Towards the Measurement of Charge Radii from Lithium to Neon

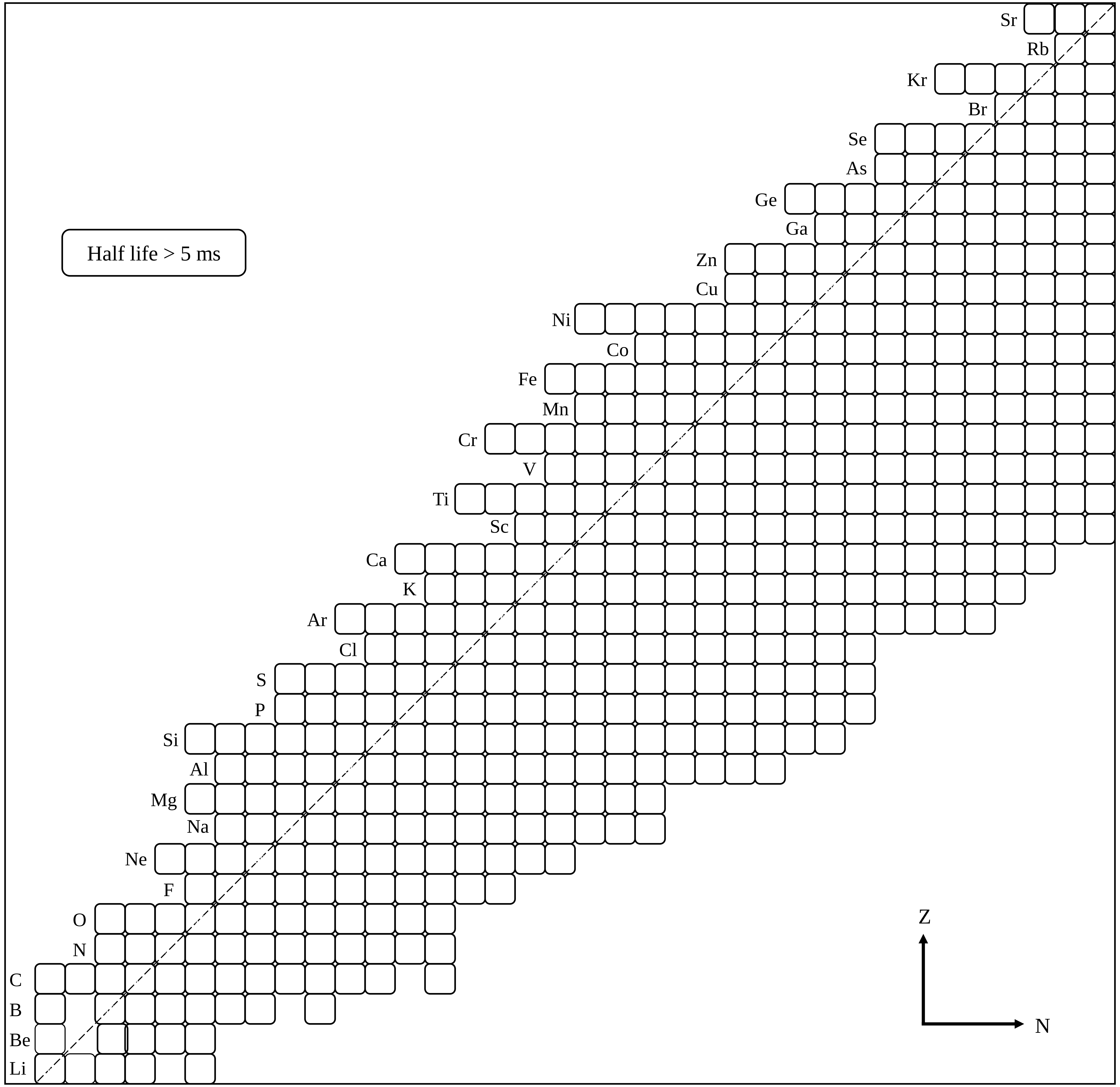
Ben Ohayon
For the QUARTET collaboration

NREC May 2024, CFNS, Stony Brook University

Role of absolute nuclear EM radii

- Mirror nuclei and equation of state Ronald’s talk
- Study nuclear structure away from stability Ronald’s talk
- Important for weak interaction studies (e.g. for CKM) Misha
- Direct comparison of with state-of-the-art nuclear calculations Phiala Evgeny
- Confronting experiment & theory @ accuracy frontier Krzysztof Wilfried Salvatore
- …

Where do charge radii come from?



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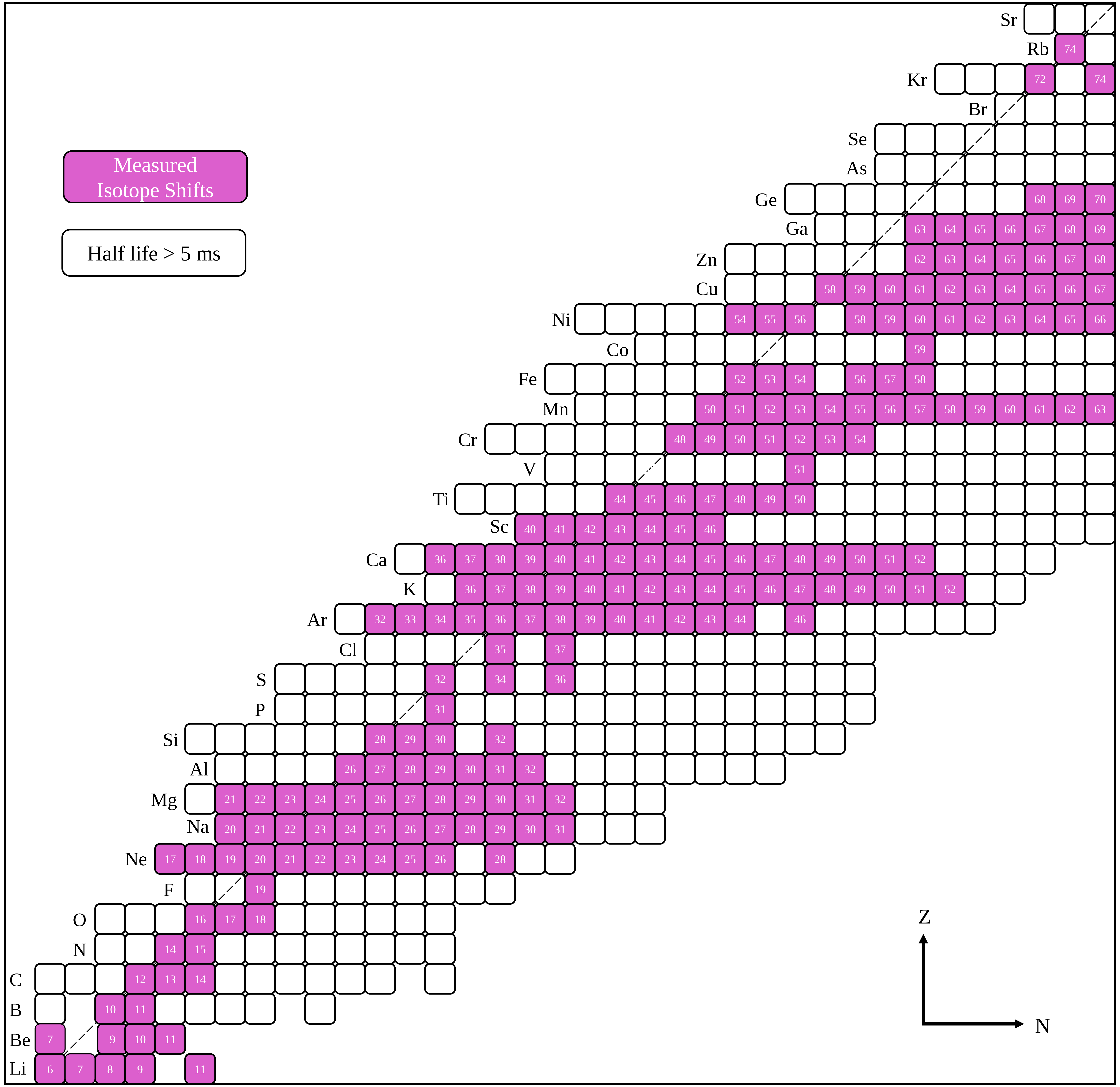
Where do charge radii come from?

Extraction of MS radius difference from measurements

$$\delta\nu_{A,A'} \approx \left(\frac{1}{M_{A'}} - \frac{1}{M_A}\right) K + F\delta r^2_{A,A'}$$



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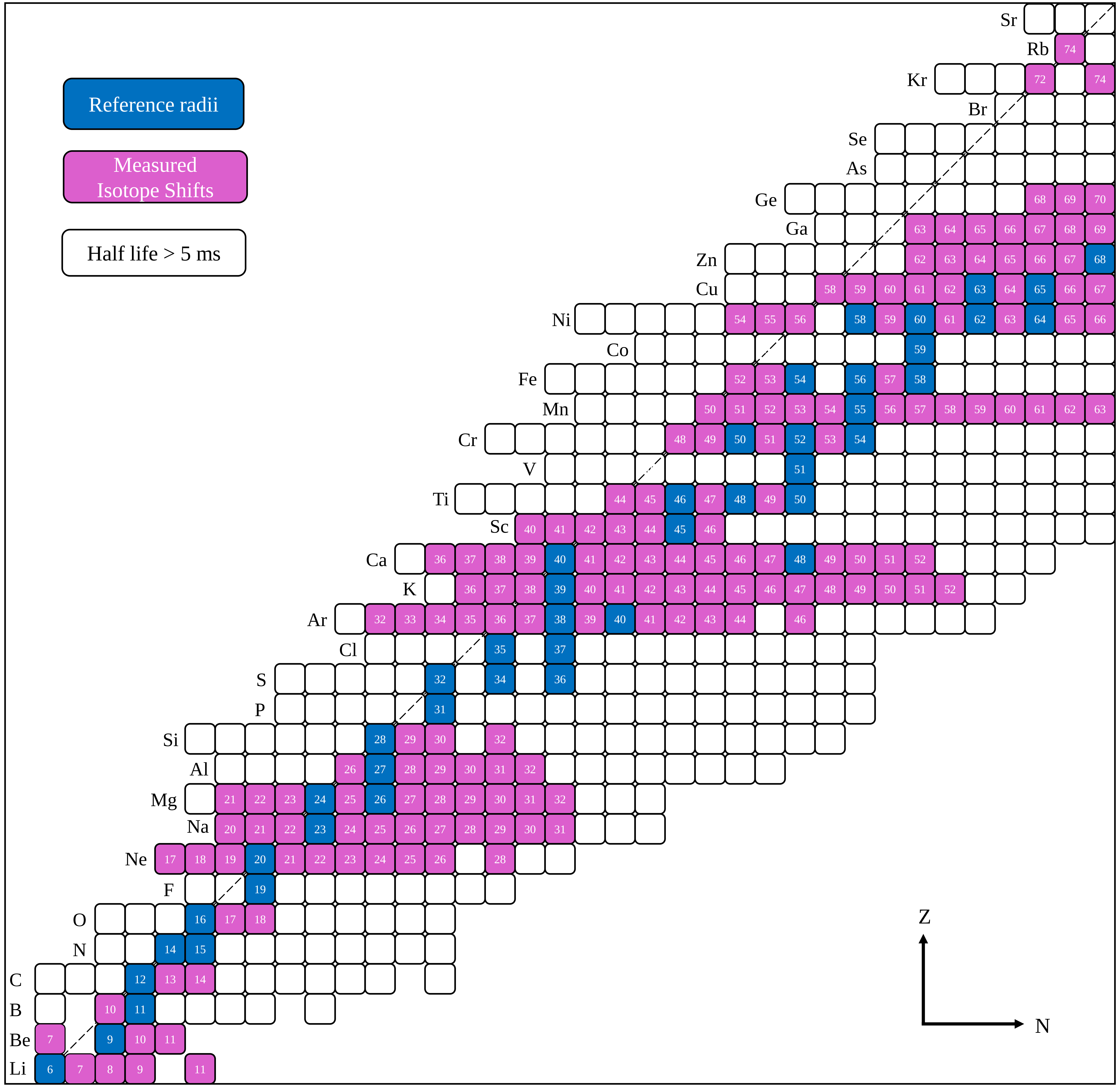
Reference radii connect MS differences with absolutes

$$r^2_{A'} = r^2_A + \delta r^2_{A,A'}$$



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$$\delta\nu_{A,A'} \approx \left(\frac{1}{M_{A'}} - \frac{1}{M_A}\right) K + F \delta r^2_{A,A'}$$

Atomic factors, either calculated or extracted from reference radii (King Plot).

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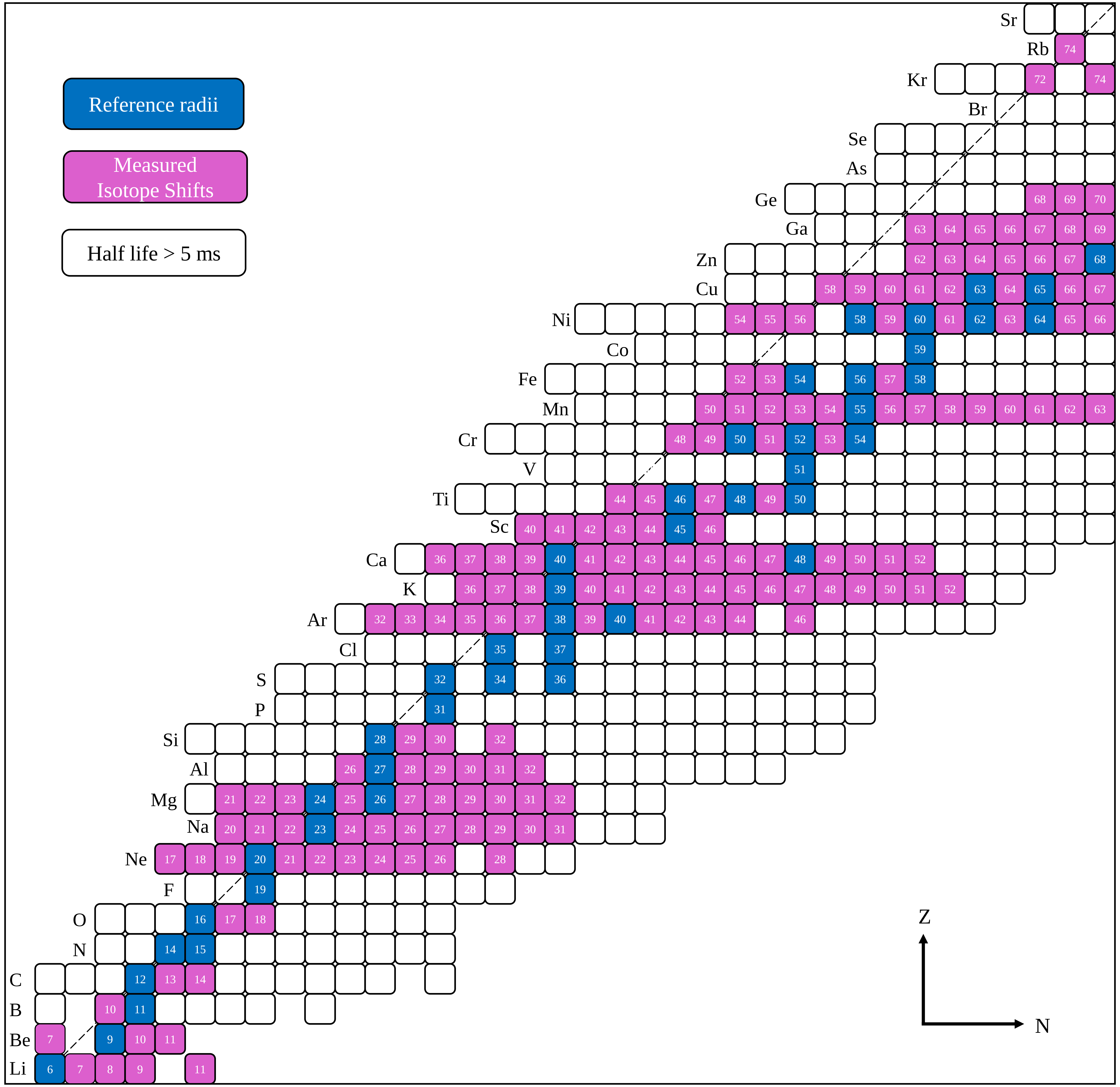
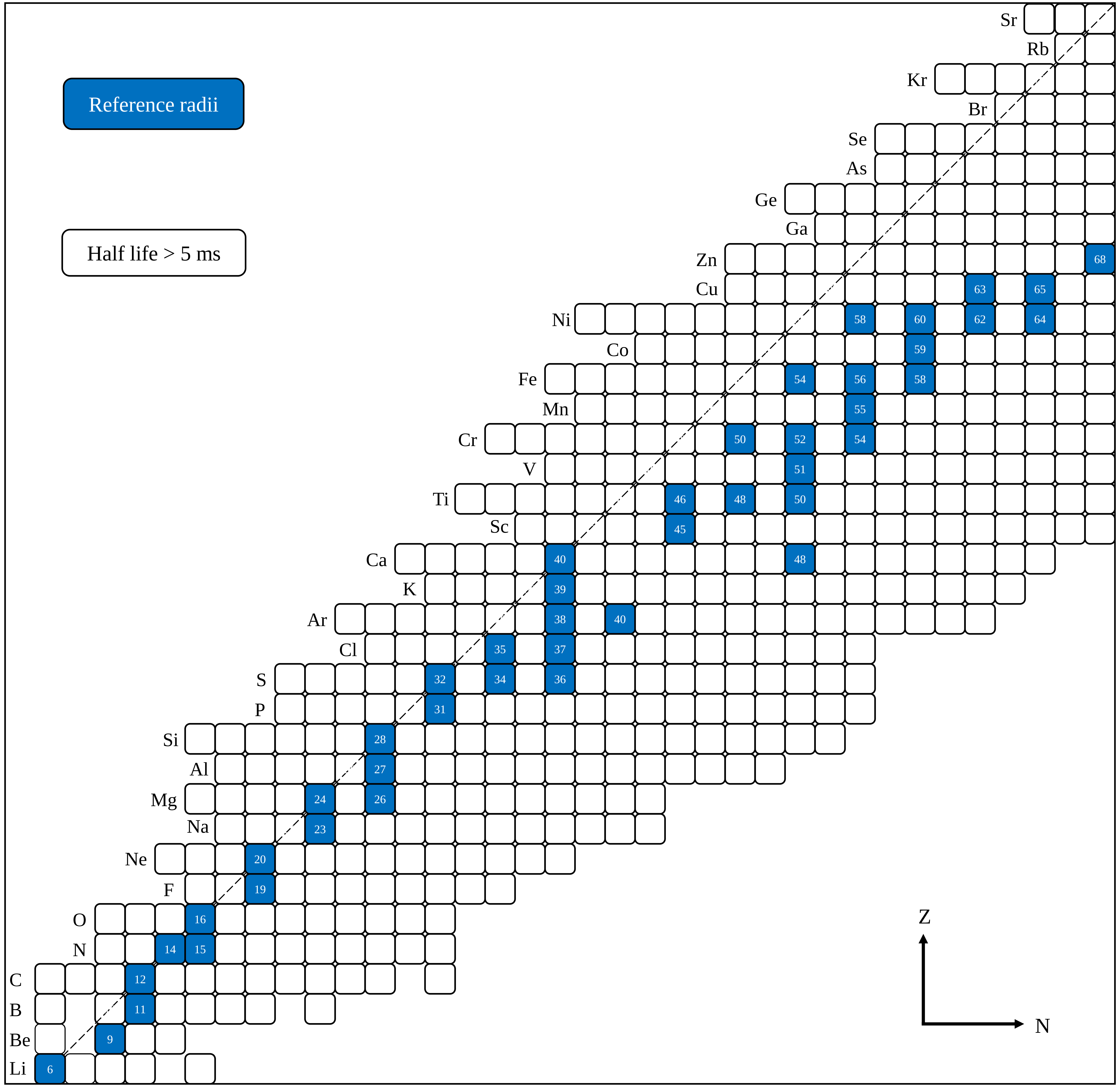


Reference radii and where to find them



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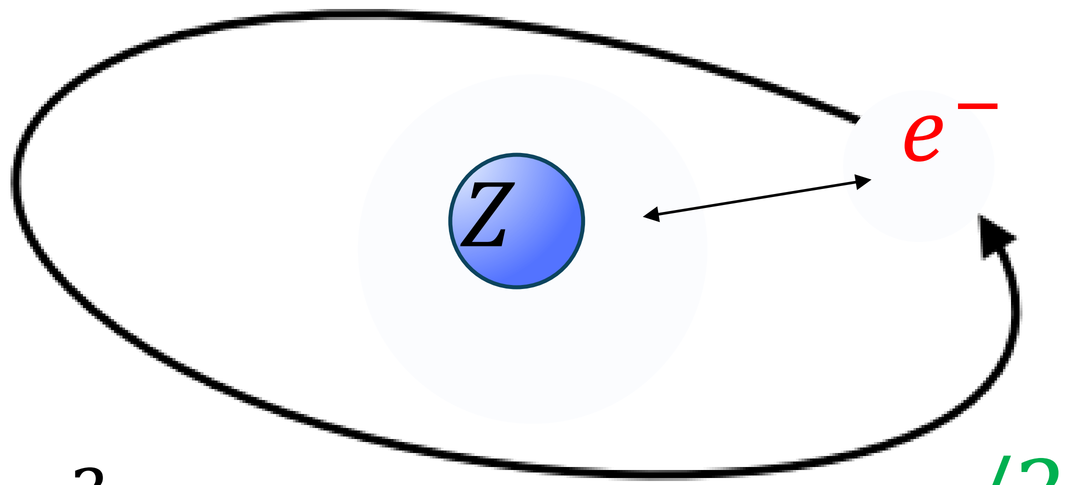
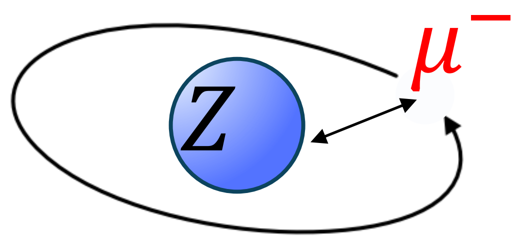
Muonic Atoms 101:

Ordinary atoms



Muonic atoms



Characteristic **length**

(Bohr radius: $a_0 = \frac{\hbar}{m_e c \alpha} \sim 0.5\text{Å}$):

$$a_n = \frac{n^2 a_0}{Z} \xrightarrow{/200} \frac{n^2 a_0}{Z} \frac{m_e}{m_\mu}$$

Shorter distances

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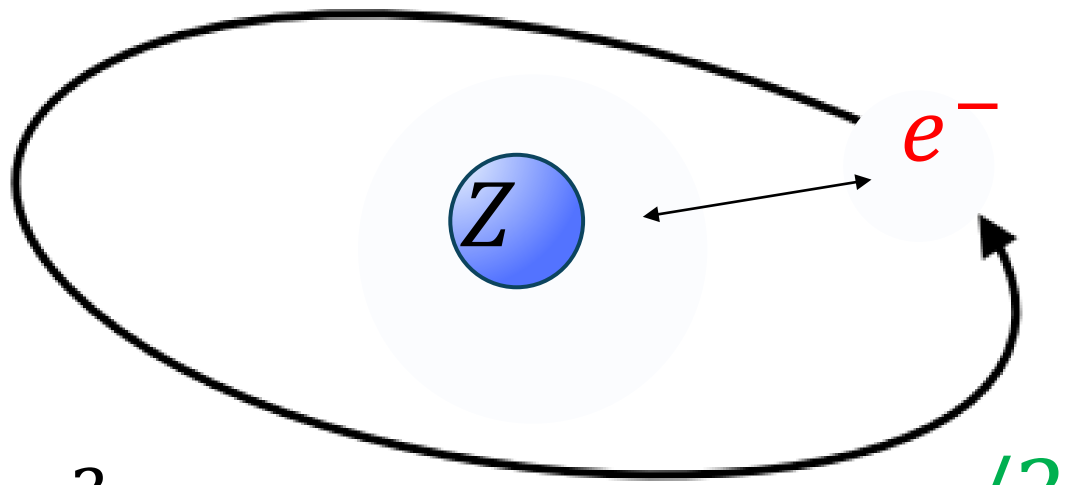
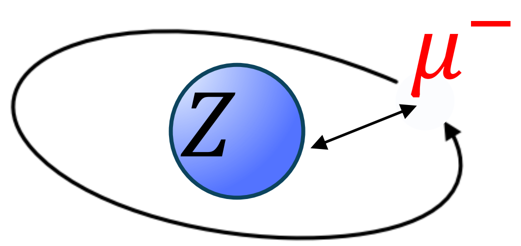


Muonic atoms



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Shorter distances

Characteristic **Energy**

(Rydberg: $R_\infty = \frac{\alpha}{2a_0} \sim 13.6\ eV$):

$$E_n = -\frac{Z\alpha}{2a_n} = -\frac{R_\infty Z^2}{n^2} \xrightarrow{\times 200} E_n = -\frac{R_\infty Z^2}{n^2}\frac{m_\mu}{m_e}$$

$MW \rightarrow Laser$

$Laser \rightarrow x - ray$

Higher energies

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Muonic Atoms 101:

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	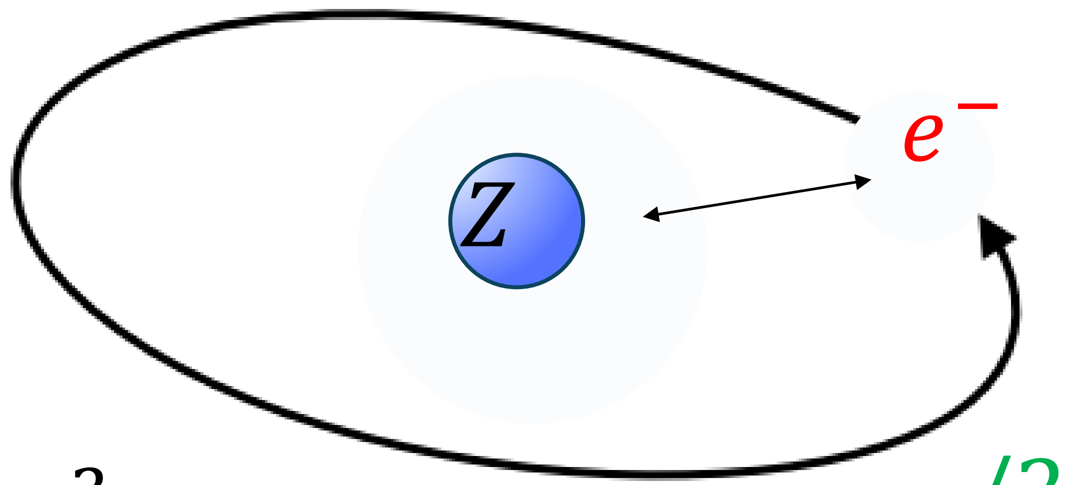		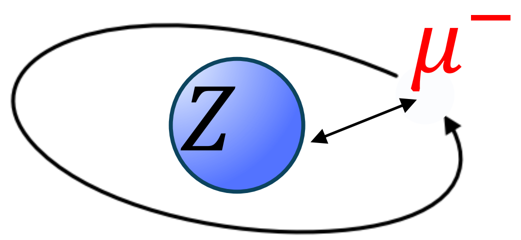	
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Characteristic **Energy** (Rydberg: $R_\infty = \frac{\alpha}{2a_0} \sim 13.6\ eV$):	$E_n = -\frac{Z\alpha}{2a_n} = -\frac{R_\infty Z^2}{n^2}$	$\times 200$ $\longrightarrow$ $MW \rightarrow Laser$ $Laser \rightarrow x-ray$	$E_n = -\frac{R_\infty Z^2}{n^2}\frac{m_\mu}{m_e}$	Higher energies
Finite Nuclear Size effect:	$\Delta E_{FNS} \sim \frac{4}{3}\frac{R_\infty Z^4}{n^3}\left(\frac{r_c}{a_0}\right)^2 \delta_{l0}$	$\times (200)^3$ $\longrightarrow$	$\frac{4}{3}\frac{R_\infty Z^4}{n^3}\left(\frac{r_c}{a_0}\right)^2\left(\frac{m_\mu}{m_e}\right)^3 \delta_{l0}$	
For Hydrogen 1s-2p:	$\sim 4\ \text{neV}\ (1\ \text{MHz, ppb})$		$\sim 30\ \text{meV}, 10\ \text{ppm}$	

