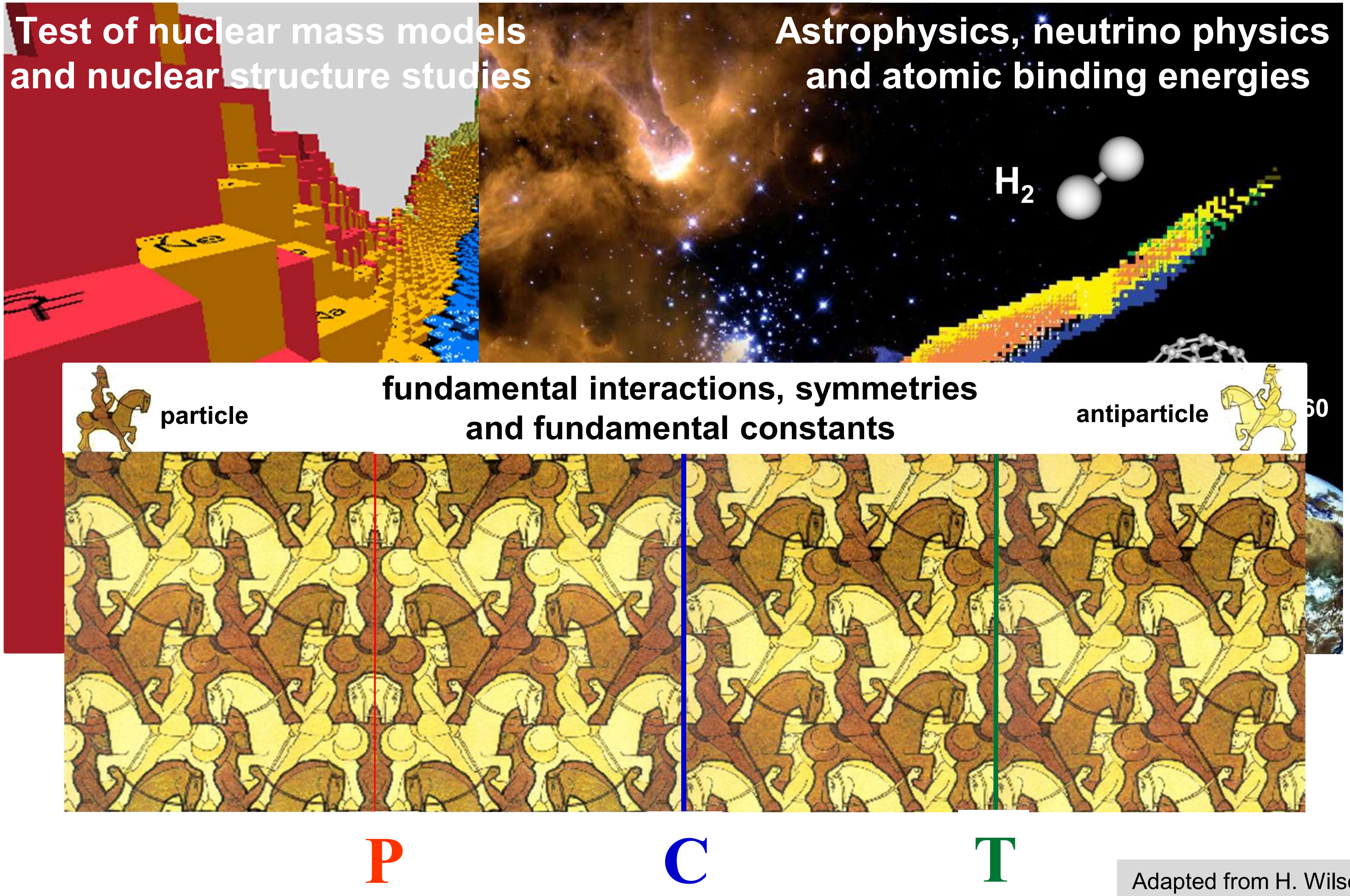
Atomic Physics Precision Experiments with Penning Traps

- Basics of Penning-trap spectroscopy
- Nuclear masses and *g*-factors
- Atomic binding and excitation energies

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

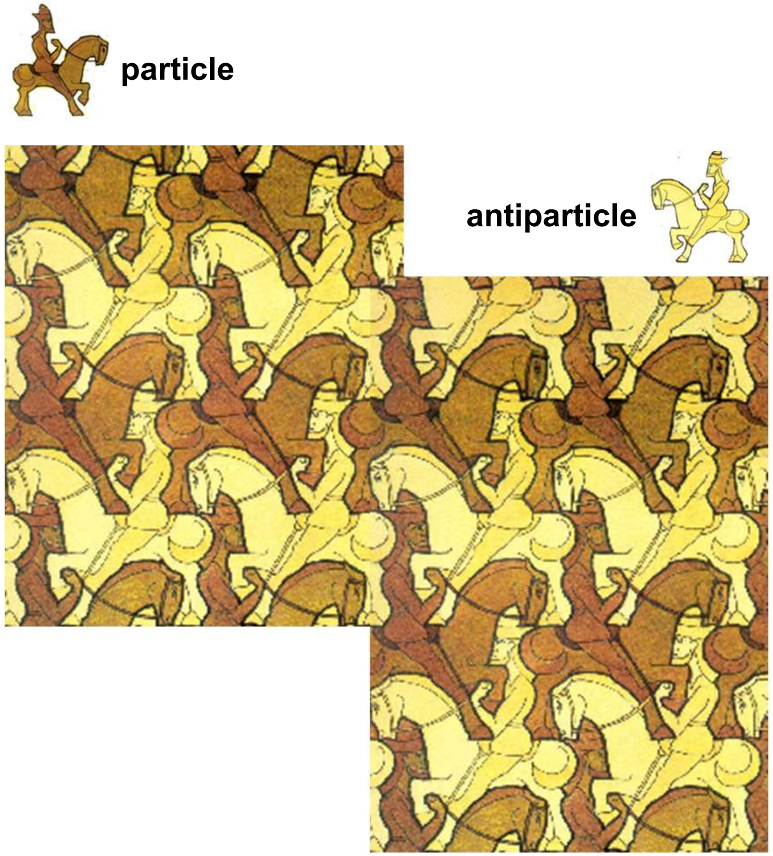
Mainz, Sep 1st, 2021

Motivation – Fields of applications



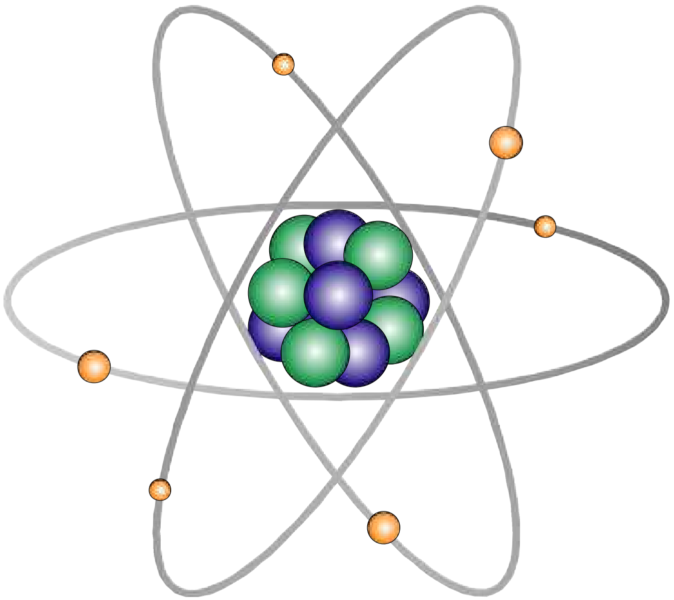
Adapted from H. Wilschut

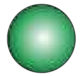
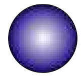
Fundamental symmetries



CPT symmetry is recognized to be a fundamental property of physical laws.
(1954 Gerhart Lüders,
1955 Wolfgang Pauli)

The mass of an atom



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

– binding energy

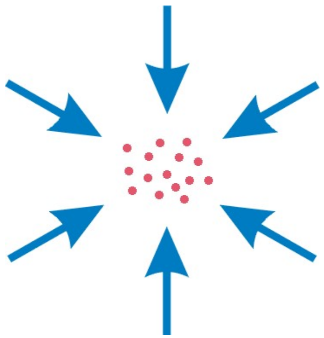
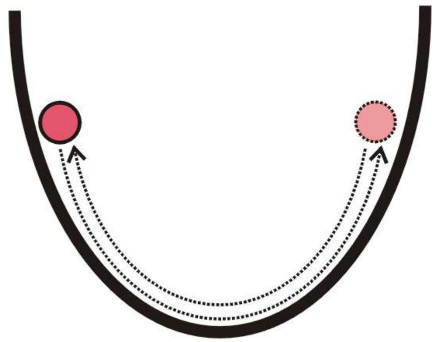
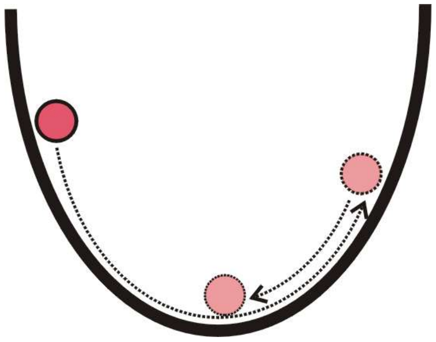
Einstein $E = mc^2$

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

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

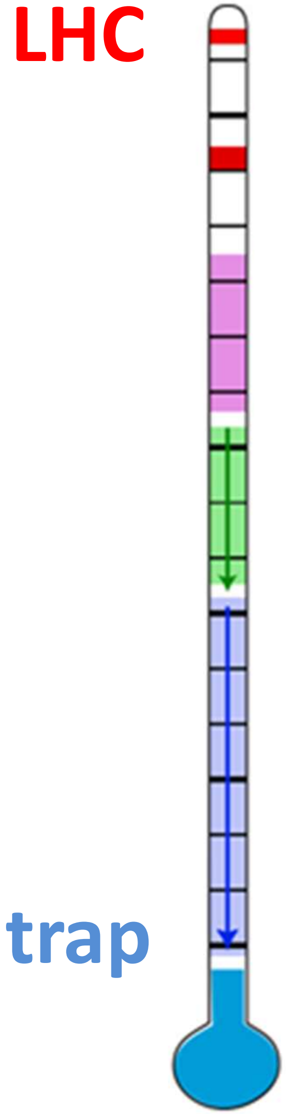
$\delta m/m = 10^{-6} – 10^{-8}$

Storage and cooling of ions

Radial force	Harmonic potential	Cooling
		
electric fields magnetic fields light fields	characteristic oscillation frequency ↓ pendulum clock	damping of oscillation amplitudes minimization of imperfections

- ➢ single ion sensitivity
- ➢ “infinite” storage time
- ➢ frequency measurements

