Precise nuclear charge radii via bound electron *g* factor measurements

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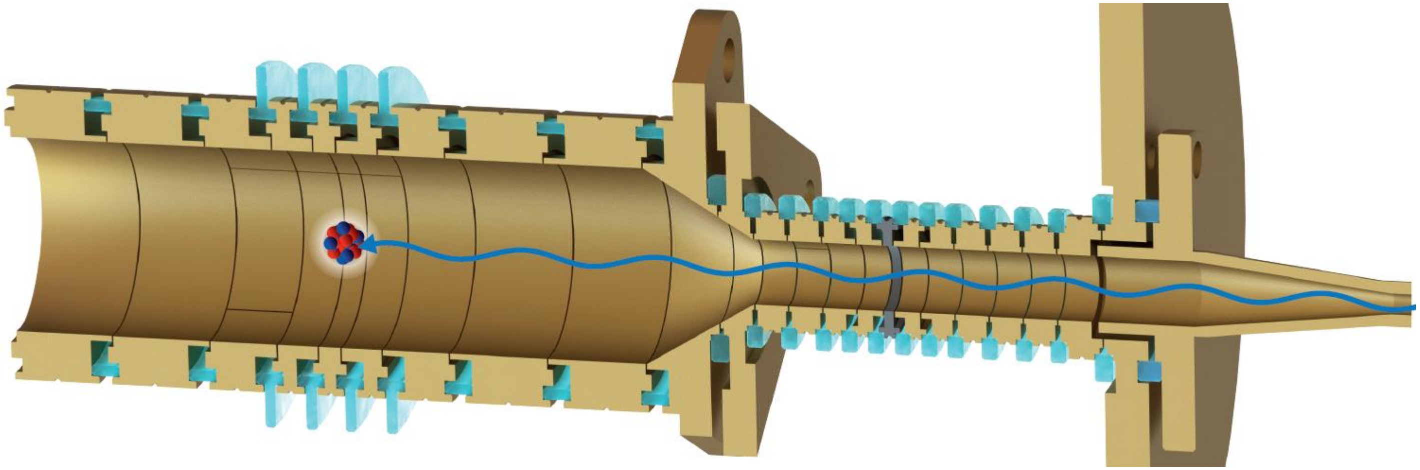
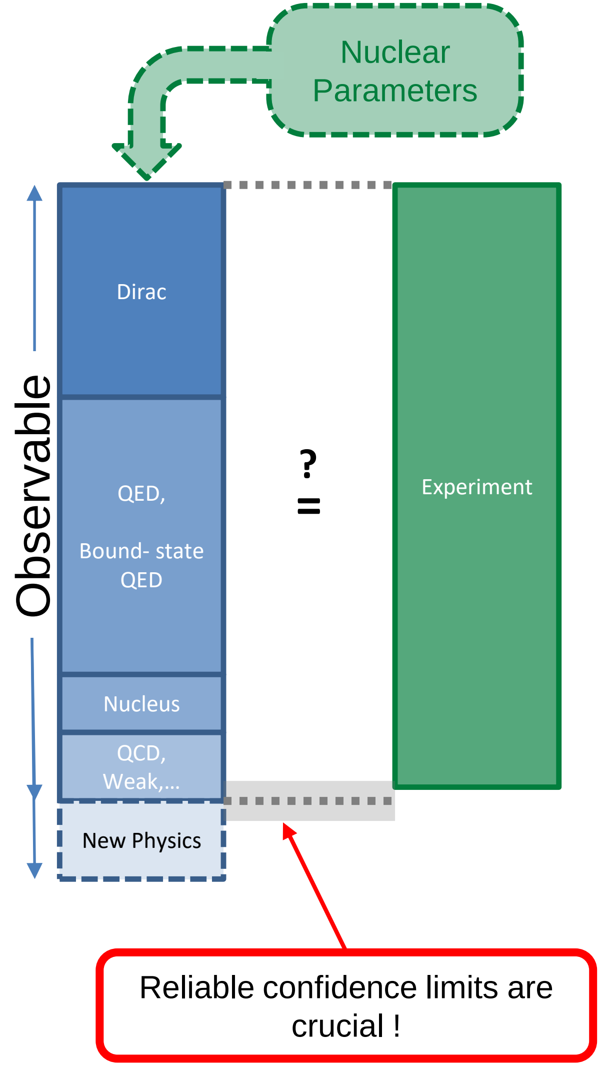


Compilation & Evaluation of Nuclear Charge Radii

ERC AdG 832848 - FunI
DFG SFB 1225

How to test a theory with precision measurements?



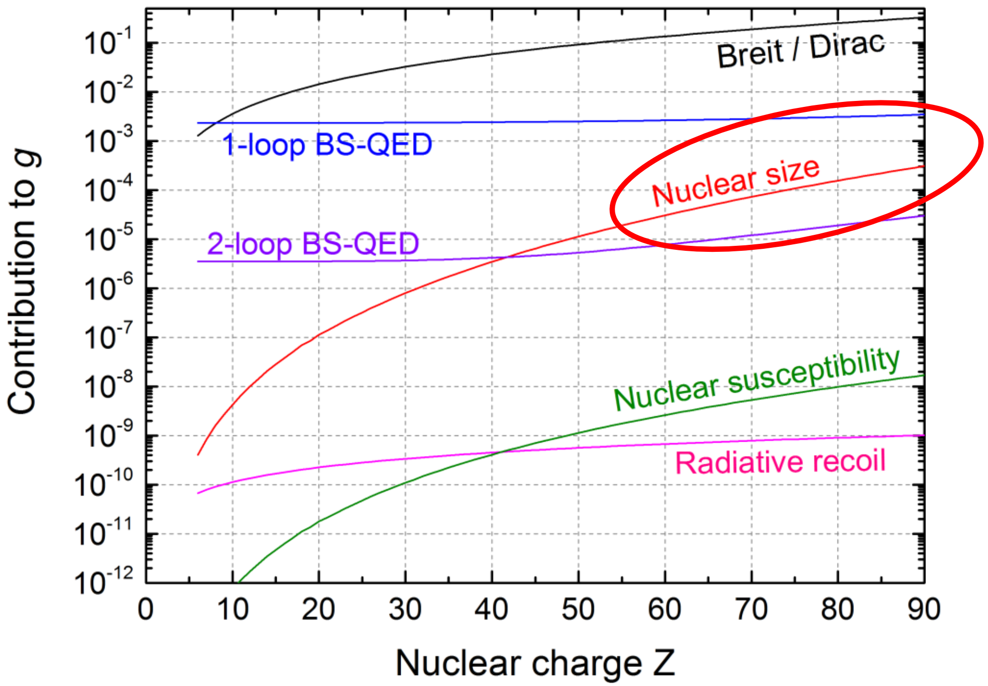
- Theory predicts observable
  – experiment confirms or falsifies
  hint for new physics ?!

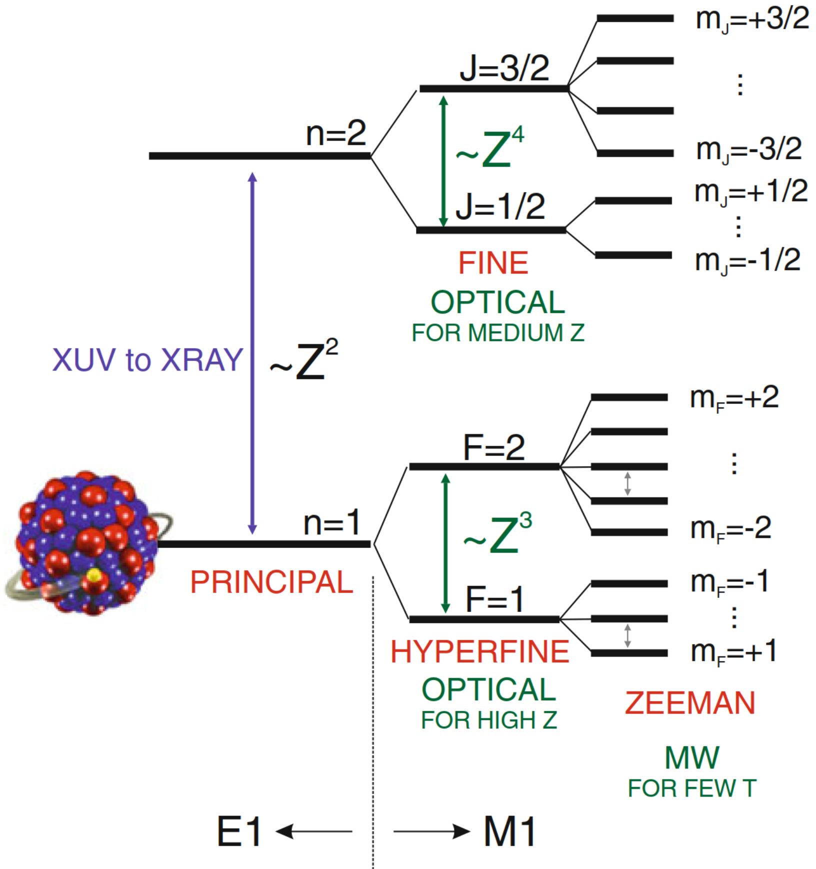
- Any fundamental theory can only predict dimensionless quantities

- **Reliable fundamental constants including nuclear properties are absolutely essential**

Harvest the rich potential of our strong field mini laboratories aka inner electrons + nuclei

Hydrogen-like ion in strong fields



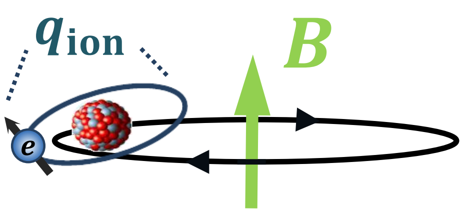


Precise nuclear charge radii accessible

Overview

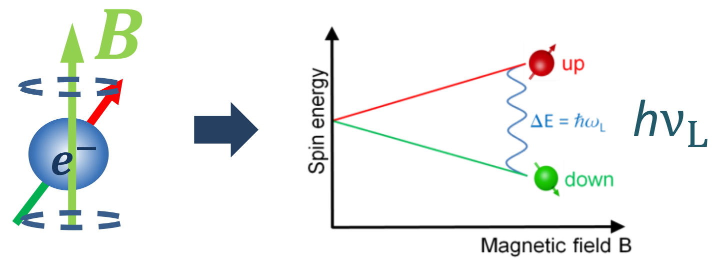
- **Measurement principle**
- **ALPHATRAP Experiment**
- **$g_j(^{118}Sn^{49+})$ measurement**
- **Direct *g*-factor difference measurement of $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$**
- **Summary & Outlook**

