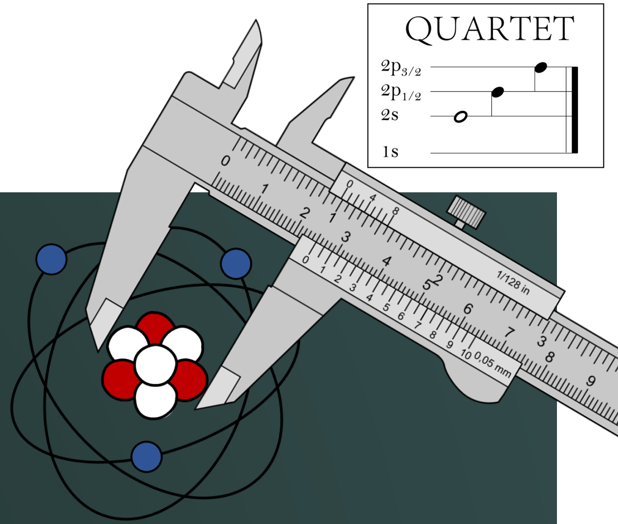
ETH zürich

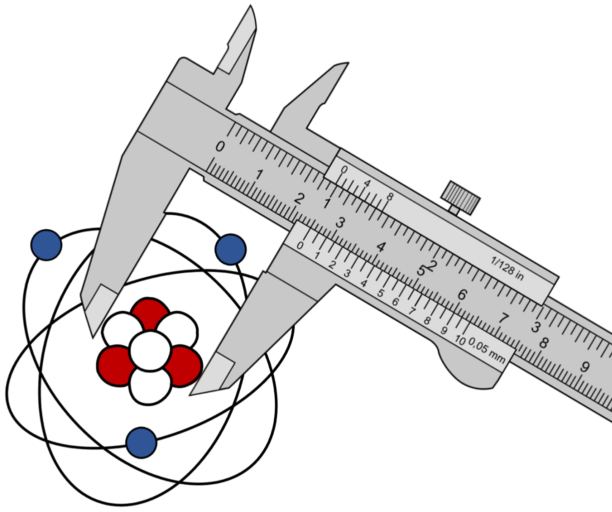


High-Resolution Spectroscopy of Muonic Lithium

First Steps and Prospects of the QUARTET Experiment

Katharina von Schoeler | ETH Zürich | QUARTET collaboration

Absolute nuclear charge radii & lithium



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
   - Extraction of fundamental constants
   - …
2. benchmarks for ab-initio nuclear theory
3. ...

rms charge radius:

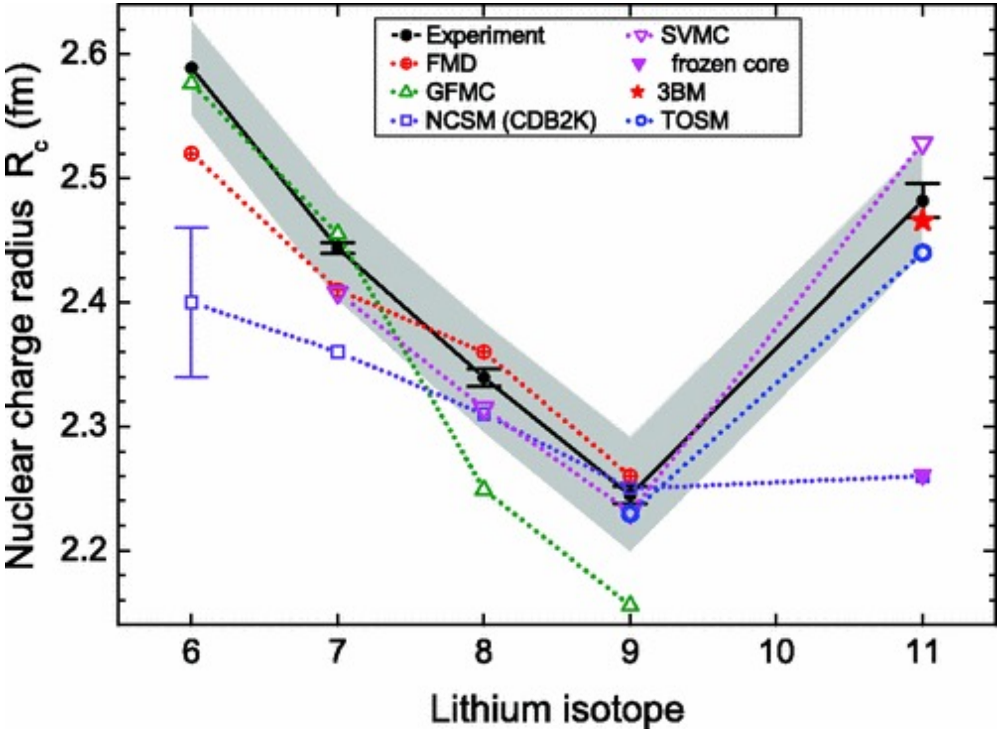
$$\sqrt{\langle r^2 \rangle} = \sqrt{\frac{1}{Ze} \int r^2 \rho(r)\, d\tau}$$

Nuclear charge density distribution

Lithium nuclear charge radii

As nuclear theory benchmarks

DOI: 10.1103/PhysRevC.84.024307



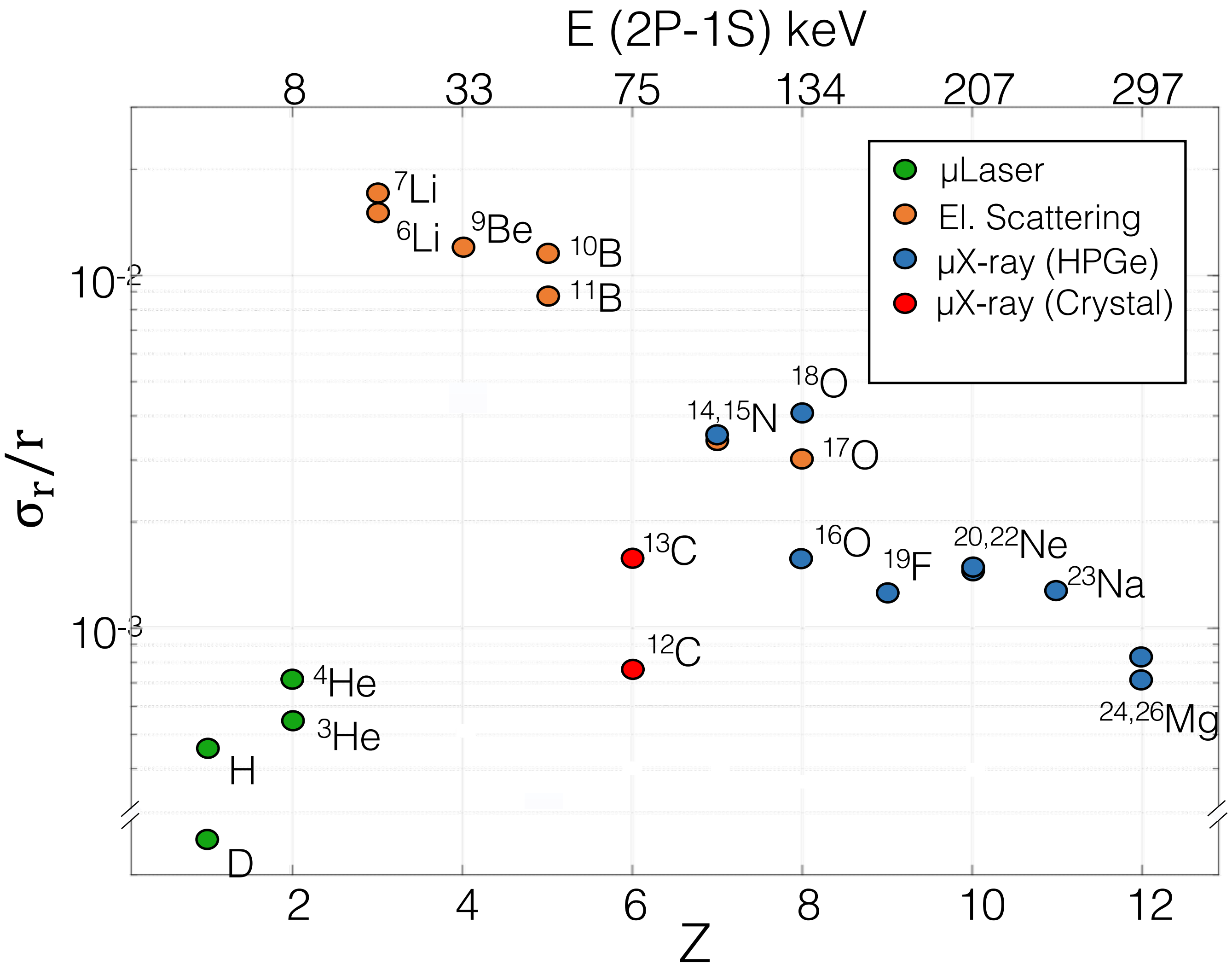
Whole isotopic chain is limited by current best Li charge radii:

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

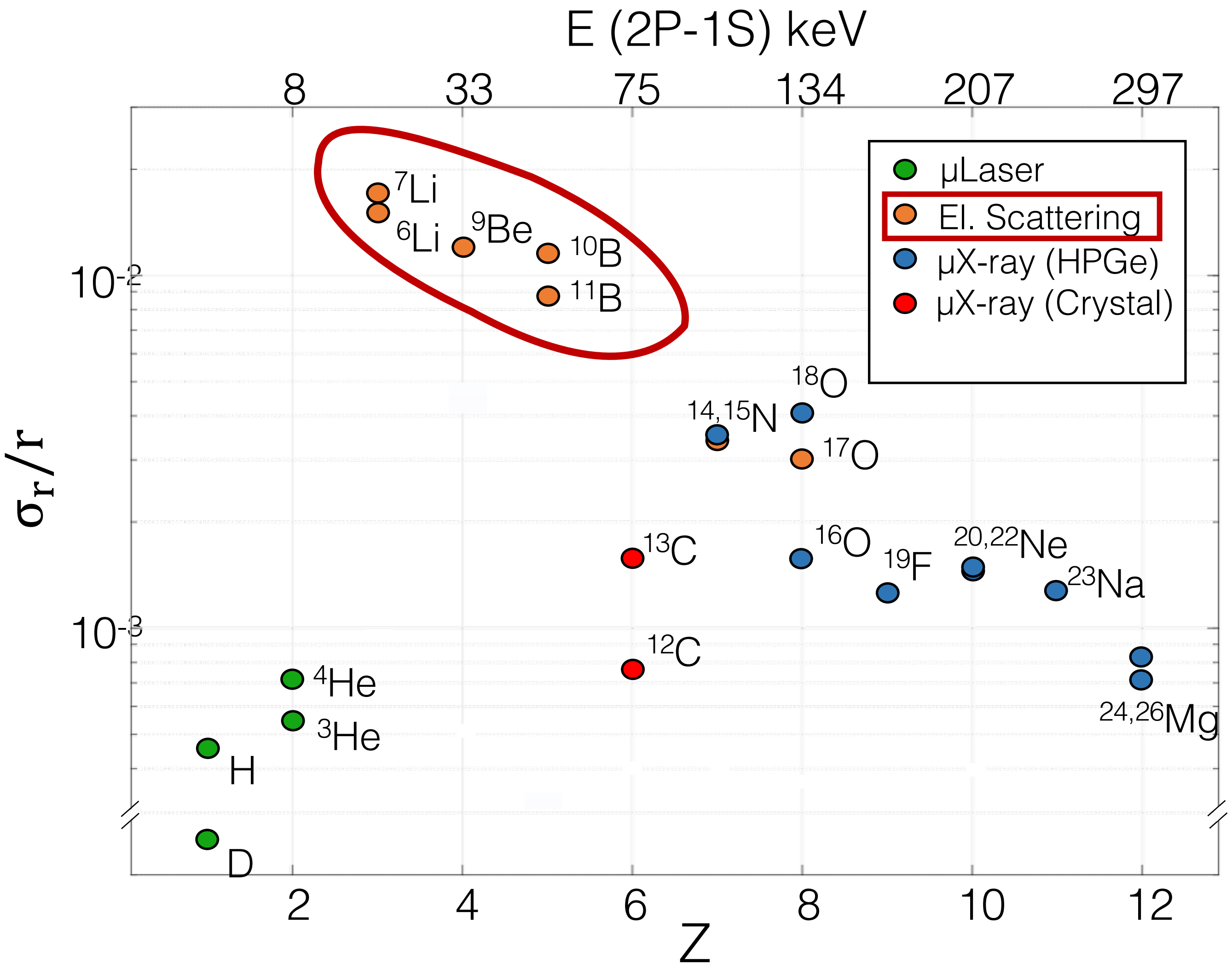
$$R_{rms}(^{7}Li) = 2.444(42)\ fm$$

from elastic electron scattering experiments.

Low-Z charge radius gap



Low-Z charge radius gap



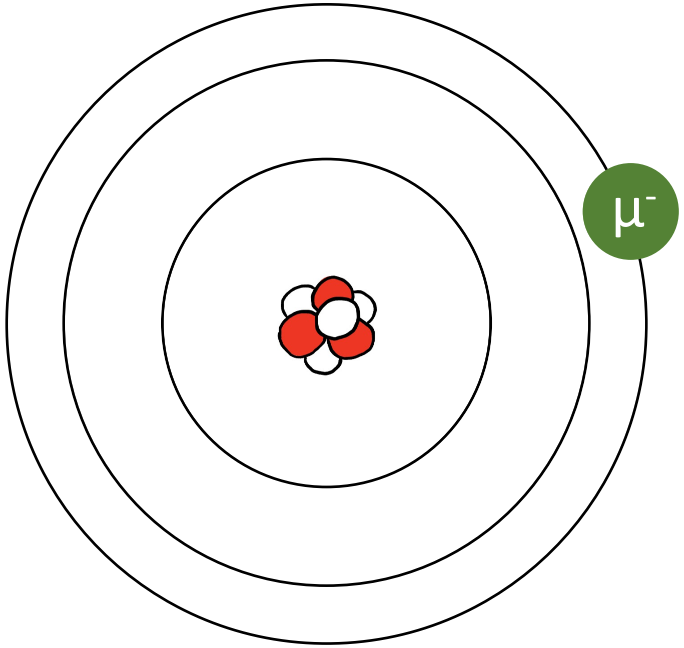
Why is muonic x-ray spectroscopy a problem?

