Precision Tests of the Standard Model at Low Energies using Stored Exotic Ions in Penning Traps

- Basics of Penning-trap spectroscopy
- Atomic and nuclear mass measurements
- Precision *g*-factor measurements

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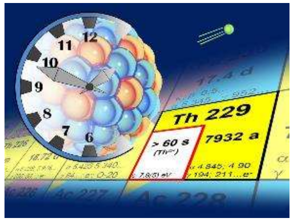
Wuhan, June 15th, 2026

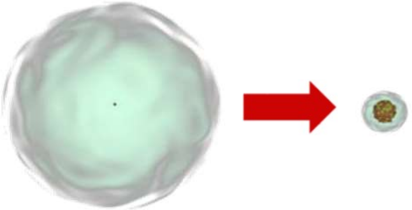
Motivation

- **Precision metrology and fundamental constants**
- **Test of fundamental interactions**
- **Physics beyond the Standard Model**



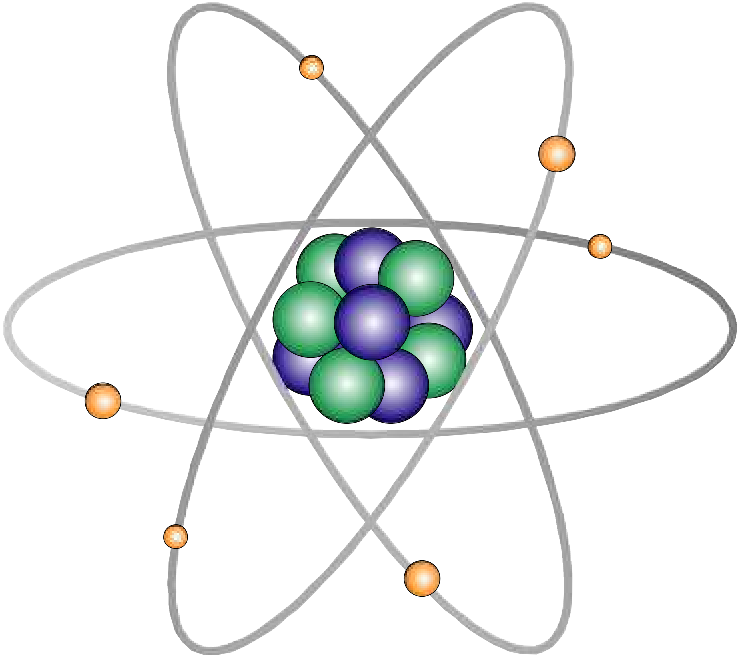
- radionuclides

- highly charged ions



- antimatter

The mass of an atom



$= N \cdot$ 🟢 $+ Z \cdot$ 🔵 $+ Z \cdot$ 🟠

– binding energy

Einstein $E = mc^2$

$$m_{\mathrm{Atom}} = N \bullet m_{\mathrm{neutron}} + Z \bullet m_{\mathrm{proton}} + Z \bullet m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

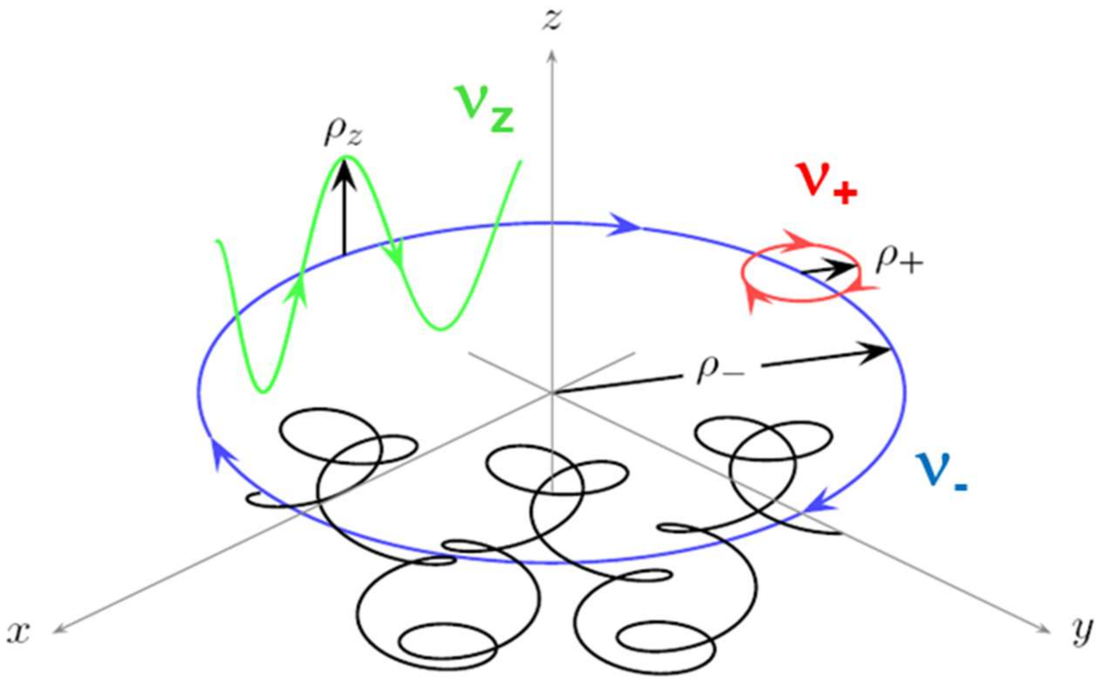
$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} – 10^{-8}$

electronic structure

nuclear structure

Storage of ions in a Penning trap



The free cyclotron frequency is inverse proportional to the mass of the ion!

