Precision tests of the Standard Model at low energies using stored exotic ions in Penning traps

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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

Klaus Blaum

Max-Planck-Institute for Nuclear Physics, Heidelberg

EMMI

GSI Darmstadt, July 22nd, 2025

TC FS

erc European Research Council

Established by the European Commission

Atomic/nuclear spectroscopy …

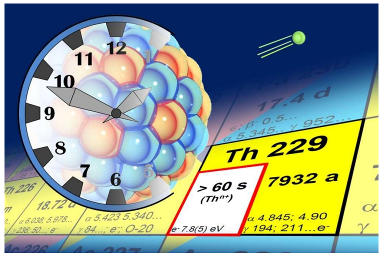
… probes fundamental physics!

How heavy are the building blocks of matter?

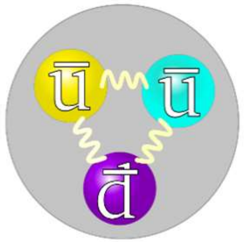
What is the mass of a neutrino?

Why is there more matter than anti-matter?

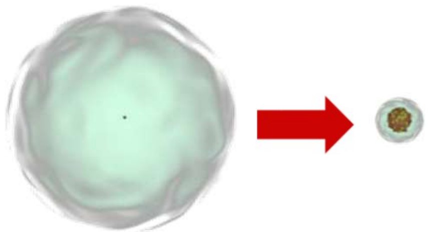
Does QED fail in the strong field regime?



- radionuclides
  e.g. TRIGA-TRAP

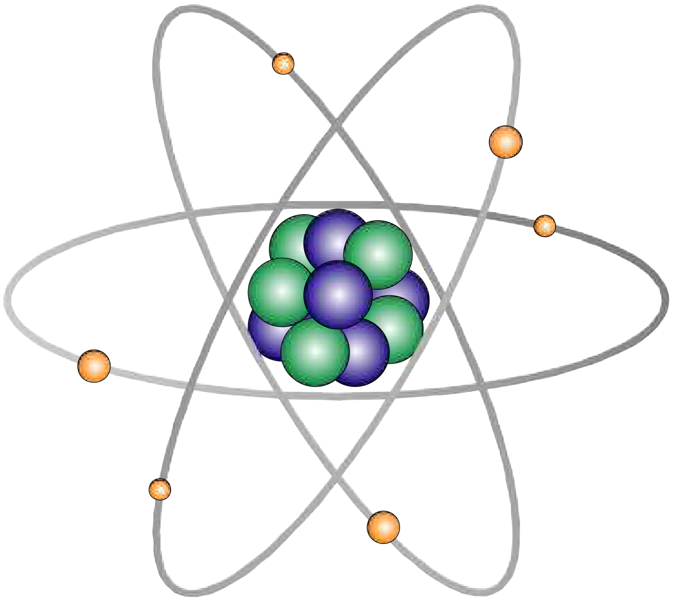


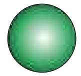
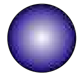
- antimatter
  e.g. BASE @ AD



- highly charged ions
  e.g. Traps @ MPIK

The mass of an atom



= $N \cdot$  + $Z \cdot$  + $Z \cdot$ 

– binding energy

Einstein $E = mc^2$

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

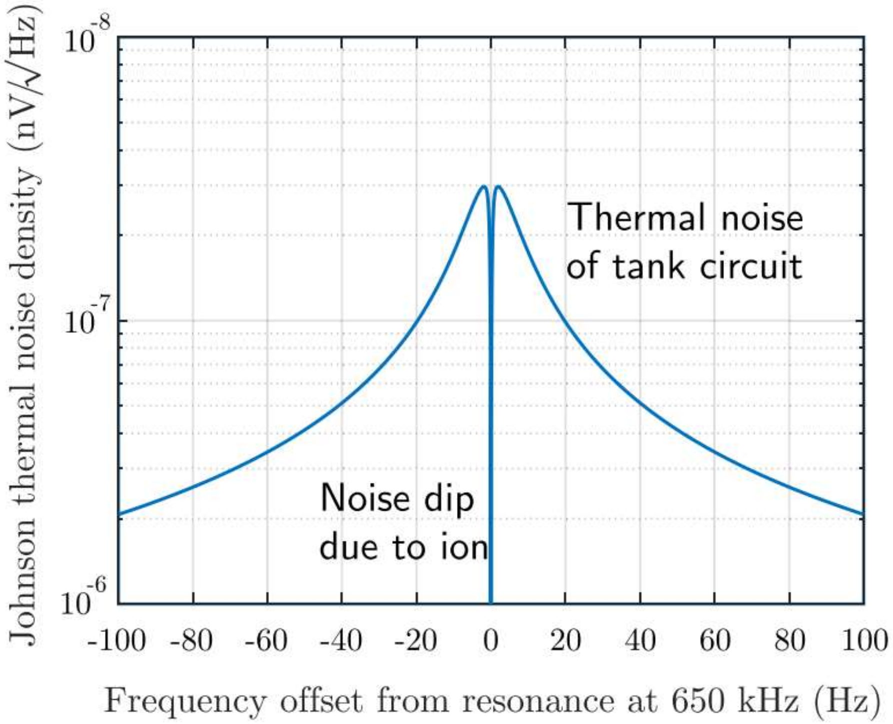
$\delta m/m < 10^{-10}$

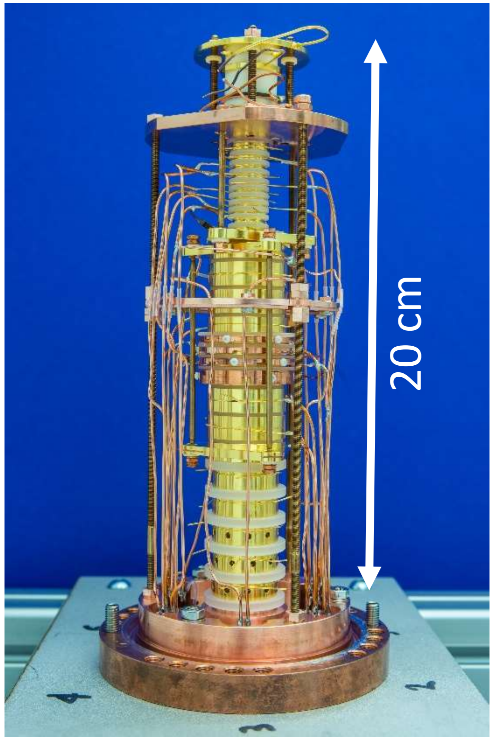
$\delta m/m = 10^{-6} – 10^{-8}$

electronic structure

nuclear structure

Storage of ions in a Penning trap





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

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

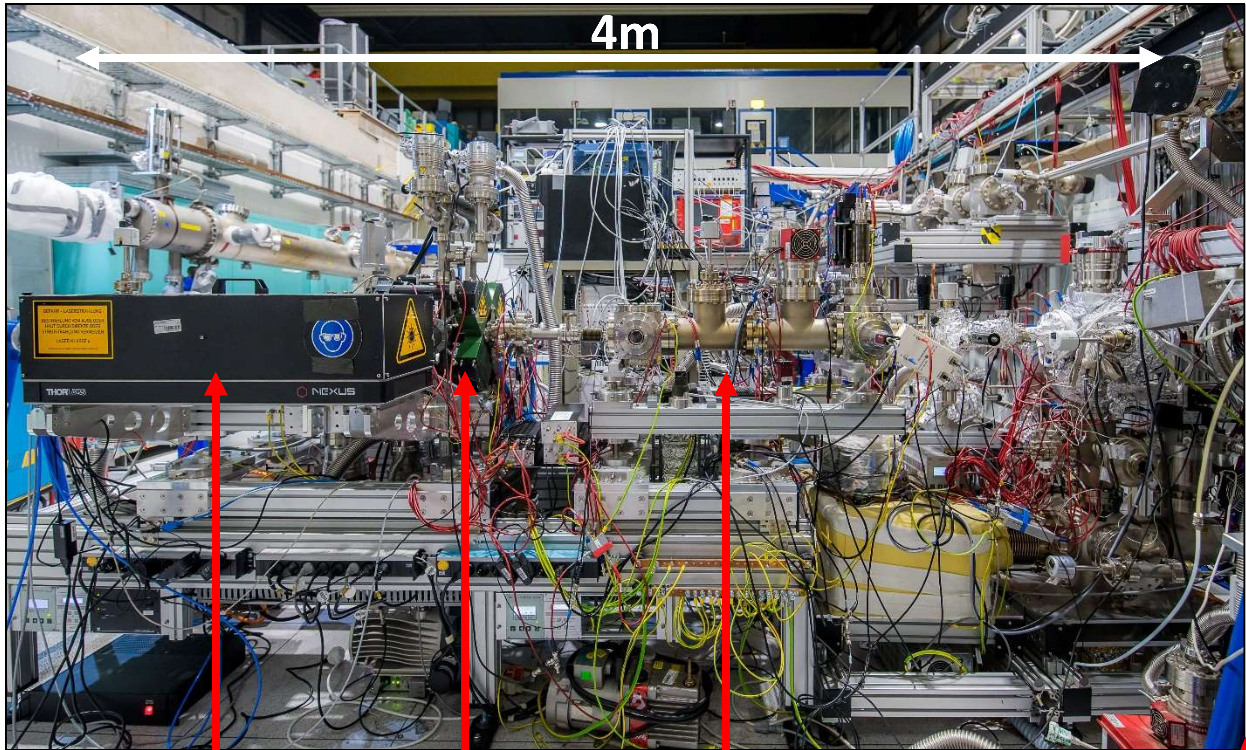
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

