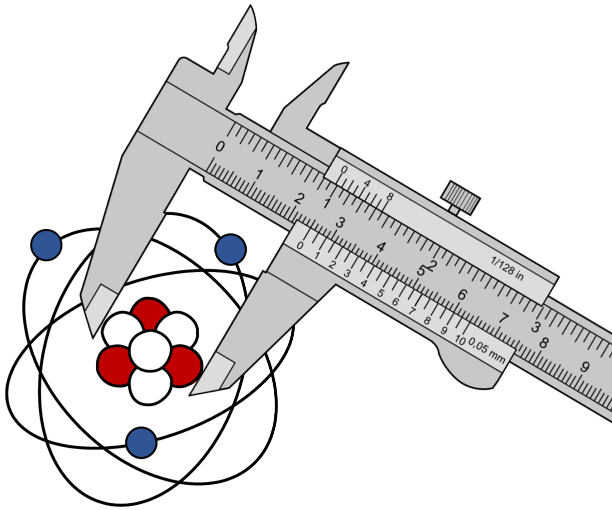
ETH zürich

High-resolution x-ray spectroscopy of muonic lithium

Towards improved nuclear charge radii

Katharina von Schoeler | ETH Zürich | QUARTET collaboration | Bormio Conference 2025

Absolute nuclear charge radii



Precise measurements of low-Z absolute nuclear charge radii are crucial as

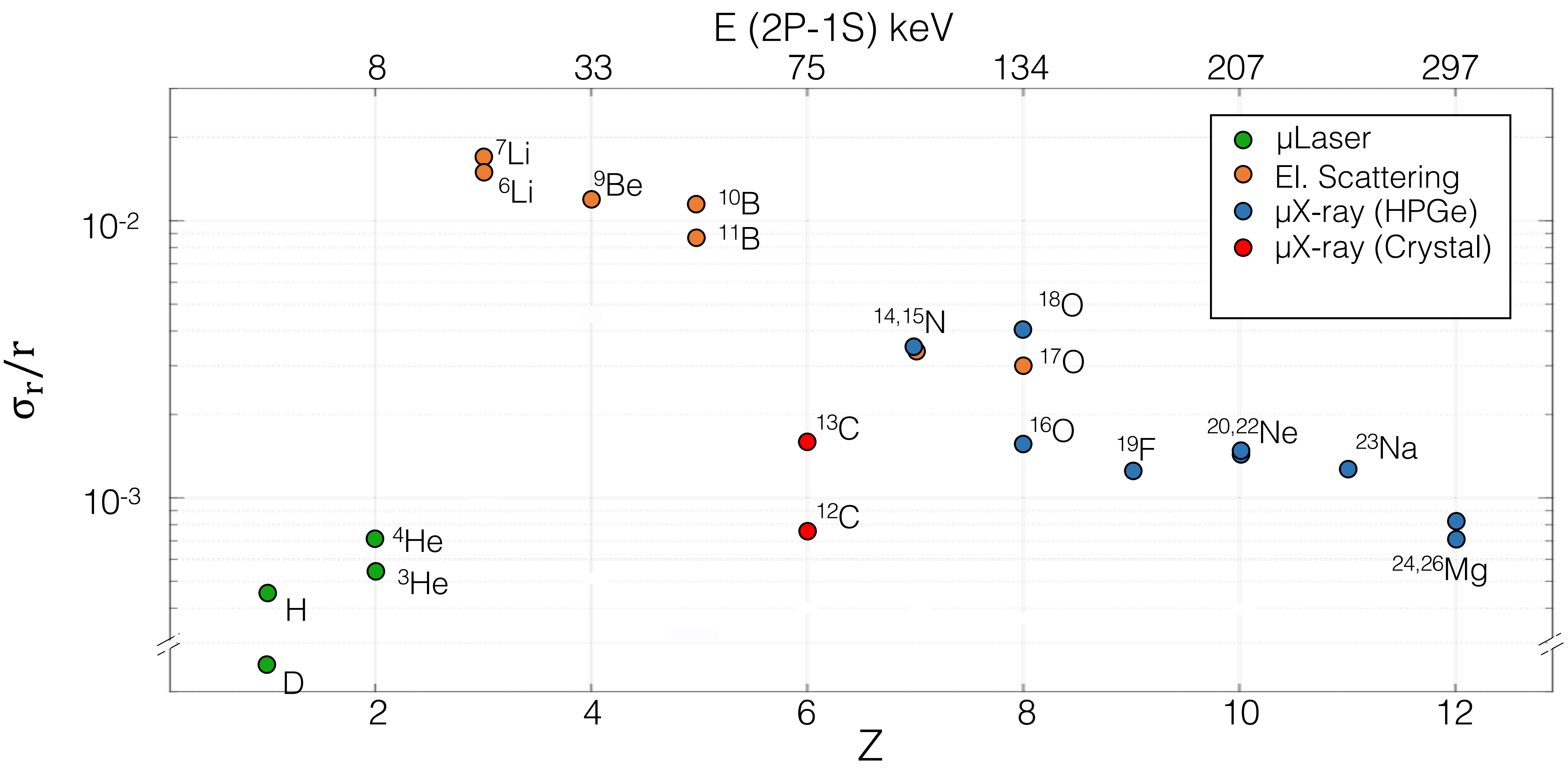
1. Input for laser spectroscopy of muonic and electronic atoms for
   - Precision QED tests & searches for new physics
   - Extraction of fundamental constants
   - …
2. benchmarks for ab-initio nuclear theory
3. ...

rms charge radius:

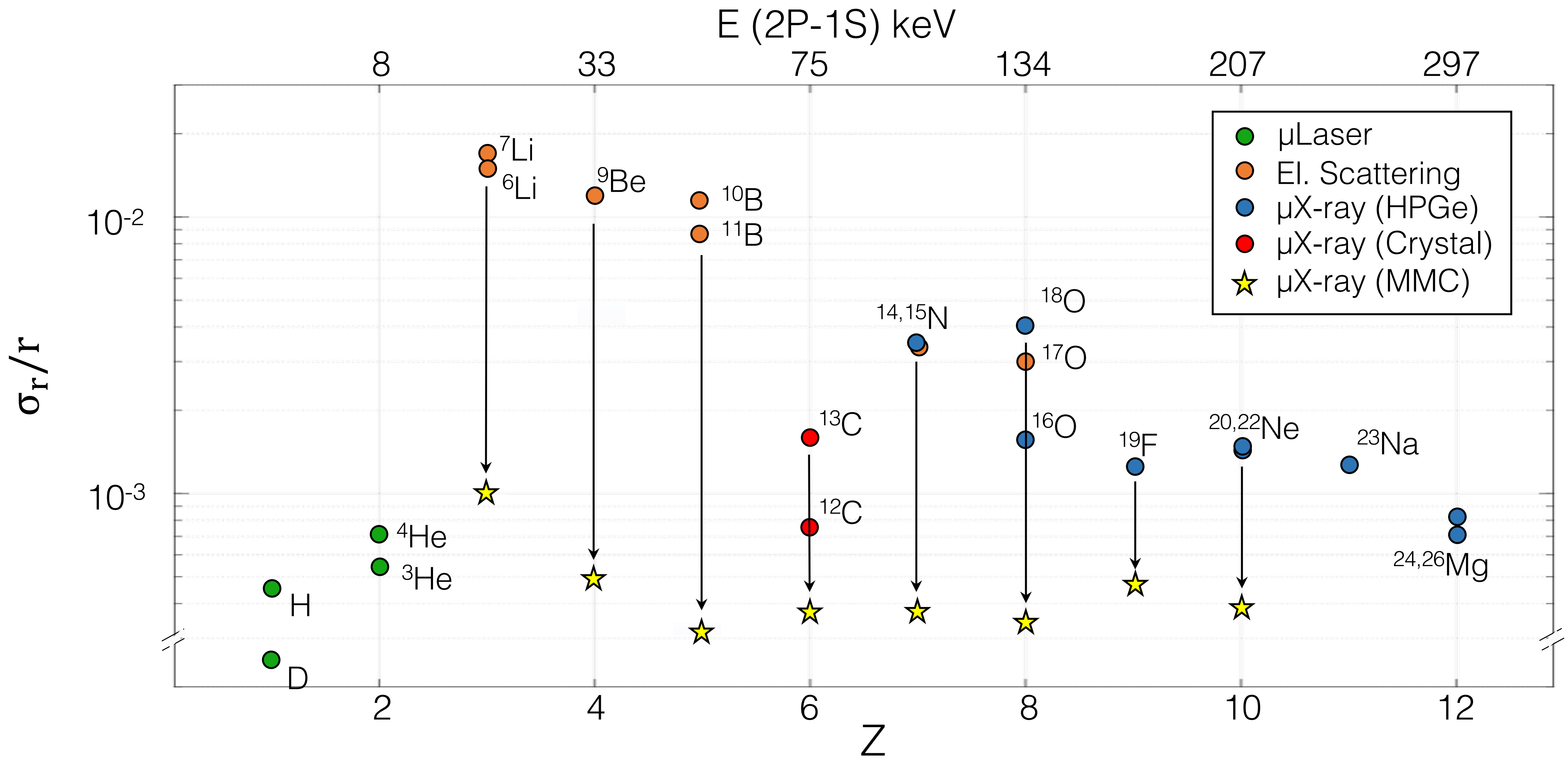
$$\langle r^2 \rangle = \frac{1}{Ze} \int r^2 \rho(r) \, d\tau$$

Nuclear charge density distribution

Uncertainties in nuclear charge radii



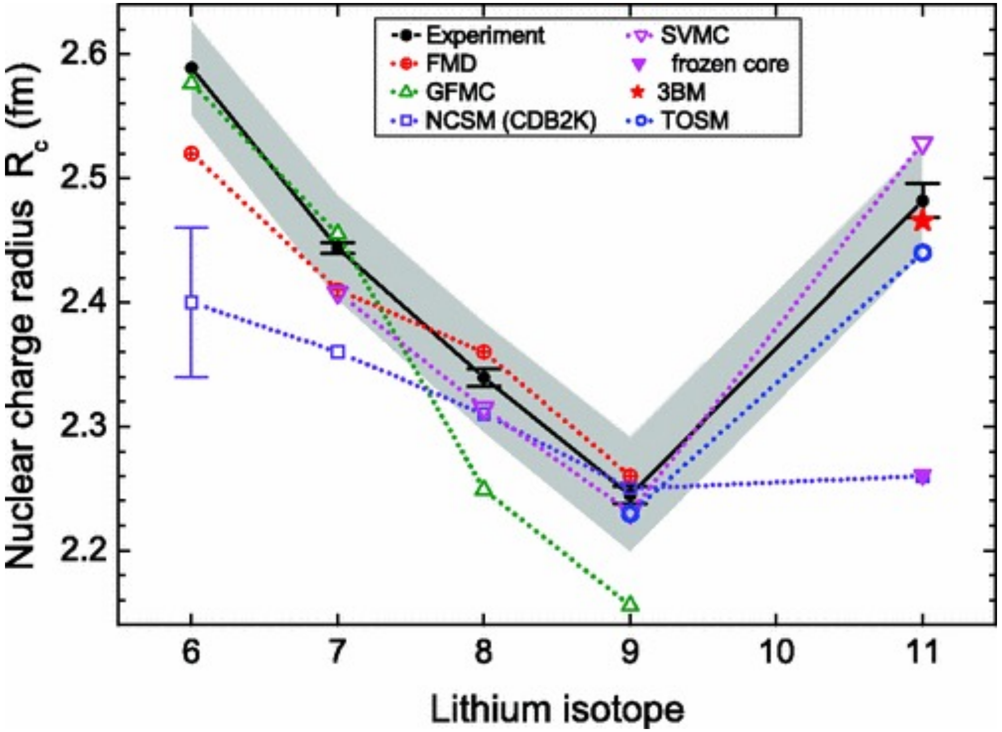
Uncertainties in nuclear charge radii



Lithium nuclear charge radii

From electron scattering and isotope shifts

DOI: 10.1103/PhysRevC.84.024307



Whole isotopic chain is limited by current best Li charge radii:

$$R_{rms}(^{6}\mathrm{Li}) = 2.589(39)\ \mathrm{fm}$$

$$R_{rms}(^{7}\mathrm{Li}) = 2.444(42)\ \mathrm{fm}$$

from elastic electron scattering experiments.

