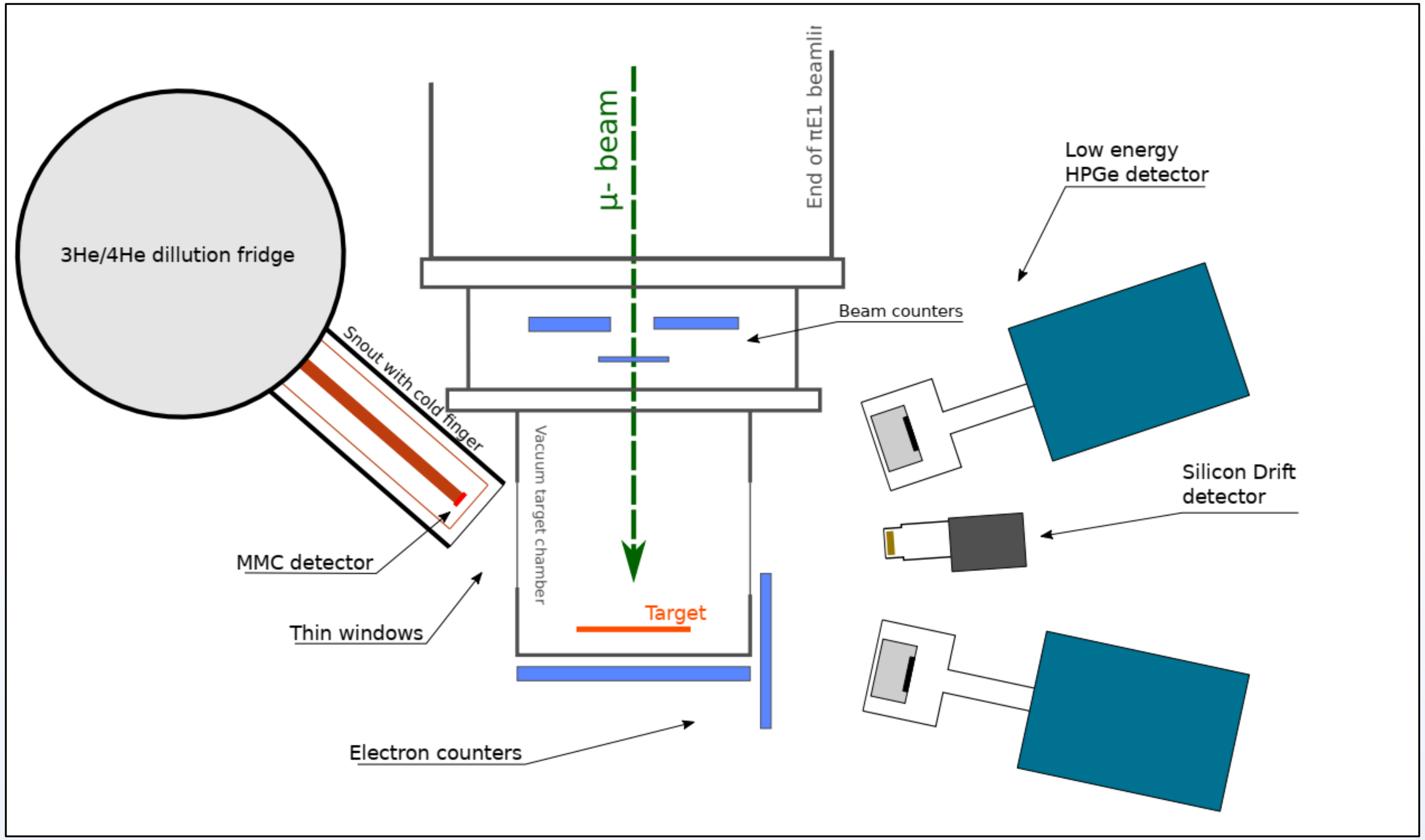
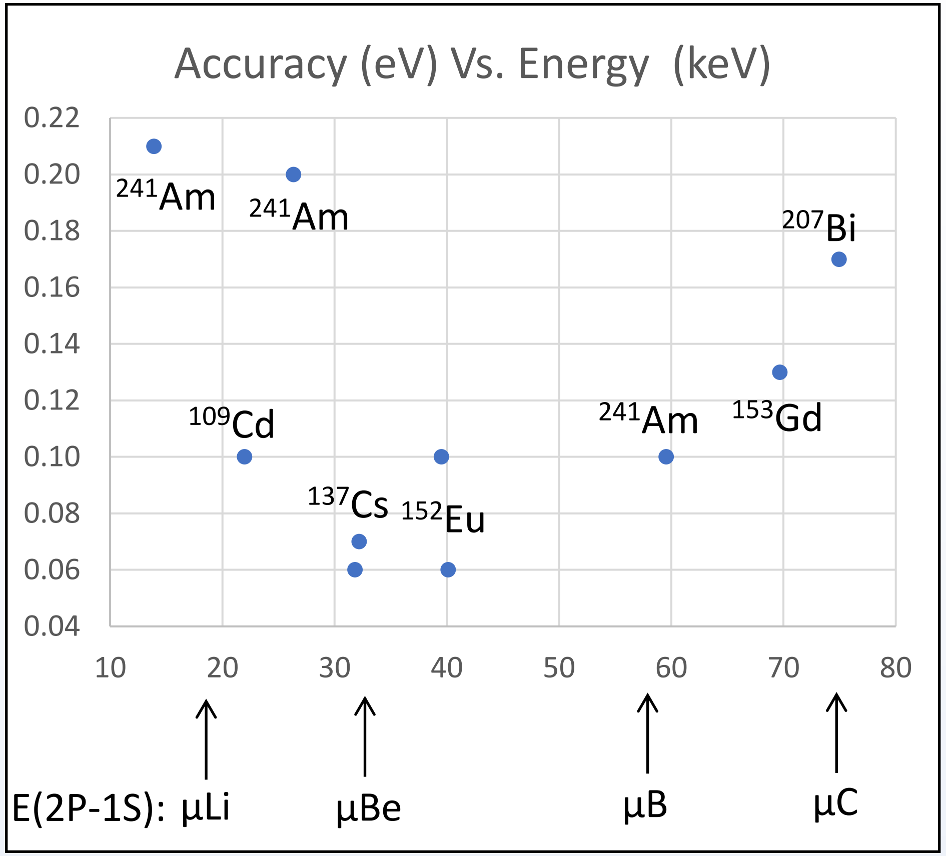


Pileup negligible, statistics more than sufficient.

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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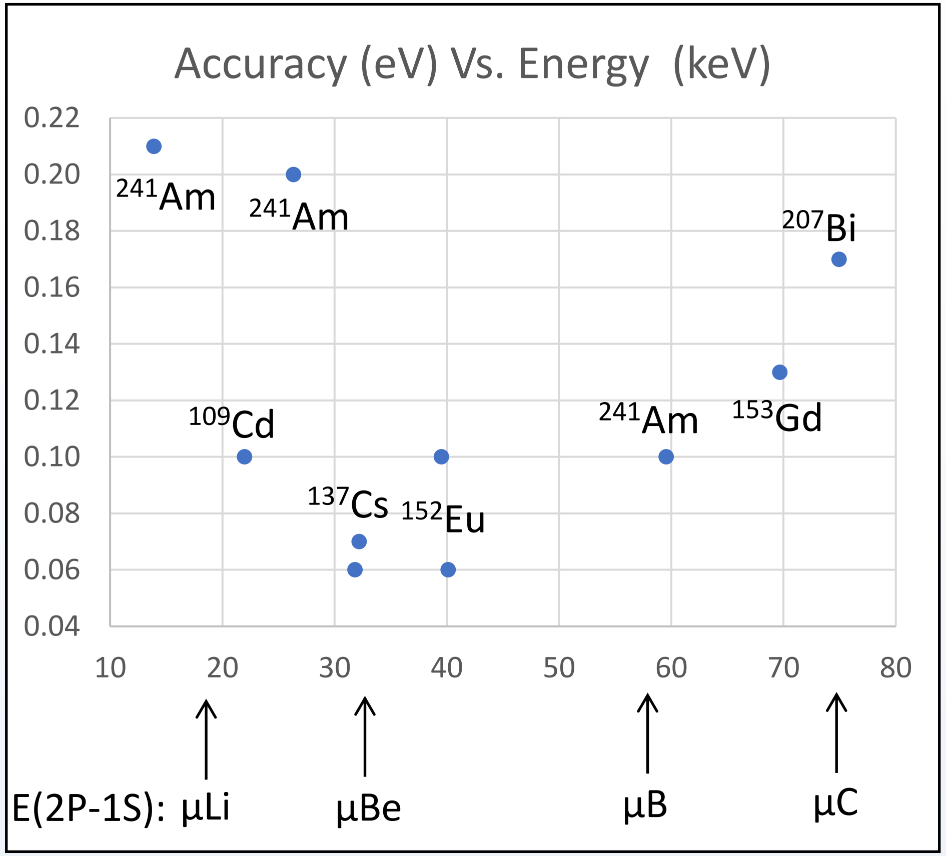