Energy and precision regimes

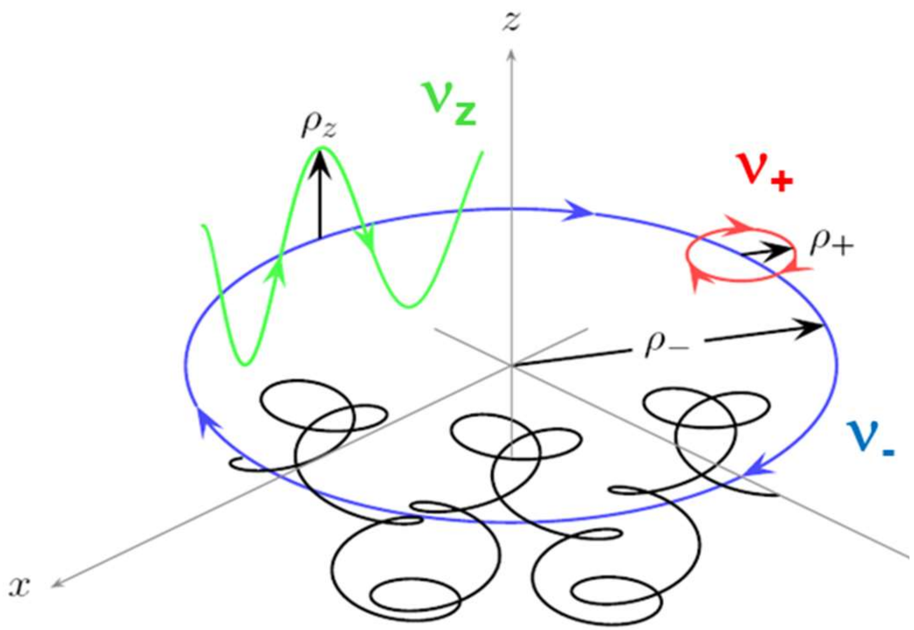


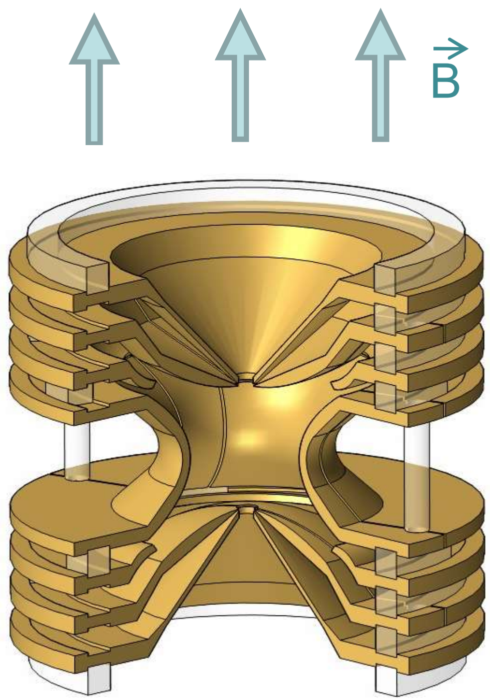
energy	temperature
1 TeV	10^{16} K
1 GeV	10^{13} K
1 MeV	10^{10} K
1 keV	10^{7} K
1 eV	10^{4} K
1 meV	10 K
1 μeV	0.01 K (ca. -273°C)

Energy frontier

Precision frontier

Storage of ions in a Penning trap





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

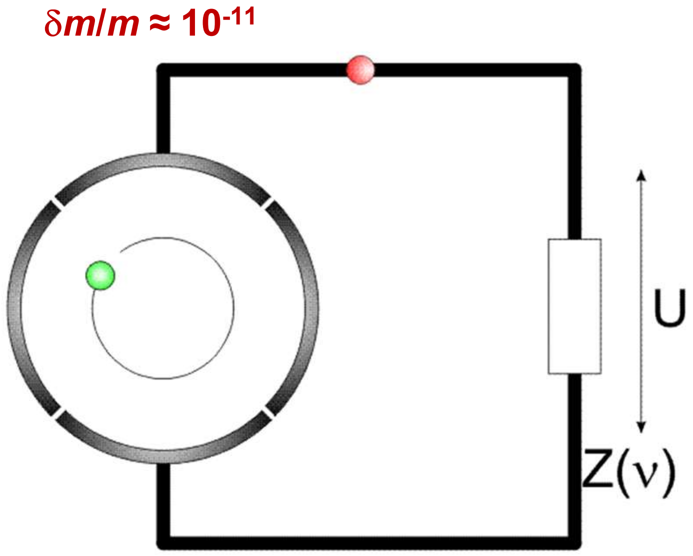
$$\nu_c = qB / (2\pi m_{ion})$$

Brown-Gabrielse invariance theorem

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

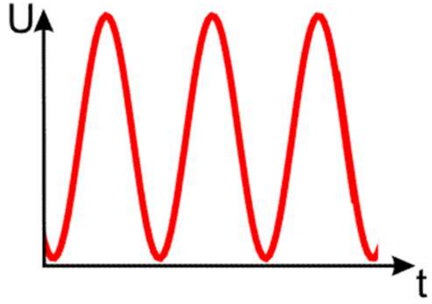
L.S. Brown, G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986).

Non-destructive detection technique



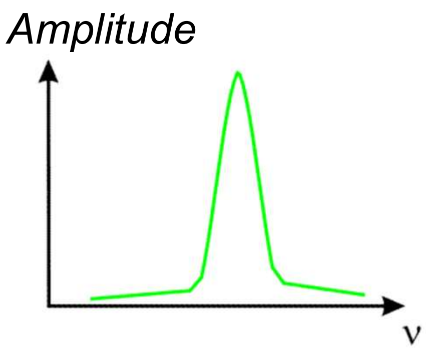
S. Sturm *et al.*, Phys. Rev. Lett. 107, 143003 (2011)

ion signal

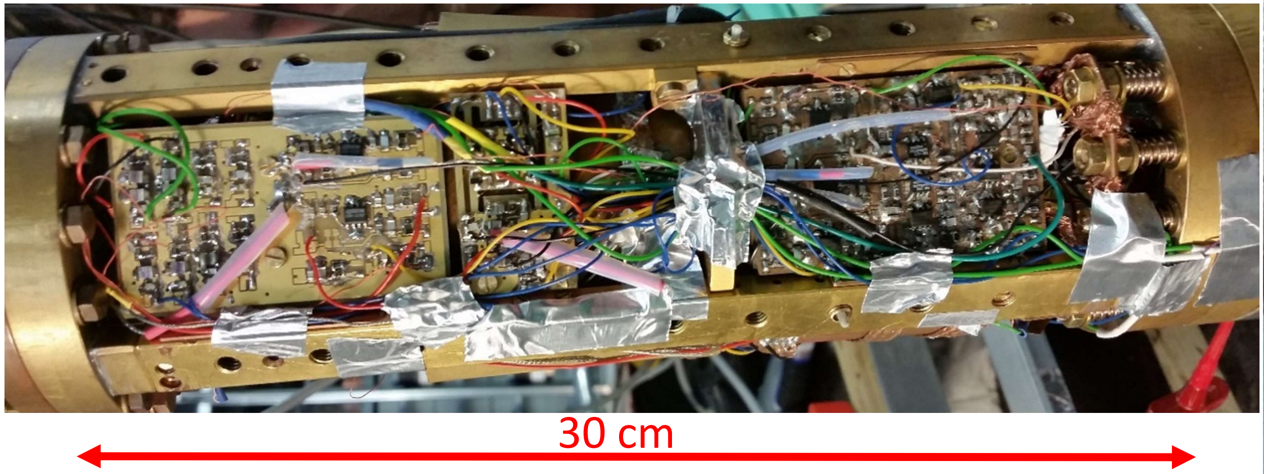


very small signal ~fA

mass/frequency spectrum

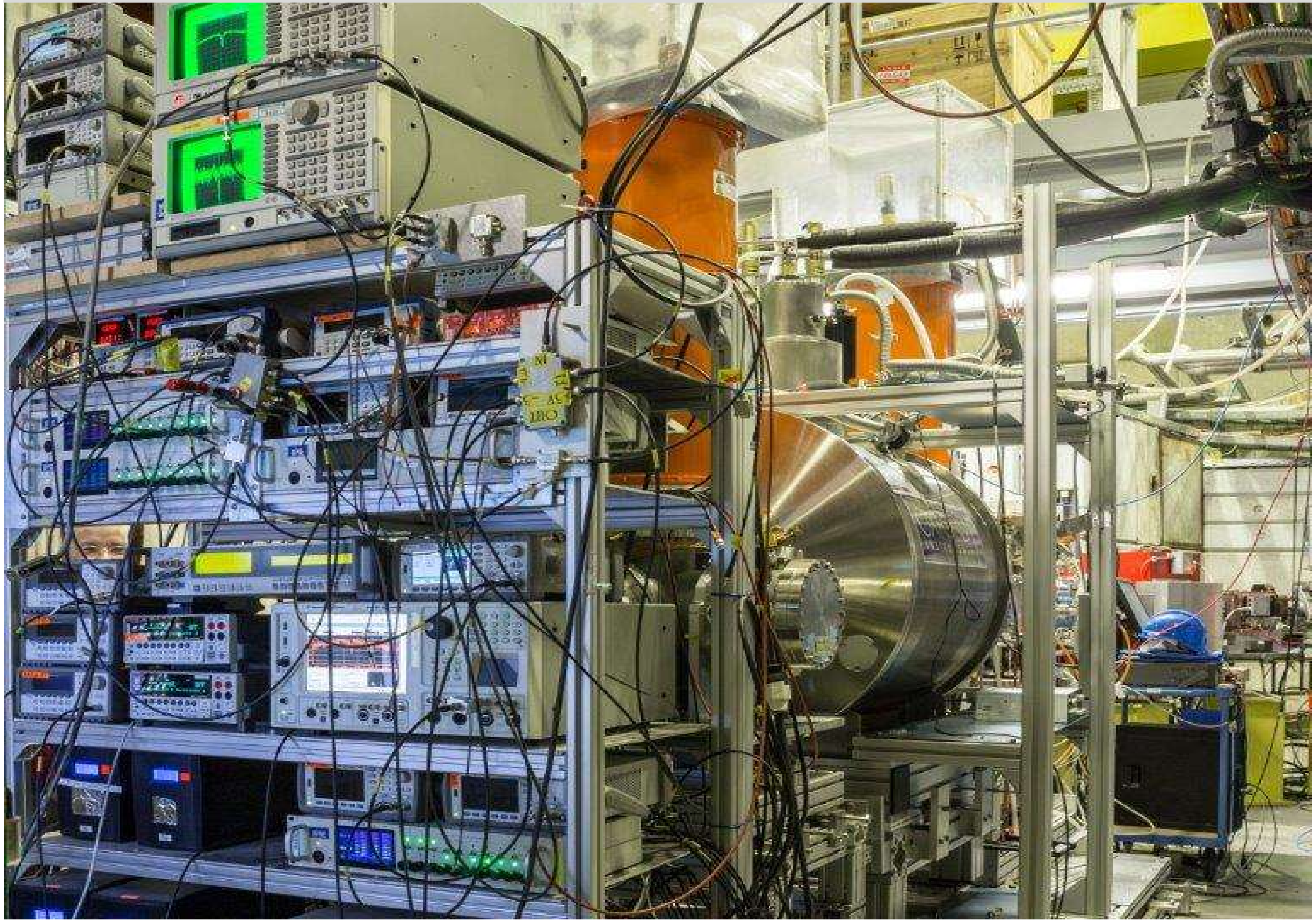


Fourier transformation



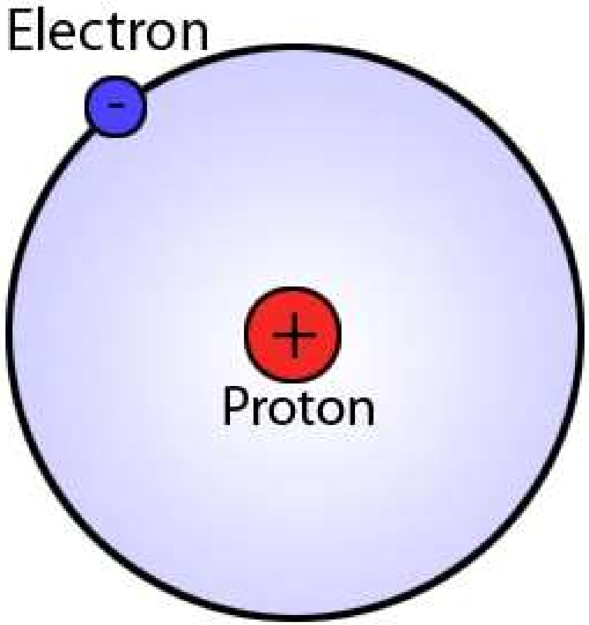
BASE – A Penning-trap setup at CERN

A balance for protons and antiprotons.