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

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

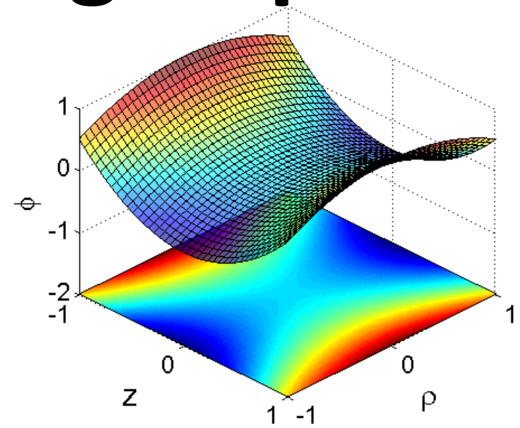
is measured

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

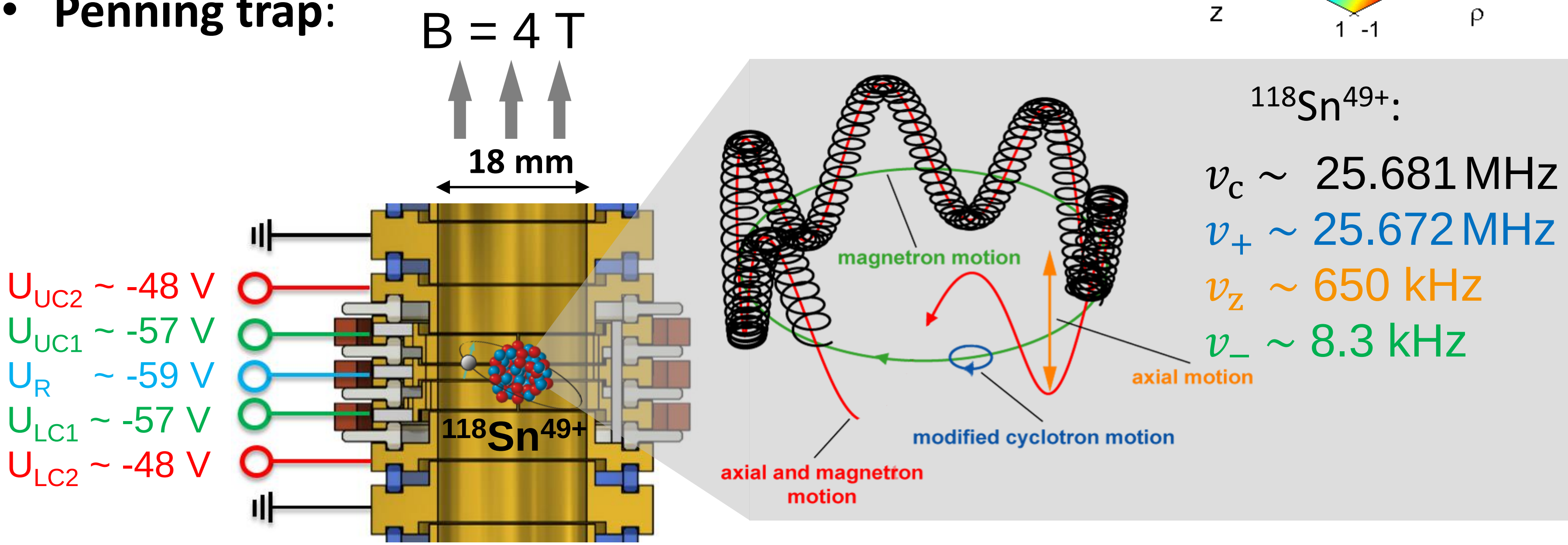
Independent precision experiments
→ e.g. PENTATRAP

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:**

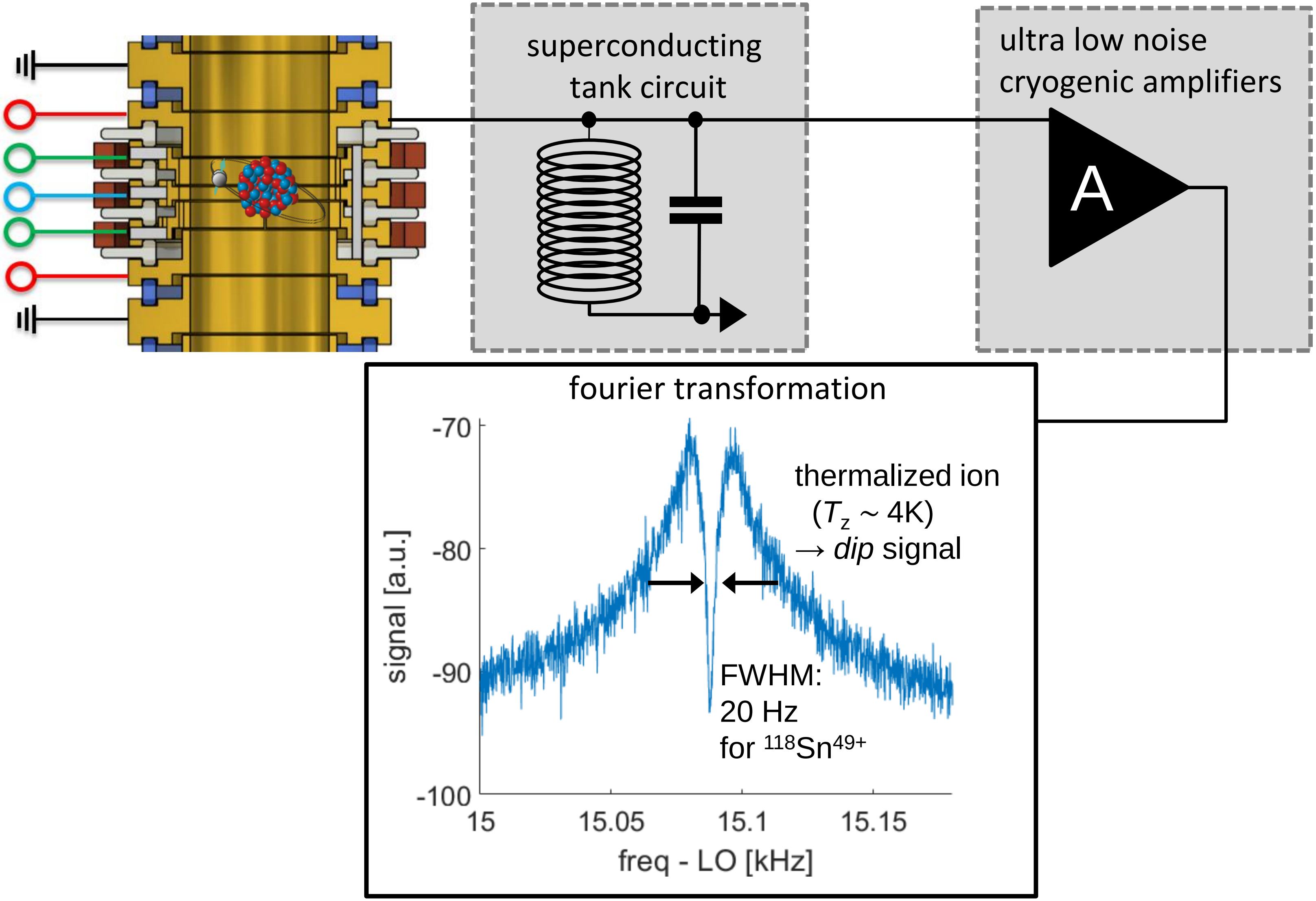
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

$$\nu_c \approx \nu_+ >> \nu_z >> \nu_-$$

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

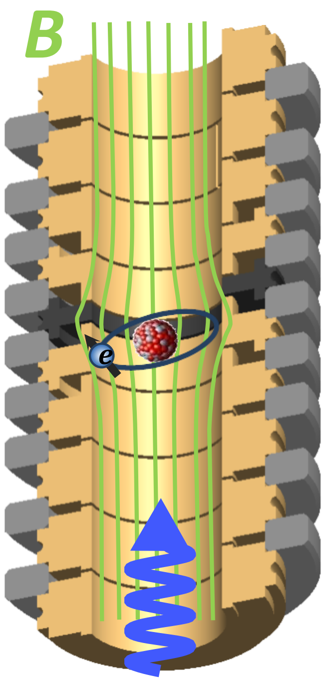
Non-destructive Eigenfrequency Detection

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



Non-destructive Spin state detection

Analysis Trap (AT)



