*Winter Meeting Nuclear Physics, Bormio 2018*

# Precision atomic/nuclear physics measurements in Penning traps and tests of fundamental symmetries

- Precision atomic/nuclear masses
- The (anti)proton charge-to-mass ratio
- *g*-factors of bound electrons and $m_e$

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

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**Jan 22nd, 2018**

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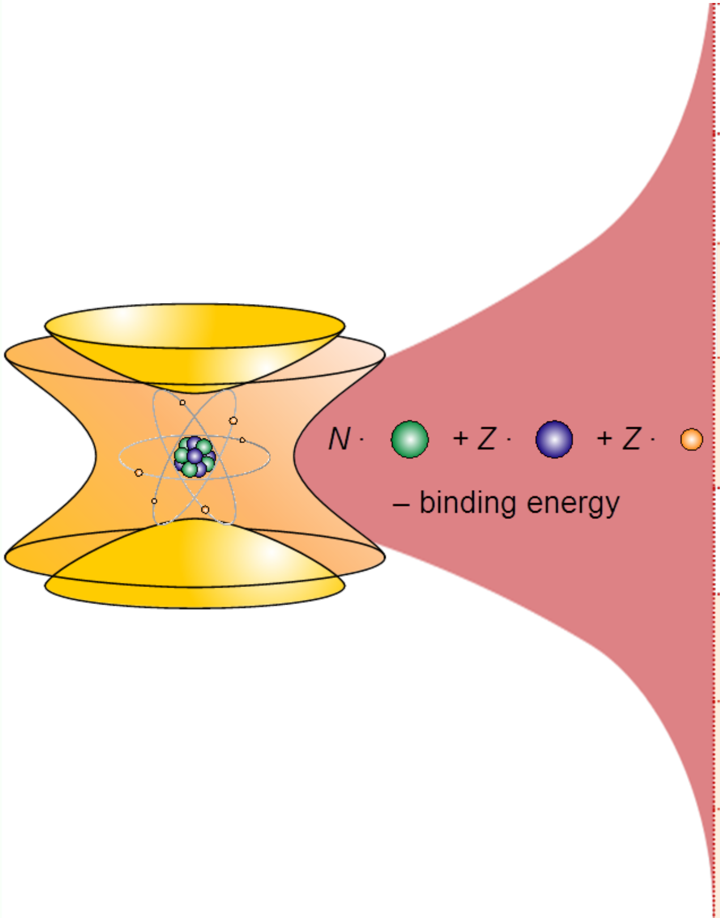
# Why measuring atomic masses?

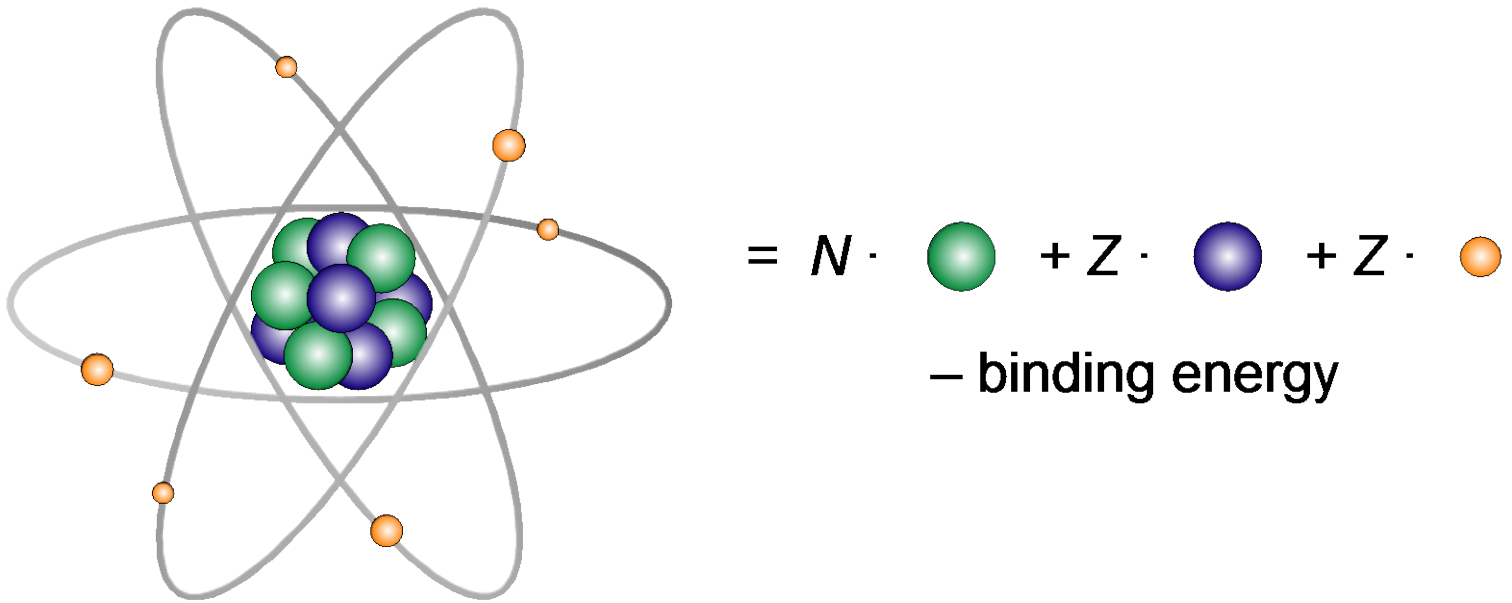



| | $\delta m/m$ | $\delta E$ |
|---|---|---|
| General physics & chemistry | $\leq 10^{-5}$ | 1 MeV |
| Nuclear structure physics<br>- separation of isobars | $\leq 10^{-6}$ | 100 keV |
| Astrophysics<br>- separation of isomers | $\leq 10^{-7}$ | 10 keV |
| Weak interaction studies | $\leq 10^{-9}$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

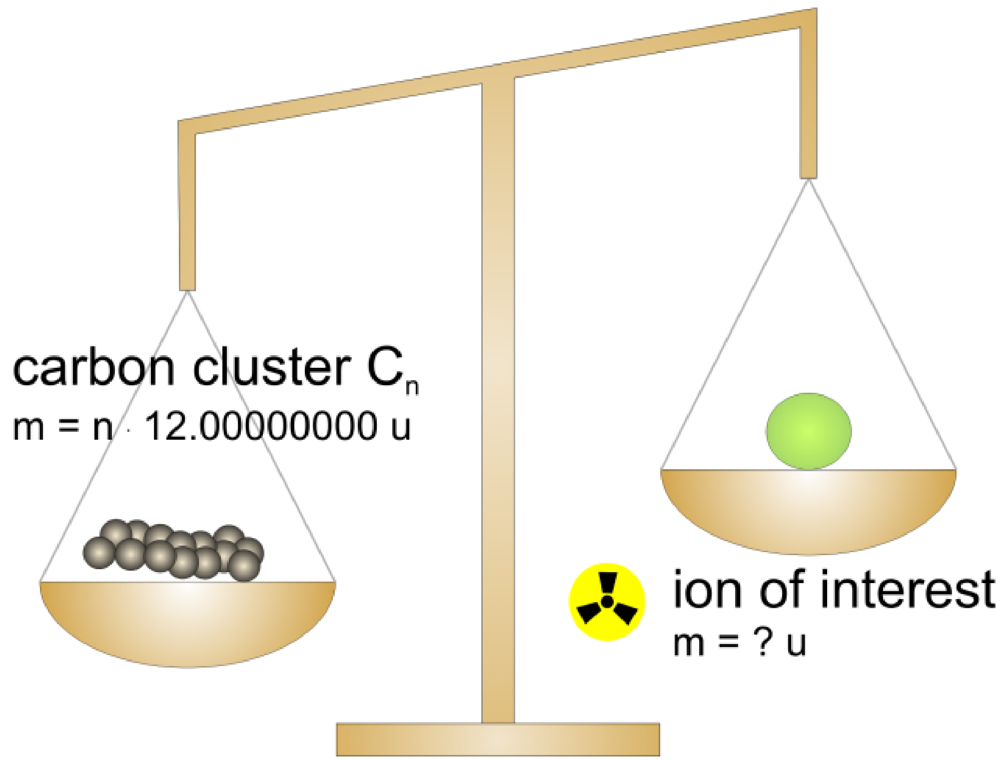



$$m_{\mathrm{Atom}} = N \bullet m_{\mathrm{neutron}} + Z \bullet m_{\mathrm{proton}} + Z \bullet m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