Lithium nuclear charge radii

From muonic atom spectroscopy

Radius uncertainty >100% from 1968 measurement:

VOLUME 20, NUMBER 10 PHYSICAL REVIEW LETTERS 4 MARCH 1968

ENERGY AND WIDTH MEASUREMENTS OF LOW-Z PIONIC X-RAY TRANSITIONS*

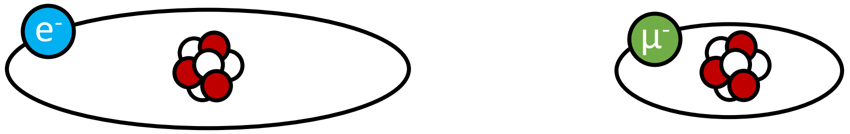
R. J. Harris, Jr.,† W. B. Shuler, M. Eckhause, R. T. Siegel, and R. E. Welsh
College of William and Mary, Williamsburg, Virginia
(Received 15 January 1968)

Element	E_{exp}		Radius (fm) - Equivalent Uniform Charge	
	This Work	Other	This Work	Electron Scattering
Li^6	18.64 ± 0.07	18.1 ± 0.4 [b]	4.96 ± 6.0	3.28 ± 0.06 [e]
Li^7	18.69 ± 0.06	18.1 ± 0.4 [b]	4.94 ± 5.0	3.09 ± 0.04 [e]

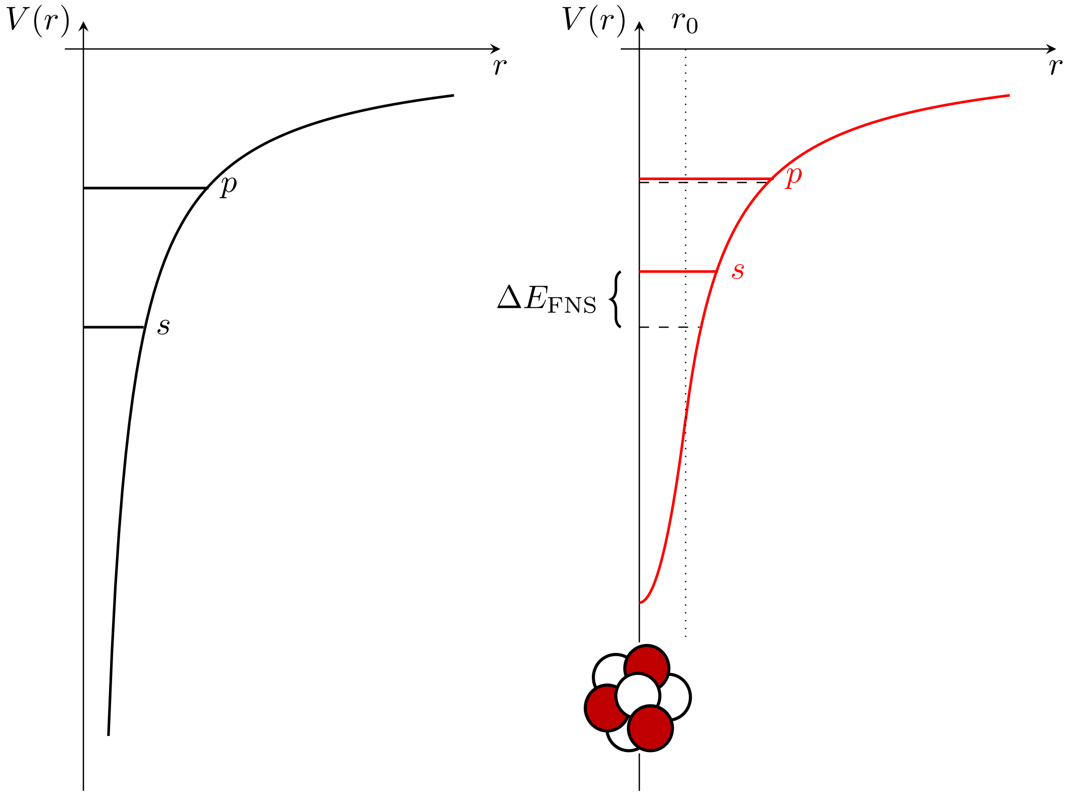
Muonic x-ray spectroscopy

In a nutshell

$m_\mu \approx 200 \cdot m_e$



Bohr radii:	$r \propto \frac{n^2}{Z} \cdot \frac{1}{m}$	200 times smaller
Bohr energies:	$E \propto \frac{Z^2}{n^2} \cdot m$	from eV to keV
Finite nuclear size effect: $\Delta E_{FNS} \propto m^3$		Enhanced by 10^7!



(a) Point nucleus (b) Finite size nucleus

Strategy: form muonic atom and observe 2p→1s transition for maximum radius sensitivity

How to measure those x-rays?

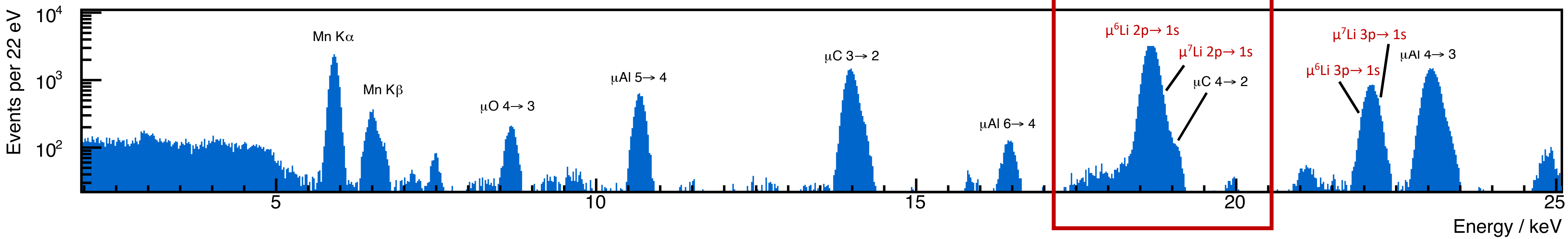
The choice of detectors

Requirements:

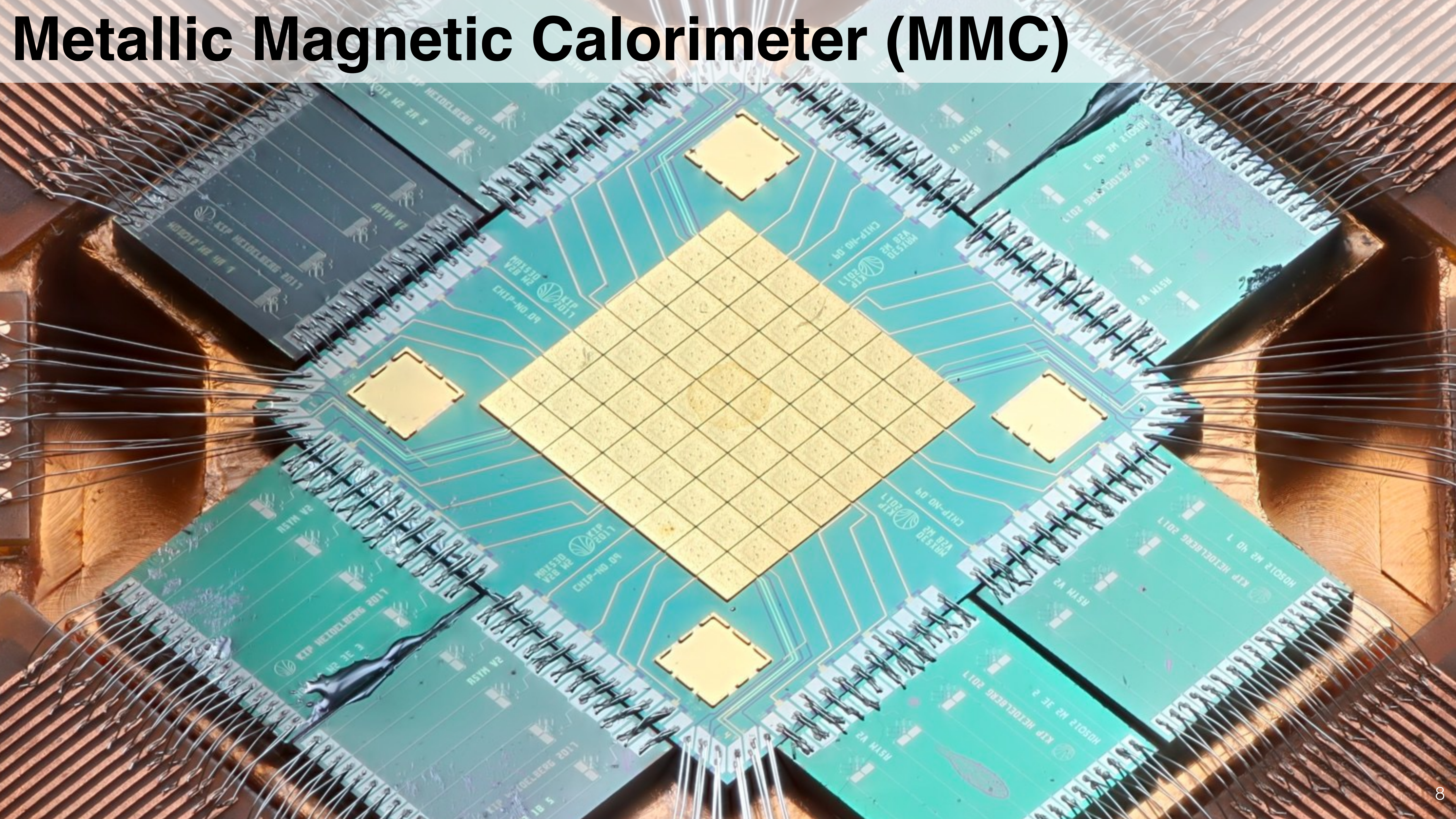
- Energy range ~18 – 210 keV (μLi to μNe 2p → 1s)
- High resolution < 50 eV (μ^6Li to μ^7Li isotope shift: 50 eV, line shape with FS & HFS, background, …)
- High efficiency (limited beam time)

Muonic x-ray spectrum of a Li target obtained with a silicon drift detector.

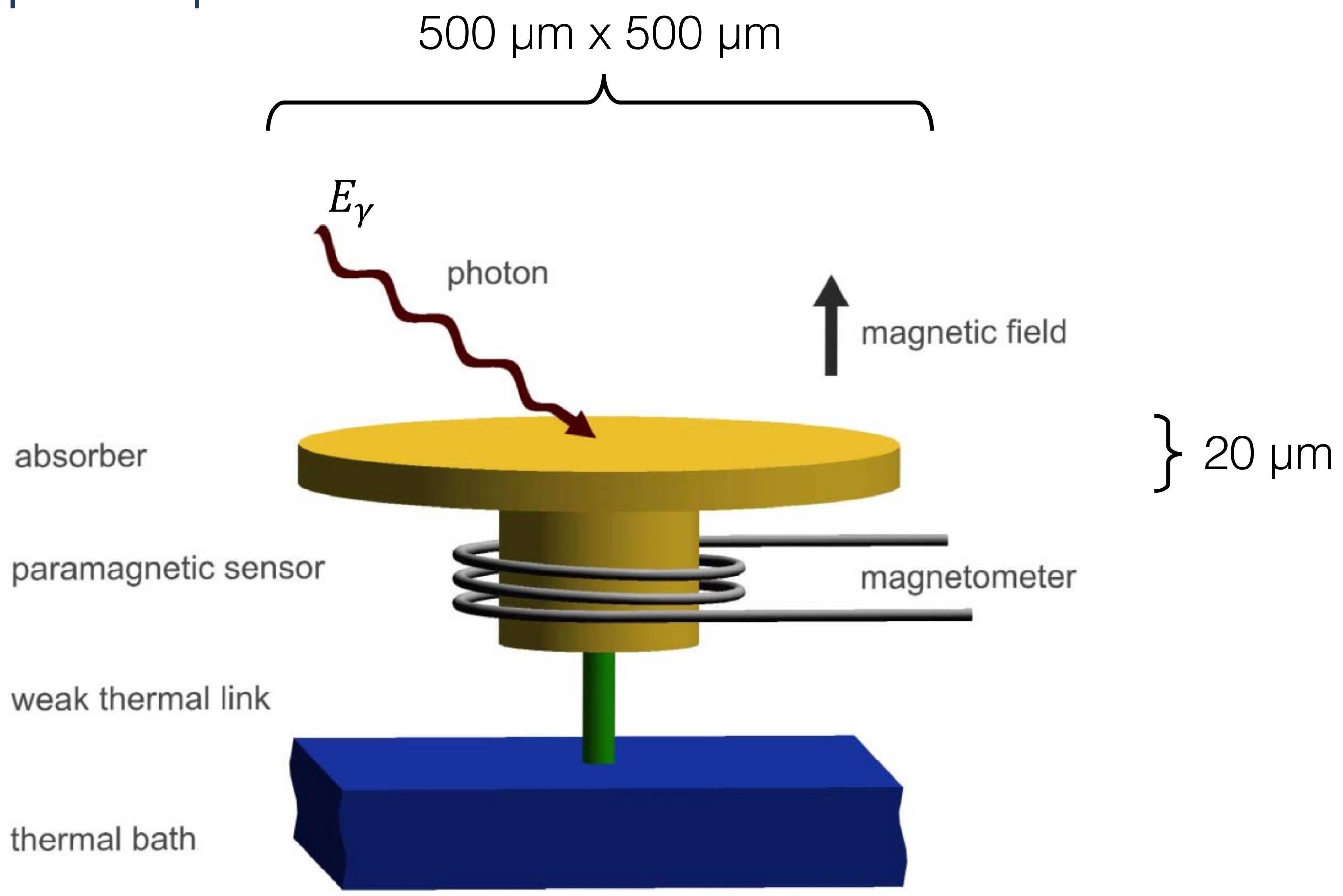
FWHM @ 18.7 keV: ~ 250 eV ☹



Metallic Magnetic Calorimeter (MMC)