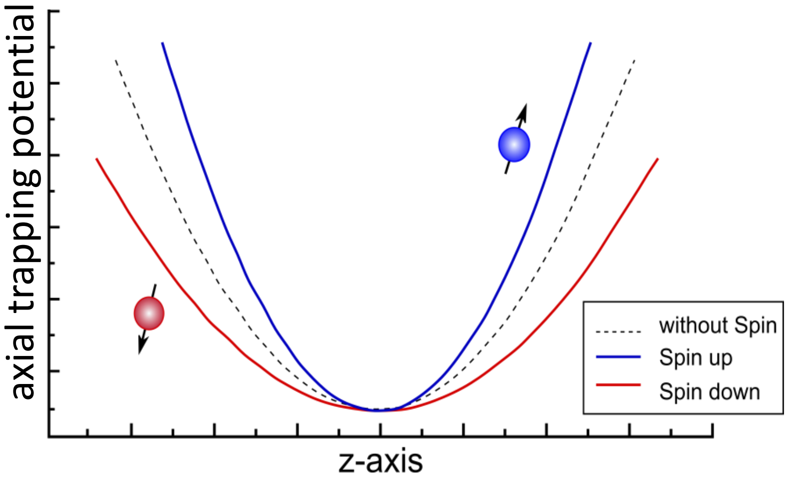
Microwave access

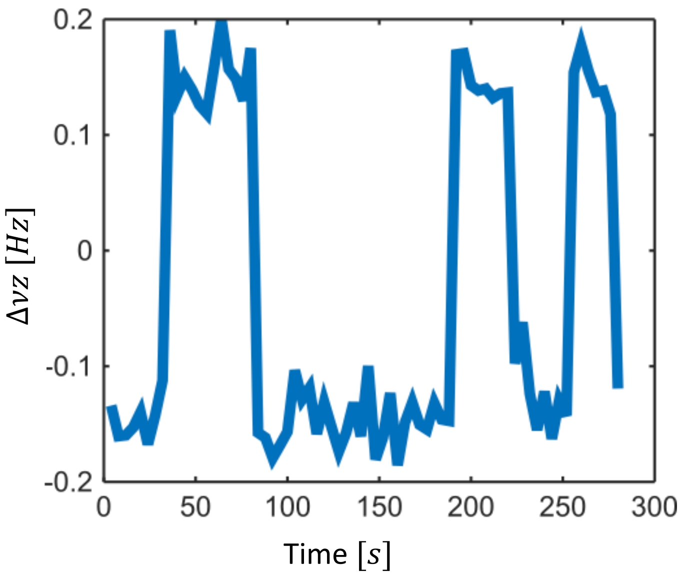
$\nu_L \sim 110$ GHz

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

Overview

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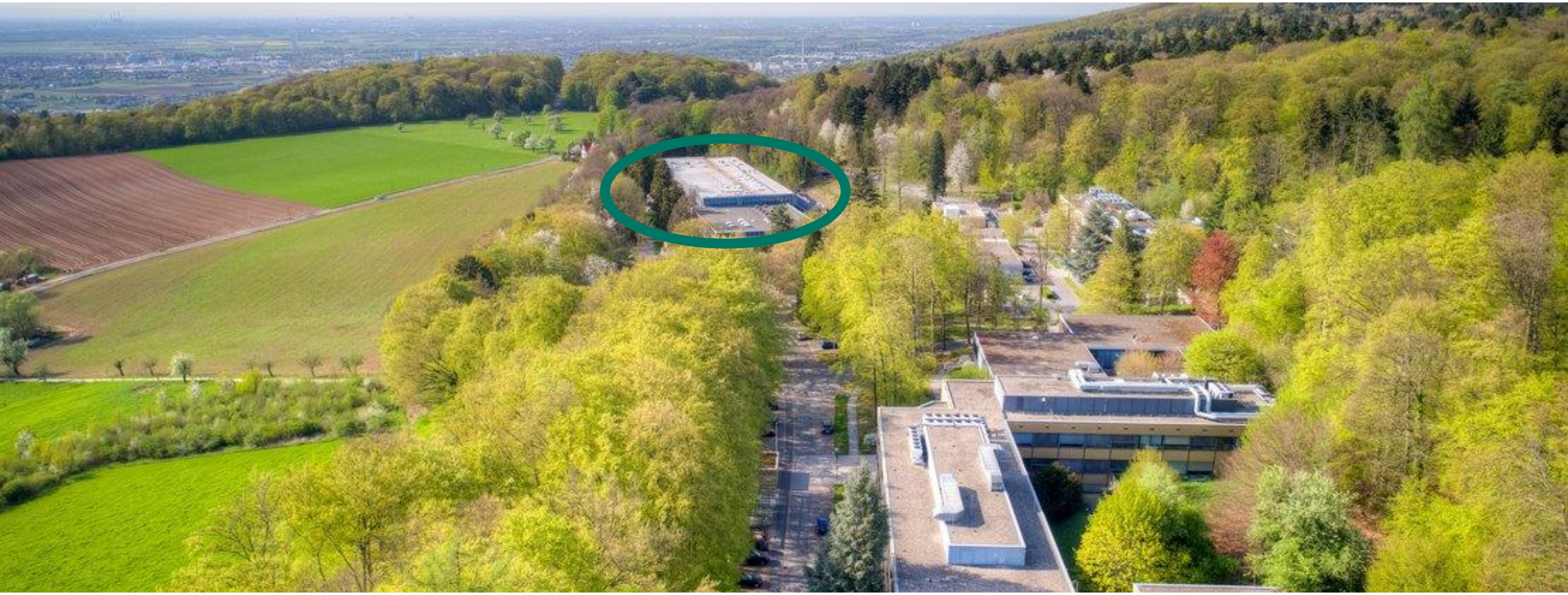
- $g_j(^{118}Sn^{49+})$ **measurement**
- **Direct *g*-factor difference measurement of $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$**
- **Outlook**

Max Planck Institute for Nuclear physics

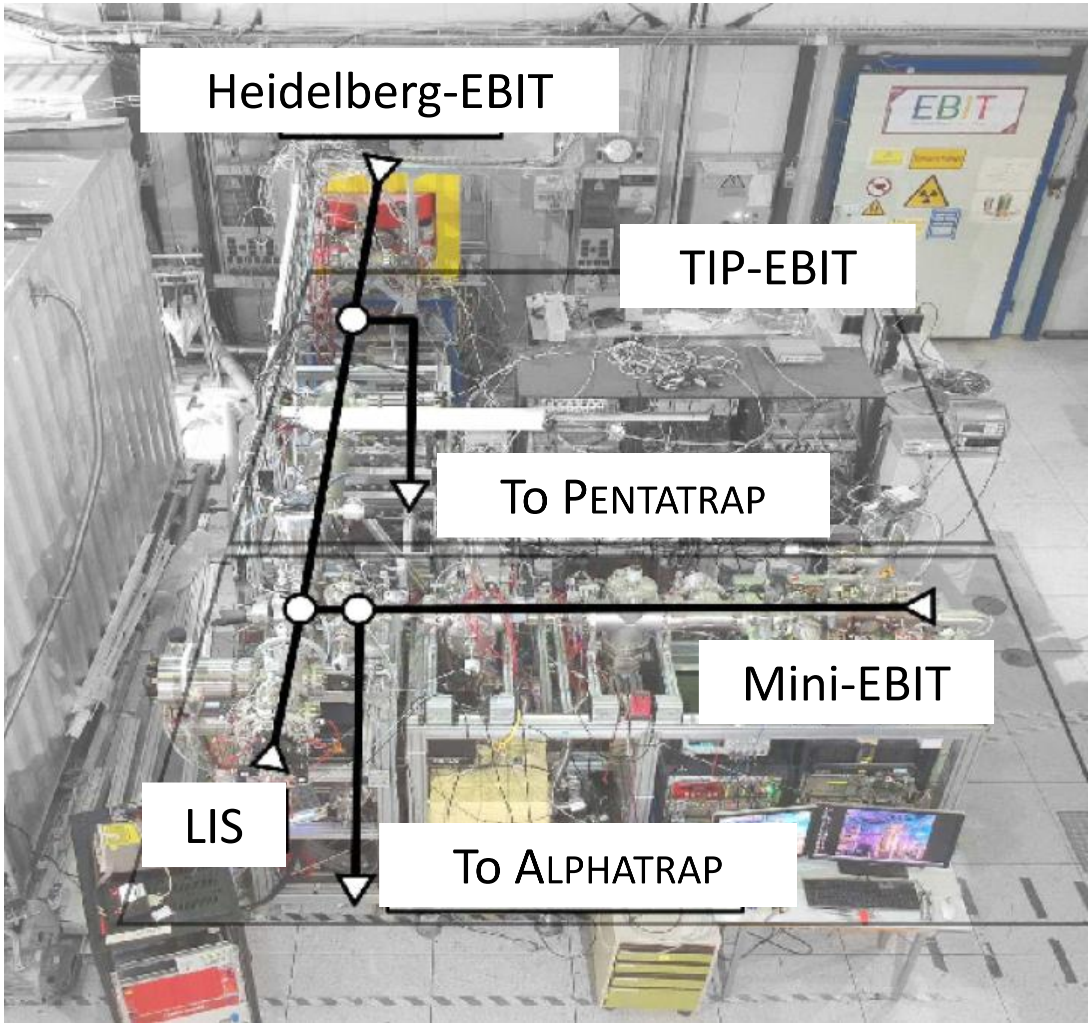


Highly charged ion sources at MPIK

EBIT facility
→ Access to highly charged ions

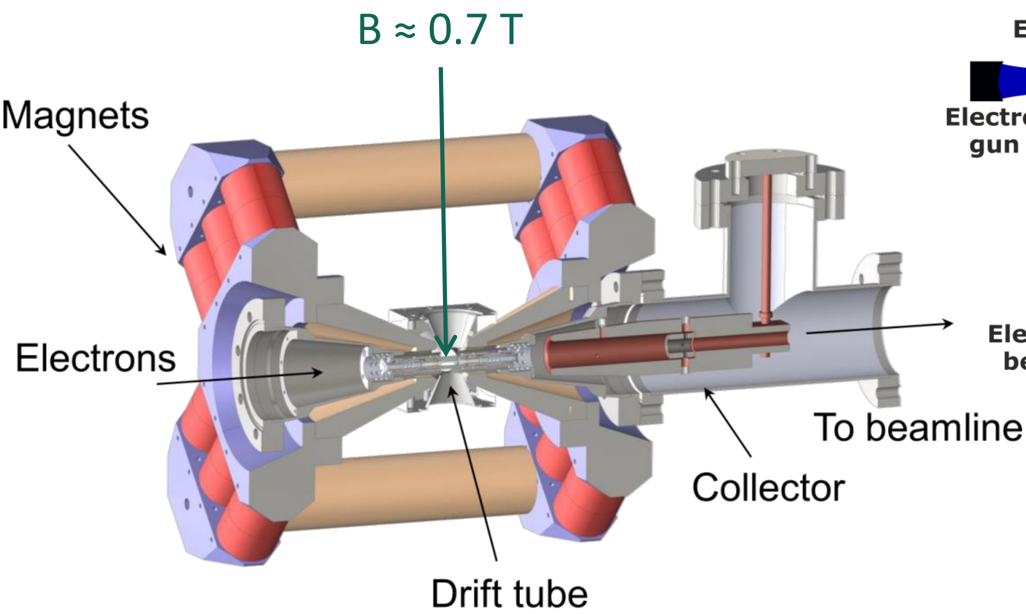
Thanks to the José Crespo group

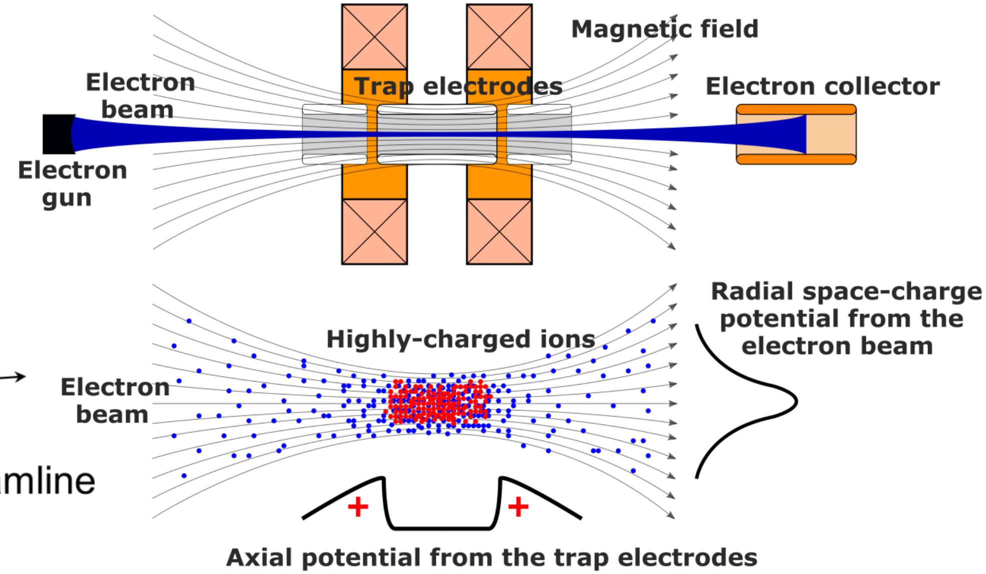
Current production status:
- **all H-like ions up to ^{132}Xe**
- **all Li-like ions up to ^{238}U**



