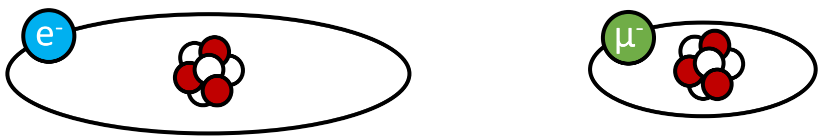
X-Ray Spectroscopy of Light Muonic Atoms

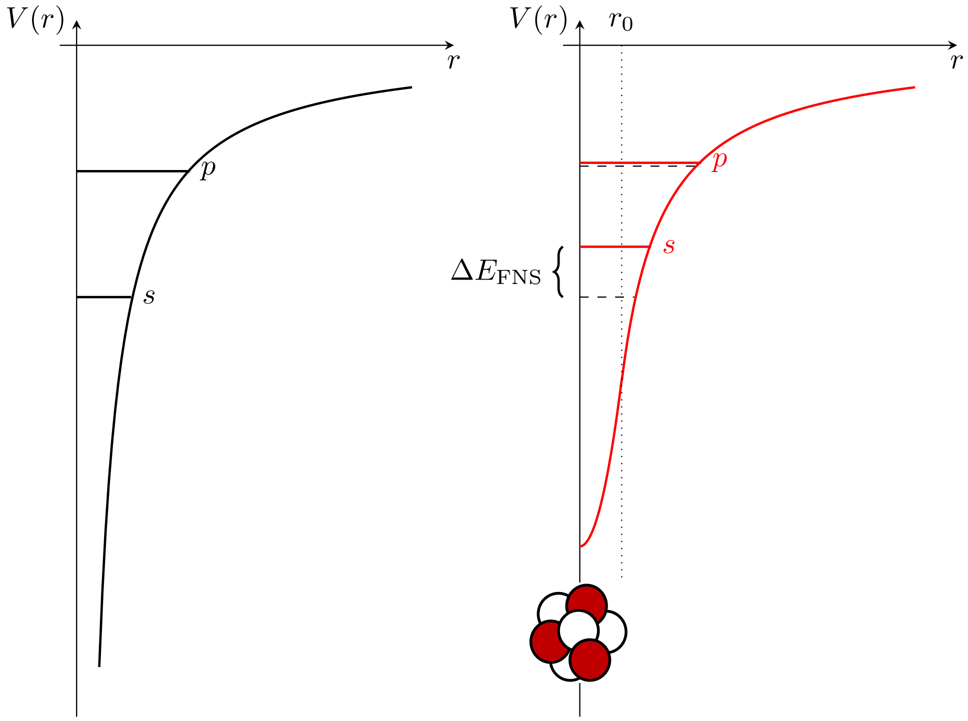
Katharina von Schoeler | Kirch group | ETH Zürich | Attract.Workshop Hamburg 2025

Muonic Atoms

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

$m_\mu \approx 200 \cdot m_e$





(a) Point nucleus

(b) Finite size nucleus

- 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!

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

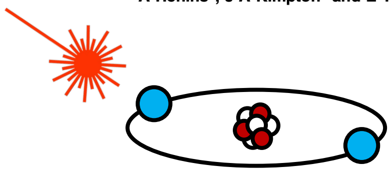
What to do with charge radii?

$\langle r^2 \rangle$

Precision QED tests in simple atomic systems

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

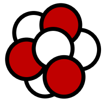
C T Chantler[1], A T Payne[1], J D Gillaspy[2], L T Hudson[2], L F Smale[1], A Henins[2], J A Kimpton[3] and E Takacs[4,5]



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]

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

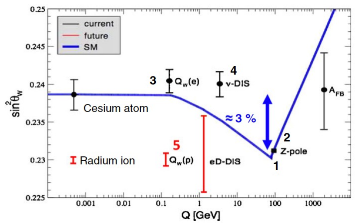
The size of the proton

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



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*

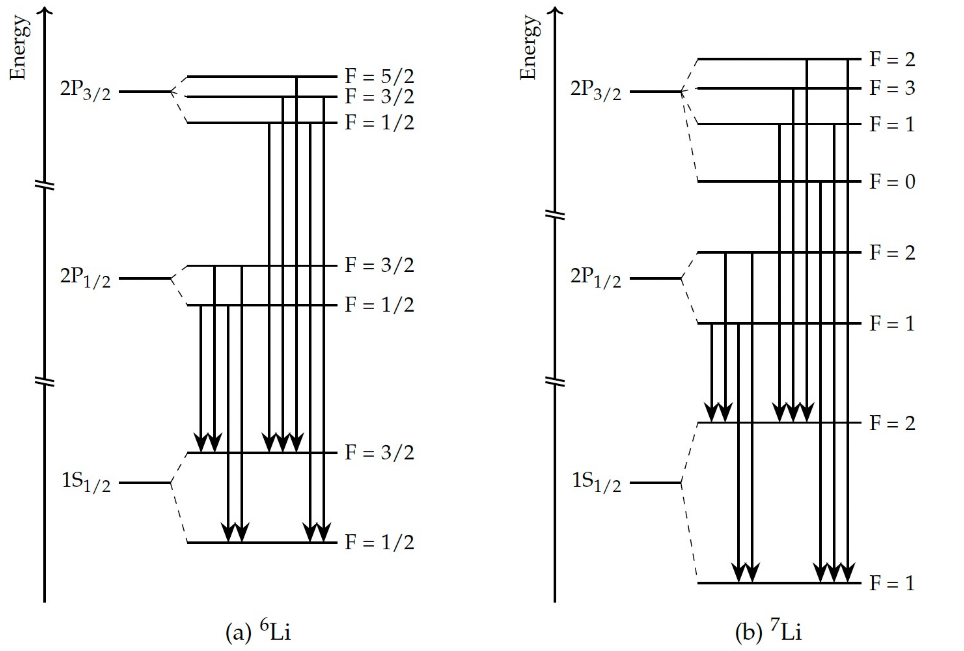
R. J. Harris, Jr.,† W. B. Shuler, M. Eckhause, R. T. Siegel, and R. E. Welsh
College of William and Mary, Williamsburg, Virginia
(Received 15 January 1968)

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 atom measurement so far not possible.

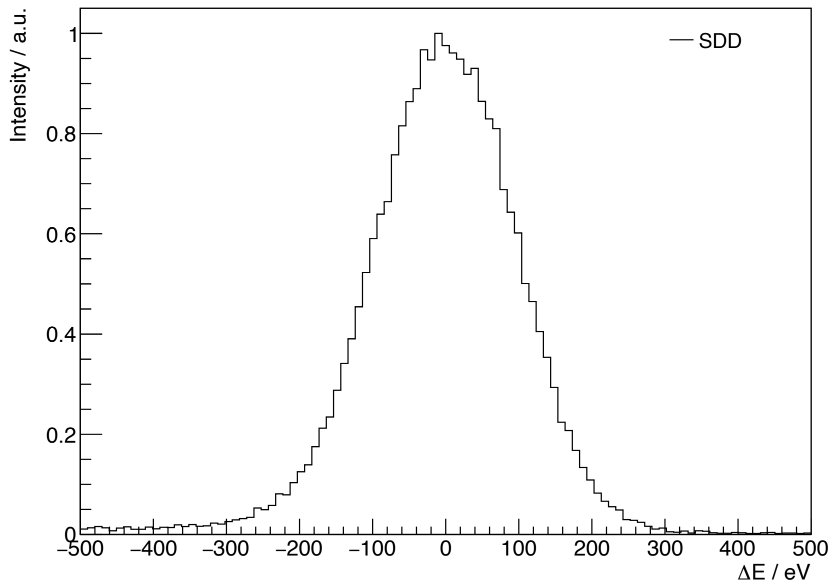
Only radii extracted from electron scattering until today.

Muonic Lithium



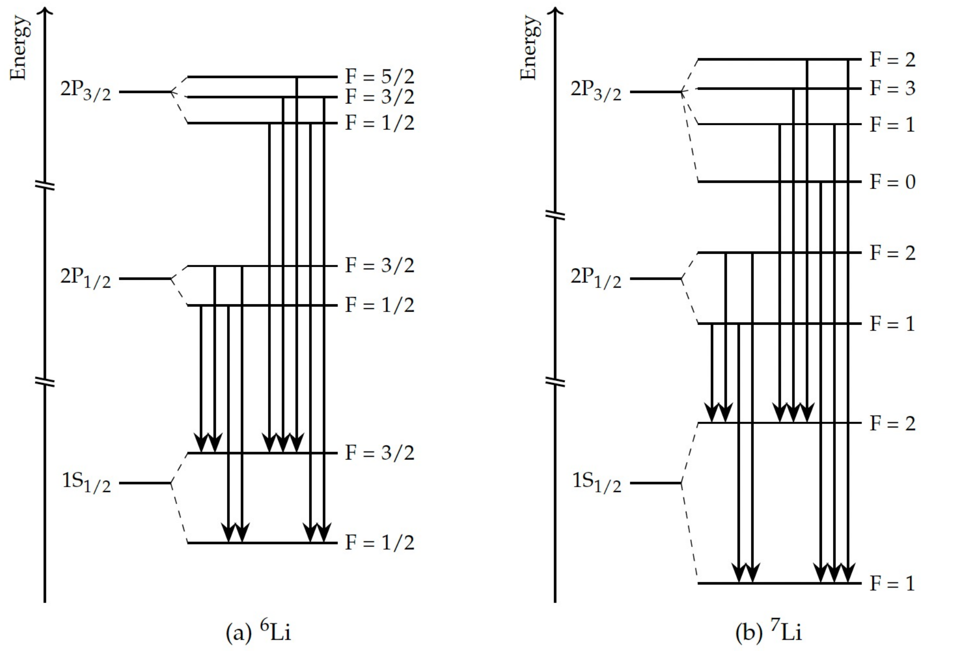
2 isotopes with hyper(fine) structure

= 19 lines within less than 100 eV!



Typical resolution of solid-state detectors @ 18 keV: > 200 eV

Muonic Lithium



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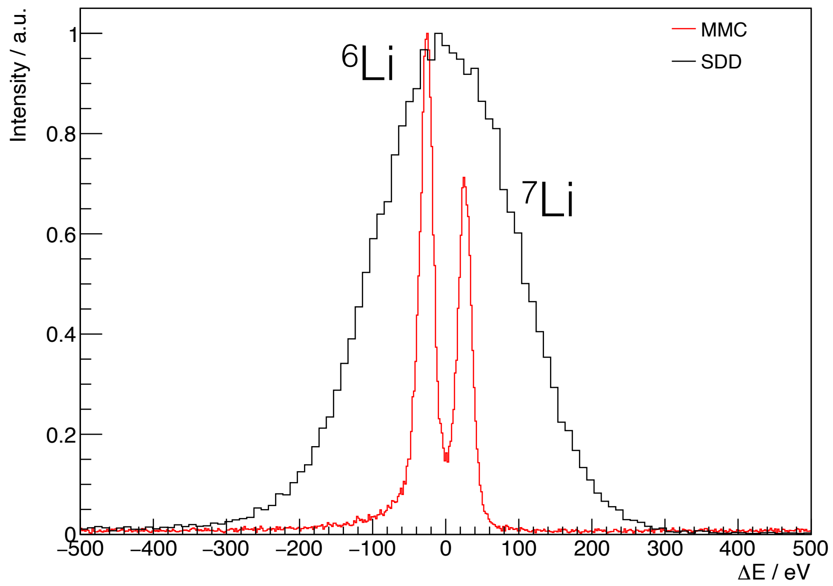
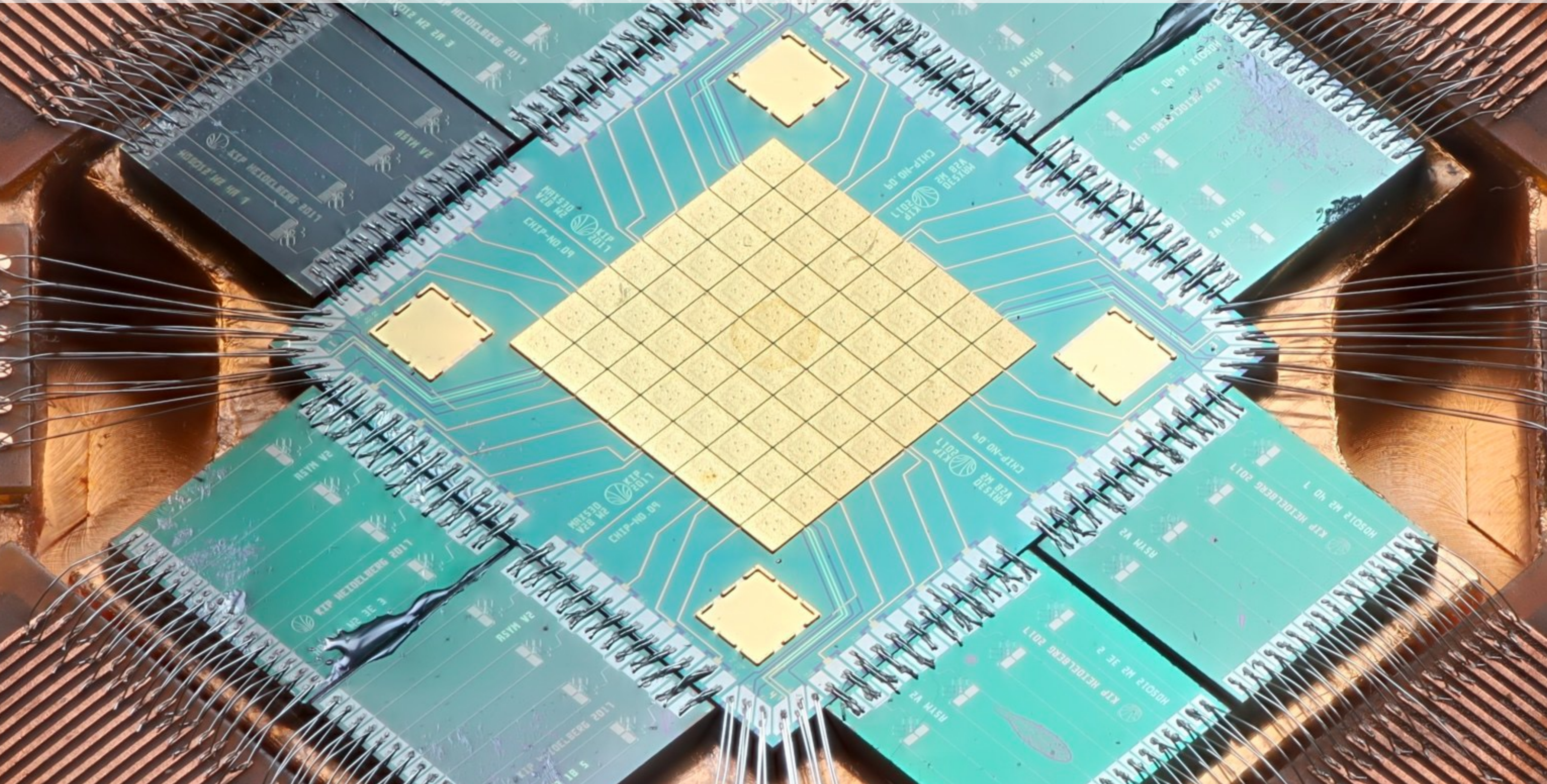


