ECT* Meeting, Trento 2018

Precision Penning-trap measurements for fundamental studies

- Precision atomic/nuclear masses
- Stringent CPT tests using baryons
- Proton and electron atomic masses

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April 26th, 2018

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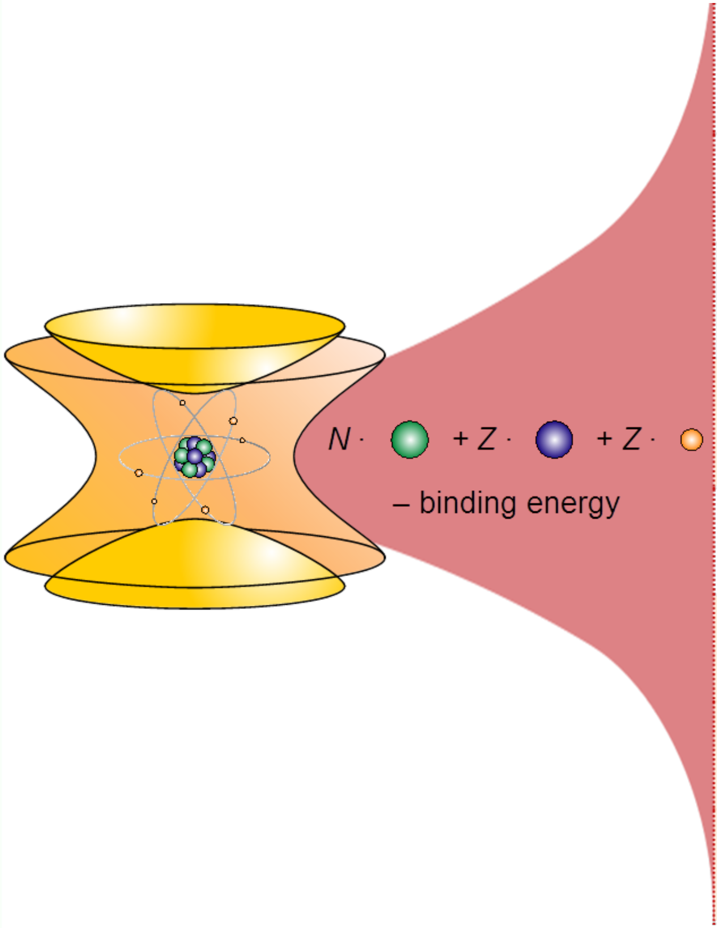
Why measuring atomic masses?

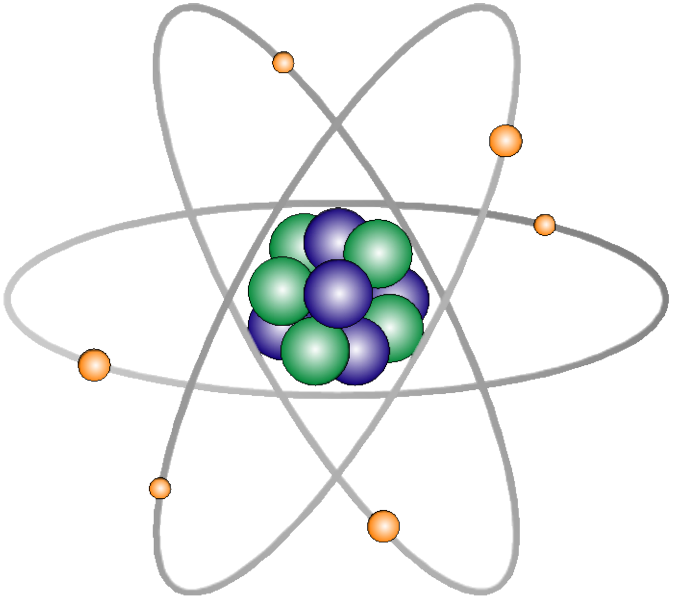


	$\delta m/m$	δE
General physics & chemistry	$\lesssim 10^{-5}$	1 MeV
Nuclear structure physics - separation of isobars	$\lesssim 10^{-6}$	100 keV
Astrophysics - separation of isomers	$\lesssim 10^{-7}$	10 keV
Weak interaction studies	$\lesssim 10^{-9}$	100 eV
Metrology - fundamental constants Neutrino physics	$\lesssim 10^{-10}$	eV-meV
CPT tests	$\lesssim 10^{-11}$	meV
QED in highly-charged ions - separation of atomic states	$\lesssim 10^{-11}$	eV-meV

Relative mass precision of 10^{-9} and below can presently ONLY be reached by Penning-trap mass spectrometry.

Atomic and nuclear masses

Masses determine the atomic and nuclear binding energies reflecting all forces in the atom/nucleus.