- ➢ Non-destructive FT-ICR / phase detection

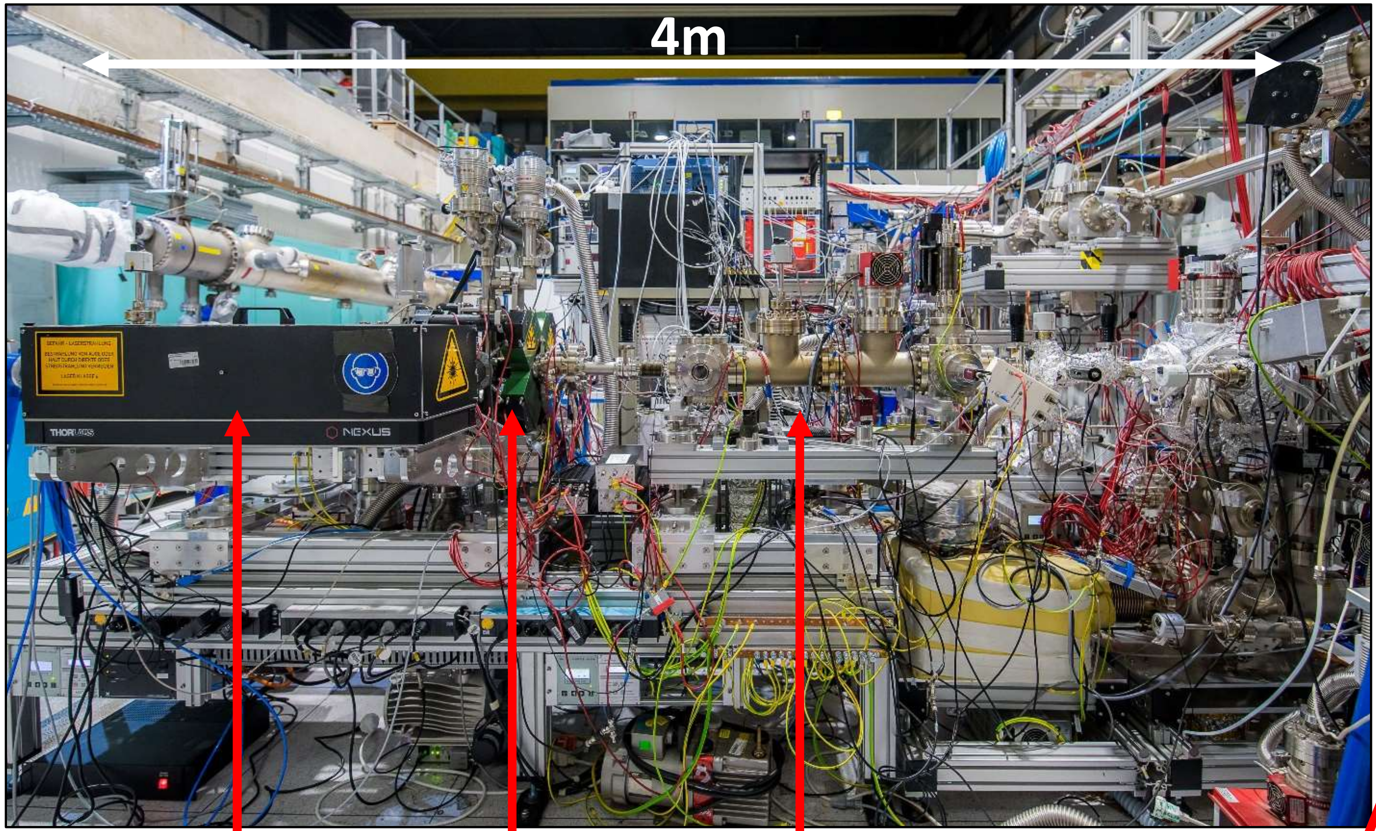
$$\nu_c = qB/(2\pi m_{ion})$$

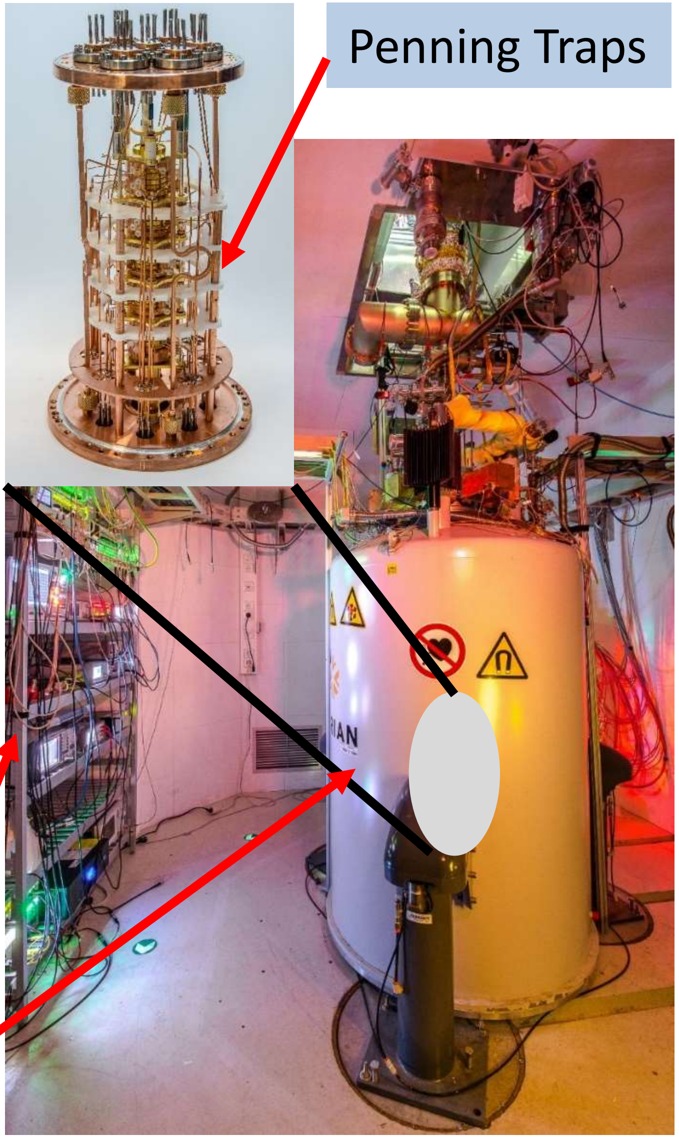
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Cyclotron frequency: 20 MHz **Axial: 600 kHz** **Magnetron: 9 kHz**

PENTATRAP – A Penning-trap setup at MPIK

A balance for highly charged ions.





Penning Traps

Laser Ion Source

EBIT

Transfer Beamline

Electronics

$T_{1/2}$ > days

Superconducting Magnet

Measurement principle at PENTATRAP

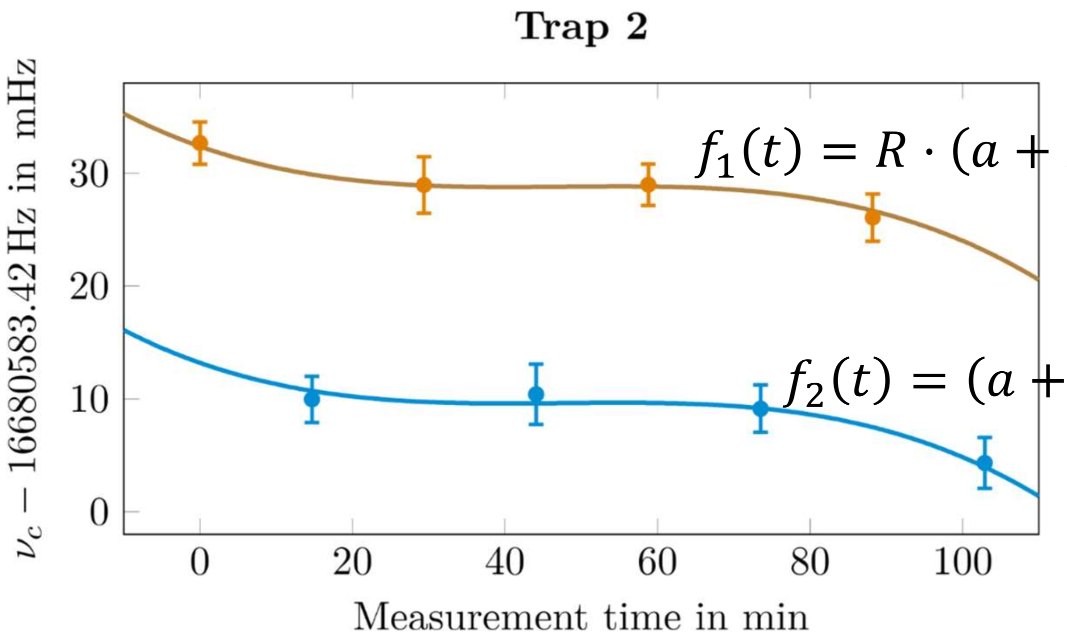
Mass Ratio determination – Polynomial Method

$$\omega_c = \frac{q}{m} \cdot B$$

Magnetic field not known!

