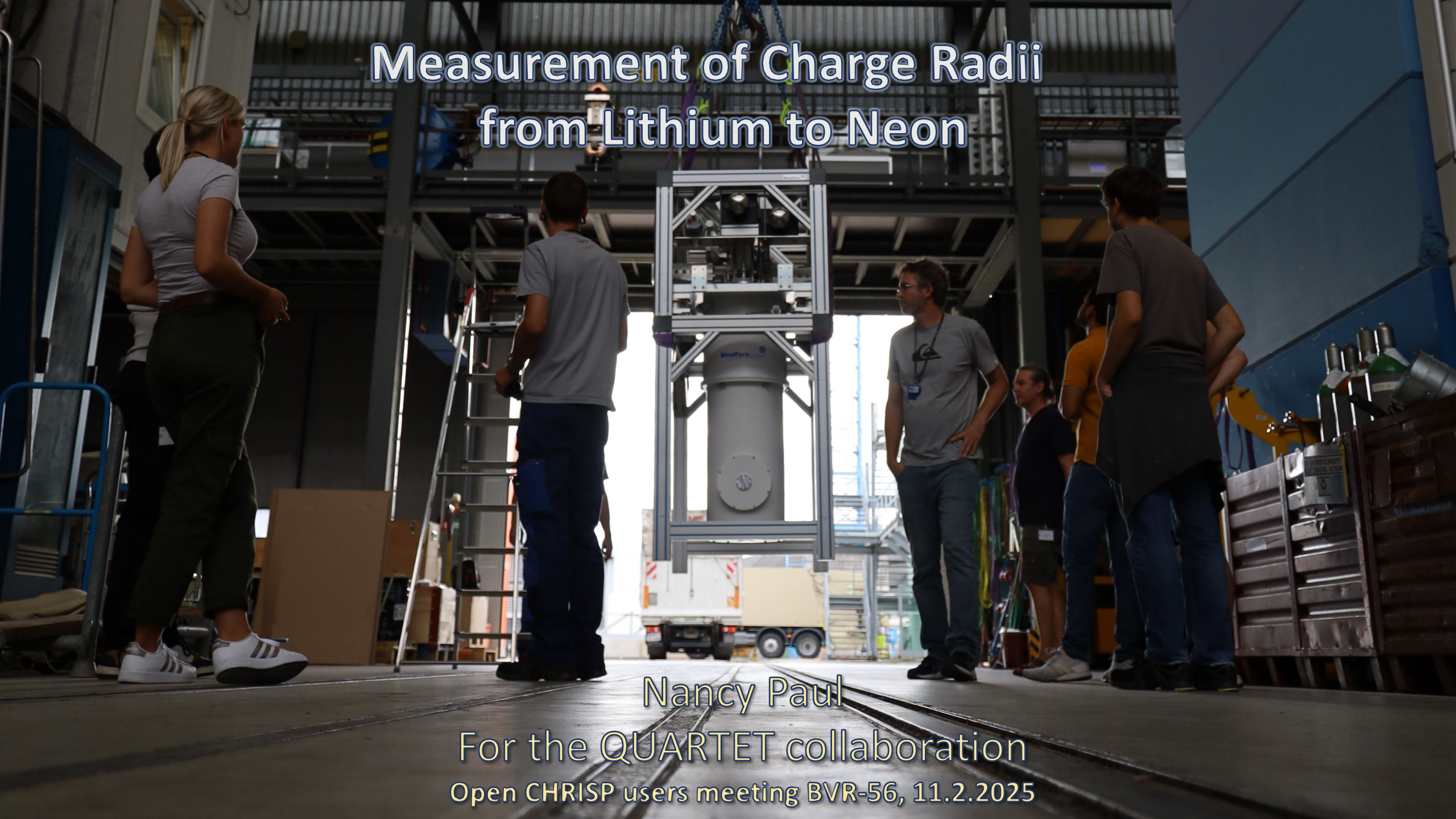
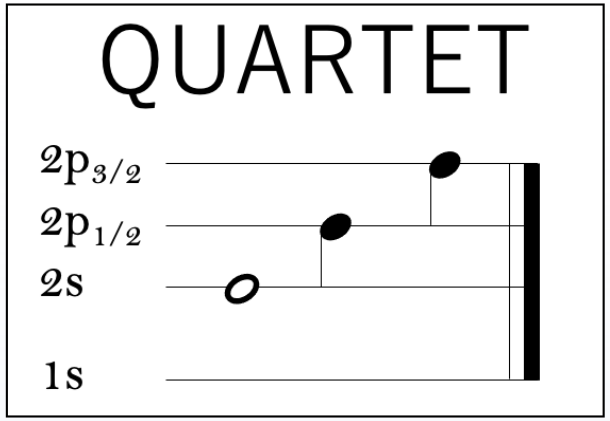


Measurement of Charge Radii from Lithium to Neon

Nancy Paul
For the QUARTET collaboration

Open CHRISP users meeting BVR-56, 11.2.2025

The QUARTET collaboration and precision goals

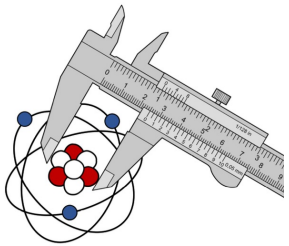


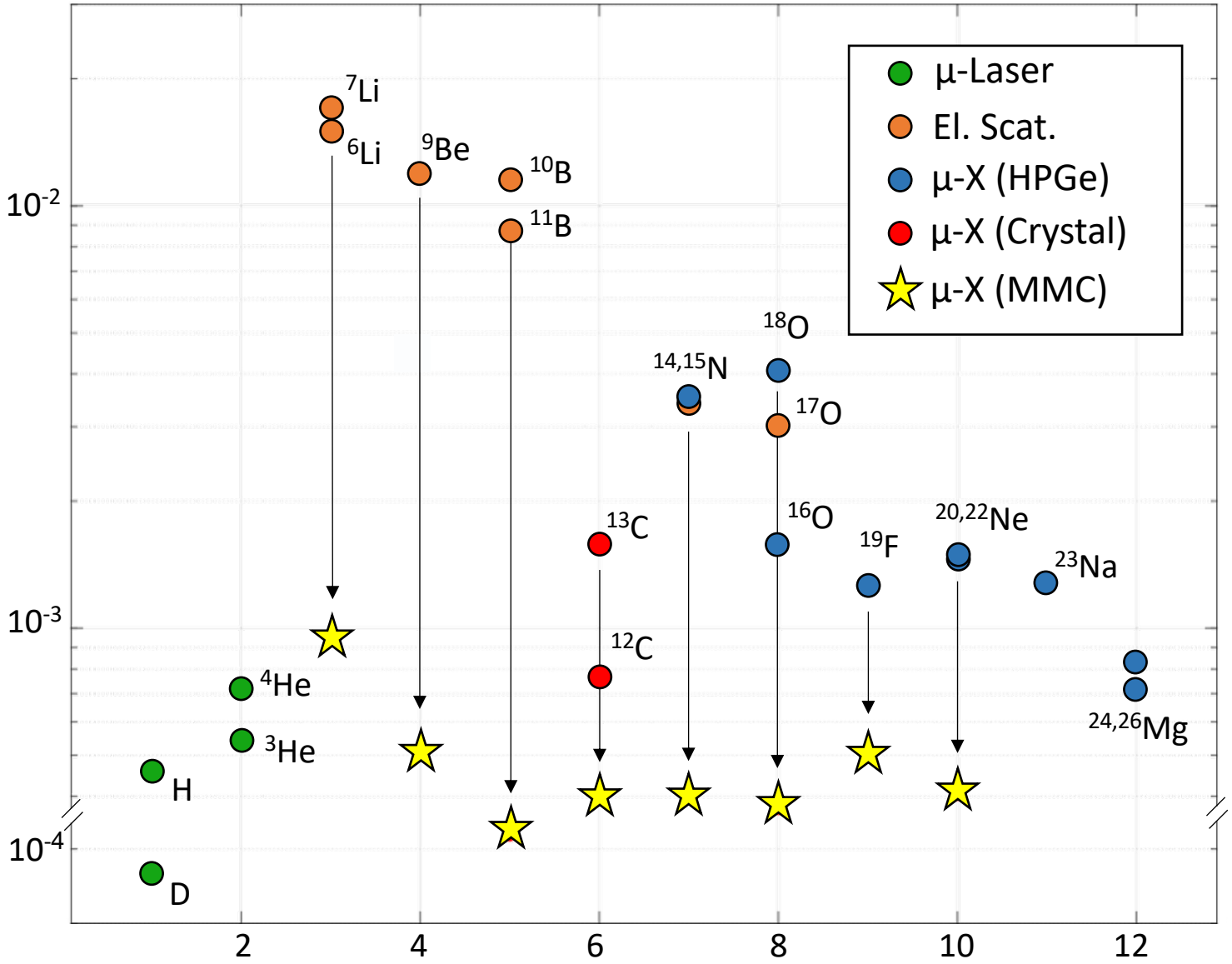
QUAntum inteRacTions with Exotic aToms

Spokespersons: B. Ohayon (Technion) and NP (LKB)

Goals

- Determine E(2P-1S) for $3 \le Z \le 10$ with few ppm accuracy, i.e. 0.2-1 eV .
- Improve radii by factor 3-10.





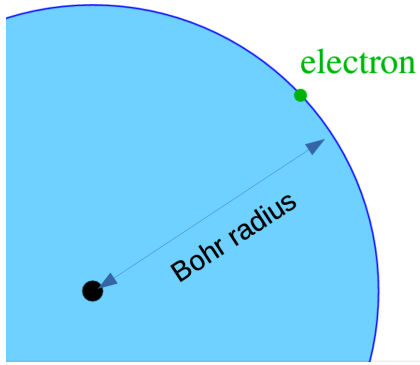
Why does it work?