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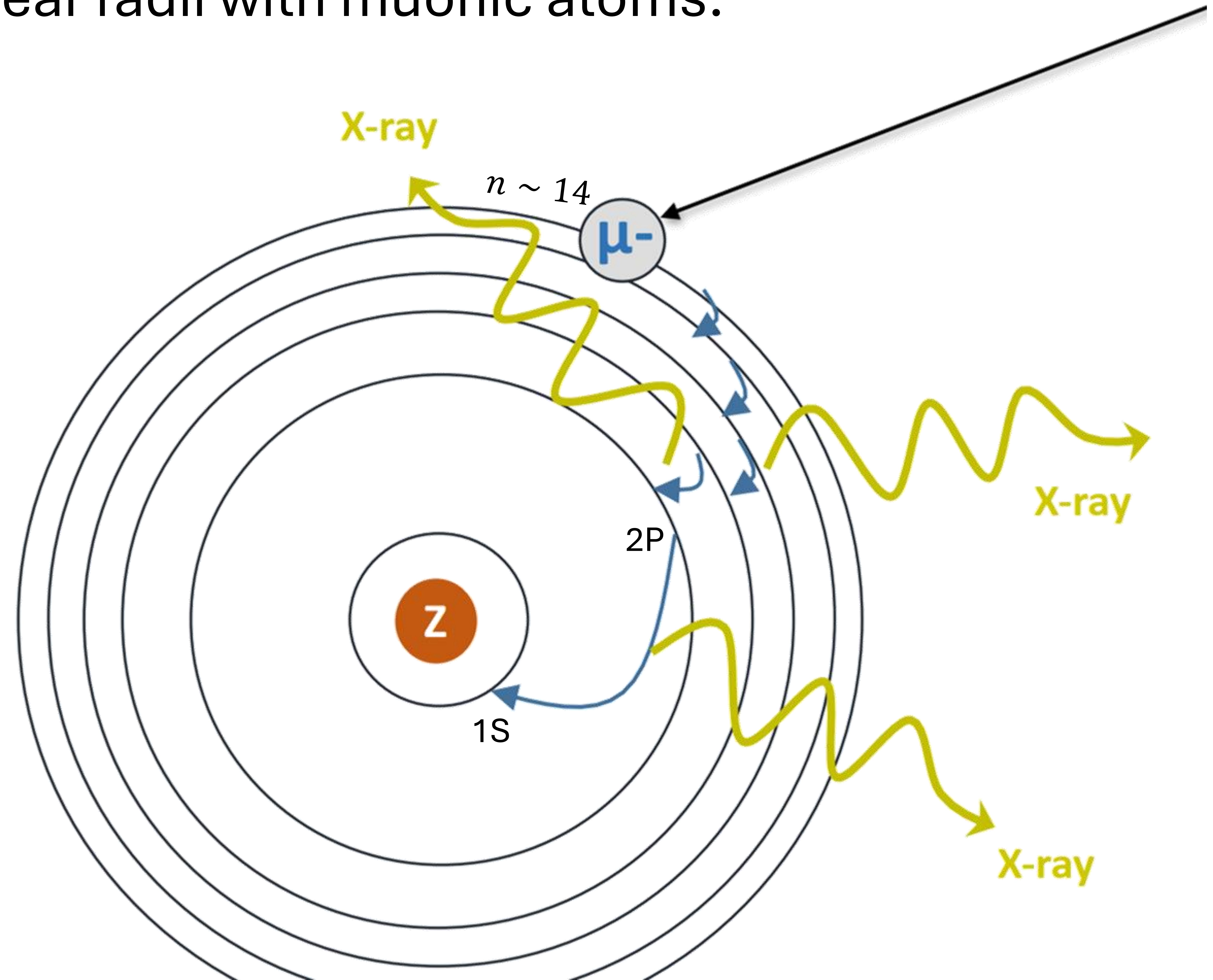
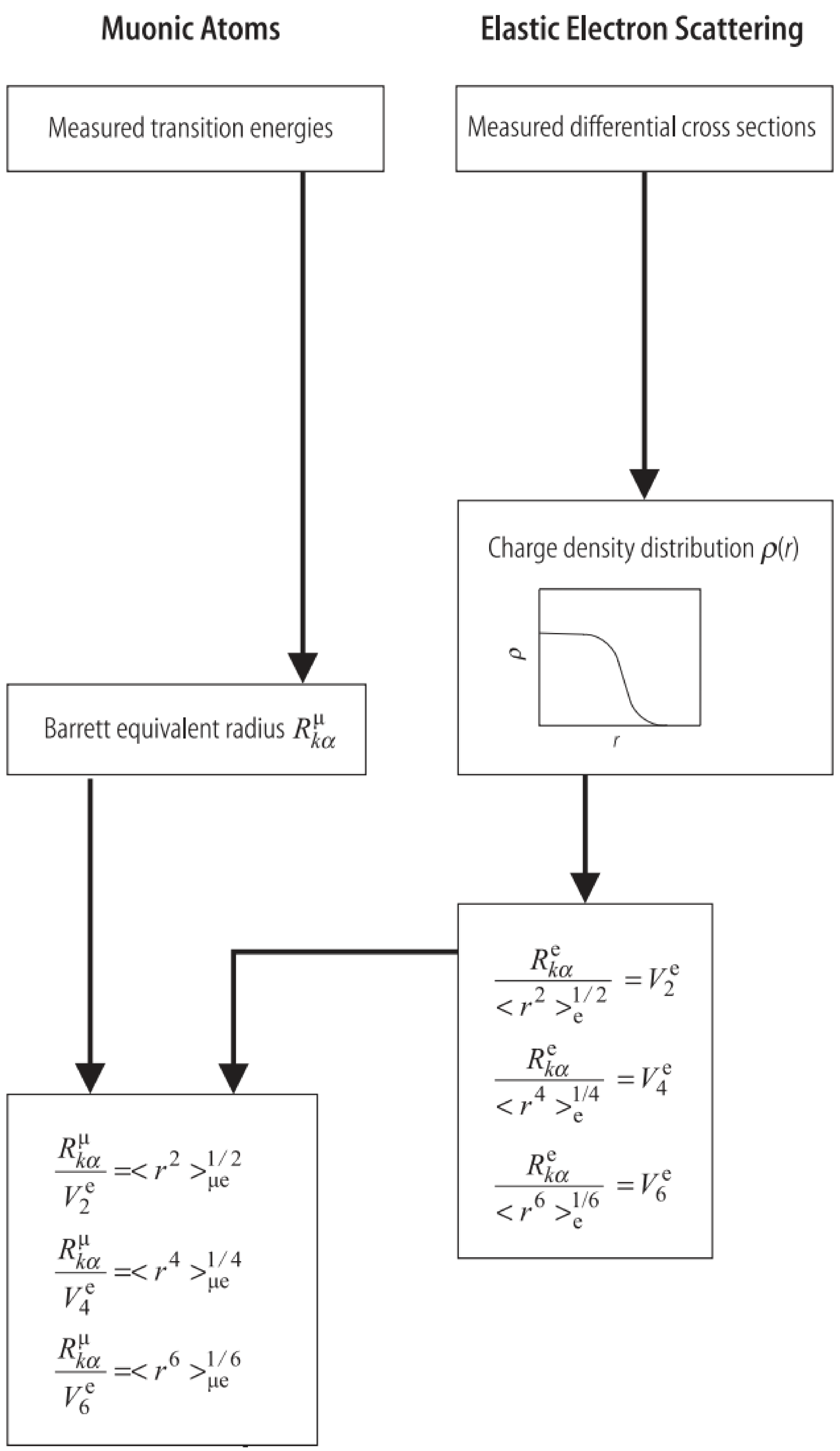
Measuring nuclear radii with muonic atoms:

1. Captured around N=14
2. All electrons are emitted
3. Cascade to ground level
4. Muon decay $\sim 2\mu s$
5. $\mathrm{E}_{2\mathrm{P}-1\mathrm{S}} = E_{QED} + \Delta E_{FNS} + \cdots$



“Old school” combined analysis of muonic atoms and electron scattering:



where to find reference-radii?

$Z = 1\ or\ 2$:

Comprehensive theory of the Lamb shift in light muonic atoms

K. Pachucki, V. Lensky, F. Hagelstein, S. S. Li Muli, S. Bacca, and R. Pohl
Rev. Mod. Phys. **96**, 015001 – Published 24 January 2024

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$Z > 2$:

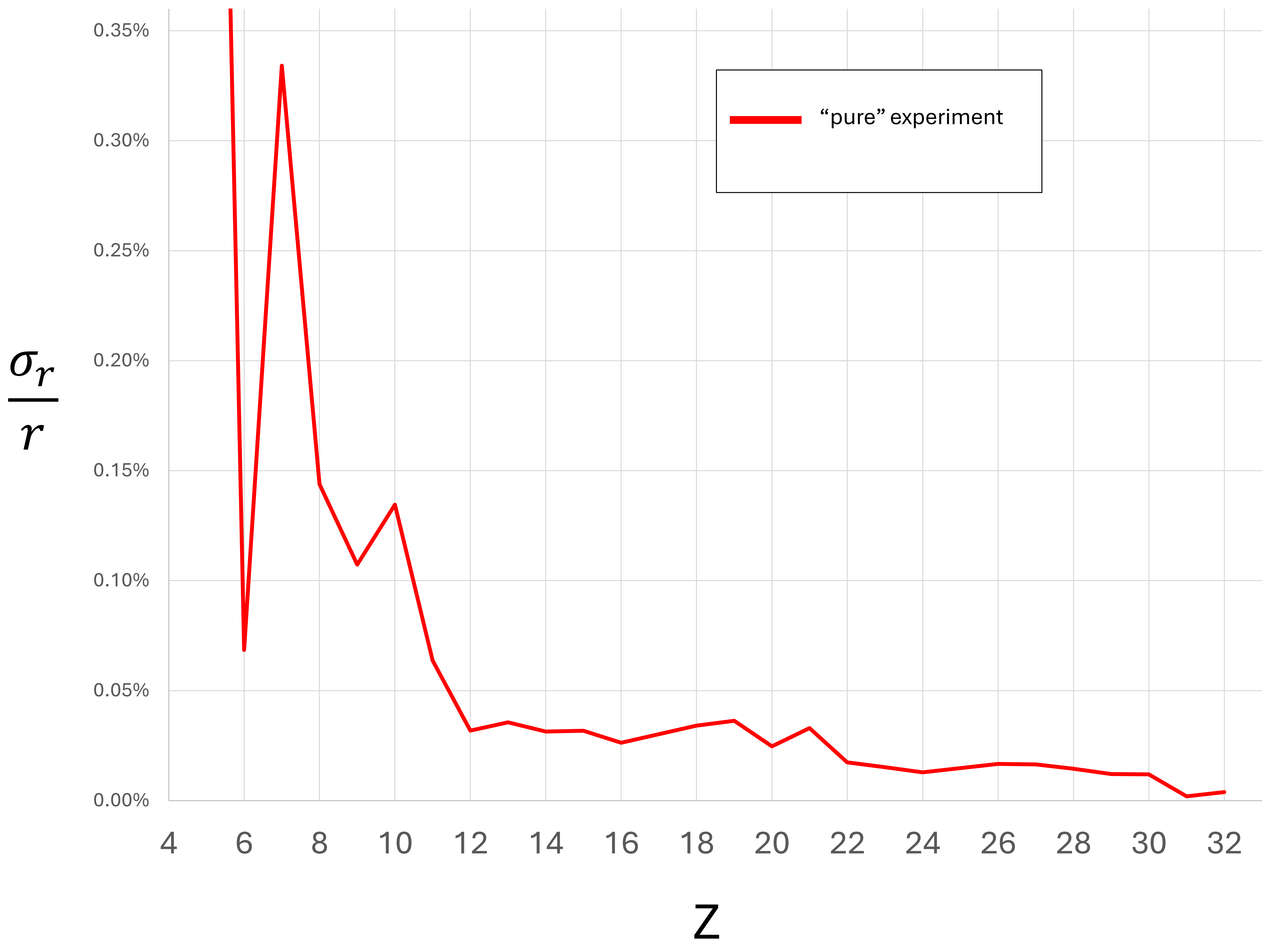
Table of experimental nuclear ground state charge radii: An update

I. Angeli [a], K.P. Marinova [b,*]

[a] *Institute of Experimental Physics, University of Debrecen, H-4010 Debrecen Pf. 105, Hungary*
[b] *Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia* 2013

Sources of uncertainty :

Radii of light nuclei from muonic atom x-ray spec.



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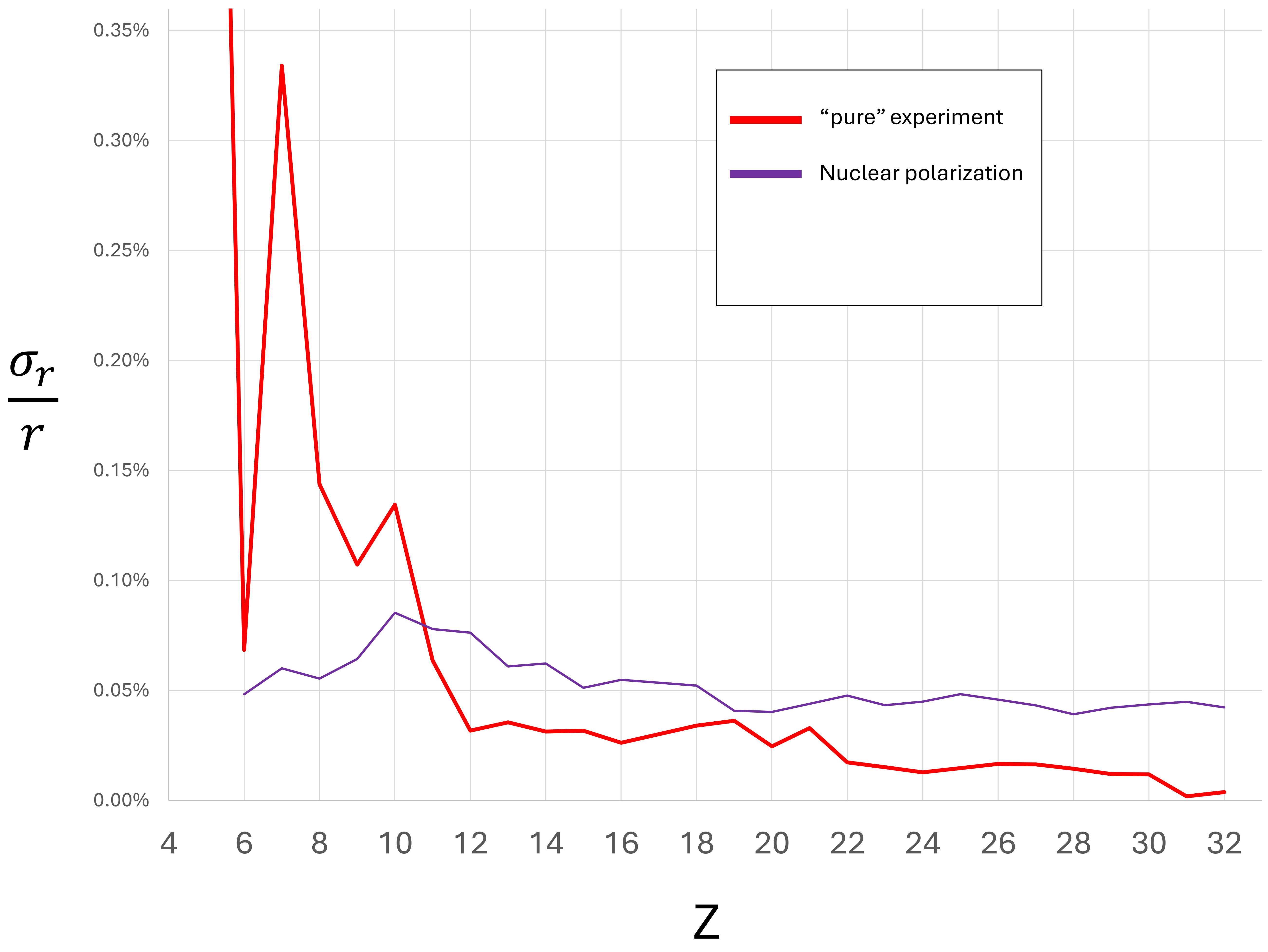

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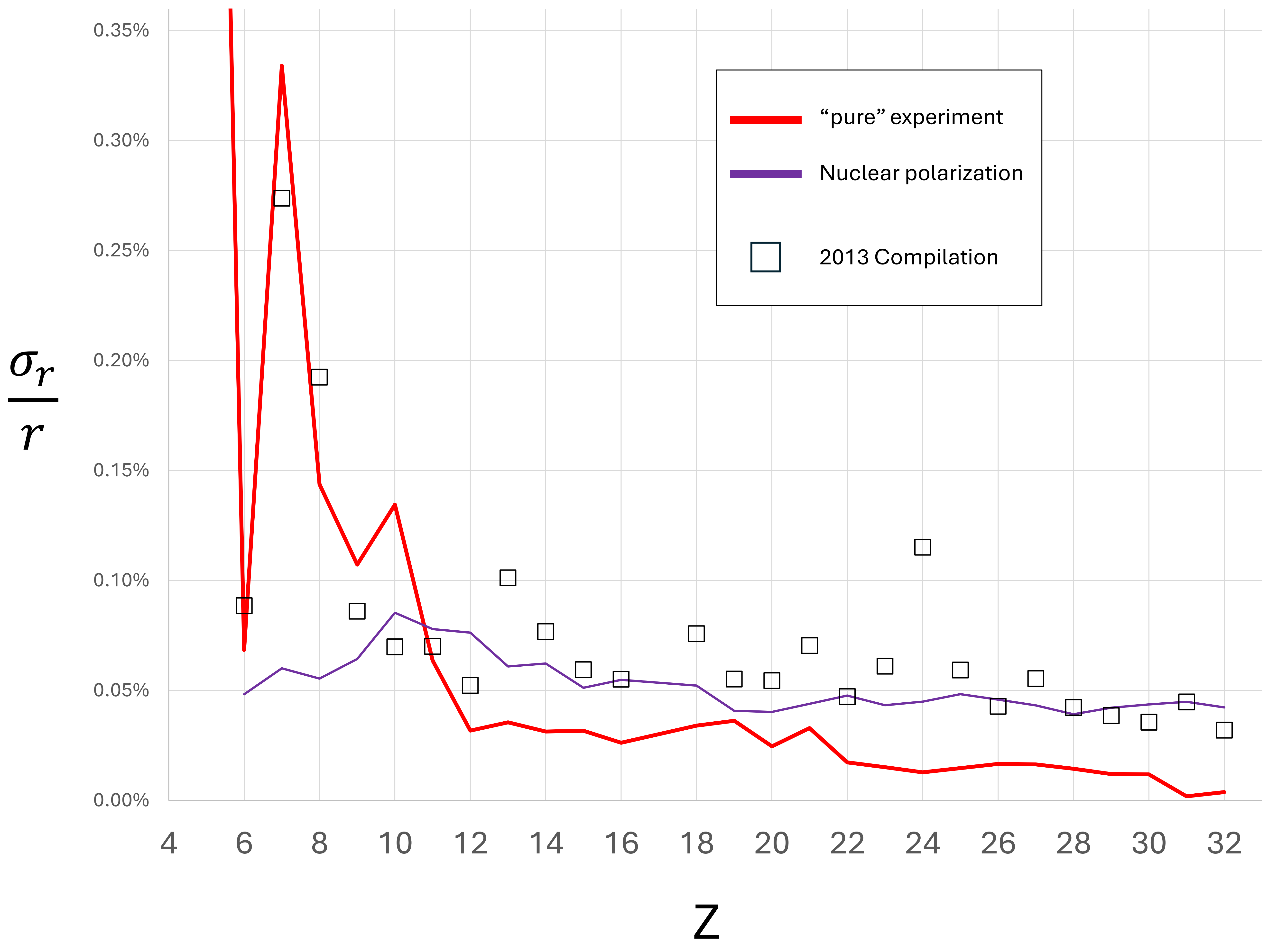

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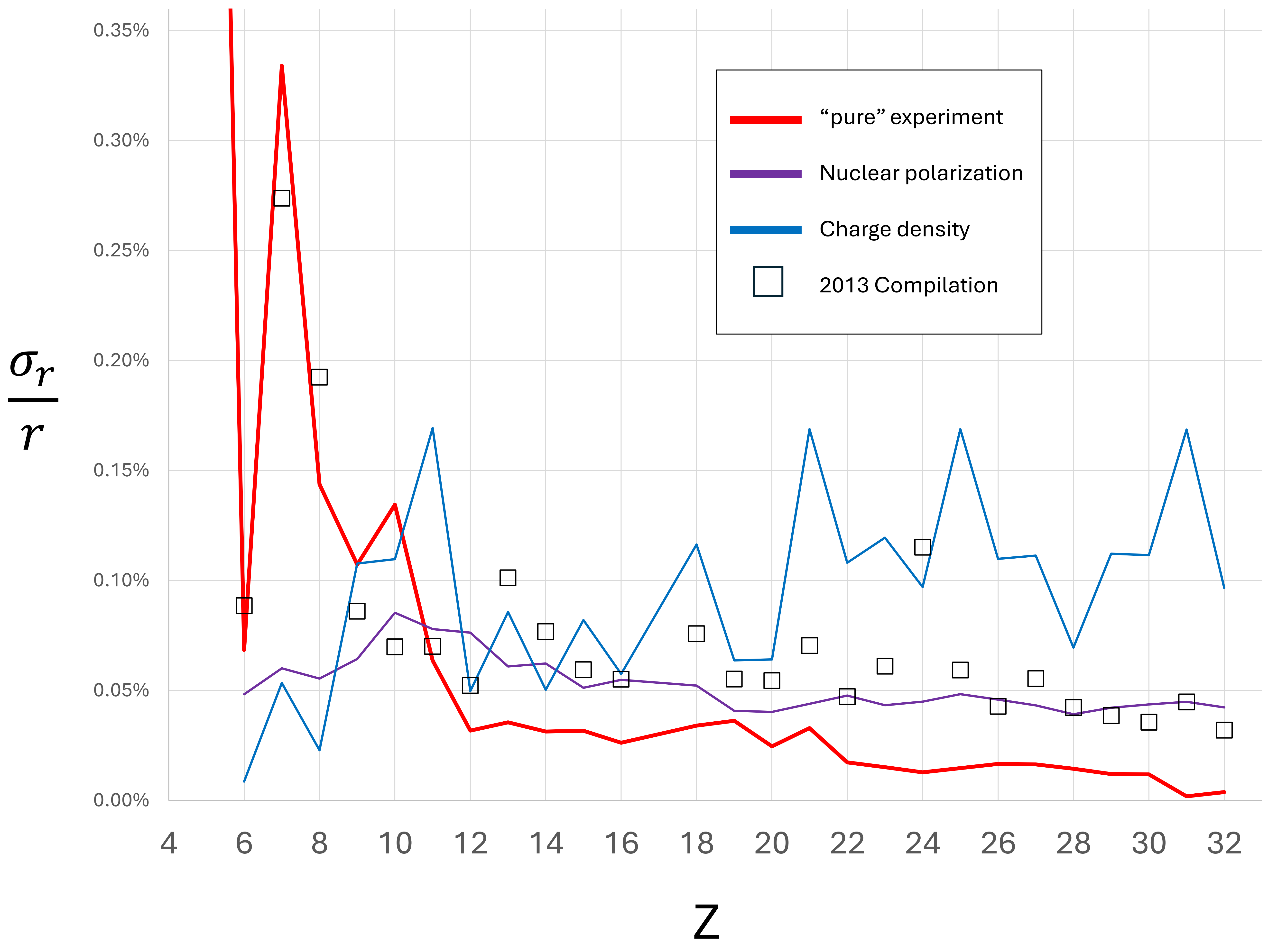

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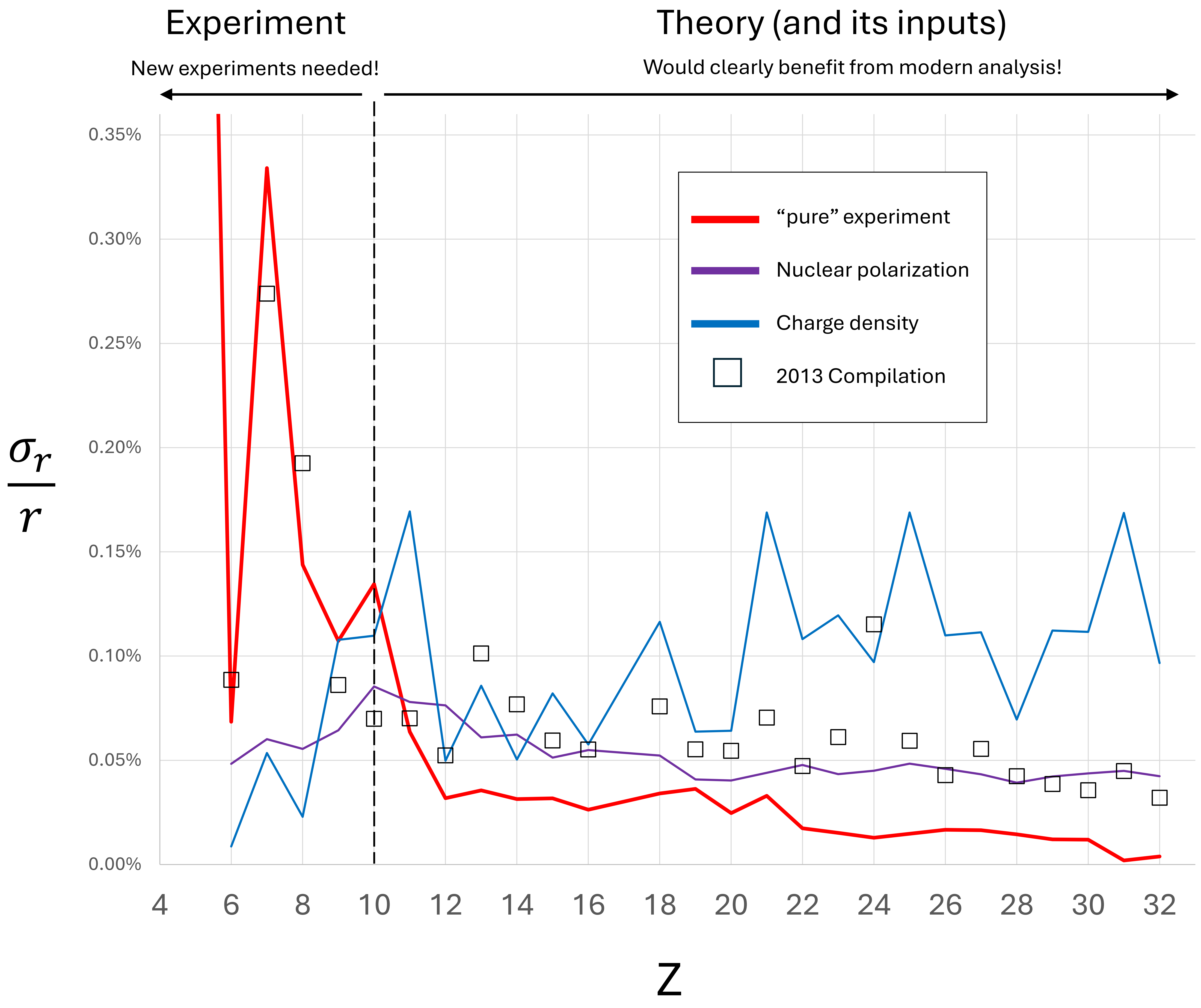

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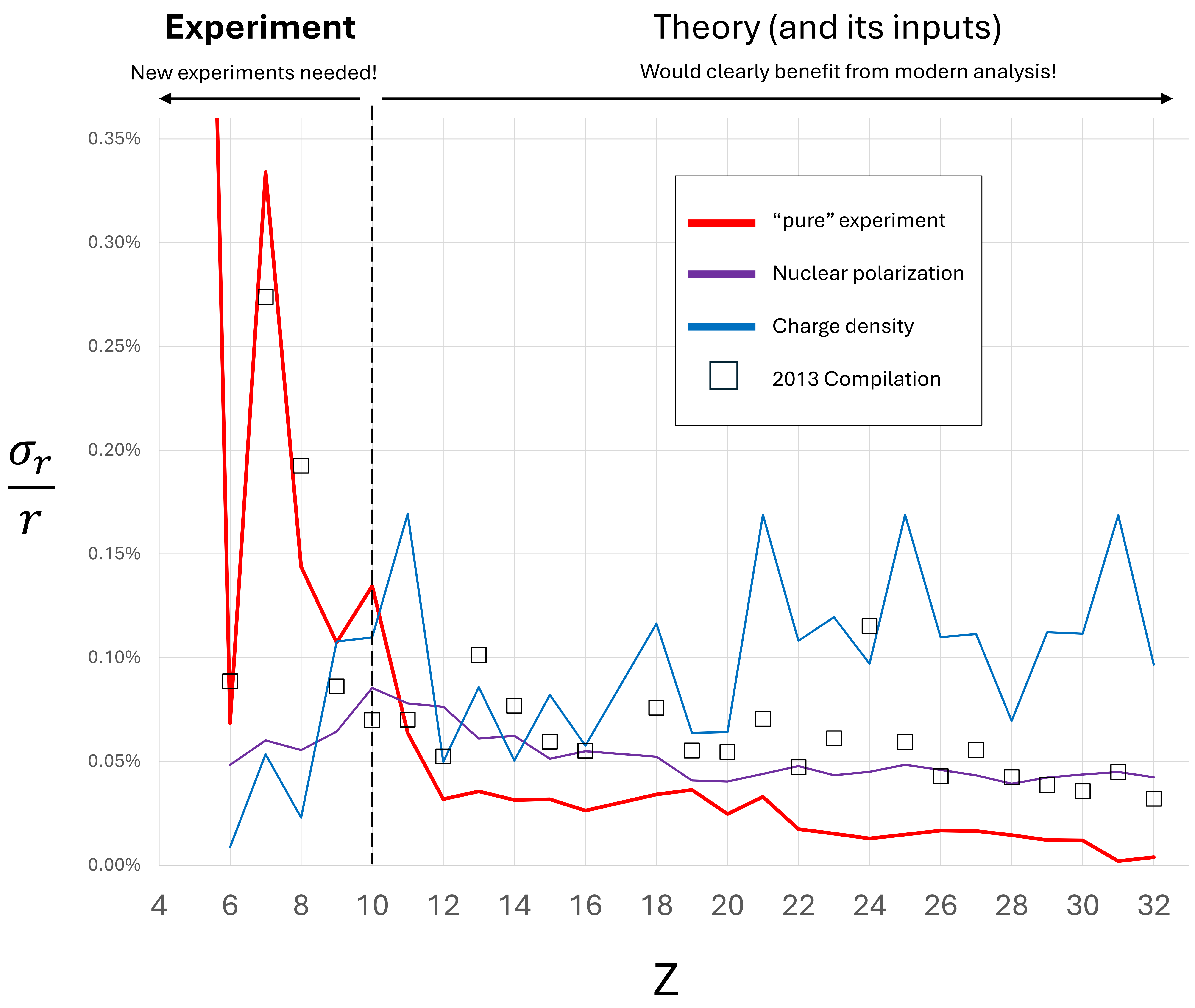
Sources of uncertainty :

Radii of light nuclei from muonic atom x-ray spec.

