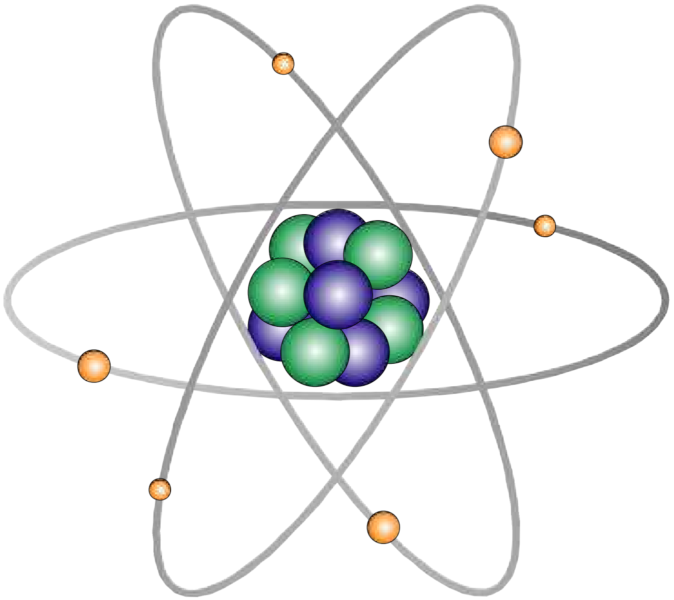
Trapped and Measured: Quantum Metrology in a Penning Trap

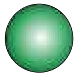
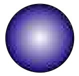
- **Basics of Penning-trap mass spectrometry**
- **Nuclear masses for neutrino physics**
- **Atomic masses for fundamental studies**