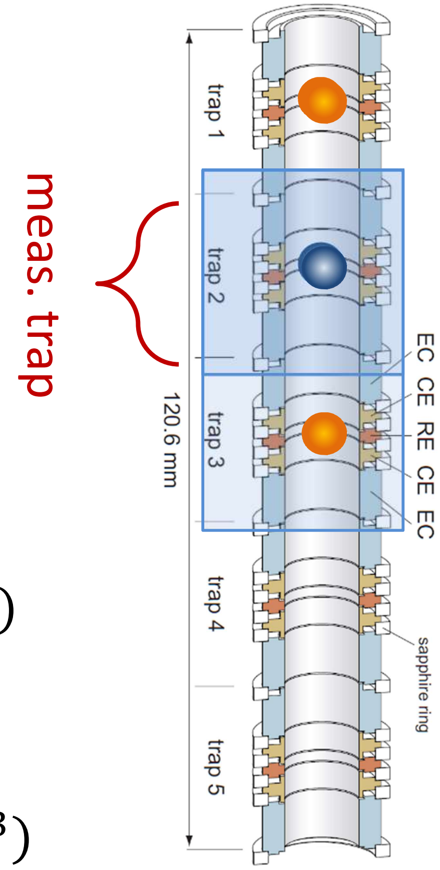
Second ion:

$$R = \frac{\omega_1}{\omega_2} = \frac{q_1 \cdot m_2}{q_2 \cdot m_1}$$



$$f_1(t) = R \cdot (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$

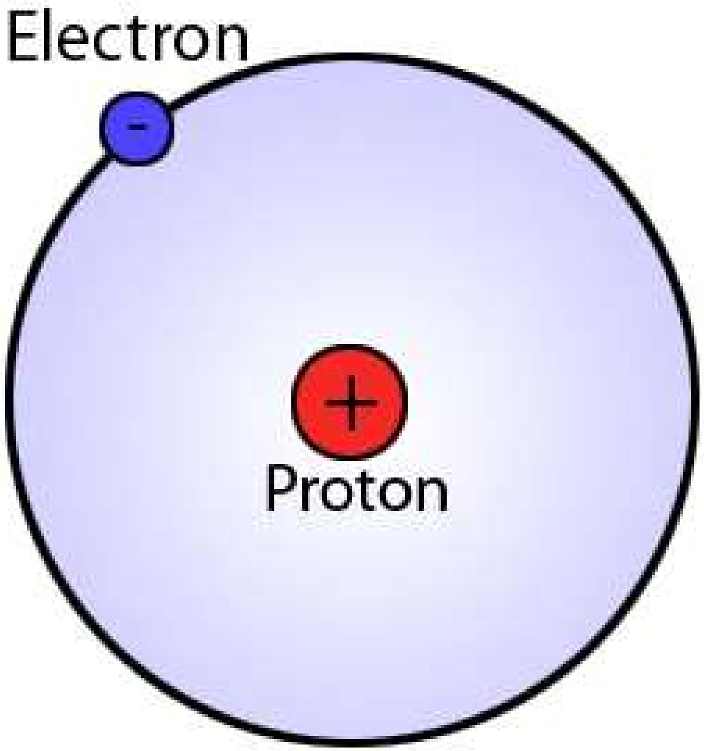
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