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

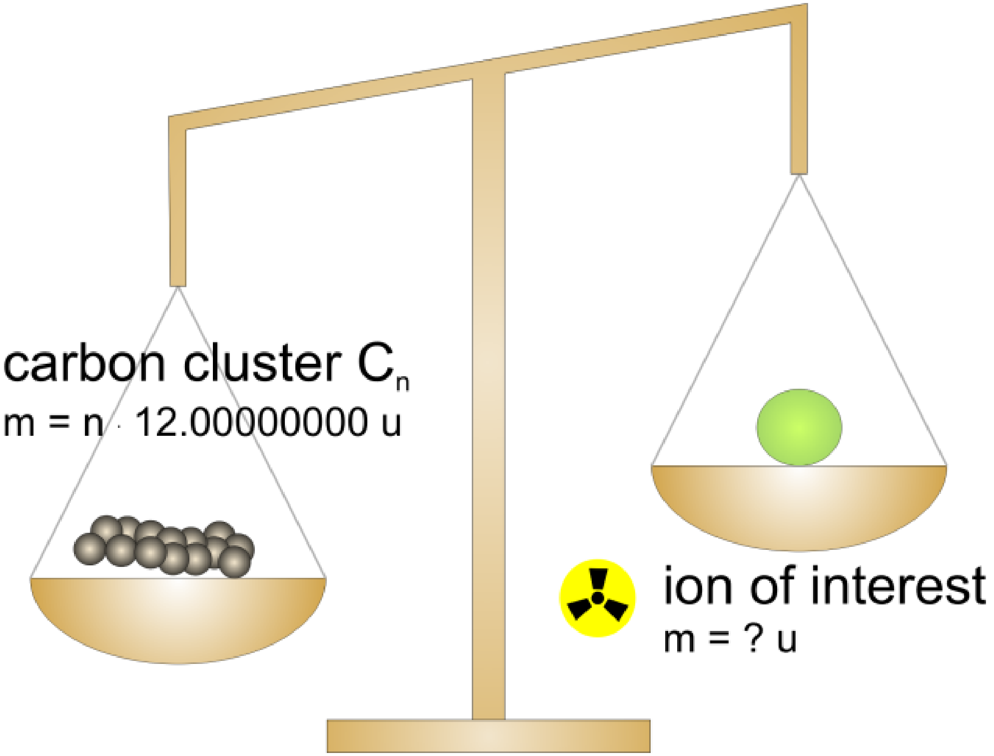
– binding energy

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

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

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

How to weigh an atom



carbon cluster C_n

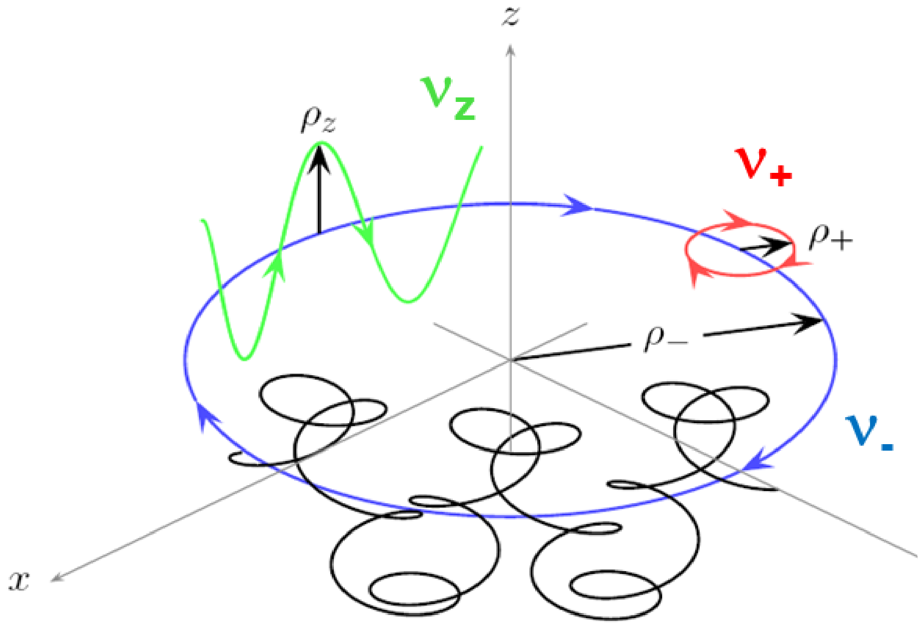
$m = n \cdot 12.00000000\ u$

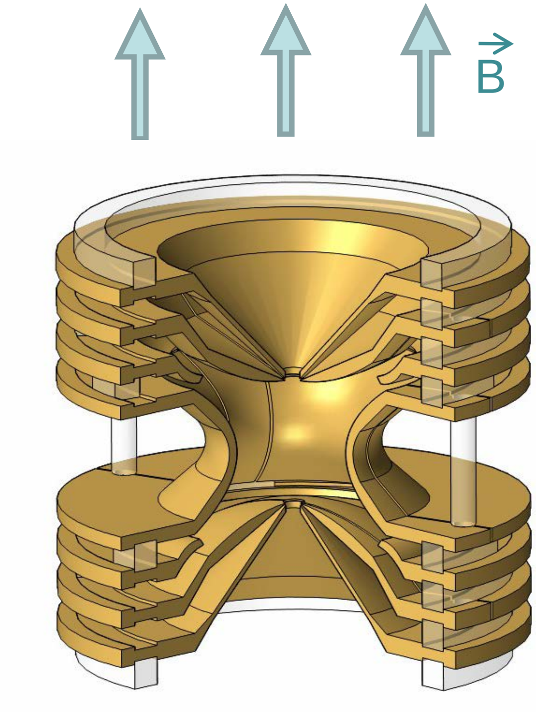
ion of interest

$m = ?\ u$

$\nu_{c,1}$ $\nu_{c,2}$ $\Rightarrow \dfrac{\nu_{c,1}}{\nu_{c,2}}$

Storage of ions in a Penning trap





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

$$\omega_c = qB / m_{ion}$$

Invariance theorem:

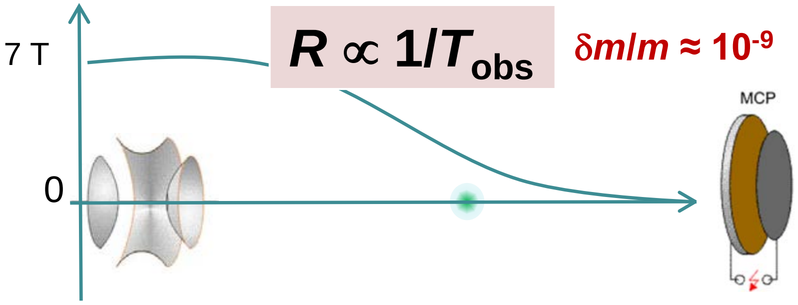
$$\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$$