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- Some x-ray transitions very well known:

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

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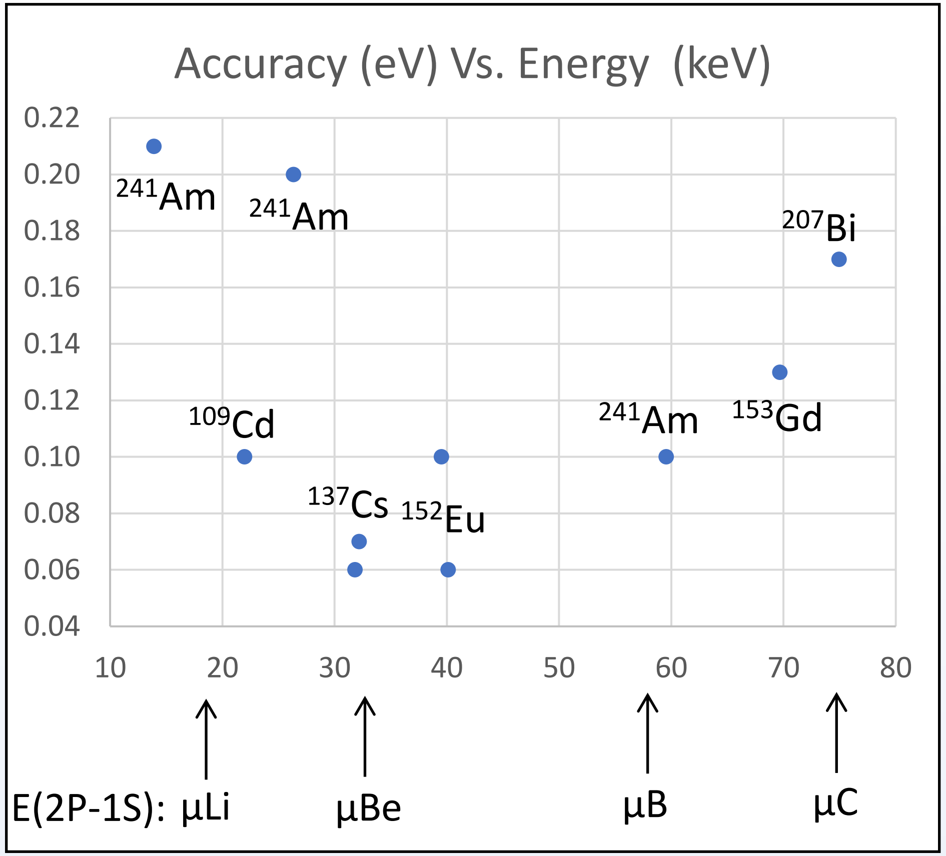

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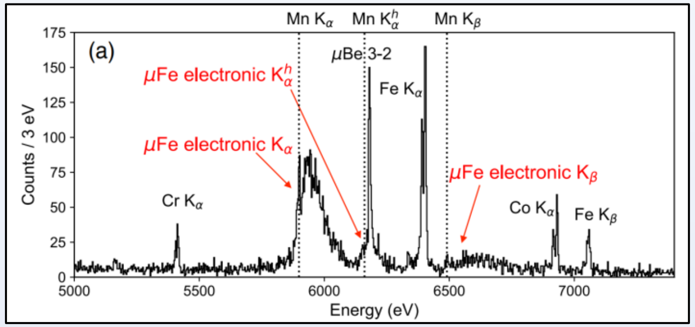
- Successfully implemented at JPARC:



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

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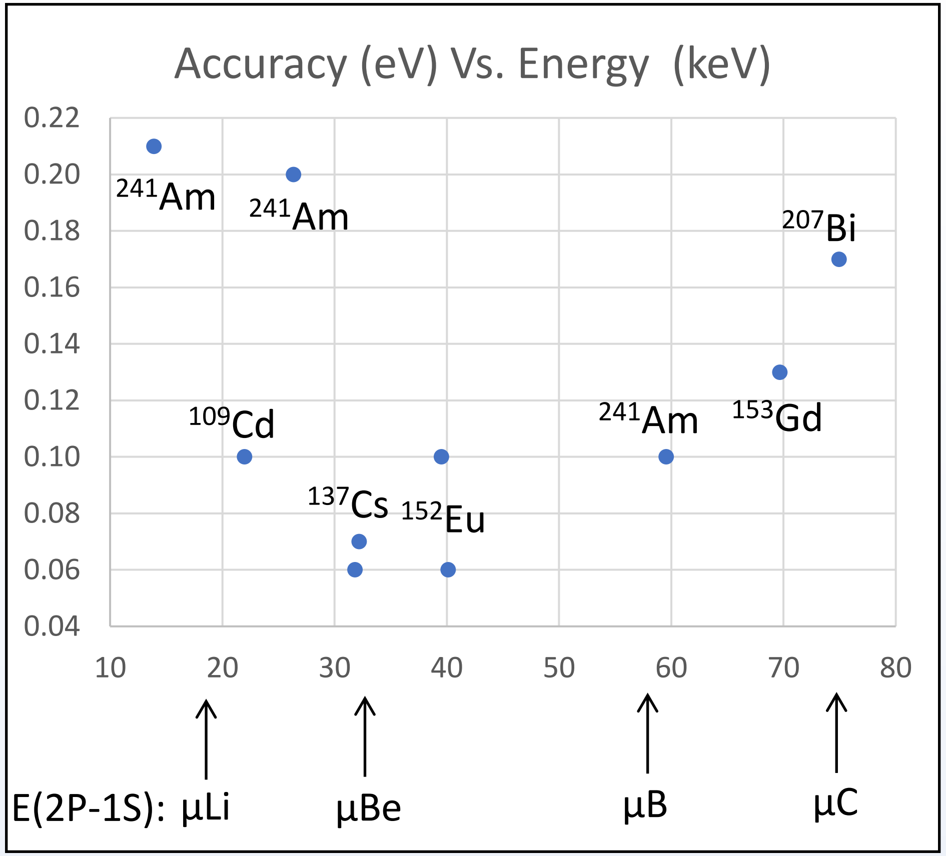

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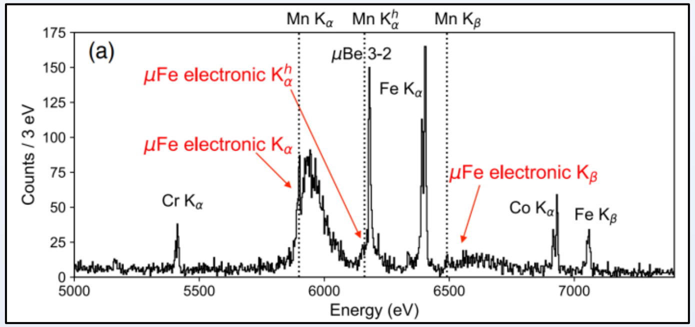
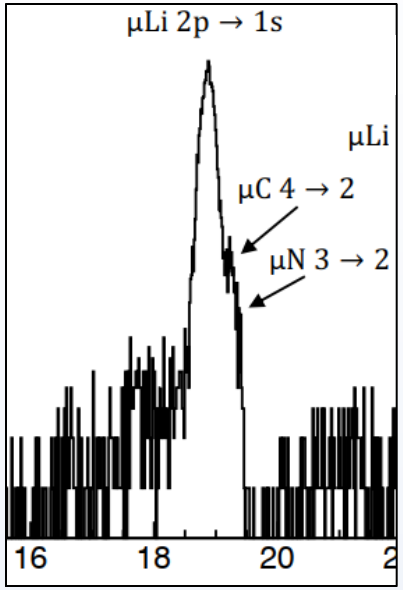


P. Indelicato, N. Paul, *et. al.*, PRL 127 (2021)

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)

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.

Thanks for listening!

QUARTETters in Paris 2022

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 $2\times10^3\,s^{-1}$ 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.