Typical resolution of solid-state detectors @ 18 keV: > 200 eV

vs. MMC: ~ 10-20 eV

Metallic Magnetic Calorimeter (MMC)



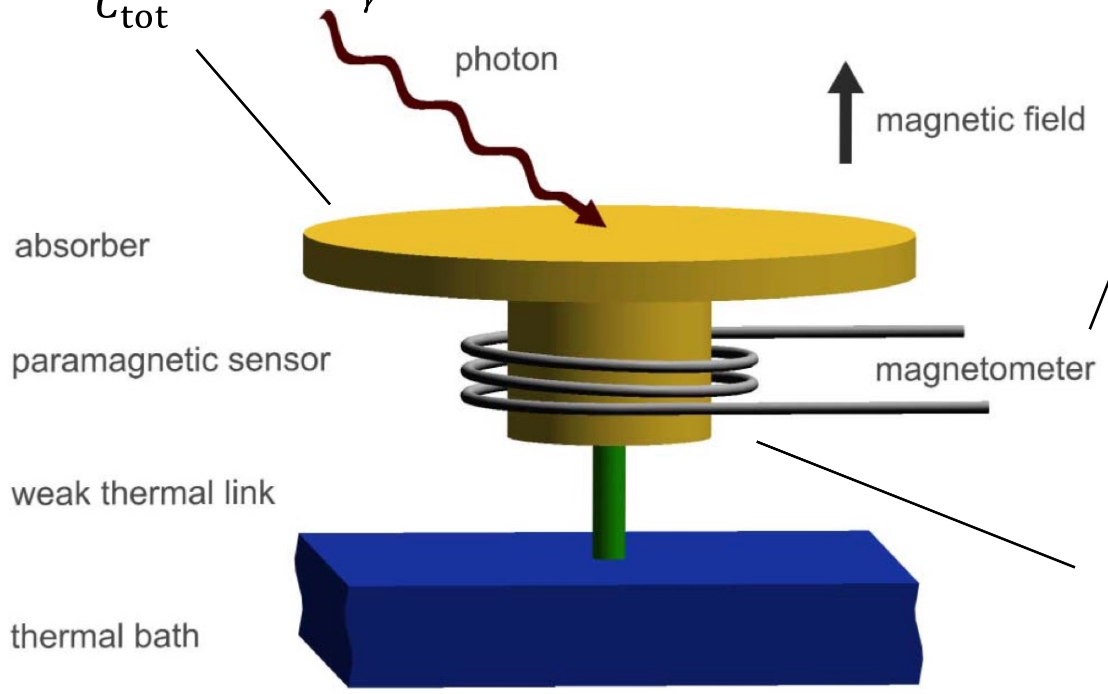
MMC working principle

tunes detection
efficiency
→ determines C_{abs}

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

E_γ

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



DOI: 10.1109/TASC.2009.2012724

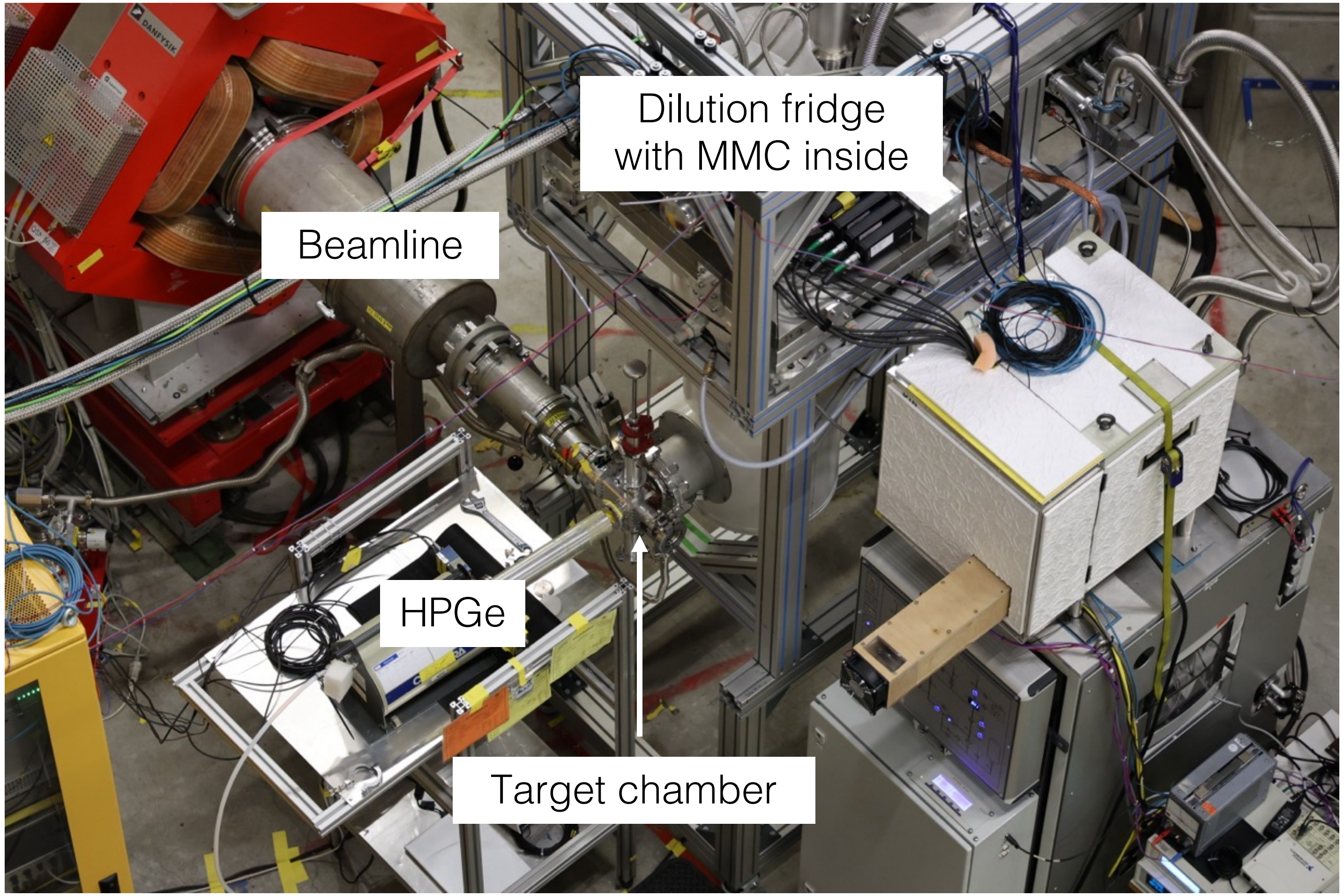
$\Delta M = \frac{\partial M}{\partial T} \Delta T$

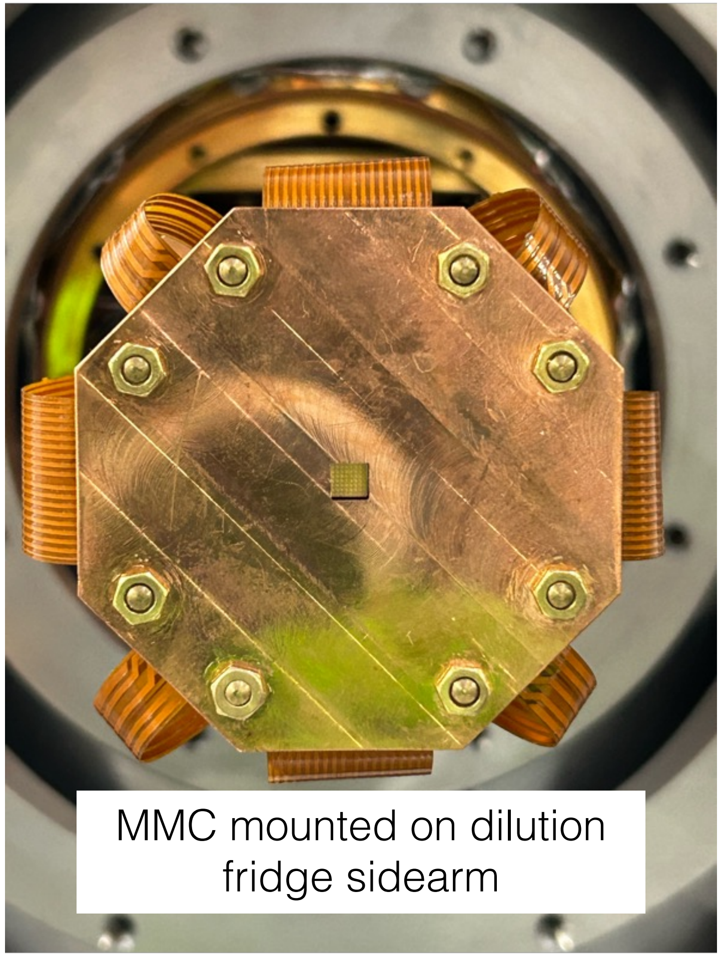
Energy resolution:

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

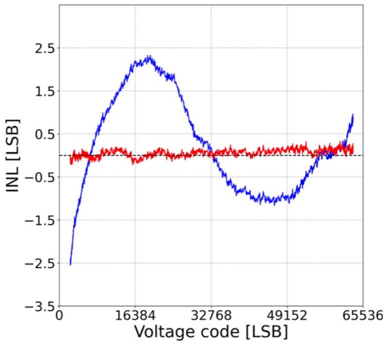
tunes signal
decay time τ_{D}
→ detection speed

