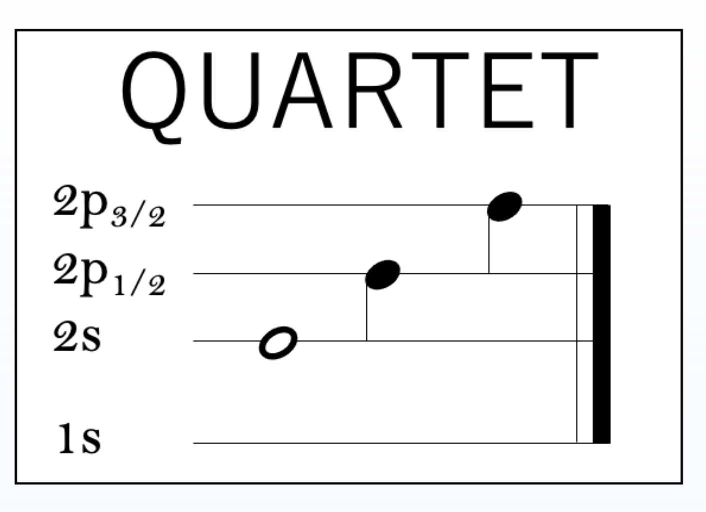
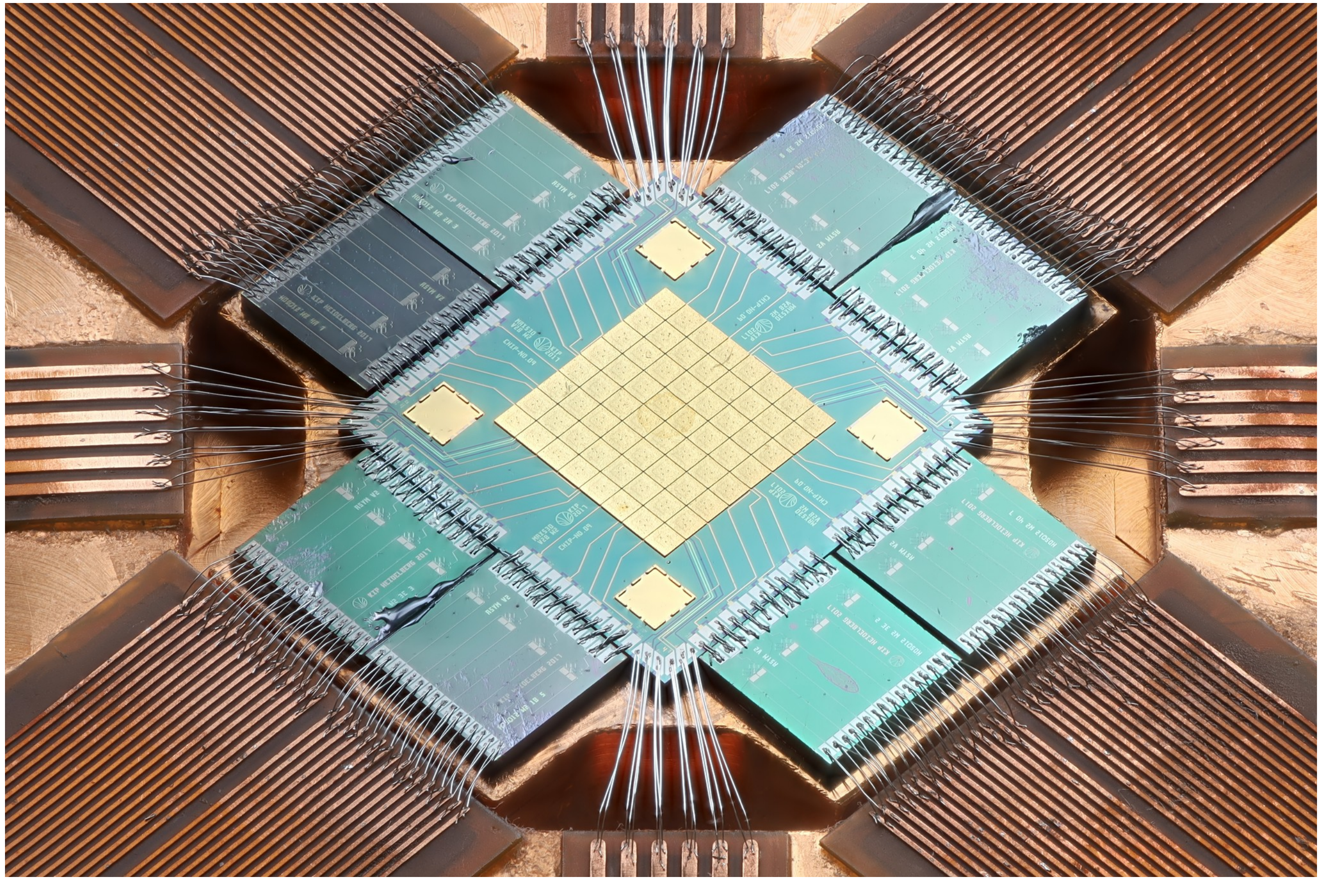
Mu4Rad: Muonic Atoms for Nuclear Radii

Lithium to Neon



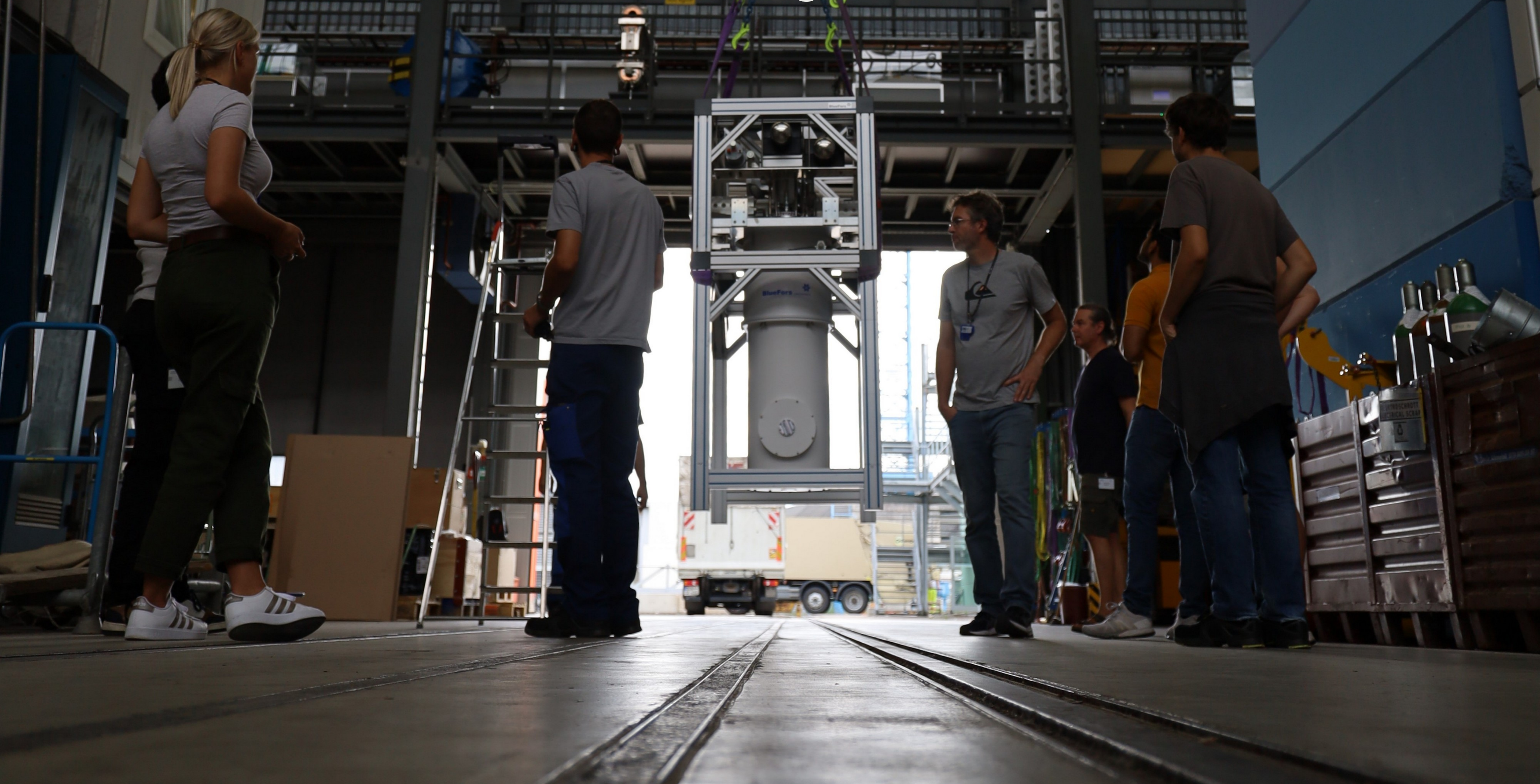
QUAntum inteRacTions with Exotic aToms

Randolf Pohl (JGU Mainz)
Nancy Paul (LKB Paris)
Ben Ohayon (Technion Haifa)
Loredana Gastaldo (KIP Heidelberg)

