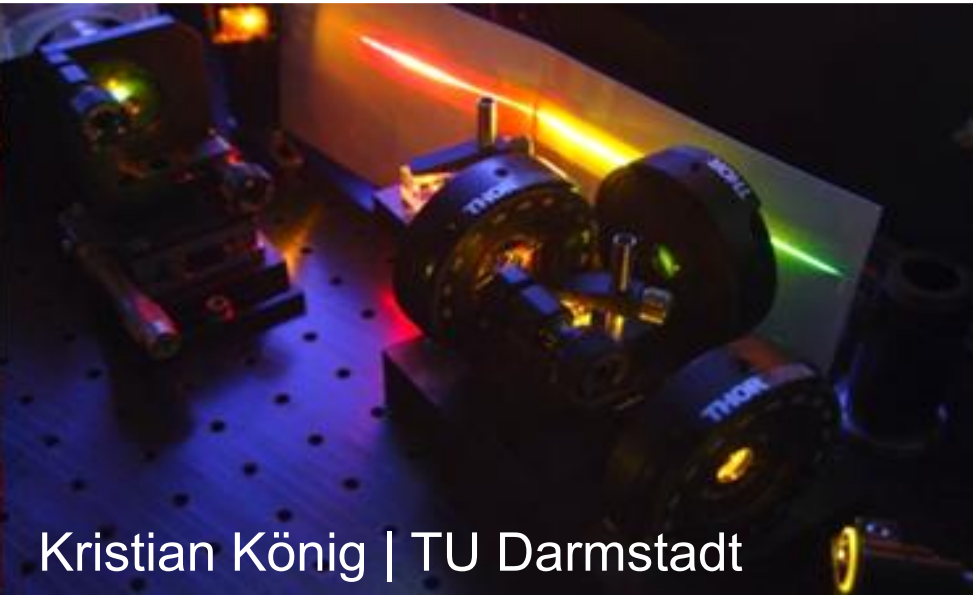
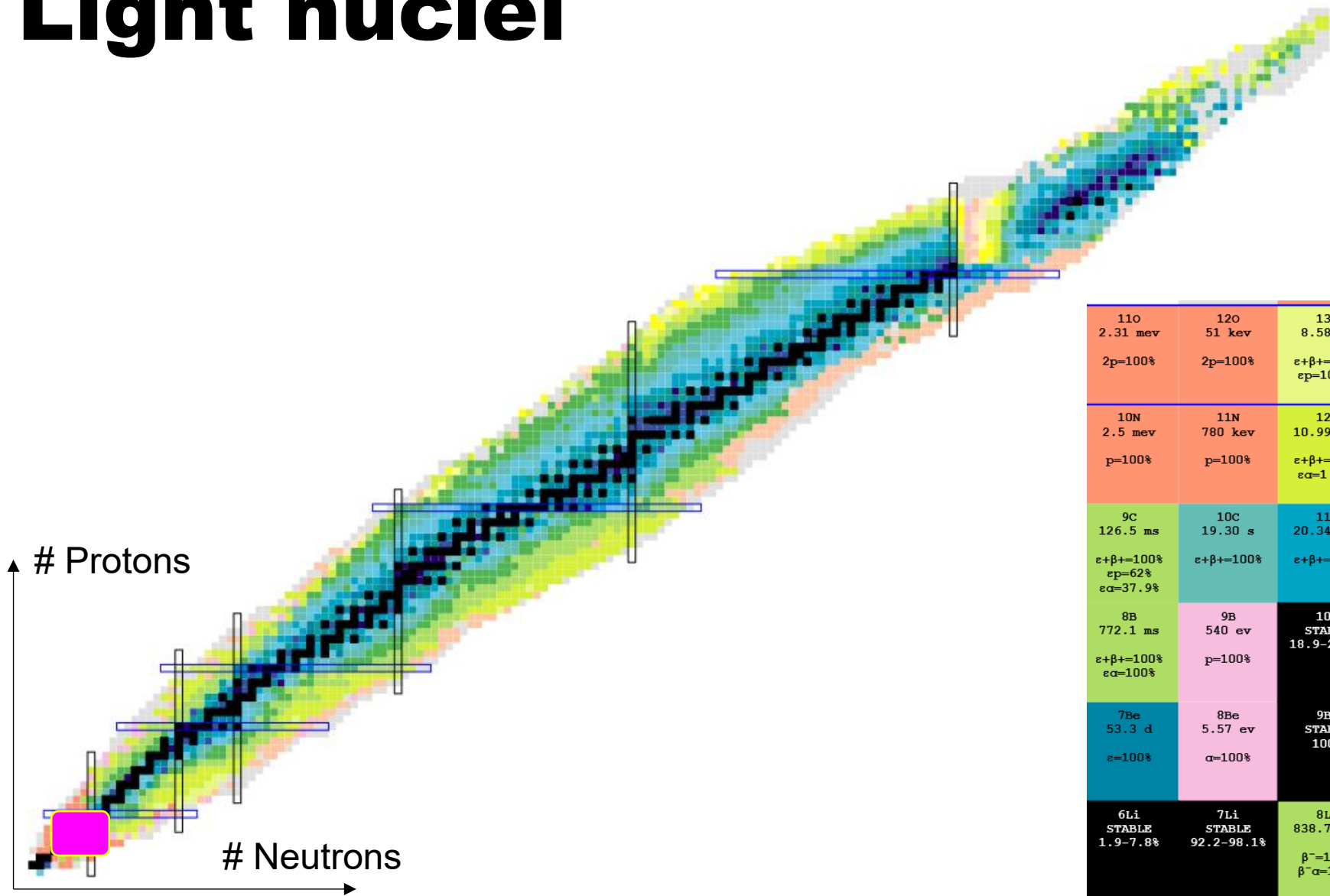


Collinear laser spectroscopy in $^{12-14}\text{C}$



Light nuclei

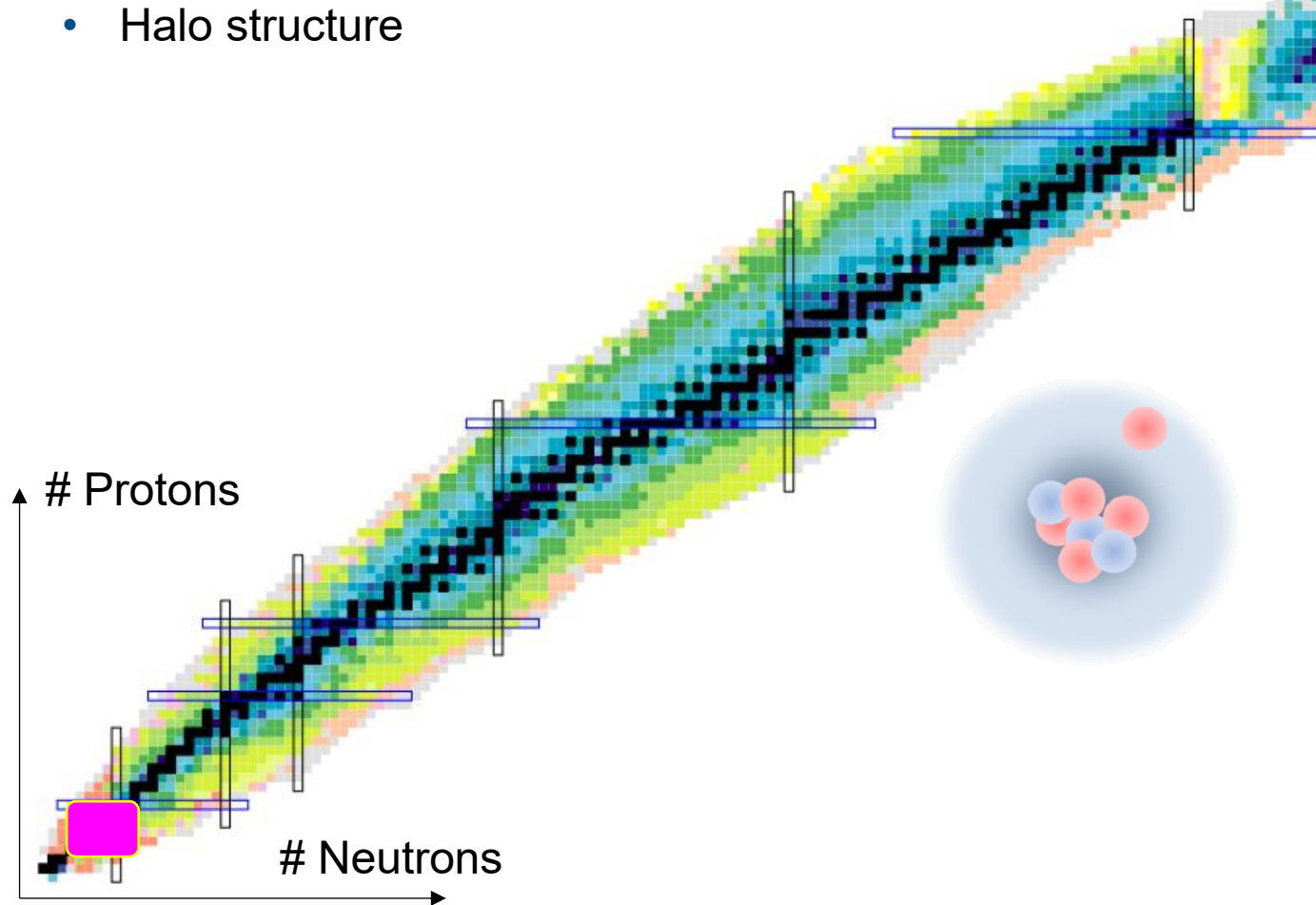


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10N 2.5 mev p=100%	11N 780 kev p=100%	12N 10.996 ms e+β+=100% εα=1.93%	13N 9.967 min e+β+=100%	14N STABLE 99.578-99.663%	15N STABLE 0.337-0.422%	16N 7.13 s β ⁻ =100% β ⁻ α=1.54e-3%	17N 4.171 s β ⁻ =100% β ⁻ n=95.1% β ⁻ α=2.5e-3%
9C 126.5 ms e+β+=100% εp=62% εα=37.9%	10C 19.30 s e+β+=100%	11C 20.34 min e+β+=100%	12C STABLE 98.84-99.04%	13C STABLE 0.96-1.16%	14C 5686 y β ⁻ =100%	15C 2.451 s β ⁻ =100%	16C 750 ms β ⁻ =100% β ⁻ n=99.28%
8B 772.1 ms e+β+=100% εα=100%	9B 540 ev p=100%	10B STABLE 18.9-20.4%	11B STABLE 79.6-81.1%	12B 20.22 ms β ⁻ =100% β ⁻ α=0.6%	13B 17.16 ms β ⁻ =100% β ⁻ n=0.266%	14B 12.34 ms β ⁻ =100% β ⁻ n=6.04%	15B 10.18 ms β ⁻ =100% β ⁻ n=99.68% β ⁻ 2n<1.5%
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6Li STABLE 1.9-7.8%	7Li STABLE 92.2-98.1%	8Li 838.79 ms β ⁻ =100% β ⁻ α=100%	9Li 178 ms β ⁻ =100% β ⁻ n=51% β ⁻ α=12.3%	10Li 0.23 mev n=100%	11Li 8.75 ms β ⁻ =100% β ⁻ n=84.3% β ⁻ 2n=4.2%	12Li n=100%	13Li 125 kev 2n=100%

<https://www.nndc.bnl.gov/nudat3/>

Light nuclei

- Alpha clustering
- Halo structure

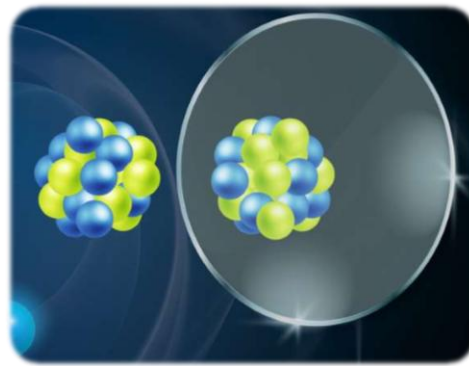
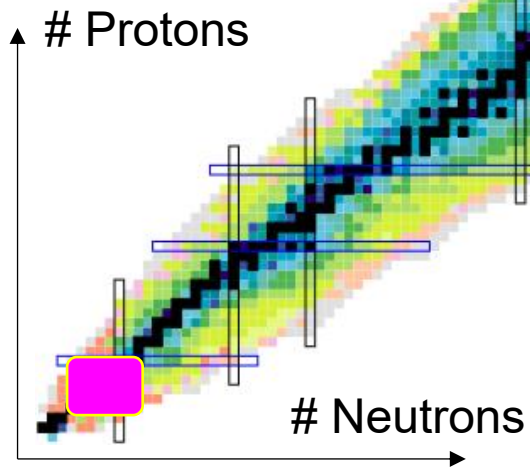


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<https://www.nndc.bnl.gov/nudat3/>

Light nuclei

- Alpha clustering
- Halo structure
- Mirror nuclei



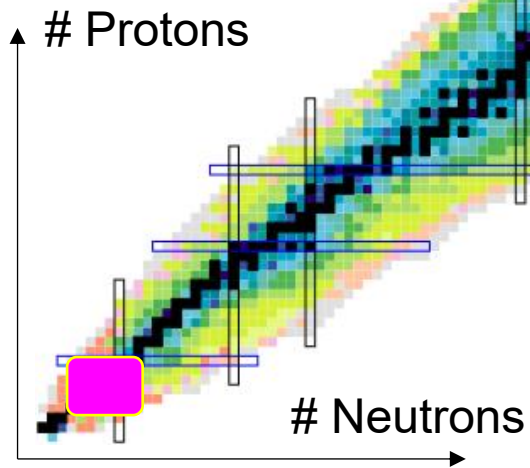
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<https://phys.org/news/2021-11-mirror-nuclei-probe-fundamental-physics.html>