Muonic x-ray spectroscopy 101

Short reminder

Finite nuclear size effect strongly enhanced in muonic atoms:

$\Delta E_{FNS} \propto m^3 \Rightarrow$ factor 10^7!



Muonic x-ray spectroscopy 101

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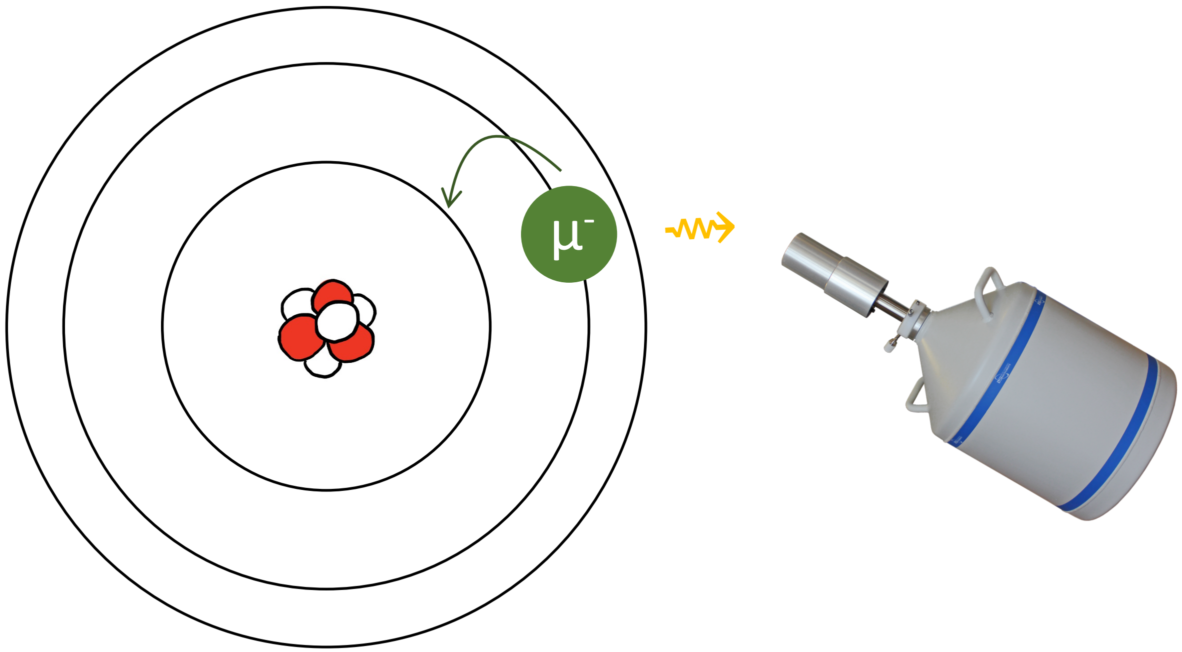

1. Muon is captured at high principal quantum number
2. Emission of x rays while cascading to ground state
3. Detect 2p-1s transition for highest sensitivity to nuclear charge radius

Muonic x-ray spectroscopy 101

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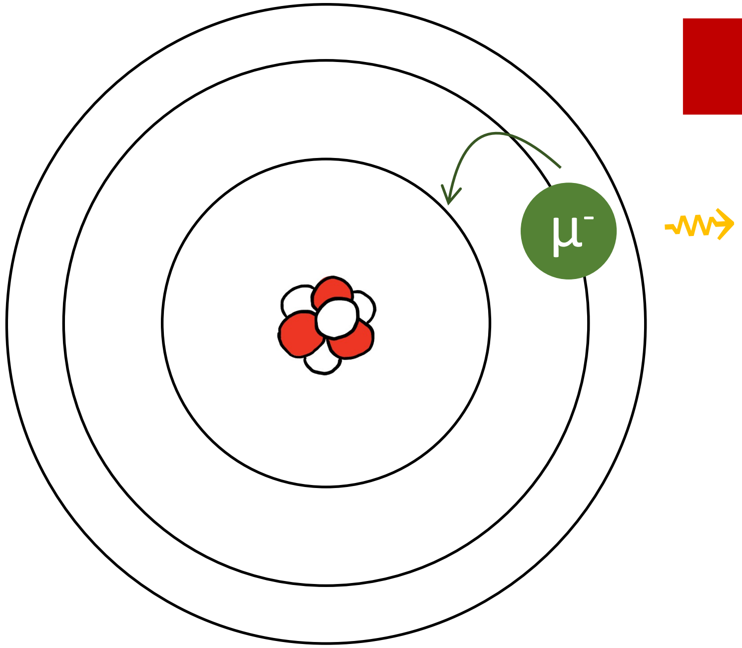
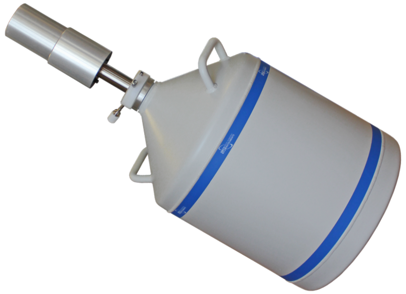


μLi 2p-1s: 19 keV

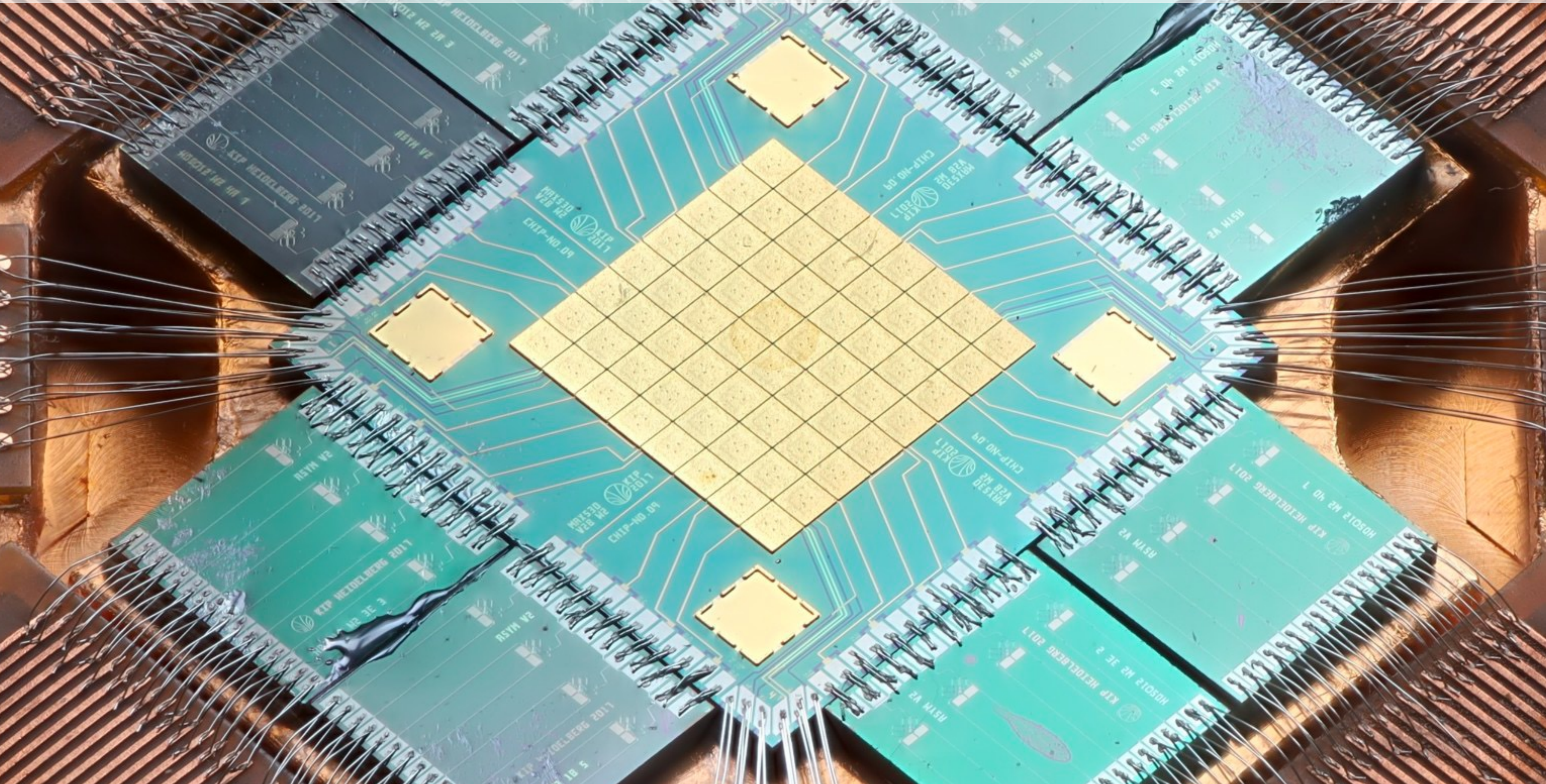


For x rays typically solid-state detectors (HPGe, SDD, …)

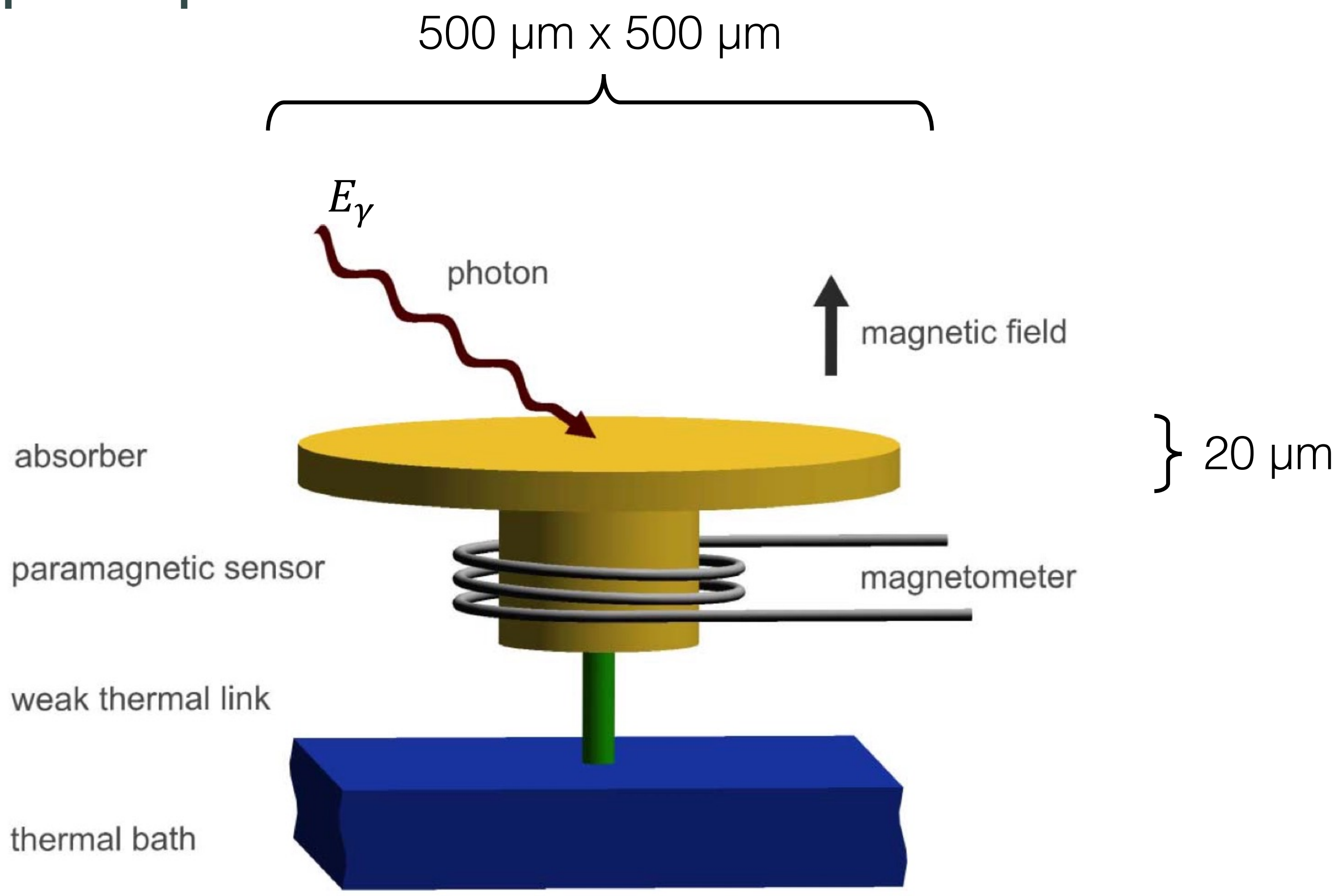
⇒ Low resolution for low energies. Cannot resolve:

- ✗ Contaminations
- ✗ Different isotopes
- ✗ ...