Setup at PSI October 2024

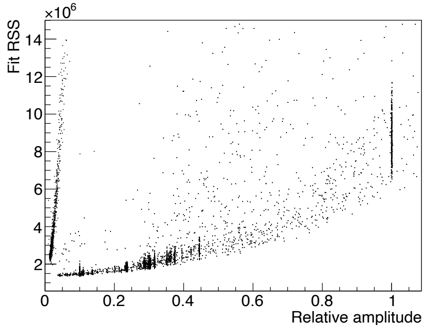


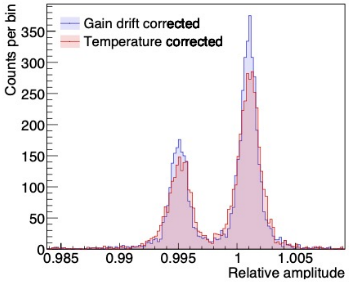


Analysis Procedure Development



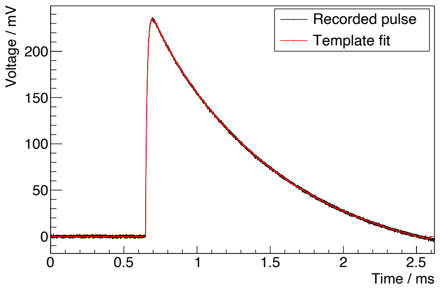
Remove electron hits



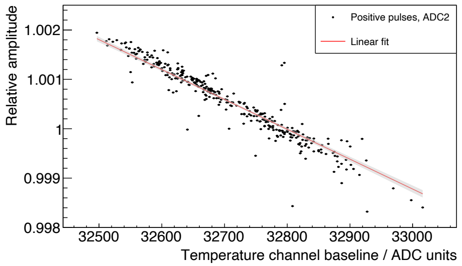


Summed high-statistics spectra for physics analysis

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



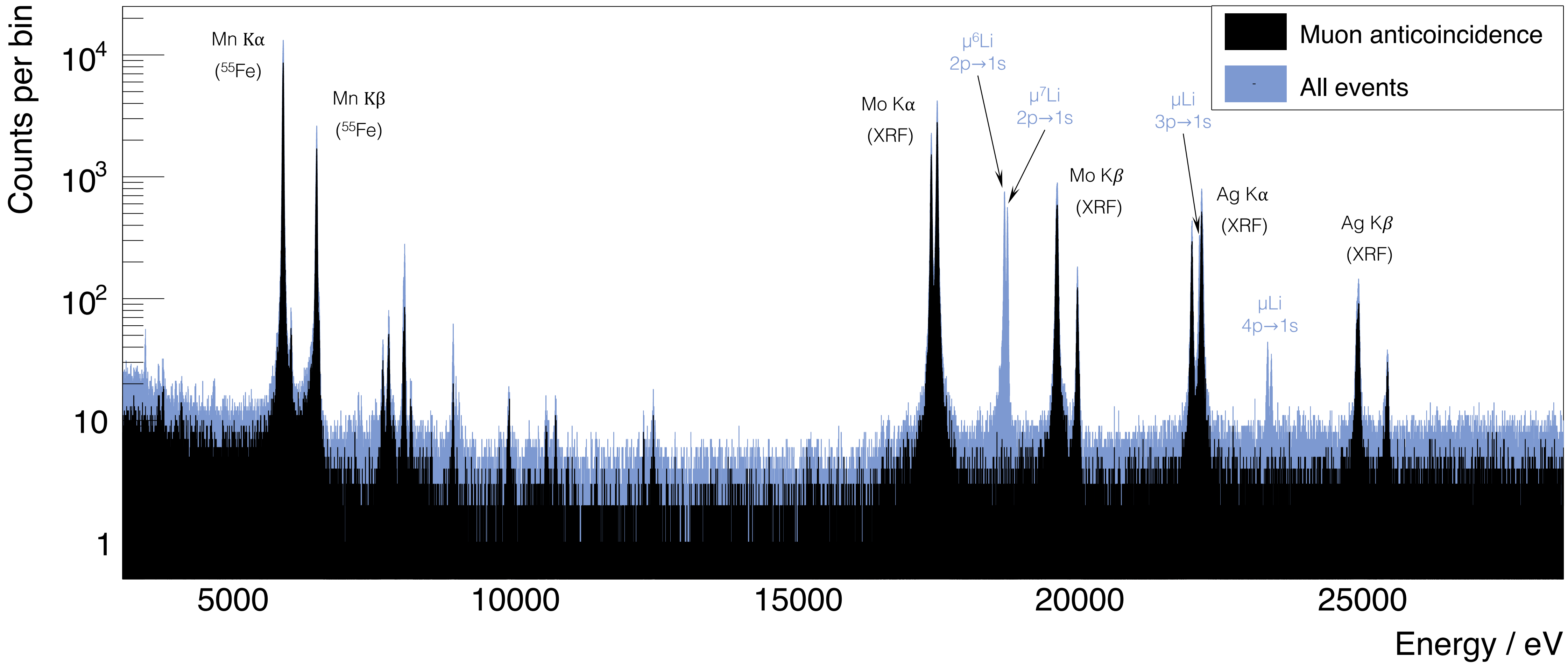
Amplitudes
Goodness-of-Fit



Correction for temperature variations

Muonic Lithium Data 2024

Preliminary results



Muonic Lithium Data 2024

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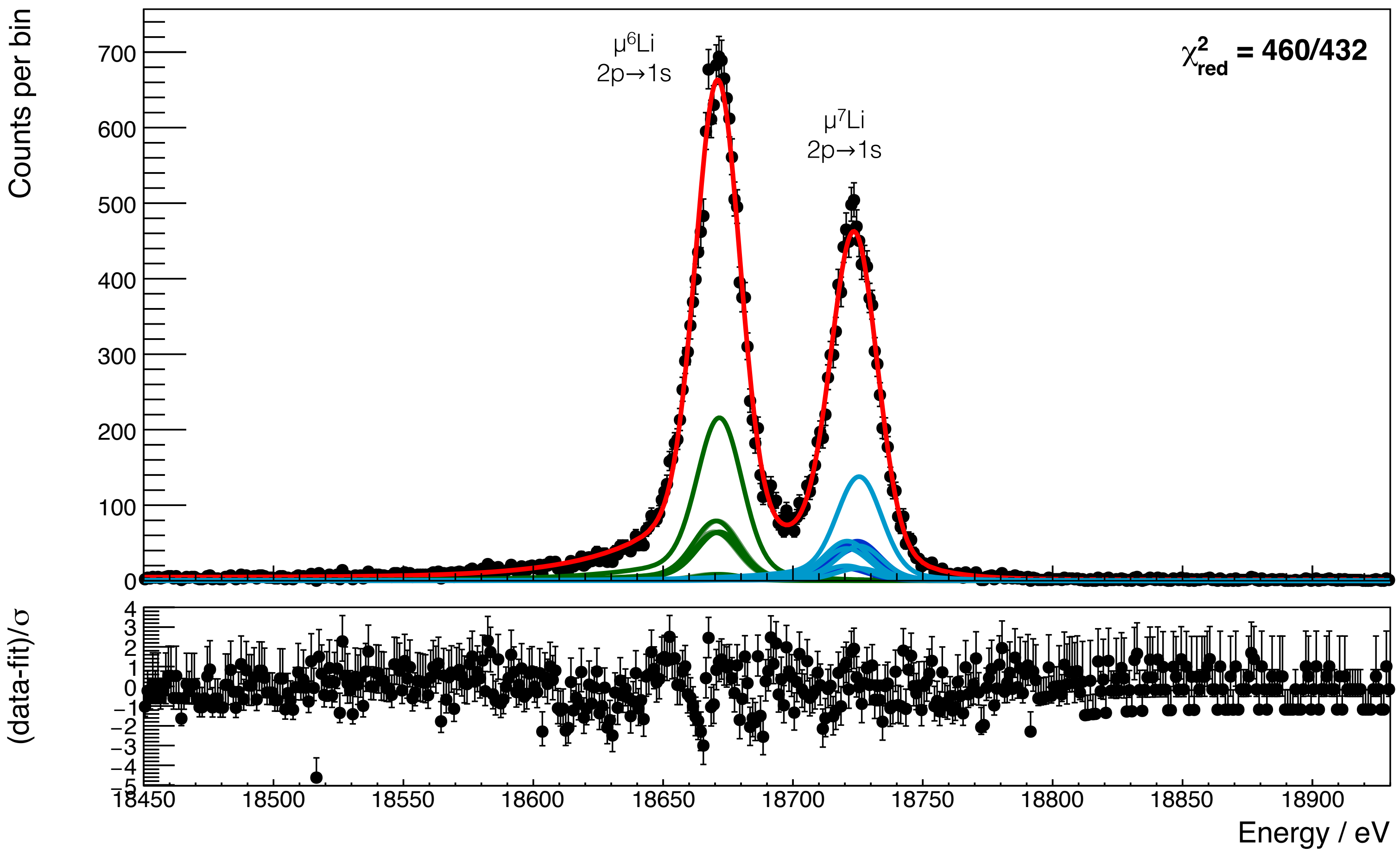

Lithium analysis nearly complete

- 42 pixels, 70h measurement, FWHM ~20 eV ⇒ stat. uncertainty ~0.2 eV
- thorough line shape analysis & systematics study in progress

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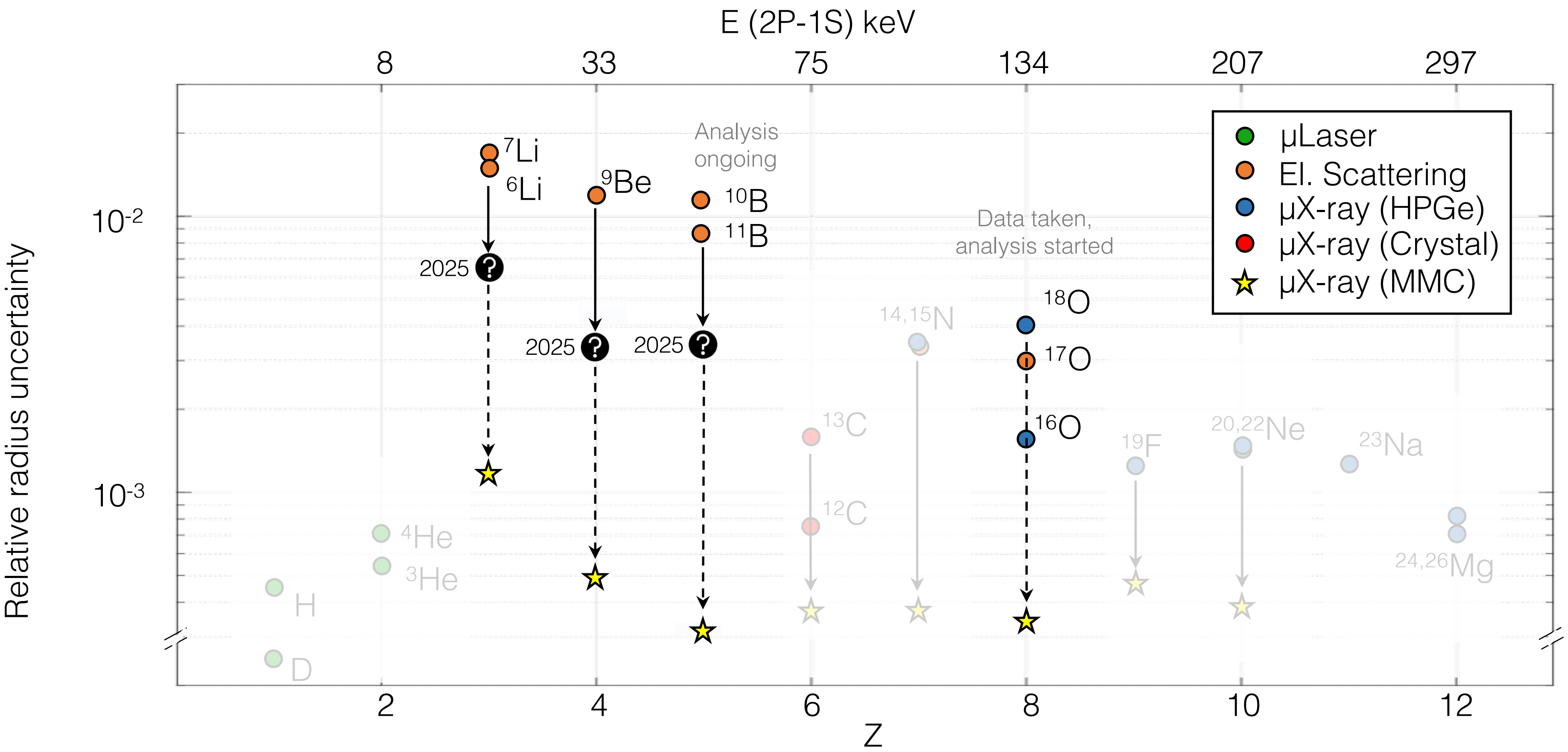
Σ Total uncertainty expected <0.5 eV

⇒ radius uncertainty of <0.02 fm

Summary & Outlook

- First measurements of light muonic atoms using MMCs successfully conducted at PSI in 2024
- Lithium results expected soon, Be & B following, $^{16,17,18}O$ data have just been taken.



UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

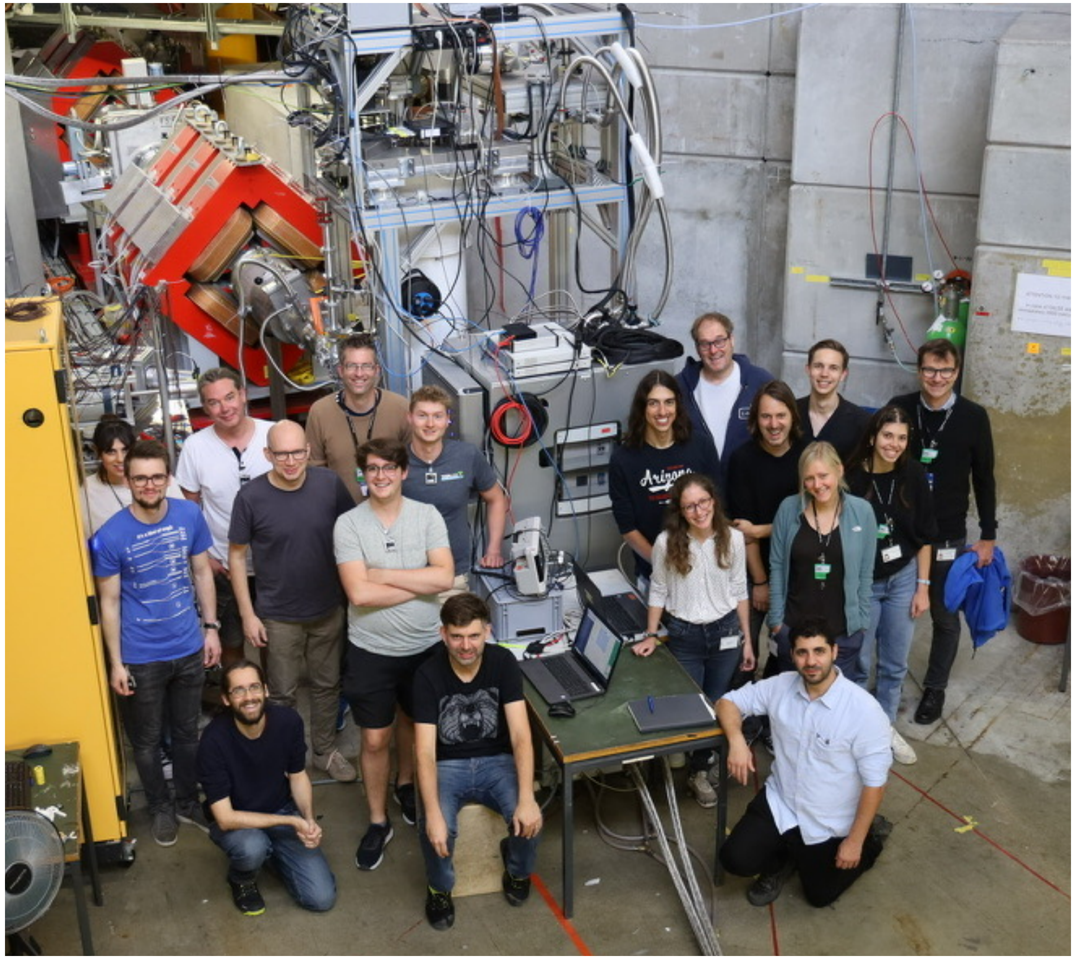
KIRCHHOFF-INSTITUT FÜR PHYSIK

QUARTET

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

ETH zürich

PSI



JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Laboratoire Kastler Brossel
Physique quantique et applications