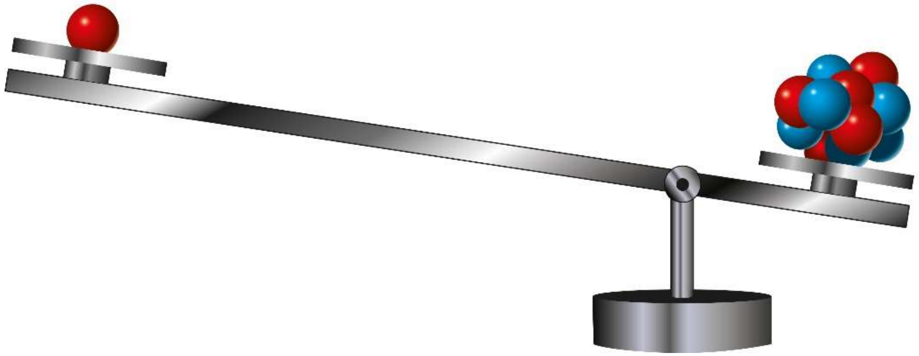
Atomic masses I

The mass of the proton and electron



A. Mooser, W. Quint, S. Sturm, S. Ulmer, G. Werth

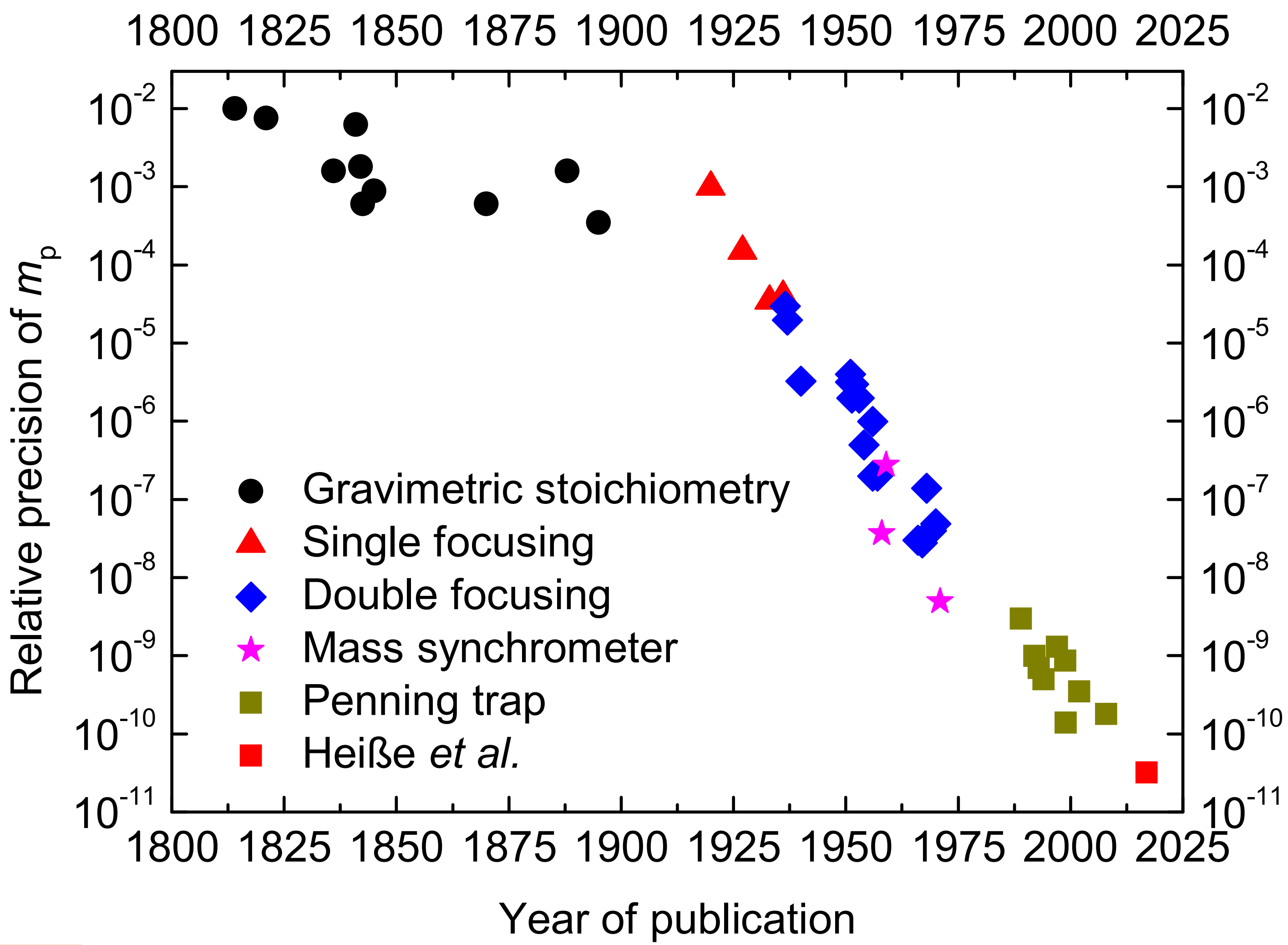
The atomic mass of the proton



$$m_p = \frac{1}{6}\frac{\nu_c(^{12}C^{6+})}{\nu_c(p)} m(^{12}C^{6+})$$

F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

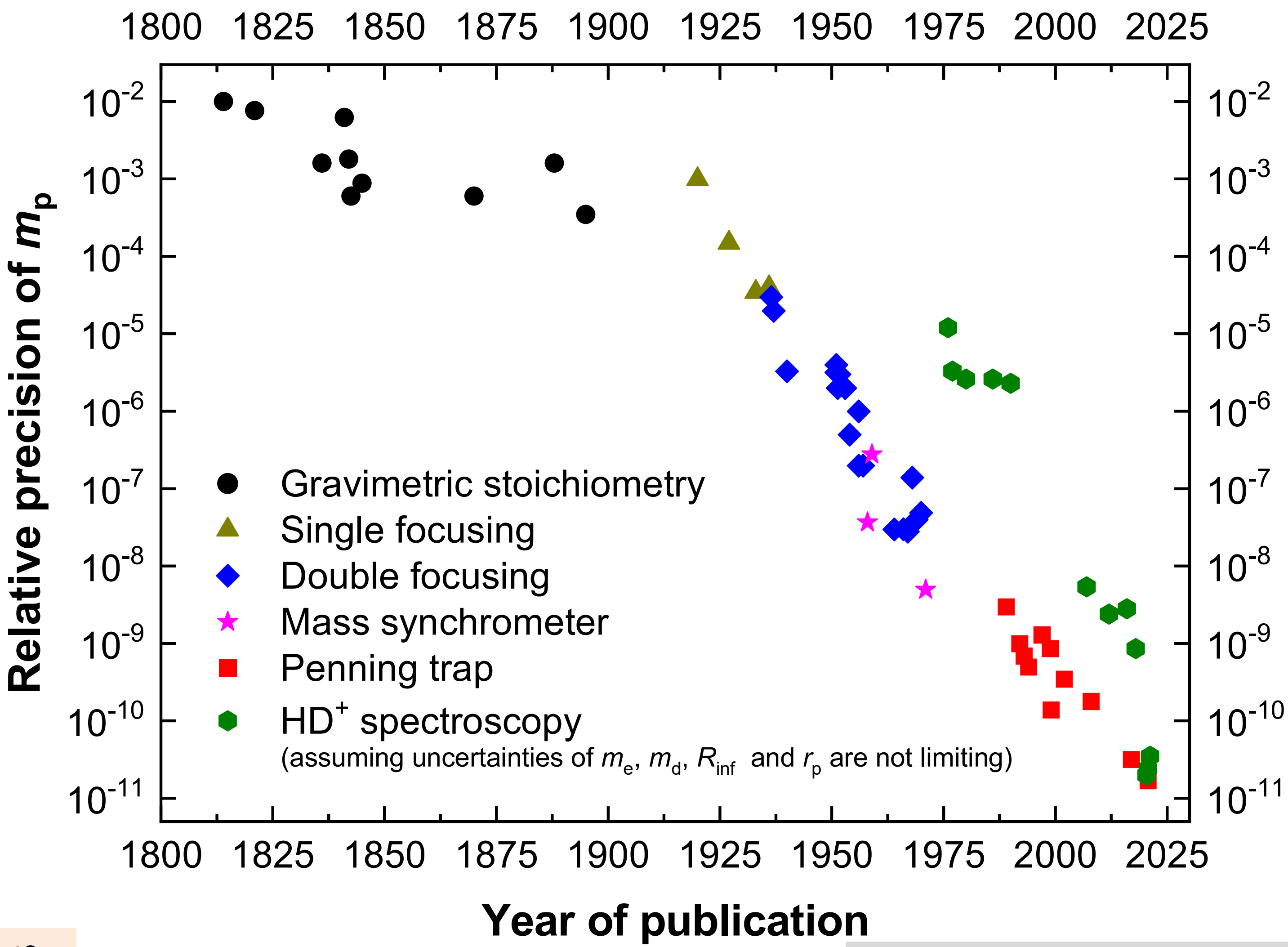
The atomic mass of the proton



Courtesy F. Heiße

F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

The atomic mass of the proton



Courtesy F. Heiße

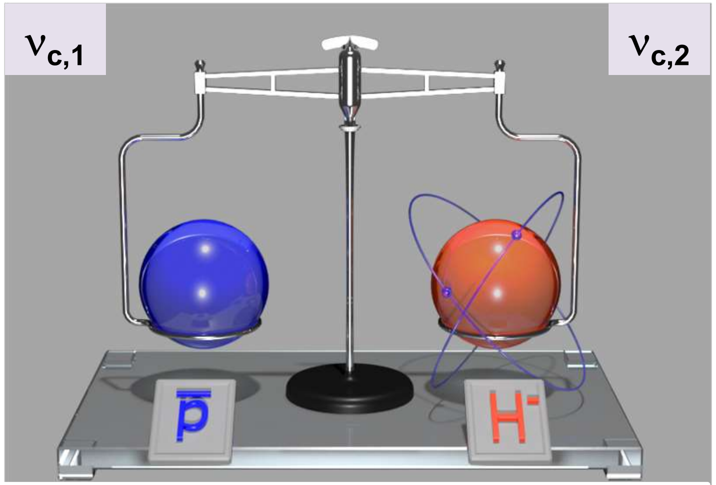
F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

Comparison of the proton and antiproton

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

$(q/m)_{\bar{p}} / (q/m)_p$ = -1.000 000 000 001 (69)

S. Ulmer *et al.*, Nature 524, 196 (2015)

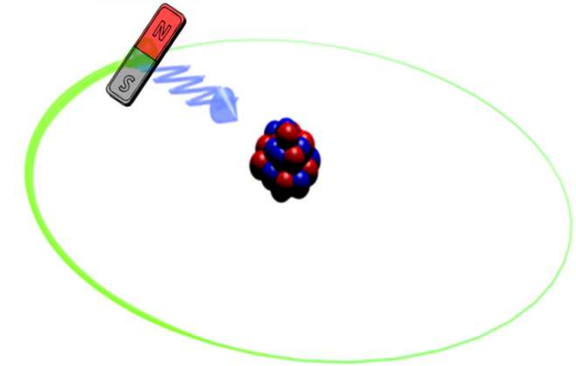


It is not that easy!