Metallic Magnetic Calorimeter (MMC)



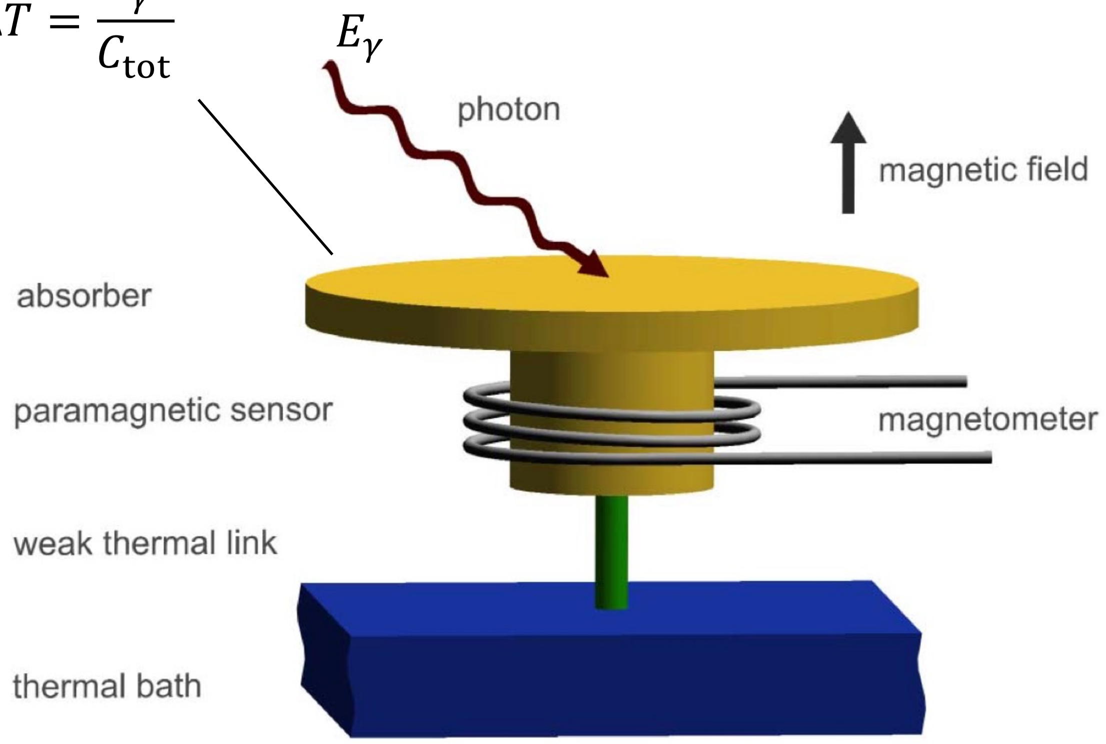
MMC working principle



DOI: 10.1109/TASC.2009.2012724

MMC working principle

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



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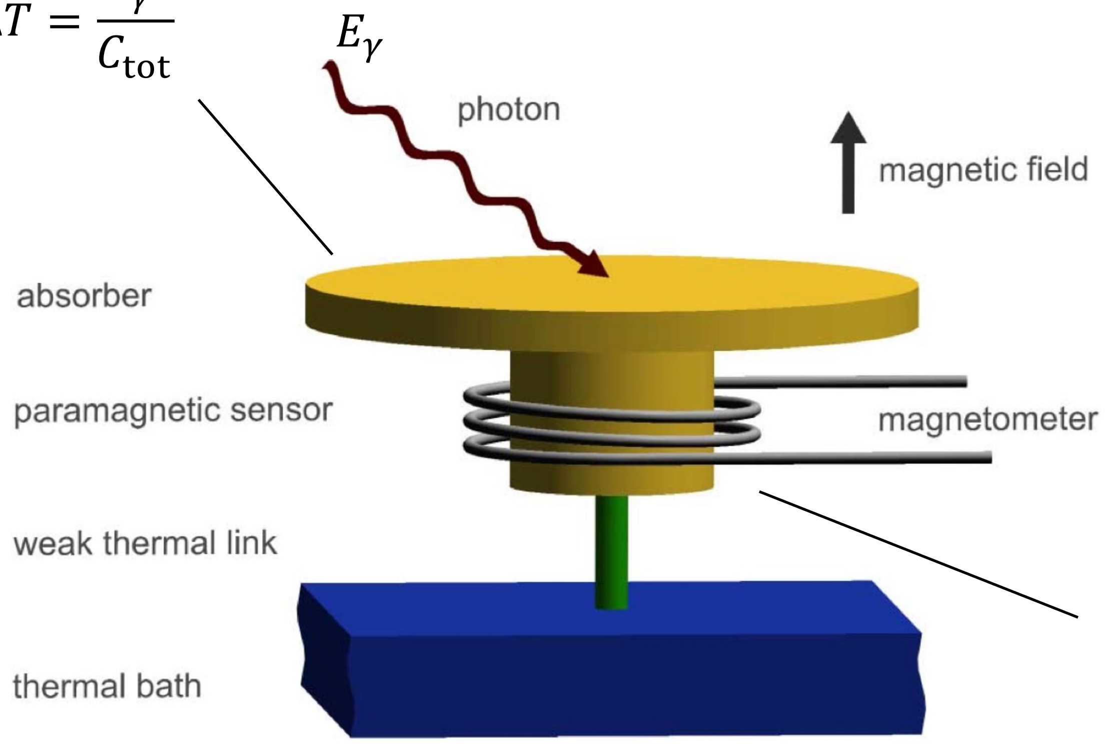


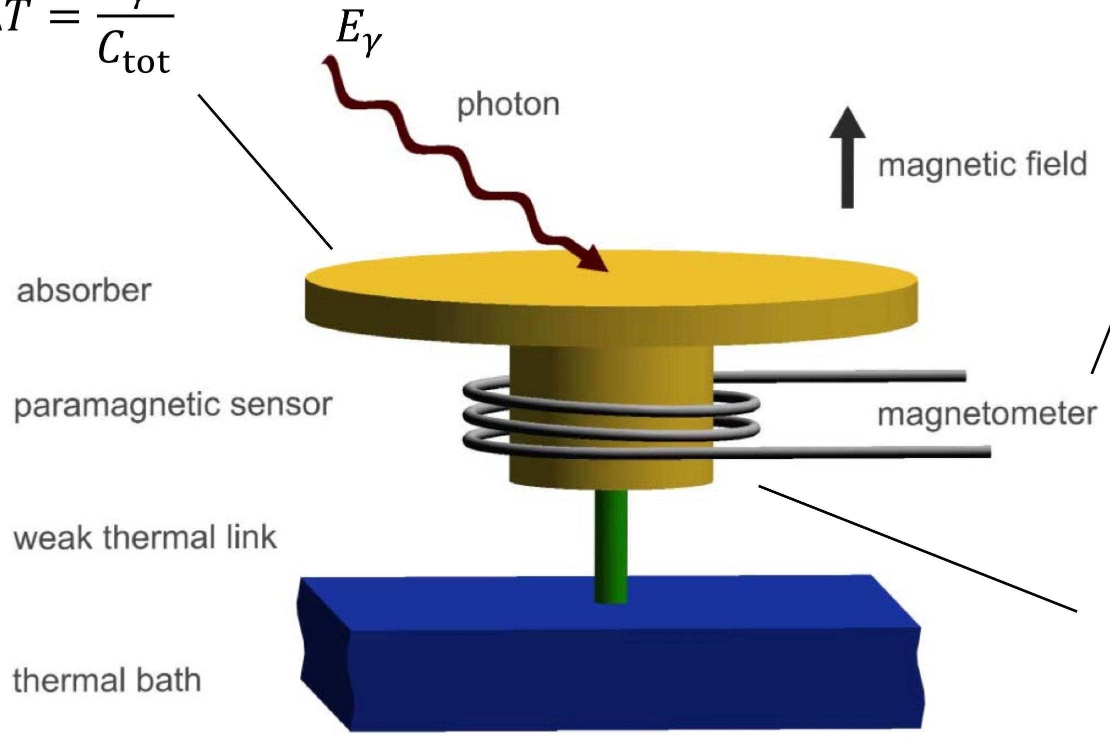
$$\Delta M = \frac{\partial M}{\partial T} \Delta T$$

DOI: 10.1109/TASC.2009.2012724

MMC working principle

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

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



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

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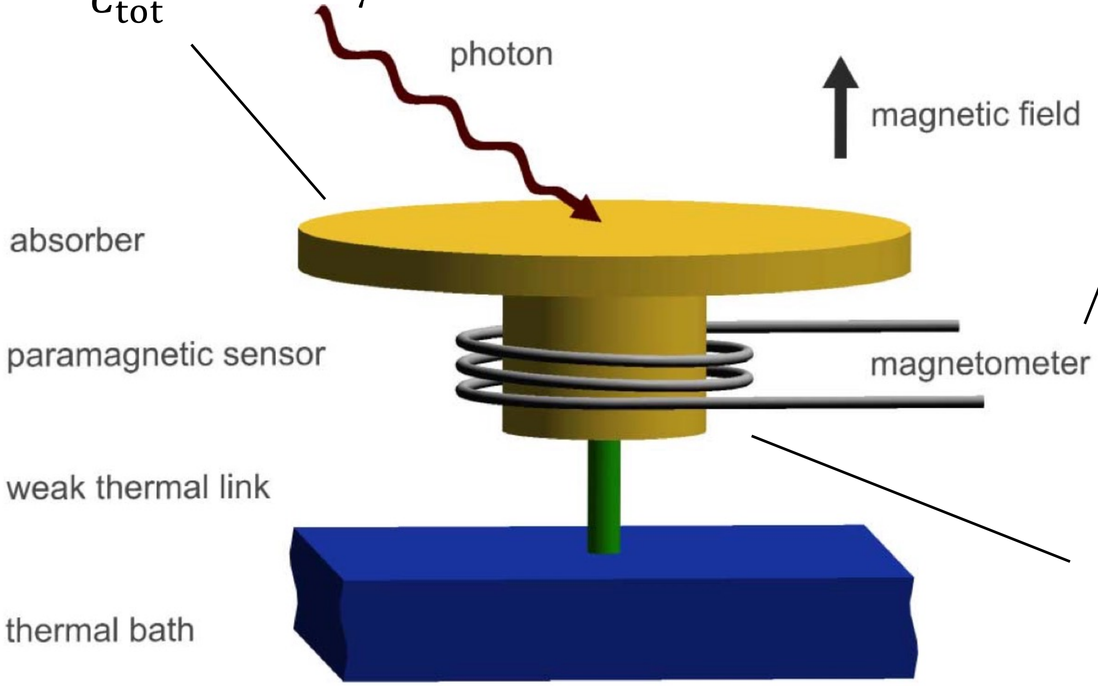
MMC working principle

tunes detection efficiency
→ determines C_{abs}

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

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



DOI: 10.1109/TASC.2009.2012724

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

tunes signal decay time τ_D
→ detection speed

Energy resolution:

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

First test @ Paul Scherrer Institute

PSI

High Intensity Proton Accelerator

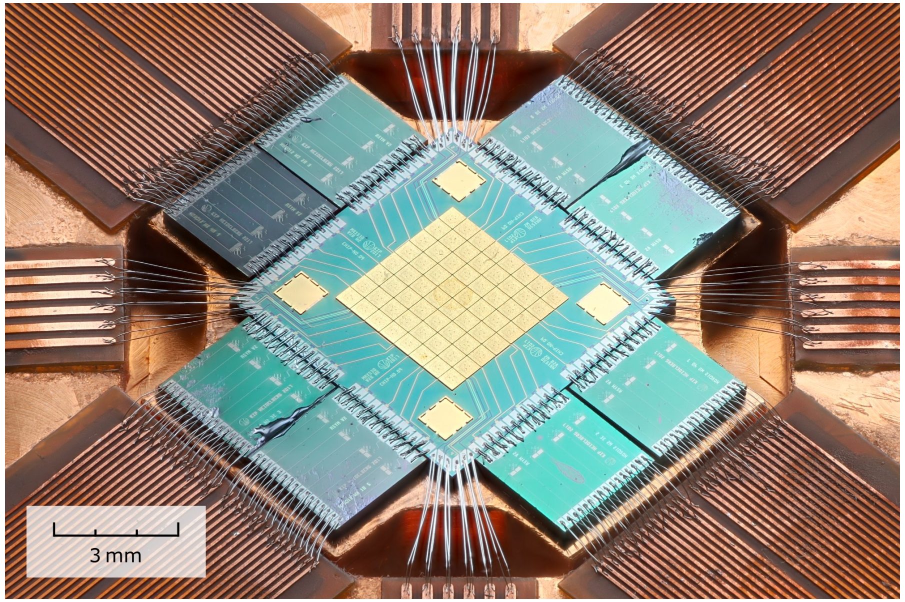
First test @ Paul Scherrer Institute

PSI

Feasibility test campaign 2023

- operated at approx. 20 mK
- 64 absorbers: each 500 µm x 500 µm x 20 µm
- max. rate per pixel ≲1 Hz
- coupled to 32 pairs of two types:

"maXs-30" detector



DOI: 10.1007/s10909-024-03141-x

Feasibility test campaign 2023

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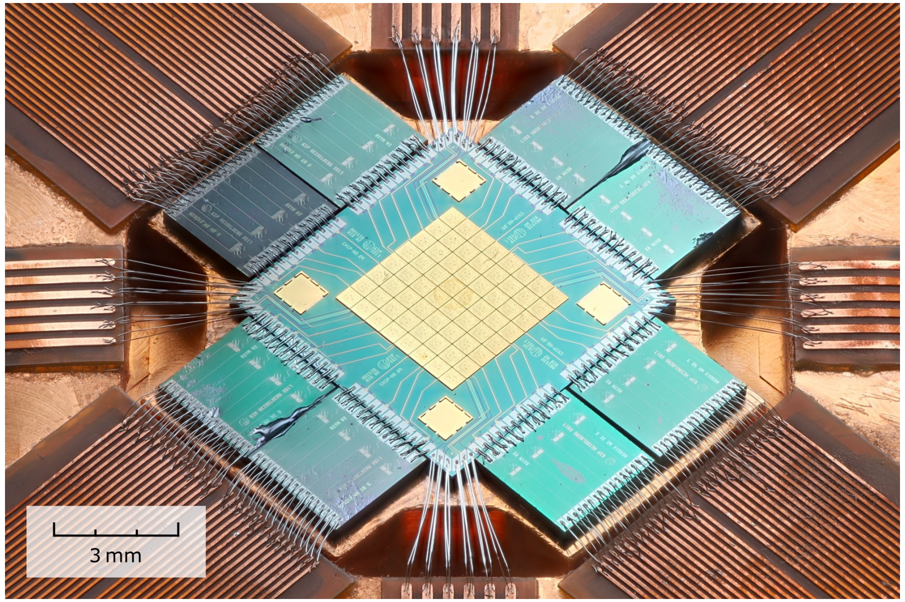
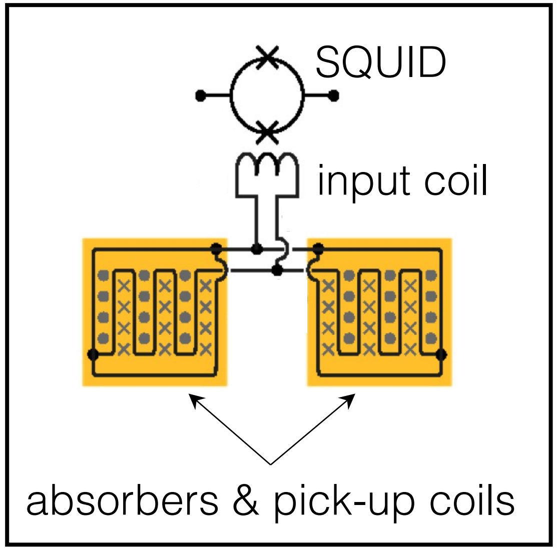
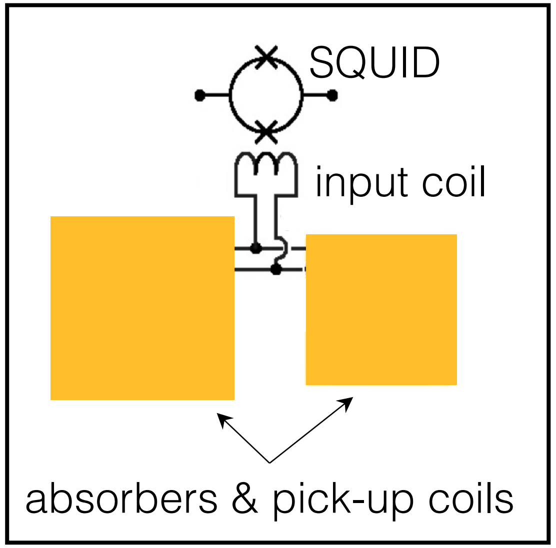


