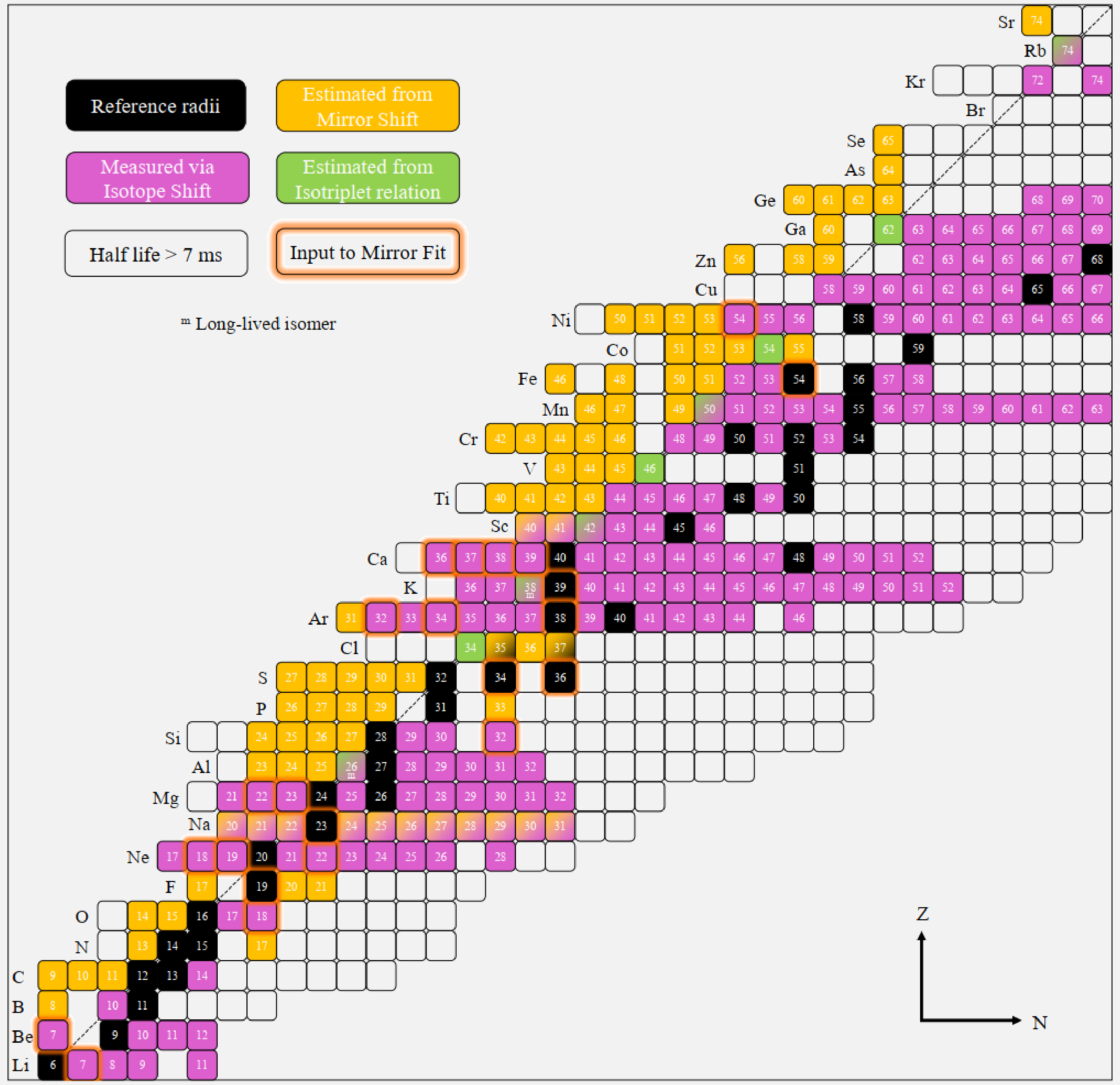
New perspectives in the charge radii determination for light nuclei



ADNDT

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ECT*, July 28th - Aug. 1st, 2025

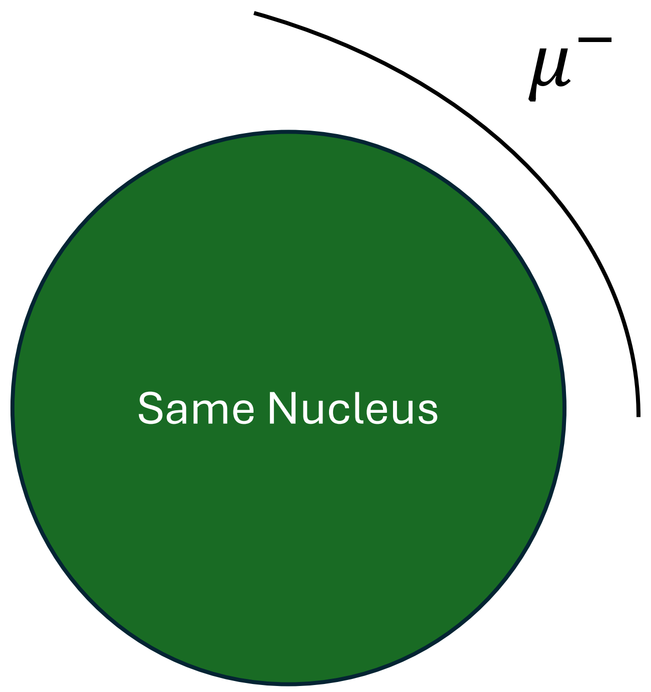
Today

- Charge radii: a story of theory and experiment
- Reference-radii and their uncertainty
- New *global* initiatives

<u>Fruitful</u> combination of experiment with theory

Measurements in

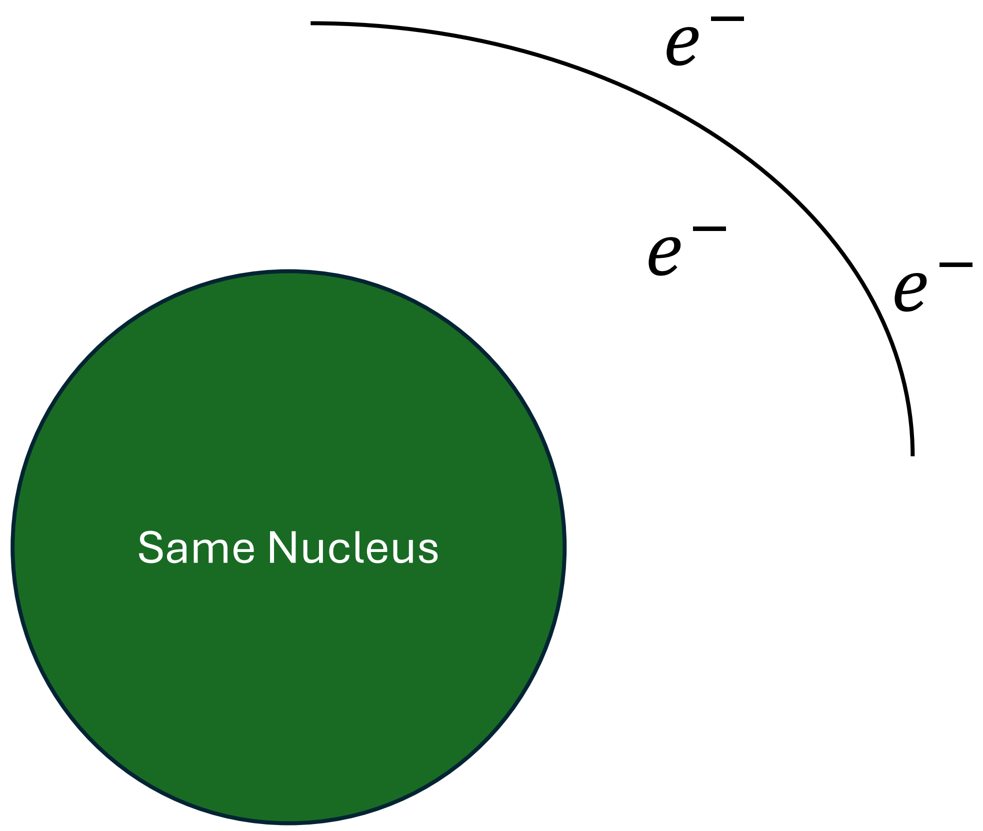
Exotic atoms



Atomic & Nuclear Theory

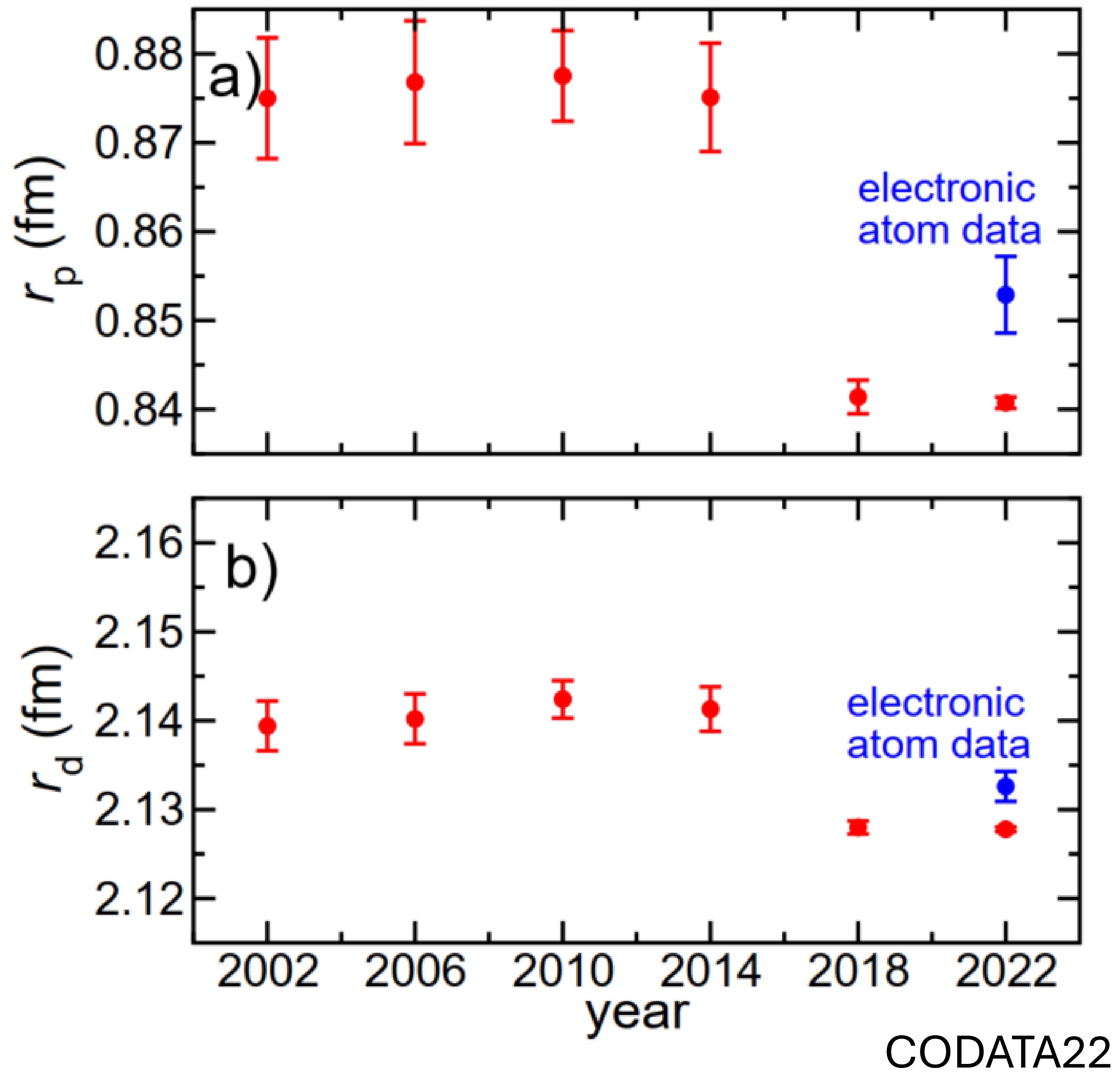
Measurements in

Electronic atoms



Some Fruits

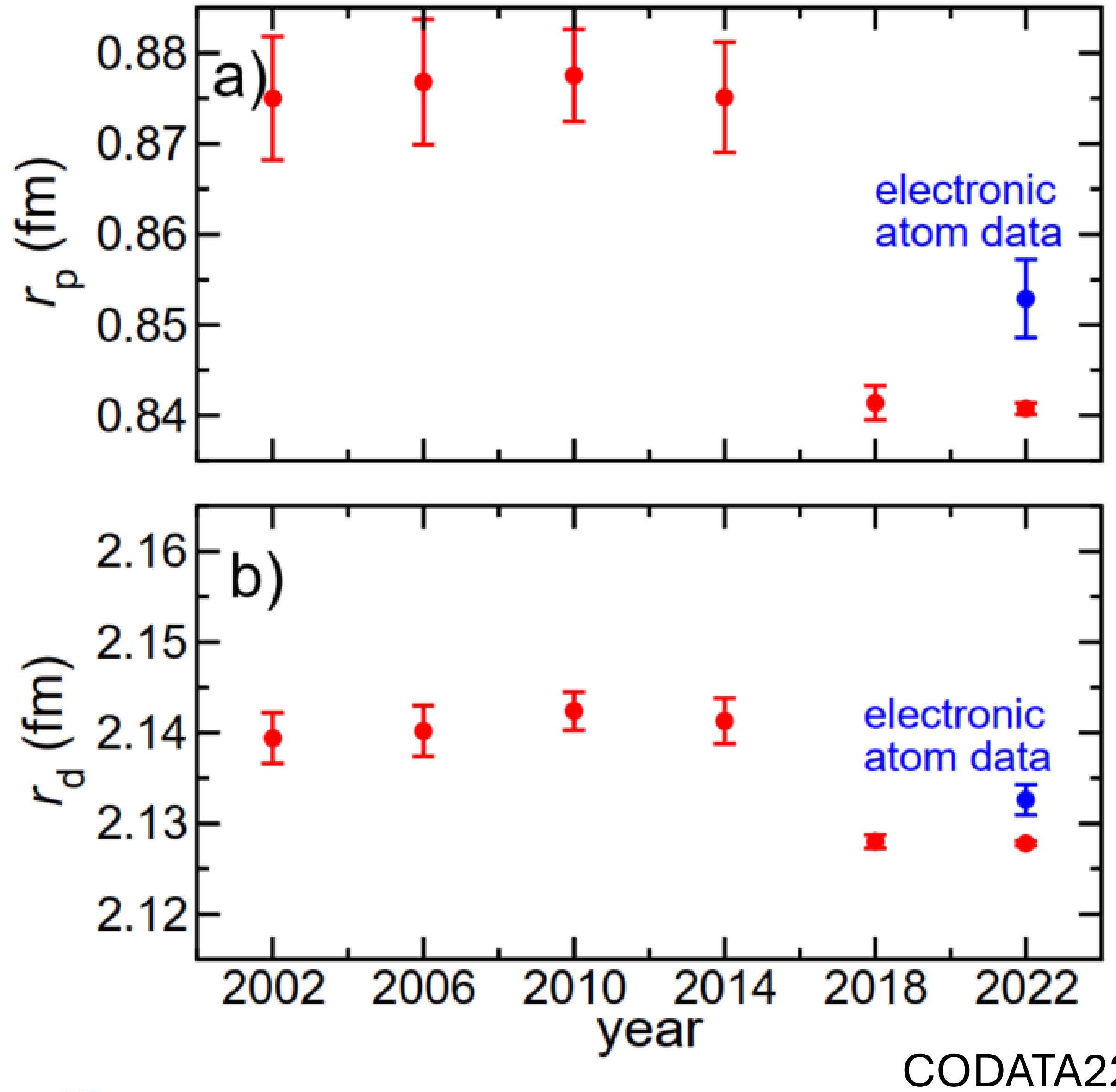
Determination of fundamental constants:



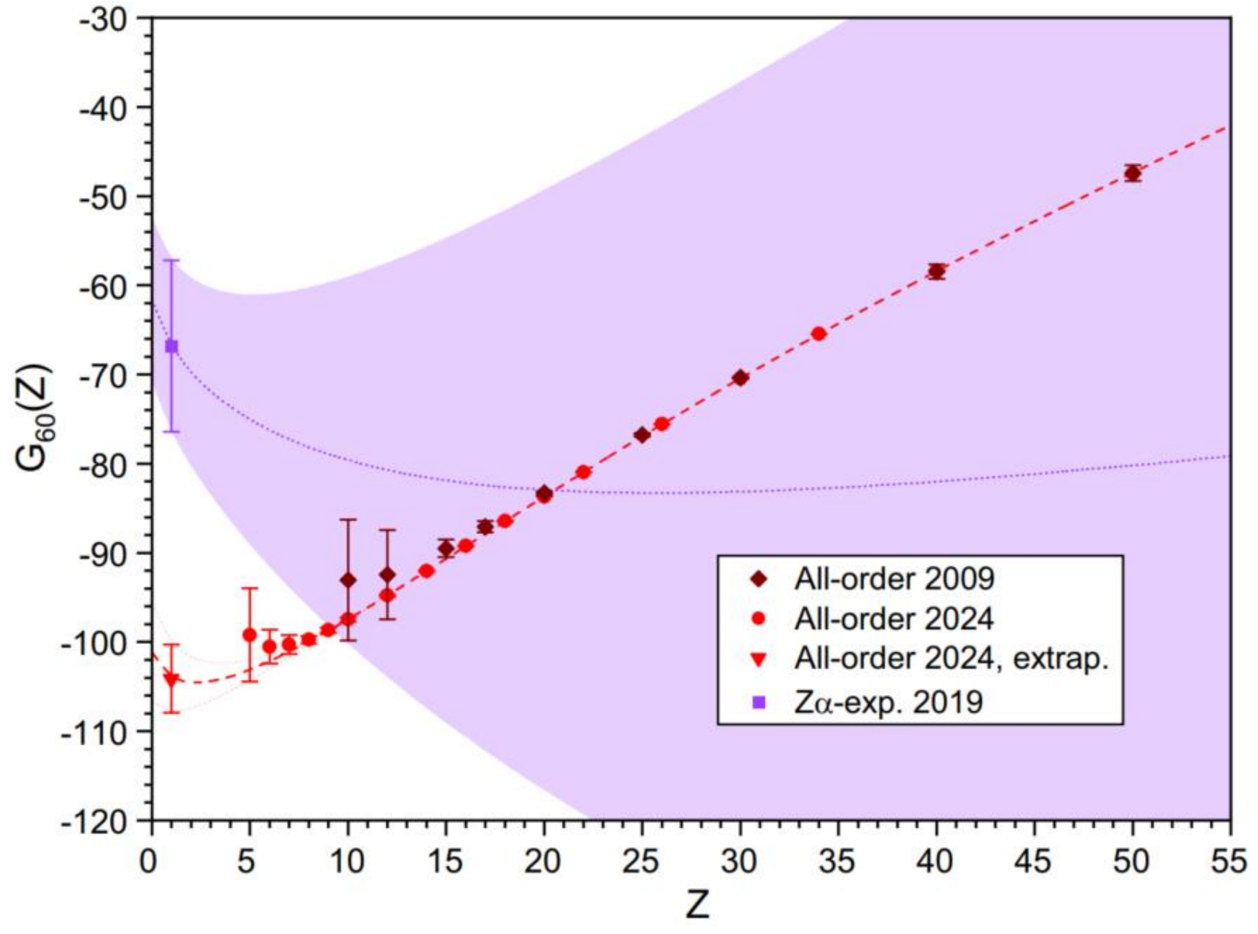
CODATA22

Some Fruits

Determination of fundamental constants:



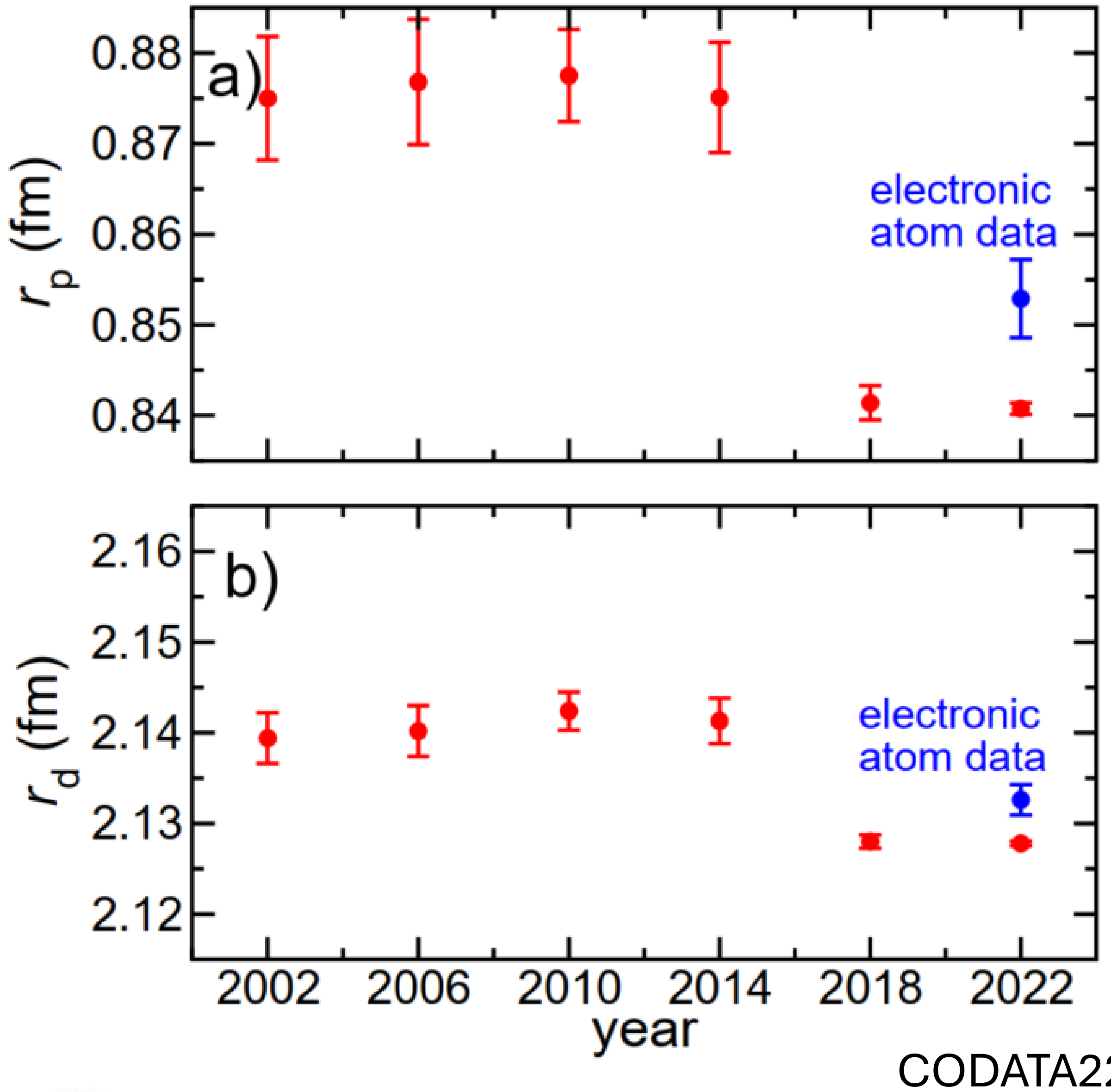
CODATA22

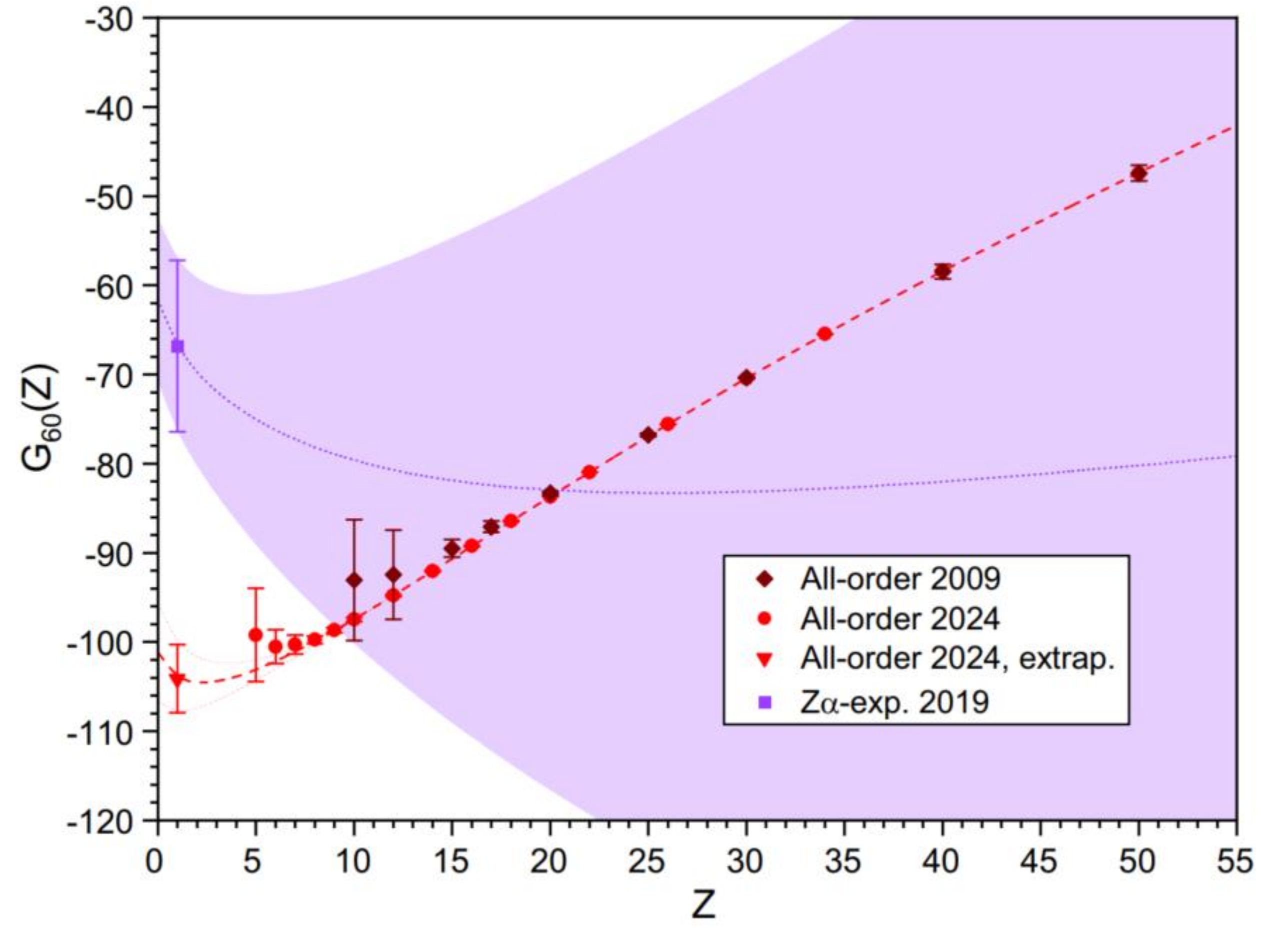


PhysRevLett.133.251803

Some Fruits

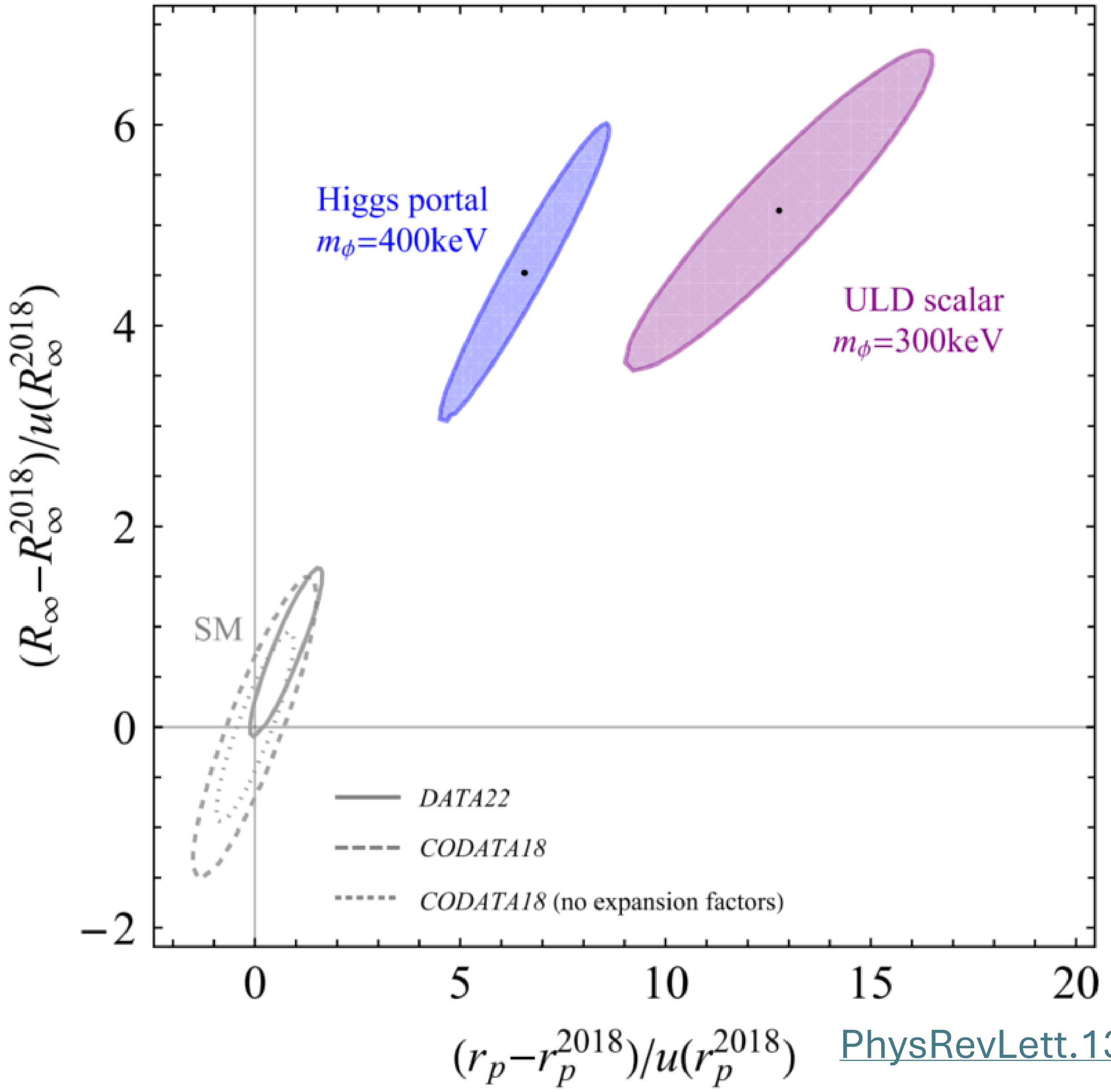
Determination of fundamental constants:





PhysRevLett.133.251803

Search for new physics:



PhysRevLett.130.121801

Some Fruits

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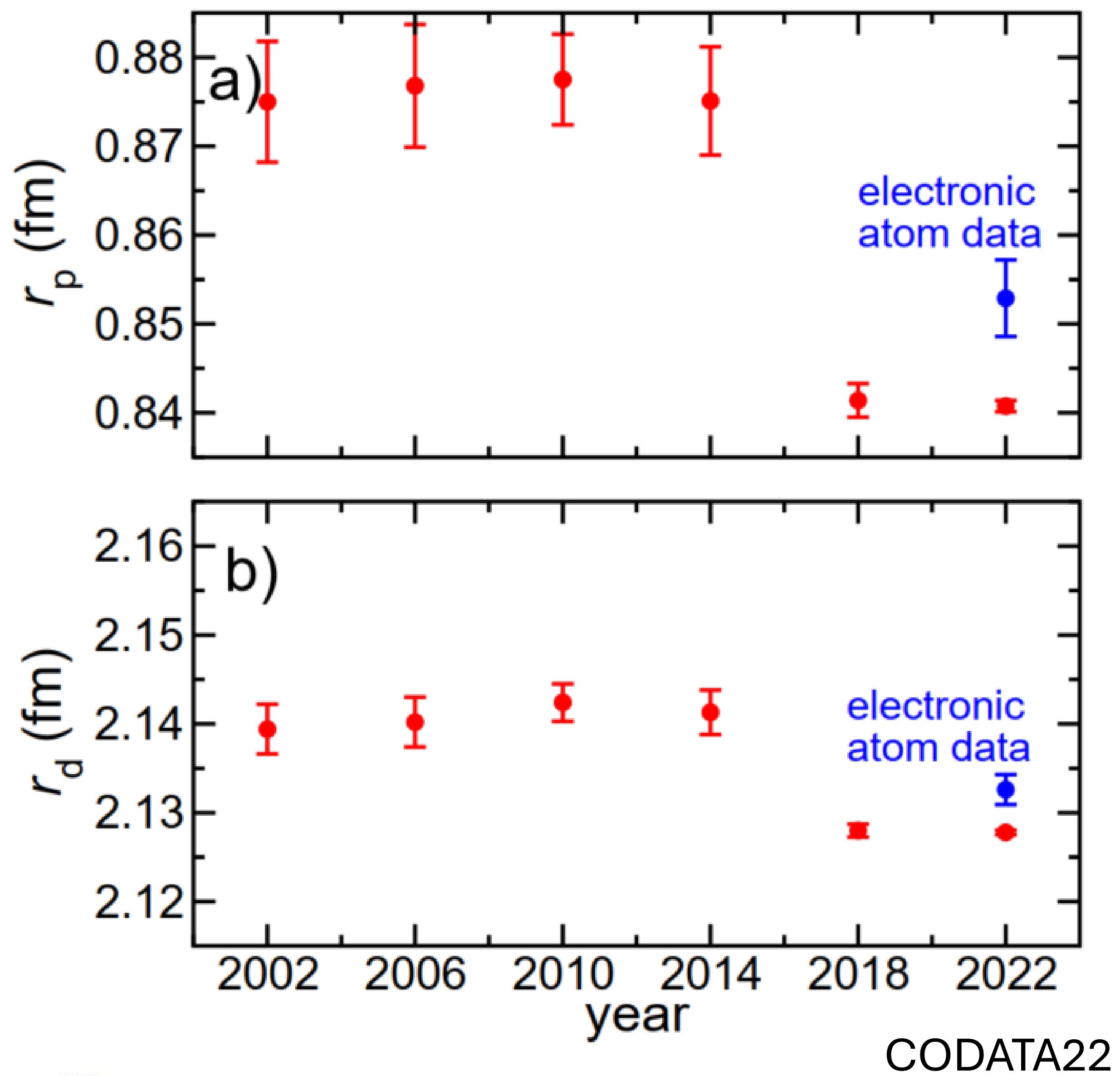

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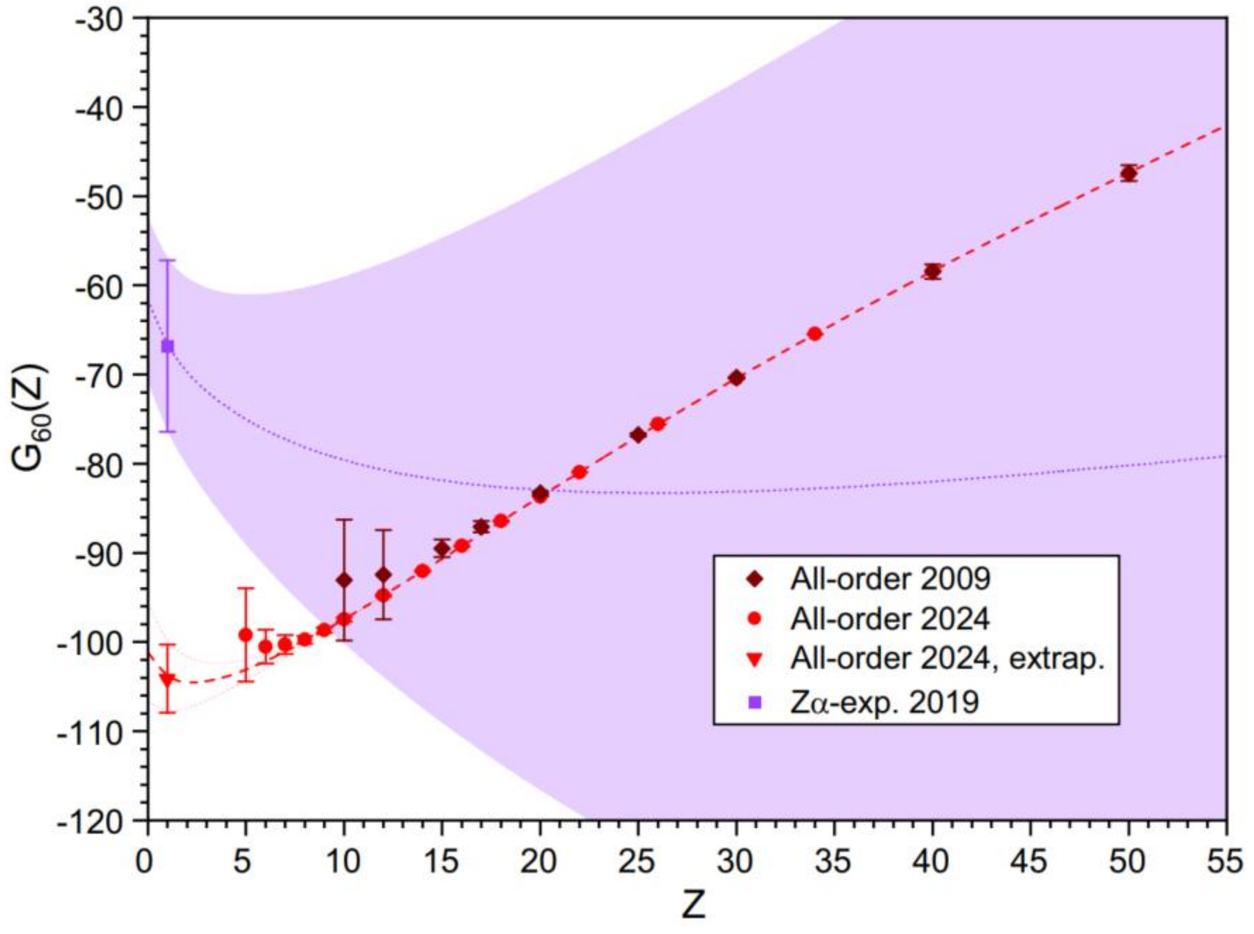

PhysRevLett.133.251803

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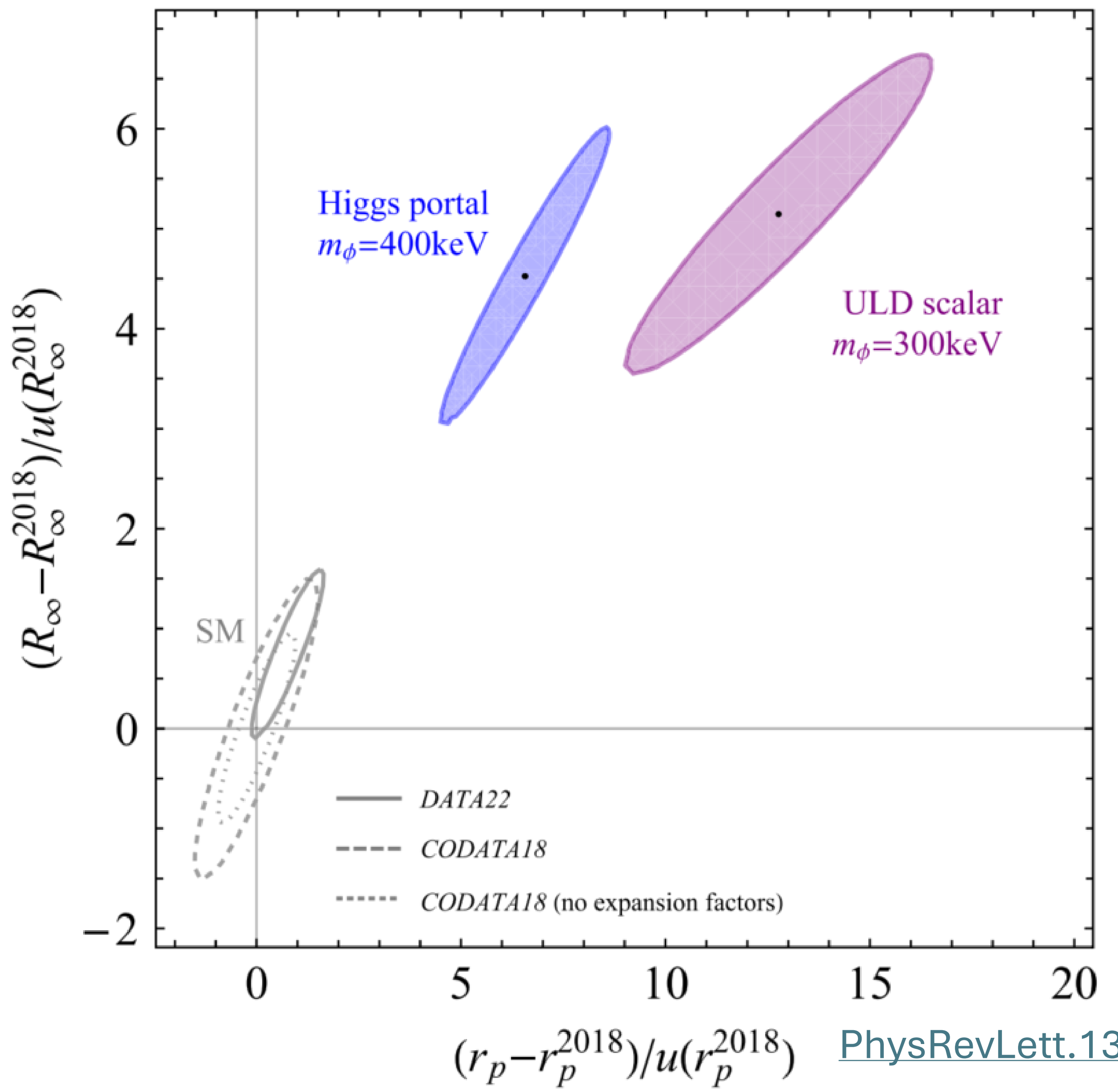
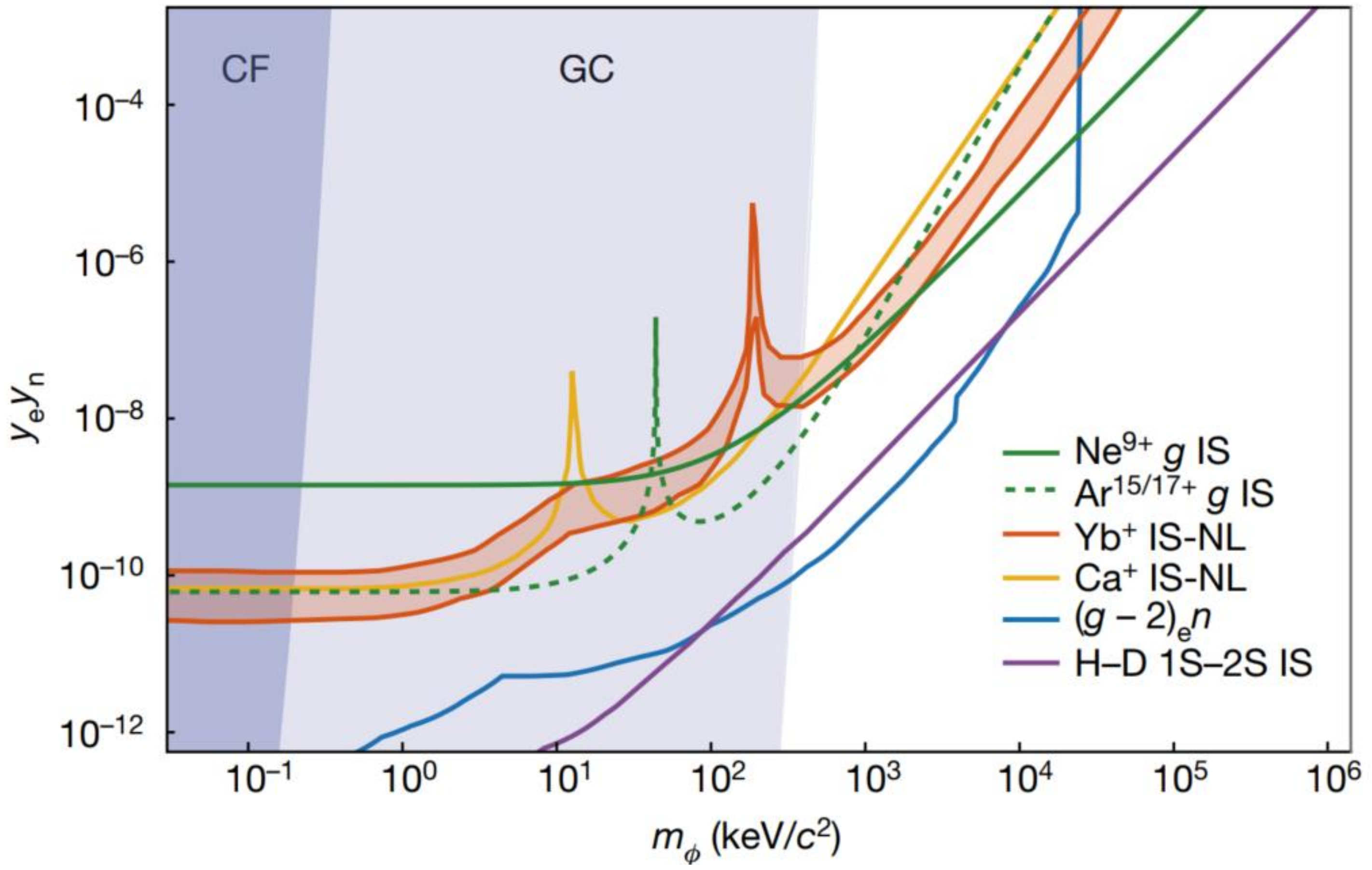


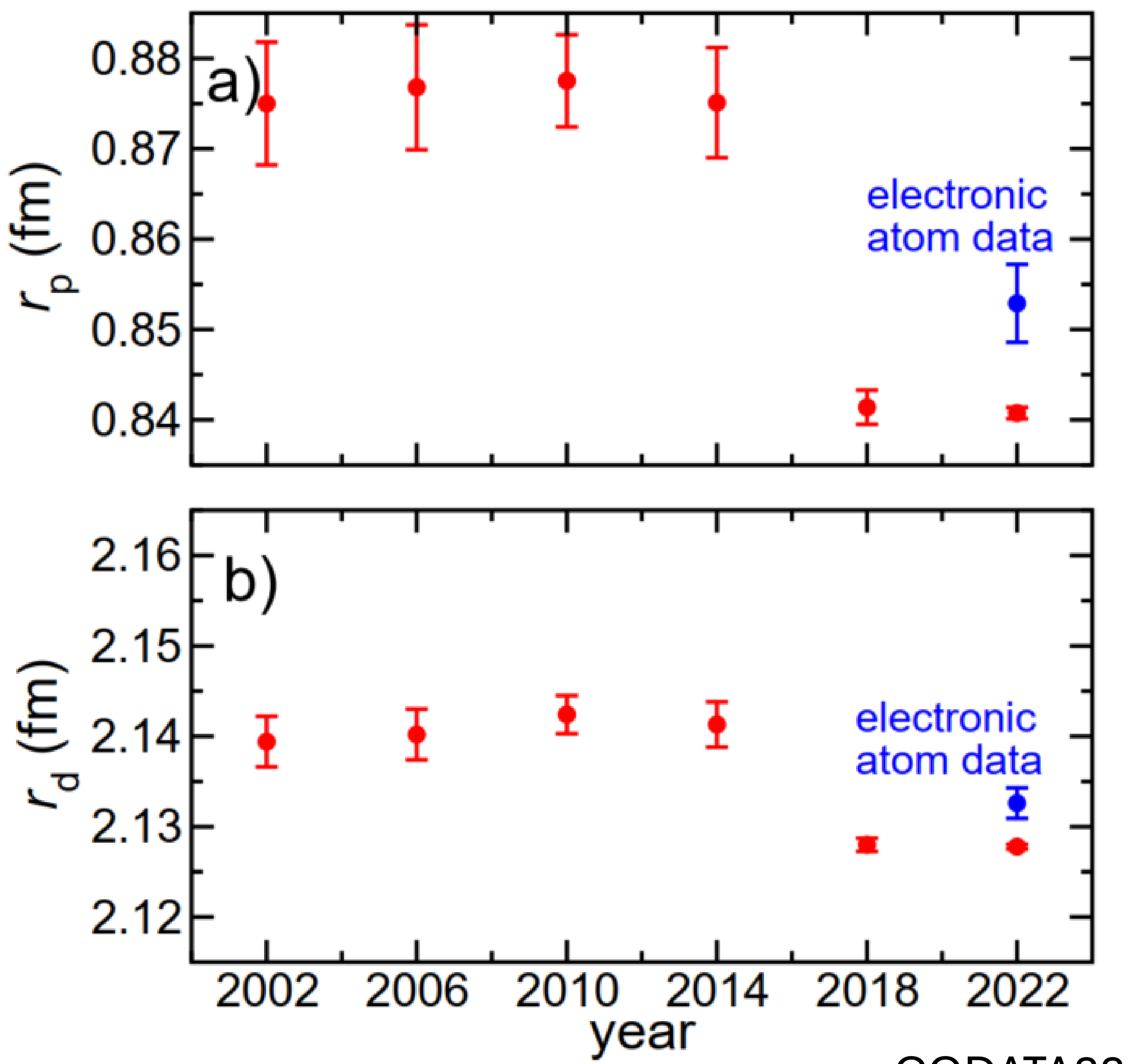
PhysRevLett.130.121801



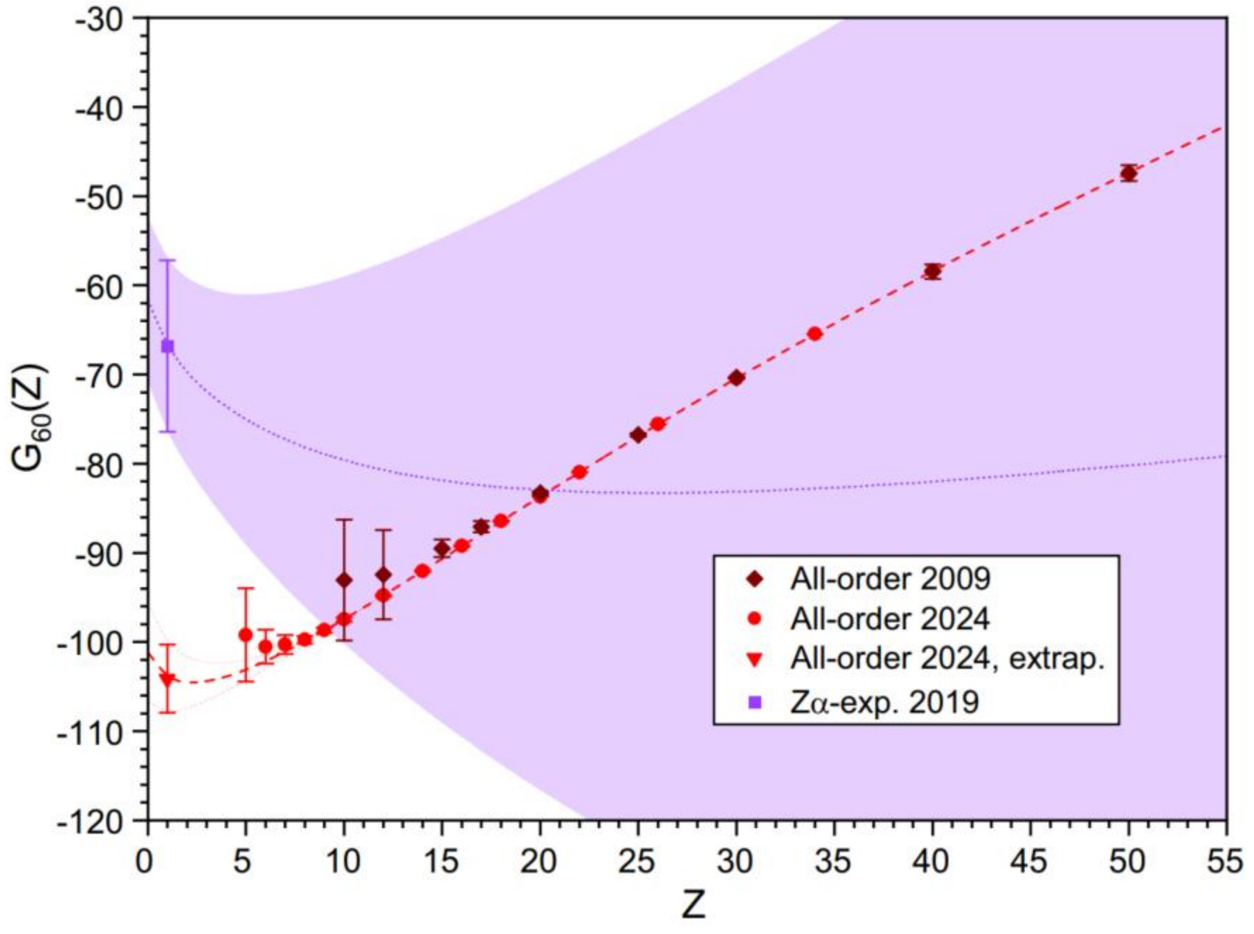
Nature **volume 606**, pages 479–483

Some Fruits

Determination of fundamental constants:



CODATA22



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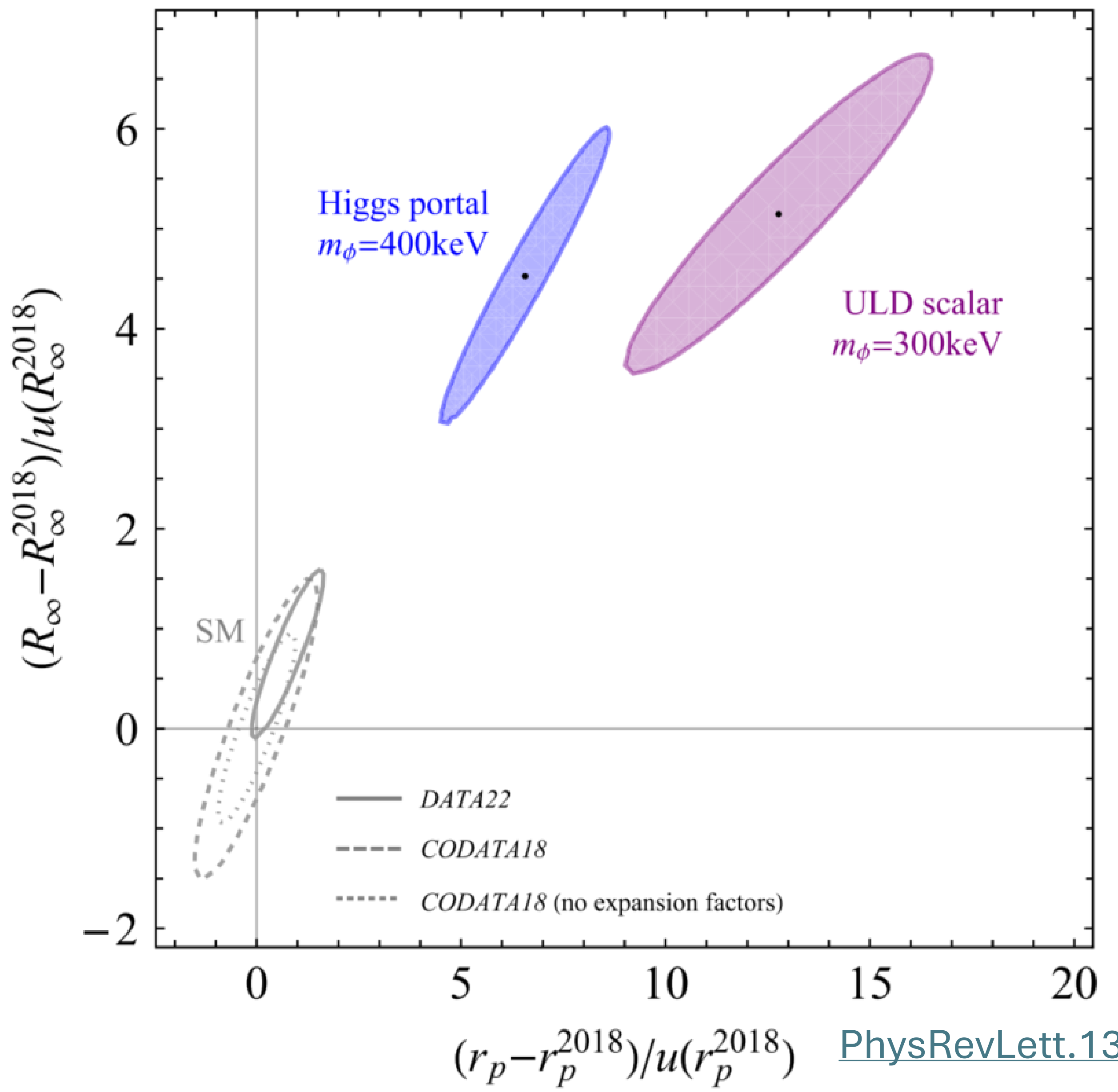

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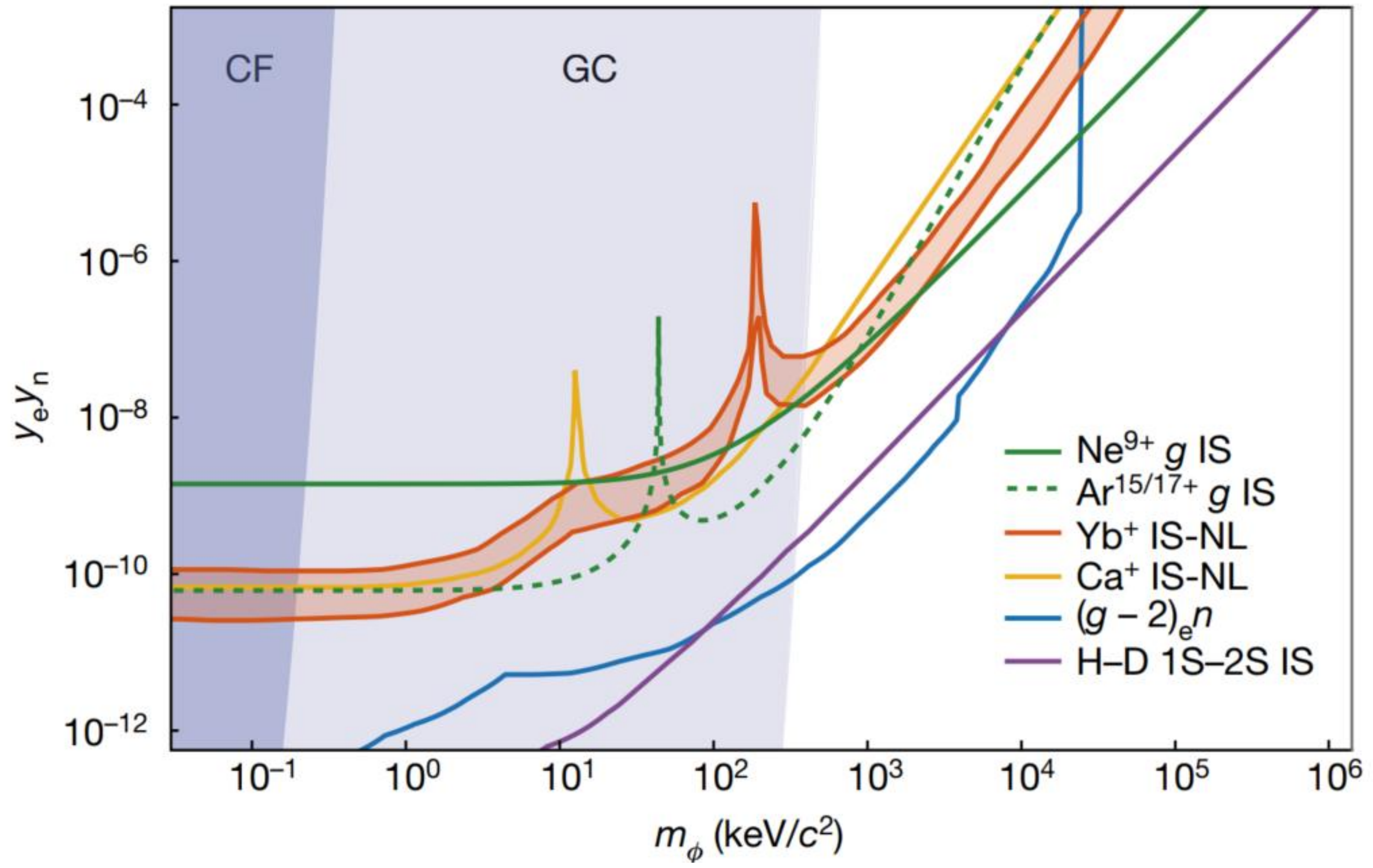
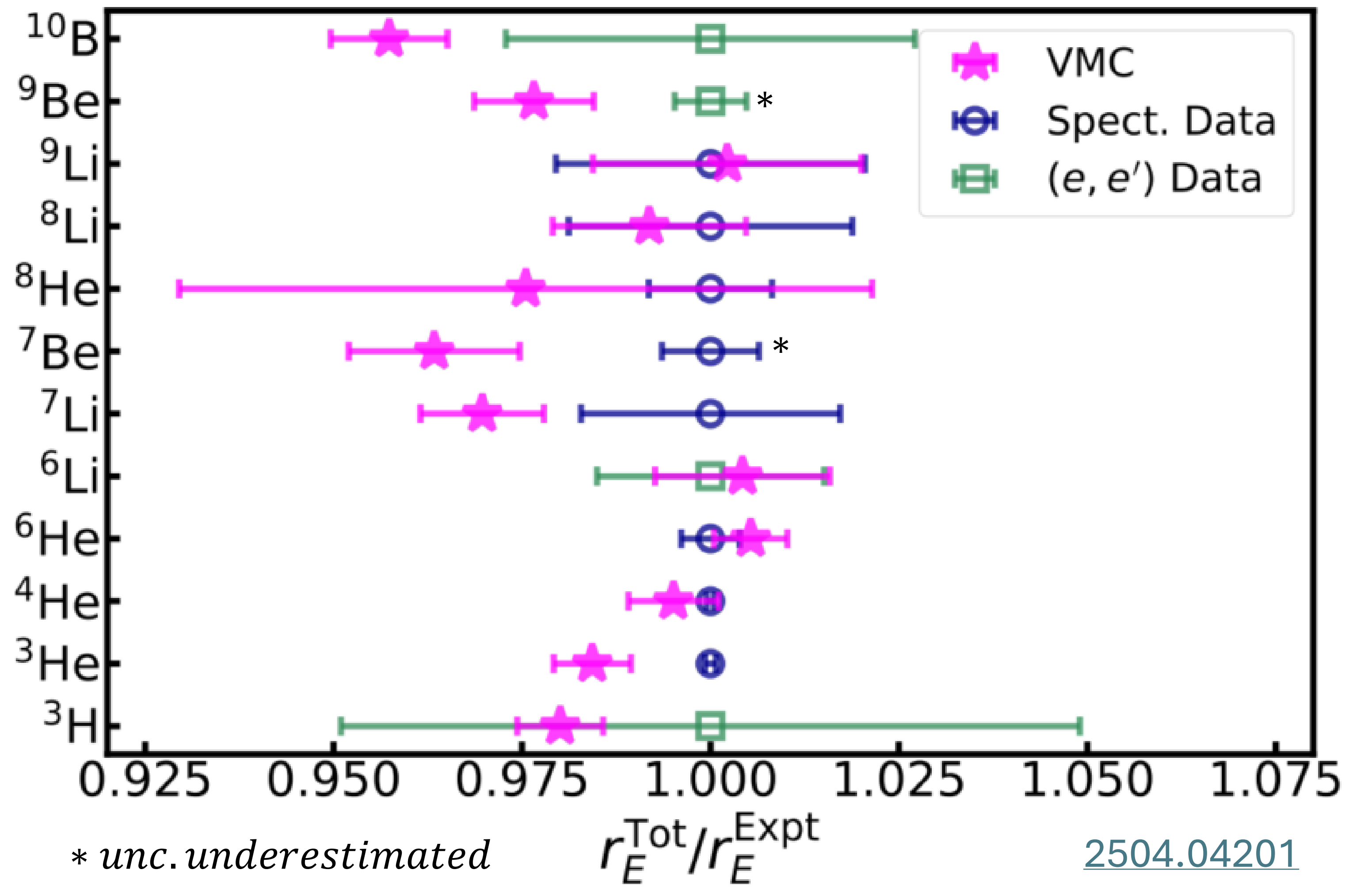


