Charge radius determination via bound electron *g* factors of H-like ions

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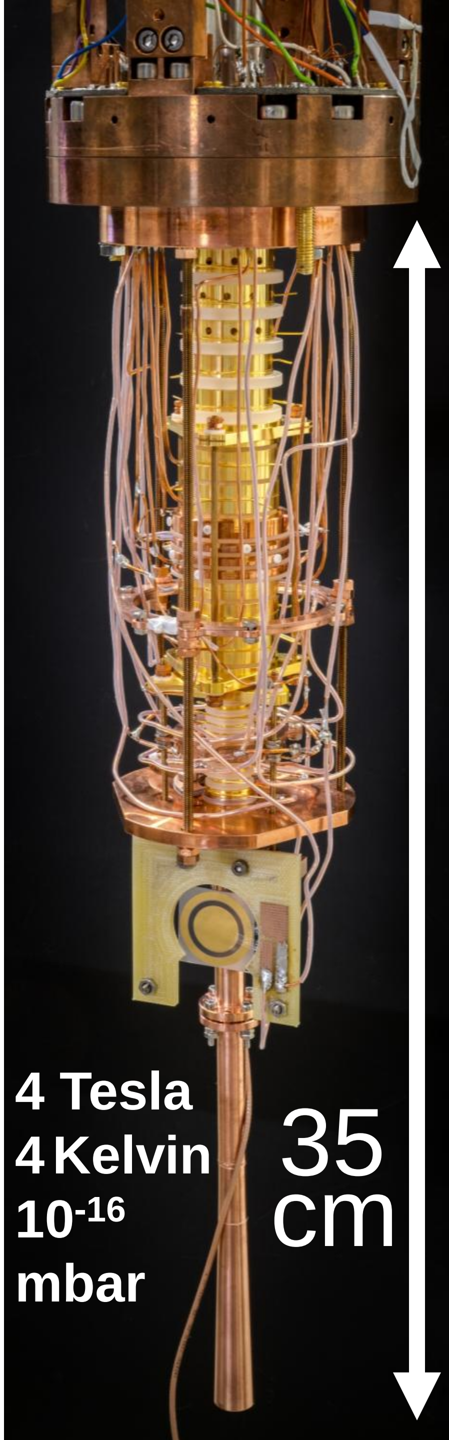
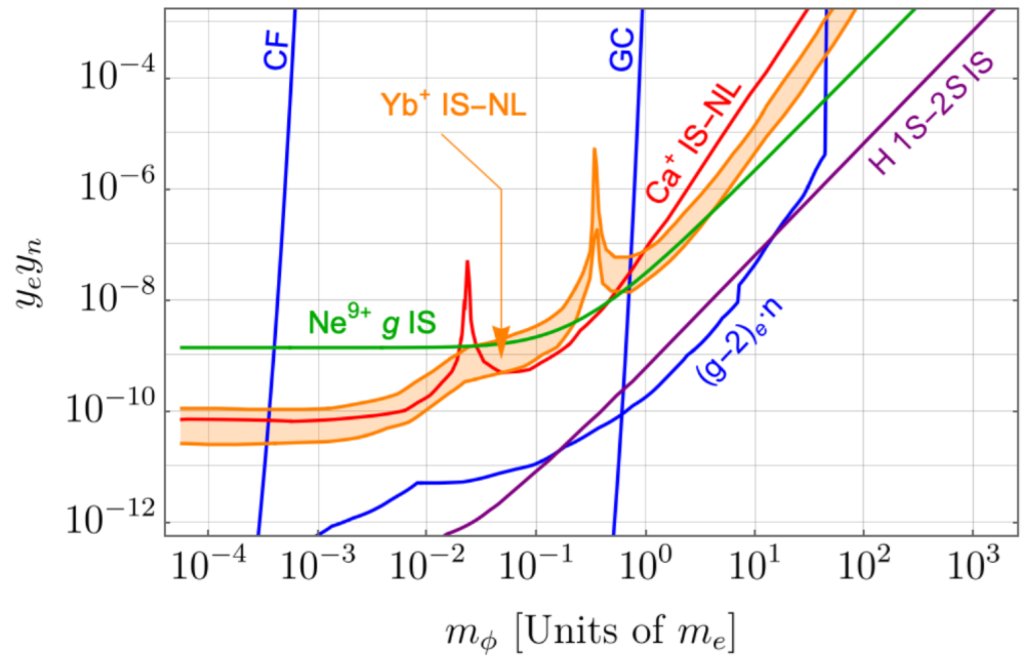
DFG SFB 1225



