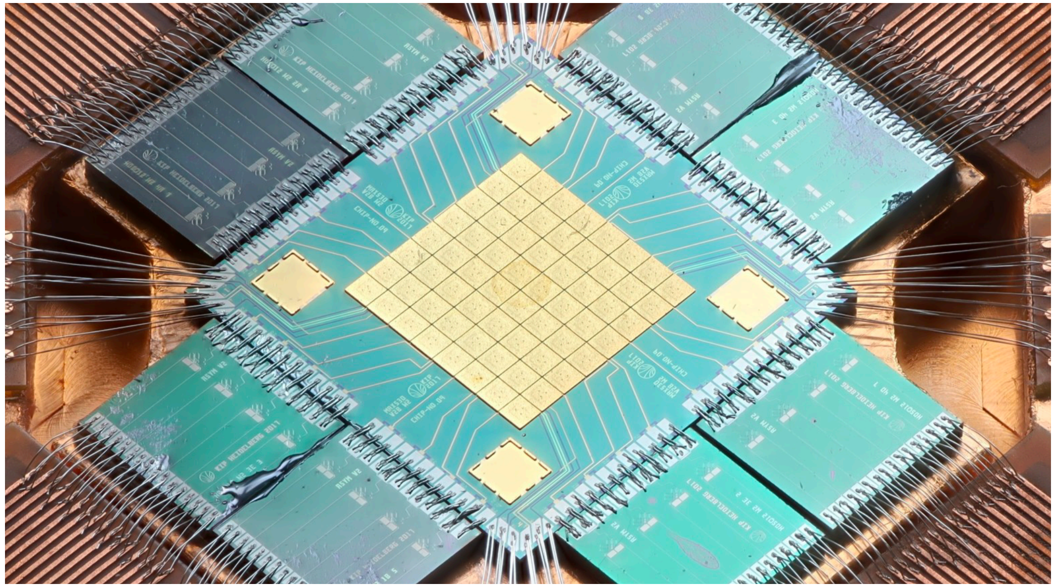
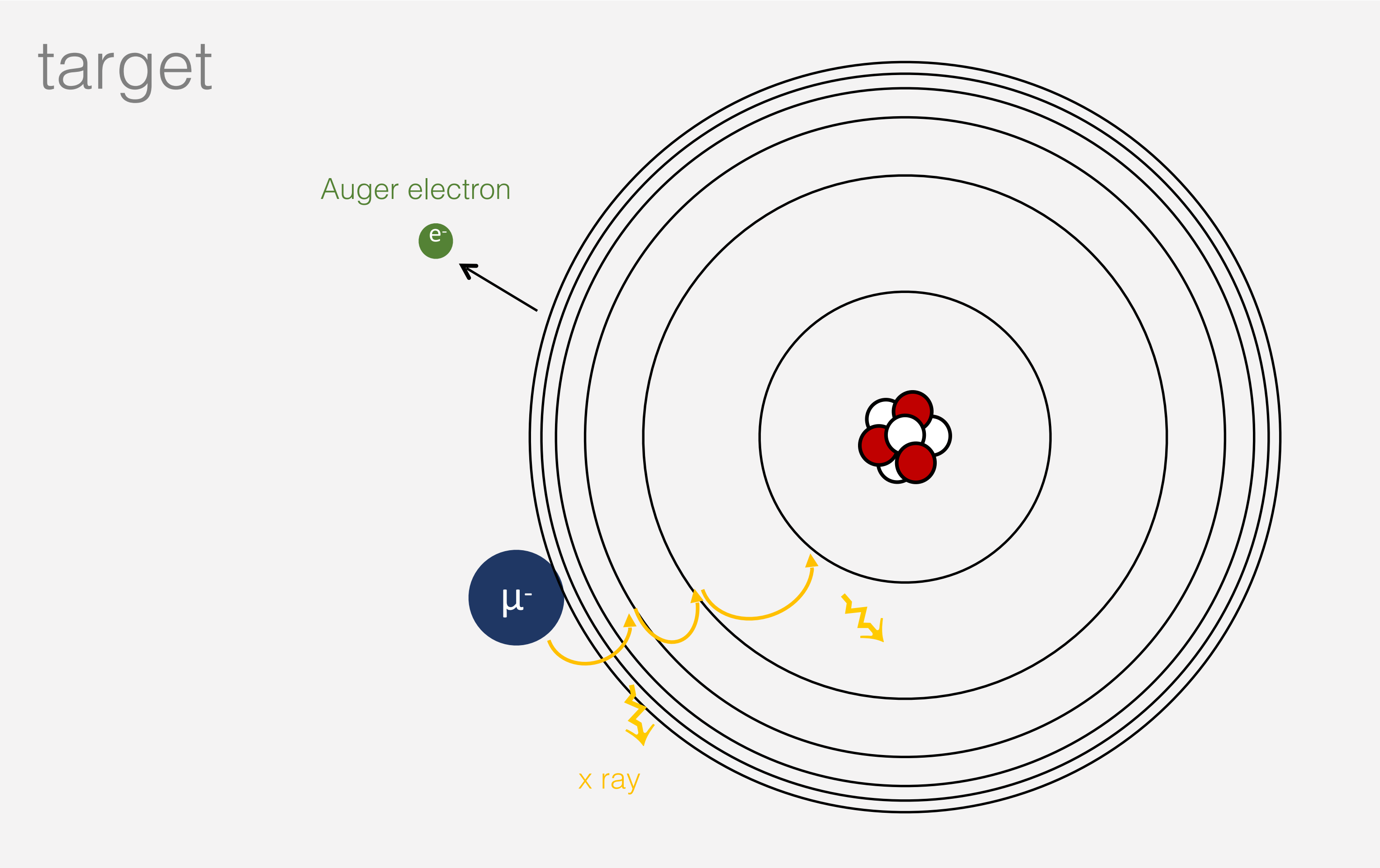
PSI Center for Neutron and Muon Sciences

High-precision muonic atom x-ray spectroscopy with a metallic magnetic calorimeter



Andreas Knecht for the QUARTET collaboration
HPXM2025, Frascati
17. June 2025

Muonic Atoms



1. Stop muons in target material

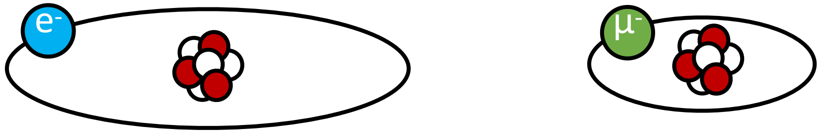
2. Atomic capture in high principal quantum number n

3. Cascade down to the ground state via
   → Auger electron emission (dominating at high n)
   → and muonic x-ray emission (dominating at low n)
      → few keV to MeV range

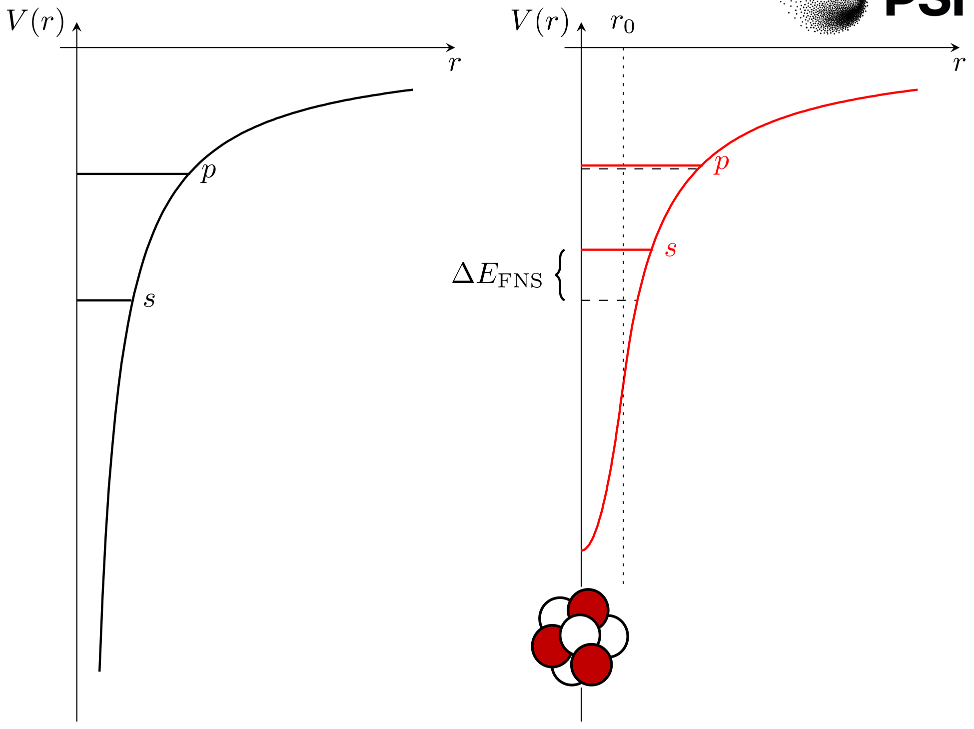
Muonic Atoms

Replace electron by muon in simple hydrogen(-like) atom that can be calculated with high precision:

$m_\mu \approx 200 \cdot m_e$



- Bohr energies: $E \propto \frac{Z^2}{n^2} \cdot m$ → from eV to keV
- Bohr radii: $r \propto \frac{n^2}{Z} \cdot \frac{1}{m}$ → 200 times smaller
- Finite nuclear size effect: $\Delta E_{FNS}(n,l) = \frac{2}{3n^3}(Z\alpha)^4 m^3 r^2 \delta_{l0}$ → Enhanced by 10^7!



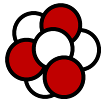
(a) Point nucleus (b) Finite size nucleus

Idea: Form muonic atom and observe 2p→1s transition for nuclear charge radius measurement

What to do with charge radii?

Benchmarking ab-initio nuclear theory

Atomic Nuclei From Quantum Monte Carlo Calculations With Chiral EFT Interactions



Stefano Gandolfi[1], Diego Lonardoni[1,2], Alessandro Lovato[3,4] and Maria Piarulli[5]*

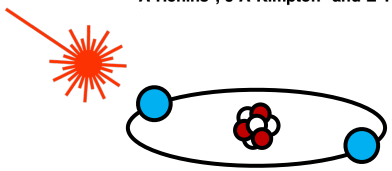
Trends of Neutron Skins and Radii of Mirror Nuclei from First Principles

S. J. Novario,[1] D. Lonardoni,[1,*] S. Gandolfi,[1] and G. Hagen[2,3]

Precision QED tests in simple atomic systems

X-ray measurements in helium-like atoms increased discrepancy between experiment and theoretical QED

C T Chantler[1], A T Payne[1], J D Gillaspy[2], L T Hudson[2], L F Smale[1], A Henins[2], J A Kimpton[3] and E Takacs[4,5]



$\langle r^2 \rangle$

Nuclear structure physics

Nuclear Charge Radii of ^{9,11}Li: The Influence of Halo Neutrons

R. Sánchez,[1] W. Nörtershäuser,[1,2] G. Ewald,[1] D. Albers,[3] J. Behr,[3] P. Bricault,[3] B. A. Bushaw,[4] A. Dax,[1,*] J. Dilling,[3] M. Dombsky,[3] G. W. F. Drake,[5] S. Götte,[1] R. Kirchner,[1] H.-J. Kluge,[1] Th. Kühl,[1] J. Lassen,[3] C. D. P. Levy,[3] M. R. Pearson,[3] E. J. Prime,[3] V. Ryjkov,[3] A. Wojtaszek,[1,†] Z.-C. Yan,[6] and C. Zimmermann[2]

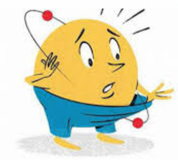
Charge radii of exotic potassium isotopes challenge nuclear theory and the magic character of $N = 32$

Á. Koszorús[1,17], X. F. Yang[1,2], W. G. Jiang[3,4,5], S. J. Novario[3,4], S. W. Bai[2], J. Billowes[6], C. L. Binnersley[6], M. L. Bissell[6], T. E. Cocolios[1], B. S. Cooper[6], R. P. de Groote[7,8], A. Ekström[5], K. T. Flanagan[6,9], C. Forssén[5], S. Franchoo[10], R. F. Garcia Ruiz[11,12], F. P. Gustafsson[1], G. Hagen[4], G. R. Jansen[4], A. Kanellakopoulos[1], M. Kortelainen[7,8], W. Nazarewicz[13], G. Neyens[1,12], T. Papenbrock[3,4], P.-G. Reinhard[14], C. M. Ricketts[6], B. K. Sahoo[15], A. R. Vernon[1,6] and S. G. Wilkins[16]

Extracting fundamental constants via atomic spectroscopy

The size of the proton

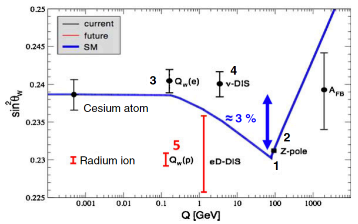
Randolf Pohl[1], Aldo Antognini[1], François Nez[2], Fernando D. Amaro[3], François Biraben[2], João M. R. Cardoso[3], Daniel S. Covita[3,4], Andreas Dax[5], Satish Dhawan[5], Luis M. P. Fernandes[3], Adolf Giesen[6]†, Thomas Graf[6], Theodor W. Hänsch[1], Paul Indelicato[2], Lucile Julien[2], Cheng-Yang Kao[7], Paul Knowles[8], Eric-Olivier Le Bigot[2], Yi-Wei Liu[7], José A. M. Lopes[3], Livia Ludhova[8], Cristina M. B. Monteiro[3], Françoise Mulhauser[8]†, Tobias Nebel[1], Paul Rabinowitz[9], Joaquim M. F. dos Santos[3], Lukas A. Schaller[8], Karsten Schuhmann[10], Catherine Schwob[2], David Taqqu[11], João F. C. A. Veloso[4] & Franz Kottmann[12]