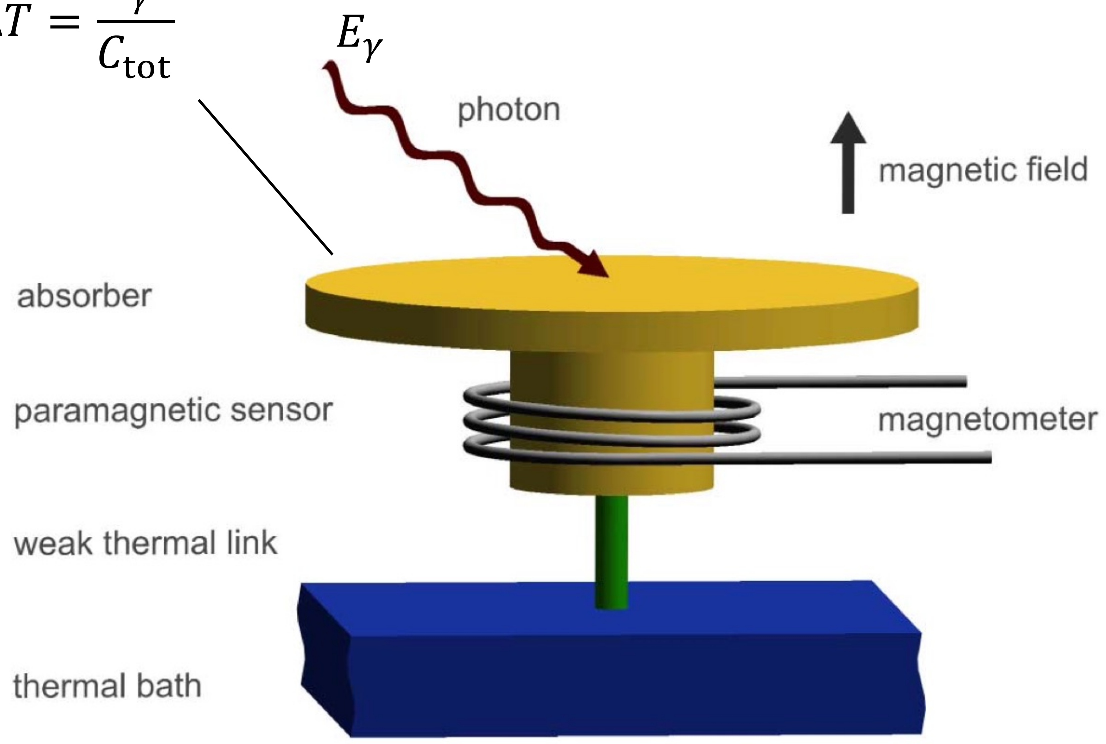
MMC working principle



DOI: 10.1109/TASC.2009.2012724

MMC working principle

$$\Delta T = \frac{E_\gamma}{C_{\text{tot}}}$$



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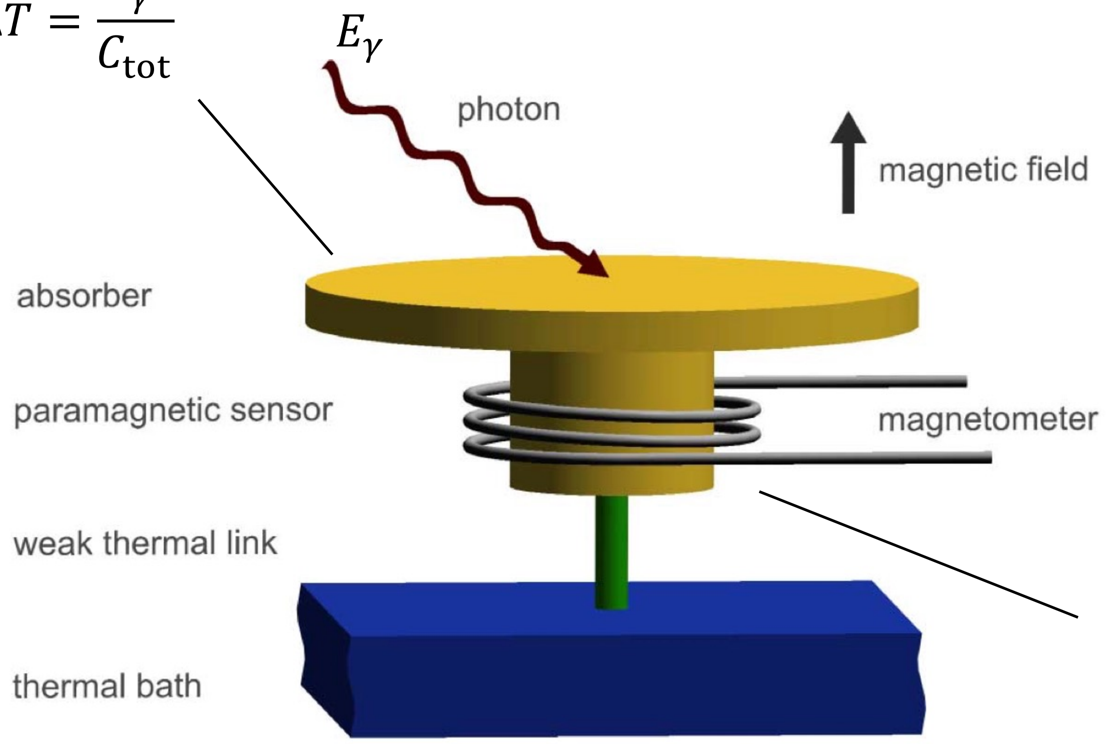


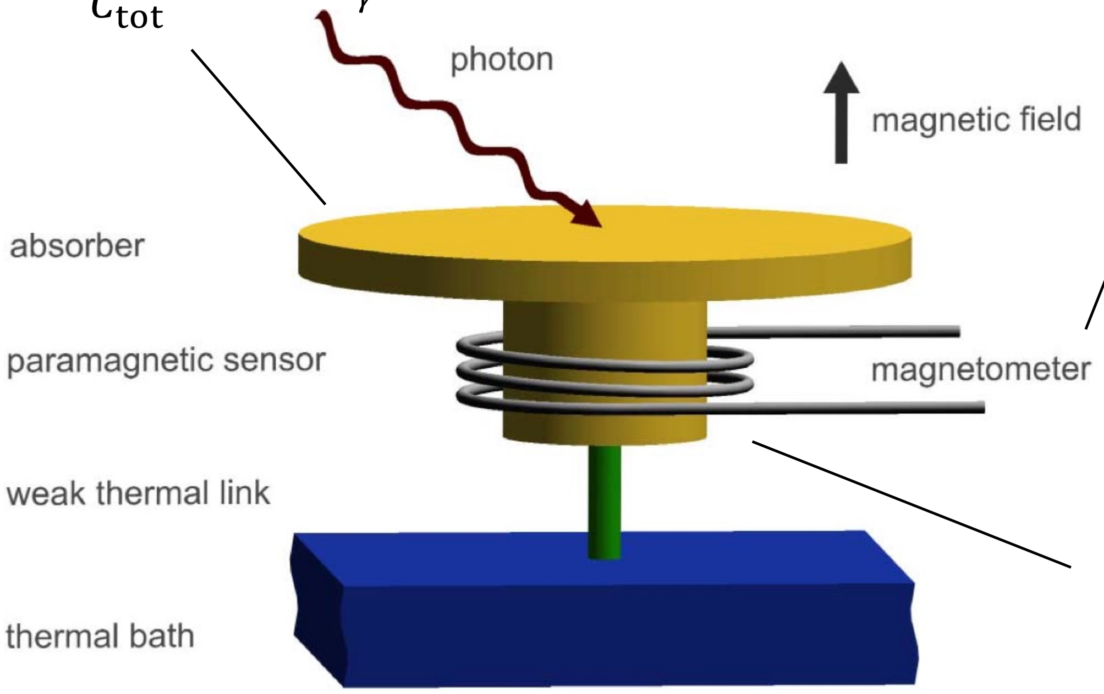
$$\Delta M = \frac{\partial M}{\partial T} \Delta T$$

DOI: 10.1109/TASC.2009.2012724

MMC working principle

$$\Delta T = \frac{E_\gamma}{C_{\text{tot}}}$$

$$\Delta V \propto \Delta M \propto E_\gamma$$



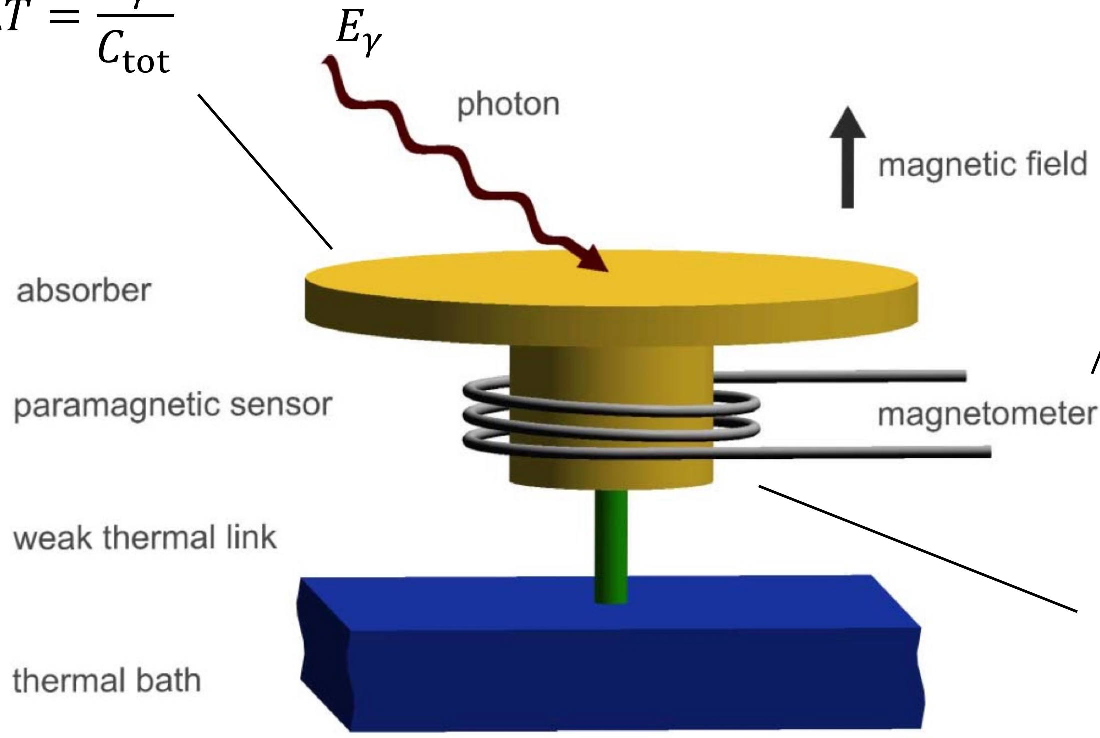
$$\Delta M = \frac{\partial M}{\partial T}\Delta T$$

DOI: 10.1109/TASC.2009.2012724

MMC working principle

tunes detection efficiency
→ determines C_{abs}

$$\Delta T = \frac{E_\gamma}{C_{\mathrm{tot}}}$$



DOI: 10.1109/TASC.2009.2012724

$$\Delta V \propto \Delta M \propto E_\gamma$$

$$\Delta M = \frac{\partial M}{\partial T} \Delta T$$

Energy resolution:

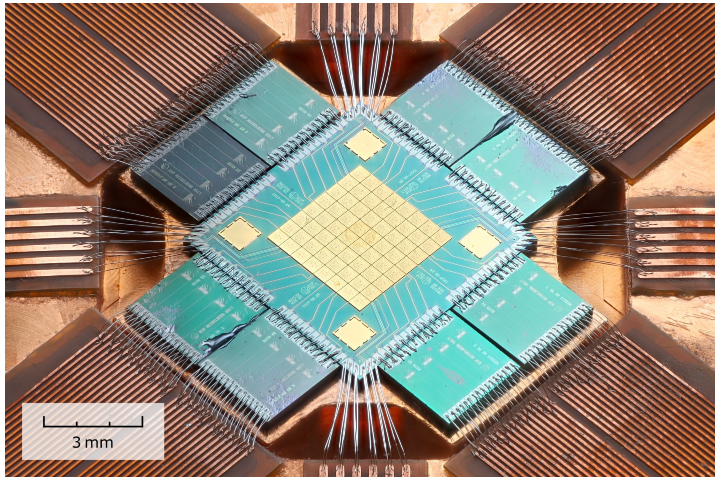
$$\Delta \mathrm{E} \propto \frac{\mathrm{T}\sqrt{\mathrm{C_{abs}}}}{\sqrt[4]{\tau_D}}$$

tunes signal decay time τ_{D}
→ detection speed

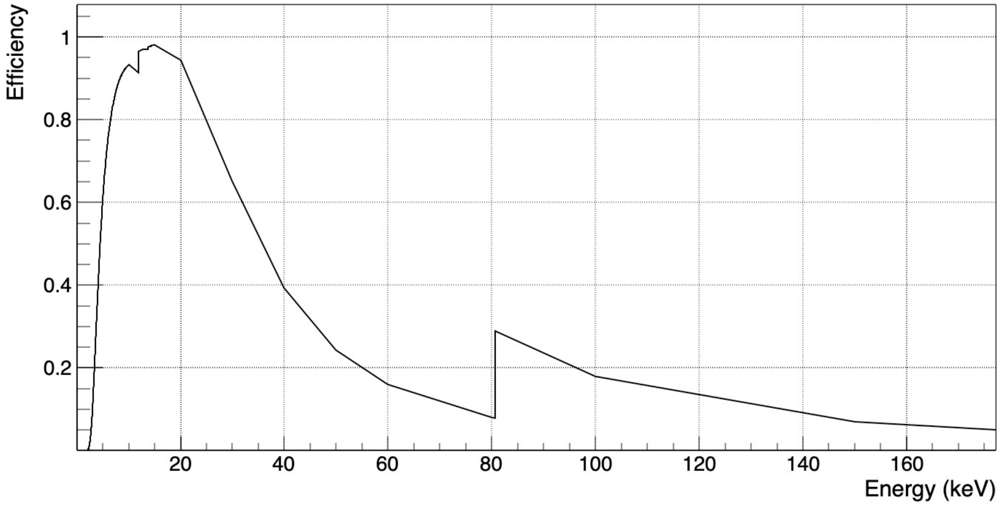
"maXs-30" MMC from Heidelberg

Detector performance

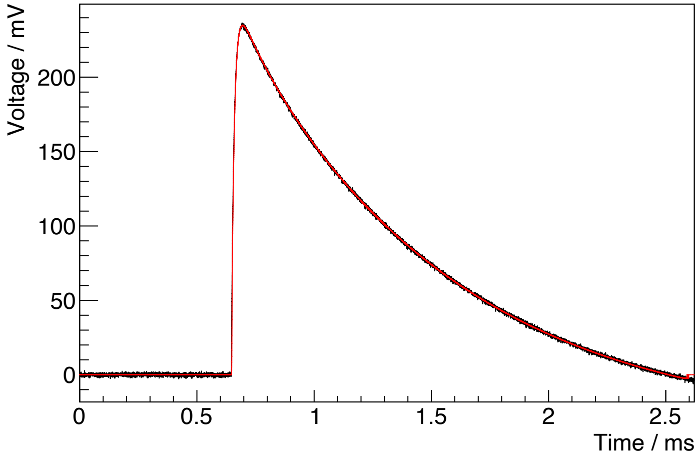
- Operated at approx. 20 mK
- High efficiency: > 90% from 8 – 22 keV
- High resolution of ~10-20 eV at 18 keV
- 64 absorbers: each 500 μm x 500 μm x 20 μm
- max. rate per pixel ≲ 0.5-1 Hz