Nuclear radii and tests of the SM

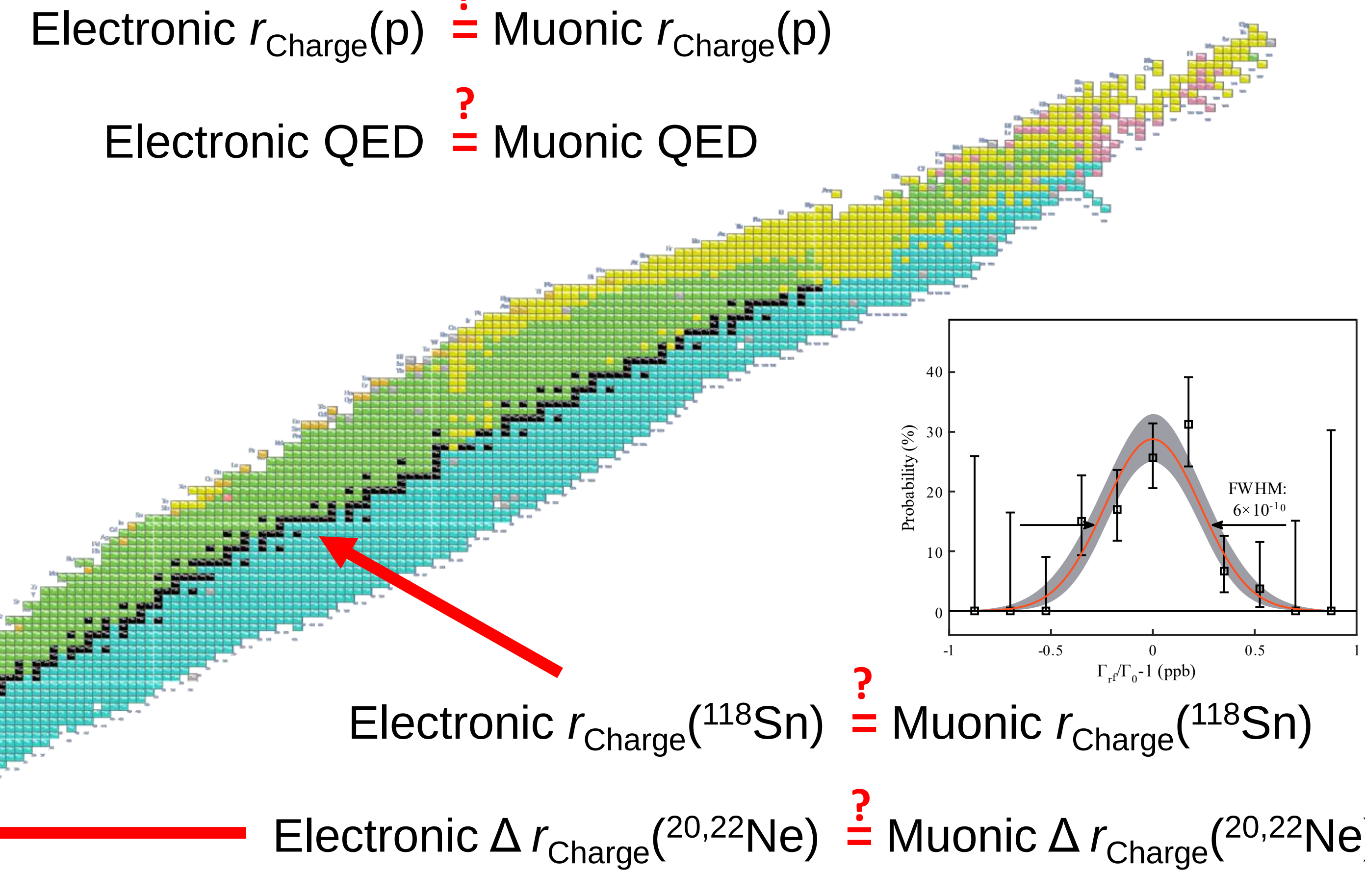


- ➢ **Precise knowledge of the proton**
- ➢ **Refine fundamental constants and QED**
- ➢ **Search for Physics beyond the SM**

Nuclear radii and tests of the SM

Electronic r_{Charge}(p) $\stackrel{?}{=}$ Muonic r_{Charge}(p)

Electronic QED $\stackrel{?}{=}$ Muonic QED



Electronic r_{Charge}(^{118}Sn) $\stackrel{?}{=}$ Muonic r_{Charge}(^{118}Sn)

Electronic Δr_{Charge}(^{20,22}Ne) $\stackrel{?}{=}$ Muonic Δr_{Charge}(^{20,22}Ne)

Harvesting the rich potential of our nuclei
Constants – Test of QED – BSM search

Challenging Physics in extreme fields

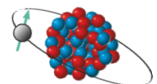
$$\mu = \frac{g}{2}\mu_B \frac{S}{\hbar/2}$$

$$\omega_L = \frac{g}{2}\frac{e}{m_e}B$$

E in V/cm

10^{15}

$^{118}Sn^{49+}$



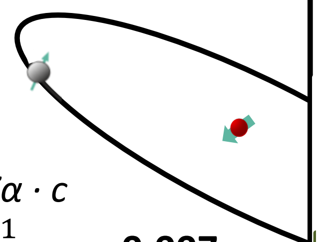
$v = Z\alpha \cdot c = \frac{55}{137} \cdot c \approx 0.4\,c$

10^{13}

$^{28}Si^{13+}$	Sturm *et al.*, PRA **87** 030501 (2013)
$^{20}Ne^{9+}$	Heiße et al., PRL **131** 253002 (2023)

10^{9}

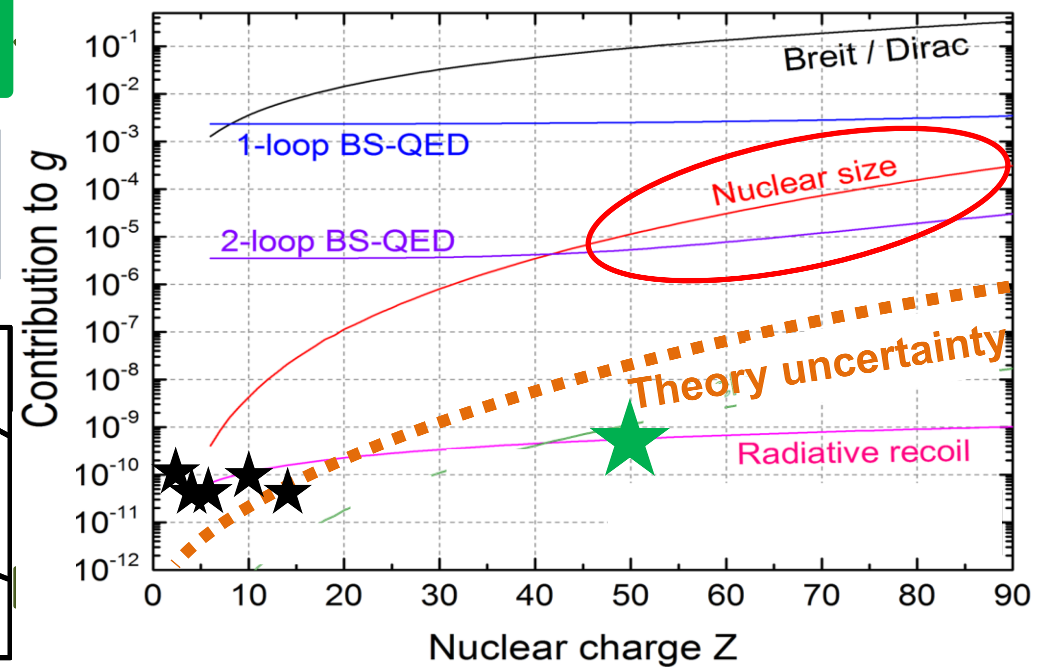
H



$v = Z\alpha \cdot c$

$= \frac{1}{137} \cdot c \approx$ **0.007** c

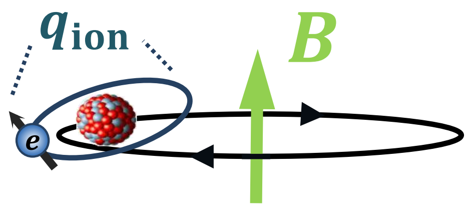
10^{4}



$$g = 2(1 + a_{Breit} + a_{1loop} + a_{NuclearSize} + a_{2loop} + \ldots)$$

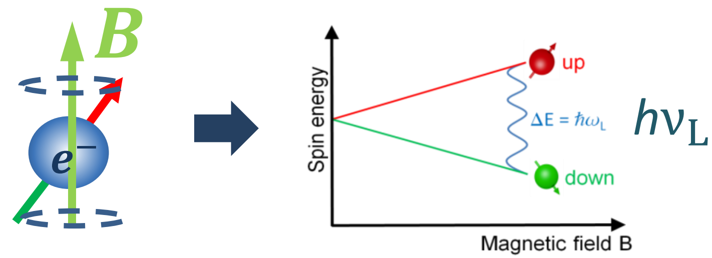
Precise absolute nuclear charge radii accessible

Measurement principle



$$\omega_c = \frac{q_{\text{ion}}}{m_{\text{ion}}} B$$

Measure the free cyclotron frequency



$$\omega_L = \frac{g}{2}\frac{e}{m_e} B$$

Measure the Larmor frequency

$$\Gamma = \frac{\omega_L}{\omega_c}$$

is measured

$$g = 2\frac{\omega_L}{\omega_c}\frac{q_{\text{ion}}}{e}\frac{m_e}{m_{\text{ion}}}$$