Muonic atoms are highly sensitive to nuclear properties

Muonic atoms in a nutshell

Regular hydrogen:

Bohr radius ~ 50'000 x nuclear radius



Muonic hydrogen:

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

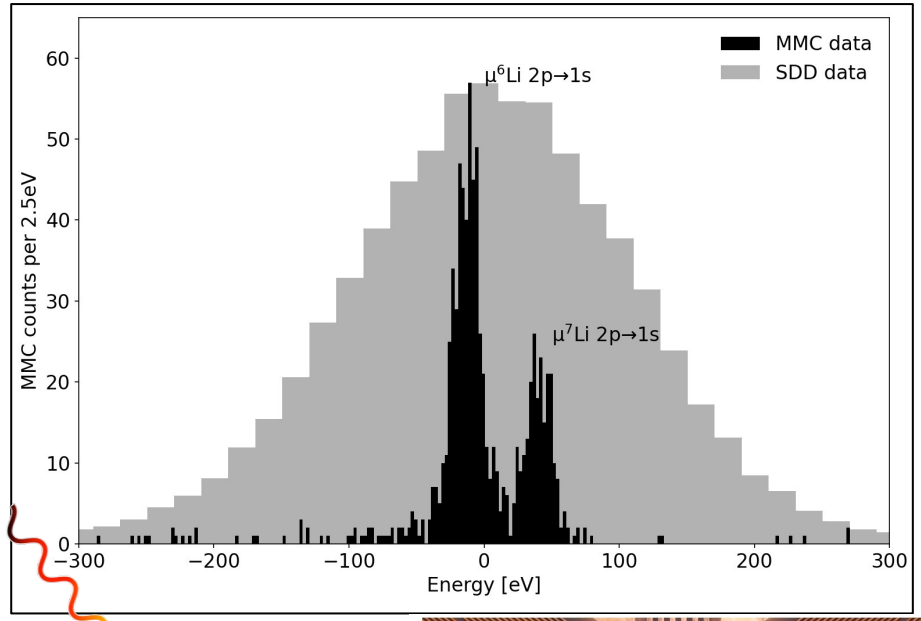
Bohr **radius** = **1/200** of H

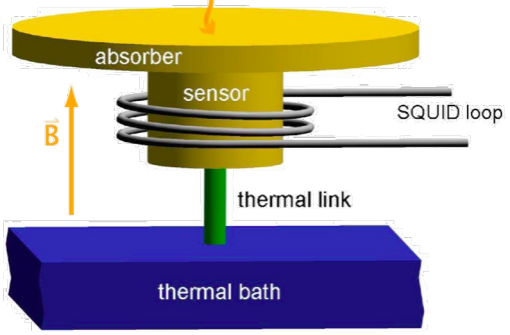
200^3 = a **ten million times** more sensitive to nuclear size & structure

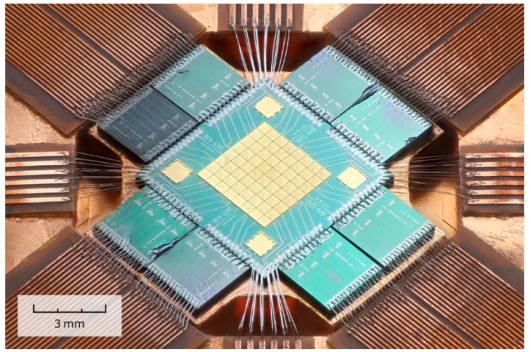
==> Our laser spectroscopy at **10^{-5}** level can compete with **10^{-12}** from normal atoms

Randolf Pohl's talk from Monday..

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



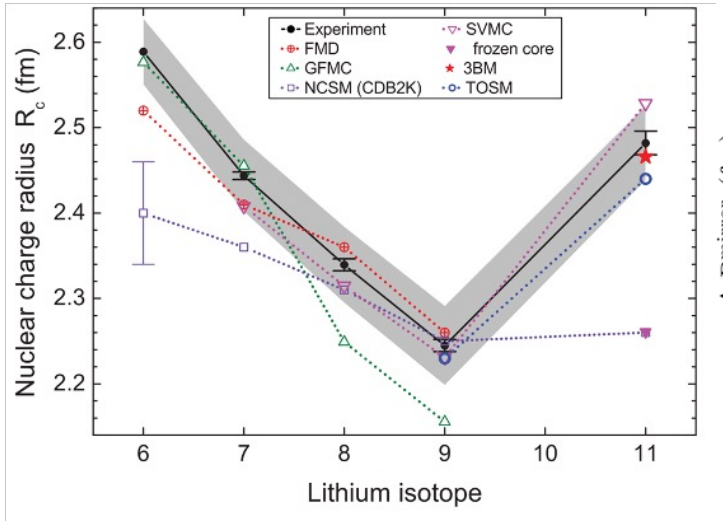




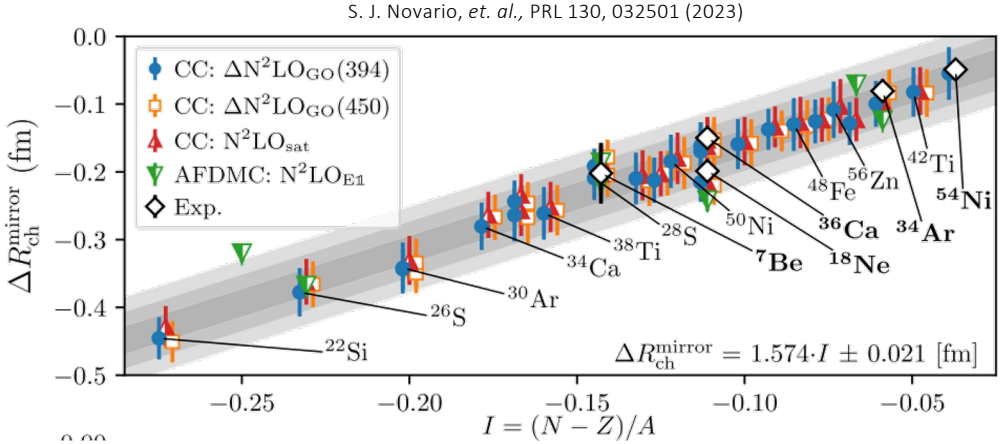
What are radii good for?

- **Absolute radius:** Li/Be/B → calibrate entire chains, test nuclear chiral EFT
- **Absolute radii** for He-like laser spectroscopy Li to C (Wuhan, Darmstadt, Mainz, MPQ).
- **Isotope shifts:** compare electronic and muonic atoms to search for new lepton-neutron interactions
- Novel measurements of g-factors in H-like ions **limited by muonic isotope shifts for new physics searches.**

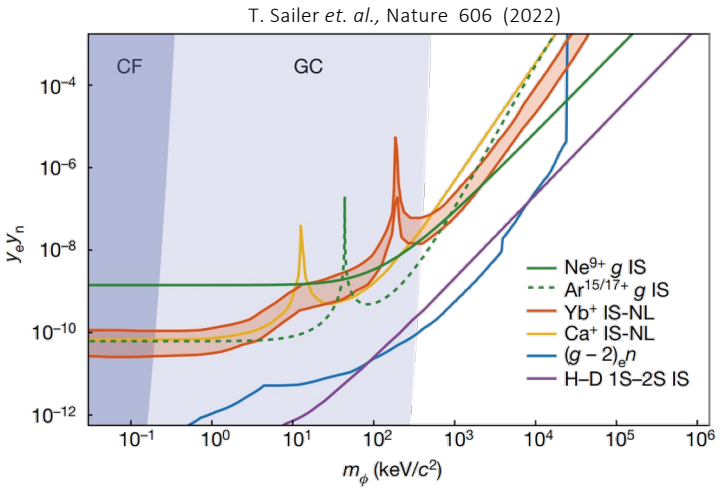
PRC 84, 024307 (2011)