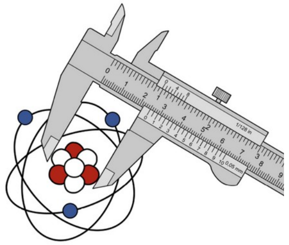


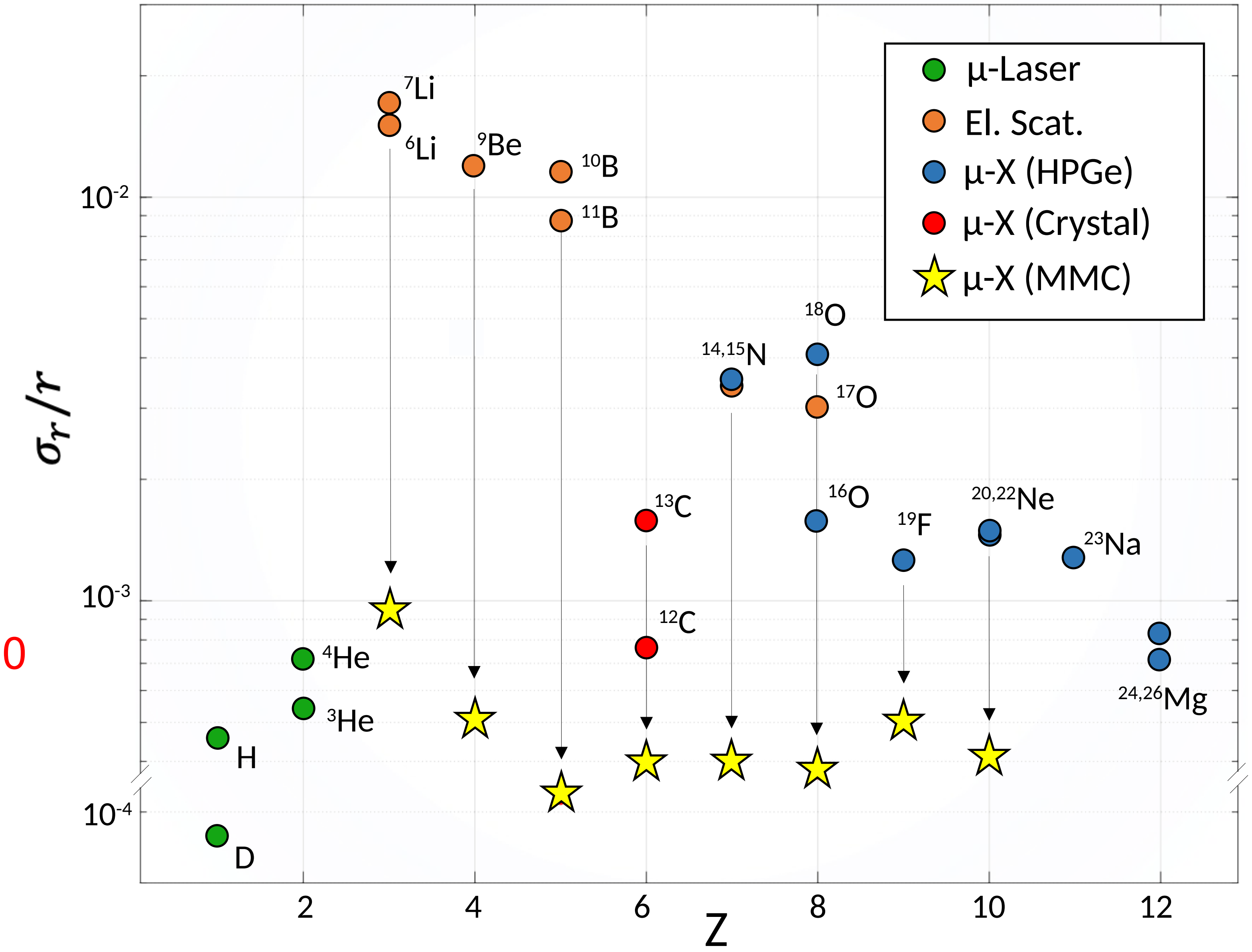
Metallic Magnetic Calorimeter (MMC)
maXs-30

QUARTET: Measurement of Charge Radii from Lithium to Neon



The QUARTET collaboration and precision goals





Goals

- Determine E(2P-1S) for $3 \leq Z \leq 10$ with few ppm accuracy i.e. 0.2-1 eV .

- Improve radii by factor 3-10.

Why does it work?

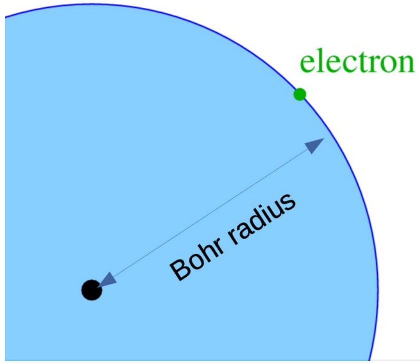
Muonic atoms are highly sensitive to nuclear properties

New quantum sensing microcalorimeter detectors
50X gain in intrinsic resolution for x rays

Muonic atoms in a nutshell

Regular hydrogen:

Bohr radius ~ 50'000 x nuclear radius



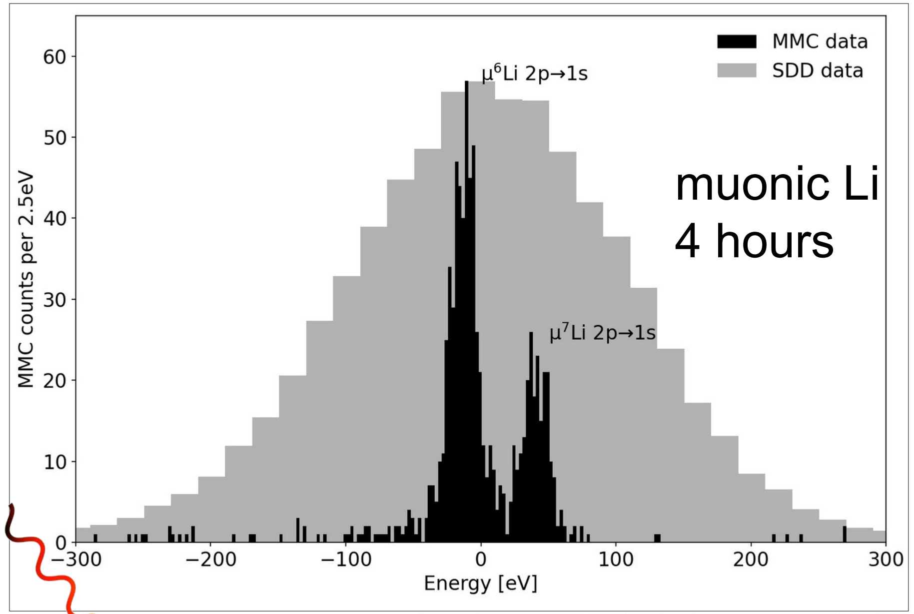
Muonic hydrogen:

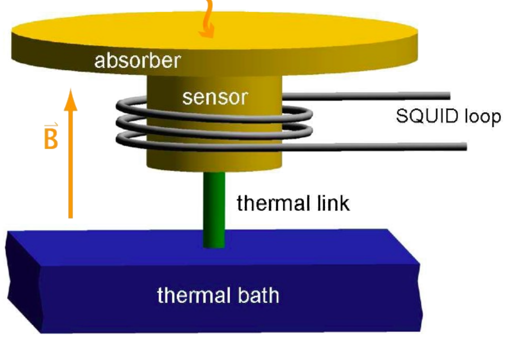
Muon **mass** = **200** * electron mass

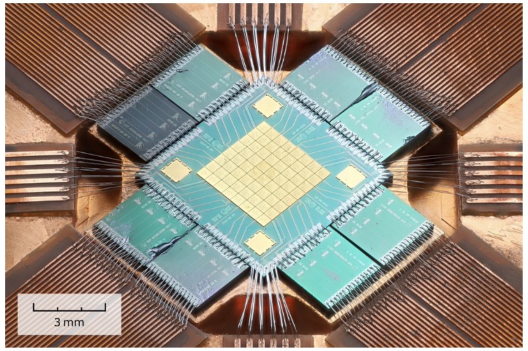
Bohr **radius** = **1/200** of H

200^3 = a **ten million times** more sensitive to nuclear size & structure

==> Our laser spectroscopy at **10^{-5}** level can compete with **10^{-12}** from normal atoms

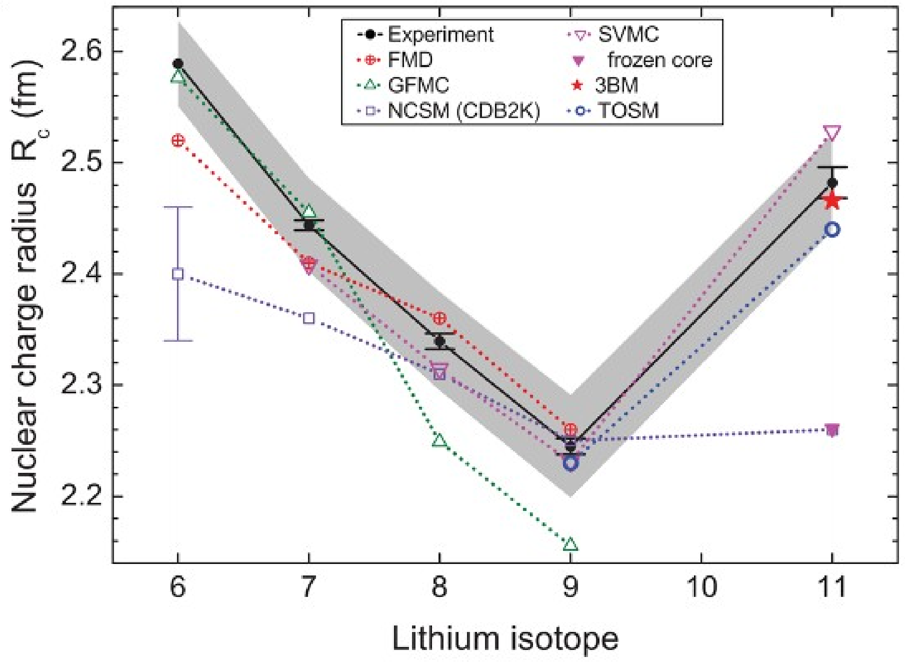




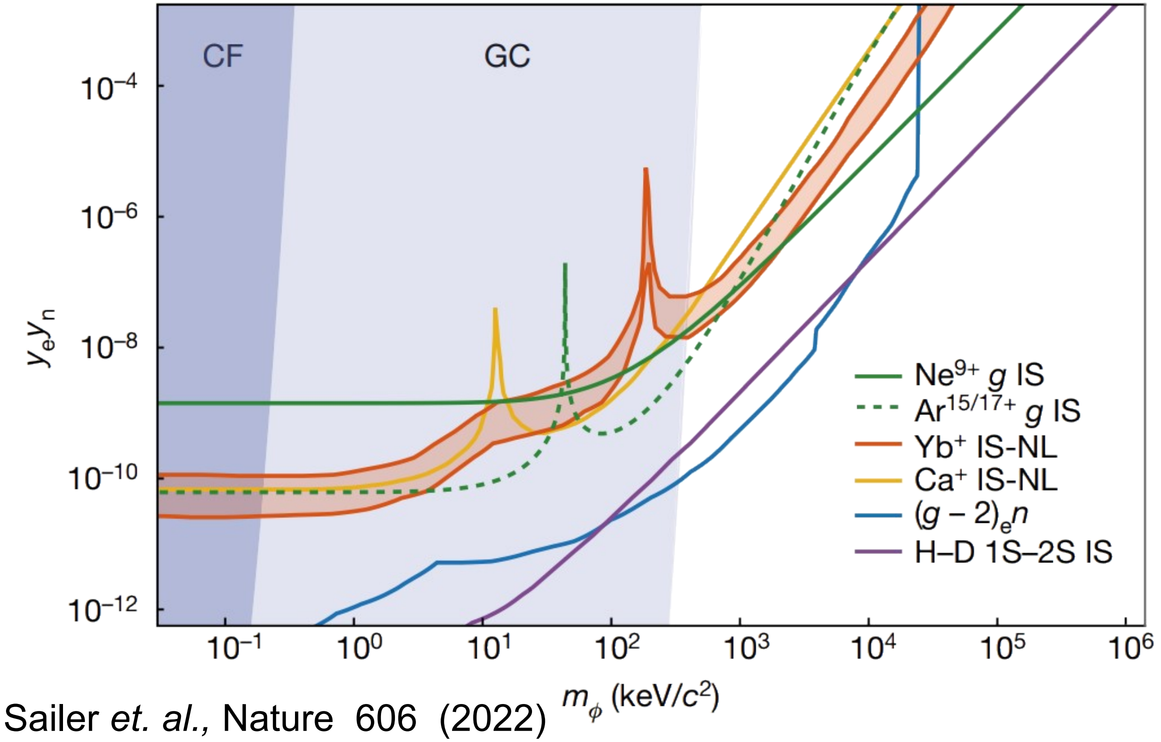


What are radii good for?