<https://www.nndc.bnl.gov/nudat3/>

Light nuclei

- Alpha clustering
- Halo structure
- Mirror nuclei
- Superallowed β decays

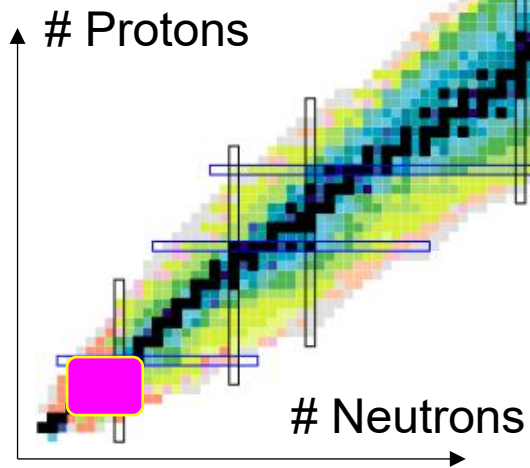


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<https://www.nndc.bnl.gov/nudat3/>

Light nuclei

- Charge radii known with limited accuracy
- Relative and absolute charge radius measurement
- Experimentally challenging:
 - Deep UV laser transition
 - Small field shift



Ideal systems to test atomic and nuclear theory

- Nuclear *ab initio* theory of high order available
- Atomic theory tests: Mass and field shift & splitting isotope shift

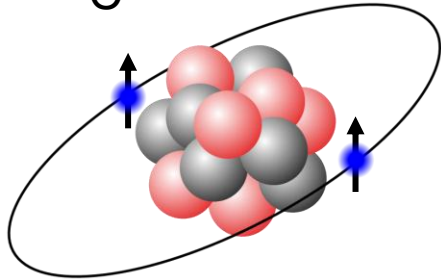


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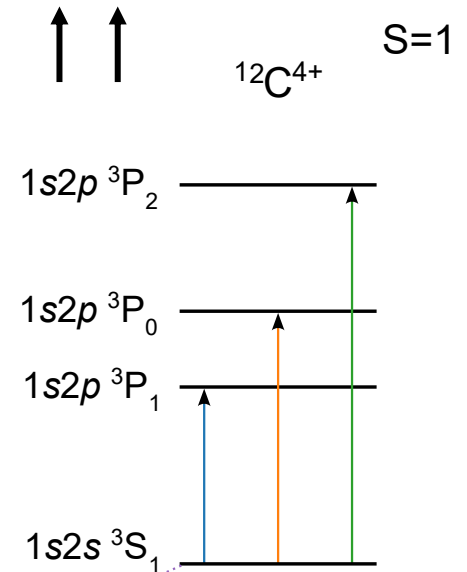
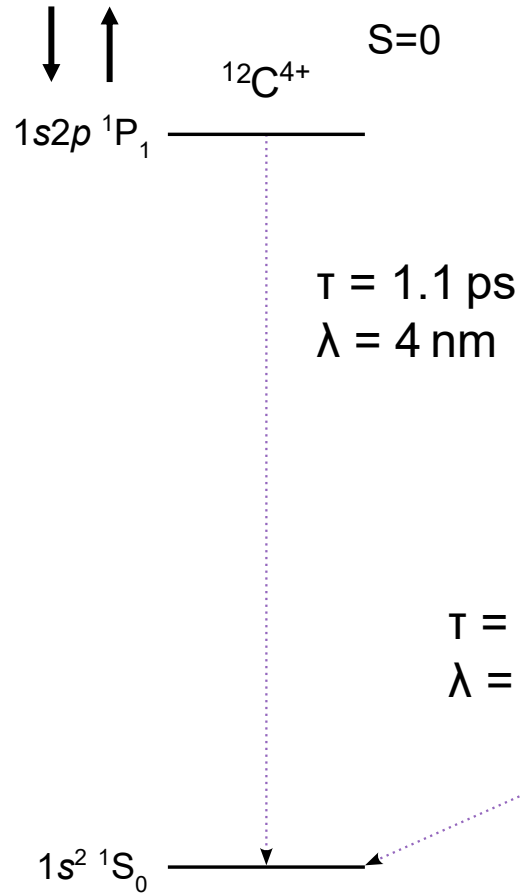
<https://www.nndc.bnl.gov/nudat3/>

Helium-like ions

$^{12,14}\text{C}^{4+}$

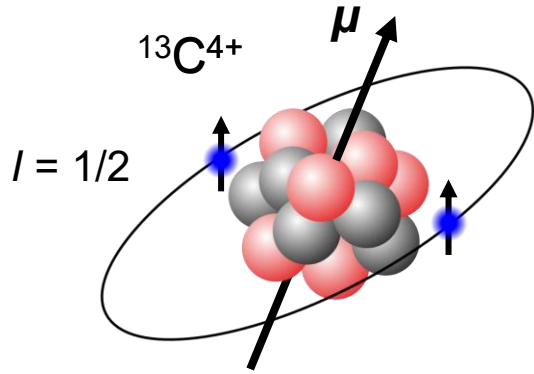


- C not charged, too many electrons
- C^+ no laser transitions
- C^{2+} no laser transitions
- C^{3+} no laser transitions
- C^{4+} 227.6 nm transitions
- C^{5+} no laser transitions

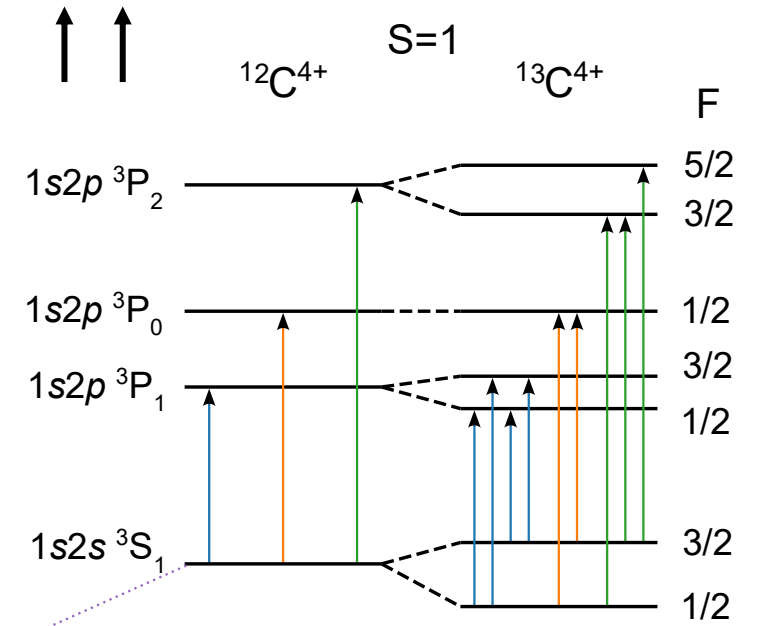
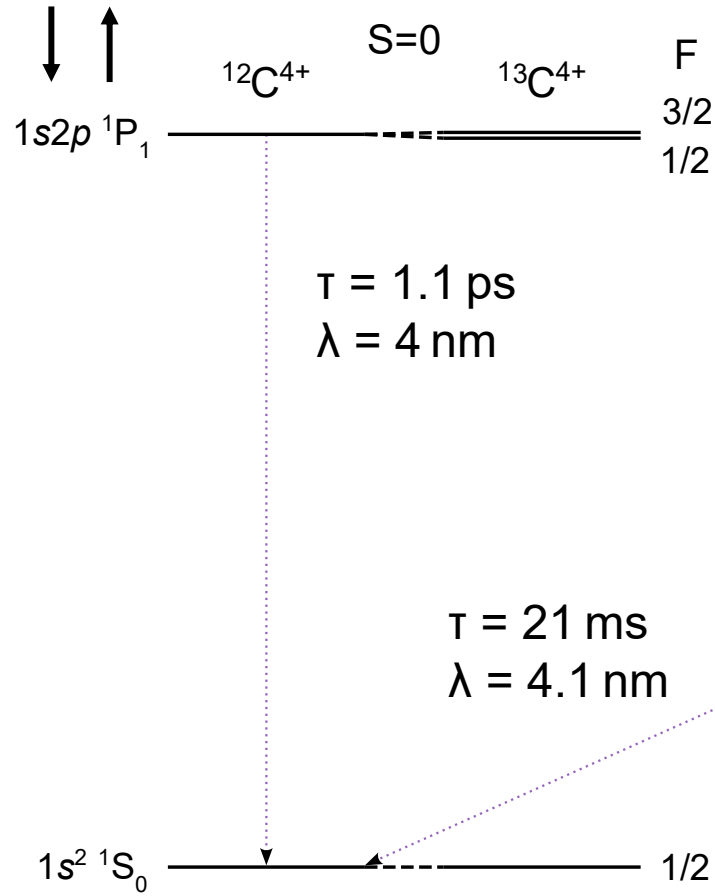


Laser-addressable transitions in the triplet system at a wavelength of $\lambda = 227.6\text{ nm}$

Helium-like ions

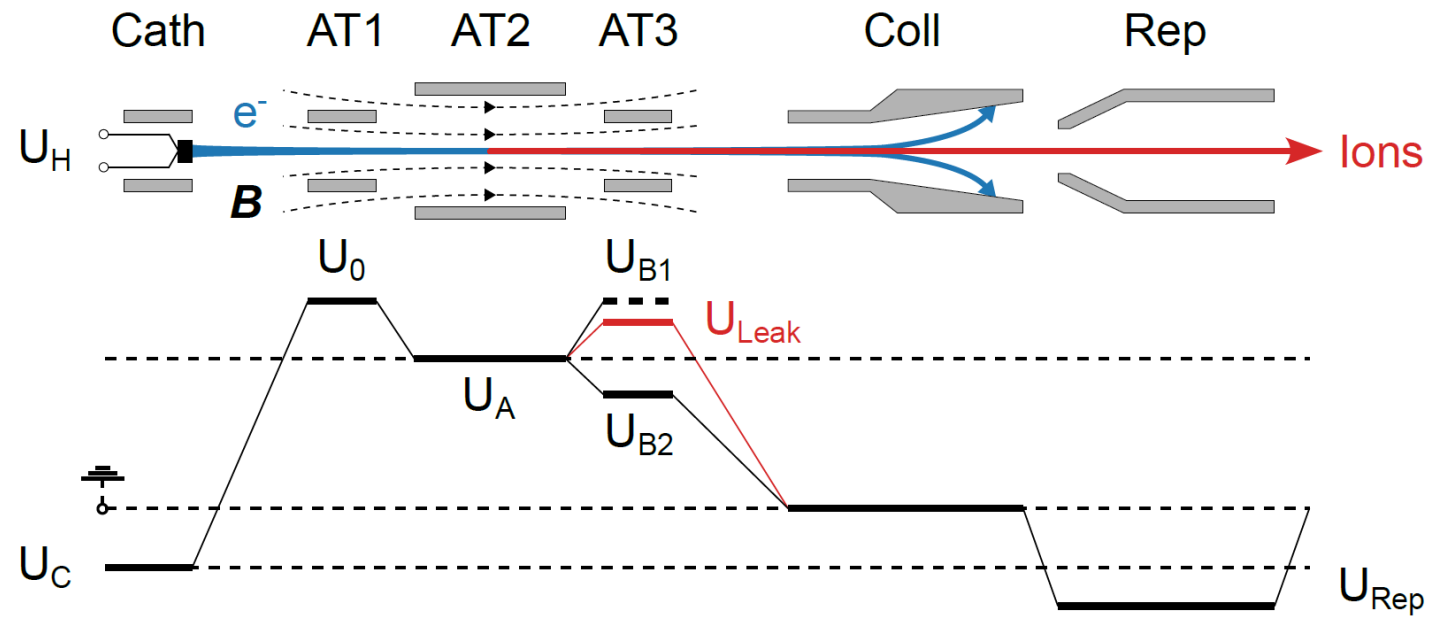
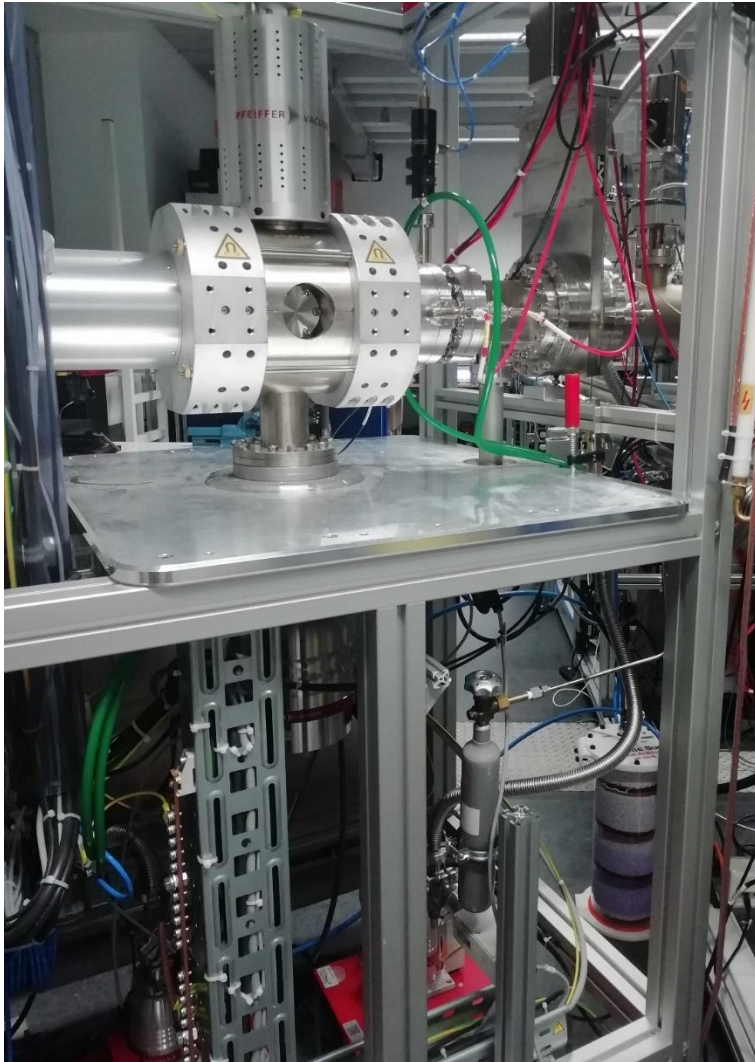