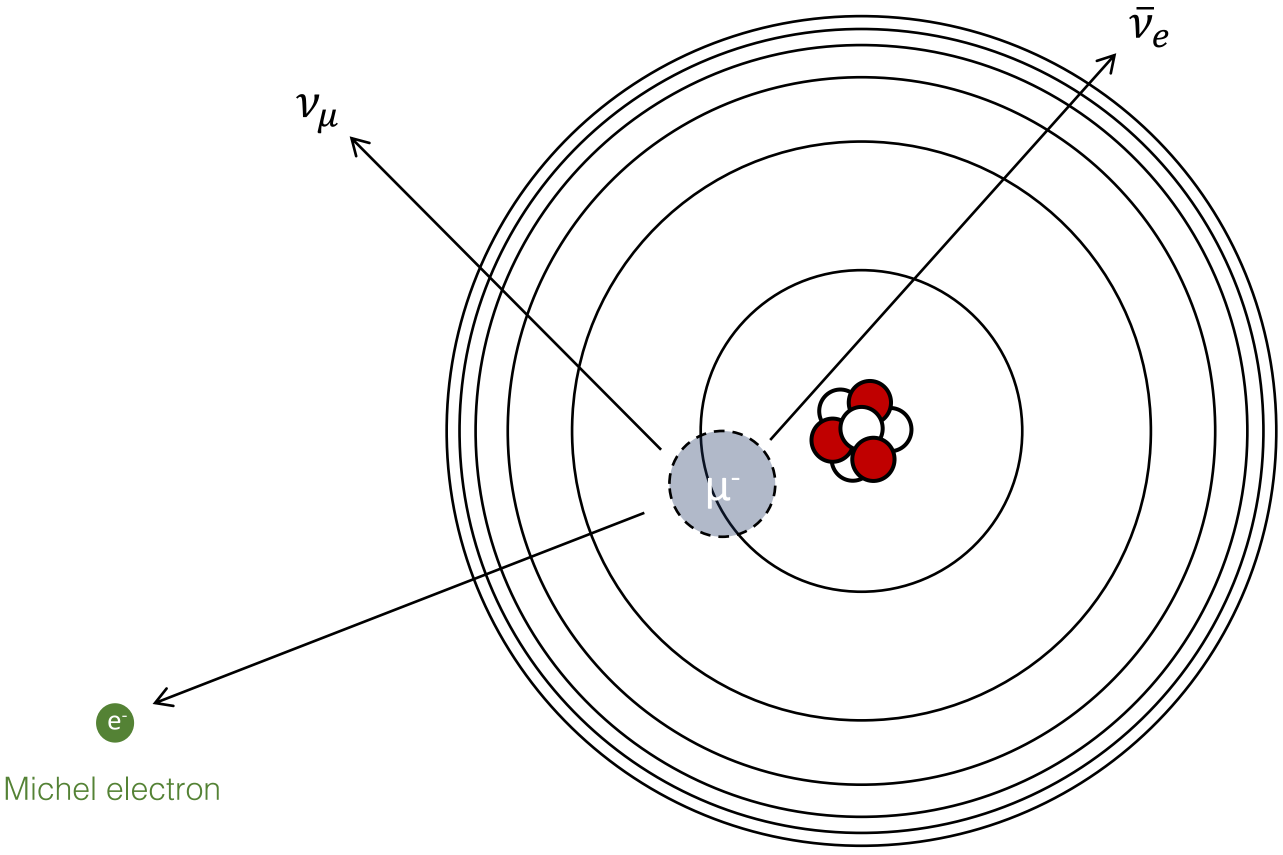
TECHNION
Israel Institute
of Technology

KU LEUVEN

NOVA
UNIVERSIDADE NOVA DE LISBOA

Backup

Muonic Atoms



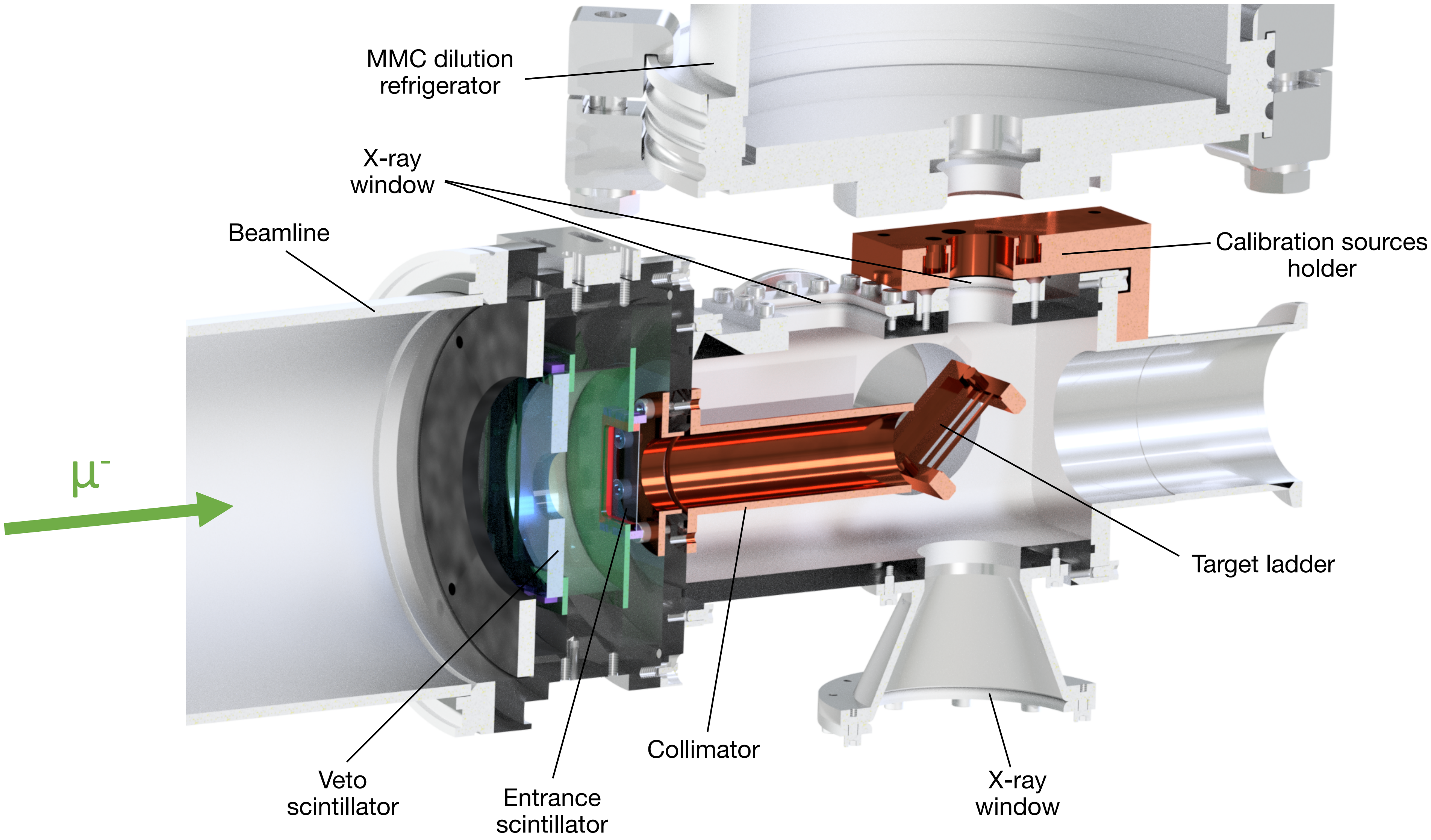
1. Stop muons in target material

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

4. Decay in orbit (→ Michel electrons) or nuclear capture $\mu^- + (A,Z) \rightarrow (A, Z-1)^* + \nu_\mu$

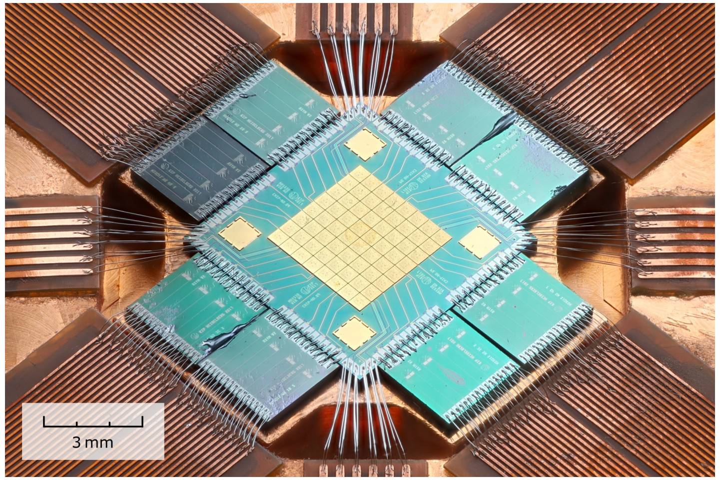
Beamtime 2024 – Setup



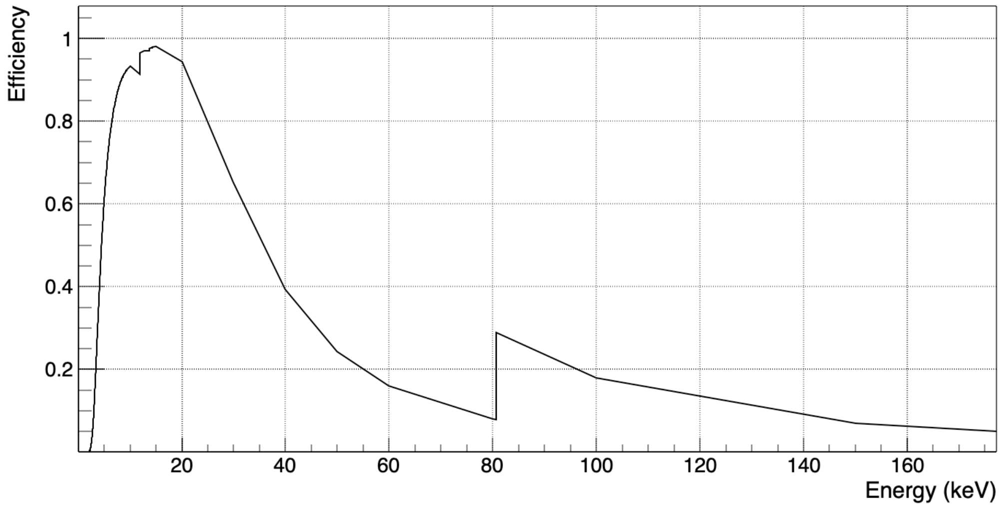
Beamtime 2024 – Setup

“maXs-30” MMC

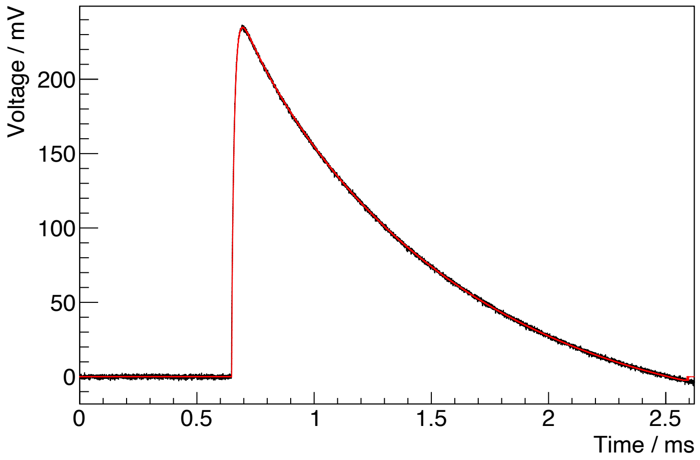
- Operated at approx. 20 mK
- High efficiency: > 90% from 8 – 22 keV
- High resolution of ~10-20 eV at 18 keV
- 64 absorbers: each 500 µm x 500 µm x 20 µm
- max. rate per pixel ≲ 0.5-1 Hz