A. Rischka *et al.*, Phys. Rev. Lett. **124** (2020) 113001

Results I

The masses of the building bocks of matter

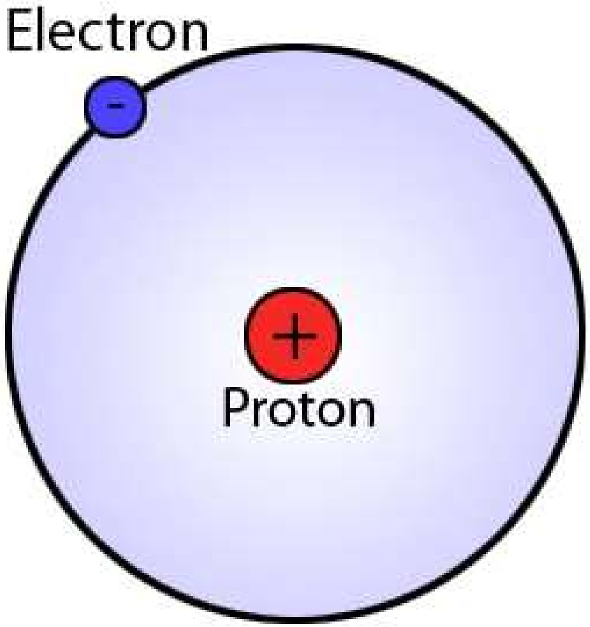


LIONTRAP: MPIK, Uni Mainz, GSI

The building blocks of matter

The atomic mass of the proton and electron

Hydrogen



Electron: previous best value improved by a factor of 13

$m_e = 0.000\,548\,579\,909\,067(17)$ u

Nature **506** (2014) 467

Proton: previous best value improved by a factor of 3

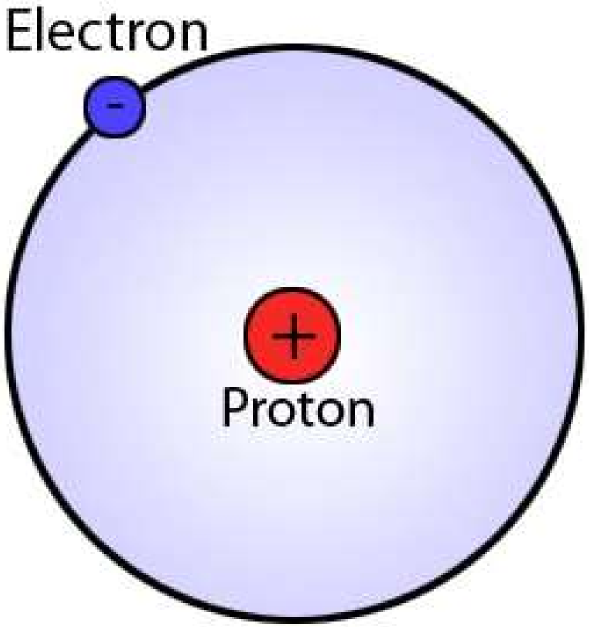
$m_p = 1.007\,276\,466\,583\,(33)$ u

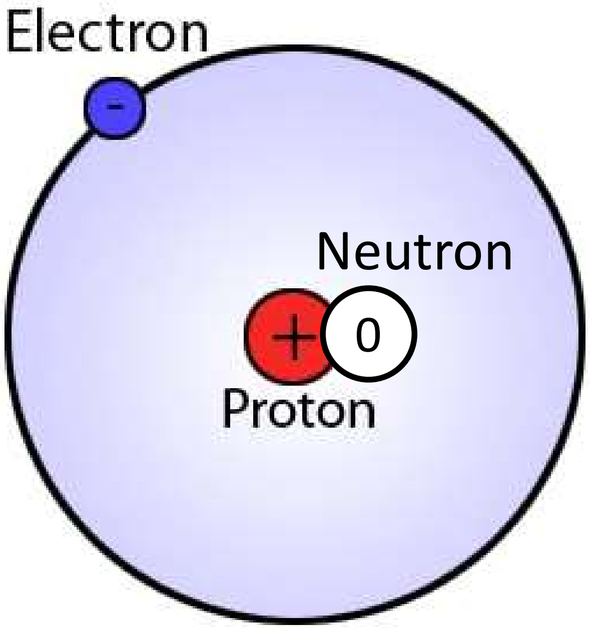
Phys. Rev. Lett. **119** (2017) 033001

The building blocks of matter

The atomic mass of the proton and electron and neutron ☺

Hydrogen





Deuterium

Electron: previous best value improved by a factor of 13

$m_e = 0.000\,548\,579\,909\,067(17)$ u

Nature **506** (2014) 467

Proton: previous best value improved by a factor of 3

$m_p = 1.007\,276\,466\,583\,(33)$ u

Phys. Rev. Lett. **119** (2017) 033001

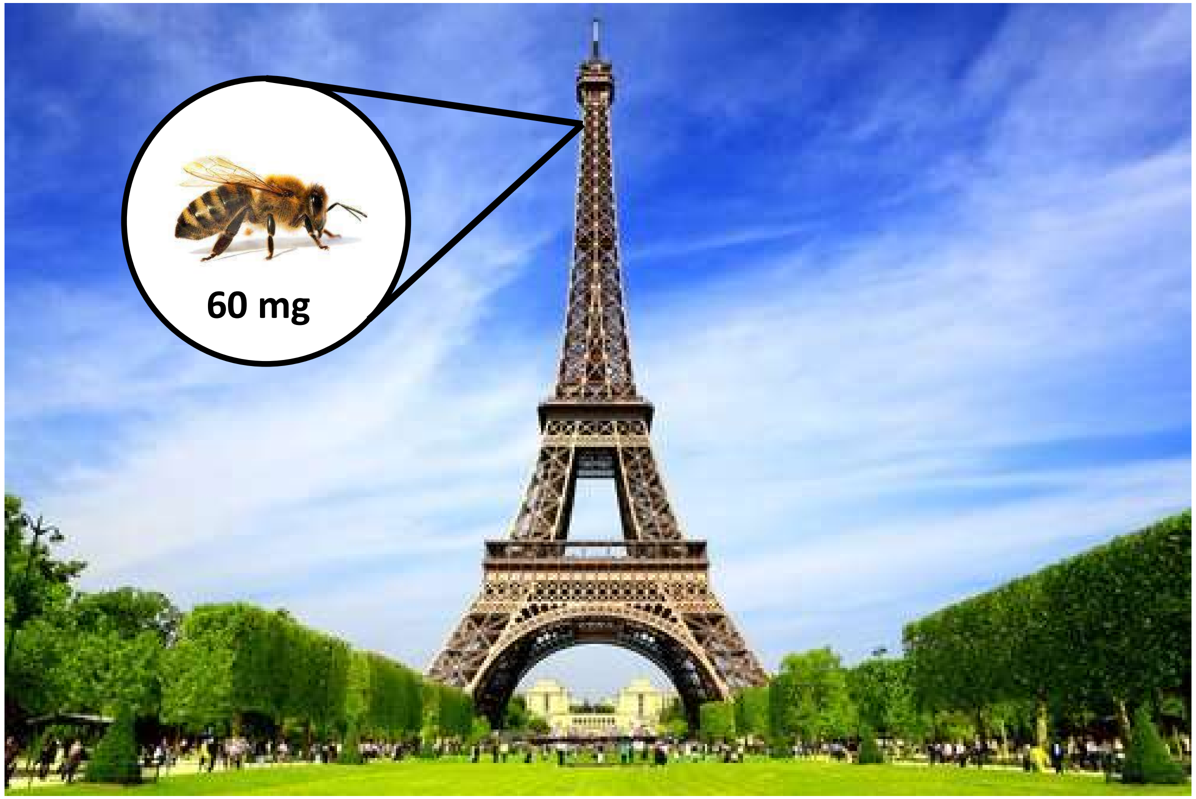
deuteron: previous best value improved by a factor of ~3

$m_d = 2.013\,553\,212\,535\,(17)$ u

Nature **585** (2020) 43

m(^{3}He): O. Bezrodnova *et al.*, PRA **111** (2025) 040801 **m (^{4}He):** S. Sasidharan *et al.*, PRL **131** (2023) 093201

An easy image of our precision regime

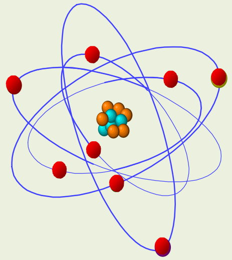


$m_{bee} \approx 60$ mg

$$\frac{m_{bee}}{m_{Eiffel}} \approx 8\cdot10^{-12}$$

m_{Eiffel} **= 7300 T = 7.300.000.000.000 mg =** $7.3\cdot10^{12}$ **mg**

BUT: Precision achieved on the atomic scale!



