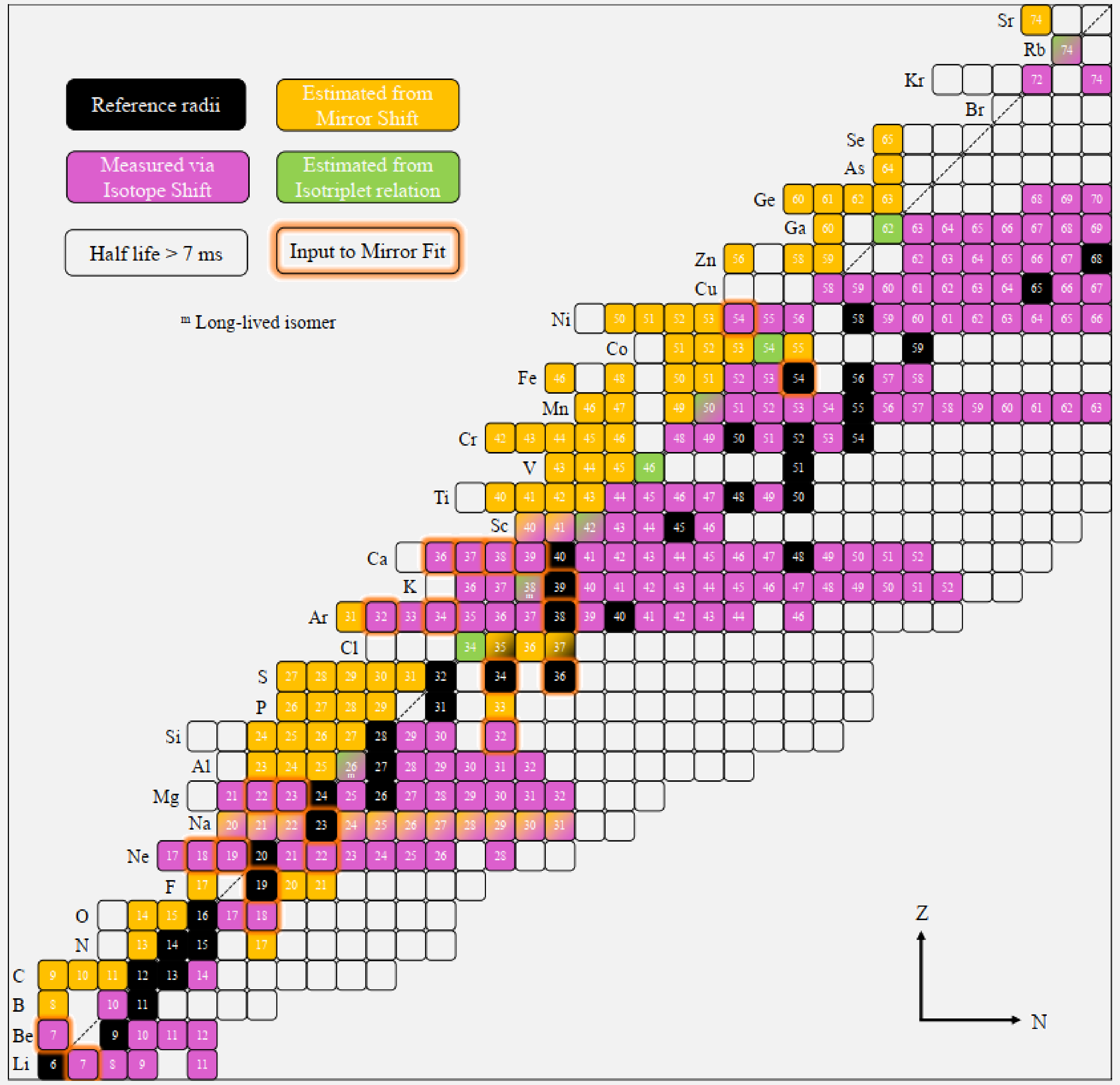
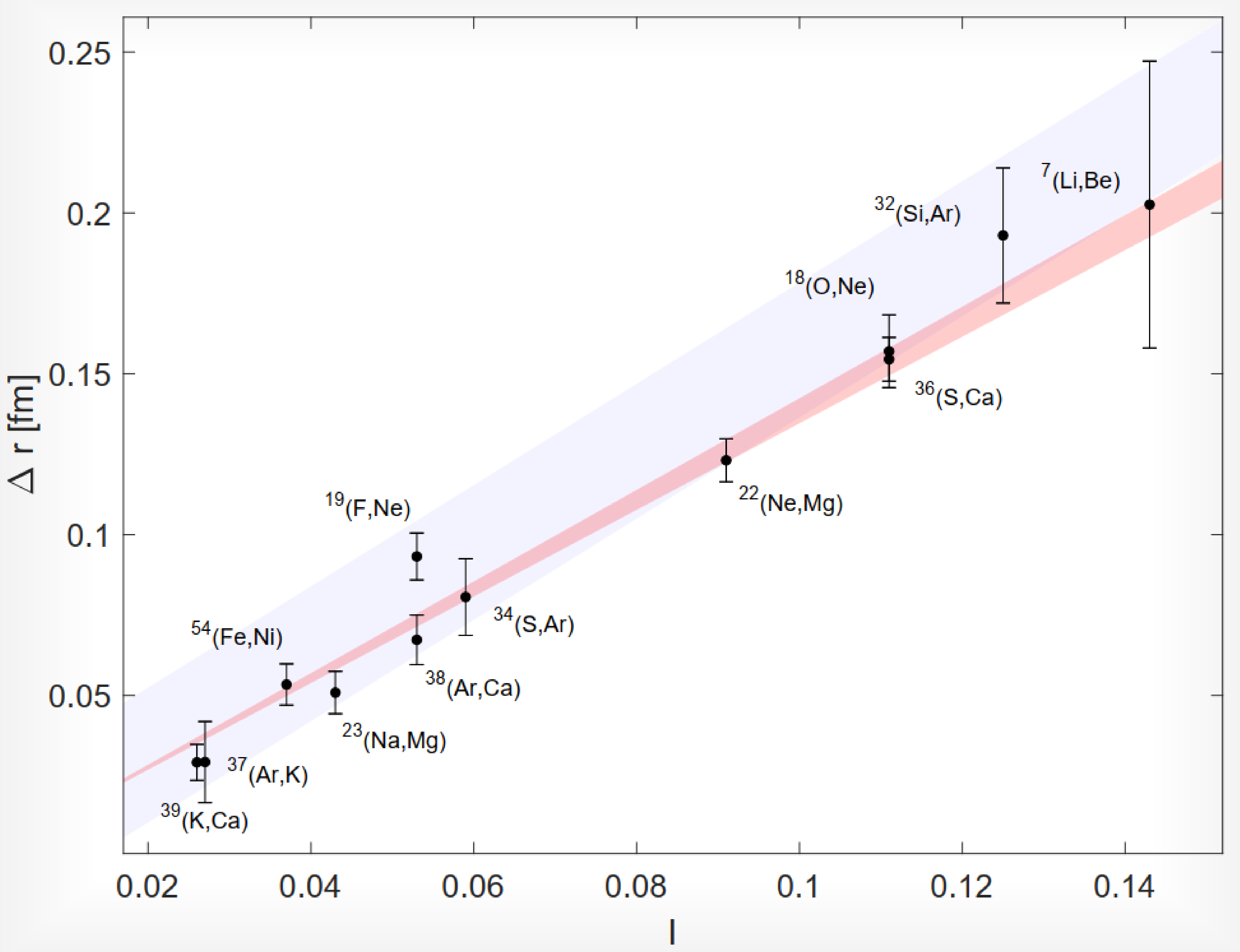
Radii of Light Mirror Nuclei

arXiv:2409.08193

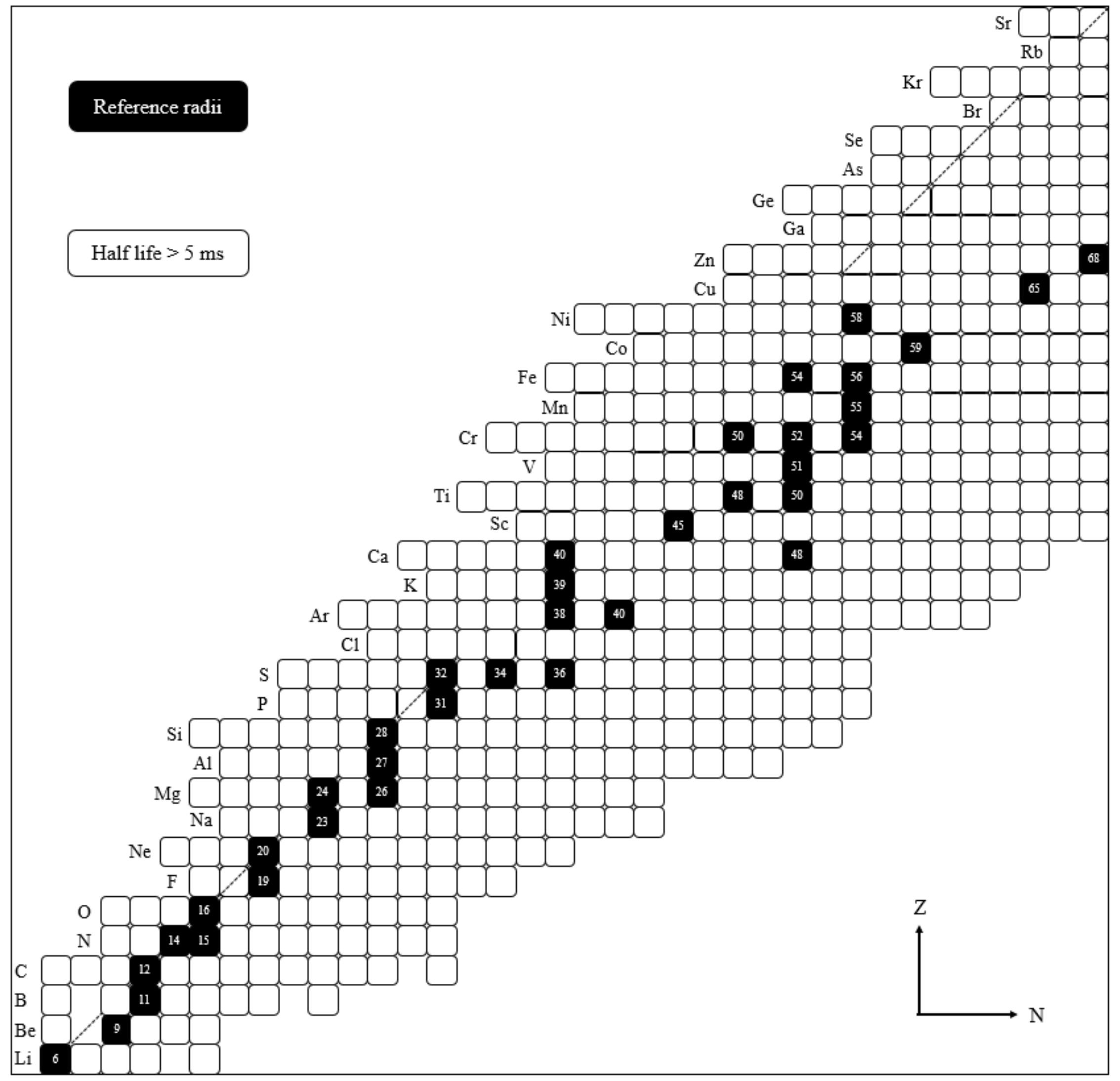




Ben Ohayon | Technion IIT | boahyon@technion.ac.il | KAMPAI Oct. 2024

Roadmap:

1. **Reference radii** (muonic atoms)



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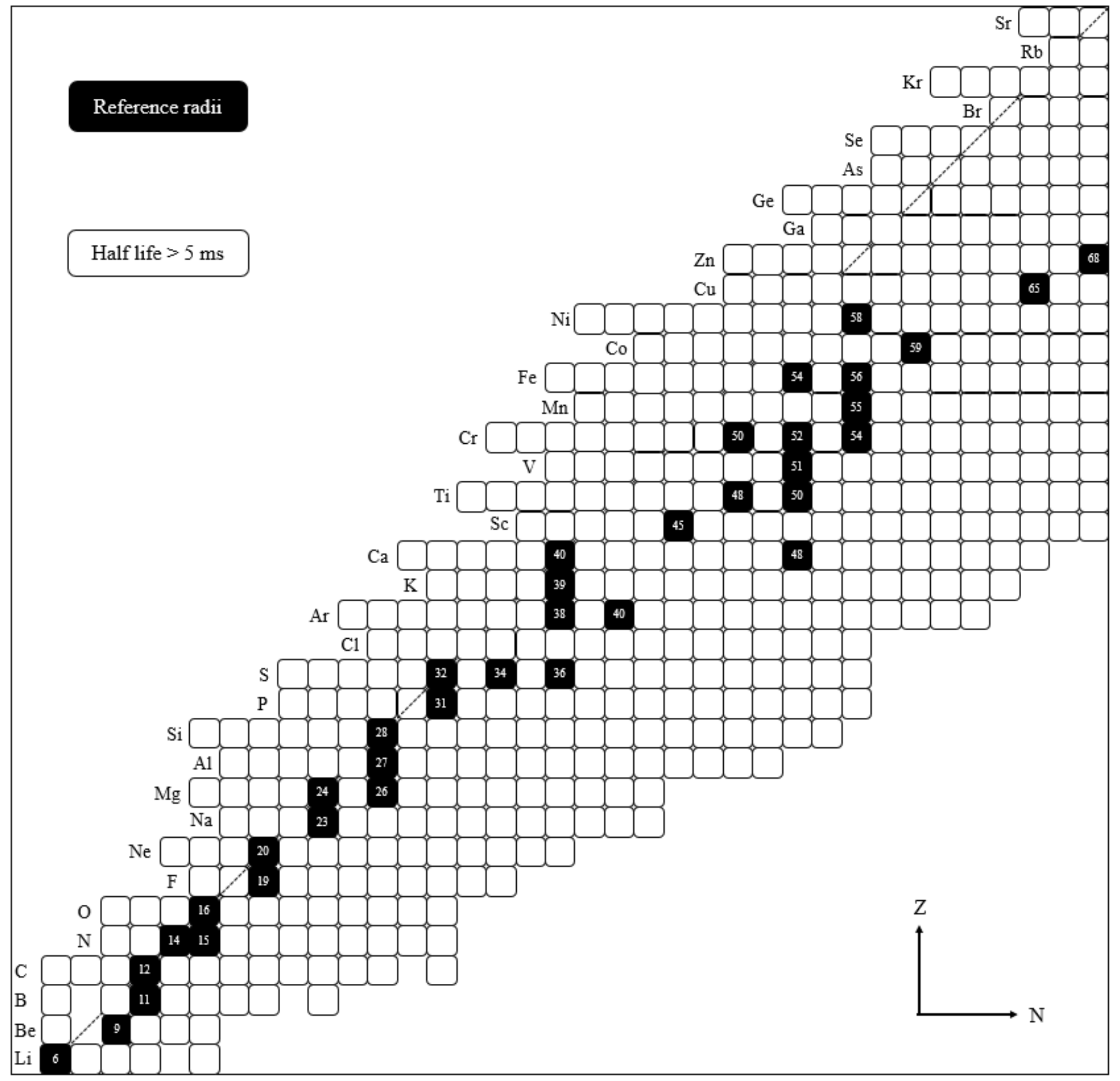
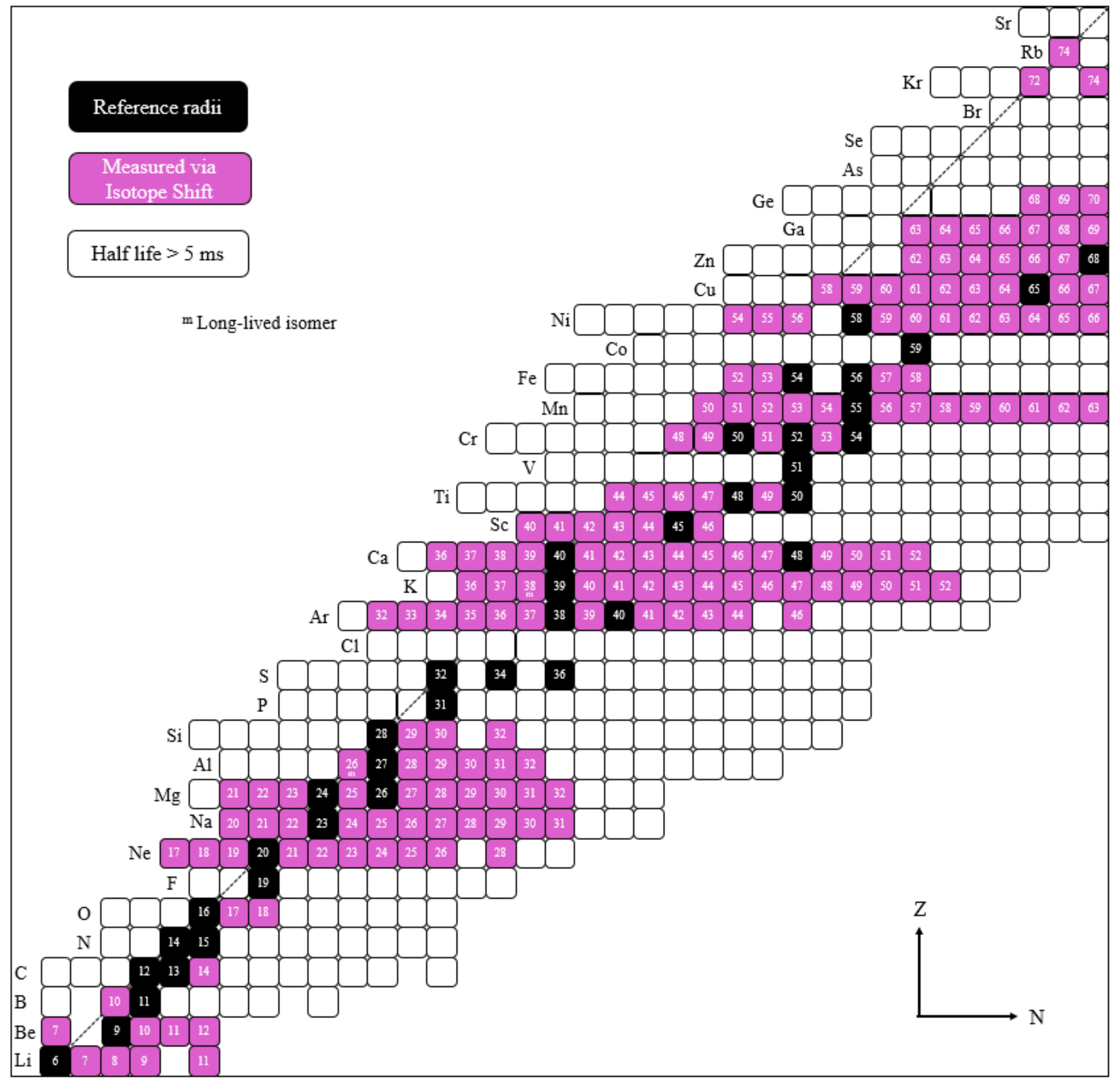


2. **Isotope shifts** (electronic atoms)



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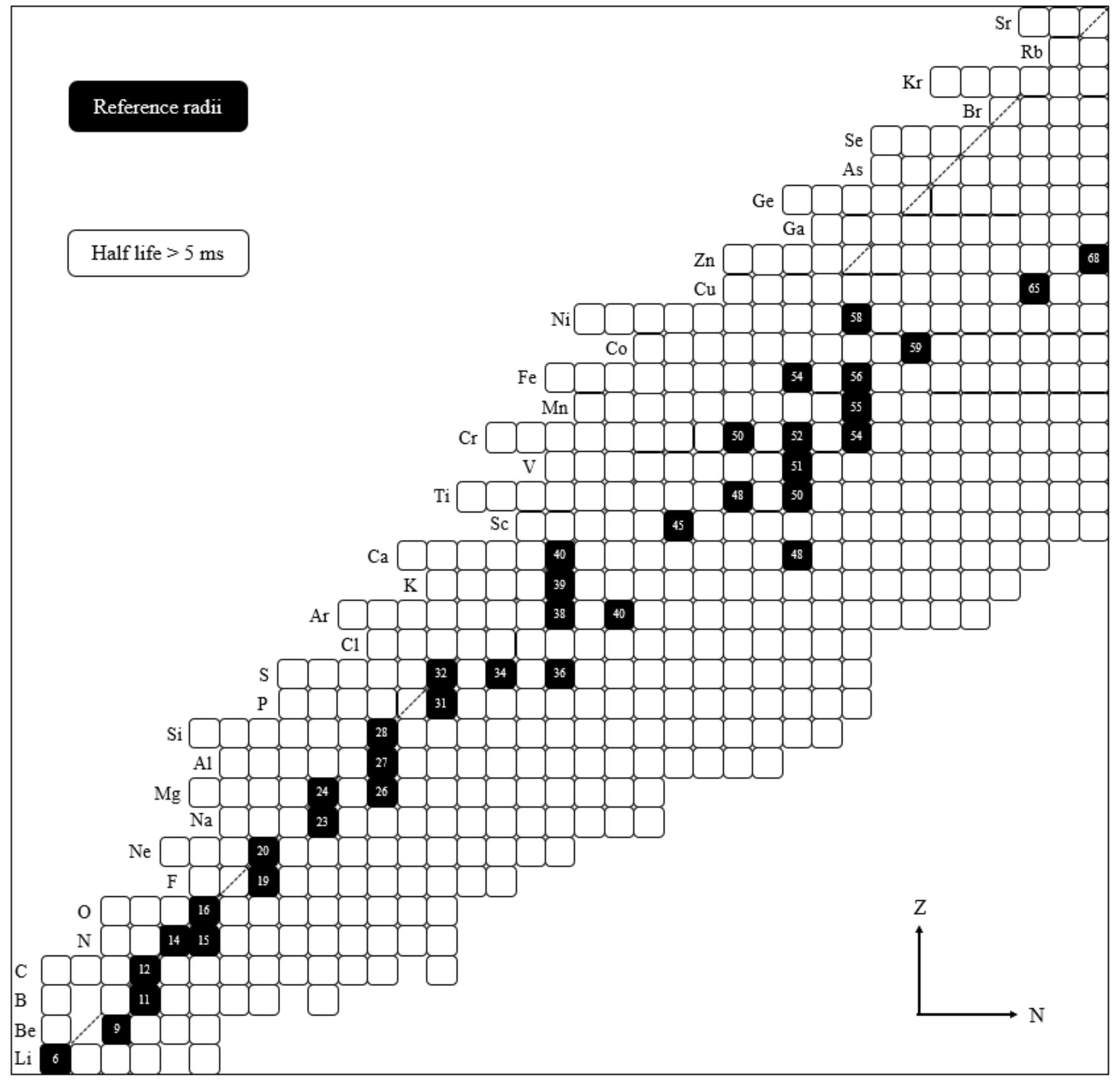

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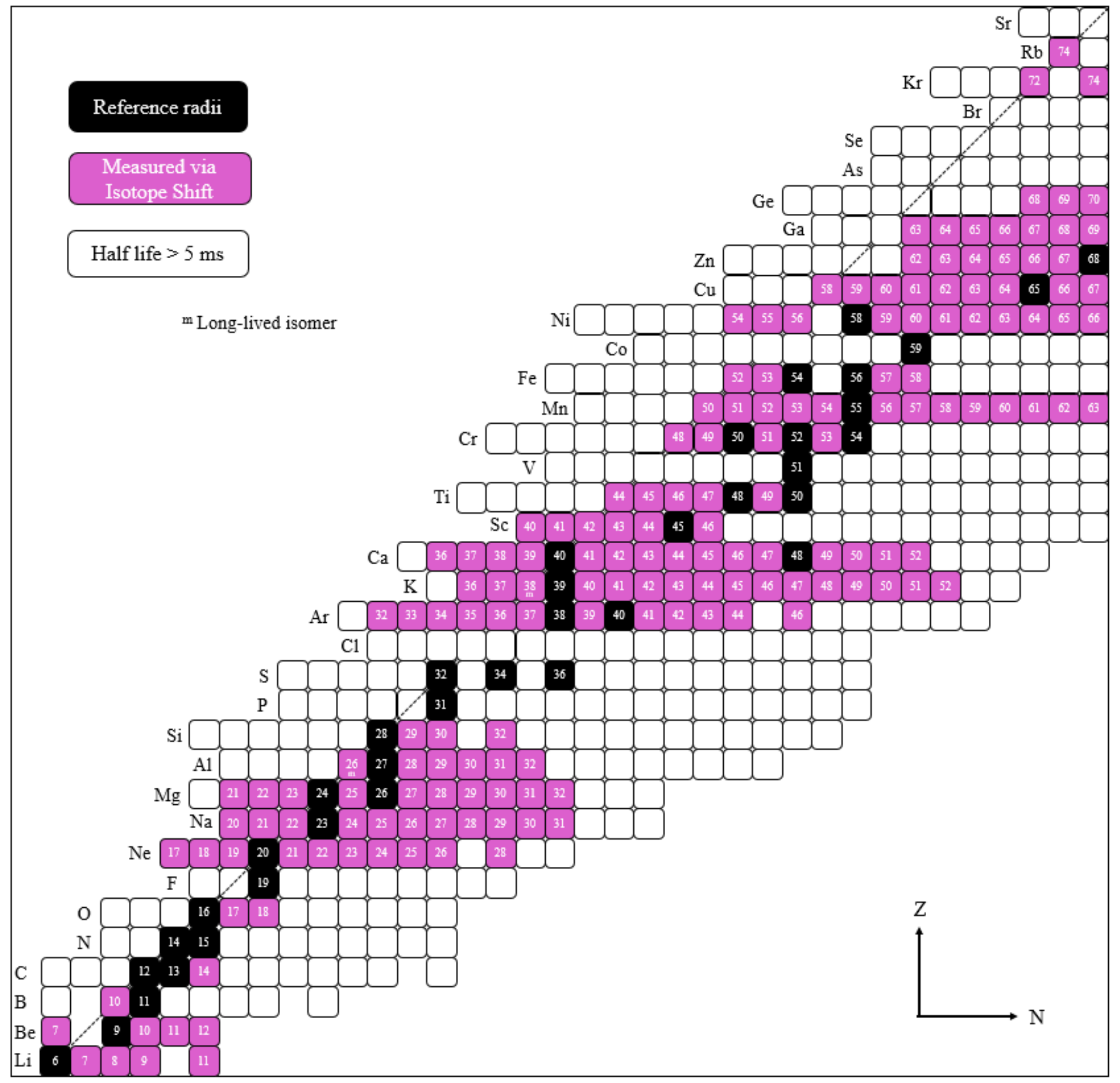

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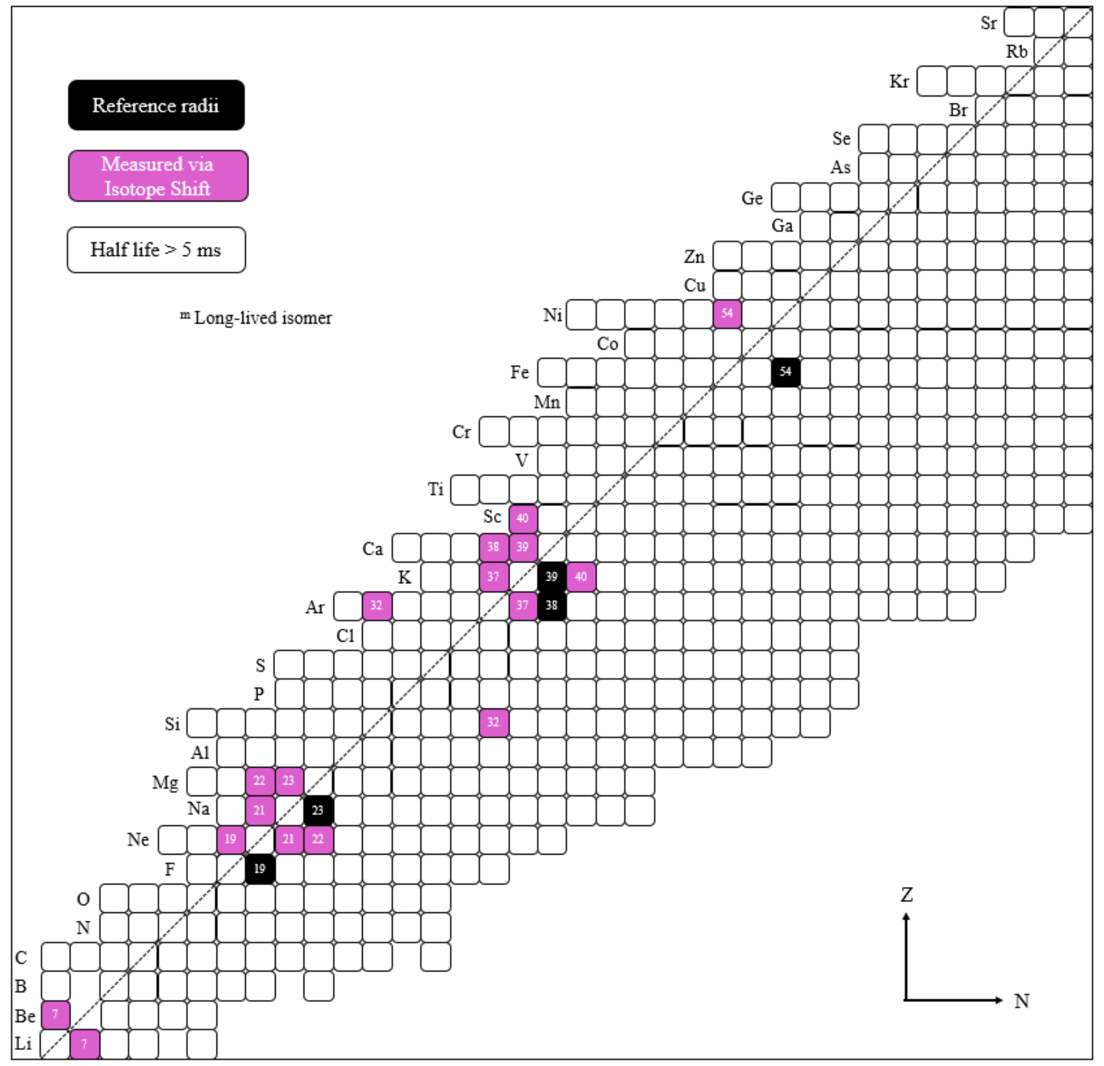

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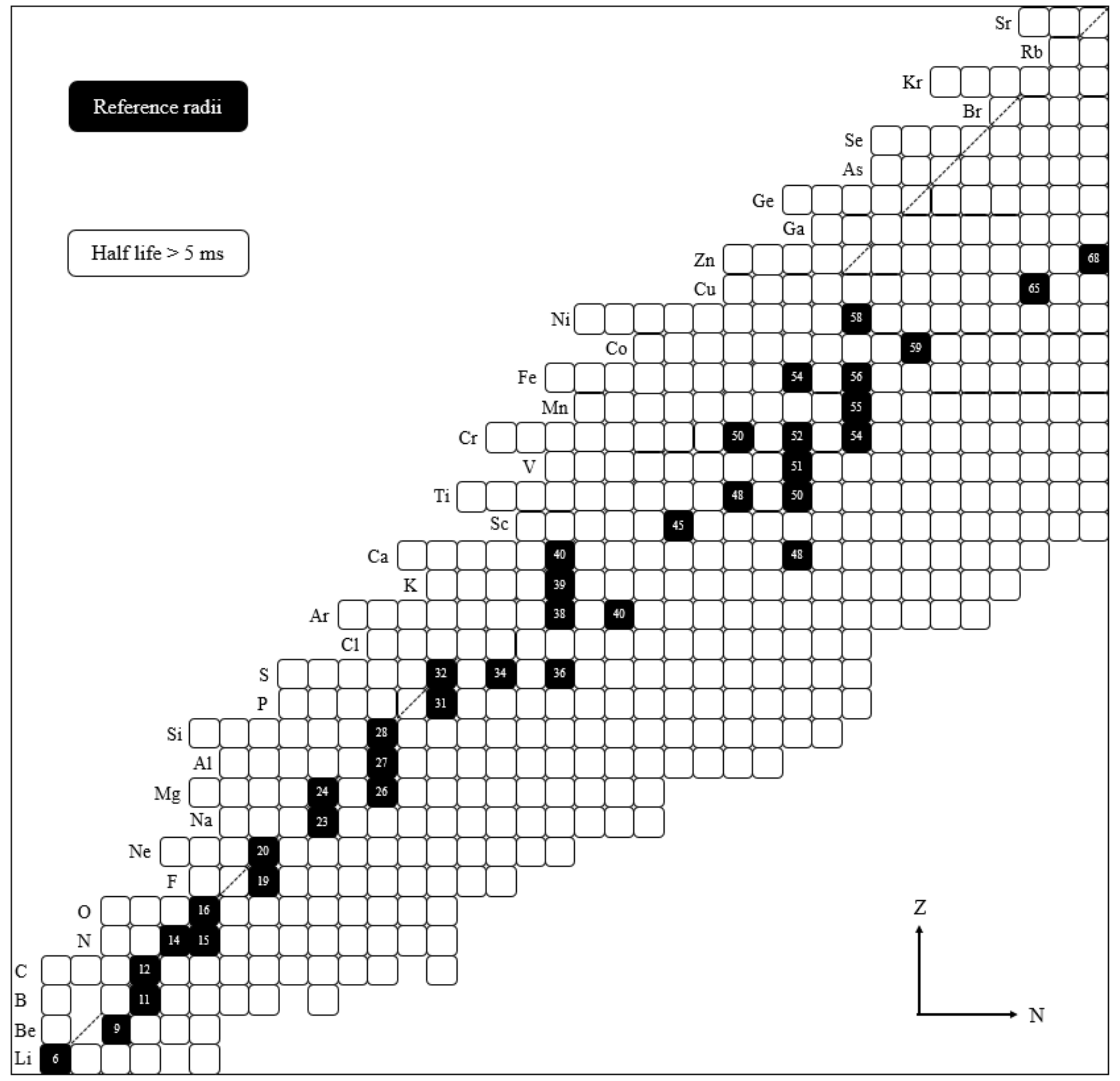

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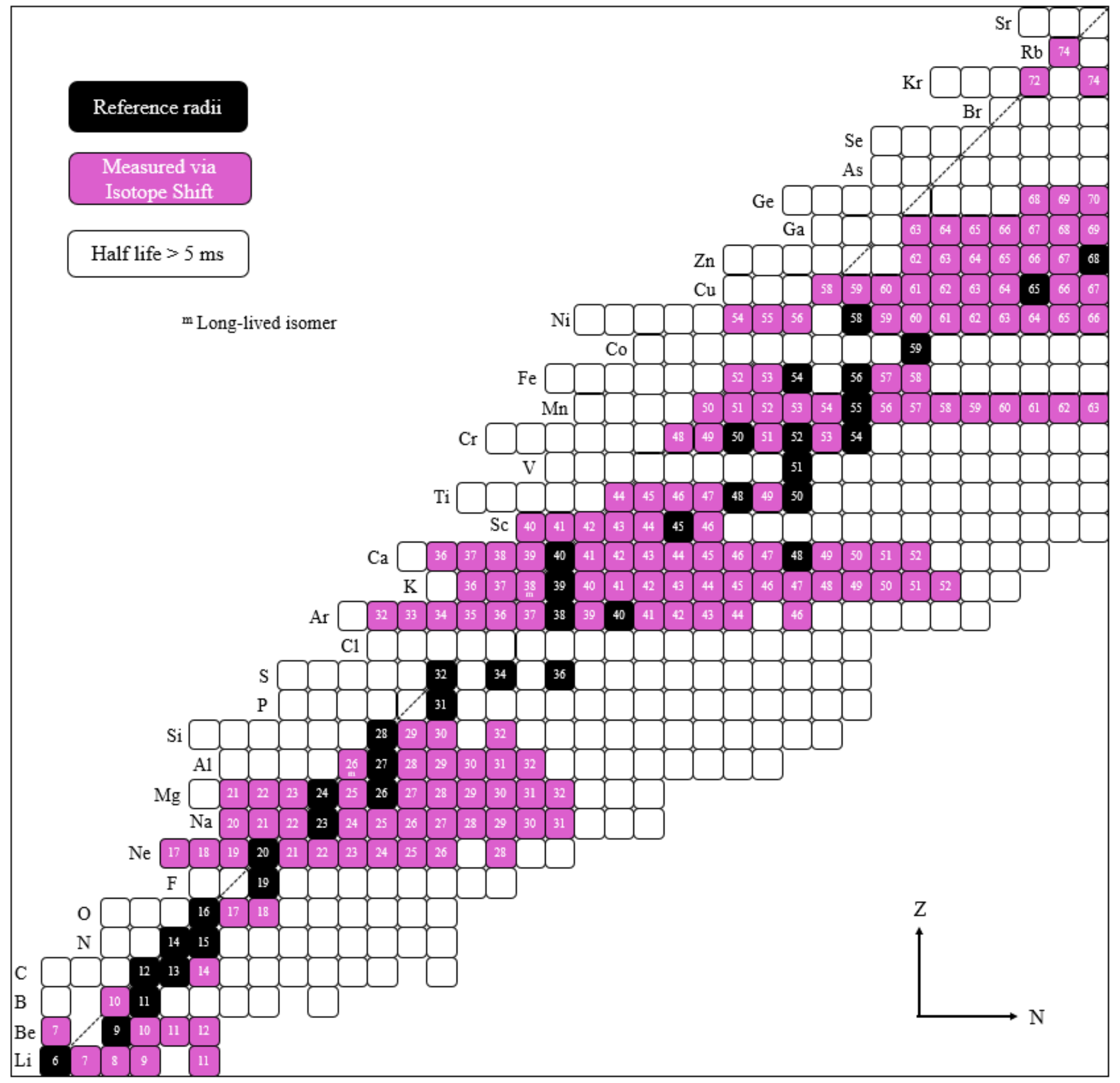

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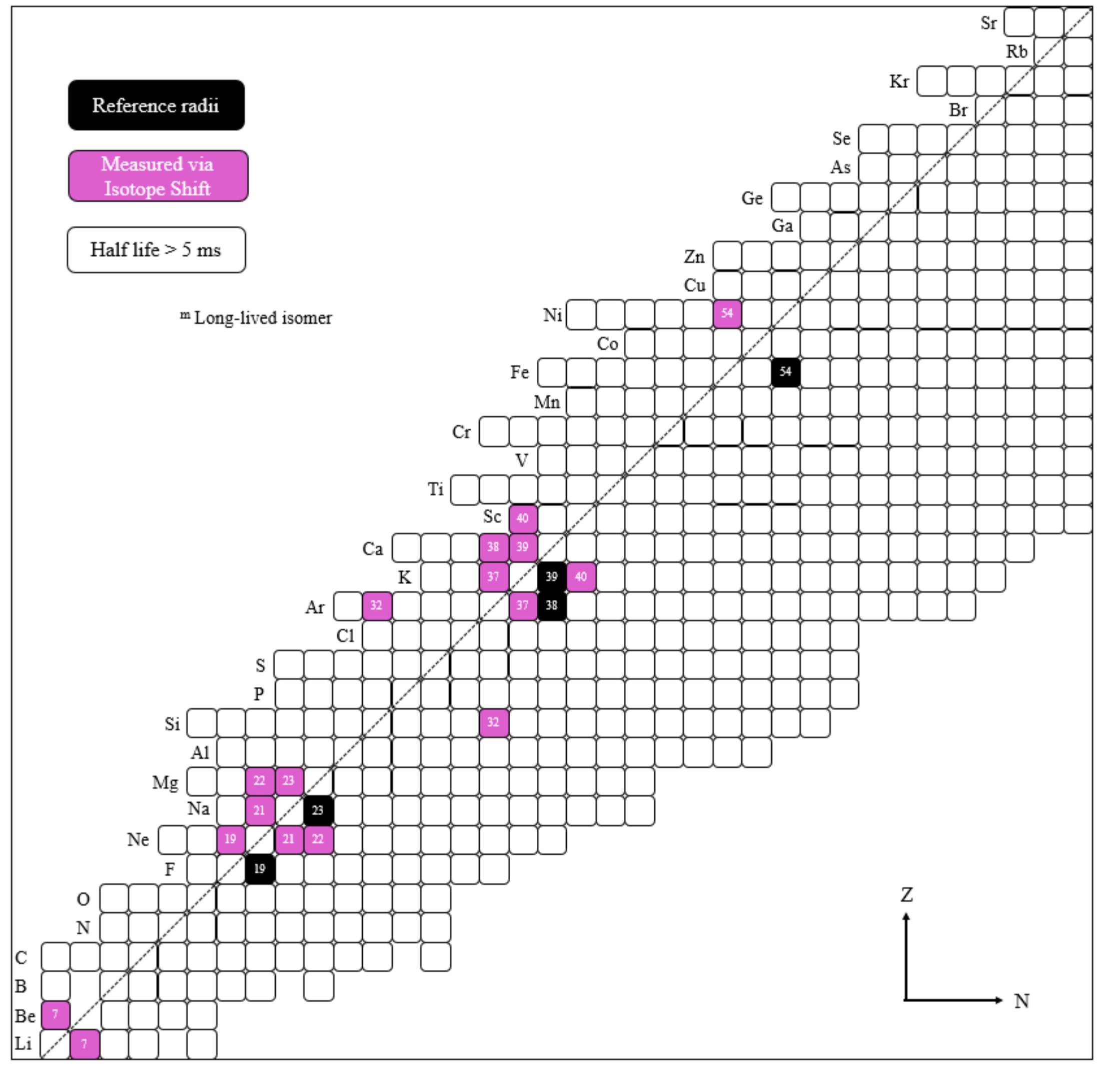

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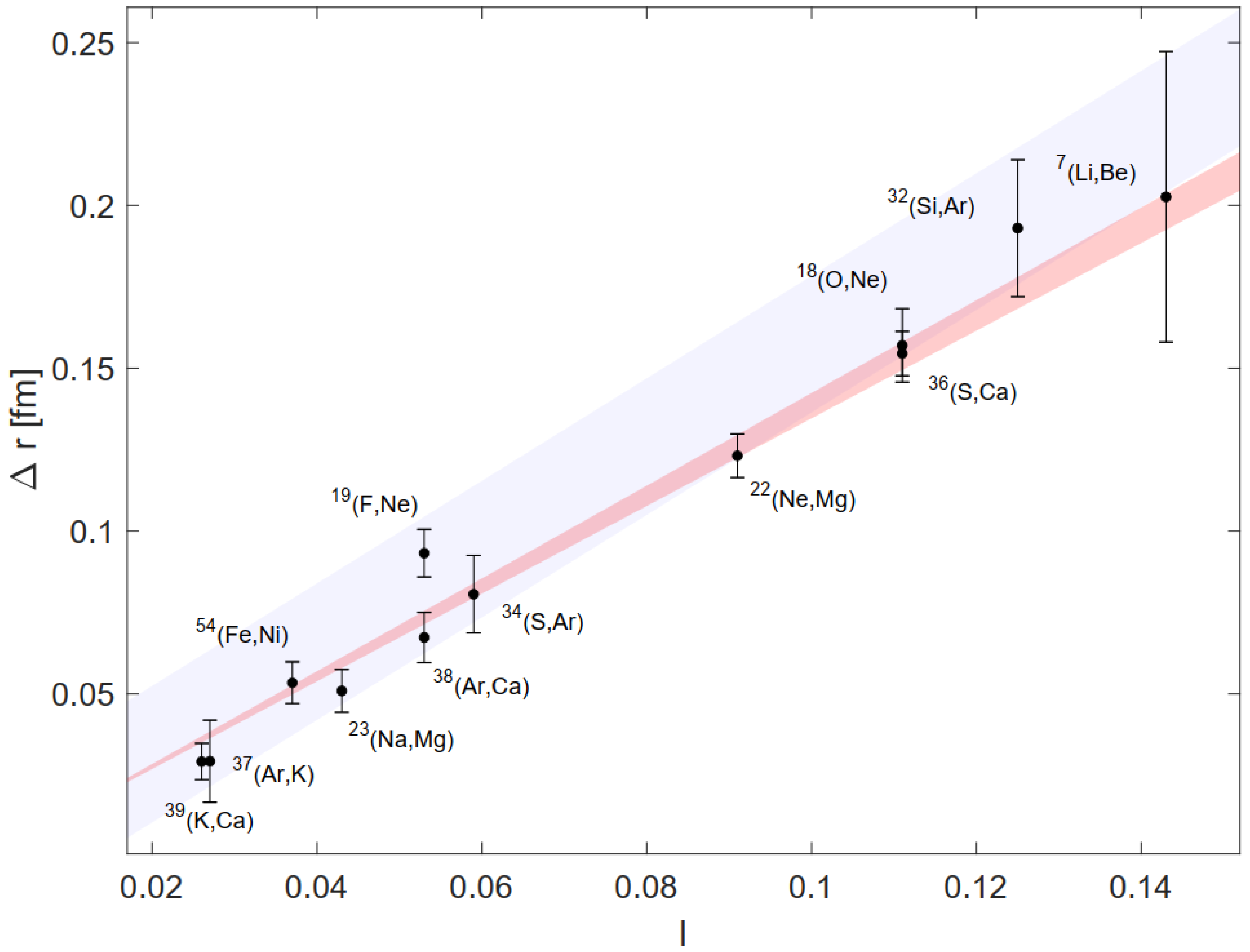

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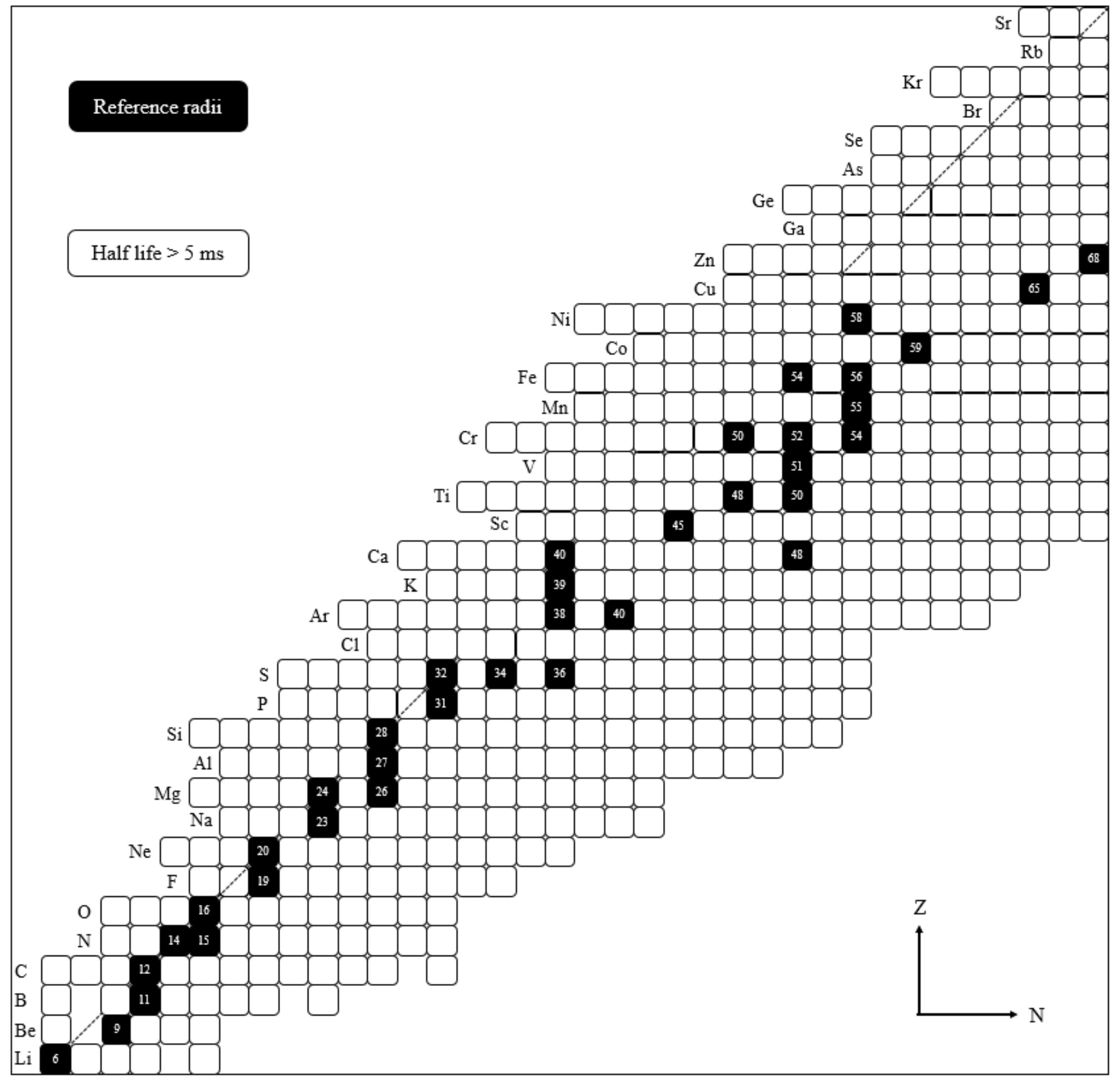

