Precision Tests of Fundamental Interactions and Their Symmetries using Exotic Ions in Penning Traps

- Basics of Penning-trap spectroscopy
- Masses of the building blocks of matter
- Nuclear masses for neutrino physics
- Tests of fundamental symmetries/forces

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

Grenoble, July 20th, 2023

European Research Council
Established by the European Commission

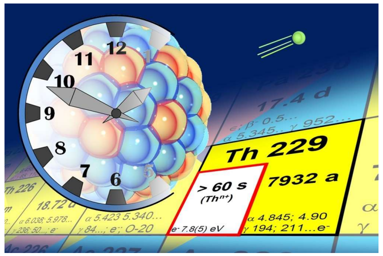
Atomic/nuclear spectroscopy …

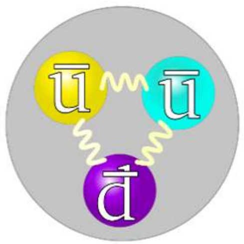
… probes fundamental physics!

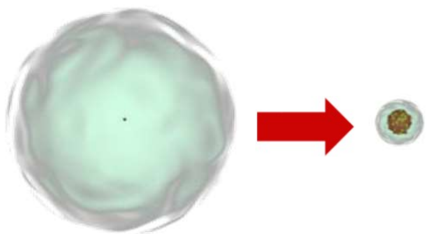
How heavy are the building blocks of matter?

Why is there more matter than anti-matter?

Does QED fail in the strong field regime?

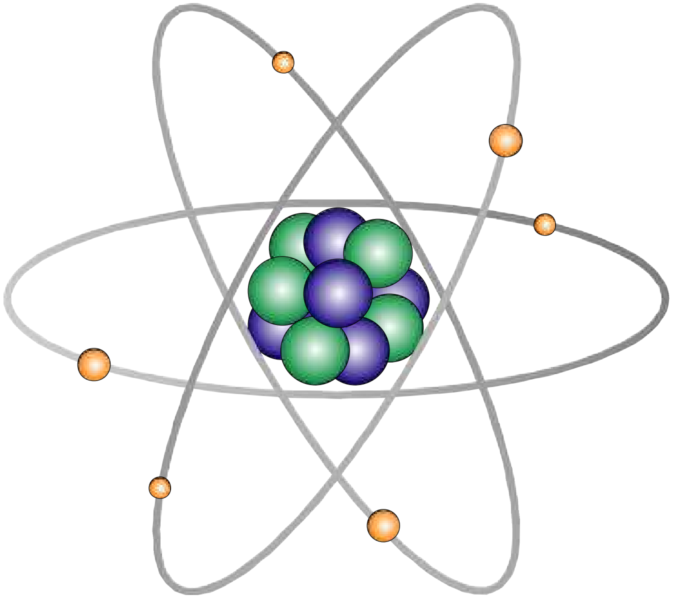


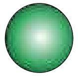
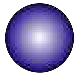




- ➢ radionuclides
- ➢ antimatter
- ➢ highly charged ions

The mass of an atom



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

– binding energy

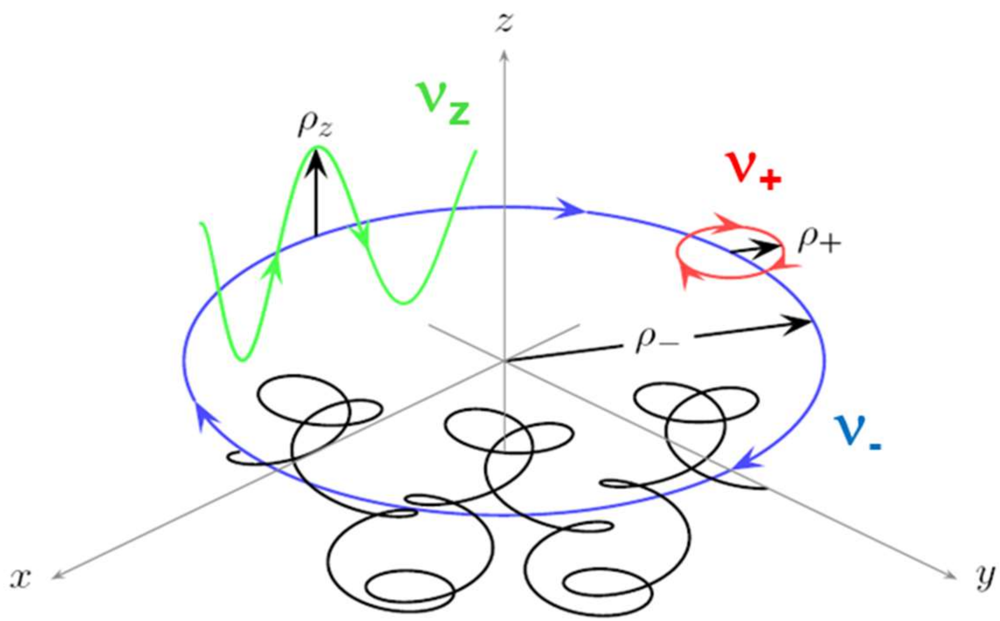
Einstein $E = mc^2$

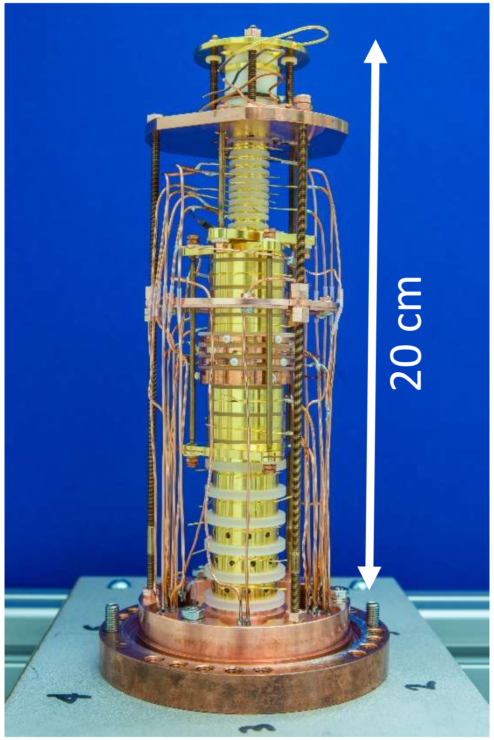
$$m_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