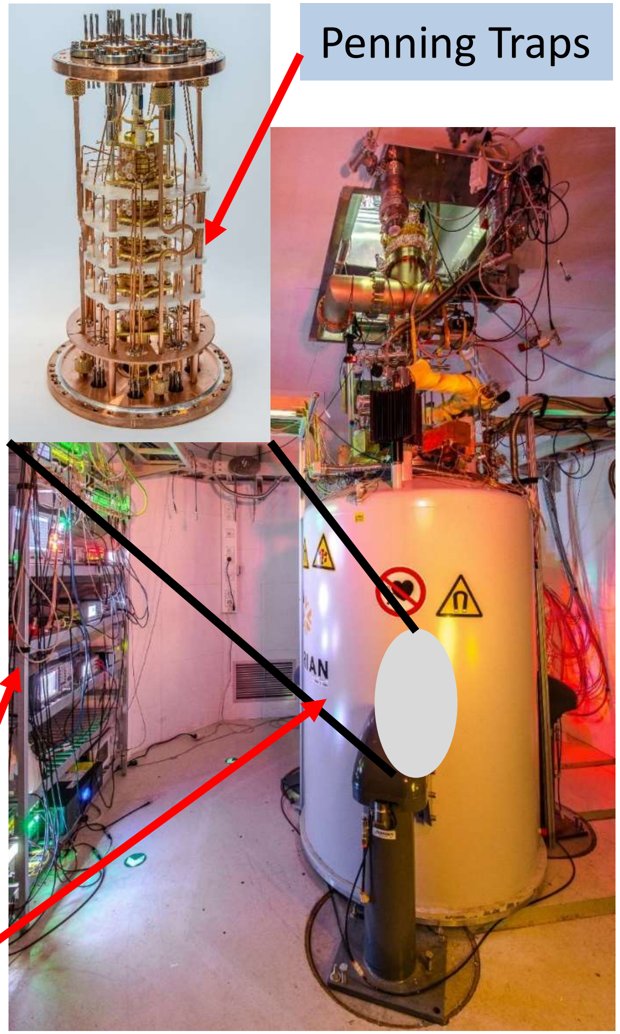
- Non-destructive FT-ICR detection technique

L.S. Brown, G. Gabrielse, Rev. Mod. Phys. **58** (1986) 233

PENTATRAP – A Penning-trap setup at MPIK

A balance for highly charged ions. – PI Sergey Eliseev





Penning Traps

Laser Ion Source

EBIT

Transfer Beamline

Electronics

Superconducting Magnet

$T_{1/2}$ > days

Measurement principle at PENTATRAP

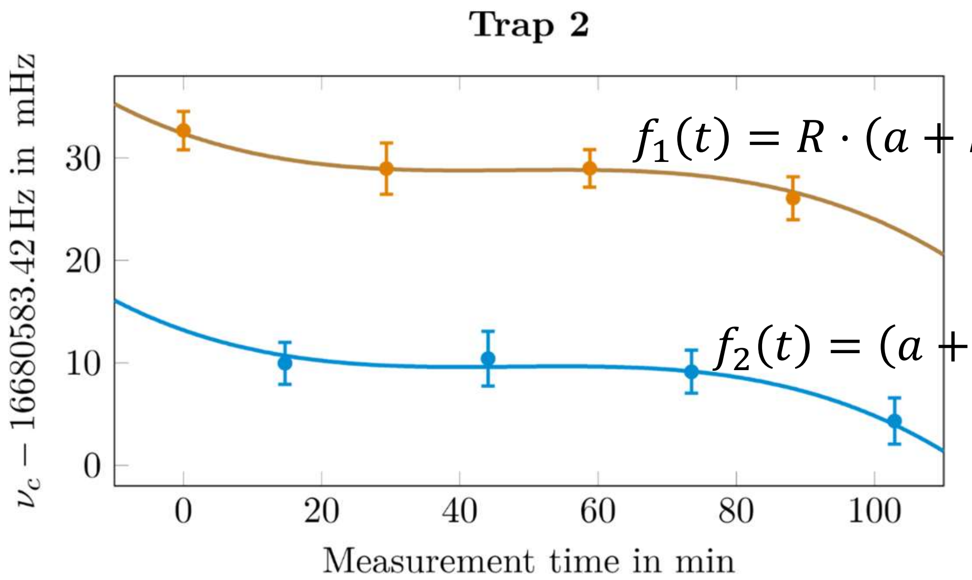
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

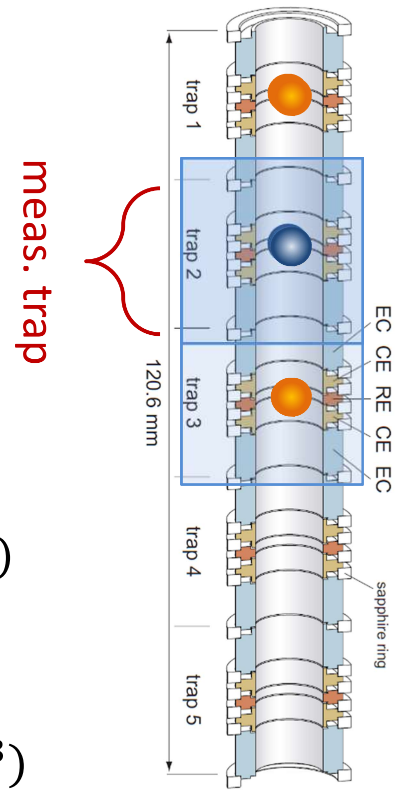
Second ion:

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



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

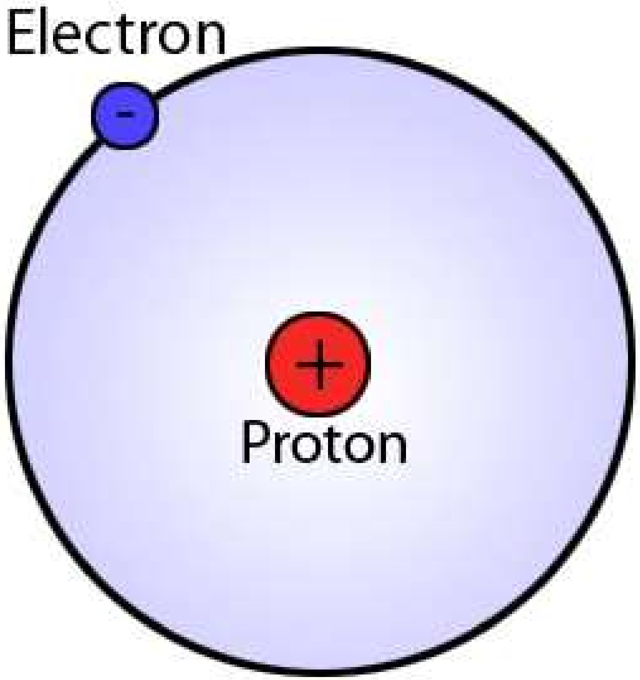
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



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

Results I

The masses of the building bocks of matter

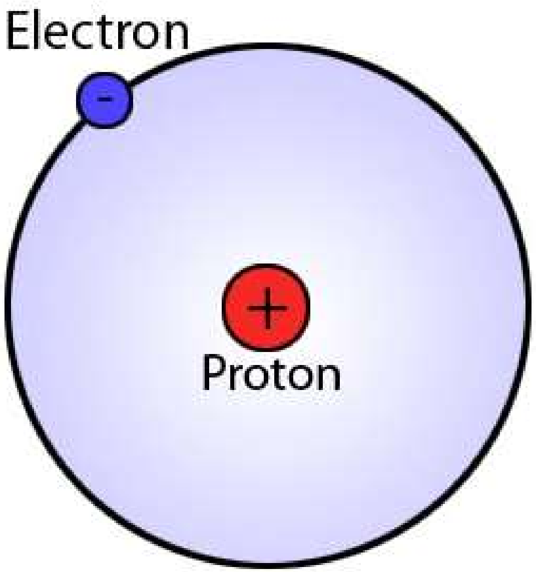


Sven Sturm

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

Proton: previous best value improved by a factor of 3

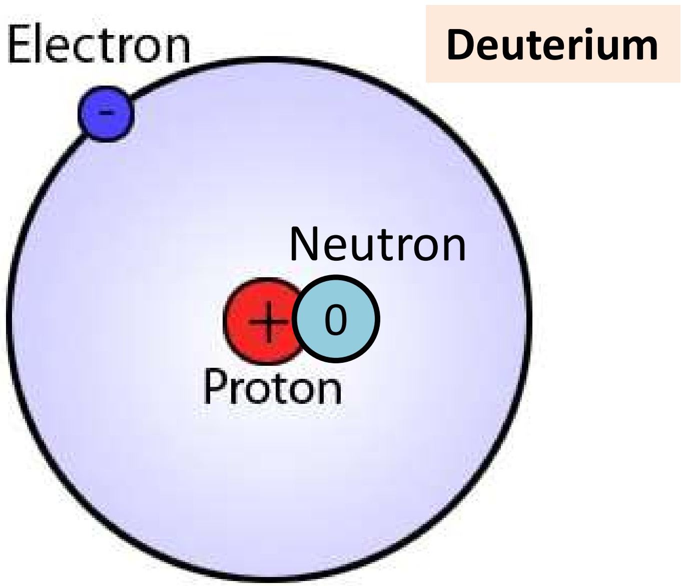
$m_e = 0.000\,548\,579\,909\,067(17)$ u

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

Nature **506** (2014) 467

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

The atomic mass of the deuteron and HD$^+$



$$m_{\mathrm{d}} = \frac{1}{6}\frac{\nu_{\mathrm{c}}(^{12}\mathrm{C}^{6+})}{\nu_{\mathrm{c}}(\mathrm{d})} m(^{12}\mathrm{C}^{6+})$$