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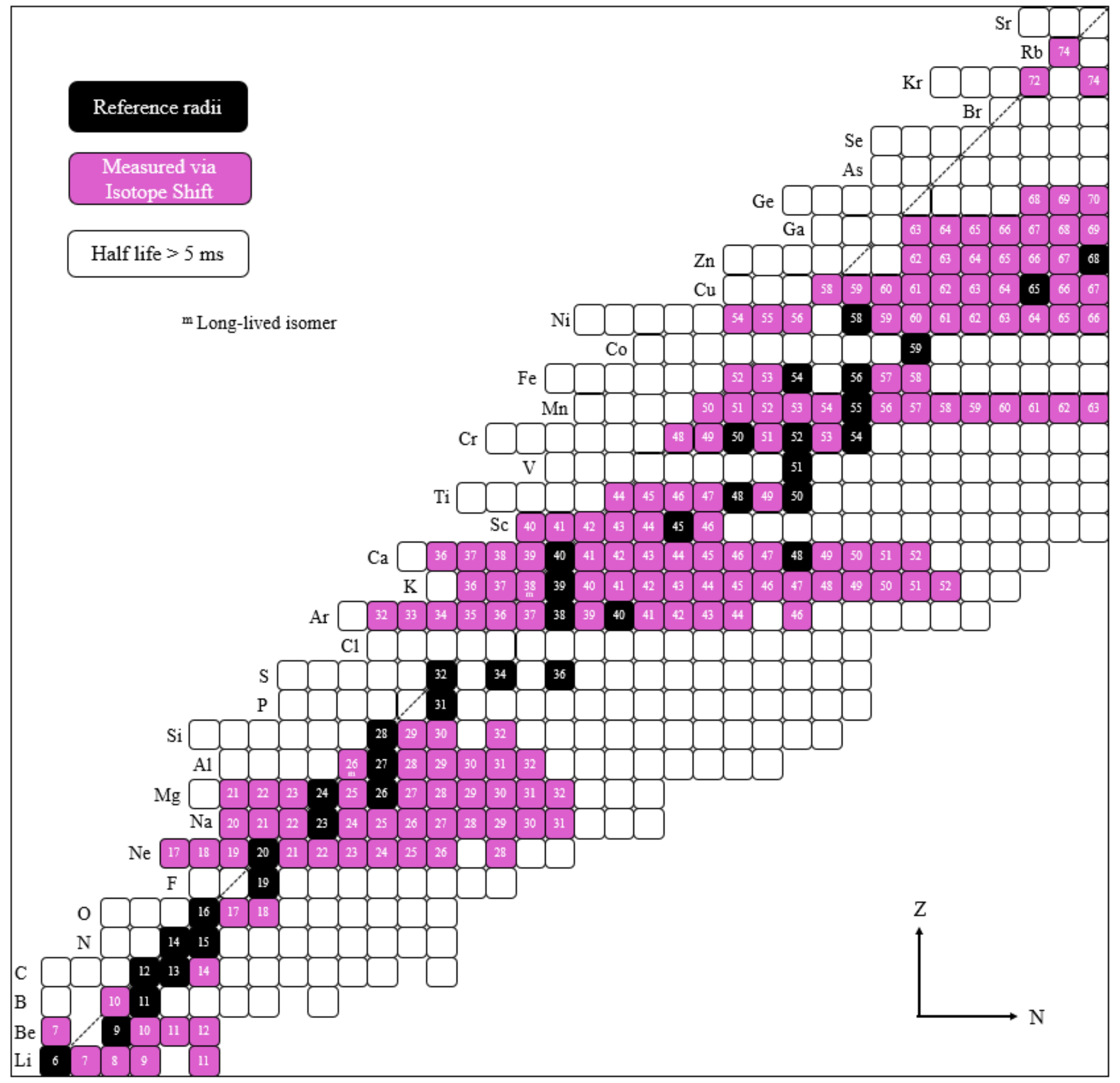

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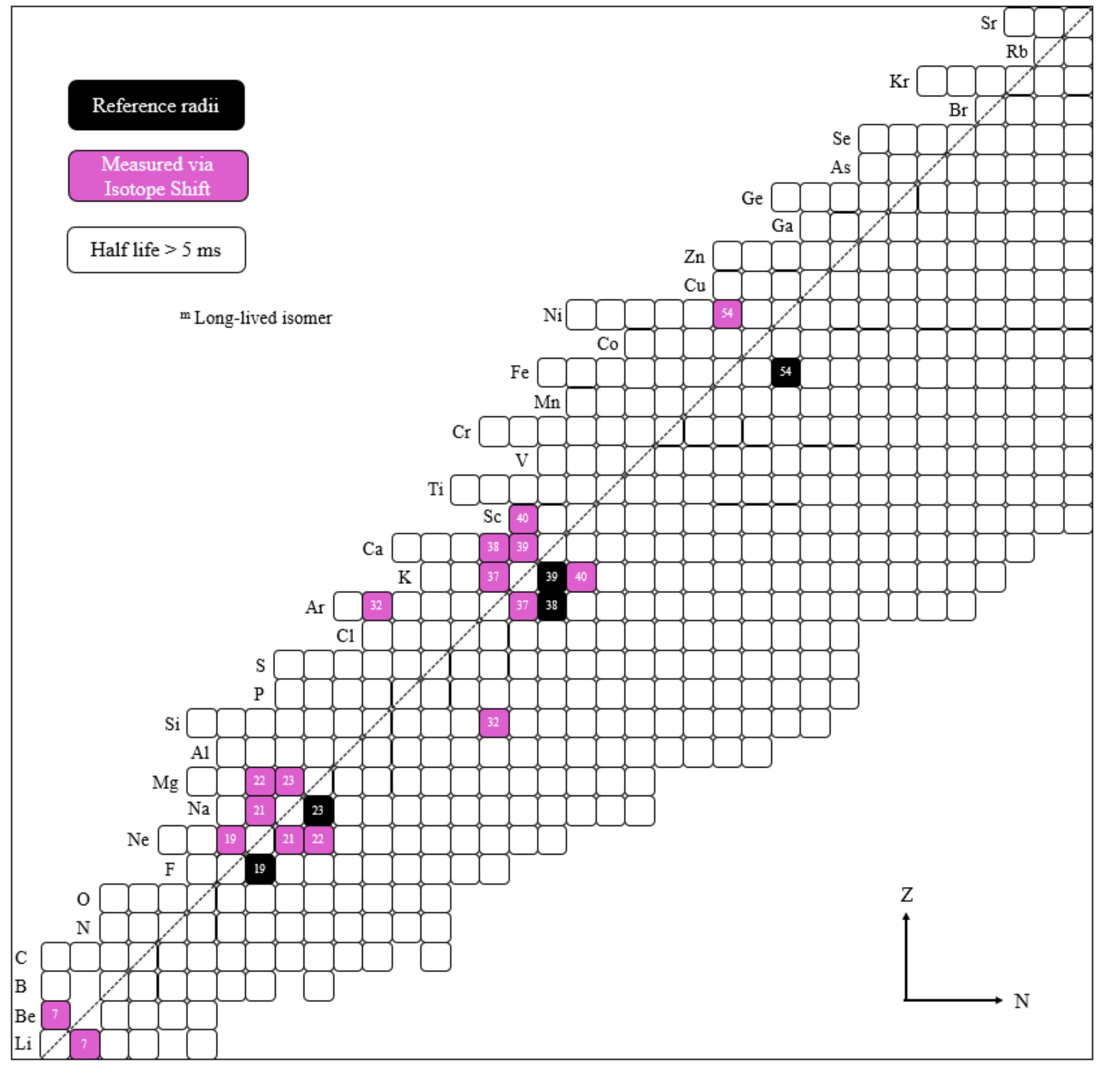

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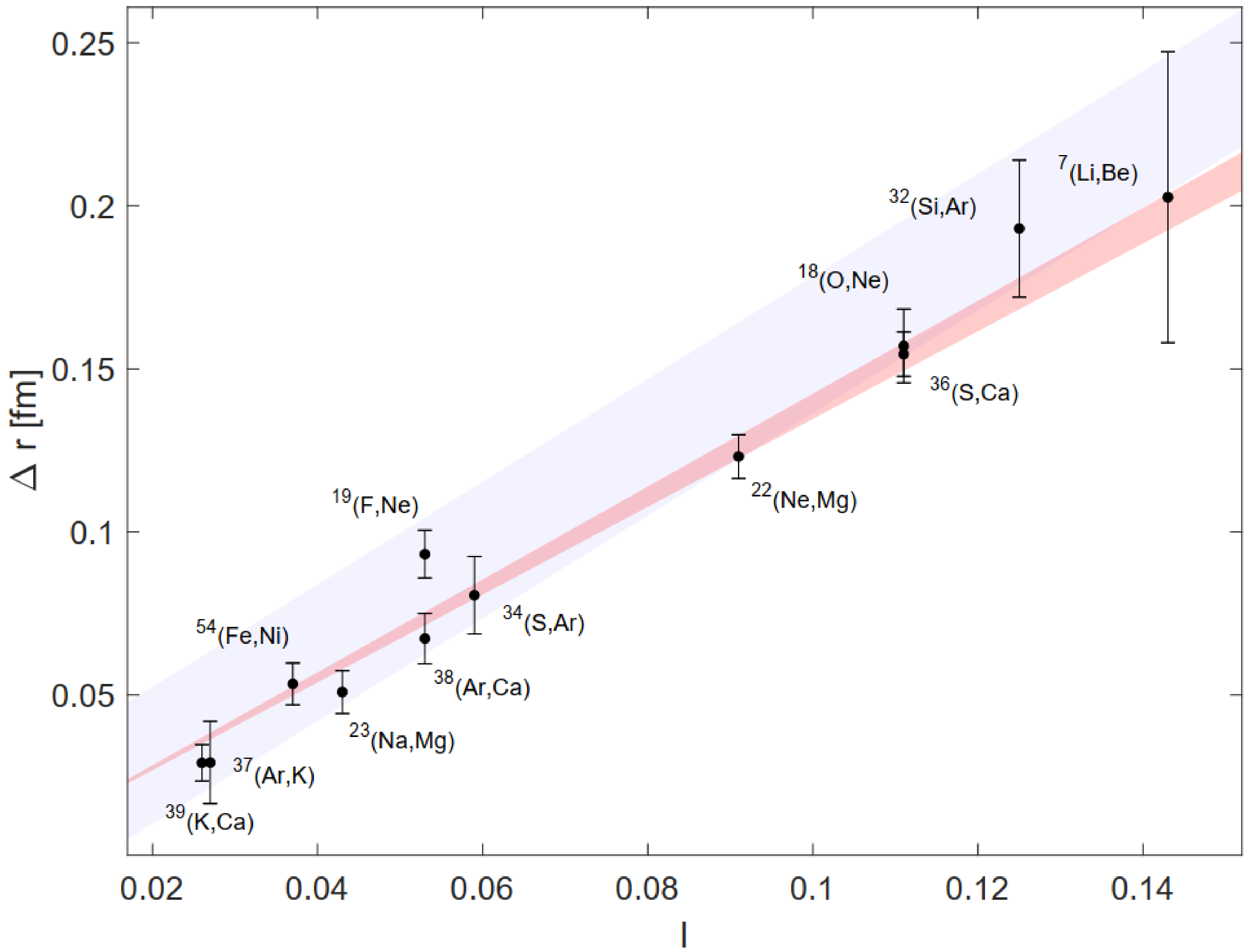
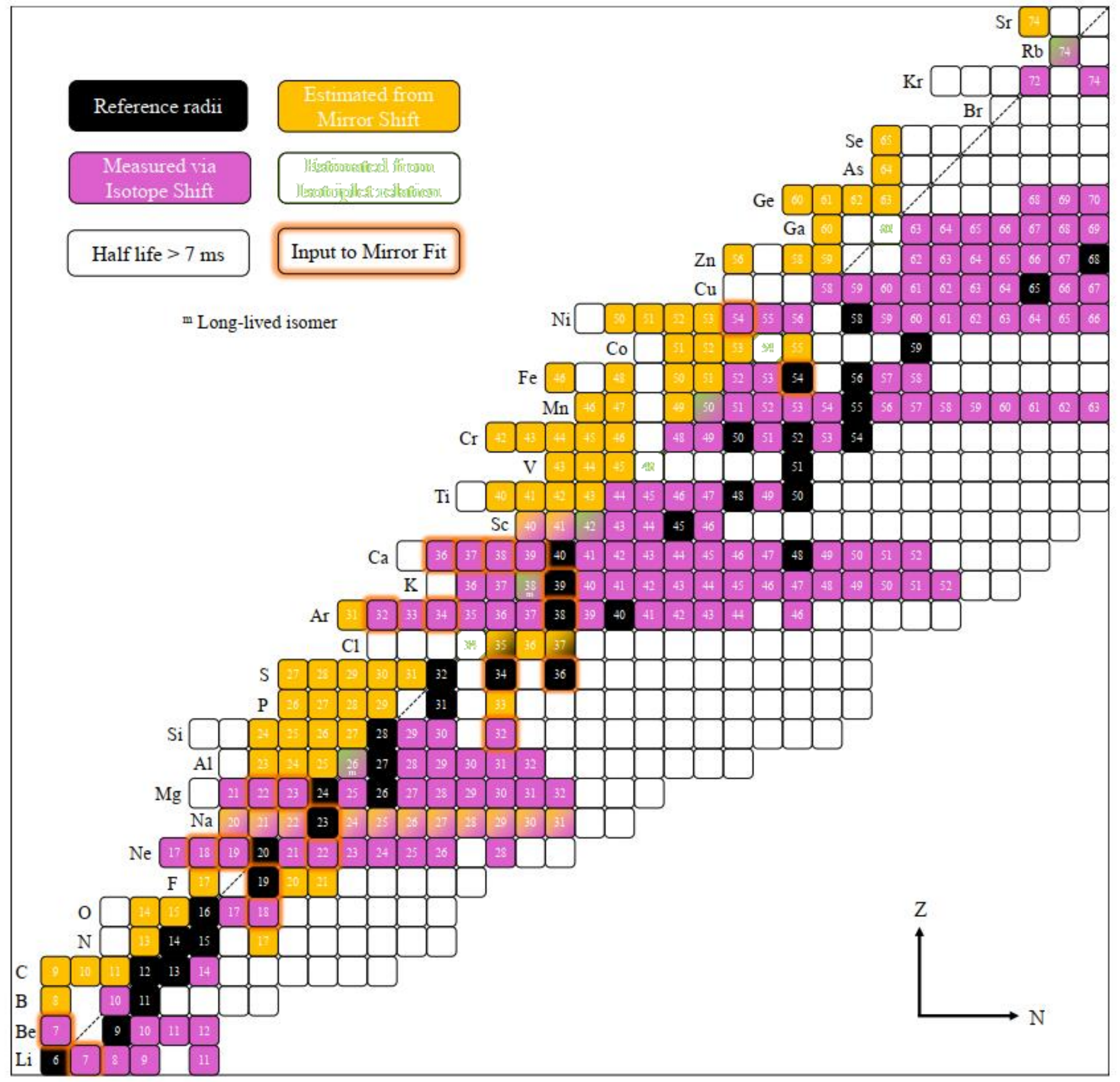


?

5. **Enhanced database**



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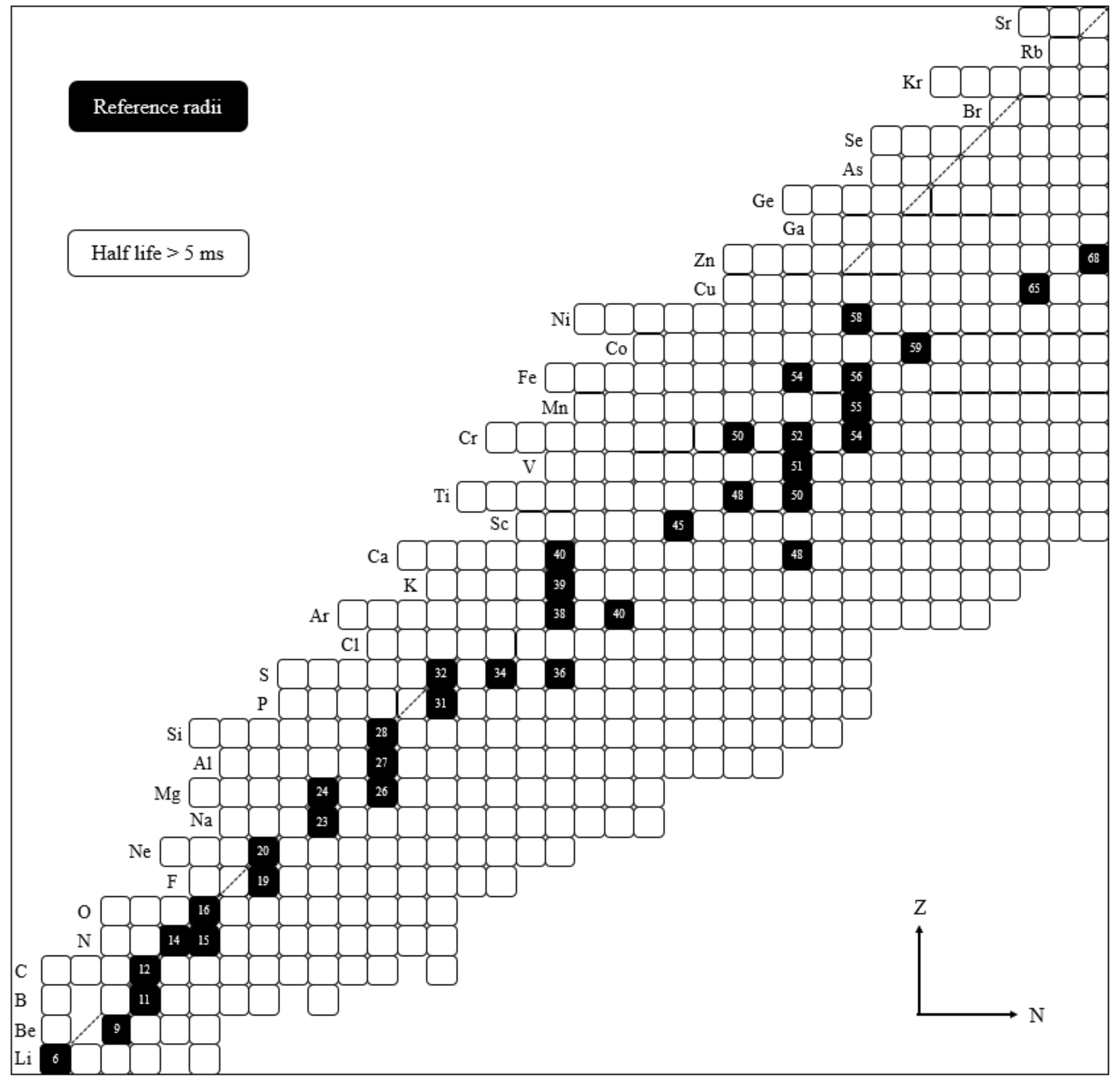

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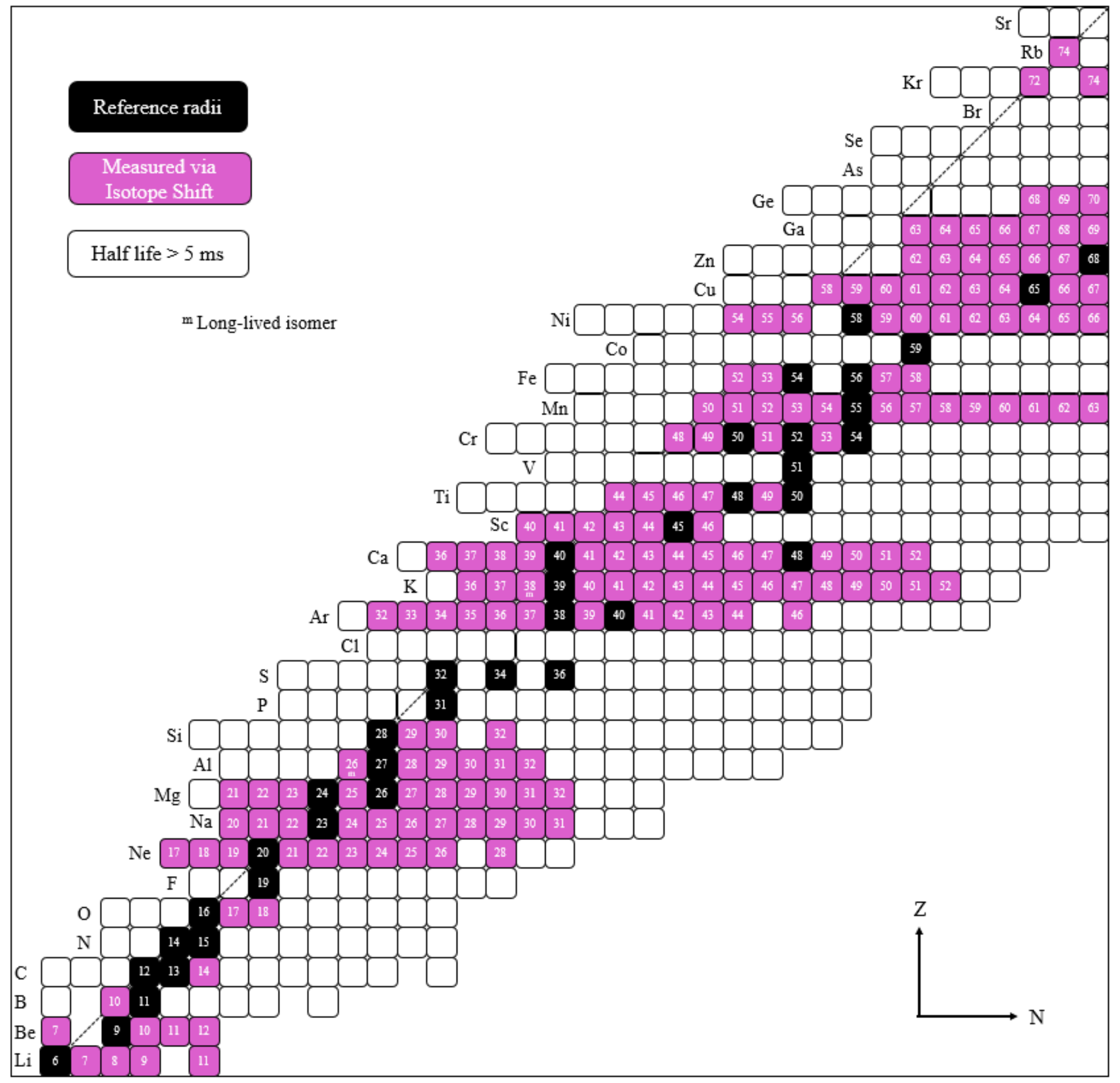

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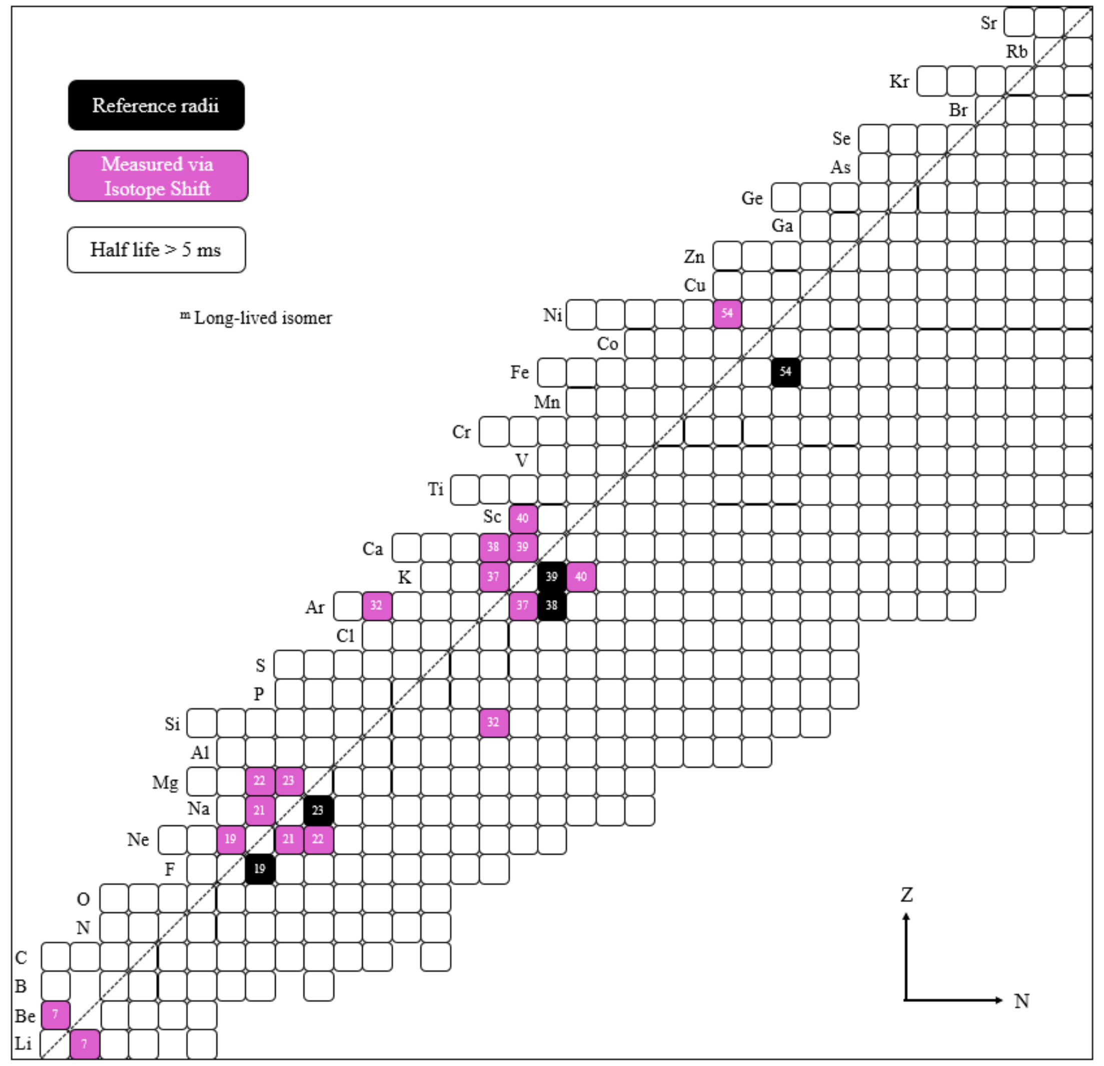

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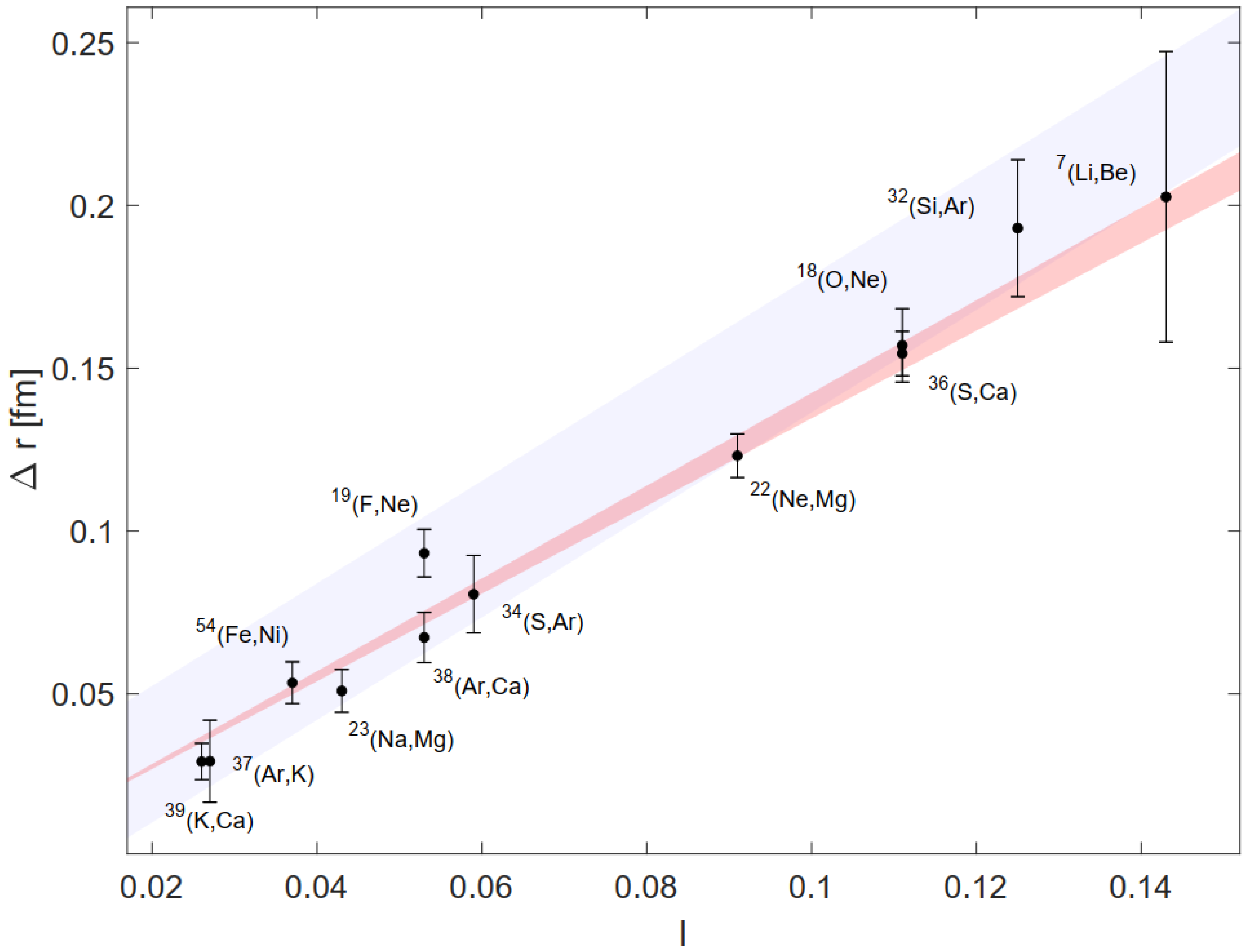

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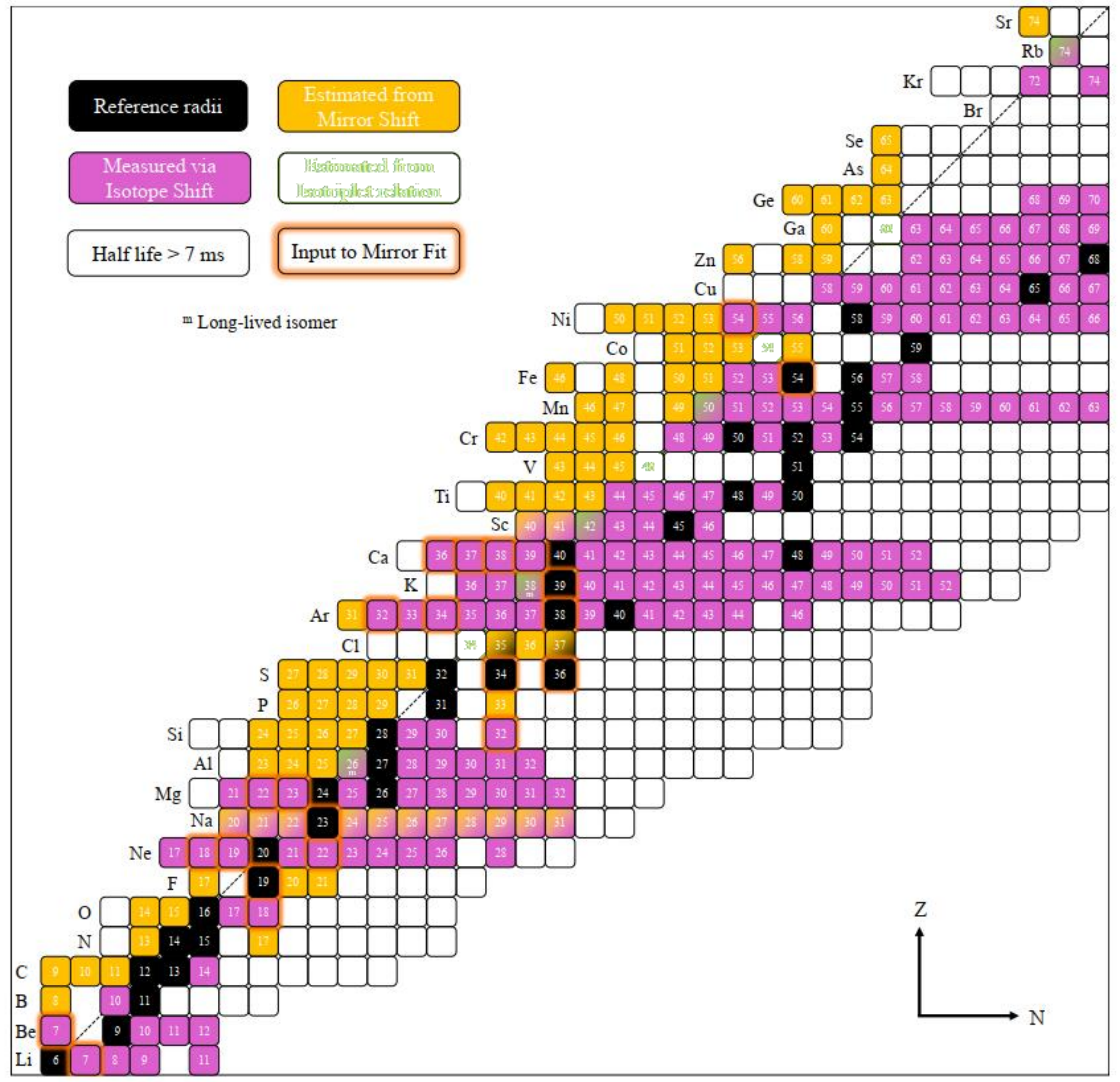
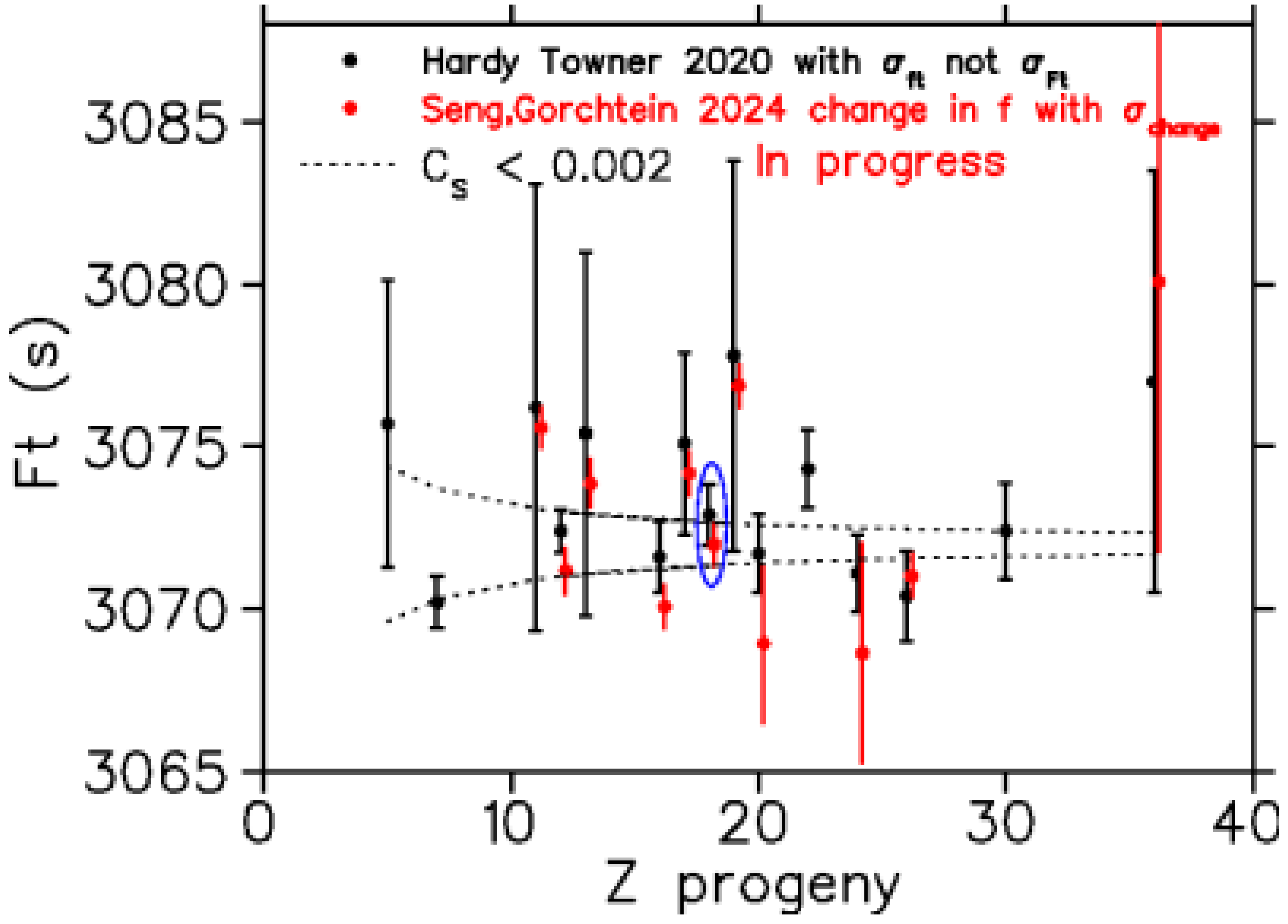


6. **Charge and Weak radii for Vud**



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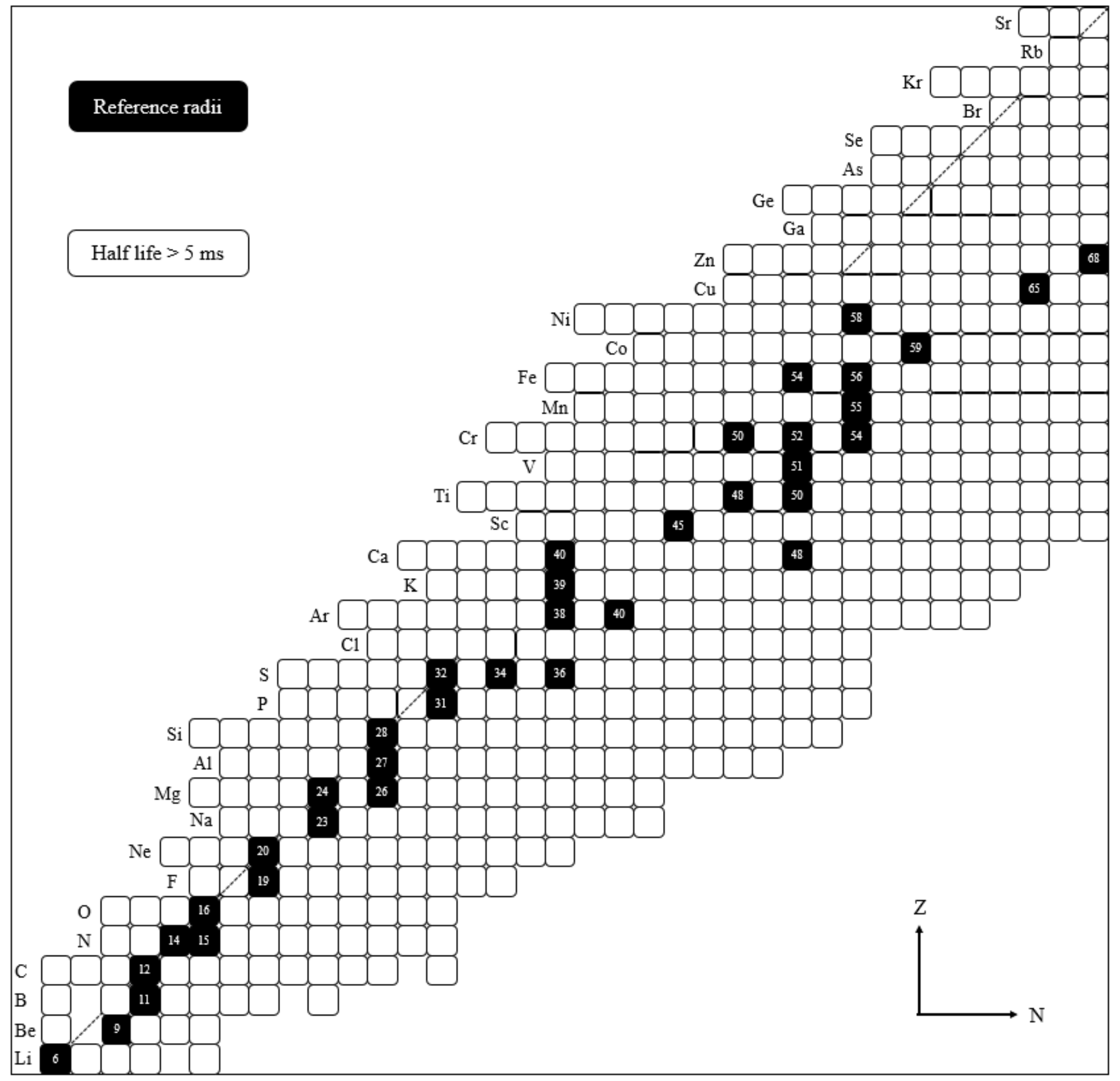

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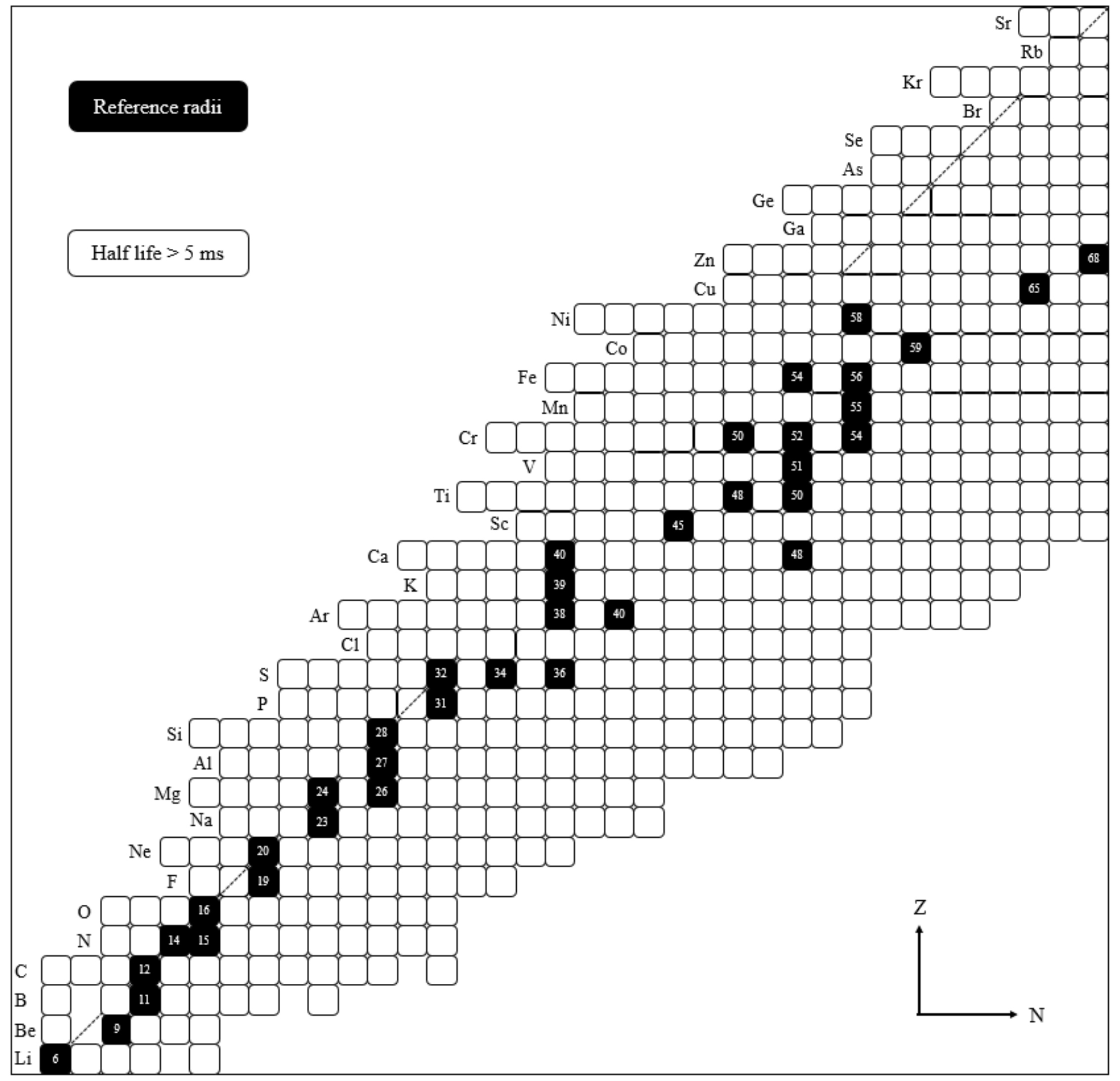

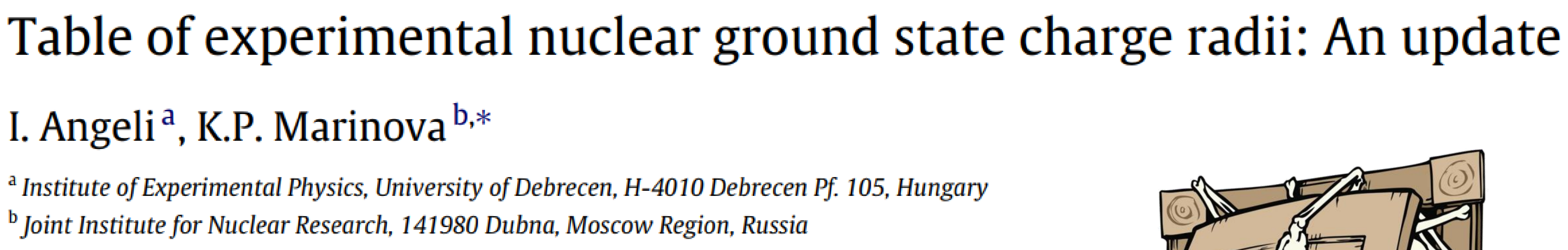

Table of experimental nuclear ground state charge radii: An update

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*

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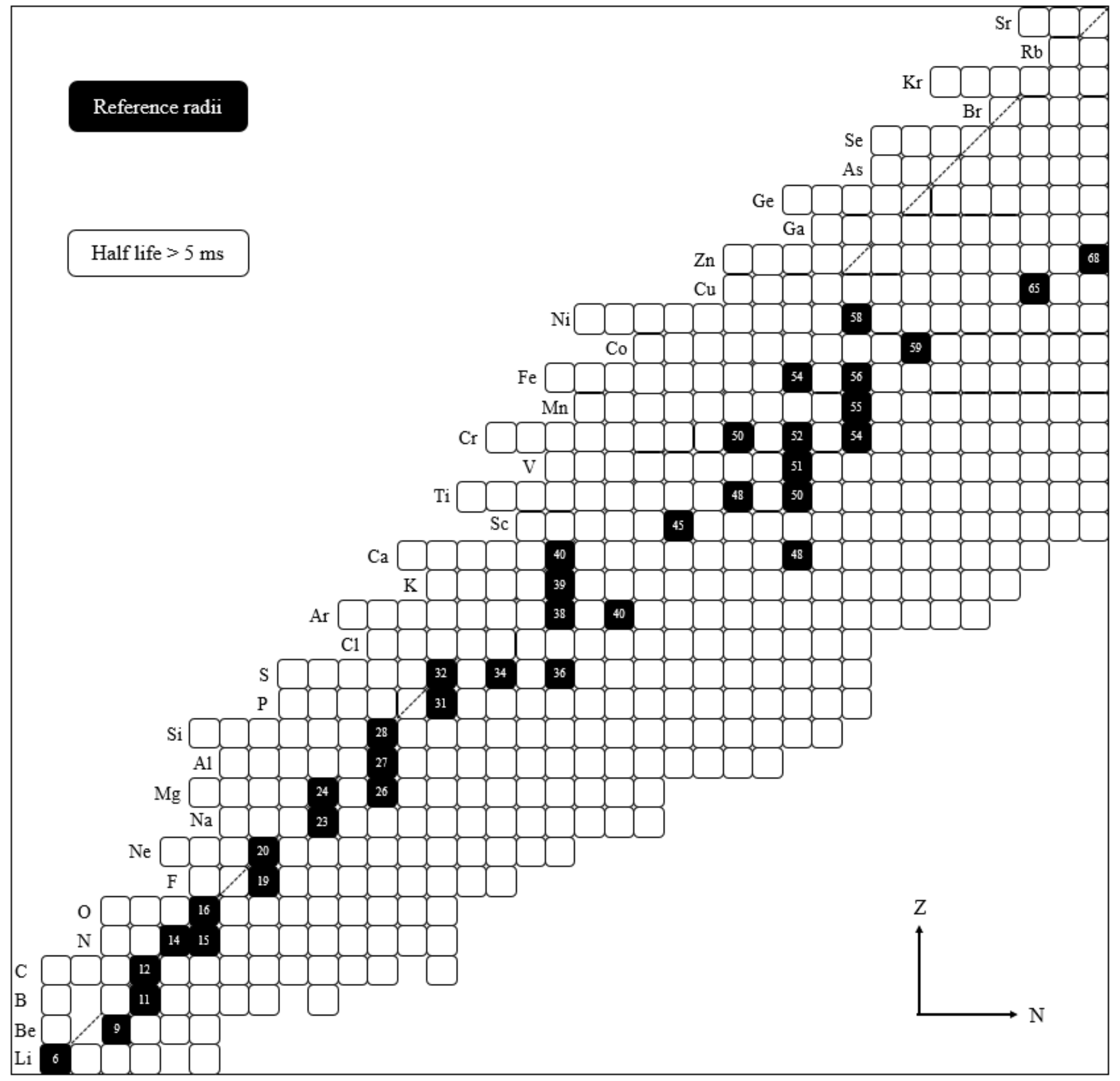