Klaus Blaum
Max-Planck-Institute for Nuclear Physics, Heidelberg

Steinbach, Sep 3rd, 2025

The mass of an atom



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

– binding energy

Einstein $E = mc^2$

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

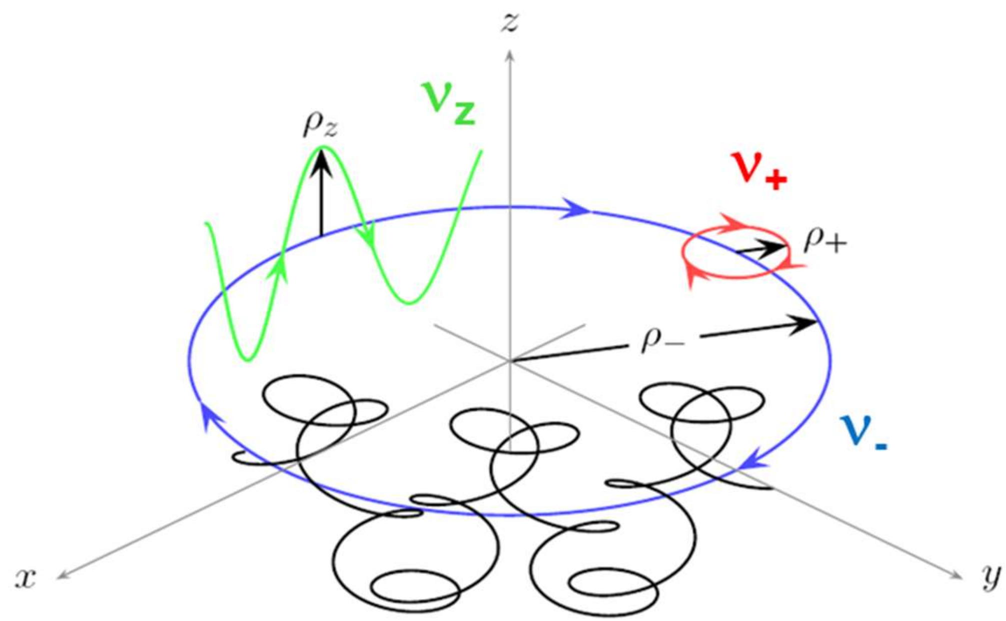
$\delta m/m < 10^{-10}$

$\delta m/m = 10^{-6} – 10^{-8}$

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 detection technique

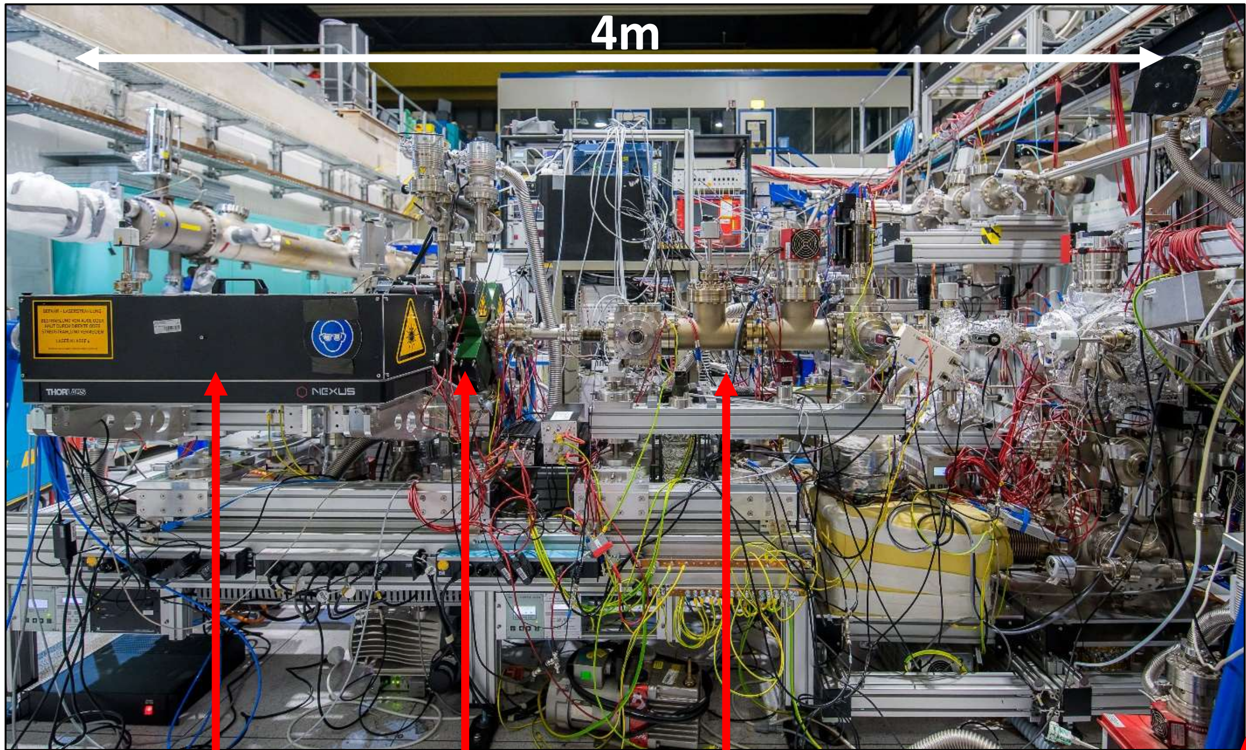
$$\nu_c = qB / (2\pi m_{ion})$$

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

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

PENTATRAP – A Penning-trap setup at MPIK

A balance for highly charged ions.

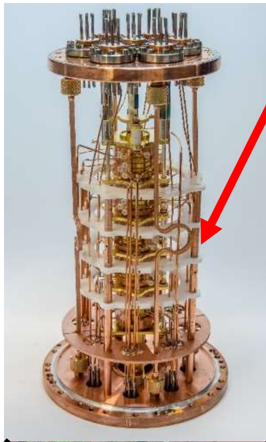


Laser Ion Source

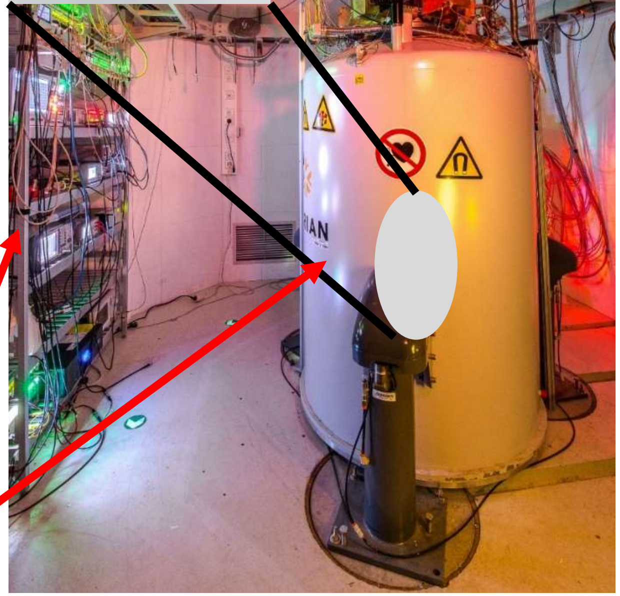
EBIT

Transfer Beamline

Electronics



Penning Traps



$T_{1/2}$ > days

Superconducting Magnet

Measurement principle at PENTATRAP

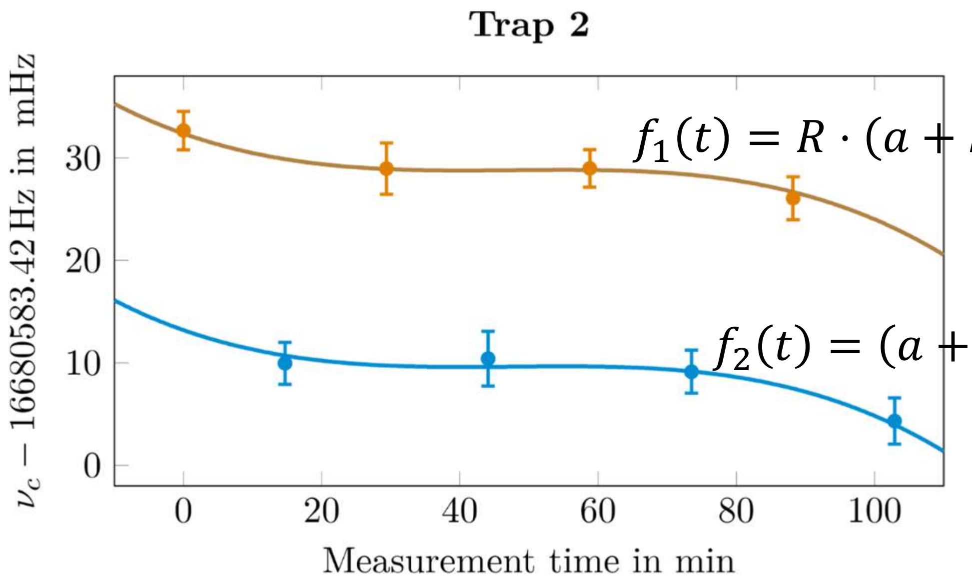
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

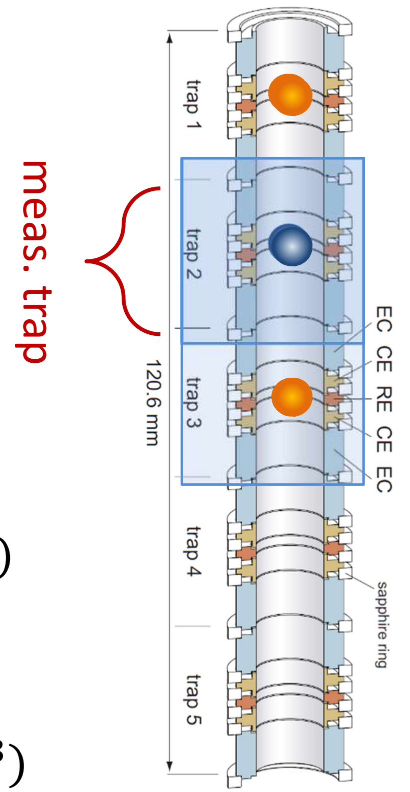
Second ion:

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



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

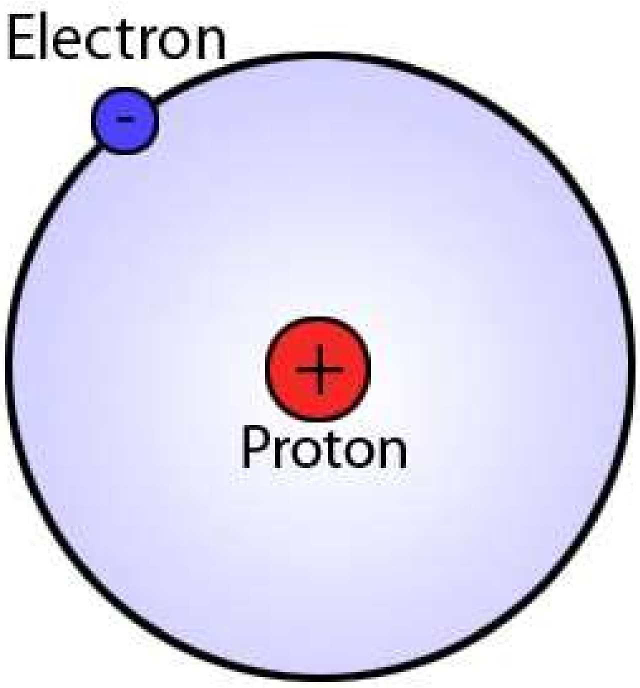
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



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

Results I

The masses of the building bocks of matter



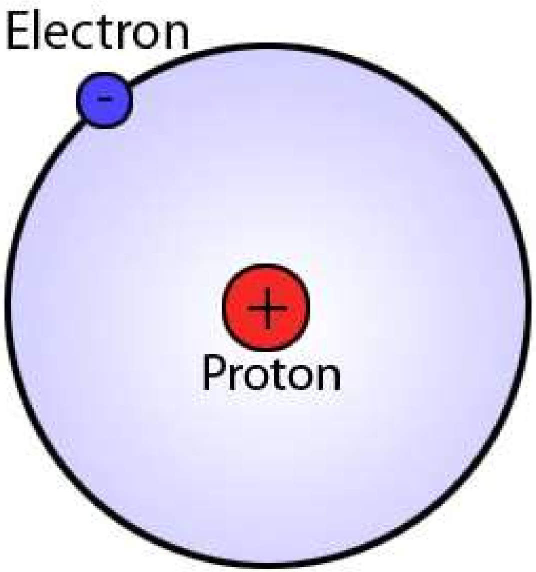
Sven Sturm

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

m_e = 0.000 548 579 909 067(17) u

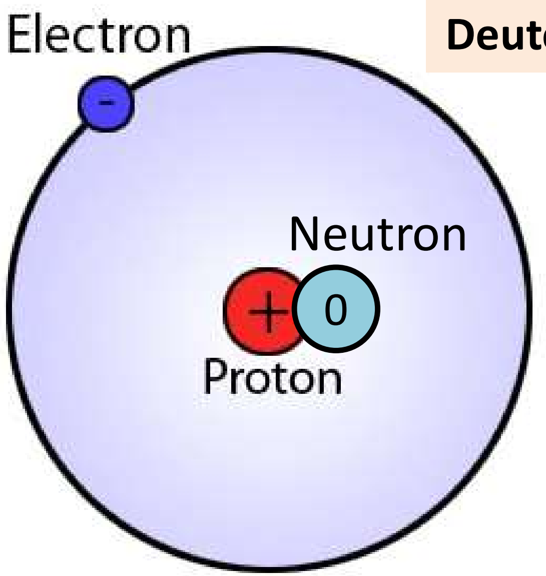
Nature **506** (2014) 467

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 atomic mass of the deuteron and HD$^+$



Deuterium

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

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

$$m_{\mathrm{d}} = 2.013553212535(11)_{\mathrm{stat}}(13)_{\mathrm{sys}}(17)_{\mathrm{tot}}\ \mathrm{AMU}$$

$$\frac{\delta m_{\mathrm{d}}}{m_{\mathrm{d}}} = 8.5\times 10^{-12}$$

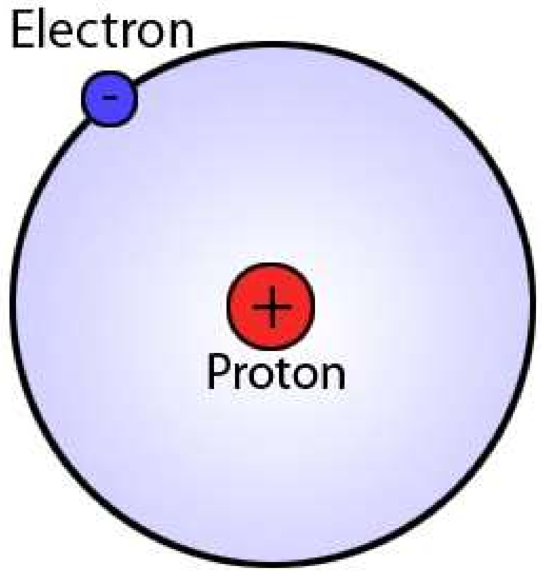
→ Provides access to the mass of the neutron

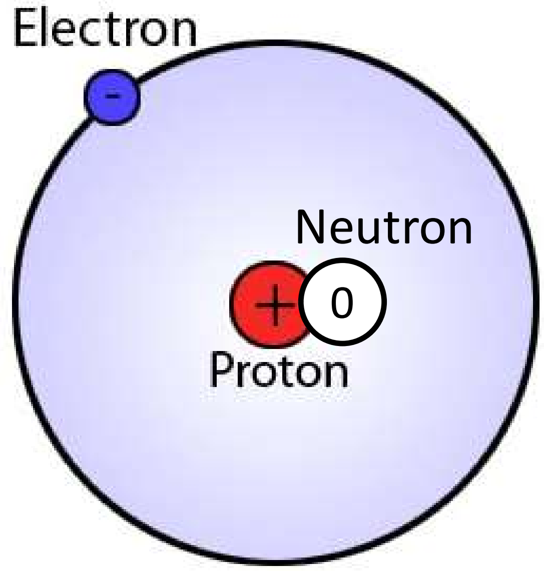
S. Rau *et al.*, Nature **585** (2020) 43