A factor of ~3 improved value and 5 sigma deviation!

$$m_{\mathrm{d}} = 2.013553212535(11)_{\mathrm{stat}}(13)_{\mathrm{sys}}(17)_{\mathrm{tot}}\ \mathrm{AMU} \qquad \frac{\delta m_{\mathrm{d}}}{m_{\mathrm{d}}} = 8.5\times10^{-12}$$

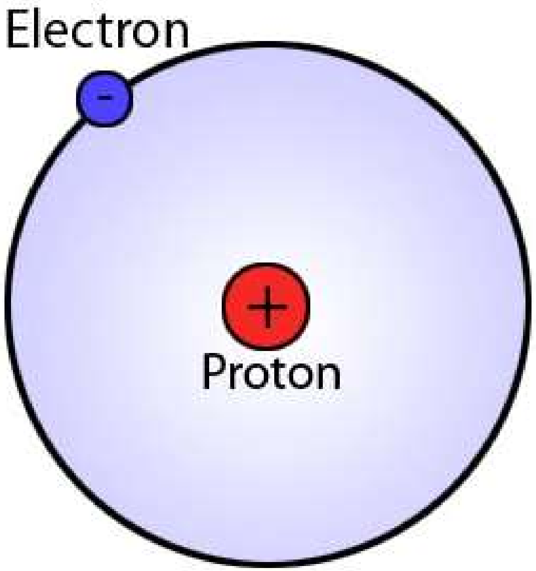
→ Provides access to the mass of the neutron

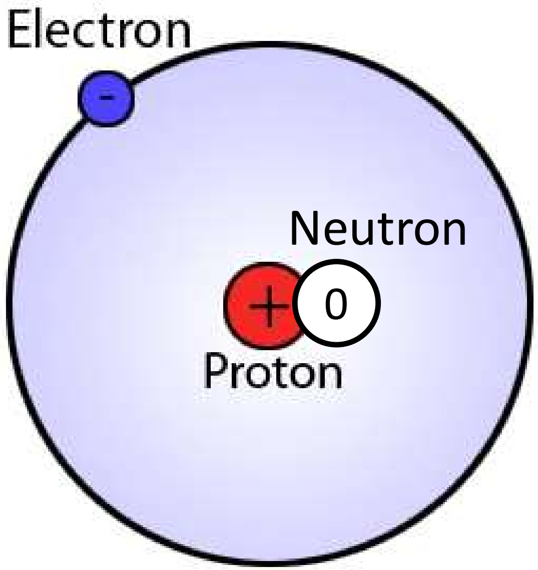
S. Rau *et al.*, Nature **585** (2020) 43

The building blocks of matter

The atomic mass of the proton and electron and neutron ☺

Hydrogen



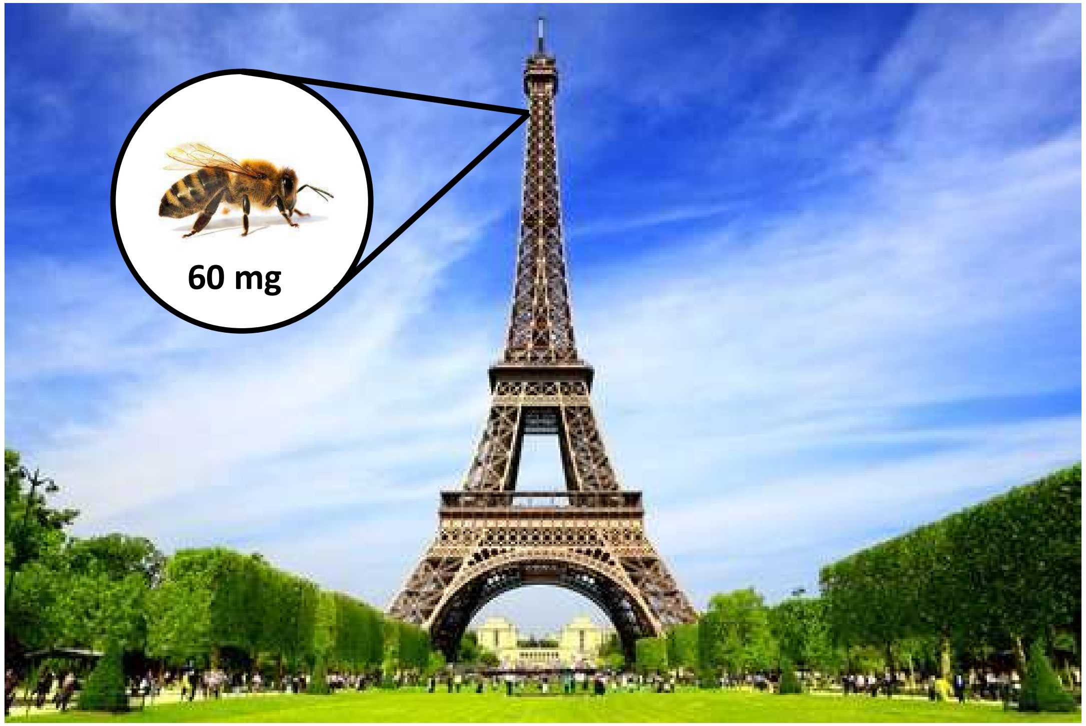


Deuterium

Electron: previous best value improved by a factor of 13	Proton: previous best value improved by a factor of 3	deuteron: previous best value improved by a factor of ~3
m_e = 0.000 548 579 909 067(17) u	m_p = 1.007 276 466 583 (33) u	m_d = 2.013 553 212 535 (17) u
Nature **506** (2014) 467	Phys. Rev. Lett. **119** (2017) 033001	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

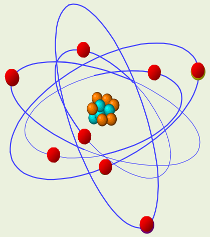


$m_{bee} \approx 60$ mg

$$\frac{m_{bee}}{m_{Eiffel}} \approx 8 \cdot 10^{-12}$$

m_{Eiffel} **= 7300 T = 7.300.000.000.000 mg = 7.3·10^{12} mg**

BUT: Precision achieved on the atomic scale!



