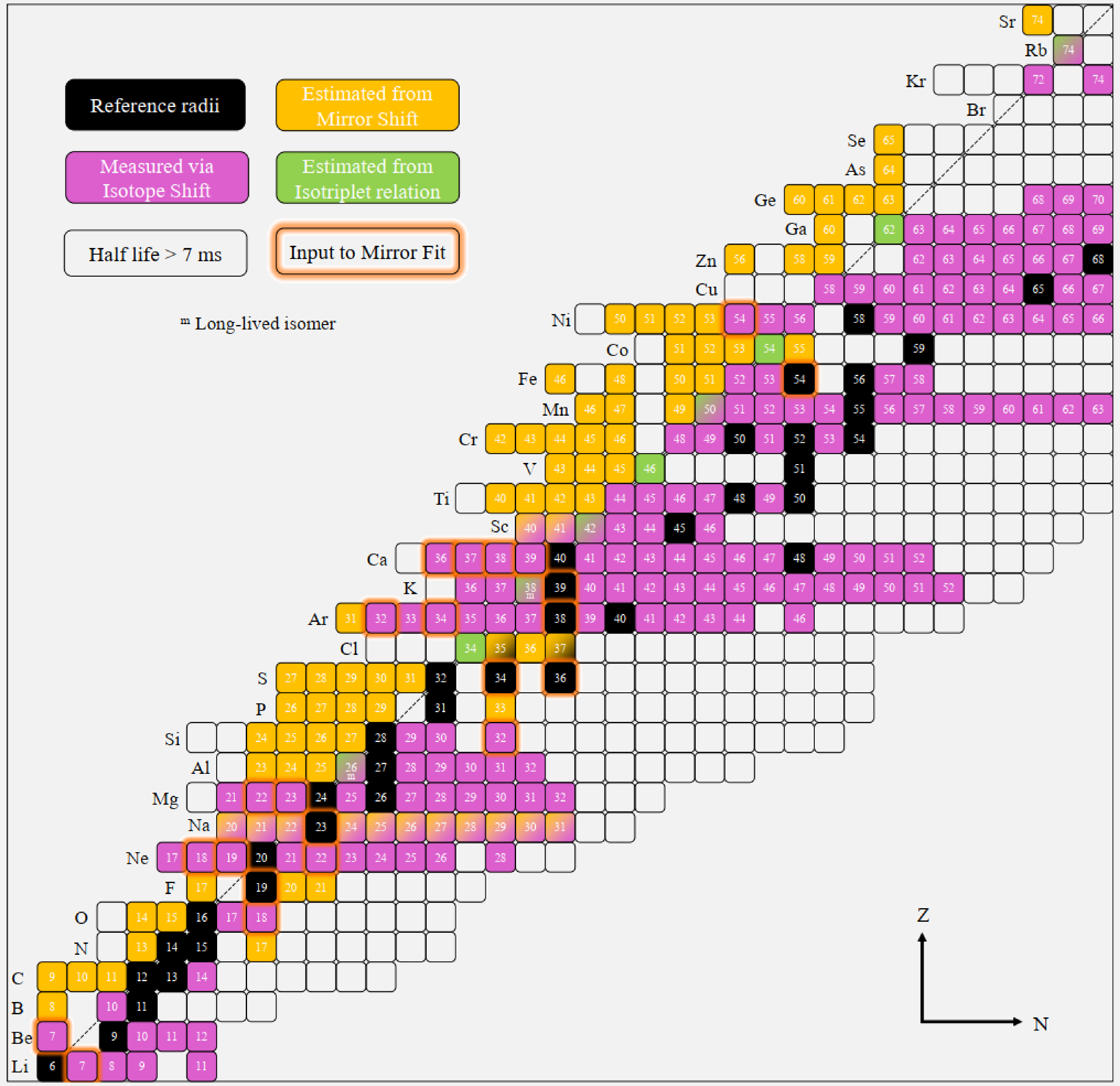
Radii for V_{UD}

arXiv:2409.08193



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

Workshop on V_{ud} from pion, neutron and nuclear beta decay, GANIL November, 5-6, 2024

This talk: Overview of charge radii for V_{ud}

$$|V_{ud}|^2_{0^+} = \frac{\pi^3 \ln 2}{G_F^2 m_e^5 \mathcal{F}t\left(1 + \Delta_R^V\right)}$$

Next talk by Michael Heines: focus radii extraction from muonic atoms

The master equation:

$$\mathcal{F}t = ft(1 + \delta'_{\mathrm{R}})(1 + \delta_{\mathrm{NS}} - \delta_{\mathrm{C}})$$

The master equation:

$$\mathcal{F}t = ft(1 + \delta'_{\mathrm{R}})(1 + \delta_{\mathrm{NS}} - \delta_{\mathrm{C}})$$

Mehdi Drissi's talk!

The master equation:

$$\mathcal{F}t = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C)$$

δ_C Modification of the Fermi Matrix element from its isospin limit value.

The master equation:

$$\mathcal{F}t = ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C)$$

δ_C Modification of the Fermi Matrix element from its isospin limit value.

In the Hardy & Towner approach (PRC 77, 025501), it depends on the charge distribution of the parent nucleus

The master equation:

$$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

δ_C Modification of the Fermi Matrix element from its isospin limit value.

In the Hardy & Towner approach (PRC 77, 025501), it depends on the charge distribution of the parent nucleus

Example from recent measurement of R(26mAl):

guesstimated

(Plattner *et al.* PRL 131, 222502)

Quantity	Previous value	This Letter
R_c	3.040(20) fm [27]	3.130(15) fm
δ_{C2}	0.280(15)% [10]	0.310(14)%
$\mathcal{F}t(^{26m}Al)$	3072.4(1.1) s [10]	3071.4(1.0) s

The master equation:

$$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

δ_C Modification of the Fermi Matrix element from its isospin limit value.

In the Hardy & Towner approach (PRC 77, 025501), it depends on the charge distribution of the parent nucleus

Example from recent measurement of R(26mAl):

guesstimated

(Plattner *et al.* PRL 131, 222502)

Quantity	Previous value	This Letter
R_c	3.040(20) fm [27]	3.130(15) fm
δ_{C2}	0.280(15)% [10]	0.310(14)%
$\mathcal{F}t(^{26m}Al)$	3072.4(1.1) s [10]	3071.4(1.0) s

To obtain Ft(26mAl) to 0.01%, accuracy of 0.03 fm is enough
Need *some* measurement, but not *accurate* measurement

Towner & Hardy:

Charge radii play a minor role in V_{ud} determination from nuclear Beta decay

Towner & Hardy:

Charge radii play a minor role in V_{ud} determination from nuclear Beta decay

Seng & Gorchtein: Radii play a **major** role

Radii effect on f:

Seng & Gorchtein PRC **109**, 045501 (2024)

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C)$$

Radii effect on f:

Seng & Gorchtein PRC **109**, 045501 (2024)

$$\mathcal{F}t = \boxed{f}t(1+\delta_R')(1+\delta_{NS}-\delta_C)$$

Statistical rate function

$$f = m_e^{-5}\int_{m_e}^{E_0} \mathbf{p}E(E_0-E)^2F(E)C(E)Q(E)R(E)r(E)dE,$$

Radii effect on f:

Seng & Gorchtein PRC **109**, 045501 (2024)

$$\mathcal{F}t = ft(1+\delta'_{\mathrm{R}})(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}})$$

Statistical rate function $$f = m_e^{-5}\int_{m_e}^{E_0} \mathbf{p}E(E_0-E)^2 F(E)C(E)Q(E)R(E)r(E)dE,$$

1. Fermi function accounts for Coulomb interaction between outgoing positron and daughter nucleus
- Solved numerically given an (EM) **charge distribution**

Radii effect on f:

Seng & Gorchtein PRC **109**, 045501 (2024)

$$\mathcal{F}t = ft(1 + \delta_R')(1 + \delta_{NS} - \delta_C)$$

Statistical rate function $$f = m_e^{-5} \int_{m_e}^{E_0} \mathbf{p}E(E_0 - E)^2 F(E) C(E) Q(E) R(E) r(E) dE,$$

1. Fermi function accounts for Coulomb interaction between outgoing positron and daughter nucleus
- Solved numerically given an (EM) **charge distribution**

2. Shape factor accounts for the influence of beta-decay form factor – needs **weak charge distribution**

Radii effect on f:

Seng & Gorchtein PRC **109**, 045501 (2024)

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C)$$

Statistical rate function $$f = m_e^{-5}\int_{m_e}^{E_0} \mathbf{p}E(E_0-E)^2F(E)C(E)Q(E)R(E)r(E)dE,$$

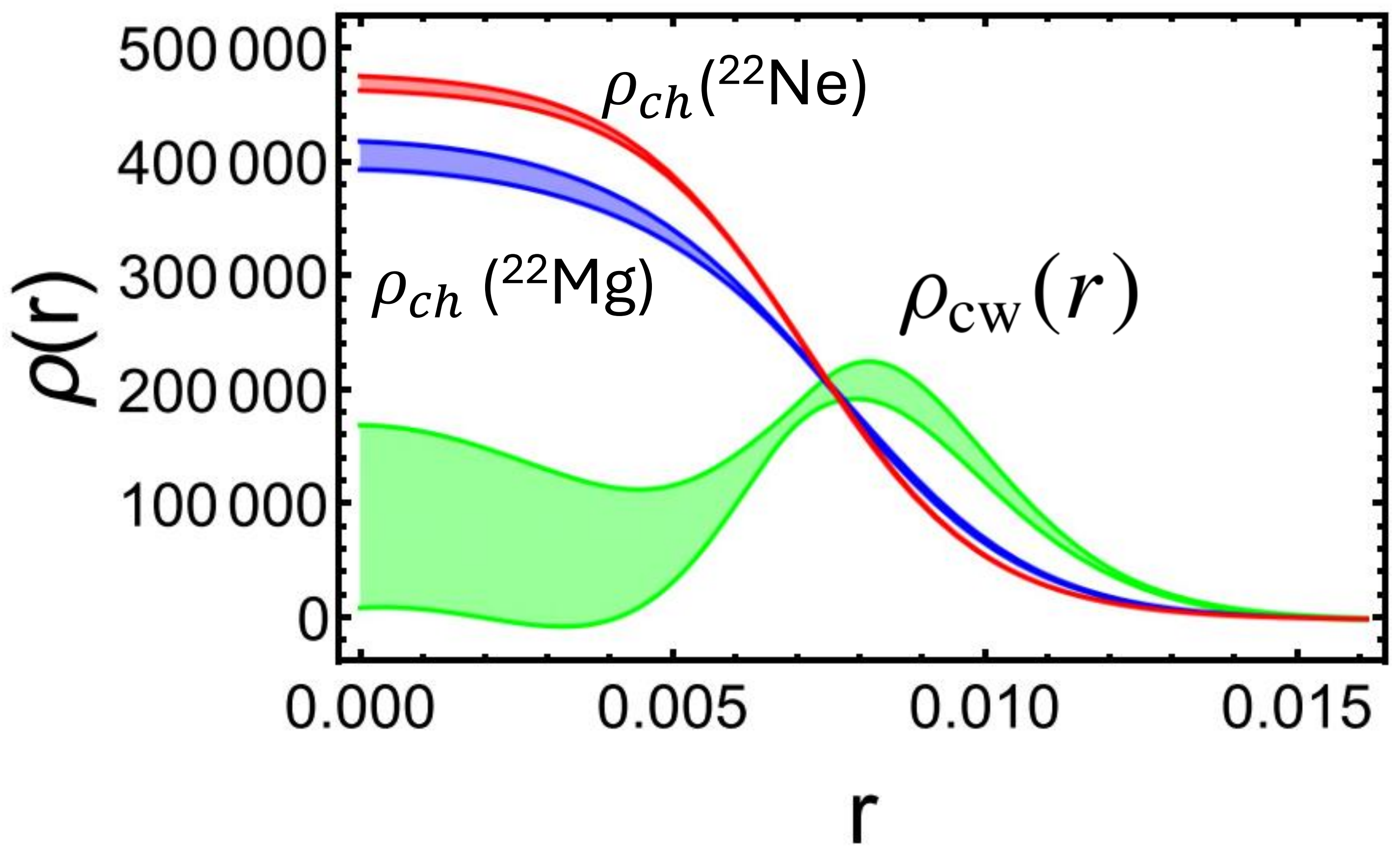
1. Fermi function accounts for Coulomb interaction between outgoing positron and daughter nucleus
- Solved numerically given an (EM) **charge distribution**

2. Shape factor accounts for the influence of beta-decay form factor – needs **weak charge distribution**

Isospin symmetry connect weak (hard to measure) and EM charge distributions:

$$\rho_{cw}(r) = \rho_{ch,1}(r) + Z_0[\rho_{ch,0}(r) - \rho_{ch,1}(r)]$$
$$= \rho_{ch,1}(r) + \frac{Z_{-1}}{2}[\rho_{ch,-1}(r) - \rho_{ch,1}(r)].$$

(need two out-of-three)



Radii effect on f:

Seng & Gorchtein PRC **109**, 045501 (2024)

$$\mathcal{F}t = ft(1+\delta_R')(1+\delta_{NS}-\delta_C)$$

Statistical rate function $$f = m_e^{-5}\int_{m_e}^{E_0} \mathbf{p}E(E_0-E)^2 F(E)C(E)Q(E)R(E)r(E)dE,$$

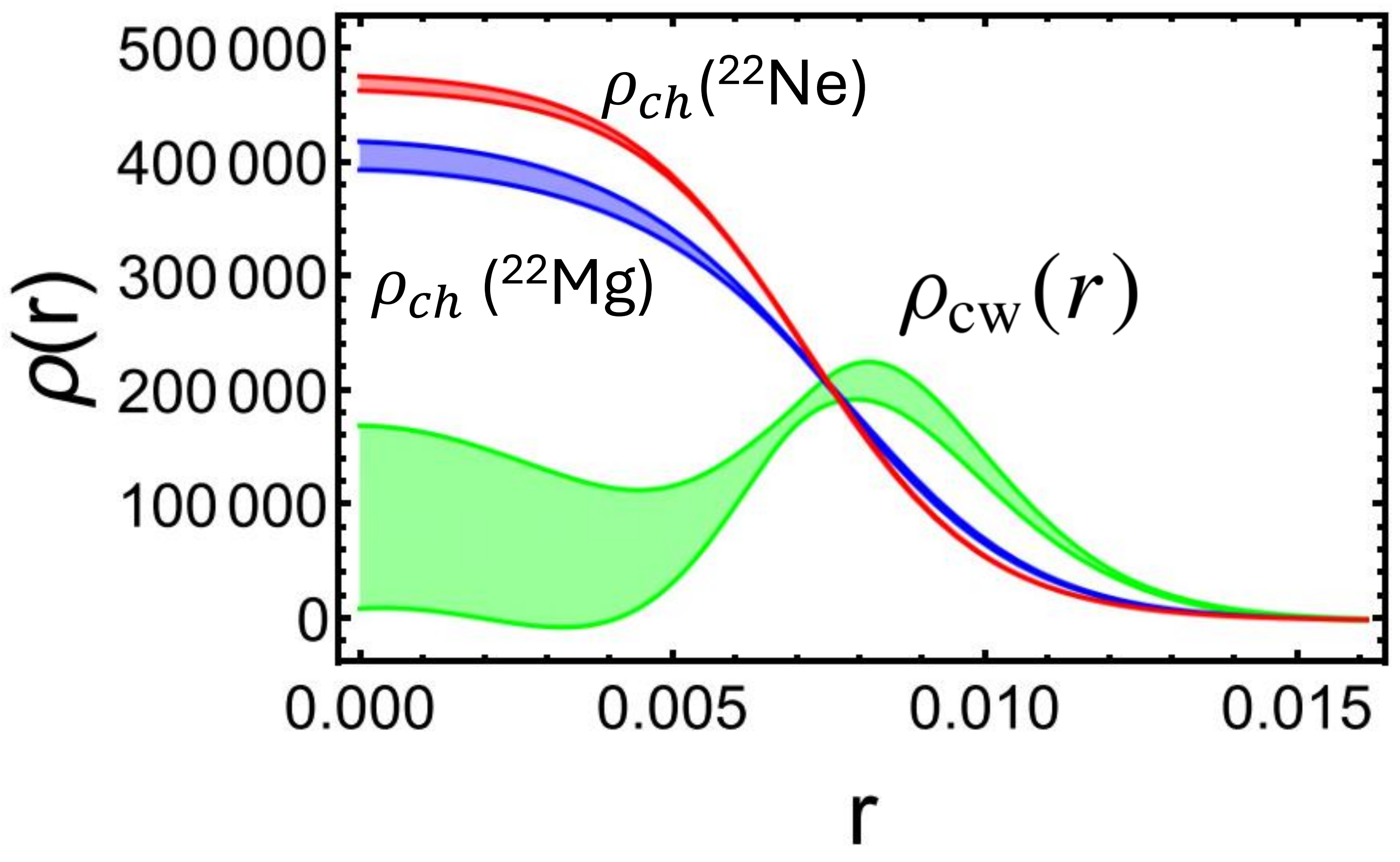
1. Fermi function accounts for Coulomb interaction between outgoing positron and daughter nucleus
- Solved numerically given an (EM) **charge distribution**