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

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

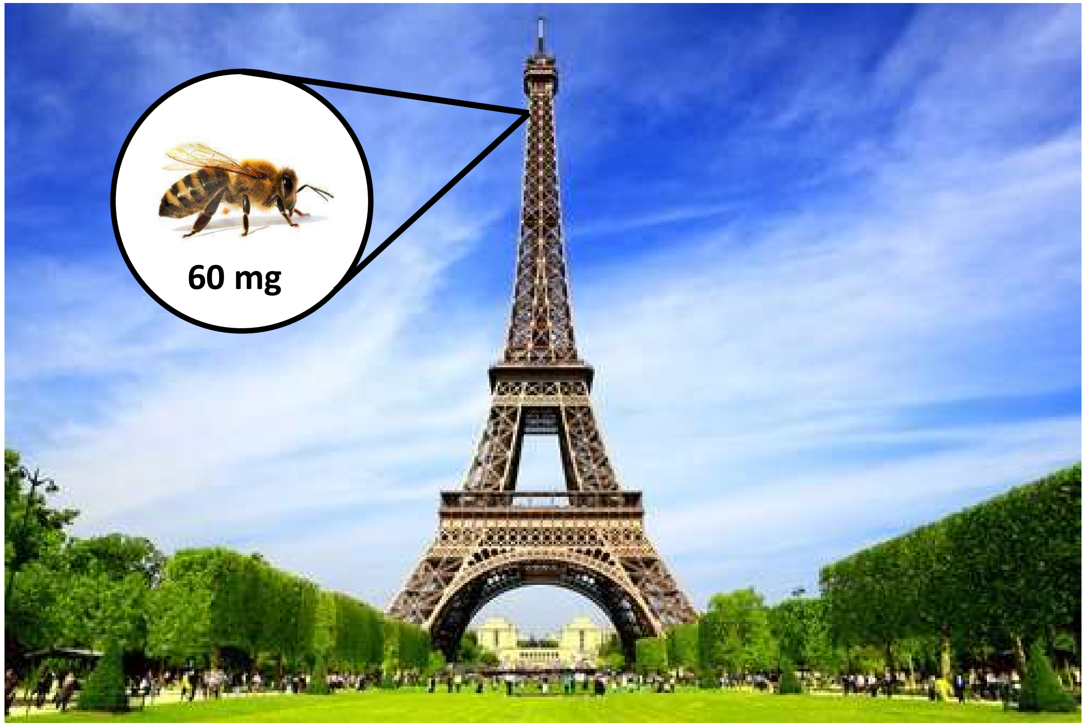
deuteron: previous best value improved by a factor of ~3

m_d = 2.013 553 212 535 (17) u

Nature **585** (2020) 43

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

An easy image of our precision regime

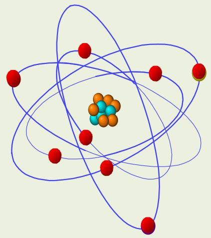


m_{Eiffel} **= 7300 T = 7.300.000.000.000 mg = 7.3·10^{12} mg**

$m_{bee} \approx 60$ mg

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

BUT: Precision achieved on the atomic scale!



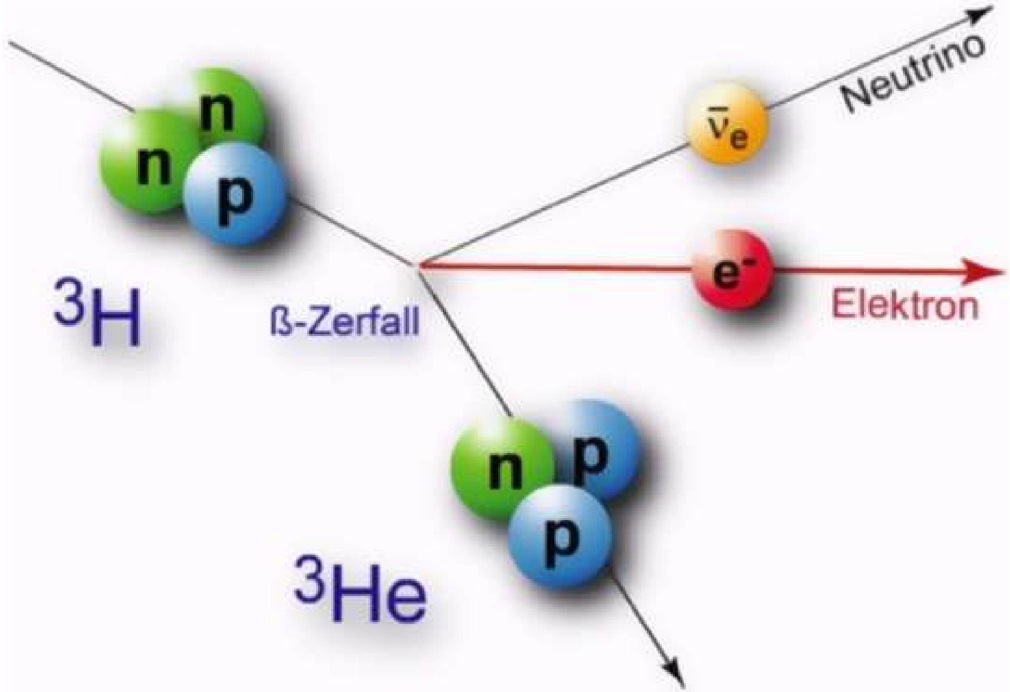
demonstrated 2·10^{-12}

Results II

Nuclear masses for neutrino physics

_Q_-values:

$^{3}T \rightarrow {}^{3}He$
$^{163}Ho \rightarrow {}^{163}Dy$
$^{187}Re \rightarrow {}^{187}Os$



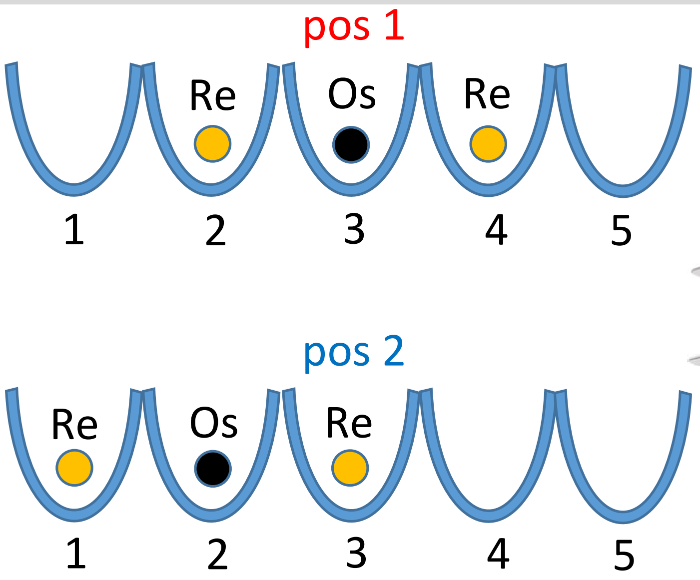
Sergey Eliseev

β^--decay of ^{187}Re

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

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

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 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 state