DOI: 10.1007/s10909-024-03141-x

Gradiometric channel:



Chip-temperature sensitive channel:



DOI: 10.1063/1.3292407

⇒ expected energy resolution:

FWHM ~10 eV @ 20 keV

Feasibility test campaign 2023

^{nat}Li

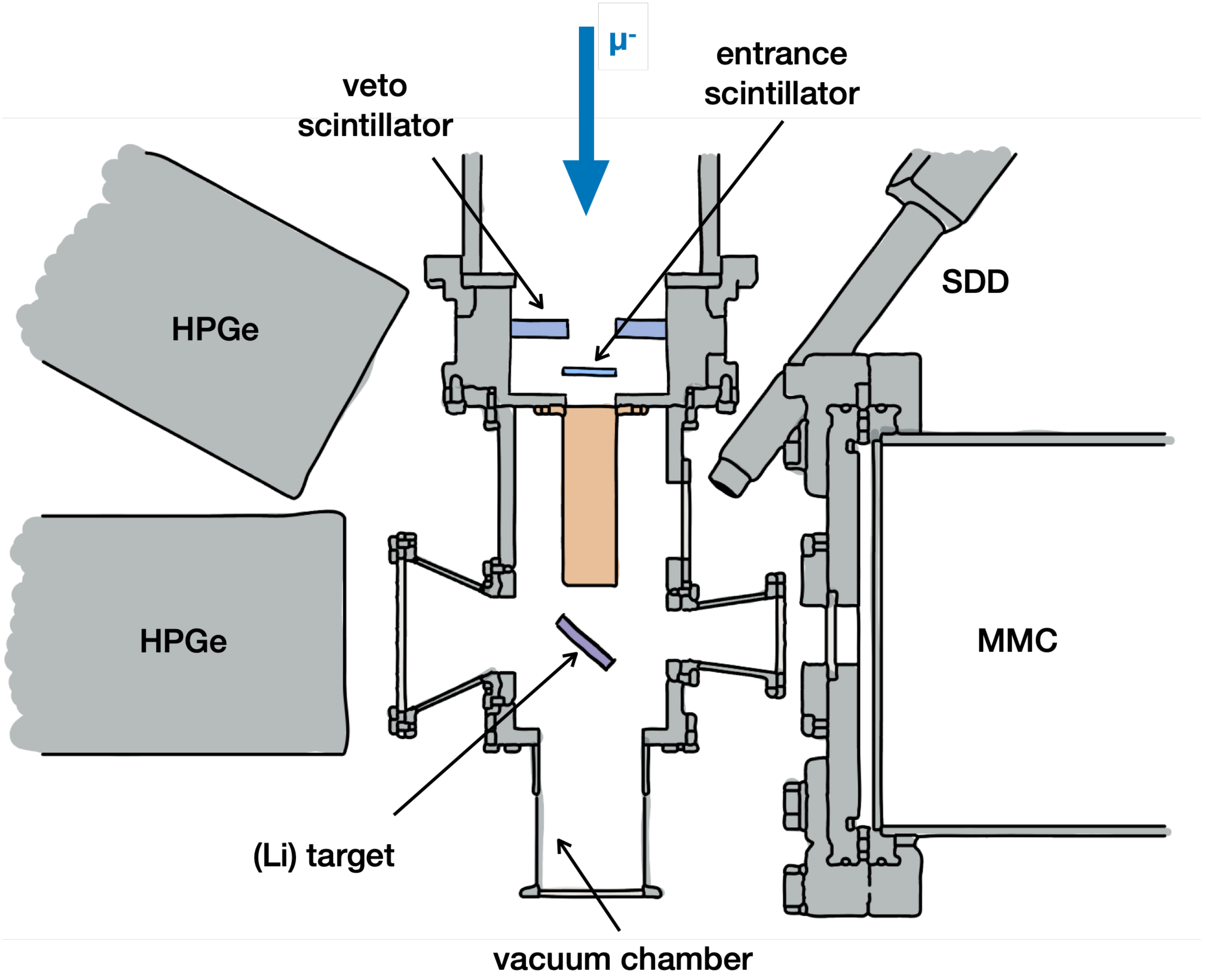
Mo + Ag

^{6}Li (> 95 %)

^{12}C

Cu

^{13}C



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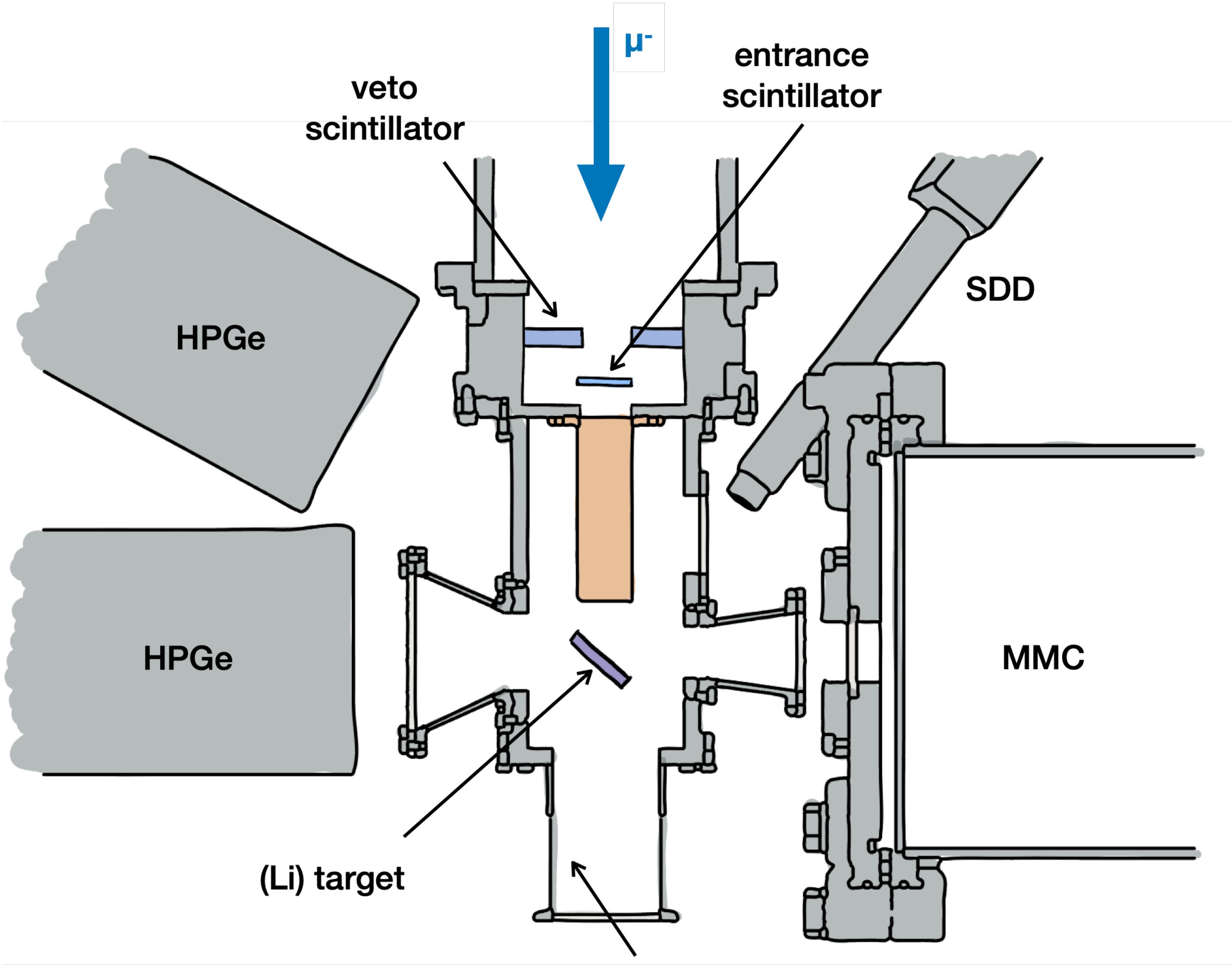


Radioactive sources & XRF for calibration

Feasibility test campaign 2023

^{nat}Li

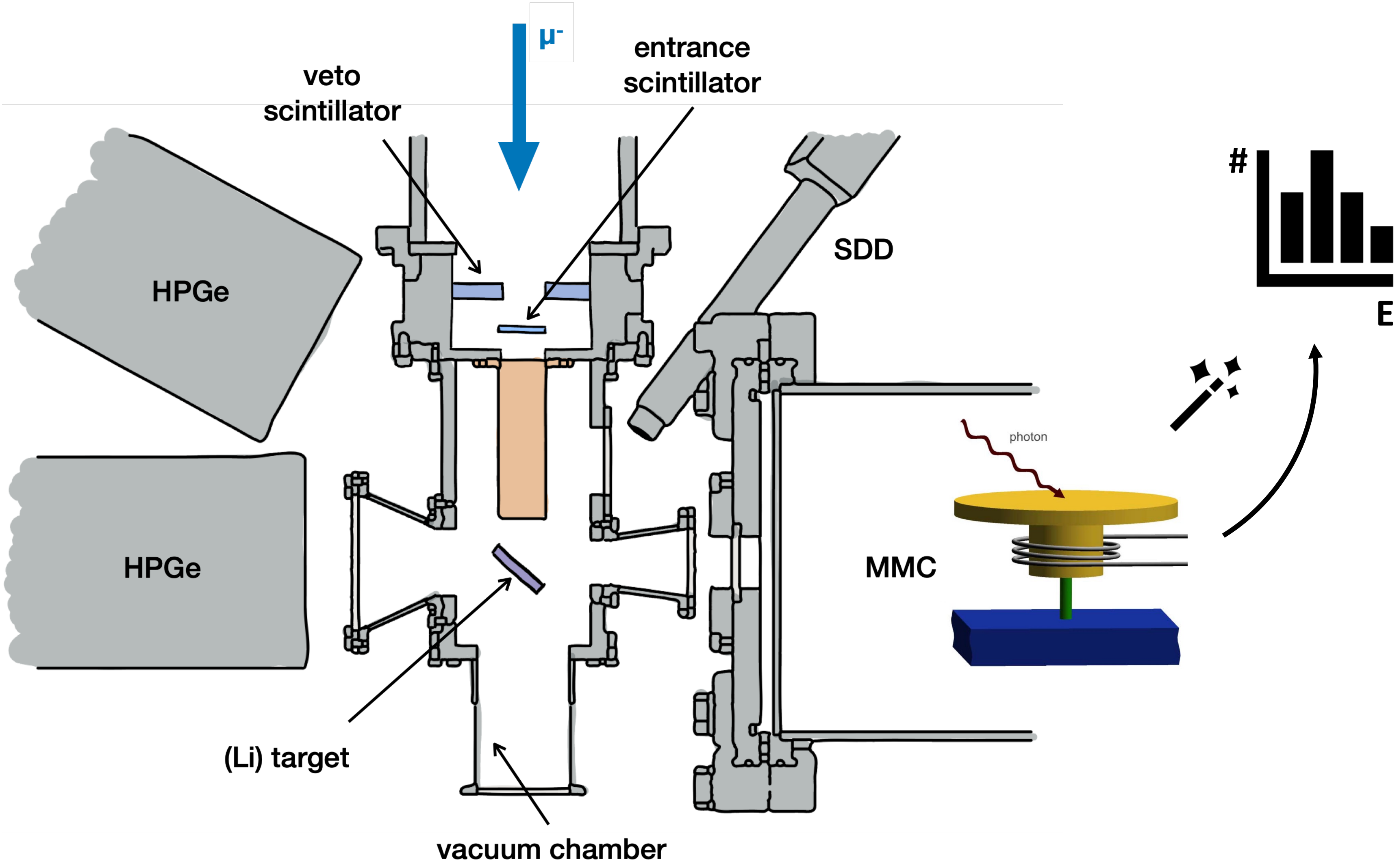
Mo + Ag

^{6}Li (> 95 %)