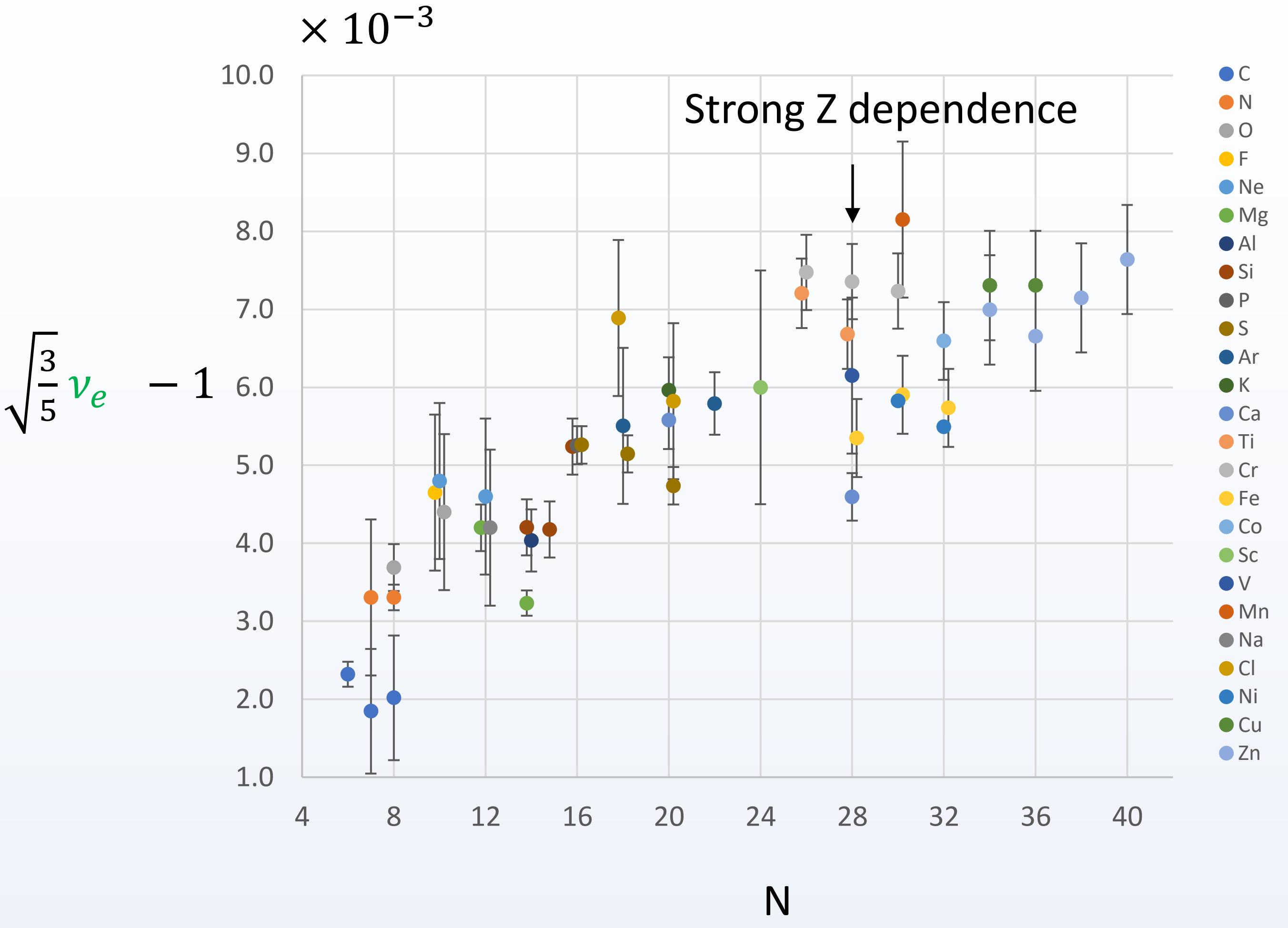
Isotopes	E_{2P-1S} [keV]	FWHM [eV]	σ_{stat} [eV]	σ_{TPE} [eV]	σ_r [am]	$\sigma_{\delta r}$ [am]
^{6,7}Li	19	4	0.01	0.02	2	0.6
^{9}Be	33	12	0.02	0.06	1	
^{10,11}B	52	18	0.02	0.1	1	0.5
^{12,13}C	75	36	0.05	0.3	1	0.7
^{14,15}N	102	39	0.05	0.6	1	0.7
^{16,18}O	134	45	0.06	1	1	0.5
^{19}F	169	50	0.07	2	2	
^{20,22}Ne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

ETH zürich

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 $\nu_e = \frac{r_e}{R_e} \rightarrow \sqrt{\frac{5}{3}}\,(\text{sphere})$
- 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

Input from Nuclear Theory:

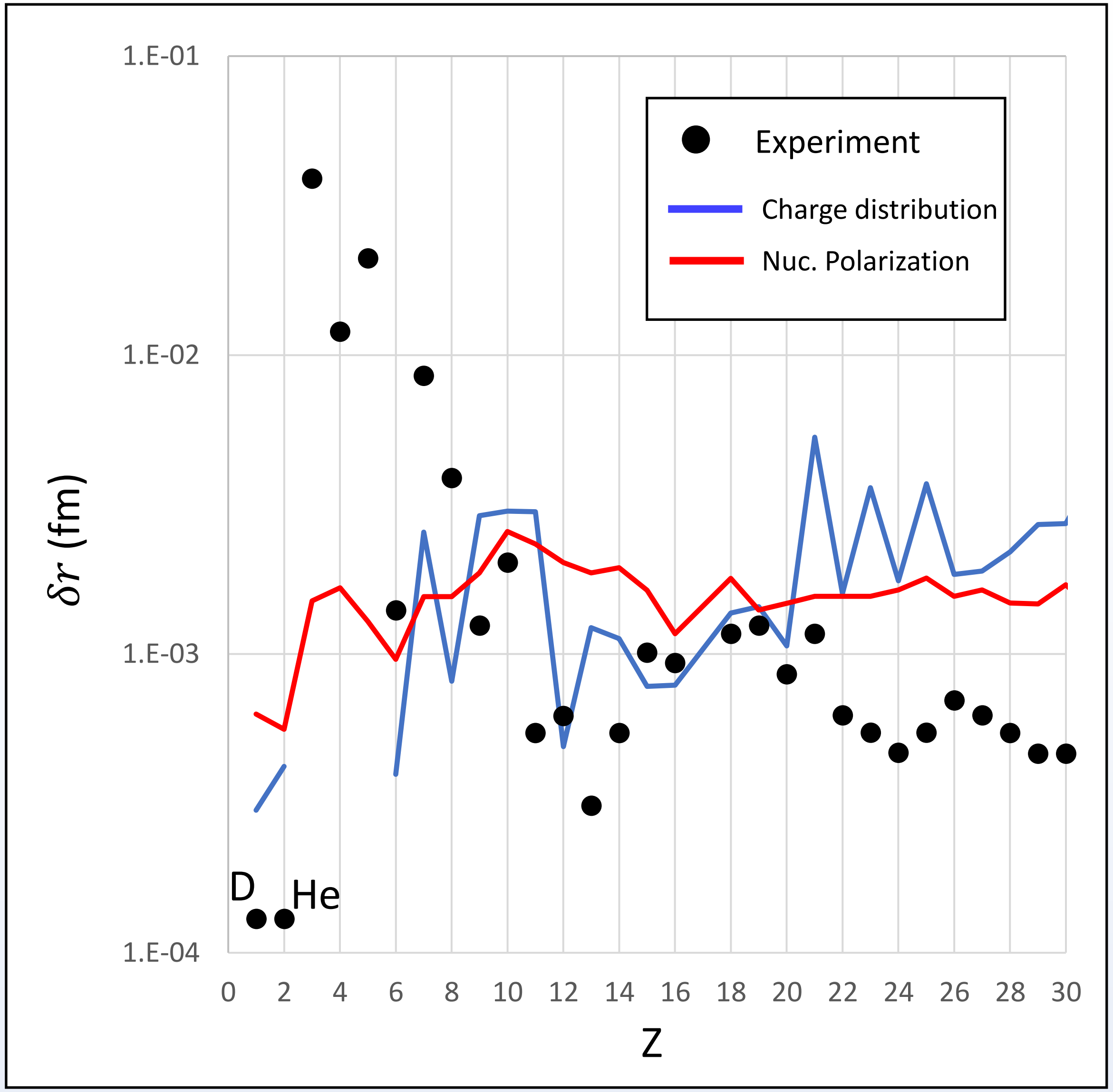
From theory, mainly nuclear polarization

- For Li-Ne $\lesssim (5\,ppm)(E_{2P-1S})$
- For isotope shifts $\lesssim (3\,ppm)(\Delta E_{2P-1S})$
- For non-S states, e.g. $\lesssim (1\,ppm)(\Delta E_{3D-2P})$

From experiment, mainly charge distributions
Motivation for modern electron scattering experiments: Li, Be, B, N, O, …