recently achieved $2\cdot10^{-12}$

Results II

Nuclear masses for neutrino physics

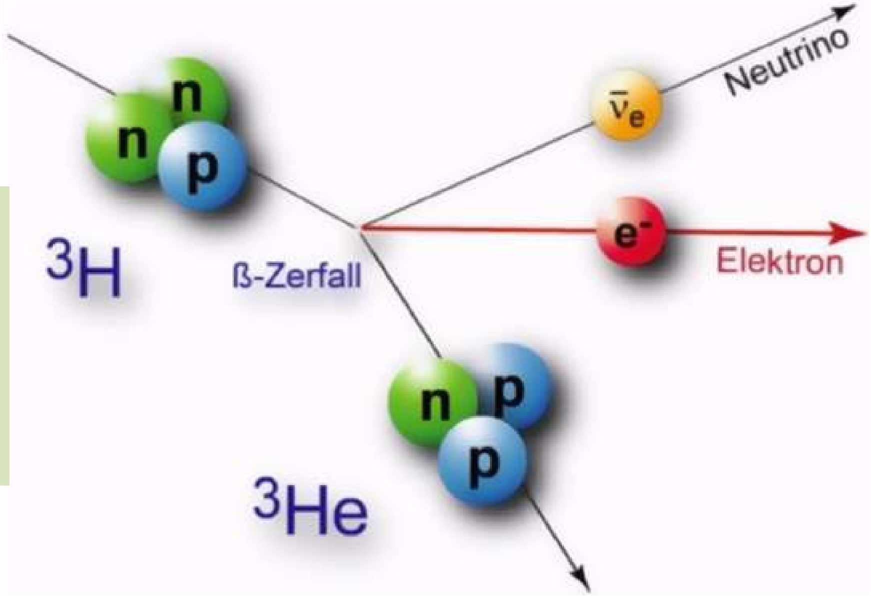
S. Eliseev

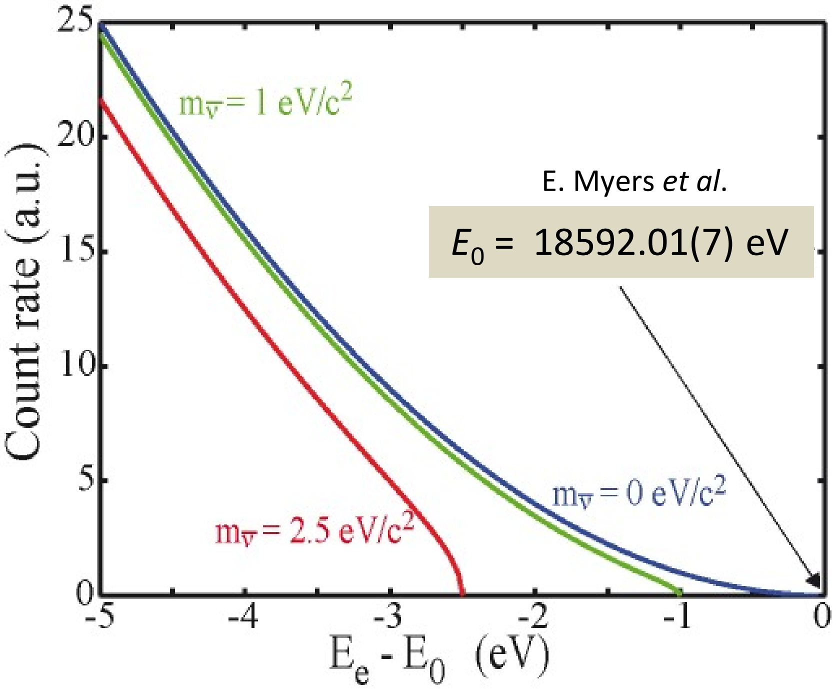
***Q*-values:**

$^{3}\mathrm{T} \rightarrow {}^{3}\mathrm{He}$

$^{163}\mathrm{Ho} \rightarrow {}^{163}\mathrm{Dy}$

$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os}$





E. Myers *et al.*

$E_0 = 18592.01(7)$ eV

Latest result: $m_{\bar{\nu}} < 0.45\ \mathrm{eV}/c^2$ (90% c.l.) @ KATRIN

The ECHo (^{163}Ho) project

EC-Decay of ^{163}Ho

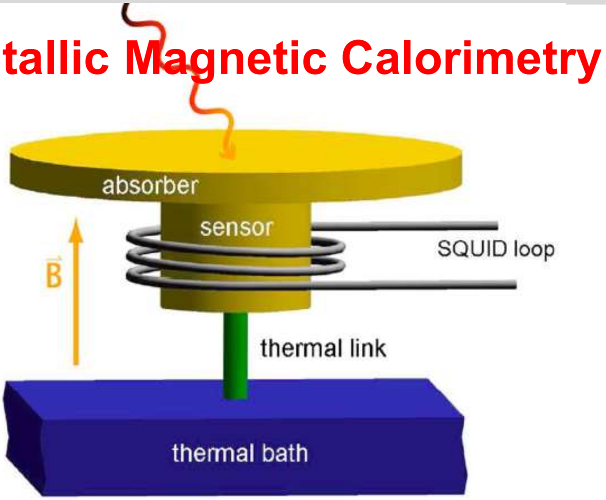
$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow {}^{163}_{66}\mathrm{Dy}^* + \nu_e$$

NEUTRONS FOR SCIENCE

$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

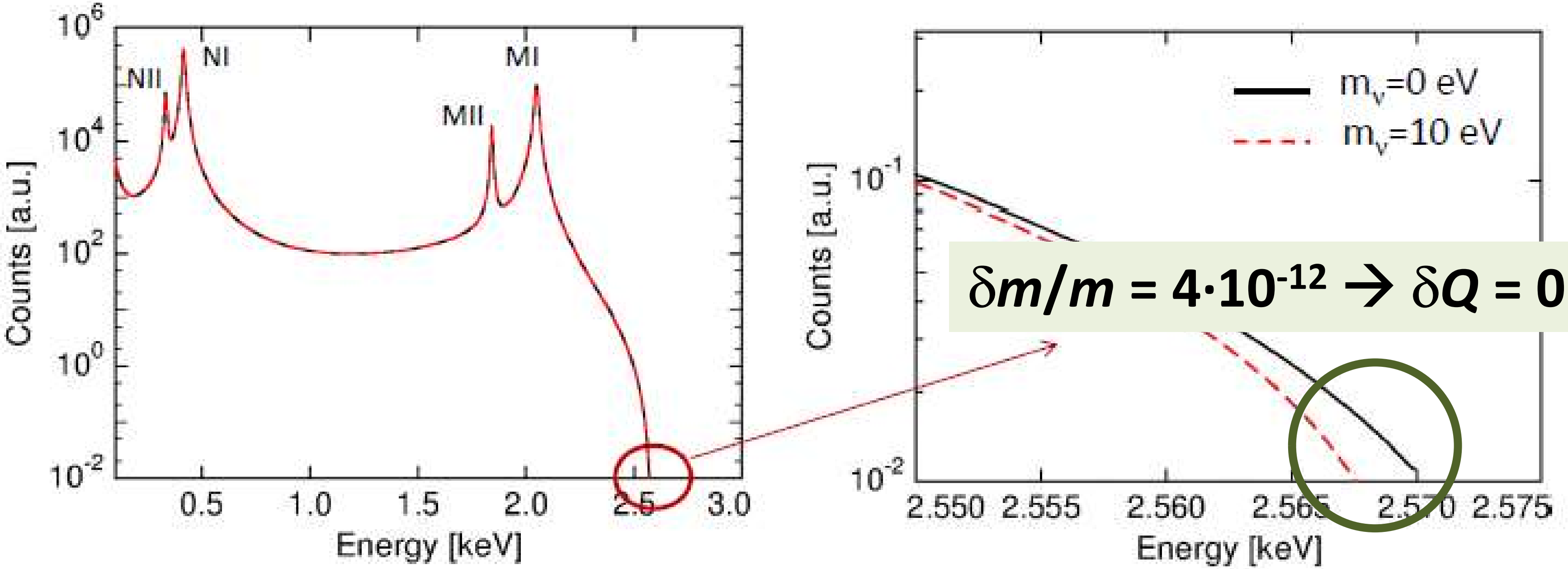
ECHo-Collaboration:
Heidelberg University

Metallic Magnetic Calorimetry



Theory

$$Q = M(^{163}\mathrm{Ho}) - M(^{163}\mathrm{Dy}) = M(^{163}\mathrm{Ho}^{39+}) - M(^{163}\mathrm{Dy}^{39+}) + \Delta B_{\mathrm{electron}}$$



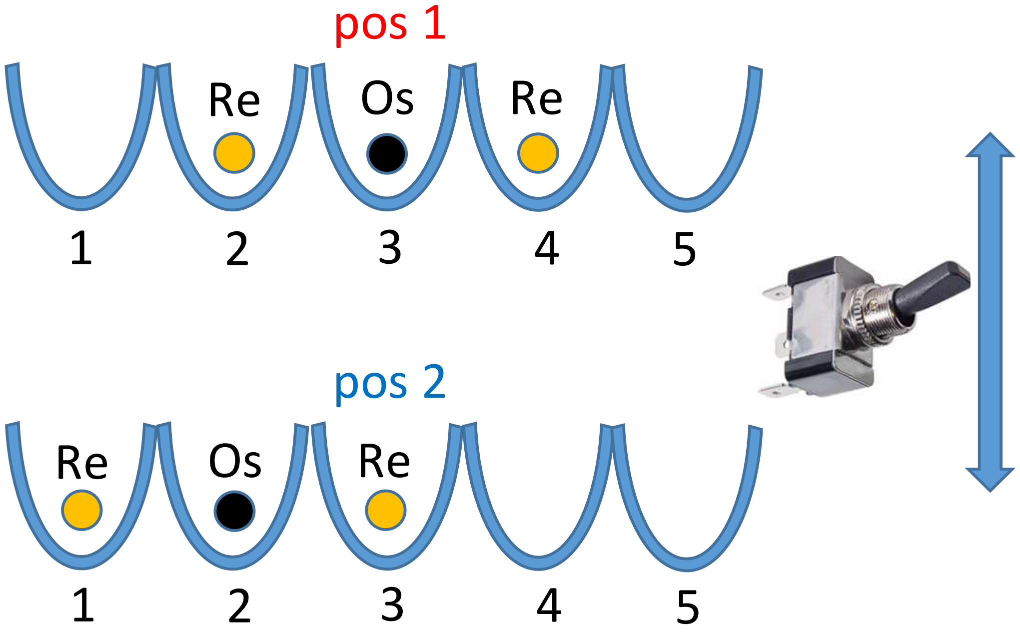
$$\delta m/m = 4{\cdot}10^{-12} \rightarrow \delta Q = 0.6\ \mathrm{eV}$$

