Charge Radii of Light Isotopes from Laser Spectroscopy of He-Like Atomic Systems

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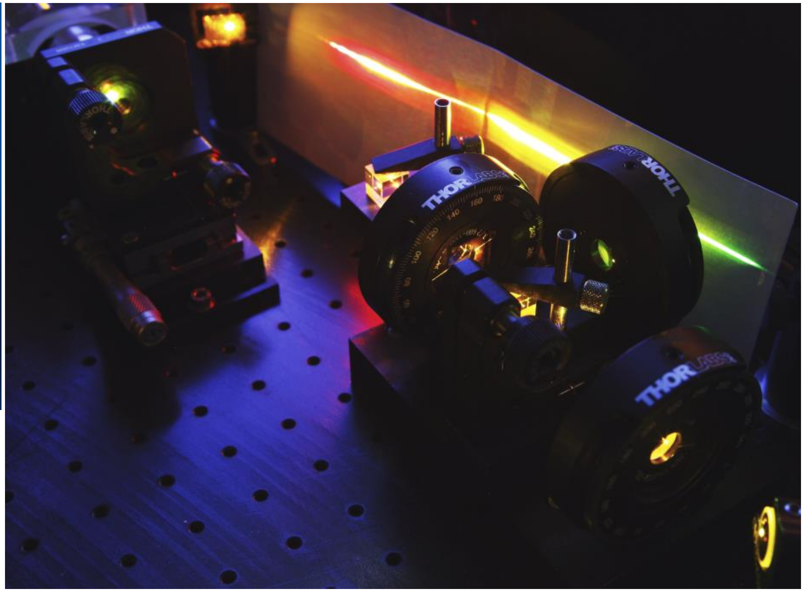


KOALA

Bundesministerium für Bildung und Forschung

HFHF Helmholtz Forschungsakademie Hessen für FAIR

HESSEN Hessisches Ministerium für Wissenschaft und Kunst

LASER SpHERe

DFG Deutsche Forschungsgemeinschaft

SFB 1245
Atomic Nuclei: From Fundamental Interactions to Structure and Stars

Outline

Introduction

Motivation

Experimental Setup

Results

Summary and Outlook

Isotope Shift in a Nutshell

$$\delta\nu_{\mathrm{IS}}^{AA'} = \nu^{A'} - \nu^{A}$$

$$\delta\nu_{\mathrm{IS}}^{AA'} \approx K_{\mathrm{MS}} \cdot \frac{M_{A'} - M_A}{M_A M_{A'}} + F\,\delta\left\langle r_c^2\right\rangle^{AA'}$$

$$\delta\left\langle r_c^2\right\rangle^{AA'} \approx \frac{1}{F}\left[\delta\nu_{\mathrm{IS}}^{AA'} - K_{\mathrm{MS}} \cdot \mu^{A'A}\right]$$

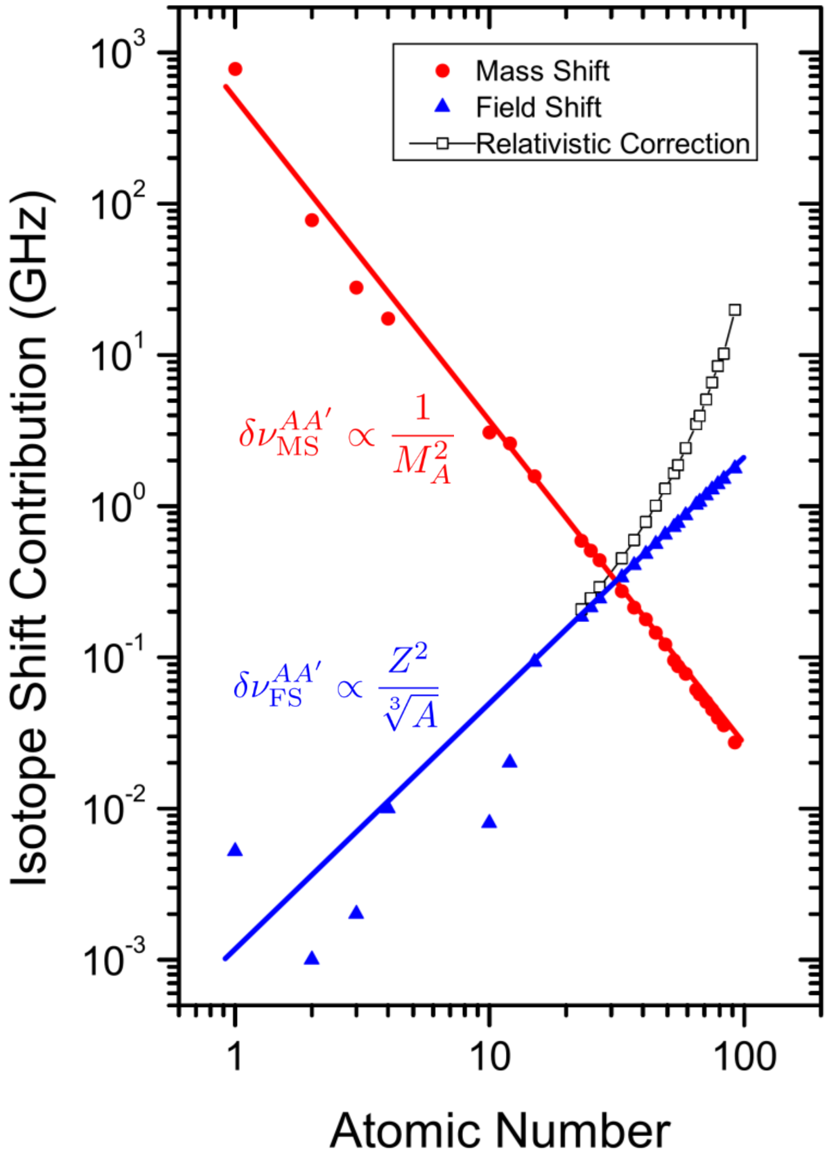
Requires knowledge of F and K_{MS} !

- ab initio NR-QED: up to 5-electron systems
- MCDHF, MBPT, ….
- King plot (requires ≥3 stable isotopes with known R_c)

How to get a radius ?

$$R_c(A) = \sqrt{\underbrace{R_c^2(A_{\mathrm{ref}})}_{} + \delta\left\langle r_c^2\right\rangle^{A_{\mathrm{ref}},A}}$$

Reference radius required from a different technique



Nuclear Charge Radii $\langle r_c^2 \rangle = \frac{1}{Z} \int d^3r\, r^2 \rho_c(\vec{r})$

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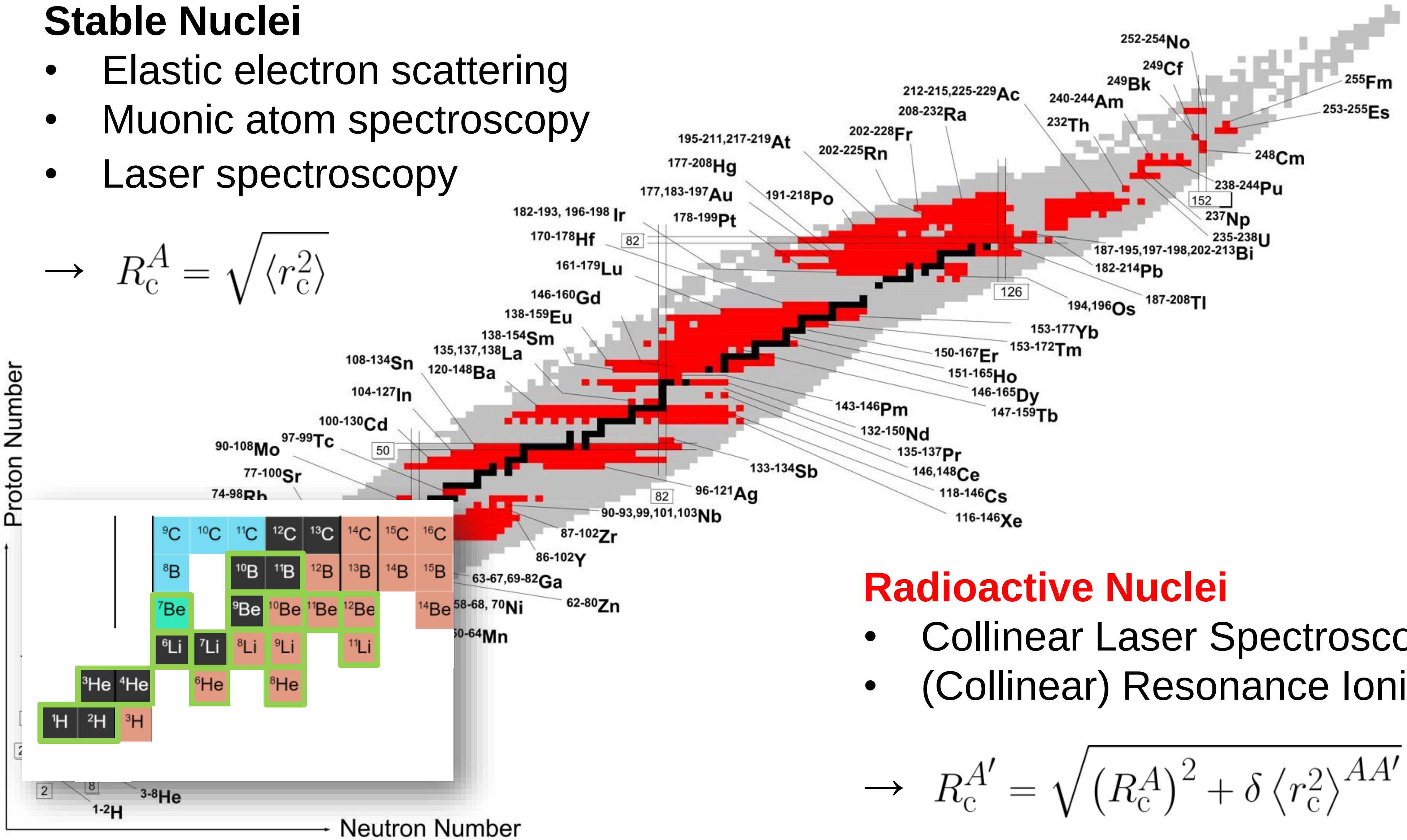
Stable Nuclei
- Elastic electron scattering
- Muonic atom spectroscopy
- Laser spectroscopy

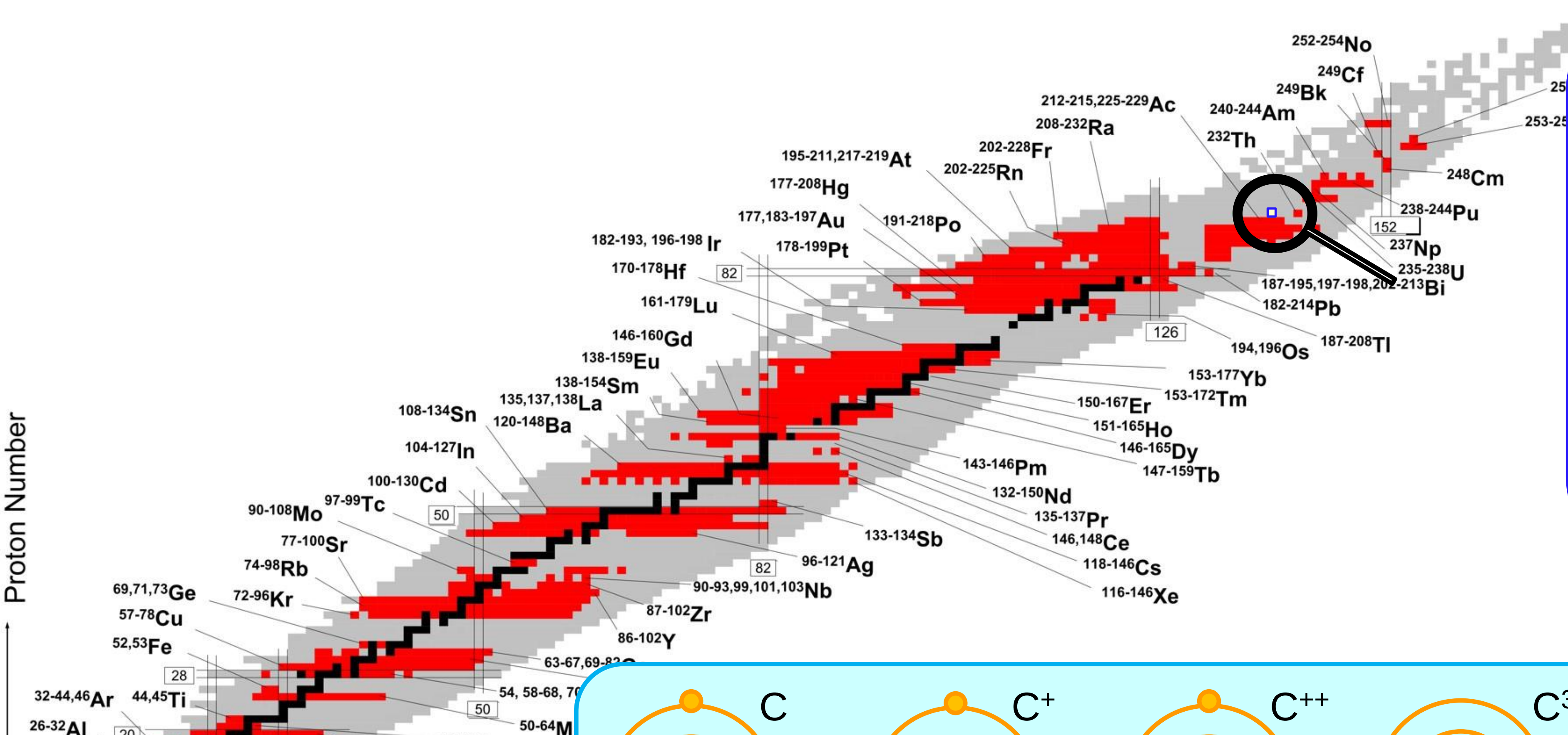
$\rightarrow \quad R_c^A = \sqrt{\langle r_c^2 \rangle}$