DOI: 10.1007/s10909-024-03141-x



Calculated detection efficiency. Limited by absorber thickness at high energies and to the entrance window thickness at low energies.



Typical pulse shape from a photon hitting one absorber pixel. The height scales with the photon energy.

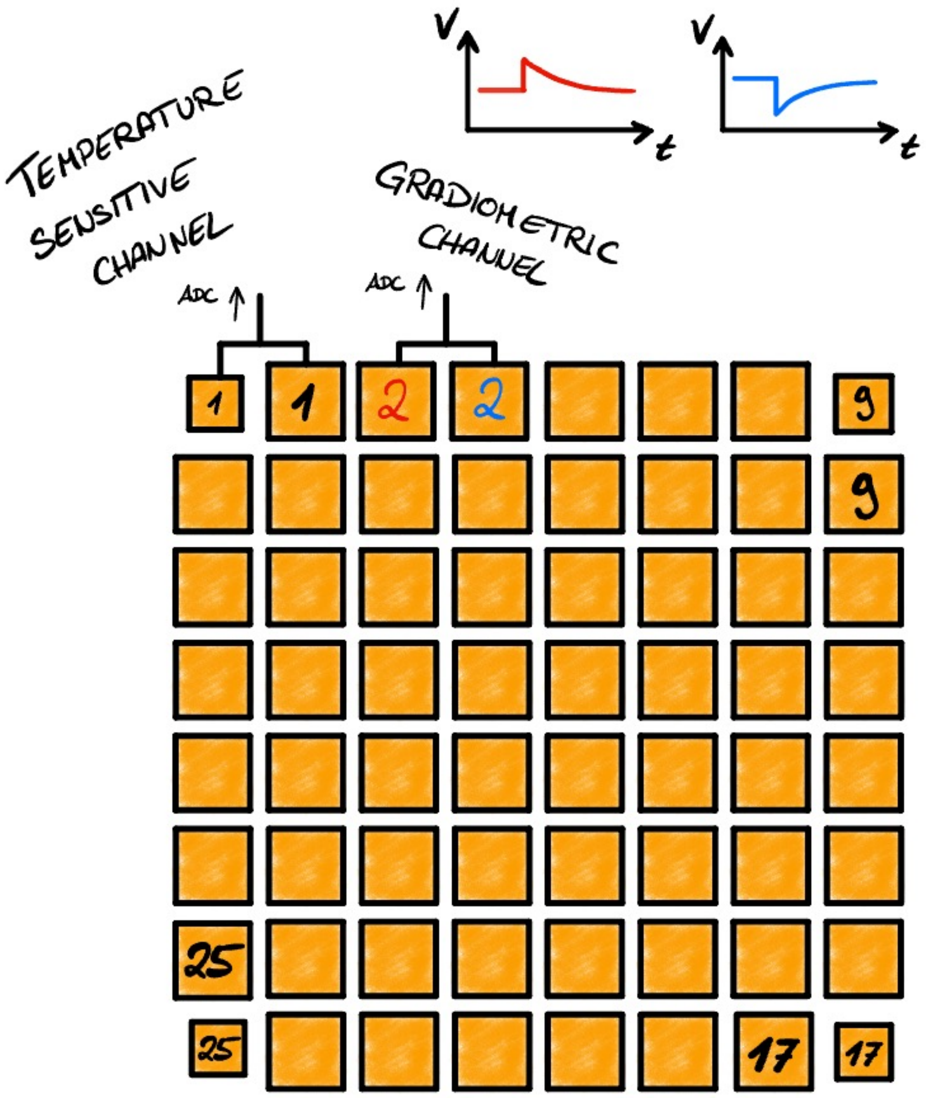
”maXs-30” MMC from Heidelberg

Detector design

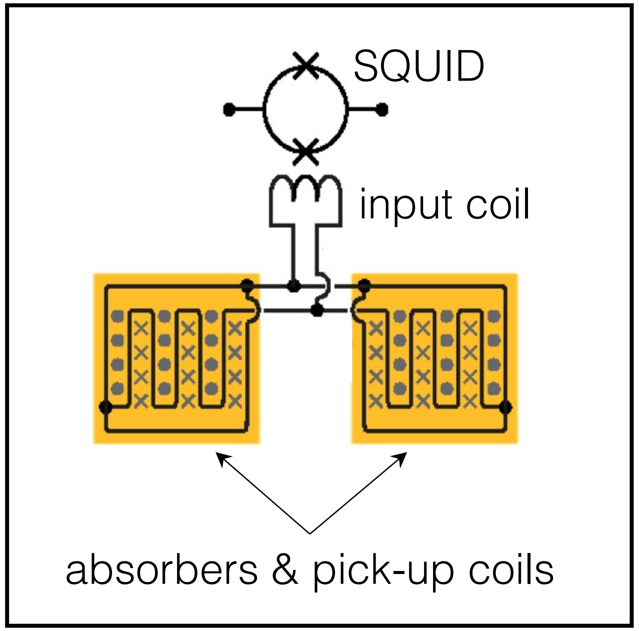
Absorber pair wise coupled

→ Reduced sensitivity towards global temperature changes

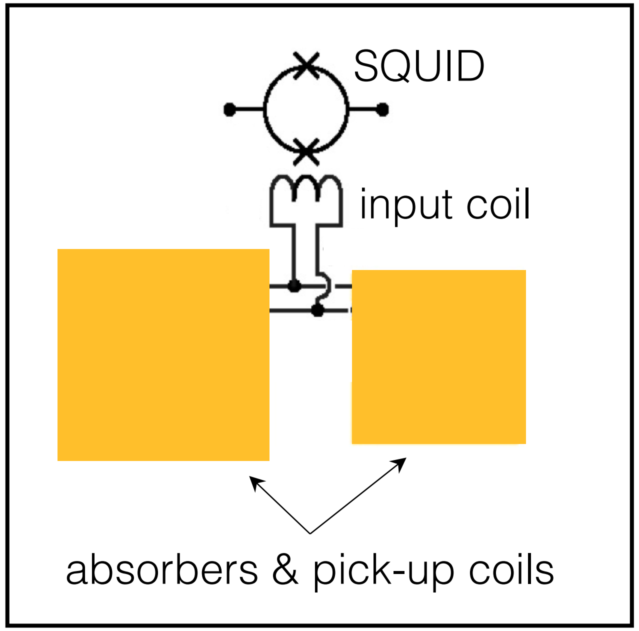
→ (Reduced number of readout channels necessary)



Gradiometric design:



Temperature sensitive design:



DOI: 10.1063/1.3292407

QUARTET

$2p_{3/2}$
$2p_{1/2}$
2s
1s

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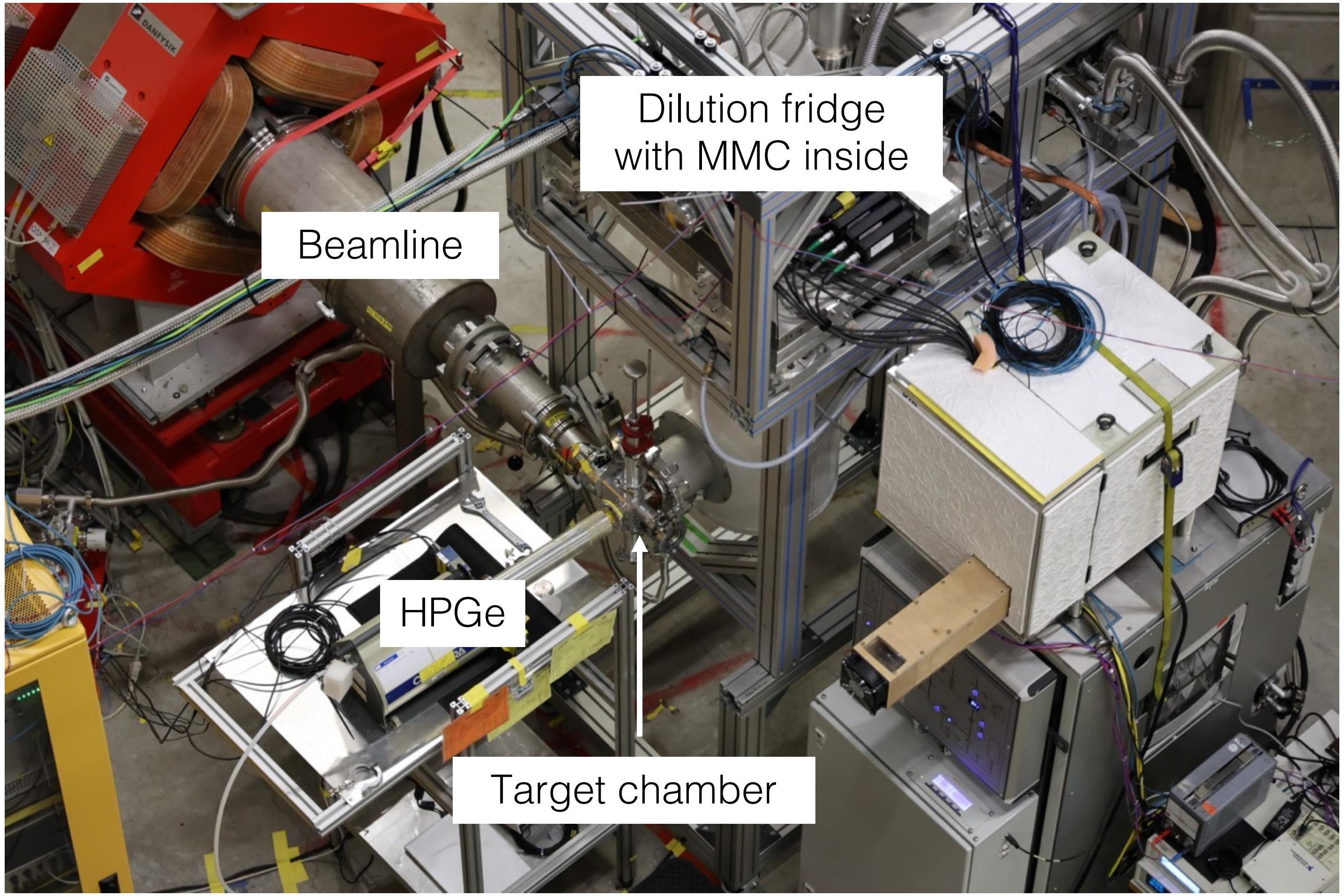
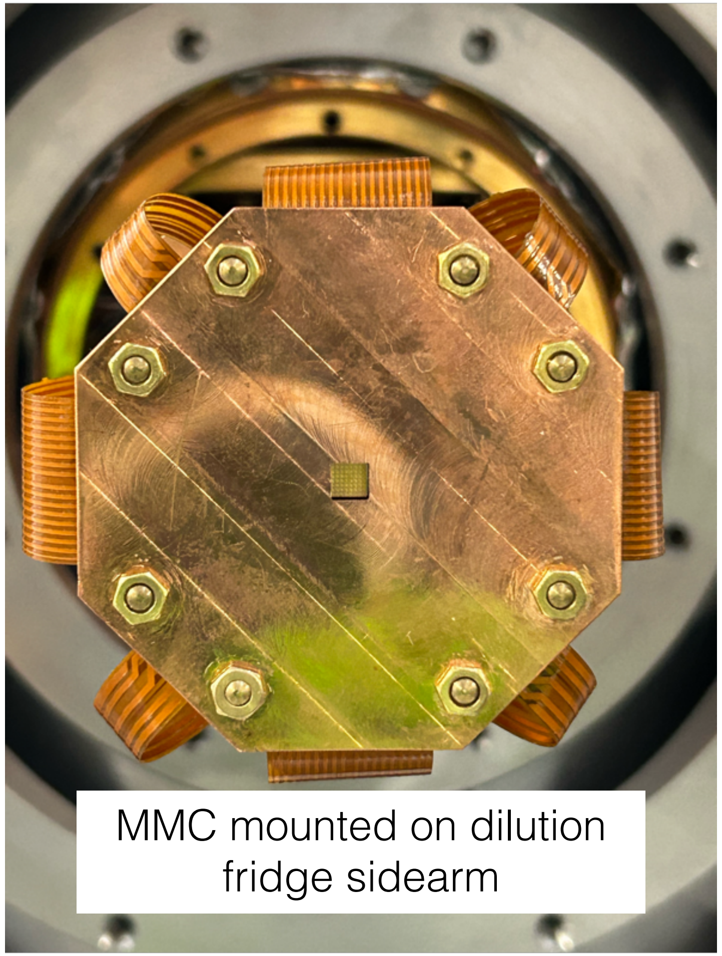
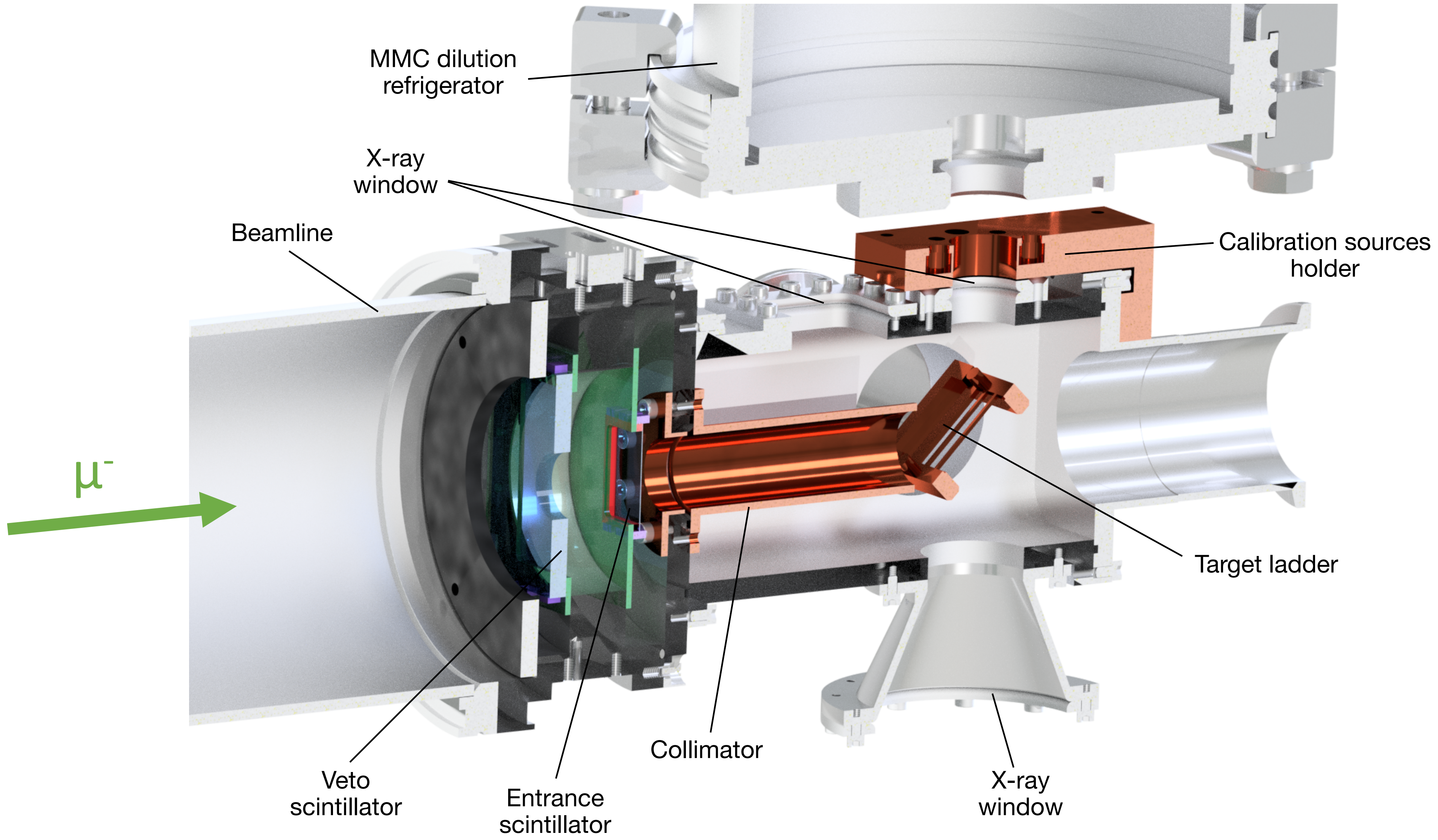
KU LEUVEN