^{12}C

Cu

^{13}C

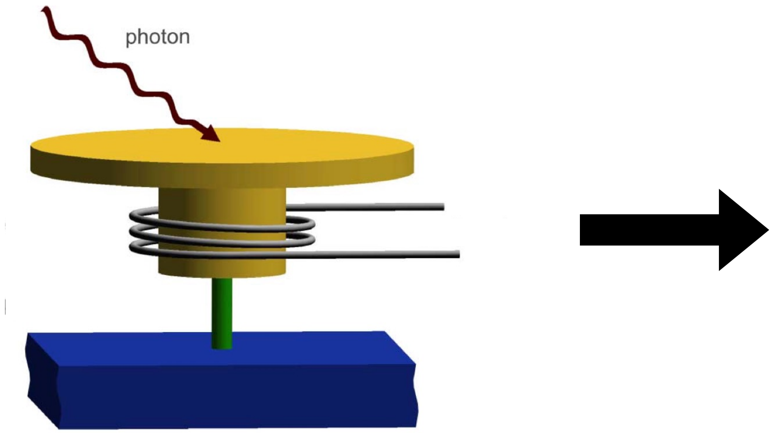


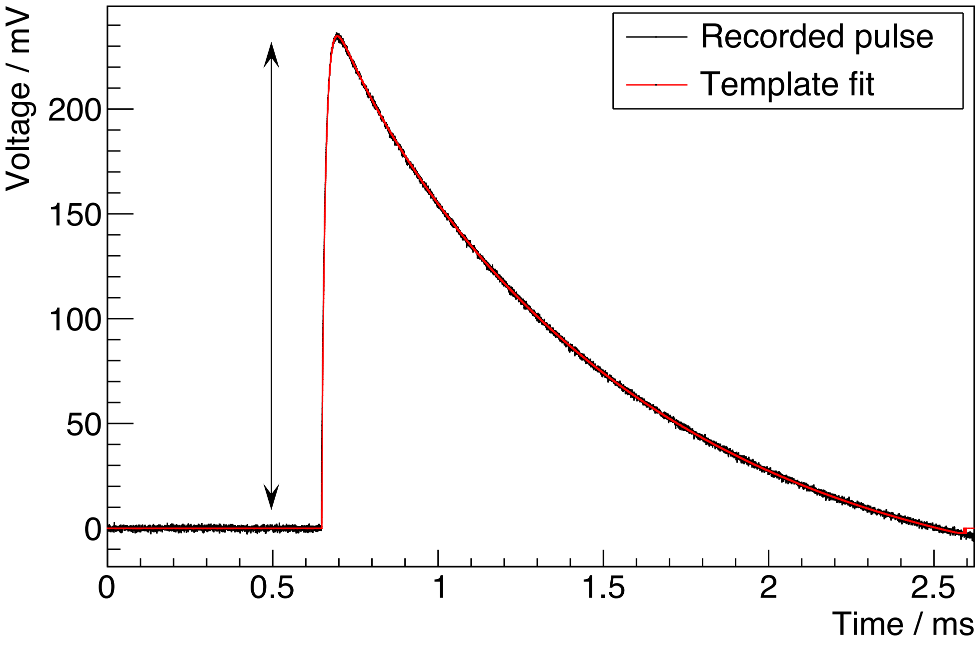
Data analysis workflow

Data analysis workflow

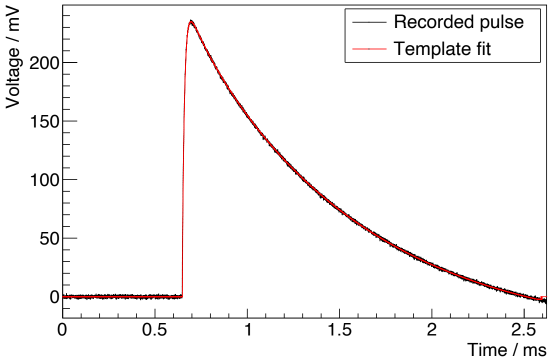
Fitting pulses

1. Full pulse shapes recorded
2. Amplitudes from template fit





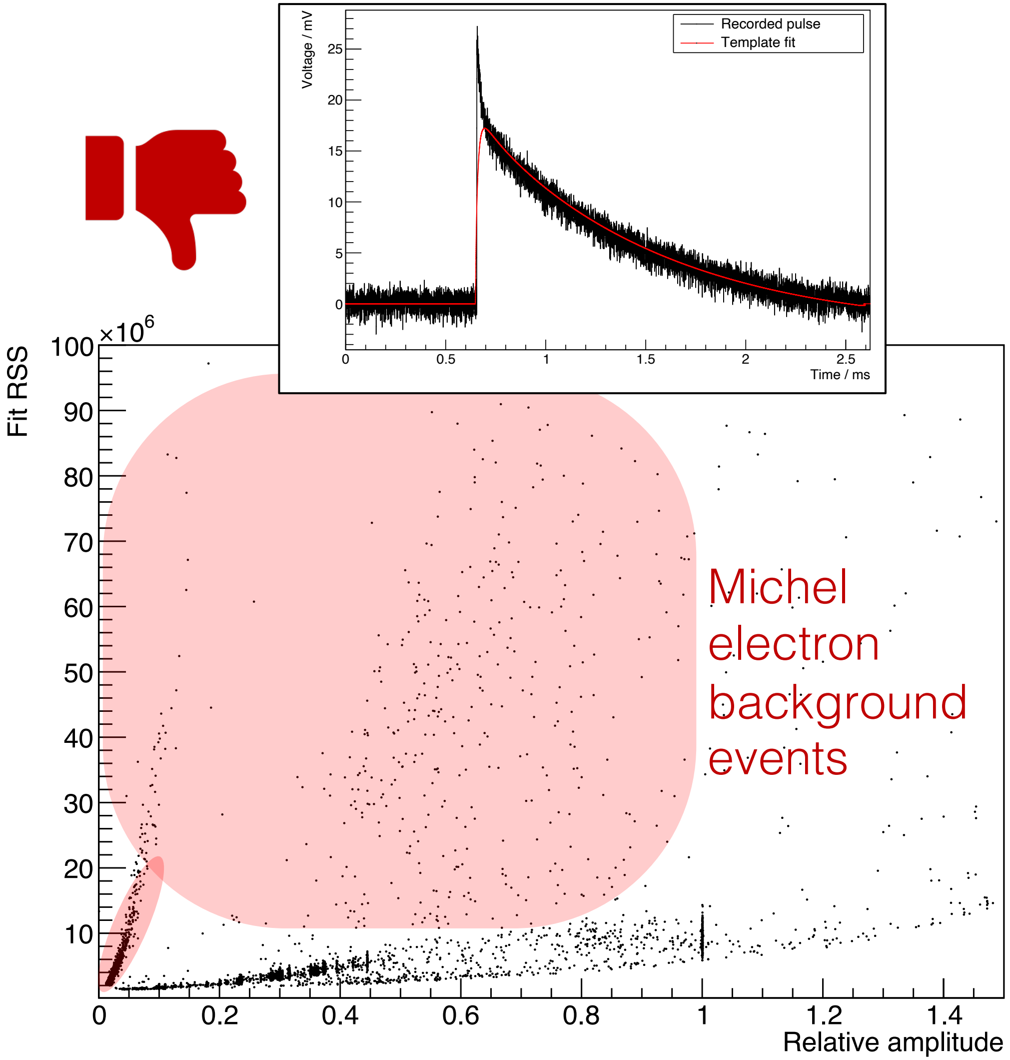
Data analysis workflow



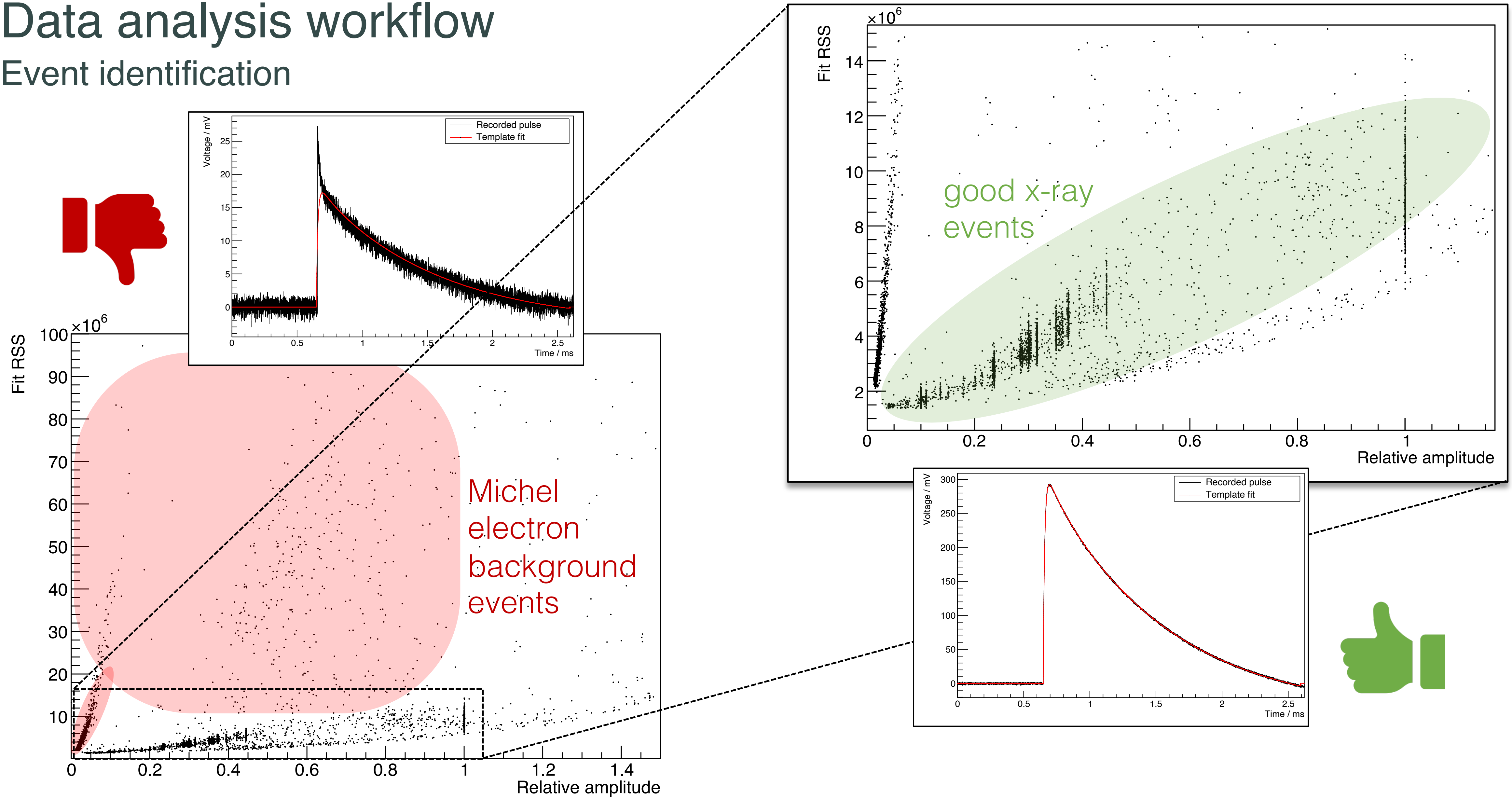
- ✓ Amplitudes
- ✓ Goodness-of-Fit (RSS)