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

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

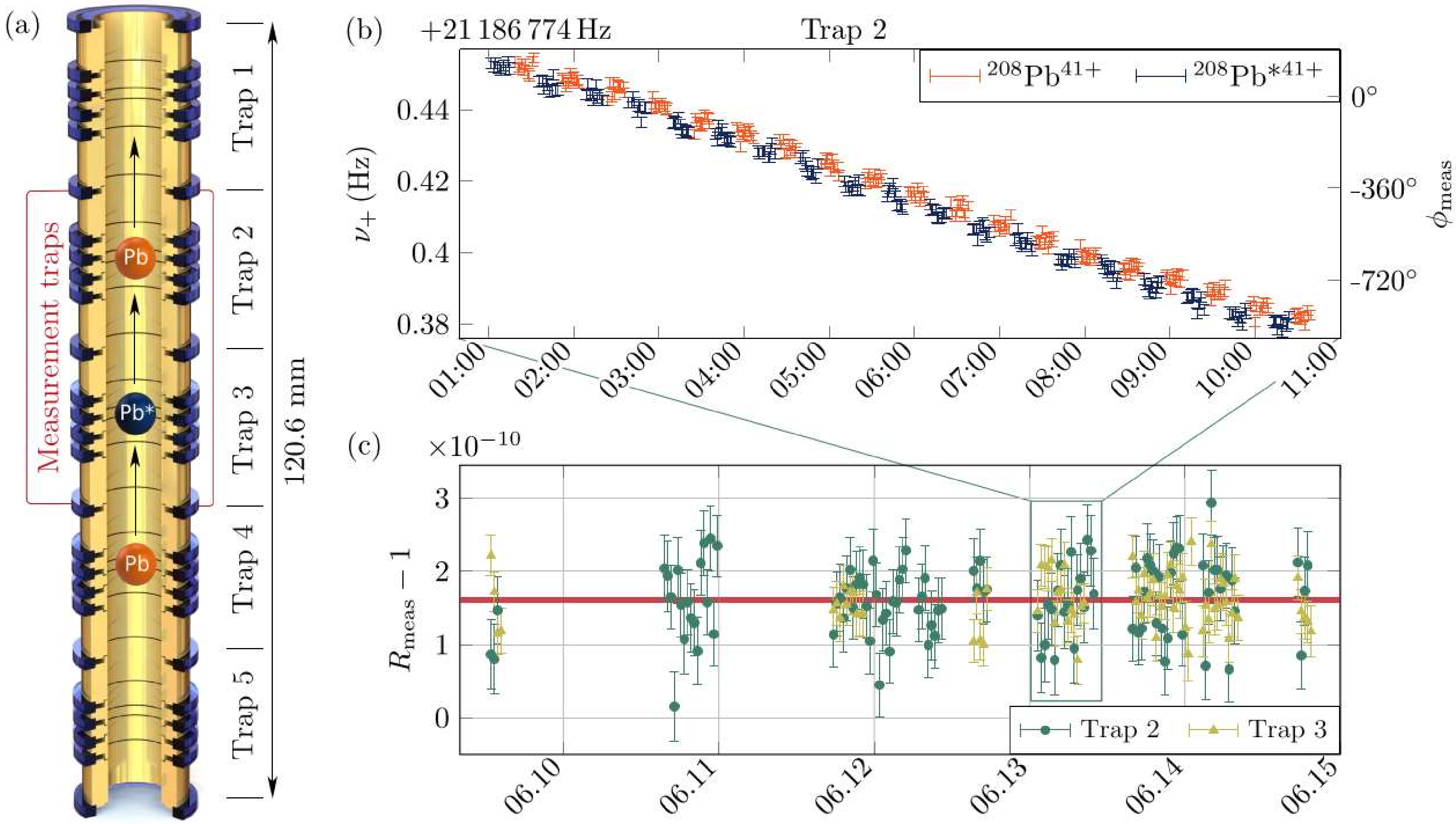
$B_{Indelicato}$ = 207(3) eV

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

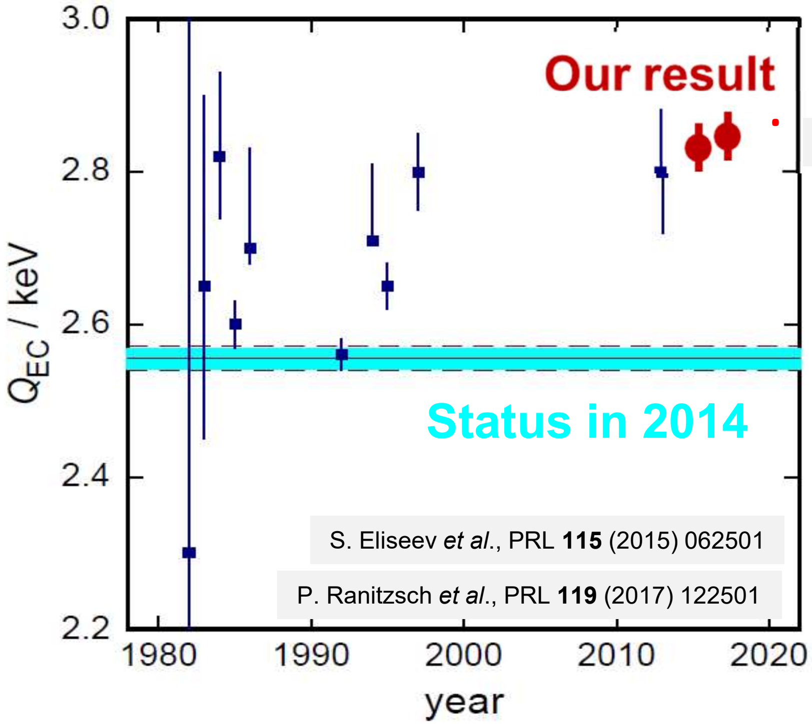
K. Kromer *et al.*, PRL **131** (2023) 223002