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

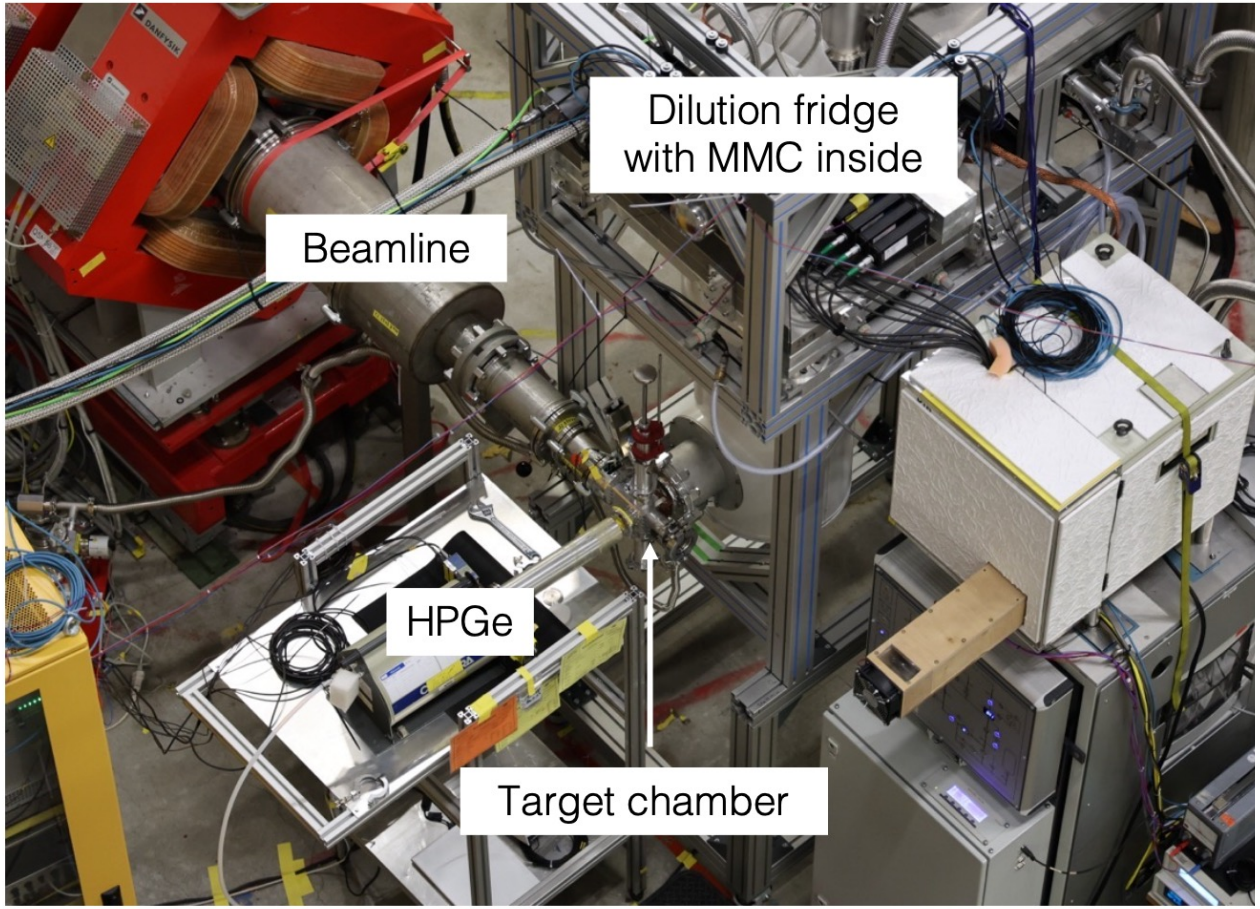


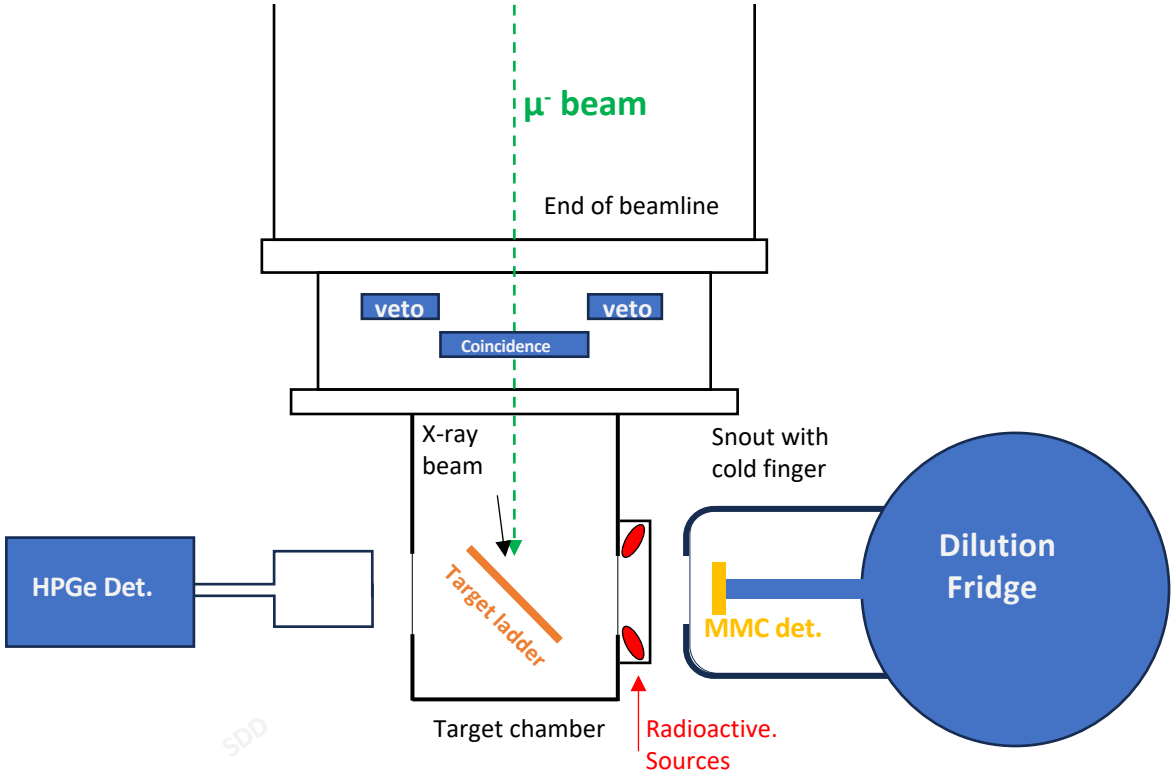
T. Sailer *et. al.*, Nature 606 (2022)