New physics searches

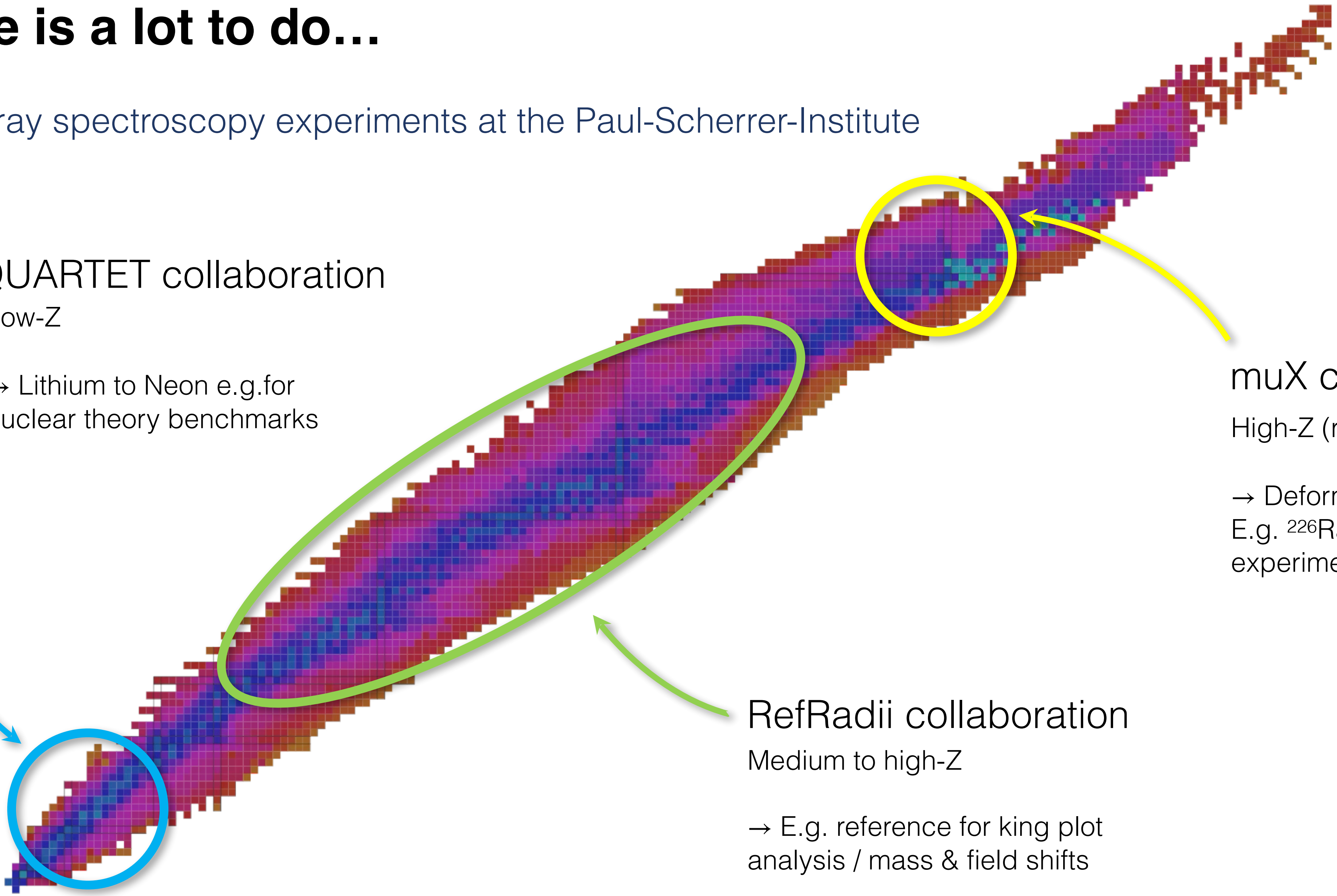
Atomic parity violation in a single trapped radium ion

O. O. Versolato · L. W. Wansbeek · G. S. Giri · J. E. van den Berg · D. J. van der Hoek · K. Jungmann · W. L. Kruithof · C. J. G. Onderwater · B. K. Sahoo · B. Santra · P. D. Shidling · R. G. E. Timmermans · L. Willmann · H. W. Wilschut



There is a lot to do…

Muonic x-ray spectroscopy experiments at the Paul-Scherrer-Institute



QUARTET collaboration

Low-Z

→ Lithium to Neon e.g.for nuclear theory benchmarks

muX collaboration

High-Z (radioactive) targets

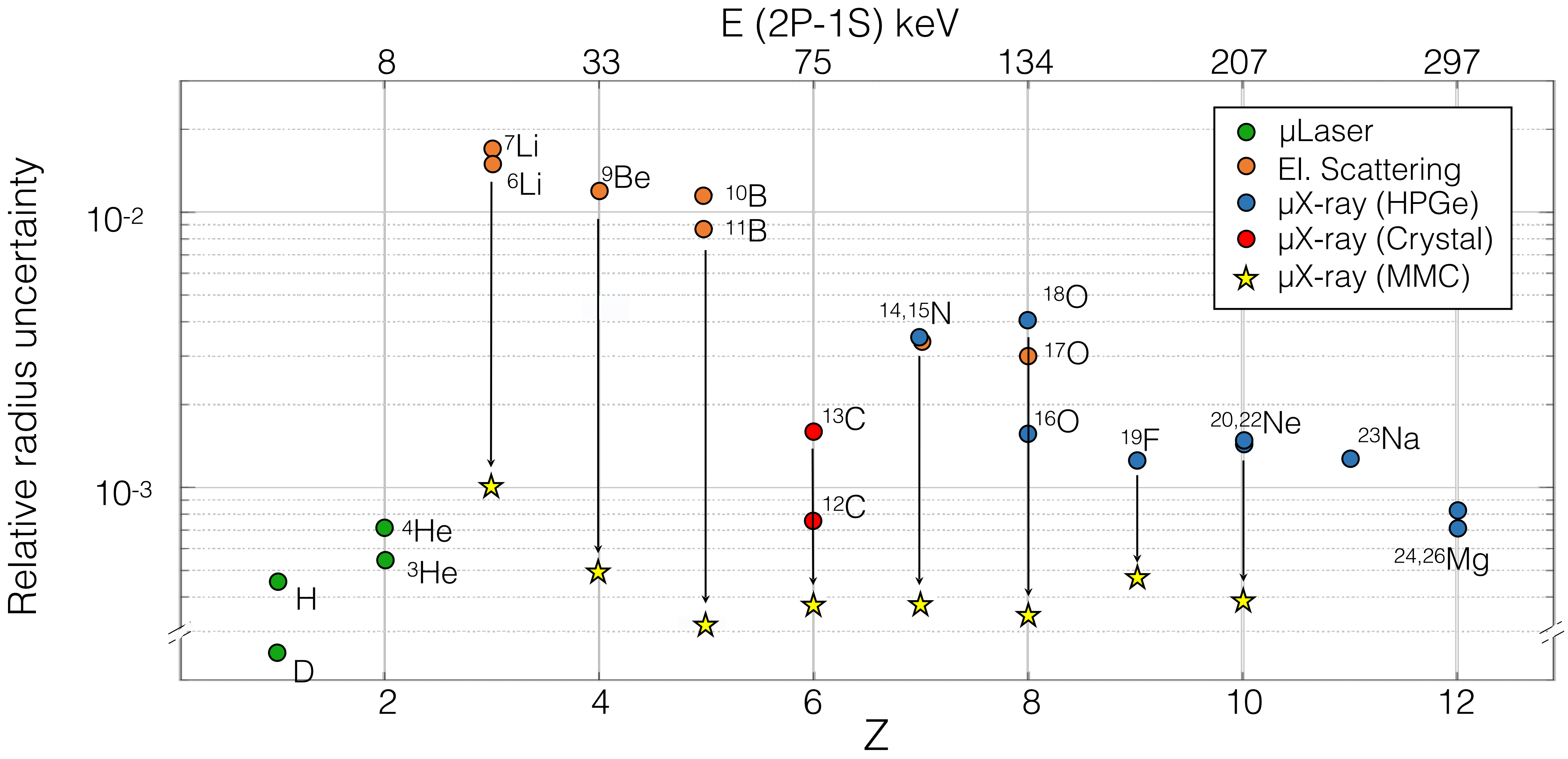
→ Deformed heavy nuclei. E.g. ^{226}Ra for APV experiments.

RefRadii collaboration

Medium to high-Z

→ E.g. reference for king plot analysis / mass & field shifts

Low-Z Charge Radii



Lithium nuclear charge radii

From muonic atom spectroscopy

Radius uncertainty >100% from 1968 measurement:

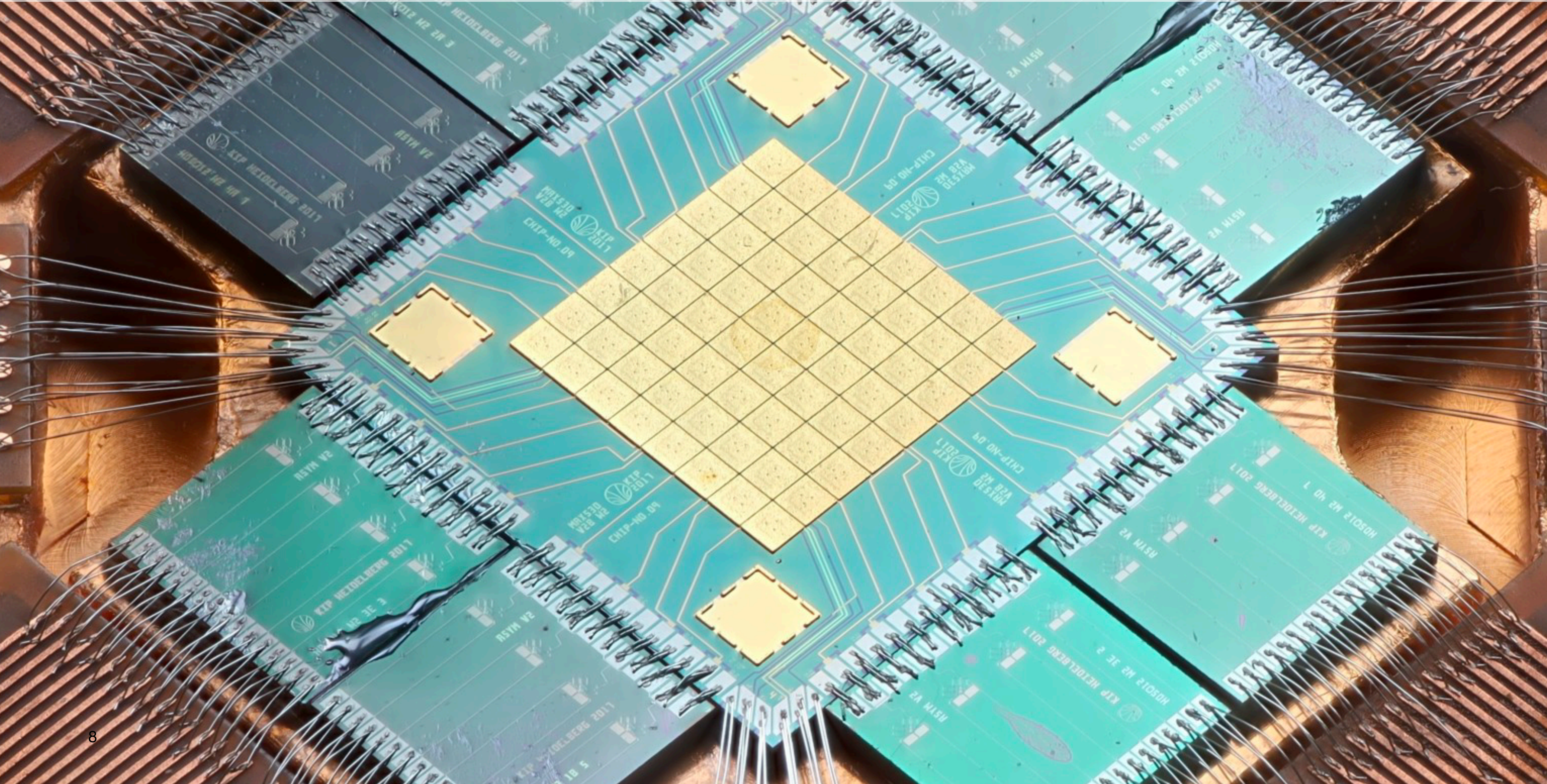
VOLUME 20, NUMBER 10 PHYSICAL REVIEW LETTERS 4 MARCH 1968

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

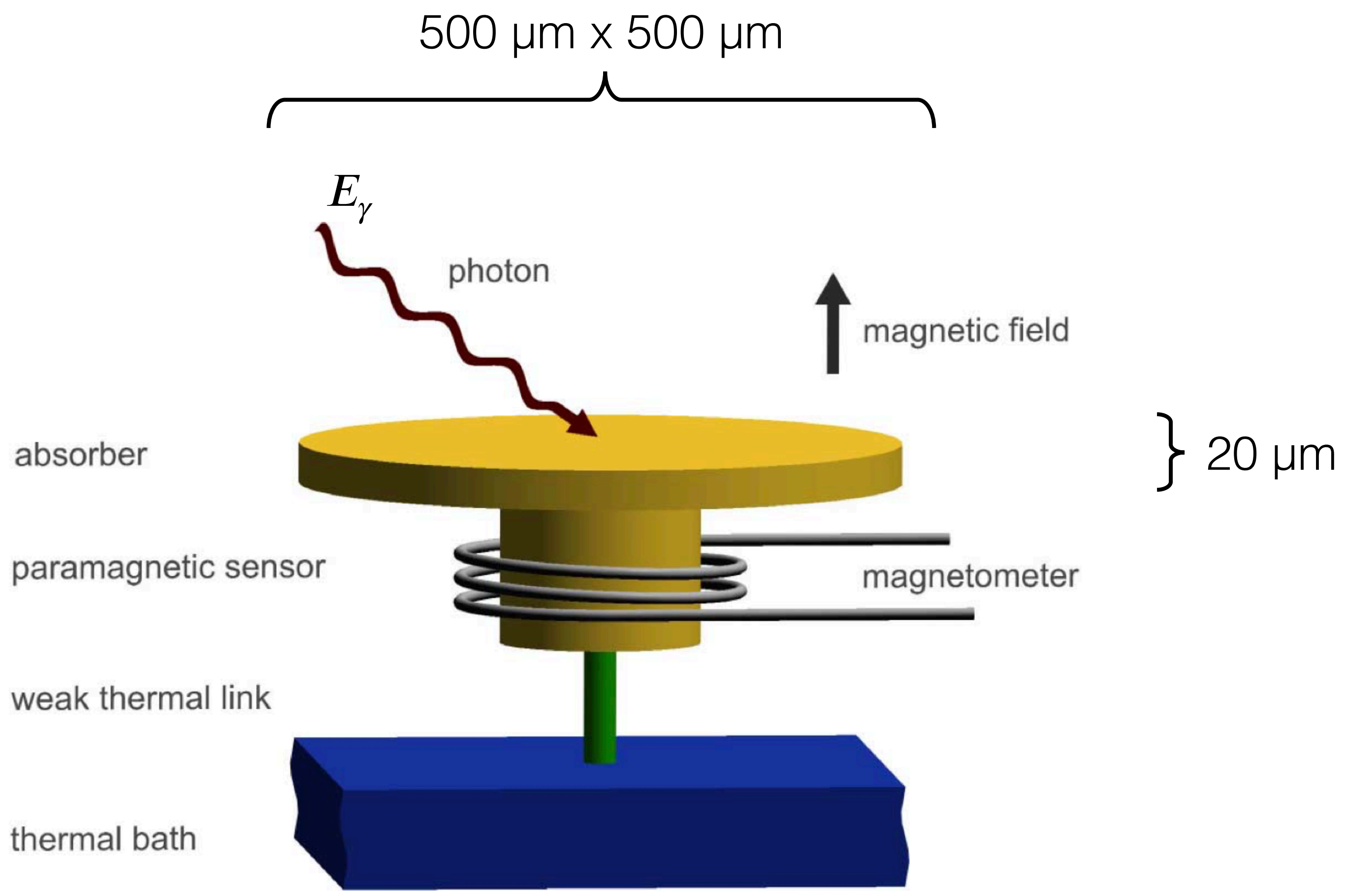
R. J. Harris, Jr.,† W. B. Shuler, M. Eckhause, R. T. Siegel, and R. E. Welsh
College of William and Mary, Williamsburg, Virginia
(Received 15 January 1968)