- C not charged, too many electrons
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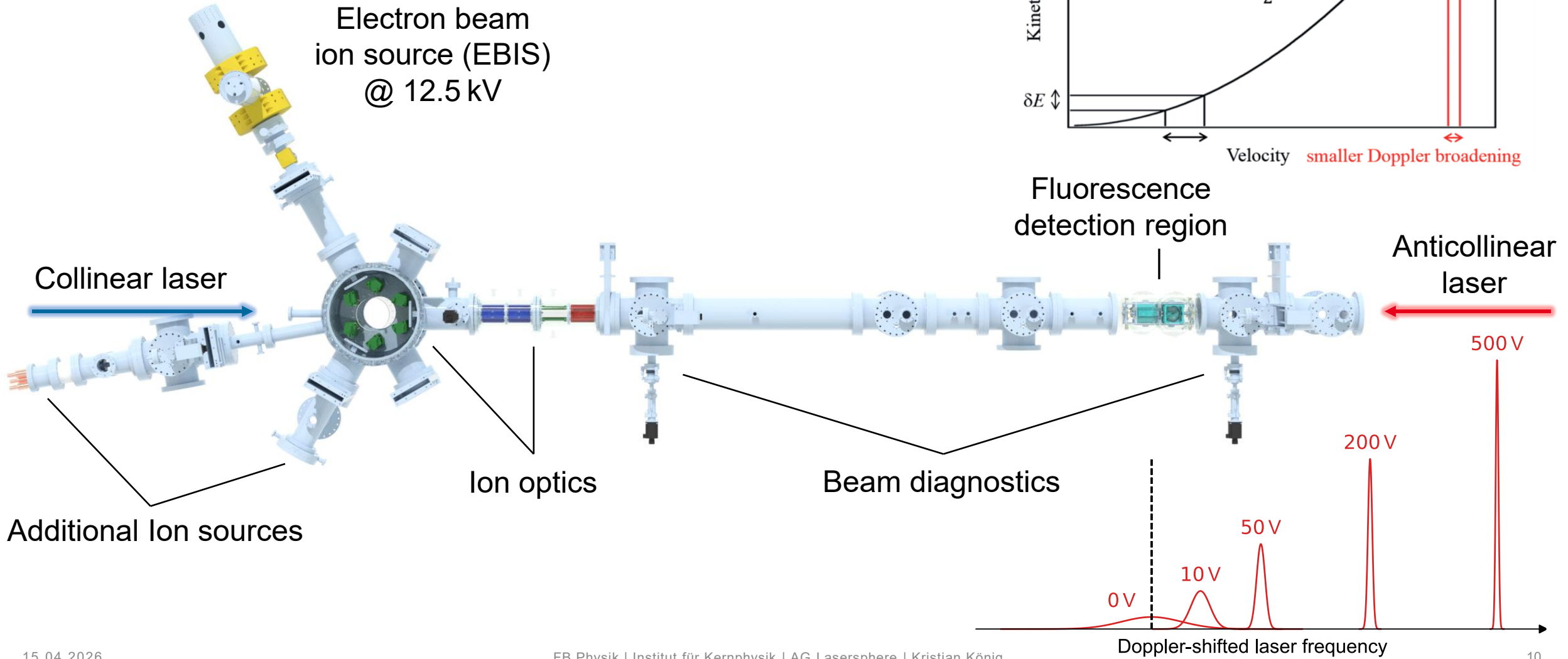
Laser-addressable transitions in the triplet system at a wavelength of $\lambda = 227.6\ \text{nm}$

