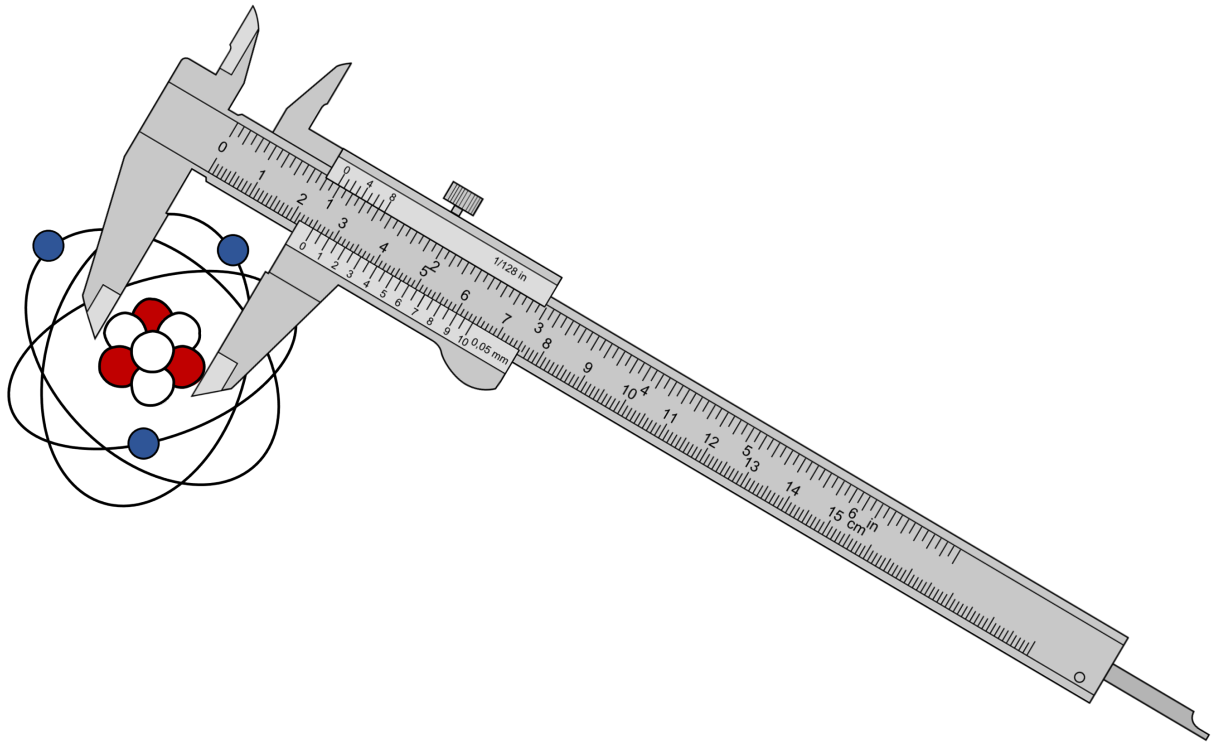
Towards High-Resolution X-Ray Spectroscopy of Muonic Lithium using Metallic Magnetic Microcalorimeters

Katharina von Schoeler

On behalf of the QUARTET collaboration

Measuring Nuclear Charge Radii



rms charge radius:

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

Nuclear charge density distribution

Nuclear Charge Radii

… are needed for

1. Benchmarks for ab-initio nuclear theory

Nuclear Charge Radii

… are needed for

1. Benchmarks for ab-initio nuclear theory
2. Input for laser spectroscopy of low-Z muonic and electronic atoms for
   - Precision bound-state QED tests
   - Extraction of fundamental constants
   - …

Nuclear Charge Radii of Lithium Isotopes

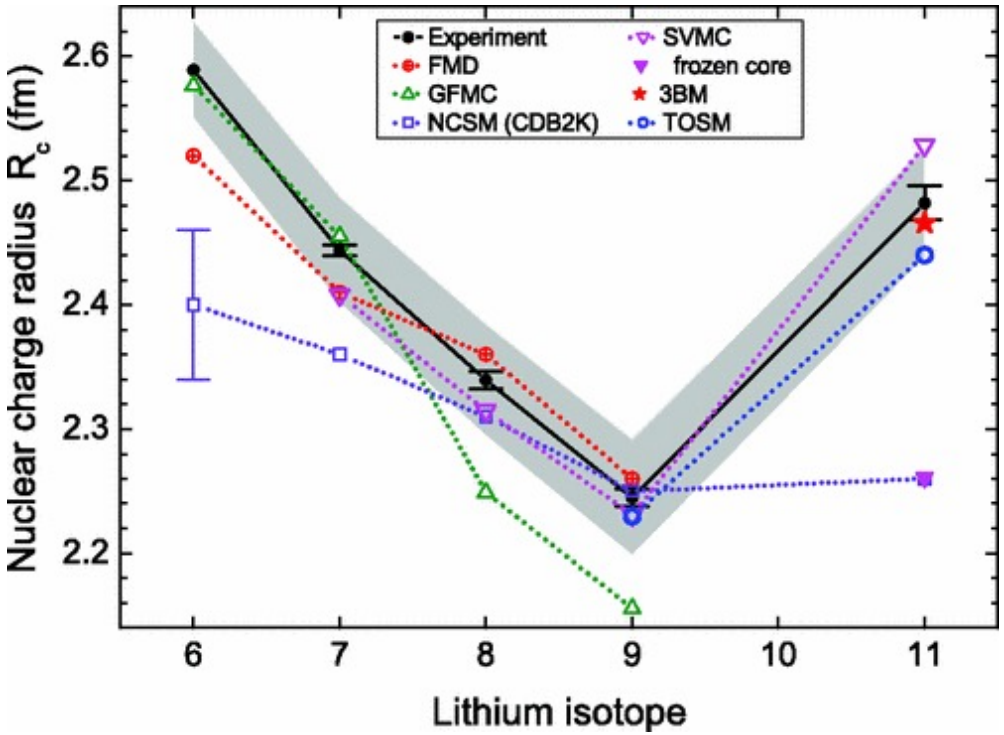


Figure: W. Nörtershäuser et al., Charge radii and ground state structure of lithium isotopes: Experiment and theory reexamined. Phys. Rev. C, 84, 024307, 2011

Nuclear Charge Radii of Lithium Isotopes

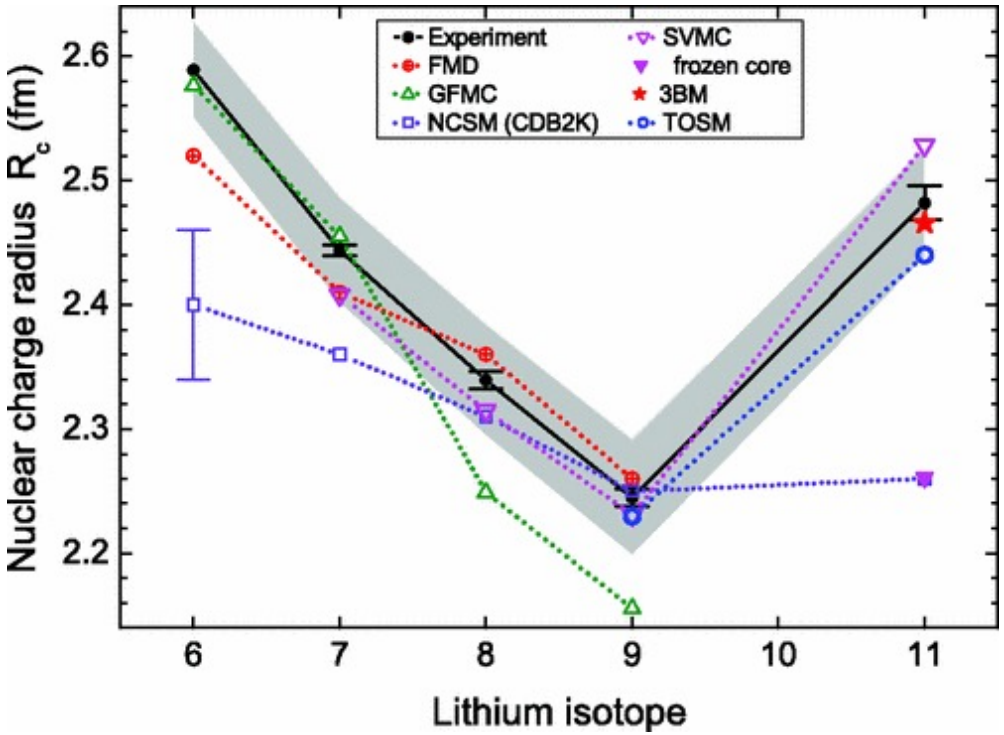


Figure: W. Nörtershäuser et al., Charge radii and ground state structure of lithium isotopes: Experiment and theory reexamined. Phys. Rev. C, 84, 024307, 2011

Limited by current best Li charge radii:

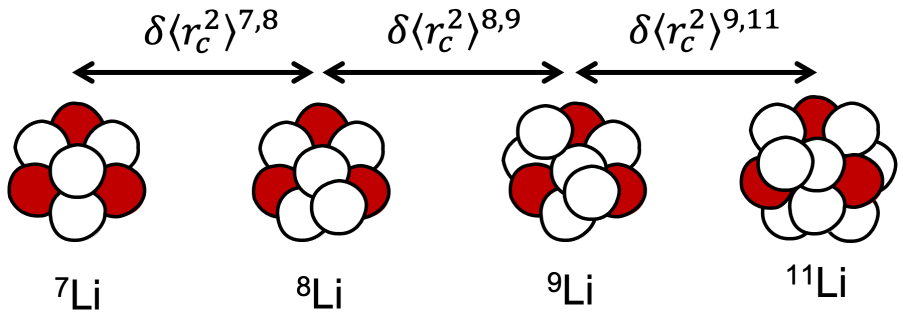
$$R_{rms}(^6Li) = 2.589(39)\ fm$$

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

from electron scattering experiments.