- **Absolute radius:**
- calibrate entire chains, test nuclear chiral EFT
- laser spectroscopy of helium-like Li to C: test QED & SM, determine fundamental constants
- **Isotope shifts:** compare electronic and muonic atoms to search for new lepton-neutron interactions
  - King plots, 1-electron g-factors



PRC 84, 024307 (2011)

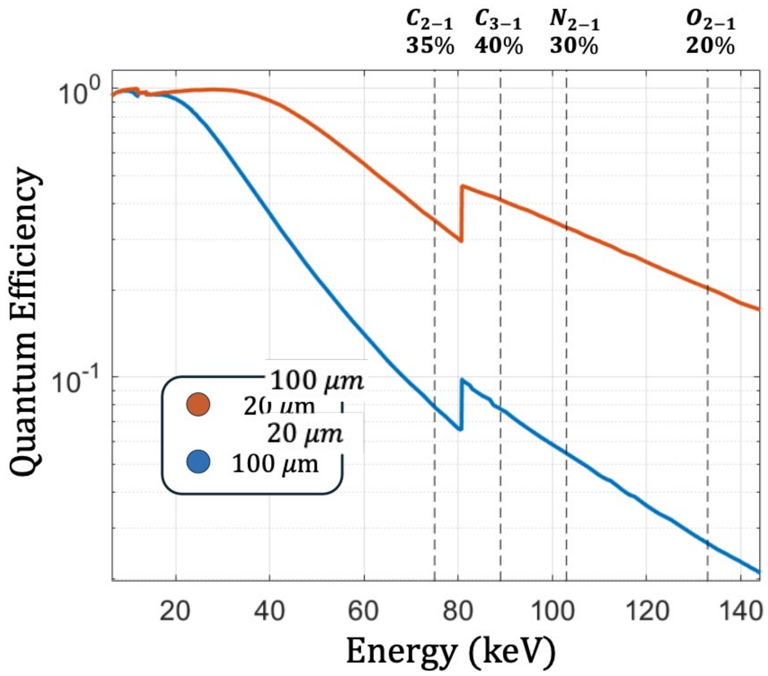


T. Sailer *et. al.*, Nature 606 (2022)

MMCs and ADCs

current MMCs are optimized for lower energy (lower Z)

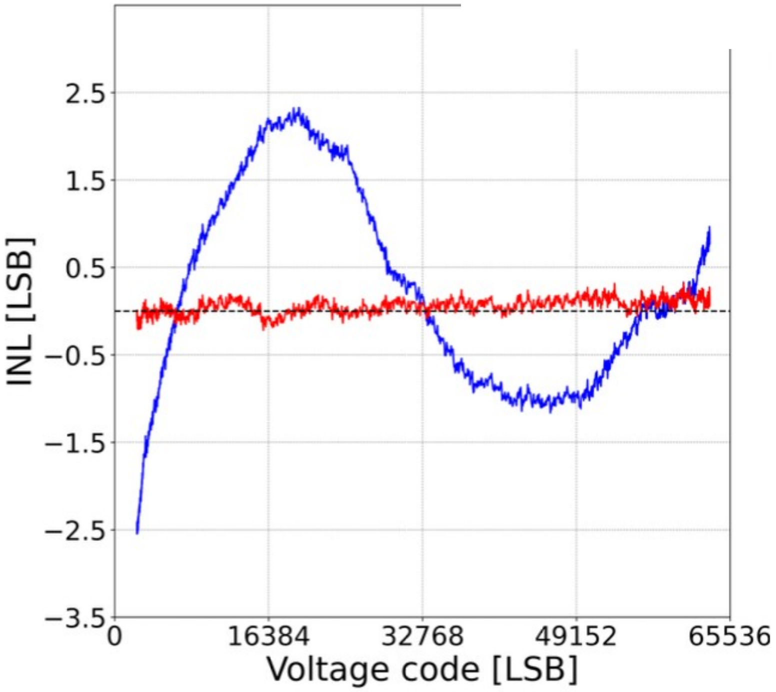
→ Ne (207 keV) needs new detectors (100 μm thickness)



current ADCs (Struck SIS3316) introduce significant systematics:

”How much is 1 LSB worth?”

→ development SIS3315, 18 bit ADC, (15 MSPS, 16channels)



Summary

QUARTET @ PSI aims at ~ 10x improved charge radii of the stable isotopes up to Z=10
→ anchor nucleus for isotope chains, nuclear physics, BSM, fundamental constants

1 PhD student (exp) for Z=10 (neon)

(DFG: 61,200 EUR p.a.)

50 kEUR for improved MMCs and SQUIDs (Heidelberg)

120 kEUR for improved 18-bit WFDs (Struck GmbH) with 18bit

280 kEUR travel support (beam times & analysis) → TNA for PSI?

30 kEUR for two workshops (detectors, nuclear theory)

dream: total 906 kEUR (incl. 25% indirect costs)

Backup

Comprehensive theory of the Lamb shift in light muonic atoms

K. Pachucki,[1] V. Lensky,[2] F. Hagelstein,[2,3] S. S. Li Muli,[2] S. Bacca,[2,4] and R. Pohl[5]
[1] *Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*
[2] *Institut für Kernphysik, Johannes Gutenberg-Universität Mainz, 55128 Mainz, Germany*
[3] *Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland*
[4] *Helmholtz-Institut Mainz, Johannes Gutenberg Universität Mainz, 55099 Mainz, Germany*
[5] *Institut für Physik, Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

(Dated: May 19, 2023) Rev. Mod. Phys. **96** (2024) 1, 015001

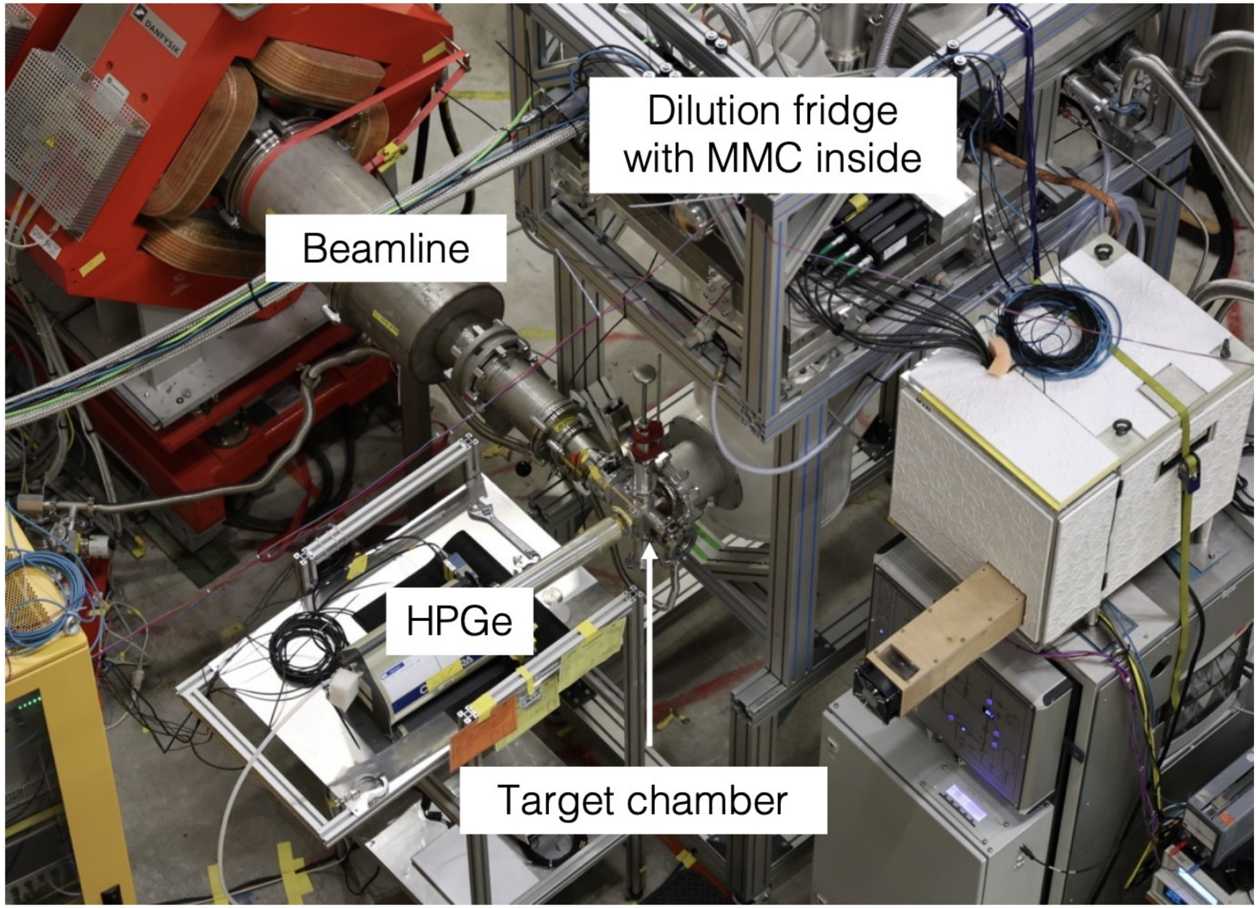
$E_{\rm QED}$	point nucleus	206.034 4(3)	228.774 0(3)	1644.348(8)	1668.491(7)
$\mathcal{C}\, r_C^2$	finite size	$-5.225\,9\, r_p^2$	$-6.107\,4\, r_d^2$	$-103.383\, r_h^2$	$-106.209\, r_\alpha^2$
$E_{\rm NS}$	nuclear structure	0.028 9(25)	1.750 3(200)	15.499(378)	9.276(433)
$E_L(\exp)$	experiment[a]	202.370 6(23)	202.878 5(34)	1258.598(48)	1378.521(48)
r_C	this work	0.840 60(39)	2.127 58(78)	1.970 07(94)	1.678 6(12)
r_C	previous[a]	0.840 87(39)	2.125 62(78)	1.970 07(94)	1.678 24(83)