What is the spike in experimental uncertainty below Z=11?



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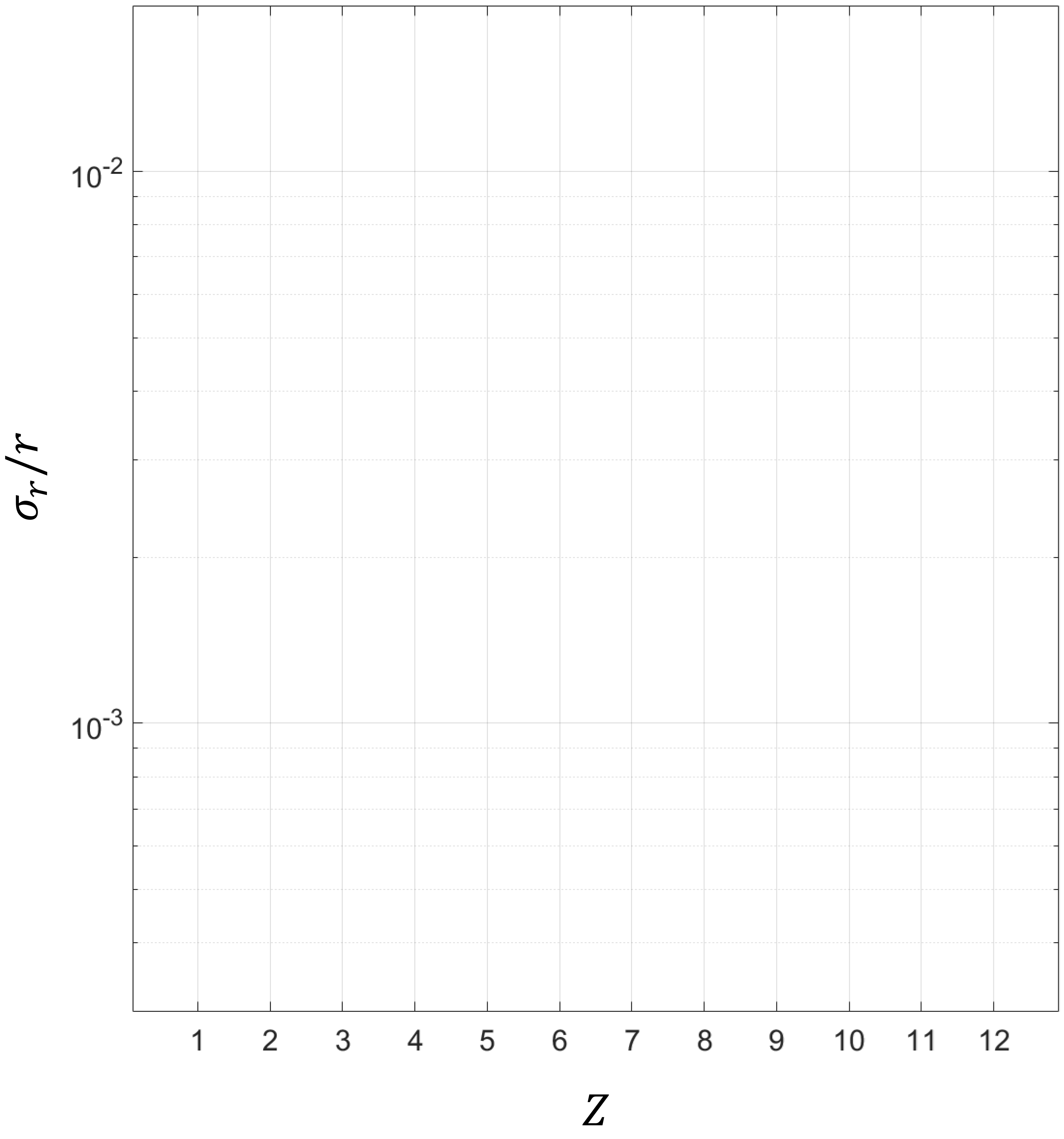
The radius gap



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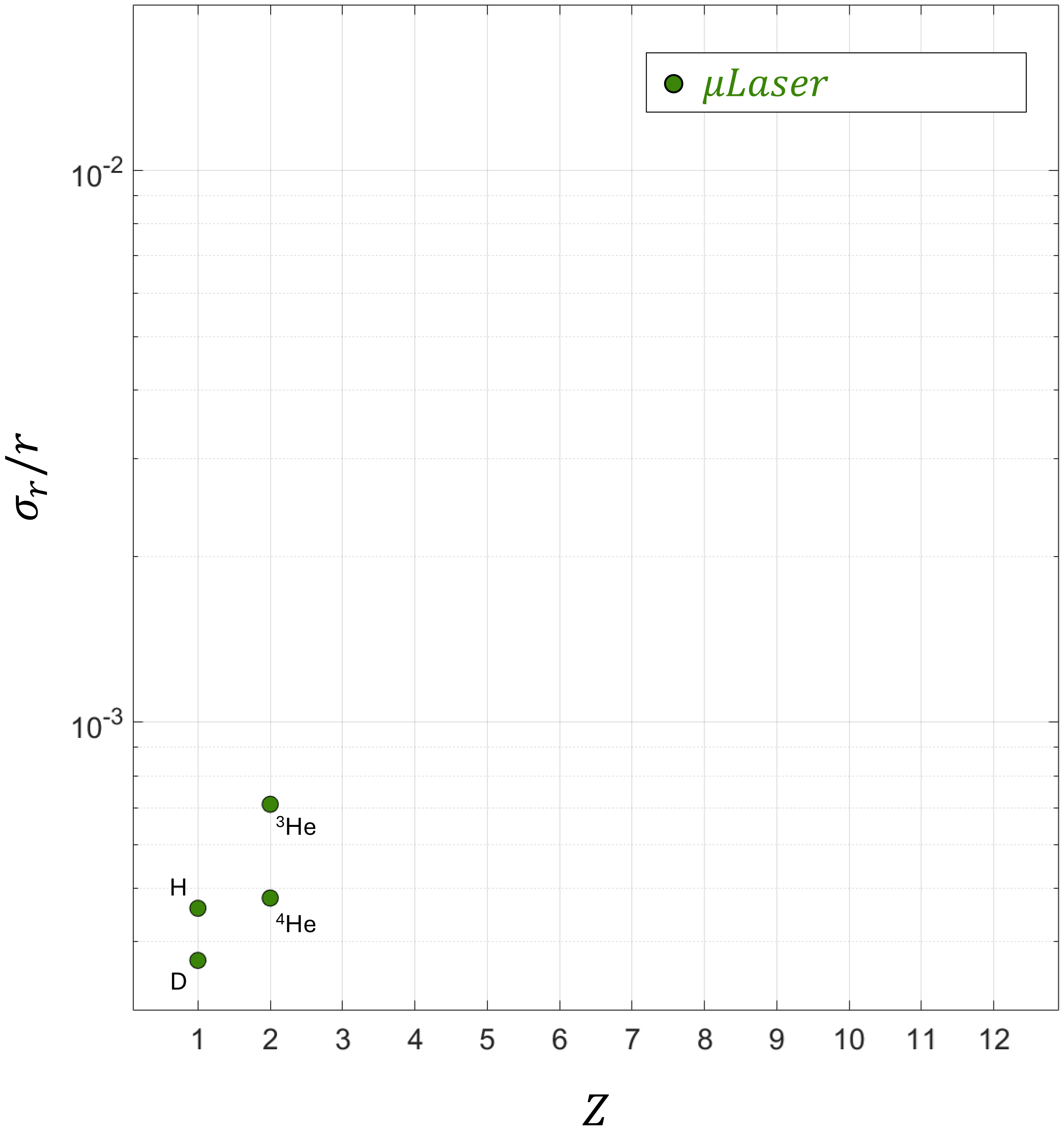
The radius gap

- **For $Z < 3$:**
  Laser spectroscopy of muonic atoms, limited by nuclear theory

Krzysztof
Salvatore
Yang
...



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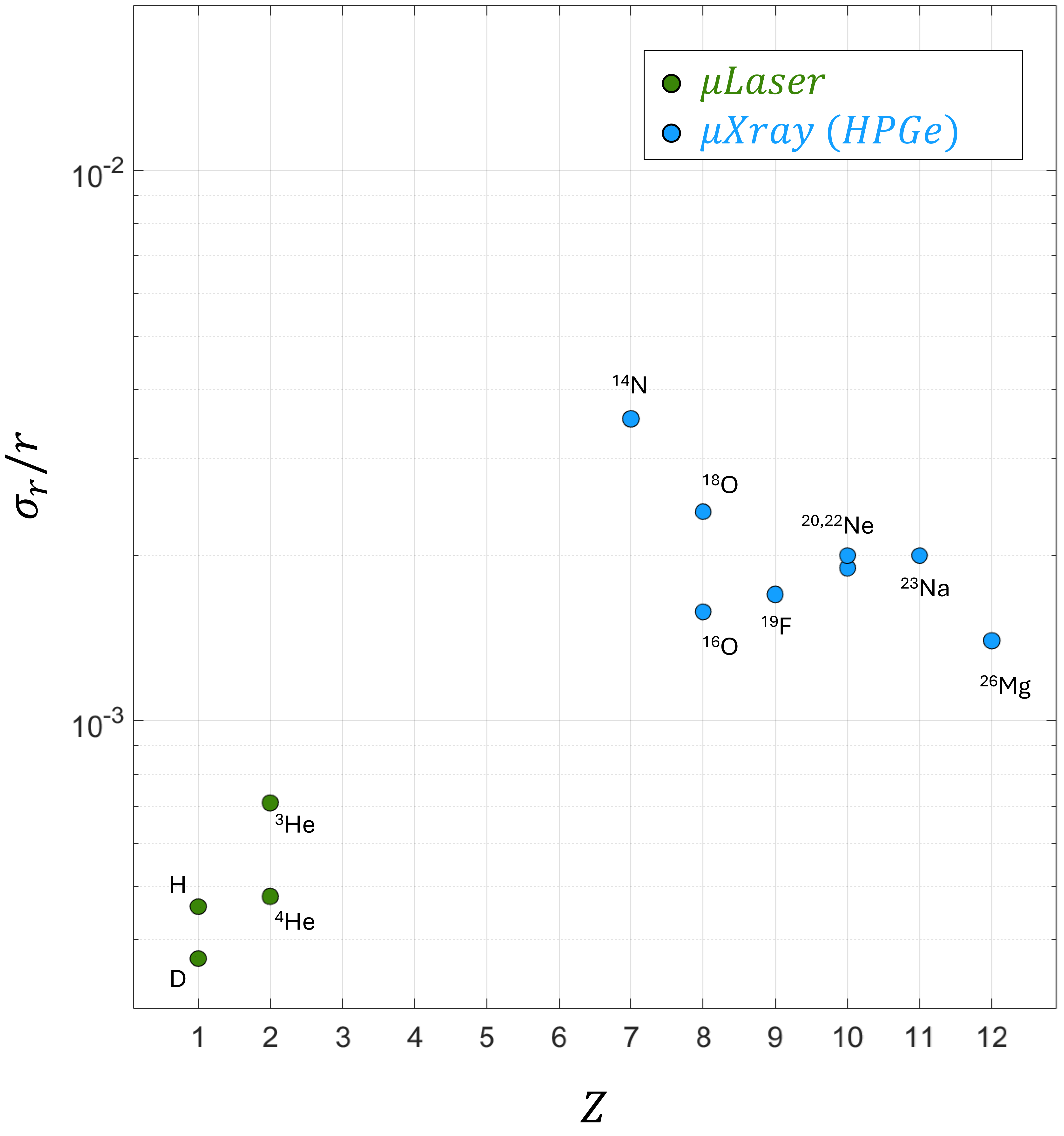
Nathalia
Konstantin



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  Yuki Honda (Tuesday),
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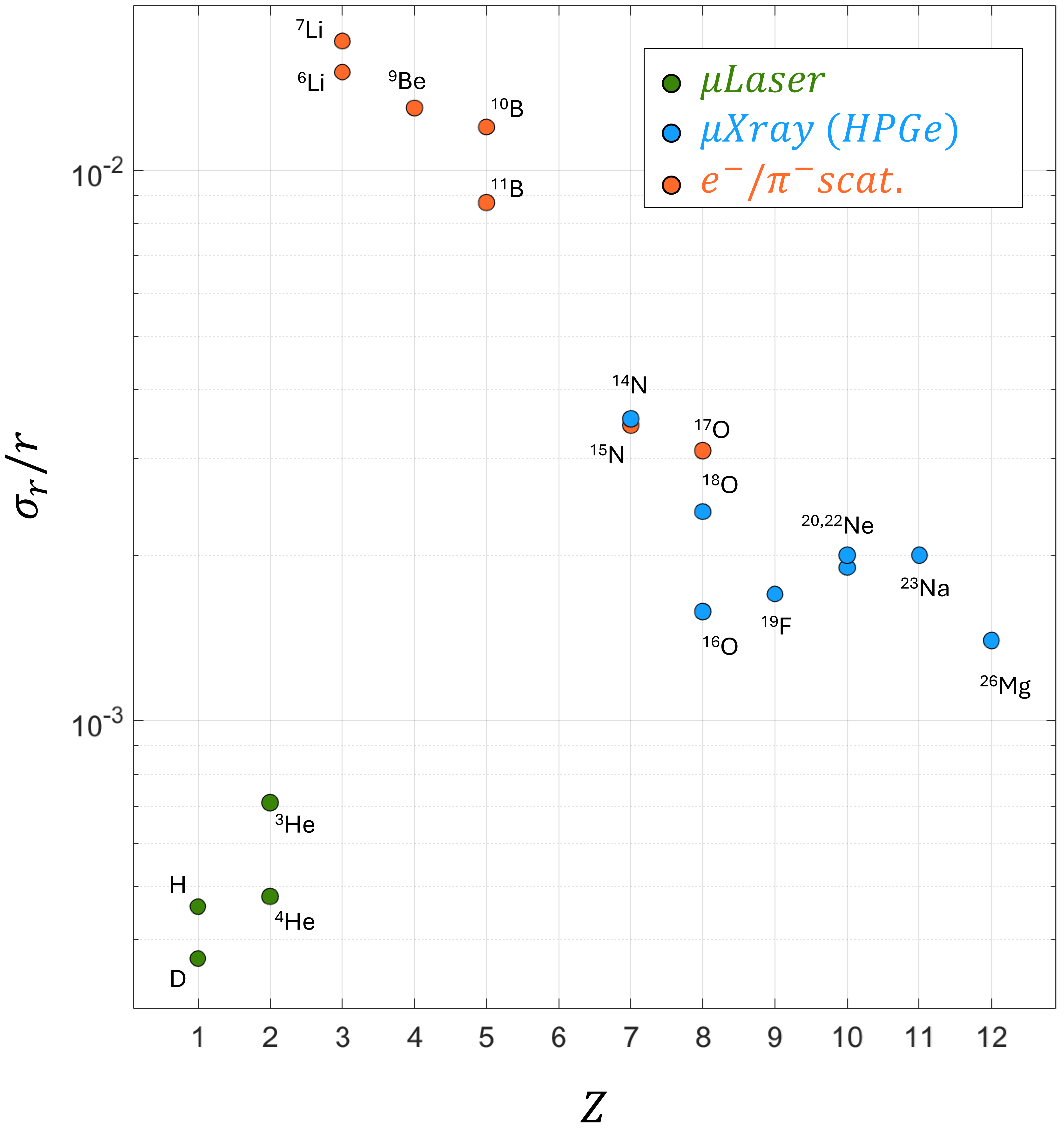
  Adrian Signer (Wednesday),
  Toshimi Suda (Friday)



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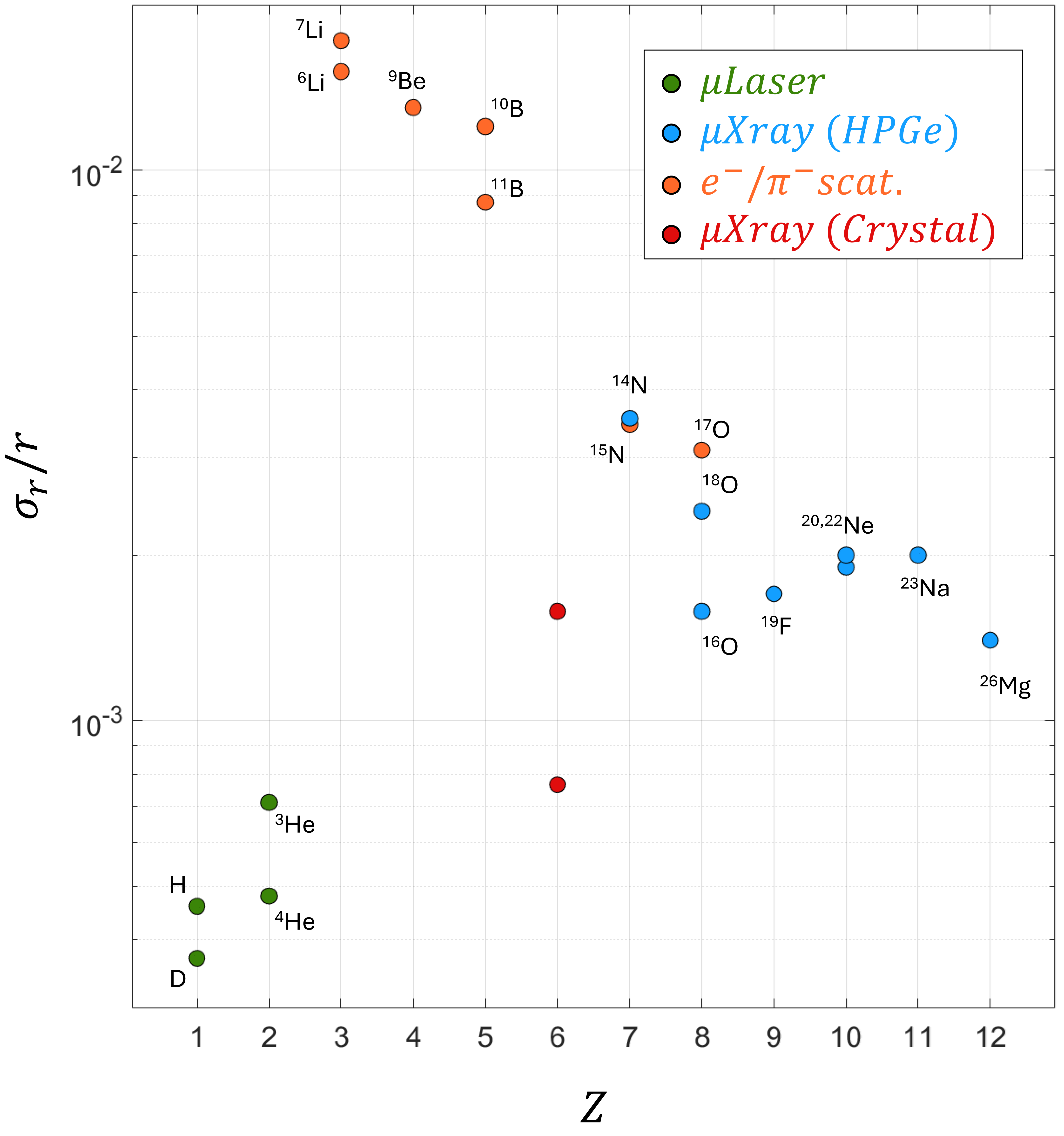
- **For $\mathbf{Z = 6}$**
  Measured with crystal spectrometer. Not widely applicable



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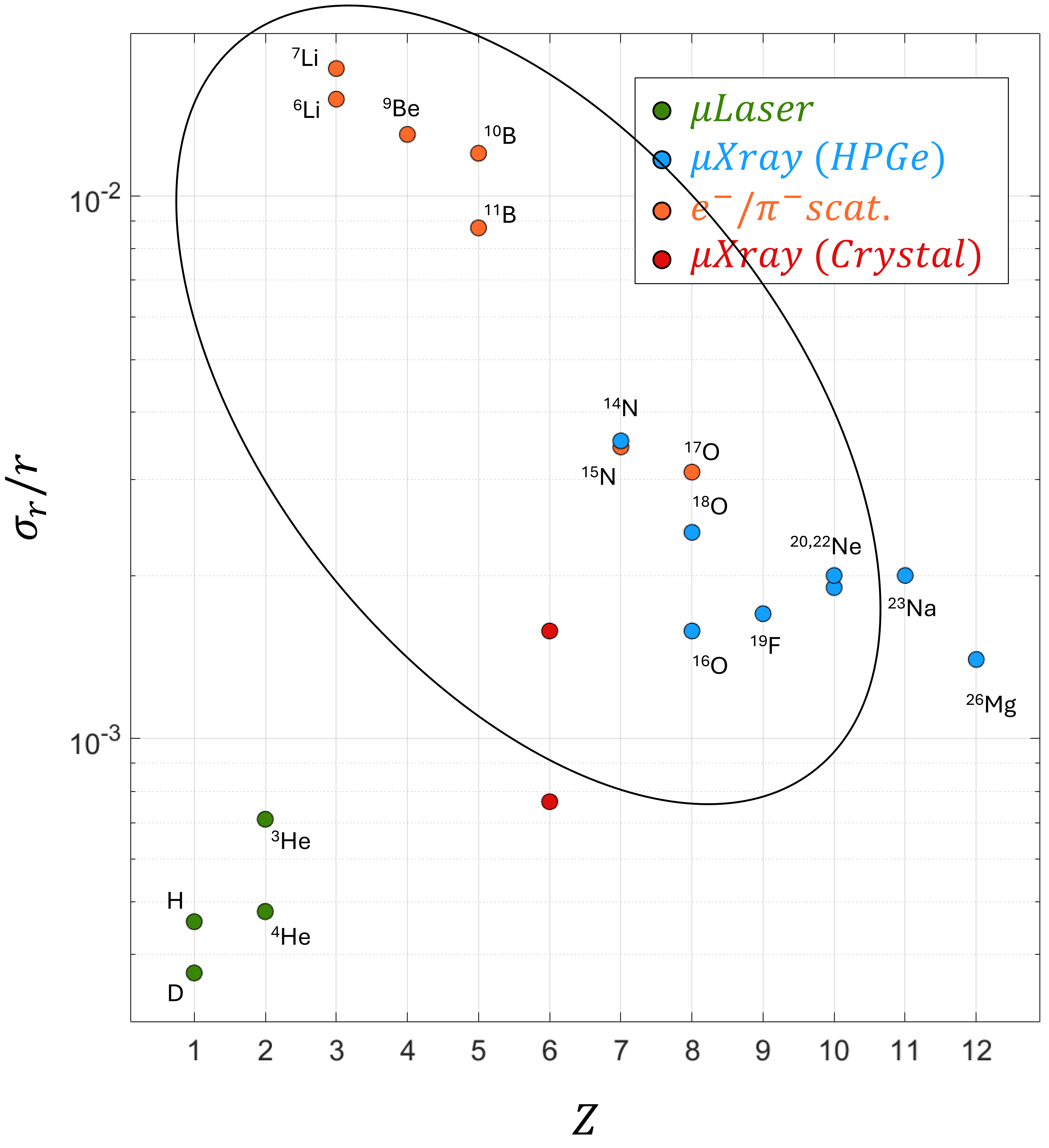

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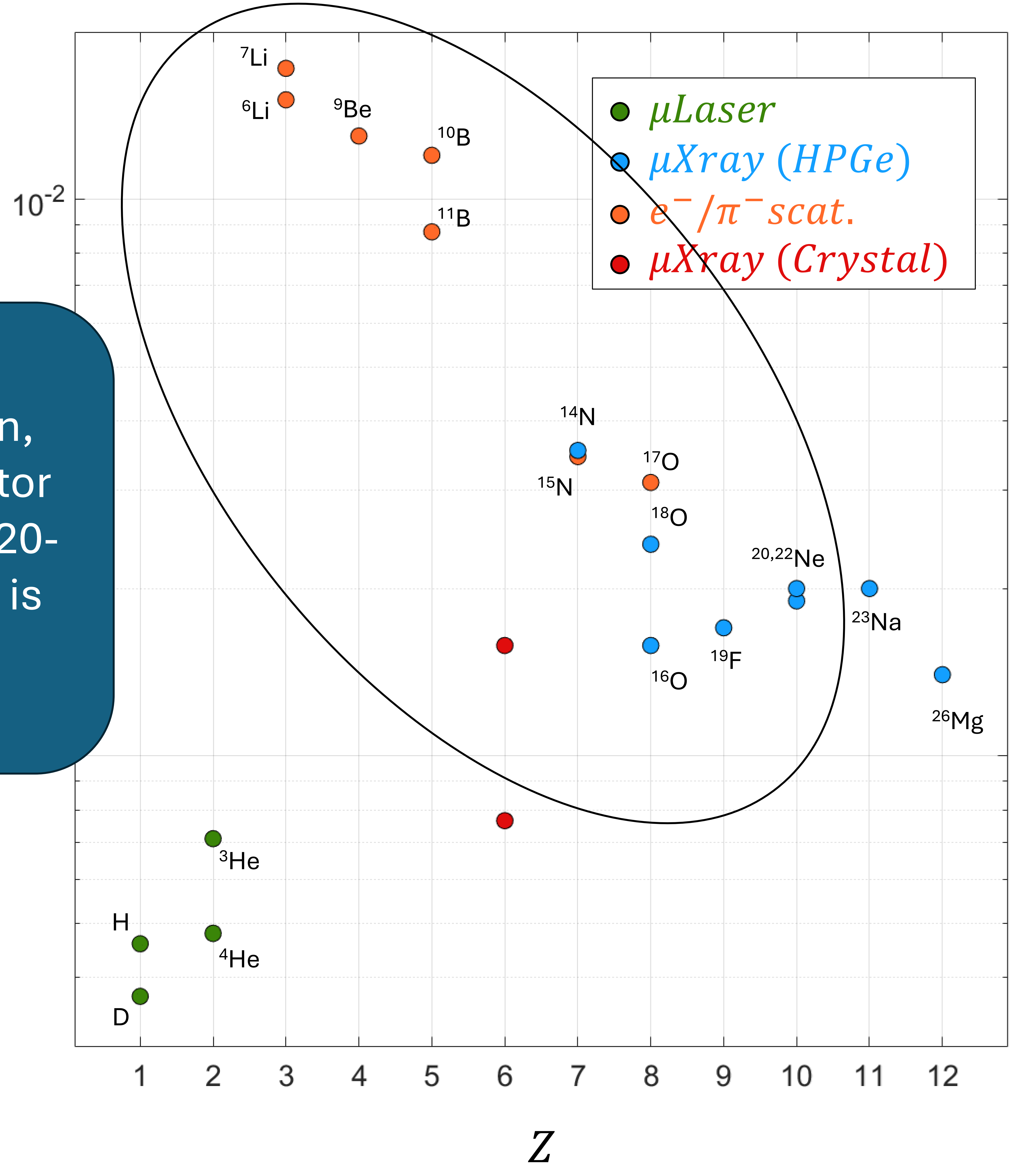
High-resolution, efficient, detector for low-energy (20-200 keV) x-rays is needed