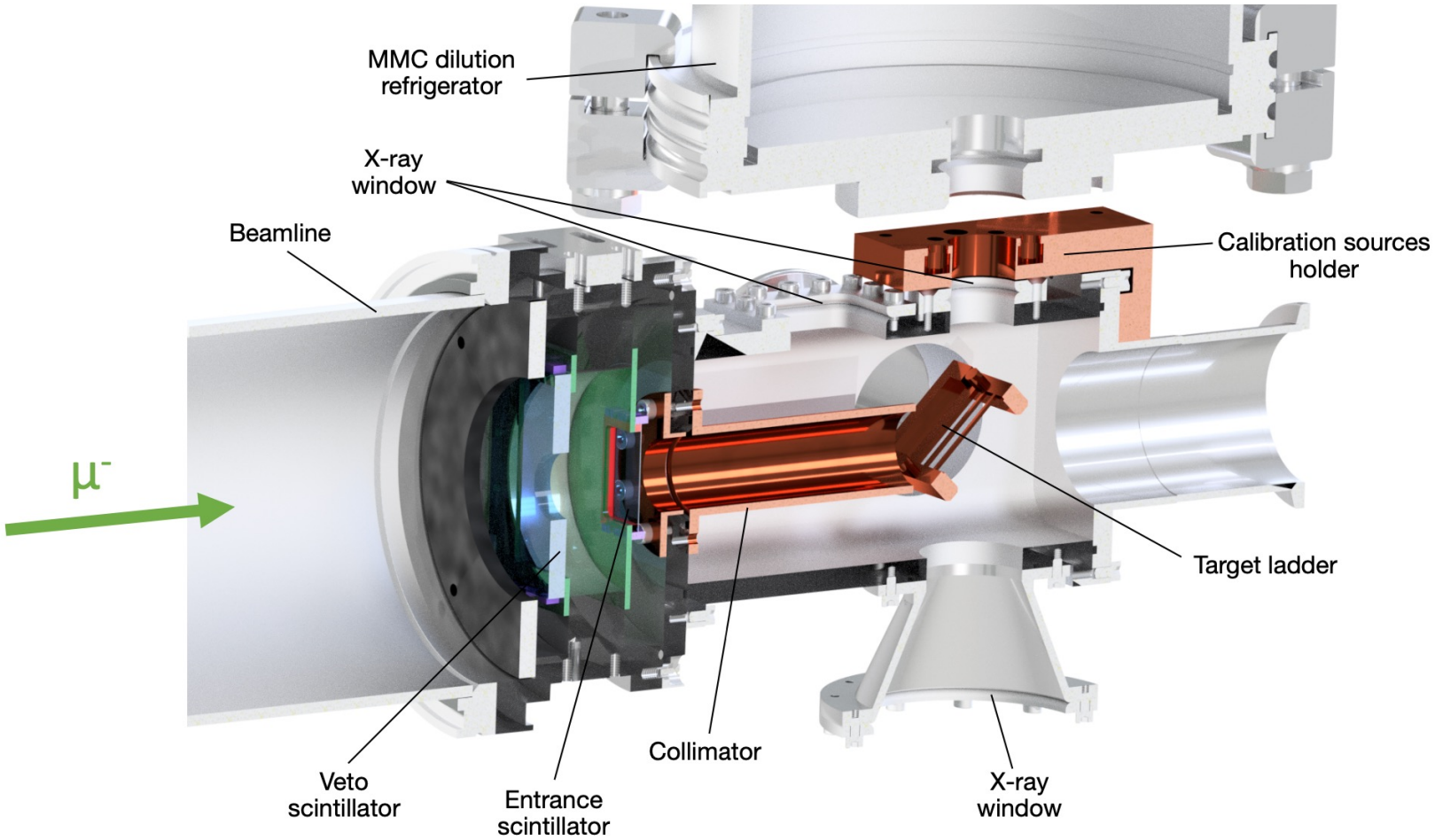
All limited by reference radii

The QUARTET experimental setup—2024



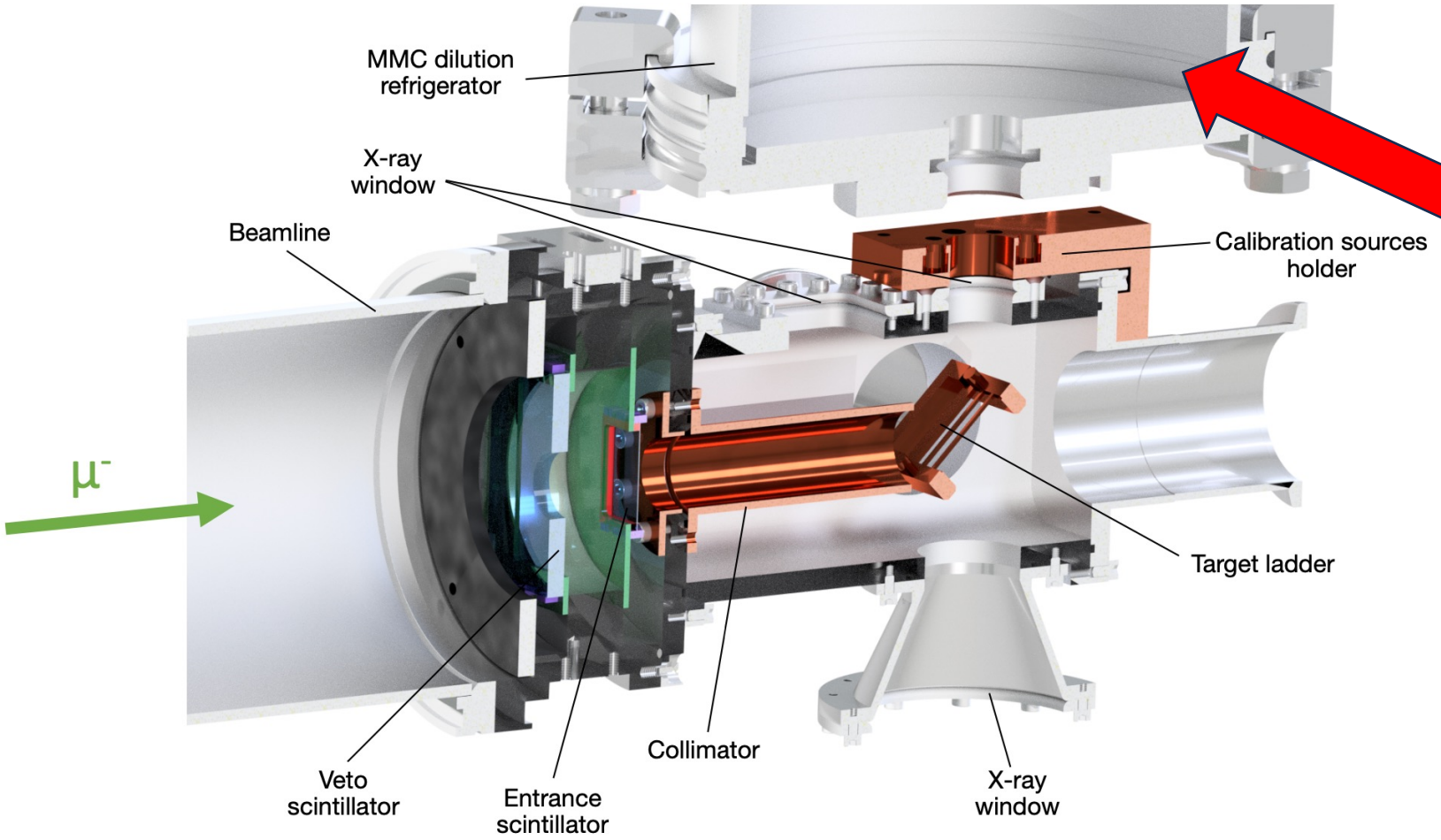


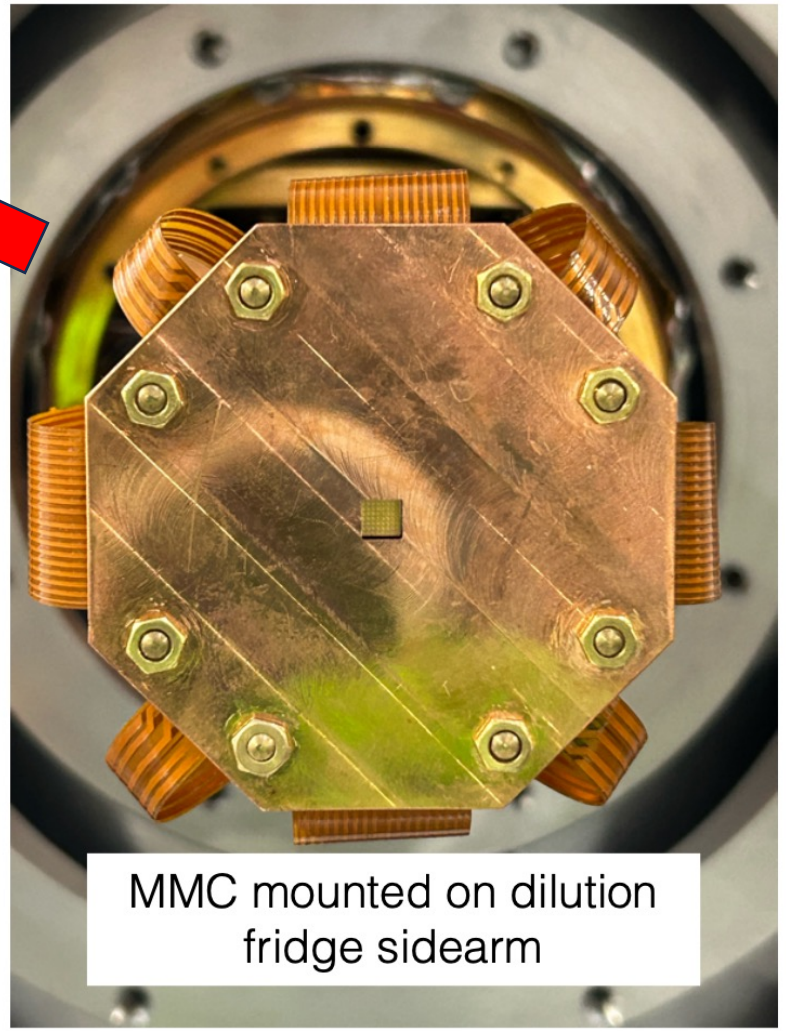
The QUARTET experimental setup—2024



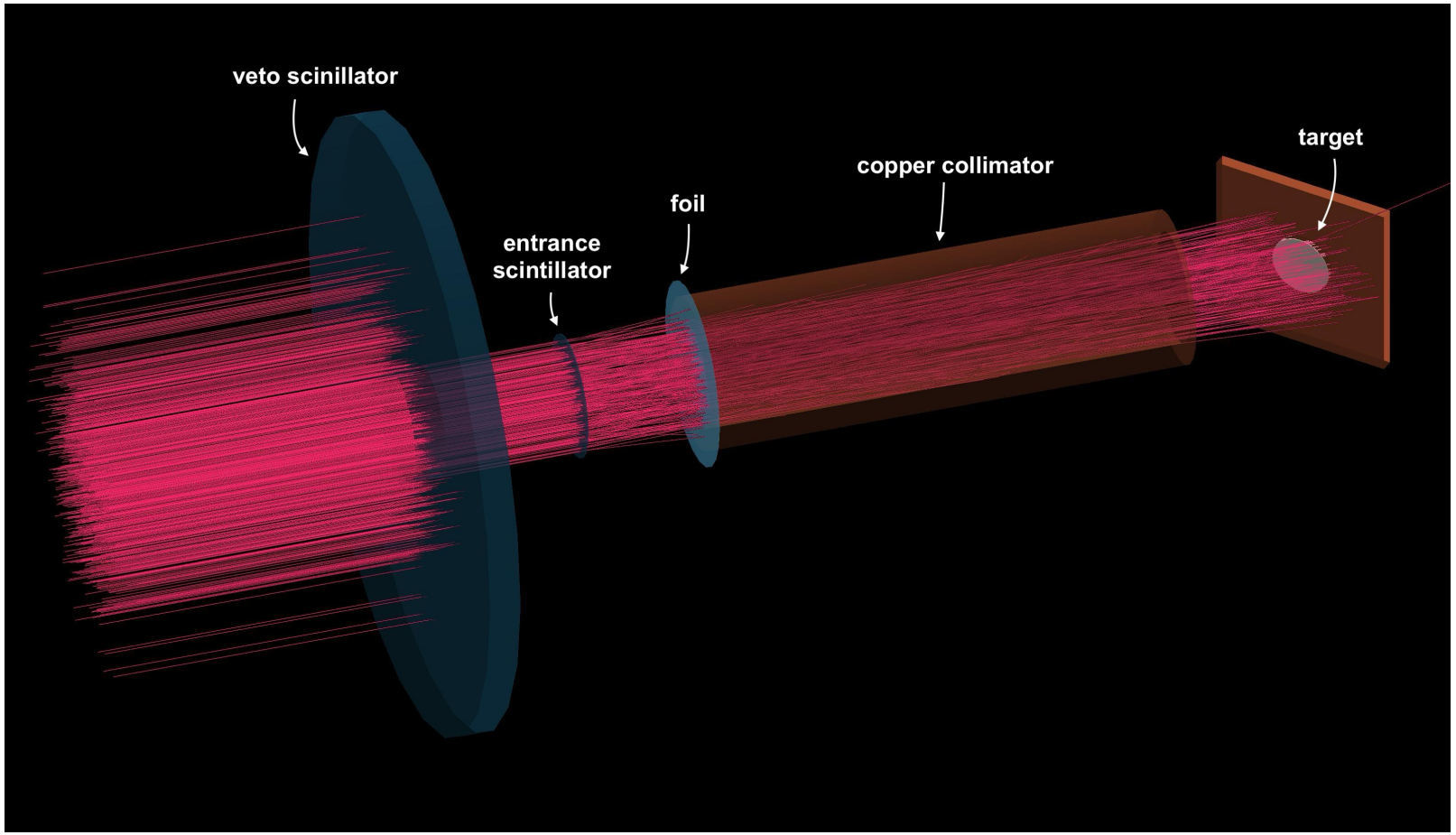
(View from below)

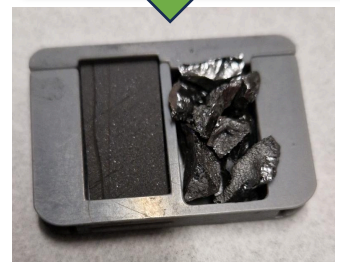
The QUARTET experimental setup—2024





Muon beam and 2024 targets

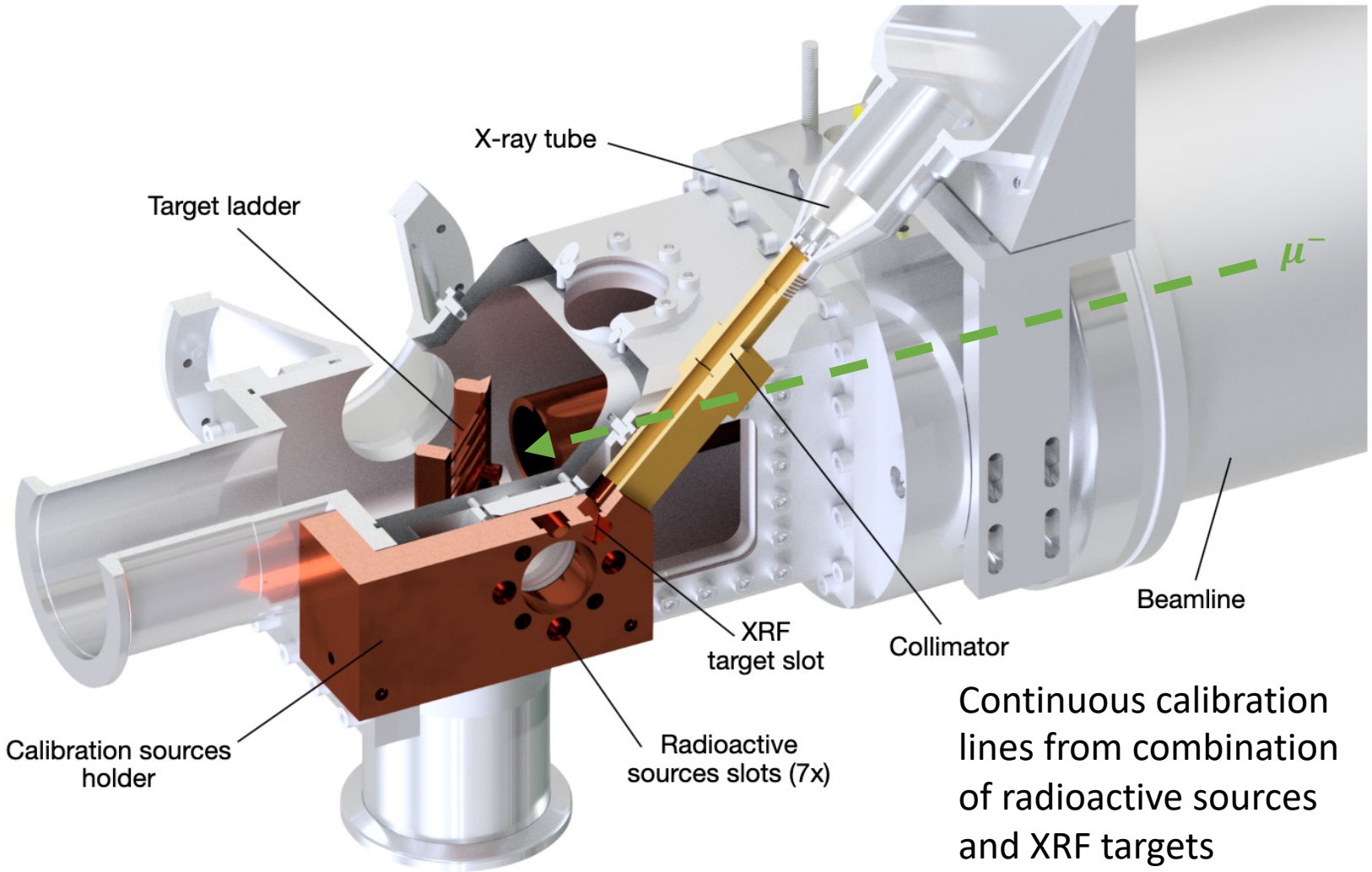


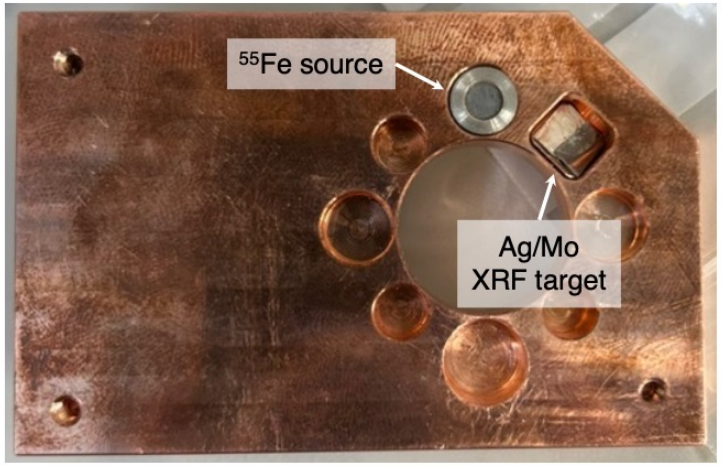


Many thanks to Dieter Ries and the PSI neutron group !