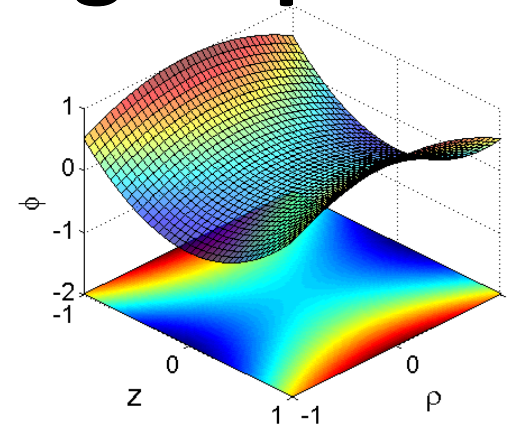
Independent precision experiments

→ e.g. PENTATRAP

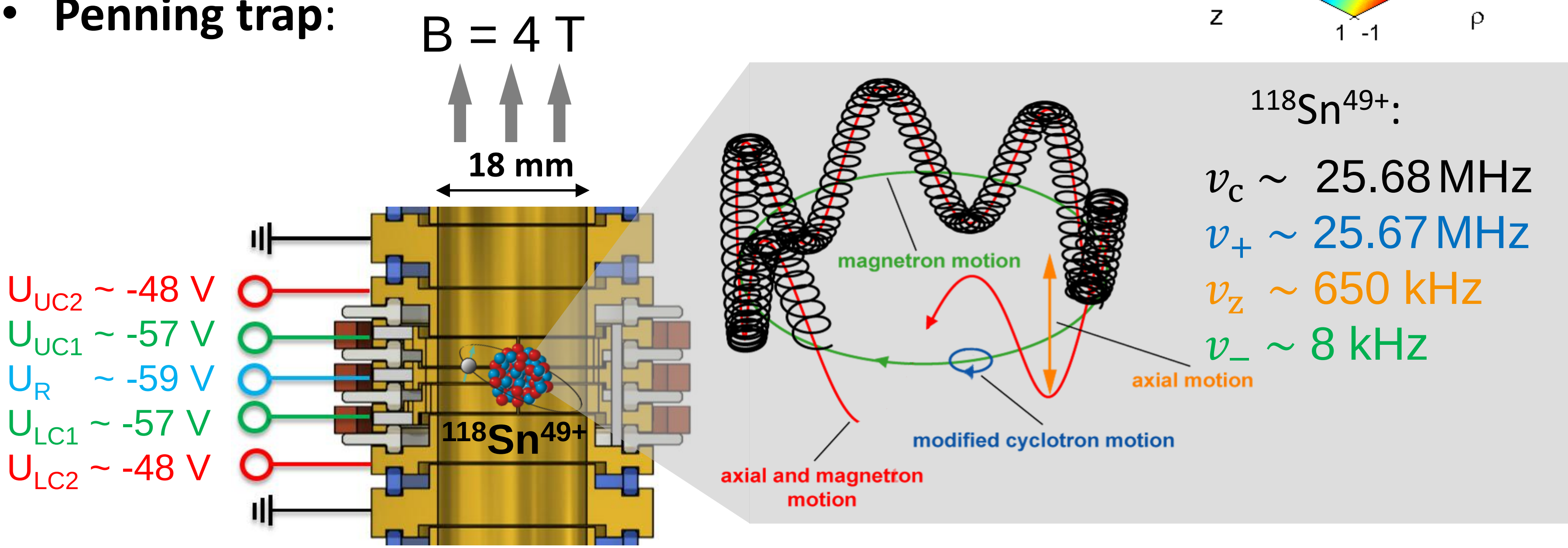
Element	g_j	1s - 2s / eV
$^{4}He^{+}$	2.002	40
$^{238}U^{91+}$	1.659	99 000

Experimental Tool: Penning trap

- **Measurement of cyclotron frequency:**
  → Homogeneous & static magnetic field
  → Electrostatic quadrupole potential for trapping



- **Penning trap**:



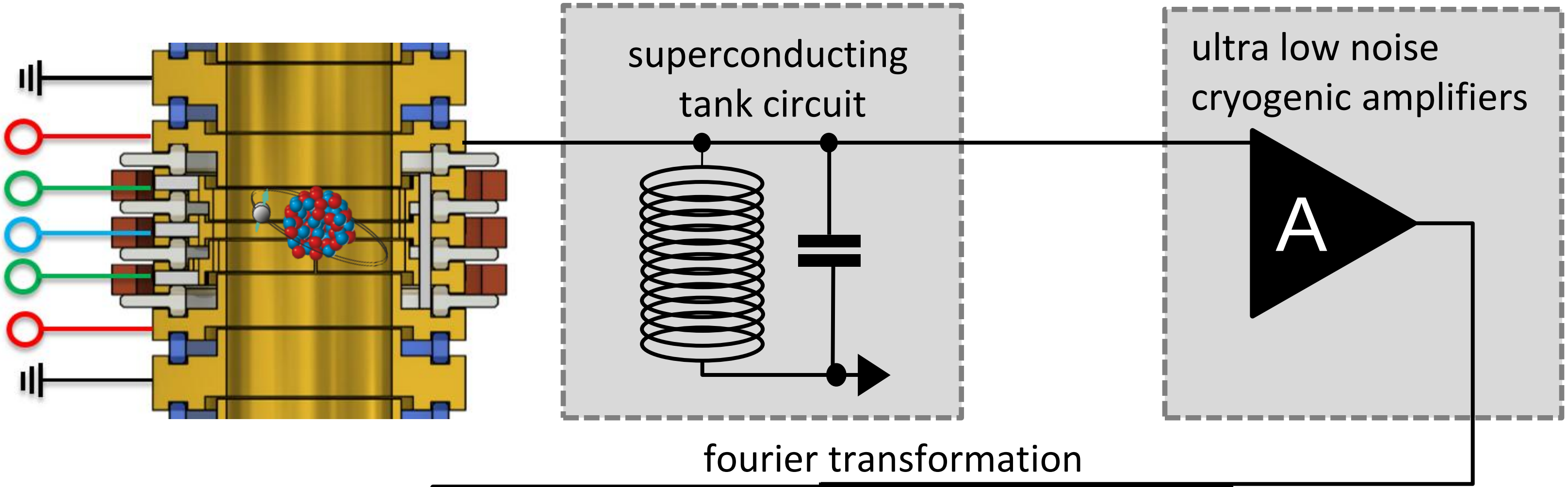
- **Cyclotron frequency via the invariance theorem:**

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2} \qquad \nu_c \approx \nu_+ >> \nu_z >> \nu_-$$