Electron beam ion source

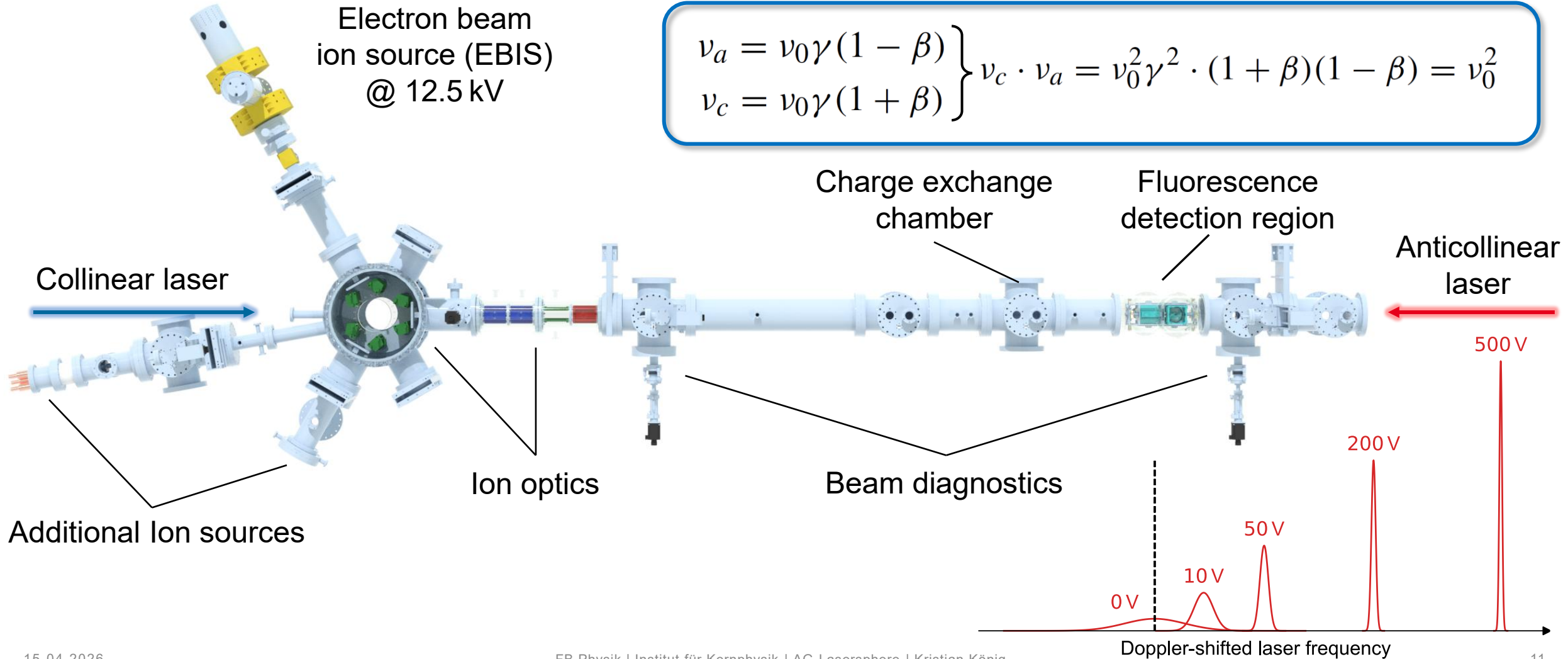


Optimized trap potentials for different charge states

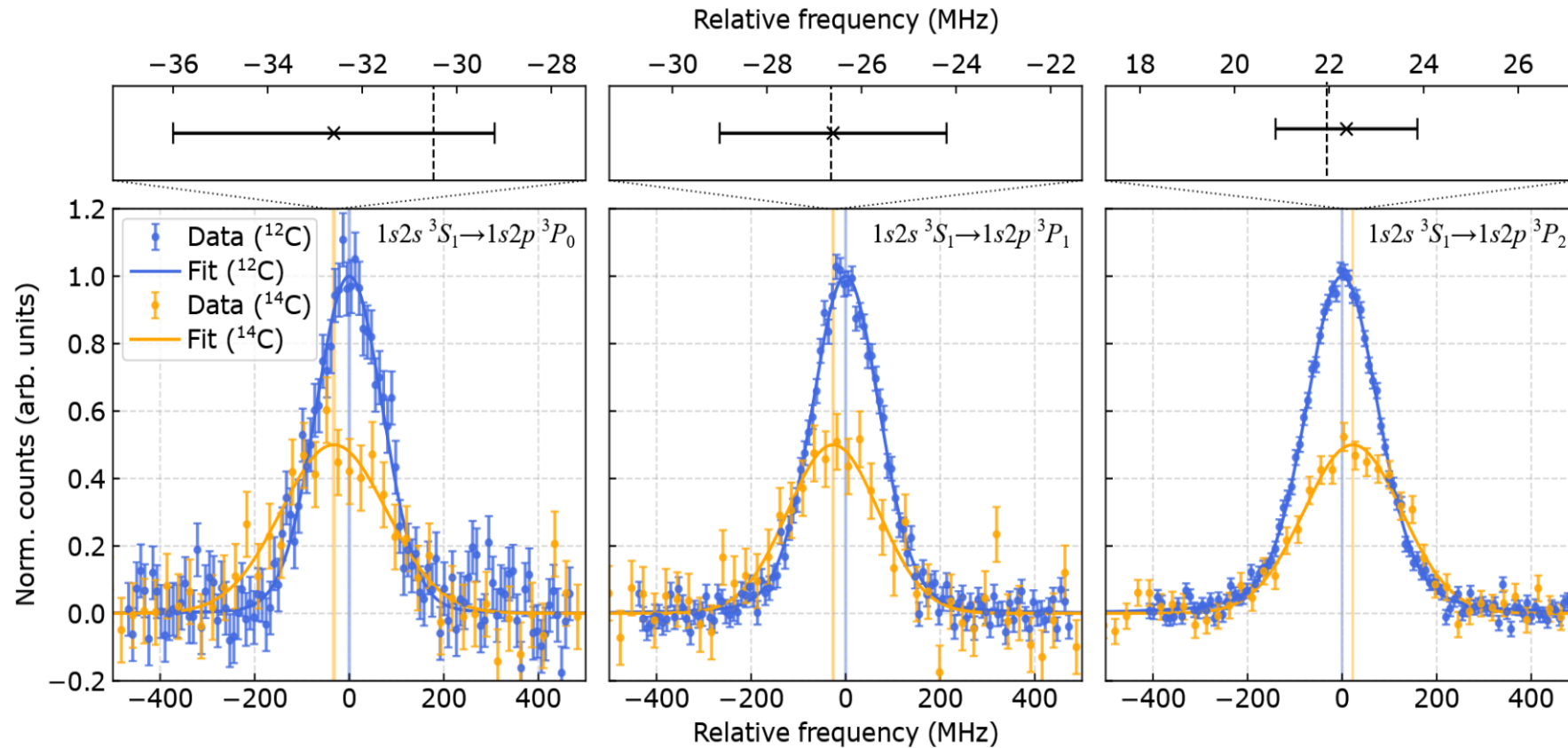
The COALA beamline



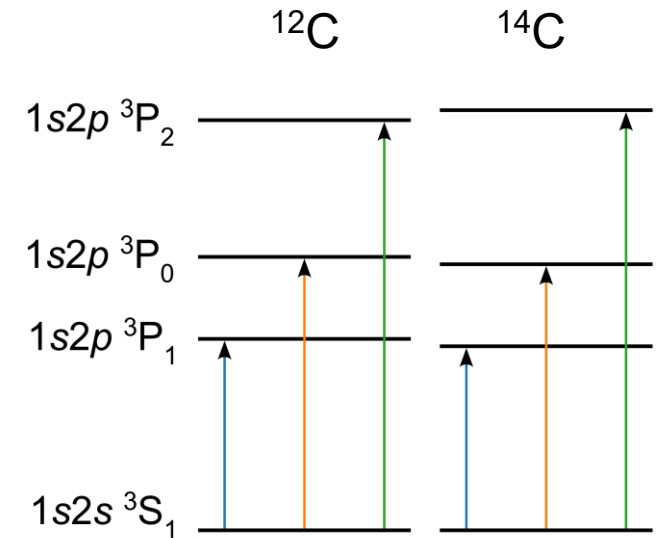
The COALA beamline



Spectra of ^{12}C , ^{14}C

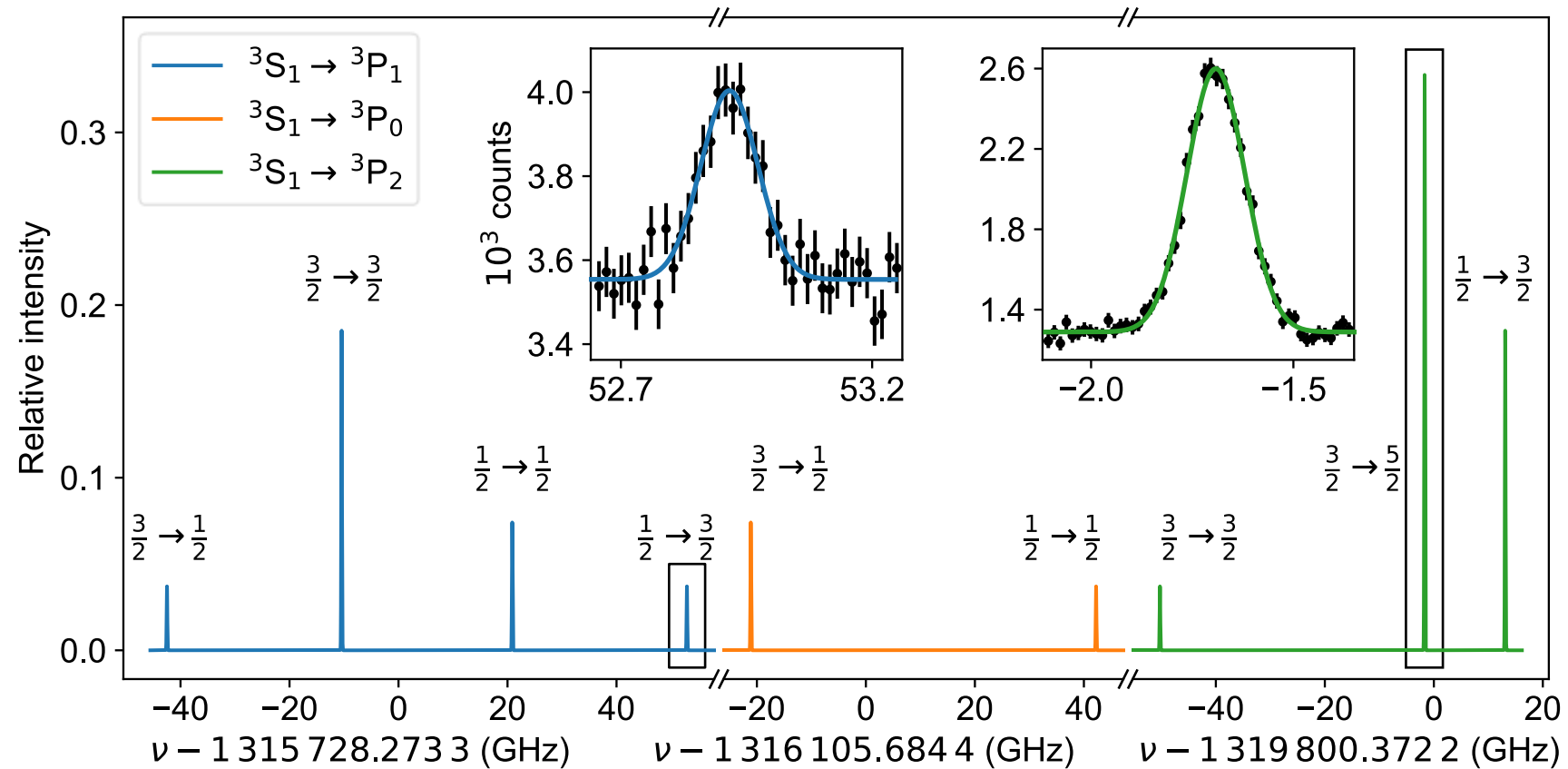


Splitting Isotope Shift



Splitting isotope shift in perfect agreement with NRQED calculations

Hyperfine spectrum of $^{13}\text{C}^{4+}$



Strong hyperfine mixing in ^{13}C

Include second order HFS, i.e., magnetic dipole matrix elements for HFS state mixing

Transition	Frequency shift
$3S_1 \rightarrow 3P_1$	652.1 MHz
$3S_1 \rightarrow 3P_0$	-1 737.5 MHz
$3S_1 \rightarrow 3P_2$	-43.0 MHz
$3S \rightarrow 3P$	0.5 MHz

Hyperfine spectrum of $^{13}\text{C}^{4+}$



Splitting isotope shift

Isotope pair		$1s2p\ ^3P_0$	$1s2p\ ^3P_1$	$1s2p\ ^3P_2$
$^{13}\text{C}^{4+} - ^{12}\text{C}^{4+}$	Theory	-16.446 (1)	-14.388 (5)	11.922 (1)
	Exp.	-18.5 (2.4)	-13.4 (1.8)	11.8 (1.2)
	Exp.*	1719.4 (2.5)	-665.1 (1.8)	55.2 (1.2)
$^{14}\text{C}^{4+} - ^{12}\text{C}^{4+}$	Theory	-30.489 (2)	-26.674 (9)	22.102 (2)
	Exp.	-32.6 (3.4)	-26.6 (2.4)	22.5 (1.5)

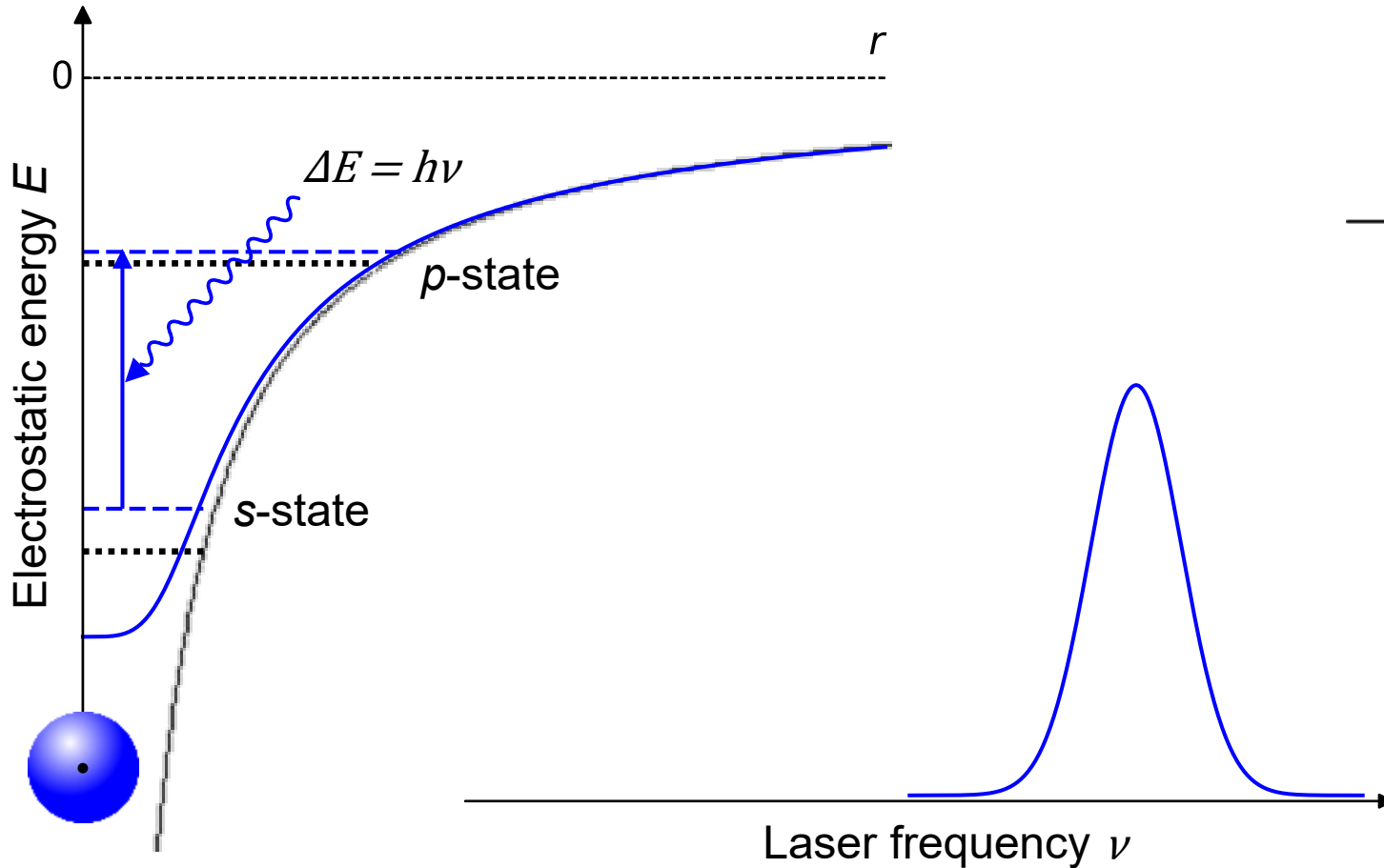
* Applying normal HFS analysis that neglects HFS mixing.

Strong hyperfine mixing in ^{13}C

Include second order HFS, i.e., magnetic dipole matrix elements for HFS state mixing

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$^3S_1 \rightarrow ^3P_0$	-1 737.5 MHz
$^3S_1 \rightarrow ^3P_2$	-43.0 MHz
$^3S \rightarrow ^3P$	0.5 MHz

Optical extraction of the nuclear charge radius



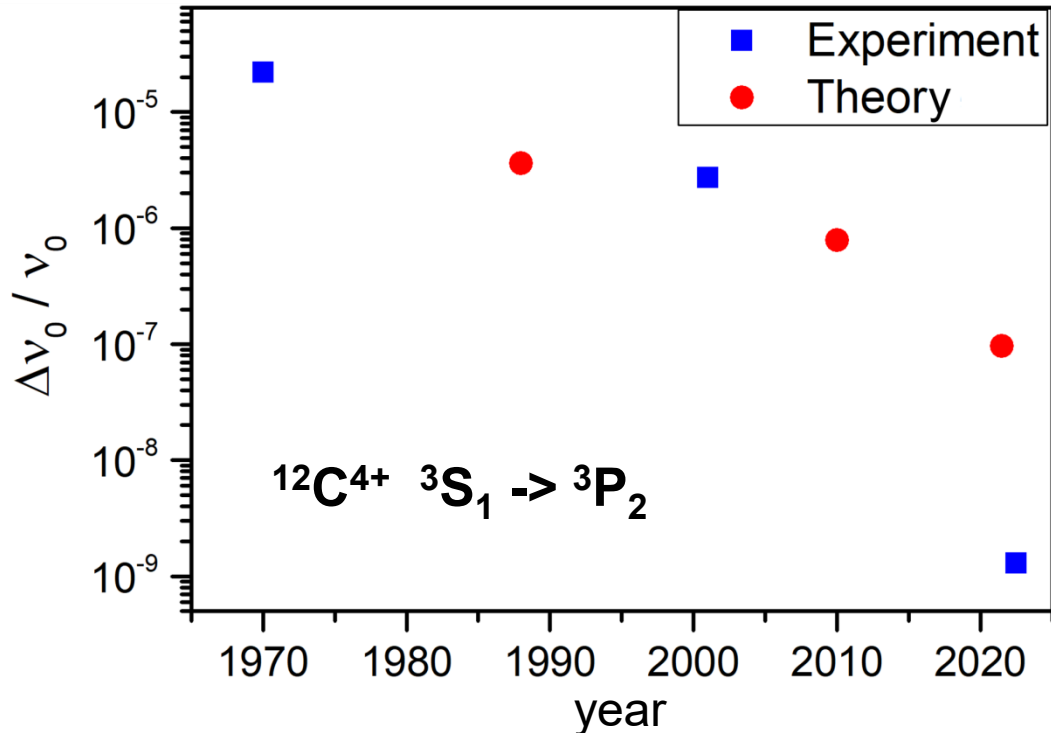
$$\rightarrow \nu_0 = \nu_{\text{point}} + F \times \langle r_c^2 \rangle$$

- ν_0 from experiment
- ν_{point} and F from atomic structure calculations of order $m\alpha^7$
- Determination of $\langle r_c^2 \rangle$

All-optical charge radius determination



Absolute rest-frame frequency



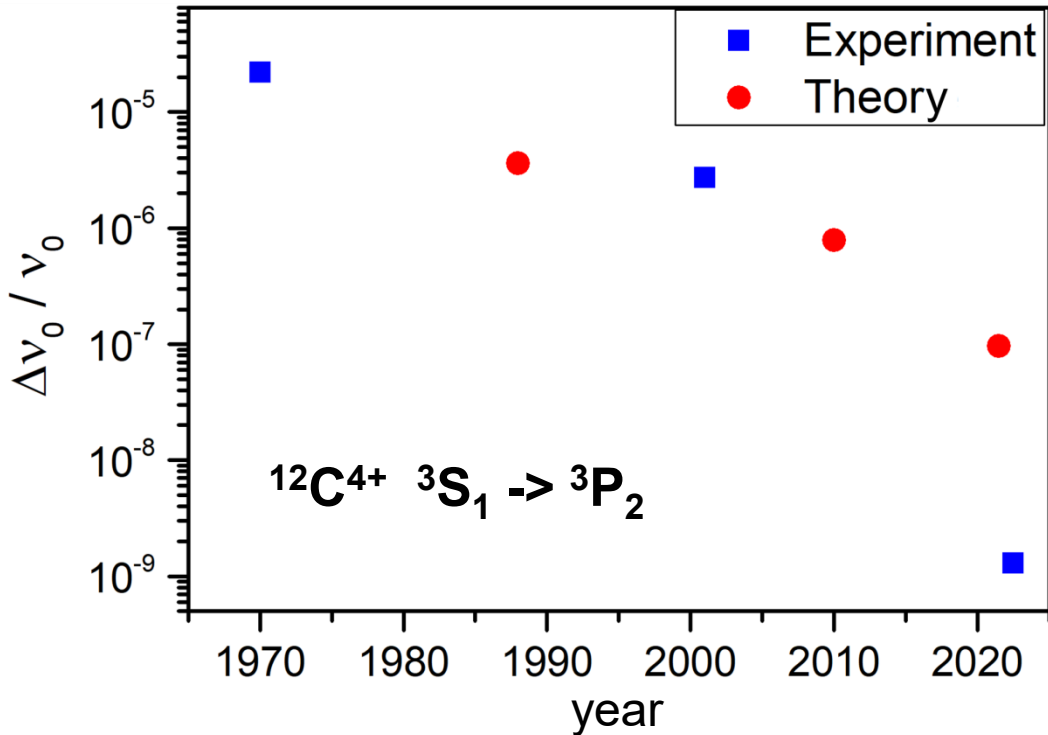
Experimental result improved
by three orders of magnitude