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]

Metallic Magnetic Calorimeter (MMC)



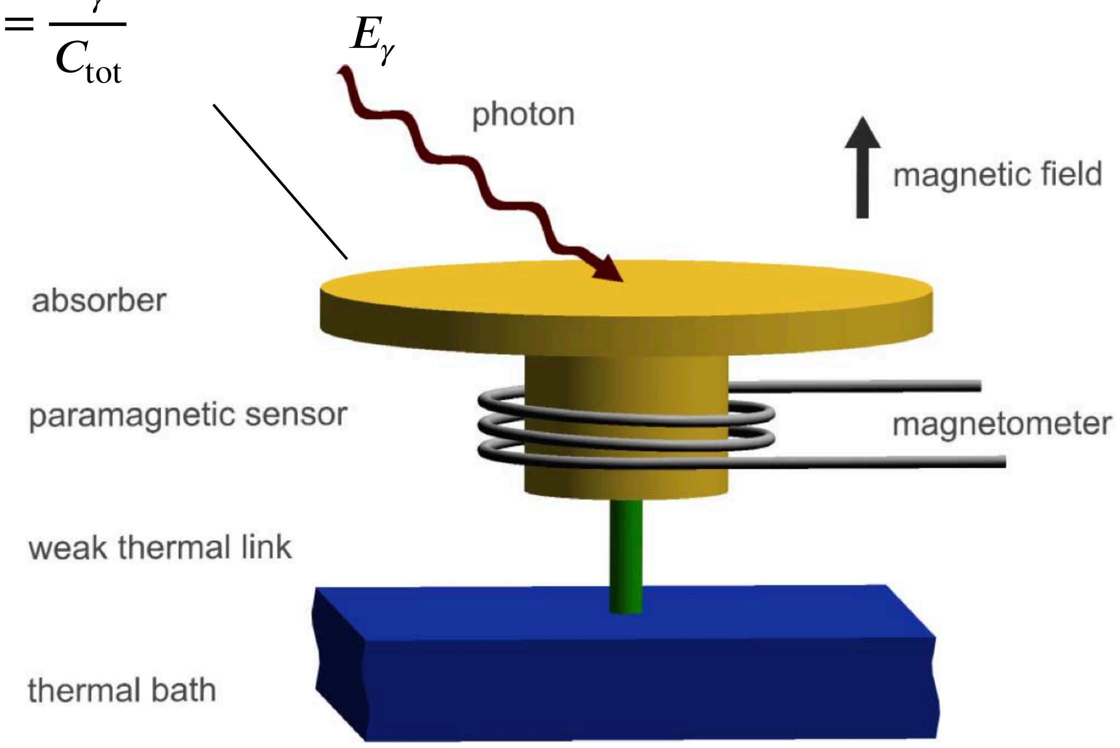
MMC working principle



DOI: 10.1109/TASC.2009.2012724

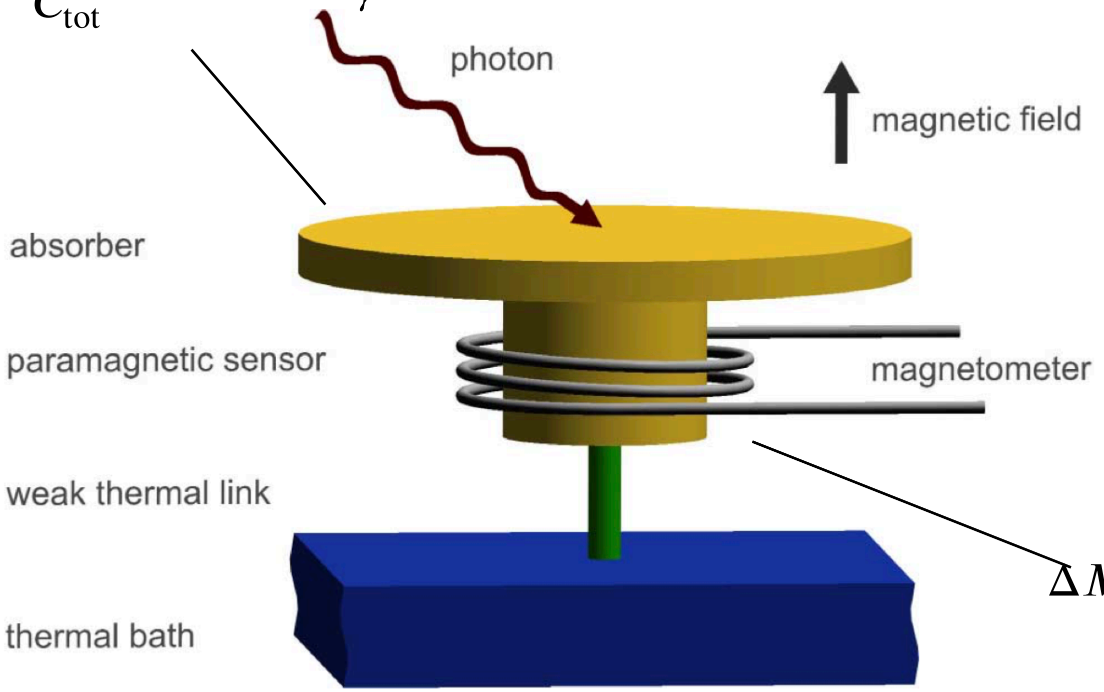
MMC working principle

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



DOI: 10.1109/TASC.2009.2012724

MMC working principle



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

$$E_\gamma$$

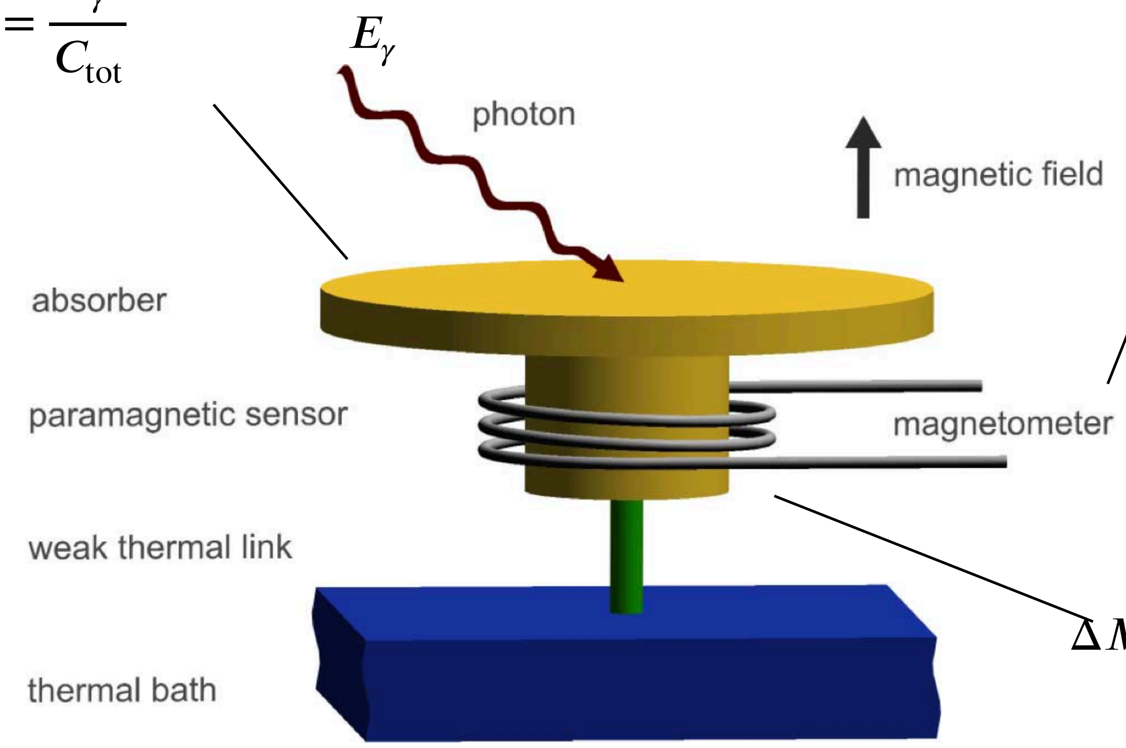
$$\Delta M = \frac{\partial M}{\partial T} \Delta T$$

DOI: 10.1109/TASC.2009.2012724

MMC working principle

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

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



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

DOI: 10.1109/TASC.2009.2012724

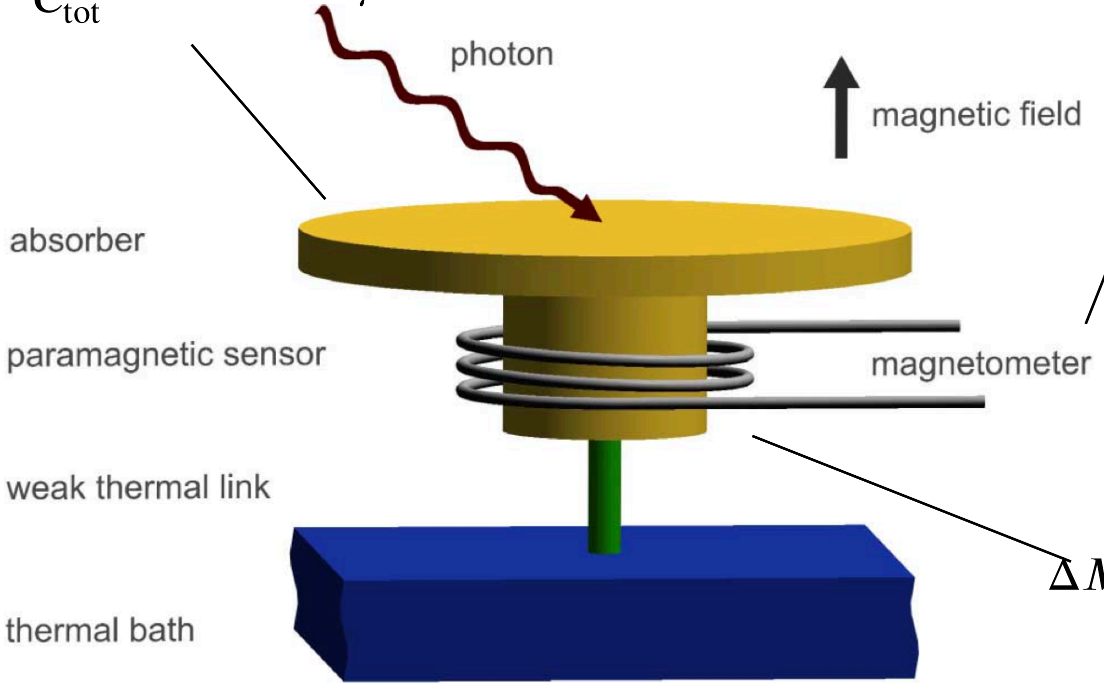
MMC working principle

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

tunes detection efficiency
→ determines C_{abs}

E_γ

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



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

DOI: 10.1109/TASC.2009.2012724

tunes signal decay time τ_D
→ detection speed

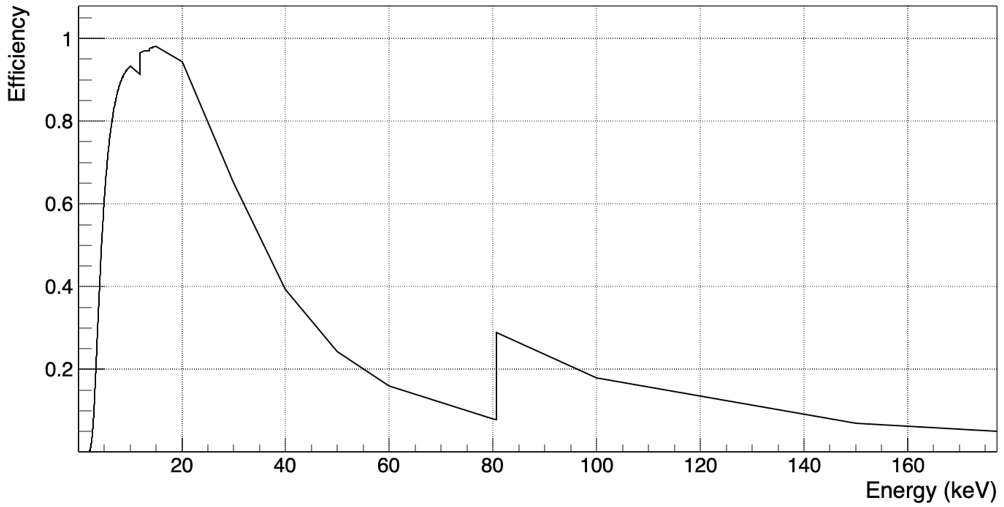
Energy resolution:

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

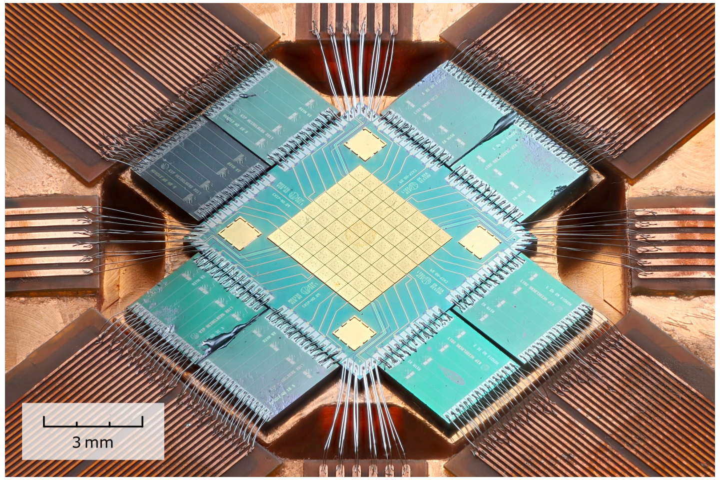
Beamtime 2024 – Setup

“maXs-30” MMC

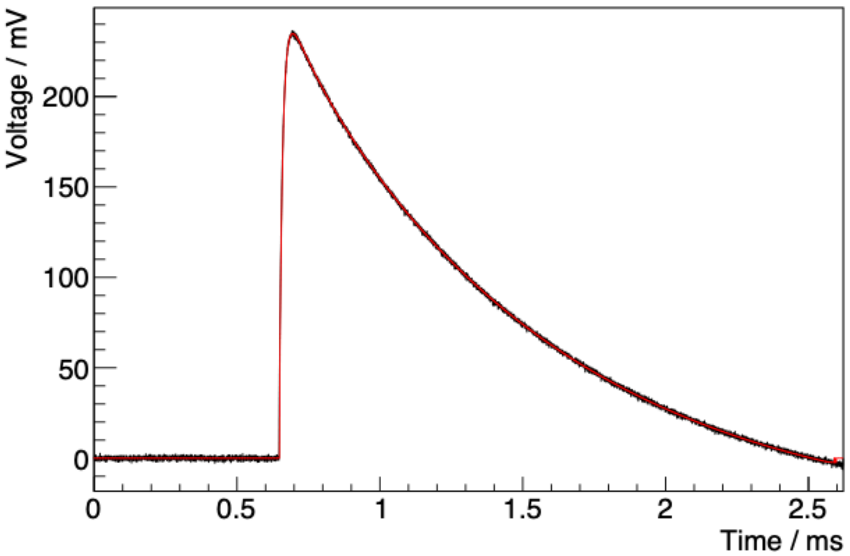
- Operated at approx. 20 mK
- High efficiency: > 90% from 8 – 22 keV
- High resolution of ~10-20 eV at 18 keV
- 64 absorbers: each 500 μm x 500 μm x 20 μm
- max. rate per pixel ≲ 0.5-1 Hz



Calculated detection efficiency for maXs-30 type detector

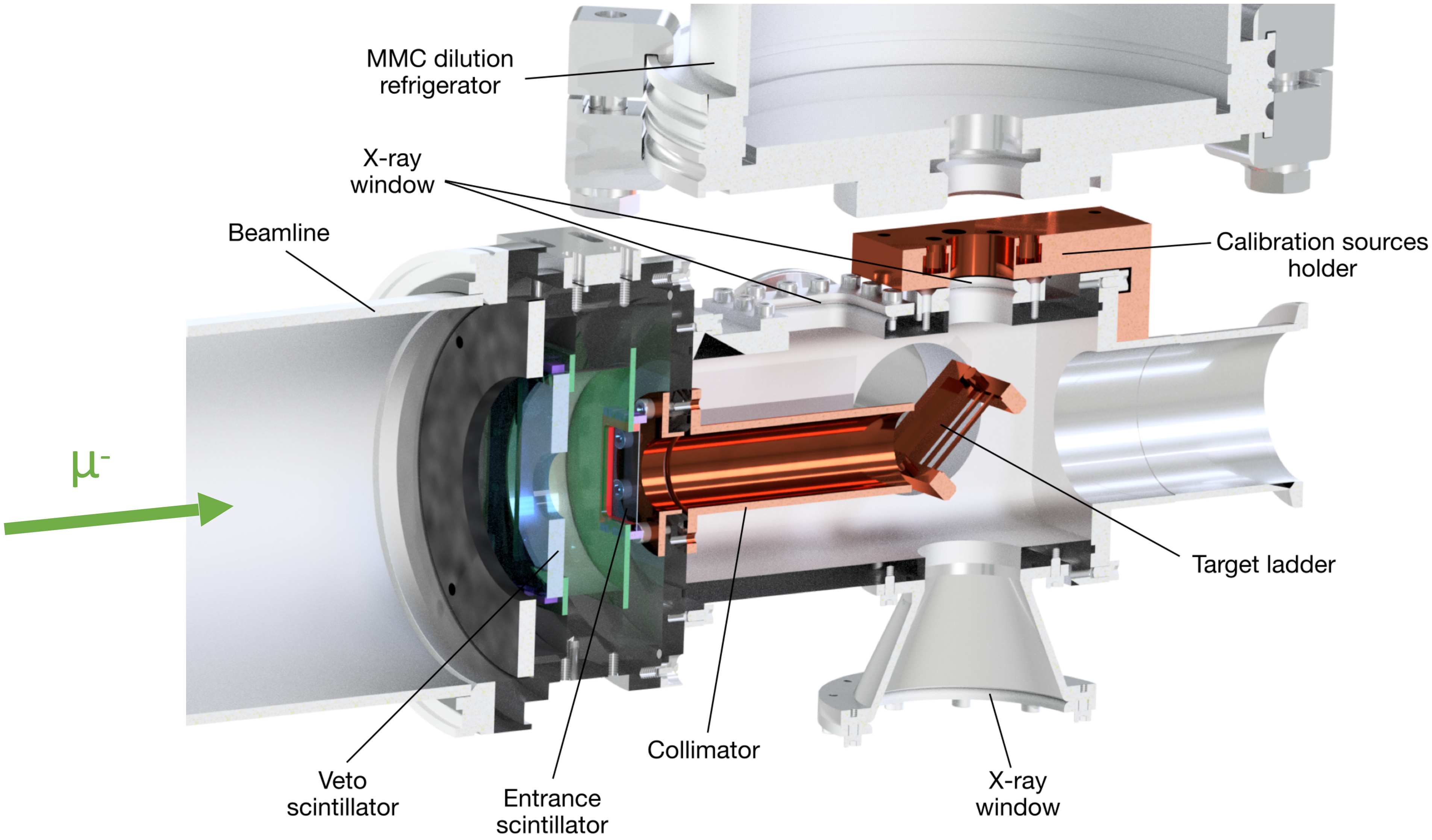


DOI: 10.1007/s10909-024-03141-x

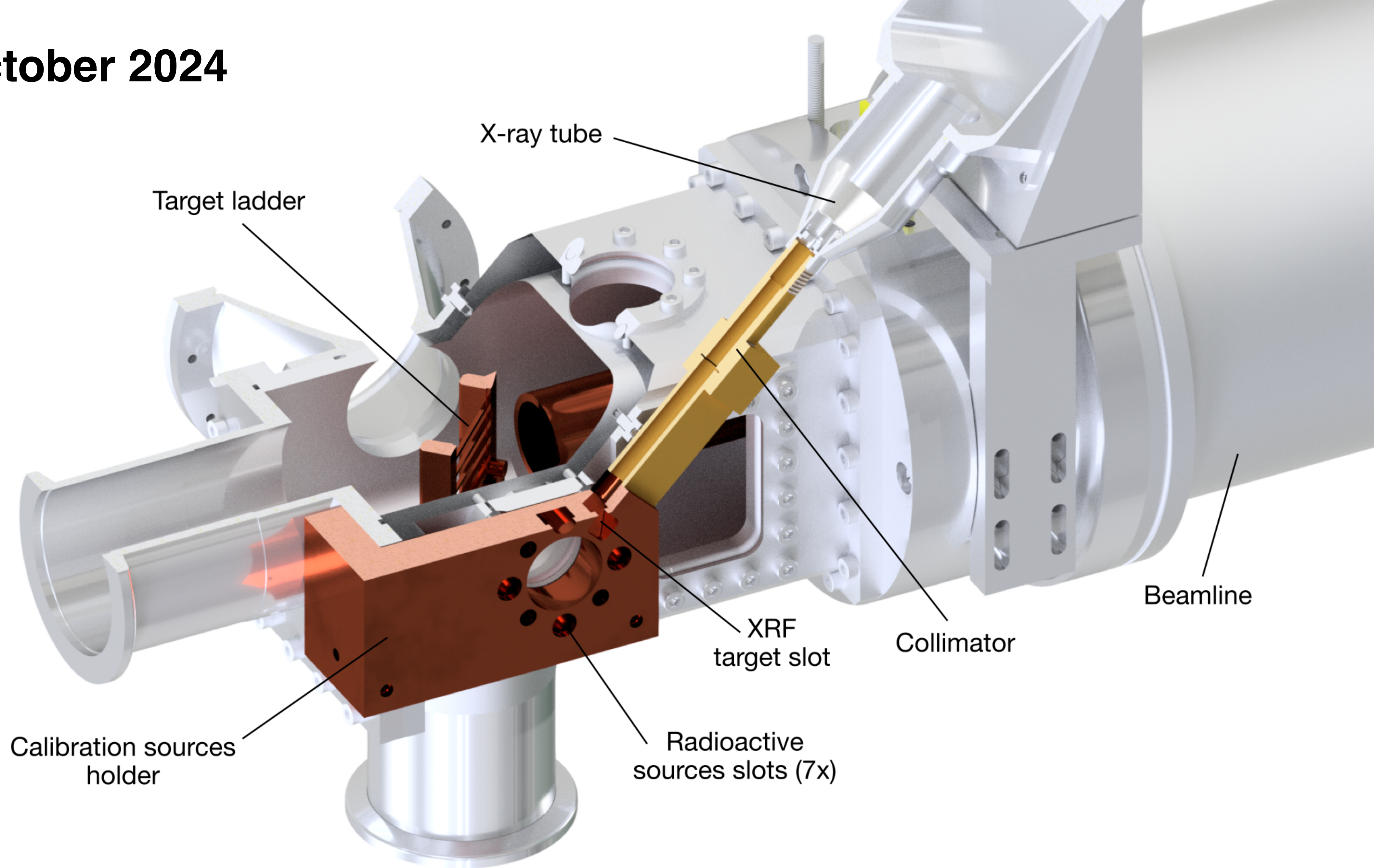


Typical photon pulse shape

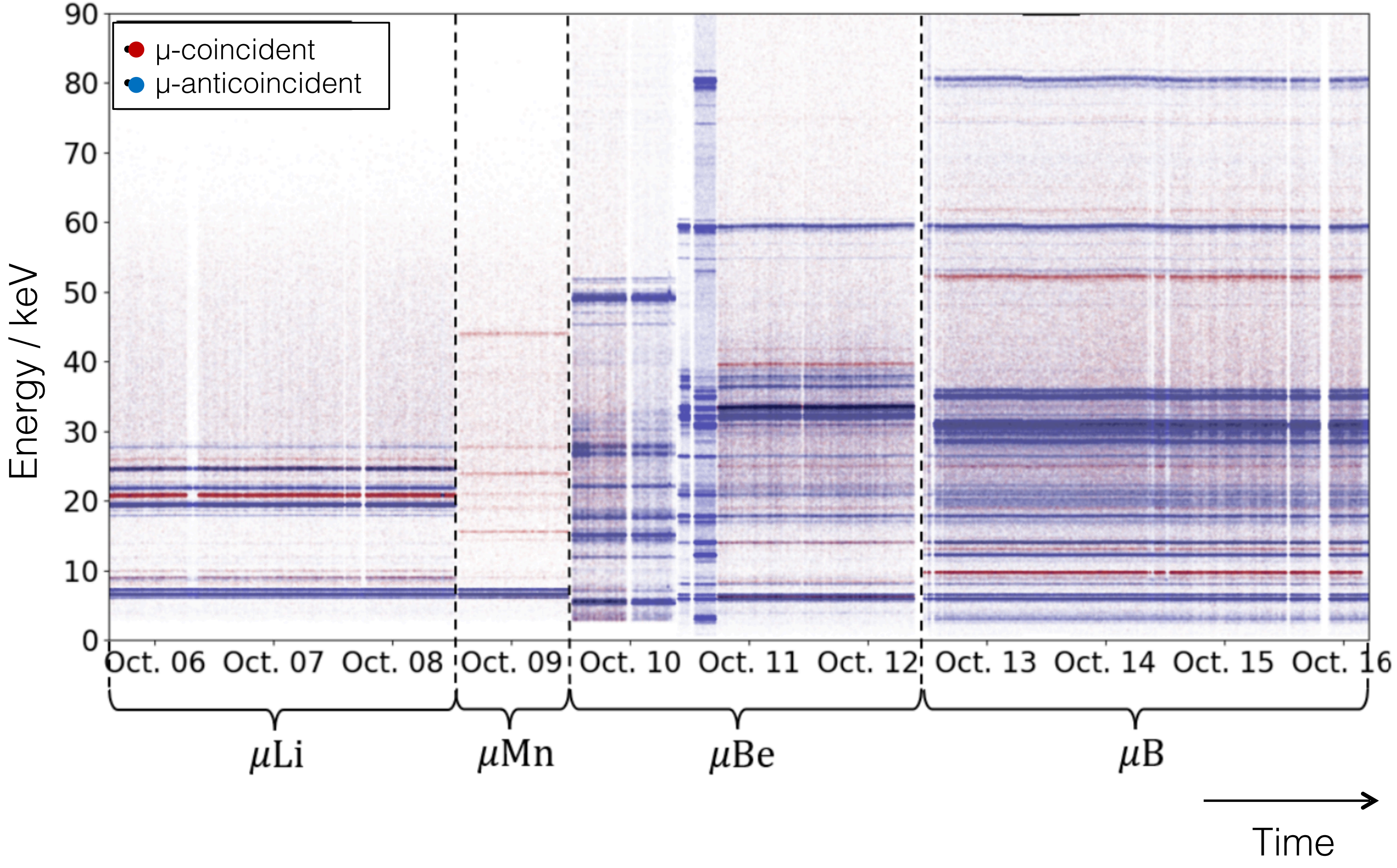
Beamtime 2024 – Setup



Setup October 2024



Beamtime 2024

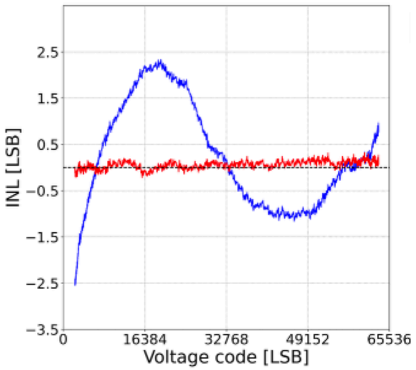


e.g. lithium targets:

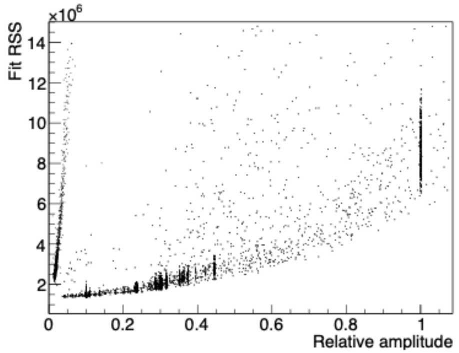
+ Calibration with:

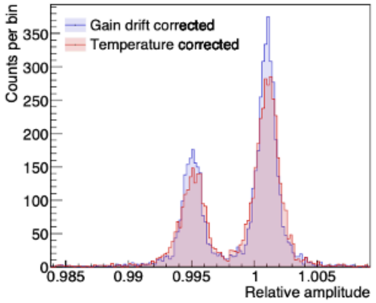
- ^{55}Fe source
- Mo & Ag XRF

Analysis Procedure Development



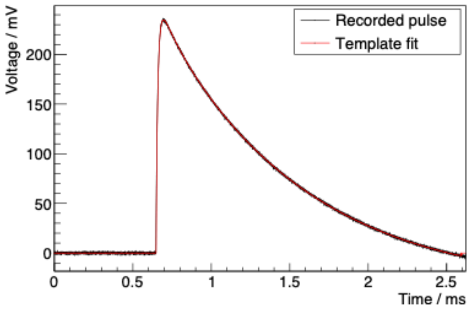
✓ Remove electron hits



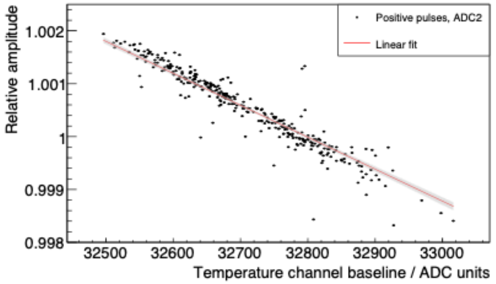


✓ Summed high-statistics spectra for physics analysis

ADC calibration → fitting pulses → event identification → Temperature & gain drift correction → calibration



✓ Amplitudes
✓ Goodness-of-Fit

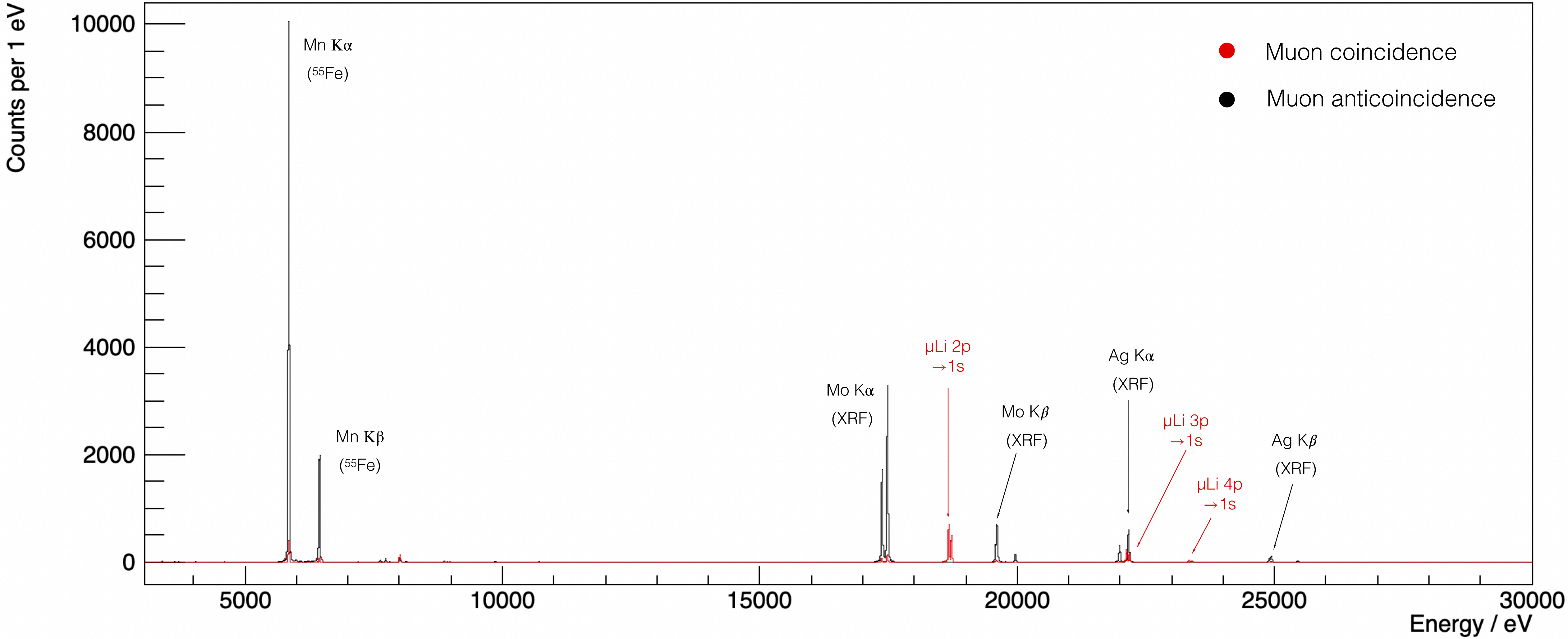


✓ Correction for temperature variations

Muonic Lithium Data 2024

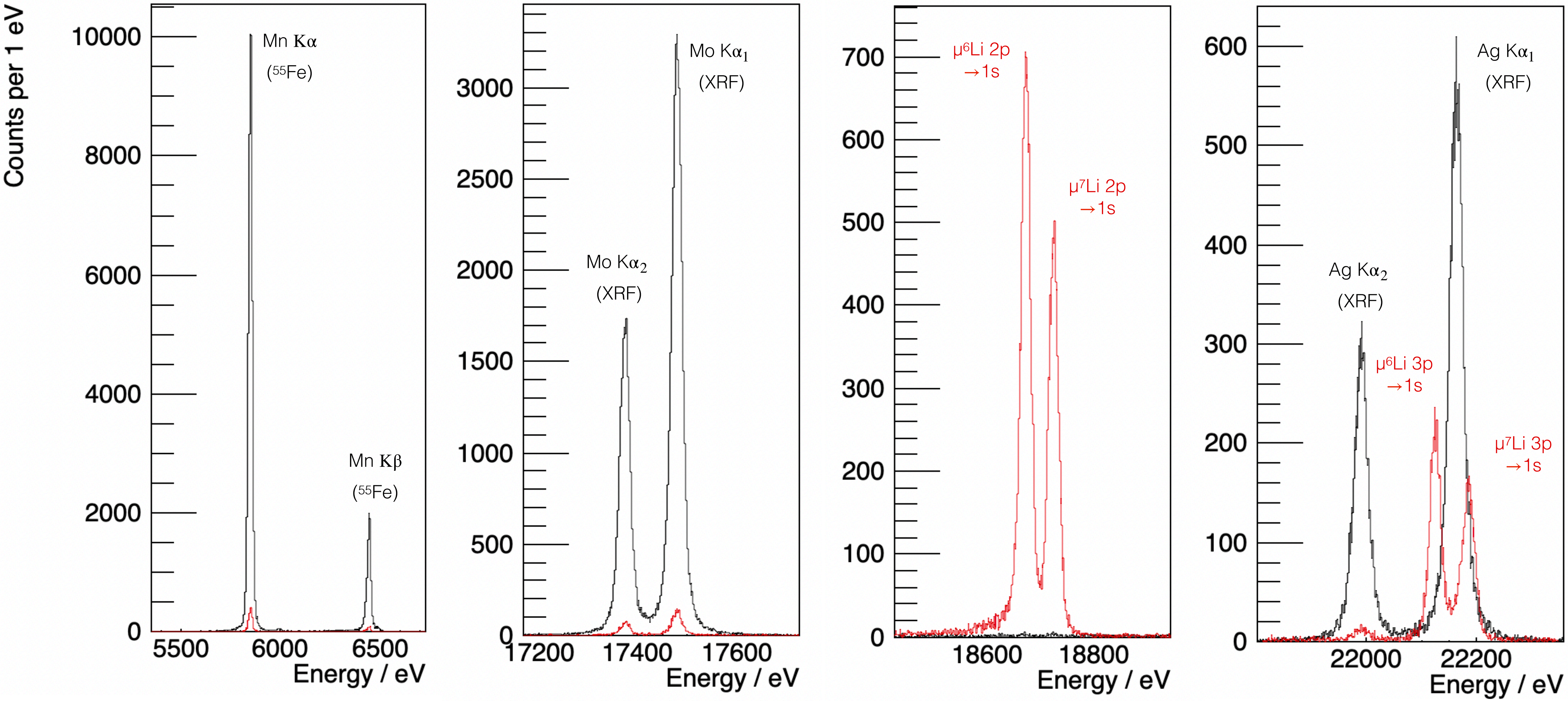
Preliminary results

50 pixels, ~70 hours measurement time



Muonic Lithium Data 2024

Preliminary results

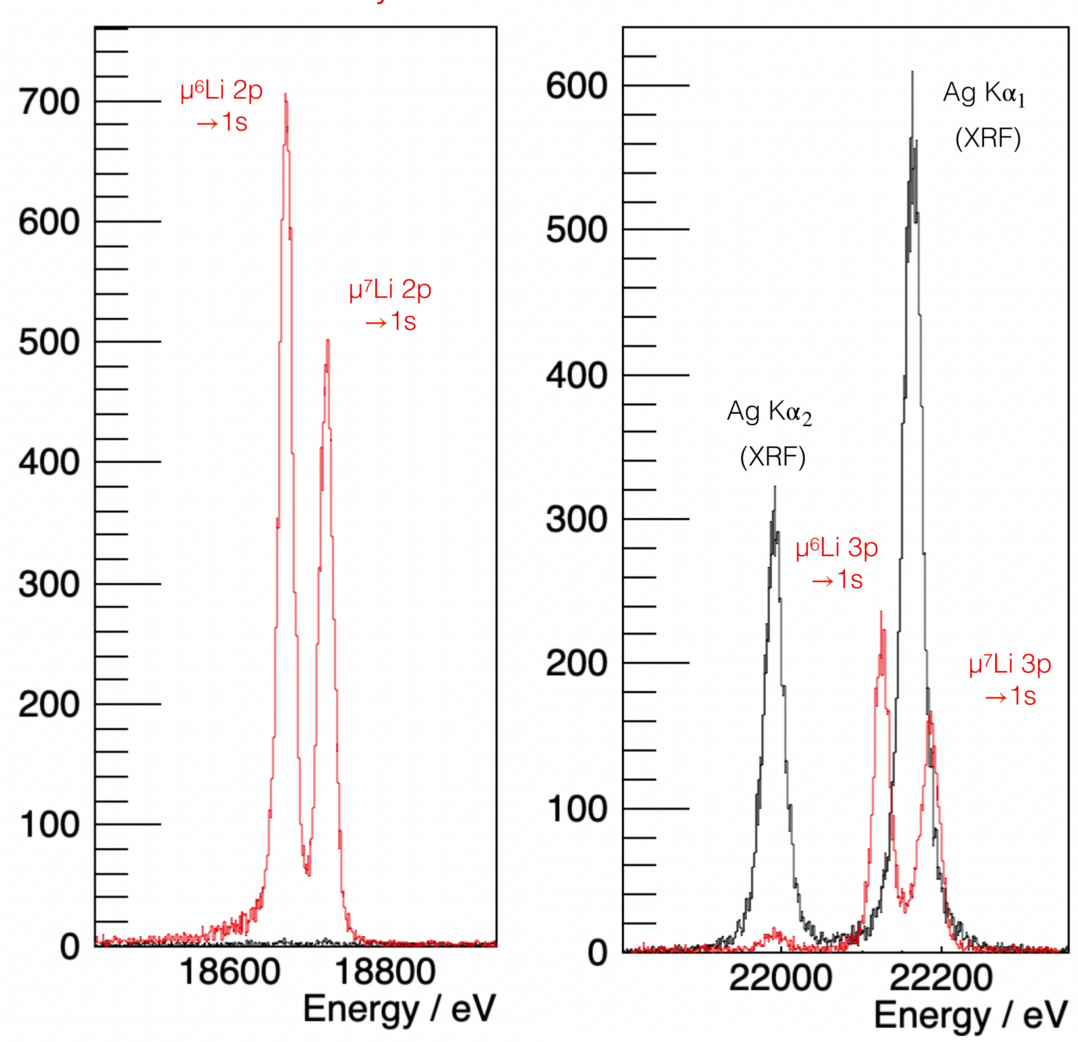


Muonic Lithium Data 2024

Preliminary results

50 pixels added, 70h measurement
FWHM: ~20 eV
⇒ stat. uncertainty ~0.1 eV

- Lithium analysis nearly complete
  → thorough line shape analysis & systematics study in progress
- Be, B work in progress

