Table-Top Experiments, Workshop at MIT 2017

Precision tests of fundamental interactions and their symmetries with cooled and stored exotic ions

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

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Aug 10th, 2017

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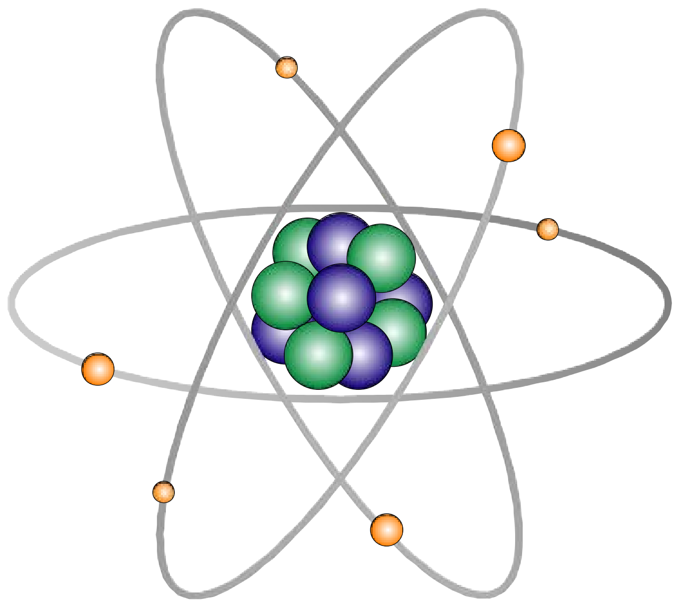
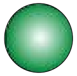
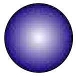
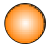
Atomic and nuclear masses