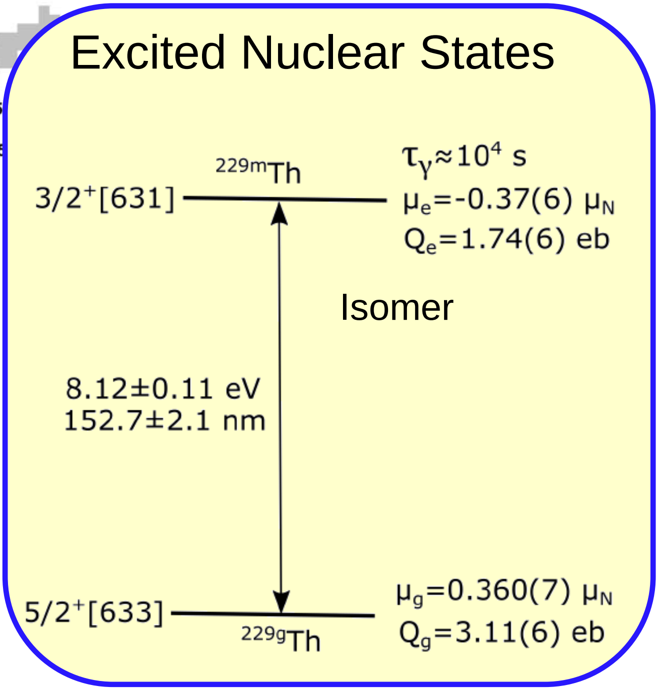


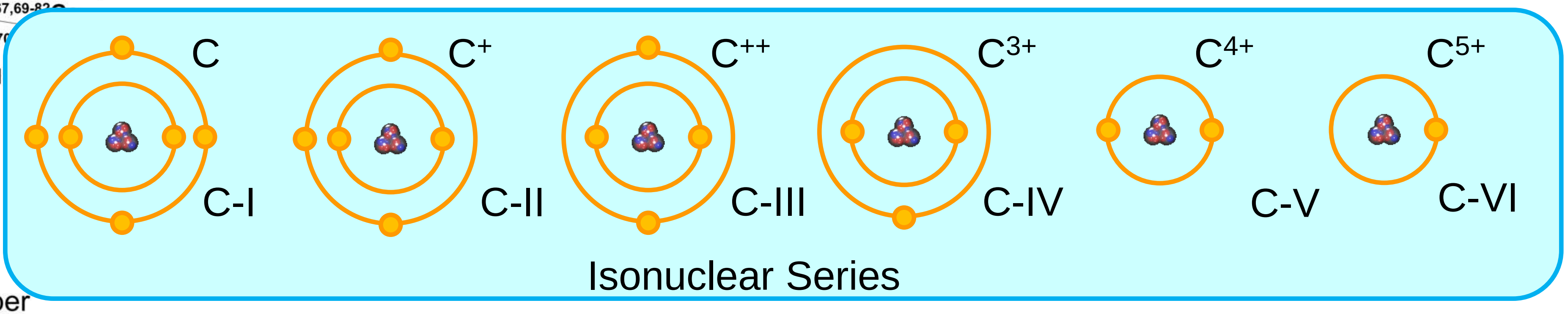
Radioactive Nuclei
- Collinear Laser Spectroscopy
- (Collinear) Resonance Ionization Spectroscopy

$\rightarrow \quad R_c^{A'} = \sqrt{(R_c^A)^2 + \delta \langle r_c^2 \rangle^{AA'}}$

Additional Dimensions

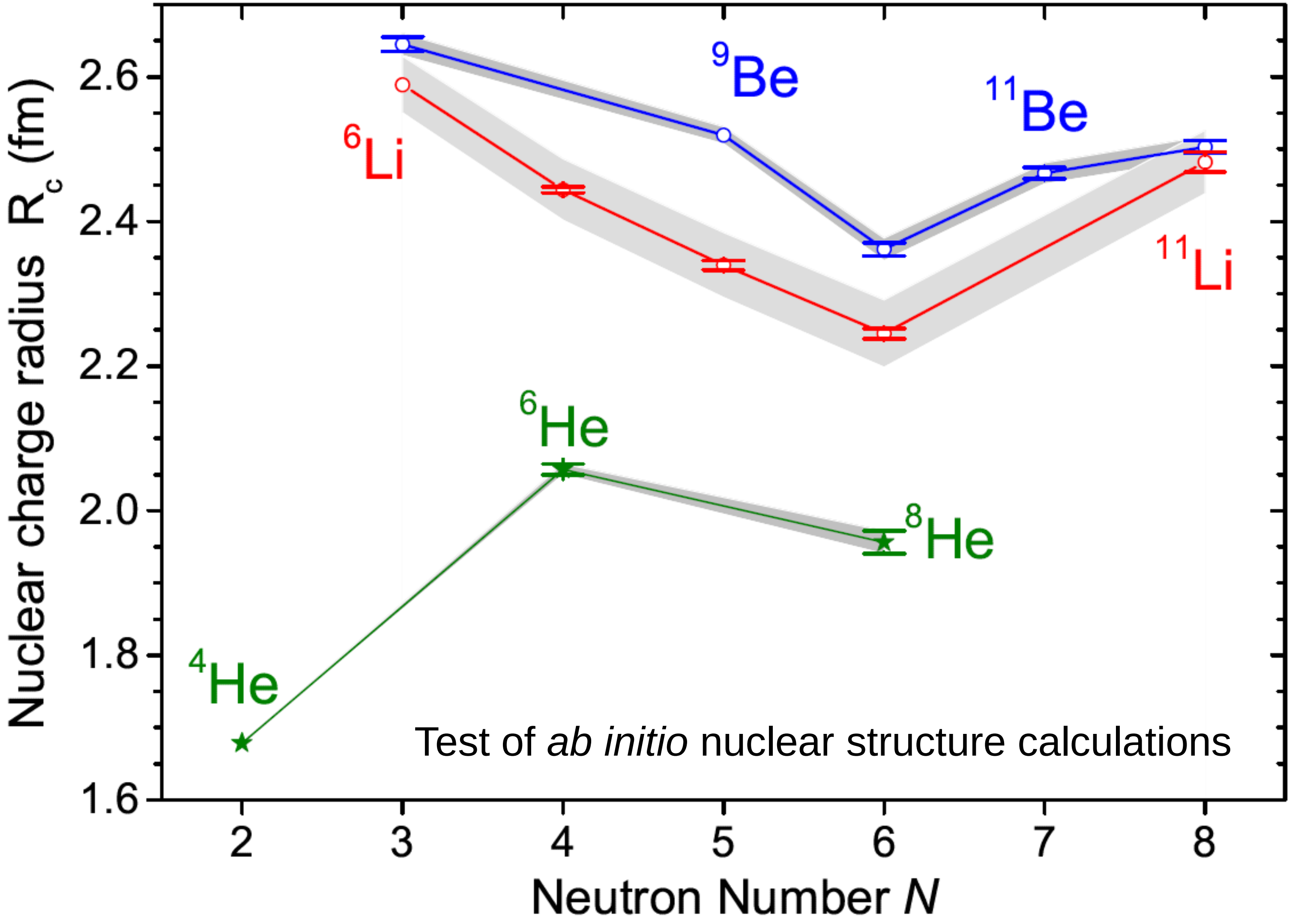






MOTIVATION

Nuclear Radii of the Lightest Isotopes



Error Bars: $\sigma(\delta\nu_{IS})$

A. Krieger *et al.*, PRL **108**, 142501 (2012)

R. Sanchez *et al.*, PRL **96**, 033002 (2006)

P. Müller *et al.*, PRL **99**, 252501 (2008)

Grey Regions: $\sigma(R_c)$

$R_c(^9\mathrm{Be}) = 2.519\,(12)\,\mathrm{fm}$

J.A. Jansen *et al.*, Nucl. Phys. A **188**, 337 (1972)

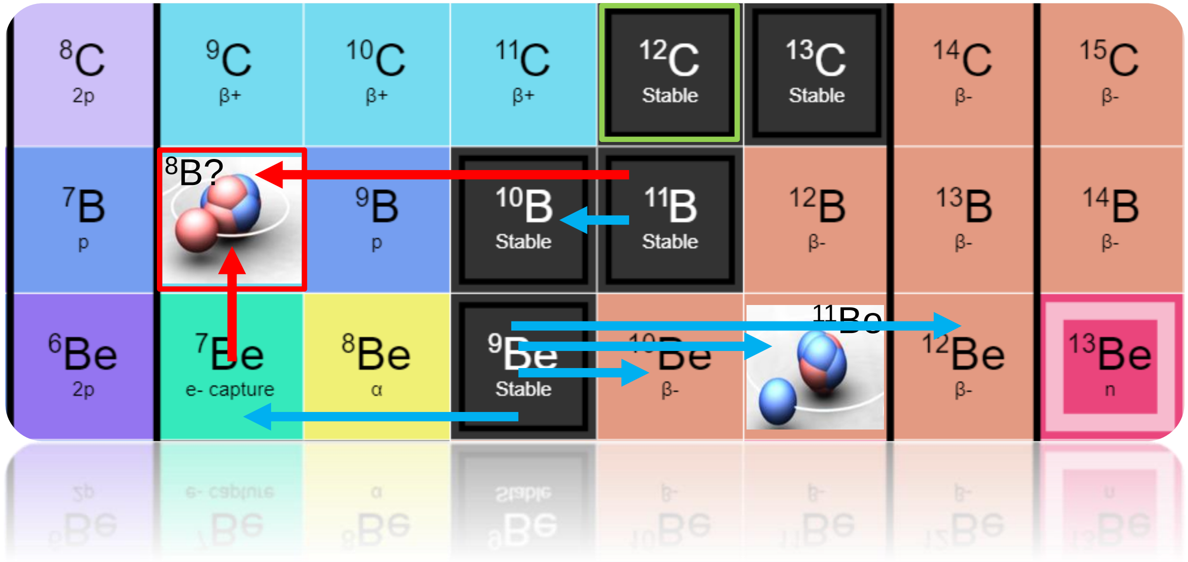
$R_c(^6\mathrm{Li}) = 2.589\,(39)\,\mathrm{fm}$

W. Nörtershäuser *et al.*, Phys. Rev. C **84**, 024307 (2011)

$\mathbf{R_c(\alpha) = 1.678\,24(83)\,fm}$

J.J. Krauth *et al.*, Nature **589**, 527 (2021)

The Proton-Halo Nucleus ^8B



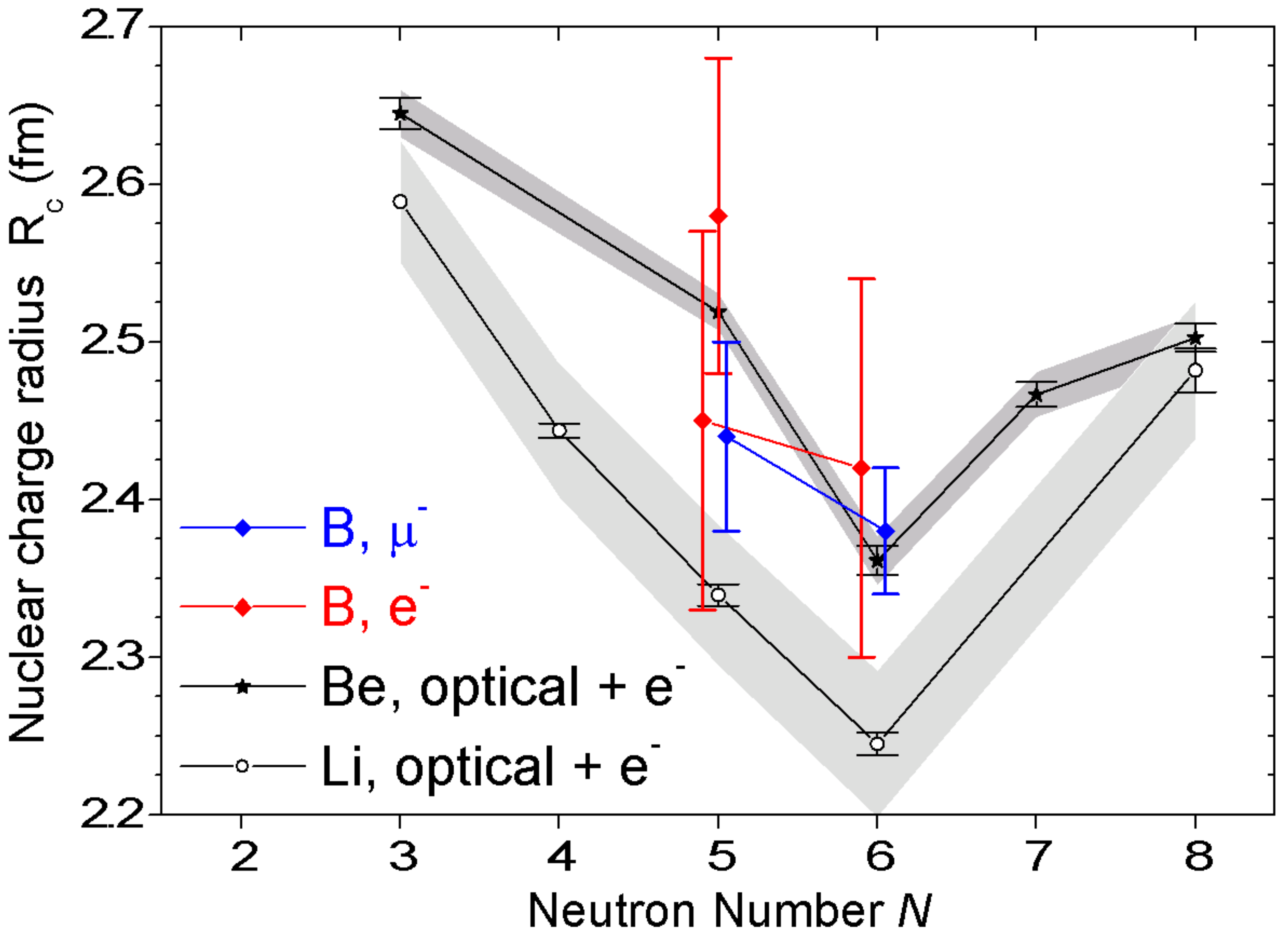
$$\delta\nu_{\mathrm{IS}} - \delta\nu_{\mathrm{MS}}^{\mathrm{Theory}} \propto \delta\langle r_{\mathrm{c}}^2\rangle \longrightarrow R_{\mathrm{c}}(A) = \sqrt{R_{\mathrm{c}}^2(A_{\mathrm{ref}}) + \delta\langle r_{\mathrm{c}}^2\rangle^{A_{\mathrm{ref}},A}}$$