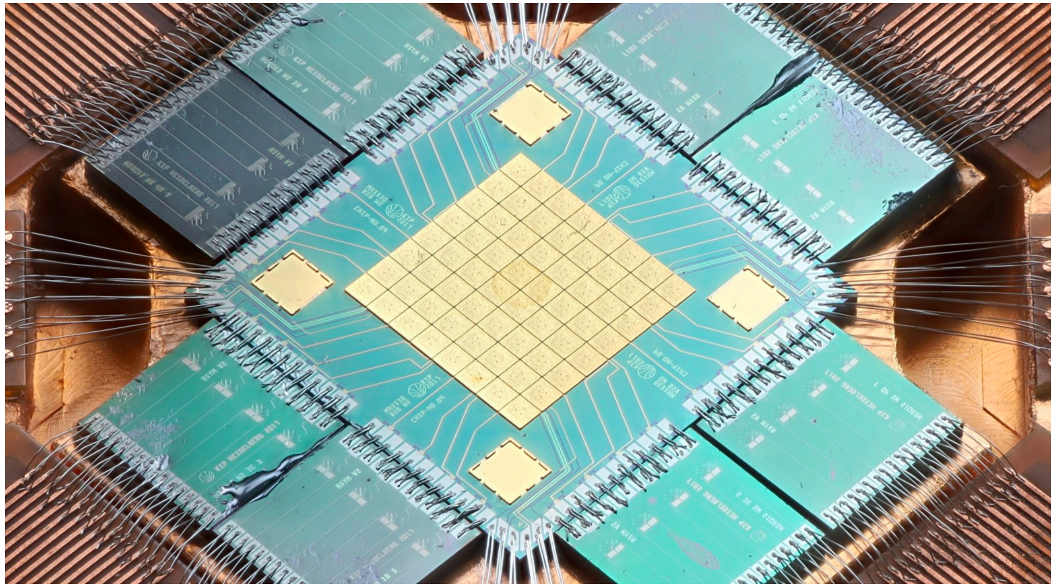


Summary & Outlook

First measurements of light muonic atoms using MMCs successfully conducted at PSI in 2024

Lithium results expected this year! Be & B following

Next beamtime at PSI granted for October this year – targeting $^{16,18}O$ & $^{12,13}C$. Using new optimized MMCs for higher energies



UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

KIRCHHOFF-INSTITUT FÜR PHYSIK

ETH zürich

PSI

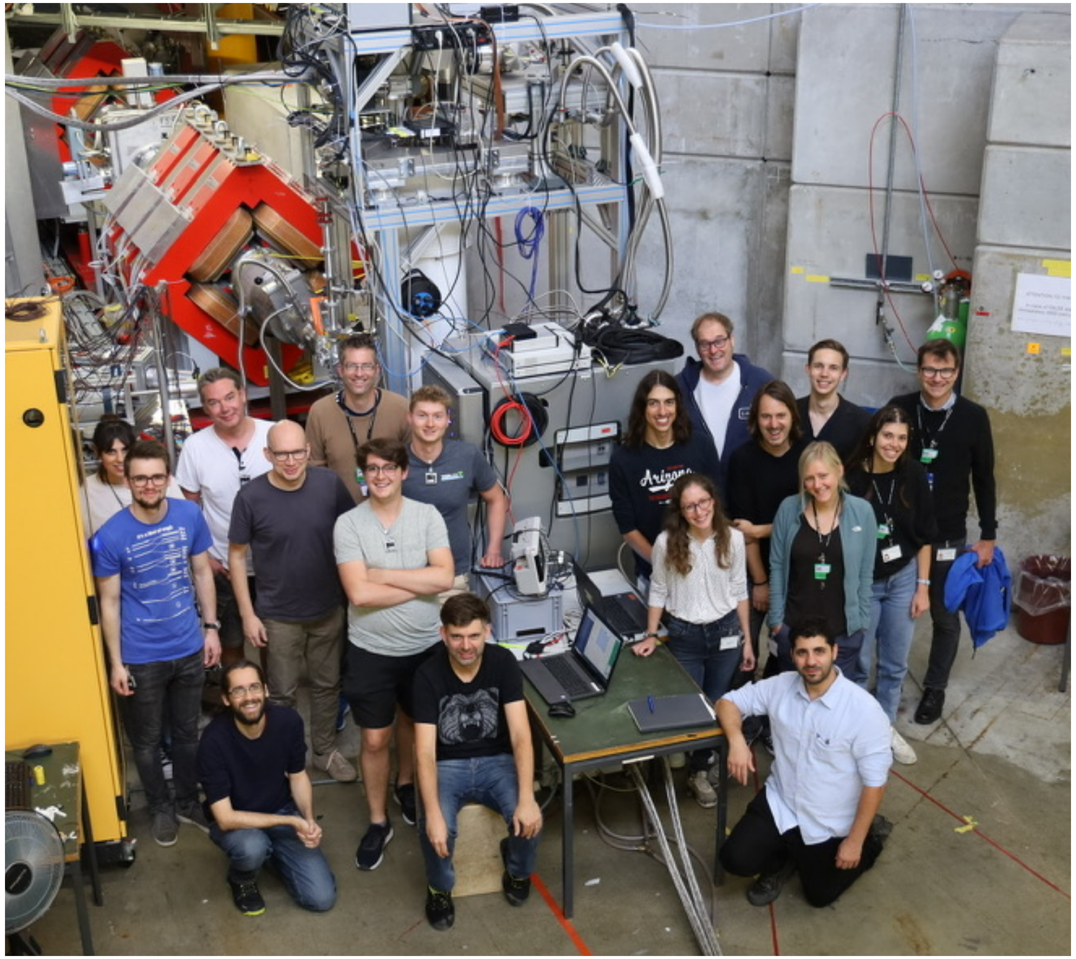
QUARTET

$2p_{3/2}$

$2p_{1/2}$

$2s$

$1s$



JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Laboratoire Kastler Brossel
Physique quantique et applications

TECHNION
Israel Institute of Technology

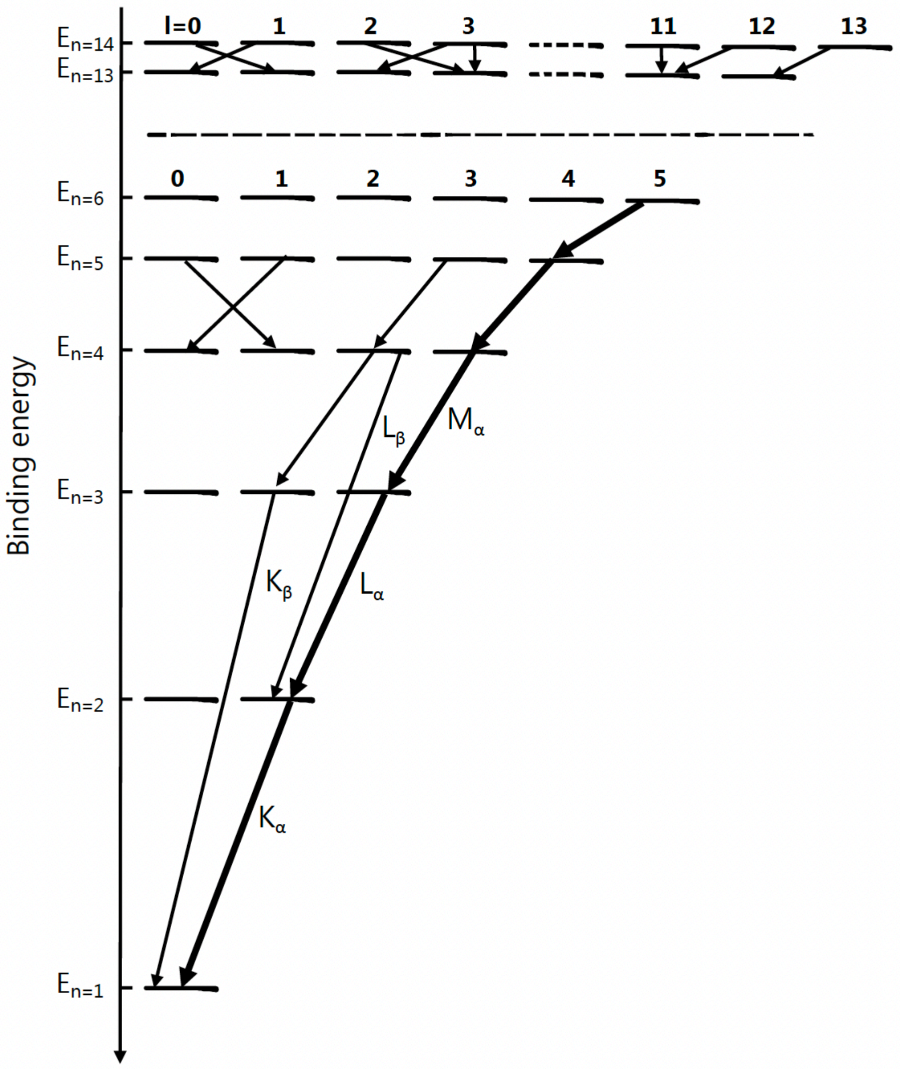
KU LEUVEN

NOVA
UNIVERSIDADE NOVA DE LISBOA

Backup

Muonic Atoms Cascade

PSI



”maXs-30” MMC from Heidelberg

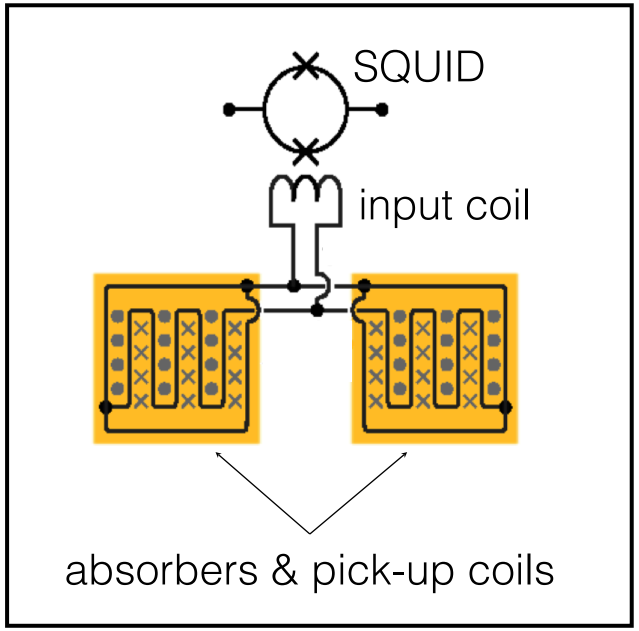
Detector design

Absorber pair wise coupled

→ Reduced sensitivity towards global temperature changes

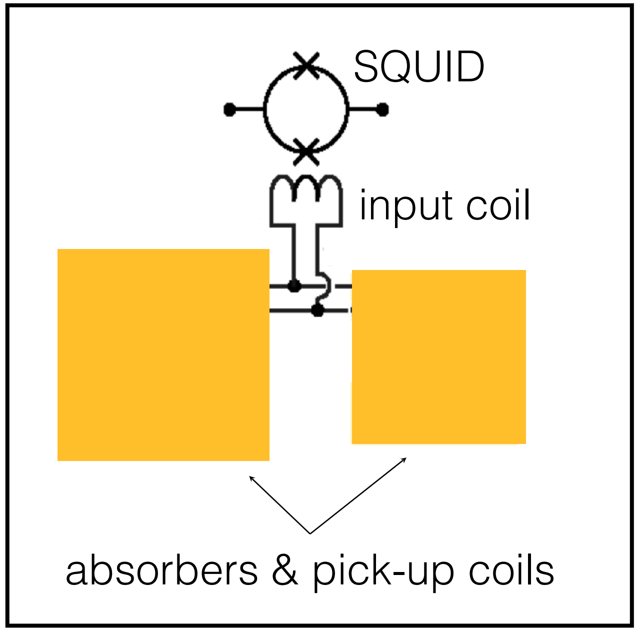
→ (Reduced number of readout channels necessary)

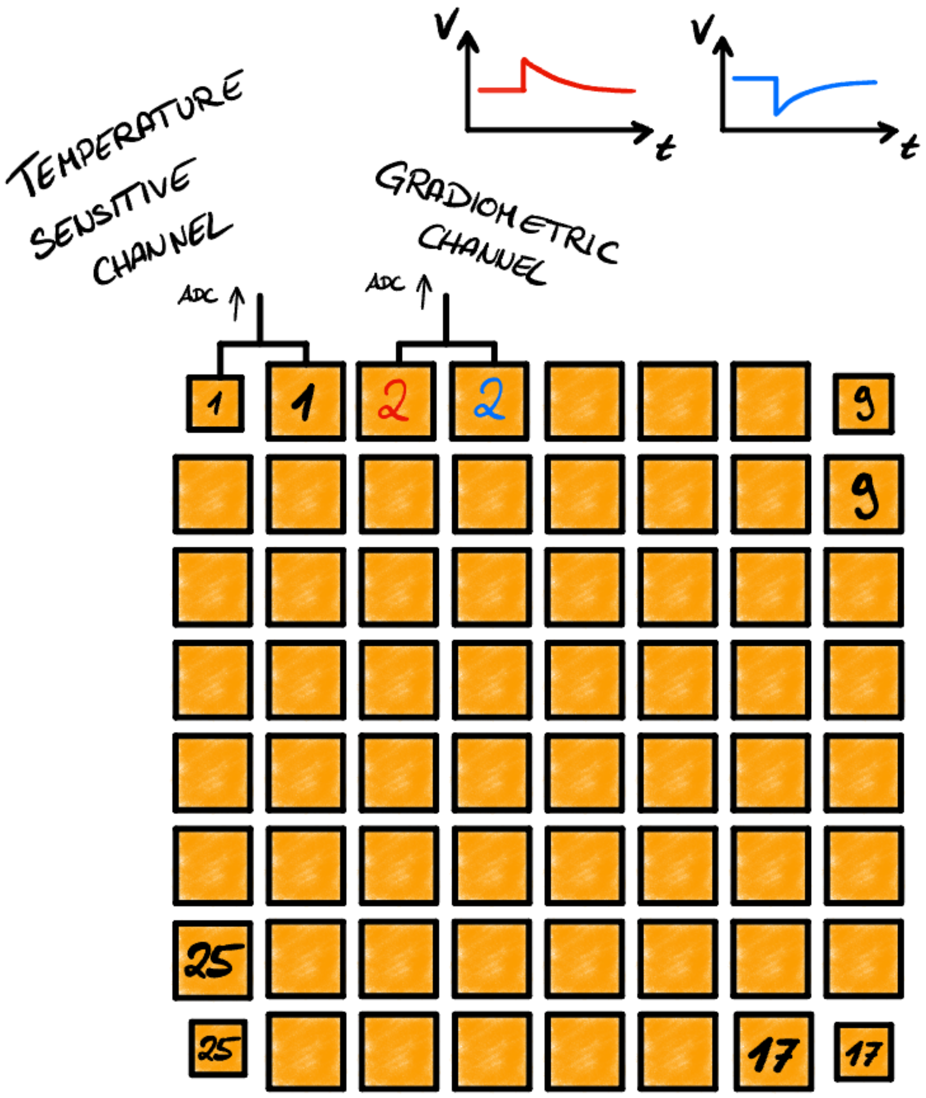
Gradiometric design:



DOI: 10.1063/1.3292407

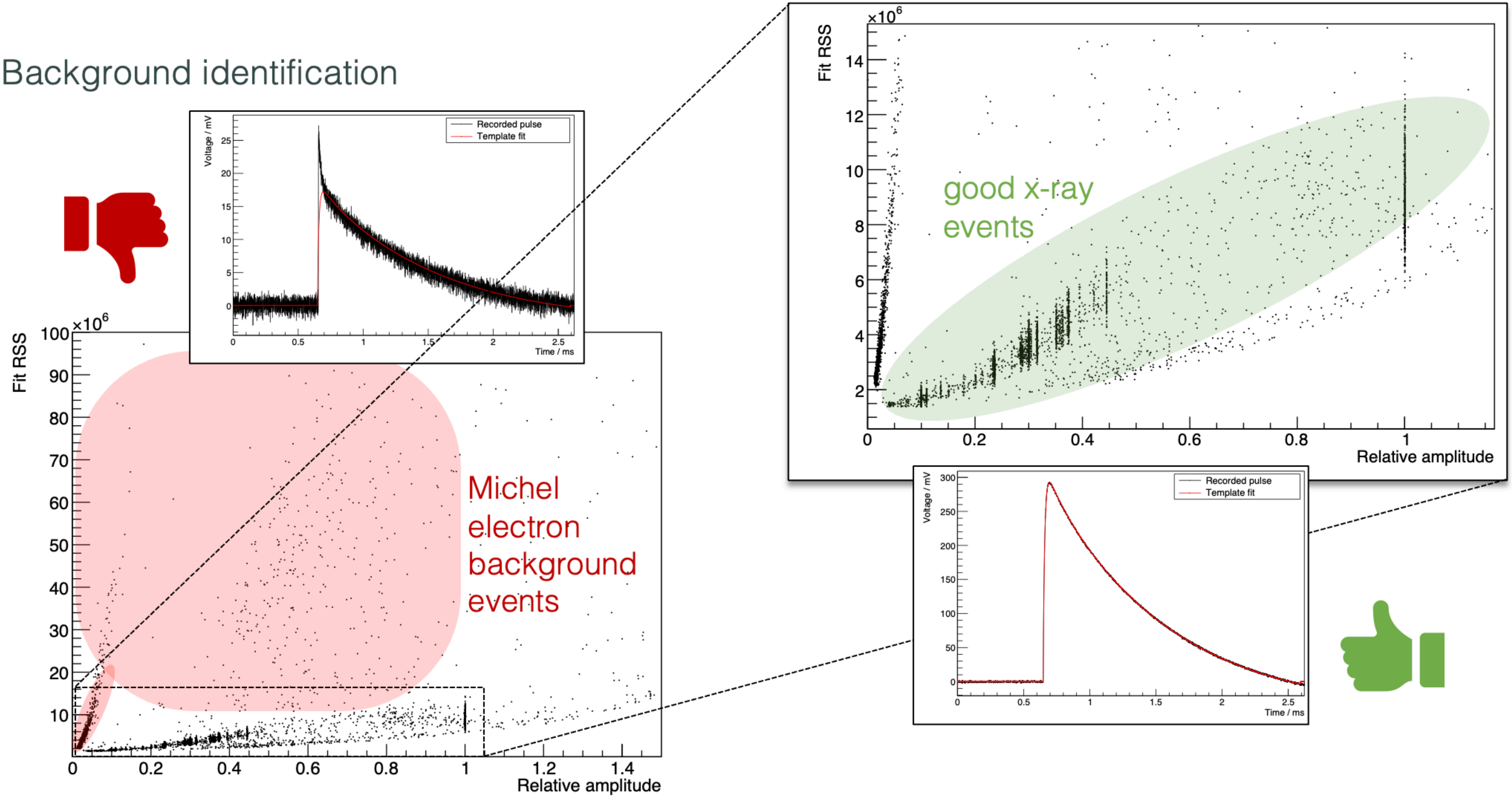
Temperature sensitive design:





Data analysis workflow

Background identification

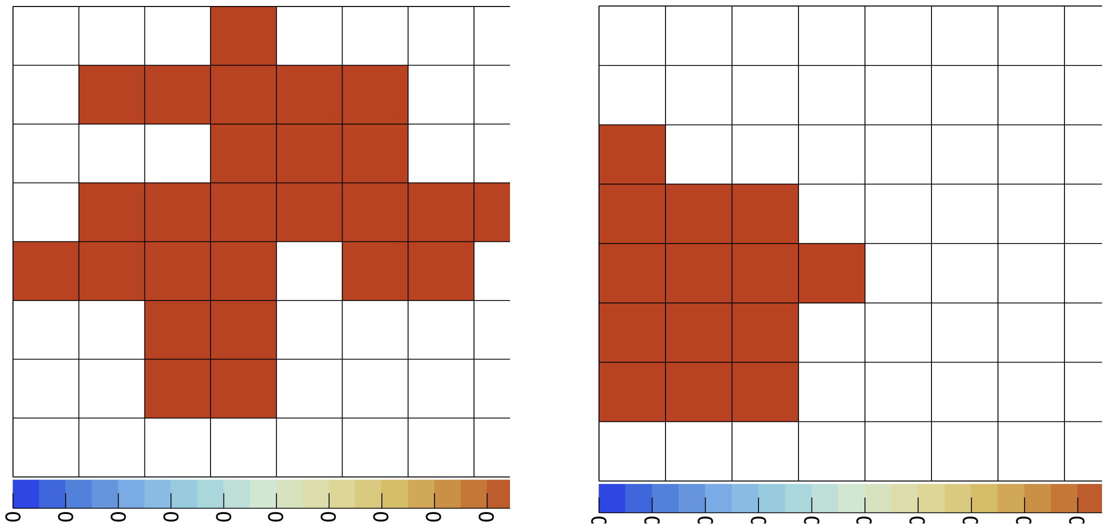


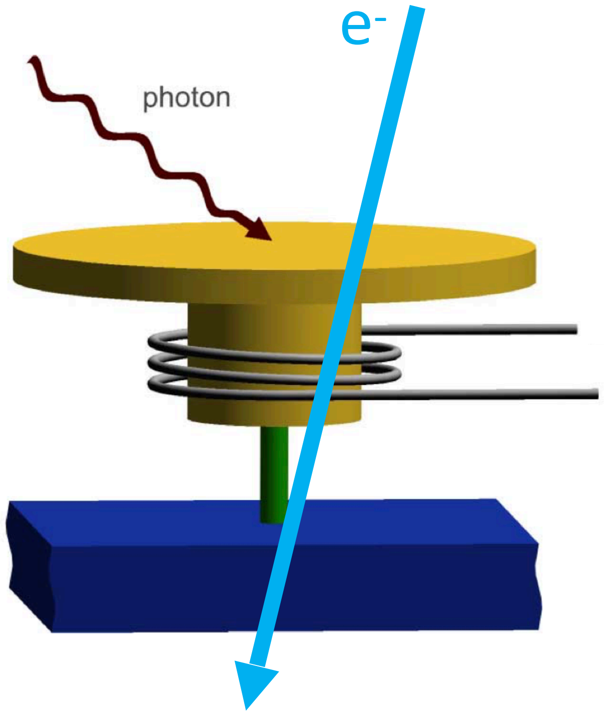
Data analysis workflow

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.:



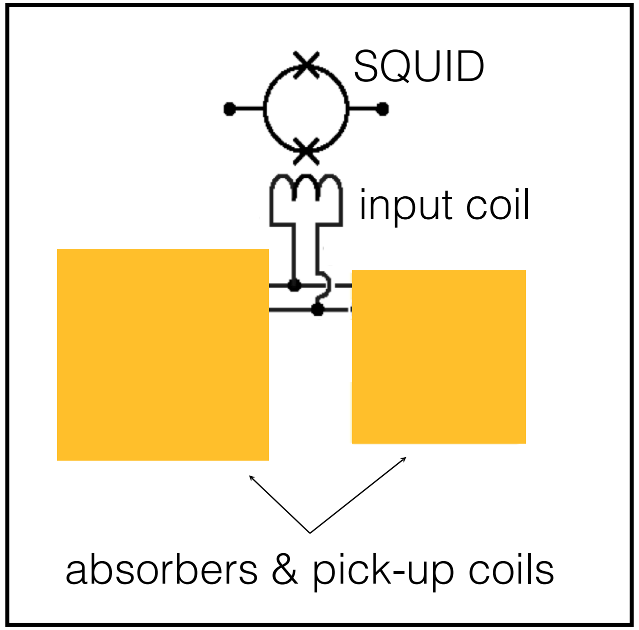


Michel electrons shoot through absorbers into silicon substrate and heat-up pixels “from the backside”

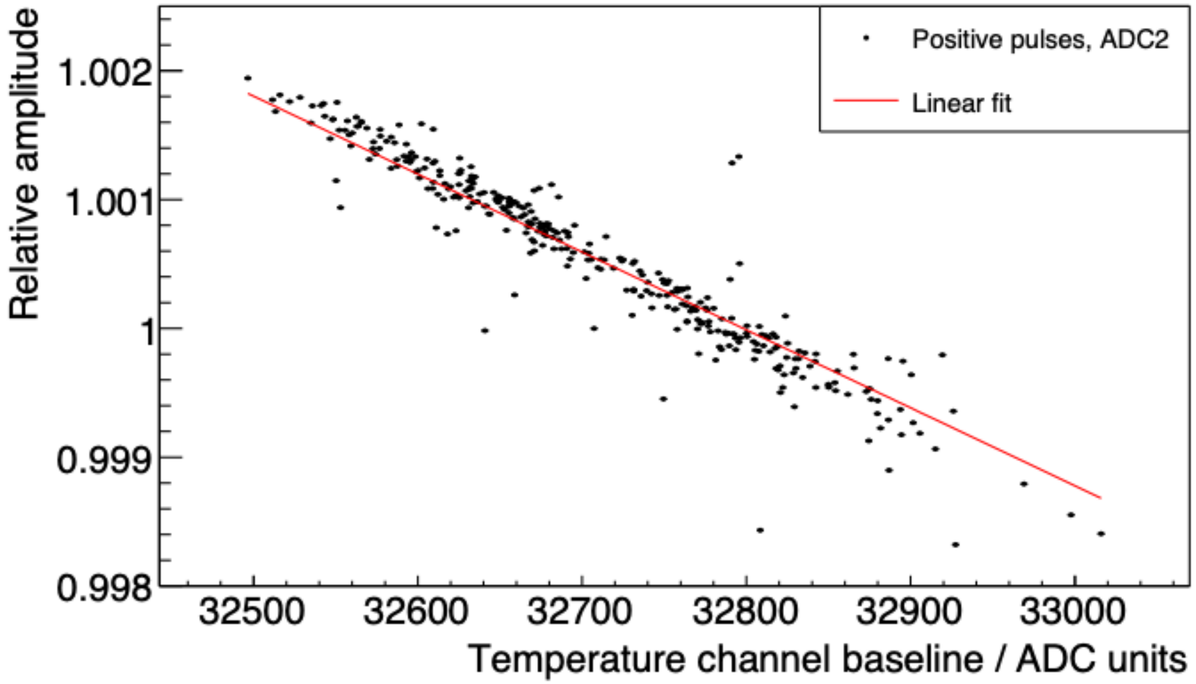
Data analysis workflow

Temperature correction

Temperature sensitive design:



Triggered with every event

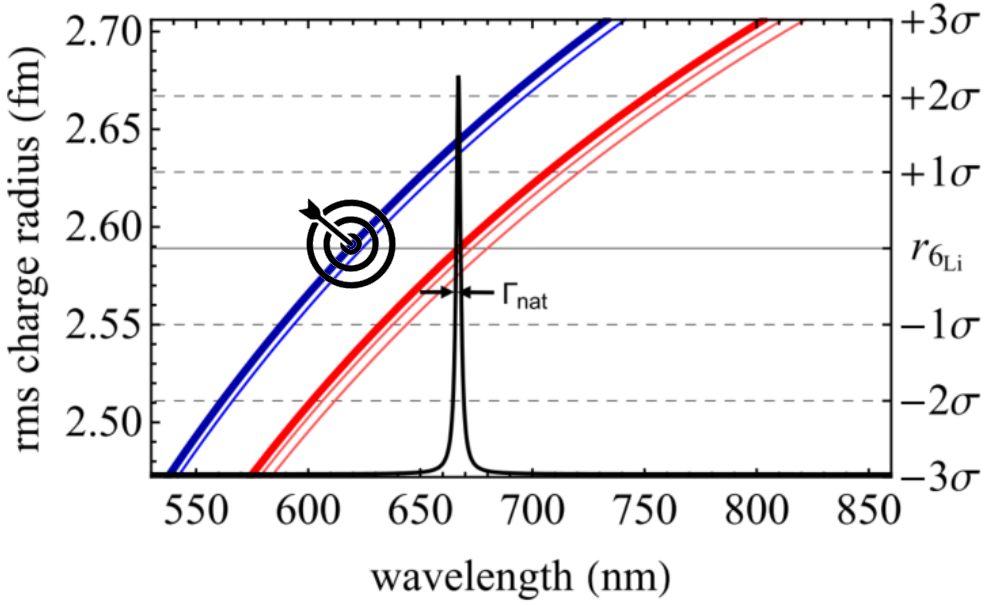


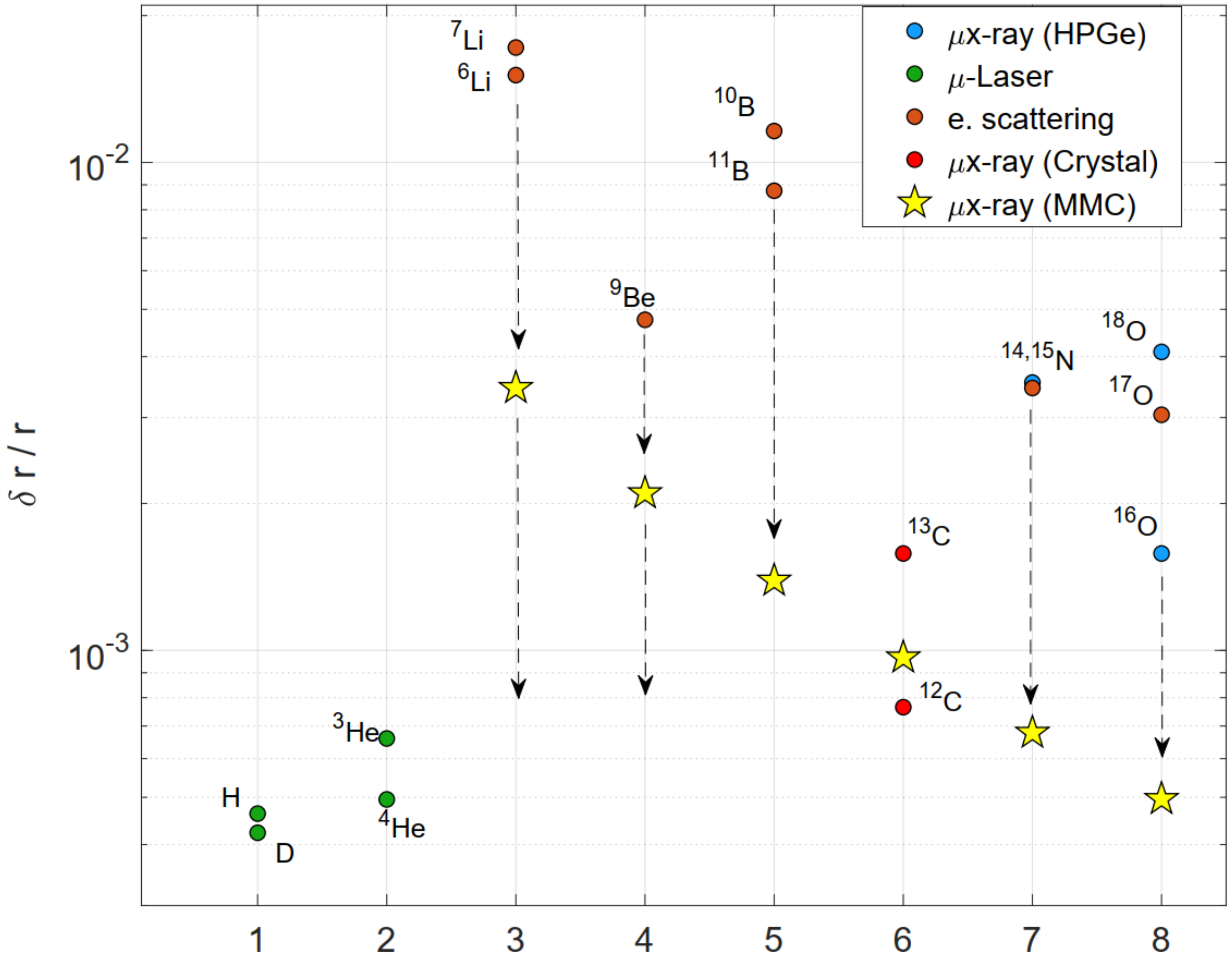
➢ Determine temperature sensitivity of gradiometric pixels and correct each event

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

PSI

- MMCs: Improve r_c of ^{6}Li by factor ~5.
- Narrow 2S-2P wavelength search from 200 nm to 20 nm
- Similarly for Be/B





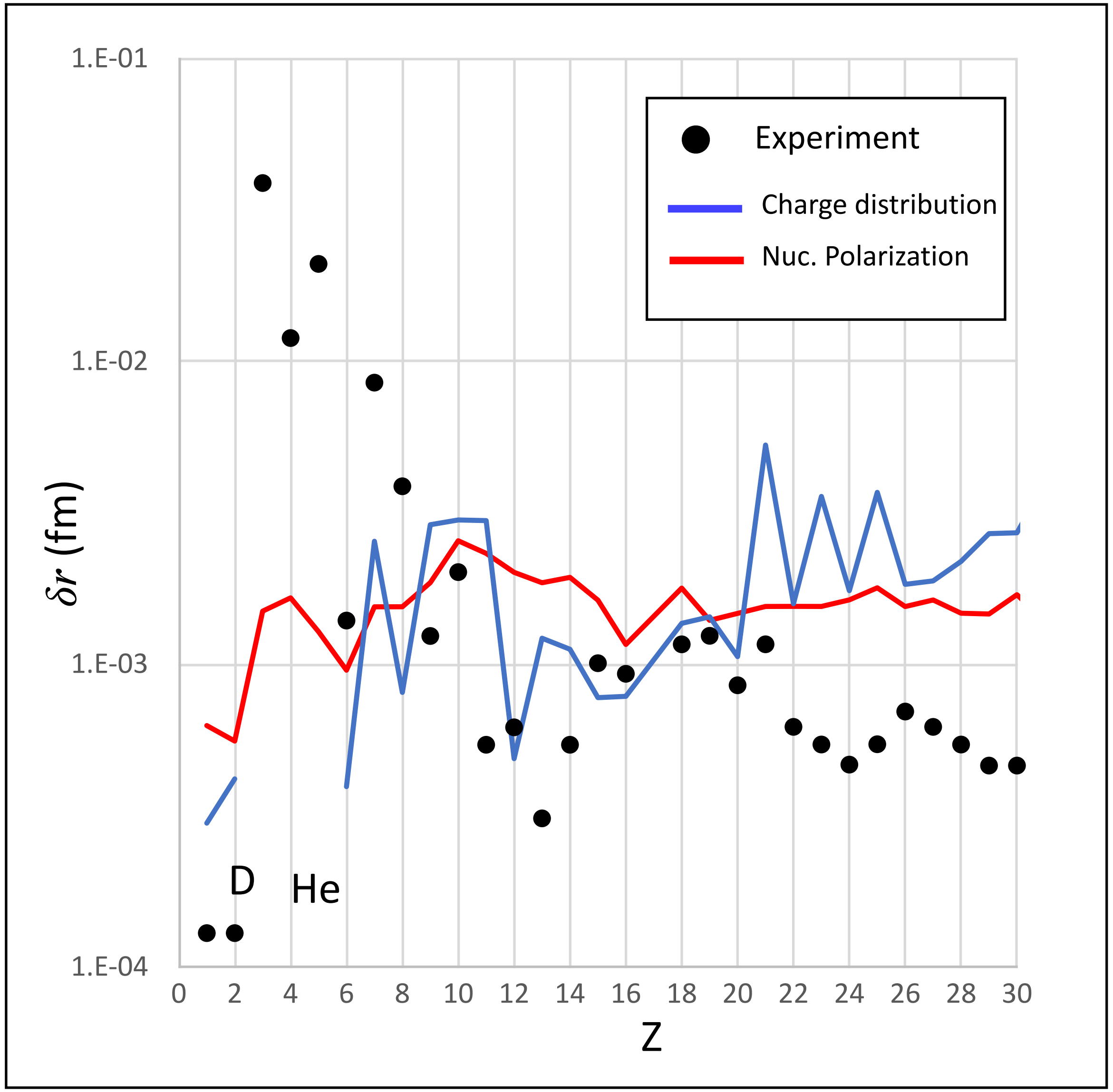
Input from Nuclear Theory

From theory, mainly nuclear polarization

- For Li-Ne $\lesssim (5\text{ ppm})(E_{2P-1S})$
- For isotope shifts $\lesssim (3\text{ ppm})(\Delta E_{2P-1S})$
- For non-S states, e.g. $\lesssim (1\text{ ppm})(\Delta E_{3D-2P})$

From experiment, mainly charge distributions
Motivation for modern electron scattering experiments: Li, Be, B, N, O, …

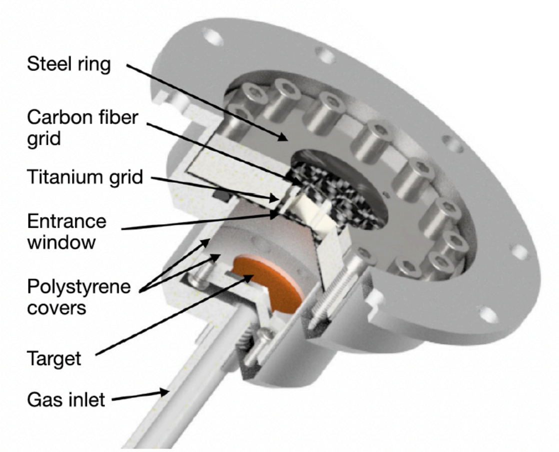
Muonic lithium atoms:
Nuclear structure corrections to the Lamb shift
Simone Salvatore Li Muli[1*], Anna Poggialini[2] and Sonia Bacca[1†]

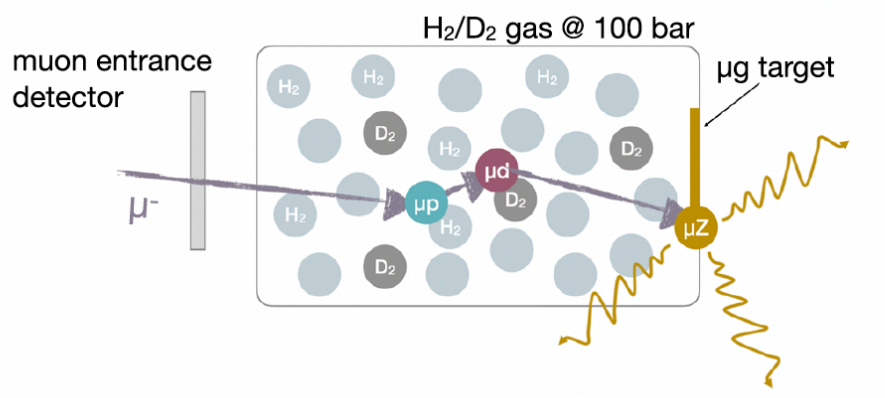


Not so light muonic atoms

PSI

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

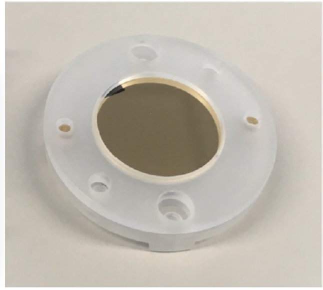




Muonic atom spectroscopy with microgram target material

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]

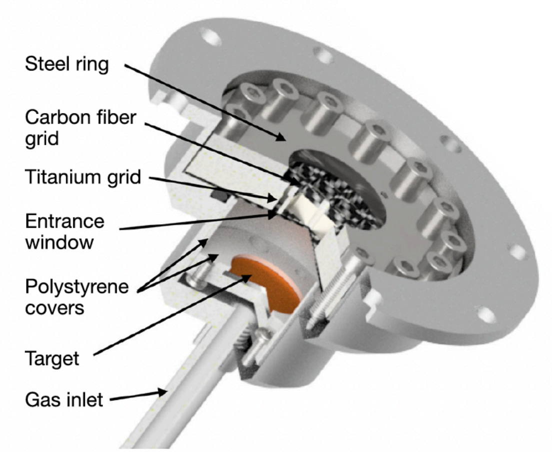
https://doi.org/10.1140/epja/s10050-023-00930-y

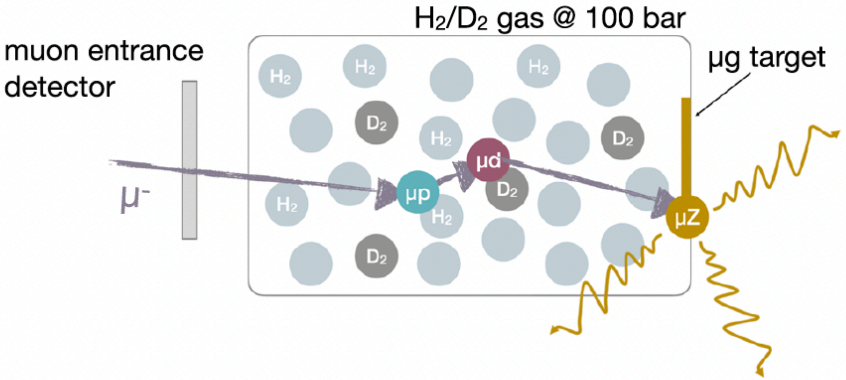


5 μg vapor deposited Au

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

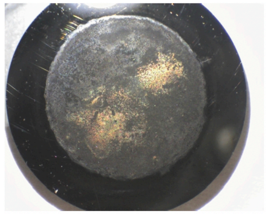
Studies of muonic ^{185,187}Re, ^{226}Ra, and ^{248}Cm for the extraction of nuclear charge radii

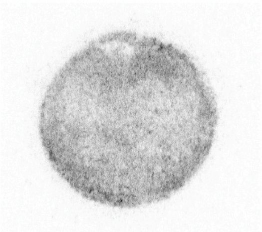
presented by

STERGIANI MARINA VOGIATZI

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

Spectroscopy of 15 μg radioactive ^{248}Cm

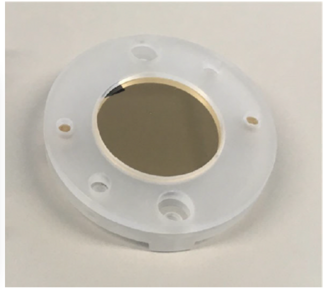




Muonic atom spectroscopy with microgram target material

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