Setup October 2024

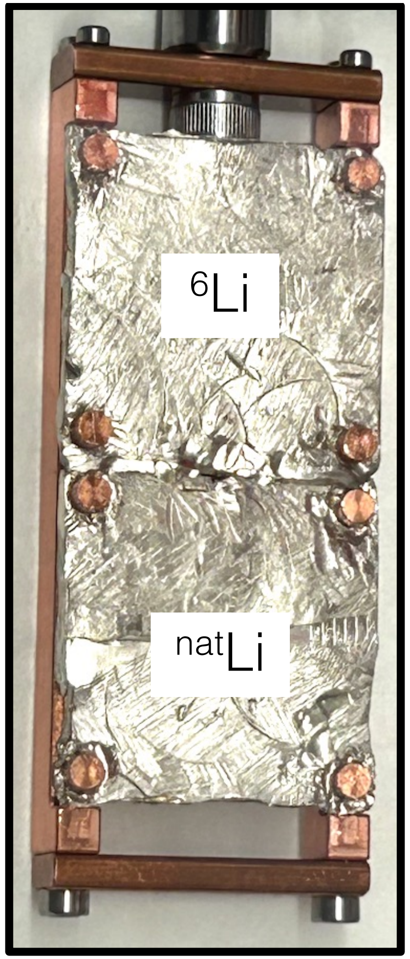




Setup October 2024



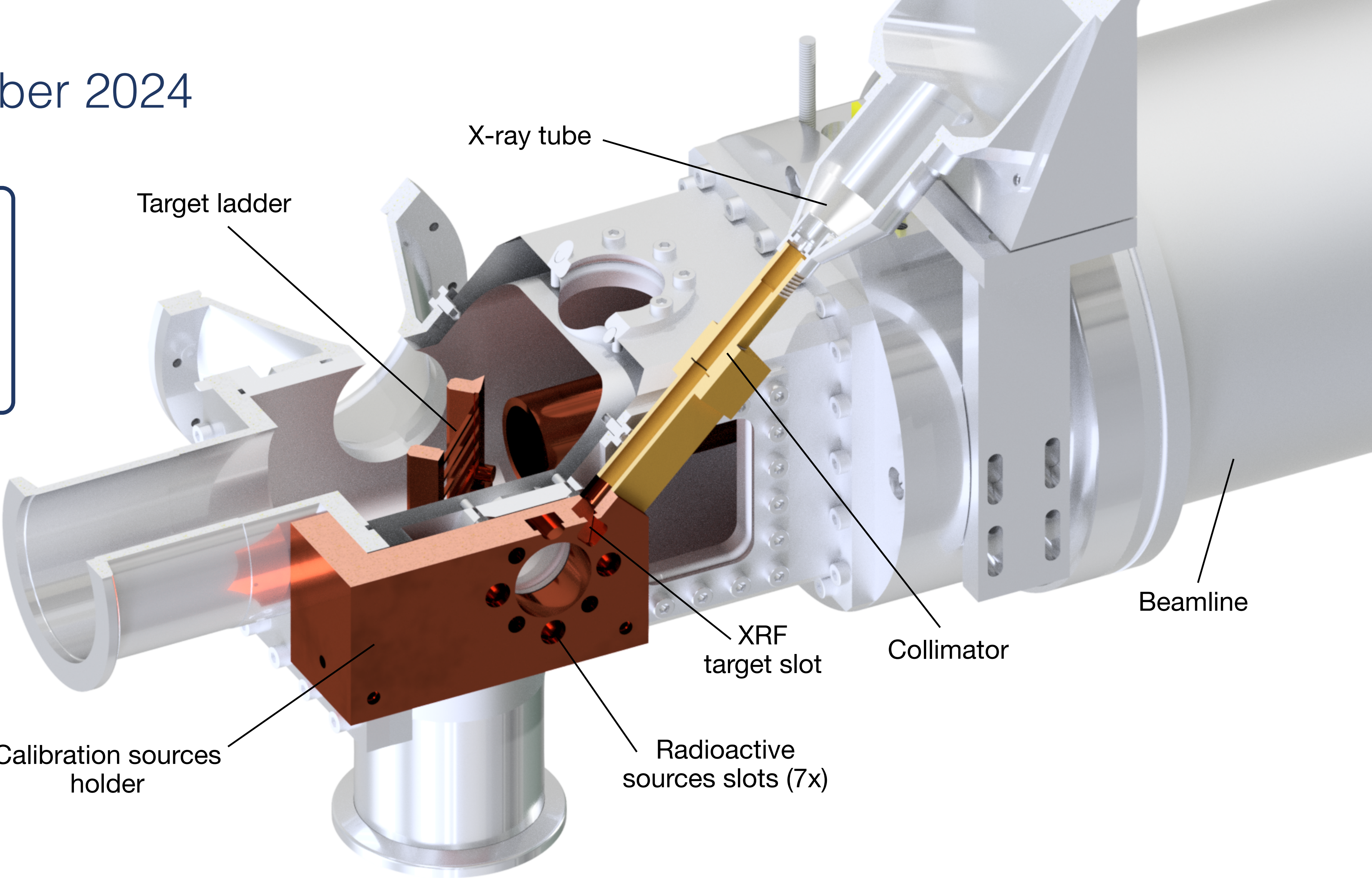
Lithium targets:



Setup October 2024

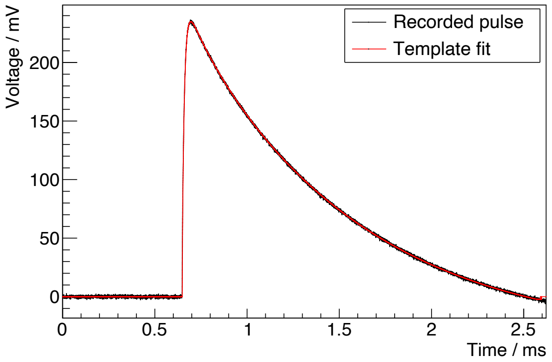
Calibration for μLi measurements:

- ^{55}Fe source
- Mo & Ag XRF



Data analysis workflow

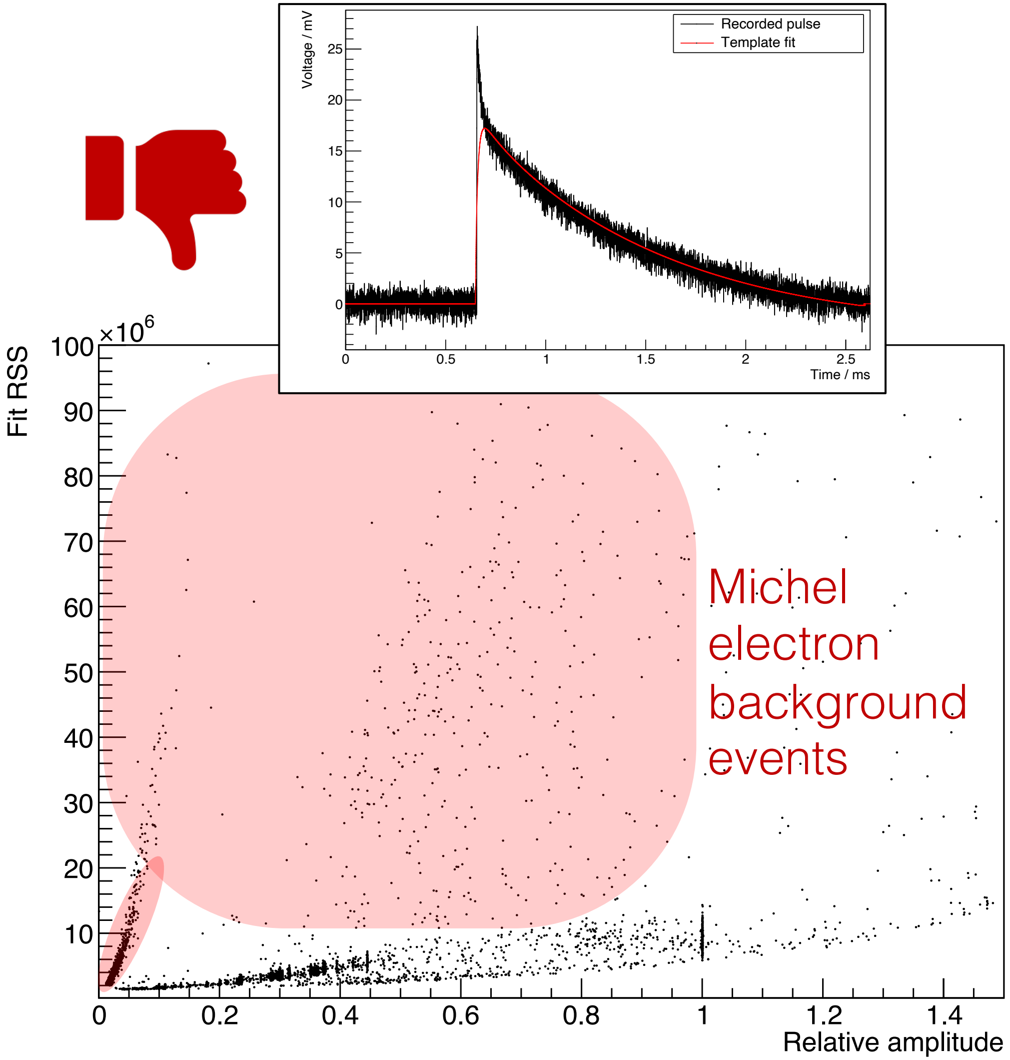
fitting pulses → event identification



- ✓ Amplitudes
- ✓ Goodness-of-Fit (RSS)