All-optical charge radius determination



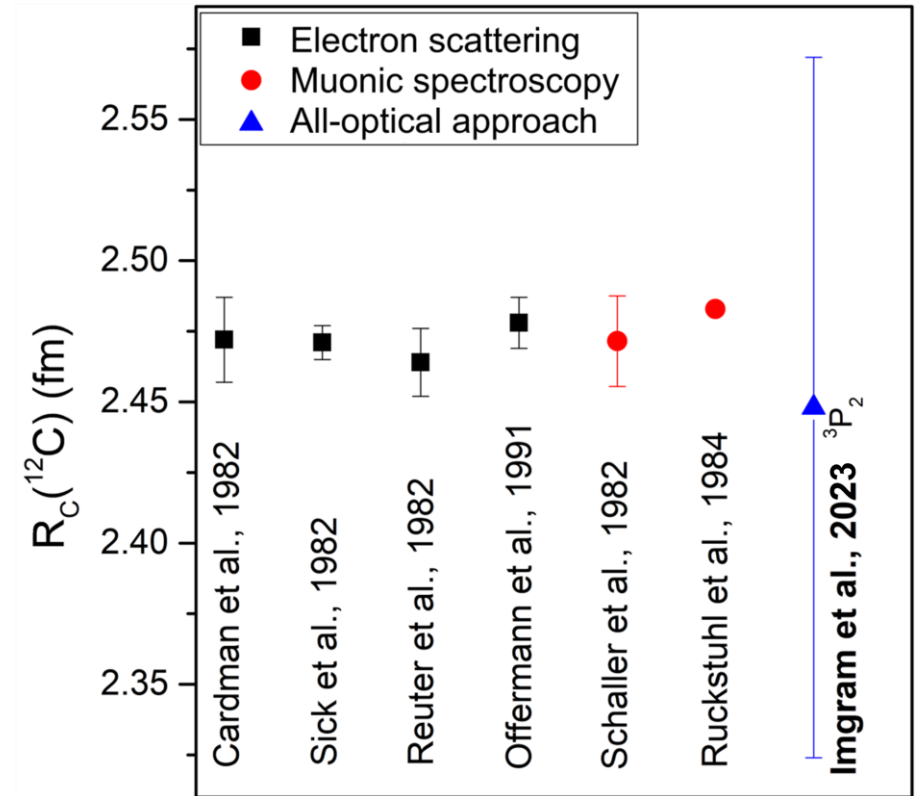
TECHNISCHE
UNIVERSITÄT
DARMSTADT

Absolute rest-frame frequency



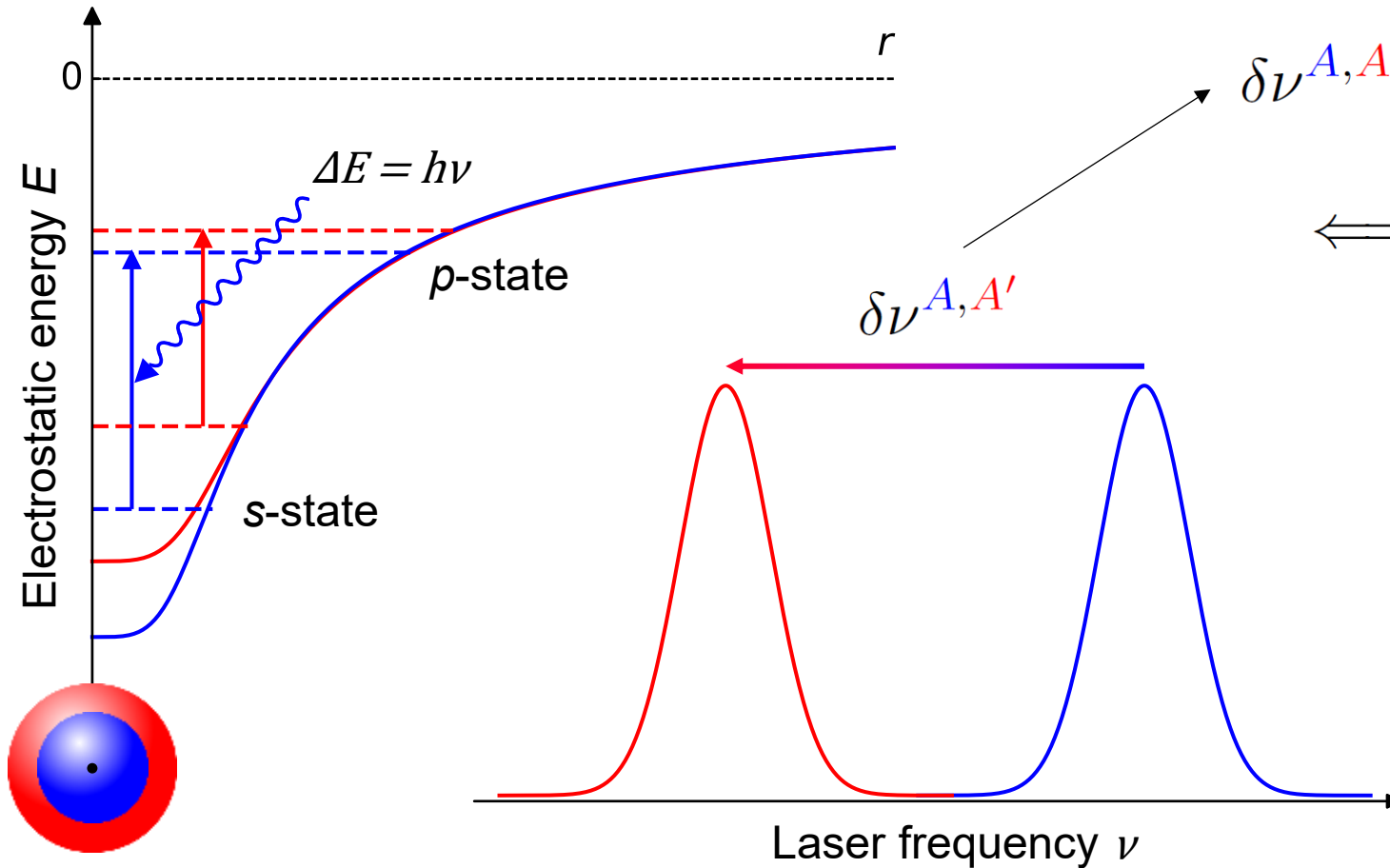
Experimental result improved
by three orders of magnitude

$$\rightarrow \nu_0 = \nu_{\text{point}} + F \times \langle r_c^2 \rangle$$



All-optical charge radius limited by theory

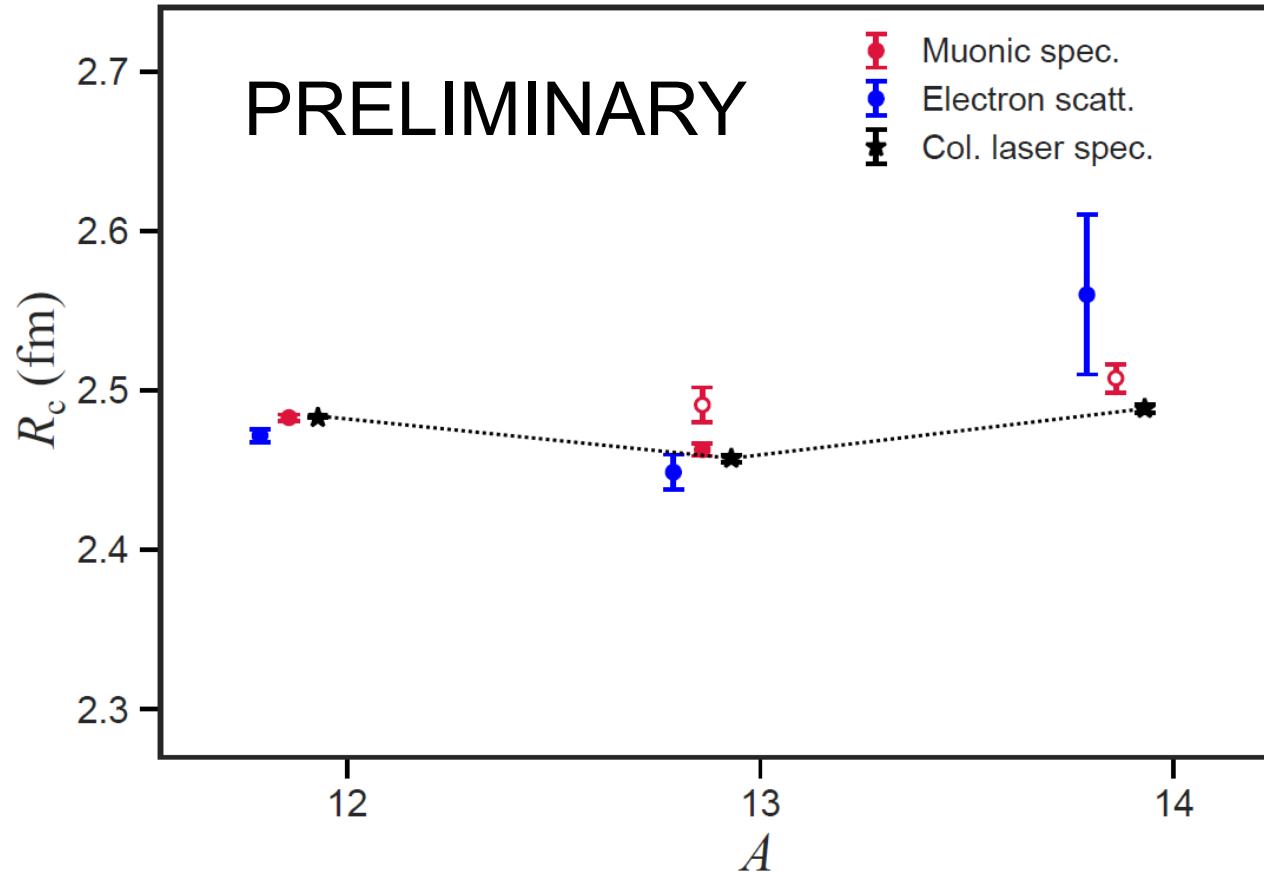
Optical extraction of the nuclear charge radius



$$\delta\nu^{A,A'} := \nu^{A'} - \nu^A = \delta\nu_M + F\delta\langle r^2 \rangle^{A,A'}$$

$$\Leftrightarrow \delta\langle r^2 \rangle^{A,A'} = \frac{\delta\nu^{A,A'} - \delta\nu_M}{F}$$

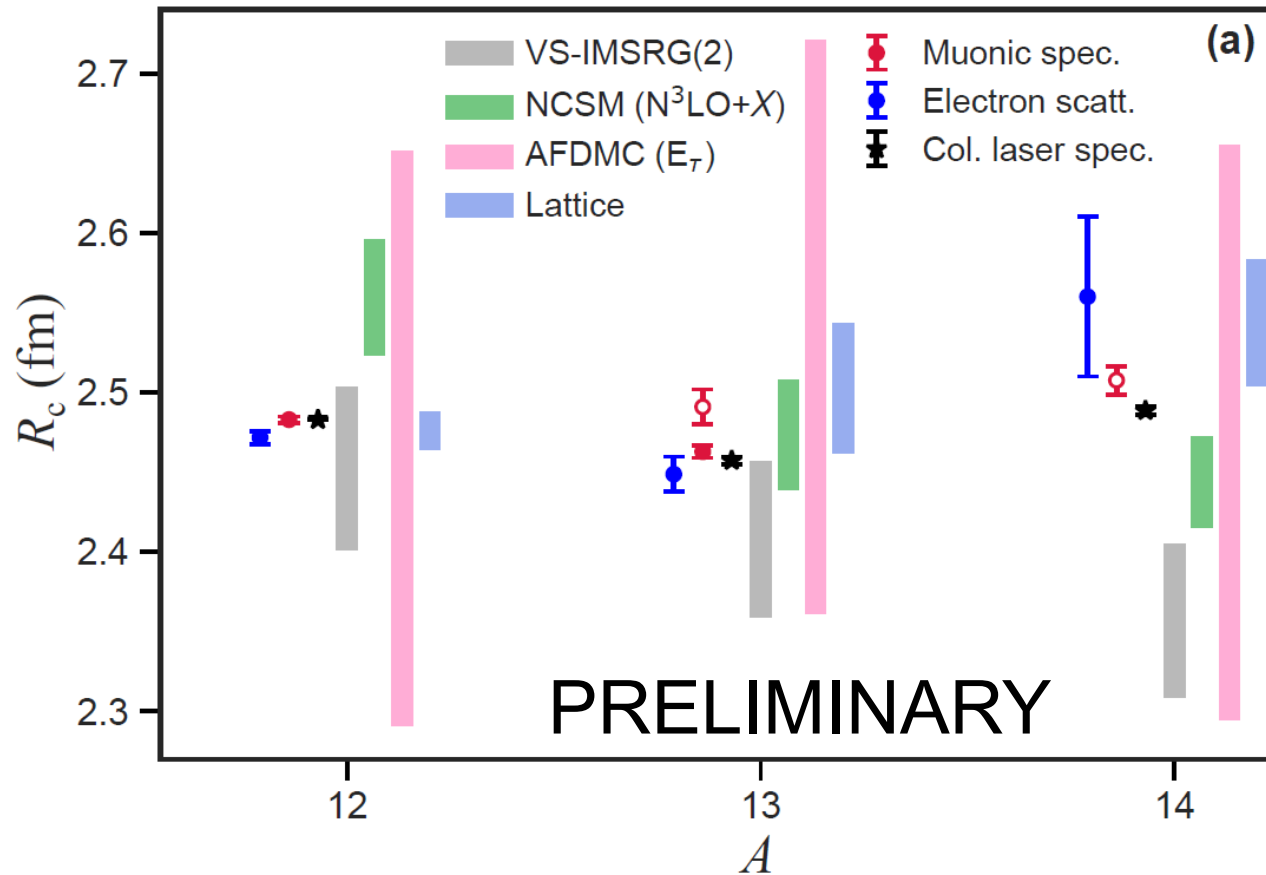
$^{12}\text{C}, ^{13}\text{C}, ^{14}\text{C}$ charge radii