DOI: 10.1007/s10909-024-03141-x

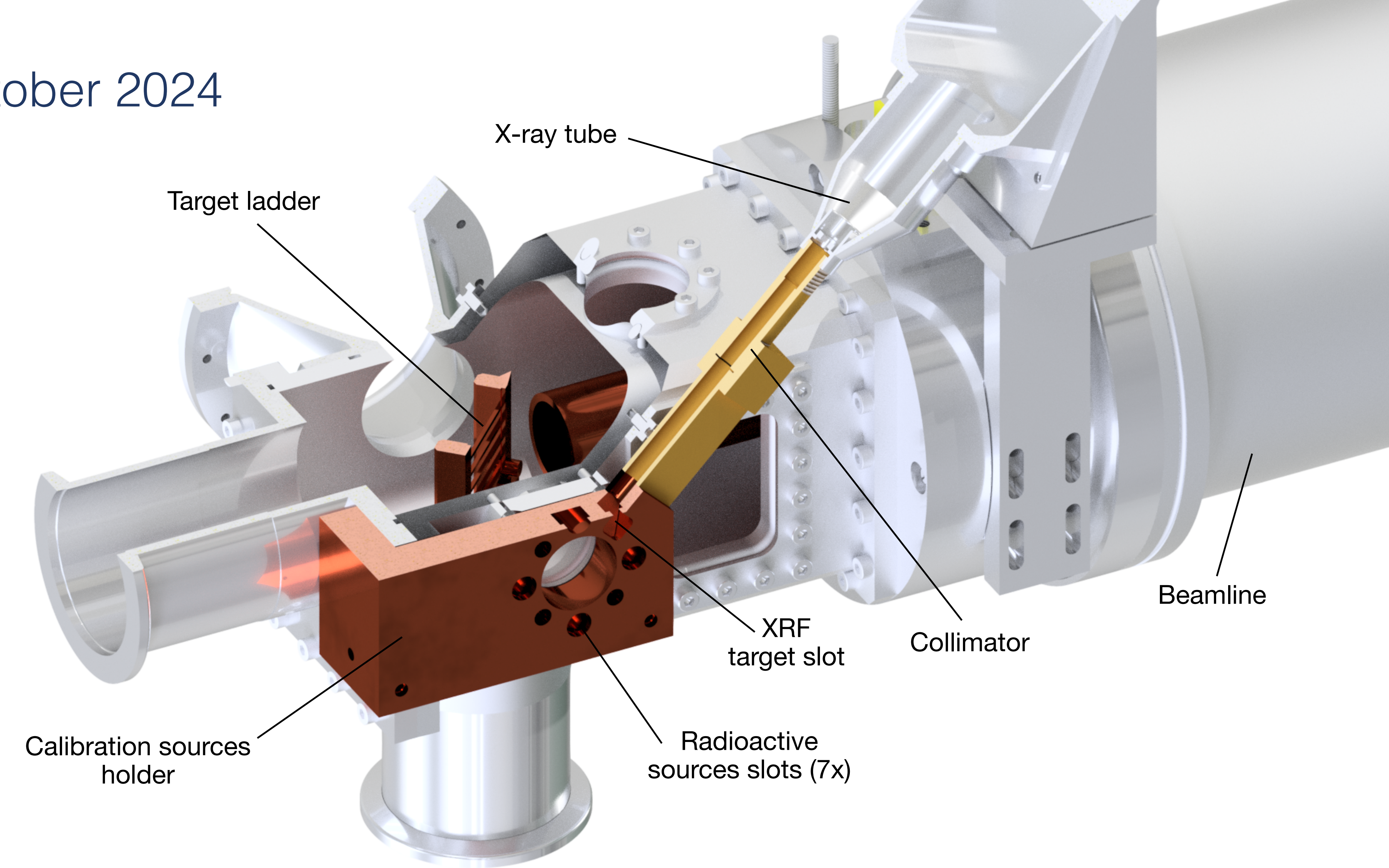


Calculated detection efficiency for maXs-30 type detector

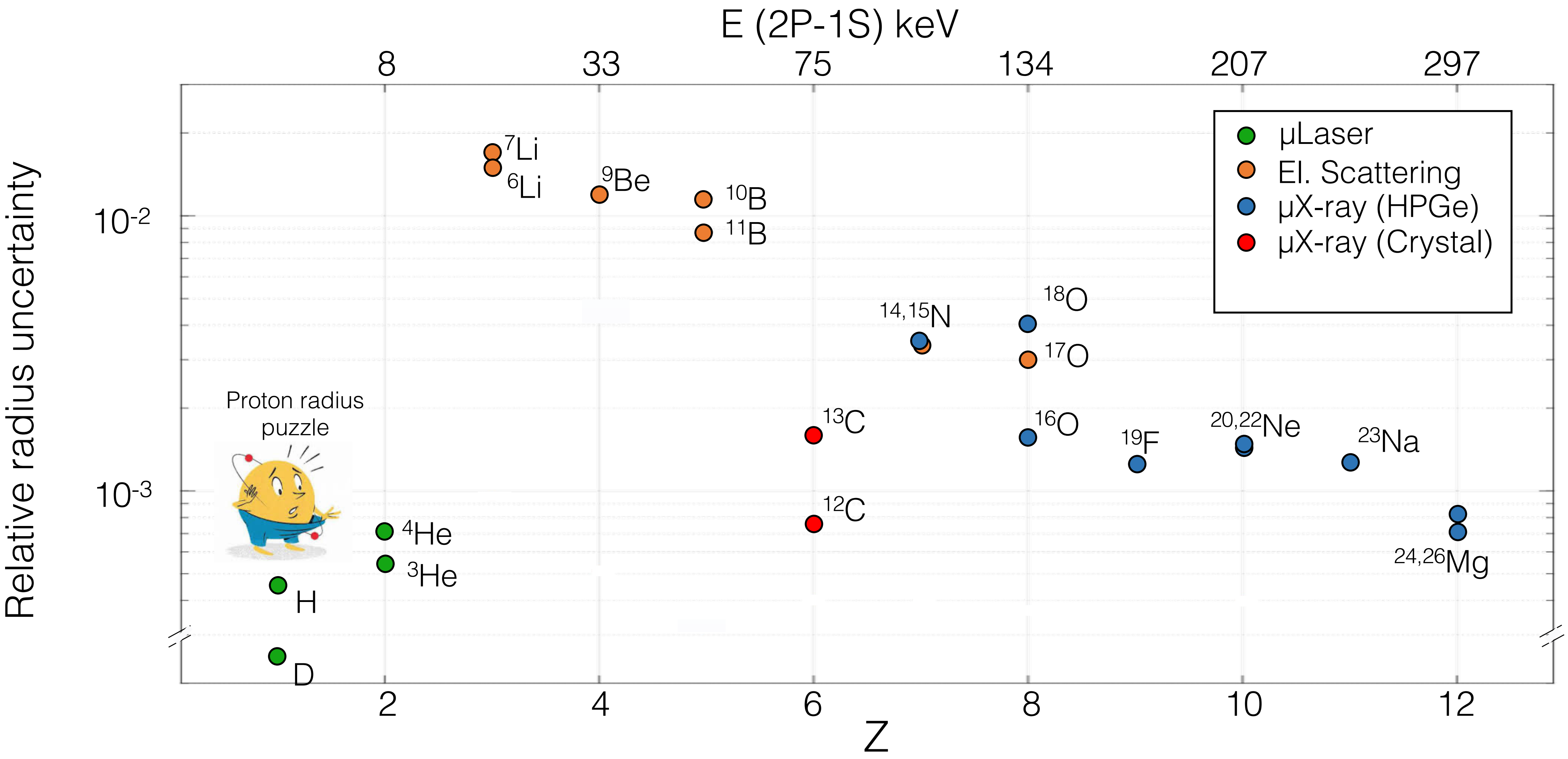


Typical photon pulse shape

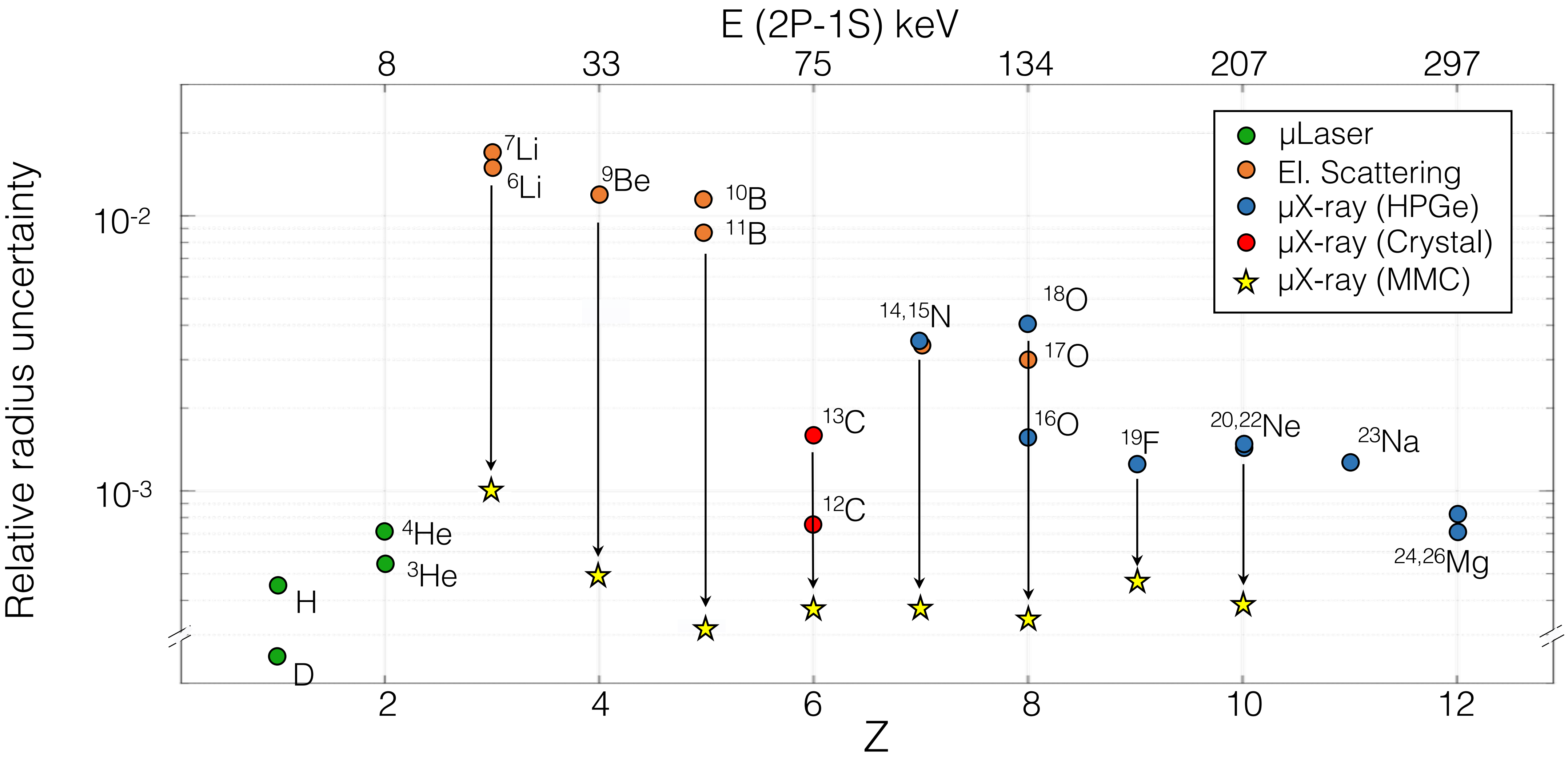
Setup October 2024



Low-Z Charge Radii



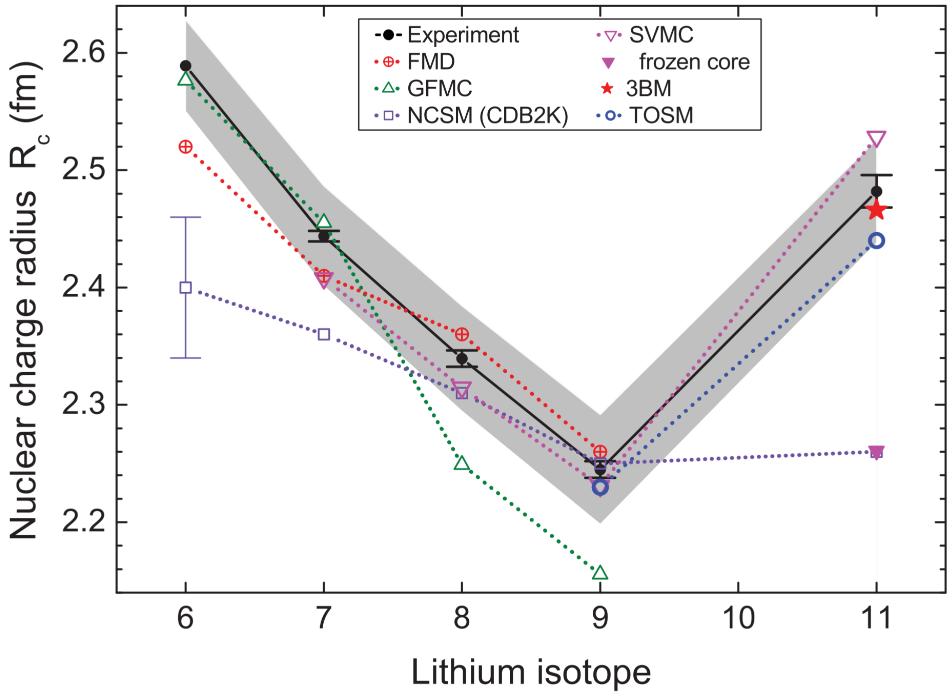
Low-Z Charge Radii



Lithium nuclear charge radii

From electron scattering and isotope shift measurements

DOI: 10.1103/PhysRevC.84.024307 (**2011**)