recently achieved $2 \cdot 10^{-12}$

Results II

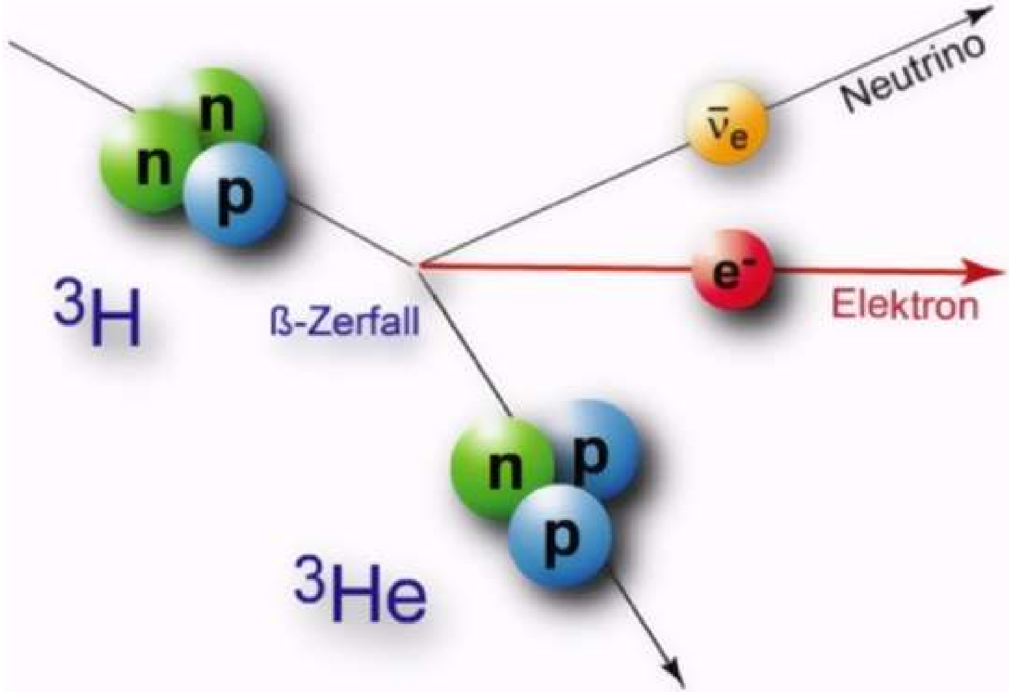
Nuclear masses for neutrino physics

***Q*-values:**

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

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

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



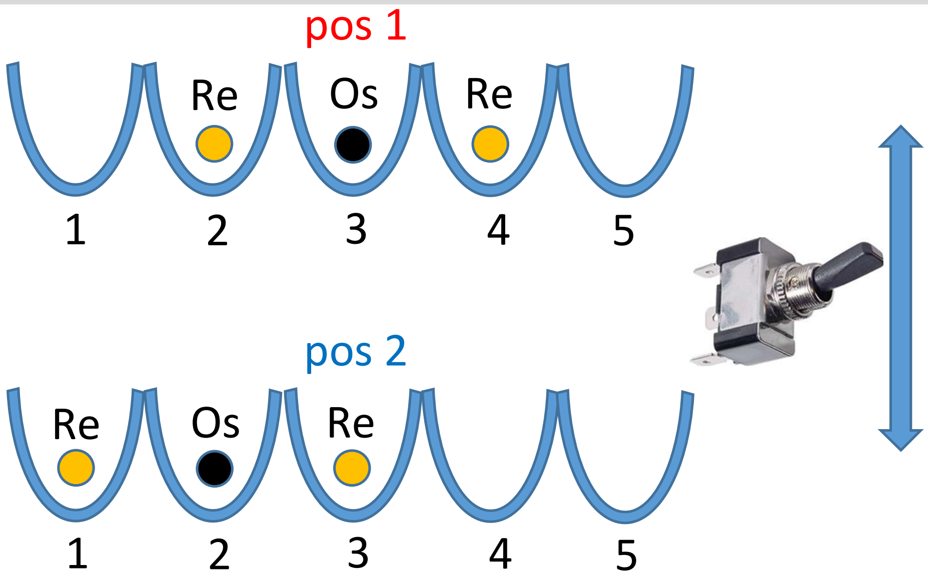
Sergey Eliseev

β^- -decay of ^{187}Re

$$R = \frac{\nu_c(^{187}Os^{29+})}{\nu_c(^{187}Re^{29+})}$$

$$Q = M(^{187}\mathrm{Re})\text{-}M(^{187}\mathrm{Os}) = M(^{187}\mathrm{Re}^{29+}) - M(^{187}\mathrm{Os}^{29+}) + \Delta B = M(^{187}\mathrm{Os}^{29+}) \cdot [R-1] + \Delta B$$

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: $6{\cdot}10^{-12}$

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+}: $[_{36}Kr]\ 4d^{10}$

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

Similar state in Os^{30+} expected!

Re^{29+}

metastable electronic state

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

B_{Harman} = 202.2(5) eV

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

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

ground state

Os^{30+}

metastable electronic state

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

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

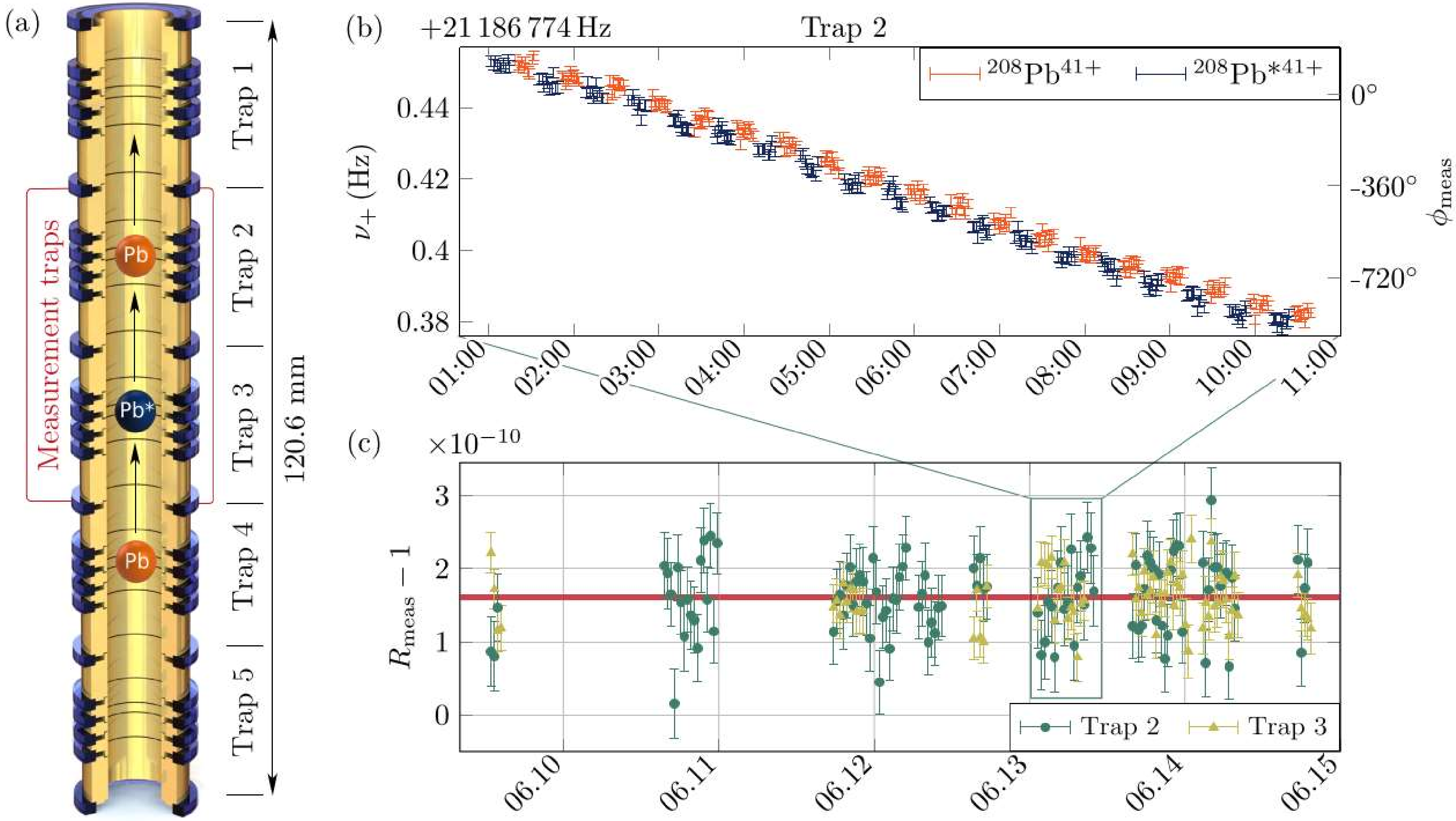
$B_{Indelicato}$ = 207(3) eV

ground state

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

Possible application: search for suitable clock transitions

Search for low-lying isomeric states



Δm = 31.2(8) eV/c²

K. Kromer *et al.*, PRL **131** (2023) 223002

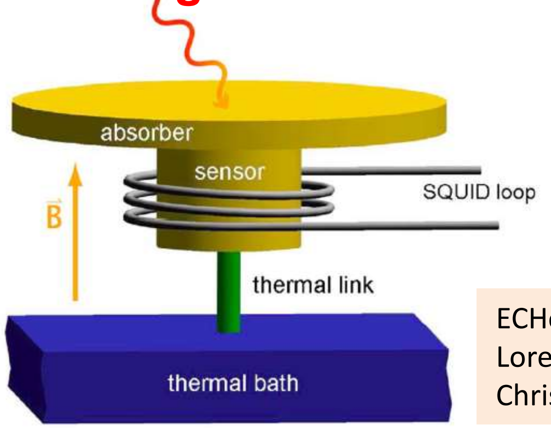
The ECHo (^{163}Ho) project

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

NEUTRONS FOR SCIENCE

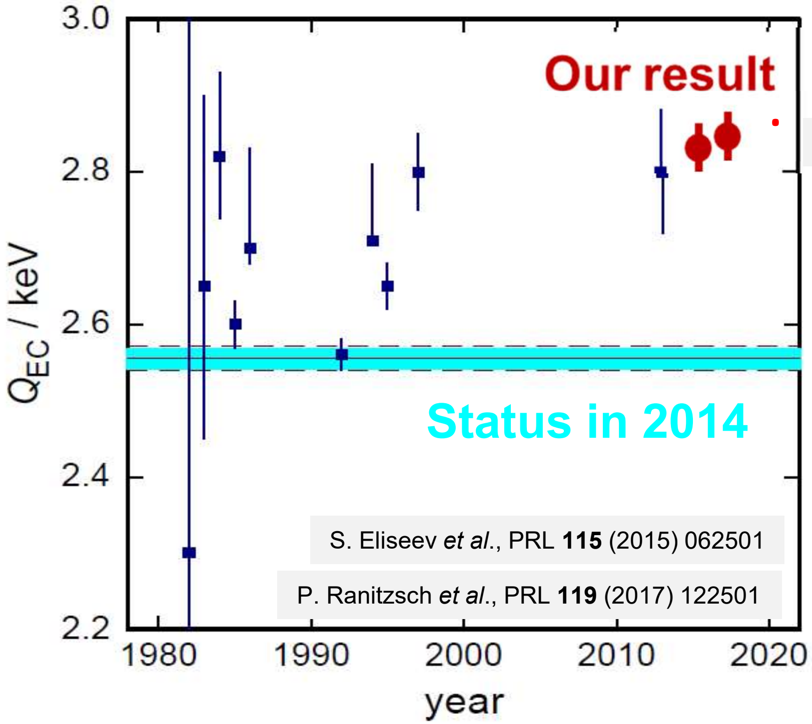
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