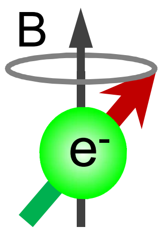
$$m_{H^-} = m_p \left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} \right)$$

The *g*-factor of the bound electron

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



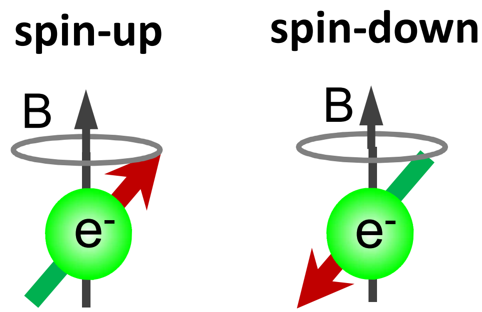
g-factor: measure for the magnetic strength of the bound electron



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

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

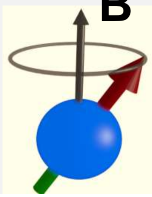
Electron can be in spin-up or spin-down state with transition frequency ω_L



Measurement principle

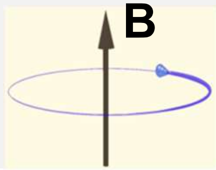
Measurement of the Larmor frequency in a well-known magnetic field:

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



Measurement of the free cyclotron frequency to determine the magnetic field:

$$\omega_c = \frac{q_{ion}}{m_{ion}}B$$

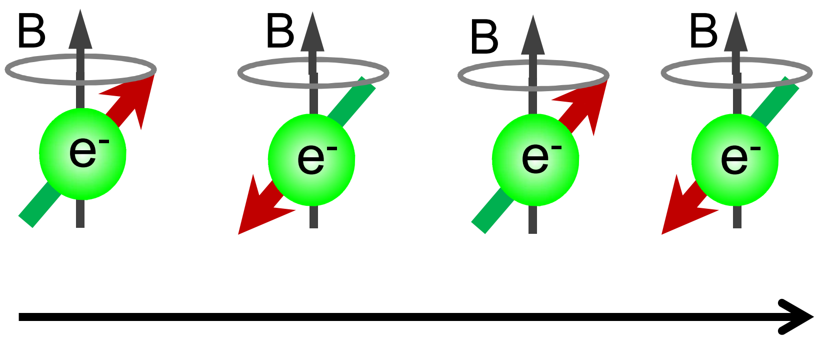


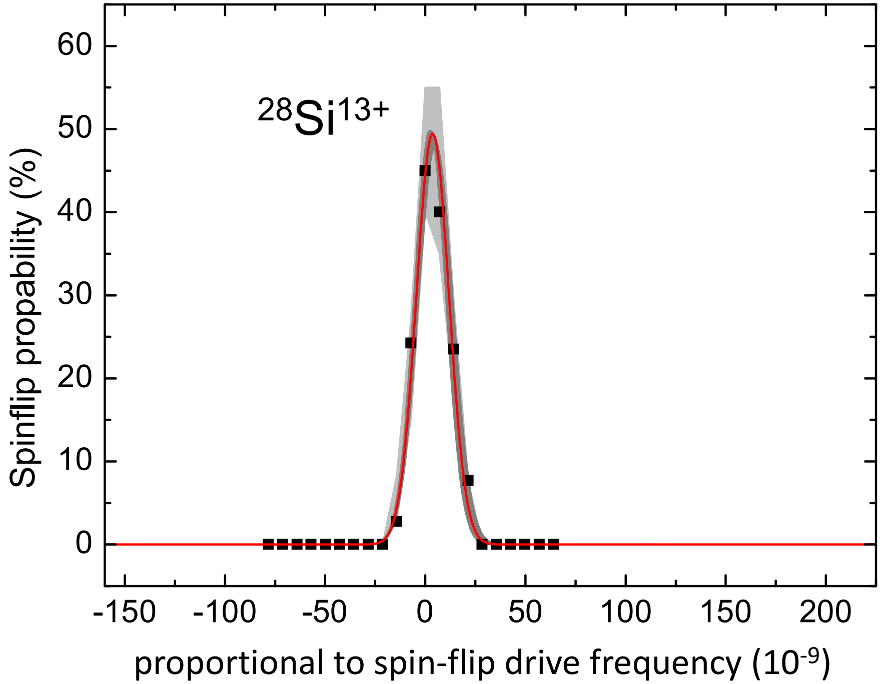
$$g = 2\frac{\omega_L}{\omega_c}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e} = 2\Gamma\frac{q_{ion}}{m_{ion}}\frac{m_e}{e}$$

has to be determined

Measured by independent precision experiments

Test of QED in strong fields





g_{exp} = 1.995 348 958 7 (5)(3)(8)
g_{theo} = 1.995 348 958 0 (17)

m_e can be improved if repeated for $^{12}C^{5+}$

most stringent test of bound-state QED in strong fields

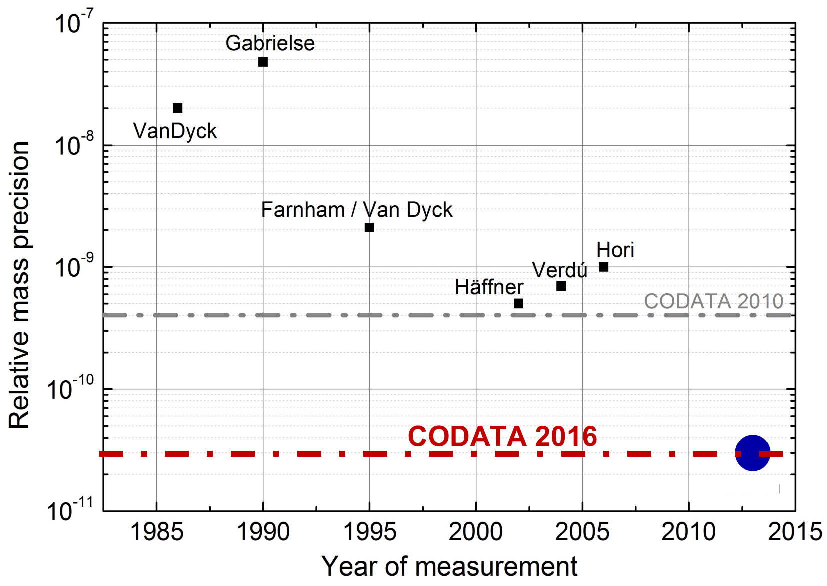
Theory colleagues: Harman, Keitel, Zatorski

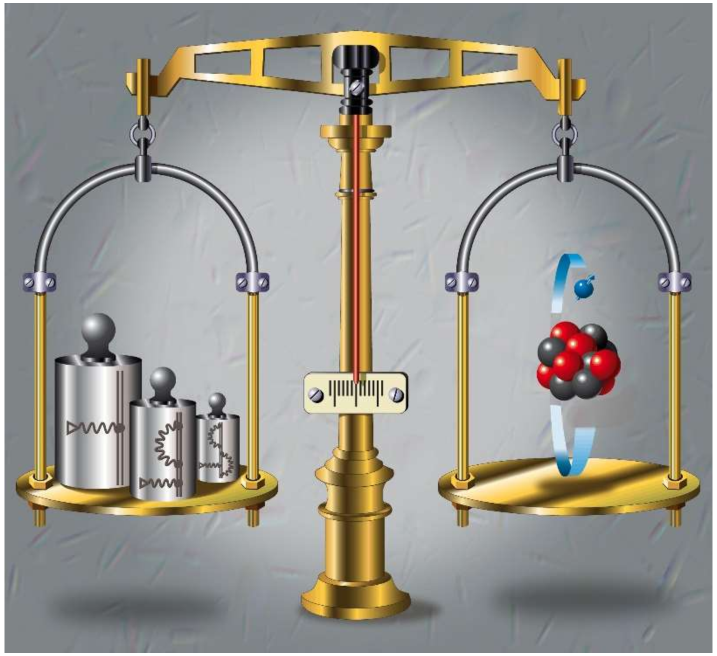
S. Sturm *et al.*, Phys. Rev. Lett. 107, 023002 (2011)
A. Wagner *et al.*, Phys. Rev. Lett. 110, 133003 (2013)
I. Arapoglou *et al.*, Phys. Rev. Lett., 122, 253001 (2019)