Nature **volume 606**, pages 479–483

Direct comparisons:



$*$ unc. underestimated $\quad r_E^{Tot}/r_E^{Expt}$

2504.04201

Some Fruits

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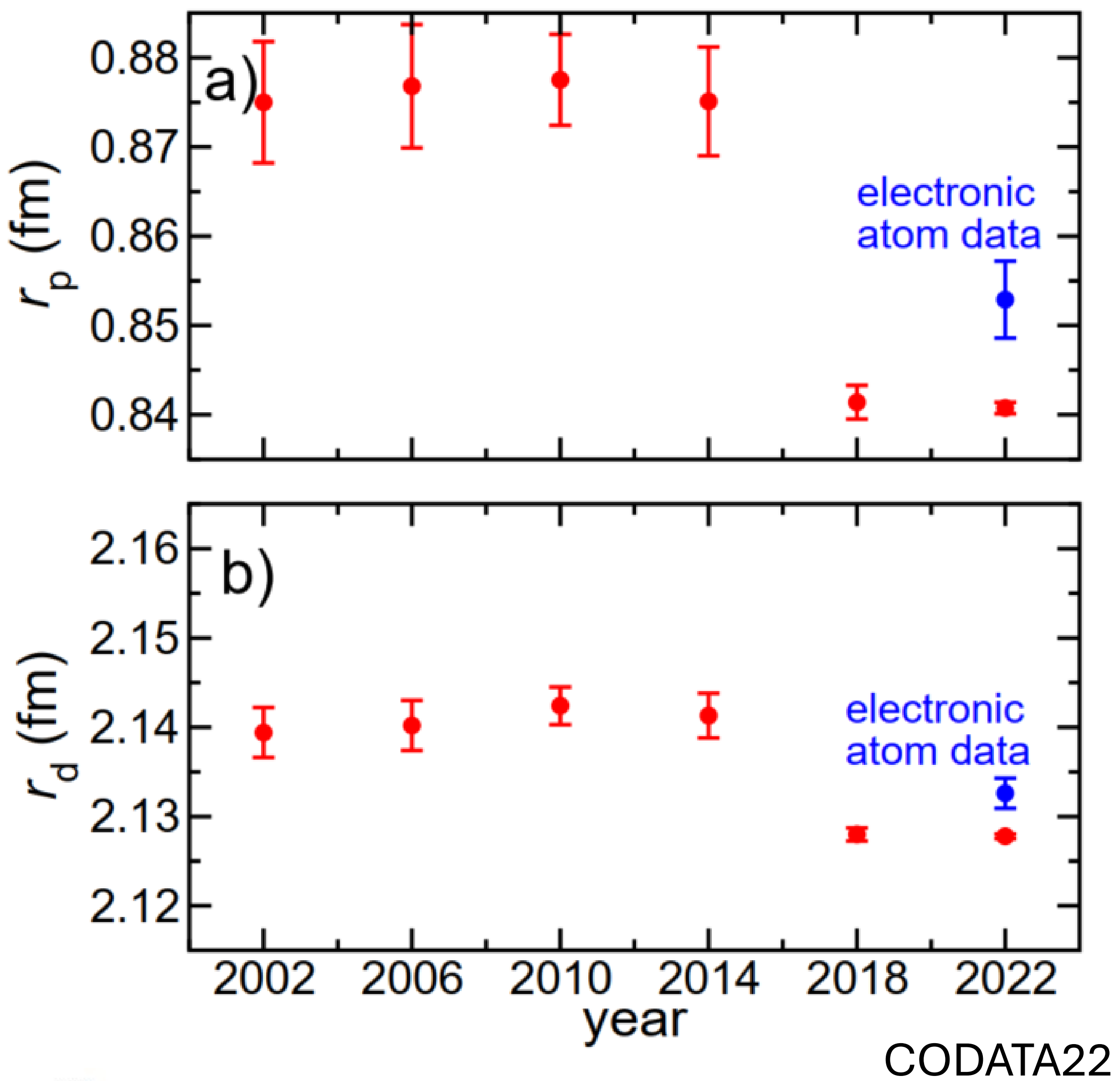

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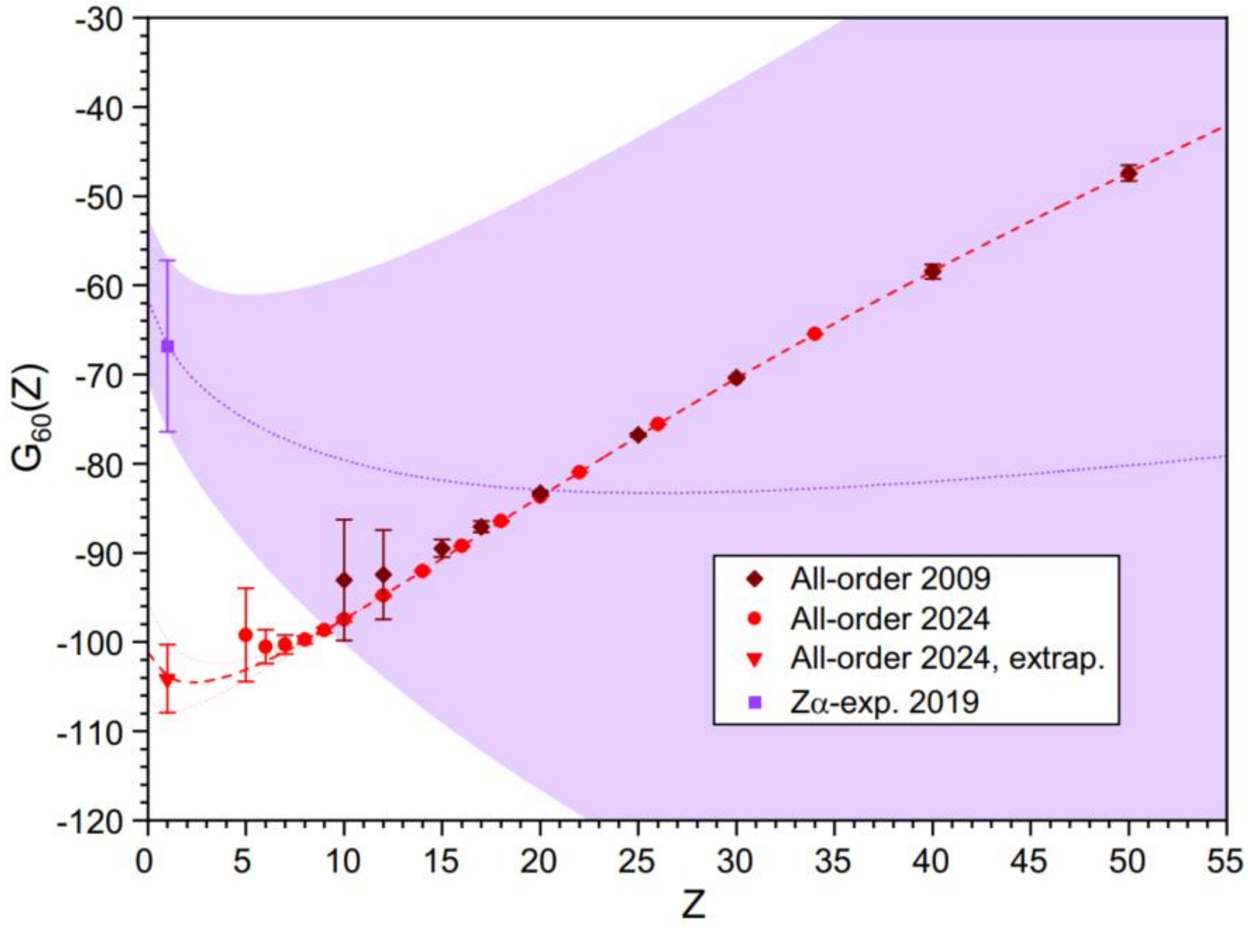

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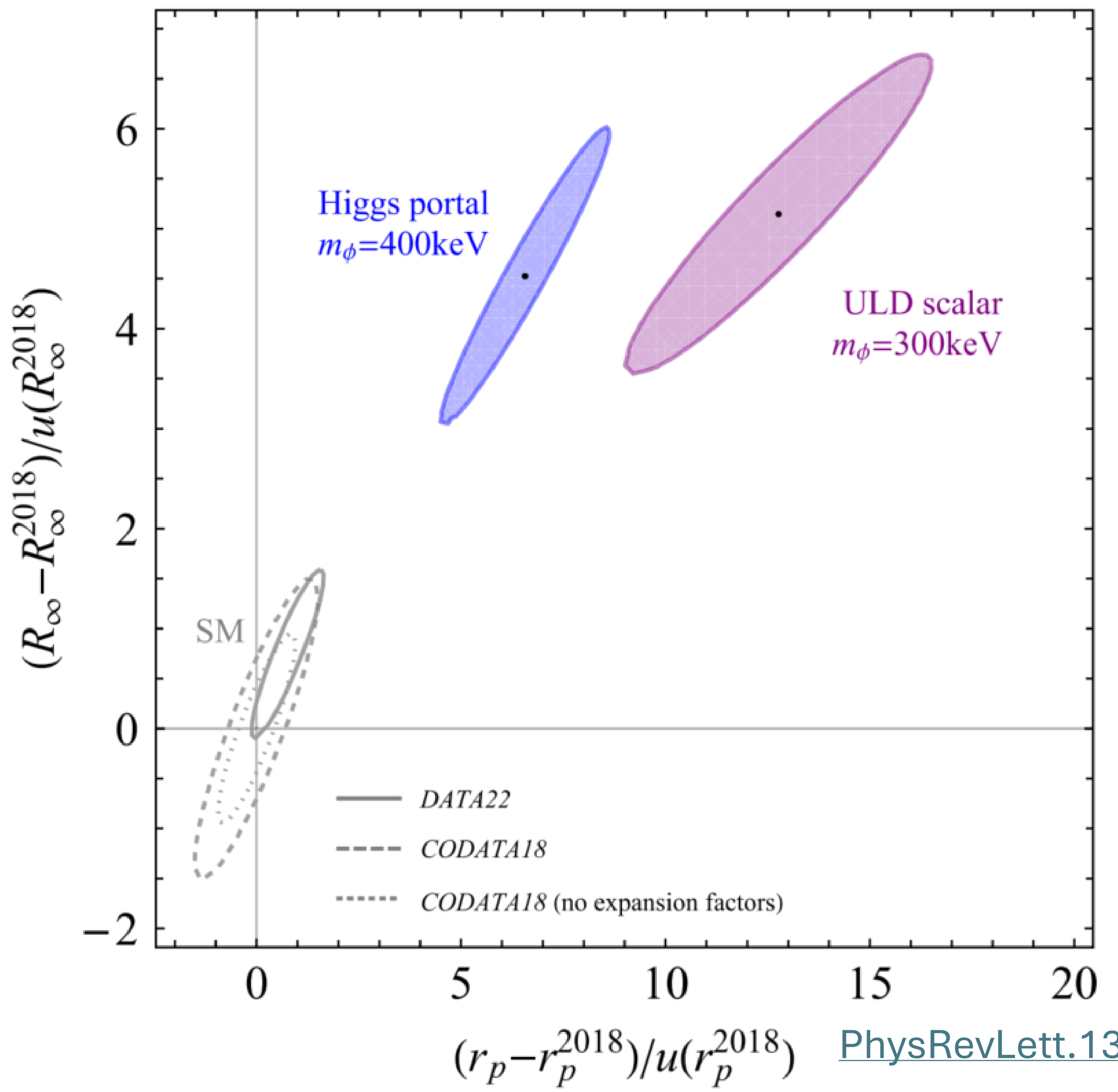

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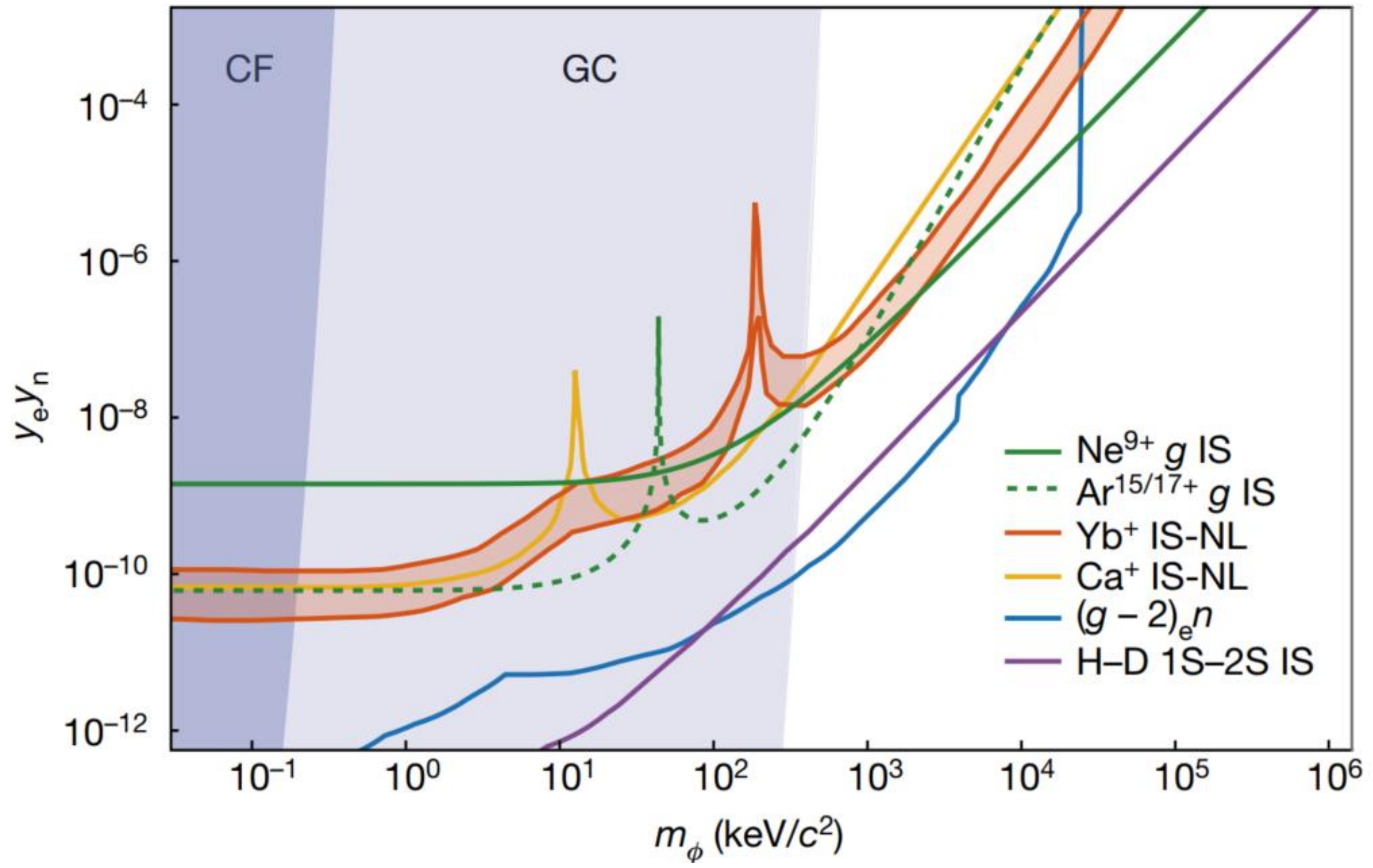

Nature **volume 606**, pages 479–483

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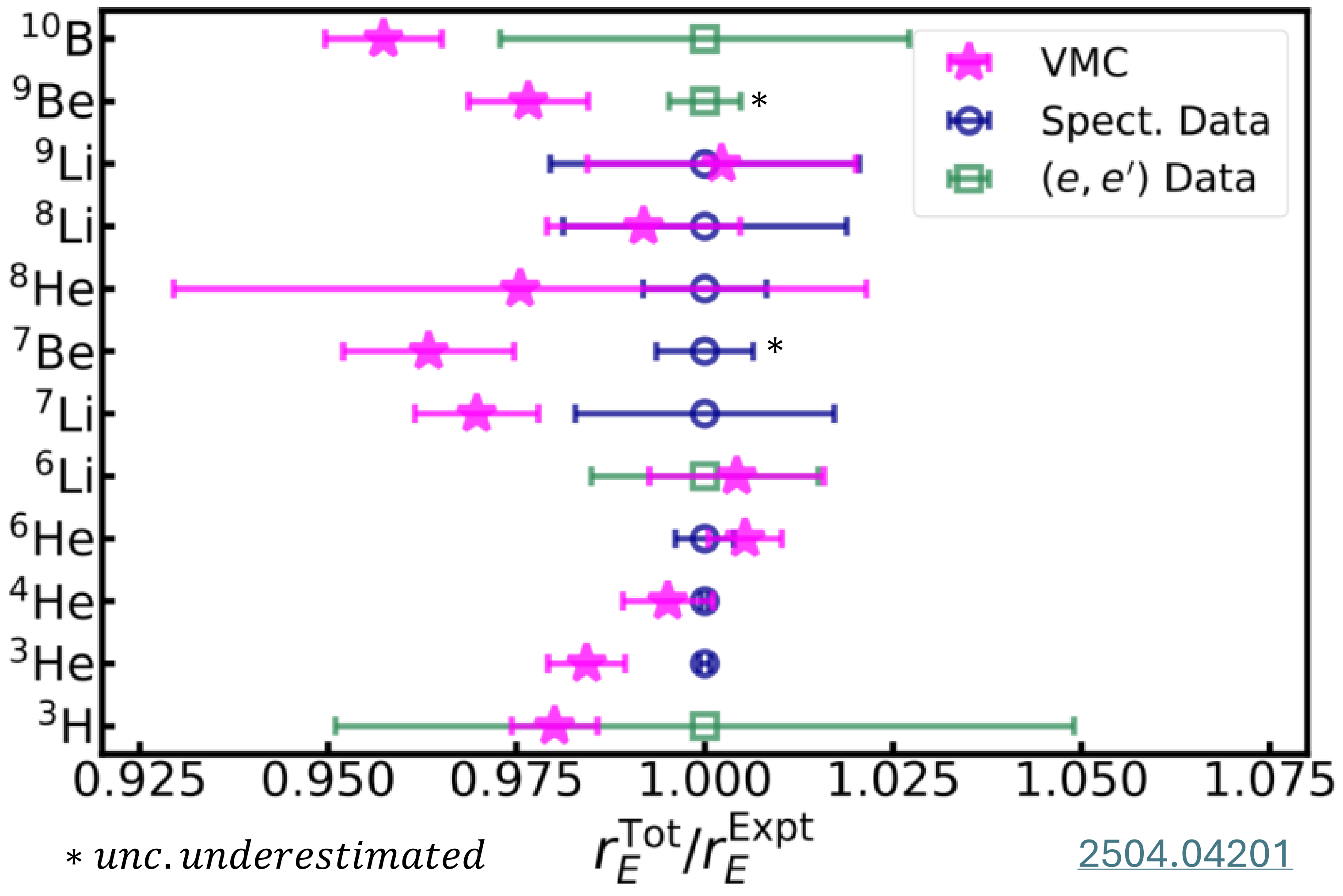
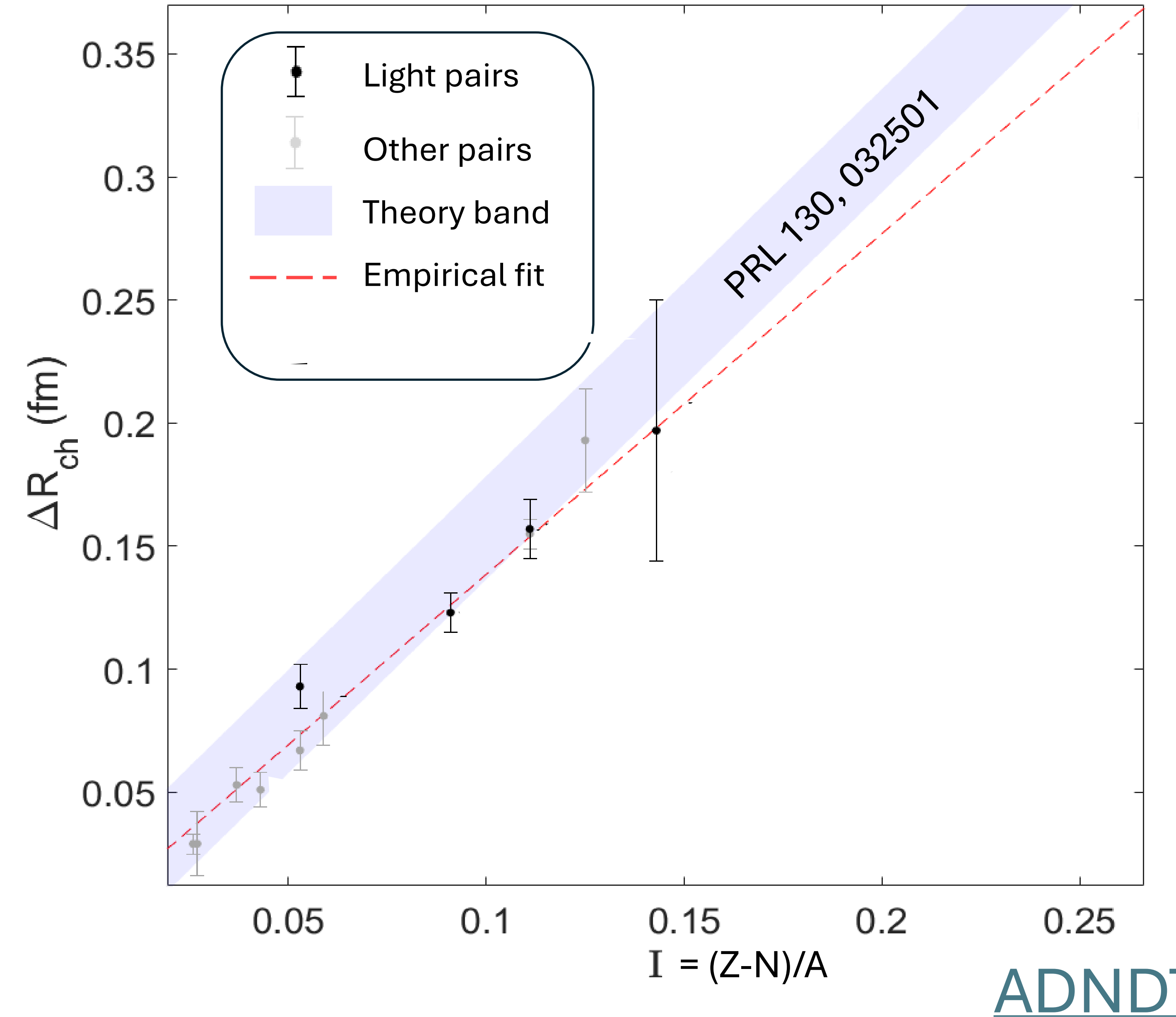


∗ *unc. underestimated*

2504.04201



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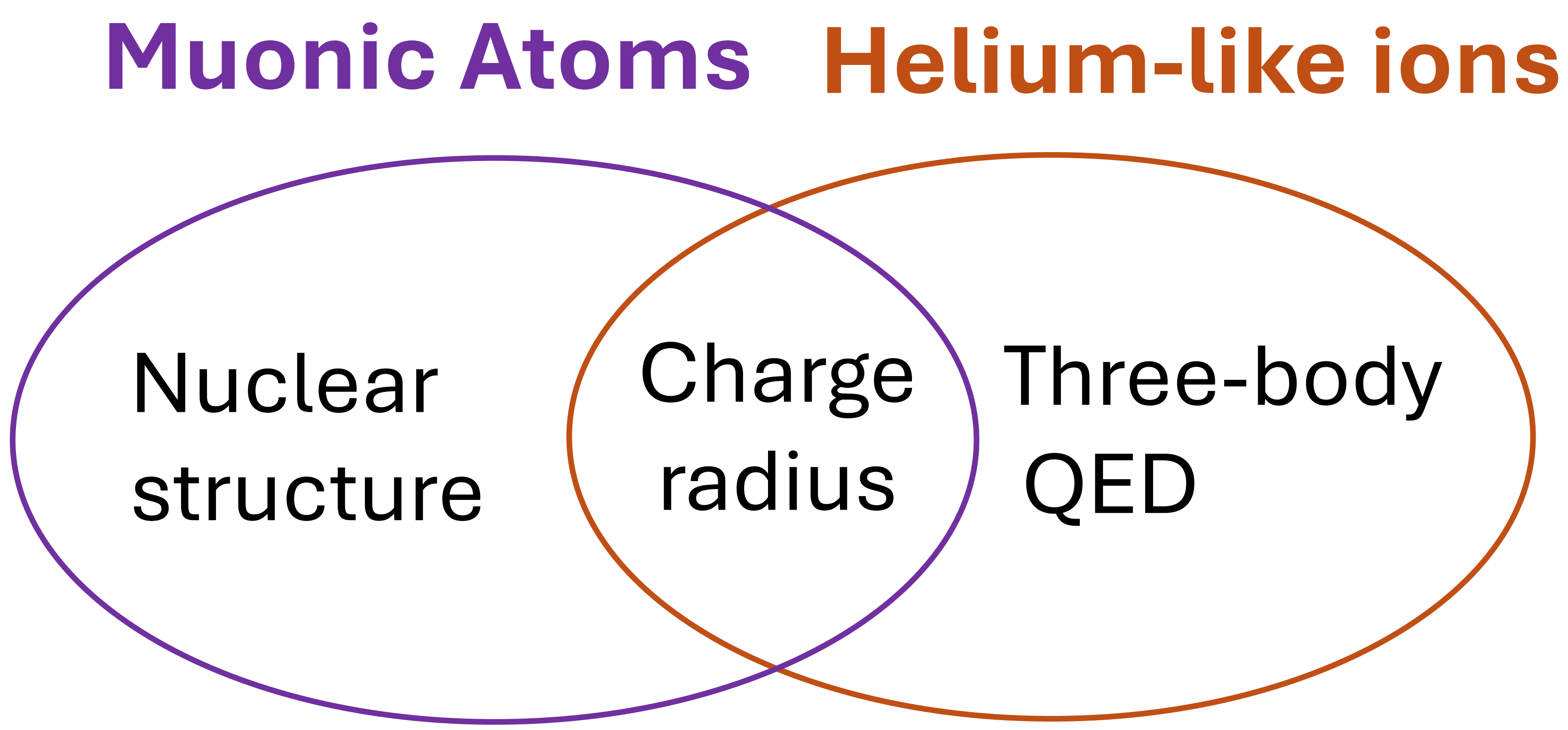
Focus on light **H**elium-**L**ike **I**ons:

Muonic Atoms

Nuclear structure

Charge radius

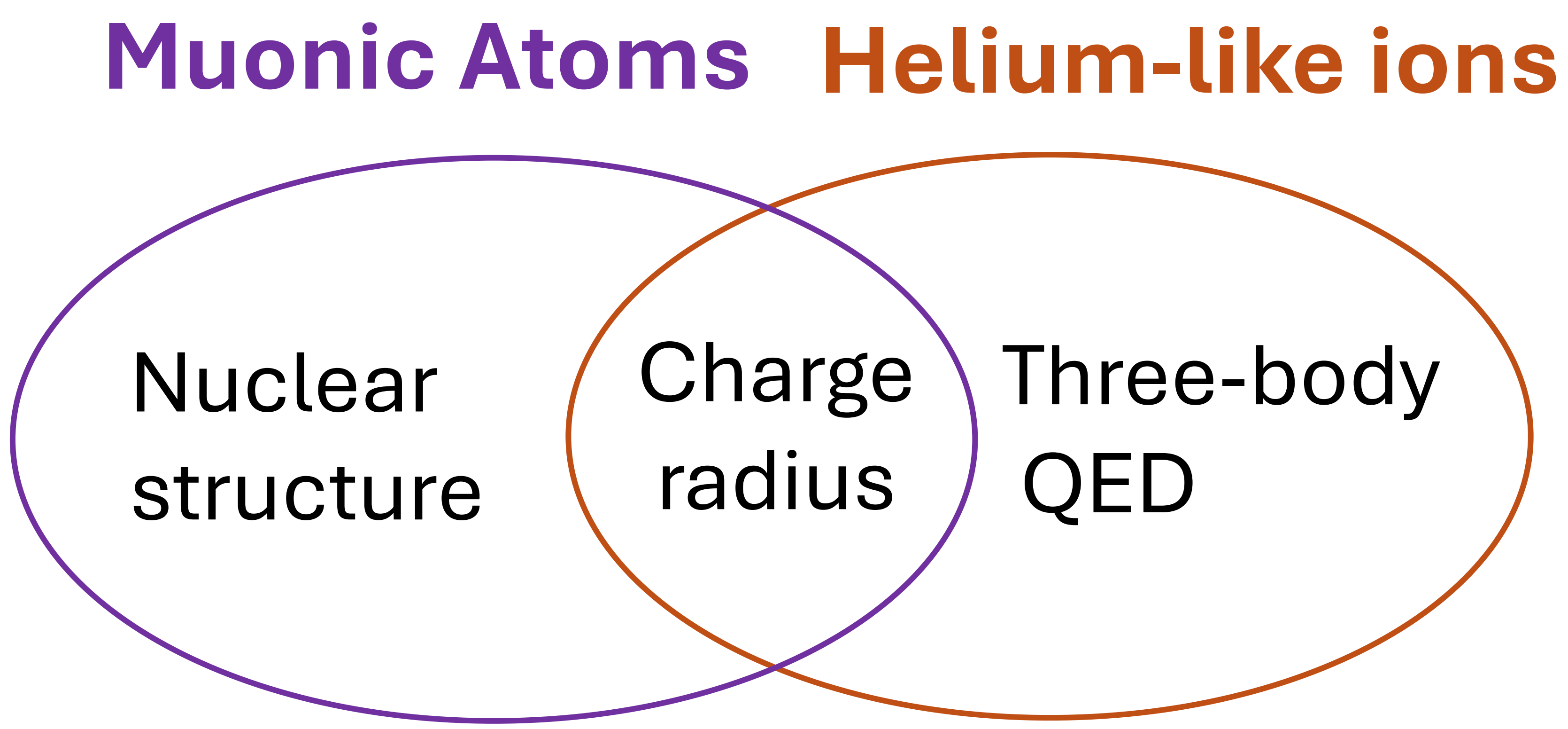
Focus on light **H**elium-**L**ike **I**ons:



Find Z dependence of missing contributions

$$E_{HO}(Z) \equiv \boldsymbol{E_{exp}} - (E_2 + E_4 + E_5 + E_6 + \boldsymbol{\delta E_{FNS}})$$

Focus on light **H**elium-**L**ike **I**ons:



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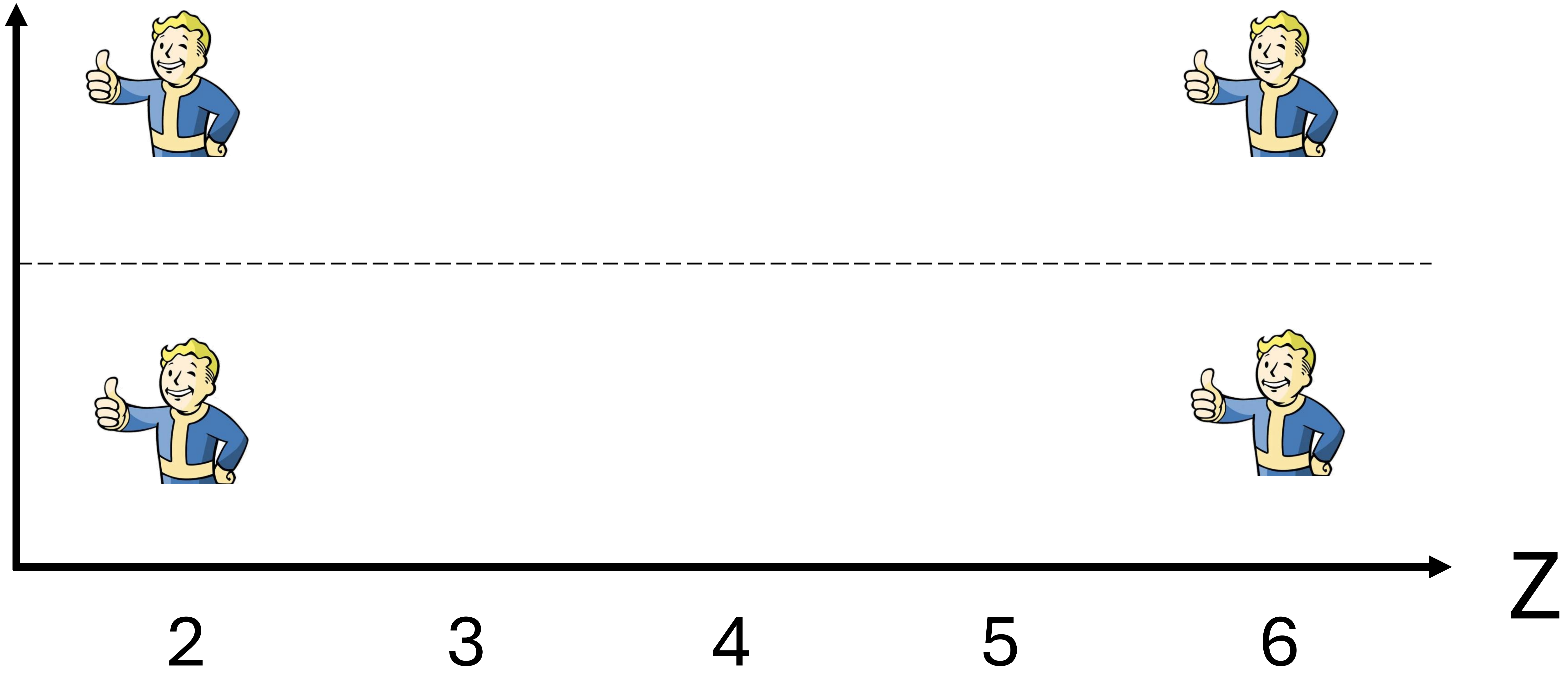
Radius from Muonic atoms:

High precision **Experiments** in HLIs:



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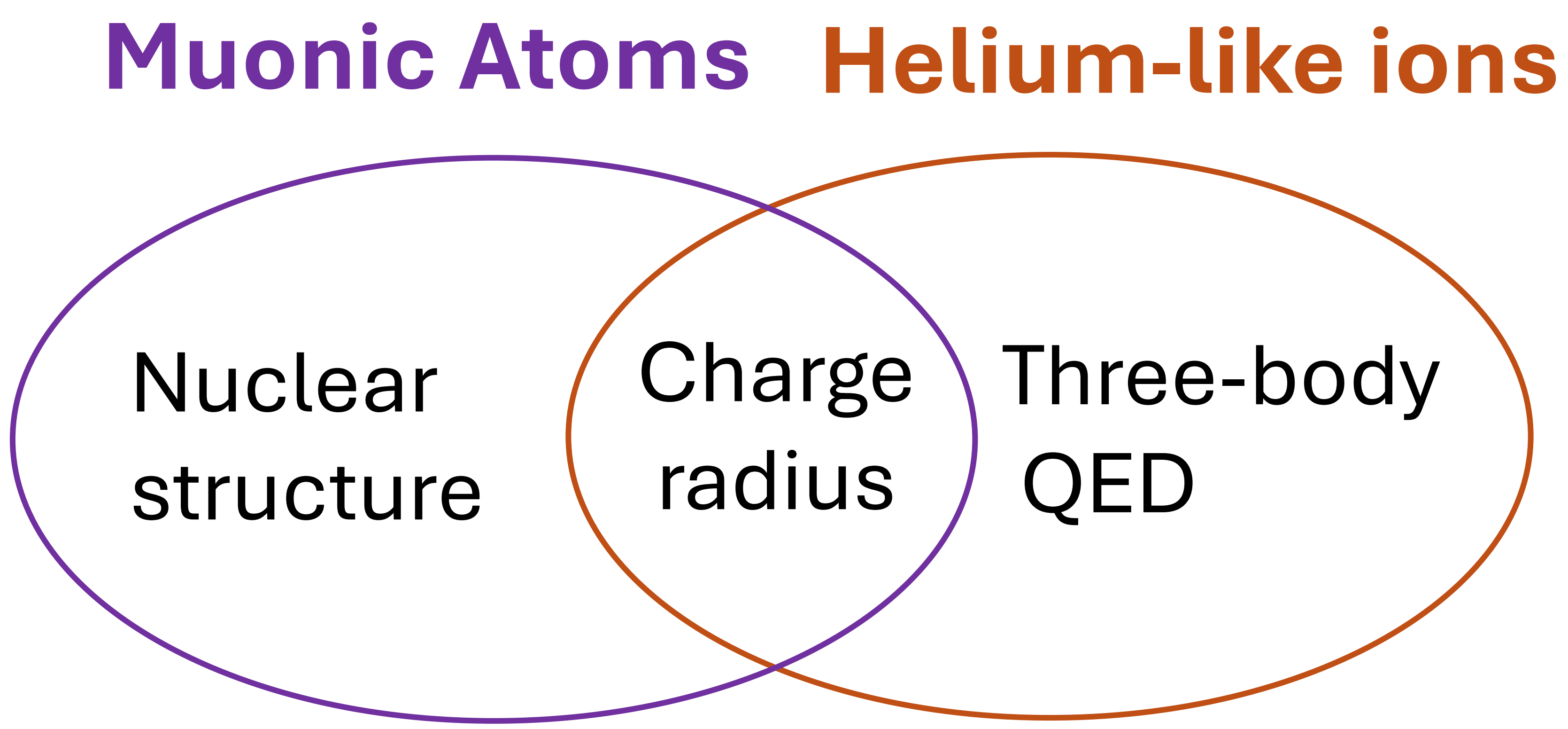

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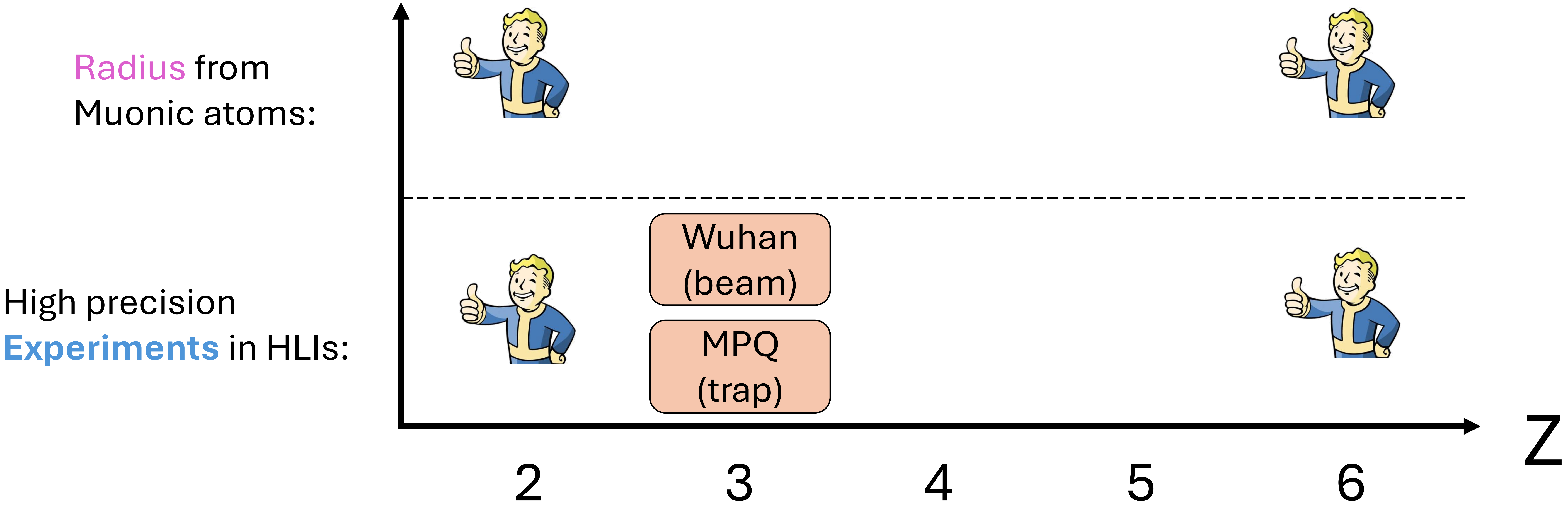

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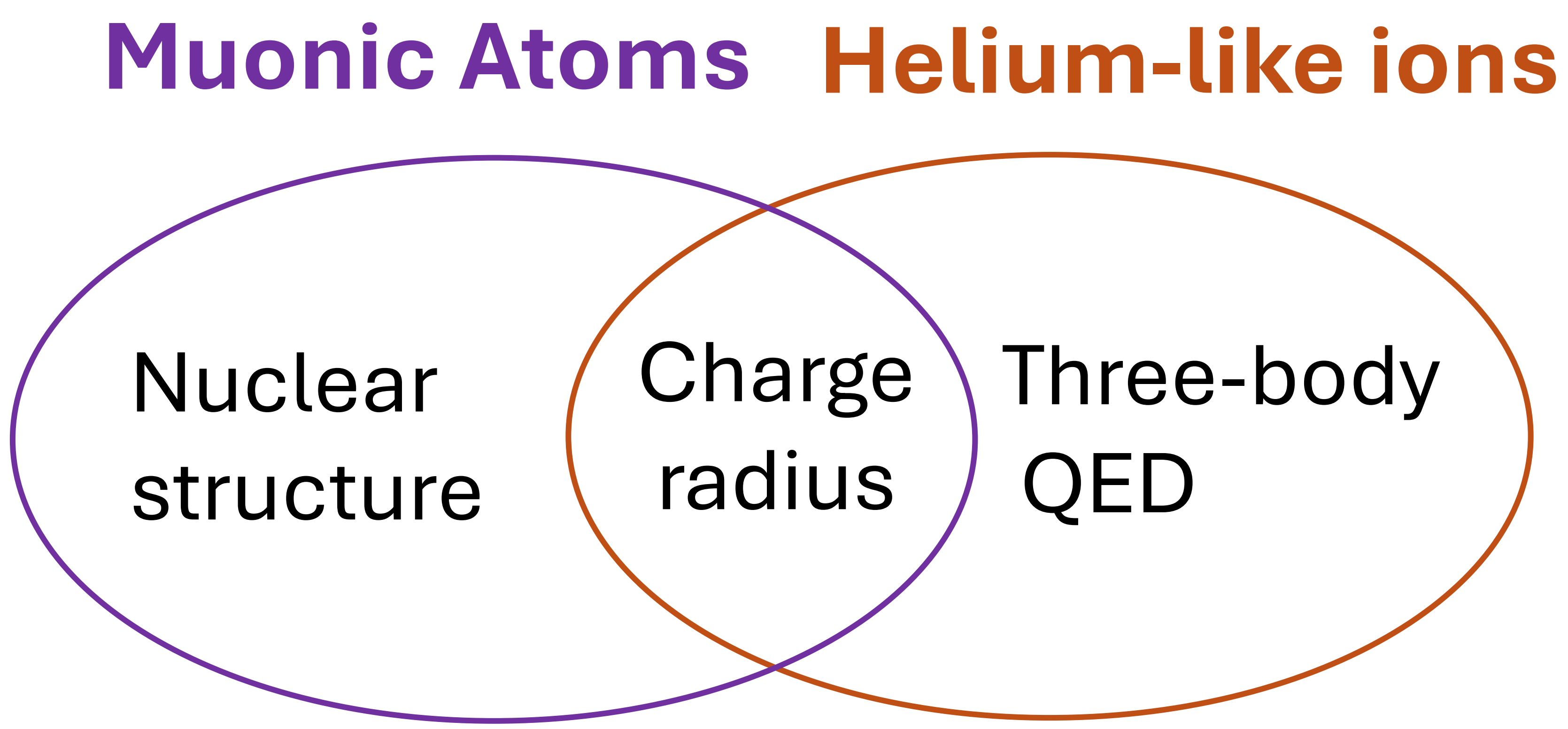

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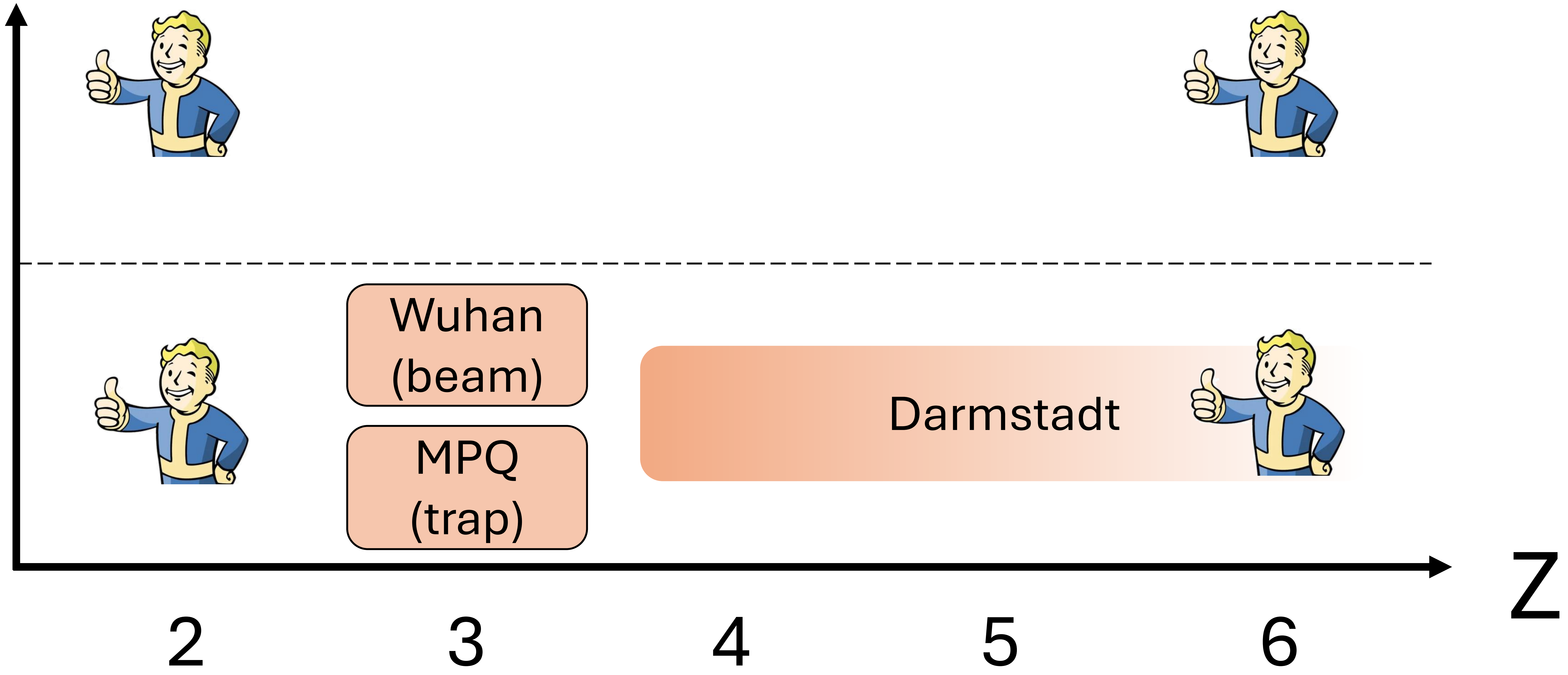

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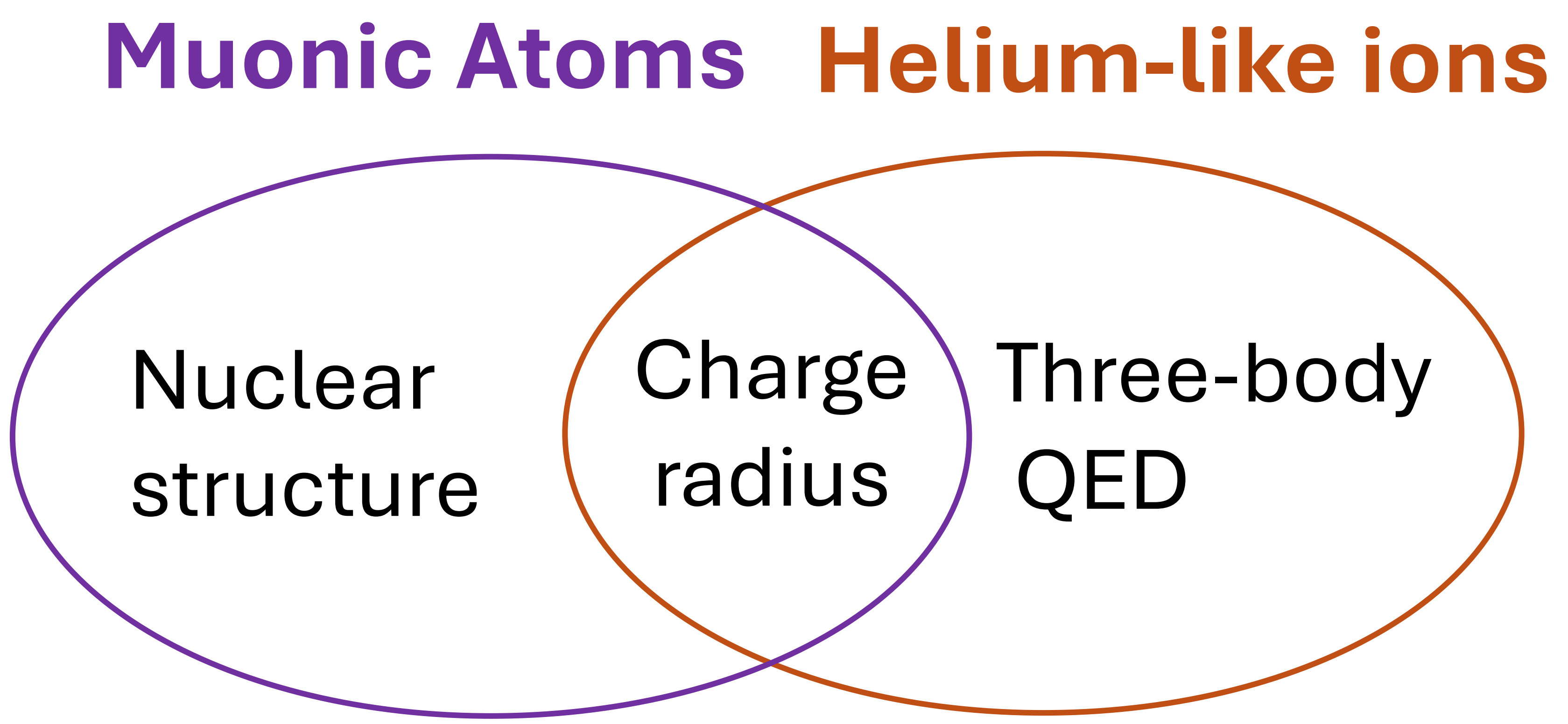
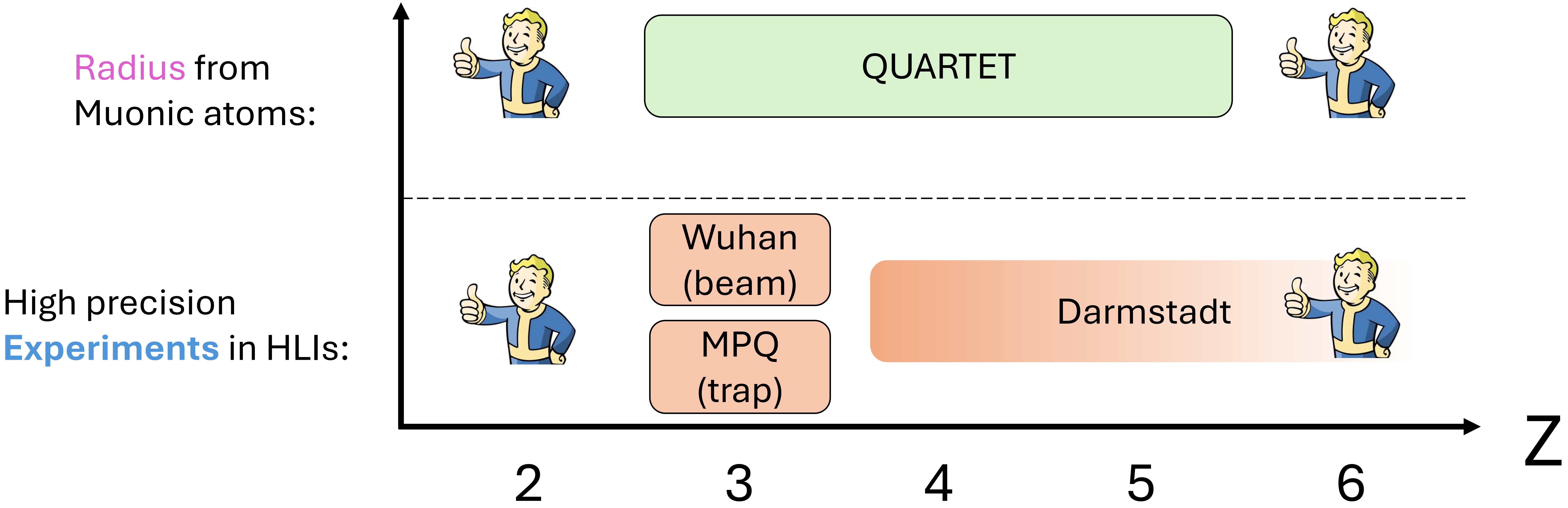
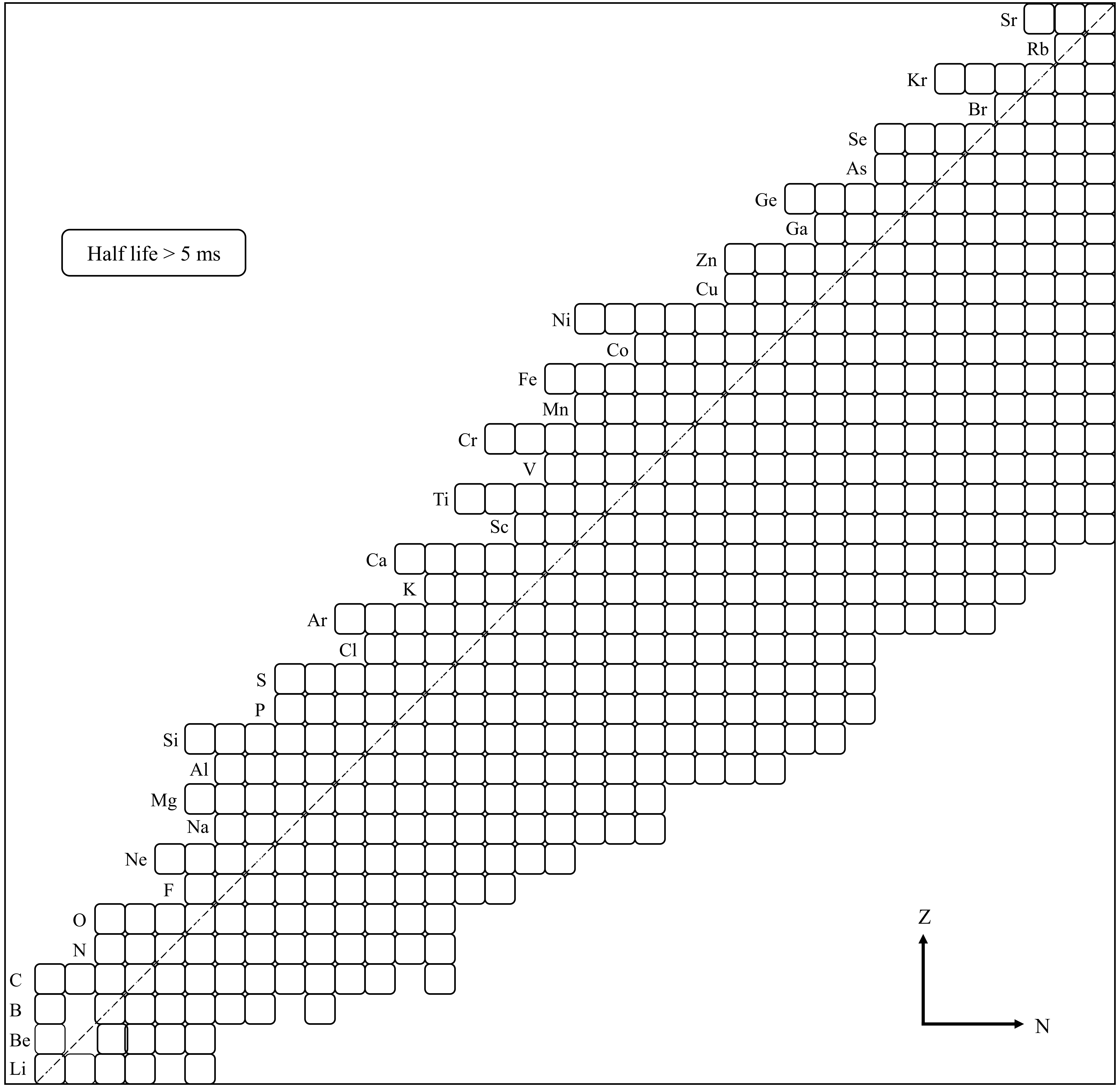




Where do charge radii come from?



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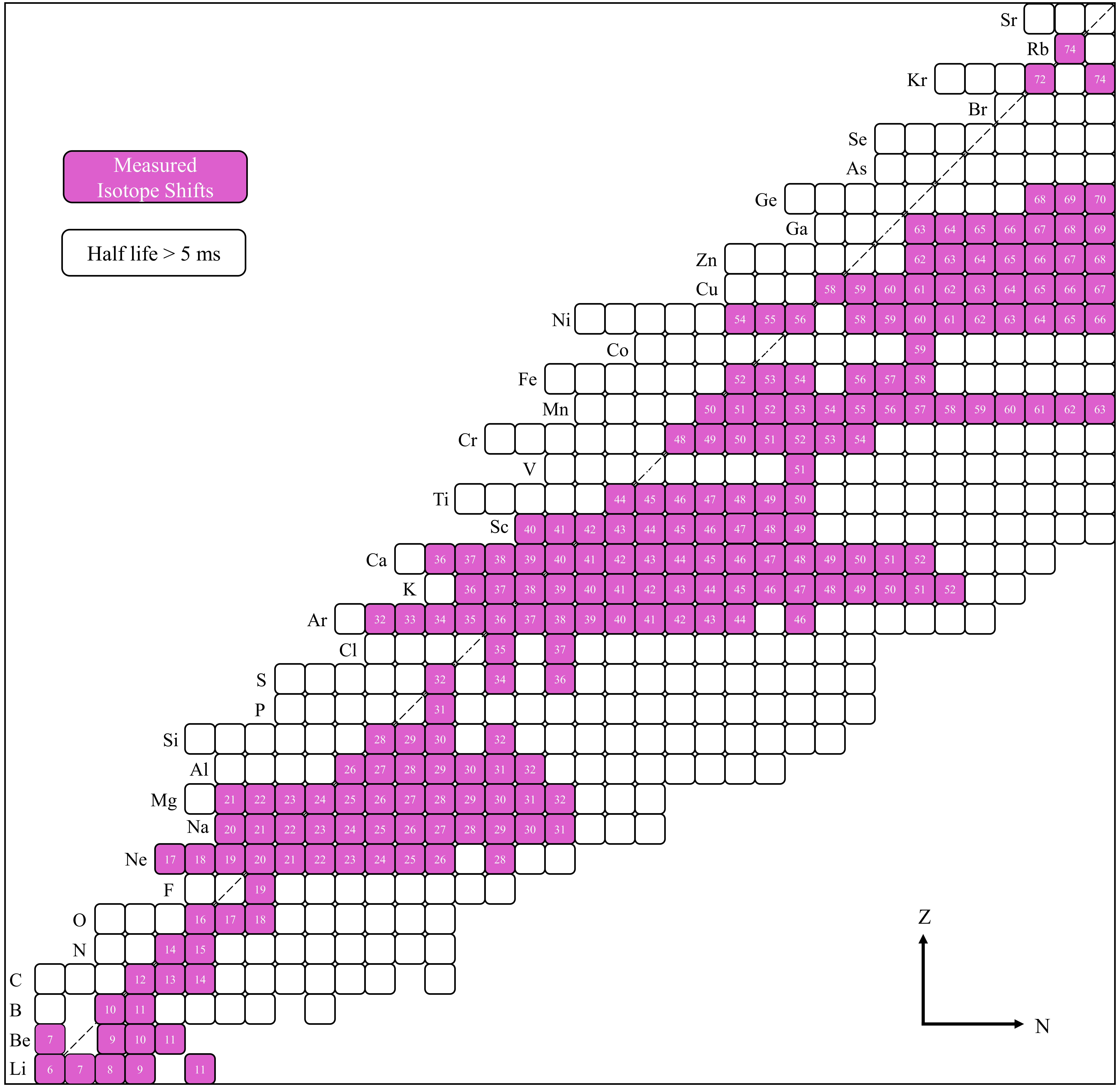
Where do charge radii come from?