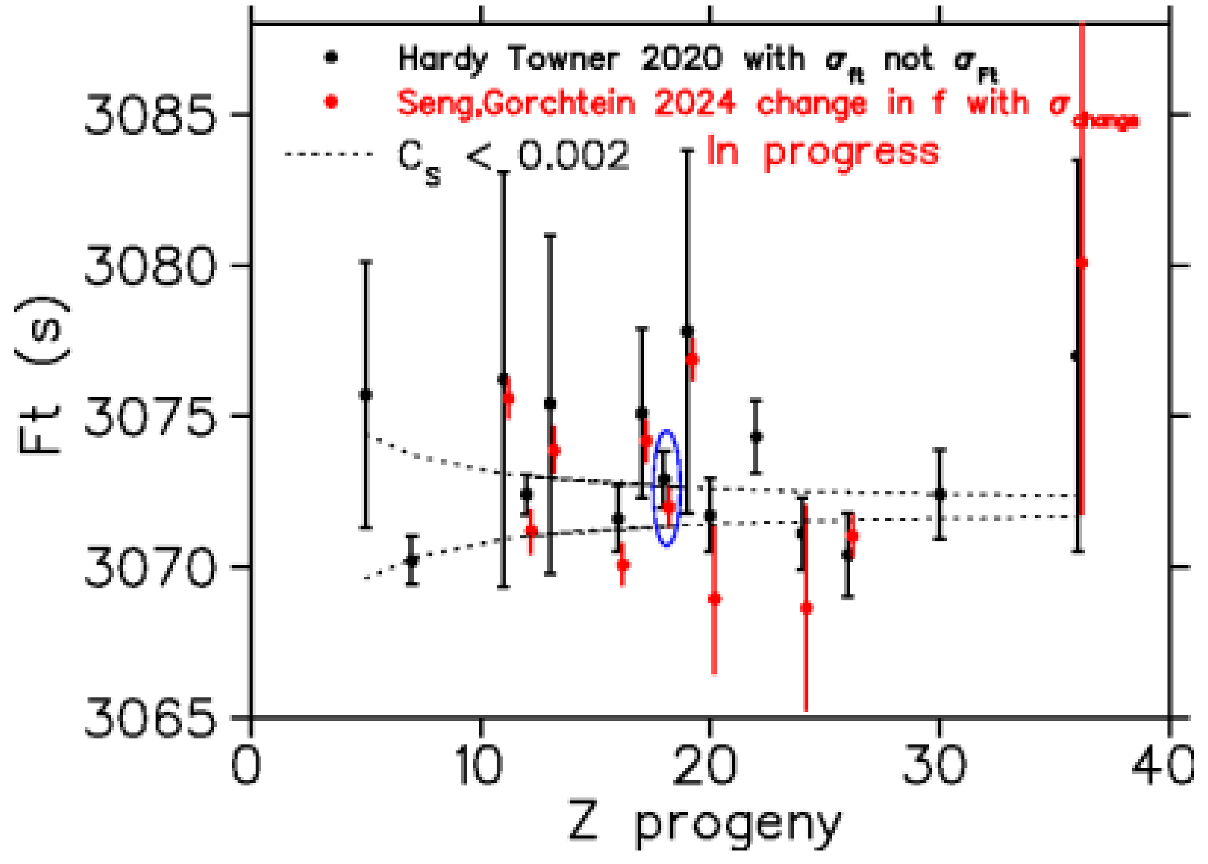
2. Shape factor accounts for the influence of beta-decay form factor – needs **weak charge distribution**

Isospin symmetry connect weak (hard to measure) and EM charge distributions:

$$\begin{aligned}\rho_{cw}(r) &= \rho_{ch,1}(r) + Z_0[\rho_{ch,0}(r) - \rho_{ch,1}(r)] \\ &= \rho_{ch,1}(r) + \frac{Z_{-1}}{2}[\rho_{ch,-1}(r) - \rho_{ch,1}(r)].\end{aligned}$$

(need two out-of-three)

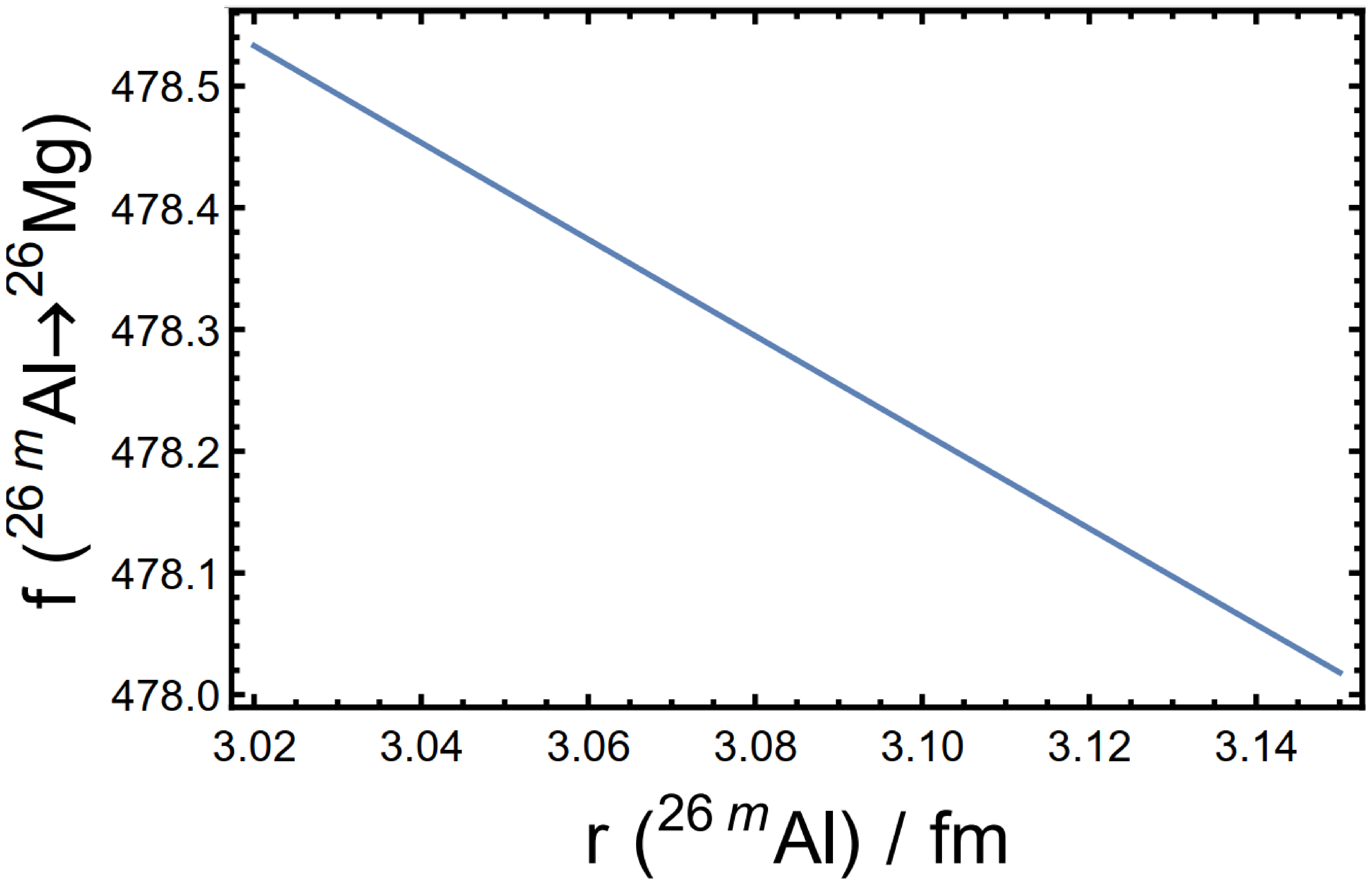




How large is the effect?

How large is the effect? Example (26mAl):

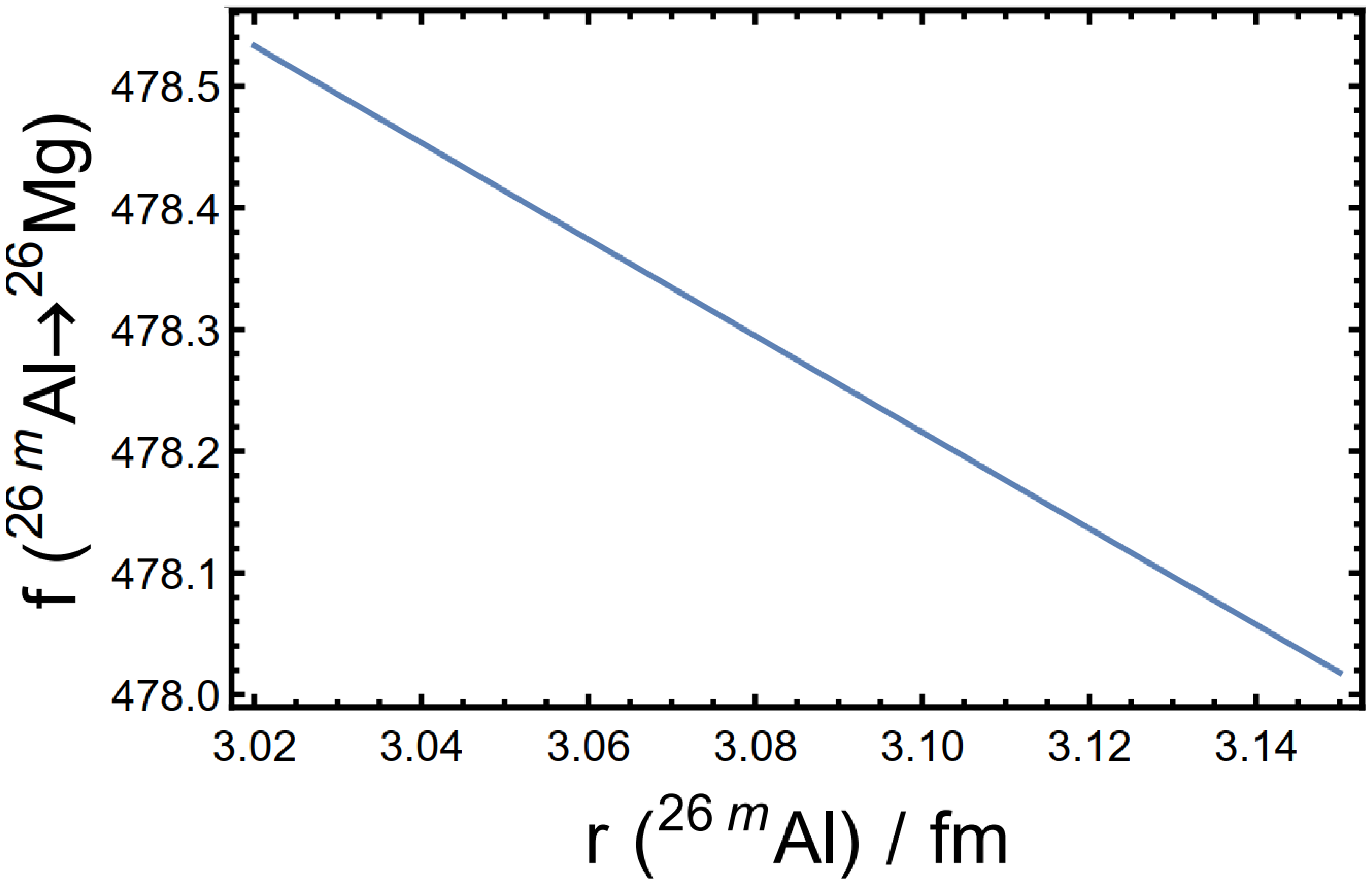
Ongoing work (with Seng, Gorchtein and Sahoo)



$$f \approx 478.45 - \frac{4.0}{\text{fm}}\left[r(^{26m}\text{Al}) - 3.040\text{fm}\right] + \frac{3.3}{\text{fm}}\left[r(^{26}\text{Mg}) - 3.0337\text{fm}\right]$$

How large is the effect? Example (26mAl):

Ongoing work (with Seng, Gorchtein and Sahoo)



$$f \approx 478.45 - \frac{4.0}{\text{fm}}\left[r(^{26m}\text{Al}) - 3.040\text{fm}\right] + \frac{3.3}{\text{fm}}\left[r(^{26}\text{Mg}) - 3.0337\text{fm}\right]$$

To obtain f(26mAl) to within 0.01%, accuracy of 0.01 fm is needed !
(three times the effect on δ_c)

What else can charge radii do?

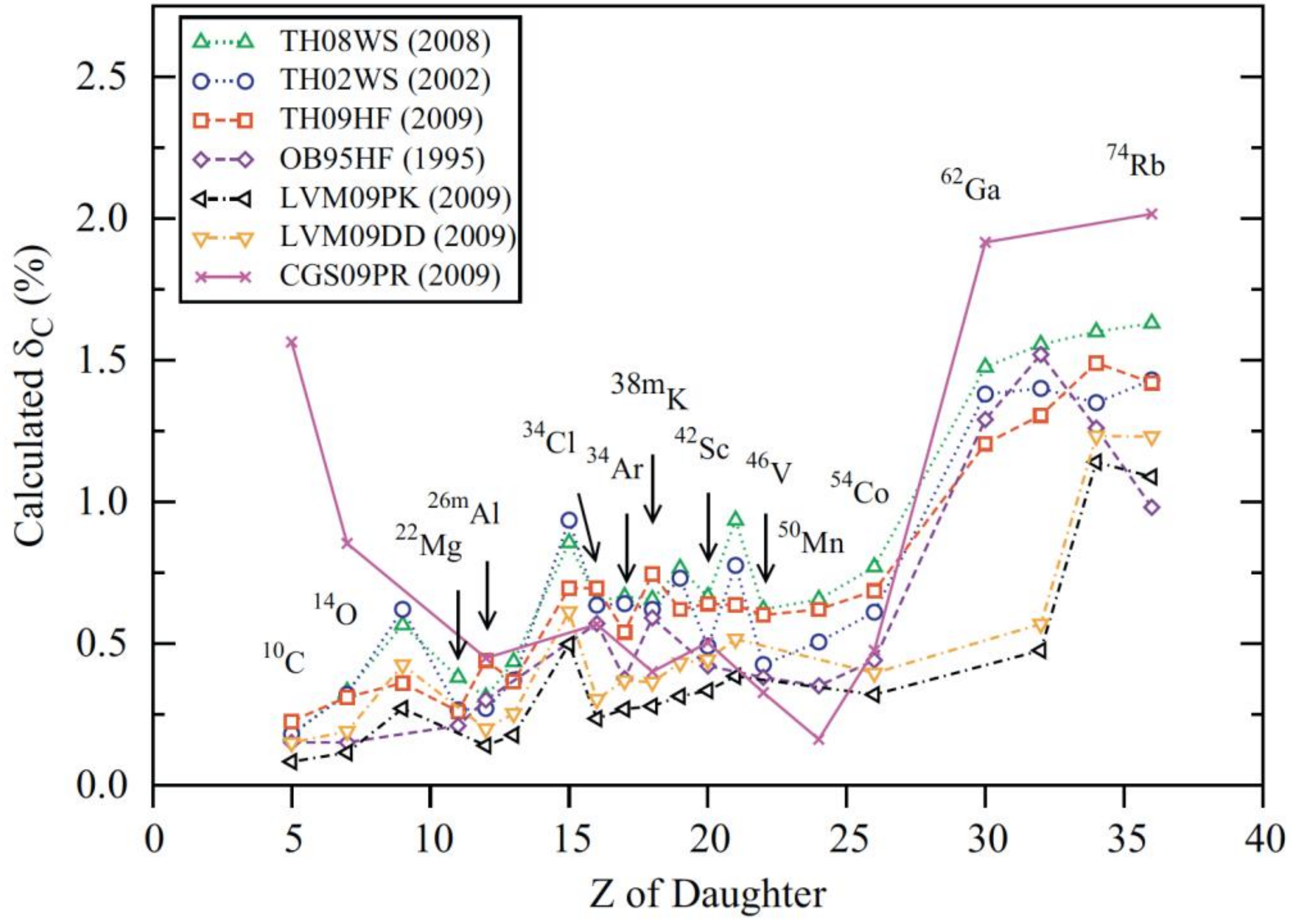
What else can charge radii do?

Bertram Blank's conclusion:

What is the conclusion ?

- **V_{us} seems to be stable**
- **Ft is stable, but depends on δ_c correction**
- **what can we do from the experimental side?**
  - **measure specific data**
    - **values where δ_c values differ a lot**
    - **heavier nuclei to test CVC on a larger range**
  - **get improved δ_c corrections**

Which model to choose?