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

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

# How to weigh an atom




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

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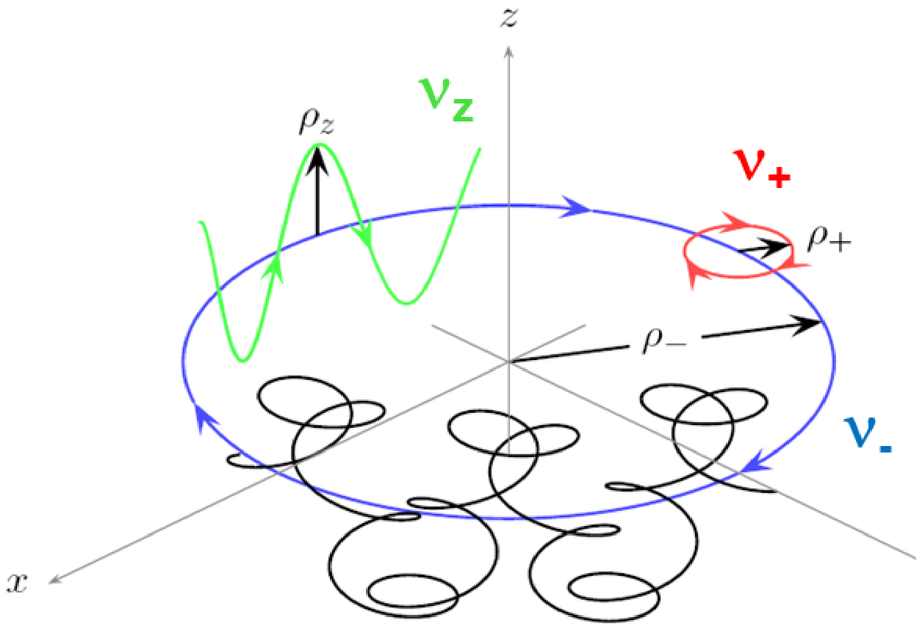
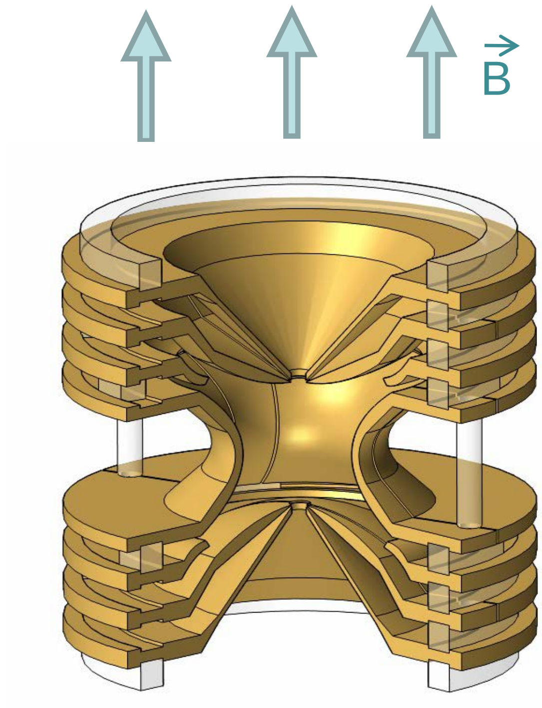
# Storage of ions in a Penning trap




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

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

***Invariance theorem:***

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

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

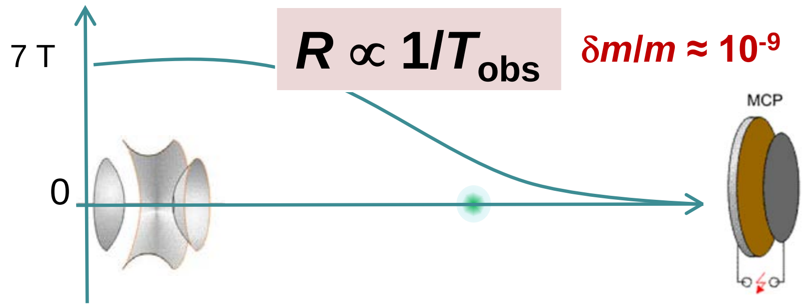
L.S. Brown, G. Gabrielse, Rev. Mod. Phys. 58, 233 (1986).

