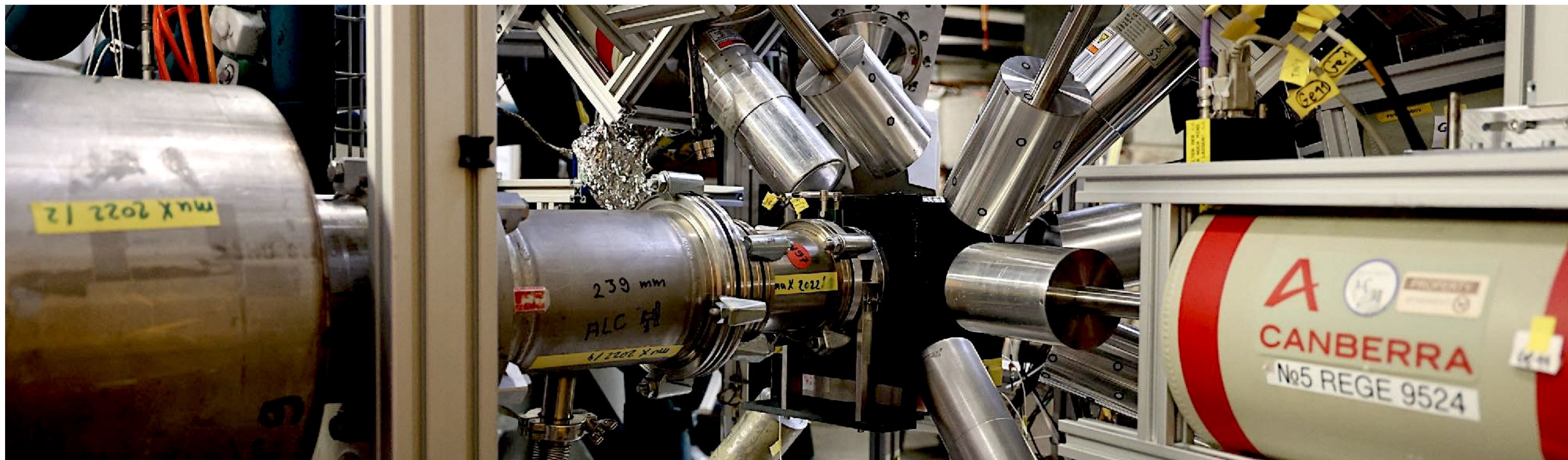


Reviving muonic atom spectroscopy to extract absolute nuclear charge radii in rare and radioactive isotopes

Stella Vogiatzi

On behalf of the **ReferenceRadii** & **muX** collaborations

21-26 September, 2025



Our *exotic* muonic atom

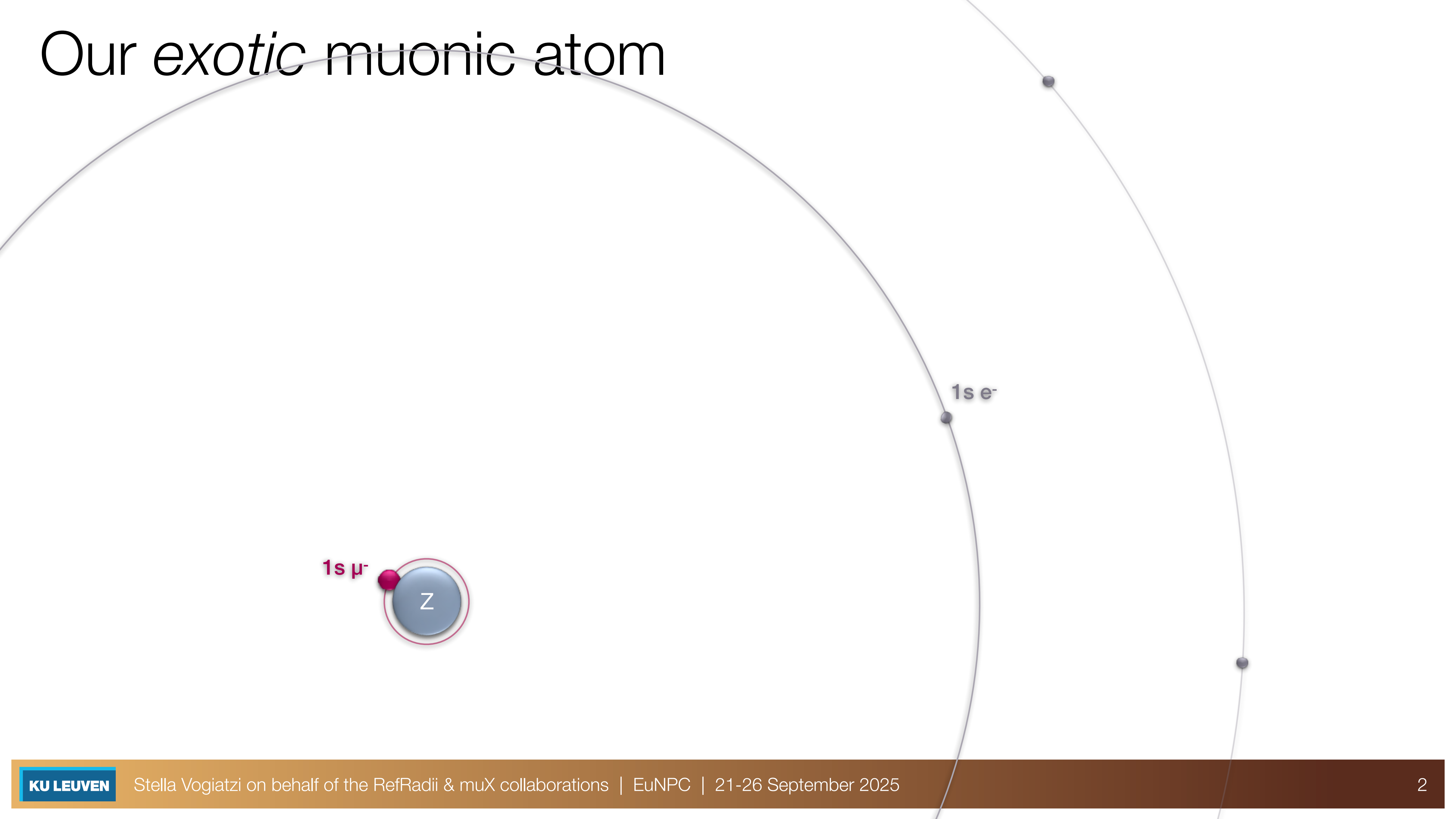
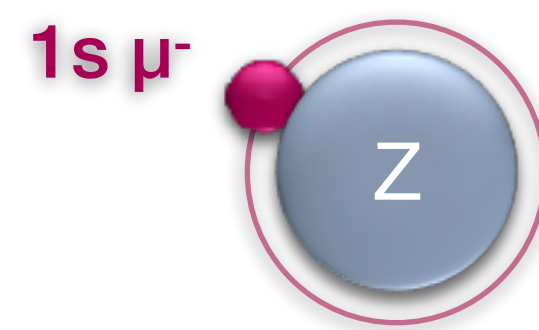


Diagram of an electron atom with a nucleus labeled Z . The inner orbit has a dot labeled $1s e^-$. The outer orbit has two dots.

$1s e^-$

Our *exotic* muonic atom

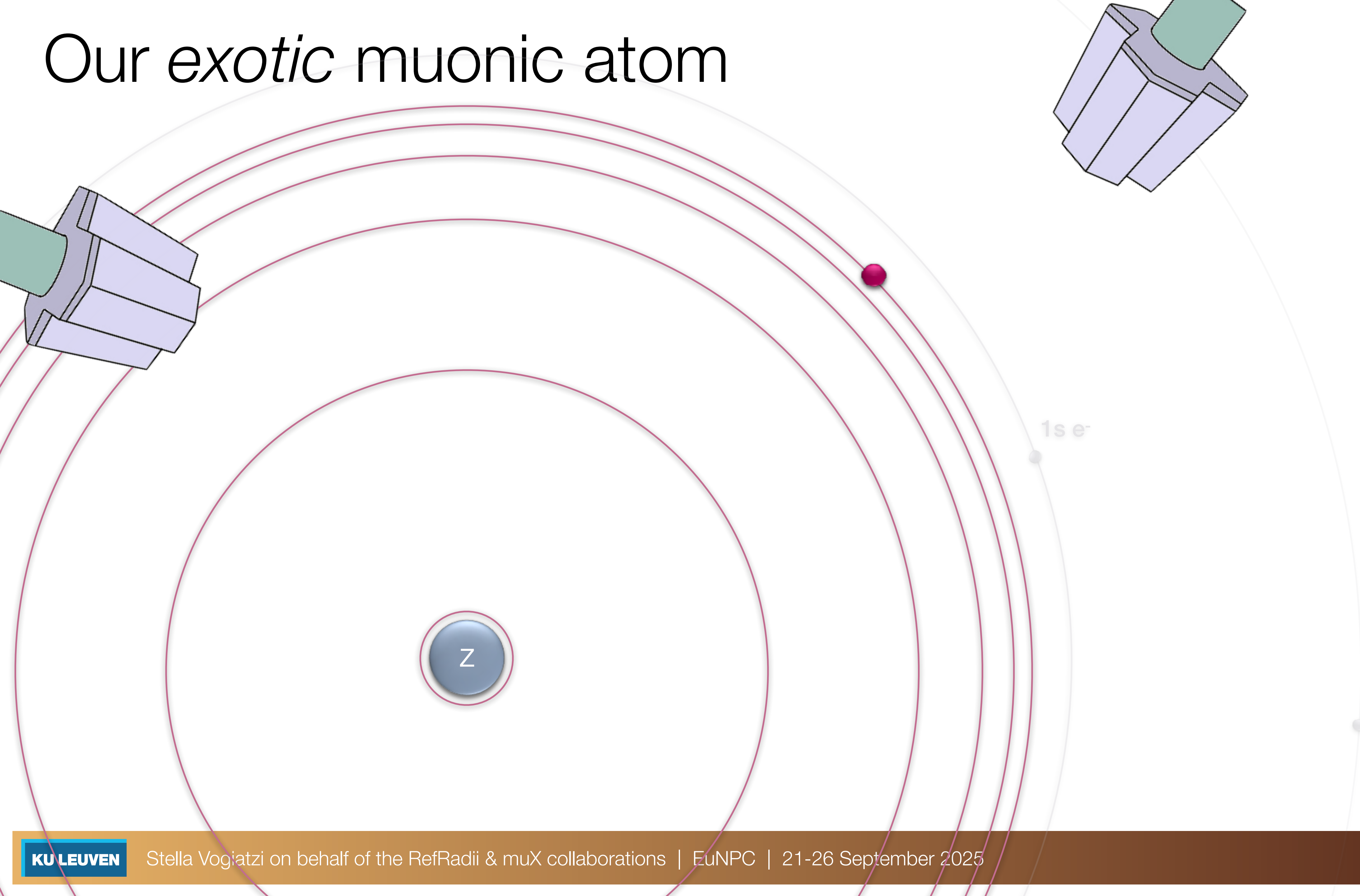


Stopping negative muons directly to
targets of >100 mg
...only when you have an abundant
and stable target

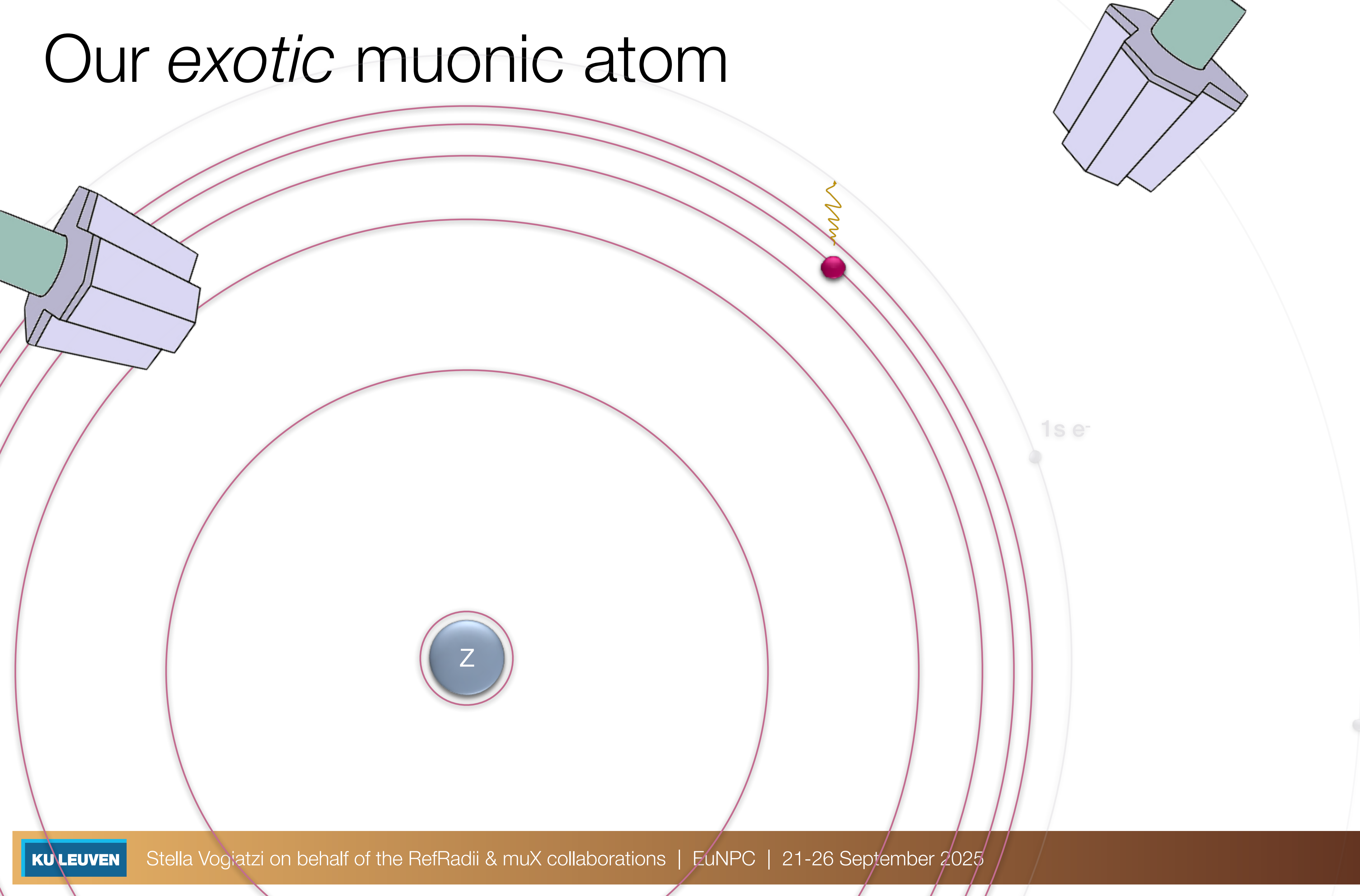
30 MeV/c μ^-



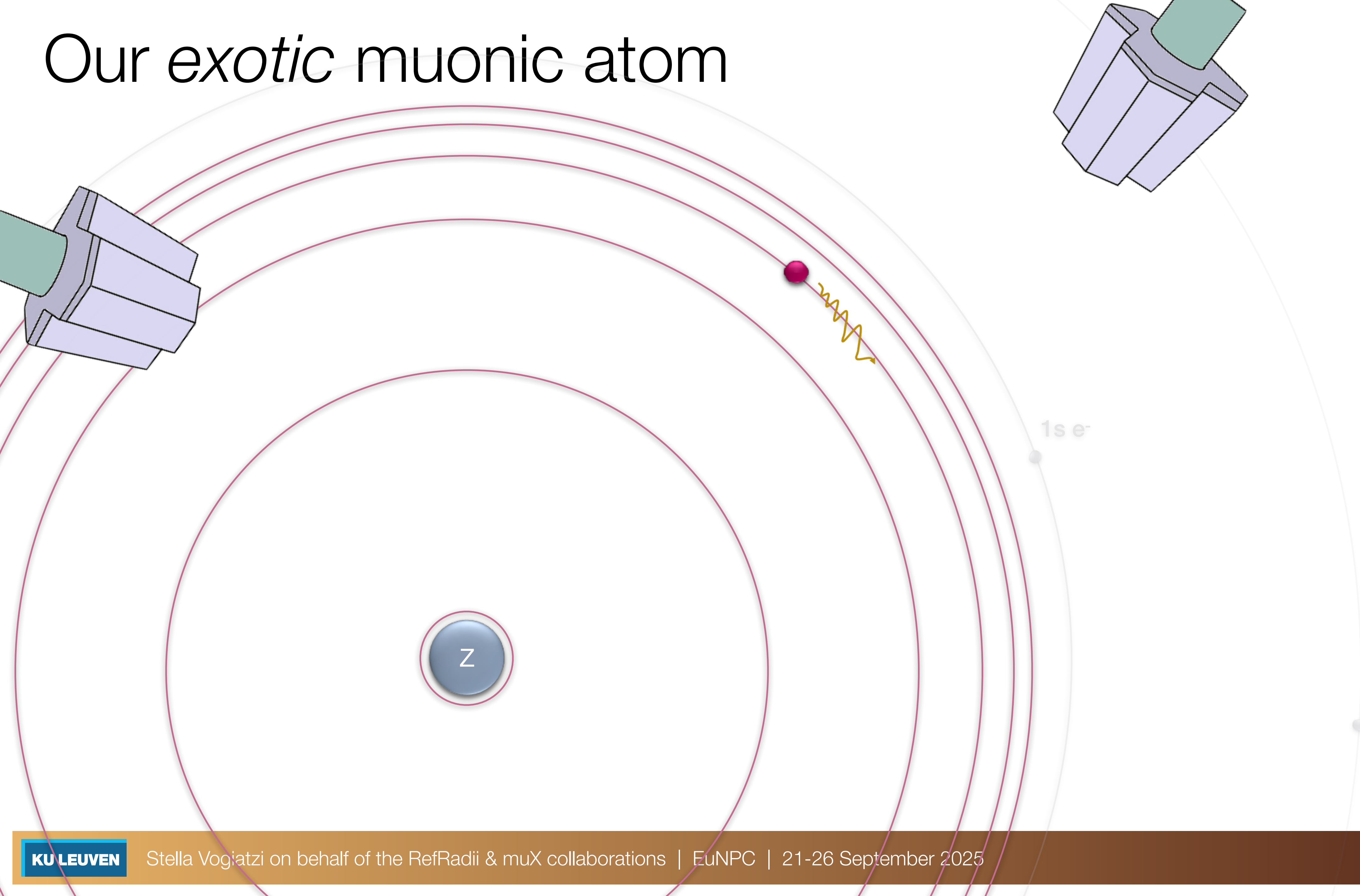
Our *exotic* muonic atom



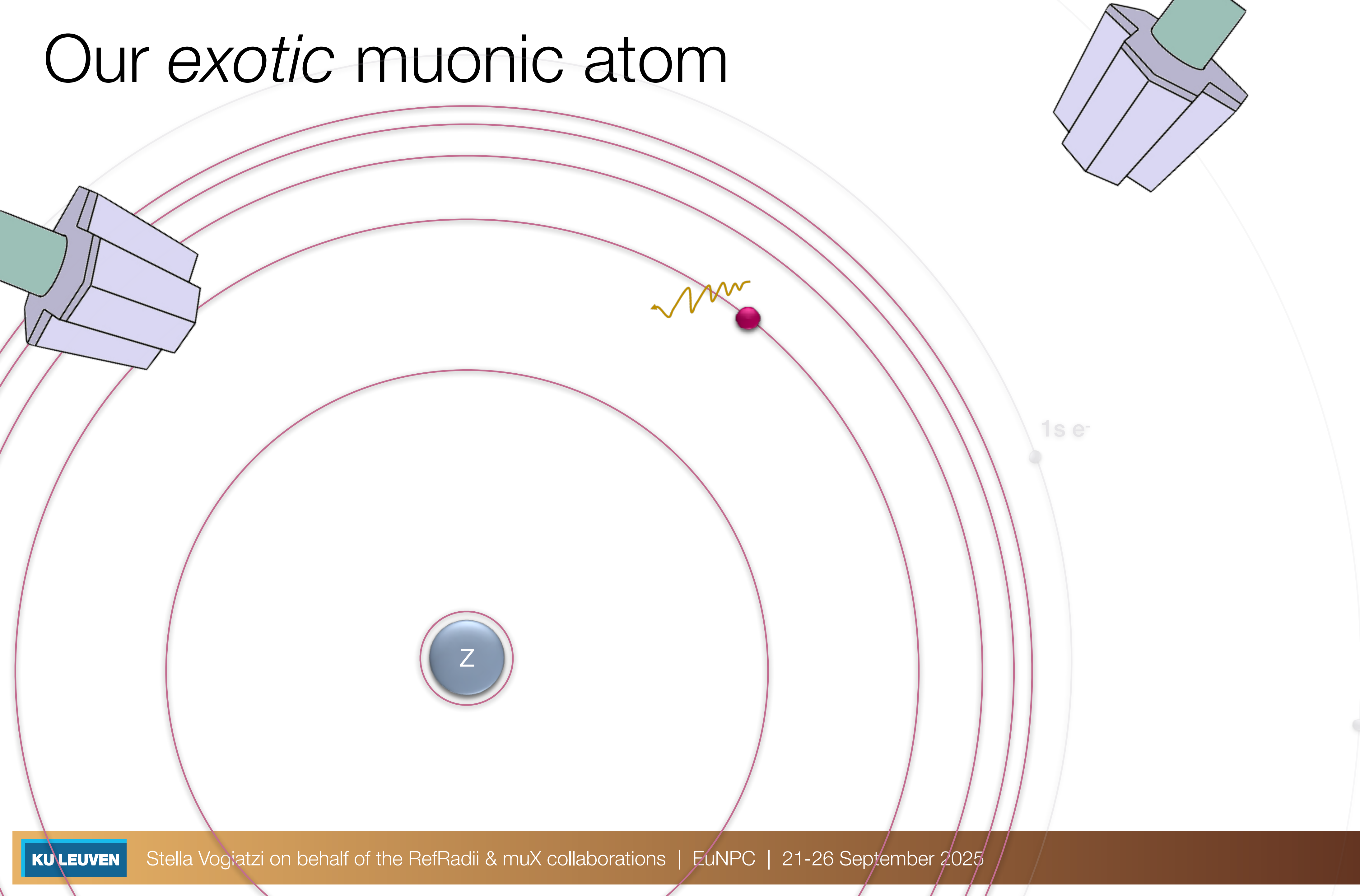
Our *exotic* muonic atom



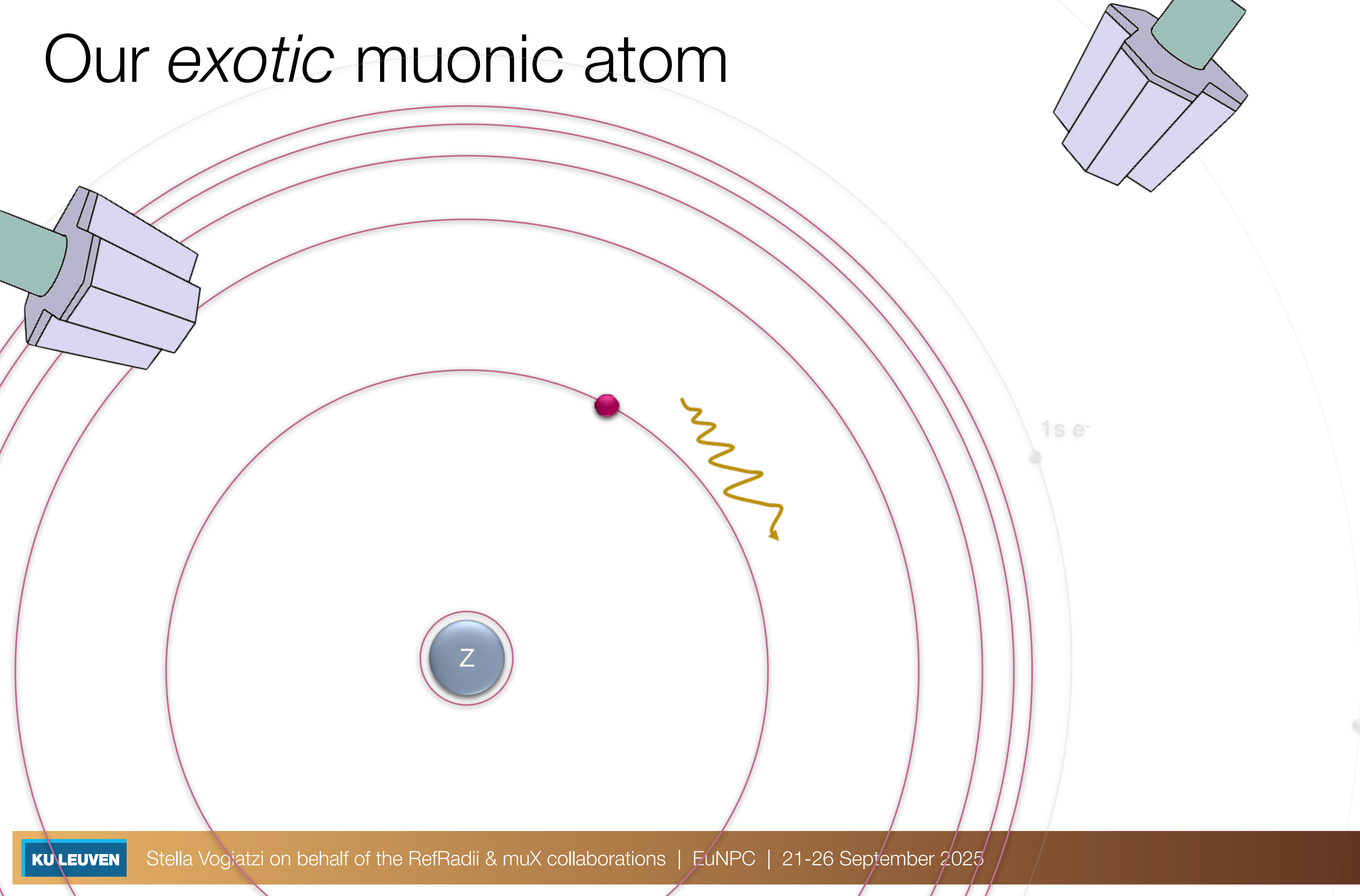
Our *exotic* muonic atom



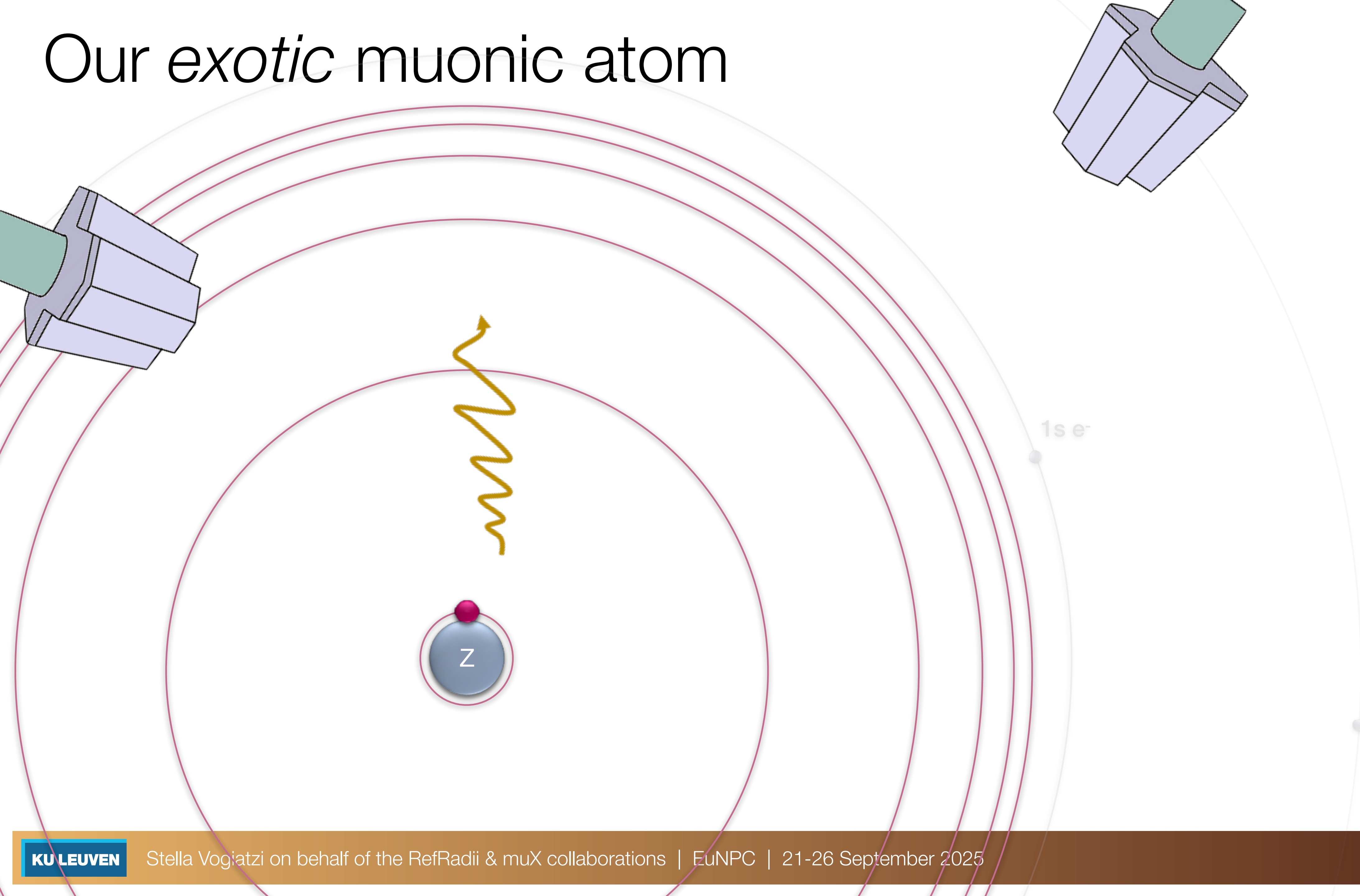
Our *exotic* muonic atom



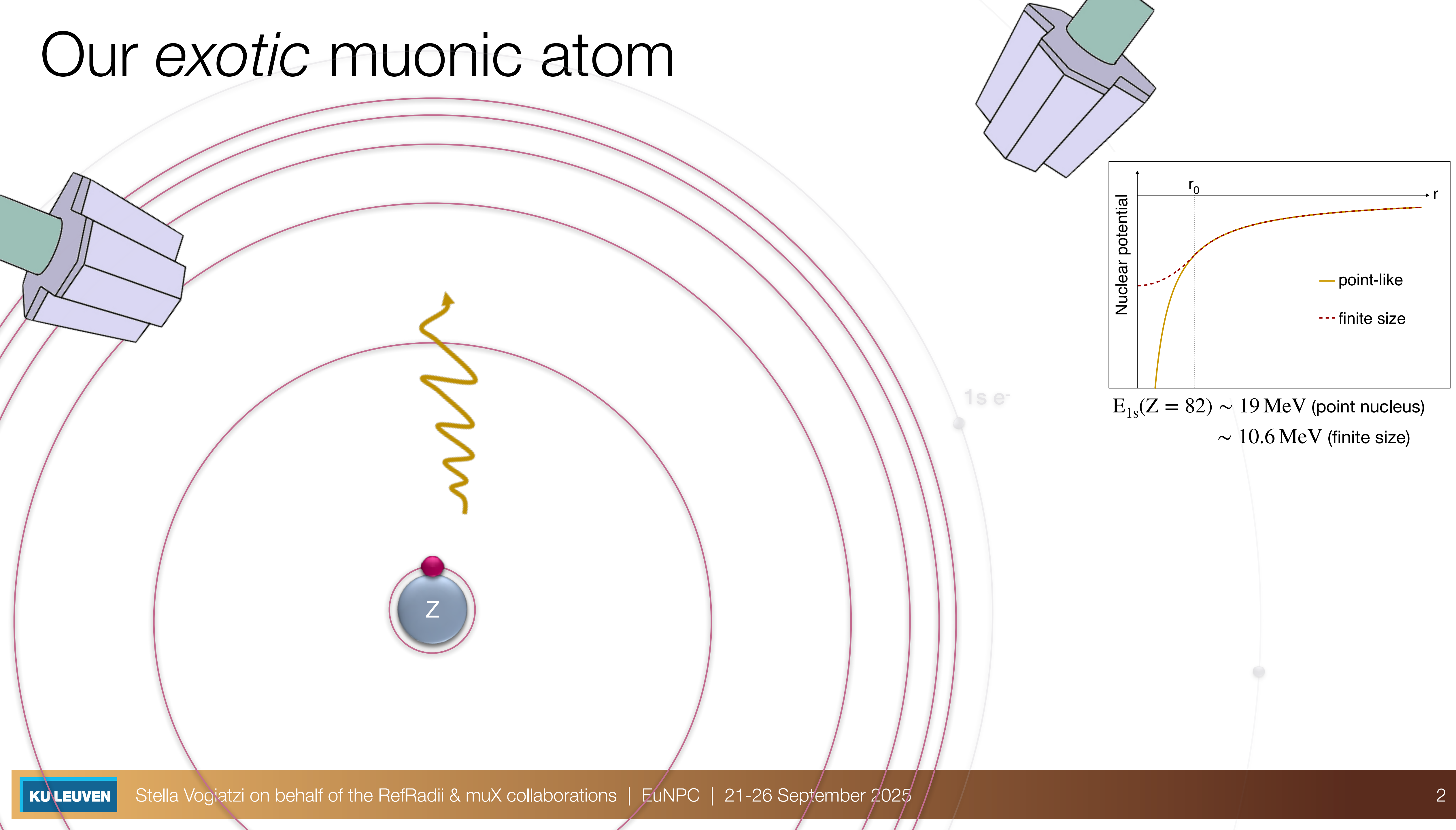
Our *exotic* muonic atom



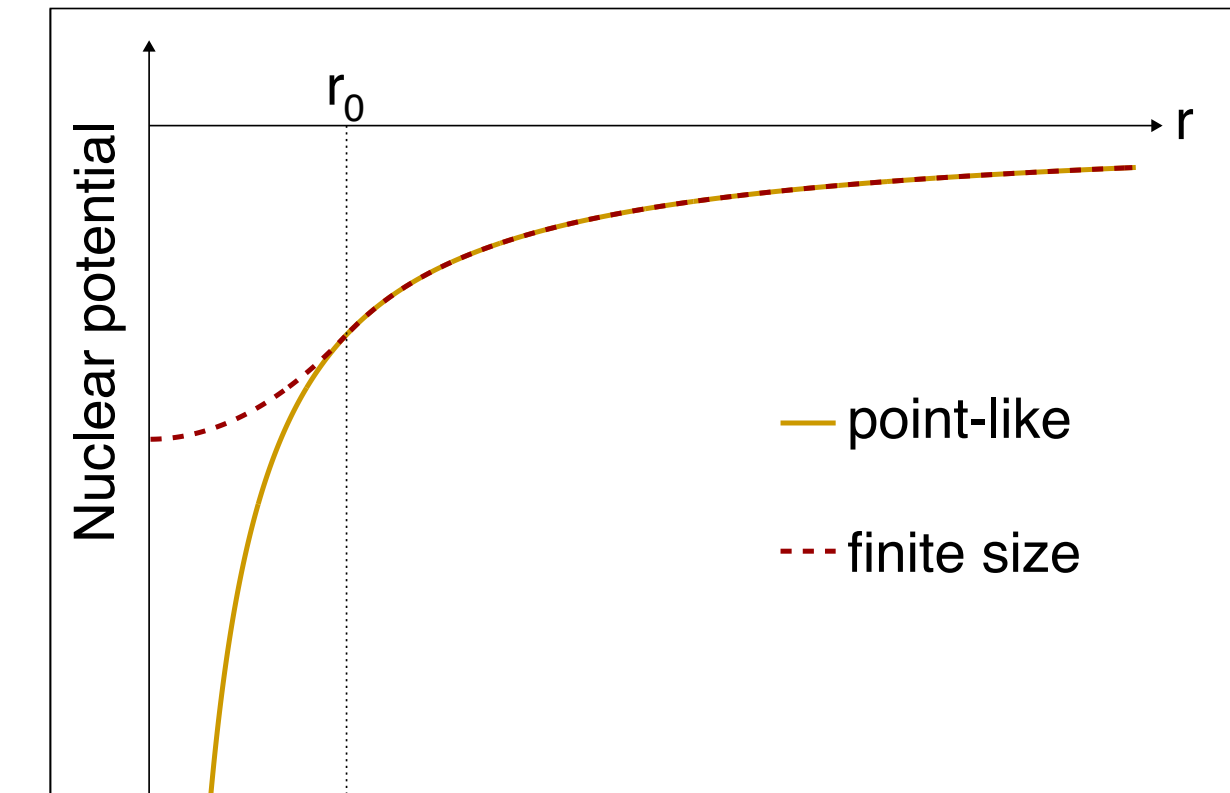
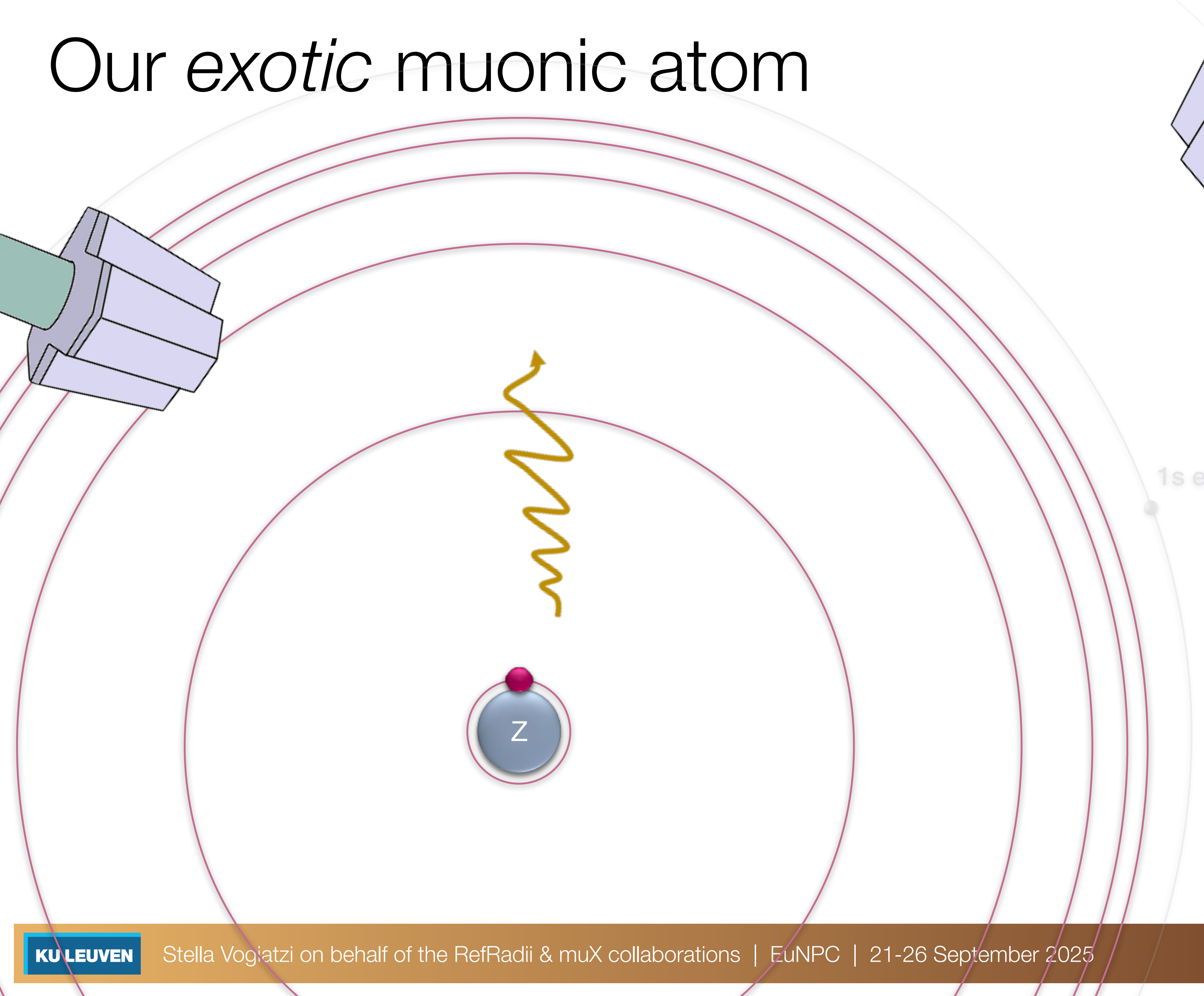
Our *exotic* muonic atom



Our *exotic* muonic atom



Our *exotic* muonic atom



$E_{1s}(Z = 82) \sim 19 \text{ MeV}$ (point nucleus)
 $\sim 10.6 \text{ MeV}$ (finite size)

2p-1s transition most sensitive to the nuclear charge radius

$$R_N^2 = \langle r^2 \rangle = \frac{1}{Ze} \int d^3\vec{r} \rho(\vec{r}) r^2$$

nuclear charge distribution

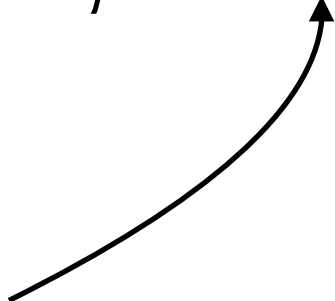
How to extract muonic energies?

$$(\vec{\alpha} \cdot \vec{b} + \beta m_{\mu} + V(r)) |\psi_{nkm} \rangle = E_{nk} |\psi_{nkm} \rangle$$

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$$(\vec{\alpha} \cdot \vec{b} + \beta m_\mu + V(r)) |\psi_{nkm}\rangle = E_{nk} |\psi_{nkm}\rangle$$

Coulomb potential that the muon feels in the
extended nuclear charge distribution
 $\rho(r) \rightarrow$ inside $V(r)$



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+higher order corrections, e.g.:

- QED corrections $\rightarrow$ well under control
- Nuclear polarisation $\rightarrow$ dominating effect

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Extracting muonic
energy levels

How to extract ~~muonic energies?~~ charge radii

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Measuring transition
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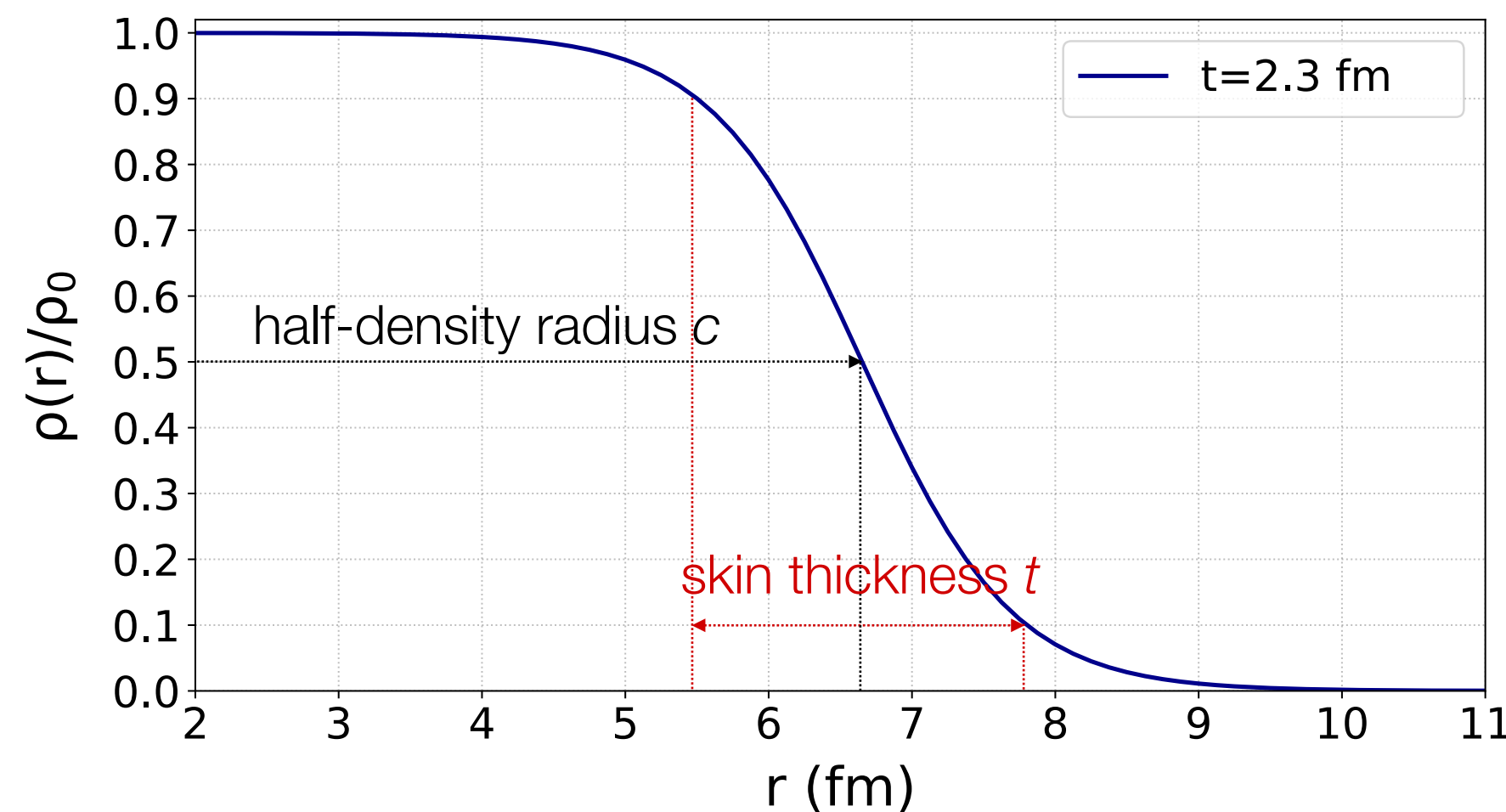
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Assuming typically a 2-parameters Fermi

$$\rho(r) = \rho_0 \left(1 + e^{4 \ln 3 \frac{r-c}{t}} \right)^{-1}$$

How to extract ~~muonic energies?~~ charge radii

$$(\vec{\alpha} \cdot \vec{b} + \beta m_\mu + V(r)) |\psi_{nkm}\rangle = E_{nk} |\psi_{nkm}\rangle$$

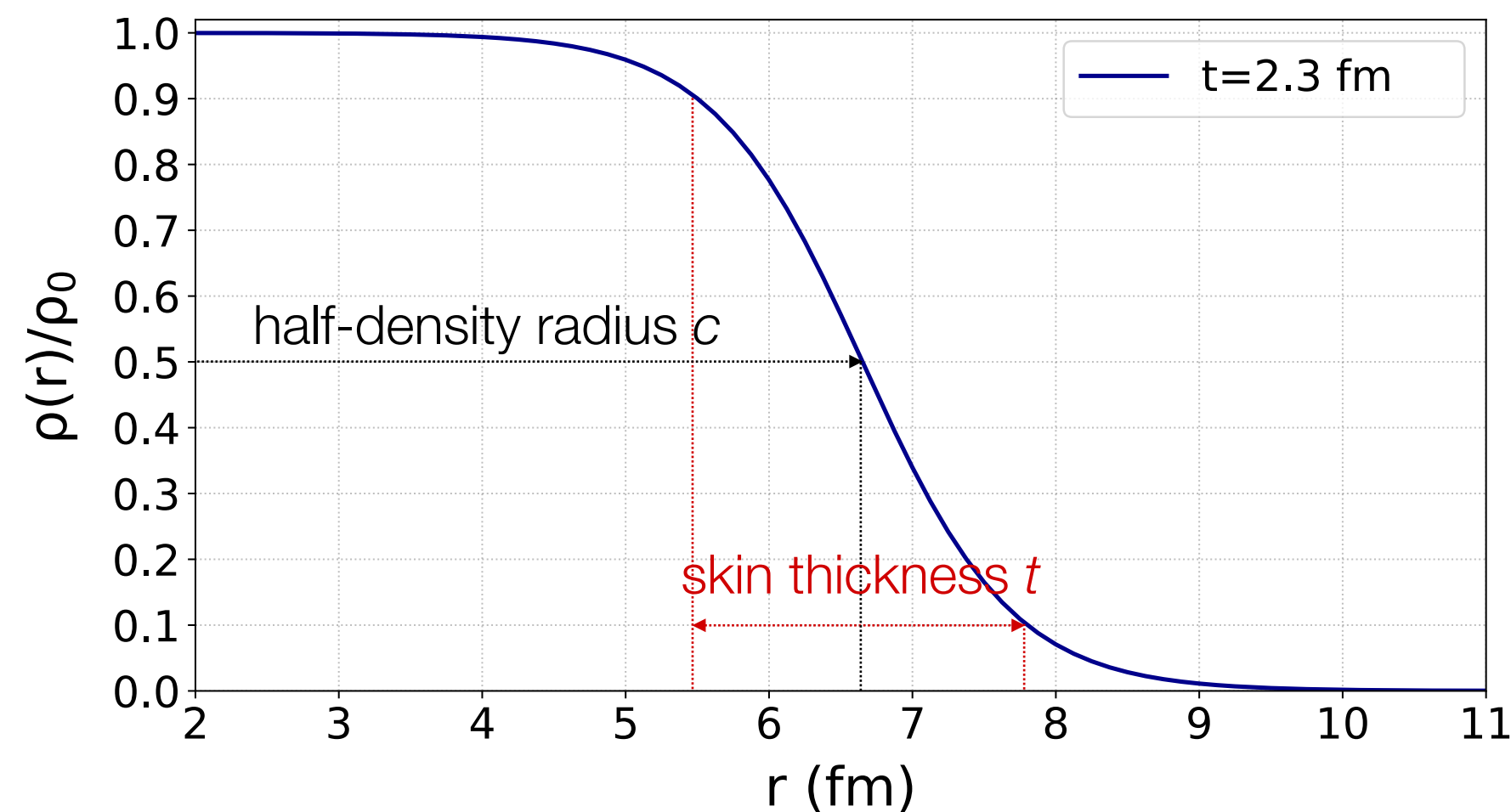
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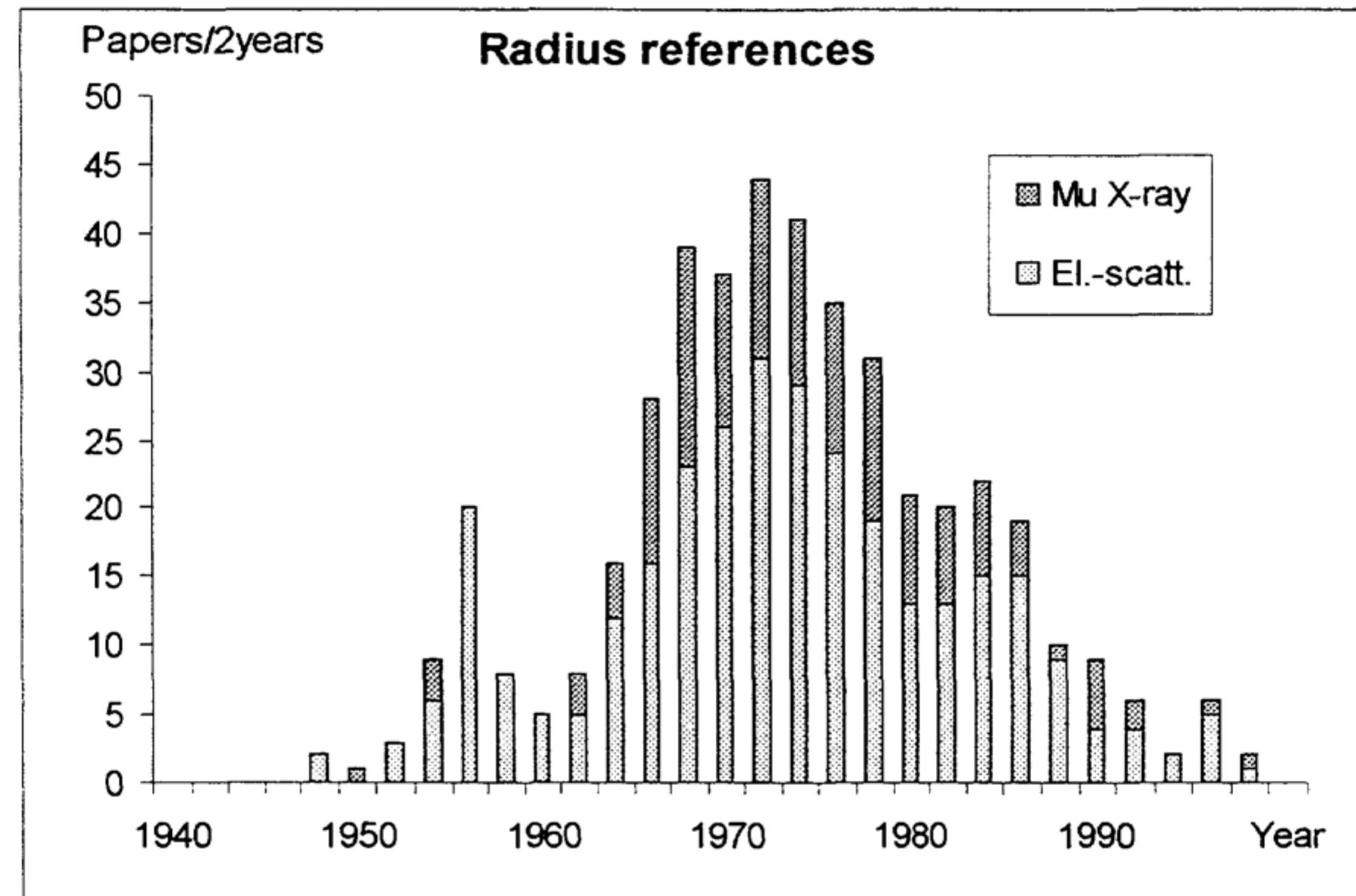
Assuming typically a 2-parameters Fermi

$$\rho(r) = \rho_0 \left(1 + e^{4 \ln 3 \frac{r-c}{t}} \right)^{-1}$$

Charge distribution model dependent charge radii!!

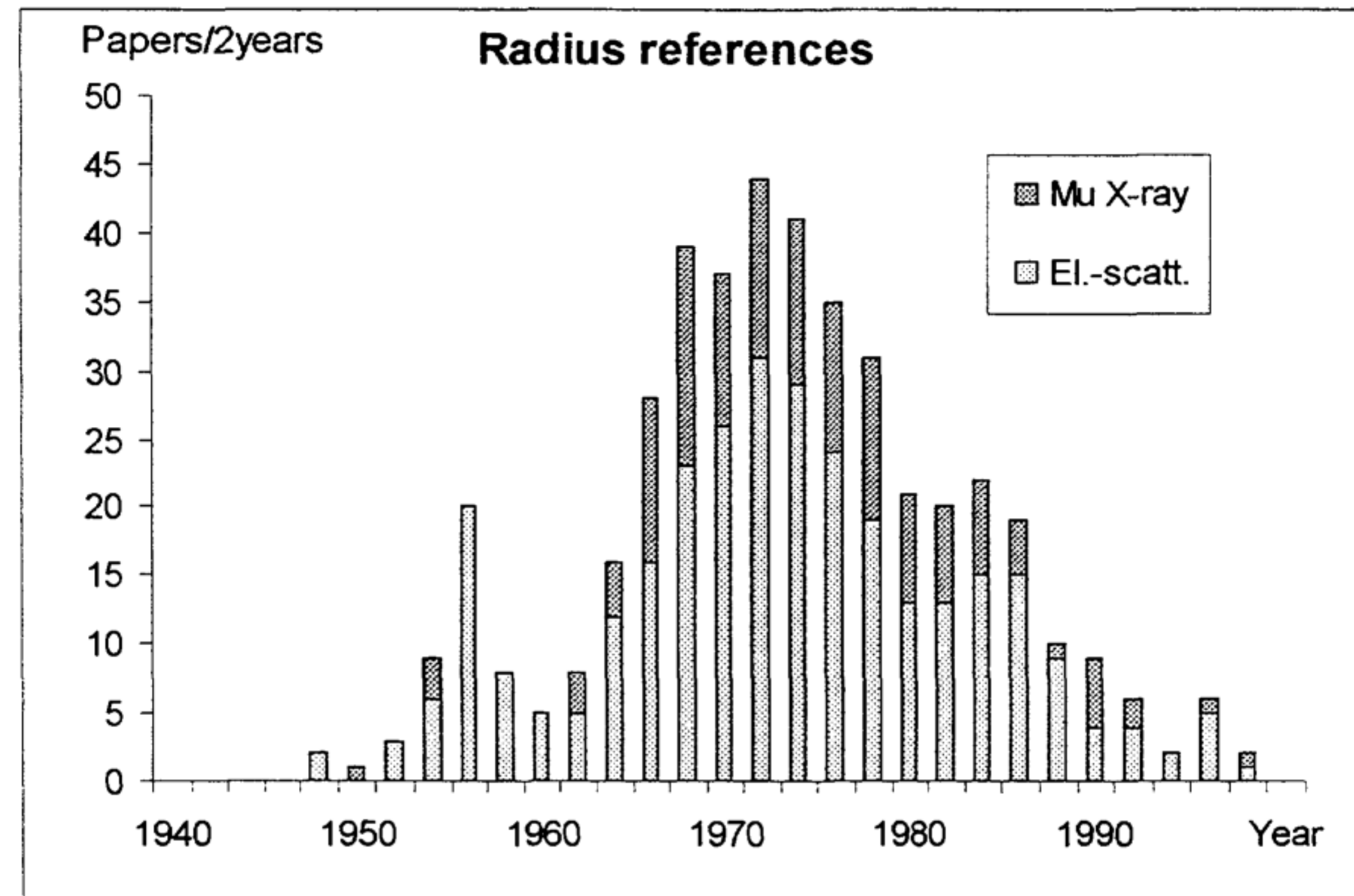
$\rightarrow$ combine with e⁻ scattering data (exp) or energy density functionals (theory) to get the shape correction

A technique used heavily in the past..



[Angeli, I., & International Atomic Energy Agency, International Nuclear Data Committee, Vienna \(Austria\). \(1999\). Table of nuclear root mean square charge radii.](#)

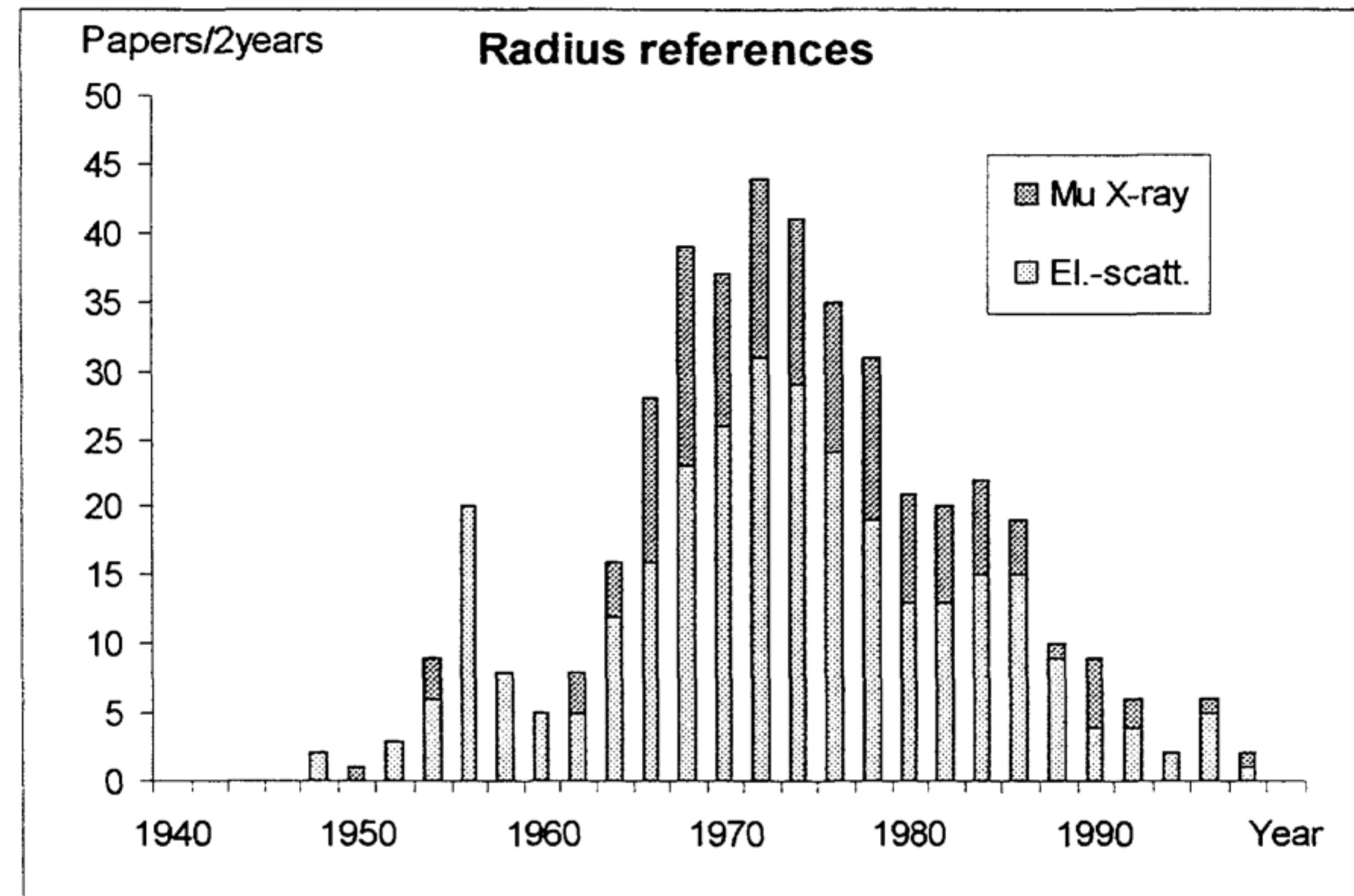
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Reevaluate some charge radii.

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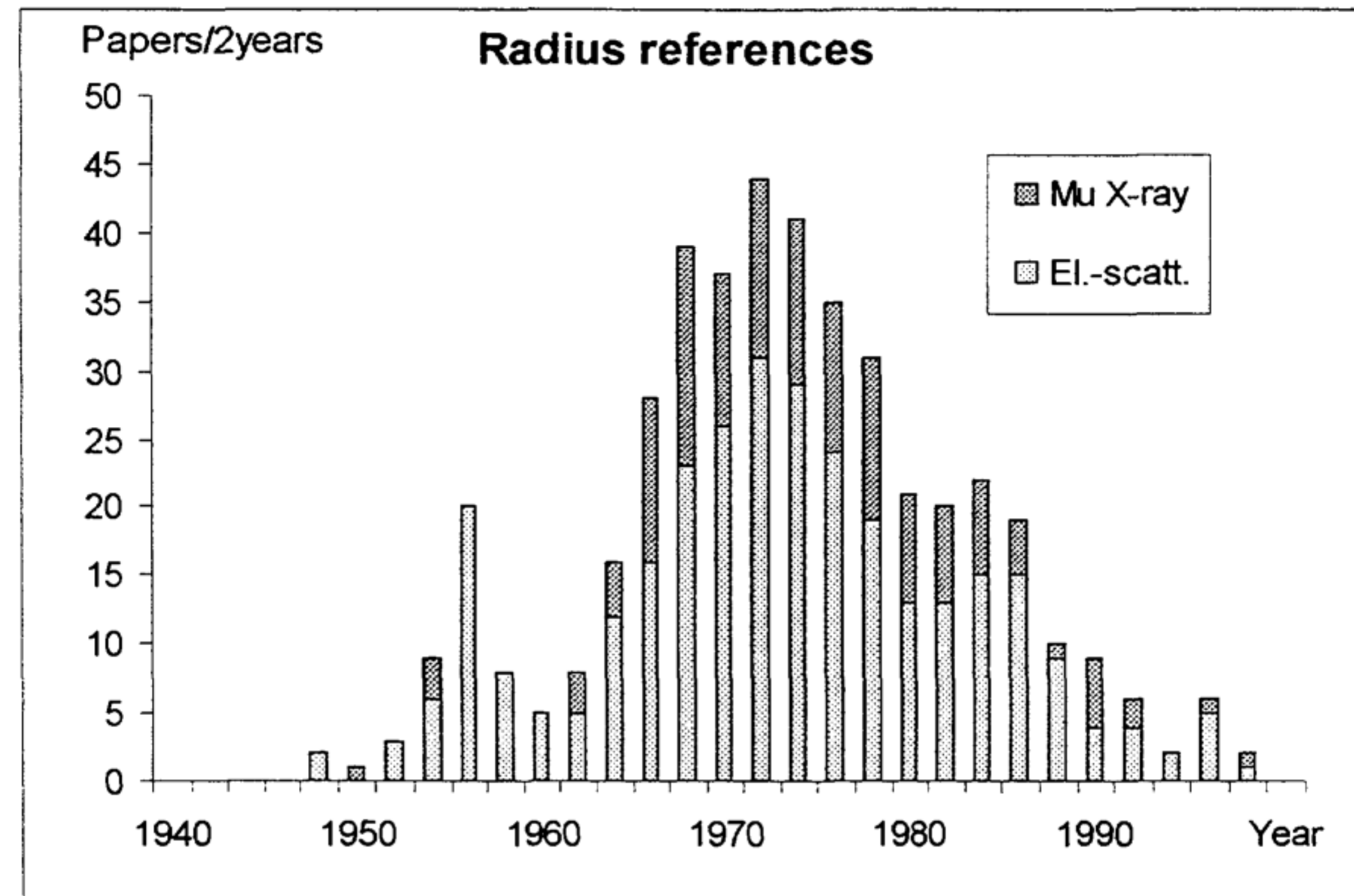


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Reevaluate some charge radii.

Extending measurements to rare and radioactive targets.

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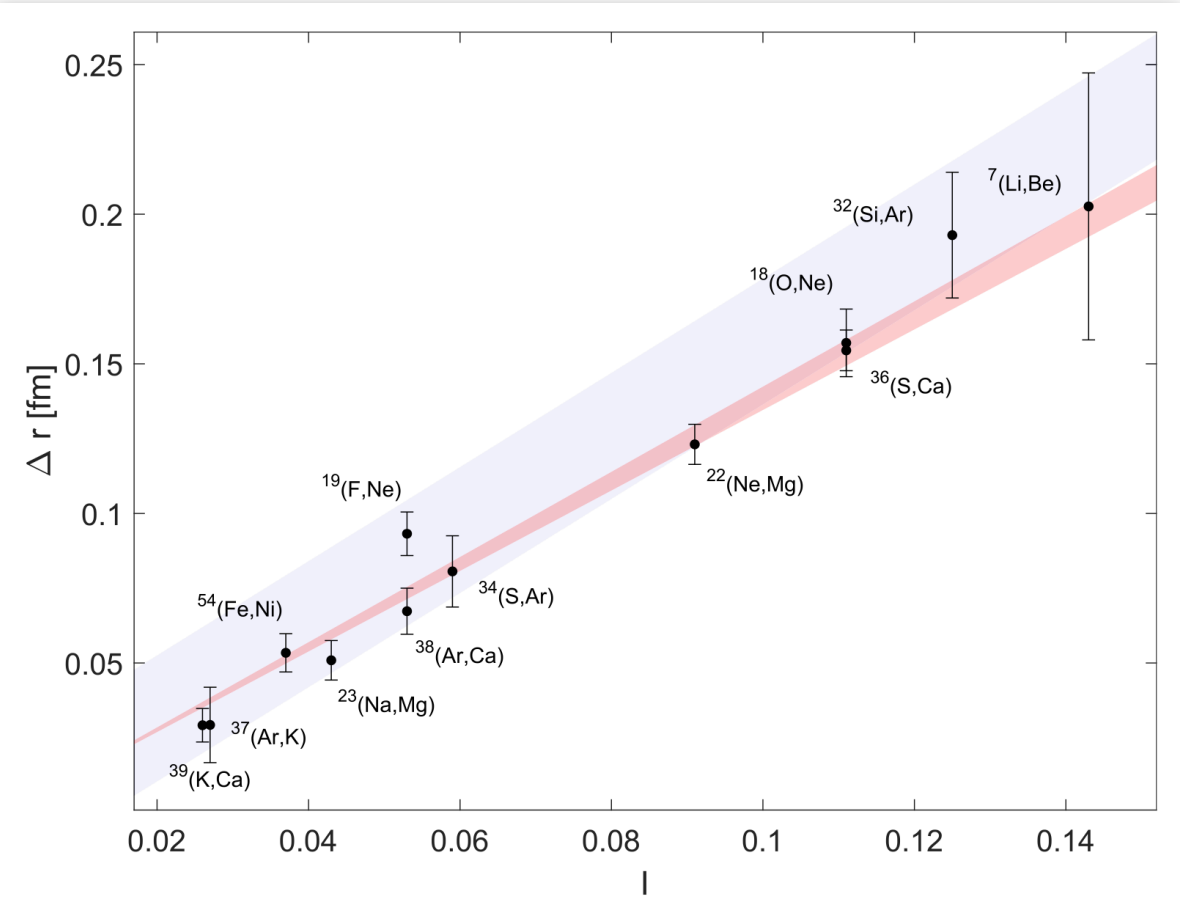
Down to a few
microgram
targets!!!

Reevaluate some charge radii.

Extending measurements to rare and radioactive targets.

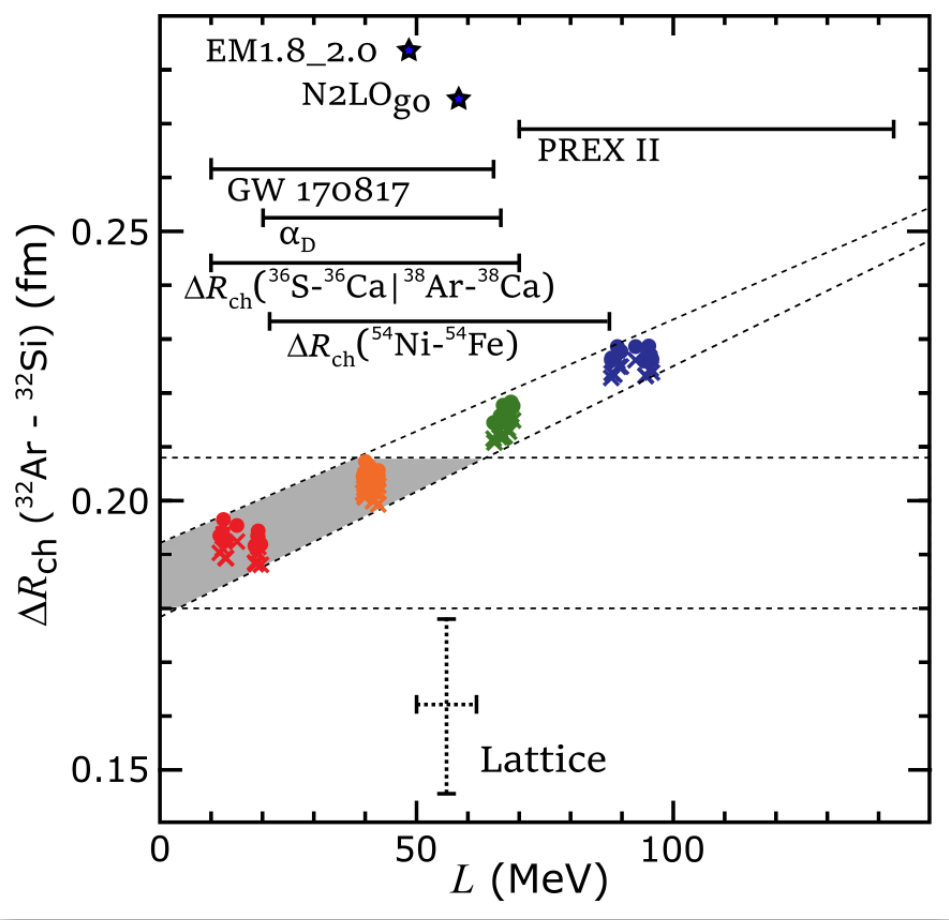
Links to fundamental physics

B. Ohayon, Atomic Data and Nuclear Data Tables 165, 101732 (2025)



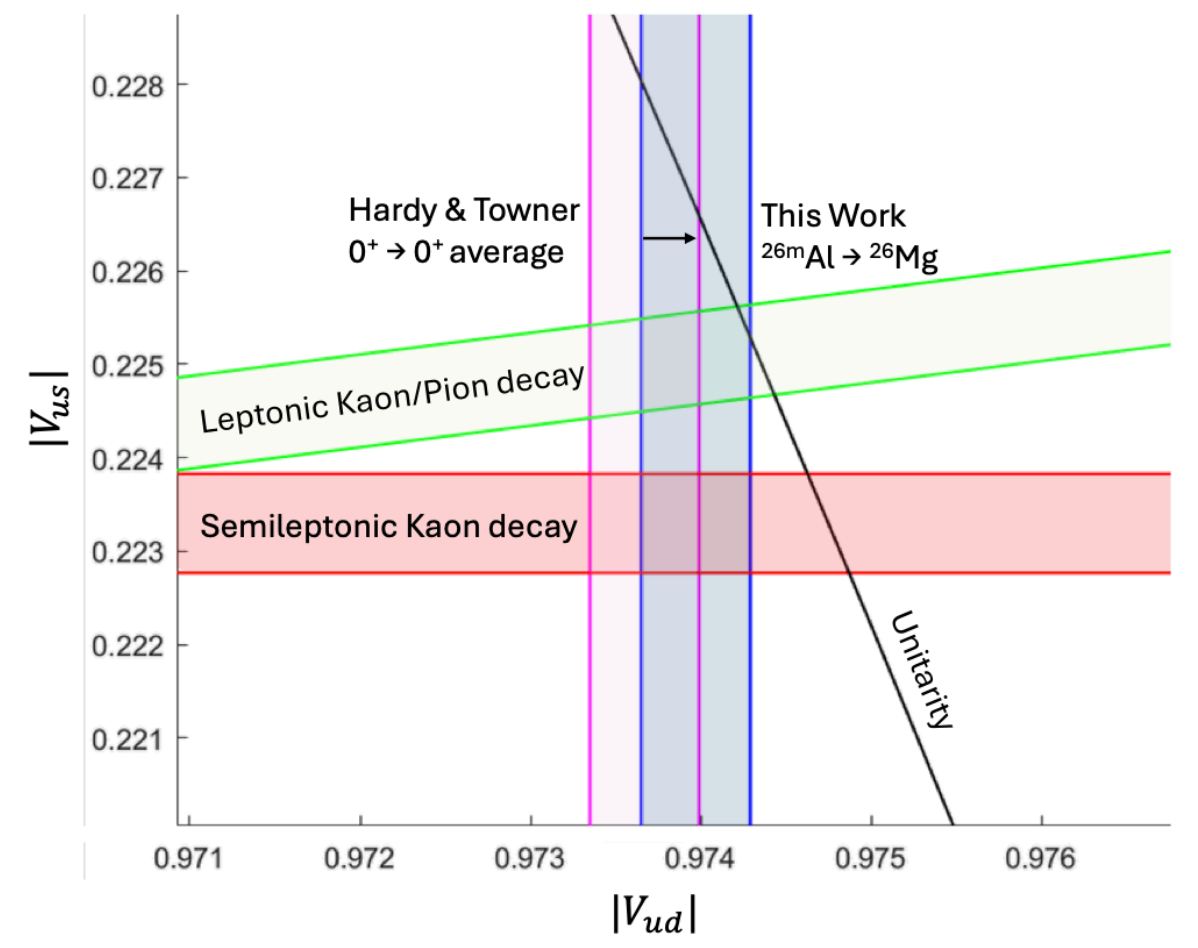
Constraint the mirror nuclei fit

K. König et al., Phys. Rev. Lett.132, 162502 (2024)



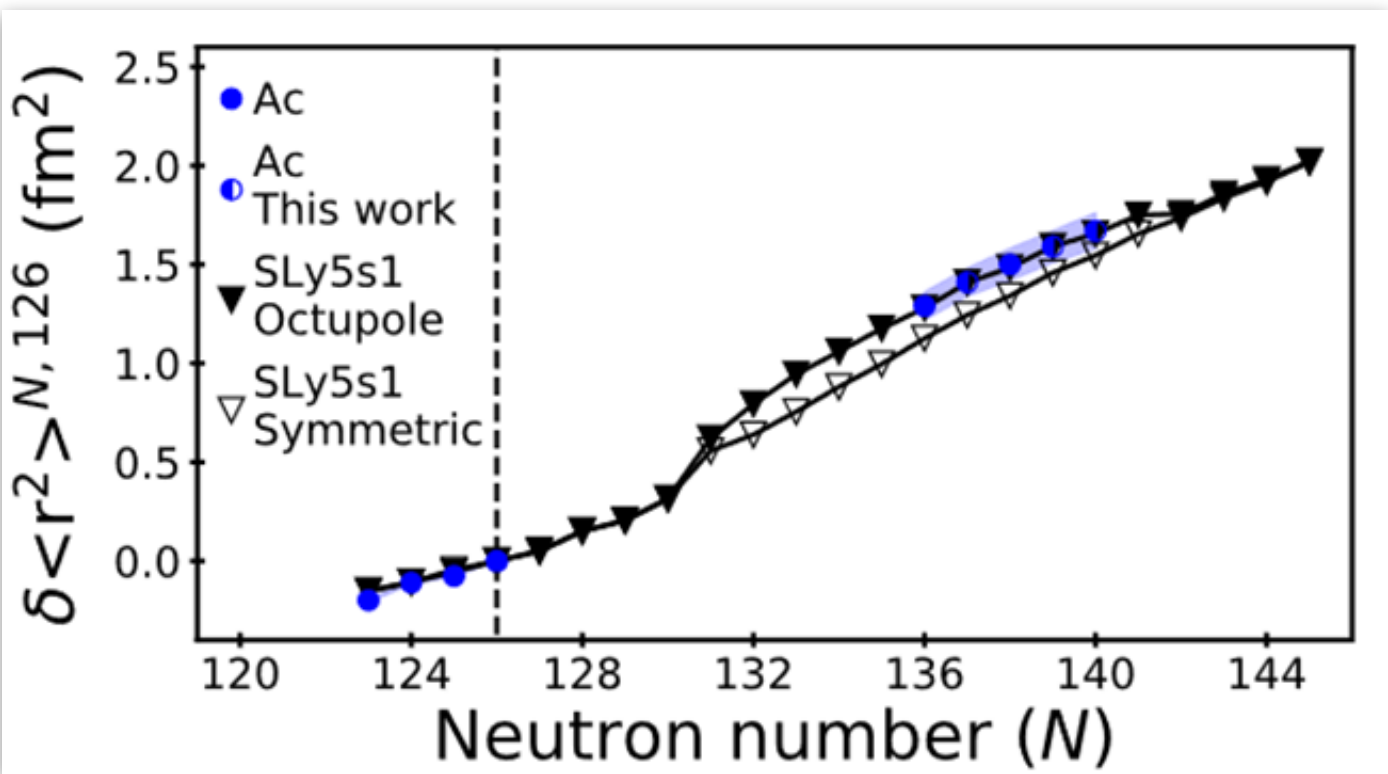
Input on neutron matter equation of state by constraining the slope of symmetry energy

M. Gorchtein et al., arXiv:2502.17070, (2025)



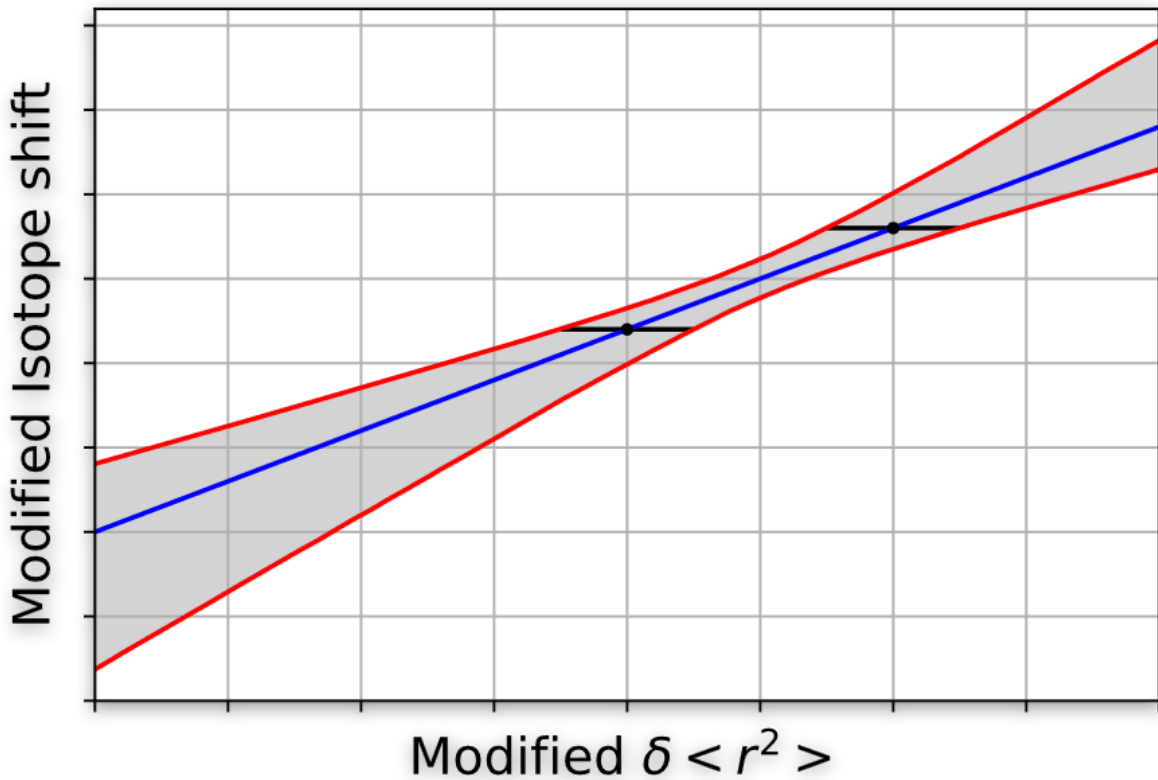
Probing $|V_{ud}|$ and testing the CKM matrix unitarity

PRC 100, 044321 (2019)



Probing octuple deformed nuclei, where atomic parity violating effects are enhanced

Figure Courtesy of M. Heines



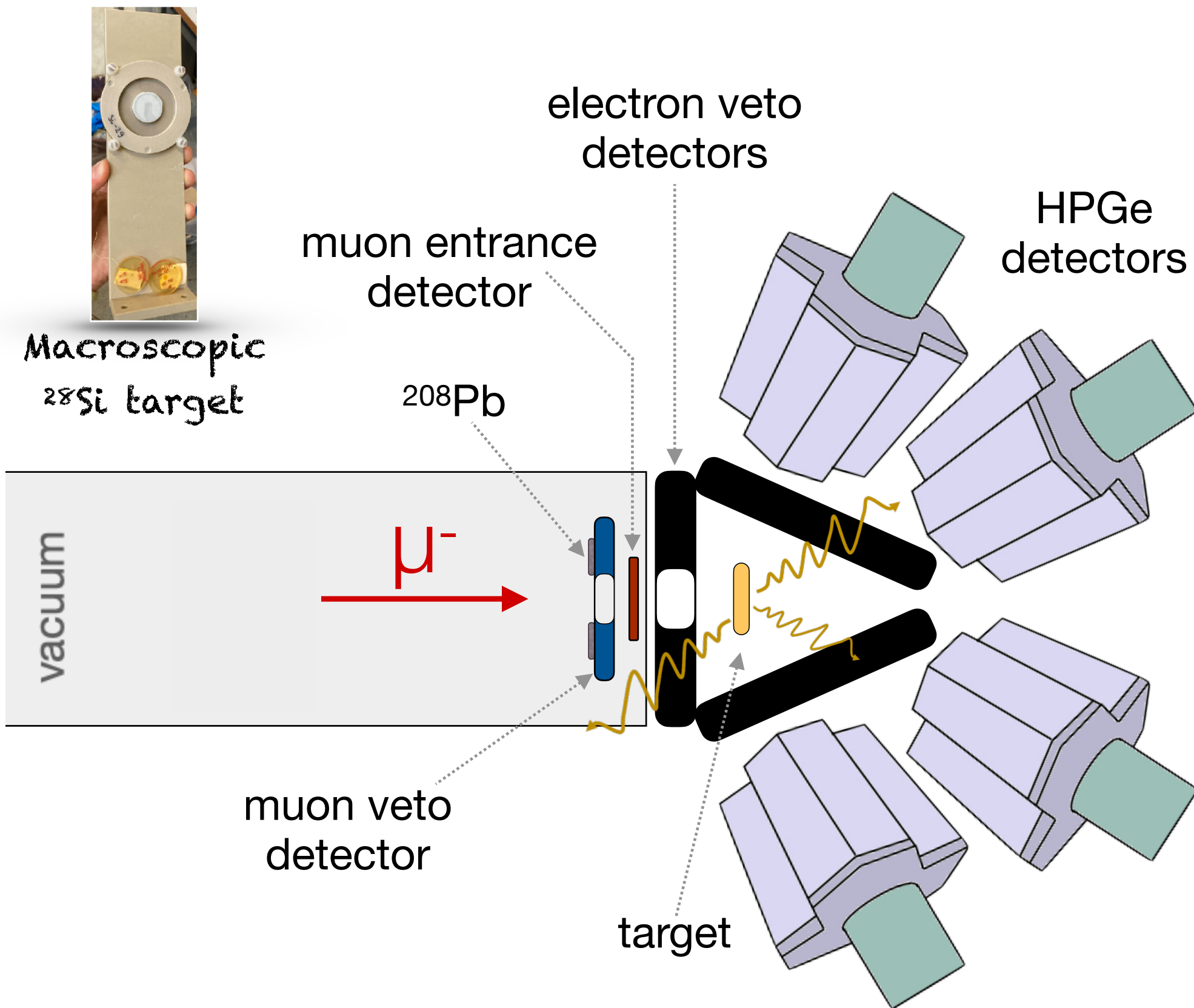
Benchmark laser spectroscopy results & challenge state-of-art nuclear models

High Intensity Proton
Accelerator (HIPA) facility at Paul
Scherrer Institute



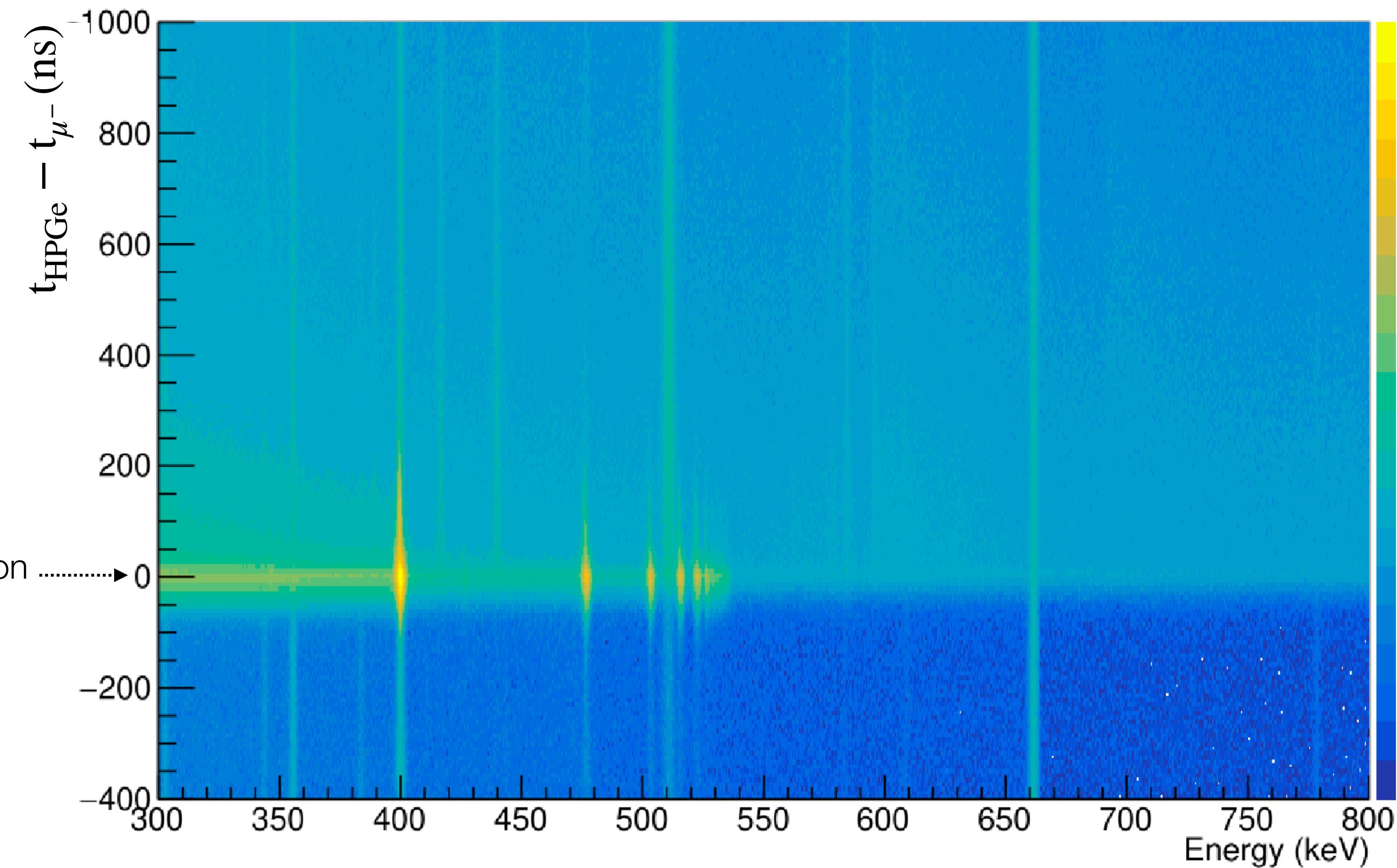
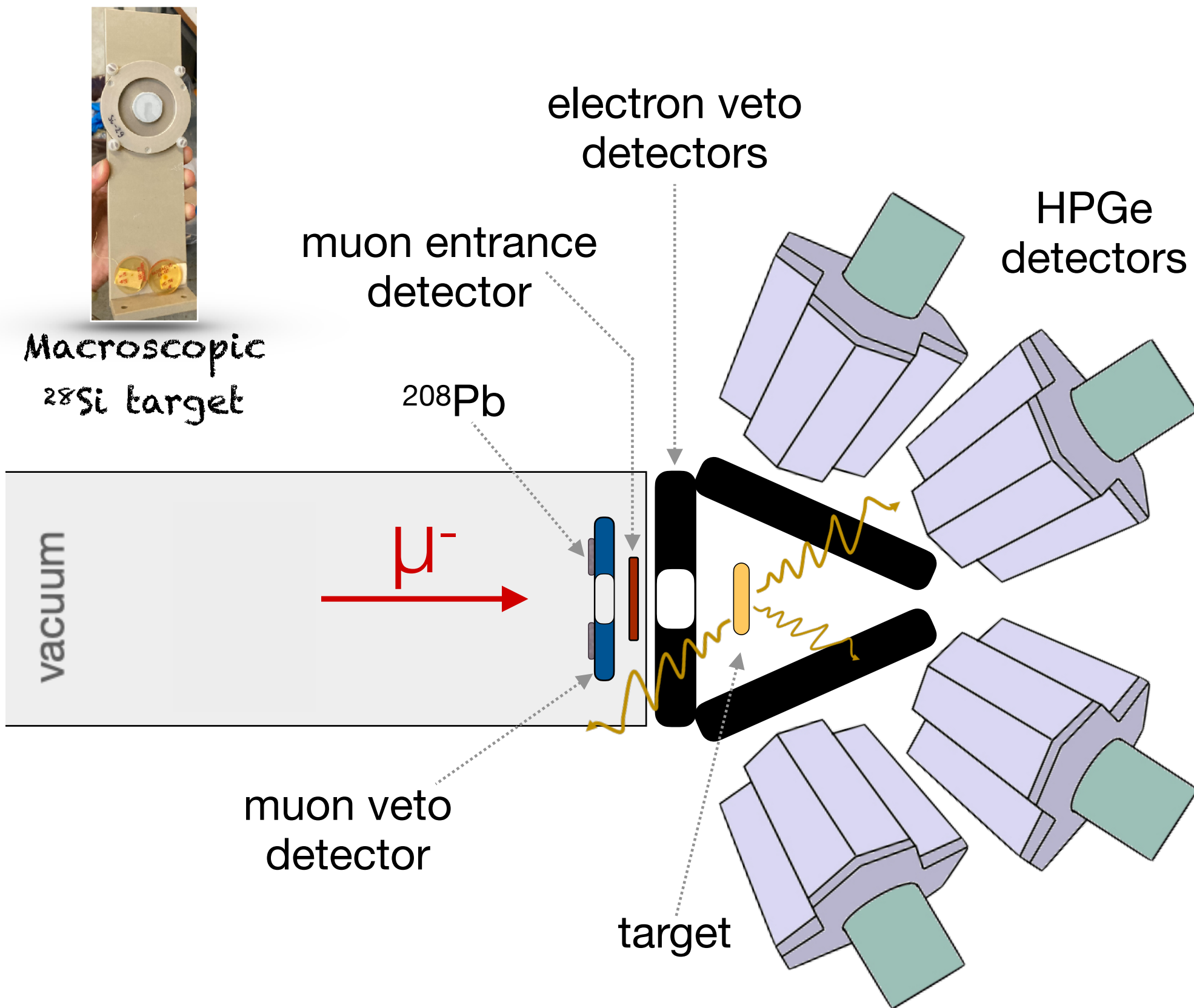
Detection system

Muon-time correlated analysis



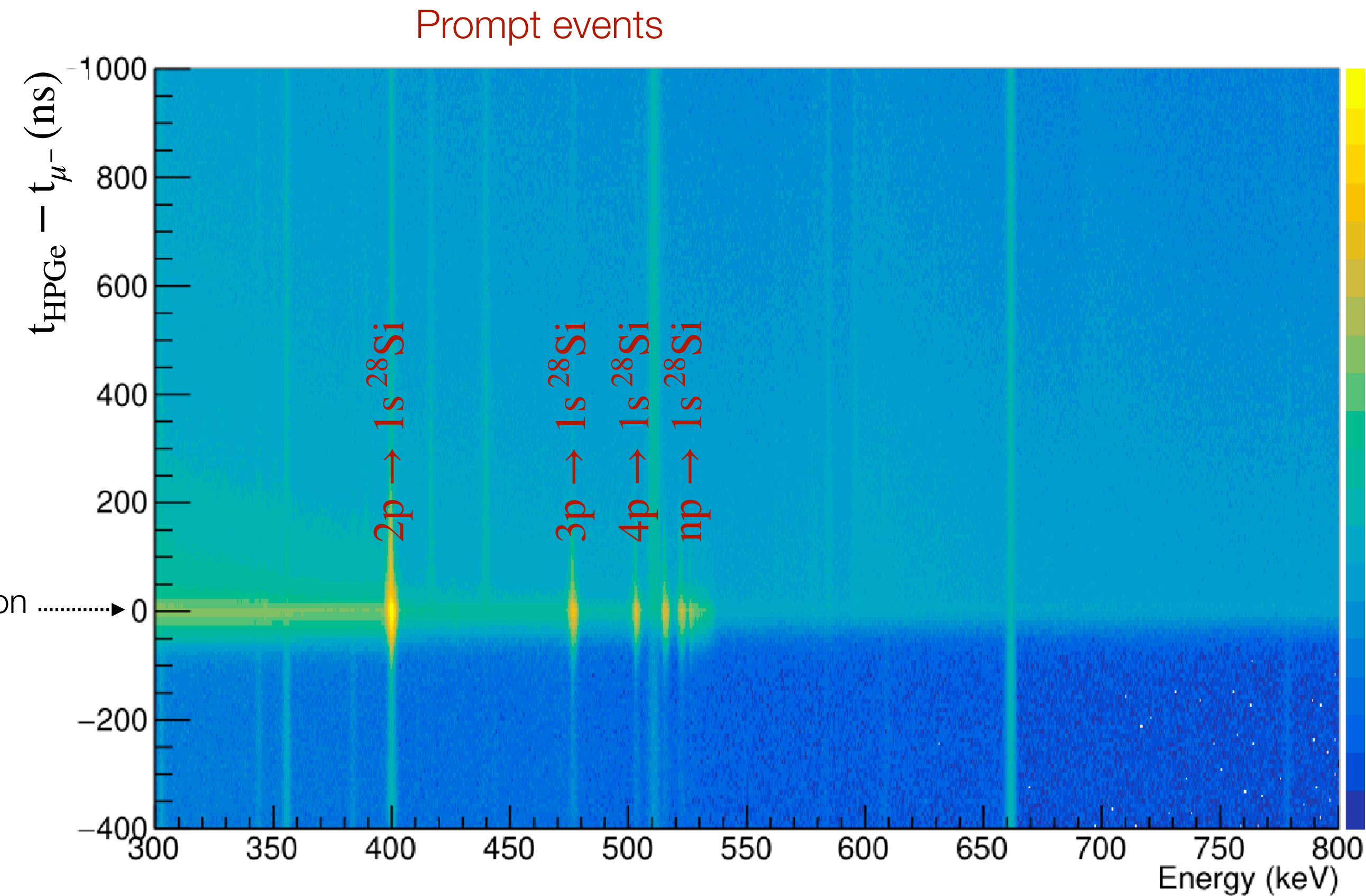
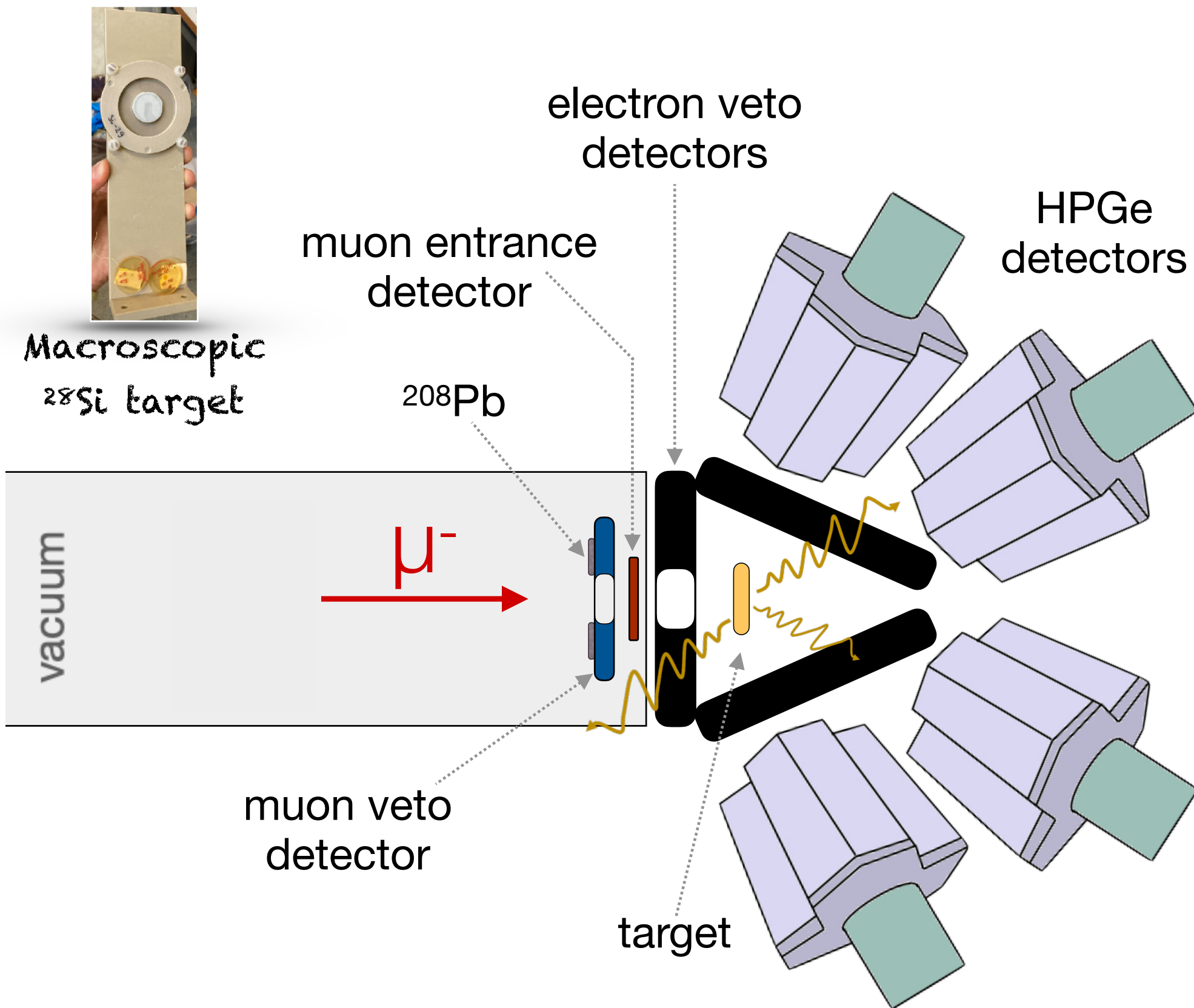
Detection system

Muon-time correlated analysis



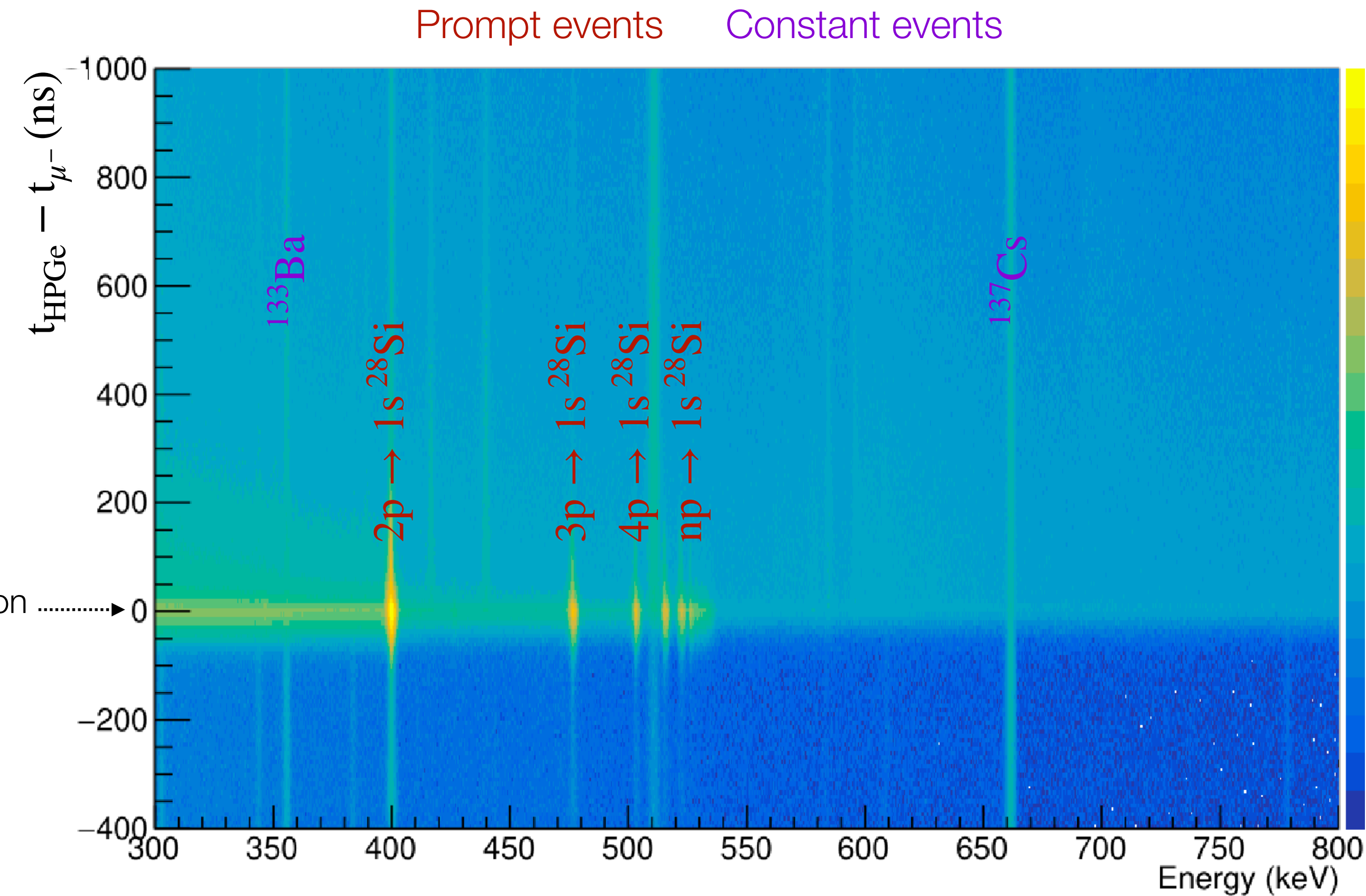
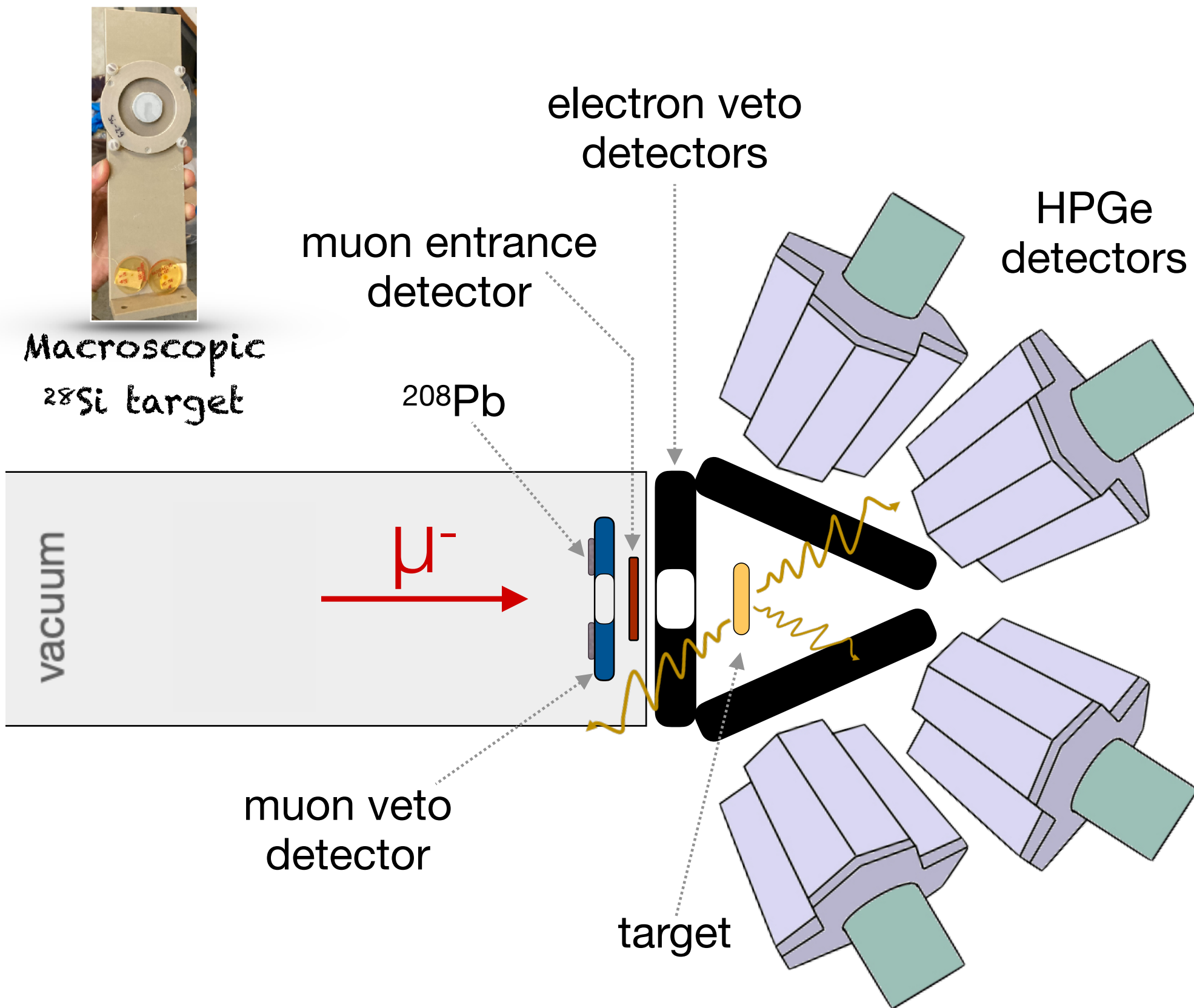
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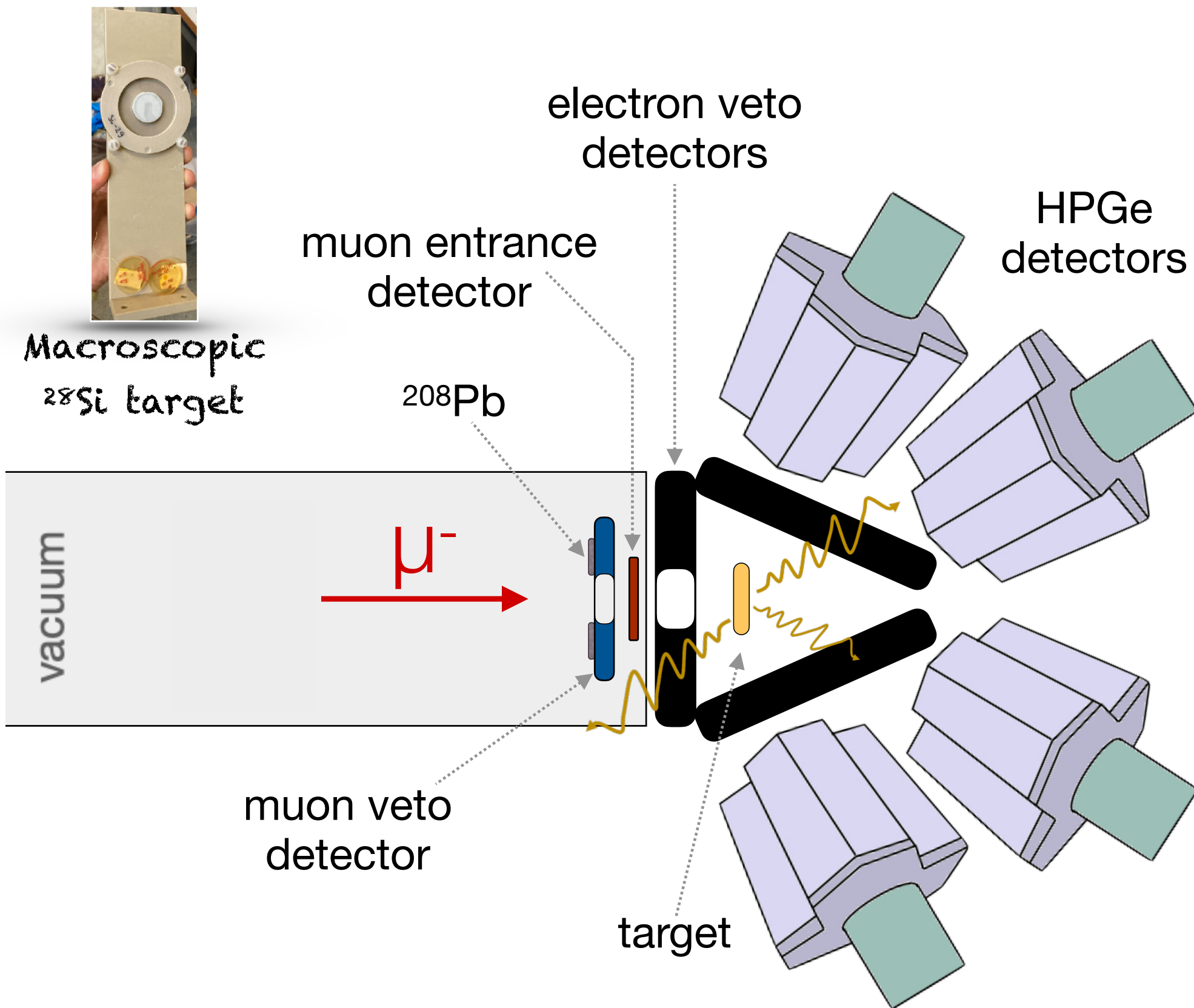
Detection system

Muon-time correlated analysis

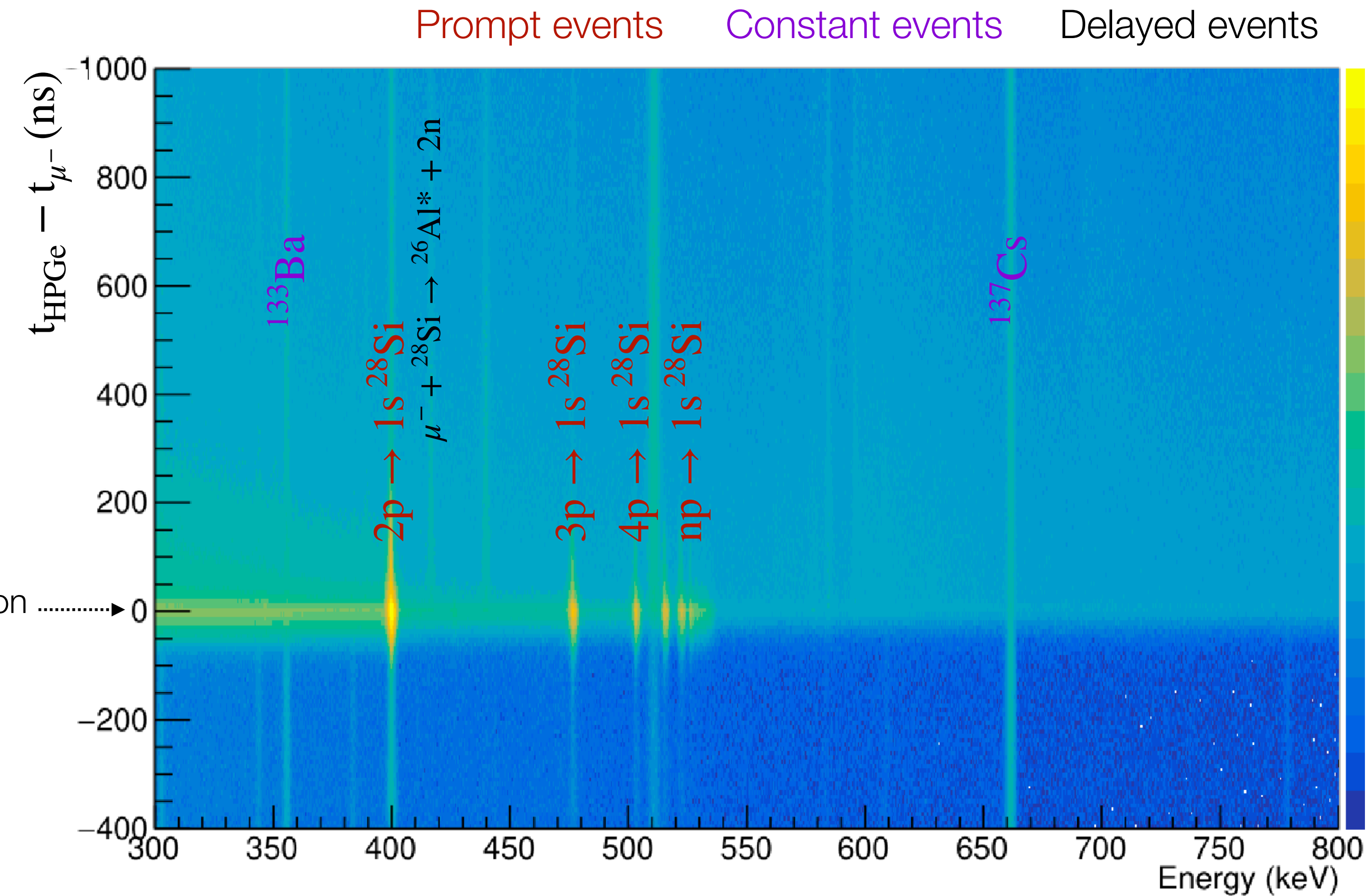


Detection system

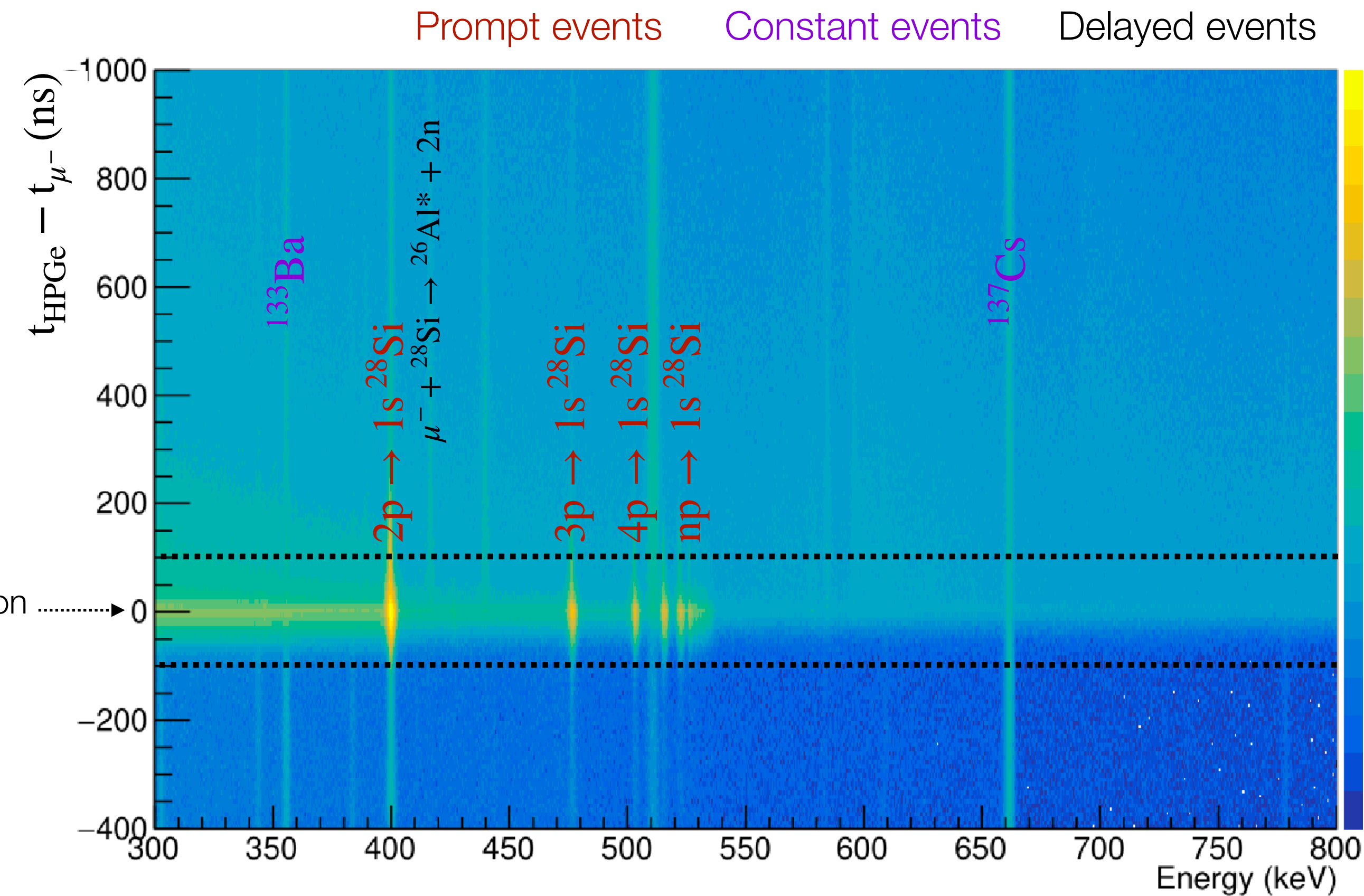
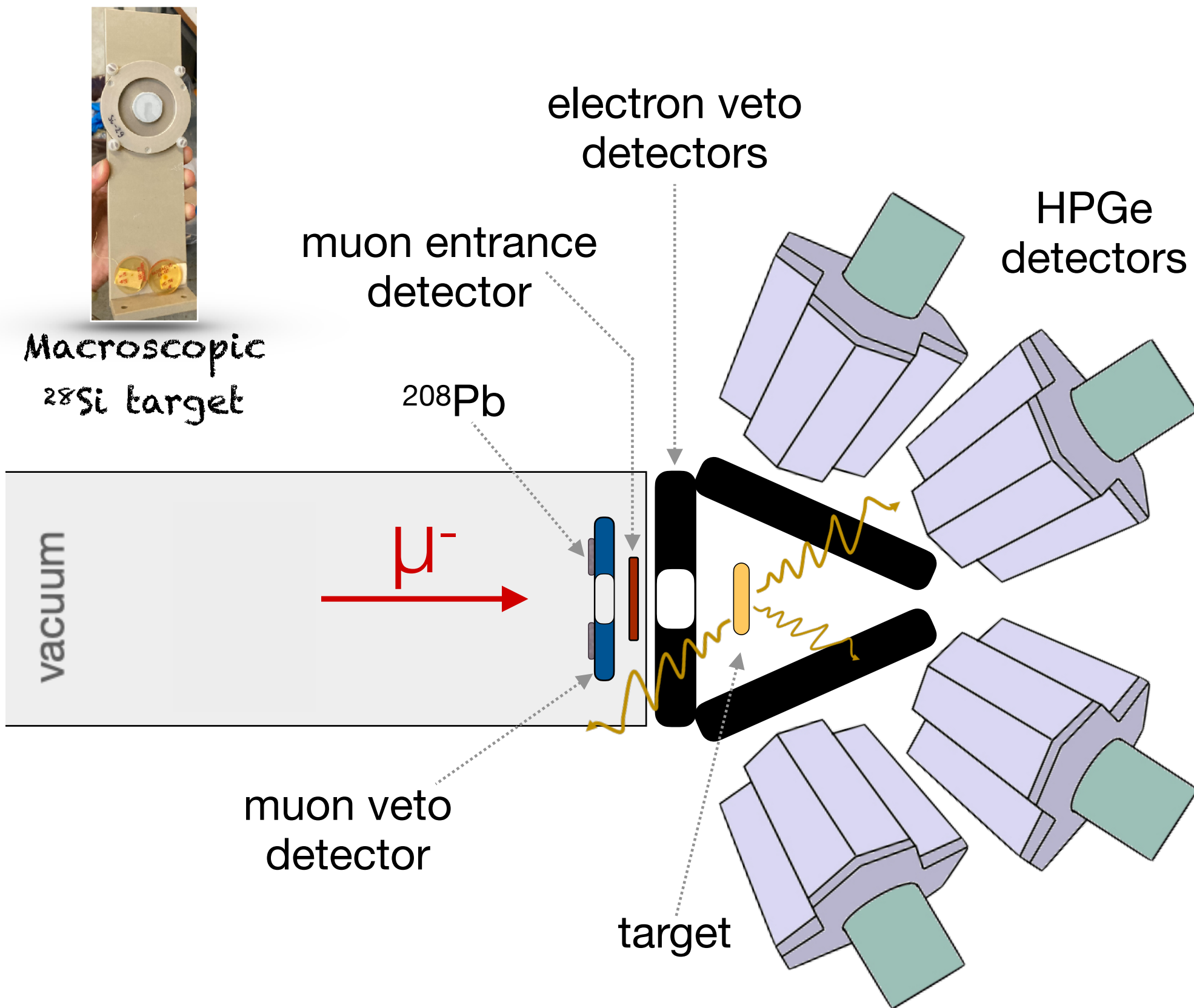
Muon-time correlated analysis



Time of the muon
impinging on
target



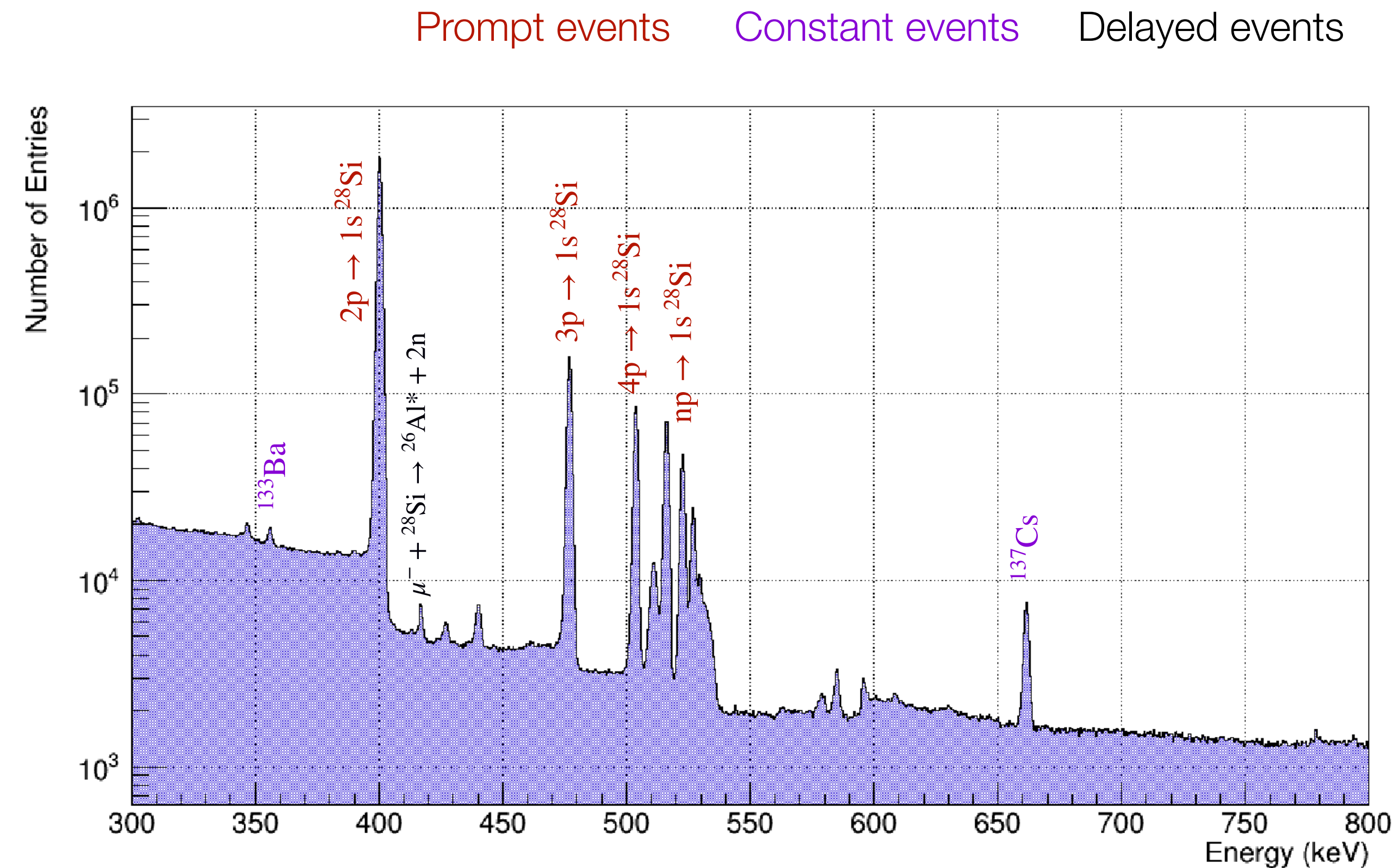
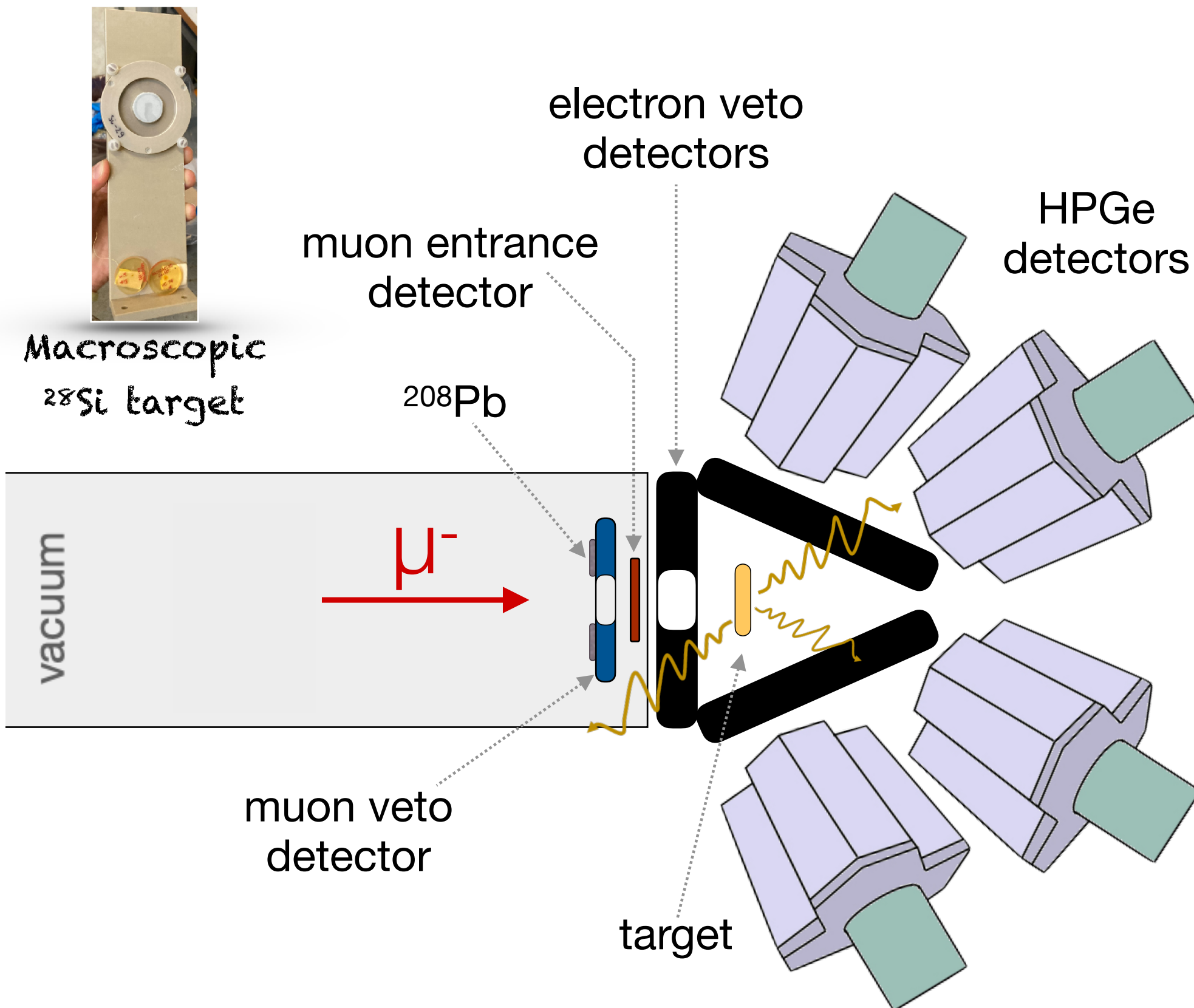
Muon-time correlated analysis



Detection system

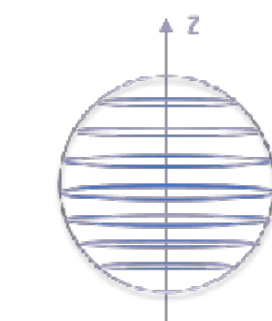
Muon-time correlated analysis

After ELET : $\text{FWHM}_{\text{dt}} \sim 14 \text{ nsec}$

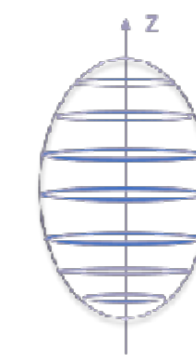


$^{185,187}\text{Re}$ 5g4f analysis

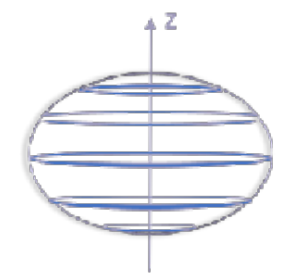
Spectroscopic quadrupole moment



Spherical
 $Q = 0$



Prolate
 $Q > 0$



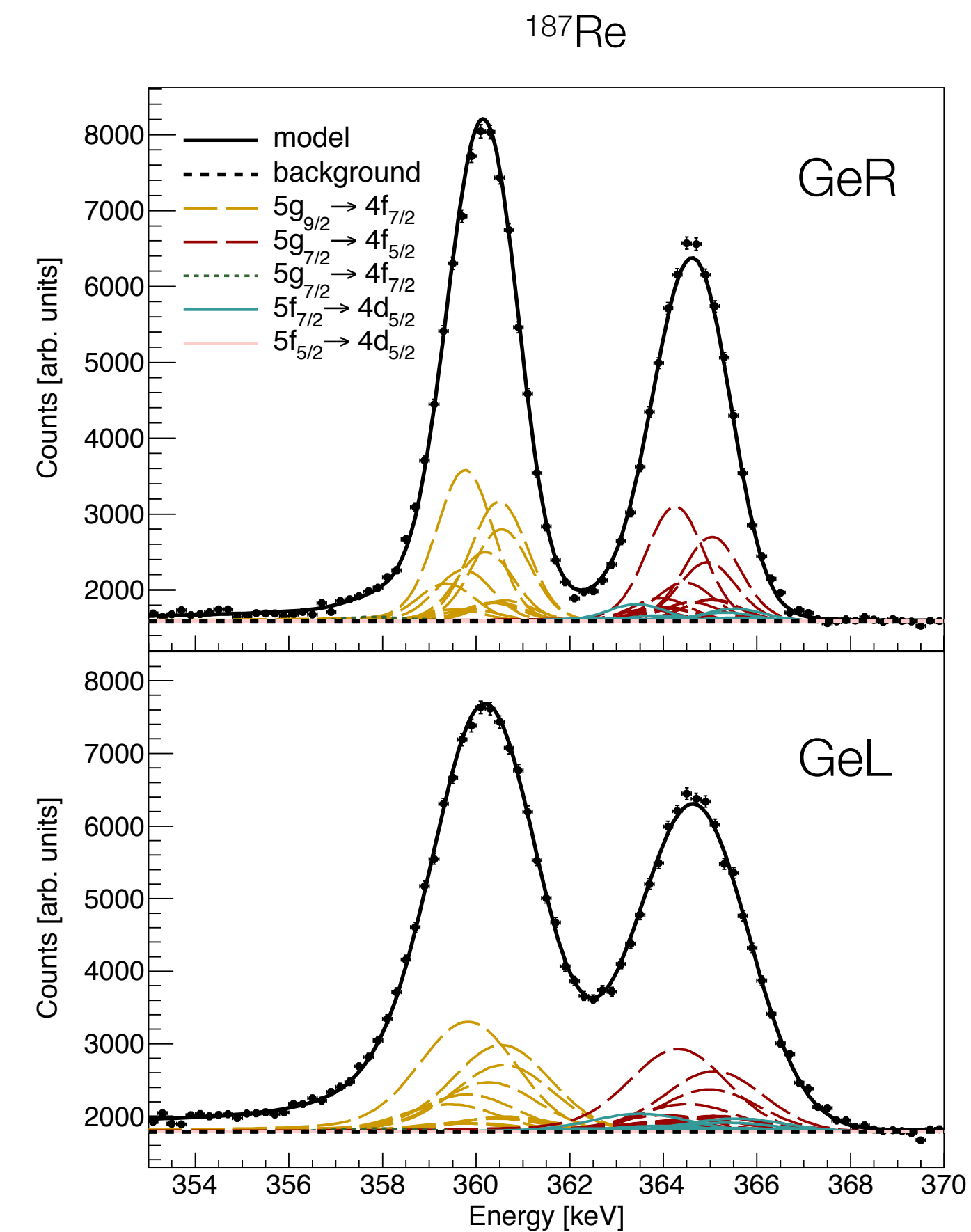
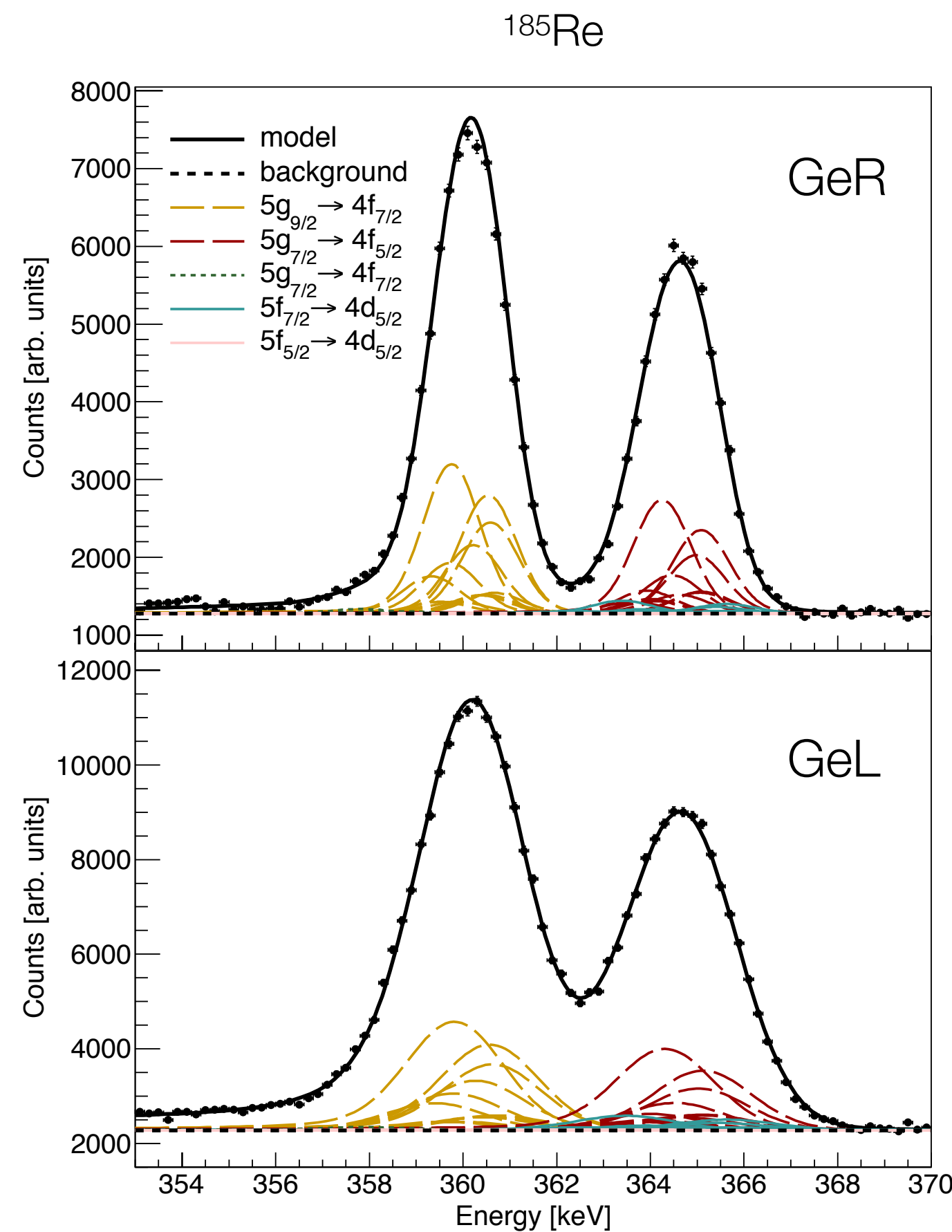
Oblate
 $Q < 0$

Our first physics
result

[Phys. Rev. C 101, 054313 \(2020\)](#)

$$Q(^{185}\text{Re}) = 2.07(5) \text{ b}$$

$$Q(^{187}\text{Re}) = 1.94(5) \text{ b}$$

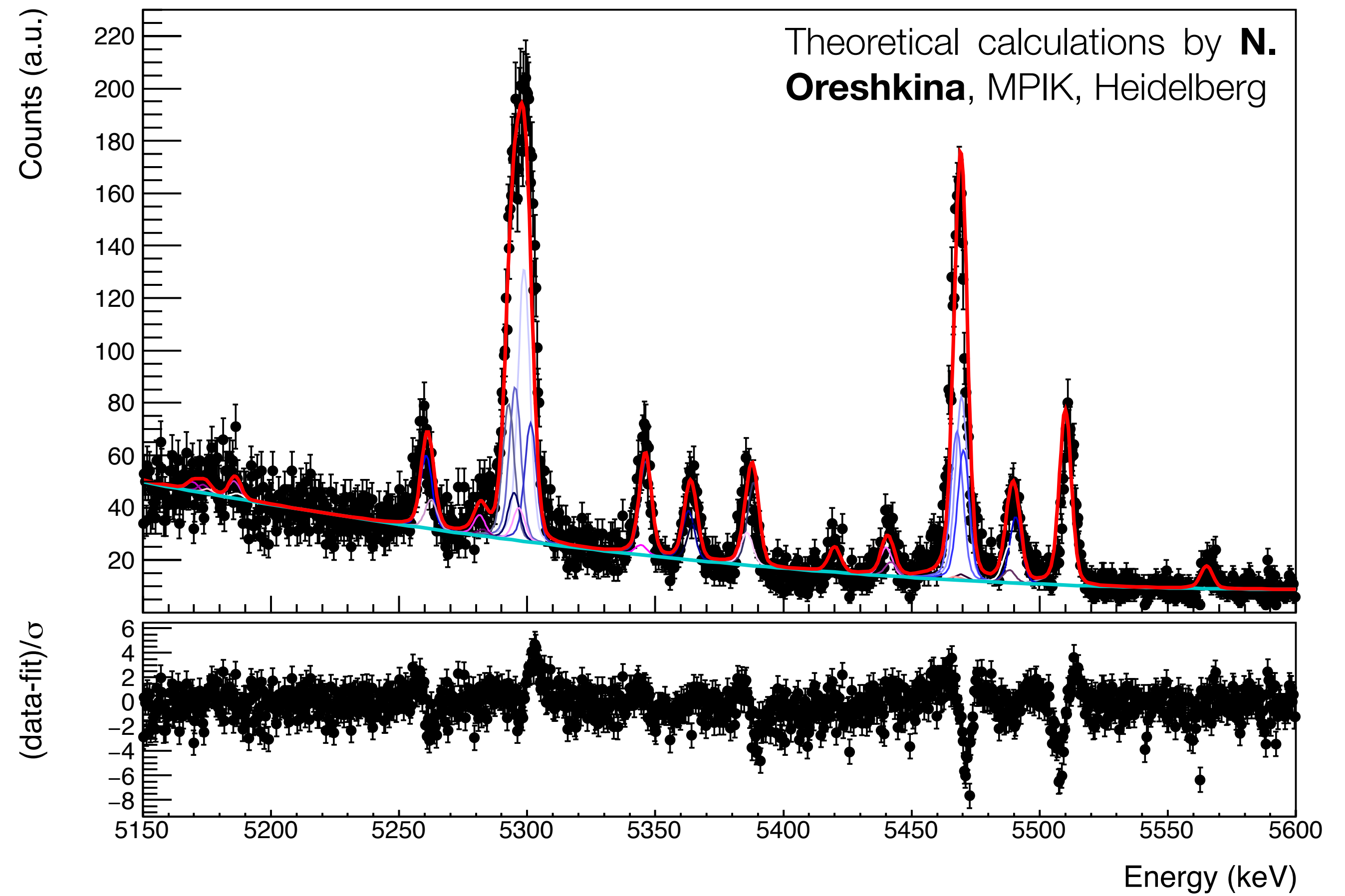


$^{185,187}\text{Re}$ 2p1s analysis

Outlook: Nuclear charge radius

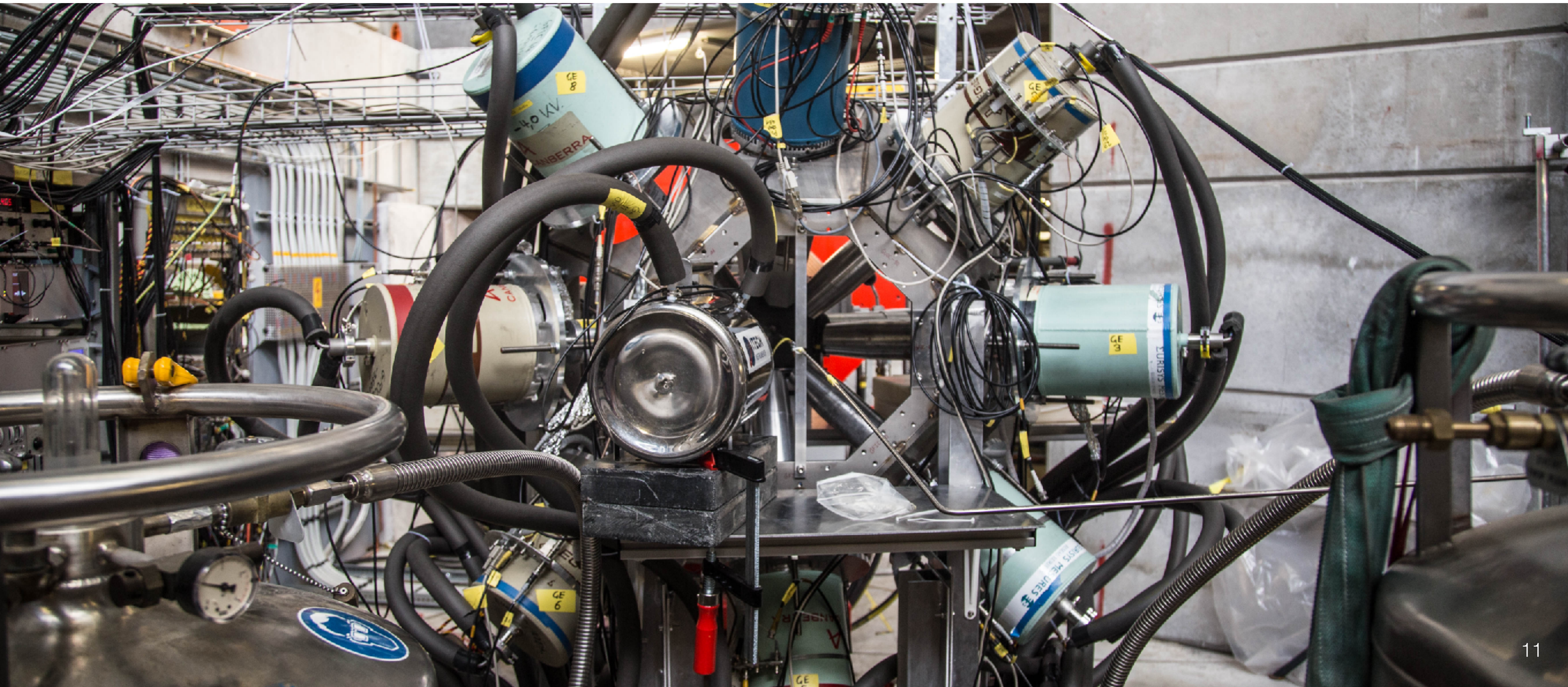
[PhD thesis of S. Vogiatzi](#)

- First time attempting to measure the last stable element with a non-measured absolute nuclear charge radius.
- Admixture of ground and excited hyperfine states due to the dynamic effect — very complicated muonic energy spectrum.



Experimental timeline

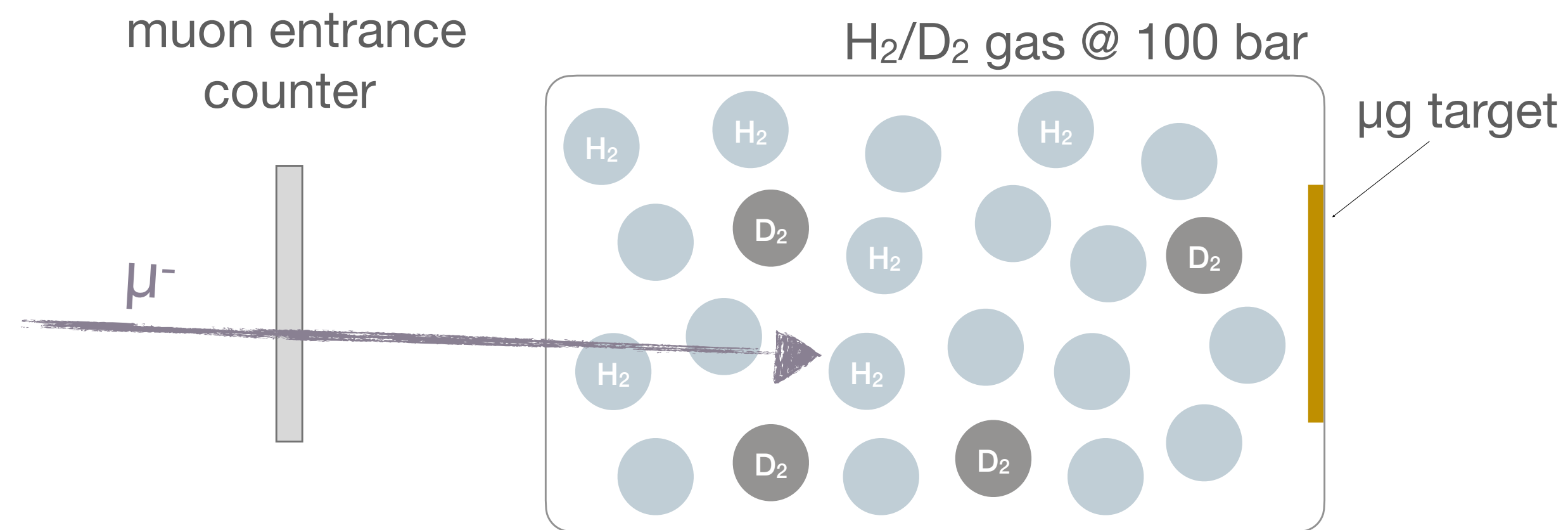
2017 — Towards microgram targets



Muon transfer to microgram targets

Developed by the muX collaboration [Eur. Phys. J. A 59, 15 \(2023\)](#)

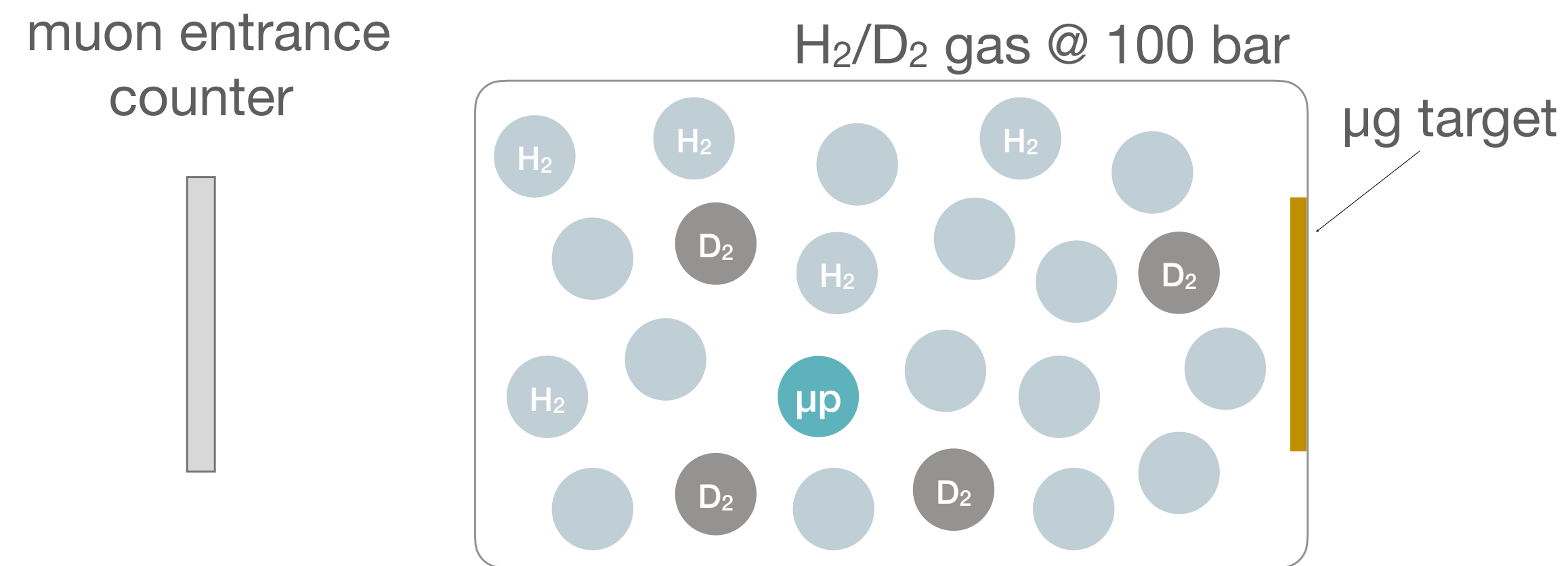
Inspired by the work of Strasser *et al.* and Kraiman *et al.*



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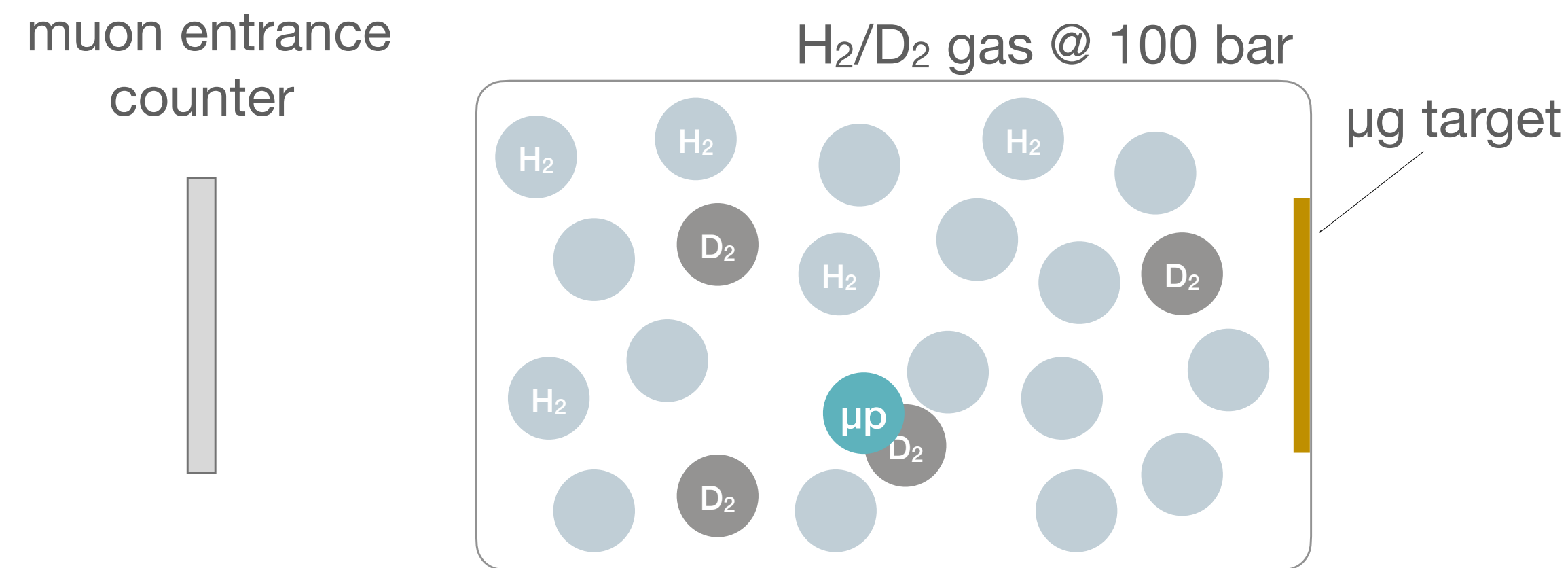


1. μ^- stops in 100 bar of H₂ + 0.25% D₂ & forms muonic hydrogen μp

Muon transfer to microgram targets

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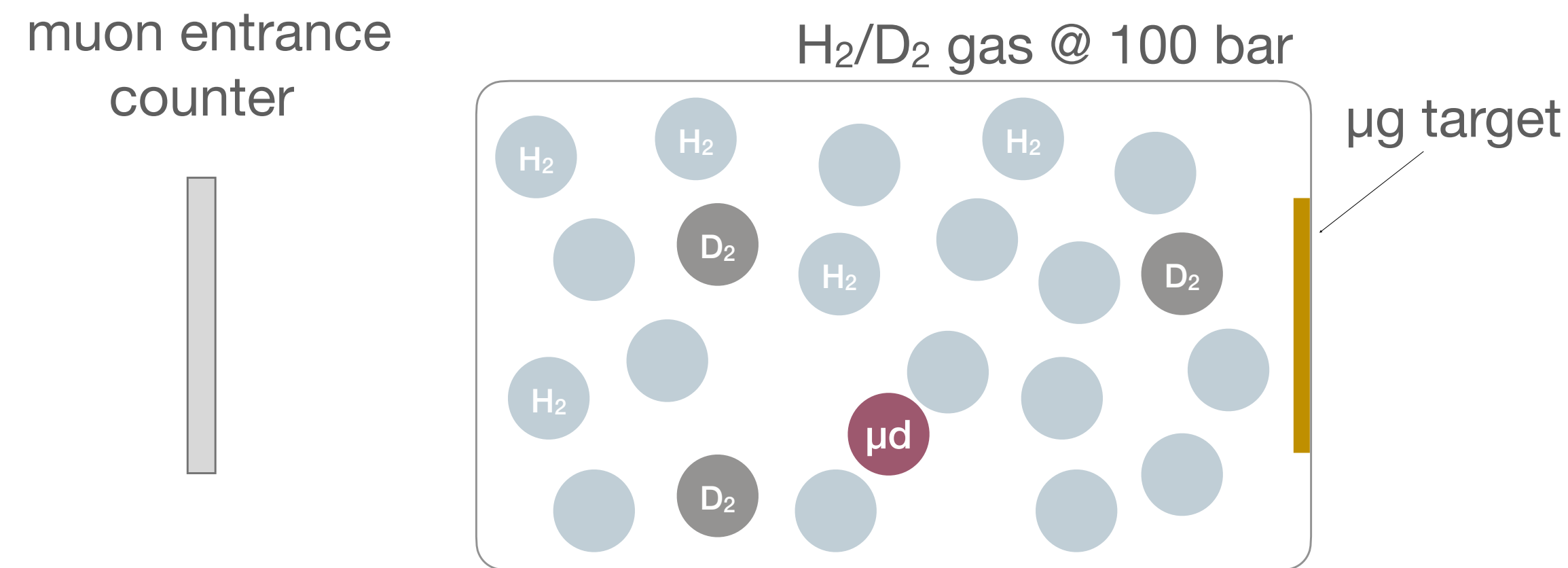


1. μ^- stops in 100 bar of H₂ + 0.25% D₂ & forms muonic hydrogen μp
2. transfer to deuterium $\mu p \rightarrow \mu d$

Muon transfer to microgram targets

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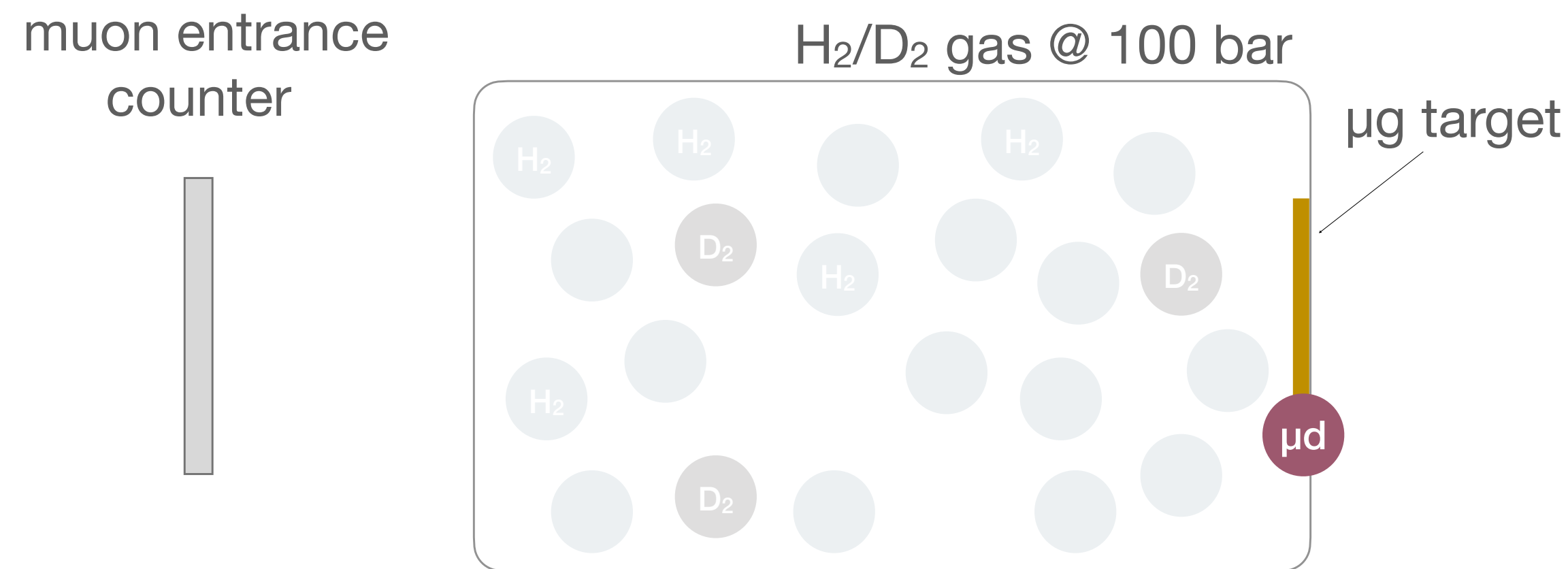


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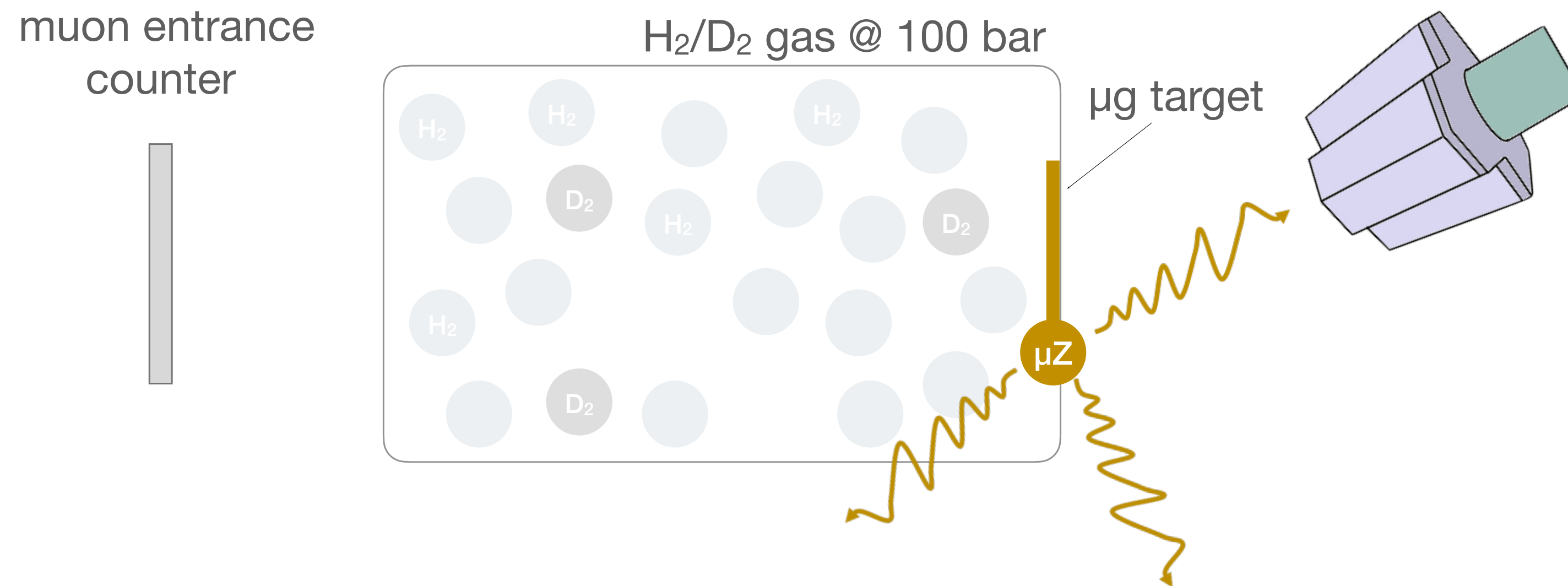


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2. transfer to deuterium $\mu\text{p} \rightarrow \mu\text{d}$
3. μd moves almost freely in the H_2 gas [Physical Review A 73, 034501 \(2006\)](#)

Muon transfer to microgram targets

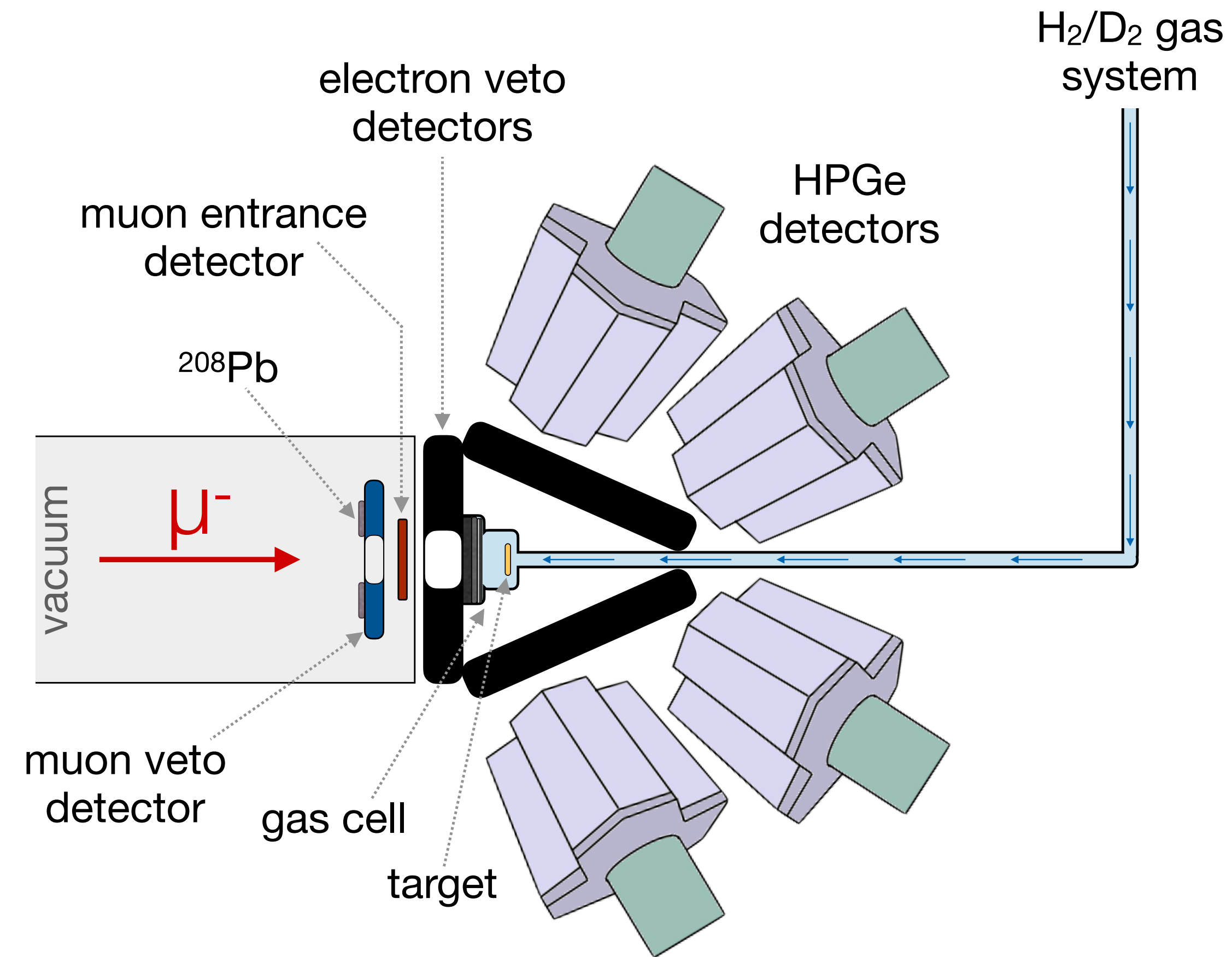
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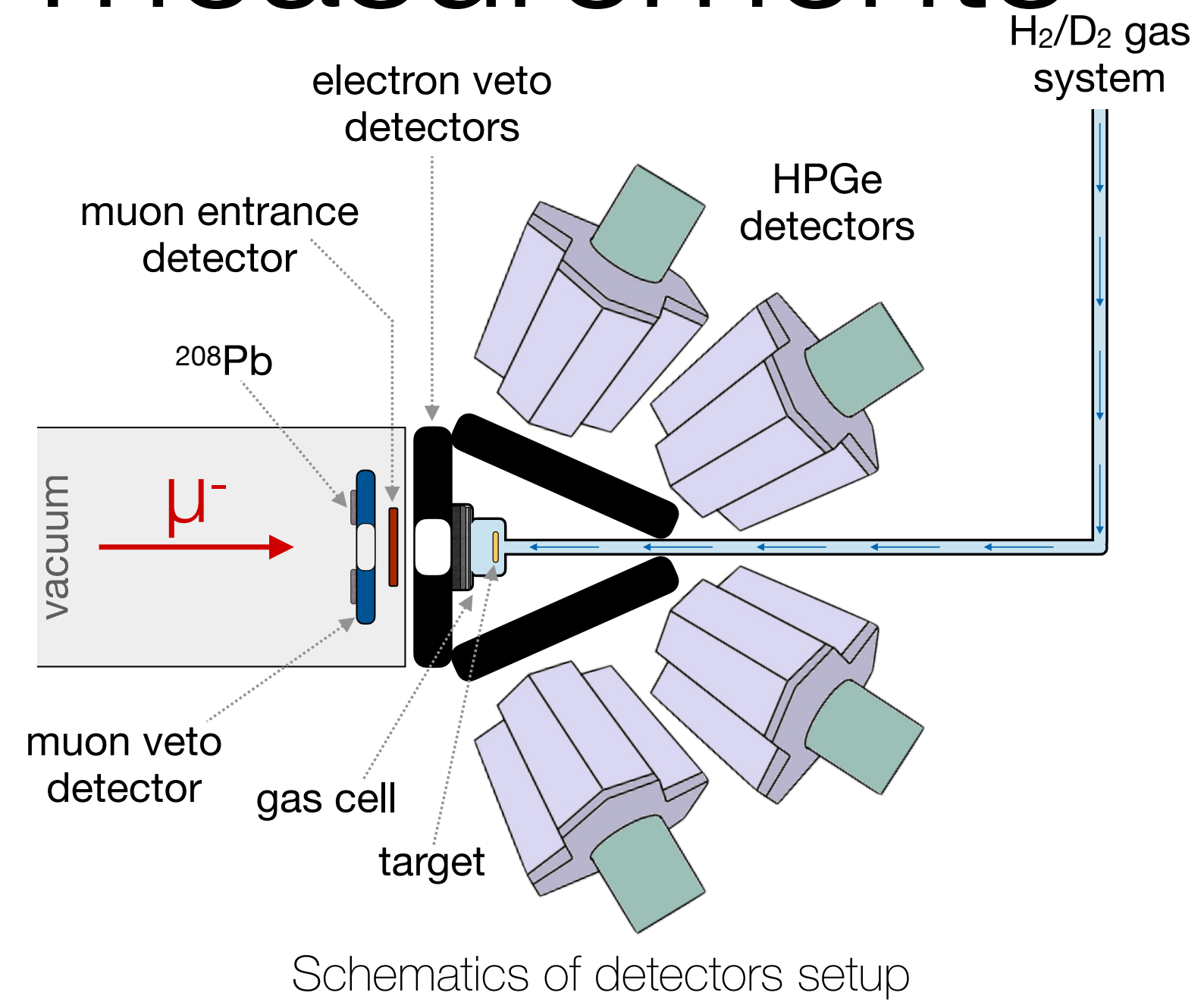


1. μ^- stops in 100 bar of H₂ + 0.25% D₂ & forms muonic hydrogen μp
2. transfer to deuterium $\mu p \rightarrow \mu d$
3. μd moves almost freely in the H₂ gas [Physical Review A 73, 034501 \(2006\)](#)
4. transfer to high-Z element $\mu d \rightarrow \mu Z$ when hitting target & emission of x rays during the atomic cascade

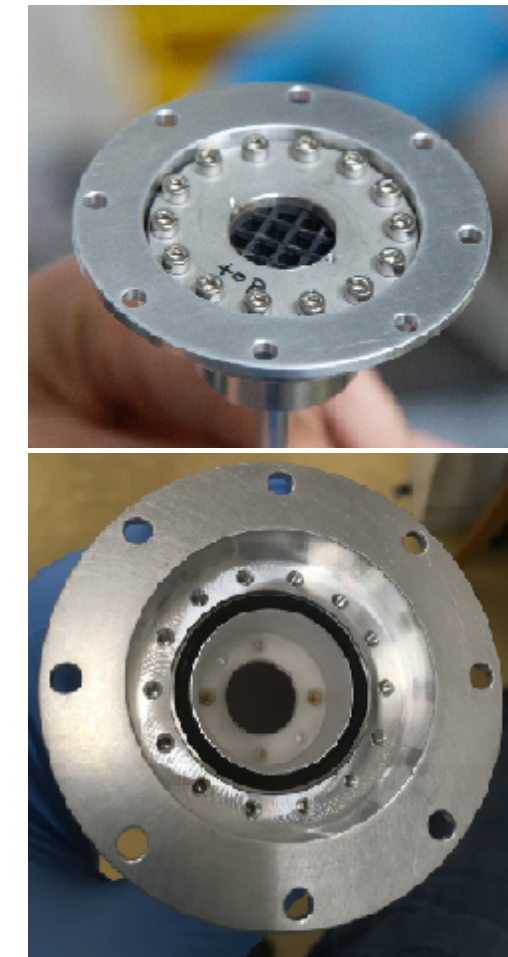
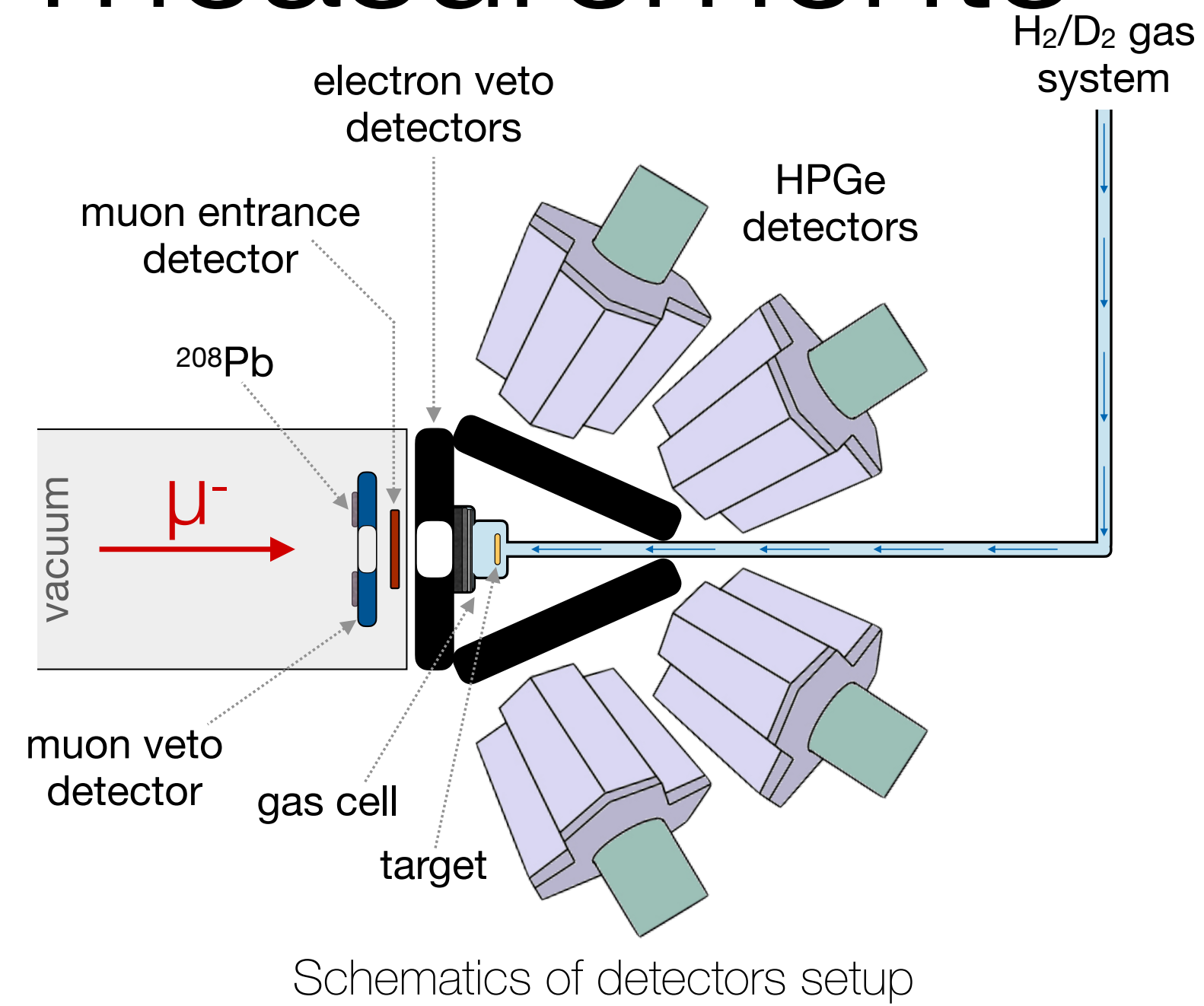
Gas cell measurements



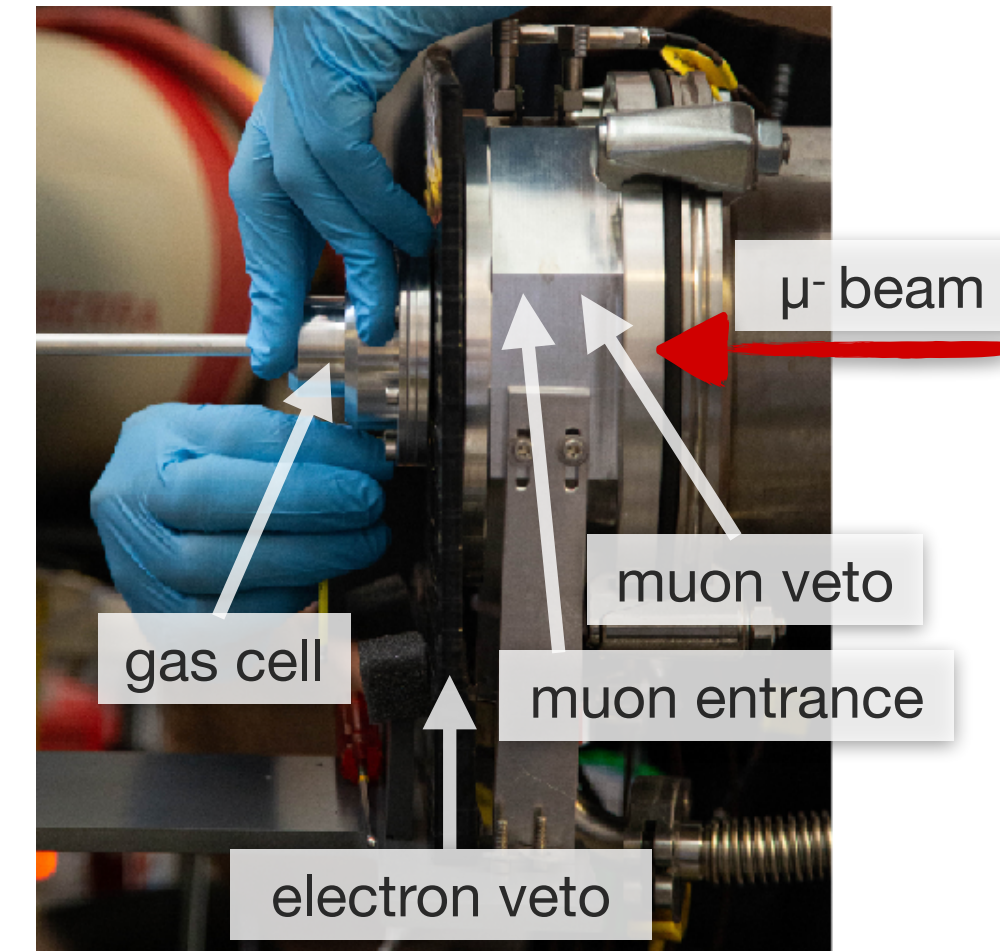
Gas cell measurements



Gas cell measurements

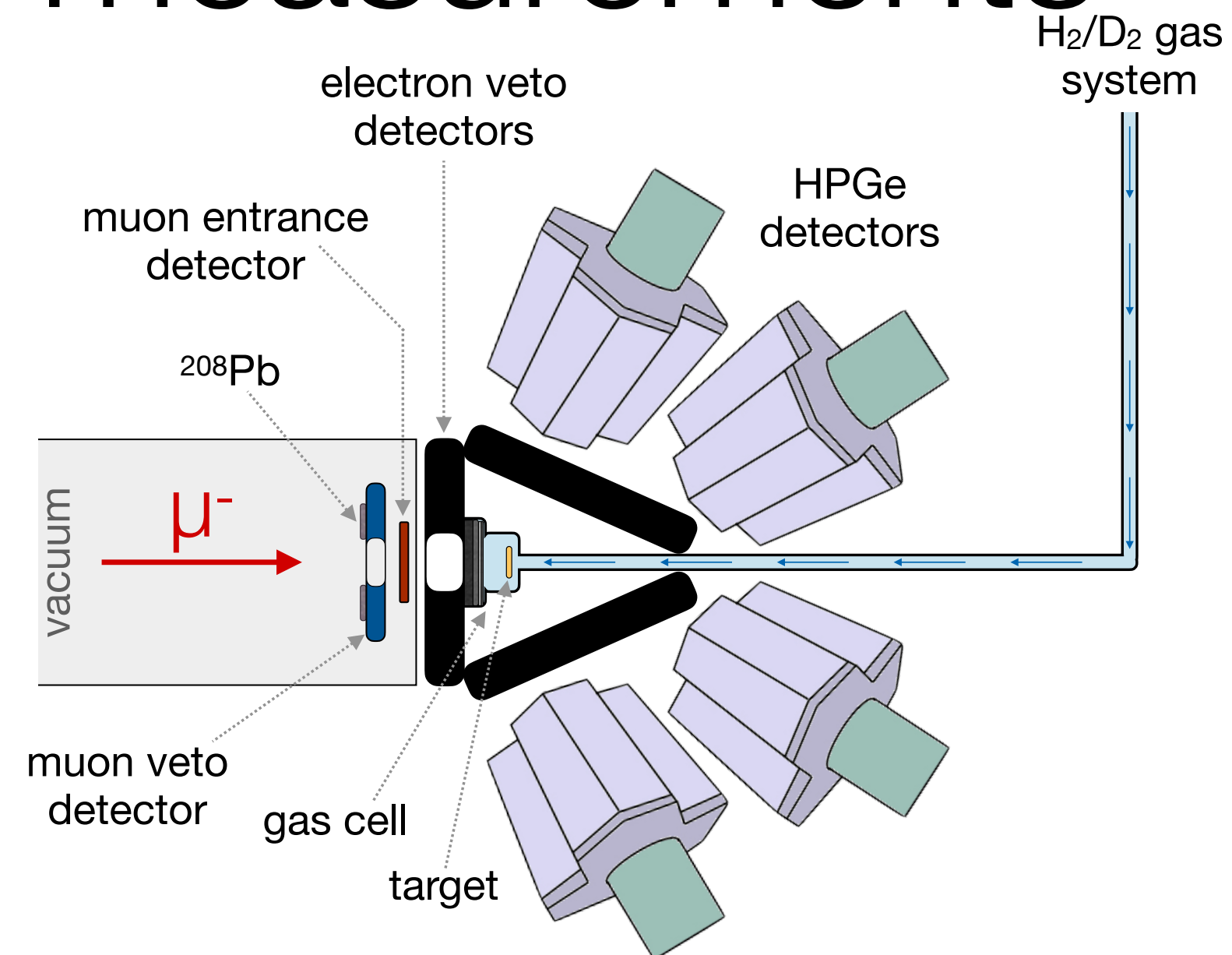


The gas cell



The muon and electron counters

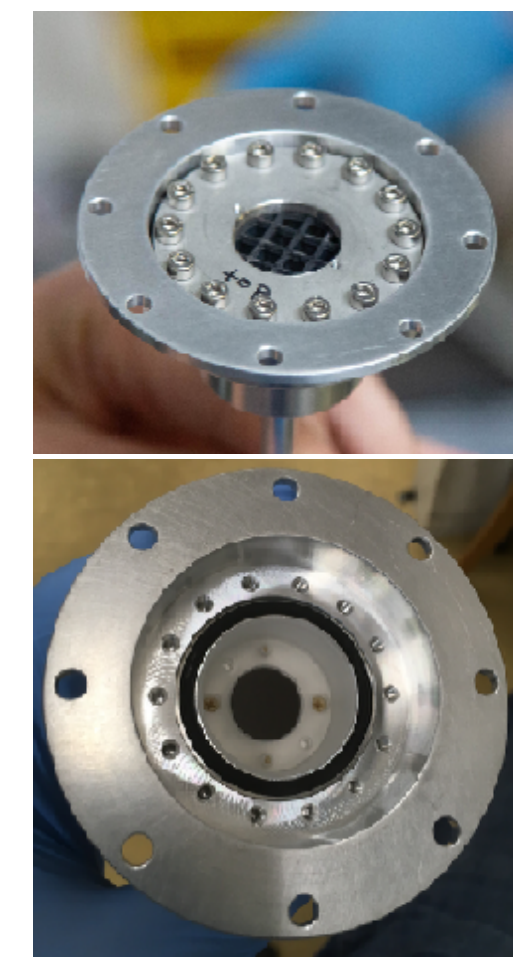
Gas cell measurements



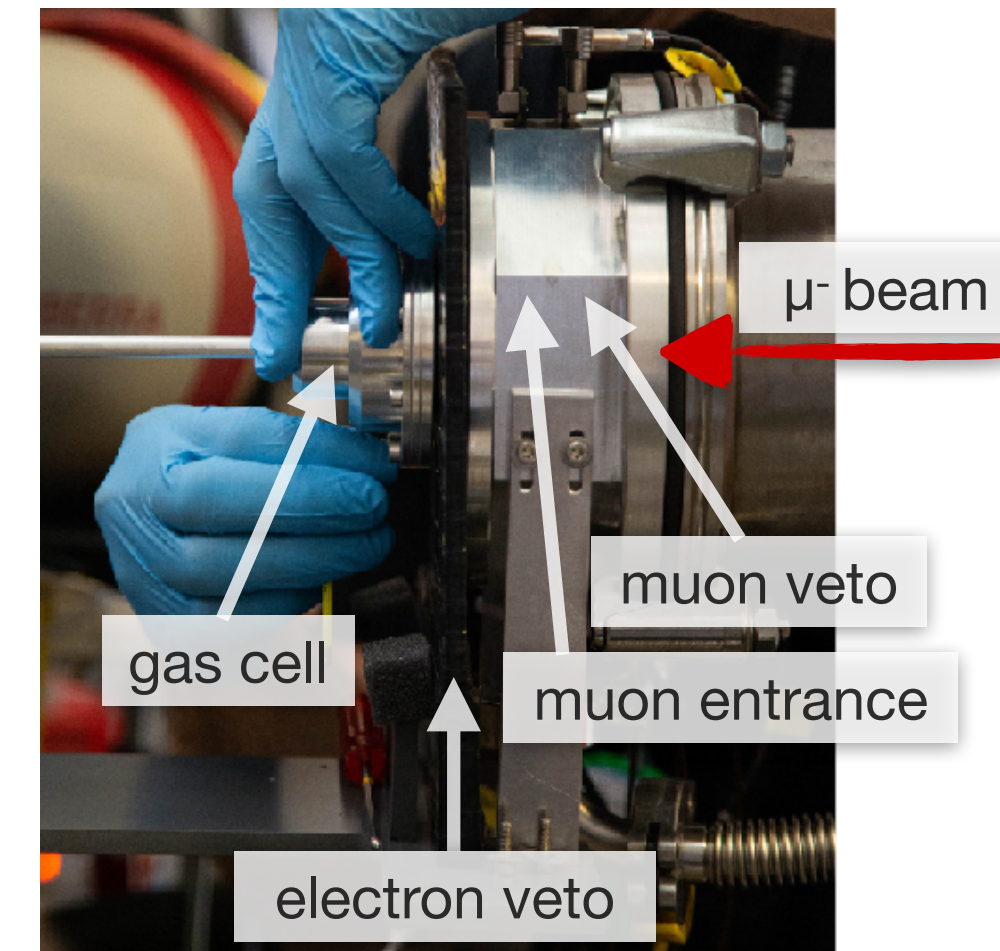
Schematics of detectors setup

Demonstration of principal in a 5 μg gold target in 2017, 18.5 h of measurement

the time the muon enters the gas cell

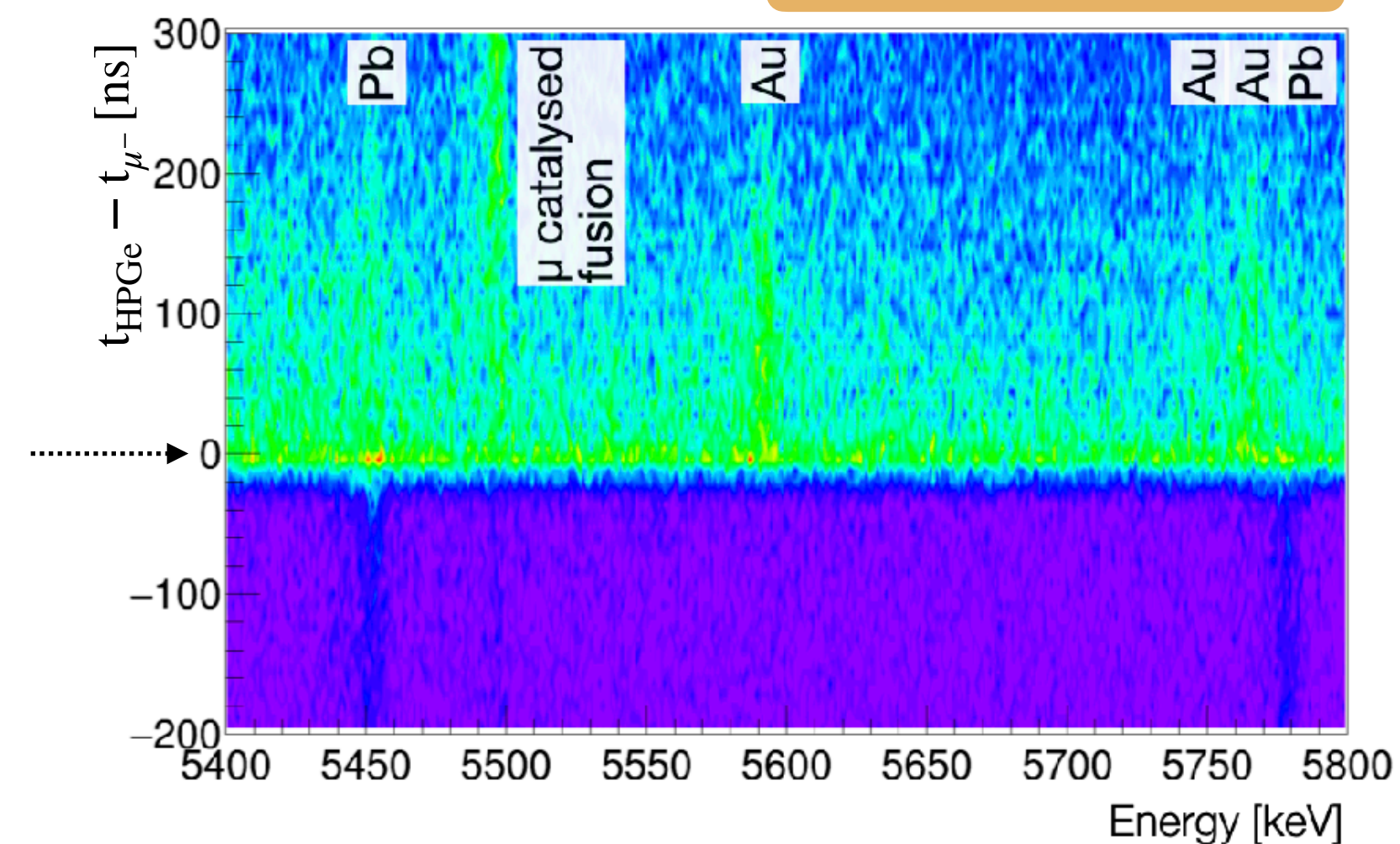


The gas cell



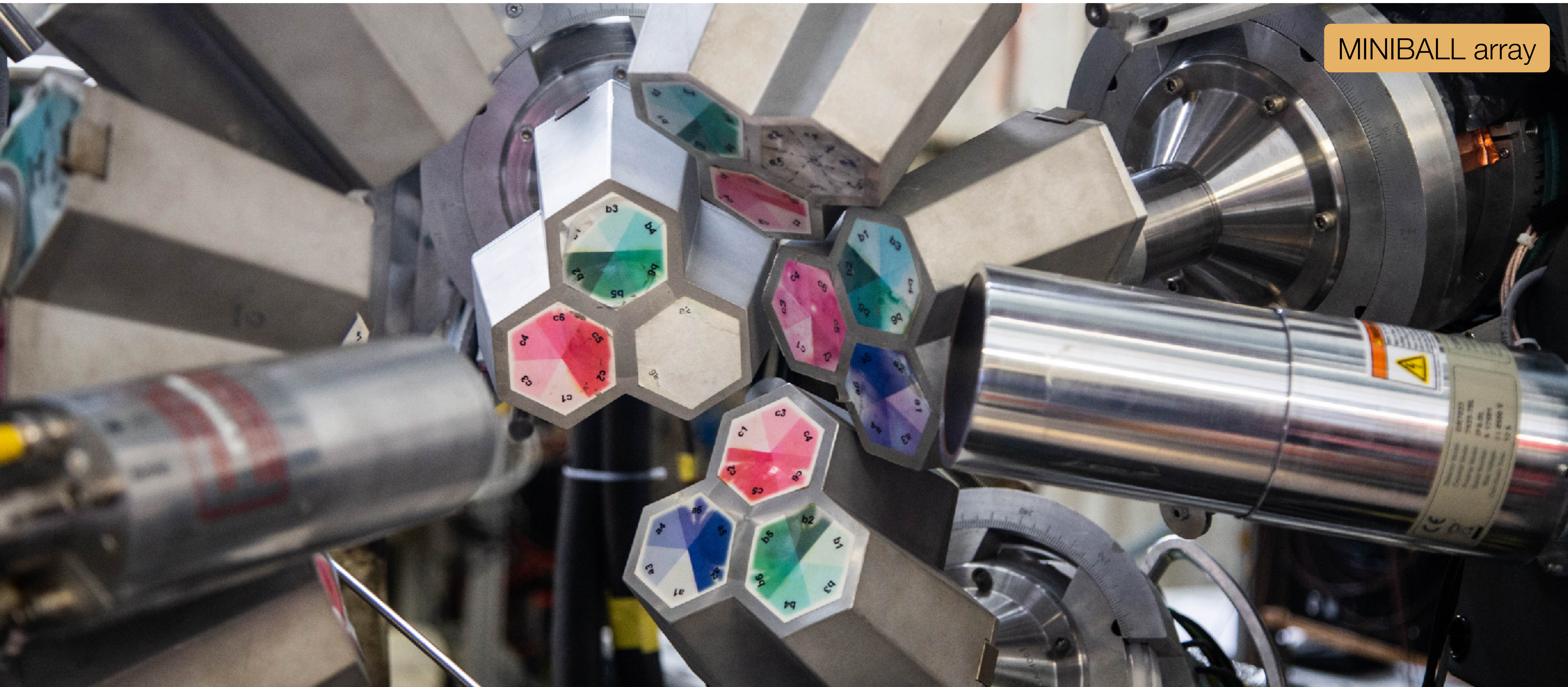
The muon and electron counters

Eur. Phys. J. A 59, 15 (2023)

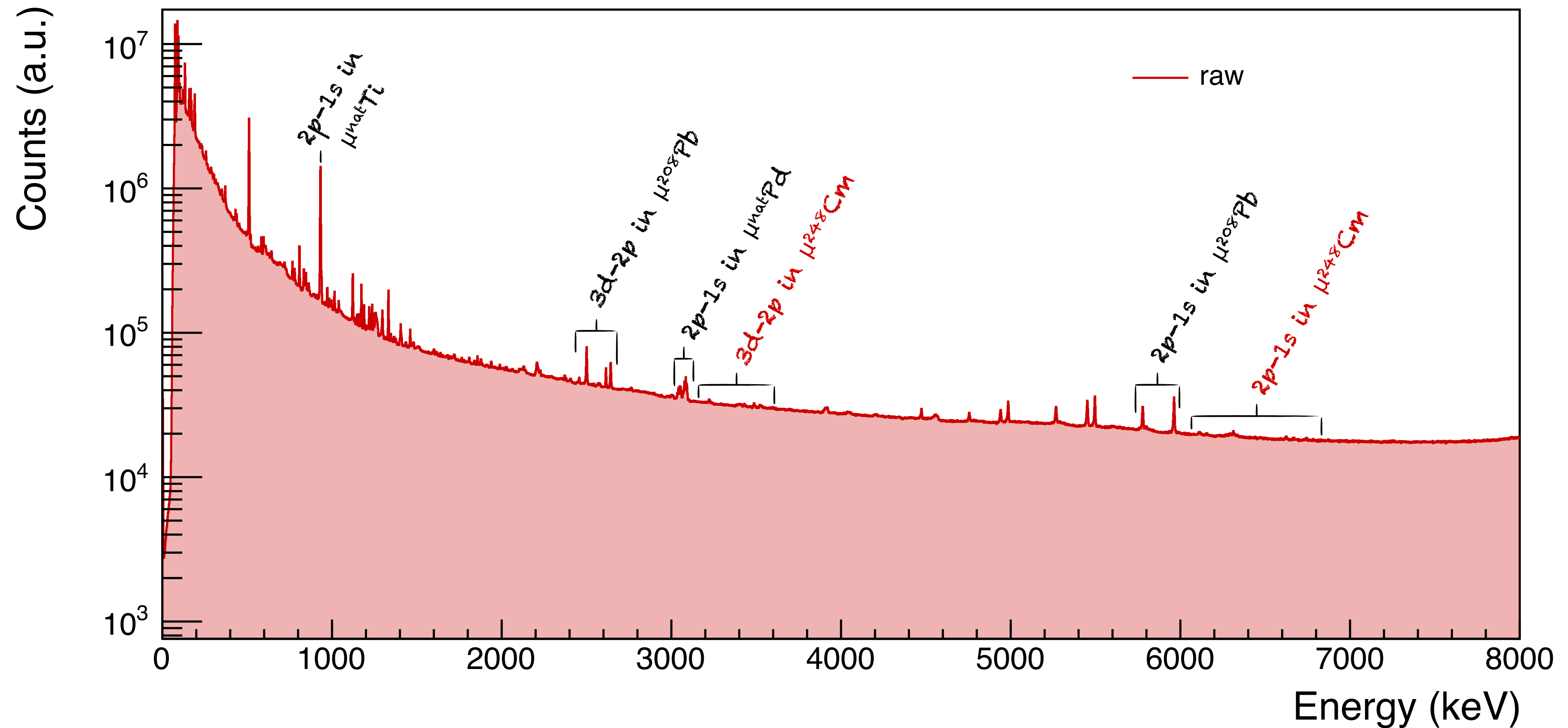


Experimental timeline

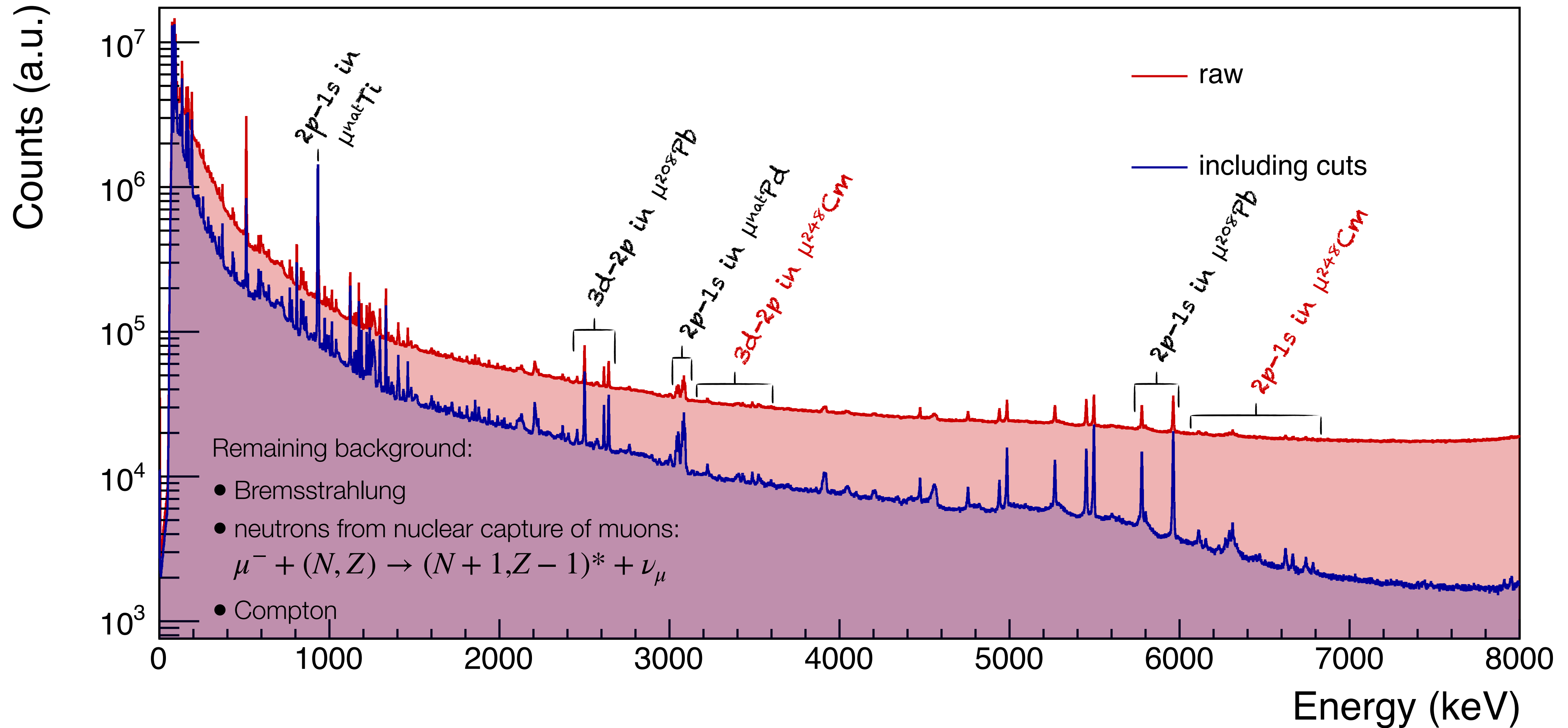
2019 — first radioactive targets ^{248}Cm & ^{226}Ra ($5\ \mu\text{g}$)



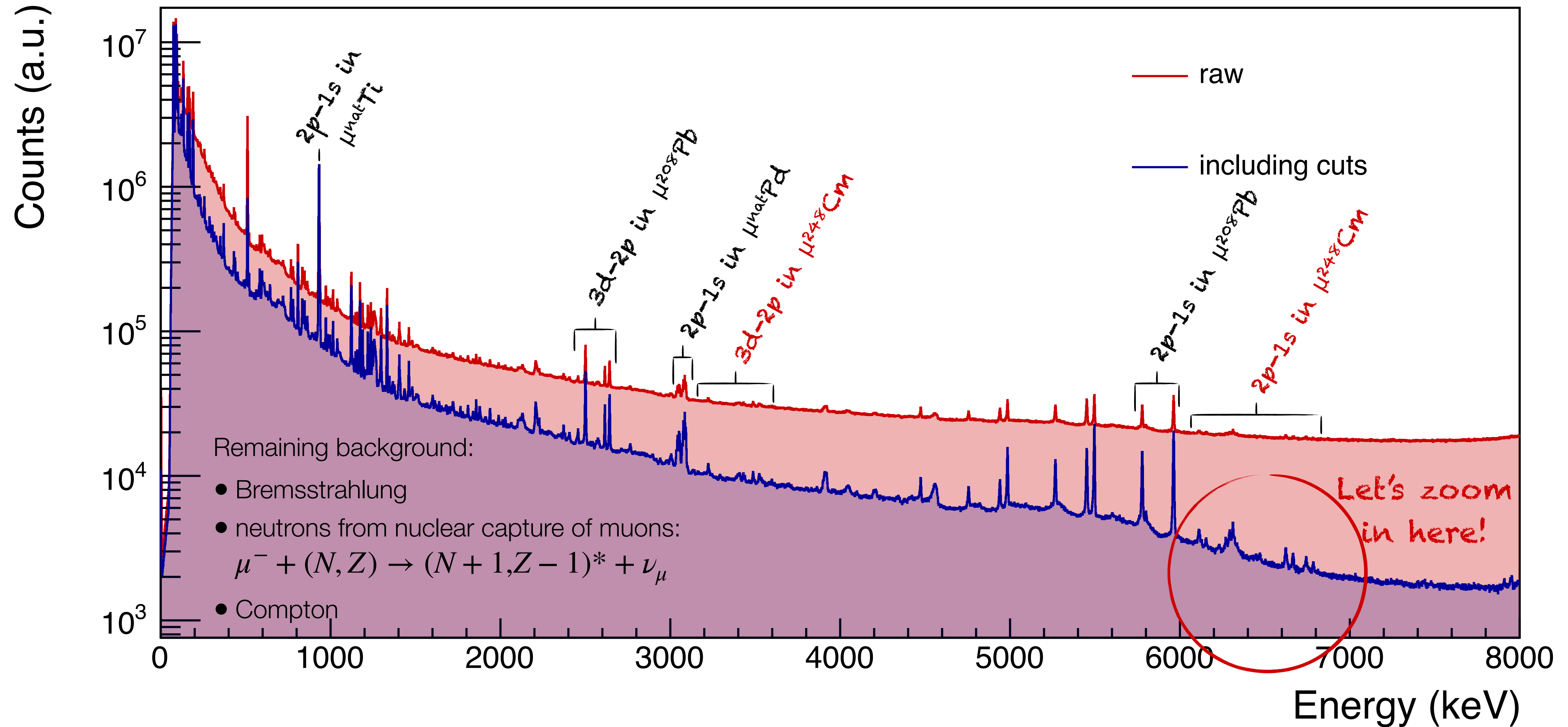
Improving S/B ratio at high energies



Improving S/B ratio at high energies



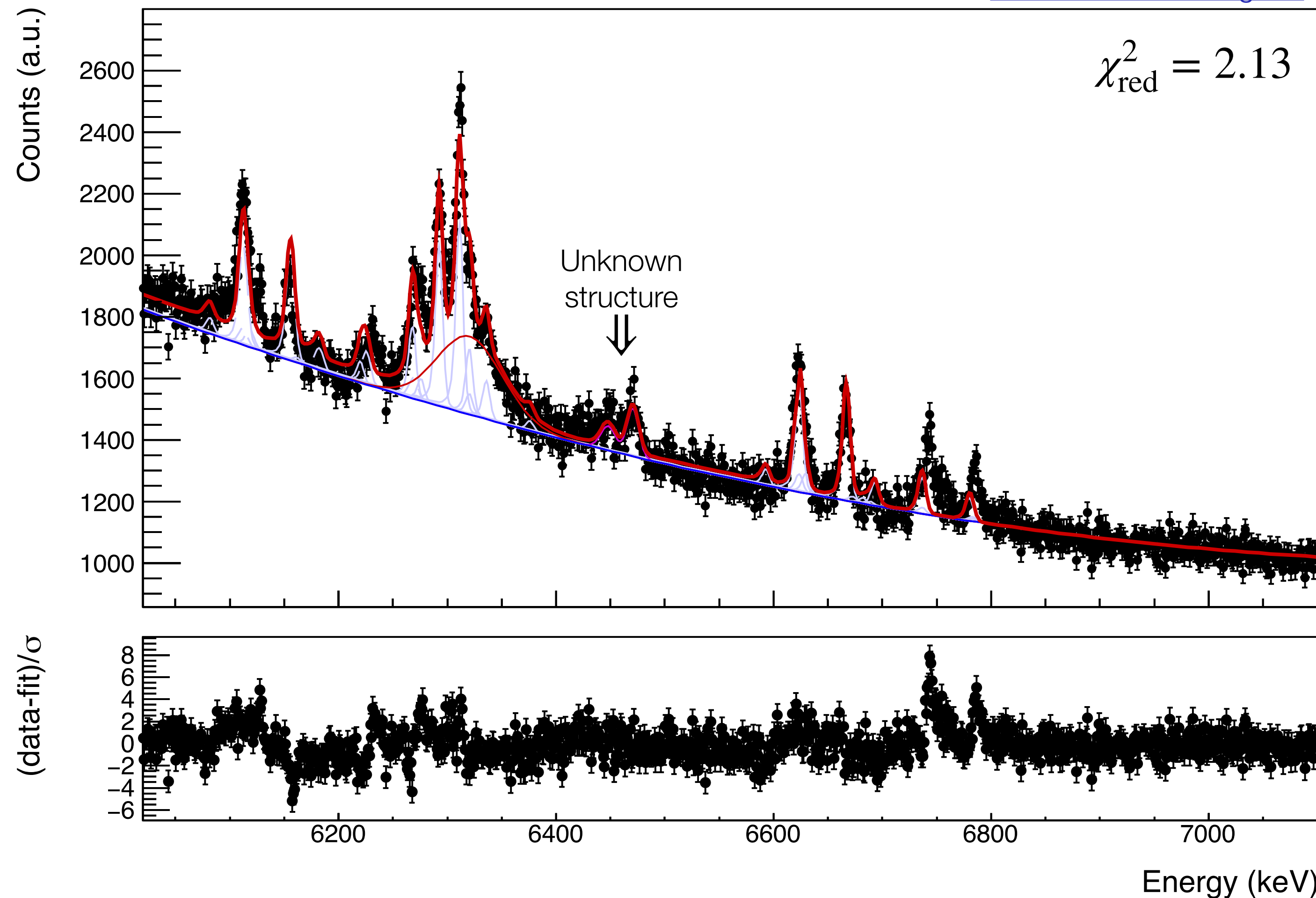
Improving S/B ratio at high energies



^{248}Cm 2p1s analysis

Nuclear charge radius

PhD thesis of S. Vogiatzi



Preliminary result

$$R = 5.9455(1)_{\text{stat}}(117)_{\text{sys}} \text{ fm}$$

$$Q = 12.003(8)_{\text{stat}}(361)_{\text{sys}} \text{ b}$$

Included corrections:

- Finite size (2-Fermi)
- Vacuum polarisation
- Nuclear polarisation

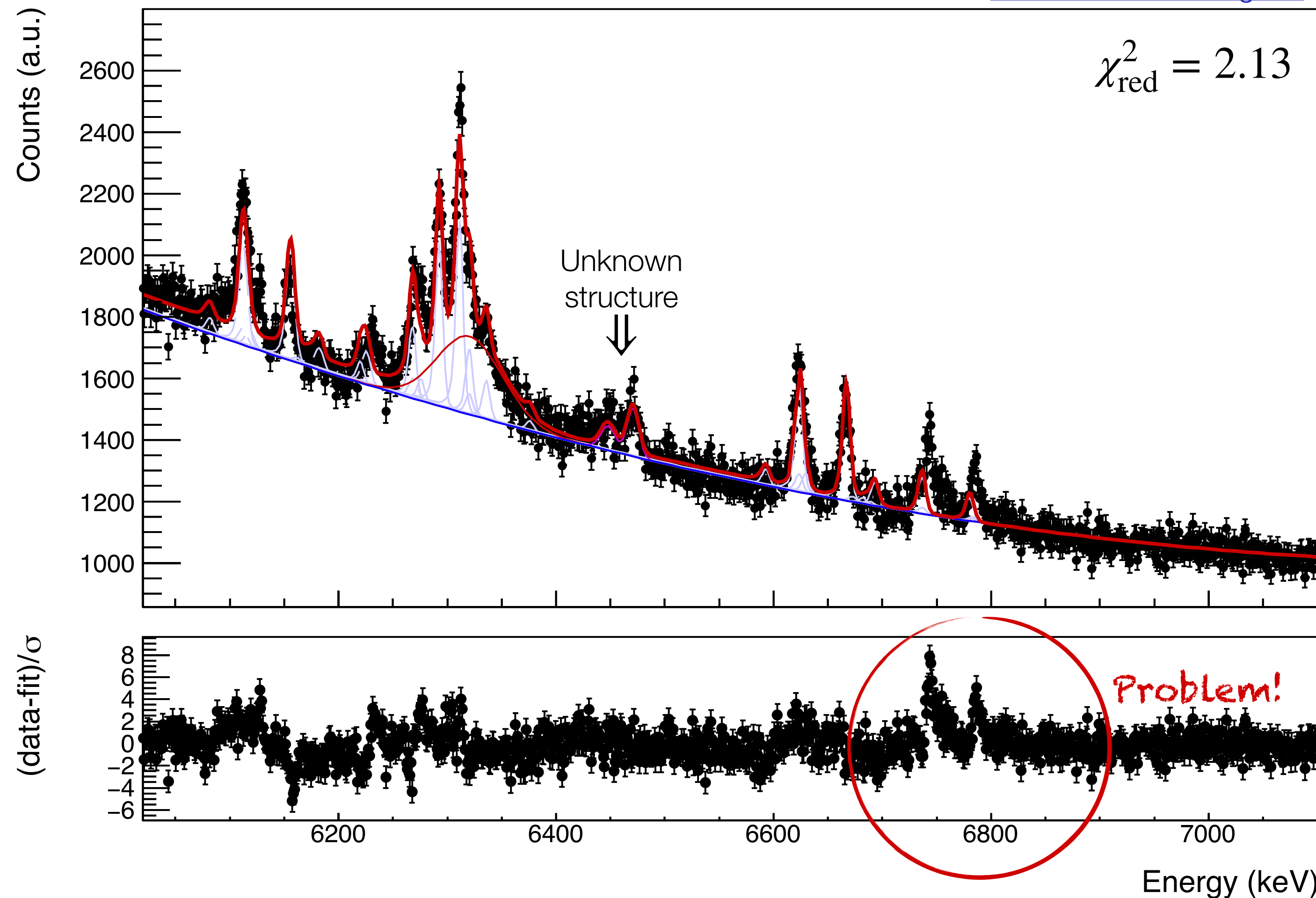
Not included corrections:

- Magnetic moment ($\sim$ sub-keV)
- Electron screening?
- Hadronic vacuum polarization
- Recoil effect

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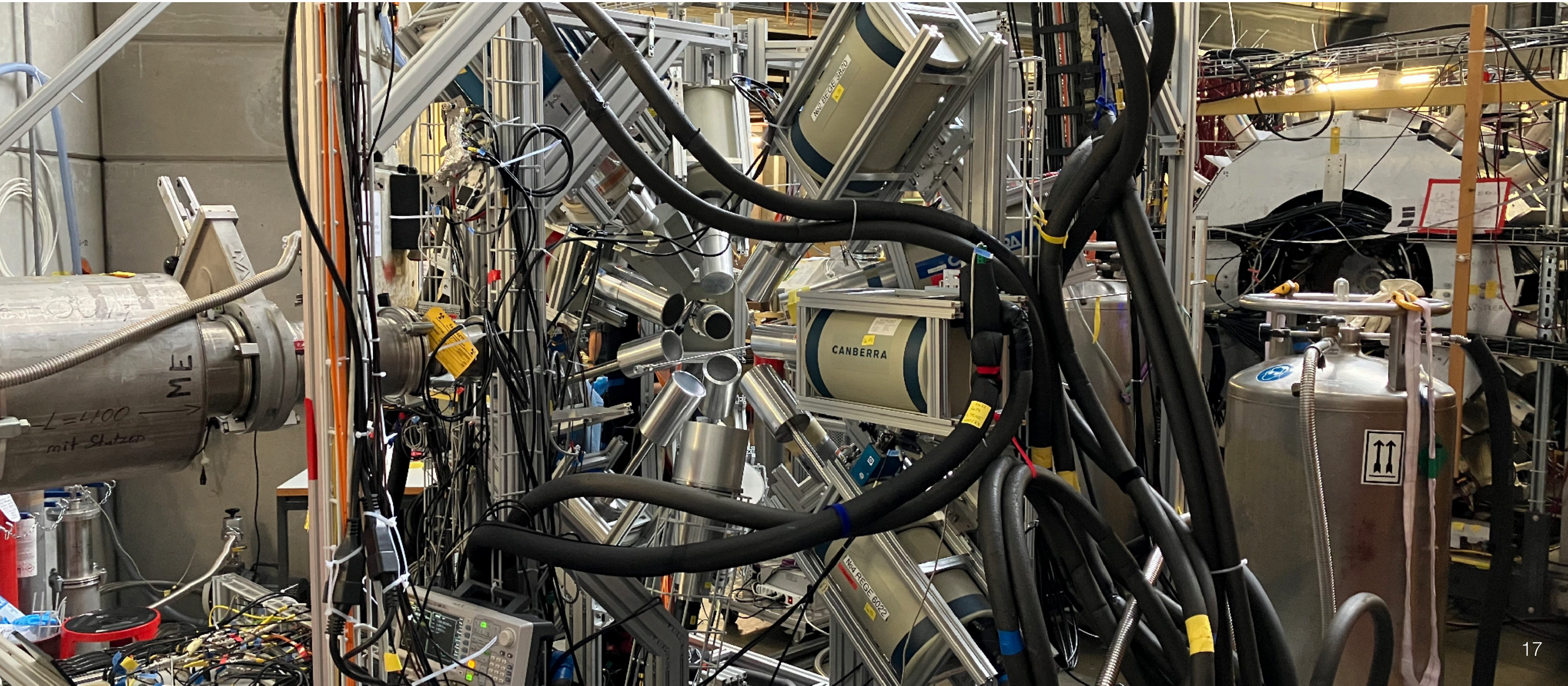
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Experimental timeline

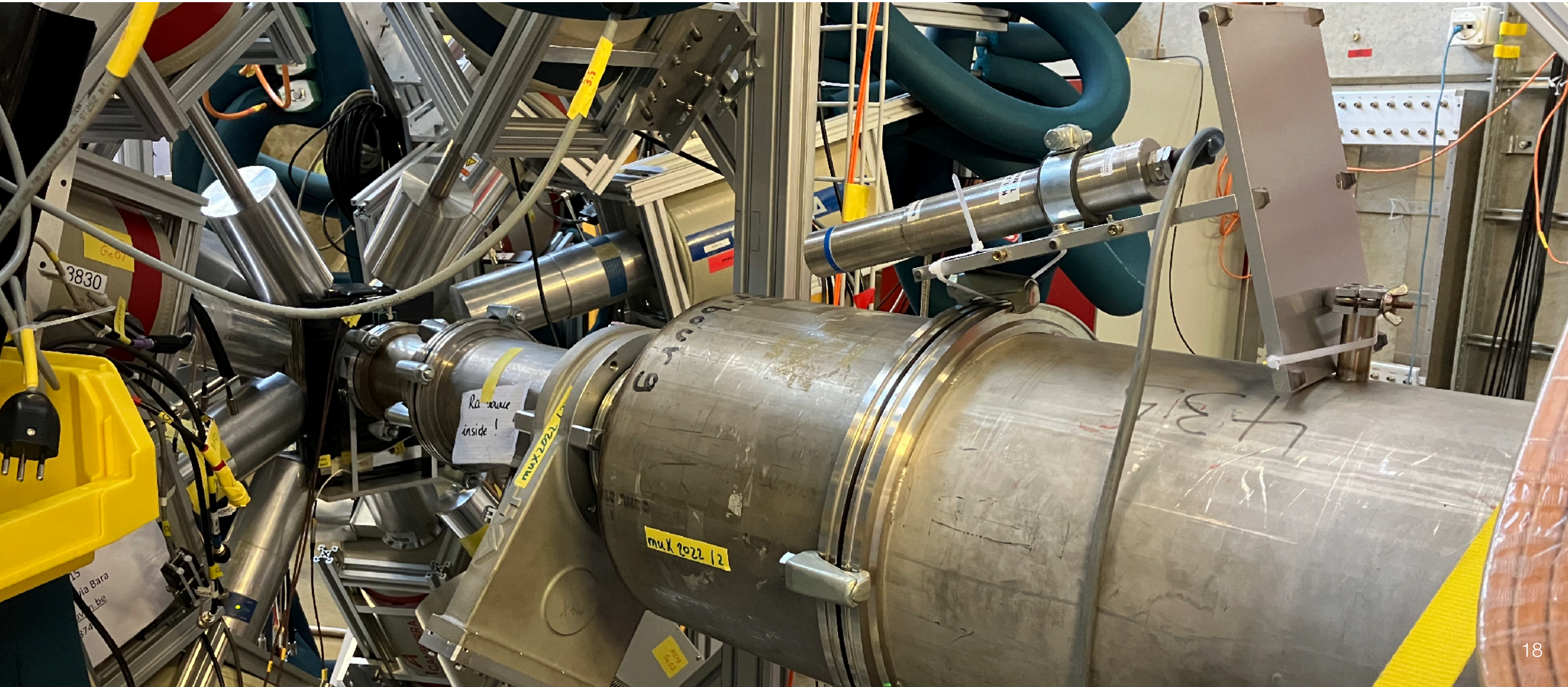
Sci Rep 15, 6939 (2025)

2022 — *Assessing the target fabrication techniques*



Experimental timeline

2023 — $^{35,37}\text{Cl}$ & $^{39,40,41}\text{K}$ & $^{107,109}\text{Ag}$ ($\mathcal{O}(\text{mg to g})$ & $7.5\ \mu\text{g}$)

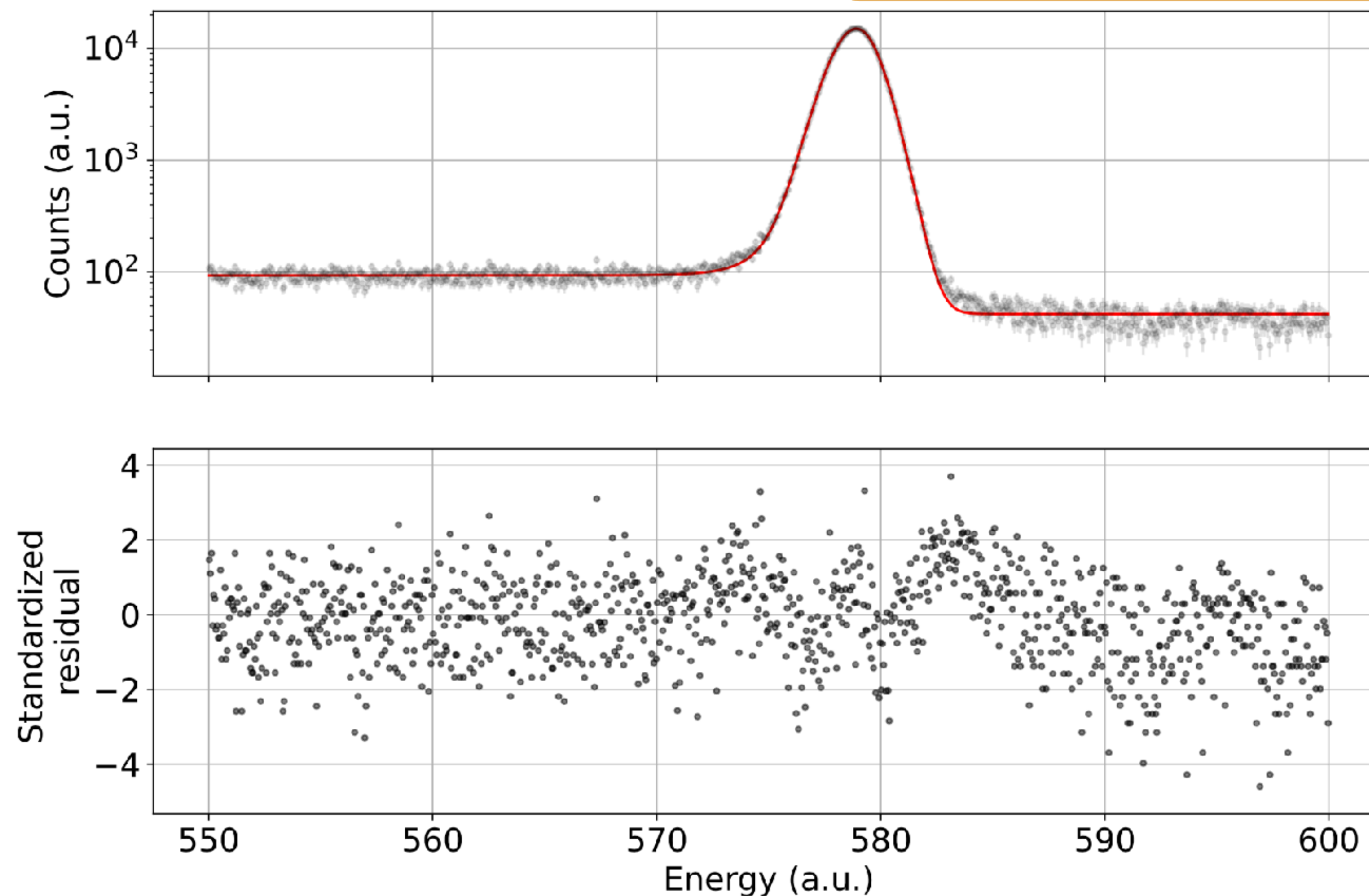


^{35}Cl 2p1s analysis (200 mg)

Nuclear charge radius

Publication in progress;
 $^{35,37}\text{Cl}$, $^{39,41}\text{K}$

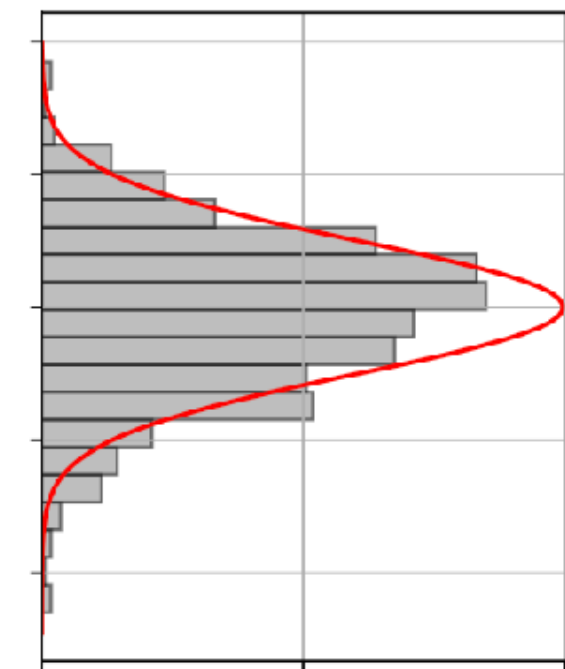
Analysis of data and image
courtesy of **Michael Heines**



Bunch of corrections for
quality data analysis pipeline:

- Thorough line-shape investigation
- Gain stabilisation
- Time algorithm correction
- Rise-time correction
- Combined detector analysis
-

Extensive analysis note written!

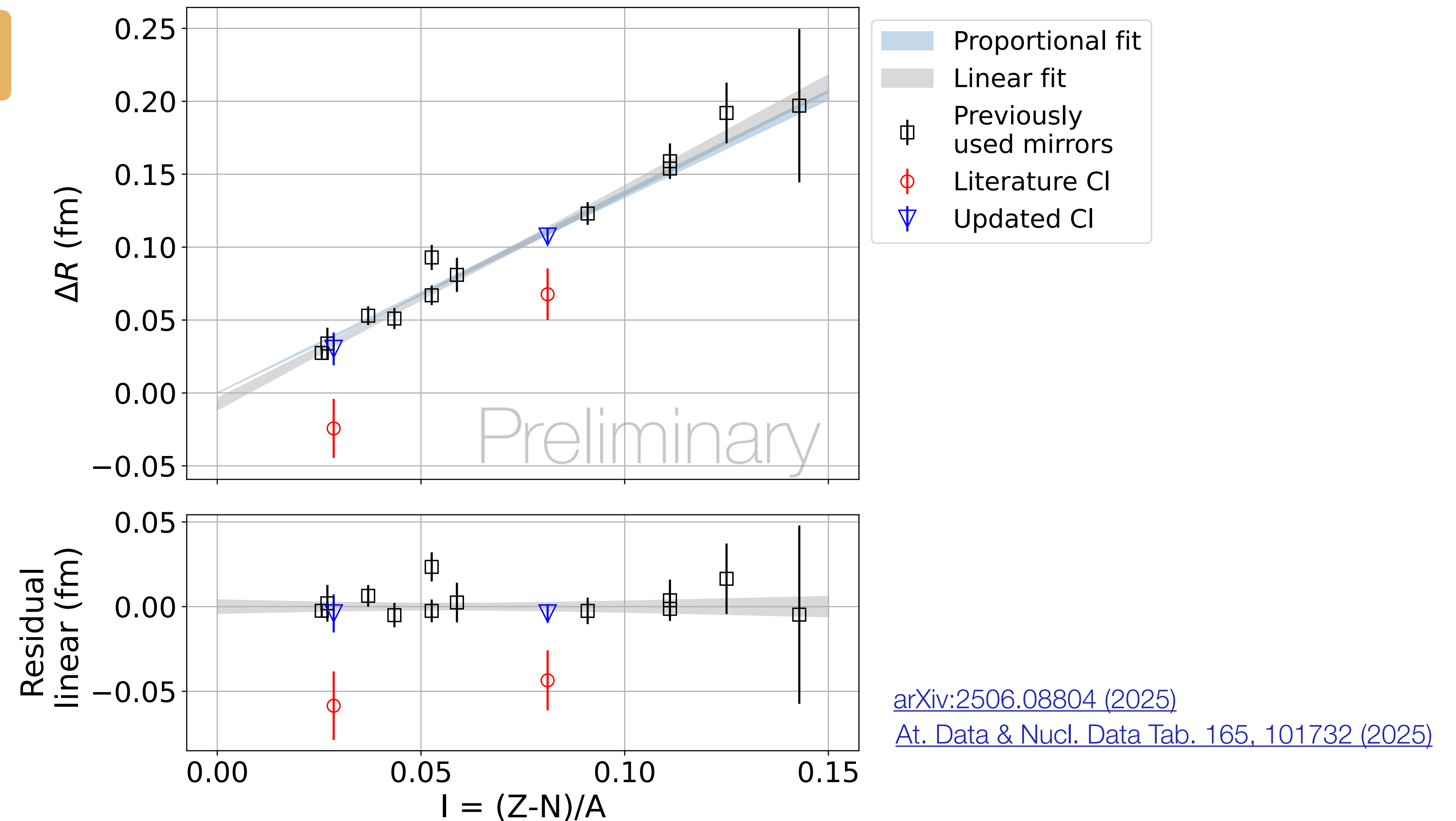


[arXiv:2506.08804 \(2025\)](https://arxiv.org/abs/2506.08804)

Impact of new $^{35,37}\text{Cl}$ charge radii

Revisiting the mirror nuclei fit

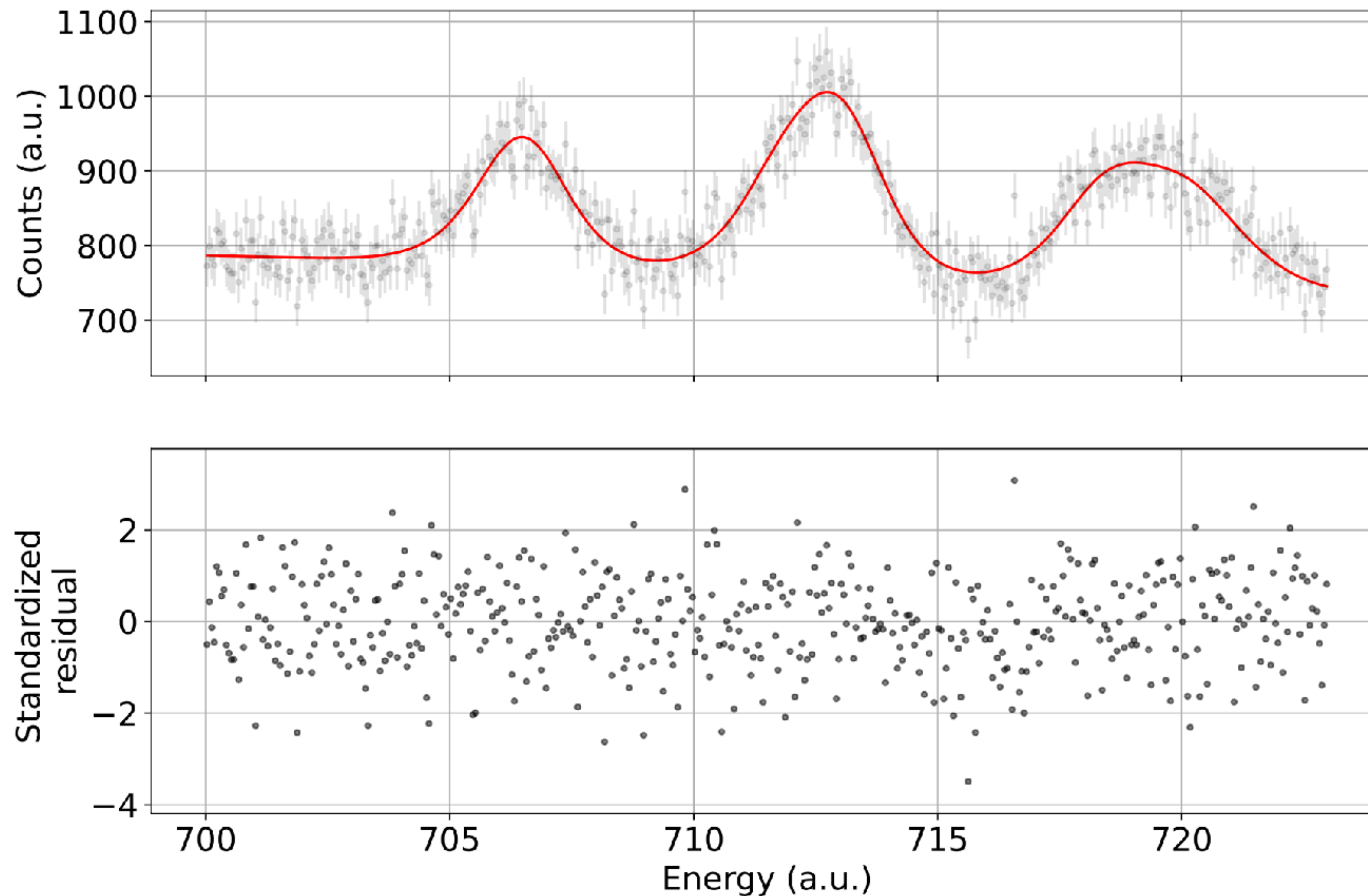
Plot courtesy of
Michael Heines



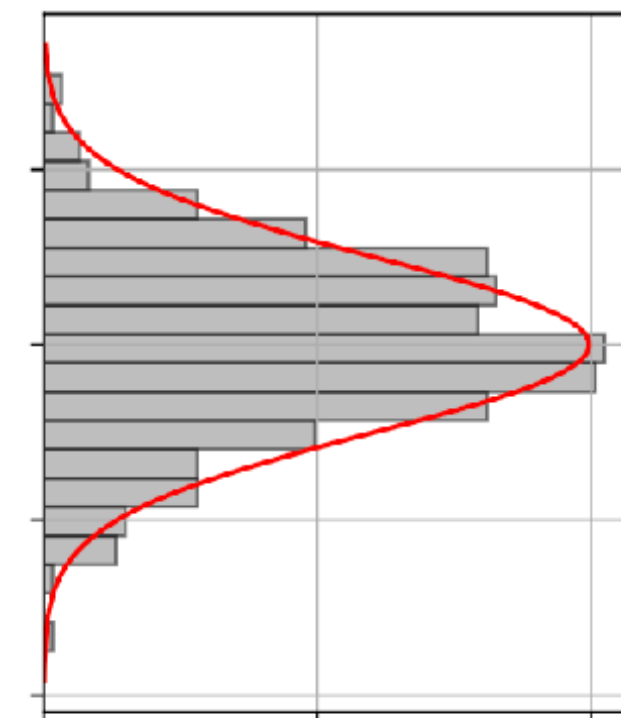
^{40}K 2p1s analysis (7.5 μg)

Nuclear charge radius

$$E_{2p-1s} = 712.\text{xxx}(\text{xx}) \text{ keV}$$

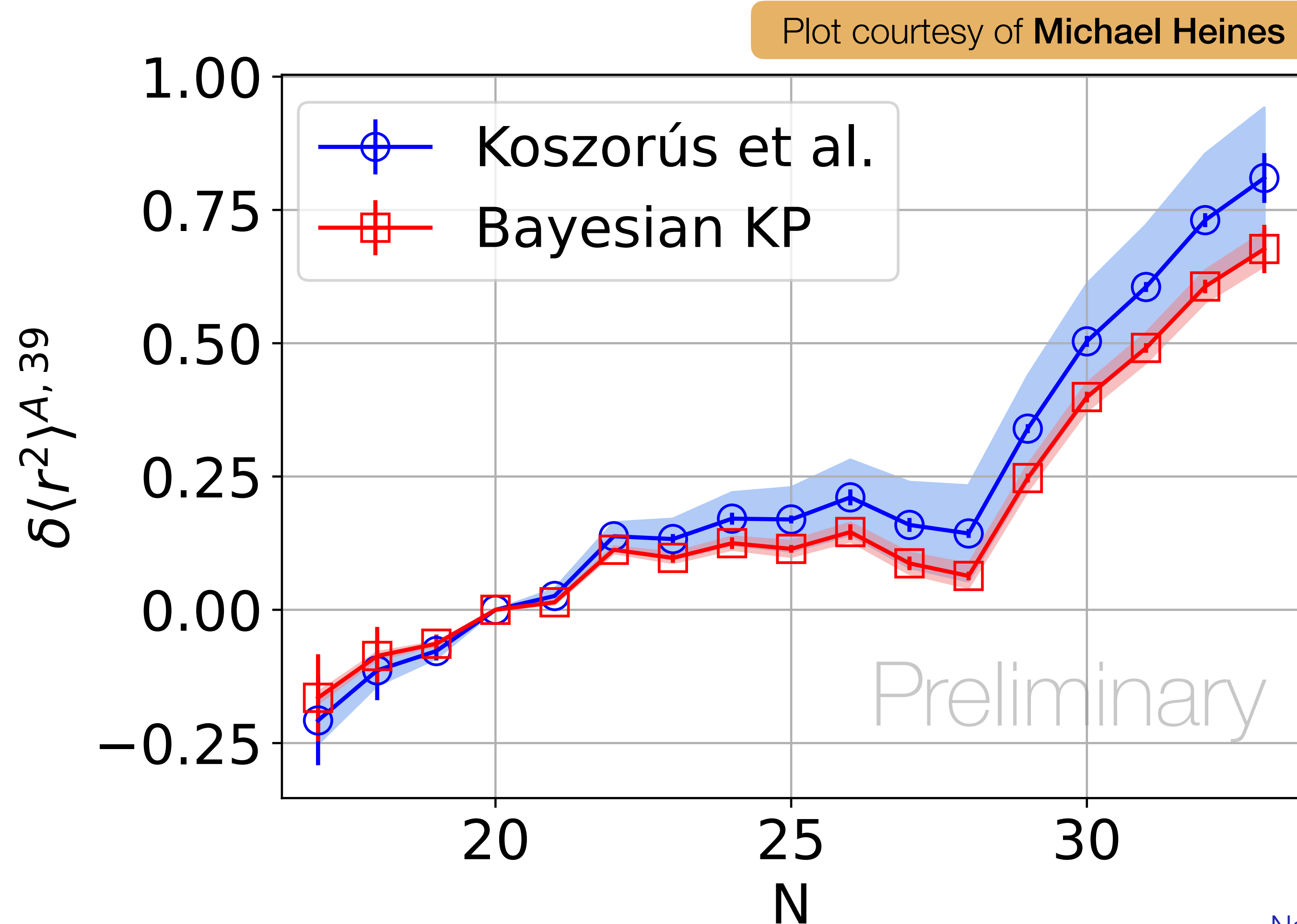


Analysis of data and image
courtesy of **Michael Heines**



Impact of new $^{39,40,41}\text{K}$ charge radii

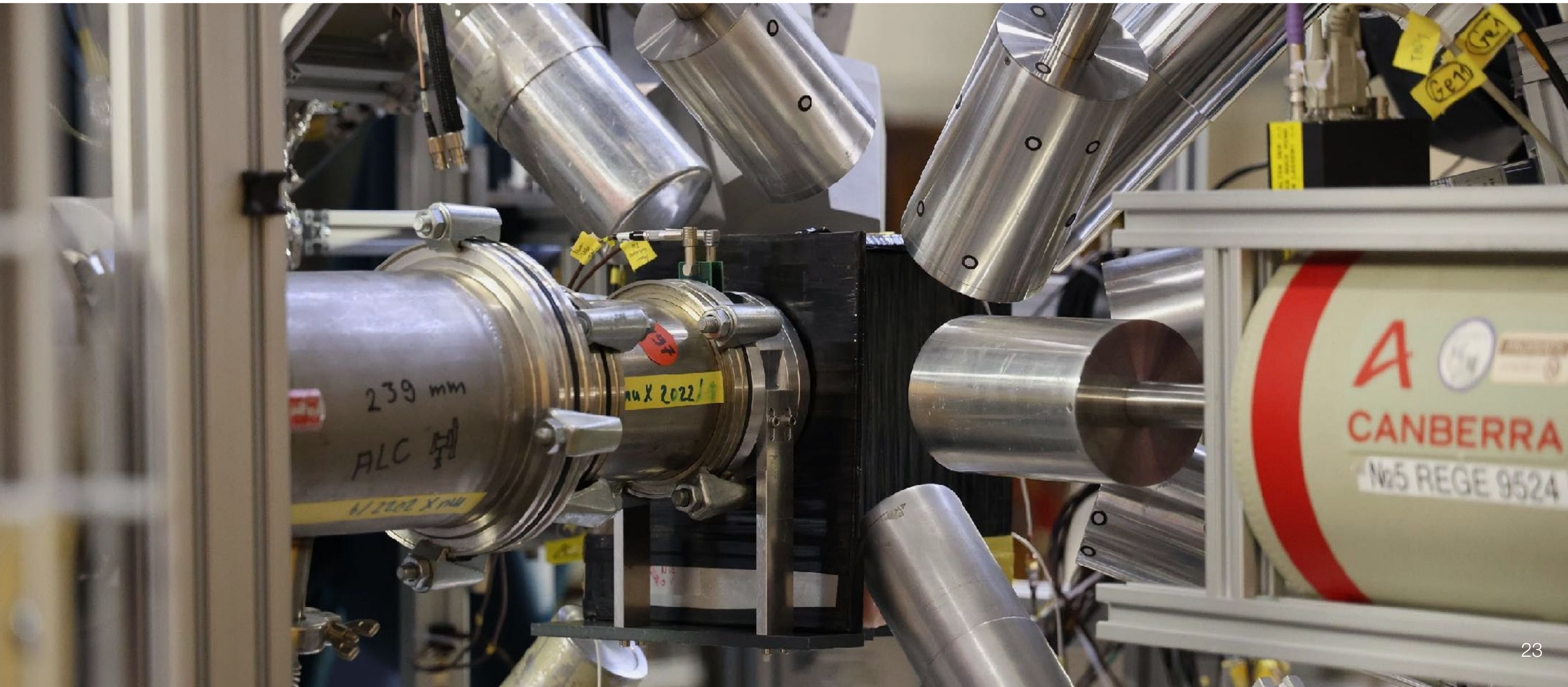
Revisiting the isotopic chain



[Nat. Phys. 17, 439–443 \(2021\)](#)

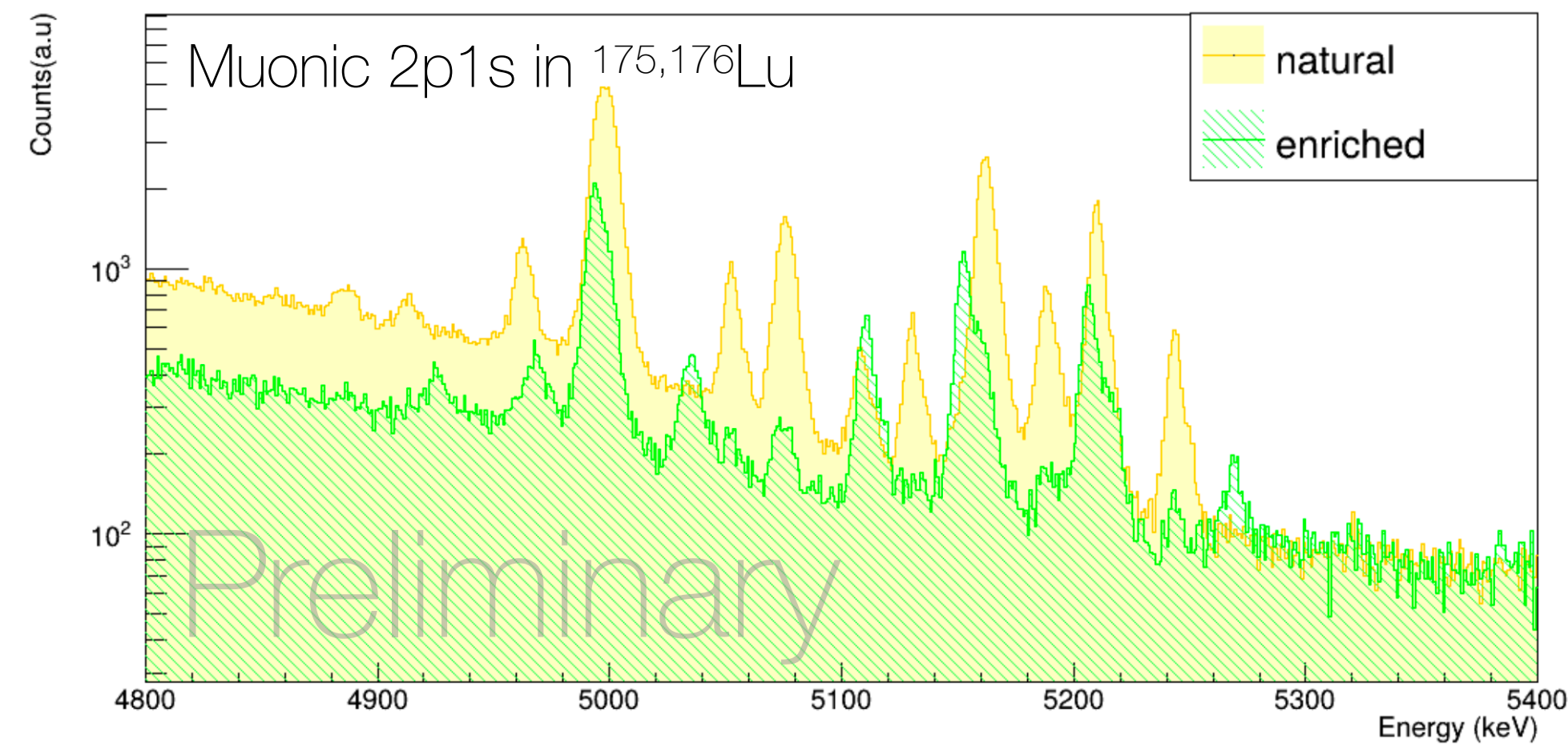
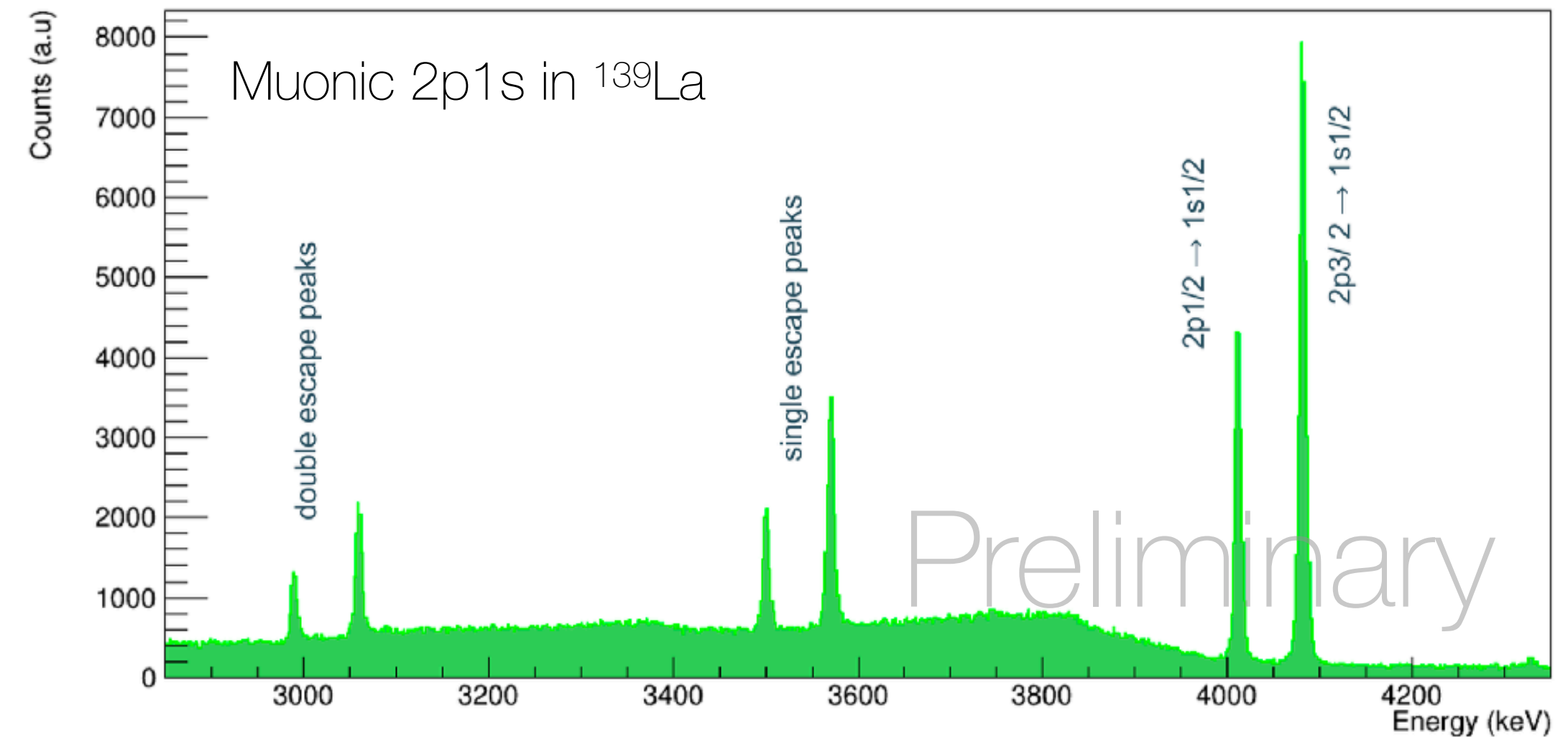
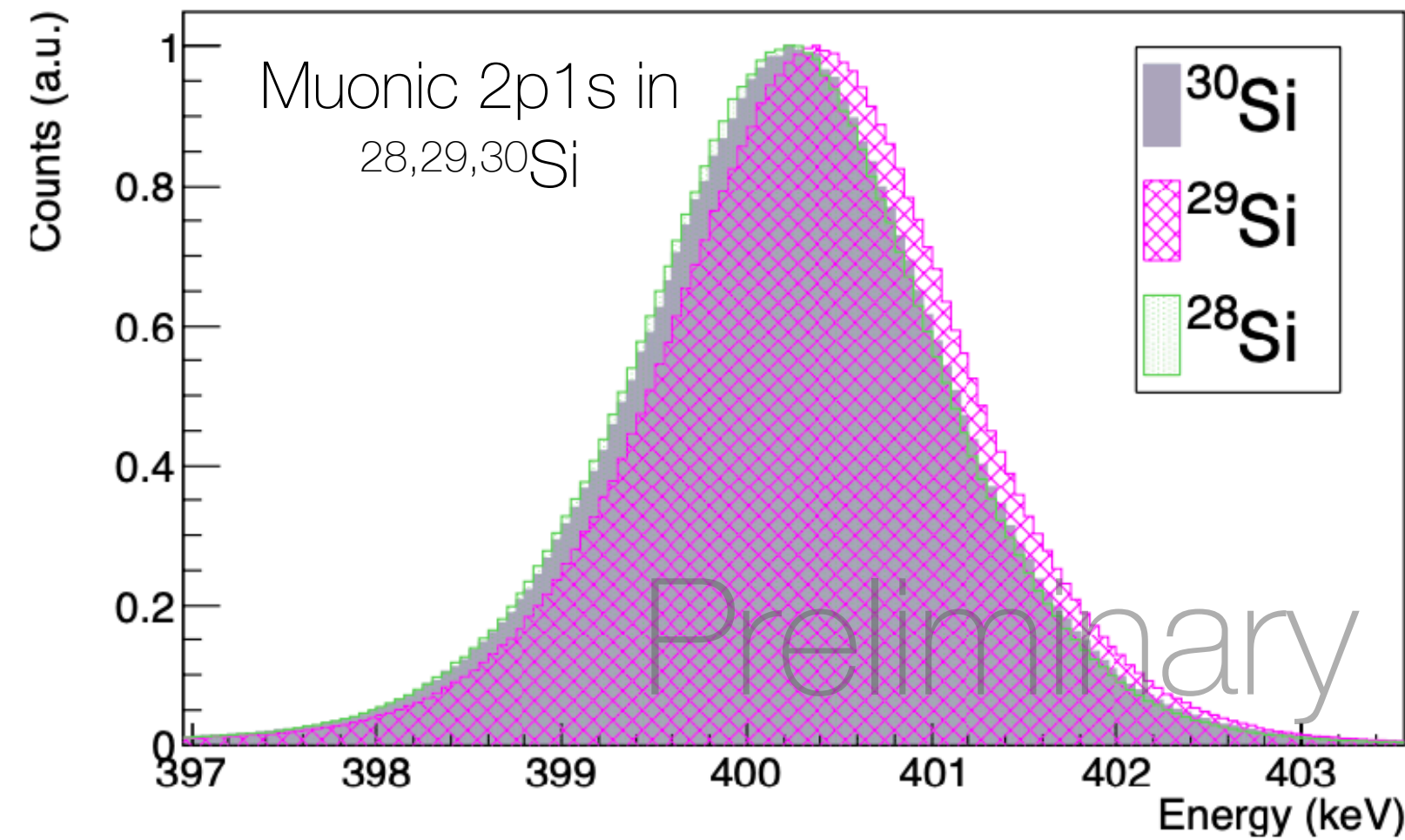
Experimental timeline

2024 — ^{27}Al , $^{28,29,30}\text{Si}$, ^{139}La , $^{175,176}\text{Lu}$ — $\mathcal{O}(\text{mg to g})$



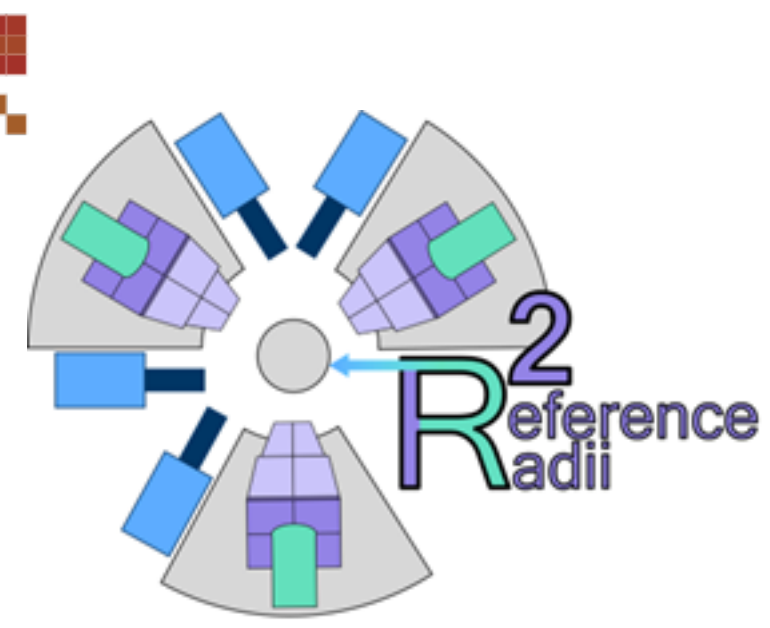
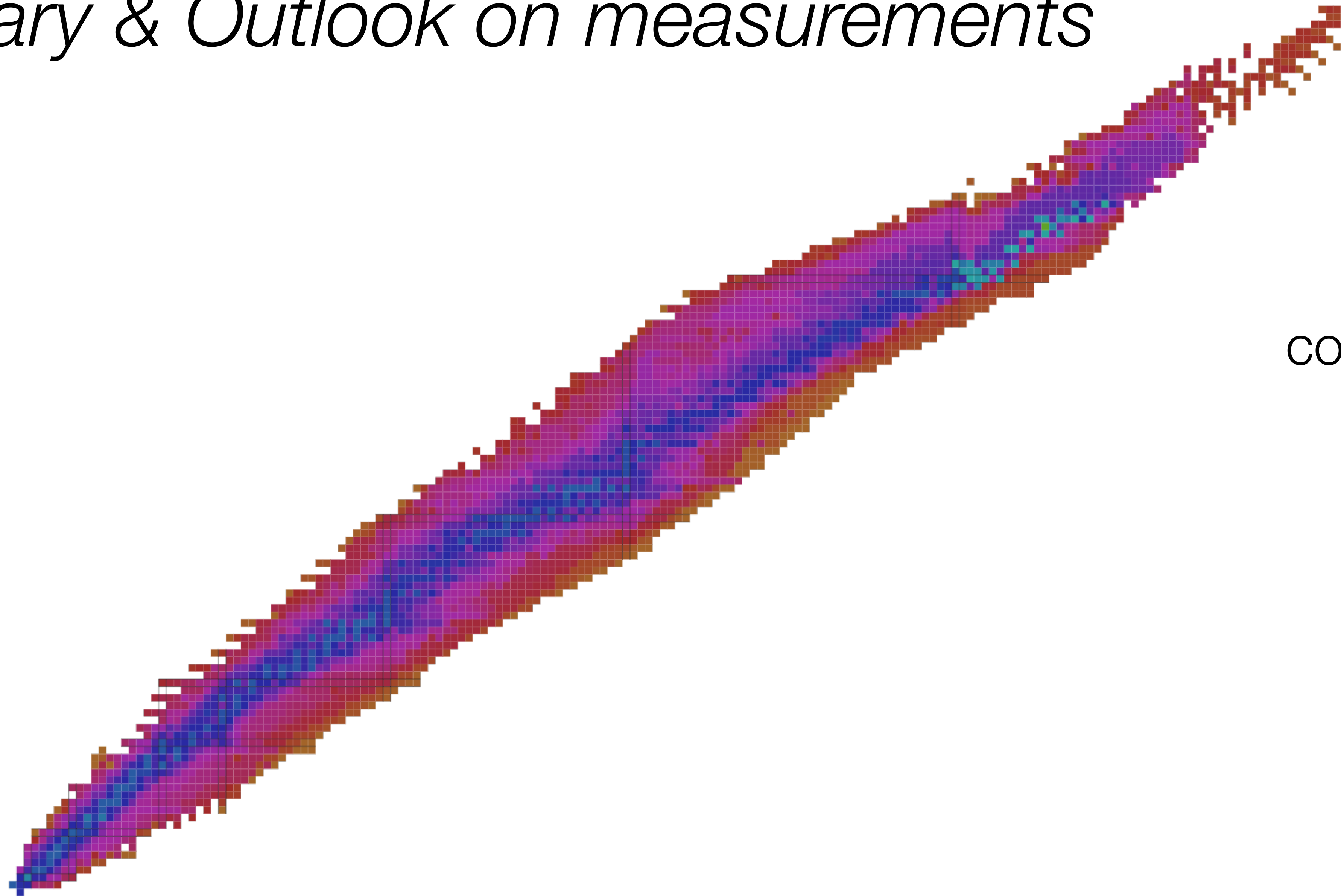
2024 data acquired

Towards nuclear charge radii extraction



Analysis of data by **Marie Deseyn & War War Myint Myat Phyo**

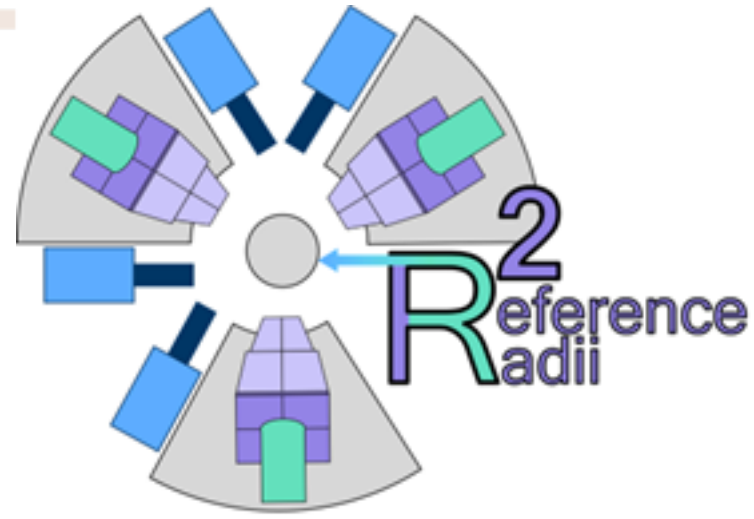
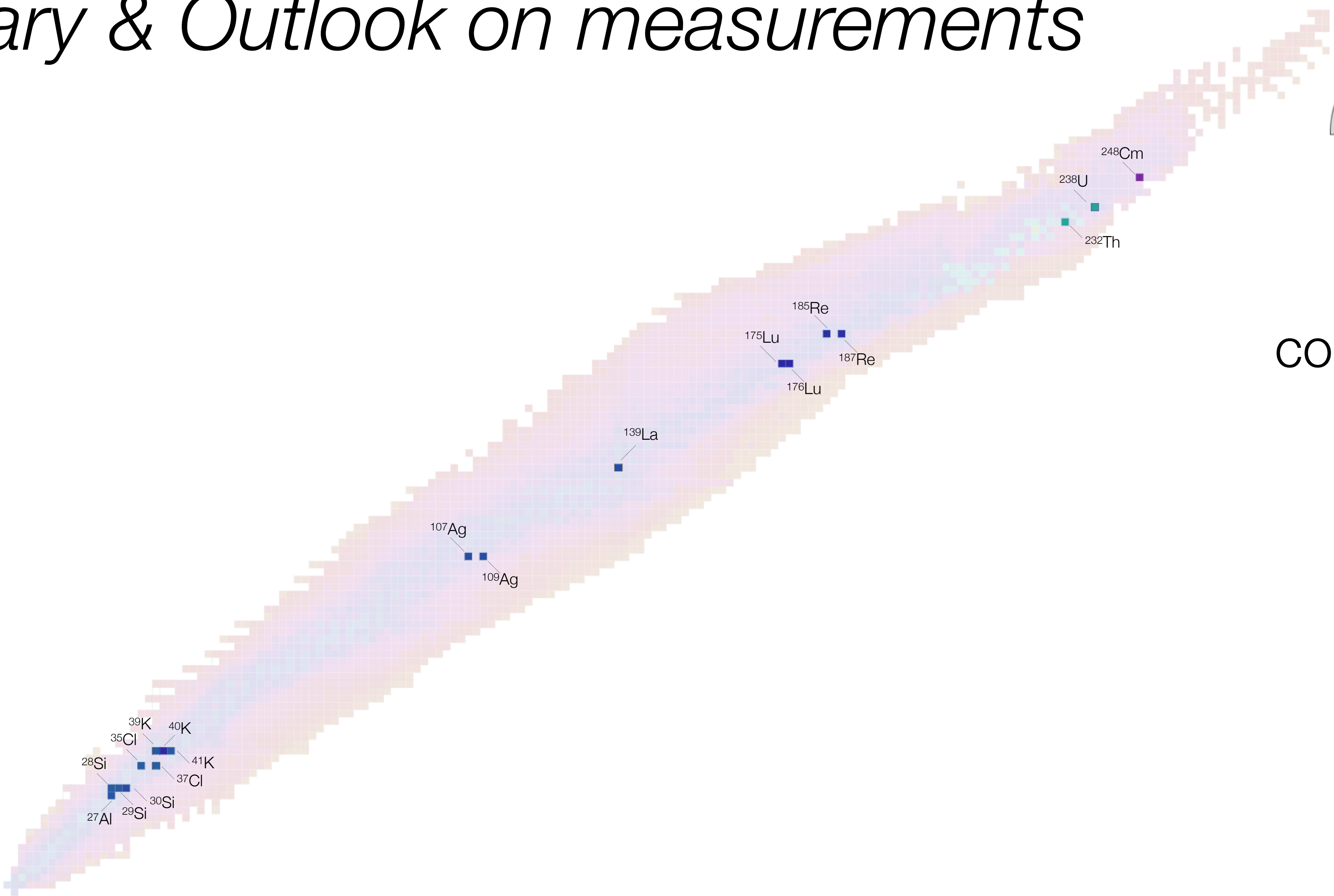
Summary & Outlook on measurements



& muX
collaborations

Summary & Outlook on measurements

Measured...

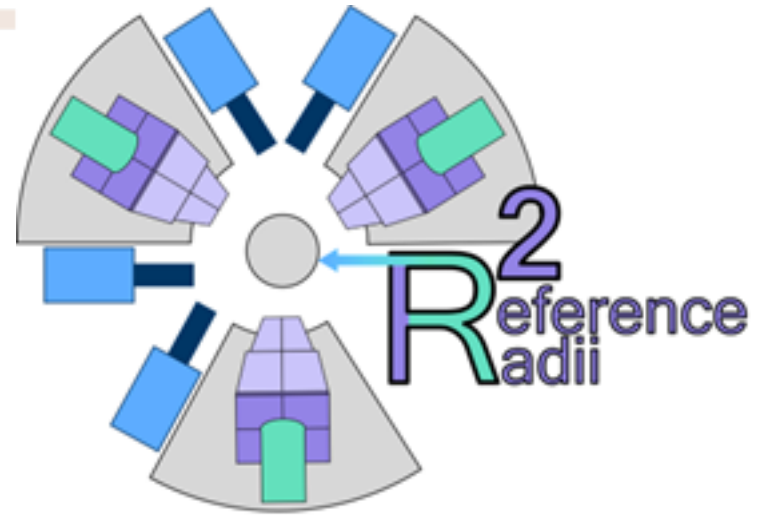
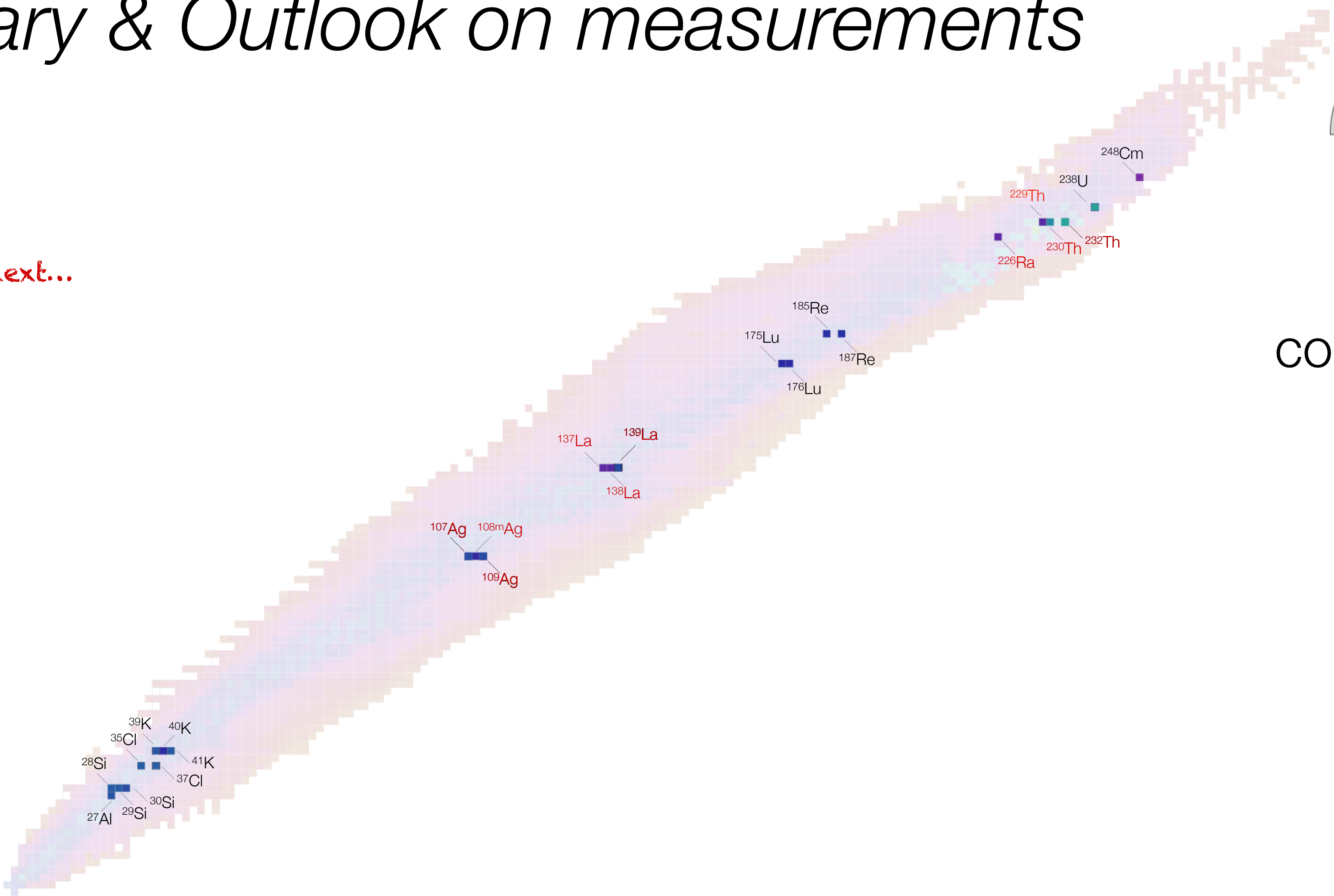


& muX
collaborations

Summary & Outlook on measurements

Measured...

Planned next...

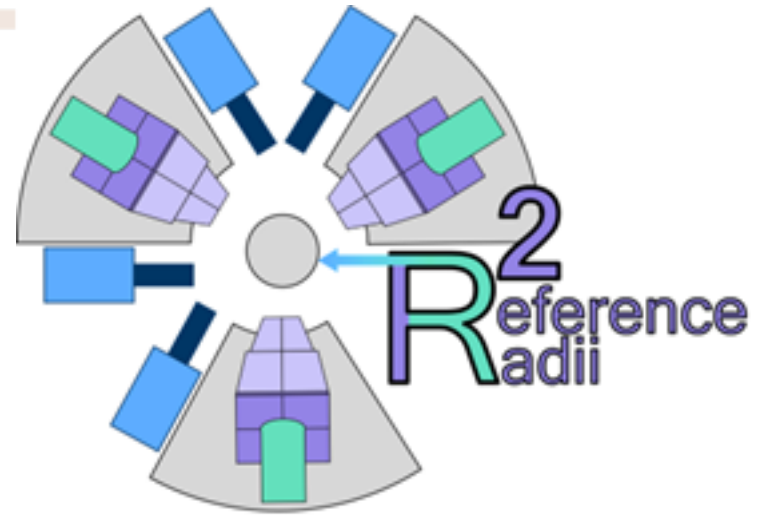
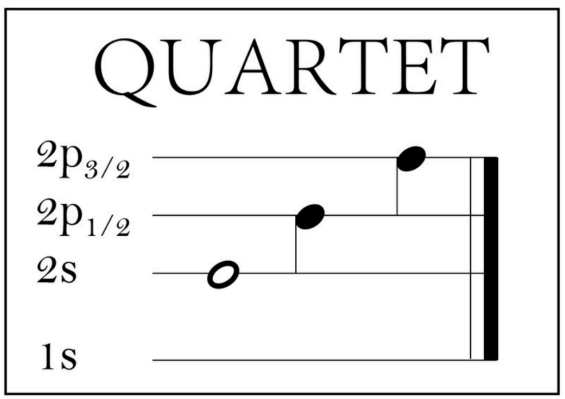
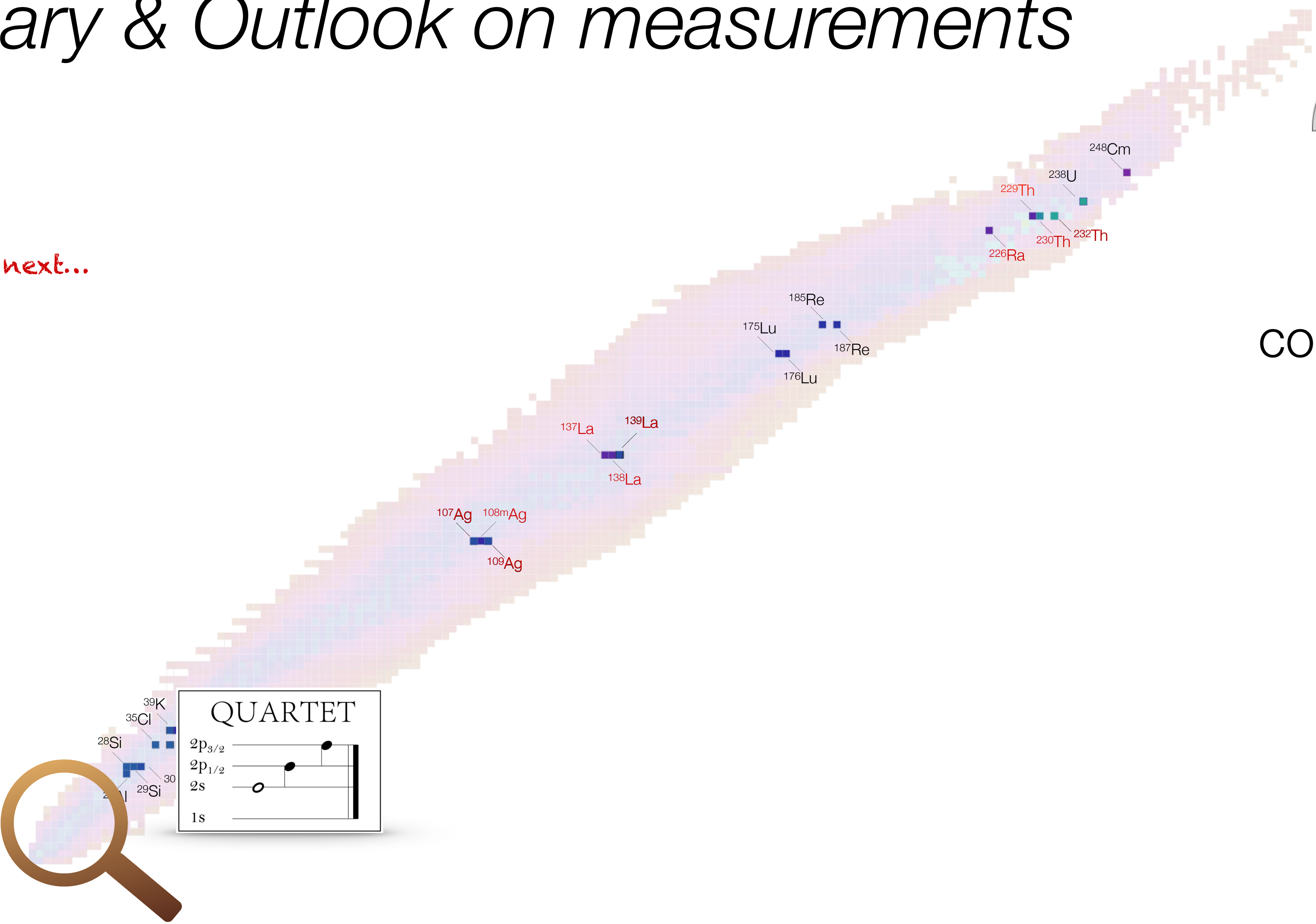


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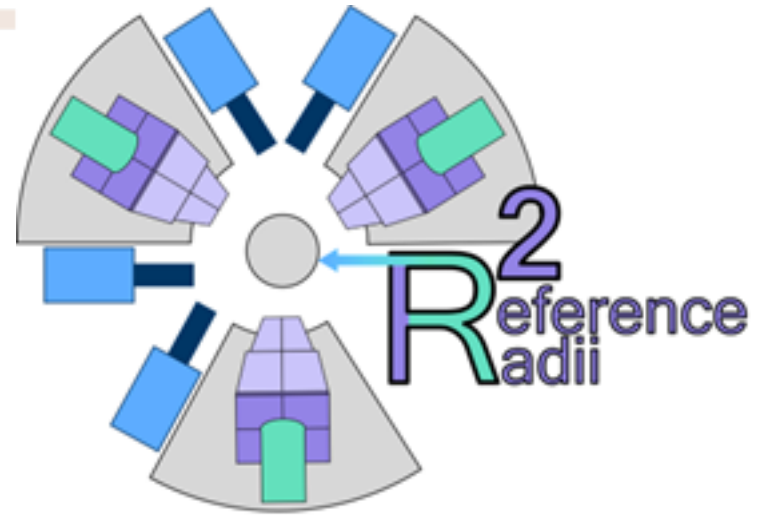
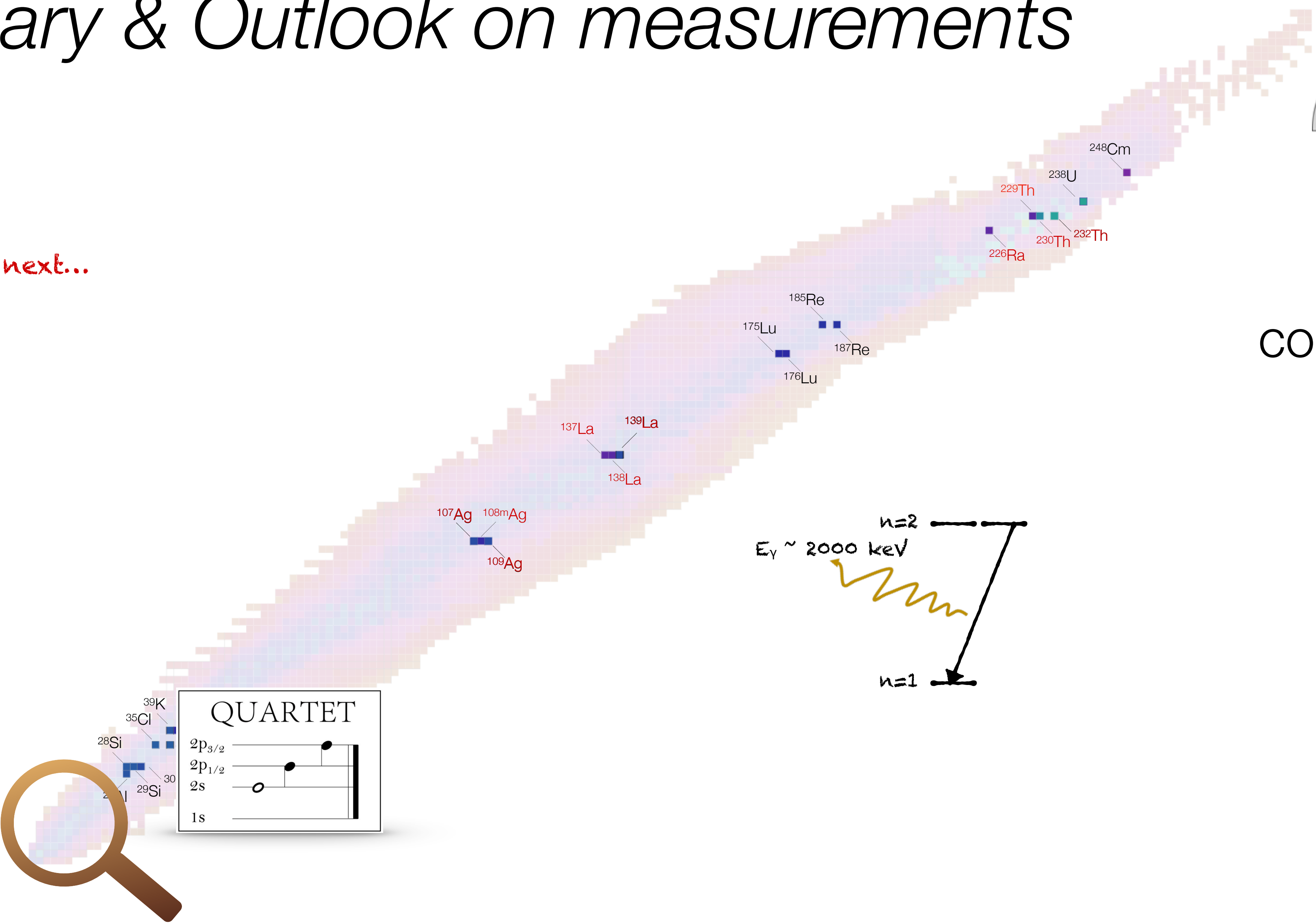


& muX
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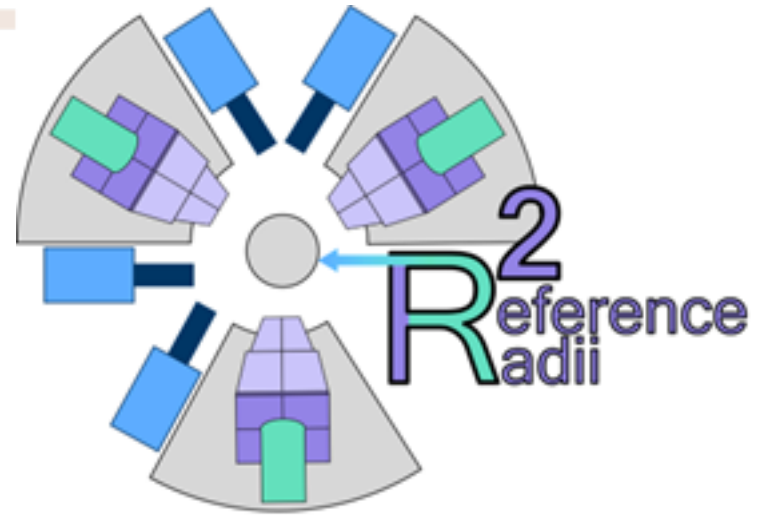
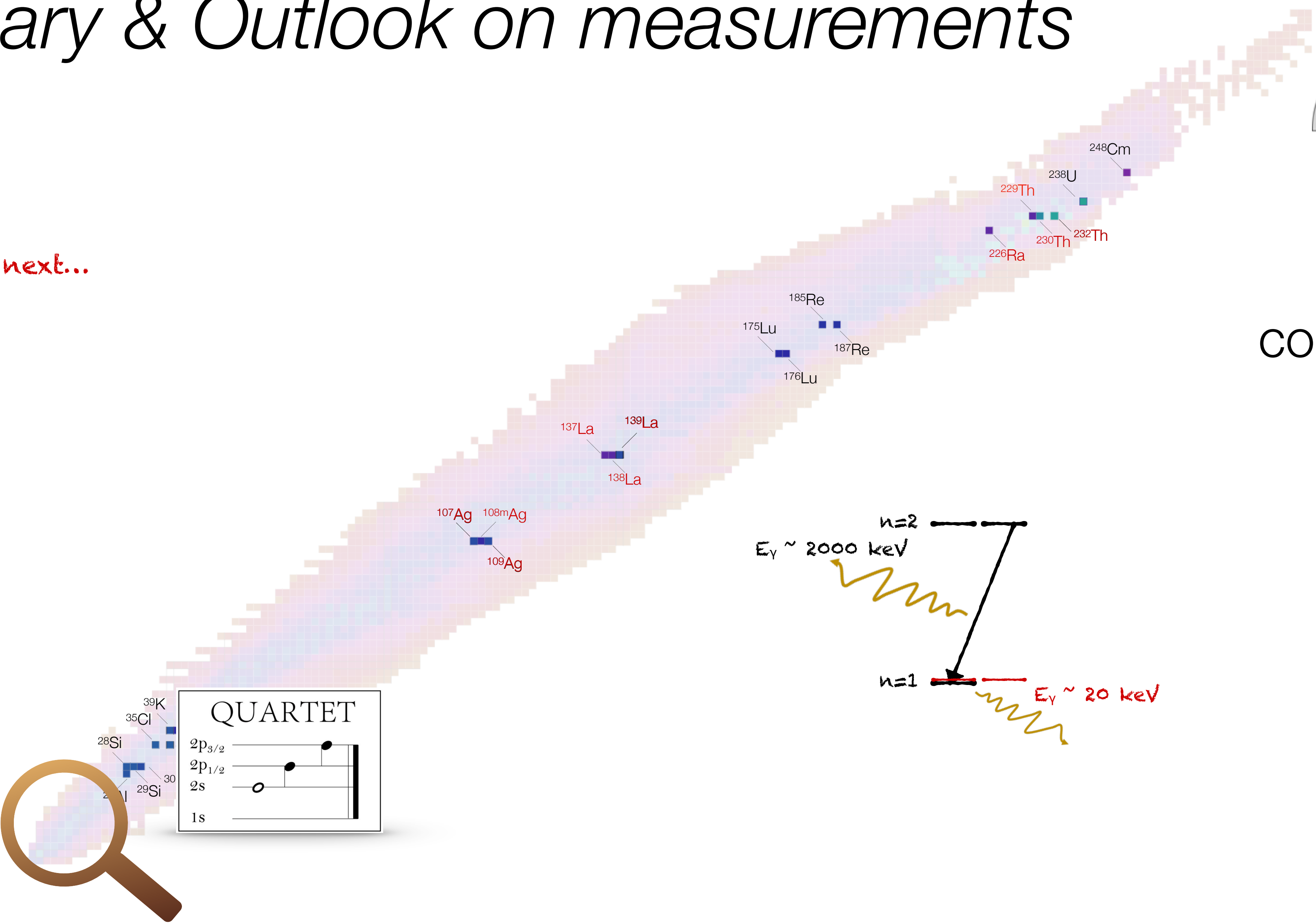


& muX
collaborations

Summary & Outlook on measurements

Measured...

Planned next...

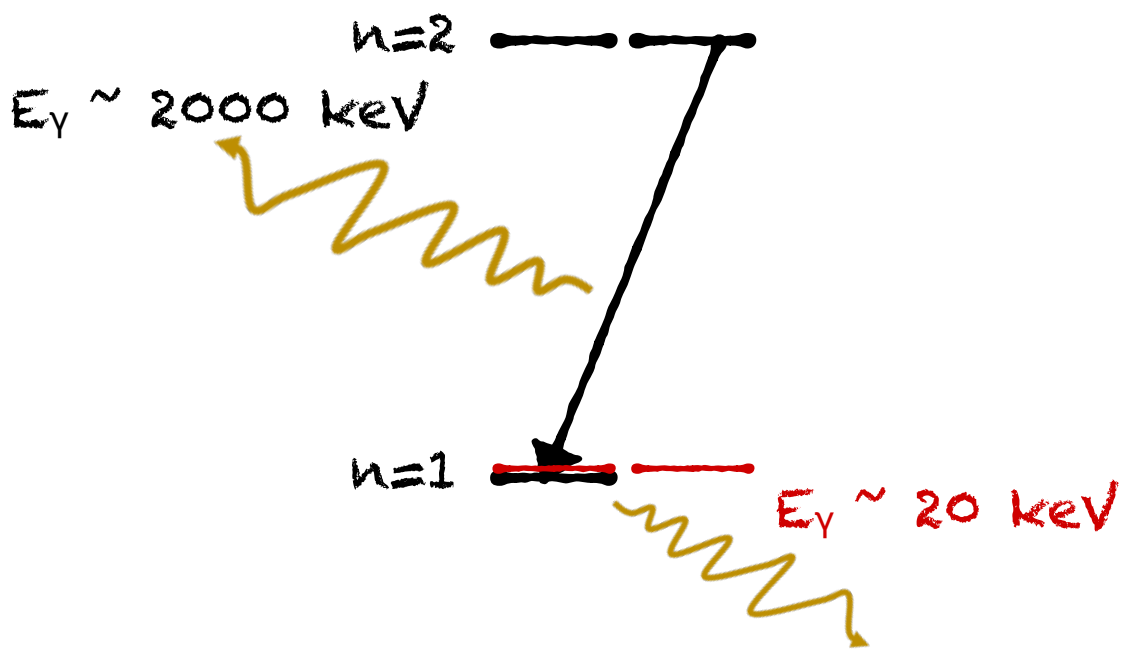
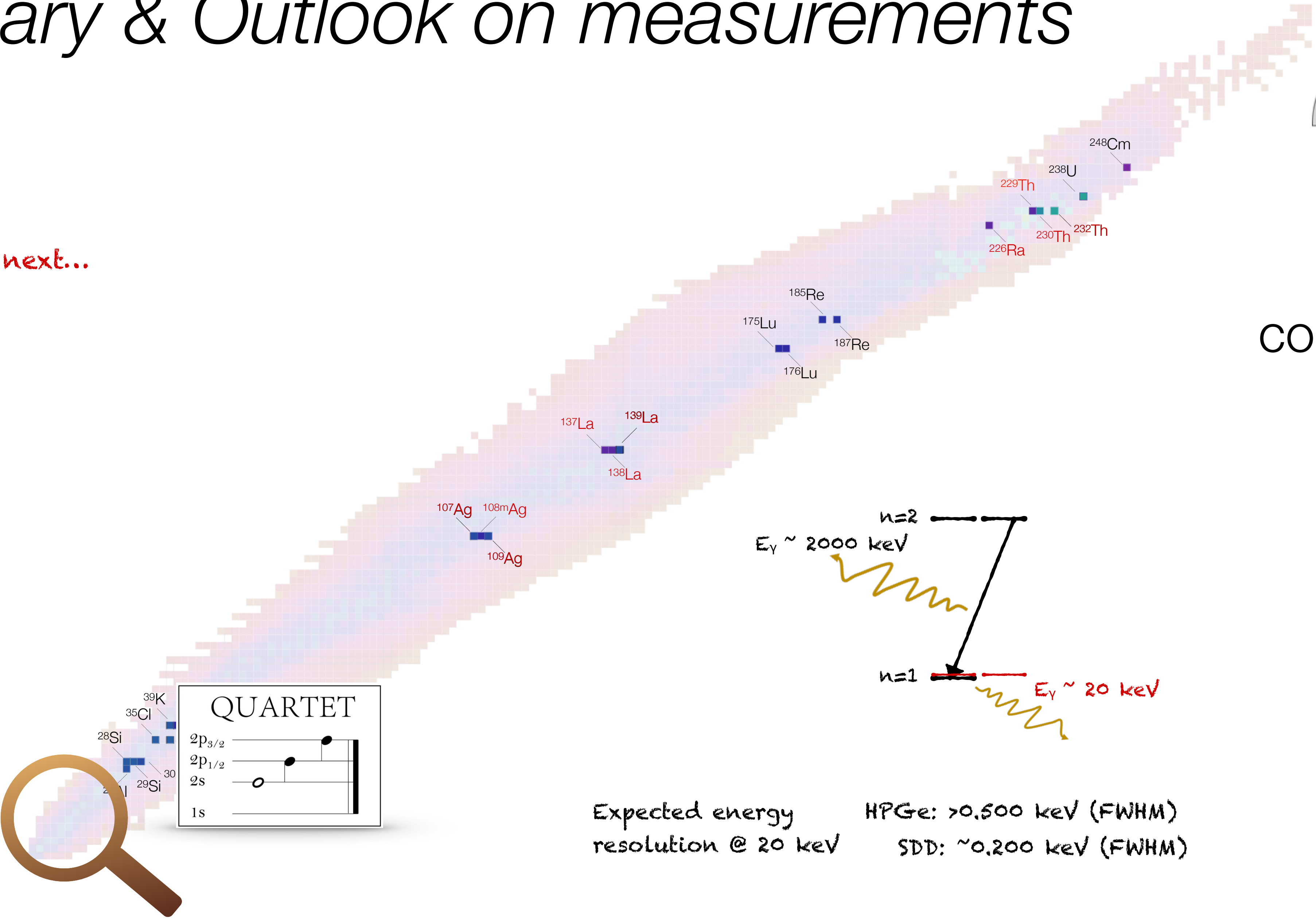


& muX collaborations

Summary & Outlook on measurements

Measured...

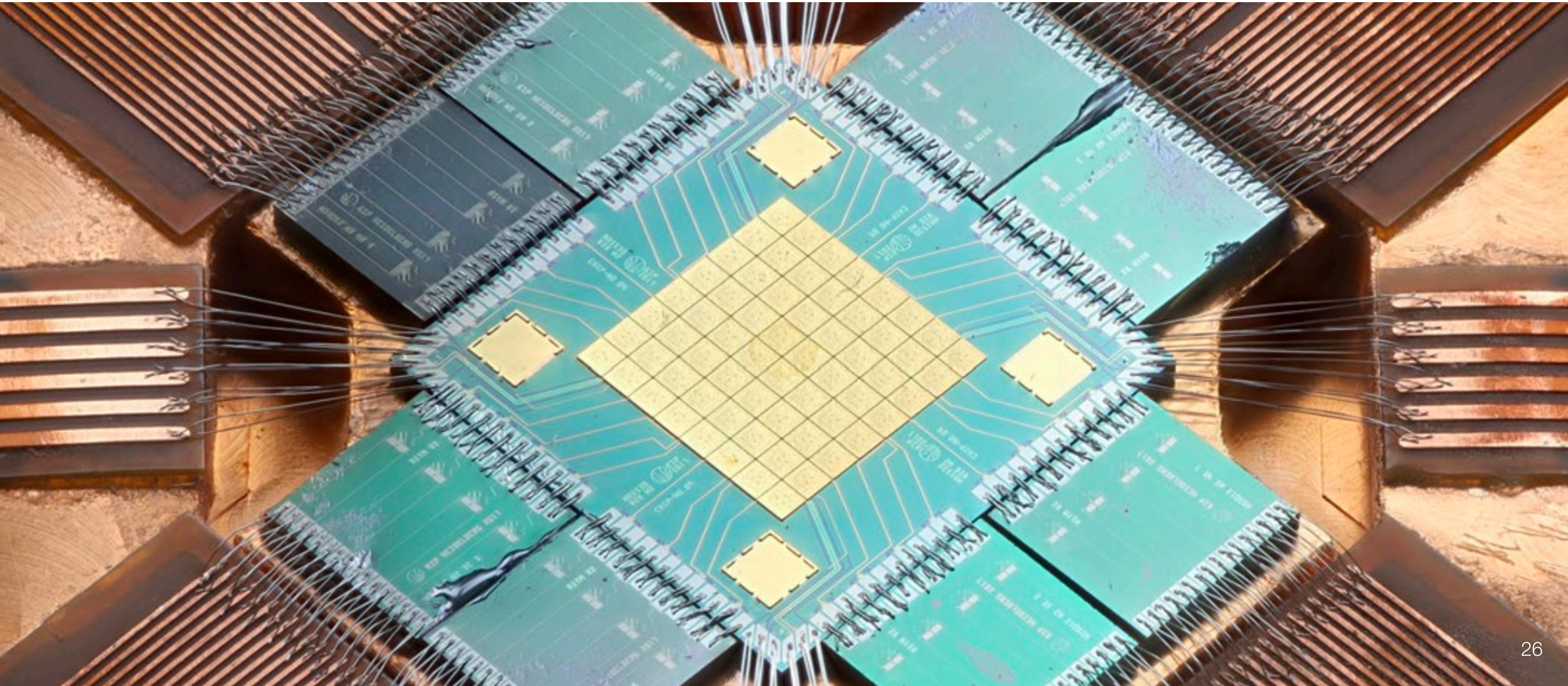
Planned next...



Expected energy resolution @ 20 keV HPGe: >0.500 keV (FWHM)
SDD: ~0.200 keV (FWHM)

Probing muonic x-ray energies with high precision with metallic magnetic calorimeters (MMC)

[J Low Temp. Phys. 216, 344–351 \(2024\)](#)



Remeasuring charge radii of low-Z isotopes

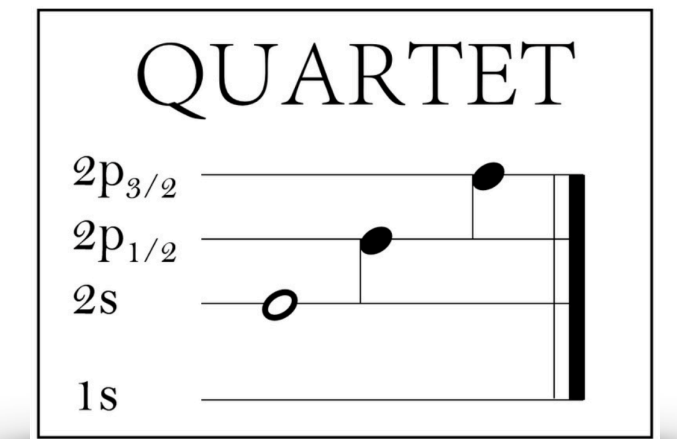
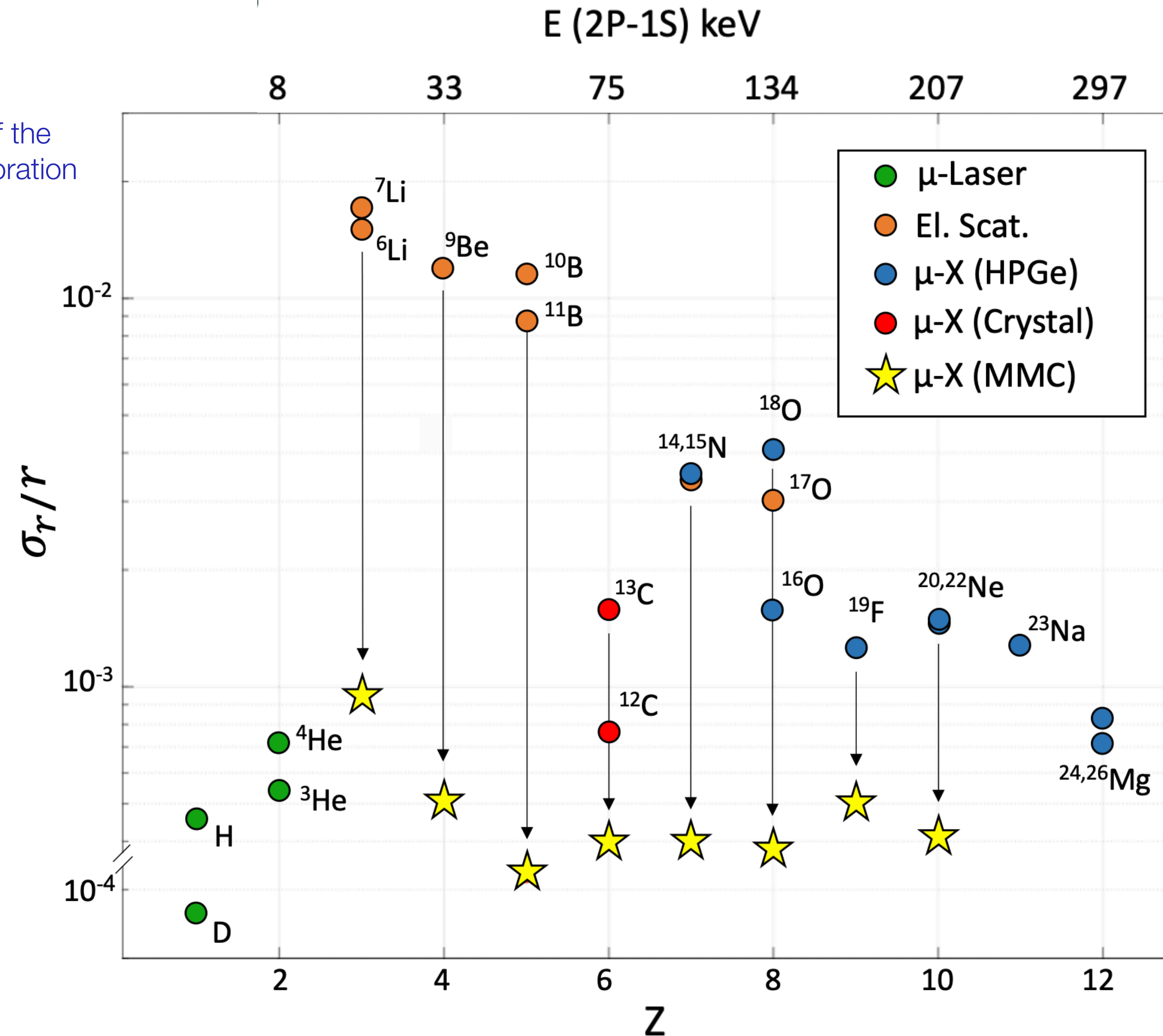


Figure courtesy of the
QUARTET collaboration



Remeasuring charge radii of low-Z isotopes

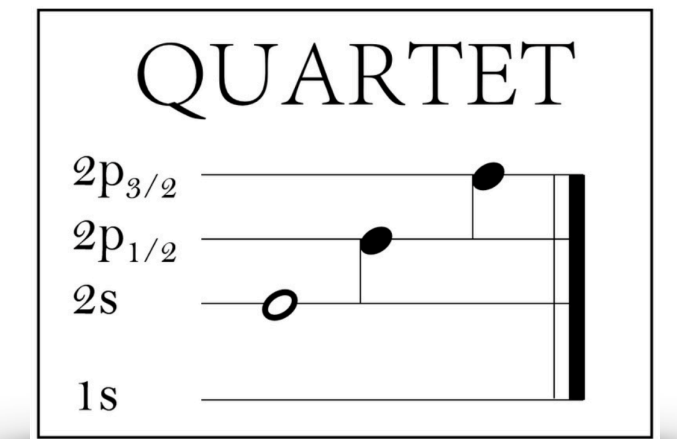
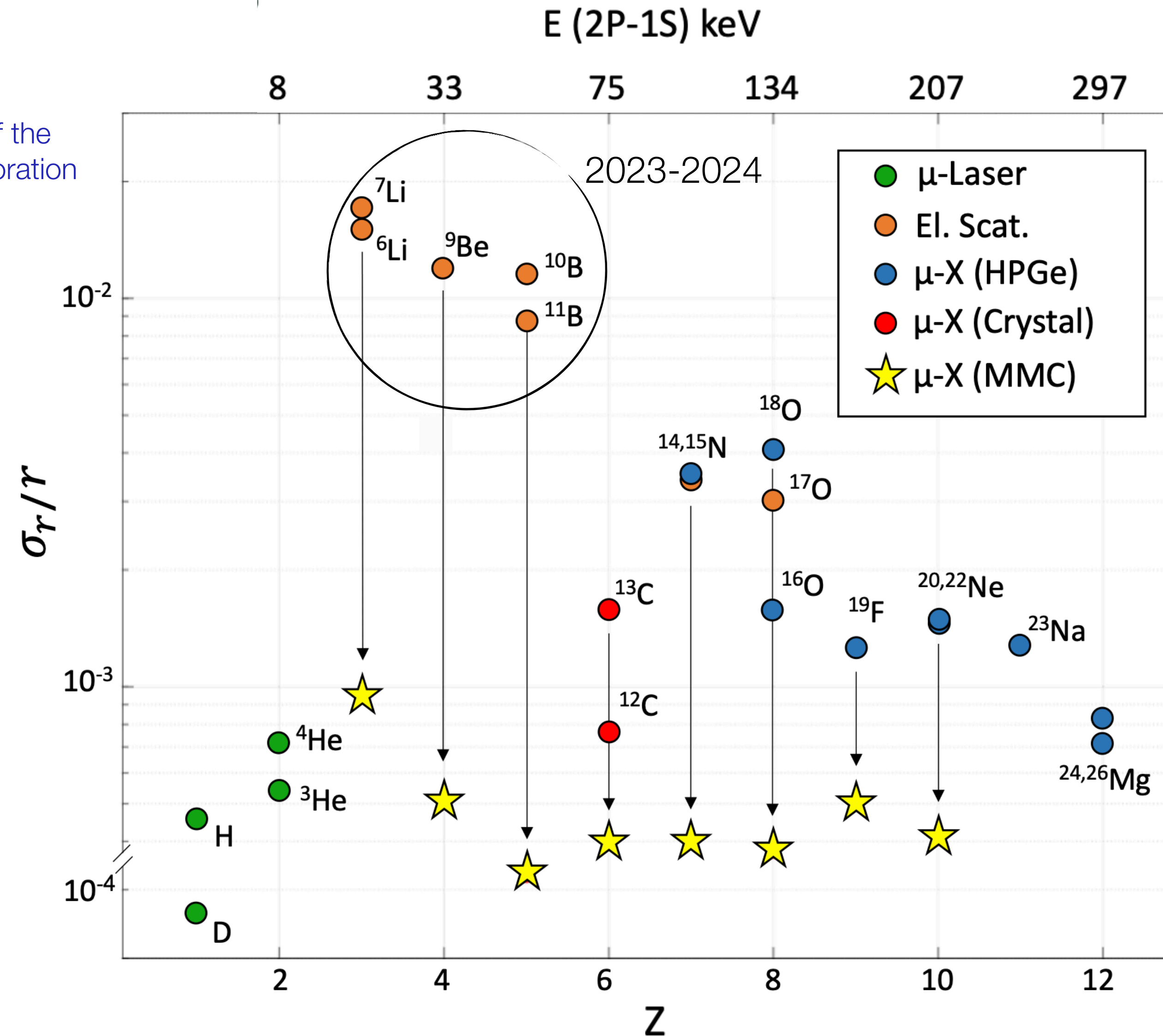


Figure courtesy of the
QUARTET collaboration



Remeasuring charge radii of low-Z isotopes

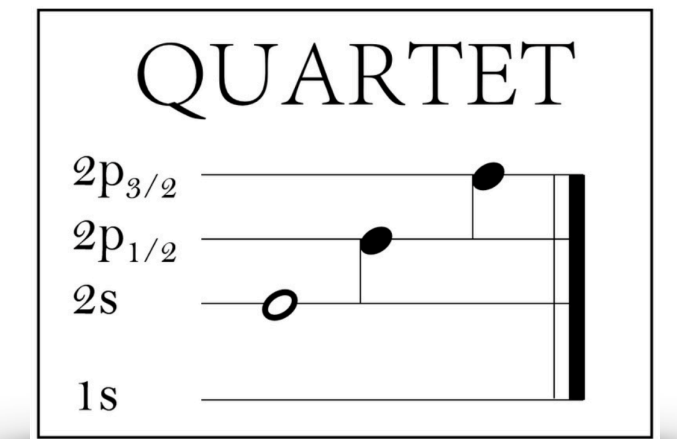
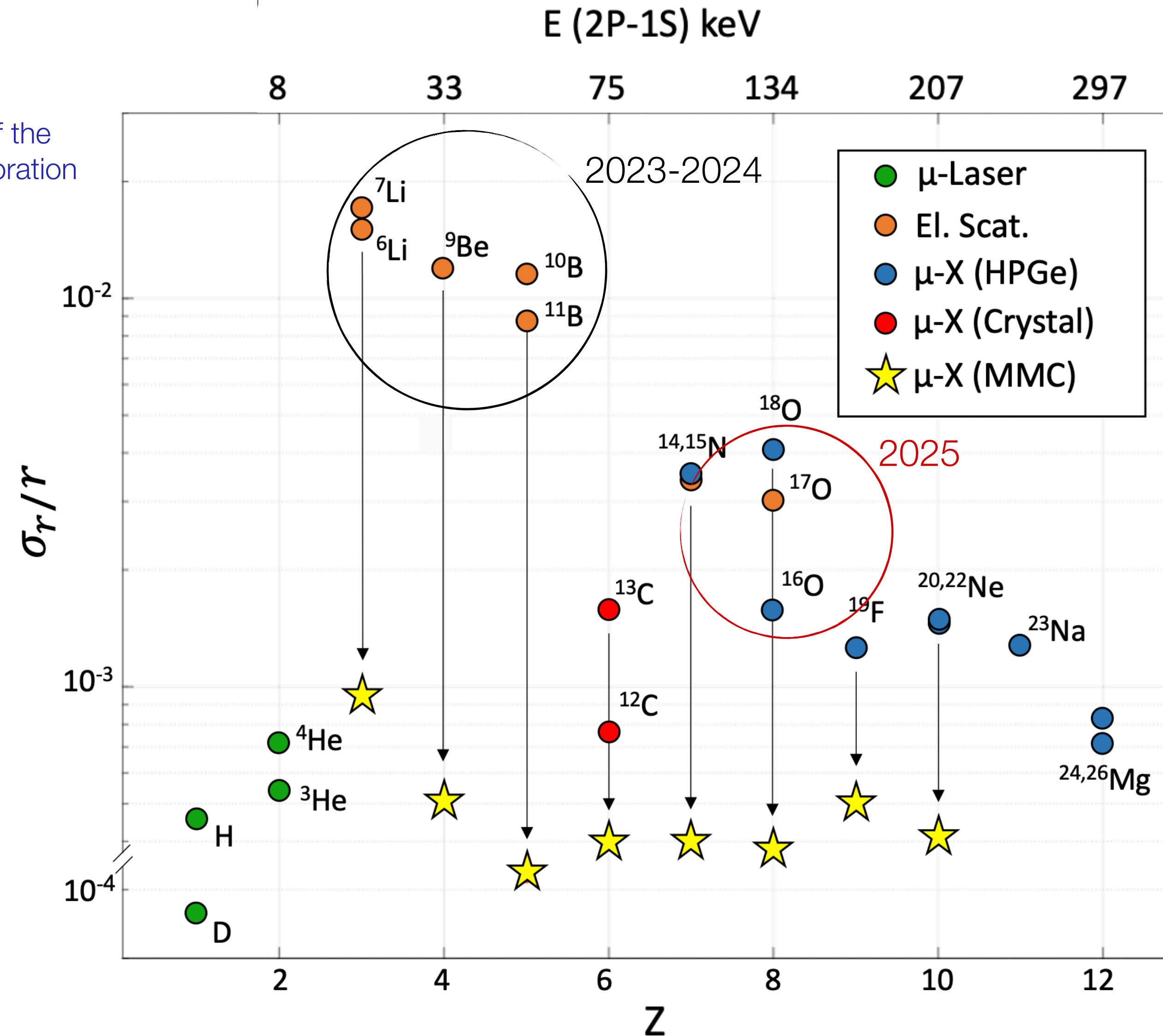


Figure courtesy of the
QUARTET collaboration



Behind the story told...



Thank you



looking forward to your
questions

Backup Slides

^{248}Cm 2p1s analysis

Transition energy dependence on (R_N, Q)

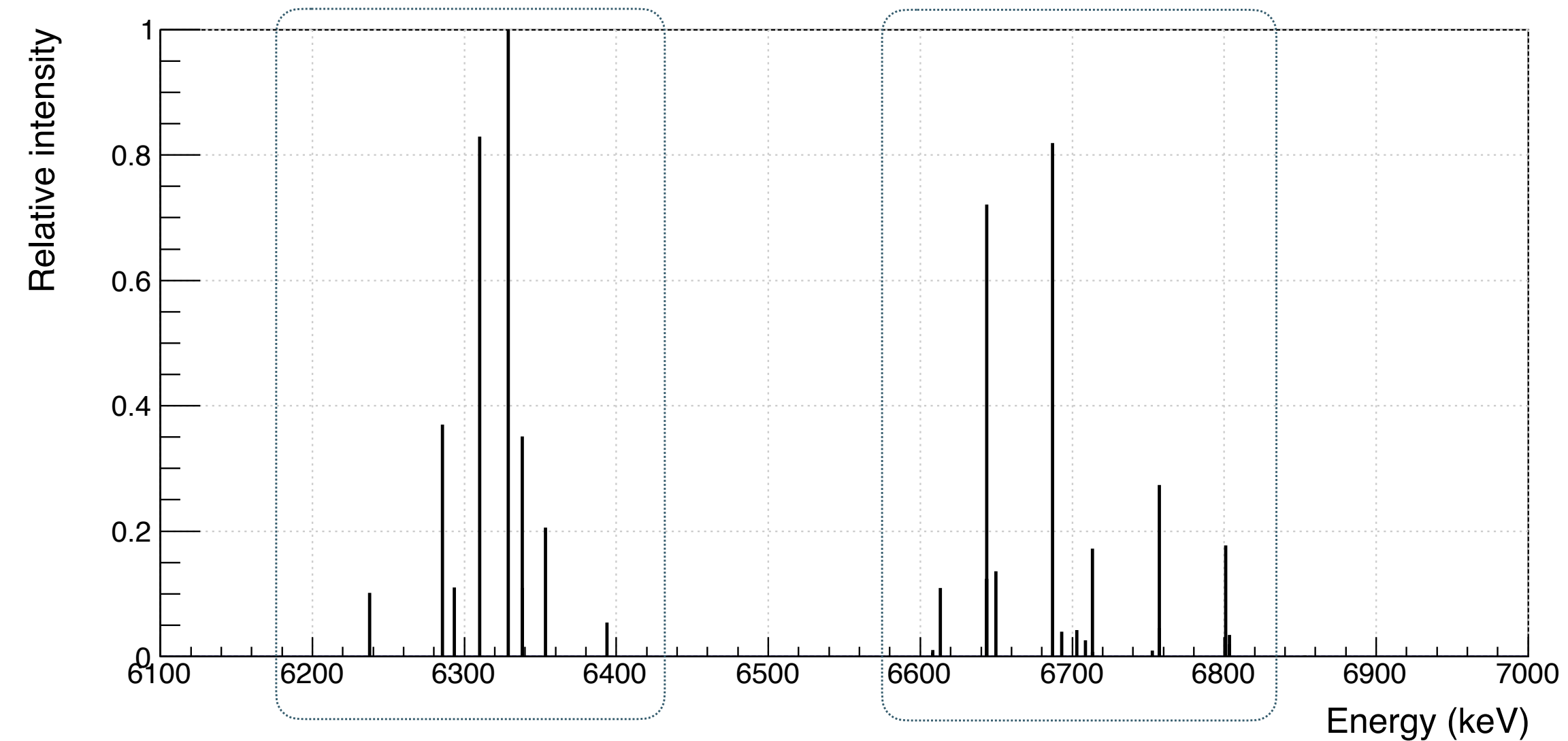
Theoretical calculations are performed by
N. Oreshkina & I. Valuev, MPIK, Heidelberg

$$dR = \frac{R}{R_N}, \text{ where } R_N = 5.8687 \text{ fm}$$

$$dQ = \frac{Q}{Q_N}, \text{ where } Q_N = 12.04 \text{ b}$$

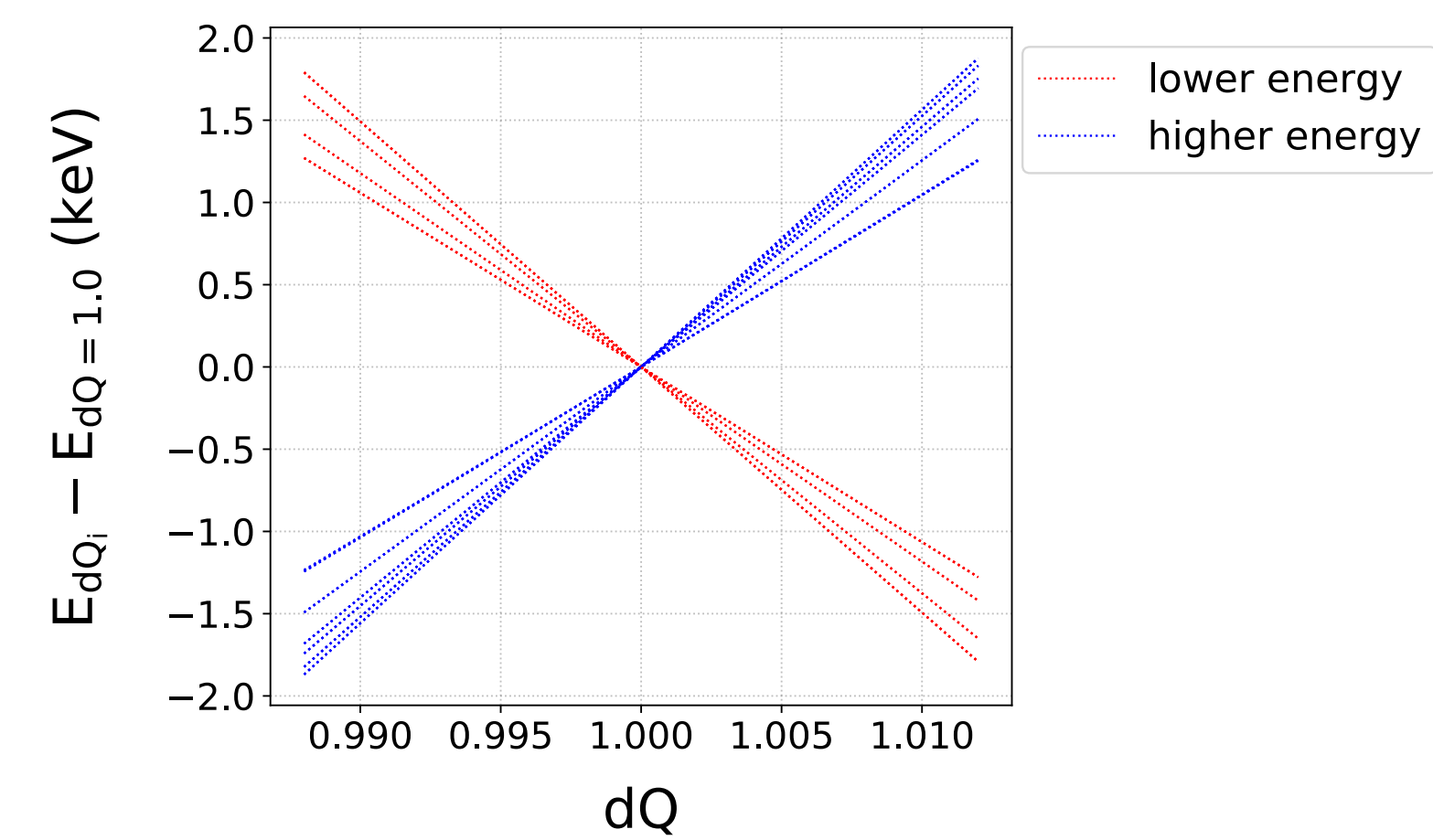
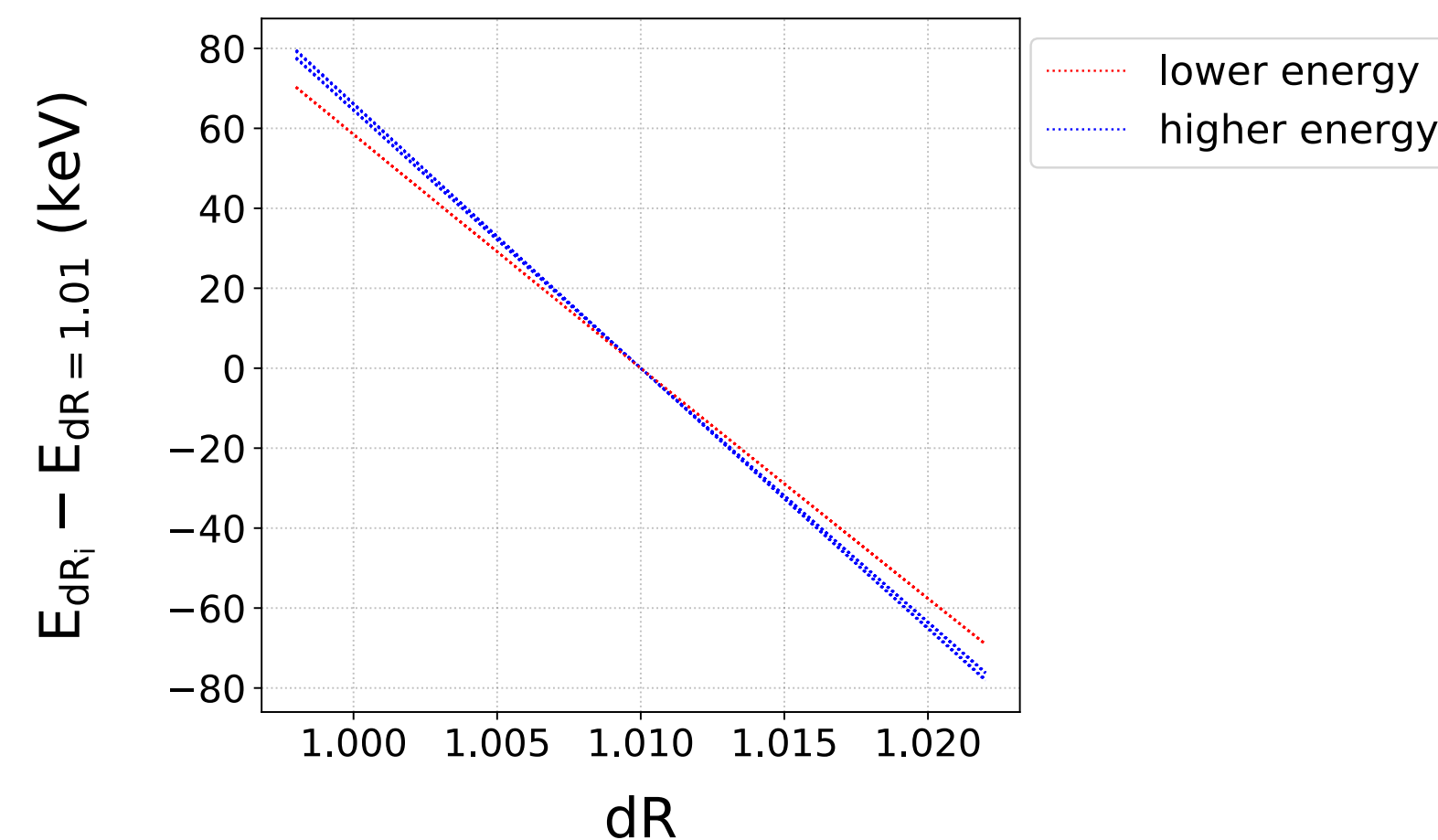
^{248}Cm is even-even $\rightarrow$ This is the **intrinsic Q** calculated as $16\pi B(E2)_{0+ \rightarrow 2+} / 5e^2]^{1/2}$, integrated in all possible orientations $\rightarrow$ spherical density (is that right?)

Dynamic hyperfine effect!!



lower-energy multiplet

higher-energy multiplet

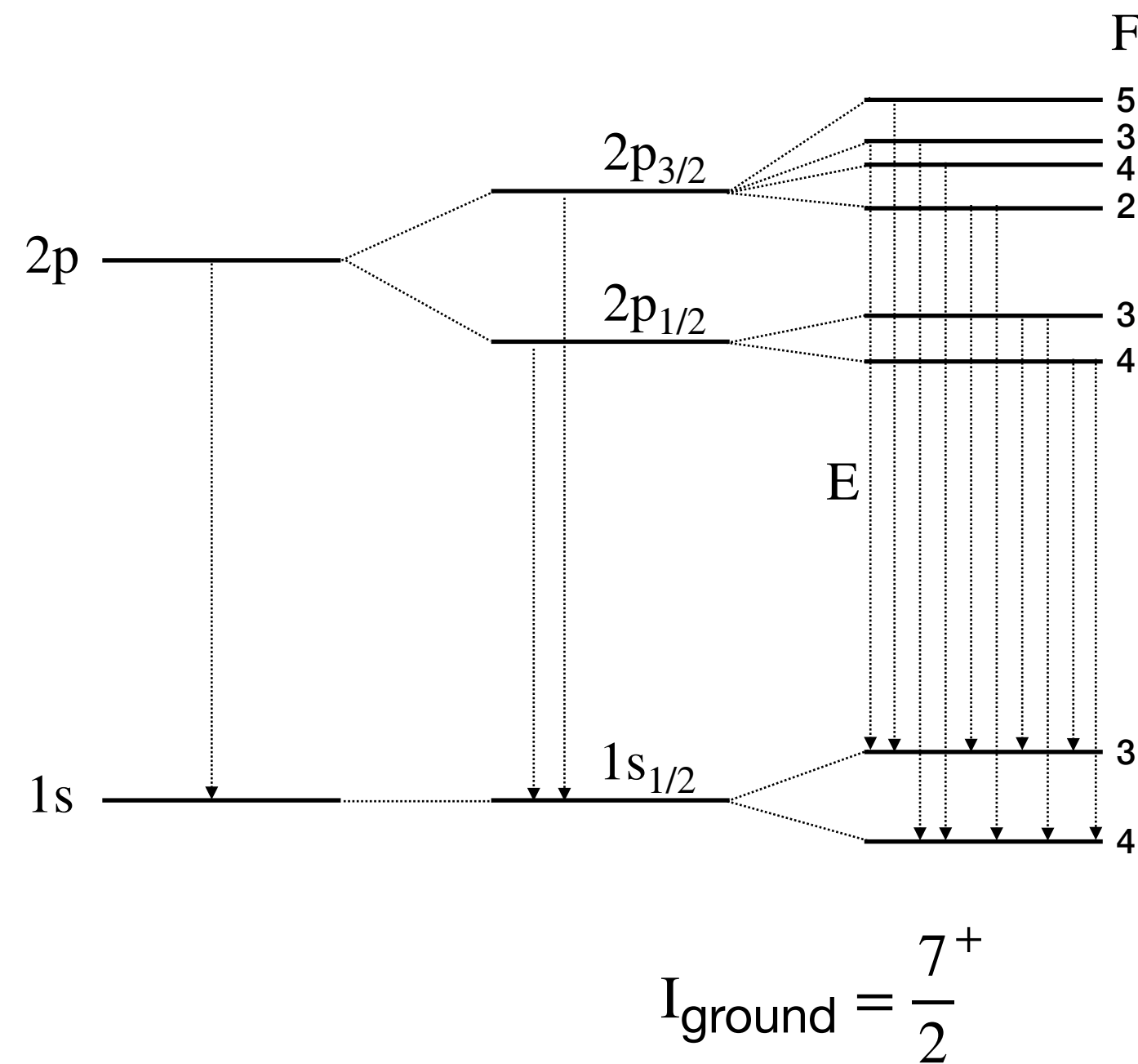


Muonic atoms & Hyperfine Splitting

The bless and the curse

Fine splitting (FS): $\vec{J} = \vec{L} + \vec{S}$

Static hyperfine splitting (HFS): $\vec{F} = \vec{I} + \vec{J}$



- Energy displacement due to the E2 and M1 interactions:

$$\Delta E_F(\text{E2}) = A_2 6 \frac{K(K+1) - 4/3 I(I+1)J(J+1)}{4I(2I-1)J(2J-1)}$$

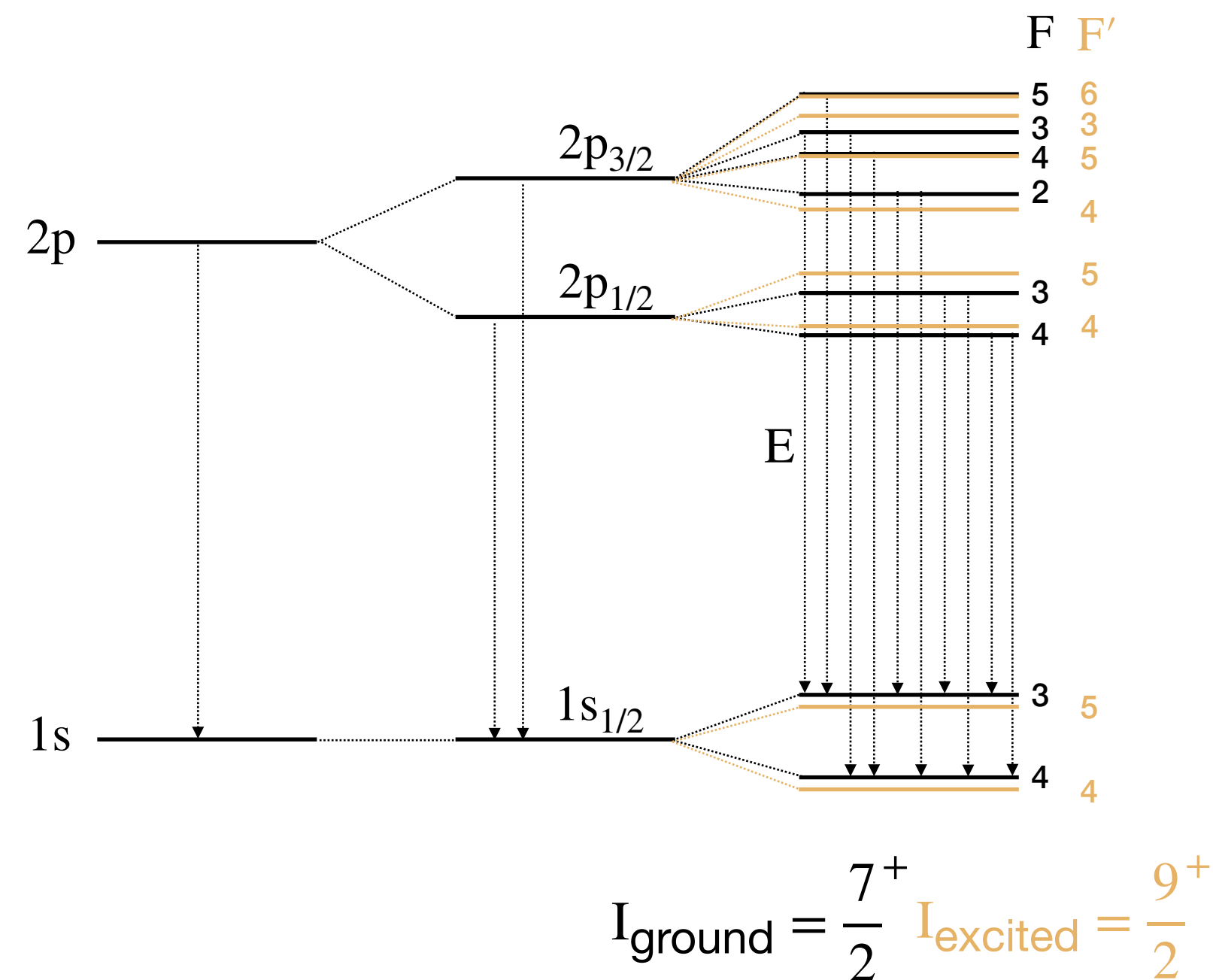
$$\Delta E_F(\text{M1}) = \frac{A_1}{2} \{F(F+1) - I(I+1) - J(J+1)\}$$

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Dynamic HFS effect

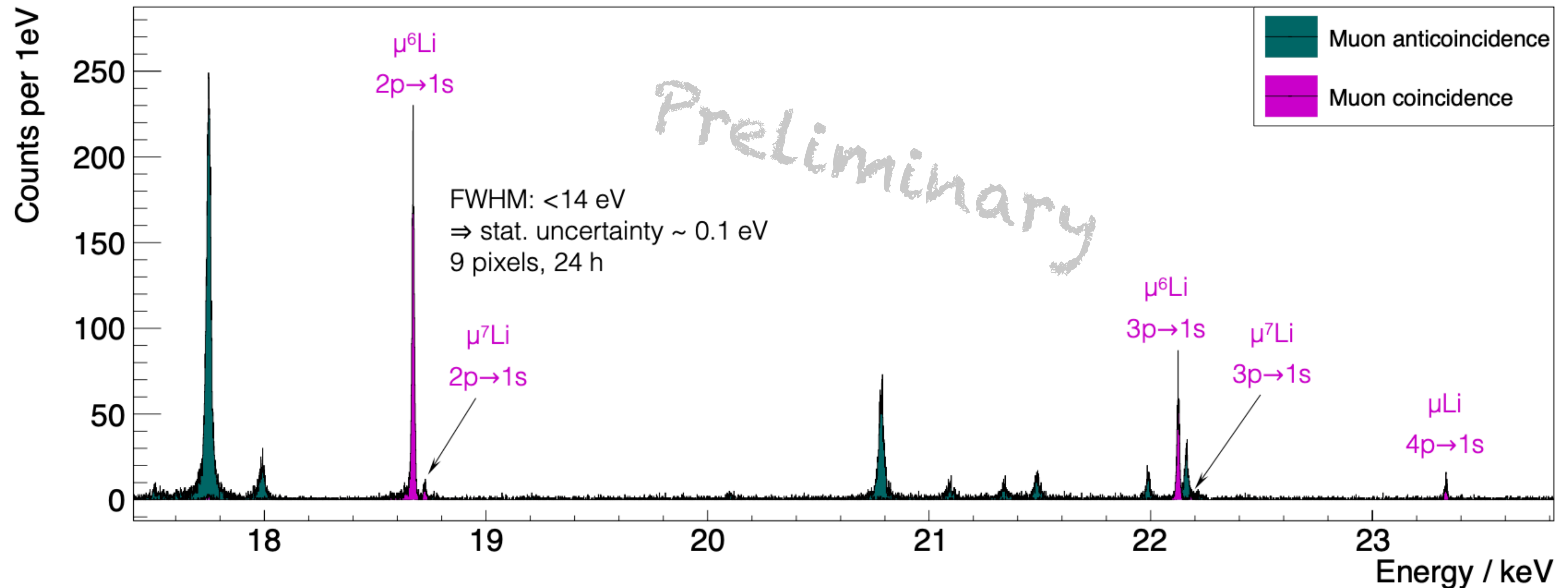
- The hyperfine levels from ground and excited nuclear states are mixed due to the high energy of muonic transitions
- HFS also observed in even-even nuclei with zero spin in the ground state

Measurement demonstration of lithium

Energy spectrum

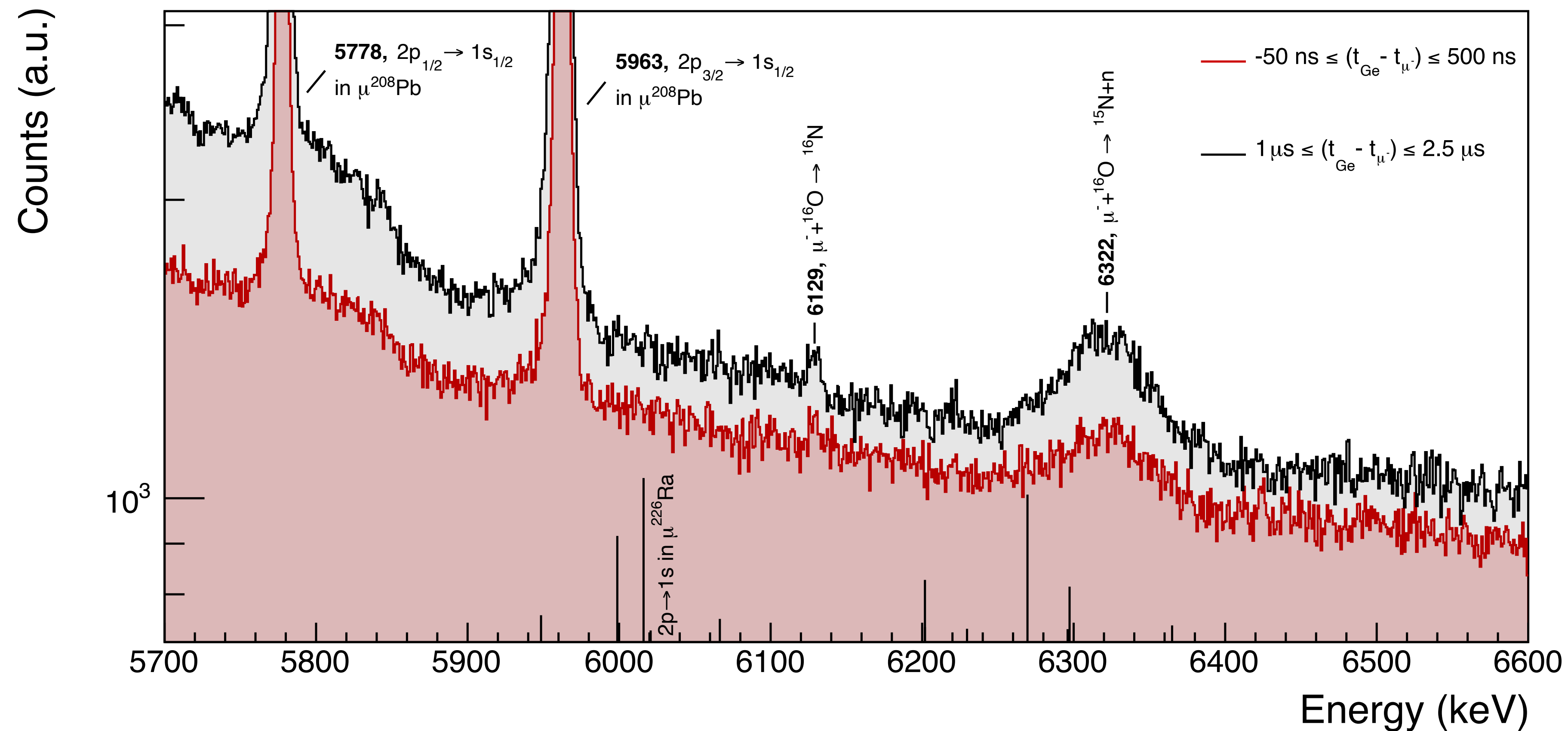
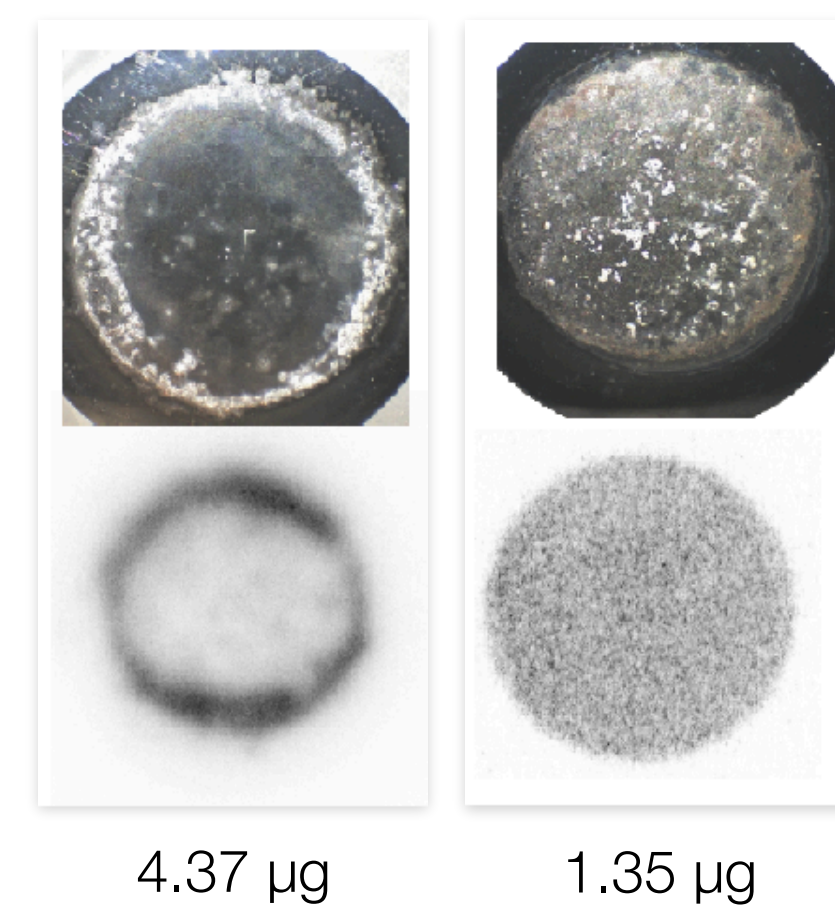
calibration sources ^{241}Am , ^{109}Cd , ^{55}Fe & $\mu^6\text{Li}$ (95% enriched)

Analysis of data and image courtesy of **Katharina von Schoeler**



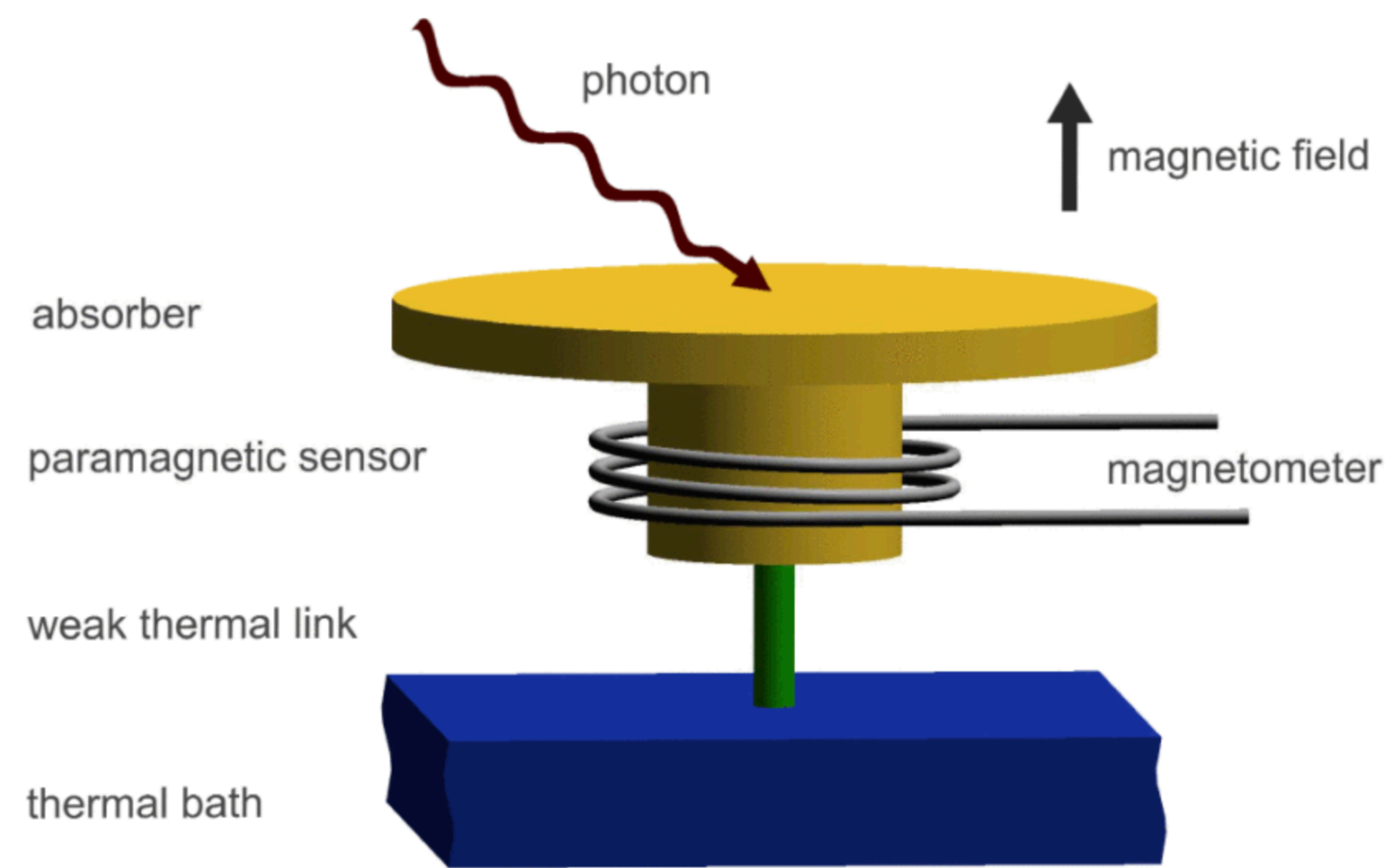
^{226}Ra spectrum in the 2p1s region

No 2p1s structure is observed



Working principle of MMC

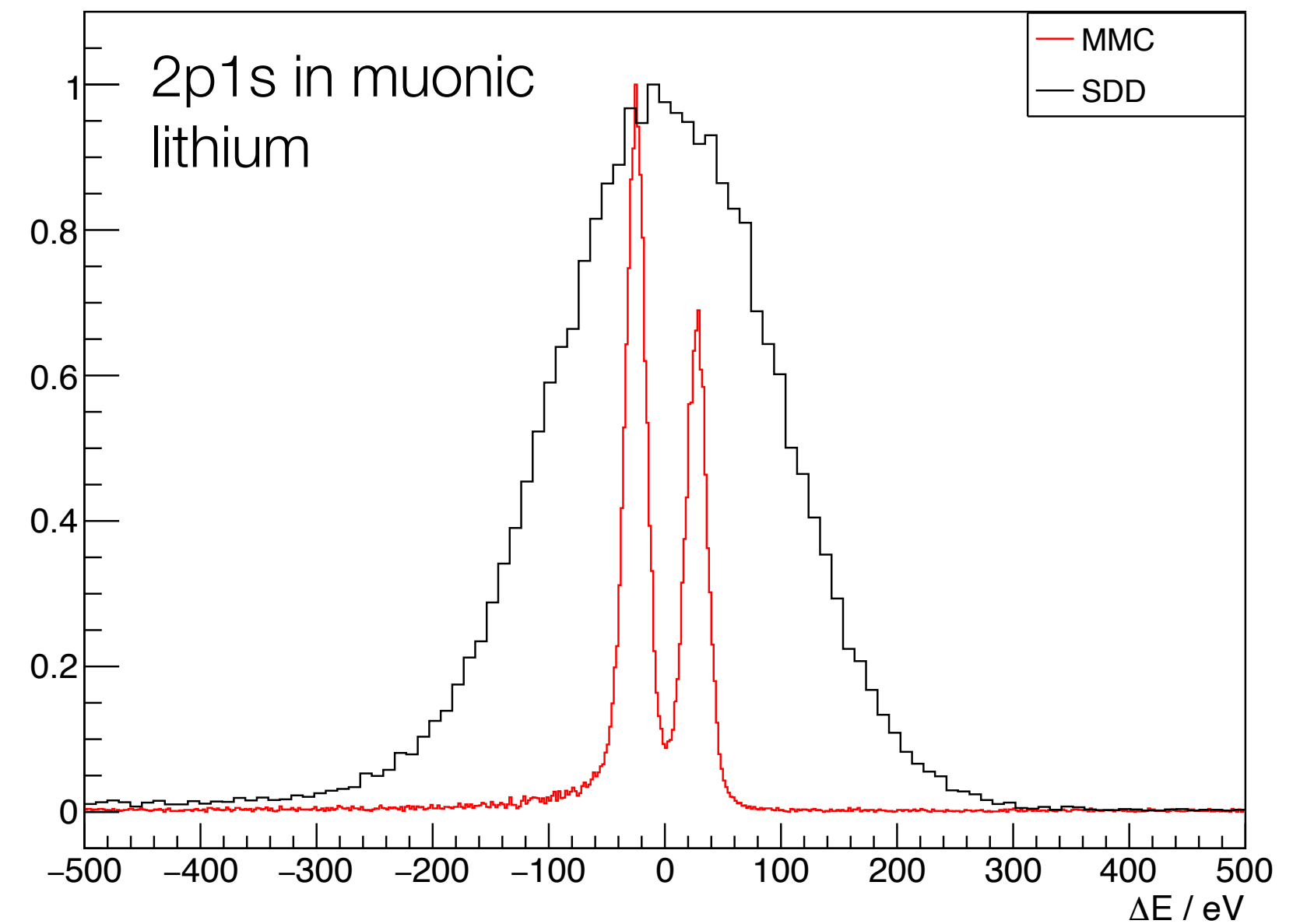
Achieving a high energy resolution



[IEEE Transactions on Applied Superconductivity 19, 63 \(2009\)](#)

- Tiny pixel $500 \times 500 \mu\text{m}^2$
- Temperature increase of the detector due to photon's absorption
- Decrease of sensor's magnetization, read by magnetometer (SQUID)
- Connected to thermal bath, the detector operates in a cryostat.

Image courtesy of Katharina von Schoeler



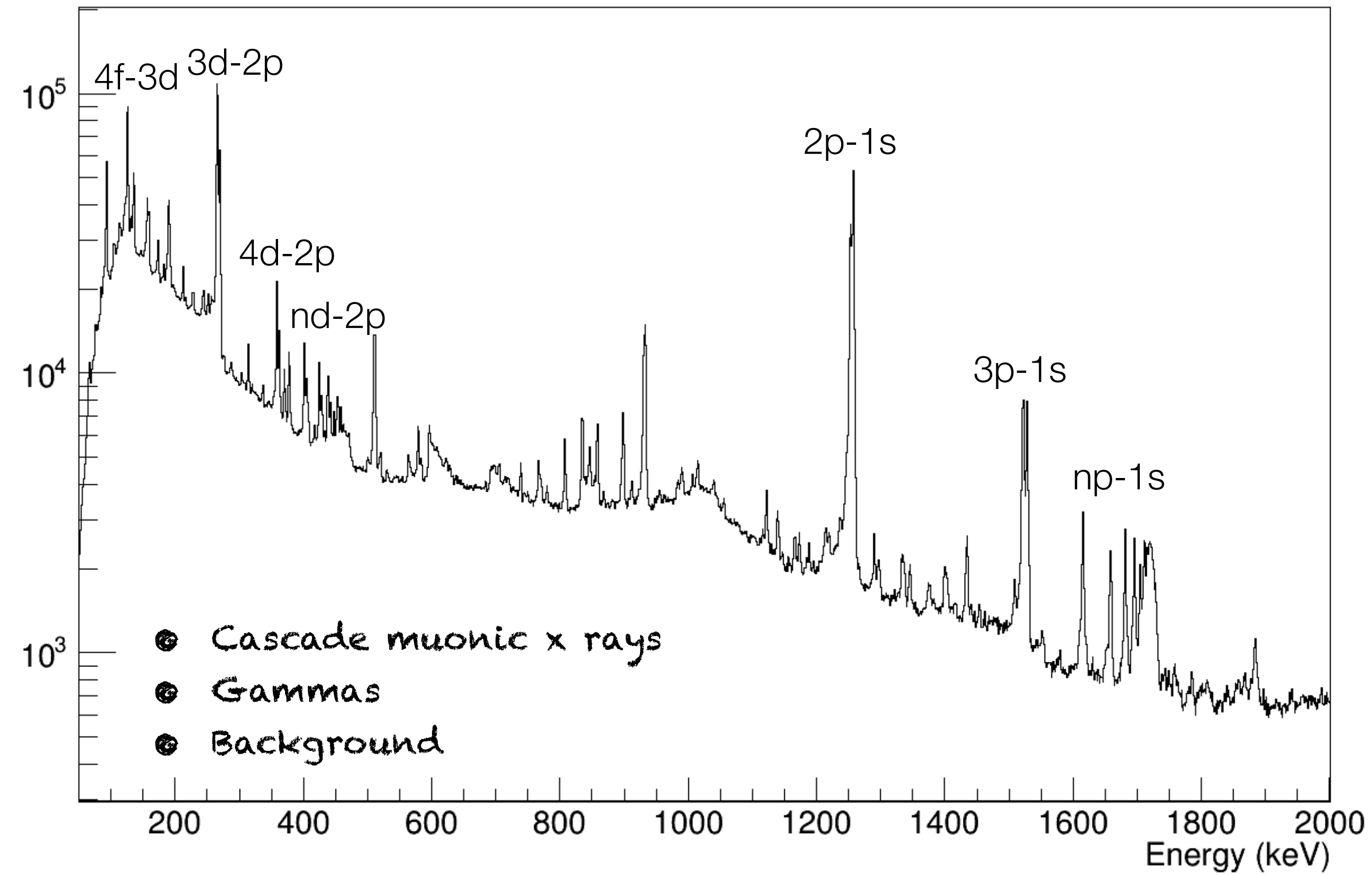
Expected energy
resolution @ 20
keV

HPGe: >0.500 keV (FWHM)
SDD: ~0.200 keV (FWHM)
MMC: ~0.010 keV (FWHM)

Muonic atoms

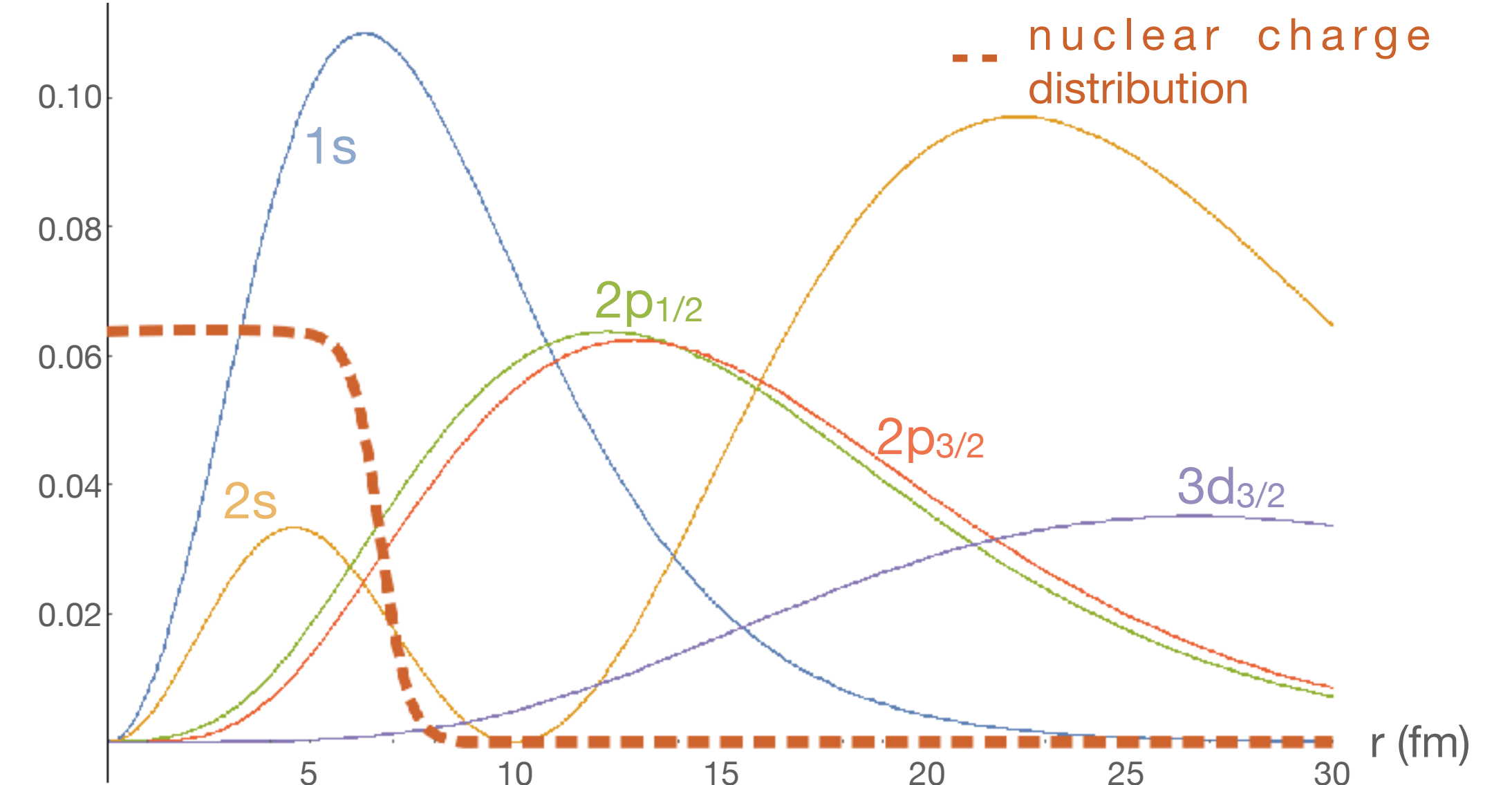
[Eur. Phys. J. Plus 135, 777 \(2020\)](#)

muonic iron



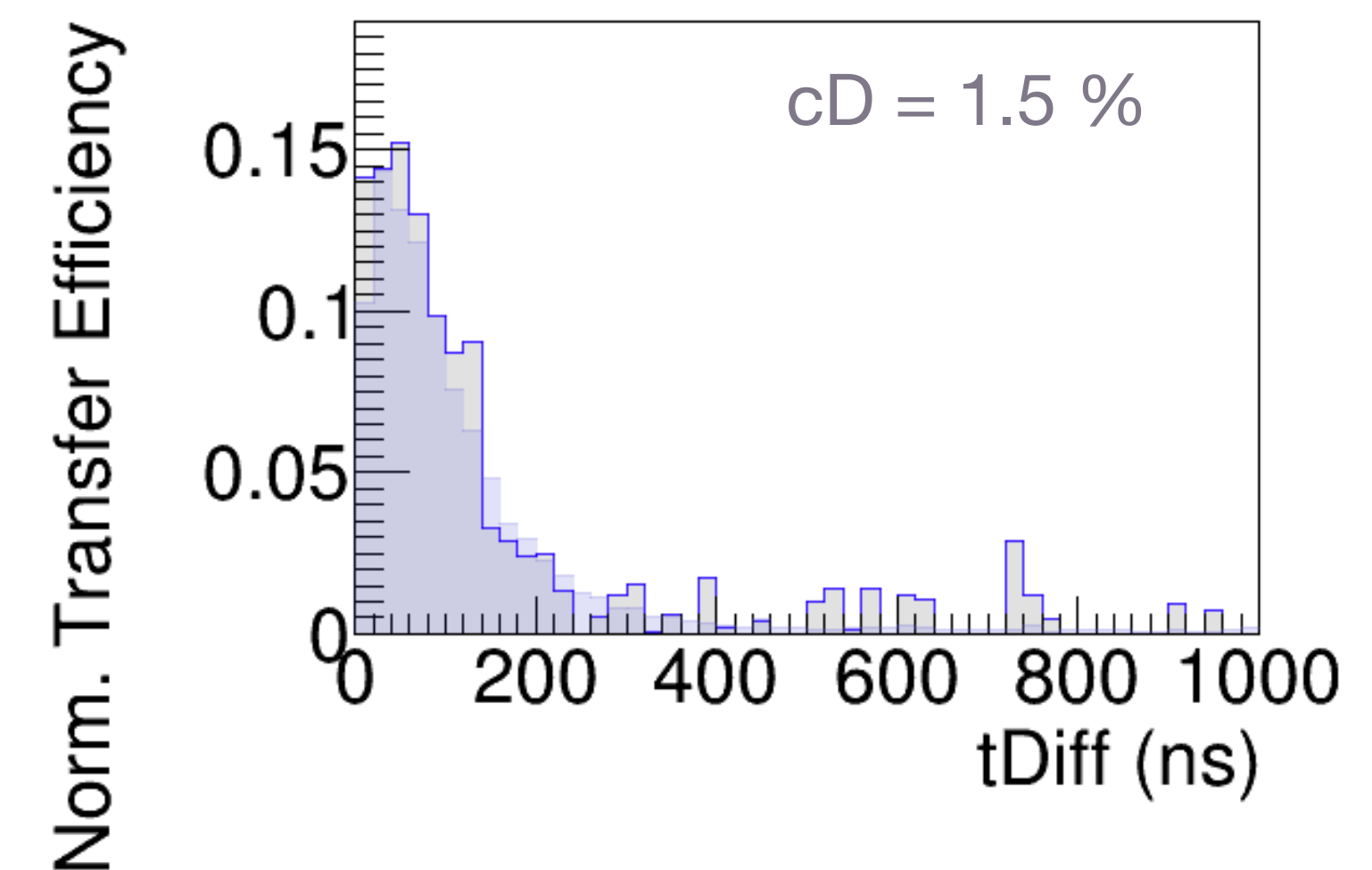
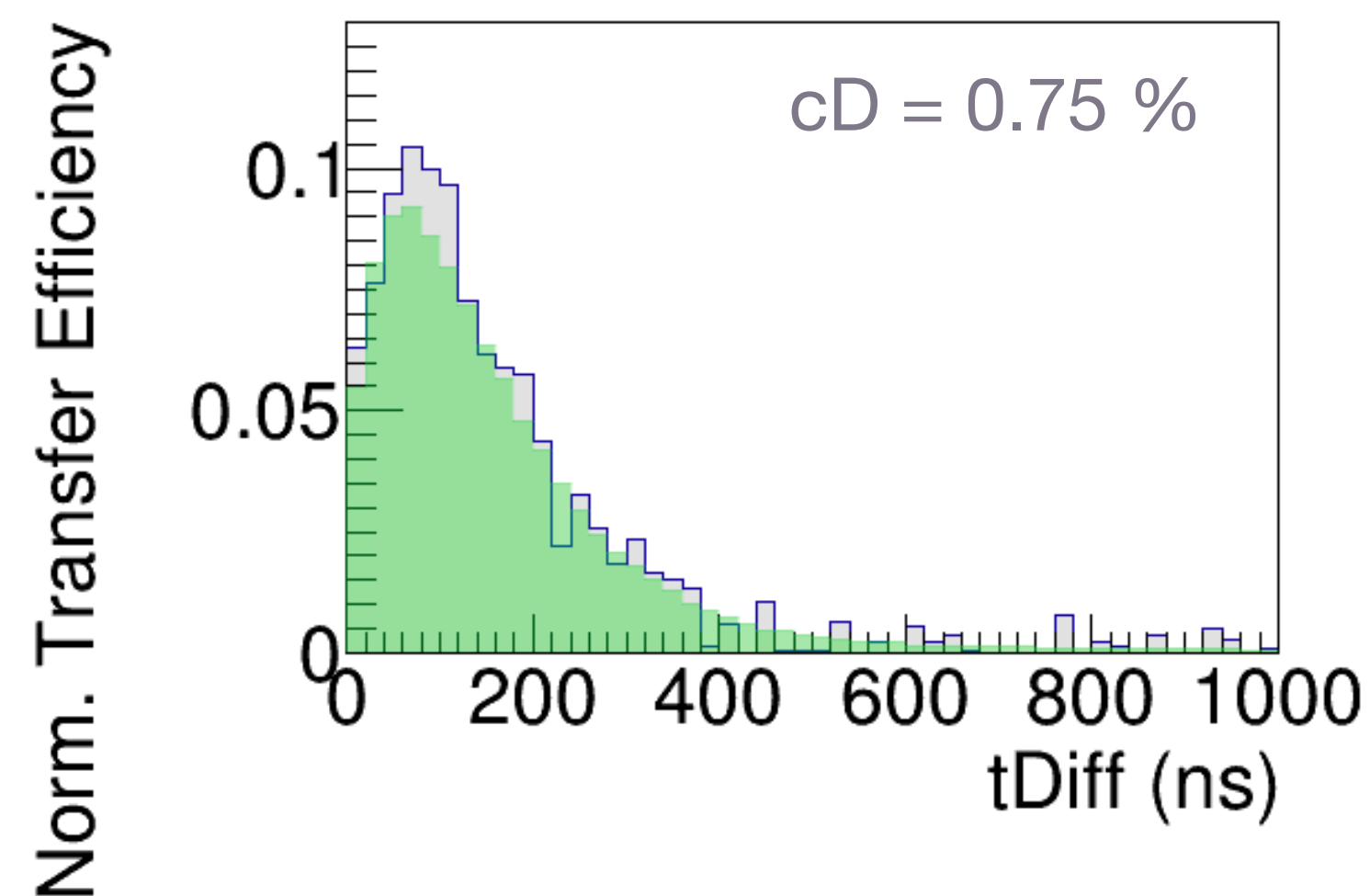
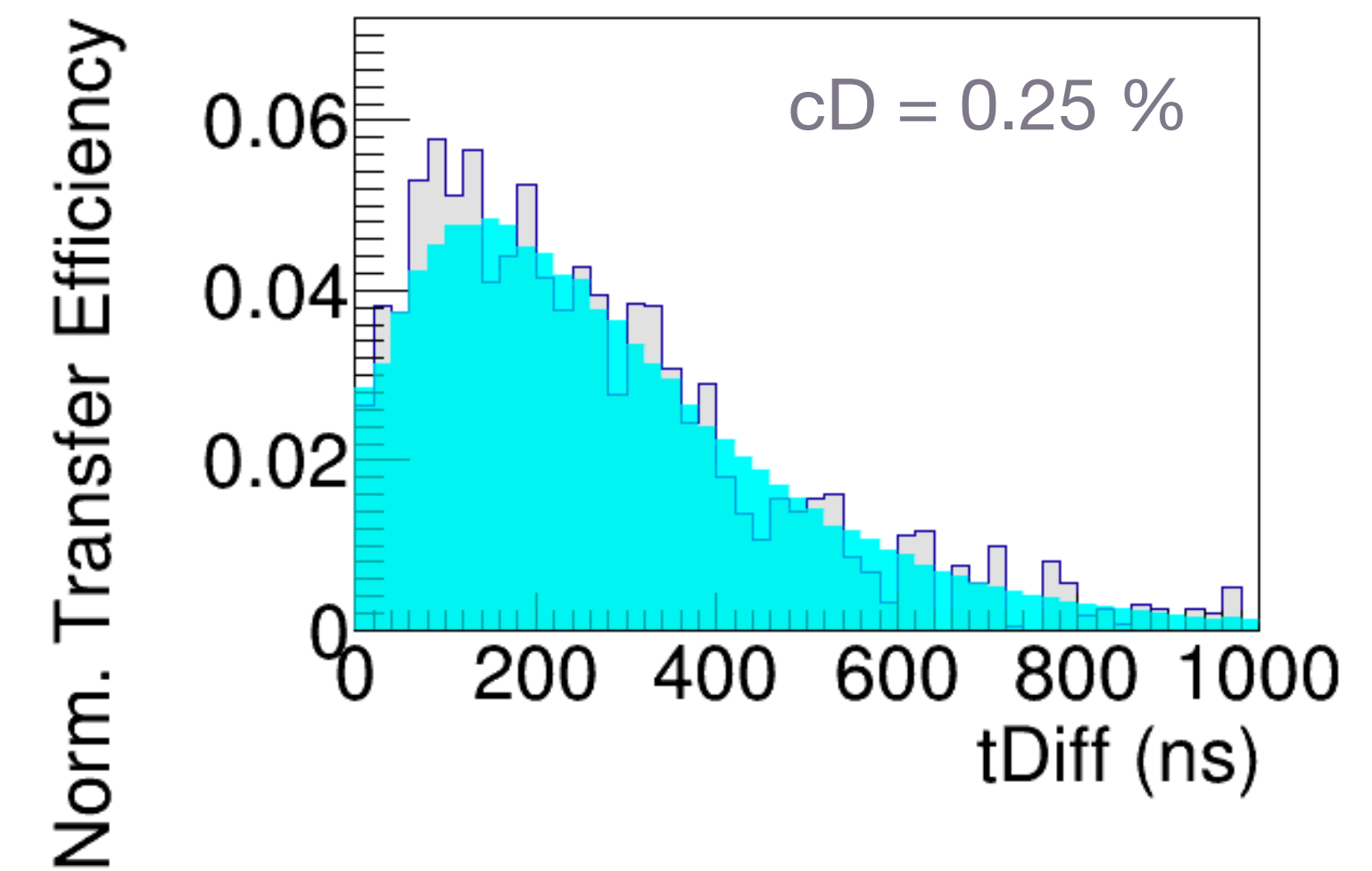
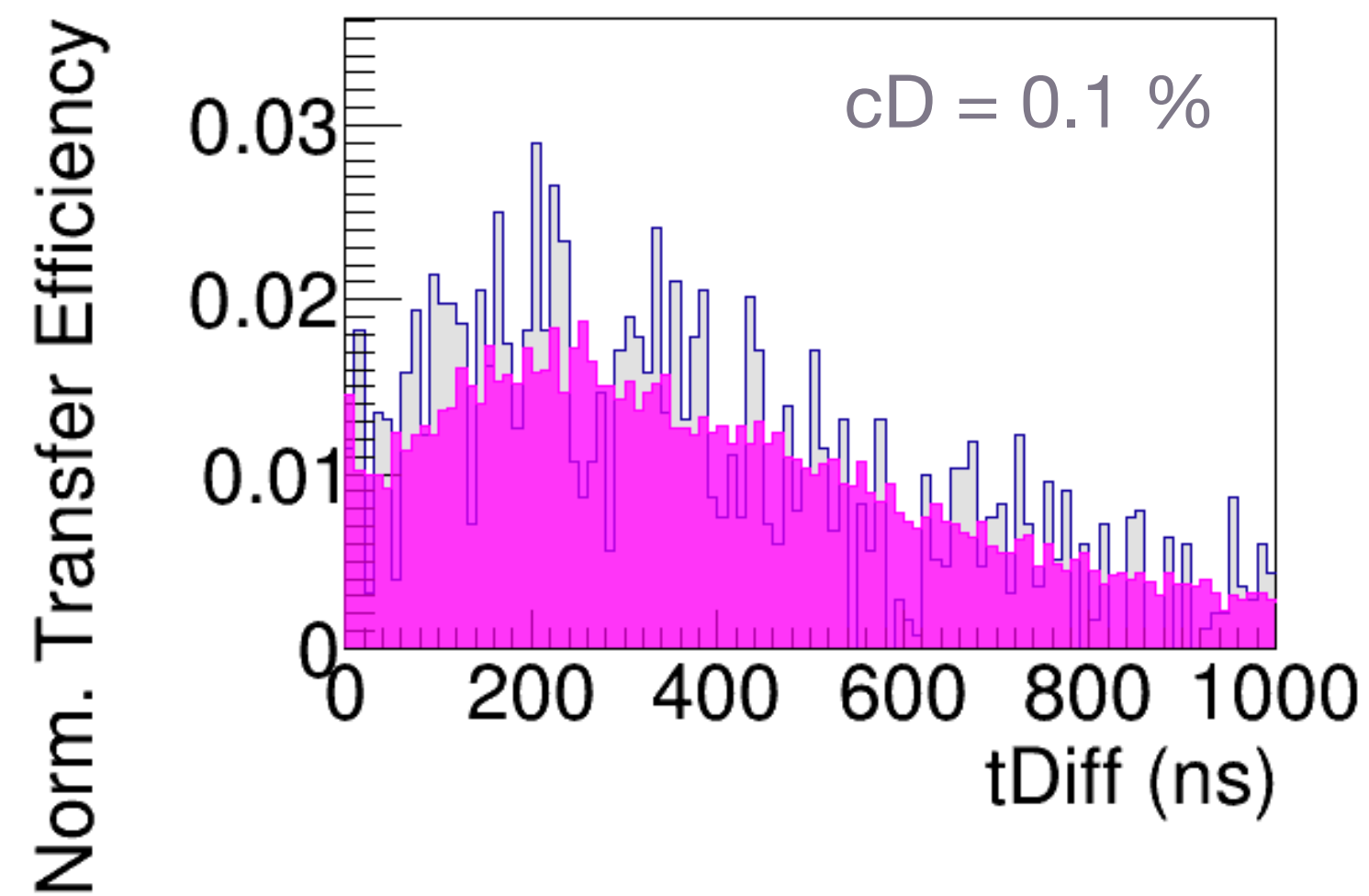
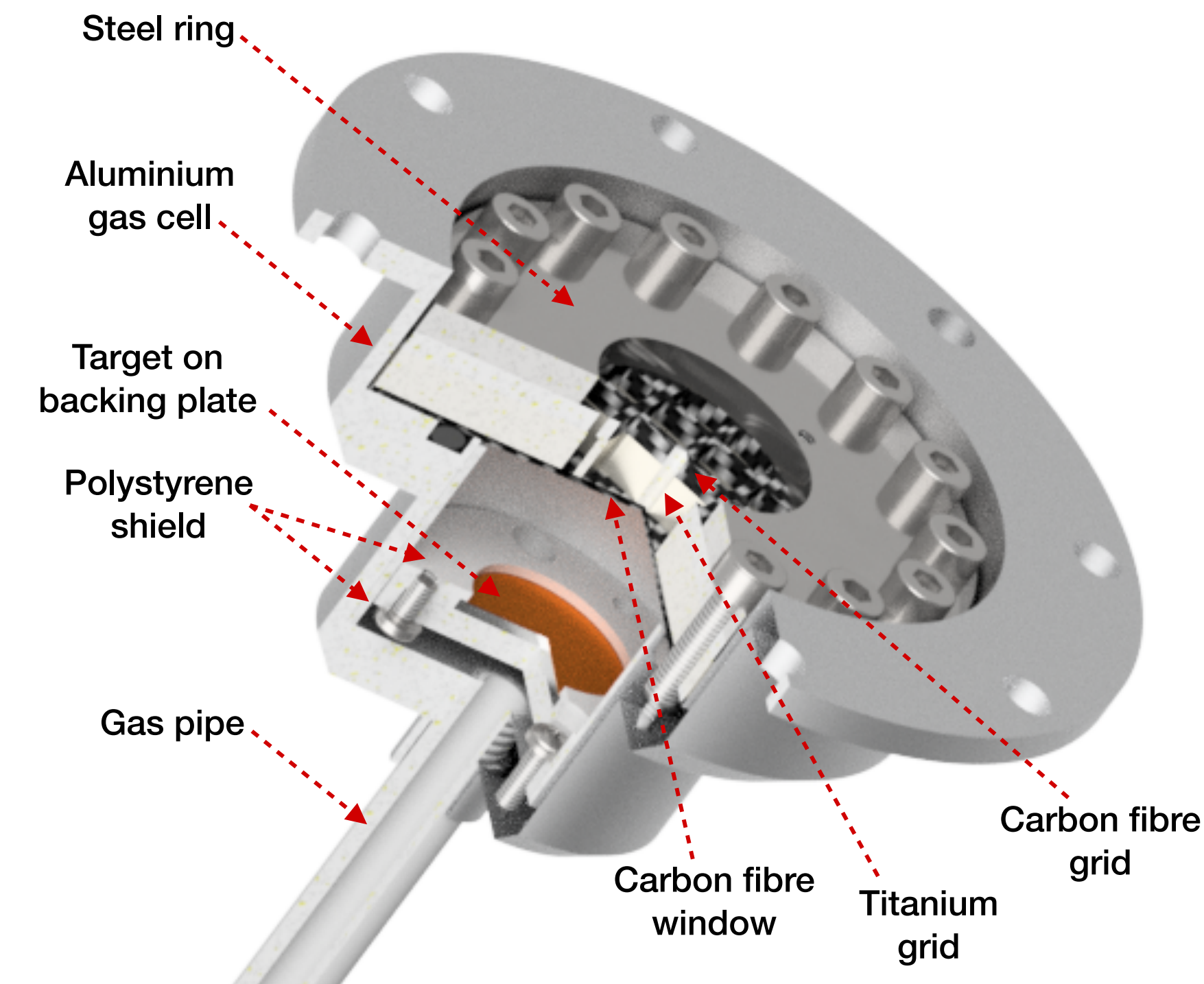
Pb-208

Probability density



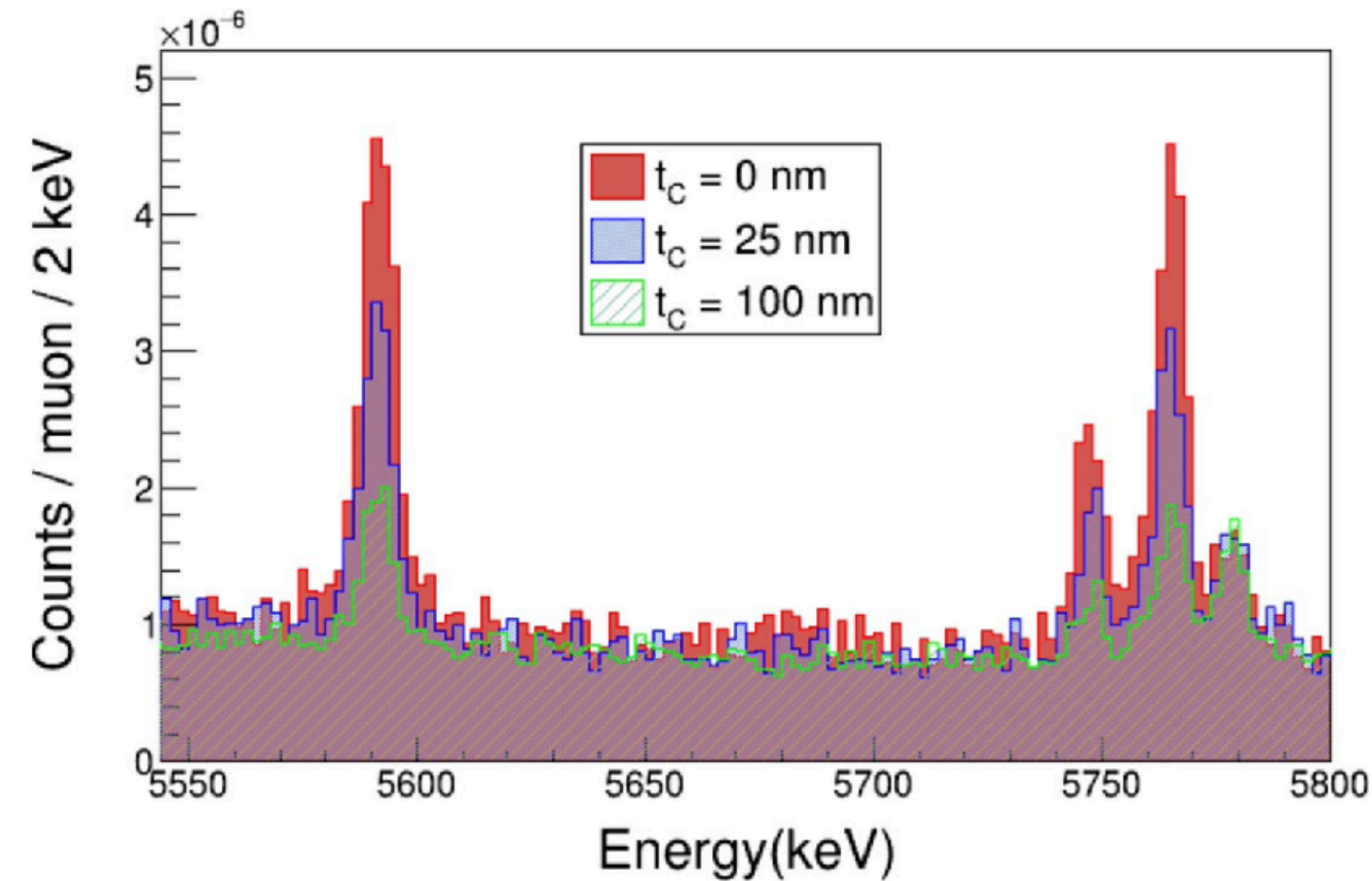
Gas cell & time distributions after transfer

PhD thesis of A. Skawran
Simulations by J. Nuber



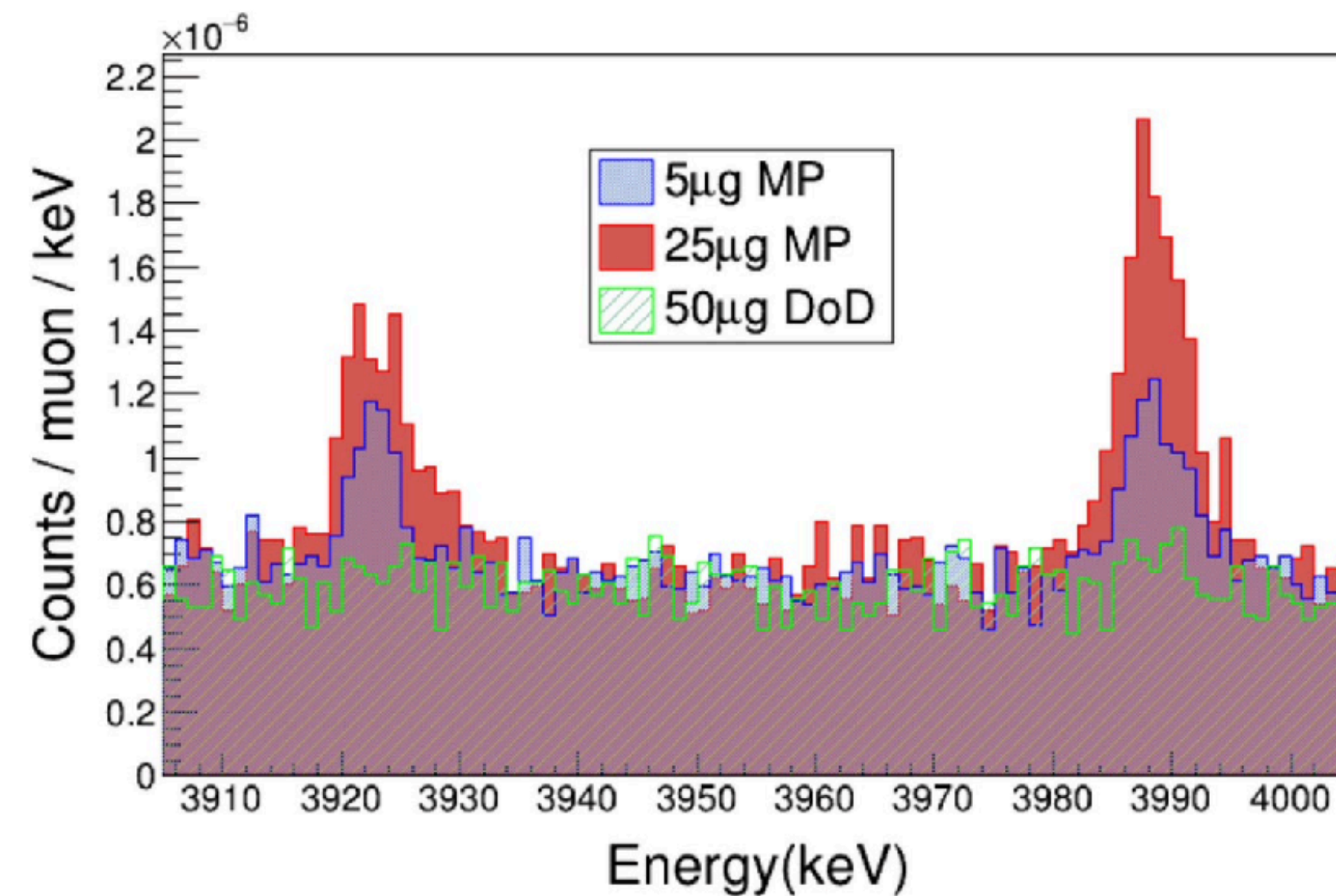
Comparing target fabrication techniques

Graphite targets

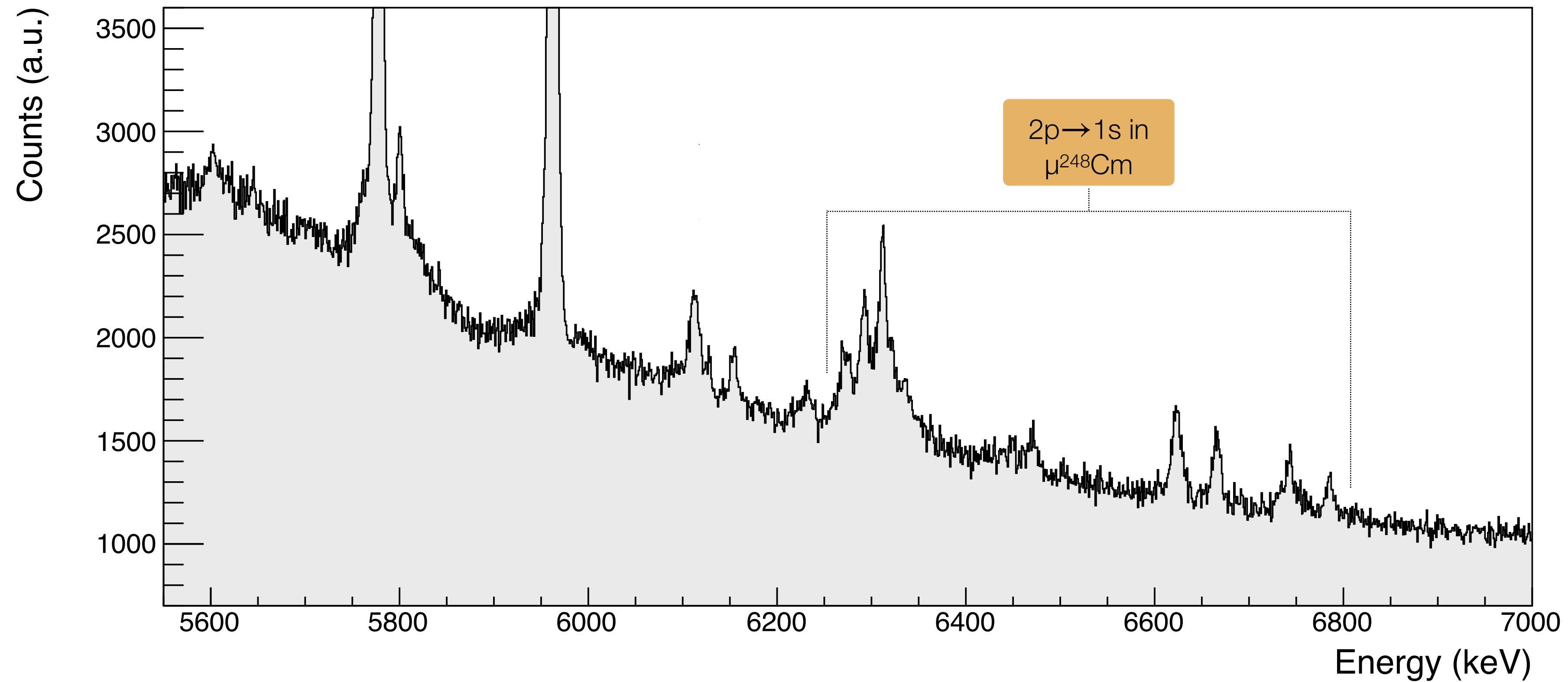


[Sci Rep 15, 6939 \(2025\)](#)

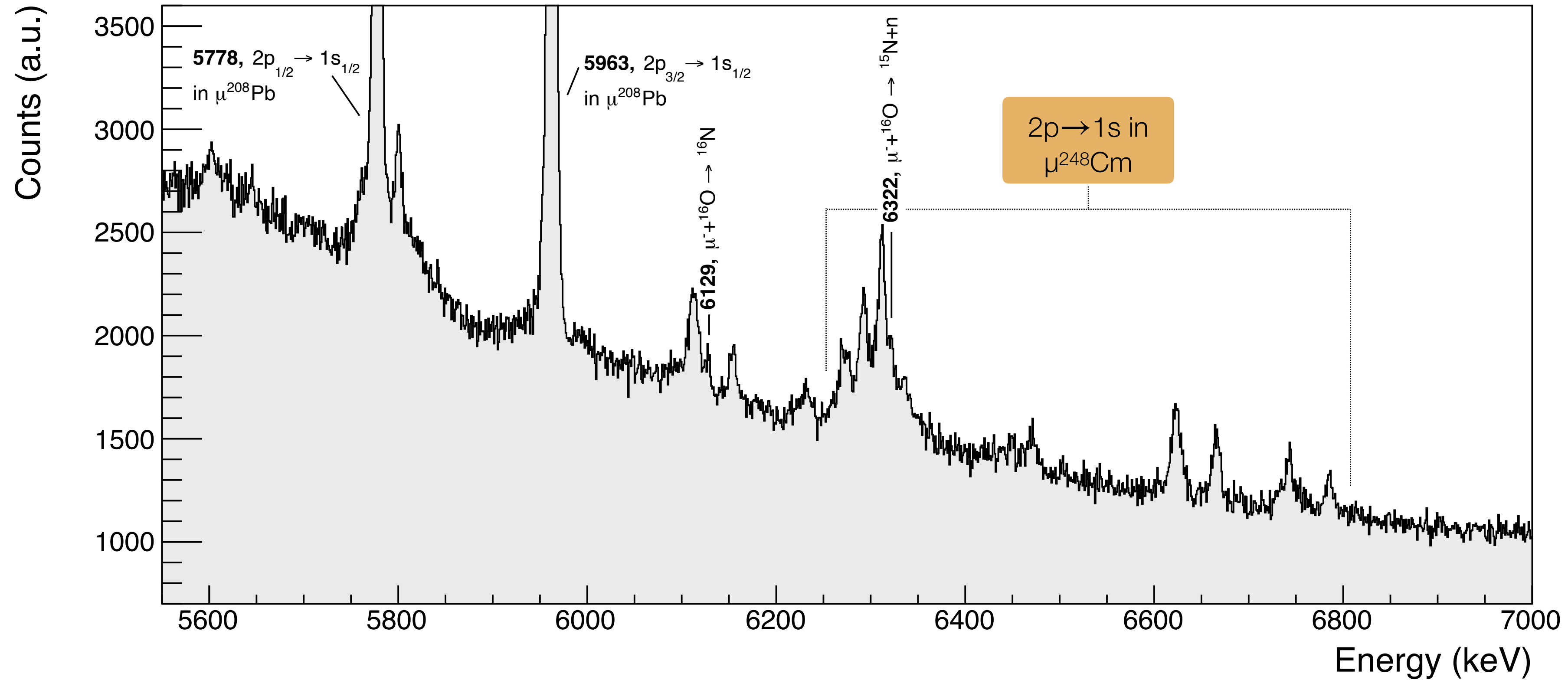
Molecular plating
& Drop-on-Demand



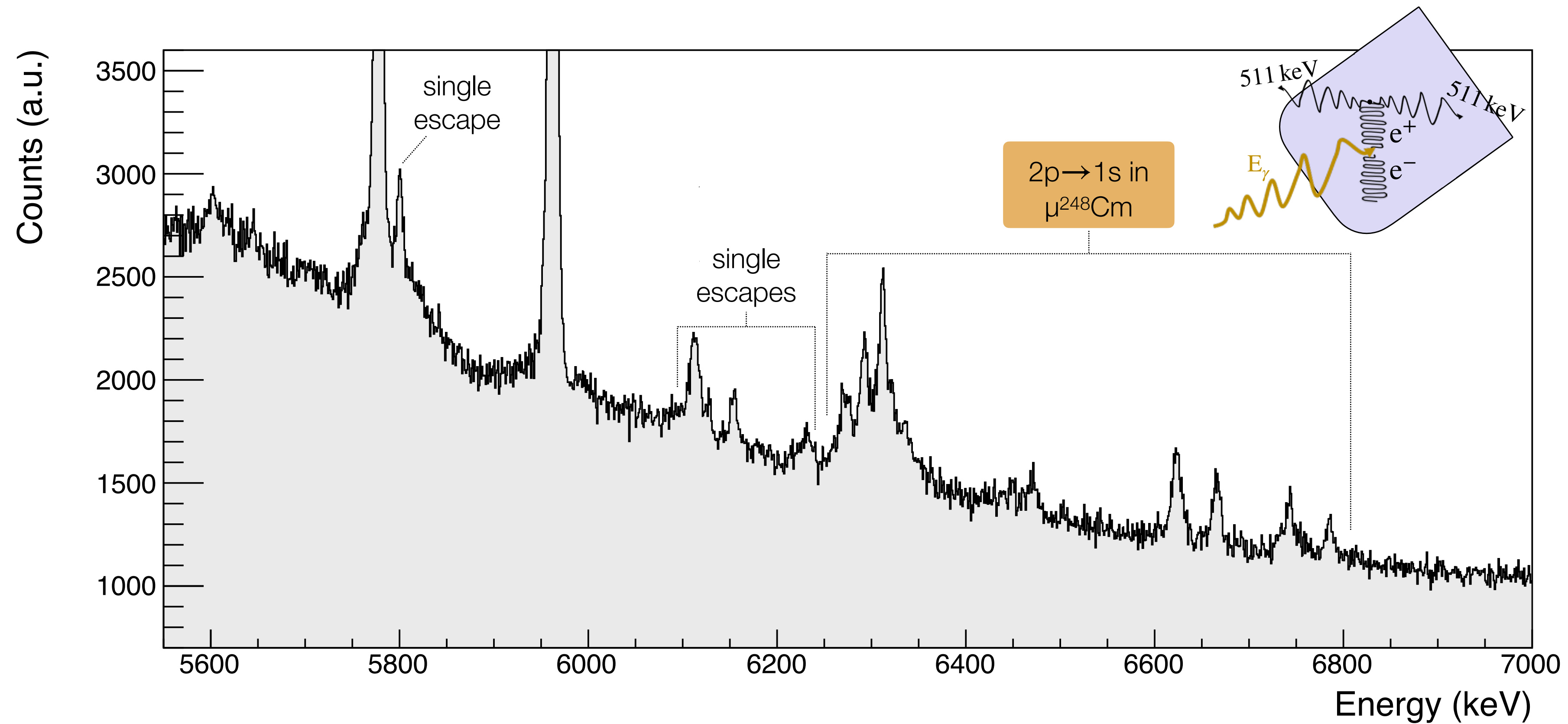
^{248}Cm 2p1s analysis



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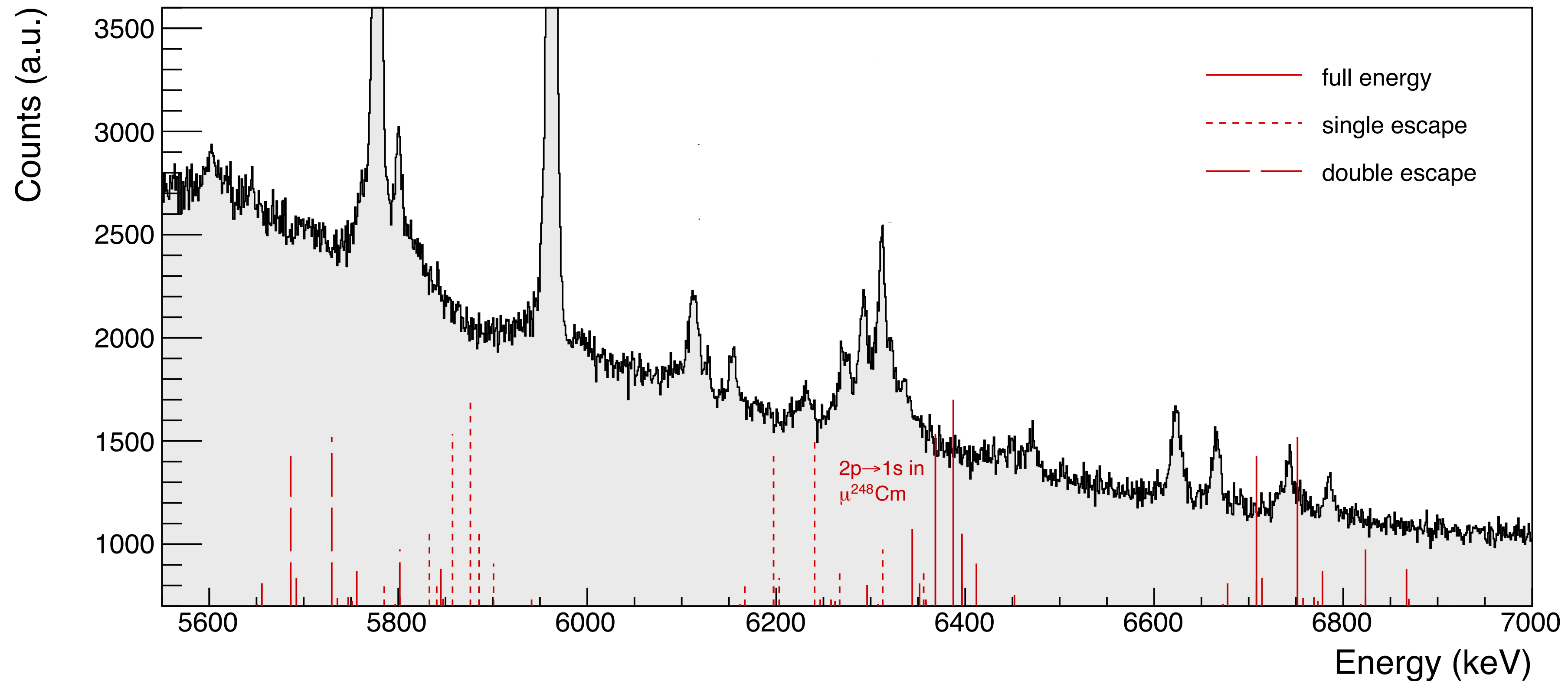


^{248}Cm 2p1s analysis



^{248}Cm 2p1s analysis

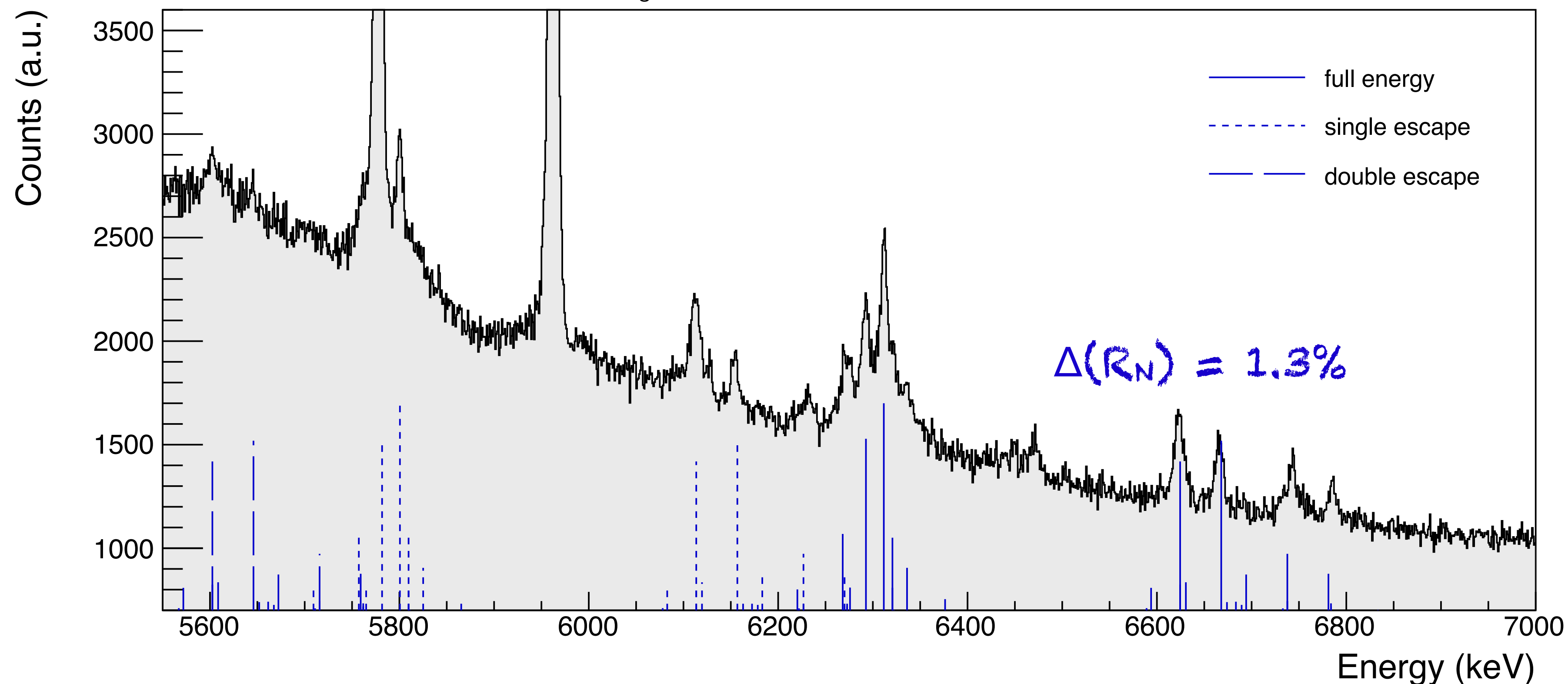
Theoretical calculations are performed by
N. Oreshkina & I. Valuev, MPIK, Heidelberg



Using the nuclear charge radius
prediction by Angeli & Marinova $R=5.8687$ fm

^{248}Cm 2p1s analysis

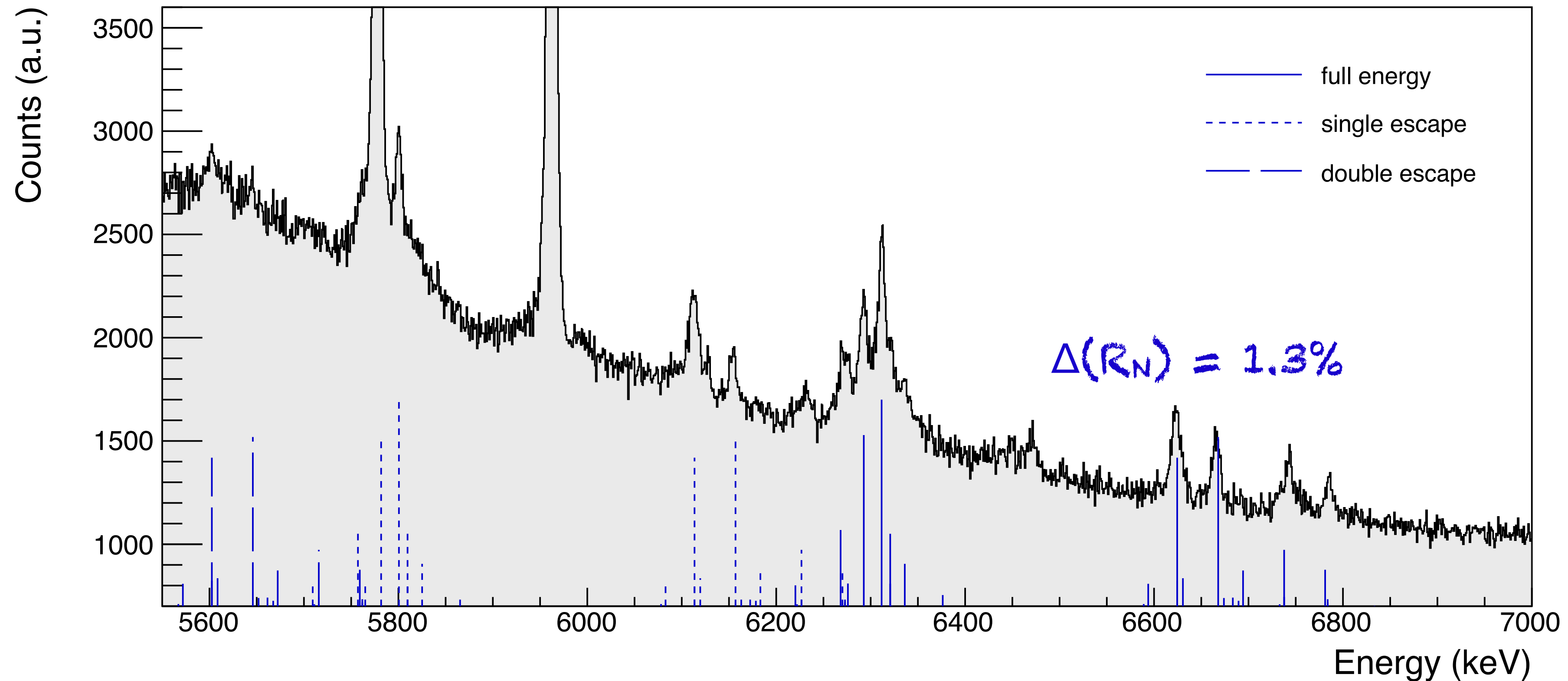
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Sensitivity on the quadrupole moment Q is also observed