Grinyer et al., NIMA 622 (2010) 236

3. Testing ISB corrections:

Seng & Gorchtein PLB 838 (2023) 137654

What we want to know

Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \to {}^{26}Mg$	0.310	0.329	0.30	0.139	0.08
$^{34}Cl \to {}^{34}S$	0.613	0.75	0.57	0.234	0.13
$^{38m}K \to {}^{38}Ar$	0.628	1.7	0.59	0.278	0.15
$^{42}Sc \to {}^{42}Ca$	0.690	0.77	0.42	0.333	0.18
$^{46}V \to {}^{46}Ti$	0.620	0.563	0.38	/	0.21
$^{50}Mn \to {}^{50}Cr$	0.660	0.476	0.35	/	0.24
$^{54}Co \to {}^{54}Fe$	0.770	0.586	0.44	0.319	0.28

3. Testing ISB corrections: Seng & Gorchtein PLB 838 (2023) 137654

What we want to know

Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \rightarrow {}^{26}Mg$	0.310	0.329	0.30	0.139	0.08
$^{34}Cl \rightarrow {}^{34}S$	0.613	0.75	0.57	0.234	0.13
$^{38m}K \rightarrow {}^{38}Ar$	0.628	1.7	0.59	0.278	0.15
$^{42}Sc \rightarrow {}^{42}Ca$	0.690	0.77	0.42	0.333	0.18
$^{46}V \rightarrow {}^{46}Ti$	0.620	0.563	0.38	/	0.21
$^{50}Mn \rightarrow {}^{50}Cr$	0.660	0.476	0.35	/	0.24
$^{54}Co \rightarrow {}^{54}Fe$	0.770	0.586	0.44	0.319	0.28

What we can measure

Transitions	$\Delta M_B^{(1)}$ (fm^2)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \rightarrow {}^{26}Mg$	-0.12	-0.12	-0.11	-0.05	-0.03
$^{34}Cl \rightarrow {}^{34}S$	-0.17	-0.21	-0.16	-0.06	-0.04
$^{38m}K \rightarrow {}^{38}Ar$	-0.15	-0.42	-0.15	-0.07	-0.04
$^{42}Sc \rightarrow {}^{42}Ca$	-0.15	-0.17	-0.09	-0.07	-0.04
$^{46}V \rightarrow {}^{46}Ti$	-0.12	-0.11	-0.08	/	-0.04
$^{50}Mn \rightarrow {}^{50}Cr$	-0.12	-0.09	-0.06	/	-0.04
$^{54}Co \rightarrow {}^{54}Fe$	-0.13	-0.10	-0.07	-0.05	-0.05

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2$$

3. Testing ISB corrections: Seng & Gorchtein PLB 838 (2023) 137654

What we want to know

Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \rightarrow {}^{26}Mg$	0.310	0.329	0.30	0.139	0.08
$^{34}Cl \rightarrow {}^{34}S$	0.613	0.75	0.57	0.234	0.13
$^{38m}K \rightarrow {}^{38}Ar$	0.628	1.7	0.59	0.278	0.15
$^{42}Sc \rightarrow {}^{42}Ca$	0.690	0.77	0.42	0.333	0.18
$^{46}V \rightarrow {}^{46}Ti$	0.620	0.563	0.38	/	0.21
$^{50}Mn \rightarrow {}^{50}Cr$	0.660	0.476	0.35	/	0.24
$^{54}Co \rightarrow {}^{54}Fe$	0.770	0.586	0.44	0.319	0.28

What we can measure

Transitions	$\Delta M_B^{(1)}$ (fm^2)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \rightarrow {}^{26}Mg$	-0.12	-0.12	-0.11	-0.05	-0.03
$^{34}Cl \rightarrow {}^{34}S$	-0.17	-0.21	-0.16	-0.06	-0.04
$^{38m}K \rightarrow {}^{38}Ar$	-0.15	-0.42	-0.15	-0.07	-0.04
$^{42}Sc \rightarrow {}^{42}Ca$	-0.15	-0.17	-0.09	-0.07	-0.04
$^{46}V \rightarrow {}^{46}Ti$	-0.12	-0.11	-0.08	/	-0.04
$^{50}Mn \rightarrow {}^{50}Cr$	-0.12	-0.09	-0.06	/	-0.04
$^{54}Co \rightarrow {}^{54}Fe$	-0.13	-0.10	-0.07	-0.05	-0.05

$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2 = 0.1 \pm 1.0 \text{ fm}^2$$

The only example: ^{38}Ar ($R_{p,1}$), ^{38}Ca ($R_{p,-1}$), ^{38m}K ($R_{p,0}$)

3. Testing ISB corrections: Seng & Gorchtein PLB 838 (2023) 137654

What we want to know

Transitions	δ_C (%)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \rightarrow {}^{26}Mg$	0.310	0.329	0.30	0.139	0.08
$^{34}Cl \rightarrow {}^{34}S$	0.613	0.75	0.57	0.234	0.13
$^{38m}K \rightarrow {}^{38}Ar$	0.628	1.7	0.59	0.278	0.15
$^{42}Sc \rightarrow {}^{42}Ca$	0.690	0.77	0.42	0.333	0.18
$^{46}V \rightarrow {}^{46}Ti$	0.620	0.563	0.38	/	0.21
$^{50}Mn \rightarrow {}^{50}Cr$	0.660	0.476	0.35	/	0.24
$^{54}Co \rightarrow {}^{54}Fe$	0.770	0.586	0.44	0.319	0.28

What we can measure

Transitions	$\Delta M_B^{(1)}$ (fm^2)				
	WS	DFT	HF	RPA	Micro
$^{26m}Al \rightarrow {}^{26}Mg$	-0.12	-0.12	-0.11	-0.05	-0.03
$^{34}Cl \rightarrow {}^{34}S$	-0.17	-0.21	-0.16	-0.06	-0.04
$^{38m}K \rightarrow {}^{38}Ar$	-0.15	-0.42	-0.15	-0.07	-0.04
$^{42}Sc \rightarrow {}^{42}Ca$	-0.15	-0.17	-0.09	-0.07	-0.04
$^{46}V \rightarrow {}^{46}Ti$	-0.12	-0.11	-0.08	/	-0.04
$^{50}Mn \rightarrow {}^{50}Cr$	-0.12	-0.09	-0.06	/	-0.04
$^{54}Co \rightarrow {}^{54}Fe$	-0.13	-0.10	-0.07	-0.05	-0.05

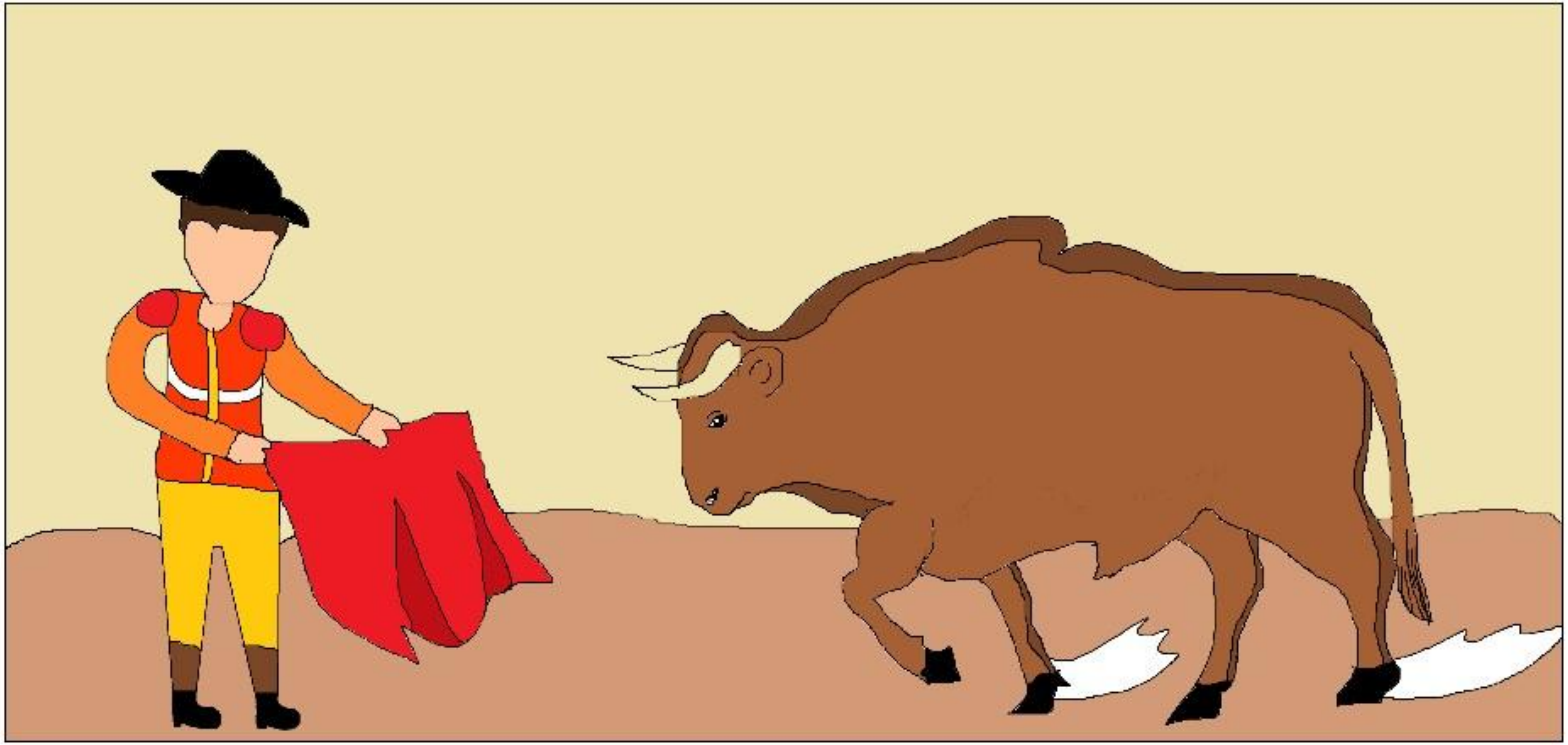
$$\Delta M_B^{(1)} \equiv \frac{1}{2}\left(Z_1 R_{p,1}^2 + Z_{-1} R_{p,-1}^2\right) - Z_0 R_{p,0}^2 = 0.1 \pm 1.0\ \mathrm{fm}^2$$

The only example: ^{38}Ar ($R_{p,1}$), ^{38}Ca ($R_{p,-1}$), ^{38m}K ($R_{p,0}$)

Very high accuracy needed to distinguish models !

What can charge radii do for us?

Use:	Nucleus of interest:	Needed accuracy
1. Within model, calculate δ_c	Father	Poor
2. Calculate f	Father, Daughter	Medium-high
3. Benchmark δ_c	Isotriplet	Very high !



Ecosystem of charge radii determinations

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

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**

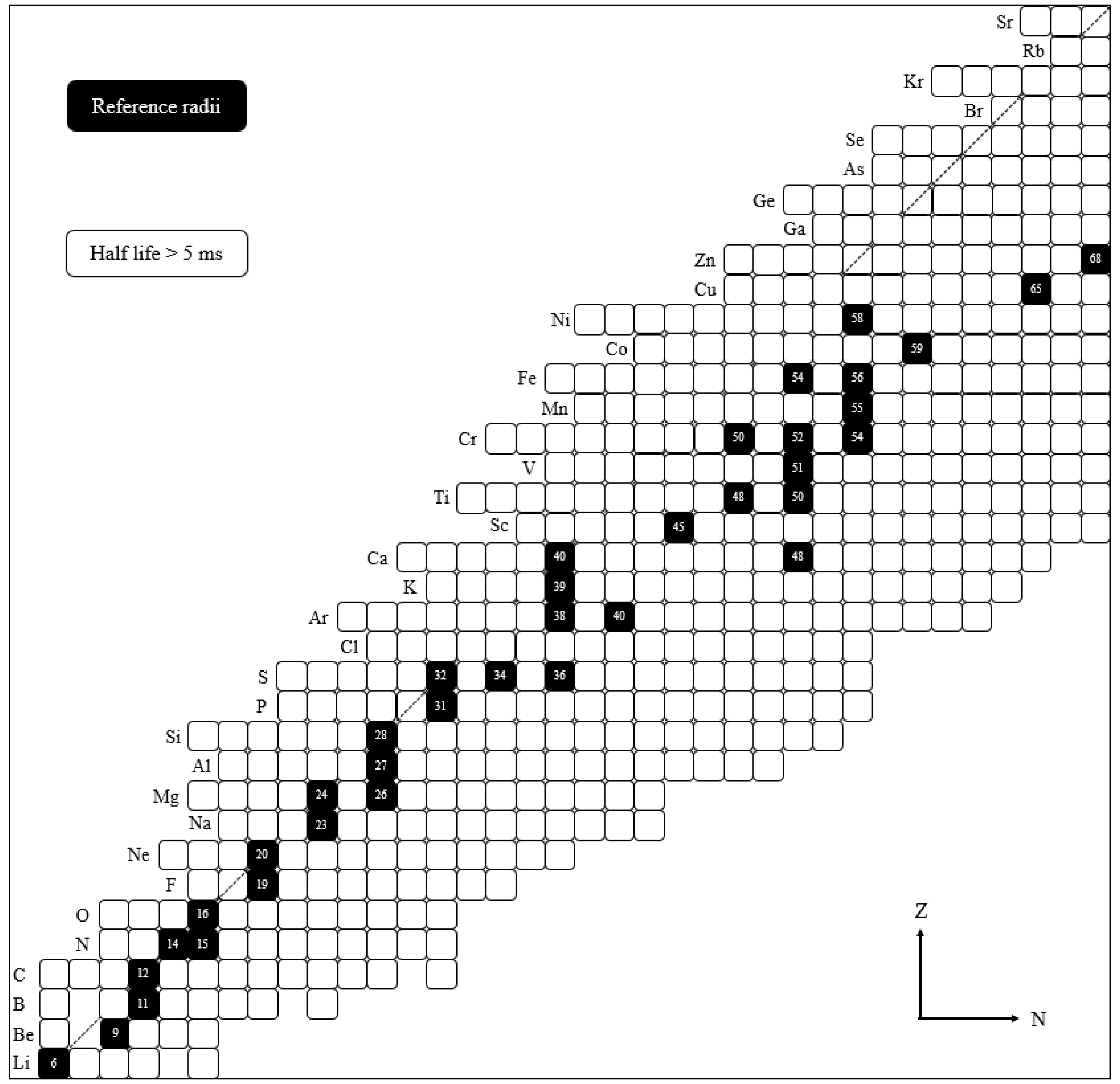
Ecosystem of charge radii determinations

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**



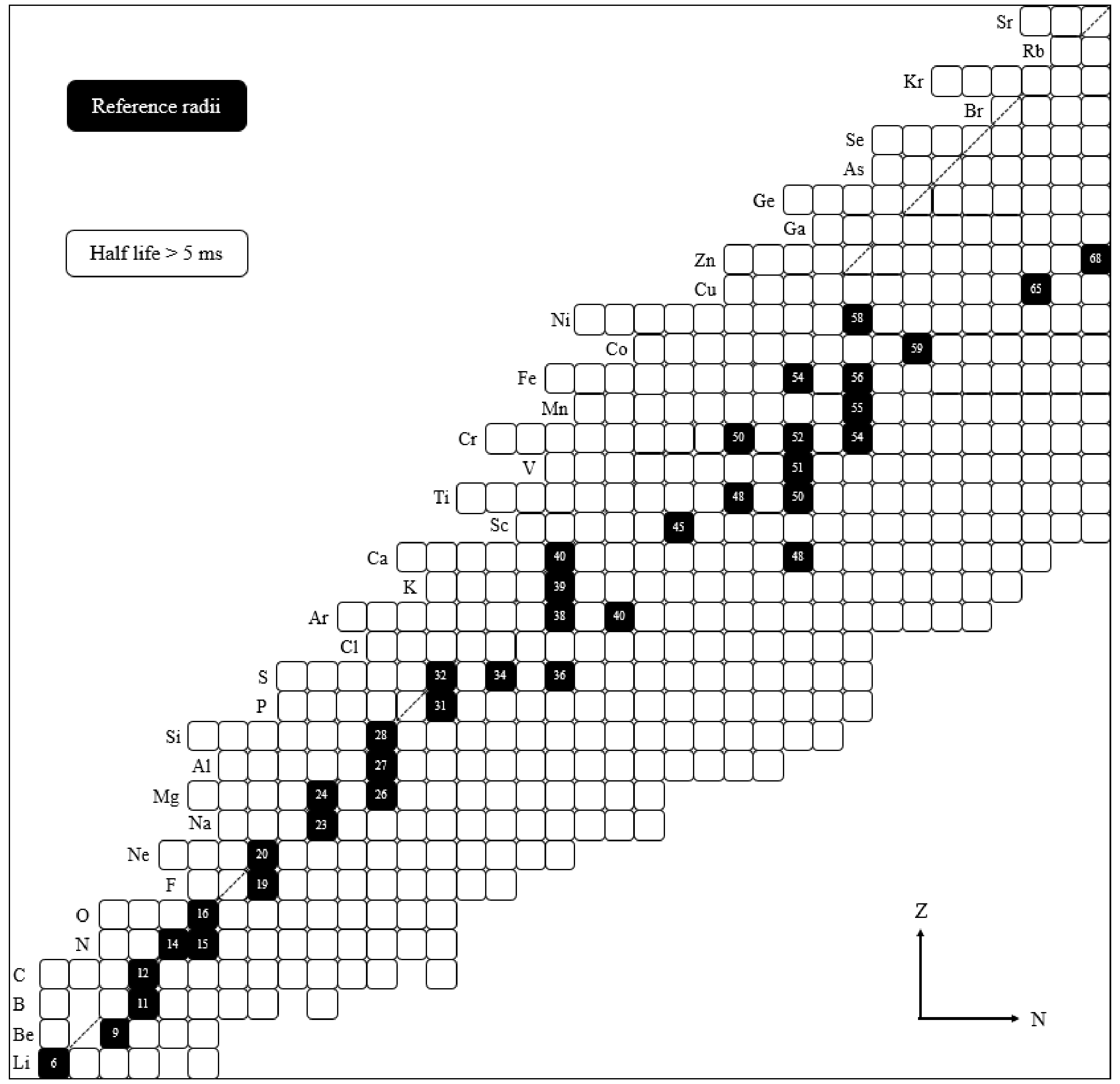
Ecosystem of charge radii determinations

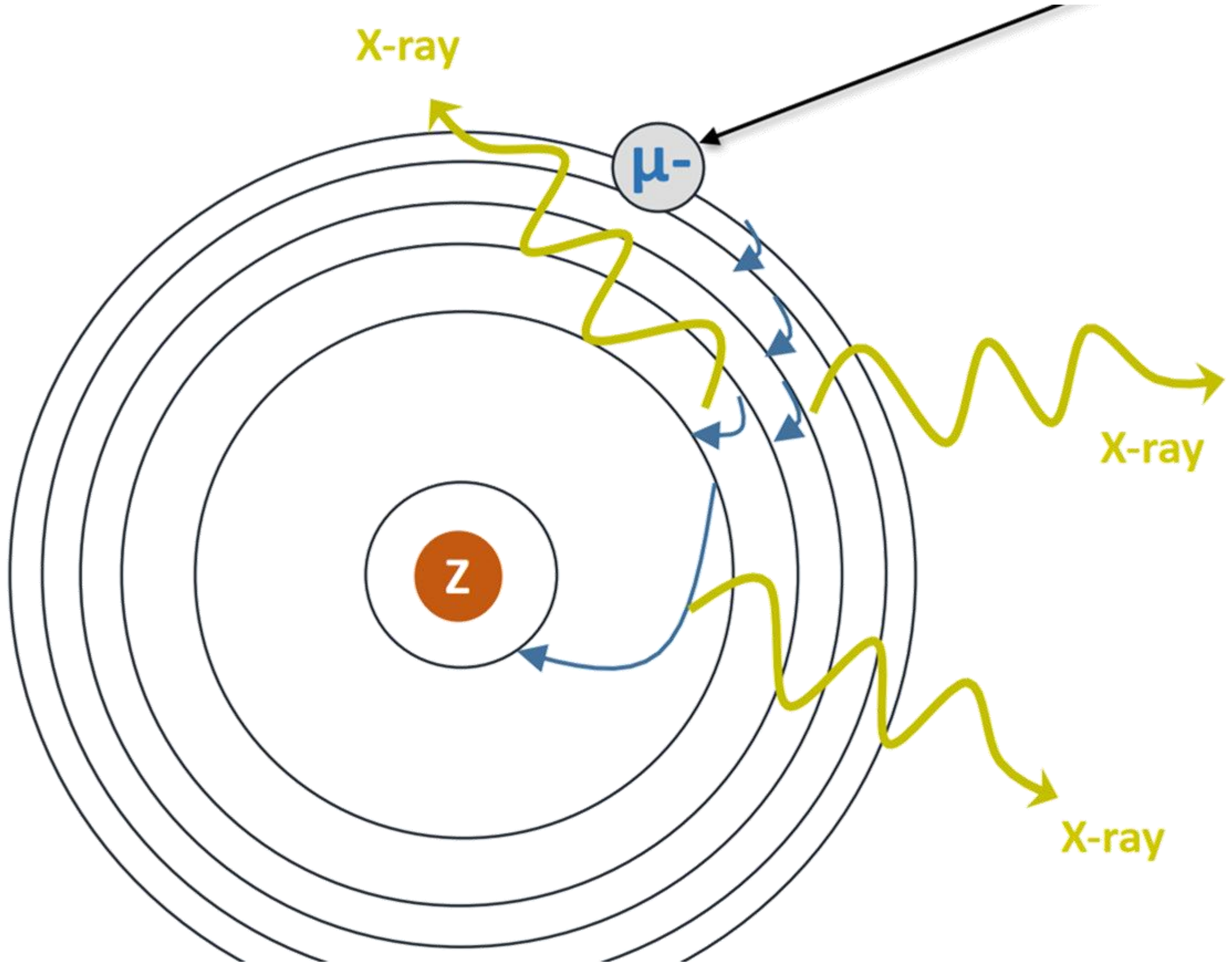
Radius of unstable nucleus $r_x^2 = r_{ref}^2 + \delta r_{a,x}^2$

Reference radius (mostly) from **Muonic atoms**

Review

Differential radii (mostly) from radioactive **electronic atoms**





See next talk!