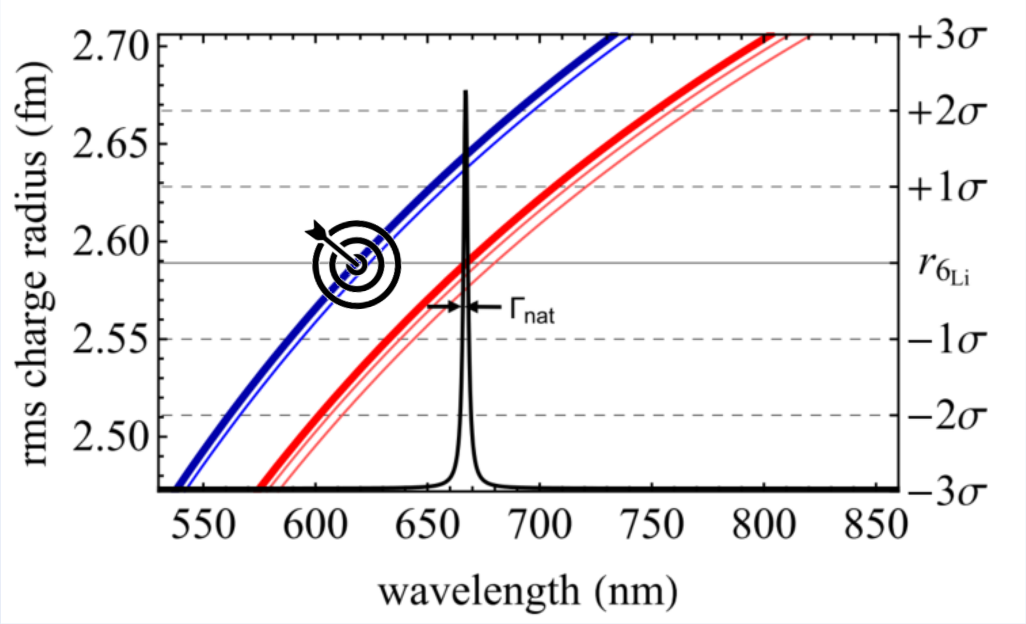
Muonic lithium atoms:
Nuclear structure corrections to the Lamb shift

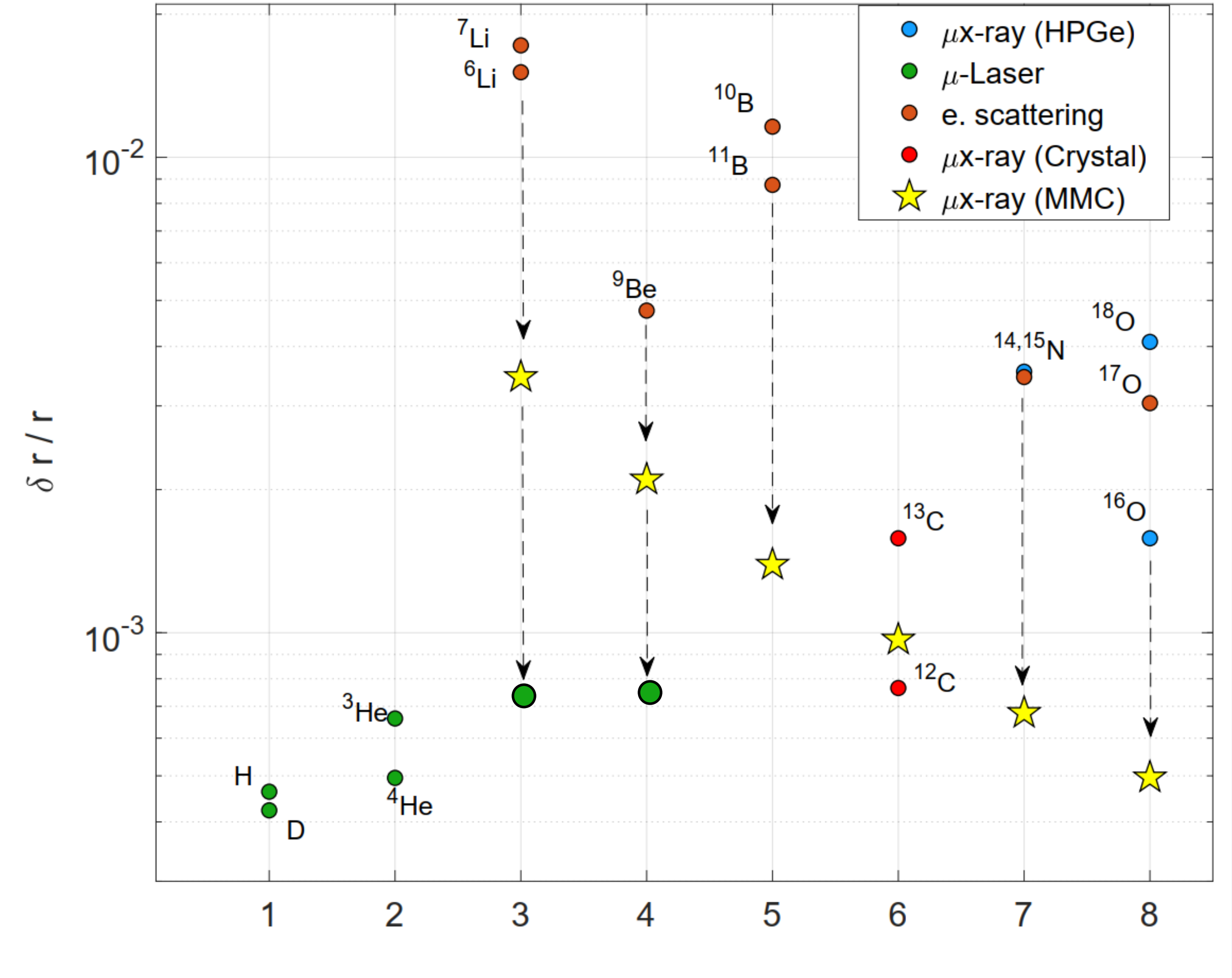
Simone Salvatore Li Muli[1*], Anna Poggialini[2] and Sonia Bacca[1†]



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)