The ECHo (^{163}Ho) project

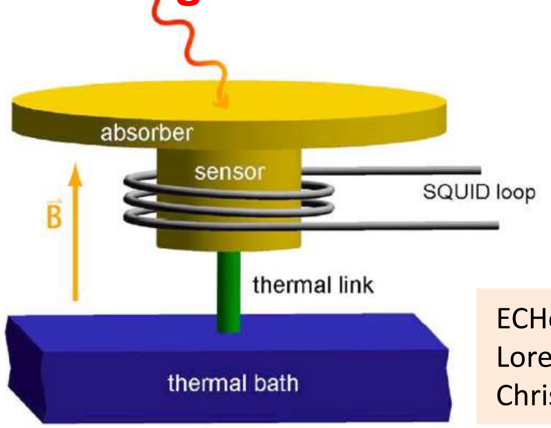
$$^{163}_{67}\mathrm{Ho} + e^- \rightarrow \, ^{163}_{66}\mathrm{Dy}^* + \nu_e$$

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

Q-value of EC in ^{163}Ho

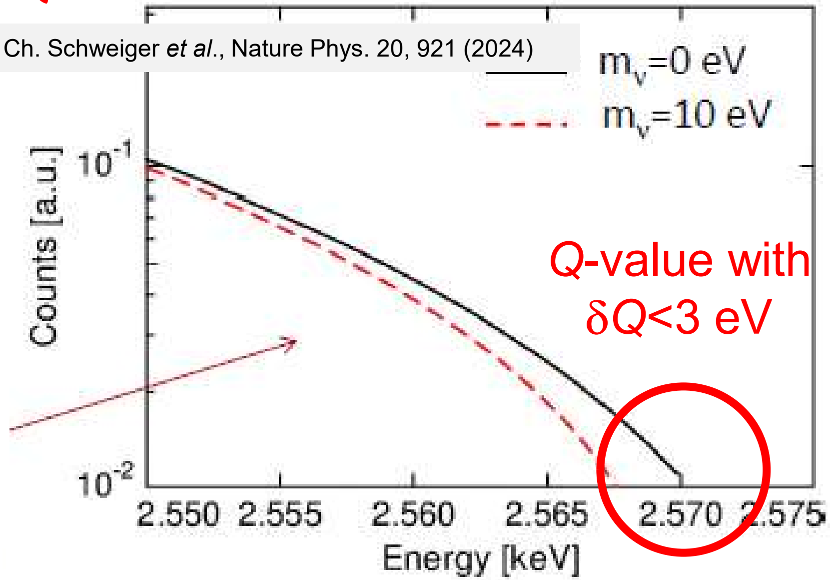


Metallic Magnetic Calorimetry



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss

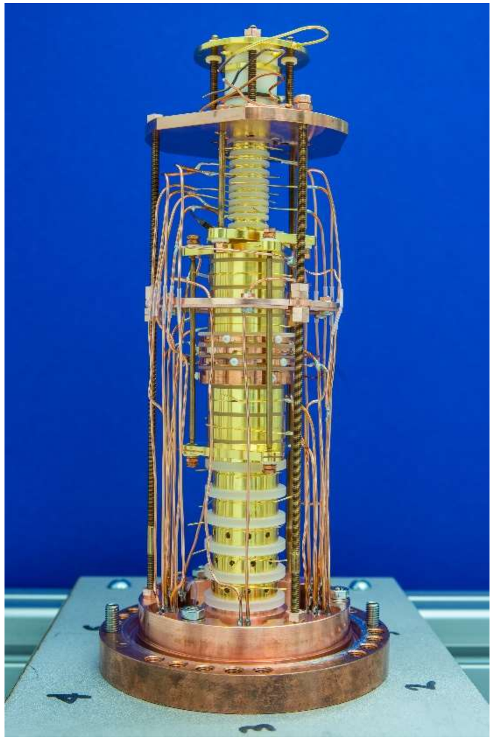
δ*Q*=0.6 eV

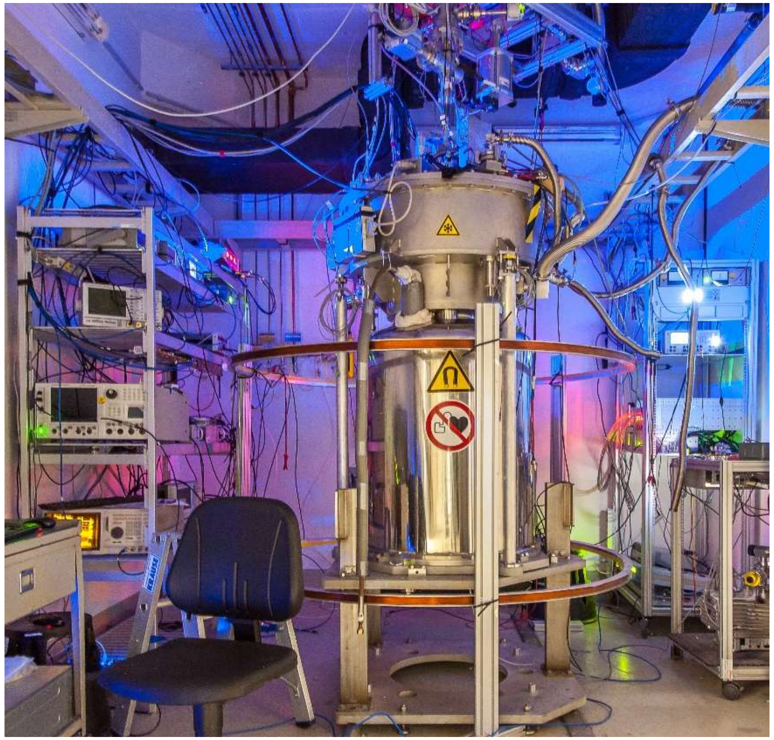


Results III

Tests of fundamental symmetries and physics beyond the SM

Stefan Ulmer



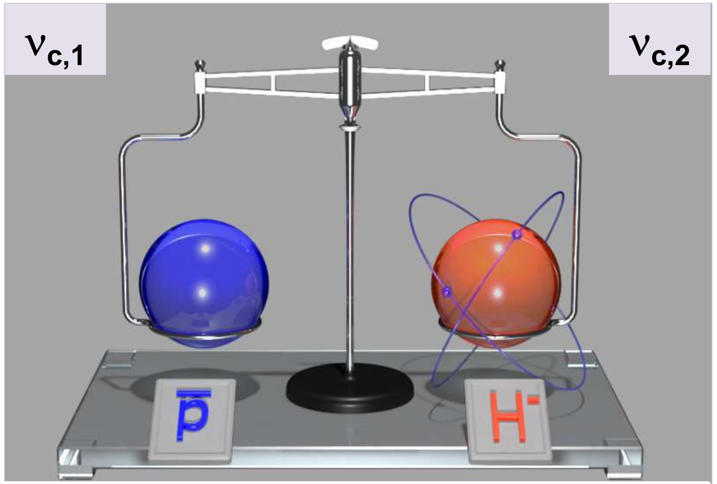


Sven Sturm

Andreas Mooser

ALPHATRAP, BASE, μTex: HHU, MPIK, RIKEN

Comparison of the proton and antiproton



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!