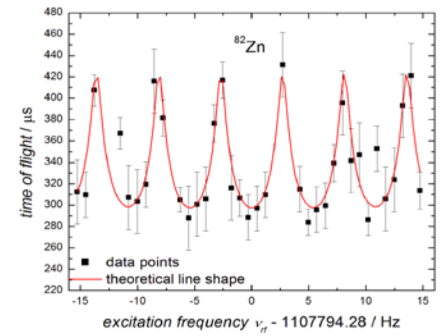
# Detection techniques

## Destructive time-of-Flight detection

$R \propto 1/T_{obs}$

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

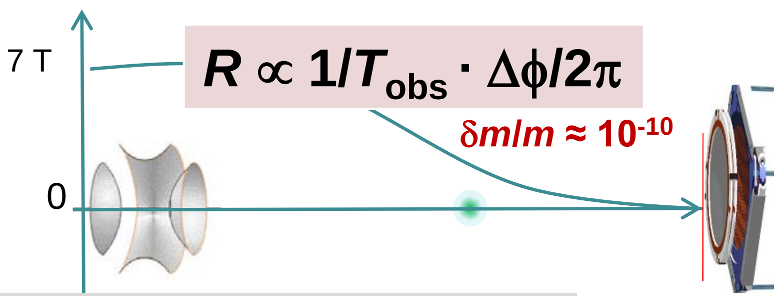


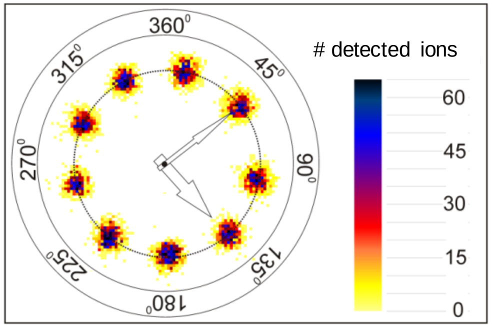




## Destructive phase-imaging detection

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

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

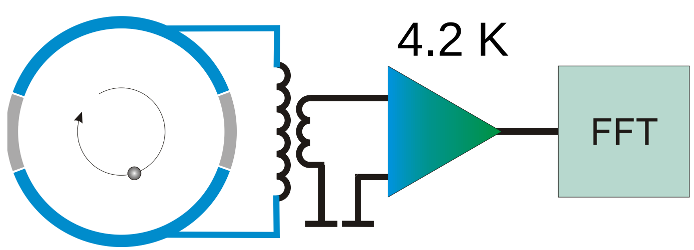


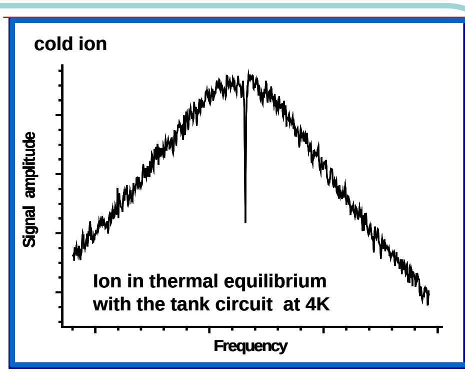




S. Eliseev *et al.*, Phys. Rev. Lett. 110, 082501 (2013)

## Non-destructive induced image current detection

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

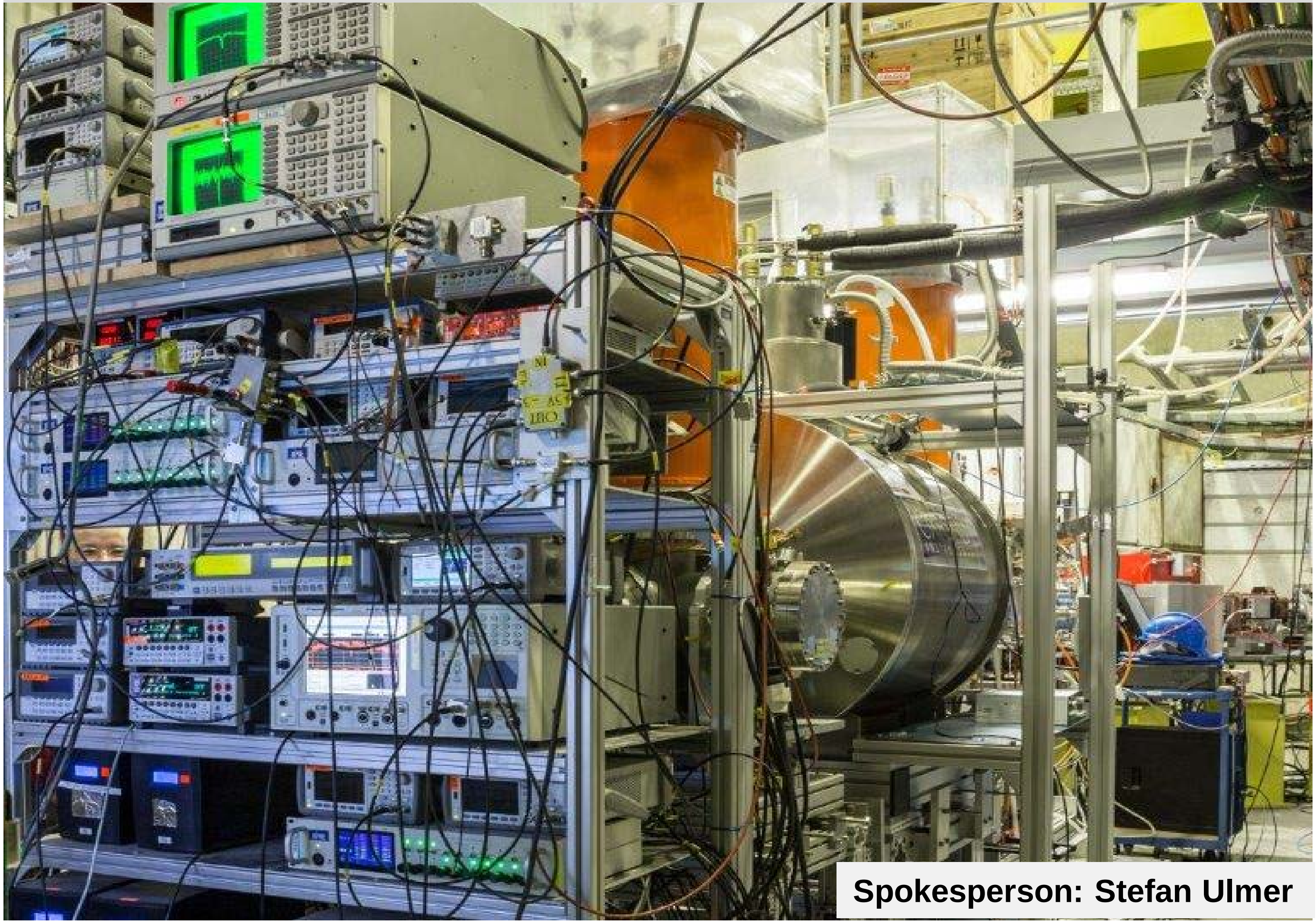



S. Sturm *et al.*, Phys. Rev. Lett. 107, 143003 (2011)

# BASE: A Penning-trap setup at CERN

## A balance for protons and antiprotons.



**Spokesperson: Stefan Ulmer**

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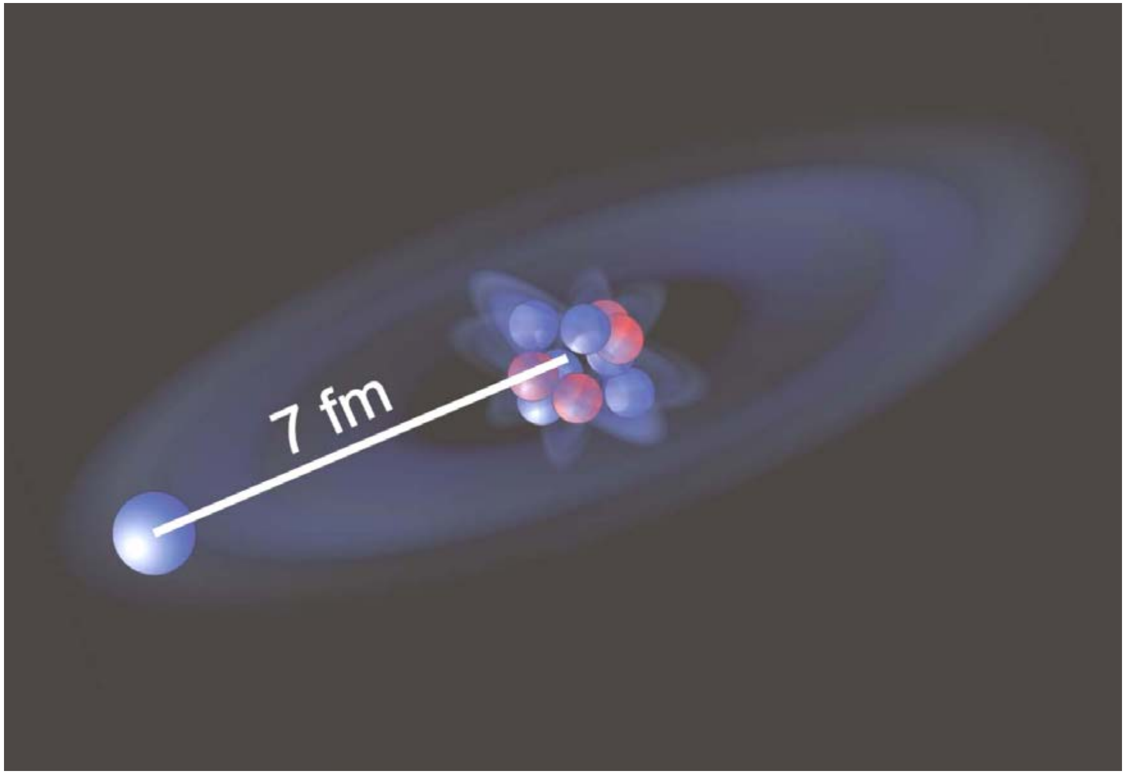
# Atomic masses I