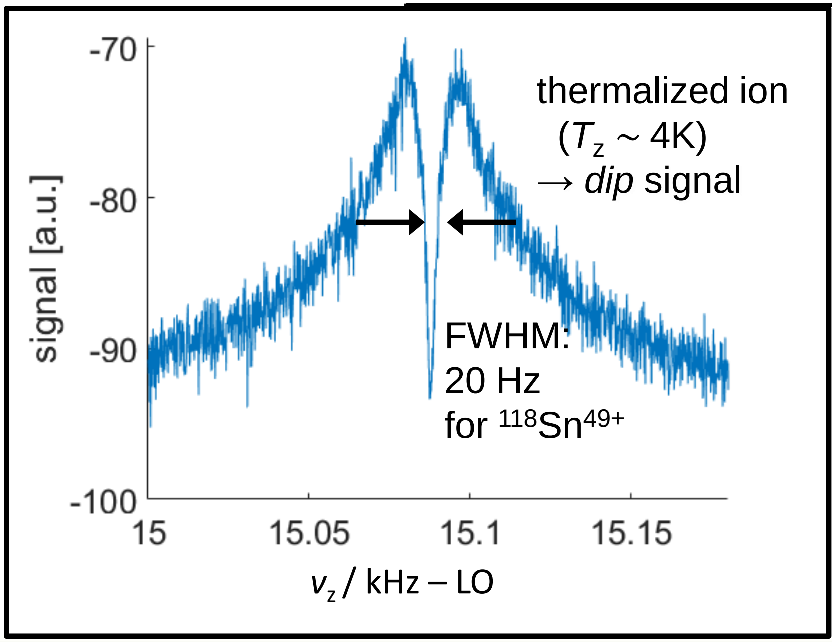
Brown & Gabrielse, Phys. Rev, A **25**, 2423 (1982)

Non-destructive Eigenfrequency Detection (ν_c)

- Measurement of induced image currents (~ fA) on trap electrodes



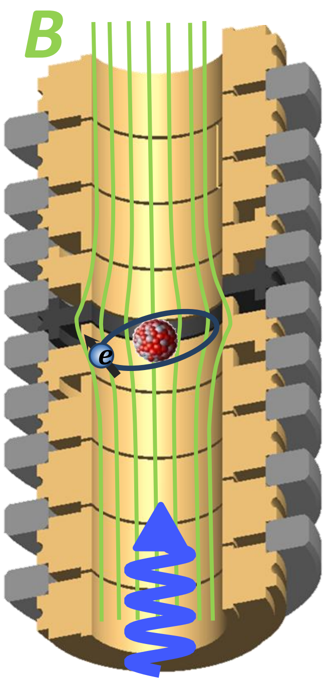
Most harmonic trap in the world (*E* field)!



Towards the most homogeneous *B* field!

Non-destructive Spin state detection (ν_L)

Analysis Trap (AT)



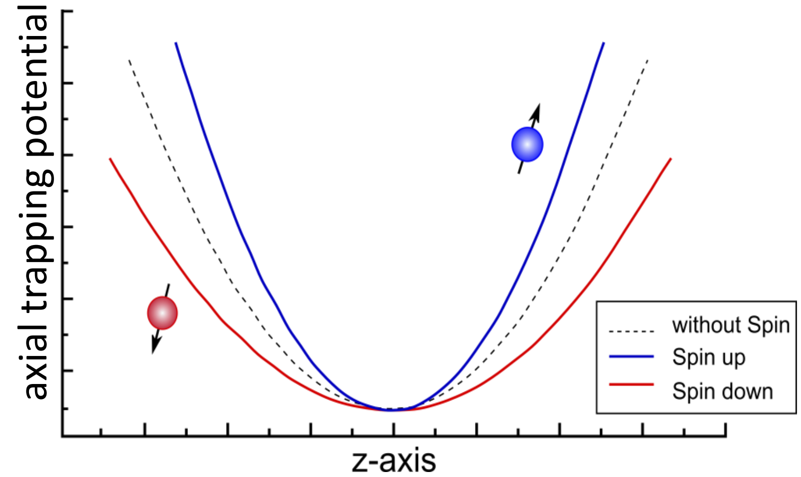
Microwave access

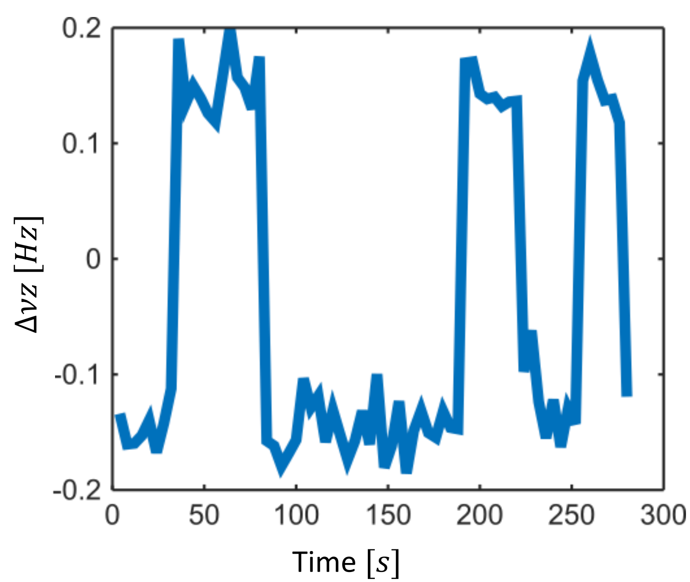
$\nu_L \sim 110$ GHz

ferromagnetic ring

Magnetic field inhomogeneity

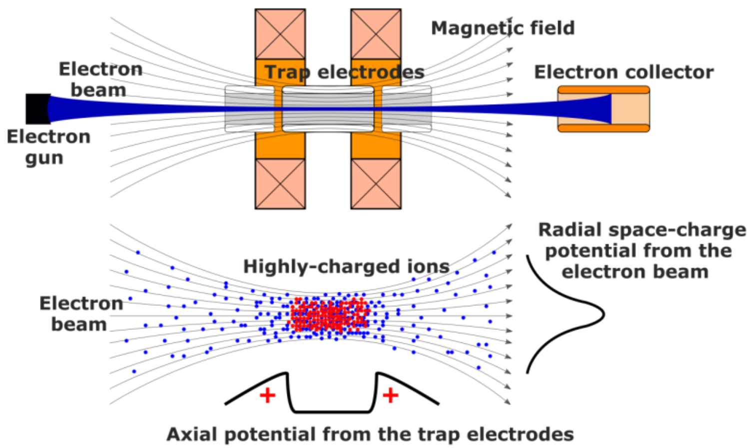
$B_2 = 45\ \mathrm{kT \cdot m^{-2}}$





- Magnetic bottle makes the axial frequency spinstate dependent
- Spinflip is driven by resonant microwave excitation