Reference Radii required

„Proton-halo size“: $R_{\mathrm{c}}(\mathrm{p_{halo}}) = R_{\mathrm{c}}(^8\mathrm{B}) - R_{\mathrm{c}}(^7\mathrm{Be})$

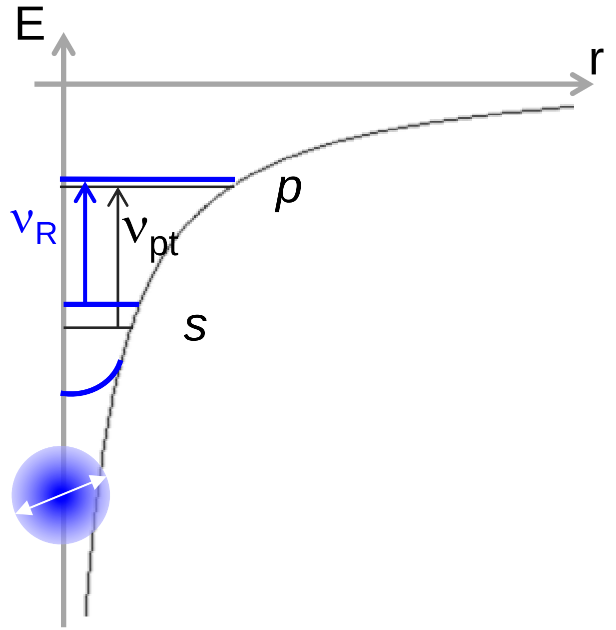
Conclusion: To gain information about the proton halo of ^8B, we need reliable reference radii for Be and B **on equal footing** !

„Reference“ Radii of Boron



[1] Stovall, Nucl. Phys. 86, 225 (1966)
[2] Cichocki et al., PRC 51, 2406 (1995)
[3] Schaller *et al*., Nucl. Phys. A 343, 333 (1980)
[4] Olin *et al*., Nucl Phys A 360, 426 (1981)

All-Optical Absolute Charge Radii



$$\delta\nu_{FS} = \nu_R - \nu_{pt}$$

$$= -\frac{Ze^2}{6\varepsilon_0}\Delta\left|\Psi_e(0)\right|^2_{i\to f} \times \langle r_c^2 \rangle$$

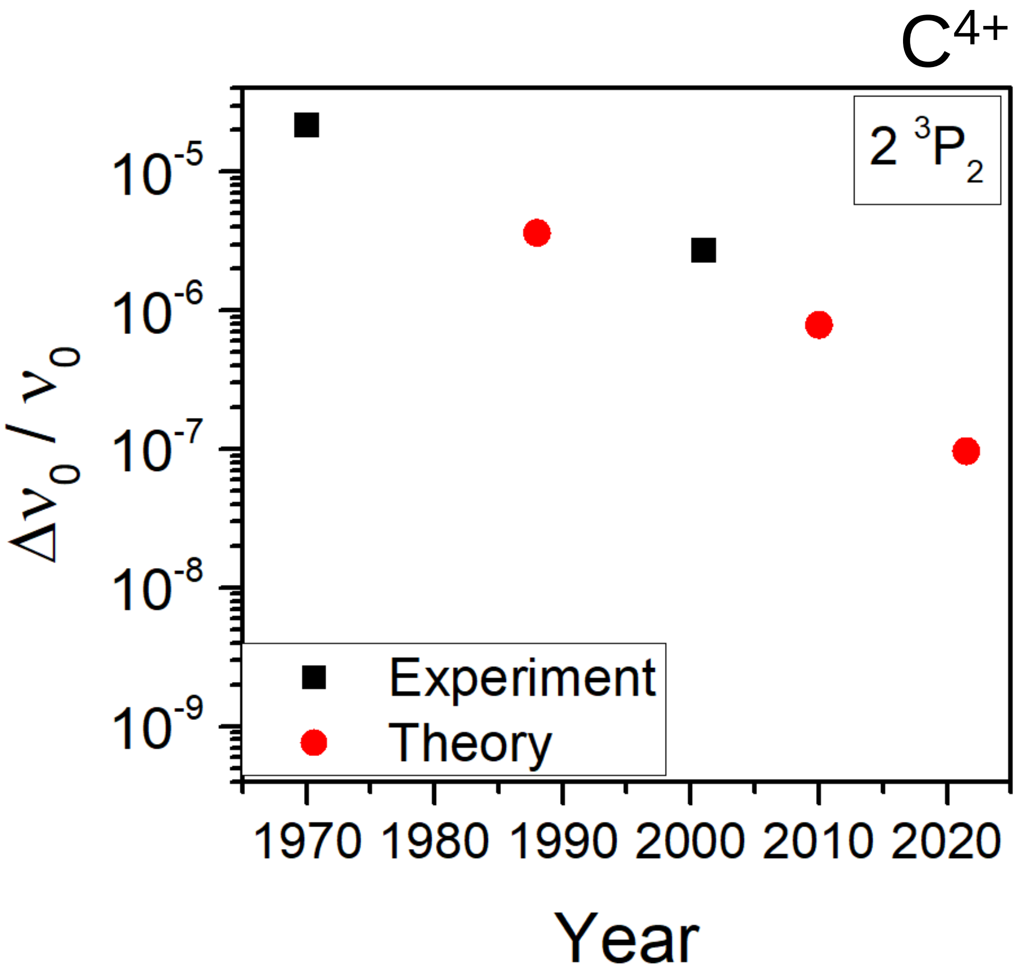
Electronic Factor
(→ Wavefunction)

$$= F_{i\to f}\langle r_c^2 \rangle$$

- Measure **transition frequency** ν_R
- Compare with high precision atomic calculation for a point-like nucleus ν_{pt}
- Difference ν_R - ν_{pt} is finite-size effect and **proportional to the ms charge radius**
- So far applied **only for H-like systems**, i.e., H, μH and μHe
- Two-electron system requires elaborate QED calculations, which have been improved considerably

V.A. Yerokhin, V. Patkóš & K. Pachucki, PRA **98**, 032503 (2018)
V. Patkóš, V.A. Yerokhin &K. Pachucki, PRA **103**, 042809 (2021)
V.A. Yerokhin, V. Patkóš & K. Pachucki, PRA **106**, 022815 (2022)

Theory



Exp: S. Ozawa *et al.*, Phys. Scr. **T92**, 195 (2001)
Beam-foil spectroscopy

TABLE X. Comparison of theoretical and experimental $n = 2$ intrashell transition energies, in cm^{-1}.

Z	Theory	Experiment	Difference	Ref.
$2\,^3S_1 - 2\,^3P_0$				
5	35 393.6211 (49)	35 393.627 (13)	−0.006 (13)	[47]
	35 393.628 (14)[a]			
8	60 978.788 (27)	60 978.44 (52)	0.35 (52)	[48]
	60 978.85 (14)[a]			

V.A. Yerokhin, V. Patkóš & K. Pachucki, PRA **106**, 022815 (2022)

C^{4+}	$1s2s\,^3S_1 \rightarrow 1s2p\,^3P_2$	$1s2s\,^3S_1 \rightarrow 1s2p\,^3P_1$	$1s2s\,^3S_1 \rightarrow 1s2p\,^3P_0$
ΔE_p (eV)	5.45804678(53)	5.4412107(31)	5.4427592(11)
F (μeV/fm^2)	-0.875	-0.875	-0.874
ν_p (GHz)	1319749.83(13)	1315678.89(75)	1316053.32(27)
F (GHz/fm^2)	0.2115	0.2115	0.2113

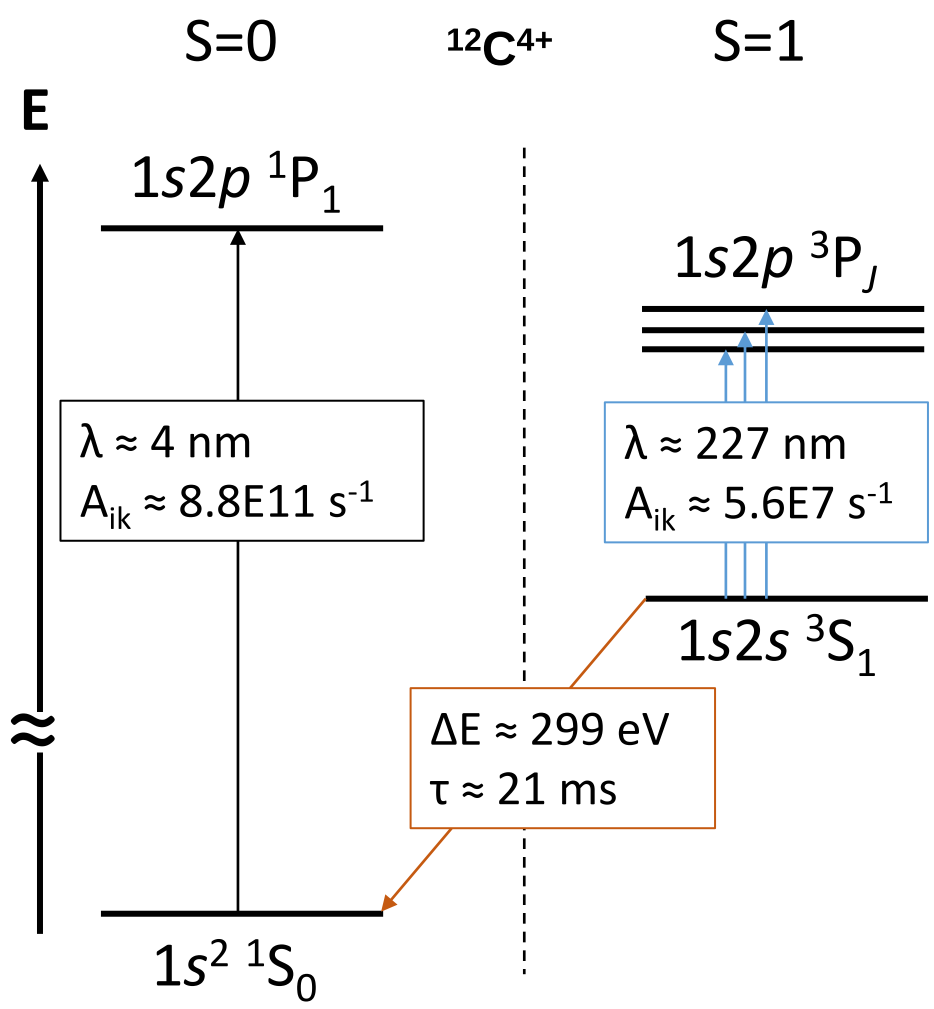
P. Imgram, Dissertation TU Darmstadt (2023)
P. Imgram, PRL**131** 243001 (2023)