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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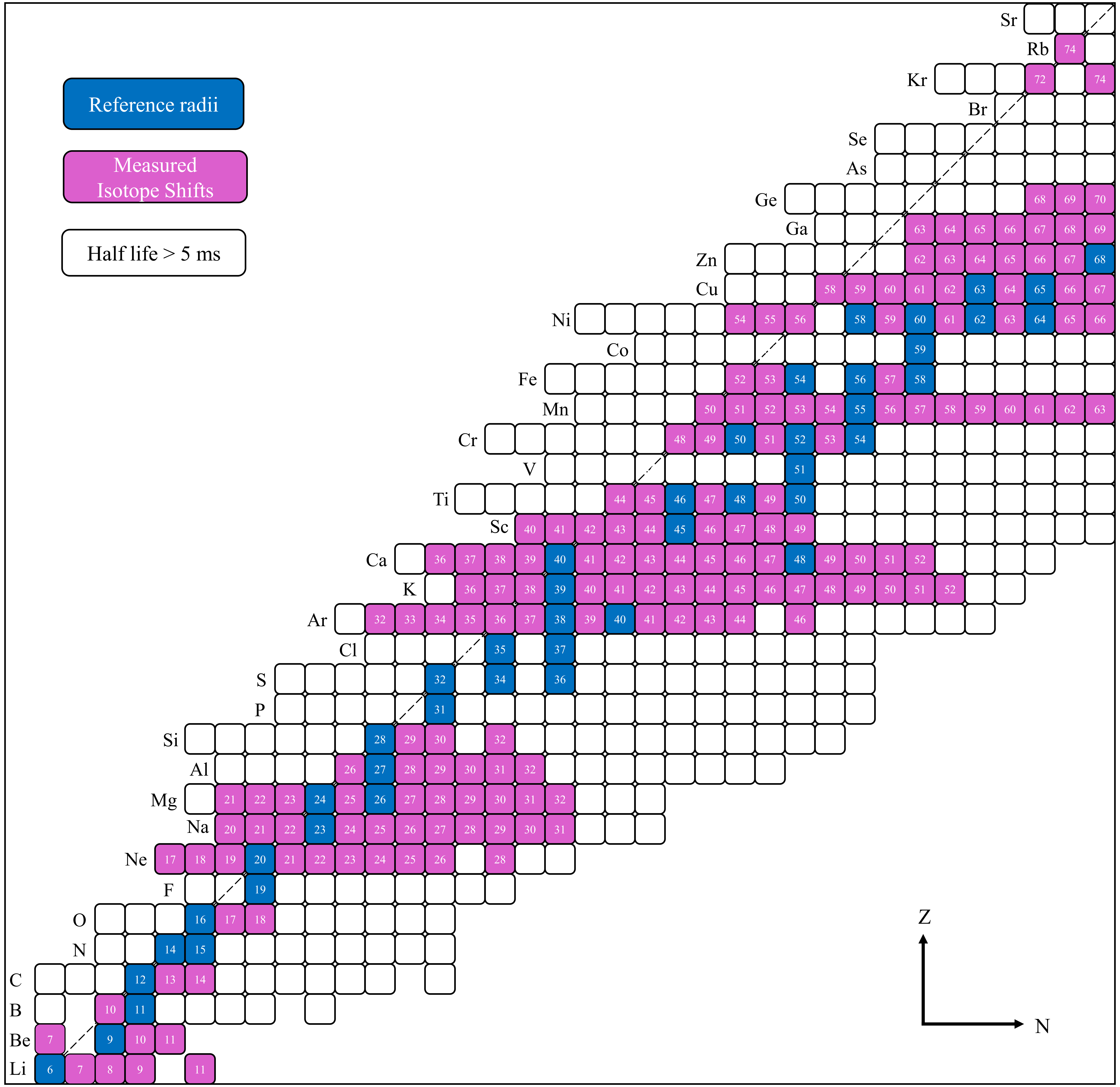
Reference radii connect MS differences with absolutes

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



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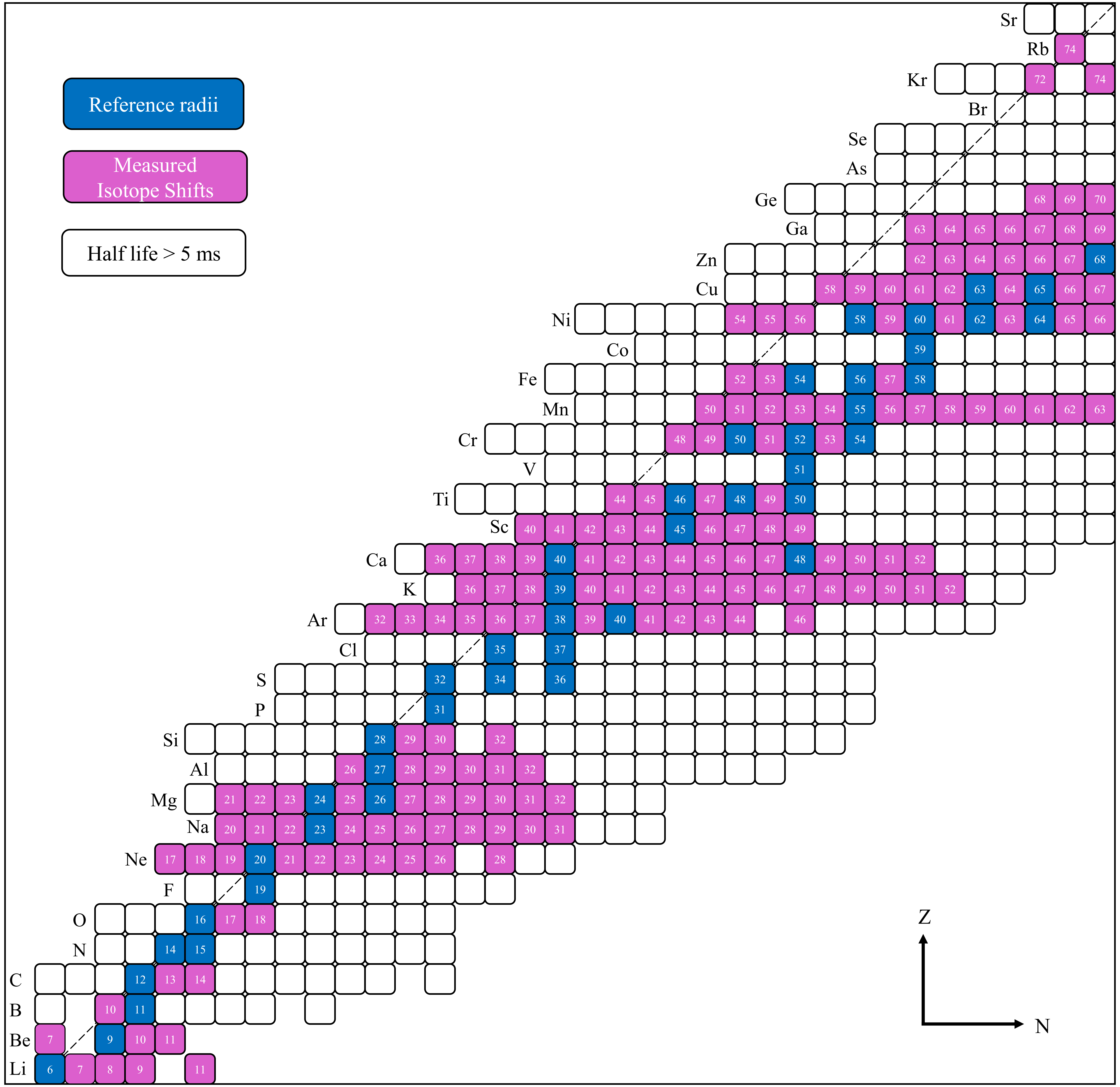
$$\delta\nu_{A,A'} \approx \left(\frac{1}{M_{A'}} - \frac{1}{M_A}\right)\boldsymbol{K} + \boldsymbol{F}\delta r^2_{A,A'}$$

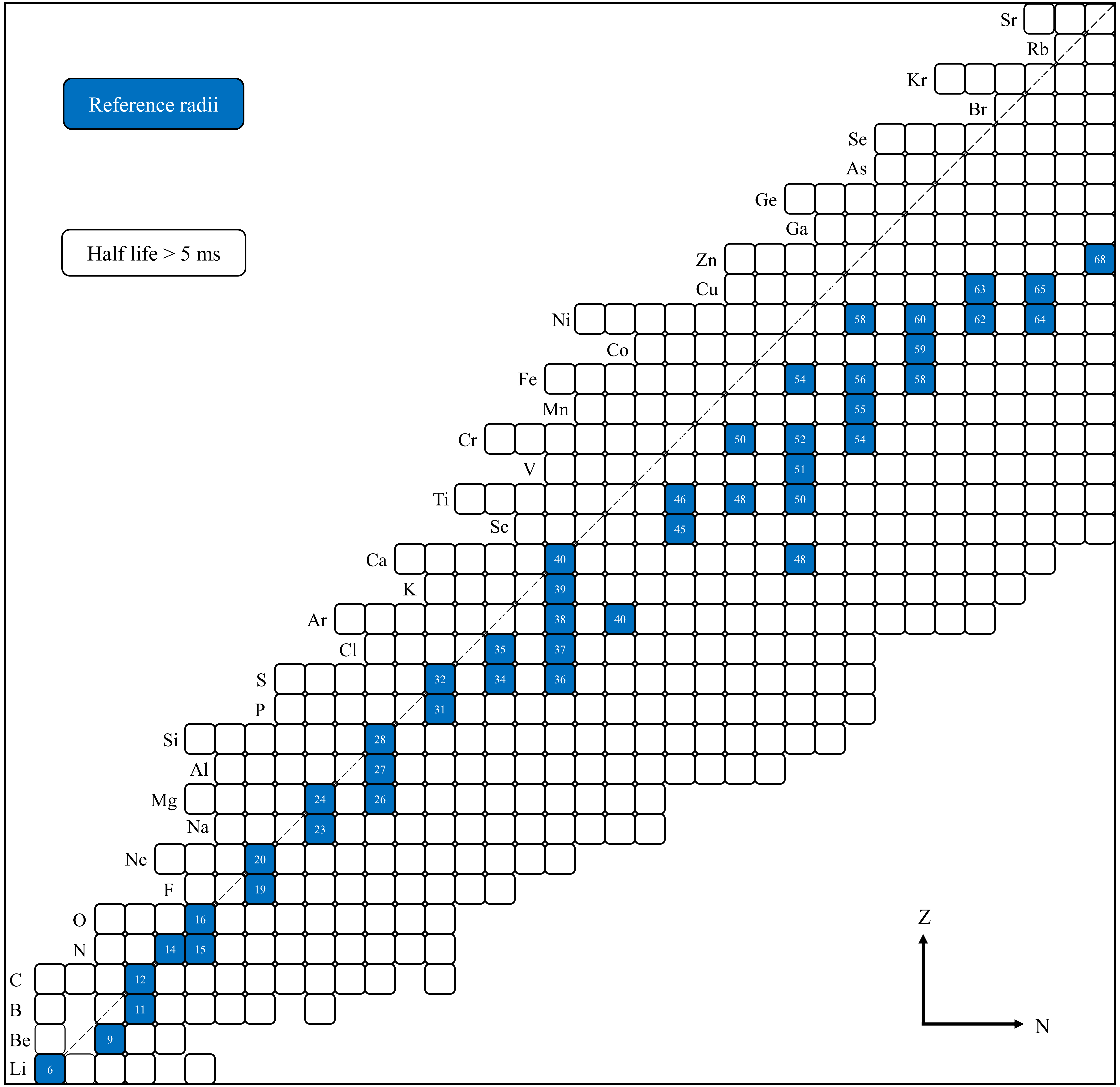
Atomic factors, either calculated or extracted from reference radii (King Plot).

Reference radii connect MS differences with absolutes

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



Reference radii and where to find them



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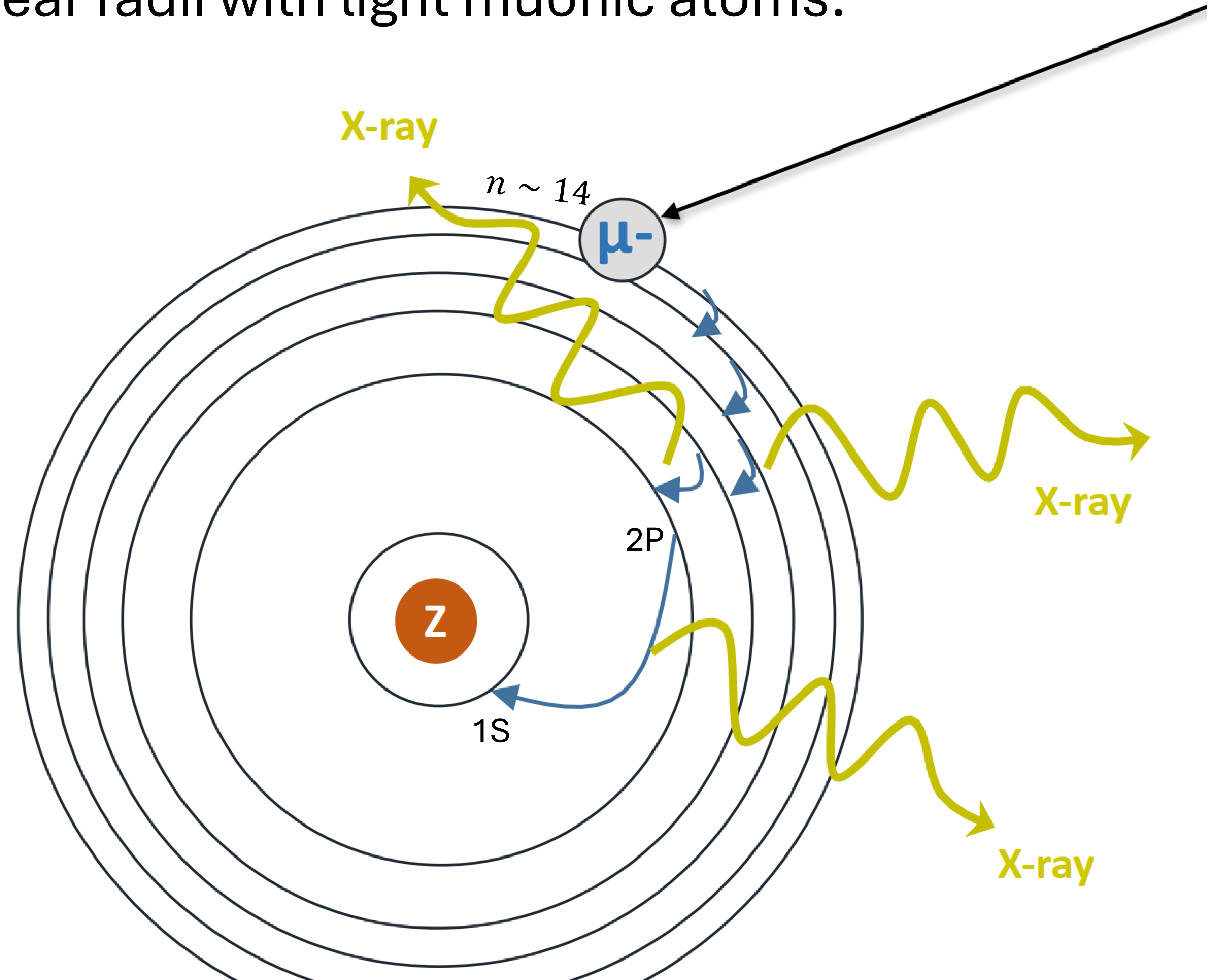
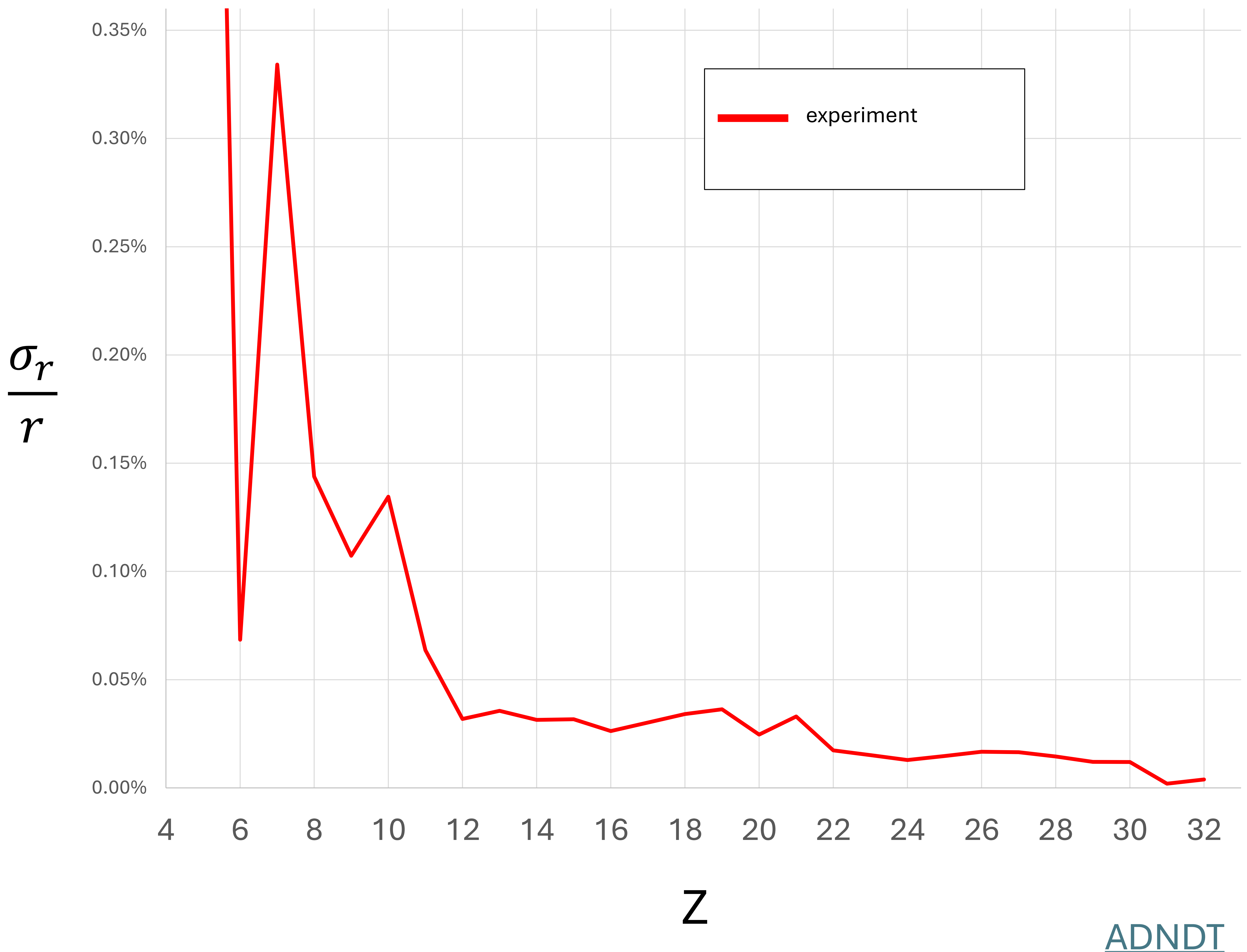
Measuring nuclear radii with light muonic atoms:

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:



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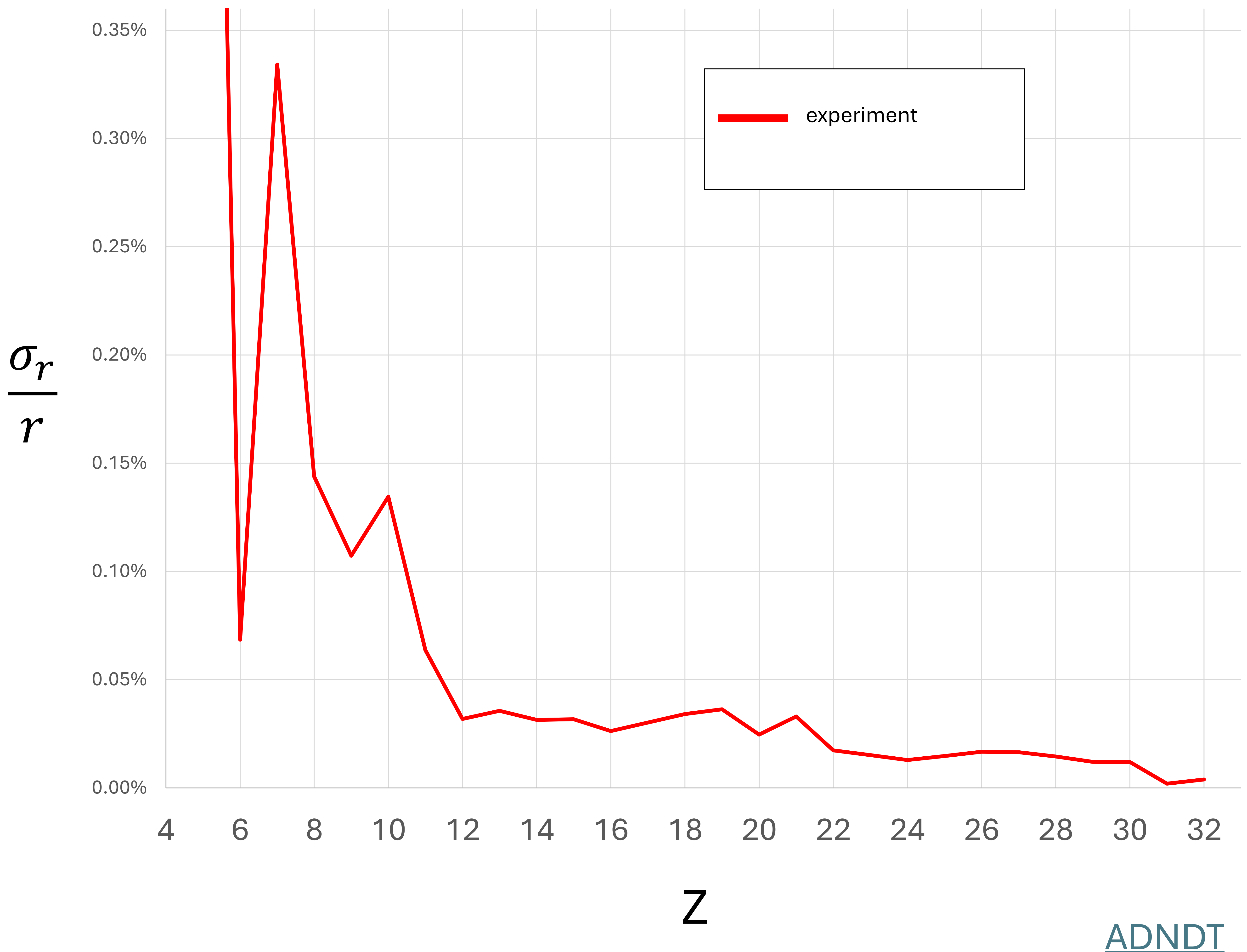
Sources of Uncertainty to Ref. Radii:

Note:
Some experimental uncertainty sources missing in F&H04 and A&M13.



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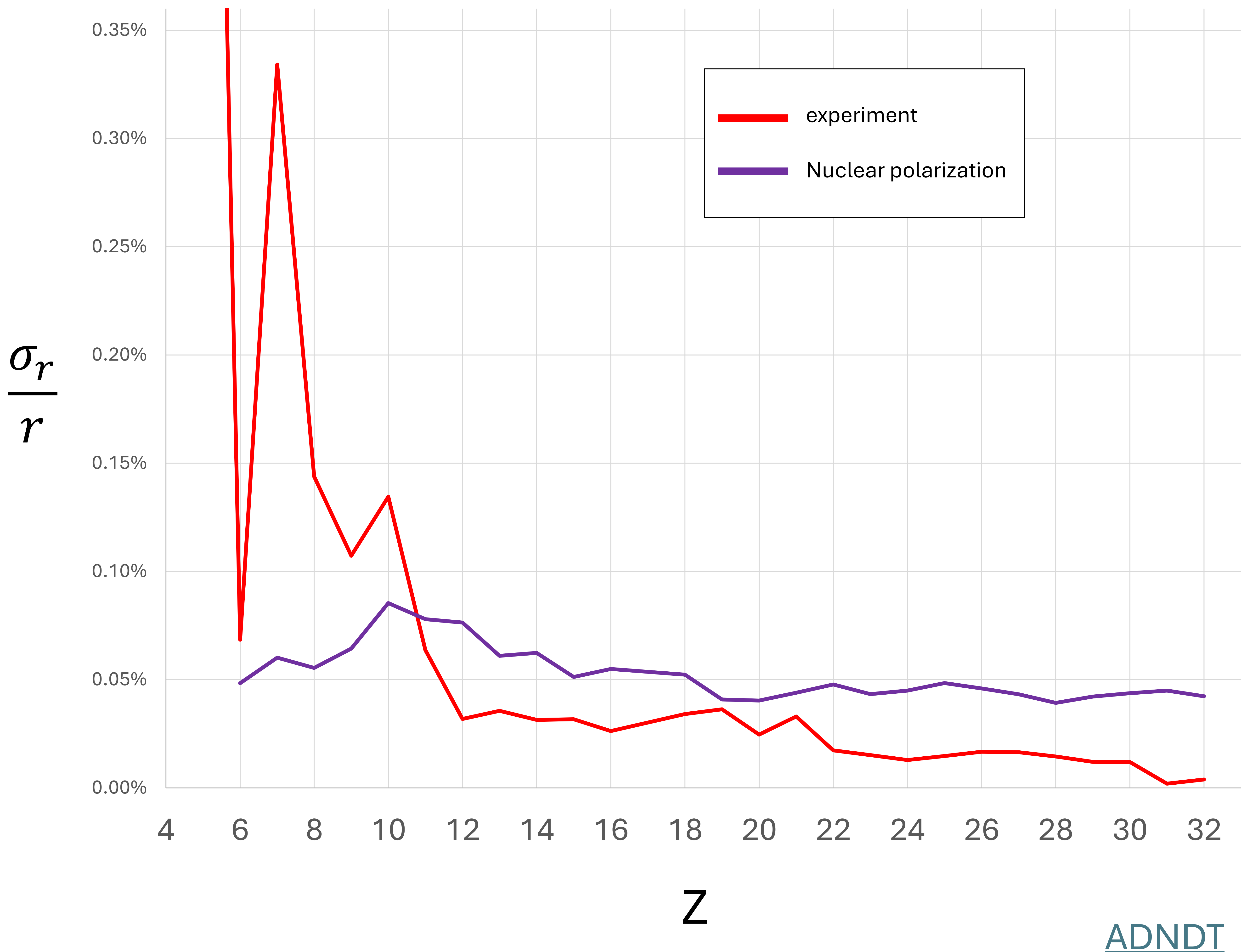

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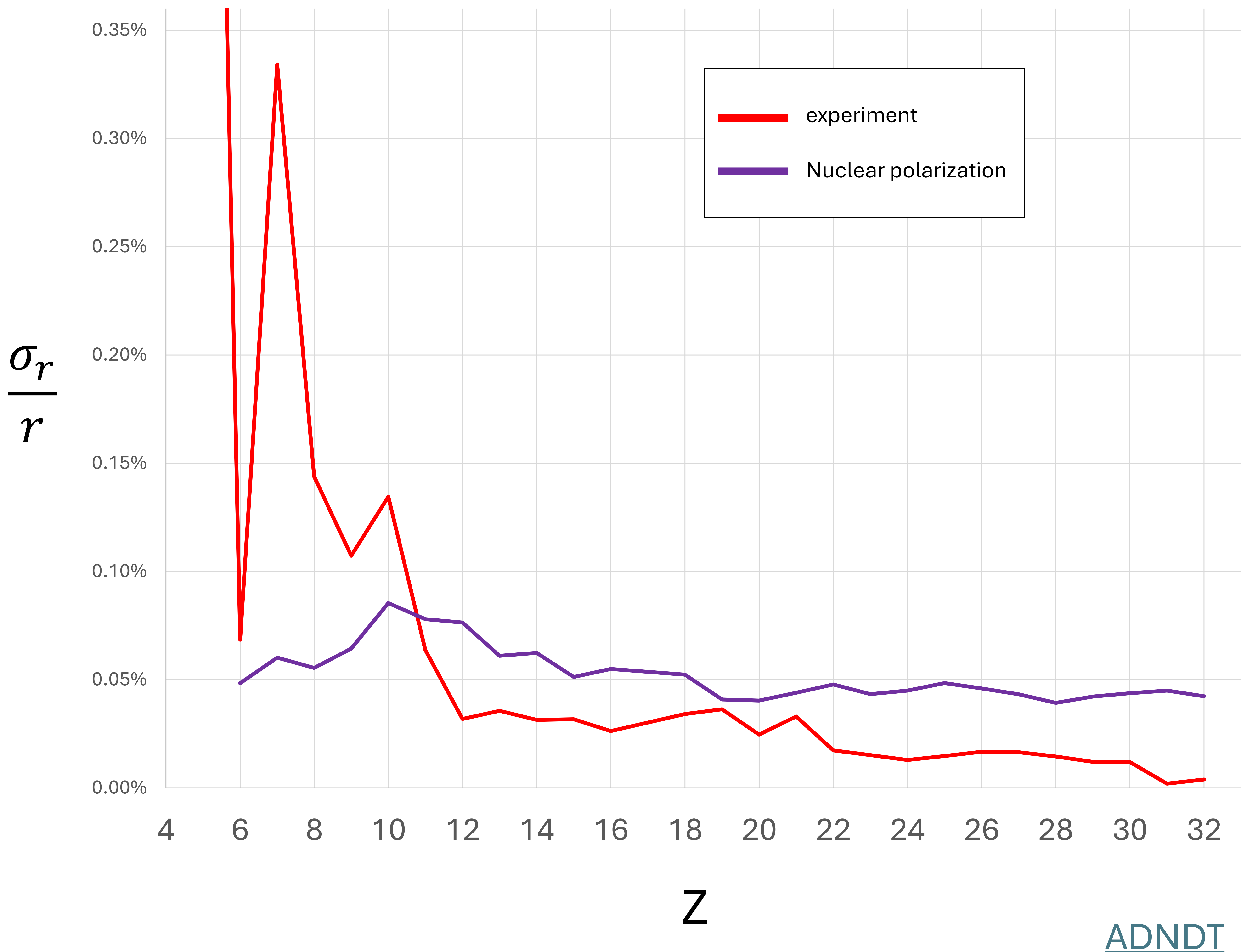
Sources of Uncertainty to Ref. Radii:

Note: “old school” data-driven Nuc. Pol.