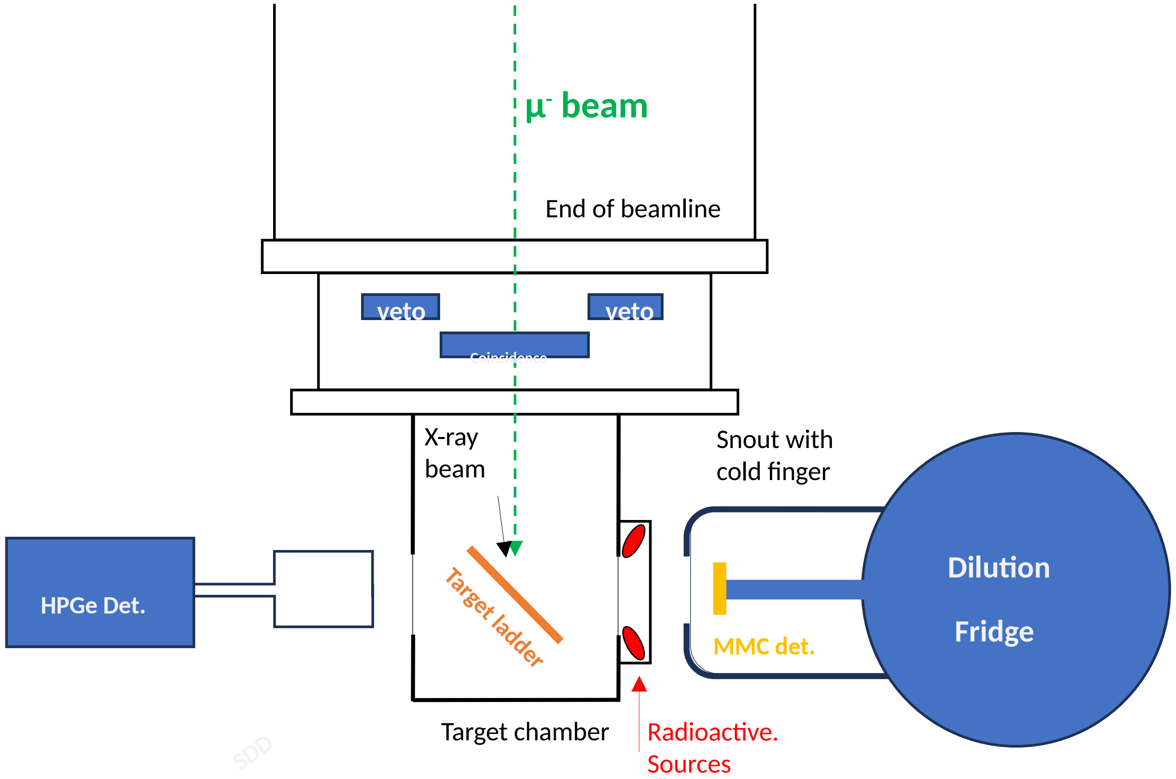
μH: present accuracy comparable with experimental precision

μD, μ³He⁺, μ⁴He⁺: present accuracy factor 5-10 worse than experimental precision

- Experiments will improve by up to a factor of 5
- Theoretical improvement needed for nuclear/nucleon 2- and 3-photon exchange

The QUARTET experimental setup—2024





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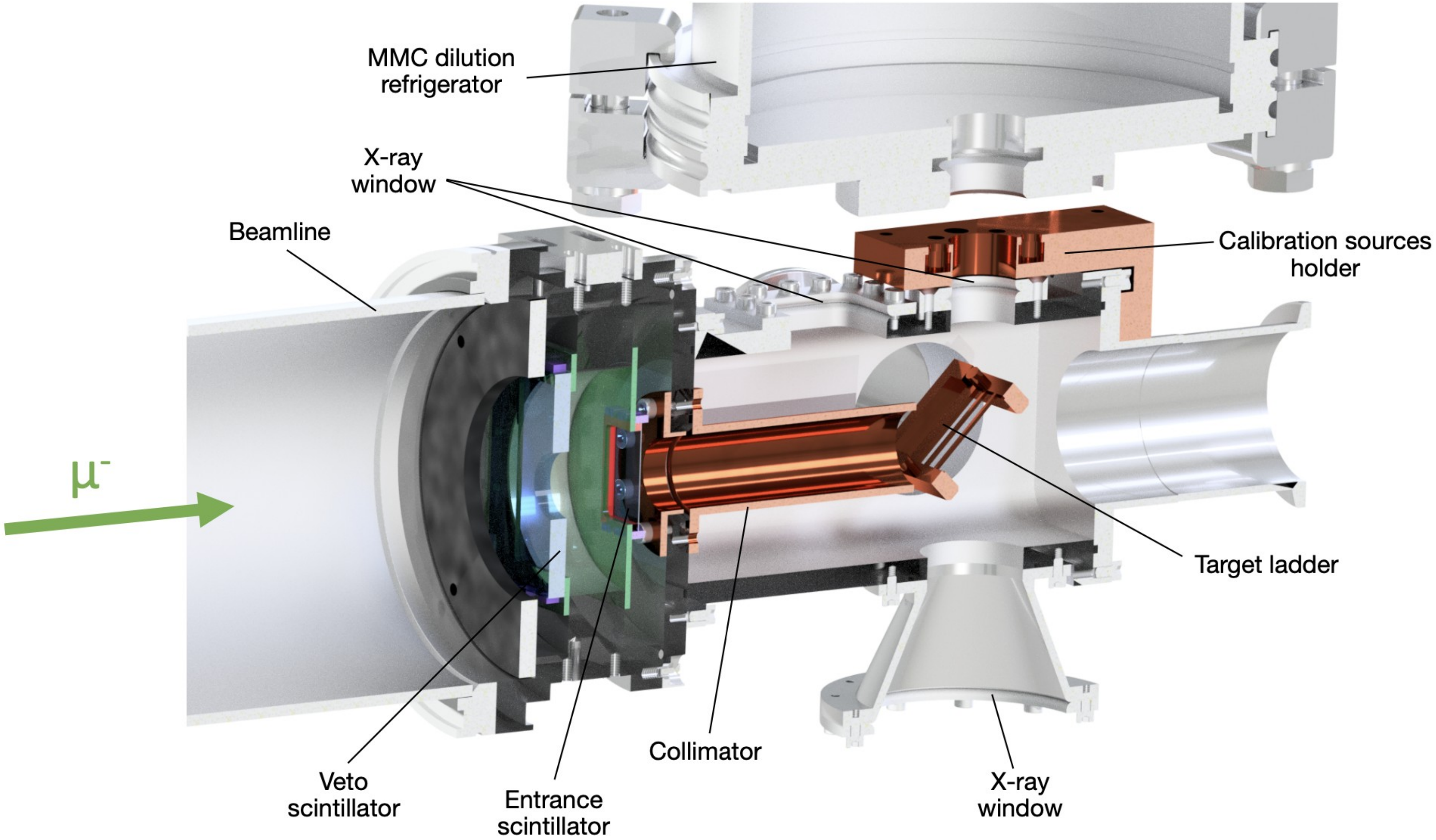
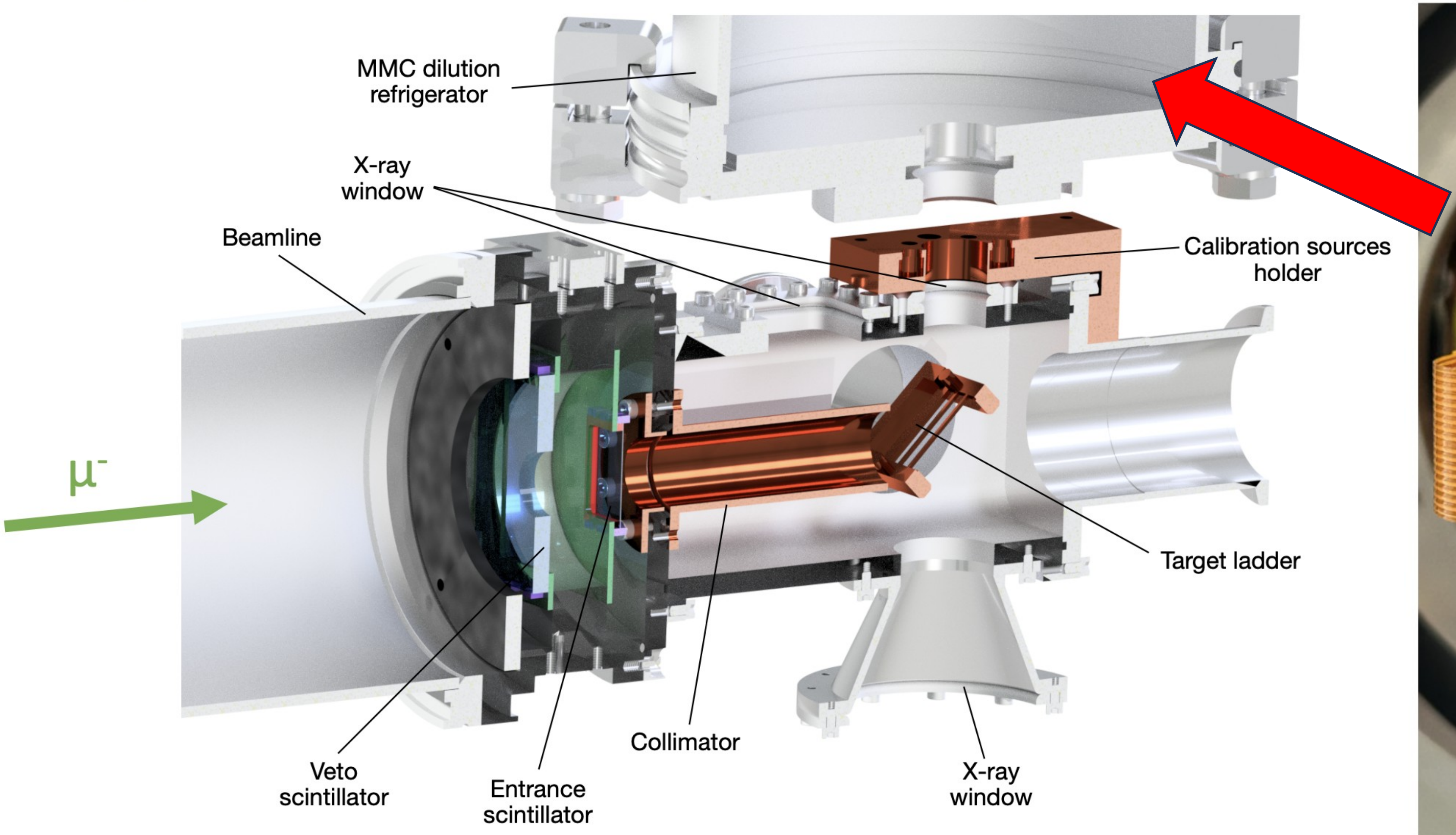
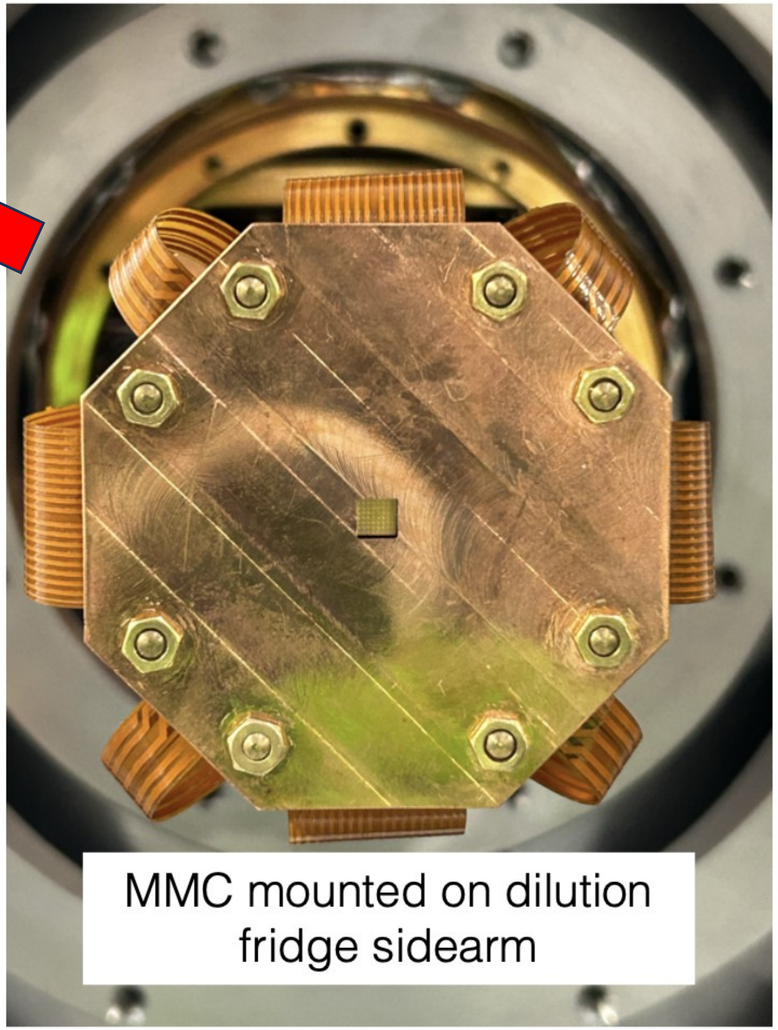