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

$\delta m/m = 10^{-6} - 10^{-8}$

Storage of ions in a Penning trap





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

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

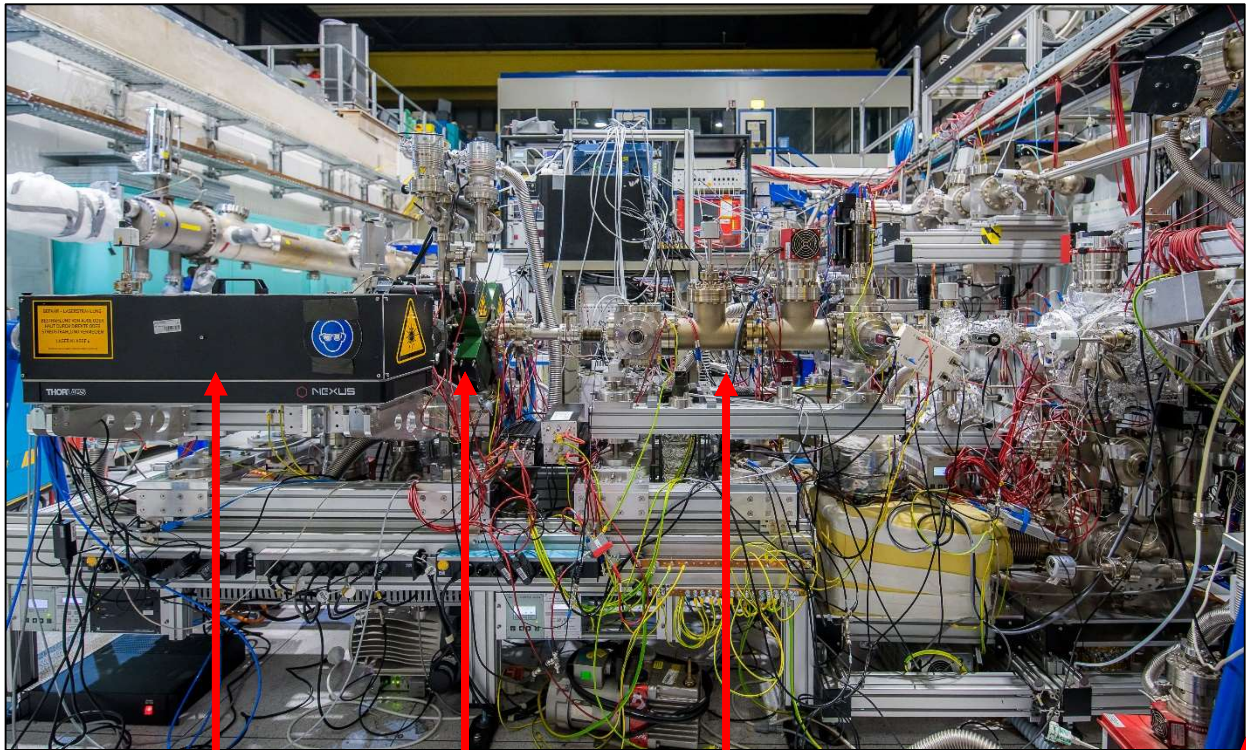
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

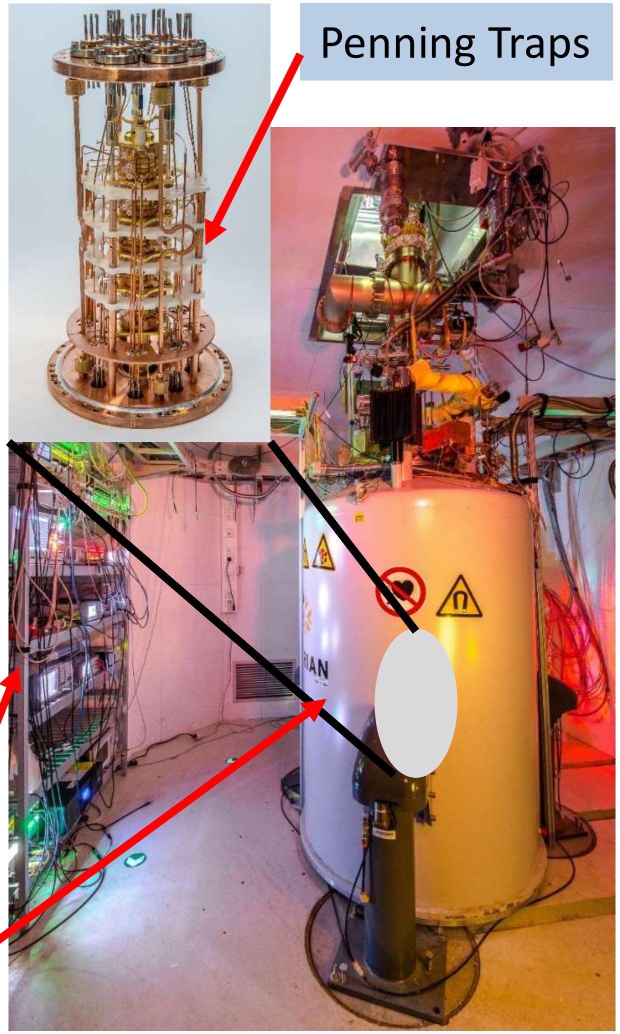
➢ Non-destructive FT-ICR detection technique

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

PENTATRAP – A Penning-trap setup at MPIK

A balance for highly charged ions.