$$\omega_c = \omega_+ + \omega_-$$

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

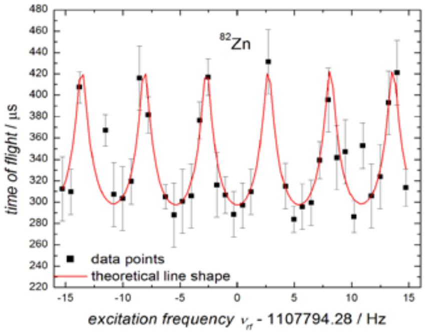
Detection techniques

Destructive time-of-Flight detection

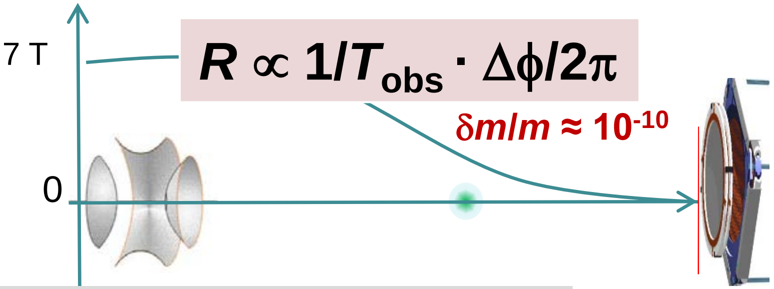


$R \propto 1/T_{obs}$

$\delta m/m \approx 10^{-9}$

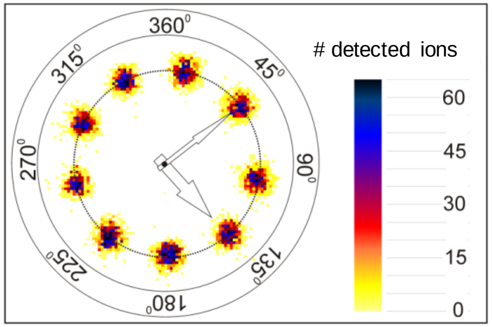


Destructive phase-imaging detection



$R \propto 1/T_{obs} \cdot \Delta\phi/2\pi$

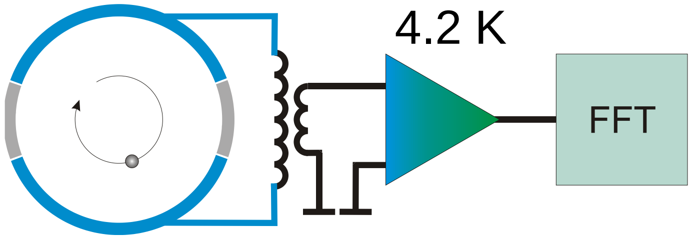
$\delta m/m \approx 10^{-10}$

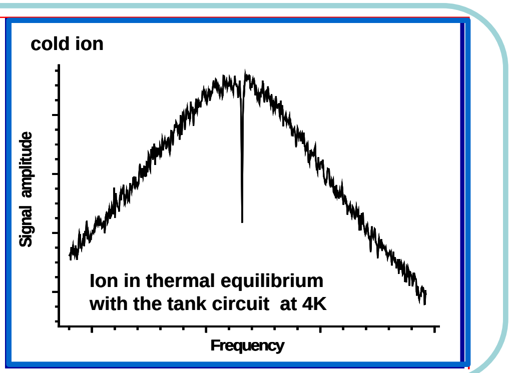