Electron beam ion traps (EBIT)

- Ionisation energy provided by electron beam energy
- Beam current ~ ampère
- Ions confined by magnetic field + electrodes + beam space charge
- Charge breeding takes ms-min



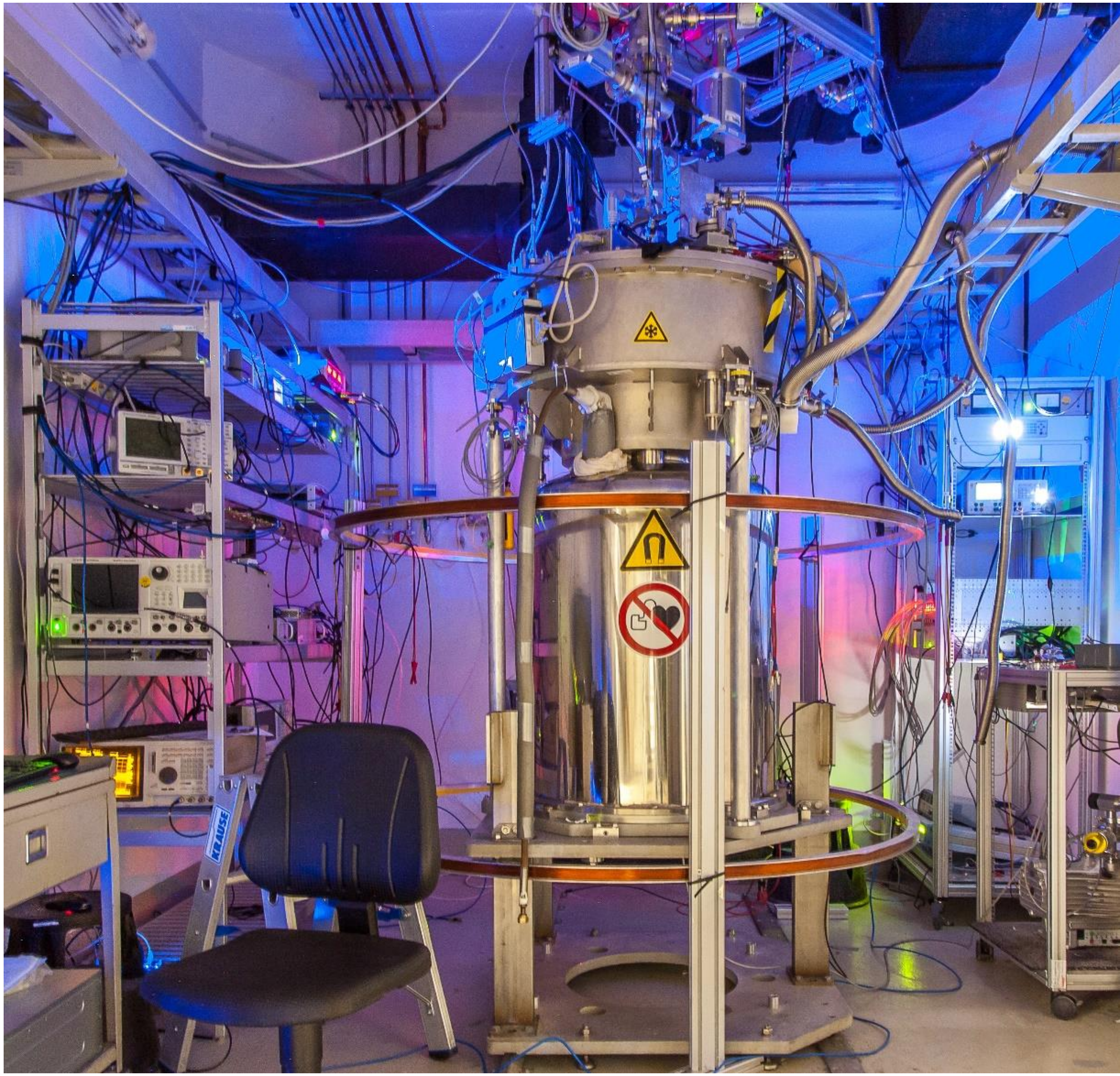


Christoph Schweiger, Master Thesis Uni HD, 2017
P. Micke et al. Rev. Sci. Instr. 89.6 (2018).

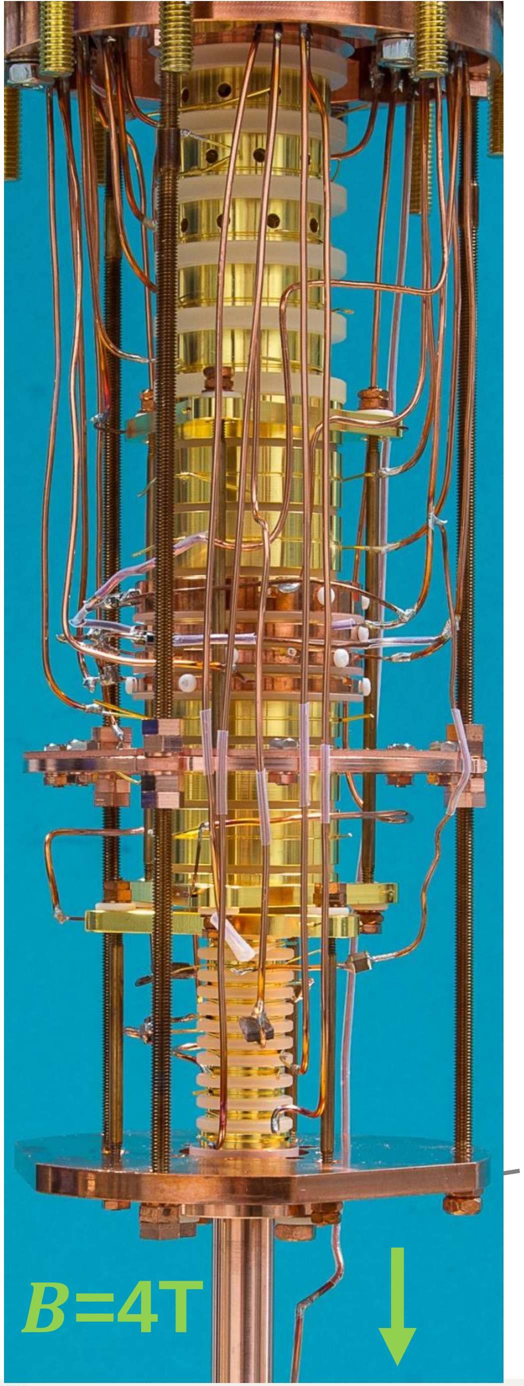
ALPHATRAP setup

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

Space Conditions



Penning trap tower



Capture electrodes
- Potential switching
- 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

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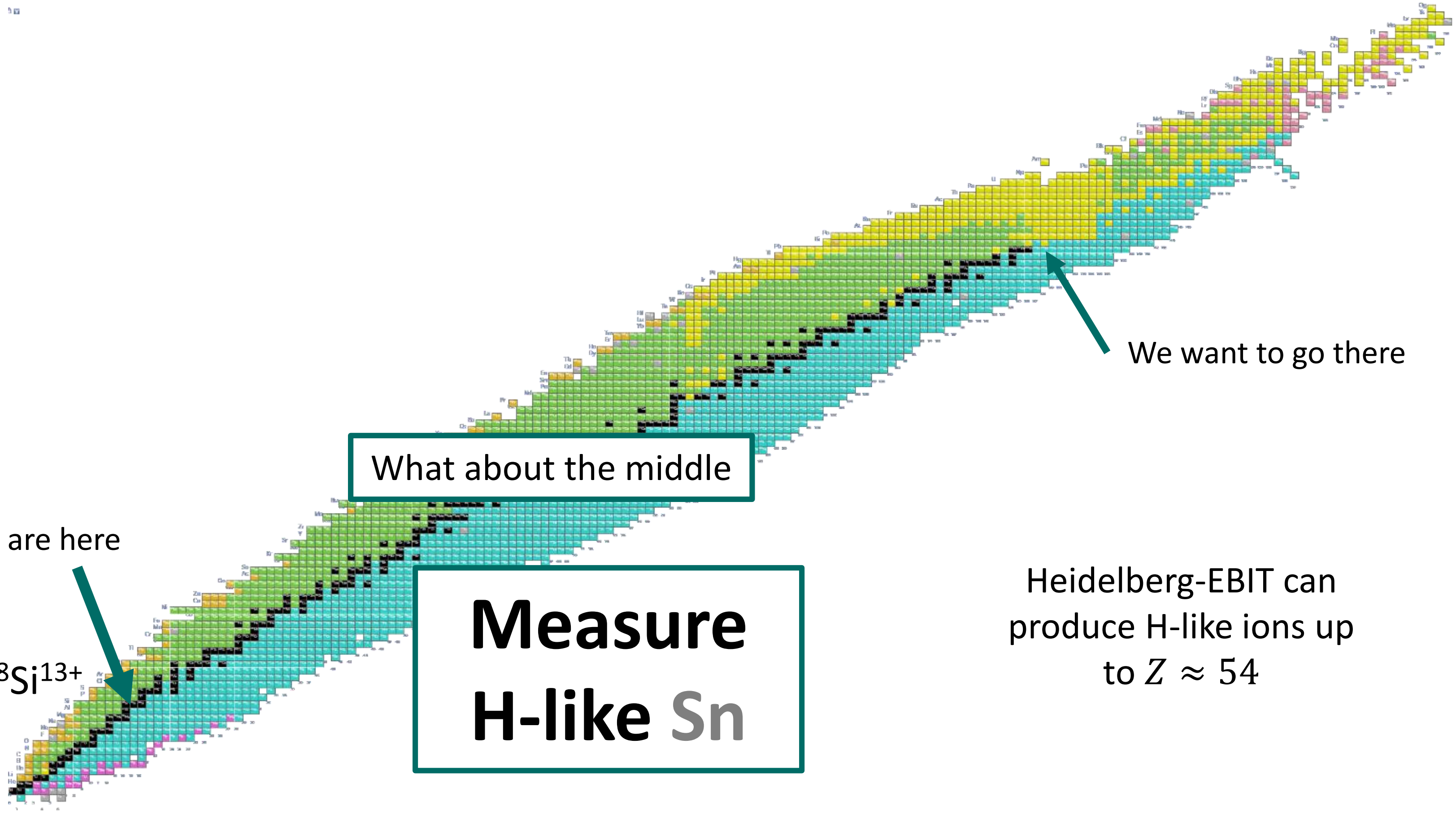
Current status