Data analysis workflow

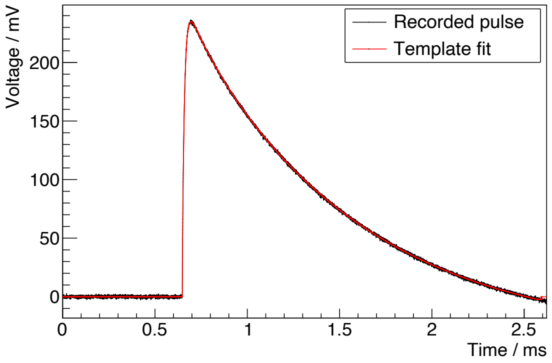
Event identification

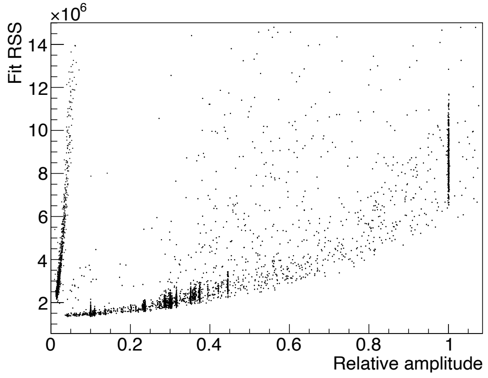


Data analysis workflow
Event identification



Data analysis workflow



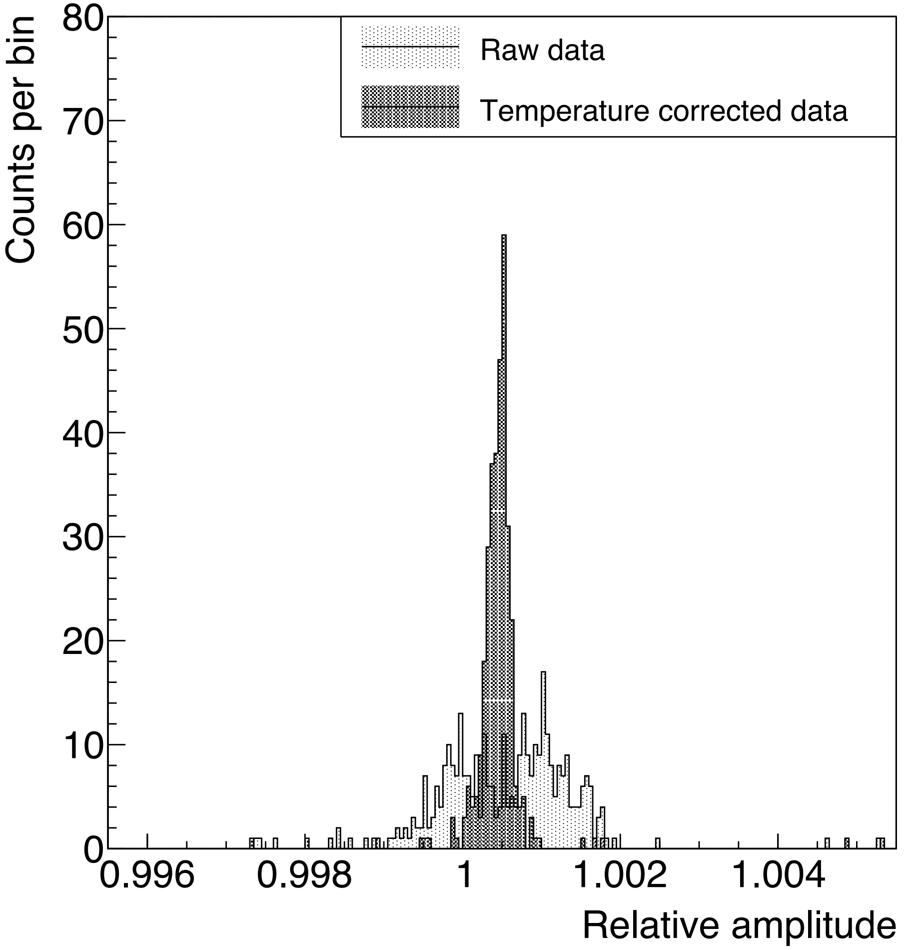


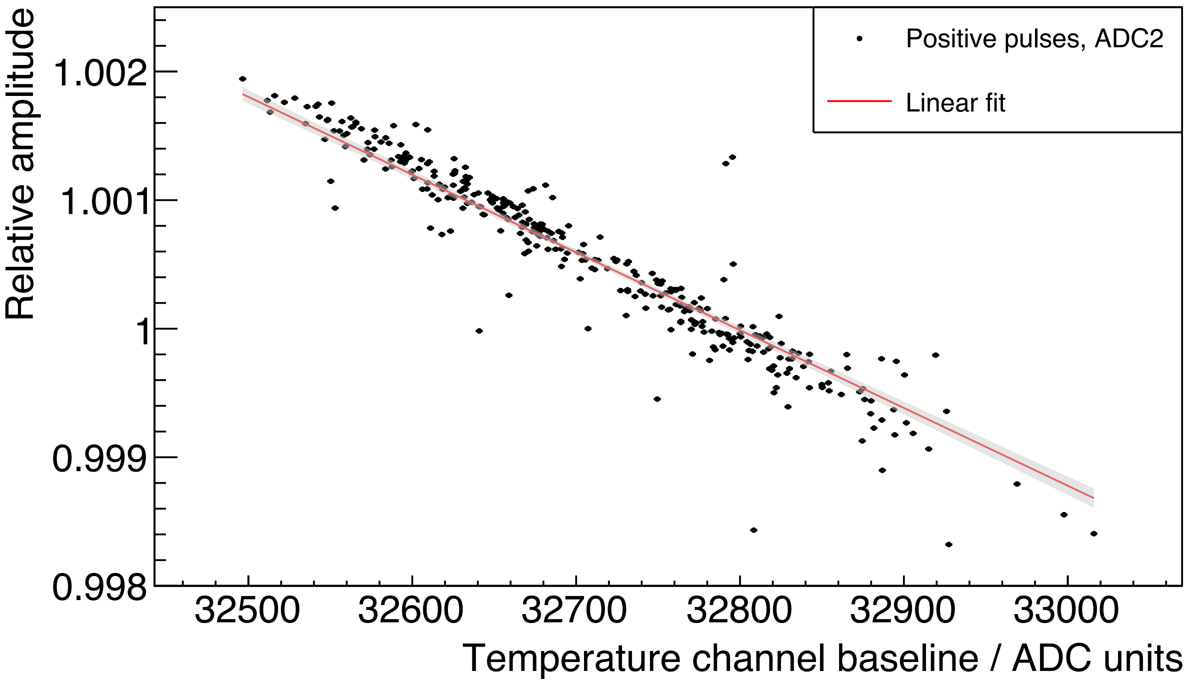
- ✓ Amplitudes
- ✓ Goodness-of-Fit (RSS)

- ✓ Background rejection

Data analysis workflow

Temperature correction

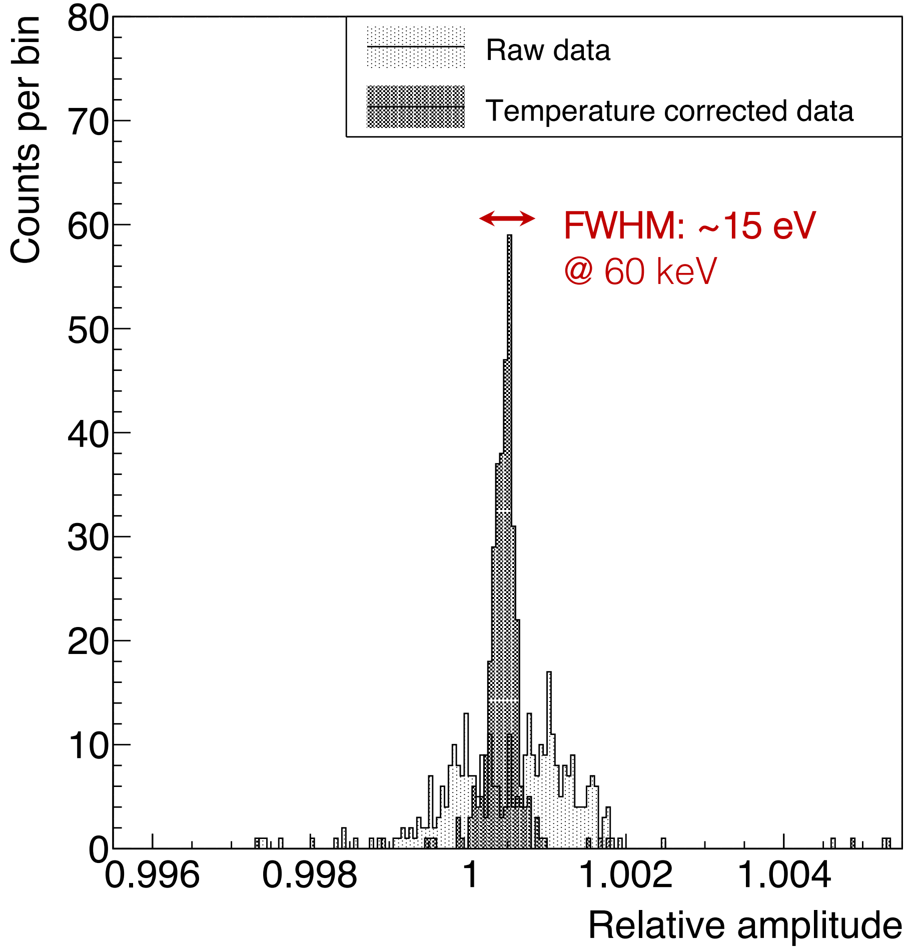


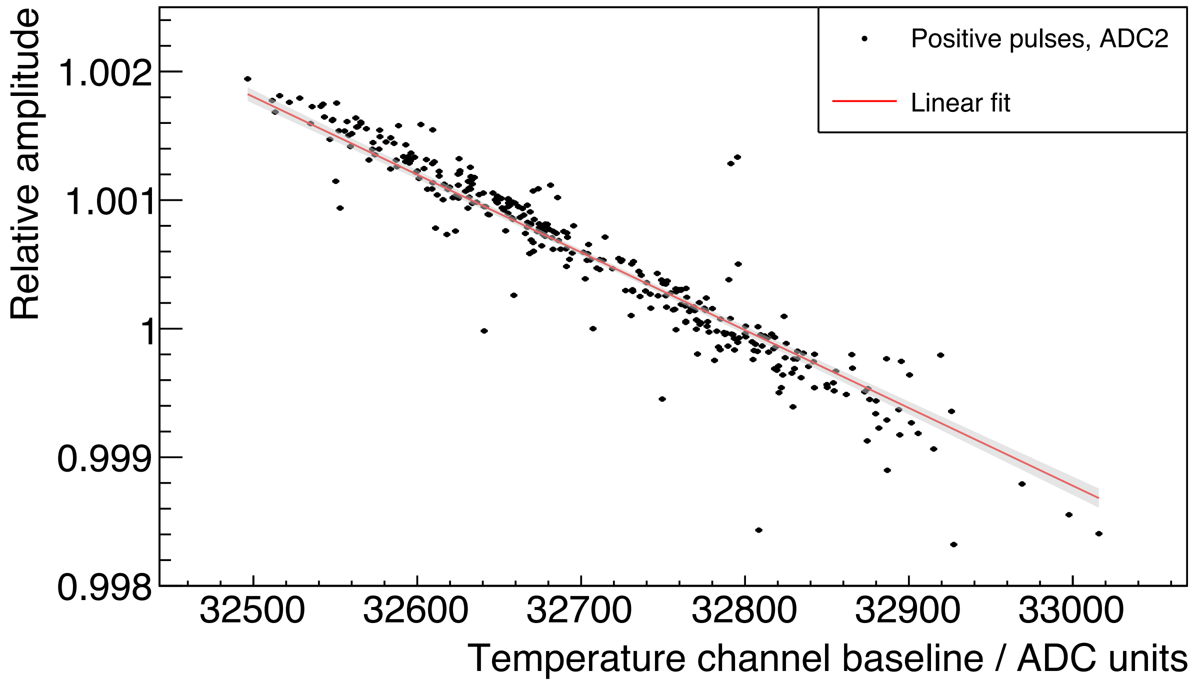


- Determine temperature sensitivity of gradiometric pixels and correct each event

Data analysis workflow

Temperature correction



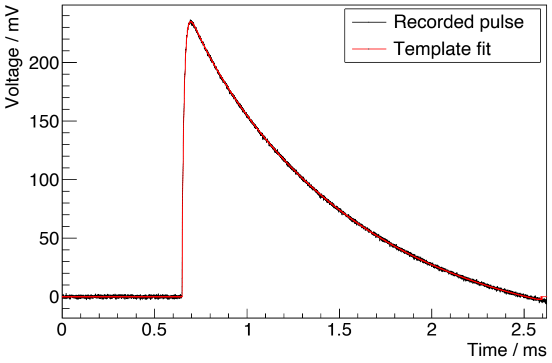


➢ Determine temperature sensitivity of gradiometric pixels and correct each event

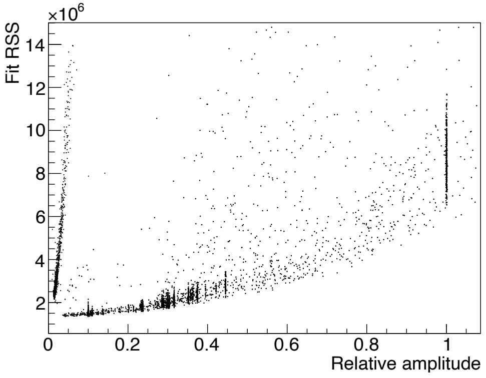
Data analysis workflow

pixel-by-pixel analysis

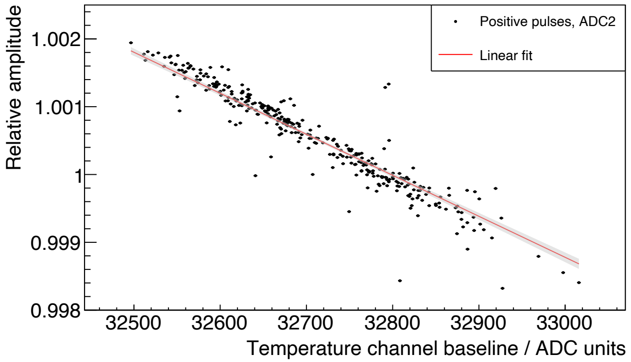
fitting pulses → event identification → temperature correction → calibration & co-adding



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



- ✓ Background rejection



- ✓ Correct for temperature variations

Data analysis workflow

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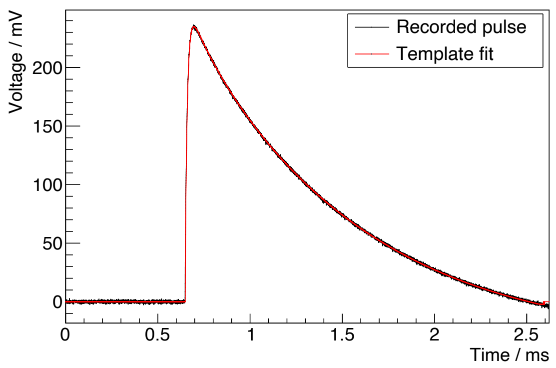

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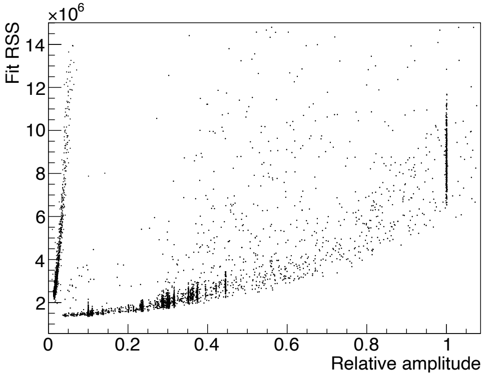

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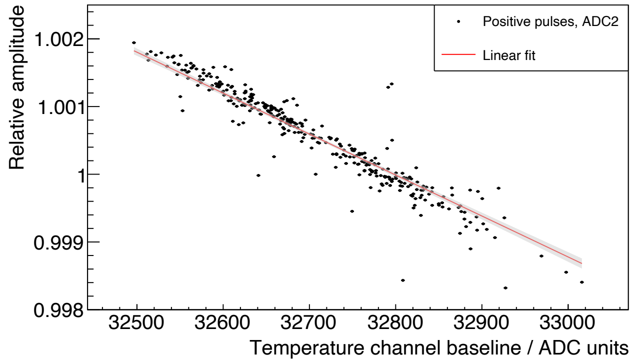