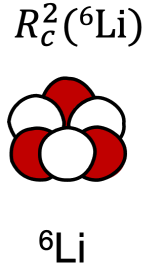
Nuclear Charge Radii

Relative charge radius changes



- Isotope shifts from (ordinary) atom spectroscopy

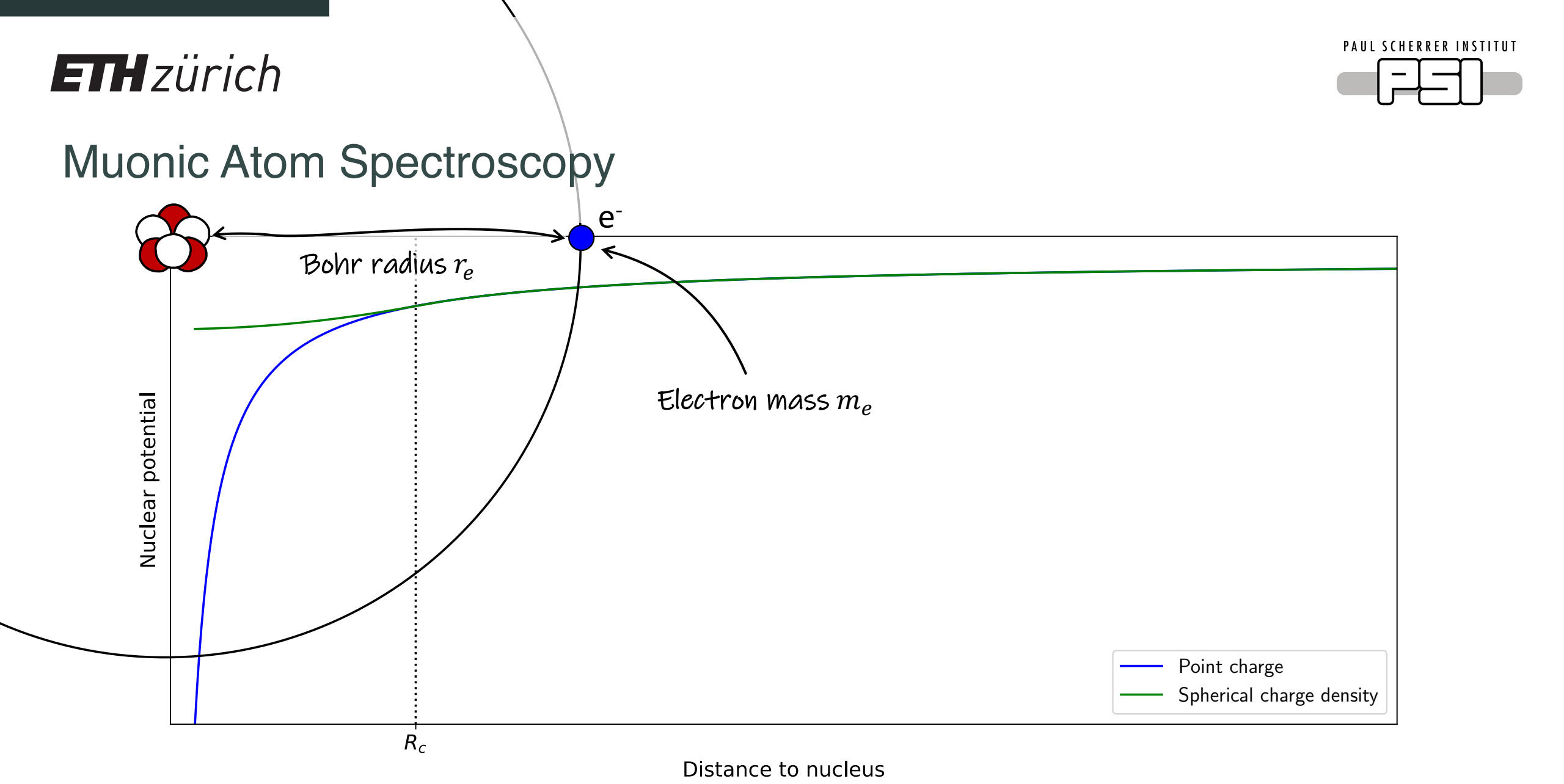
Absolute charge radii



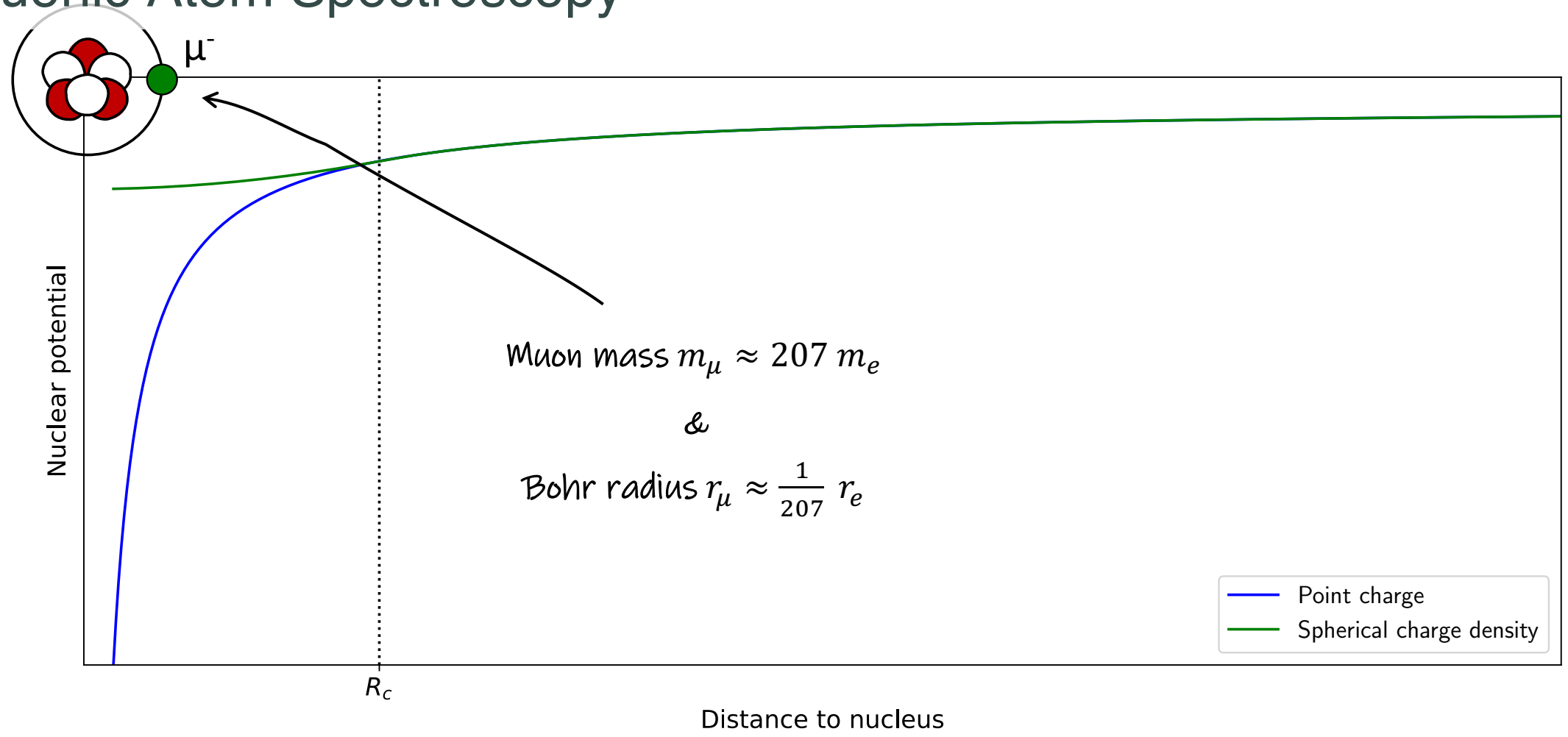
- Elastic electron scattering
- Muonic atom spectroscopy