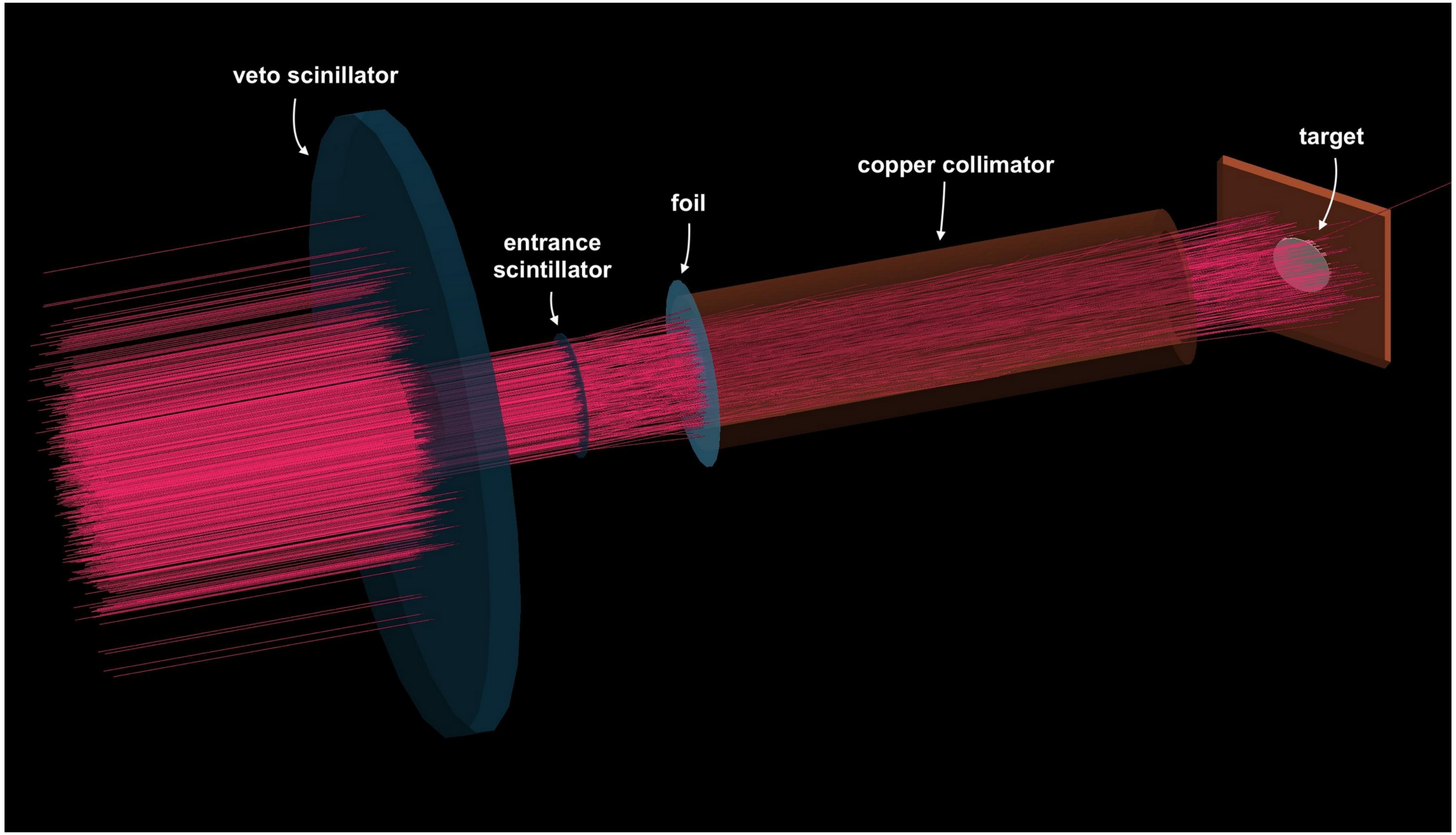
(View from below)