A 13-fold improved mass of the electron

g-factor of **hydrogenlike carbon**

$$m_e = \frac{g_{theo}}{2} \frac{\omega_c}{\omega_L} \frac{e}{q_{ion}} m_{ion}$$



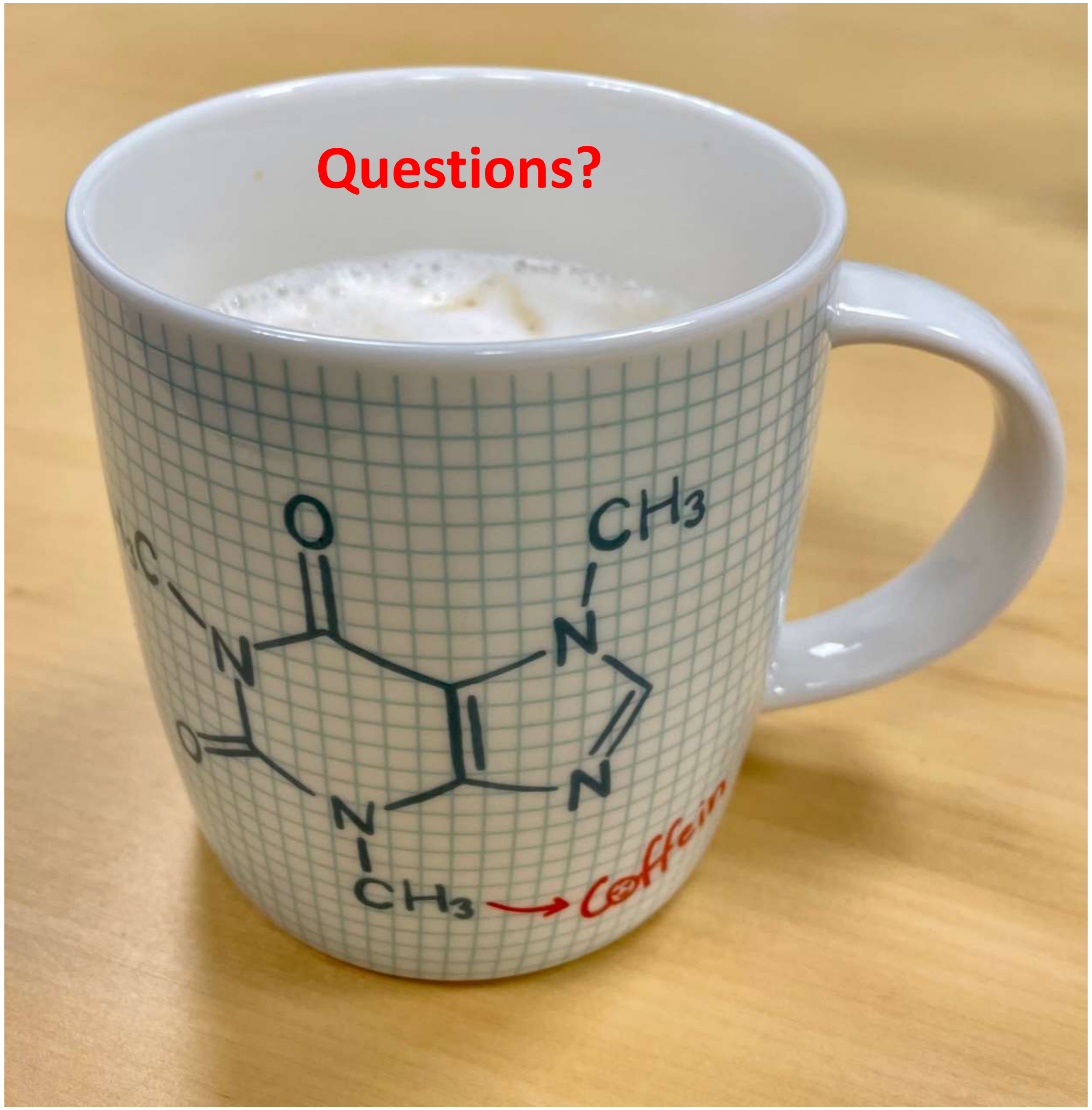


$m_e = 0.000\,548\,579\,909\,067(14)(9)(2)$u

A factor of 13 improved value !

S. Sturm *et al.*, Nature 506, 467 (2014)

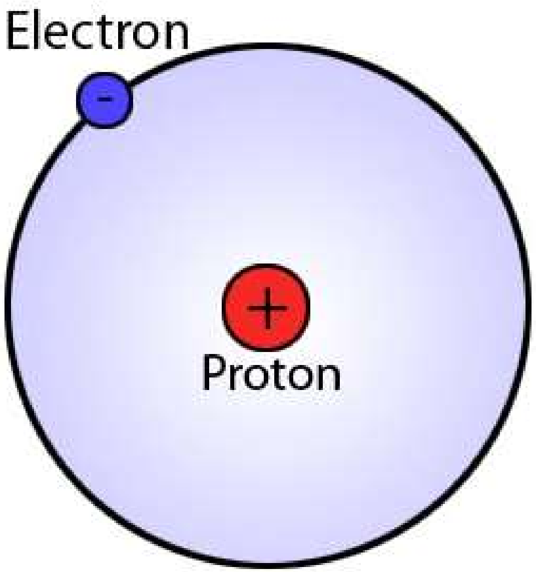
Time for a short break



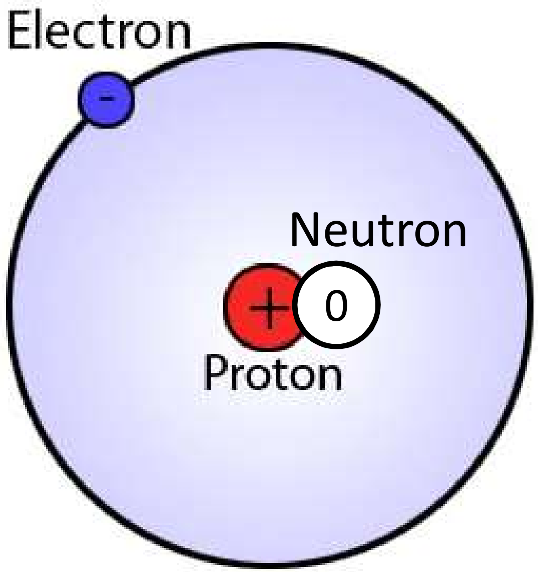
The building blocks of matter

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

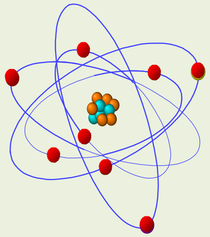
An easy image of our precision regime

$m_{stamp} \approx 4$ mg

$$\frac{m_{stamp}}{m_{A380}} \approx 8 \cdot 10^{-12}$$

m_{A380} **= 500 T = 500.000.000.000 mg = $5 \cdot 10^{11}$ mg**

<u>BUT:</u> Precision achieved on the atomic scale!



in the near future
$1\text{-}3 \cdot 10^{-12}$

Impact of precision fundamental masses

2018 CODATA Recommended Values of the Fundamental Constants of Physics and Chemistry

2018 CODATA RECOMMENDED VALUES OF THE FUNDAMENTAL CONSTANTS OF PHYSICS AND CHEMISTRY NIST SP 959 (June 2019)

An extensive constants list is available at physics.nist.gov/constants.

Quantity	Symbol	Numerical value	Unit
* ^{133}Cs hyperfine transition frequency	$\Delta\nu_{Cs}$	9 192 631 770	Hz
*speed of light in vacuum	c	299 792 458	$m\,s^{-1}$
*Planck constant	h	$6.626\,070\,15 \times 10^{-34}$	$J\,Hz^{-1}$
	$\hbar$	$1.054\,571\,817\ldots \times 10^{-34}$	J s
*elementary charge	e	$1.602\,176\,634 \times 10^{-19}$	C
*Avogadro constant	N_A	$6.022\,140\,76 \times 10^{23}$	mol^{-1}
*Boltzmann constant	k	$1.380\,649 \times 10^{-23}$	$J\,K^{-1}$
*luminous efficacy	K_{cd}	683	$lm\,W^{-1}$
electron volt (e/C) J	eV	$1.602\,176\,634 \times 10^{-19}$	J
Josephson constant $2e/h$	K_J	$483\,597.848\,4\ldots \times 10^{9}$	$Hz\,V^{-1}$
von Klitzing constant $2\pi\hbar/e^2$	R_K	$25\,812.807\,45\ldots$	Ω
molar gas constant $N_A k$	R	$8.314\,462\,618\ldots$	$J\,mol^{-1}\,K^{-1}$
Stefan-Boltzmann const. $\pi^2 k^4/(60\hbar^3 c^2)$	σ	$5.670\,374\,419\ldots \times 10^{-8}$	$W\,m^{-2}\,K^{-4}$

*Defining constants of the International System of Units (SI).

Quantity	Symbol	Numerical value	Unit
(unified) atomic mass unit $\frac{1}{12}m(^{12}C)$	u	$1.660\,539\,066\,60(50) \times 10^{-27}$	kg
Newtonian constant of gravitation	G	$6.674\,30(15) \times 10^{-11}$	$m^3\,kg^{-1}\,s^{-2}$
fine-structure constant $e^2/(4\pi\epsilon_0\hbar c)$	α	$7.297\,352\,5693(11) \times 10^{-3}$	
inverse fine-structure constant	α^{-1}	$137.035\,999\,084(21)$	
Rydberg frequency $\alpha^2 m_e c^2/(2h)$	cR_∞	$3.289\,841\,960\,2508(64) \times 10^{15}$	Hz
vac. magnetic permeability $4\pi\alpha\hbar/(e^2 c)$	μ_0	$1.256\,637\,062\,12(19) \times 10^{-6}$	$N\,A^{-2}$
vac. electric permittivity $1/(\mu_0 c^2)$	ϵ_0	$8.854\,187\,8128(13) \times 10^{-12}$	$F\,m^{-1}$
electron mass	m_e	$9.109\,383\,7015(28) \times 10^{-31}$	kg
proton mass	m_p	$1.672\,621\,923\,69(51) \times 10^{-27}$	kg
proton-electron mass ratio	m_p/m_e	$1836.152\,673\,43(11)$	
reduced Compton wavelength $\hbar/(m_e c)$	λ_C	$3.861\,592\,6796(12) \times 10^{-13}$	m
Bohr radius $\hbar/(\alpha m_e c)$	a_0	$5.291\,772\,109\,03(80) \times 10^{-11}$	m
Bohr magneton $e\hbar/(2m_e)$	μ_B	$9.274\,010\,0783(28) \times 10^{-24}$	$J\,T^{-1}$

The number in parentheses is the one-sigma (1σ) uncertainty in the last two digits of the given value.