$$R_c(^{A'}Li) = \sqrt{R_c^2(^{A}Li) + \delta\langle r_c^2\rangle^{A,A'}}$$

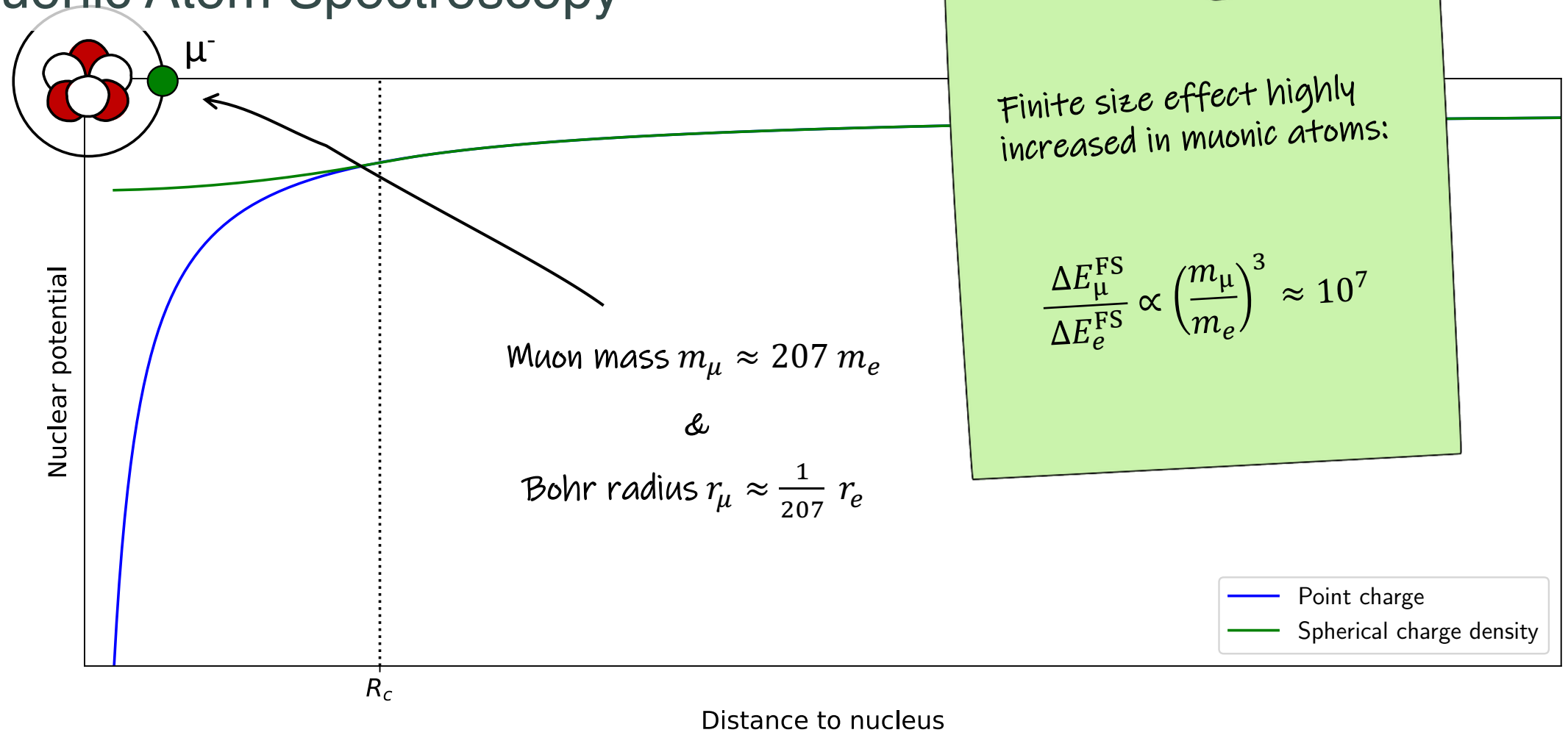
Muonic Atom Spectroscopy



Muonic Atom Spectroscopy



Muonic Atom Spectroscopy



Muon mass $m_\mu \approx 207\, m_e$

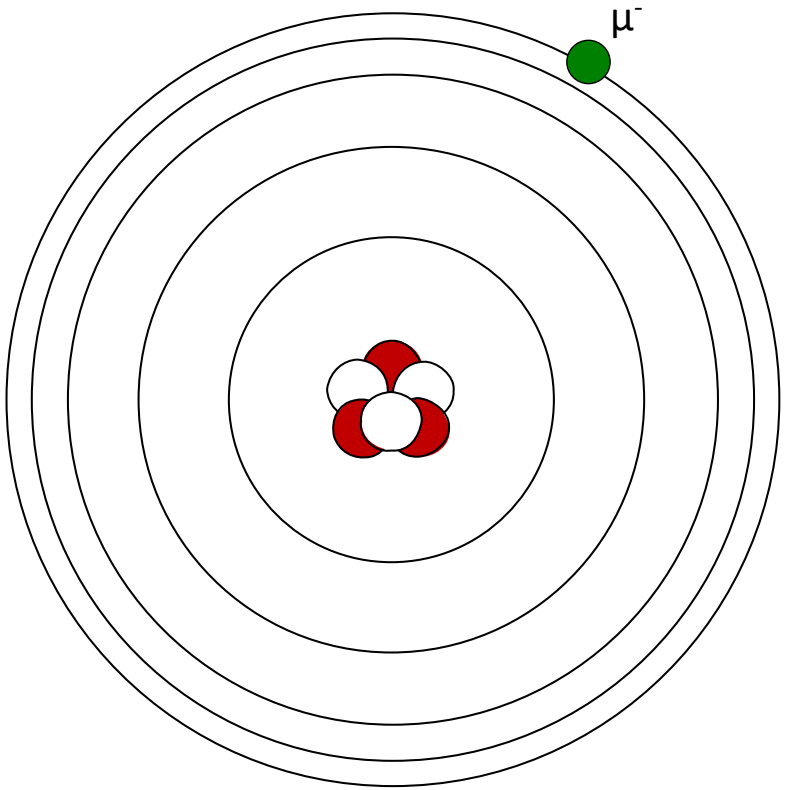
&

Bohr radius $r_\mu \approx \frac{1}{207}\, r_e$

Finite size effect highly increased in muonic atoms:

$$\frac{\Delta E_\mu^{\mathrm{FS}}}{\Delta E_e^{\mathrm{FS}}} \propto \left(\frac{m_\mu}{m_e}\right)^3 \approx 10^7$$

Muonic Atom Spectroscopy



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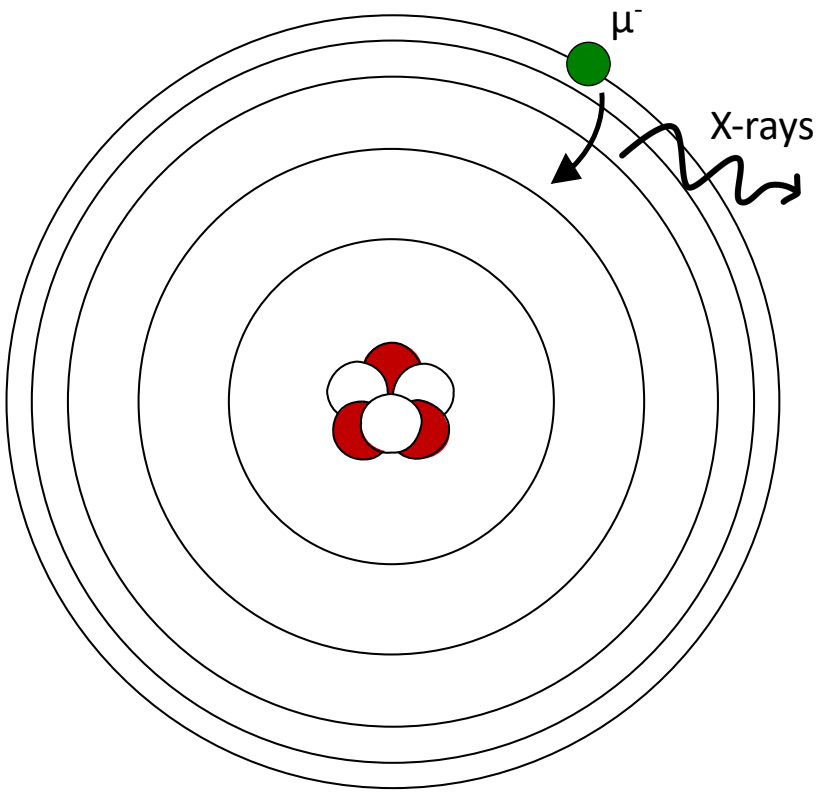

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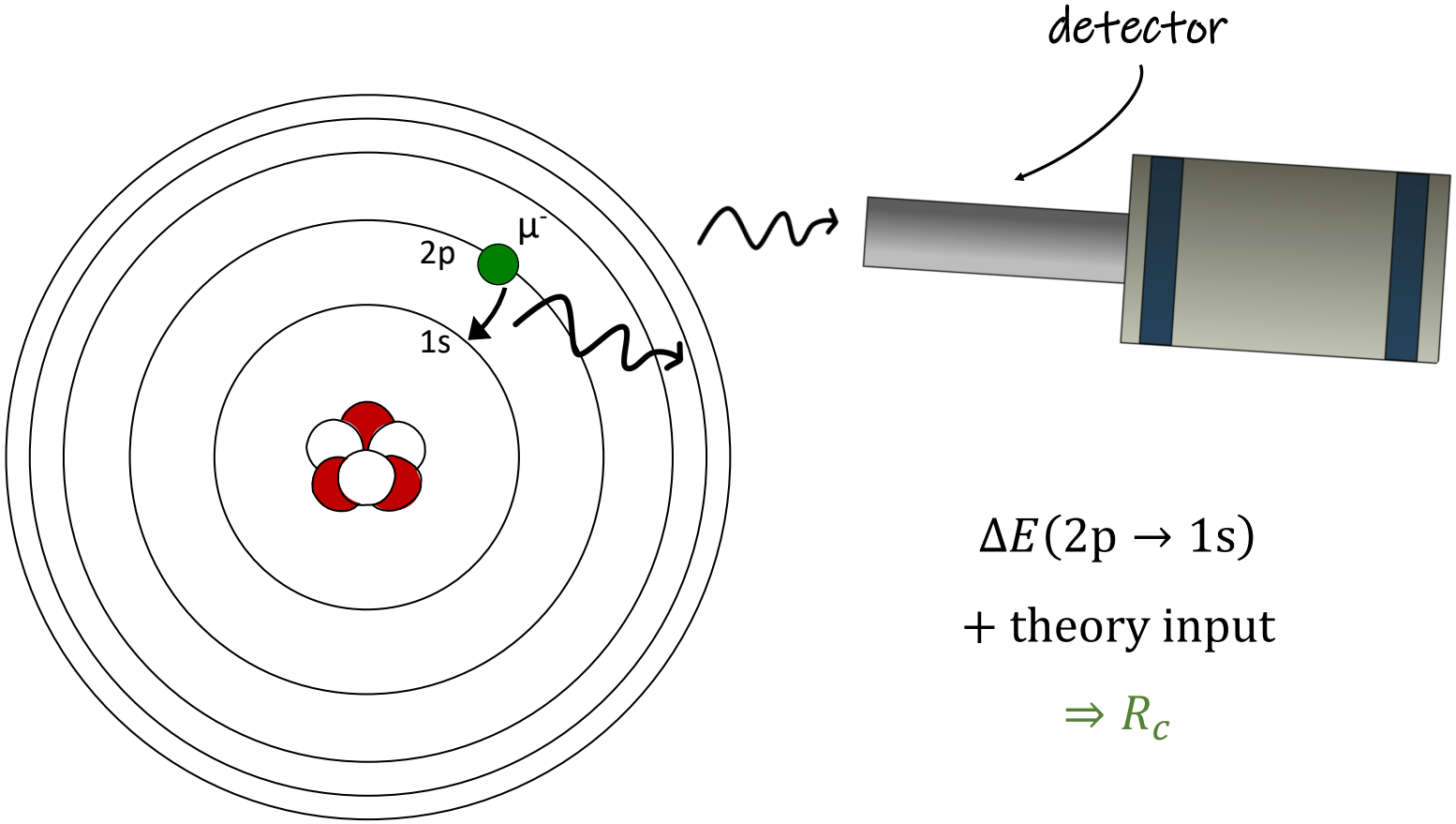


$\Delta E(2\mathrm{p} \rightarrow 1\mathrm{s})$

$+$ theory input

$\Rightarrow R_c$

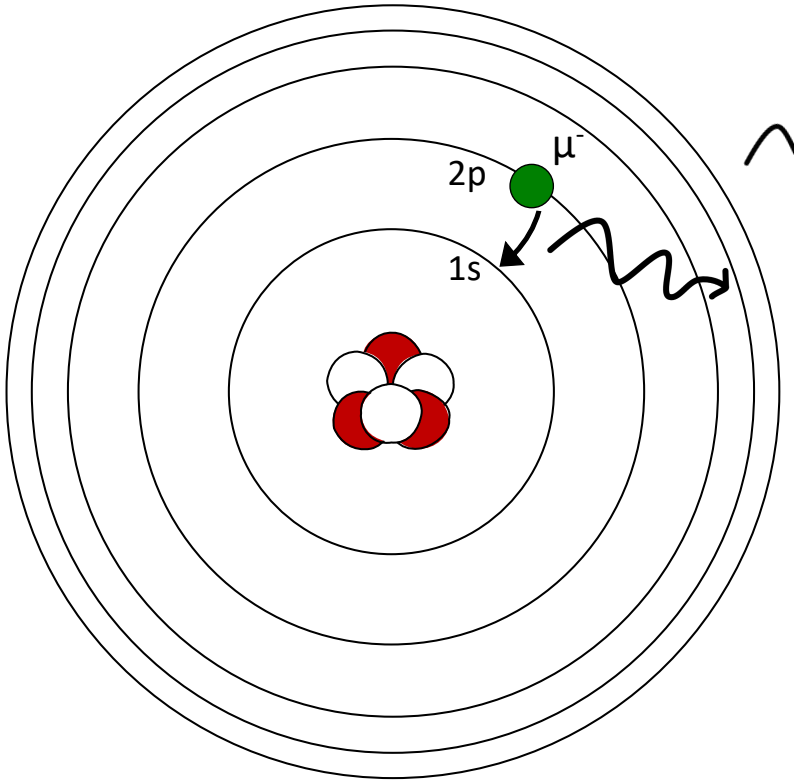
Muonic Atom Spectroscopy

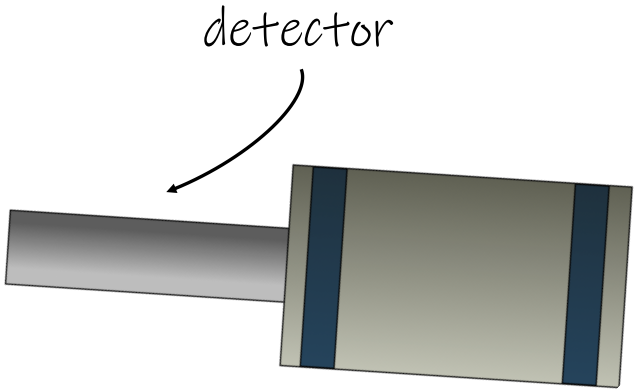
3
Li
6.94

For μLi:

$\Delta E(2p \rightarrow 1s)$

$\approx 18.7\ \text{keV}$





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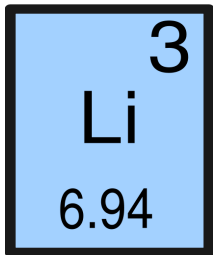
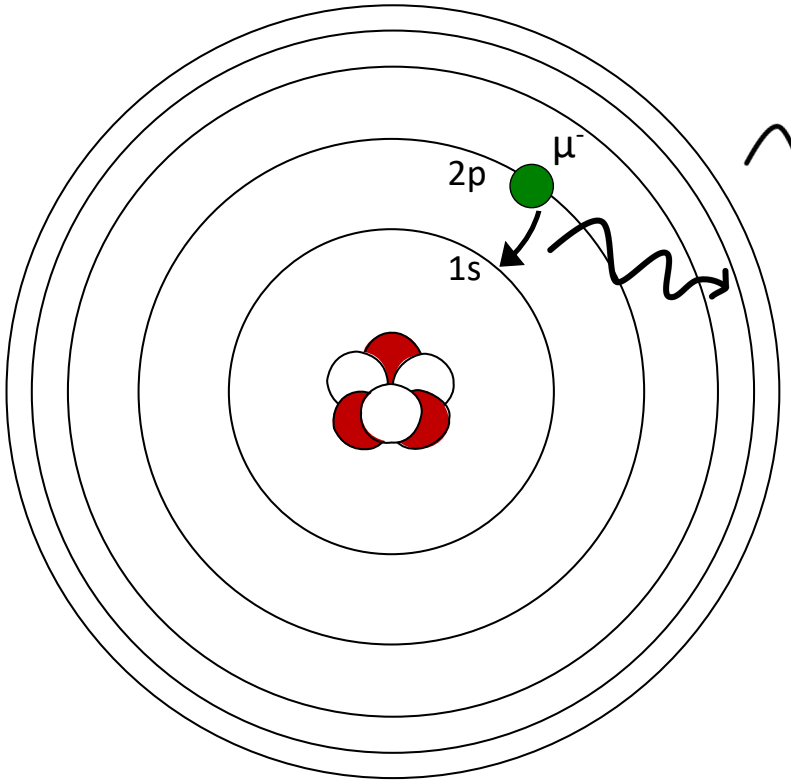


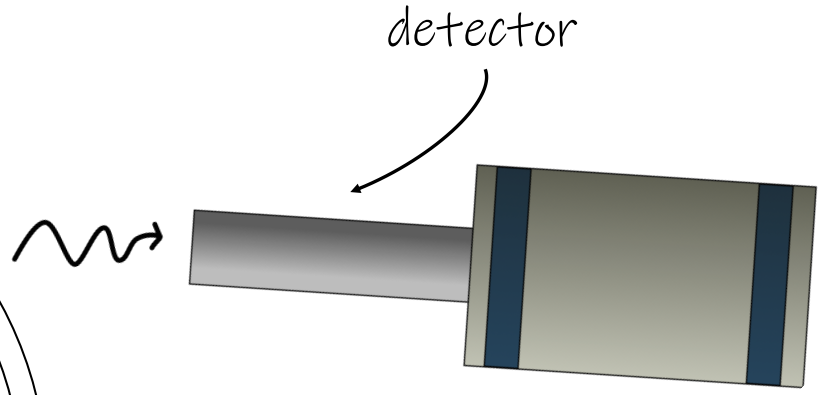
For μLi:

$\Delta E(2p \rightarrow 1s)$

≈ 18.7 keV

Detector	Resolution	@ Energy
HPGe	500-1000 eV	< 100 keV
SDD	100-300 eV	< 30 keV





$\Delta E(2p \rightarrow 1s)$

$+$ theory input

$\Rightarrow R_c$

Muonic Lithium

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)

Current best μLi results:

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]

First Tests of μLi Spectroscopy

CHECKLIST

- [x] Lithium target(s)
- [ ] μ^- from PSI
- [ ] (Silicon drift) detector
- [ ] DAQ + beam time from muX

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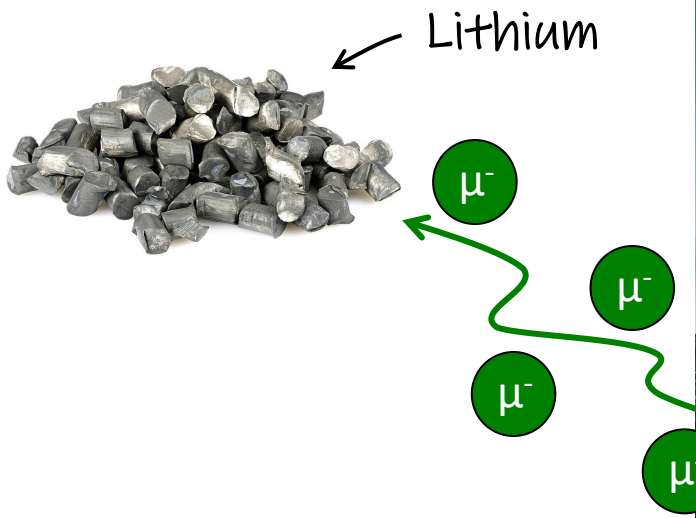

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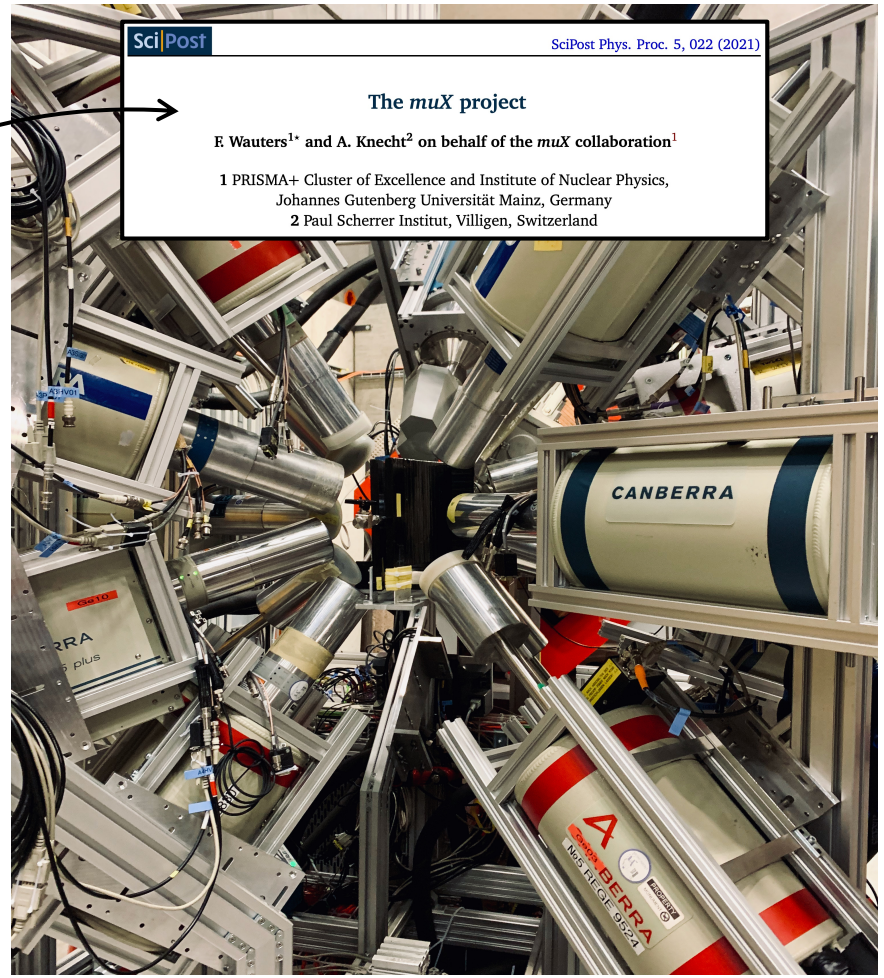
First Tests of μLi Spectroscopy

data taking during muX beam time

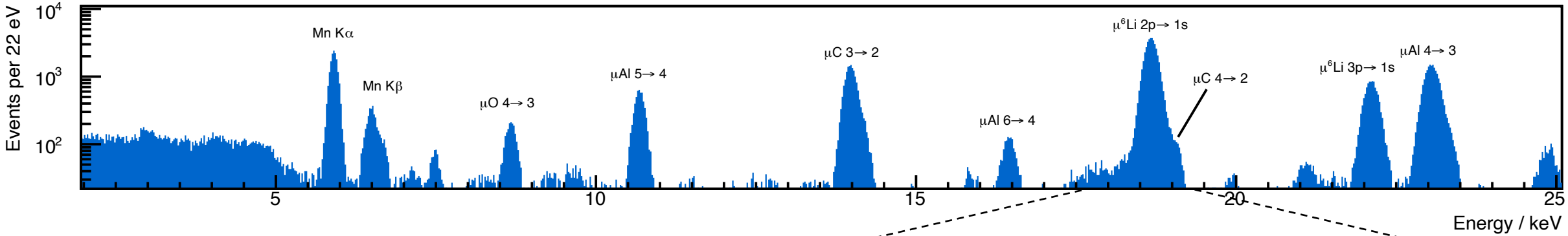


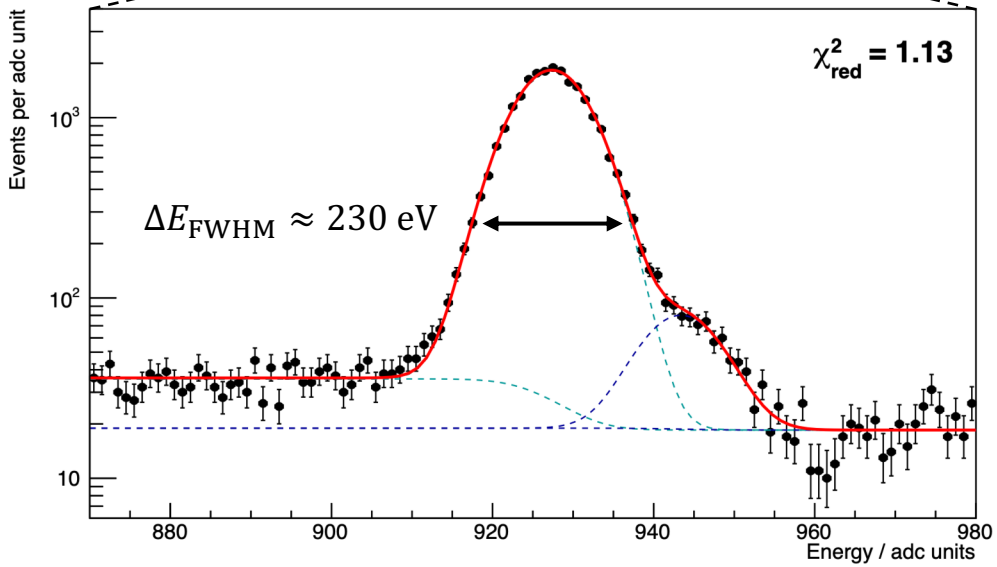
CHECKLIST

- ✓ Lithium target(s)
- ✓ μ^- from PSI
- ✓ (Silicon drift) detector
- ✓ DAQ + beam time from muX

See Stella's talk in 30 min!

