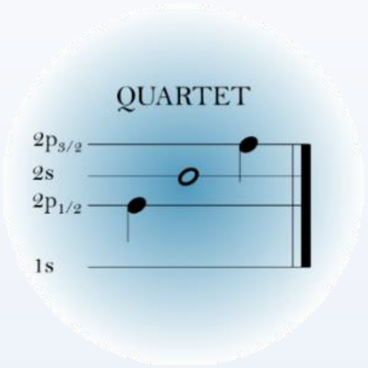
Spectroscopy of light muonic atoms with metallic magnetic calorimeters

Ben Ohayon
ETH Zürich & Technion IIT

For the QUARTET collaboration



Workshop on Proton structure in and out of muonic hydrogen — the ground-state hyperfine splitting

Oct. 15, 2022

Related talks and posters:

Monday afternoon:

14:30 **Testing QED and Beyond with Exotic Atoms** 30m

Despite decades of effort, quantum electrodynamics (QED) is poorly tested in the regime of strong coulomb fields due to a confluence of difficulties linked to experimental limitations in highly-charged ion spectroscopy and nuclear uncertainties. I will present a new paradigm for probing higher-order QED effects using Rydberg states in exotic atoms, where orders of magnitude stronger field strengths can be achieved while nuclear uncertainties may be neglected [1]. Such tests are now possible due to the advent of quantum sensing detectors and new facilities providing low-energy intense beams of exotic particles for precision physics. I will present first results from experiments with muonic atoms at JPARC within the context of the HEATES collaboration, and discuss new ideas for synergies with muonic and antiprotonic atom spectroscopy in Europe.

[1] N. Paul et al, Physical Review Letters 126, 173001 (2021)

Speaker: Nancy Paul (Laboratoire Kastler Brossel)

Poster Session:

Microcalorimetric high-resolution spectroscopy of muonic lithium 1m

Metallic magnetic microcalorimeters (MMCs) represent a promising detection method for broadband high-resolution x-ray spectroscopy. These systems are particularly suitable for the detection of low-energy x-rays, as found in the spectroscopy of low-Z muonic atoms. Such high-resolution spectra would enable precision measurements of charge radii of light nuclei and could thus provide important benchmarks for modern nuclear theory. In this context, plans are presented for the spectroscopy of muonic lithium using MMCs as part of an upcoming experiment at the Paul Scherrer Institute.

Speaker: Katharina von Schoeler (ETH Zurich)

The Holmes Ion Implanter commissioning runs 1m

The HOLMES experiment aims to measure directly the neutrino mass with a calorimet- ric approach studying the end point of the 163Ho electron-capture decay spectrum. This isotope is produced via neutron capture by 162Er and its very low Q-value (2.8 keV) makes it a very good choice but introduces two critical aspects. The first one is the need to embed the isotope inside the cryogenic microcalorimeters so that the energy released in the decay process is entirely contained within the detectors, except for the fraction taken away by the neutrino. The second one is the rejection of 166mHo radioactive isotope, created from impurities during the neutron irradiation, that could produce false signal in the region of interest. So a dedicated implanter with a sputter ion source, an acceleration section (up to 50 keV) and a magnetic dipole (for ion selection and beam focusing) has been designed and developed. Different targets for the implanter ion source have been also developed in collaboration with Genoa Chemistry Department and PSI (Paul Scherrer Institute). This work will show the status of the machine development and the results on the different target solutions.

Speaker: Giovanni Gallucci (INFN - Genova)

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Today: Charge radii from muonic atom cascades measured with MMCs

Physics reach of muonic atom measurements

Experiment

1. Test r_c calculations:

Muonic: $r_c + TPE$
(Electronic: Δr_c)

Physics reach of muonic atom measurements

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

Physics reach of muonic atom measurements

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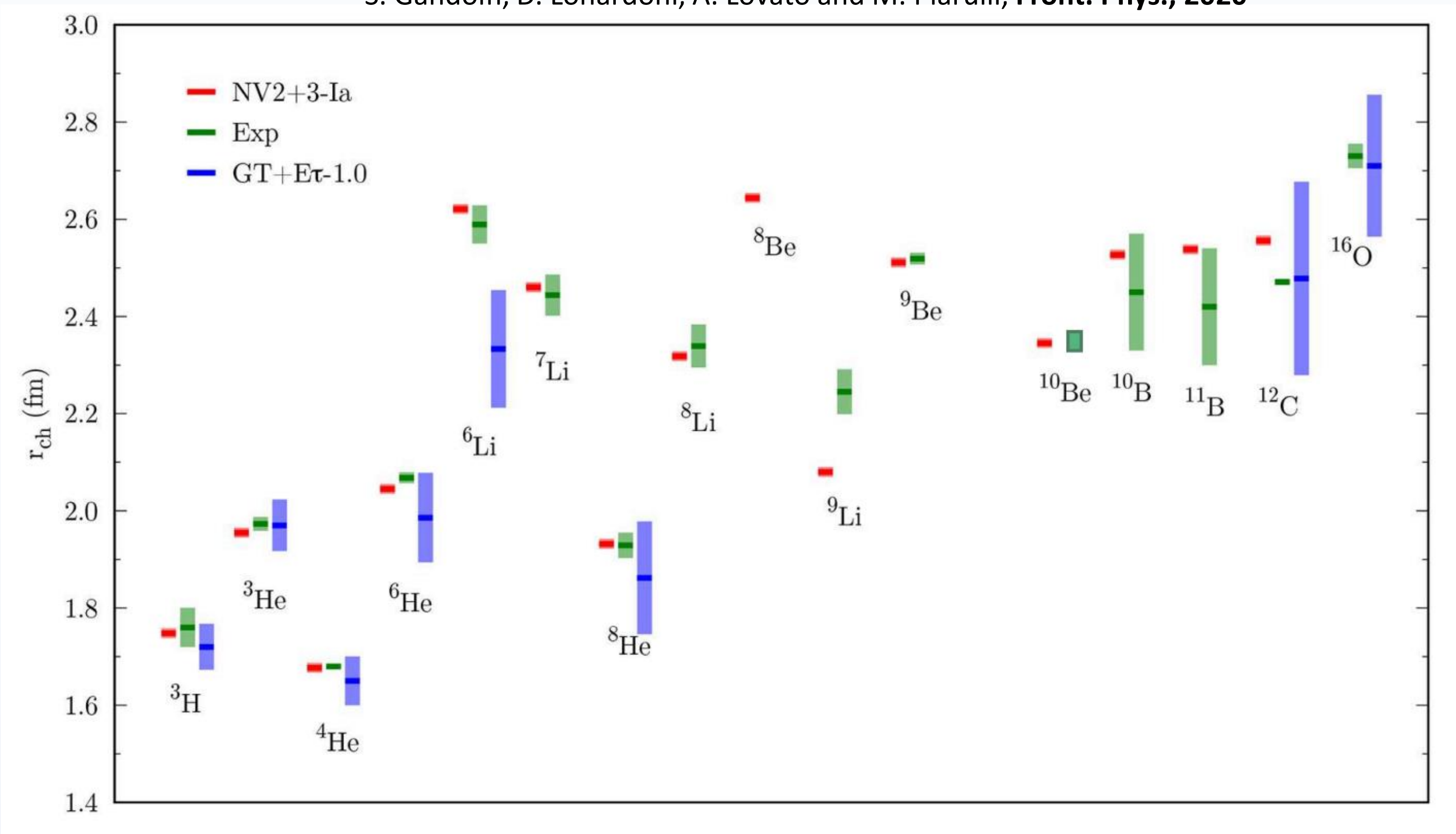
Atomic Nuclei From Quantum Monte Carlo Calculations With Chiral EFT Interactions
S. Gandolfi, D. Lonardoni, A. Lovato and M. Piarulli, **Front. Phys., 2020**



Physics reach of muonic atom measurements

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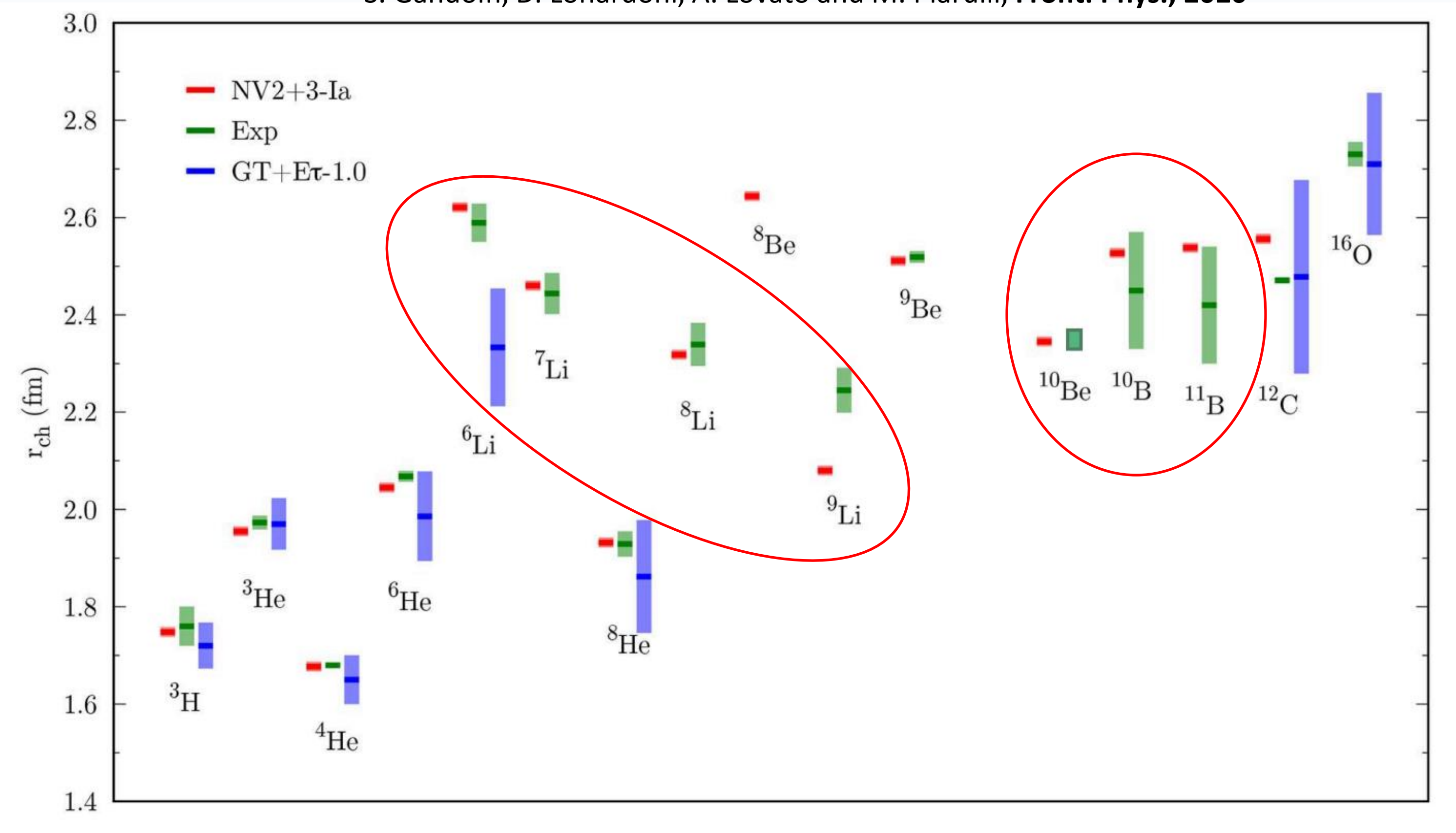

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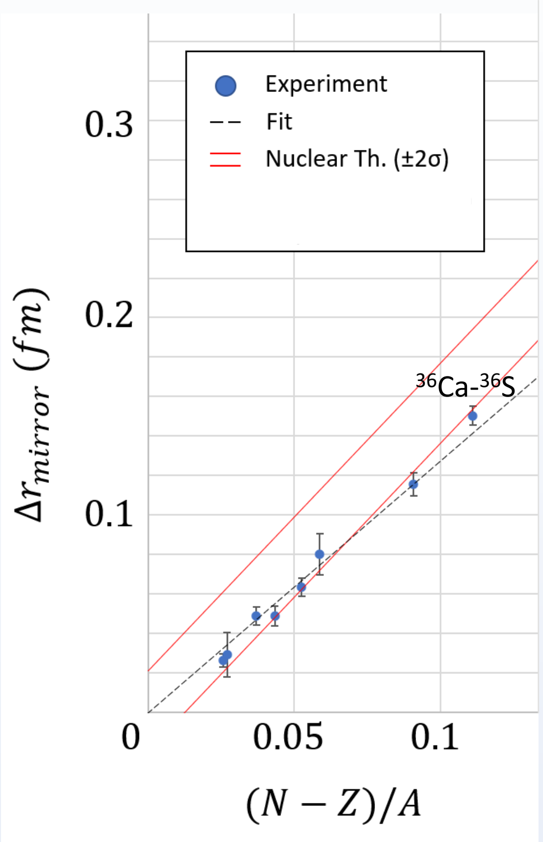

Theory : S. J. Novario, D. Lonardoni, S. Gandolfi, and G. Hagen, arXiv:2111.12775

Physics reach of muonic atom measurements

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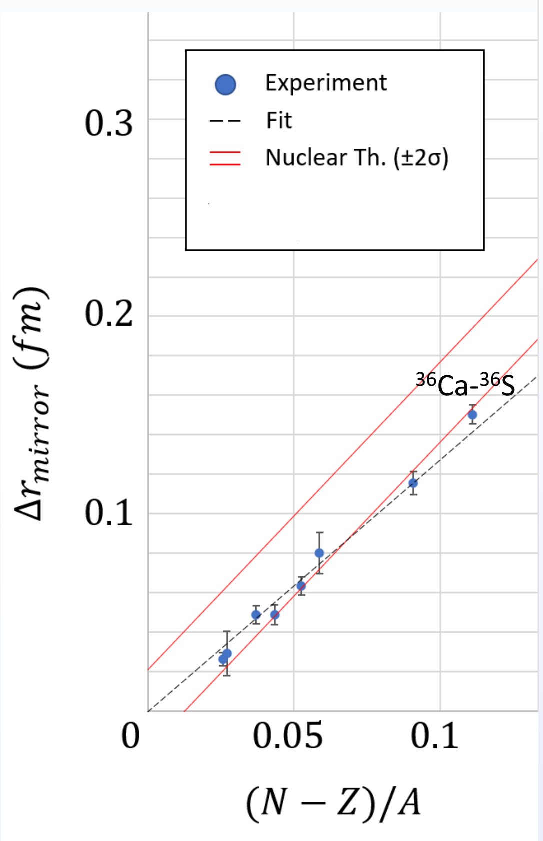
1. Test r_c calculations:	Muonic: $r_c + TPE$ (Electronic: Δr_c)	- TPE →	r_c	← Comparison →	r_c

- $\Delta r_c \propto Neutron\ Skin$
- Motivates $\frac{\delta r_c}{r_c} < 10^{-3}$
- Light nuclei needed (Large $(N-Z)/A$)



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Physics reach of muonic atom measurements

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

Physics reach of muonic atom measurements

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

Muonic Deuterium
(Stolen from Randolf Pohl):

(2) **polarizability**, using **charge radius from isotope shift**

ΔE_{TPE} (theo) = 1.7500 (210) meV vs.