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

Calibration—combination of XRF and gamma-ray standards

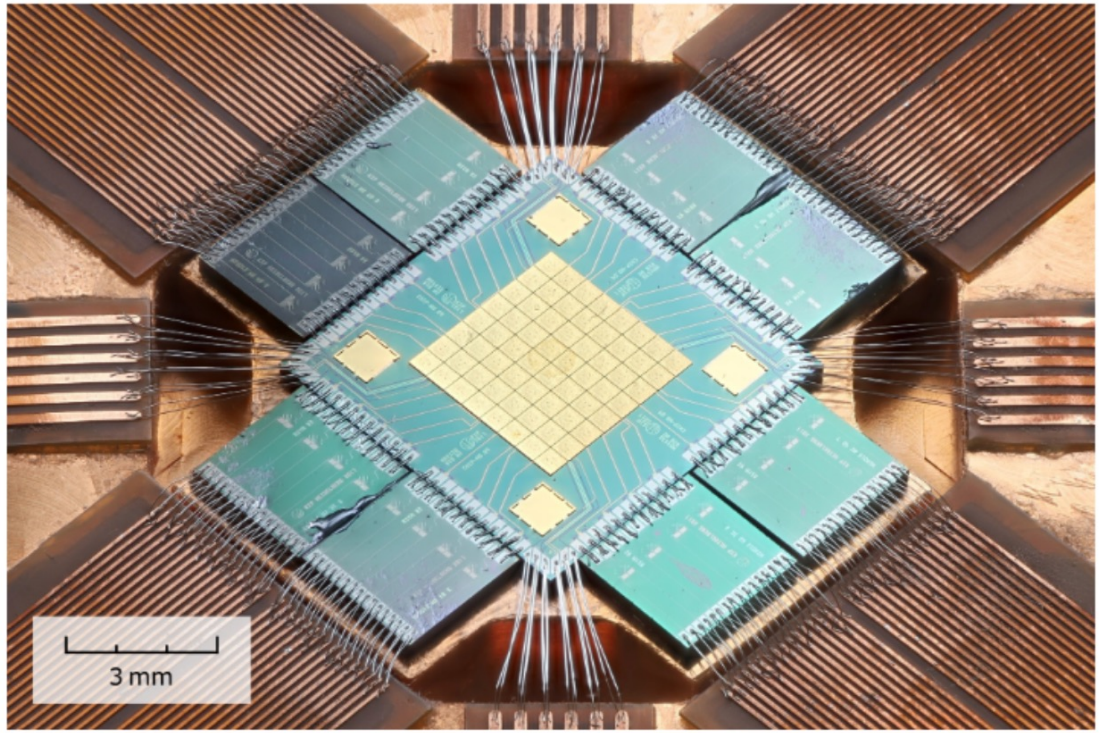


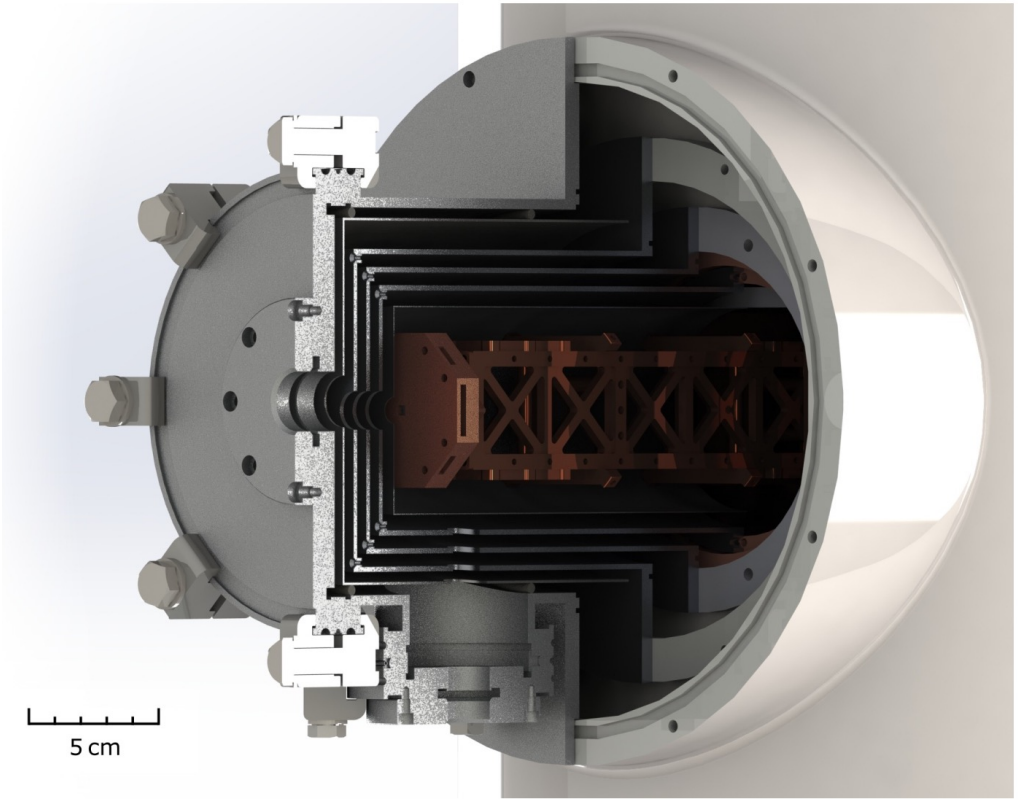


Continuous calibration lines from combination of radioactive sources and XRF targets