$R_c(^{12}C) = 2.471(6)$ fm

I. Sick, PLB 116, 212 (1982)

Required accuracy for $\Delta R_C \leq 0.006$ fm: $\Delta\nu \leq 6$ MHz

The Case of $^{12}C^{4+}$



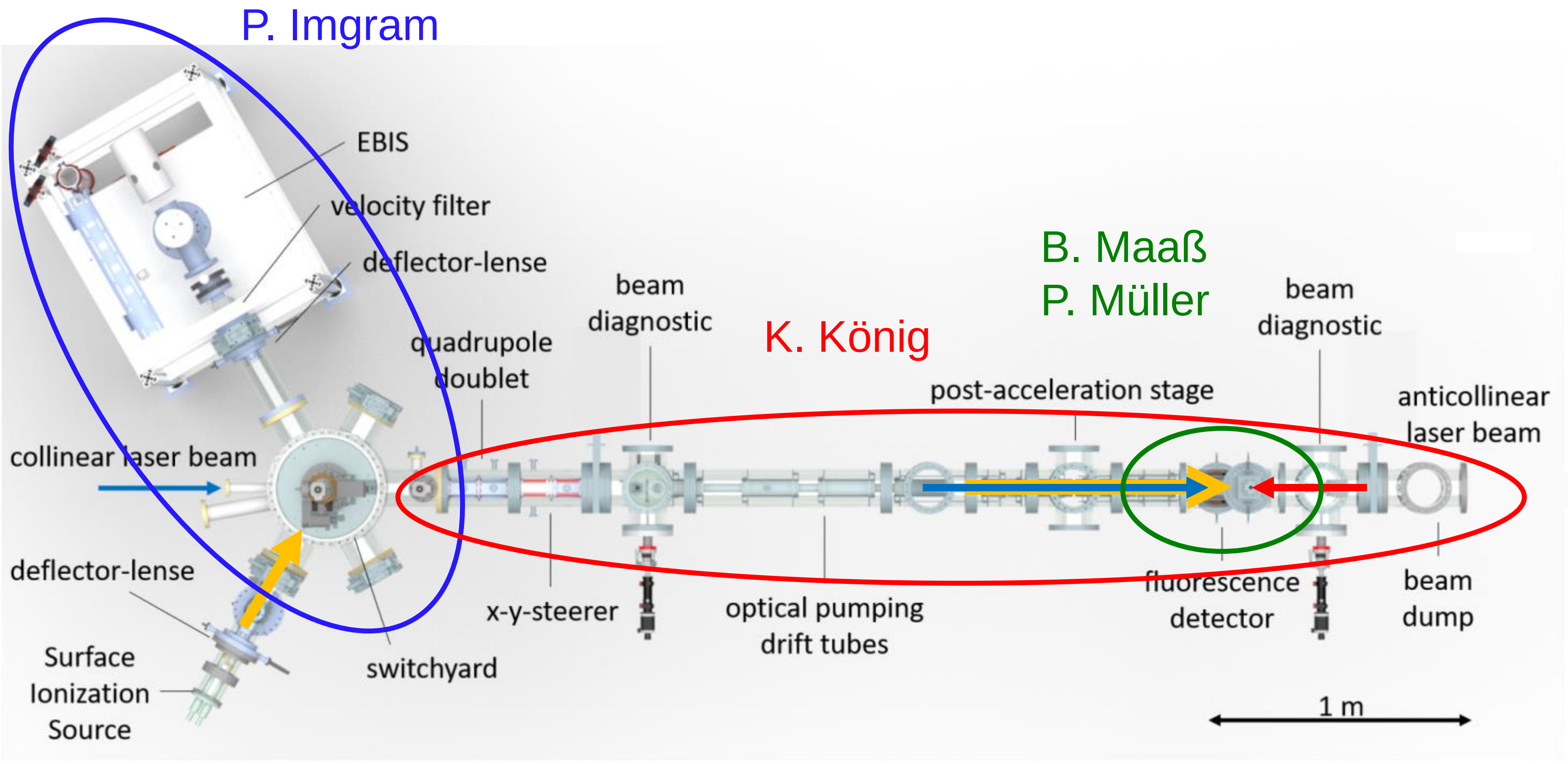
e⁻ scattering: $R_c(^{12}C) = 2.471(6)$ fm
I. Sick, PLB **116**, 212 (1982)

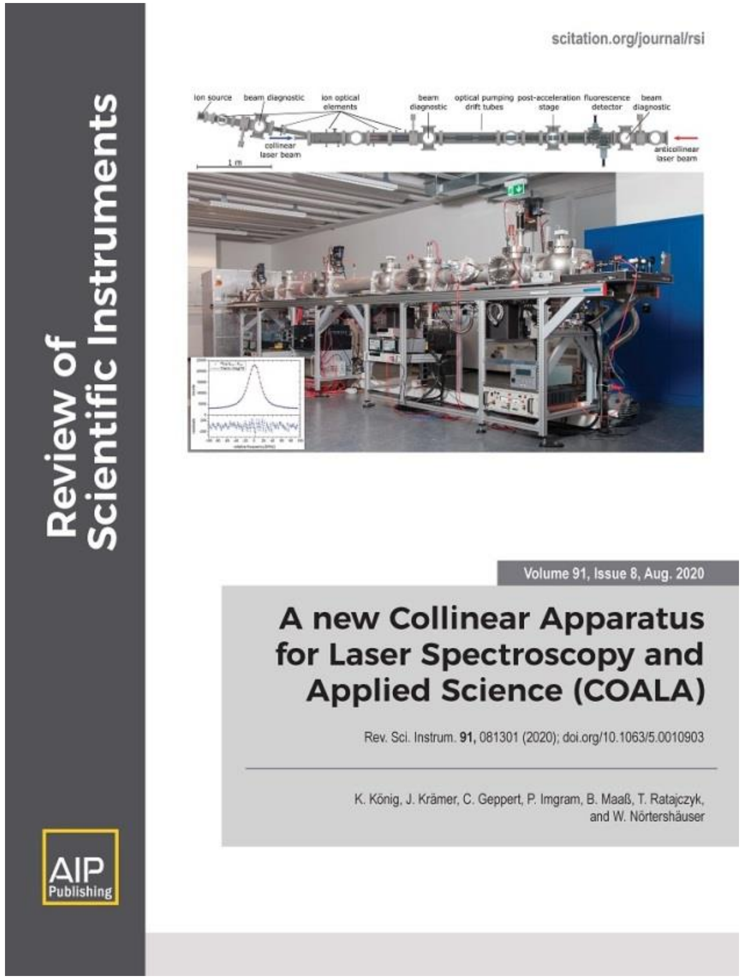
Muonic atoms: $R_c(^{12}C) = 2.4829(19)$ fm
W. Ruckstuhl *et al.*, NPA **430**, 685 (1984)

- Nuclear Charge Radius of ^{12}C well known
  → Test of Theory
- Easy to produce in an EBIS
- $\lambda \approx 227$ nm → Ti:Sa × 4 stabilized to frequency comb
- $I = 0 \rightarrow$ no hyperfine-structure induced level mixing

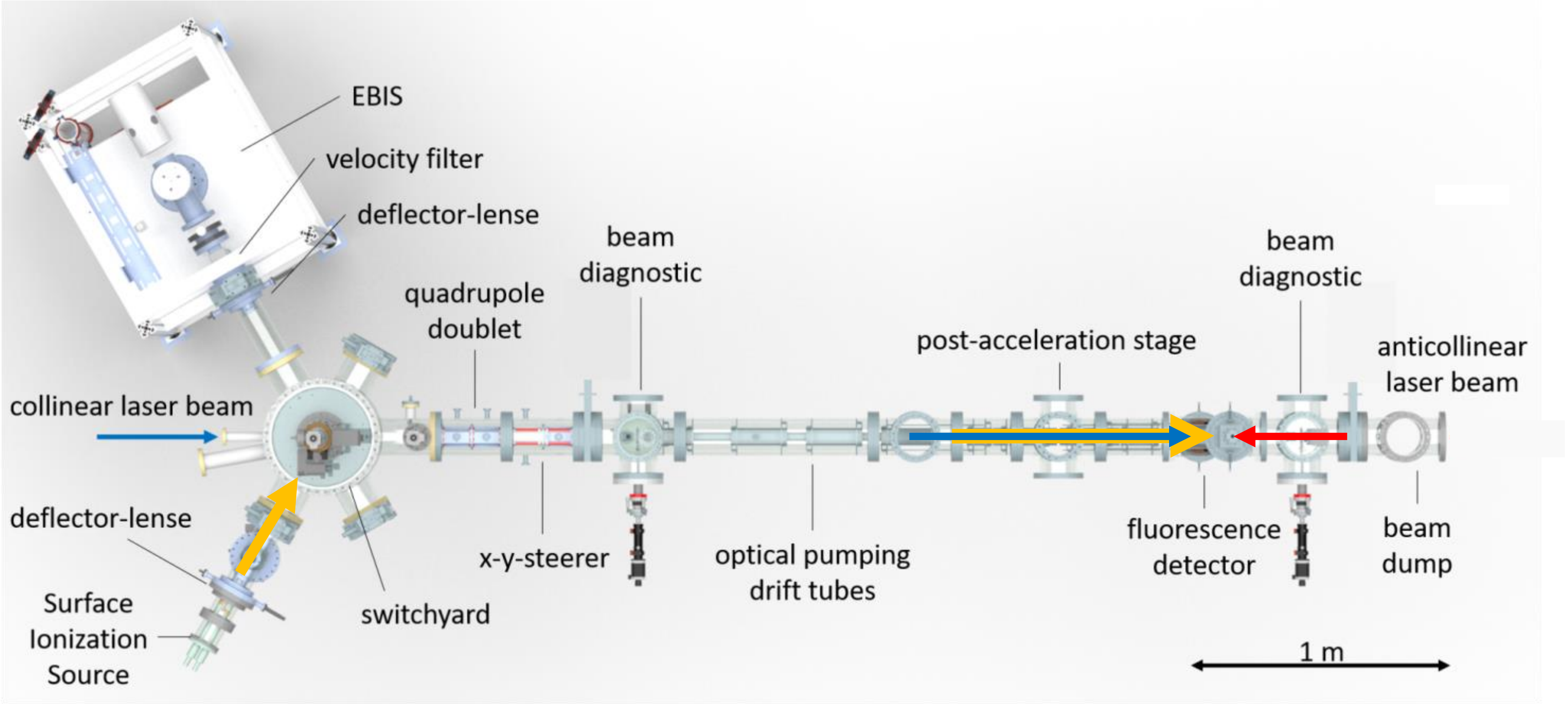
EXPERIMENTAL SETUP

COALA = Collinear Apparatus for Laser Spectroscopy and Applied Physics





Measurement Scheme



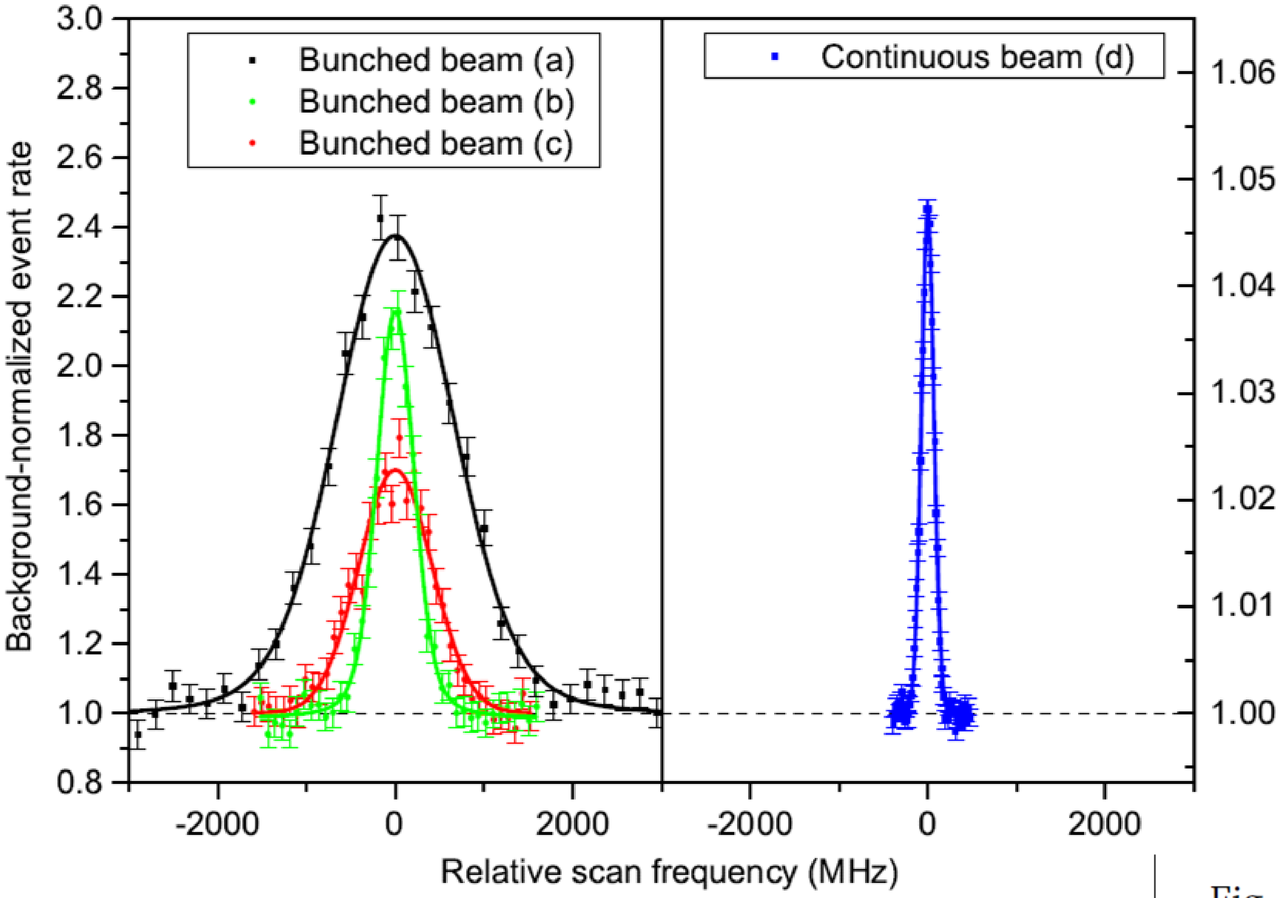
$$\left.\begin{aligned}\nu_c &= \nu_0\gamma(1+\beta)\\ \nu_a &= \nu_0\gamma(1-\beta)\end{aligned}\right\} \quad \boxed{\nu_c \cdot \nu_a = \nu_0^2\gamma^2 \cdot (1+\beta)(1-\beta) = \nu_0^2}$$

→ Measurement of ν_0 instead of $\delta\nu^{A',A}$ removes uncertainties caused by the inaccurate knowledge of β (and γ).