Metallic Magnetic Calorimetry



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss

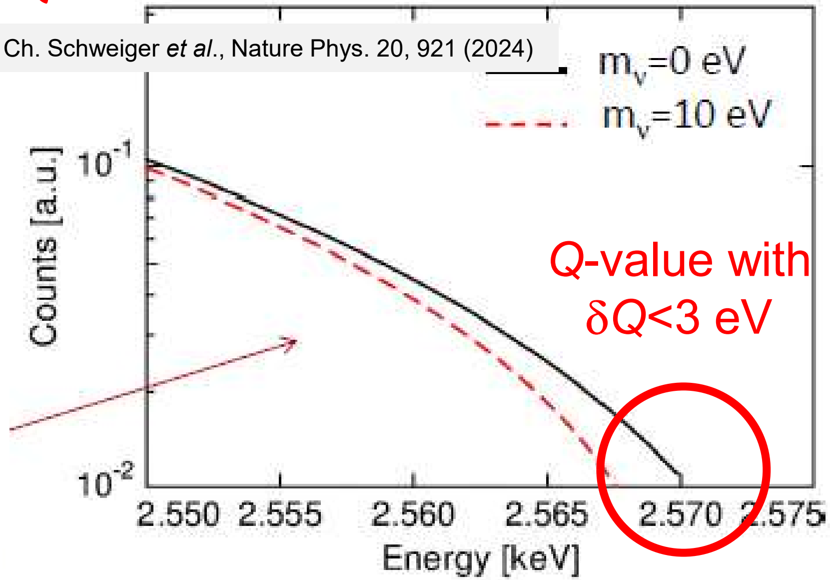
Q-value of EC in ^{163}Ho



S. Eliseev *et al.*, PRL **115** (2015) 062501

P. Ranitzsch *et al.*, PRL **119** (2017) 122501

δQ=0.6 eV

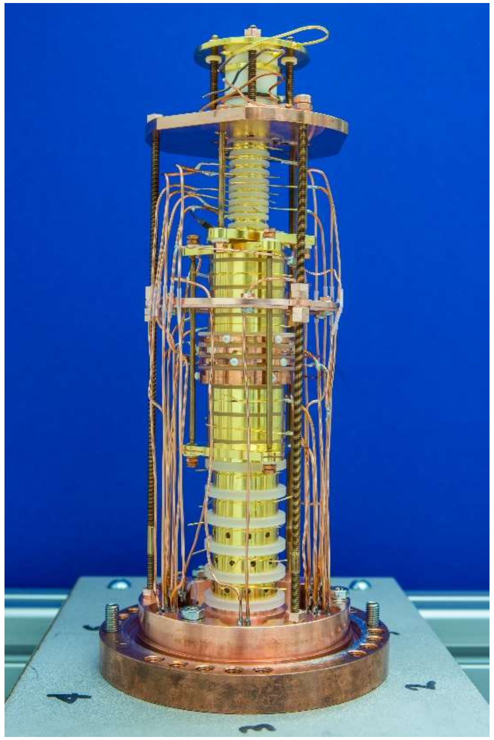


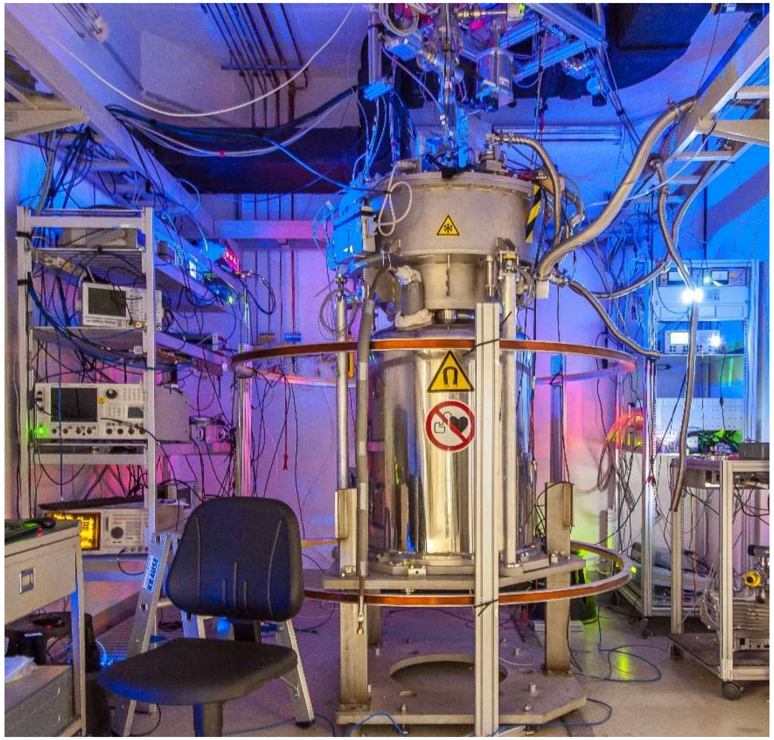
Ch. Schweiger *et al.*, Nature Phys. 20, 921 (2024)

Results III

Tests of fundamental interactions and their symmetries

Stefan Ulmer





Sven Sturm

Andreas Mooser

ALPHATRAP, BASE, PENTATRAP: MPIK, PTB, RIKEN

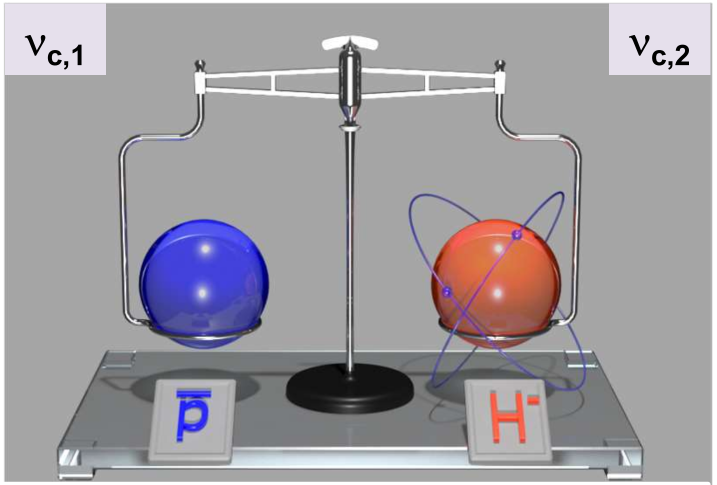
Comparison of the proton and antiproton

Baryon-Antibaryon Symmetry Experiment

Compare charge-to-mass ratios R of p and $\overline{\text{p}}$:

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

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



It is not that easy!

$$m_{\text{H}^-} = m_p \left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{\text{pol,H}^-} B_0^2}{m_p} - \frac{E_\text{b}}{m_p} - \frac{E_\text{a}}{m_p} \right)$$

Most stringent test of CPT symmetry in the baryon sector!

physicsworld TOP 10 BREAKTHROUGH 2021

Next step: sympathetic laser cooling

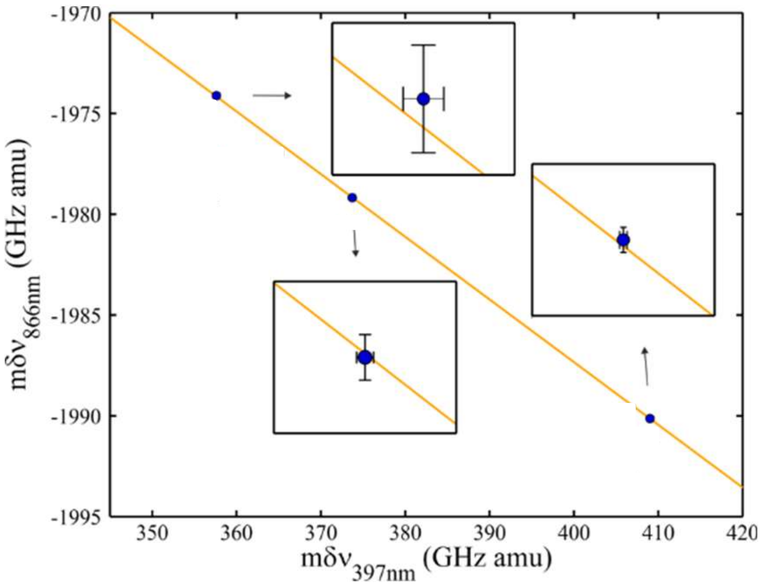
M.Bohman *et al.*, Nature **596** (2021) 514

Ch. Will *et al.*, PRL **133** (2024) 023002

Probe for new force carriers

Isotope shift spectroscopy: 5th force?