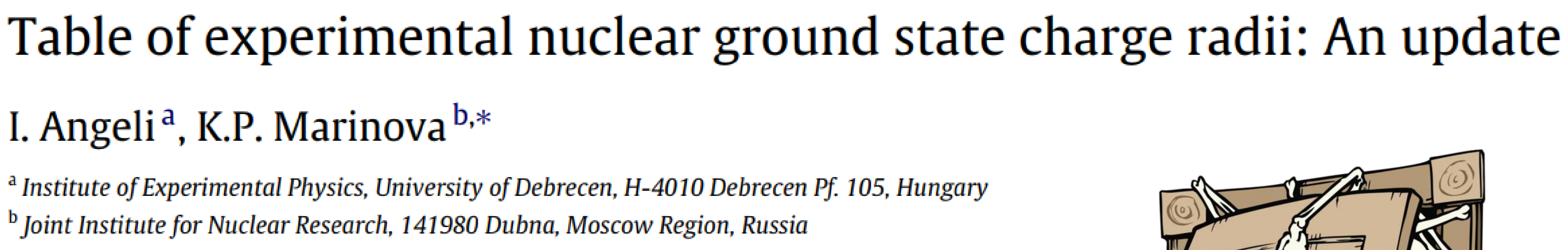

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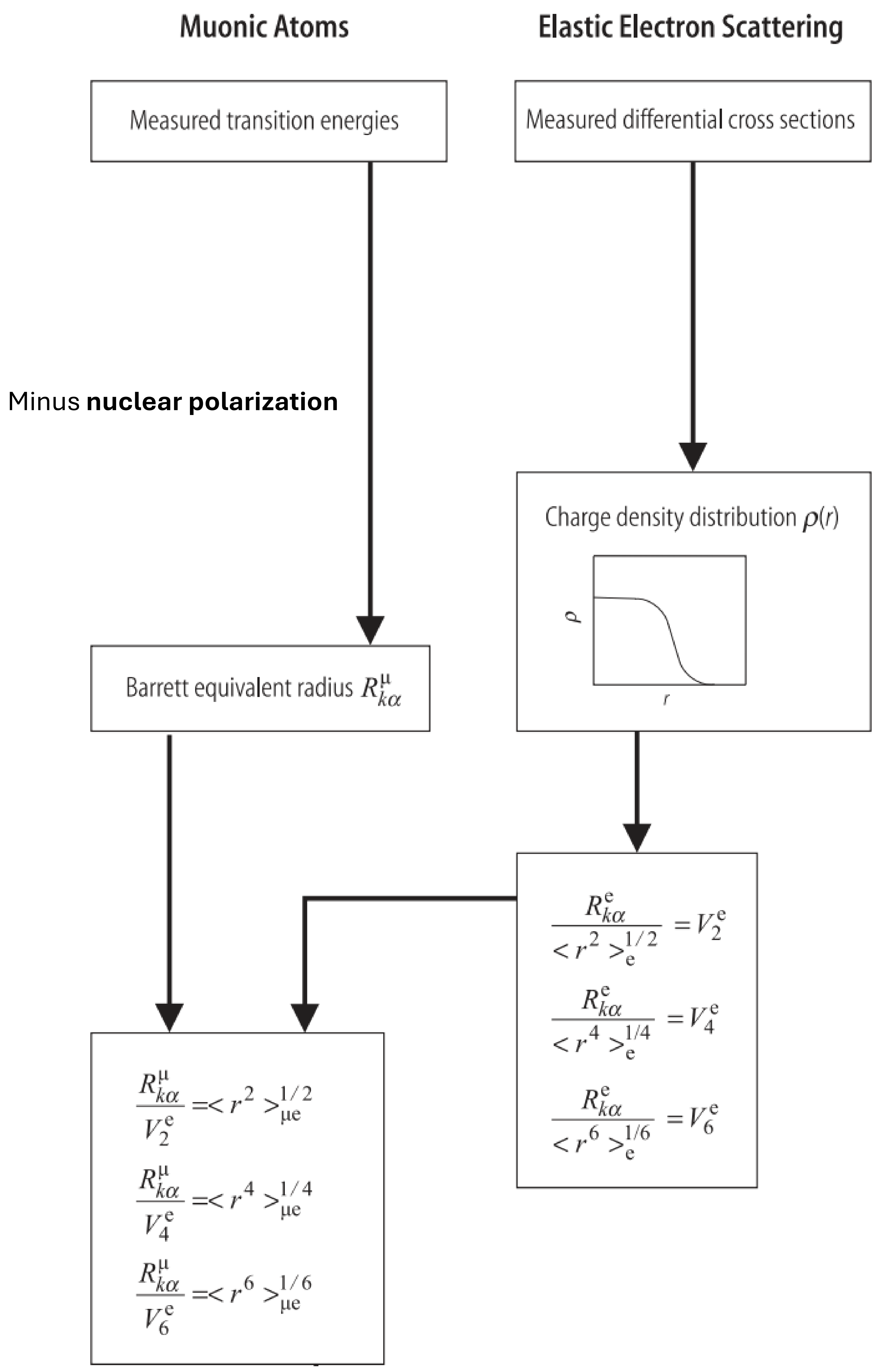
- Step 1 : Update reference radii to reflect uncertainties

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



Muonic Atoms

Measured transition energies

Minus **nuclear polarization**

Barrett equivalent radius $R^{\mu}_{k\alpha}$

$$\frac{R^{\mu}_{k\alpha}}{V^{e}_{2}} = \langle r^{2} \rangle^{1/2}_{\mu e}$$

$$\frac{R^{\mu}_{k\alpha}}{V^{e}_{4}} = \langle r^{4} \rangle^{1/4}_{\mu e}$$

$$\frac{R^{\mu}_{k\alpha}}{V^{e}_{6}} = \langle r^{6} \rangle^{1/6}_{\mu e}$$

Elastic Electron Scattering

Measured differential cross sections

Charge density distribution $\rho(r)$

$$\frac{R^{e}_{k\alpha}}{\langle r^{2} \rangle^{1/2}_{e}} = V^{e}_{2}$$

$$\frac{R^{e}_{k\alpha}}{\langle r^{4} \rangle^{1/4}_{e}} = V^{e}_{4}$$

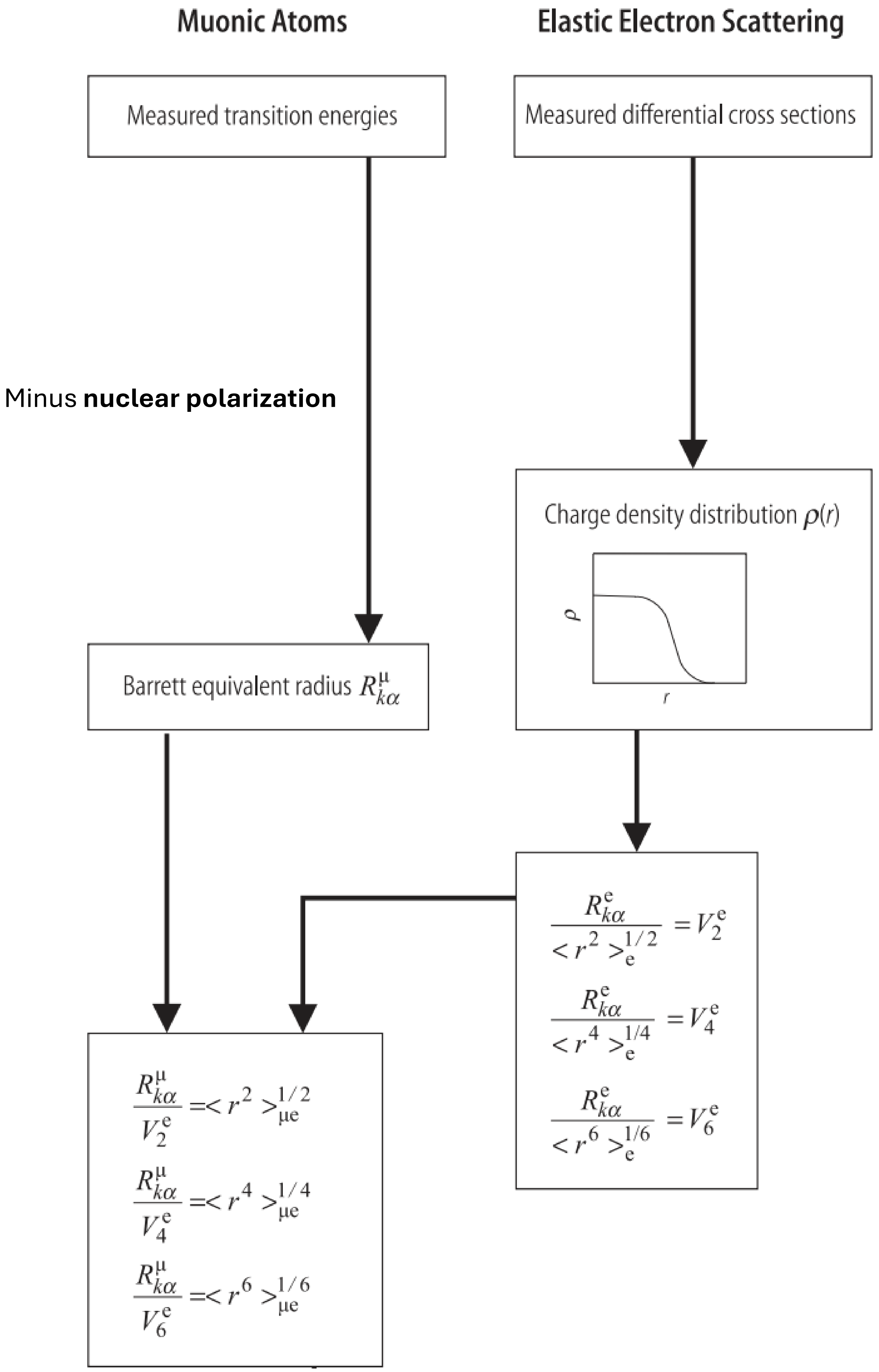
$$\frac{R^{e}_{k\alpha}}{\langle r^{6} \rangle^{1/6}_{e}} = V^{e}_{6}$$

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

- What is the limitation of the “Barret recipe?”

Three sources of uncertainty:

1. Experiment (muonic atom energies)
2. Theory (nuclear polarization)
3. **Charge distribution** (scattering)



Muonic Atoms

Elastic Electron Scattering

Measured transition energies

Measured differential cross sections

Minus **nuclear polarization**

Charge density distribution $\rho(r)$

Barrett equivalent radius $R^{\mu}_{k\alpha}$

$$\frac{R^{e}_{k\alpha}}{<r^2>_{e}^{1/2}} = V_2^{e}$$

$$\frac{R^{e}_{k\alpha}}{<r^4>_{e}^{1/4}} = V_4^{e}$$

$$\frac{R^{e}_{k\alpha}}{<r^6>_{e}^{1/6}} = V_6^{e}$$

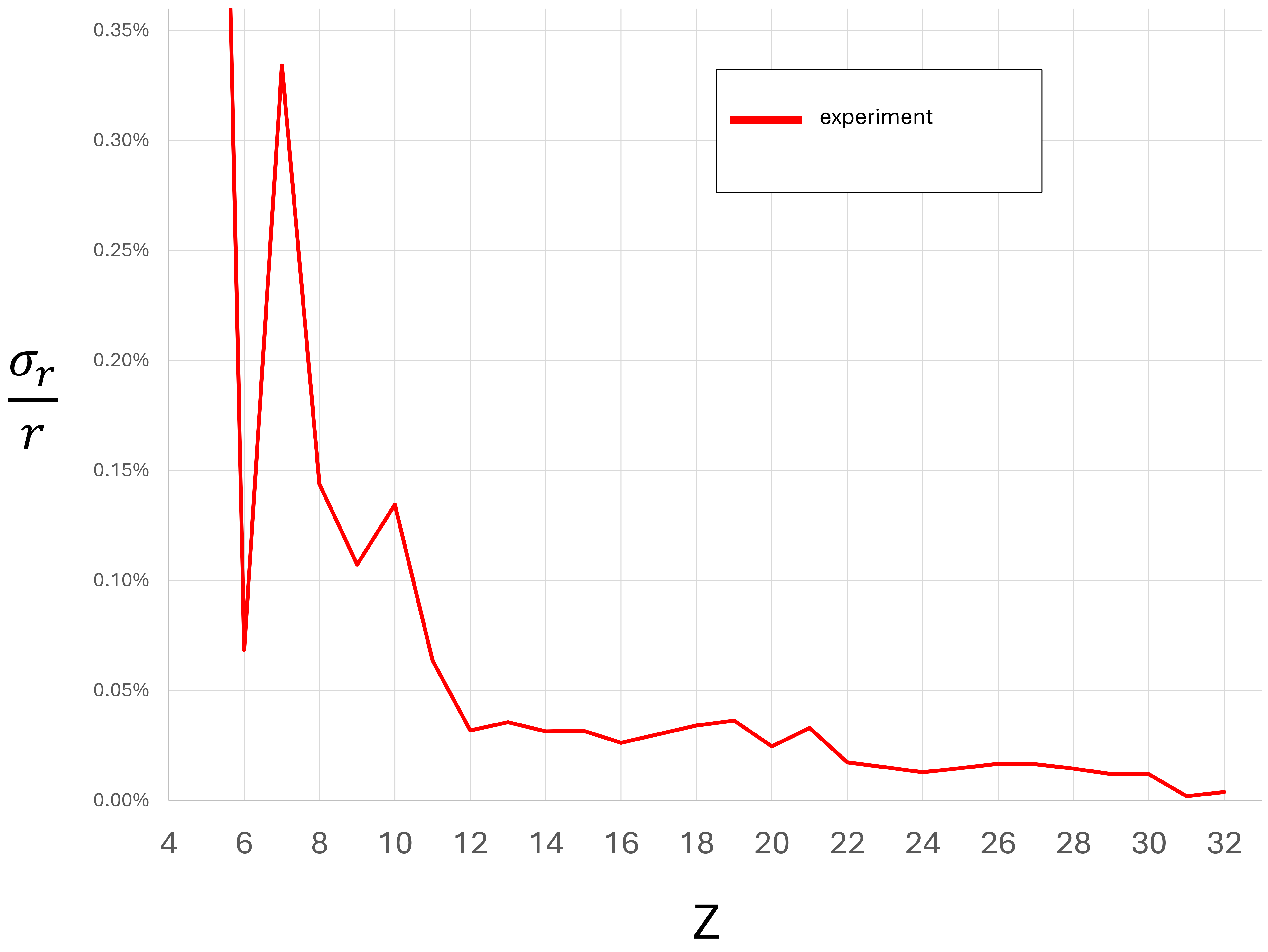
$$\frac{R^{\mu}_{k\alpha}}{V_2^{e}} = <r^2>_{\mu e}^{1/2}$$

$$\frac{R^{\mu}_{k\alpha}}{V_4^{e}} = <r^4>_{\mu e}^{1/4}$$

$$\frac{R^{\mu}_{k\alpha}}{V_6^{e}} = <r^6>_{\mu e}^{1/6}$$

Sources of uncertainty :

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



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Sources of uncertainty :

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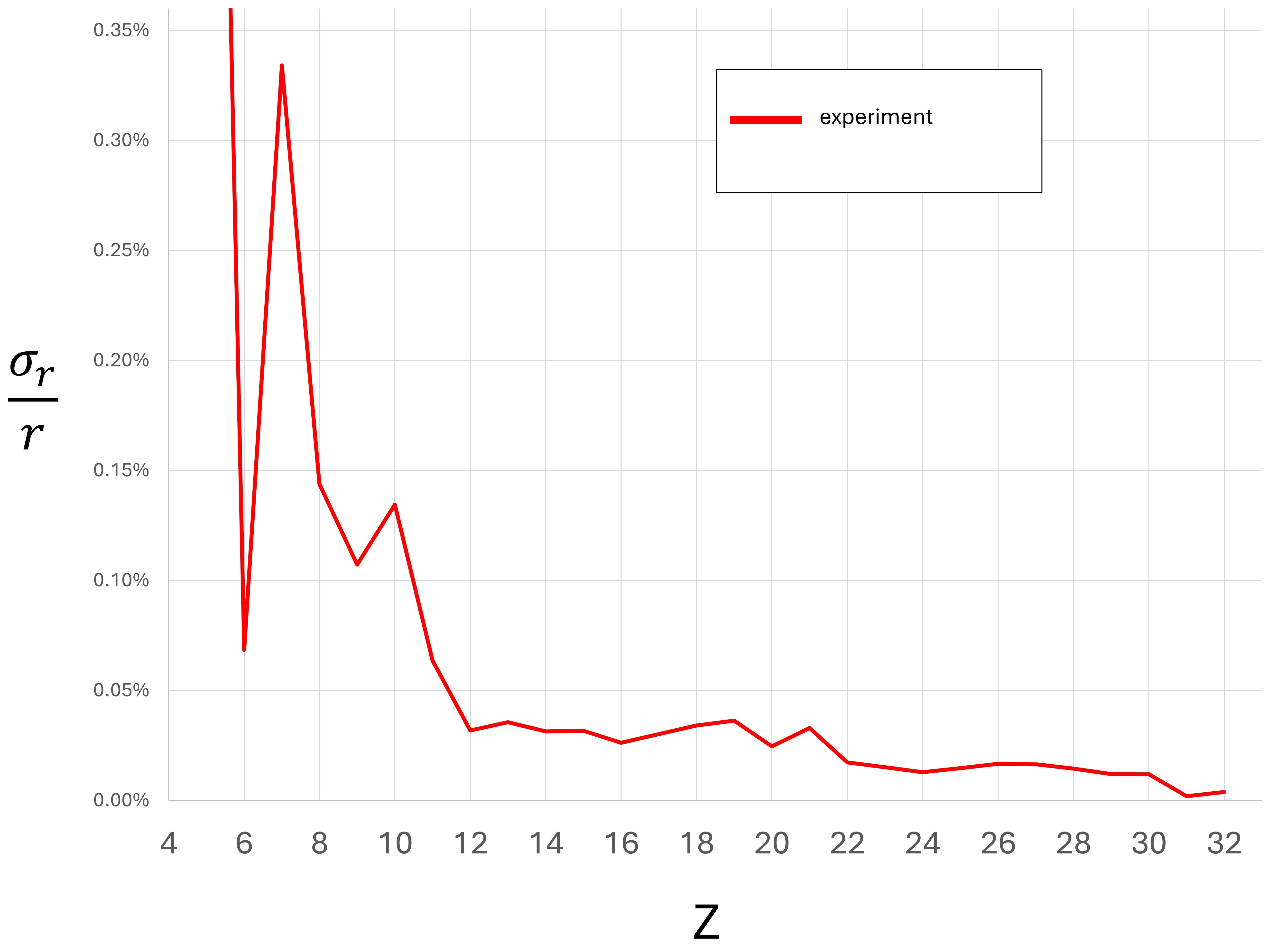
- Notice: Fricke & Heilig only include statistical unc. -> consult original papers



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Sources of uncertainty :

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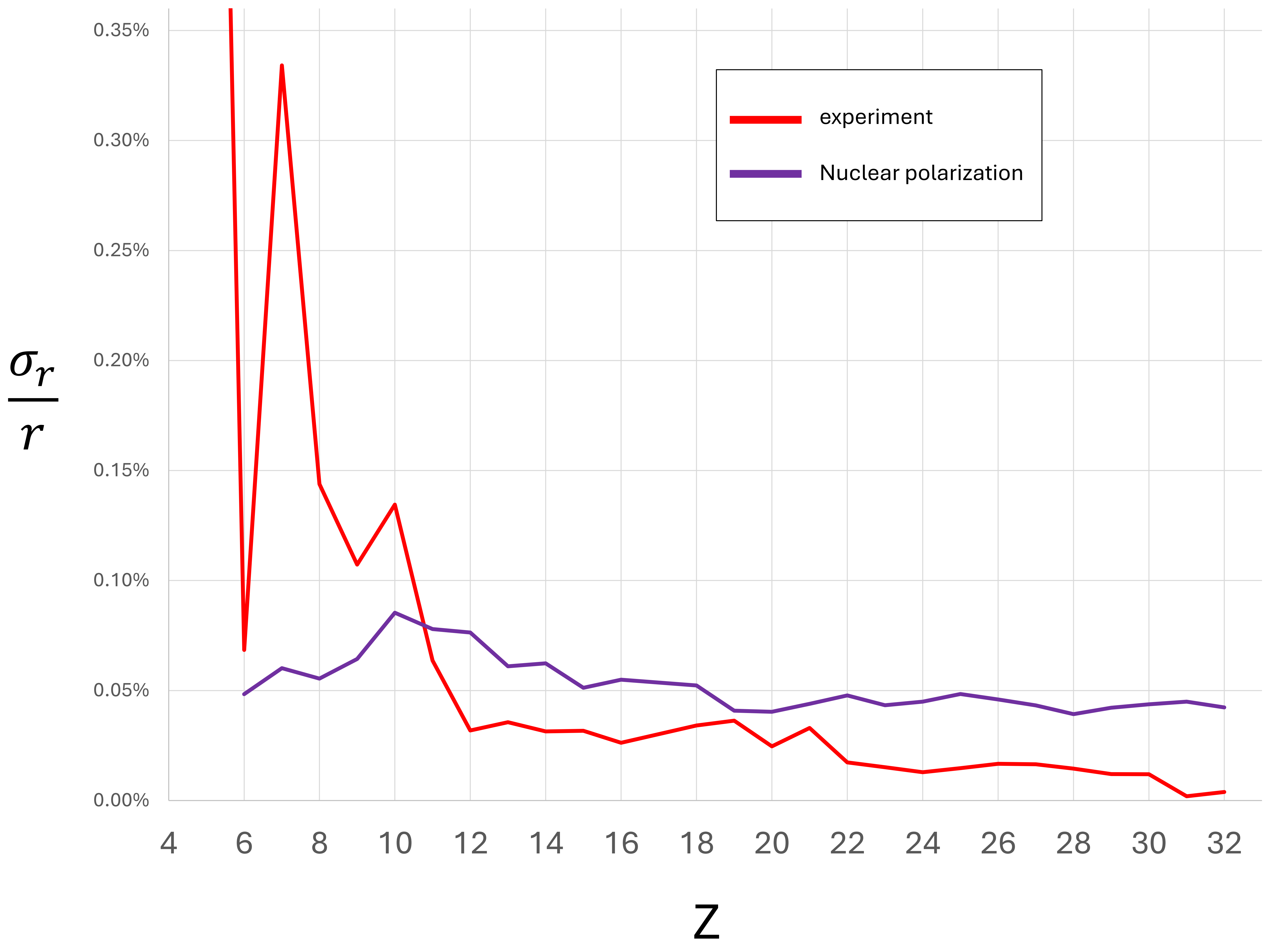
- Notice: nuclear polarization from Rinker & Speth 1970s, assumed 30% unc. Reliable?



How about electron scattering?

Idea by Ingo Sick, applied here

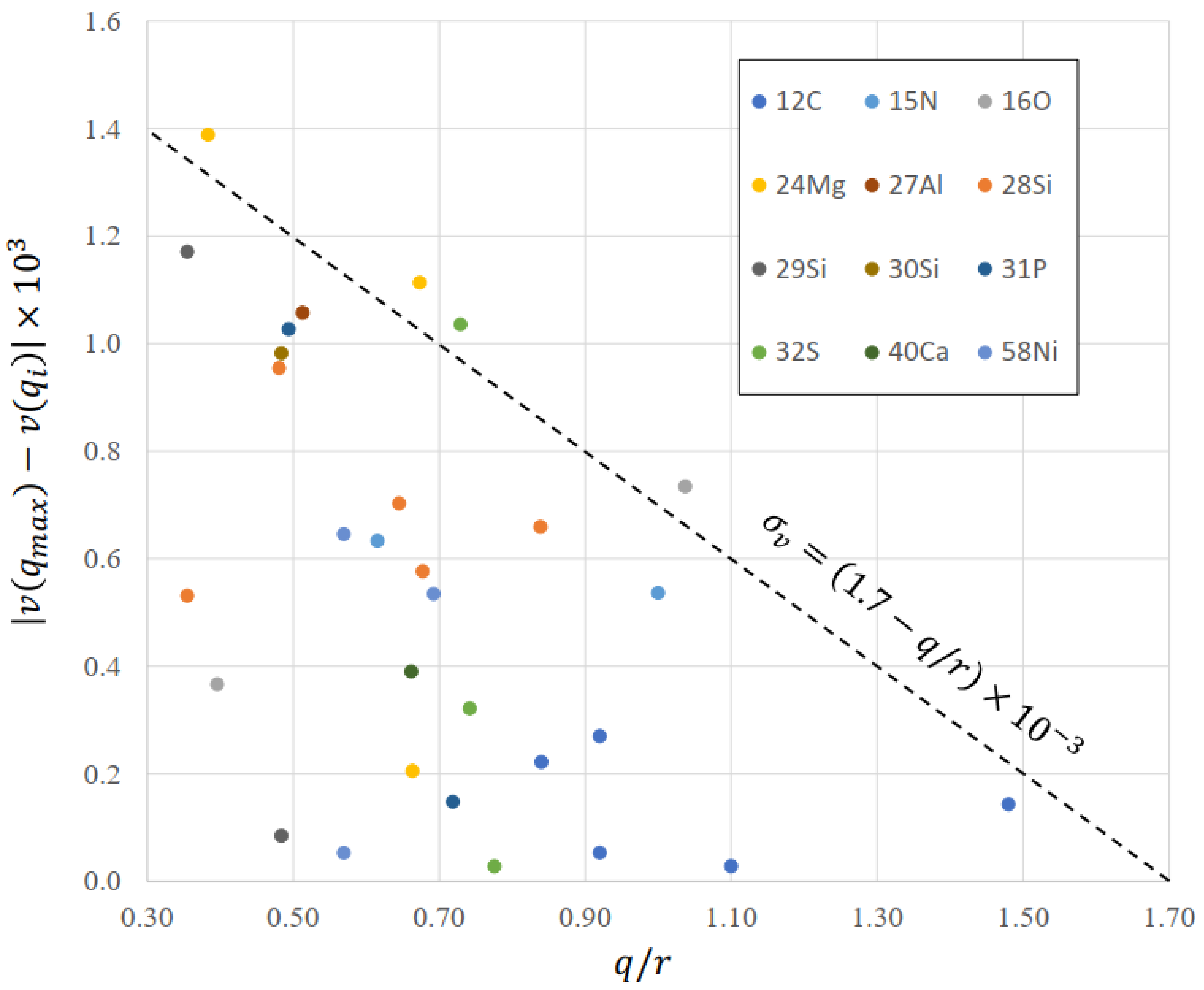
- Experimental uncertainty (normalization) goes away for ratios
- Residual model-dependency from finite momentum transfer. Hard to quantify!

Uncertainty in ratios of moments?

- Experimental uncertainty (normalization) goes away for ratios
- Residual model-dependency from finite momentum transfer
- How much does the second-best scattering measurement deviates from the best one?

Quantify our intuition:

Best experiment has broad momentum transfer compared to nuclear size.



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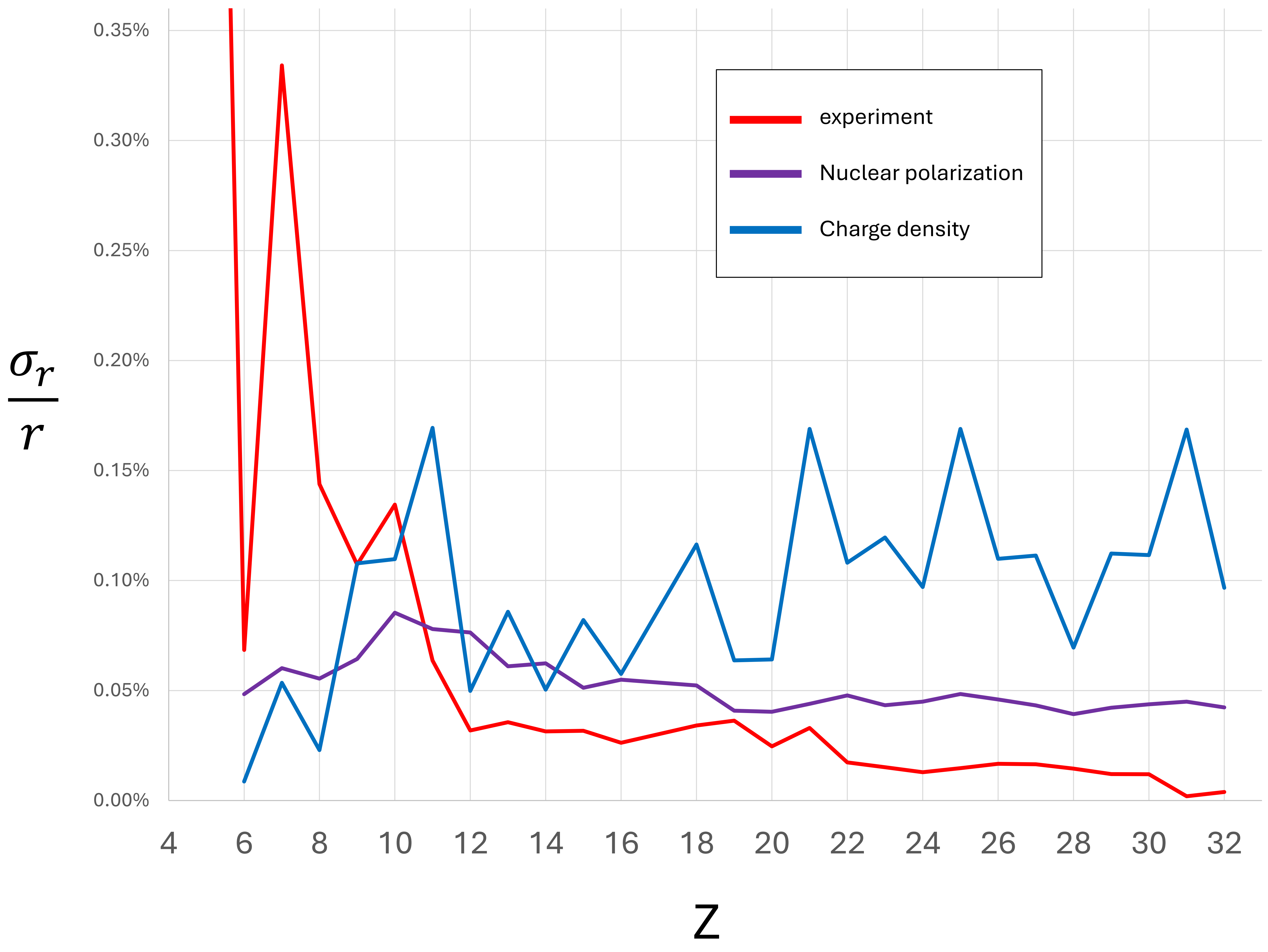

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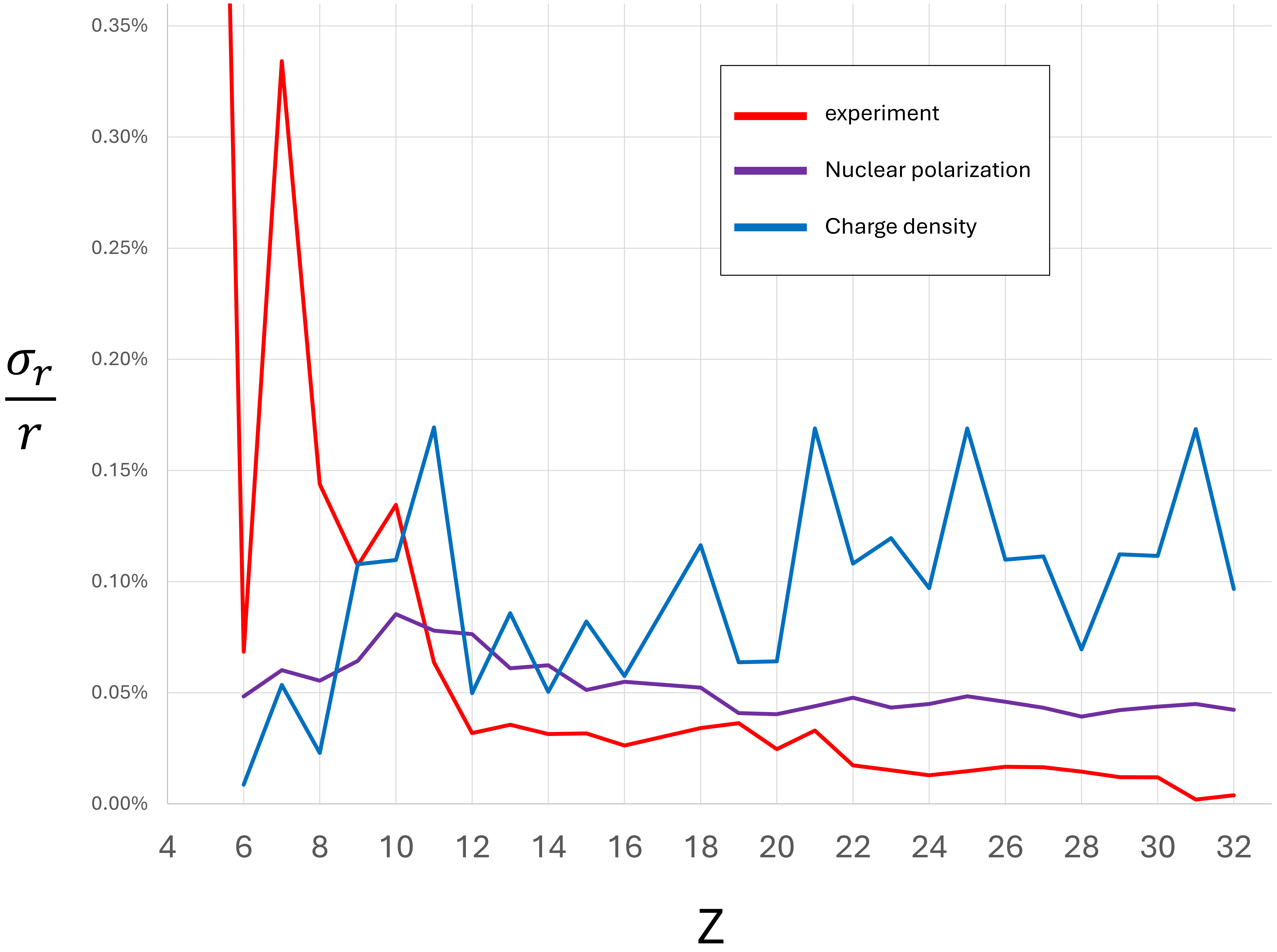
- Within Barret-recipe: scattering model dependency matters !



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Transparent tabulation (inviting your input!)

arXiv:2409.08193

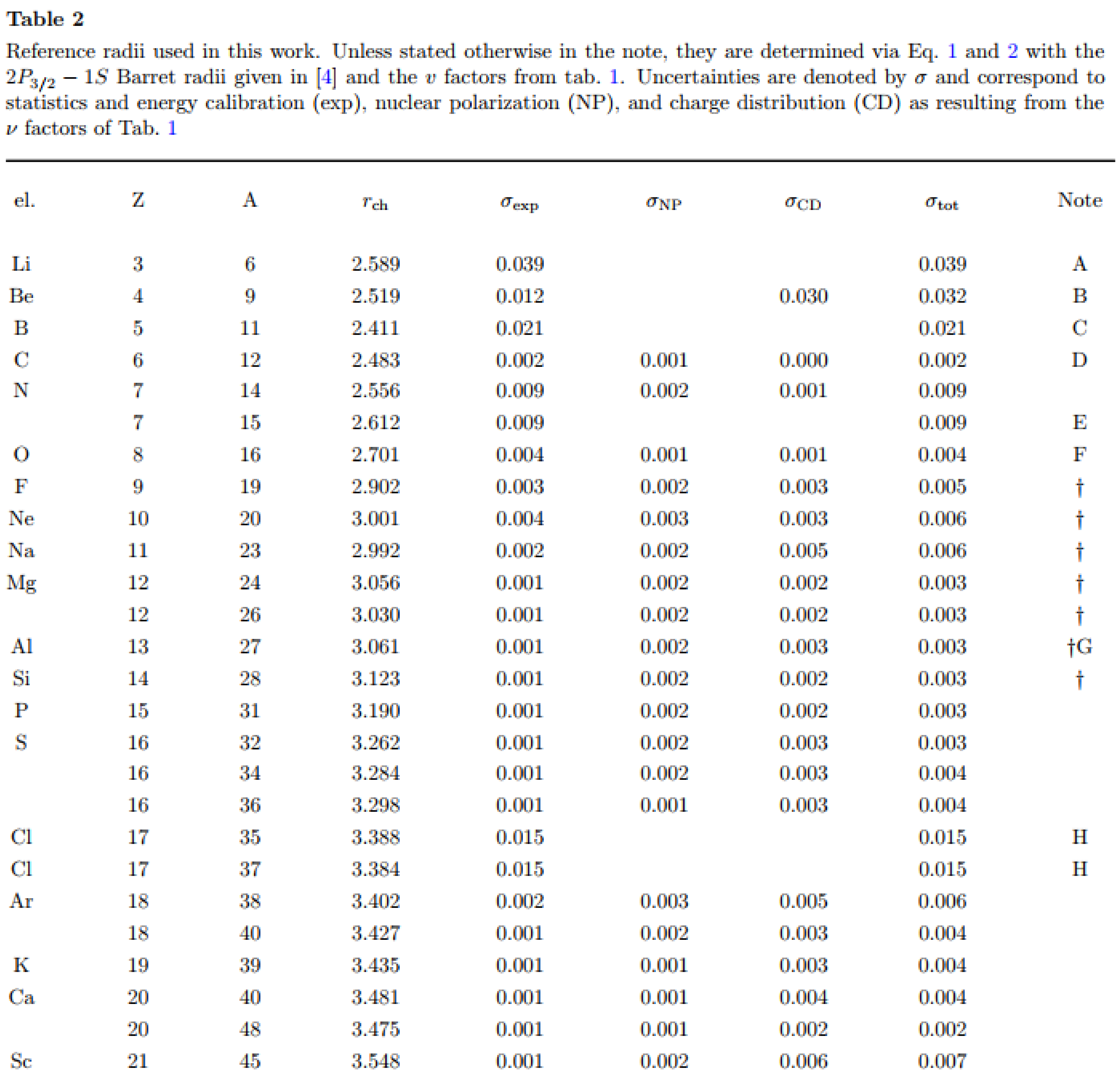

Table 2

Reference radii used in this work. Unless stated otherwise in the note, they are determined via Eq. 1 and 2 with the $2P_{3/2}-1S$ Barret radii given in [4] and the v factors from tab. 1. Uncertainties are denoted by σ and correspond to statistics and energy calibration (exp), nuclear polarization (NP), and charge distribution (CD) as resulting from the ν factors of Tab. 1

el.	Z	A	r_{ch}	σ_{exp}	σ_{NP}	σ_{CD}	σ_{tot}	Note
Li	3	6	2.589	0.039			0.039	A
Be	4	9	2.519	0.012		0.030	0.032	B
B	5	11	2.411	0.021			0.021	C
C	6	12	2.483	0.002	0.001	0.000	0.002	D
N	7	14	2.556	0.009	0.002	0.001	0.009	
	7	15	2.612	0.009			0.009	E
O	8	16	2.701	0.004	0.001	0.001	0.004	F
F	9	19	2.902	0.003	0.002	0.003	0.005	†
Ne	10	20	3.001	0.004	0.003	0.003	0.006	†
Na	11	23	2.992	0.002	0.002	0.005	0.006	†
Mg	12	24	3.056	0.001	0.002	0.002	0.003	†
	12	26	3.030	0.001	0.002	0.002	0.003	†
Al	13	27	3.061	0.001	0.002	0.003	0.003	†G
Si	14	28	3.123	0.001	0.002	0.002	0.003	†
P	15	31	3.190	0.001	0.002	0.002	0.003	
S	16	32	3.262	0.001	0.002	0.003	0.003	
	16	34	3.284	0.001	0.002	0.003	0.004	
	16	36	3.298	0.001	0.001	0.003	0.004	
Cl	17	35	3.388	0.015			0.015	H
Cl	17	37	3.384	0.015			0.015	H
Ar	18	38	3.402	0.002	0.003	0.005	0.006	
	18	40	3.427	0.001	0.002	0.003	0.004	
K	19	39	3.435	0.001	0.001	0.003	0.004	
Ca	20	40	3.481	0.001	0.001	0.004	0.004	
	20	48	3.475	0.001	0.001	0.002	0.002	
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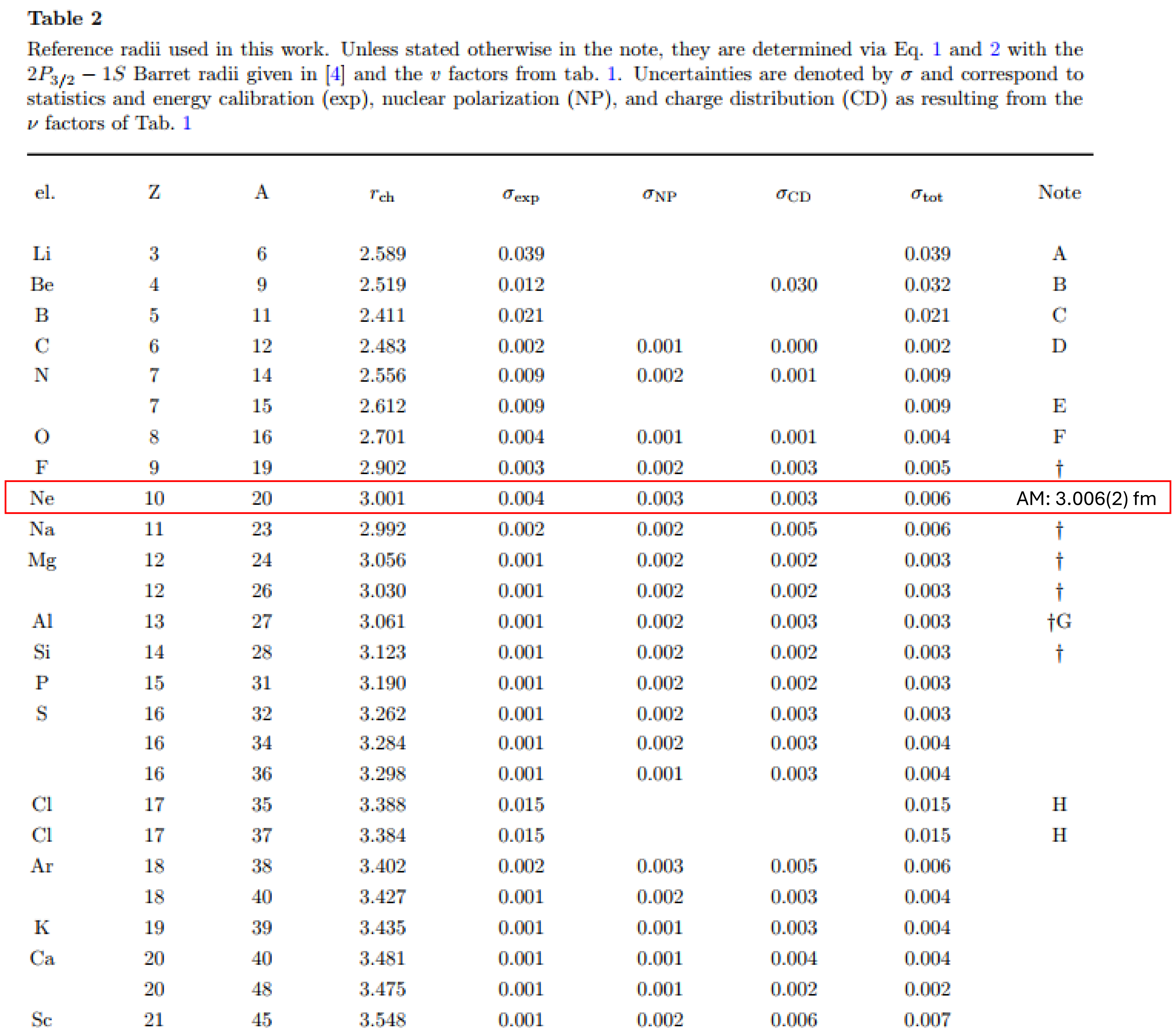

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Example:

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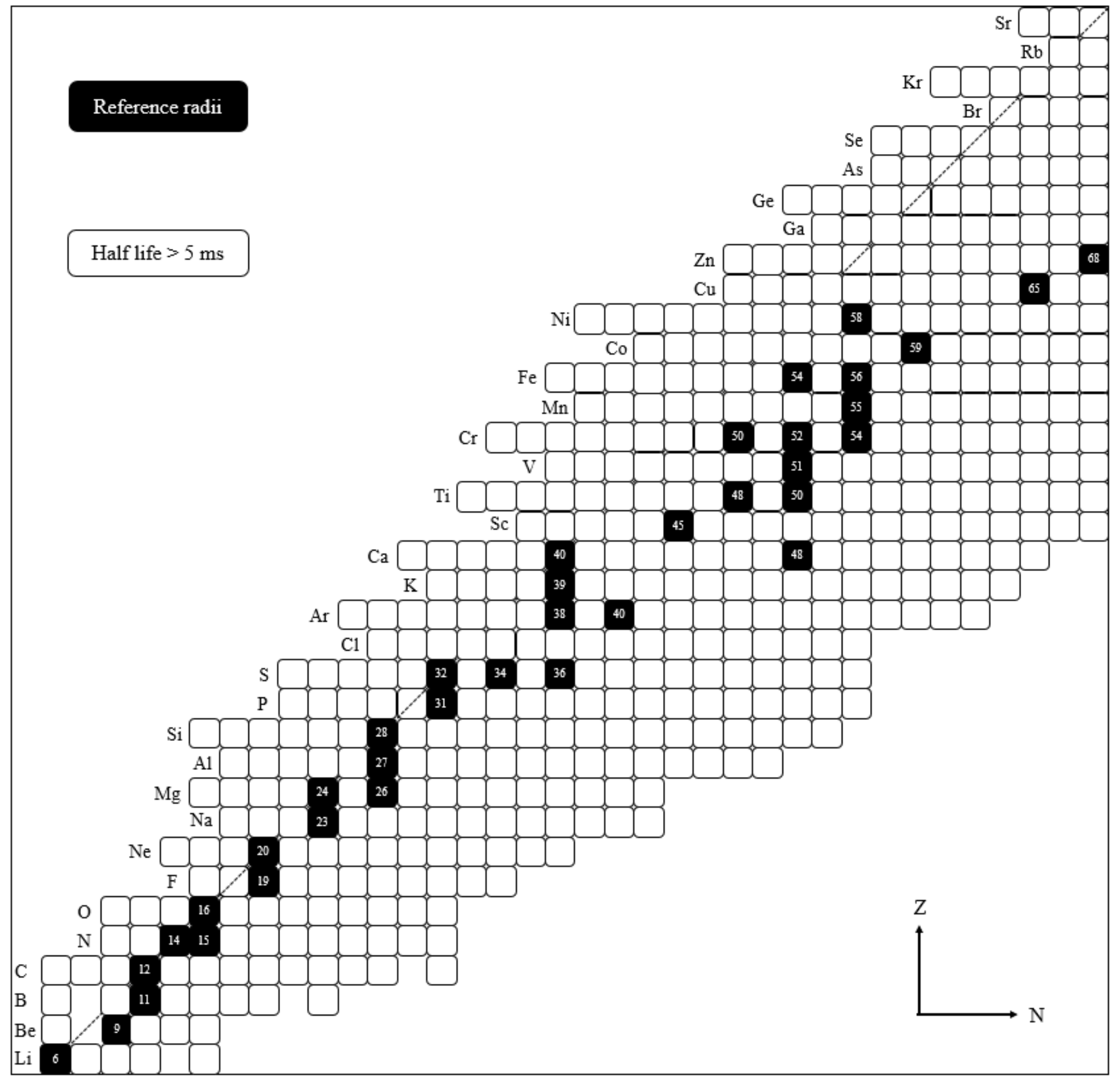

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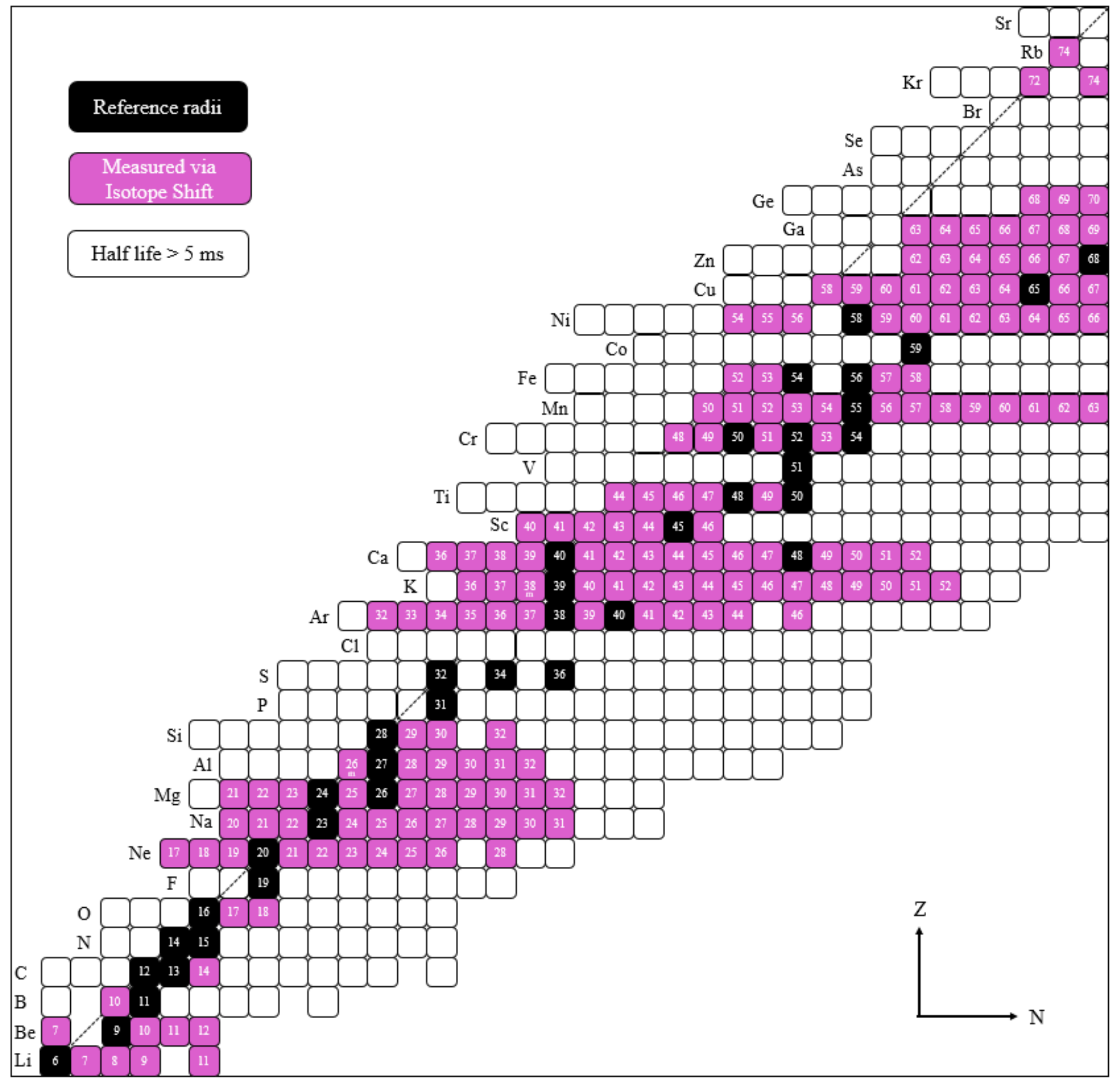