- Experimental values extracted from two inputs:

  1. Electron scattering for absolute radius reference
  2. Isotope shifts connecting within the chain

- Whole isotopic chain currently limited by the uncertainty from absolute radius (grey band):

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

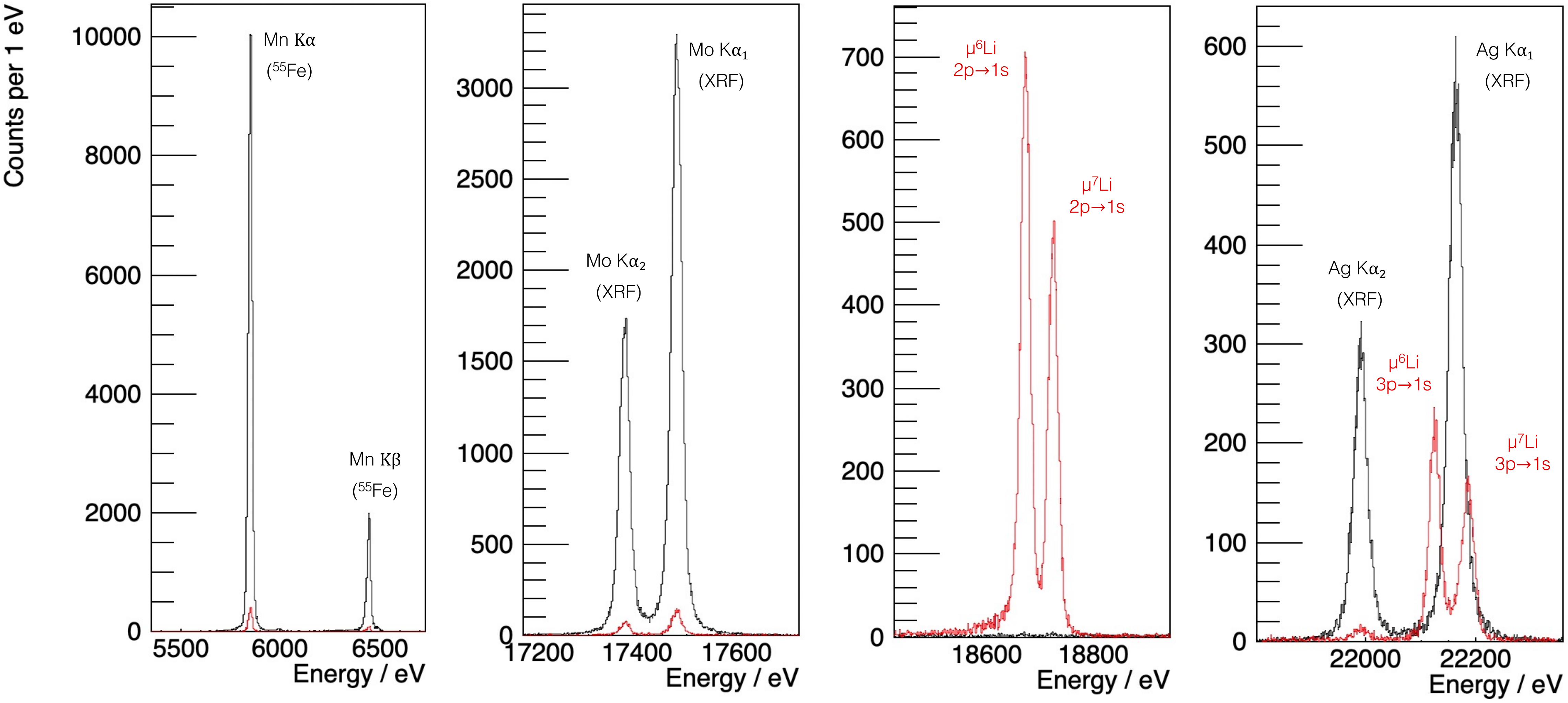
⇒ ultimate goal: shrink uncertainty-band by an order of magnitude

Theory community still actively updating, e.g.:

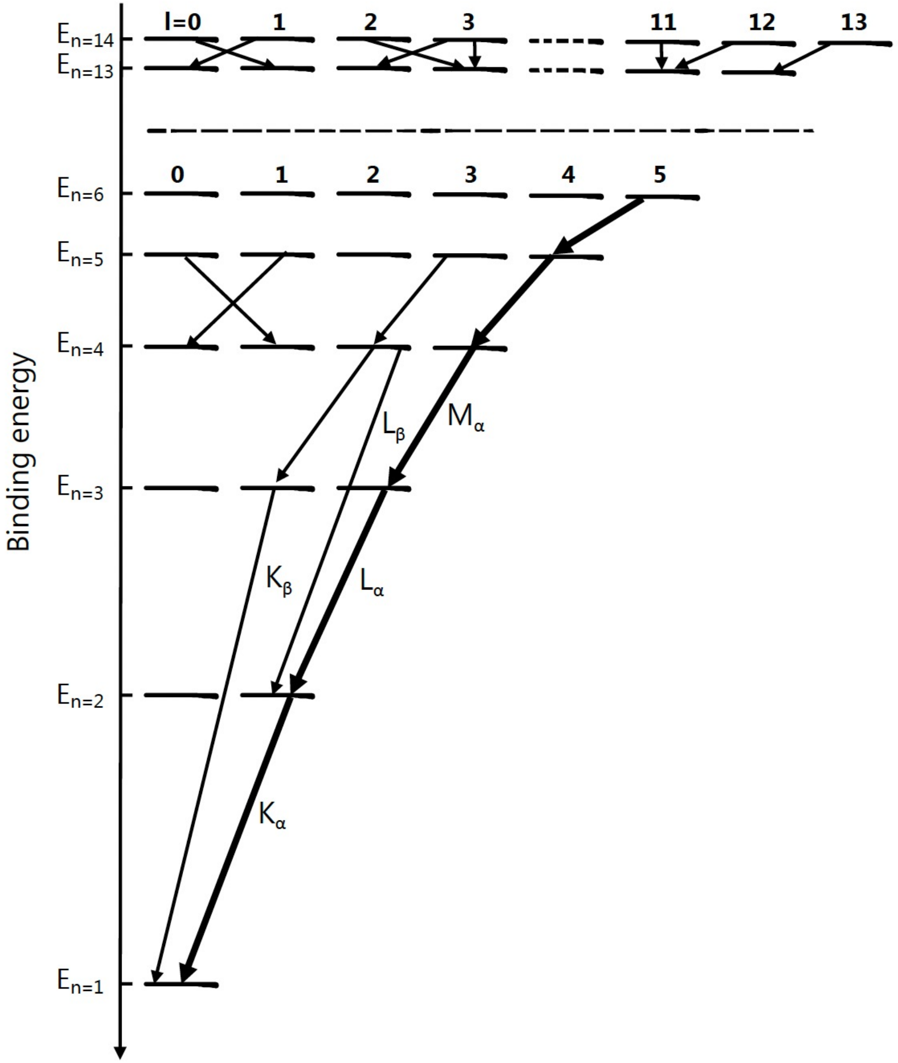
- X.-X. Sun, H. Le, U.-G. Meißner, and A. Nogga, "Radii of light nuclei from the Jacobi no-core shell model", *Phys. Rev. C* 112, 024317 (**2025**).
- M. Knöll, M. Lockner, P. Maris, R. J. McCarty, R. Roth, J. P. Vary, and T. Wolfgruber, "Benchmarking ANN extrapolations of the ground-state energies and radii of Li isotopes", arXiv:2501.18252 (**2025**).

Muonic Lithium Data 2024

Preliminary results



Muonic Atoms Cascade



From Energies to Radii

Add QED corrections

Muonic atom transition energies

$$E = E_D + \delta E_{QED} + \delta E_{FNS}(\langle r^2 \rangle) + \delta E_{TPE}$$

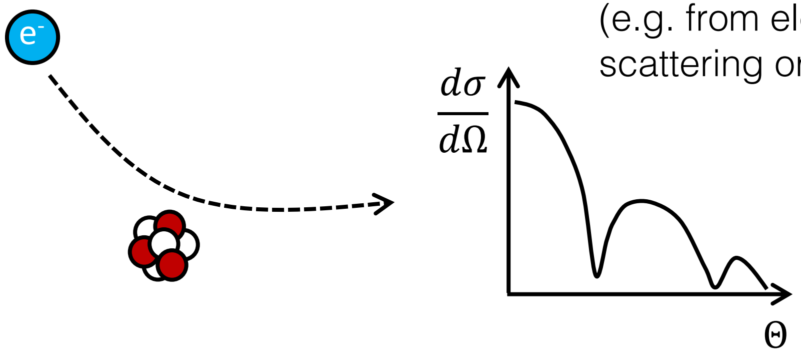
Absolute $\langle r^2 \rangle$

Solve point nucleus Dirac equation

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

Charge density distribution (e.g. from electron scattering or model)

Add corrections for two-photon exchange (mainly nuclear polarization)



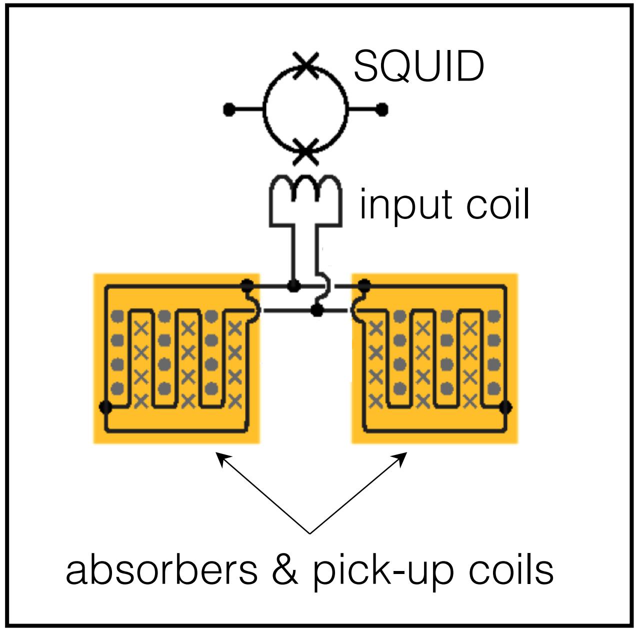
”maXs-30” MMC from Heidelberg
Detector design

Absorber pair wise coupled

→ Reduced sensitivity towards global temperature changes

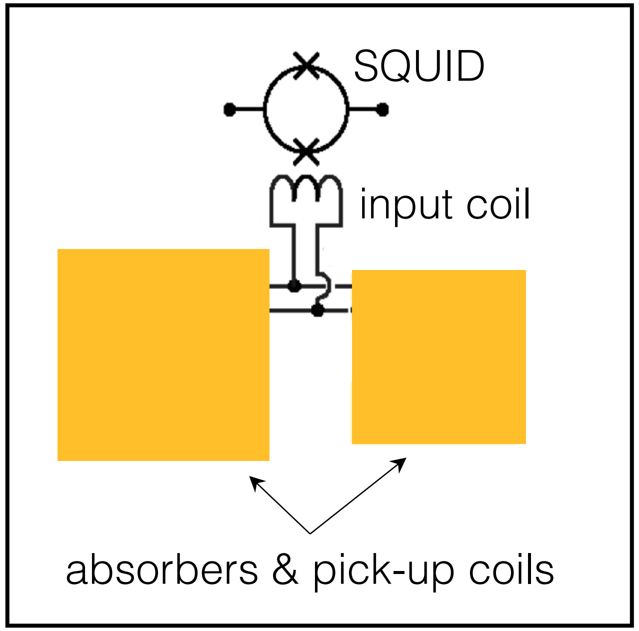
→ (Reduced number of readout channels necessary)