Latest result: $m_\nu < 15\ \mathrm{eV}/c^2$ (90% c.l.) @ ECHo

Ch. Schweiger *et al.*, Nature Phys. **20**, 921 (2024)

ECHo Collab., Phys. Rev. Lett. **136,** 121801 (2026)

Q-value of ^{187}Re-^{187}Os for neutrino physics



- Change position every 30 min
- Measurement of ν_+, ν_z, ν_-
- Phase detection method
- Storage time of days

P. Filianin *et al.*, Phys. Rev. Lett. **127** (2021) 072502

relative nuclear mass precision achieved: $6\cdot10^{-12}$

BUT

For Re^{29+} ($Z = 75$) vs. Os^{29+} ($Z = 76$) we measure two ratios with a 50/50 probability:

$$R_1 = 1.000000013886(15)$$

$$R_2 = 1.000000015024(12)$$

Weighing of different electron config.

Ground-state configuration of Re^{29+} and Os^{30+}: $[{}_{36}\mathrm{Kr}]\ 4d^{10}$

Metastable state $[{}_{36}\mathrm{Kr}]\ 4d^{9}\,4f^{1}$ with $E_{\mathrm{exc}} \approx 200$ eV in Re^{29+}

Similar state in Os^{30+} expected!

Re^{29+}

metastable electronic state

$B_{\text{PENTATRAP}} = 202.2(17)$ eV

$B_{\text{Harman}} = 202.2(5)$ eV

$B_{\text{Indelicato}} = 202.1\ (27)$ eV

$B_{\text{Haverkort}} = 202.8(4)$ eV

ground state

Os^{30+}

metastable electronic state

$B_{\text{PENTATRAP}} = 207(3)$ eV

$B_{\text{Haverkort}} = 209(2)$ eV

$B_{\text{Indelicato}} = 207(3)$ eV

ground state

R. Schüssler *et al.*, Nature **581** (2020) 42

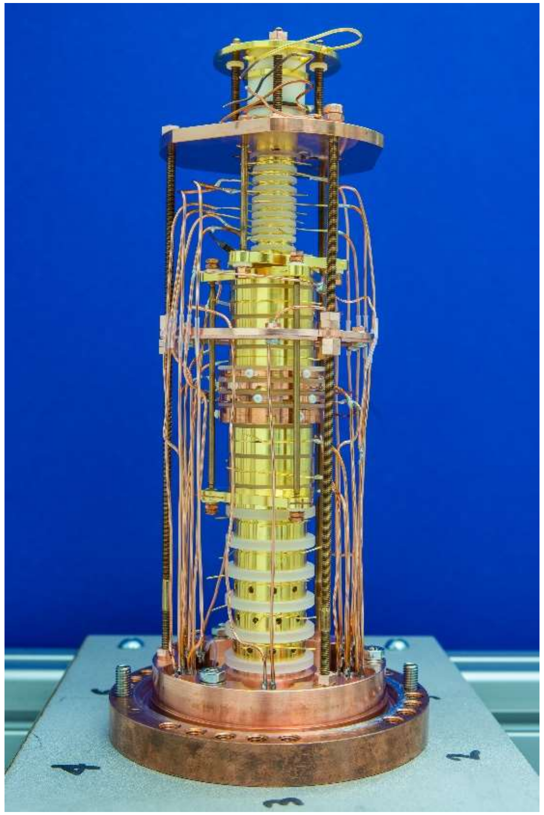
Possible application: search for suitable clock transitions

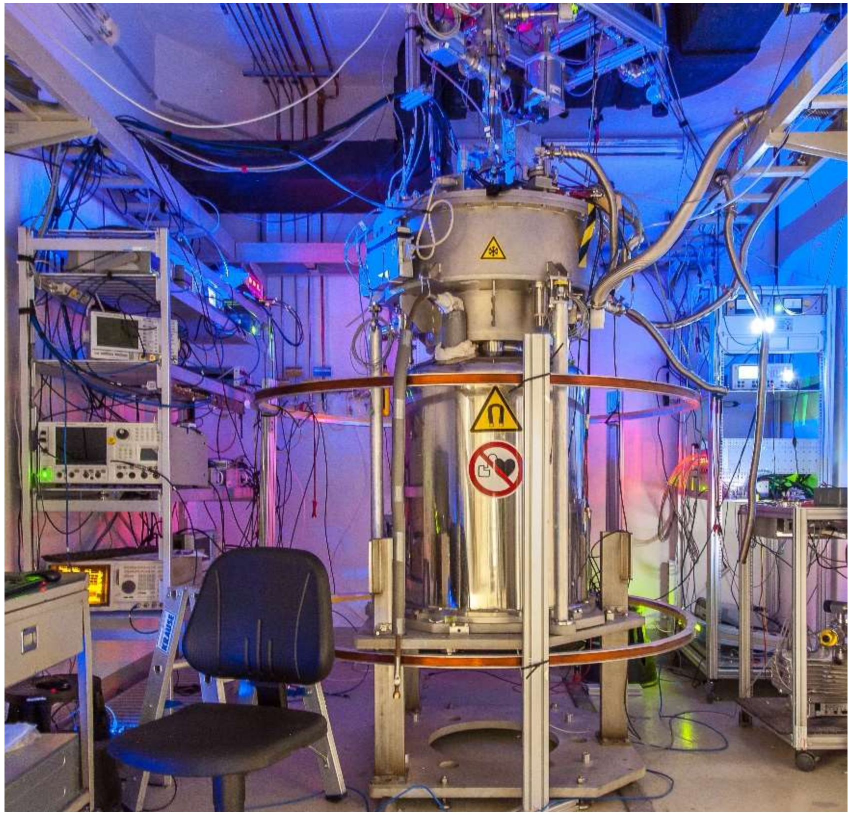
K. Kromer *et al.*, Phys. Rev. Lett. **131** (2023) 223002