Penning Traps

Laser Ion Source

EBIT

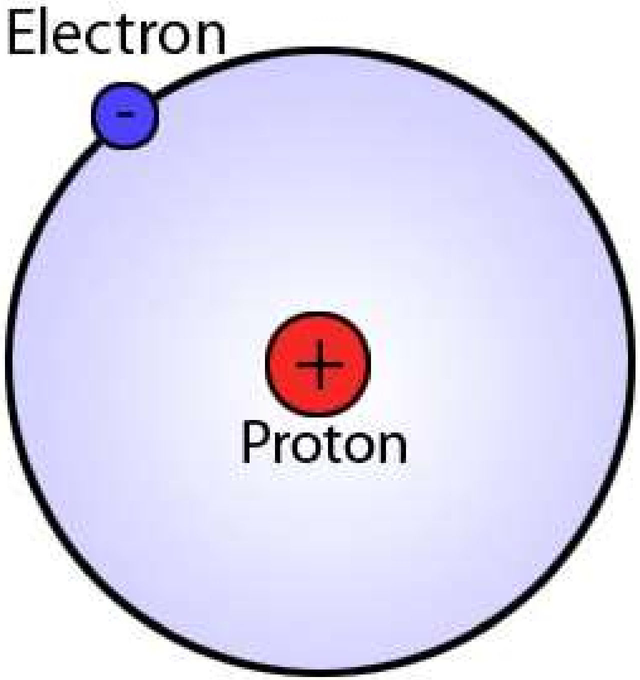
Transfer Beamline

Electronics

Superconducting Magnet

Results I

The masses of the building bocks of matter

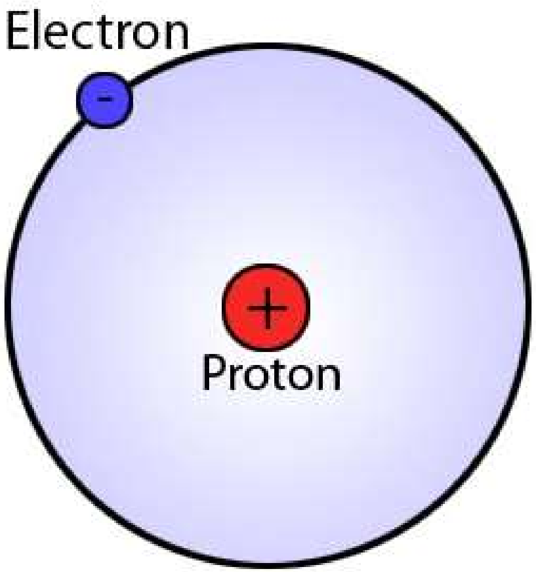


LIONTRAP: MPIK, Uni Mainz, GSI

The building blocks of matter

The atomic mass of the proton and electron

Hydrogen



Electron: previous best value improved by a factor of 13

Proton: previous best value improved by a factor of 3

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

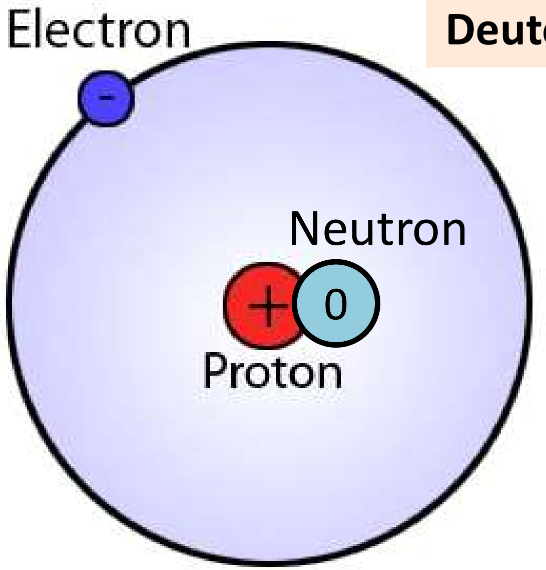
$m_p = 1.007\,276\,466\,583\,(33)$ u

Nature **506** (2014) 467

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

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

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!

$$m_{\mathrm{d}} = 2.013553212535(11)_{\mathrm{stat}}(13)_{\mathrm{sys}}(17)_{\mathrm{tot}}\ \mathrm{AMU} \qquad \frac{\delta m_{\mathrm{d}}}{m_{\mathrm{d}}} = 8.5\times 10^{-12}$$

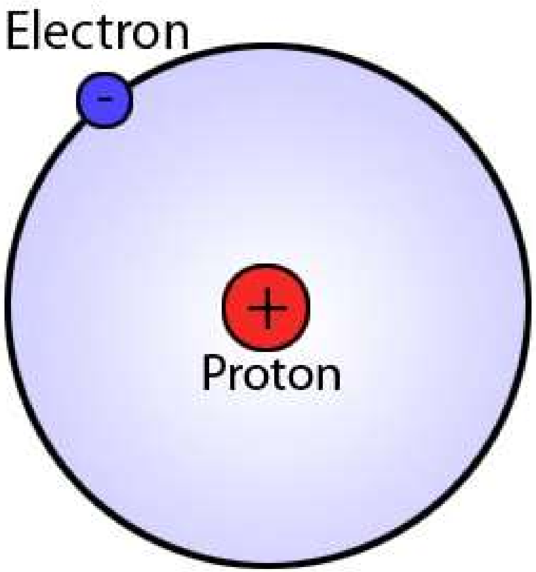
→ Provides access to the mass of the neutron