LASER SPECTROSCOPY

OPTIMIZATION AND RESULTS

Comparison of Pulsed and Continuous Extraction

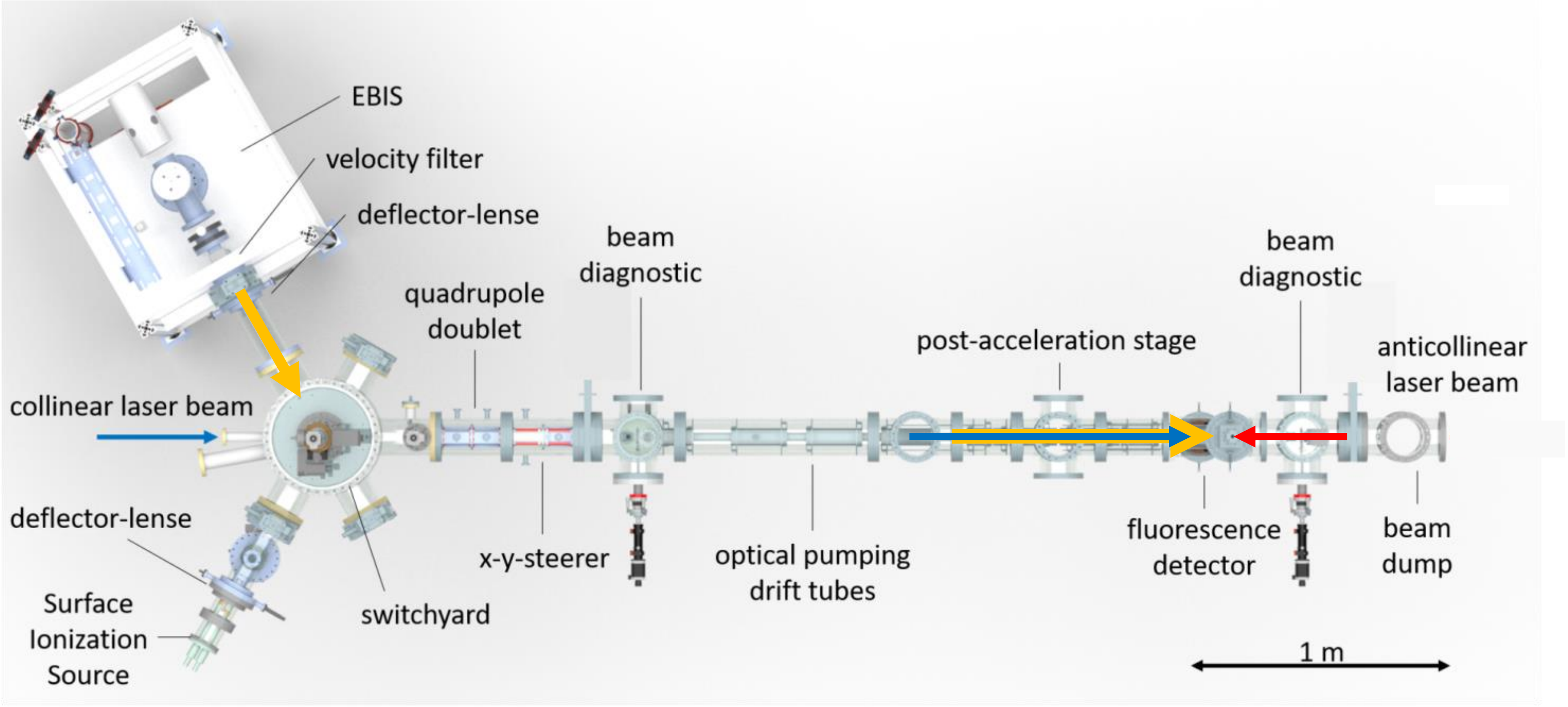


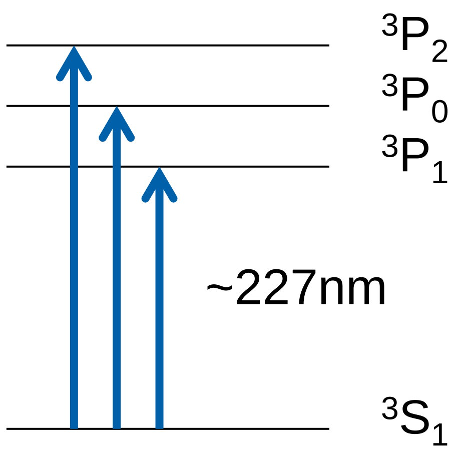
continuous extraction (leaky mode):

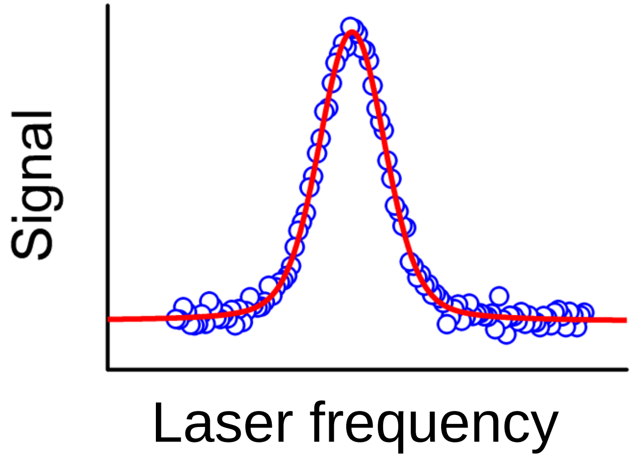
- good signal/noise ratio (similar to pulsed)
- smallest linewidth (gain factor 3)
- smallest statistical uncertainty for line centre

	Fig.	I_e / mA	ΔU_{trap} / V	p_{gas} / mbar	t_{breed} / ms	SNR	FWHM / GHz	$\Delta\nu_{center}$ / MHz
(a)	5.1/5.2	80	71	$6 \cdot 10^{-8}$	15	58	1.59(4)	16.6
(b)		25	26	$6 \cdot 10^{-8}$	15	51	0.50(1)	5.7
(c)	5.2	25	26	$2 \cdot 10^{-8}$	15	17	0.97(4)	17.8
(d)		80	171	$6 \cdot 10^{-8}$	leaky	59	0.168(2)	0.7

Laser spectroscopy of He-like ions





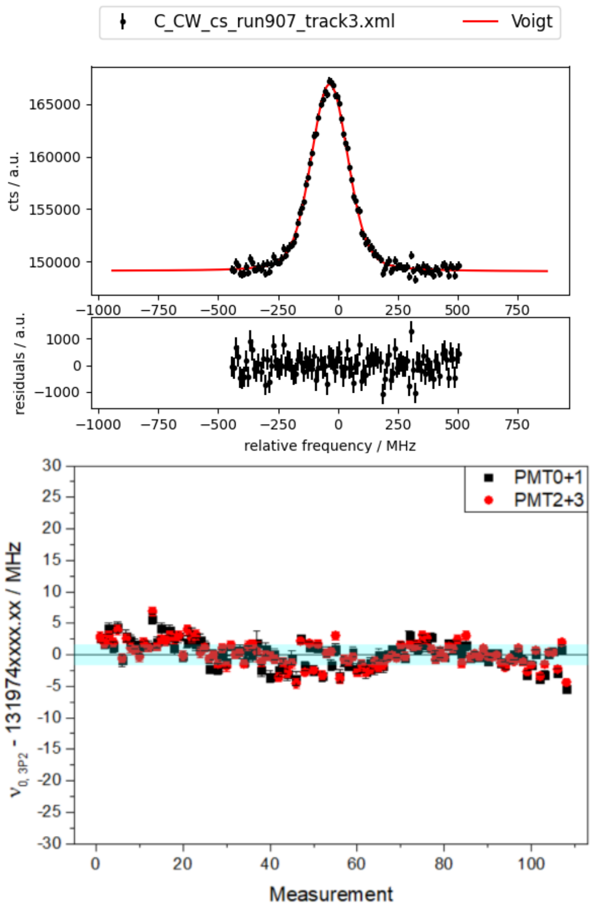


$$\nu_c = \nu_0 \gamma (1 + \beta)$$
$$\nu_a = \nu_0 \gamma (1 - \beta)$$

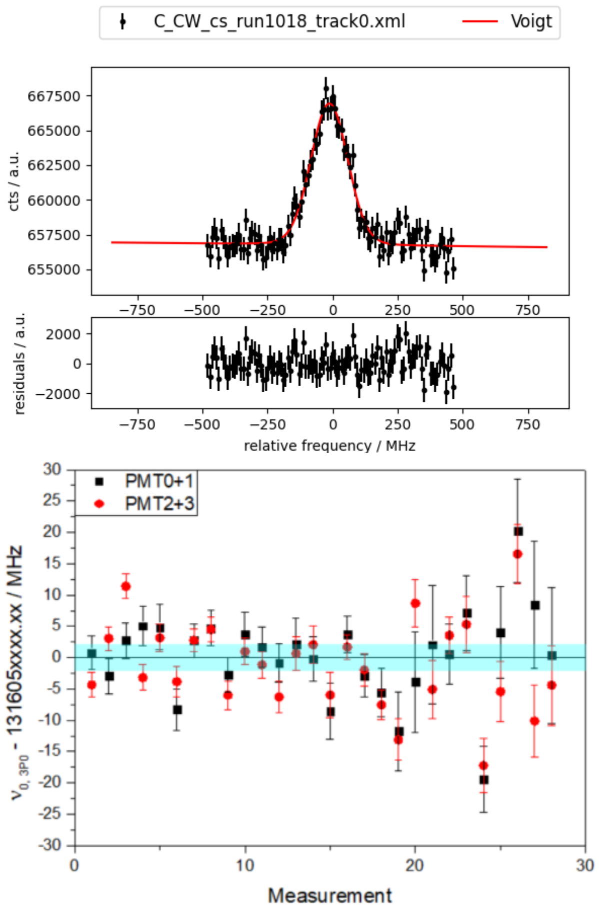
$$\nu_c \cdot \nu_a = \nu_0^2 \gamma^2 \cdot (1 + \beta)(1 - \beta) = \nu_0^2$$