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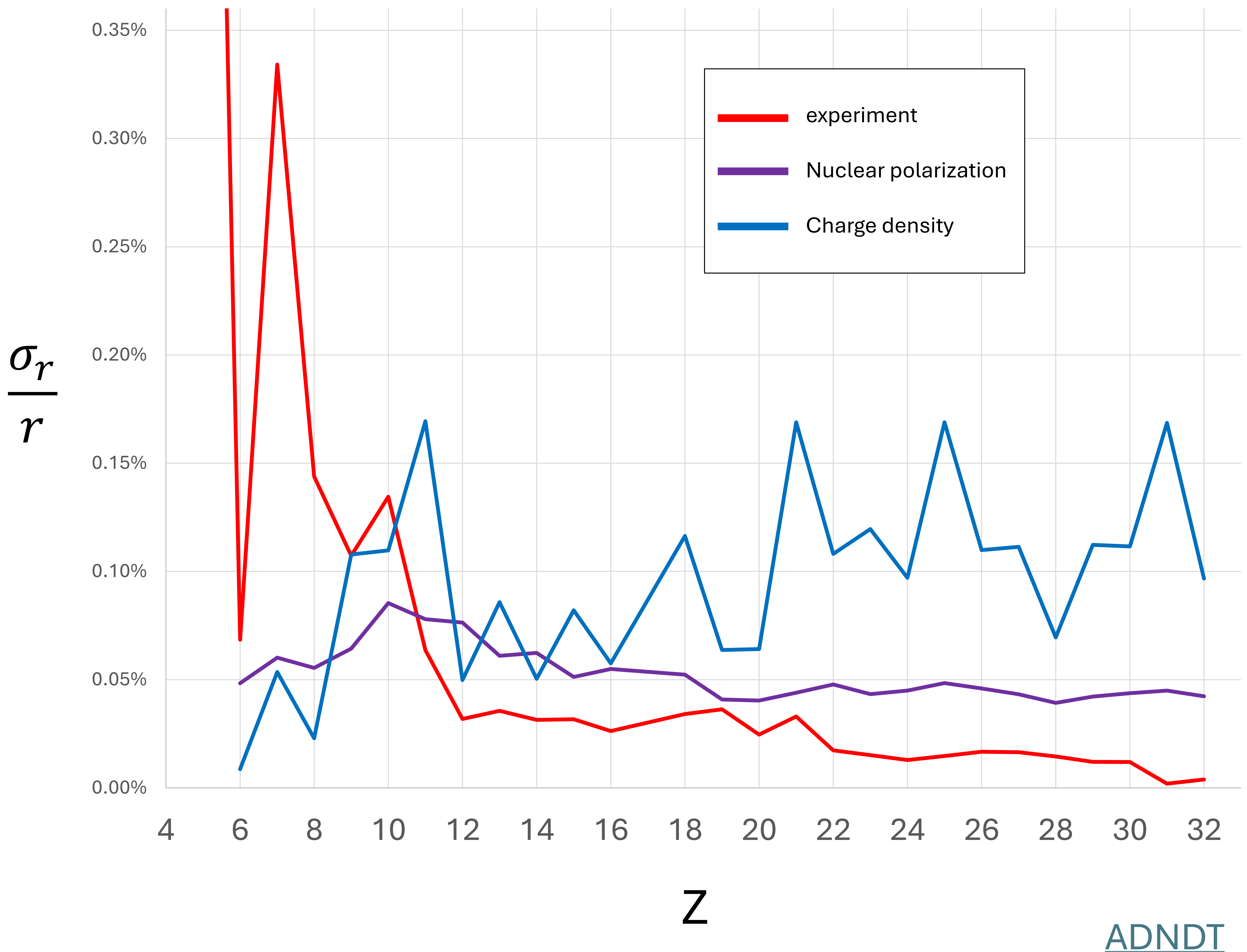

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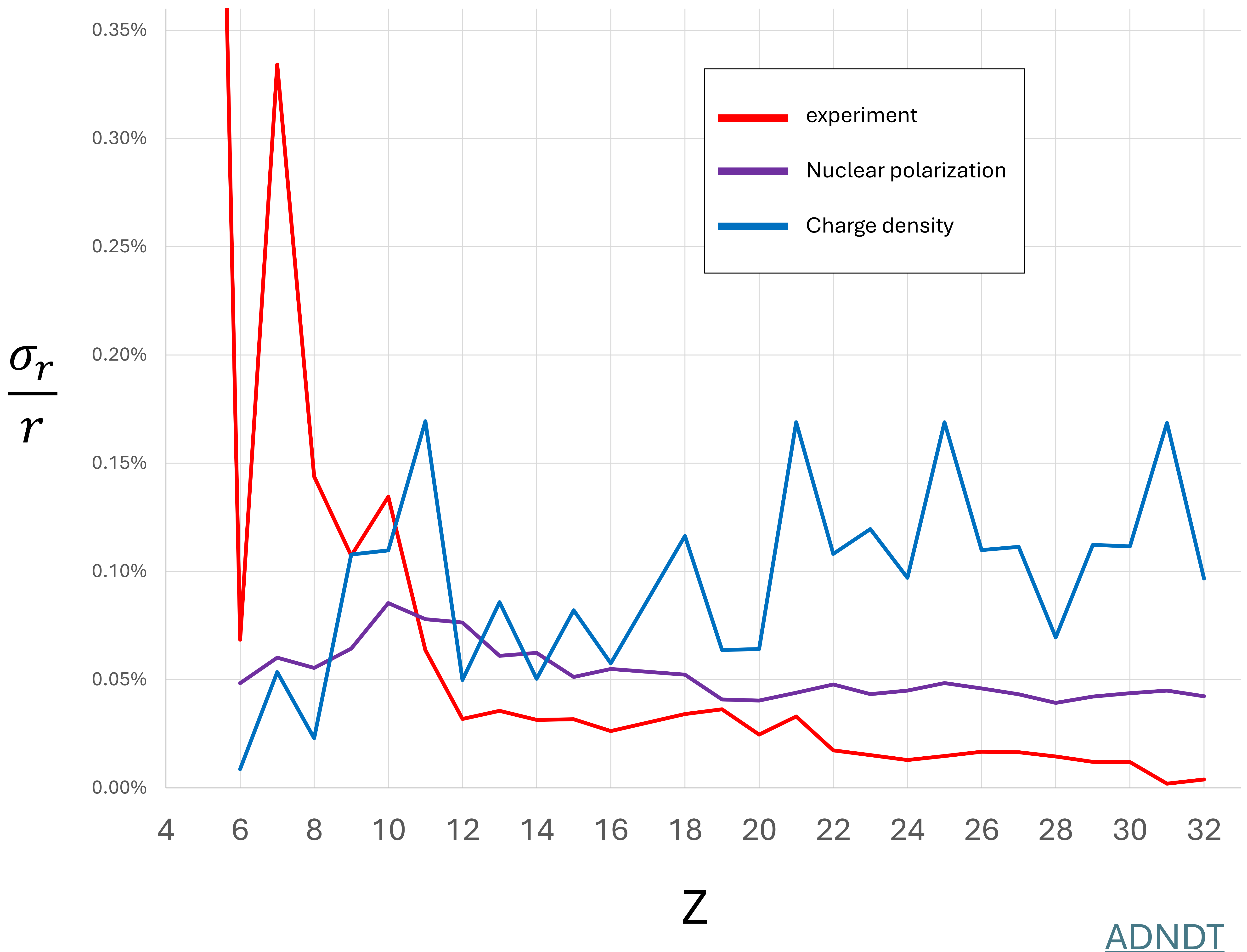
Sources of Uncertainty to Ref. Radii:

Within Barret moment recipe with moment ratios from scattering.

Can be improved with modern tools



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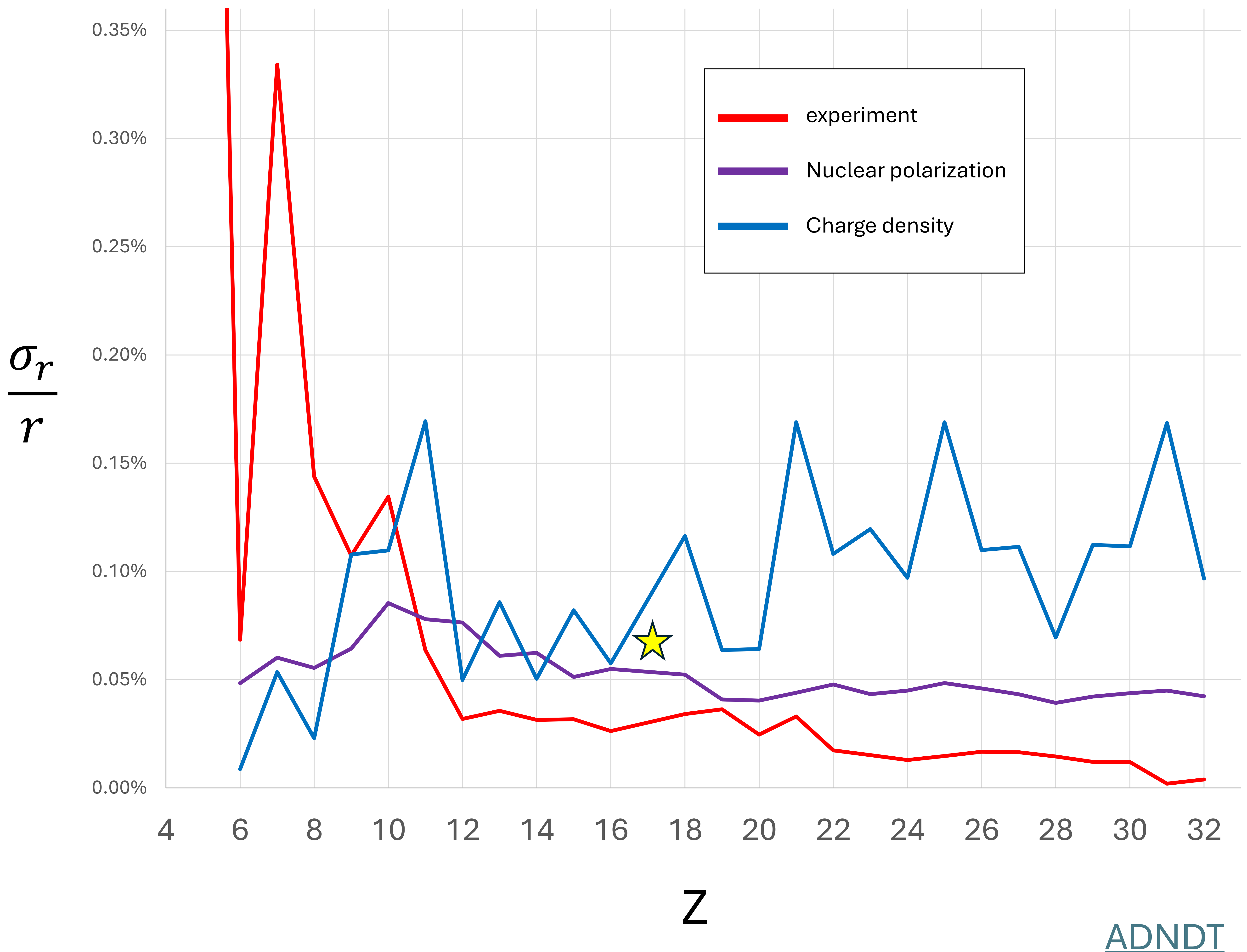
Sources of Uncertainty to Ref. Radii:

Modern Chlorine measurement + Theory arXiv:2506.08804



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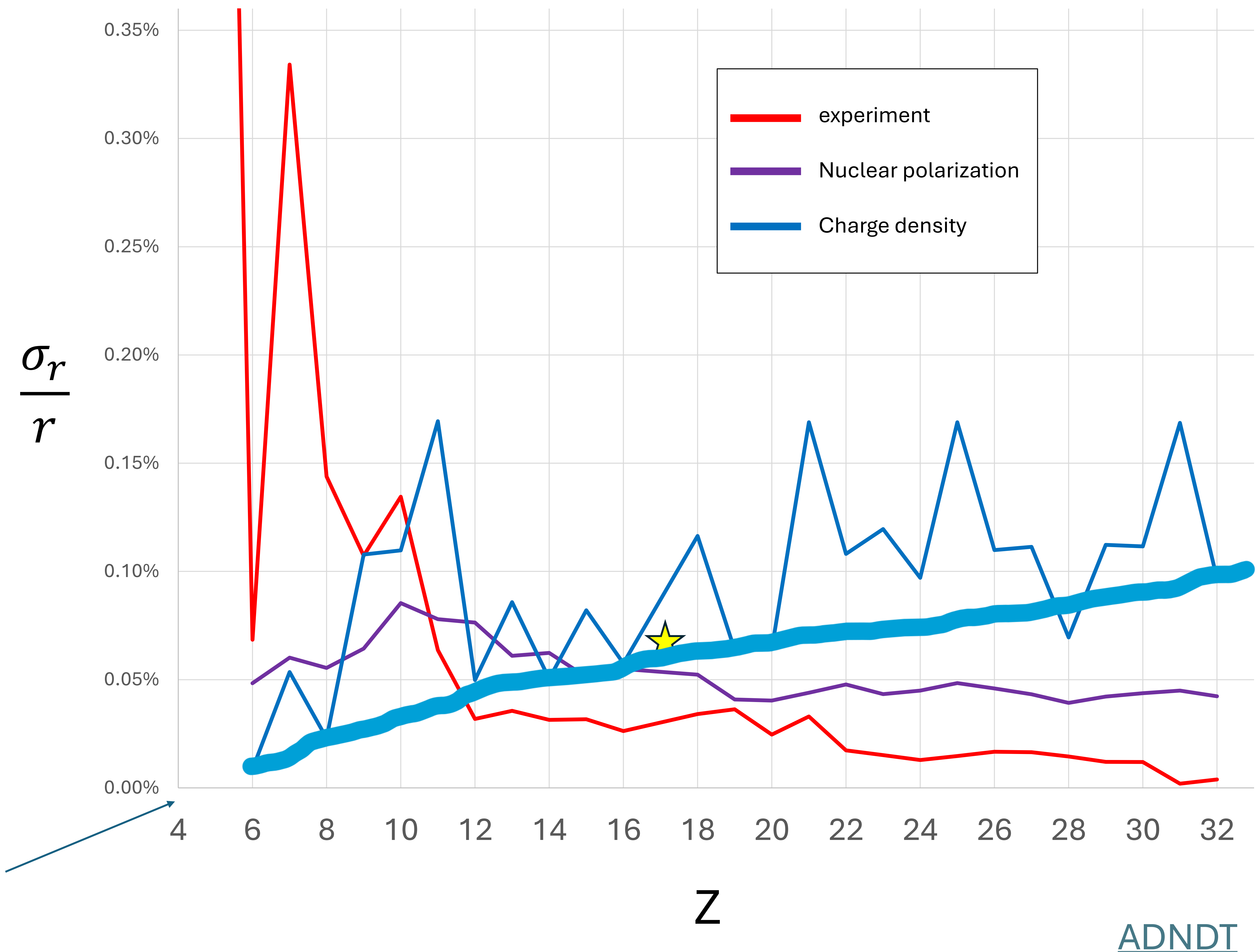

Guess on best you can do with modern calculations

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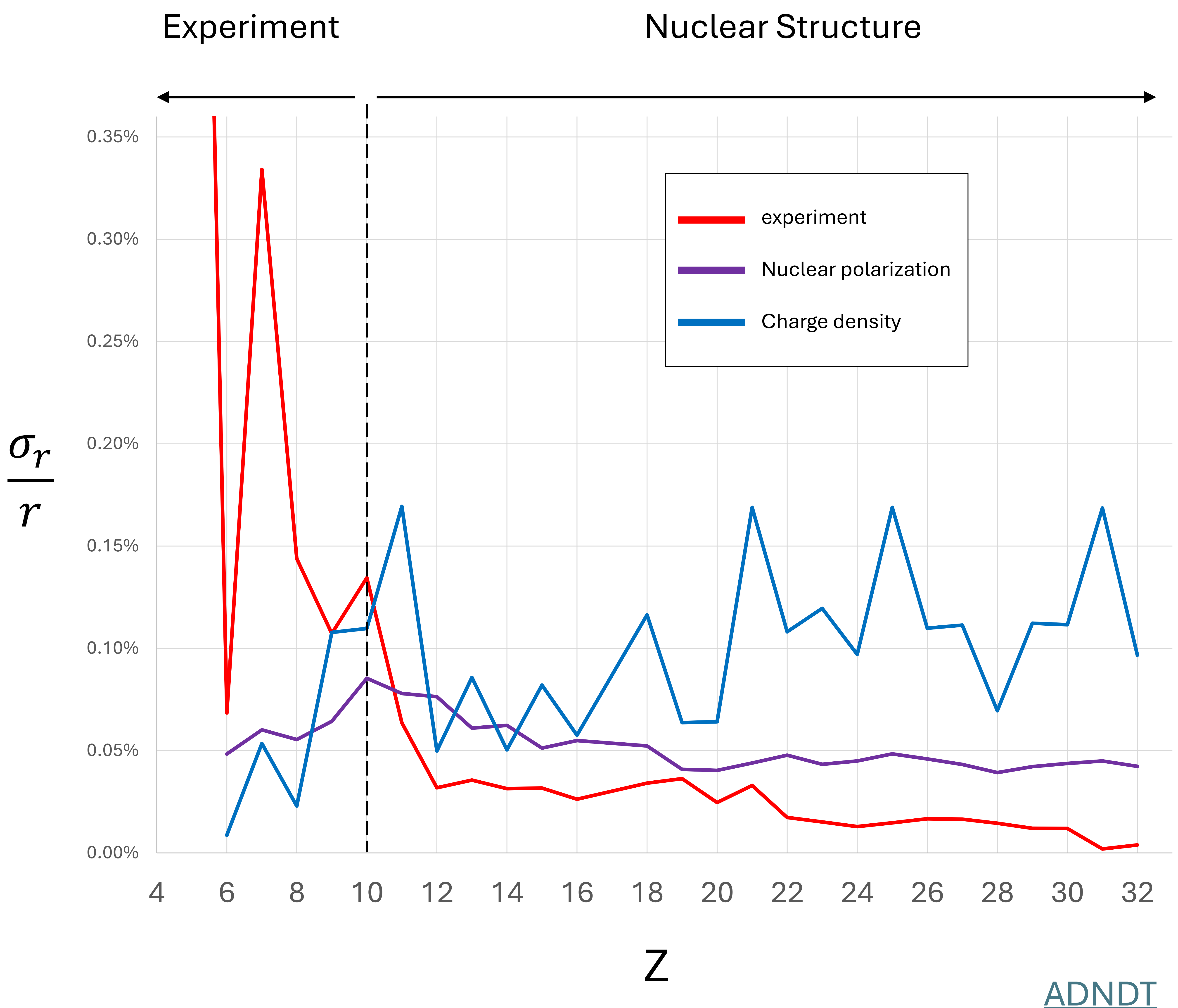
Sources of Uncertainty to Ref. Radii:



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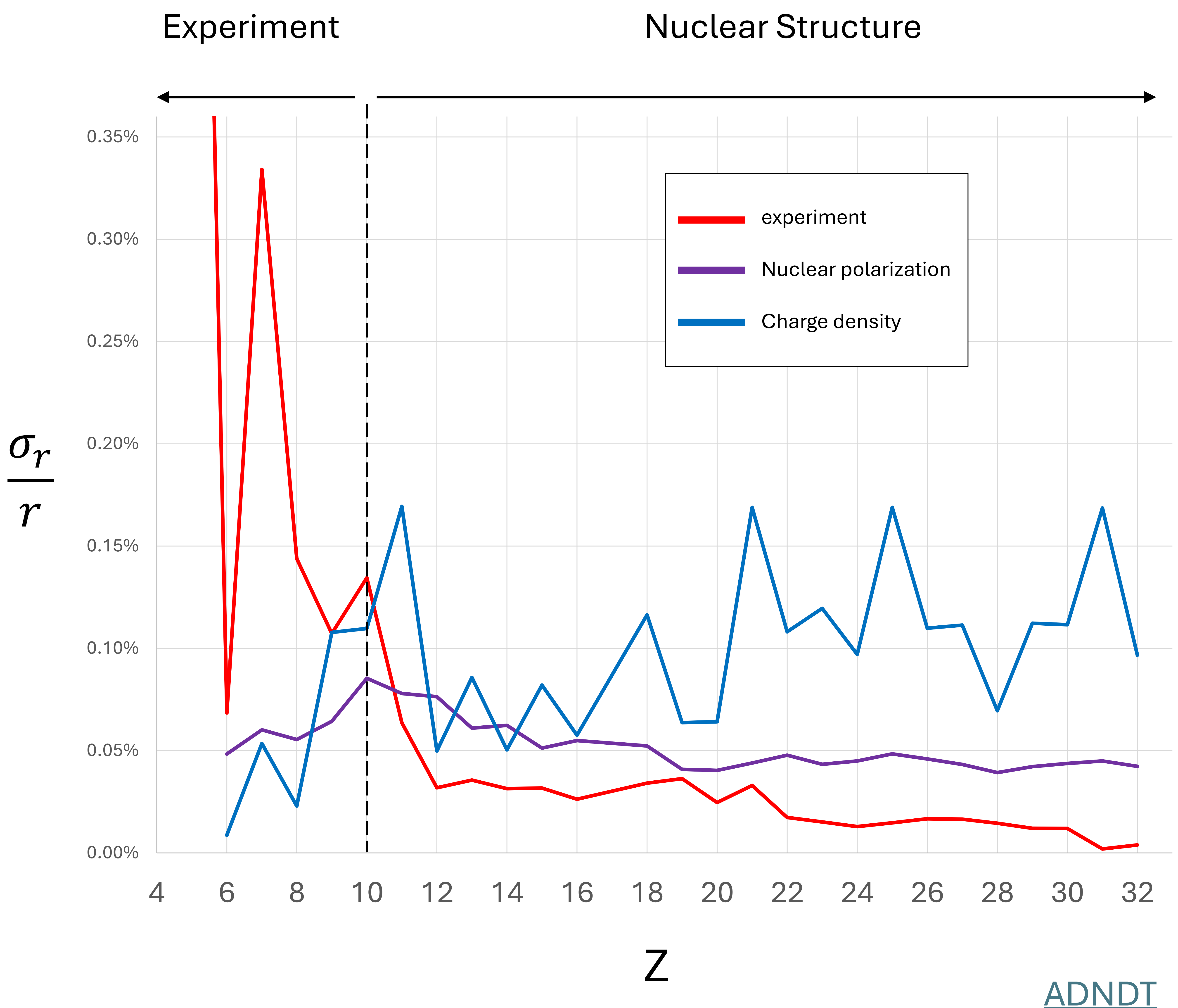
Sources of Uncertainty to Ref. Radii:

Not the final word !

Open the door to ongoing efforts



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Nuclear structure effects and how to handle them

Ab initio perturbative
Calculations:
elastic ≈ shape
Inelastic ≈ Nuc. Pol.

$(Z\alpha)^5$	TPE
$\alpha^2(Z\alpha)^4$	Coulomb distortion
$(Z\alpha)^6$	3PE
$\alpha(Z\alpha)^5$	$\mathrm{eVP}^{(1)}$ with TPE
$\alpha(Z\alpha)^5$	$\mu\mathrm{SE}^{(1)} + \mu\mathrm{VP}^{(1)}$ with TPE

RevModPhys.96.015001

Z = 1, 2

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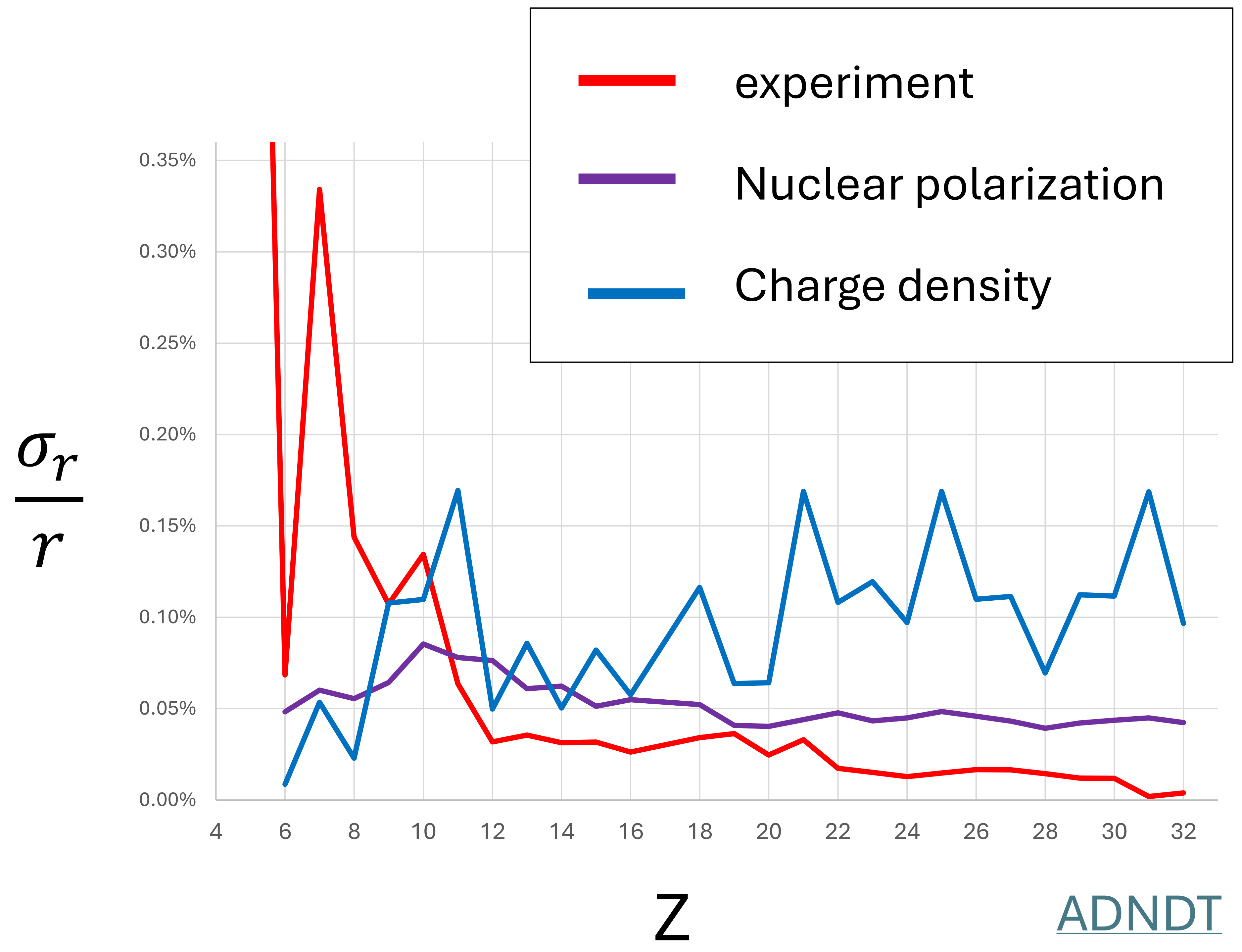
RevModPhys.96.015001

Z = 1, 2

Elastic from electron scattering

Nuclear Pol. from calculation / data driven



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RevModPhys.96.015001

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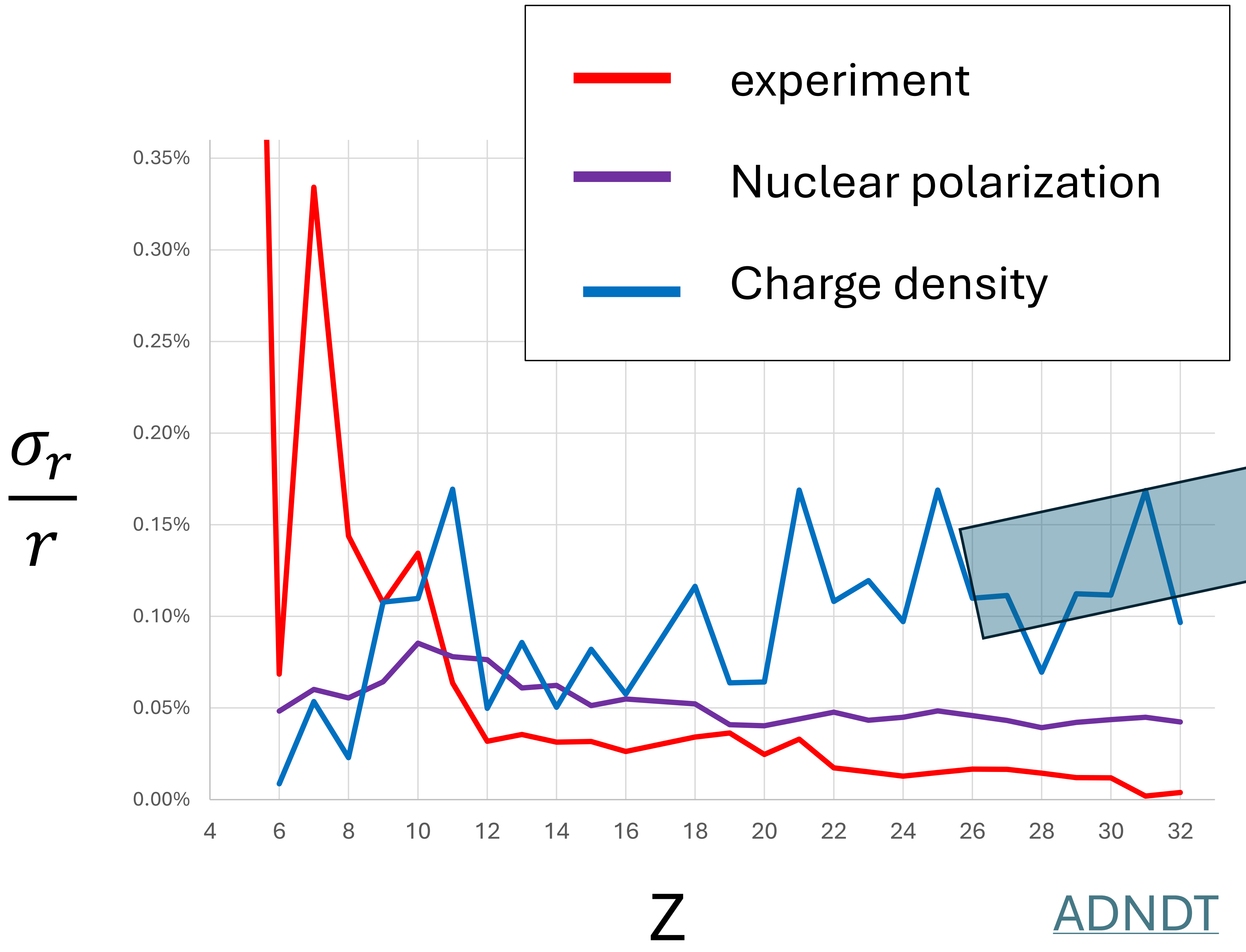

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Expected to get worse at higher Z !

Nuclear structure effects and how to handle them

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Inelastic ≈ Nuc. Pol.