ΔE_{TPE} (exp) = 1.7591 (59) meV 3.5x more accurate

Krauth et al. (2016) + Pachucki et al. (2018) + Hernandez et al. (2018) + Kalinowski (2018)

Physics reach of muonic atom measurements

3. bsQED test

Experiment	Theory	Combined		Theory
Muonic: $r_c + TPE$ Electronic: $r_c + QED$	- TPE →	QED	← Comparison →	QED

Physics reach of muonic atom measurements

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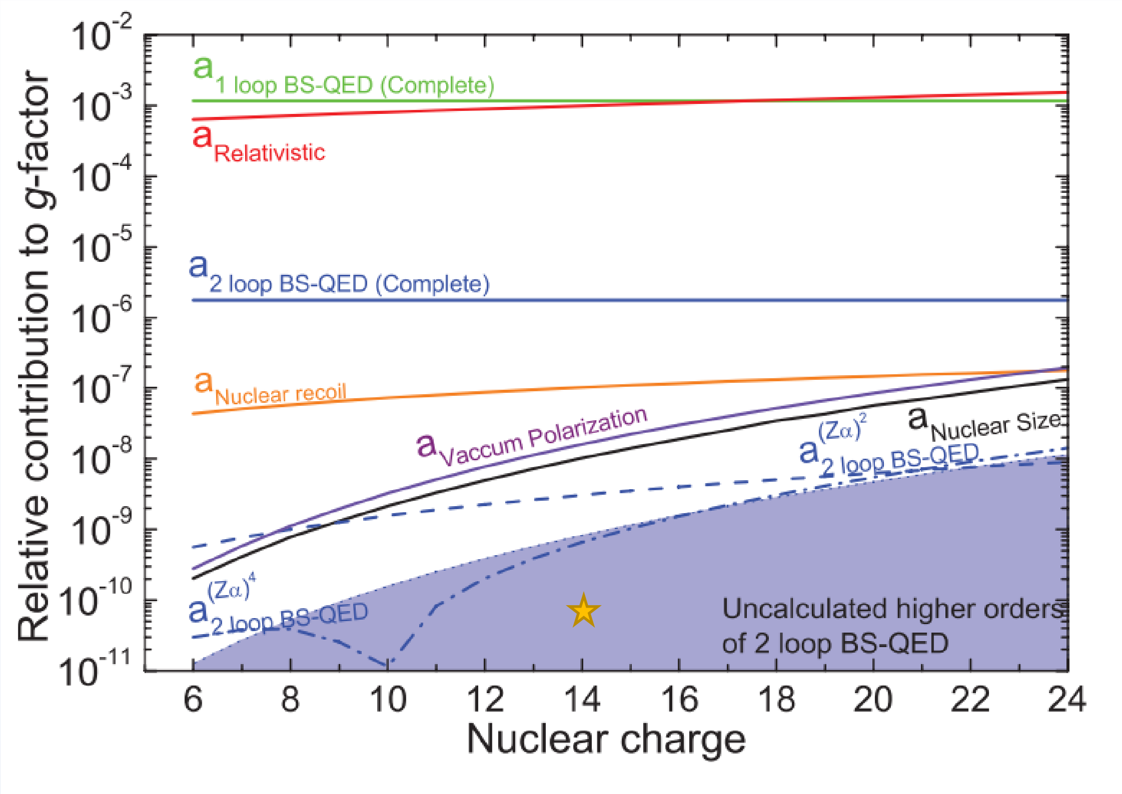
Contributions to bound-electron g-factors in hydrogen-like ions



S. Sturm, et. al. PRA 87, 030501(R) (2013)

Physics reach of muonic atom measurements

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

Next generation experiments for light nuclei would be limited by knowledge of radius

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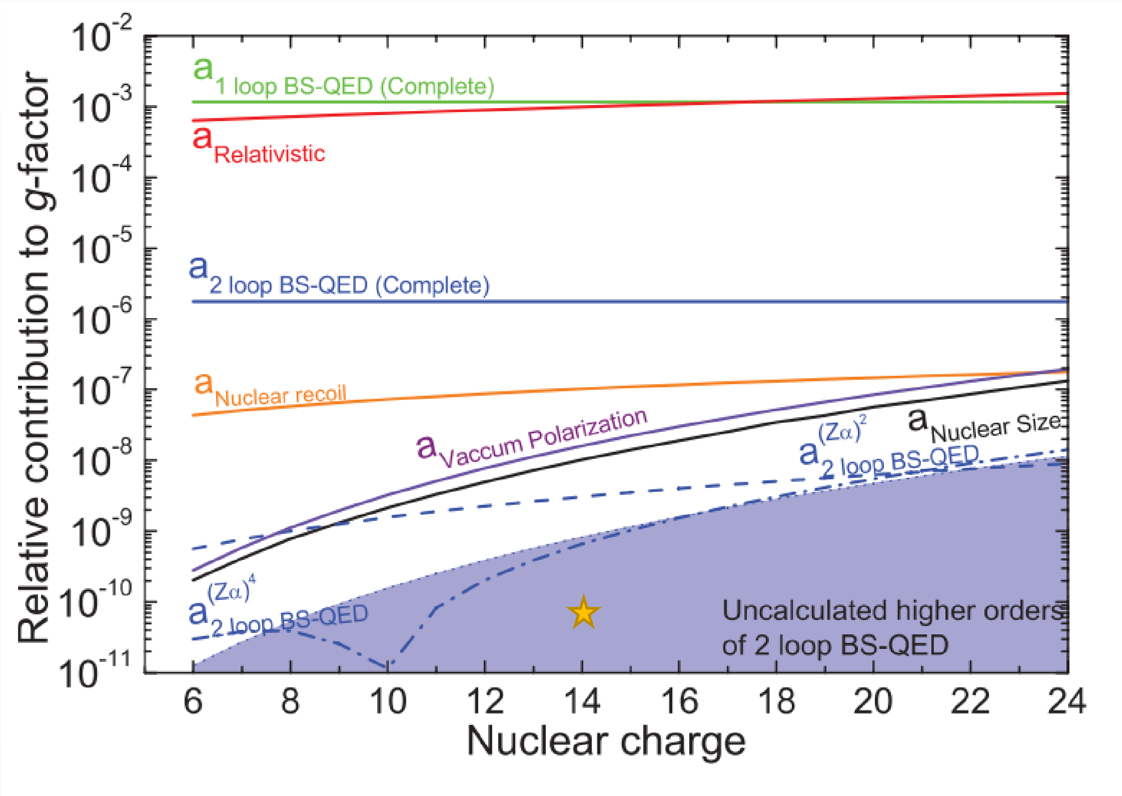

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Physics reach of muonic atom measurements

Experiment | Theory | Combined | | Theory

4. BSM search

Muonic: $\Delta r_c + TPE + BSM$
Electronic: $\Delta r_c + QED + BSM$

- TPE - QED →

$BSM?$

Comparison ↔

$BSM\ model$

Physics reach of muonic atom measurements

	Experiment	Theory	Combined		Theory
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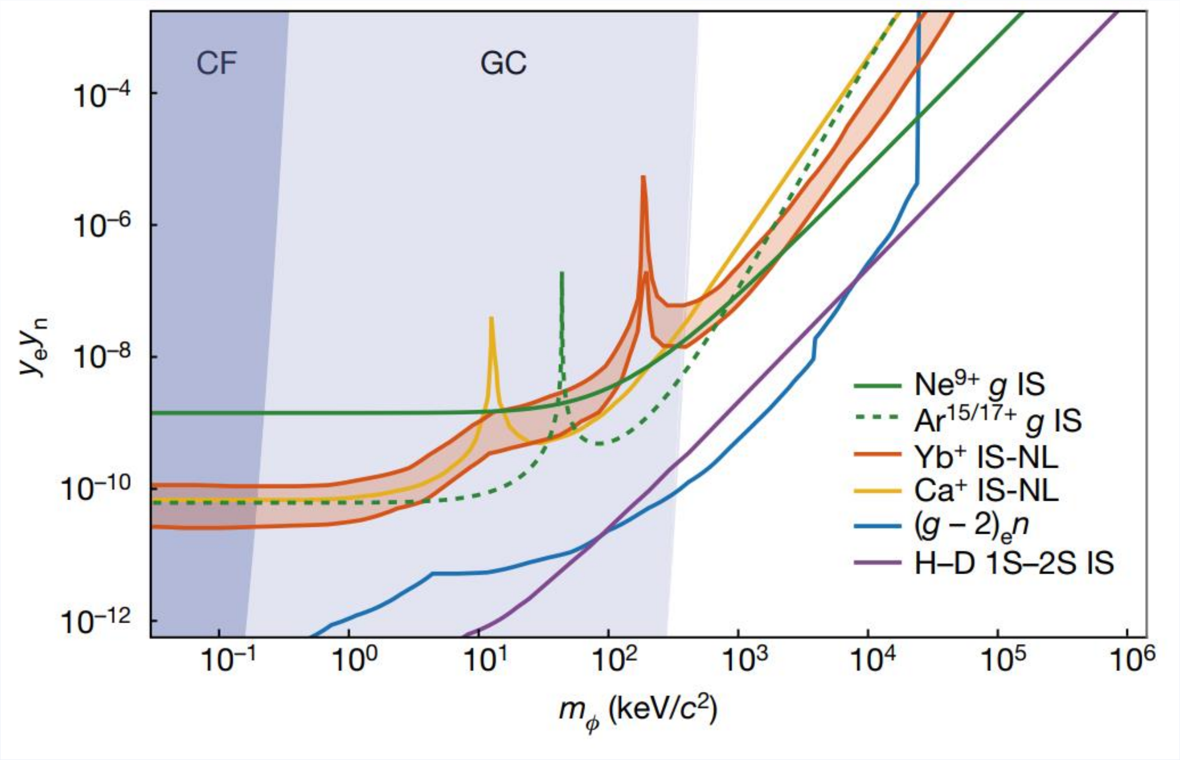

Nature **volume 606**, pages 479–483 (2022)

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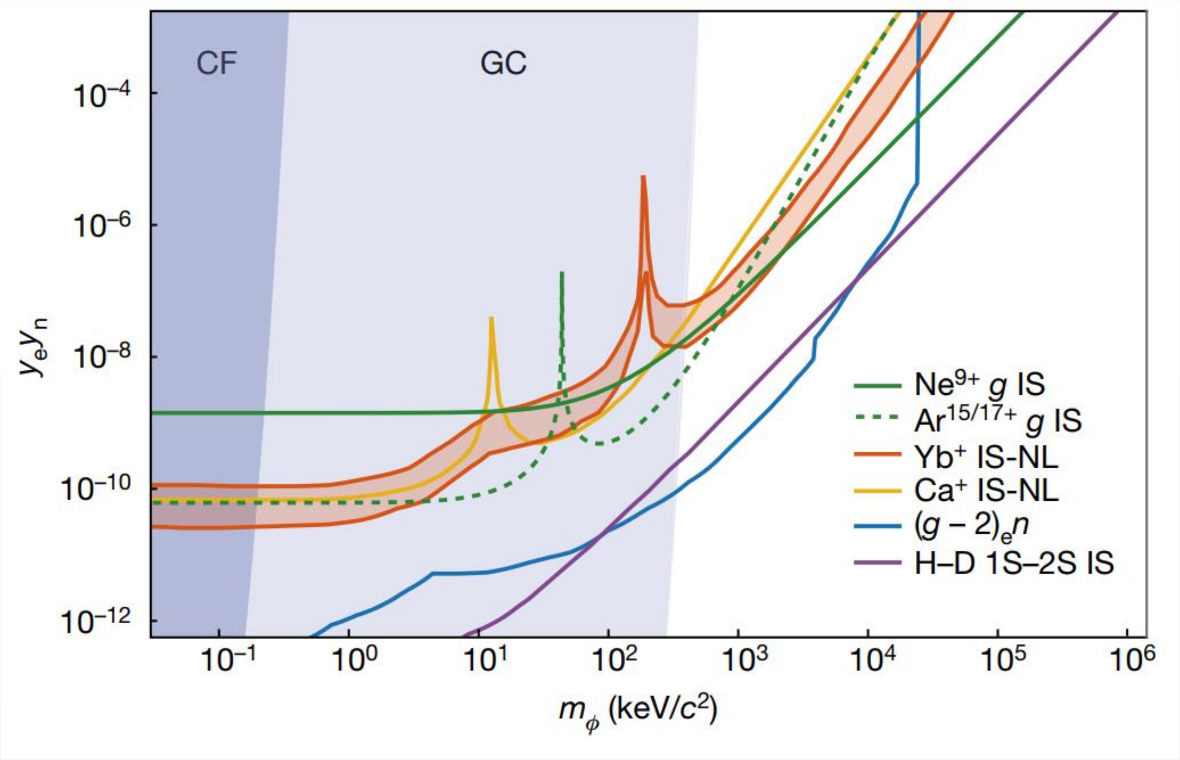
- Best bound $> 10 MeV$ from H-D electronic (1S-2S) and muonic (2S-2P) isotope shifts
- 2^{nd} best: ^{20,22}Ne Muonic (1S-2P) vs. electronic (g-factor) isotope shifts. Limited by muonic experiment + Nuclear Polarization.
- Motivation for improved isotope shifts experiment and theory in light even-even pairs: $\mu^{16,18}$O, $\mu^{20,22}$Ne…

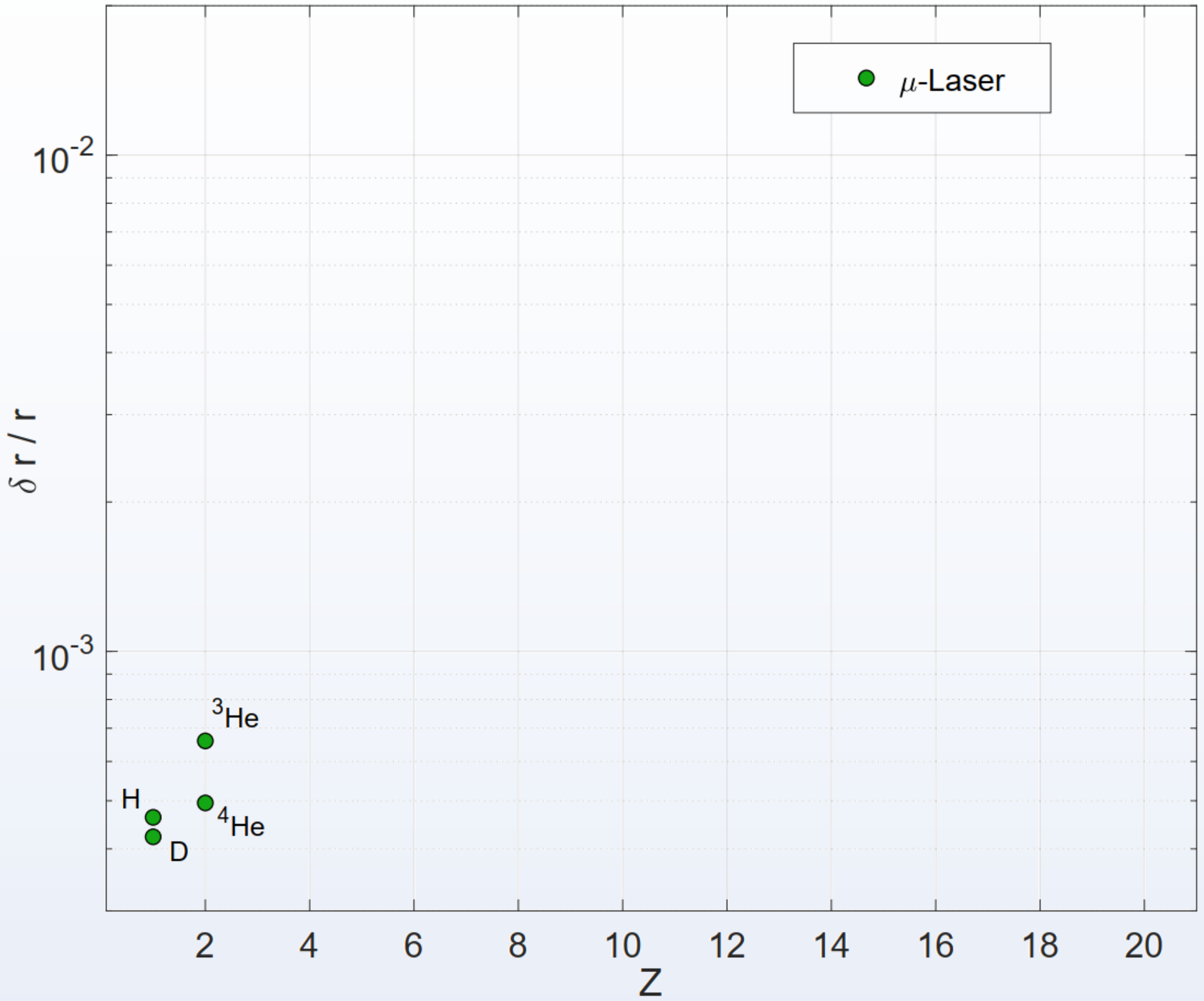


Nature **volume 606**, pages 479–483 (2022)

Determinations of nuclear RMS charge radii

- **For $Z < 3$:**

  Laser spectroscopy of muonic atoms $E(2P - 2S) \sim \mathrm{eV}$, limited by theory (TPE).