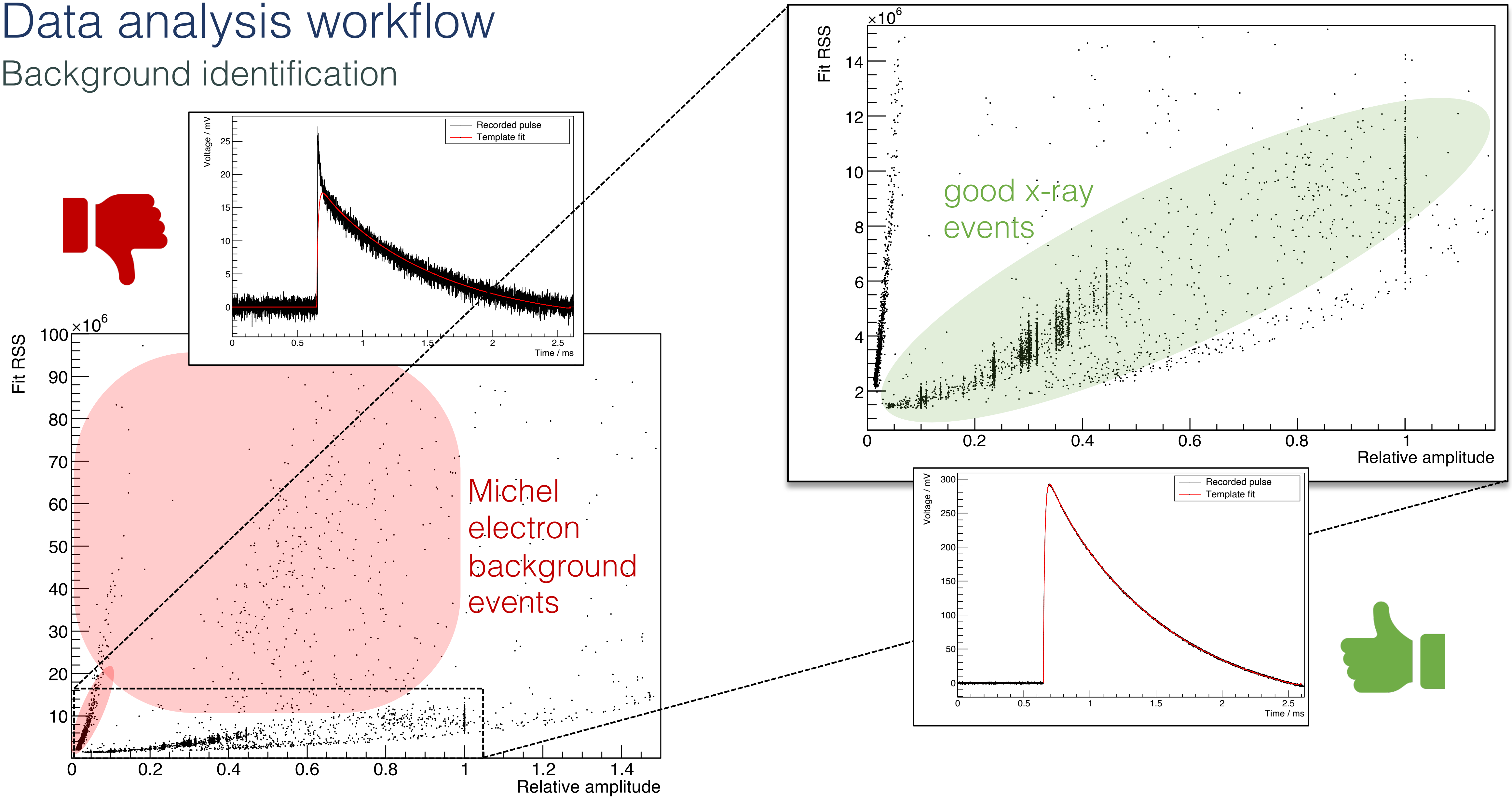
Data analysis workflow

Background identification



Data analysis workflow

Background identification

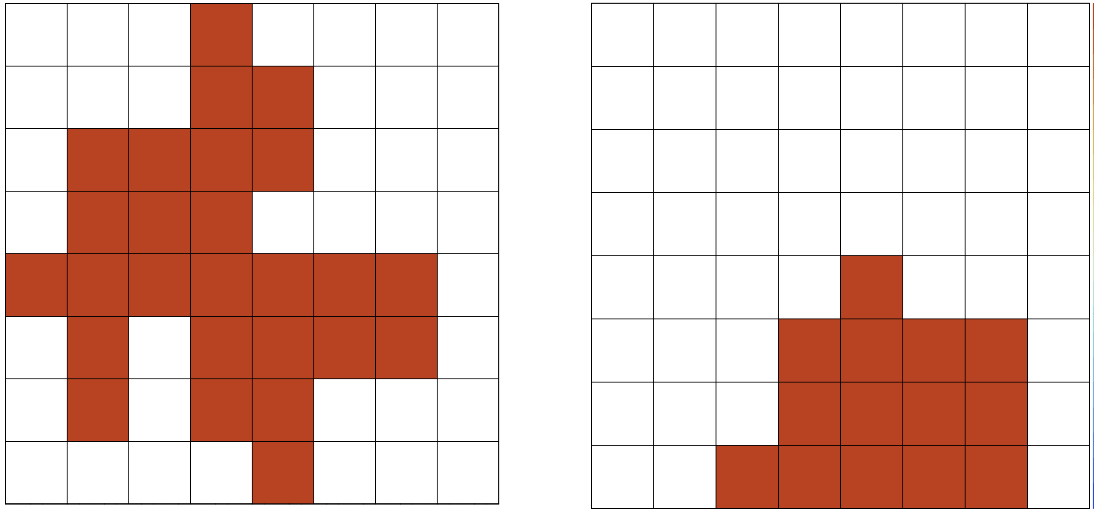


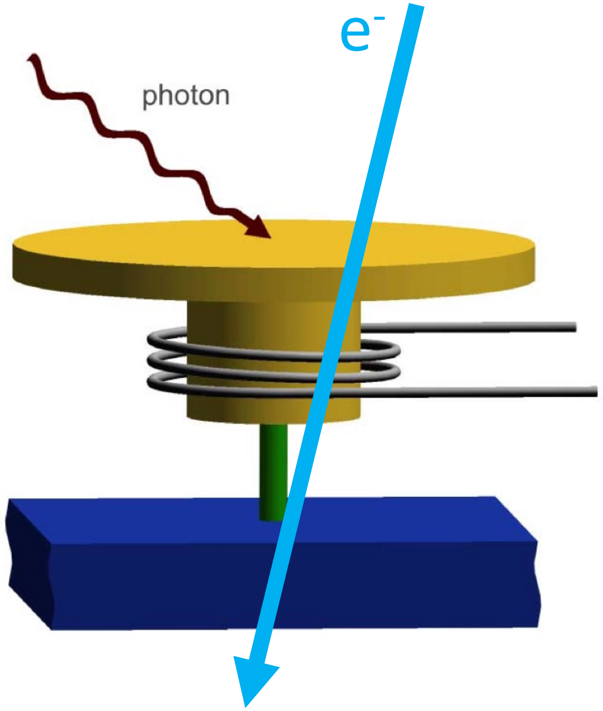
Data analysis workflow

Background identification

- Electron hits not only recognizable by pulse shape but also via coincidences between pixels

Spatial distribution of coincident triggers on the detector e.g.:

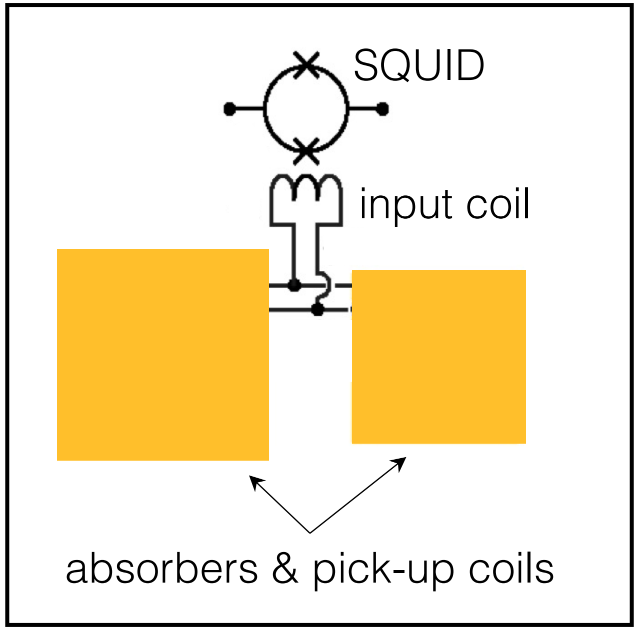




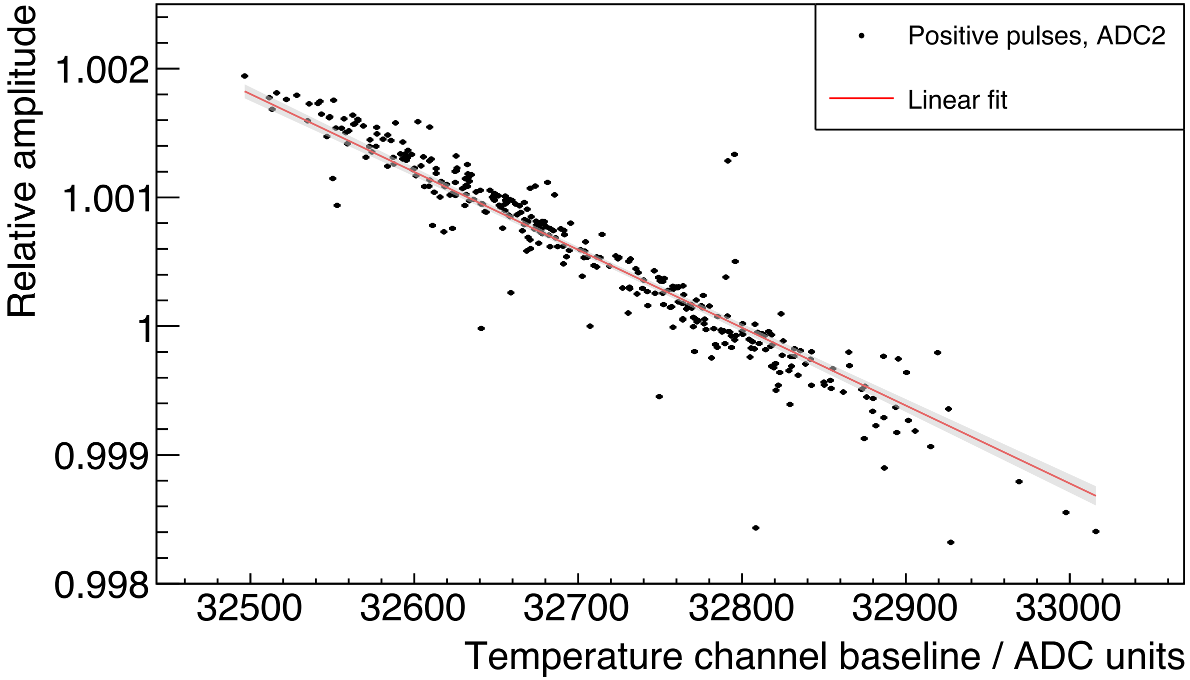
Michel electrons shoot through absorbers into silicon substrate and heat-up pixels “from the backside”

Data analysis workflow
Temperature correction

Temperature sensitive design:



Triggered with every event

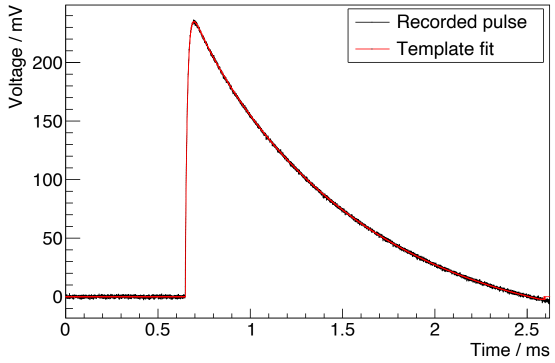


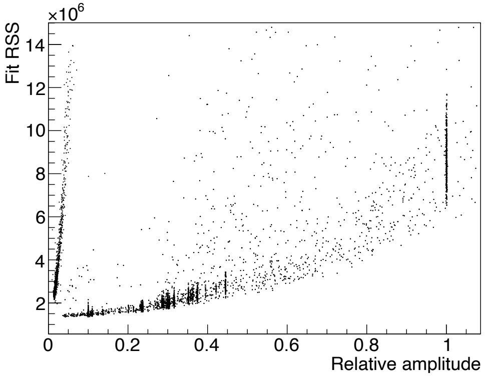
- Determine temperature sensitivity of gradiometric pixels and correct each event