CODATA

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

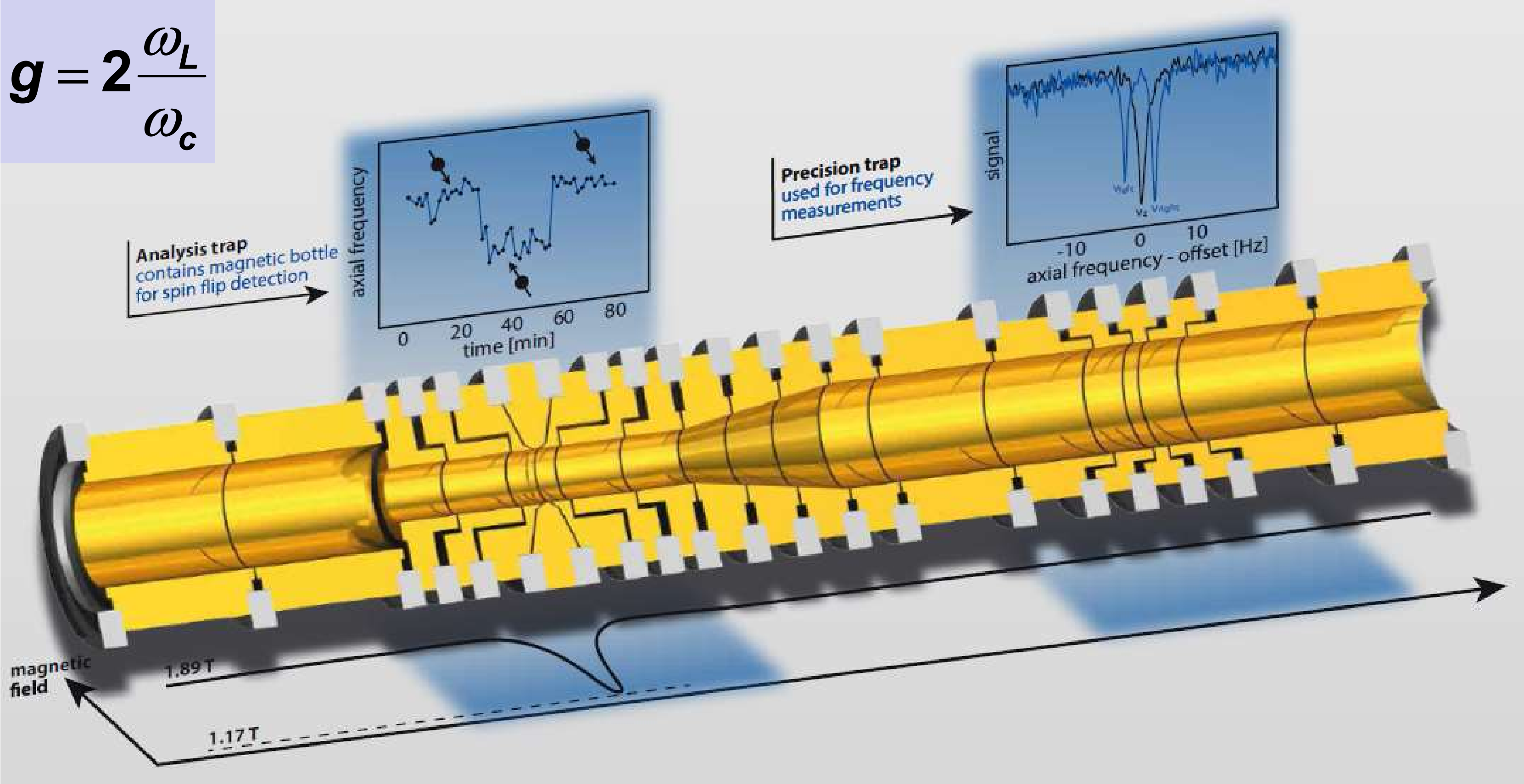
FRONT SIDE

BACK SIDE

5 out of 13 secondary fundamental constants are determined by our results!

The (anti-)proton magnetic moment

$$g = 2\frac{\omega_L}{\omega_c}$$



μ_p = 2.792 847 344 62(82) μ_N

(0.3 ppb)

G. Schneider *et al.*, Science 358, 1081 (2017)

$\mu_{\bar{p}}$ = −2.792 847 344 1(42) μ_N

(1.5 ppb)

Ch. Smorra *et al.*, Nature 550, 371 (2017)

g-factor ^{3}He

g_I (nuclear g-factor)

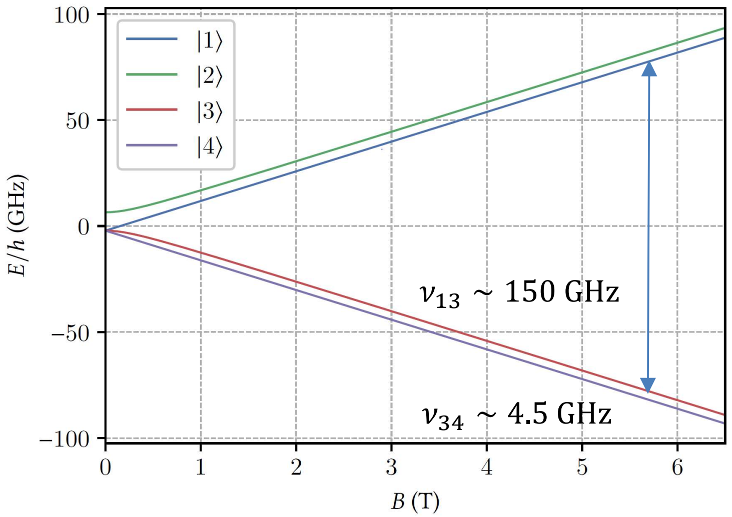
➢Establish ^{3}He NMR probes for accurate magnetometry

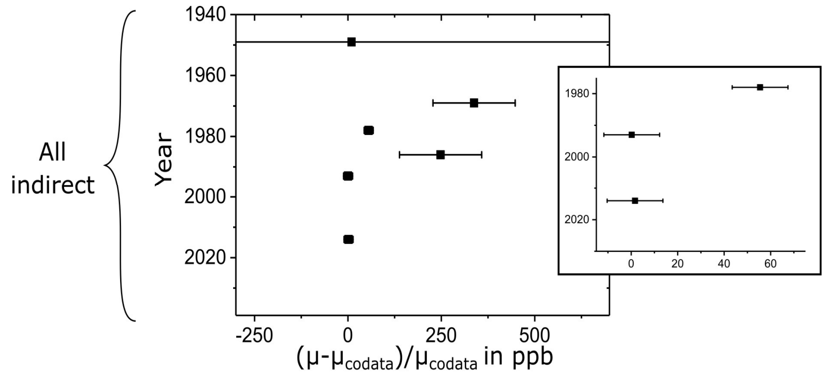
Dependence on temperature	1	1/100
Dependence on probe shape	1	1/1000
Diamagnetic shielding	1 measured	1/10 calculated

➢Application: muon g-2

ΔE_{HFS} (zero-field hyperfine splitting)

➢Extract nuclear structure, e.g. Zemach radius, with help by theory

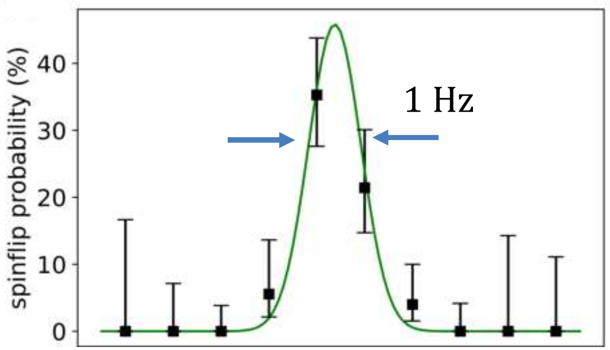




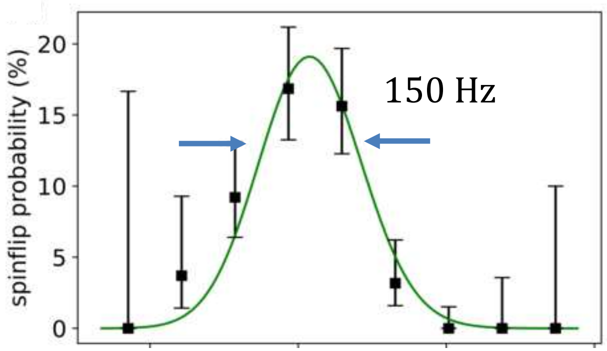
Past, indirect measurements of the nuclear magnetic moment

g-factor ^{3}He

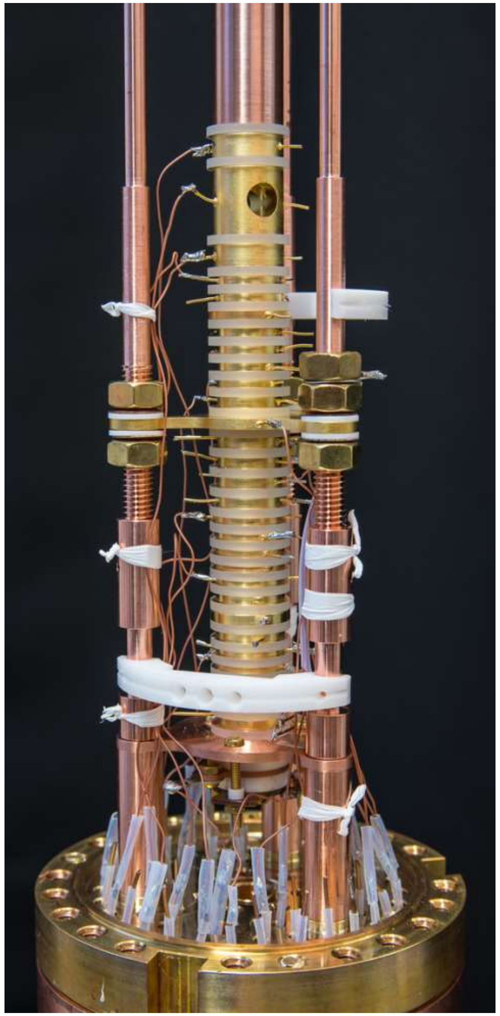
HFS measurement is completed – preliminary results



$\nu_{34} \sim 4.5$ GHz



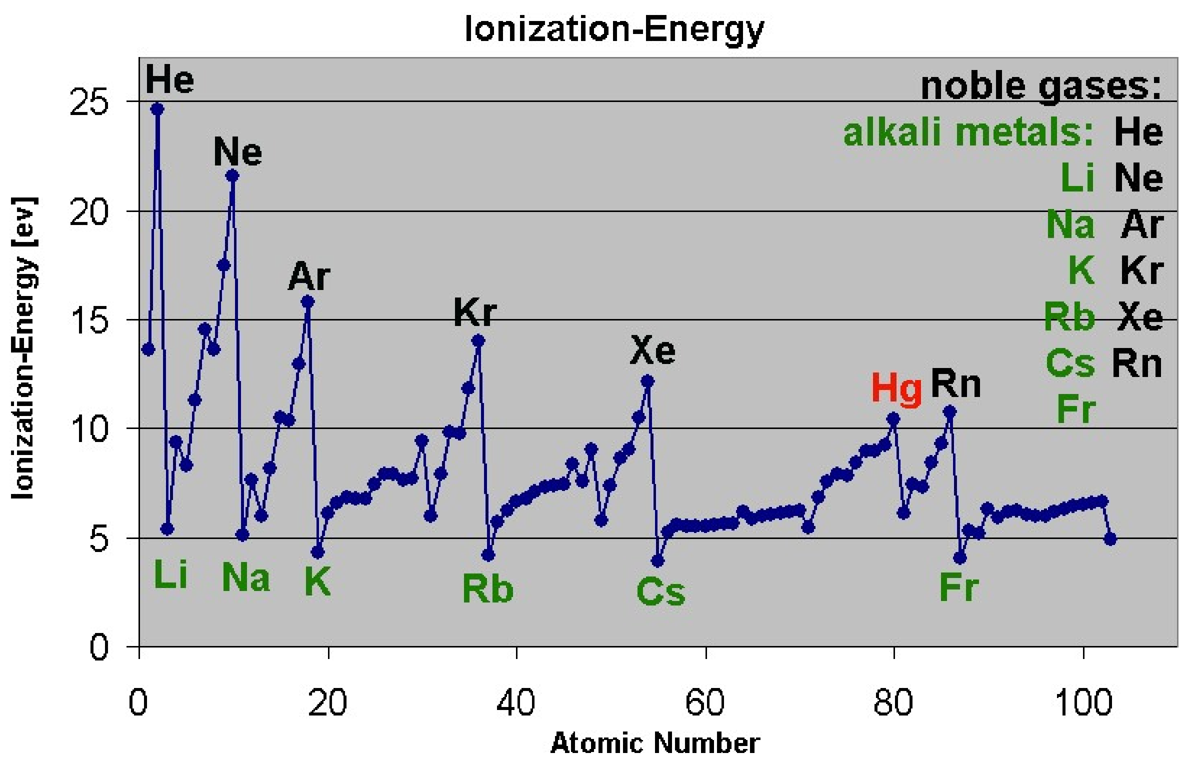
$\nu_{13} \sim 150$ GHz



- ➢ g_I improved by factor of 20 to precision of 1ppb
- ➢ Zemach radius determined
- ➢ g_e tested against BS-QED on the 10^{-10} level