Laser spectroscopy results for $^{12}C^{4+}$

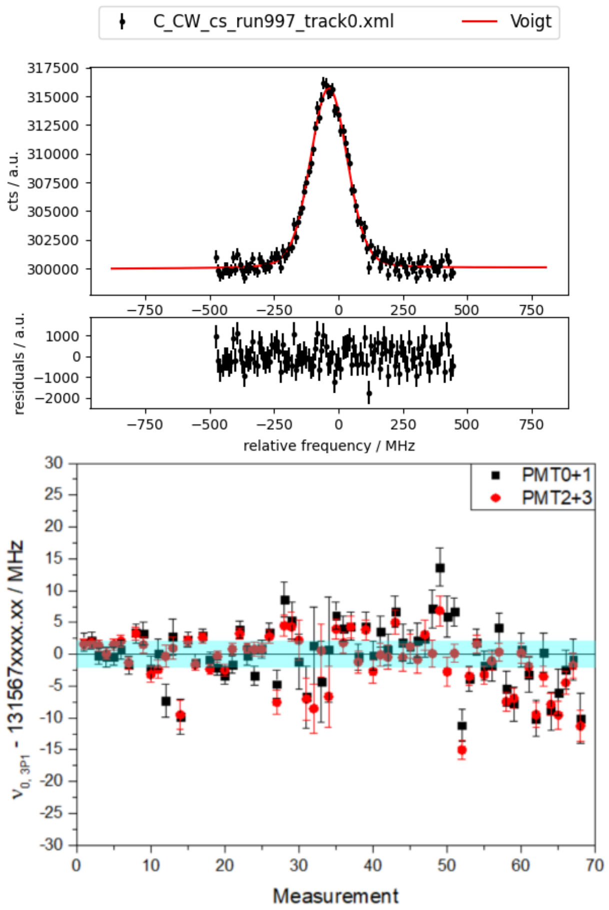
$^3P_2$

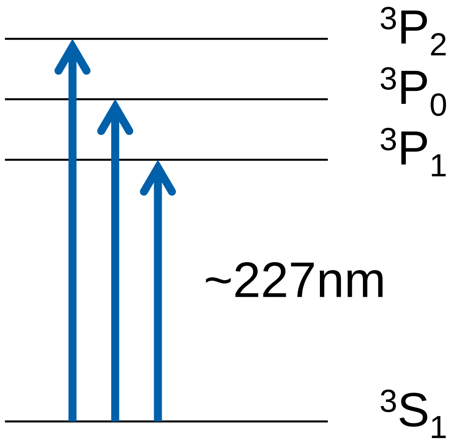


$^3P_0$

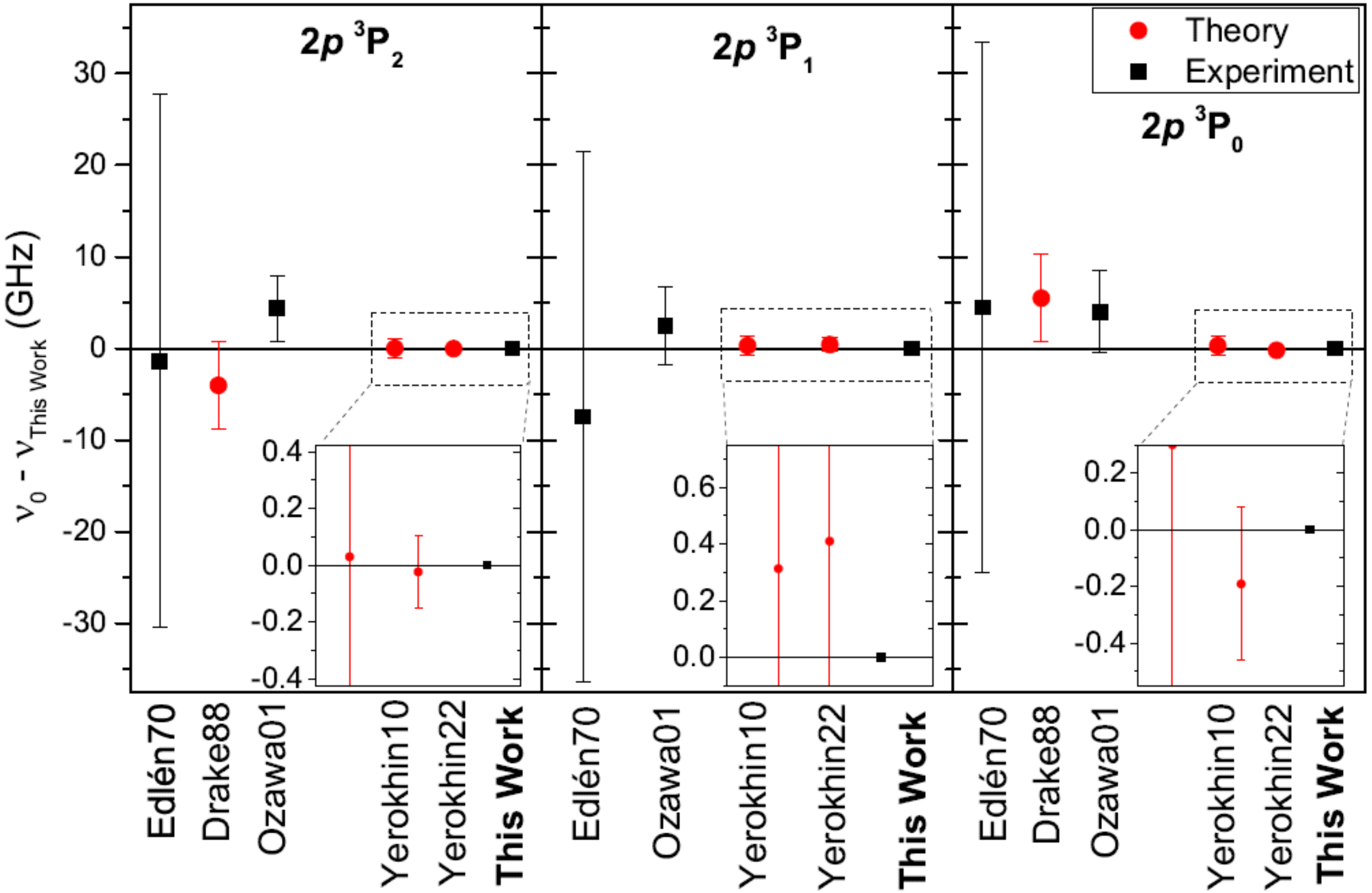


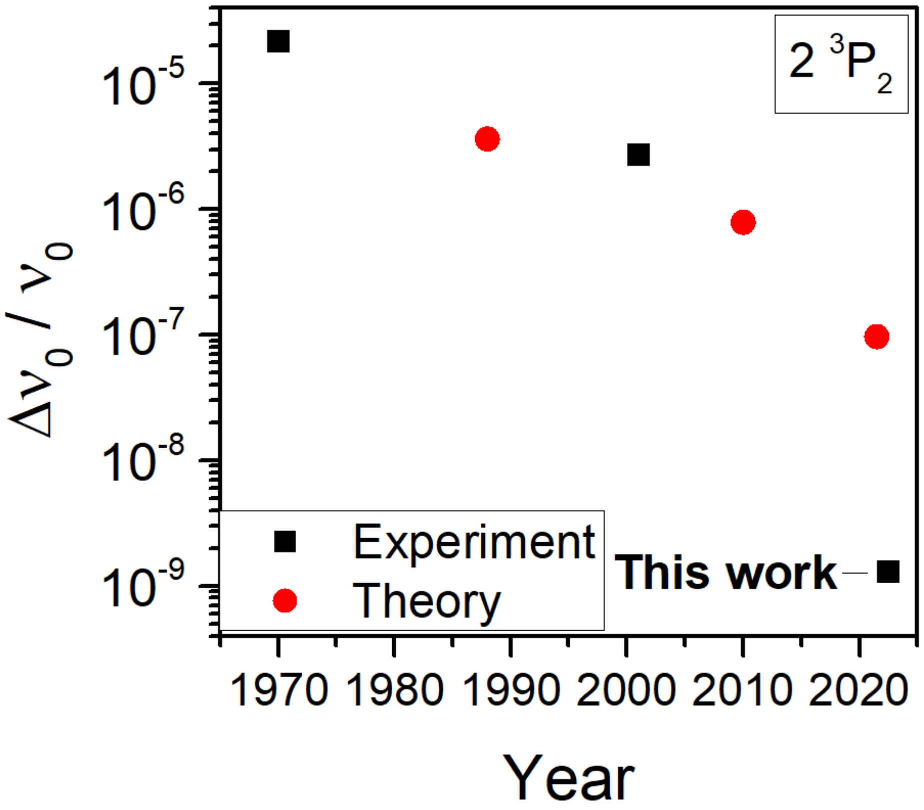
$^3P_1$





Transition Frequencies: Comparison to Literature





Uncertainty Budget and Fine Structure Splitting

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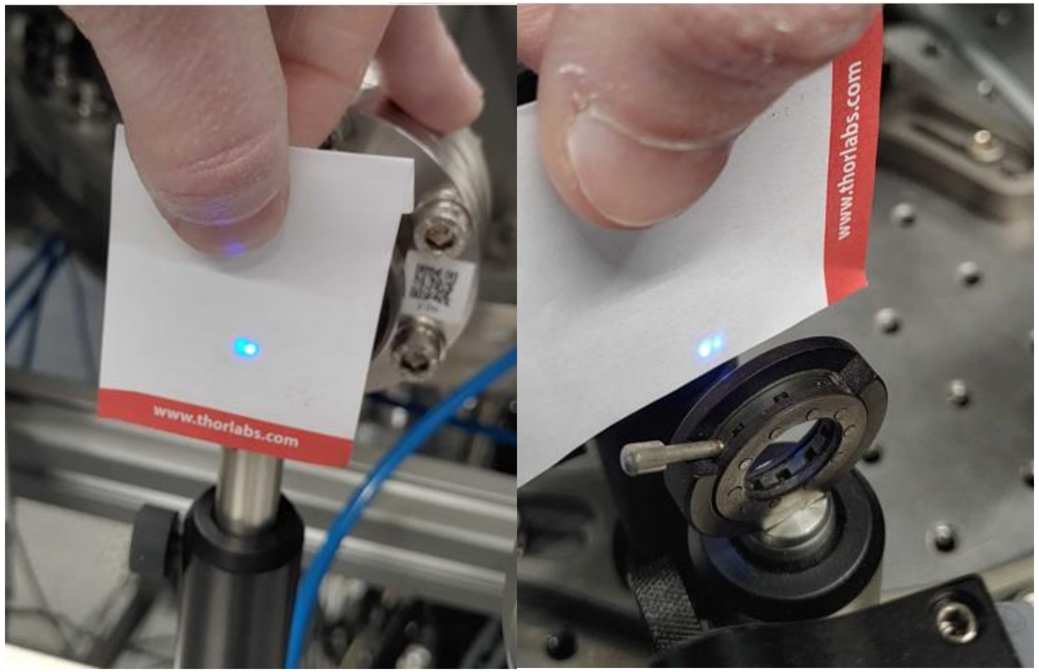
TABLE IV. All investigated systematic uncertainties in MHz. The main systematic uncertainty originates from the alignment of the two laser beams.

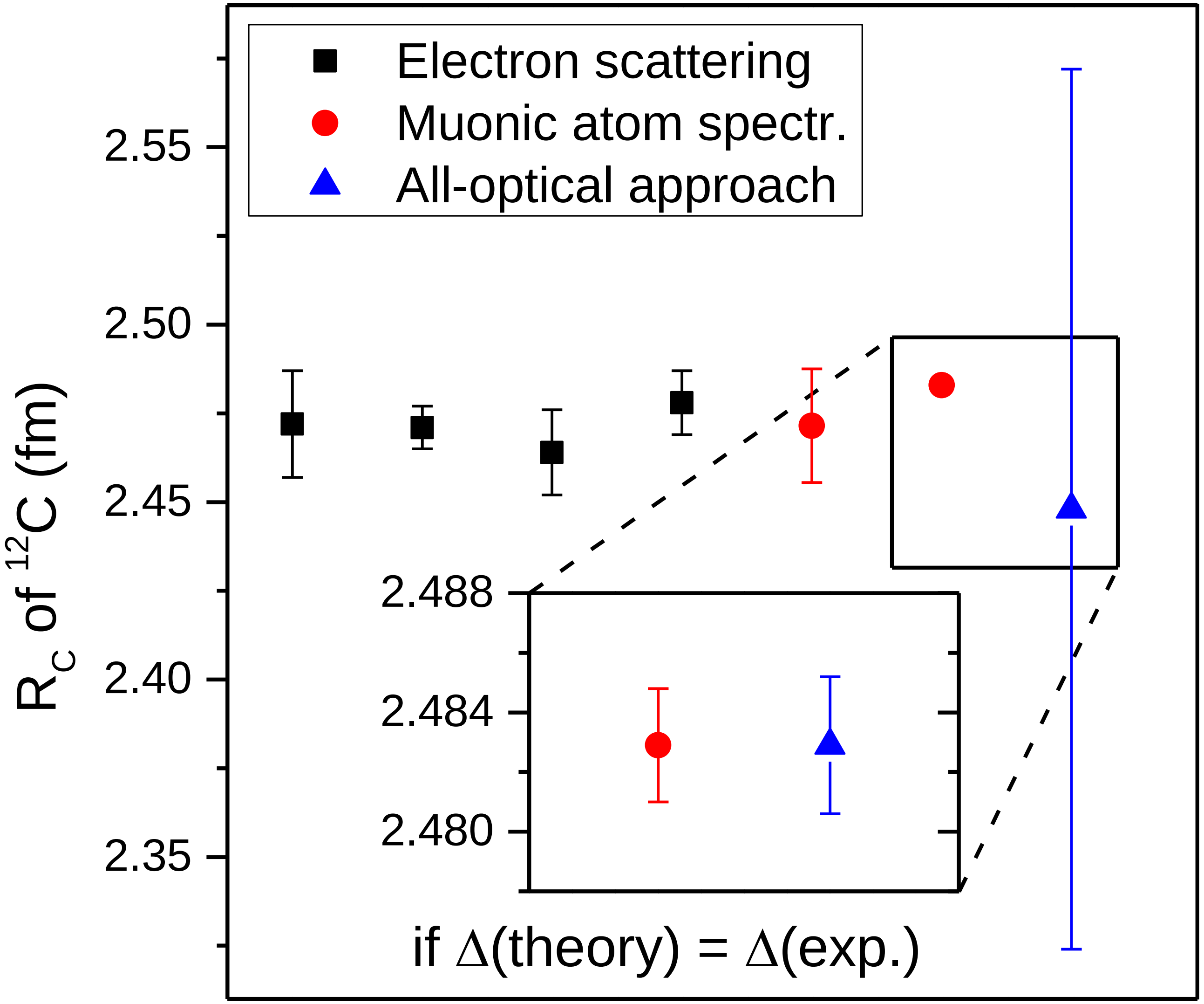
Uncertainty	
Line shape	<0.01
Start potential	0.01
Beam alignment	1.7
Photon recoil	<0.1
Scan voltage	<0.07
Laser polarization	0
Total	1.7



(J, J')	This work	Theory [52]	$m\alpha^{8+}$ contr.
$(0,1)$	$-375\,026.5\,(2.5)$	$-374\,996.3\,(48.0)$	$-30.2\,(2.5)$
$(0,2)$	$3\,696\,352.1\,(2.5)$	$3\,696\,343.5\,(10.0)$	$8.6\,(2.5)$

Relatively large contribution of higher orders
$\Rightarrow$ may guide further QED calculations