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

The QUARTET detector

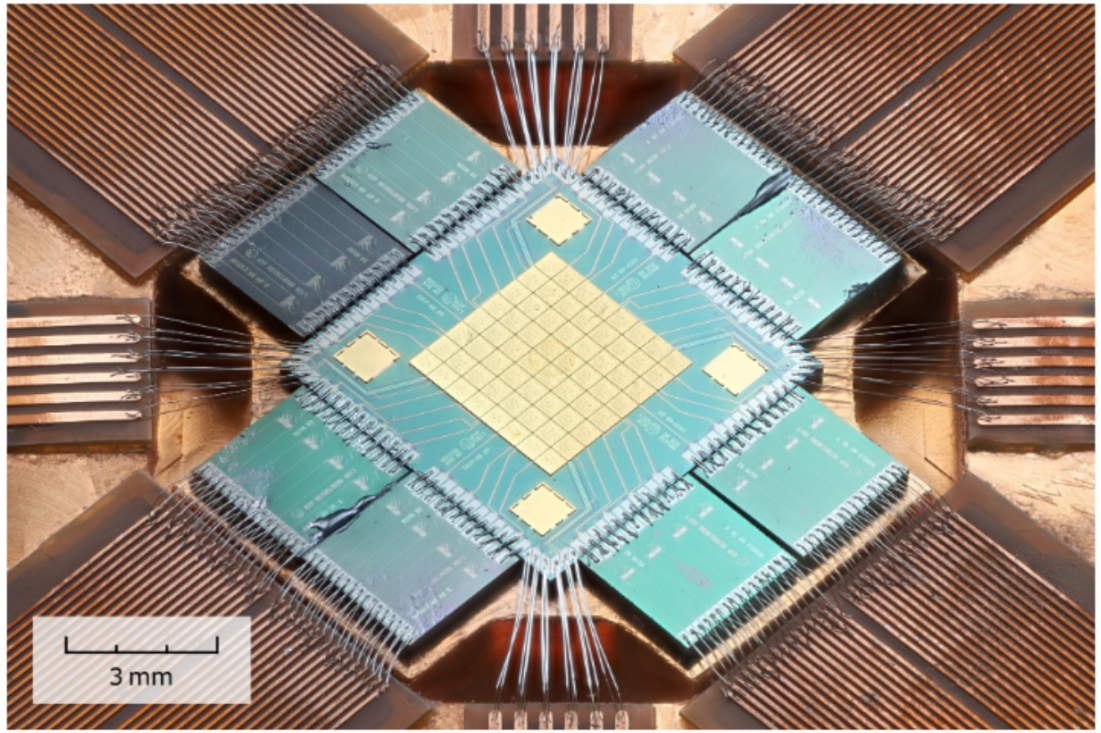


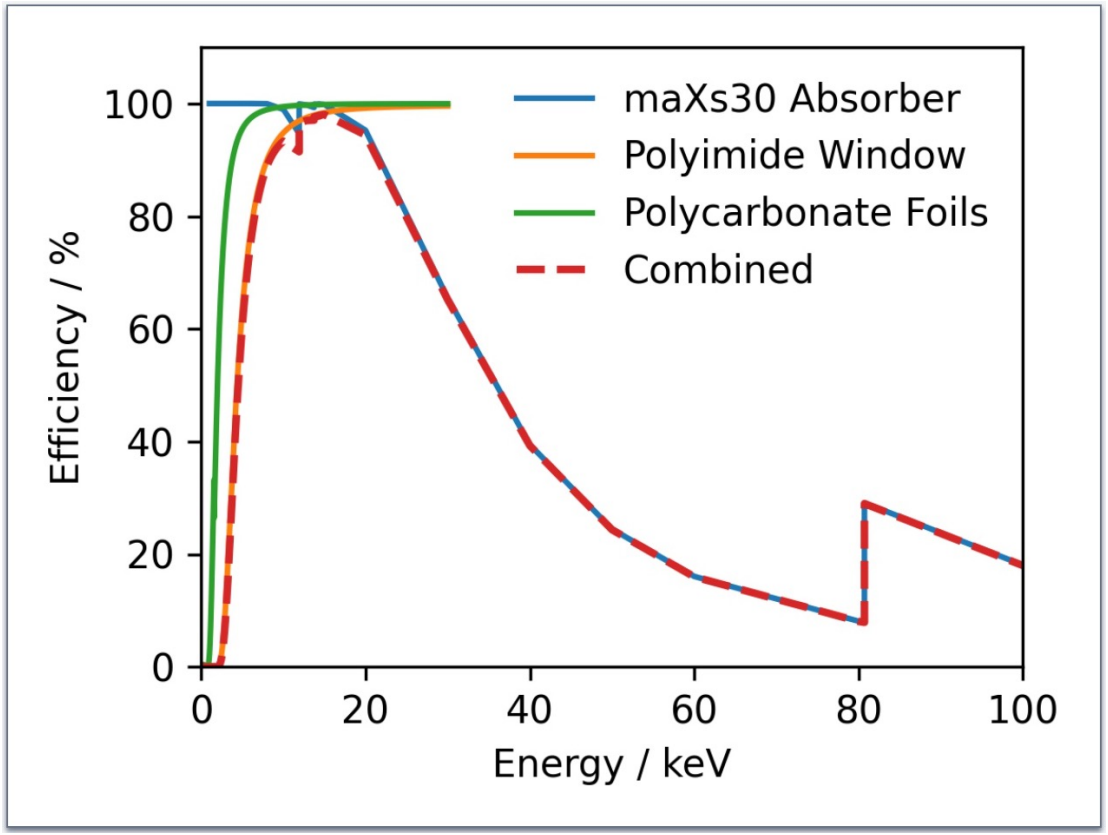


- 64 pixel maX-30 MMC detector, *developed for IAXO experiment*
- Mounted in custom sidearm designed to reduce vibrations
- 5 thermal shields and x-ray windows
- Calibration sources mounted outside the detector

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

The QUARTET detector

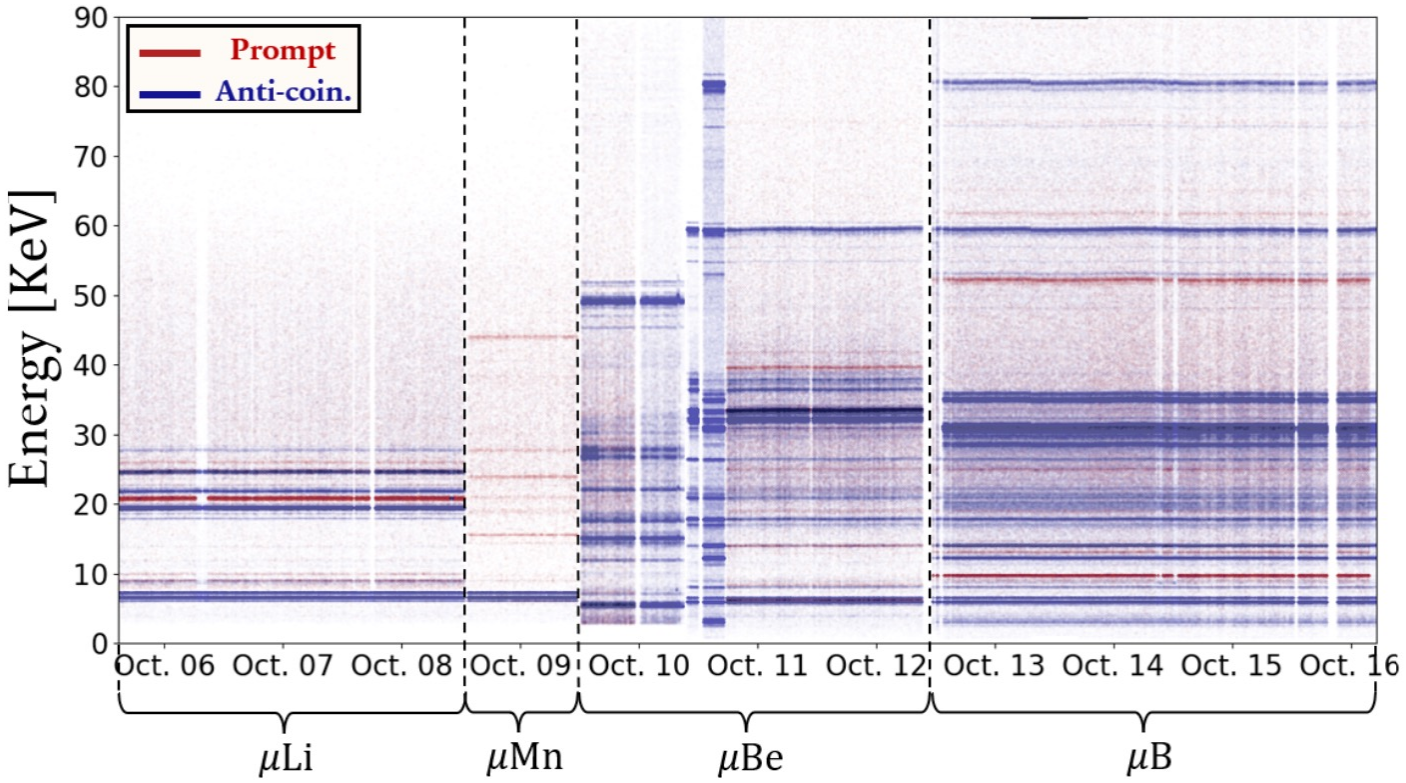




- 64 pixel maX-30 MMC detector, *developed for IAXO experiment*
- Mounted in custom sidearm designed to reduce vibrations
- 5 thermal shields and x-ray windows
- Calibration sources mounted outside the detector

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

QUARTET 2024 beamtime—high statistics data for all channels of interest

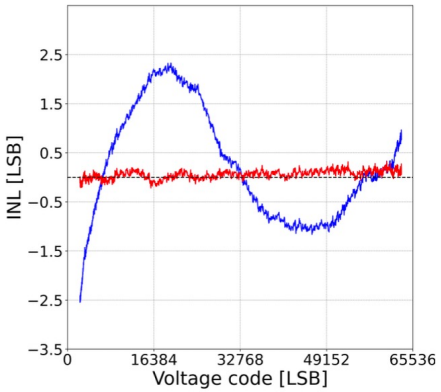


Target	Production	Calibration	Conclusion
^{6,7}Li	70 h	^{55}Fe Mo/Ag XRF	✓
Mn	20 h	^{55}Fe	Proof-of-principle
^{9}Be	40 h	^{55}Fe Ba/La XRF ^{241}Am	✓
^{10,11}B	80 h	^{55}Fe ^{241}Am ^{133}Ba	✓

High statistics data suitable for physics analysis obtained for all main channels of interest

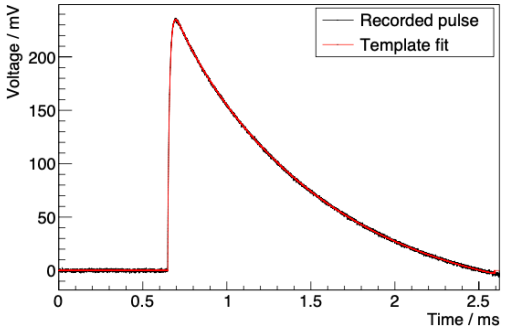
QUARTET 2024 beamtime—Key analysis steps

ADC calibration → Pulse fitting → Event Identification and Temperature Correction → Calibration and Pixel Co-adding

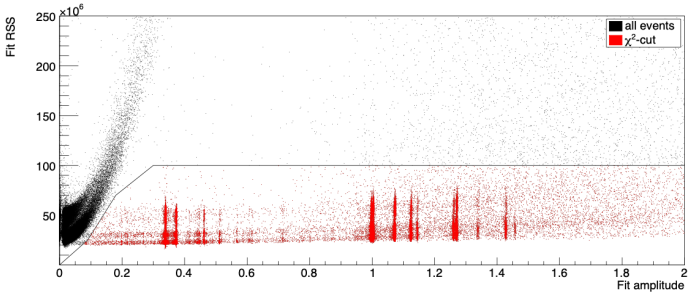


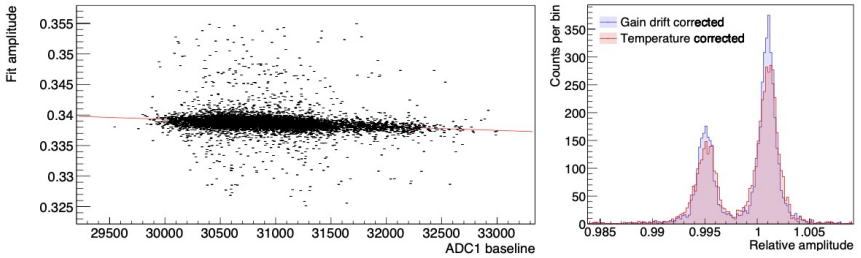
NEW!