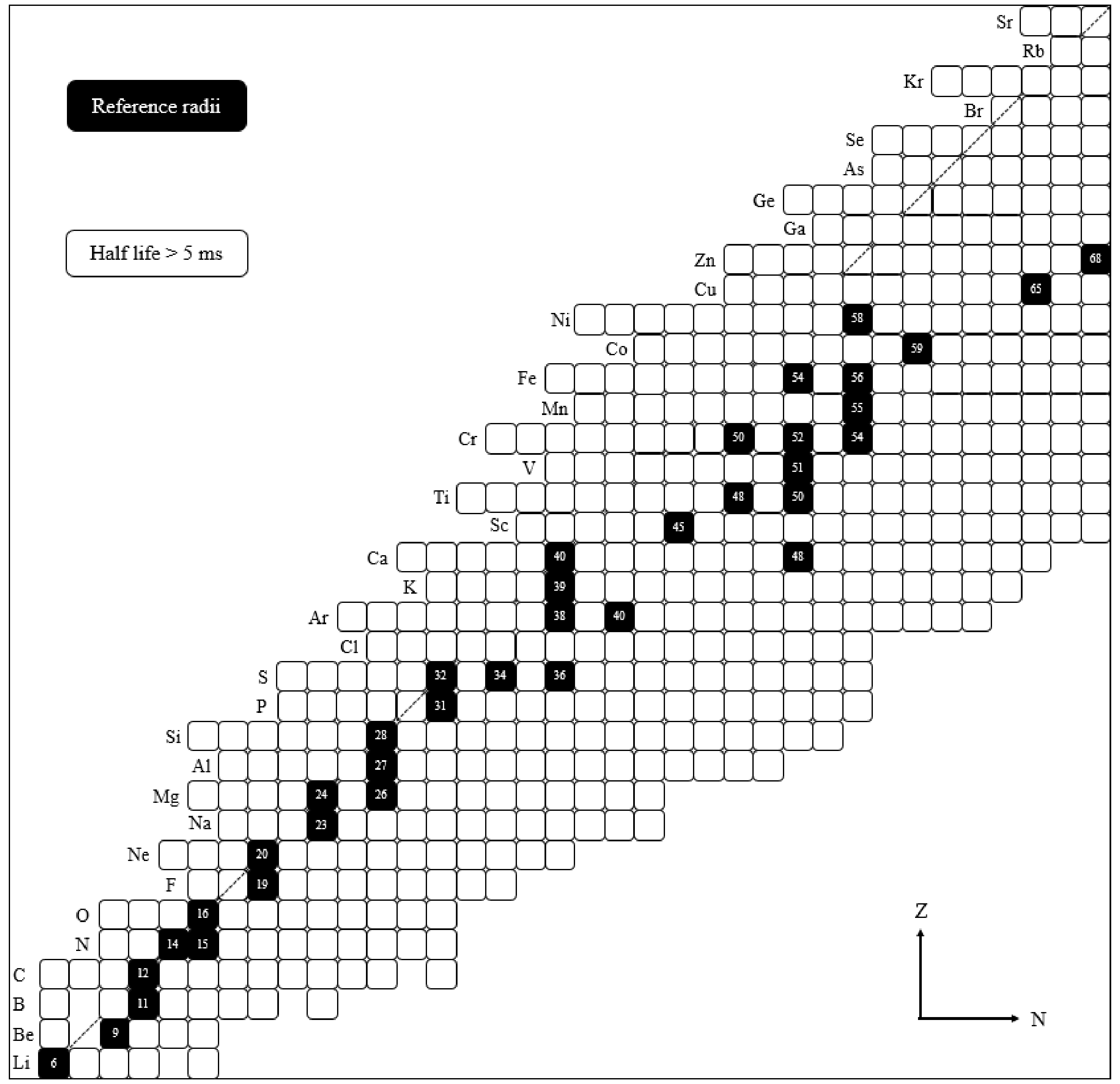
Ecosystem of charge radii determinations

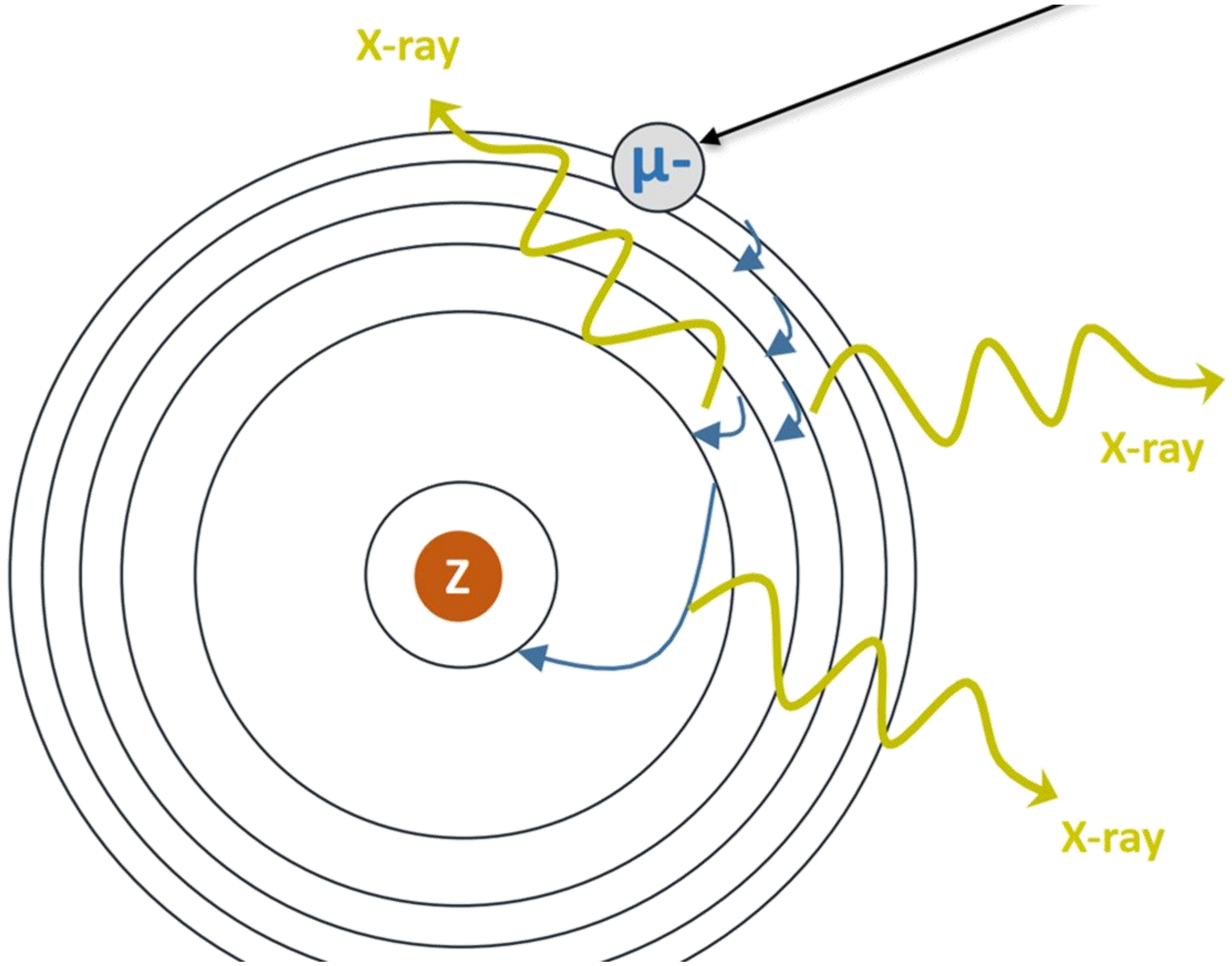
Radius of unstable nucleus $r_x^2 = r_{ref}^2 + \delta r_{a,x}^2$

Reference radius (mostly) from **Muonic atoms**

Review

Differential radii (mostly) from radioactive **electronic atoms**





What is in the literature?

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**

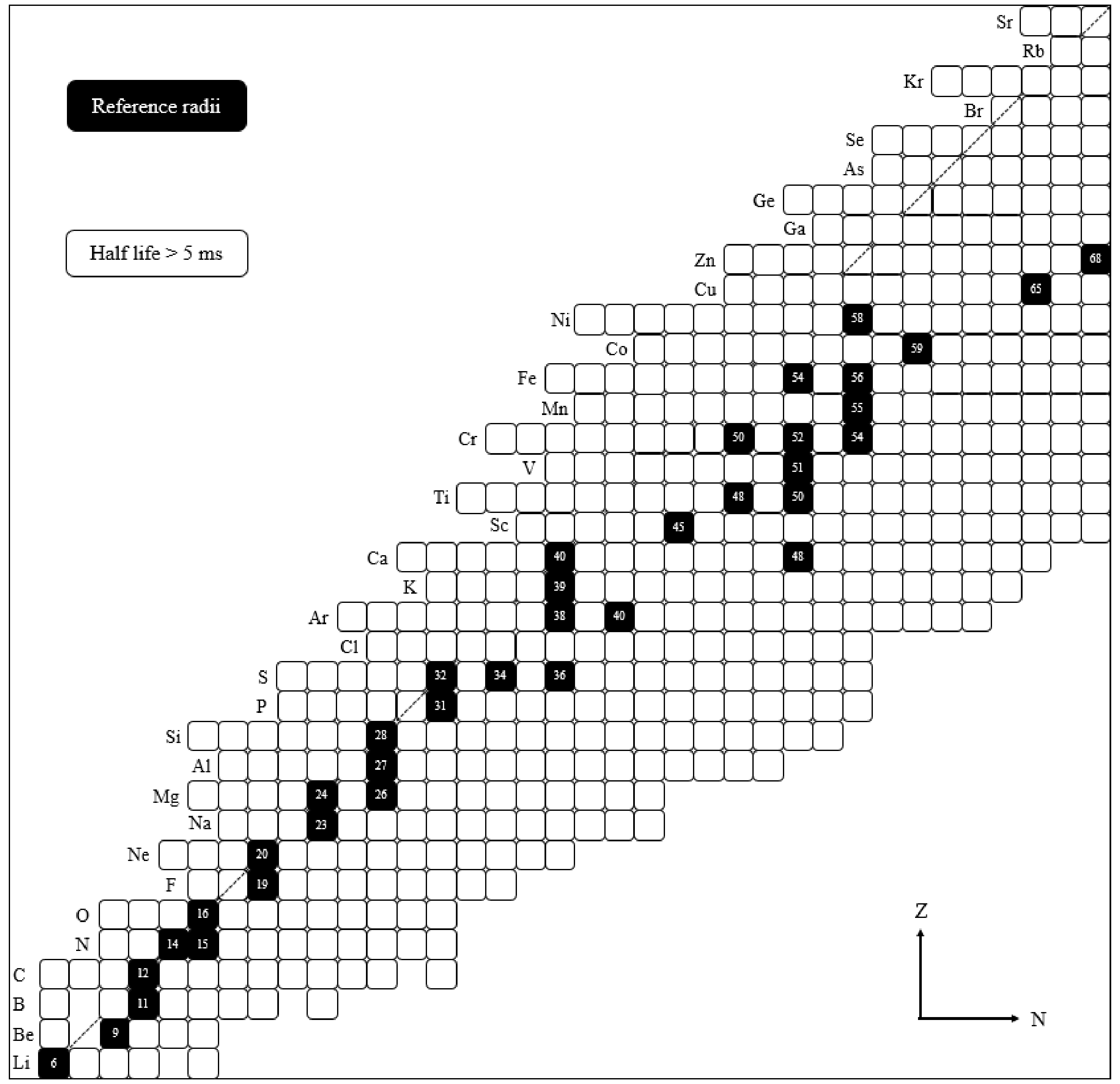


Table of experimental nuclear ground state charge radii: An update

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

What is in the literature?

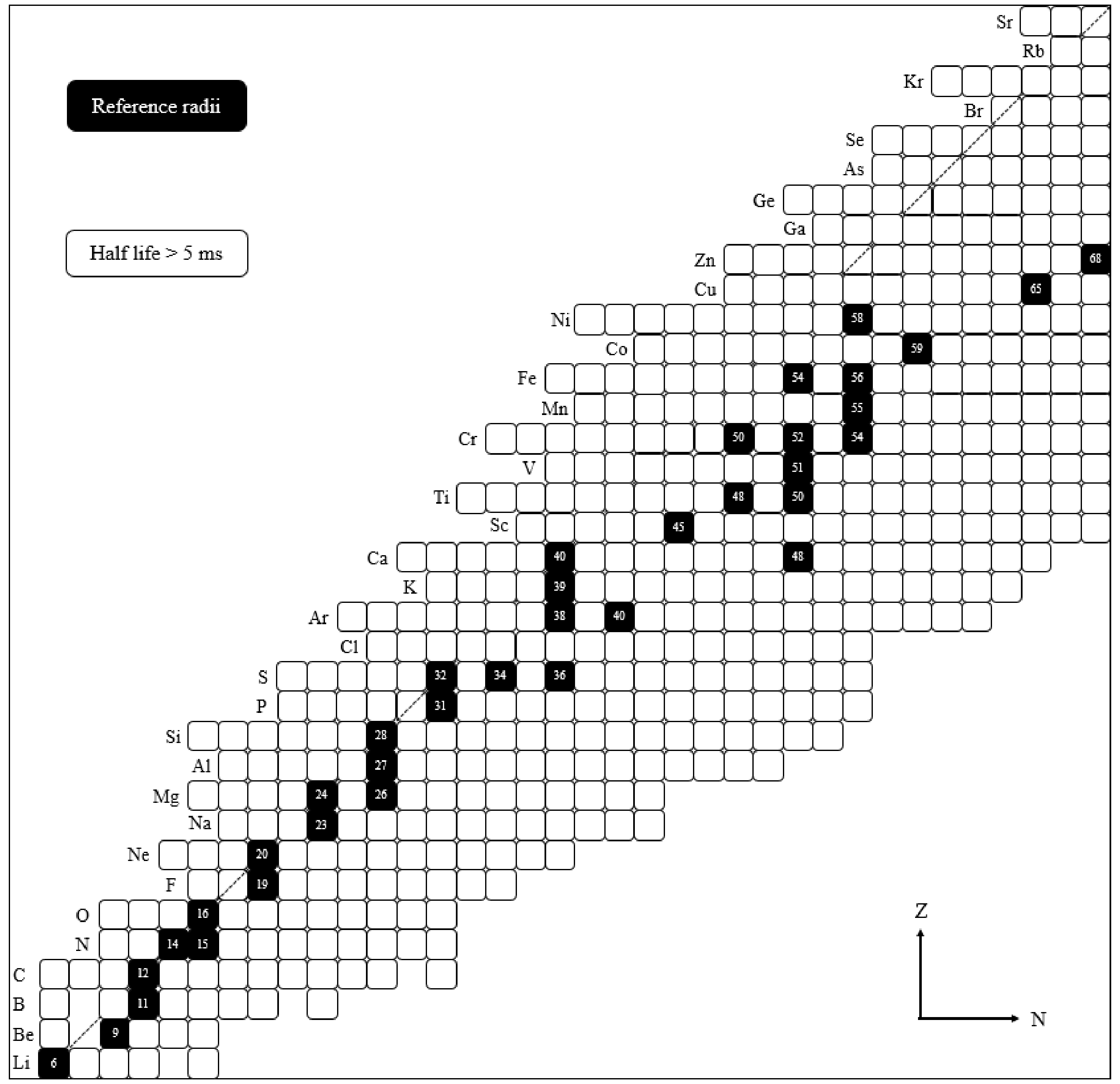
Ecosystem of charge radii determinations