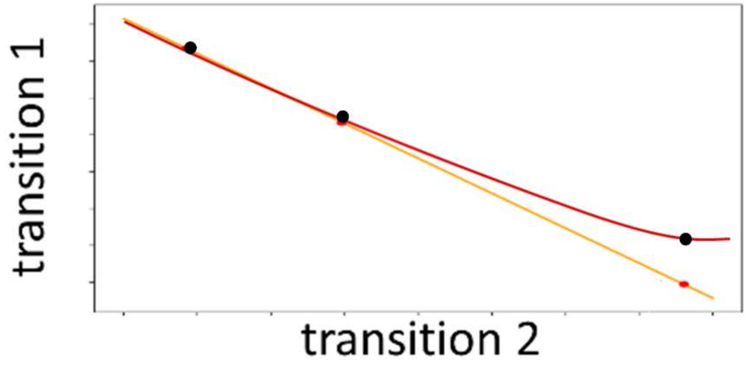
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'}$
- use 2 transitions i, j
  ➔ eliminate $\delta\langle r^2\rangle_{A,A'}$



- new force mediated through scalar field with boson mass $m_\phi \rightarrow X_i$
- coupling to neutrons: y_n
- coupling to electrons: y_e

➔ nonlinearity in King's plot:

$$\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'} + +\alpha_{NP} X_i (\mathrm{A}-\mathrm{A}')$$

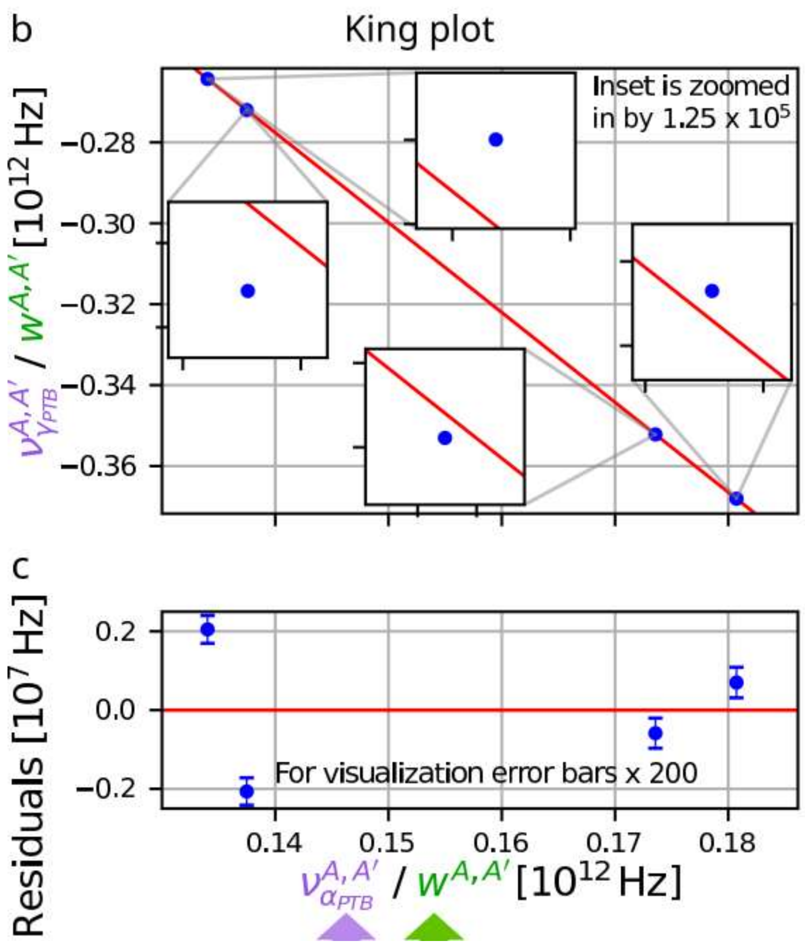


J. Berengut *et al.*, PRL **120** (2018) 091801

High-precision atomic and nuclear spectroscopy measurements at 10^{-12} needed!

Results from the Yb isotopic chain

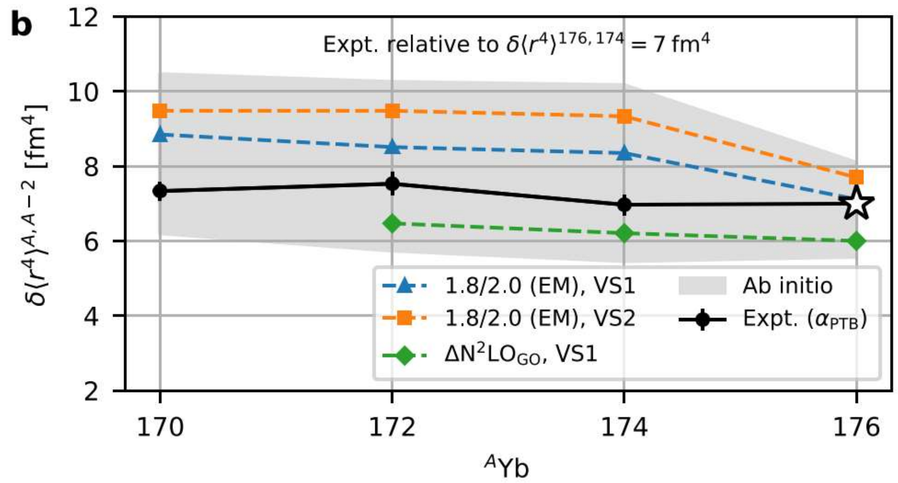
→ a 200σ (!!!) non-linearity observed



→ an additional nuclear structure term prop. to δ<*r*⁴> is considered

$$\boldsymbol{\nu}_\alpha = F_\alpha \boldsymbol{\delta}\langle r^2\rangle + K_\alpha \boldsymbol{w} + G^{(2)}_\alpha \boldsymbol{\delta}\langle r^2\rangle^2 + G^{(4)}_\alpha \boldsymbol{\delta}\langle r^4\rangle + \frac{\alpha_{\rm NP}}{\alpha_{\rm EM}} D_\alpha \boldsymbol{h} + \ldots .$$

→ nuclear structure theory needed

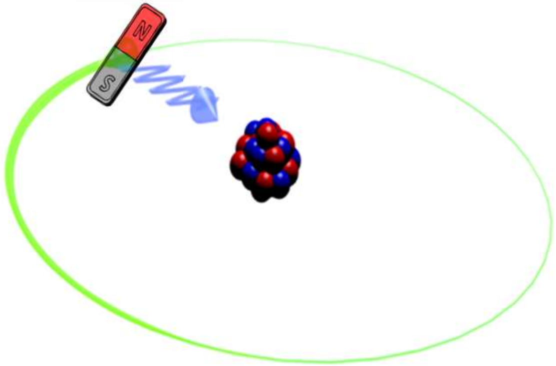


M. Door *et al.*, PRL, **134** (2025) 063002

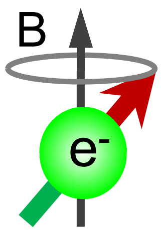
New bounds on a fifth force in the keV/c² to MeV/c² range coupling to electrons and neutrons.

The *g*-factor of the bound electron

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



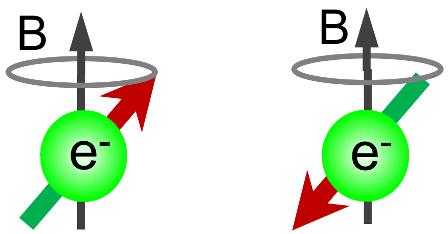
g-factor: measure for the magnetic strength of the bound electron



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

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

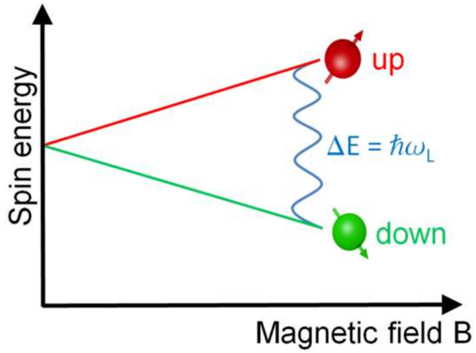
Electron can be in spin-up or spin-down state with transition frequency ω_L



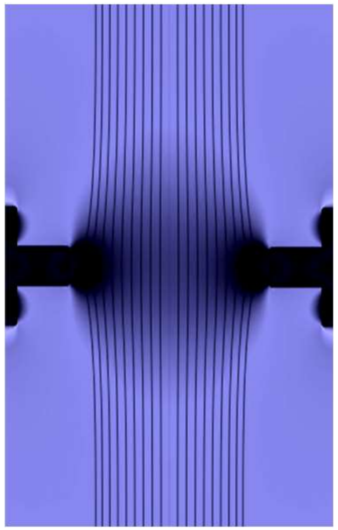
Continuous Stern-Gerlach effect

- Larmor frequency cannot be detected directly
- Microwaves probe spin transition

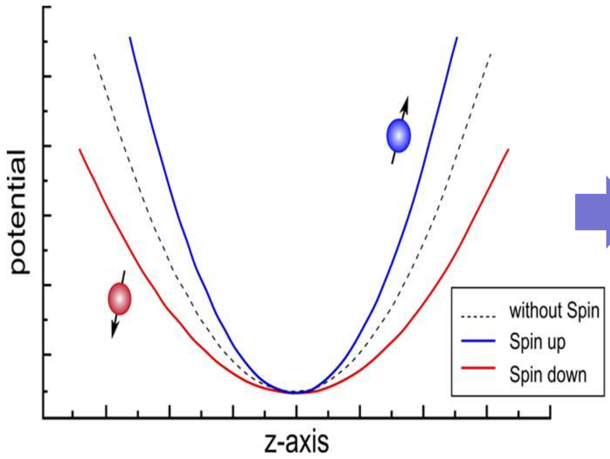
How to detect a successful spinflip ?