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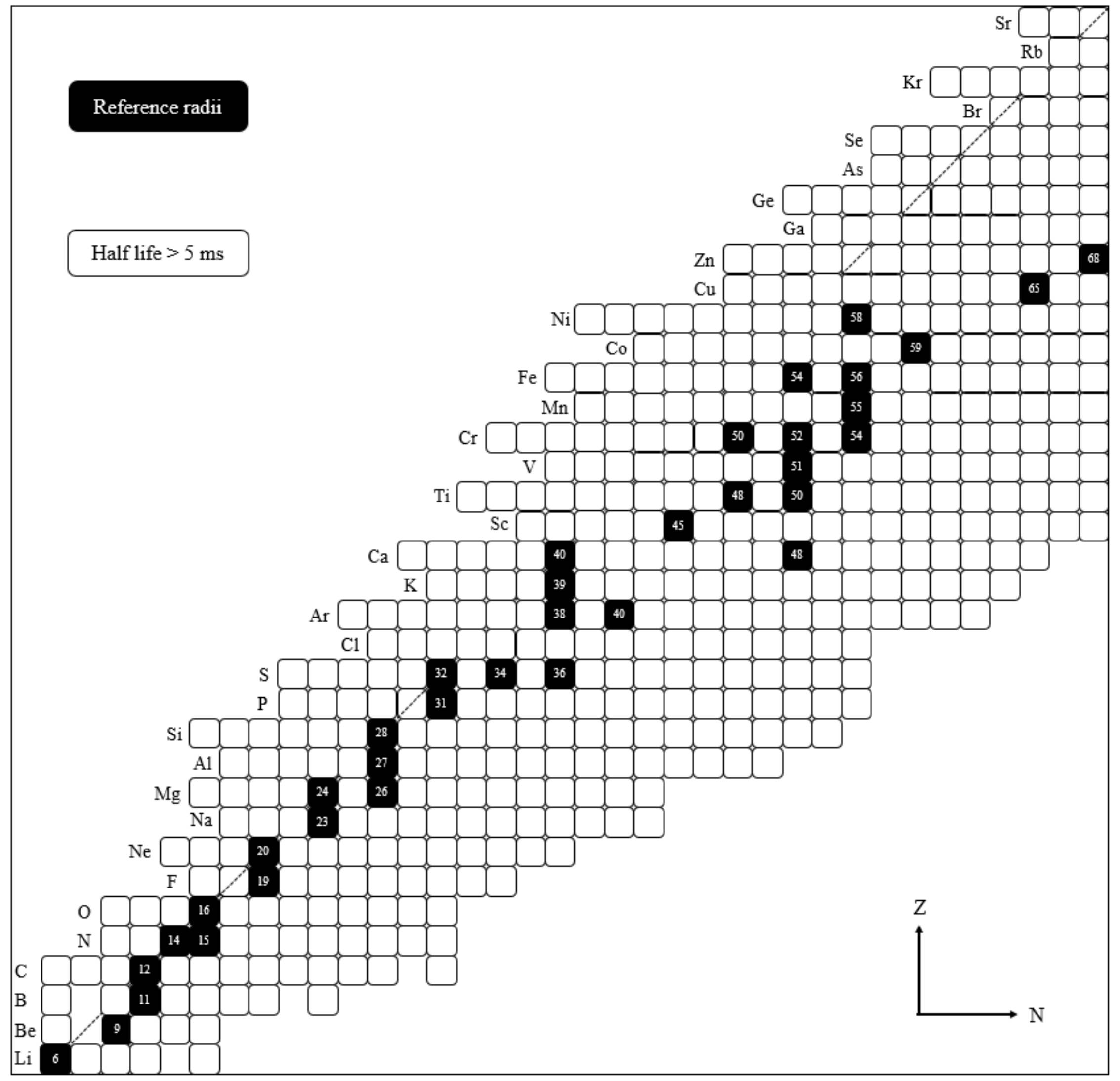

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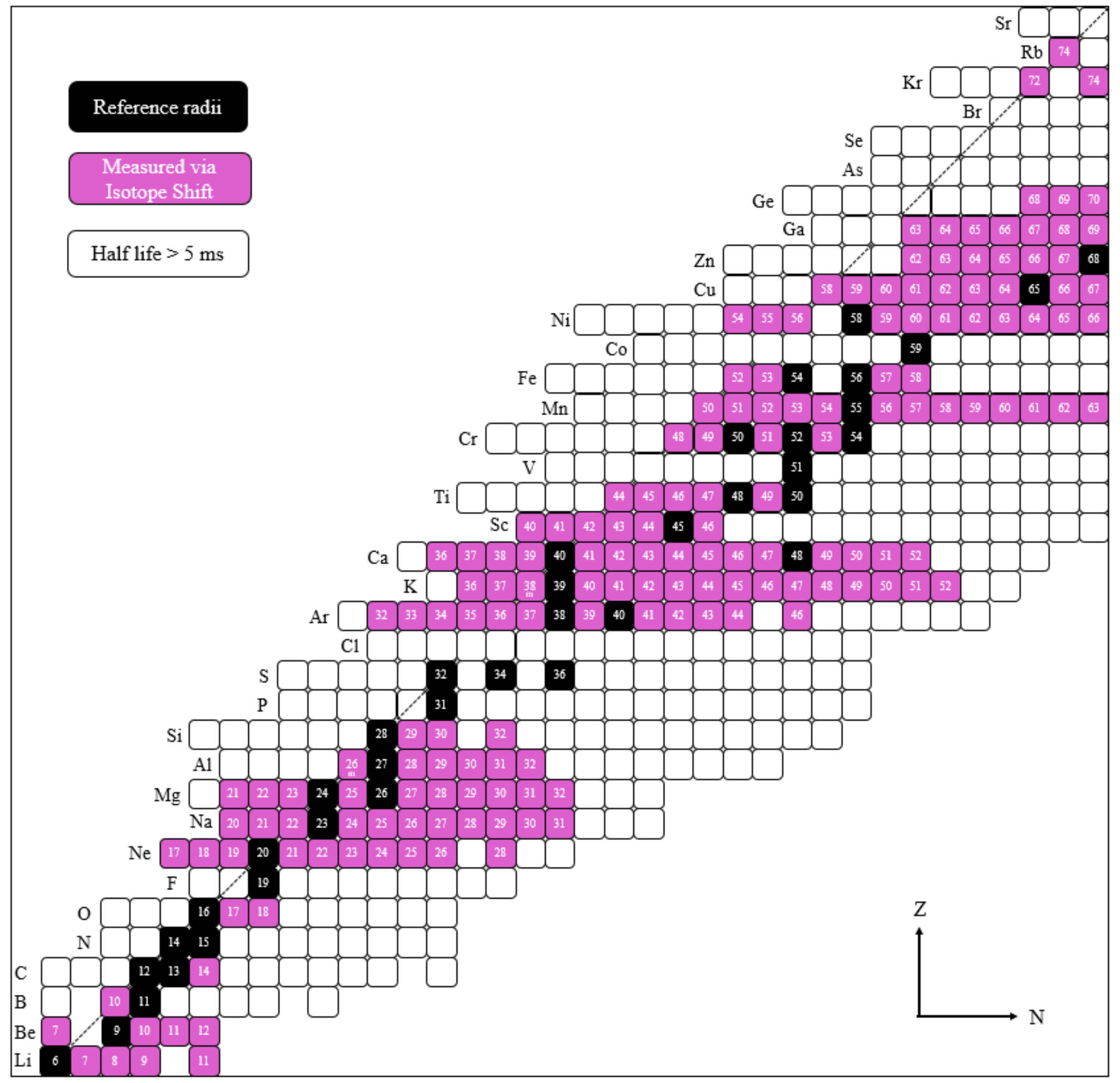

$$r_x^2 = r_{ref}^2 + \delta r_{a,x}^2$$

$$\wr$$

$$\frac{IS_{a,x} - K\mu_{a,x}}{F}$$

Isotope shift

Mass factor - Penning traps

Atomic Factors (King plot / Calc.)

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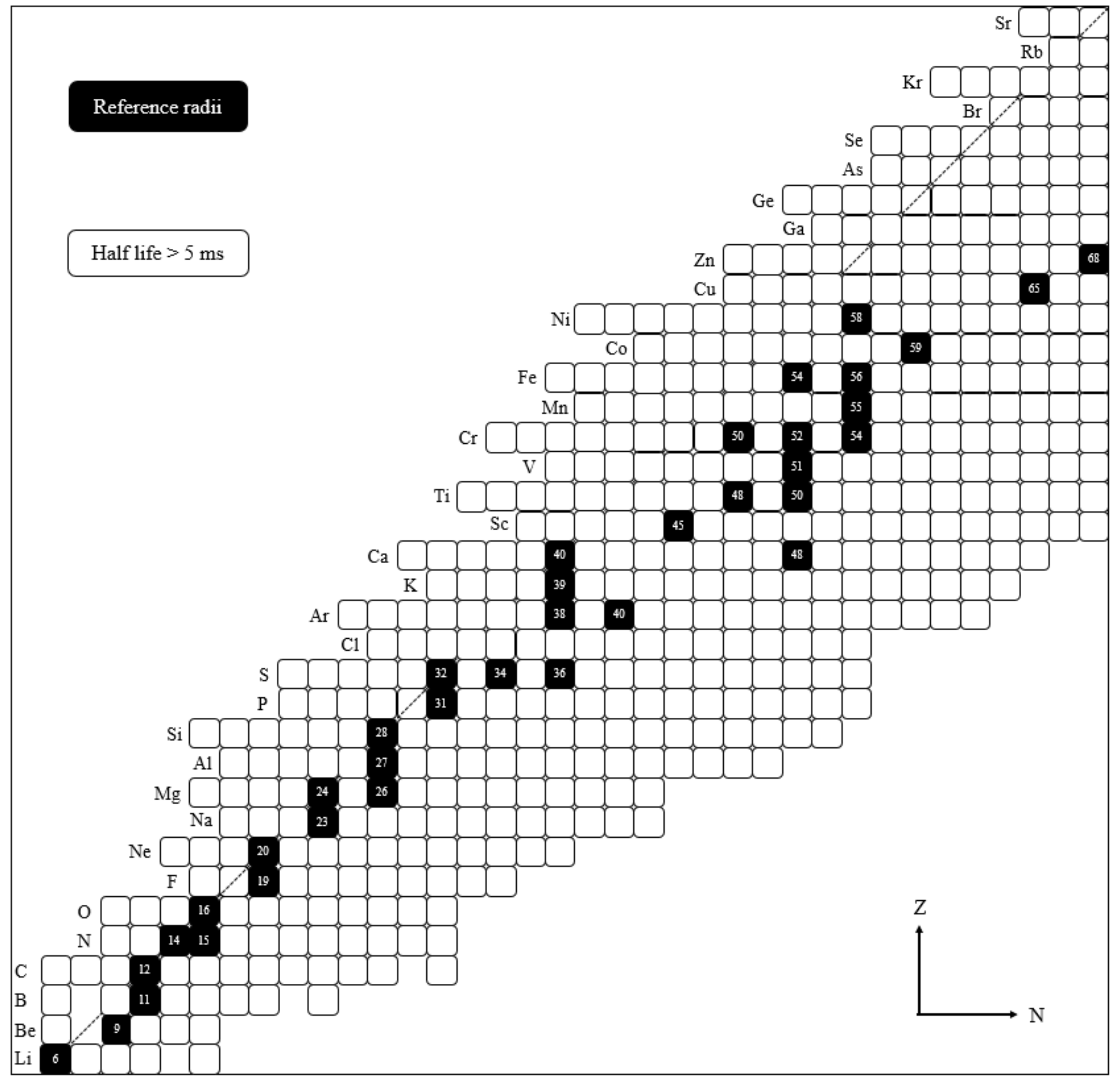

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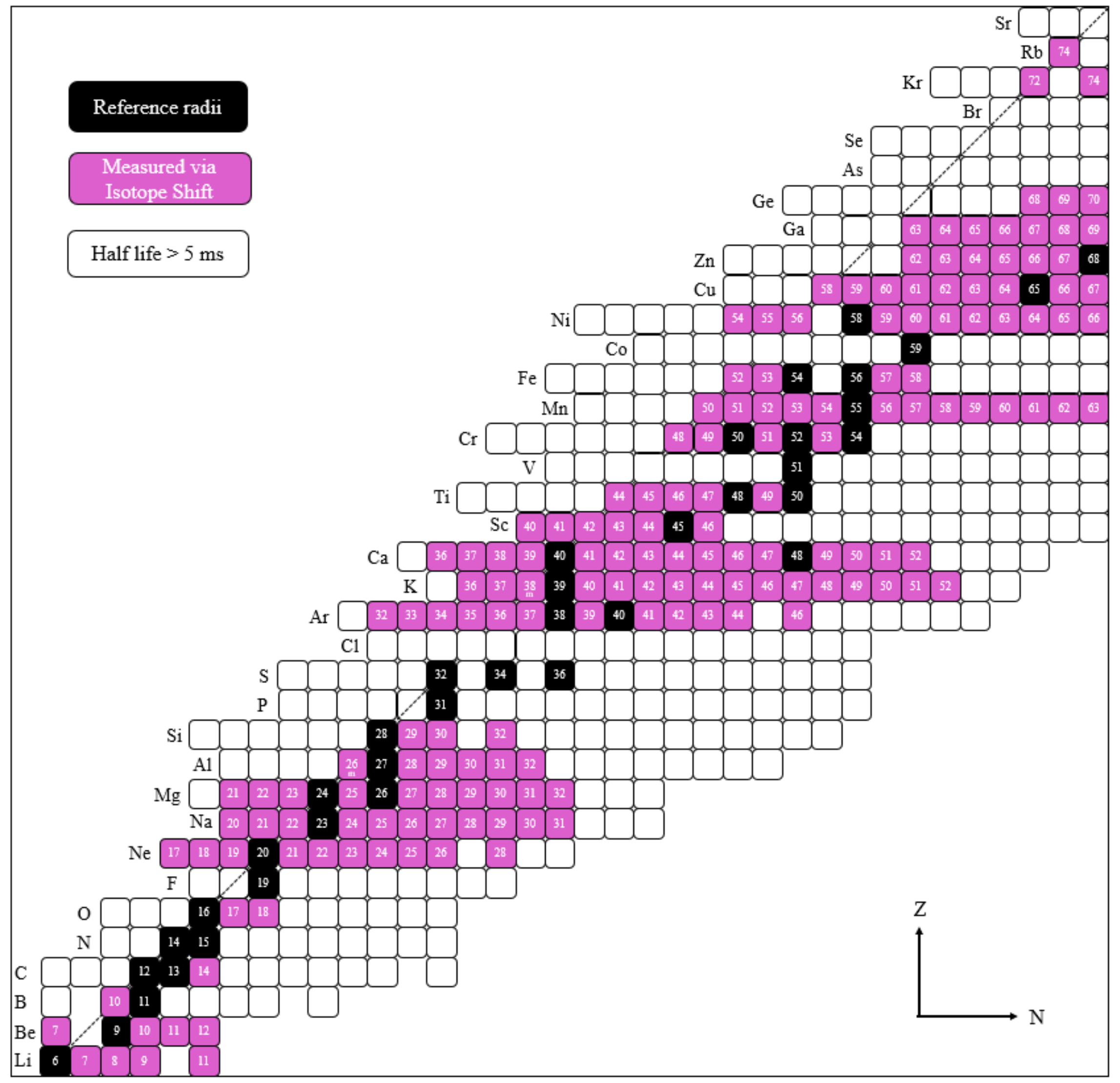


$$r_x^2 = r_{ref}^2 + \delta r_{a,x}^2$$

$$\approx \frac{IS_{a,x} - K\mu_{a,x}}{F}$$

Isotope shift

Mass factor - Penning traps

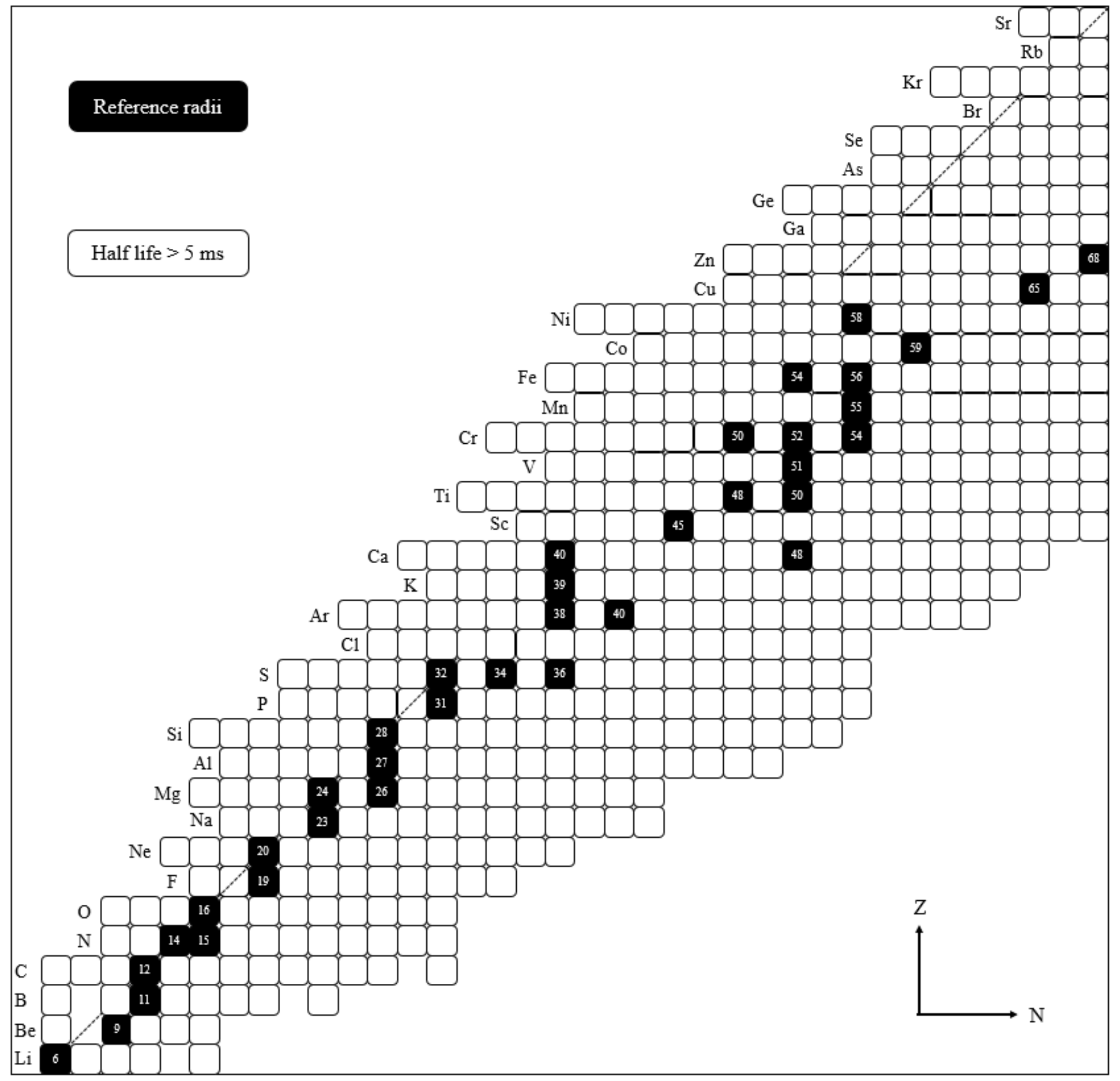
Atomic Factors (King plot / Calc.)

Step 2 : Update differential radii:

- Go over original publications (no compilations)
- Include some missing atomic theory uncertainties.
- Update neon chain using novel g-factor difference measurement at MPK

Roadmap:

1. **Reference radii** (muonic atoms)



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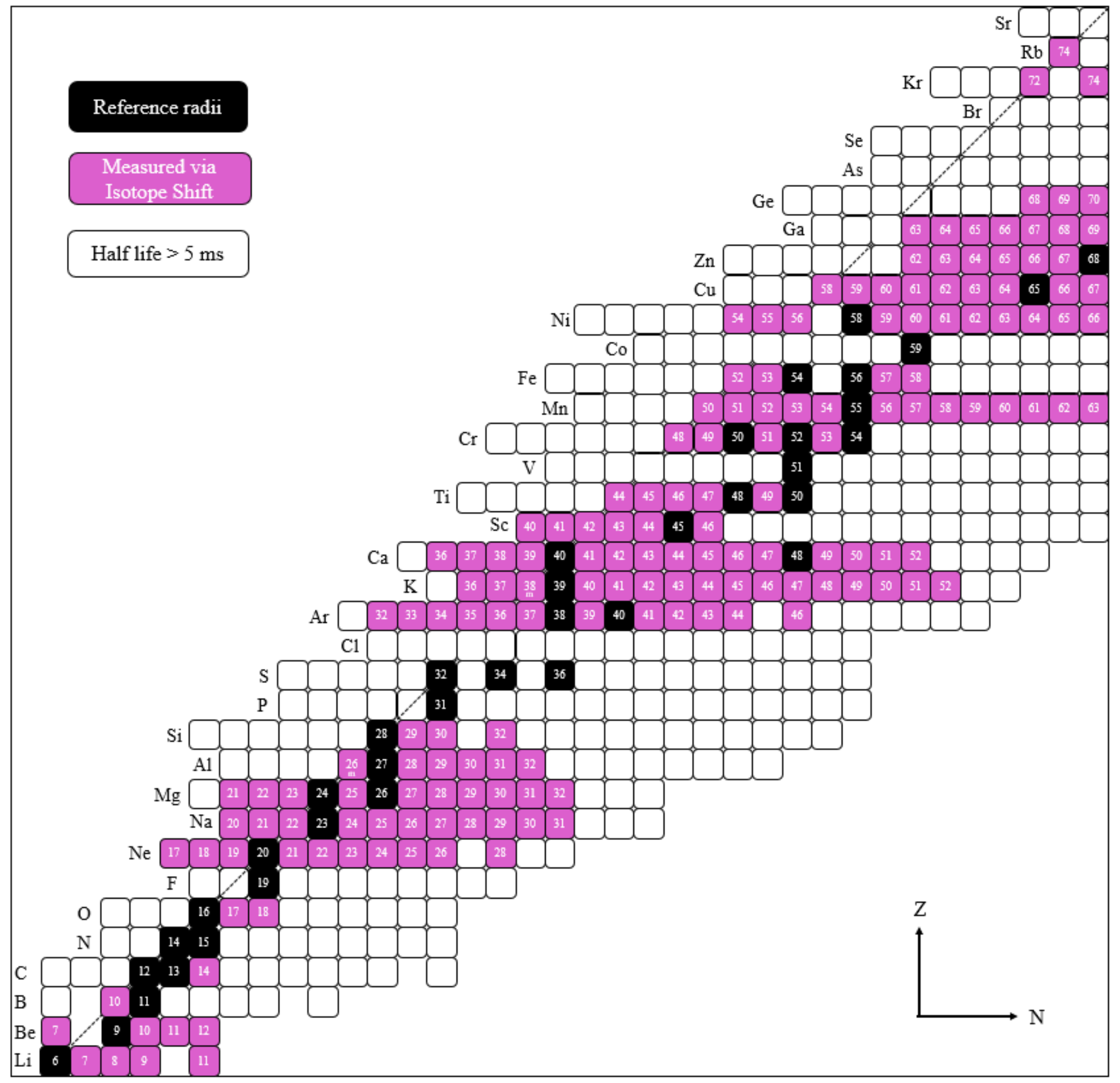

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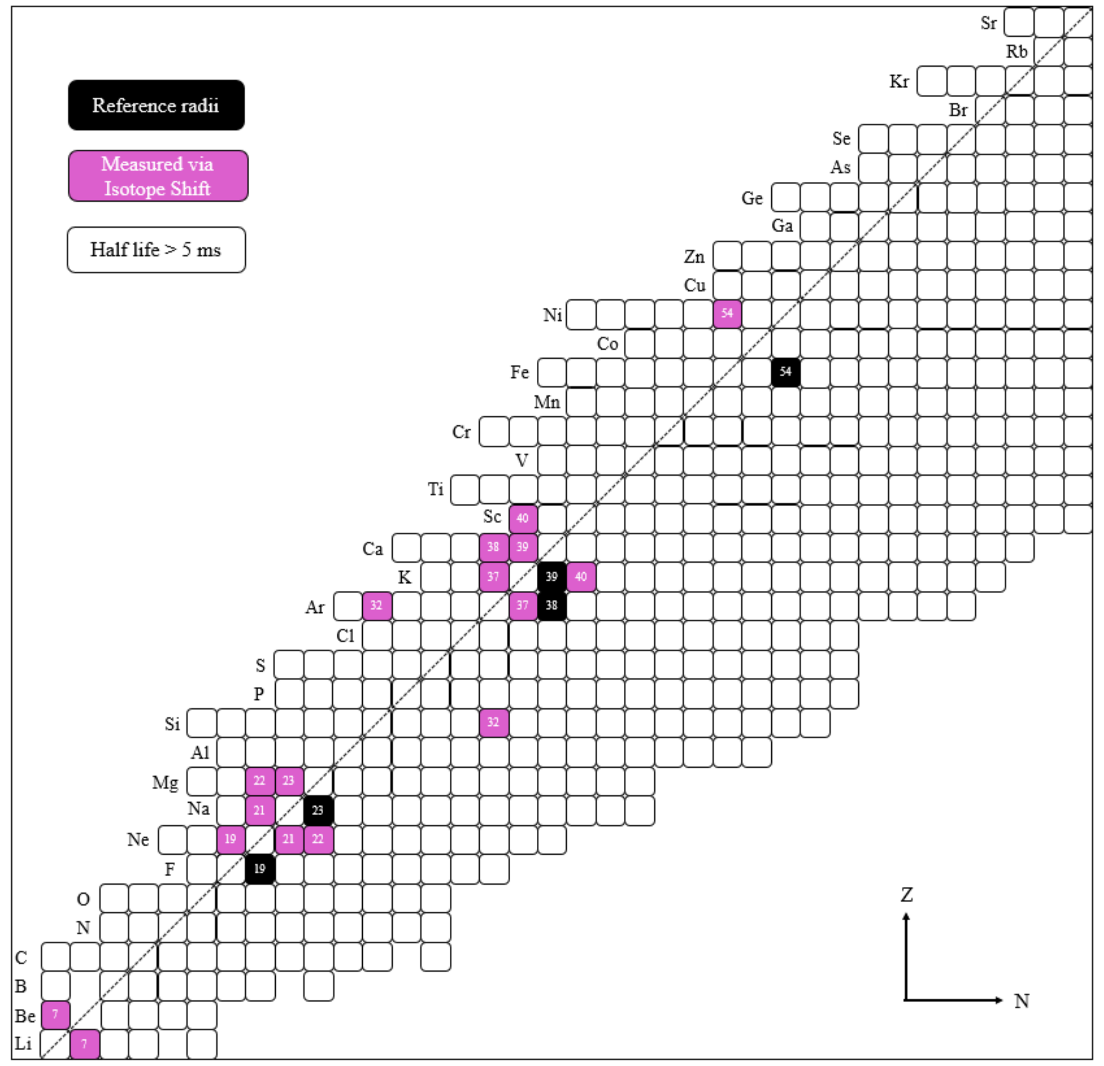

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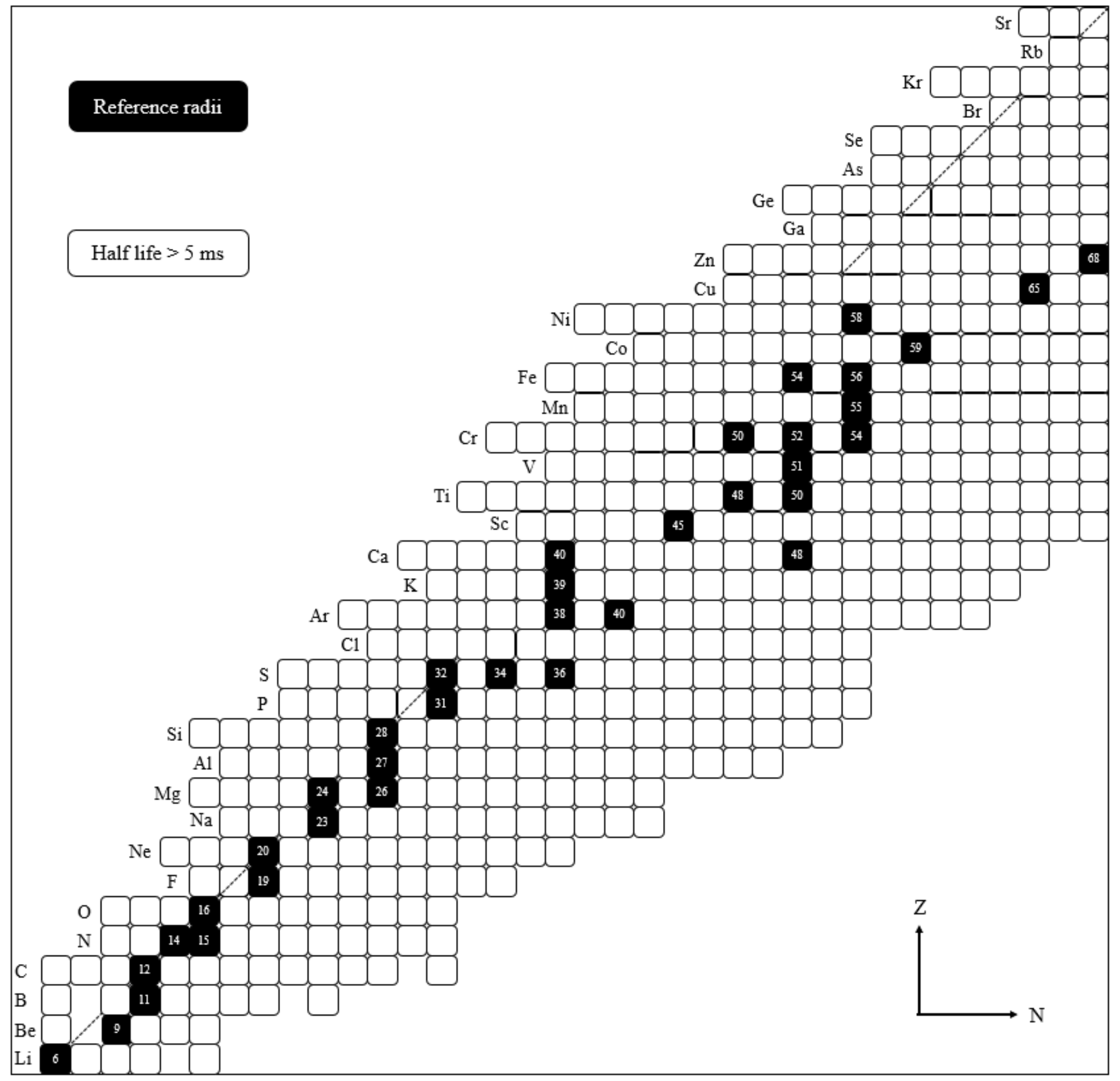

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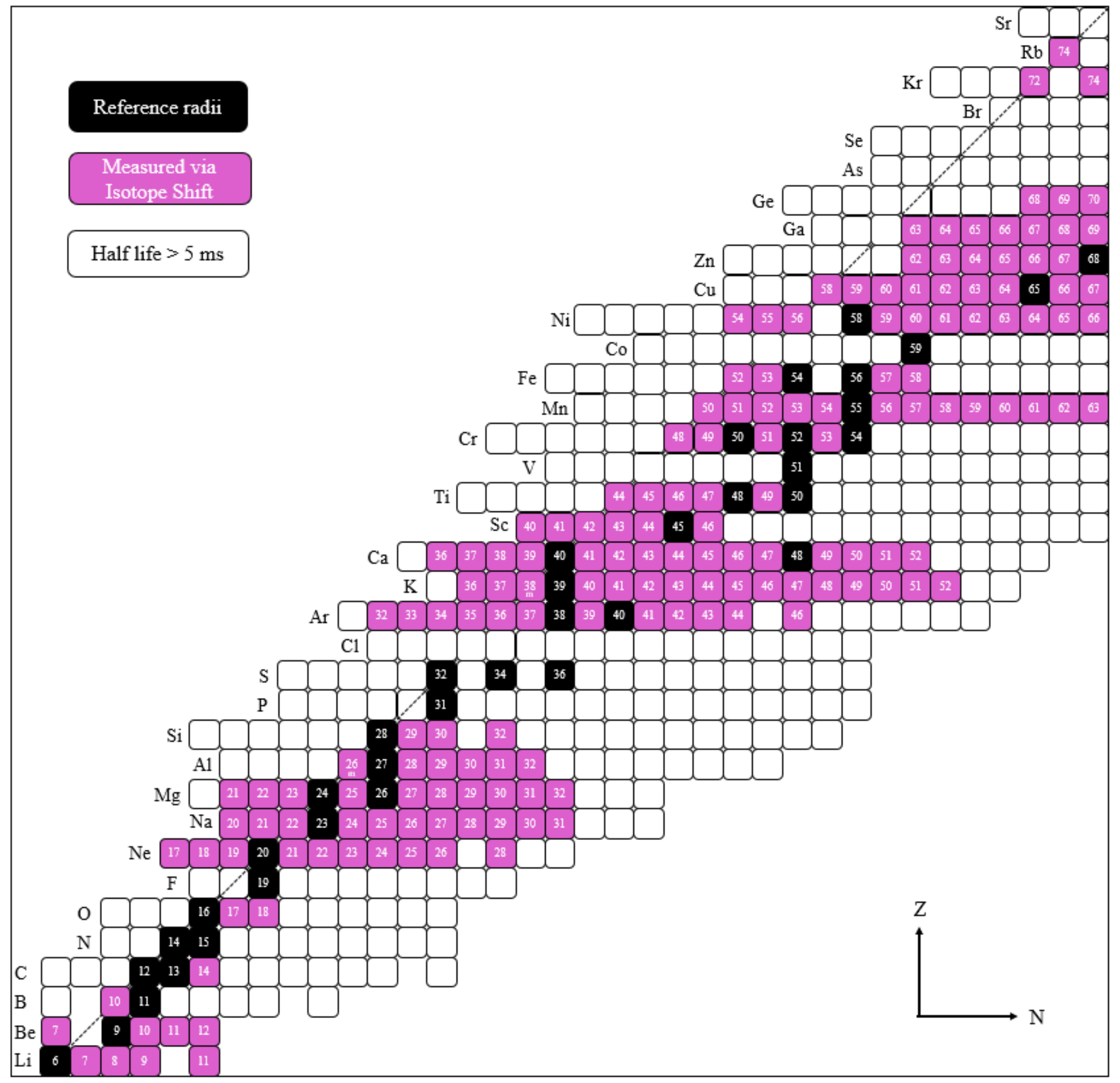

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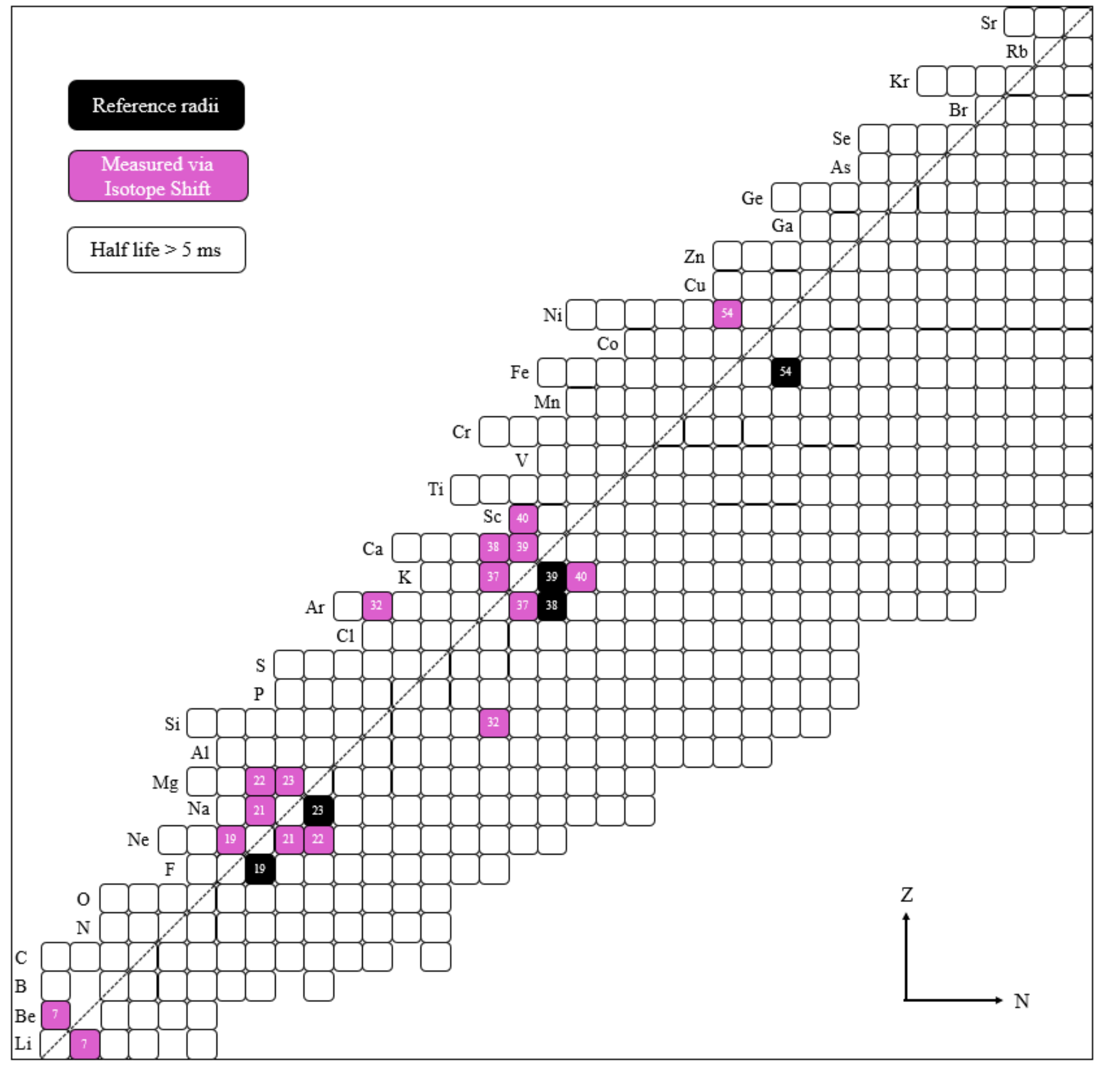

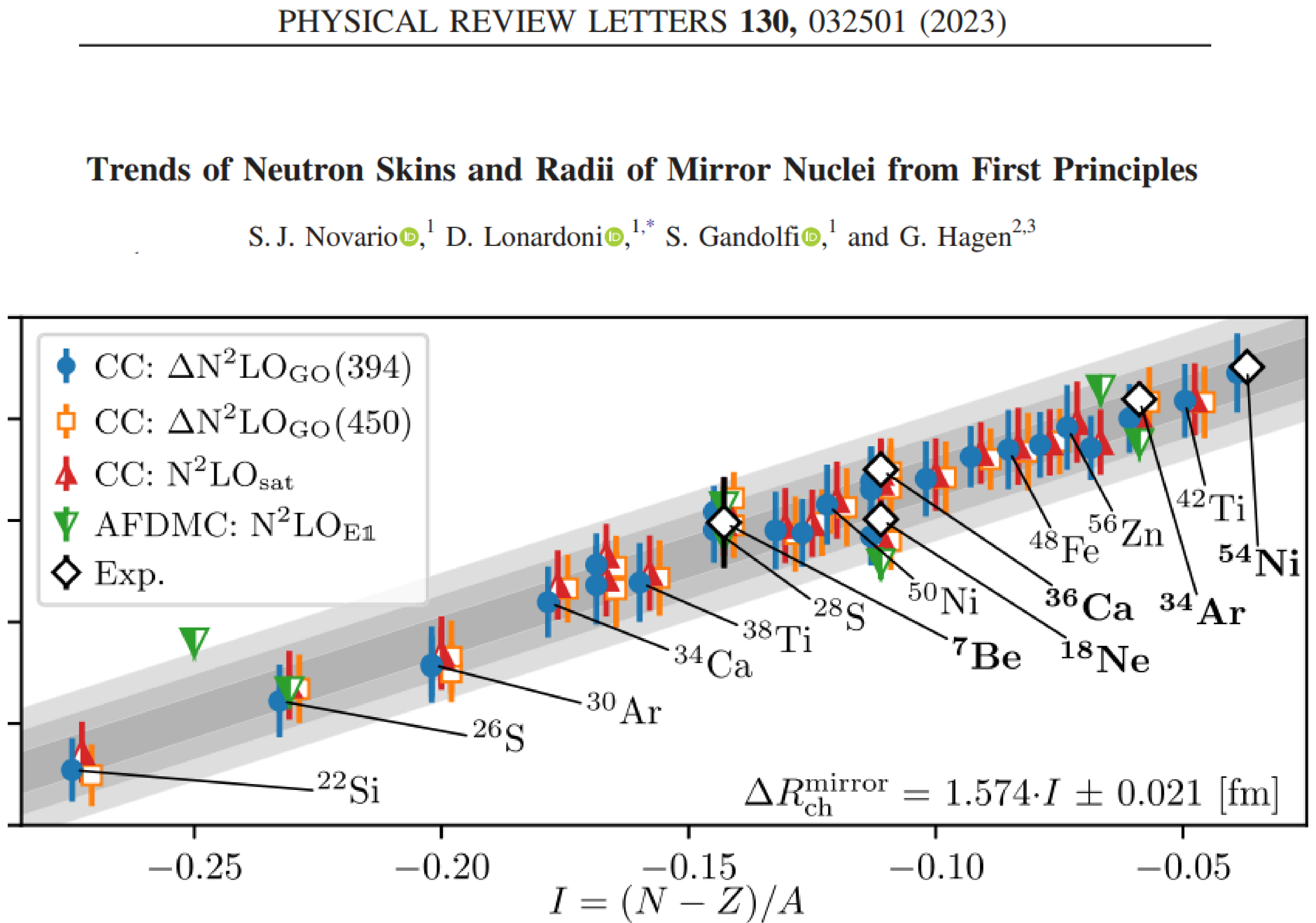

PHYSICAL REVIEW LETTERS **130,** 032501 (2023)

Trends of Neutron Skins and Radii of Mirror Nuclei from First Principles

S. J. Novario,[1] D. Lonardoni,[1,*] S. Gandolfi,[1] and G. Hagen[2,3]

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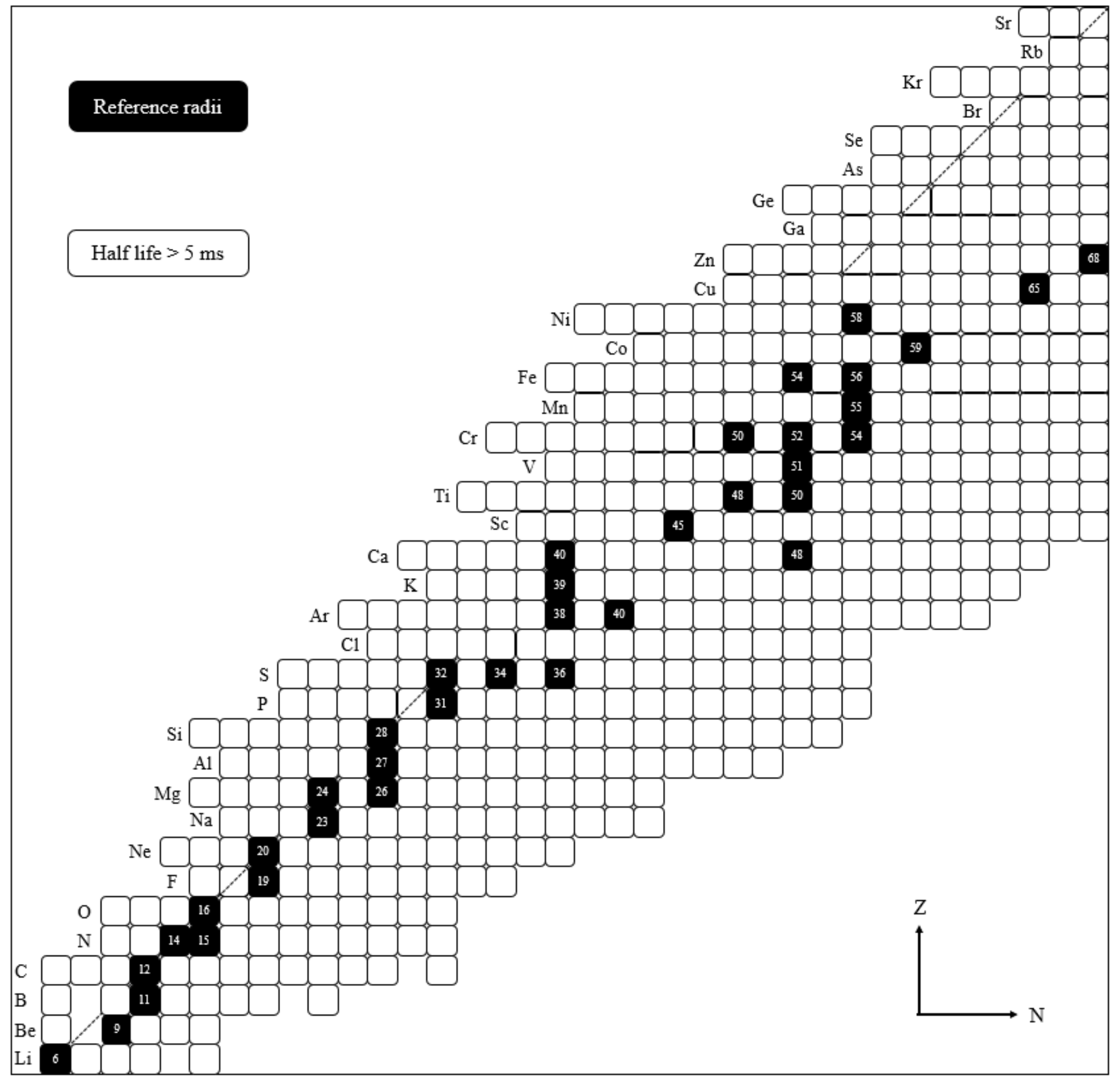

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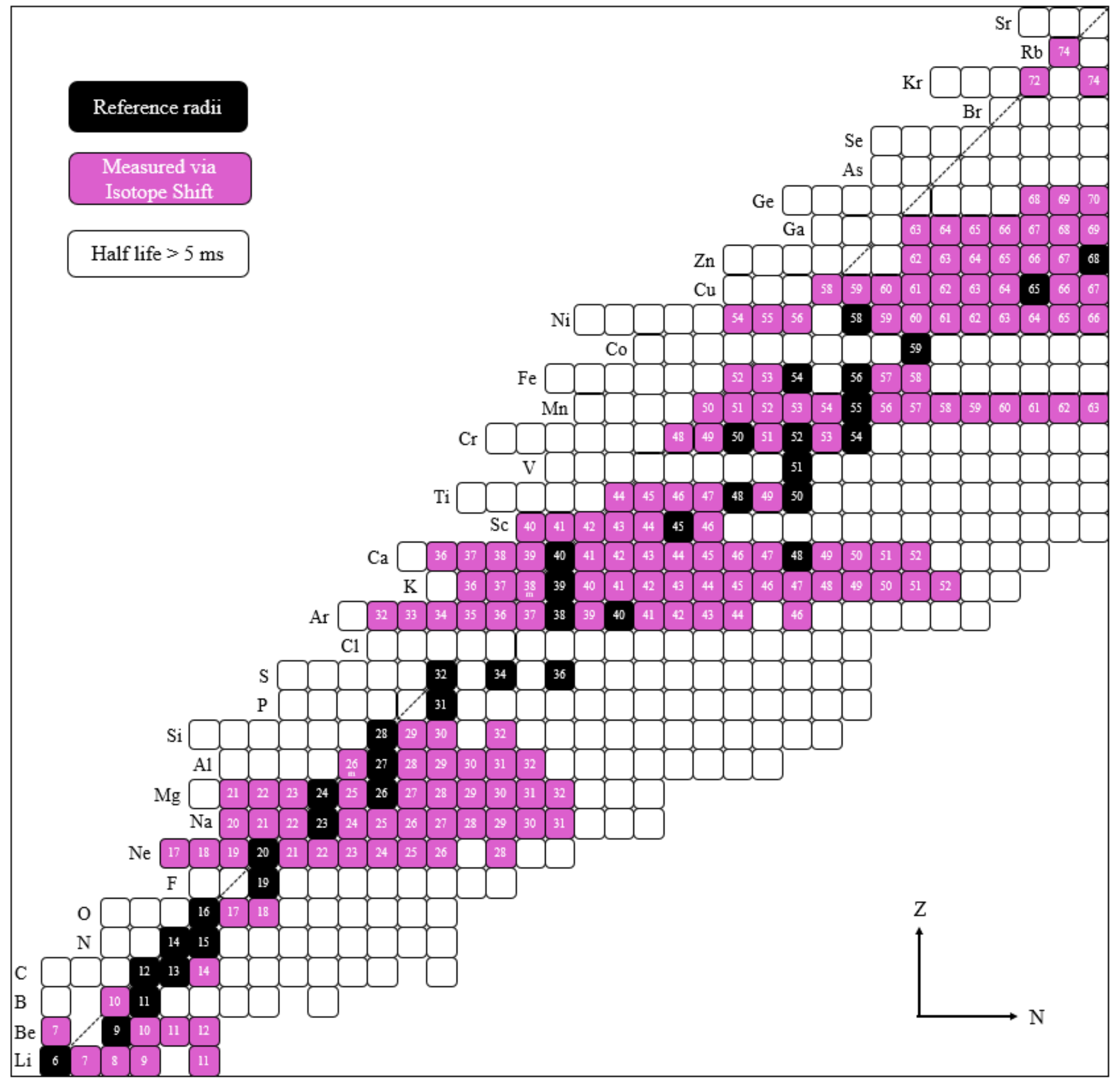