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



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

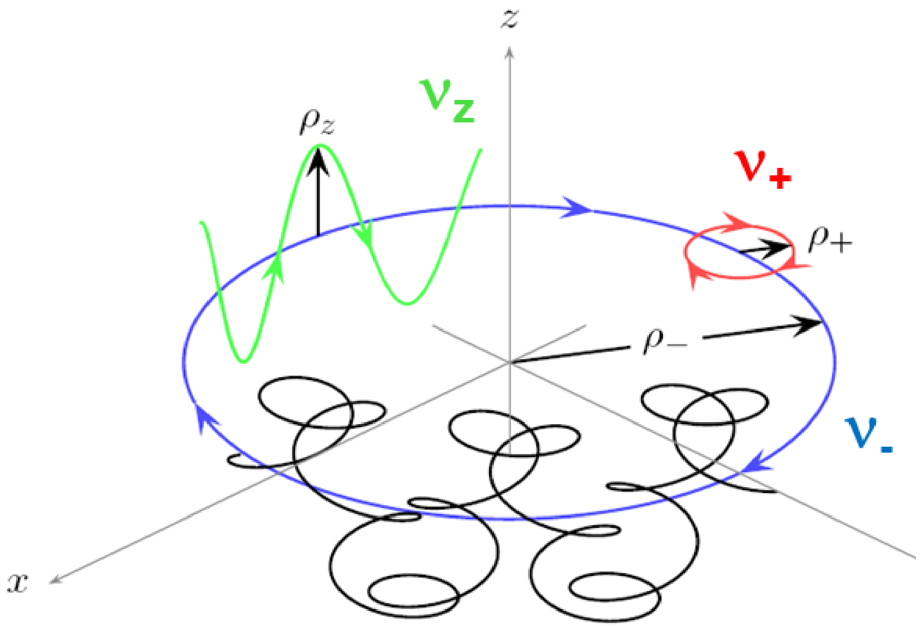
– binding energy

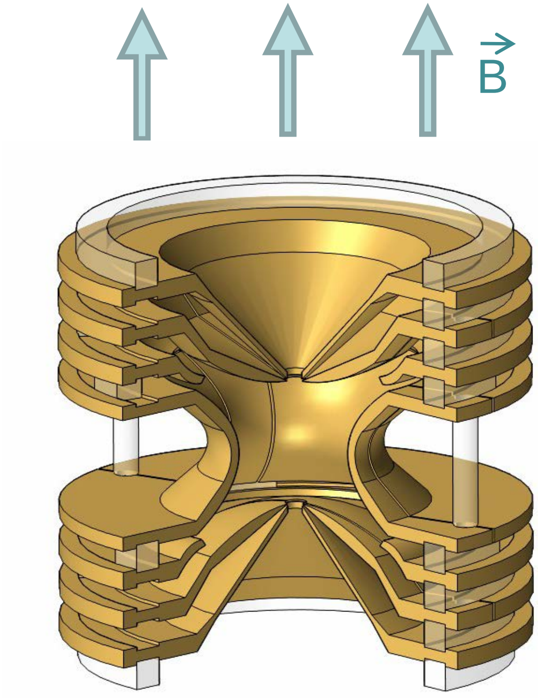
$$m_{\text{Atom}} = N \bullet m_{\text{neutron}} + Z \bullet m_{\text{proton}} + Z \bullet m_{\text{electron}} - (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

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

$\delta m/m = 10^{-6} – 10^{-8}$

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).

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Detection techniques

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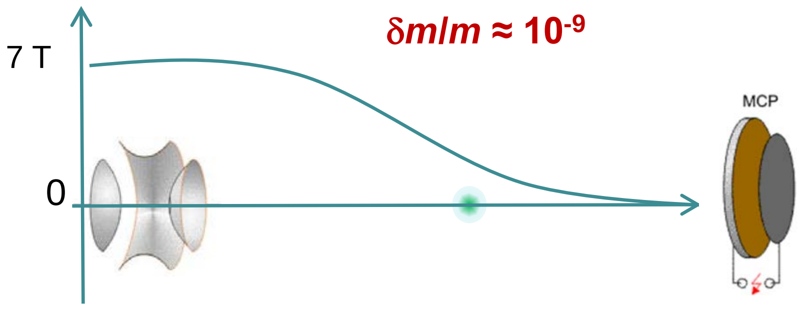
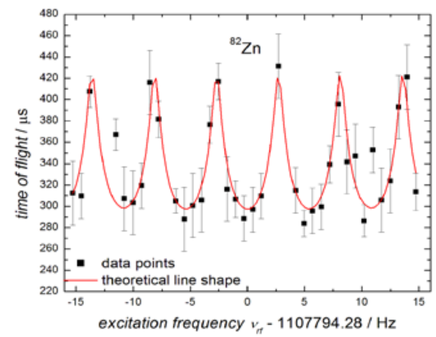
Destructive time-of-Flight detection