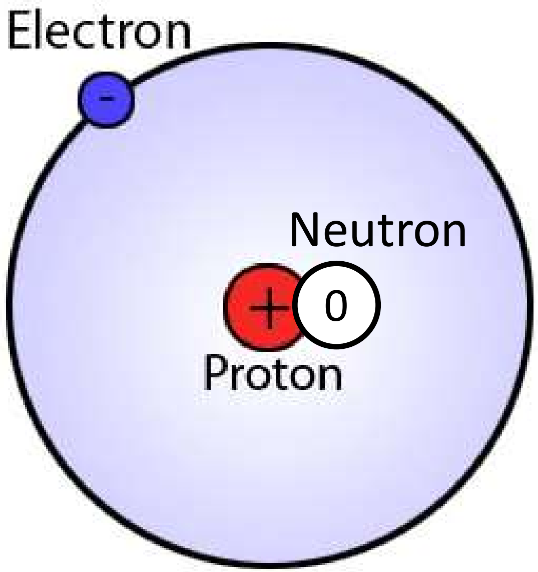
S. Rau *et al.*, Nature **585** (2020) 43

The building blocks of matter

The atomic masses 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

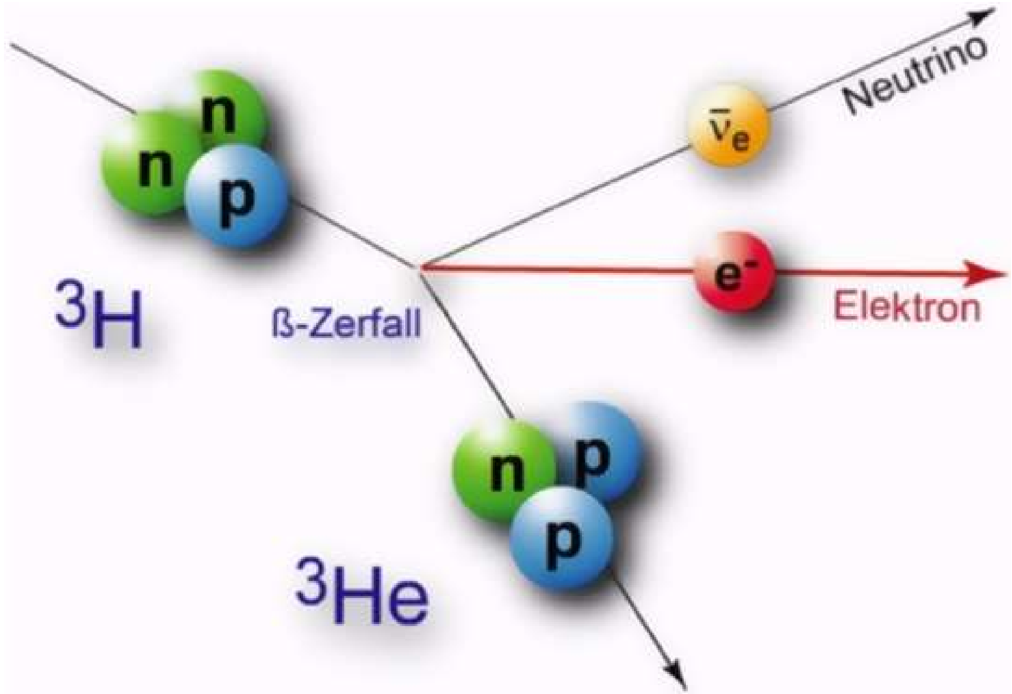
deuteron: previous best value improved by a factor of ~3

m_d = 2.013 553 212 535 (17) u

Nature **585** (2020) 43

Results II

Nuclear masses for neutrino physics



***Q*-values:**

^{3}T → ^{3}He
^{163}Ho → ^{163}Dy
^{187}Re → ^{187}Os

β^- -decay of ^{187}Re

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

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

Measurement principle at PENTATRAP

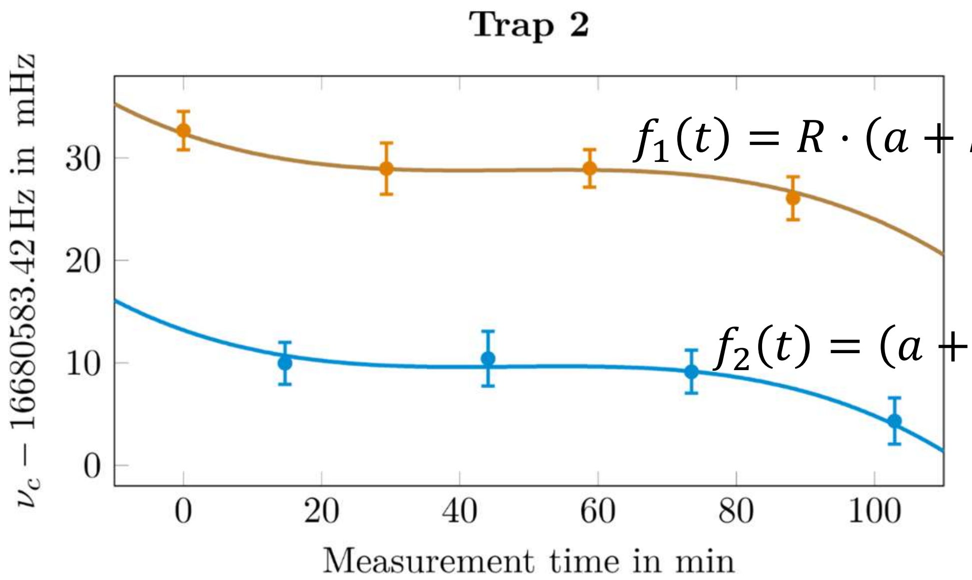
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