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

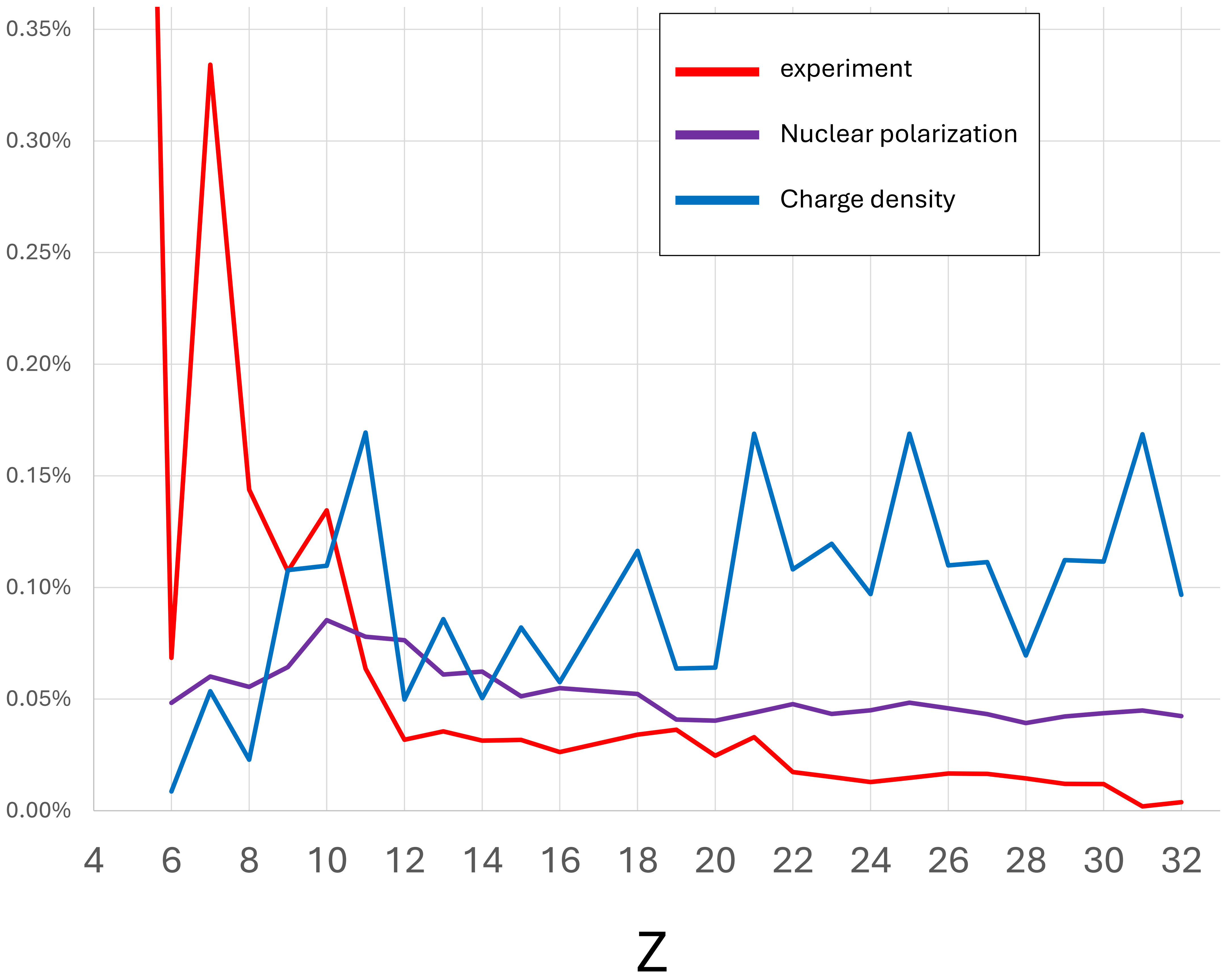
Reference radius (mostly) from **Muonic atoms**

Review

Differential radii (mostly) from radioactive **electronic atoms**



$\frac{\sigma_r}{r}$



New review of reference radii with recalculated values and uncertainties

Transparent tabulation of ref. radii

arXiv:2409.08193

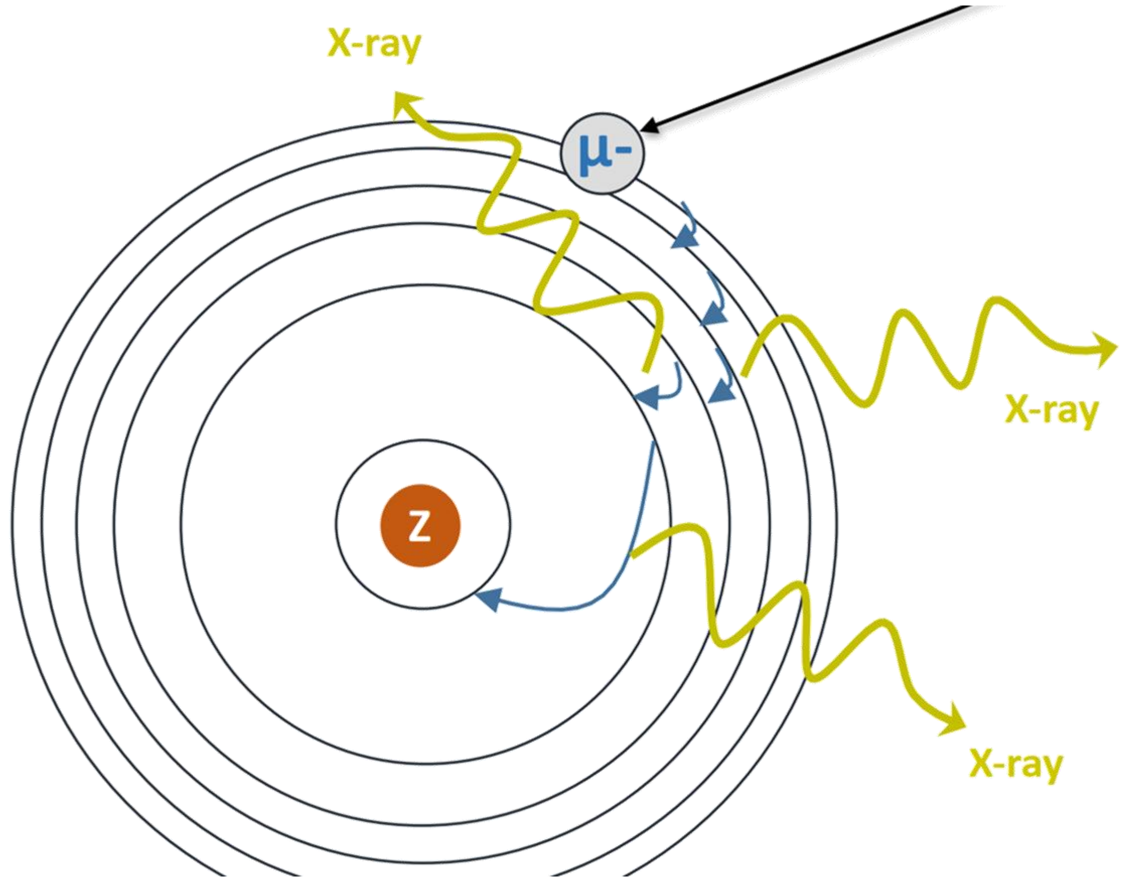
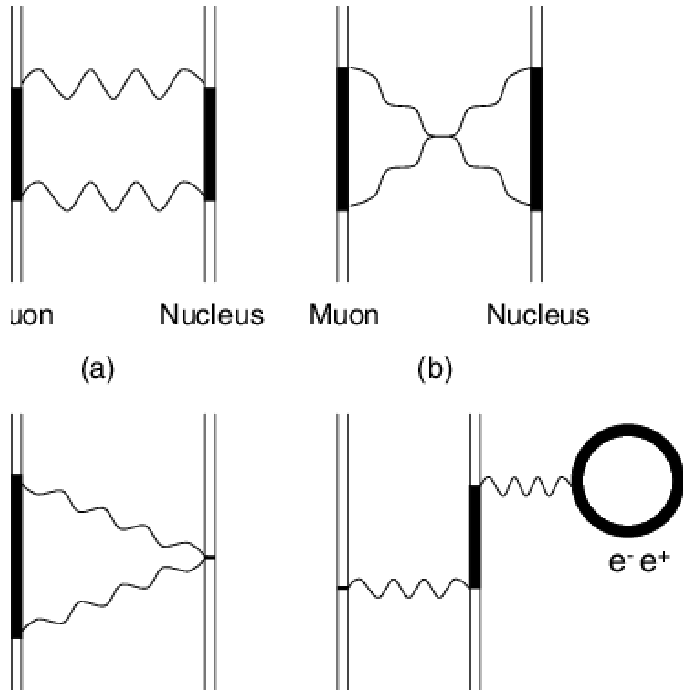
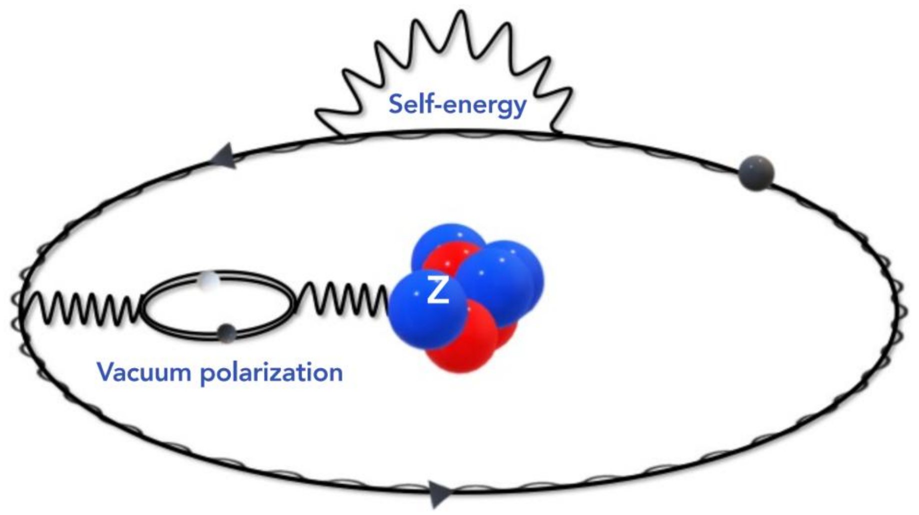
Table 2

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	
Sc	21	45	3.548	0.001	0.002	0.006	0.007	

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 Next talk by M. Heines !	
Theory calculations	Nuclear:  Non-perturbative QED 	

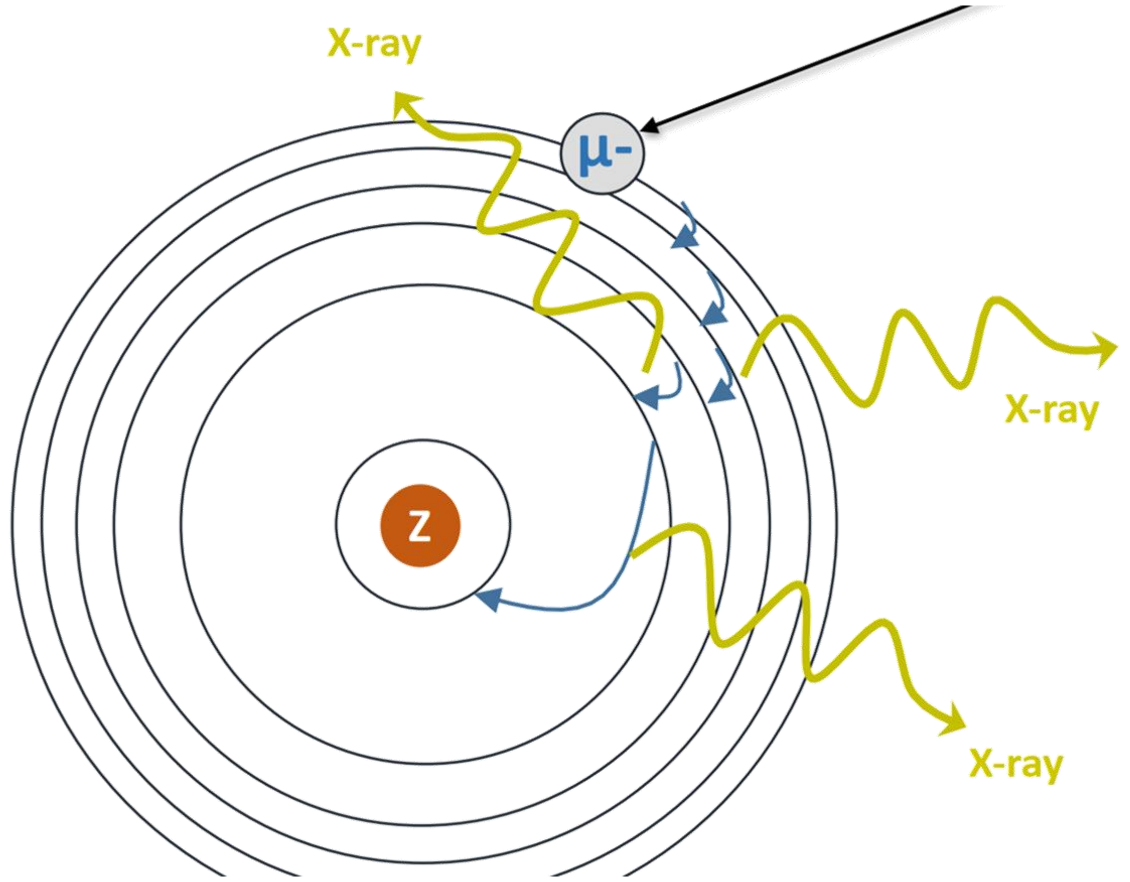
Ecosystem of charge radii determinations

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	Collinear laser spectroscopy
Theory calculations	Nuclear: / Non-perturbative QED	Atomic many body calculations

Experiments with exotic atoms

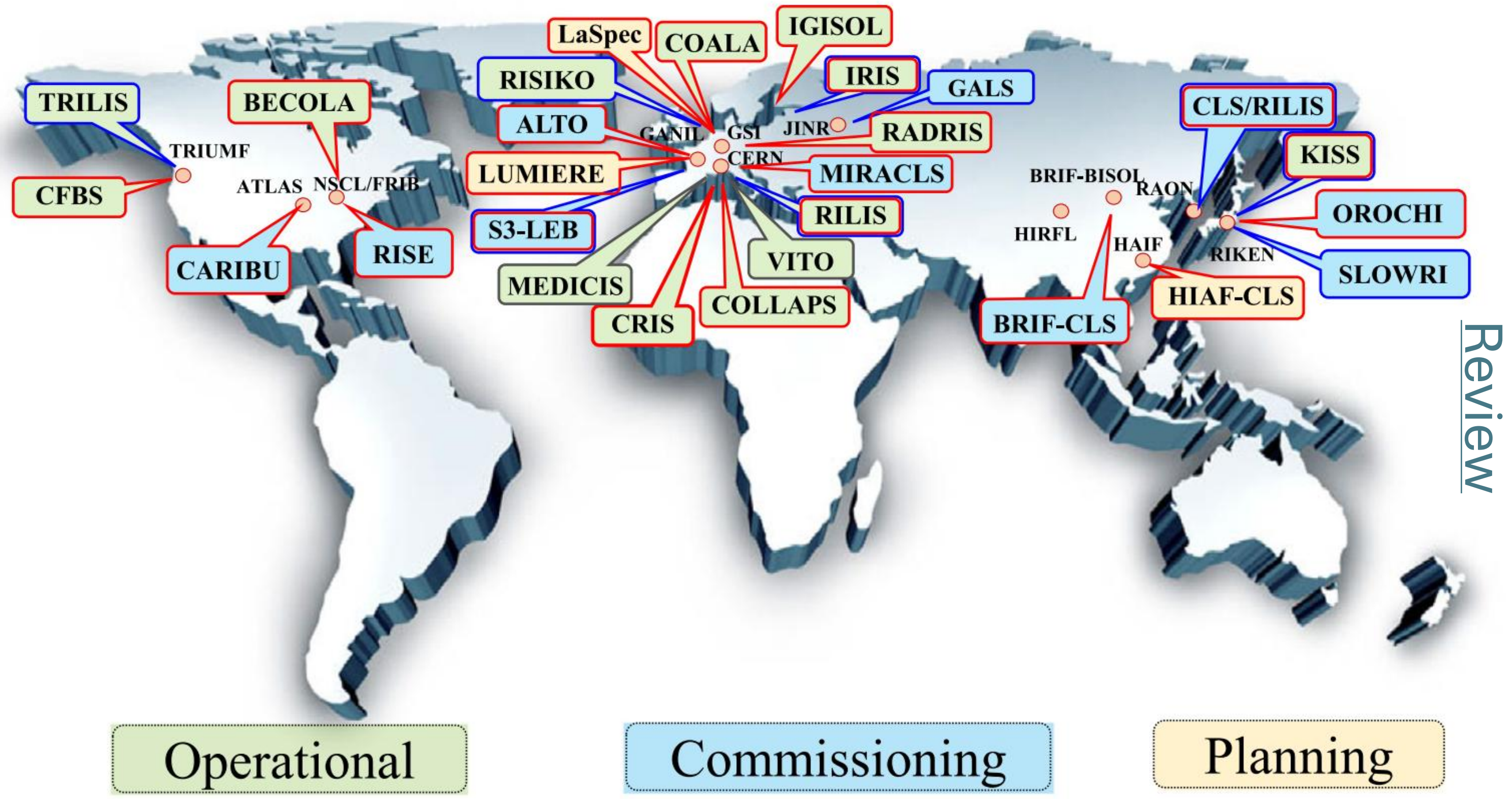
Muonic-atom spectroscopy



Recent Updates

Next talk by M. Heines !