Atomic masses II

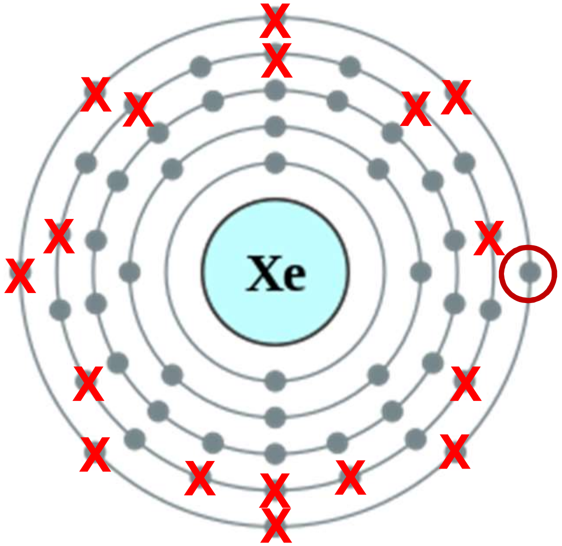
Electron binding and excitation energies



PENTATRAP: MPIK, Uni HD, St. Petersburg

J. Crespo, S. Eliseev, *M. Haverkort*, Y. Novikov, *Z. Harman*

Weighing electron binding energies

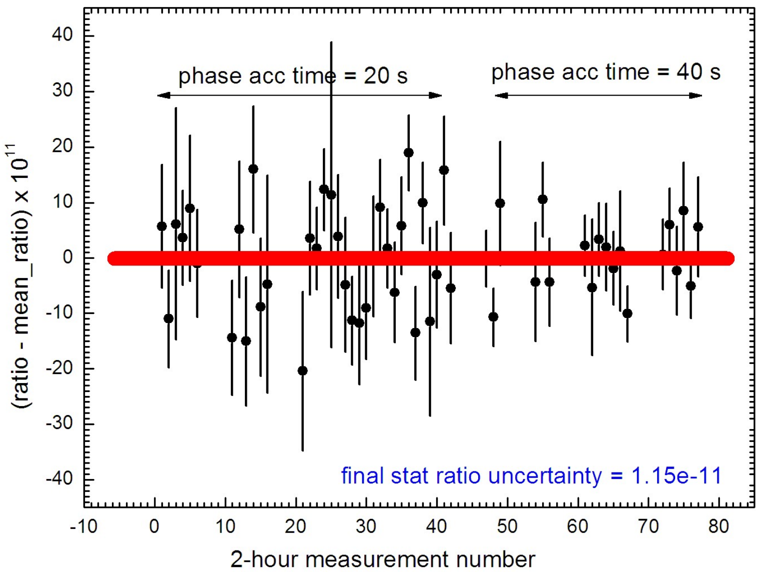


Electron configuration of xenon (Z = 54):

$1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 4s^2\ 3d^{10}\ 4p^6\ 5s^2\ 4d^{10}\ 5p^6$

$[Kr]\ 5s^2\ 4d^{10}\ 5p^6$

Measure the mass difference of Xe^{17+} and Xe^{18+} yields the binding energy of the 18th electron.
→ *Stringent tests of many electron calculations!*



PENTATRAP@MPIK:
$\delta m/m_{stat} = 1.1 \cdot 10^{-11}$ (δm ~ 1.4 eV)

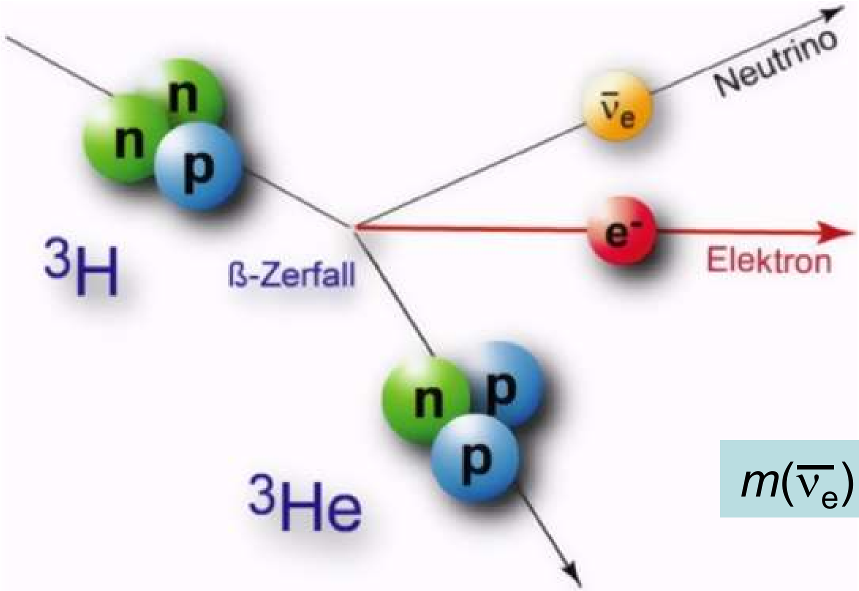
Exp.:	**$B(4d^1)_{Xe}$ = 432.4 (1.3)(3.4) eV**
Theorie :	**$B(4d^1)_{Xe}$ = 432.4 (3.0) eV (*PI*)**
	$B(4d^1)_{Xe}$ = 435.1 (1.0) eV (*ZH*)

Test of many electron calculations

Rischka *et al.*, PRL **124**, 111301 (2020)

Atomic physics isn‘t that easy

Atomic mass differences and ν-physics



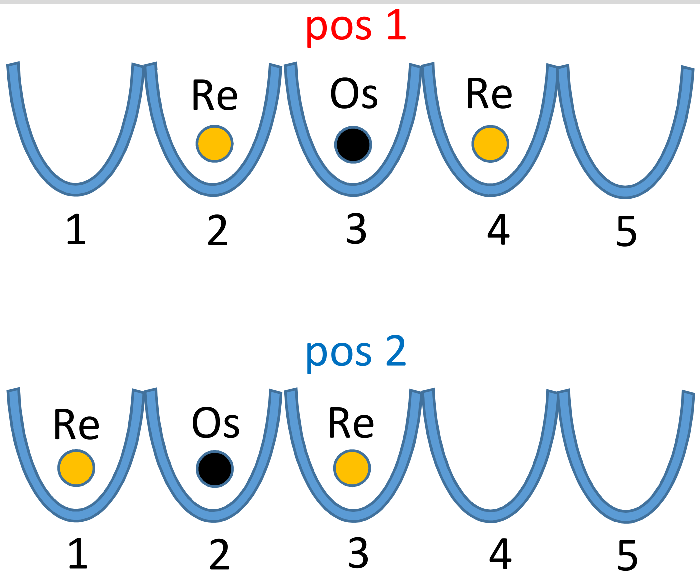
$m(\overline{\nu}_e) < 1.1$ eV/c^2 (95% CL)

β^--decay of ^{187}Re

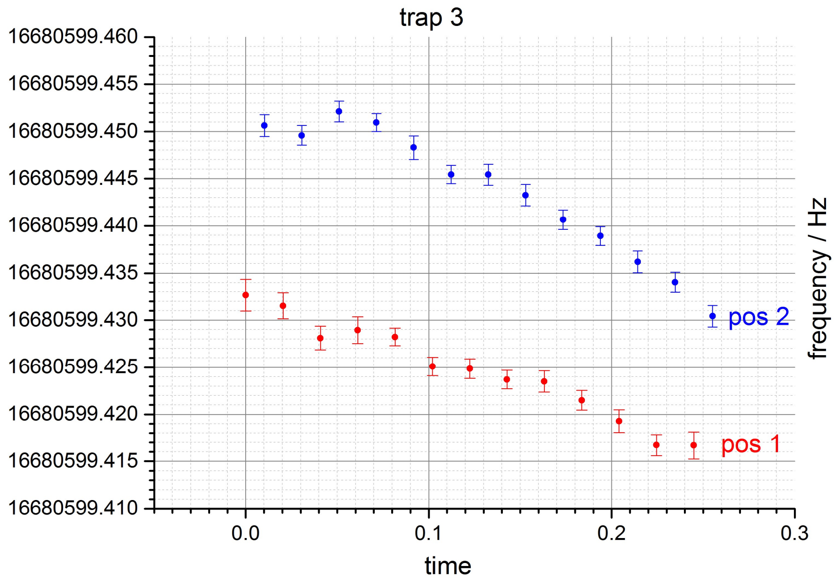
$R = \frac{\nu_c(^{187}\mathrm{Os}^{29+})}{\nu_c(^{187}\mathrm{Re}^{29+})}$

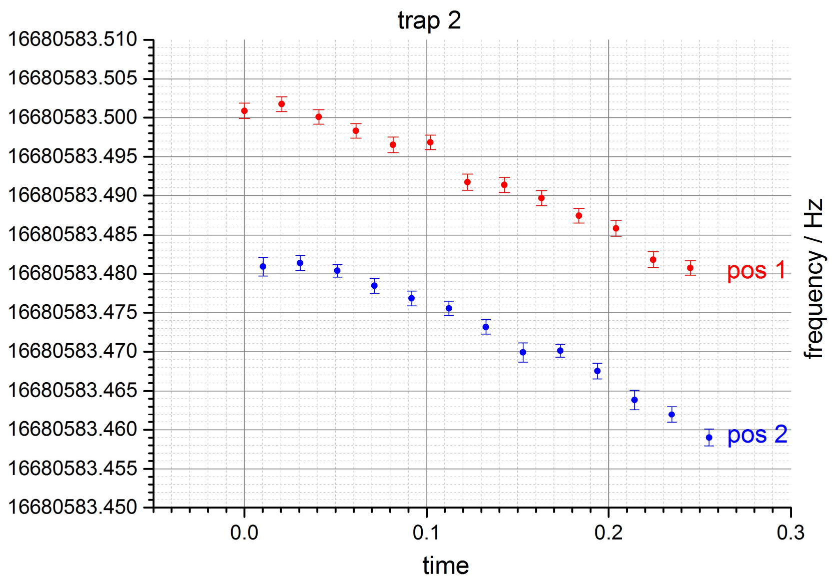
$$Q = M(^{187}\mathrm{Re})\text{-}M(^{187}\mathrm{Os}) = M(^{187}\mathrm{Re}^{29+}) - M(^{187}\mathrm{Os}^{29+}) + \Delta B = M(^{187}\mathrm{Os}^{29+}) \cdot [R-1] + \Delta B$$

Highly charged Re and Os ions



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





Results

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)

- Os^{29+} vs. Os^{29+} measurements yield always unity.
- Re^{29+} vs. Re^{29+} measurements yield either unity or $1+1.14\cdot10^{-9}$.

Conclusions:

(1) Ions in the EBIT can be produced in various stable electron configurations.
(2) In Re^{29+} we observe two stable states. One with R_1 is probably the ground state.

Tasks for theoreticians:

(1) Calculation of the total binding-energy difference for Re^{29+}/Os^{29+} in order to calculate the Q-value of the beta-decay of ^{187}Re.