We are here

$^{28}Si^{13+}$

What about the middle

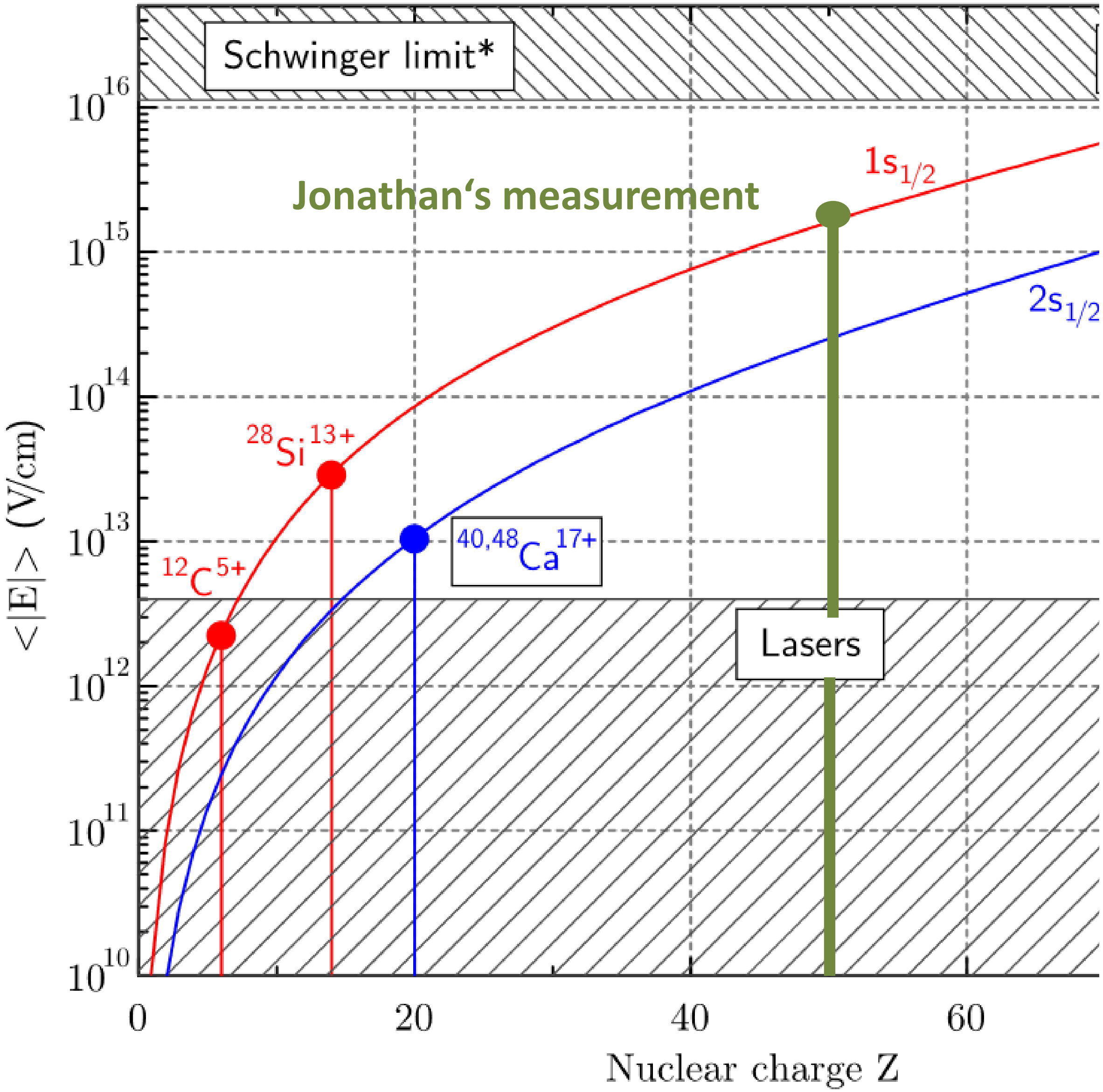
We want to go there

Measure H-like Sn

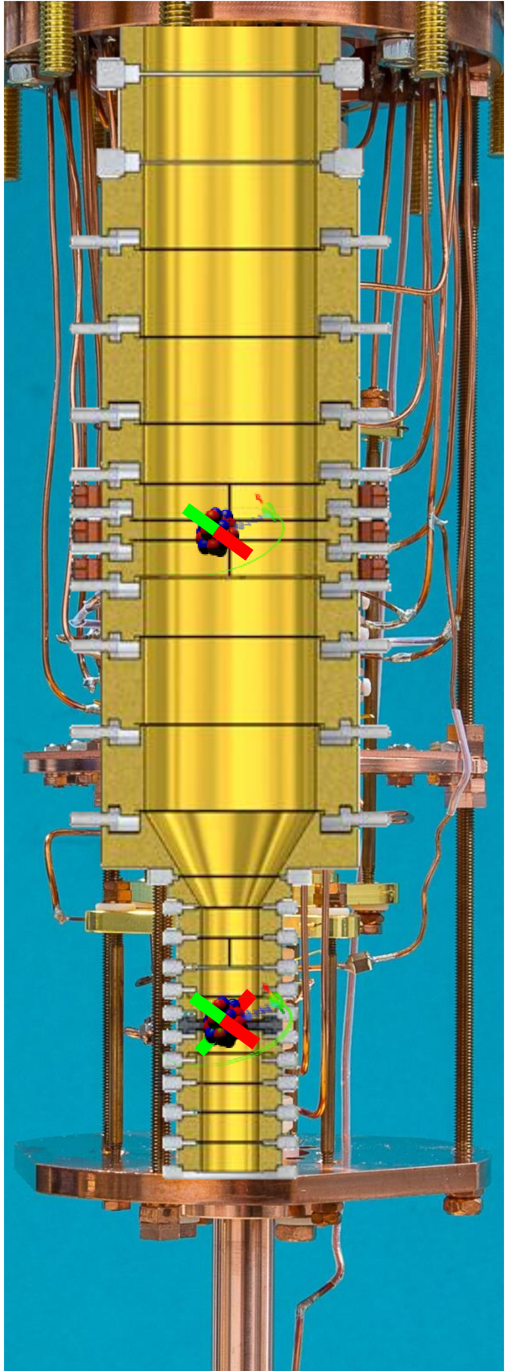
Heidelberg-EBIT can produce H-like ions up to $Z \approx 54$