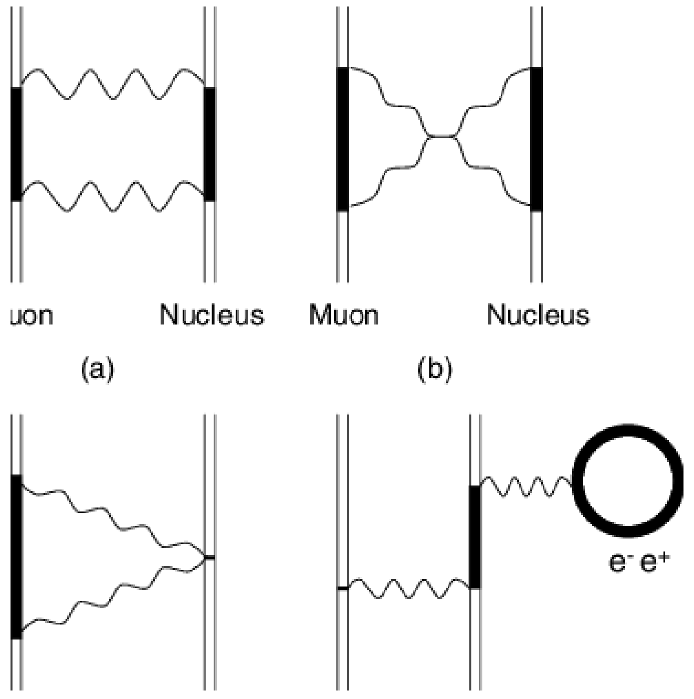
Collinear laser spectroscopy



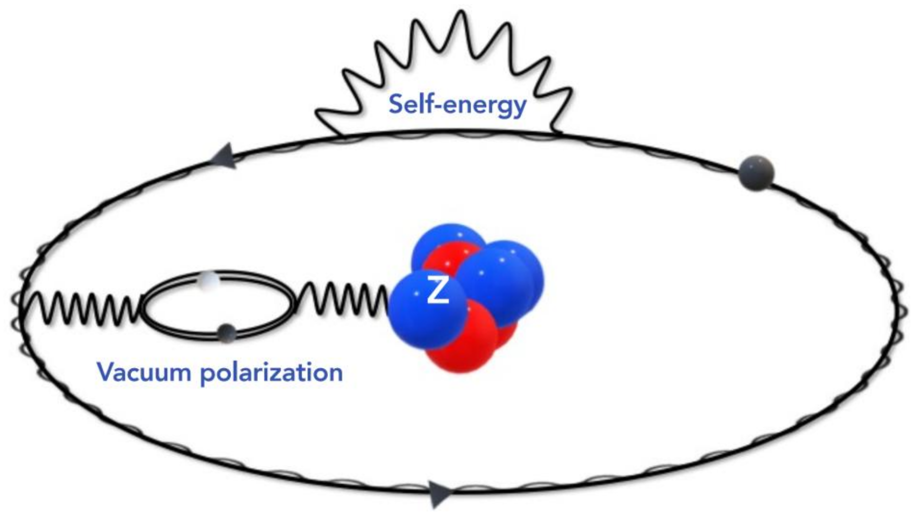
Review

Theory calculations

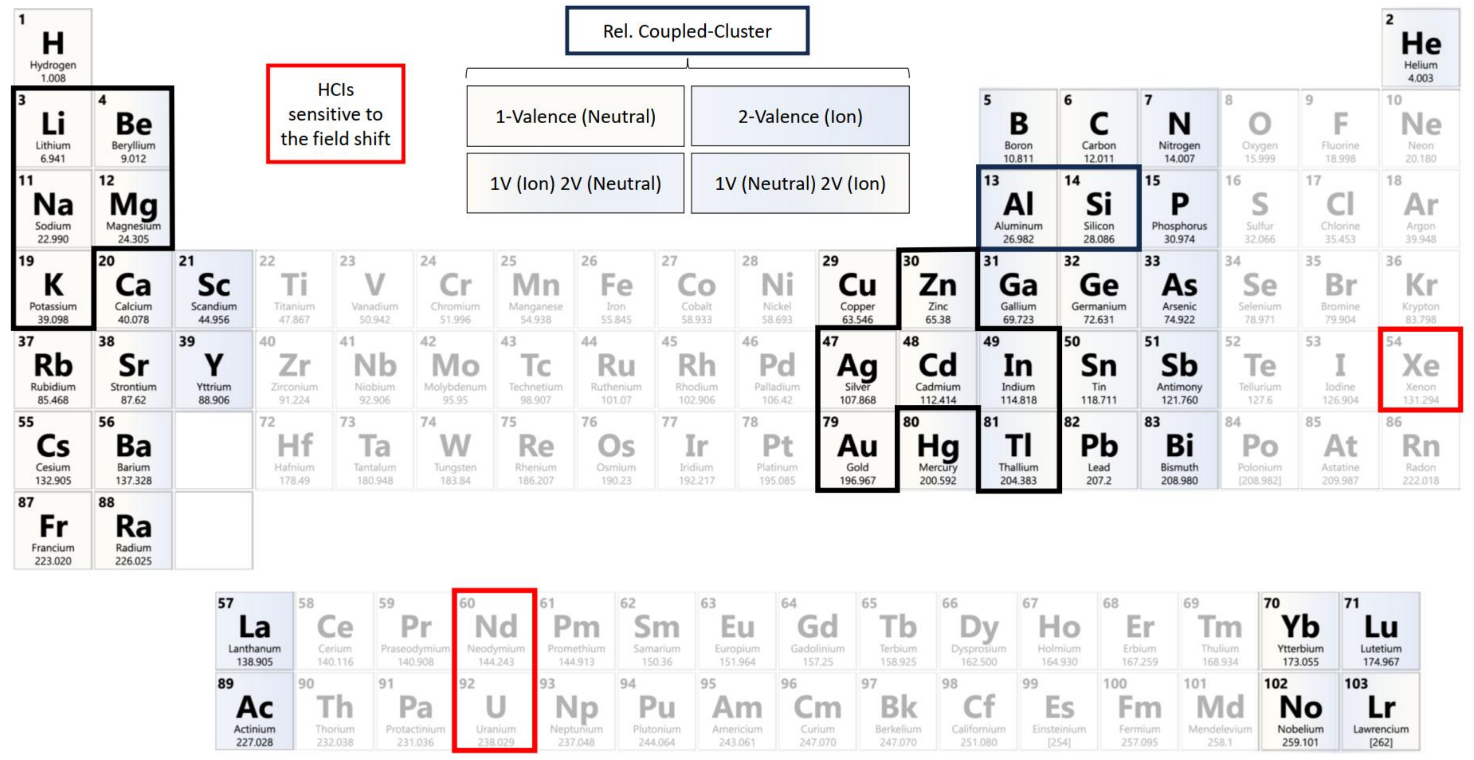
Nuclear:



Non-perturbative QED



Atomic many body calculations



Review

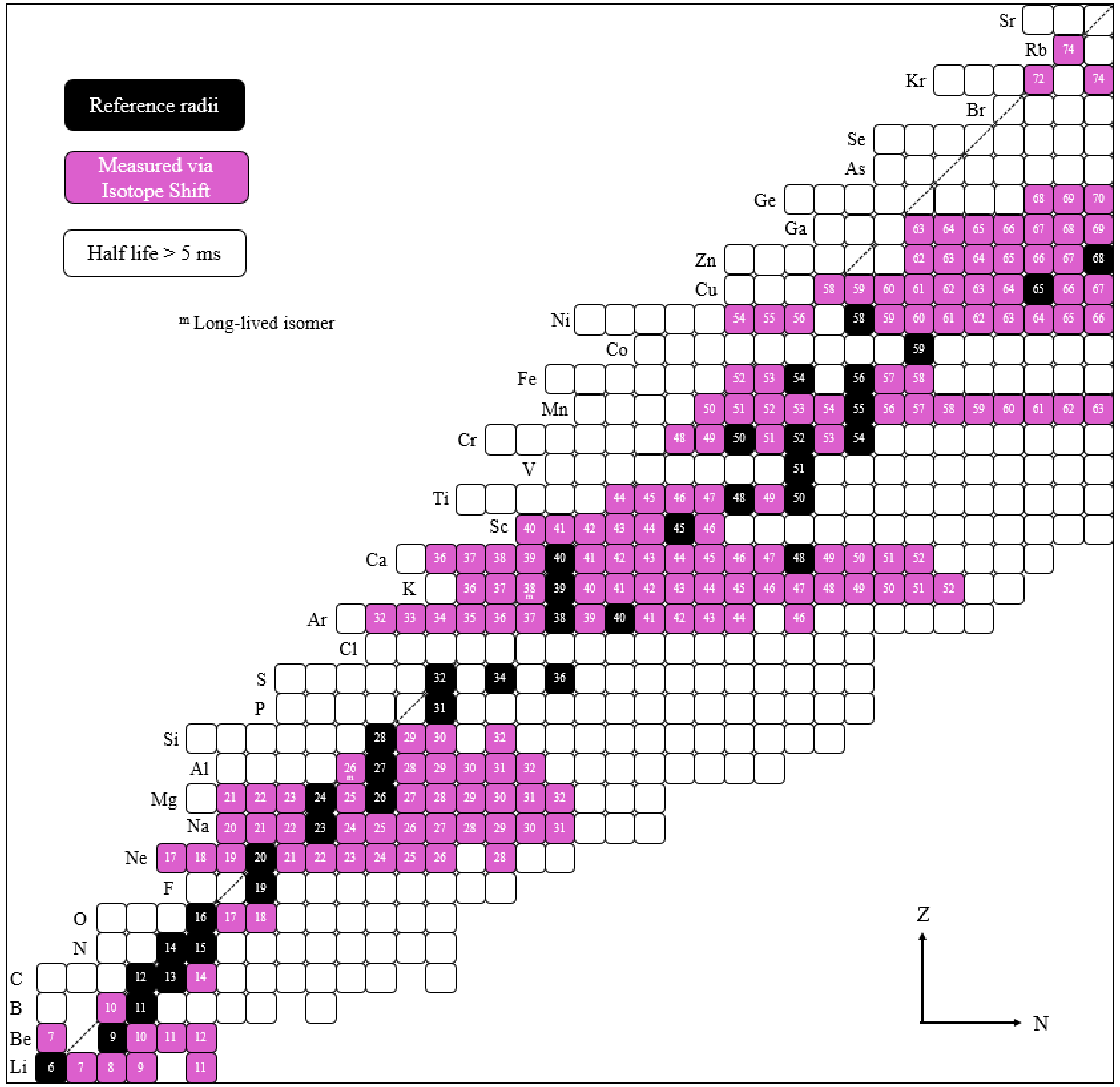
Ecosystem of charge radii determinations

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

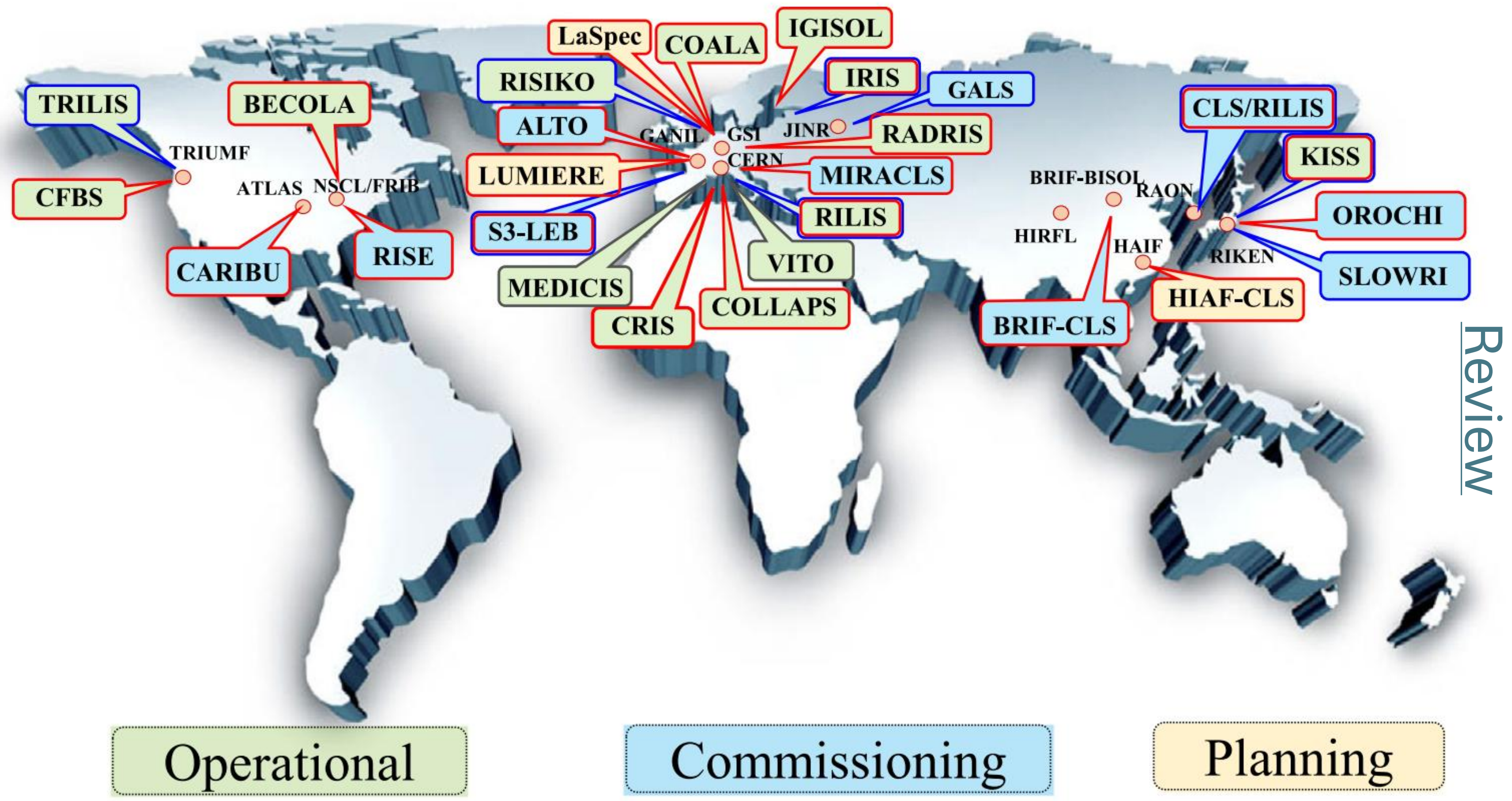
Reference radius (mostly) from **Muonic atoms**

Review

Differential radii (mostly) from radioactive **electronic atoms**

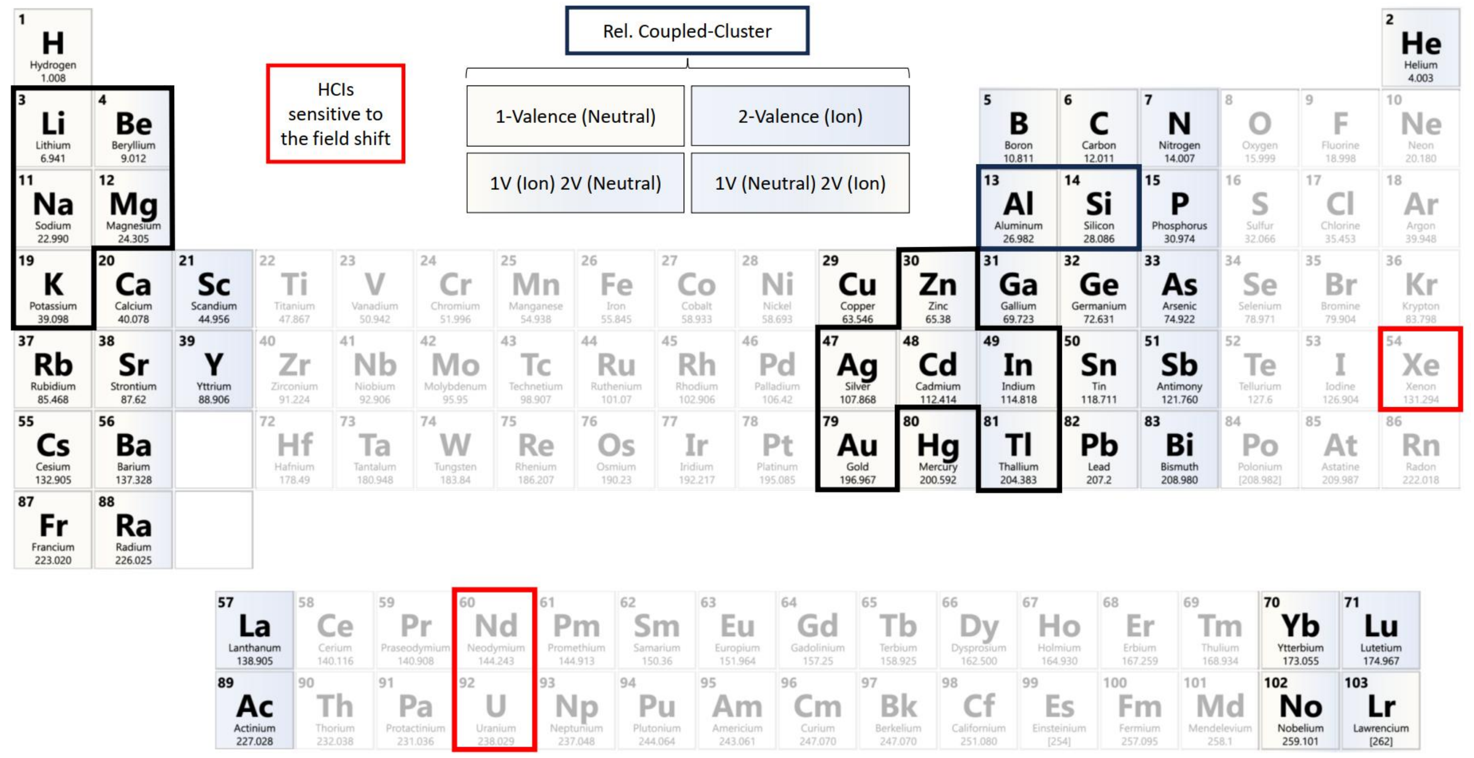


Collinear laser spectroscopy



Review

Atomic many body calculations



Review

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**

Many opportunities for laser spec.: (@GANIL?)