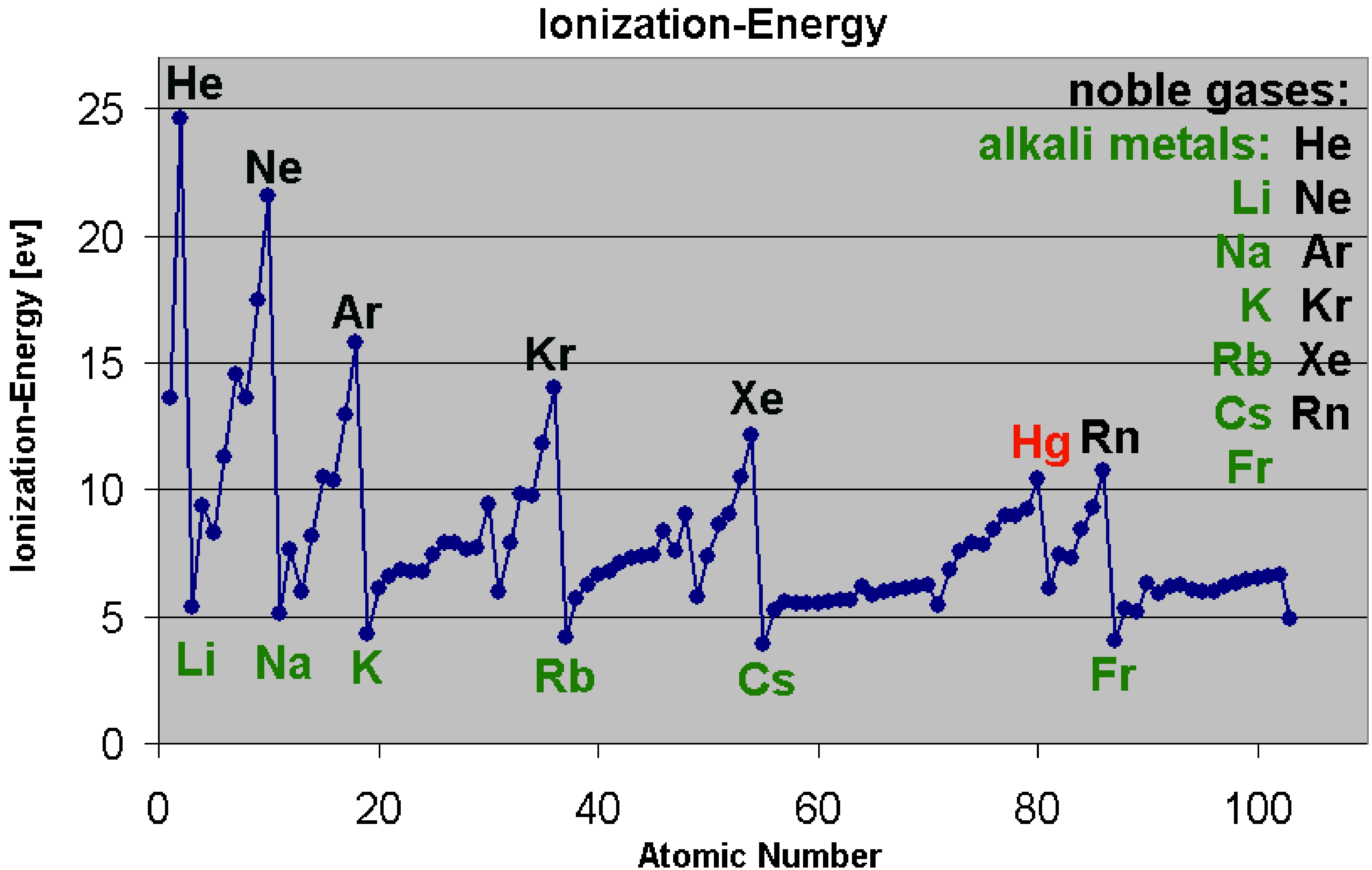
## Nuclear magic numbers




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

**M. Block, S. Eliseev, V. Manea, L. Schweikhard, *A. Schwenk***

# Atomic and nuclear structure: Basics

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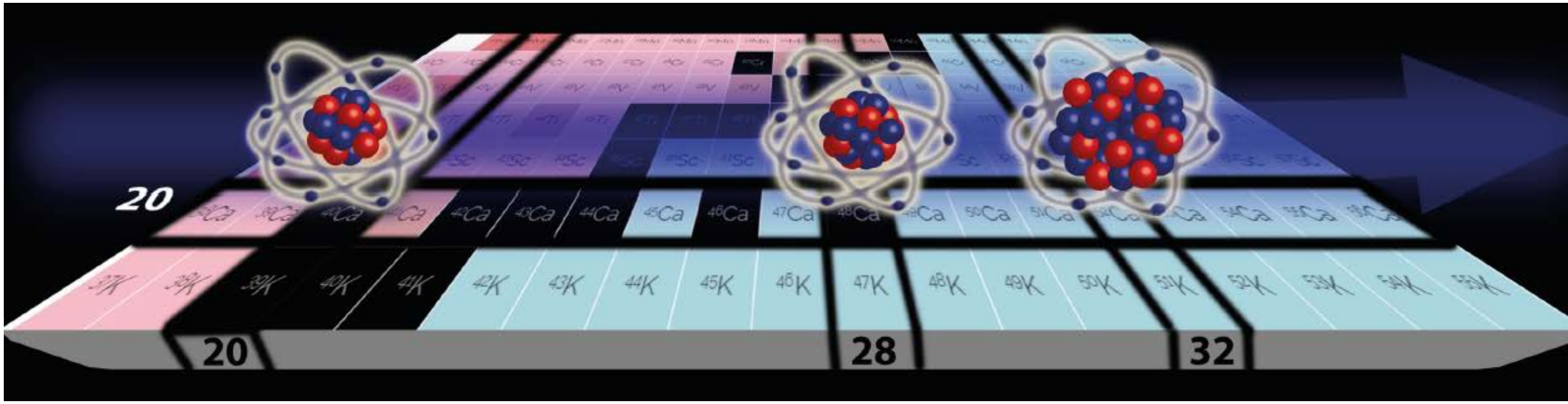
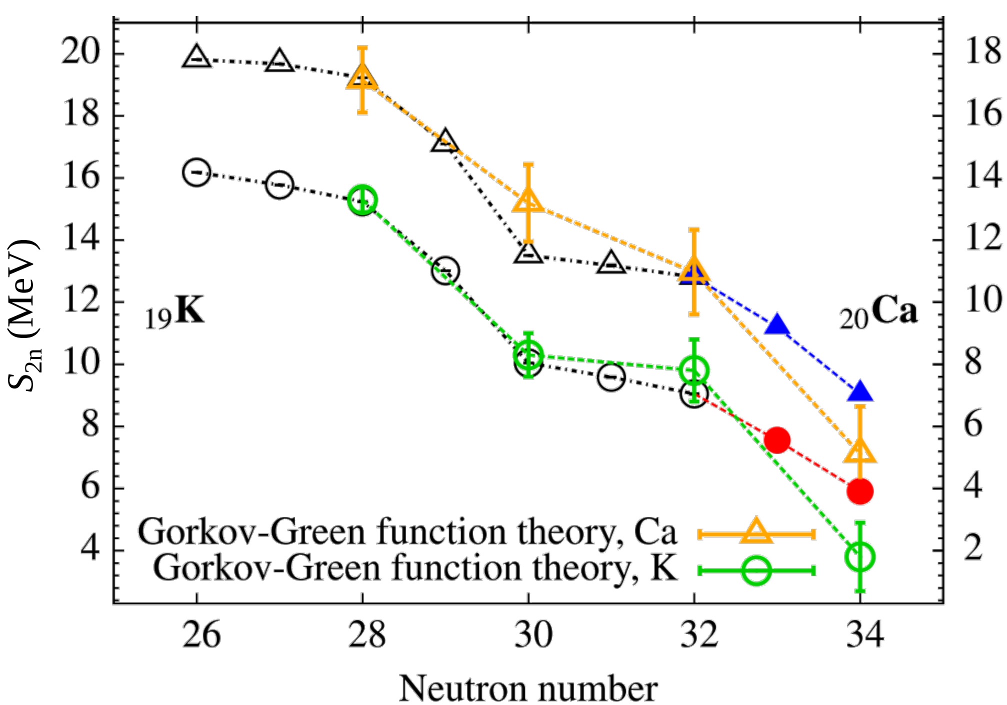
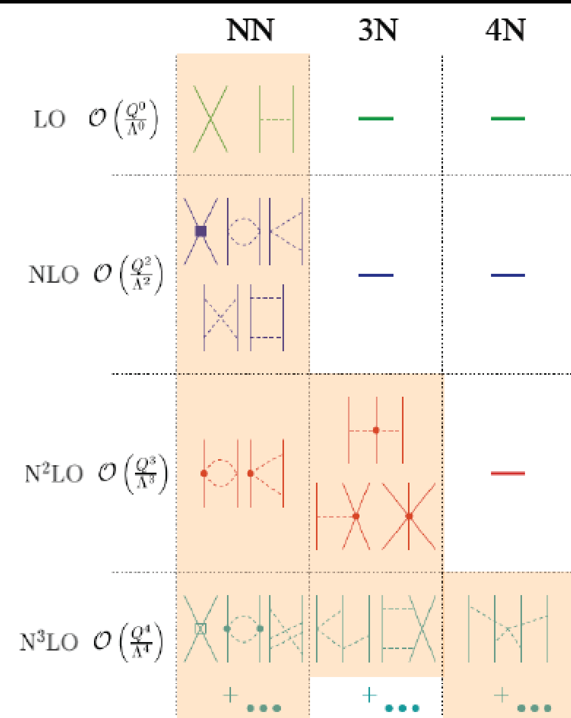
# New magic number ($N$=32) and 3N-forces