S. Eliseev *et al.*, Phys. Rev. Lett. 110, 082501 (2013)

Non-destructive induced image current detection

$\delta m/m \approx 10^{-11}$

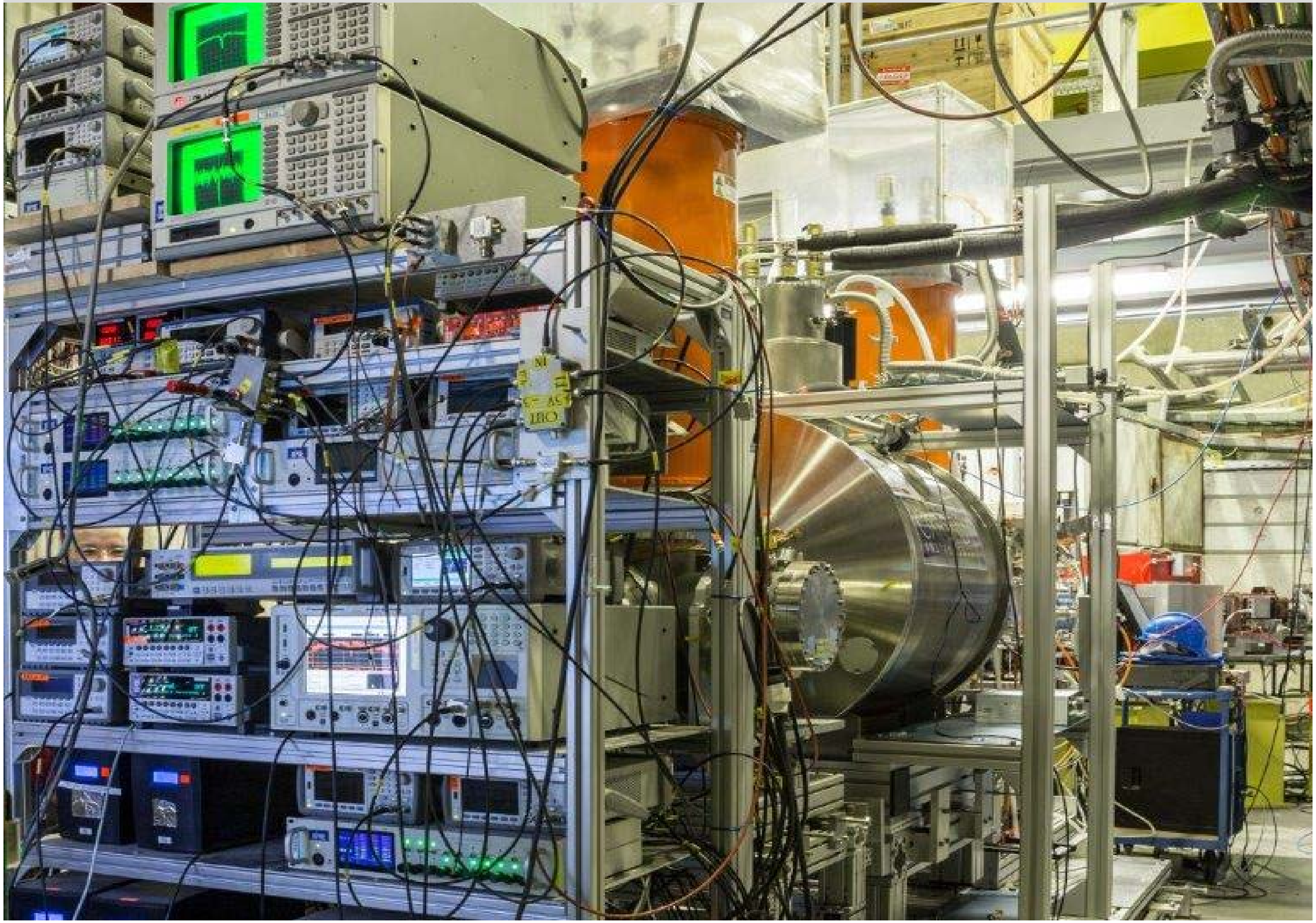




S. Sturm *et al.*, Phys. Rev. Lett. 107, 143003 (2011)

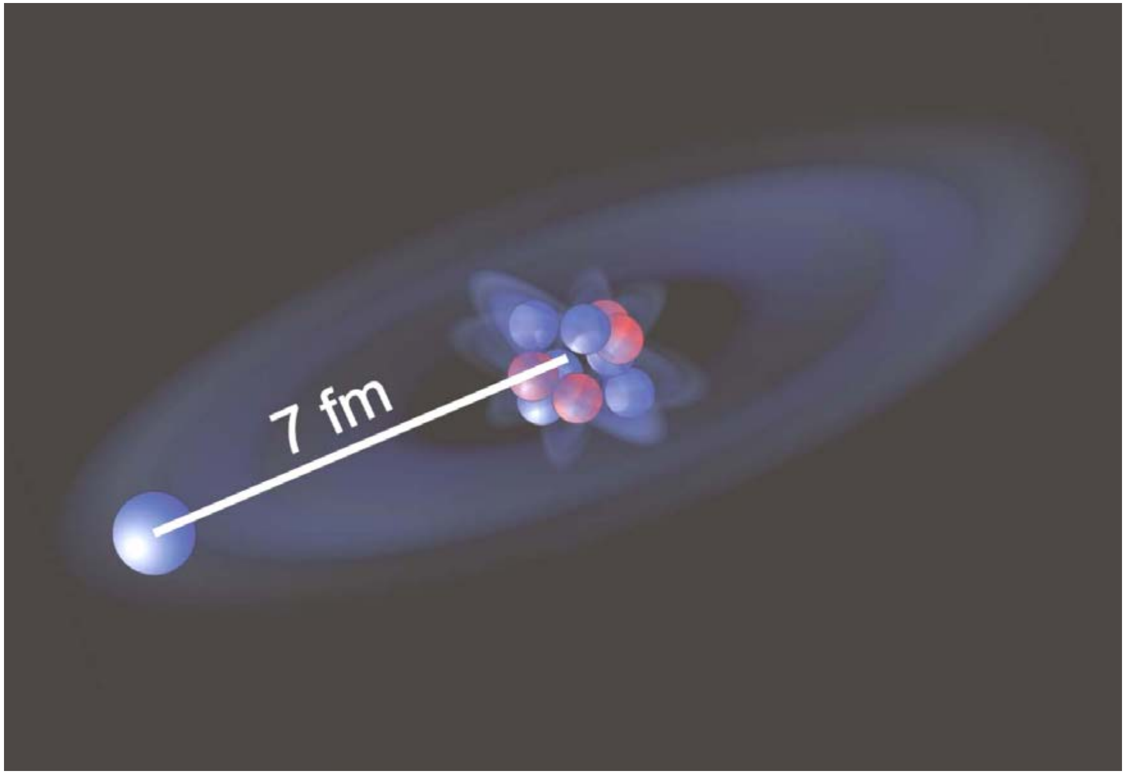
BASE: A Penning-trap setup at CERN

A balance for protons and antiprotons.



Atomic masses I

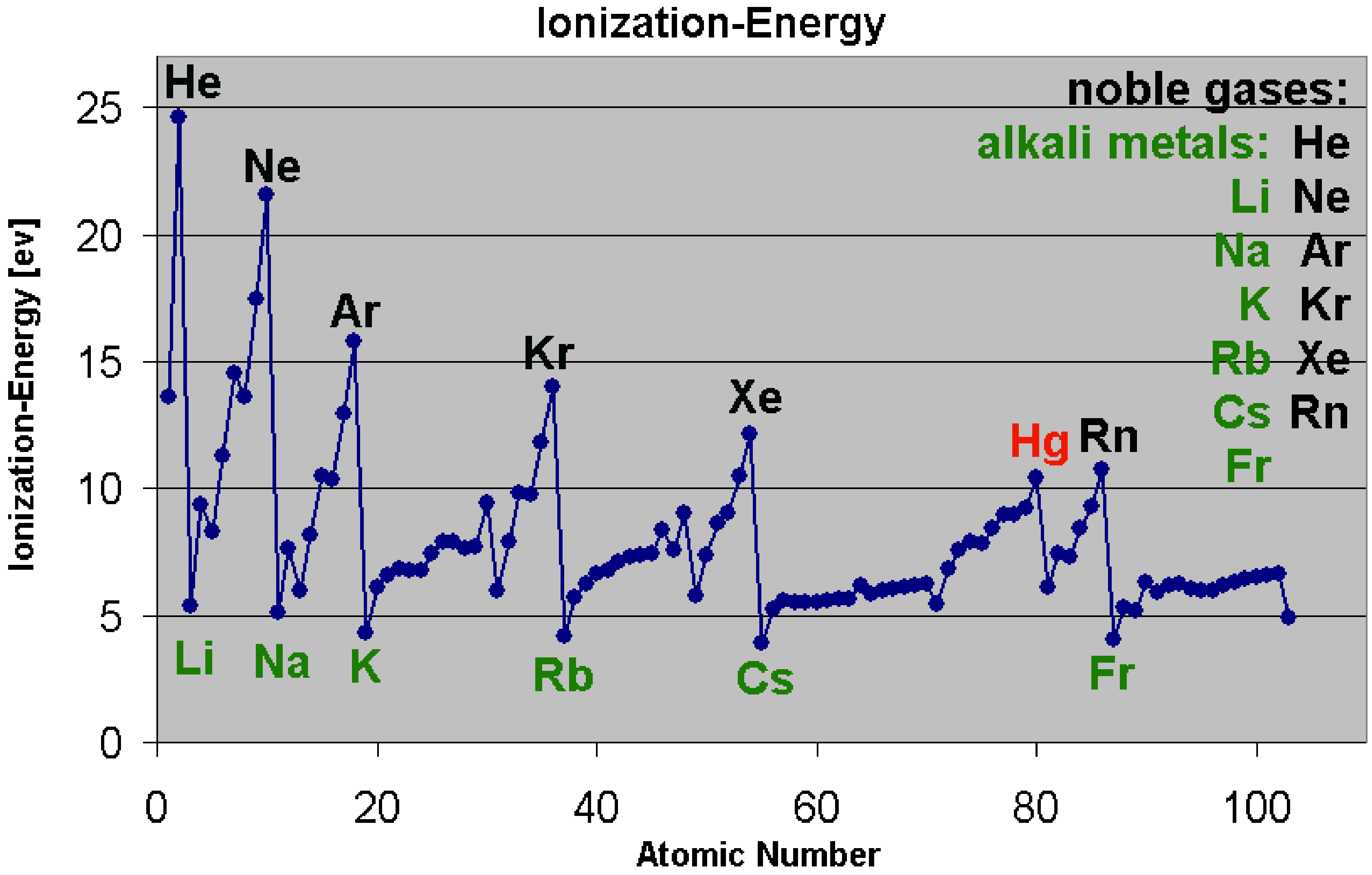
Nuclear magic numbers



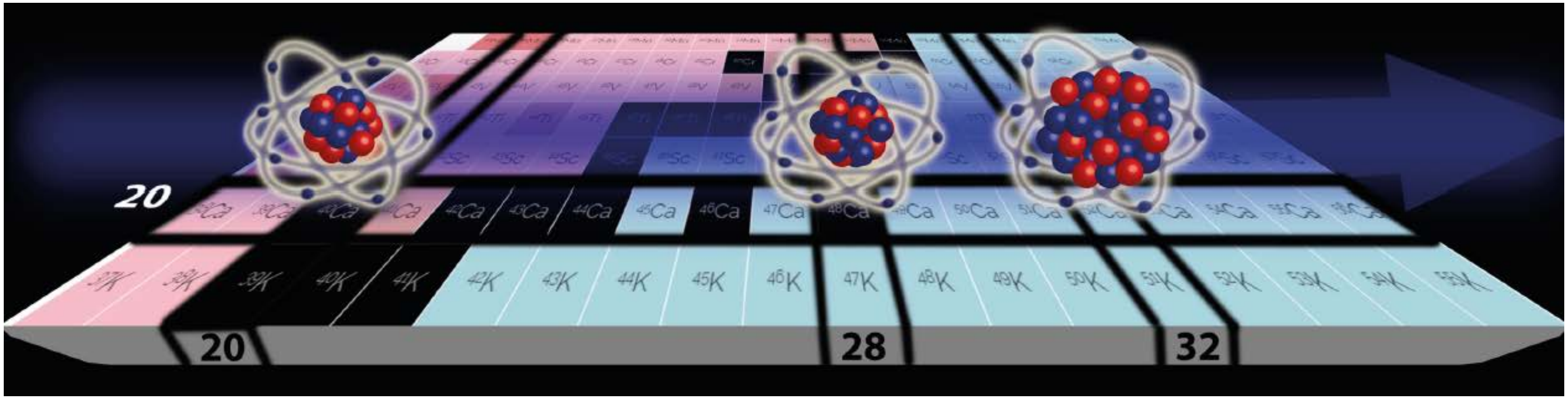
ISOLTRAP (CERN), SHIPTRAP (GSI), TRIGATRAP (Mainz)