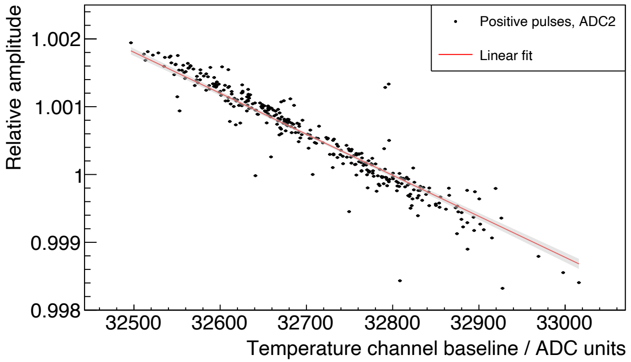
Data analysis workflow

WORK IN PROGRESS

fitting pulses → event identification → temperature correction → ... → calibration → physics output







- ✓ Amplitudes
- ✓ Goodness-of-Fit (RSS)

- ✓ Background rejection

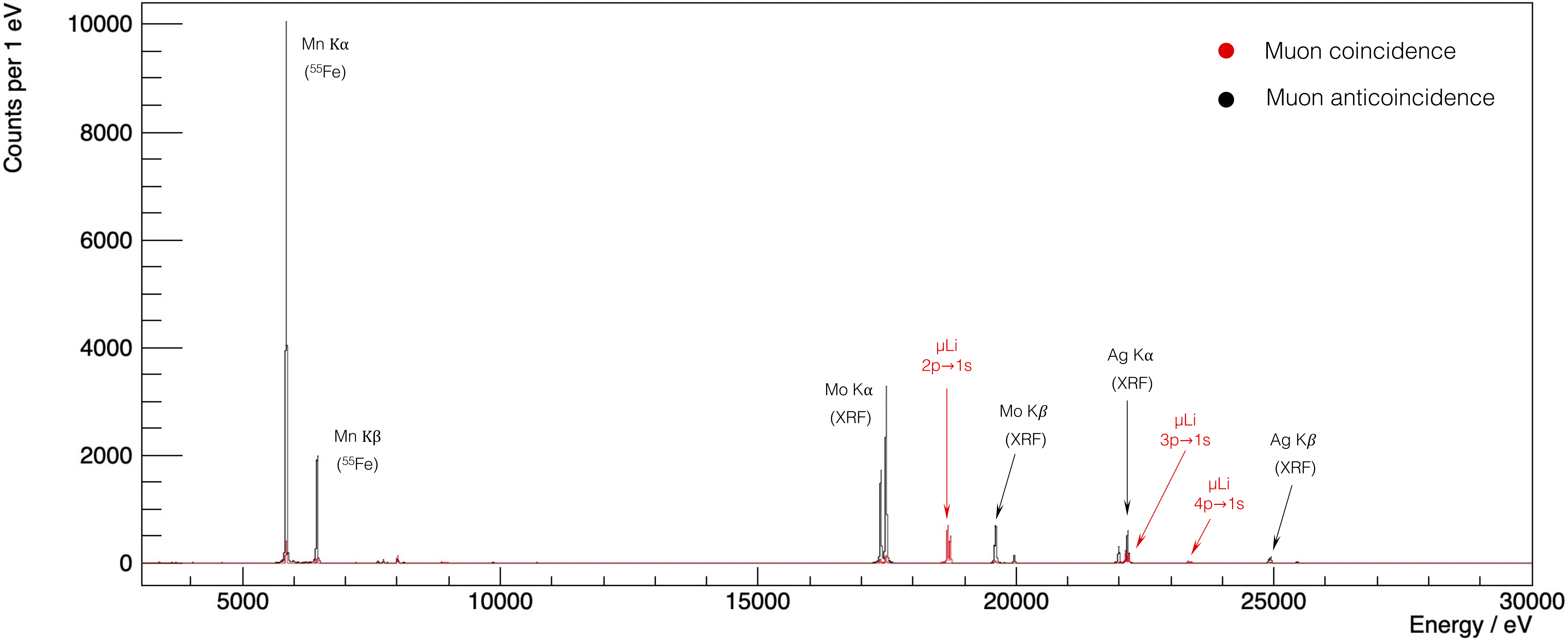
- ✓ Correction for temperature variations