Preliminary Results





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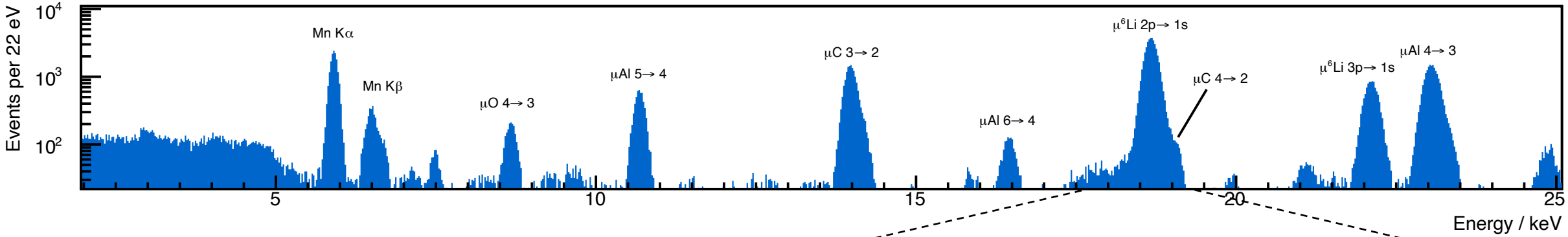
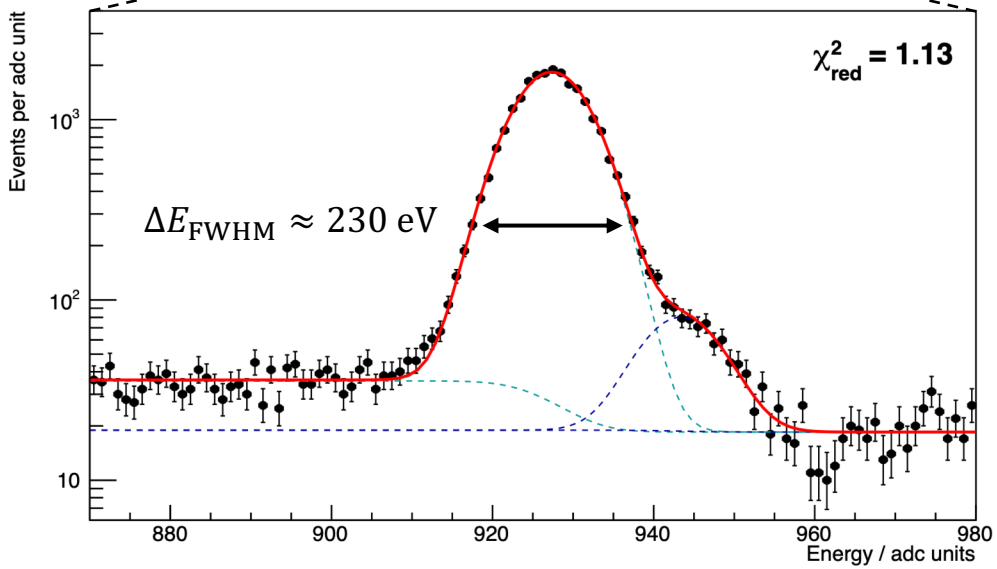


Preliminary analysis of μ^{6}Li 2p → 1s:

$$E_{exp} = 18.670 \pm 0.008(stat + calib)\ keV$$



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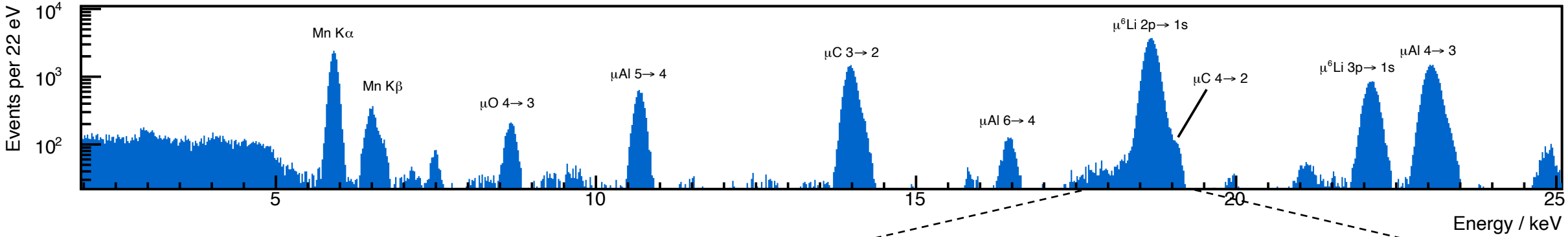
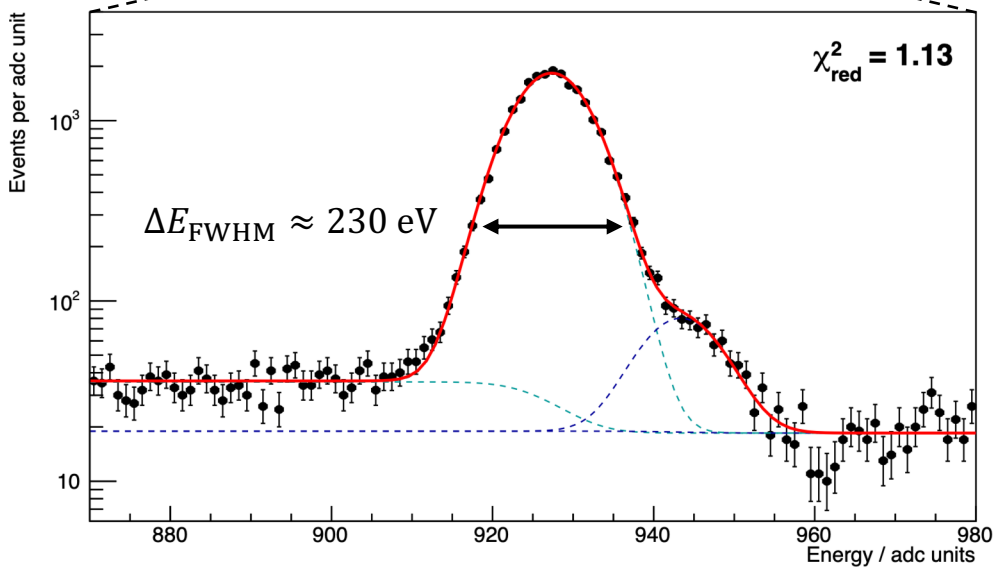


Preliminary analysis of μ^{6}Li 2p → 1s:

$$E_{exp} = 18.670 \pm 0.008(stat + calib)\ keV$$

$$E_{calc} = 18.6716 \pm 0.0008\ keV$$

based on charge radius uncertainty



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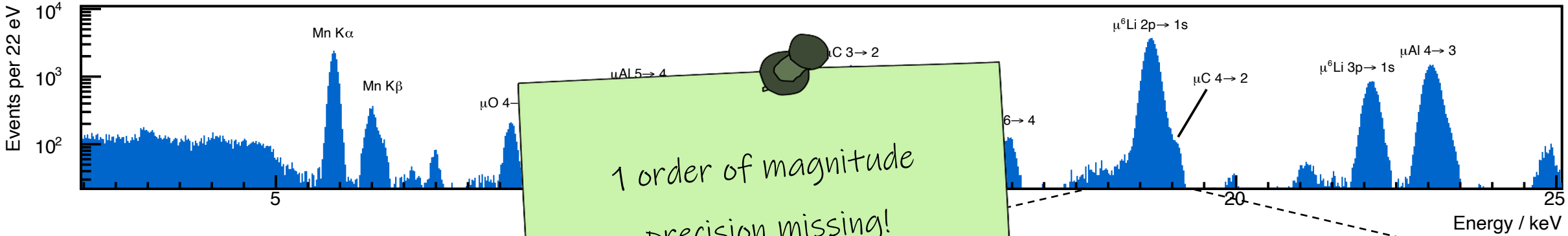