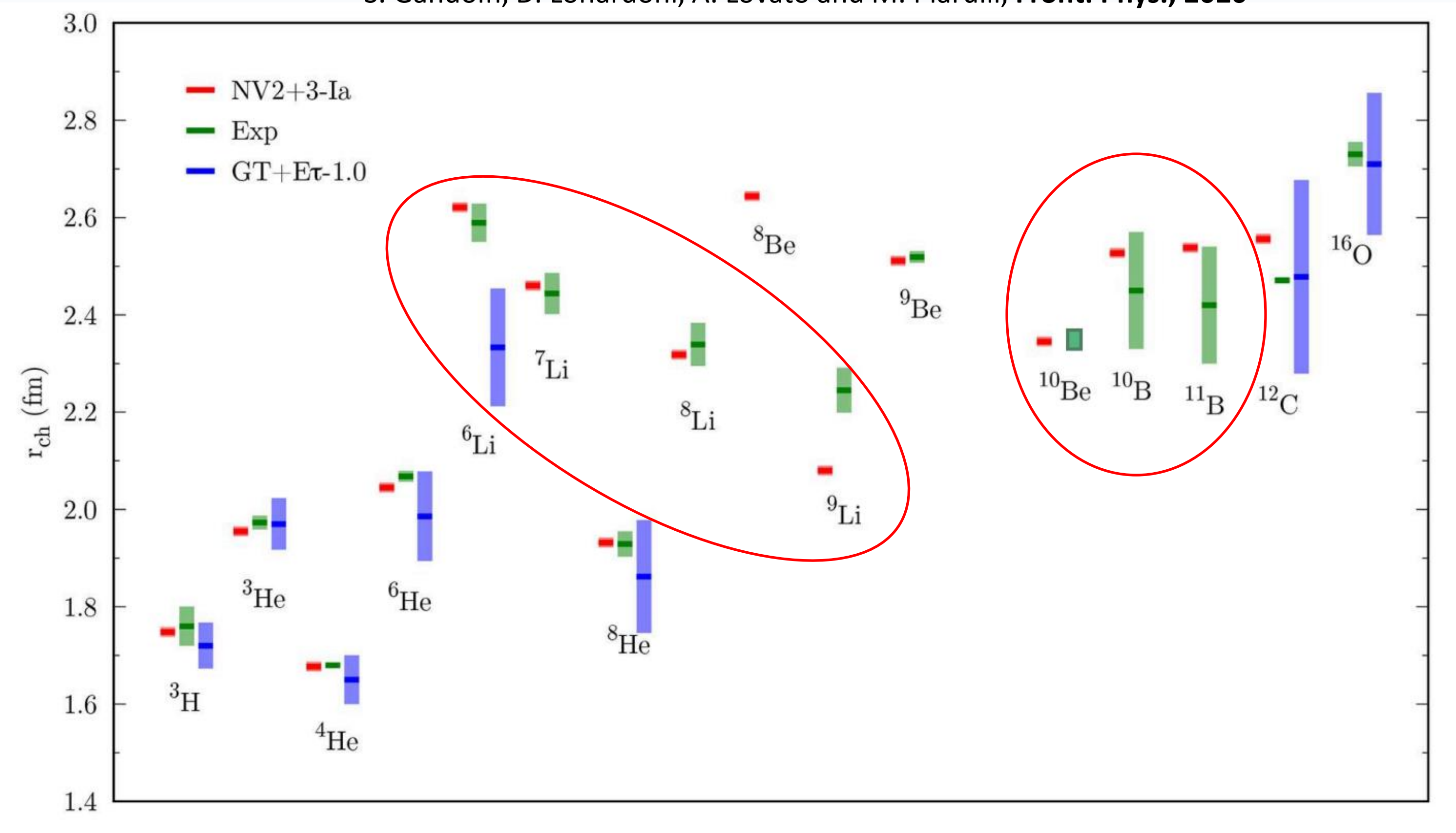


Moving MMC from Heidelberg to Vienna

What can we do with radii?

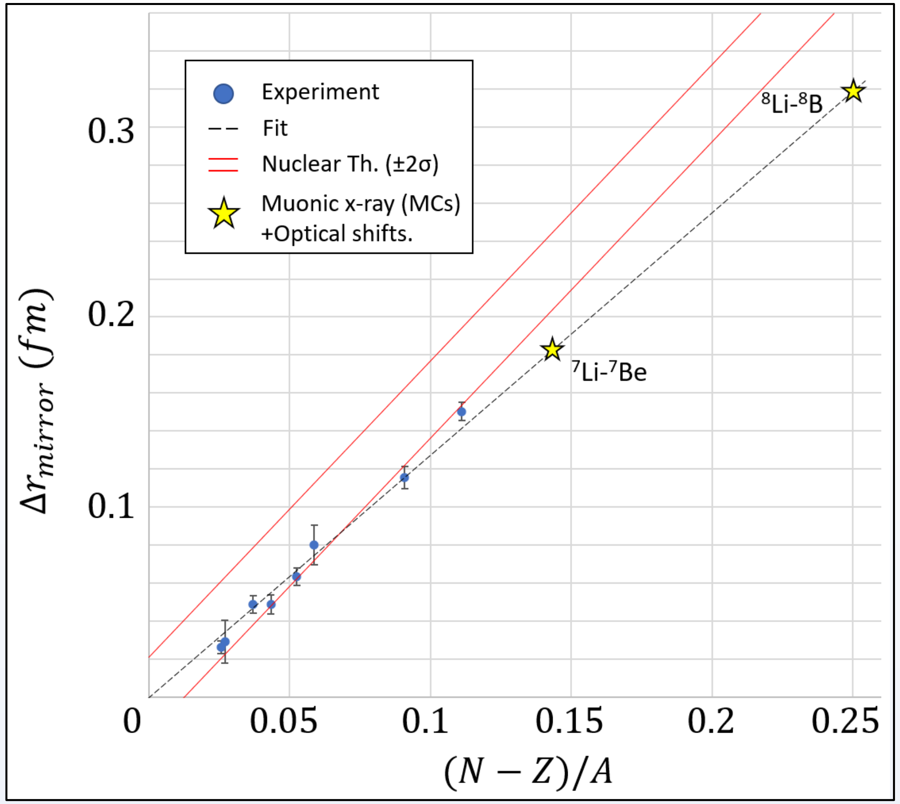
	Experiment	Theory	Combined		Theory
1. Test r_c calculations:	Muonic: $r_c + TPE$ (Electronic: Δr_c)	- TPE →	r_c	Comparison ↔	r_c

Atomic Nuclei From Quantum Monte Carlo Calculations With Chiral EFT Interactions
S. Gandolfi, D. Lonardoni, A. Lovato and M. Piarulli, **Front. Phys., 2020**



Applications of QUARTET phase 1:

Mirror radii at large asymmetry:



Empirical predictions:

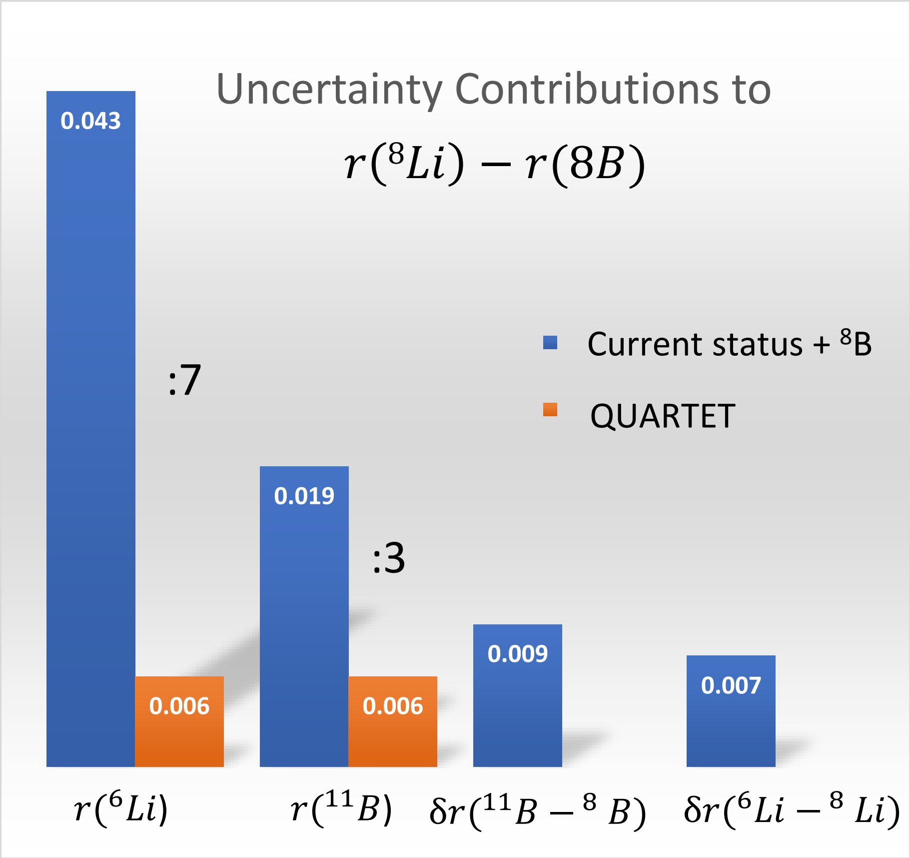
$r_c(^8B) - r_c(^8Li) = 0.33(1)$ fm

$r_c(^8B) = 2.67(5)$ fm

$r_c^2(^8B) - r_c^2(^{11}B) = 1.3(3)$ fm²

Asumming $\delta r^2_{11B-8B} = 4\%$

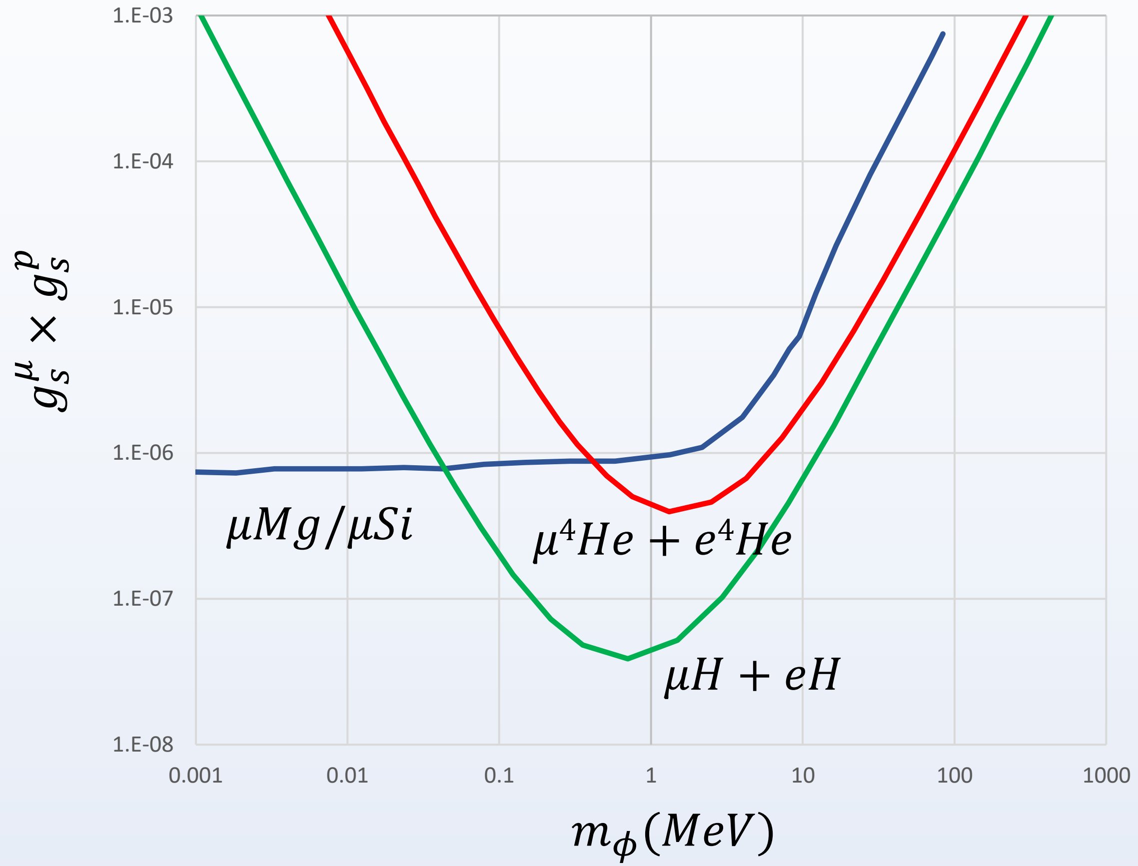
Must improve r_{6Li} and r_{11B} !