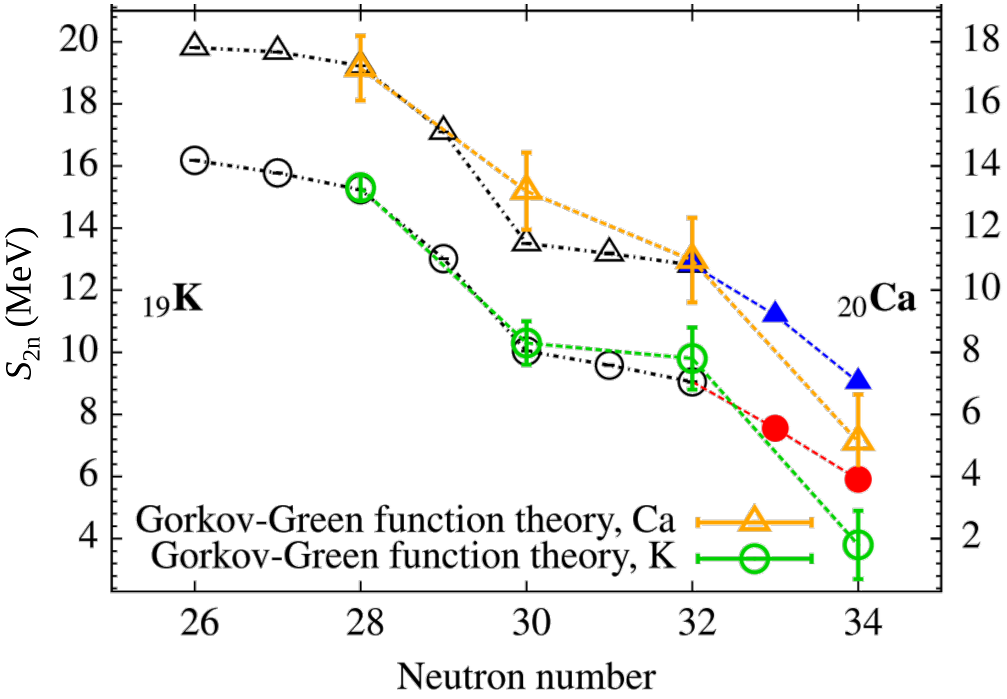
S. Eliseev, *J.D. Holt*, V. Manea, L. Schweikhard, *A. Schwenk*

Atomic and nuclear structure: Basics



New magic number (*N*=32) and 3N-forces





$T_{1/2}$ = ms – s
Yield = 1-10 p/s

Ca:
A.T. Gallant *et al.*, PRL 109, 032506 (2012)
F. Wienholtz *et al.*, Nature 498, 346 (2013)

K:
M. Rosenbusch *et al.*, PRL 114, 202501 (2015)

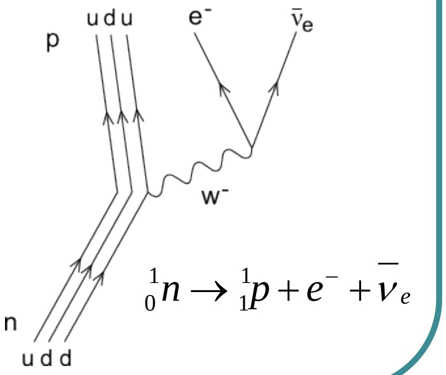
ISOLTRAP (CERN)
TITAN (TRIUMF)

Masses II

Test of the unitarity of the quark-mixing matrix

Weak Interaction

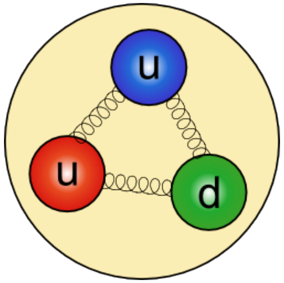
- Radioactive decay



$$^1_0n \rightarrow {}^1_1p + e^- + \overline{\nu}_e$$

Strong Interaction

- Binding between quarks within hadrons



Superallowed β-decays

- Corrected value:

$$\mathcal{F}t = ft\,(1+\delta'_R)\,(1+\delta_{\mathrm{NS}}-\delta_C) = \frac{K}{2G_V^2\,(1+\Delta_V^R)}$$

- Corrections about 1% [Towner and Hardy, Phys. Rev. C 77, 025501 (2008)]
- Cabibbo-Kobayashi-Maskawa quark mixing matrix

$$\begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix} = \begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix}$$

- Quark-mass eigenstates $|x\rangle$ to weak eigenstates $|x'\rangle$

$$V_{\mathrm{ud}} = \frac{K}{2G_F^2\,(1+\Delta_R^V)\,\overline{\mathcal{F}t}}$$

Test of the CKM unitarity

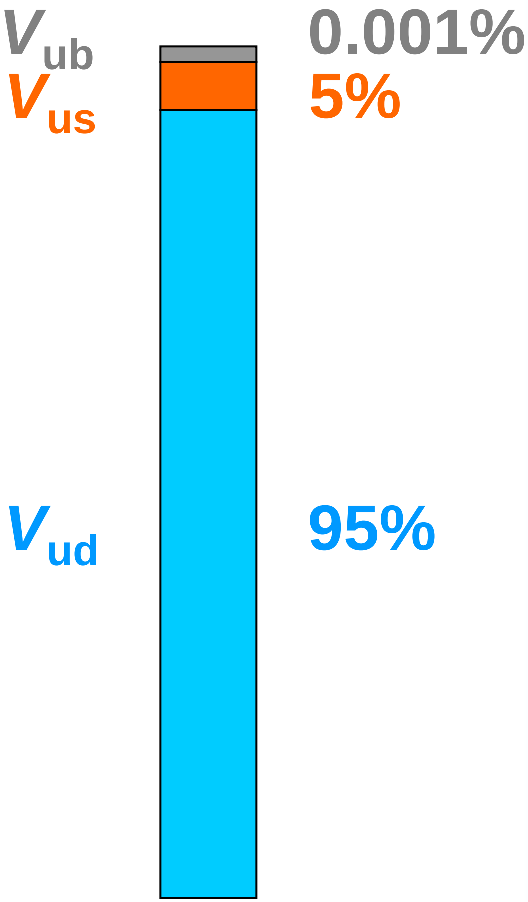
Check unitarity via first row elements:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \mathit{\Delta}$$

V_{us} and V_{ub} from particle physics data

(*K* and *B* meson decays)

Unitarity contribution:



Present status:

V_{ud} **(nuclear β-decay) = 0.97417(21)**

V_{us} **(kaon-decay) = 0.2253(14)**

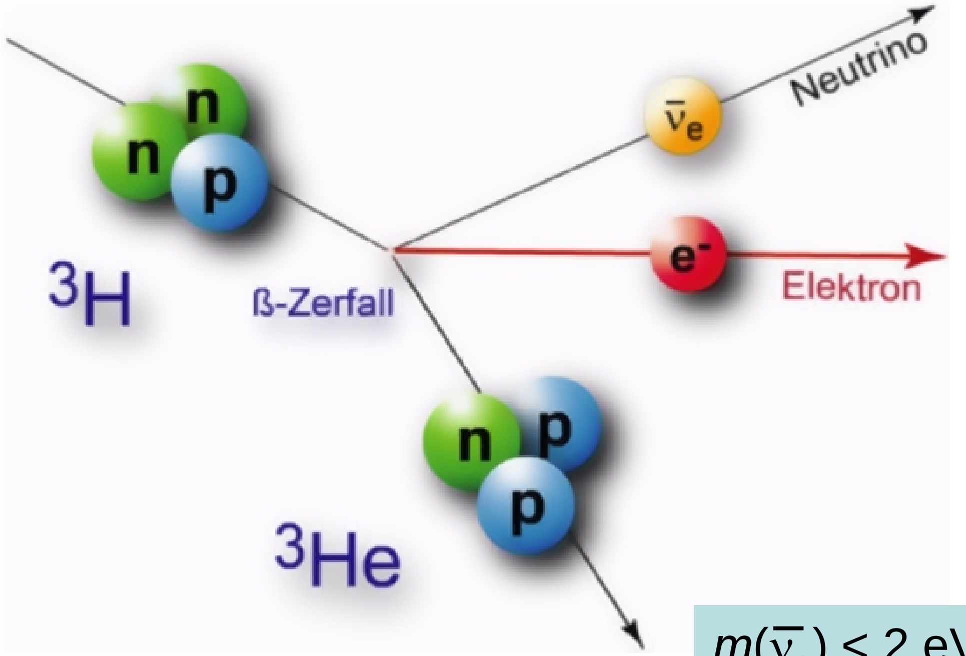
V_{ub} **(B meson decay) = 0.0037(5)**

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99978(55)$$

Hardy&Towner, Phys. Rev. C 91 (2015) 025501

Masses III

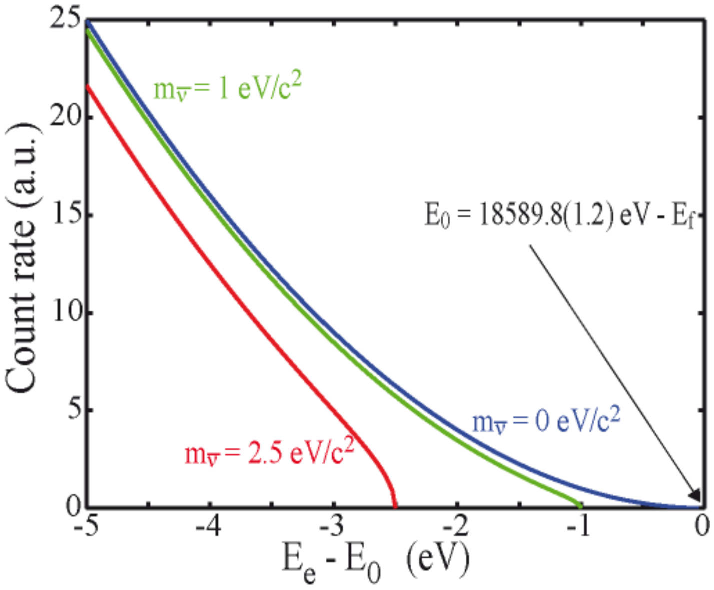
Neutrino physics applications



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

THe-TRAP for KATRIN

A high-precision $Q(^3T\text{-}^3He)$-value measurement



$^3_1H \rightarrow {}^3_2He + e^- + \overline{\nu}$ Q_{lit} =18 589.8 (1.2) eV

Q_{lit} =18 592.01(7) eV [E. Myers, PRL (2015)]

We aim for: $\delta Q(^3T \rightarrow {}^3He) = 20$ meV
$\delta m/m = 7\cdot10^{-12}$

$\Delta T < 0.02$ K/d at 24°C
$\Delta B/B < 10$ ppt / h $\Delta x \leq 0.1$ μm

First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m = 1.4\cdot10^{-11}$ performed.