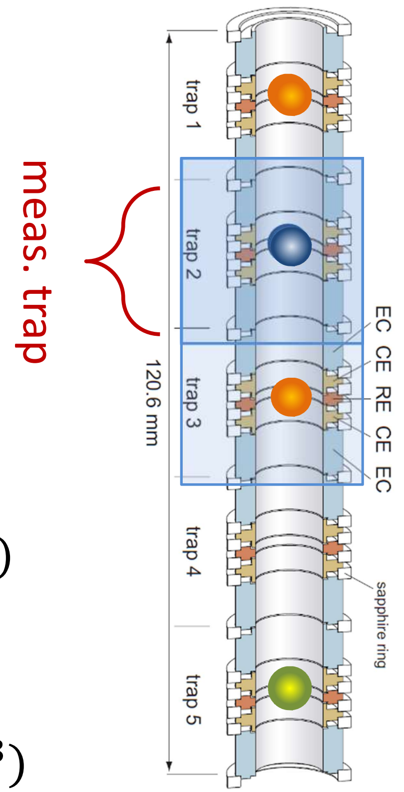
Second ion:

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



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

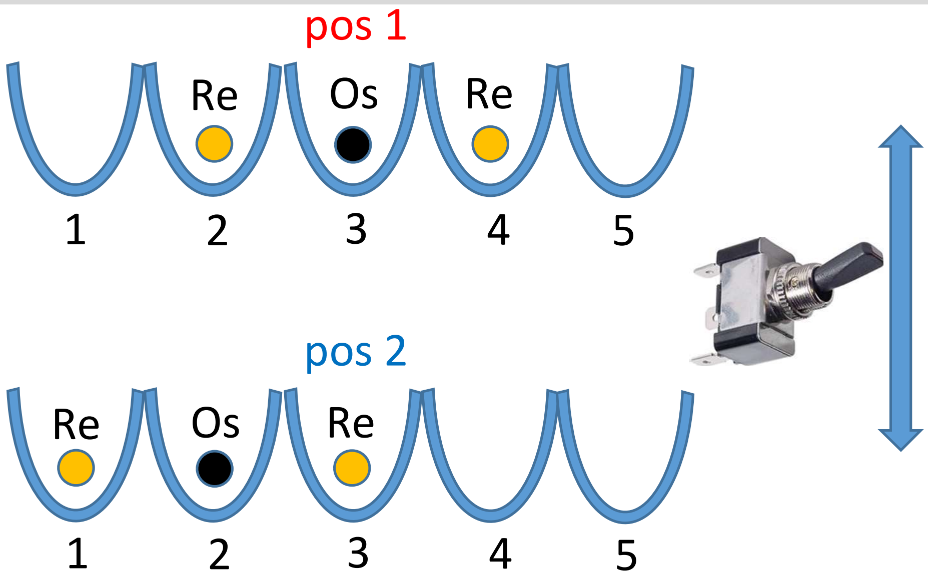
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