Results III

Tests of fundamental interactions and their symmetries

Stefan Ulmer





Sven Sturm

Andreas Mooser

ALPHATRAP, BASE, μTEx: MPIK, PTB, RIKEN

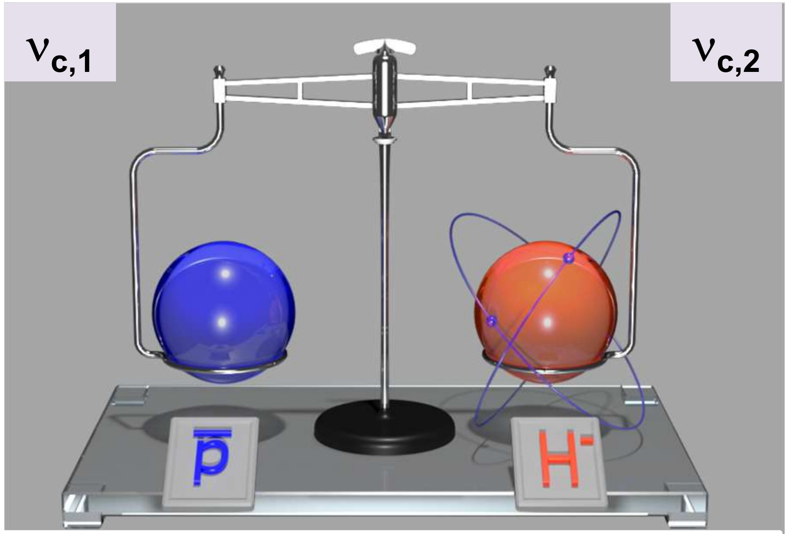
Comparison of the proton and antiproton

Baryon-Antibaryon Symmetry Experiment

Compare charge-to-mass ratios *R* of p and $\bar{p}$:

$$(q/m)_{\bar{p}} / (q/m)_p = -1.000\,000\,000\,003\,(16)$$

M.J. Borchert *et al*., Nature **601** (2022) 53



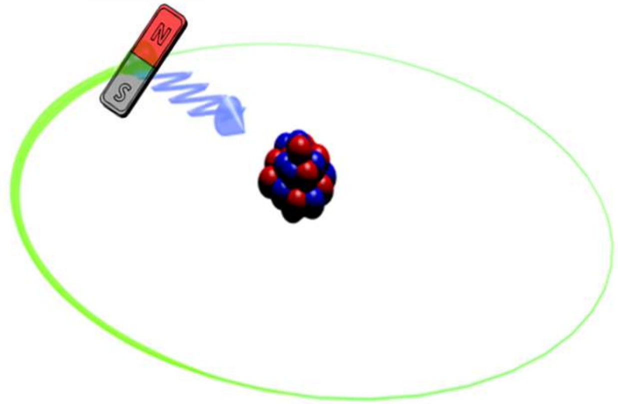
It is not that easy!

$$m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{\mathrm{pol,H^-}} B_0^2}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p}\right)$$

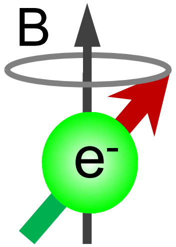
Most stringent test of CPT symmetry in the baryon sector!

The *g*-factor of the bound electron

Study one electron bound to the nucleus, e.g. $^{12}C^{5+}$ (highly charged ions)



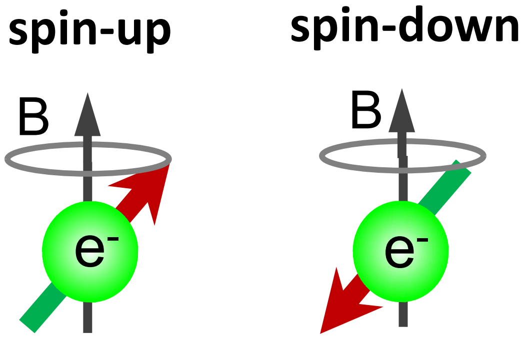
g-factor: measure for the magnetic strength of the bound electron



Electron acts like a spinning top in the magnetic field with frequency ω_L

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

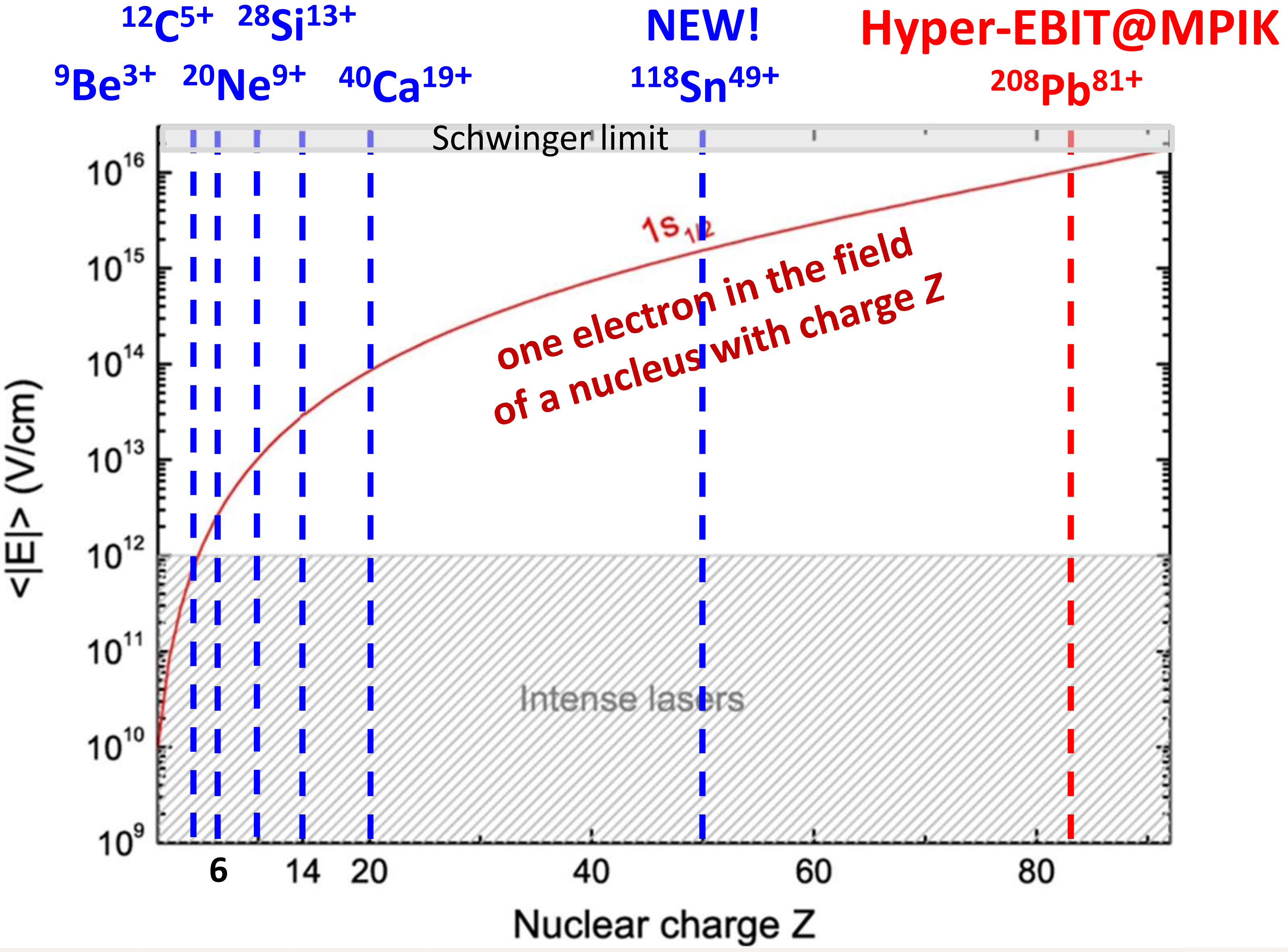
Electron can be in spin-up or spin-down state with transition frequency ω_L



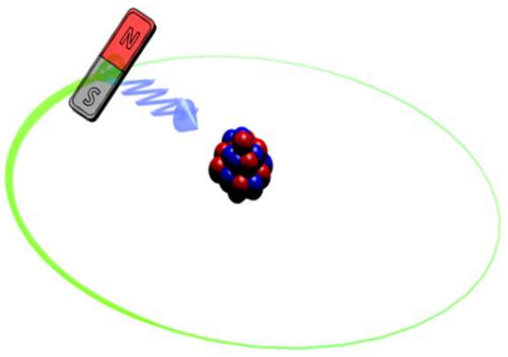
Employing the continuous Stern-Gerlach effect to determine ω_L