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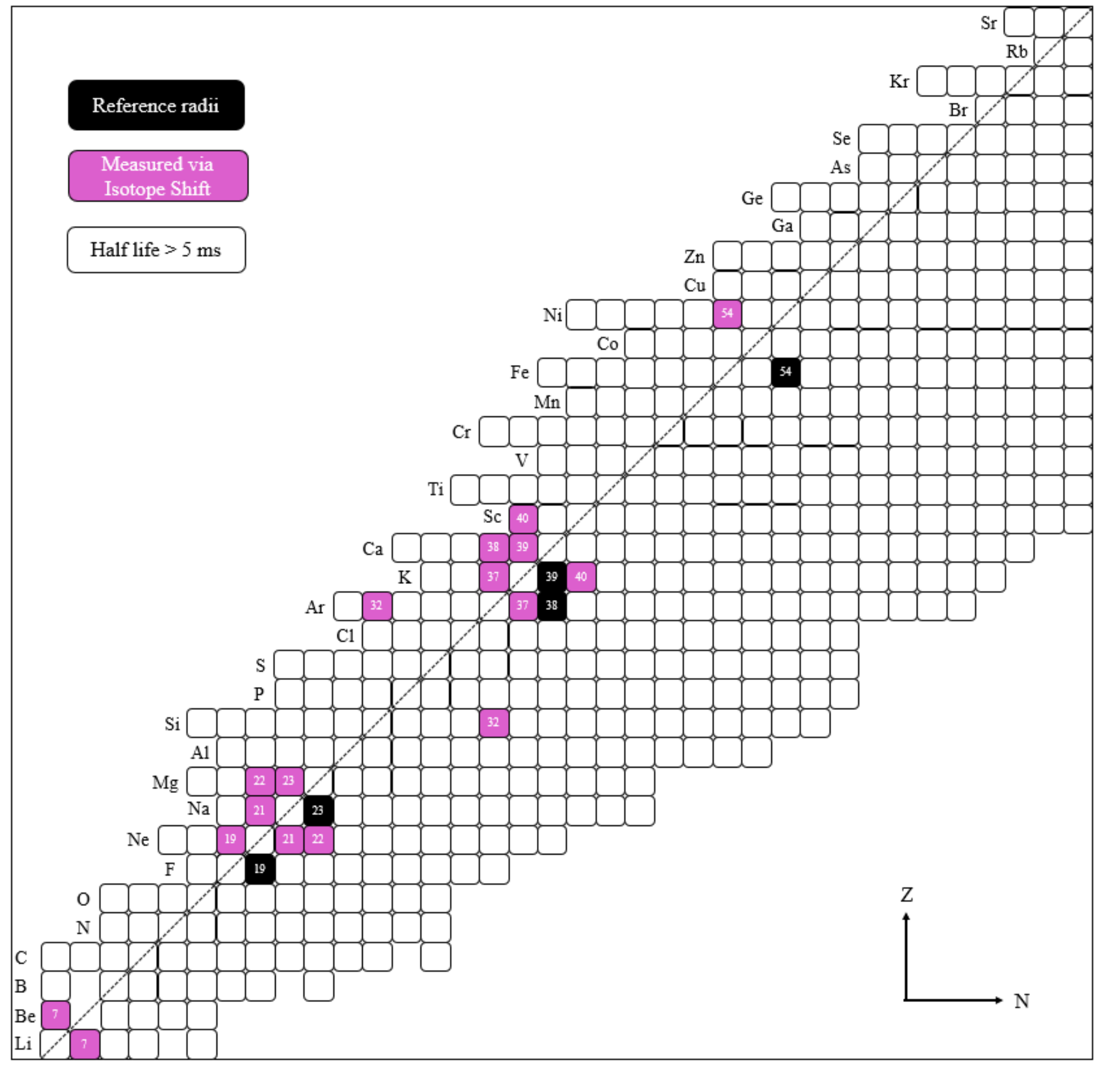

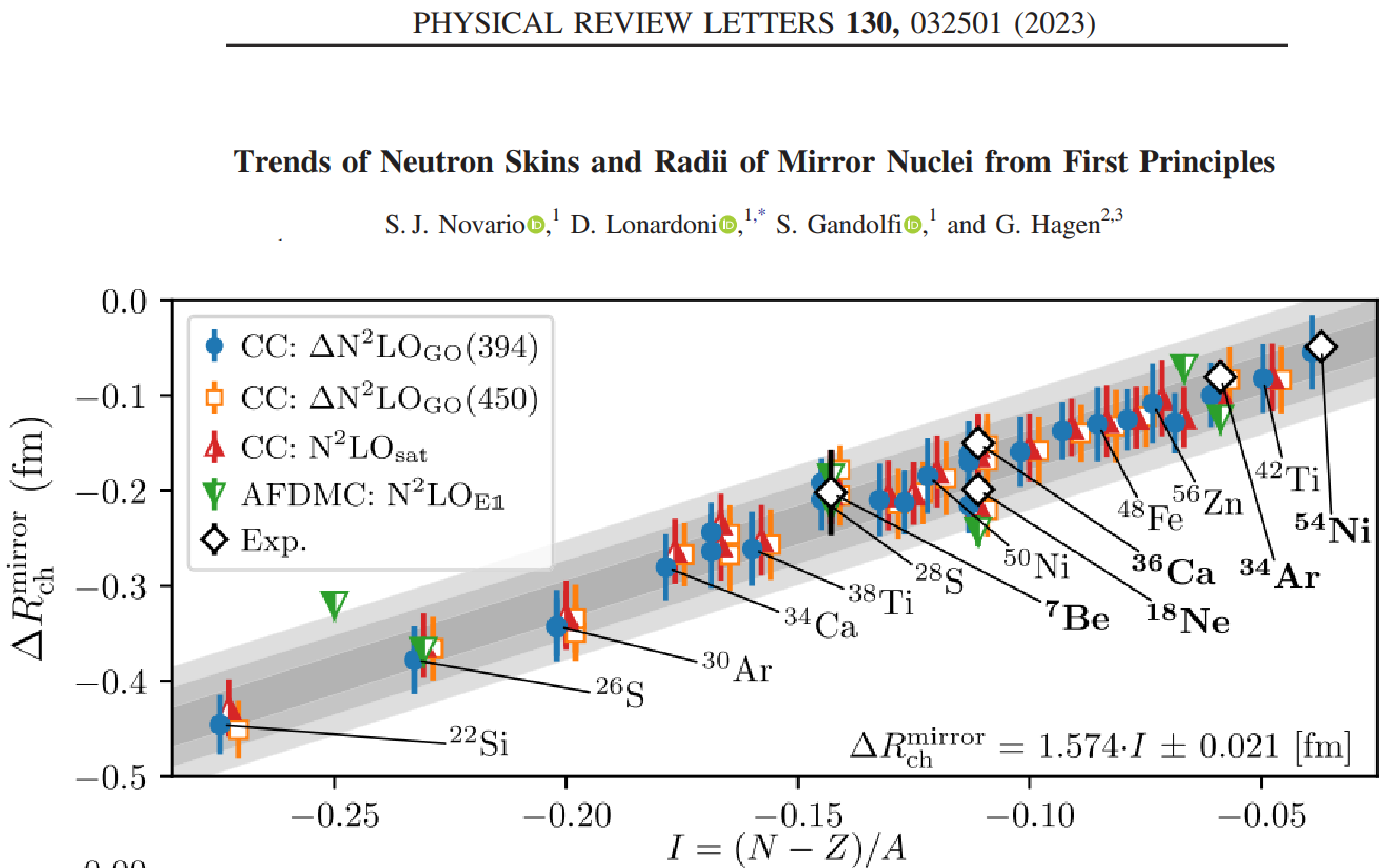

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Step 3 : Update experimental data on mirror nuclei

Updated mirror shift fit:

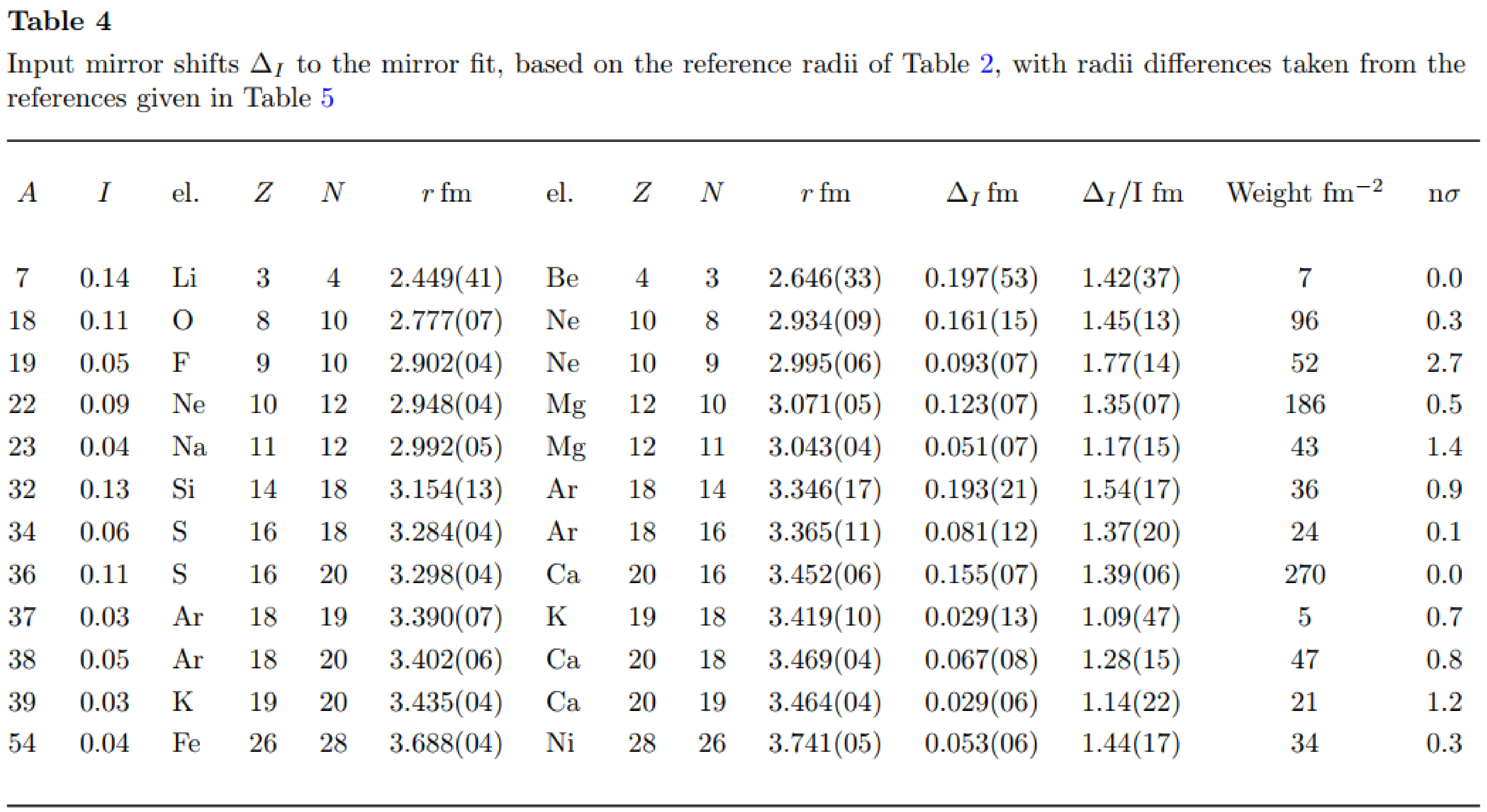

Table 4

Input mirror shifts Δ_I to the mirror fit, based on the reference radii of Table 2, with radii differences taken from the references given in Table 5

A	I	el.	Z	N	r fm	el.	Z	N	r fm	Δ_I fm	Δ_I/I fm	Weight fm^{-2}	nσ
7	0.14	Li	3	4	2.449(41)	Be	4	3	2.646(33)	0.197(53)	1.42(37)	7	0.0
18	0.11	O	8	10	2.777(07)	Ne	10	8	2.934(09)	0.161(15)	1.45(13)	96	0.3
19	0.05	F	9	10	2.902(04)	Ne	10	9	2.995(06)	0.093(07)	1.77(14)	52	2.7
22	0.09	Ne	10	12	2.948(04)	Mg	12	10	3.071(05)	0.123(07)	1.35(07)	186	0.5
23	0.04	Na	11	12	2.992(05)	Mg	12	11	3.043(04)	0.051(07)	1.17(15)	43	1.4
32	0.13	Si	14	18	3.154(13)	Ar	18	14	3.346(17)	0.193(21)	1.54(17)	36	0.9
34	0.06	S	16	18	3.284(04)	Ar	18	16	3.365(11)	0.081(12)	1.37(20)	24	0.1
36	0.11	S	16	20	3.298(04)	Ca	20	16	3.452(06)	0.155(07)	1.39(06)	270	0.0
37	0.03	Ar	18	19	3.390(07)	K	19	18	3.419(10)	0.029(13)	1.09(47)	5	0.7
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arXiv:2409.08193

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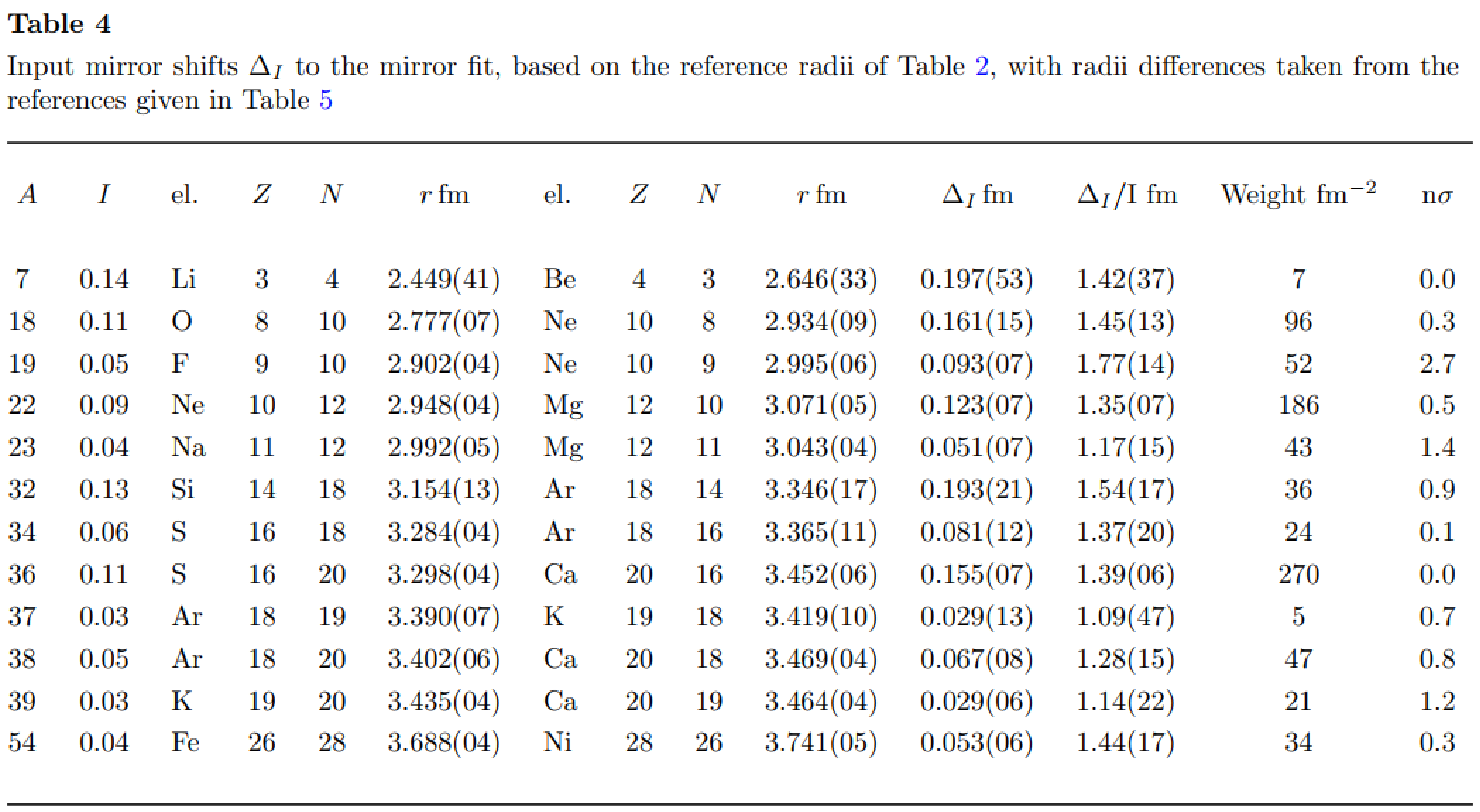

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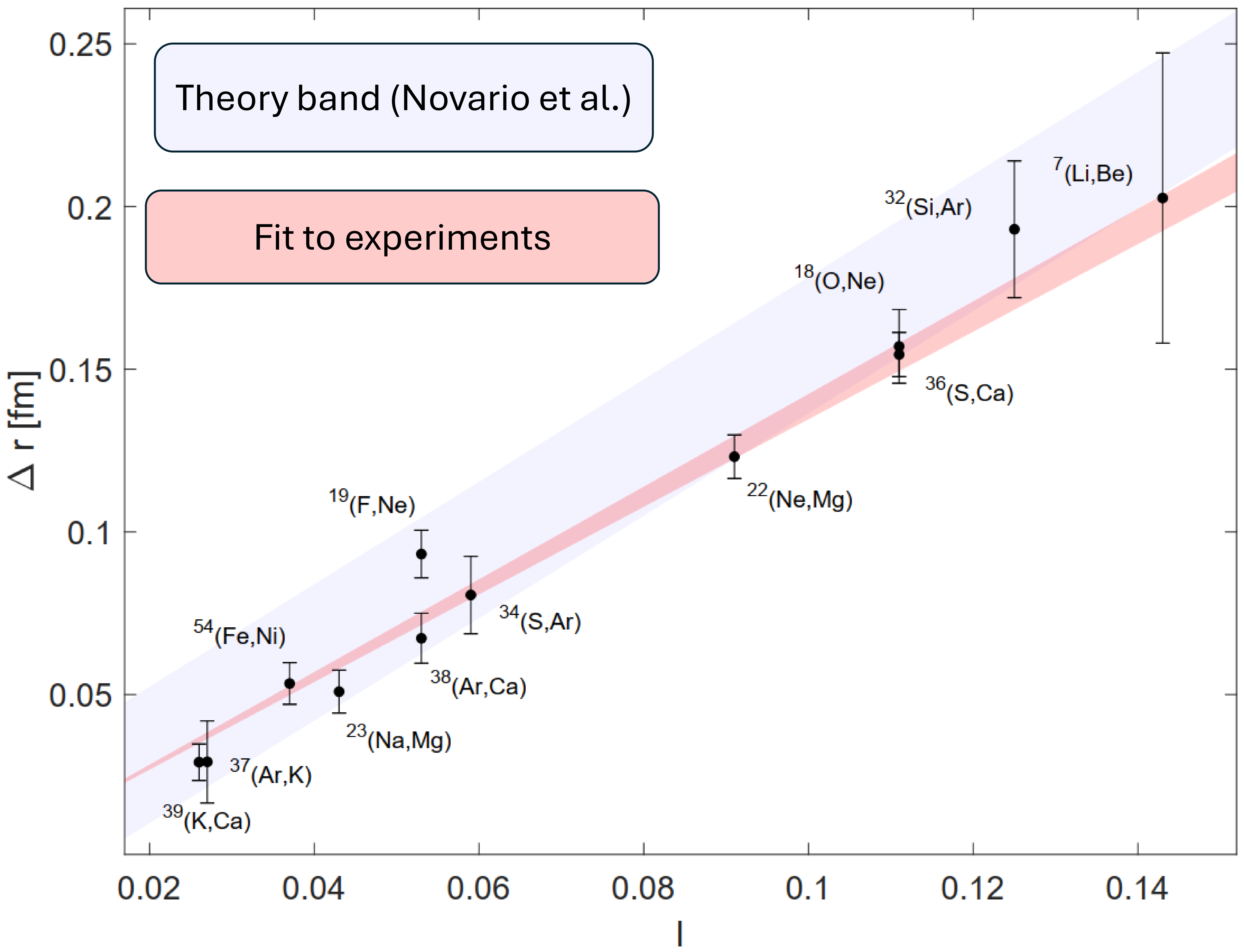
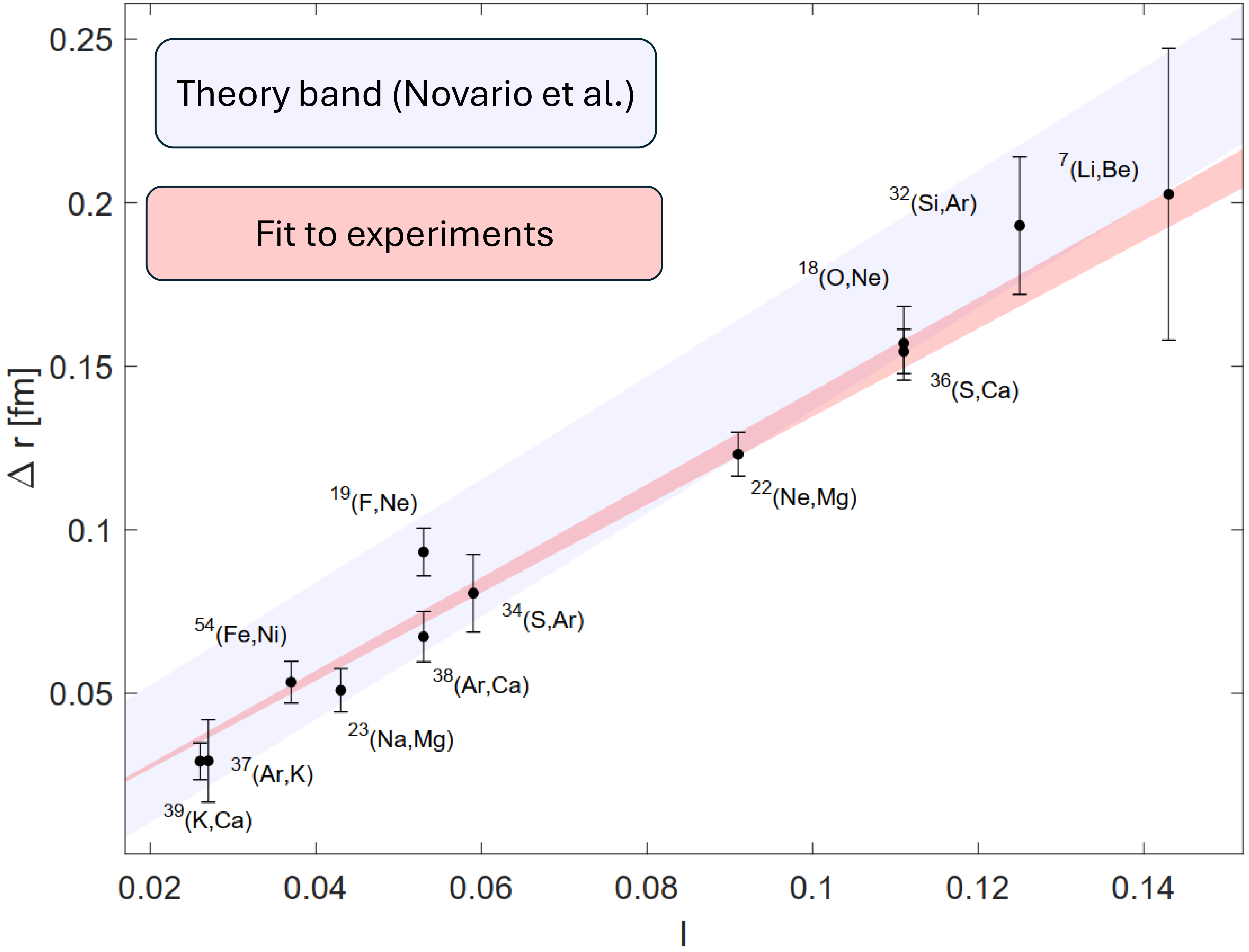


Step 4 - Updated mirror shift fit:

Fit result:

$$\Delta R_{ch}^{mirr}(I) = 1.38(3) \times I$$

- Agrees with theory band where these is accurate data, up to $I = 0.11$
- But missing accuracy for $0.11 < I$



Open questions:

- Does linearity hod at large asymmetry *I* ?
- Does the slope depend on mass?

PHYSICAL REVIEW C **110**, 014316 (2024)

Investigation of the difference in charge radii of mirror pairs with deep Bayesian neural networks

X. Zhang (张鑫),[1] H. He (何红斌),[2] G. Qu (曲国峰),[1] X. Liu (刘星泉),[1,*] H. Zheng (郑华),[2,†]
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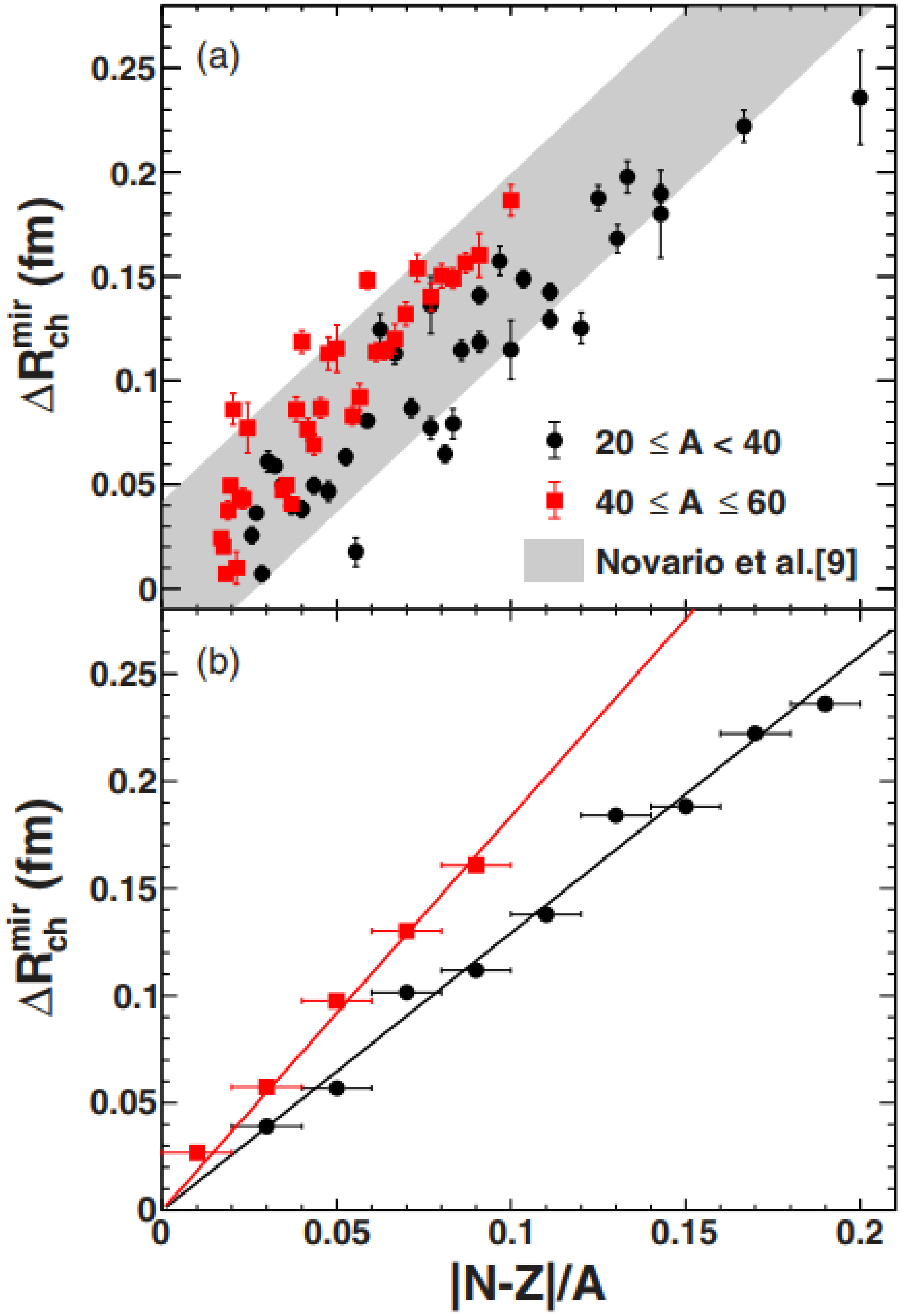

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- **Light nuclei are key**

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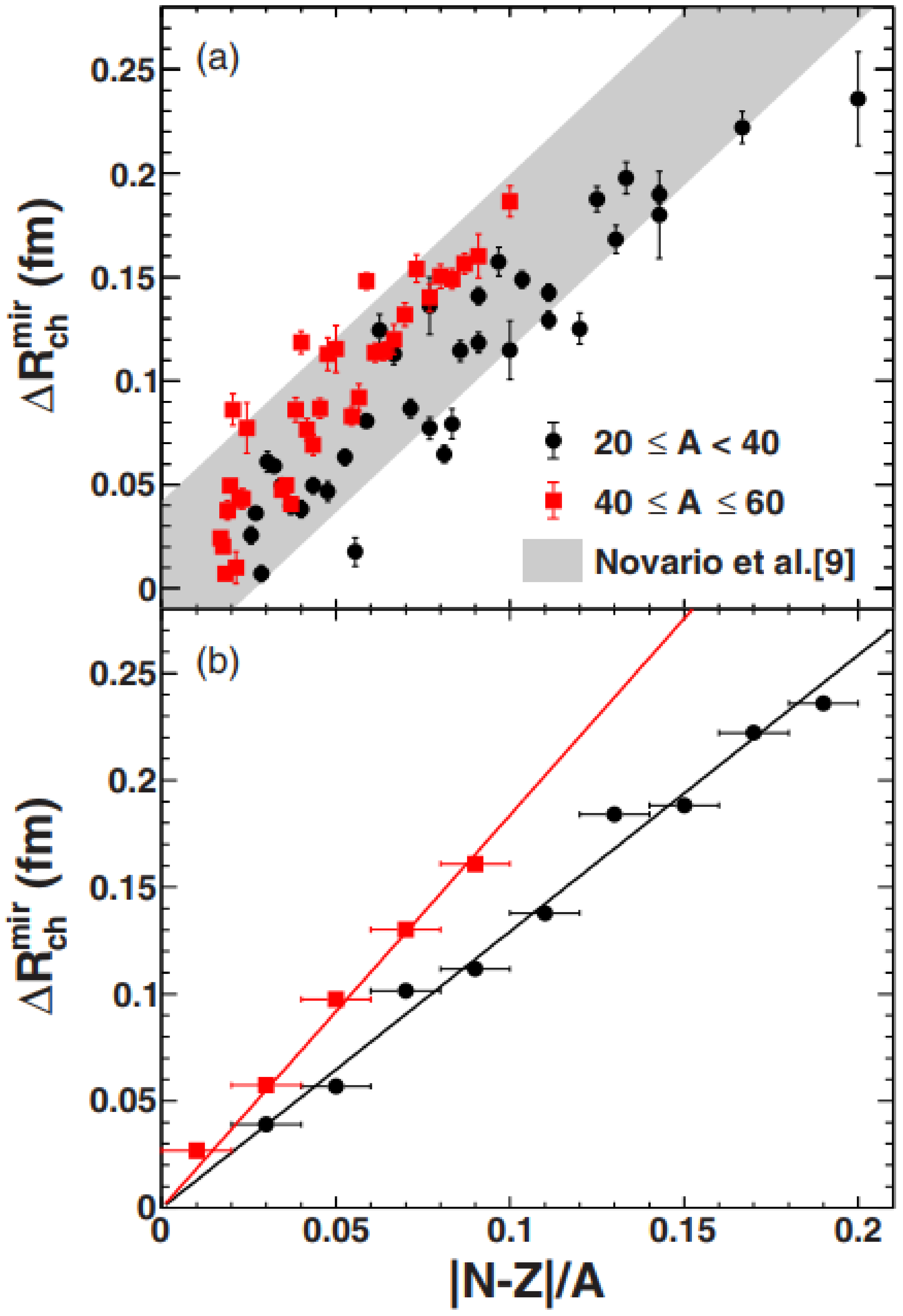
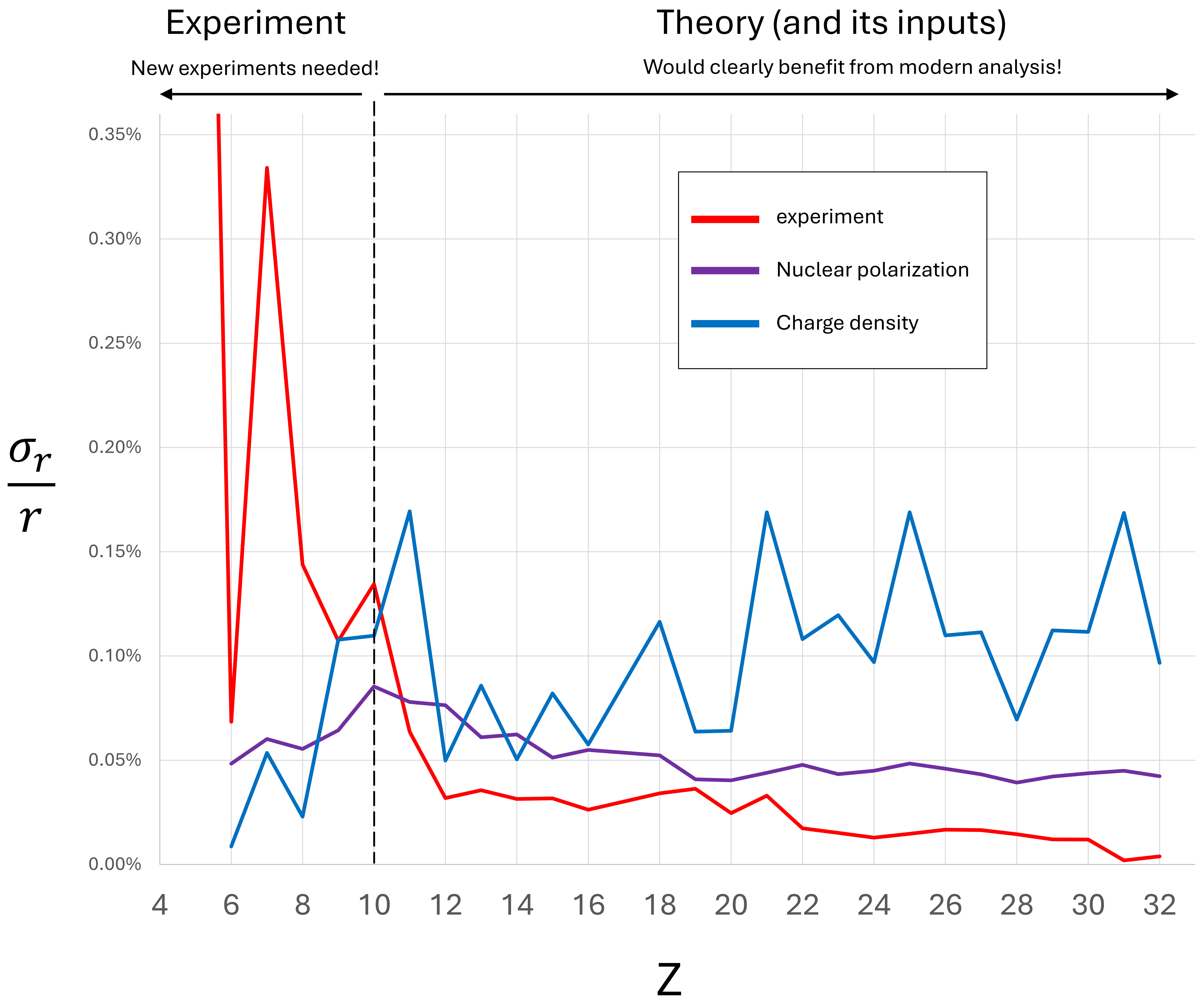


Sources of uncertainty :

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



Experiment

New experiments needed!

Theory (and its inputs)

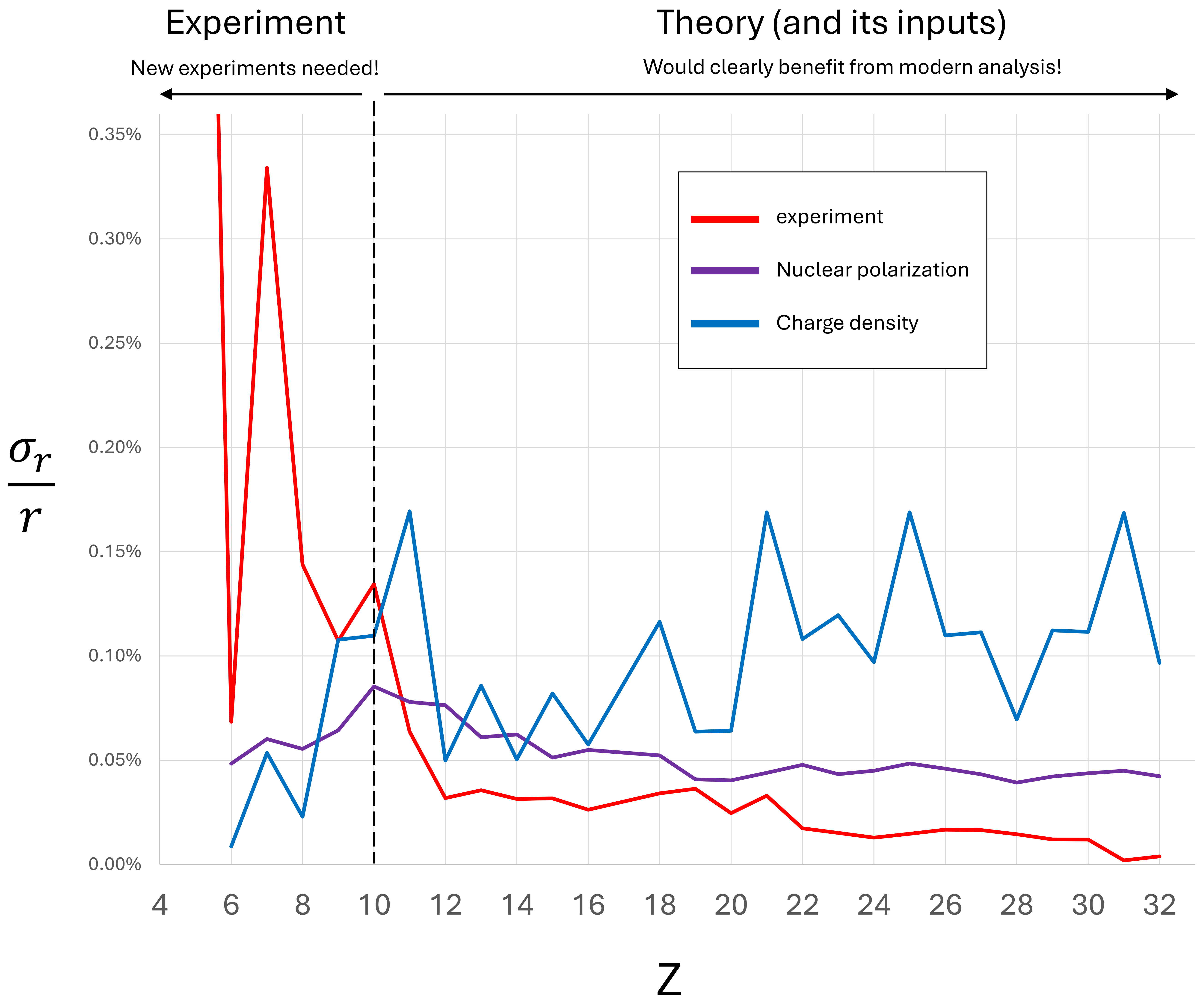
Would clearly benefit from modern analysis!

bohayon@technion.ac.il

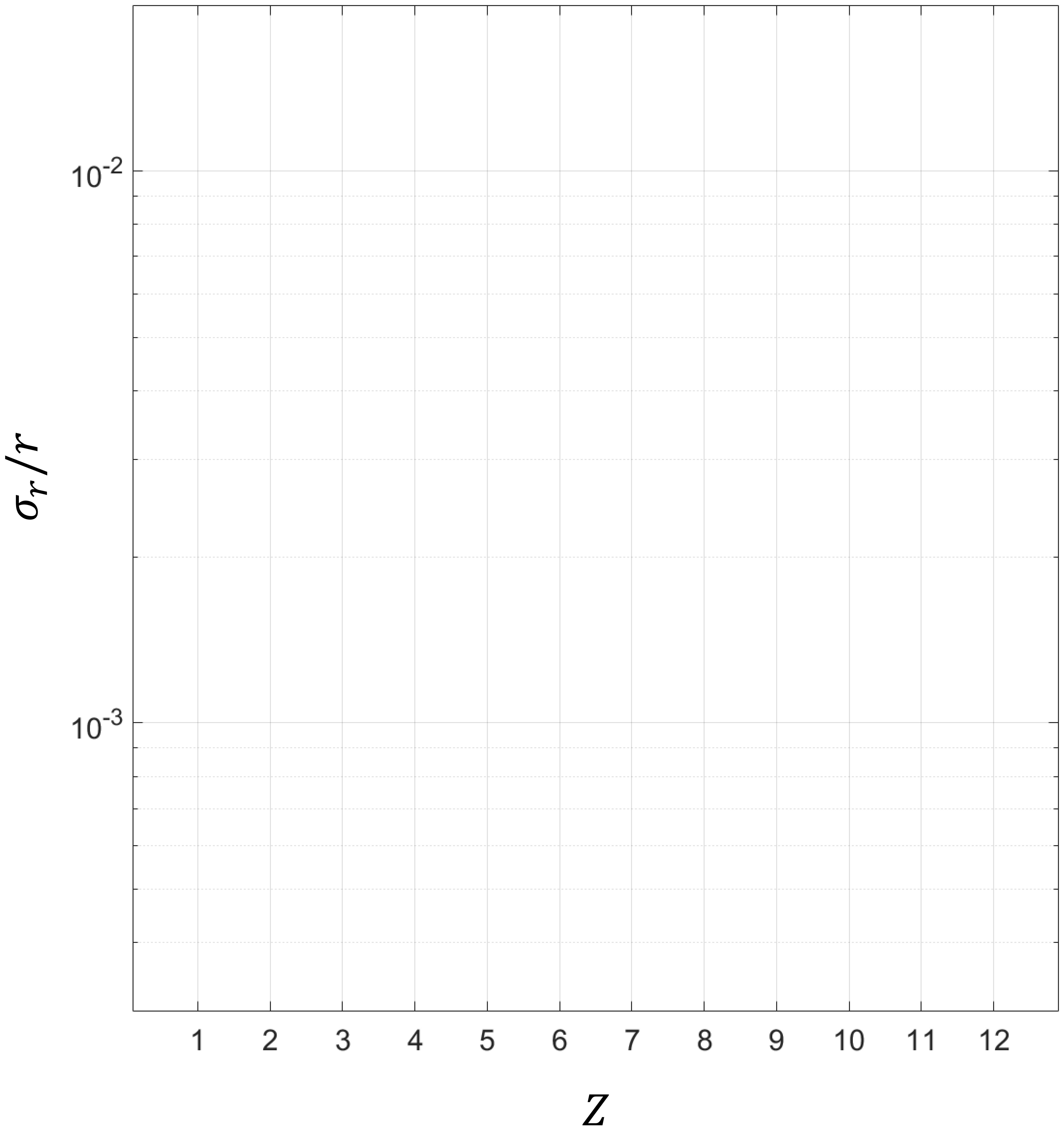
Sources of uncertainty :

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

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



The radius gap



The radius gap

- **For $Z < 3$:**
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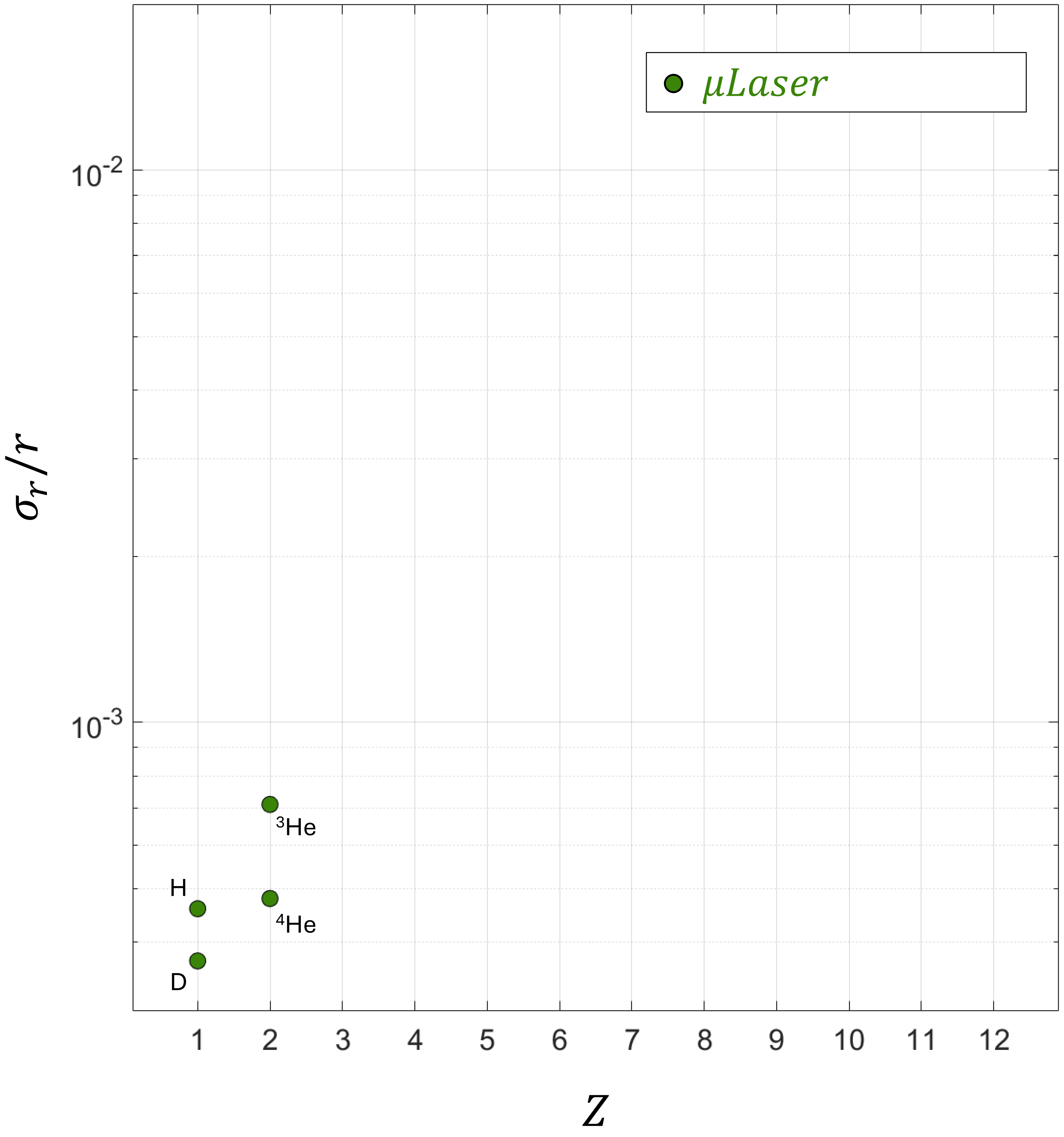

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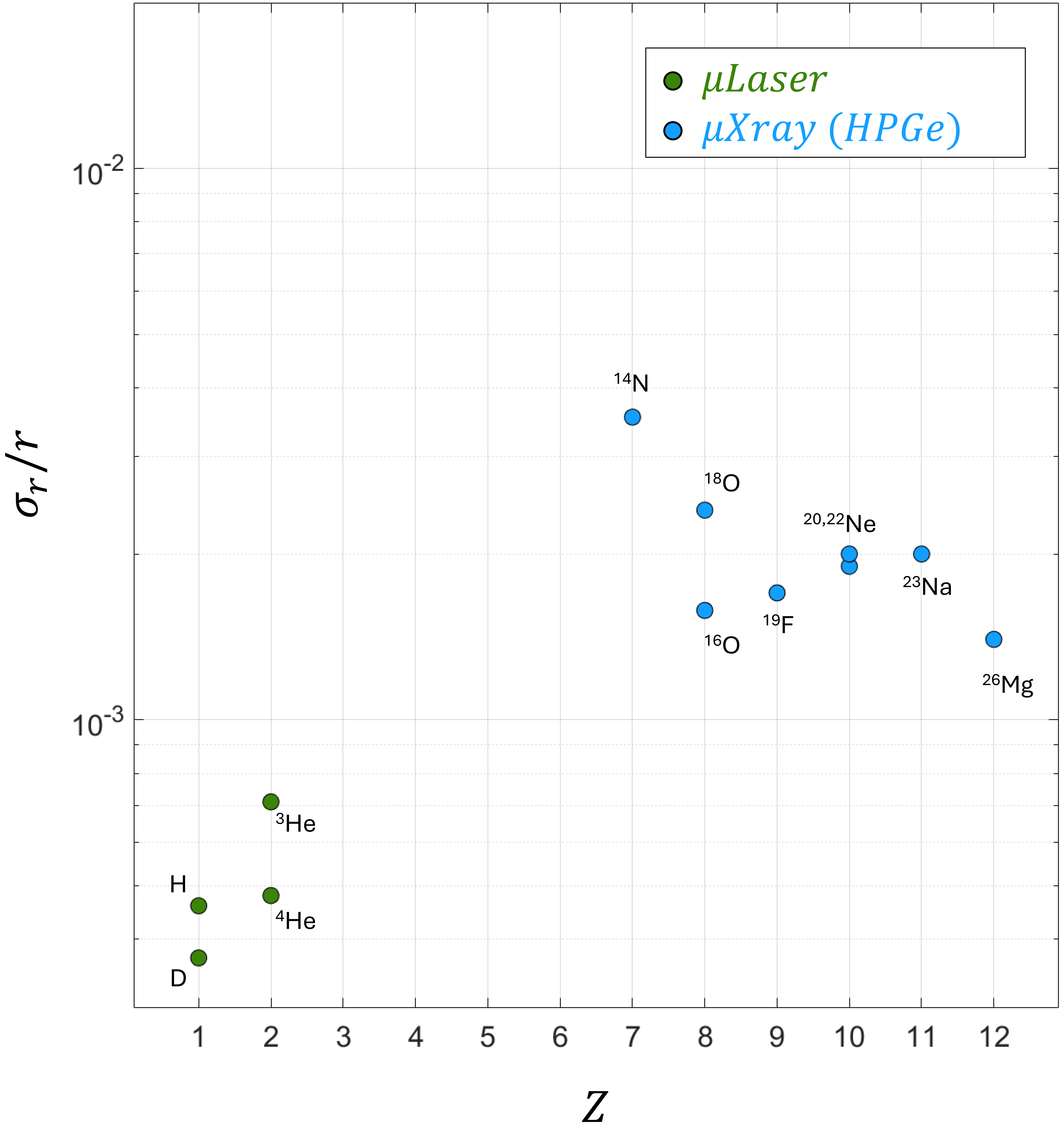