Future: Monitoring trap

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

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

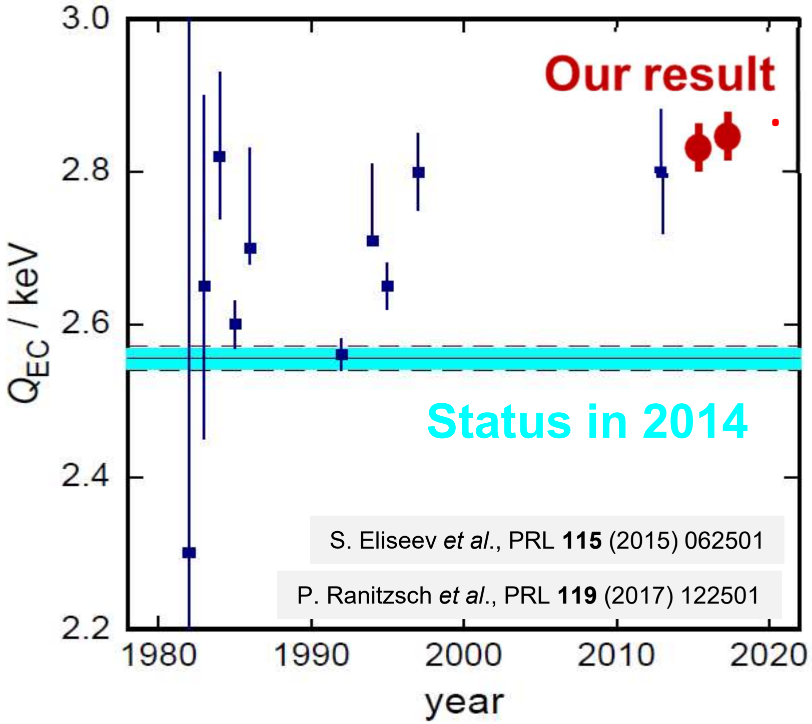
The ECHo (^{163}Ho) project

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

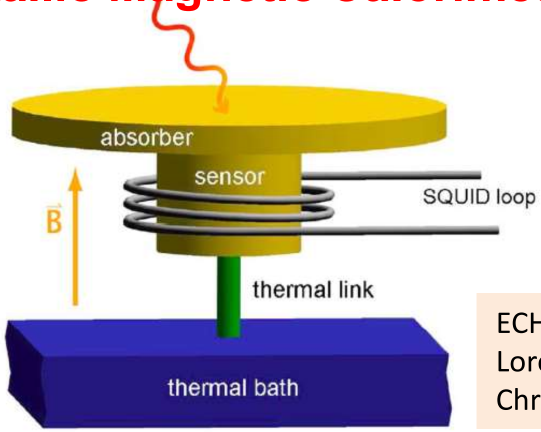
NEUTRONS FOR SCIENCE

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

Q-value of EC in ^{163}Ho

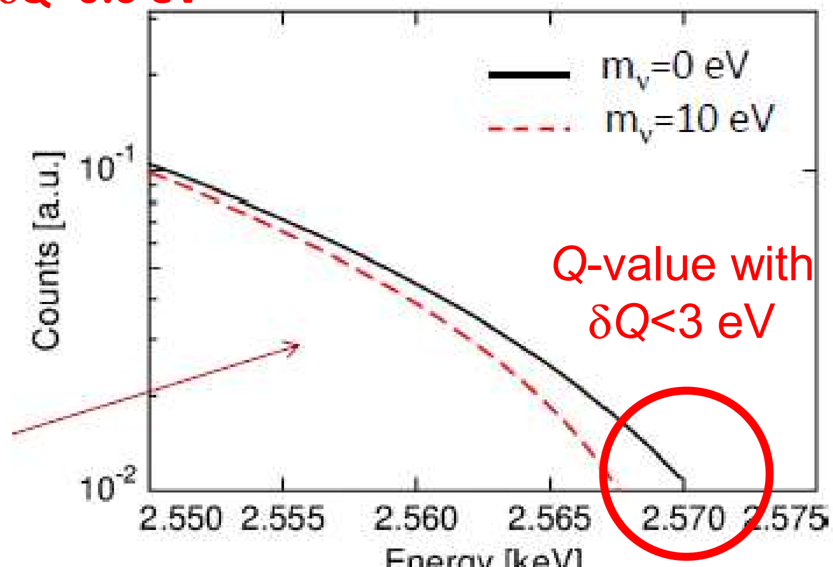


Metallic Magnetic Calorimetry



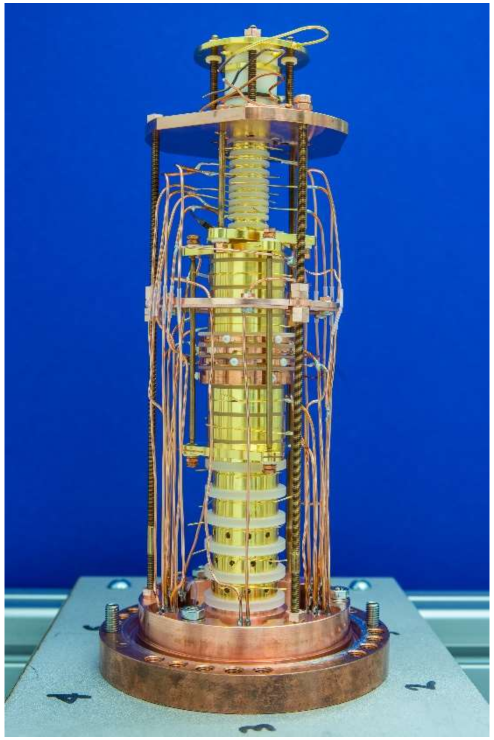
ECHo-Collaboration:
Loredana Gastaldo
Christian Enss

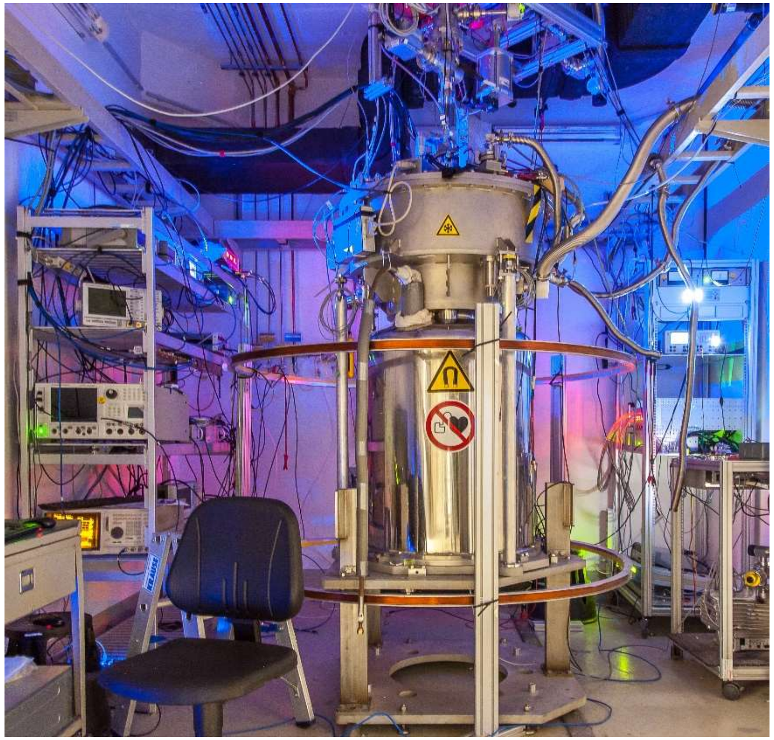
δ*Q*=0.6 eV



Results III

Tests of fundamental interactions and their symmetries





ALPHATRAP, BASE, PENTATRAP: MPIK, PTB, RIKEN

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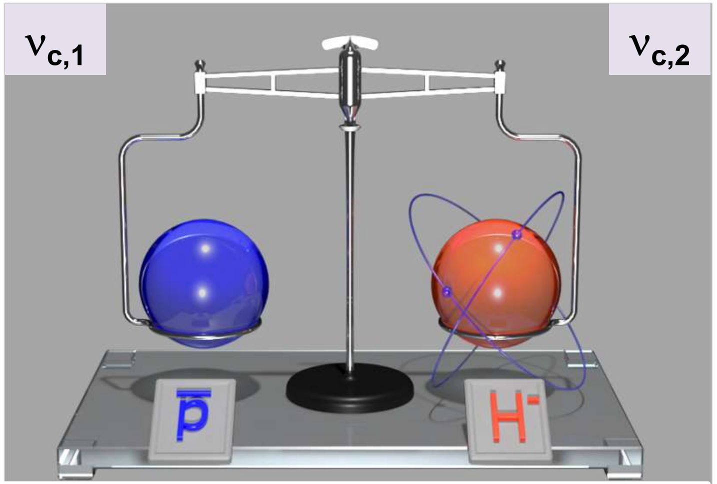
Established by the European Commission

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

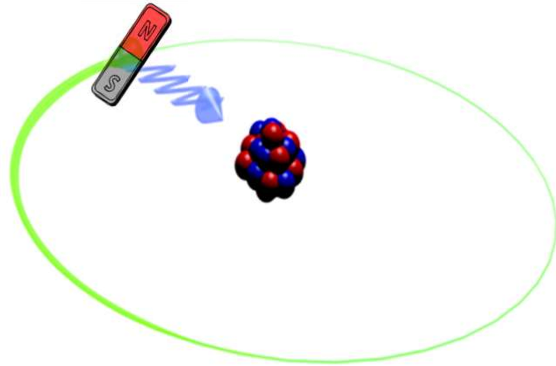
It is not that easy!