ALPHATRAP



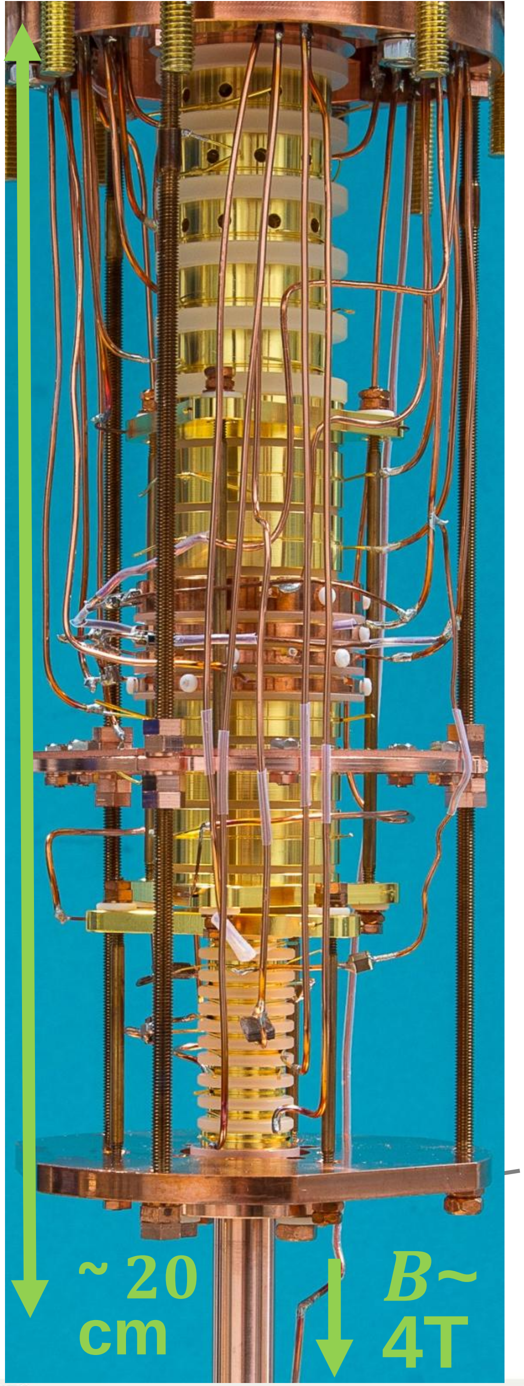
Beamline

Thanks to the Crespo group

- **4T magnet**
- **4 K Setup**
- **Pressure below 10^{-16} mbar**

→ **Space-like Conditions**

Penning trap tower



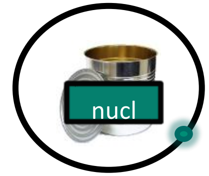
Capture electrodes
- Dynamic ion capture/storage

Precision trap
- 18mm diameter
- 7-electrode trap
- Homogeneous *B*-field: measure $\boldsymbol{\Gamma = \omega_L/\omega_c}$

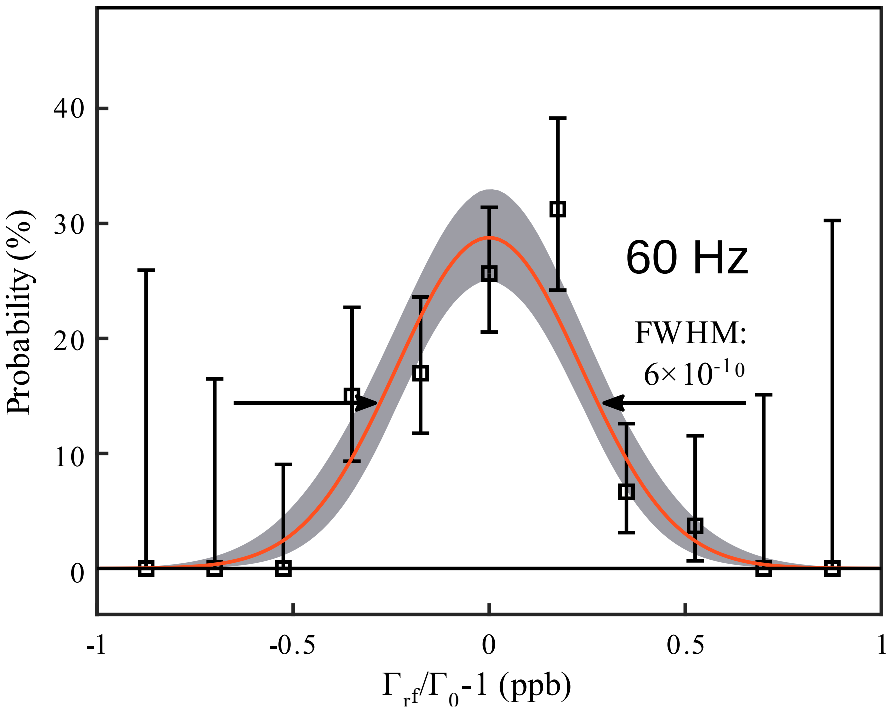
Analysis trap
- 6mm diameter
- Ferromagnetic ring electrode: spin detection

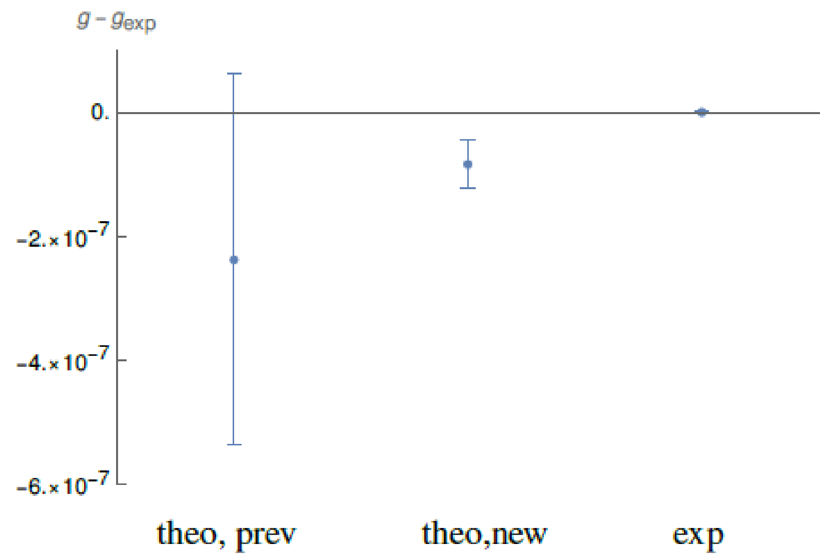
Microwave horn
- mm – wave coupling
- Laser access

$g_j(^{118}Sn^{49+})$



Thanks to Yerokhin's & Harman's groups





$g_{\mathrm{Experiment}} = 1.910\,562\,059\,(1)$ → 5×10^{-10} J. Morgner *et al.*, Nature **622**, 53 (2023)

$g_{\mathrm{Theory}} = 1.910\,561\,975\,(39)$ → 2×10^{-8} B. Sikora *et. al.*, PRL **134**, 123001 (2025)

[Lit. value]