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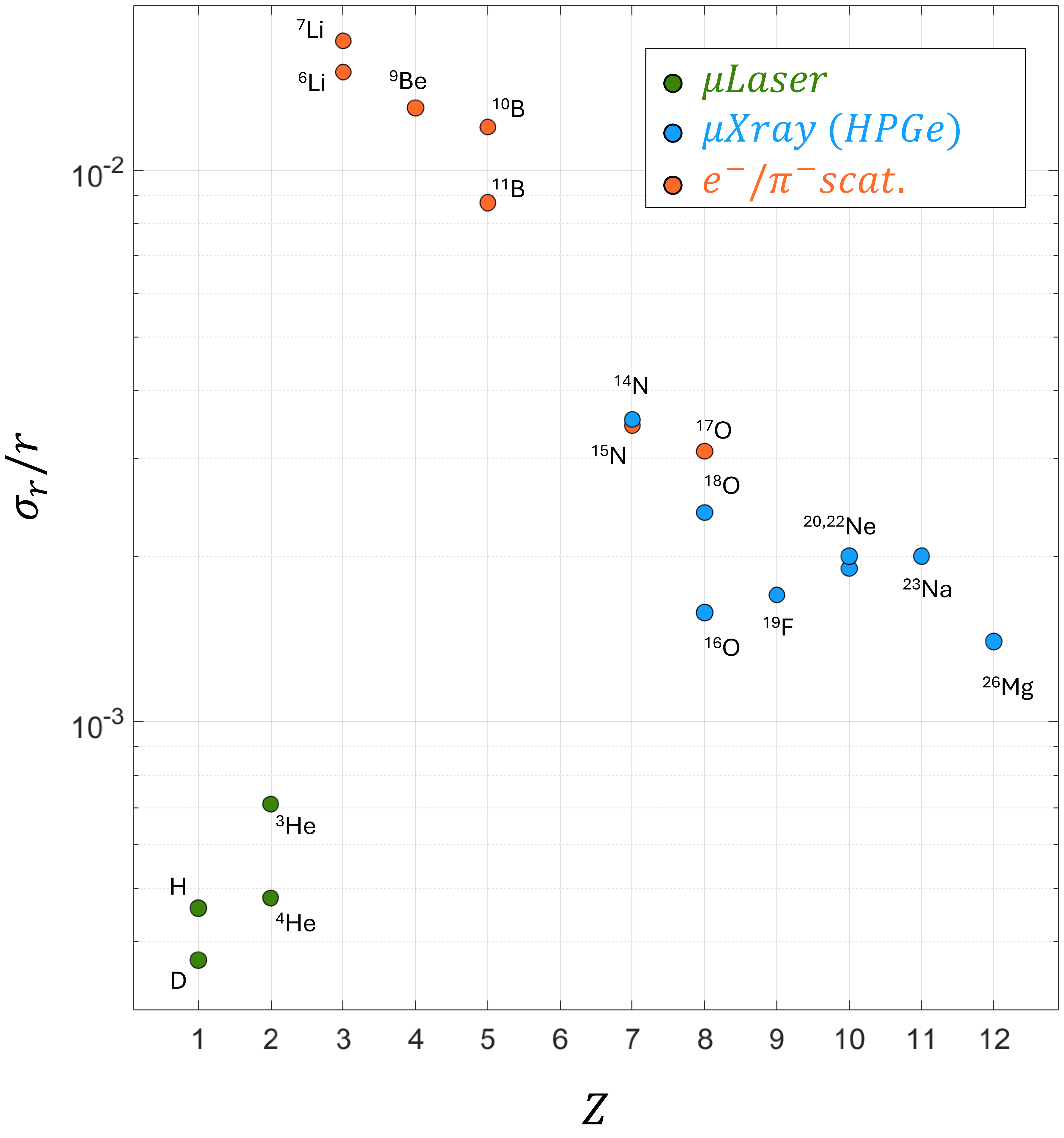

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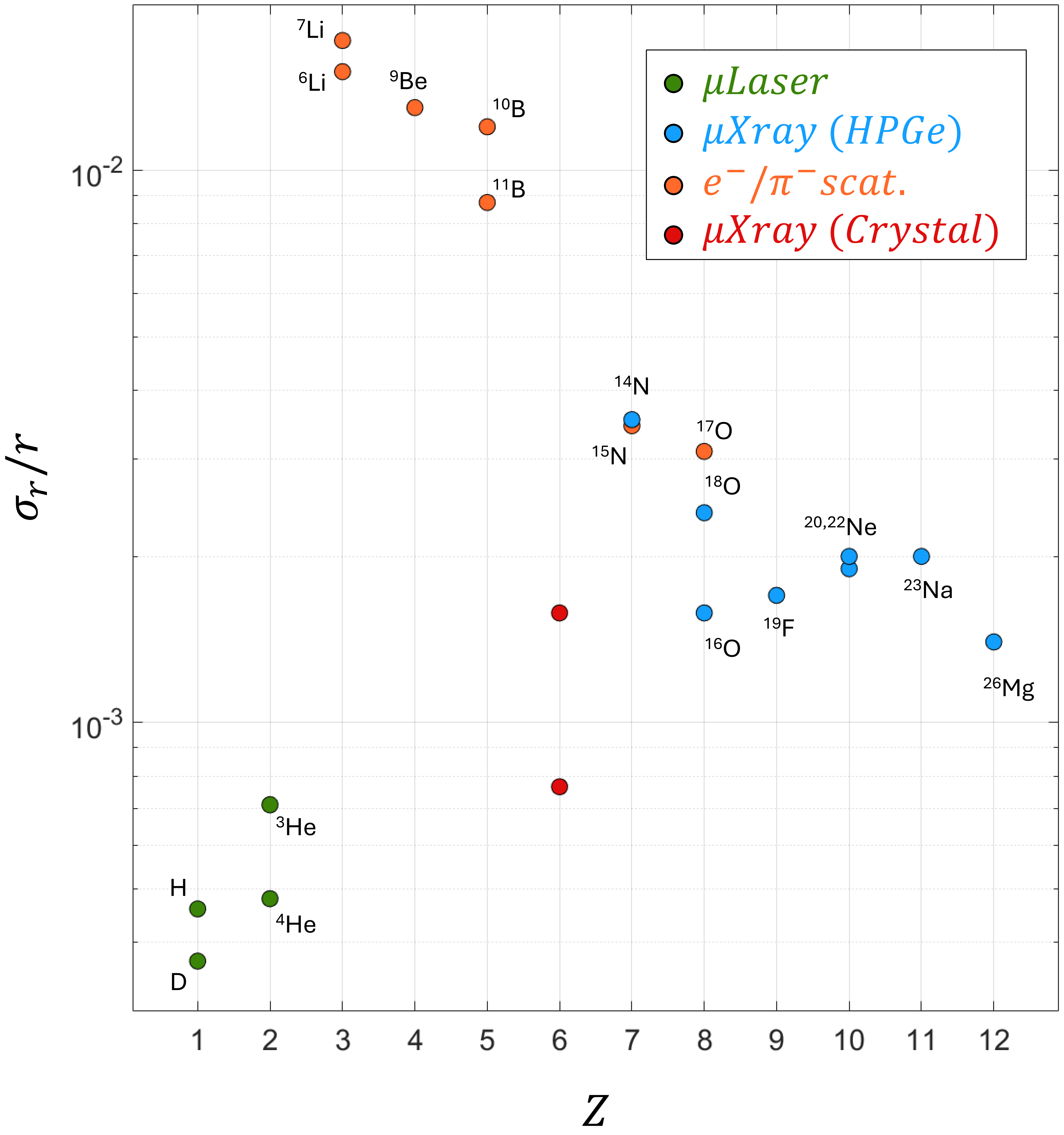
  Measured with crystal spectrometer. Not widely applicable



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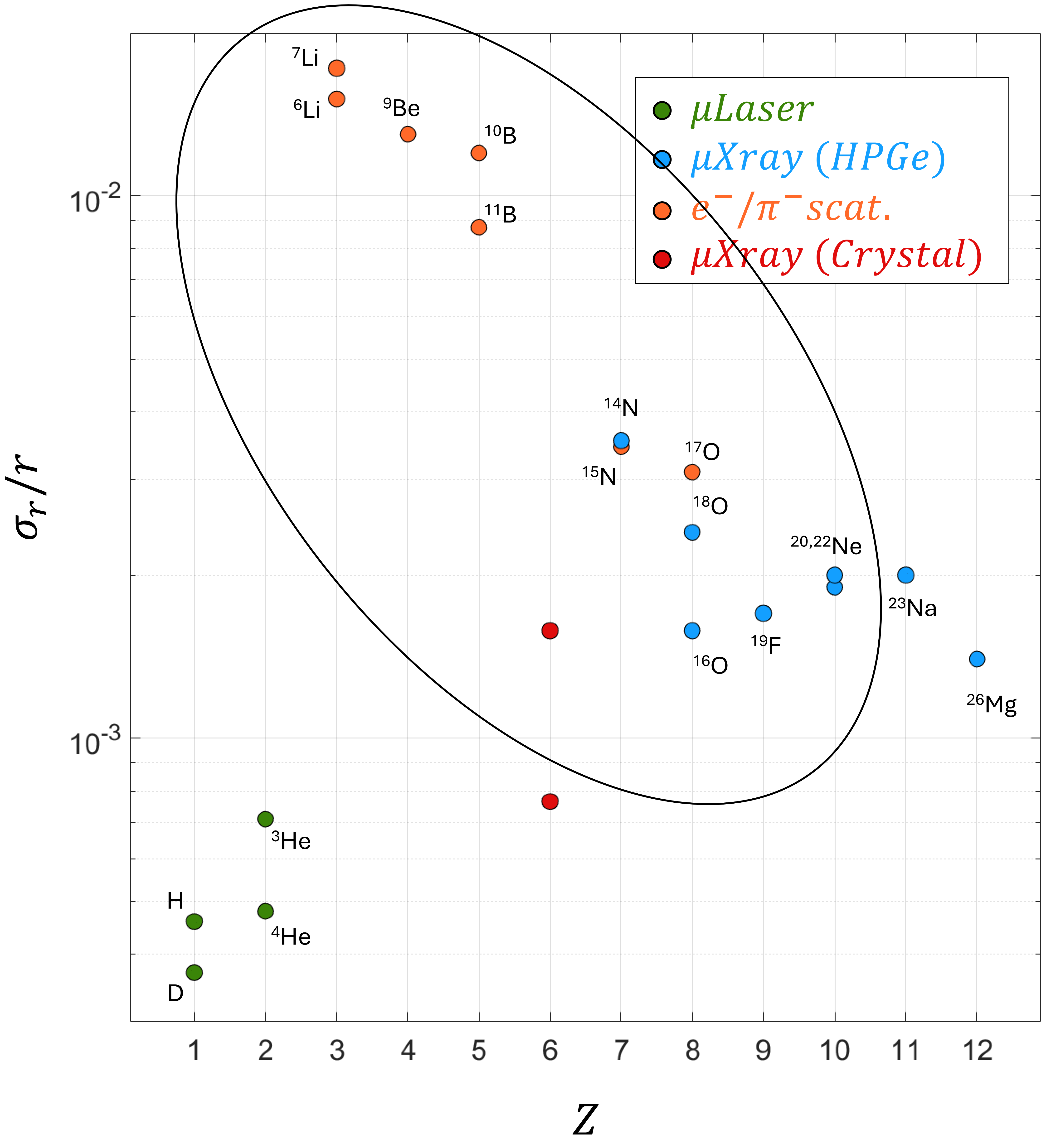

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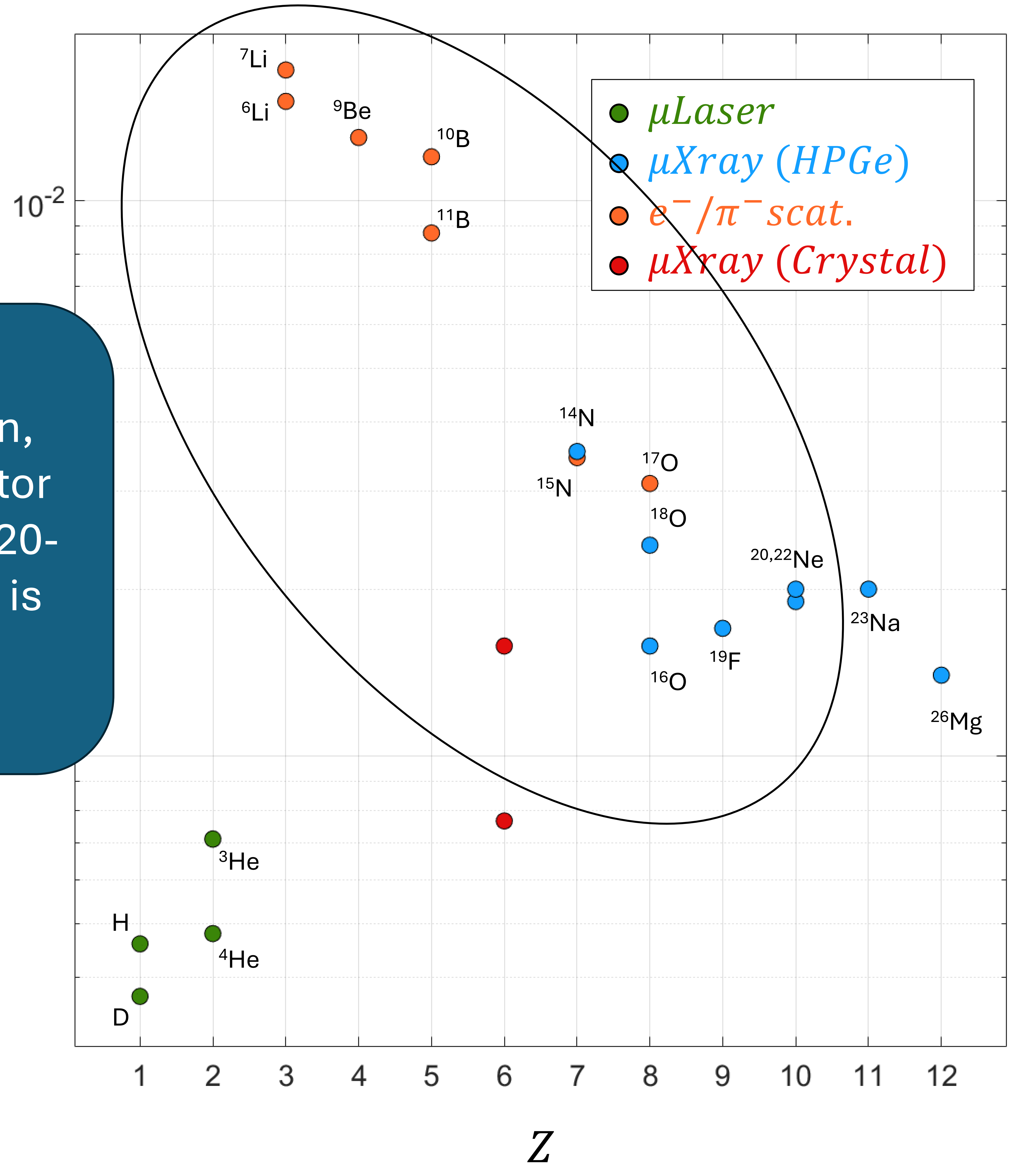
High-resolution, efficient, detector for low-energy (20-200 keV) x-rays is needed



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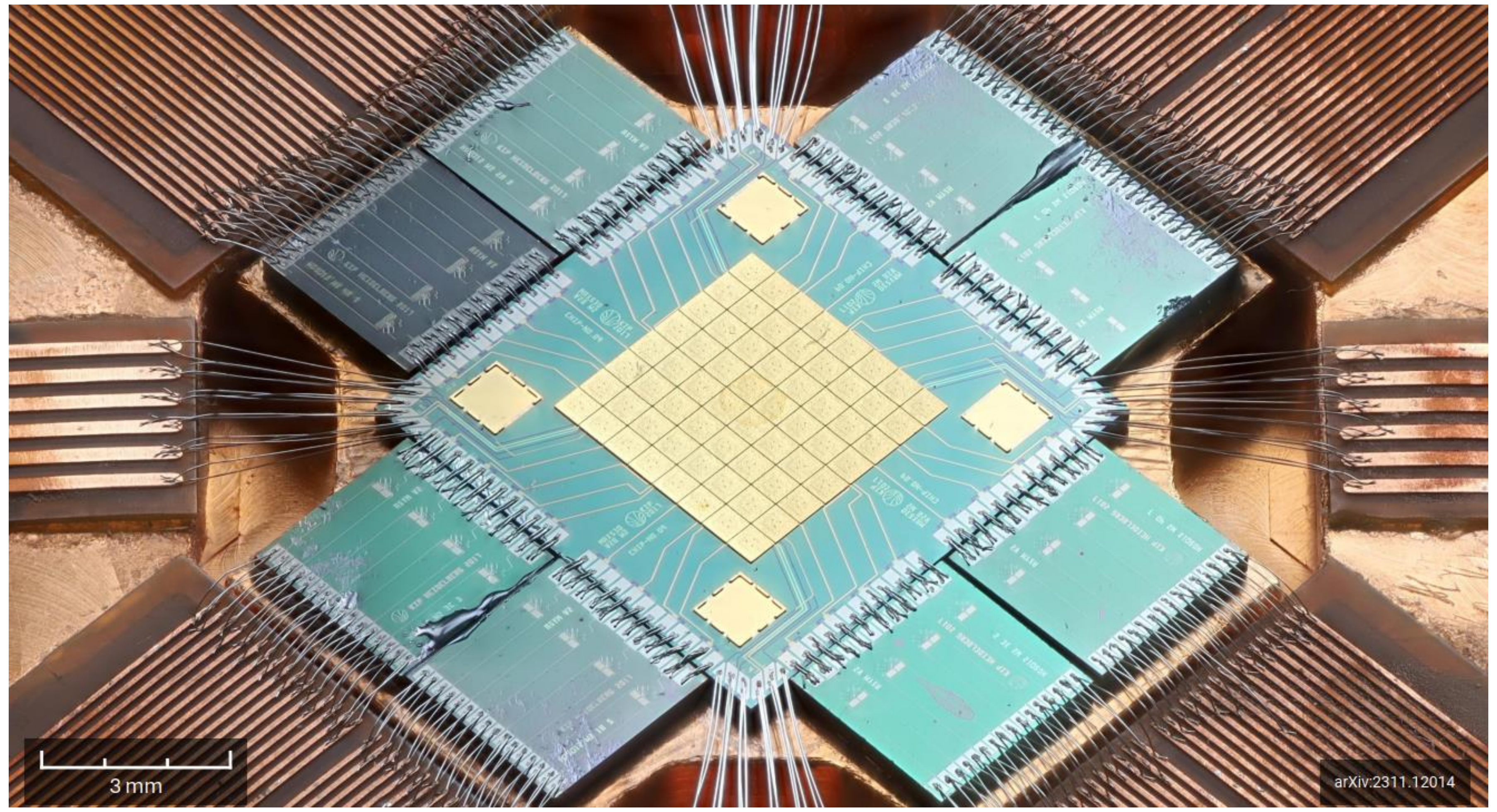
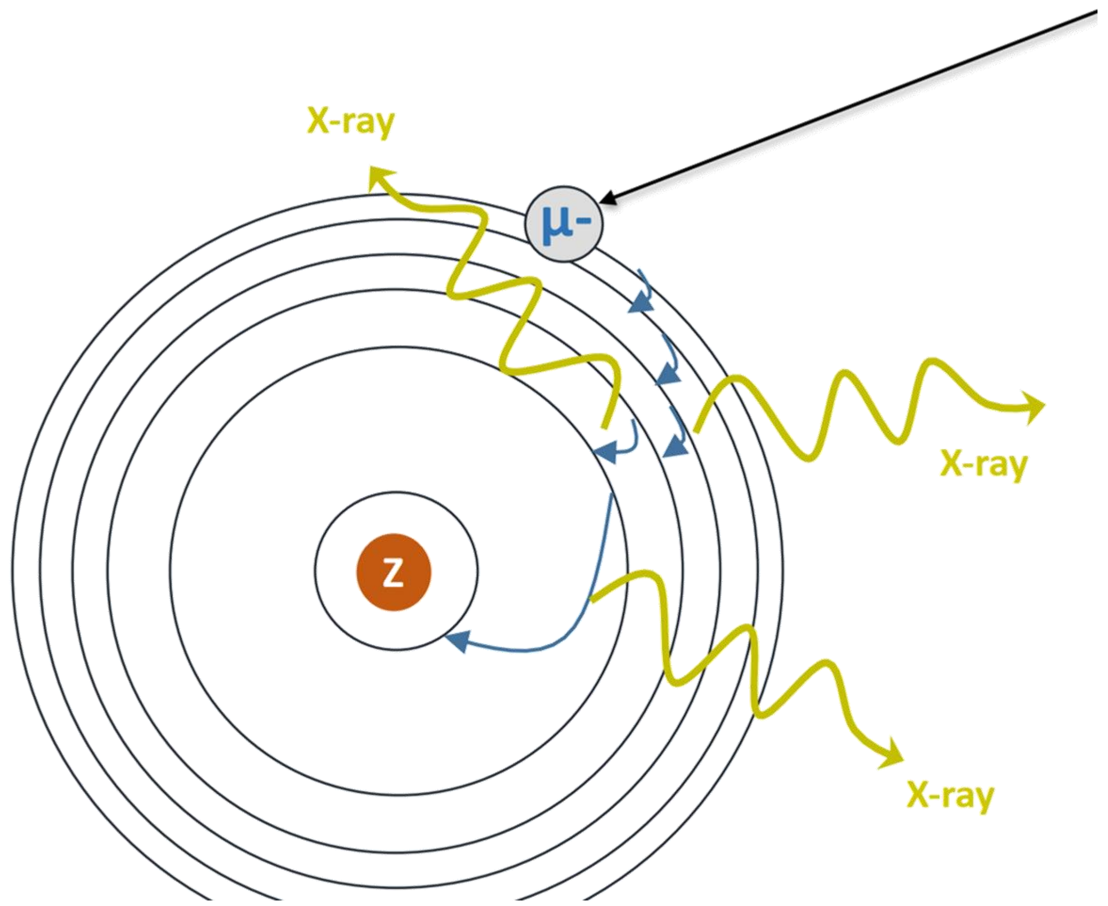
Enter microcalorimeters

Cryogenic microcalorimeters



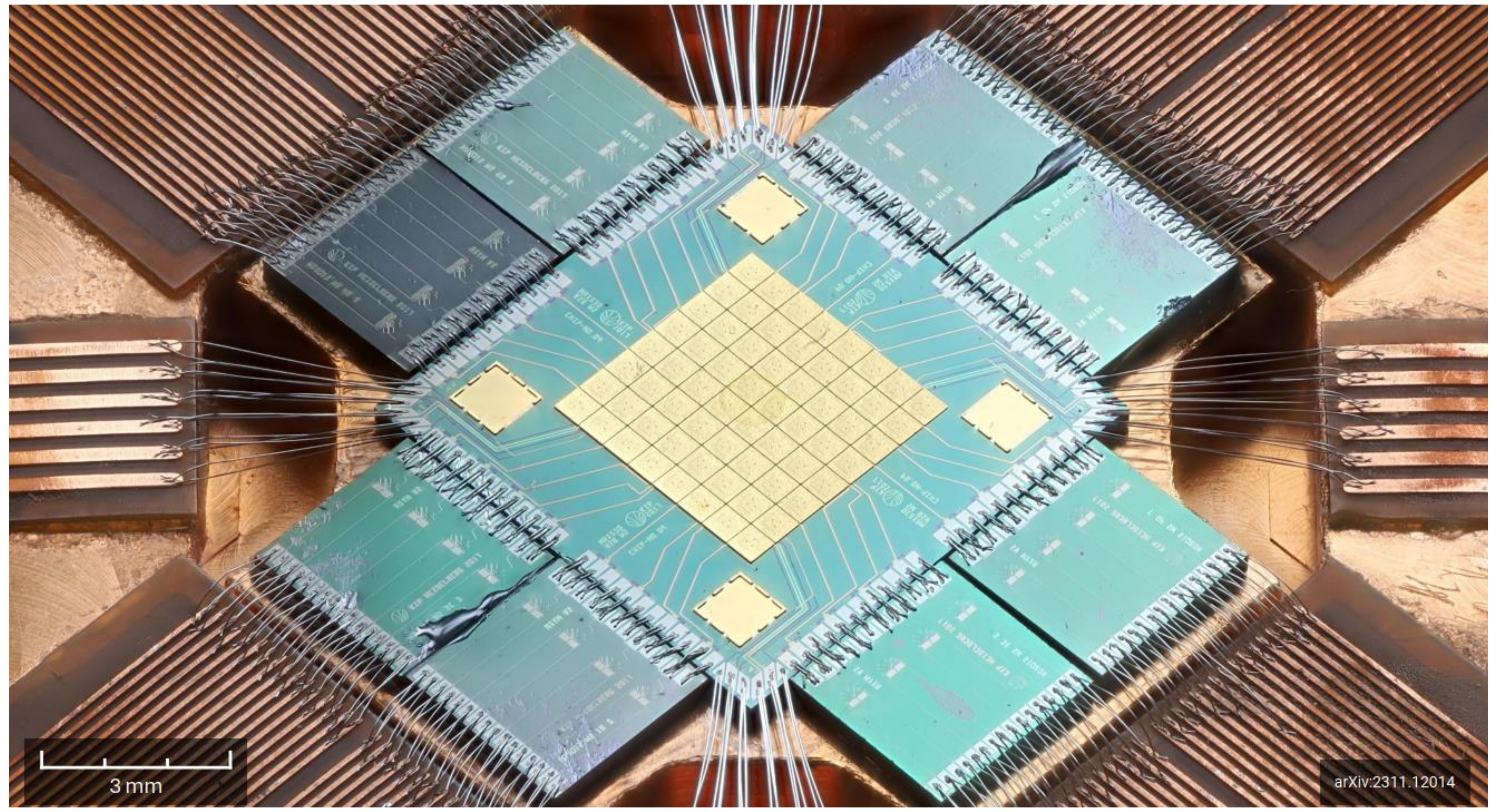
- High quantum efficiency
- Broadband (important for calibration)
- **Superb resolution $\left(\frac{E}{\Gamma_E} > 10^3\right)$**
- Fast rise time

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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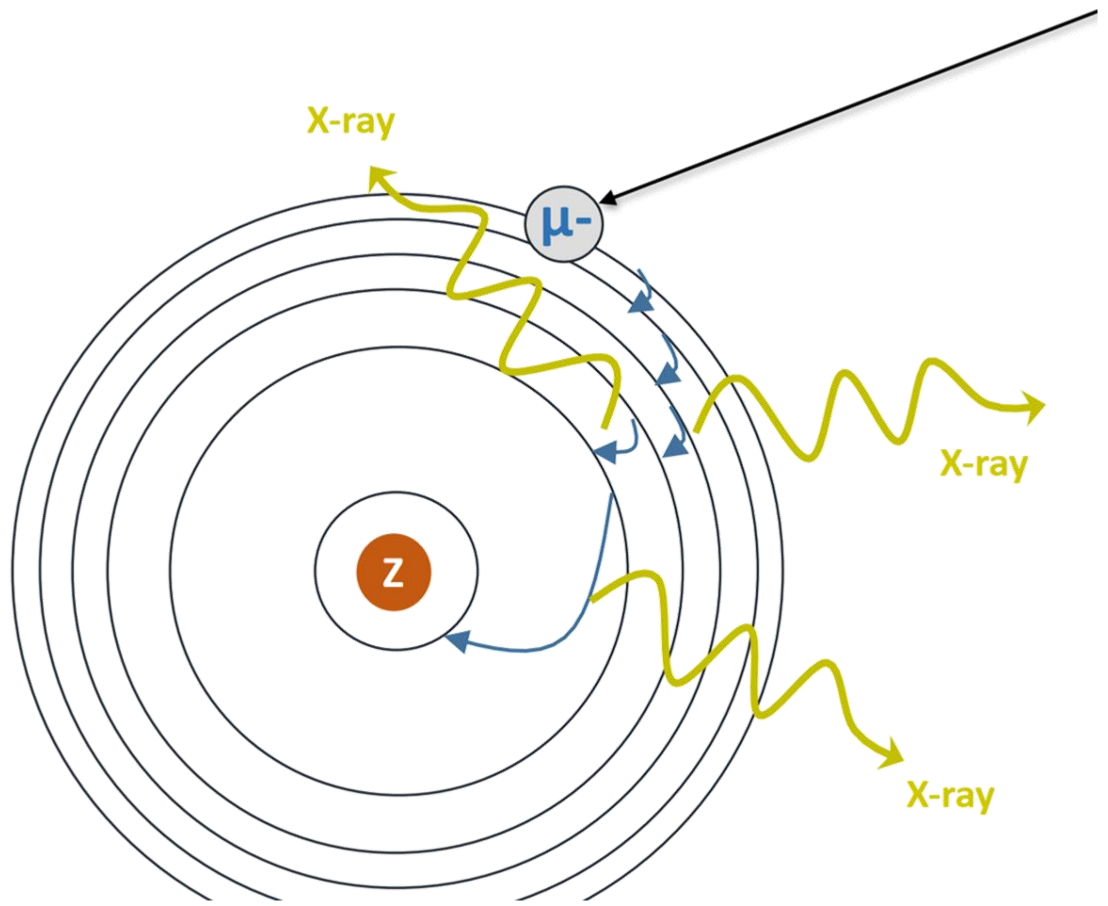

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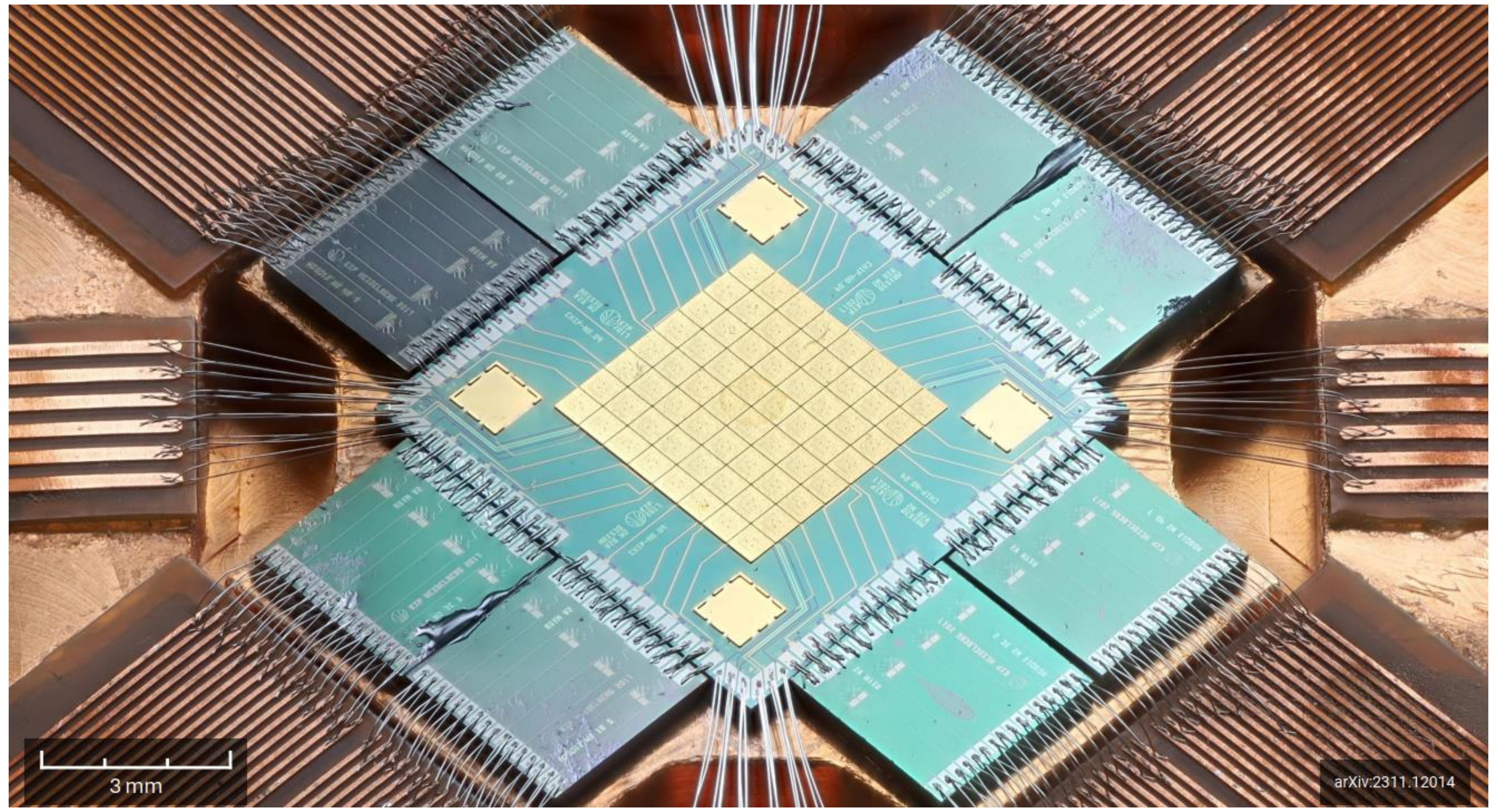
Cryogenic microcalorimeters



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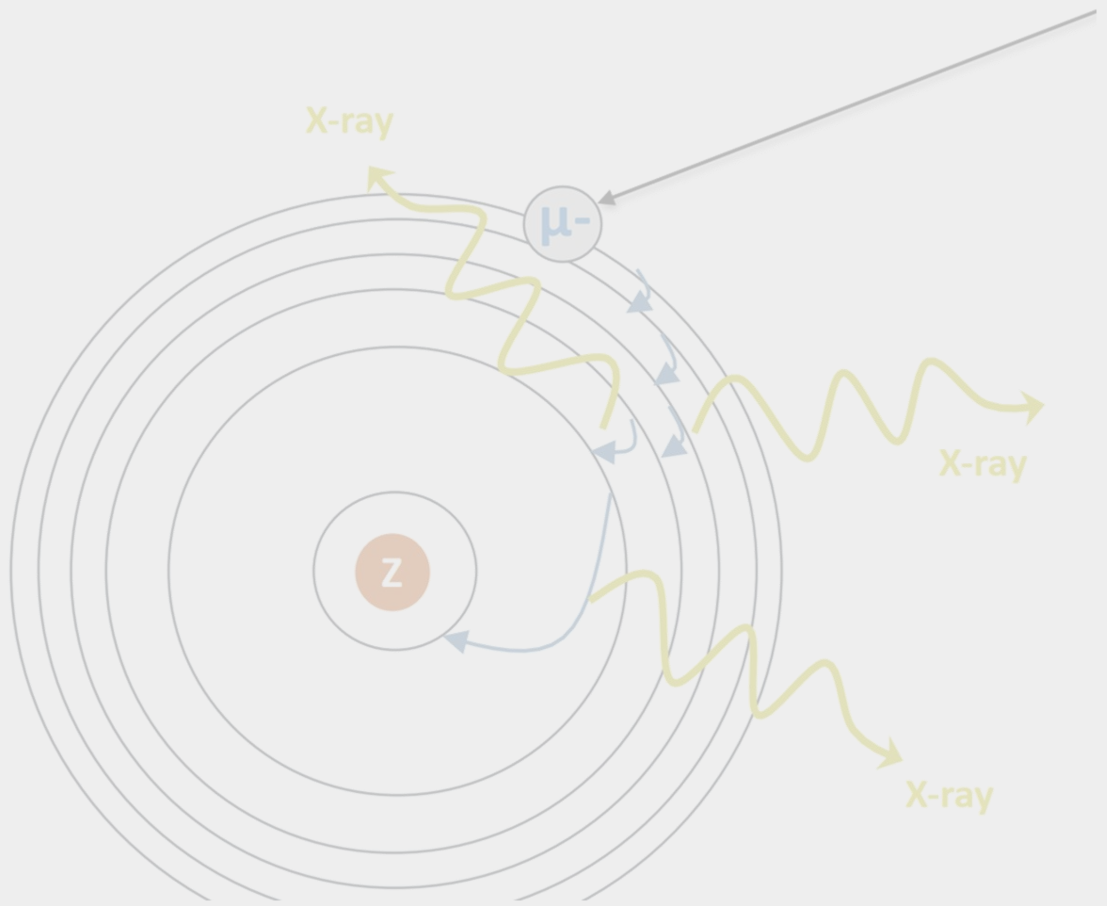

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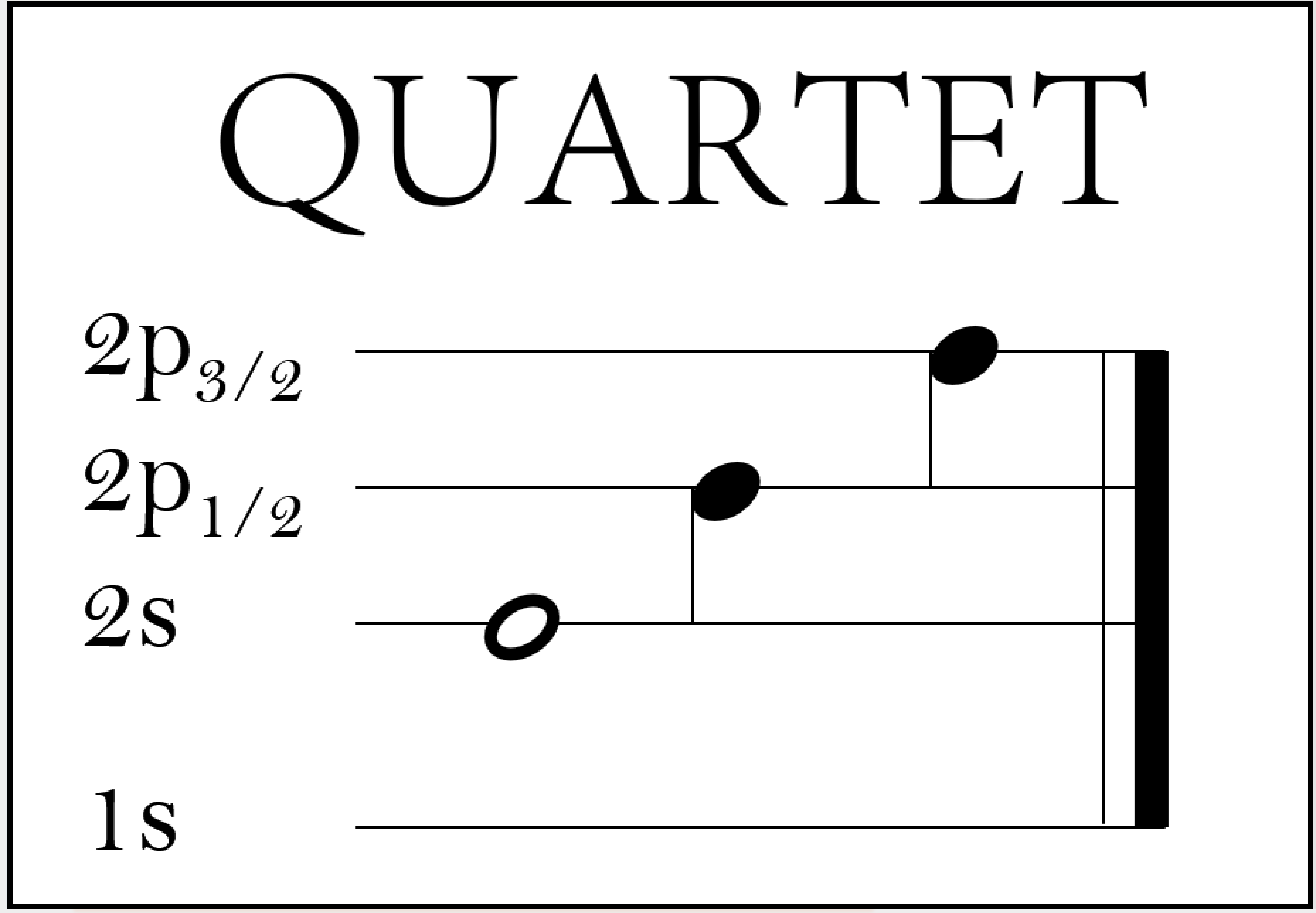
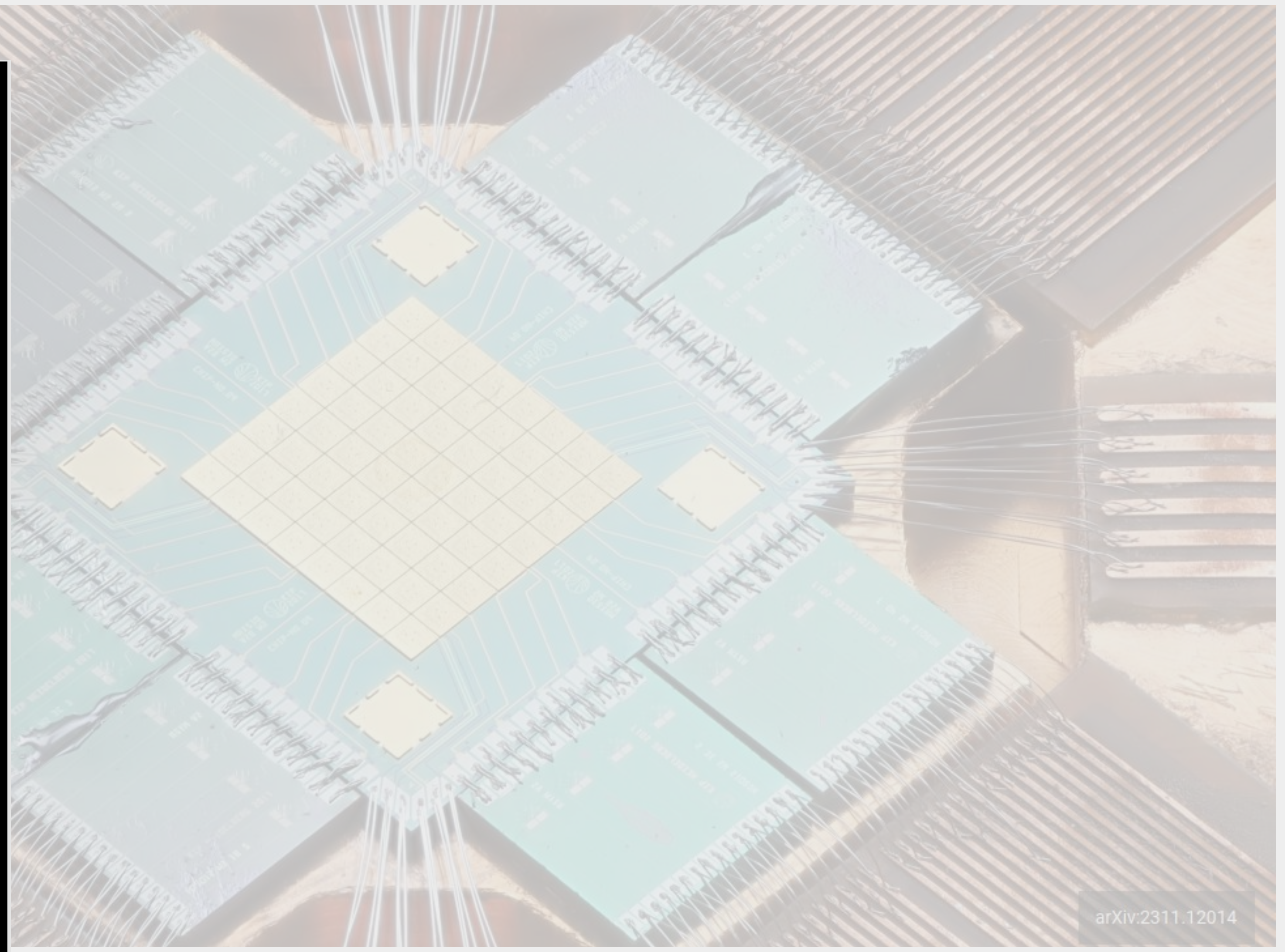
Quantum Interactions with Exotic Atoms



More info:

arXiv:2311.12014
arXiv:2310.03846

Cryogenic microcalorimeters



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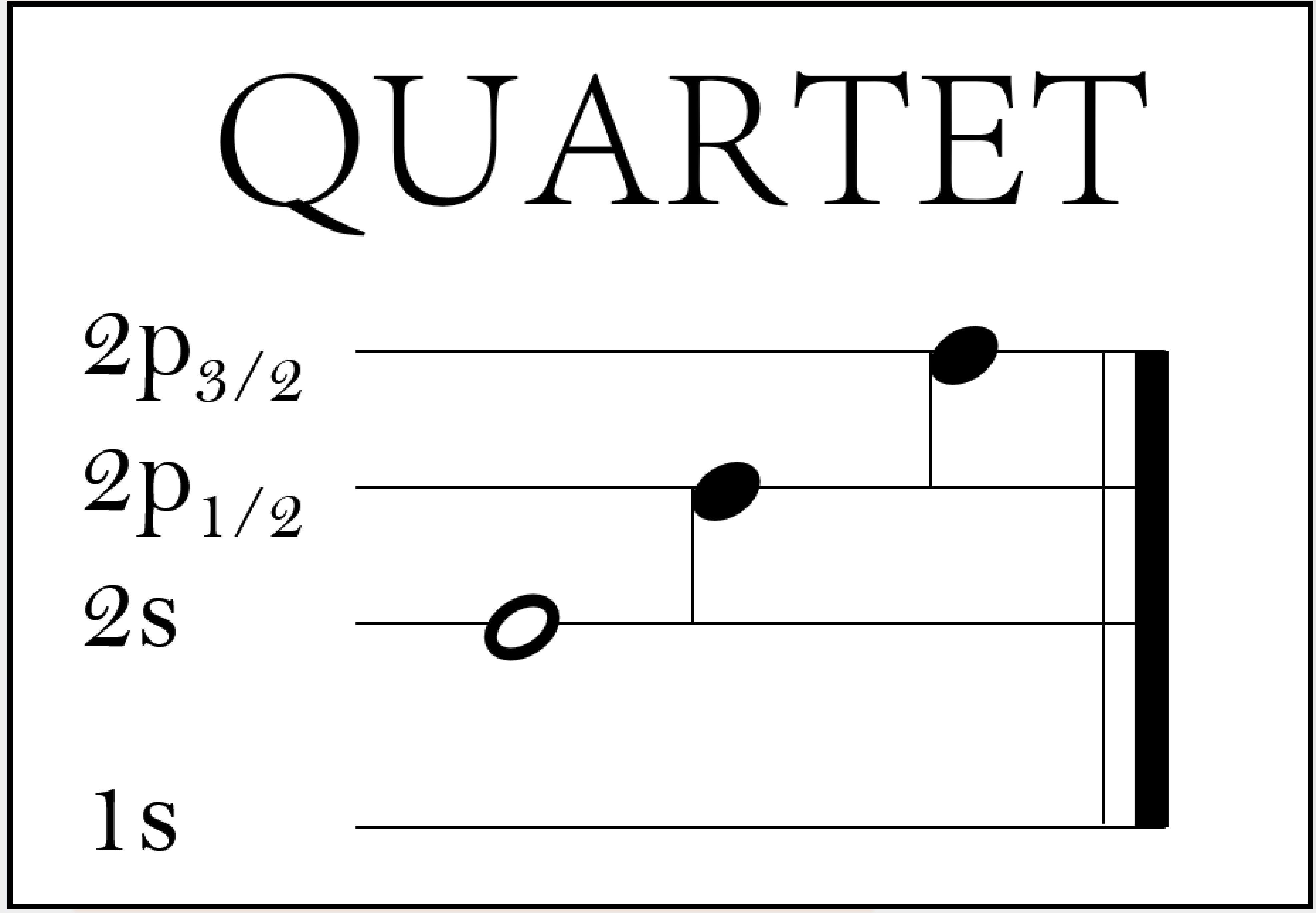

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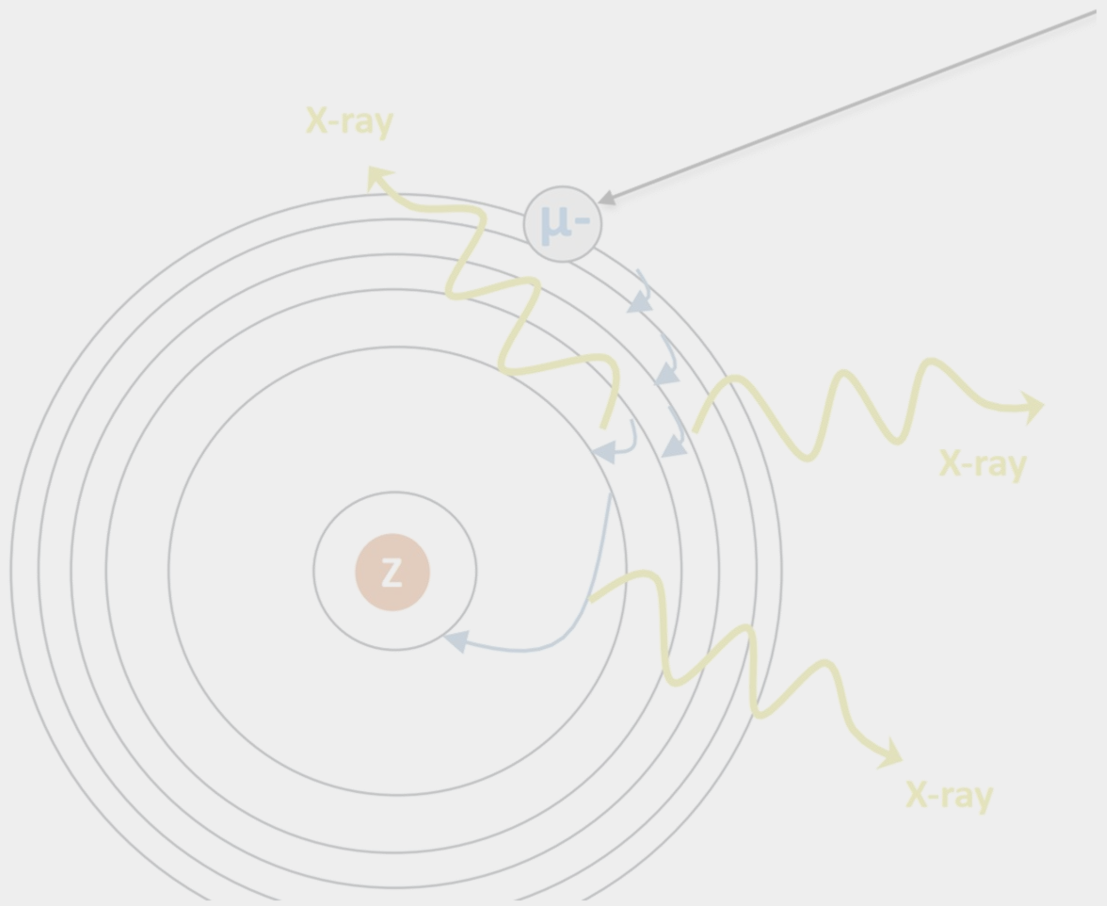
Stay tuned for Loredana’s talk !!!