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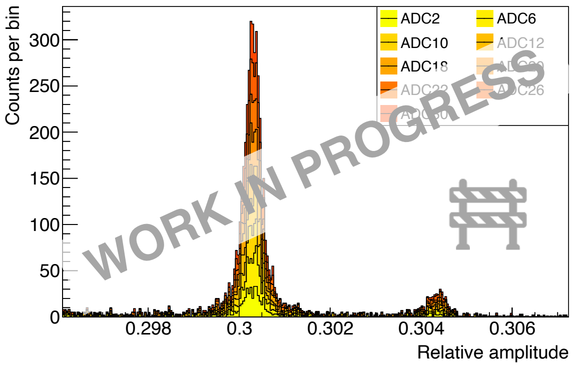
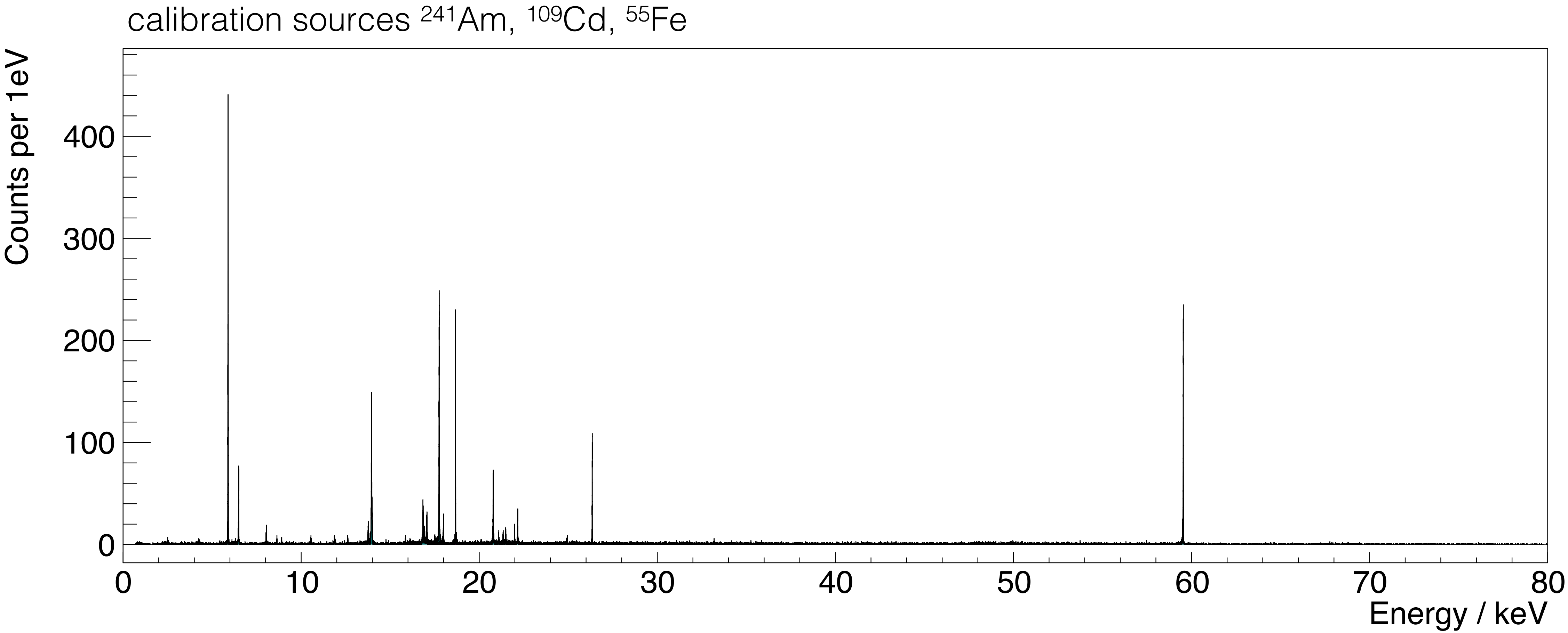


- ✗ Continuous (+ higher rate) calibration lines needed
- ✗ ADC nonlinearity needs calibration

Preliminary results

Muonic lithium broadband spectrum



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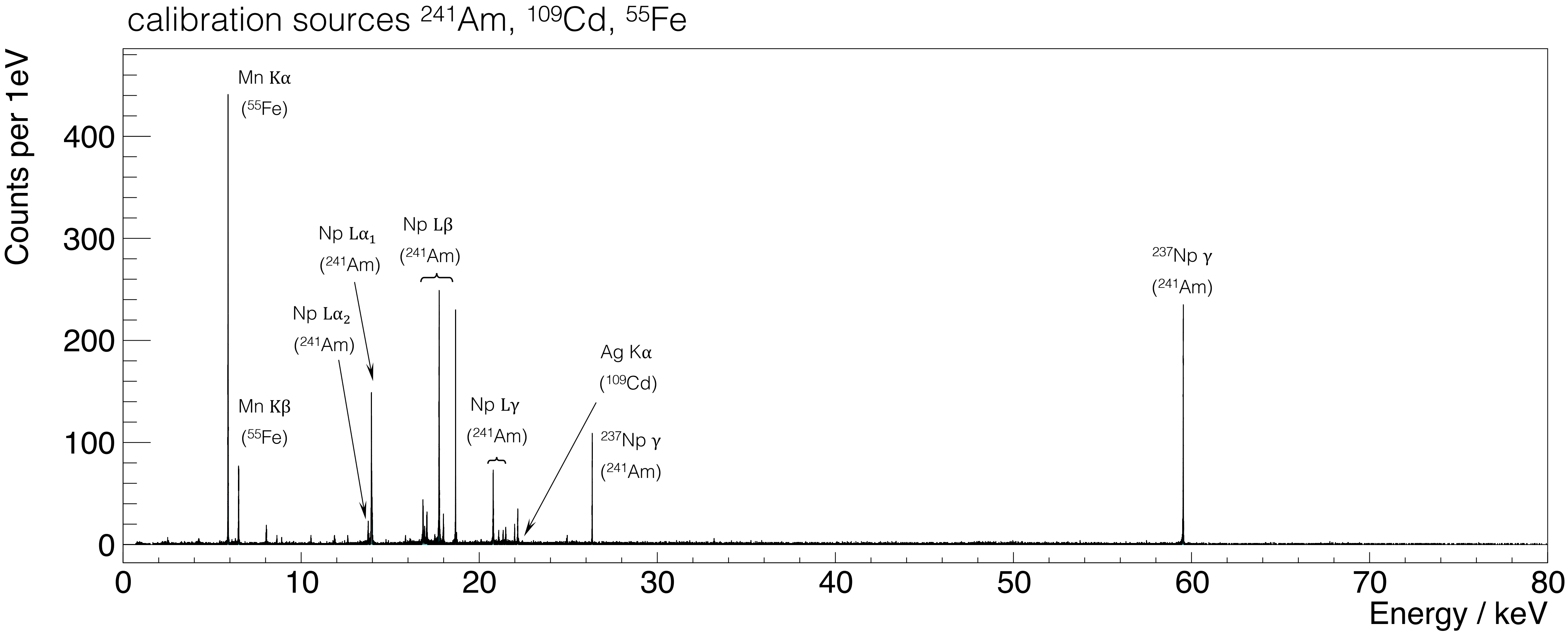

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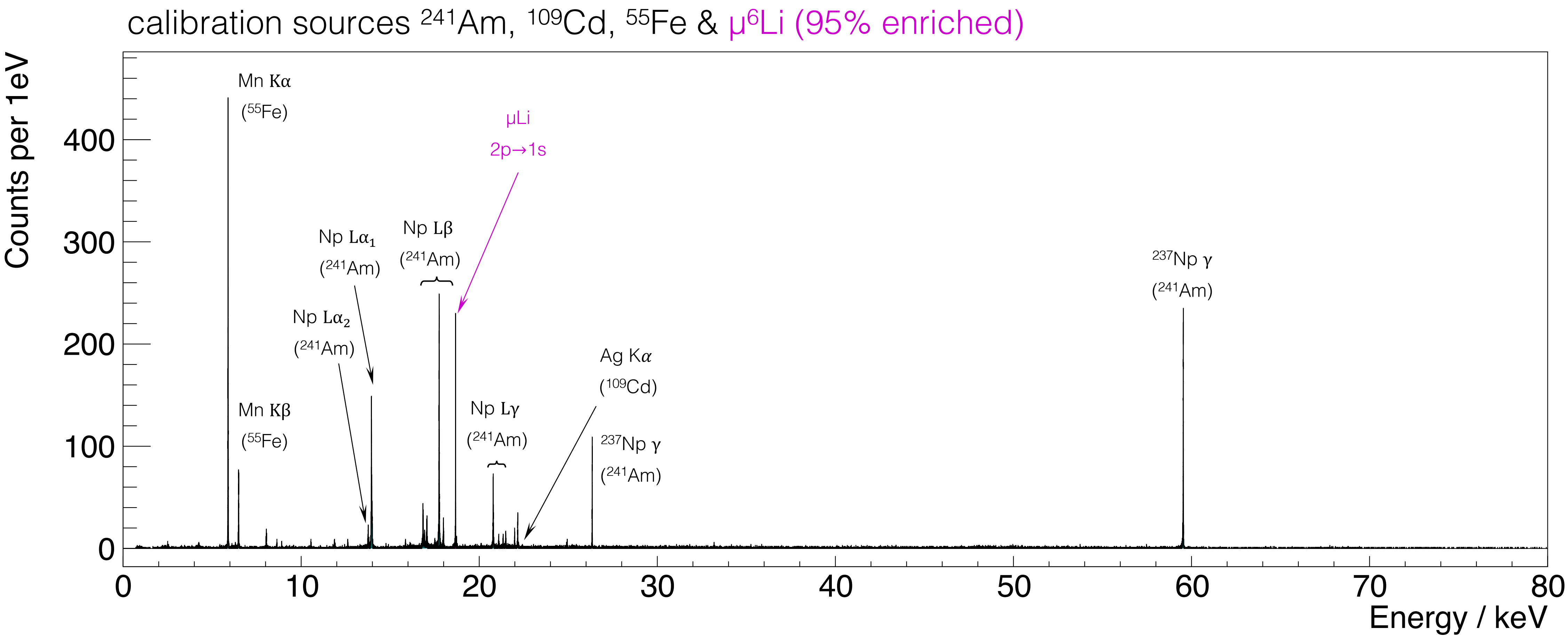

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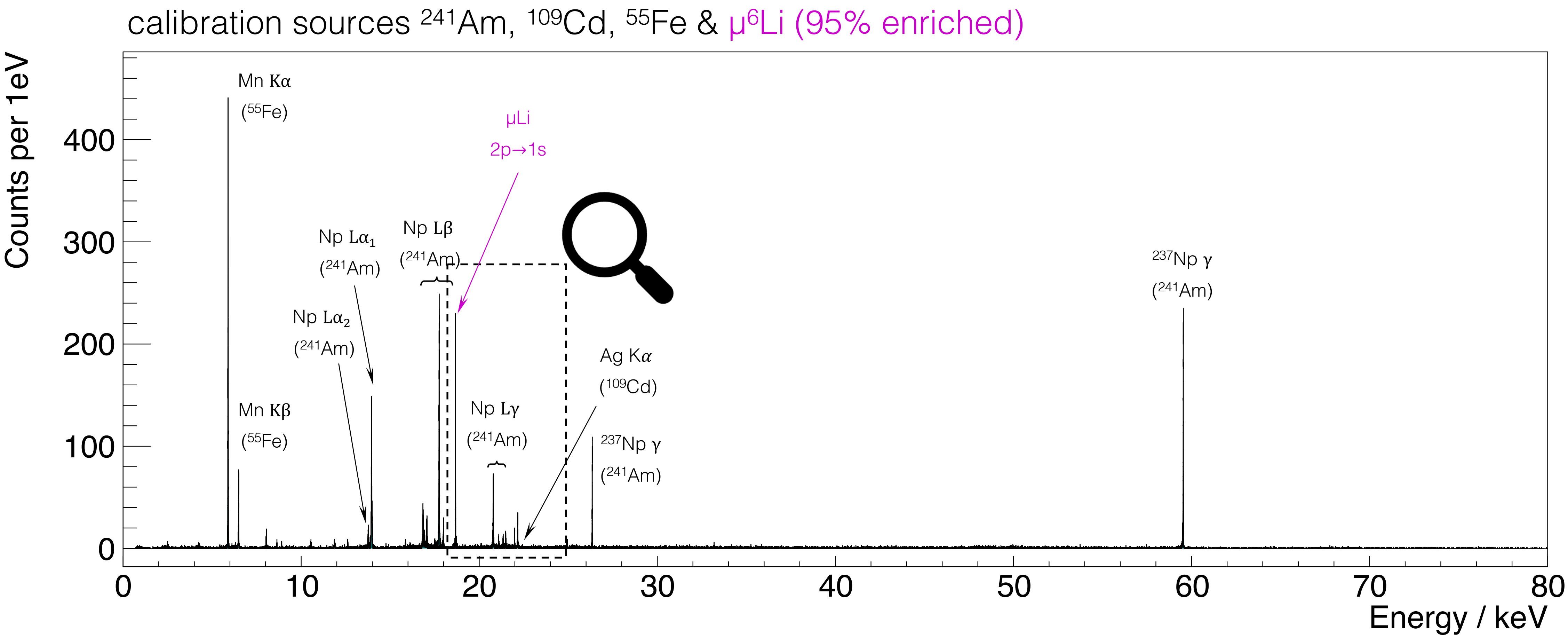
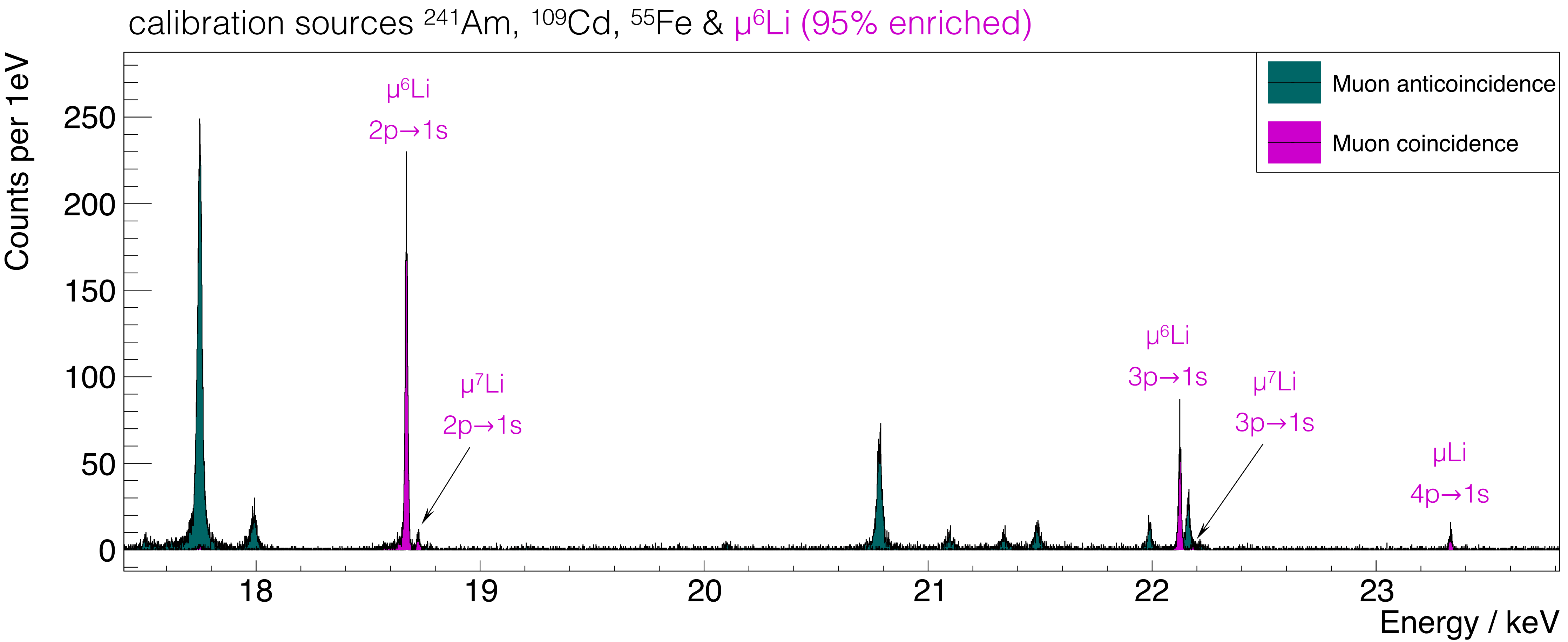