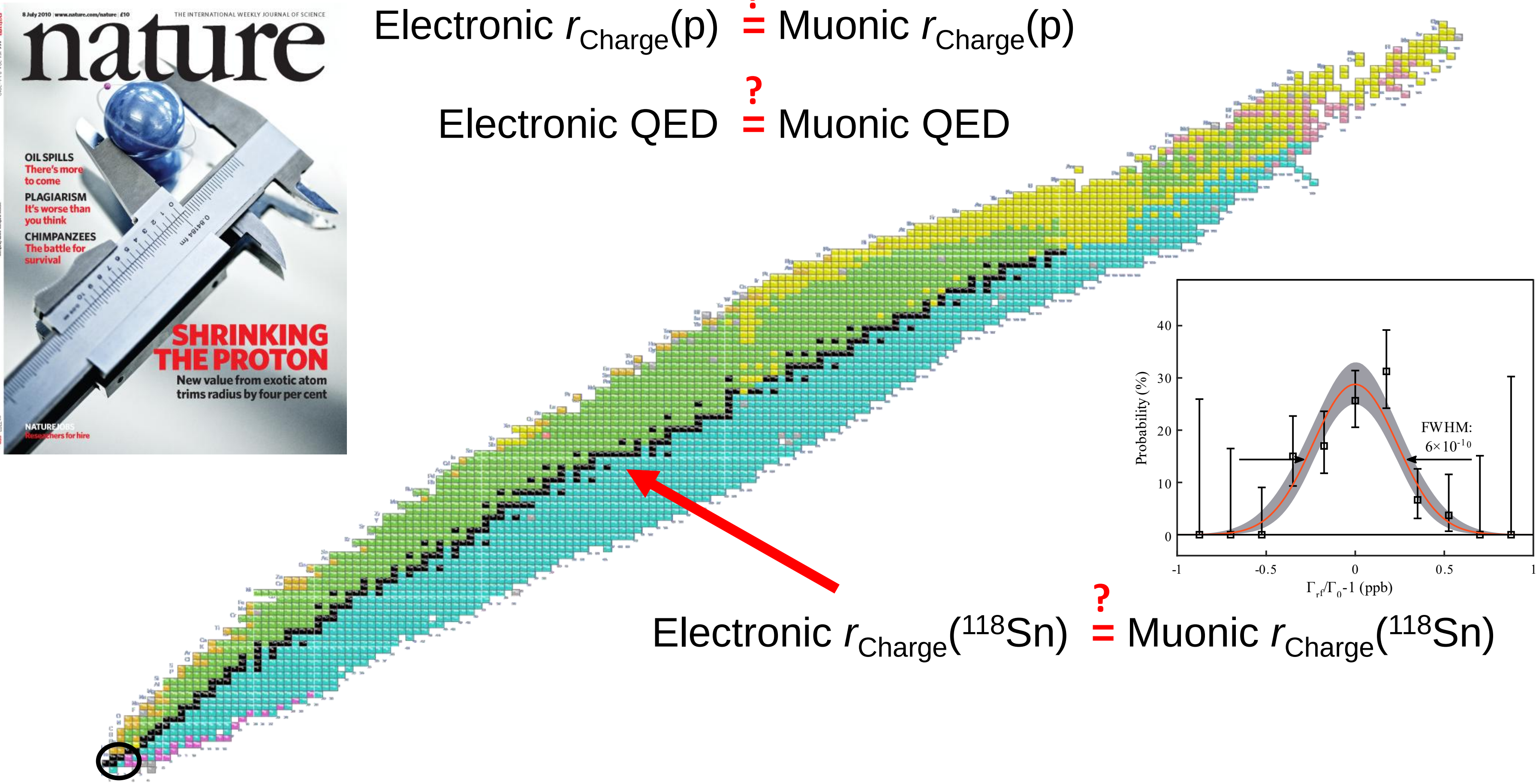
- Bounds on New Physics based on $g_j(^{118}Sn^{49+})$

Moretti *et al.*, PRL **136**, 011803 (2026)

Nuclear charge radius based on $g_j(^{118}Sn^{49+})$

Electronic r_{Charge}(p) ≟ Muonic r_{Charge}(p)

Electronic QED ≟ Muonic QED



Electronic $r_{Charge}(^{118}Sn)$ ≟ Muonic $r_{Charge}(^{118}Sn)$

Electronic $r_{Charge}(^{118}Sn)$ = 4.6 x y (5) fm — based on Yerokhin *et al.*, PRA **113**, 012804 (2026)

?

Muonic $r_{Charge}(^{118}Sn)$ = 4.6 a b (3) fm — based on Beyer *et al.*, arxiv 2511.22298

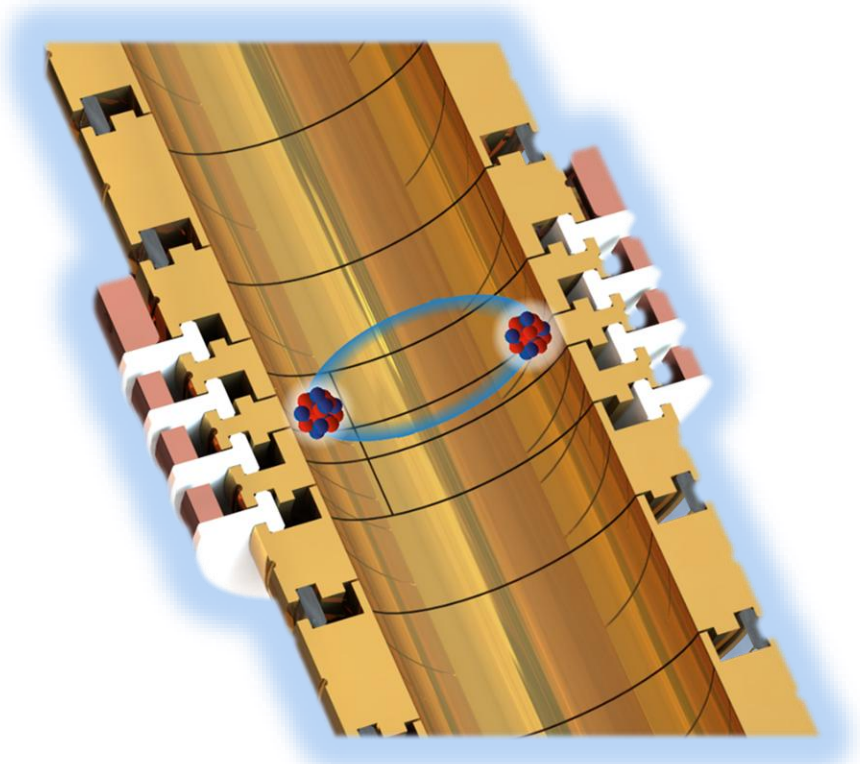
Preliminary!

New upcoming paper!