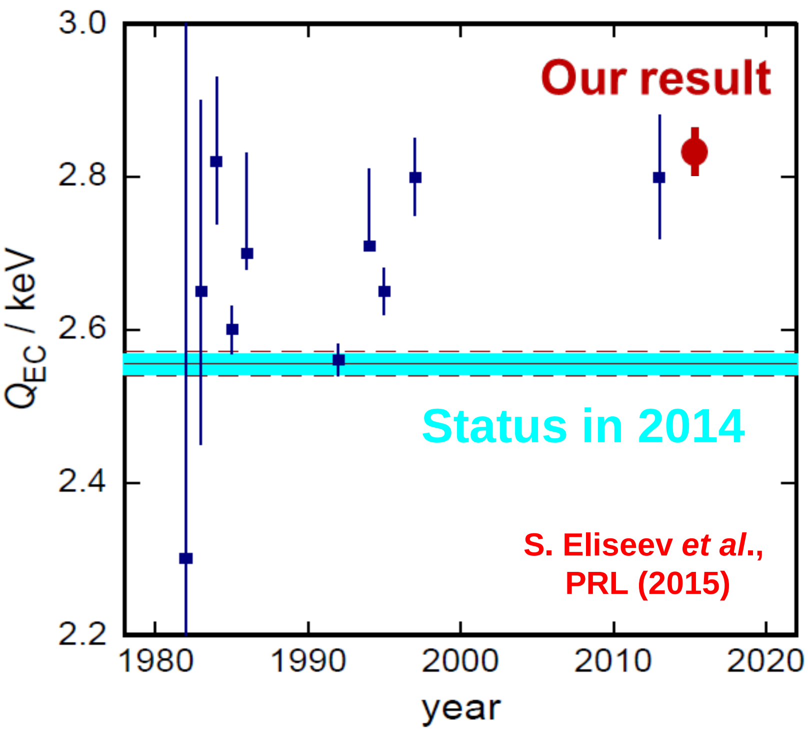
The ECHo (^{163}Ho) project

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

NEUTRONS FOR SCIENCE

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

Q-value of EC in ^{163}Ho

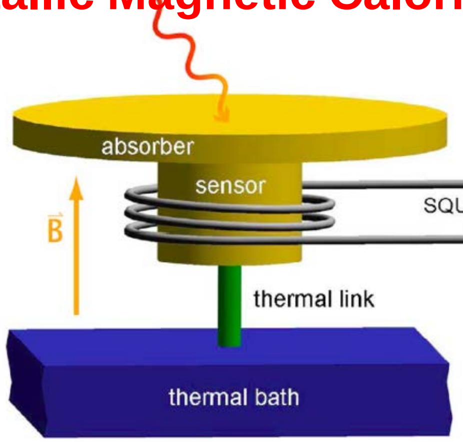


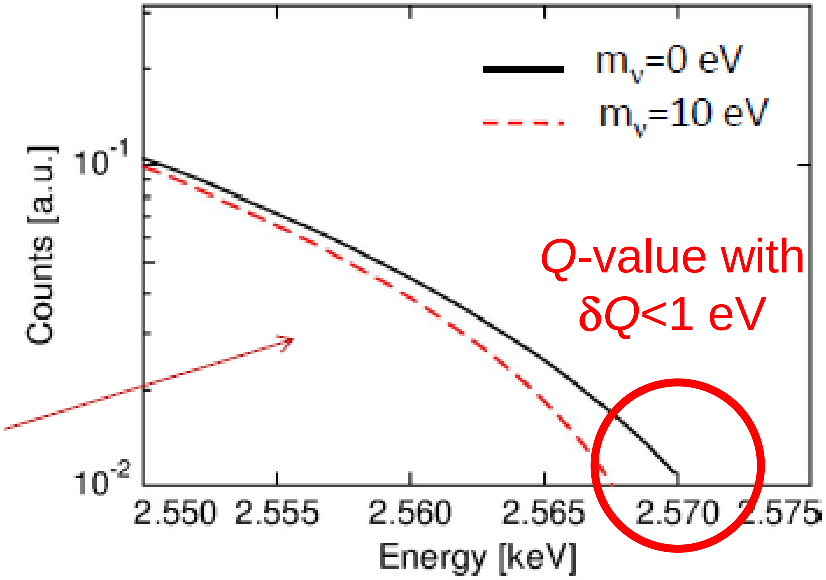
Our result

Status in 2014

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

Metallic Magnetic Calorimetry





Q-value with δQ<1 eV

Atomic masses IV

Test of CPT symmetry

BASE: CERN, GSI, Hannover, Mainz, MPIK, RIKEN

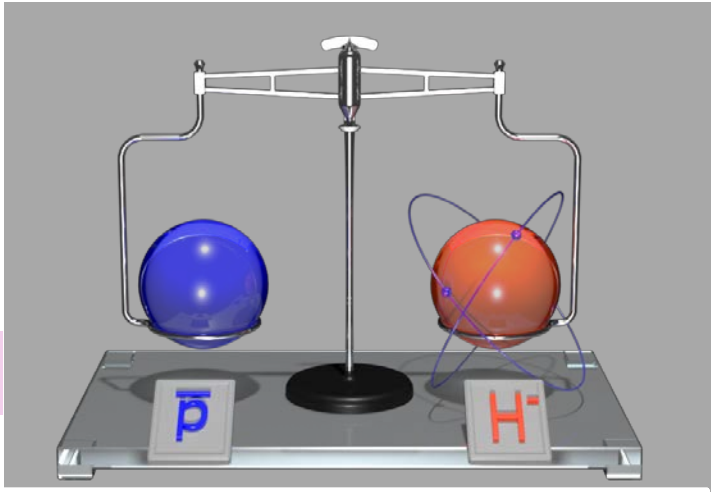
A. Mooser, Ch. Ospelkaus, W. Quint, S. Smorra, S. Ulmer, J. Walz

Most stringent baryonic CPT test

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)



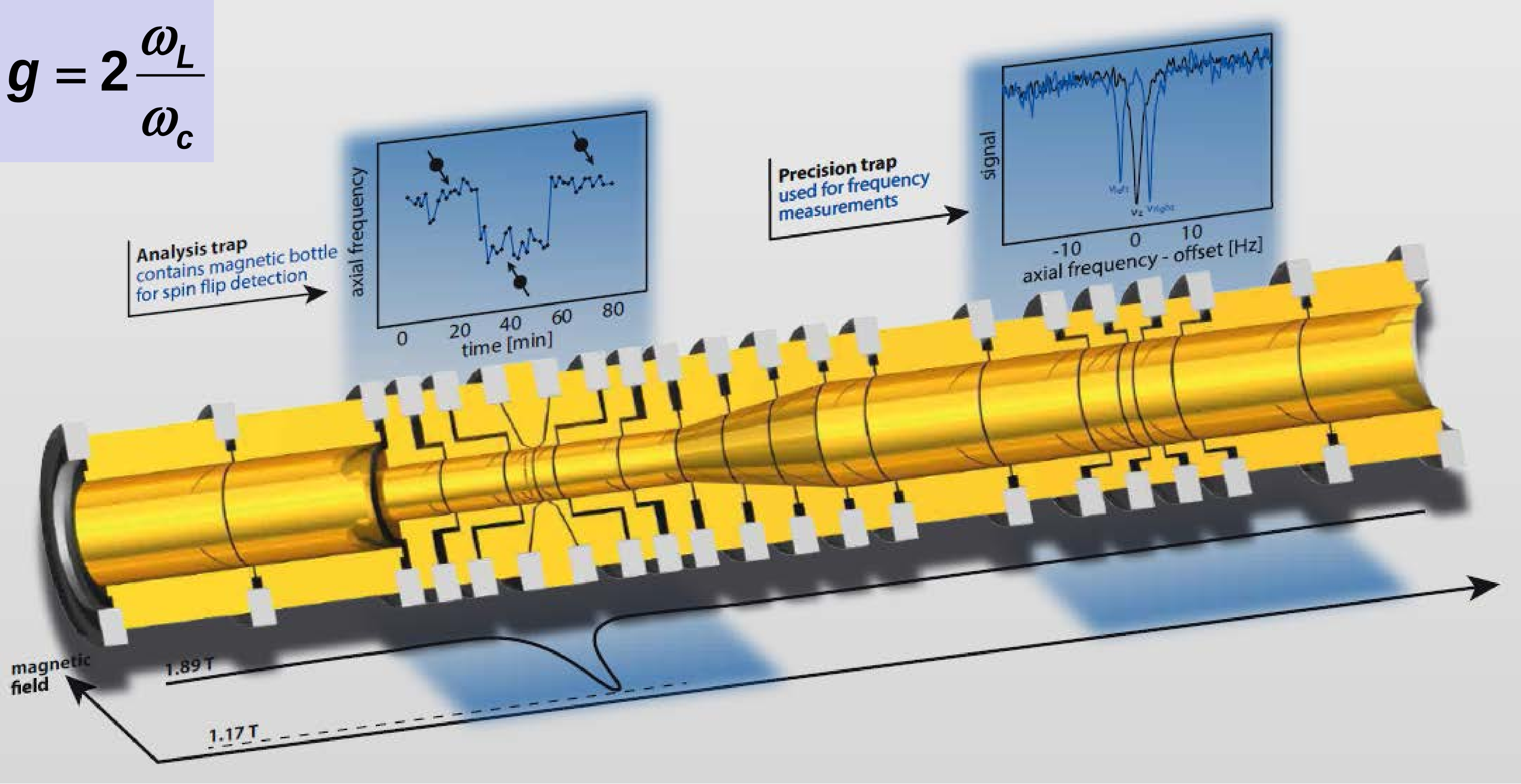
It is not that easy!