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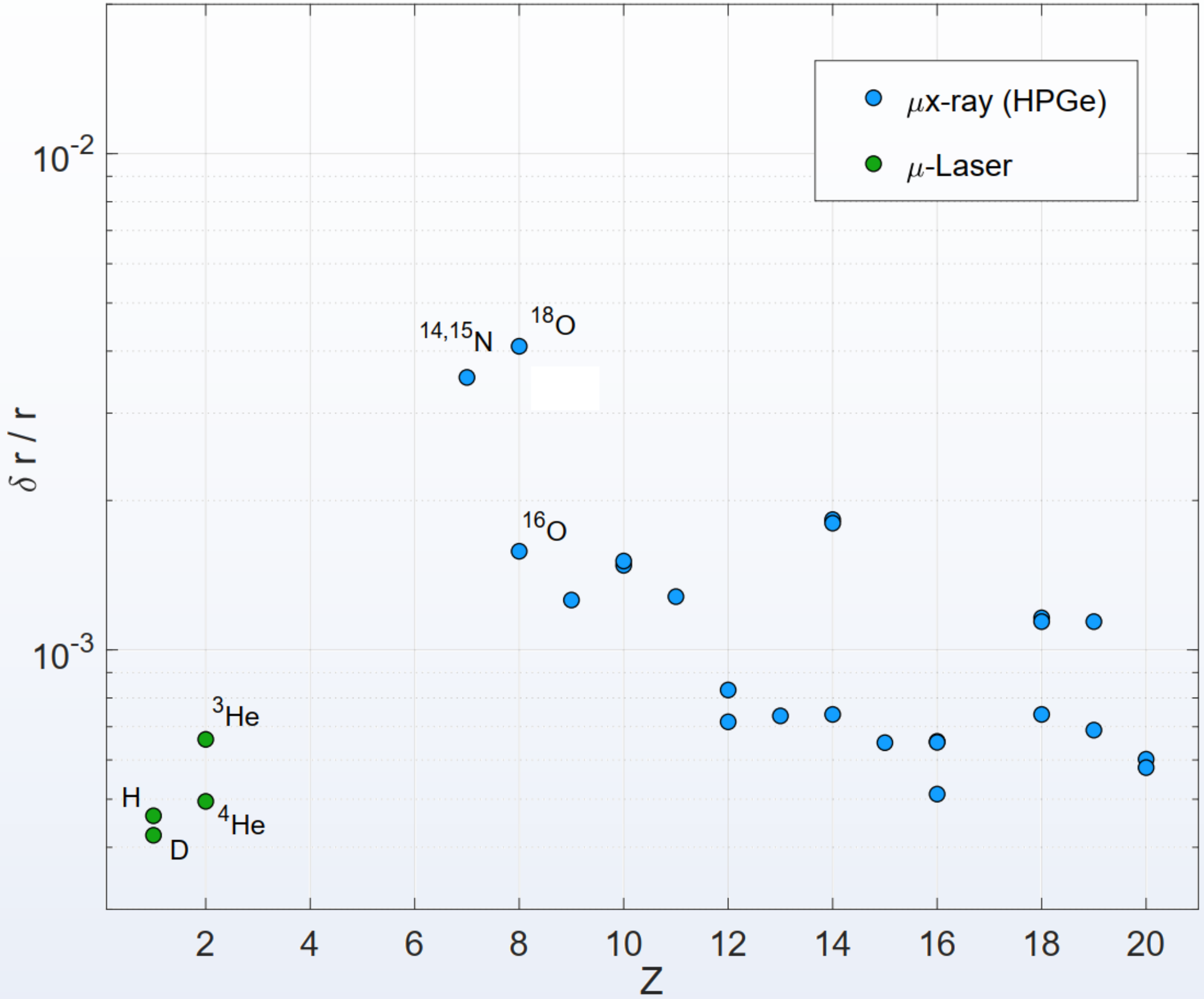
- **For $\mathbf{Z} > 6$:**

  $E(2P - 1S) > 200\ \mathrm{keV}$, measured with solid-state detectors.
  Z>10: limited by theory.
  10>Z>5: limited by experiment (resolution).



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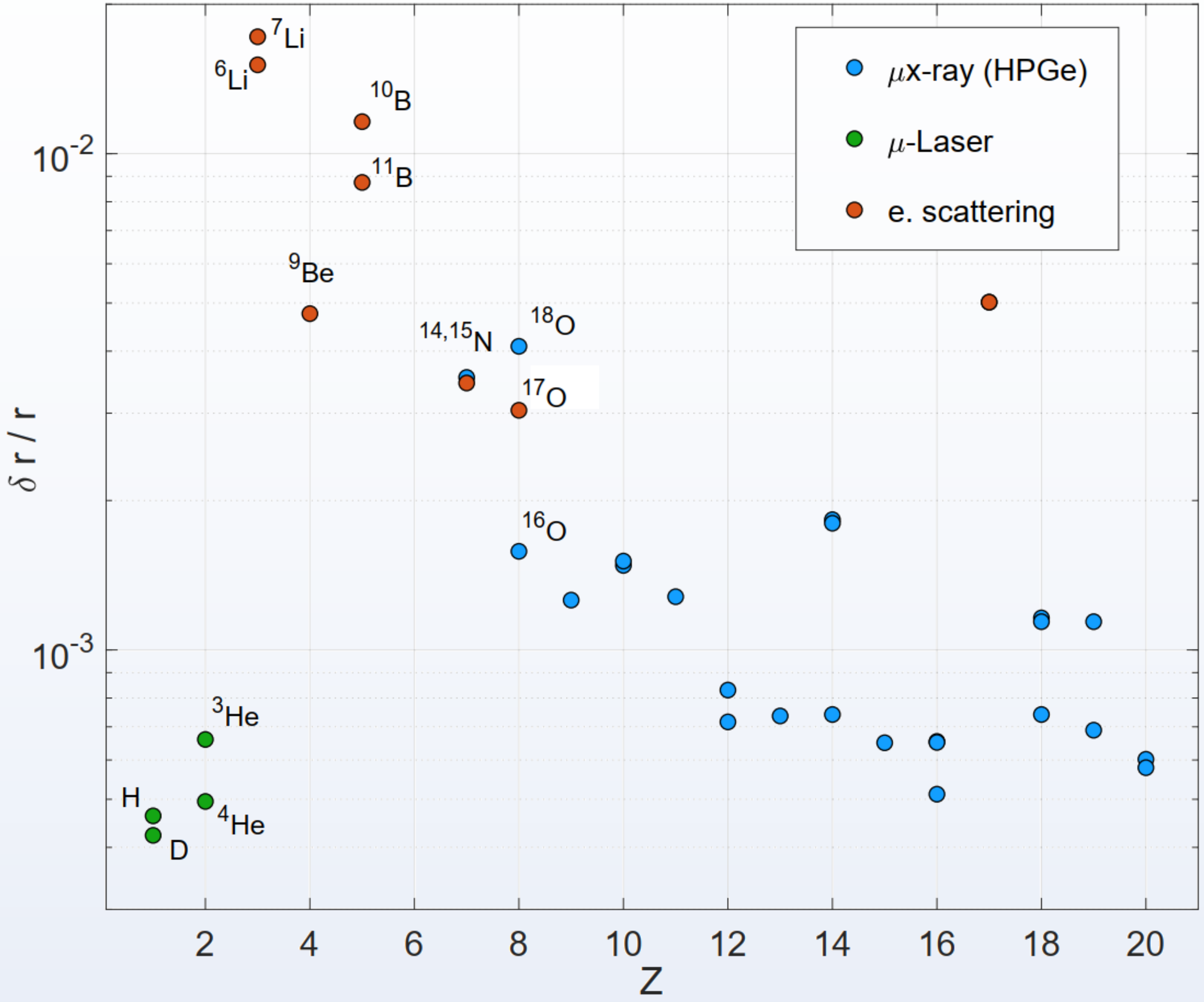
  Electron scattering, less accurate and systematics usually NOT under control



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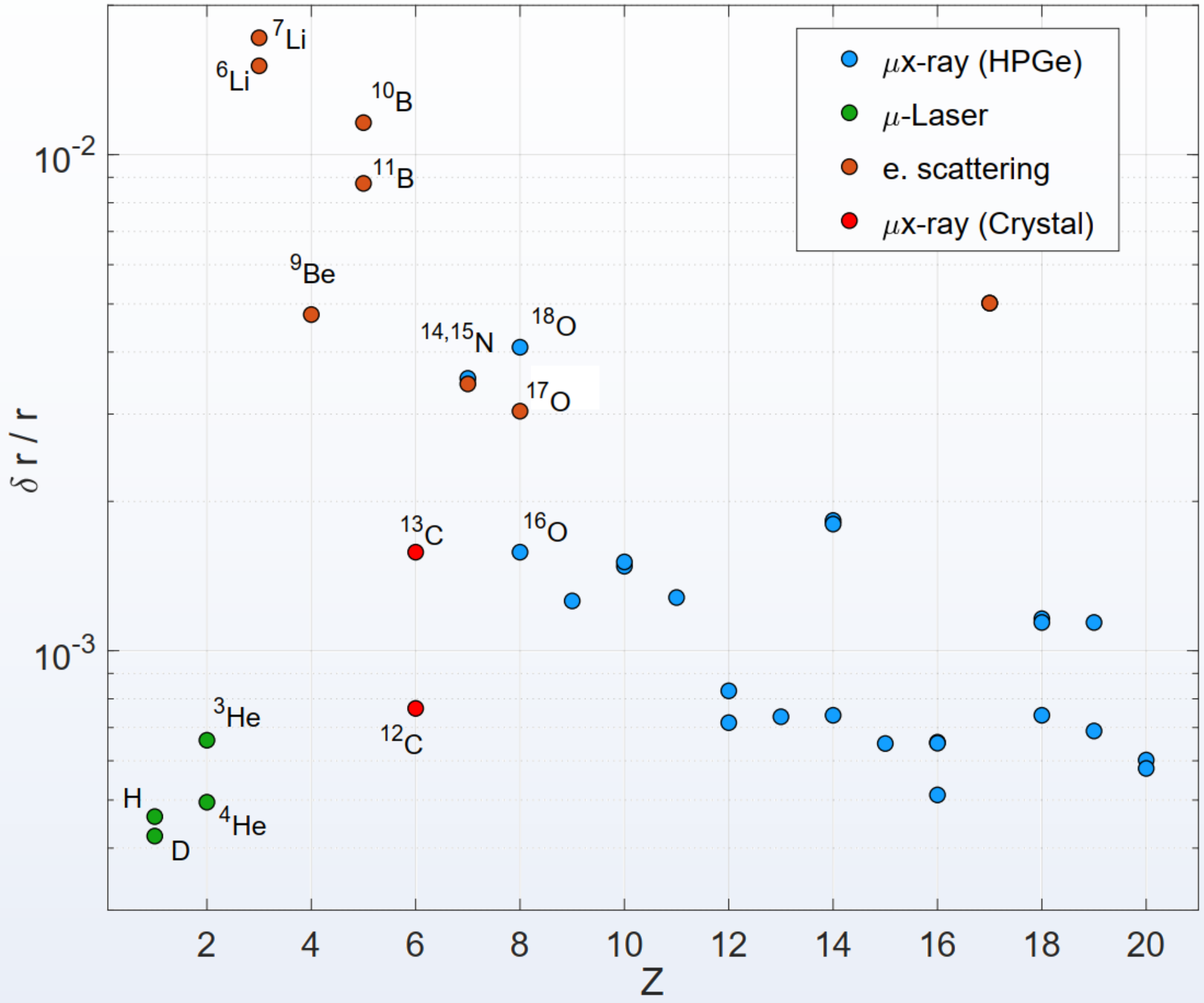
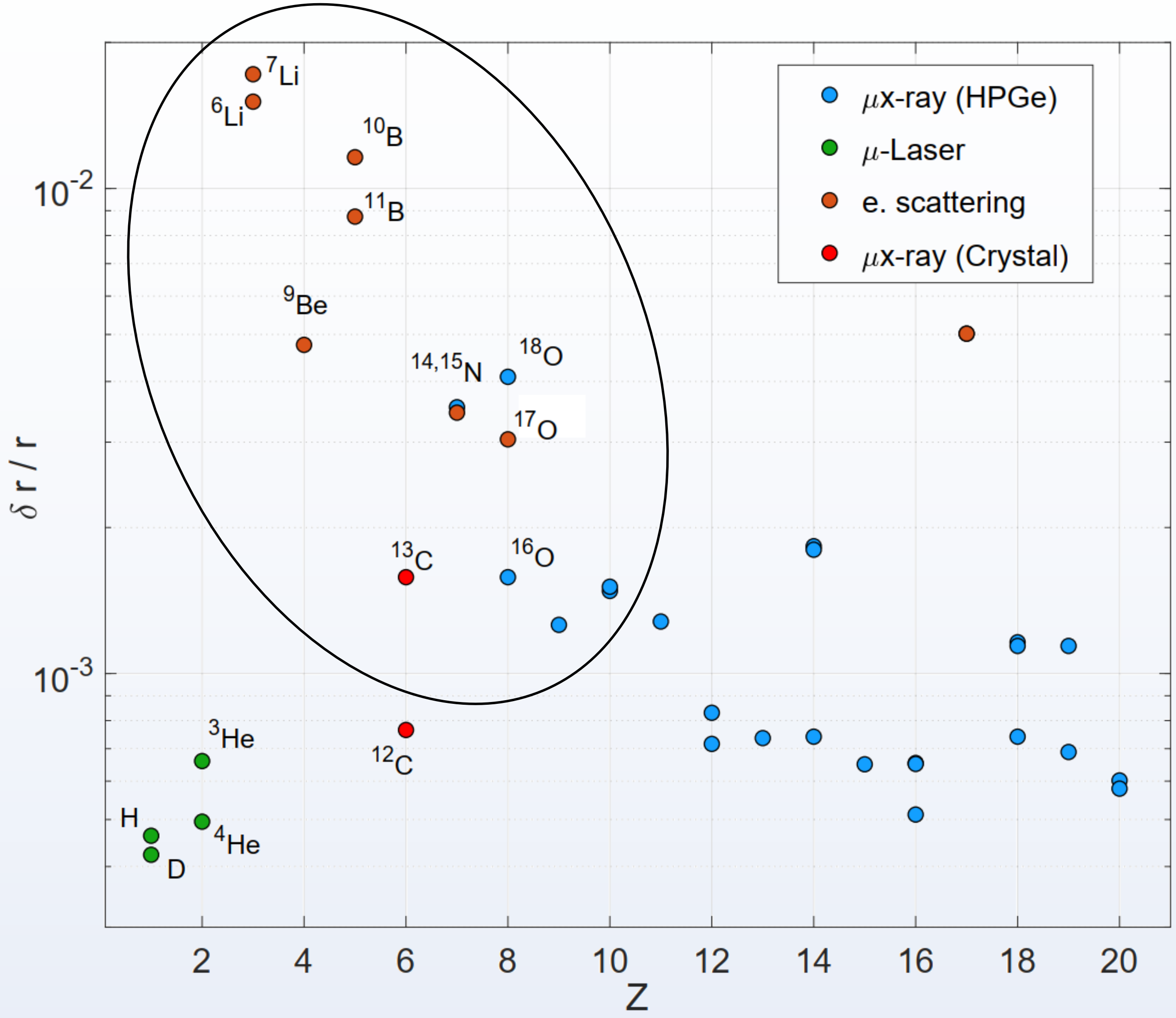
- **For $Z = 6$**

  E(2P-1S)~75 keV, measured with crystal spectrometer. Limited by resolution ~75 eV



The experimental gap:

- Large accuracy gap in the range $2 < Z < 11$
- Limited by HPGe resolution, and Crystal-spec bandwidth
- Laser spec. hasn't been applied (yet?)
- Need broadband, efficient, high-resolution detector for x-rays in the range 19-200 keV