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RevModPhys.96.015001

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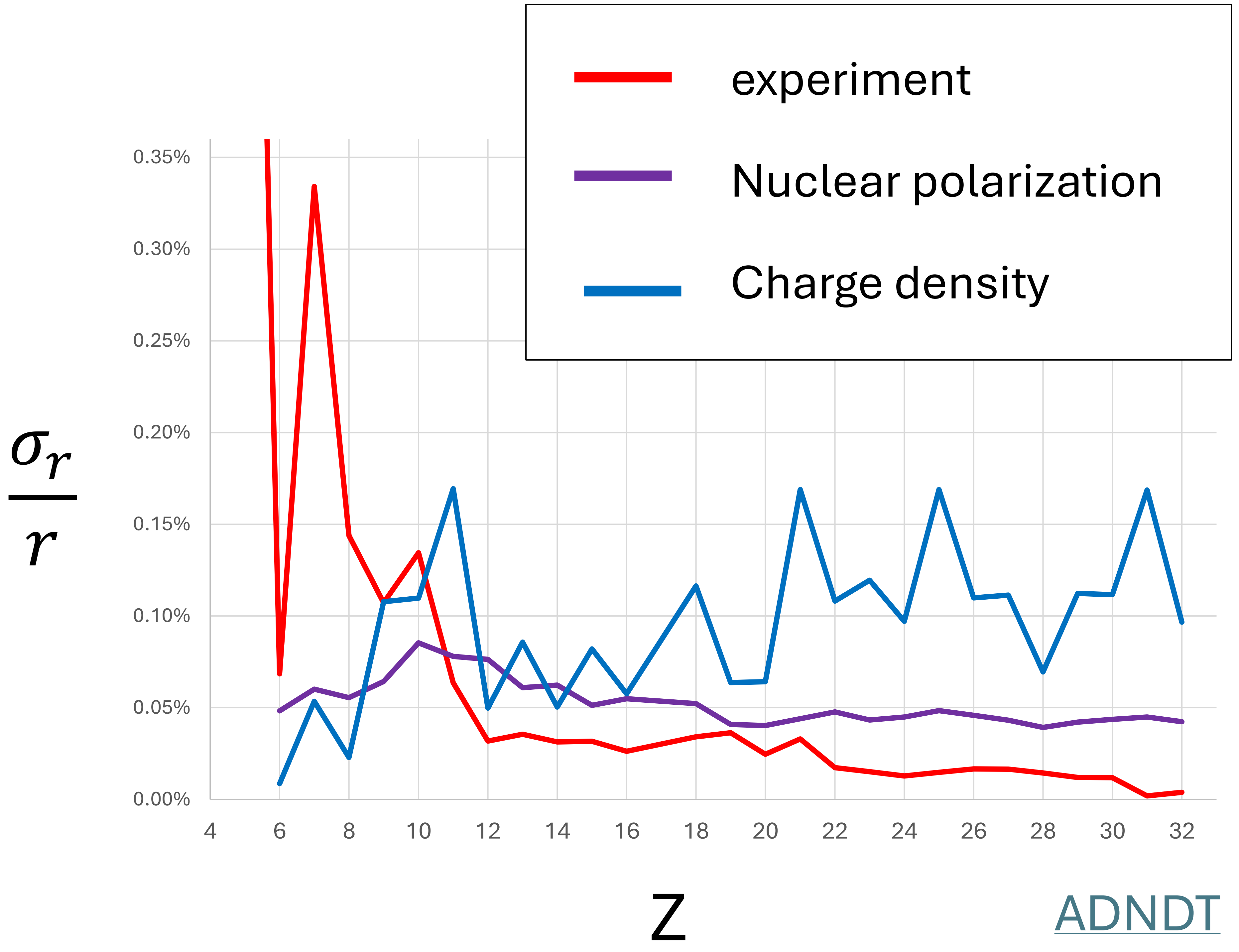
Elastic from electron scattering

Nuclear Pol. from calculation / data driven



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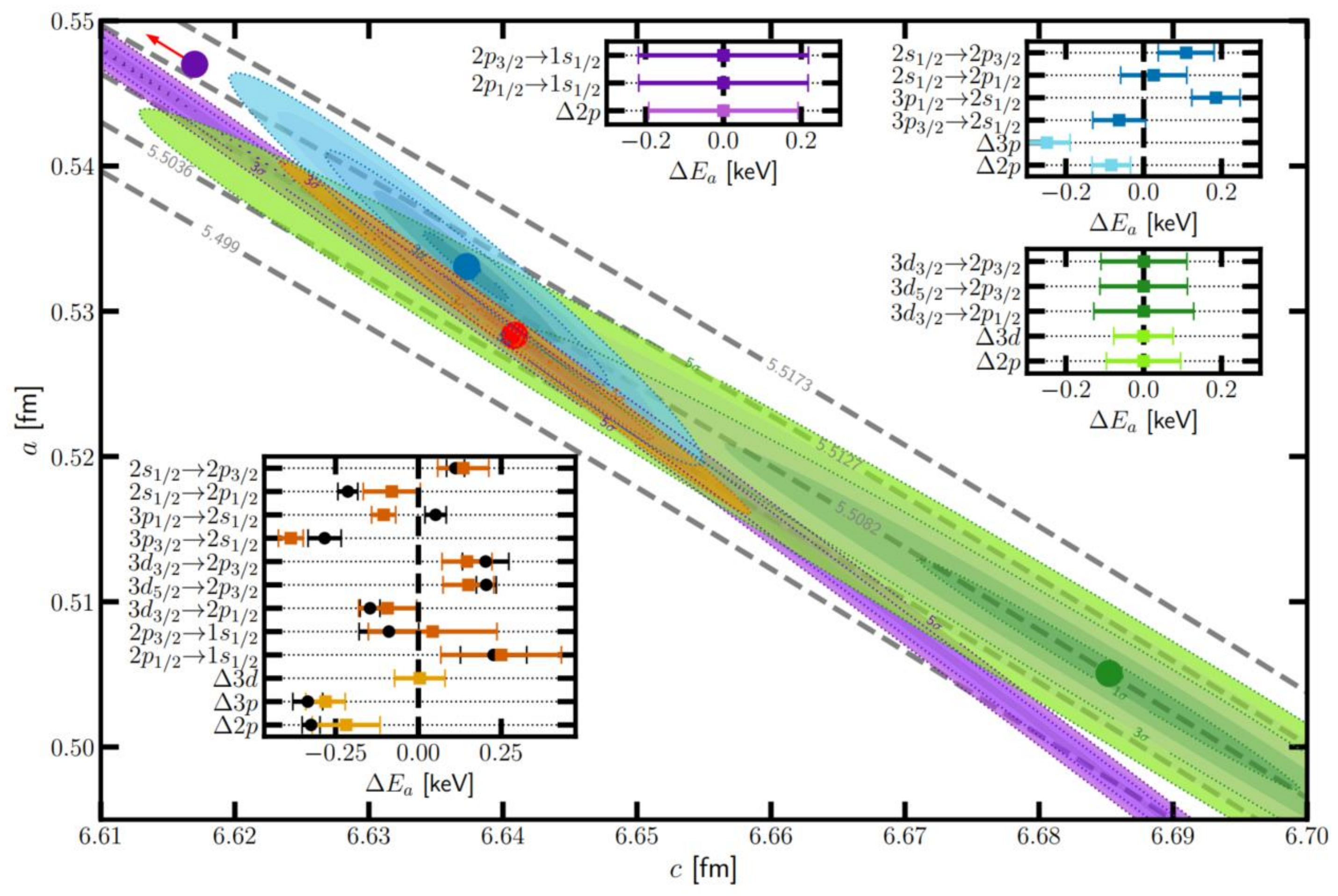
Elastic from fit with several transitions
Npol from calculation



Z = 82

arXiv:2504.19977

Nuclear structure effects and how to handle them

Ab initio perturbative
Calculations:
elastic ≈ shape
Inelastic ≈ Nuc. Pol.

$(Z\alpha)^5$	TPE
$\alpha^2(Z\alpha)^4$	Coulomb disto
$(Z\alpha)^6$	3PE
$\alpha(Z\alpha)^5$	eVP$^{(1)}$ with T
$\alpha(Z\alpha)^5$	μSE$^{(1)}$ + μVP

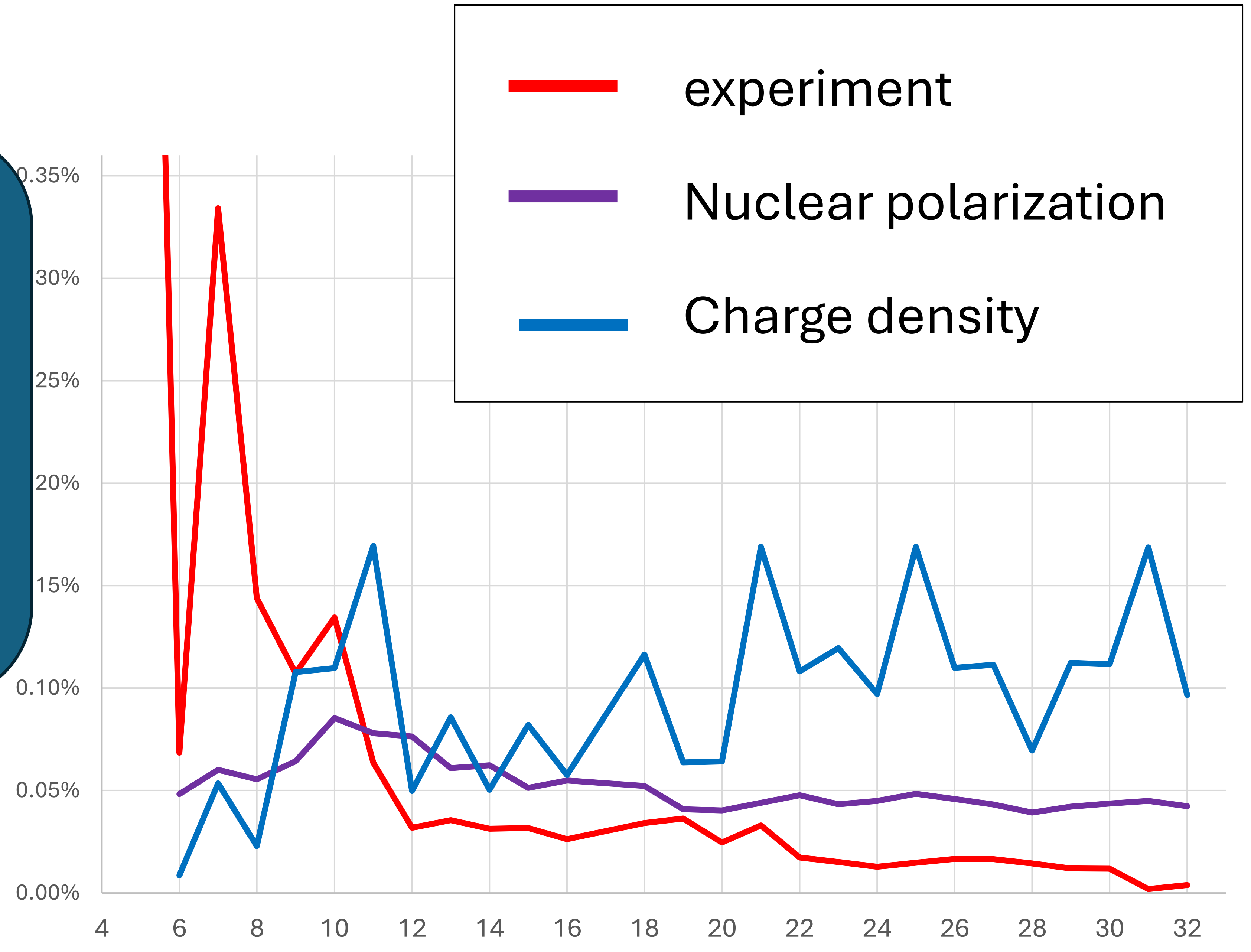
Where can we push TPE calculations?

RevModPhys.96.015001

Z = 1, 2

Elastic from electron scattering

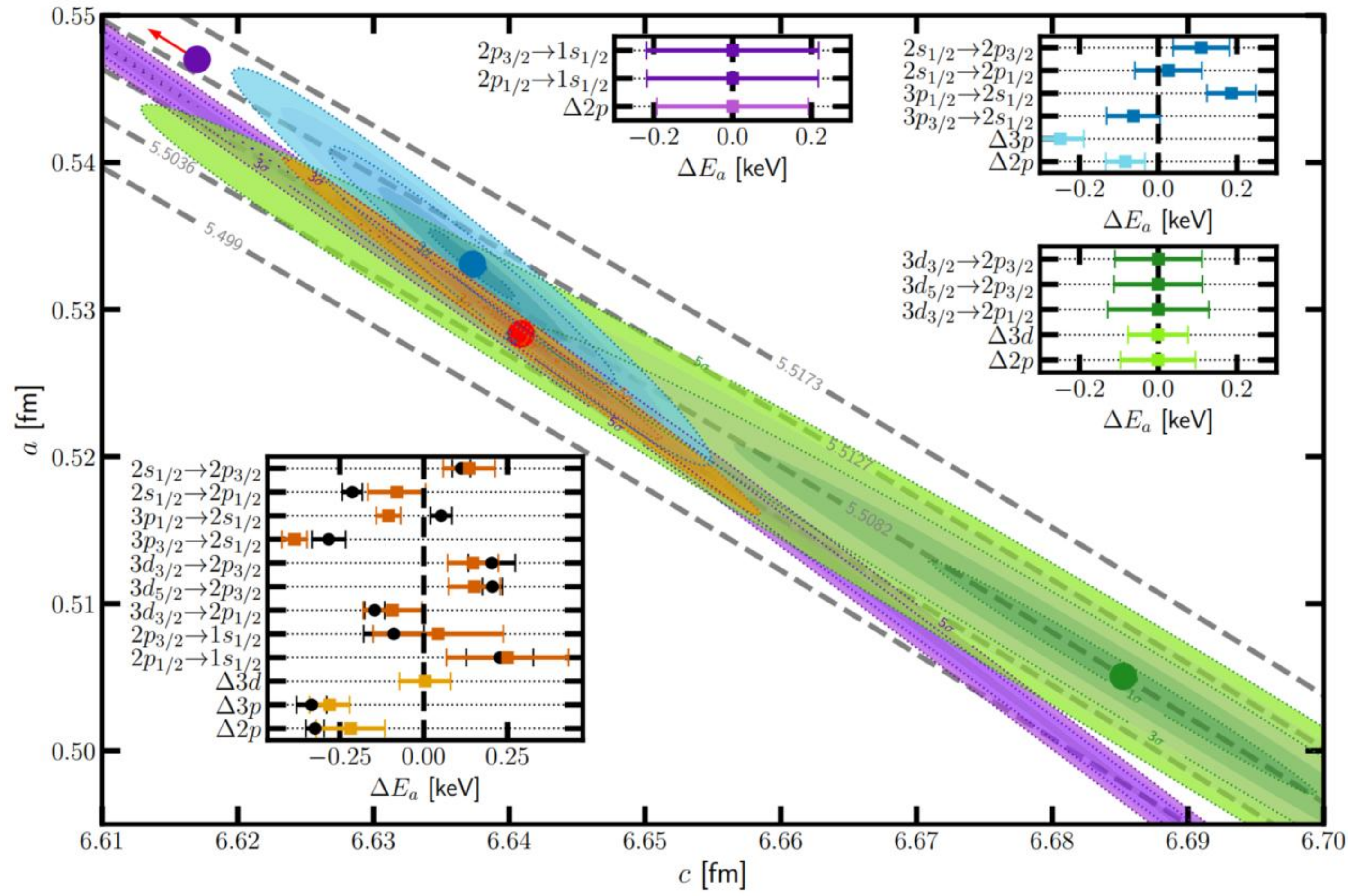
Nuclear Pol. from calculation / data driven



Z

ADNDT

Elastic from fit with several transitions
Npol from calculation



Z = 82

arXiv:2504.19977

Nuclear structure effects and how to handle them

Ab initio perturbative Calculations:
elastic ≈ shape
Inelastic ≈ Nuc. Pol.

$(Z\alpha)^5$	TPE
$\alpha^2(Z\alpha)^4$	Coulomb disto
$(Z\alpha)^6$	3PE
$\alpha(Z\alpha)^5$	$\mathrm{eVP}^{(1)}$ with T
$\alpha(Z\alpha)^5$	$\mu\mathrm{SE}^{(1)} + \mu\mathrm{VP}$

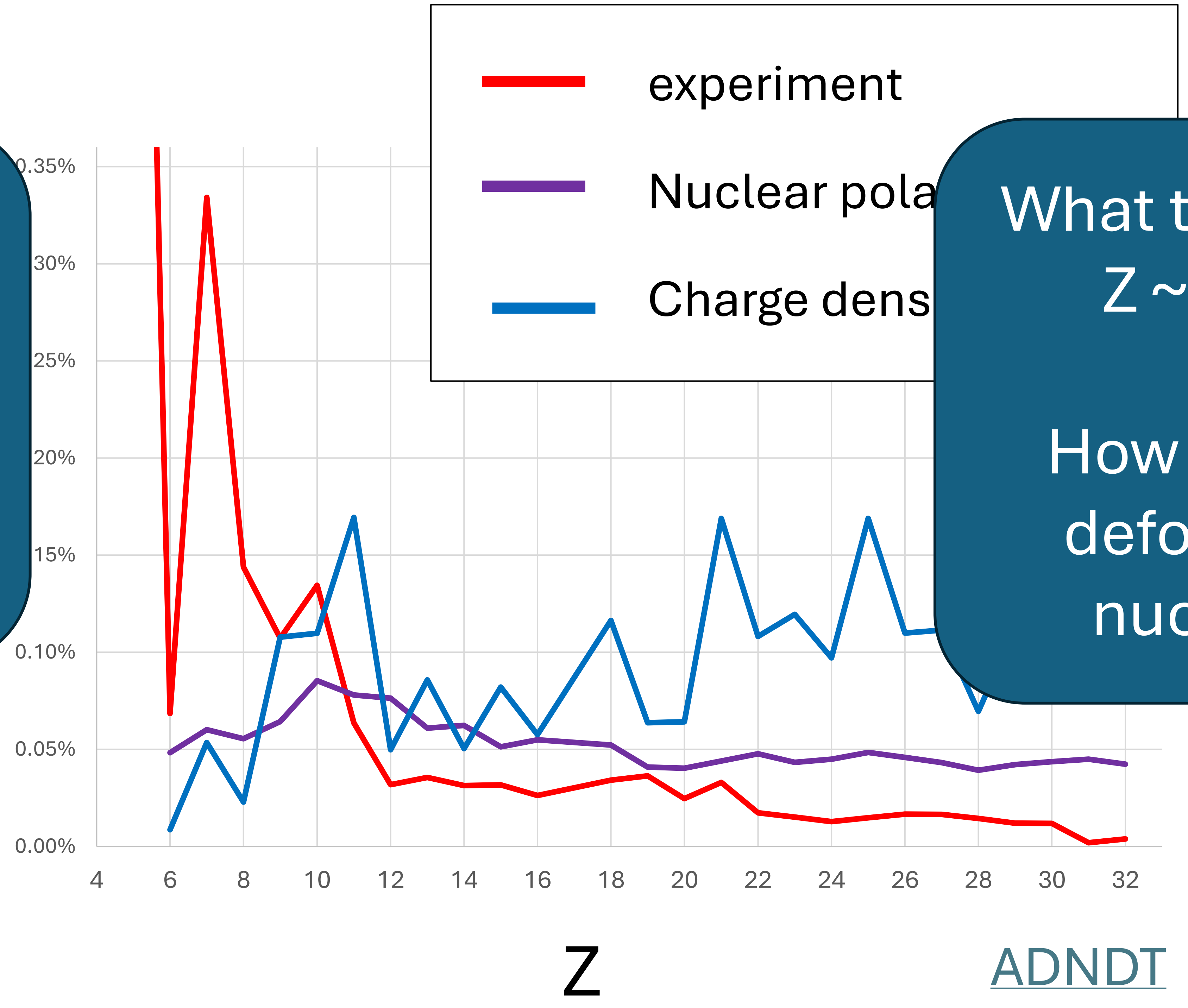
RevModPhys.96.015001

Where can we push TPE calculations?

Z = 1, 2

Elastic from electron scattering

Nuclear Pol. from calculation / data driven

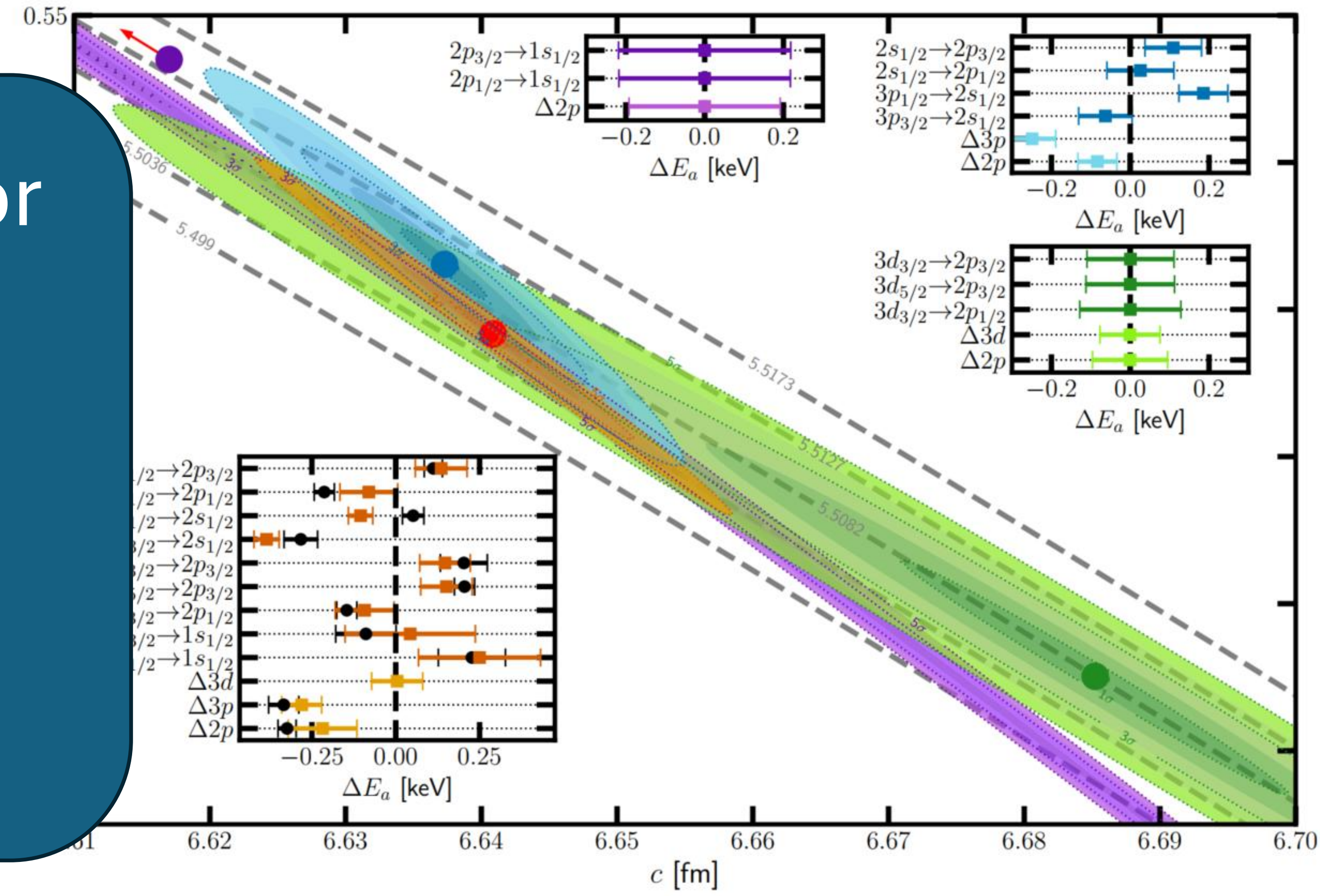


ADNDT

What to do for Z ~ 50 ?

How about deformed nuclei ?

Elastic from fit with several transitions
Npol from calculation



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arXiv:2504.19977

What's in the table:

ADNDT

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

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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	†
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	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	

What’s going on?

ADNDT

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Recent work:

Muonic

He-Like

g-factor

Muonic,

Muonic

Muonic

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ADNDT

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Muonic

He-Like

g-factor

Muonic,

Muonic

Muonic

Planned

He-Like

g-factor

Muonic

Muonic

Wish

g-factor

g-factor

g-factor

g-factor

What’s going on?

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Recent work: **Planned** **Wish**

Muonic

He-Like

He-Like

g-factor

Muonic

Plus a ton of laser-spectroscopy and theory

g-factor

g-factor

Muonic

Muonic

g-factor

Muonic

g-factor

ADNDT (section 3)

Complementarity in Action:

$$\delta\nu_{20,22} \approx \boldsymbol{K}\mu_{20,22} + \boldsymbol{F}\delta r^2_{20,22}$$

ADNDT (section 3)

Complementarity in Action:

Isotope shift (ISOLDE)

Penning trap (MPK)

Atomic many body
(BO & Berengut)

Diff. g-factor (MPK)

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$$\delta\nu_{20,22} \approx \boldsymbol{K}\mu_{20,22} + \boldsymbol{F}\delta r^2_{20,22}$$

Get K

$$\delta\nu_{20,18} \approx \boldsymbol{K}\mu_{20,18} + \boldsymbol{F}\delta r^2_{20,18}$$

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Get K

$$\delta\nu_{20,18} \approx \boldsymbol{K}\mu_{20,18} + \boldsymbol{F}\delta r^2_{20,18}$$

Get $\delta r^2_{20,18}$

$$r^2_{18} = r^2_{20} + \delta r^2_{20,18}$$

Muonic atoms

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Get K

$$\delta\nu_{20,18} \approx \boldsymbol{K}\mu_{20,18} + \boldsymbol{F}\delta r^2_{20,18}$$