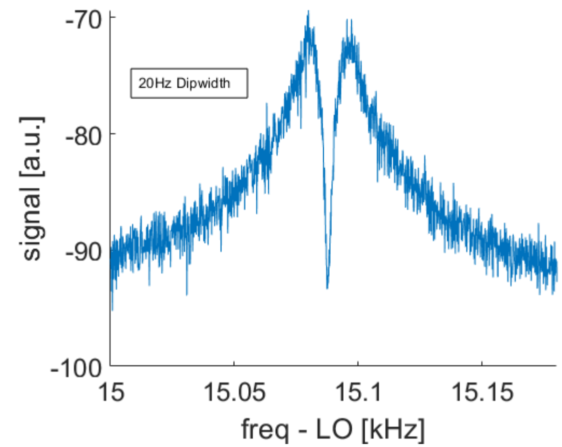
Picture from IAEA

Current status



g factor measurement cycle





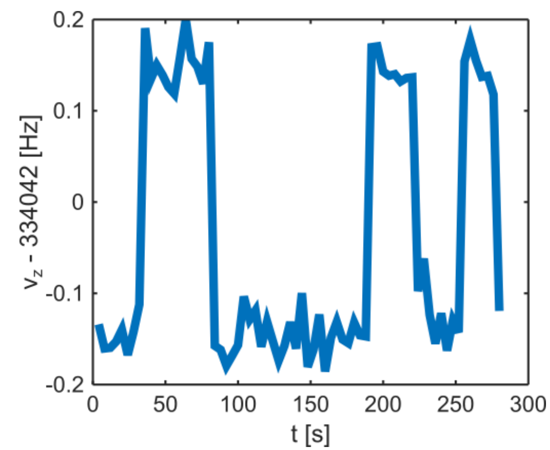
Measure ν_c
Inject MW ν_L

Transport to PT

$\sim$20 min

Transport to AT

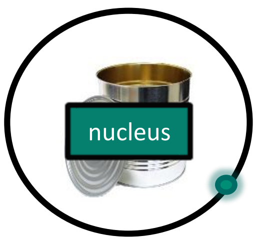
Measure Spinstate



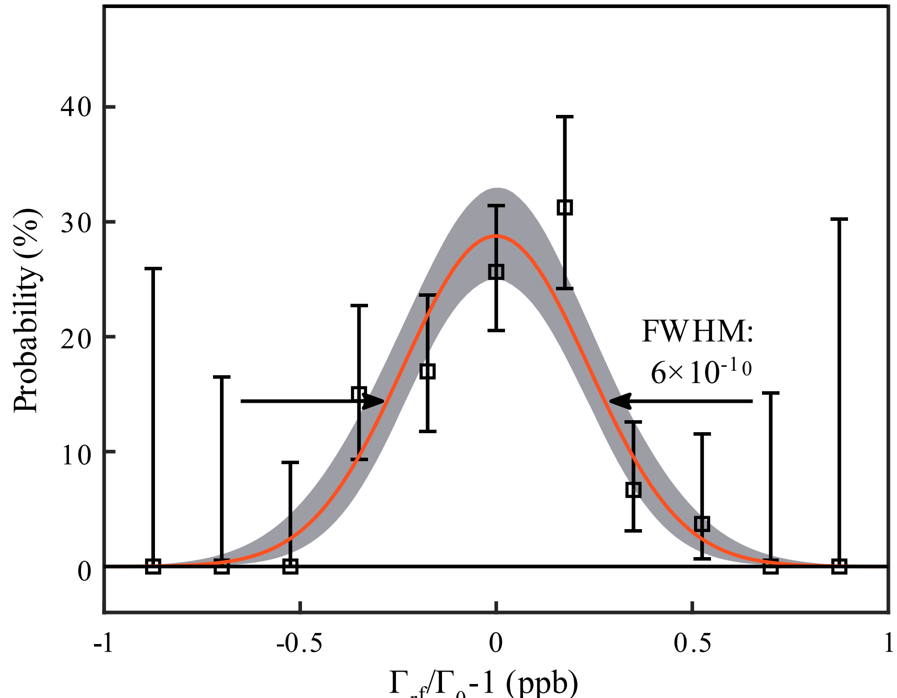
Resonance for $g_j(^{118}Sn^{49+})$

Transistion probability as a function of $\frac{\omega_L}{\omega_c}$

Maximum-Likelihood fit of the data



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



Thanks to the theoreticians

$$g_{\text{Experiment}} = 1.910\,562\,059\,(1) \rightarrow 5 \times 10^{-10}$$

$$g_{\text{Theory}} = 1.910\,561\,821\,(299) \rightarrow 1.5 \times 10^{-7}$$

J. Morgner *et. al.* Nature 622, 53 (2023)

We also measured $g_j(^{118}Sn^{47+})$ & $g_j(^{118}Sn^{45+})$

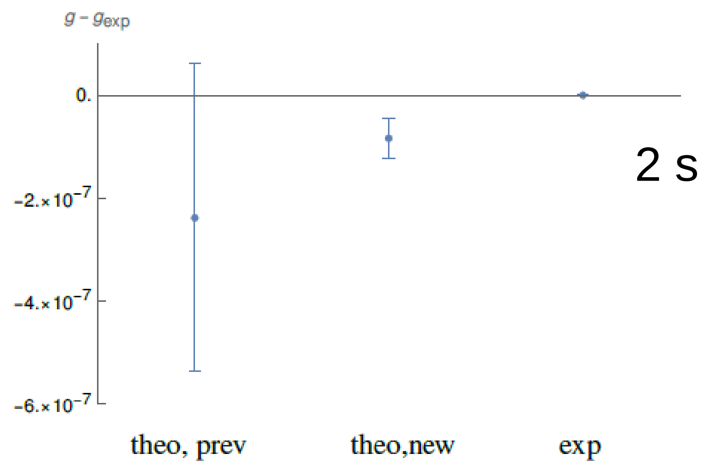
g-factor contribution $^{118}Sn^{49+}$

- Nuclear parameters (radius, polarization, …) are accessible

Contribution		$^{118}Sn^{49+}$
Dirac value		1.908 079 205 3(1)
Finite size		0.000 014 489 4(110)(188)
Nuclear	deformation	0.000 000 000 0(10)
Nuclear	polarization	0.000 000 000 0(94)
Nuclear	susceptibility	0.000 000 000 0(13)
1-loop QED	$(Z\alpha)^0$	0.002 322 819 5
	$(Z\alpha)^2$	0.000 051 538 9
	$(Z\alpha)^4$	-0.000 170 171 8
	$(Z\alpha)^{5+}$ SE	0.000 256 890 8(7)
	$(Z\alpha)^{5+}$ VP-EL, Uehling	0.000 008 708 8
	$(Z\alpha)^{6+}$ VP-EL, WK (incl. FS)	0.000 000 658 4
	$(Z\alpha)^{5+}$ VP-ML (incl. FS)	0.000 001 225 0(40)
	remaining 1-loop-FS	-0.000 000 045 7(1)
	Muonic VP	-0.000 000 002 7(14)
2-loop QED	$(Z\alpha)^0$	-0.000 003 544 6
	$(Z\alpha)^2$	-0.000 000 078 6
	$(Z\alpha)^4$	-0.000 000 971 9
	$(Z\alpha)^4$, LBL	-0.000 000 151 9
	$(Z\alpha)^5$ SESE	0.000 000 202 3
	$(Z\alpha)^5$ LBL	-0.000 000 013 5
	$(Z\alpha)^{5+}$ ML	0.000 000 022 2(215)(52)
	$(Z\alpha)^{5+}$ S(VP)E, SEVP, VPVP	0.000 000 286 5(1)
	$(Z\alpha)^{6+}$ SESE	0.000 000 000 0(2968)
$\geq$ 3-loop QED	$(Z\alpha)^0$	0.000 000 029 5
	binding	0.000 000 000 7(105)
Recoil	$\frac{m}{M}$, all-order $Z\alpha$	0.000 000 726 8
	h.o $\frac{m}{M}$	-0.000 000 000 1
	rad-rec	-0.000 000 000 5(4)
Hadronic	$(Z\alpha)^0$	0.000 000 000 0
	$(Z\alpha)^2$	0.000 000 000 0
Hadronic	Uehling	-0.000 000 001 8(14)
Electroweak		0.000 000 000 0
Sum		1.910 561 821 0(2988)

(190)

New Theory 2024



2 sigma

$$g_{\text{Experiment}} = 1.910\,562\,059 \quad (1)$$
$$g_{\text{Theory}} = 1.910\,561\,975\,(39)$$

Sikora et al.,
arxiv 2410.10421v1

Overview

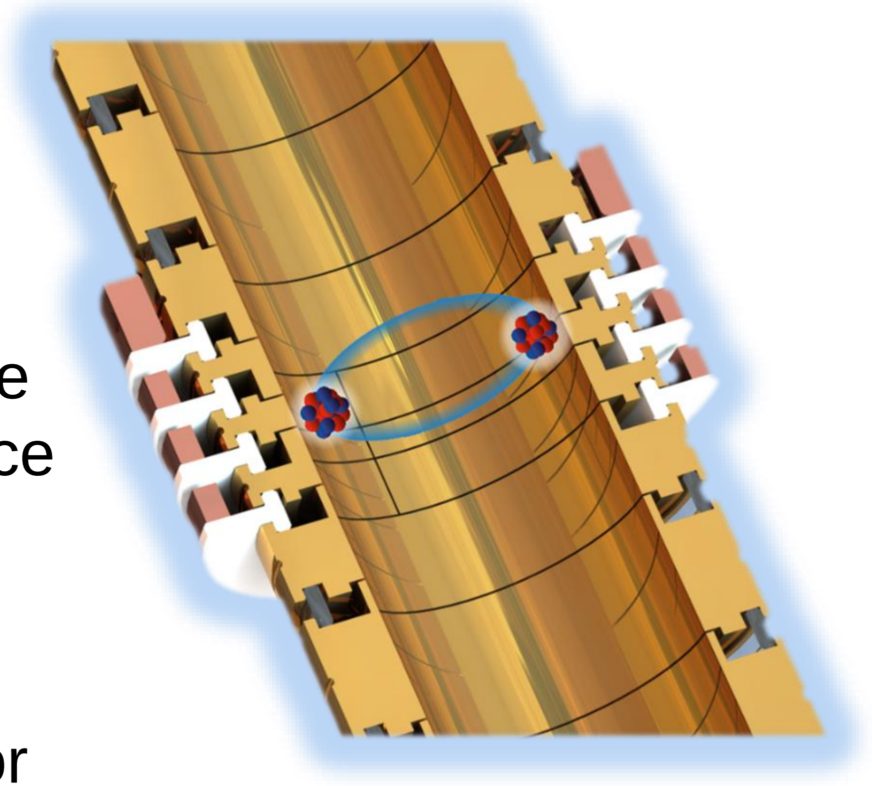
- Measurement principle
- ALPHATRAP Experiment
- $g_j(^{118}Sn^{49+})$ measurement
- **Direct *g*-factor difference measurement of $^{20}Ne^{9+}$ and $^{22}Ne^{9+}$**
- Summary & Outlook

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

- Controlled ion crystal in a Penning-Trap

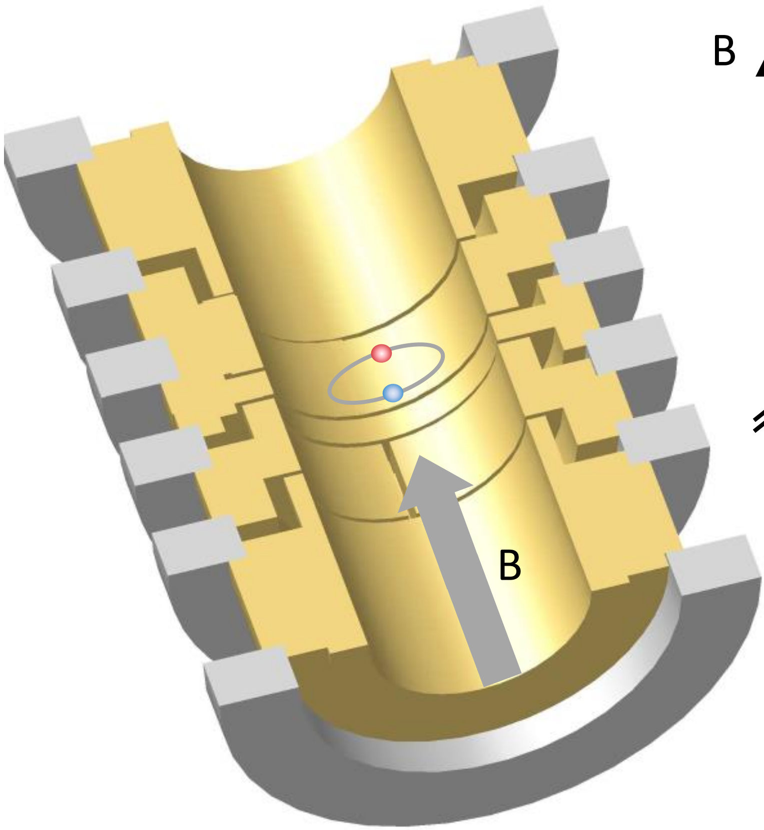
- Measure the *g*-factor difference in a decoherence-free subspace

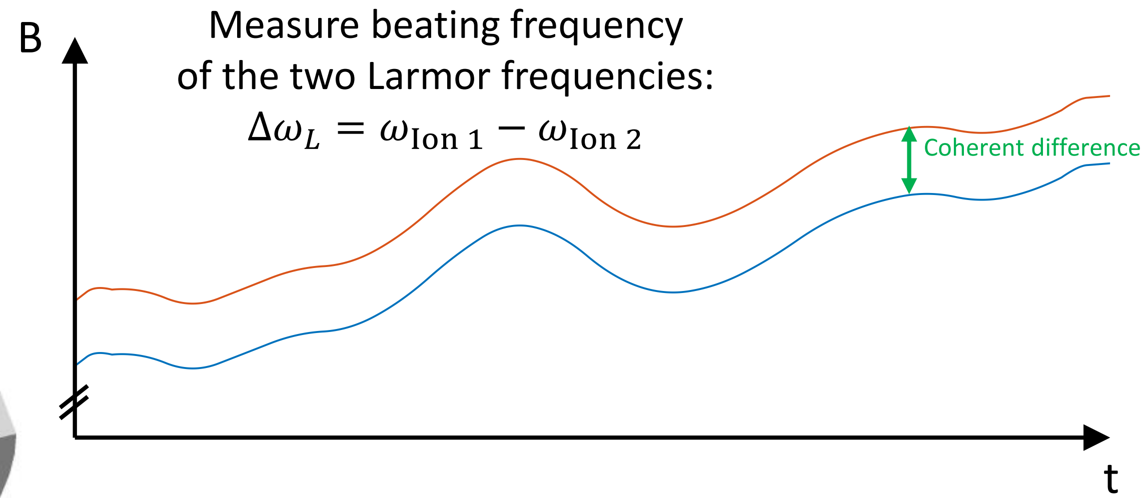
- Achieve high accuracy compared to a “typical” *g*-factor measurement



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

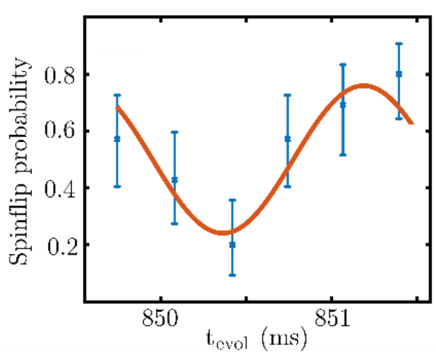
Coherent g_1-g_2 difference measurement



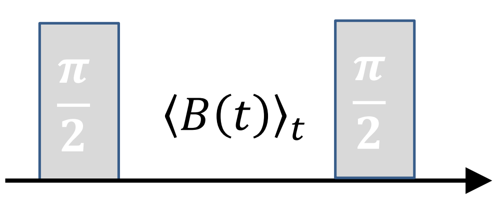


- Magnetic field fluctuations quickly (~ms) render Larmor precession **incoherent**
- Crystallized ions see the identical field
  - The **phase difference (correlation)** stays coherent (>seconds!)