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

BASE

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)

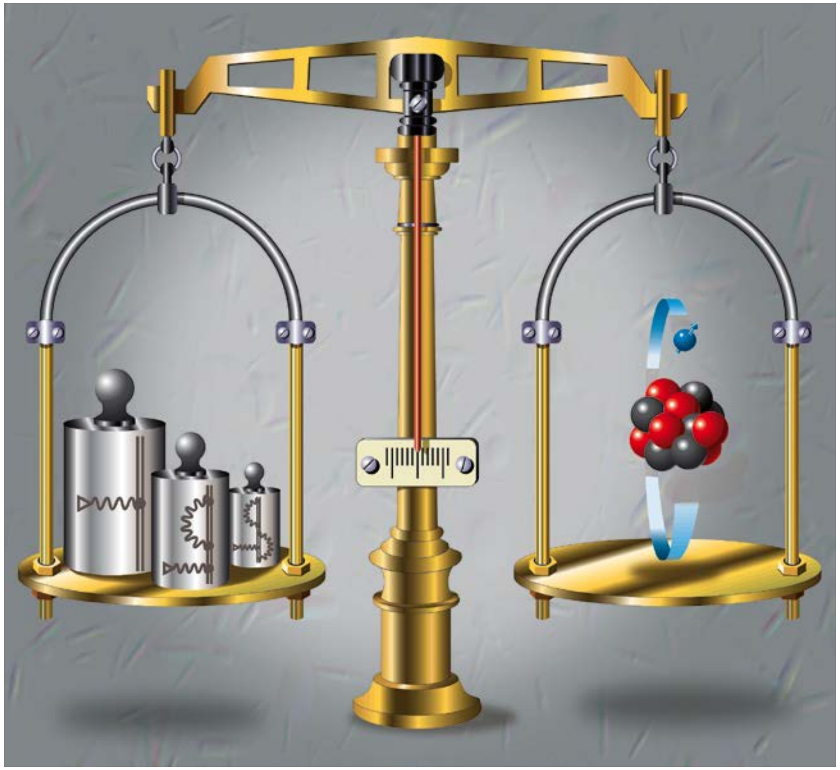
$\mu_{\bar{p}}$ = −2.792 847 344 1(42) μ_N

(1.5 ppb)

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

Atomic masses V

Fundamental constants



HCI-Trap: GSI, Mainz, MPIK, St. Petersburg

Z. Harman, ***Ch. Keitel***, **F. Köhler-Langes, W. Quint,** ***V. Shabaev***, **S. Sturm**

A 3-fold improved proton mass

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

$$m_p = 1.007\ 276\ 466\ 583\ (15)(29)\ u$$

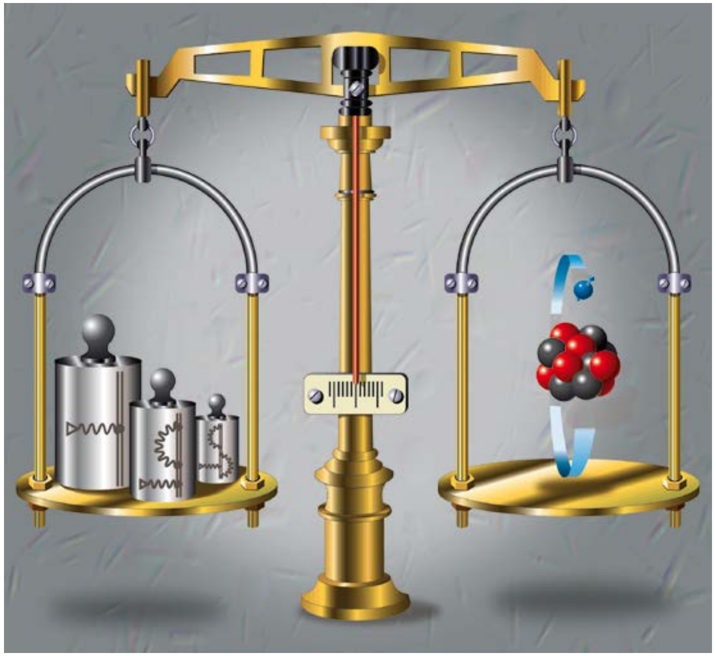
$$\frac{\delta m_p}{m_p} = 3.2 \cdot 10^{-11}$$

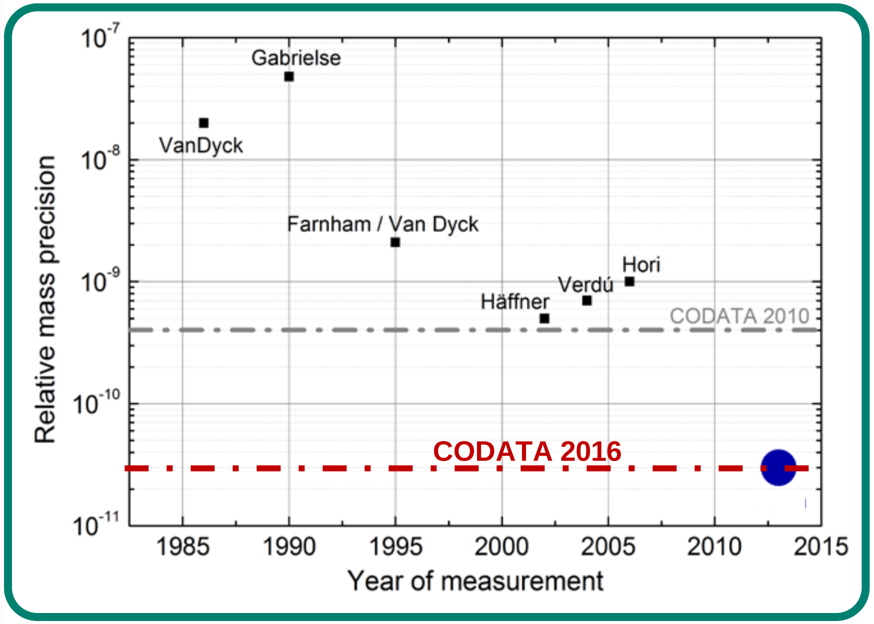
F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

A 13-fold improved electron mass

Electron mass from ultra-high precision *g*-factor of **hydrogenlike carbon:**

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





$m_e = 0.000548\,579\,909\,067(14)(9)(2)\mathrm{u}$

A factor of 13 improved value !

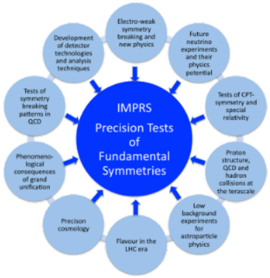
S. Sturm *et al.*, Nature 506, 467 (2014)

Conclusion

Exciting results in high-precision experiments with stored and cooled exotic ions have been achieved!

Thanks a lot for the invitation and your attention!

Max Planck Society



IMPRS-PTFS

Adv. Grant MEFUCO

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