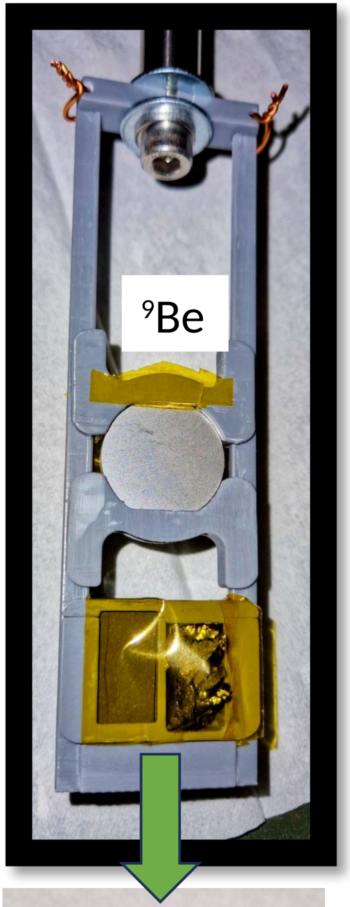
The QUARTET experimental setup—2024





Muon beam and 2024 targets

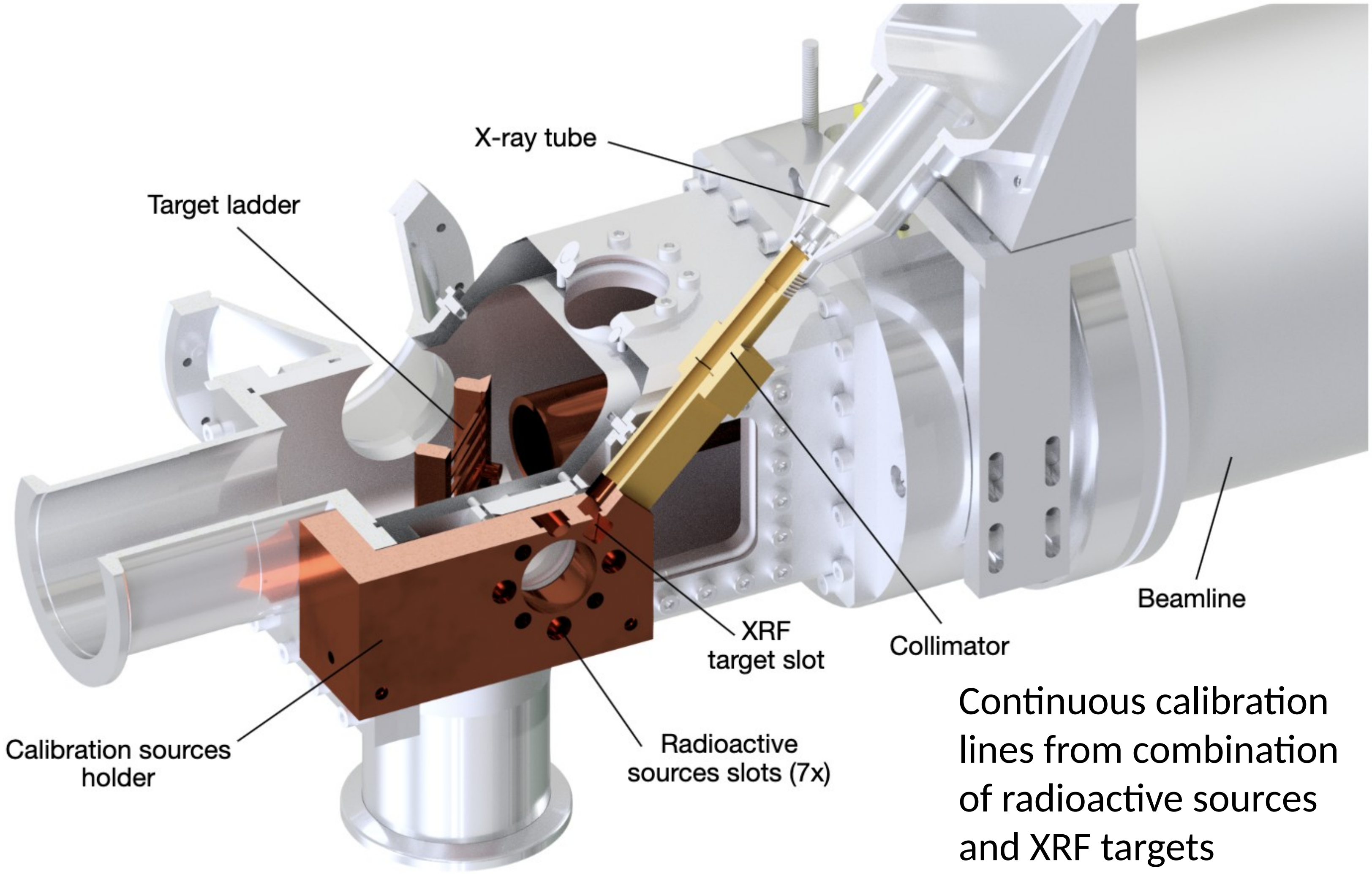




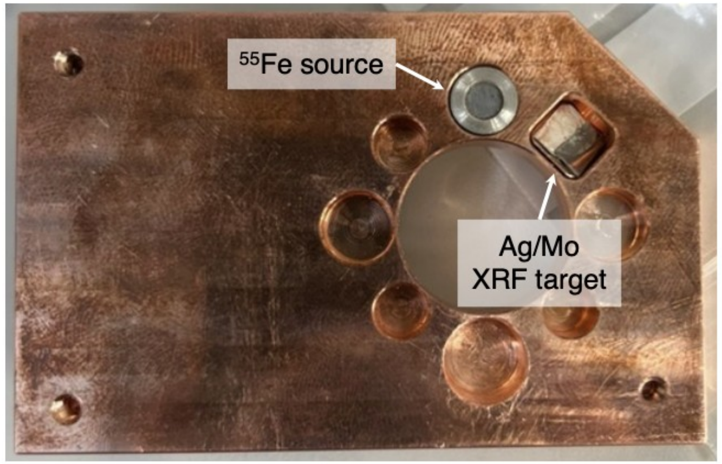
^{nat}B, ^{10}B (obtained from PSI)

Many thanks to Dieter Ries and the PSI neutron group !

Calibration—combination of XRF and gamma-ray standards

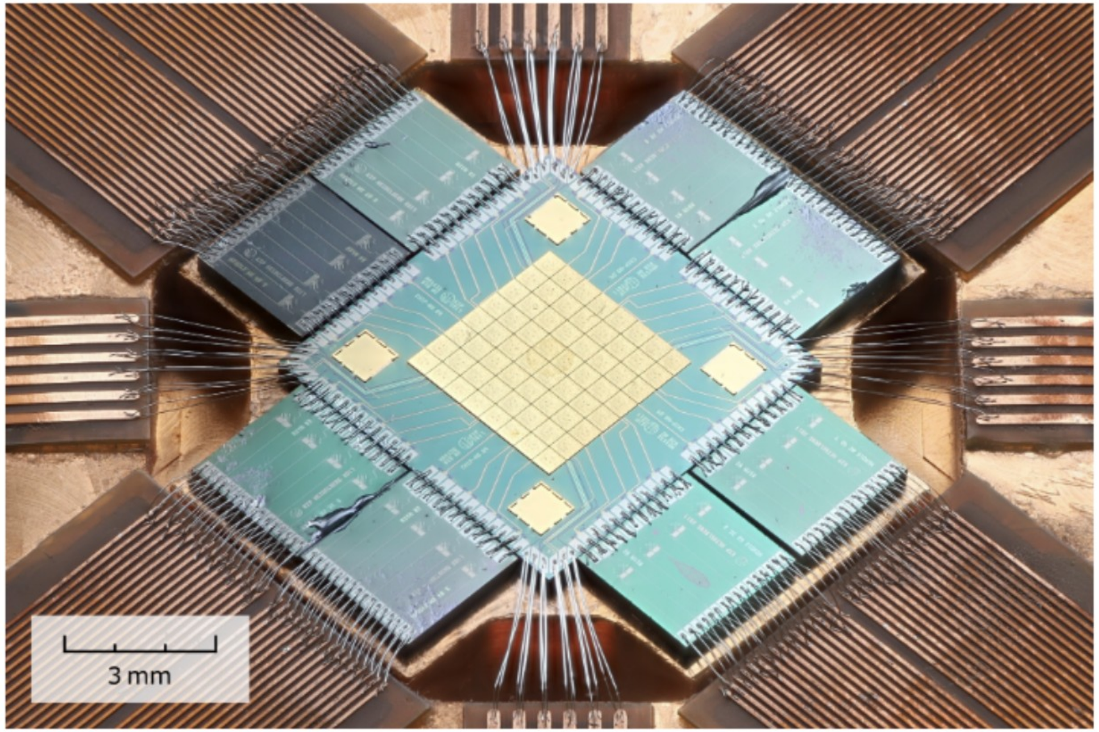


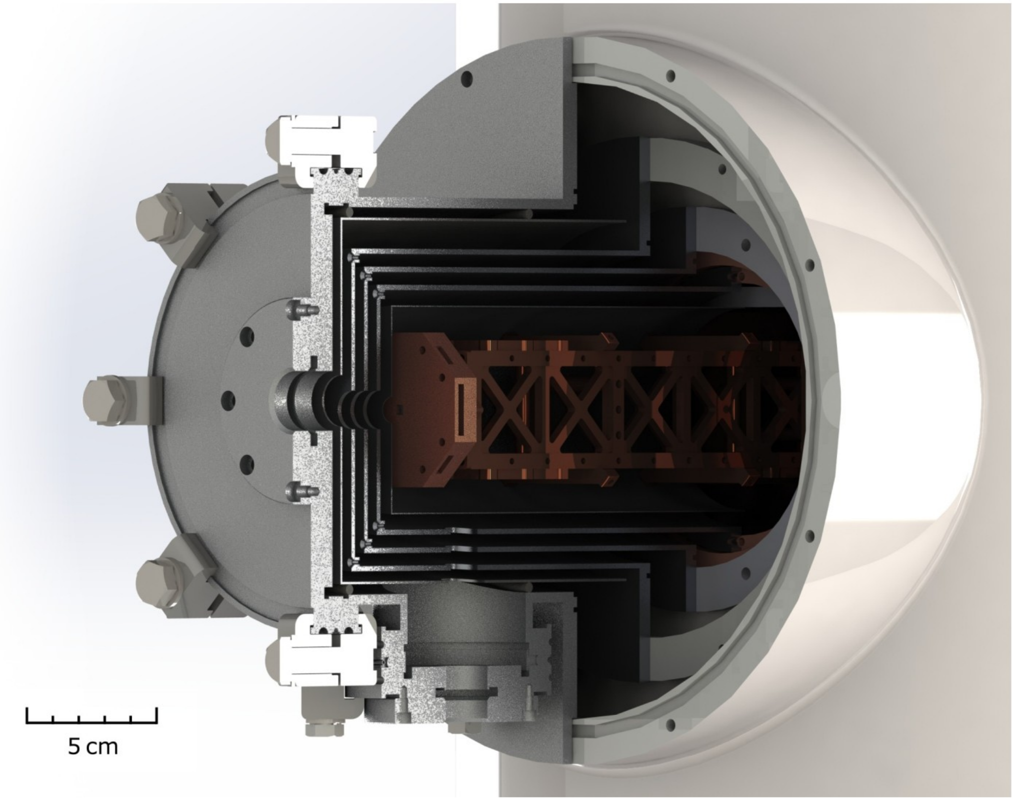
Continuous calibration lines from combination of radioactive sources and XRF targets



Many thanks to PSI radiochemistry for the ^{133}Ba source !