First all-optical nuclear charge radius of ^{12}C



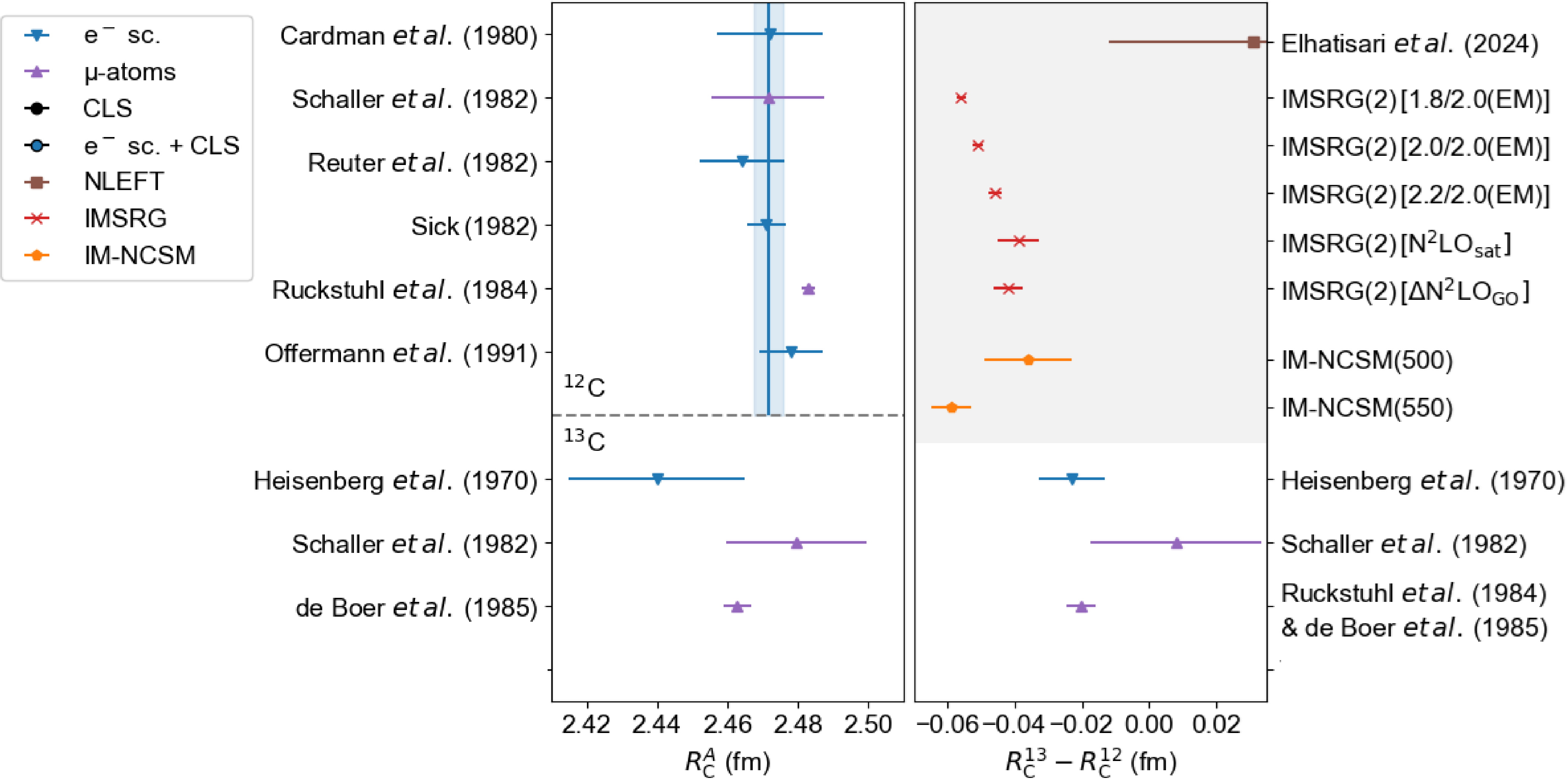
→ more work needed for competitive all-optical R_C

If **theory** gets **better by two orders of magnitude,** we are **competitive** with the most precise **muonic atom results.**

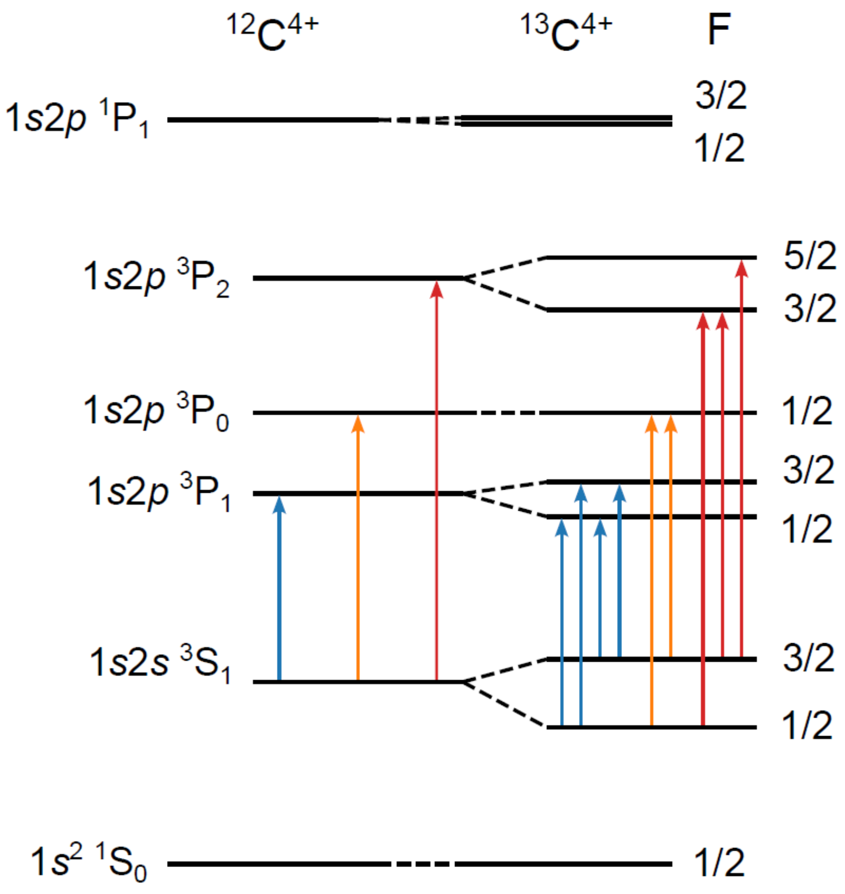
→ may resolve the discrepancies between muonic and elastic electron scattering results

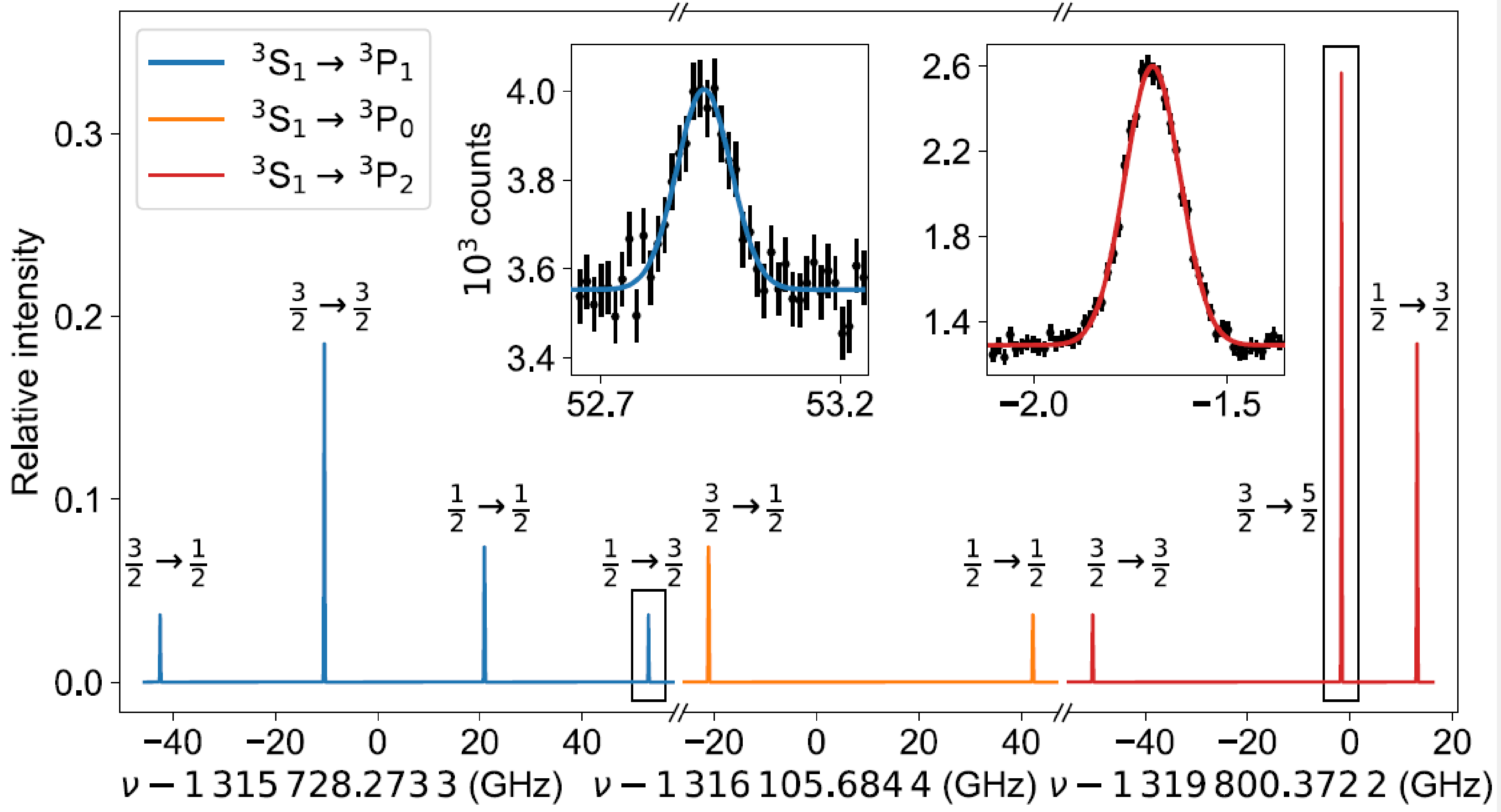
First high-precision laser spectroscopy in C isotope chain
→ starting point for regular isotope shift measurements to extract $\delta\langle r^2\rangle$ **of ^{13}C and ^{14}C**

Motivation for ^{13}C



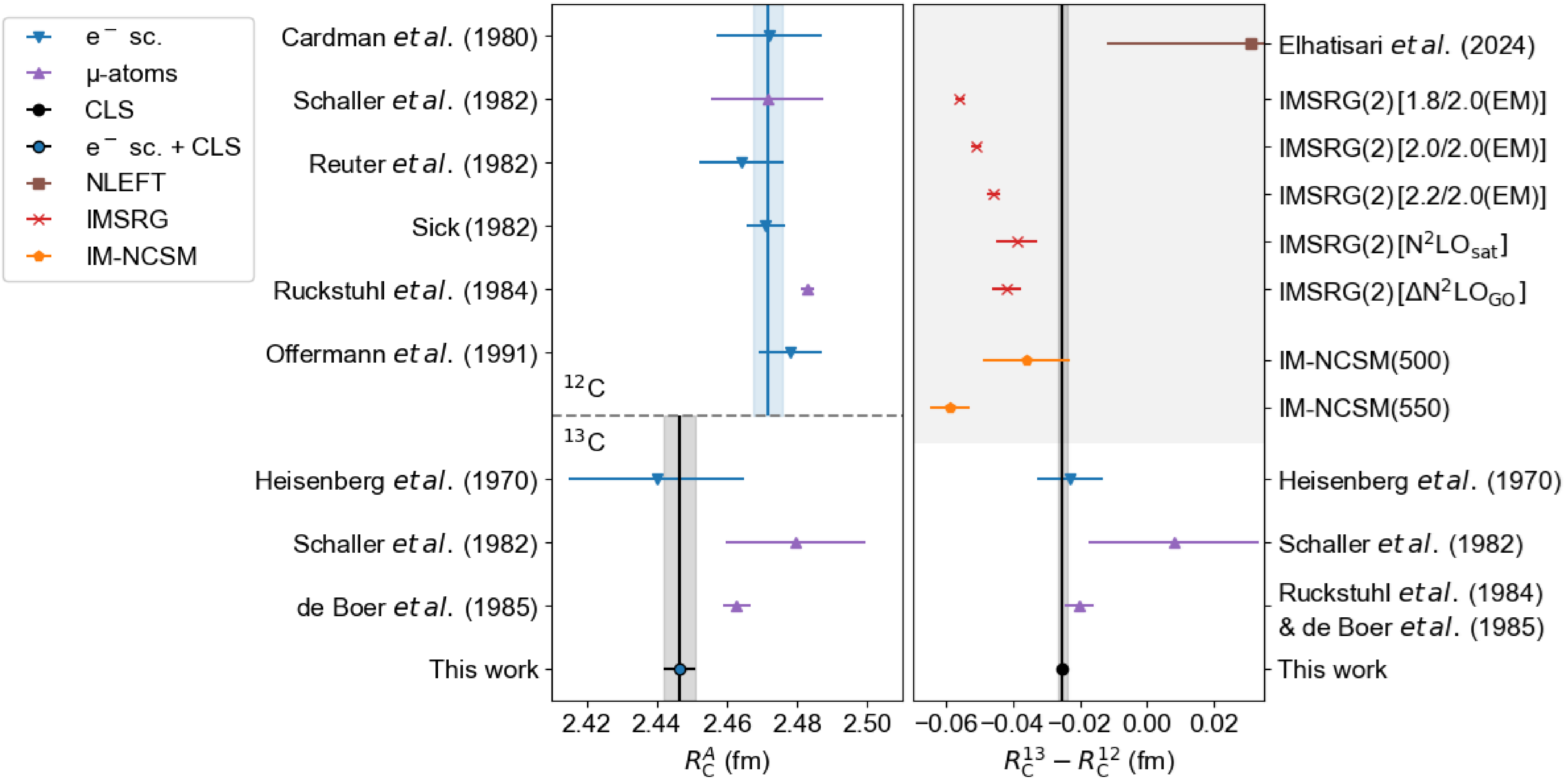
Spectrum of ^{13}C



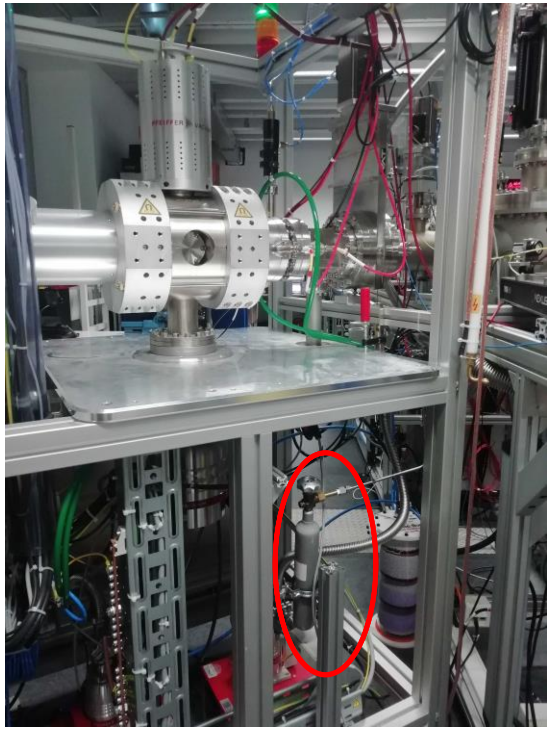


Mixed HFS calculated using matrix elements from
Johnson et al., Phys. Rev. A **55**, 2728 (1997)