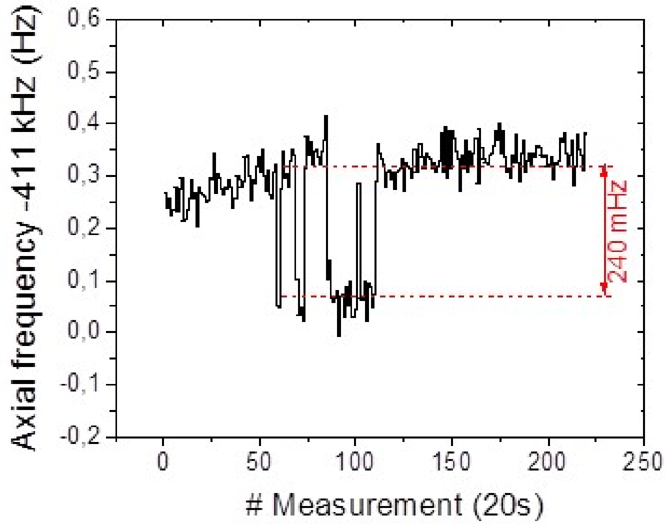
$$\omega_z = \sqrt{\frac{2e_0U_0}{md_0^2}}$$



Ferromagnetic ring
→ magnetic bottle

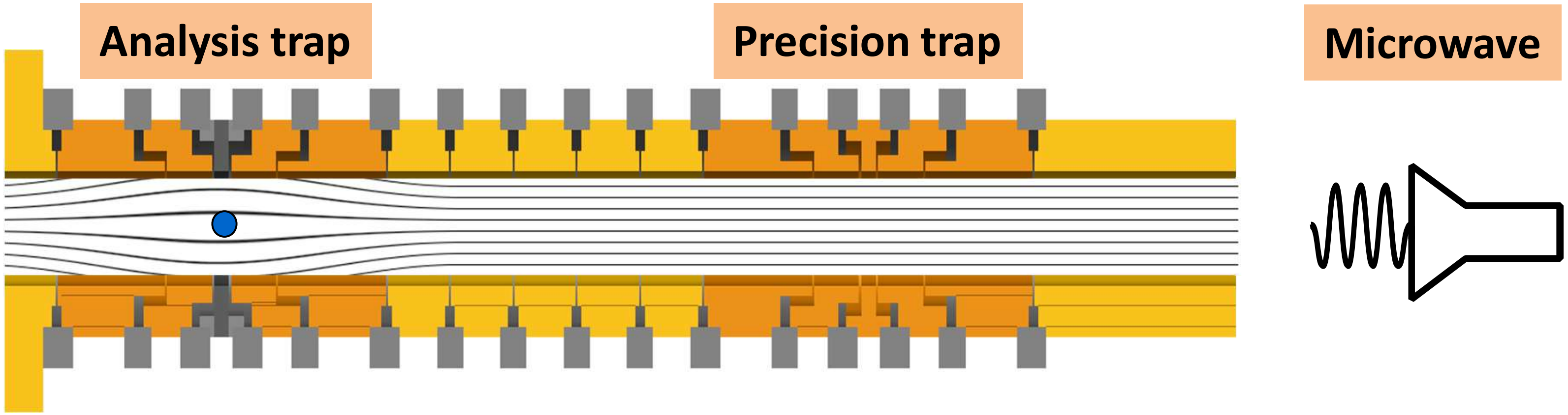


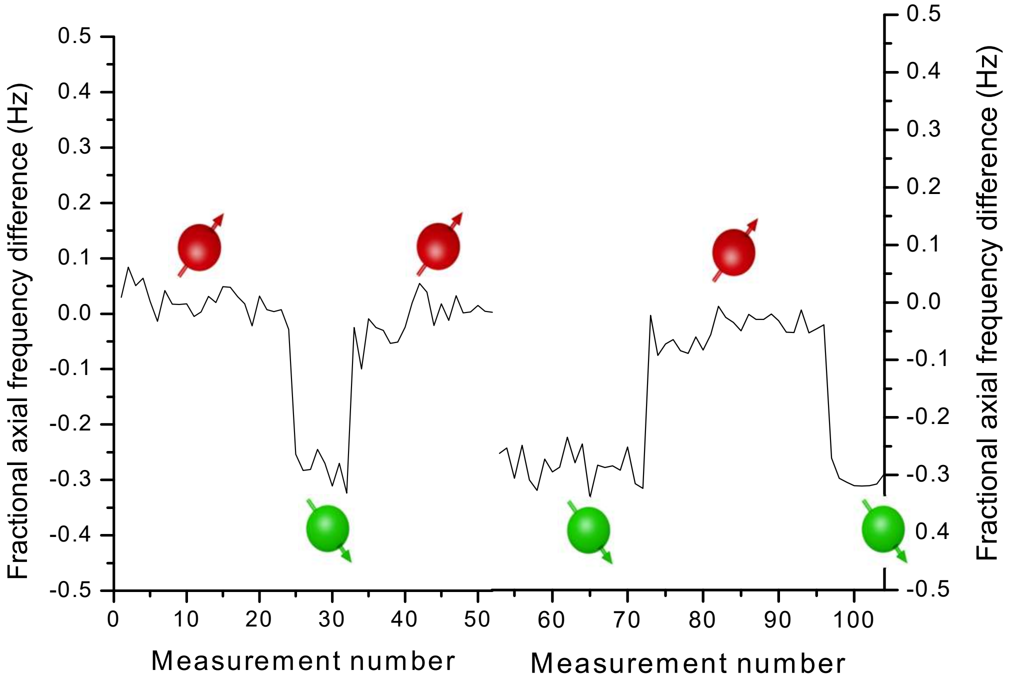
Spin dependent
trapping potential



Tiny axial frequency difference
between spin up and down.

g-factor measurement process

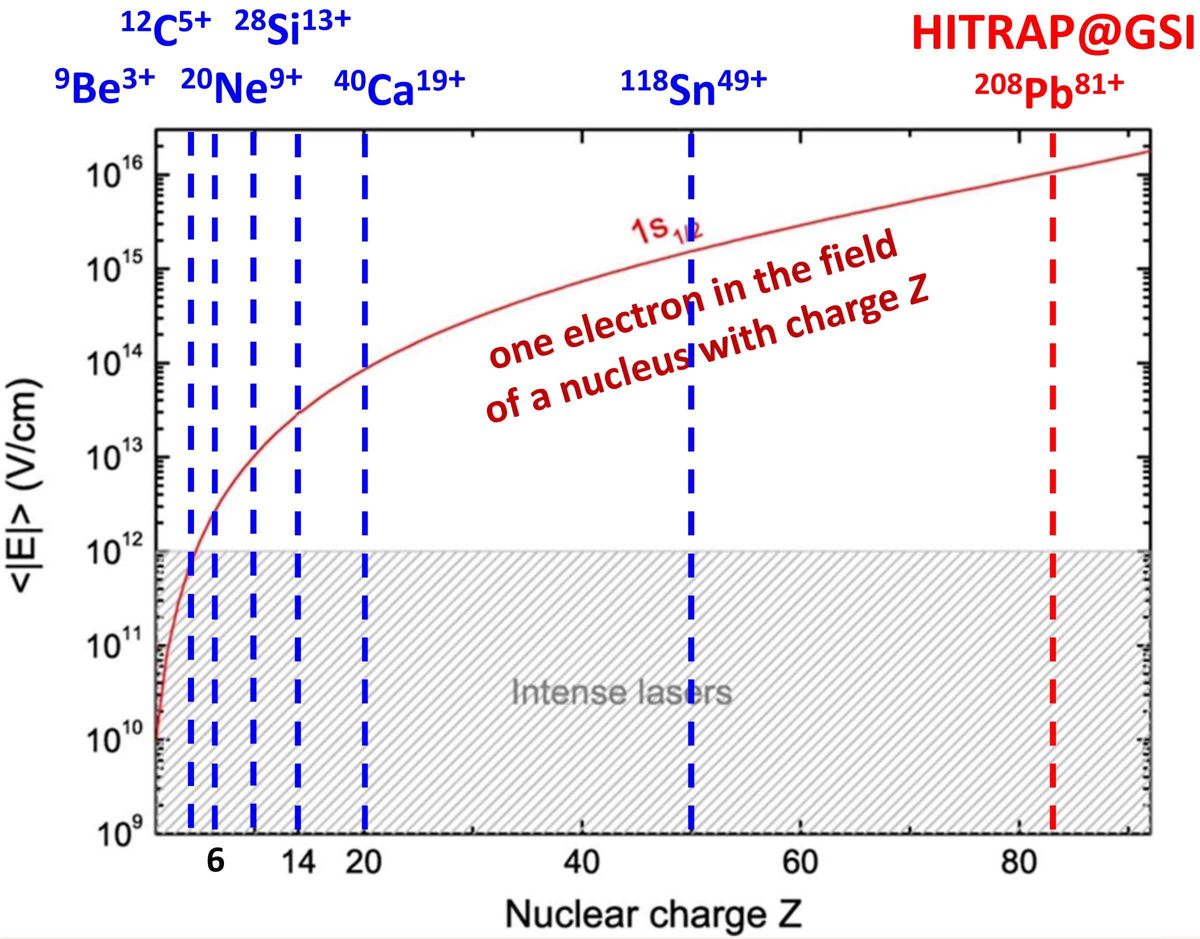


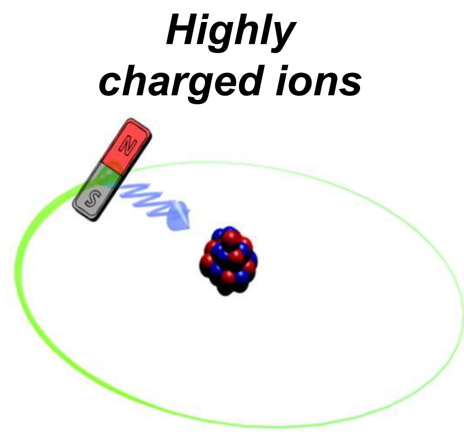


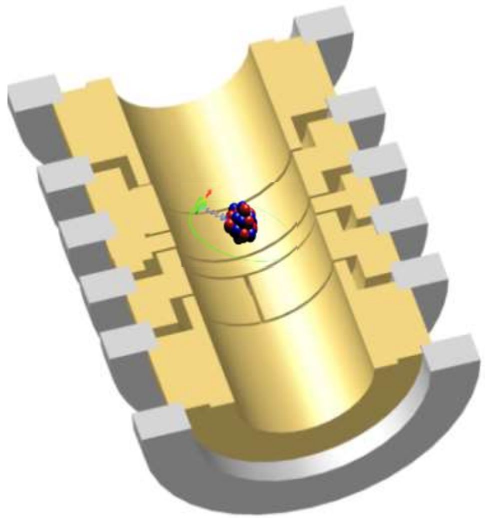
<u>Measurement cycle</u>	time
▪ Detection of spin-state	2-3min
▪ Transport	20s
▪ ν_c measurement and microwave irradiation	10min
▪ Transport	20s
▪ Detection of spin-state	