The QUARTET detector

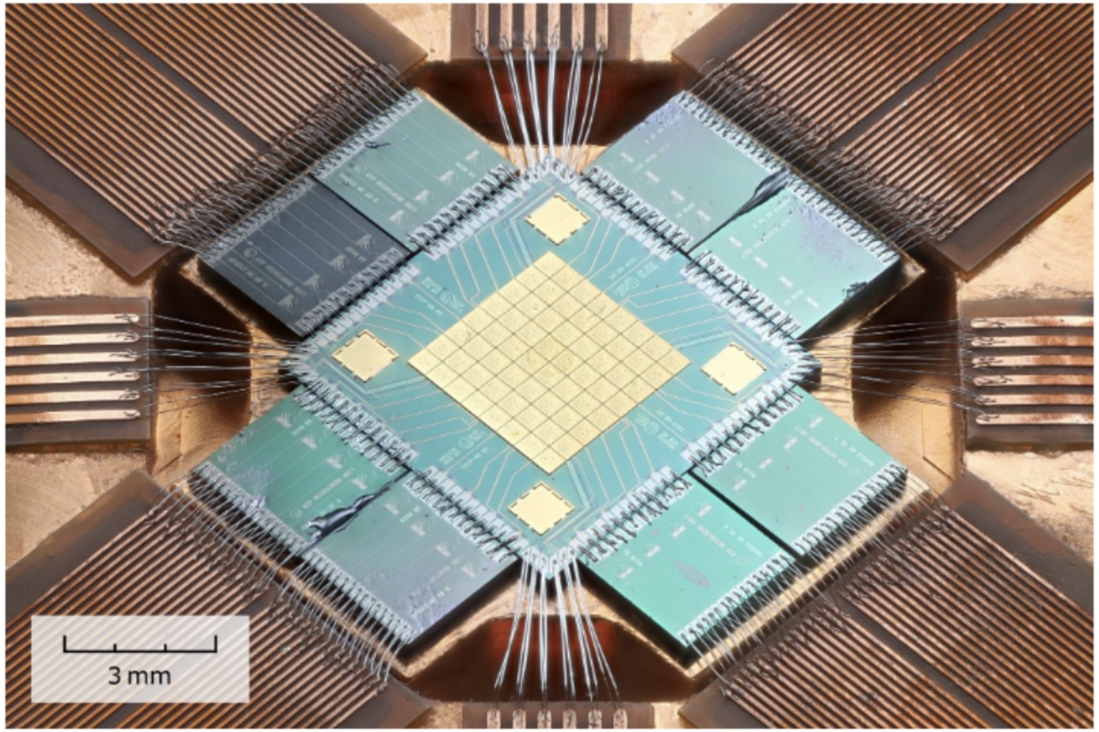


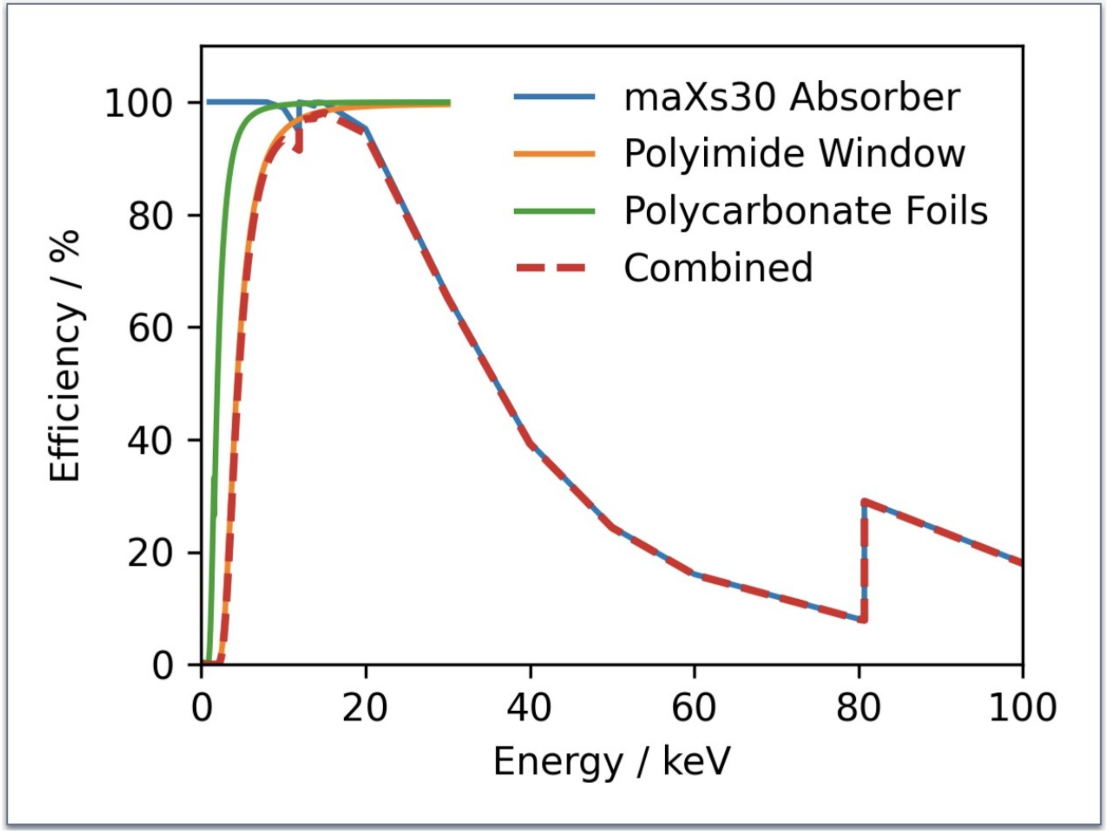


- 64 pixel maX-30 MMC detector, *developed for IAXO experiment*
- Mounted in custom sidearm designed to reduce vibrations
- 5 thermal shields and x-ray windows
- Calibration sources mounted outside the detector

Figures from D. Unger et al LTD2023 proceeding, for the QUARTET collaboration

The QUARTET detector





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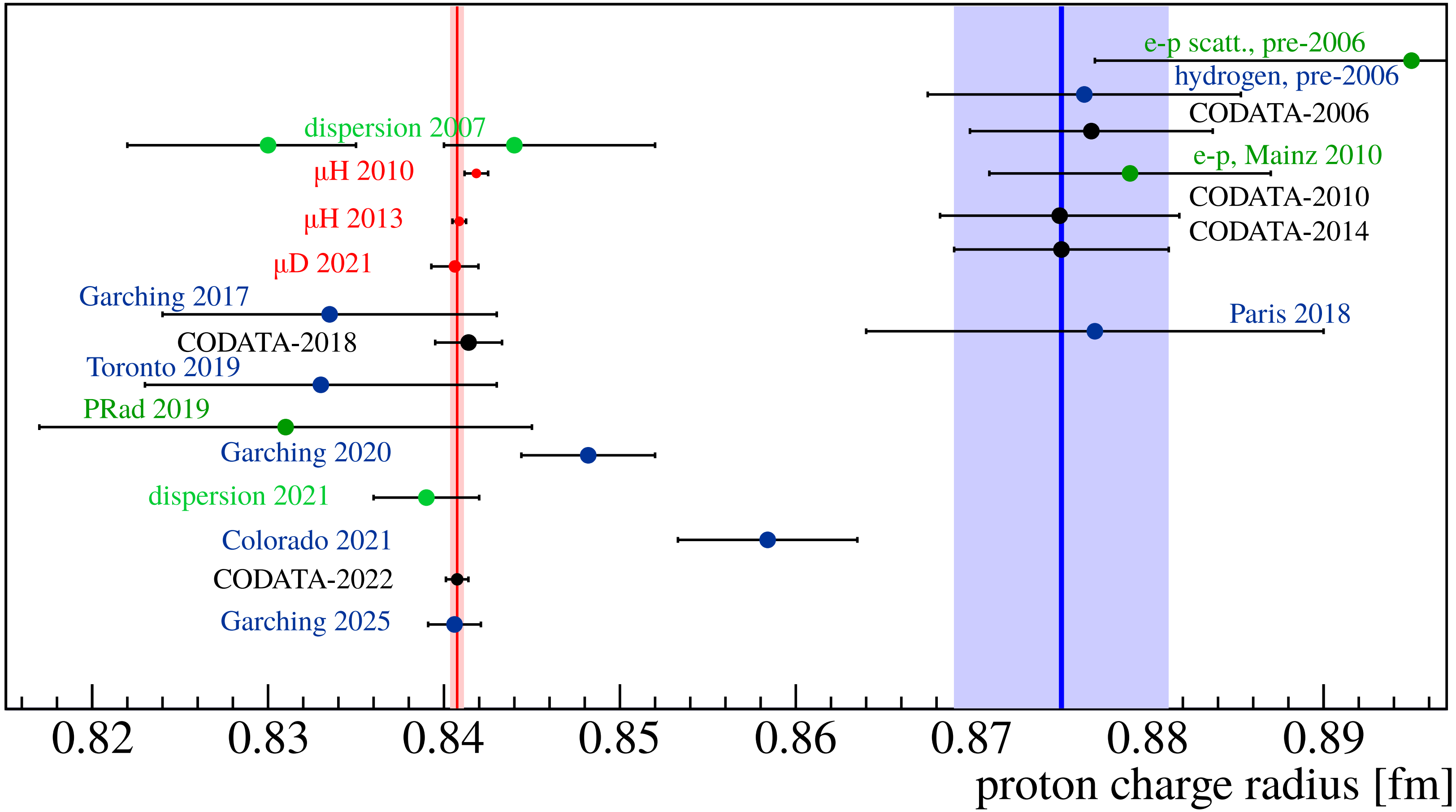
Muonic Hydrogen and the Proton CHARGE Radius



e-p scattering

slope of G_E at $Q^2 = 0$

$$r_p^2 \equiv -6 \frac{d G_E}{d Q^2}\bigg|_{Q^2=0}$$

hydrogen spectroscopy

muonic atoms

Lamb shift

$$\Delta E = \frac{2}{3}\pi\alpha \left|\Psi_S(0)\right|^2 r_p^2$$

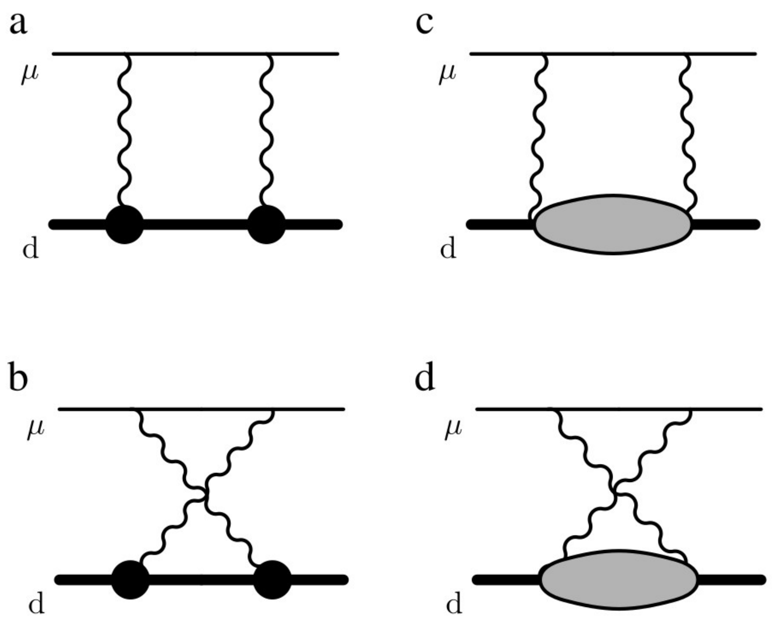
CODATA / PDG average

Theory: Lamb shift in muonic D

$\Delta E^{\mu D}_{Lamb}$ = 228.7740 (3) meV_{QED} + 1.7503 (**200**) meV_{TPE} – 6.1074 meV/fm^2 * $\mathbf{R_d}^{\mathbf{2}}$

$$\Delta E^{\mathrm{exp}}_{\mathrm{LS}} = 202.8785(31)_{\mathrm{stat}}(14)_{\mathrm{syst}}\,\mathrm{meV}$$

Nuclear structure two (and three!)-photon contributions to the Lamb shift in muonic deuterium.



Pachucki, RP et al, arXiv 2212.13782

see also Krauth, RP et al. (2016) using calculations from
Pachucki (2011), Friar (2013), Carlson, Gorchtein, Vanderhaeghen (2014), Hernandez et al. (2014), Pachucki + Wienczek (2015)

+ Pachucki et al., PRA 97, 062511 (2018): Sizeable three-photon !!