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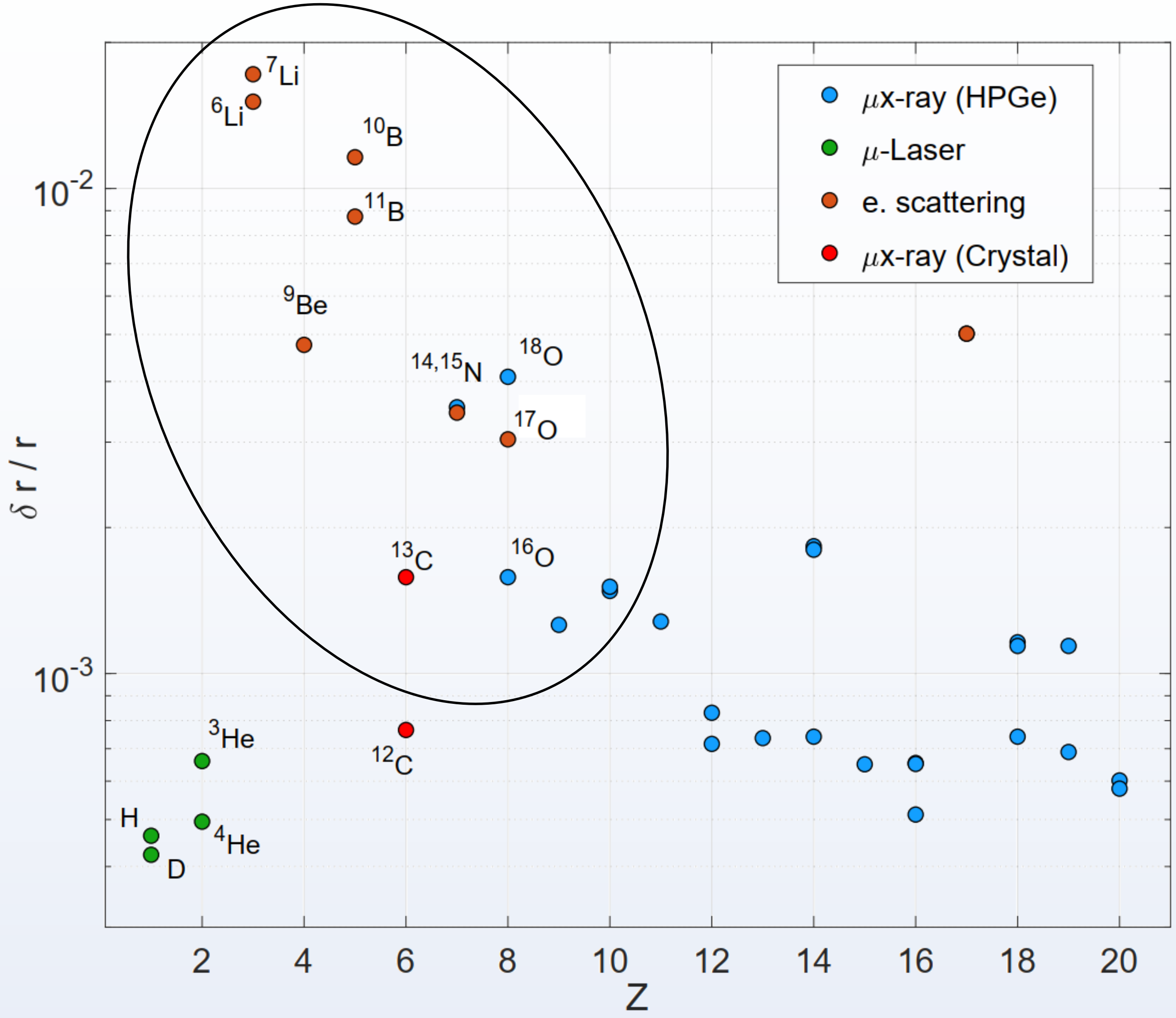
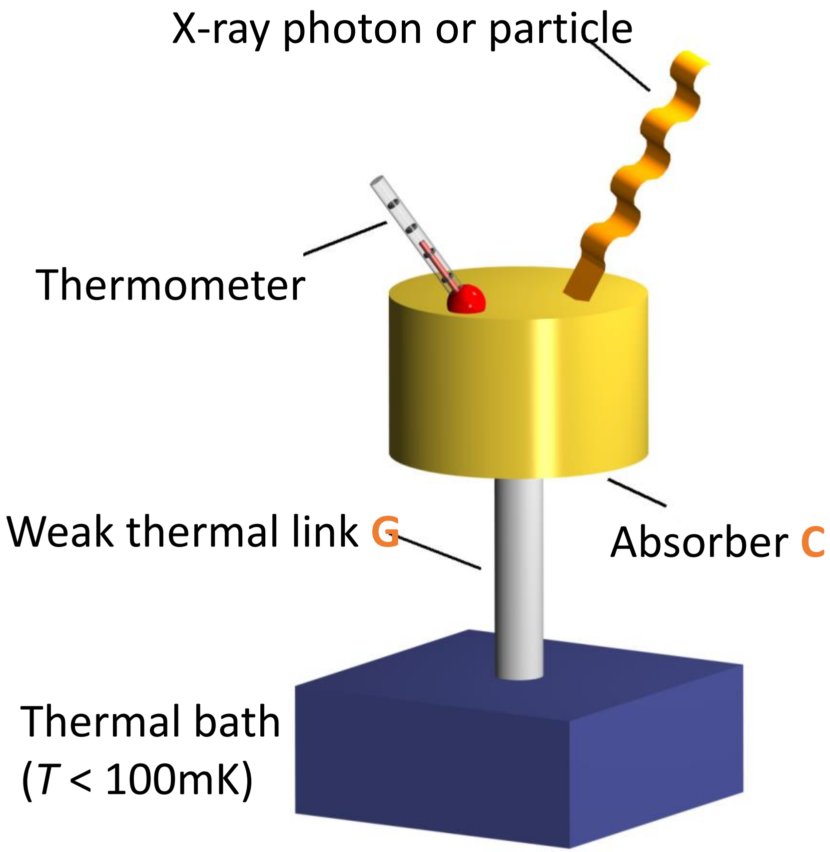
Enter Microcalorimeters



micro-calorimeters

Slides courtesy of Andreas Fleischmann



Temperature change

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

Relaxation to bath temperature

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

Operation at low temperature ($T < 0.1$ K):

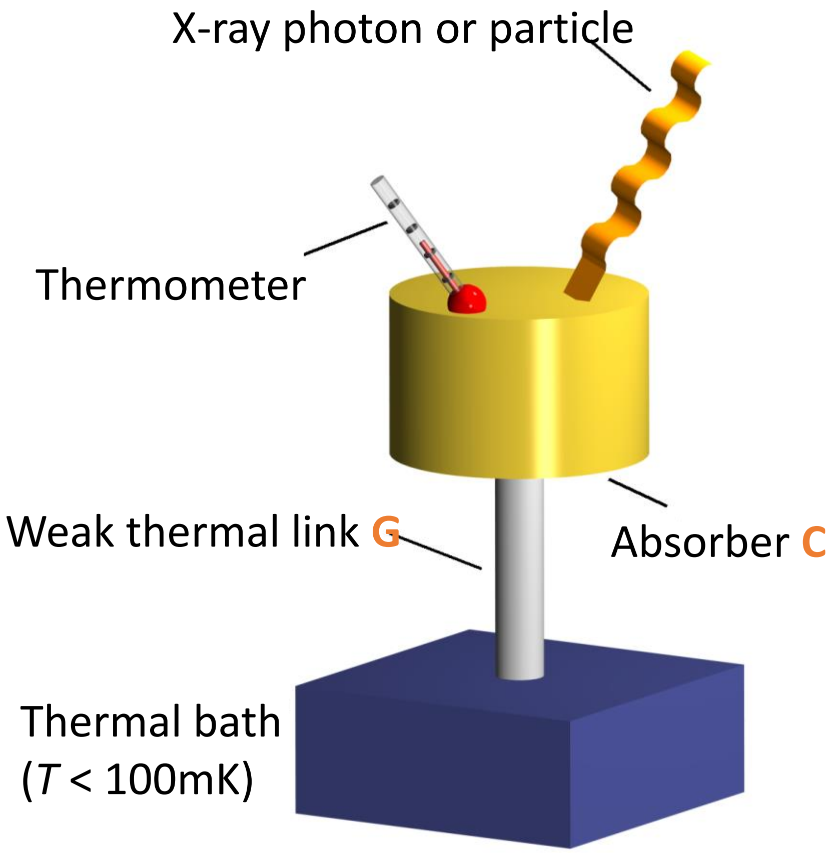
small specific heat

large temperature change

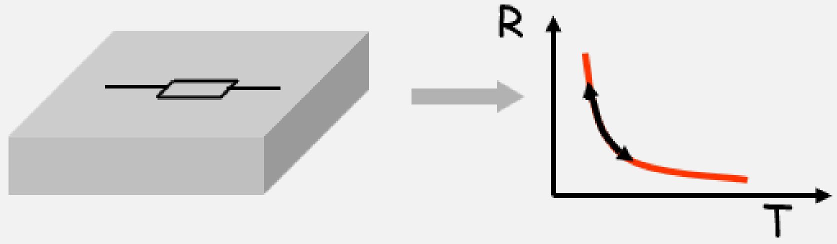
small thermal noise

thermometer concepts

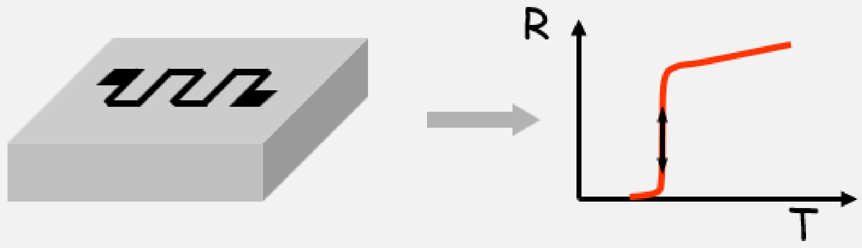
Slides courtesy of Andreas Fleischmann



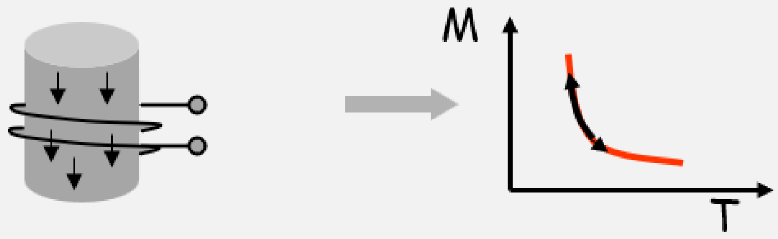
Resistance of highly doped semiconductors



Resistance at superconducting transition,TES

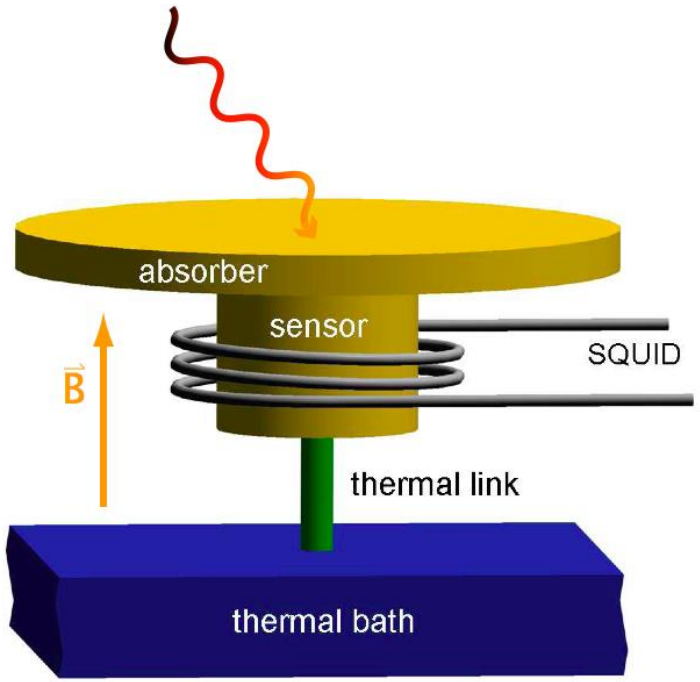


Magnetization of paramagnetic material

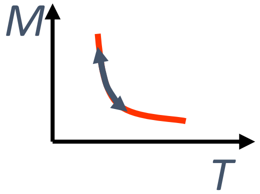


metallic magnetic calorimeters

Slides courtesy of Andreas Fleischmann



paramagnetic sensor: **Au**:Er$_{500ppm}$, **Ag**:Er



signal size:

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

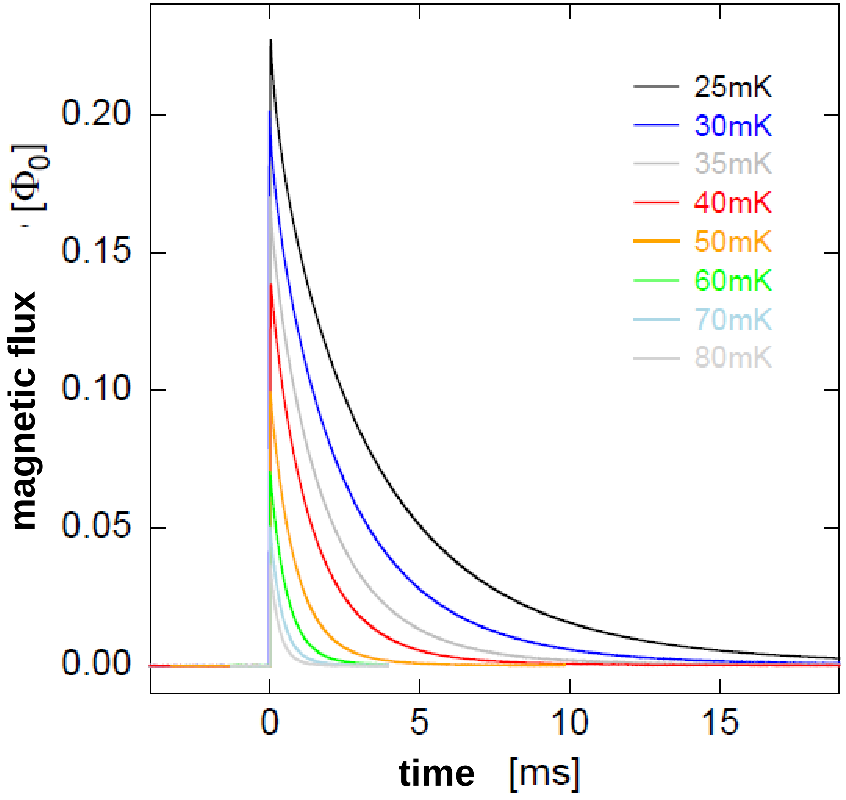
signal decay

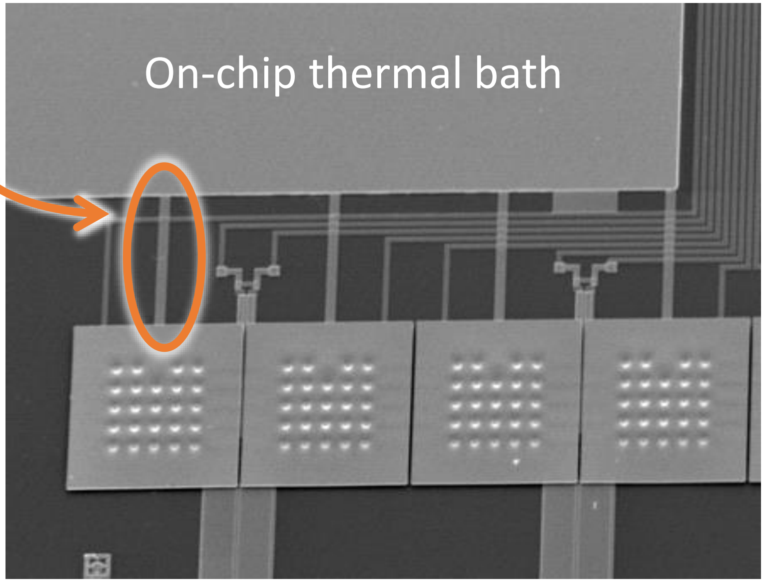
Slides courtesy of Andreas Fleischmann

decay time

adjusted by sputtered thermal link (Au)