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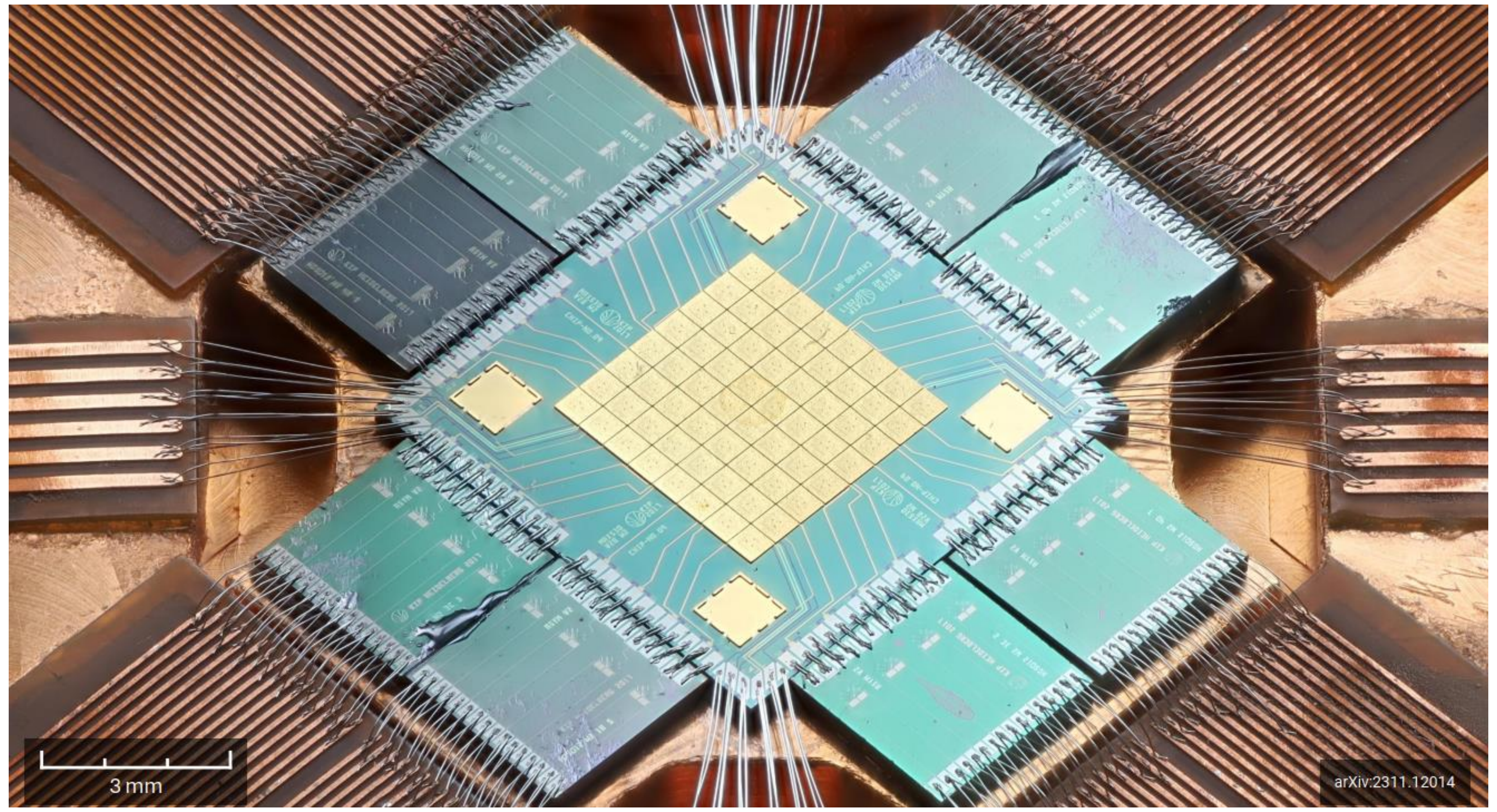
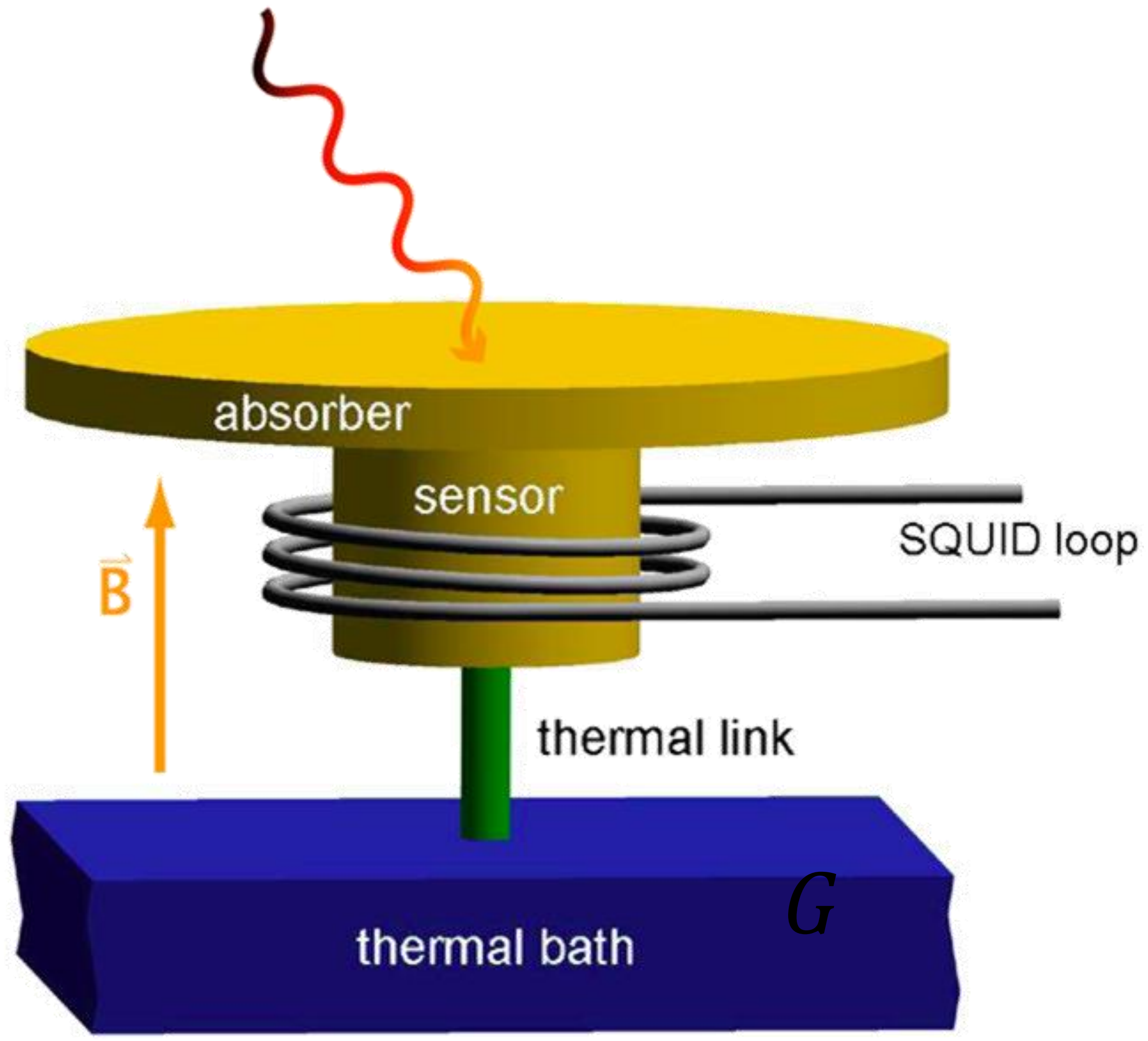
Enter microcalorimeters

Cryogenic microcalorimeters

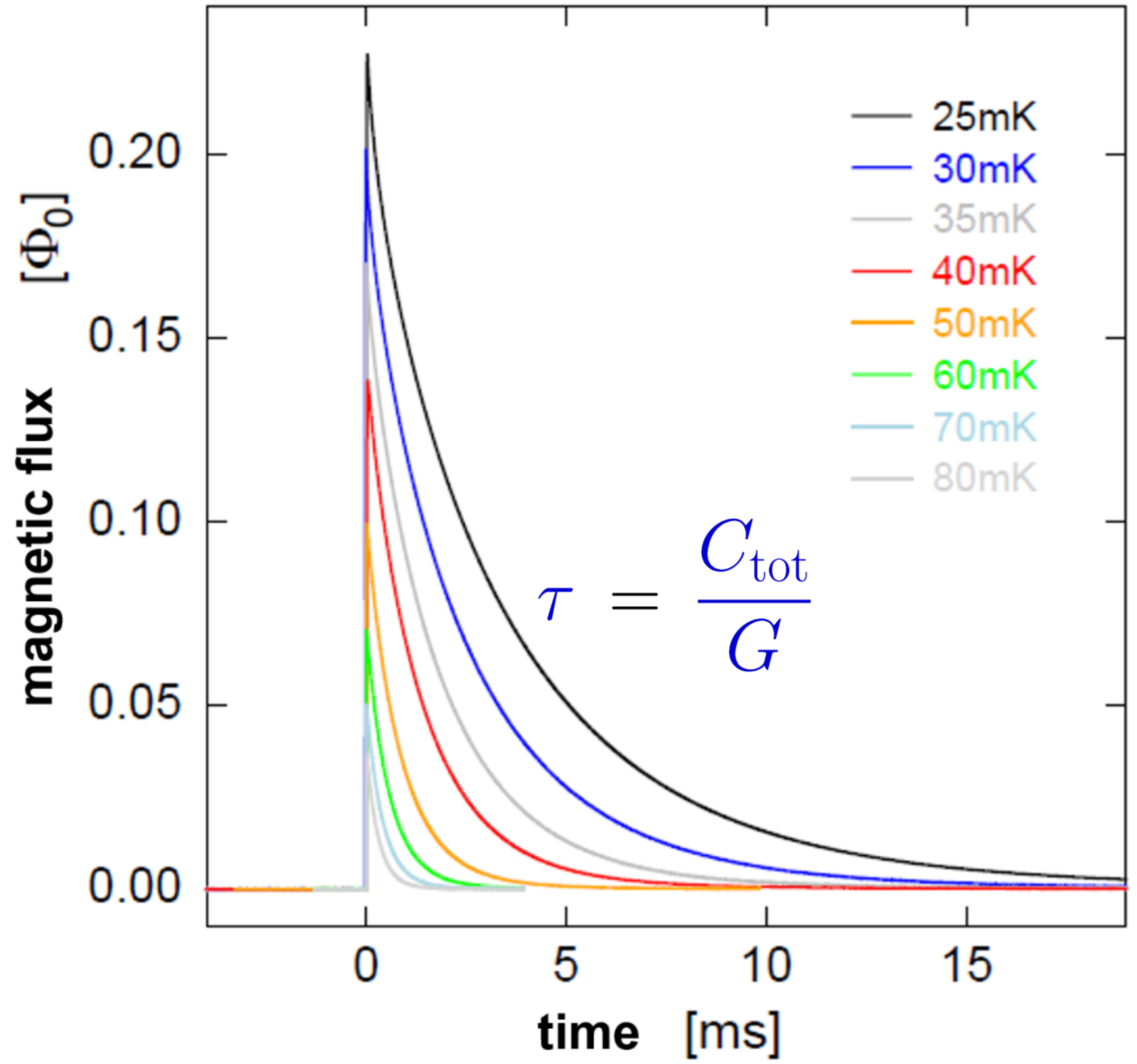


- High quantum efficiency
- Broadband (important for calibration)
- **Superb resolution $\left(\frac{E}{\Gamma_E} > 10^3\right)$**
- Fast rise time

Metallic Magnetic Calorimeters (MMCs)



* Absorber thickness determines efficiency at given energy

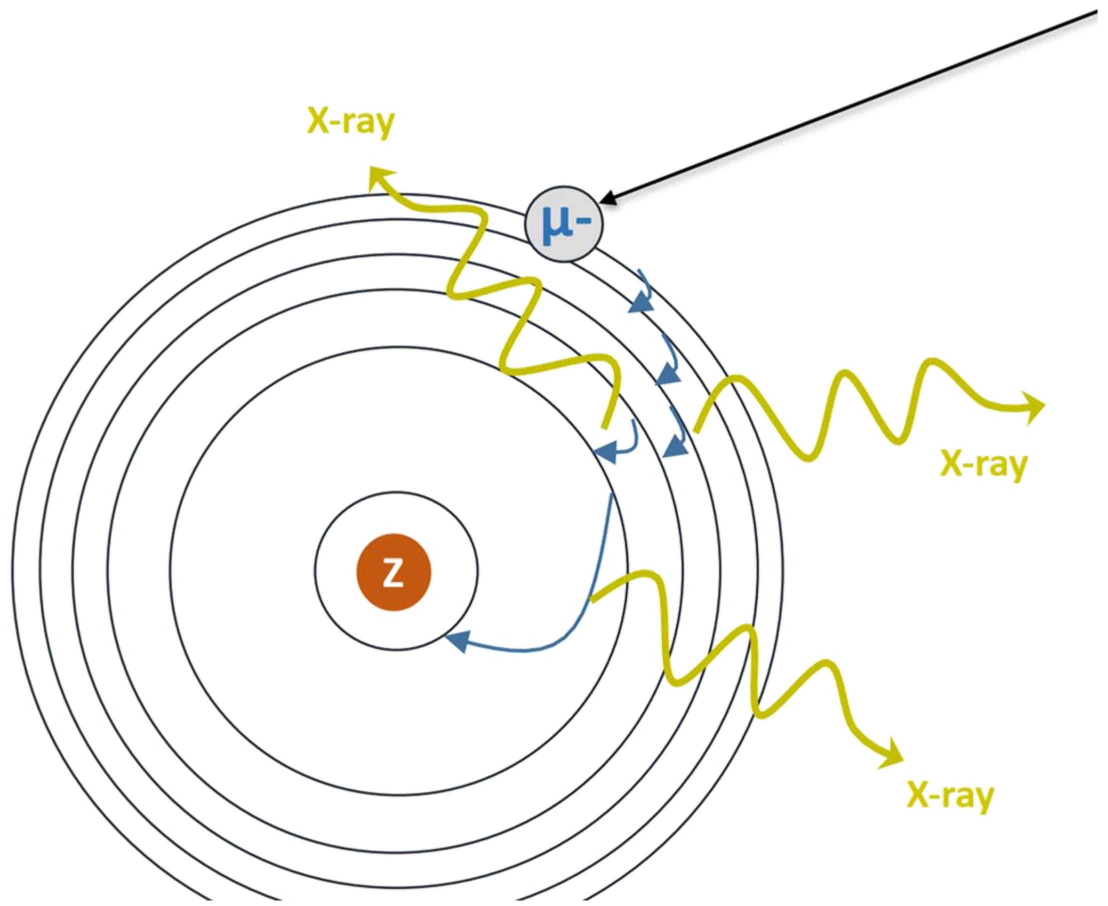


δE ⇨ $\delta T = \frac{\delta E}{C}$ ⇨ $\delta M = \frac{\partial M}{\partial T}\frac{\delta E}{C}$ ⇨ $\delta \Phi \sim \delta M \sim \delta T \sim \delta E$

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

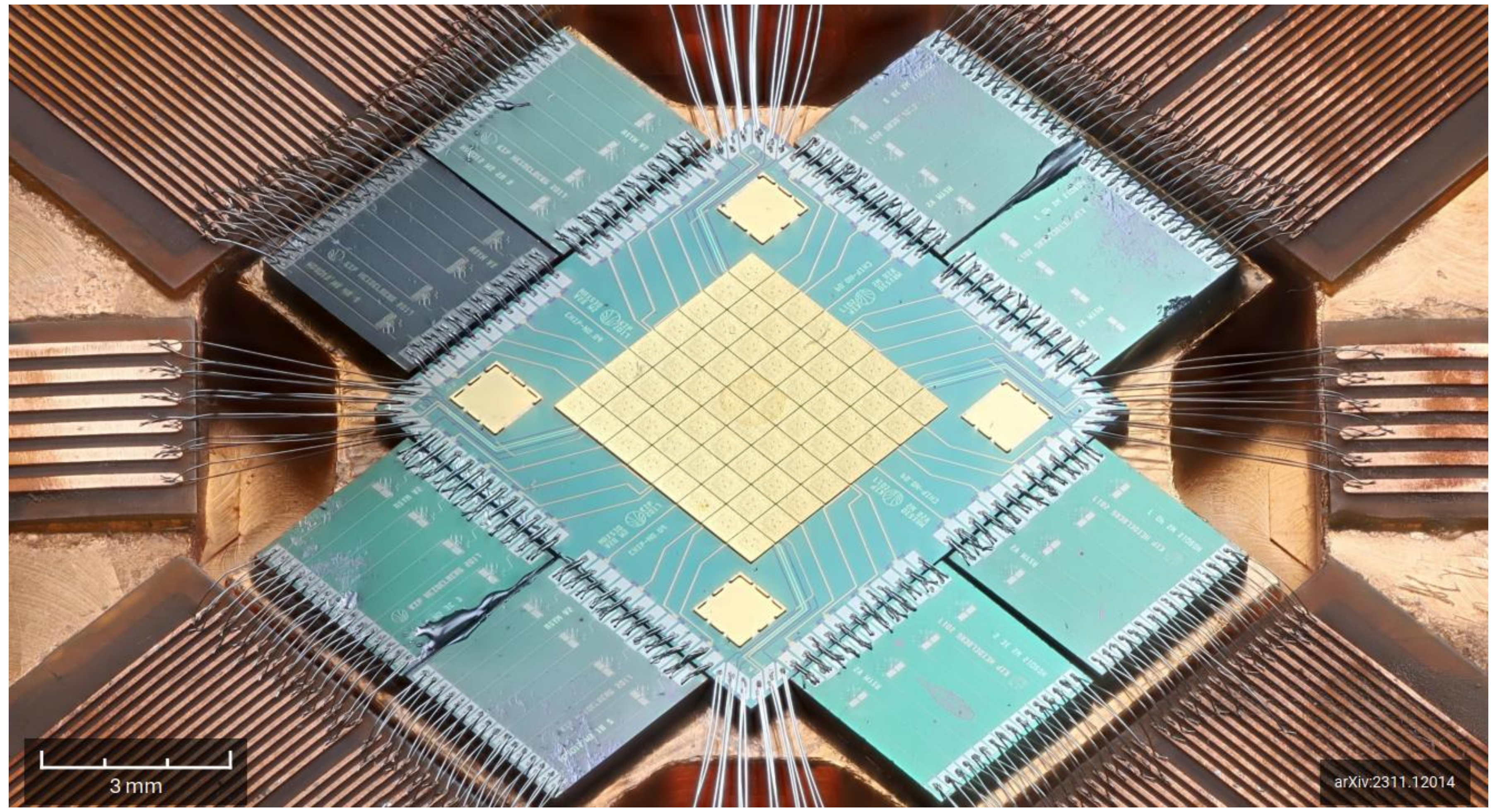
Enter microcalorimeters

Muonic atoms



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

Cryogenic microcalorimeters



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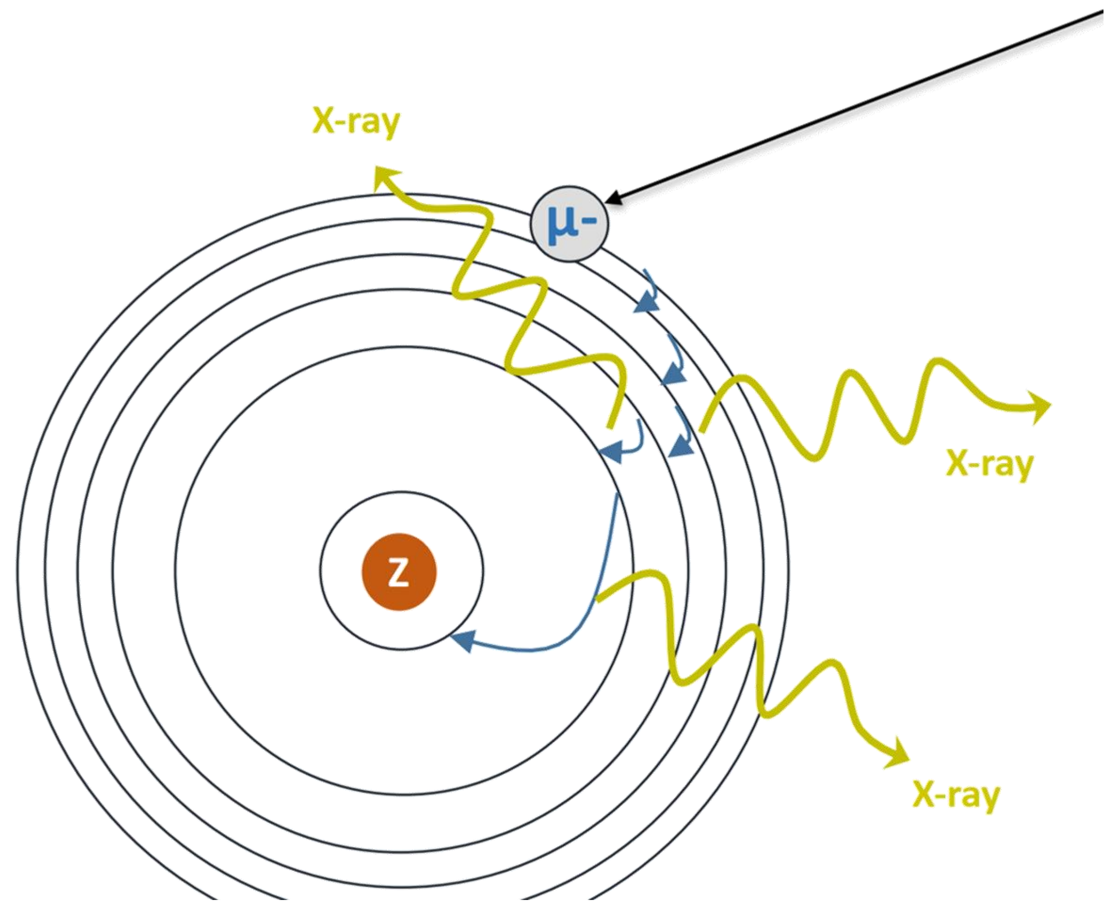

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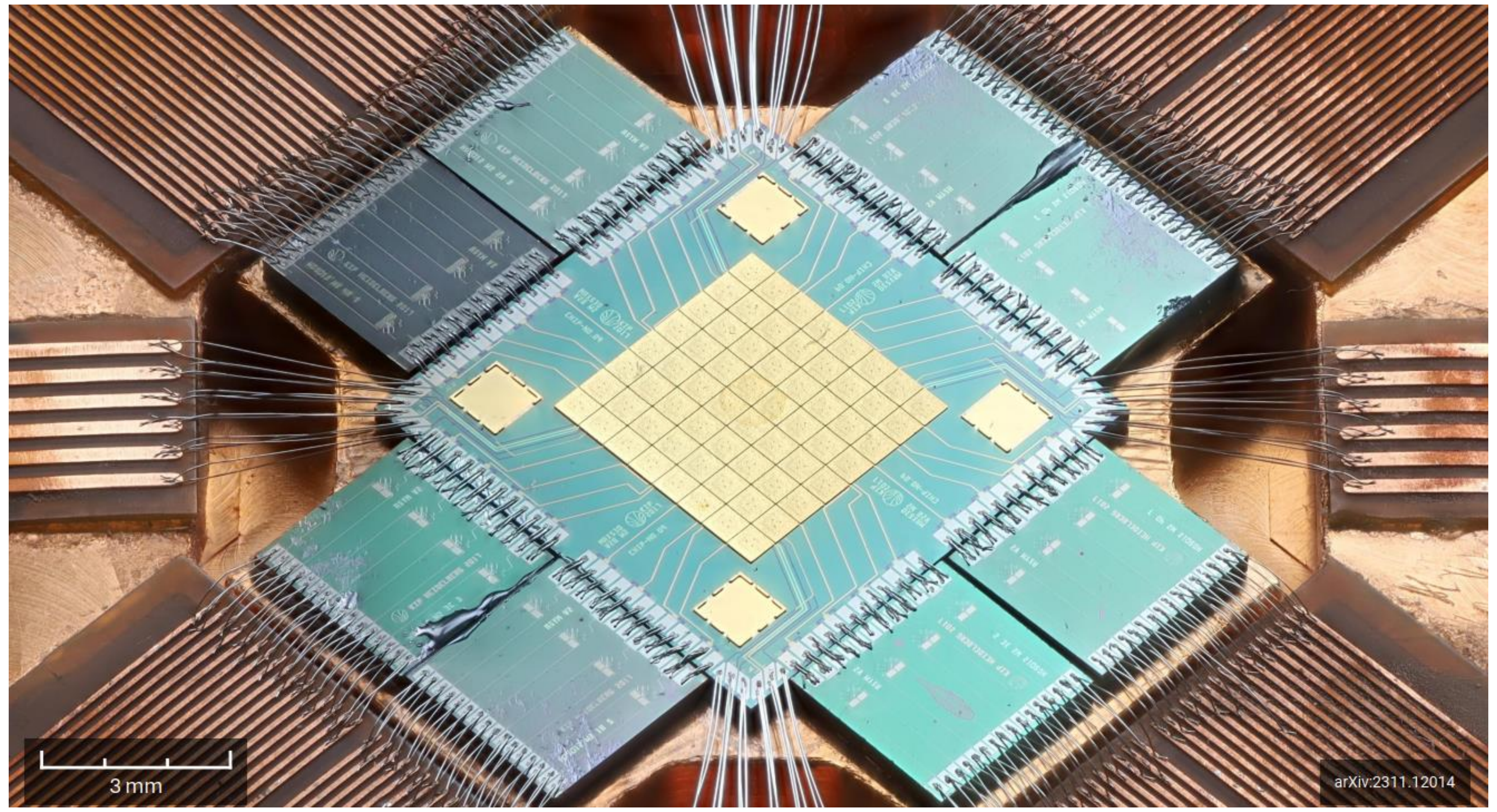

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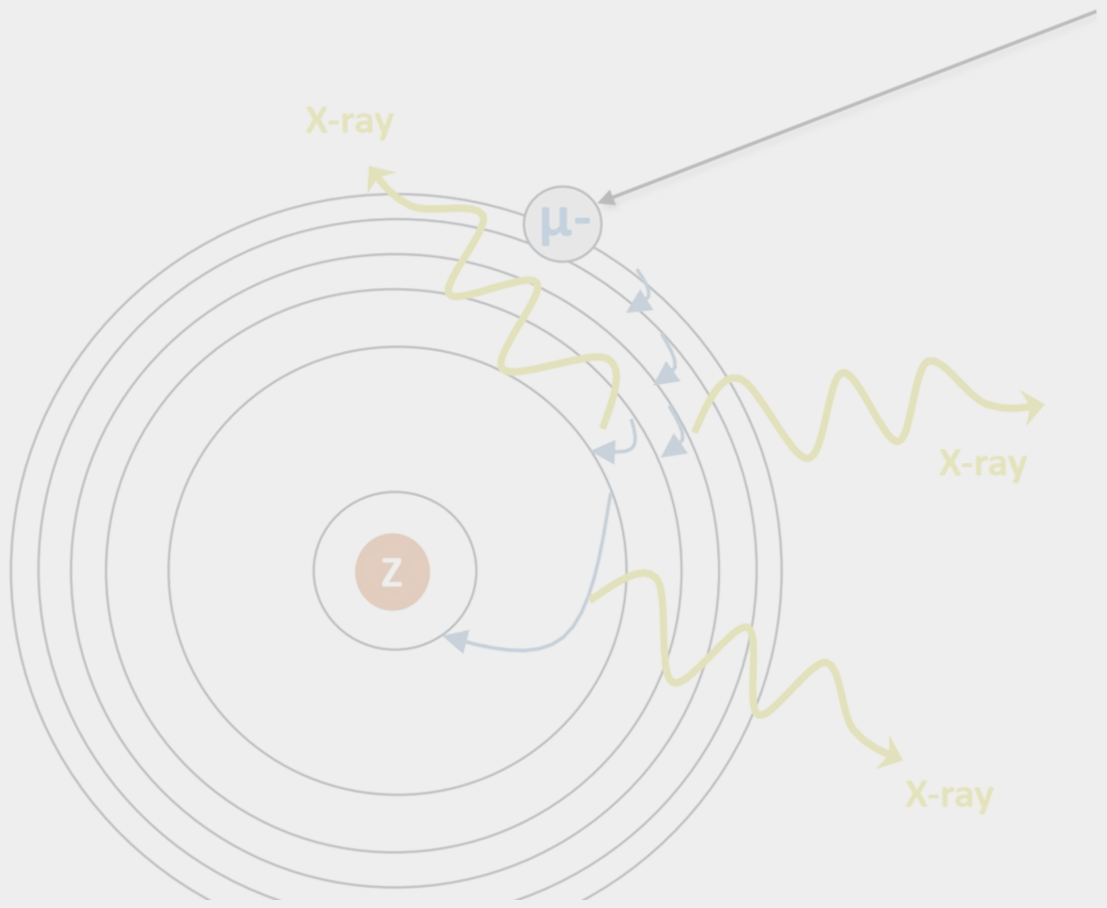