^{10}C

^{14}O

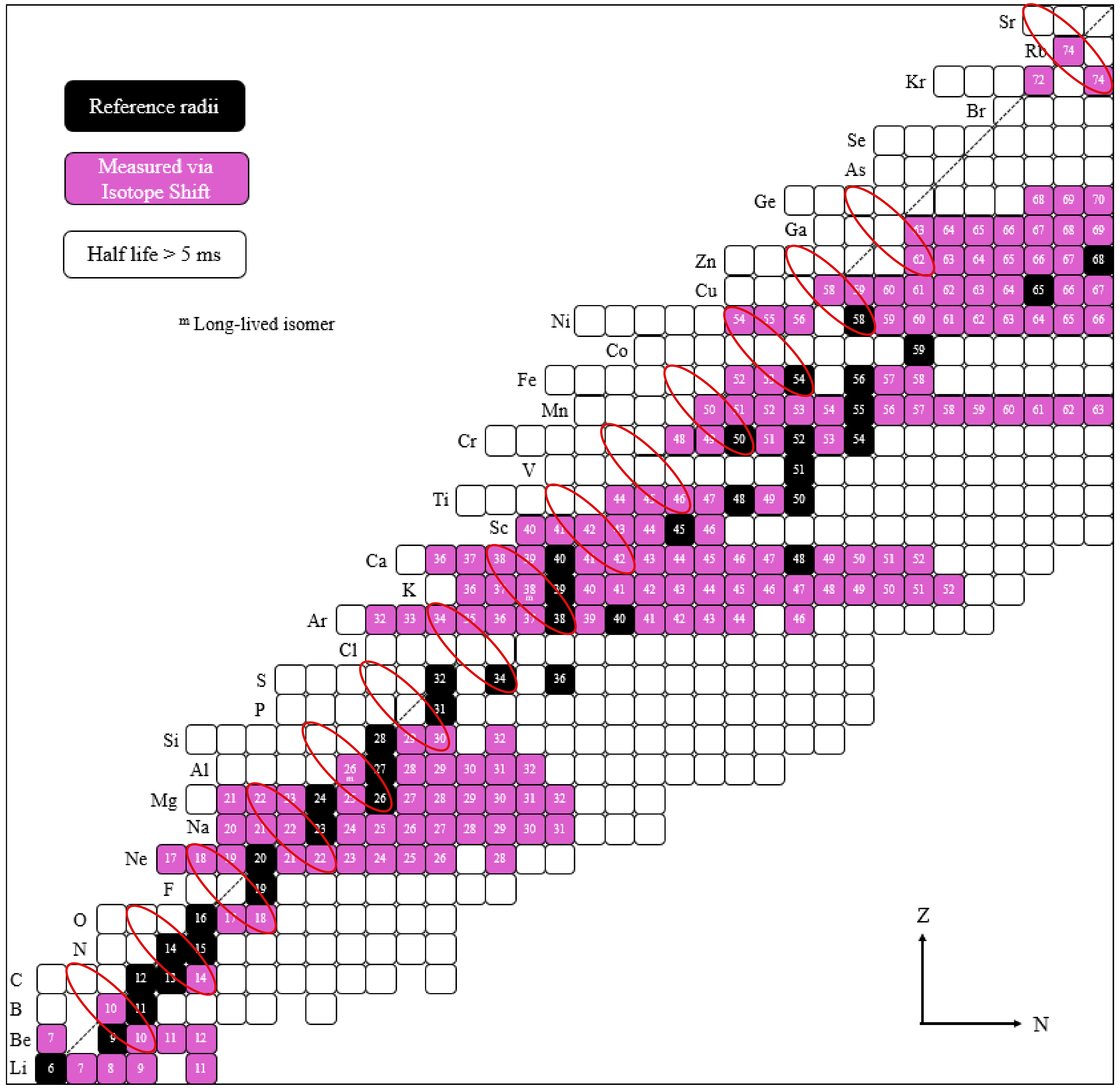
^{26}Si

^{42}Ti

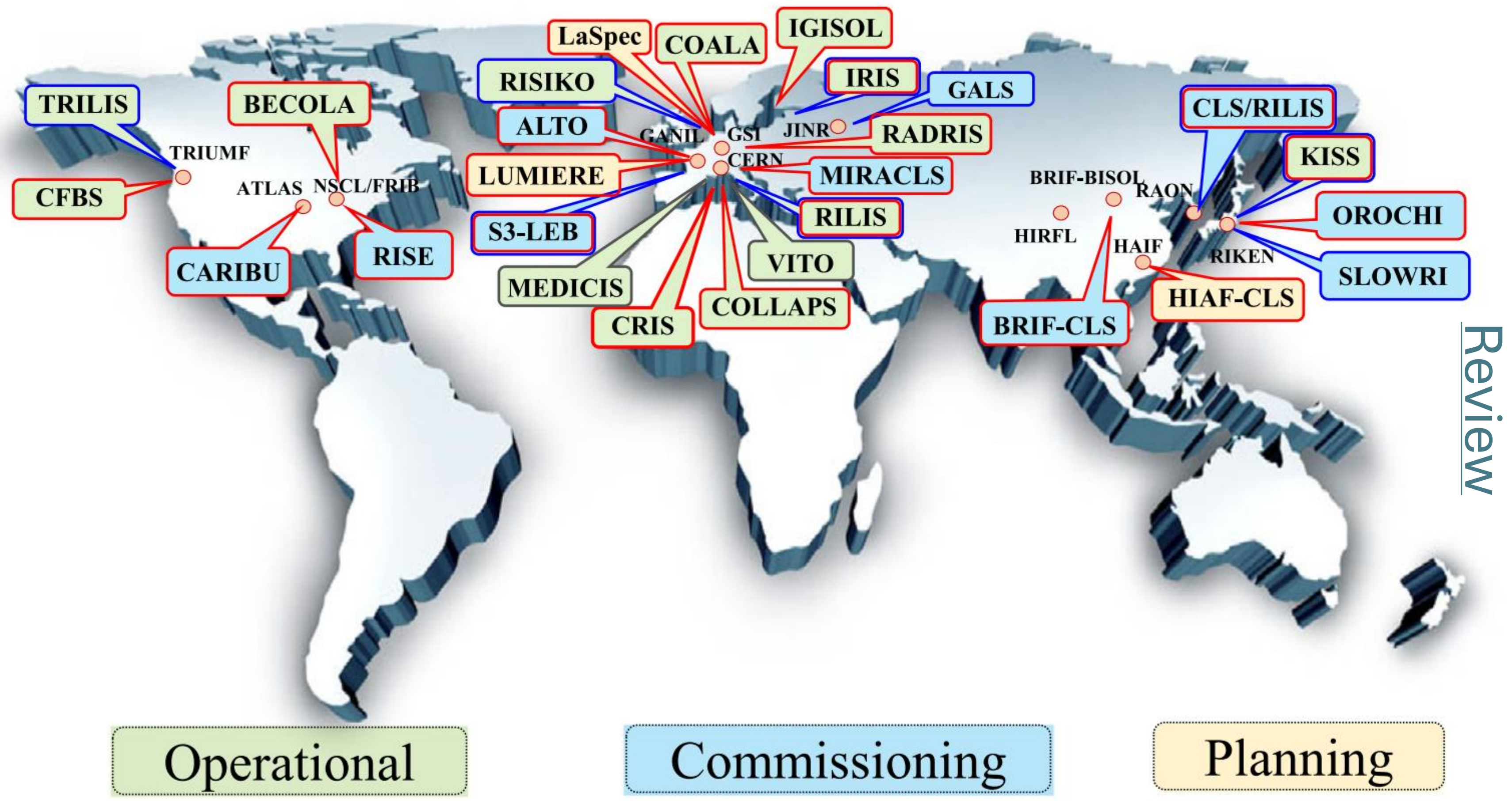
^{46}Cr

^{50}Fe

…

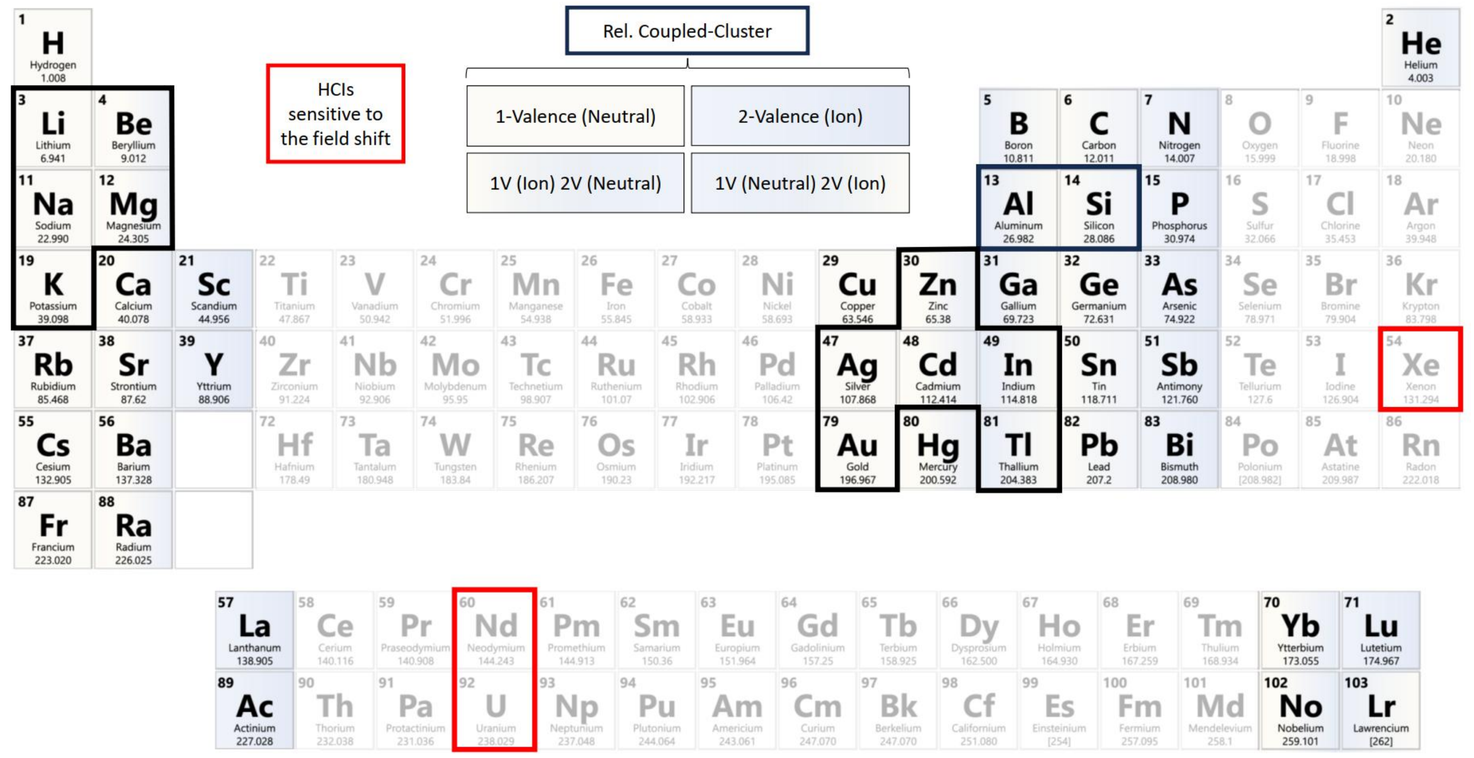


Collinear laser spectroscopy



Review

Atomic many body calculations



Review

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**

Many opportunities for laser spec.: (@GANIL?)