Direct *g*-factor difference measurement of $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$

T. Sailer *et al.*, Nature **606**, 479 (2022)

- Controlled ion crystal in a Penning-Trap
- Measure the *g*-factor difference in a decoherence-free subspace
- **Two order of magnitude improvement for comparing *g* factors (most precise difference of *g* factors)**



Direct *g*-factor difference measurement of $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$

Theoretical *g* factor	
$^{20}Ne^{9+}$	1.998 767 276 921(117)
$^{22}Ne^{9+}$	1.998 767 263 446(117)
Theoretical difference (x 10^{-9})	
Nuclear size	**0.166** (11)
Recoil, non-QED	13.265
Recoil, QED	0.044
Polarization	**0.000 1 (3)**
Total	13.474 (11)
Experiment	13.475 $2(5)_{stat}(10)_{sys}$

- **Perfect agreement with theory at 5 x 10^{-12} level**
- **Confirmation of QED recoil contribution in *g* factors!**
- **Factor 9 improved rms nuclear charge radius difference**
- **Improved Ne chain by up to a factor of two**

$\sim 6 \times 10^{-13}$ precision relative to the *g* factor

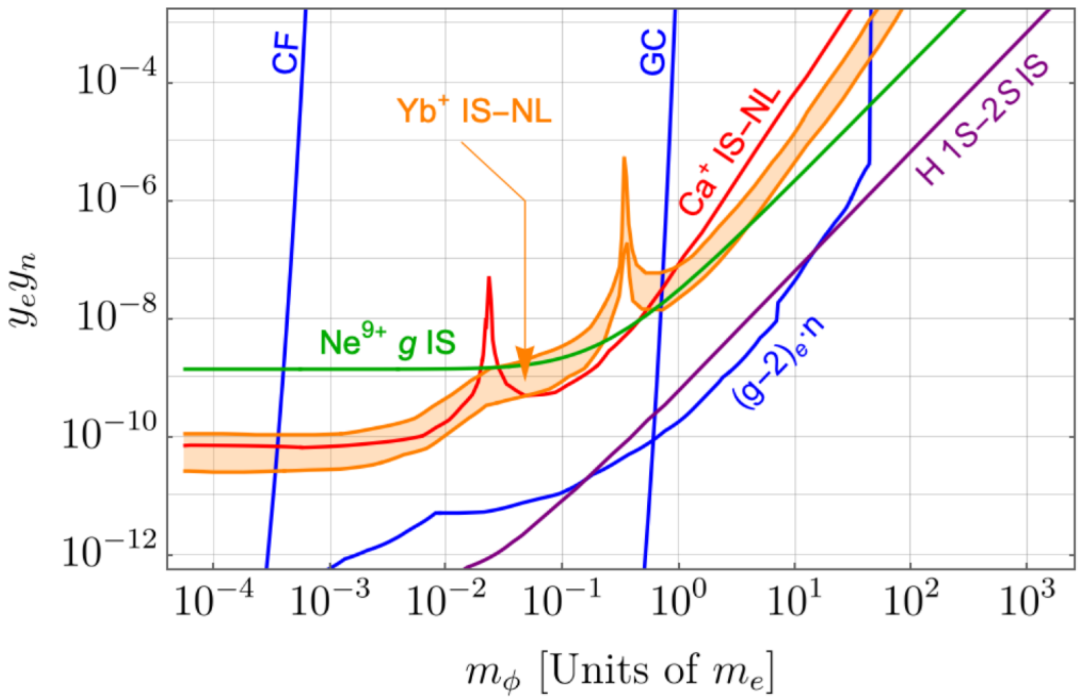
Lit: $\delta\langle r^2\rangle^{1/2} = 0.0530(34)\,\text{fm}$

New: $\delta\langle r^2\rangle^{1/2} = 0.0533(4)\,\text{fm}$

4x improvement still possible

Bounds on New Physics

- Higgs portal mechanism involves the coupling of a potential new scalar boson with the Higgs boson
- Limit on the coupling strength $y_e y_n$



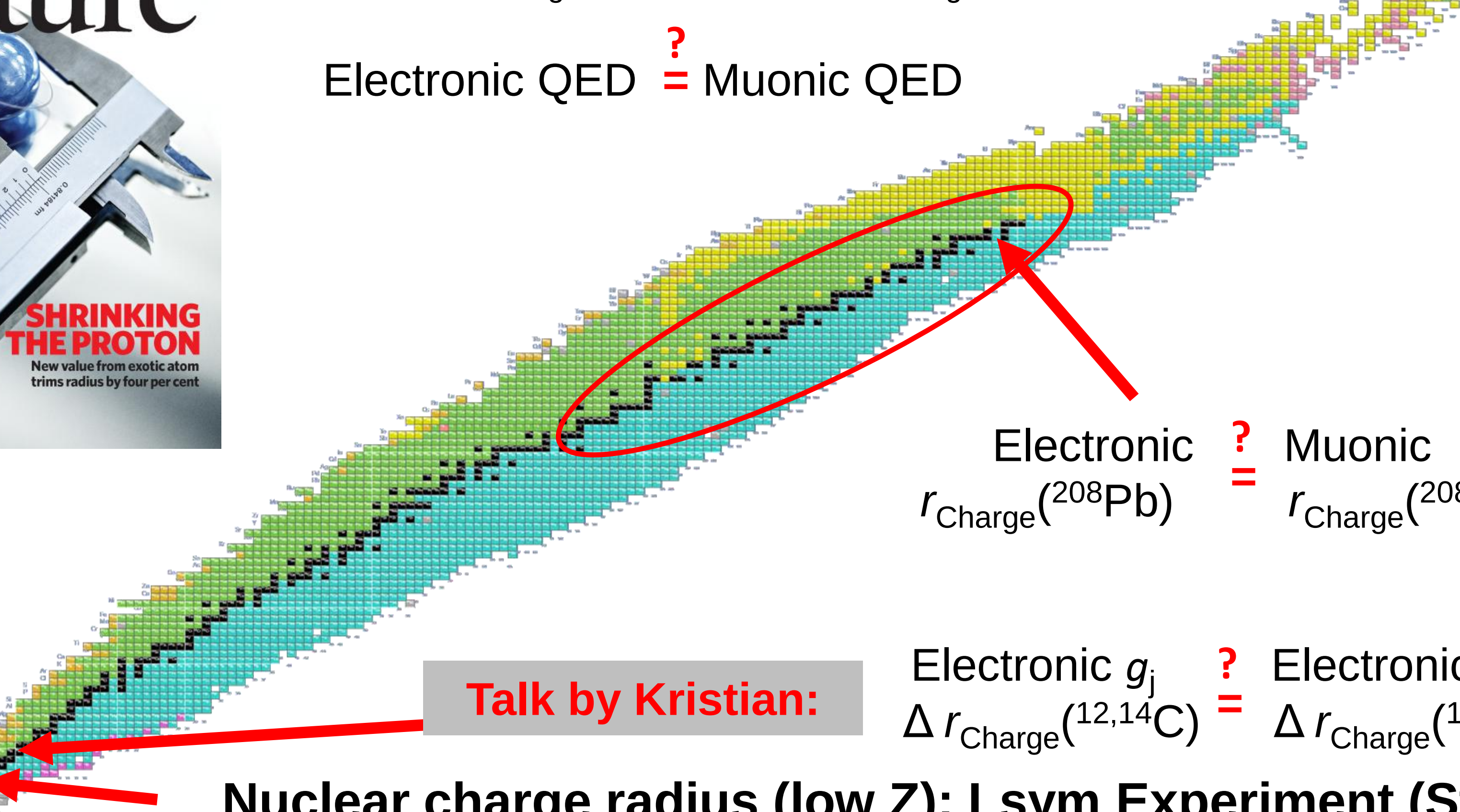
Limit is competitive with H 1s-2s IS with independent rms nuclear charge radius difference

T. Sailer *et al.*, Nature **606**, 479 (2022)

What is next?