- ✓ Correct for non-linearities
- ✓ Stable, repeatable
- ✓ Reduce systematic non-linearities by 20 (<<1 eV)



- ✓ Amplitudes
- ✓ Goodness-of-fit

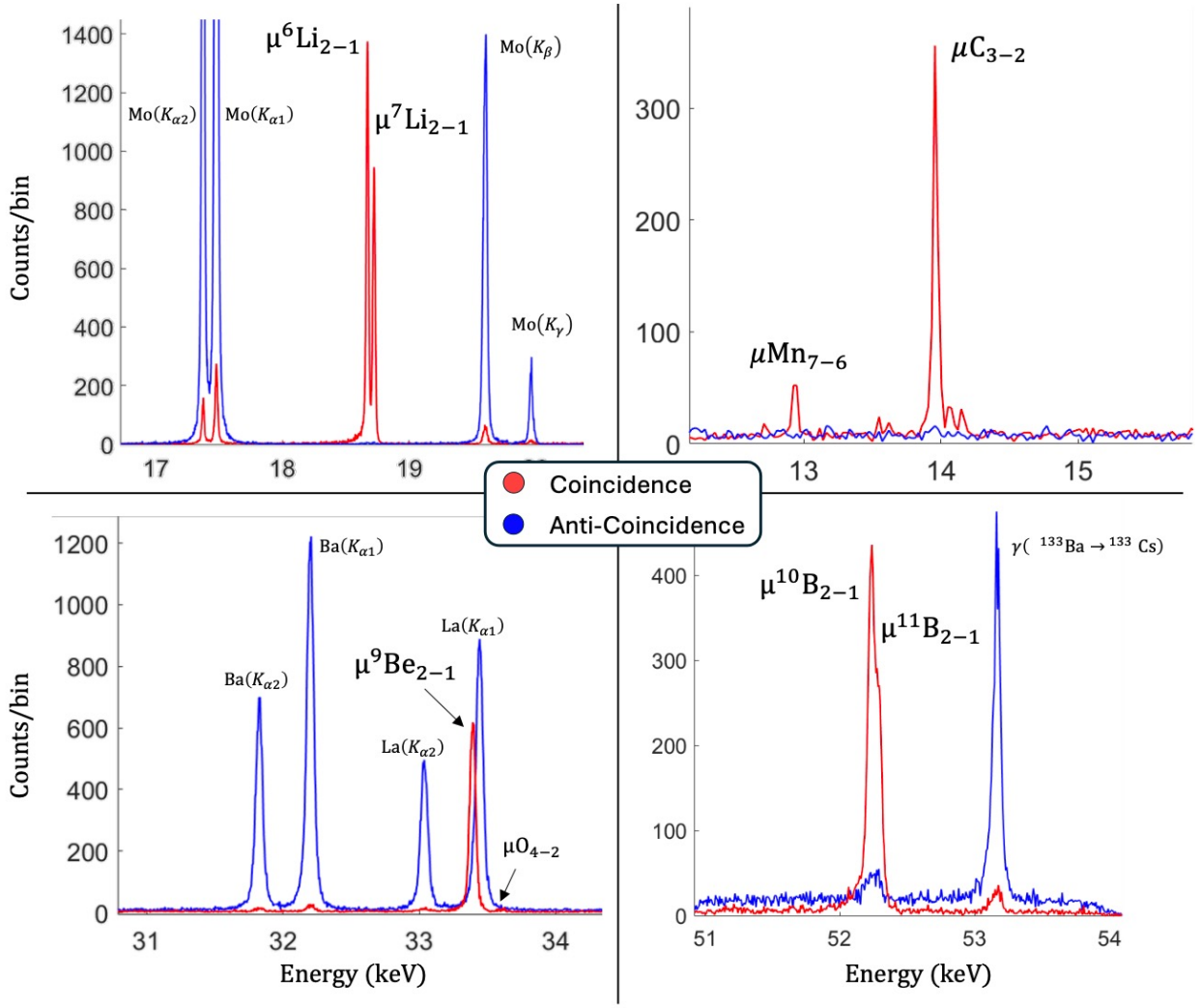




- ✓ X^2 cut to remove electron events
- ✓ Temperature correction for optimal resolution

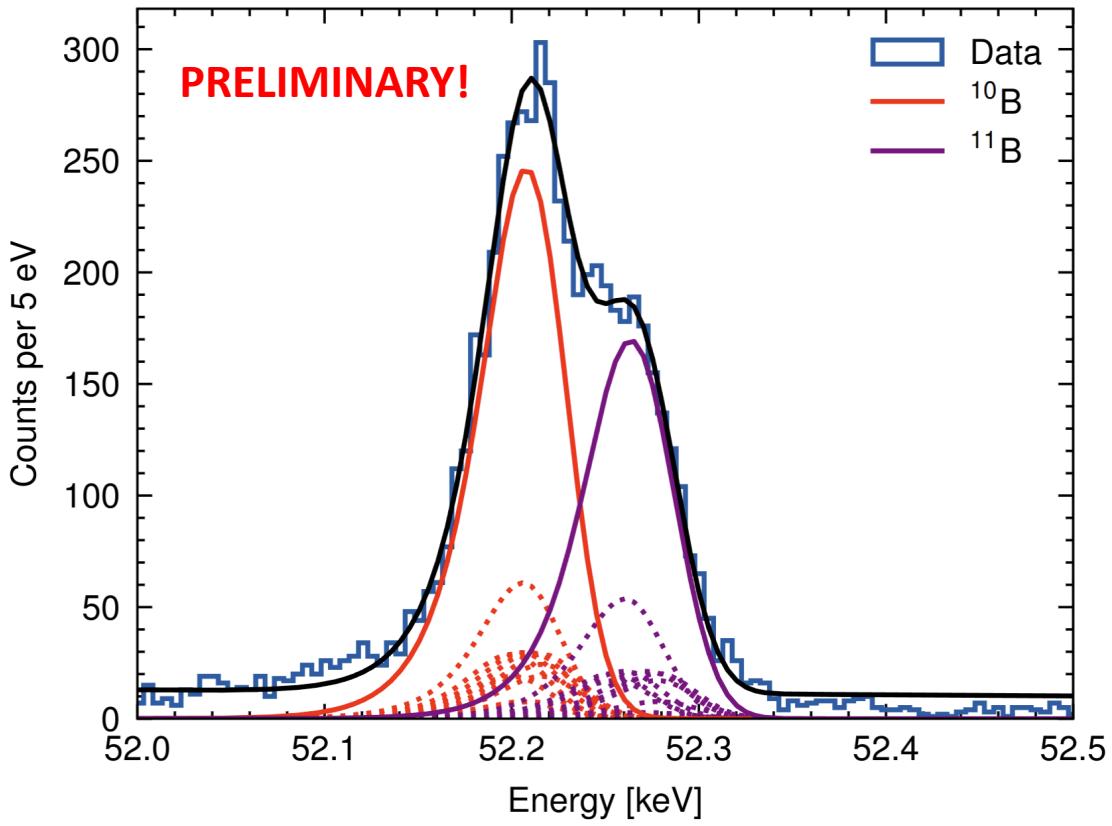
- ✓ Local calibration around line of interest, pixel-by-pixel
- ✓ Summed spectrum for physics analysis

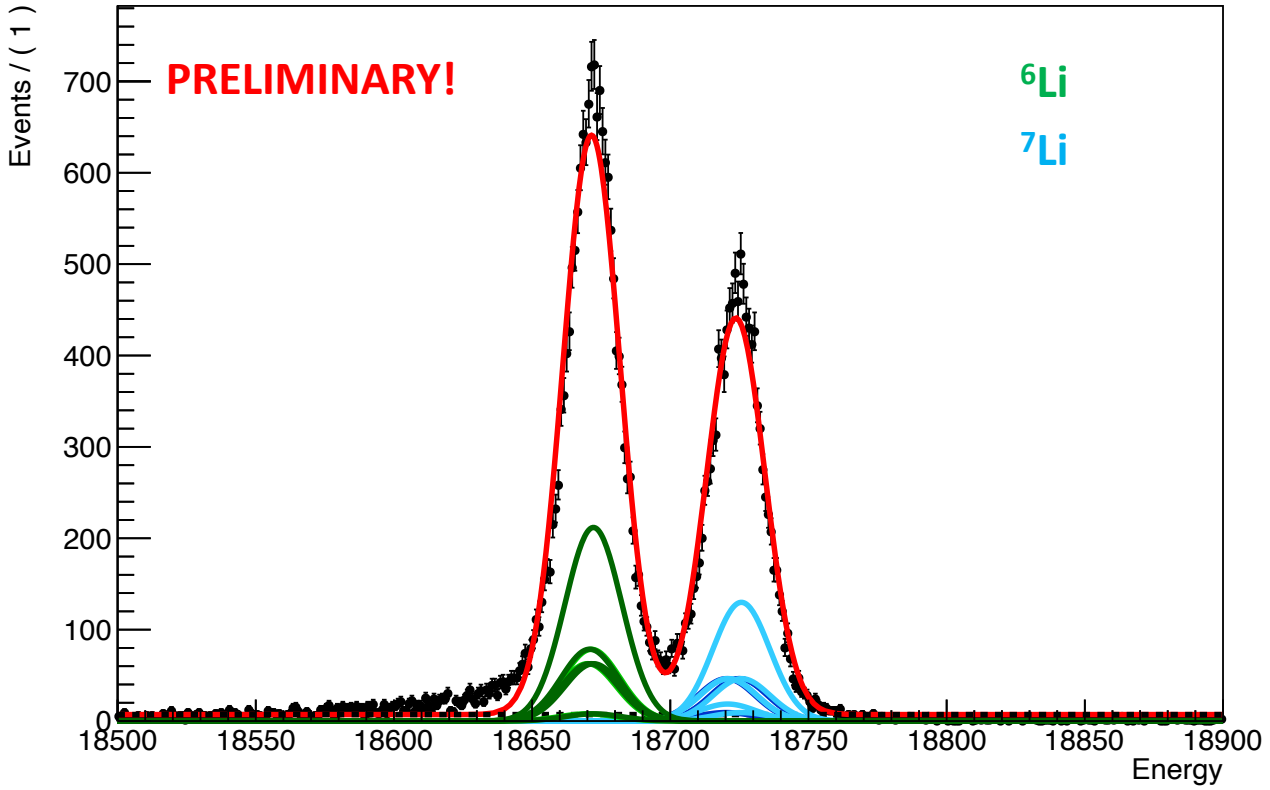
QUARTET 2024 beamtime—Promising first spectra



- ✓ High quality spectra for all main channels of interest
- ✓ Muon coincidence allows to separate muonic atom lines from calibration lines
- ✓ Main steps of spectral treatment and calibration have been accomplished for all channels.
- ✓ Statistics allow <1 eV centroid determination