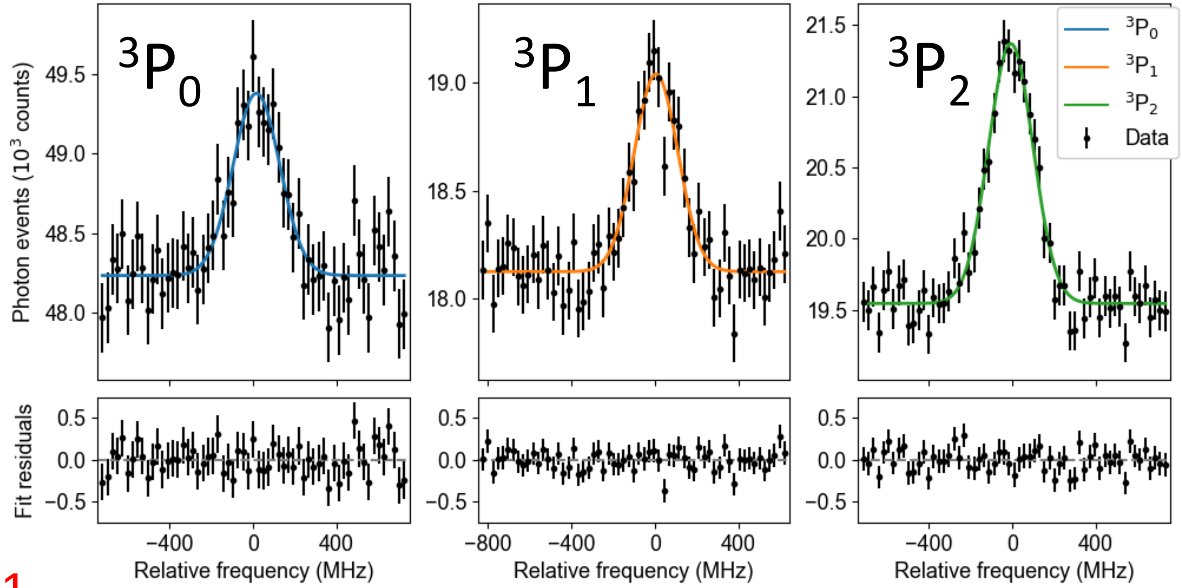
The Nuclear Charge Radius of ^{13}C

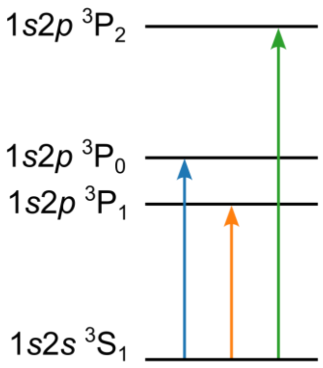


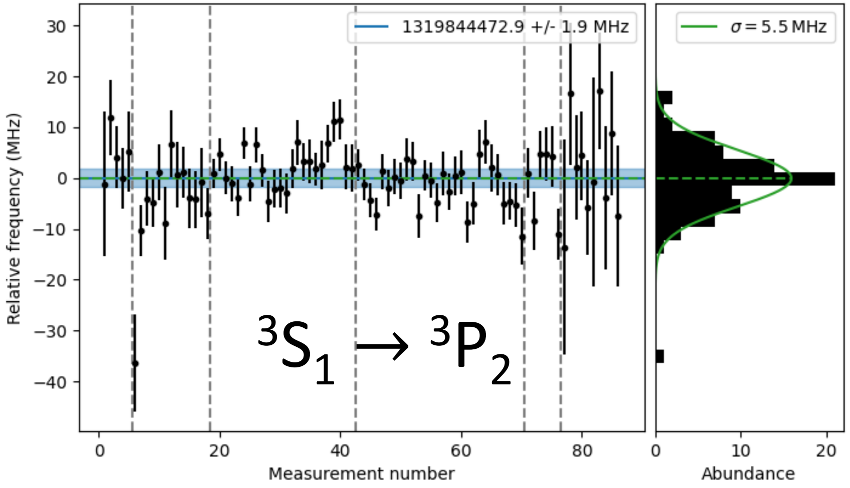
Measurements of ^{14}C



$^{14}CO_2$:$^{12}CO_2$ = 1:1
1.4 l, 50 mbar,
2 mmol ^{14}C, 50 mCi



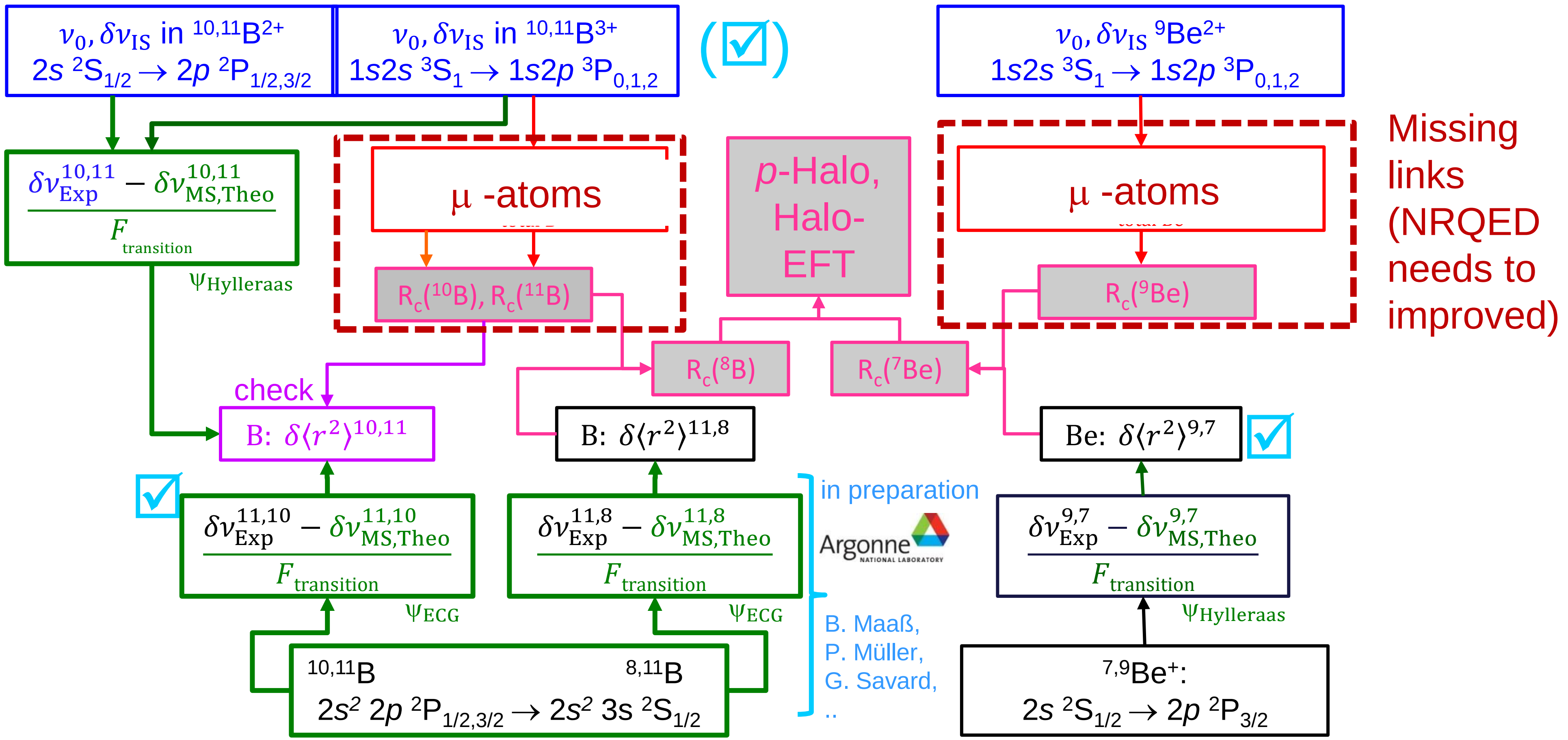




Analysis ongoing … stay tuned

- Determination of the $^3S_1 \rightarrow {}^3P_J$ transition frequencies in $^{14}C^{4+}$ on a 2-MHz precision level
- Extraction of the differential nuclear charge radius $\delta\langle r^2\rangle^{12,14}$ from the isotope shifts
- Additional check of theory: Splitting Isotope Shift

Measurement of the Proton-Halo of ^{8}B



Experimental data, multiply charged

Experimental data: neutral or singly charged

Conventional mass-shift calculations

Theory of He-like systems

Consistency Checks

Goal

Outlook

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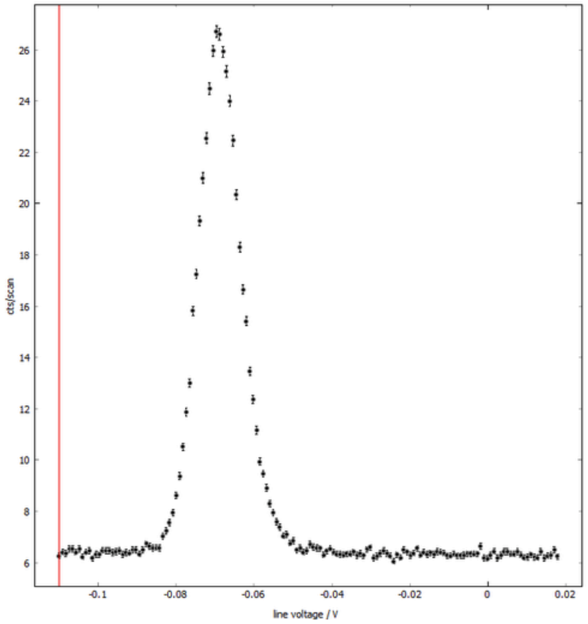
Atomic structure theory (NR-QED calculations)

- Remaining uncertainty originating from **neglected higher order terms** ($m\alpha^{8+}$)
  → Measured fine-structure splitting in $^{12}C^{4+}$ will **benchmark new calculations**
- This will **improve** the extraction of **α** from fine-structure measurements in He & (hopefully) as well the all-optical nuclear charge radius determination
- For Boron a factor 3 in improvement would already be sufficient

He-like ions at COALA

- Measurement of $^{14}C^{4+}$ already completed
  → TBP
- $^{10,11}B^{3+}$ ongoing
  @ 280 nm



- $^{10,11}B^{2+,0}$
- @ 206 nm, 250 nm until June 2025
- $^{9}Be^{2+}$ in 2025
  → Feeding of Be^{+} into EBIS needs further development

Far-Reach: Measurements on Short-Lived Isotopes (LOI INTC-I-265)

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Physics cases:

- **$^{7}Be^{2+}$** (QP moment & Zemach radius)
  → influence in $^{7}Be(p, \gamma)^{8}B$ reaction rate

- **$^{8}B^{2+,3+}$** (QP moment & CR)
  → consistency check or even improvement to Argonne experiment

- **$^{12,13,14}B^{2+,3+}$** (CR & moments)
  → Radii across N=8 shell closure, important benchmarks for nuclear ab-initio calc.

- **$^{15,16}C^{4+}$** (CR & moments)
  → similar to B

	$\tau(2\,^3S_1)$	$\lambda(2\,^3S \rightarrow 2\,^3P)$
He	2.2 h	1082 nm
Li^{+}	50 s	548 nm
Be^{2+}	1.8 s	372 nm
B^{3+}	150 ms	282 nm
C^{4+}	21 ms	227 nm
N^{5+}	3.9 ms	190 nm

But first: Consider and find the most efficient way to produce the ions and populate the $^{3}S_{1}$ state → LOI

Thank you!

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DFG Deutsche Forschungsgemeinschaft

SFB 1245

Federal Ministry of Education and Research

HFHF Helmholtz Forschungsakademie Hessen für FAIR

HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research