Next steps: sympathetic laser cooling and transport of p-bar

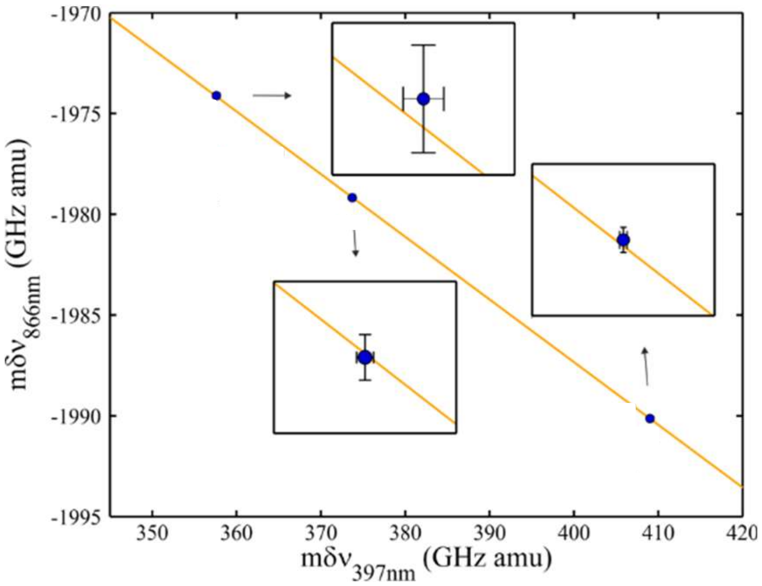
M.Bohman *et al.*, Nature **596** (2021) 514
Ch. Will *et al.*, PRL **133** (2024) 023002
M. Leonhardt *et al.*, Nature **641** (2025) 841

physicsworld TOP 10 BREAKTHROUGH 2021

Probe for new force carriers

Isotope shift spectroscopy: 5th force?

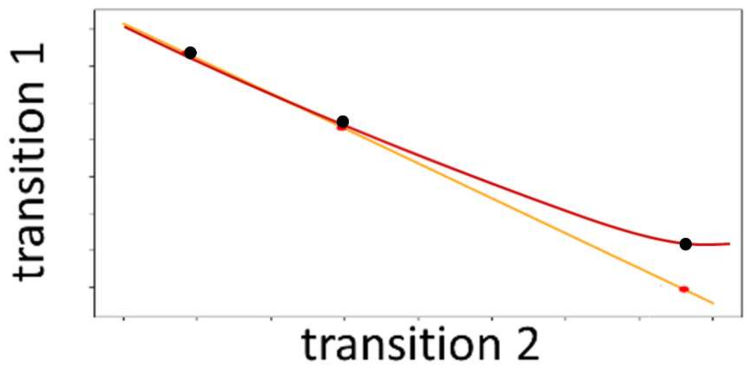
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2 \rangle_{A,A'} + k_i \frac{A-A'}{AA'}$
- use 2 transitions i, j
  ➔ eliminate $\delta\langle r^2 \rangle_{A,A'}$



- 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:

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



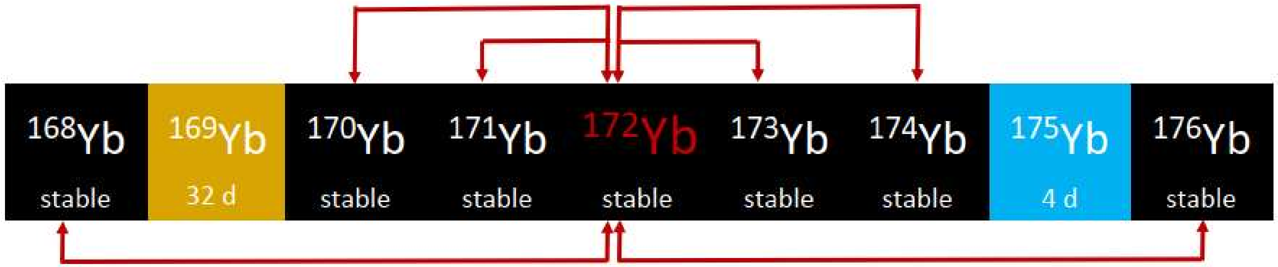
Berengut *et al.*, PRL **120**, 091801 (2018); Ozeri *et al.* (2020)