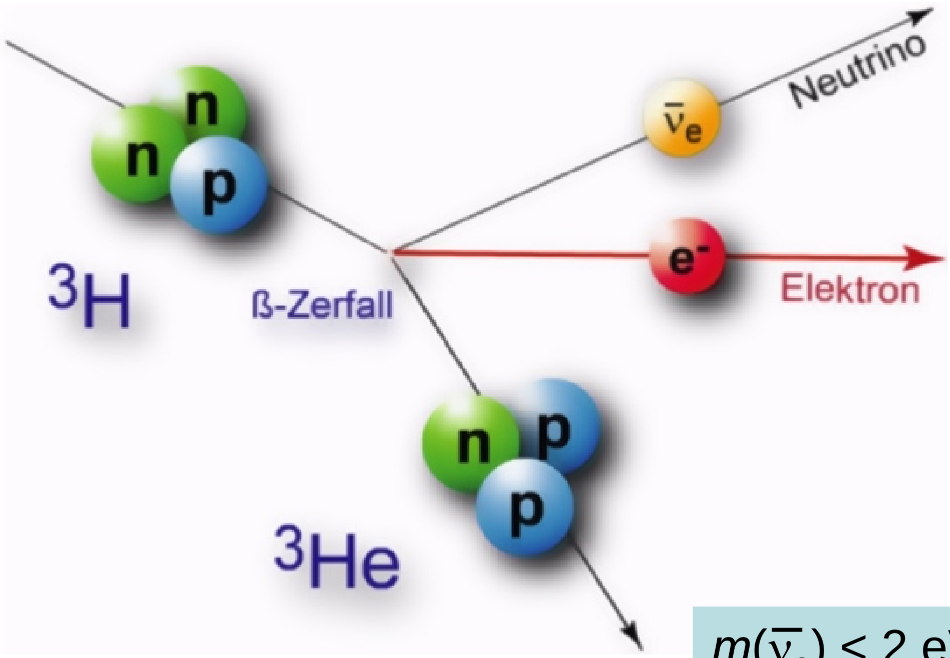


# Masses II

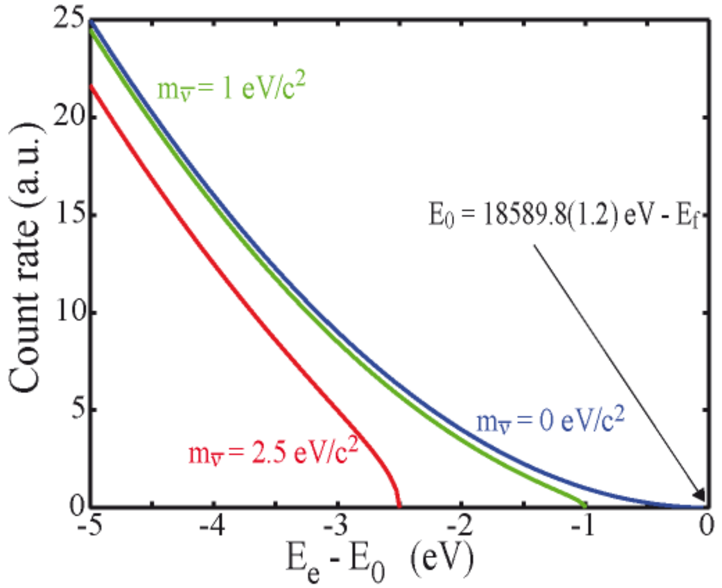
## Neutrino physics applications




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

# THe-TRAP for KATRIN

## A high-precision $Q(^3T-^3He)$-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)]

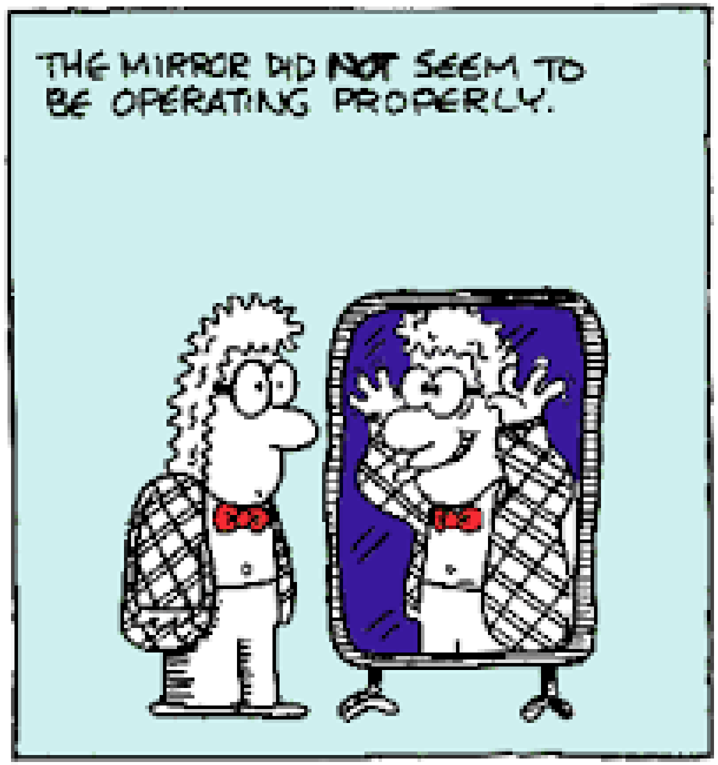
We aim for: $\delta Q(^3T \rightarrow ^3He)$ = 20 meV
$\delta m/m = 7 \cdot 10^{-12}$

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

First $^{12}C^{4+}/^{16}O^{6+}$ mass ratio measurement at $\delta m/m = 1.4 \cdot 10^{-11}$ performed.

# Atomic masses III

## Test of CPT symmetry




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

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

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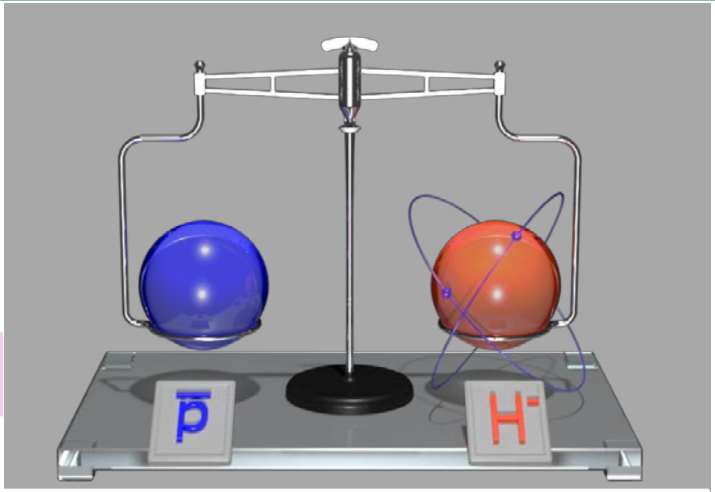
# Most stringent baryonic CPT test