Extreme conditions in highly charged ions

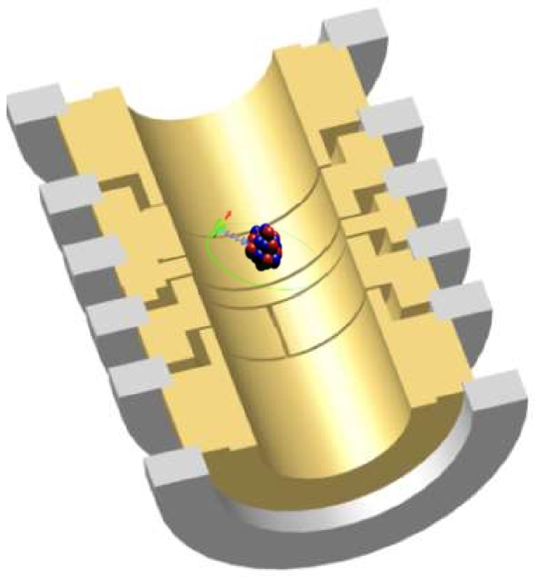
- ➢ QED is the best tested quantum field theory (see *g*-2 of the electron; Dehmelt, Gabrielse)
- ➢ we would like to test QED in ultra strong fields



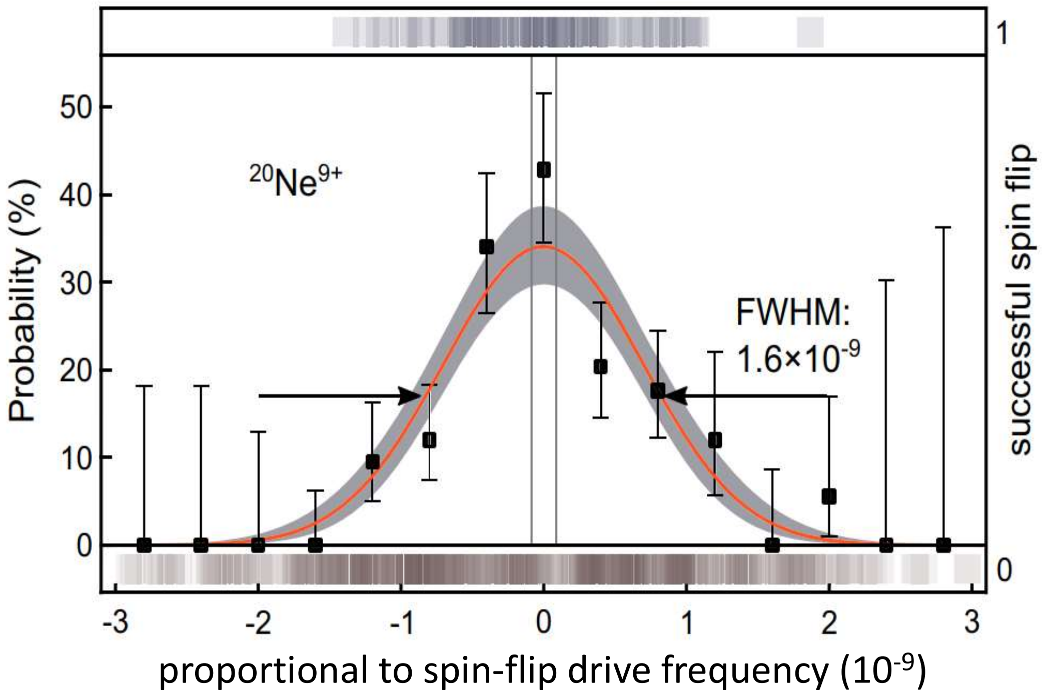
Highly charged ions

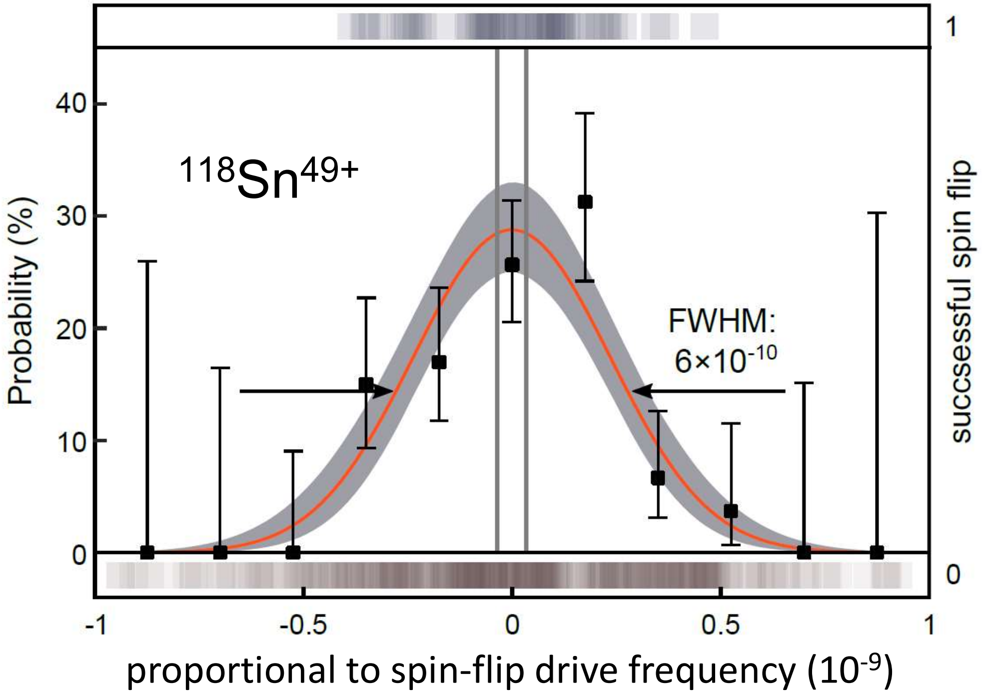


Penning trap



Test of QED in strong fields





^{20}Ne^{9+}

g_{exp} = 1.998 767 276 93 (16)
g_{theo} = 1.998 767 277 11 (12)

^{118}Sn^{49+}

g_{exp} = 1.910 562 059 (1)
g_{theo} = 1.910 561 975 (39)

Most stringent test of bound-state QED in strong fields!

T. Sailer *et al.*, Nature **606**, 479 (2022)
F. Heiße *et al.*, Phys. Rev. Lett. **131**, 253001 (2023)

Theory colleagues:
Harman, Keitel, Oreshkina, Yerokhin

J. Morgner *et al.*, Nature **622**, 53 (2023)	H-like
J. Morgner *et al.*, Science **388**, 945 (2025)	Li-Like
J. Morgner *et al.*, PRL **134,** 123201 (2025)	B-like
B. Sikora *et al.*, PRL **134**, 123001 (2025)	Theory

Summary

Precision Penning-trap spectroscopy has reached an amazing precision even on exotic systems and has opened up many new fields of research in atomic, nuclear and particle physics as well as quantum metrology!

Max Planck Society **EMMI** **IMPRS-PTFS** **IMPRS-QD** **ERC AdG 832848 - FunI** **DFG**

Thanks …

to all my Division members and

you for the invitation and your attention!