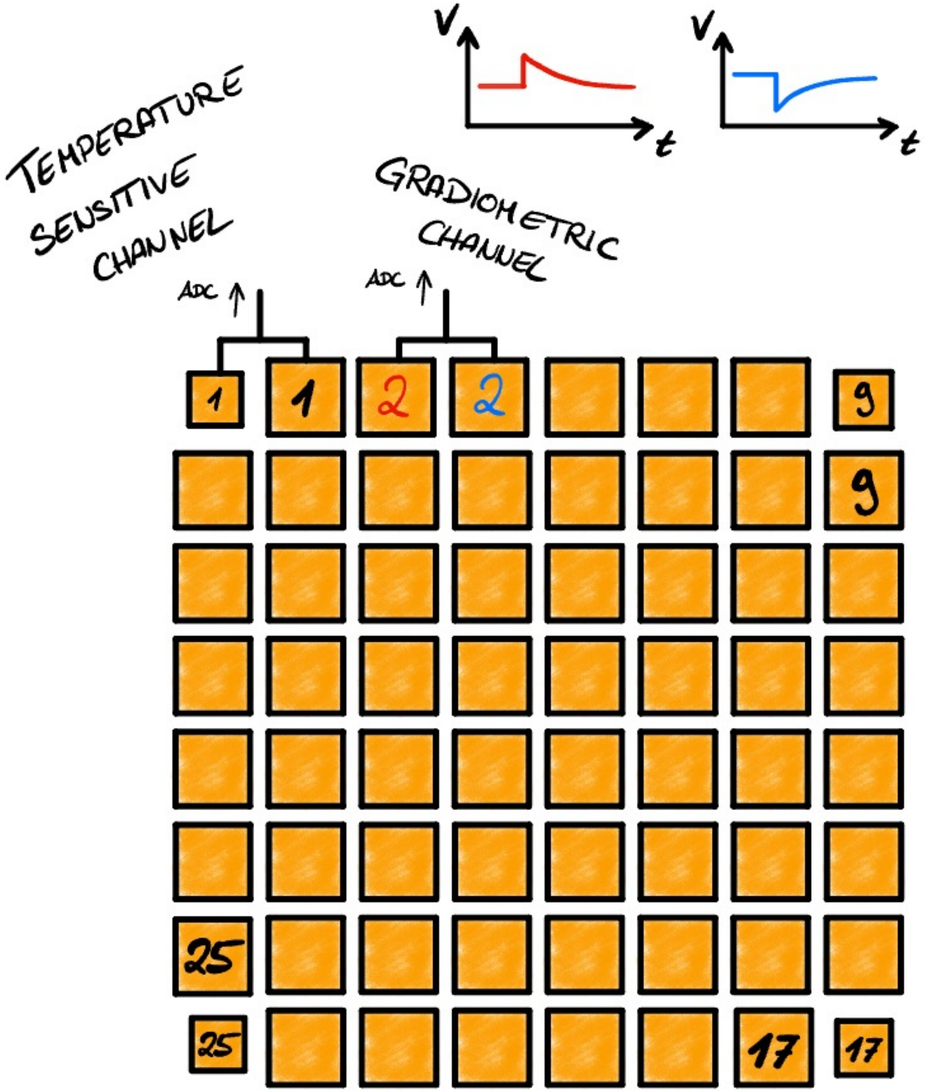
Gradiometric design:



DOI: 10.1063/1.3292407

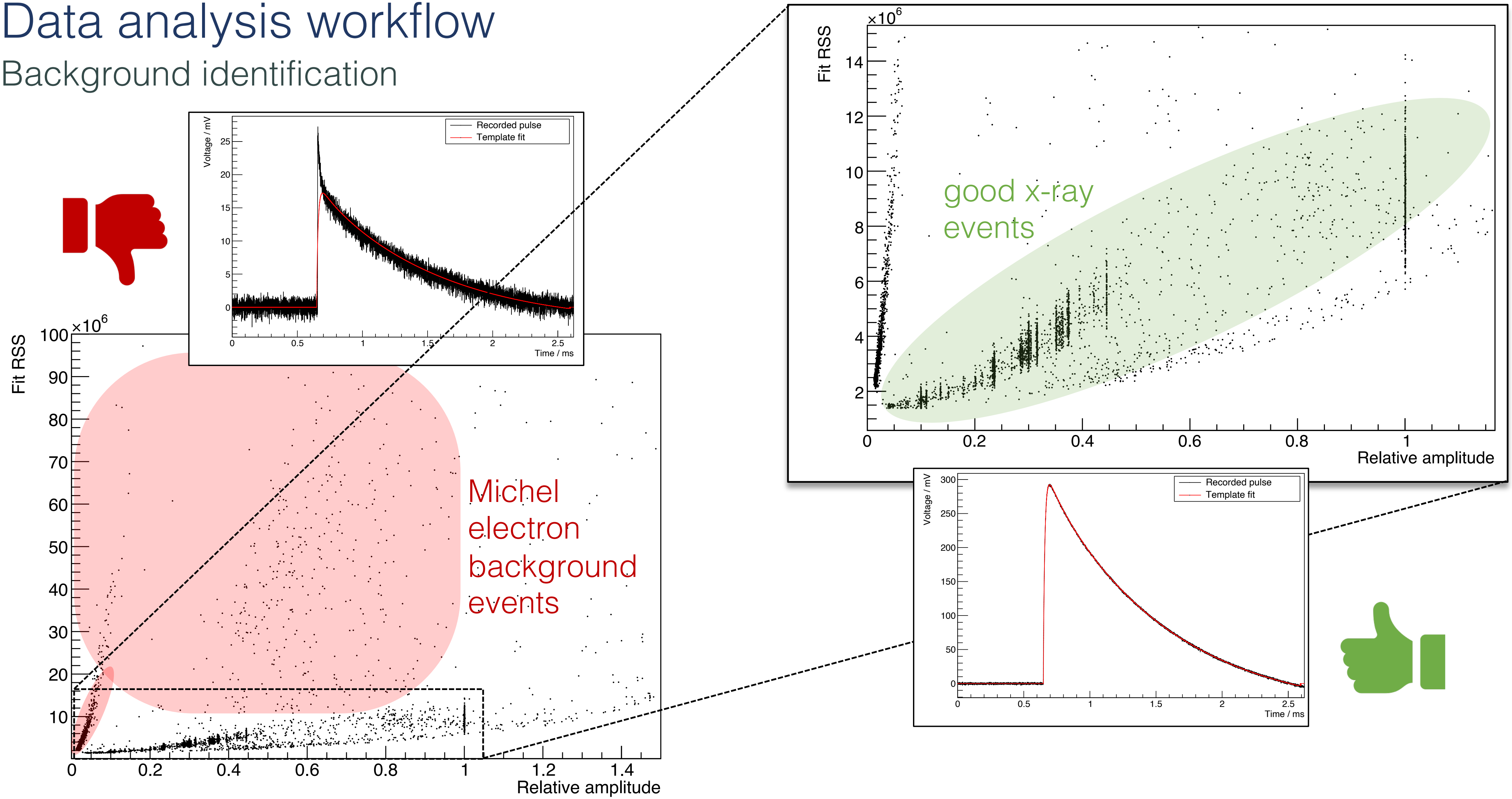
Temperature sensitive design:





Data analysis workflow

Background identification

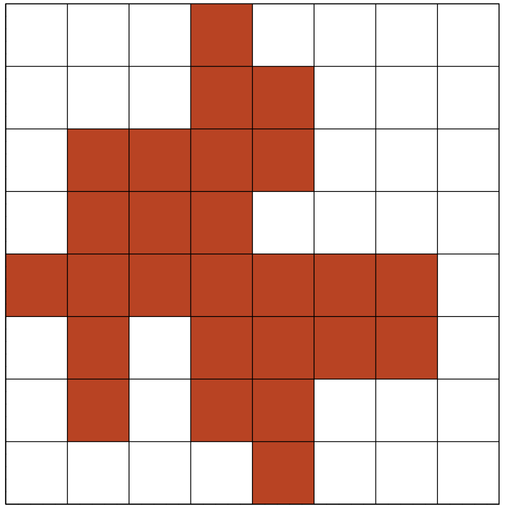


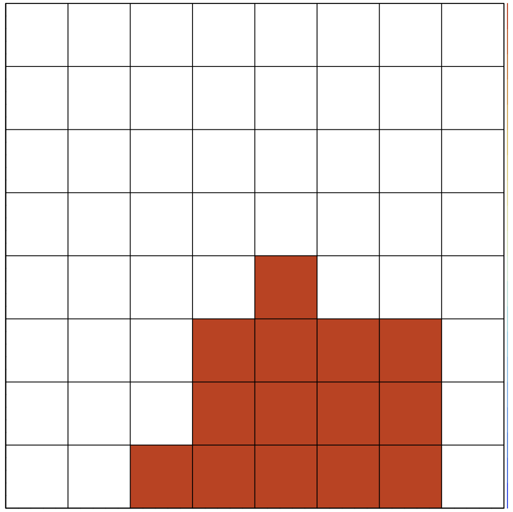
Data analysis workflow

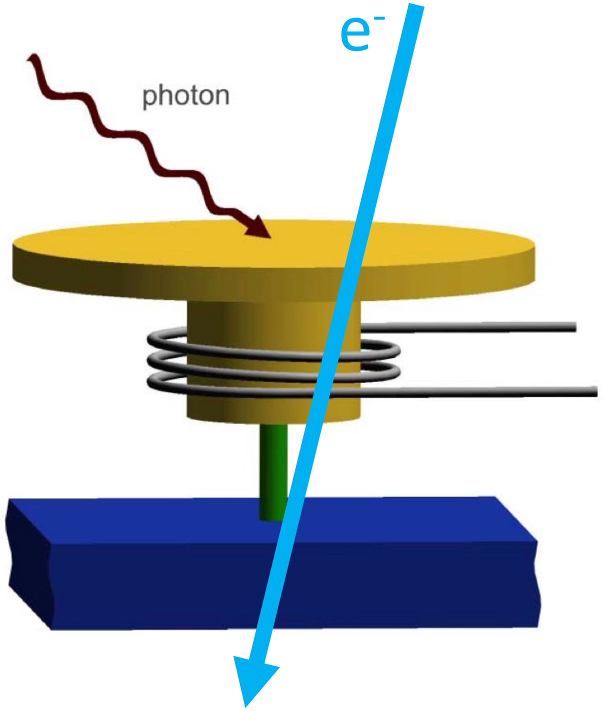
Background identification

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

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



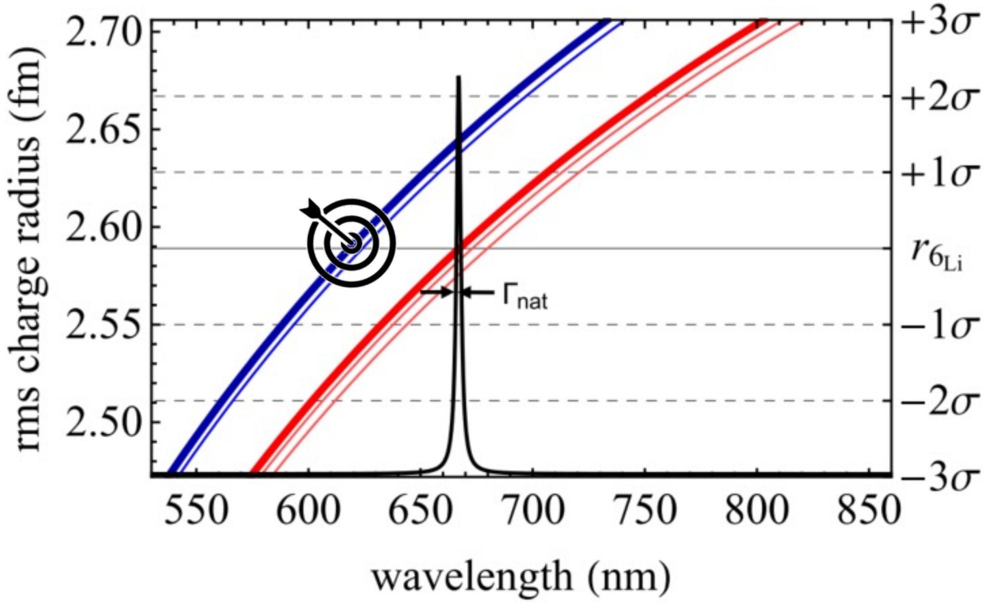


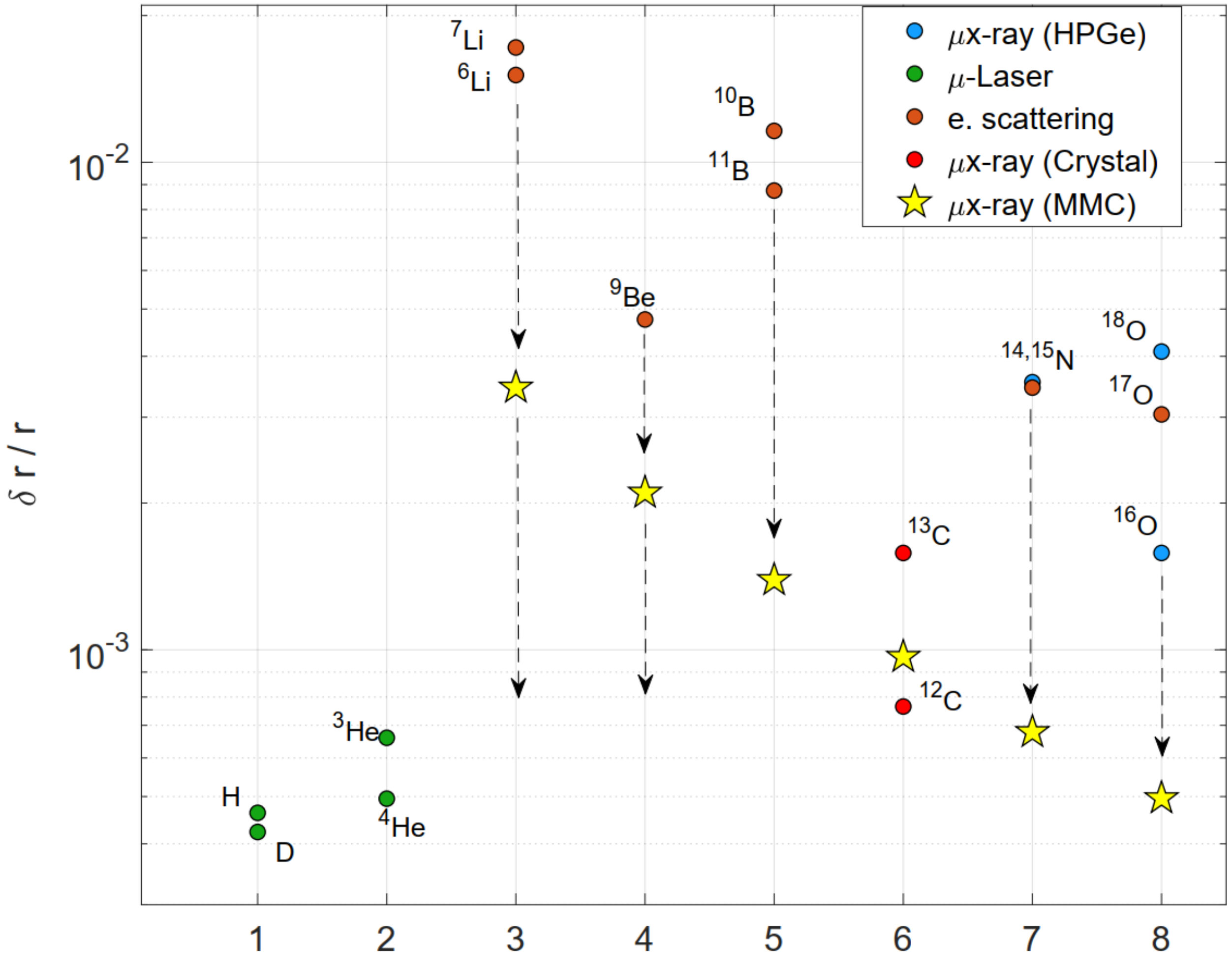


Michel electrons shoot through absorbers into silicon substrate and heat-up pixels “from the backside”