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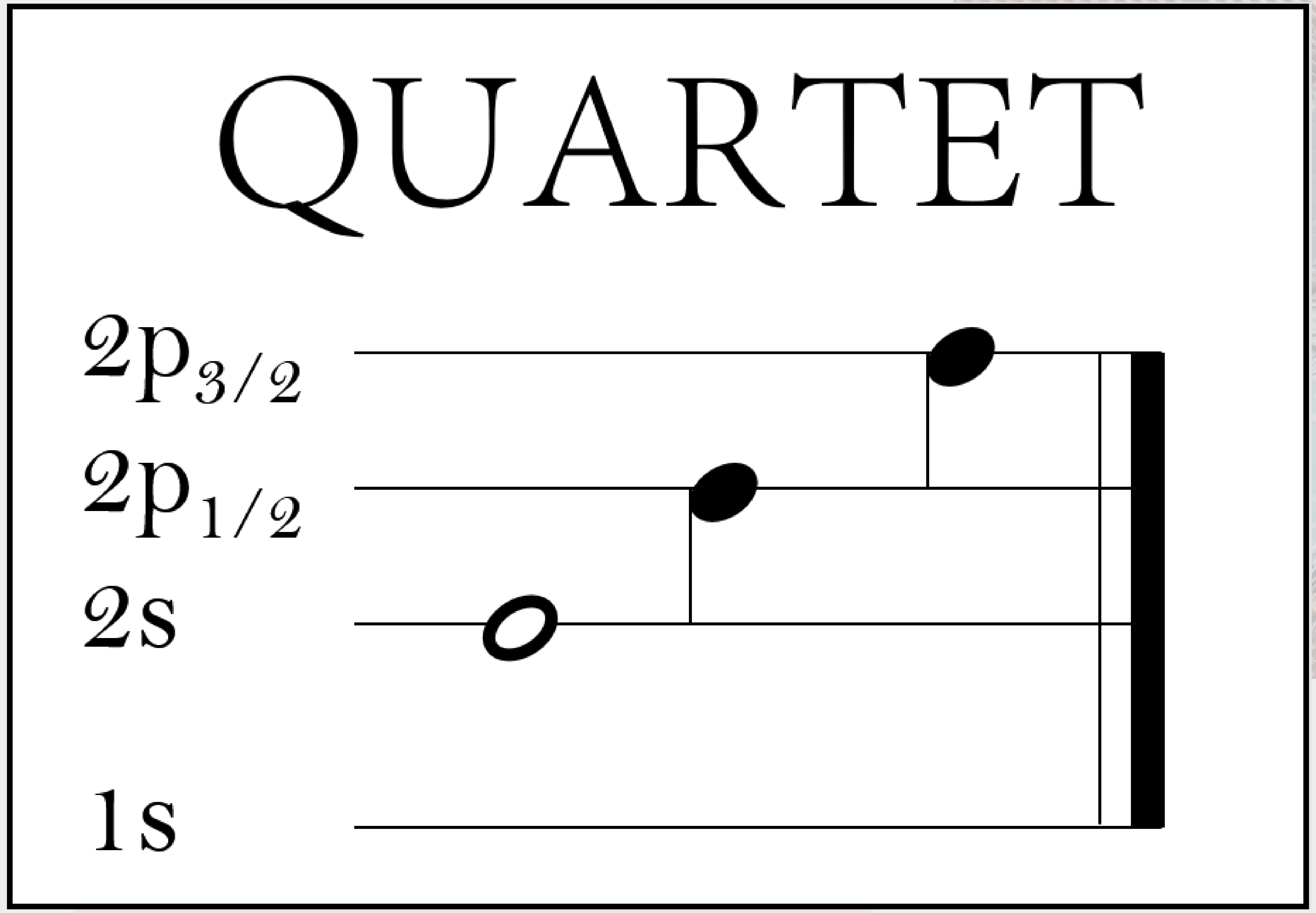
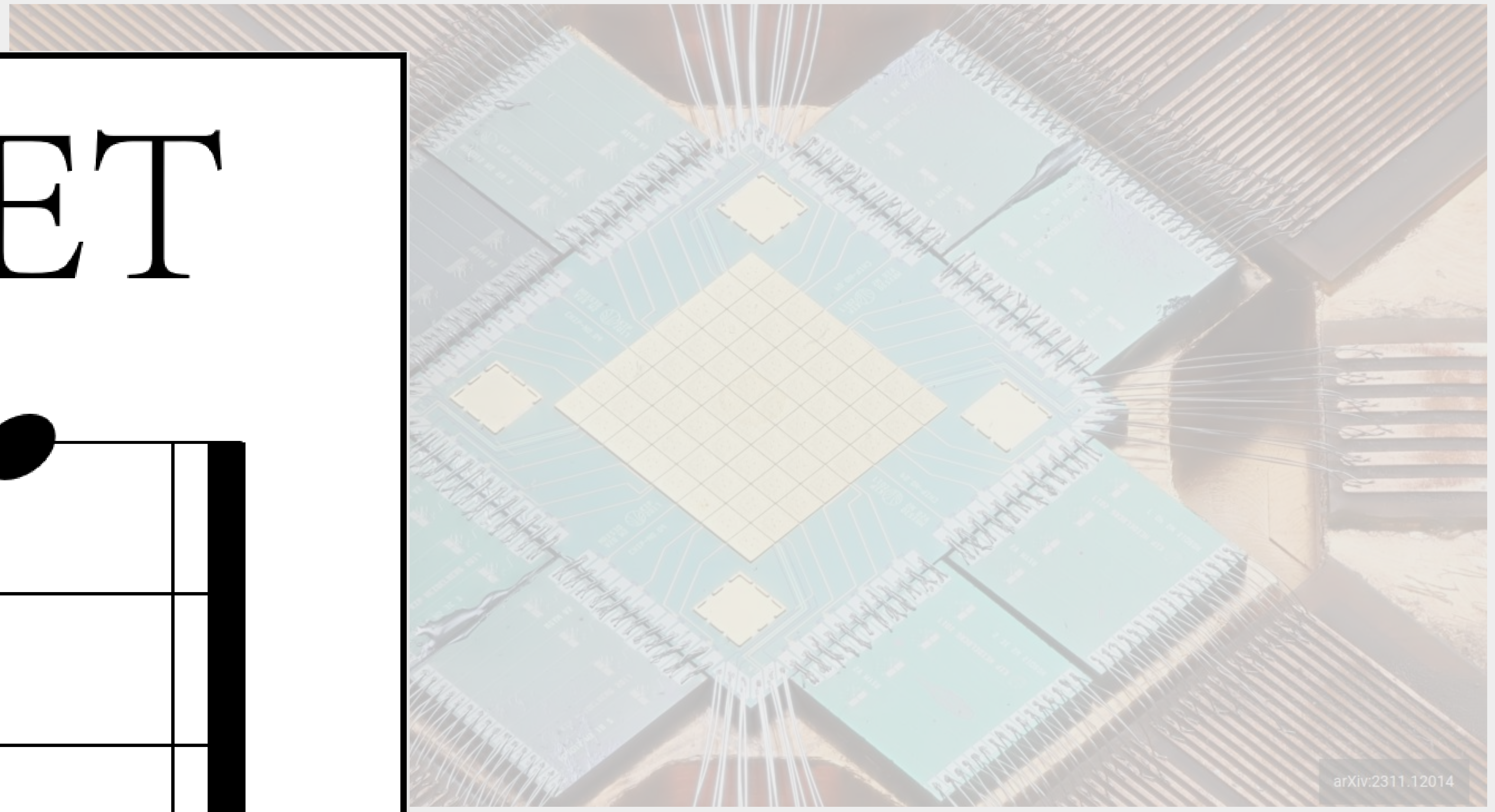
Quantum Interactions with Exotic Atoms



More info:

arXiv:2311.12014
arXiv:2310.03846

Cryogenic microcalorimeters



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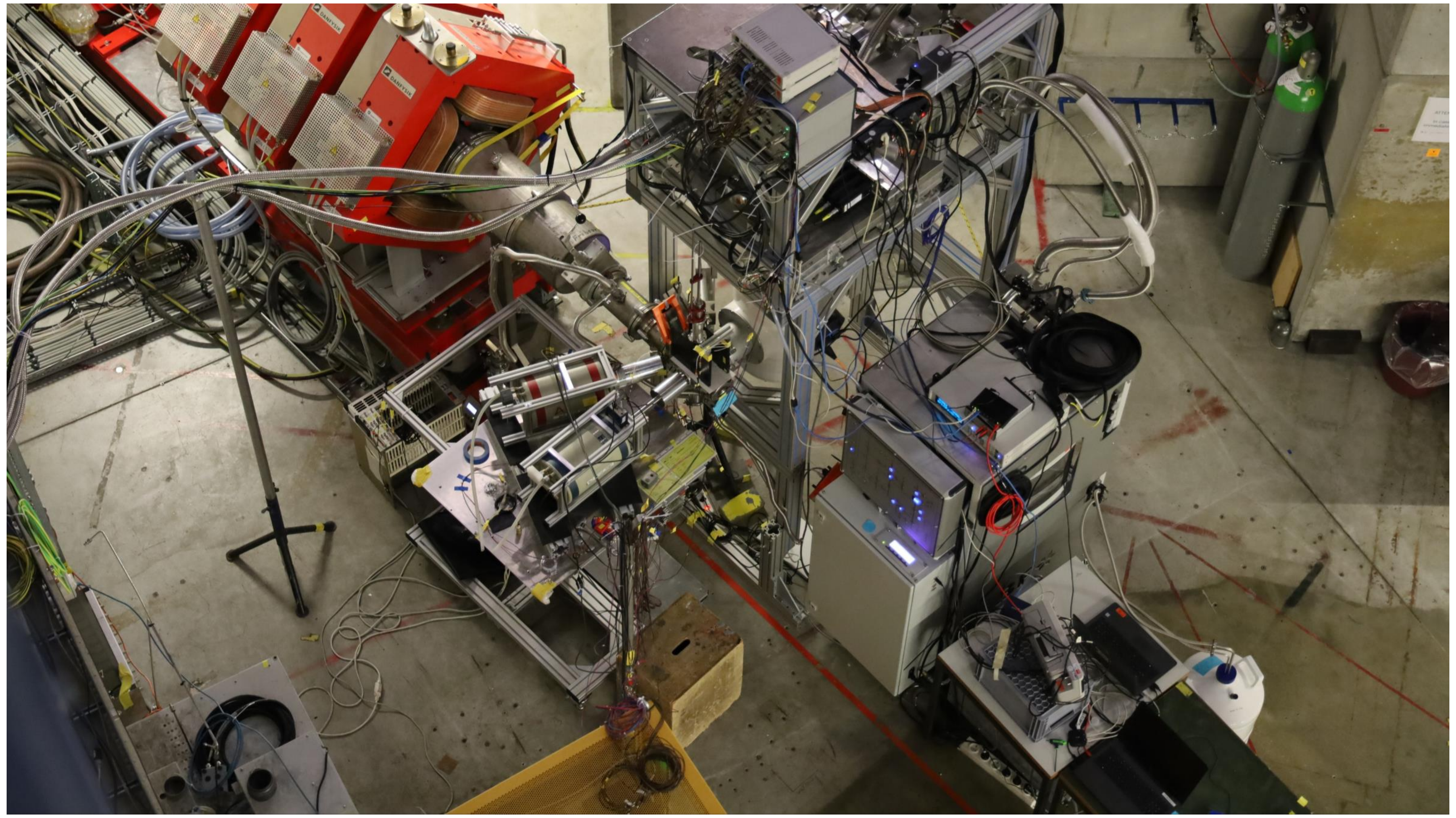
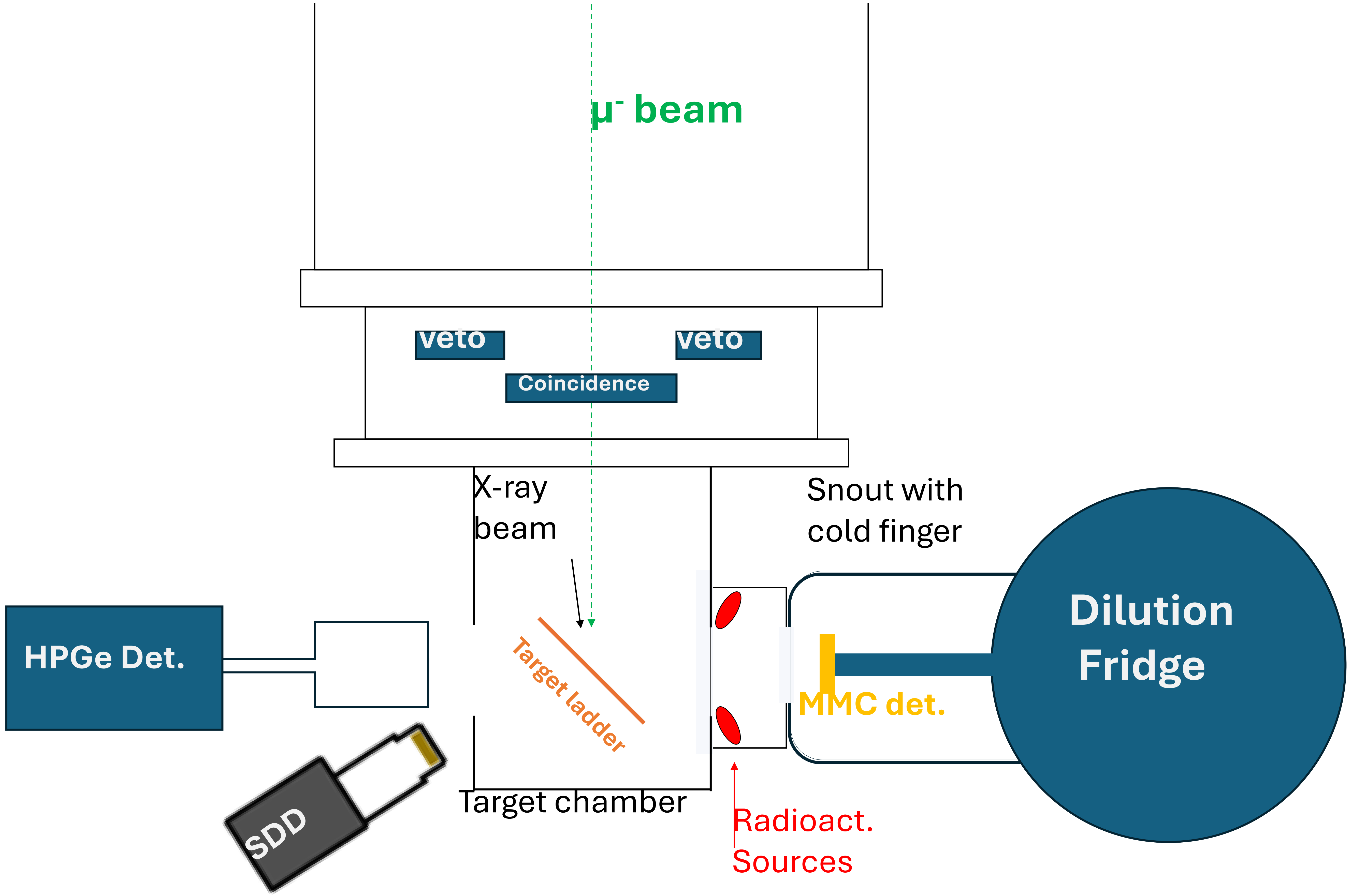
Experimental scheme



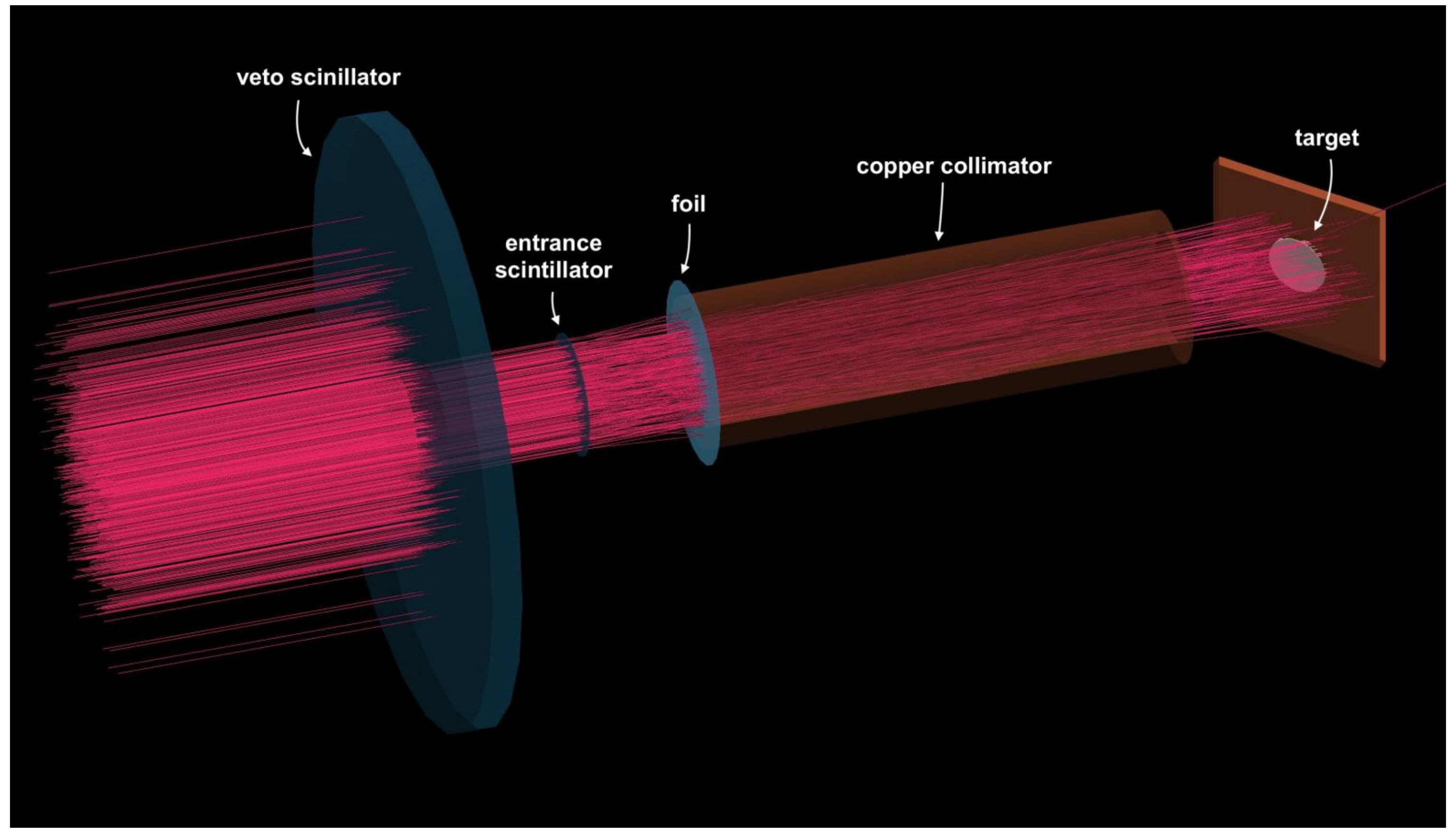


Target choice and preparation

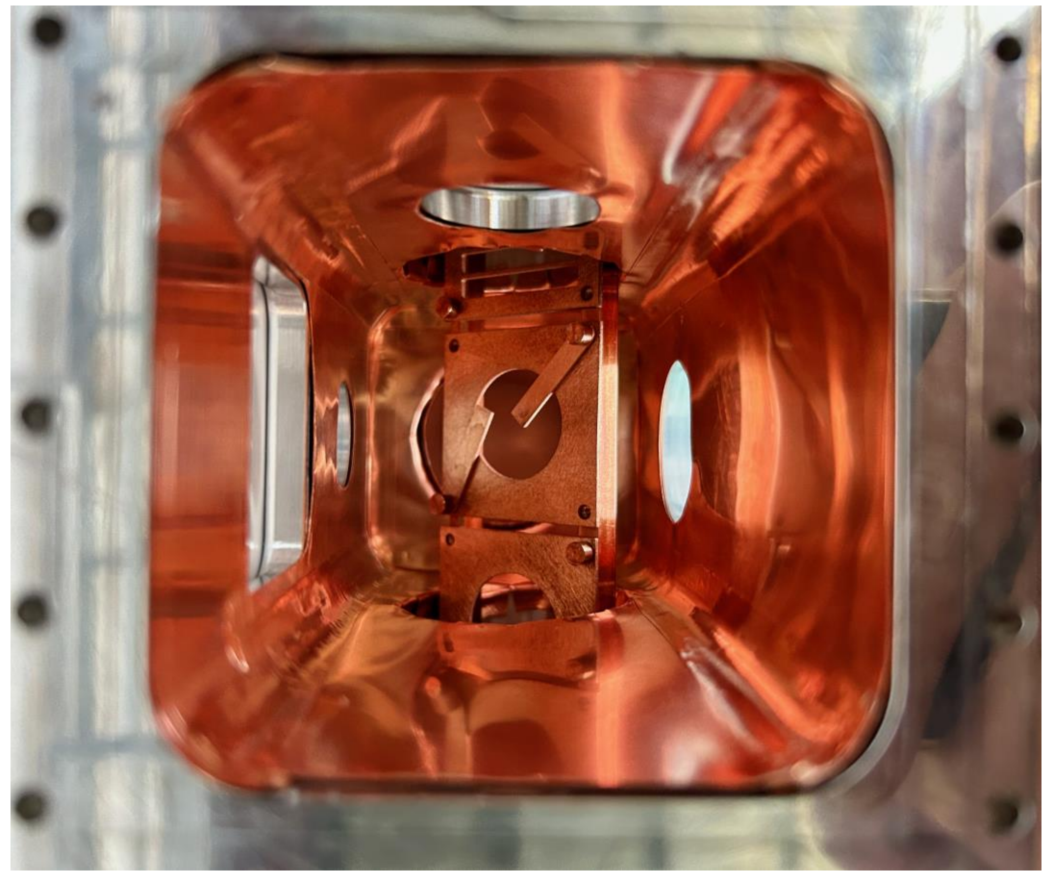
Used targets:

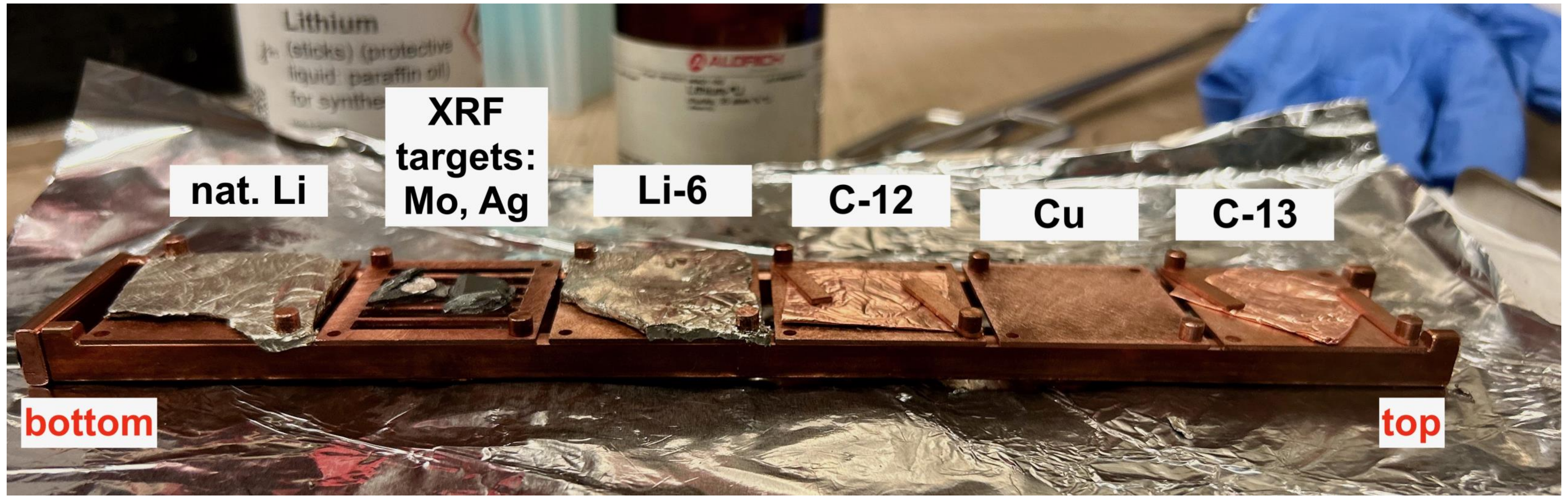
- Blank Cu
- $^{nat}Li = 92\%\ ^{7}Li, 8\%\ ^{6}Li$ 2 mm thick
- $^{6}Li = 95\%\ ^{6}Li, 5\%\ ^{7}Li$ 2 mm thick
- ^{9}Be, 99.0% pure, 2.5 mm thick
- $^{nat}B = 80\%^{11}B, 20\%^{10}B$ 2 mm thick
- $^{12}C(> 99\%)$ powder in Cu or Alu pouch, 0.5 g
- $^{13}C(> 99\%)$, D-fructose in Cu or Alu pouch, 1 g
- XRF targets: Mo and Ag foils on Cu grid

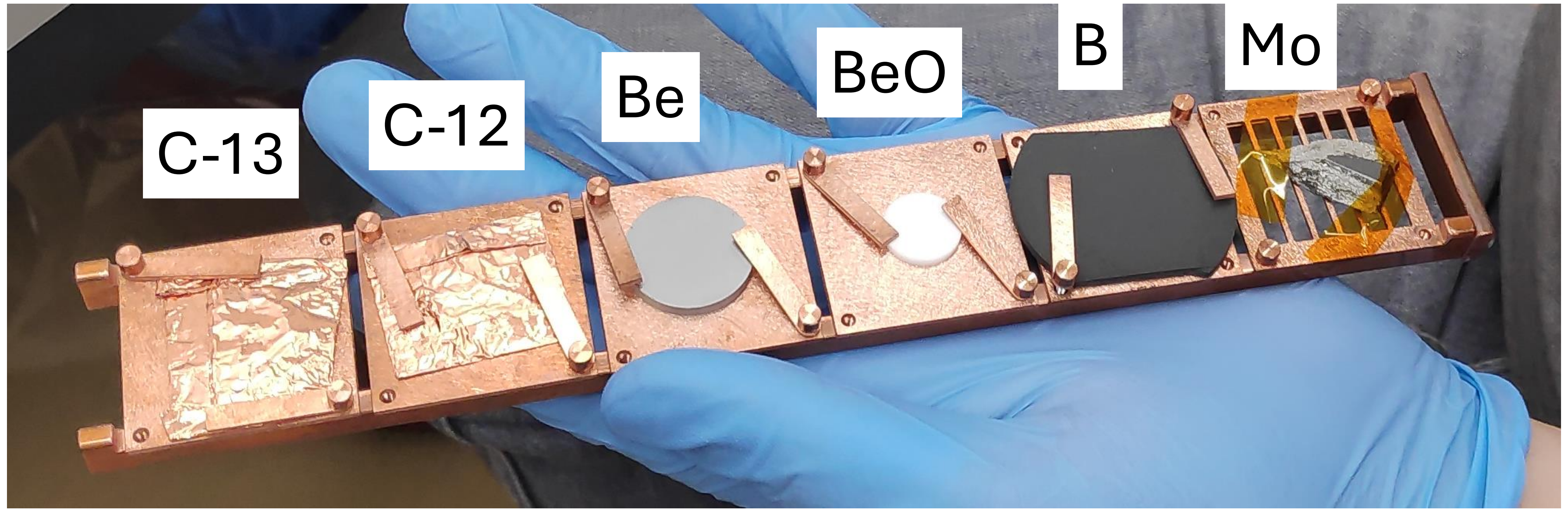
Stopping power optimized with G4beamline



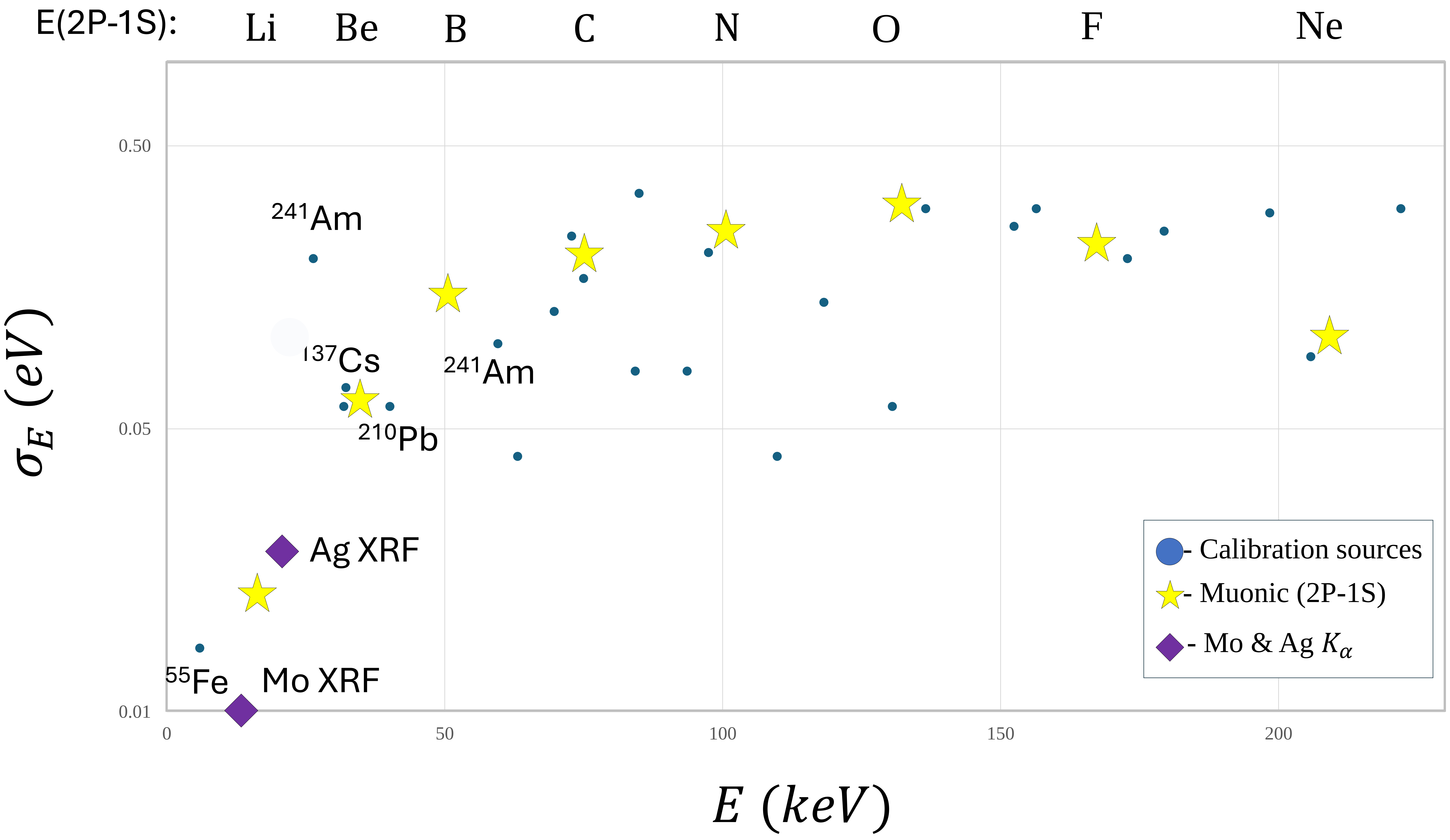
Chamber covered with Cu



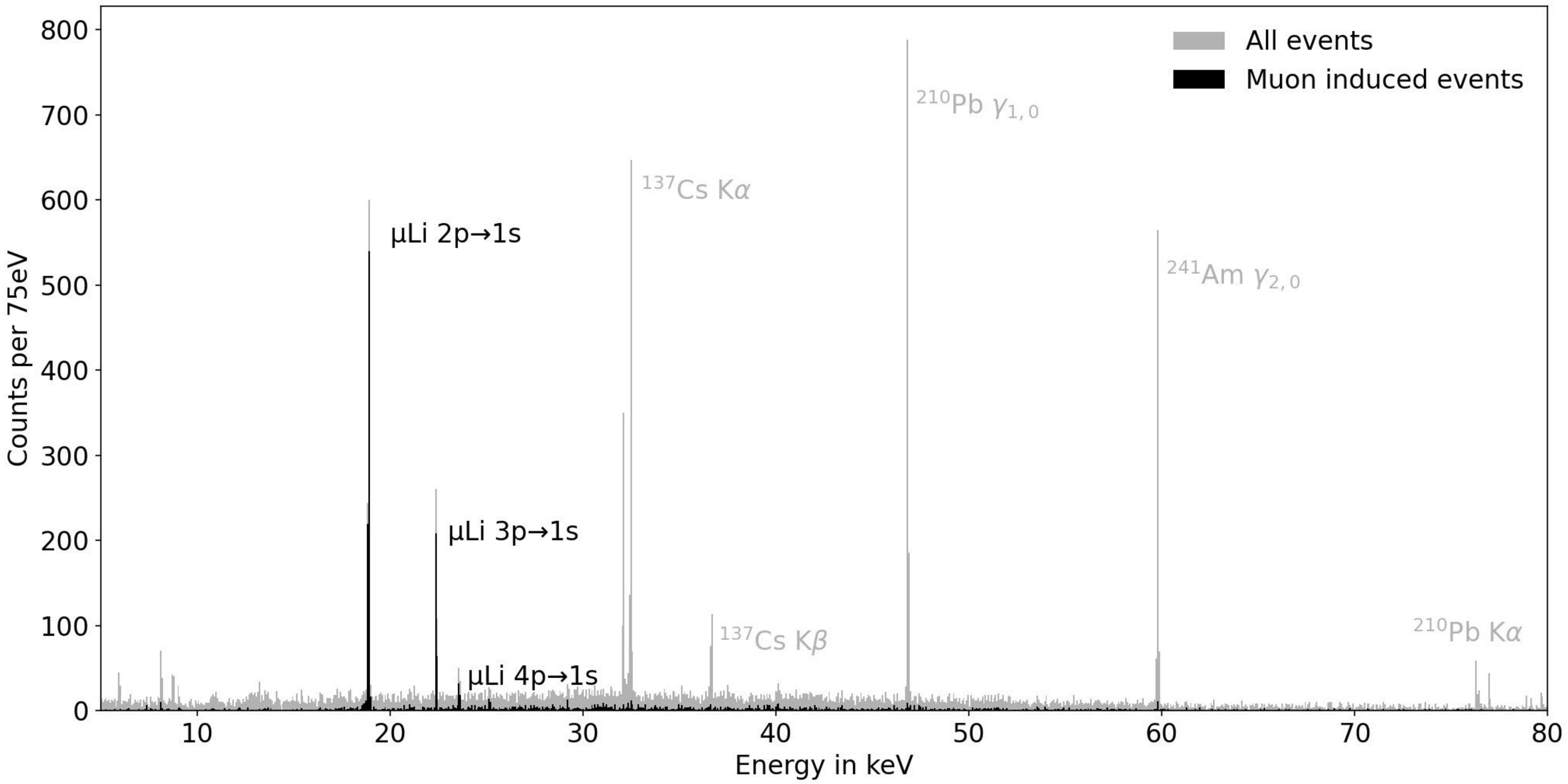




Test-beam summary: Tested calibration sources



Preliminary calibrated spectrum with mixed Li target



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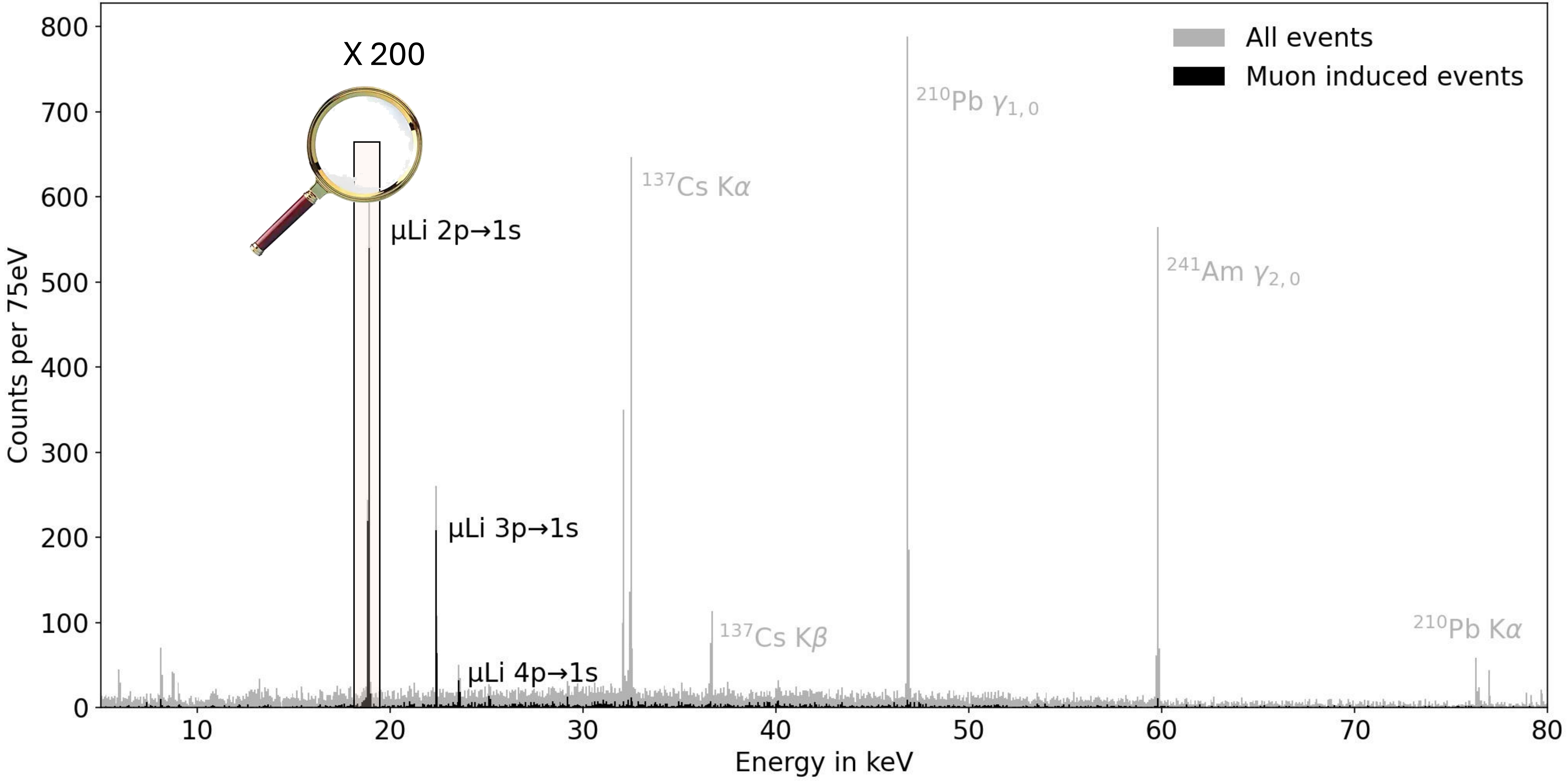
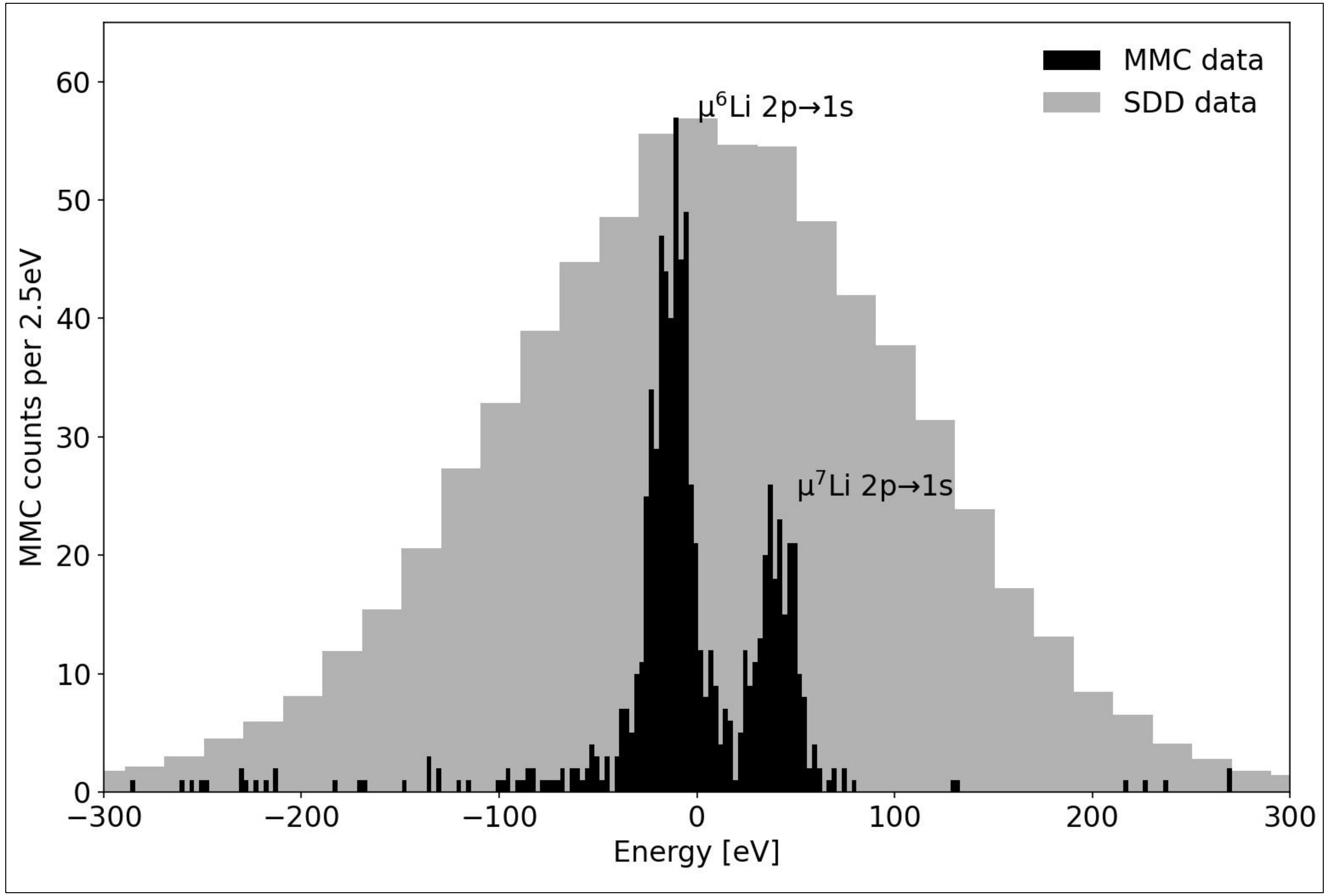
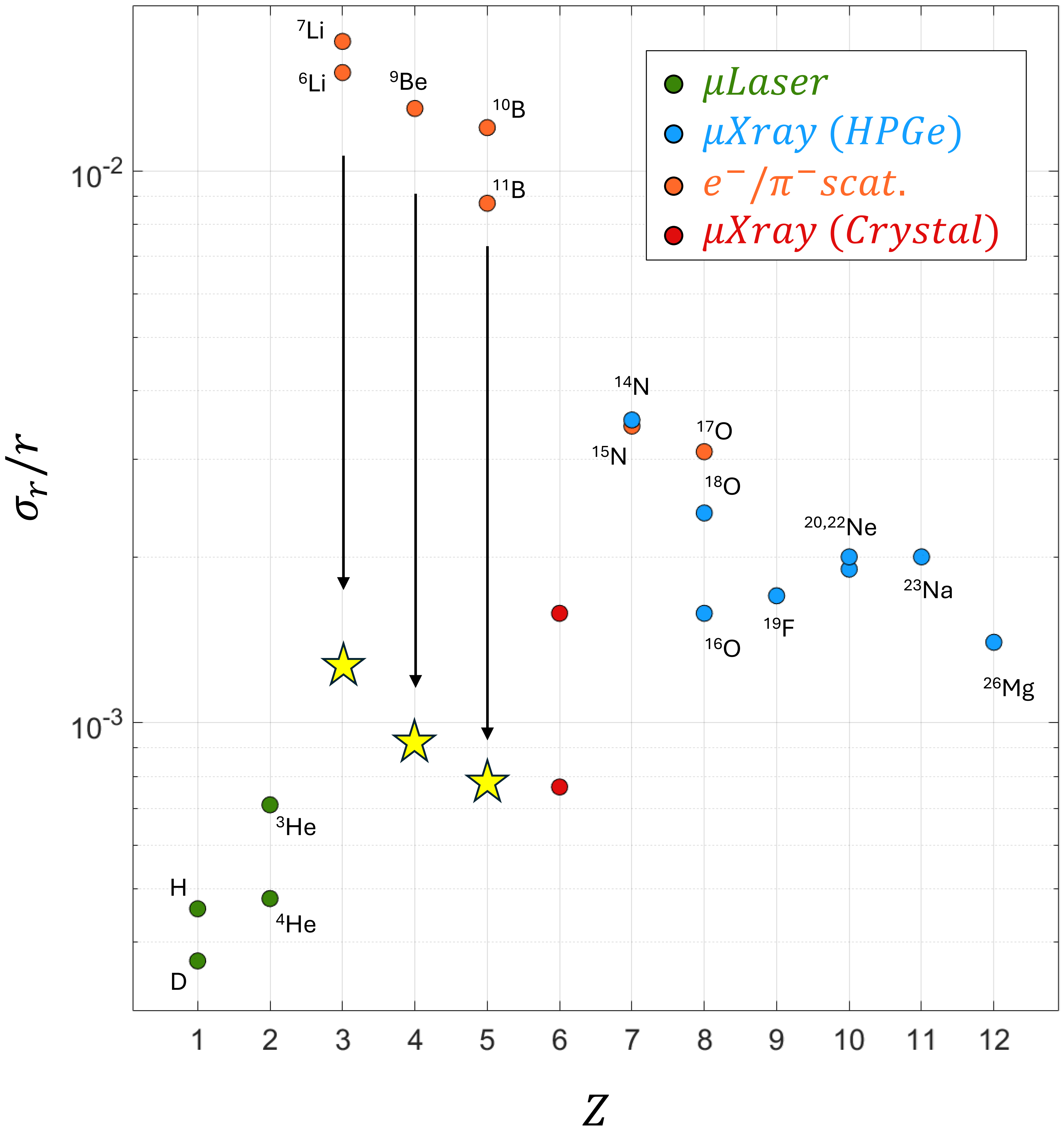


Preliminary zoomed-in spectrum of mixed Li target



QUARTET goals

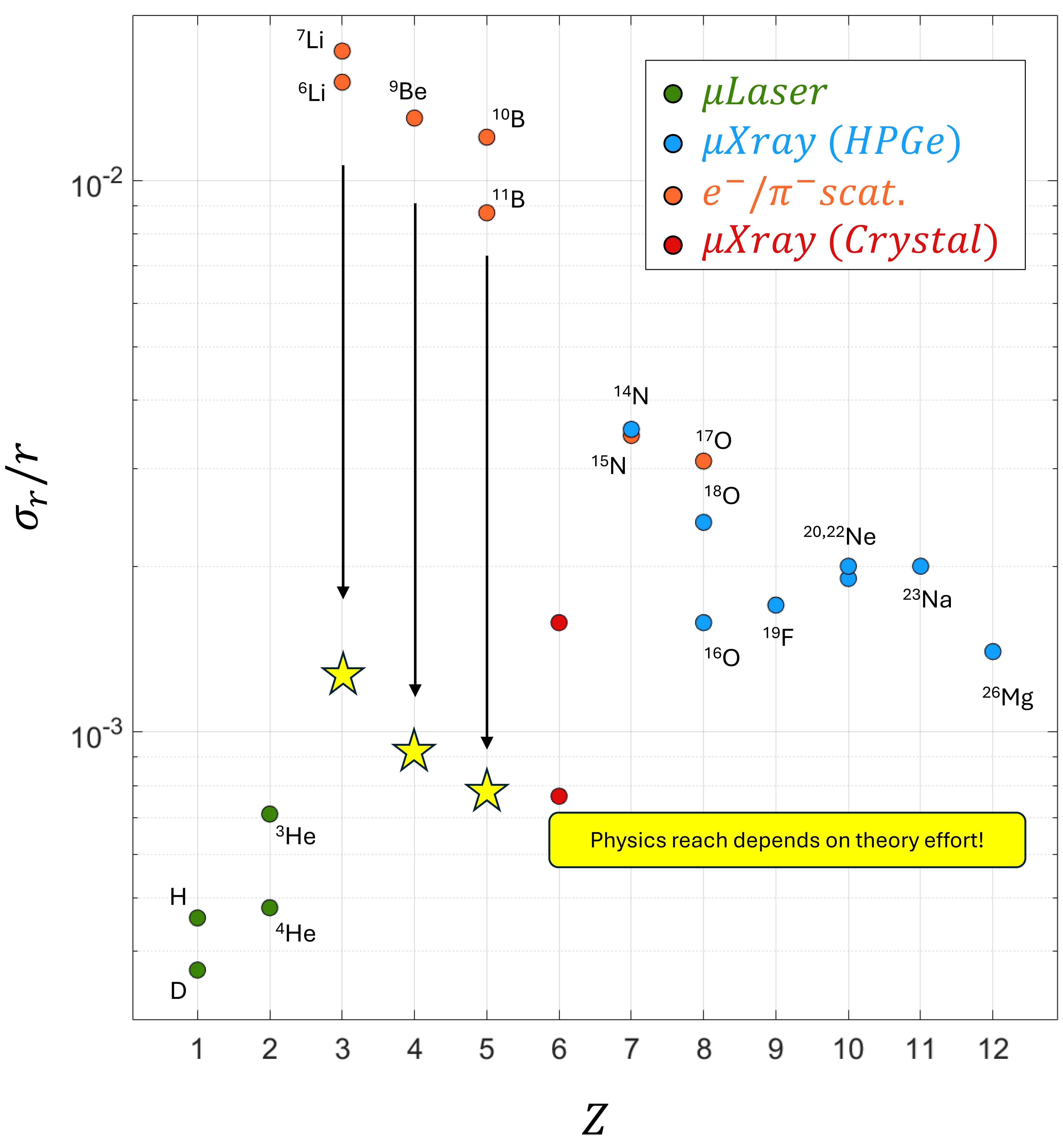
- Phase I: order of magnitude improvement in radii of Li, Be, B



QUARTET goals

- Phase I: order of magnitude improvement in radii of Li, Be, B

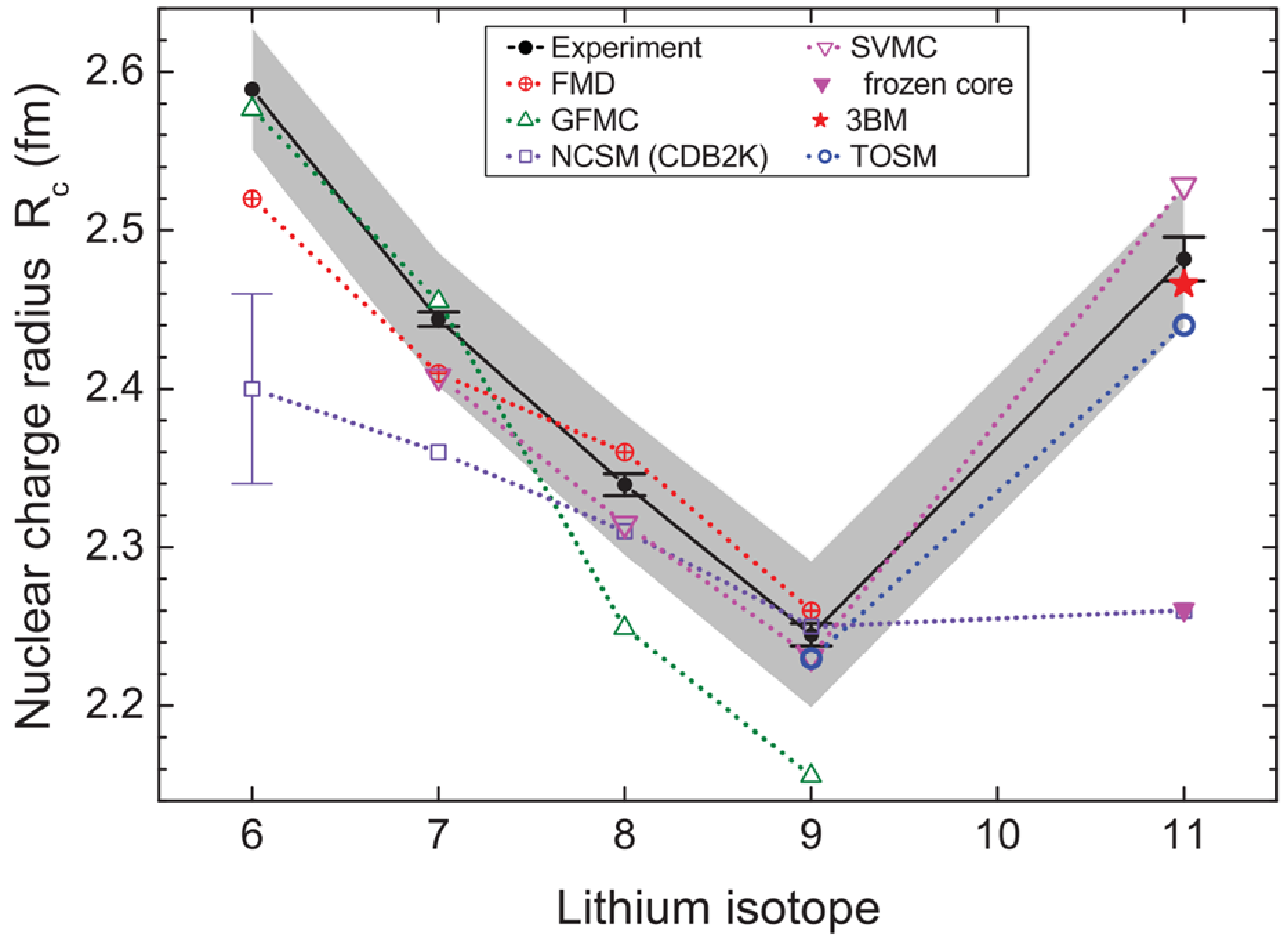
- Phase II: Heavier systems



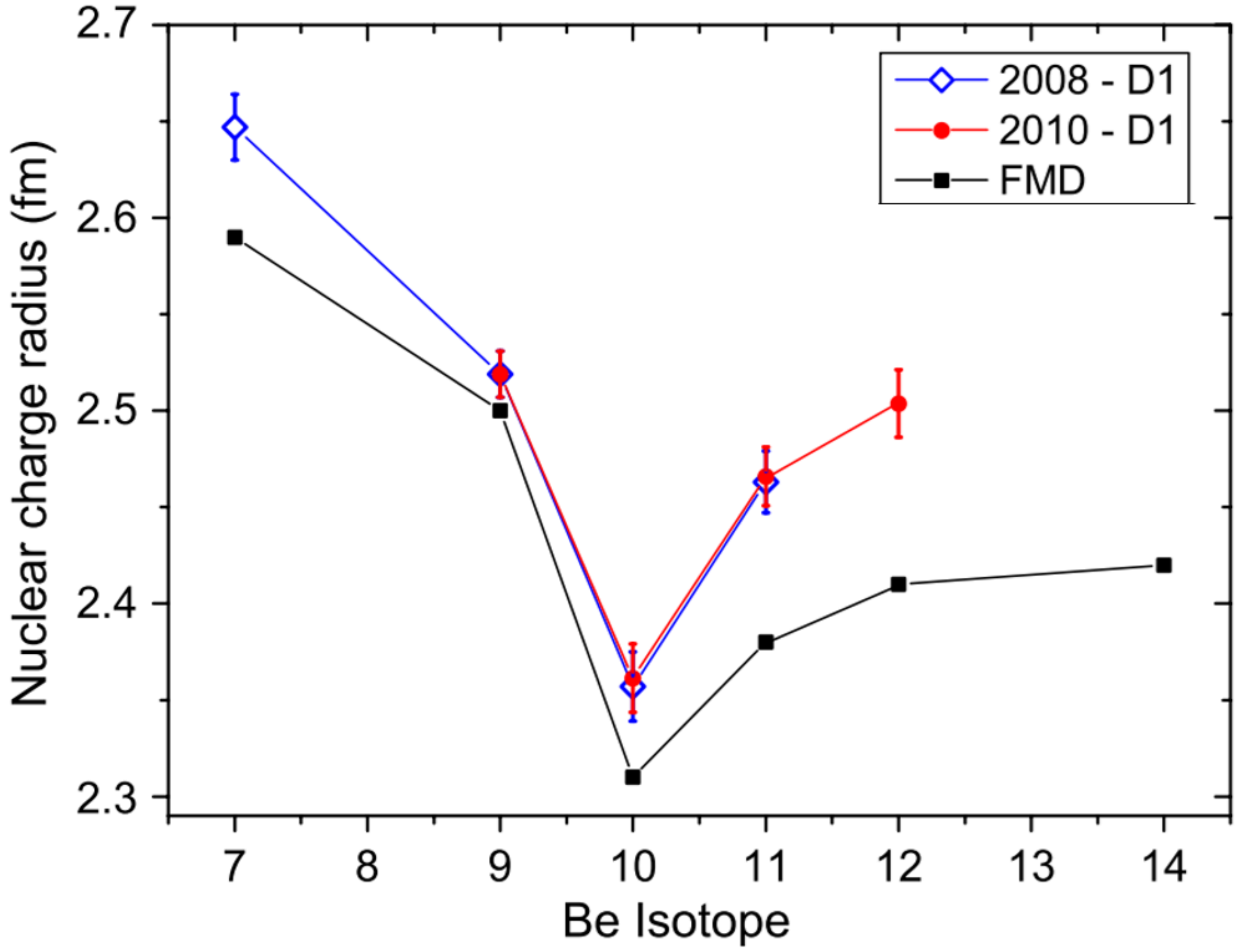
Output I: Reference radii

Improve entire chains:

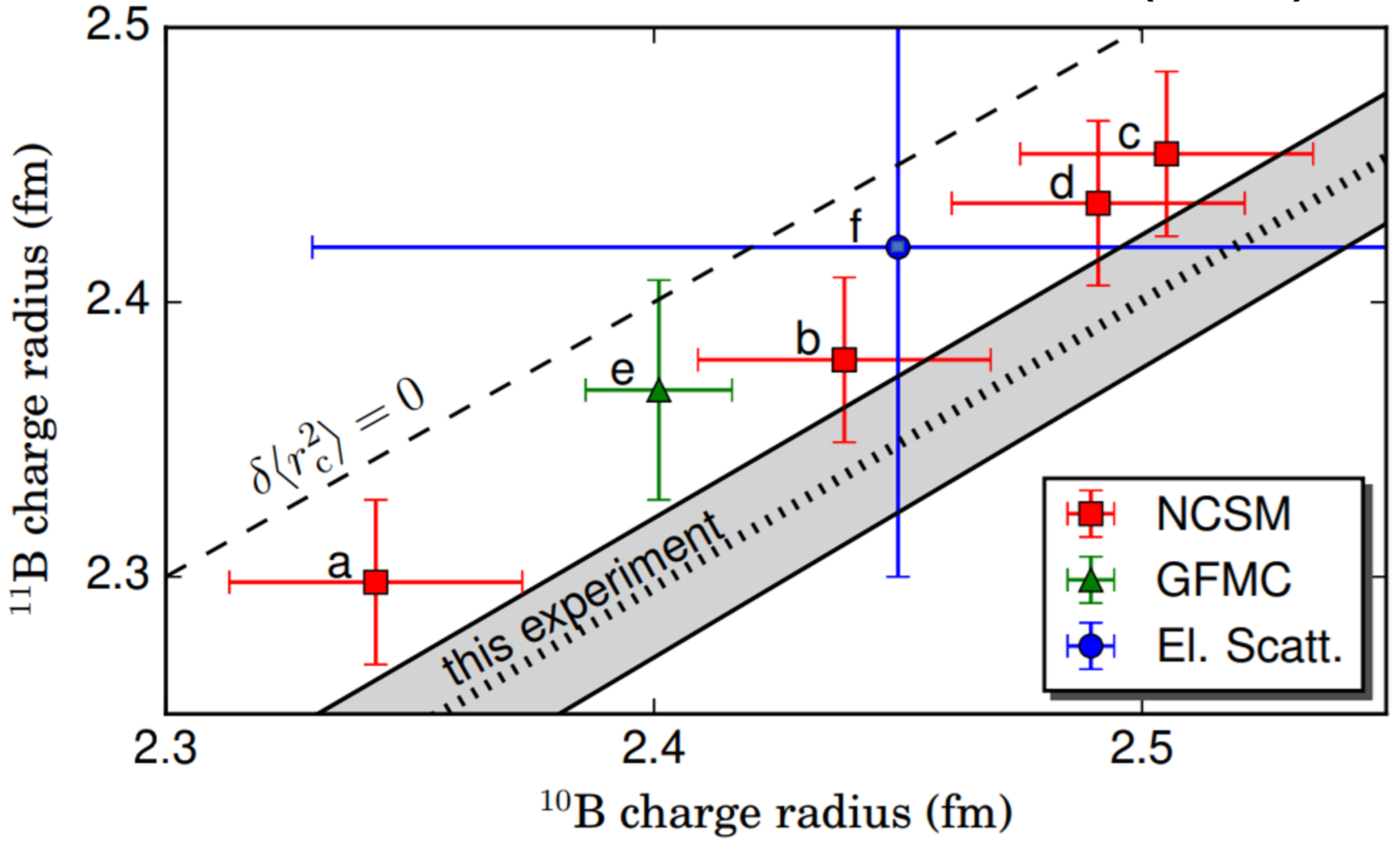
$^{6-9,11}$Li: PRC 84, 024307 (2011)



$^{7-12}$Be: PRL 122, 182501 (2019)



^{10,11}B: PRL 108, 142501 (2012)



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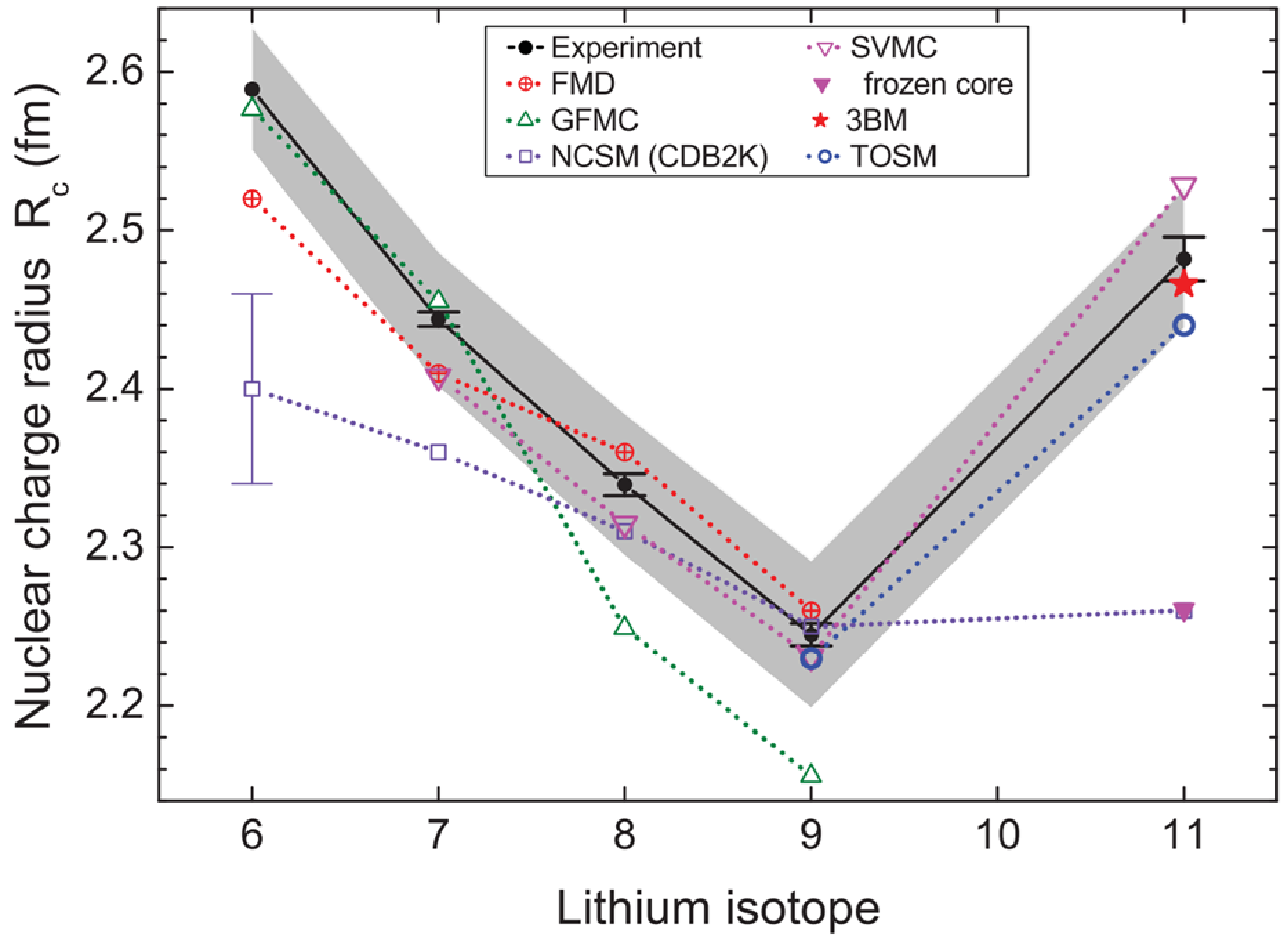

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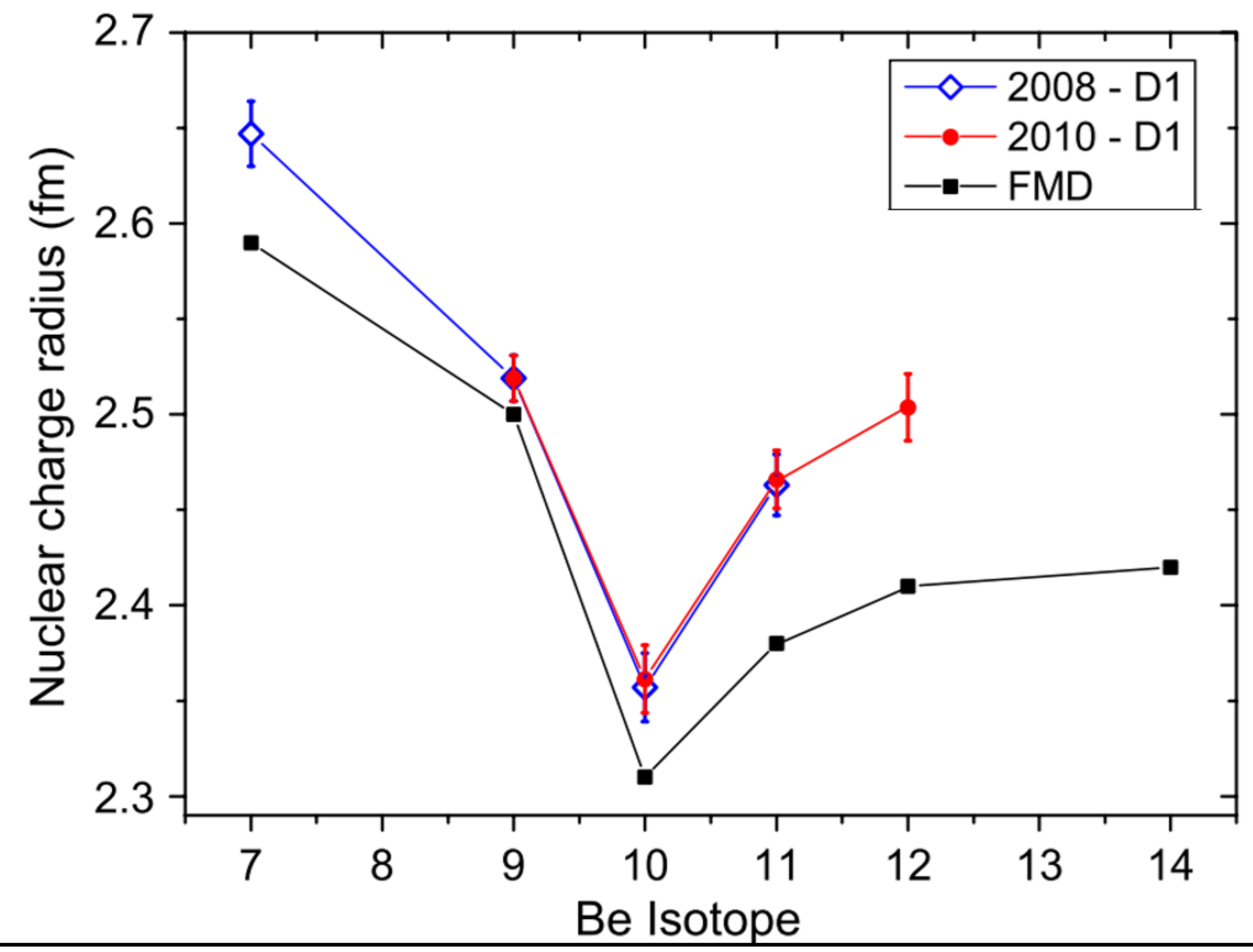

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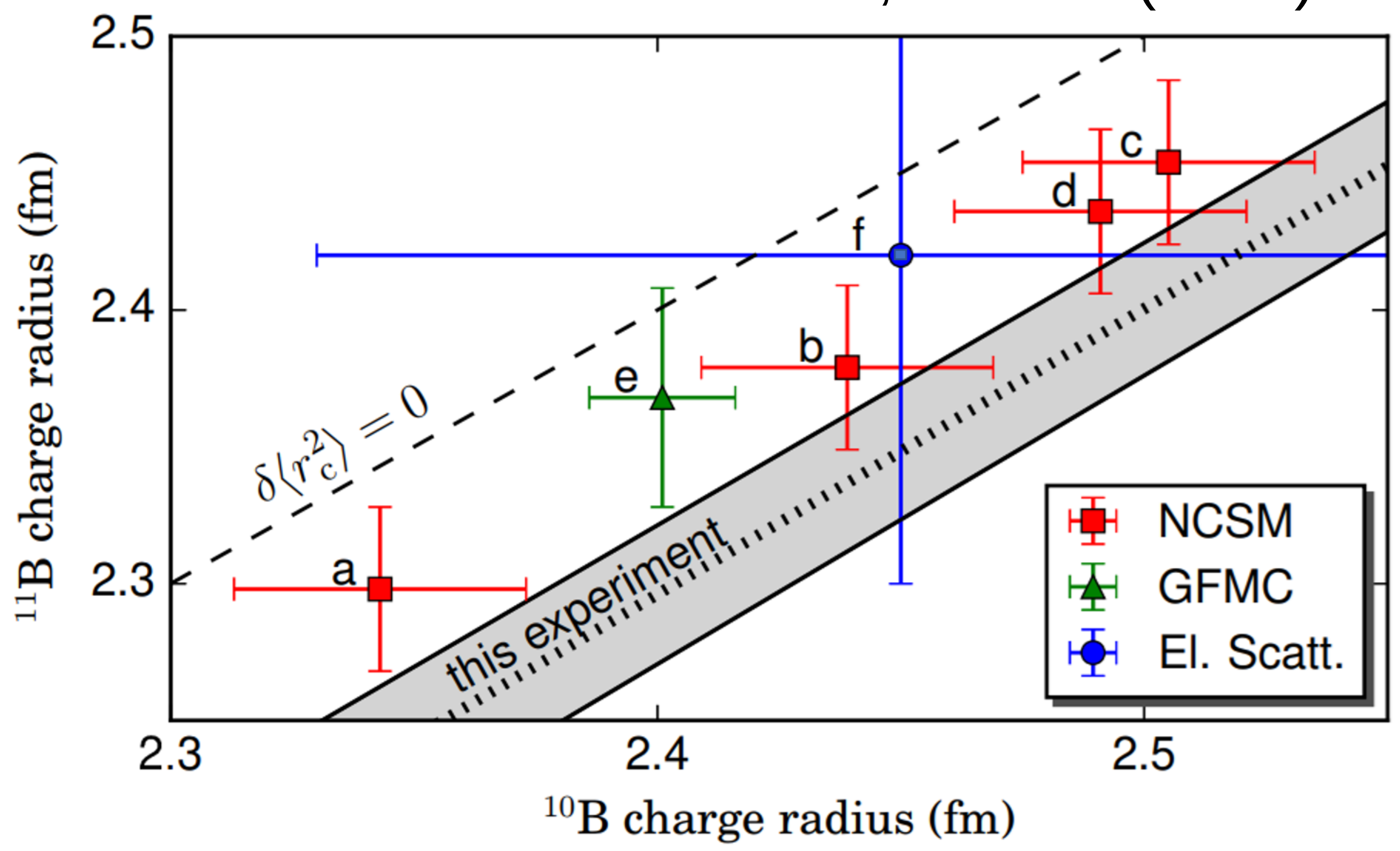


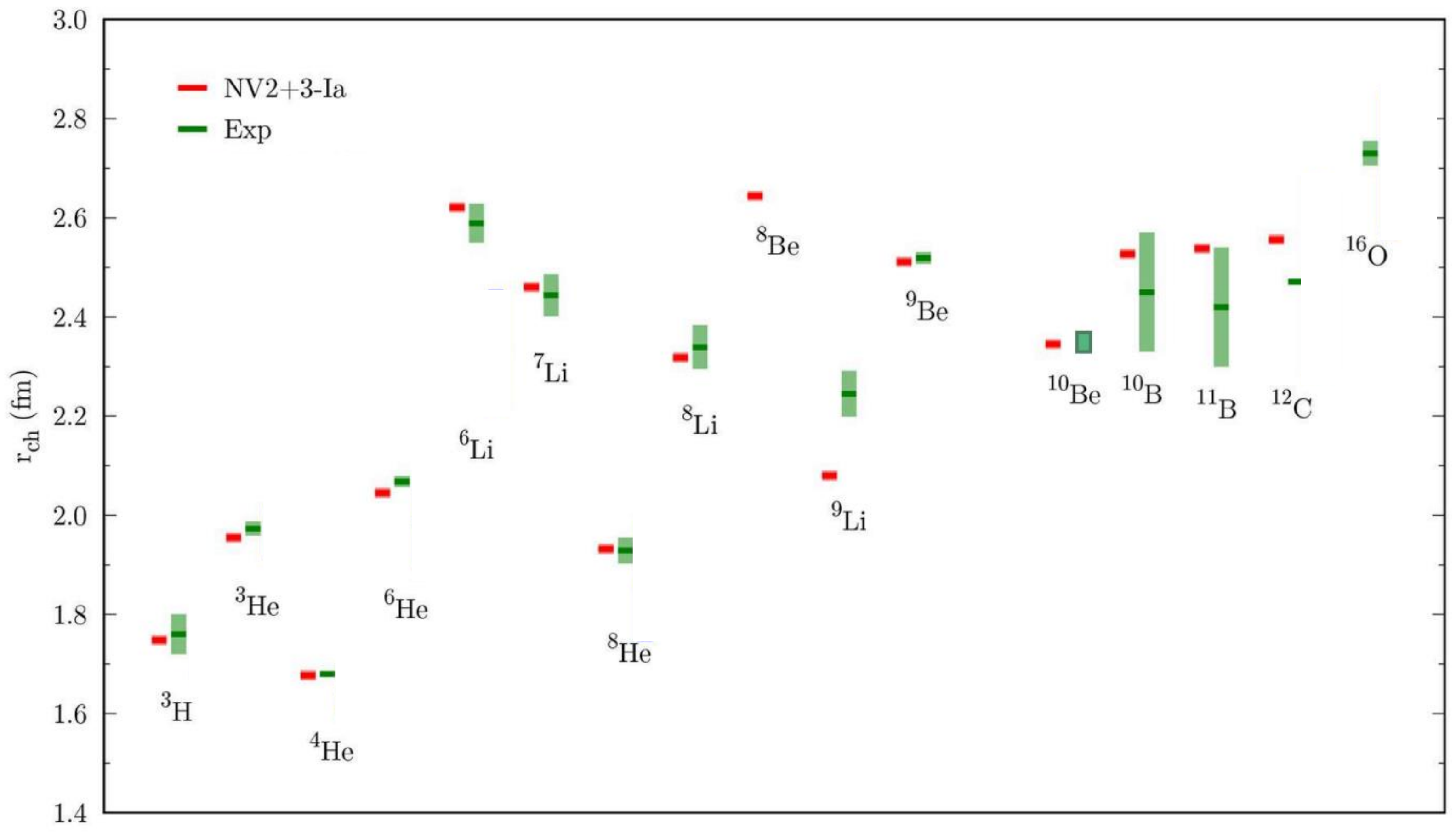
- Testing nuclear theory

Evgeny's talk

- Accuracy goals for learning about QED in helium-like-ions?

Wilfried's talk

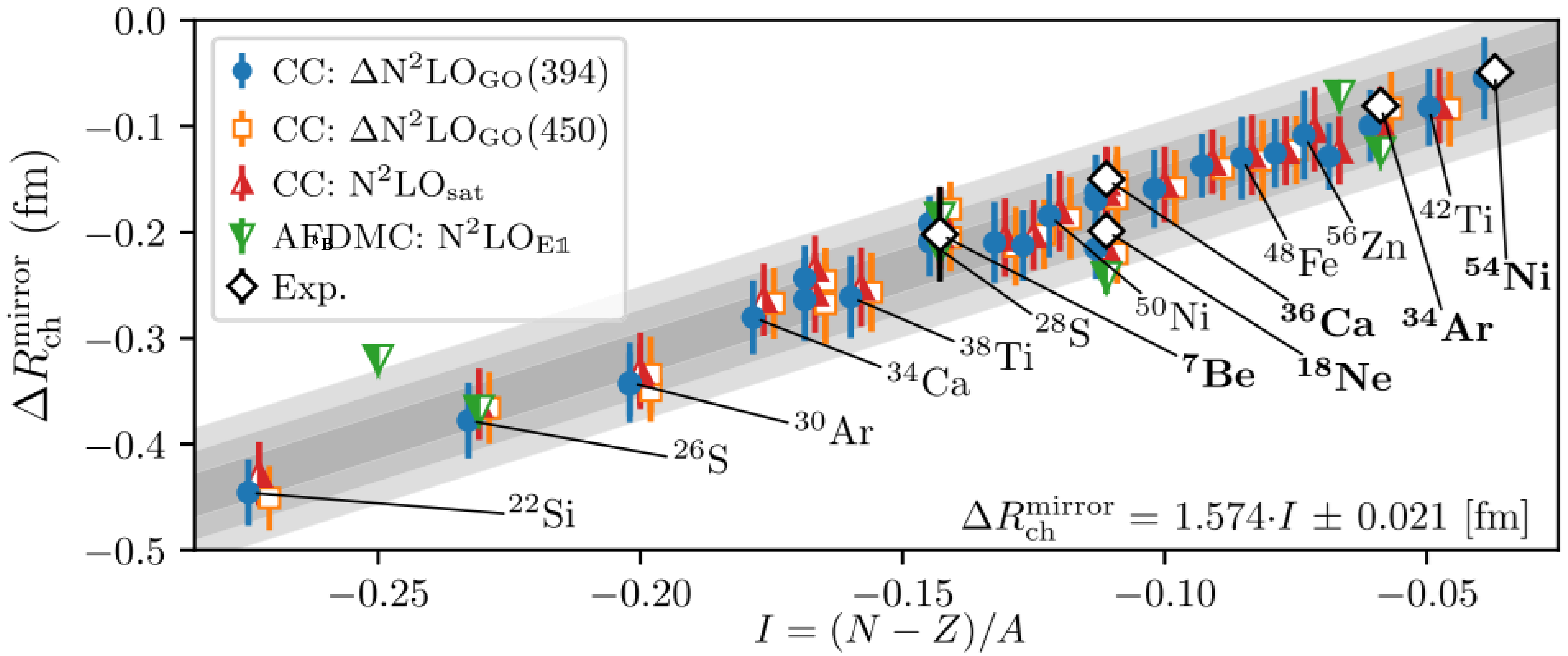
S. Gandolfi, D. Lonardoni, A. Lovato and M. Piarulli, **Front. Phys., 2020**



Output II: light Mirror Nuclei

Ronald's talk

S. J. Novario, *et. al.,* PRL 130, 032501 (2023)



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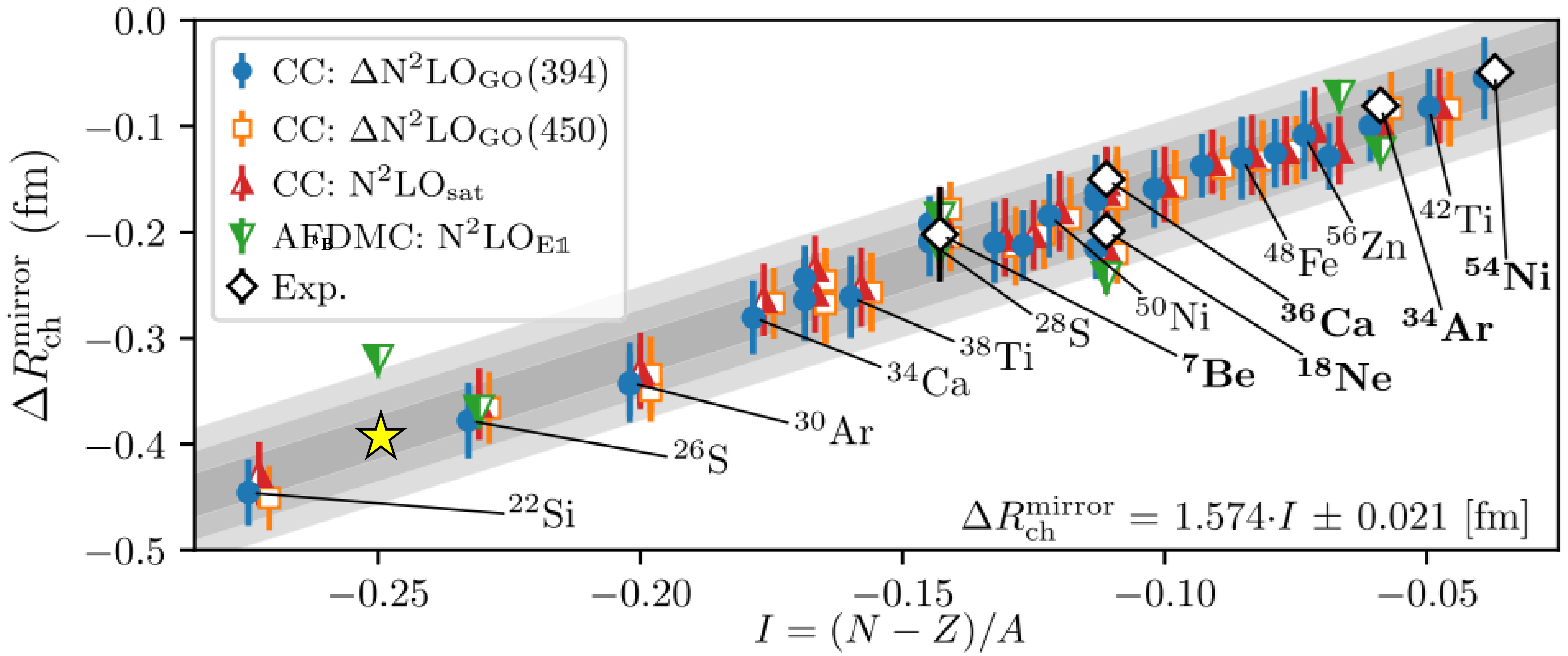
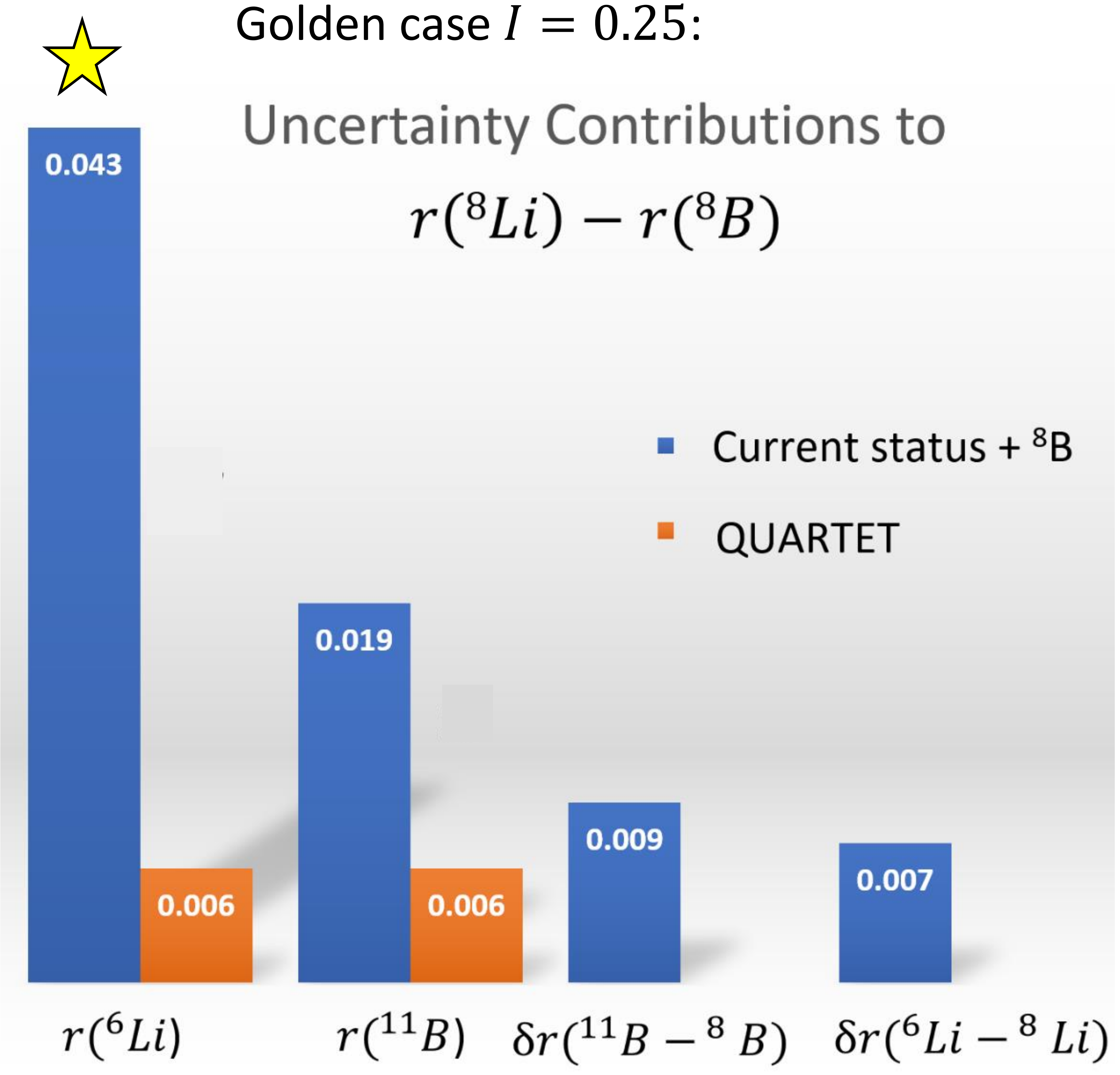


Golden case $I = 0.25$:



*Priv. Com. With W. Nörtershäuser

Output III: Muonic vs. electronic Isotope shifts

Pachucki's talk:

Deuteron-proton charge radii difference: perfect agreement

Z=1

$$r_d^2 - r_p^2|_{\text{muonic}} = 3.820\,0(7)_{\text{exp}}(30)_{\text{theo}}\ \text{fm}^2$$
$$r_d^2 - r_p^2|_{\text{electronic}} = 3.820\,7(3)\ \text{fm}^2\ .$$

Helion-alpha charge radii diference: 3.6 σ disagreement !!!

Z=2

$$r_h^2 - r_\alpha^2|_{\text{muonic}} = 1.063\,6(6)_{\text{exp}}(30)_{\text{theo}}\ \text{fm}^2\ \text{(CREMA, 2023)}$$
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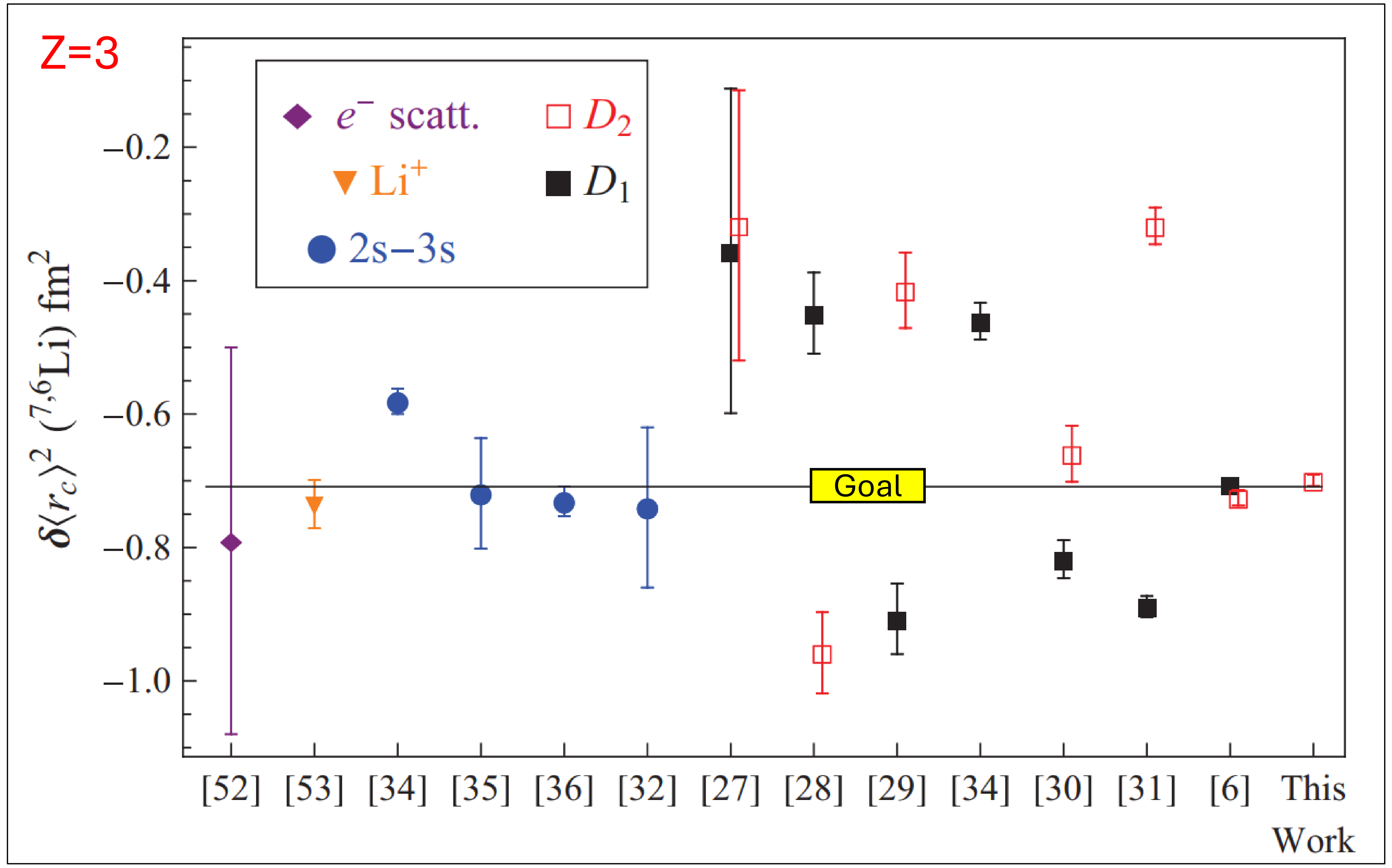
Motivation to measure lithium:



PRA **87**, 032504 (2013)

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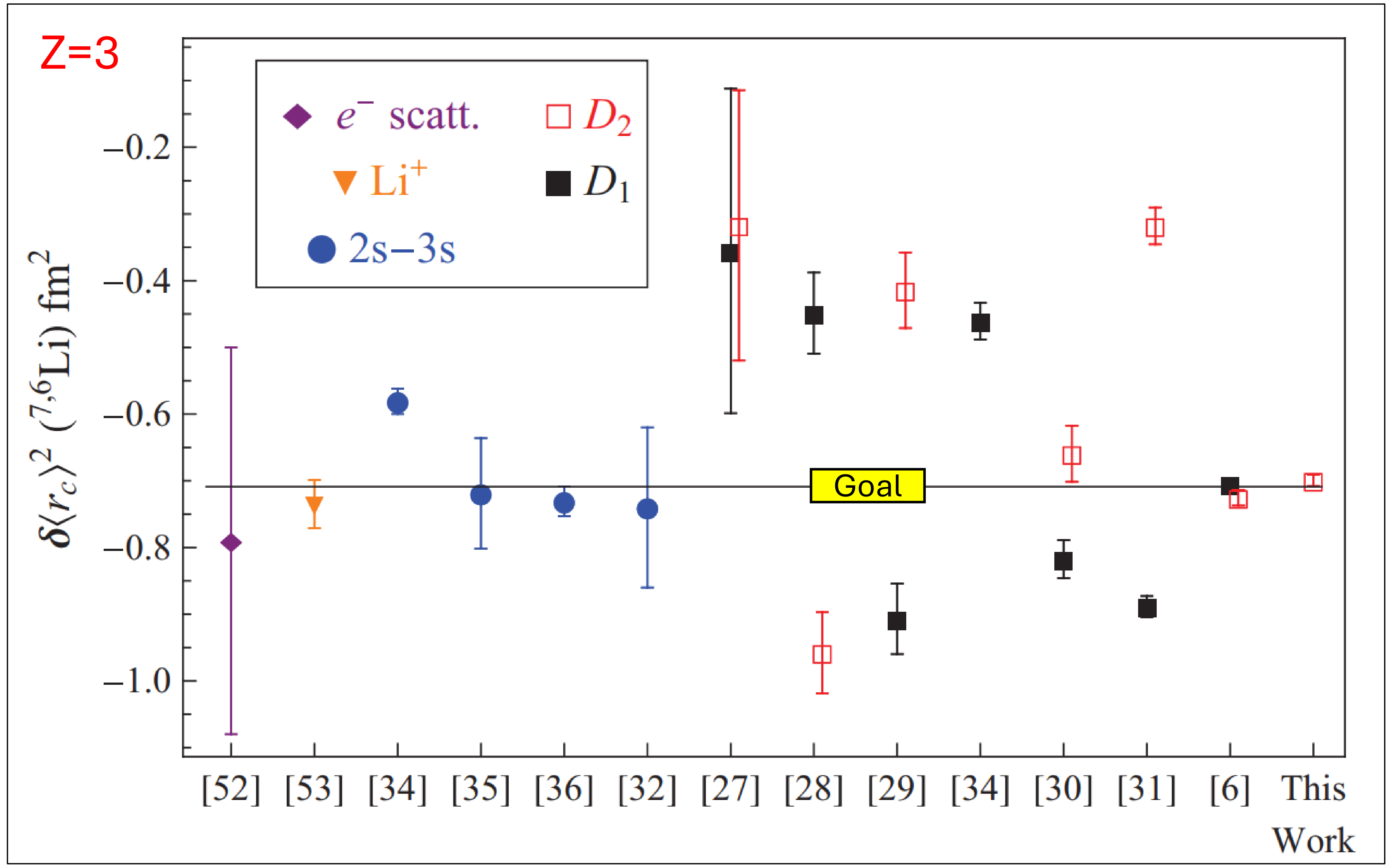
Motivation to measure lithium:

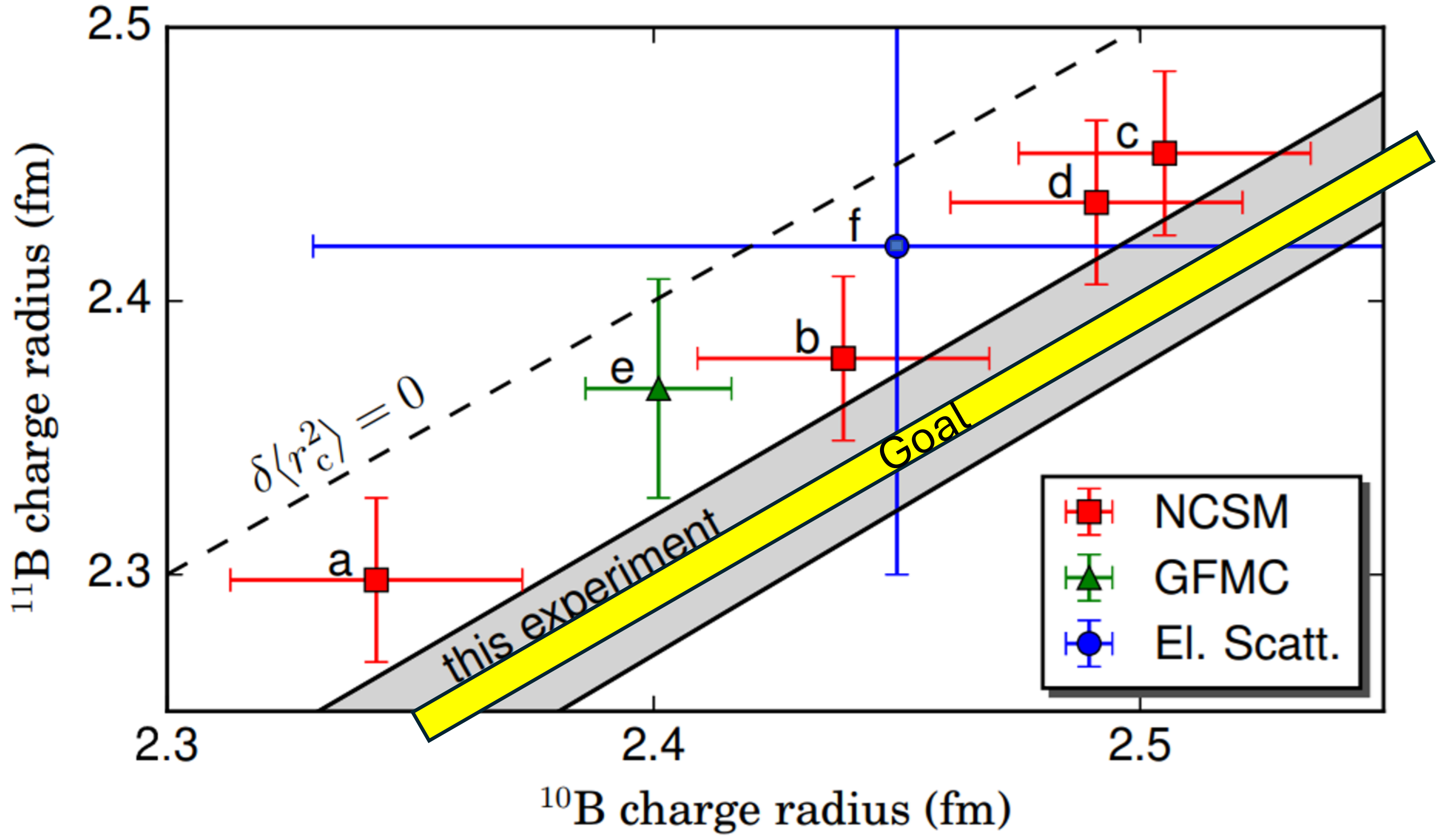
Z=3



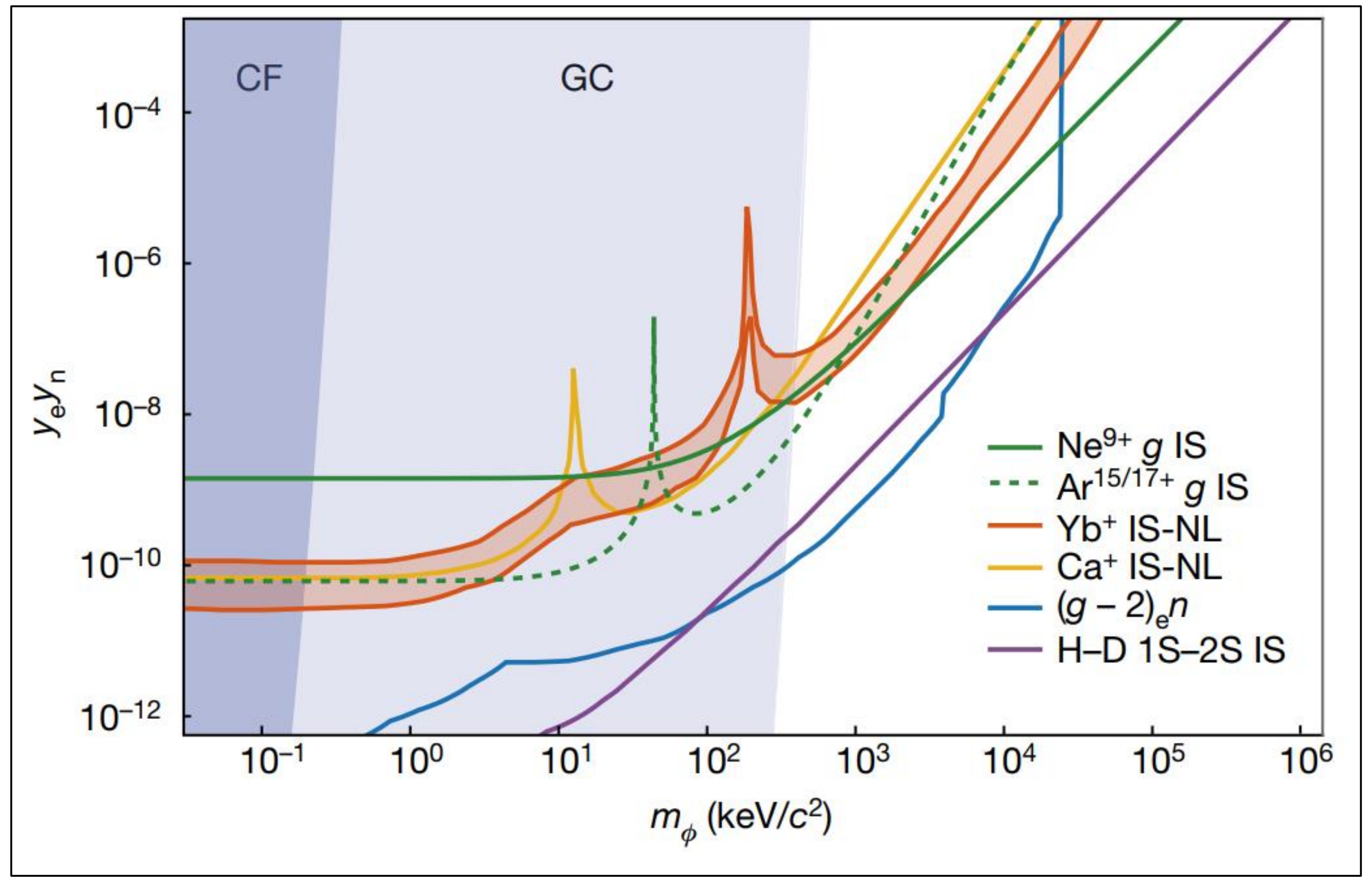
PRA **87**, 032504 (2013)

Boron IS (desire to improve electronic measurements) Z=5

PRL 108, 142501 (2012)



Neon 20 and 22 (phase II): Z=10



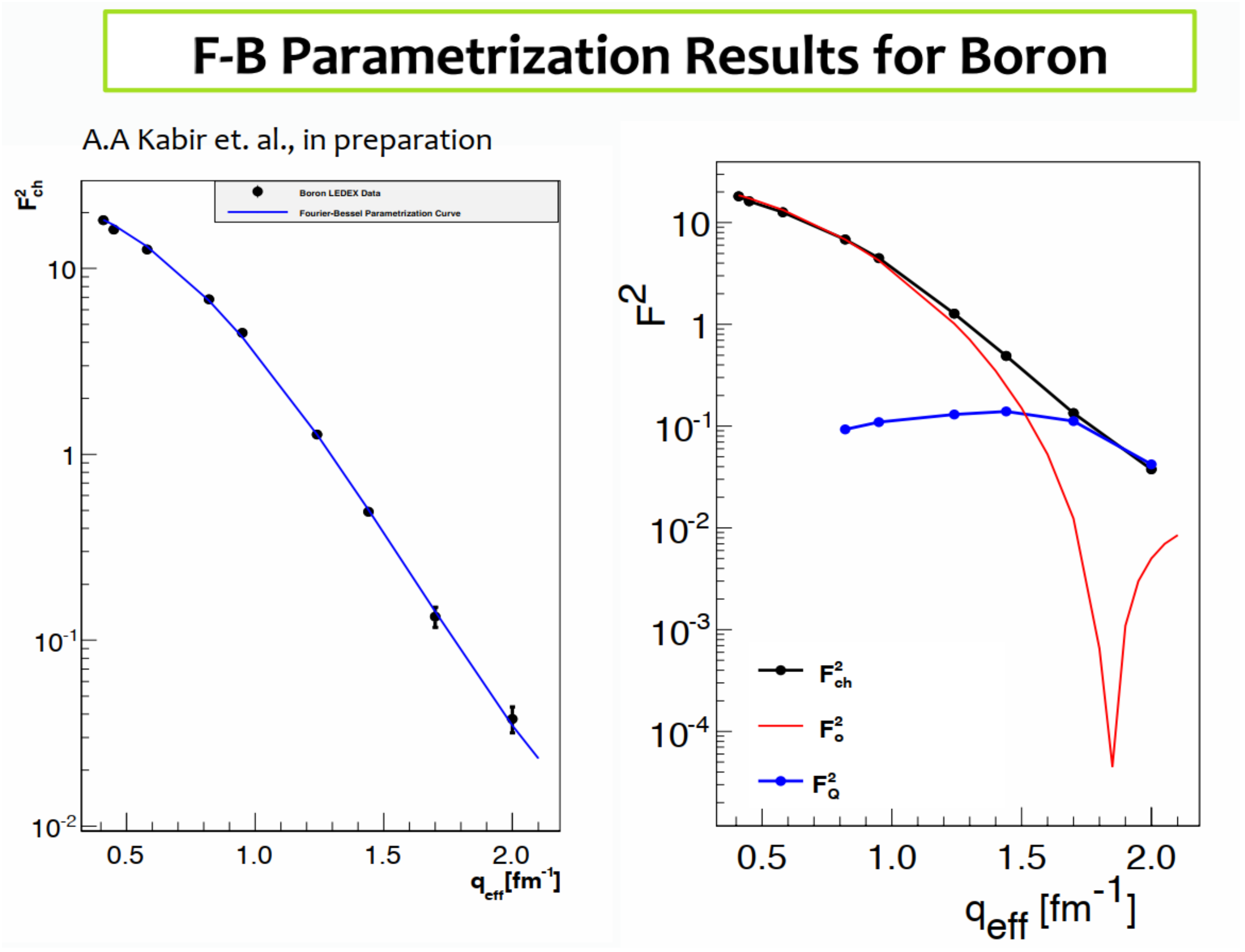
Nature **volume 606**, pages 479–483 (2022)

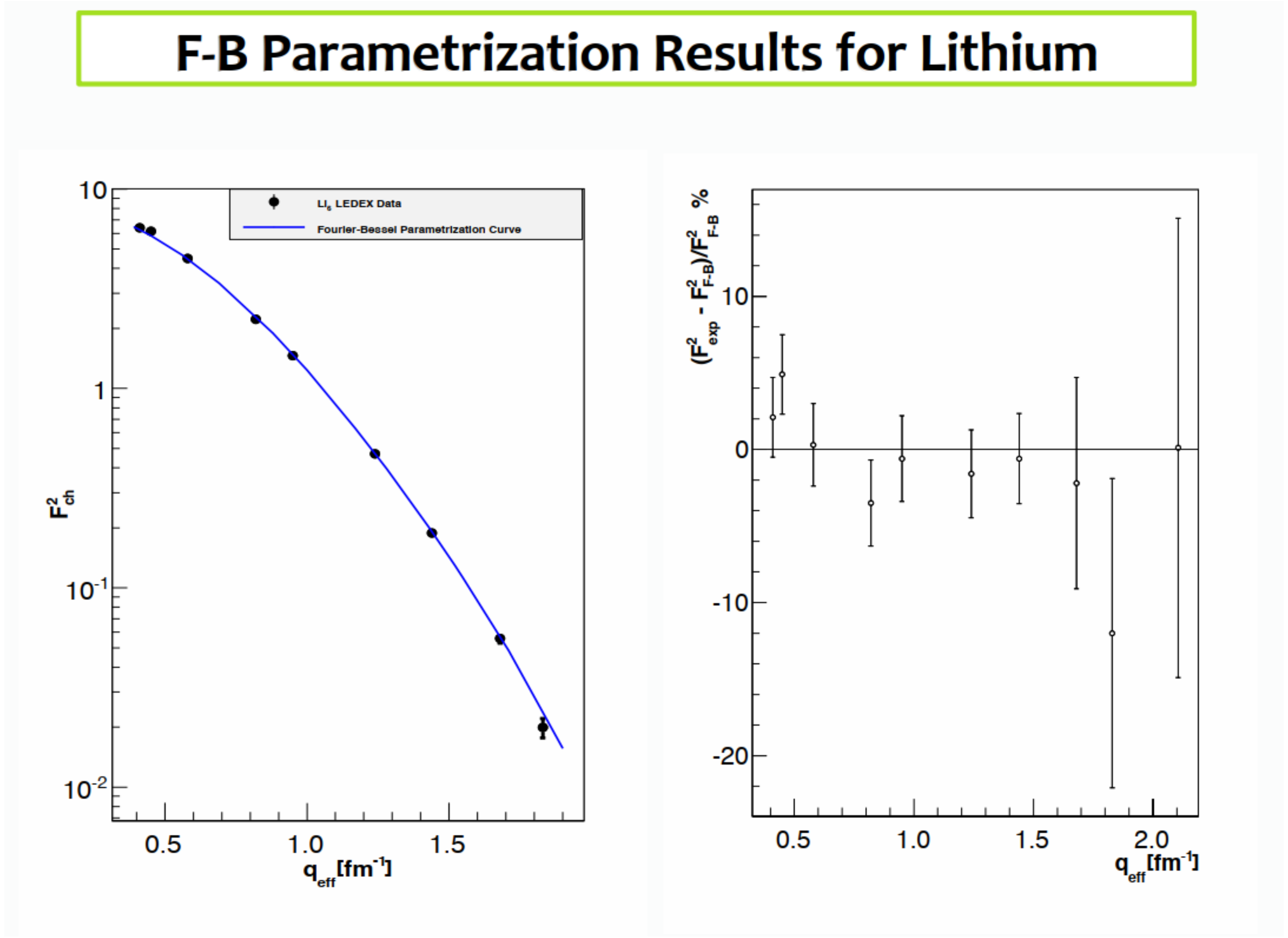
Summary

1. Charge radii are central for confronting theory with experiment
2. Only for Z=1,2, they are both **precise** & **reliable**
3. For Z>10, they are **precise** bot not **reliable** (opportunities for theory)
4. For Z=3-10, not **precise**. Limited by available **experimental** methods
5. New collaboration – QUARTET: Determine radii via x-ray spectroscopy of light muonic atoms using novel cryo-calorimeters
6. Successful test last October, physics run next September, stay tuned...

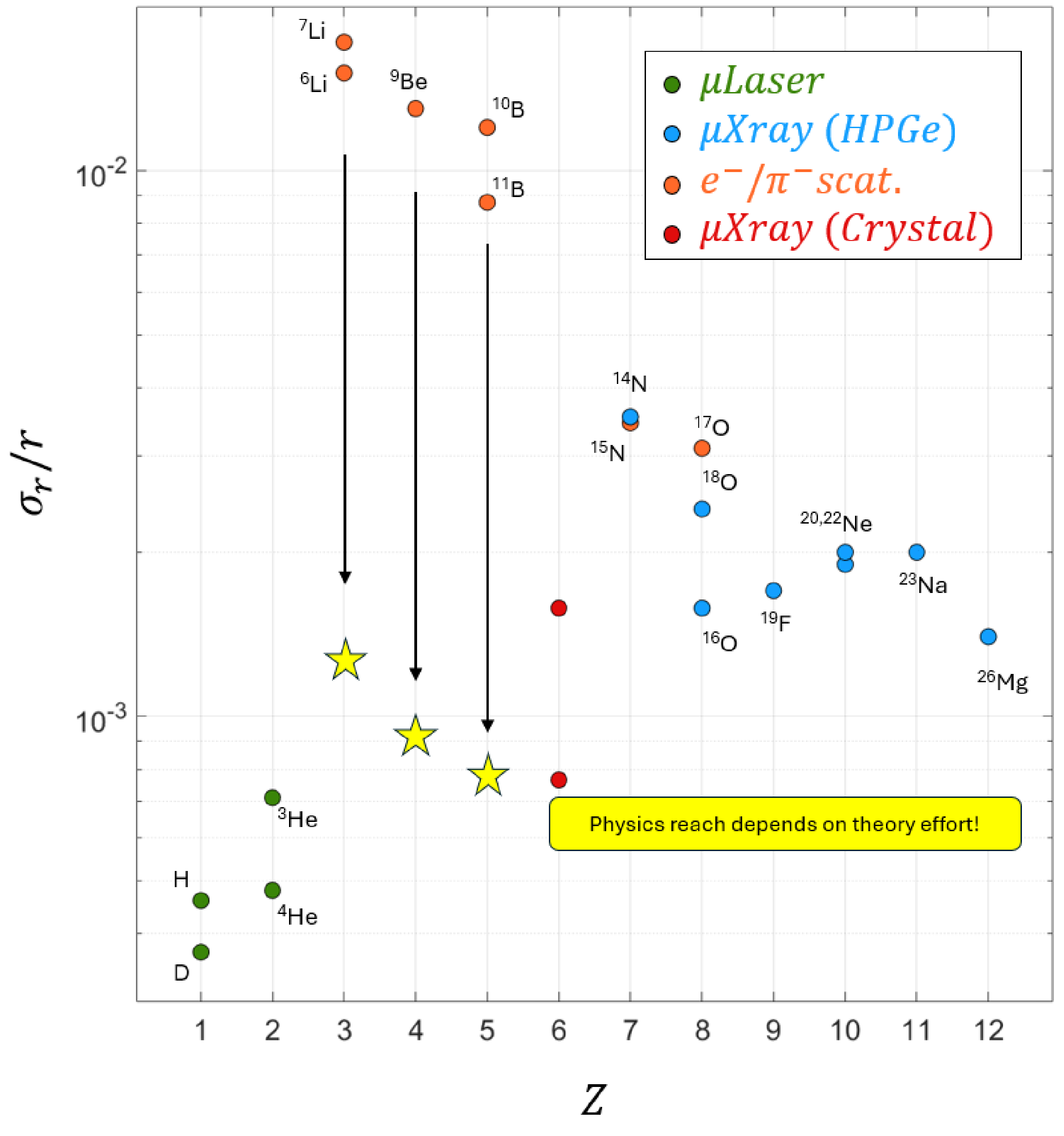
Points of discussion:

Modern scattering on Lithium and Boron in JLAB





Modern QED and
Nuclear polarization in μLi - μNe



What are the accuracy goals for :

- testing nuclear theory?
- Learning about mirror nuclei?
- Comparing with helium-like-ions?

Is NREC the right platform to lunch a new EM radii table (à-la AME)?