Filianin *et al.*, PRL **127**, 072502 (2021) $\delta m/m = 5\cdot10^{-12}$

(2) Calculation of the energy of the metastable states.

Weighing of different electron config.

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

In collaboration with Harman, Haverkort, Indelicato, Keitel

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

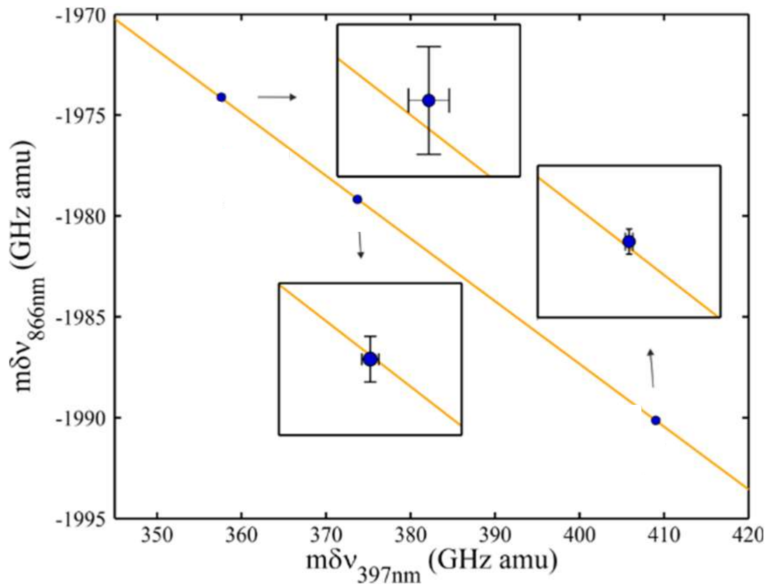
R. Schüssler *et al.*, Nature **581** (2020) 42

Possible application: search for suitable clock transitions

Probe for new force carriers

Isotope shift spectroscopy: 5th force?

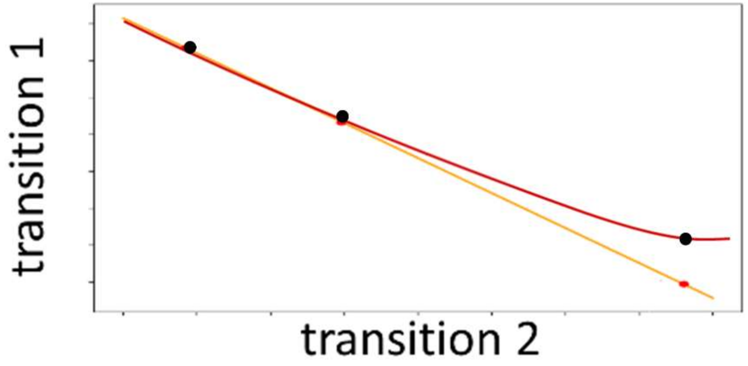
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'}$
- use 2 transitions i, j
  ➔ eliminate $\delta\langle r^2\rangle_{A,A'}$



- 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:

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



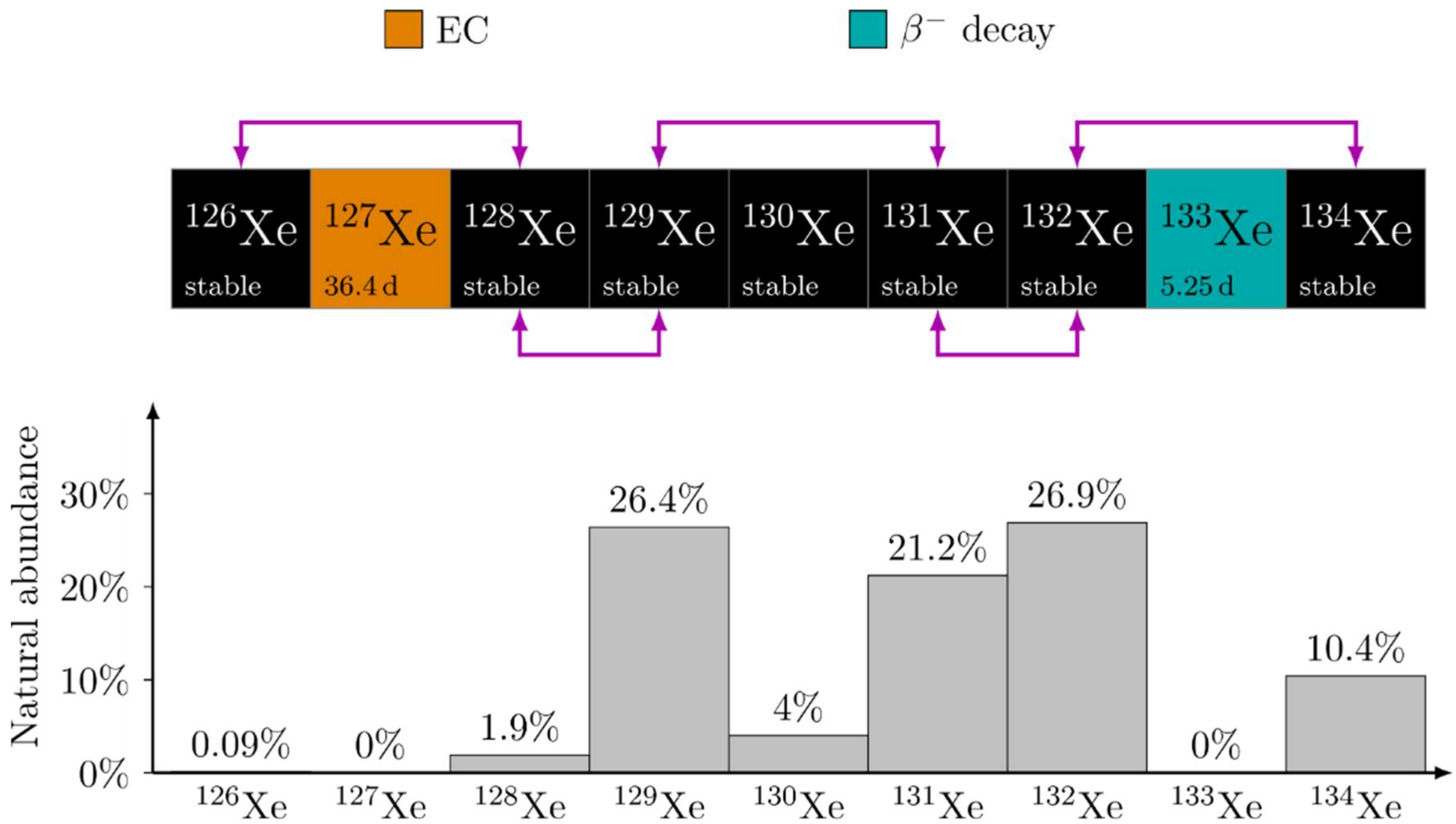
Berengut *et al.*, PRL **120**, 091801 (2018); Ozeri *et al.* (2020)

High-precision atomic and nuclear spectroscopy measurements needed!

Xe mass-ratio measurements

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

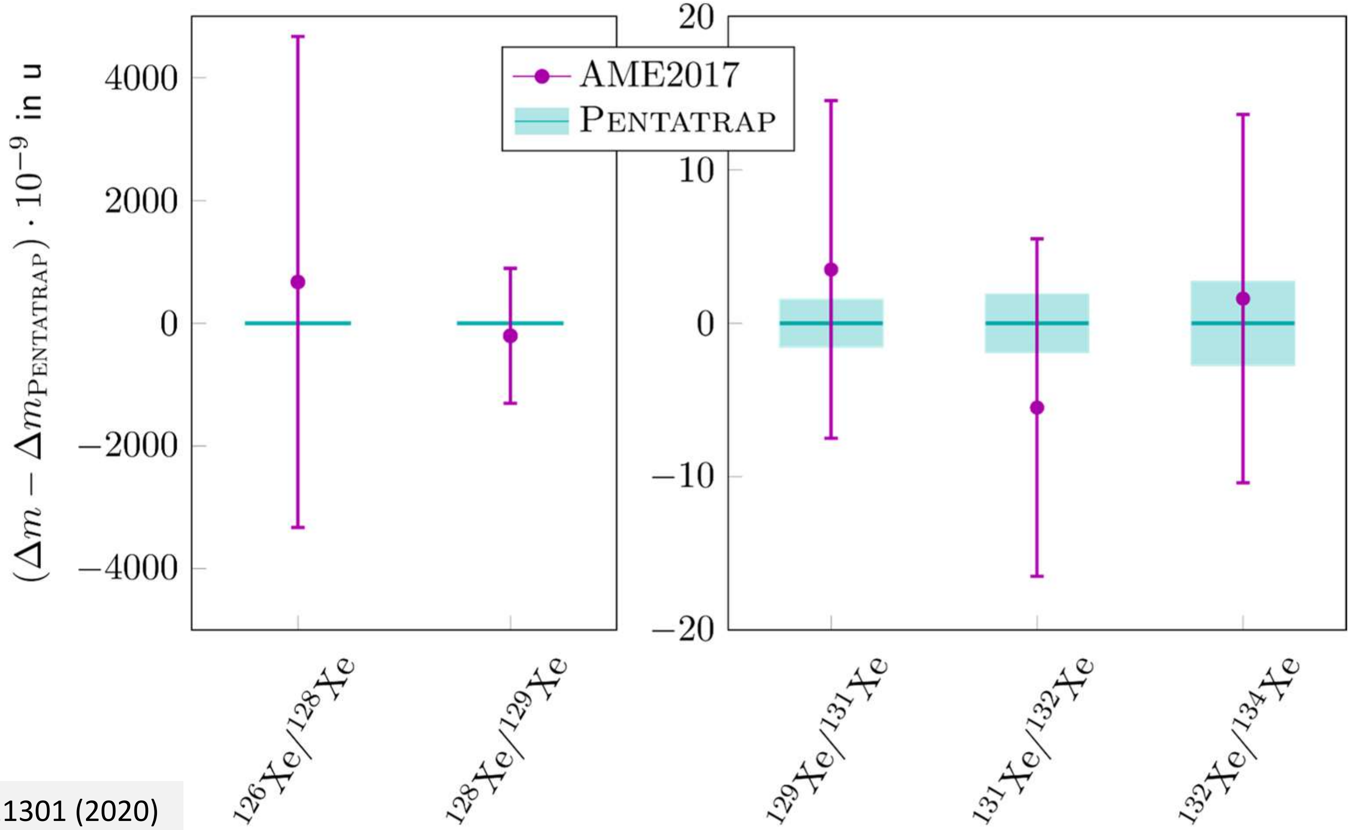
Mass-ratio uncertainties of 10^{-11} and below required!



Xe mass-ratio measurements

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

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



Rischka *et al.*, PRL **124**, 111301 (2020)

Improvement factor:	**1700**	**740**	**7**	**6**	**4**

Summary and Outlook

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

What comes next:

(1) Laser cooling of protons, antiprotons and HCI — Bohman *et al.*, Nature **596**, 514 (2021)

(2) Reaching hydrogenlike Pb^{81+}

(3) Determination of finestructure constant α

(4) Most stringent test of $E = mc^2$

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