QUARTET 2024 beamtime—Promising first spectra, physics analysis ongoing





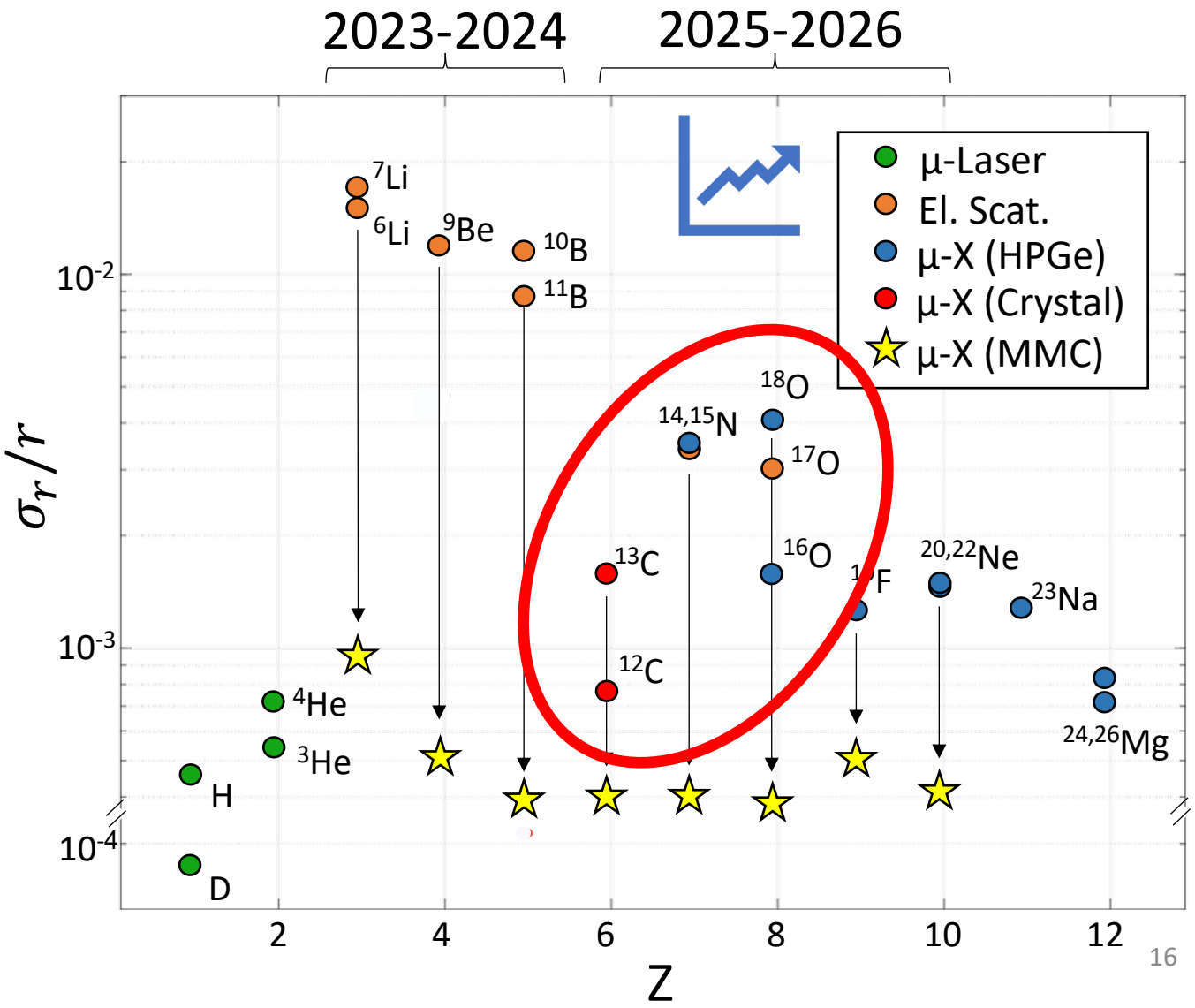
- ✓ Fitting of the isotope shifts with hyperfine structure in B and Li, in collaboration with nuclear and atomic theorists
- ✓ Article submissions for isotope shift measurements with ~1eV accuracies (or better) expected in 2025.

QUARTET 2025—Onwards and Upwards (in energy) !

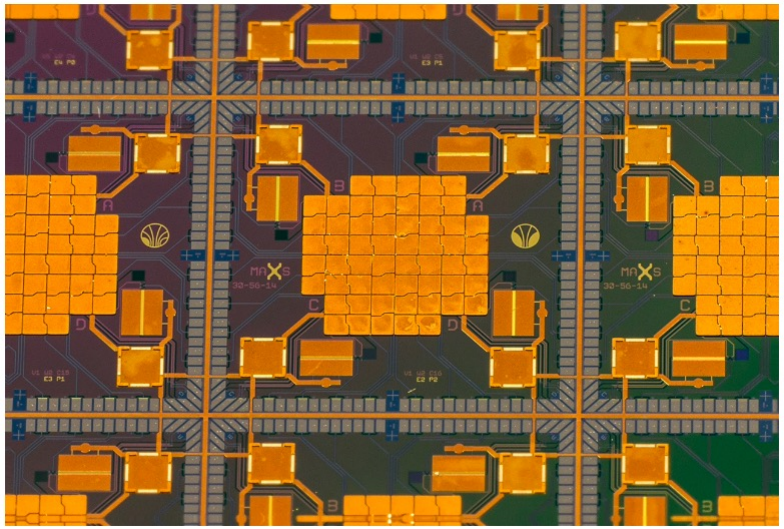
- First data sets obtained for Li, Be, B. Publication quality for first improvements in existing radii.
- 2025 goals :
  - ❑ ^{12,13}C (tests already done in 2023)
  - ❑ ^{14}N
  - ❑ ^{16,18}O

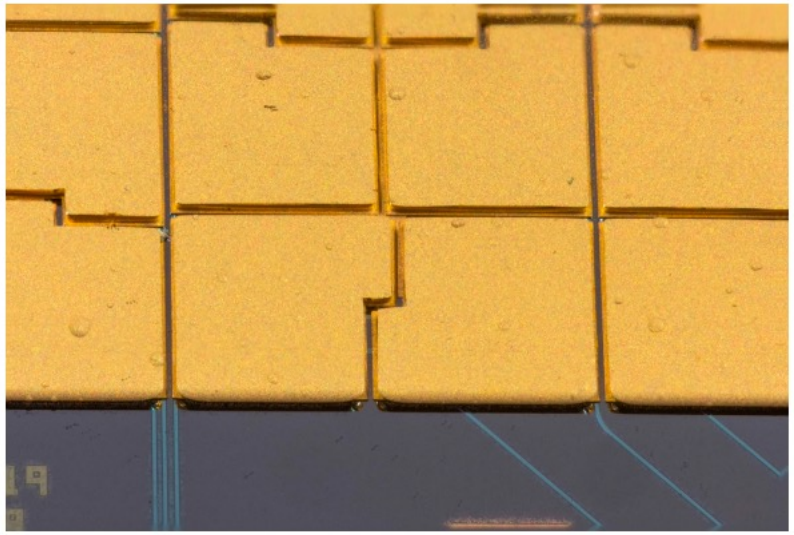
  →Better, optimized MMC detector

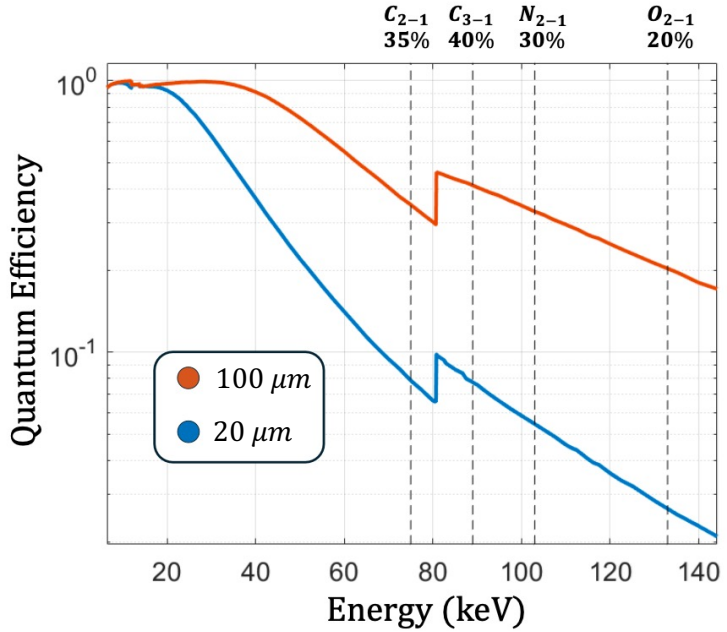
  →New ADC with reduced non-linearity (Development with Struck)



New, optimized high-energy MMC detector for QUARTET

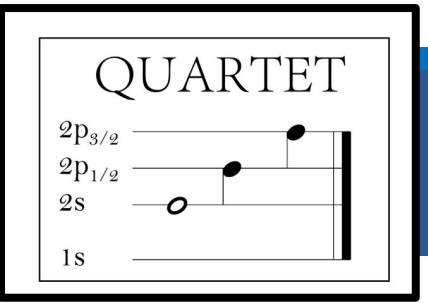






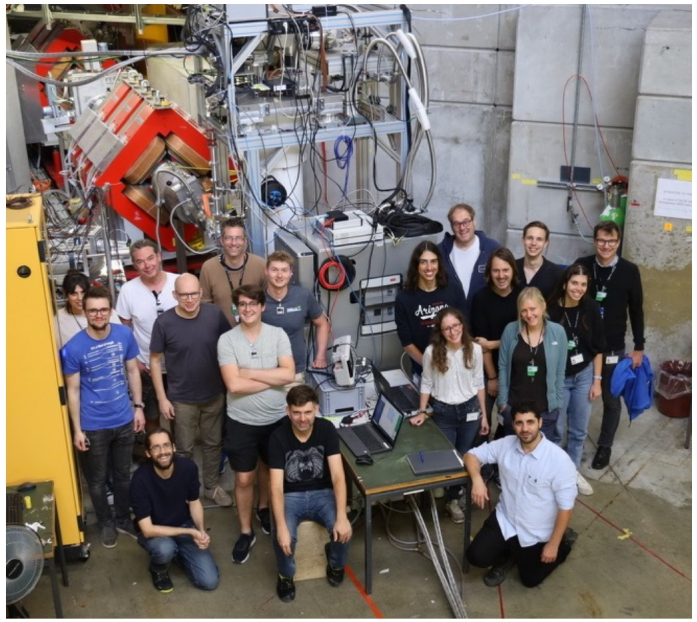
- New, optimized MMC pixel design for QUARTET developed by KIP
- Dedicated channels for electron vetoes (asymmetric pixels)
- Faster heat sinks→higher rates
- 100 micrometer thick x-ray absorbers made of electroplated gold
- New fabrication process, used for QUARTET and GSI detectors (maXs-100)
- High quantum efficiency for 100 keV x rays

2025 Goals and Summary



Request: 2.5 weeks in PiE1

- Setup—4 days
- ^{12,13}C—5 days
- ^{14}N—3 days
- ^{16,18}O—5 days
- Tear down—1 day



✓ **First physics results for Li, B, and B expected in 2025**

✓ **Factors of 3-5 improvement in radii expected from 2024 data, still factors 2-3 from nuclear theory limits**

✓ **Improved, faster MMCs optimized for QUARTET to be deployed in 2025**

Thank you for your attention and consideration

Determinations of nuclear RMS charge radii

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

- **For $Z > 6$:**
  Measured x-rays from muonic atoms using solid-state detectors.
  10<Z: limited by theory.
  Z<10: limited by experiment (resolution).

- **For $Z = 3 - 5$, and others:**
  Electron scattering, less accurate and systematics usually NOT under control

- **For $Z = 6$**
  E(2P-1S)~75 keV, measured with crystal spectrometer.
  Limited by resolution ~75 eV