^{10}C

^{14}O

^{26}Si

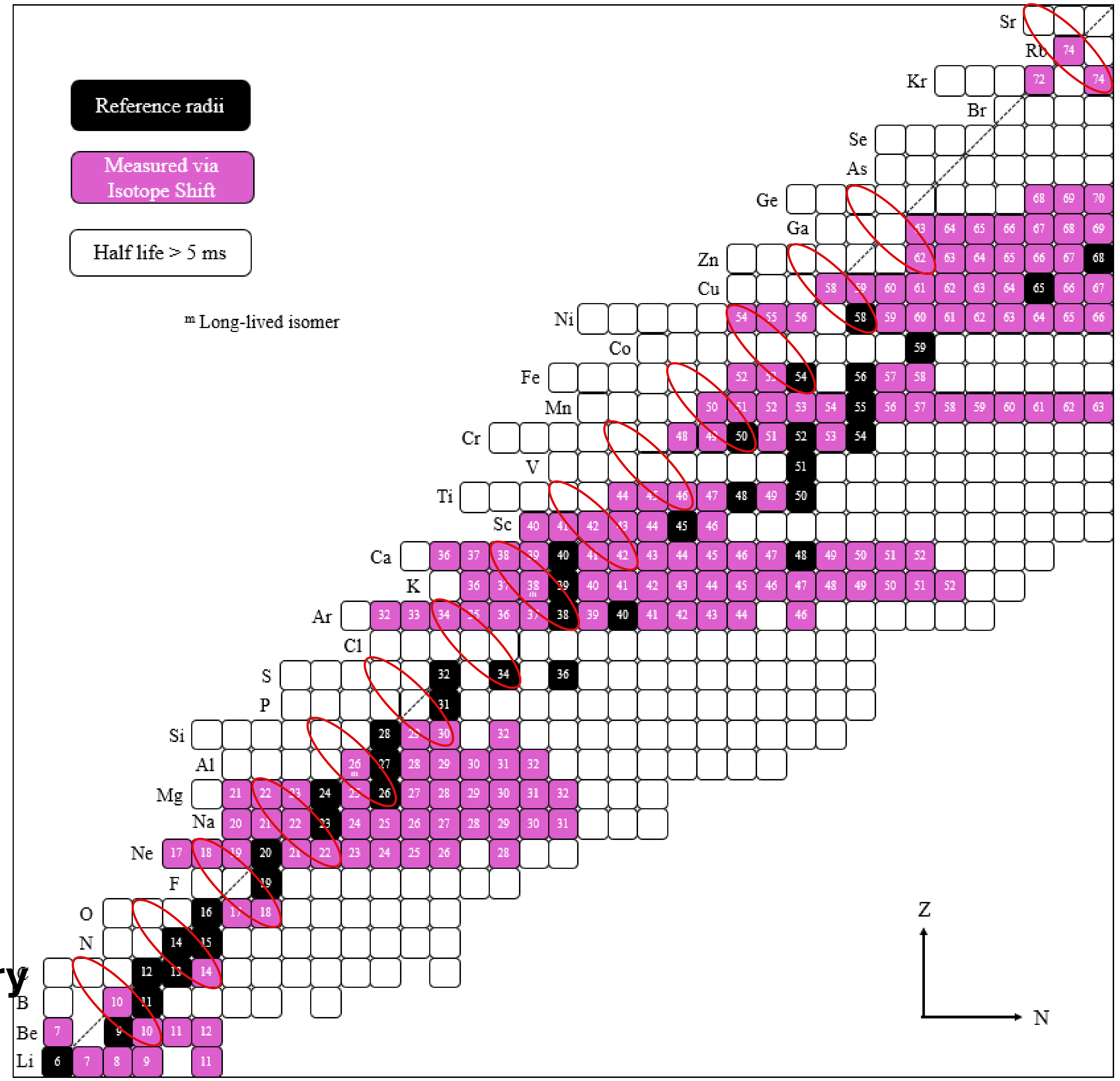
^{42}Ti

^{46}Cr

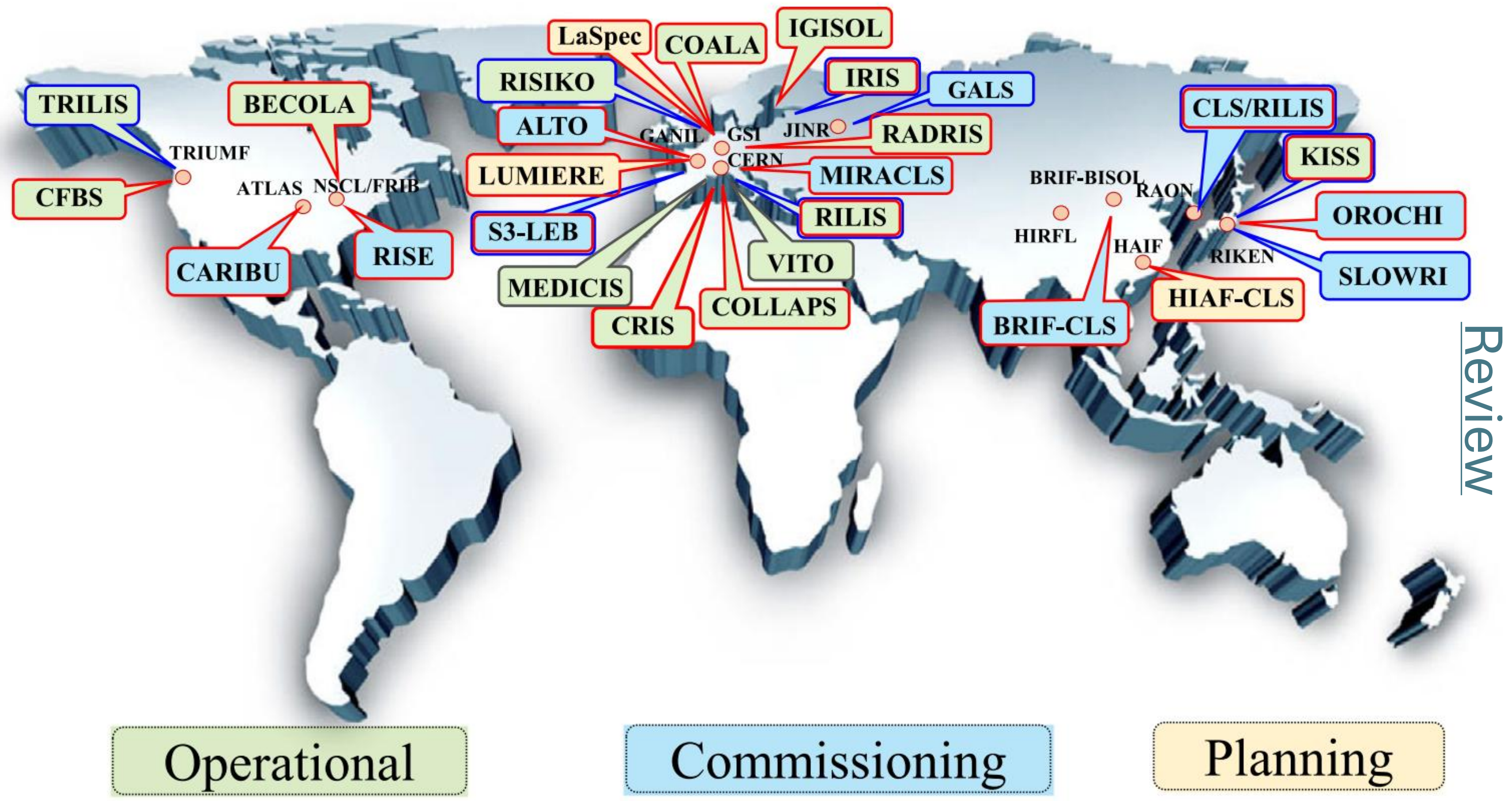
^{50}Fe

…

+ improved experiment and theory

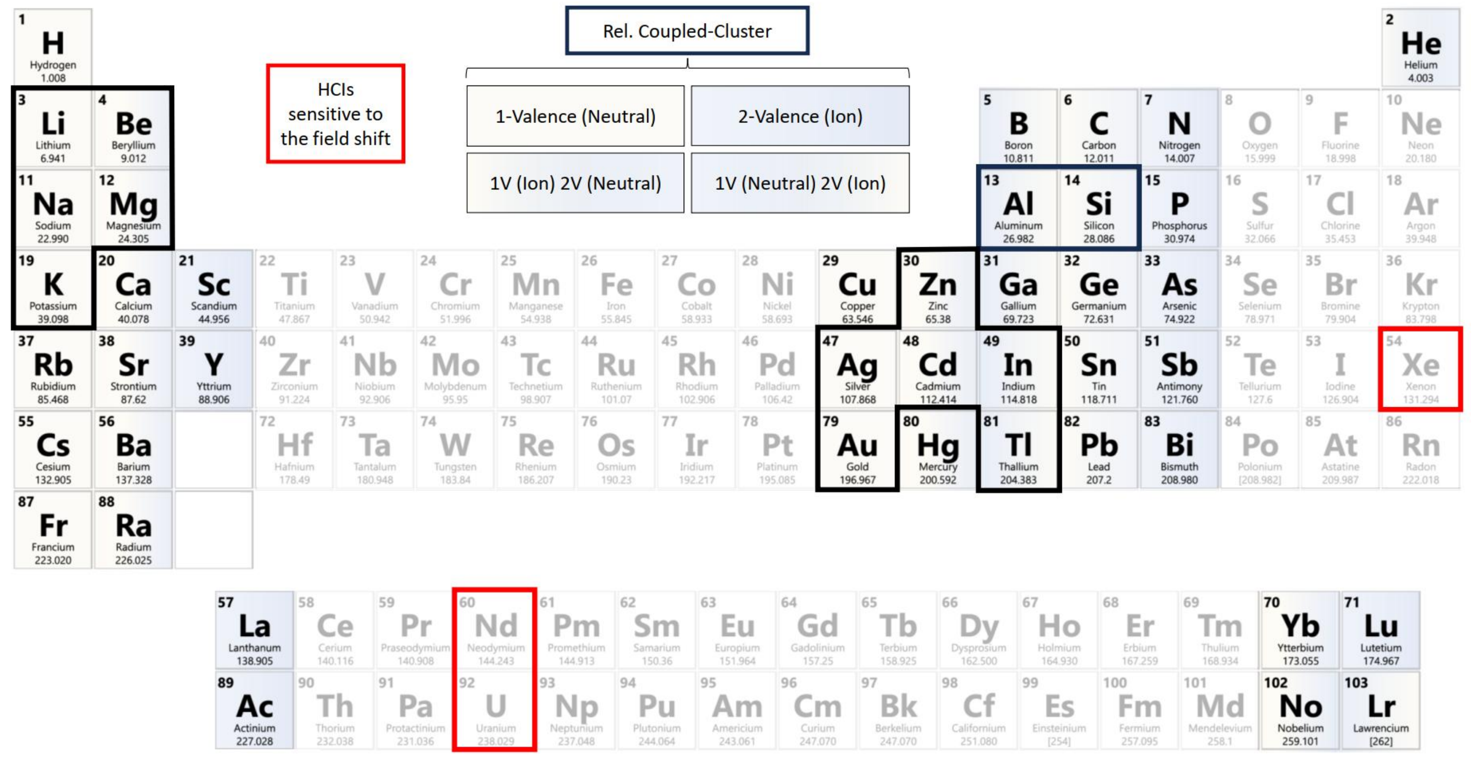


Collinear laser spectroscopy



Review

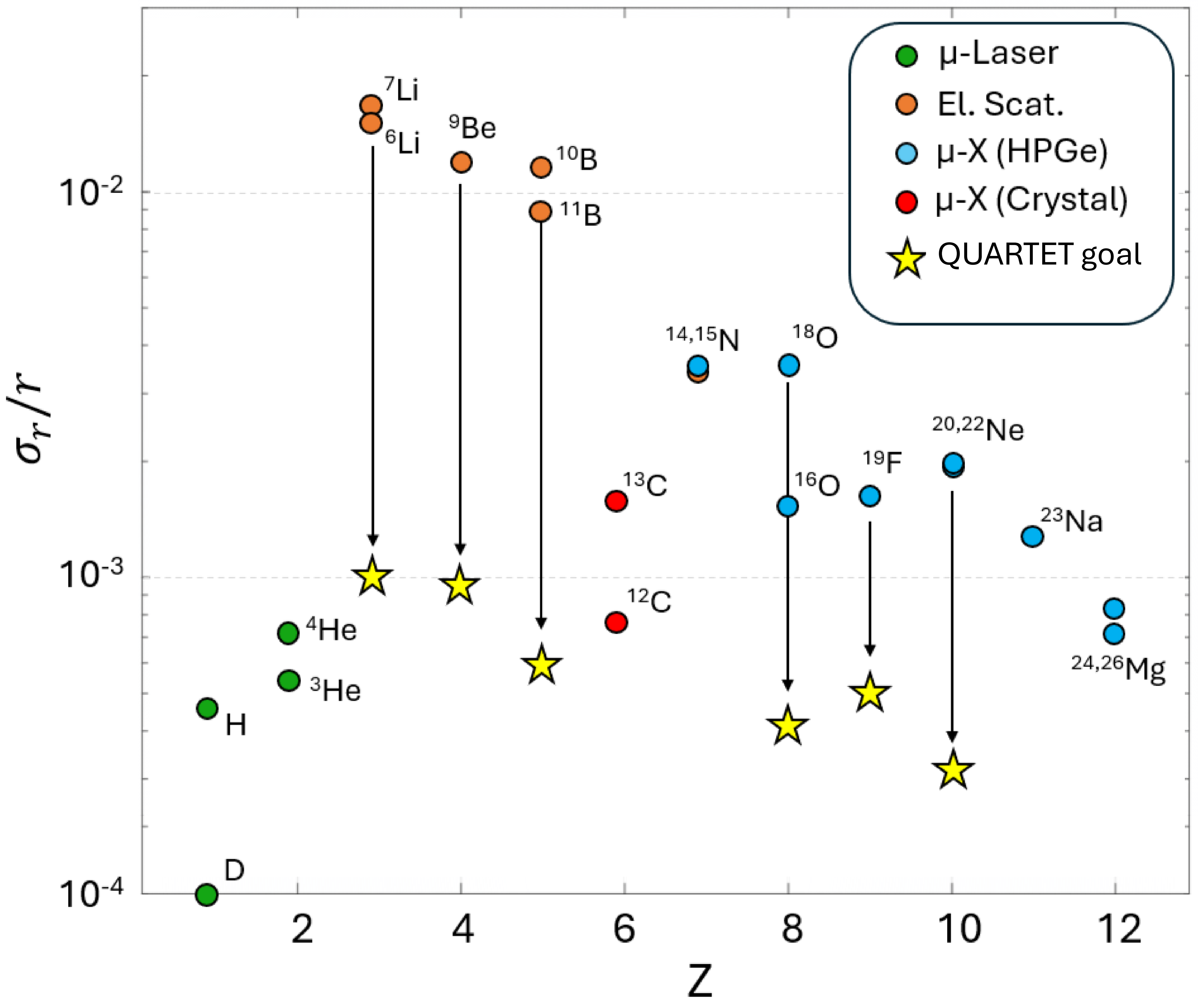
Atomic many body calculations



Review

Role of radii beyond Superallowed?

- Radius affect spectrum shapes (e.g. in ^{20}F), how well do we need to daughter radius?



For more information about QUARTET
See here, and next talk.

Summary

Nuclear charge radii important for V_{ud}

1. Within model, calculate δ_c

(need R_{father} to 1%)

2. Calculate f

(need $R_{father} + R_{daughter}$ to few 0.1%)

3. Benchmark δ_c models

(need R of triplet to <0.1%)

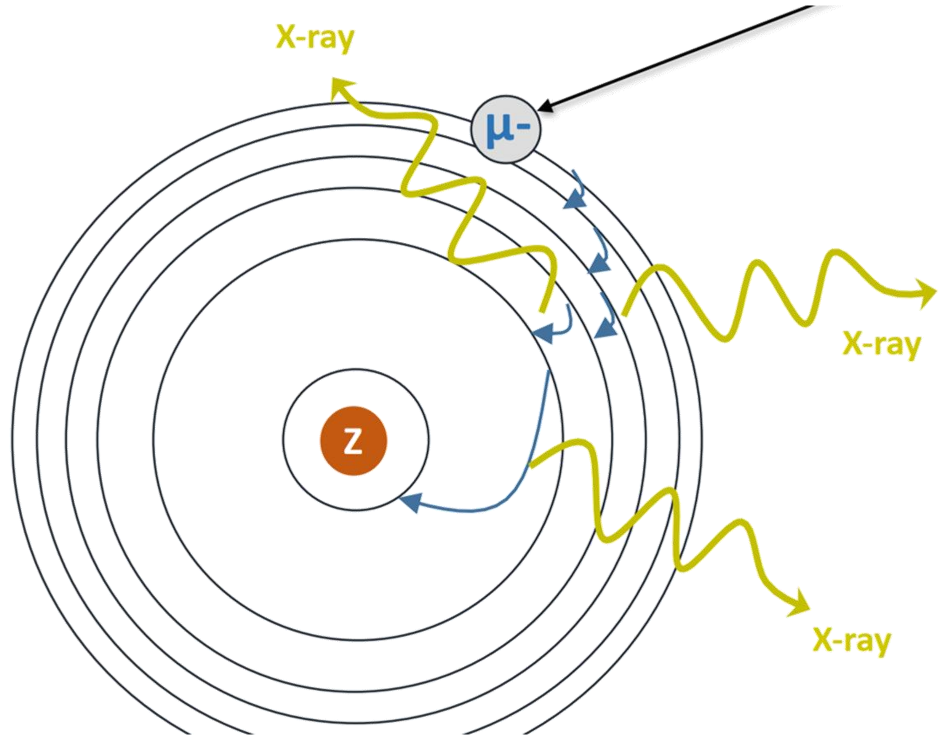
Ecosystem of charge radii determinations

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

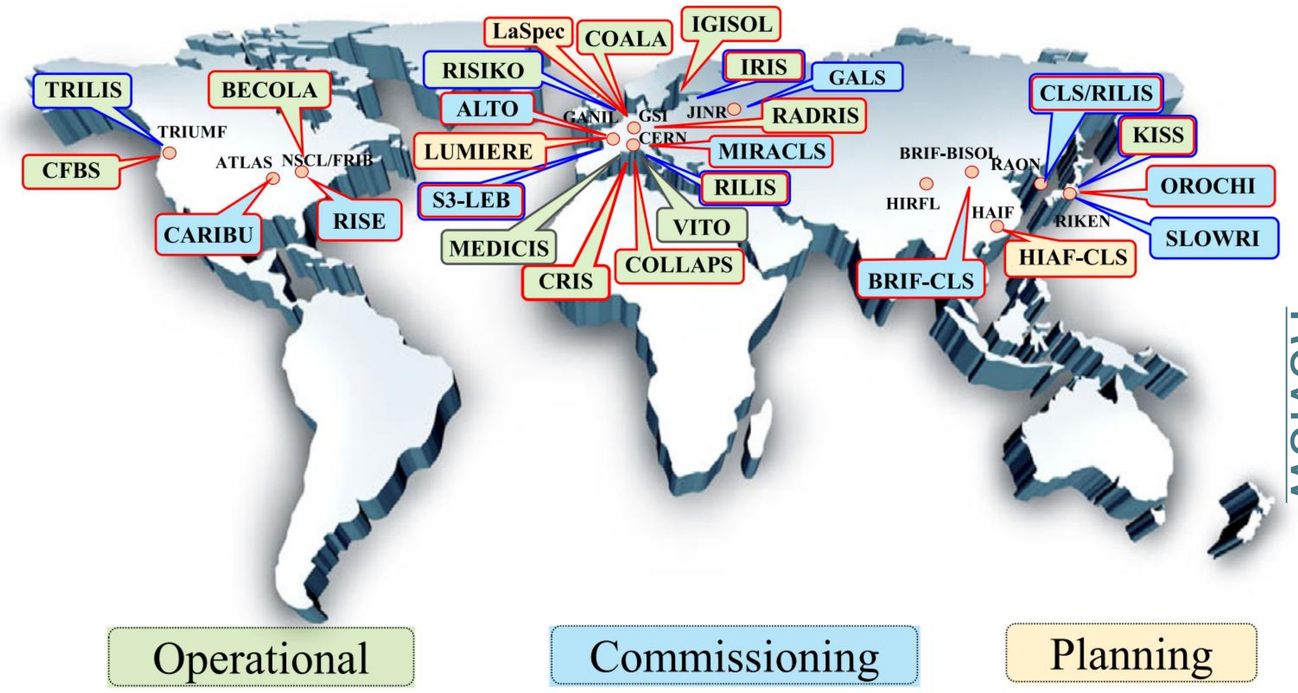
Reference radius (mostly) from **Muonic atoms**

Differential radii (mostly) from radioactive **electronic atoms**

Experiments:

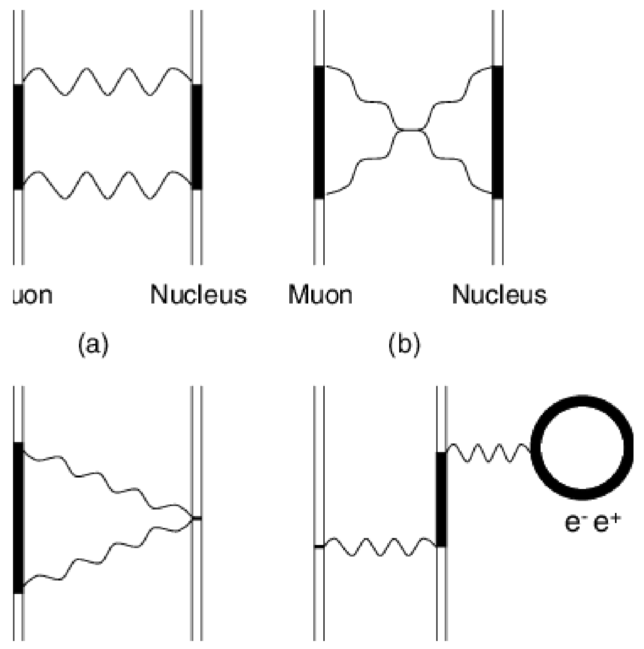


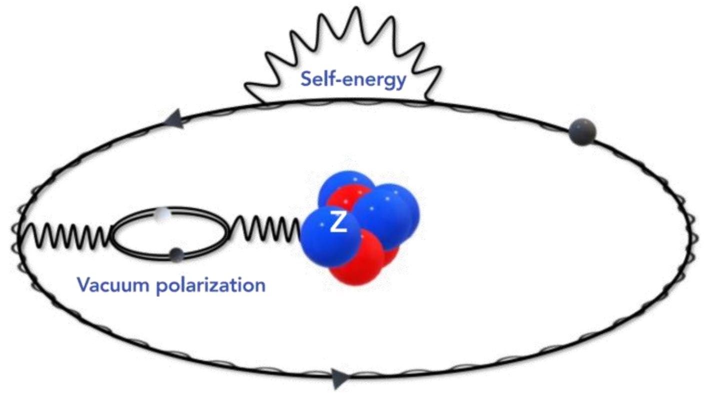
Recent Updates

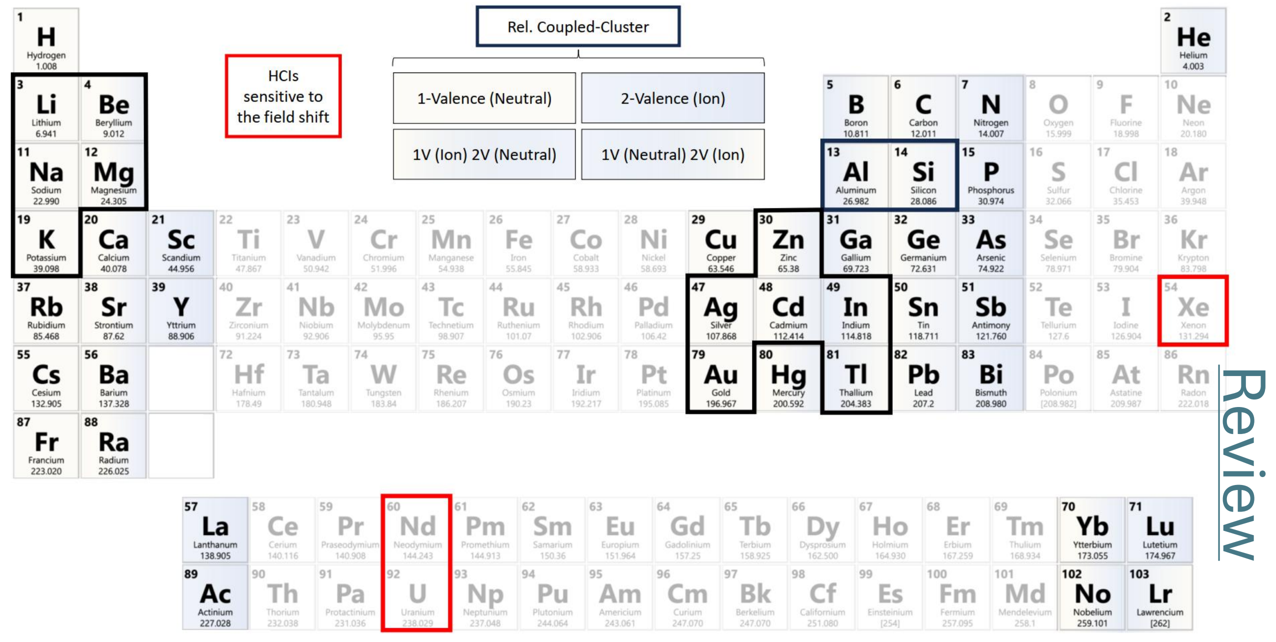


Review

Theories:







Review