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

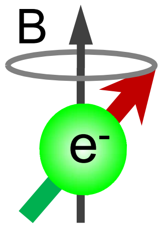
Most stringent test of CPT symmetry in the baryon sector!

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

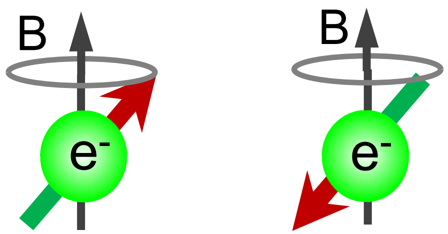


Electron acts like a spinning top in the magnetic field with frequency ω_L

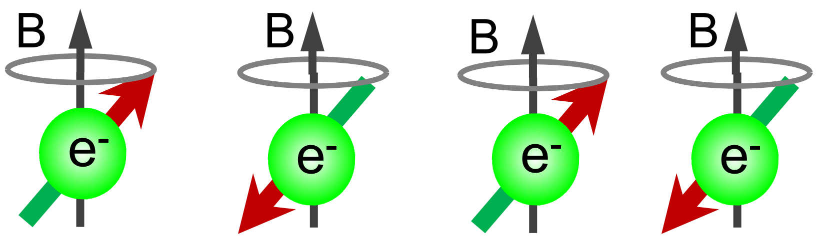
$$\omega_L = \frac{g}{2}\frac{e}{m_e}B$$

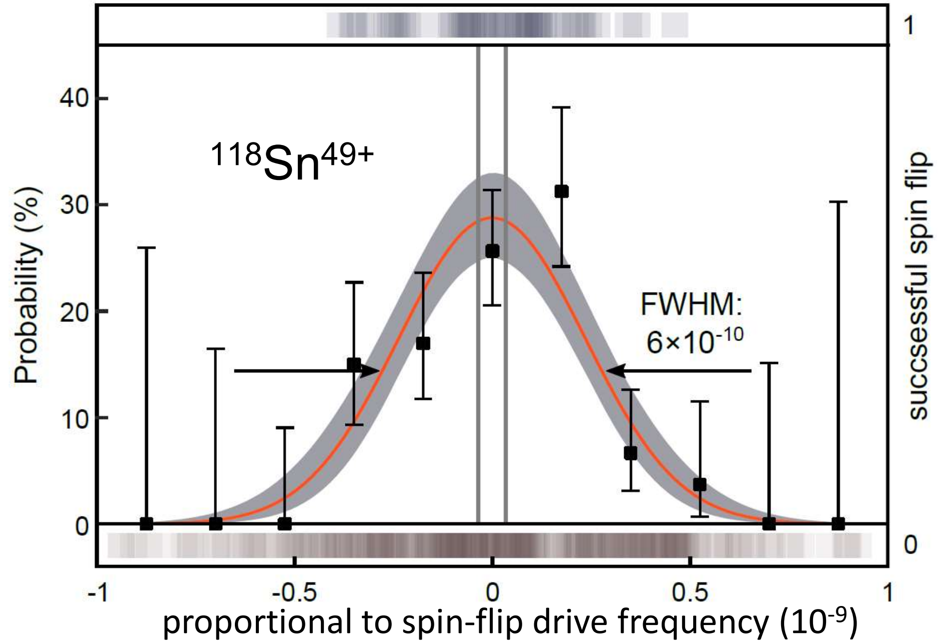
Electron can be in spin-up or spin-down state with transition frequency ω_L

spin-up spin-down



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!

Theory colleagues: Harman, Keitel, Oreshkina, Yerokhin

T. Sailer *et al.*, Nature **606**, 479 (2022)
F. Heiße *et al.*, Phys. Rev. Lett. **submitted** (2023)
J. Morgner *et al.*, Nature **in print** (2023)

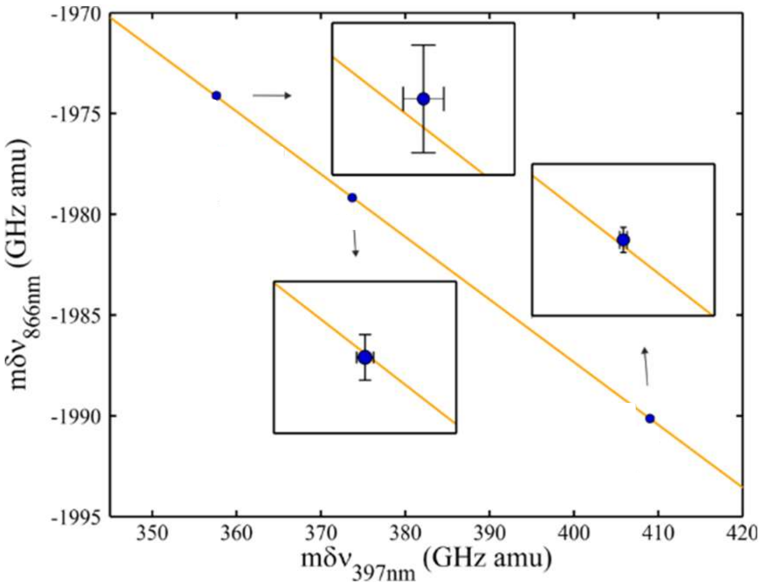
Results IV

Nuclear masses for fifth force search

Probe for new force carriers

Isotope shift spectroscopy: 5th force?