Electronic r_{Charge}(p) $\overset{?}{=}$ Muonic r_{Charge}(p)

Electronic QED $\overset{?}{=}$ Muonic QED



Electronic $r_{Charge}(^{208}Pb)$ $\overset{?}{=}$ Muonic $r_{Charge}(^{208}Pb)$

Talk by Kristian:

Electronic g_j $\Delta r_{Charge}(^{12,14}C)$ $\overset{?}{=}$ Electronic laser $\Delta r_{Charge}(^{12,14}C)$

Nuclear charge radius (low Z): Lsym Experiment (Sturm)

Fully exploiting the rich potential of our nuclei

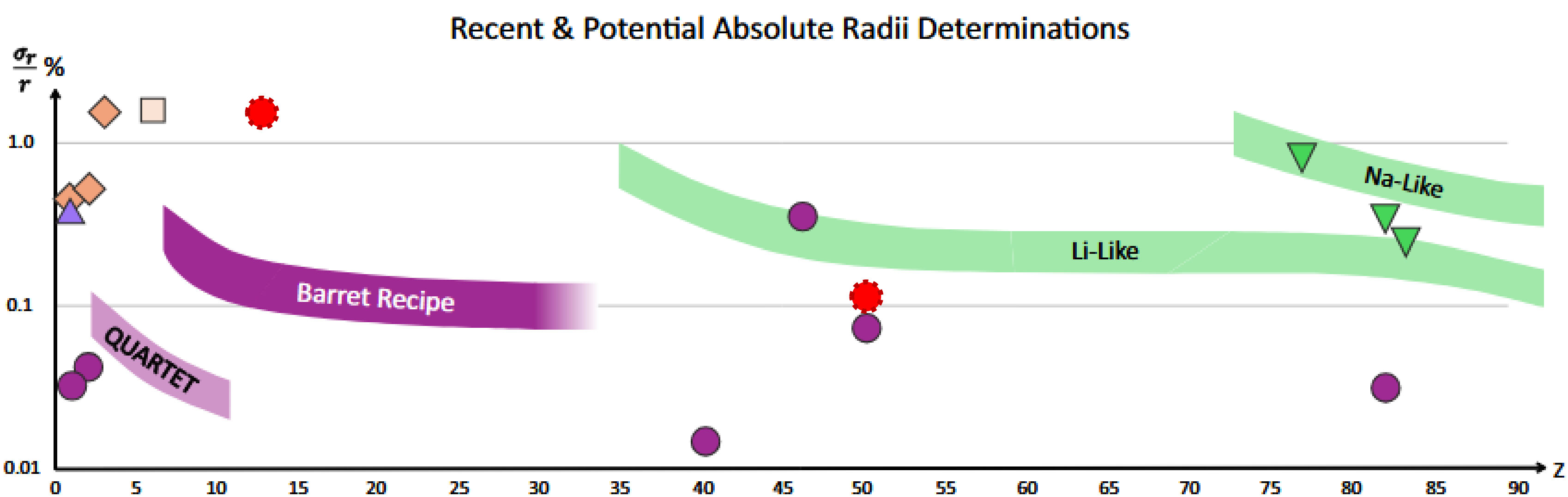
Constants – Test of QED – BSM search

What is next?

Towards better nuclear charge radii

István Angeli,[1] Dimiter L. Balabanski,[2] Paraskevi Dimitriou,[3] Dipti,[4] Kieran T. Flanagan,[5] Georgi Georgiev,[6] Mikhail Gorchtein,[7,8] Paul Guèye,[9] Fabian Heiße,[10] Andreas Knecht,[11] Kei Minamisono,[9] Wilfried Nörtershäuser,[12,13] Ben Ohayon,[14,*] Natalia S. Oreshkina,[10] B. K. Sahoo,[15] Hunter Staiger,[4] Endre Takacs,[4] Xiaofei Yang,[16] and Deyan T. Yordanov[17,18]
(Working Group on Nuclear Charge Radii)

Today

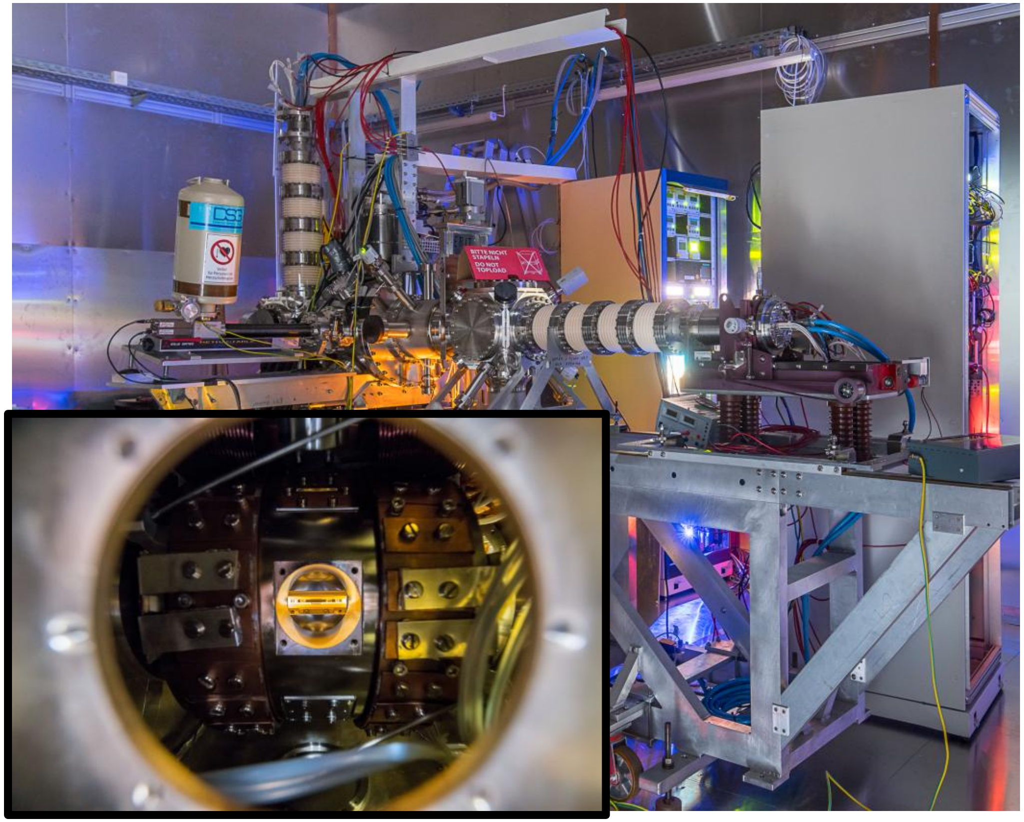


arXiv:2604.08985

Hyper-EBIT

Access to hydrogen-like ions beyond lead

Electron beam:
300 keV
500 mA



Thank you for your attention!

- Phillip Justus
- Luca Geißler
- Max Anton Gramberg
- Charlotte König
- Matthew Bohman
- Jacob Schrader
- Jonathan Morgner
- Jialin Liu
- José Crespo
- Sven Sturm
- Klaus Blaum

New physics starts at the next digit of precision!