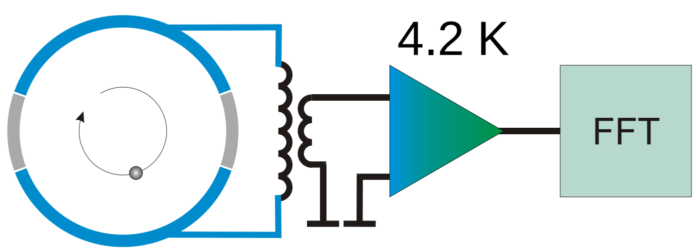
$\delta m/m \approx 10^{-9}$

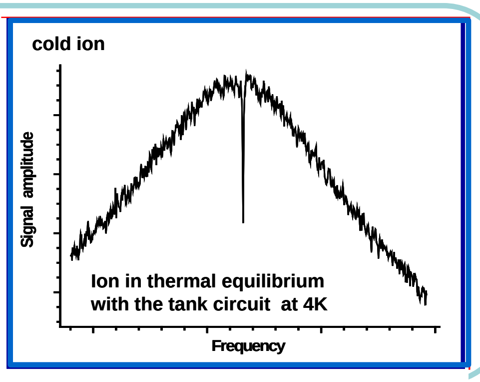




Non-destructive induced image current detection

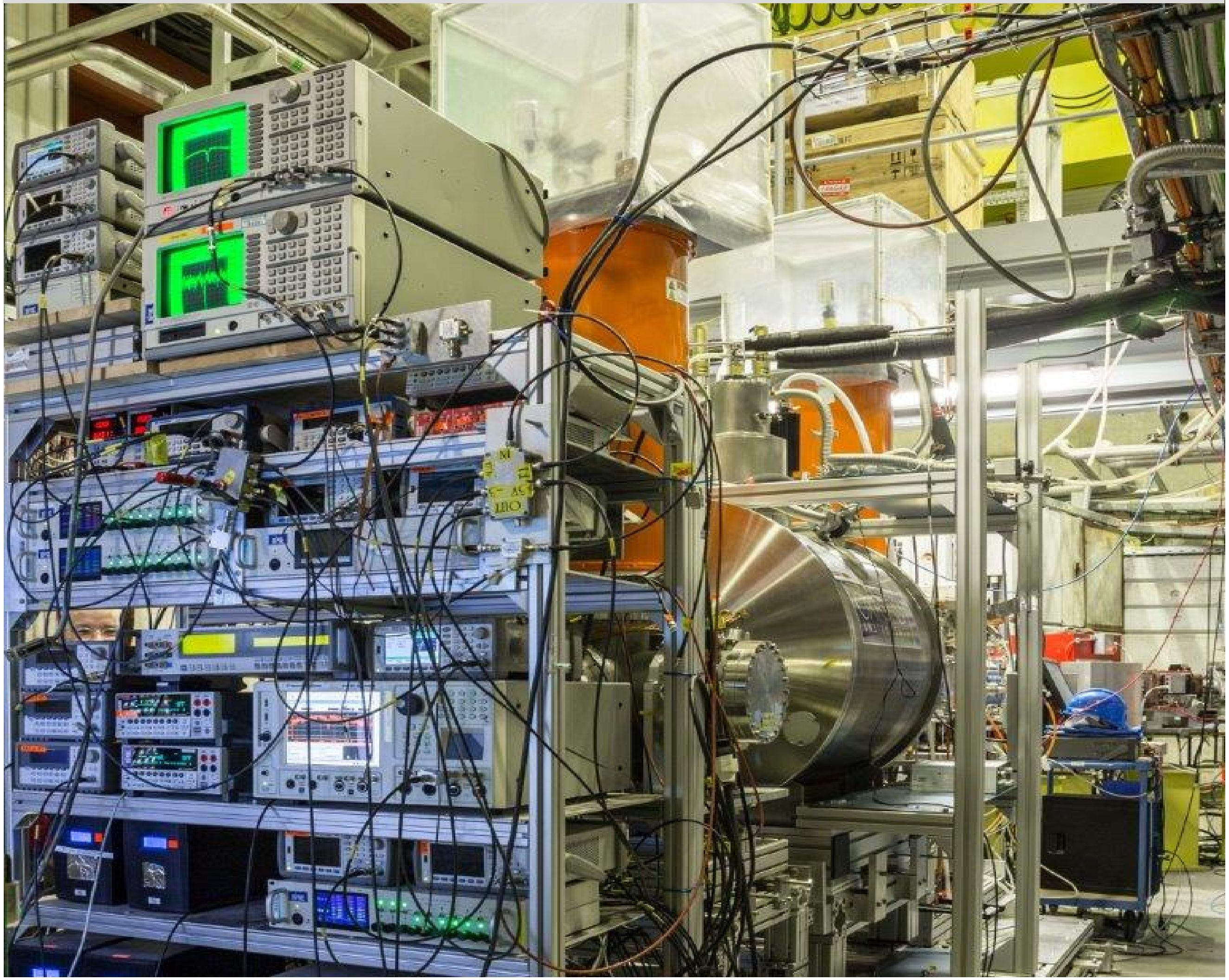
$\delta m/m \approx 10^{-11}$





BASE: A Penning-trap setup at CERN

A balance for protons and antiprotons.



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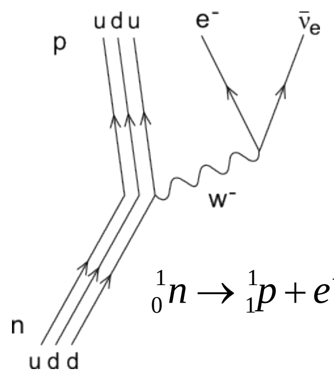
Masses I

Test of the unitarity of the quark-mixing matrix

Weak Interaction

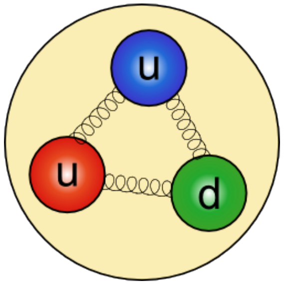
- Radioactive decay



$$ {}^{1}_{0}n \rightarrow {}^{1}_{1}p + e^{-} + \overline{\nu}_{e} $$

Strong Interaction

- Binding between quarks within hadrons



Superallowed β-decays

- Corrected value:

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

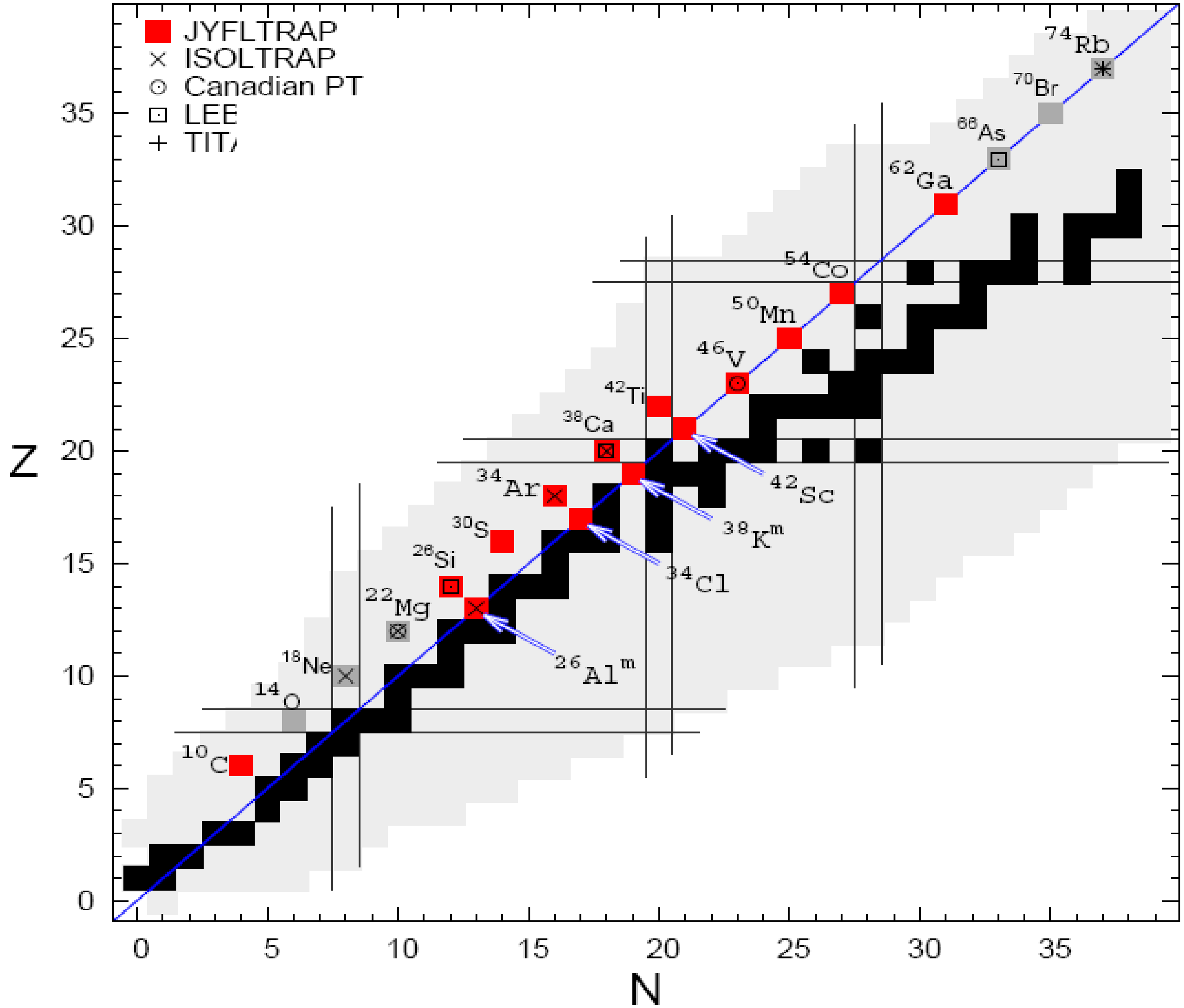
- Corrections about 1% [Towner and Hardy, Phys. Rev. C 77, 025501 (2008)]
- Cabibbo-Kobayashi-Maskawa quark mixing matrix