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

# A 3-fold improved proton mass


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

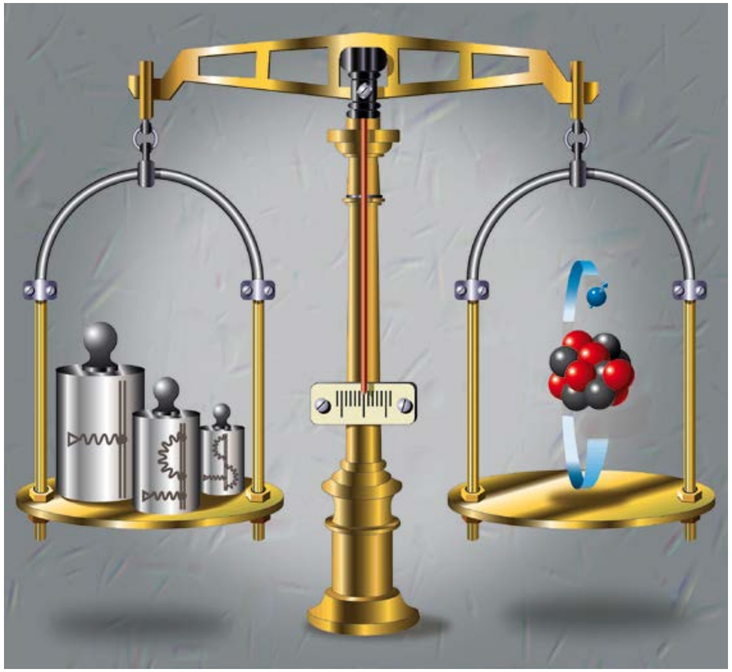
$$m_p = 1.007\,276\,466\,583\,(15)(29)\;u$$

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

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

# Atomic masses IV

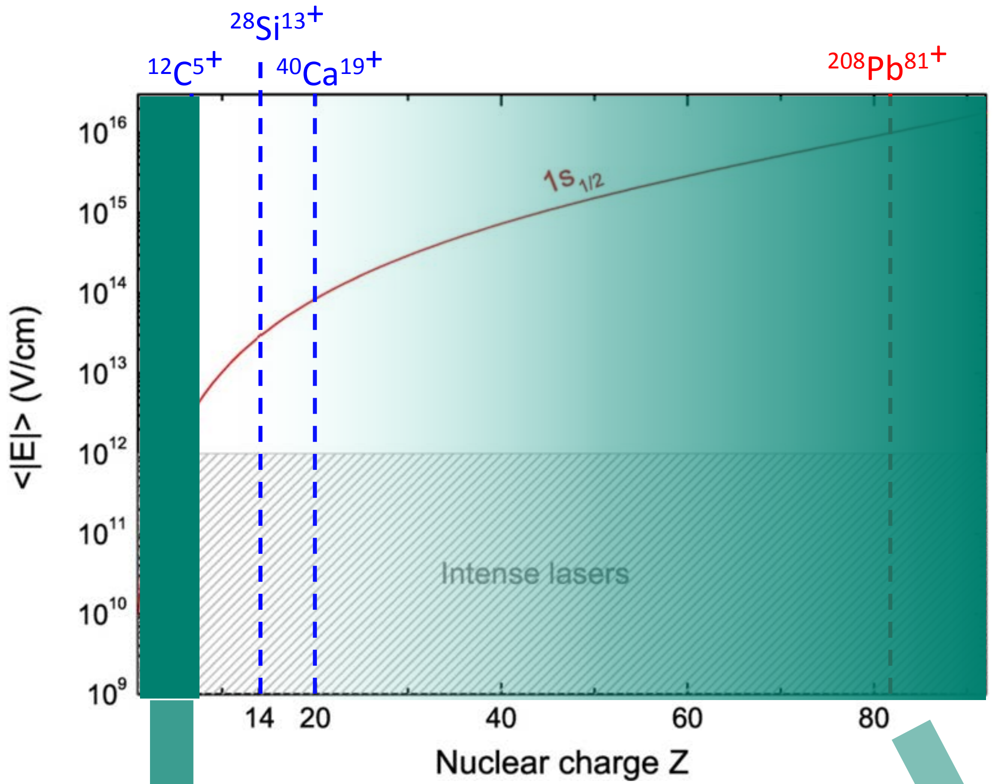
## The mass of the electron – A fundamental constant

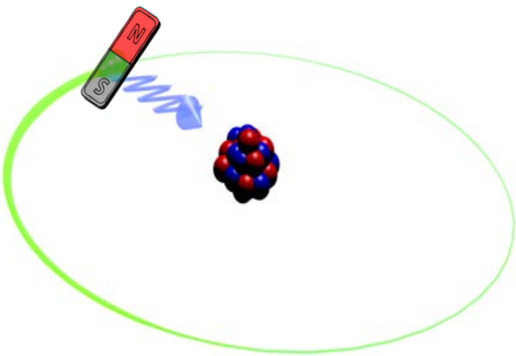


**HCI-Trap: GSI, Mainz, MPIK, St. Petersburg**

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

# Quantum electrodynamics of bound states




**Low** field strength

**High to ultra-high** field strength

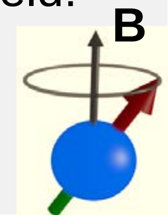
Extract fundamental constants (electron mass, fine structure constant)

The Standard Model in extreme conditions

# Measurement principle

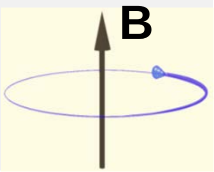
Measurement of the Larmor frequency in a well-known magnetic field:

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




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

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




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

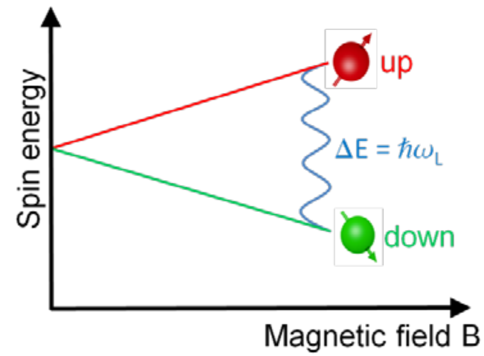
has to be determined

Measured by independent precision experiments

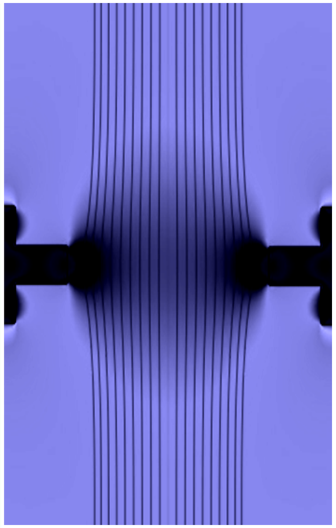
# Continuous Stern-Gerlach effect

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

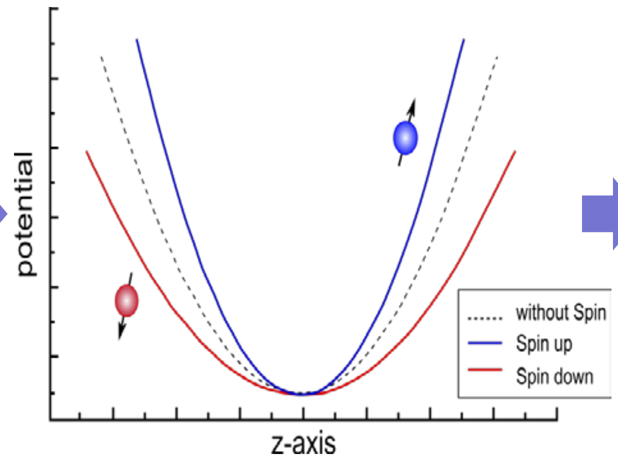
How to detect a successful spinflip ?