Phase determination



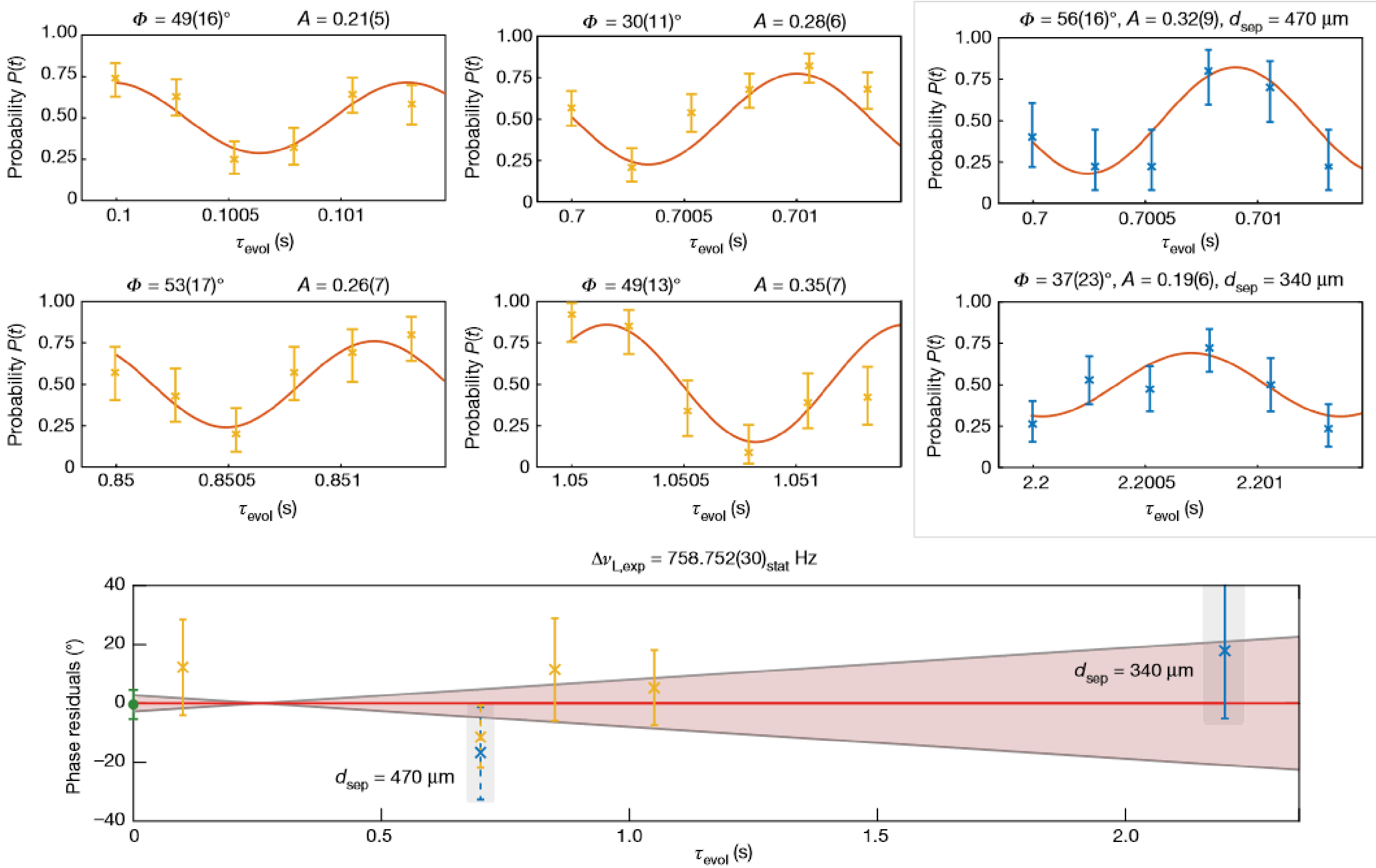
Simultaneous Ramsey cycle



$$p(|\downarrow\downarrow\rangle \rightarrow |\uparrow\uparrow\rangle)$$
$$= \cos\left((\omega_1 - \omega_{rf})t\right)^2 \times \cos\left((\omega_2 - \omega_{rf})t\right)^2$$
$$= \frac{1}{4}\left[\cos(2\underbrace{(\omega_1 - \omega_2)}_{\text{Small difference}}t) + \cdots\right]$$

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

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



- **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 $^{22}Ne^{9+}$

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

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
Total	13.474(11)
Experiment	13.475 24(53)$_{stat}$(99)$_{sys}$

- **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**

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

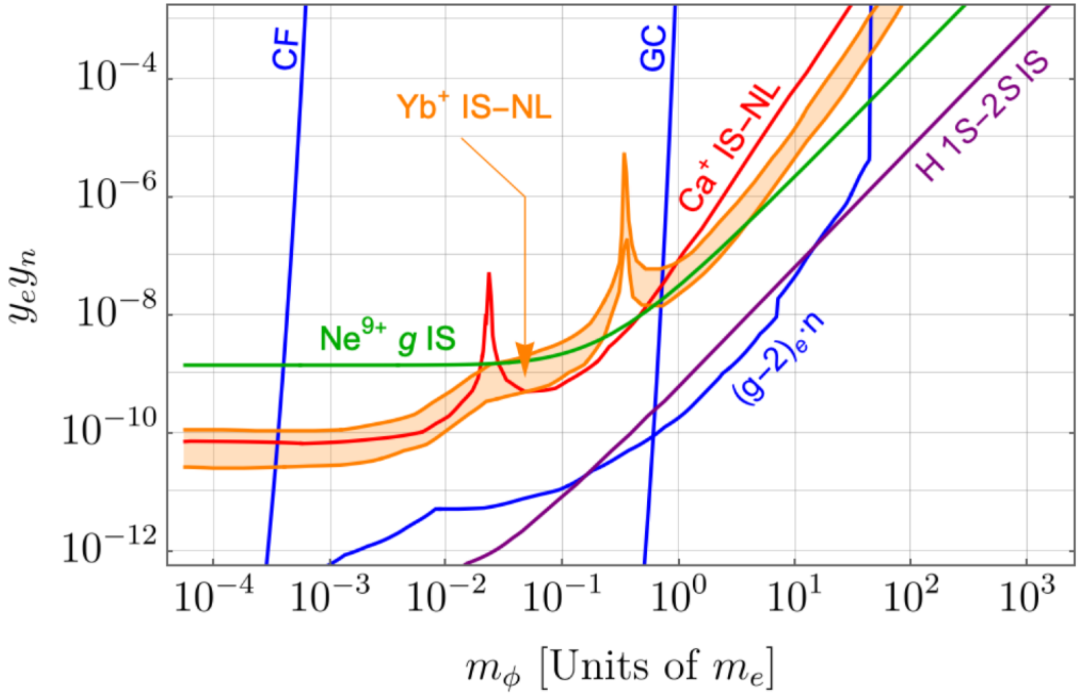
Lit: $\delta\langle r^2\rangle^{1/2} = 0.0530(34)\,\mathrm{fm}$

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

4x improvement still possible

Bounds on New Physics

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

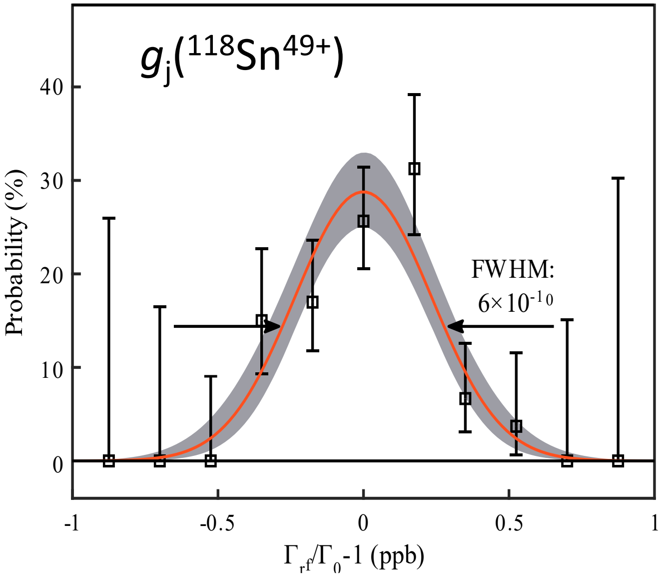


Limit is competitive with H 1s-2s IS with independent rms nuclear charge radius difference