Preliminary analysis of μ^6L

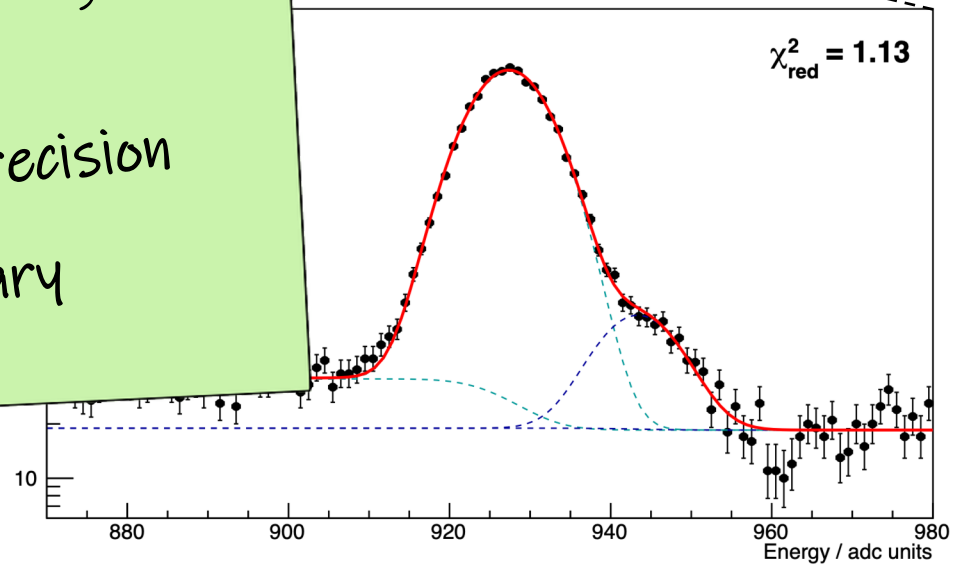
$E_{exp} = 18.670 \pm 0.008(stat$

$E_{calc} = 18.6716 \pm 0.00$

based on charge radius uncertainty

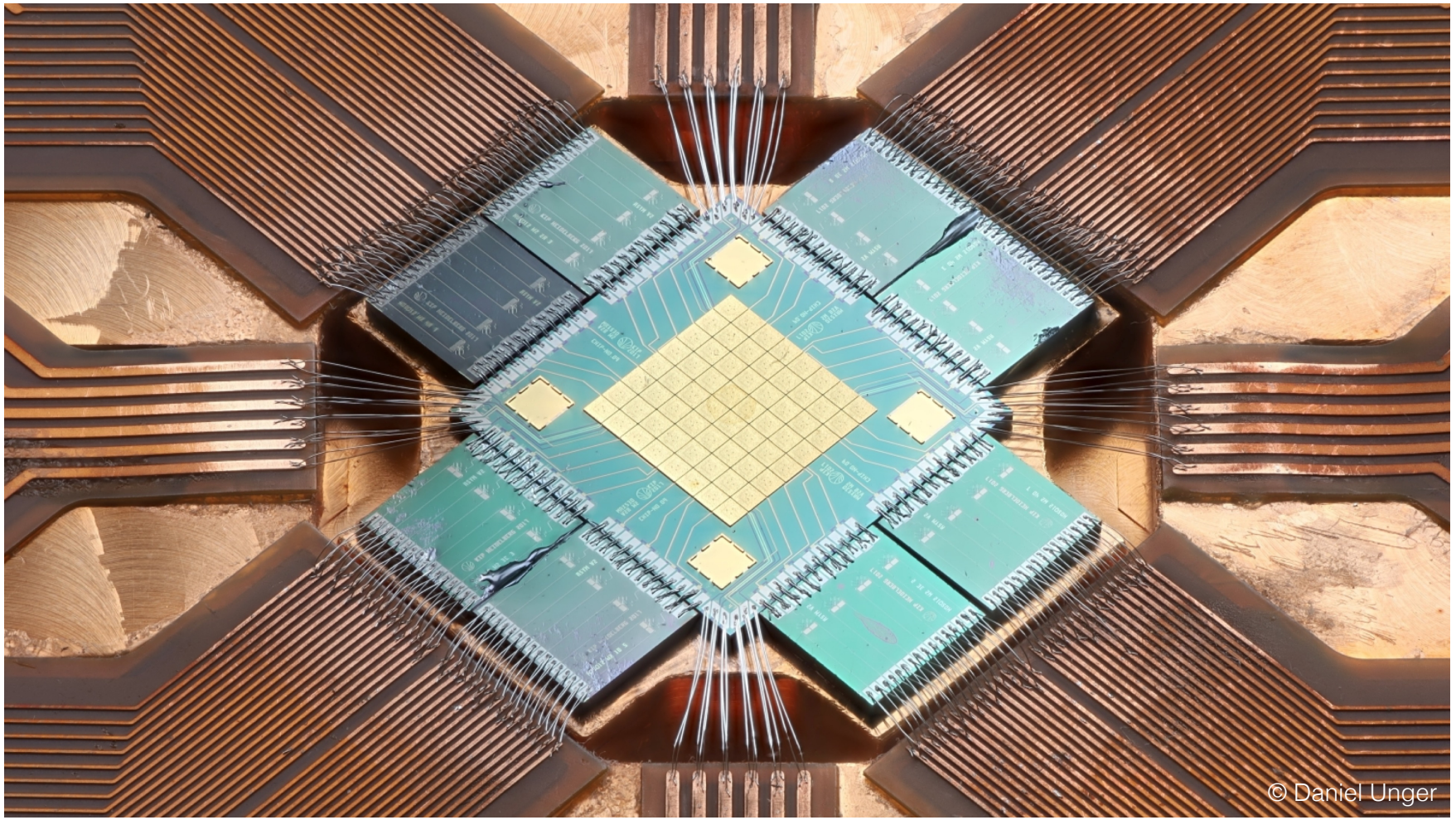
1 order of magnitude precision missing!

⇒ sub-eV precision necessary

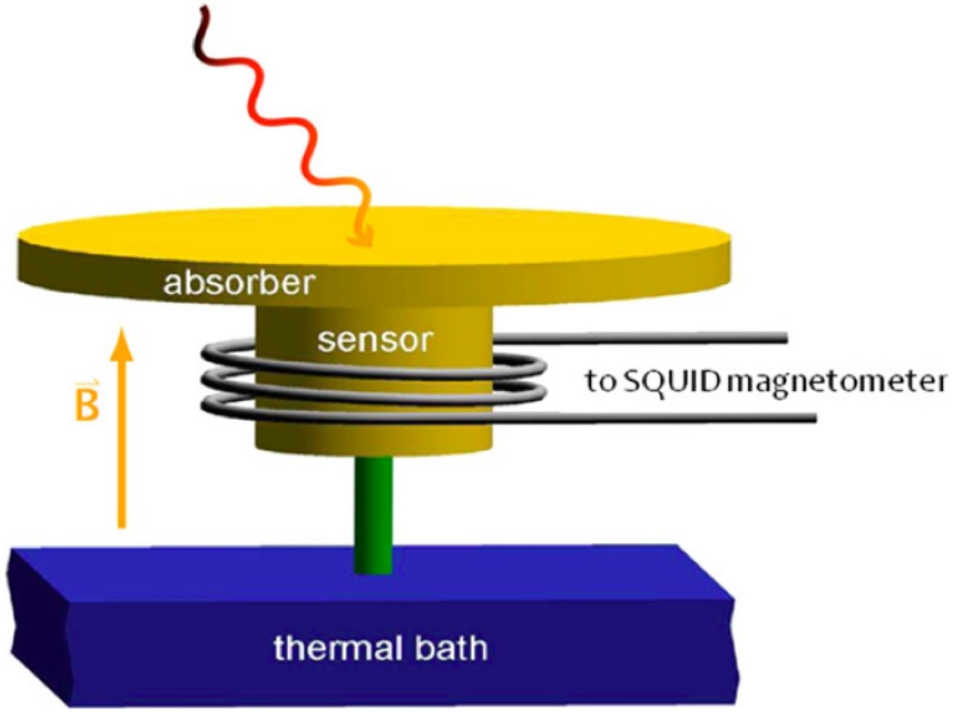


"MMC"

Metallic Magnetic Microcalorimeters



Metallic Magnetic Microcalorimeters



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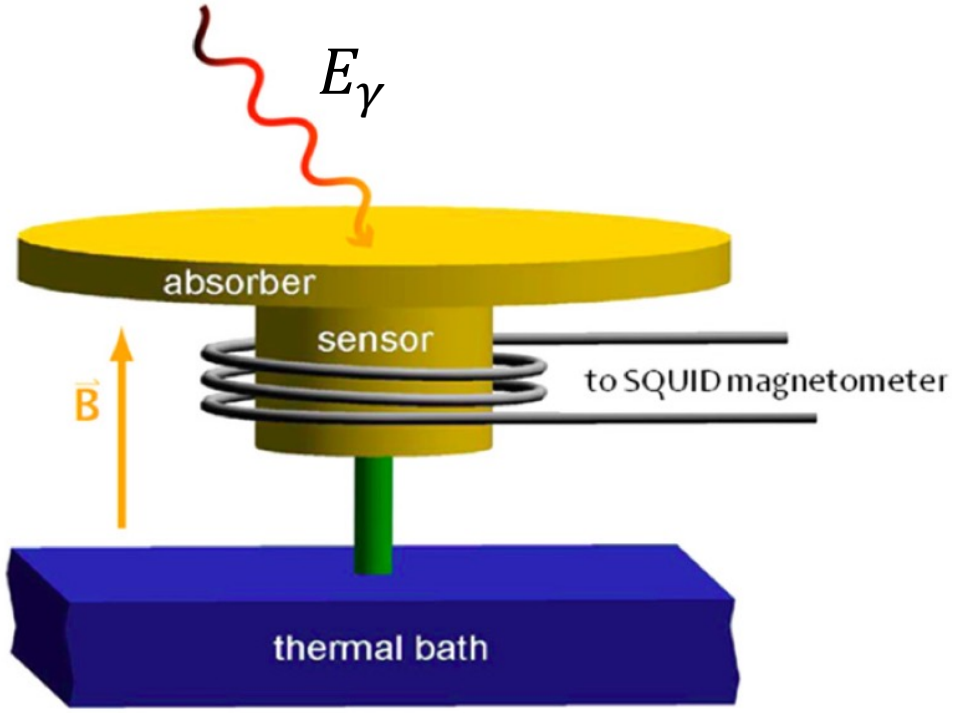

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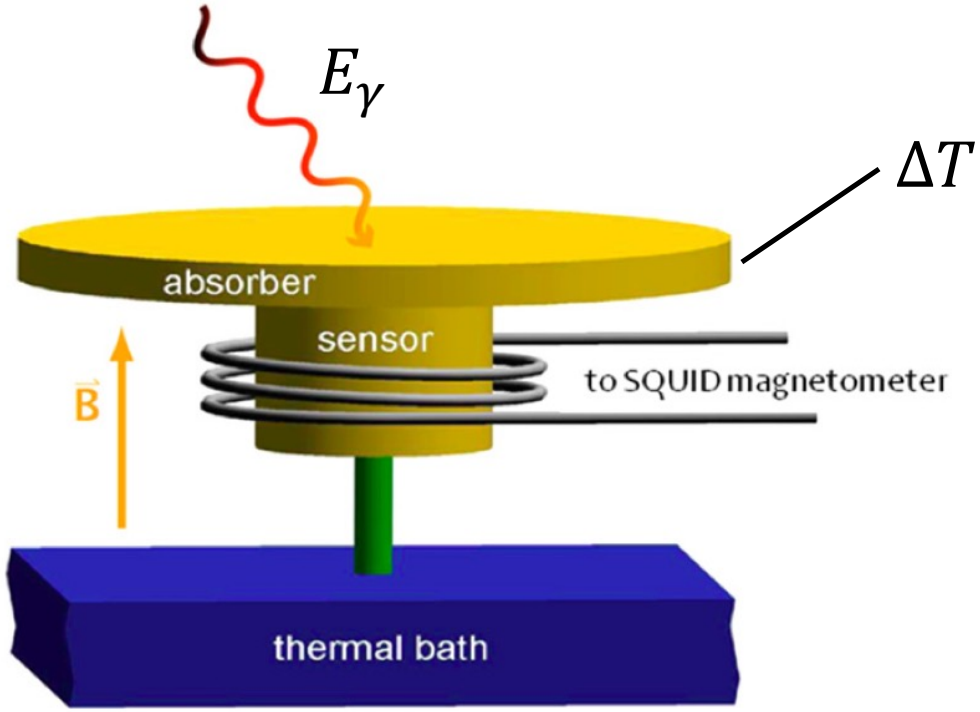
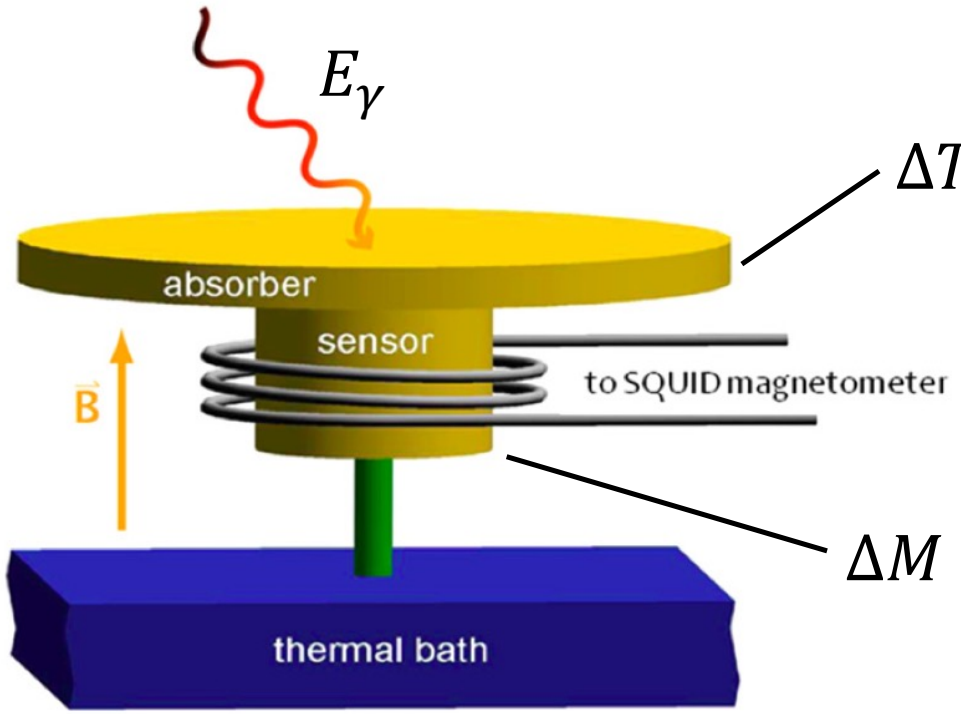