here: 3 ms @ 30 mK



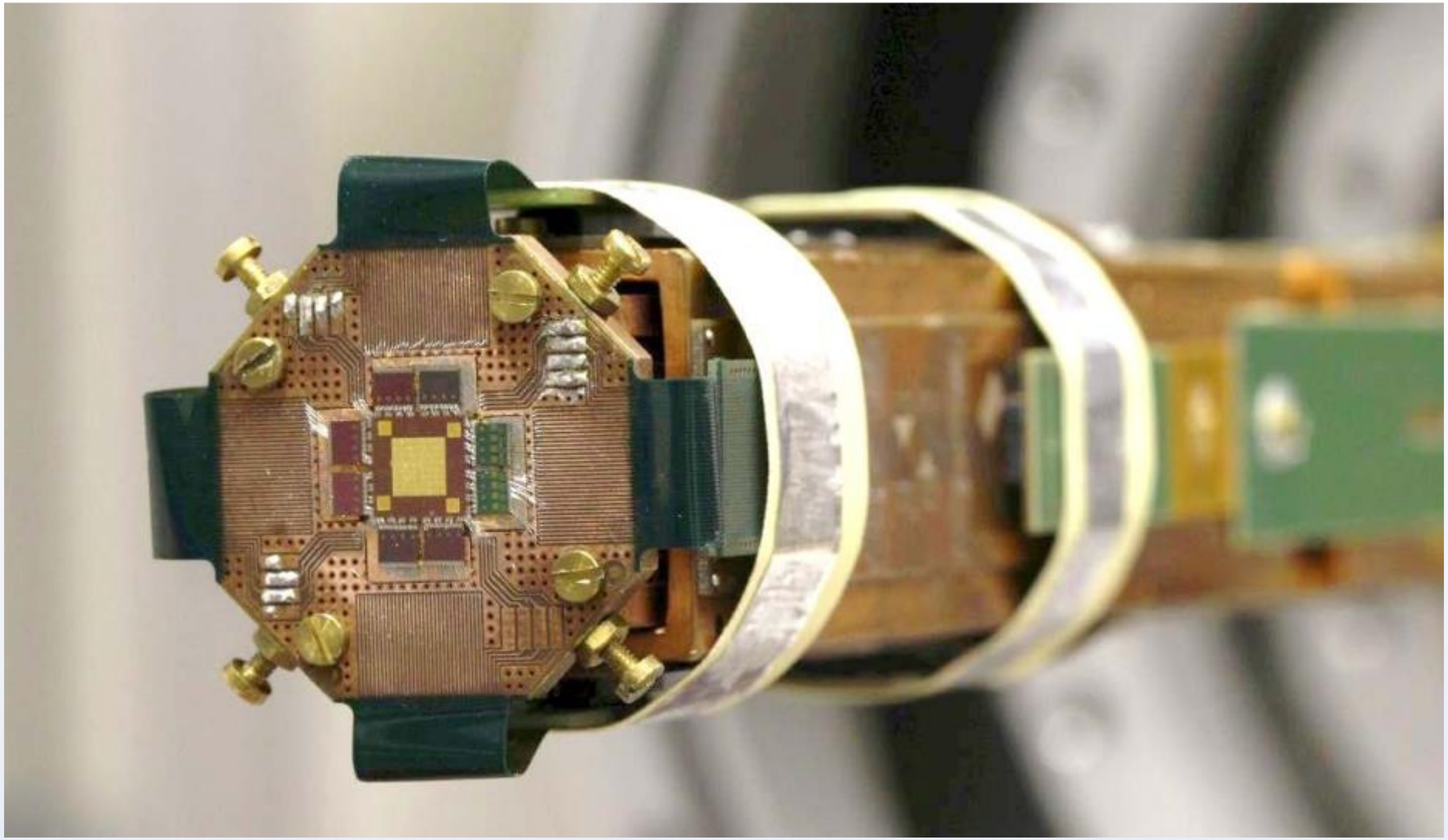


Keep rates < 10 Hz per pixel to avoid pileup

Slides courtesy of Andreas Fleischmann

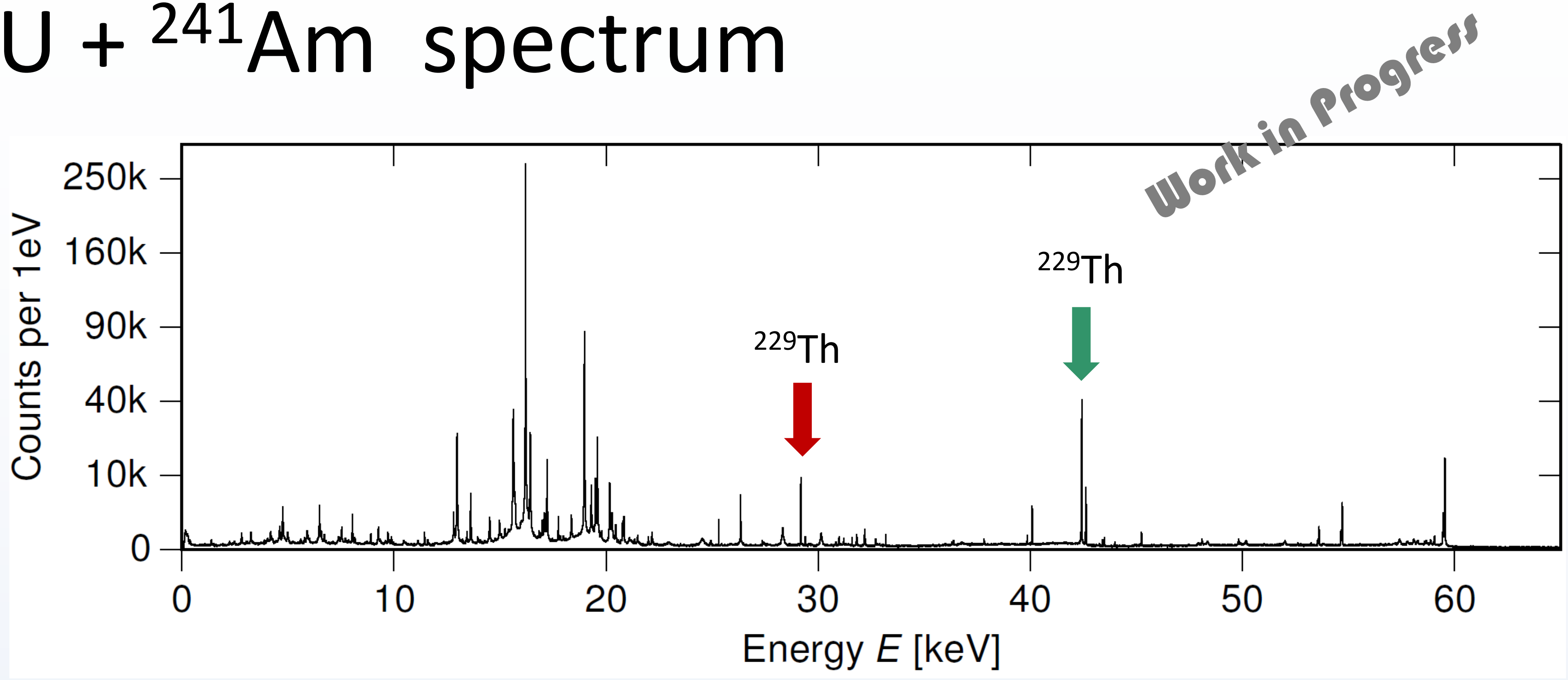
(One of) The Heidelberg Metallic magnetic calorimeter (MMC)

maXs-30 mounted on coldfinger of a dry dilution fridge



Slides courtesy of Andreas Fleischmann

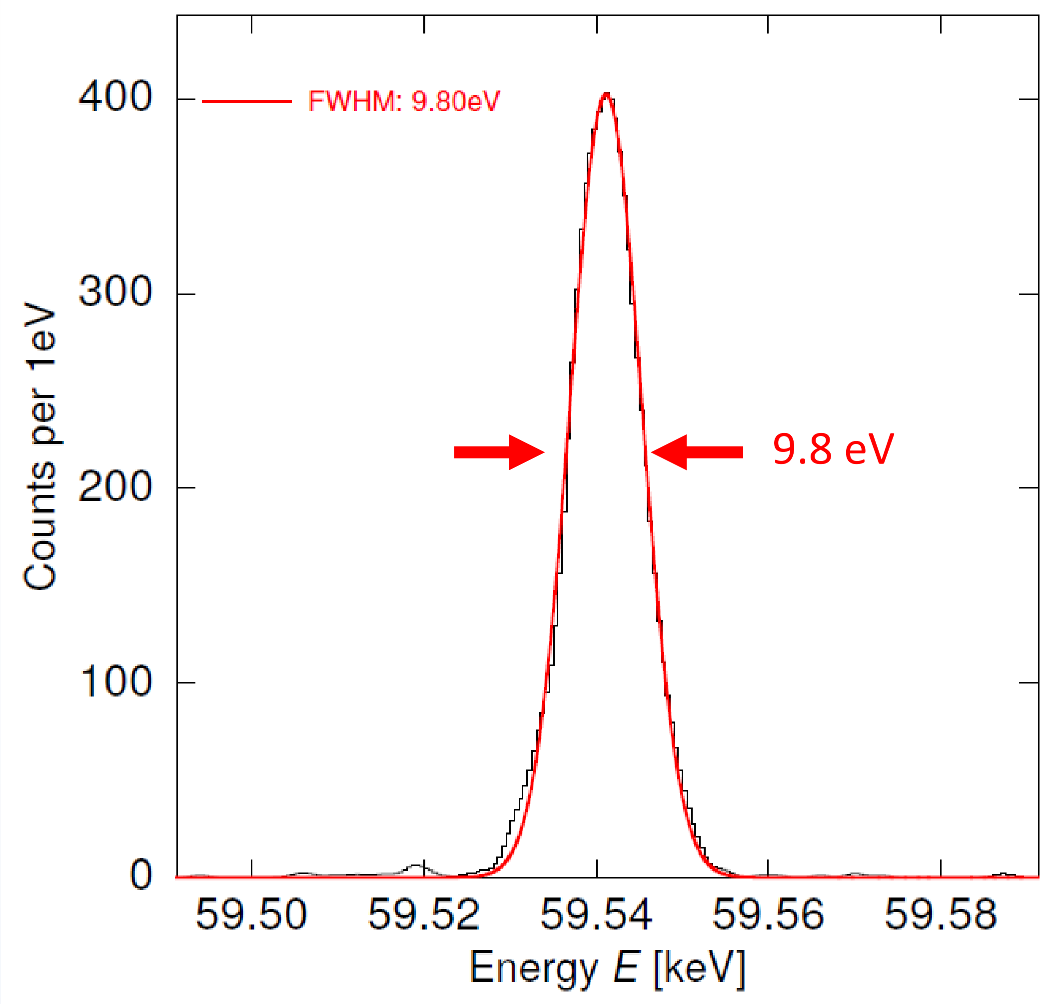
$^{233}U + ^{241}Am$ spectrum



Co-added 20 channels

Slides courtesy of Andreas Fleischmann

energy resolution at 60 keV

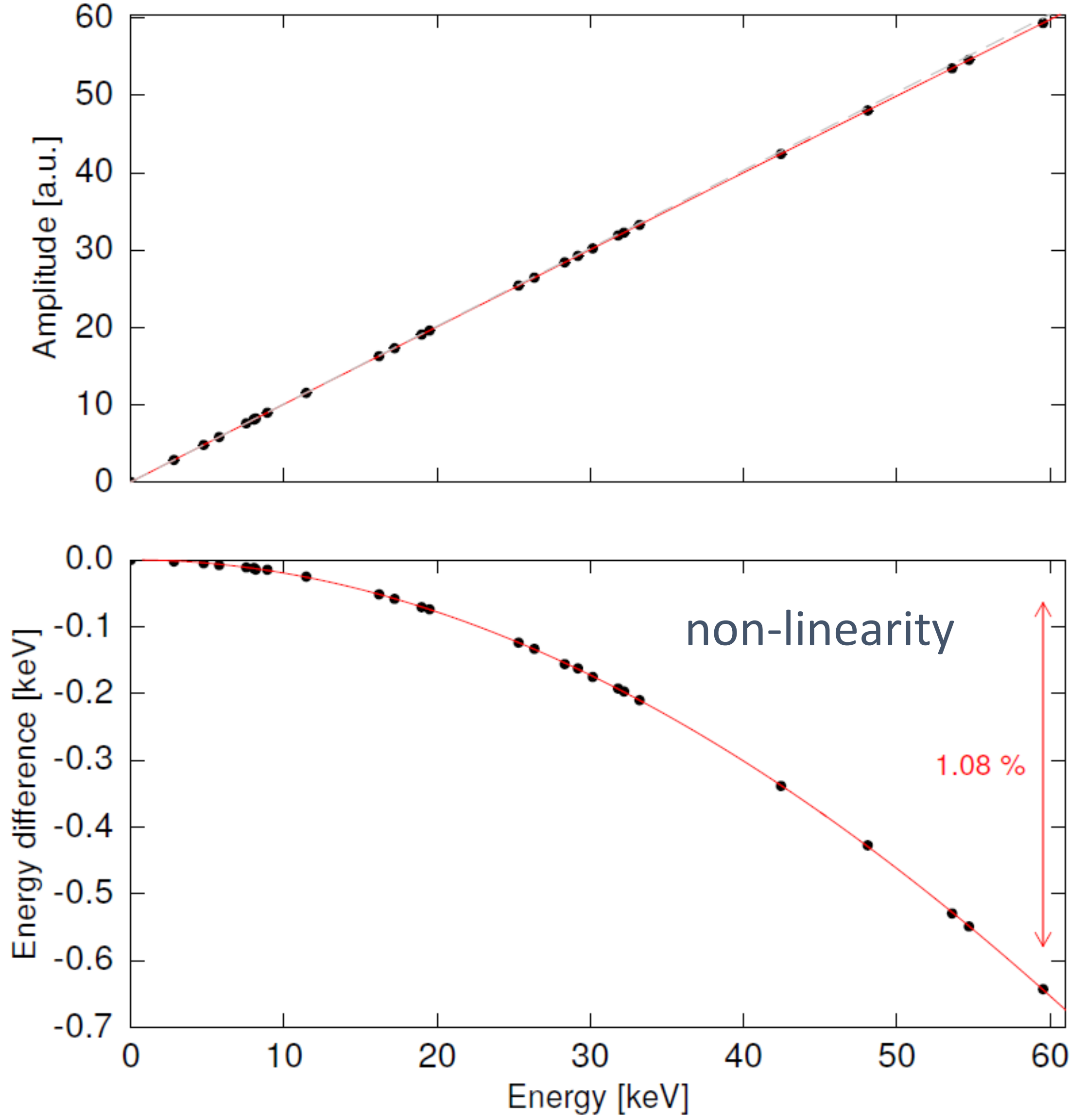


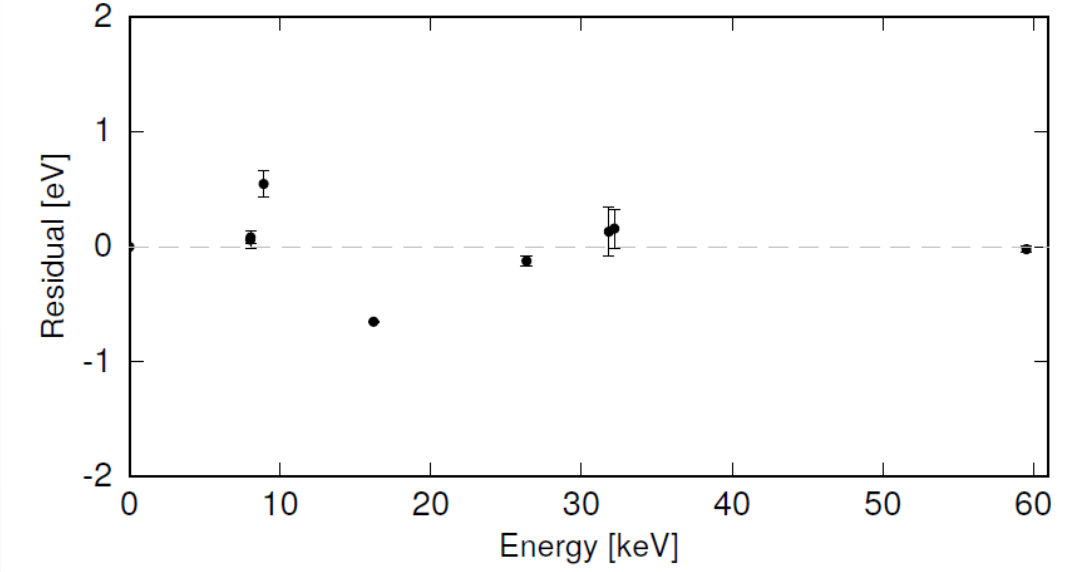
Energy resolution ΔE_{FWHM} = 9.8 eV @ 59 keV

World record resolving power: 6000

Calibration

Slides courtesy of Andreas Fleischmann





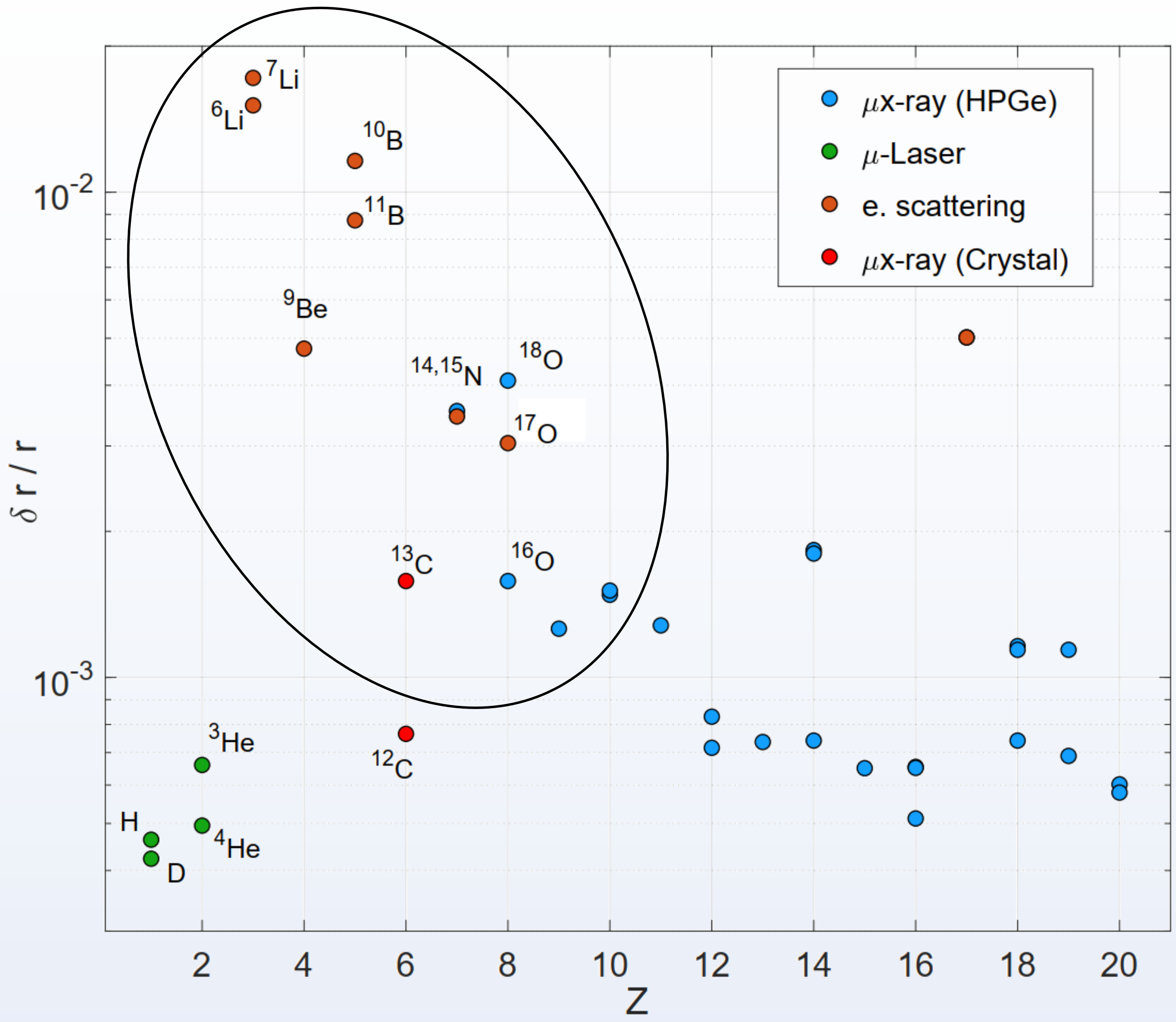
- non-linearity well-understoop and thermodynamically expected
- Sub-eV agreement for carefully selected calibration lines.
- Careful check of calibration lines for $\ll eV$ accuracy
Use crystal spectrometer @ LKB