What can we do with radii?

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

Bounds on muon proton spin-independent interactions



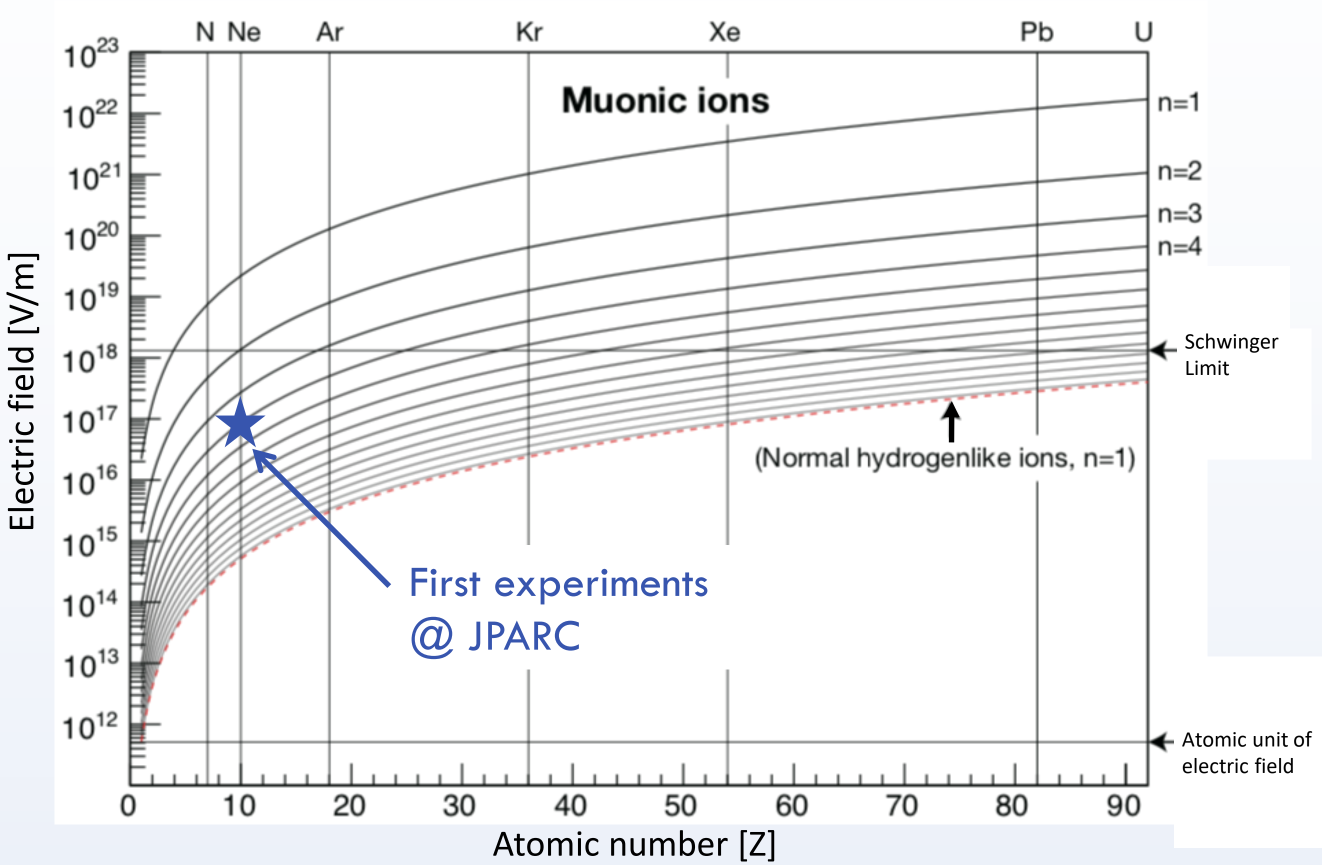
- Sensitivity@$(m_\phi > a_0)$ scales as $N_p Z^3/n^3$ for 1S-2P transitions gain is $8Z^4$
- Needs improved muonic and electronic measurements.
- **Muonic vs. electronic ^{12}C could be competitive!**

Applications of QUARTET "phase 2":

QED at high fields:

See talk on Monday by Nancy Paul

- First measurements with TES microcalorimeter @ JPARC
- $\mu Ne(5g-4f)@6\ keV$. Limited by pileup to $\sim 0.1\ eV$
- PSI CW beam, higher rates with negligible pileup. Order of magnitude improvement "straightforward".
- **Measurements of transitions between non-S states in noble gasses @ PSI with MMCs**



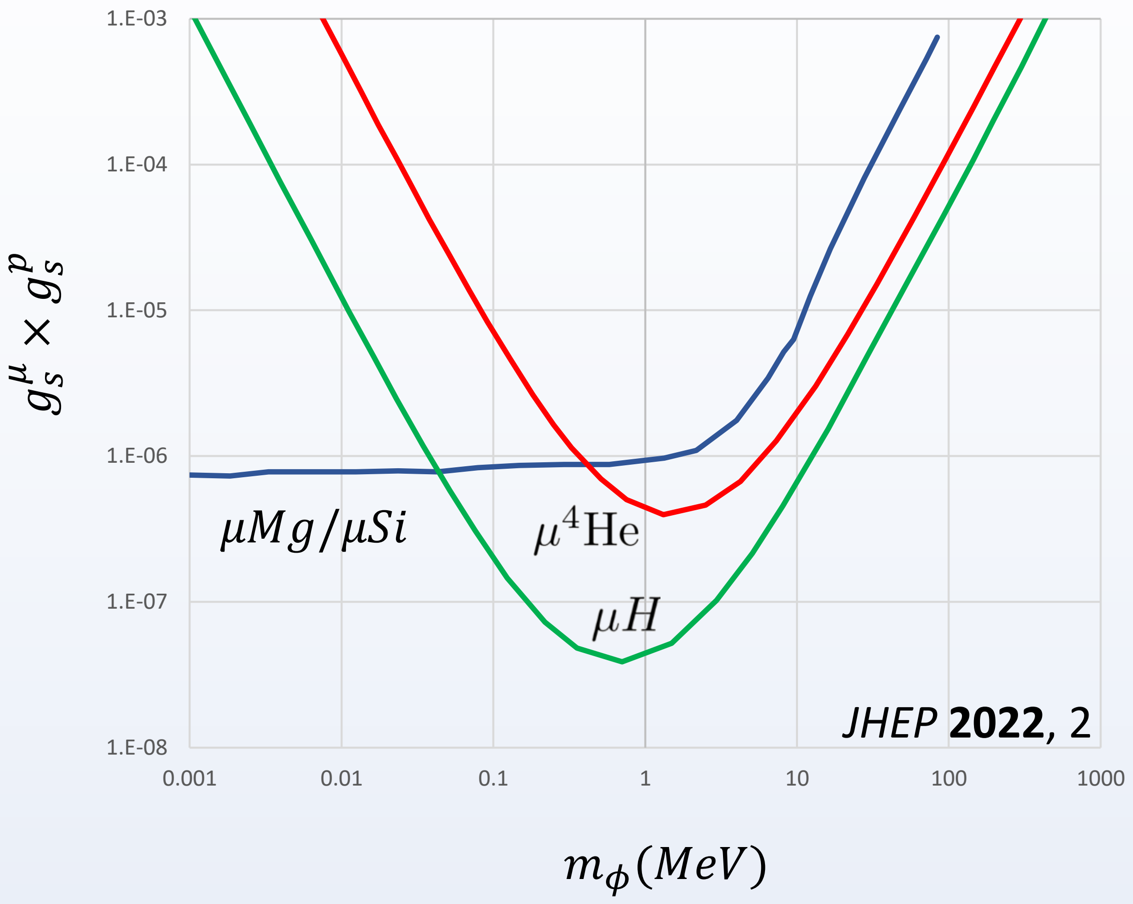
Physics reach of muonic atom measurements