$$\Delta T = \frac{E_\gamma}{C_{\mathrm{tot}}}$$

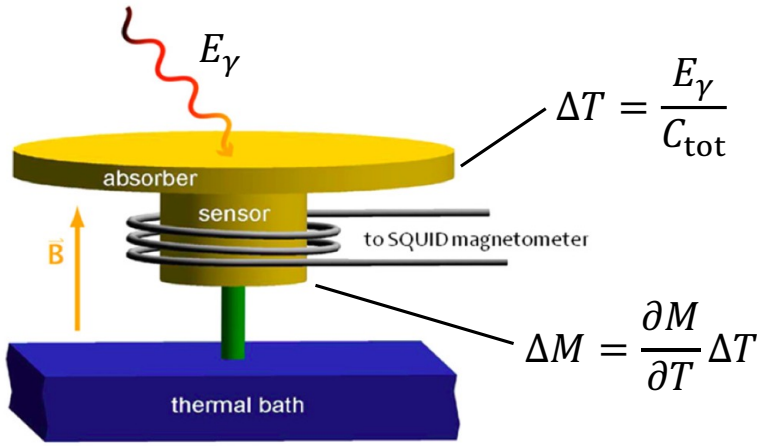
Metallic Magnetic Microcalorimeters



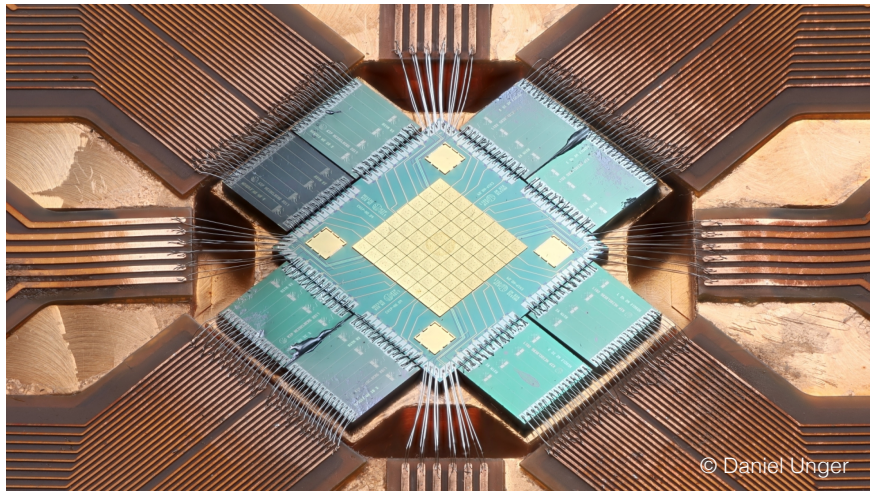
$$\Delta T = \frac{E_\gamma}{C_{\mathrm{tot}}}$$

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

Metallic Magnetic Microcalorimeters



The Heidelberg "maXs-30"

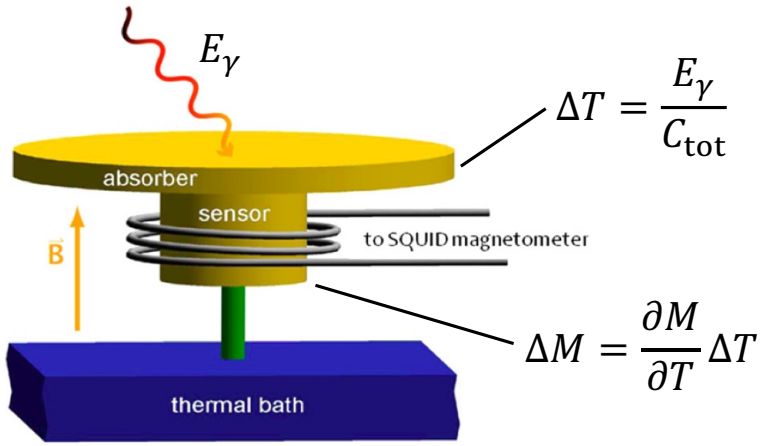


Energy resolution: $\Delta E \propto T\sqrt{C_{\mathrm{abs}}}$

Typically: T~ 20 mK

Det.-design dependent

Metallic Magnetic Microcalorimeters



Energy resolution: $\Delta E \propto T\sqrt{C_{\mathrm{abs}}}$

Typically: $T \sim 20$ mK

Det.-design dependent

The Heidelberg "maXs-30"

maXs-30

Energy resolution:

$\Delta E_{\mathrm{FWHM}} < 10$ eV

In range:

$\sim 3 - 40$ keV
(> 50% efficiency)

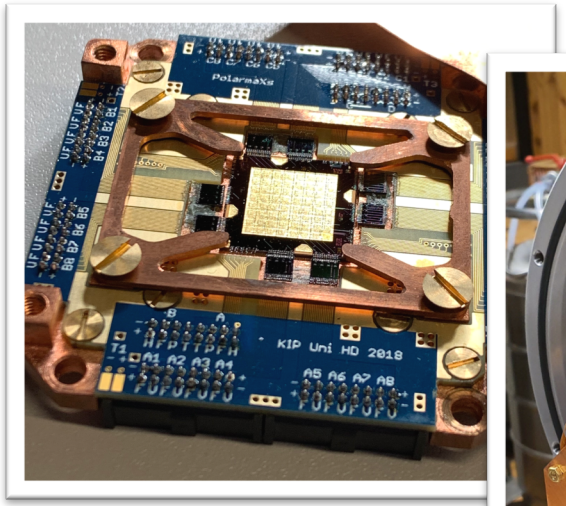
ETH zürich

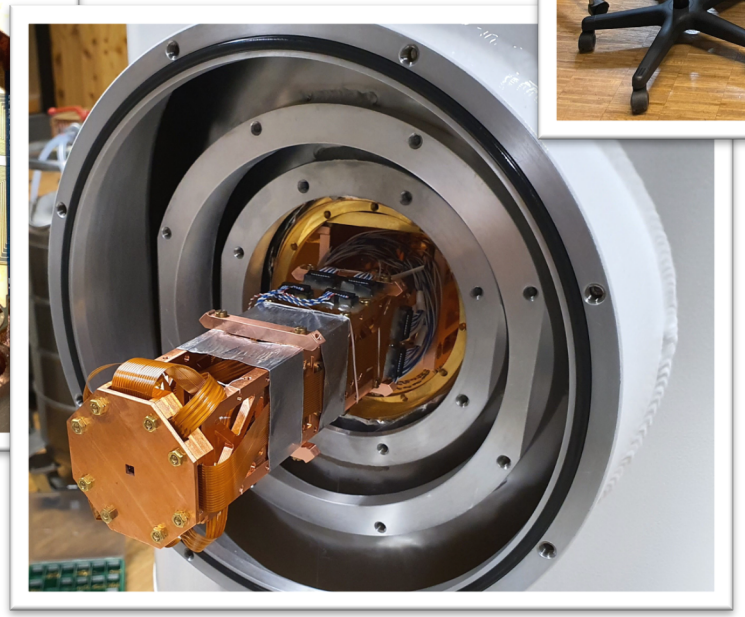
PAUL SCHERRER INSTITUT PSI

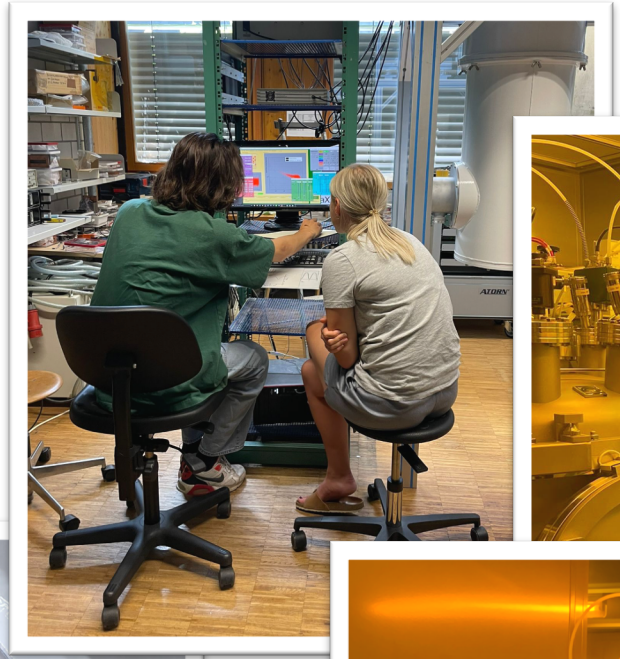
Where the MMCs are made…

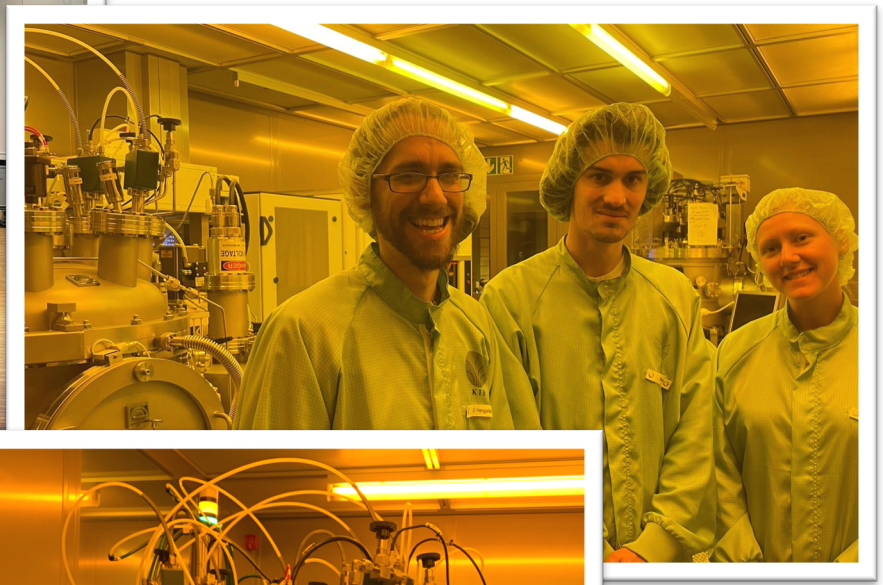
UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