pixel-by-pixel analysis

Muonic Lithium MMC Data 2024

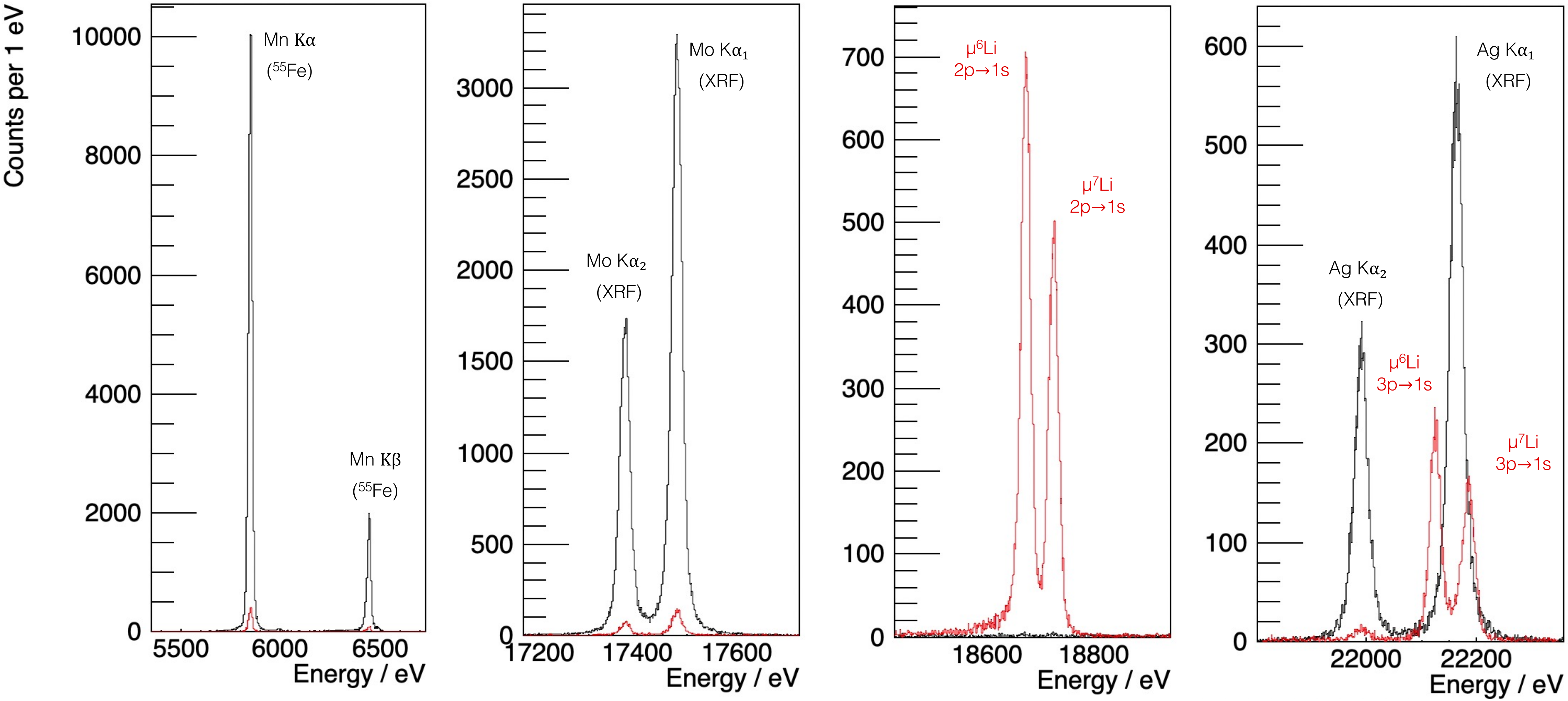
Preliminary results

50 pixels, ~70 hours measurement time



Muonic Lithium MMC Data 2024

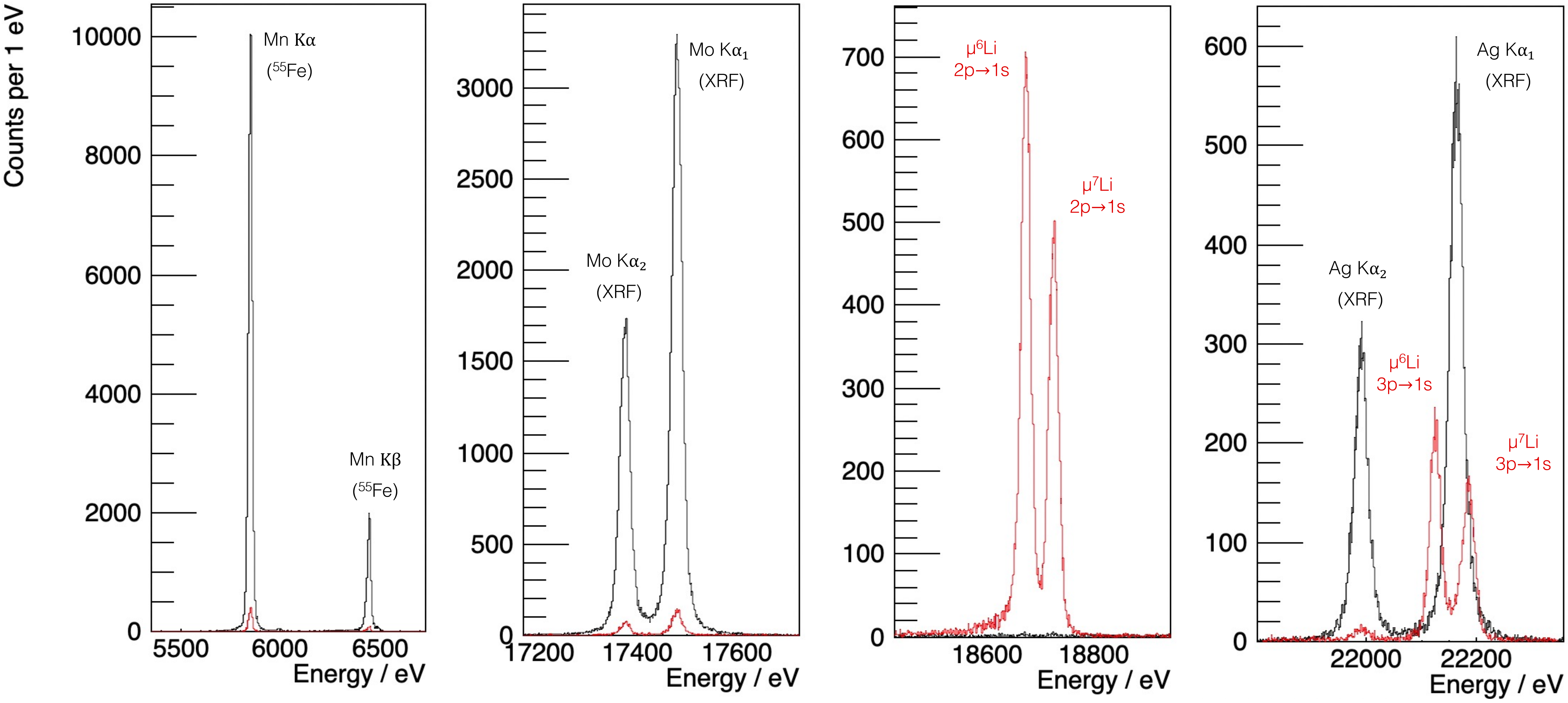
Preliminary results



Muonic Lithium MMC Data 2024

Preliminary results

50 pixels added, 70h measurement
FWHM: ~23 eV
⇒ stat. uncertainty ~0.1 eV



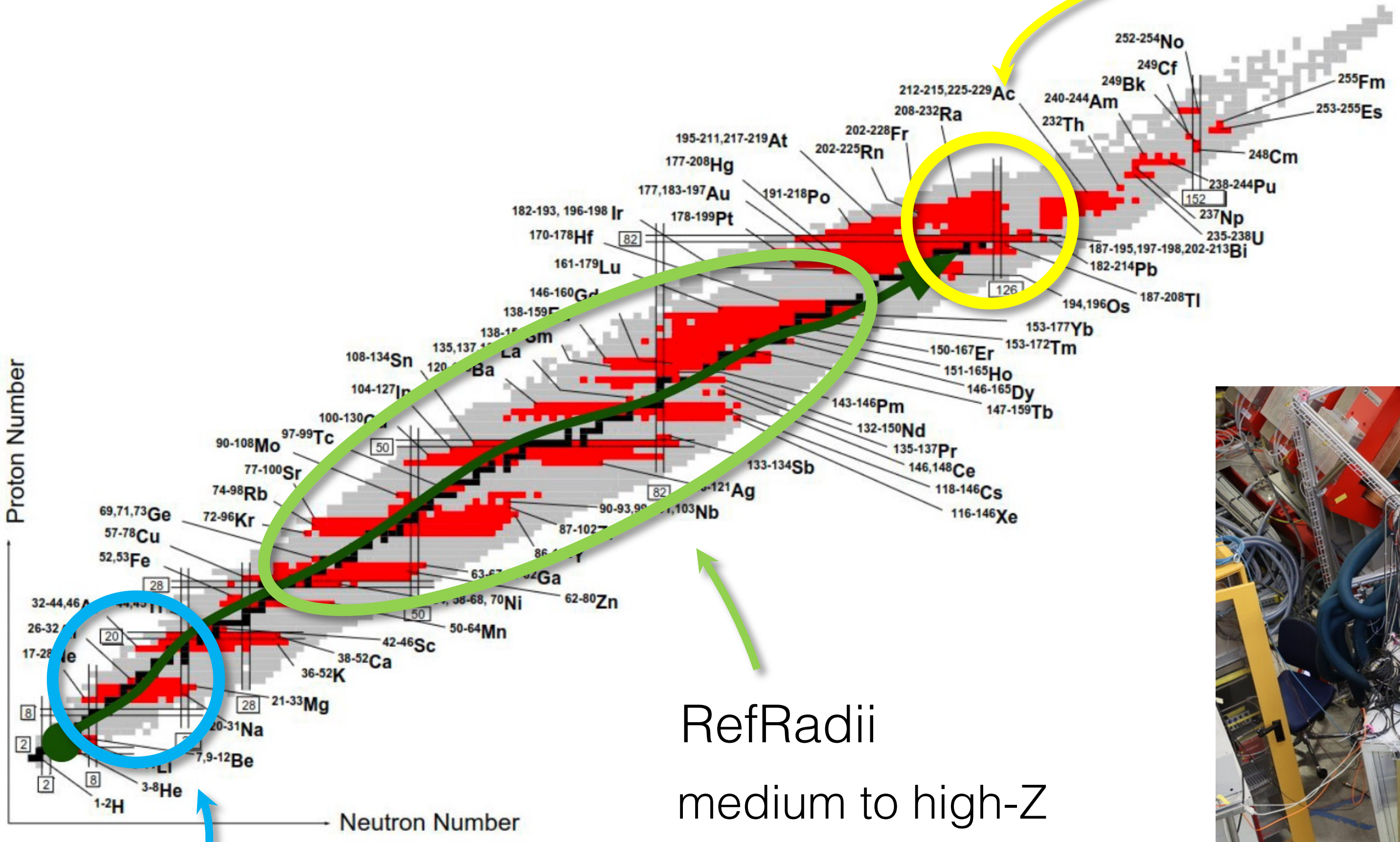
Muonic atoms beyond QUARTET

Not so light muonic atoms

muX

radioactive targets

→ Deformed heavy nuclei. E.g. ^{226}Ra is a candidate for APV experiments. Radius needed as an input

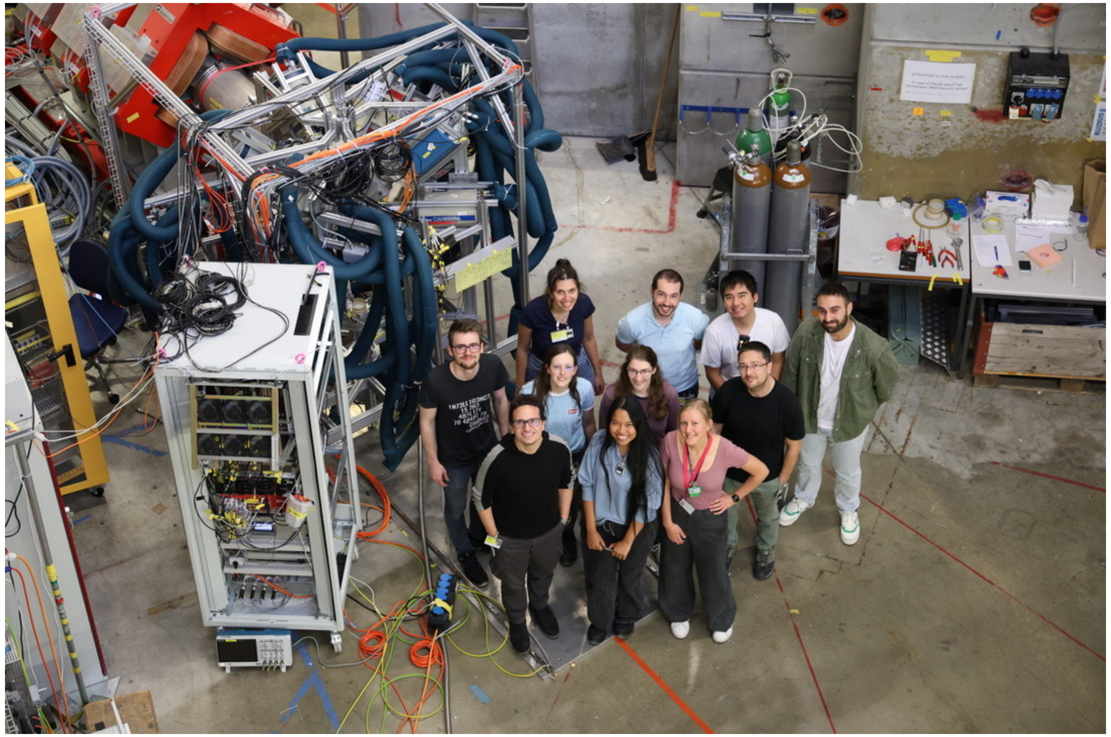


RefRadii

medium to high-Z

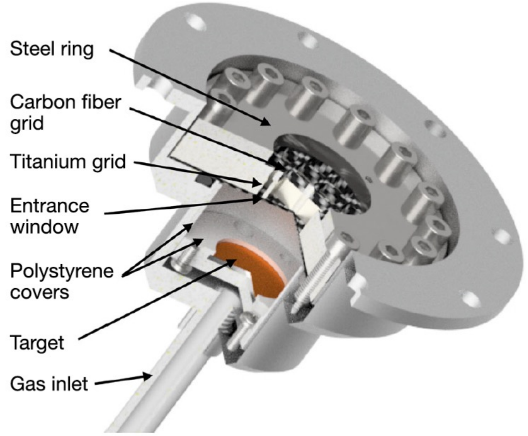
→ Reference for king plot analysis / mass & field shifts

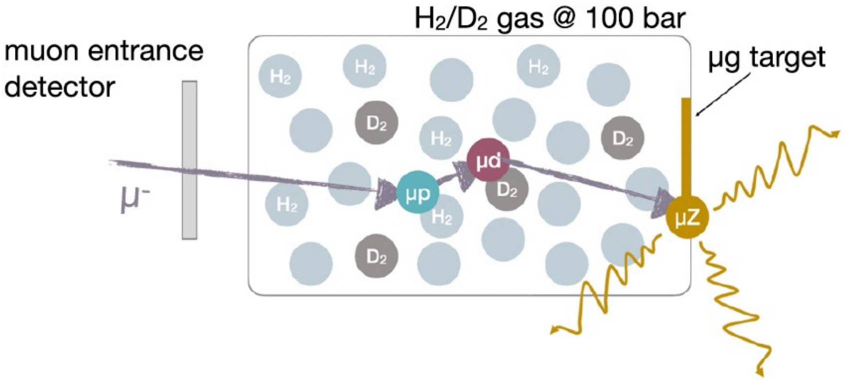
QUARTET

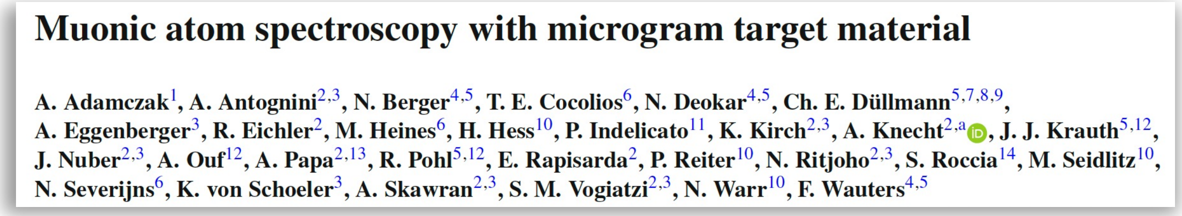


Not so light muonic atoms

Challenge for radioactive targets:
stopping 30 MeV/c muons in μg-quantities



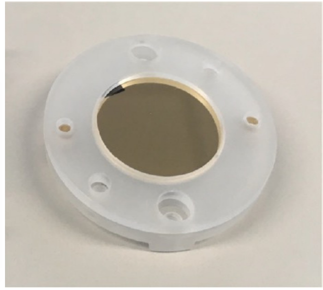




Muonic atom spectroscopy with microgram target material

A. Adamczak[1], A. Antognini[2,3], N. Berger[4,5], T. E. Cocolios[6], N. Deokar[4,5], Ch. E. Düllmann[5,7,8,9], A. Eggenberger[3], R. Eichler[2], M. Heines[6], H. Hess[10], P. Indelicato[11], K. Kirch[2,3], A. Knecht[2,a], J. J. Krauth[5,12], J. Nuber[2,3], A. Ouf[12], A. Papa[2,13], R. Pohl[5,12], E. Rapisarda[2], P. Reiter[10], N. Ritjoho[2,3], S. Roccia[14], M. Seidlitz[10], N. Severijns[6], K. von Schoeler[3], A. Skawran[2,3], S. M. Vogiatzi[2,3], N. Warr[10], F. Wauters[4,5]

https://doi.org/10.1140/epja/s10050-023-00930-y



5 μg vapor deposited Au

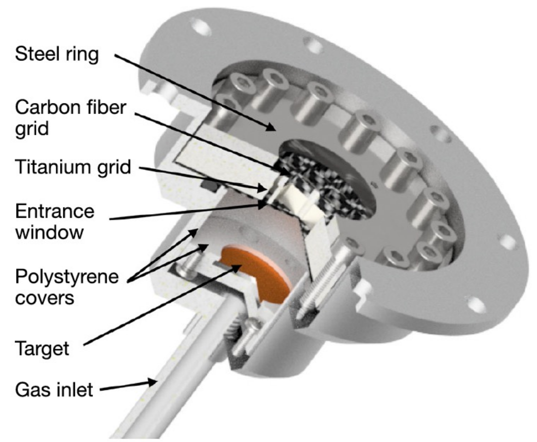
Not so light muonic atoms

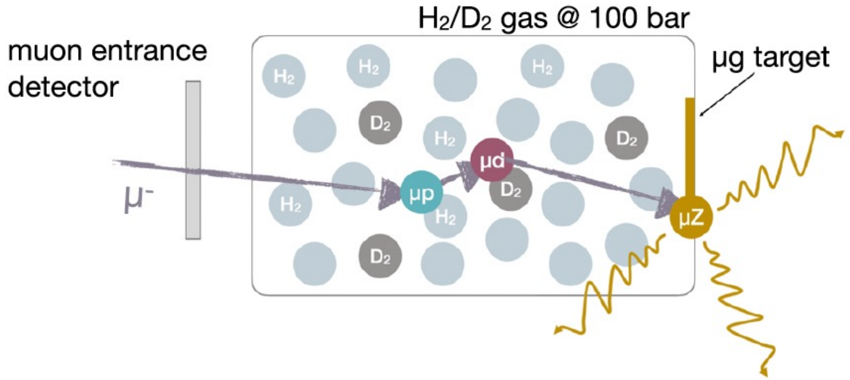
Challenge for radioactive targets:
stopping 30 MeV/c muons in µg-quantities

Muonic x-ray spectroscopy on implanted targets

Michael Heines[a,*], Luke Antwis[b], Silvia Bara[a], Bart Caerts[c], Thomas E. Cocolios[a], Stefan Eisenwinder[d], Julian Fletcher[b], Tom Kieck[e], Andreas Knecht[f], Megumi Niikura[g], Narongrit Ritjoho[h], Lino M.C. Pereira[c], Randolf Pohl[i], André Vantomme[c], Stergiani M. Vogiatzi[f,j], Katharina von Schoeler[f,j], Frederik Wauters[i], Roger Webb[b], Qiang Zhao[c], Sami Zweidler[j]

https://doi.org/10.1016/j.nimb.2023.05.036





DISS. ETH NO. 29082

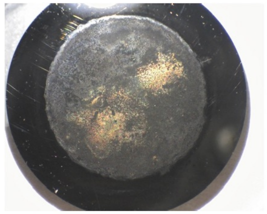
Studies of muonic ^{185,187}Re, ^{226}Ra, and ^{248}Cm for the extraction of nuclear charge radii

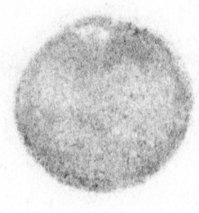
presented by

STERGIANI MARINA VOGIATZI

https://doi.org/10.3929/ethz-b-000612640

Spectroscopy of 15 µg radioactive ^{248}Cm





Muonic atom spectroscopy with microgram target material

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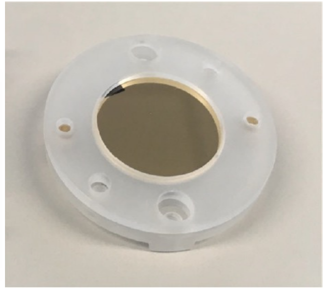

5 µg vapor deposited Au

Summary

- QUARTET: high-precision measurements of low-Z charge radii from Li to Ne via muonic atom spectroscopy
- First promising measurements of muonic lithium with an MMC were conducted at PSI in 2024, analysis ongoing
- Improved, faster MMCs under development