	Experiment	Theory	Combined		Theory
1. Test r_c calculations:	Muonic: $r_c + TPE$	- TPE →	r_c	Comparison ↔	r_c
2. Test TPE calculations:	Muonic: $r_c + TPE$ Electronic: $r_c + QED$	- r_c →	TPE	Comparison ↔	TPE
3. bsQED test	Muonic: $r_c + TPE$ Electronic: $r_c + QED$	- TPE →	QED	Comparison ↔	QED
4. BSM search	Muonic: $r_c + TPE + BSM$ Electronic: $r_c + QED + BSM$	- TPE - QED →	BSM	Comparison ↔	$BSM\ model$

New physics search 1: Muon-proton interactions

- Best laboratory bounds ($< 40keV$) from 3D-2P x-ray transitions in $\mu(Mg/Si)$.
- Above $40keV$, best bounds from μD(2S-2P), with radius from optical isotope shift and μP(2S-2P)
- Sensitivity scales as $N_p Z^3/n^3$ for 1S-2P transitions gain is $8Z^4$
- Needs improved muonic and electronic measurements.

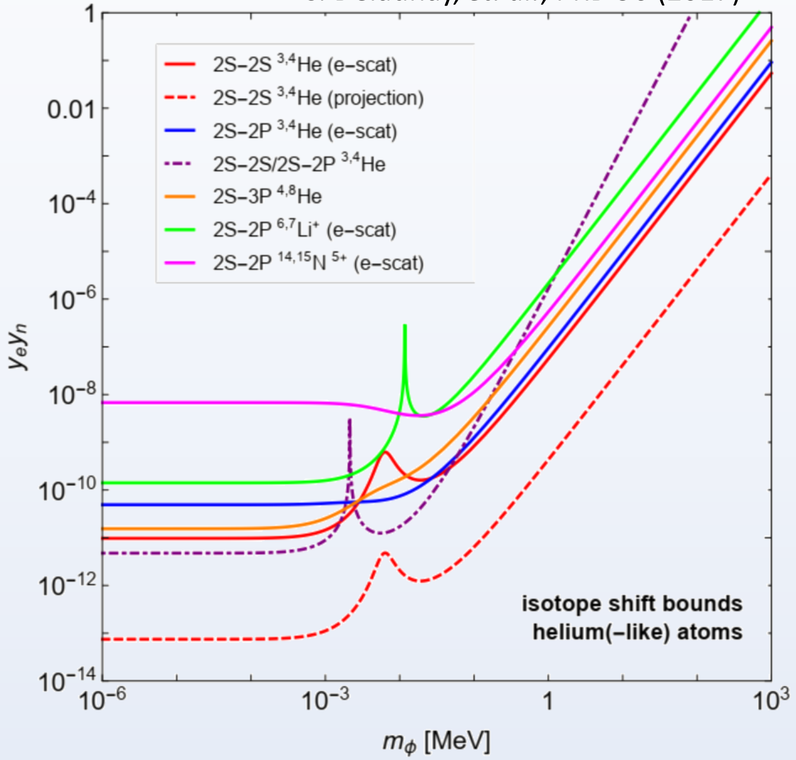
Bounds on muon proton spin-independent interactions



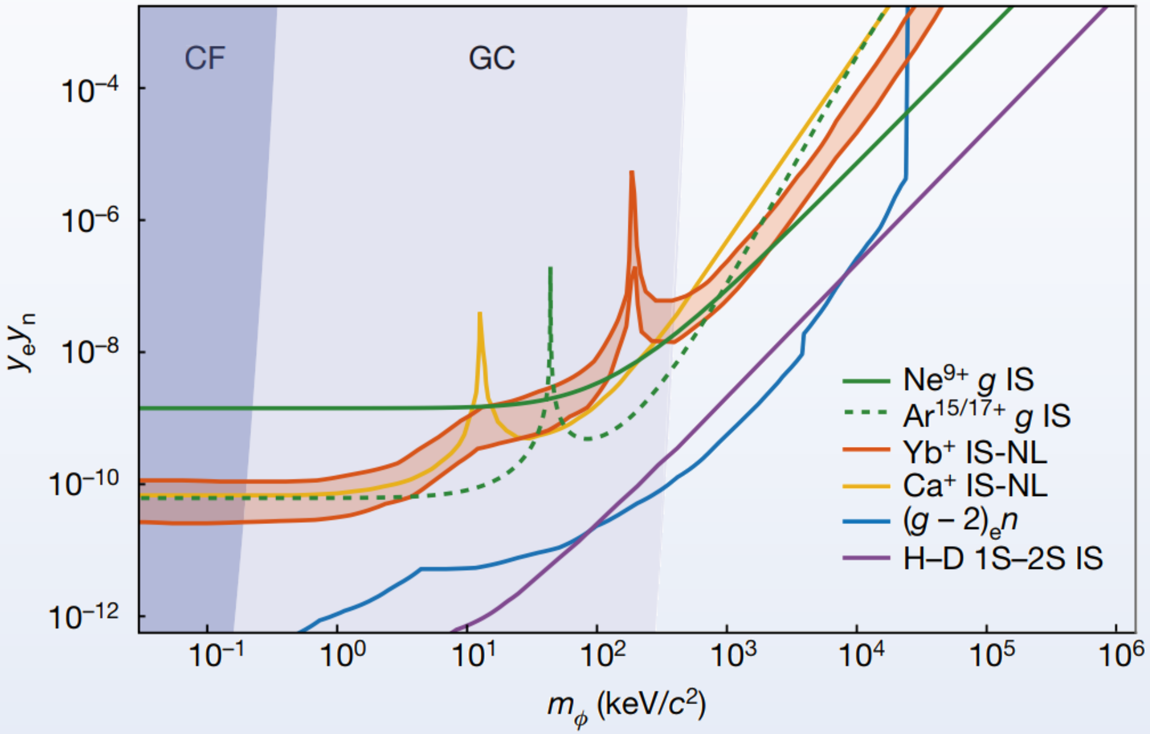
Physics case 4: Beyond Standard Model

- combining isotope shifts between electronic and muonic atoms to search for new lepton-neutron interactions
- Best limits come from Hydrogen-Deuterium pair. Z^3 enhancement favors heavier pairs.
- Novel measurements of bound electron g-factors in H-like ions **limited by muonic isotope shifts**
- Ongoing experiments in He-like ions **limited by muonic isotope shifts**