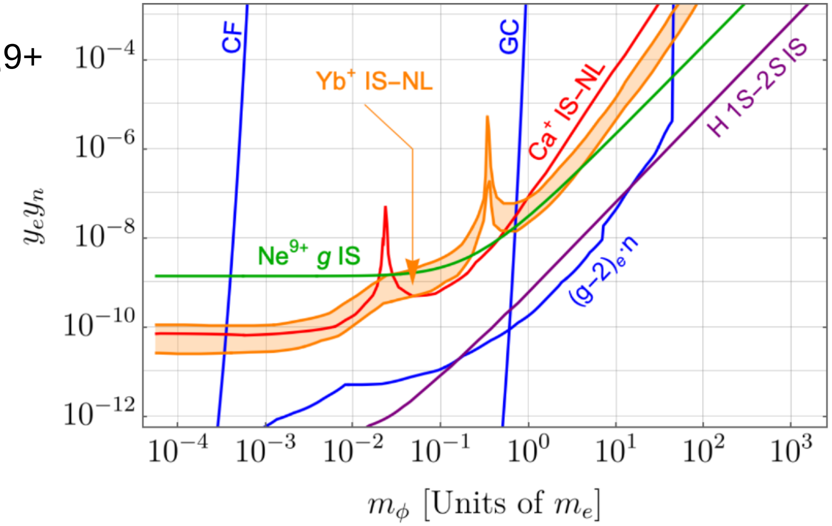
T. Sailer *et al.*, Nature **606**, 479 (2022)

Summary

- Ion production of medium-to-high hydrogenlike ions
- **H-like *g* factors up to ^{132}Xe & all Li-like *g* factor up to ^{238}U & *g* factor differences below 10^{-10}**
- Potential to improve nuclear charge radius for nuclei with Z > 50

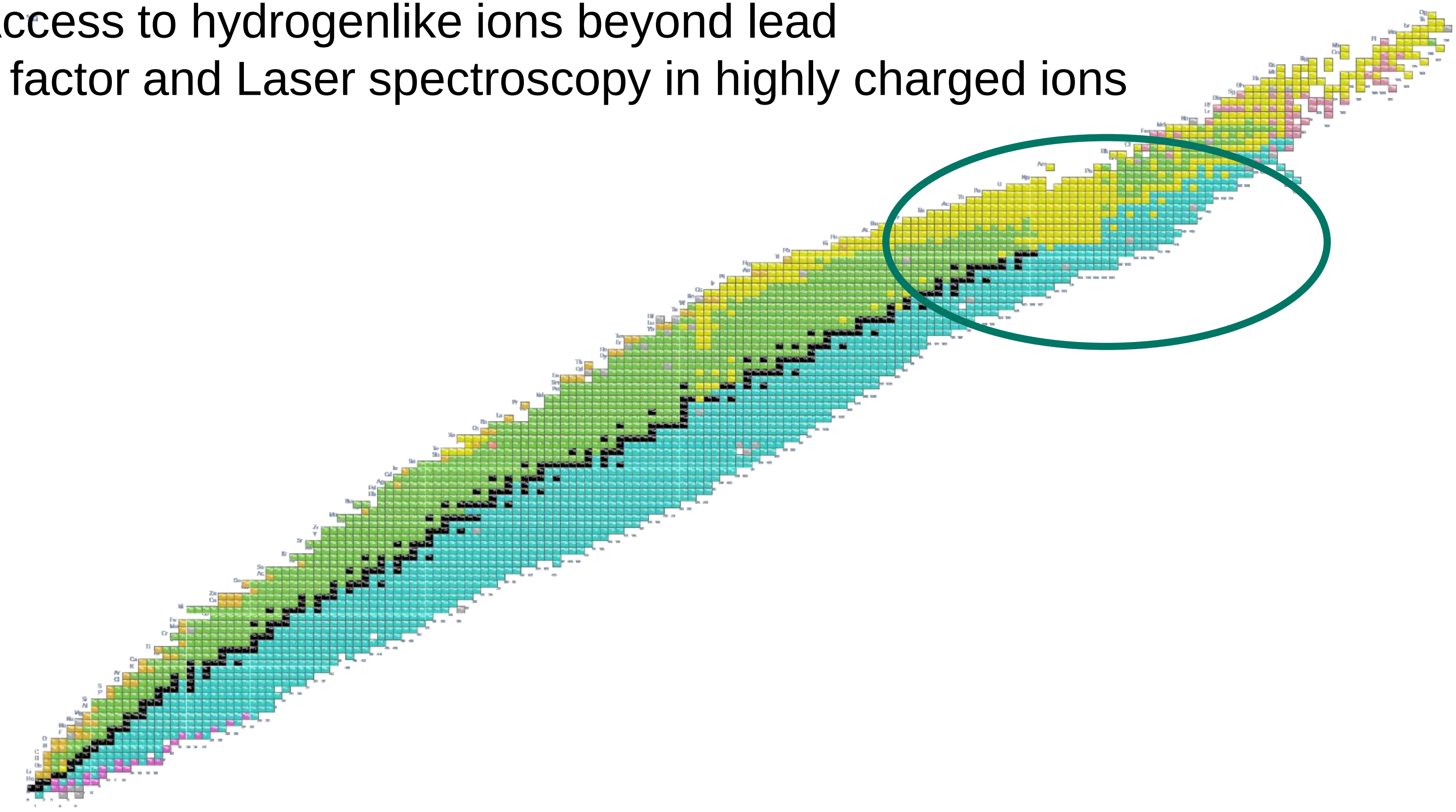


- Measure *g*-factor differences of $^{20,22}Ne^{9+}$ with extremely high precision (~10^{-13})
- **9x improved rms charge radius difference**
- Limits on „New Physics“
- Different Isotope shifts measurements possible

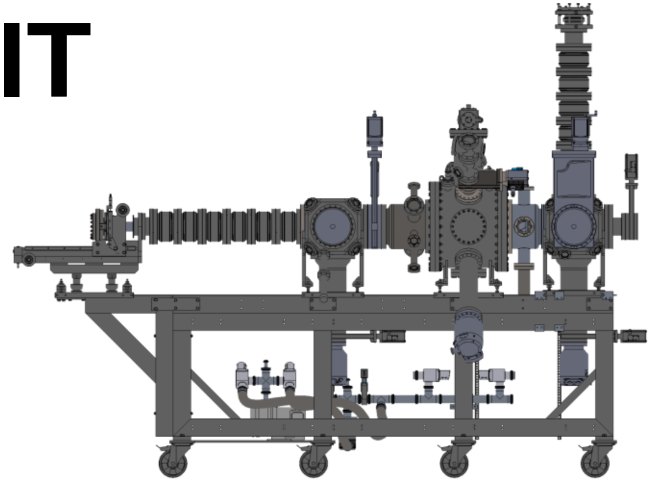


Outlook

- Access to hydrogenlike ions beyond lead
- *g* factor and Laser spectroscopy in highly charged ions



Hyper-EBIT



- Produce hydrogenlike ions beyond lead

Planned Specifications	
Electron beam energy	200keV
Beam current	>200mA

Moving the EBIT to the test laboratory

- First commissioning after long shutdown
- Currently: High-voltage upgrade

High voltage laboratory

Lepton Symmetry Experiment

LSYM

Sven Sturm

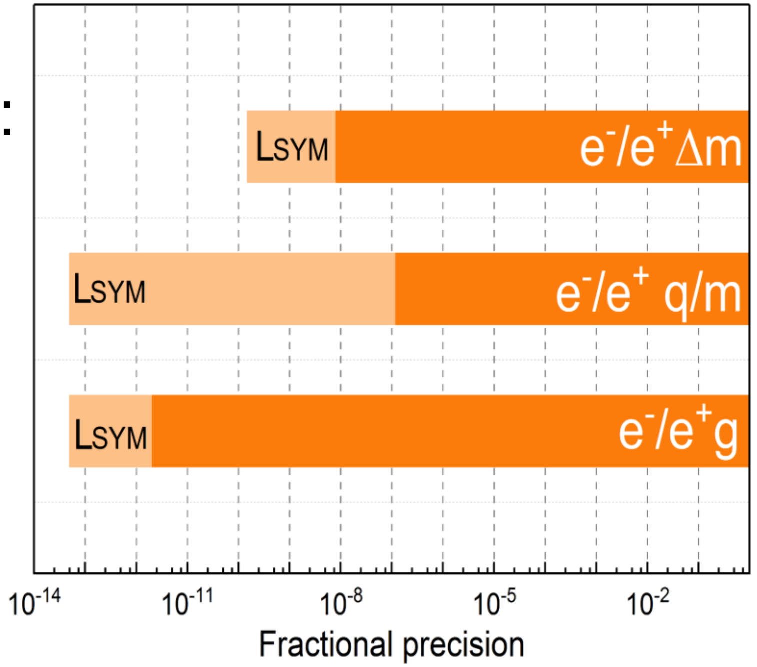
Max-Planck-Institut für Kernphysik Heidelberg

European Research Council
Established by the European Commission

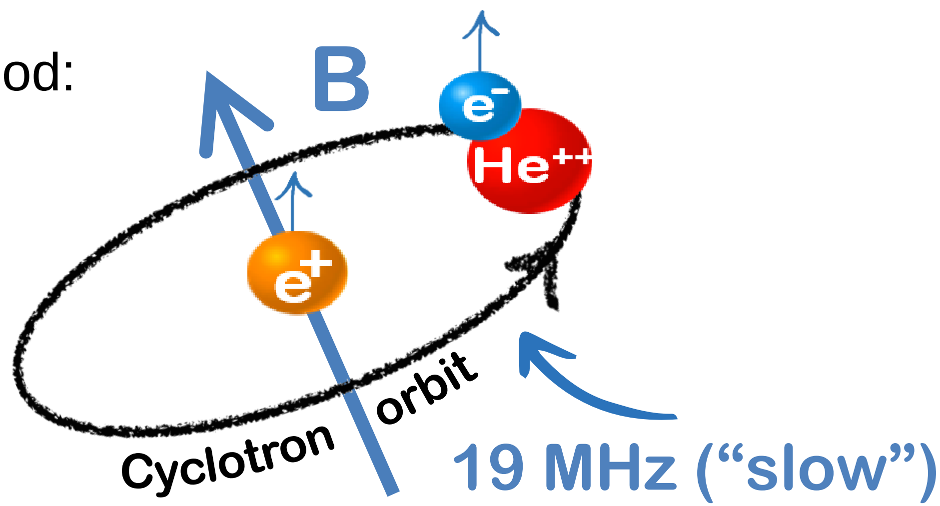
Where did all the antimatter go?

- Uniquely stringent CPT test with LSYM:
  - **q/m** (direct) 1,000,000x better
  - ***g*-factor**: >50x better

  …than any previous experiment



- Method:



Nuclear charge radius determination for low Z possible

FUTURE: Network of Precision for HCI

Bound electron
***g_j* factors**
Nuclear *g_I* factors

Precision theory

Energy (Lamb) shifts in electronic, muonic and pionic ions

Precision theory

(1) Test QED
(2) Determine fundamental constants
(3) Set "New Physics" limits

Precision theory

Hyperfine strcuture of electronic & muonic ions

Precision theory

Electron & neutron scatter

Precise nuclear parameters
(charge & magnetic radius, polarization, ...)

Thank you for your attention!

ERC AdG 832848 - FunI

DFG SFB 1225

Questions?