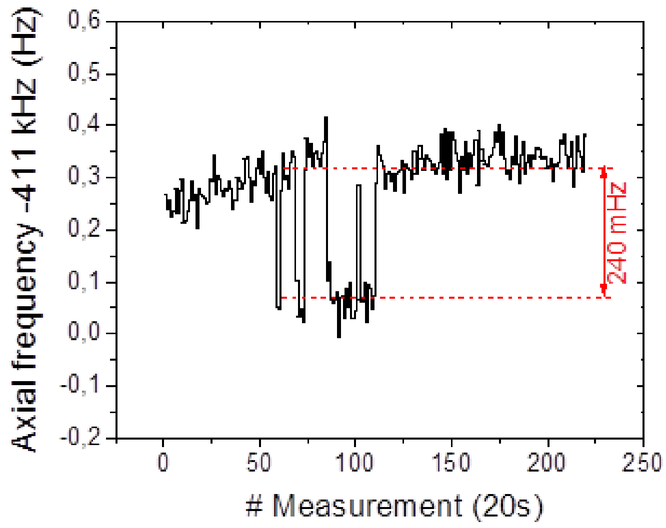

$$\omega_z = \sqrt{\frac{2e_0 U_0}{m d_0^2}}$$



Ferromagnetic ring
→ magnetic bottle




Spin dependent
trapping potential




Tiny axial frequency difference
between spin up and down.

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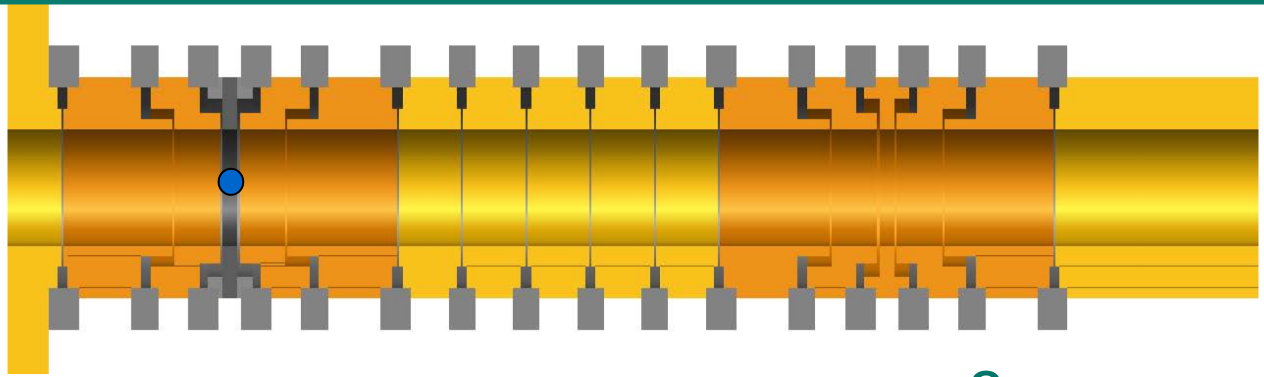
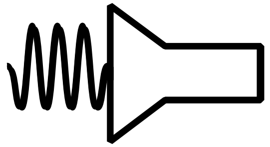
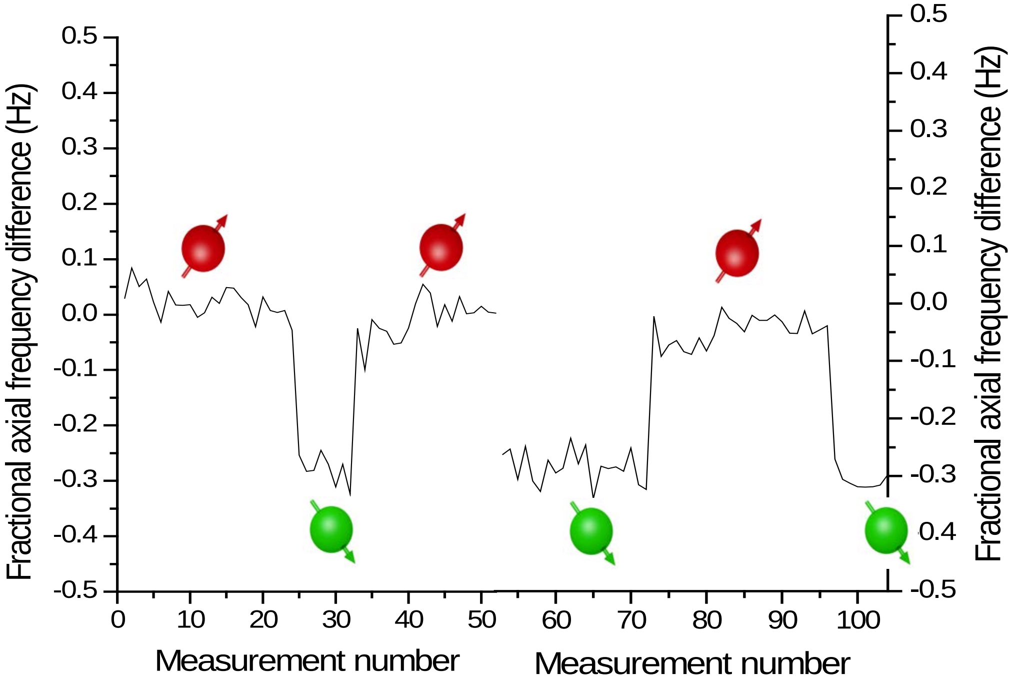
# *g*-factor measurement process








**One measurement cycle**

- **Detection of spin-orientation in analysis trap** **2-3min**
- **Transport to precision trap** **20s**
- **Measurement of eigenfrequencies and simultaneous irradiation with microwaves** **10min**
- **Transport to analysis trap** **20s**
- **Detection of spin orientation in analysis trap**

**→Spin flip in the precision trap?**

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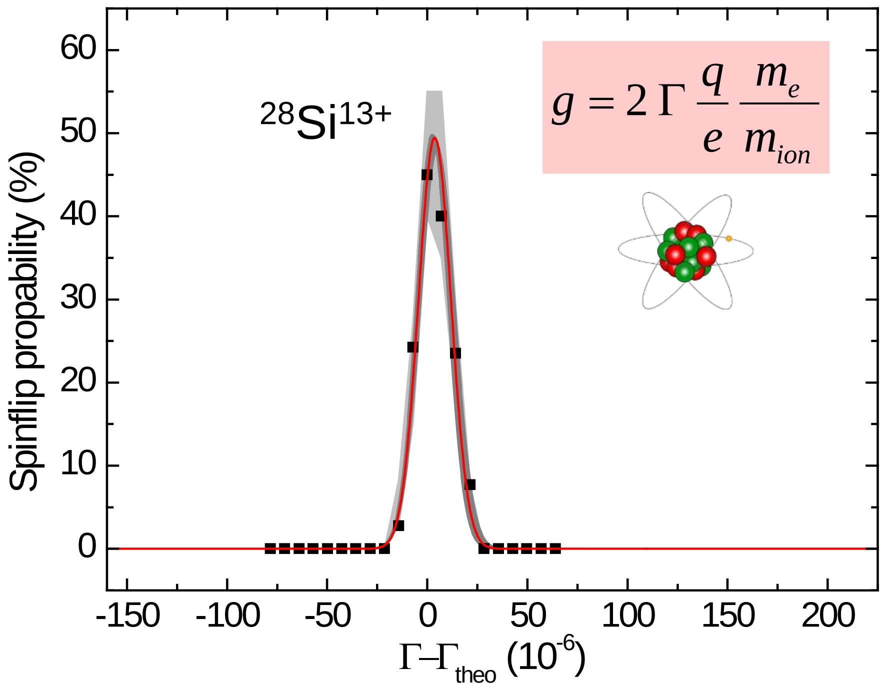
# *g*-factor resonance of a single $^{28}Si^{13+}$ ion




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

Electron mass can be improved by a factor of >10 if repeated for $^{12}C^{5+}$.