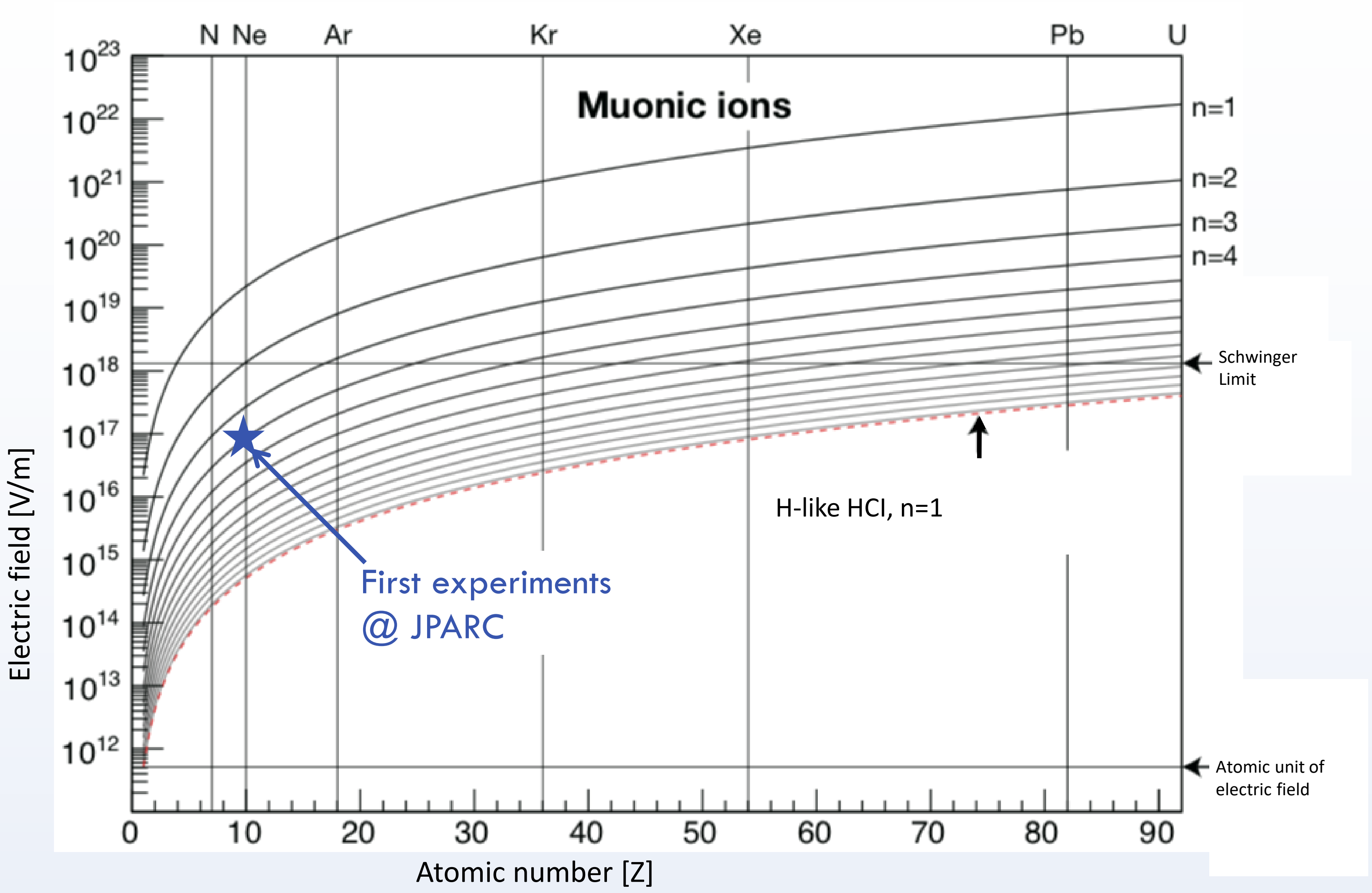
C. Delaunay, *et. al.*, PRD 96 (2017)

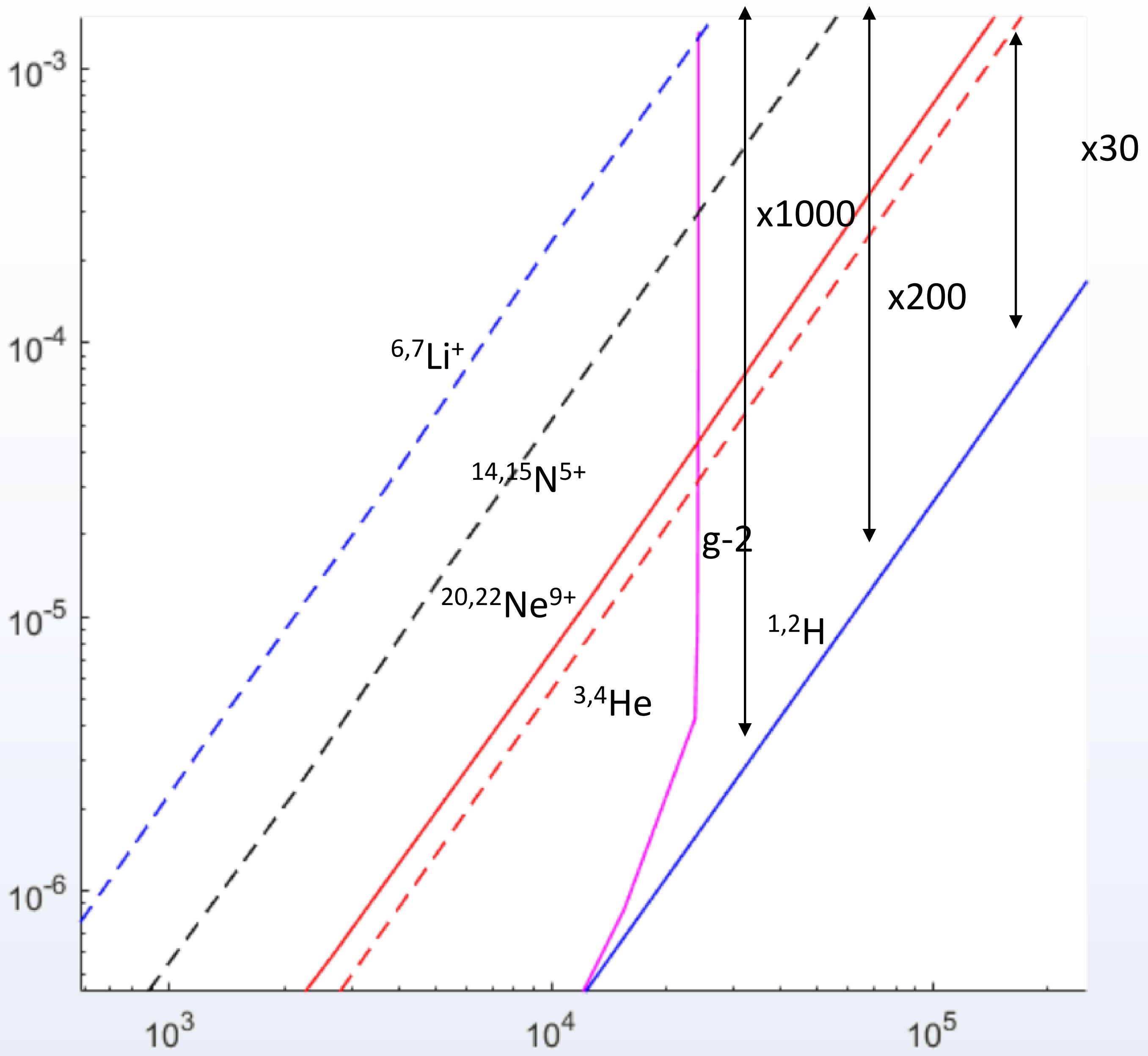


T. Sailer *et. al.*, Nature 606 (2022)



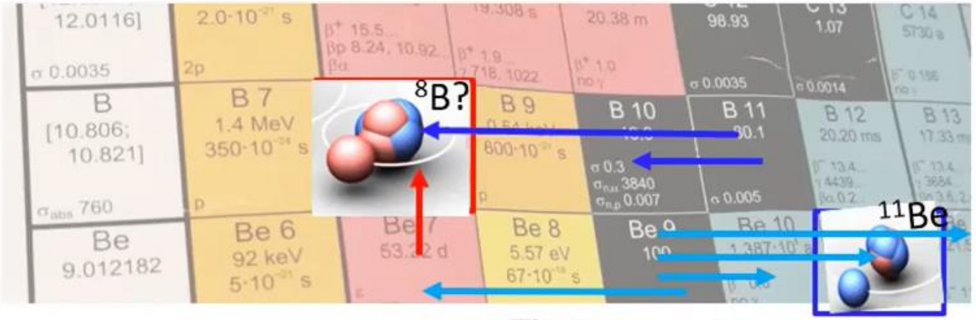
Strong-field QED with muonic atoms





10-3
10-4
10-5
10-6
10^3
10^4
10^5
6,7Li+
14,15N5+
20,22Ne9+
3,4He
1,2H
g-2
x1000
x200
x30

Halo-Nuclei: ^{11}Be and ^{8}B



$$\delta\nu_{\mathrm{IS}} - \delta\nu_{\mathrm{MS}}^{\mathrm{Theory}} \propto \delta\langle r_c^2 \rangle$$

$$R_c(A) = R_c(A_{\mathrm{ref}}) + \delta\langle r_c^2 \rangle^{A_{\mathrm{ref}},A}$$

„Proton-halo size“: $R_c(\mathrm{p_{halo}}) = R_c(^{8}\mathrm{B}) - R_c(^{7}\mathrm{Be})$

Reference Radius required

To gain information about the proton halo of ^{8}B, we need reliable reference radii for Be and B on equal footing!

Ion species	Lifetime $^3S_1$	$^3S_1 \rightarrow {^3P_0}$ wavelength
He	2.2 h	1082 nm
Li^{+}	50 s	548 nm
Be^{2+}	1.8 s	372 nm
B^{3+}	150 ms	282 nm
C^{4+}	21 ms	227 nm
N^{5+}	3.9 ms	190 nm
...	...	...