Muonic atoms



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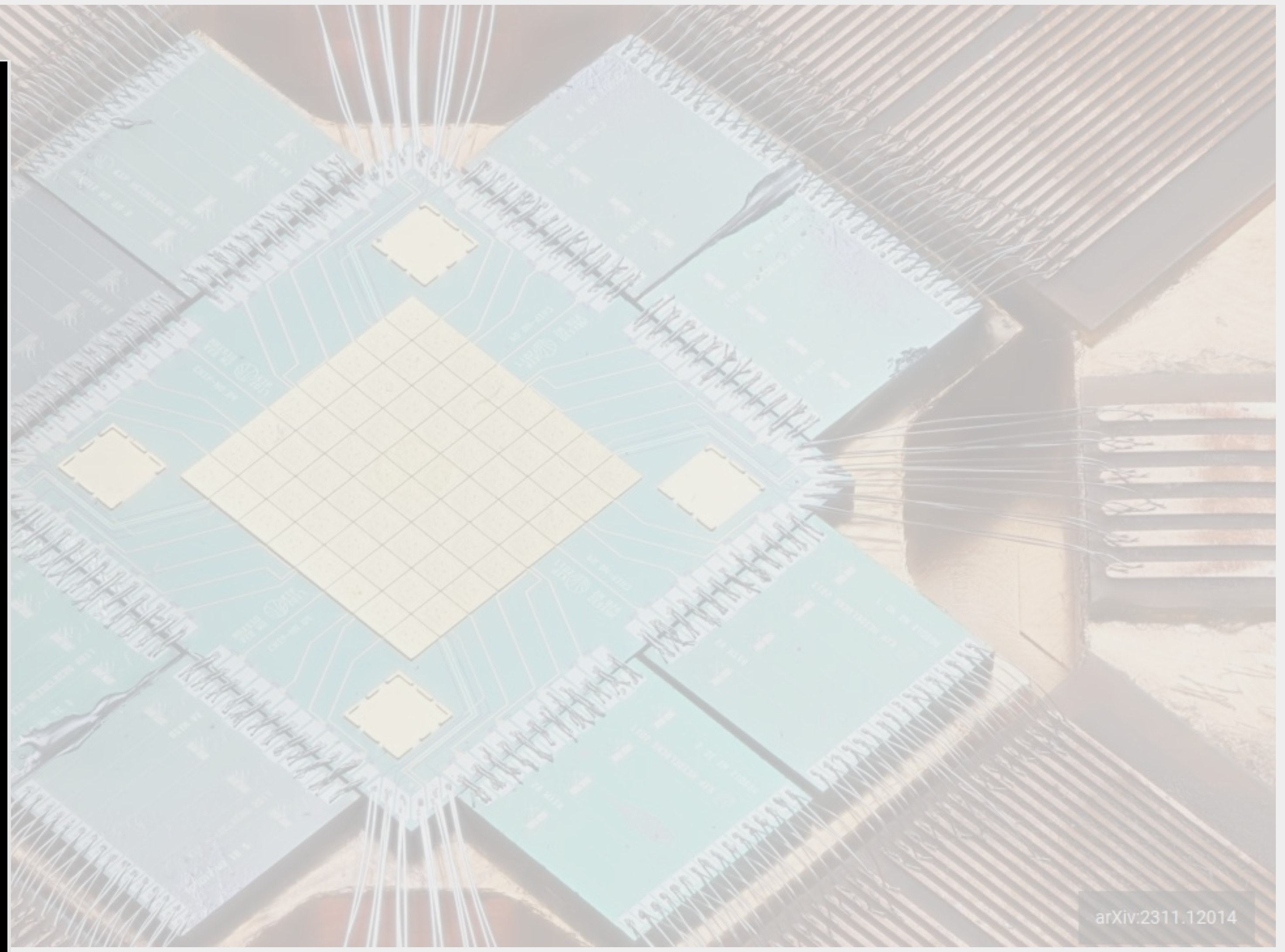

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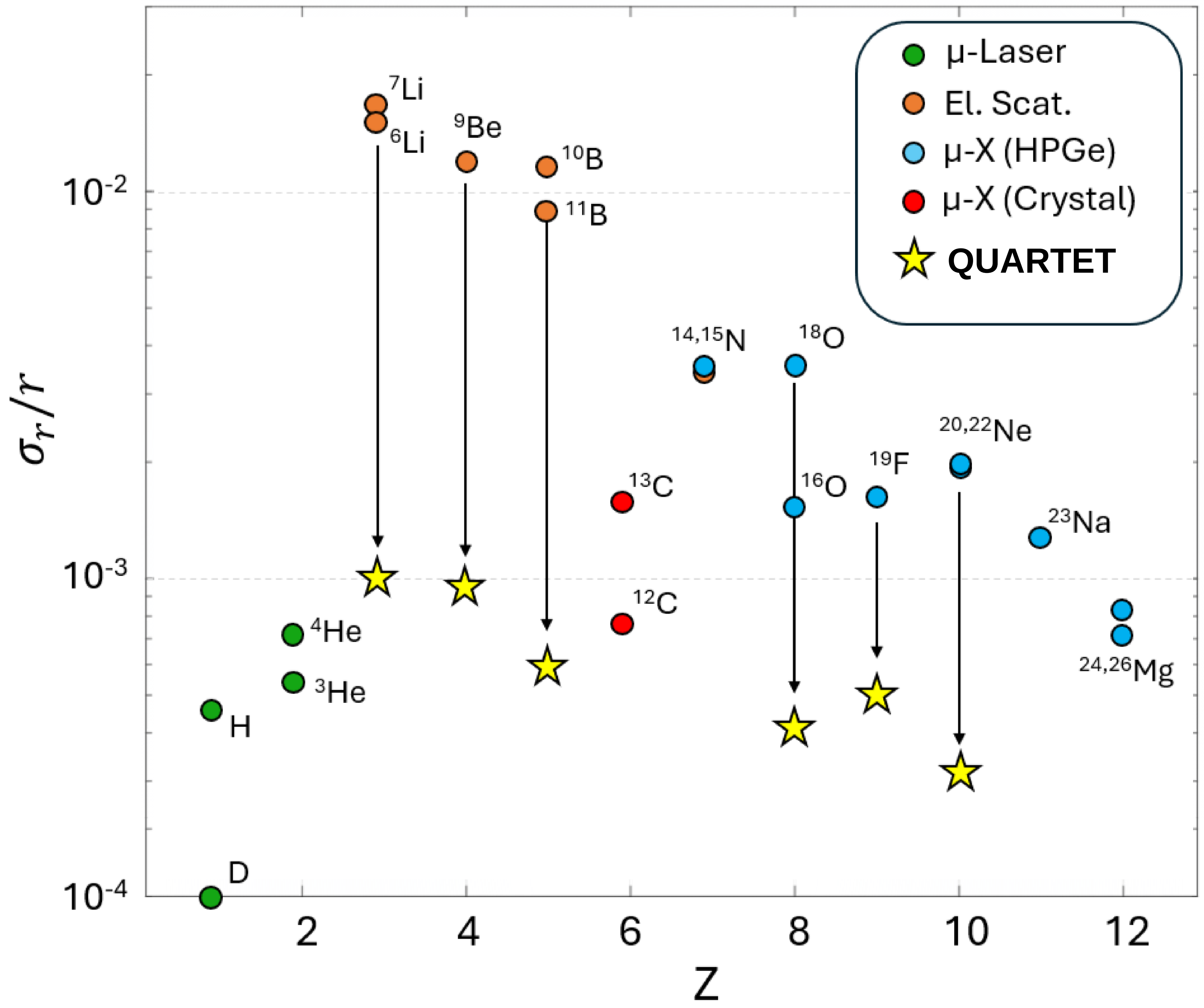
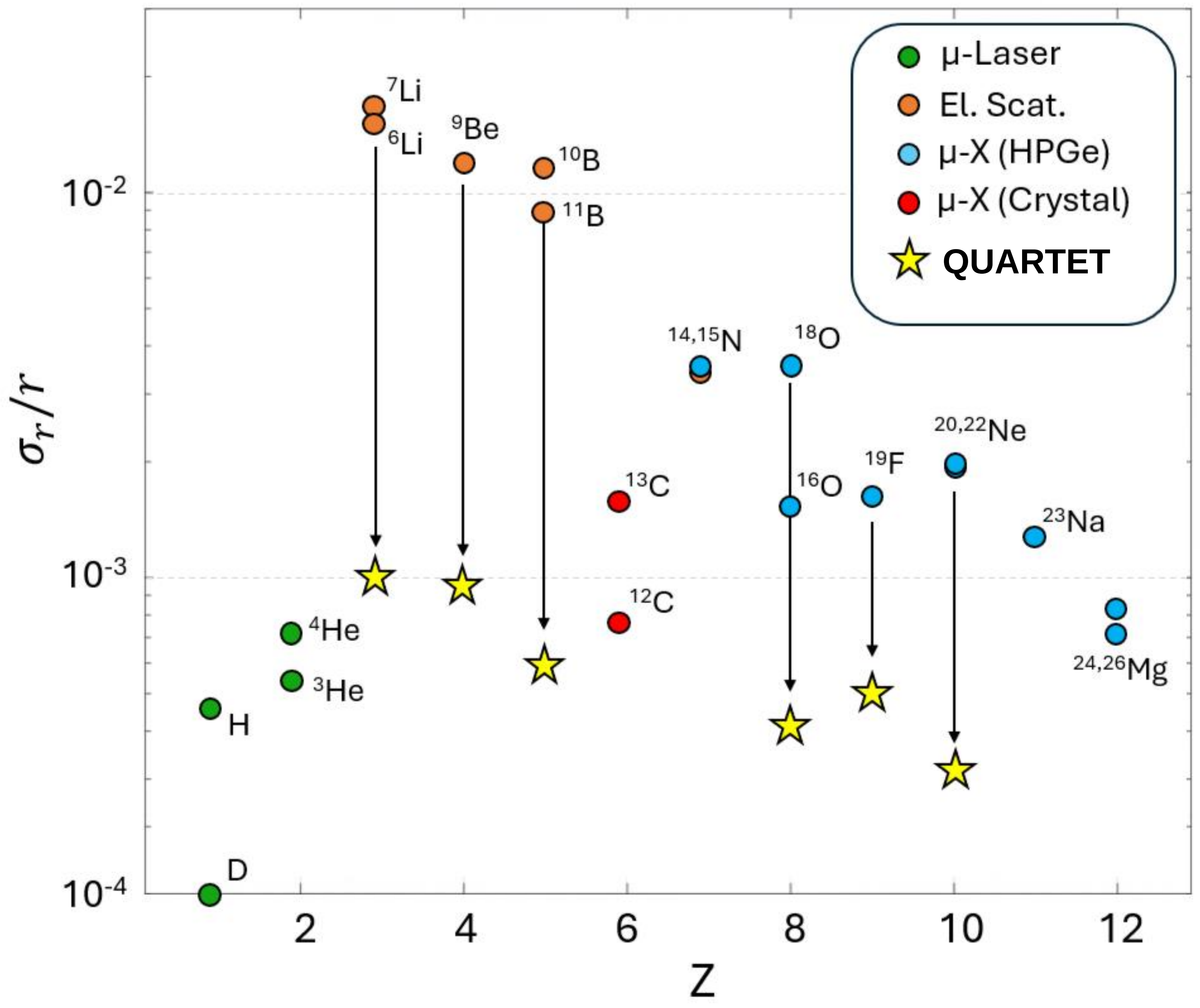
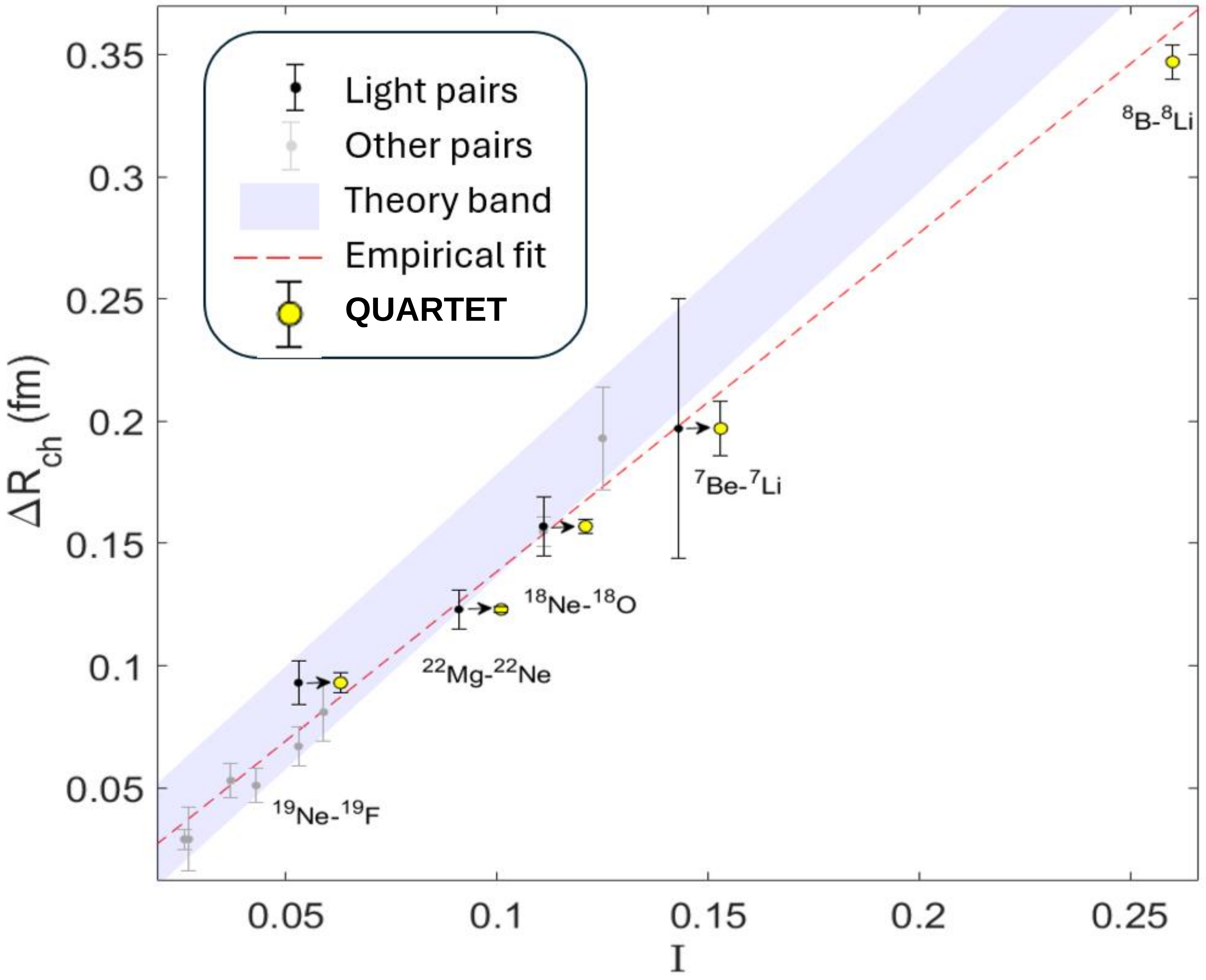
What can better radii of light nuclei do for the mirror fit?



What can better radii of light nuclei do for the mirror fit?





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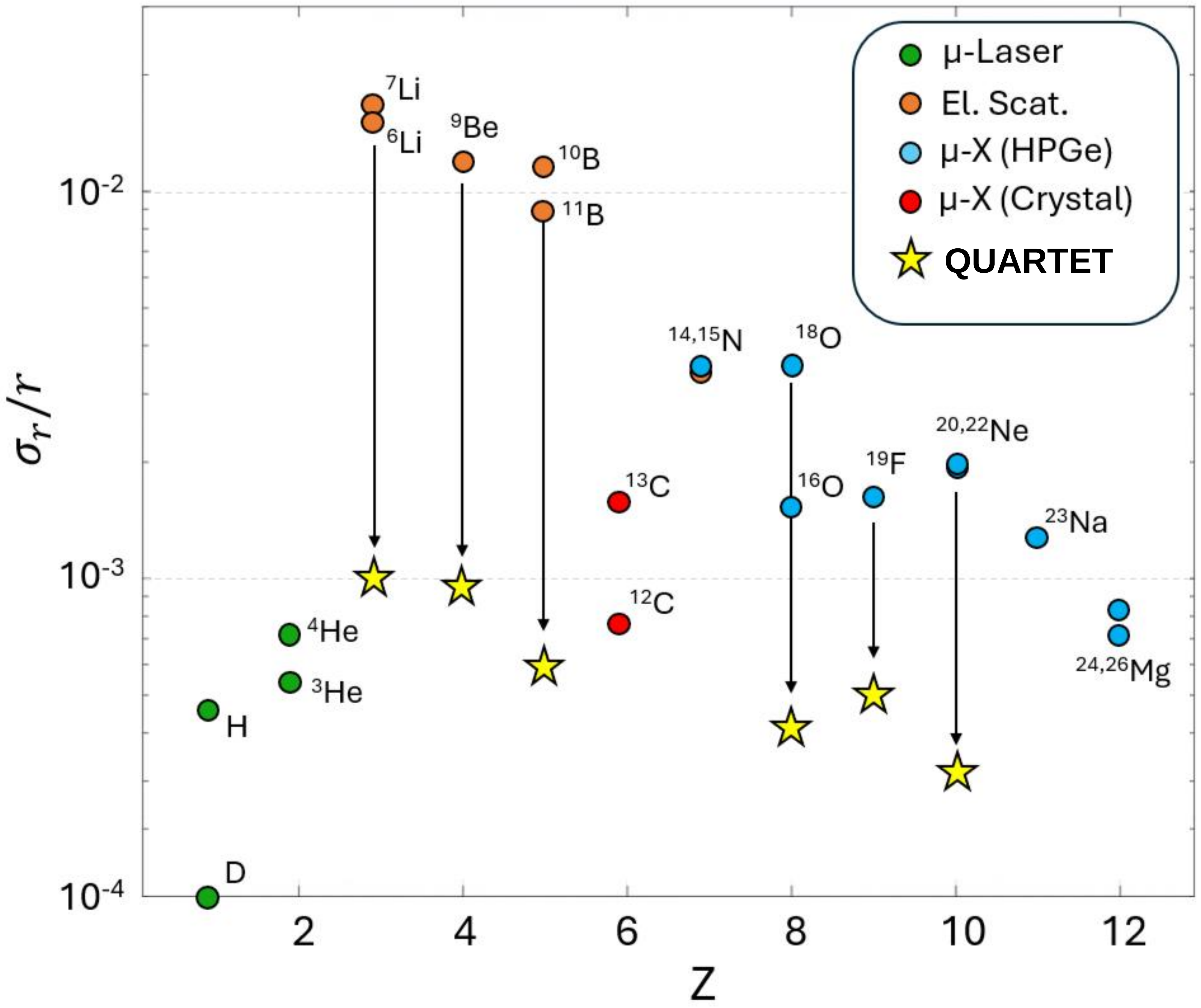
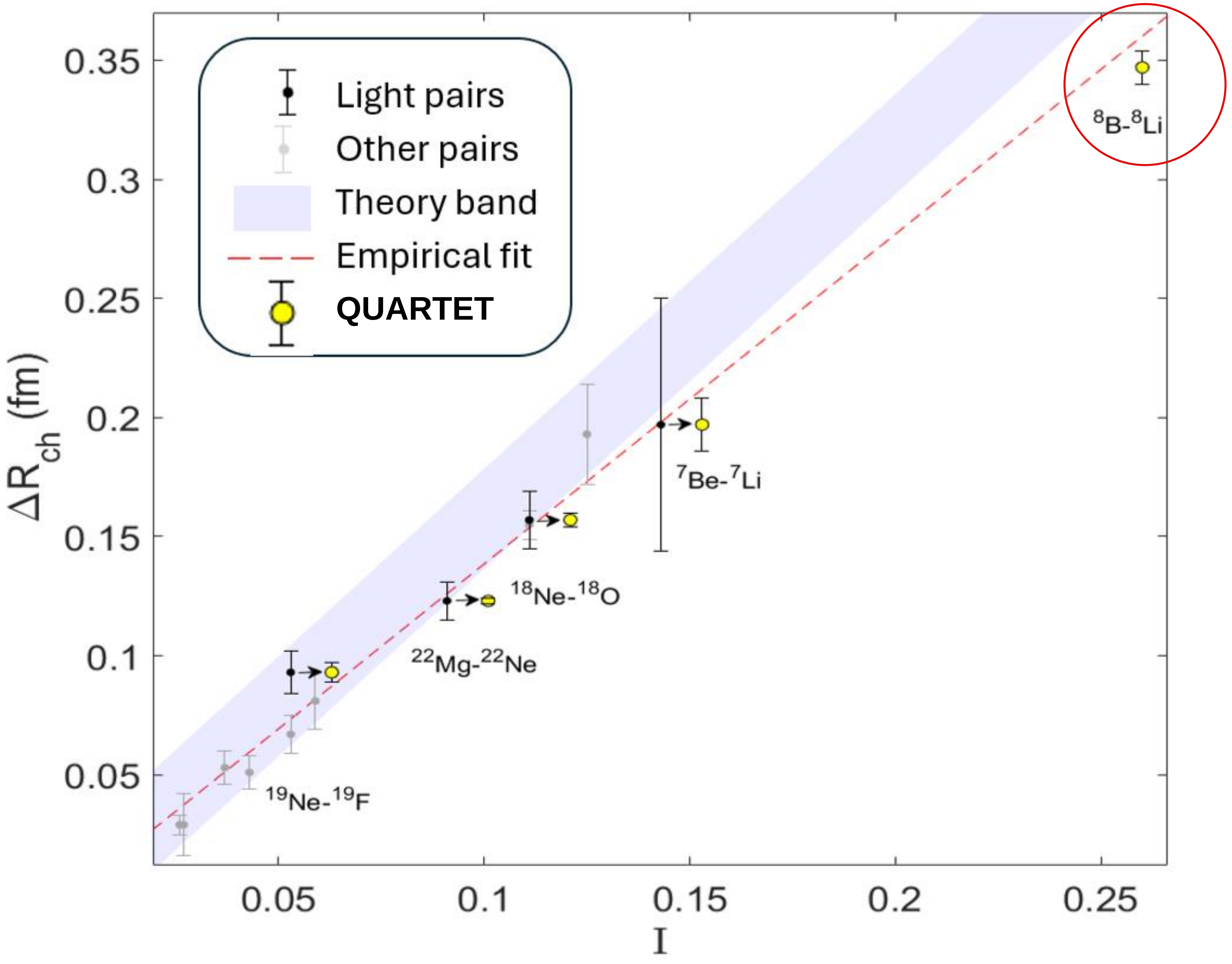
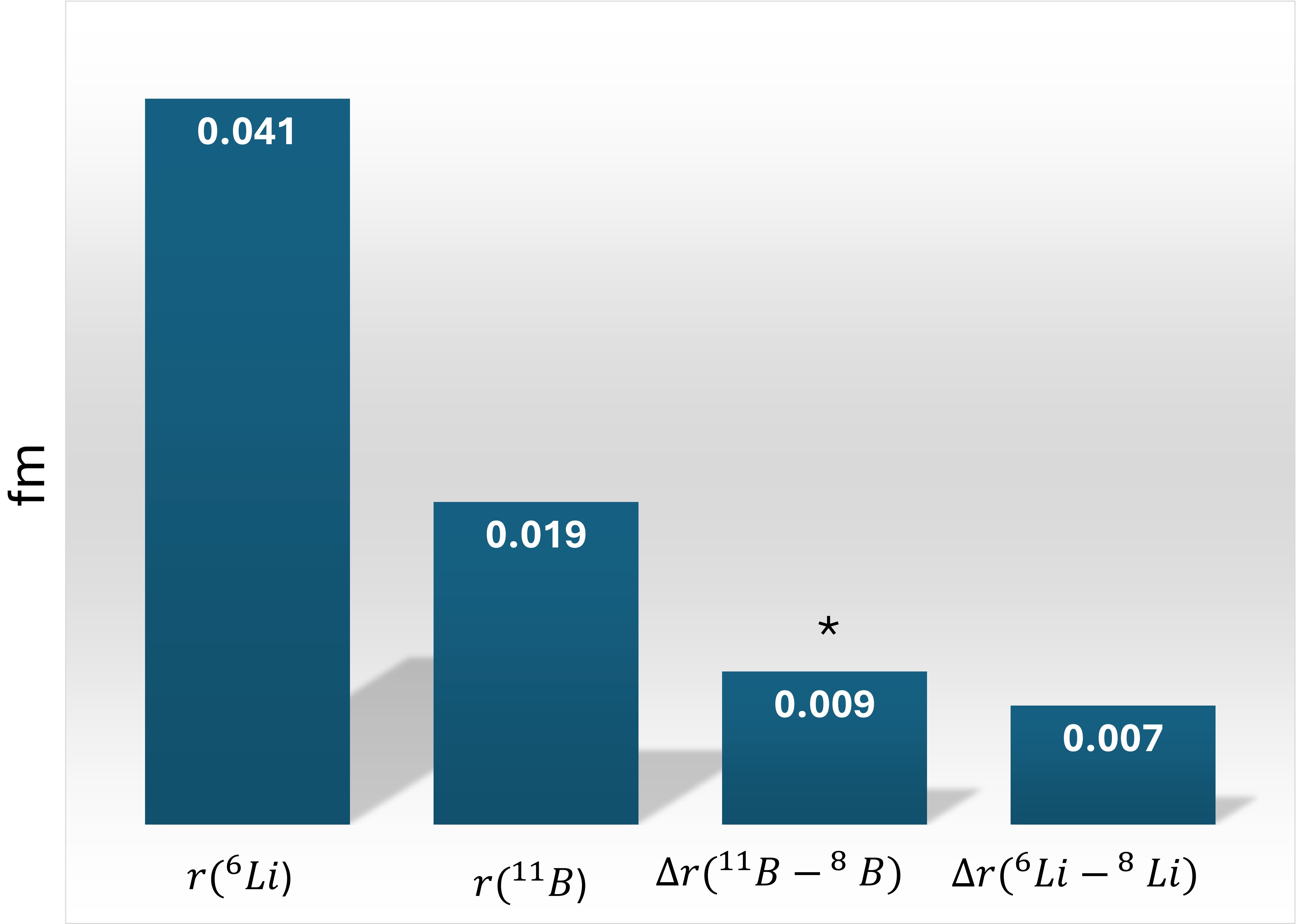
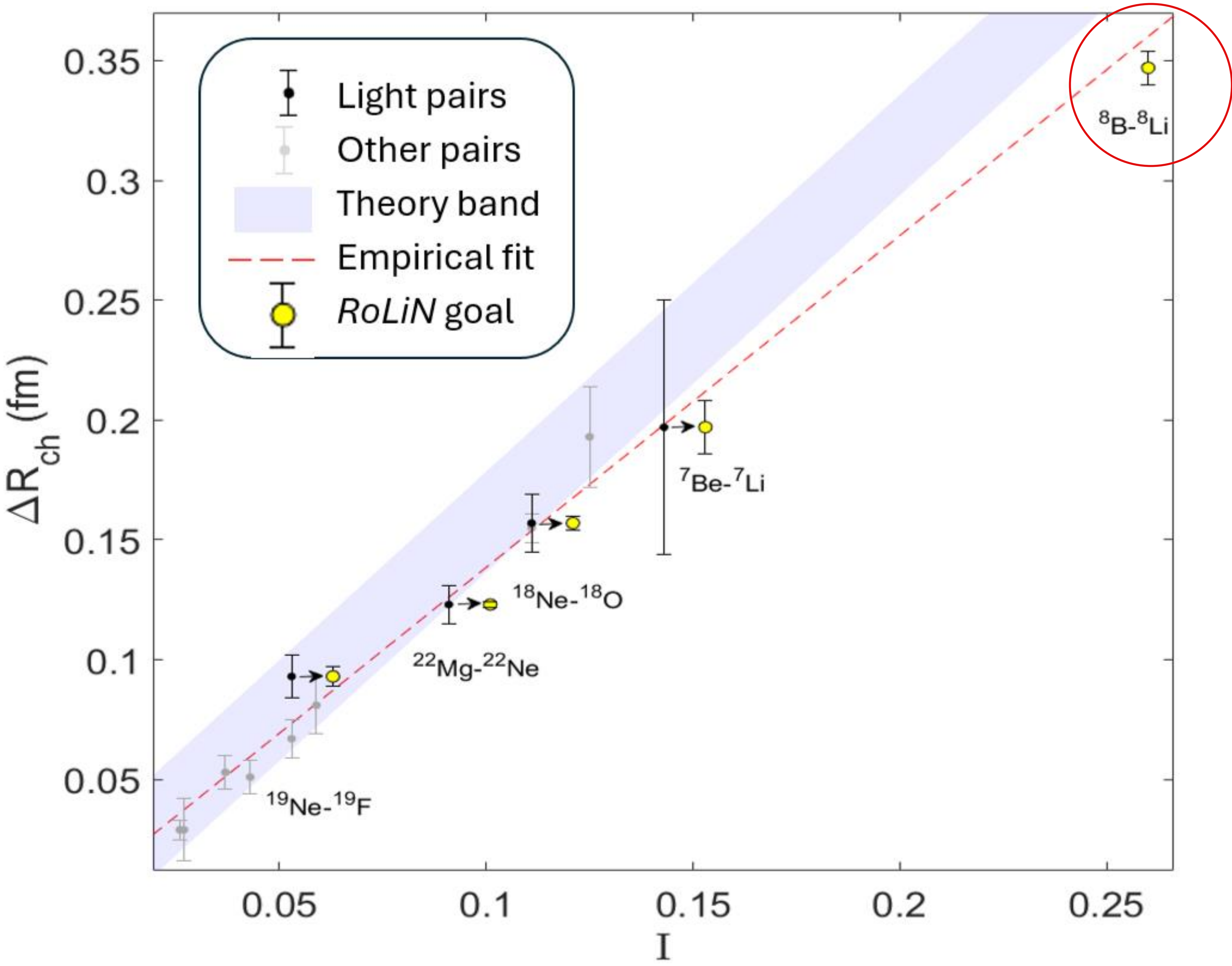




Golden case: A=8

Uncertinaty contributions to $\Delta_{ch}^{mirr}(A = 8)$ *

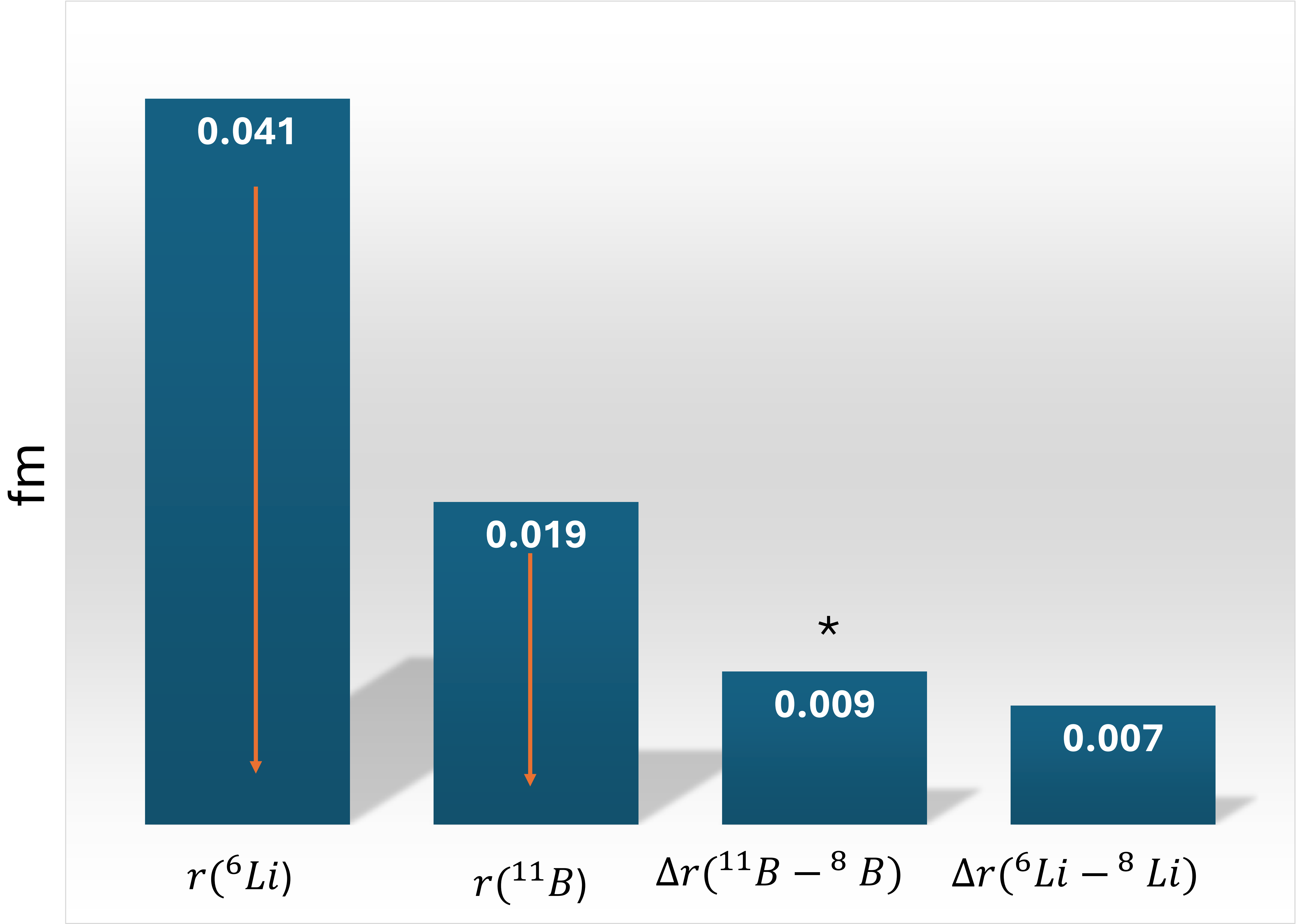


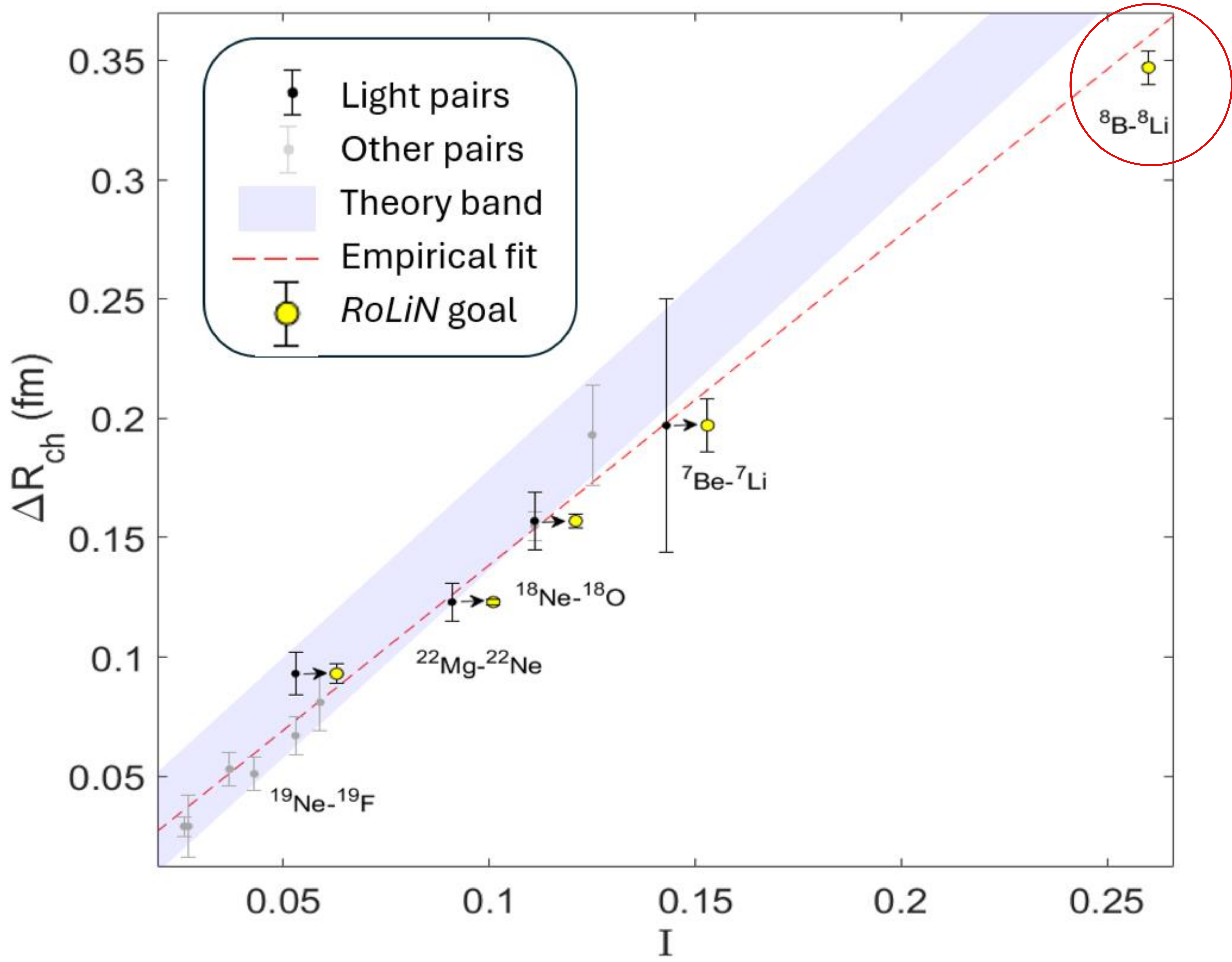


* Private com. Wilfried Nörtershäuser

Golden case: A=8

Uncertinaty contributions to $\Delta_{ch}^{mirr}(A=8)$ *



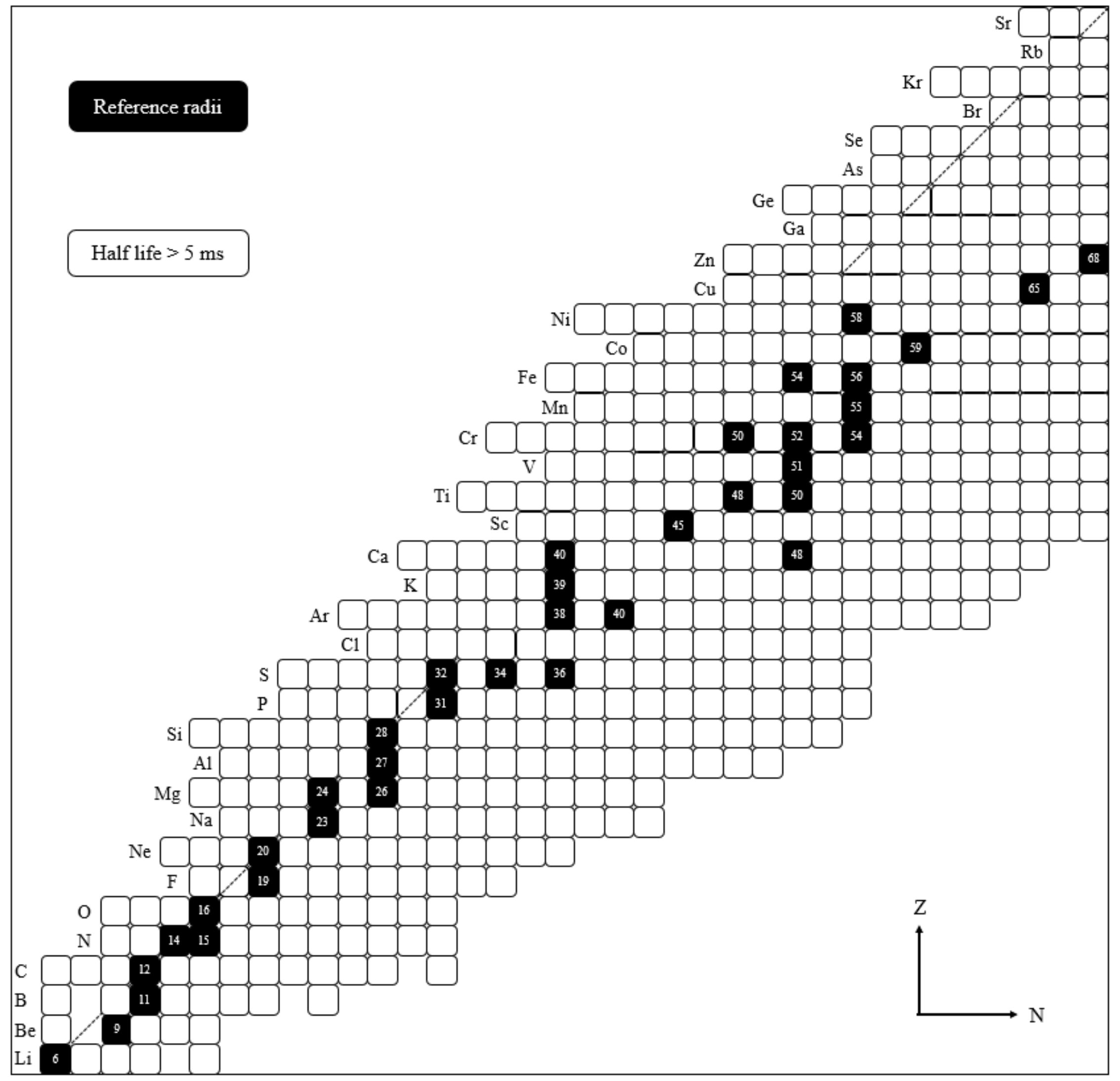


* Private com. Wilfried Nörtershäuser

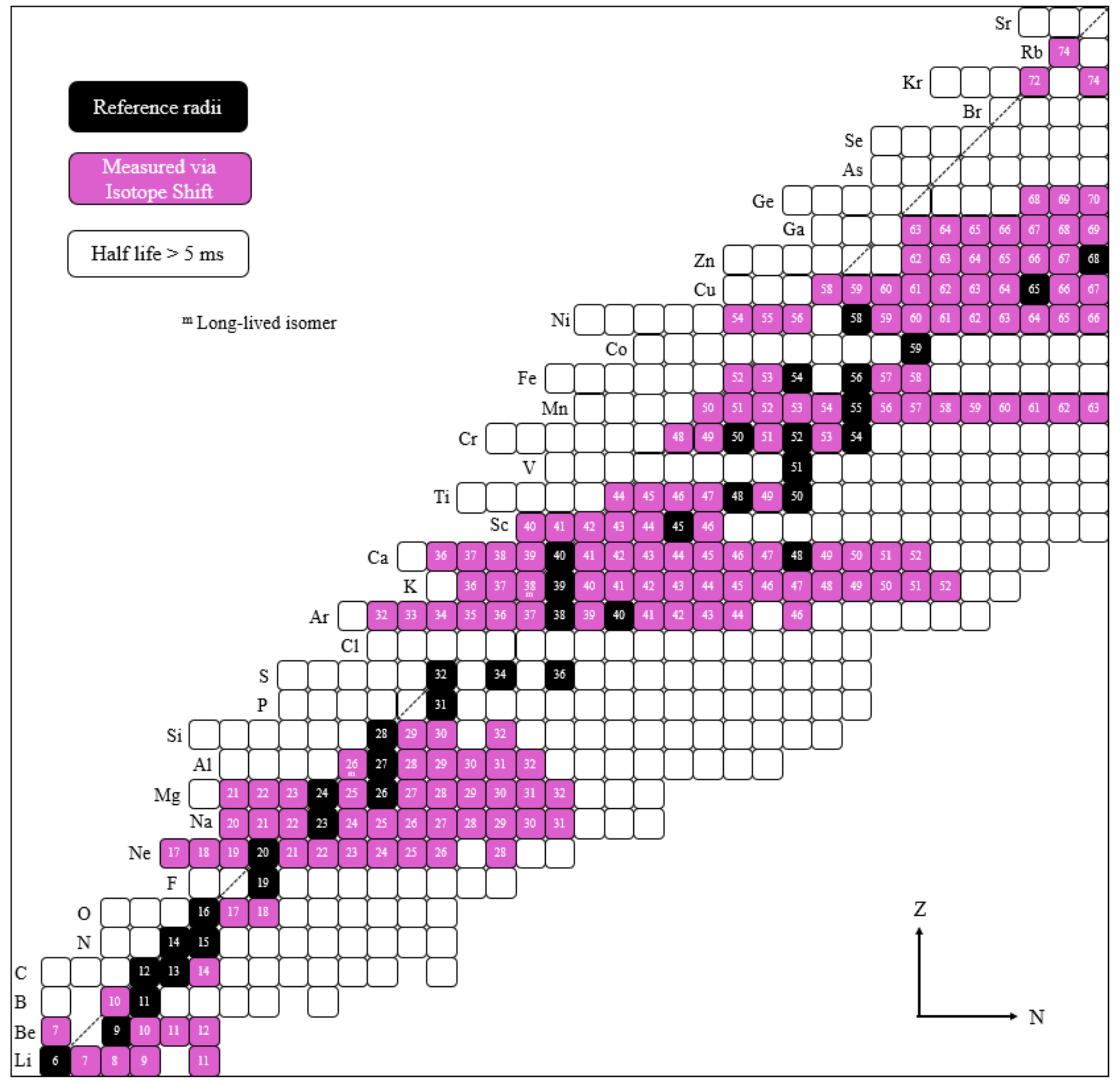
What can we do if the mirror fit holds?