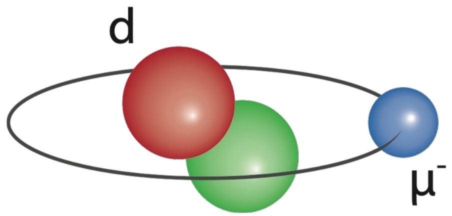
+ Hernandez et al., PLB 778, 377 (2018): χEFT

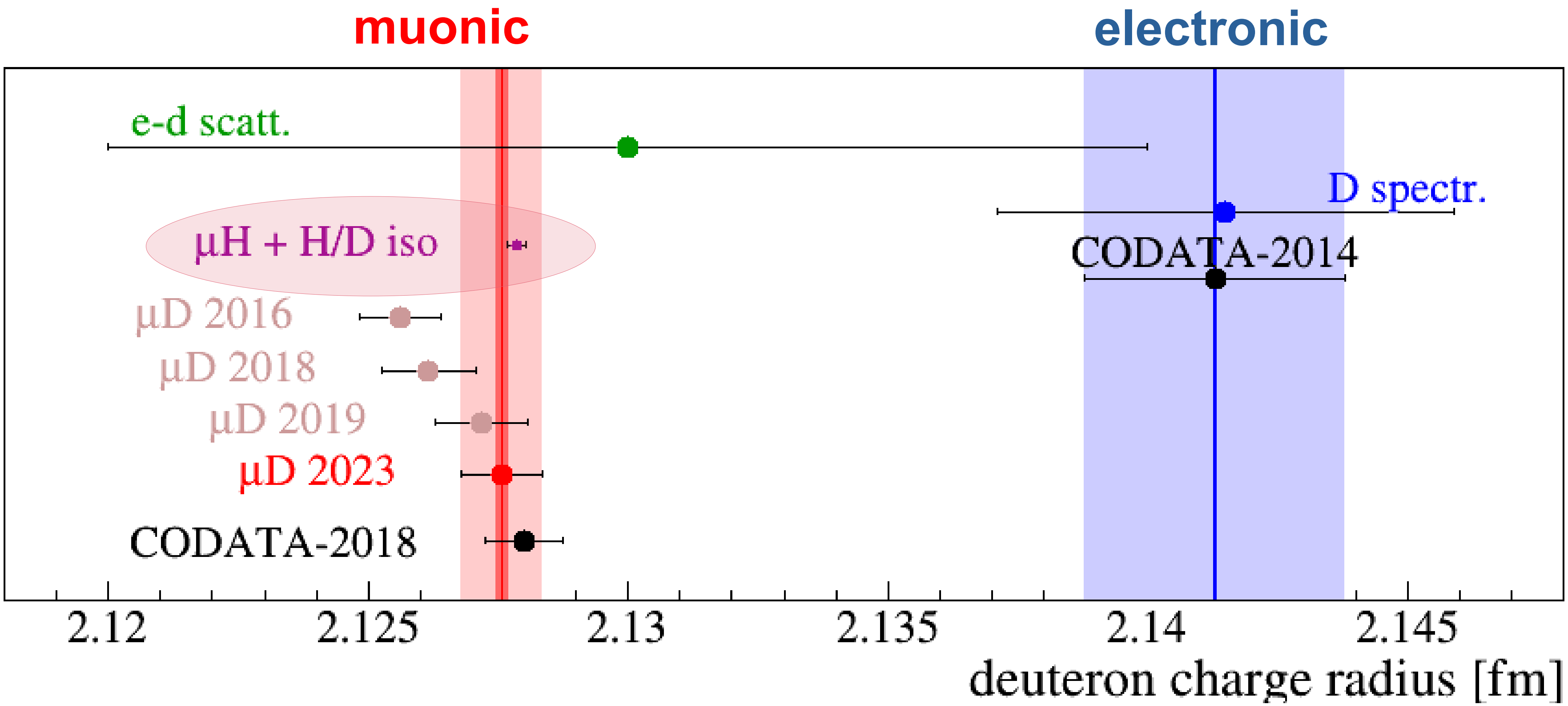
+ Kalinowski (2019): eVP to nucl. struct.

+ Acharya et al., PRC 103, 024001 (2021)
χEFT + Disperson relations

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, Pohl, RMP (2024)

Muonic Deuterium





μD: 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

μH + H/D(1S-2S): 2.12785 (17) fm

Theory in muonic D

$$\Delta E_{Lamb}^{\mu D} = 228.7740\,(3)\ \mathrm{meV}_{QED} + 1.7503\,(\mathbf{200})\ \mathrm{meV}_{TPE} - 6.1074\ \ \mathrm{meV/fm^2} * \mathbf{R_d^2}$$

ΔE_{TPE} (theo) = 1.7503 +- 0.0200 meV **Bacca group**
vs. +- 0.0034 meV **experimental uncertainty**

(1) **charge radius**, using **calculated TPE**

r_d (μD) = 2.12758 $(13)_{exp}$ $(78)_{theo}$ fm

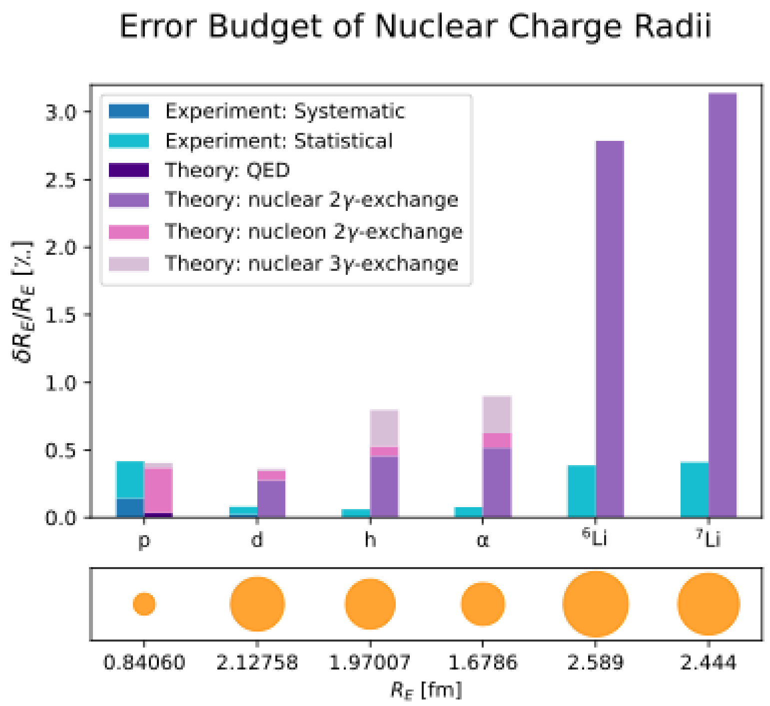
(2) **polarizability**, using **charge radius from isotope shift**

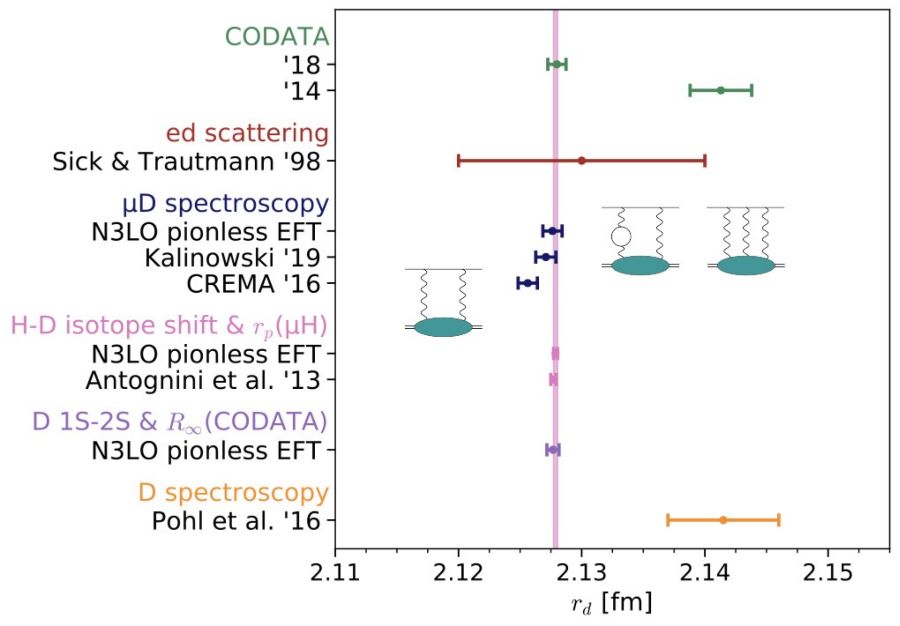
ΔE_{TPE} (theo) = 1.7503 (200) meV vs.
ΔE_{TPE} (exp) = 1.7591 (59) meV 3x more accurate

Pachucki, Lensky, Hagelstein, LiMuli, Bacca, Pohl, RMP (2024)

Muonic Deuterium Lamb Shift

- ❑ Deuteron (proton) charge radius extractions from μH & μD Lamb shift, and 1S-2S H-D isotope shift are consistent
- ❑ Higher-order radiative corrections are important
  - ➢ Nuclear and nucleon two-photon exchange (2γ)
  - ➢ Three-photon exchange (3γ)
  - ➢ Radiative corrections to 2γ, e.g., electron vacuum polarization
- ❑ Extraction of nuclear structure from atomic spectroscopy factor 4 more precise than (chiral and pionless) EFT predictions or data-driven evaluations
  - ➢ Experiment as benchmark for nuclear theory





Muonic Atom Spectroscopy Theory Initiative

https://asti.uni-mainz.de

- Coordinated effort to support the experiments (inspired by “Muon g-2 Theory Initiative”)
- Initials objectives:
  - Accurate theory predictions for light muonic atoms to test fundamental interactions by comparing to electronic atoms
  - Community consensus on SM predictions
  - Emphasis on the hyperfine splitting in μH
- Steering committee: Aldo Antognini (PSI), Carl Carlson (William & Mary), Franziska Hagelstein (Mainz), Paul Indelicato (CNRS), Krzysztof Pachucki (Warschau), Vladimir Pascalutsa (Mainz)
- So far 5 (satellite-)workshops @ PSI, Crete, Mainz, Stony Brook, ETH Zurich
- Next workshop: “New perspectives in the charge radii determination of light nuclei”, ECT* Trento, 28.07.25 — 01.08.25