Extreme conditions in highly charged ions

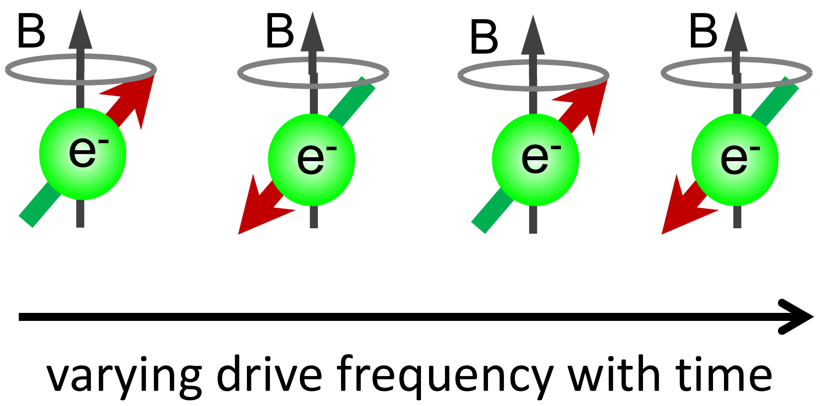
- QED is the best tested quantum field theory (see *g*-2 of the electron; Dehmelt, Gabrielse)
- we would like to test QED in ultra strong fields

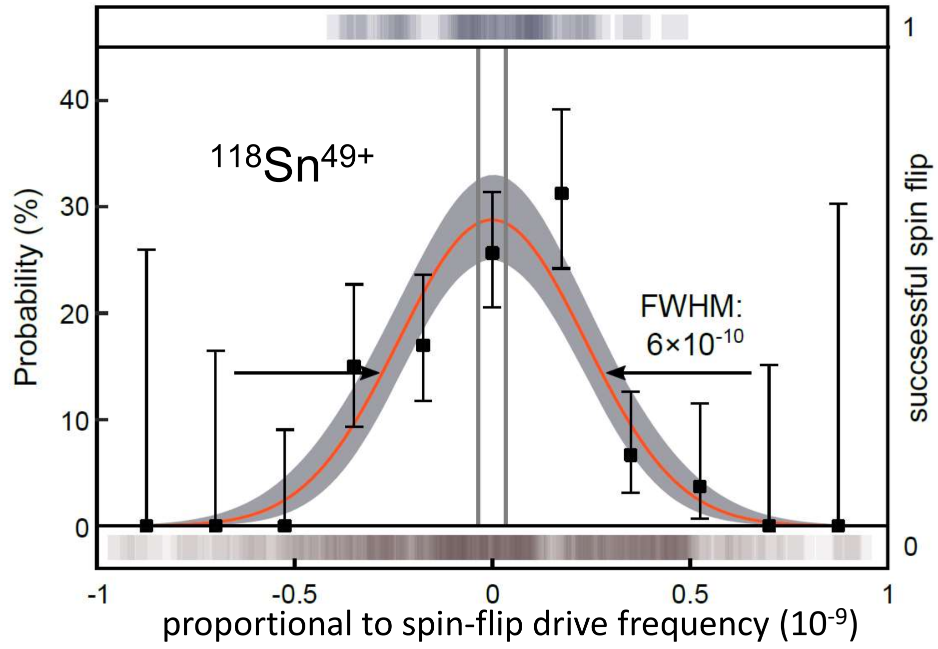






Test of QED in strong fields





$^{20}Ne^{9+}$

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

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

g_{exp} = 1.910 562 058 (1)
g_{theo} = 1.910 561 821 (299)

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)

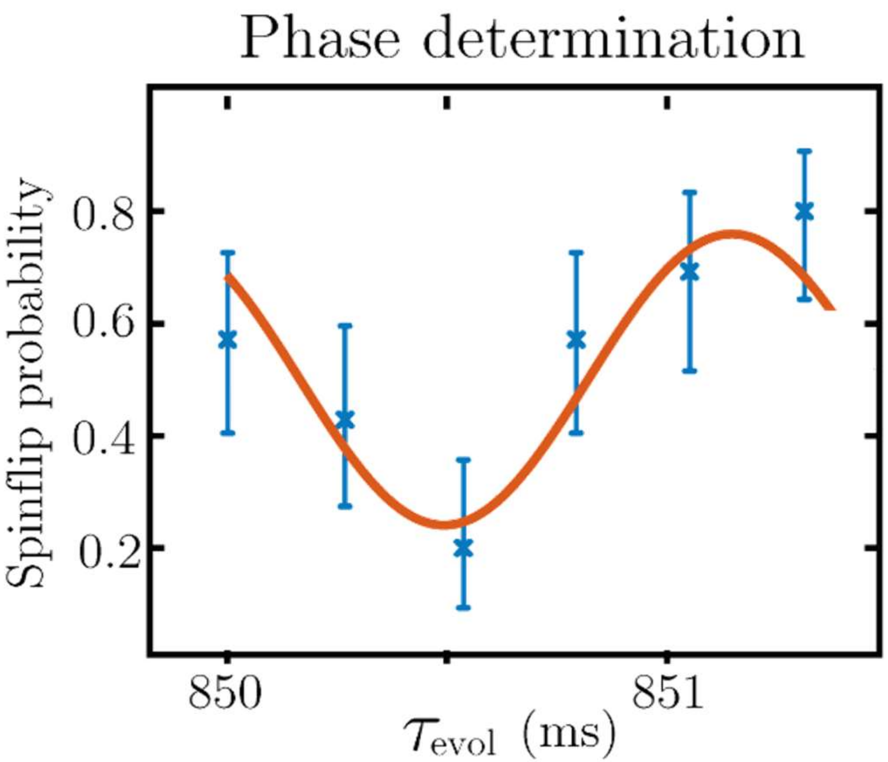
Theory colleagues:
Harman, Keitel, Oreshkina, Yerokhin

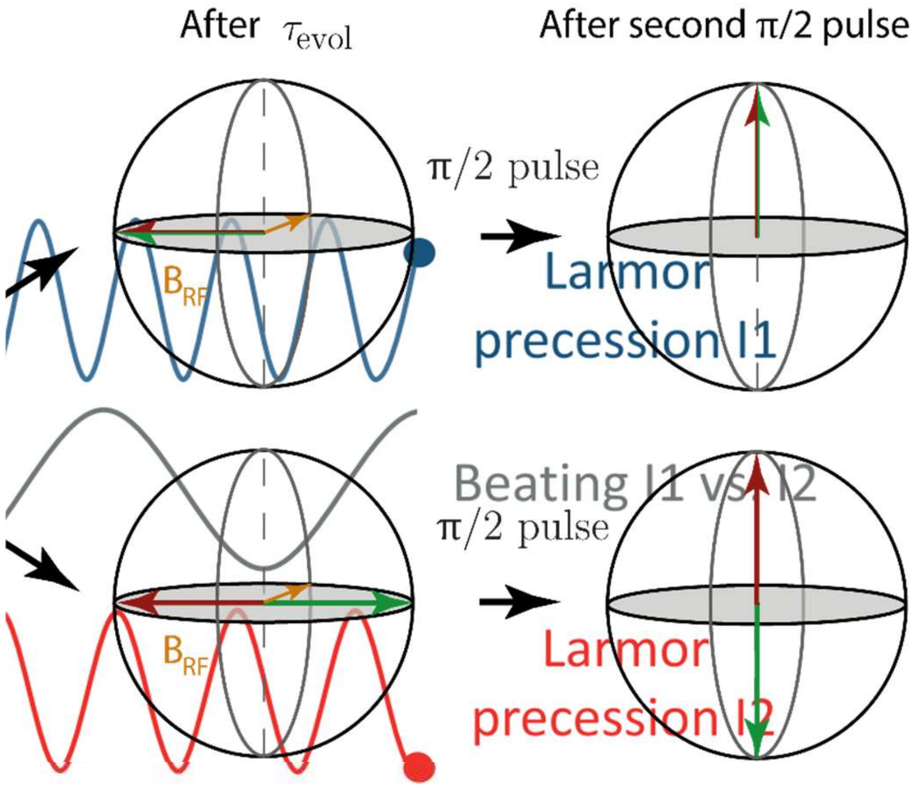
J. Morgner *et al.*, Nature **622**, 53 (2023) H-like
J. Morgner *et al.*, Science **388**, 945 (2025) Li-Like
J. Morgner *et al.*, PRL **134,** 123201 (2025) B-like

Bound g-factor difference in coupled ions

Delta-g measurement in $^{20,22}Ne^{9+}$: how to get ν_L

Probability of common spin behavior modulated by beat frequency!





Relative precision of $5 \cdot 10^{-13}$ achieved, most stringent BS-QED test!

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

Summary

Precision Penning-trap spectroscopy has reached an amazing precision even on exotic systems and has opened up many new fields of research!

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!