Most stringent test of BS-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)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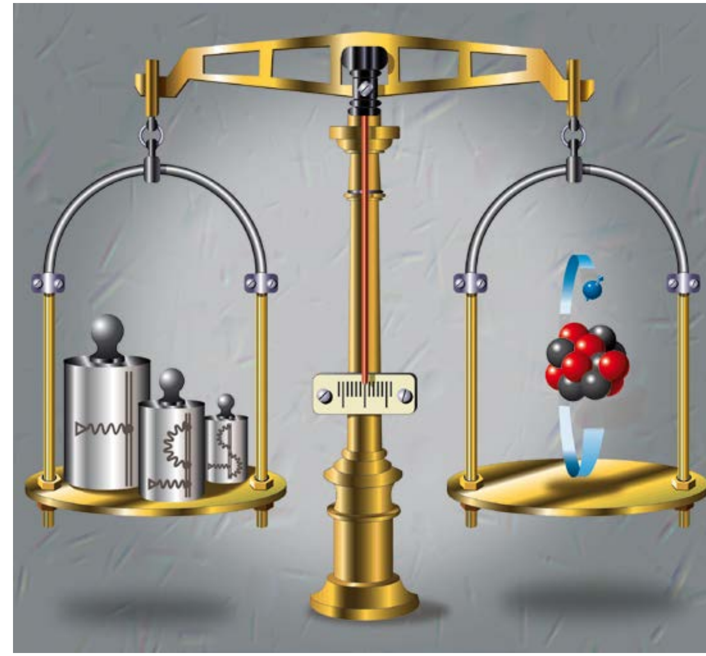
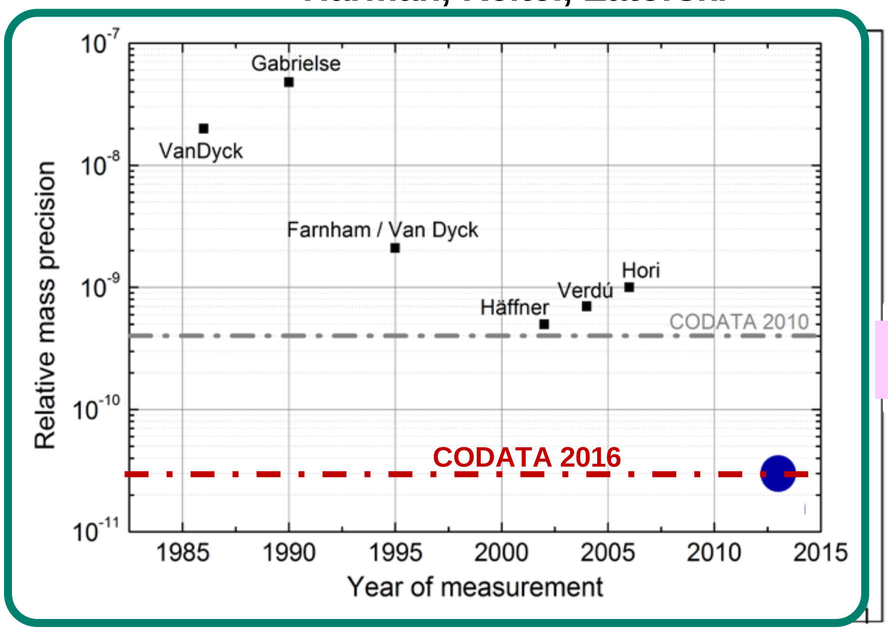
# A 13-fold improved electron mass

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

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



**Harman, Keitel, Zatorski**



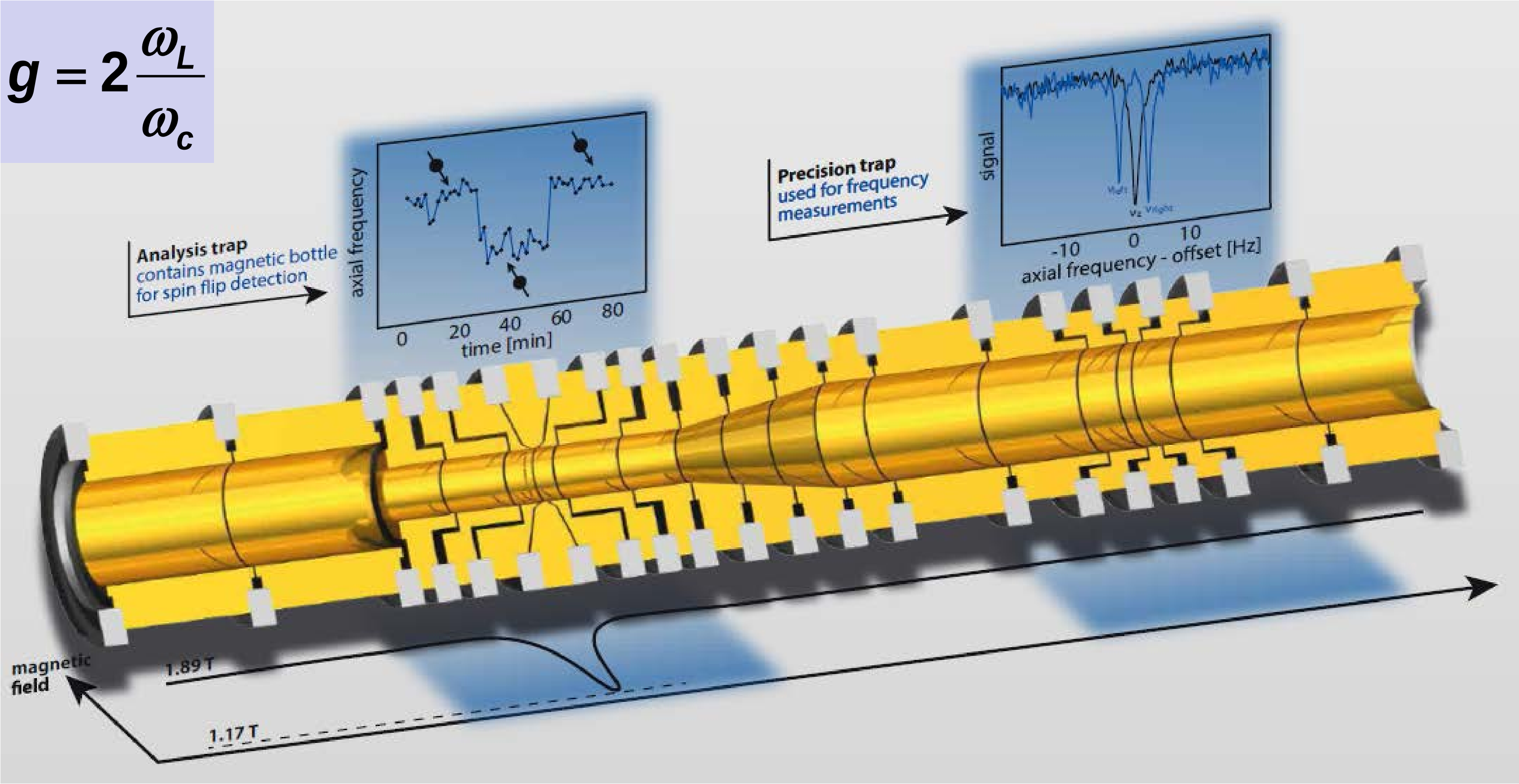

$m_e = 0.000548\,579\,909\,067(14)(9)(2)\text{u}$

**A factor of 13 improved value !**

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

# The (anti-)proton magnetic moment

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




$\mu_p$ = 2.792 847 344 62(82) $\mu_N$

**(0.3 ppb)**

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

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

**(1.5 ppb)**

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

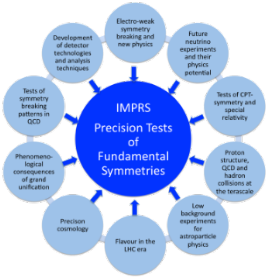
# Conclusion

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

***Presently running or planned experiments:***

**the mass of the neutron**
**improved *E=mc²* test**
**improved value for $\alpha$**
**(anti-)p *g*-factor measurement**

**Thanks a lot for the invitation and your attention!**




*Max Planck Society* *IMPRS-PTFS* *Adv. Grant MEFUCO* *Helmholtz Alliance*

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