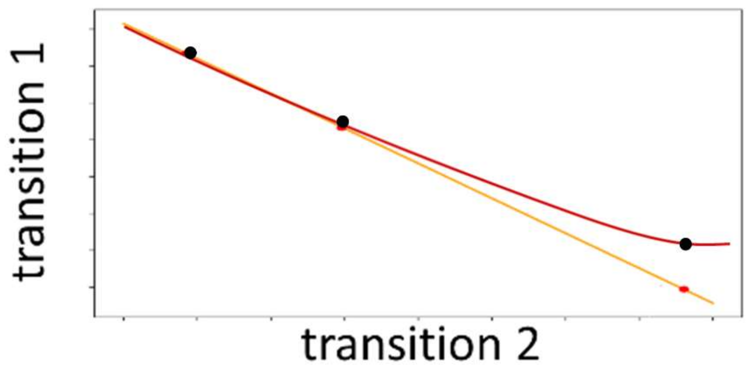
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'}$
- use 2 transitions i, j
  ➔ eliminate $\delta\langle r^2\rangle_{A,A'}$



- new force mediated through scalar field with 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)

High-precision atomic and nuclear spectroscopy measurements needed!

Dark matter and the 5th force

Isotope shift spectroscopy

$$\Delta\nu_i = C_1 \cdot \frac{m_1 - m_2}{m_1 m_2} + C_2 \cdot \Delta\nu_j + \text{[higher–order SM effects + LDM bosons]}$$

$$\nu_i(\text{isotope}_1) - \nu_i(\text{isotope}_2) \equiv \Delta\nu_i$$

one needs elements with many even-even isotopes
and quadrupole/octupole (narrow optical) transitions:

$^{168,170,172,174,176}Yb$	I. Counts et al., PRL 125, 123002 (2020) K. Ono et al., arXiv: 2110.13544v2 J. Hur et al., arXiv: 2201.03578v2 N.L. Figueroa et al., PRL 128, 073001 (2022)
$^{40,42,44,46,48}Ca$	C. Solaro et al., PRL 125, 123003 (2020) F.W. Knollmann et al., PRA 100, 022514 (2019)
$^{84,86,88,90}Sr$	T. Manowitz et al., PRL 123, 203001 (2019) H. Miyake et al., PRR 1, 033113 (2019)

(maybe) near future

$$\delta(\Delta\nu_i) \approx 100 \text{ mHz}$$

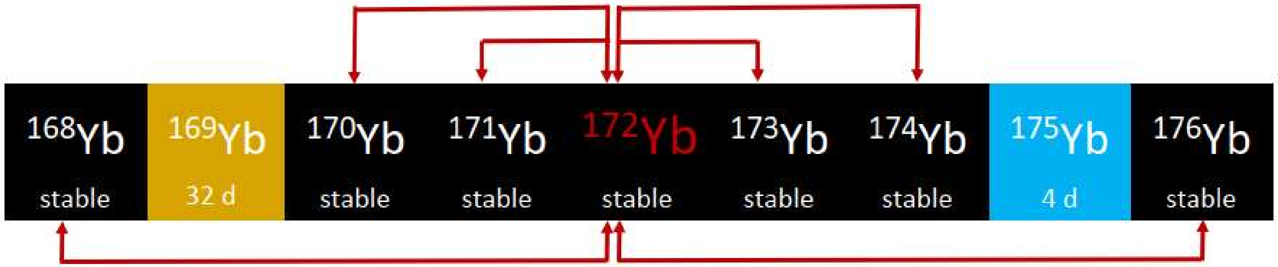
↕

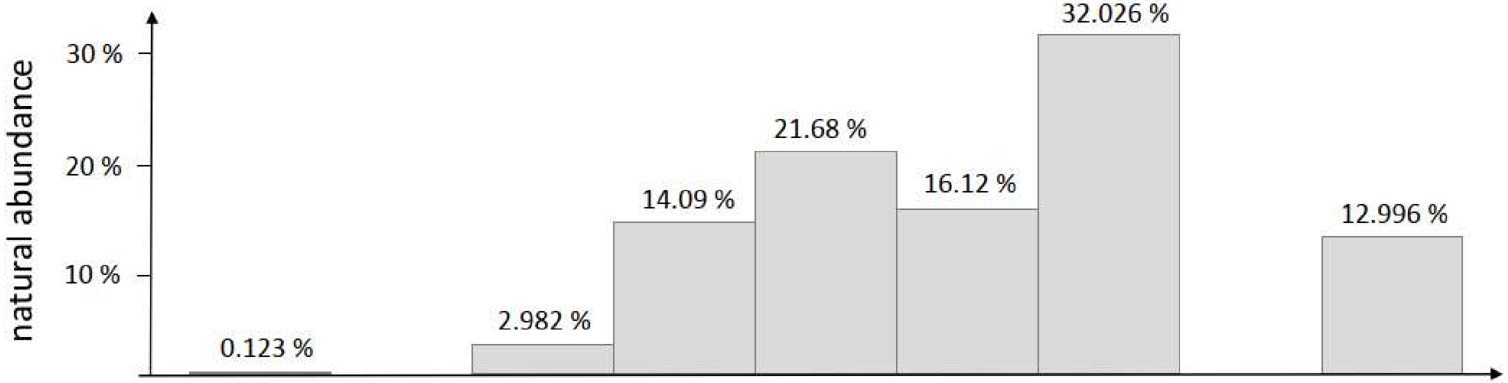
$$\delta\left(\frac{m_1}{m_2}\right) \approx 5 \cdot 10^{-1}$$

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

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 ***IMPRS-PTFS*** ***IMPRS-QD*** ***ERC AdG 832848 - FunI*** ***DFG***