Moving MMC from Heidelberg to Vienna

Moving MMC from Heidelberg to Vienna

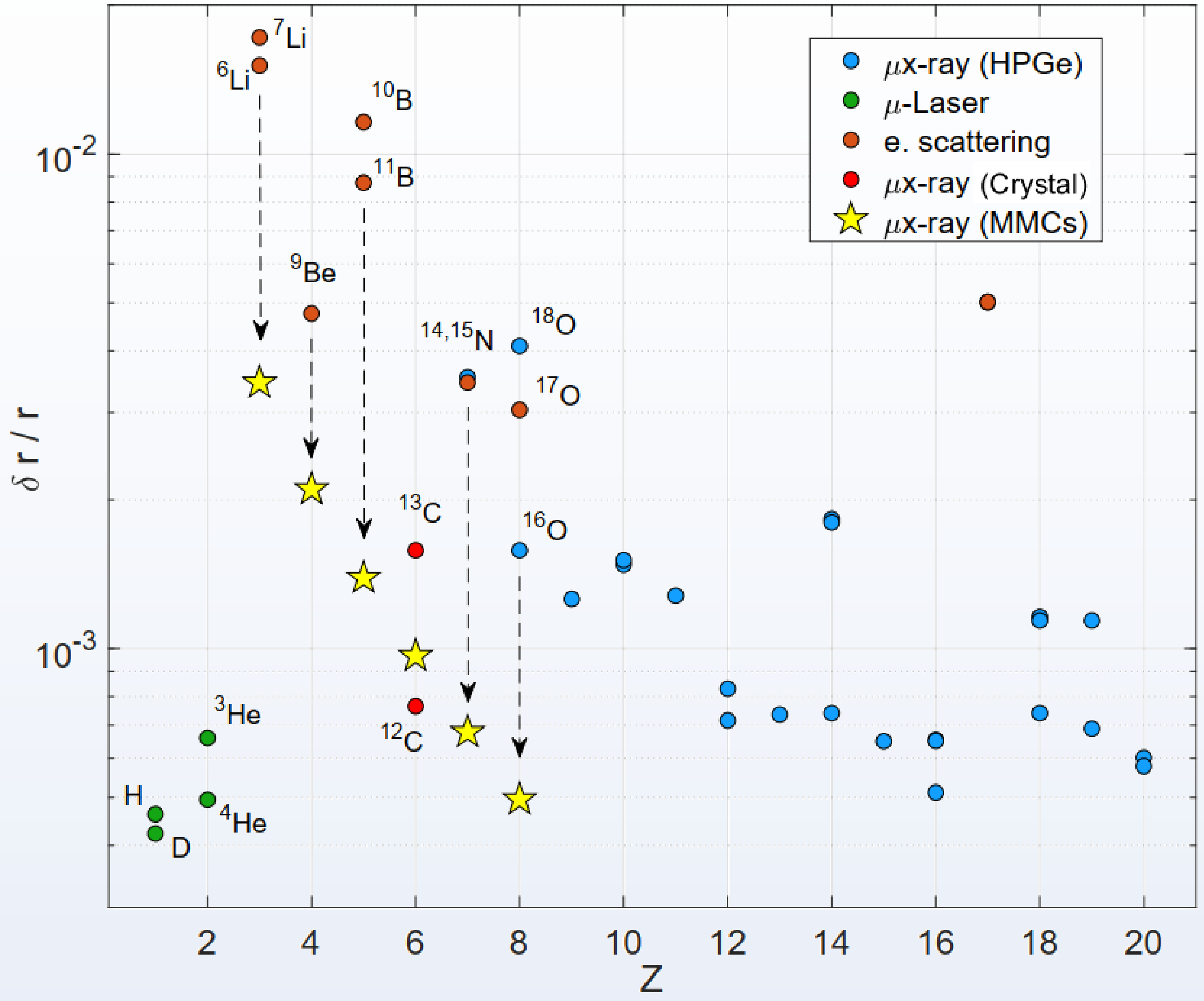
What can we do with them at PSI?

The experimental gap:



QUARTET precision goals (“phase 1”):

- Determine $E(2P-1S)$ for $3 \leq Z \leq 8$ with 10 ppm accuracy $0.2-1$ eV .
- ^{12}C as benchmark
- Improve radii by factor $3-10$.
- maXs-30 up to 60keV (Li, Be, B)

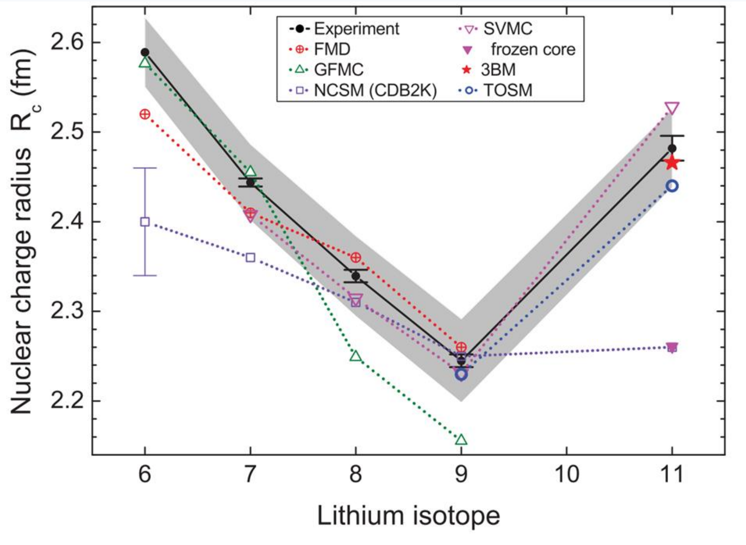


Applications of QUARTET phase 1:

- Improve radii of all measured isotopes of Li, Be, and B.
- Benchmark nuclear theory
- Muonic isotope shift -> Benchmark many-body QED

Li chain:

PRC 84, 024307 (2011)



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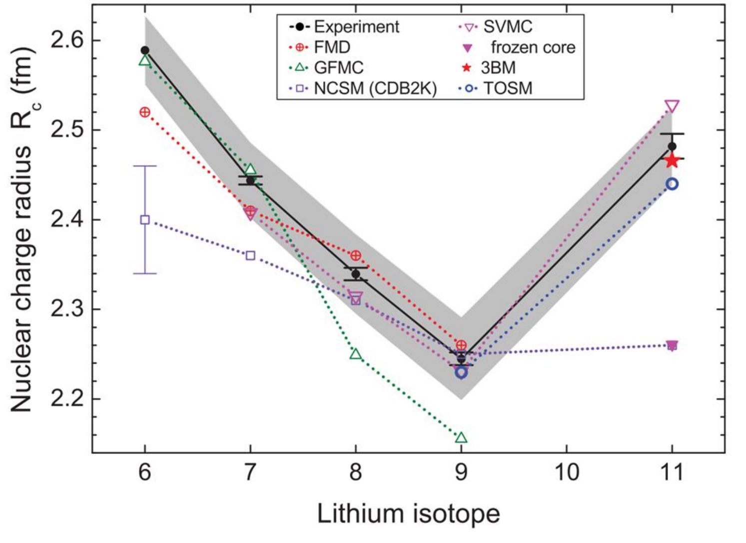
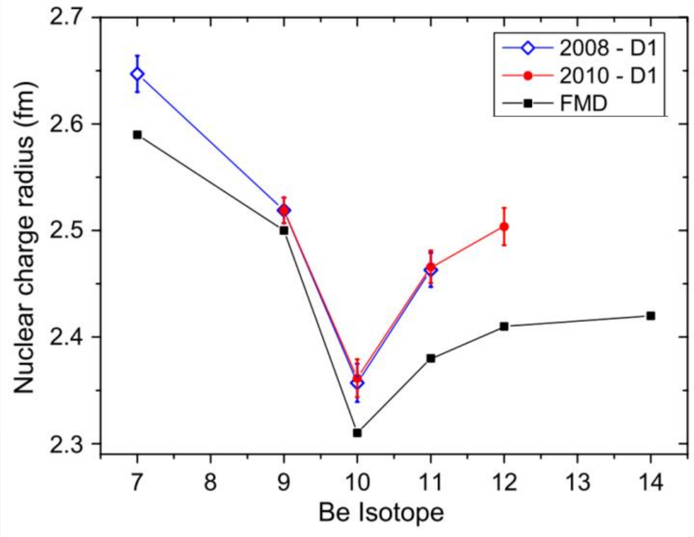


Be chain:

PRL 122, 182501 (2019)



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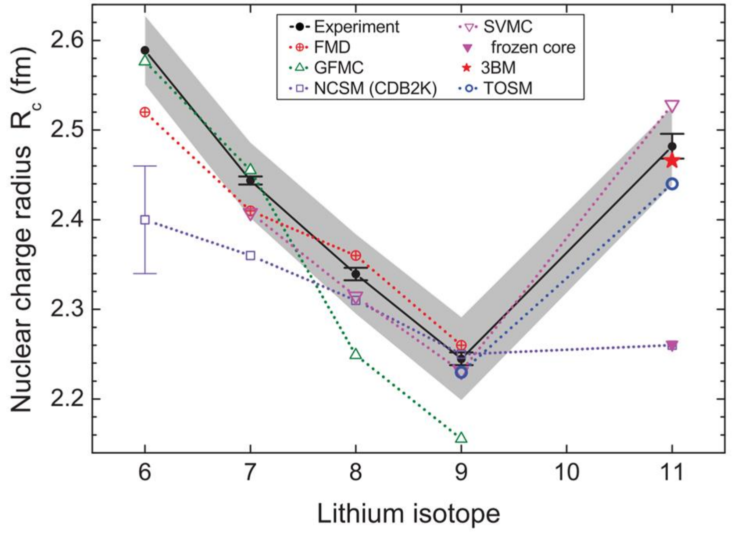
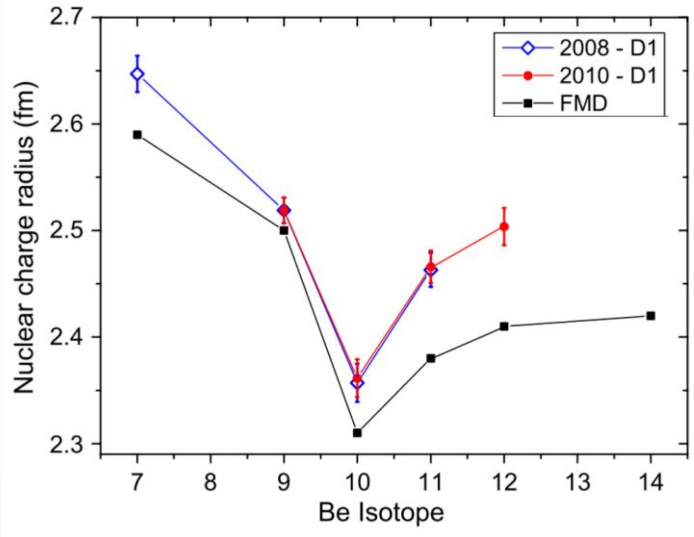


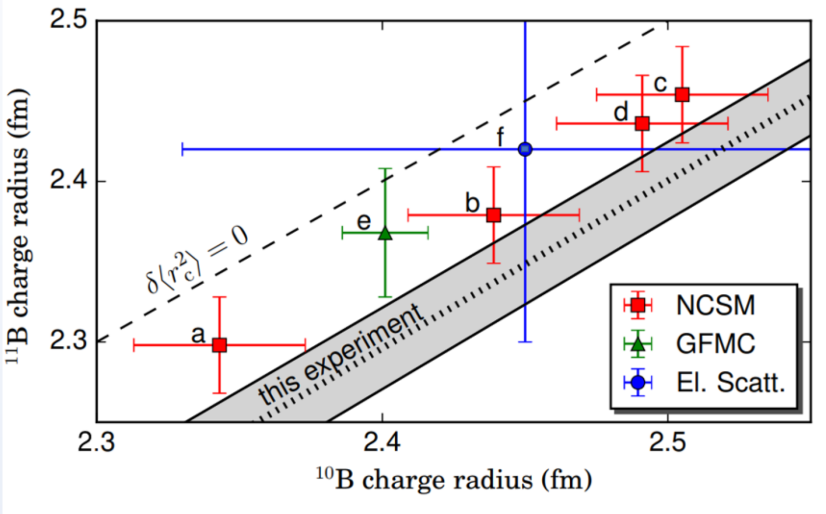
Be chain:

PRL 122, 182501 (2019)



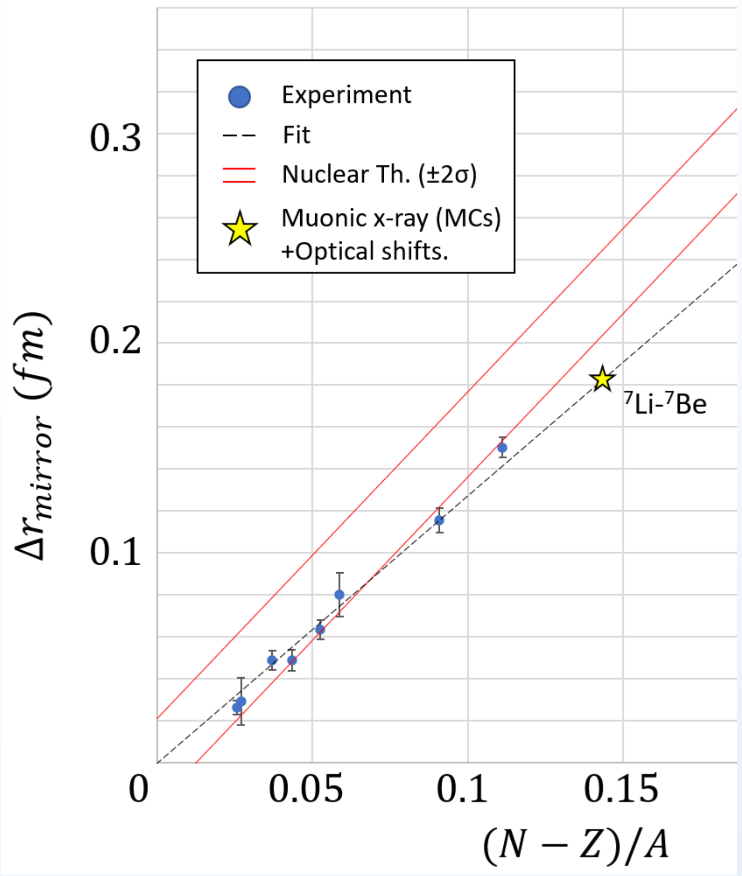
^{10,11}B:

PRL 108, 142501 (2012)



Applications of QUARTET phase 1:

Mirror radii at large asymmetry:



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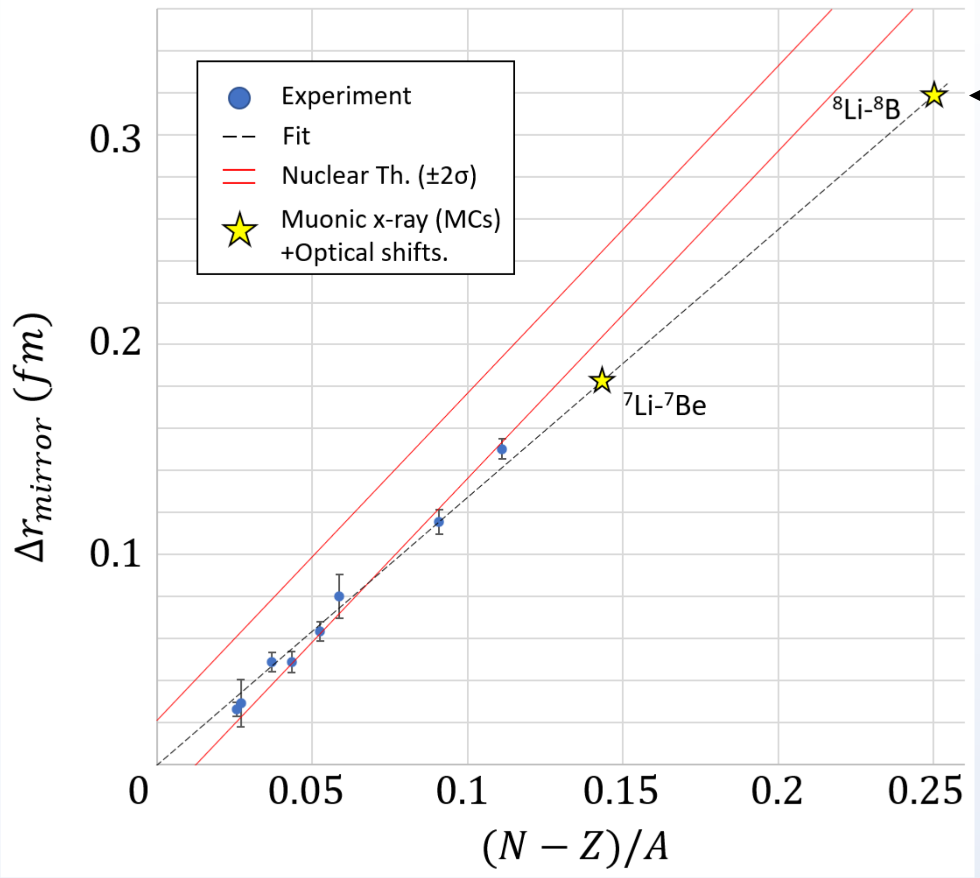
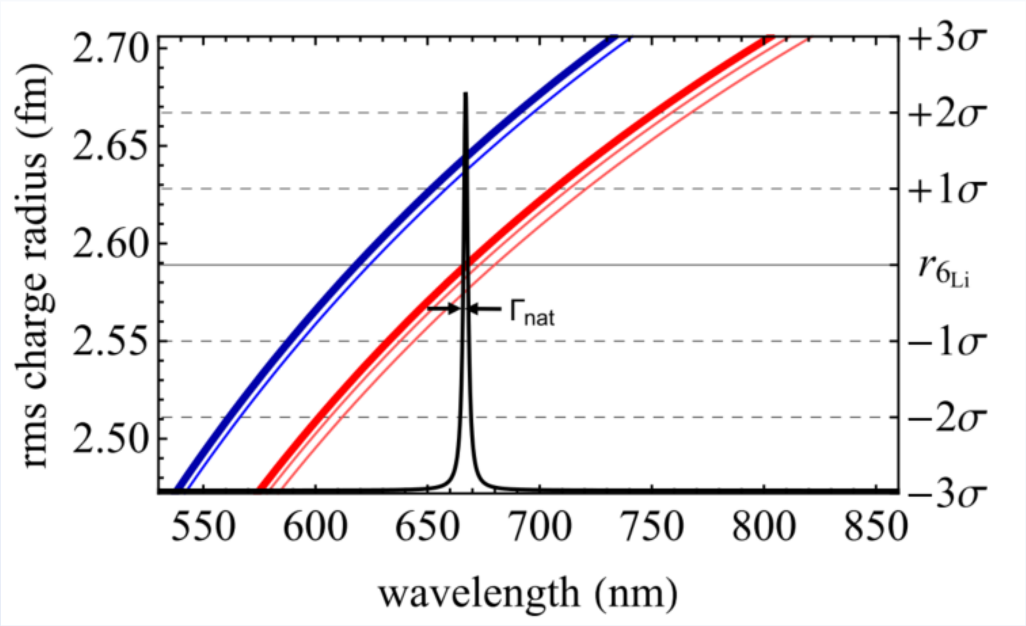


^{8}B isotope shift measurements ongoing at NSCL

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

- MMCs: Improve r_c of ^{6}Li by factor ~5.
- Narrow 2S-2P wavelength search from 200 nm to 50 nm
- Similarly for Be (but more challenging)



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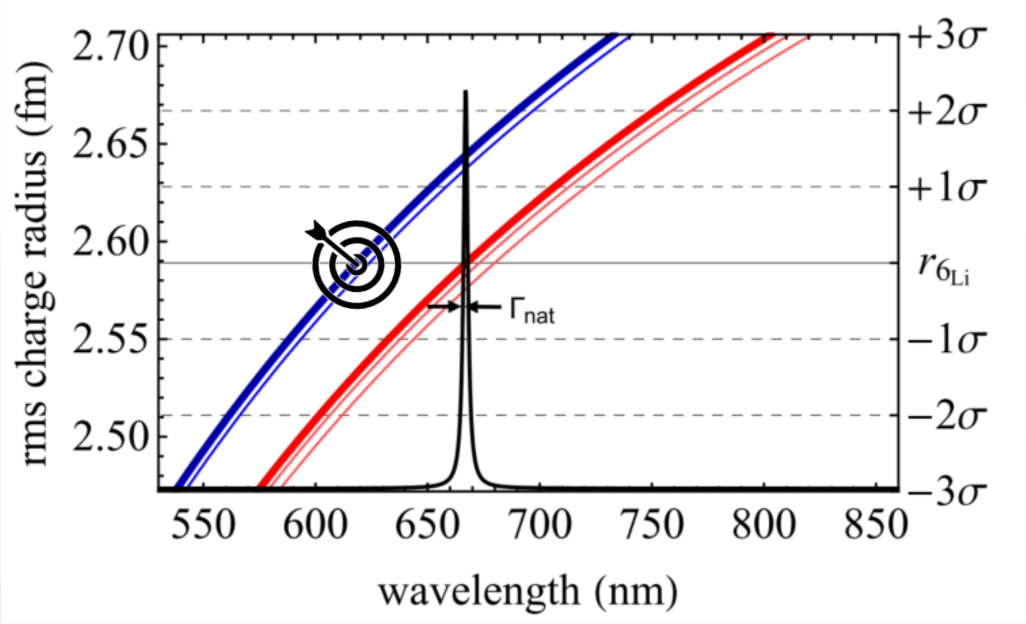
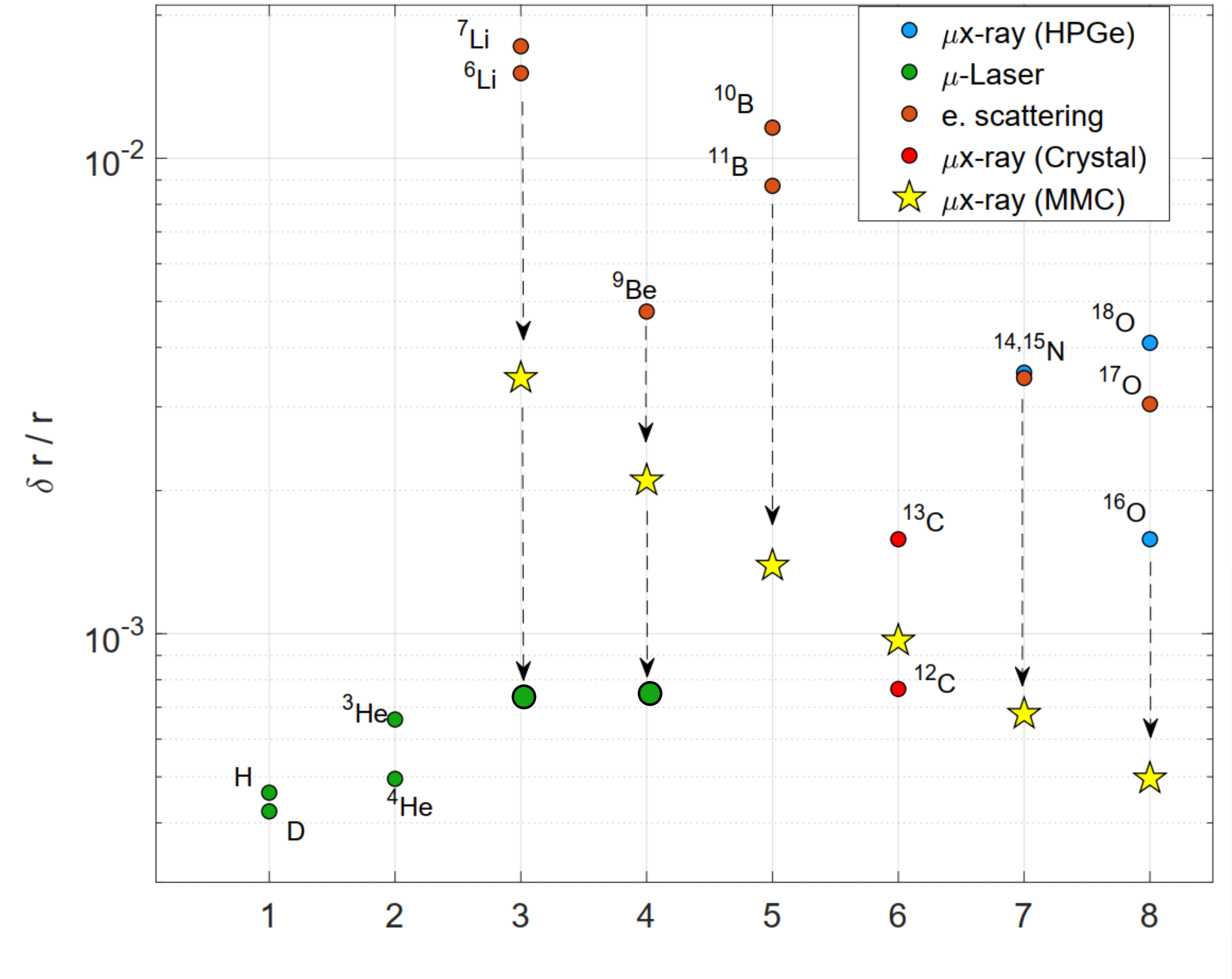
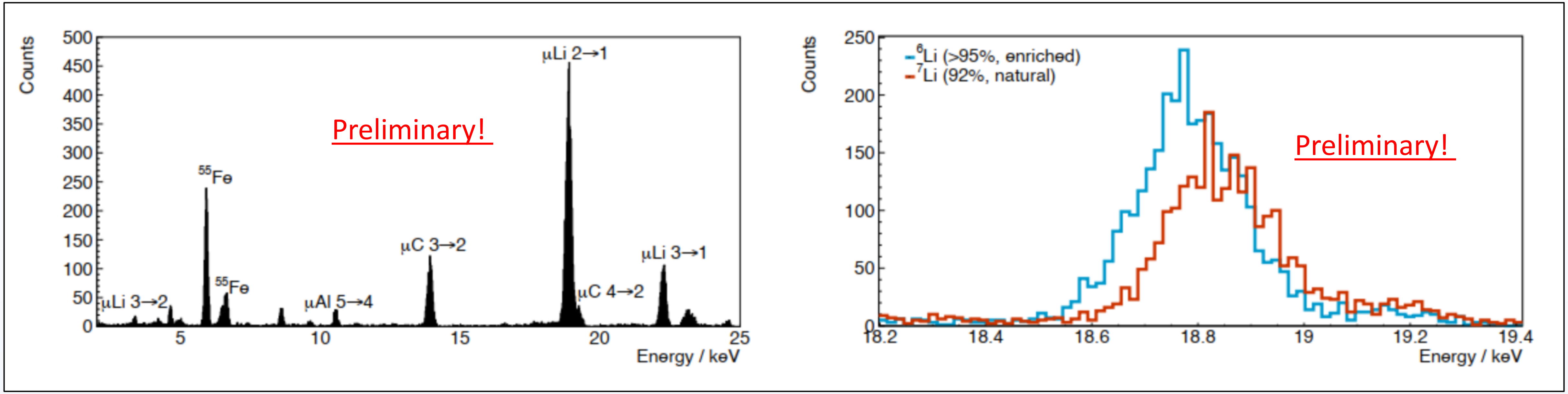




New from the oven: ^{6,7}Li 1S-nP measured with Silicon drift detector



FWHM 245 eV

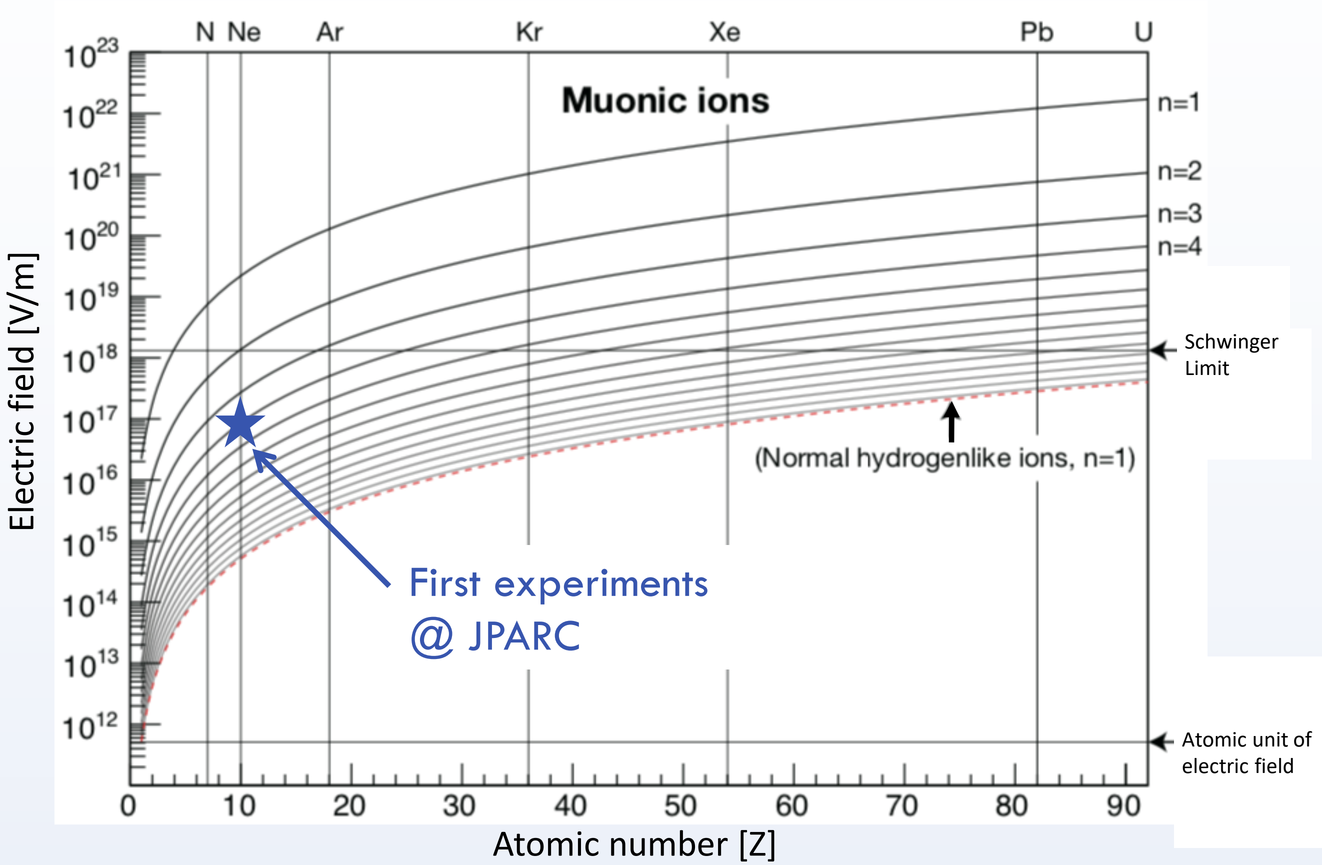
Very exciting result going already beyond the state-of-the-art!