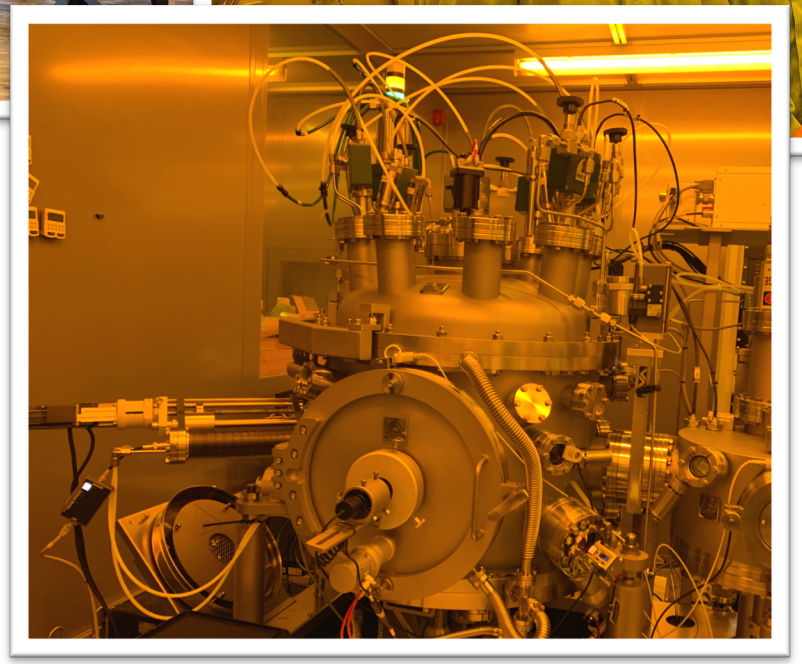
KIRCHHOFF-INSTITUT FÜR PHYSIK



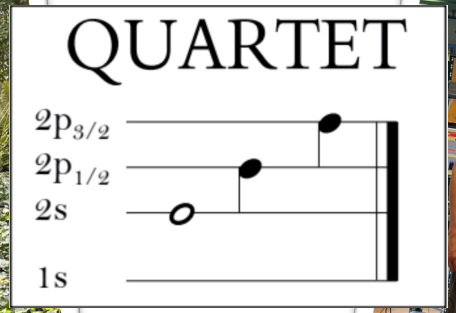


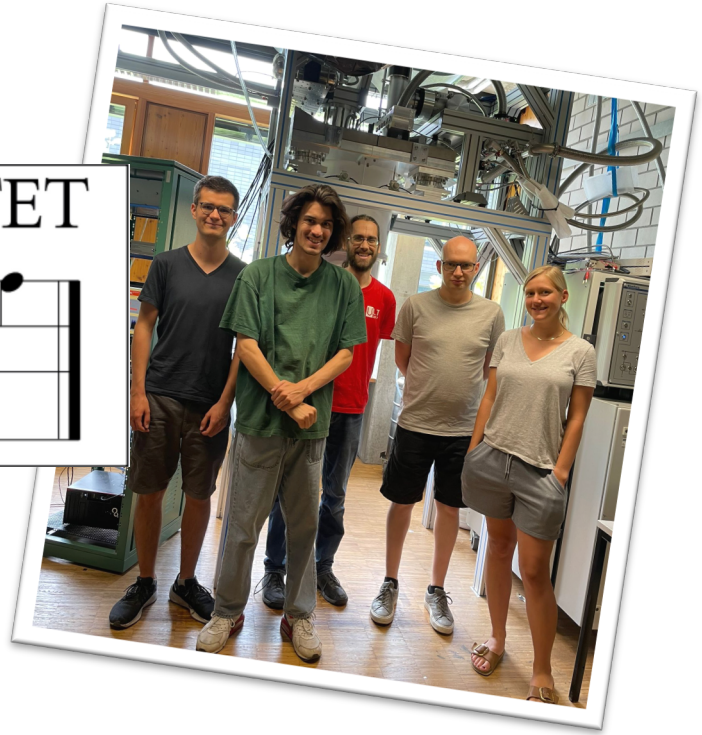




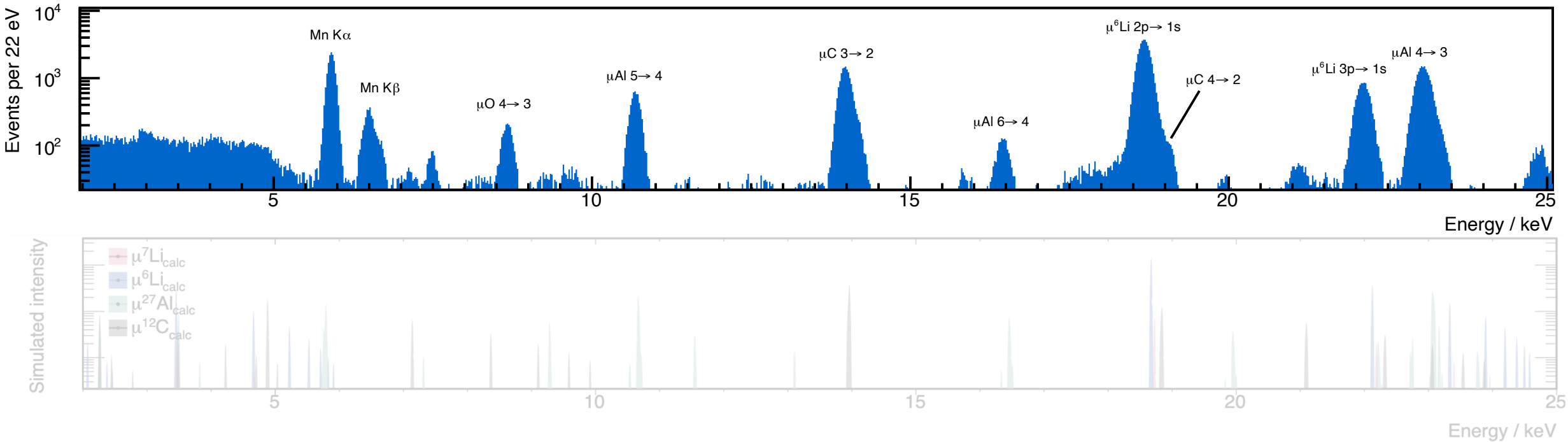


Our new Collaboration:





Summary & Outlook



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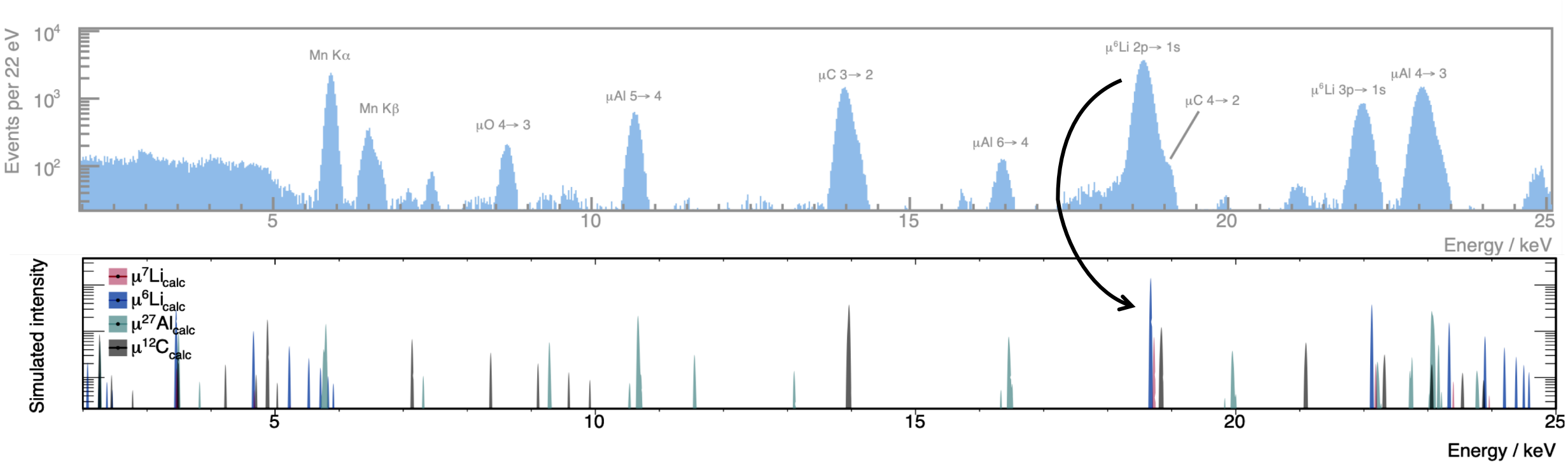
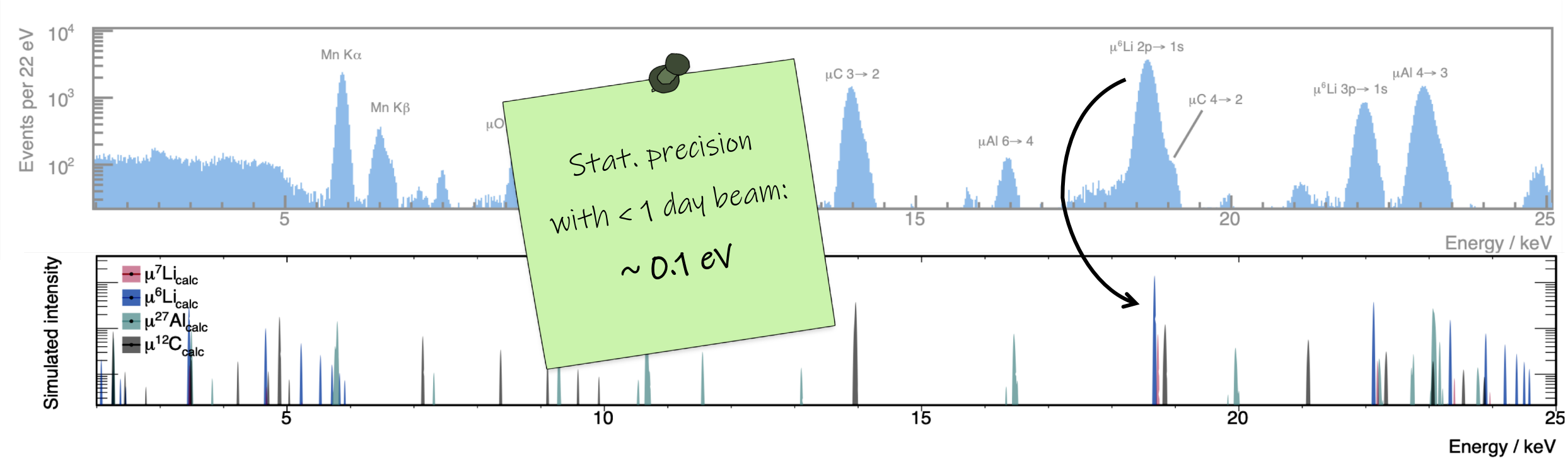


1. Introduce MMCs to muonic x-ray spectroscopy

Summary & Outlook



1. Introduce MMCs to muonic x-ray spectroscopy
2. Extract ^{6}Li and ^{7}Li charge radii with rel. uncertainty of 10^{-3}

Outlook – QUARTET Goals