Roadmap:

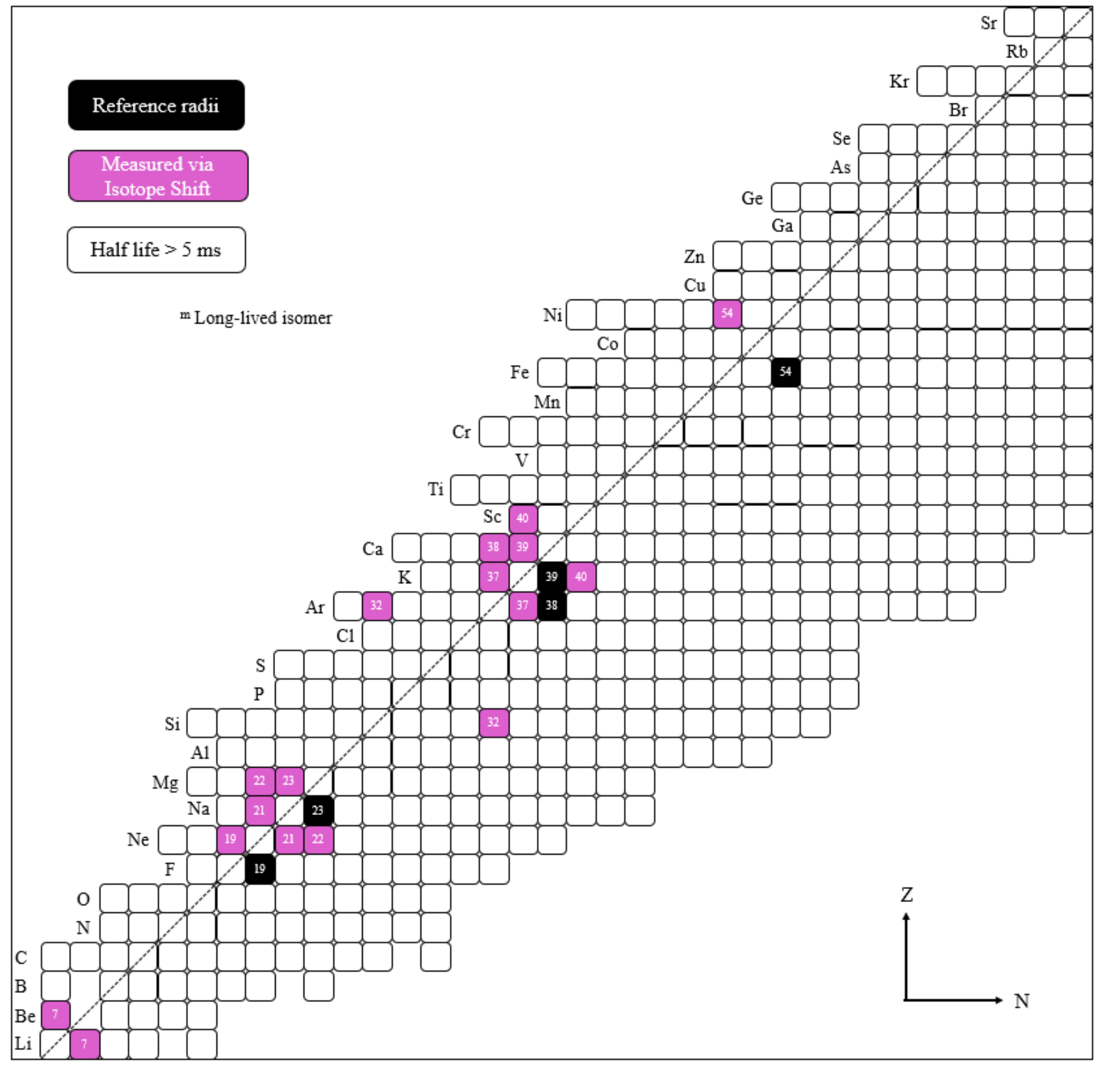
1. **Reference radii** (muonic atoms)



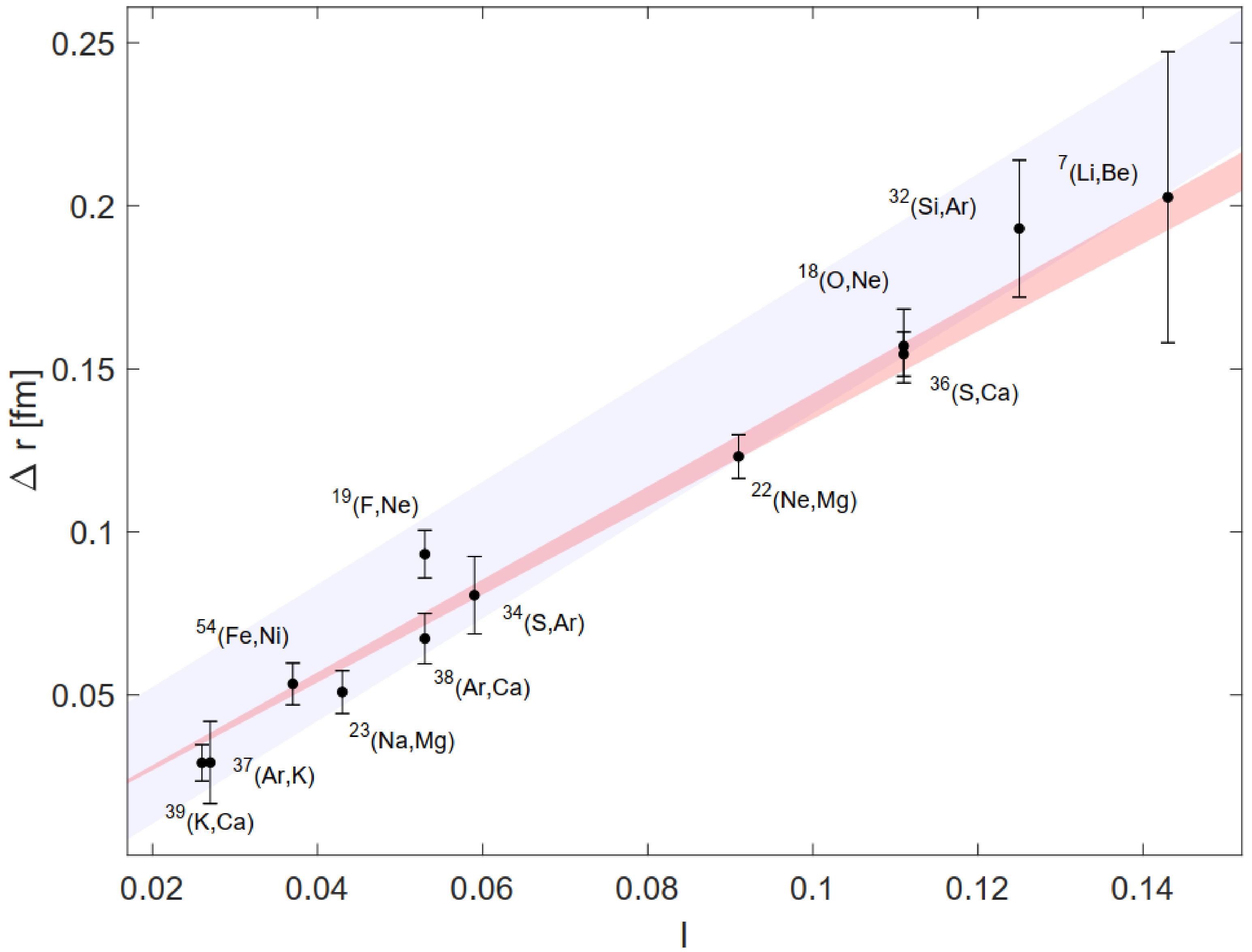
2. **With Isotope shifts** (electronic atoms)



3. **Mirror nuclei**

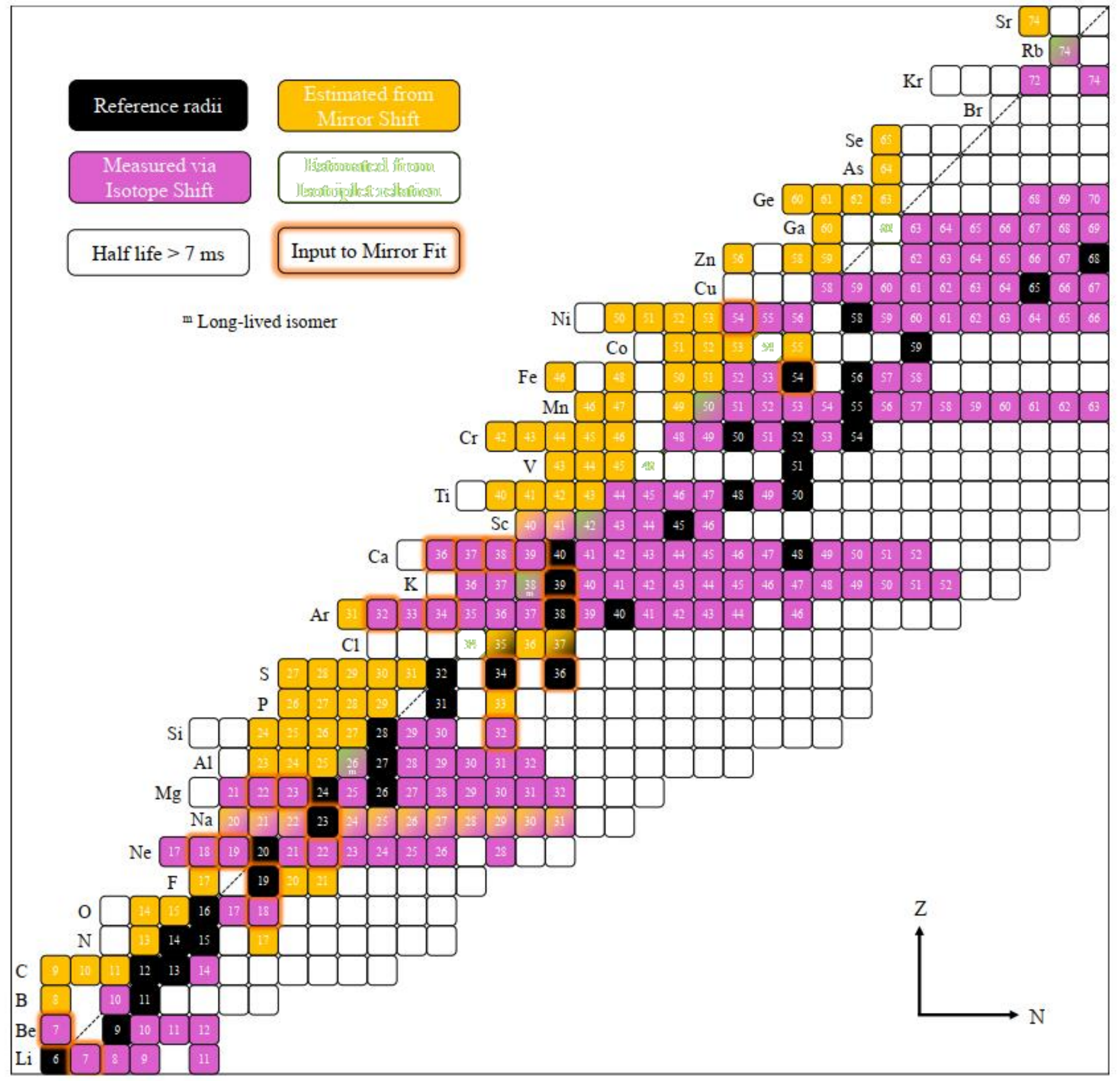


4. **Mirror fit**



?

5. **Predict 74 charge radii**



Transparent tabulation of measured and predicted radii of mirror nuclei

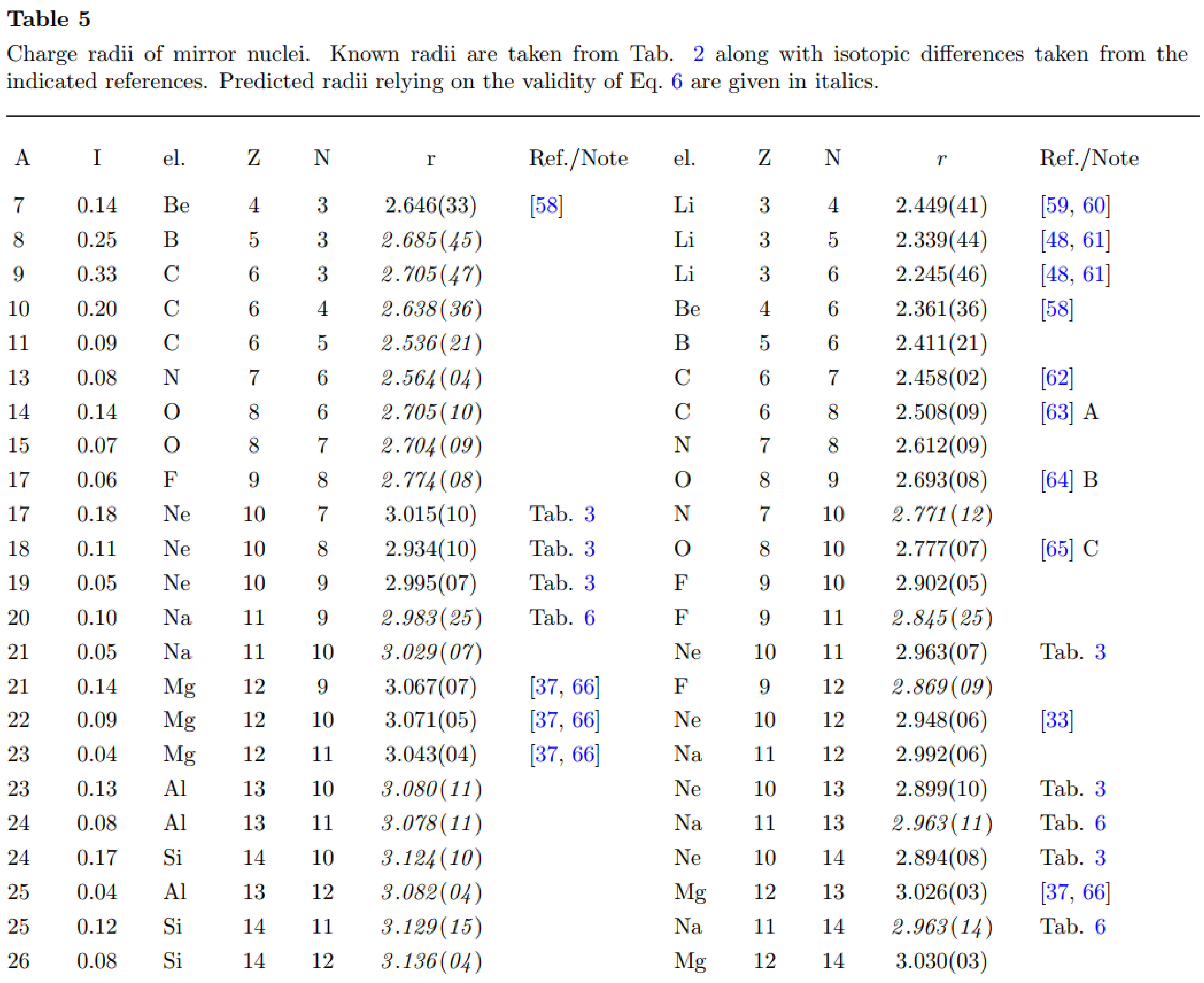


Table 5

Charge radii of mirror nuclei. Known radii are taken from Tab. 2 along with isotopic differences taken from the indicated references. Predicted radii relying on the validity of Eq. 6 are given in italics.

A	I	el.	Z	N	r	Ref./Note	el.	Z	N	*r*	Ref./Note
7	0.14	Be	4	3	2.646(33)	[58]	Li	3	4	2.449(41)	[59, 60]
8	0.25	B	5	3	*2.685(45)*		Li	3	5	2.339(44)	[48, 61]
9	0.33	C	6	3	*2.705(47)*		Li	3	6	2.245(46)	[48, 61]
10	0.20	C	6	4	*2.638(36)*		Be	4	6	2.361(36)	[58]
11	0.09	C	6	5	*2.536(21)*		B	5	6	2.411(21)	
13	0.08	N	7	6	*2.564(04)*		C	6	7	2.458(02)	[62]
14	0.14	O	8	6	*2.705(10)*		C	6	8	2.508(09)	[63] A
15	0.07	O	8	7	*2.704(09)*		N	7	8	2.612(09)	
17	0.06	F	9	8	*2.774(08)*		O	8	9	2.693(08)	[64] B
17	0.18	Ne	10	7	3.015(10)	Tab. 3	N	7	10	*2.771(12)*	
18	0.11	Ne	10	8	2.934(10)	Tab. 3	O	8	10	2.777(07)	[65] C
19	0.05	Ne	10	9	2.995(07)	Tab. 3	F	9	10	2.902(05)	
20	0.10	Na	11	9	*2.983(25)*	Tab. 6	F	9	11	*2.845(25)*	
21	0.05	Na	11	10	*3.029(07)*		Ne	10	11	2.963(07)	Tab. 3
21	0.14	Mg	12	9	3.067(07)	[37, 66]	F	9	12	*2.869(09)*	
22	0.09	Mg	12	10	3.071(05)	[37, 66]	Ne	10	12	2.948(06)	[33]
23	0.04	Mg	12	11	3.043(04)	[37, 66]	Na	11	12	2.992(06)	
23	0.13	Al	13	10	*3.080(11)*		Ne	10	13	2.899(10)	Tab. 3
24	0.08	Al	13	11	*3.078(11)*		Na	11	13	*2.963(11)*	Tab. 6
24	0.17	Si	14	10	*3.124(10)*		Ne	10	14	2.894(08)	Tab. 3
25	0.04	Al	13	12	*3.082(04)*		Mg	12	13	3.026(03)	[37, 66]
25	0.12	Si	14	11	*3.129(15)*		Na	11	14	*2.963(14)*	Tab. 6
26	0.08	Si	14	12	*3.136(04)*		Mg	12	14	3.030(03)	

…

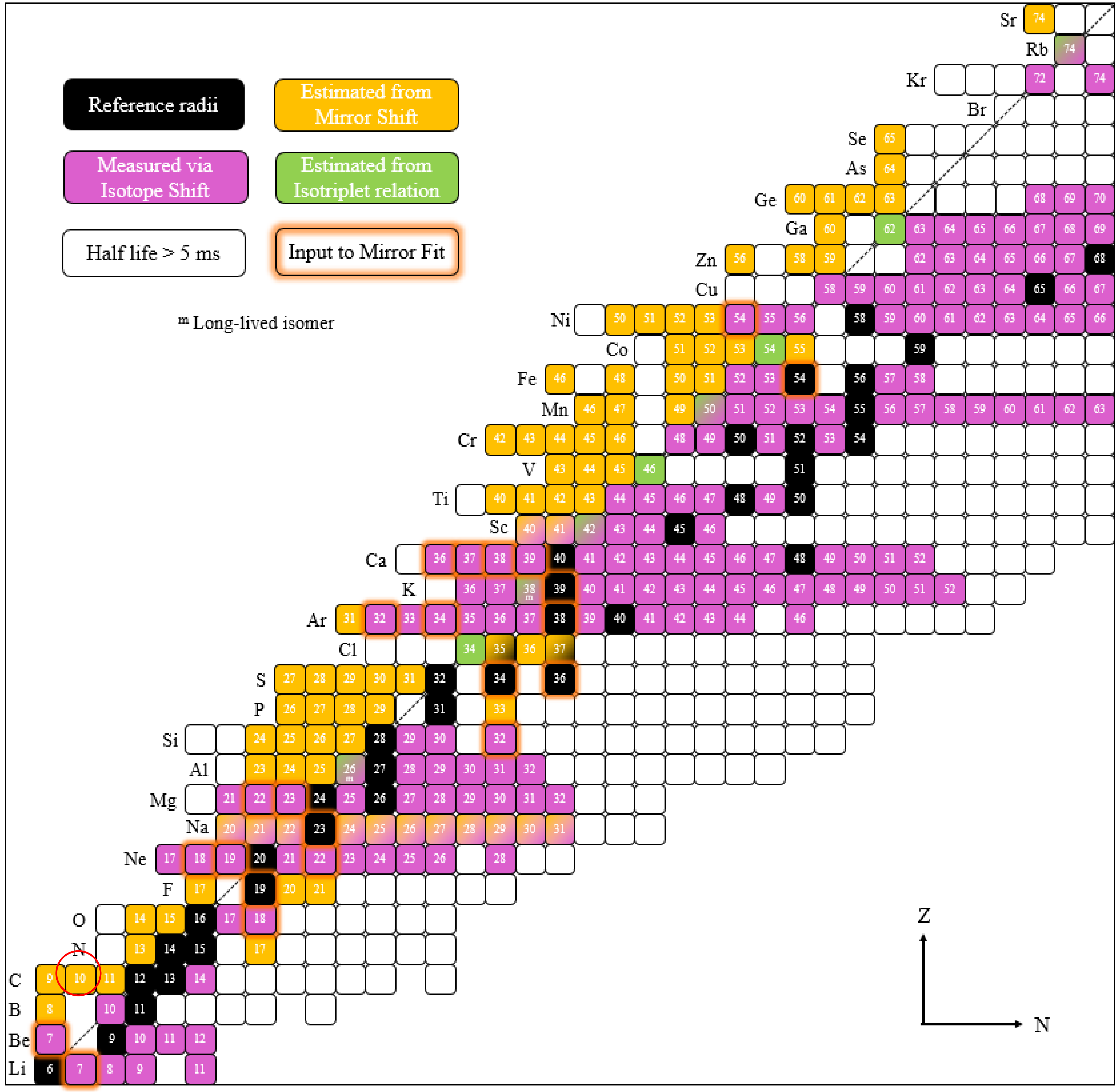
arXiv:2409.08193

What can we do with this table?

What can we do with this table?

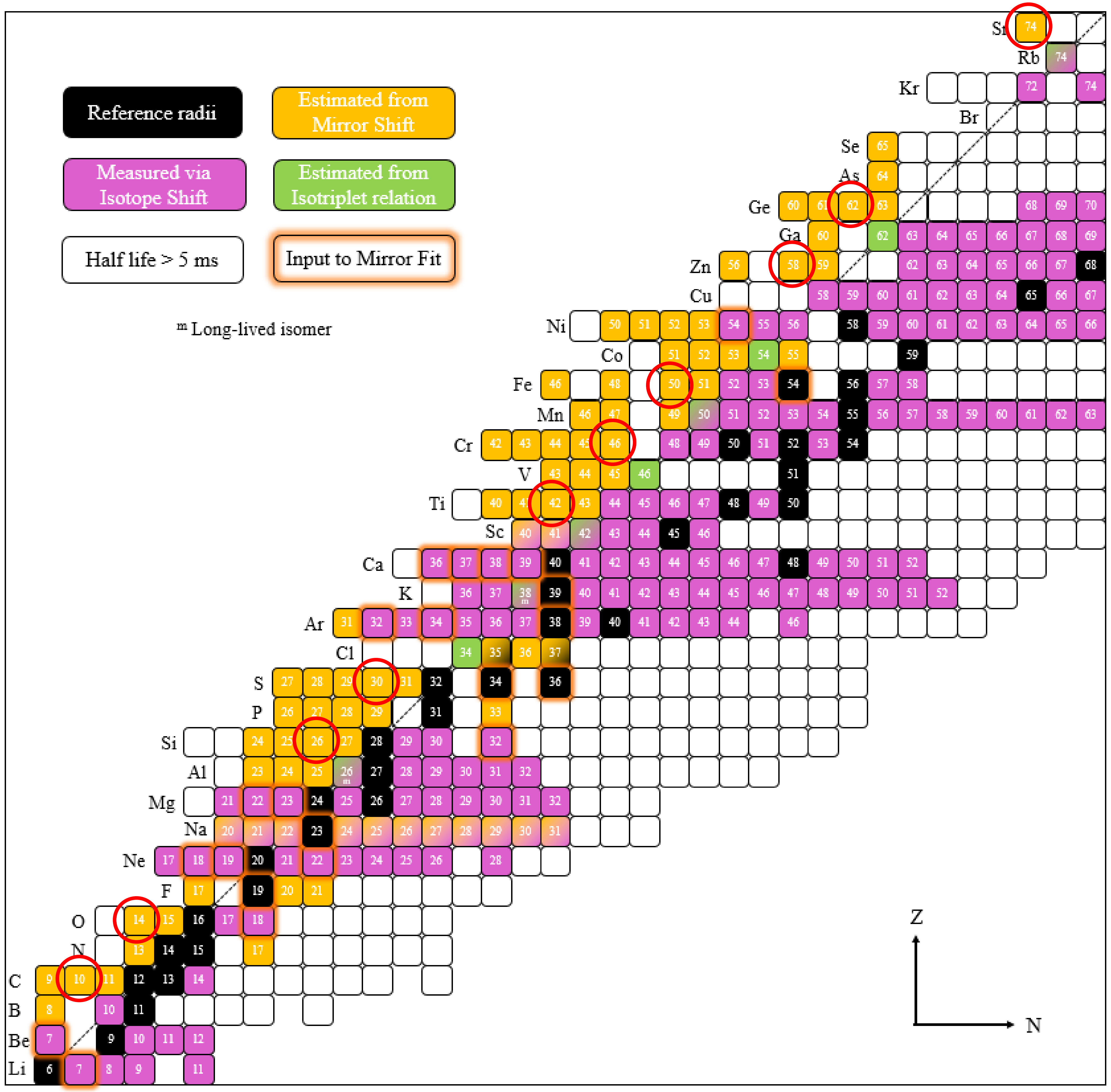
Much! I’ll focus on V_{ud}

Example 1: Missing charge radii for CKM



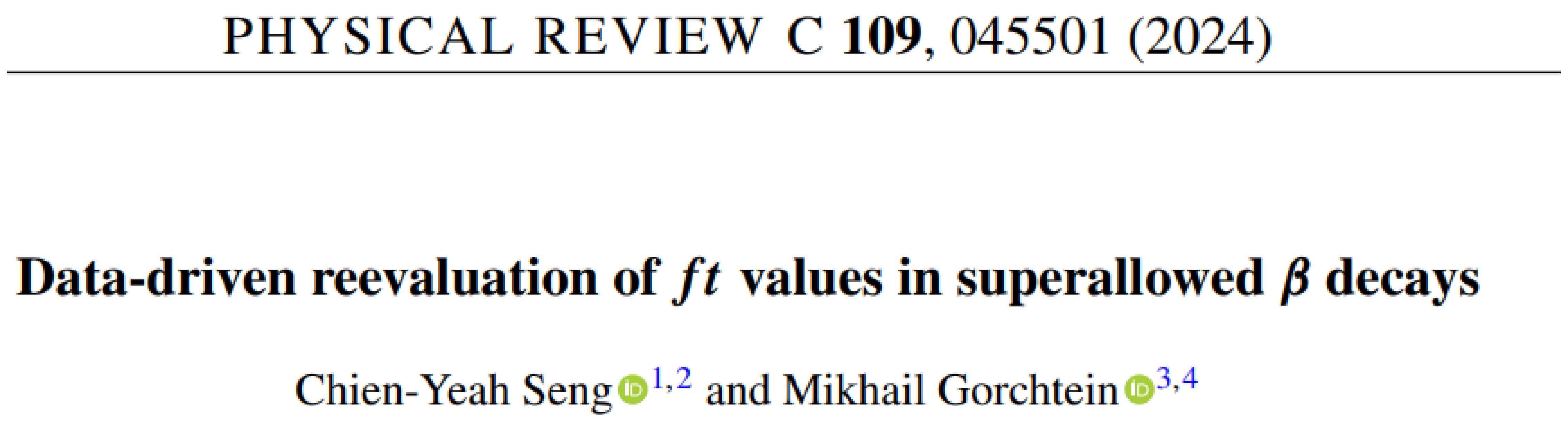
Example 1: Missing charge radii for CKM

- Important for analysis of superallowed beta-decays:



Example 1: Missing charge radii for CKM

- Important for analysis of superallowed beta-decays:



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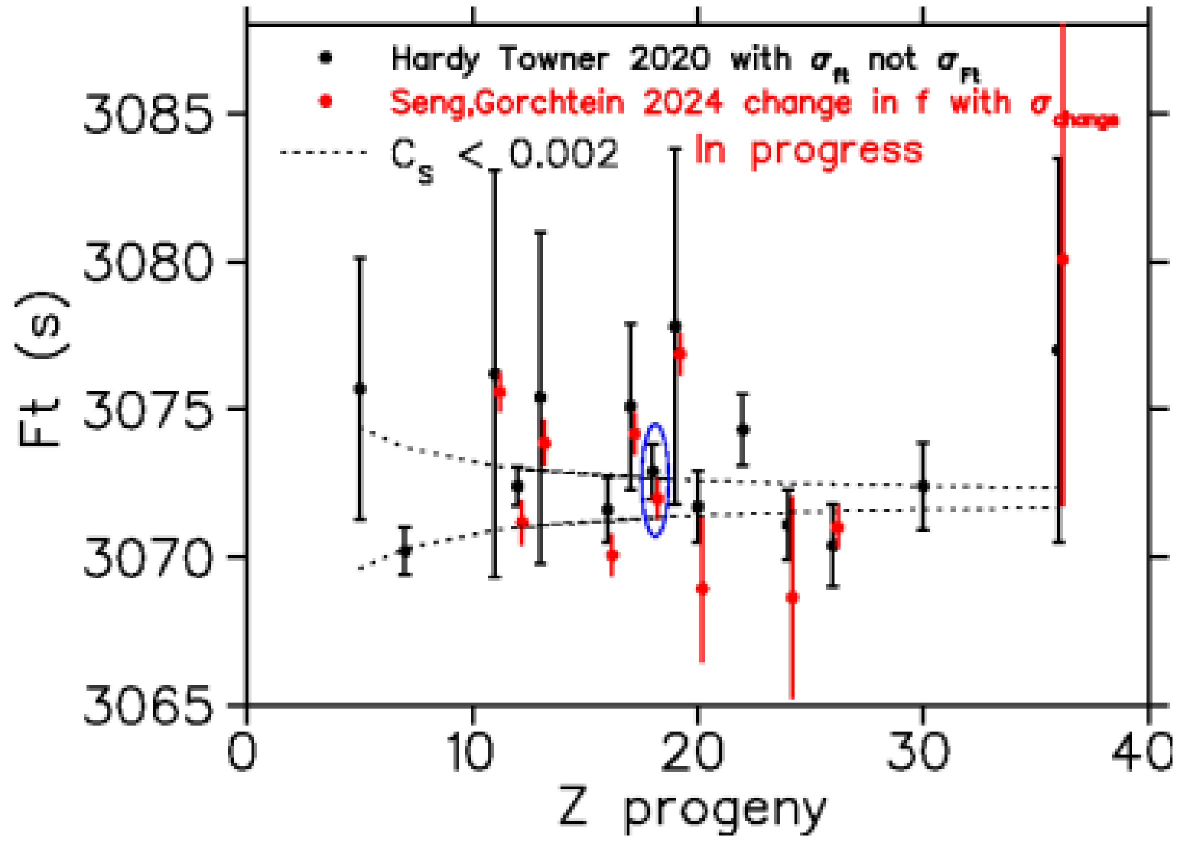
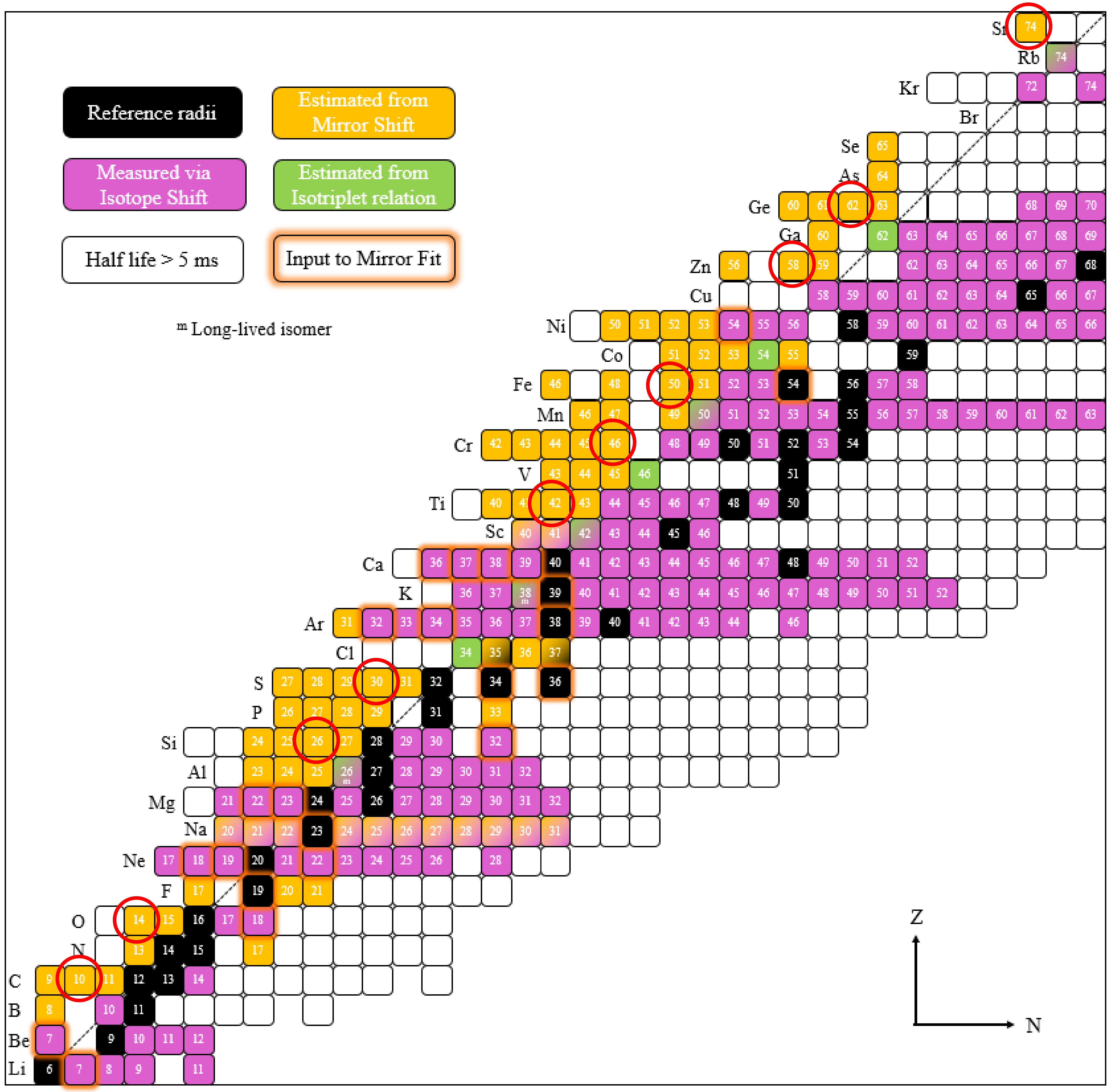
Data-driven reevaluation of *ft* values in superallowed *β* decays

Chien-Yeah Seng[1,2] and Mikhail Gorchtein[3,4]

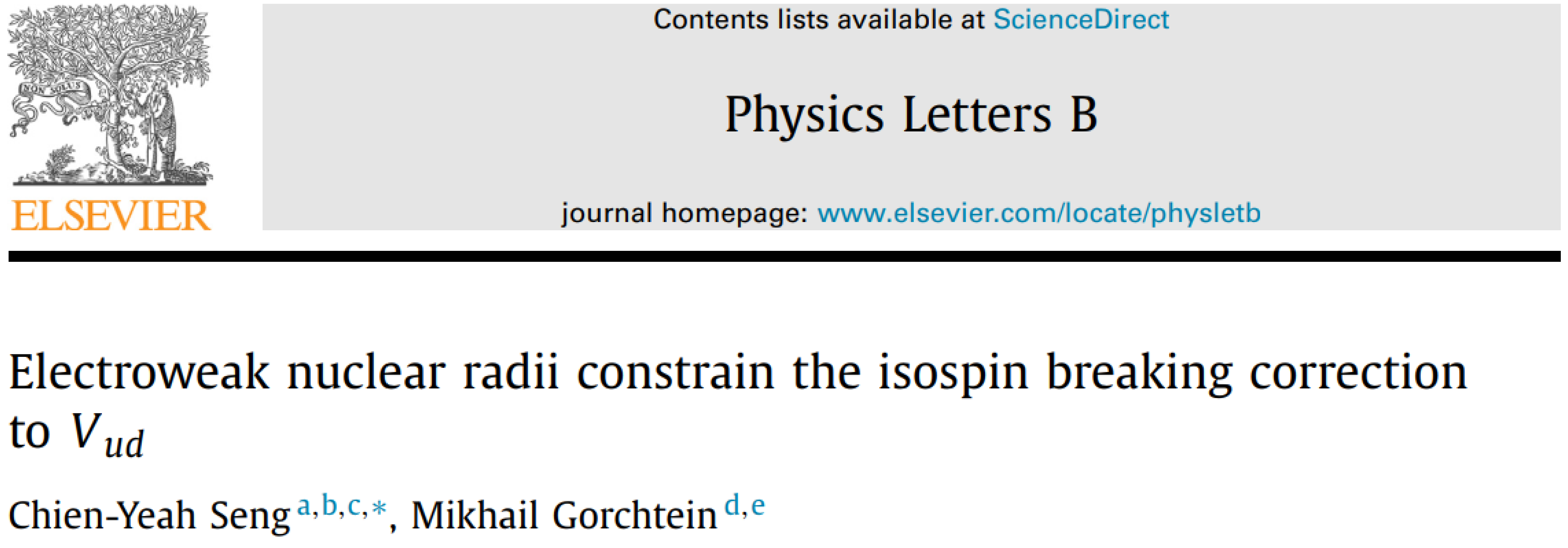
- Figure by J. Behr:





- New values not implemented (yet?)

Example 2: Test of isospin-symmetry breaking (ISB)



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Electroweak nuclear radii constrain the isospin breaking correction to V_{ud}

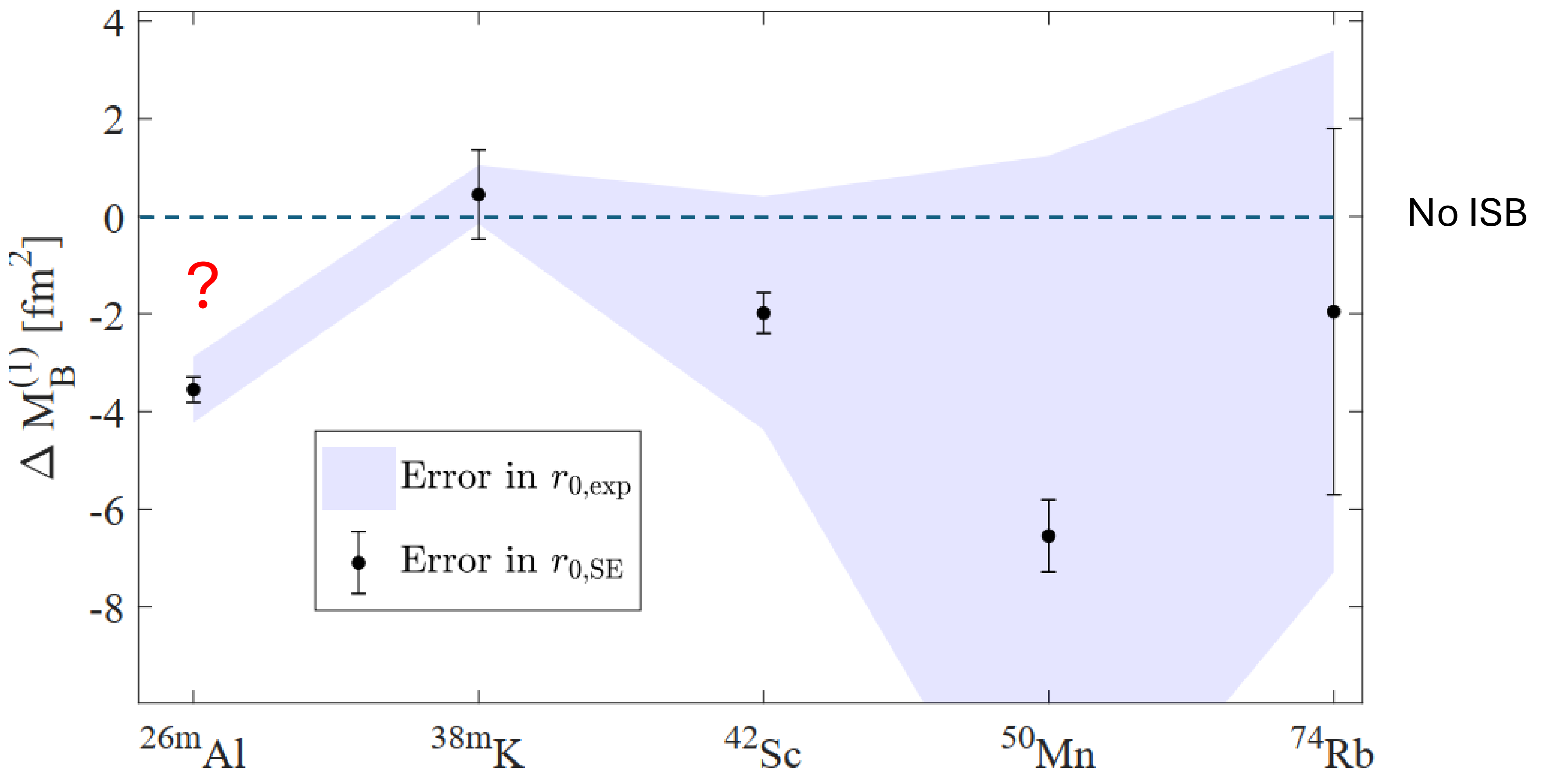
Chien-Yeah Seng [a,b,c,*], Mikhail Gorchtein [d,e]

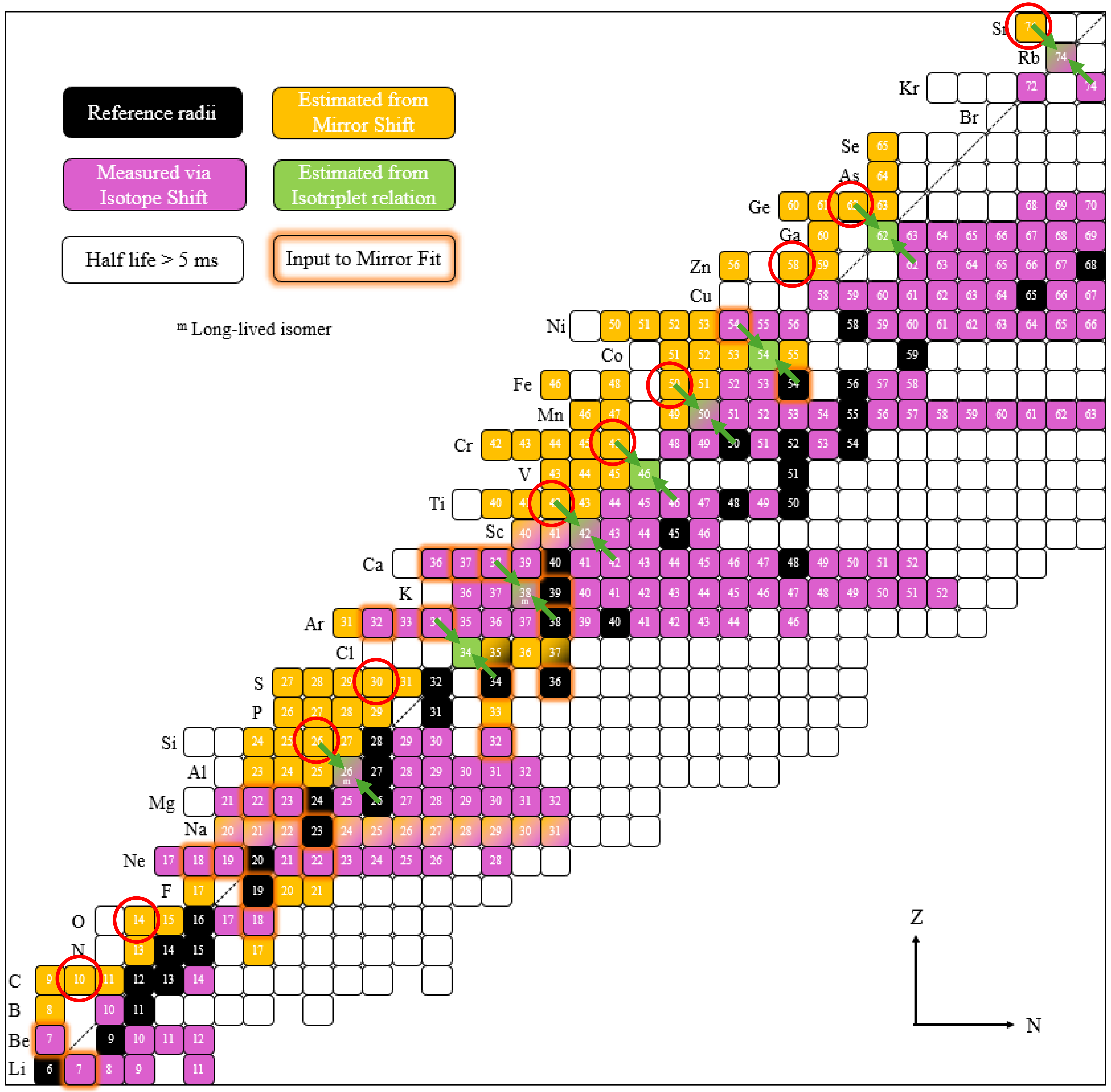
Interpolated radii without ISB:

$$r^2_{0,\mathrm{SE}} = r^2_{+1} + \frac{Z_{-1}}{2Z_0}\Delta_I(2r_{+1}+\Delta_I).$$

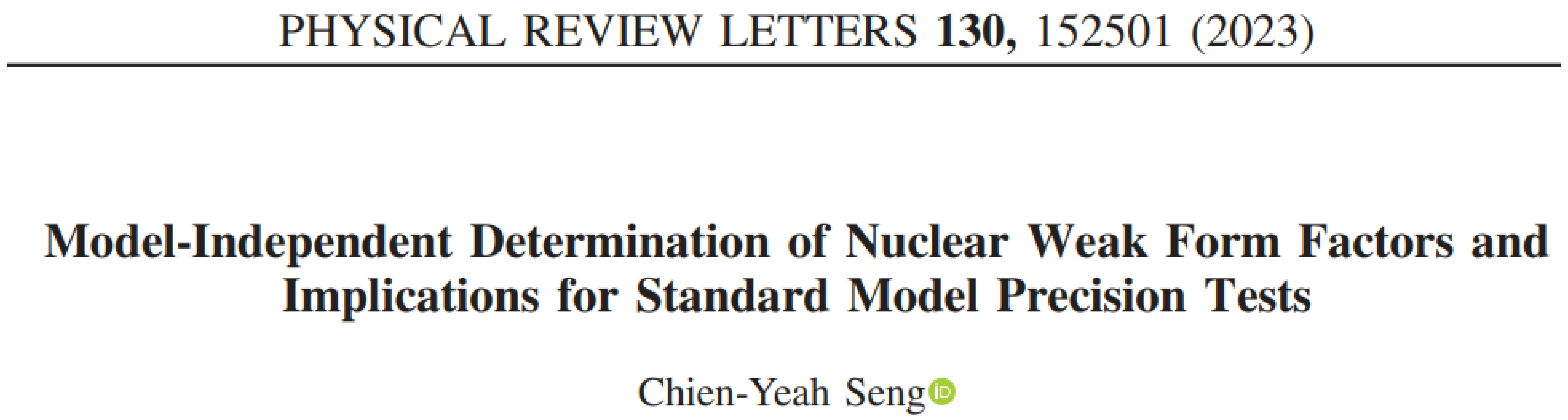
ISB test:

$$\Delta M_B^{(1)} = Z_0(r^2_{0,\mathrm{SE}} - r^2_{0,\mathrm{exp}})$$





Example 3: Weak radii for (recoil corrections to) Vud



PHYSICAL REVIEW LETTERS **130,** 152501 (2023)

Model-Independent Determination of Nuclear Weak Form Factors and Implications for Standard Model Precision Tests

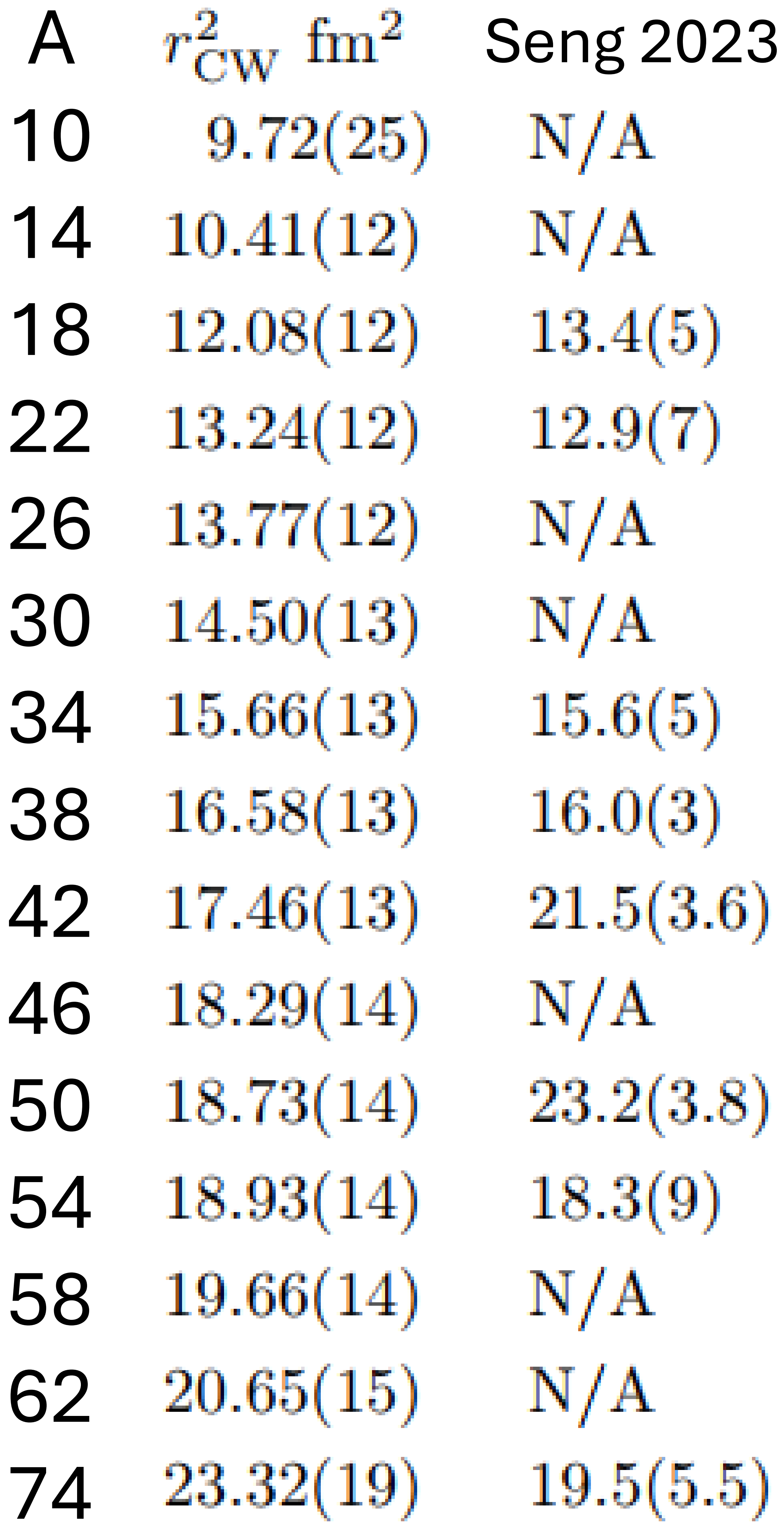
Chien-Yeah Seng

$$R^2_{\mathrm{CW}} = R^2_{\mathrm{Ch},1} + \frac{Z_{-1}}{2}\left(R^2_{\mathrm{Ch},-1} - R^2_{\mathrm{Ch},1}\right),$$

With mirror fit

$$R^2_{\mathrm{CW}} = r^2_{+1} + \frac{Z_{-1}}{2}\Delta_I(2r_{+1} + \Delta_I)$$

arXiv:2409.08193



A	r^2_{CW} fm^2	Seng 2023
10	9.72(25)	N/A
14	10.41(12)	N/A
18	12.08(12)	13.4(5)
22	13.24(12)	12.9(7)
26	13.77(12)	N/A
30	14.50(13)	N/A
34	15.66(13)	15.6(5)
38	16.58(13)	16.0(3)
42	17.46(13)	21.5(3.6)
46	18.29(14)	N/A
50	18.73(14)	23.2(3.8)
54	18.93(14)	18.3(9)
58	19.66(14)	N/A
62	20.65(15)	N/A
74	23.32(19)	19.5(5.5)

Summary

1. Charge Radii of mirror nuclei crucial to determining V_{ud}
2. If mirror relation holds, then can be predicted by global analysis
3. Missing information on light nuclei, and asymmetric pairs
4. QUARTET focused on improved Reference radii from muonic atoms using MMC detectors (next talk!)