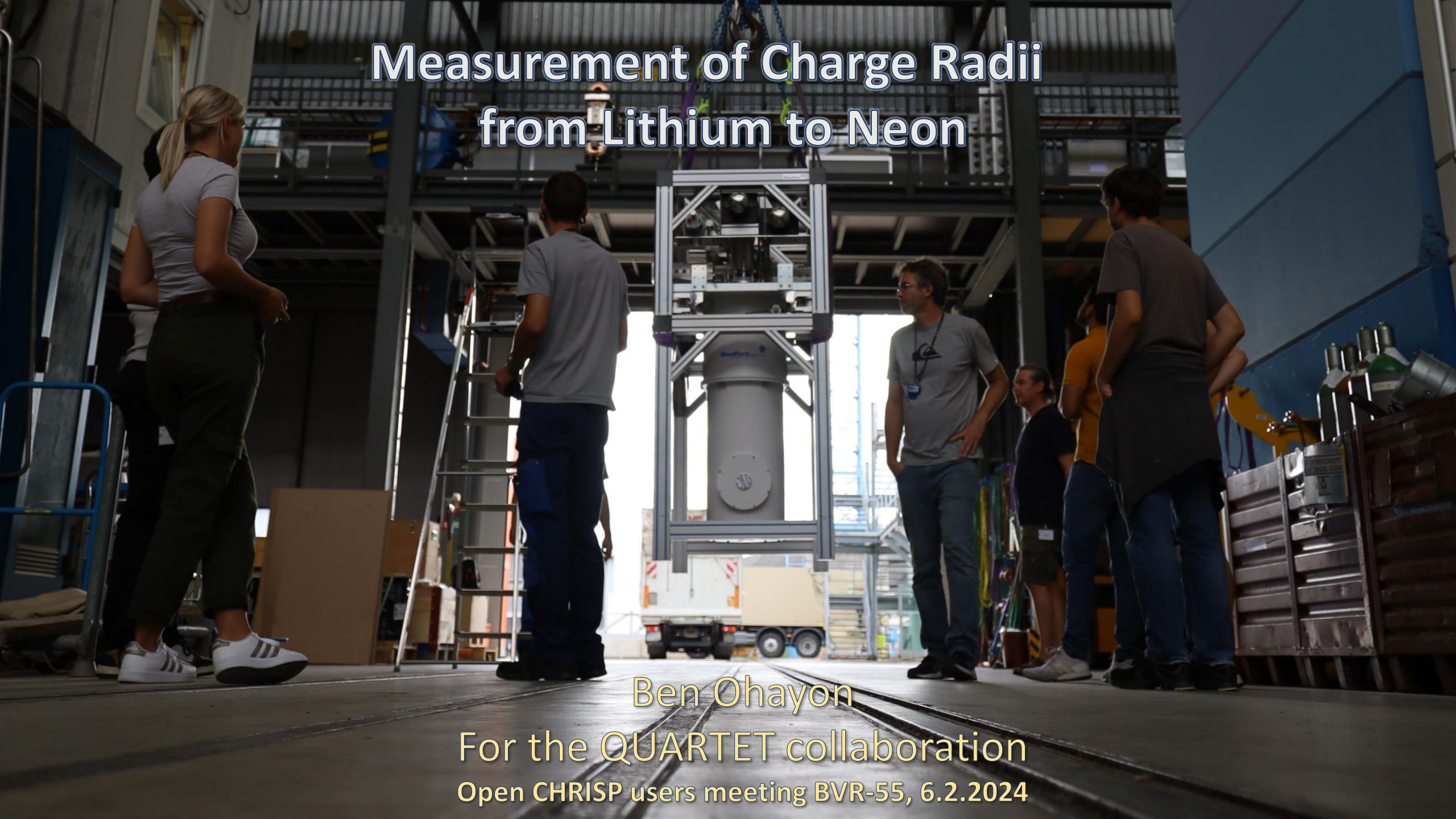


Measurement of Charge Radii from Lithium to Neon

Ben Ohayon
For the QUARTET collaboration

Open CHRISP users meeting BVR-55, 6.2.2024

We are

workers in the fields of:

- Exotic atoms
- Quantum sensing

TECHNION Israel Institute of Technology

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

Laboratoire Kastler Brossel Physique quantique et applications

PAUL SCHERRER INSTITUT PSI

NOVA UNIVERSIDADE NOVA DE LISBOA

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

université PARIS-SACLAY

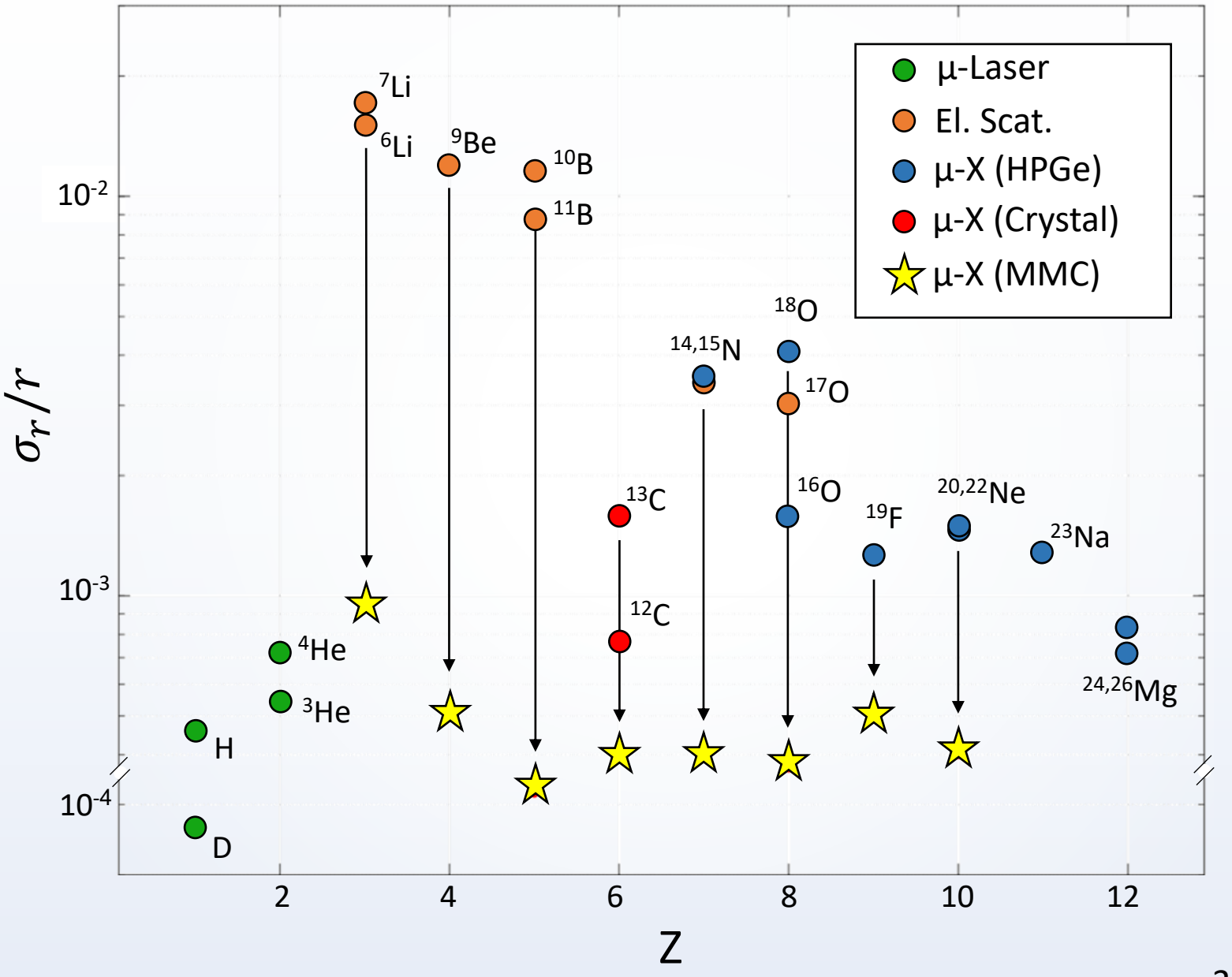
ETH zürich

KU LEUVEN

* Spokespersons: bohayon@technion.ac.il, npaul@lkb.upmc.fr

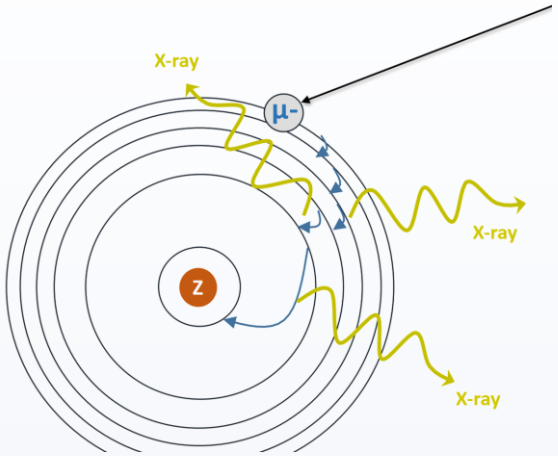
We want to

- Accurately measure absolute nuclear charge radii of stable nuclei from ^{6}Li to ^{22}Ne



How?

Muonic atoms



- s levels very sensitive to nuclear radius:

$$\frac{\delta E_{FNS}}{E_0} \sim Z^2 \left(\frac{r_c}{a_0}\right)^2 \left(\frac{m_\mu}{m_e}\right)^2 \sim 10^{-4}\, Z^2$$

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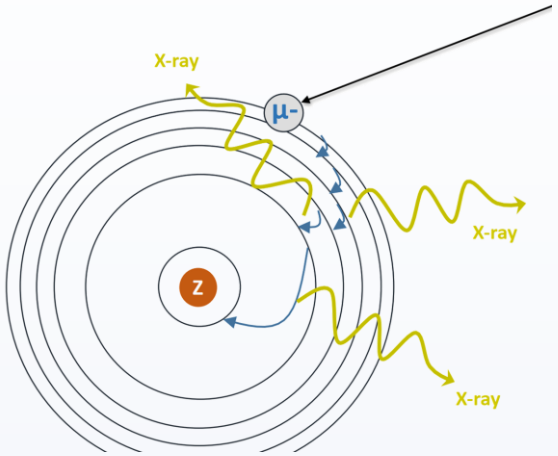

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- Needed resolving power $\frac{E}{\Gamma_E} > 10^3$ for $3 \leq Z$.
- Solid-state detectors not adequate under $\sim$200 keV ($Z = 10$)
- Laser spectroscopy not (yet) possible.

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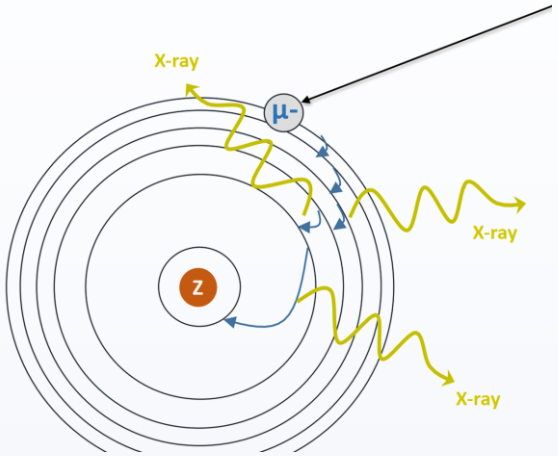

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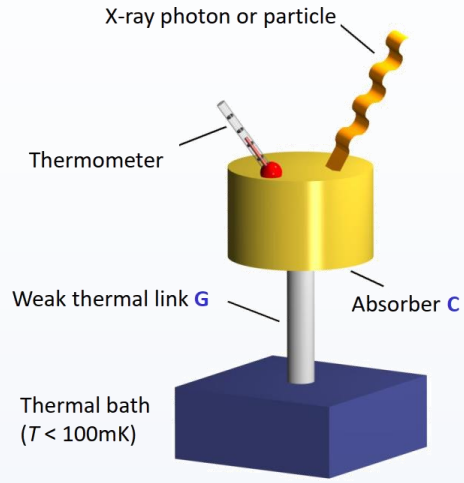

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- Broadband (important for calibration)
- **Superb resolution** $\left(\frac{E}{\Gamma_E} > 10^3\right)$
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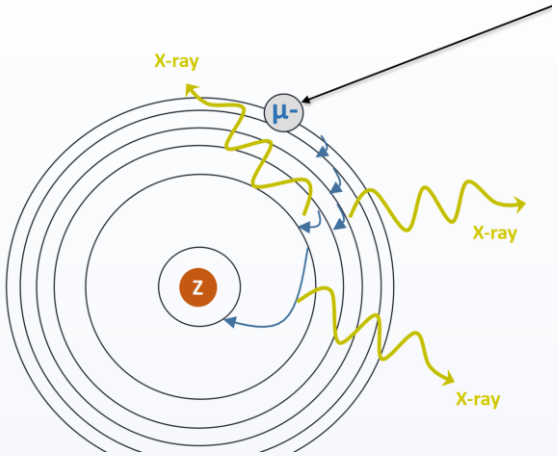

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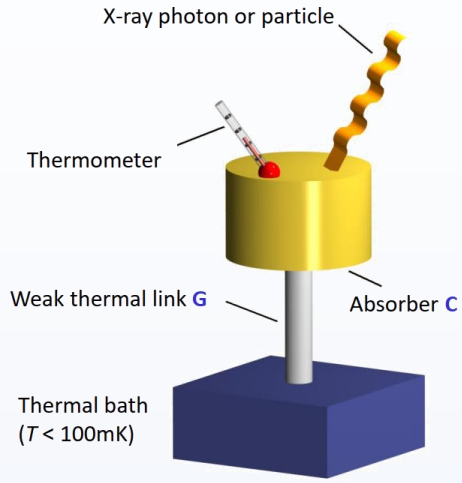

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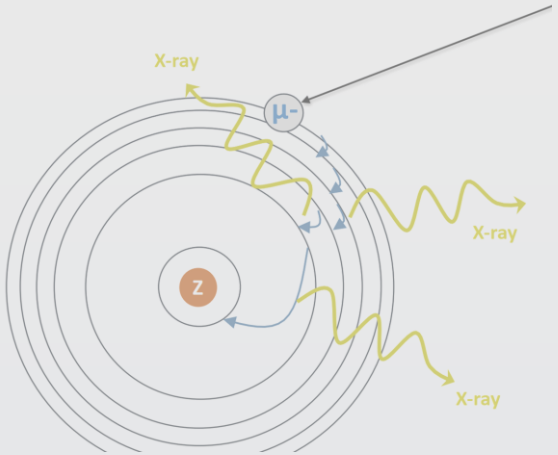
Quantum Interactions with Exotic Atoms

Muonic atoms



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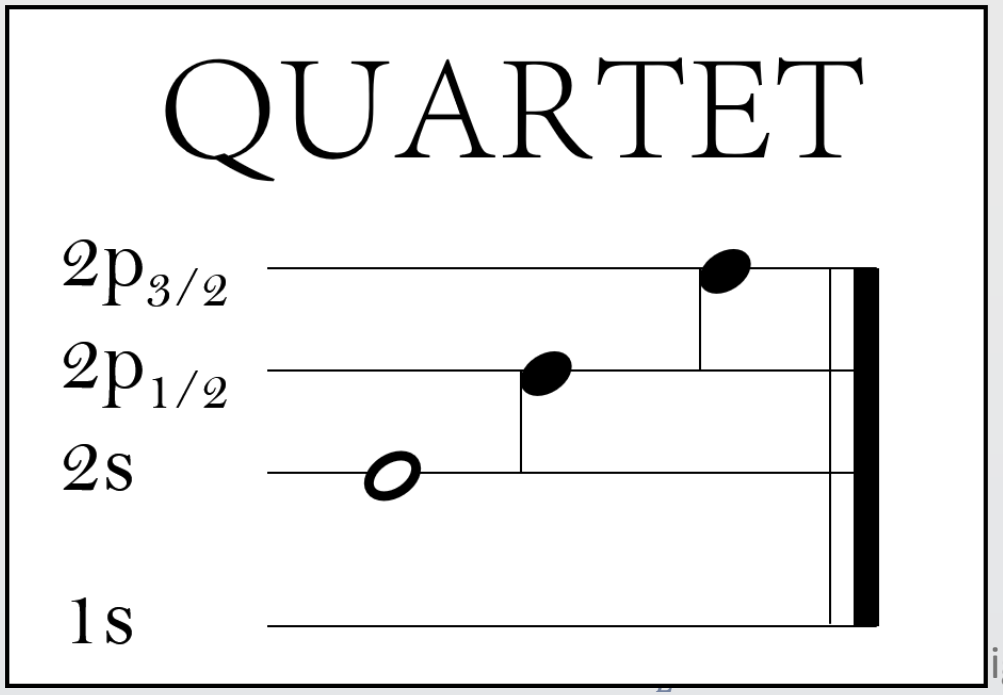

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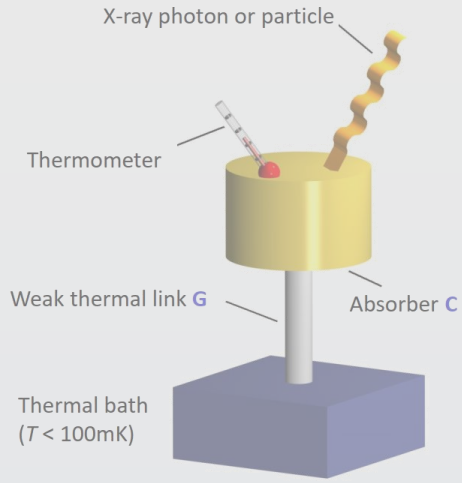

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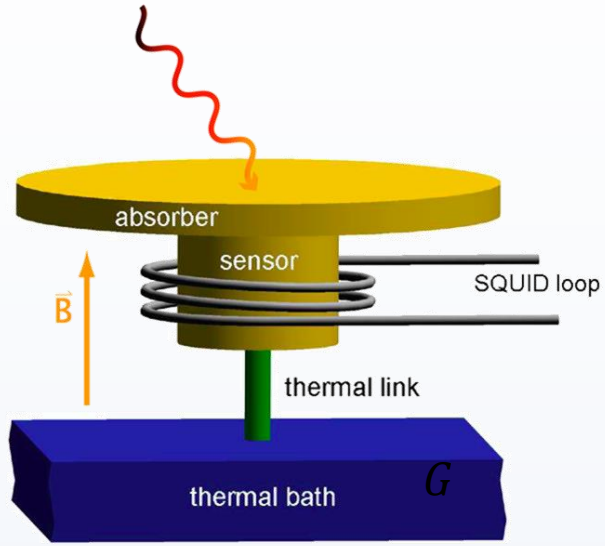

δE ⇨ $\delta T = \frac{\delta E}{C}$ ⇨ $\delta M = \frac{\partial M}{\partial T}\frac{\delta E}{C}$ ⇨ $\delta\Phi \sim \delta M \sim \delta T \sim \delta E$

Absorption of energy | Increase of temperature | Change of magnetisation | Change of magnetic flux

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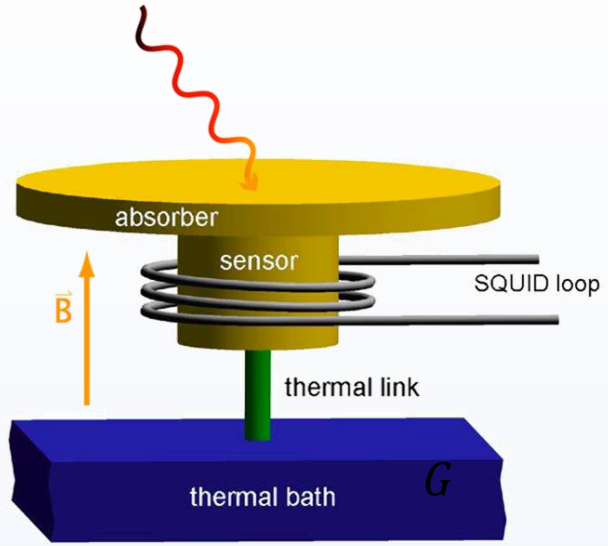

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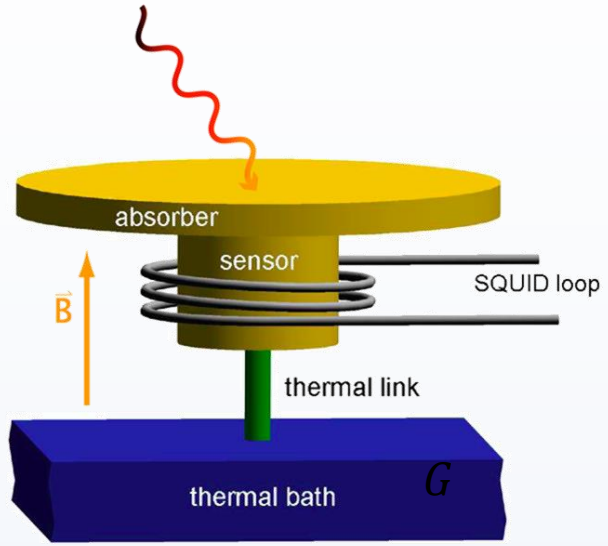

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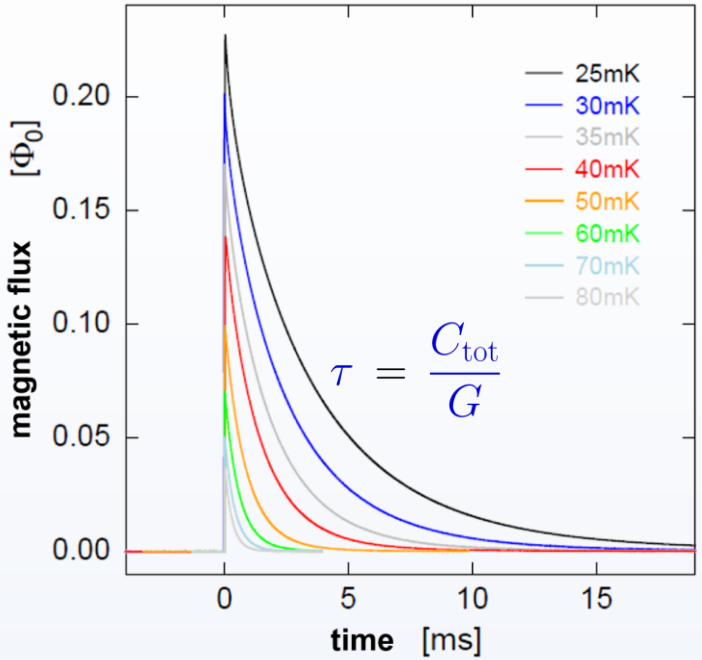

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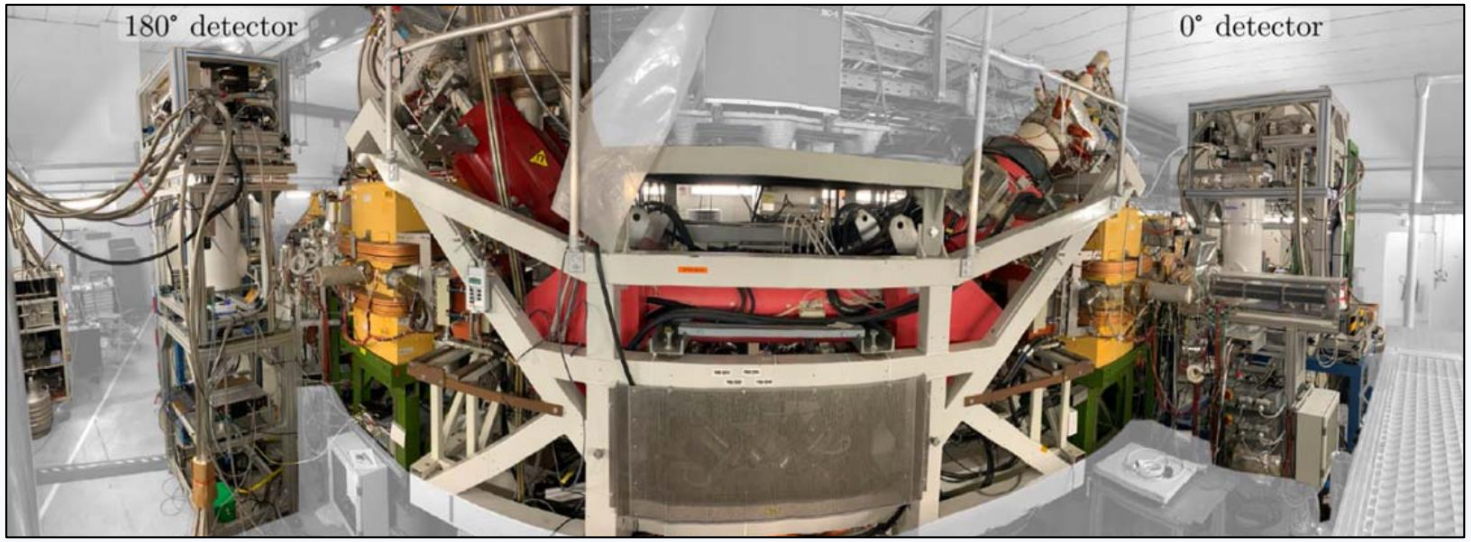
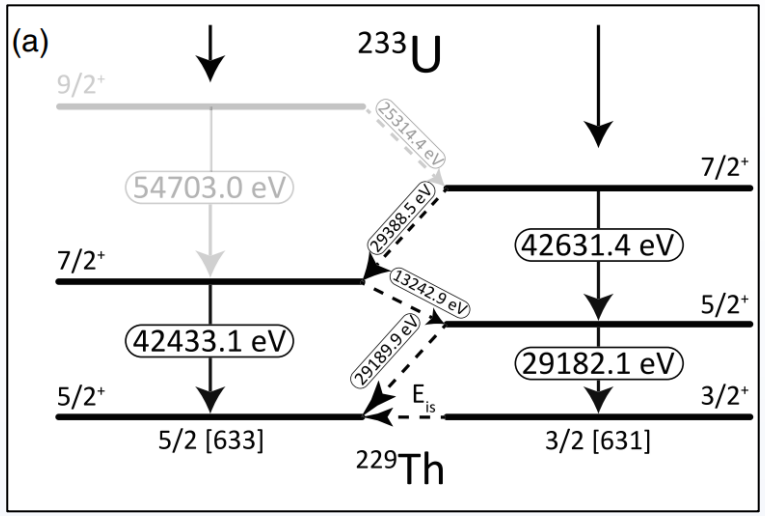
Frontier applications of MMCs:

X-ray spectroscopy of highly charged ions @ storage rings



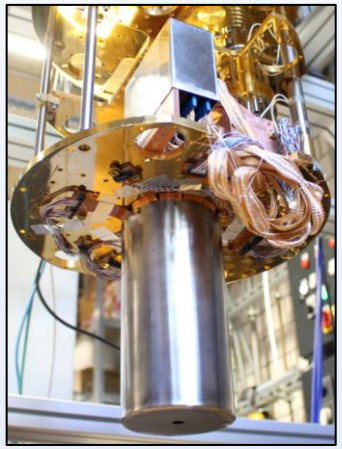
Ph. Pfäfflein, *et. al.,* Phys. Scr. 97 (2022). M.O. Herdrich*et. al.,* Atoms 11, 13 (2023), …

^{229m}Th optical excitation energy 8.1(2) eV:



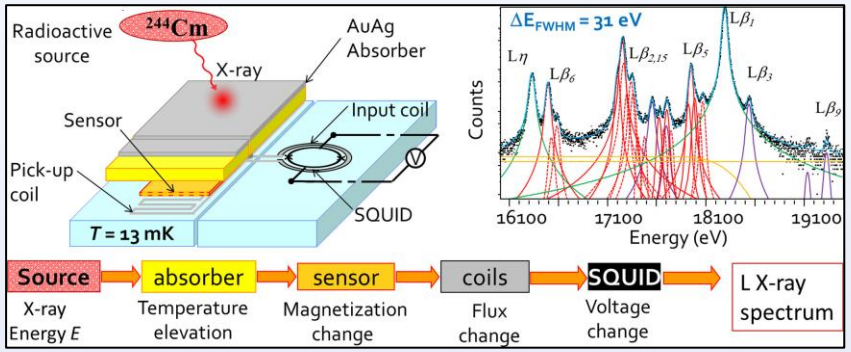
Th Sikorsky, *et. al.,* PRL 125, 142503 (2020)

Search for Axion-like particles:



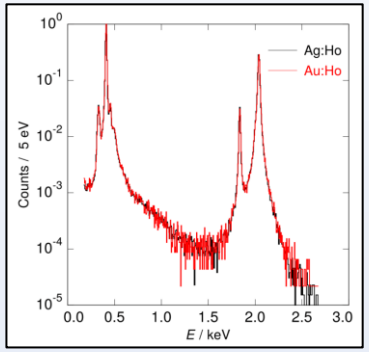
D. Unger, L. Gastaldo, A. Fleischmann, *et. al.,* JINST 16 (2021)

Determination X-ray absolute emission intensities:



R Mariam, *et. al.,* Spectrochimica Acta B 187 (2022)

Electron capture in ^{163}Ho:



L. Gastaldo, A. Fleischmann, *et. al.,*
Journal of Low Temperature Physics 209 (2022)

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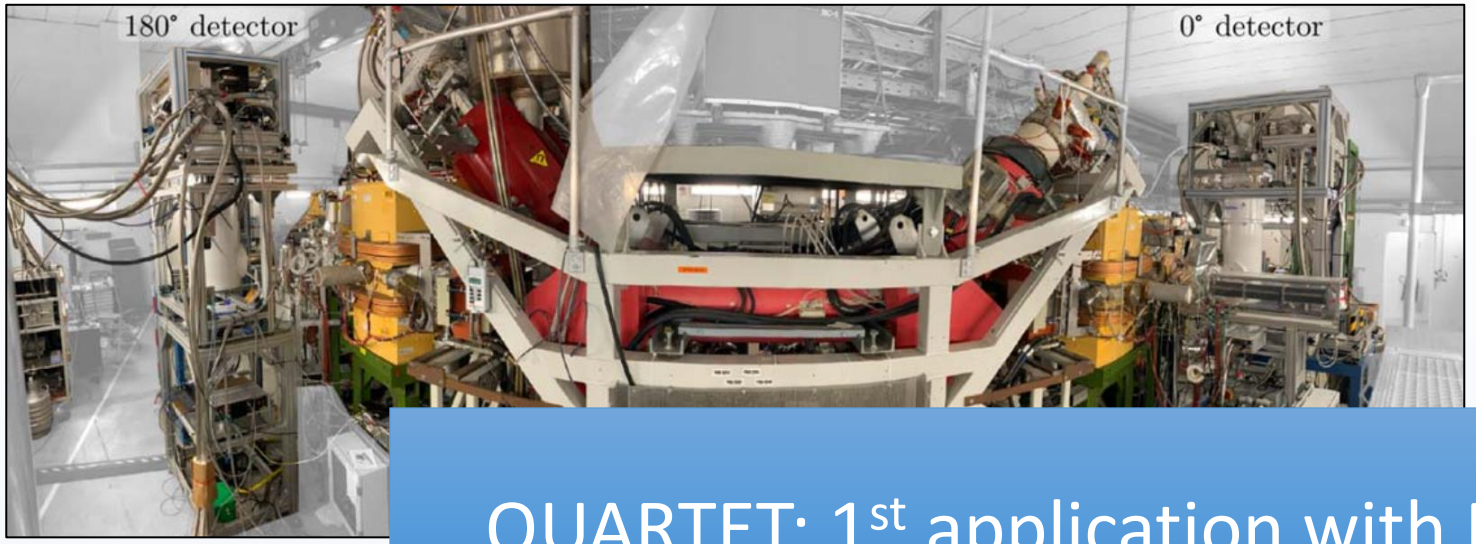

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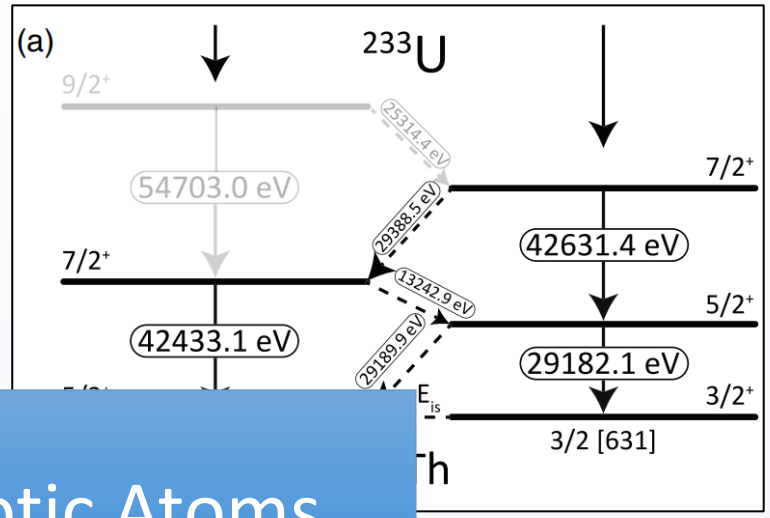

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QUARTET: 1st application with Exotic Atoms

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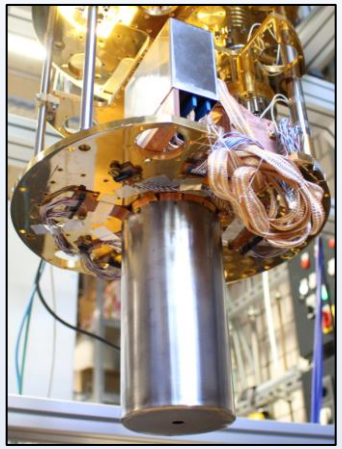

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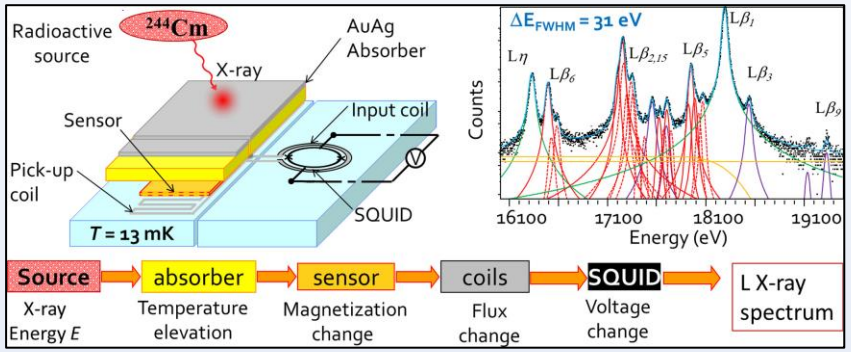

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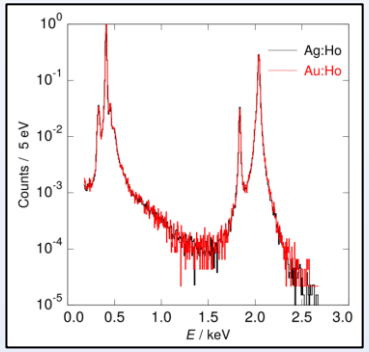

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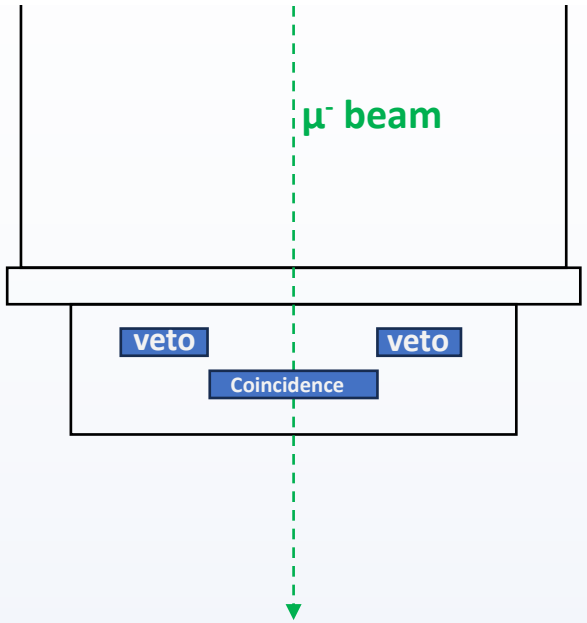
Experimental scheme

- $10^4\ \mu^-/s, \sim 30\ \mathrm{MeV/c}$
- Entrance counter and veto for tagging and timing



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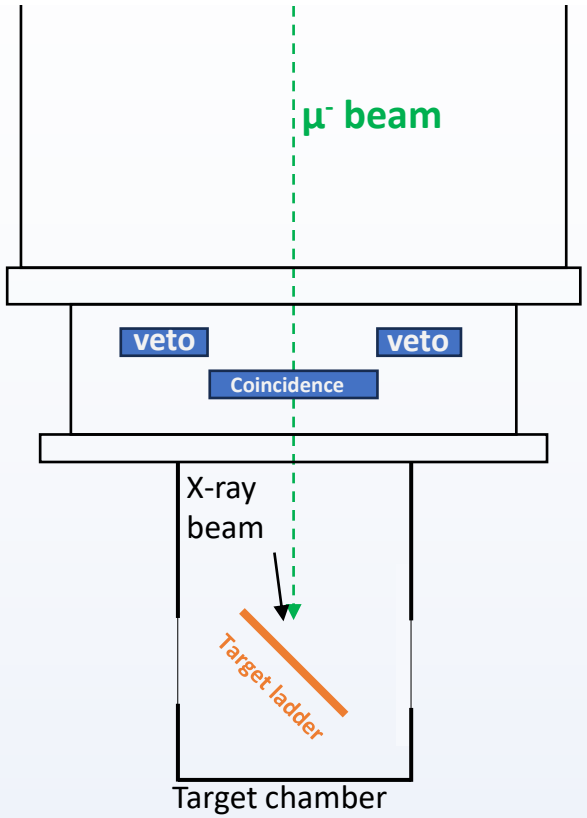

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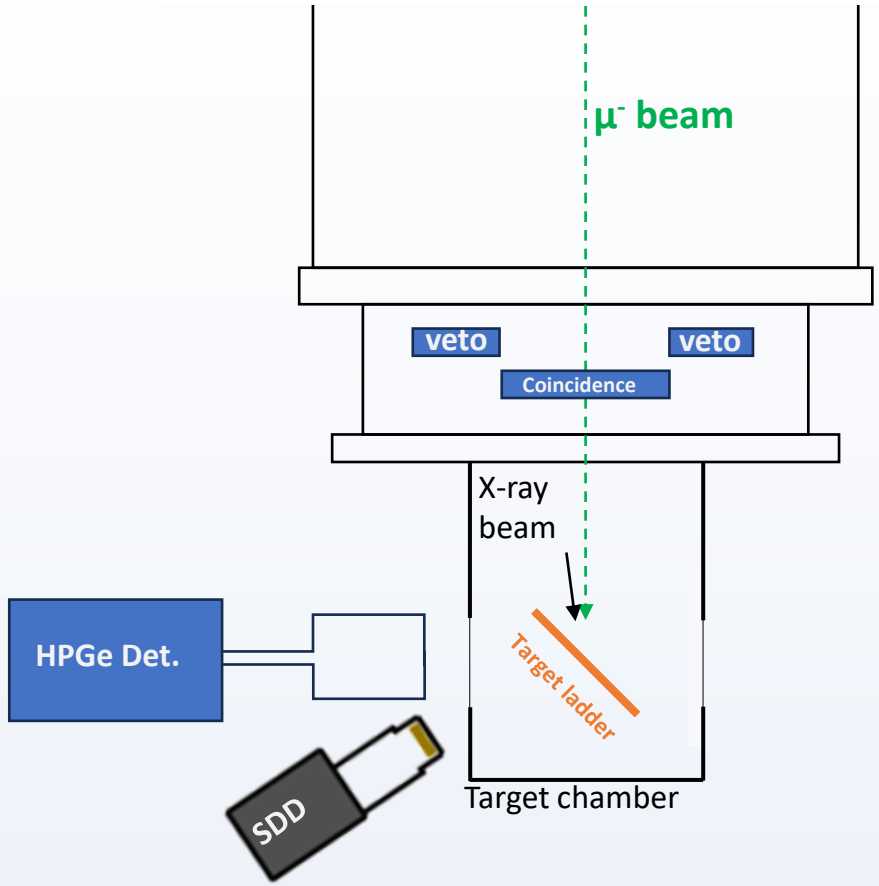

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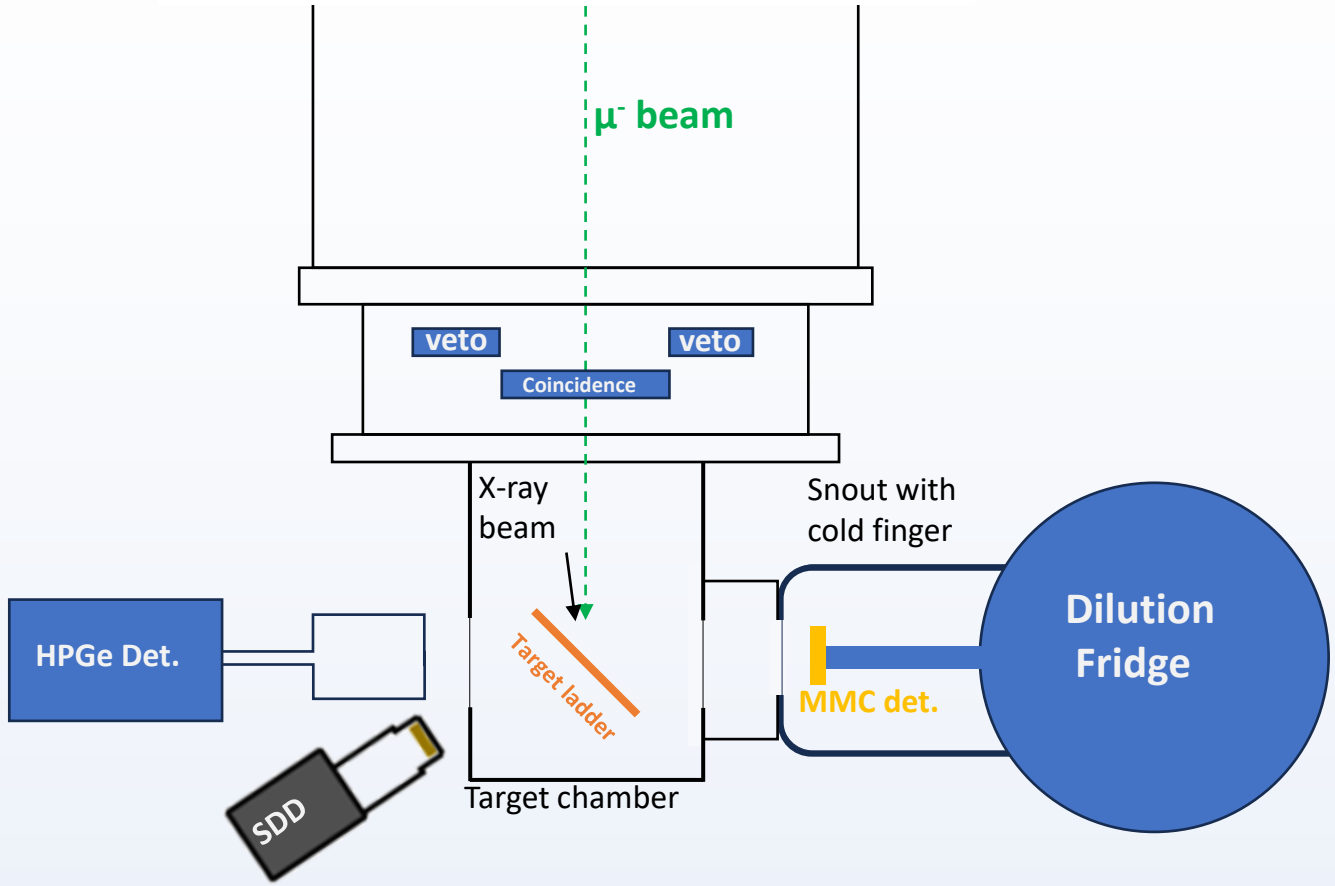

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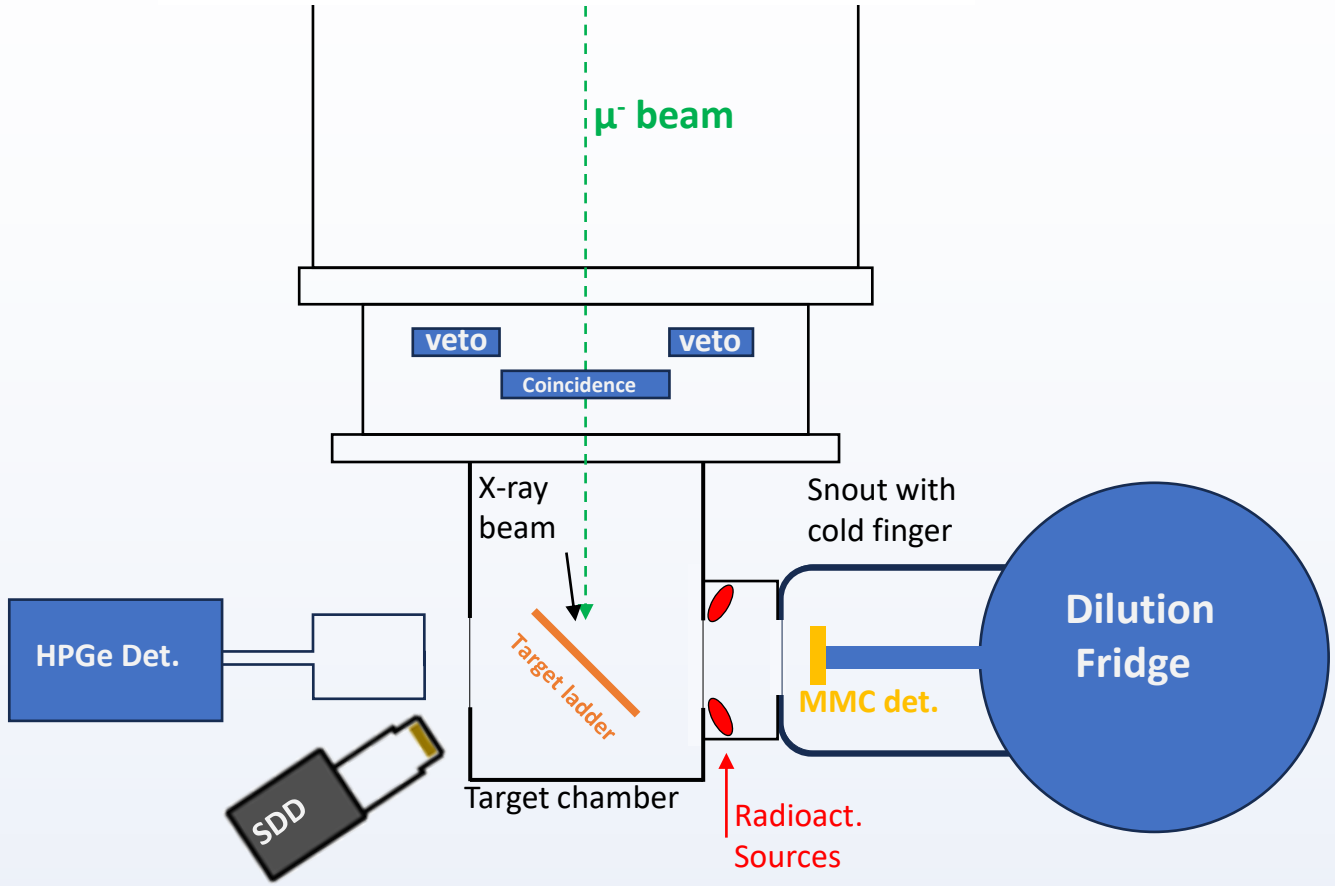
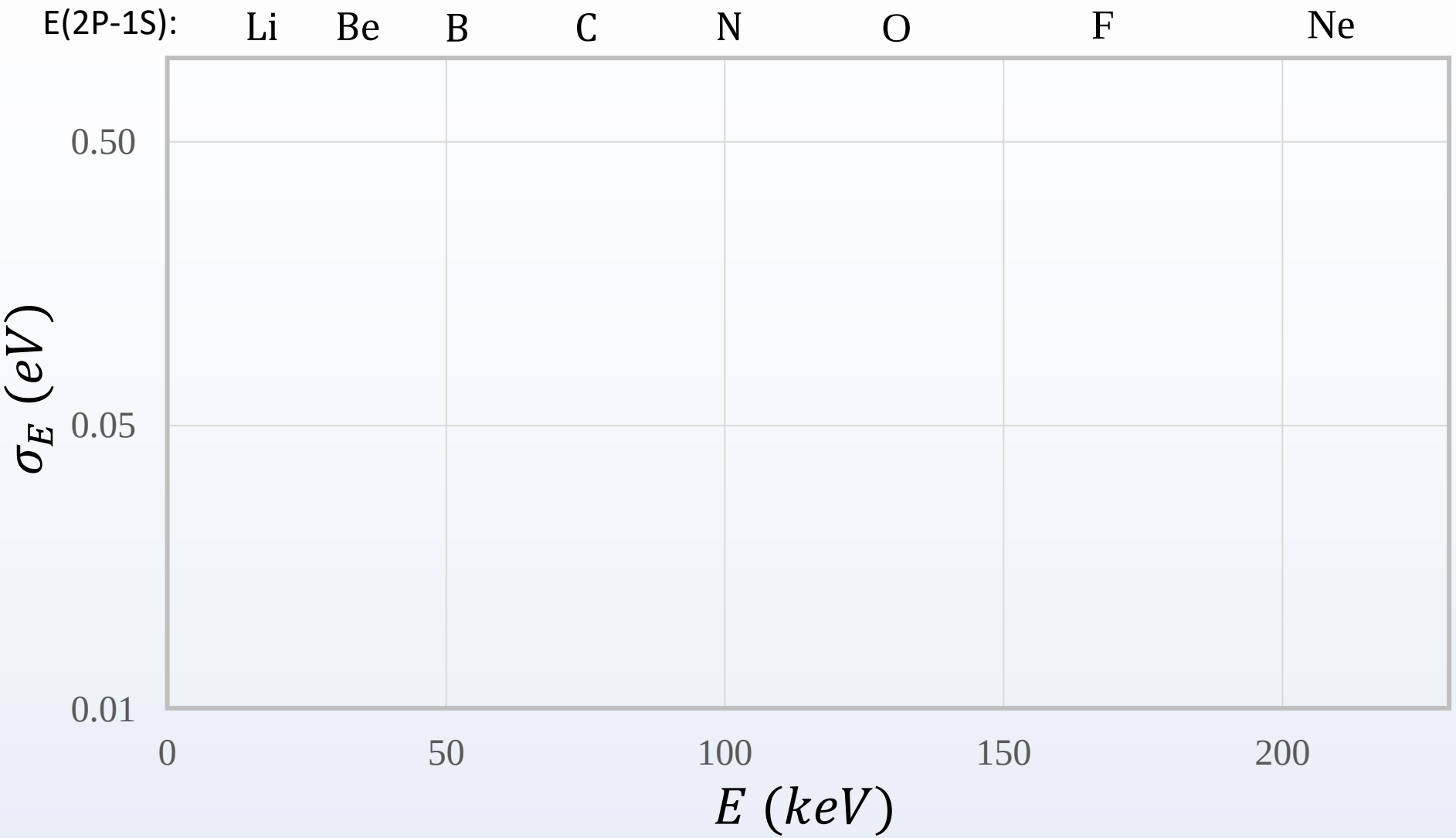


Calibration Strategy



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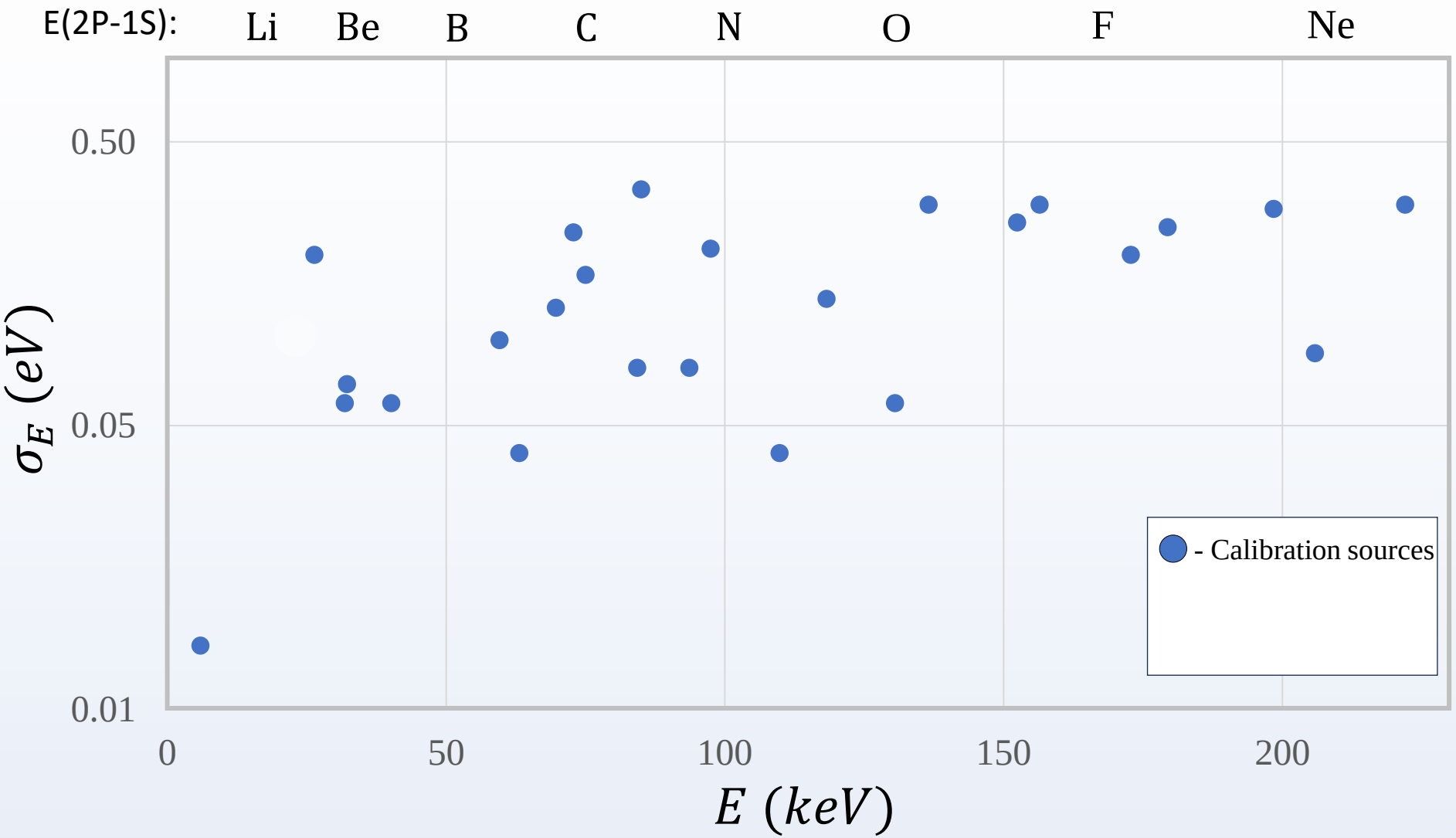

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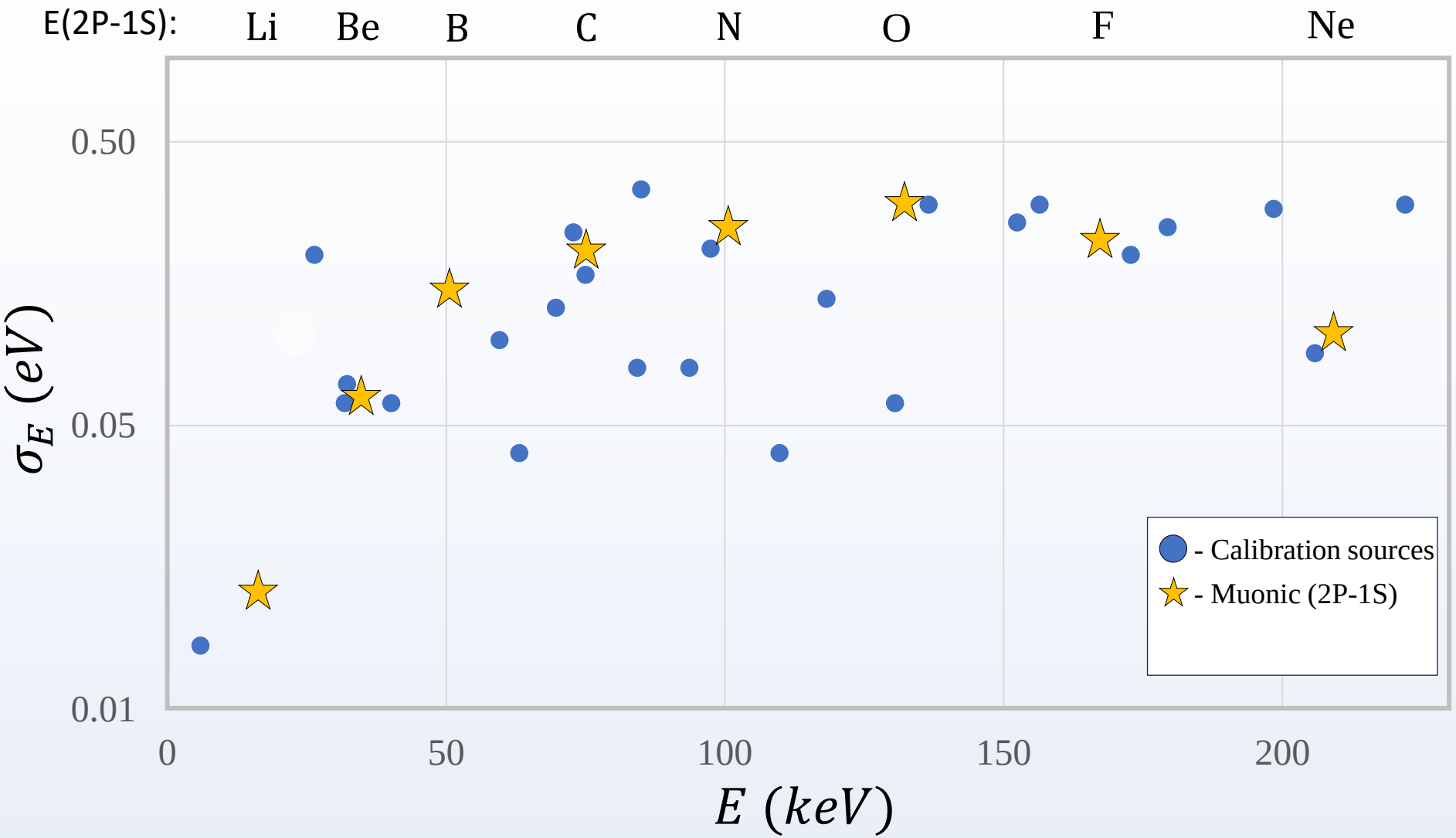

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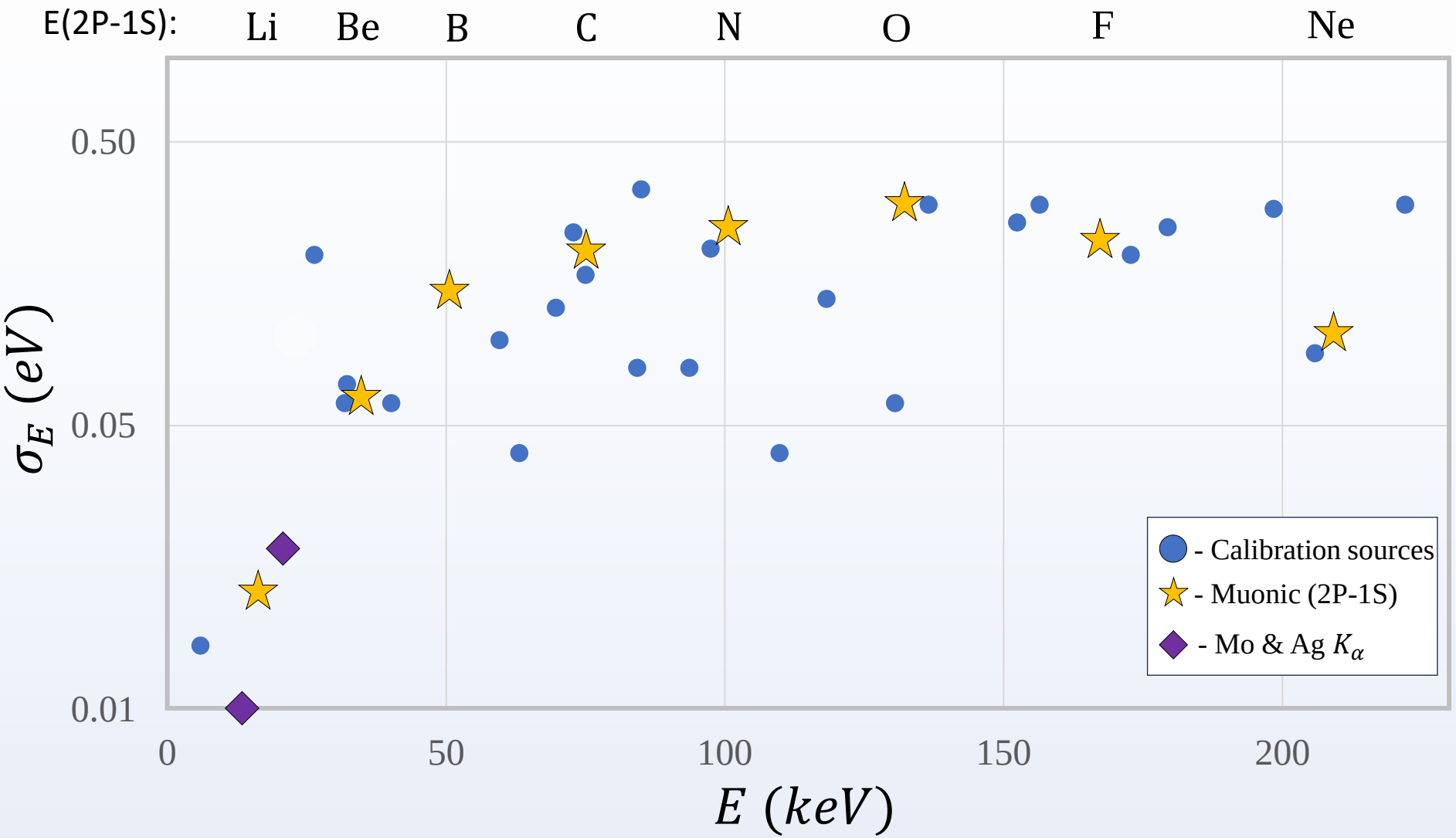

Some open questions

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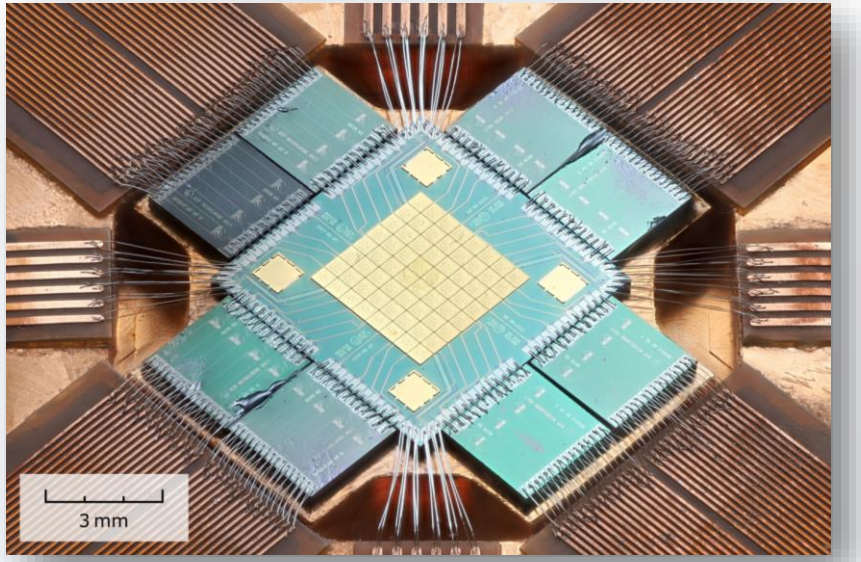
Test beam:

October 23

1 week online

Test-beam summary: The detector

Use existing MaXs-30 detector



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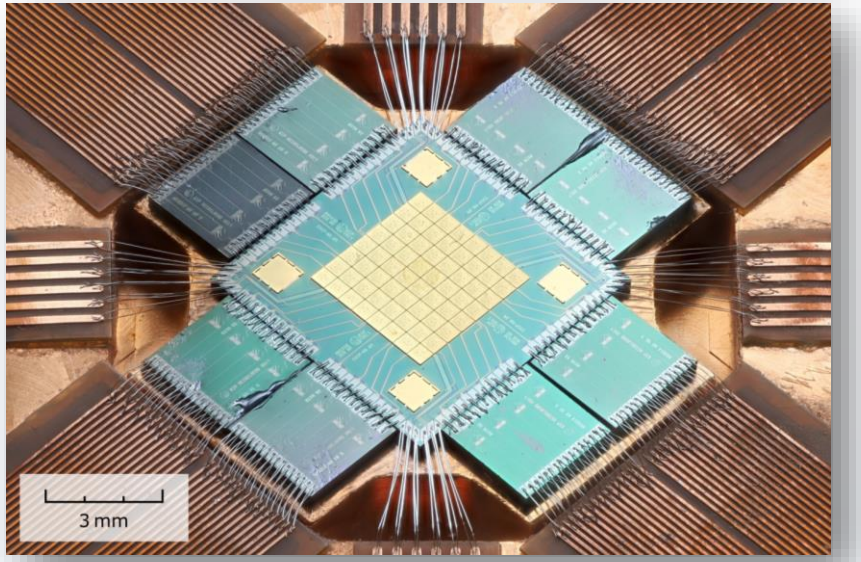
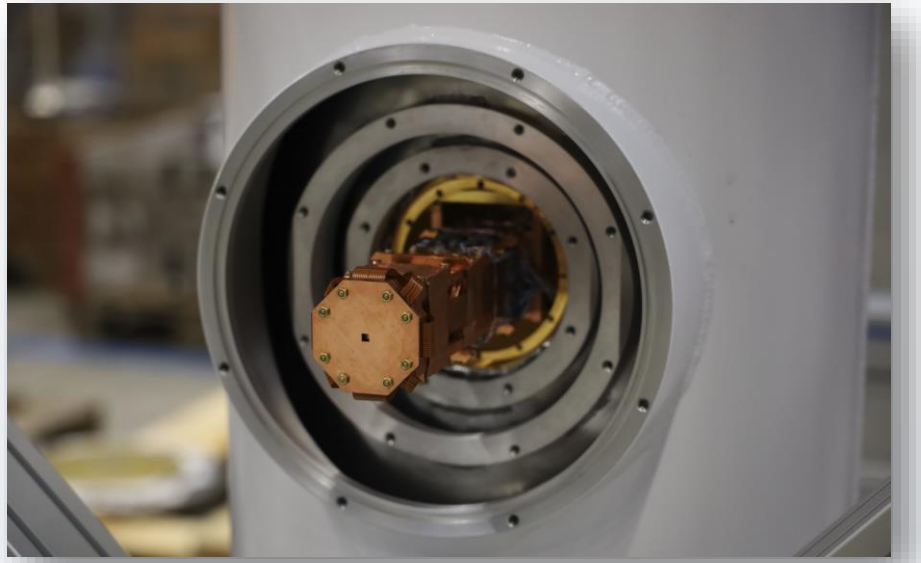


With dedicated sidearm



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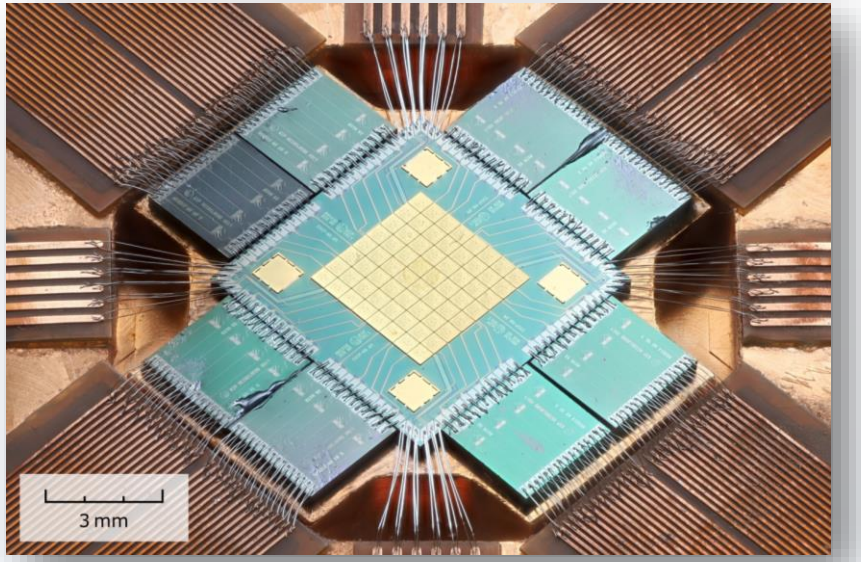

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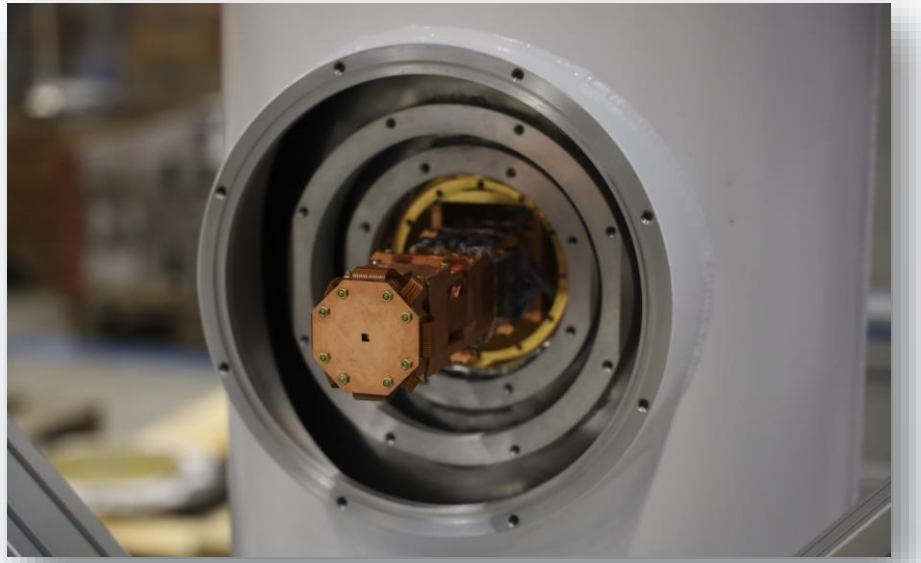

Efficiency: 97% @ 19 keV, 7% @ 75 keV

Good for np-1s in muonic: Li, Be, B & (C)

Test-beam summary: Target choice and preparation

Used targets:

- Blank Cu
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- $^{6}Li = 95\%\ ^{6}Li, 5\%\ ^{7}Li$ 2 mm thick
- ^{9}Be, 99.0% pure, 2.5 mm thick
- $^{nat}B = 80\%^{11}B, 20\%^{10}B$ 2 mm thick
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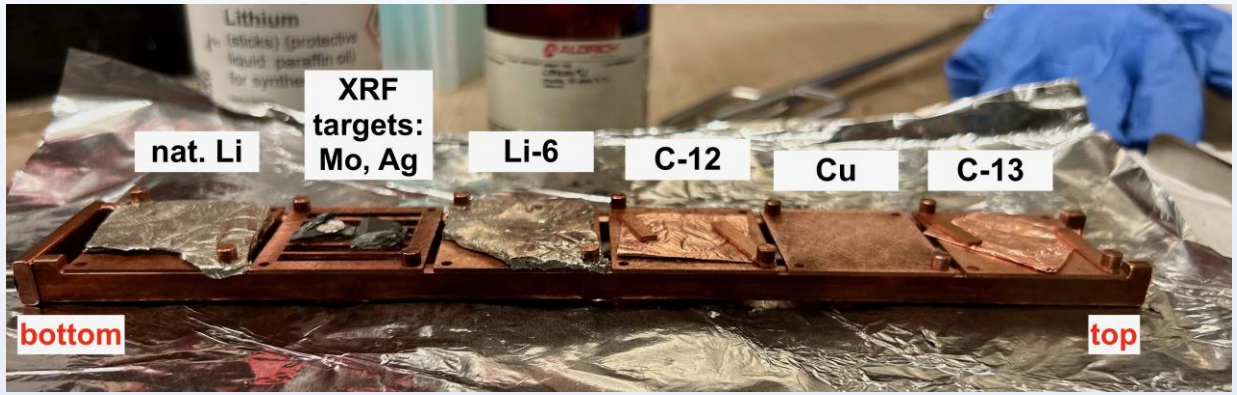
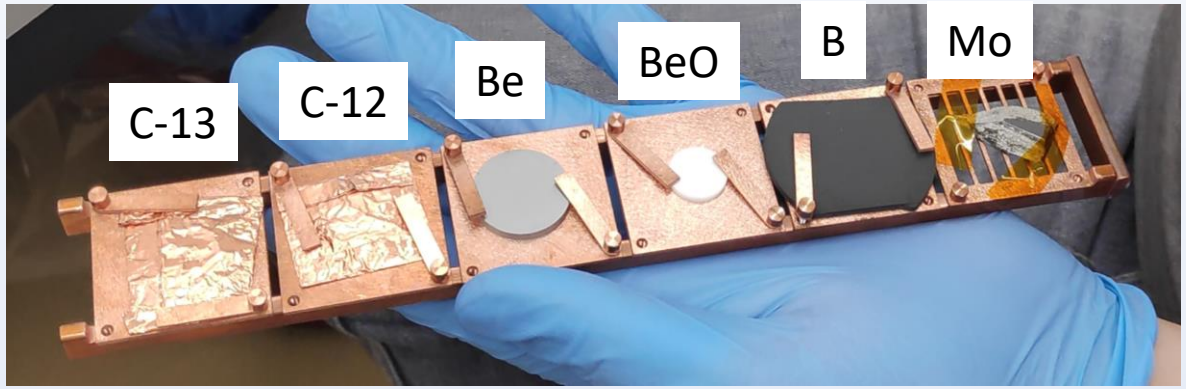
- XRF targets: Mo and Ag foils on Cu grid





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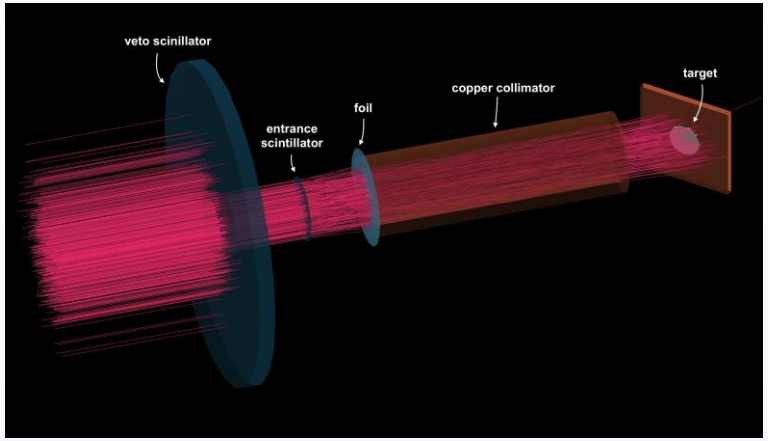
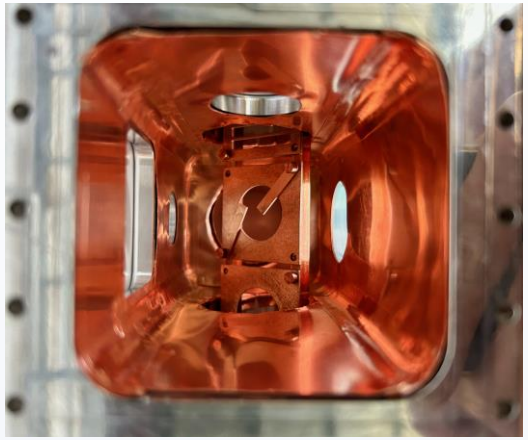
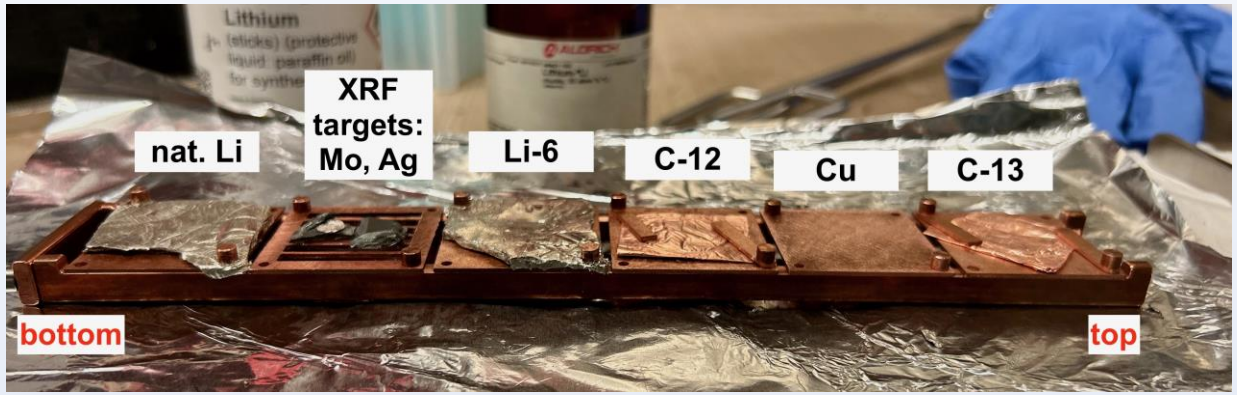
- XRF targets: Mo and Ag foils on Cu grid

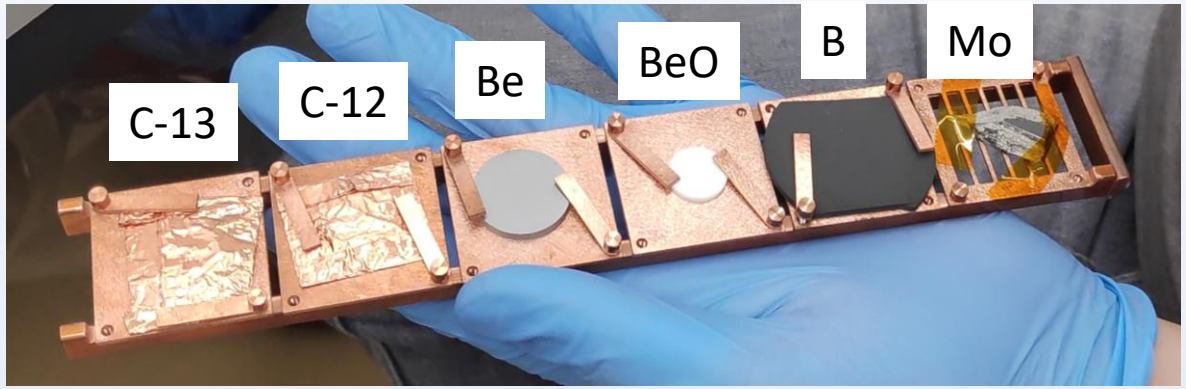
Stopping power optimized with G4beamline



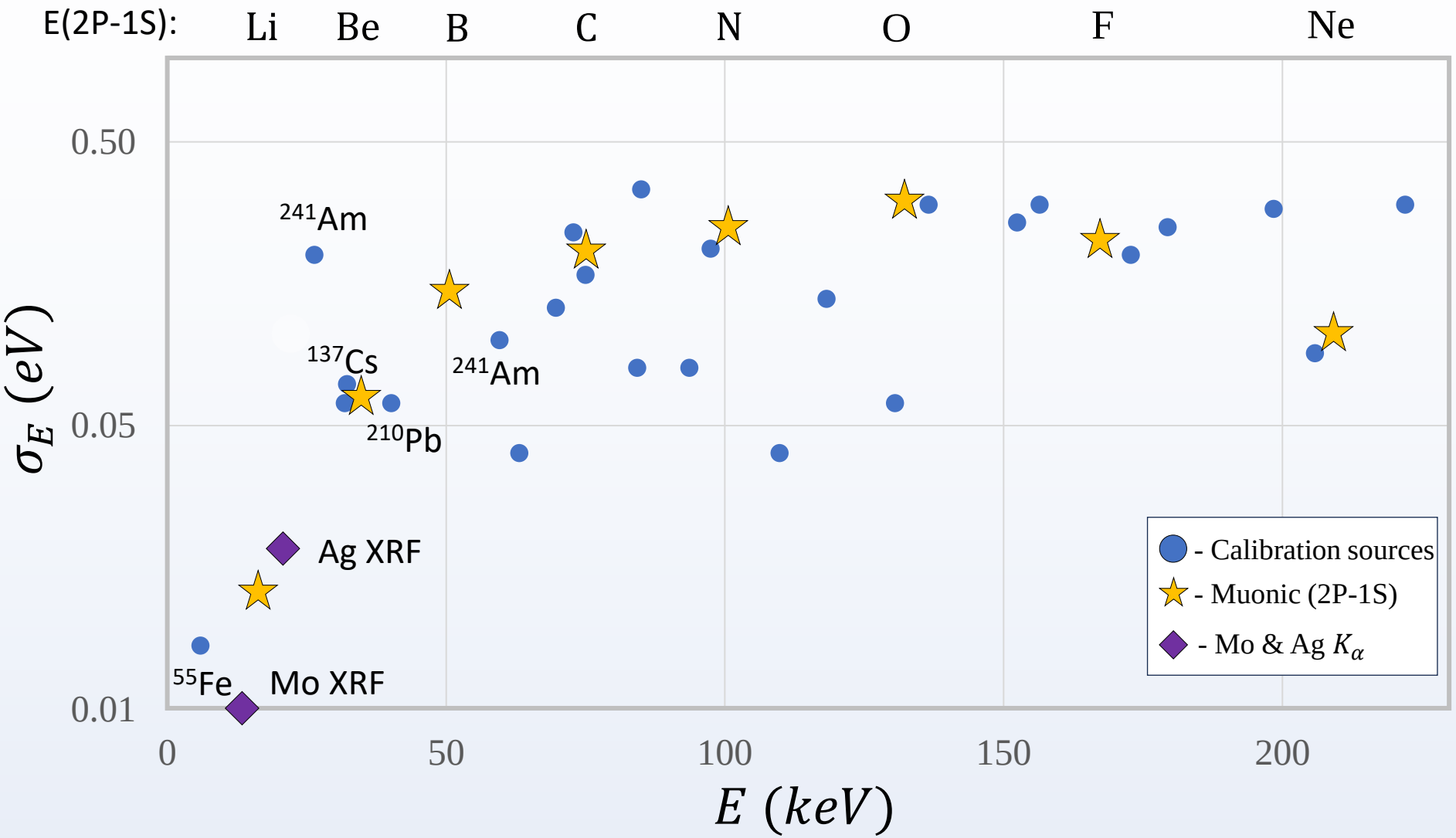
Chamber covered with Cu







Test-beam summary: Tested calibration sources

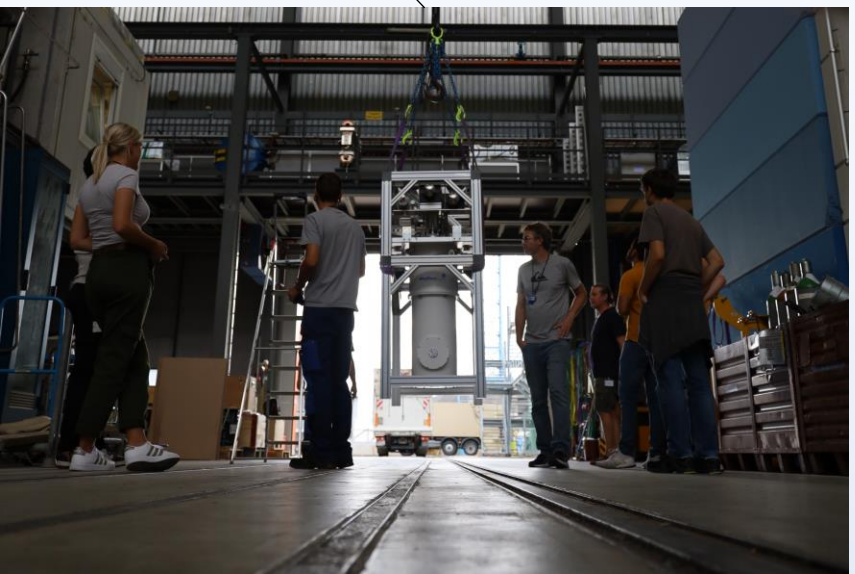


Test-beam summary: Preparation schedule

Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…

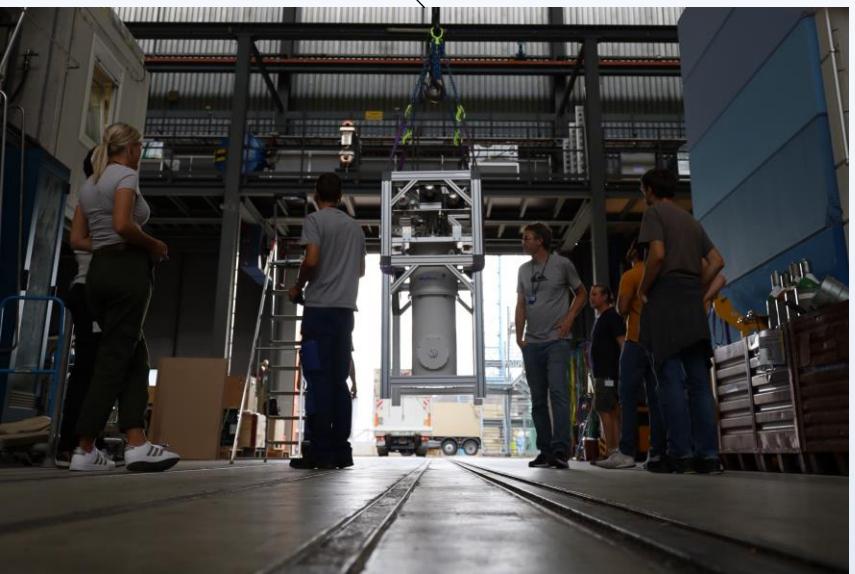
Test-beam summary: Preparation schedule

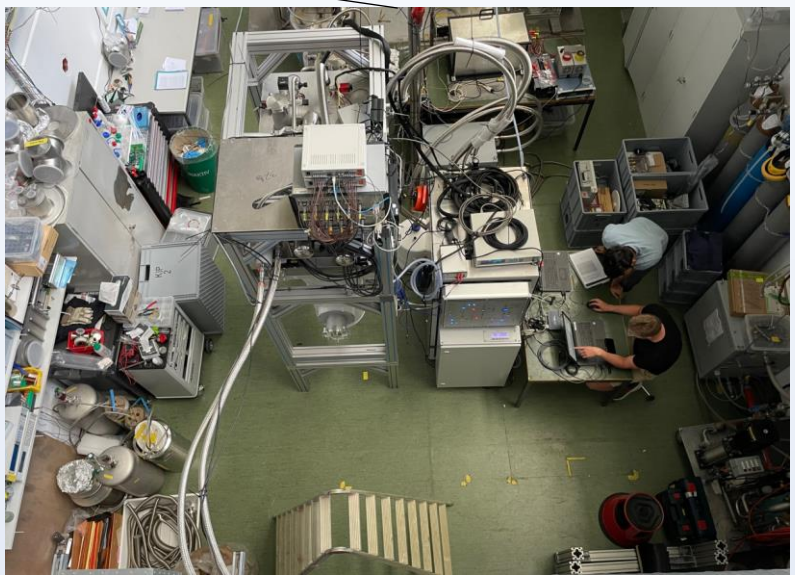
Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…



Test-beam summary: Preparation schedule

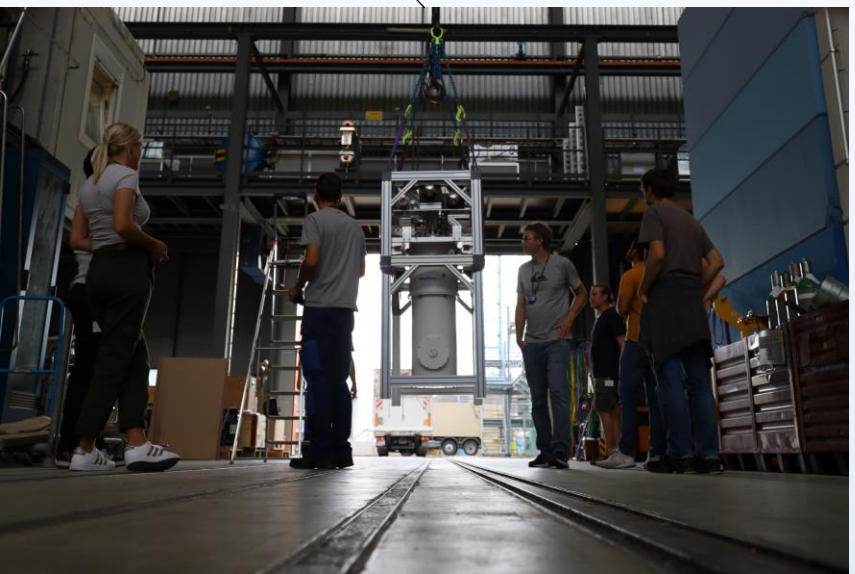
Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…

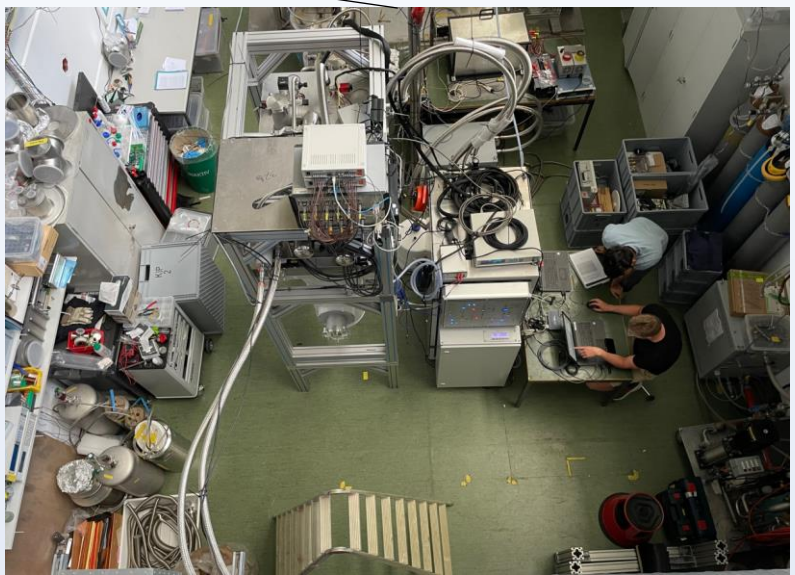




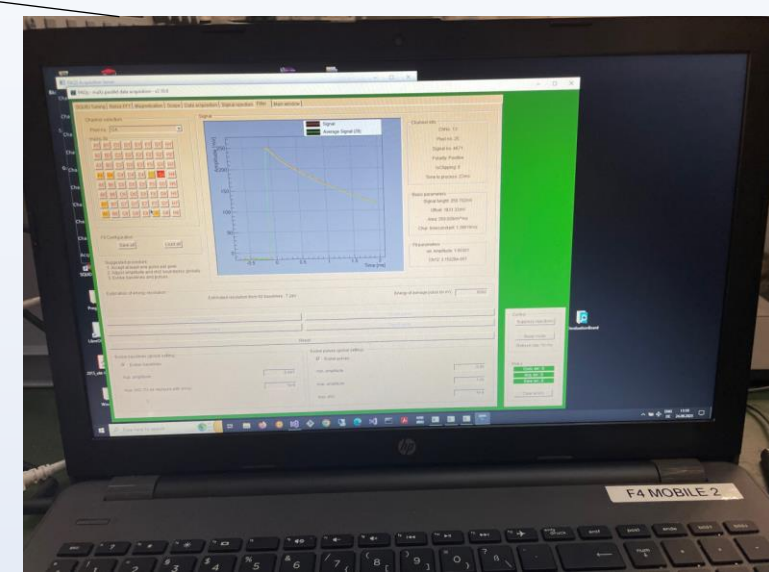
Test-beam summary: Preparation schedule

Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…



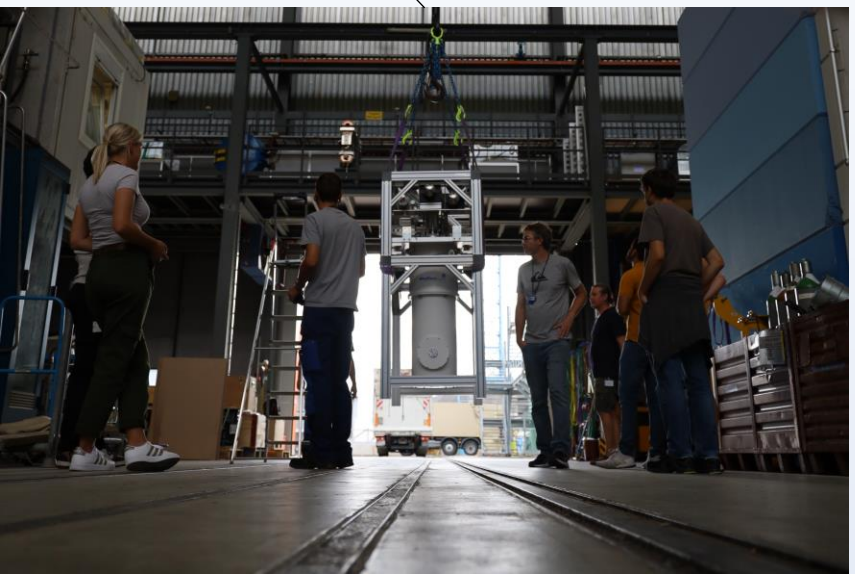


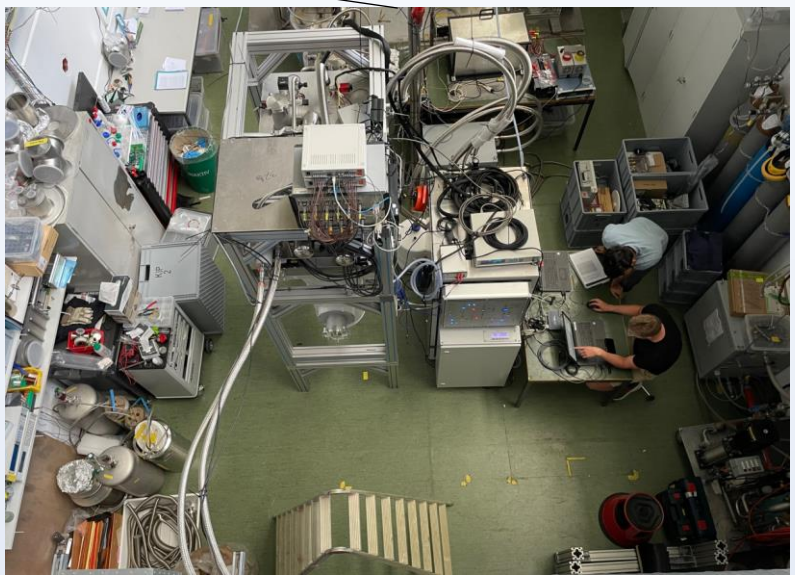
First photon pulses



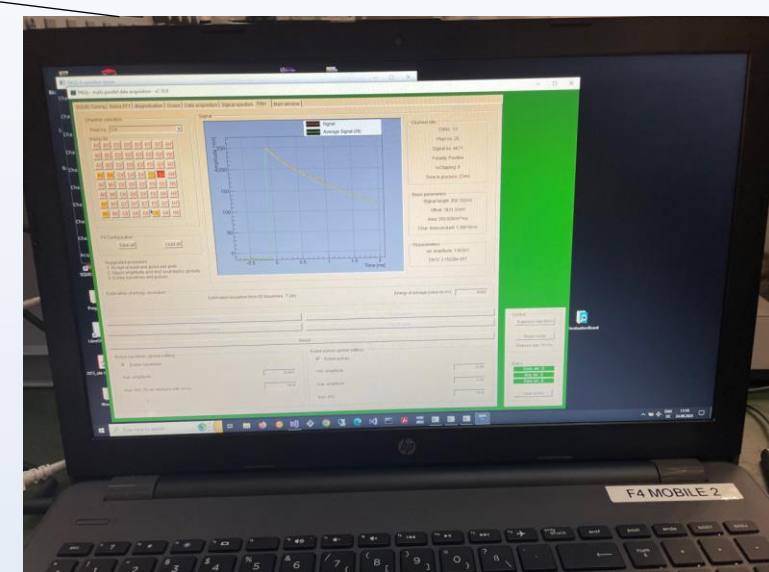
Test-beam summary: Preparation schedule

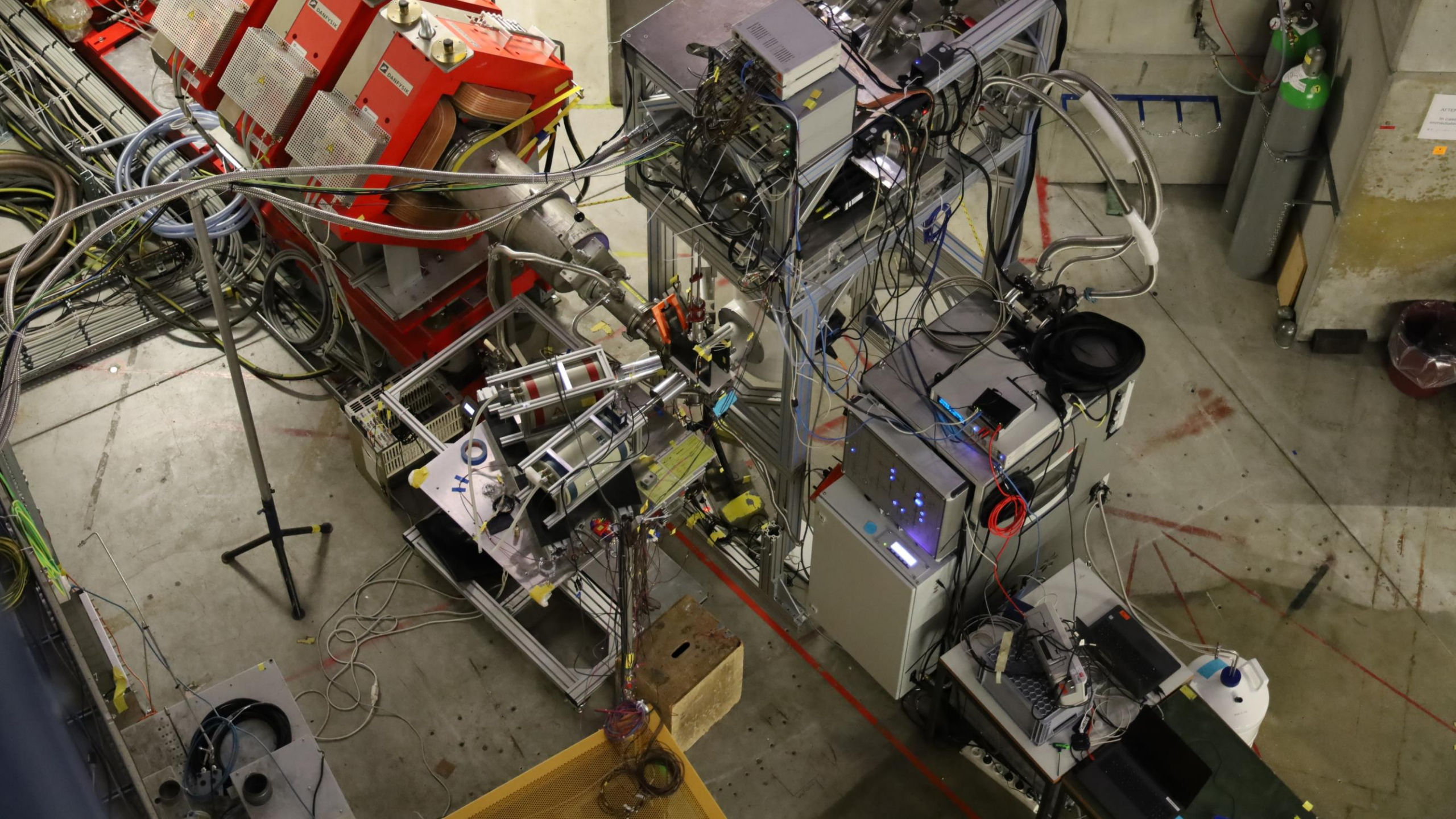
Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…



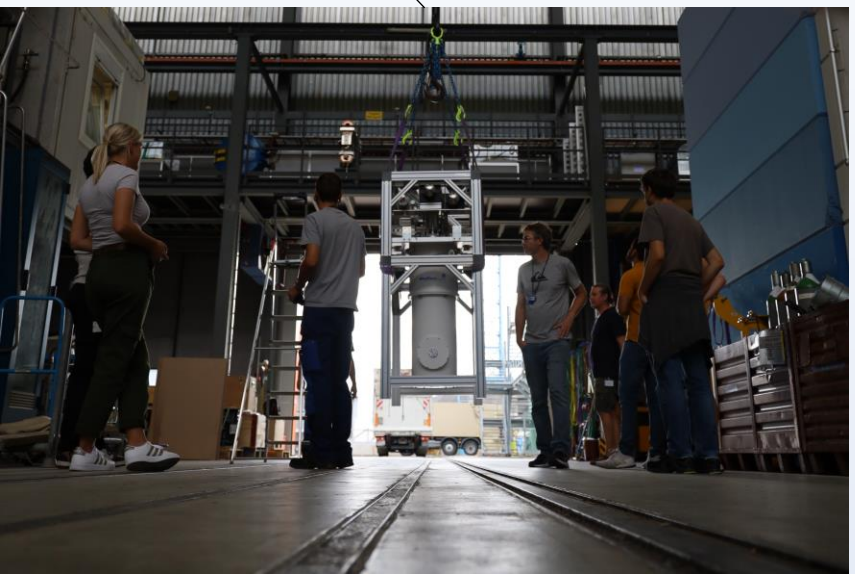


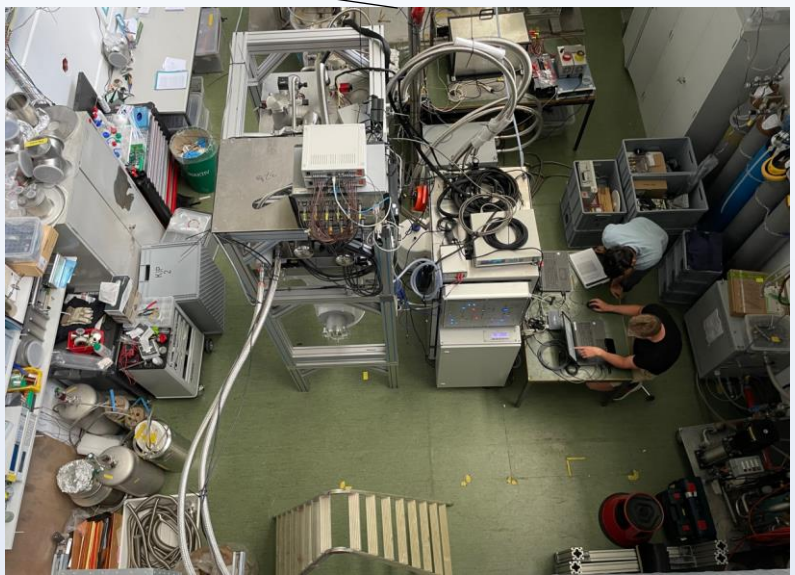
First photon pulses

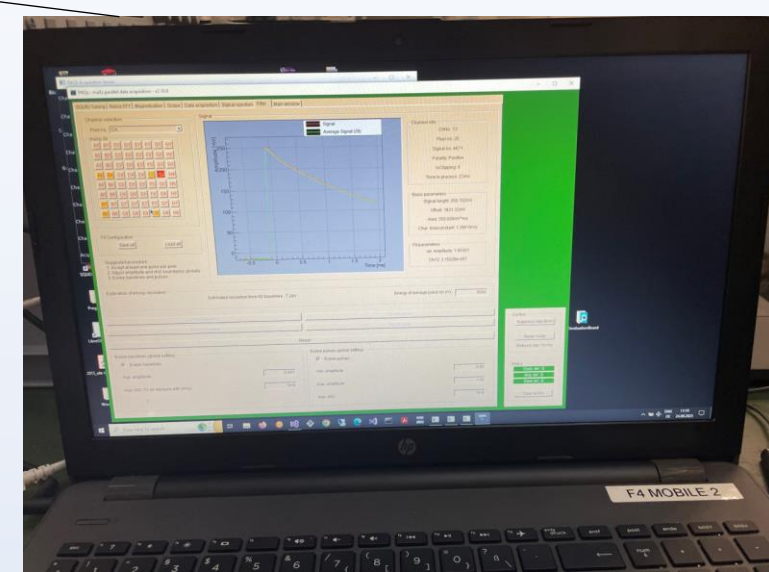




Date	21.9	22-23	24-27	28.9 - 4.10	5-9	10-11	12	13-15	16-17	18	19	20-25
MMC Det.	Transport & Crane	Set up, Cooling, Prepare electronics	< 10 mK tuning	Tests complete det.	Long calibration test	Rate test	Source test (high-E photon)	Warm up & Prepare for craning	Crane Cool down	Tunning First pulses		**Beamtime!**
DAQ		Cryo data in MIDAS	←		Data-Syncing	←	←	←	←	←	Pixel fit	**…**
Source			55Fe	55Fe	Fe Cd Ba Y	Ba	137Cs			Rate tests 241Am	55Fe, 241Am	…
Target Chamber	Design mounts			Gluing windows		Assembly & leak test	Final Assembly	Cover with Copper	Assemble target Ladder I		Assemble target Ladder II	…
SDD & HPGe	Test (MuX exp.)	←	←	←						Set up	Opt. Calib.	…



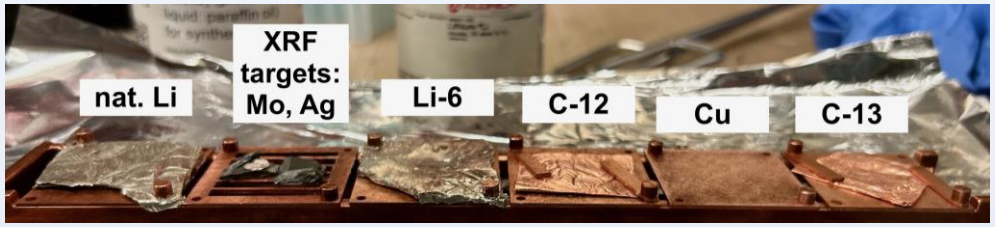




Test-beam summary: Online schedule

Day	I				II				III					IV					V		(VI)
Time	00:00 - 1:00	**2:00 - 11:00**	11:00 - 12:00	12:00 -13:30	**13:30 - 11:30**	11:30 - 12:30	12:30 -16:30	17:00 - 18:30	**19:00 – 10:00**	10:00 – 11:00	11:00 – 12:00	**12:00 – 19:00**	21:30 - 23:00	23:30 - 1:30	**1:30 - 13:30**	14:00 - 15:00	**15:00 – 19:00**	19:00 – 21:00	**21:00 – 9:30**	9:30 – 14:00	**14:30- 7:00**
Goal	Calib.	**Production**	Calib.	Bgnd	**Production**	Calib.	Implant. test	Bgnd	**Production**	Calib.	Rate test	**Production** + beam tuning	Beam tuning while reset	Beam tuning while reset	**Production**	Pile-up test	**Production?**	Calib.	**Production**	Calib. + rate study	**Production**
Target	Mo-Ag	^{7}Li	Mo-Ag	Cu	^{6}Li	Mo-Ag	^{12}C	Empty	^{10,11}B	Mo	Be	^{10,11}B	^{13}C	^{12}C	^{9}Be	^{12}C	^{12}C	Mo-Ag	^{6}Li / (^{7}Li)	Mo-Ag	^{6}Li / ^{7}Li
Source		^{55}Fe, ^{109}Cd, ^{241}Am	←	←	←	←	^{55}Fe	←	^{55}Fe, *^{210}Pb*, ^{241}Am, *^{137}Cs*	^{55}Fe, ^{210}Pb, ^{241}Am, ^{137}Cs	←	←	←	←	←	←	←	←	←	←	←
Ladder	I	I	I	I	I	I	I		II	II	II	II	II	II	II	III	III	III	III	III	III
MMC Det.	V	V	V	V	V	V	V	V	V	V	V	V	Soft reset	Soft reset	V	V	V	V	V	V	V
DAQ					sync				MMC CSV output												

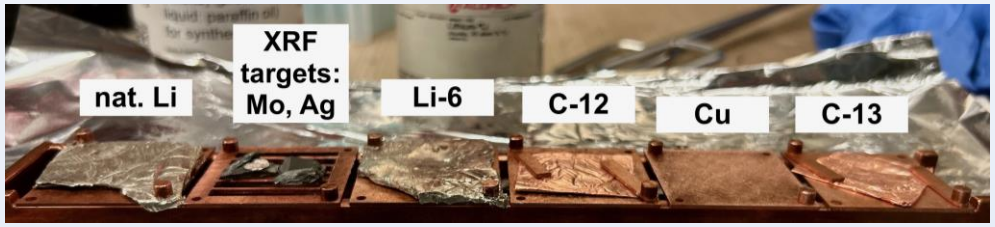
Ladder I



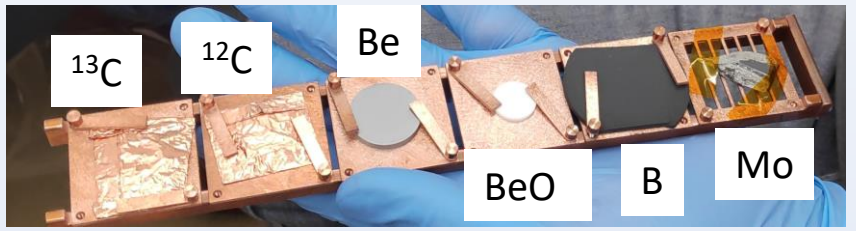
Test-beam summary: Preparation schedule

Day	I				II				III					IV					V		(VI)
Time	00:00 - 1:00	**2:00 - 11:00**	11:00 - 12:00	12:00 -13:30	**13:30 - 11:30**	11:30 - 12:30	12:30 -16:30	17:00 - 18:30	**19:00 – 10:00**	10:00 – 11:00	11:00 – 12:00	**12:00 – 19:00**	21:30 - 23:00	23:30 - 1:30	**1:30 - 13:30**	14:00 - 15:00	**15:00 – 19:00**	19:00 – 21:00	**21:00 – 9:30**	9:30 – 14:00	**14:30- 7:00**
Goal	Calib.	**Production**	Calib.	Bgnd	**Production**	Calib.	Implant. test	Bgnd	**Production**	Calib.	Rate test	**Production** + beam tuning	Beam tuning while reset	Beam tuning while reset	**Production**	Pile-up test	**Production?**	Calib.	**Production**	Calib. + rate study	**Production**
Target	Mo-Ag	^{7}Li	Mo-Ag	Cu	^{6}Li	Mo-Ag	^{12}C	Empty	^{10,11}B	Mo	Be	^{10,11}B	^{13}C	^{12}C	^{9}Be	^{12}C	^{12}C	Mo-Ag	^{6}Li / (^{7}Li)	Mo-Ag	^{6}Li / ^{7}Li
Source		^{55}Fe, ^{109}Cd, ^{241}Am	←	←	←	←	^{55}Fe	←	^{55}Fe, *^{210}Pb*, ^{241}Am, *^{137}Cs*	^{55}Fe, ^{210}Pb, ^{241}Am, ^{137}Cs	←	←	←	←	←	←	←	←	←	←	←
Ladder	I	I	I	I	I	I	I		II	II	II	II	II	II	II	III	III	III	III	III	III
MMC Det.	V	V	V	V	V	V	V	V	V	V	V	V	Soft reset	Soft reset	V	V	V	V	V	V	V
DAQ					sync				MMC CSV output												

Ladder I



Ladder II



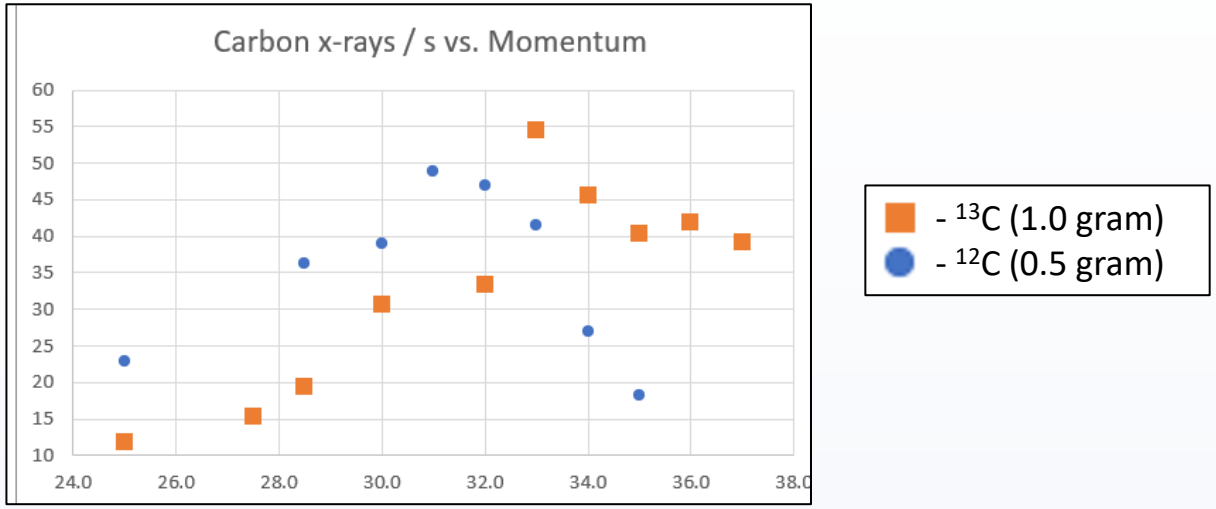
Test-beam summary: Preparation schedule

Day	I				II				III					IV					V		(VI)
Time	00:00 - 1:00	**2:00 - 11:00**	11:00 - 12:00	12:00 -13:30	**13:30 - 11:30**	11:30 - 12:30	12:30 -16:30	17:00 - 18:30	**19:00 – 10:00**	10:00 – 11:00	11:00 – 12:00	**12:00 – 19:00**	21:30 - 23:00	23:30 - 1:30	**1:30 - 13:30**	14:00 - 15:00	**15:00 – 19:00**	19:00 – 21:00	**21:00 – 9:30**	9:30 – 14:00	**14:30- 7:00**
Goal	Calib.	**Production**	Calib.	Bgnd	**Production**	Calib.	Implant. test	Bgnd	**Production**	Calib.	Rate test	**Production** + beam tuning	Beam tuning while reset	Beam tuning while reset	**Production**	Pile-up test	**Production?**	Calib.	**Production**	Calib. + rate study	**Production**
Target	Mo-Ag	^{7}Li	Mo-Ag	Cu	^{6}Li	Mo-Ag	^{12}C	Empty	^{10,11}B	Mo	Be	^{10,11}B	^{13}C	^{12}C	^{9}Be	^{12}C	^{12}C	Mo-Ag	^{6}Li / (^{7}Li)	Mo-Ag	^{6}Li / ^{7}Li
Source		^{55}Fe, ^{109}Cd, ^{241}Am	←	←	←	←	^{55}Fe	←	^{55}Fe, *^{210}Pb*, ^{241}Am, *^{137}Cs*	^{55}Fe, ^{210}Pb, ^{241}Am, ^{137}Cs	←	←	←	←	←	←	←	←	←	←	←
Ladder	I	I	I	I	I	I	I		II	II	II	II	II	II	II	III	III	III	III	III	III
MMC Det.	V	V	V	V	V	V	V	V	V	V	V	V	Soft reset	Soft reset	V	V	V	V	V	V	V
DAQ					sync				MMC CSV output												

- 4 hours downtime of the MMC detector refrigerator
- Detector up time: **96%**
- During reset, optimize implantation using solid-state detectors

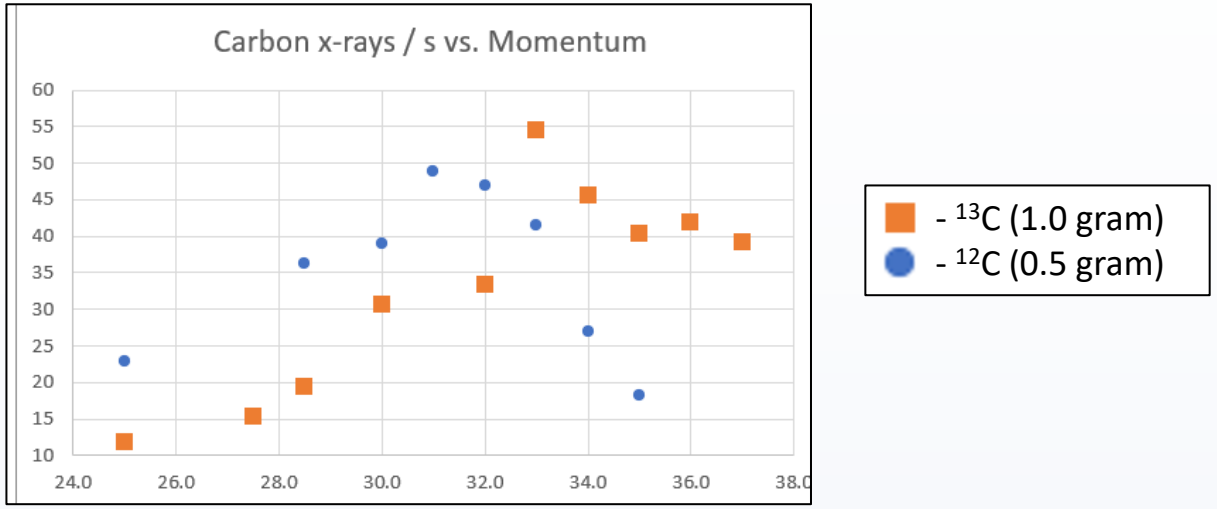
Test-beam summary: Role of solid-state detectors

Optimize Signal to background:

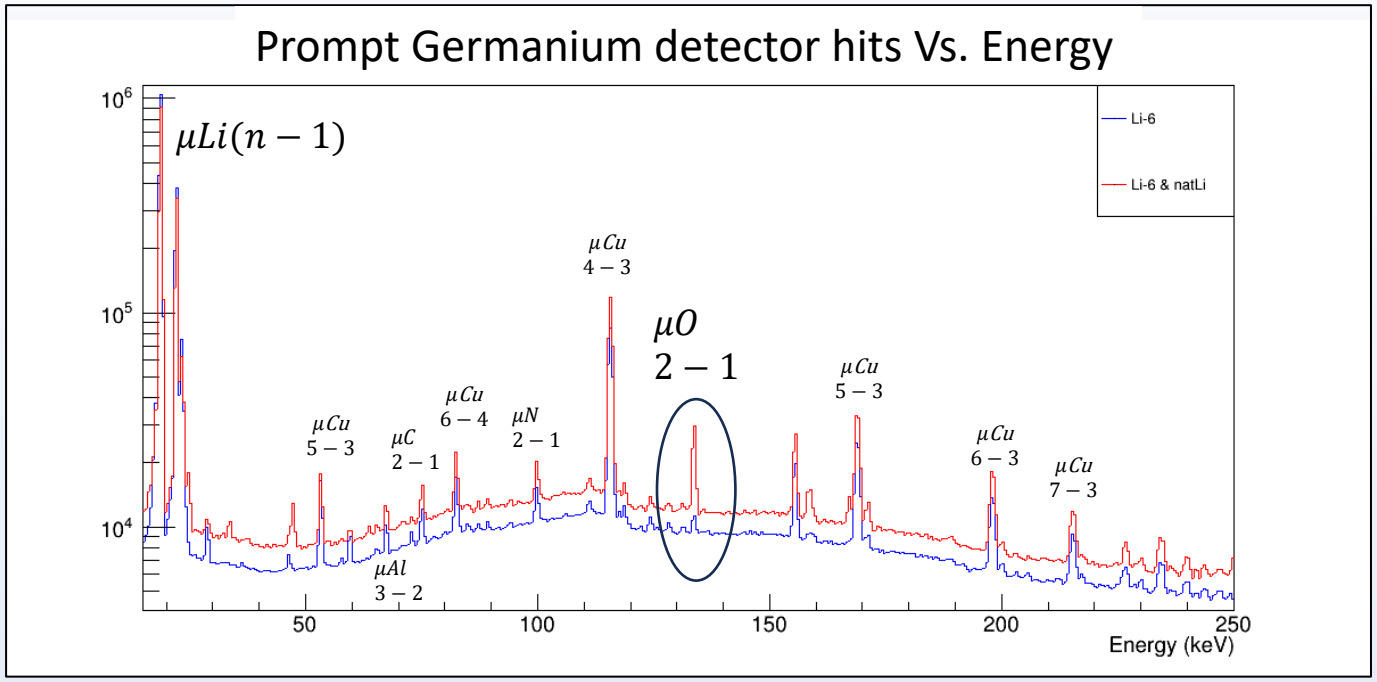


Test-beam summary: Role of solid-state detectors

Optimize Signal to background:

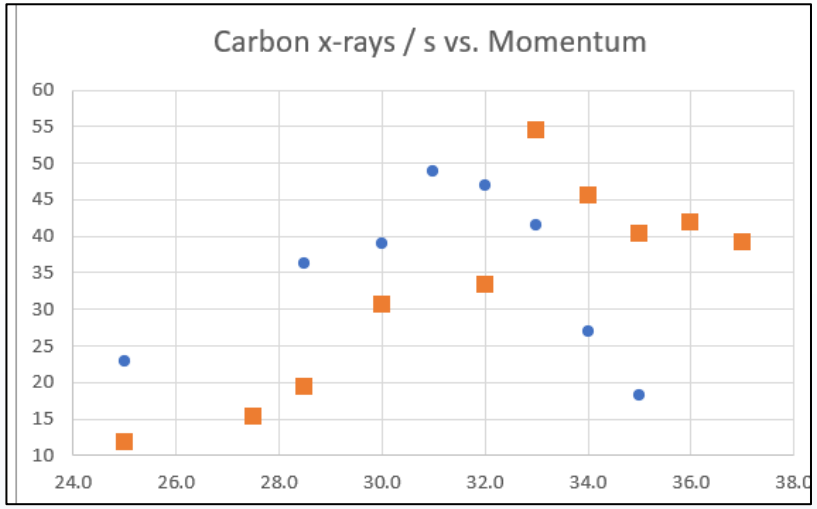


Contamination analysis
("Where do the muons stop")



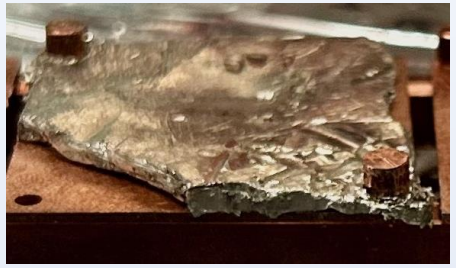
Test-beam summary: Role of solid-state detectors

Optimize Signal to background:

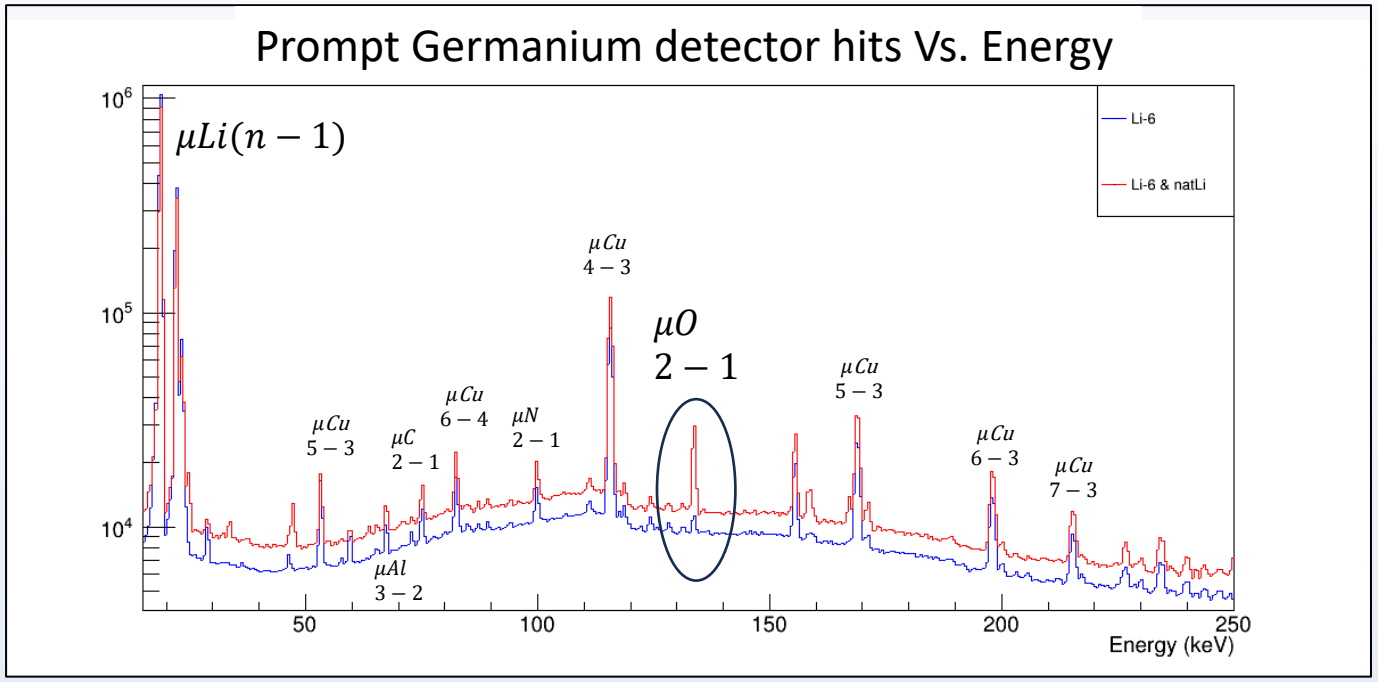


Contamination analysis
("Where do the muons stop")

^{6}Li target (not oxidized)



$Mixed$ Li target (oxidized)



Data-Stream

Single-pixel level

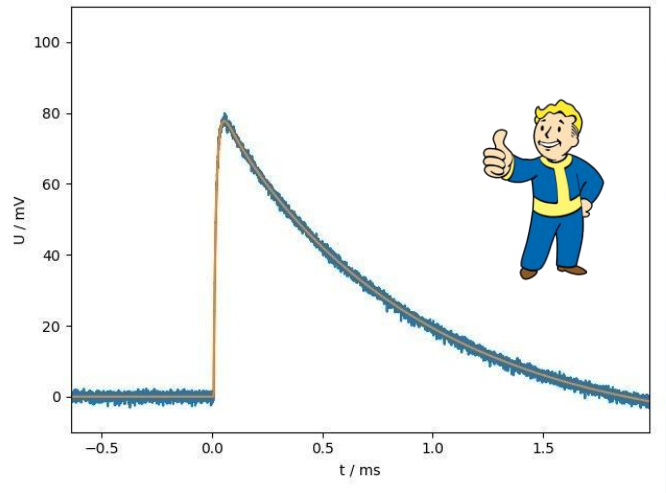
Single event
pulse shape fitting

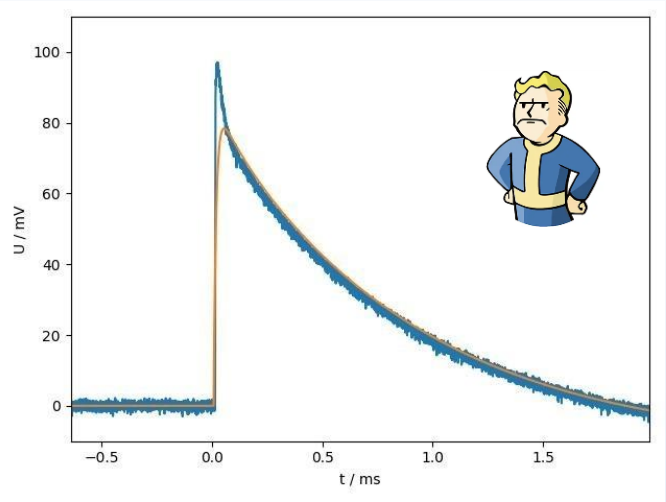
Data-Stream

Single-pixel level

Single event
pulse shape fitting

Chi2, Amplitude





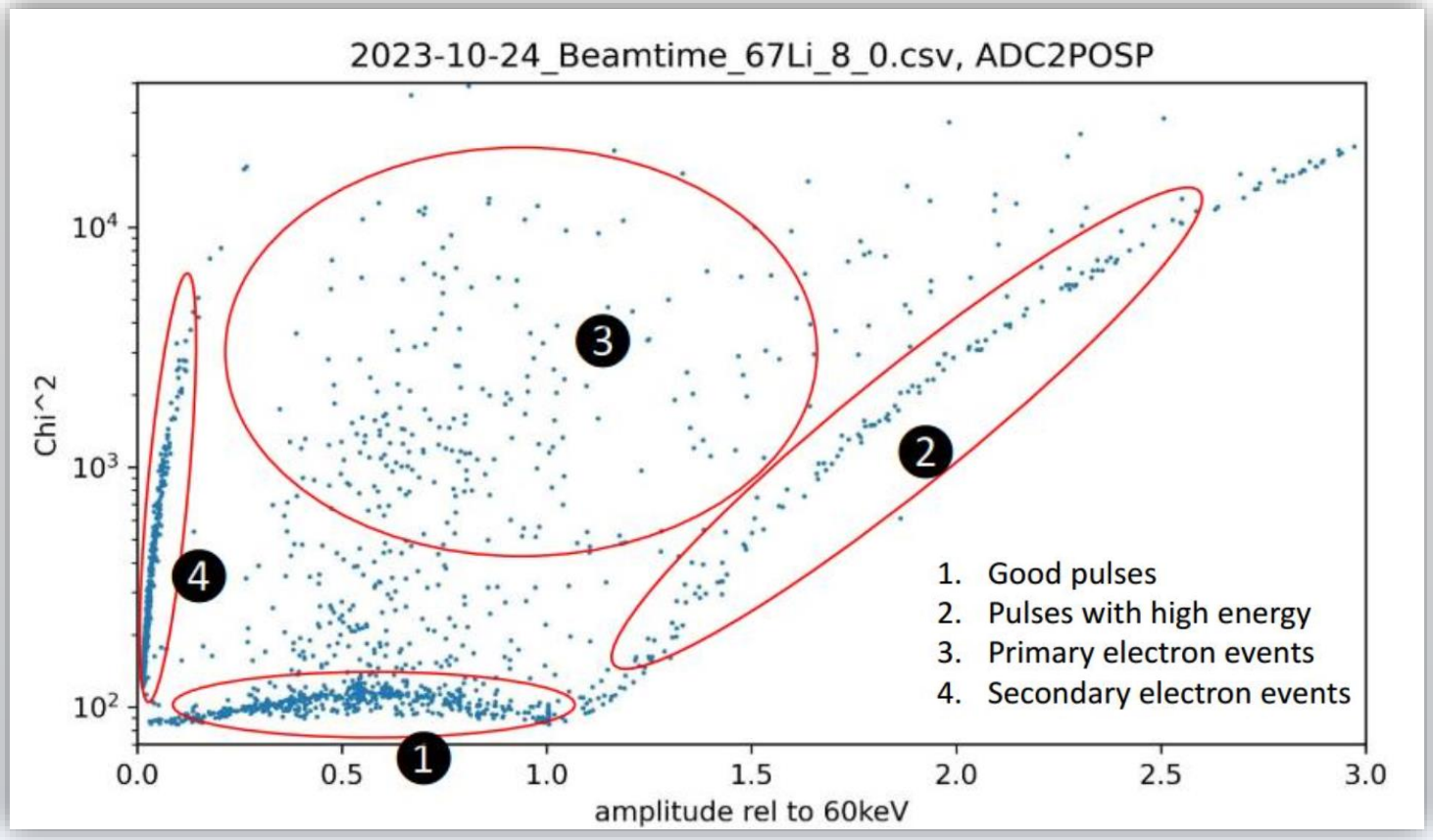
Data-Stream

Single-pixel level

Single event
pulse shape fitting

Chi2, Amplitude

Clustering and
filtering



Data-Stream

Single-pixel level

Single event pulse shape fitting

Chi2, Amplitude

Clustering and filtering

Filtered Amplitude

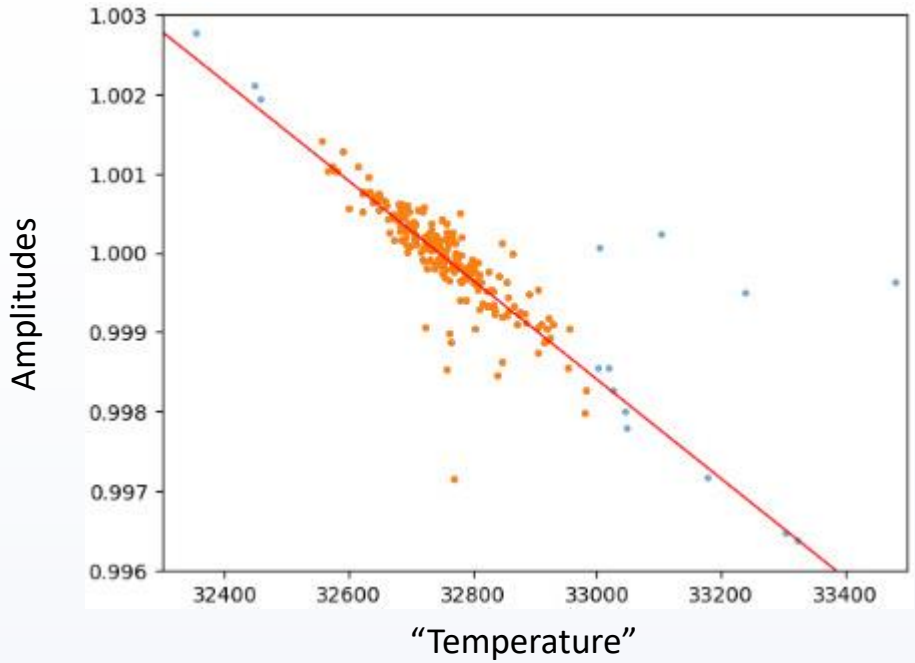
Pile-up filter

Filtered Amplitude

Temperature baselines

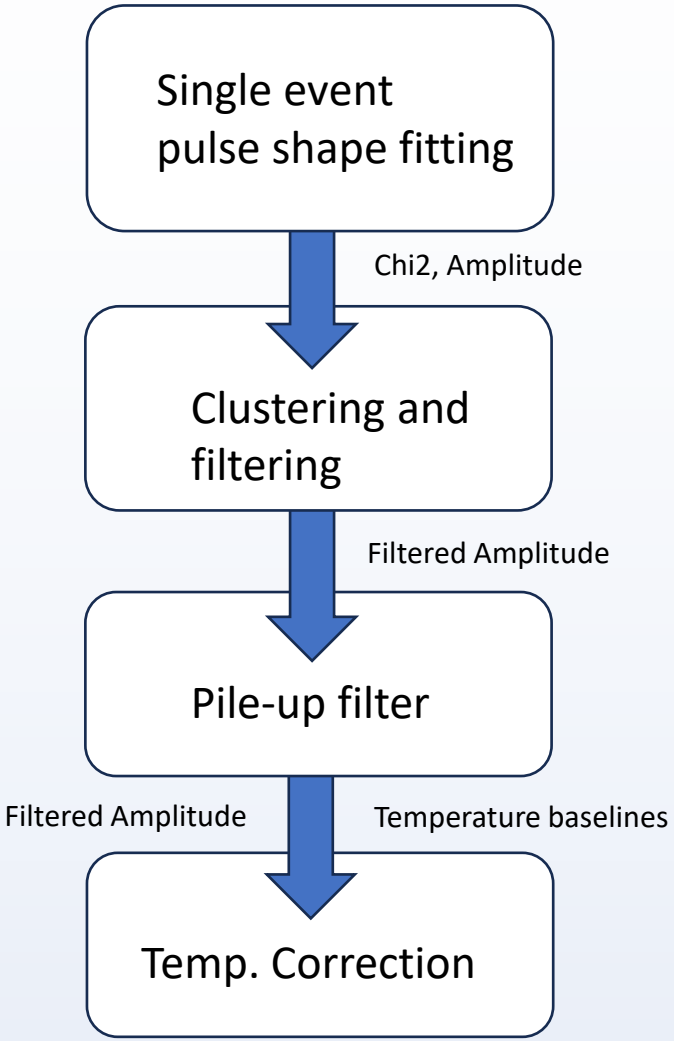
Temp. Correction

Temperature correction for single pixel

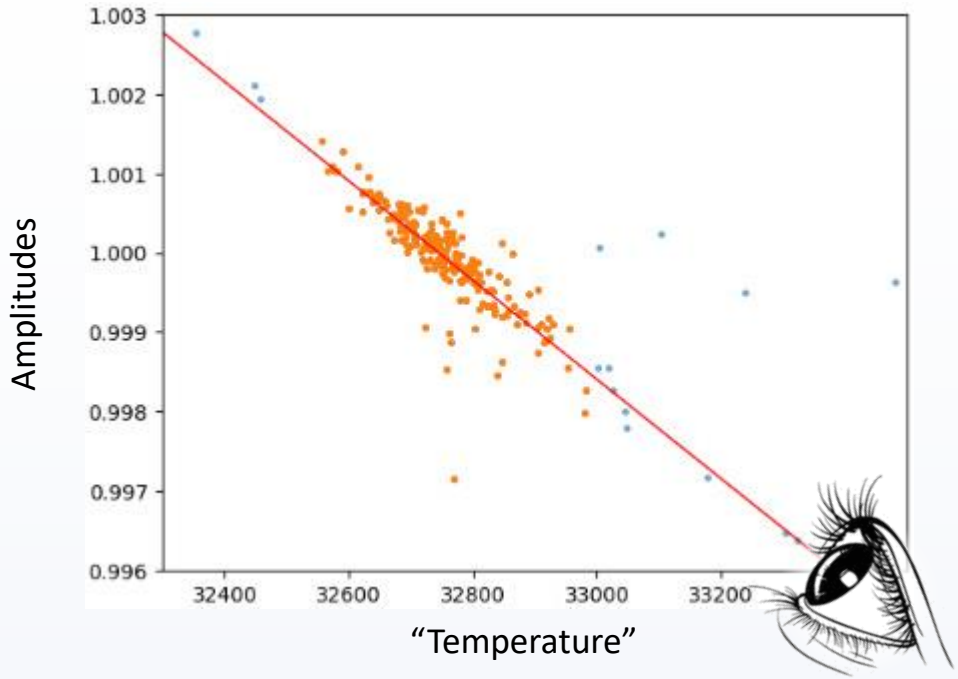


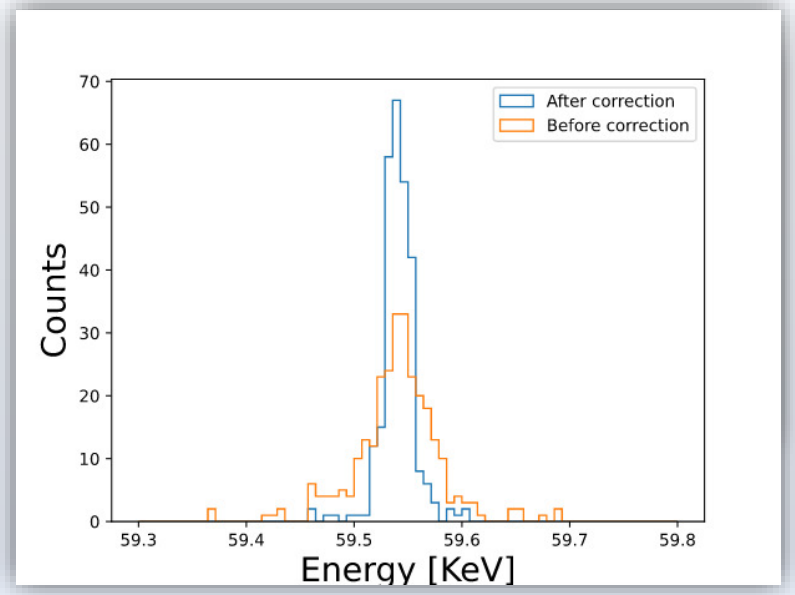
Data-Stream

Single-pixel level

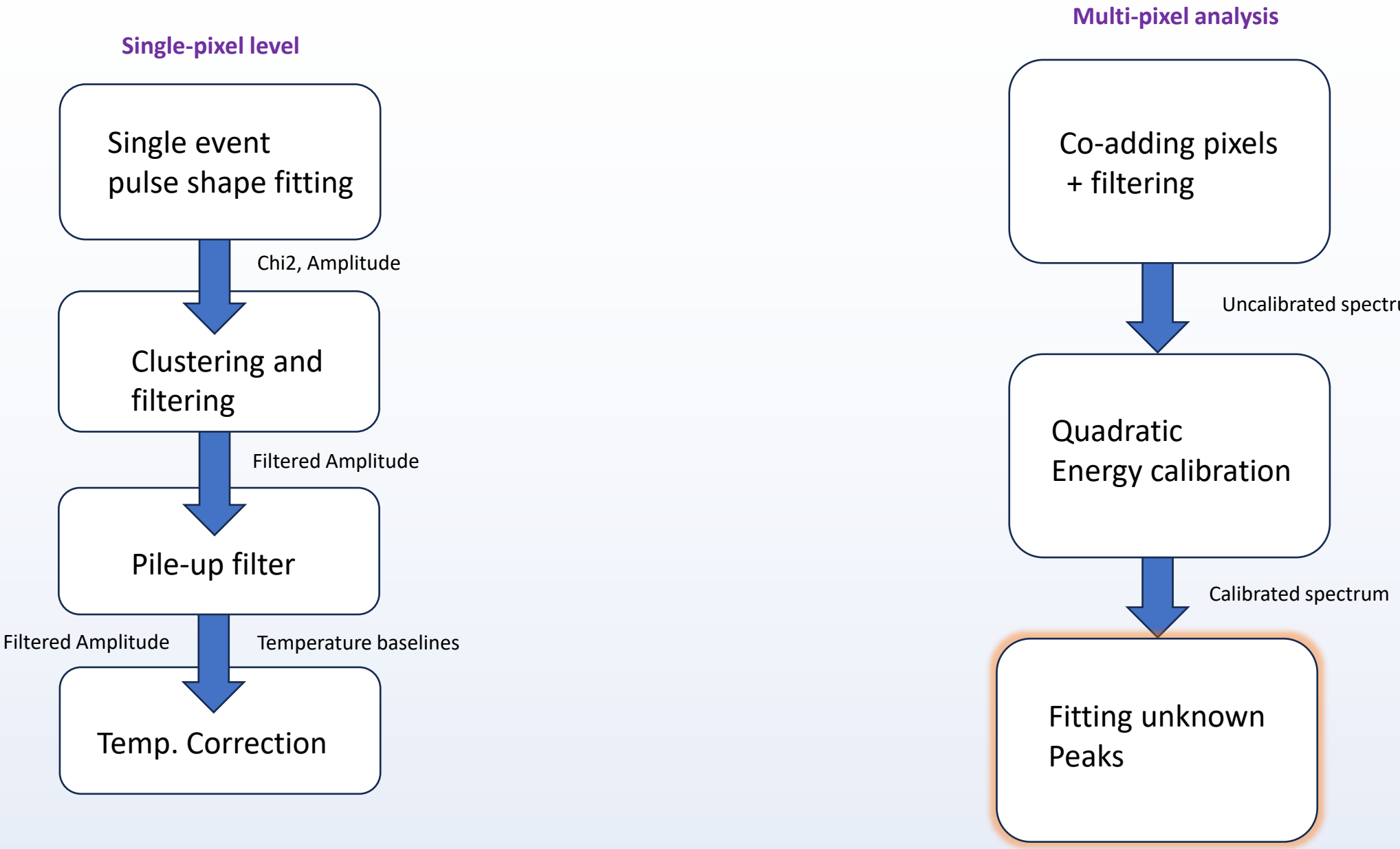


Temperature correction for single pixel

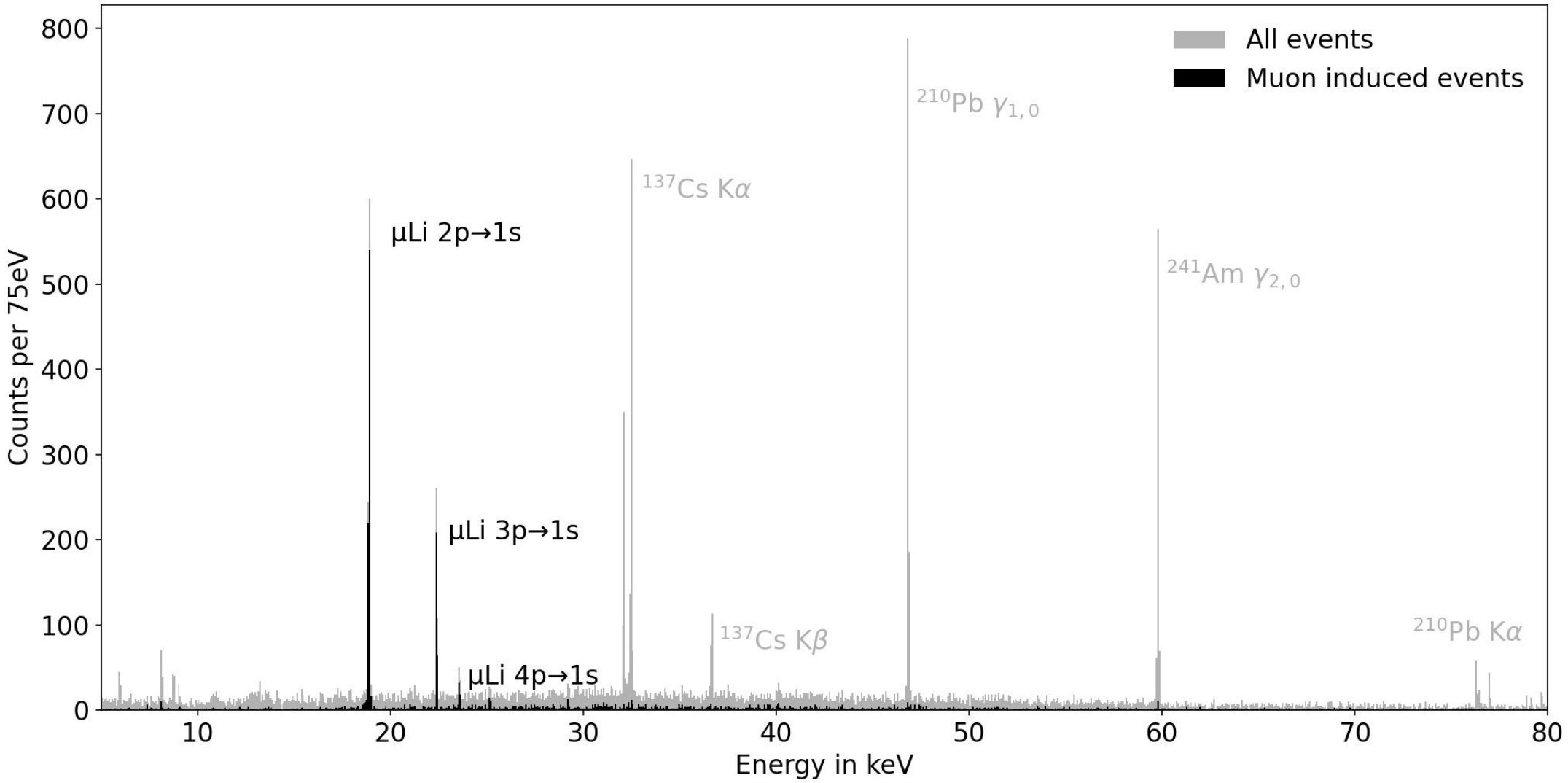




Data-Stream


Single-pixel level
Single event
pulse shape fitting
Chi2, Amplitude
Clustering and
filtering
Filtered Amplitude
Pile-up filter
Filtered Amplitude
Temperature baselines
Temp. Correction
Multi-pixel analysis
Co-adding pixels
+ filtering
Uncalibrated spectrum
Quadratic
Energy calibration
Calibrated spectrum
Fitting unknown
Peaks

Preliminary calibrated spectrum with mixed Li target



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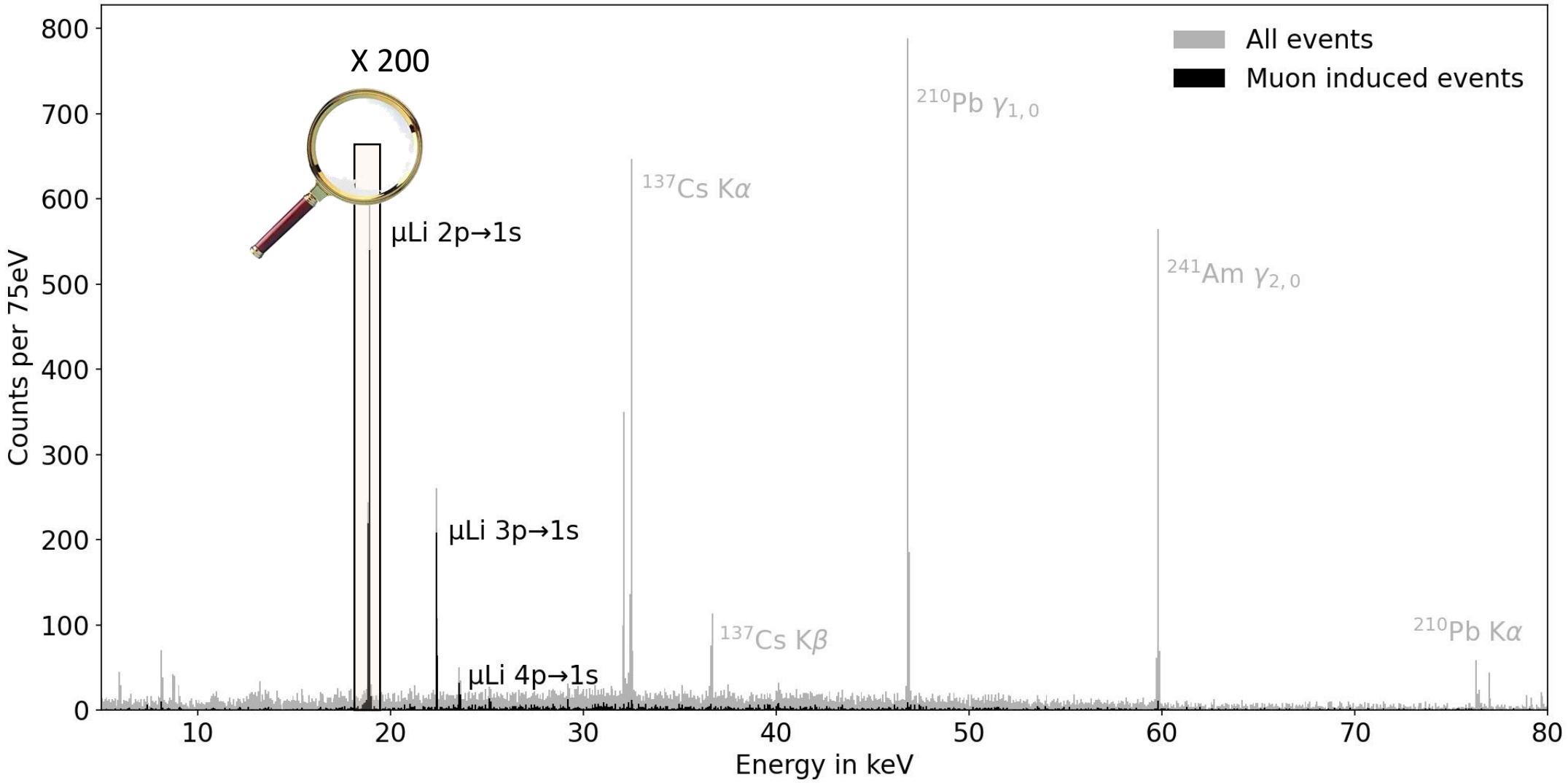
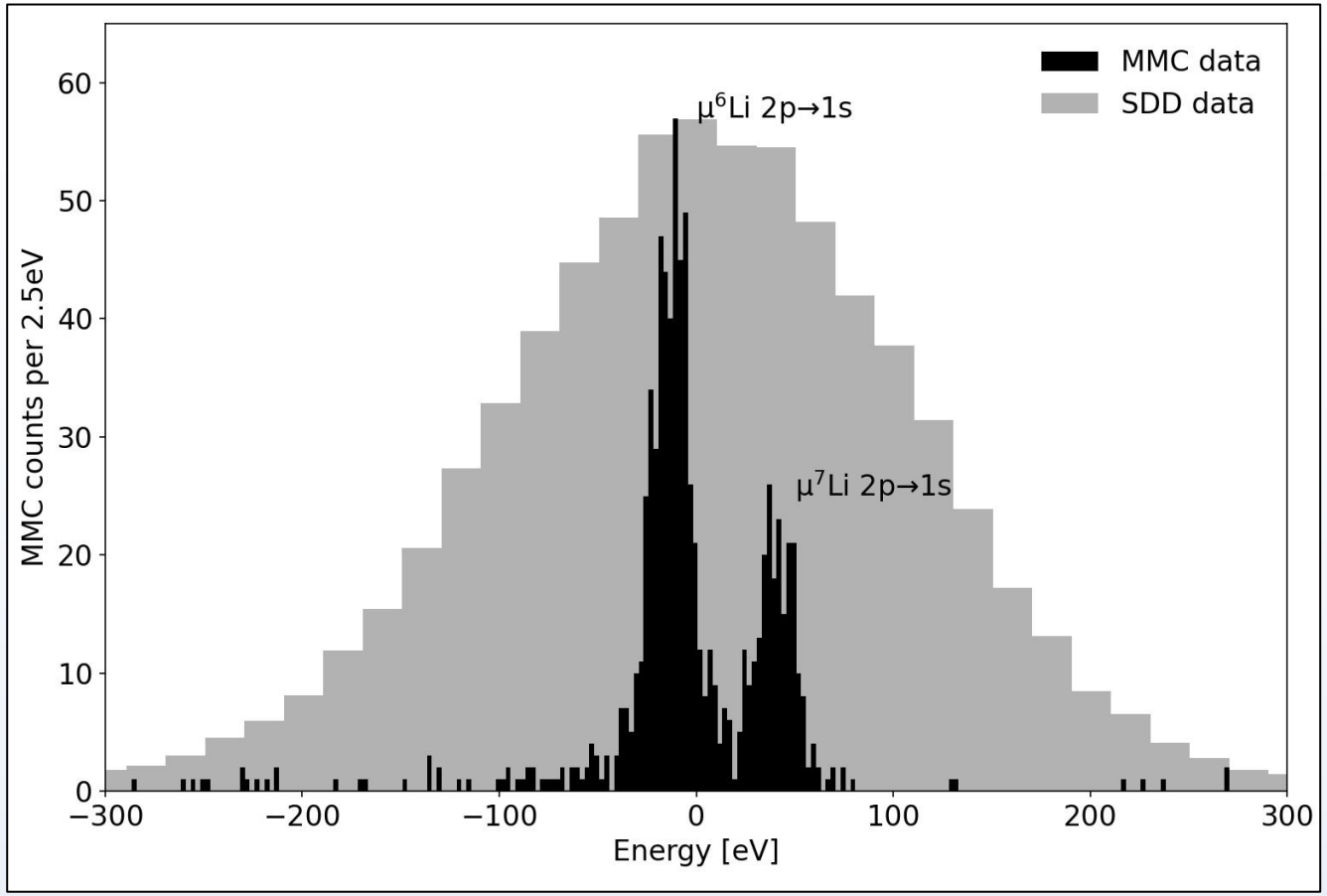


Preliminary zoomed-in spectrum of mixed Li target

- High resolution critical!
- Determine abundances



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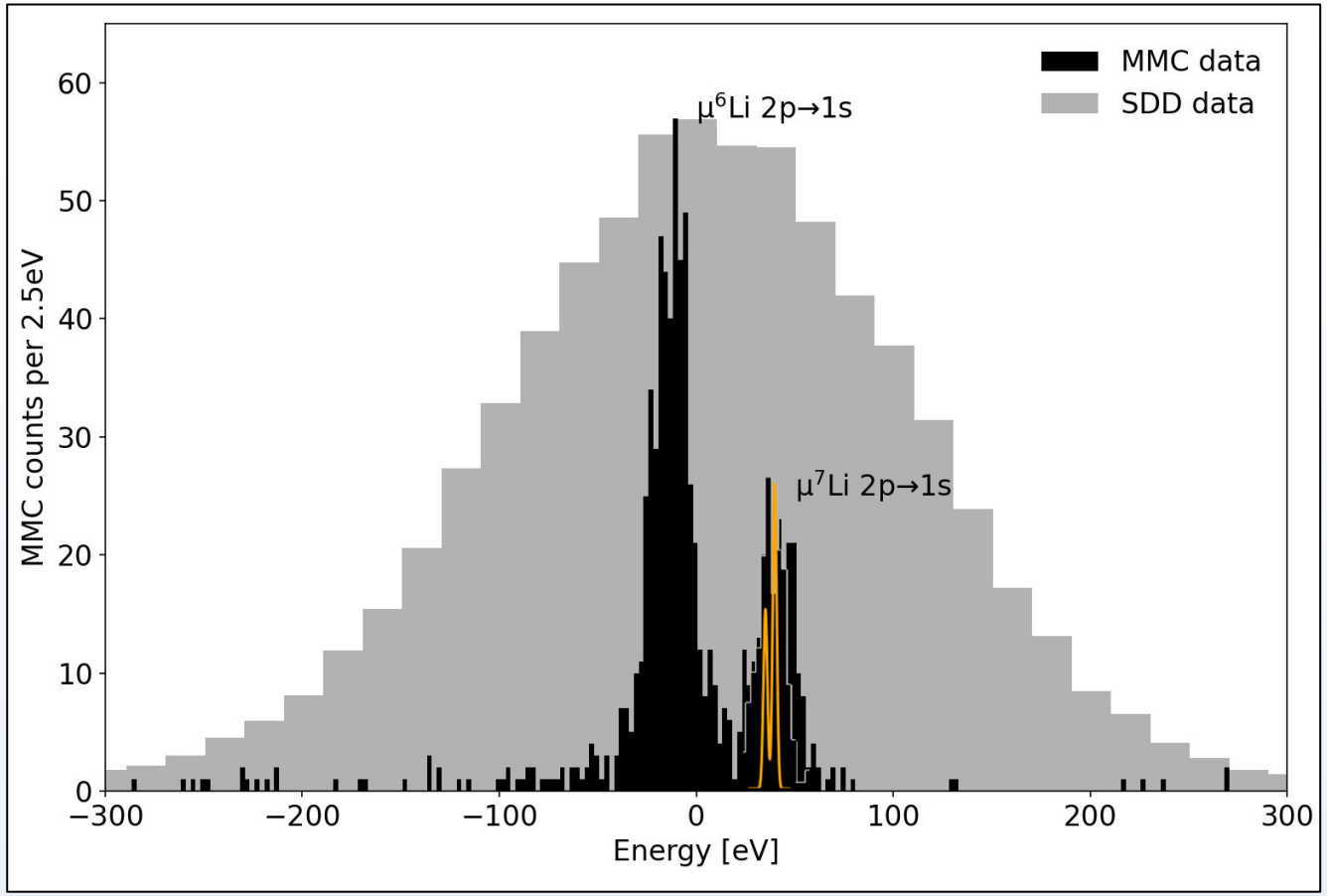

Preliminary zoomed-in spectrum of mixed Li target

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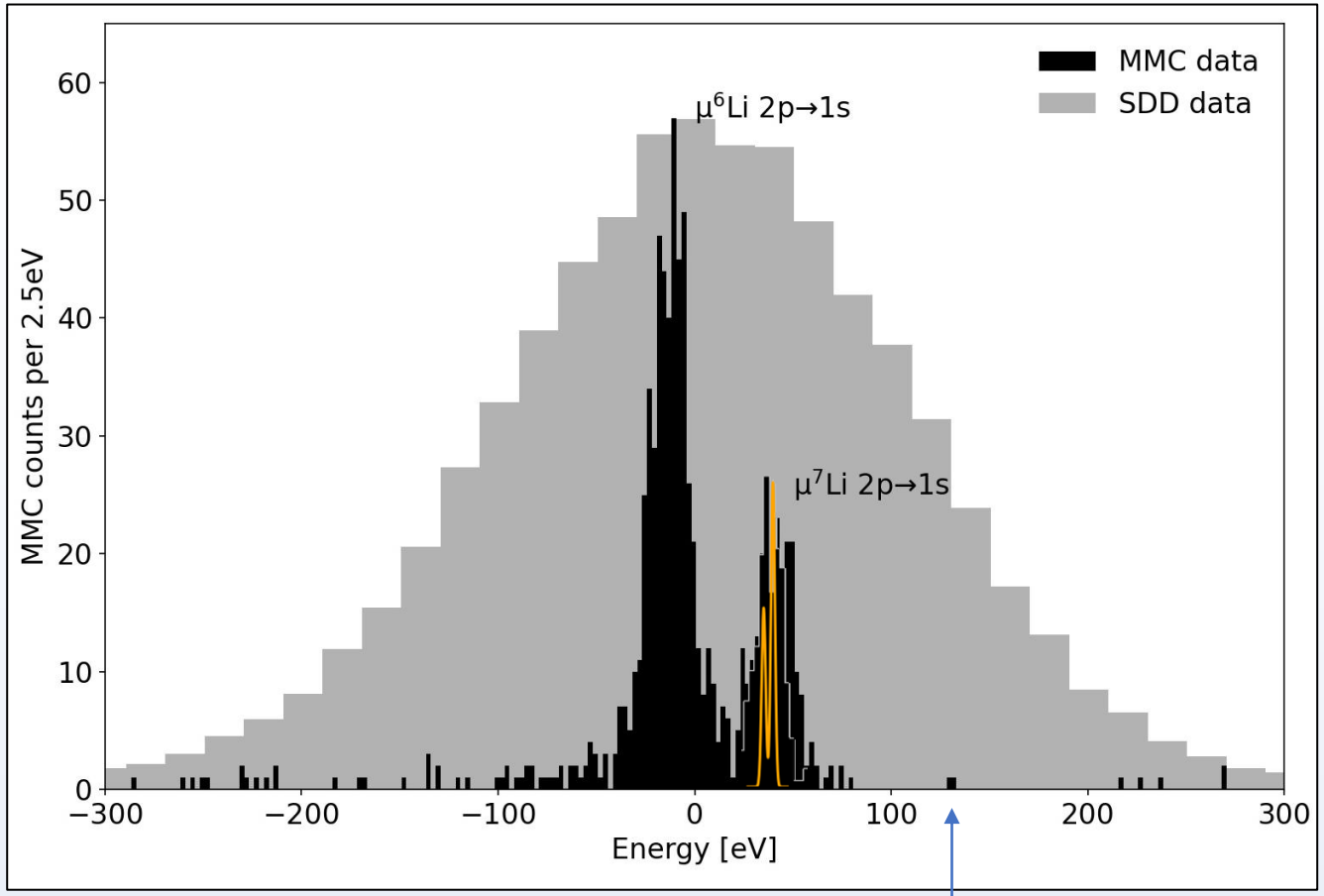
- Determine abundances
- Fit correct lineshape (FS-HFS)
- Determine contaminations



$\mu C(4 \rightarrow 2)?$

QUARTET goals and impact

Goals for 2024 and how to reach them:

With existing maXs-30 detector:

- Assuming resolution and rates as in test
- 48 hours per isotope
- Upgrade digitizer modules to ppm-level non-linearity and ppm/°C-gain drift
- Improved sources' positioning

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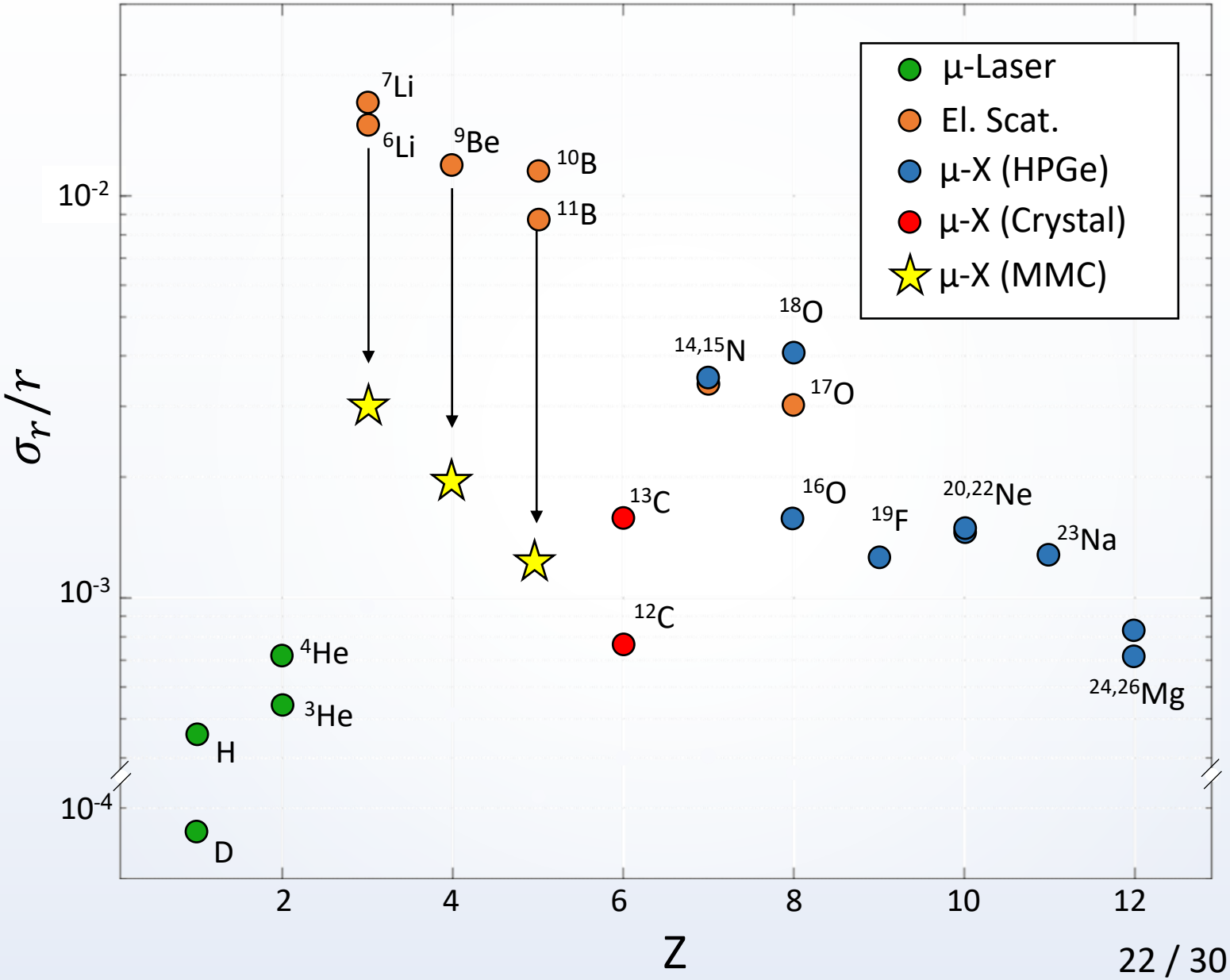
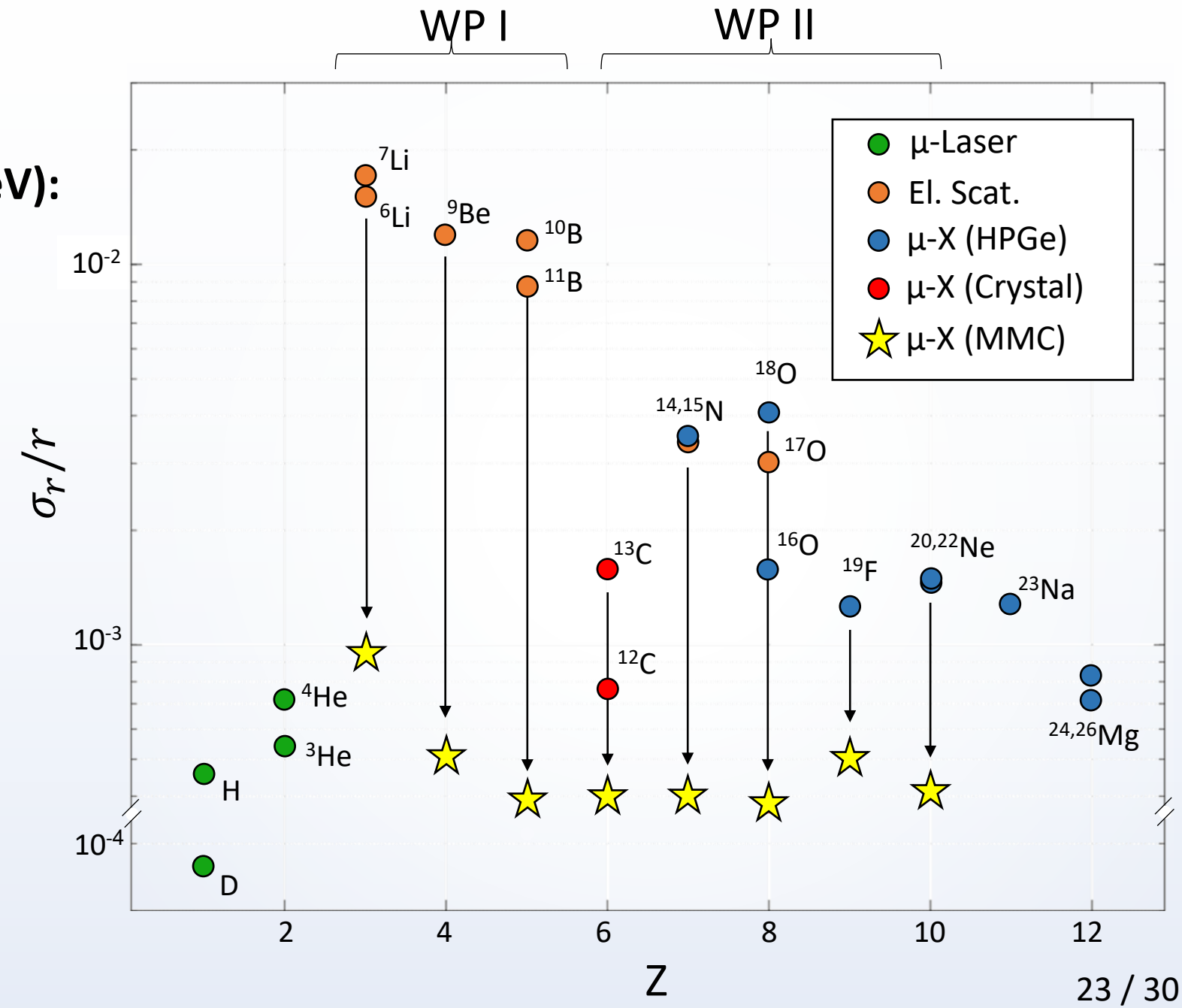


Goals until 2027:

With dedicated detector (10-200 keV):

- optimized absorber dimensions balancing active area, stopping power & resolution
- Protected on-chip T sensors to eliminate dead-time caused by x-ray events in them.
- x10-100 increased rate hardness by improved pixel-heatsinking



Immediate Impacts:

1. Test state-of-the art ab. Initio. **Nuclear theory**

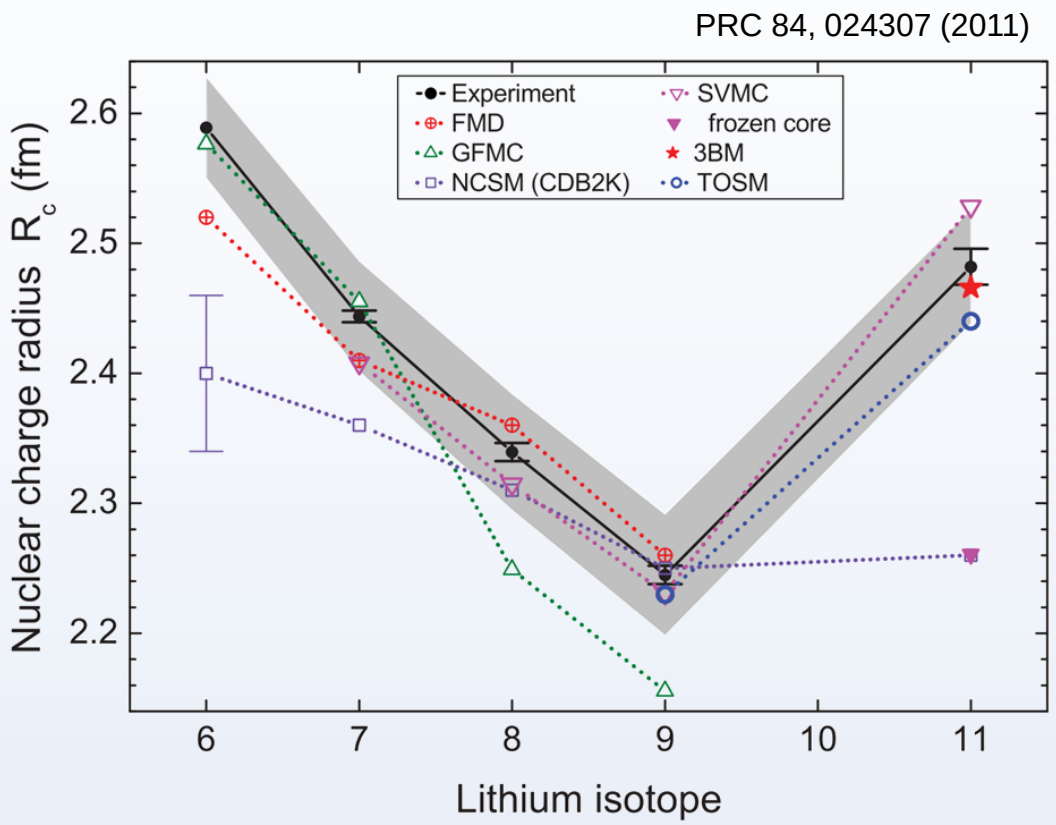
2. Benchmark state-of-the-art **QED** calculations

3. **New physics** searches via isotope shifts

Physics case 1: Test ab initio nuclear theory

Distinguish nuclear models
(remove gray band):

PRC 84, 024307 (2011)



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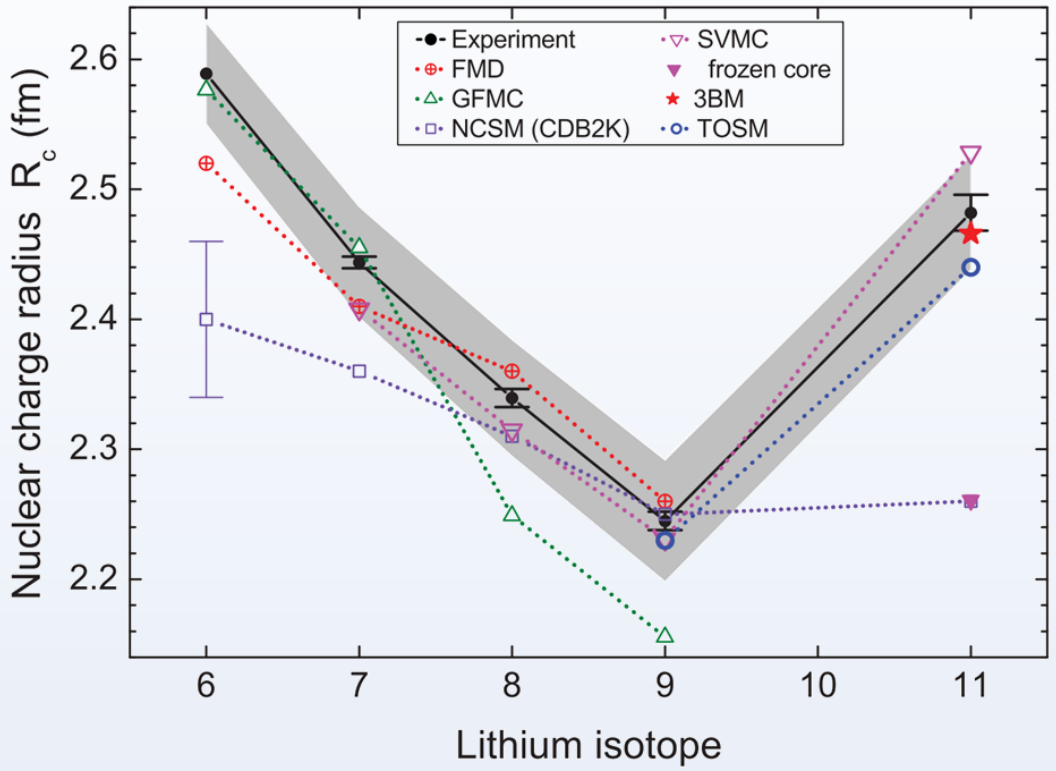
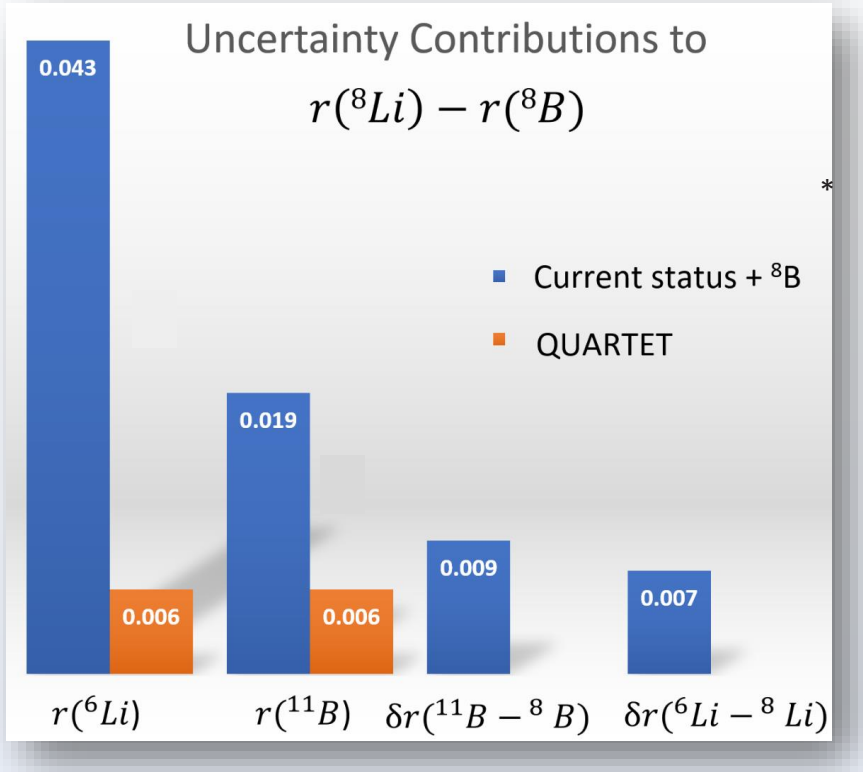
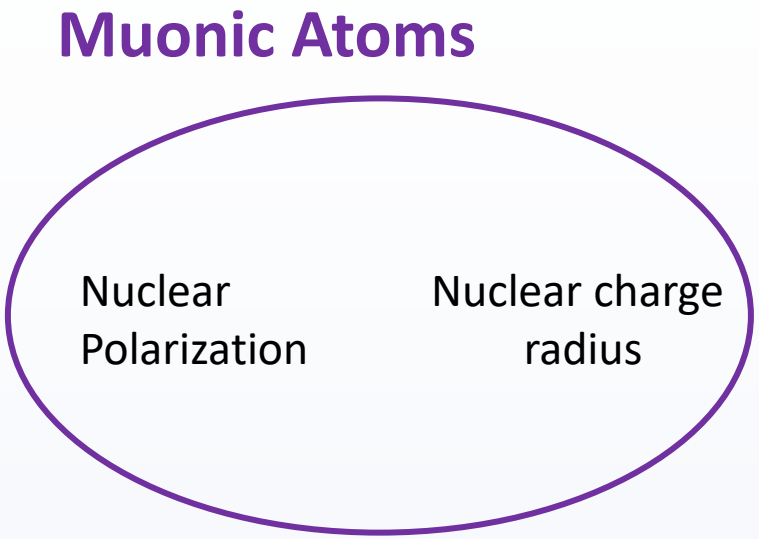


Facilitate determination of the radii of mirror nuclei:

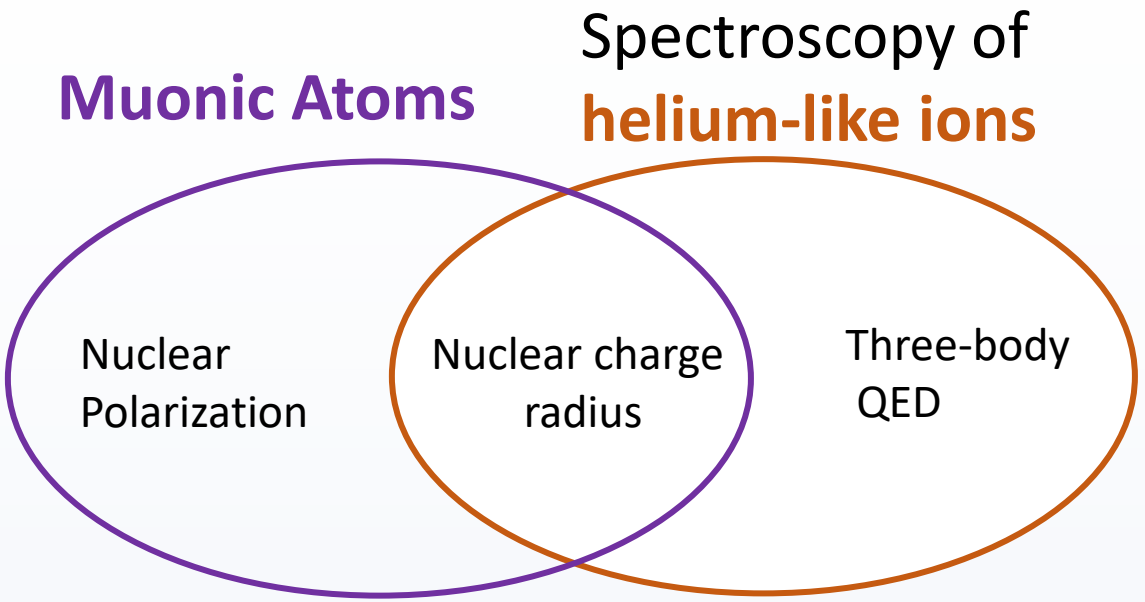


*Priv. Com. With W. Nörtershäuser

Physics case 2:



Physics case 2:



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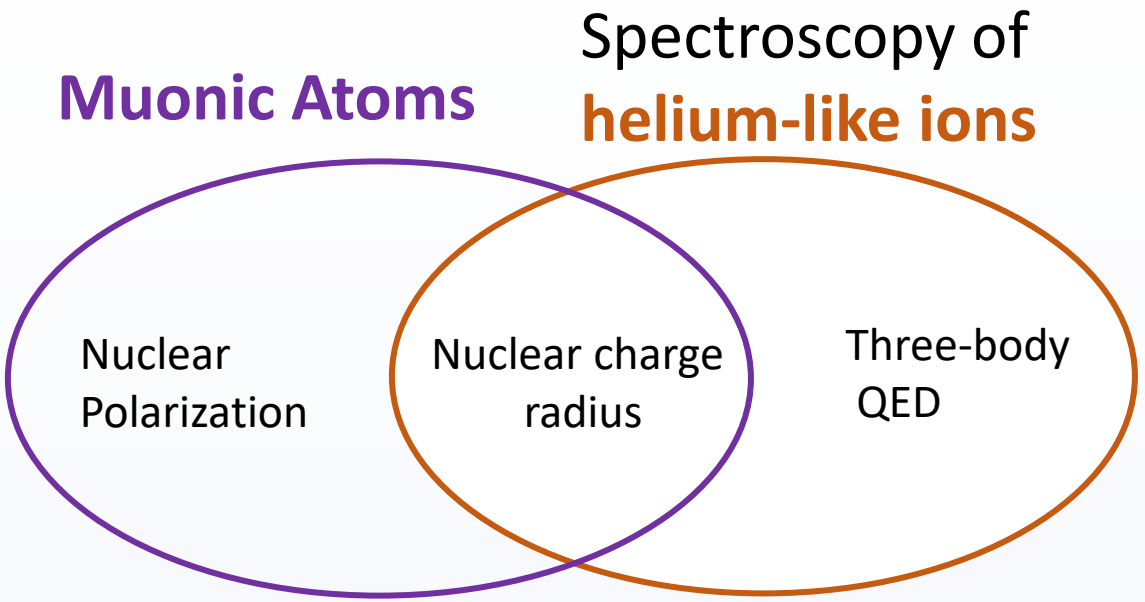
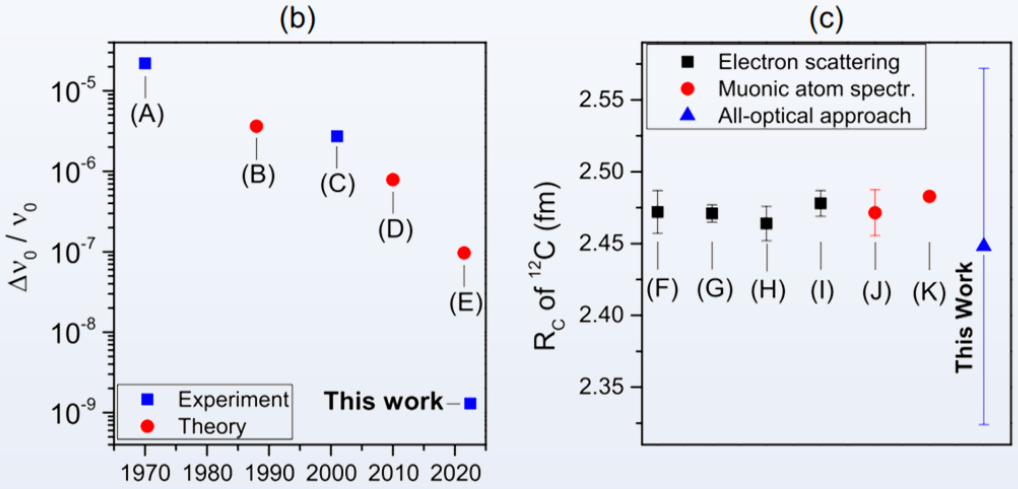
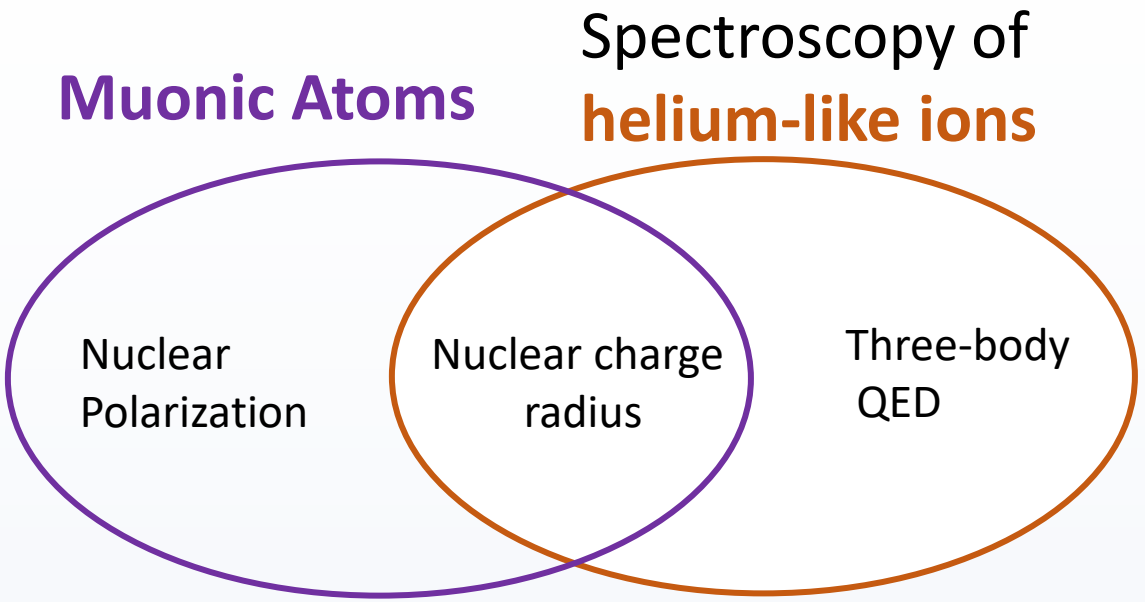


Completed: Helium-like ^{12}C (Darmstadt):



PRL 131, 243001
PRA 108, 062809

Physics case 2:



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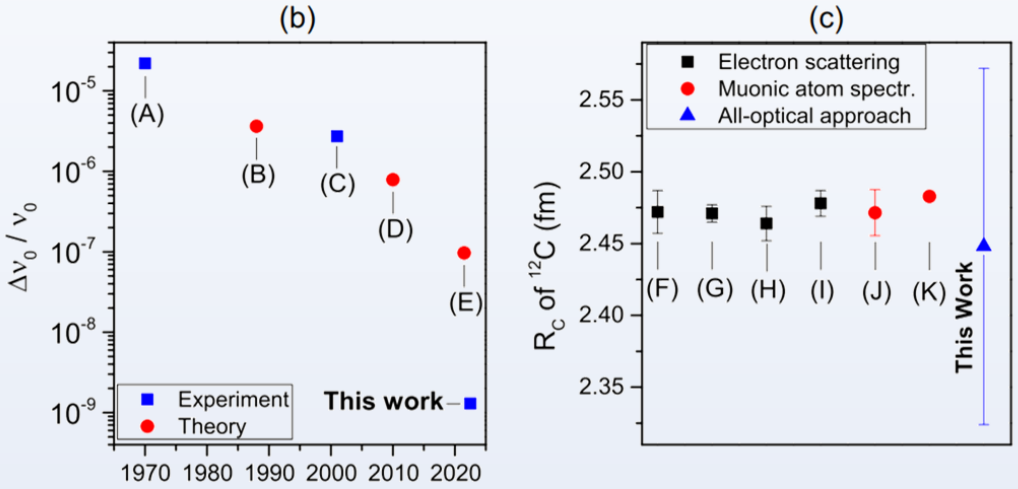

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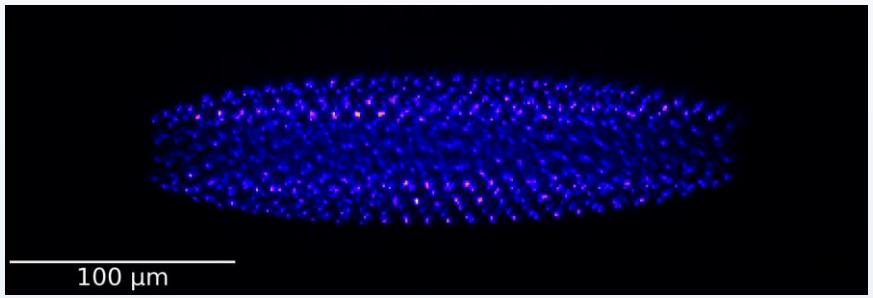
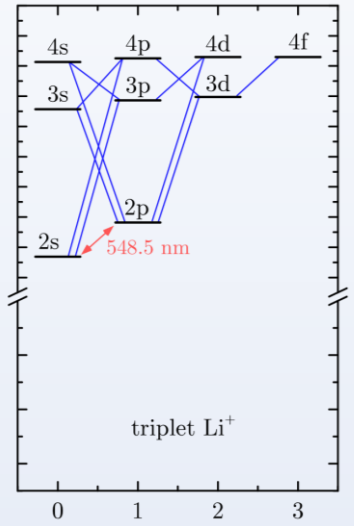


New experiment: precision measurements in cooled trapped **Helium like Lithium**
Courtesy of Akira Ozawa & Thomas Udem

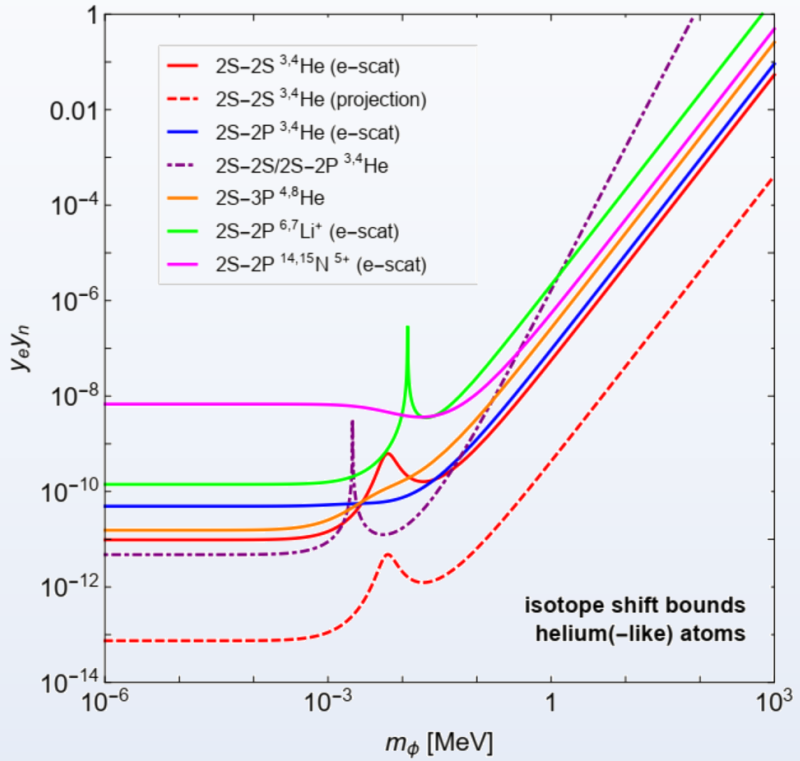


Physics case 3: BSM with isotope shifts

$$\delta r^2(muonic)\ Vs.\ \delta r^2(electronic)$$

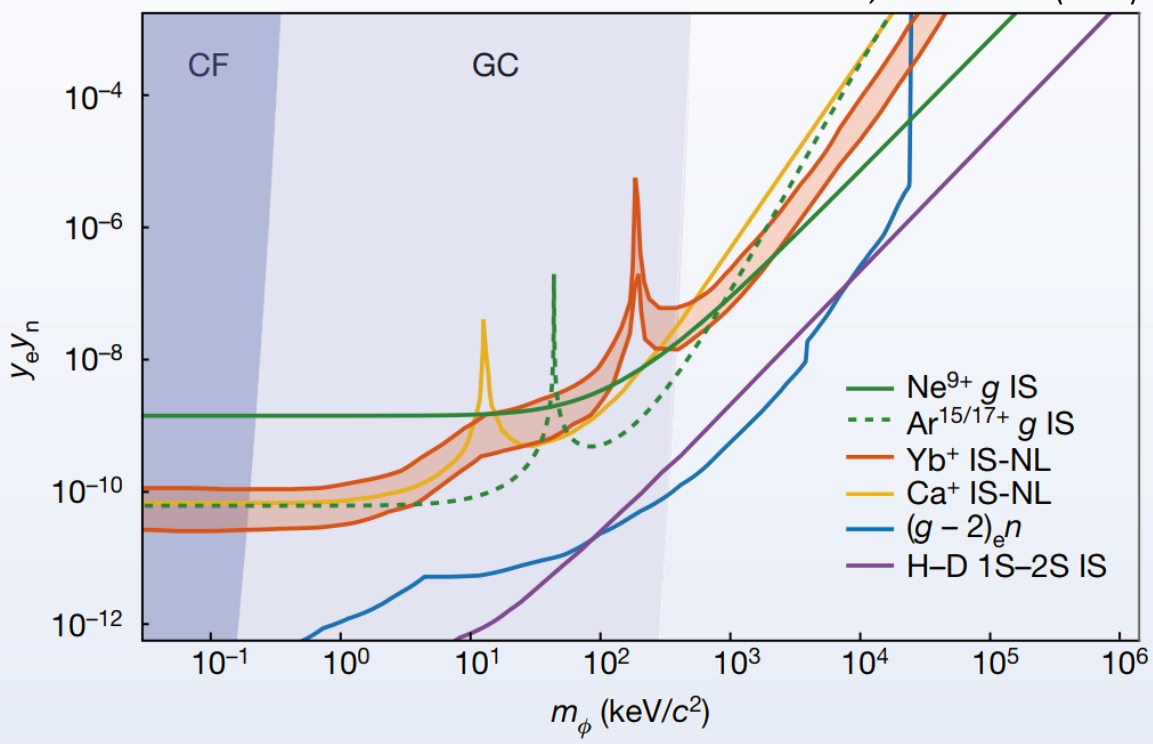
Helium-like ions:

C. Delaunay, C. Frugiuele, E. Fuchs, Y. Soreq PRD 96 (2017)



g-factors in hydrogen-like ions:

T. Sailer *et. al.,* Nature 606 (2022)



Why go up to neon?

Radius **crucial** for confronting experiment and theory in beta spectrum of ^{20}F

TABLE II: Systematic effects considered in the analysis.

Source	Δb_{WM}	Δb_{GT} (10^{-3})
End-point energy, E_0	0.19	0.71
Charge radius, R	0.46	1.67
GT matrix element, c_1	0.021	0.077
Quadratic term, c_2	0.001	0.013
Weak magnetism, b_{WM}	−−	2.62
Induced tensor, d^I	0.17	0.63

*Curtesy of Oscar Naviliat-Cuncic

Nuclear Theory

New Physics

Summary

- Goal: Radii from ^{6}Li to ^{22}Ne up to 20 times better
- Muonic Atoms + Cryogenic Calorimeters = Coffee + Donuts
- Successful test beam on Oct. 23. **No show-stoppers**, Analysis ongoing
- 2024: $\mu Li, Be, B$ radii x 3-5 with (upgraded) existing system
- Until 2027: Ultimate precision with dedicated detector(s)


ATTENTION TO THE ALARM!
In case of FALSE alarm call immediately 2600 (security center)
Thanks for listening!