Get $\delta r^2_{20,18}$

$$r^2_{18} = r^2_{20} + \delta r^2_{20,18}$$

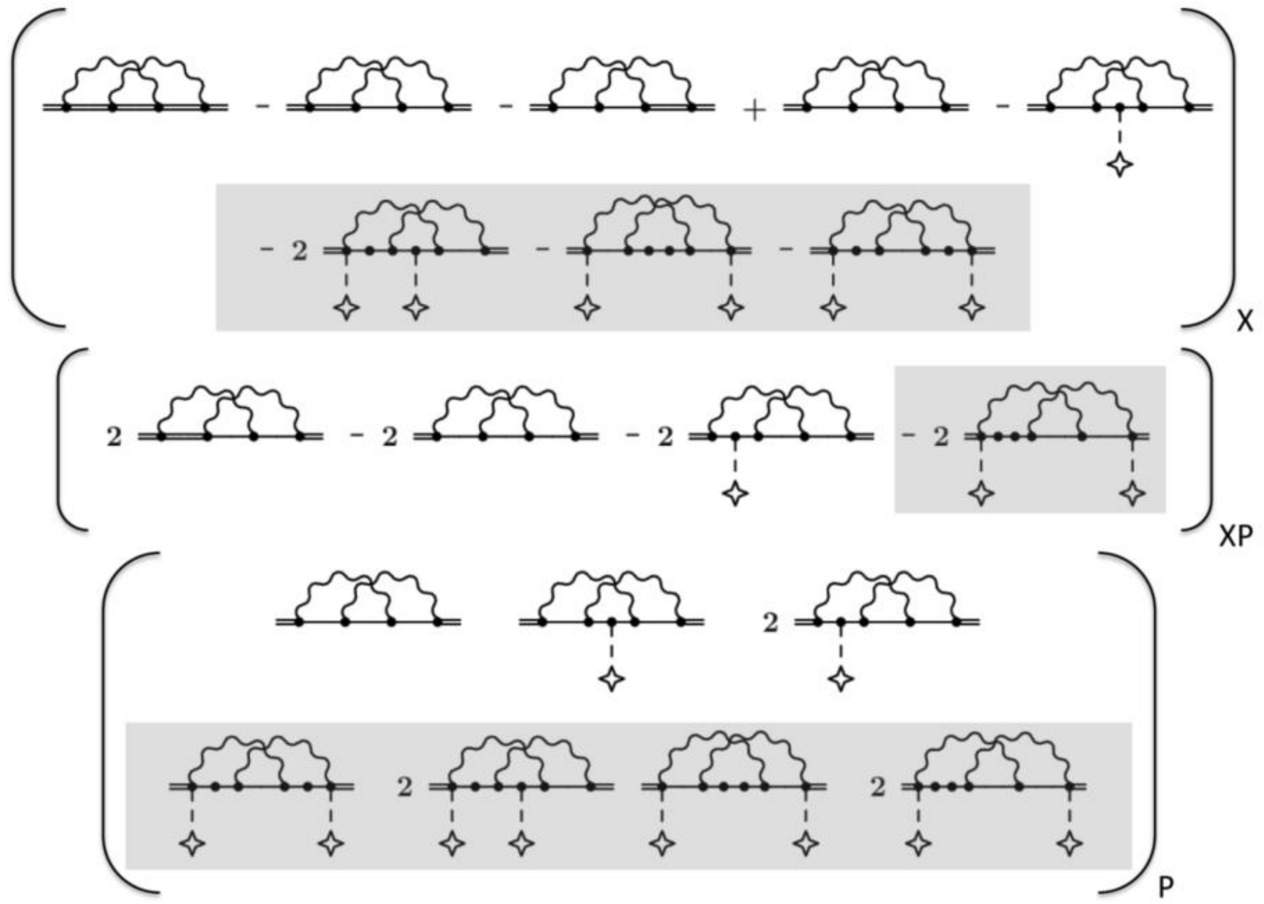
Vud determination

New physics in b-decay

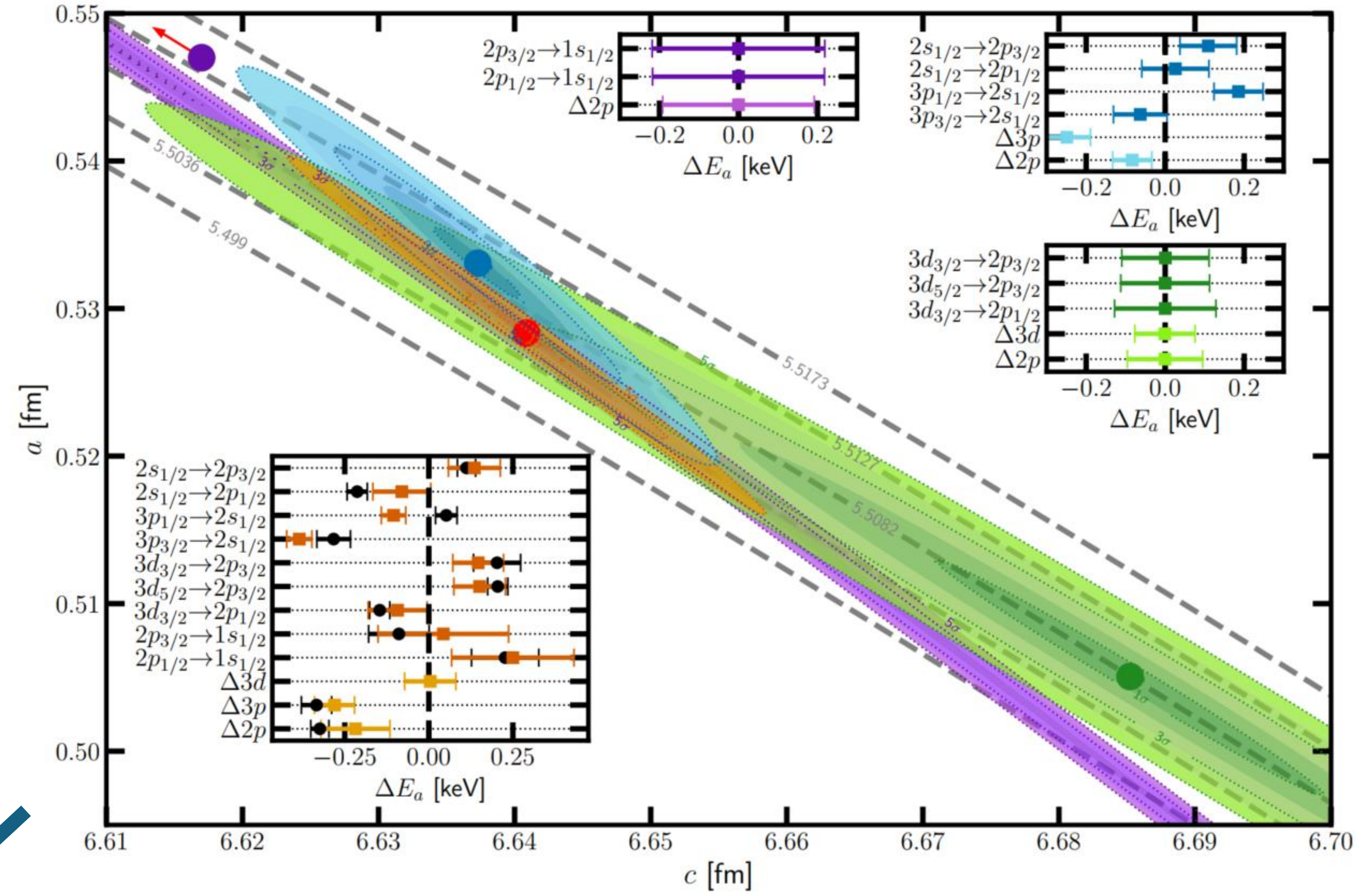
Muonic atoms

Vision and Precision

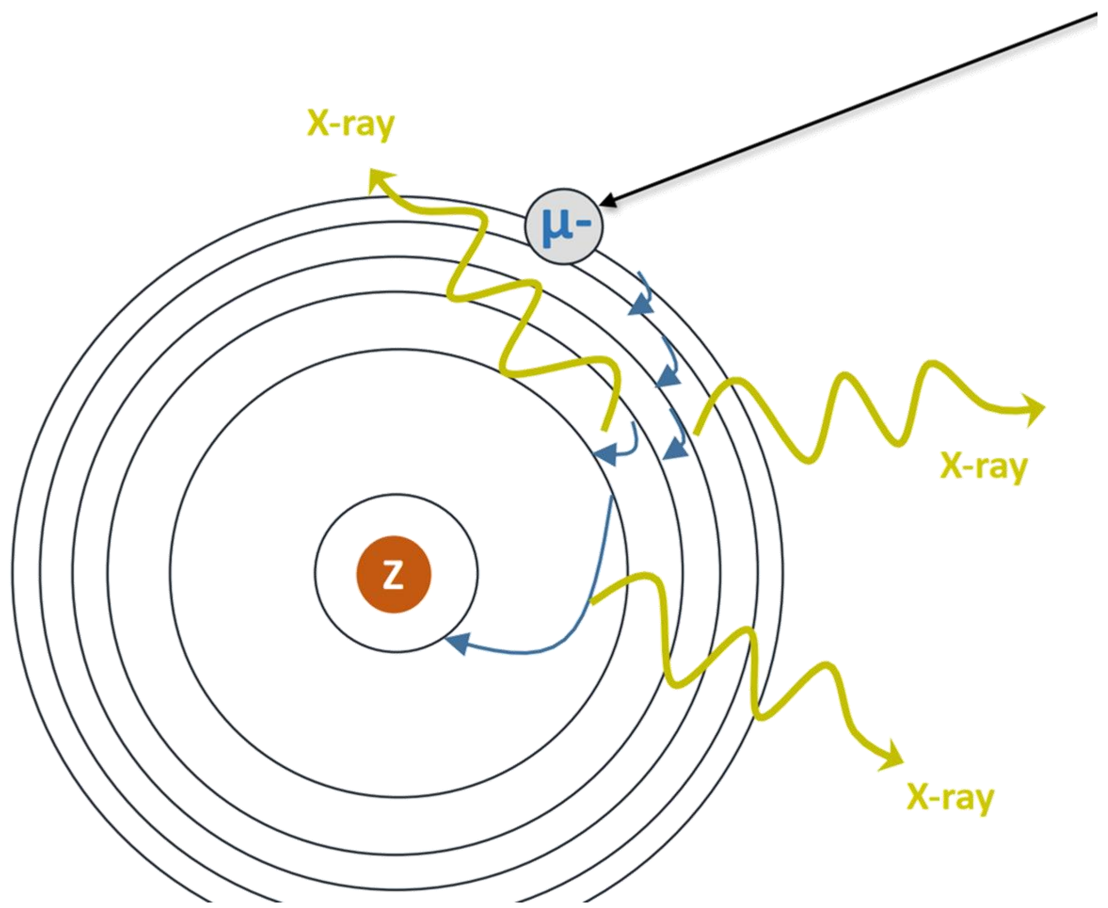
Theory



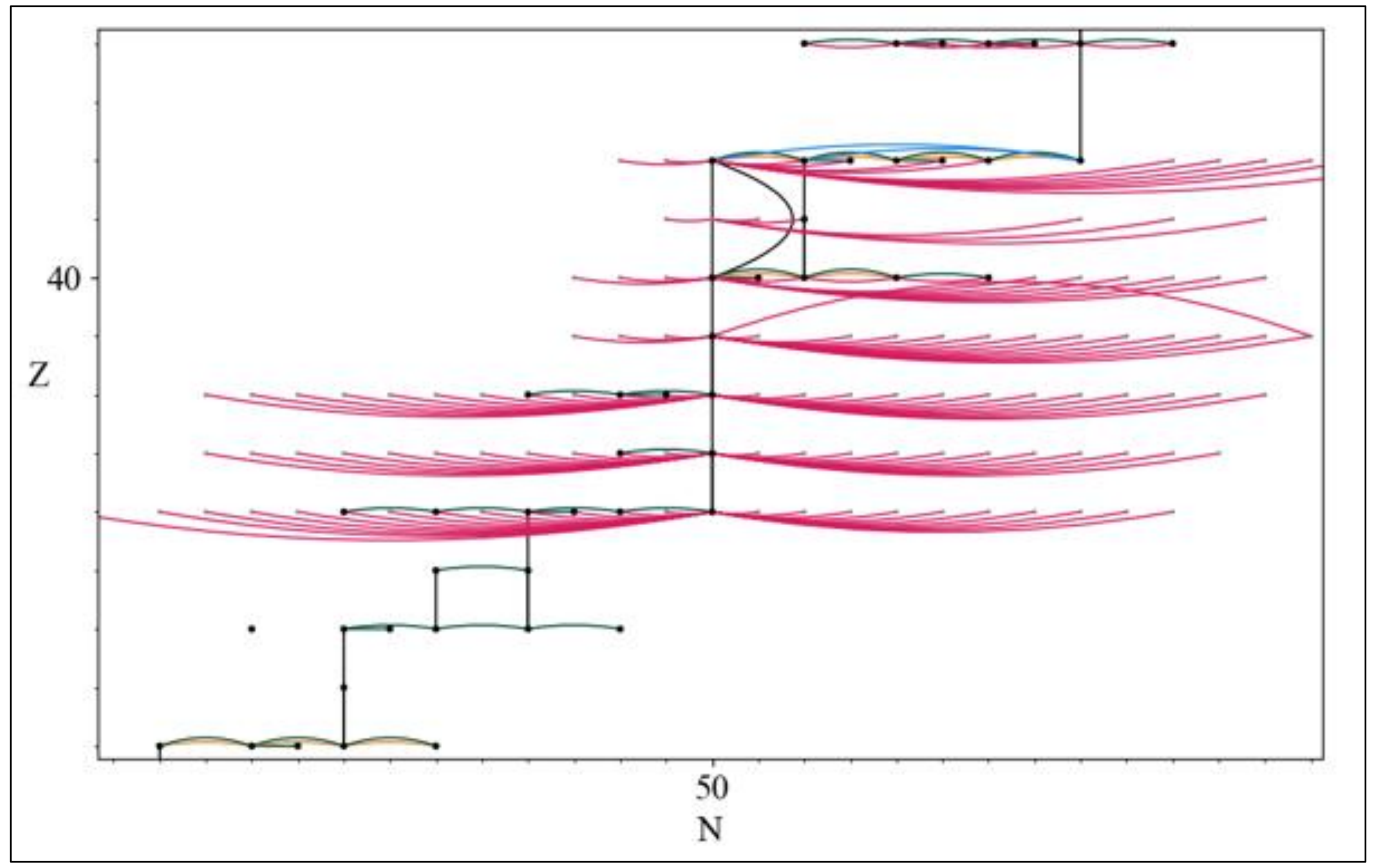
Combined analysis



Experiments

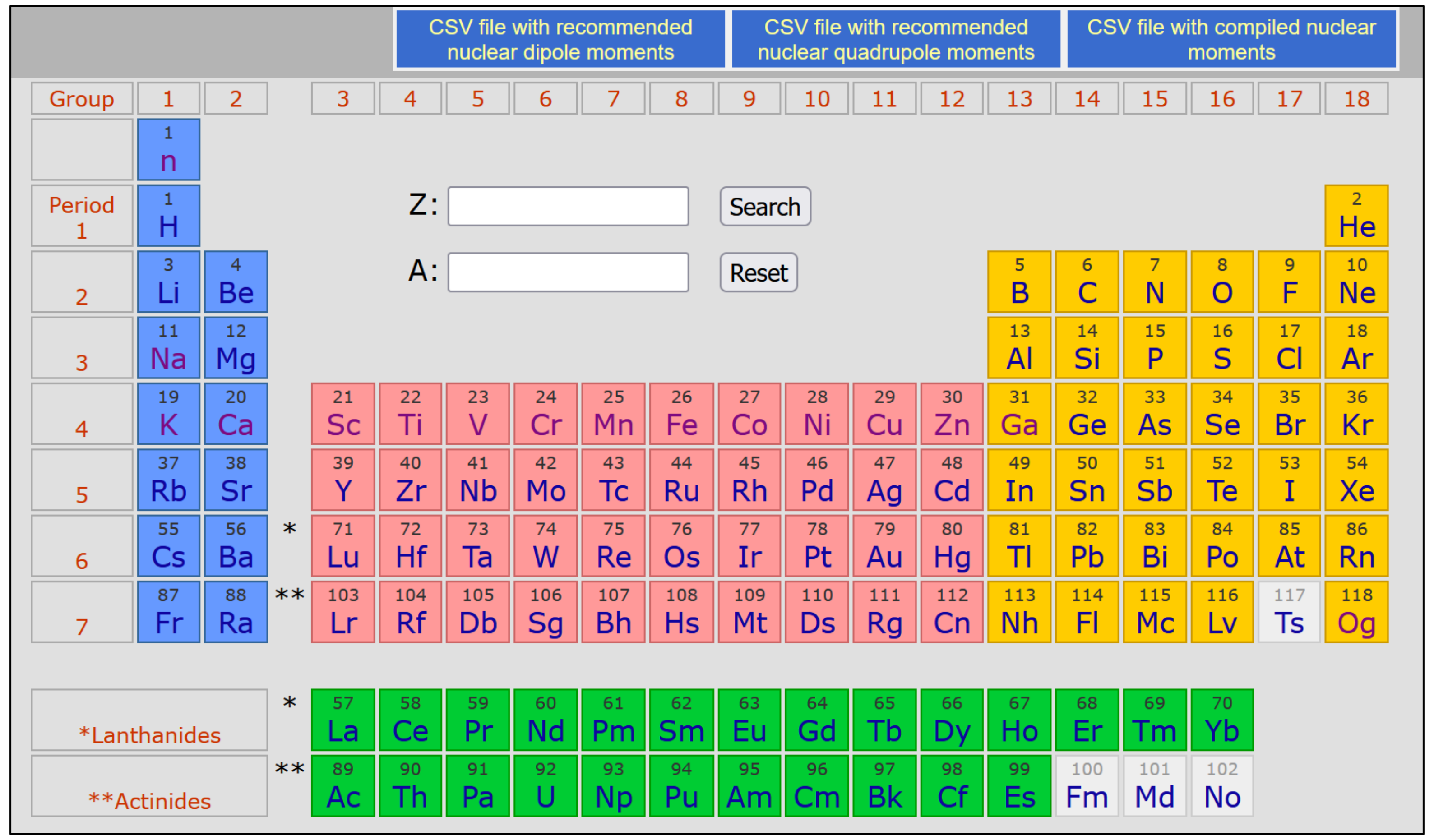


Combining data



Clemson

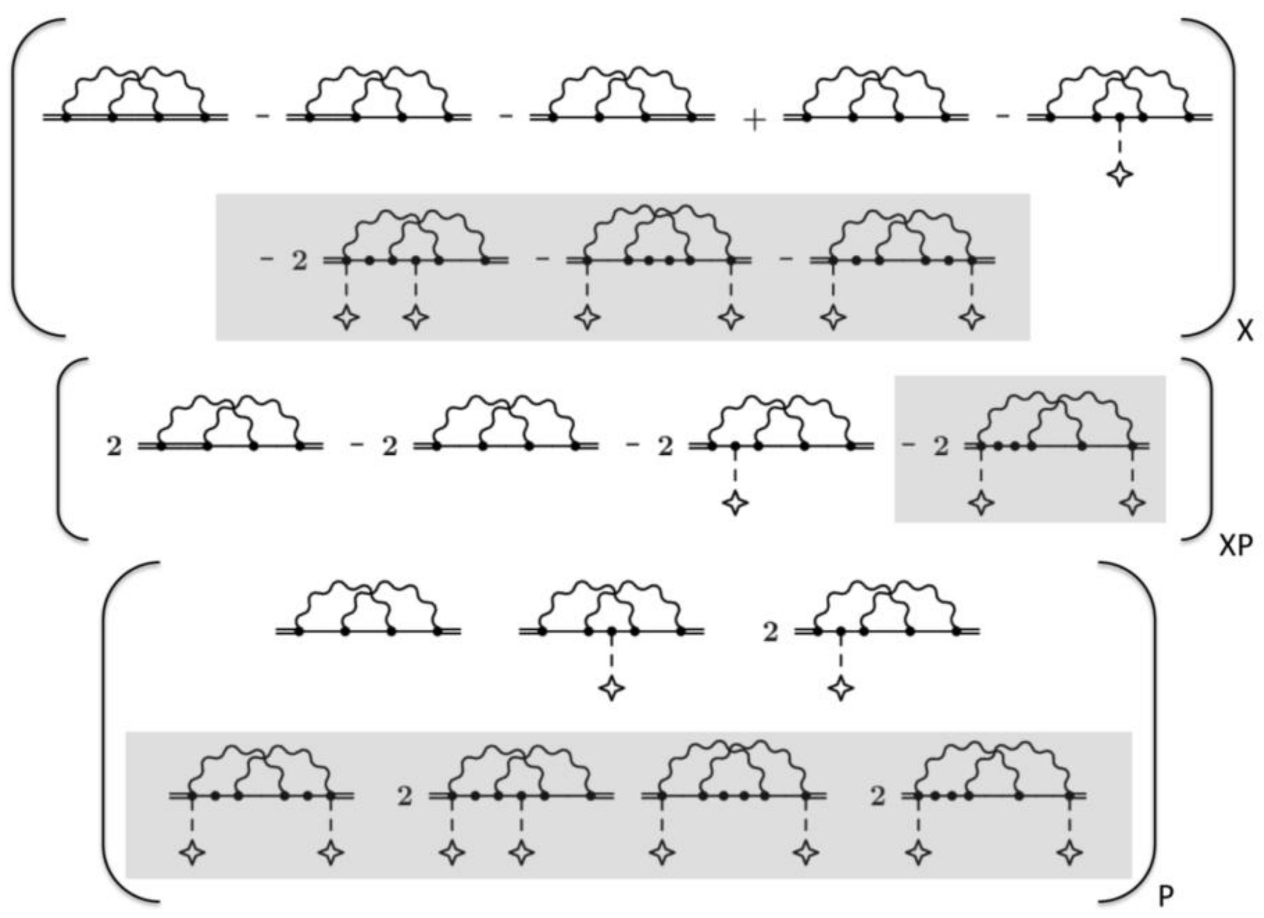
Curation & Dissemination



IAEA

Vision and Precision

Theory



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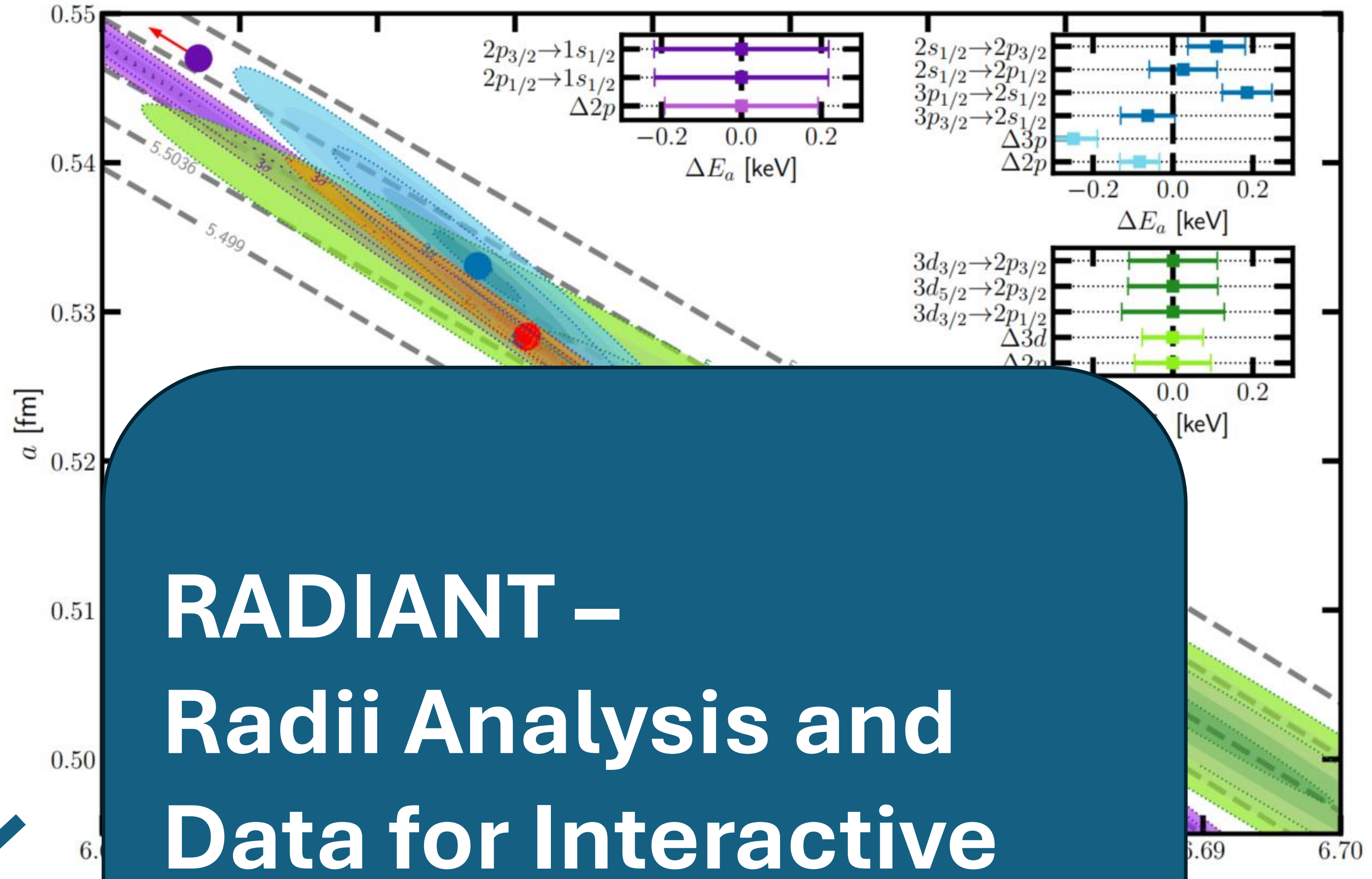

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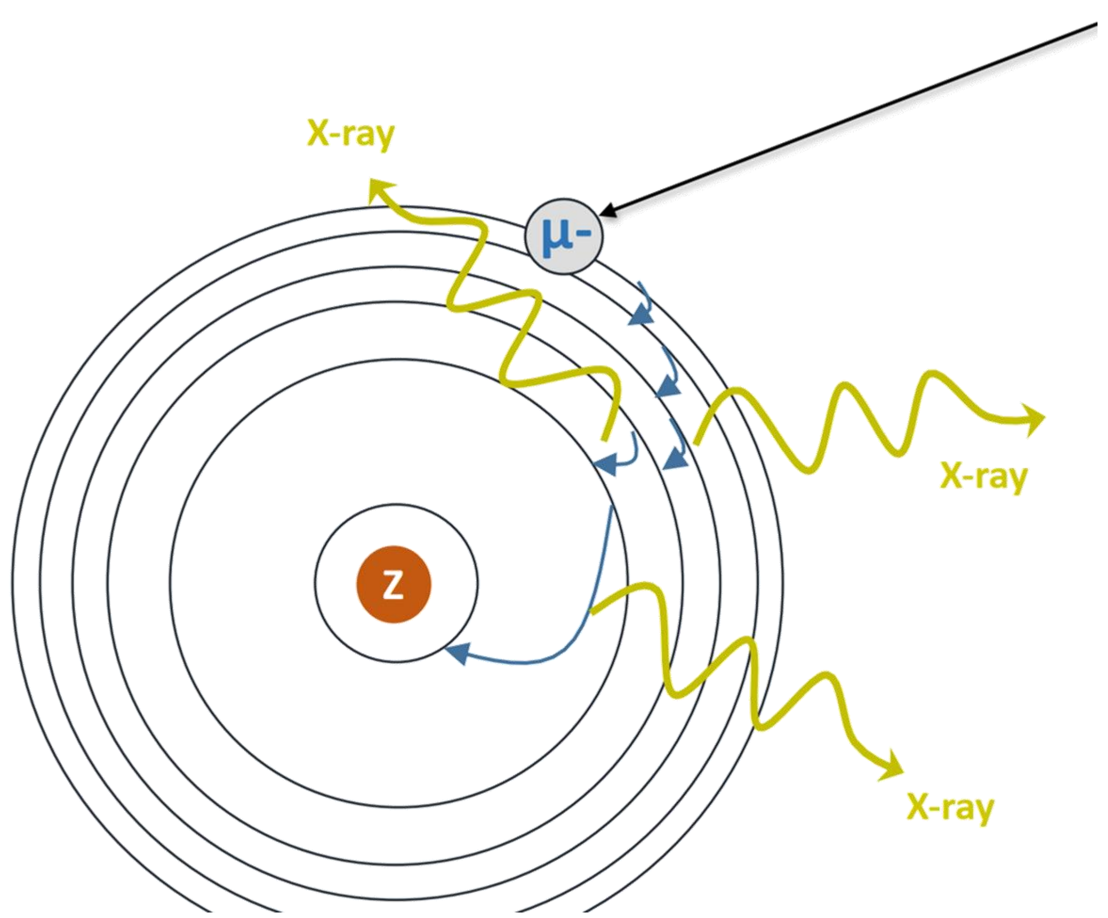
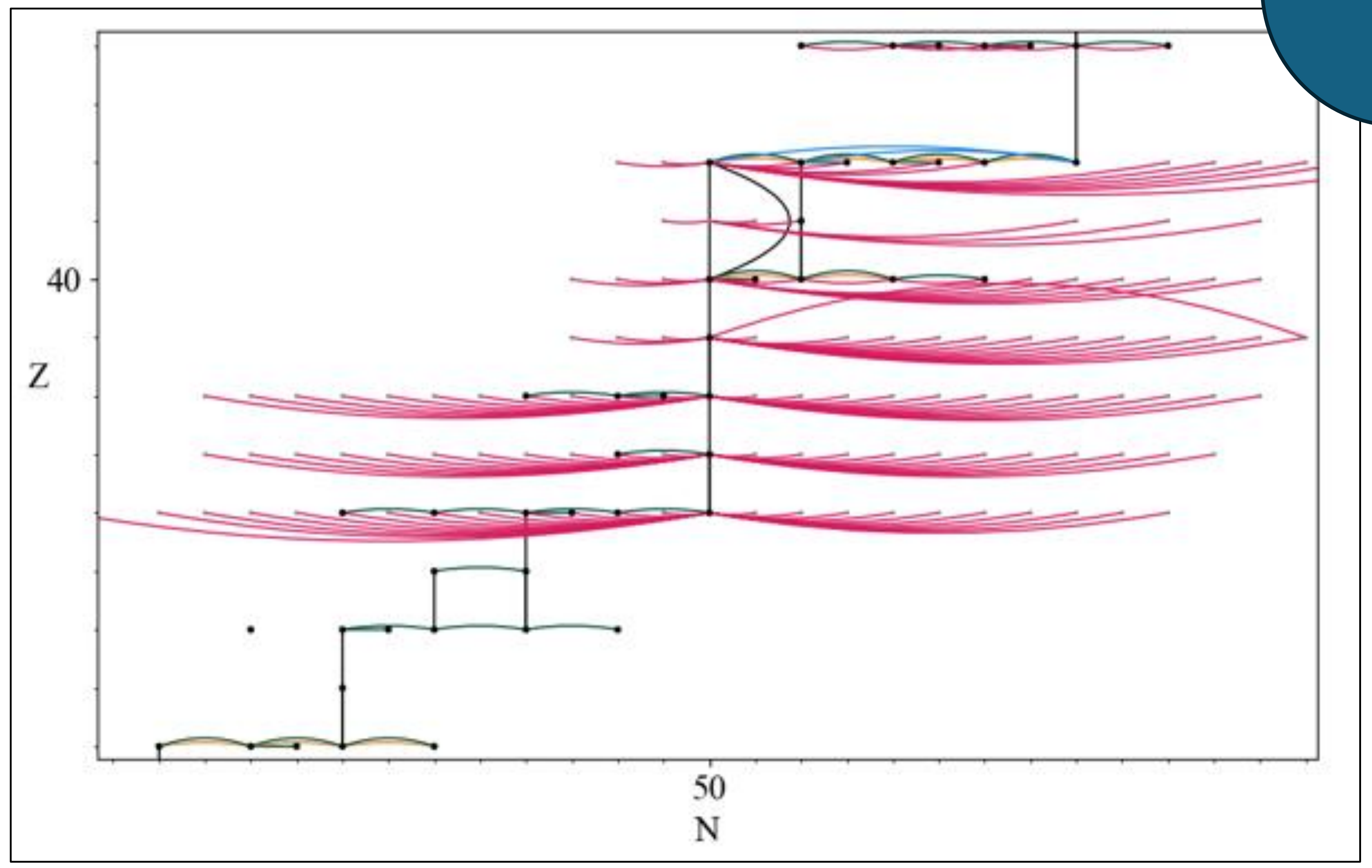


RADIANT –
Radii Analysis and Data for Interactive Nuclear Table

Combining data



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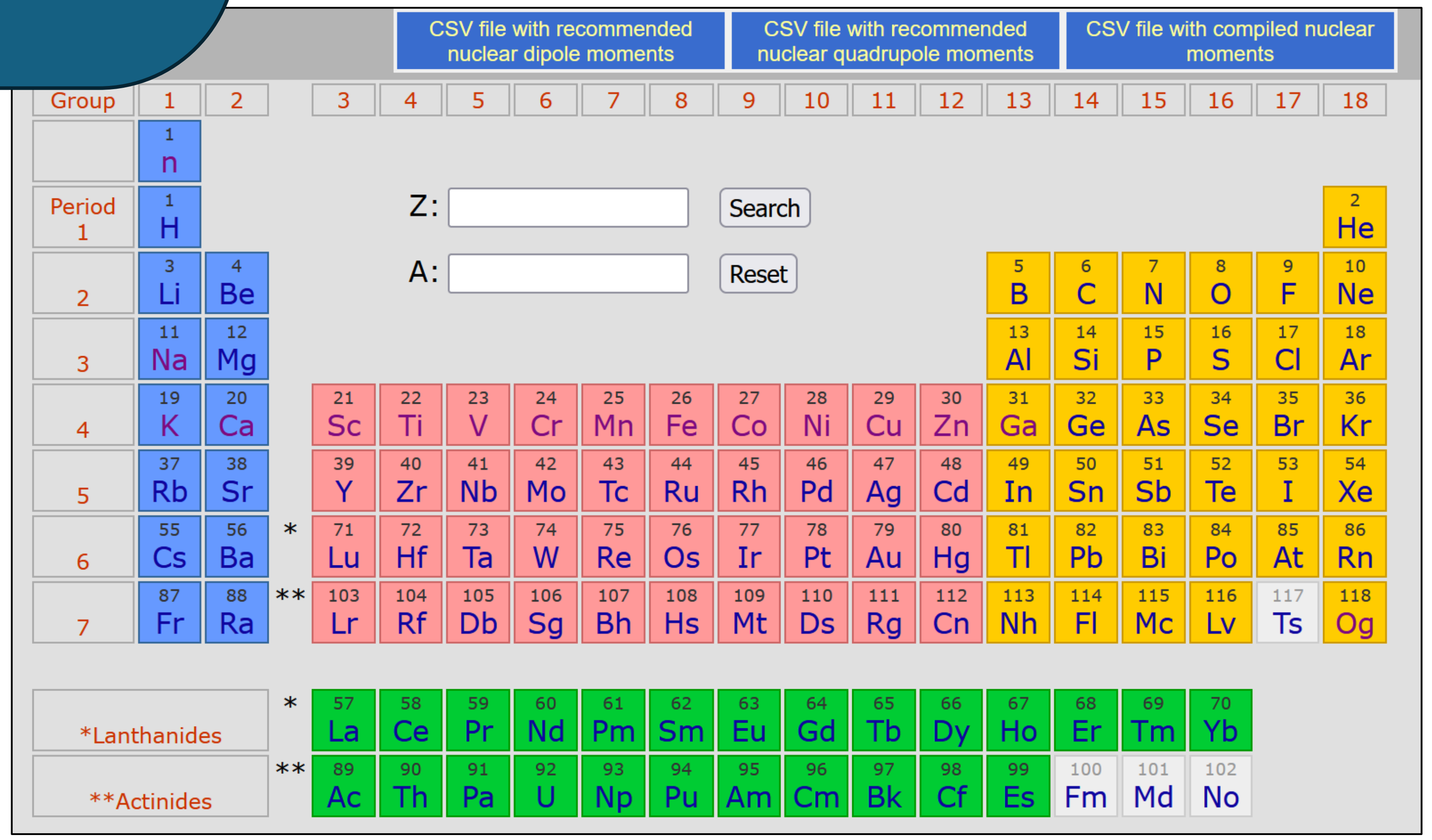

IAEA


Take home message:
It is best to be the second best …