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

- MMCs: Improve $\mathbf{r_c}$ 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

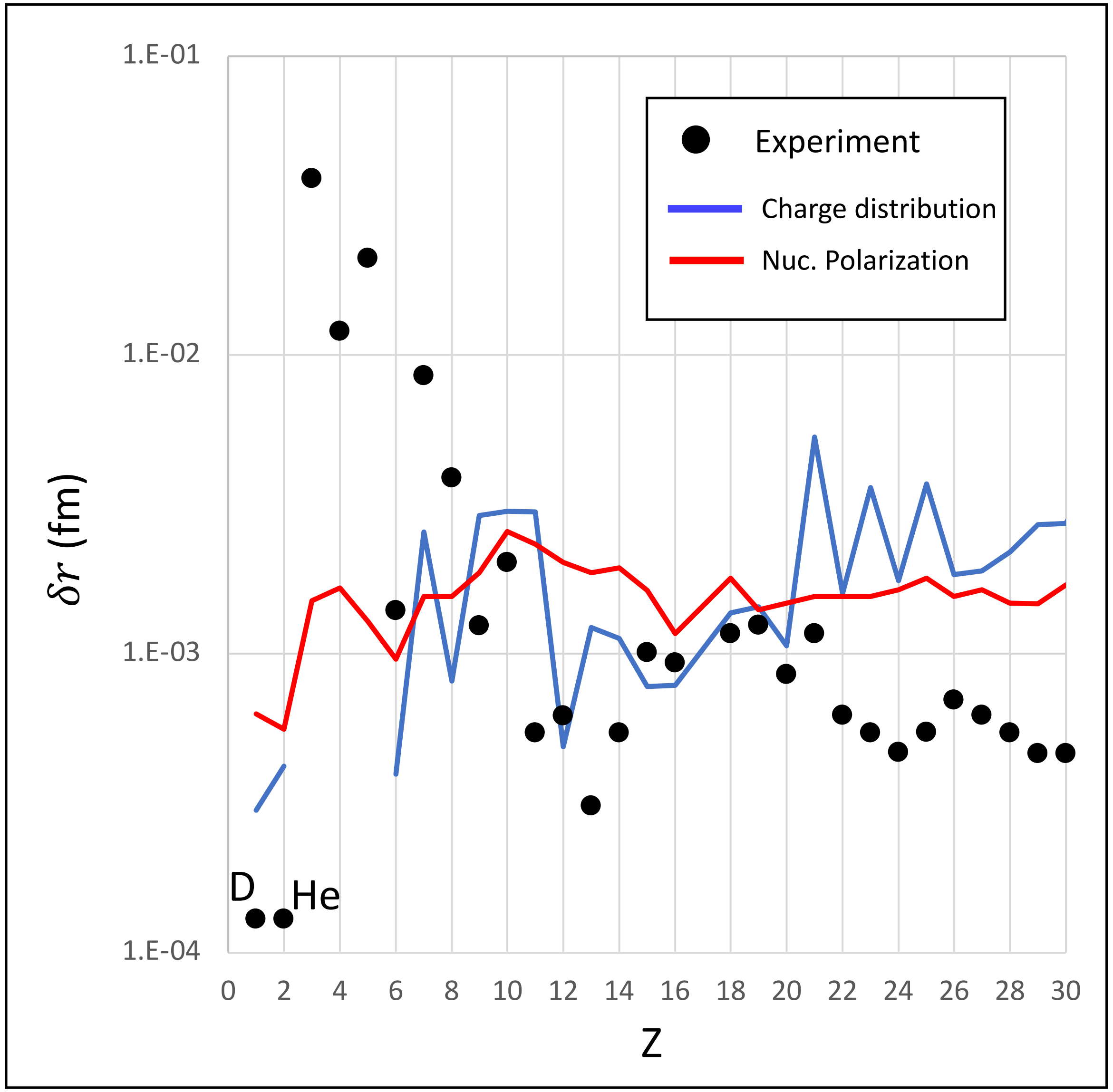
From theory, mainly <u>nuclear polarization</u>

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

From experiment, mainly <u>charge distributions</u>
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

Muonic x-ray spectroscopy on implanted targets

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

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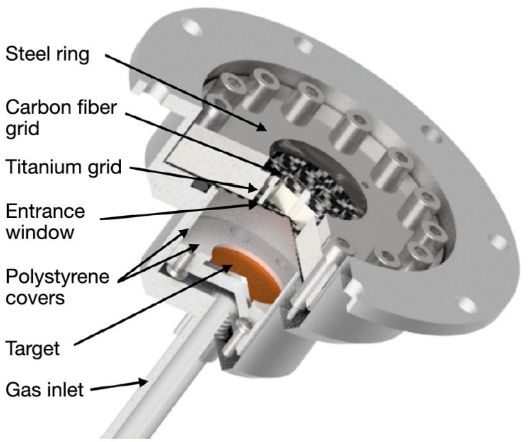
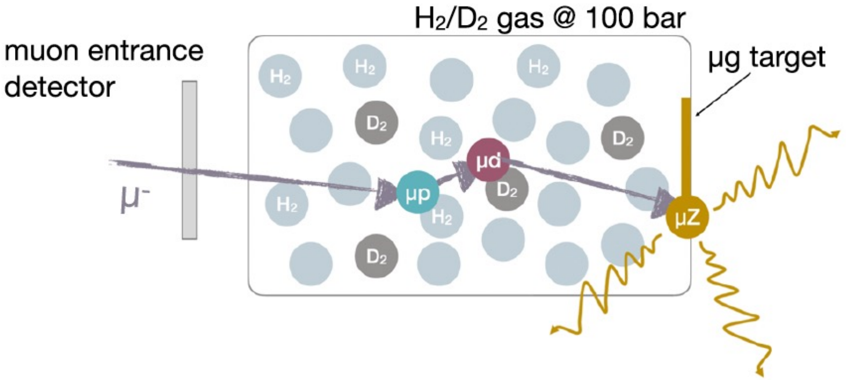
Studies of muonic ^{185,187}Re, ^{226}Ra, and ^{248}Cm for the extraction of nuclear charge radii

presented by

STERGIANI MARINA VOGIATZI

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

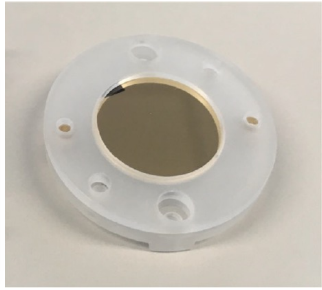




Muonic atom spectroscopy with microgram target material

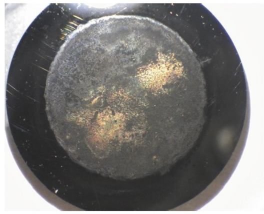
A. Adamczak[1], A. Antognini[2,3], N. Berger[4,5], T. E. Cocolios[6], N. Deokar[4,5], Ch. E. Düllmann[5,7,8,9], A. Eggenberger[3], R. Eichler[2], M. Heines[6], H. Hess[10], P. Indelicato[11], K. Kirch[2,3], A. Knecht[2,a], J. J. Krauth[5,12], J. Nuber[2,3], A. Ouf[12], A. Papa[2,13], R. Pohl[5,12], E. 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]

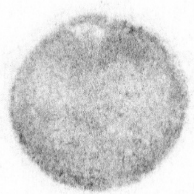
https://doi.org/10.1140/epja/s10050-023-00930-y



5 μg vapor deposited Au

Spectroscopy of 15 μg radioactive ^{248}Cm





There is a lot to do…

Muonic atoms at the Paul-Scherrer-Institute

QUARTET collaboration

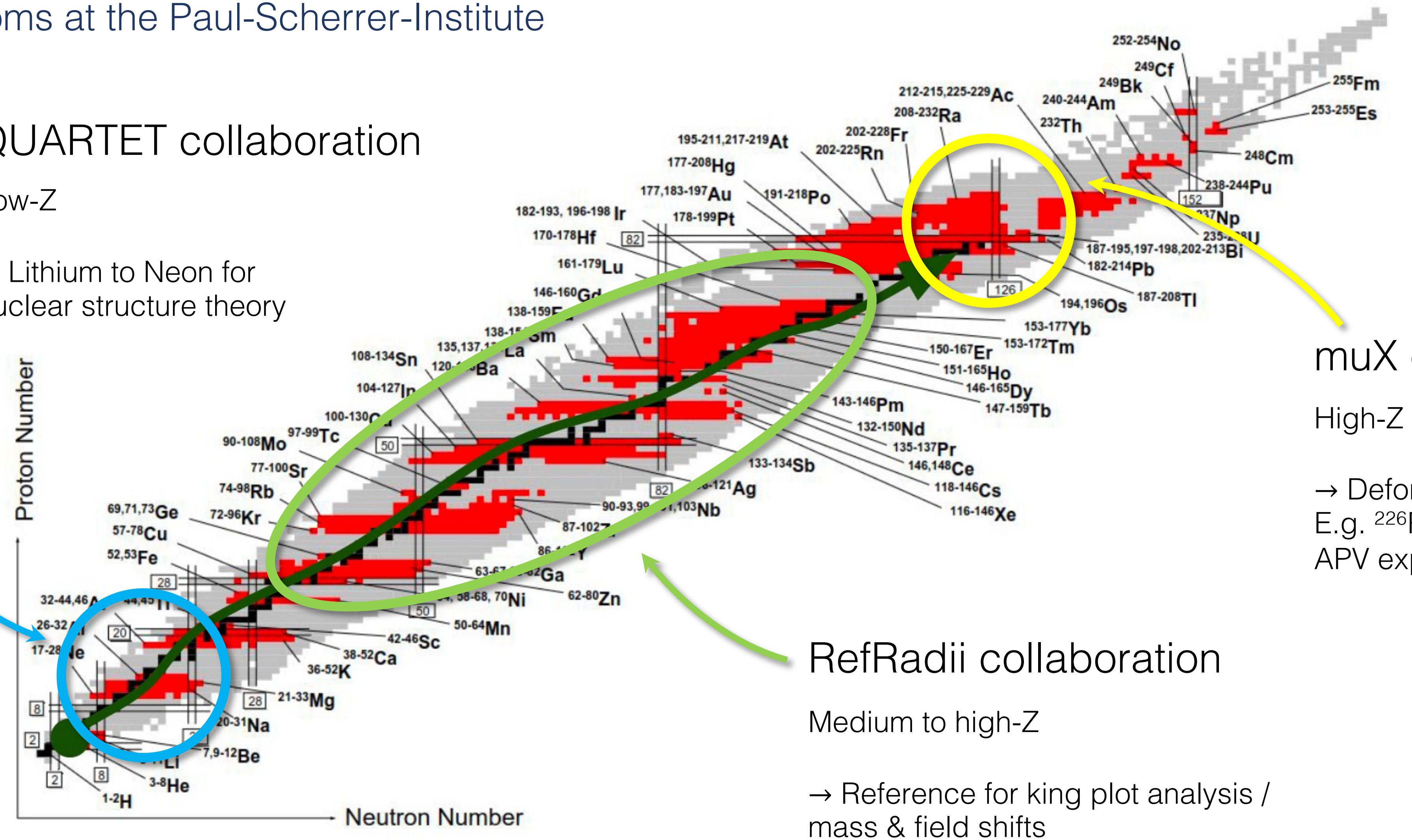
Low-Z

→ Lithium to Neon for nuclear structure theory

muX collaboration

High-Z (radioactive) targets

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



RefRadii collaboration

Medium to high-Z

→ Reference for king plot analysis / mass & field shifts