Applications of QUARTET "phase 2":

QED at high fields:

- First measurements with TES microcalorimeter @ JPARC

See talk on Monday by Nancy Paul



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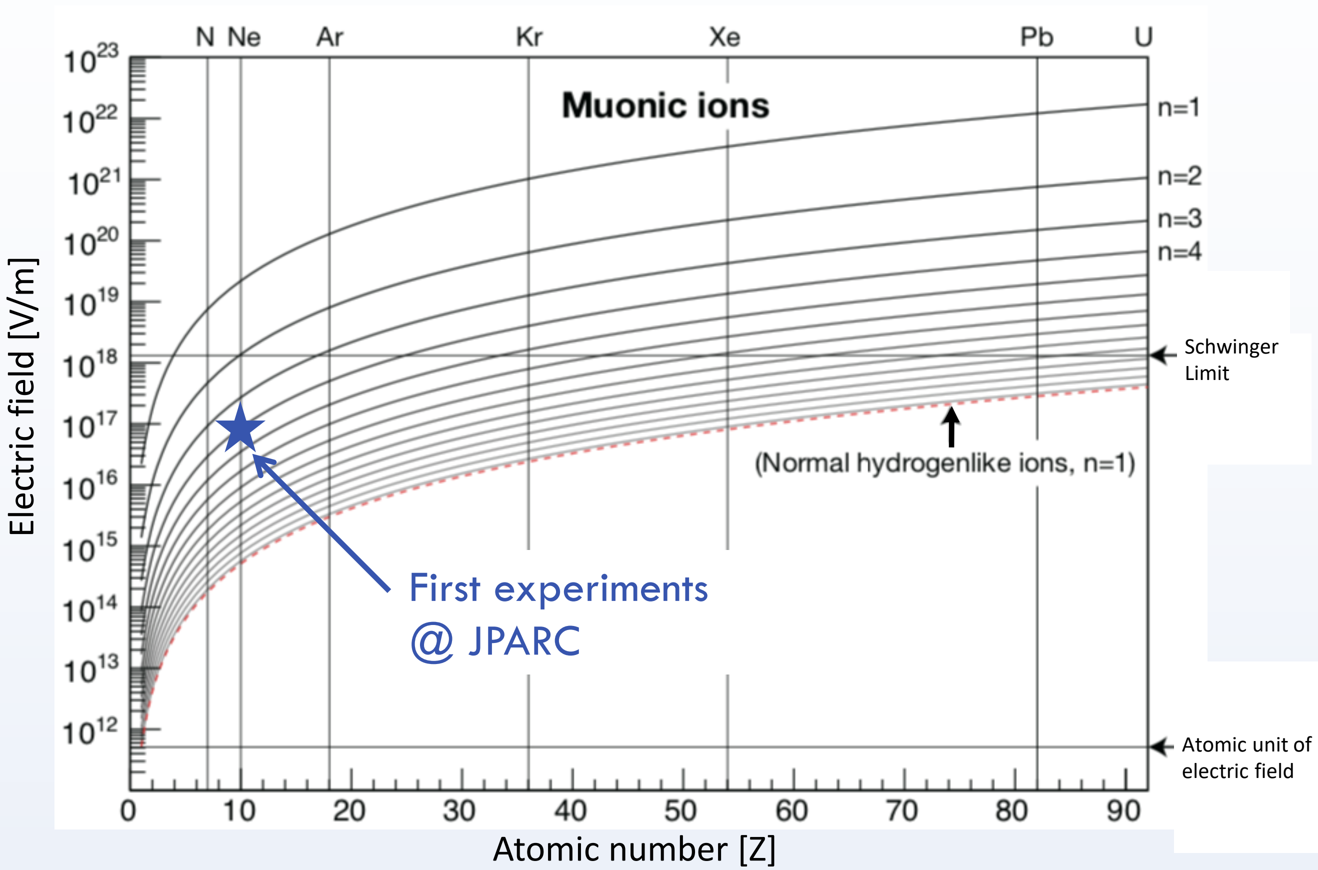
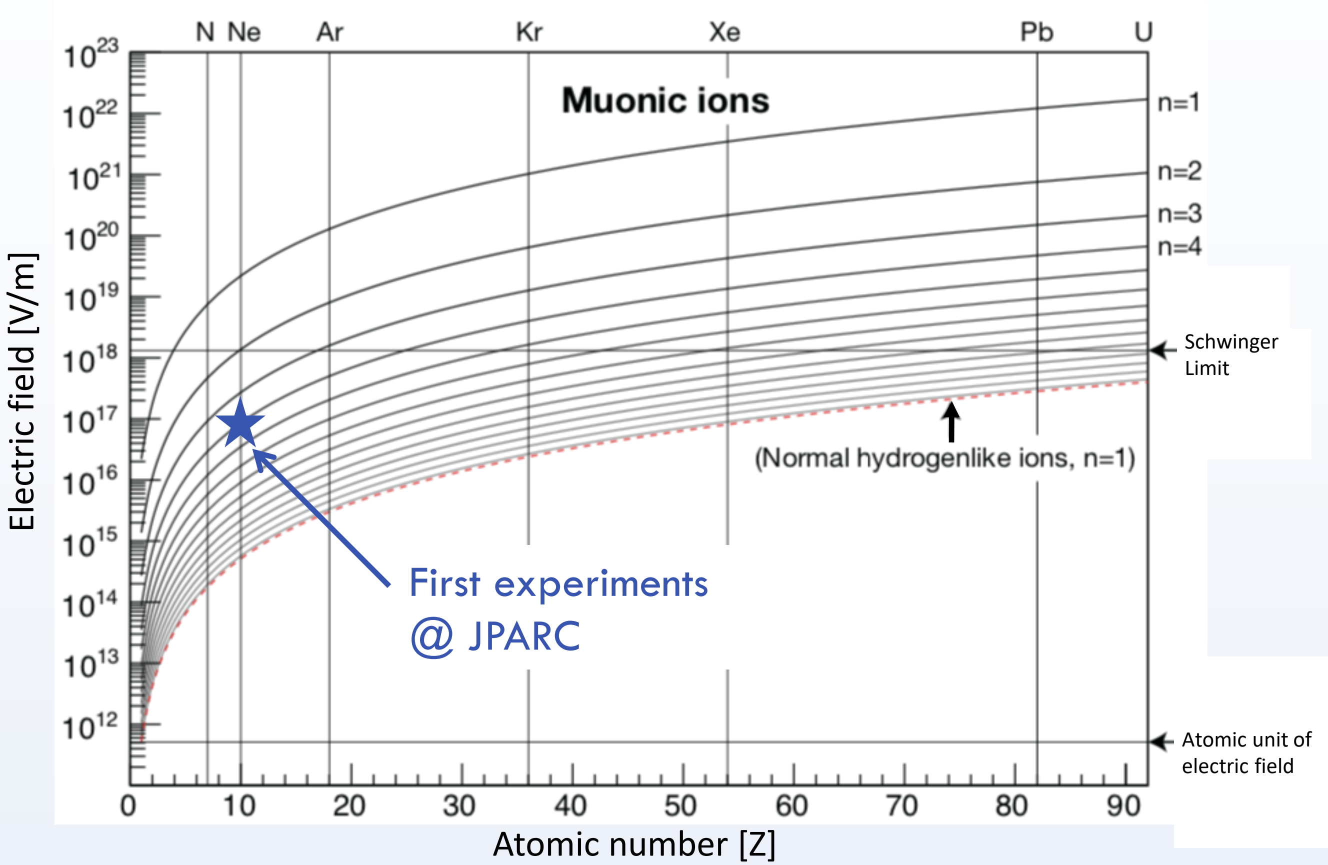


Applications of QUARTET "phase 2":

QED at high fields:

See talk on Monday by Nancy Paul

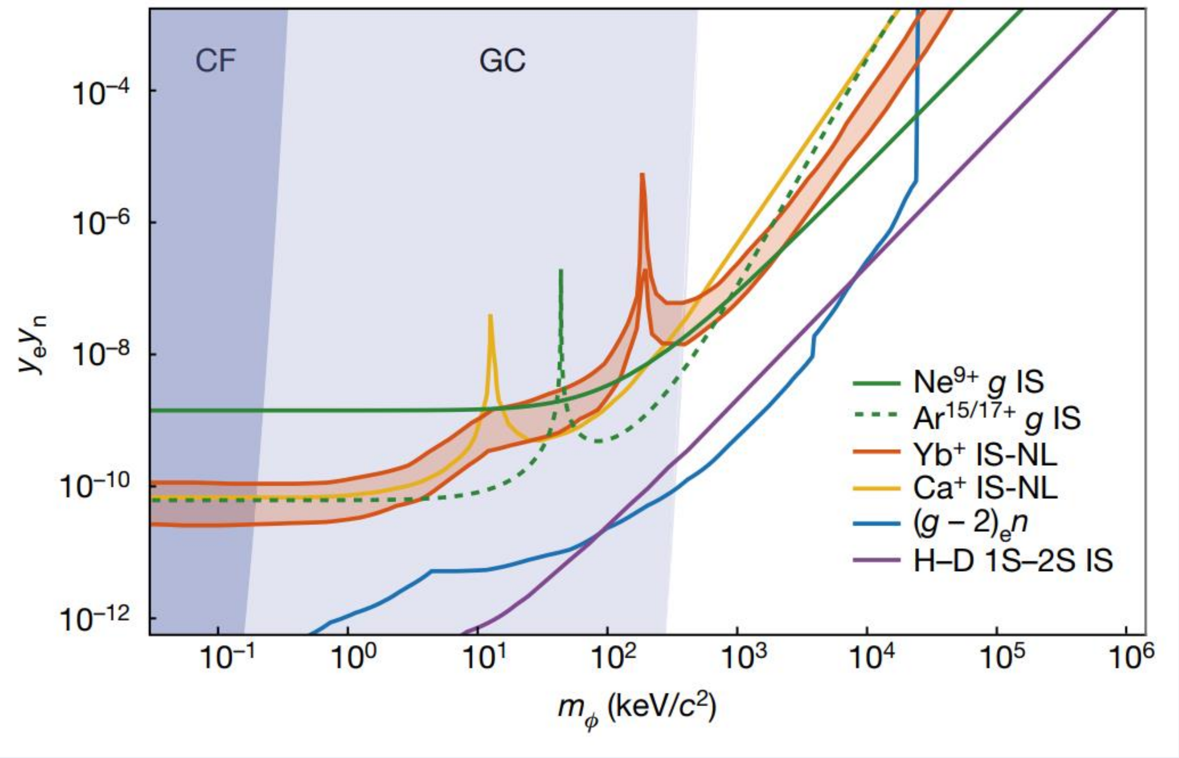
- First measurements with TES microcalorimeter @ JPARC
- $\mu Ne(5g - 4f) @ 6\ keV$. Limited by pileup to $\sim 0.1\ eV$
- PSI CW beam, higher rates with negligible pileup. Order of magnitude improvement "straightforward".
- **Measurements of transitions between non-S states in noble gasses @ PSI with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



Applications of QUARTET “phase 2”:

Muonic isotope shifts for new physics searches

- From g-factor: $\Delta r_c(eNe) = -0.318(3) fm$
- BSM reach limited by $\Delta r_c(\mu Ne) = -0.310(35) fm$
- Motivation to improve μNe by factor 12
- Measure Δ(1S-2S)@200keV with 0.5eV uncertainty
- Note: Isotope shifts depends less on calibration & theory

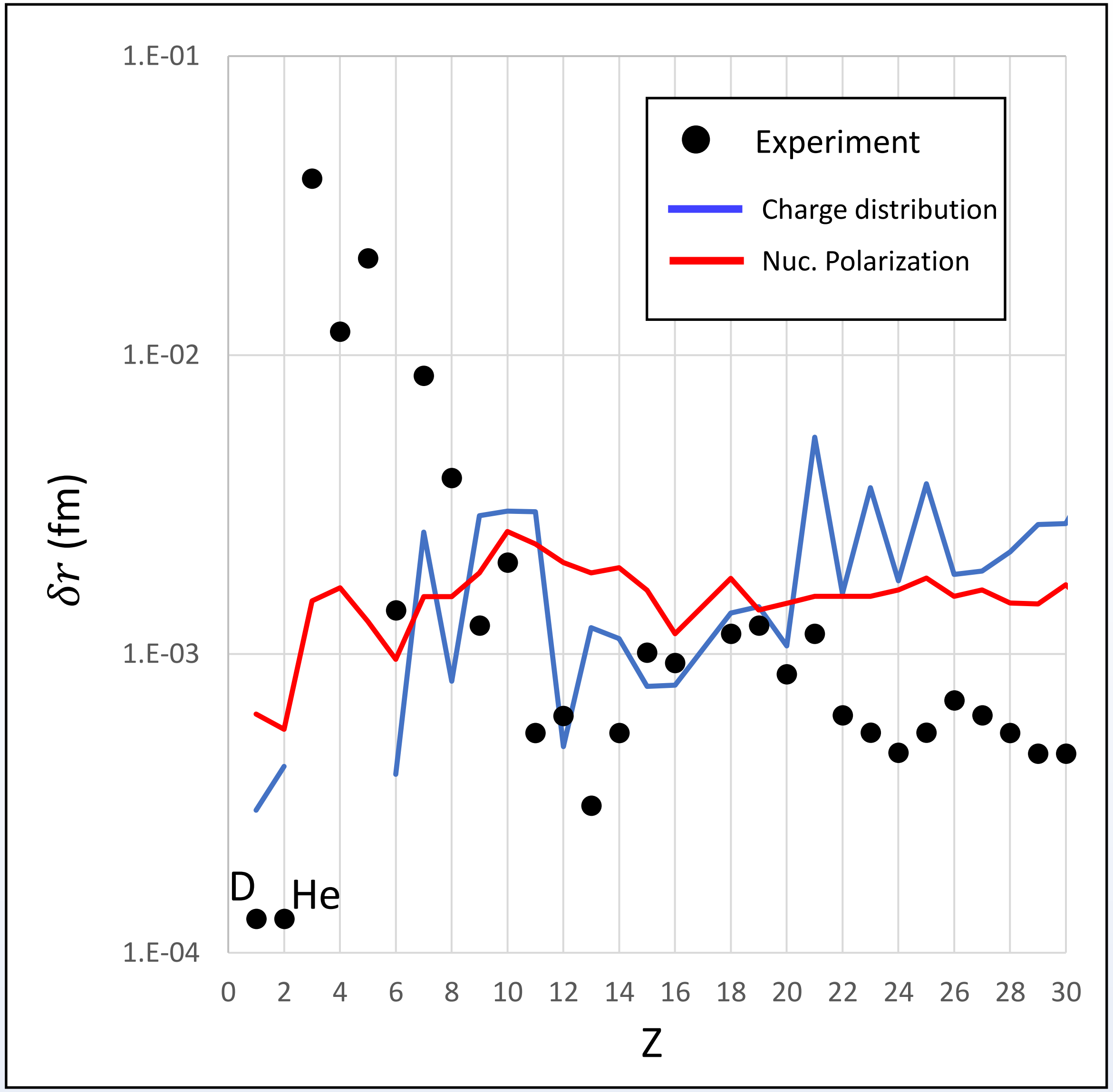


Main needed inputs:

From theory, mainly nuclear polarization

- For Li-Ne $\lesssim (5\ ppm)(E_{2P-1S})$ (~10%)
- For isotope shifts $\lesssim (3\ ppm)(\Delta E_{2P-1S})$ (~5%)
- 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, …



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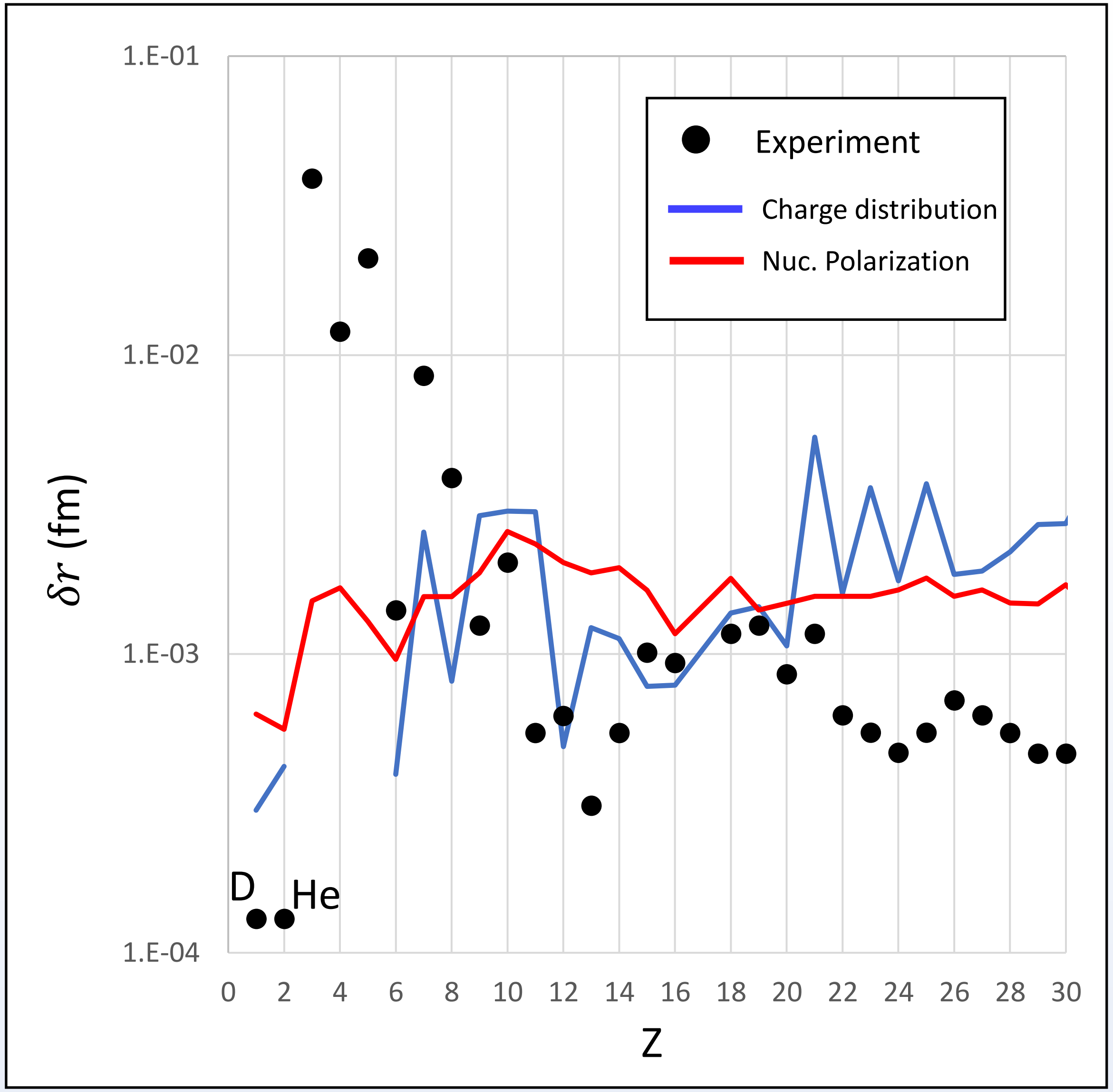
Muonic lithium atoms:
Nuclear structure corrections to the Lamb shift

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



Thank you

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

PAUL SCHERRER INSTITUT
PSI

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Cluster of Excellence PRiSMA+
Precision Physics, Fundamental Interactions and Structure of Matter

ETH zürich

TECHNION
Israel Institute of Technology

Laboratoire Kastler Brossel
Physique quantique et applications

Benchmarking TPE calculations. Muonic vs. electronic isotope shifts: