QUARTET: precision measurements of the charge radii of light nuclei

Ben Ohayon | Technion IIT | boahyon@technion.ac.il

NREC, April 13th - 18th, 2026

In this talk:

- Overview: Reference charge radii
- QURTET : measuring light muonic atoms
- A word on the RADIANT initiative

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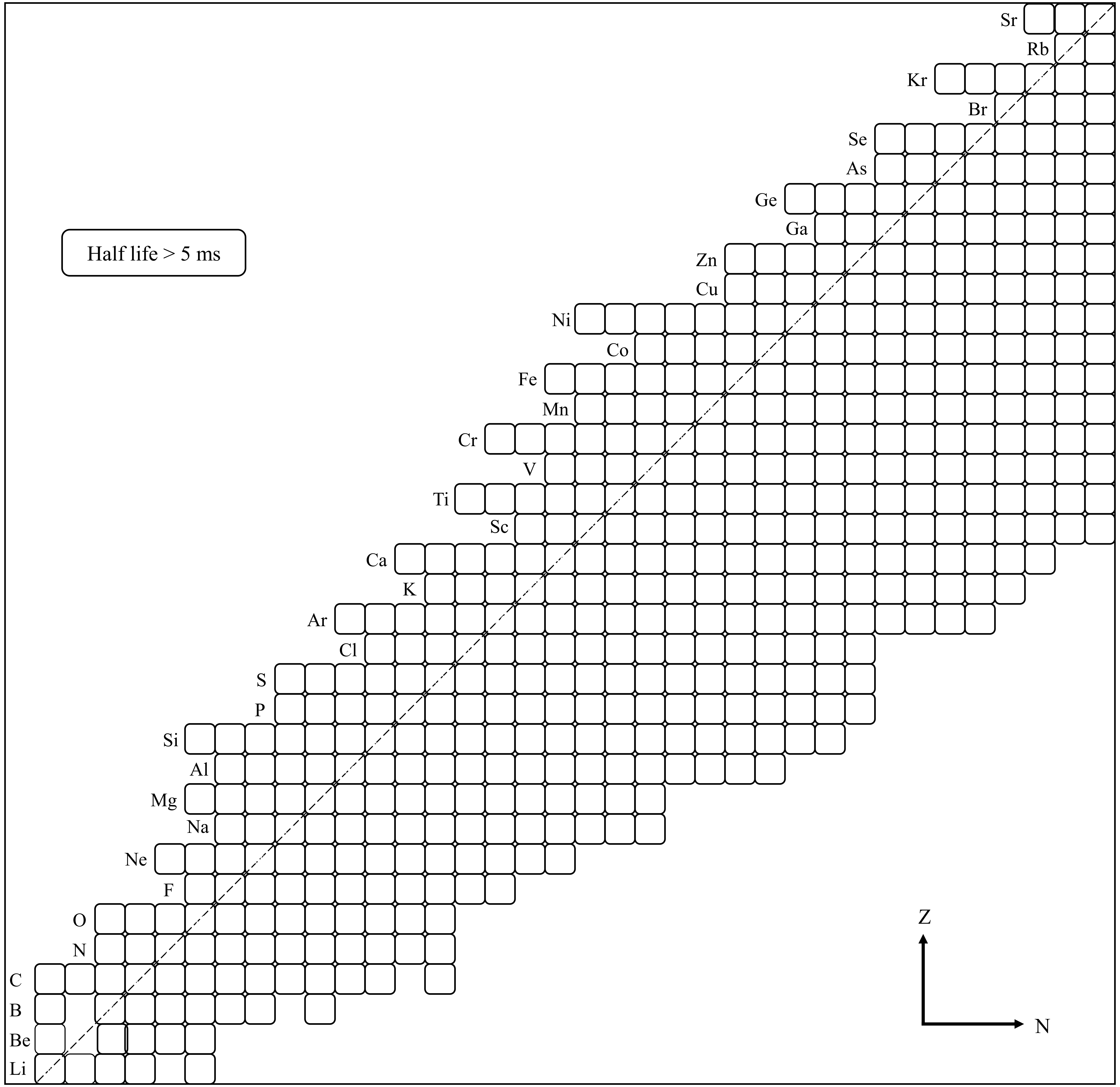
- **Overview: Reference charge radii**
- QURTET : measuring light muonic atoms
- A word on the RADIANT initiative

Where do charge radii come from?

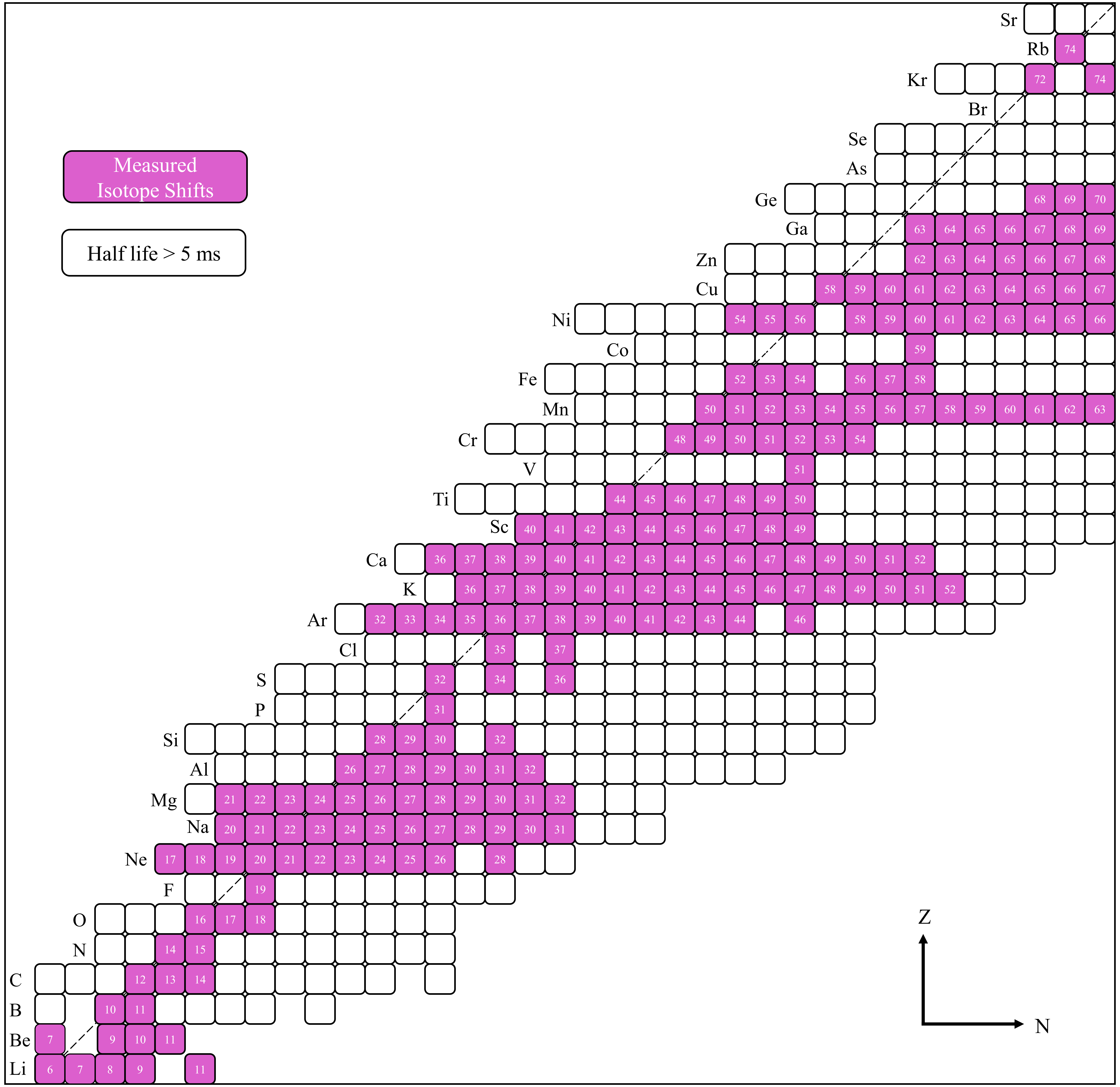


bohayon@technion.ac.il

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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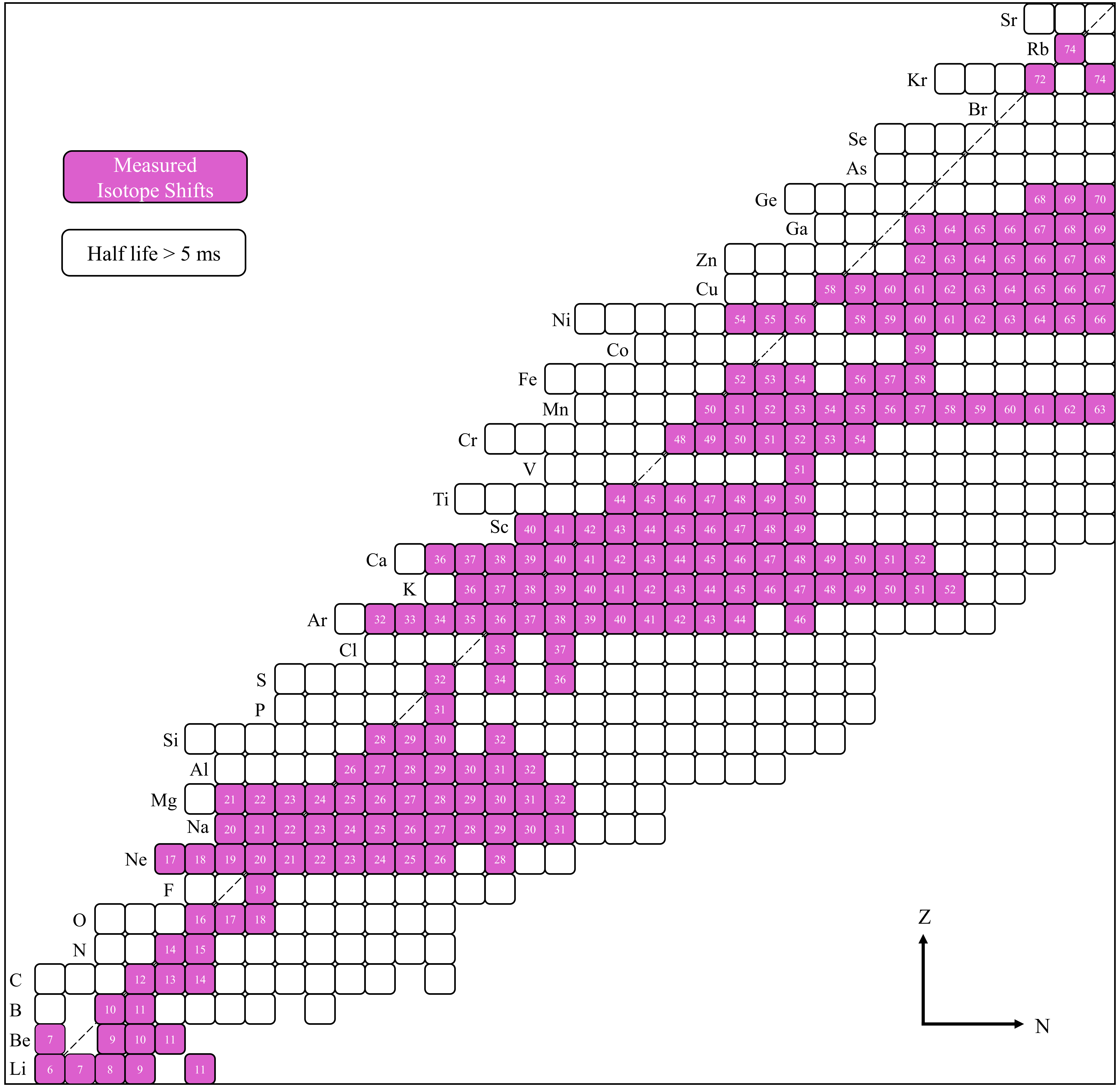
See Shane Wilkins' talk today!



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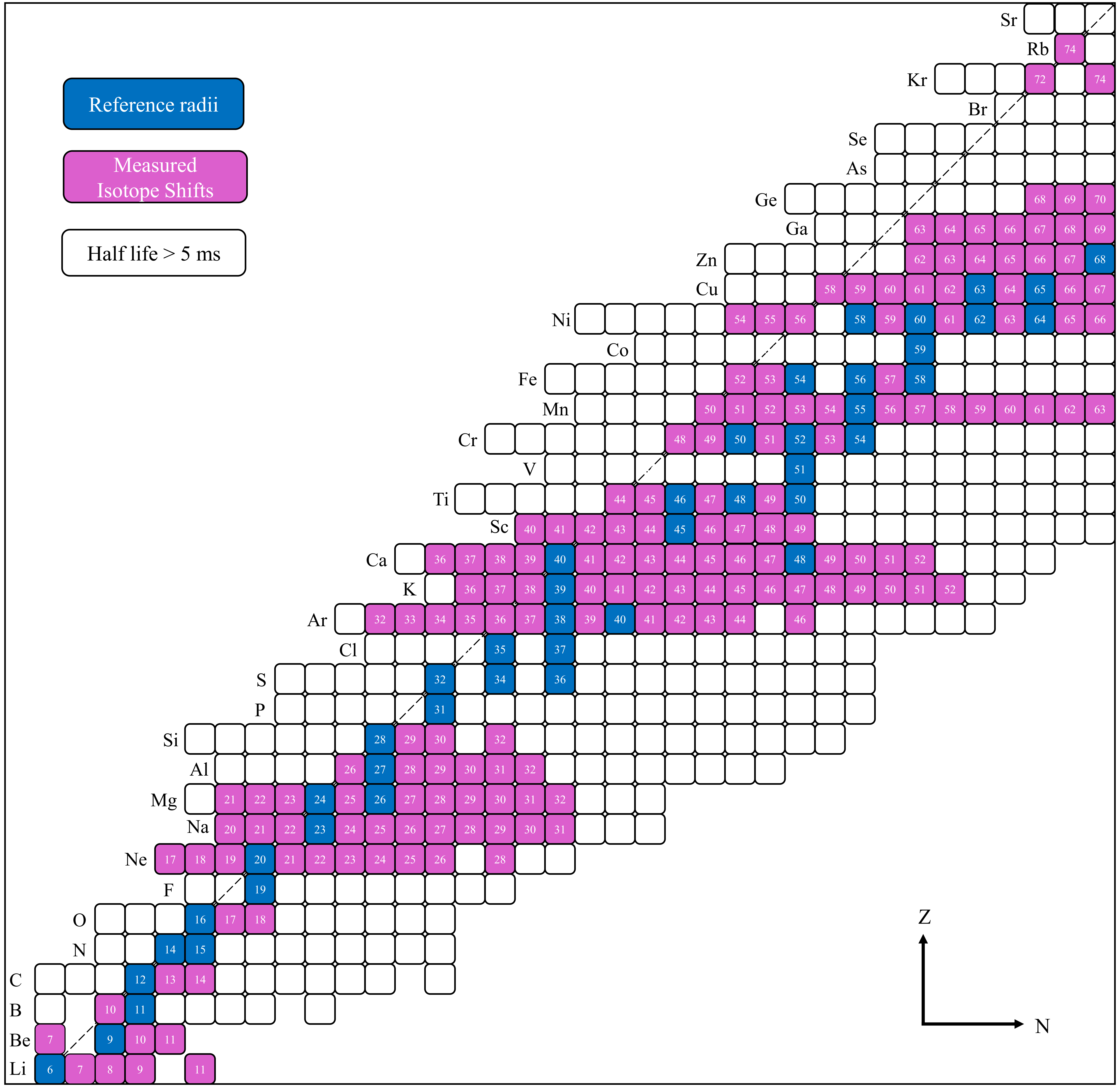
Reference radii connect MS differences with absolutes

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



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

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

Reference radii connect MS differences with absolutes

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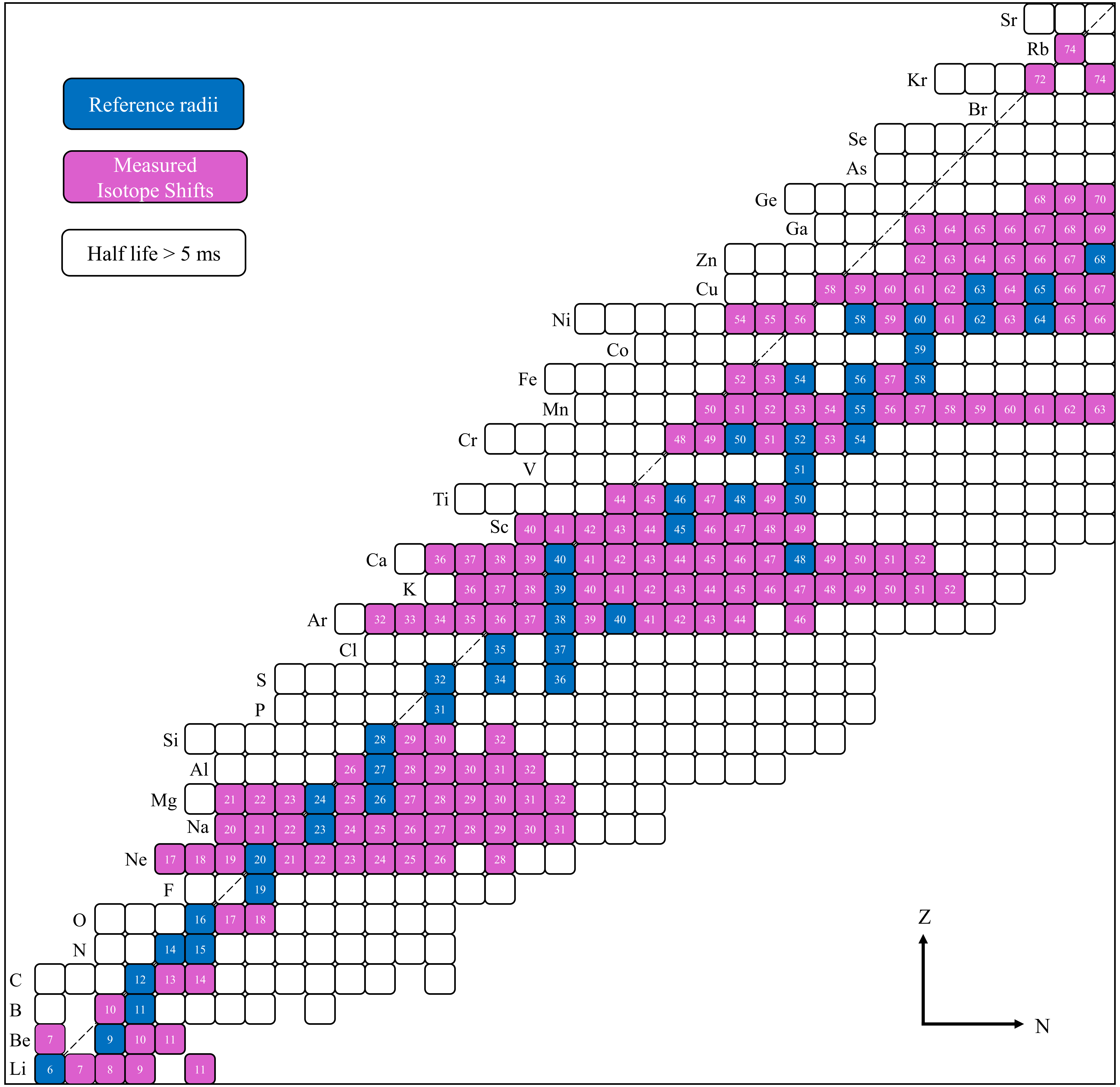

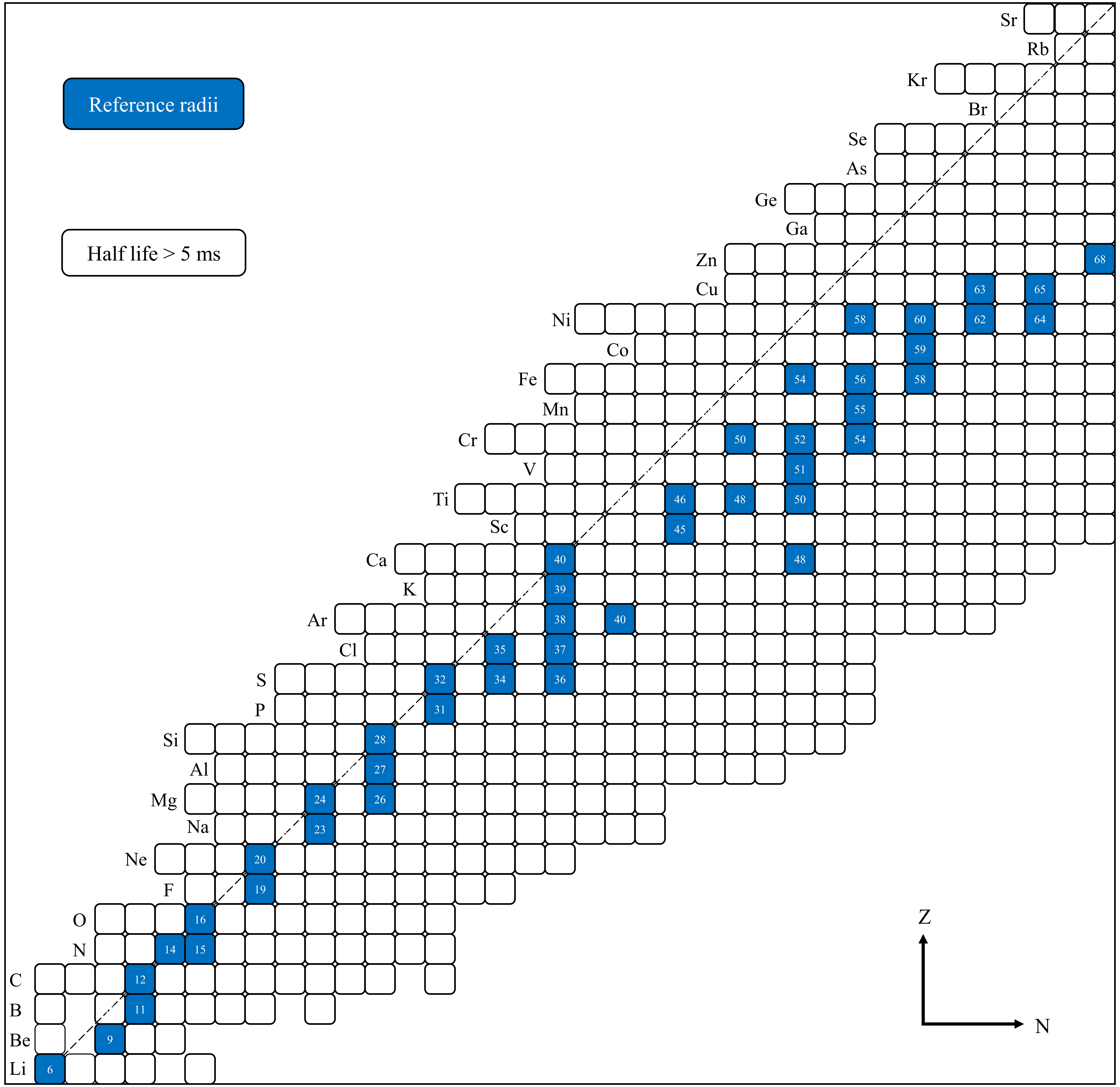

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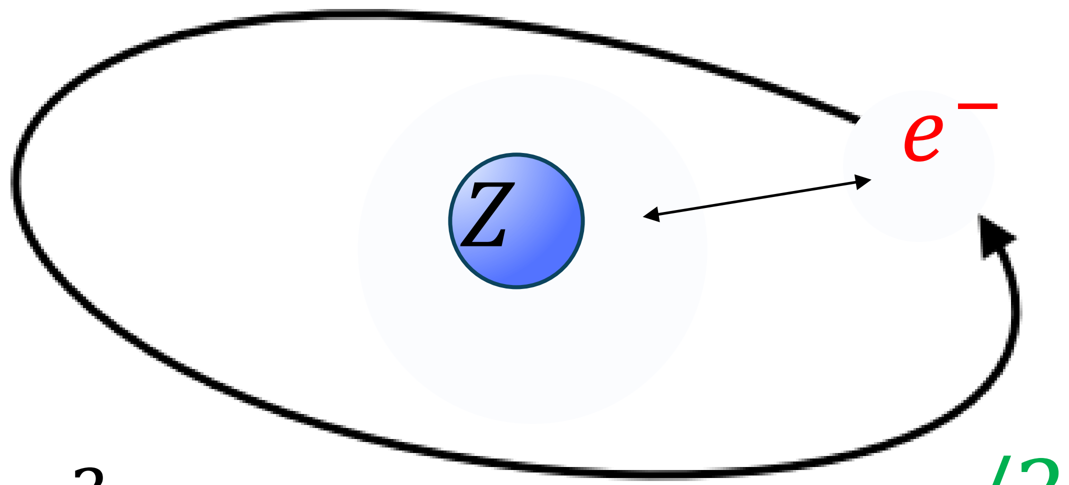
Muonic Atoms 101:

Ordinary atoms



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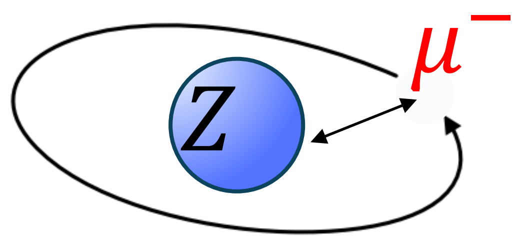

Characteristic **length**
(Bohr radius: $a_0 = \frac{\hbar}{m_e c\alpha} \sim 0.5\text{Å}$):

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

Shorter distances

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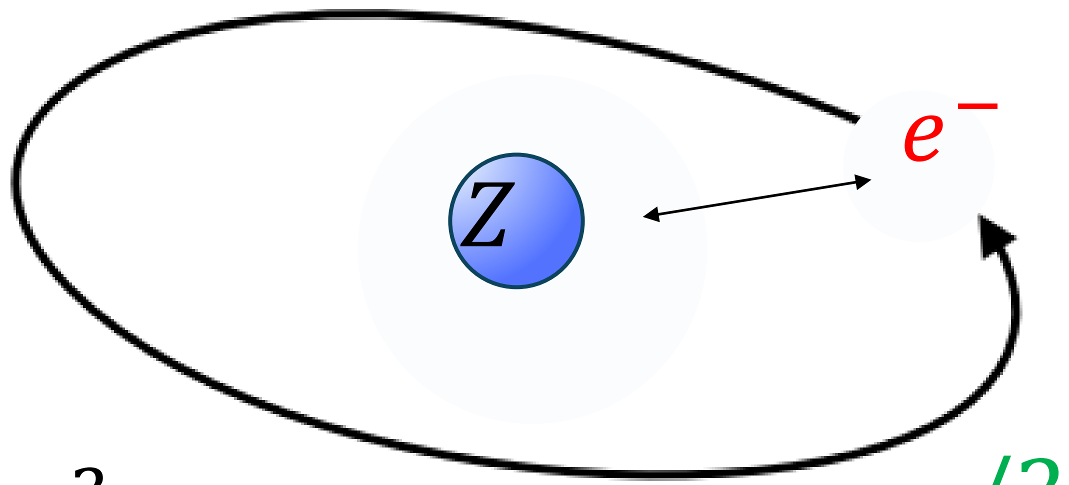

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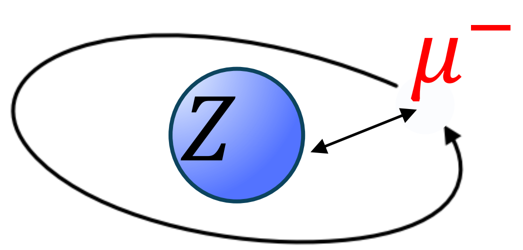

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Shorter distances

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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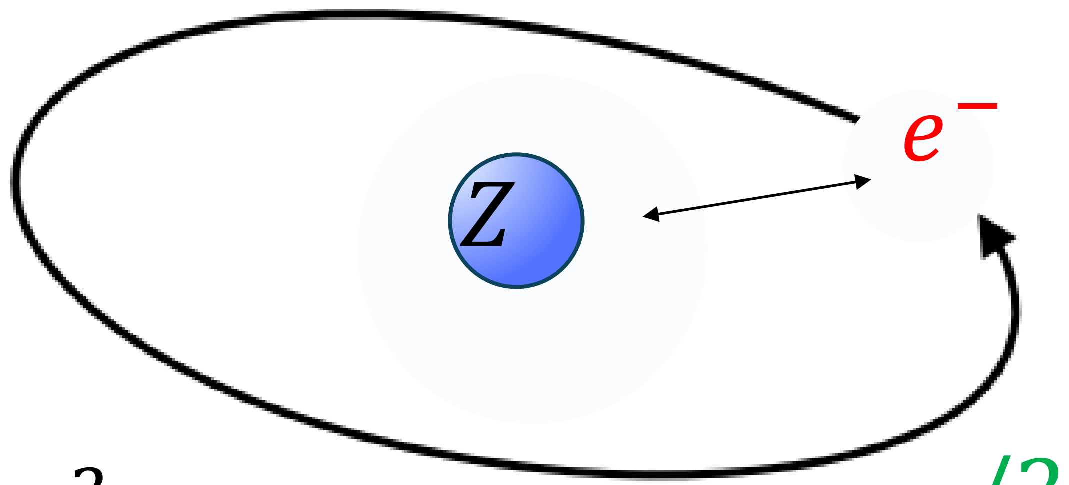
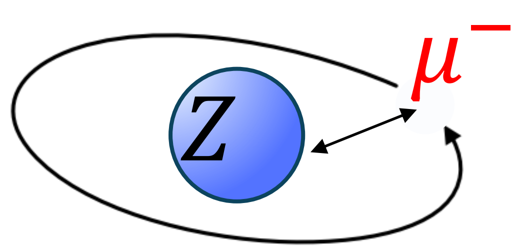


Muonic atoms



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$MW \rightarrow Laser$
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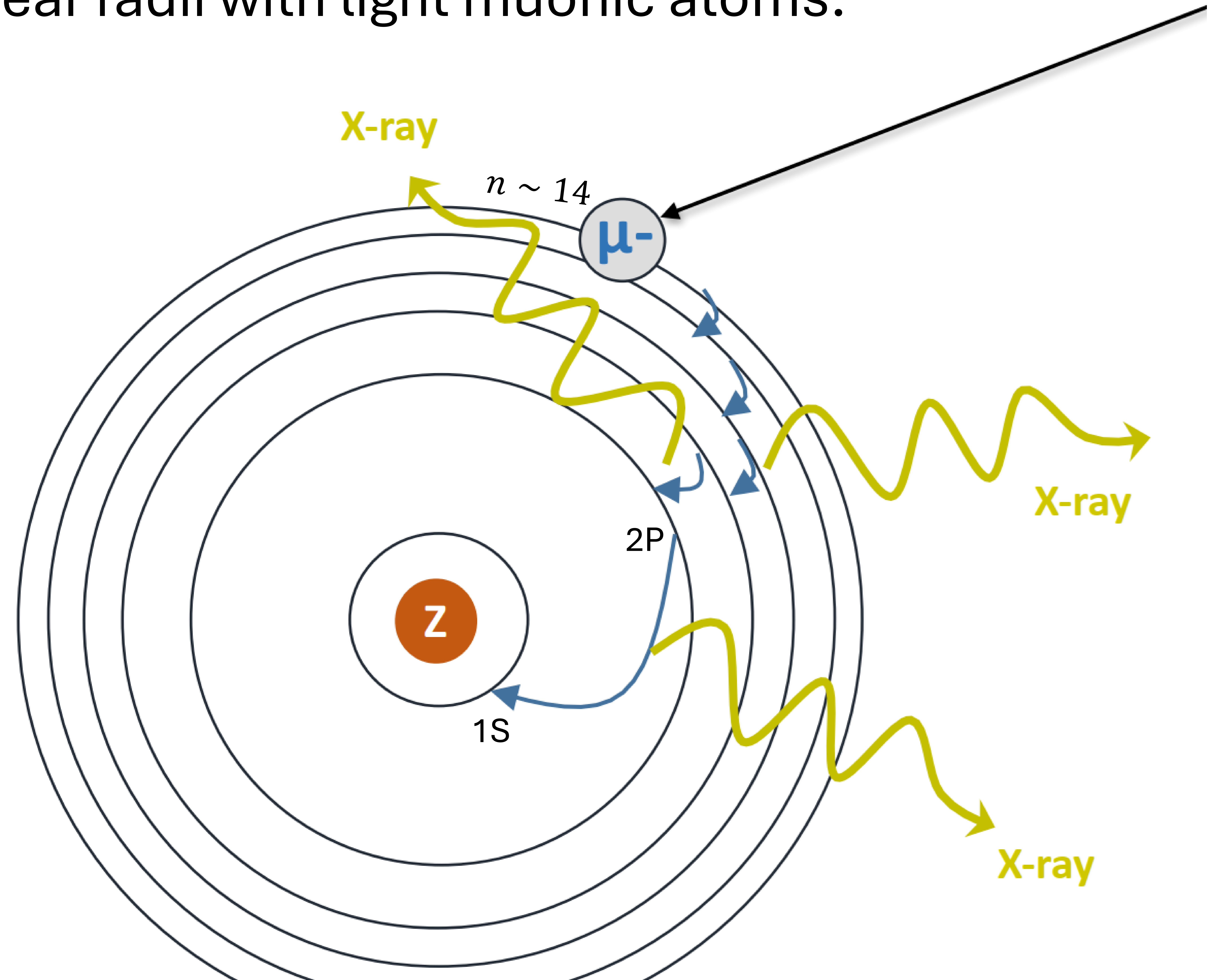
Higher energies

Finite Nuclear Size effect: $\Delta E_{FNS} \sim \frac{4}{3}\frac{R_\infty Z^4}{n^3}\left(\frac{r_c}{a_0}\right)^2 \delta_{l0} \xrightarrow{\times (200)^3} \frac{4}{3}\frac{R_\infty Z^4}{n^3}\left(\frac{r_c}{a_0}\right)^2 \left(\frac{m_\mu}{m_e}\right)^3 \delta_{l0}$

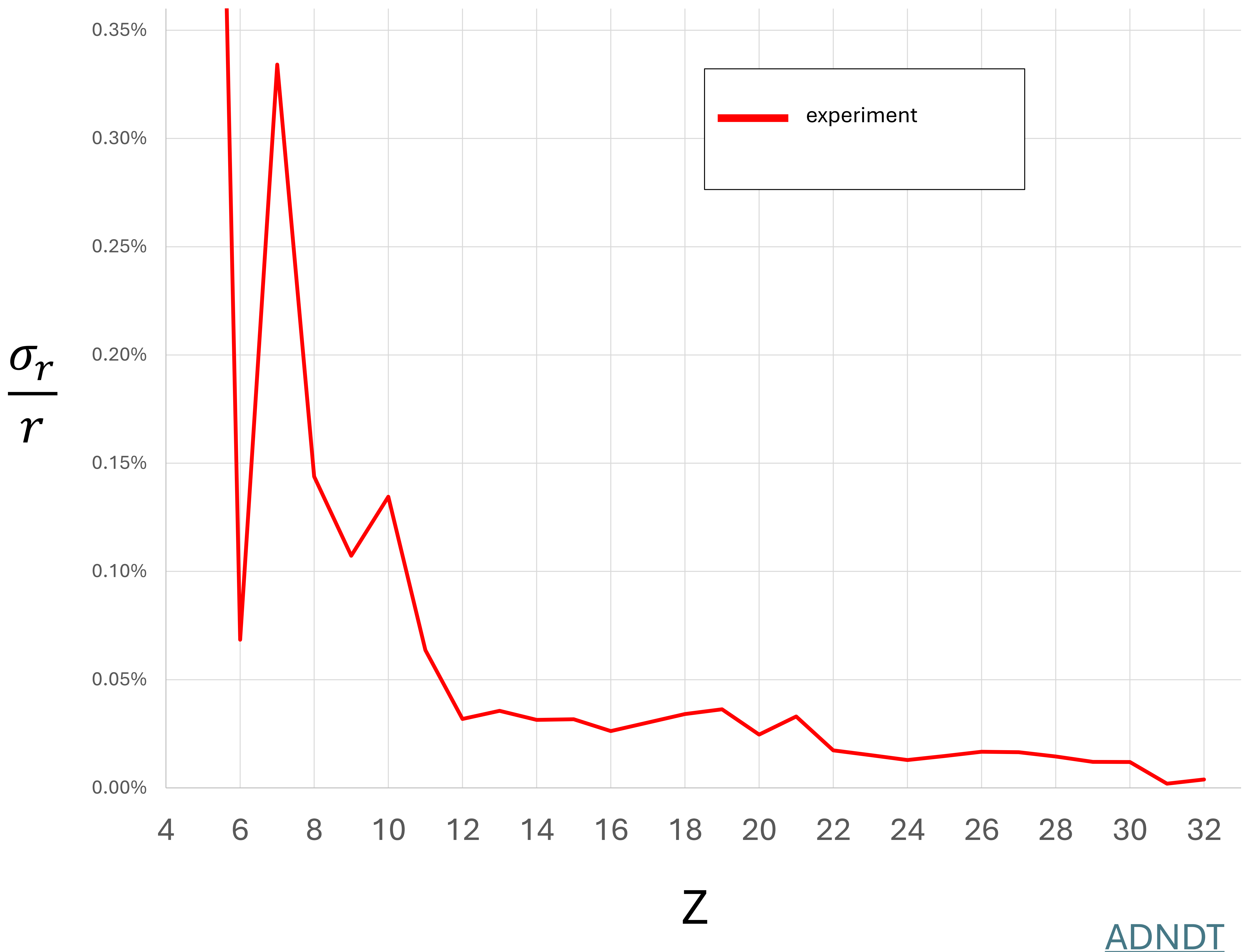
For Hydrogen 1s-2p: $\sim 4\ \text{neV}\ (1\ \text{MHz, ppb})$ $\qquad \sim 30\ \text{meV, 10 ppm}$

Measuring nuclear radii with light 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. $\mathrm{E}_{2\mathrm{P}-1\mathrm{S}} = E_{QED} + \Delta E_{FNS} + \cdots$



Sources of Uncertainty to Ref. Radii:



ADNDT

bohayon@technion.ac.il

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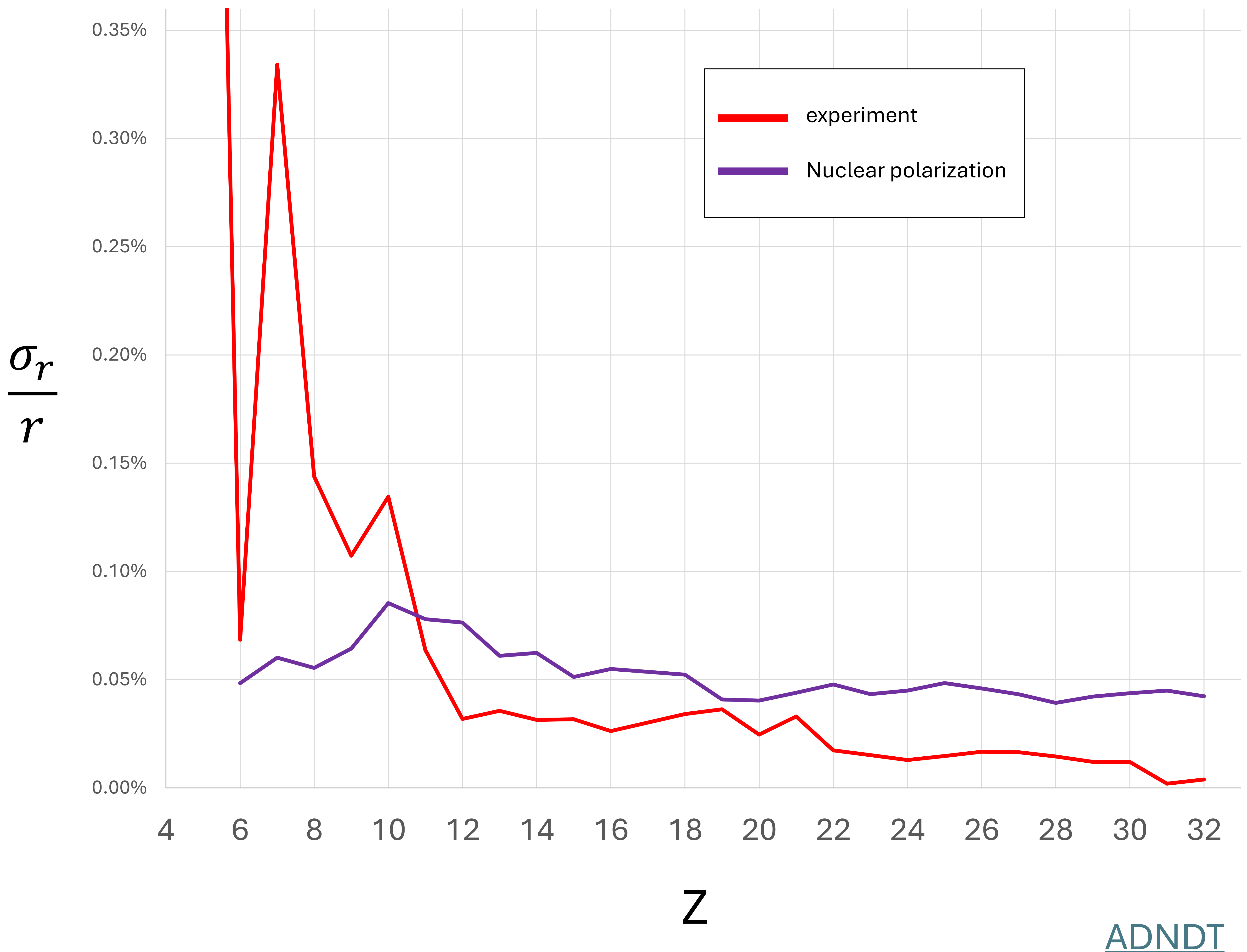

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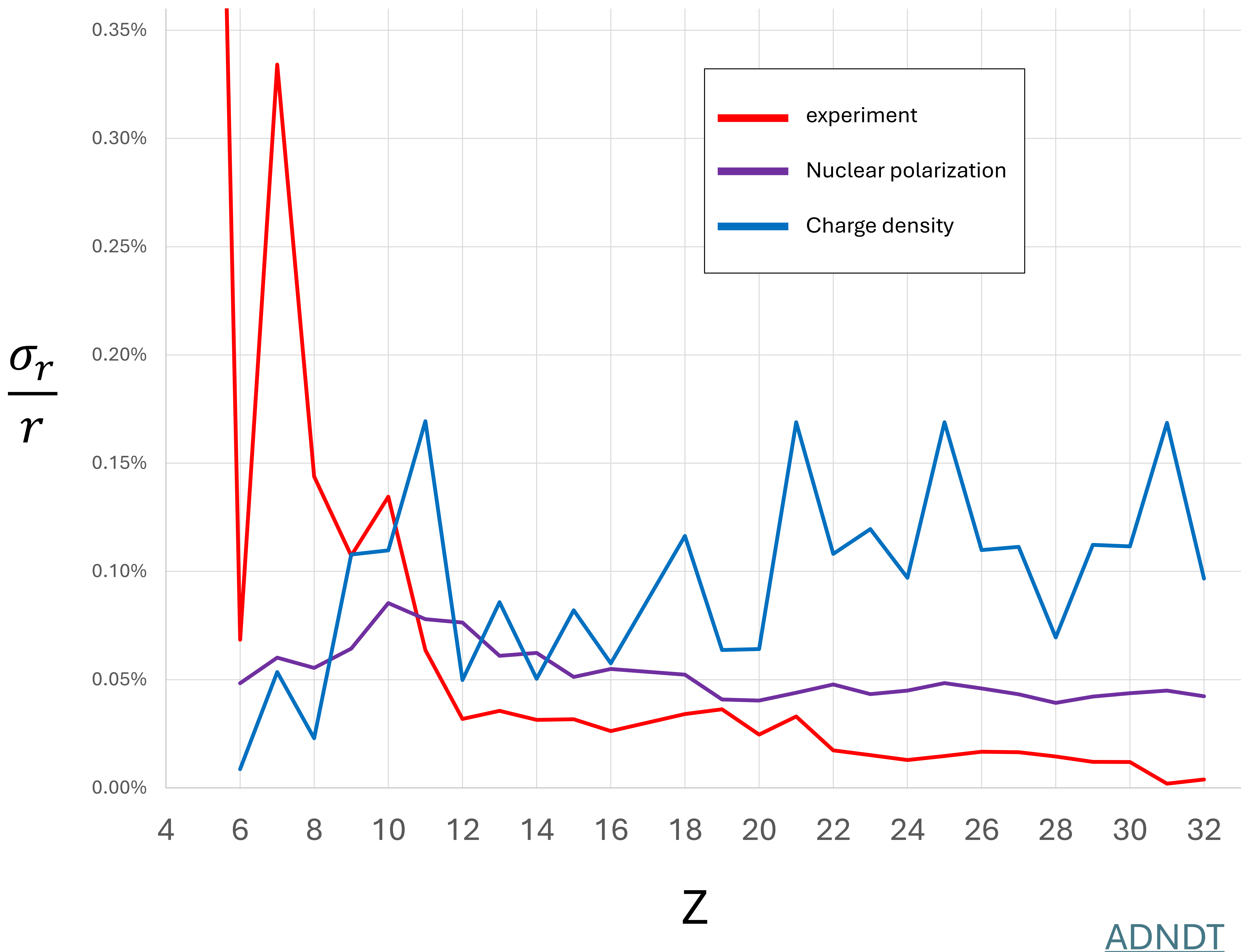

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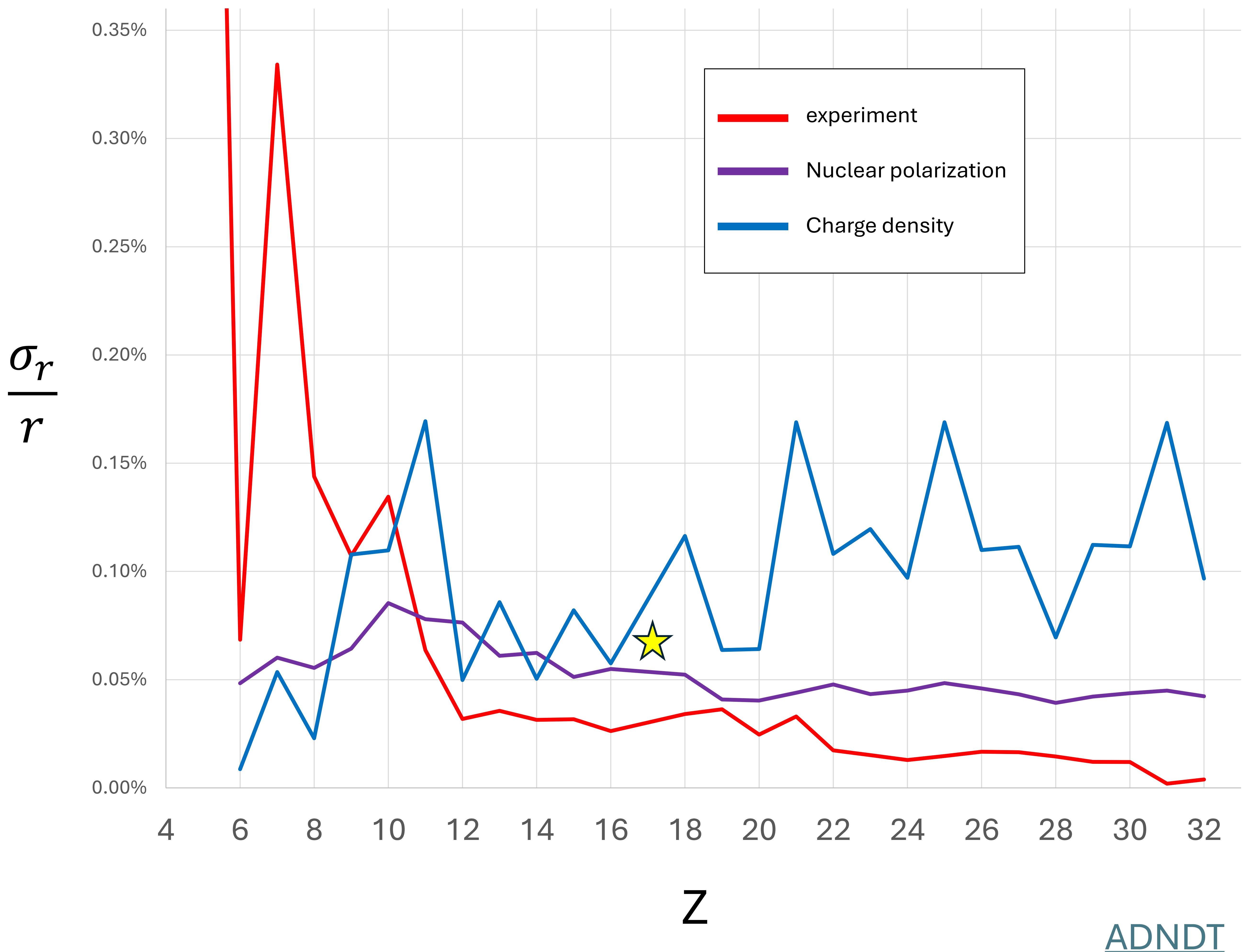
Sources of Uncertainty to Ref. Radii:

Modern Chlorine measurement:
arXiv:2506.08804
Revised theory:
arXiv:2603.22021



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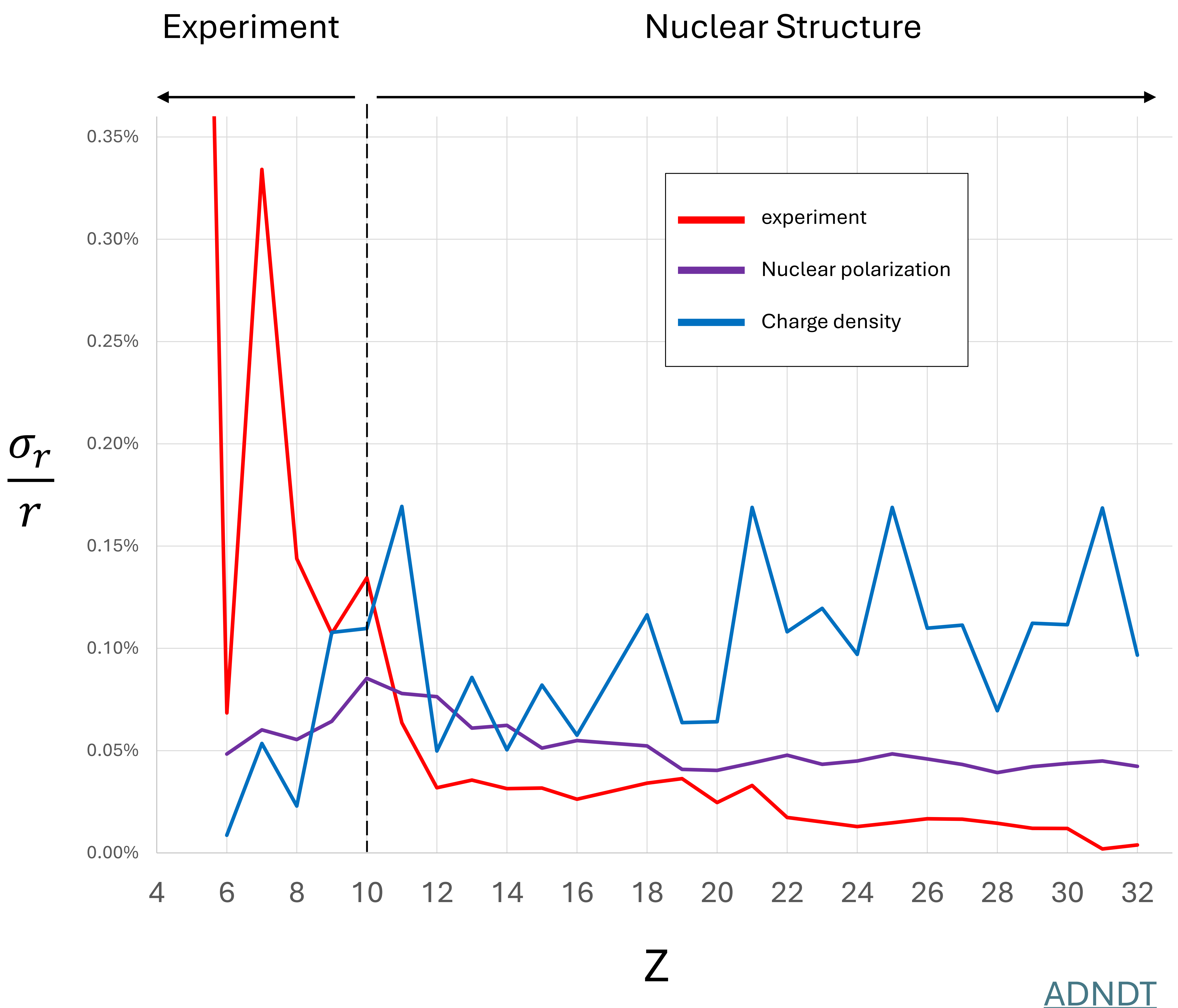

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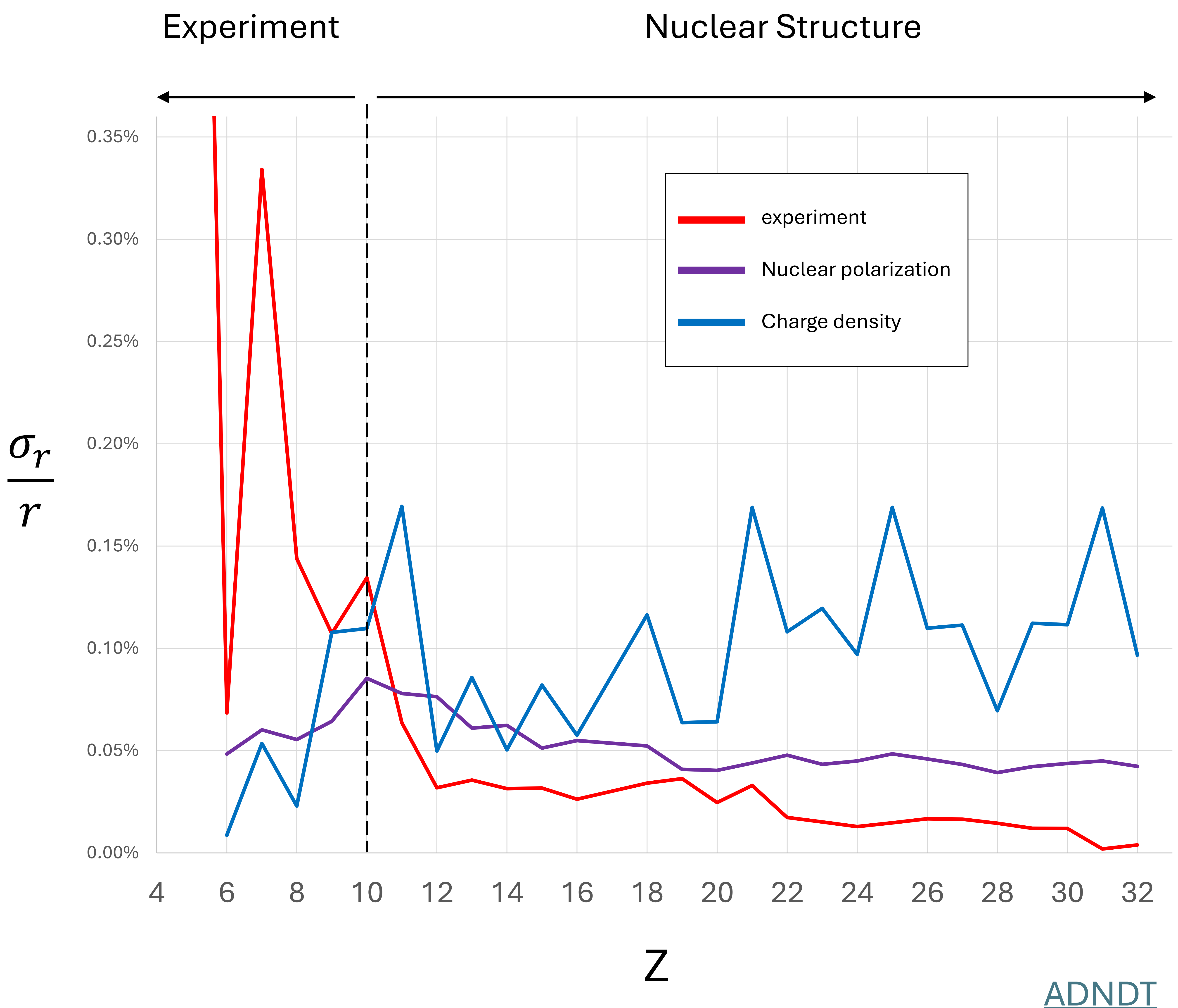
Sources of Uncertainty to Ref. Radii:

What is the spike in
exp. uncertainty < Z=11?



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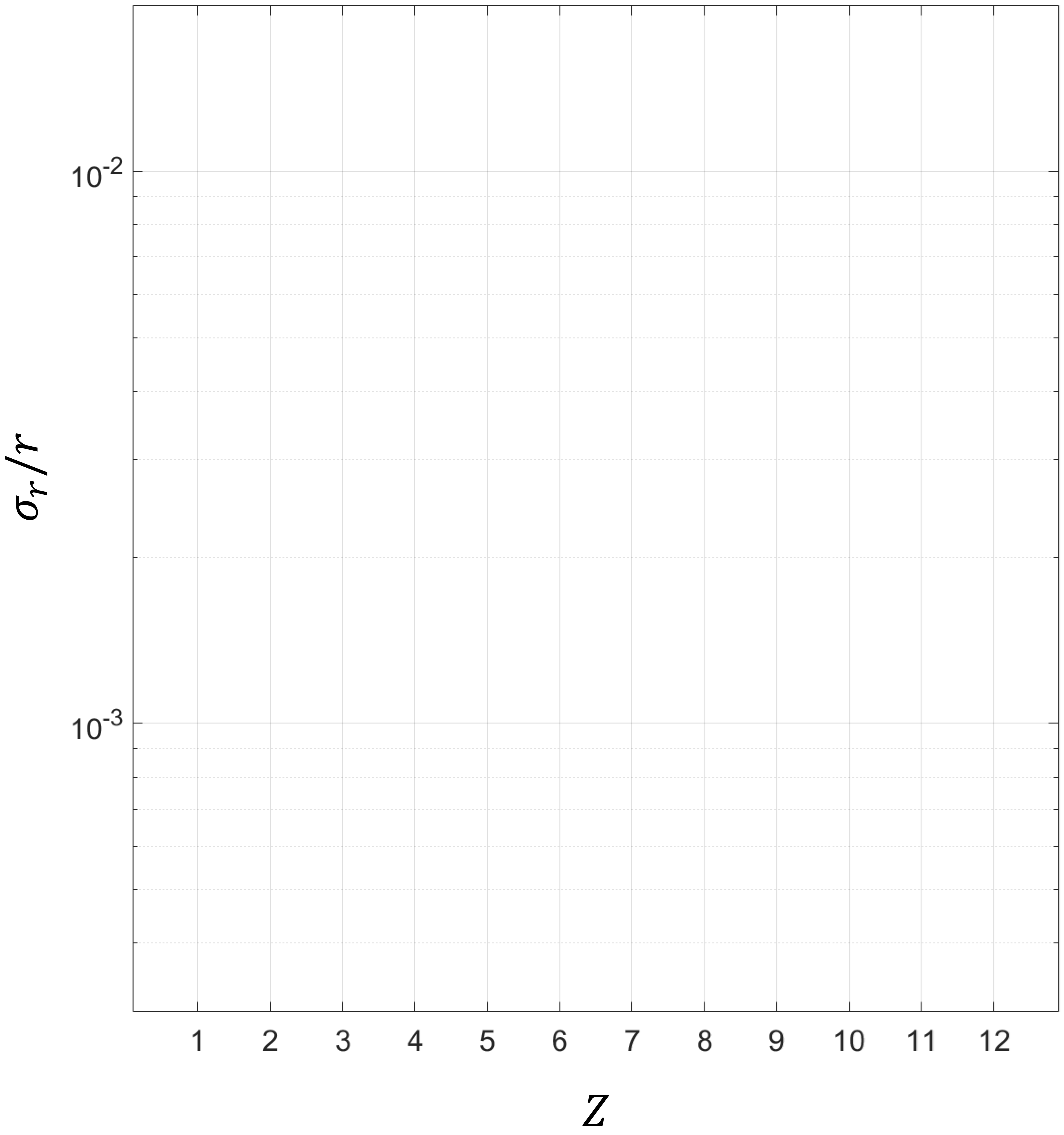
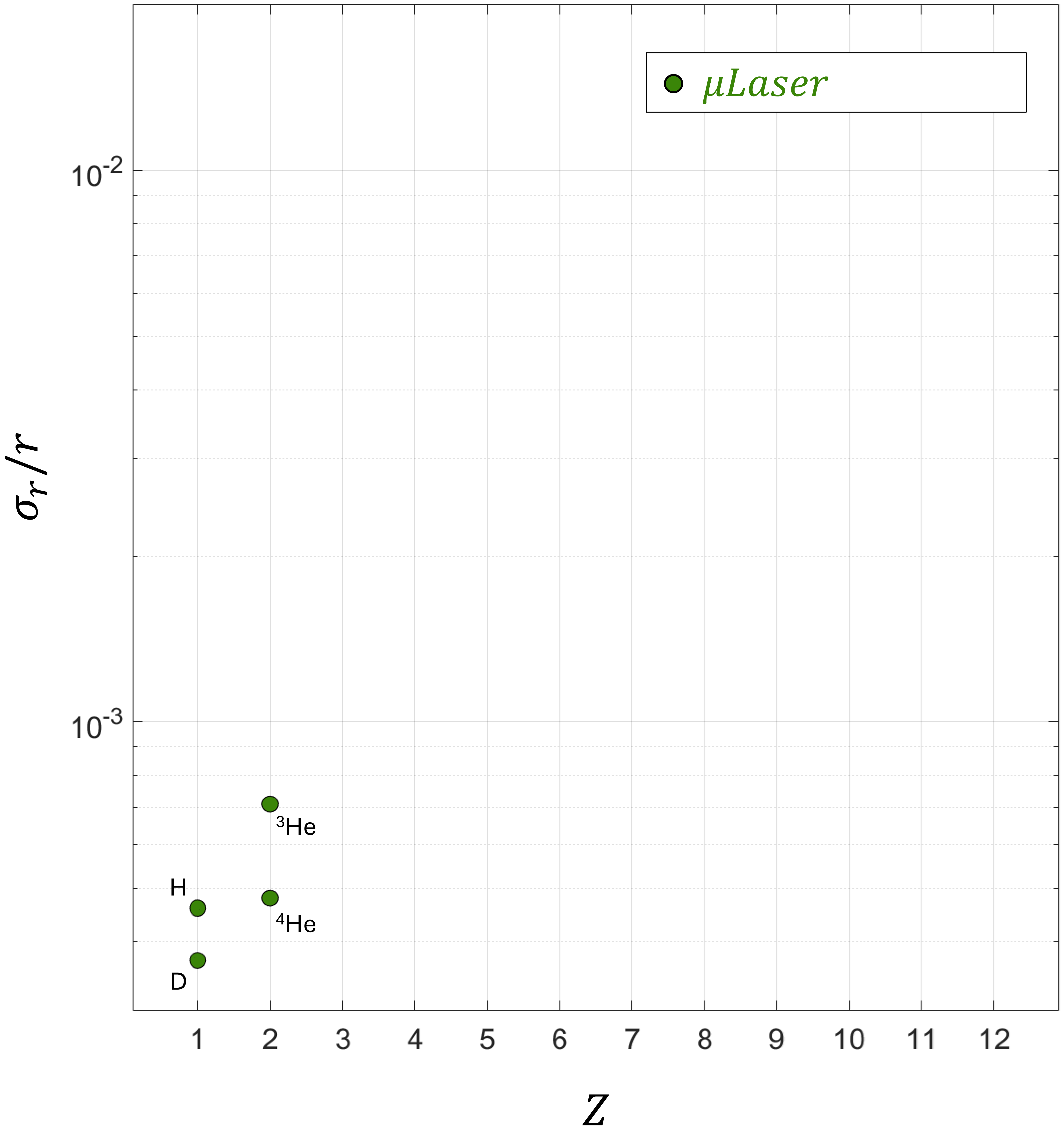
The radius gap



The radius gap

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



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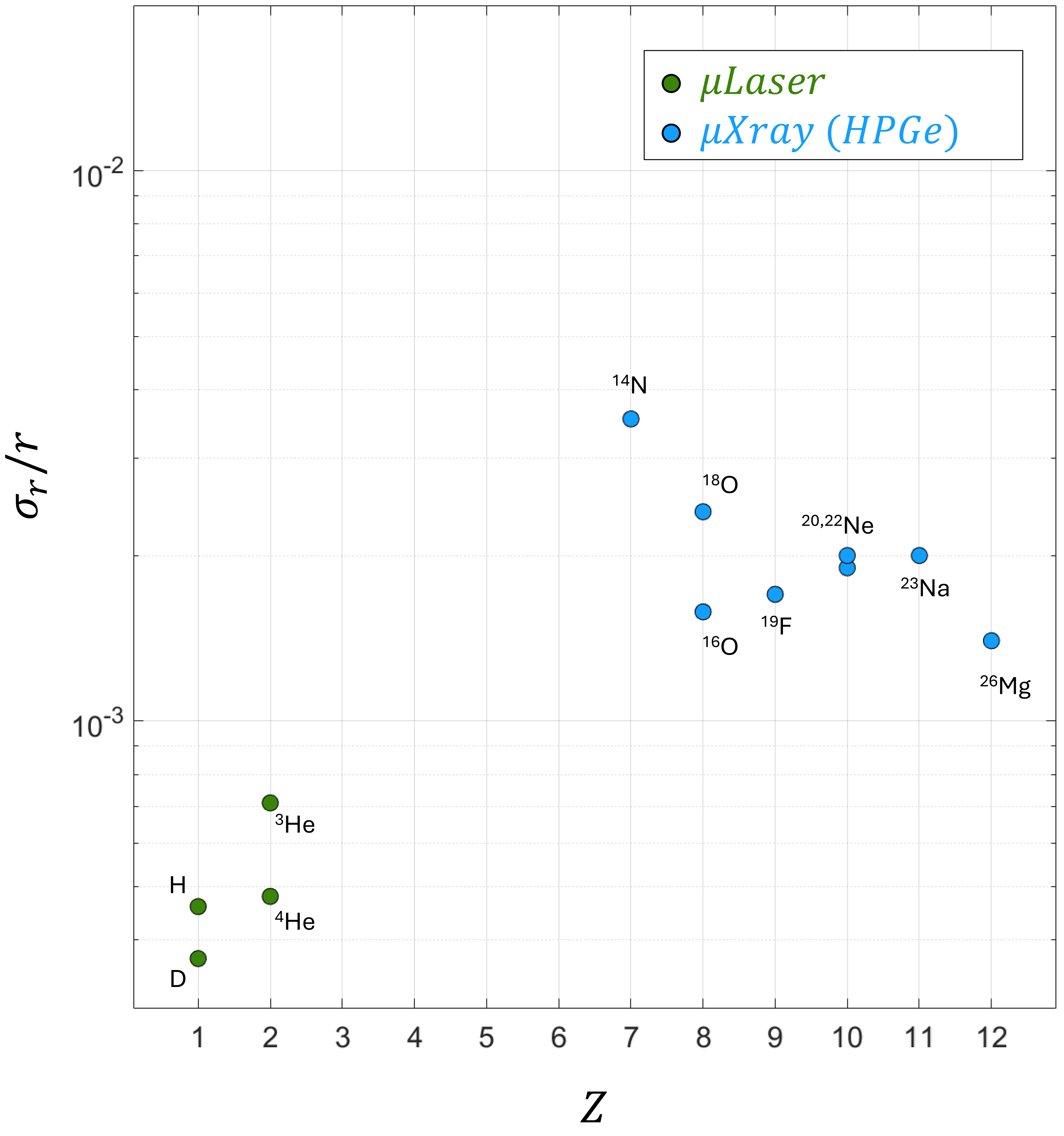
- **For $Z > 6$:**
  Measured x-rays from muonic atoms using solid-state detectors.



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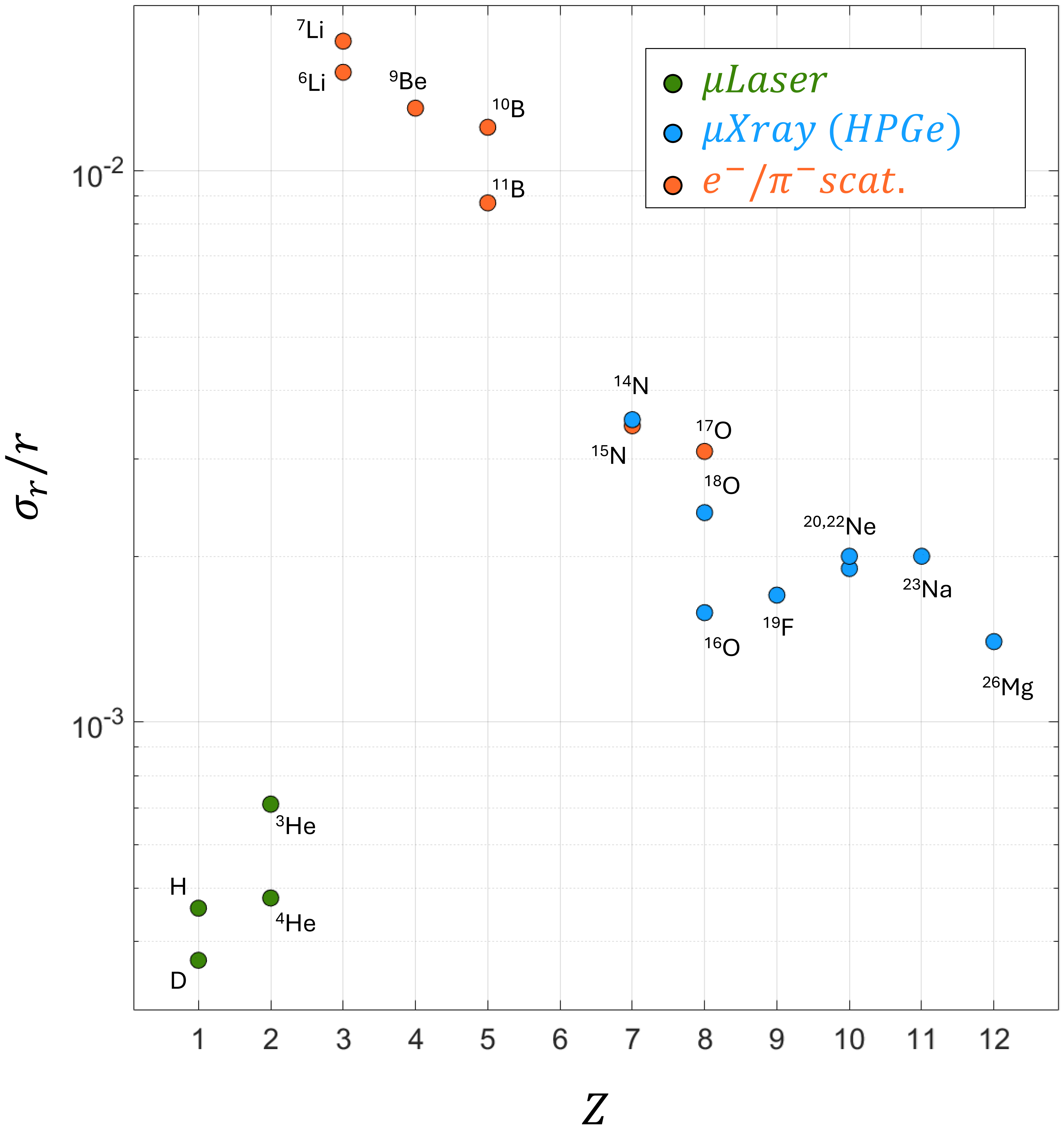
- **For $Z = 3 - 5$, and others:**
  Electron scattering



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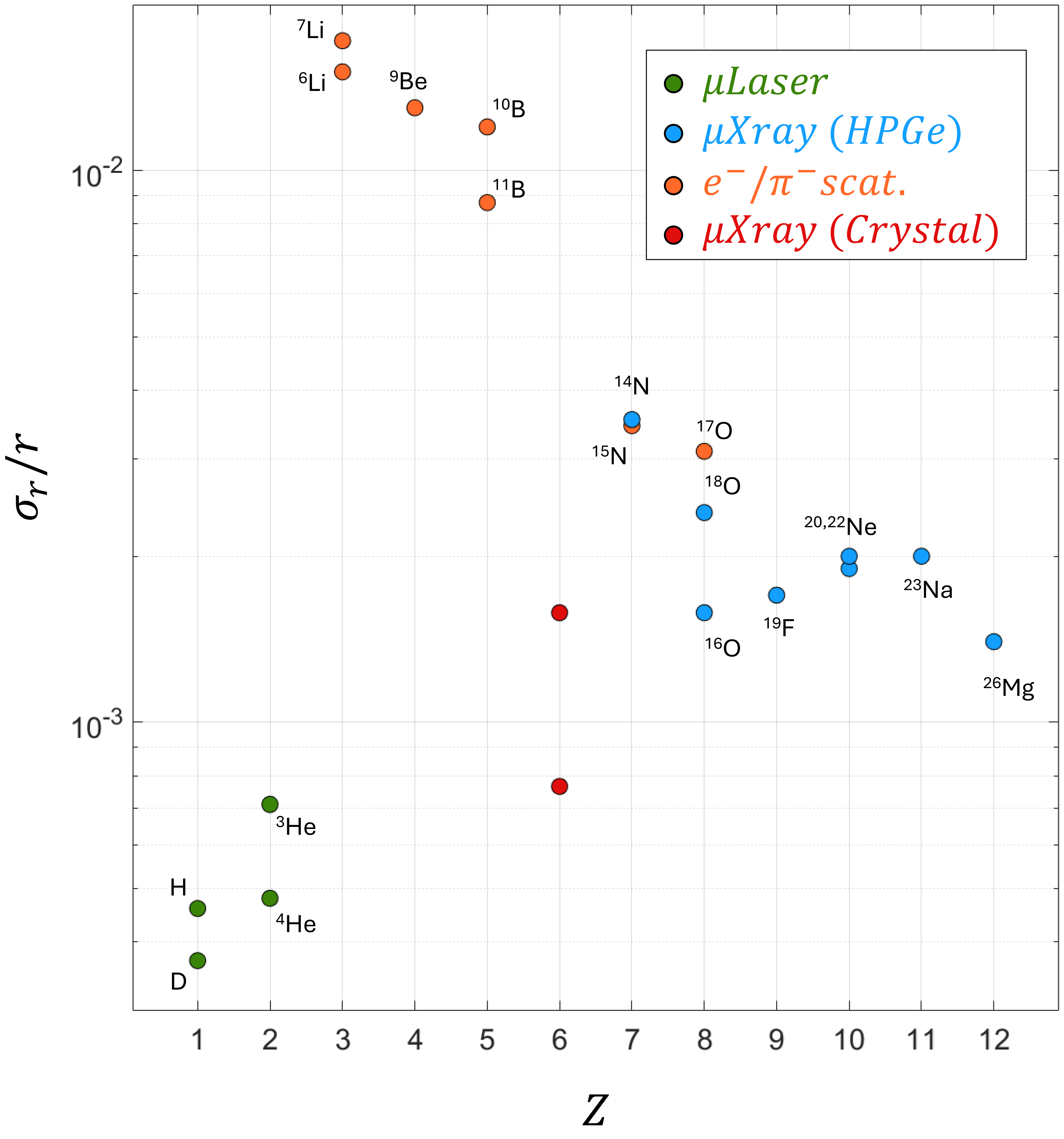
- **For $Z = 6$**
  Measured with crystal spectrometer. Not widely applicable



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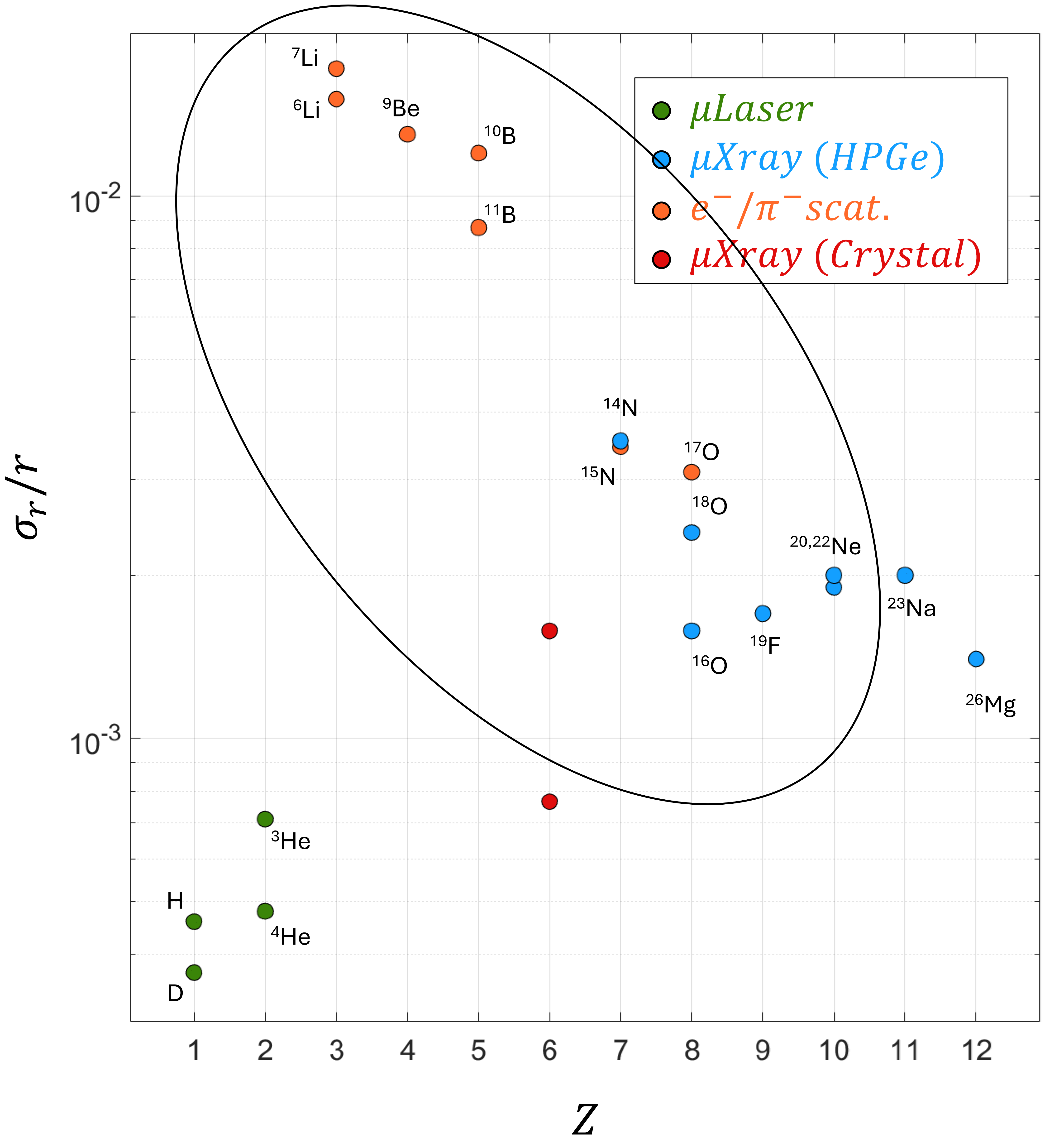

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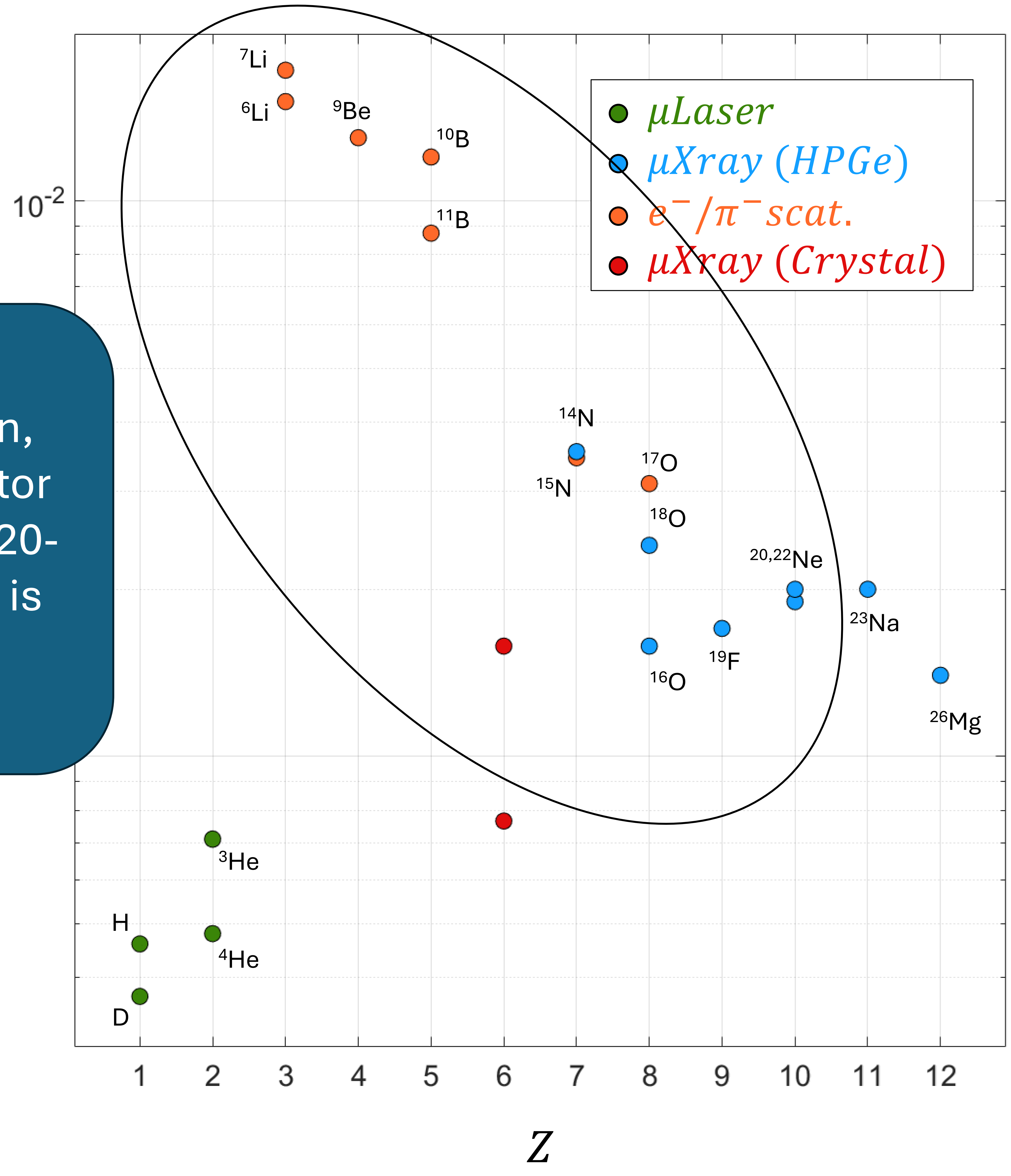
High-resolution, efficient, detector for low-energy (20-200 keV) x-rays is needed



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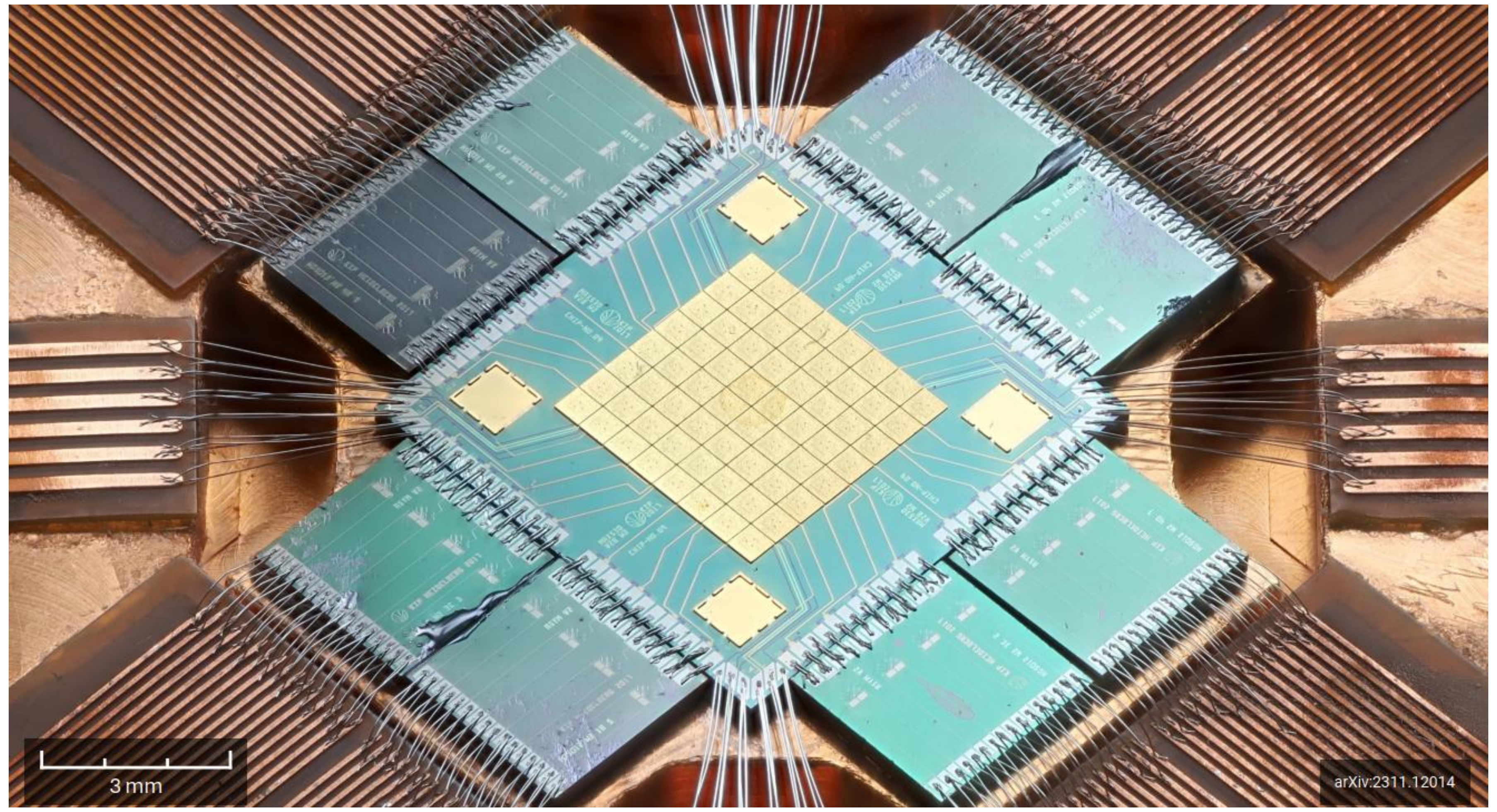
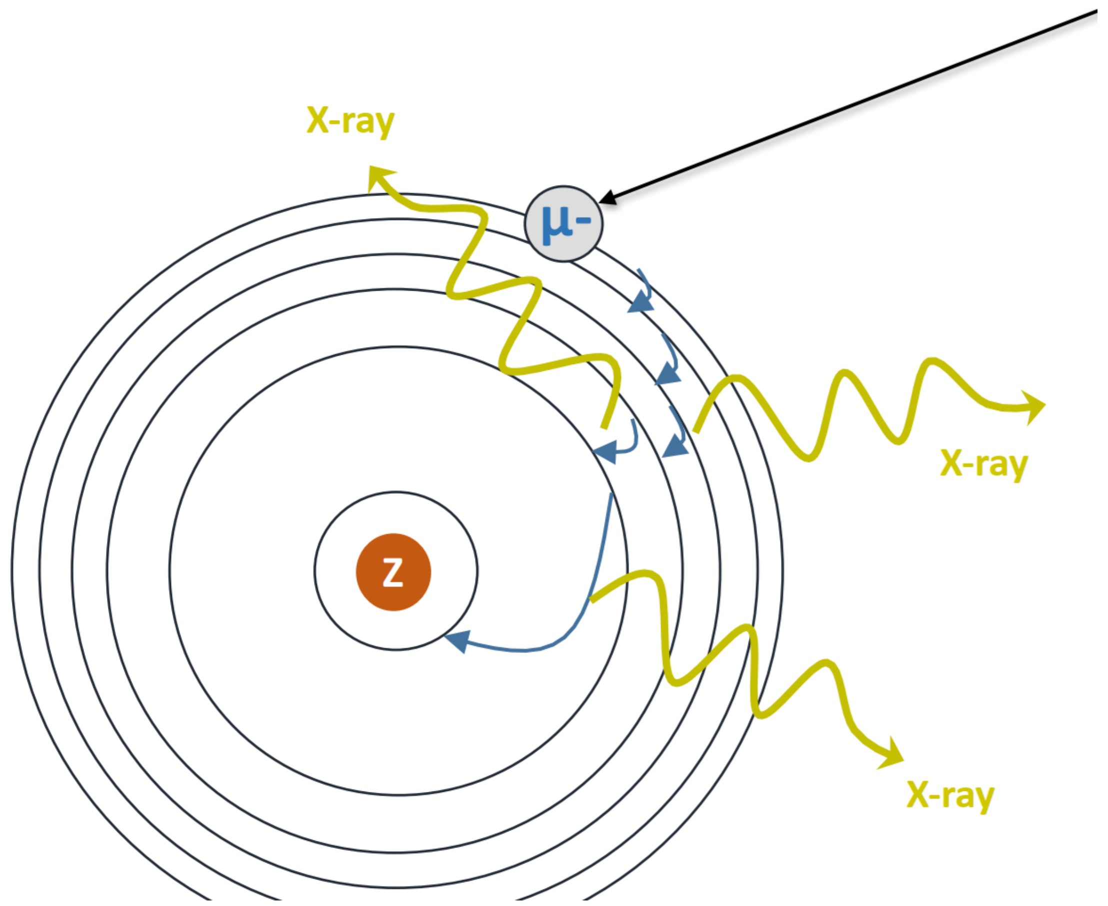
Enter microcalorimeters

Cryogenic microcalorimeters



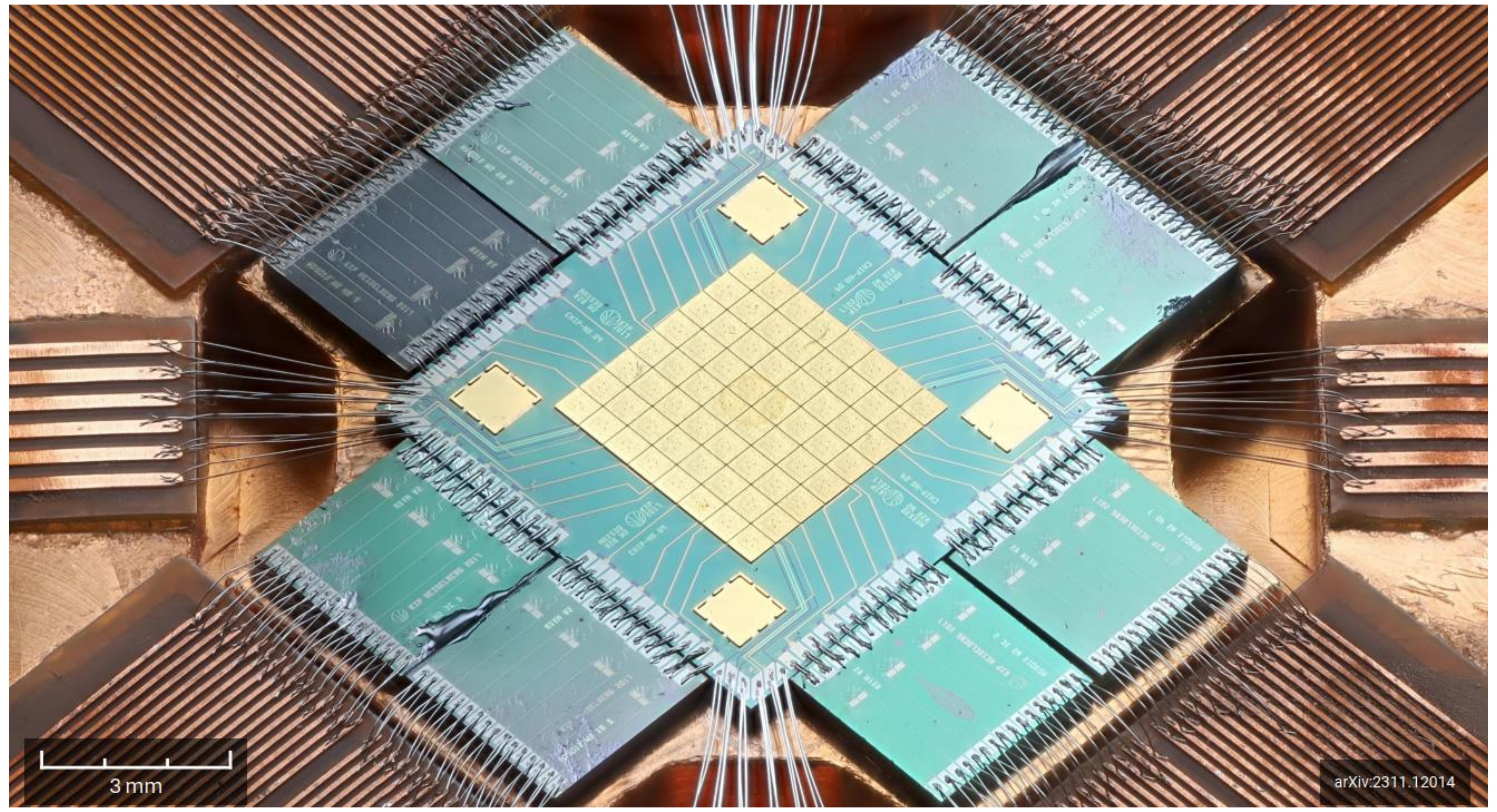
- High quantum efficiency
- Broadband (important for calibration)
- **Superb resolution $\left(\frac{E}{\Gamma_E} > 10^3\right)$**
- Fast rise time

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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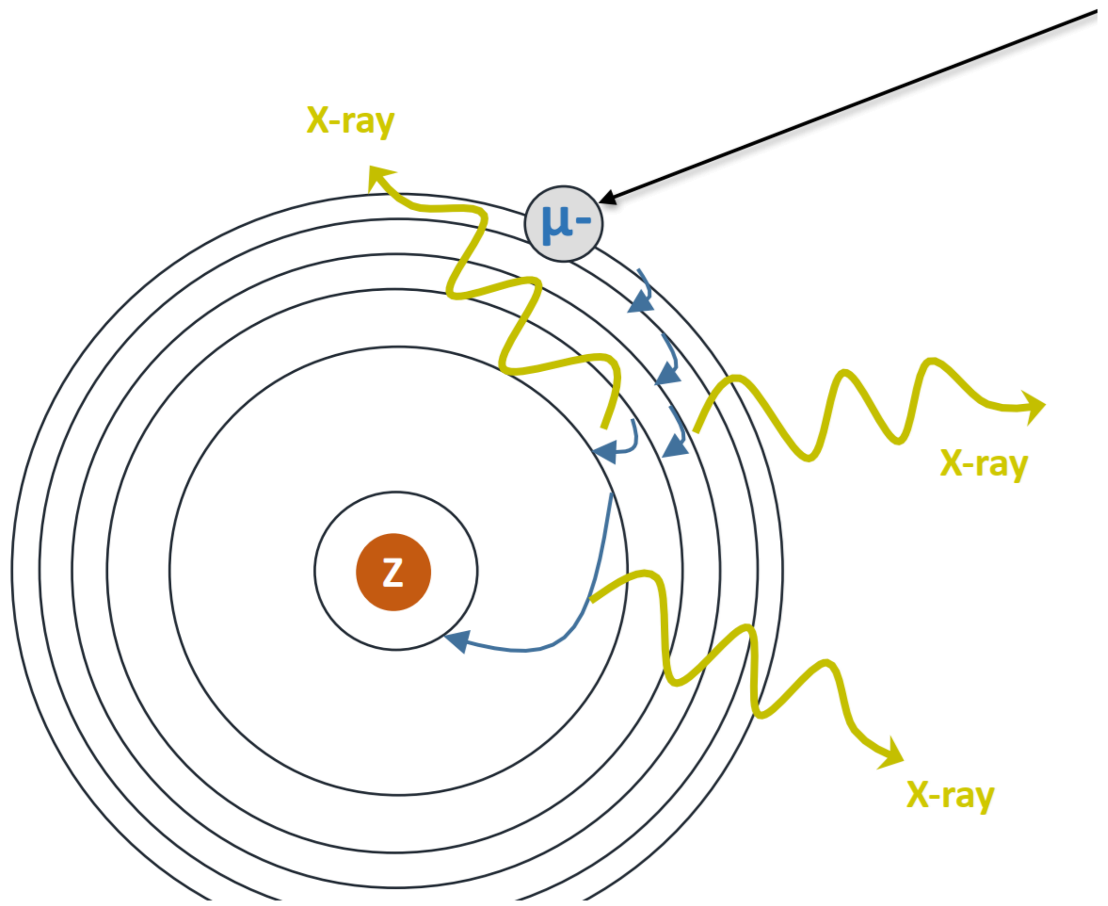

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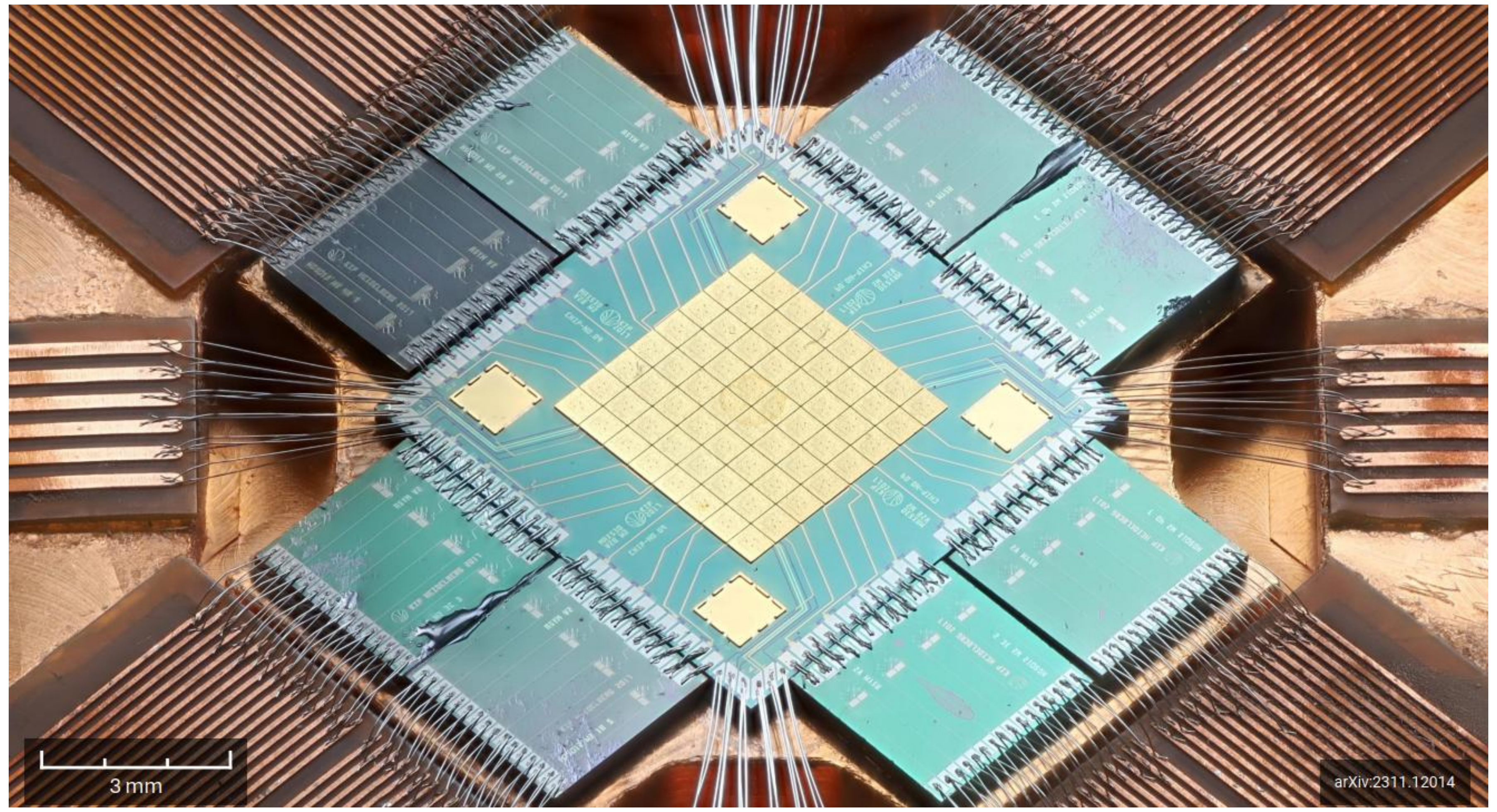
Cryogenic microcalorimeters



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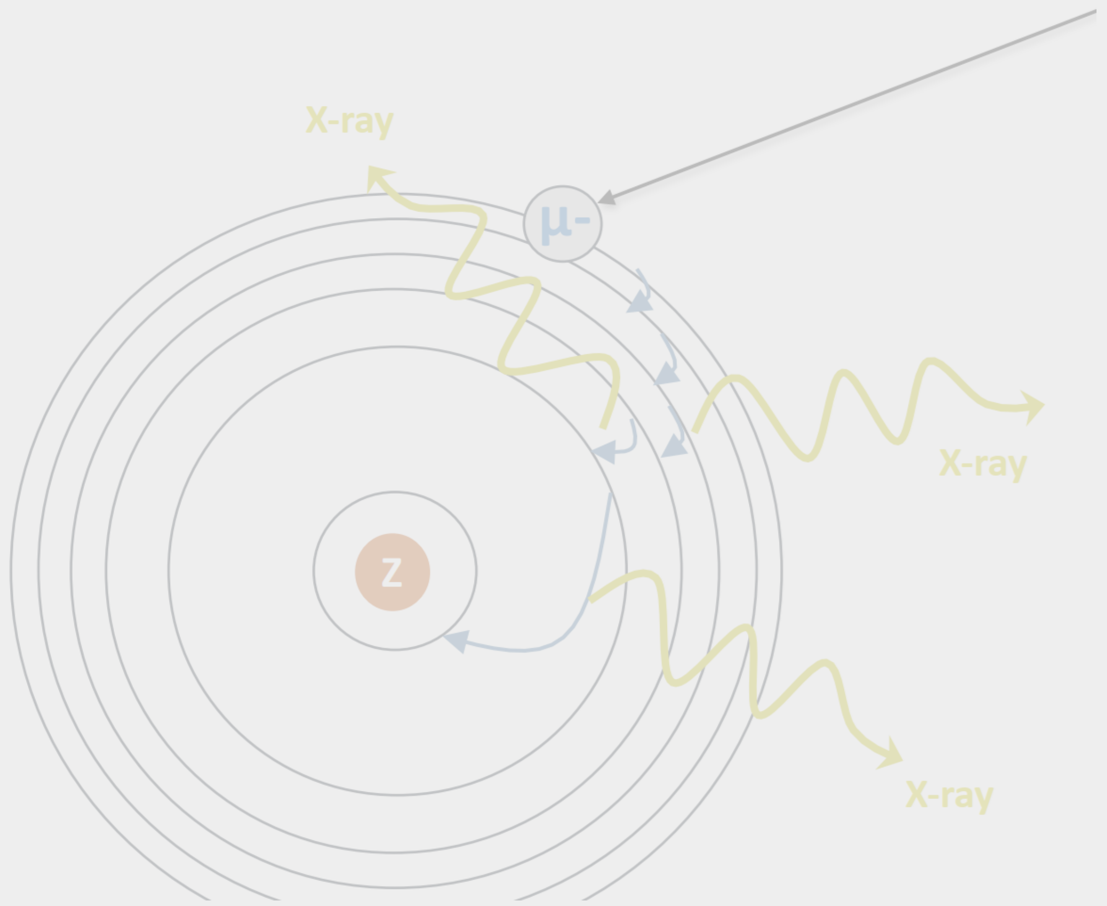

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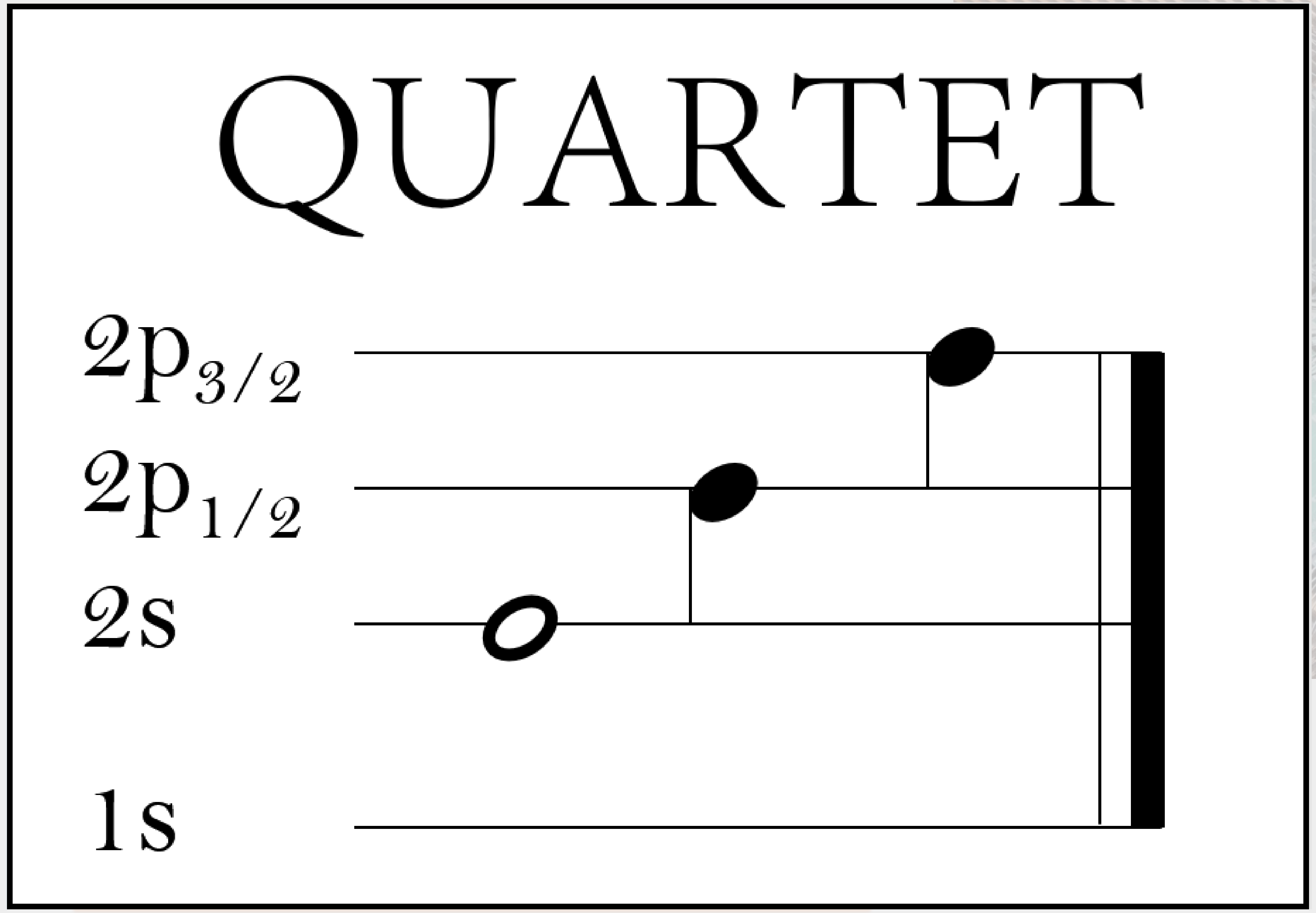
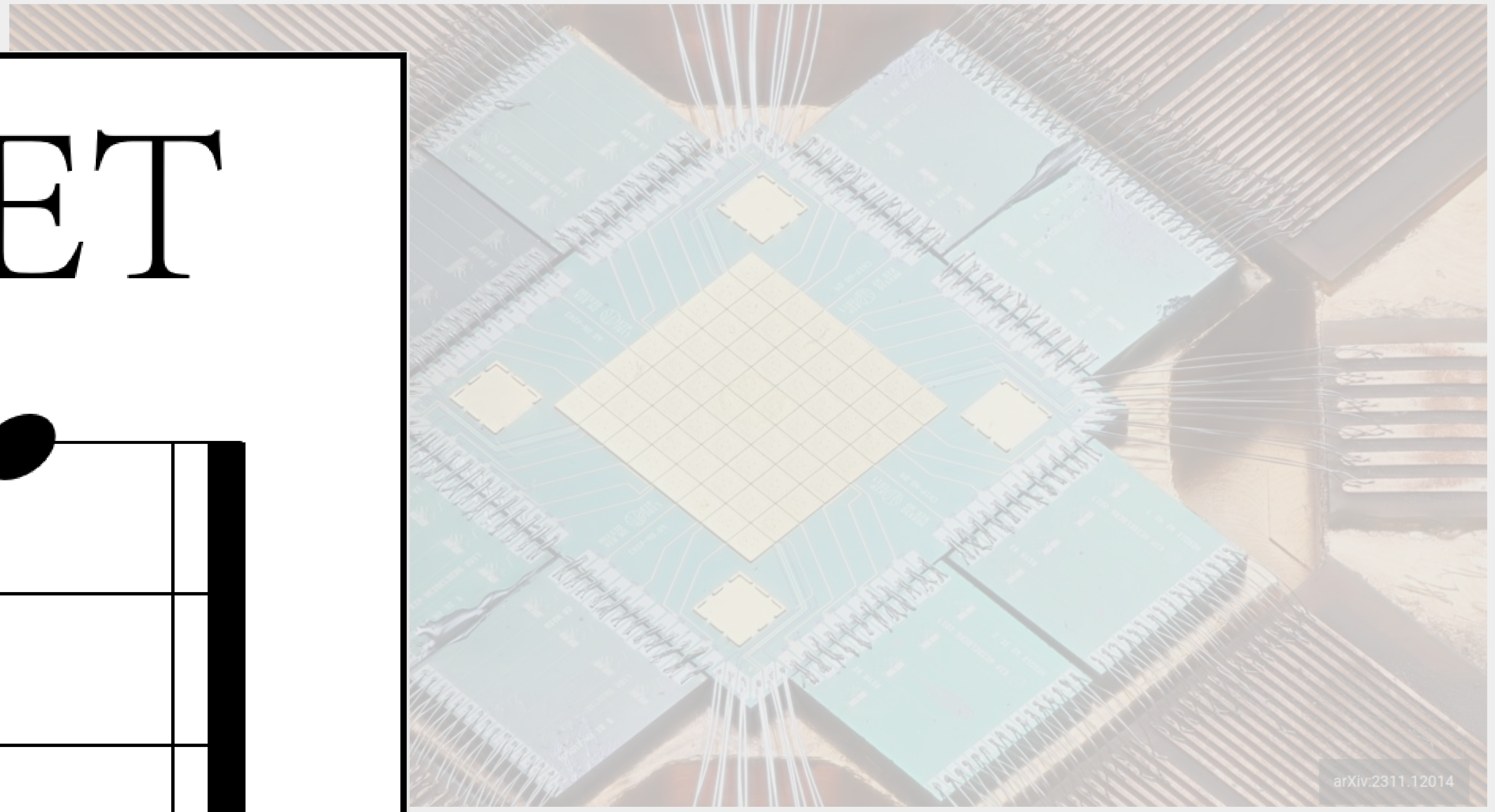
Quantum Interactions with Exotic Atoms



More info:

arXiv:2311.12014
arXiv:2310.03846

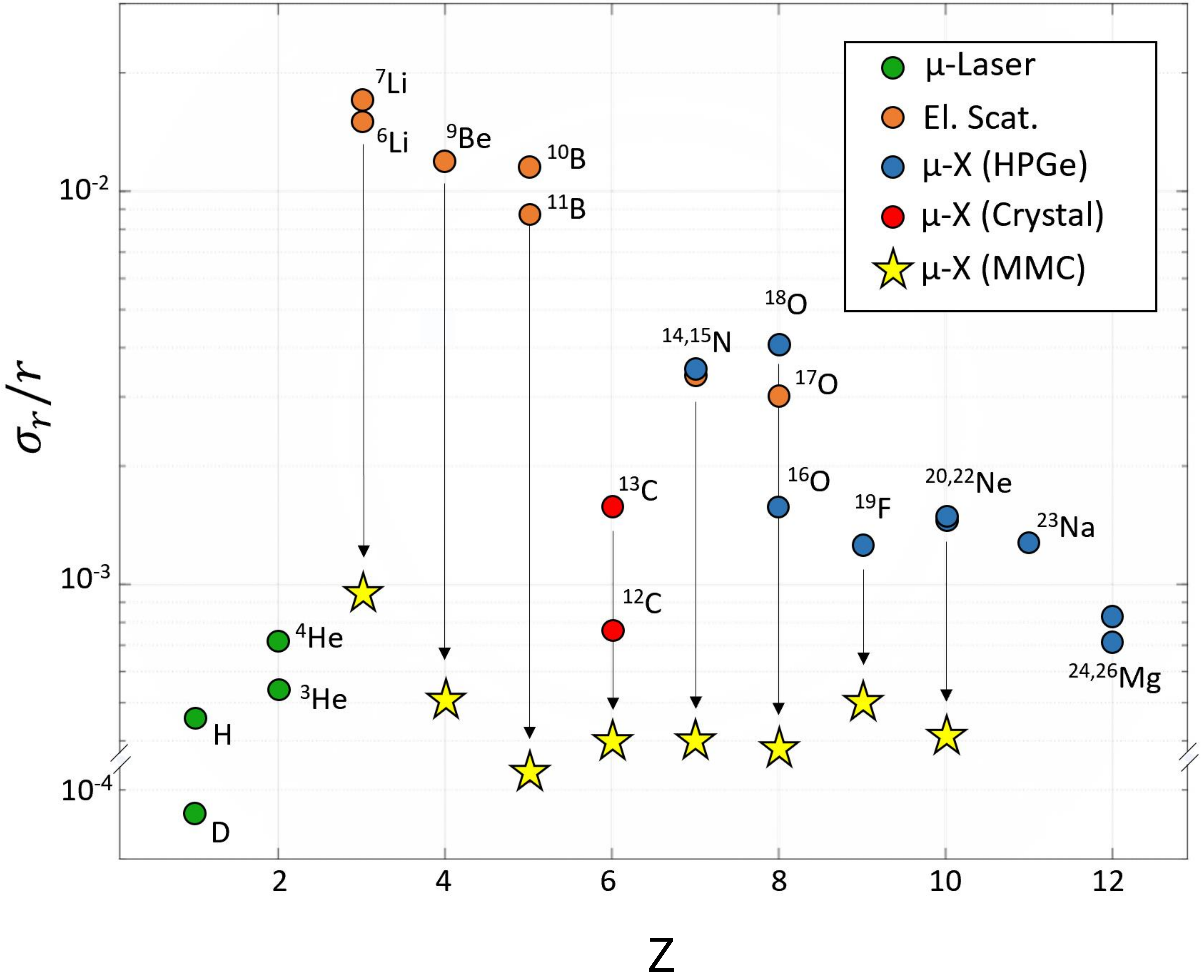
Cryogenic microcalorimeters



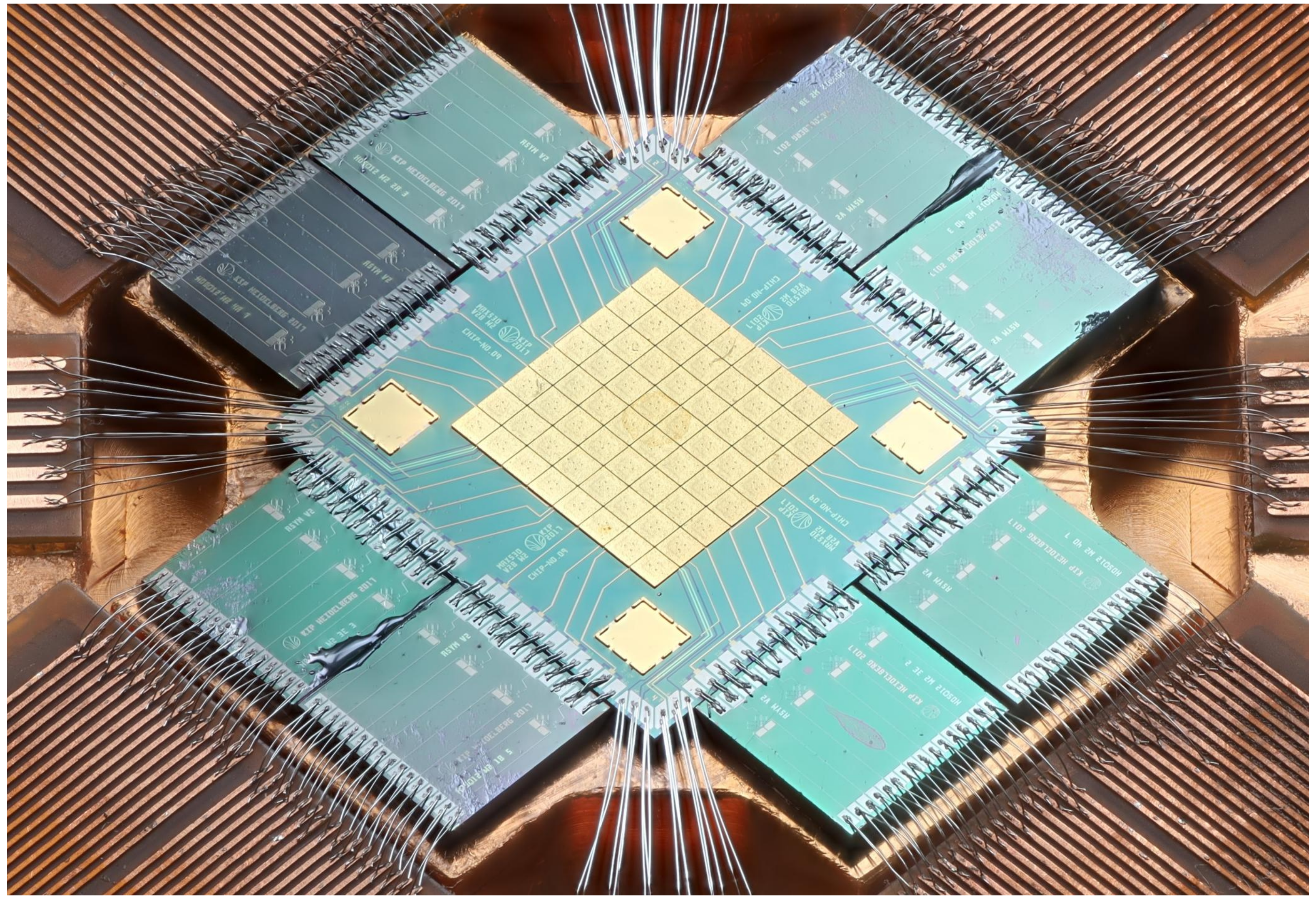
- High quantum efficiency
- Broadband (important for calibration)
- **Superb resolution $\left(\frac{E}{\Gamma_E} > 10^3\right)$**
- Fast rise time (important for background suppression)

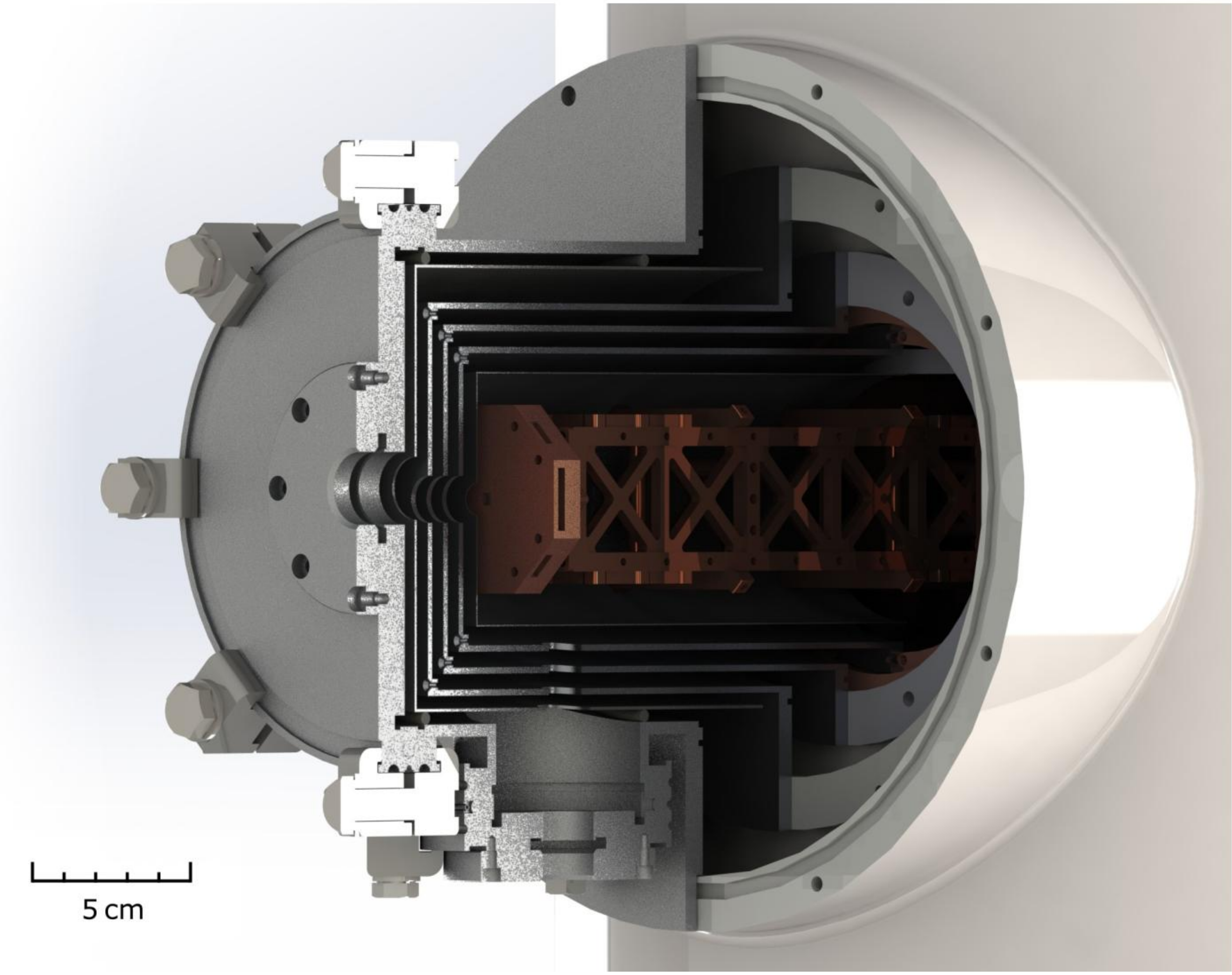
QUARTET Goals:

Contribution to NuPECC LRP: arXiv:2210.16929



The QUARTET 2023-2024 detector

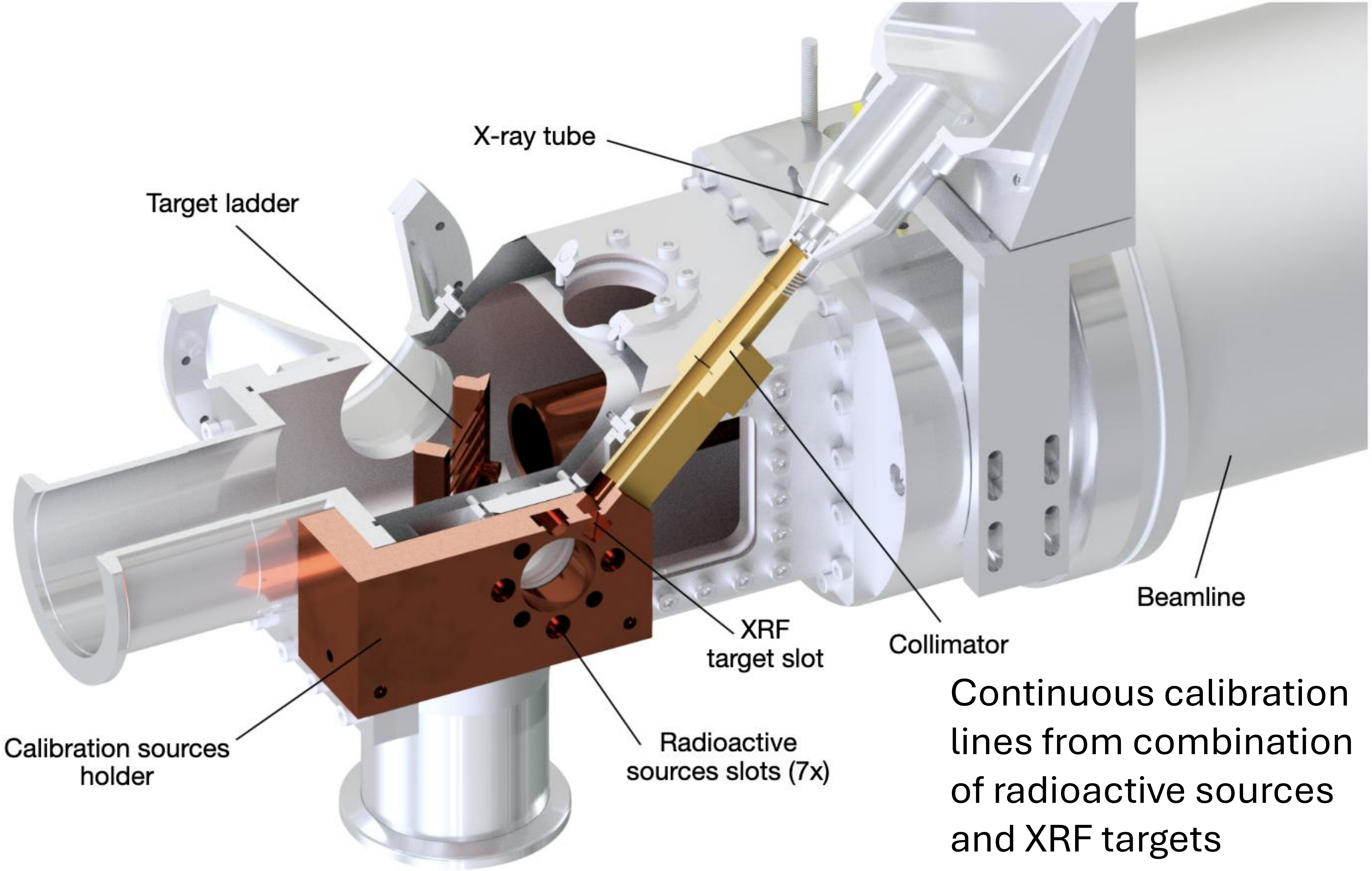




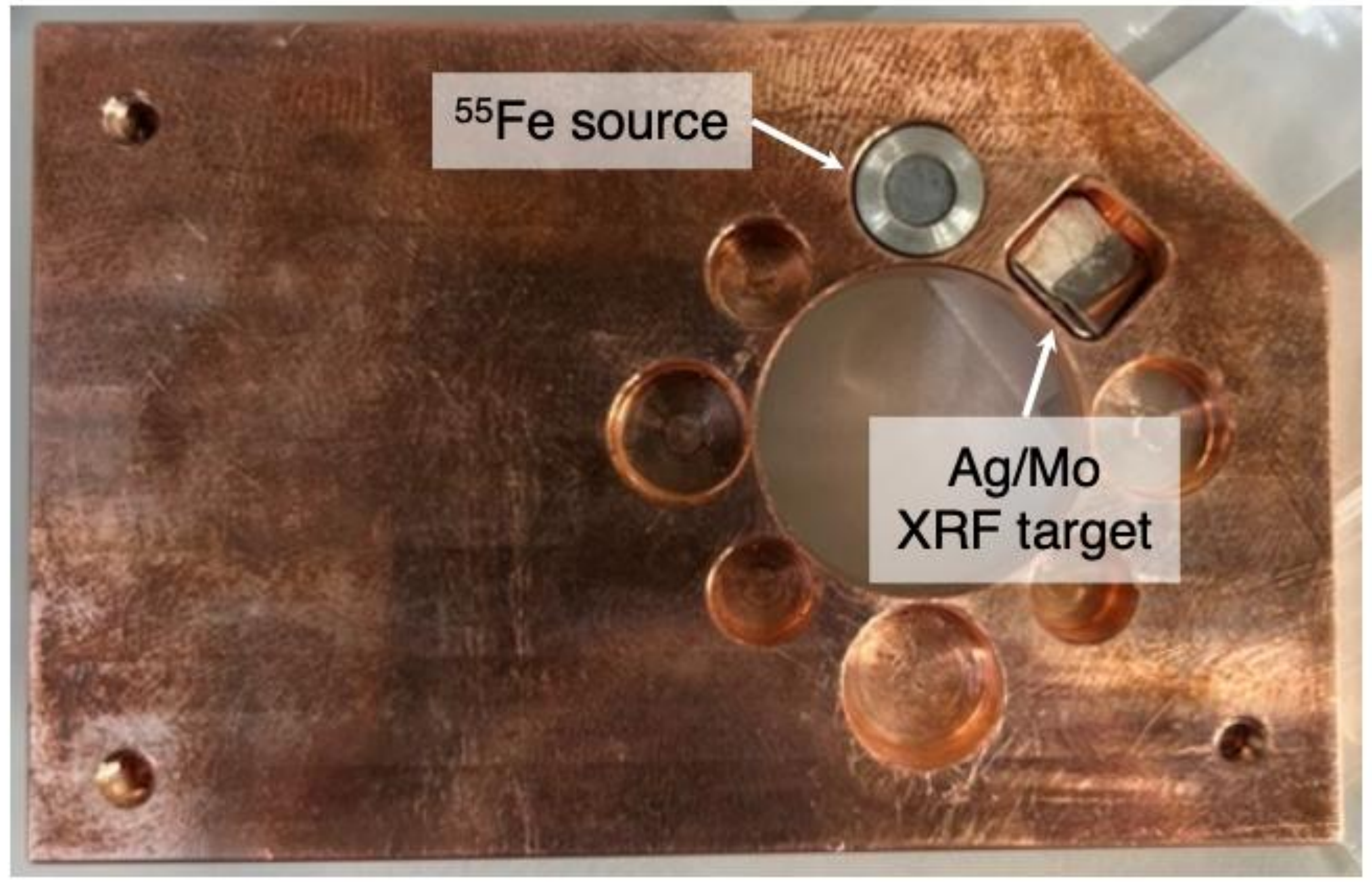
- 64 pixel maX-30 MMC detector, *developed for IAXO experiment*
- Mounted in custom sidearm designed to reduce vibrations
- 5 thermal shields and x-ray windows
- Calibration sources mounted outside the detector

Figures from D. Unger et al LTD2023 proceeding, for the QUARTET collaboration

Calibration—combination of XRF and gamma-ray standards



Continuous calibration lines from combination of radioactive sources and XRF targets



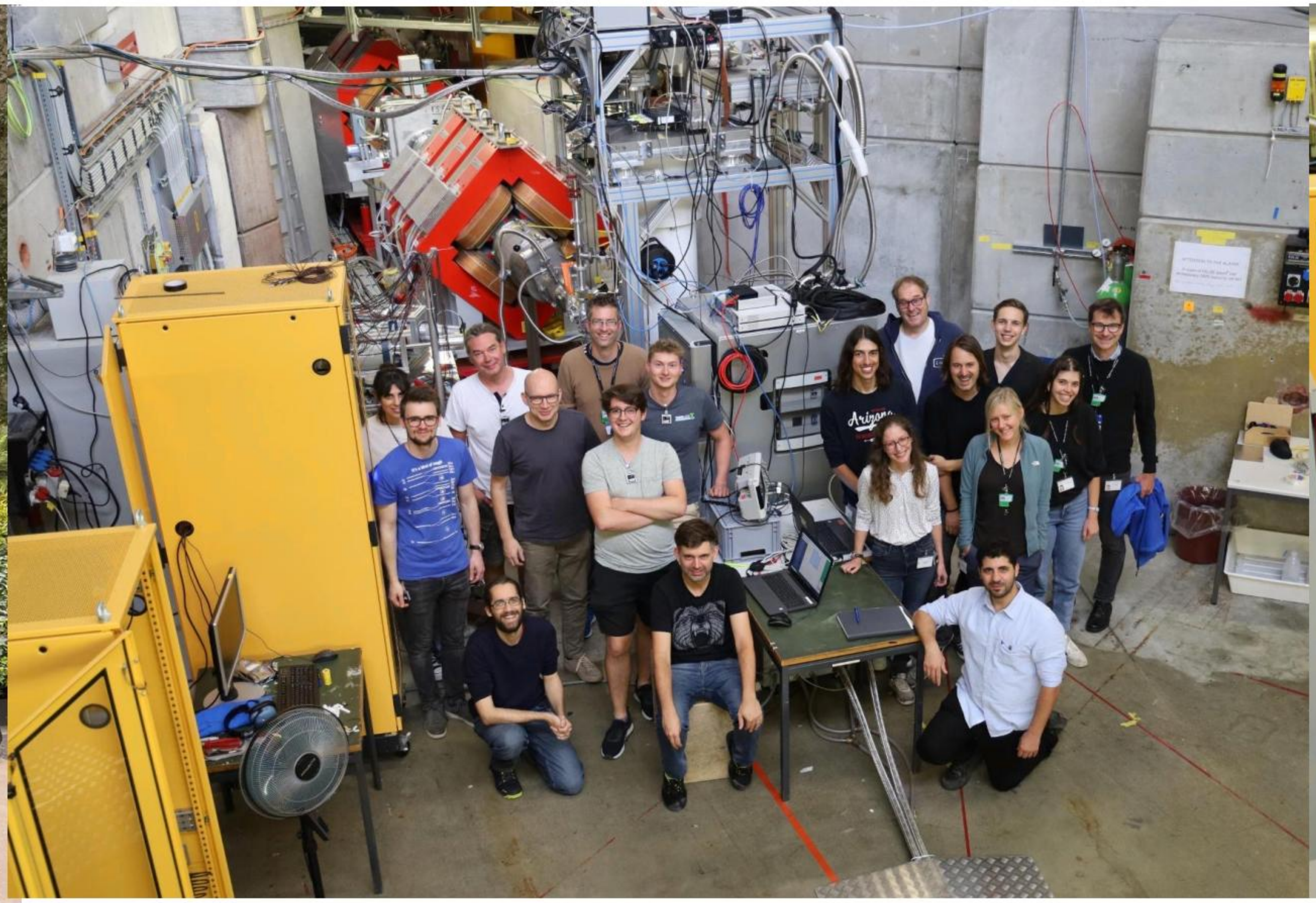
Many thanks to PSI radiochemistry for the ^{133}Ba source !


DANFYSIK

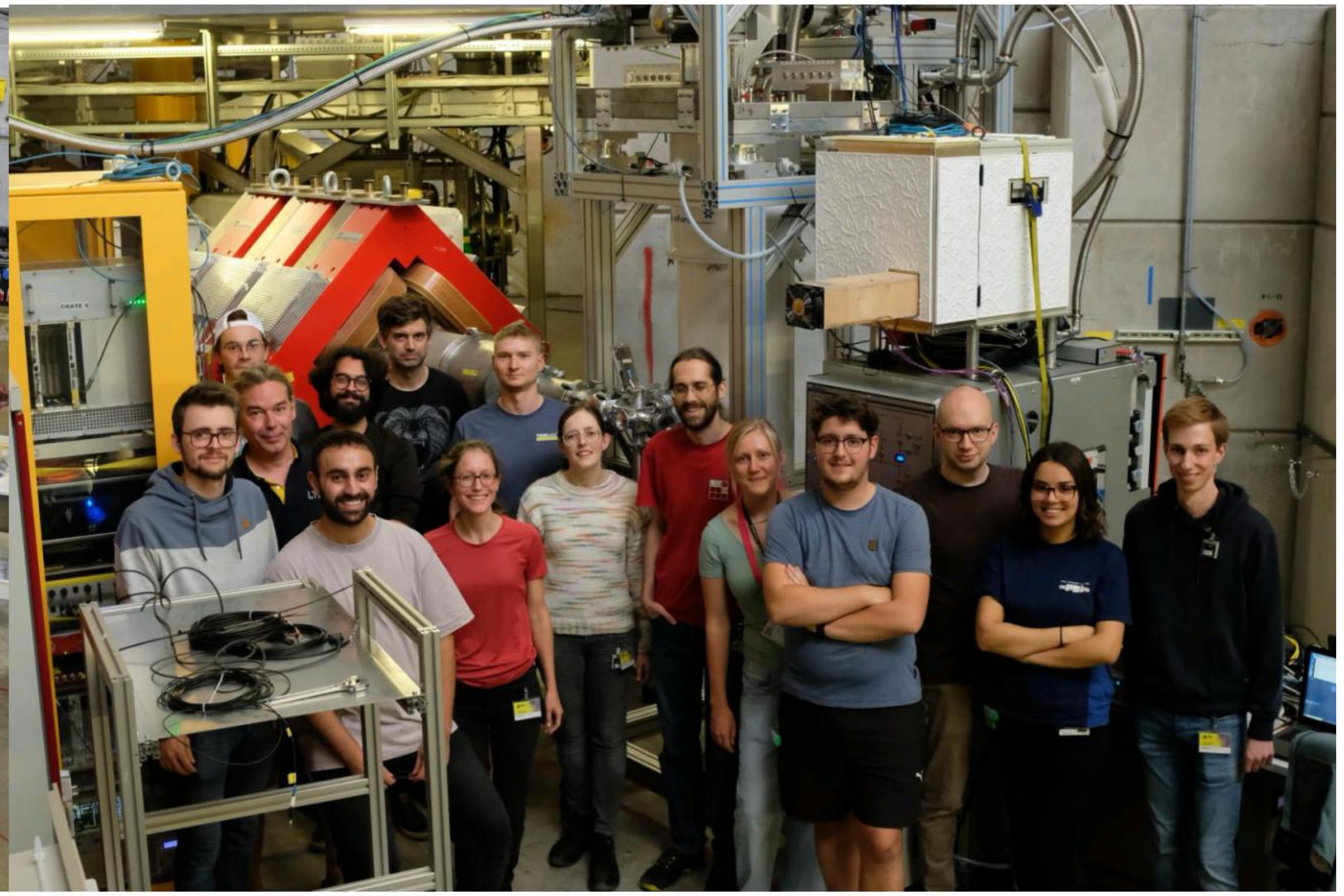
The QUARTET collaboration timeline

First meeting @ Jussieu (2022)

Test beam @ PSI (2023)



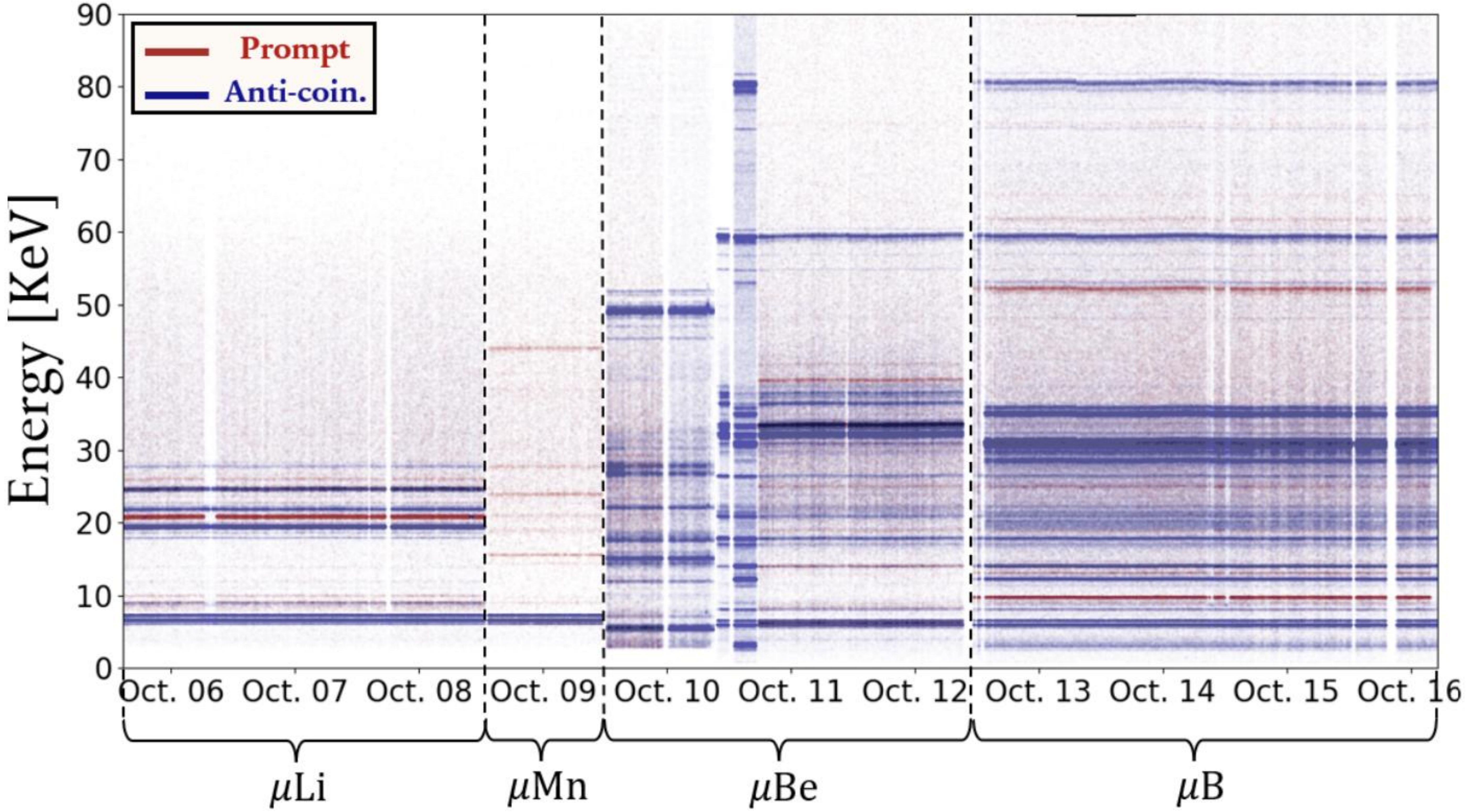
Li/Be/B beamtime (2024)



Oxygen charge radii (2025)

C to Ne charge radii (2026/2027)

QUARTET 2024 beamtime—high statistics data for all channels of interest



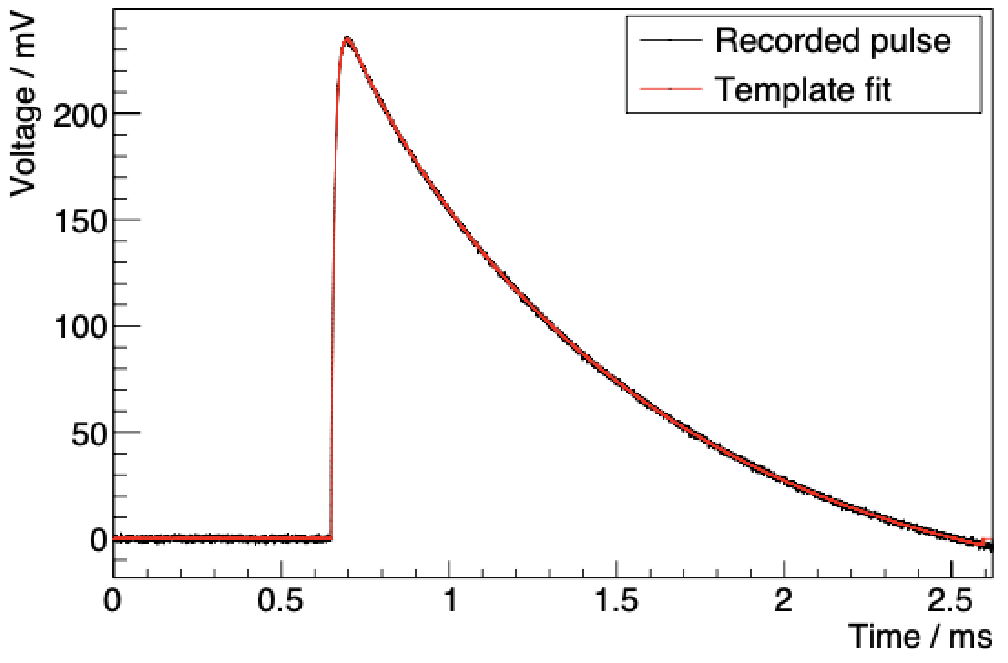
Target	Production	Calibration	Conclusion
$^{6,7}Li$	70 h	^{55}Fe Mo/Ag XRF	✓
Mn	20 h	^{55}Fe	Proof-of-principle
^{9}Be	40 h	^{55}Fe Ba/La XRF ^{241}Am	✓
$^{10,11}B$	80 h	^{55}Fe ^{241}Am ^{133}Ba	✓

High statistics data suitable for physics analysis obtained for all main channels of interest

QUARTET 2024 beamtime—Key analysis steps

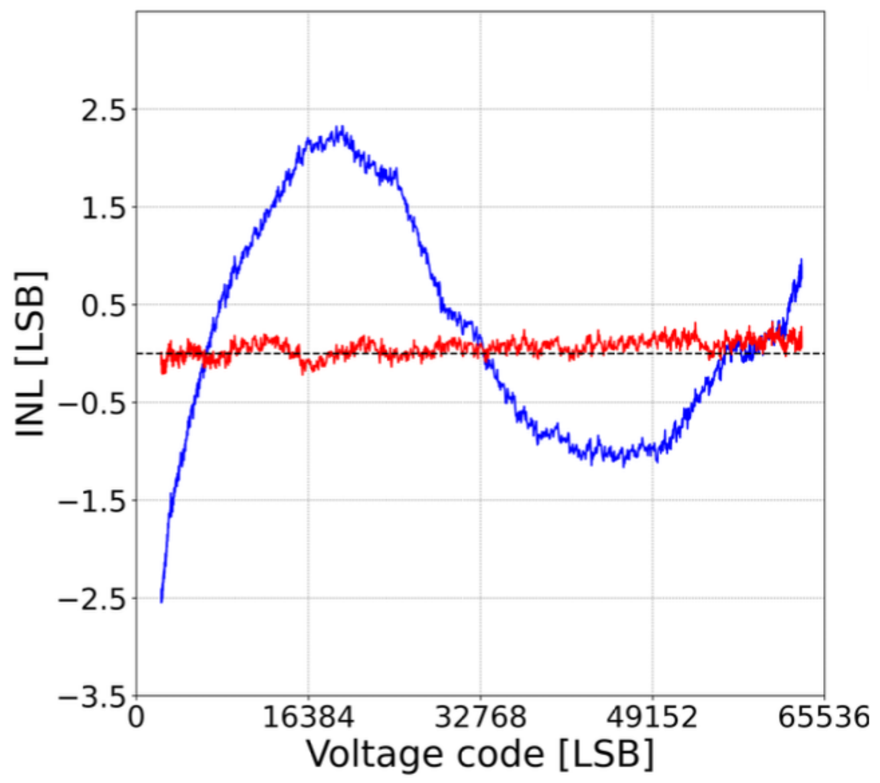
Pulse fitting → ADC calibration → Event Identification and Temperature Correction → Calibration and Pixel Co-adding

Pulse fitting



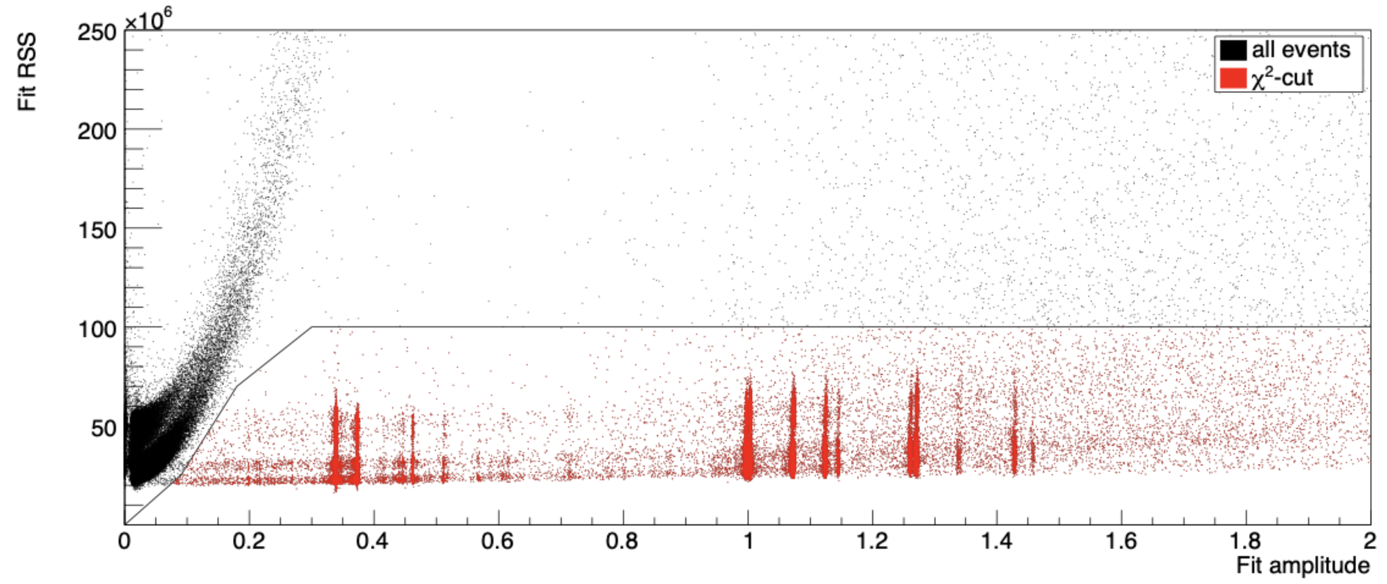
- ✓ Amplitudes
- ✓ Goodness-of-fit

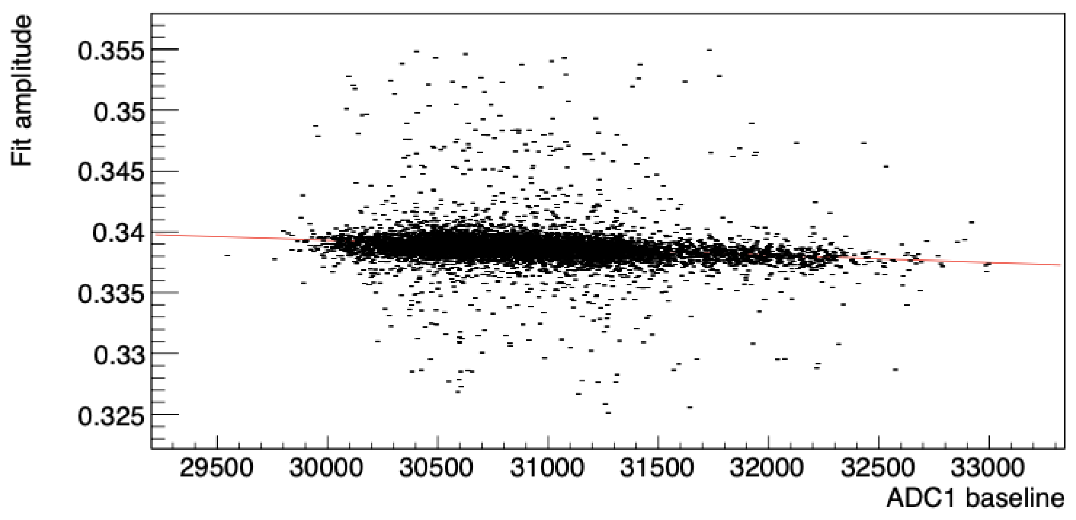
ADC calibration

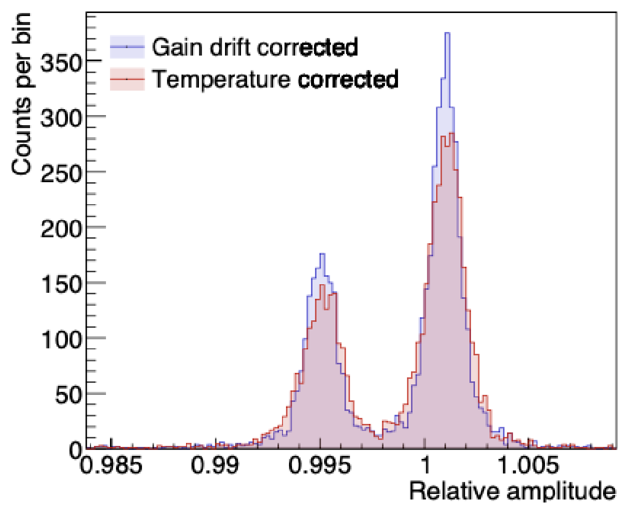


- ✓ Correct for non-linearities
- ✓ Stable, repeatable
- ✓ Reduce systematic non-linearities by 20 (<<1 eV)

Event Identification and Temperature Correction





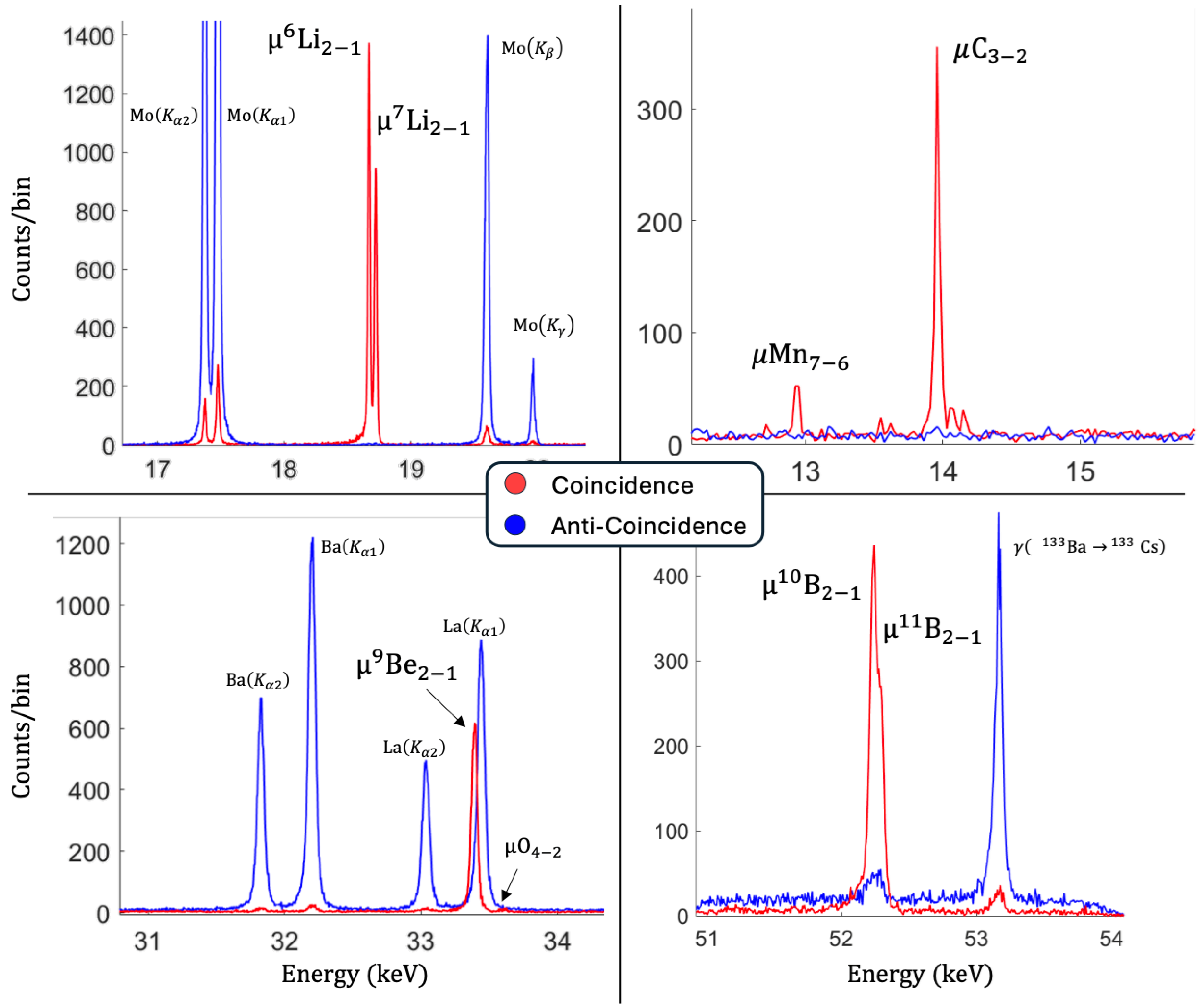


- ✓ X^2 cut to remove electron events
- ✓ Temperature correction for optimal resolution

Calibration and Pixel Co-adding

- ✓ Local calibration around line of interest, pixel-by-pixel
- ✓ Summed spectrum for physics analysis

QUARTET 2024 beamtime—first spectra



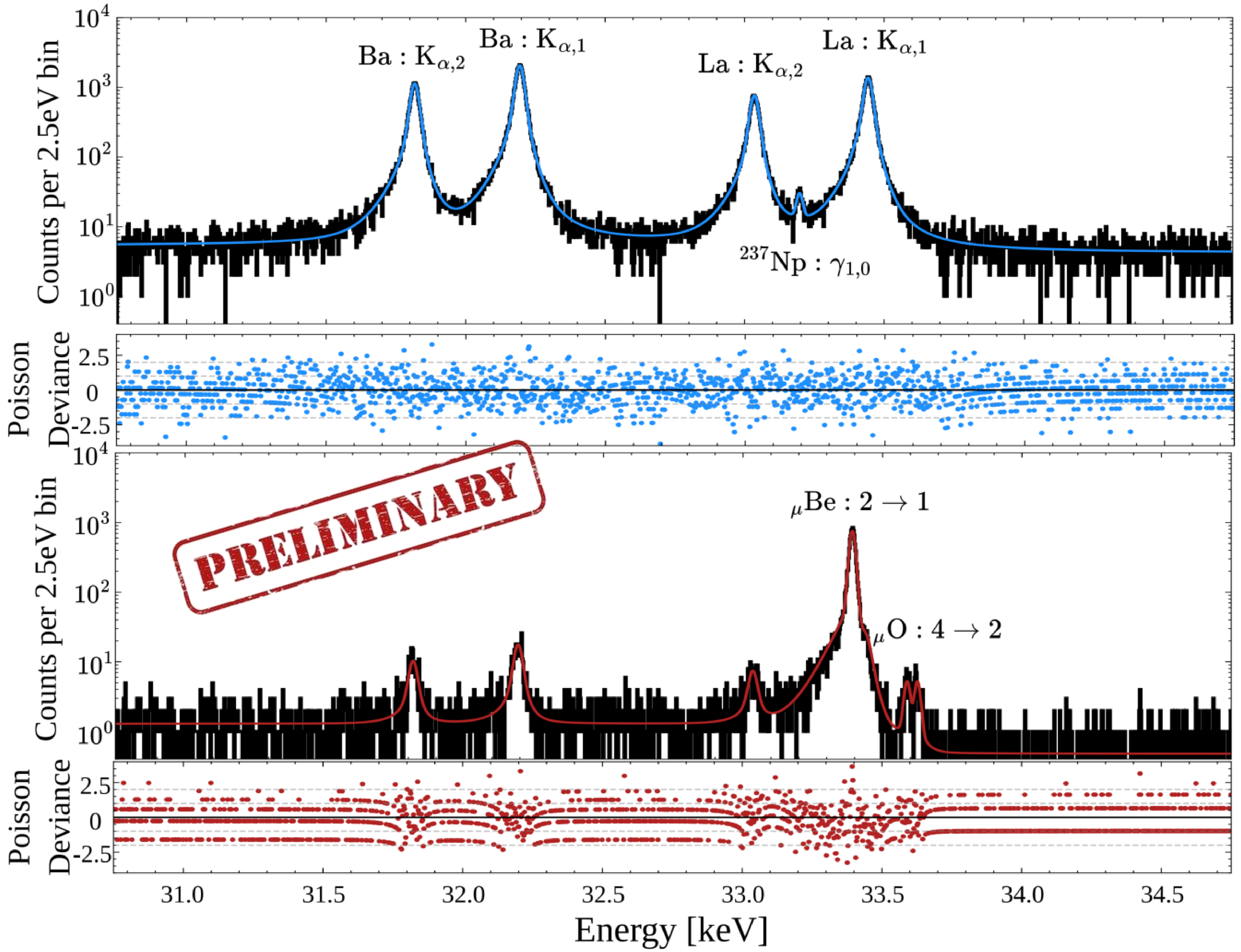
- ✓ High quality spectra for all main channels of interest
- ✓ Muon coincidence allows to separate muonic atom lines from calibration lines
- ✓ Main steps of spectral treatment and calibration have been accomplished for all channels.
- ✓ Statistics allow <1 eV centroid determination

QUARTET 2025 beamtime—Promising first spectra of muonic O

QUARTET 2025 beamtime—Promising first spectra of muonic $^{16,17,18}O$

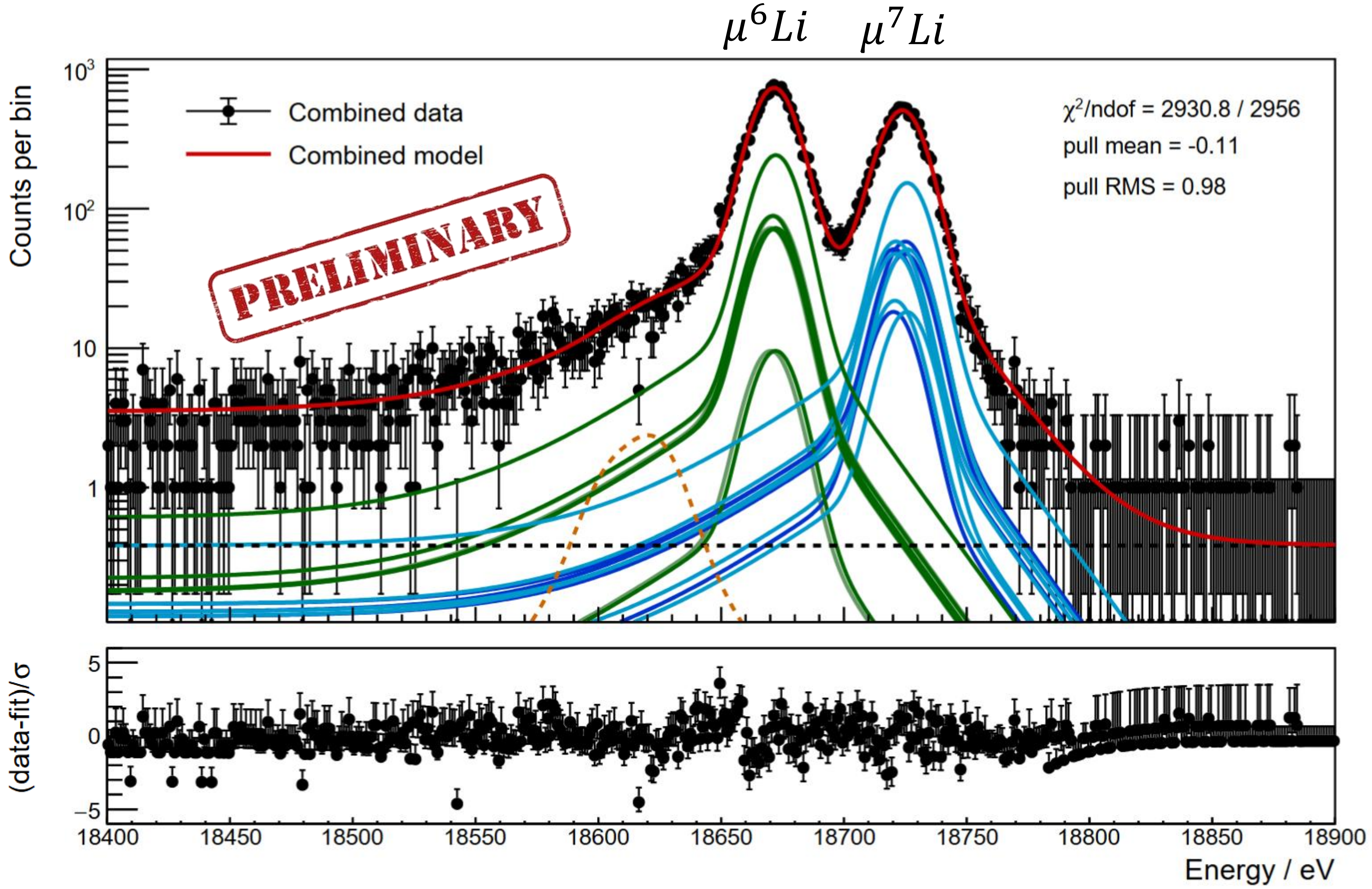
Preliminary results from 2024 beamtime:

O. Eizenberg et. al., *in preparation*



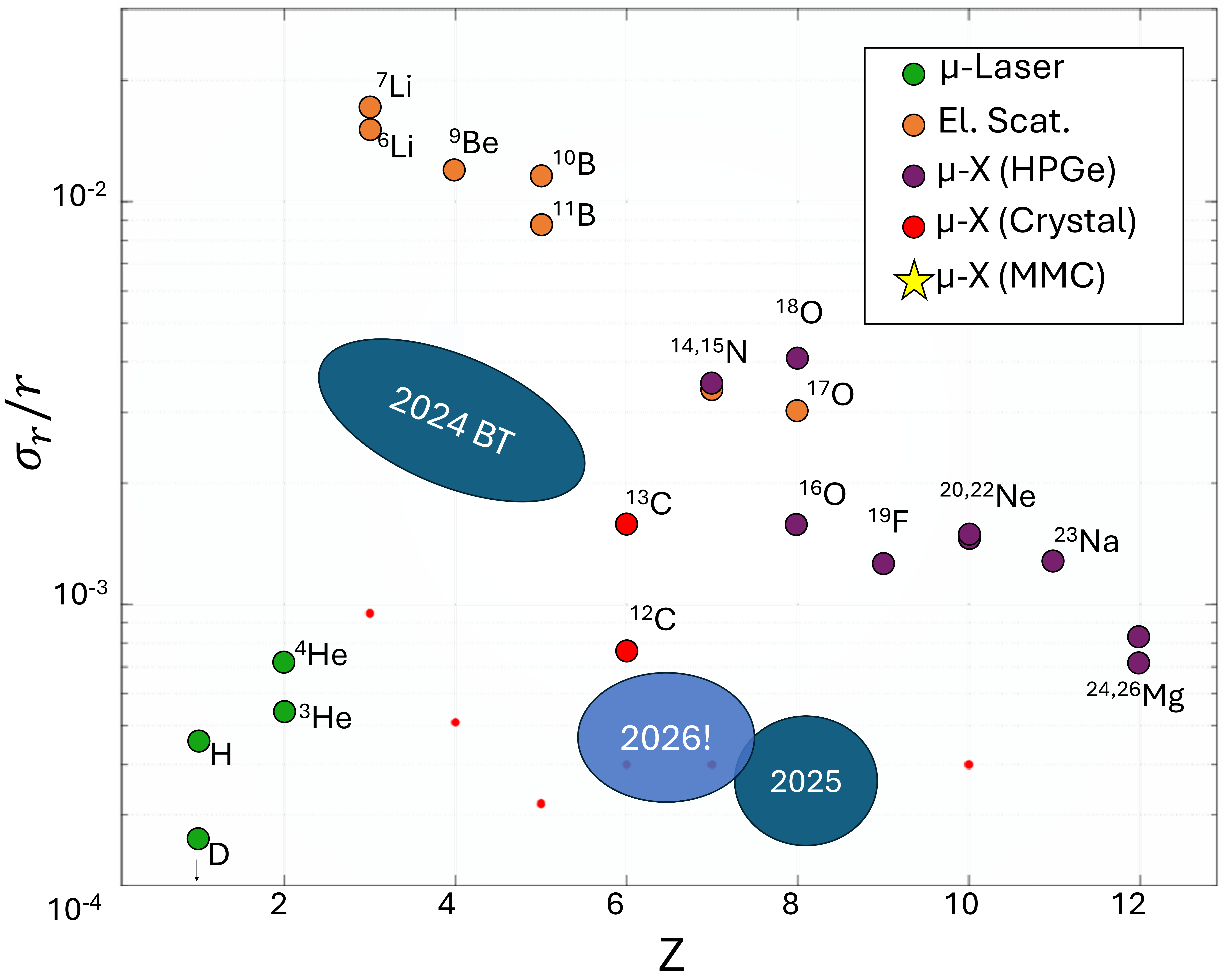
- Improve by factor of 30 upon best prior energy measurement
- Improve radius determination by a factor of 3-4

K. Von Schoeler et. al., *in preparation*



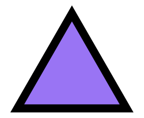
- Improve by factor of 300 upon best prior energy measurement
- Improve radius determination by a factor of 4-5

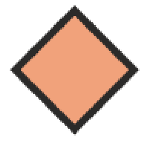
Outlook for 2026: ^{12,13}C & ^{14,15}N:

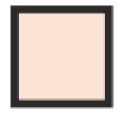


Panorama of absolute radii determinations:

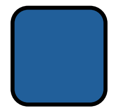
arXiv:2604.08985

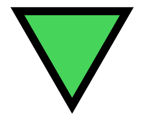
 **H/D spectroscopy** (Lothar Maisenbacher, Soroosh Alighanbari, Christian Regenfus)

 **Scattering** (Clement Legris, Haiyan Gao, Jan Friedrich, Patrick Achenbach, Thomas Krahulik, Arjun Kumar, Chandan Ghosh, Michael Paolone, Christian Weiss, Nikos Sparveris, Martha Constantinou, Udit Raha, Steffen Strauch, Peter Blunden, Igor Akushevich, Dipangkar Dutta)

 **Helium-like atoms** (Kristian König)

 **Muonic Atoms** (BO)

 **Bound el. G-factors** (Fabian Heisse)

 **Highly charged ions** (Hunter Staiger)

Working group on nuclear charge radii

Whitepaper available: **arXiv:2604.08985**

Welcoming your feedback! bohayon@technion.ac.il

2025 Meeting of at IAEA headquarters

ECT*
EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS
FONDAZIONE BRUNO KESSLER

WORKSHOP

FROM NUCLEAR STRUCTURE TO NEW PHYSICS

3 - 7 August 2026

ECT* - Villa Tambosi, Villazzano

ORGANIZERS

Mikhail **Gorshteyn** - JGU Mainz
Ayala **Glick-Magid** - University of Tel Aviv
Ben **Ohayon** - Technion IIT
Chien-Yeah **Seng** - University of Tennessee

MAIN TOPICS

- Beta decays and CKM unitarity
- Nuclear radii, structure and reactions
- Muonic and ordinary atoms
- Precision measurements
- Global electroweak fit
- SMEFT

ECT* Director: Prof. Ubirajara van Kolck

The ECT* is part of the Fondazione Bruno Kessler. The Centre is funded by the Autonomous Province of Trento, funding agencies of EU Member and Associated states, and by INFN-TIFPA and has the support of the Department of Physics of the University of Trento.

For the organization please contact: Anna Pancheri – ECT* Secretariat - Villa Tambosi
Strada delle Tabarelle 286 | 38123 Villazzano (Trento) – Italy | Tel.:(+39-0461) 314722
E-mail: apancheri@ectstar.eu or visit http://www.ectstar.eu

SUPPORTING INSTITUTIONS

EURO-LABS EUROPEAN LABORATORIES FOR ACCELERATOR BASED SCIENCES
INFN Istituto Nazionale di Fisica Nucleare
FRIB Theory Alliance

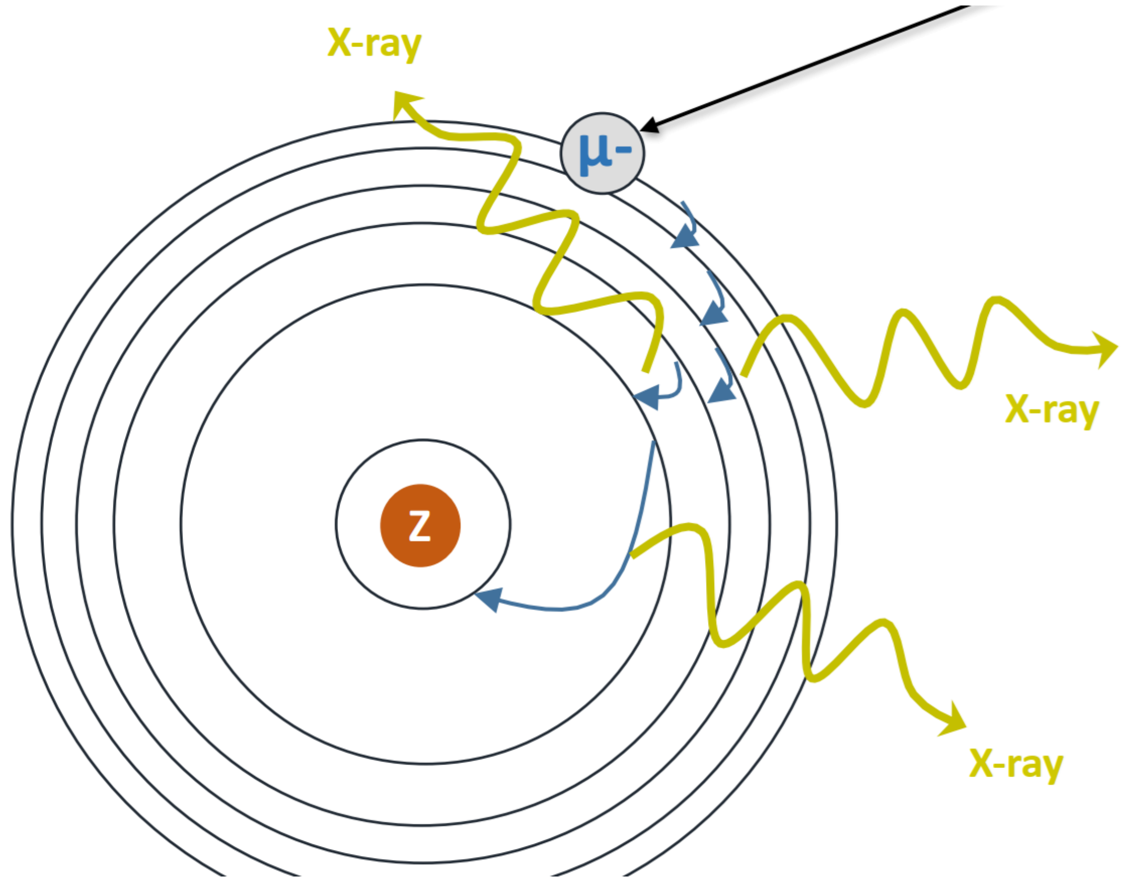
Thanks for listening!

Ecosystem of charge radii determinations

Radius of unstable nucleus $r_x^2 = r_{ref}^2 + \delta r_{a,x}^2$

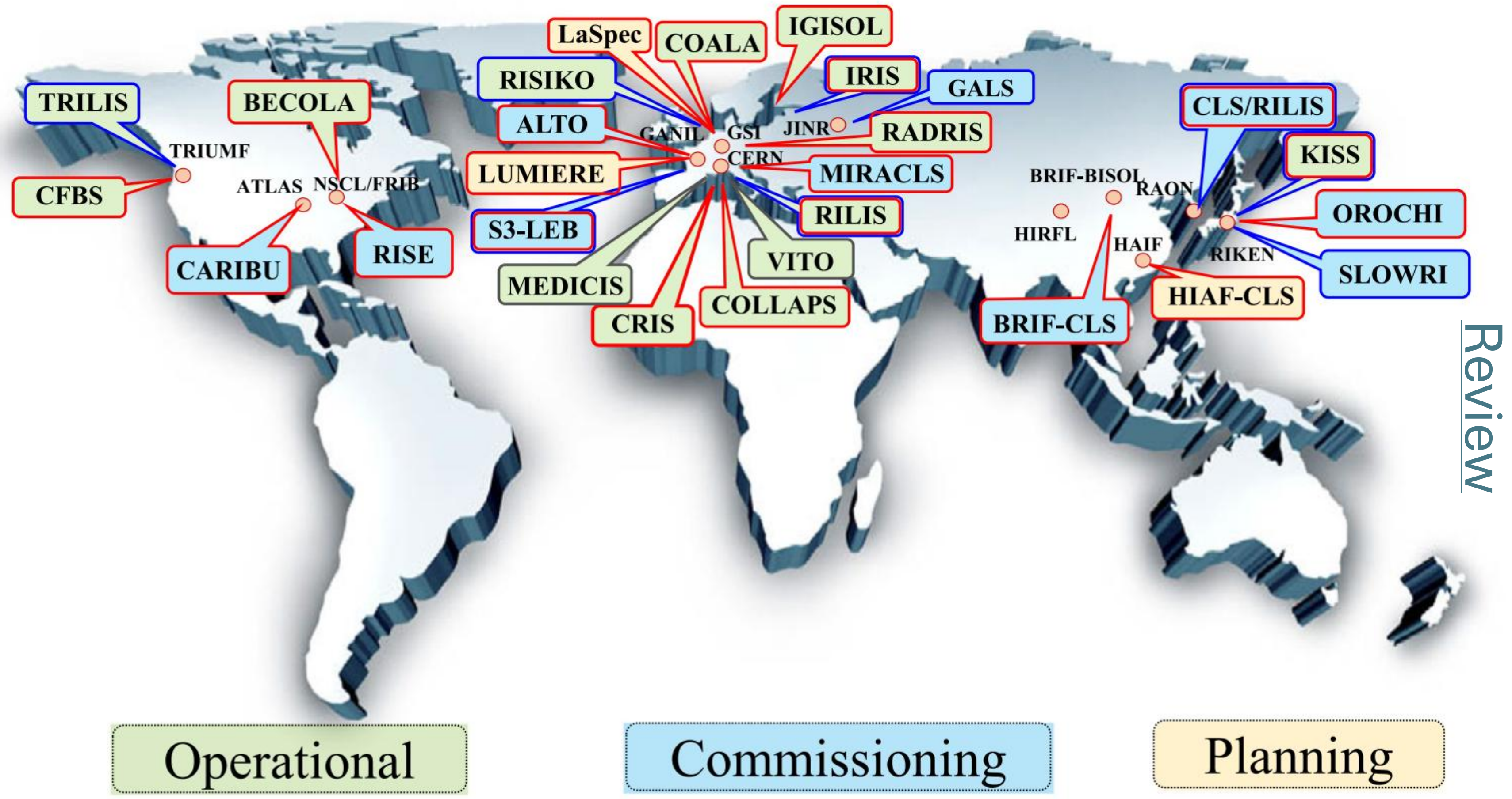
	Reference radius (mostly) from **Muonic atoms** (Review)	Differential radii (mostly) from radioactive **electronic atoms**
Experiments with exotic atoms	Muonic-atom spectroscopy (Recent Updates)	Collinear laser spectroscopy (Review)
Theory calculations	Nuclear: / Non-perturbative QED	Atomic many body calculations (Review)

Muonic-atom spectroscopy



Recent Updates

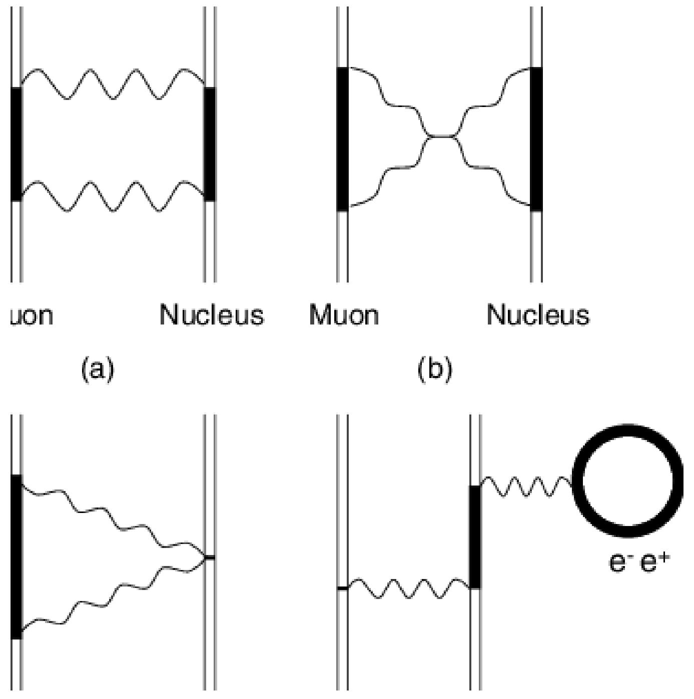
Collinear laser spectroscopy



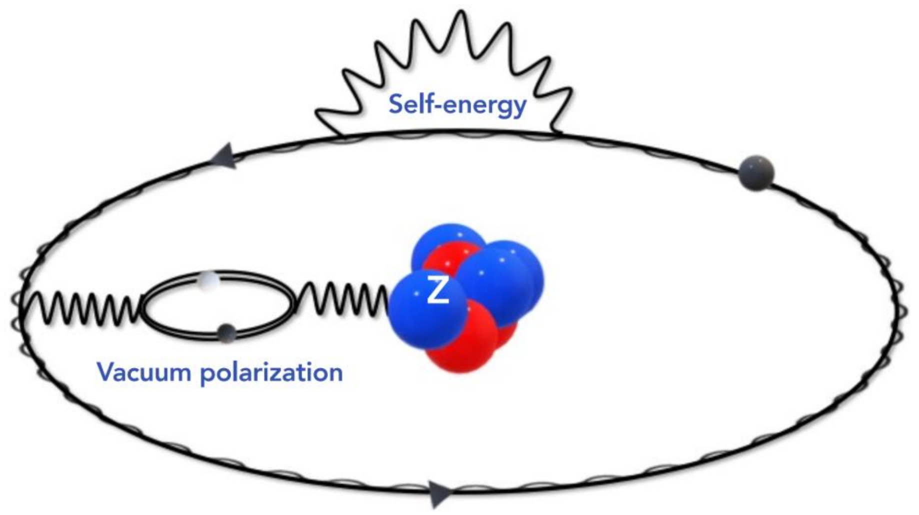
Review

Theory calculations

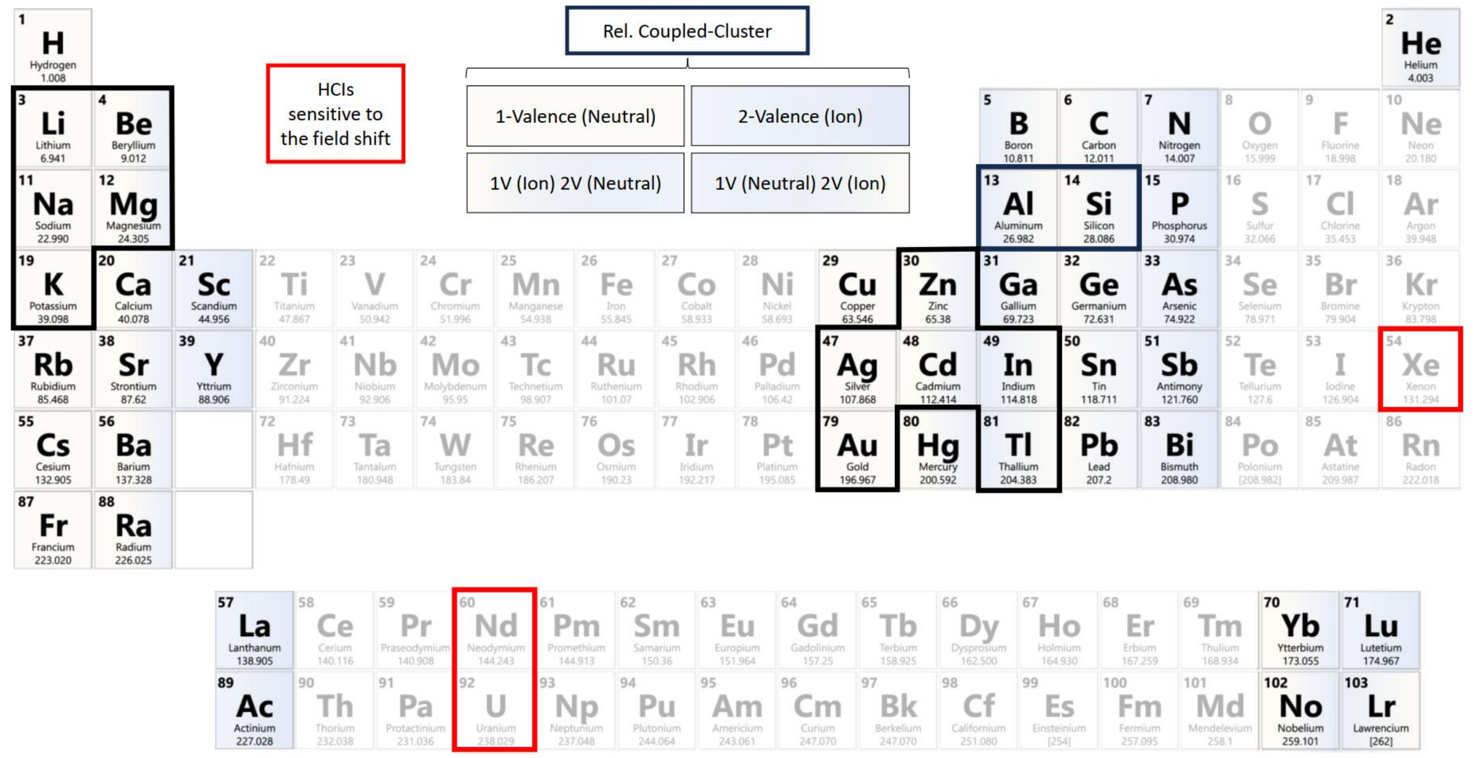
Nuclear:



Non-perturbative QED

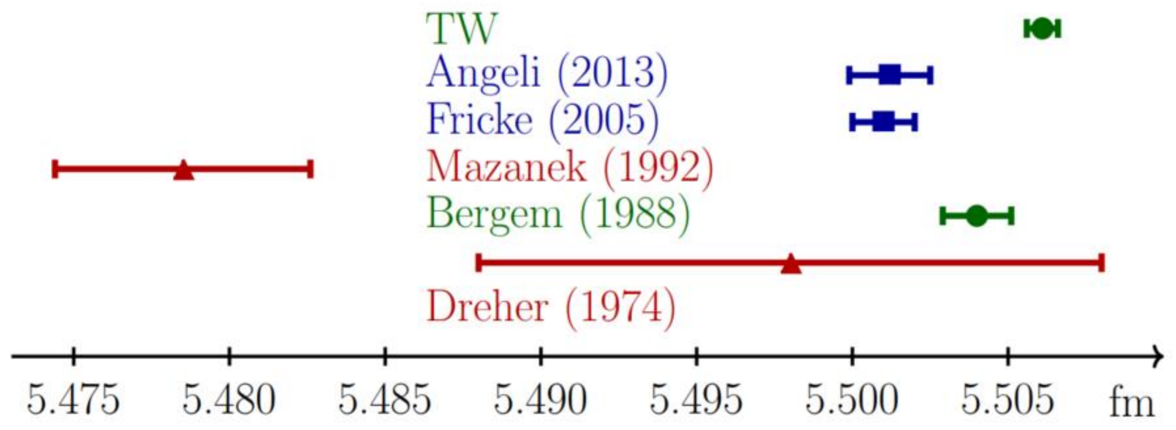


Atomic many body calculations

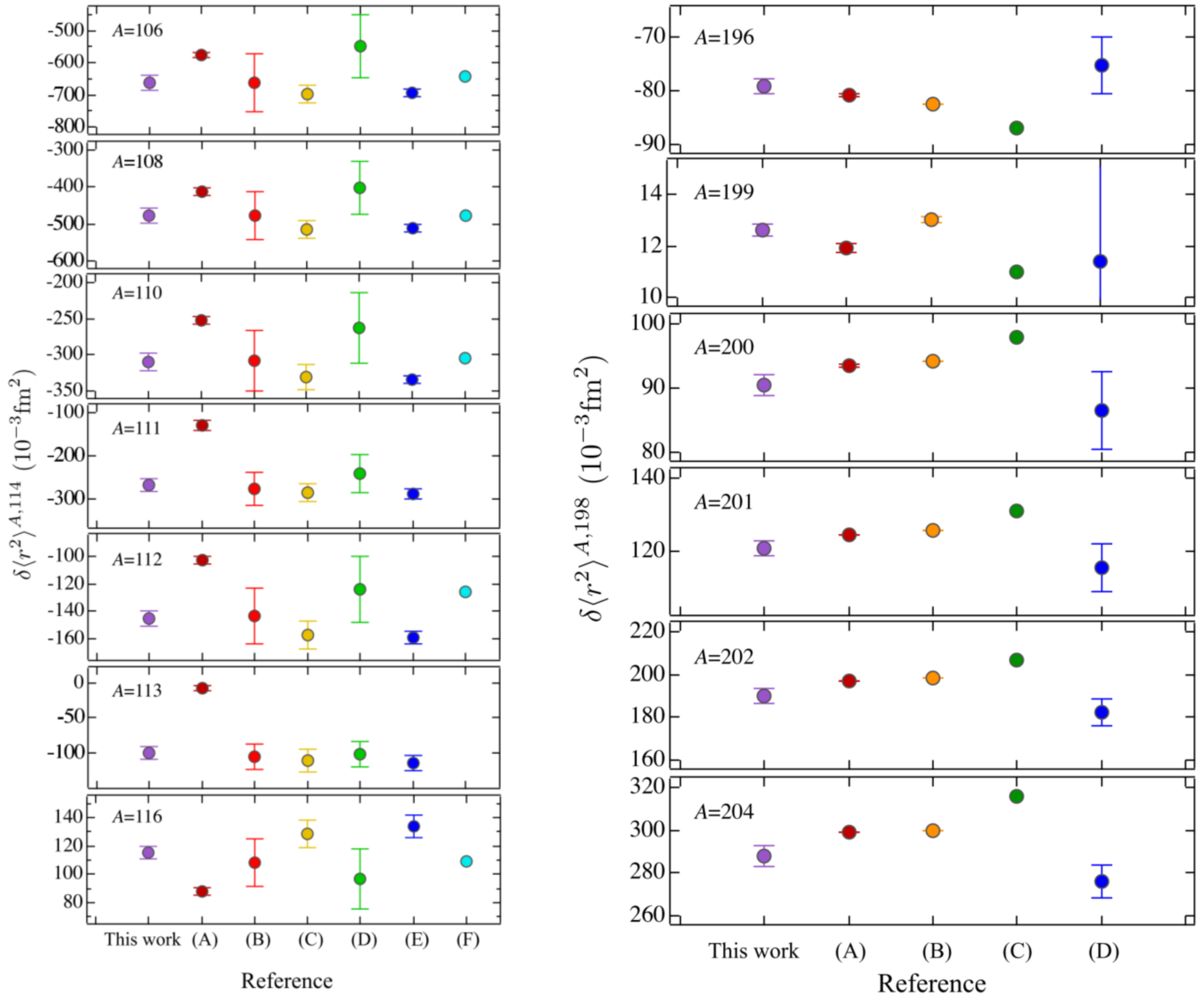


Review

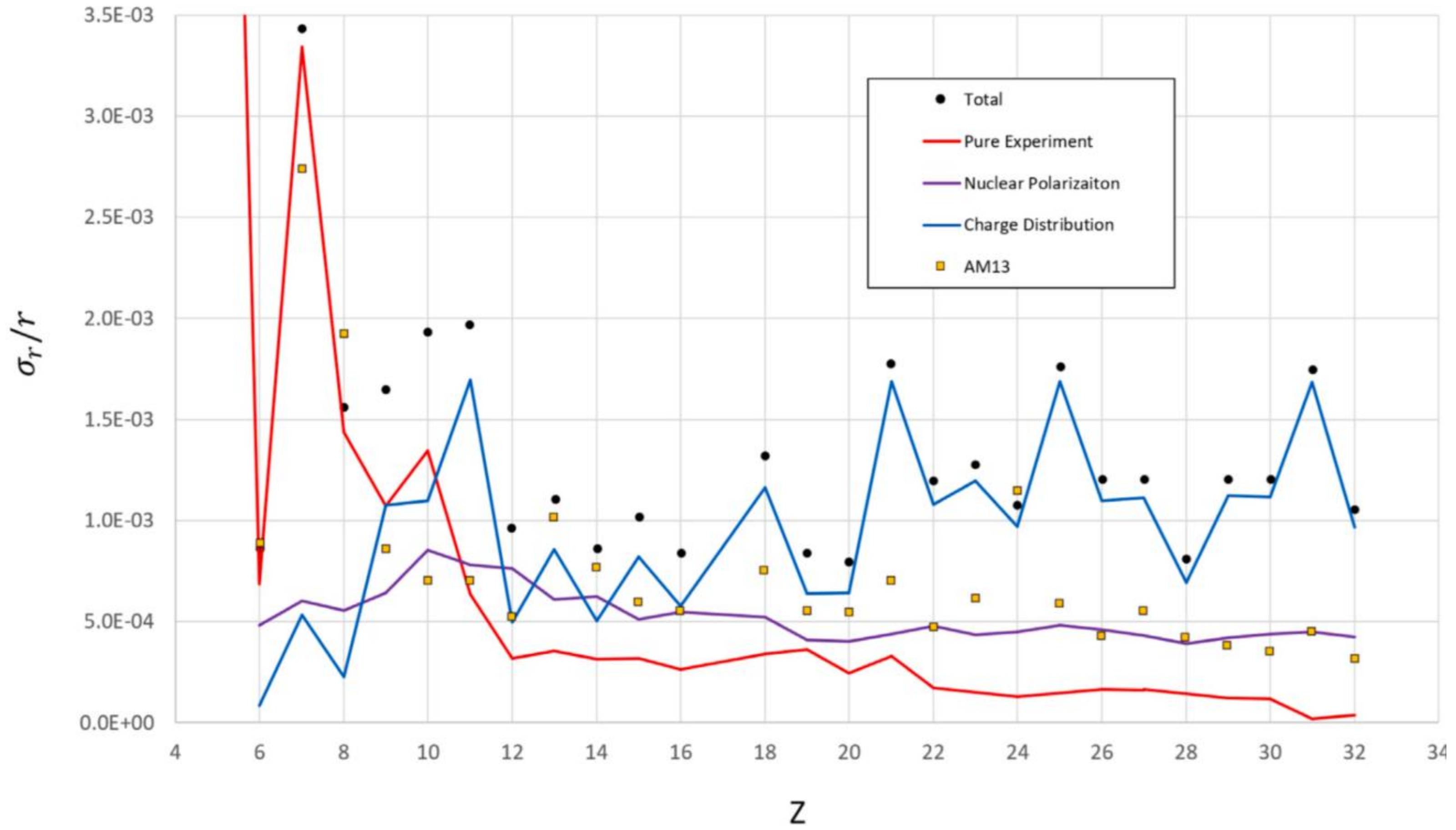
Illustrating the need for a new compilation



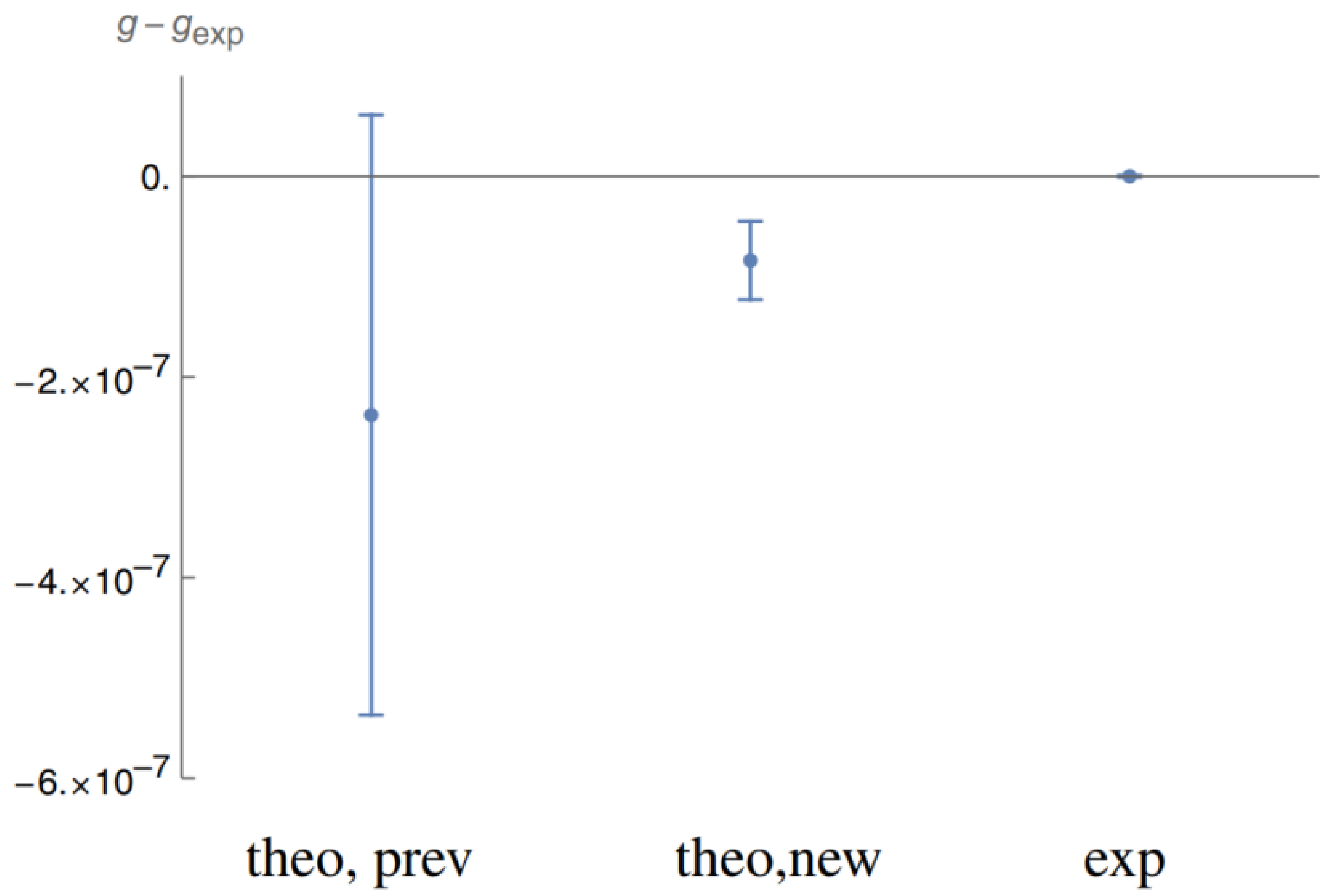
arXiv:2504.19977



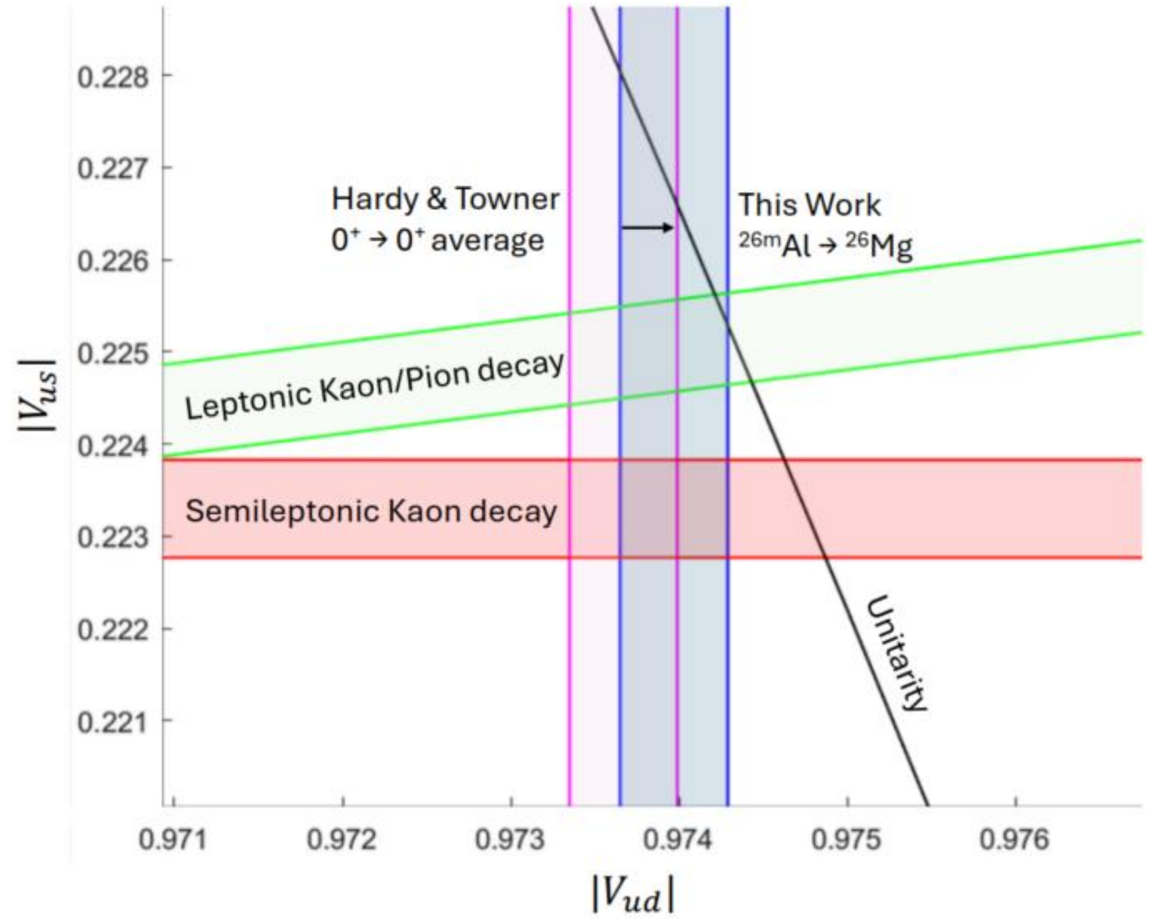
https://doi.org/10.1103/PhysRevA.105.022805



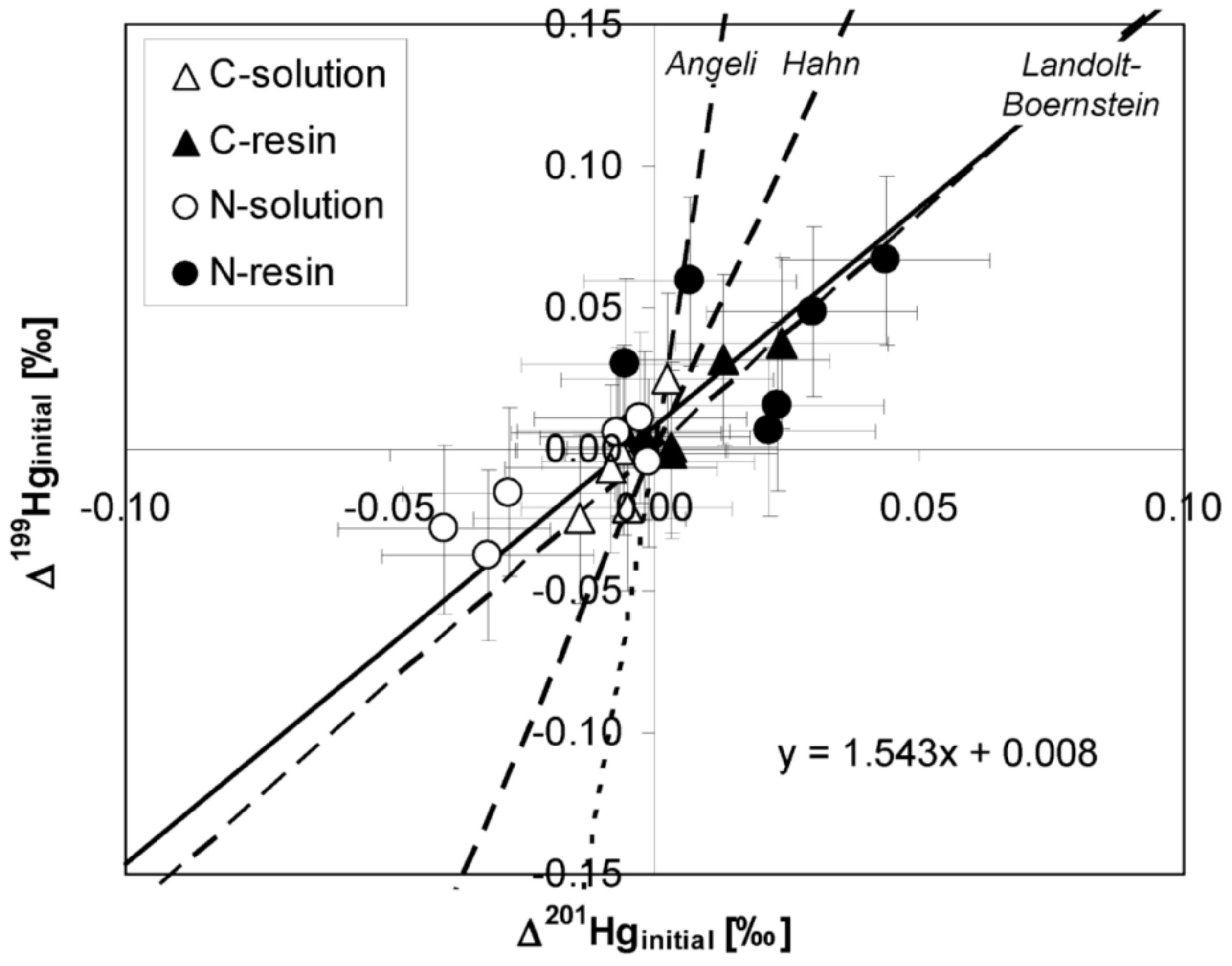
https://doi.org/10.1016/j.adt.2025.101732



https://doi.org/10.1103/PhysRevLett.134.123001



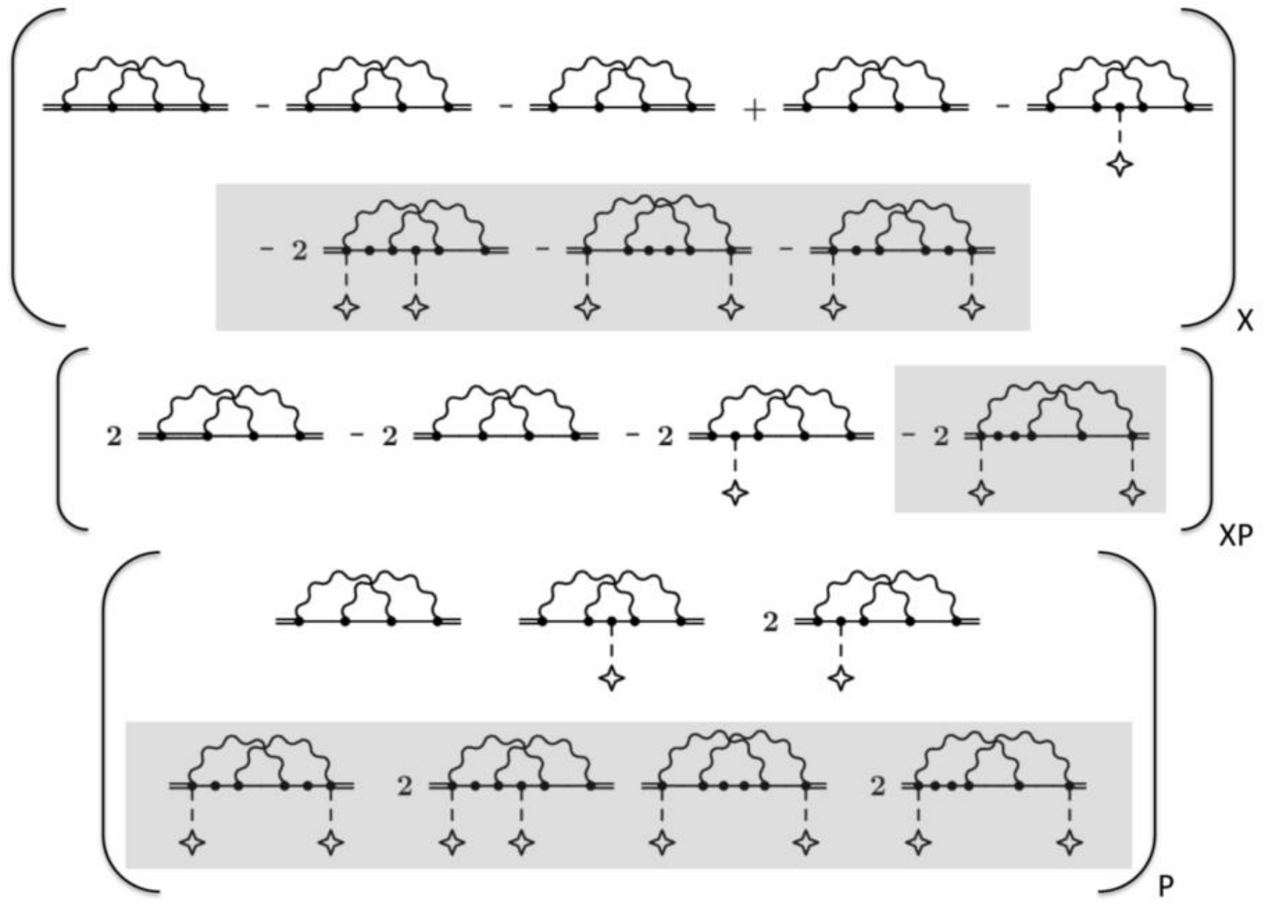
https://doi.org/10.48550/arXiv.2502.17070



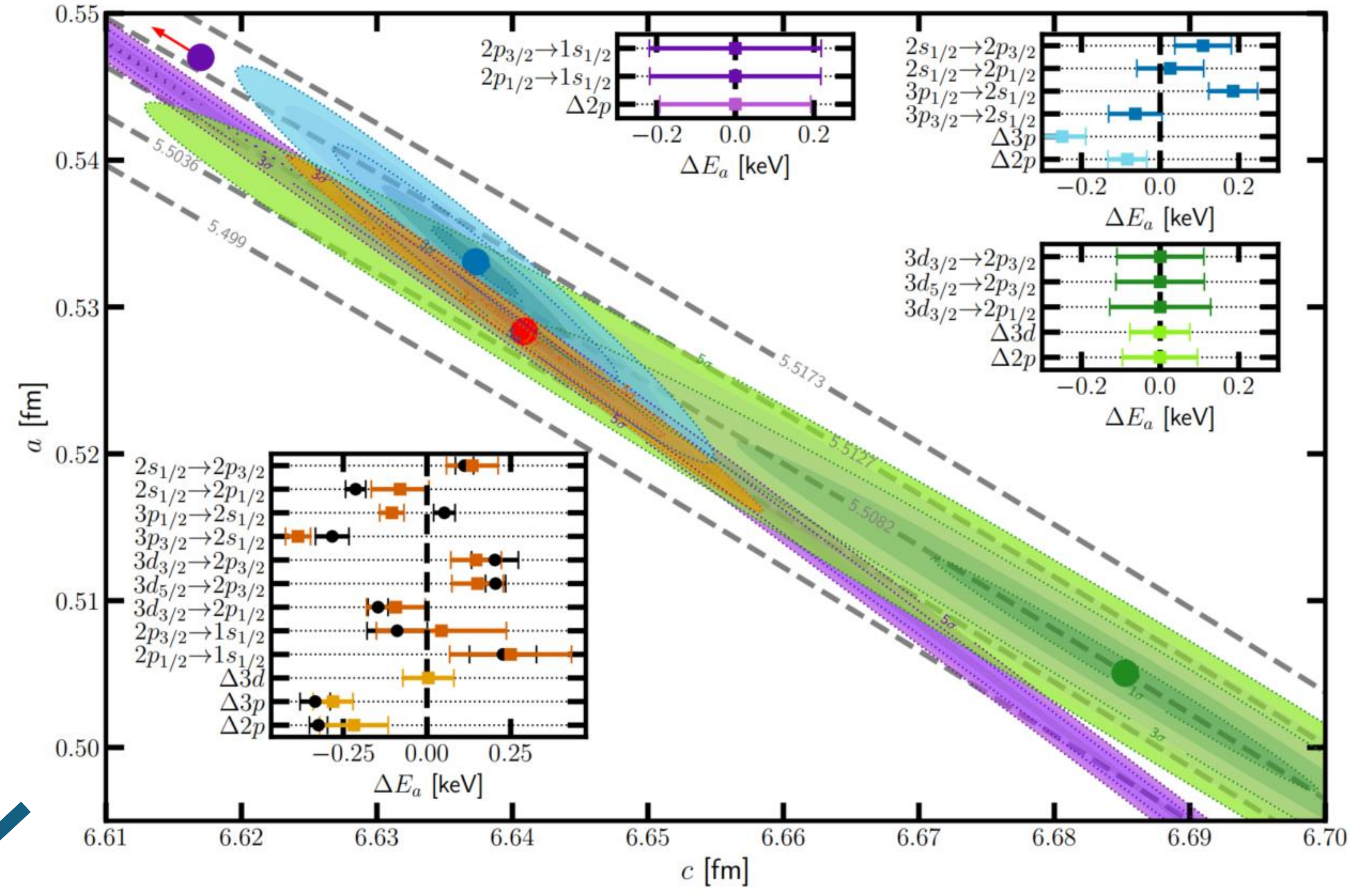
https://pubs.acs.org/doi/10.1021/es100205t

RADIANT – Radii Analysis and Data for Interactive Nuclear Table

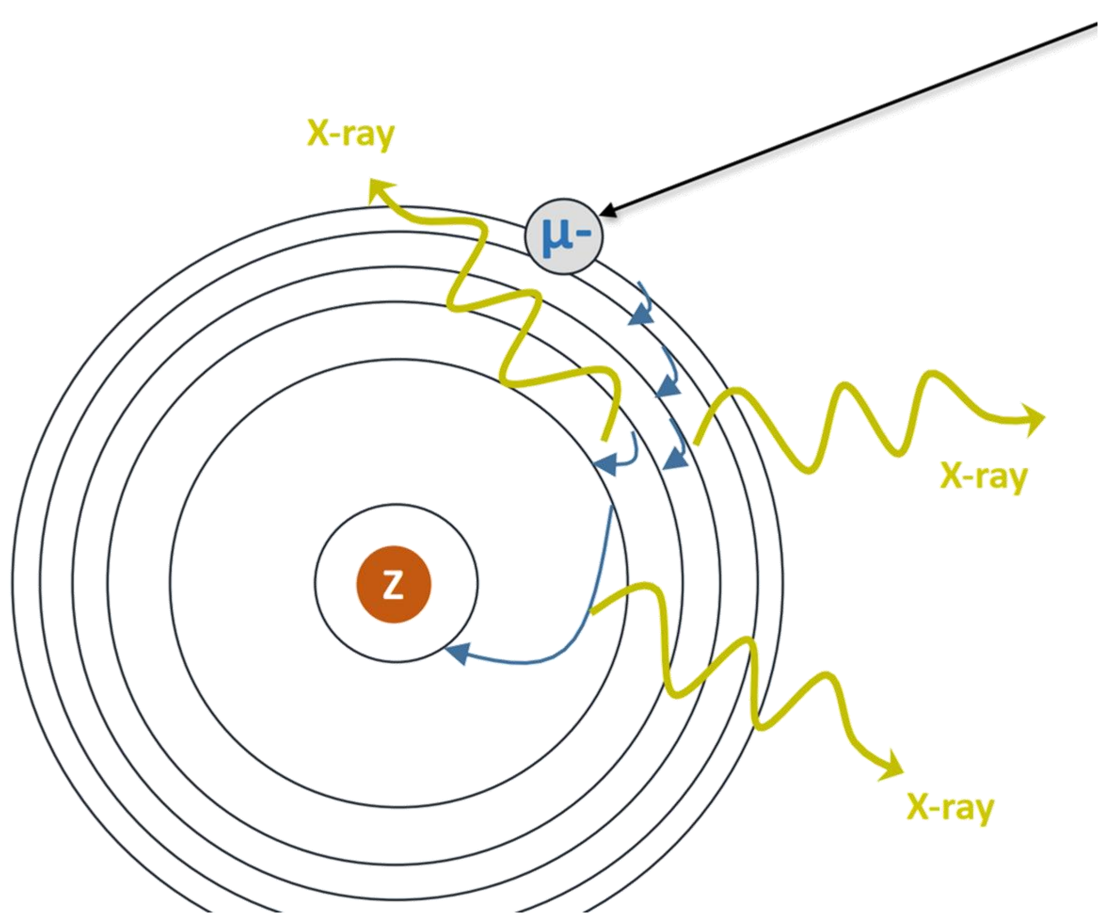
Theory



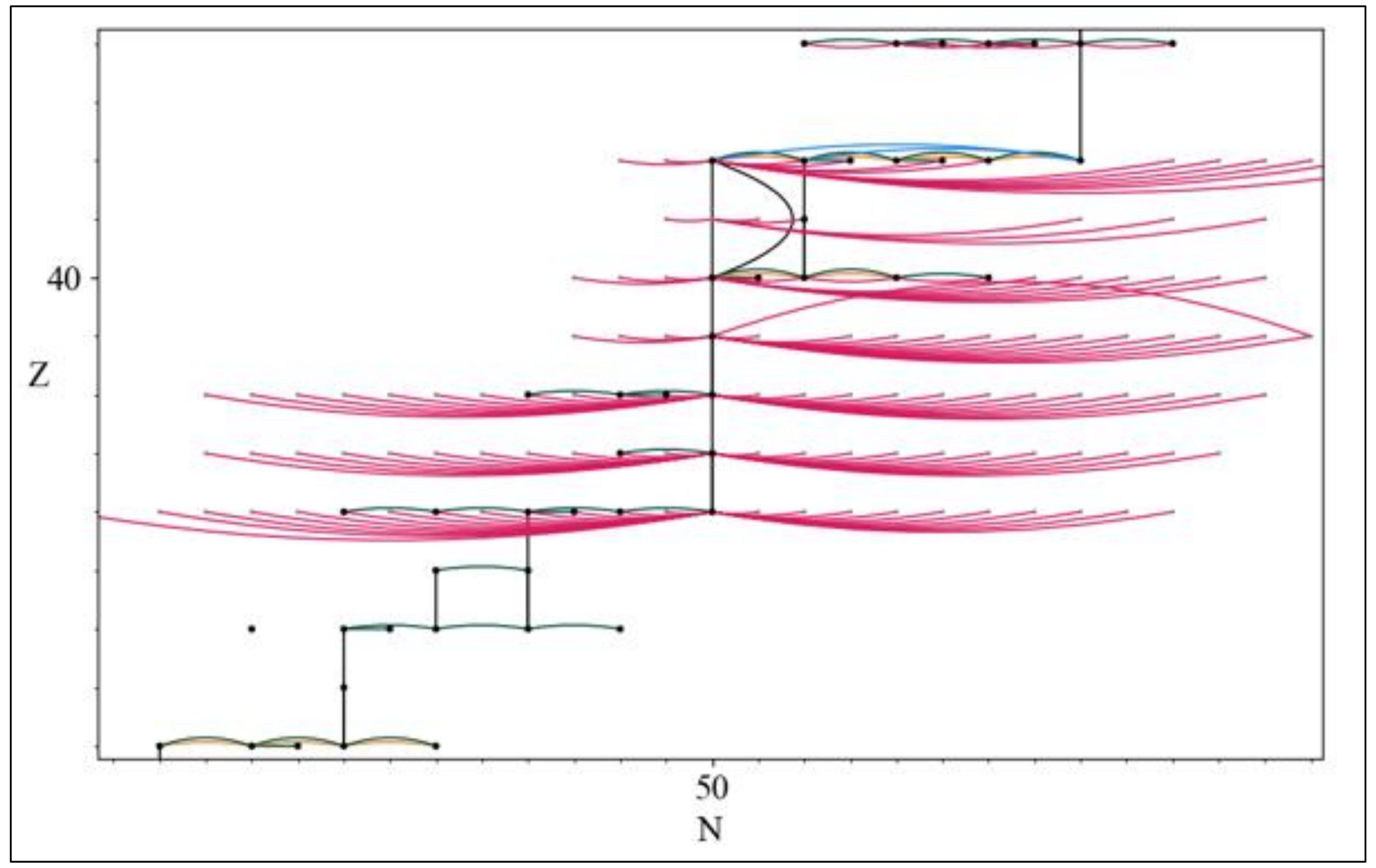
Combined analysis



Experiments

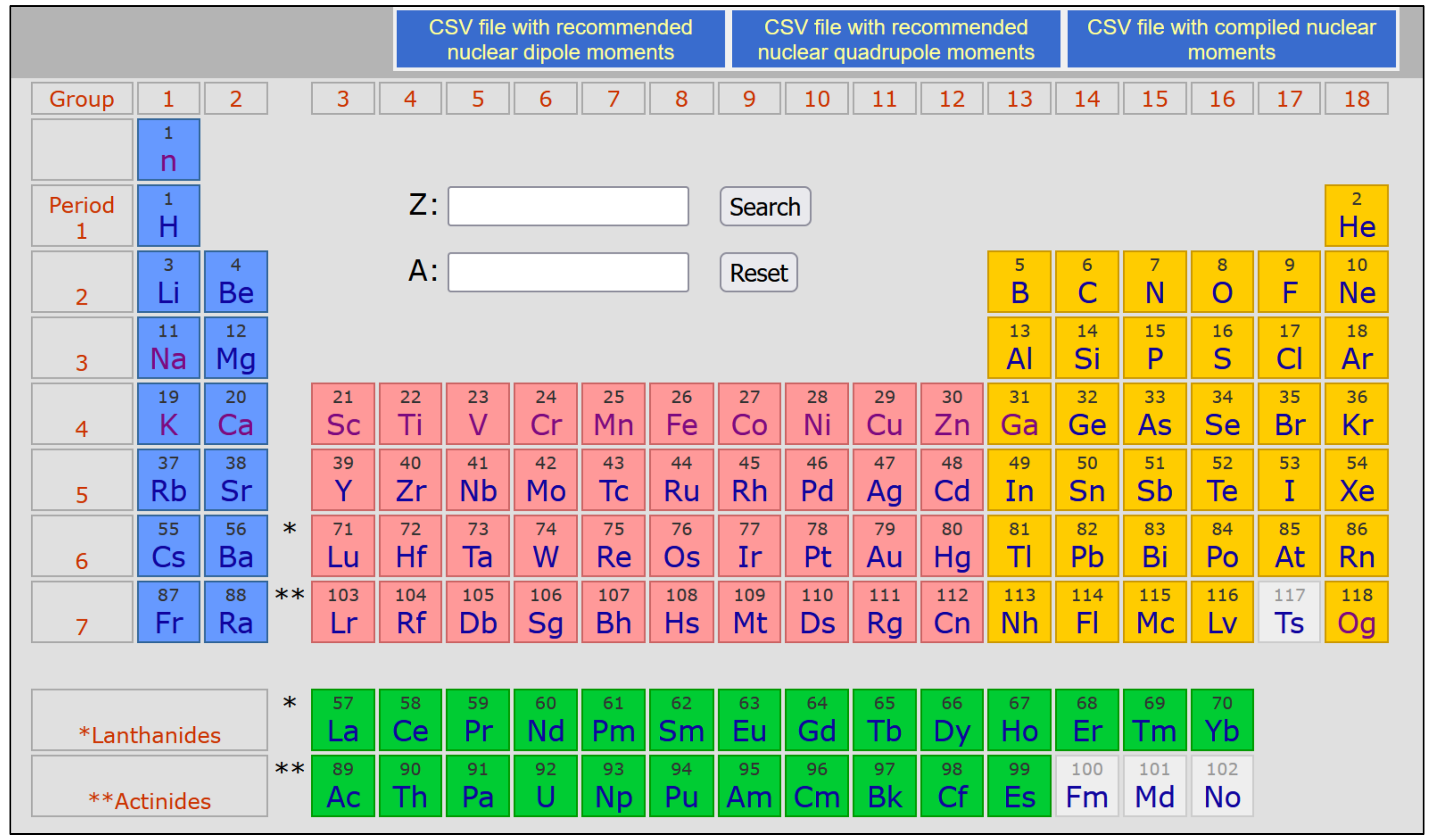


Combining data



Clemson

Curation & Dissemination



IAEA