Precision ^{12}C radius from μ spectroscopy used as reference for CLS and other muonic measurements

- Good agreement for ^{13}C
 - 2σ deviation from muonic ^{14}C
 - Systematical deviation of that muonic measurement campaign
 - Important for mirror nuclei analysis
- „Normal“ charge radius trend:
- Increase from ^{12}C to ^{14}C
 - Smaller ^{13}C due to odd-even staggering

$^{12,13,14}\text{C}$ charge radii

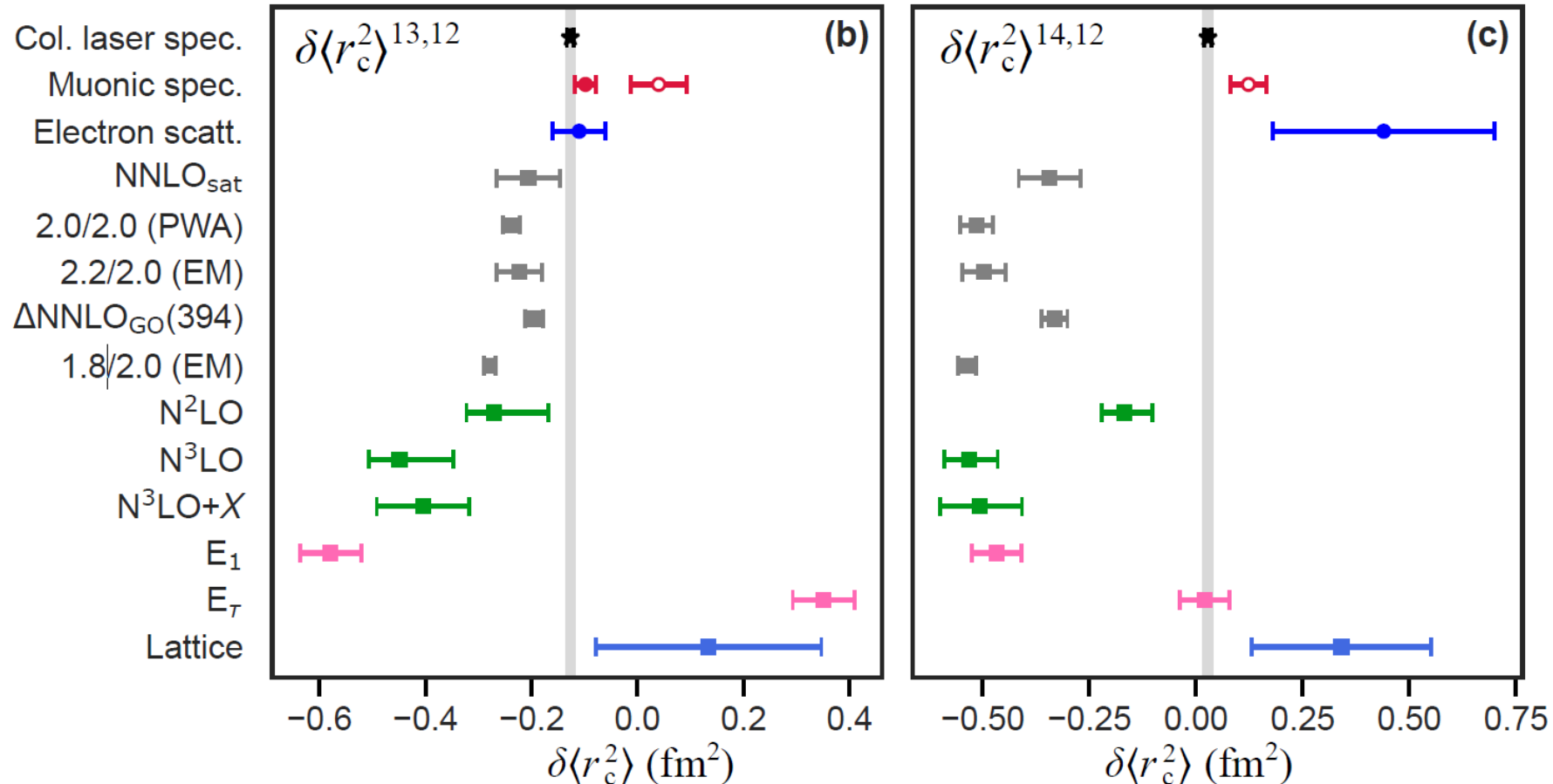


Ab initio nuclear theory shows limitations in precision

Charge radius trend deviates

Precision ^{12}C radius from μ spectroscopy used as reference for CLS and other muonic measurements

12,13,14C charge radii



- NCSM(N2LO) and AFDMC (E₁) describe charge radius trend
 - AFDMC (E_T) successfully predicts 12,14C radius difference
- ⇒ 12,14C may become a new anchor point for future precision theories

Summary and outlook



- Sparse knowledge of charge radii
 - Precision CLS measurements required due to small field shift contribution
 - Successful measurement of $^{12-14}\text{C}$
 - Expand to short-lived isotopes
- Multiple nuclear phenomena and applications
 - Clustering and halo structures
 - Test of atomic and nuclear *ab initio* theory
 - Constrain slope parameter L of nuclear EOS
 - Contribute to the V_{ud} matrix element
 - Physics beyond the standard model

110 2.31 mev 2p=100%	120 51 kev 2p=100%	130 8.58 ms e+β+=100% εp=10.8%	140 70.62 s e+β+=100%	150 122.268 s e+β+=100%	160 STABLE 99.738-99.776%	170 STABLE 0.0367-0.04%	180 STABLE 0.187-0.222%
10N 2.5 mev p=100%	11N 780 kev p=100%	12N 10.996 ms e+β+=100% εα=1.93%	13N 9.967 min e+β+=100%	14N STABLE 99.578-99.663%	15N STABLE 0.337-0.422%	16N 7.13 s β ⁻ =100% β ⁻ α=1.54e-3%	17N 4.171 s β ⁻ =100% β ⁻ n=99.51% β ⁻ α=2.5e-3%
9C 126.5 ms e+β+=100% εp=62% εα=37.9%	10C 19.30 s e+β+=100%	11C 20.34 min e+β+=100%	12C STABLE 98.84-99.04%	13C STABLE 0.96-1.16%	14C 5686 y β ⁻ =100%	15C 2.451 s β ⁻ =100%	16C 750 ms β ⁻ =100% β ⁻ n=99.28%
8B 772.1 ms e+β+=100% εα=100%	9B 540 ev p=100%	10B STABLE 18.9-20.4%	11B STABLE 79.6-81.1%	12B 20.22 ms β ⁻ =100% β ⁻ α=0.6%	13B 17.16 ms β ⁻ =100% β ⁻ n=0.266%	14B 12.34 ms β ⁻ =100% β ⁻ n=6.04%	15B 10.18 ms β ⁻ =100% β ⁻ n=99.68% β ⁻ 2n<1.5%
7Be 53.3 d ε=100%	8Be 5.57 ev α=100%	9Be STABLE 100%	10Be 1.39e+6 y β ⁻ =100%	11Be 13.77 s β ⁻ =100% β ⁻ α=3.3% β ⁻ p=1.3e-5%	12Be 21.46 ms β ⁻ =100% β ⁻ n=0.5%	13Be 450 kev n ?	14Be 4.65 ms β ⁻ =100% β ⁻ n=86% β ⁻ 2n=5%
6Li STABLE 1.9-7.8%	7Li STABLE 92.2-98.1%	8Li 838.79 ms β ⁻ =100% β ⁻ α=100%	9Li 178 ms β ⁻ =100% β ⁻ n=51% β ⁻ α=12.3%	10Li 0.23 mev n=100%	11Li 8.75 ms β ⁻ =100% β ⁻ n=84.3% β ⁻ 2n=4.2%	12Li n=100%	13Li 125 kev 2n=100%

<https://www.nndc.bnl.gov/nudat3/>

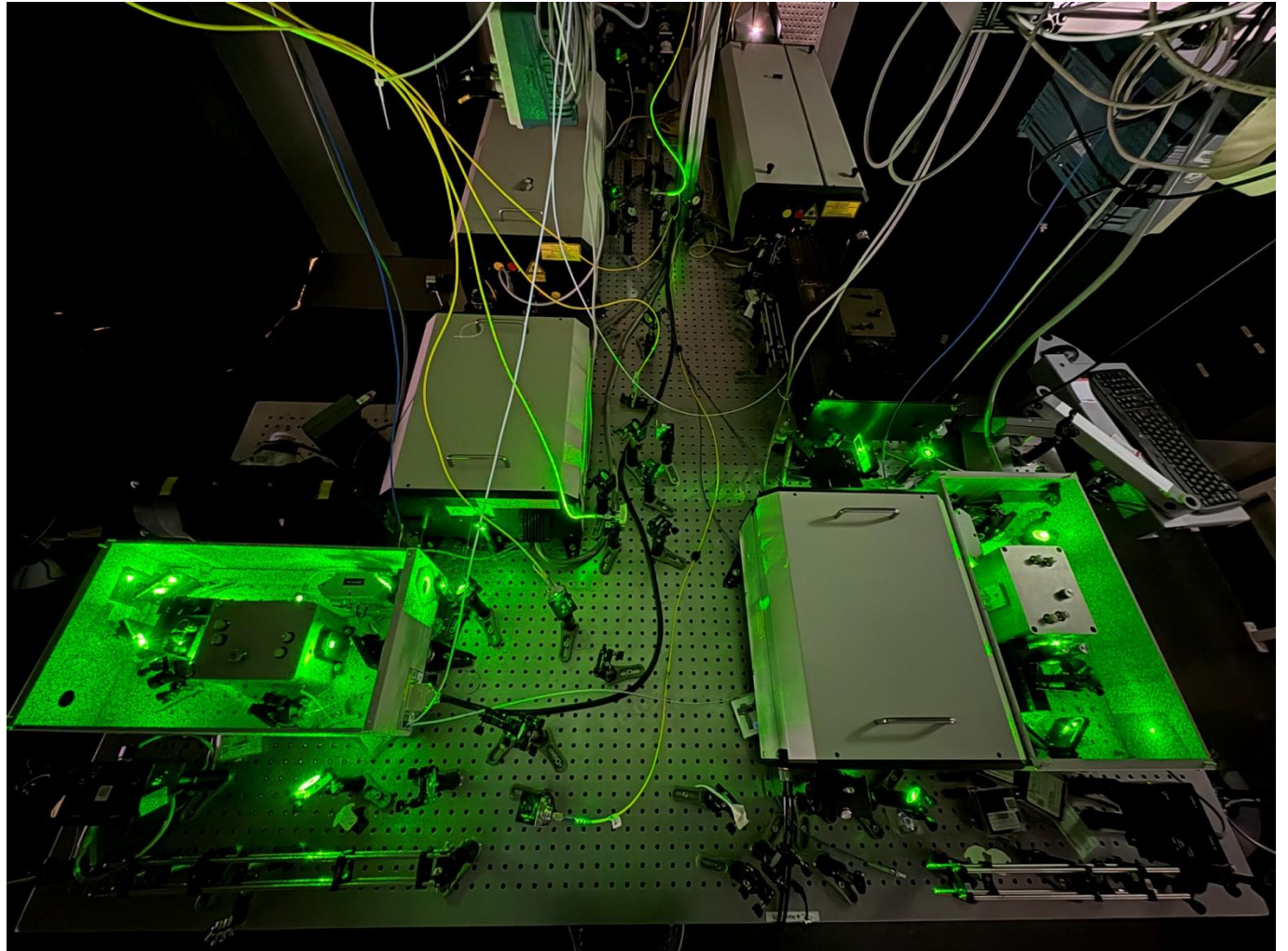
Laser Spectroscopy in $B^{3+,2+,0}$



- B 250 nm, neutral beam
- B^+ No laser transition
- B^{2+} 206 nm, very deep UV
- B^{3+} 282 nm, from metastable state
- B^{4+} No laser transition