Preliminary results

Muonic lithium broadband spectrum

events with and without muon entrance in the last 1 μs



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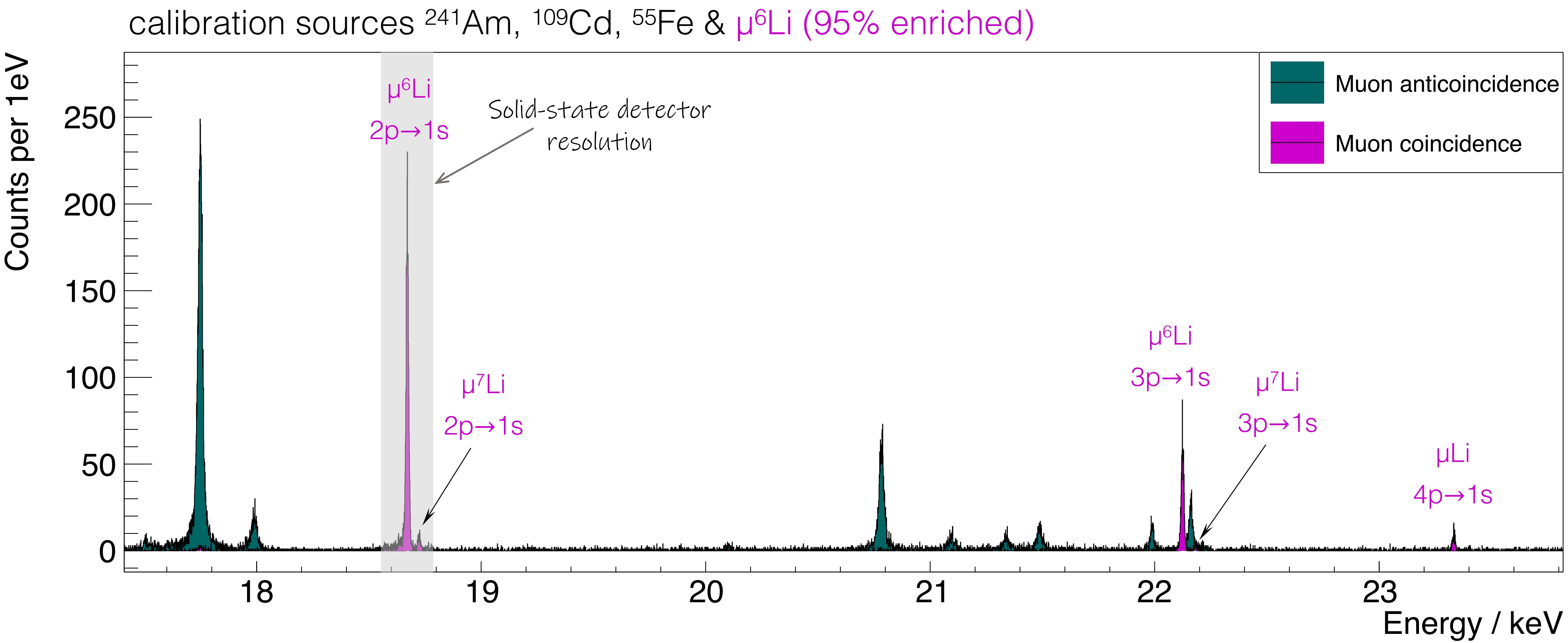

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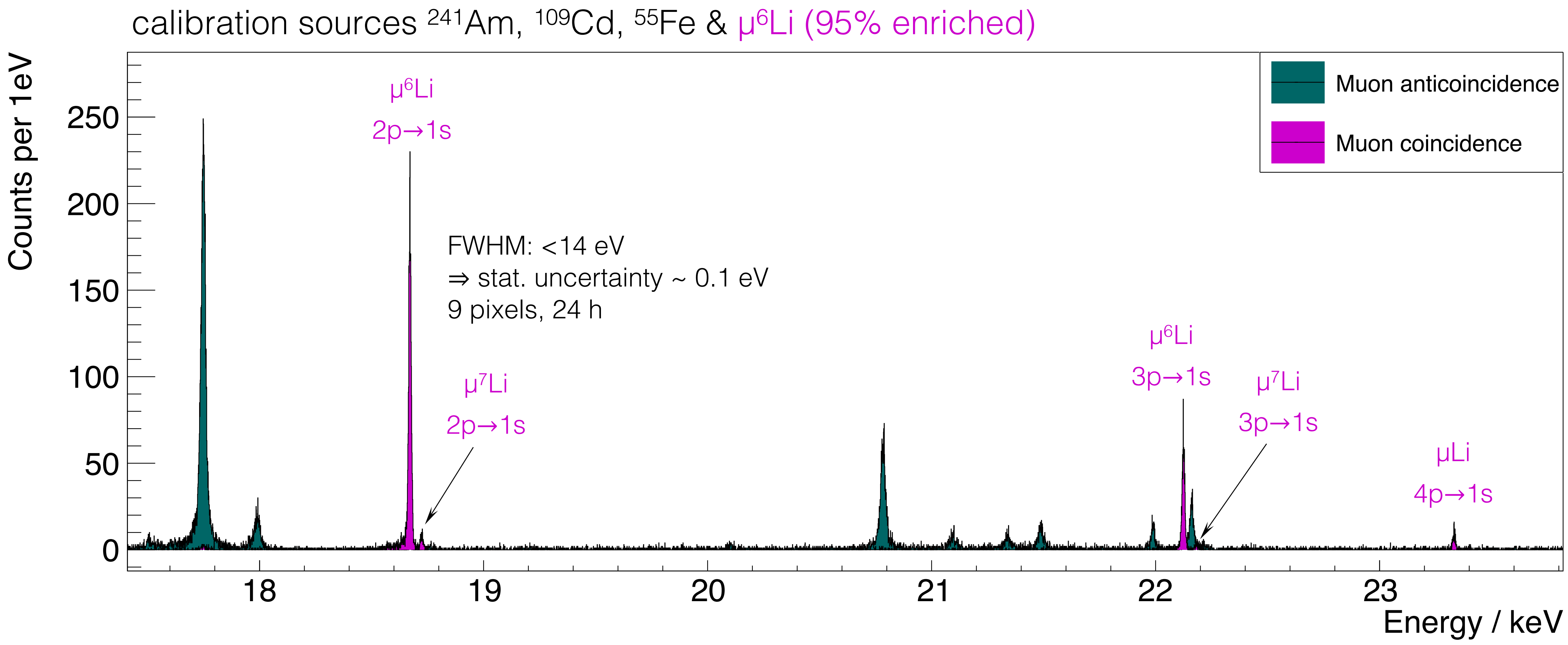

Summary & Outlook

- Goal: improving precision of low-Z charge radii, starting with $^{6,7}Li$ via muonic atom spectroscopy

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  - Background understood and under control
  - Statistical uncertainty: ~ 0.1 eV in 24 h of beam time
  - Current limitation: calibration

Summary & Outlook

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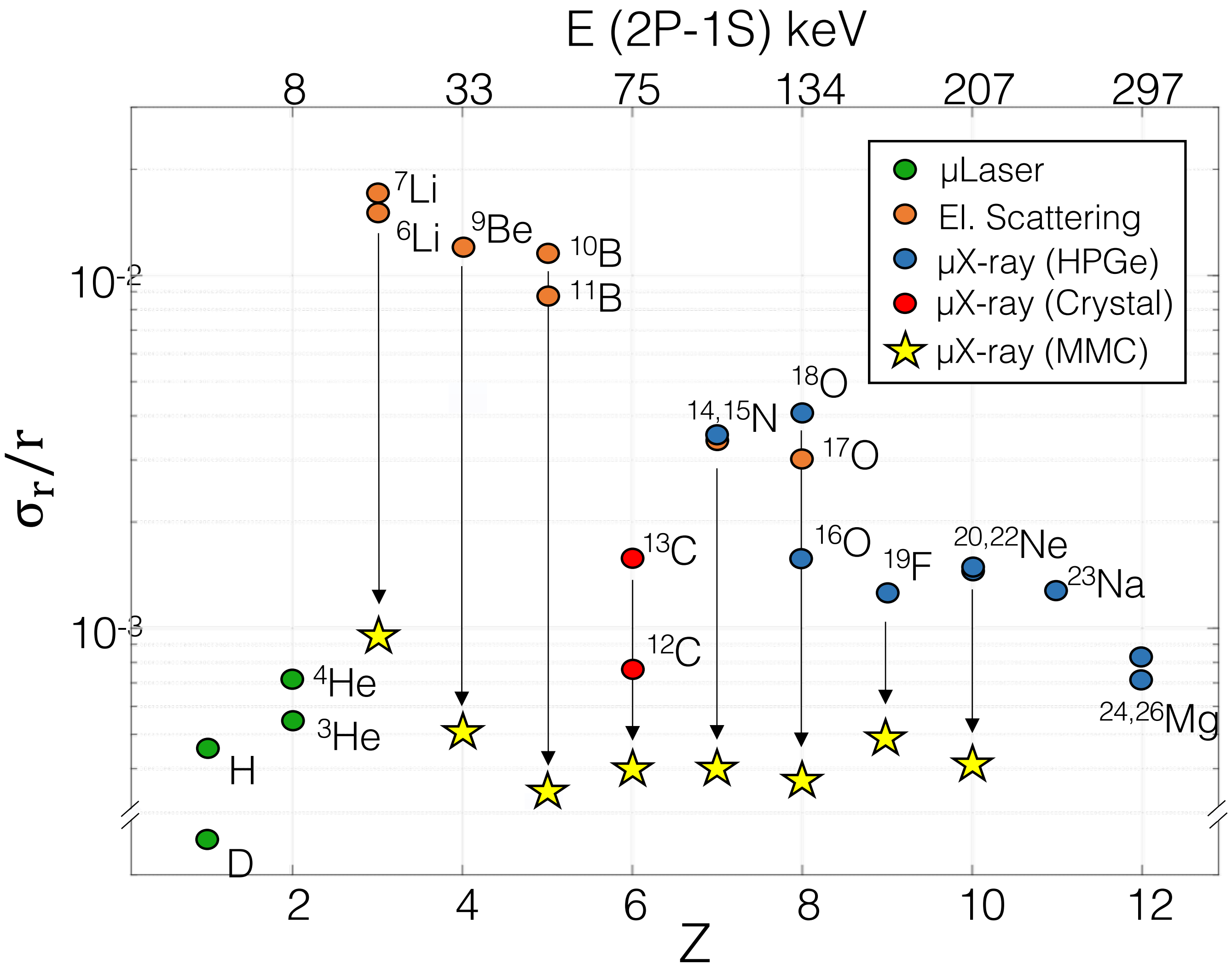
- So far: first successful demonstration of an MMC for muonic atom spectroscopy
  - Background understood and under control
  - Statistical uncertainty: ~ 0.1 eV in 24 h of beam time
  - Current limitation: calibration
- To-do's: next beam time in October 2024
  - Improved and continuous calibration + ADC calibration
  - Physics analysis!

Backup

Outlook – QUARTET goals



Lithium nuclear charge radii

Available muonic atom spectroscopy data

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*

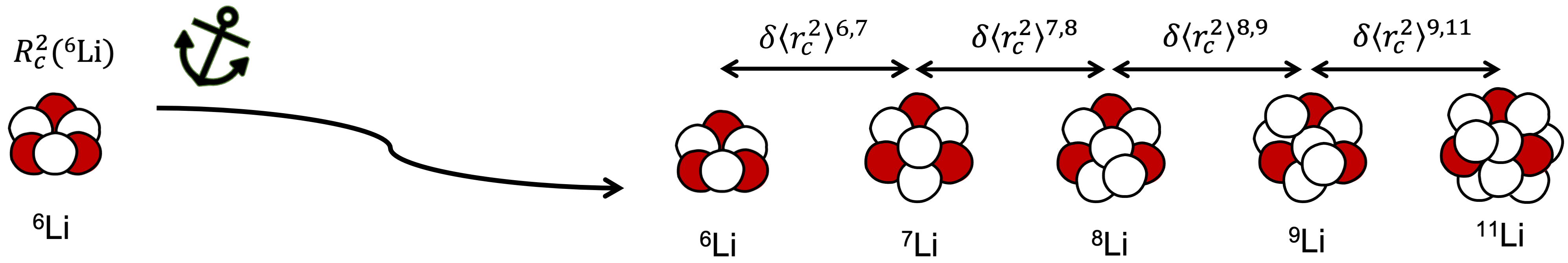
R. J. Harris, Jr.,† W. B. Shuler, M. Eckhause, R. T. Siegel, and R. E. Welsh
College of William and Mary, Williamsburg, Virginia
(Received 15 January 1968)

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]

Measuring nuclear charge radii

Absolute charge radii

Relative charge radius changes



- Elastic electron scattering
- Muonic atom spectroscopy

- Isotope shifts from (ordinary) atom spectroscopy

Muonic x-ray spectroscopy 101

Bohr radii: $r_n \propto \frac{n^2}{Z} \cdot \frac{1}{m}$

Bohr energies: $E_n \propto \frac{Z^2}{n^2} \cdot m$

Finite nuclear size effect: $\Delta E_{FNS} \propto m^3$

$m_\mu \approx 200 \cdot m_e$

radii: 200x smaller

energies: 200x higher

finite nuclear size effect: 10^7x higher