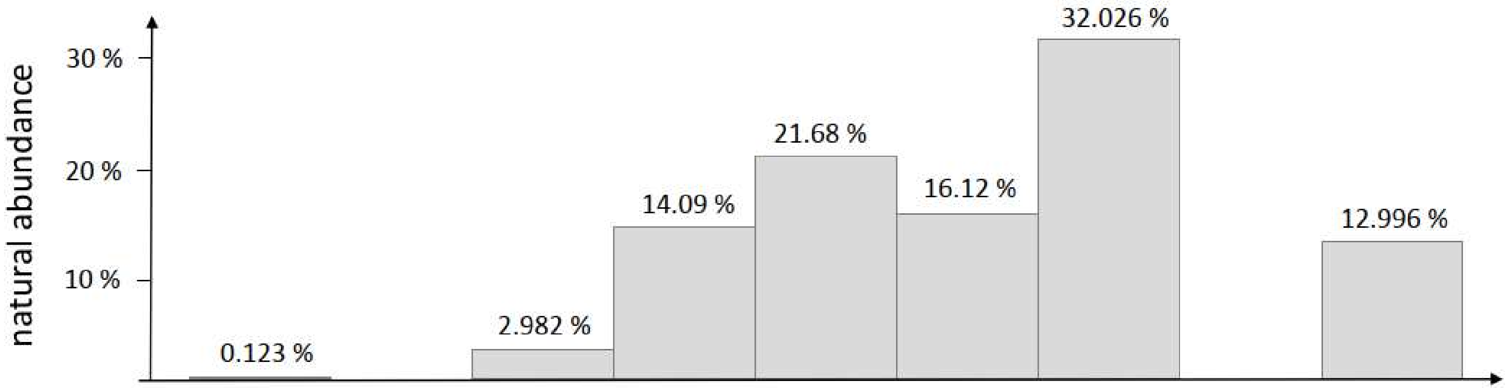
High-precision atomic and nuclear spectroscopy measurements needed!

Yb mass-ratio measurements

Motivation: 5th force search using King-plot analysis in Ca, Sr, Yb

Mass-ratio uncertainties of 10^{-11} and below required!

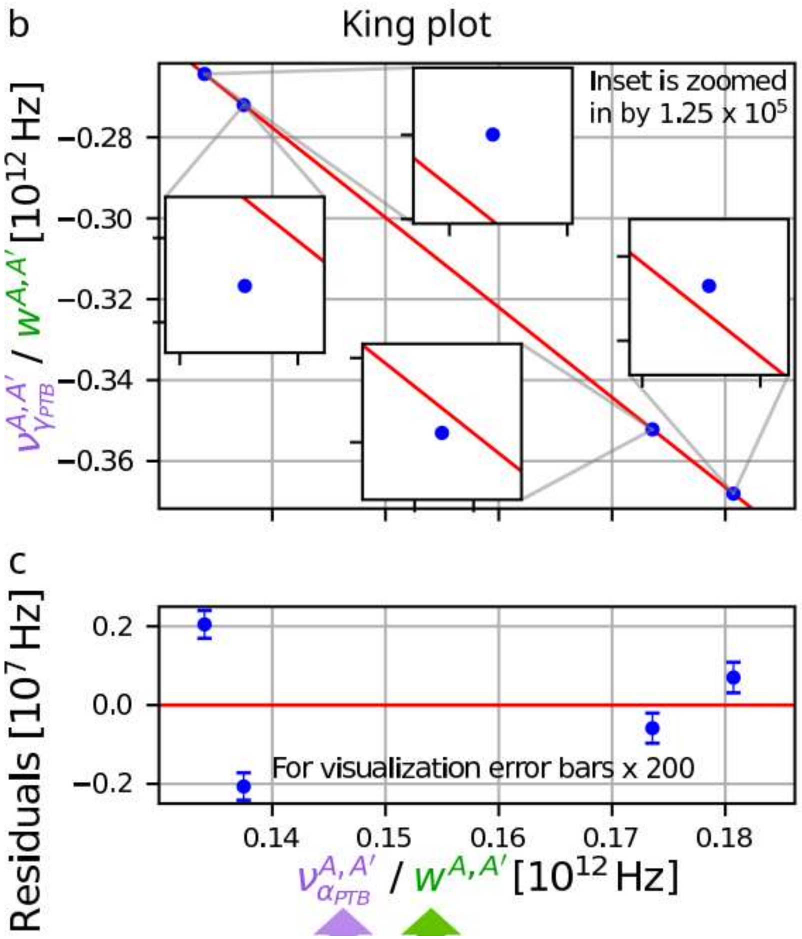




All even-even mass ratios measured. ☺
Relative mass uncertainty: ~$4\cdot10^{-12}$, improvement factor: typically >50

Results from the Yb isotopic chain

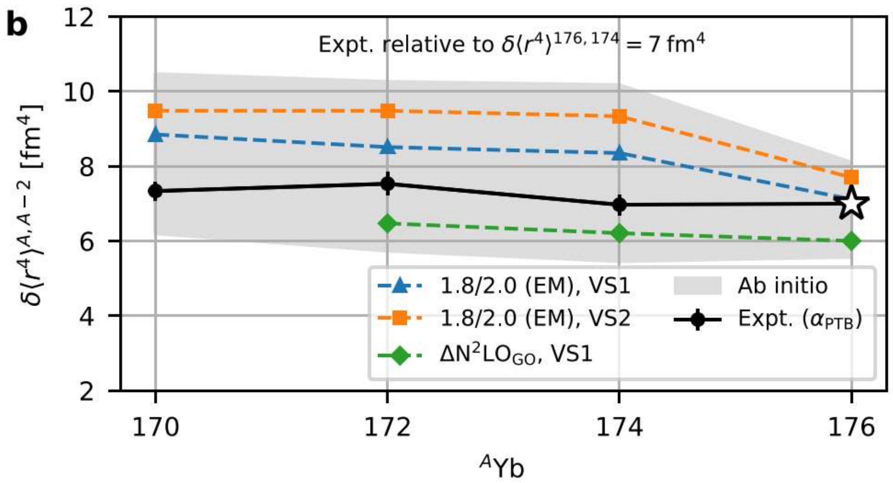
→ a 200σ (!!!) non-linearity observed



→ an additional nuclear structure term prop. to δ<r⁴> is considered

$$\nu_\alpha = F_\alpha \delta\langle r^2\rangle + K_\alpha w + G_\alpha^{(2)} \delta\langle r^2\rangle^2 + G_\alpha^{(4)} \delta\langle r^4\rangle + \frac{\alpha_{NP}}{\alpha_{EM}} D_\alpha h + \ldots .$$

→ 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.

Summary

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

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

European Research Council
Established by the European Commission

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