Perfect testing ground for ab initio atomic theory

8B measurements upcoming at Argonne National Laboratory



Thank you for your attention



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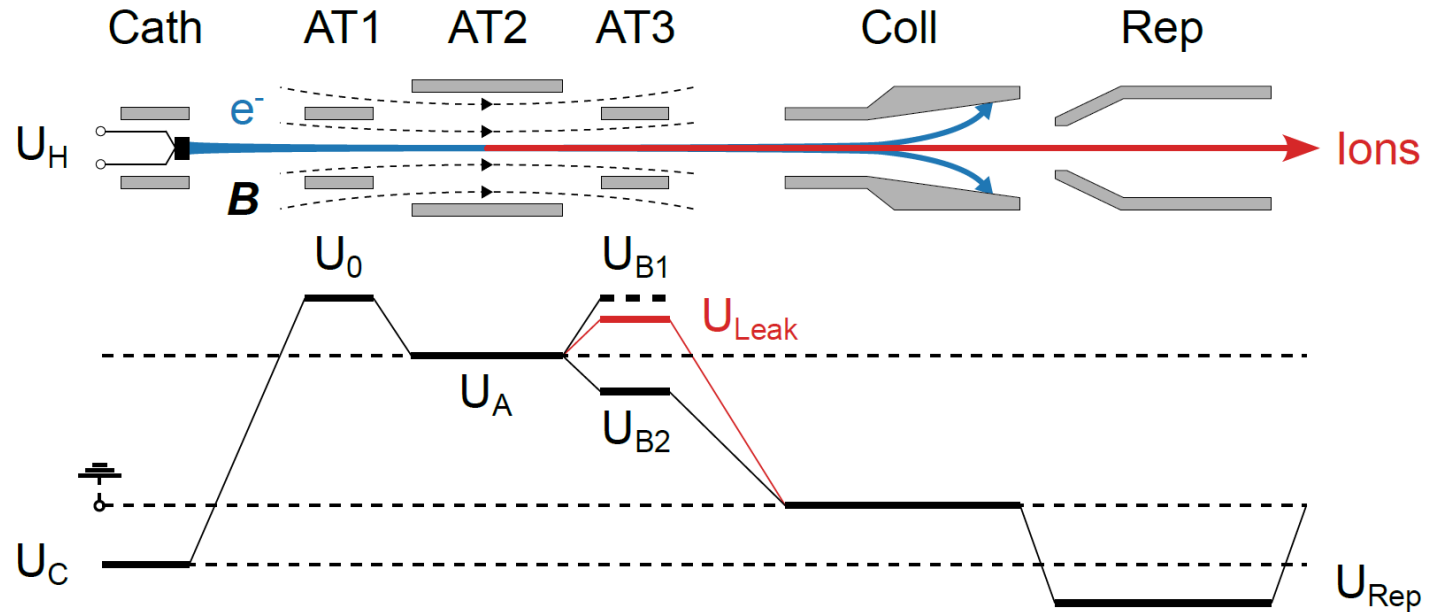
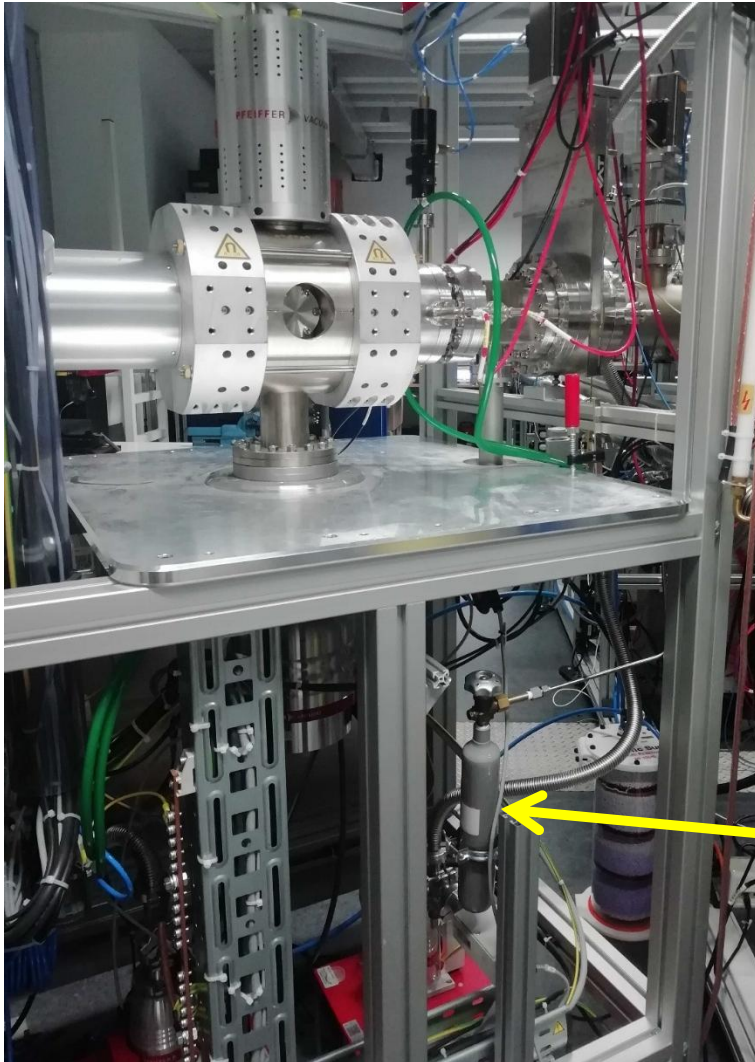


Federal Ministry
of Education
and Research



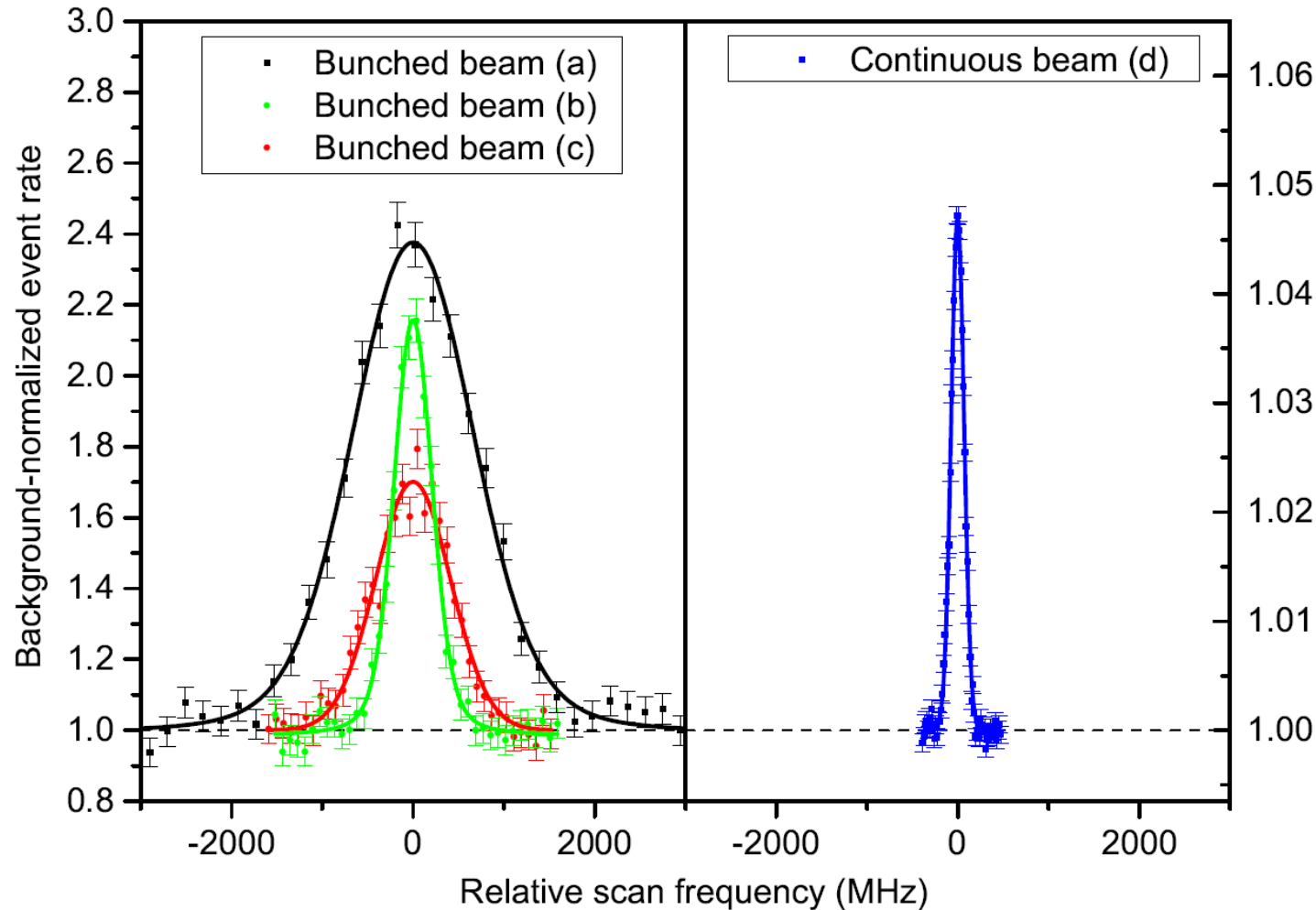
HESSEN
Hessisches Ministerium
für Wissenschaft und Kunst

Electron beam ion source



- 2 nA beam current
- 1 eV energy width

CW spectroscopy



- EBIS endcap permanently at slightly lower potential (leaky mode)
- No laser background suppression
- No switching
- ⇒ No asymmetry and smaller linewidth
- ⇒ 4-5 times higher population of metastable 3S_1 state
- Similar signal-to-noise ratio
- Improved determination of resonance center by factor 8

Mirror nuclei

- Constrain the slope of the symmetry energy at nuclear saturation density (L)

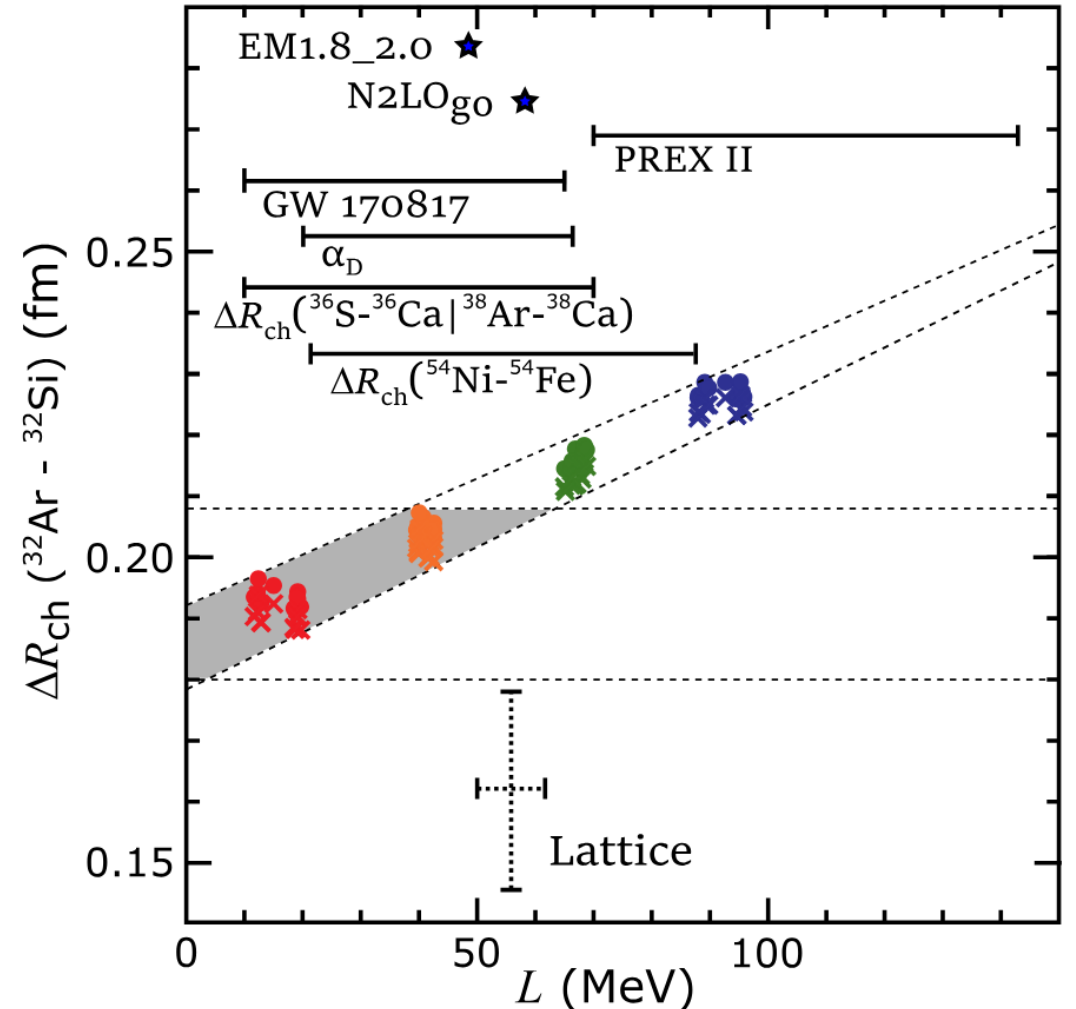
$$L = 3\rho_0 \left[\frac{\partial E_{sym}(\rho)}{\partial \rho} \right]_{\rho=\rho_0}$$

- Important to predict the properties of both super-heavy nuclei and neutron stars
- Neutron skin R_{np} of neutron-rich nuclei strongly correlated to L

$$\Delta R_{np} \sim R_{ch} \left(\begin{smallmatrix} A \\ Z \end{smallmatrix} X_N \right) - R_{ch} \left(\begin{smallmatrix} A \\ N \end{smallmatrix} Y_Z \right) = \Delta R_{ch}$$

- Proportional to $|N-Z|$

$$\Delta R_{ch} \propto (N - Z) \cdot L$$



Mirror nuclei



- Discussion about the theoretical sensitivity on the correlation between ΔR_{ch} and L

P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 105, L021301 (2022).

B. A. Brown and K. Minamisono, Phys. Rev. C 106, L011304 (2022).

Y. N. Huang, Z. Z. Li, and Y. F. Niu, Phys. Rev. C 107, 034319 (2023).

R. An, S. Sun, L.-G. Cao, and F.-S. Zhang, Nucl. Sci. Tech. 34, 119(2023).

P. Bano, S. P. Pattnaik, M. Centelles, X. Vinas, and T. R. Routray, Phys. Rev. C 108, 015802 (2023)

- All investigated mirror pairs (^{32}Ar - ^{32}Si ; ^{54}Ni - ^{54}Fe ; ^{36}Ca - ^{36}S ; ^{38}Ca - ^{38}Ar) yield consistent results

⇒ Favoring a soft neutron matter EOS

⇒ Good agreement with many theoretical approaches

Mirror nuclei



- Discussion about the theoretical sensitivity on the correlation between ΔR_{ch} and L

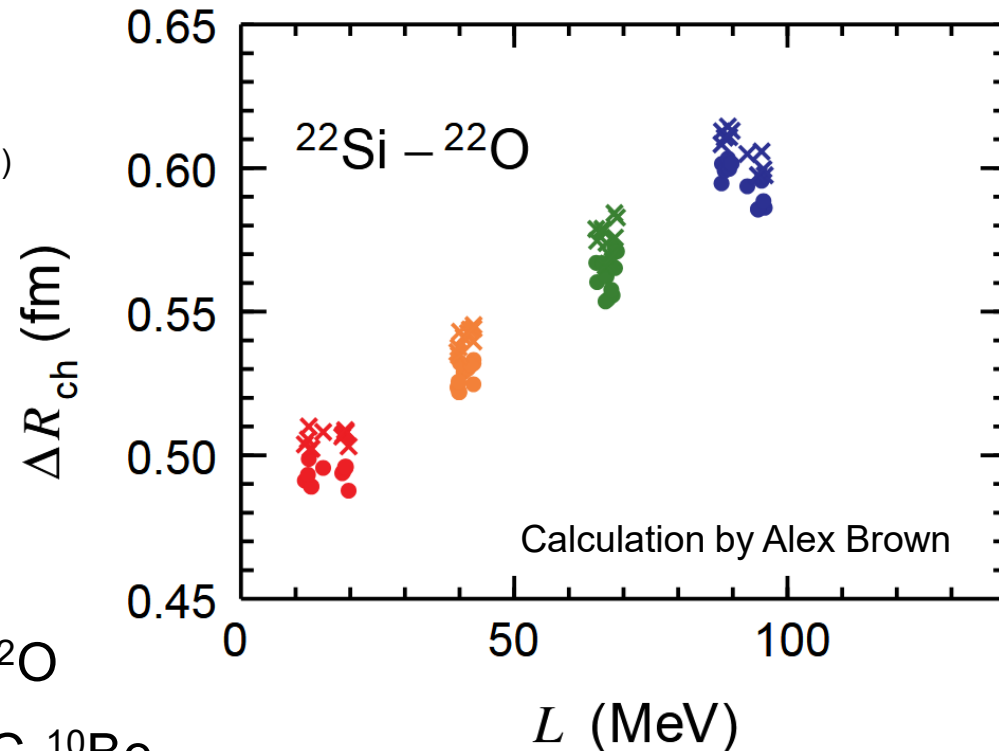
P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 105, L021301 (2022).
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⇒ Favoring a soft neutron matter EOS

⇒ Good agreement with many theoretical approaches

- Upcoming measurements with large $|N-Z|$: ^{52}Ni - ^{52}Cr ; ^{22}Si - ^{22}O
- High precision measurements in light systems: ^{14}O - ^{14}C ; ^{10}C - ^{10}Be



Implications for V_{ud}

CKM matrix differs $\approx 2 \sigma$ from unitarity

$$V_{ud} = G_V / G_F$$

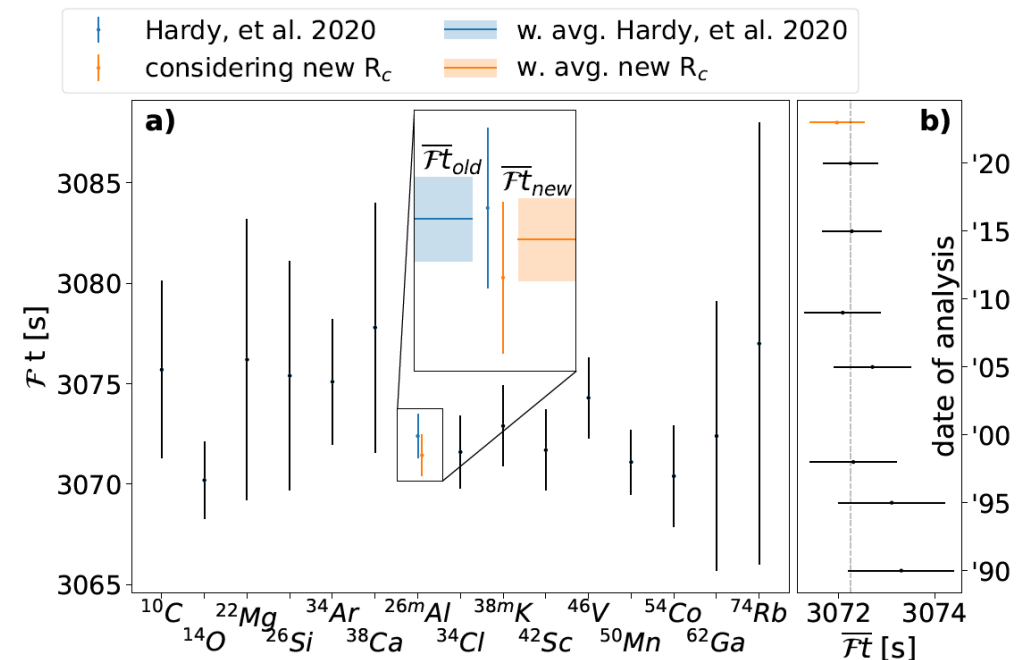
At present, superallowed $0^+ \rightarrow 0^+$ nuclear β decays remain the most precise way to access V_{ud}

$$\mathcal{F}t \equiv ft(1 + \delta'_R)(1 + \delta_{NS} - \delta_C) = \frac{K}{2G_V^2(1 + \Delta_R^V)}$$

Charge radius essential input parameter for isospin-symmetry breaking (ISB) corrections

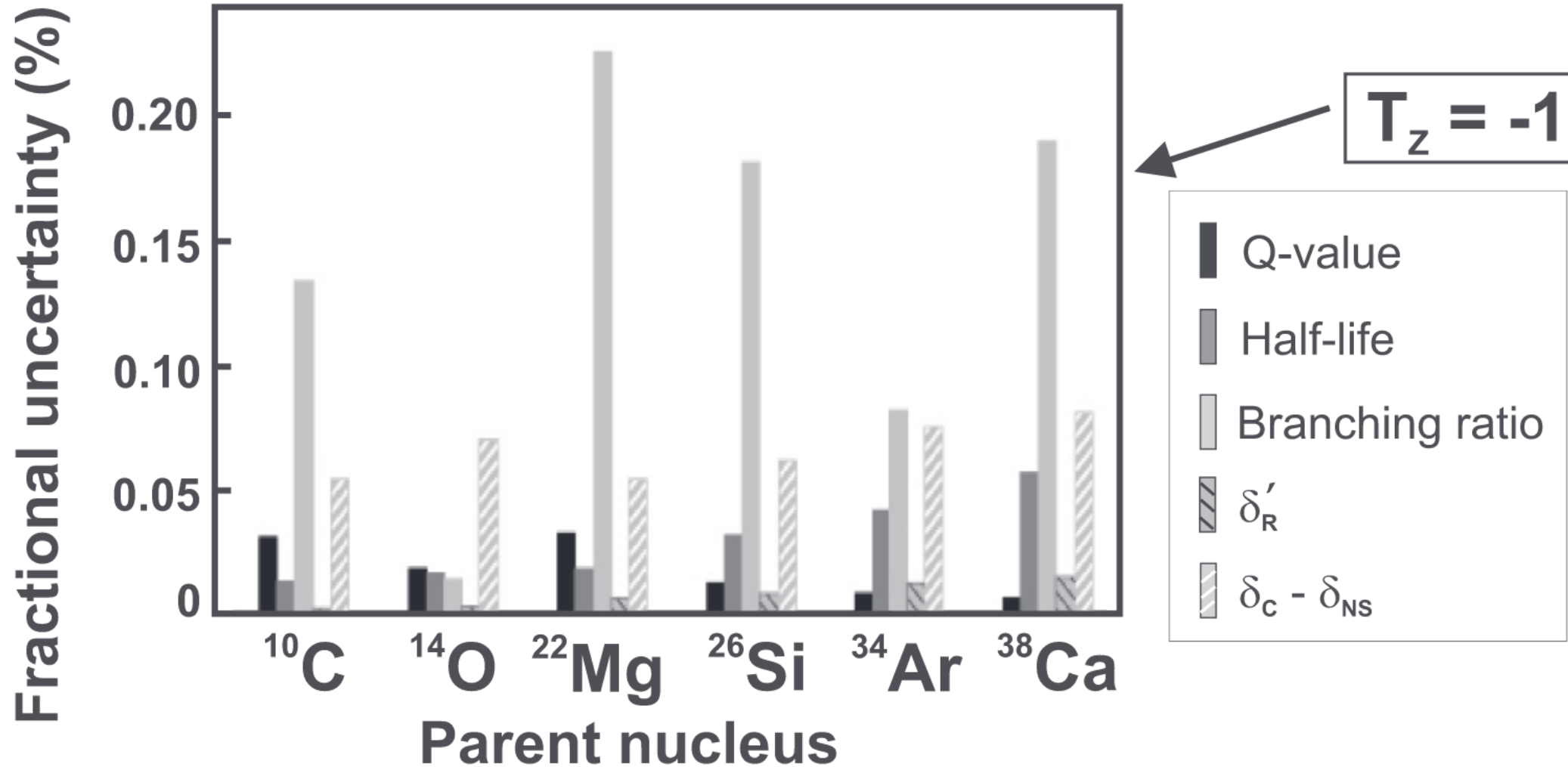
^{74}Rb : Mane et al., Phys. Rev. Lett. **107**, 212502 (2011)

^{26m}Al : Plattner et al., Phys. Rev. Lett. **131**, 222502 (2023)



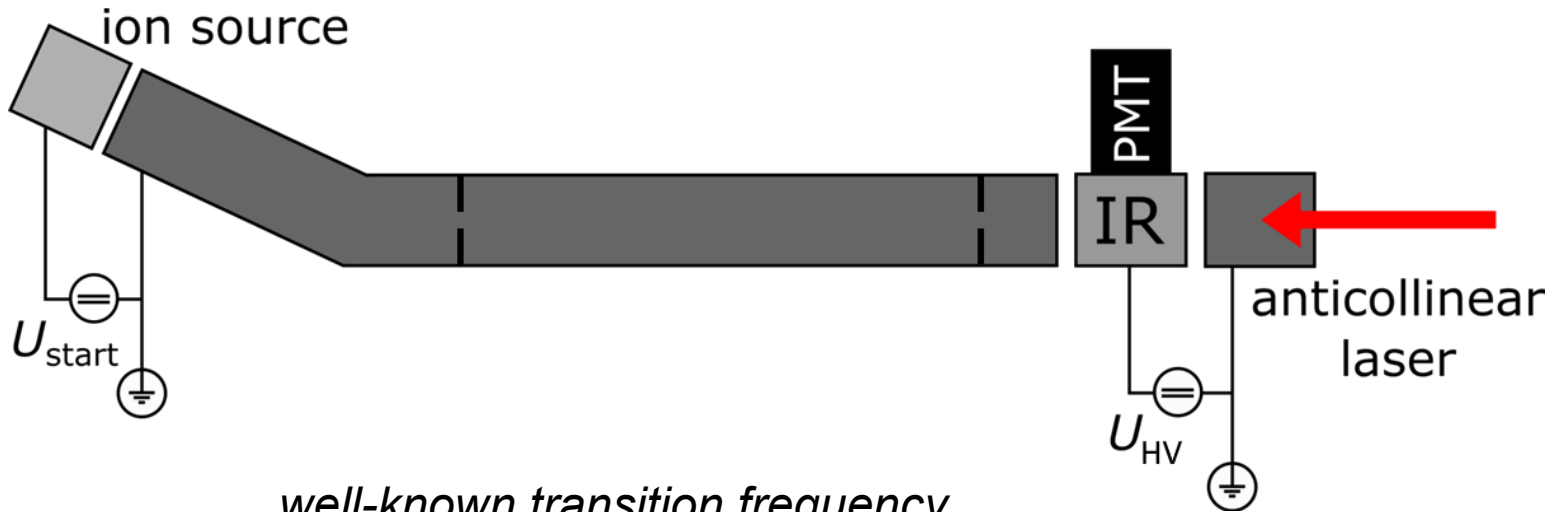
$\approx 1/10 \sigma$ closer towards unitarity

Implications for V_{ud}



Hardy and Towner, Phys. Rev. C 102, 045501 (2020)

HV metrology



well-known transition frequency

$$E_{\text{kin}} = mc^2 \left(\frac{1}{\sqrt{1 - \beta^2}} - 1 \right) = qU$$

$$U_{\text{start}} = \frac{mc^2}{2q} \frac{(f_0 - f_L)^2}{f_0 f_L} - U_{\text{scan}}$$