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

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

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

Superallowed β-decays



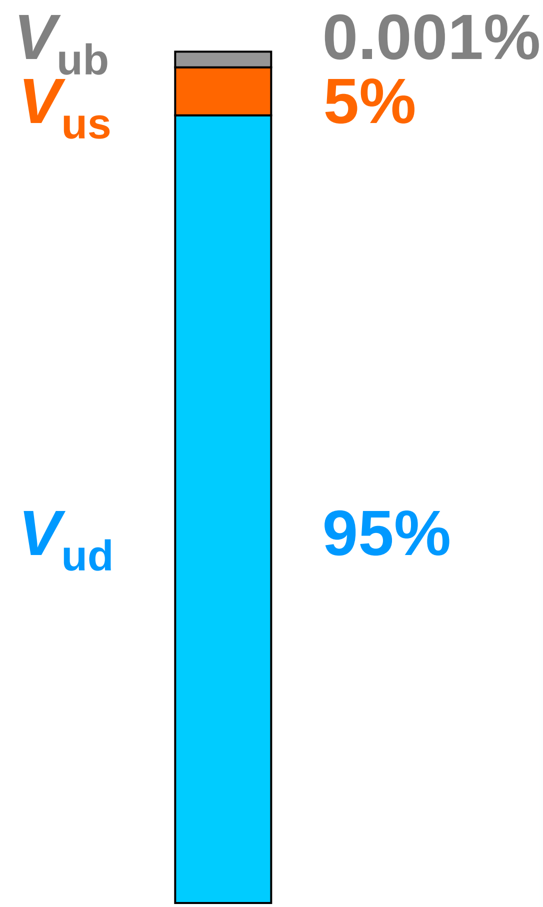
Test of the CKM unitarity

Check unitarity via first row elements:

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

V_{us} and V_{ub} from particle physics data
(*K* and *B* meson decays)

Unitarity contribution:



Present status:

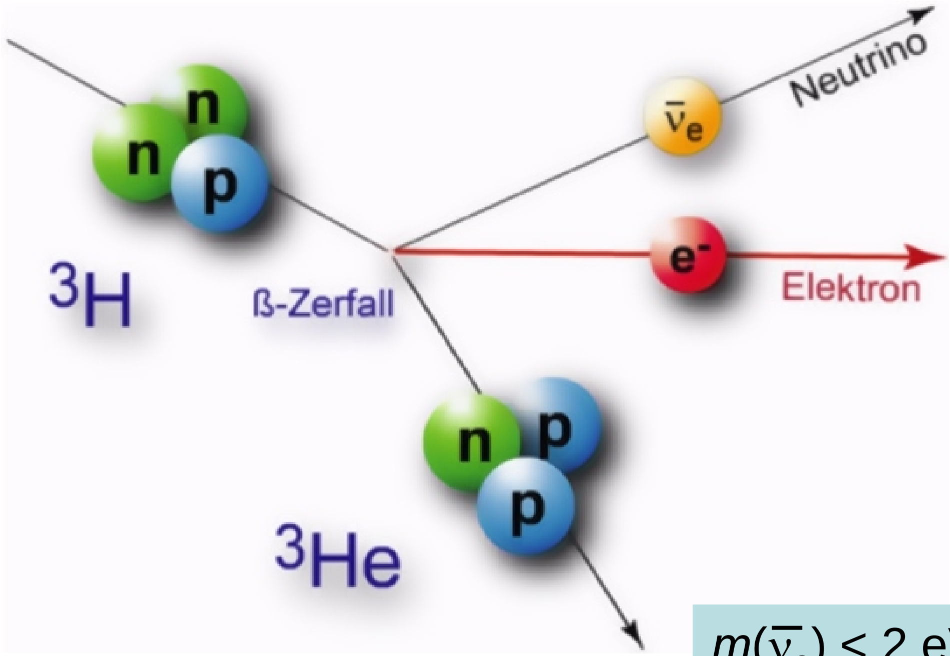
V_{ud} (nuclear β-decay) = 0.97417(21)
V_{us} (kaon-decay) = 0.2253(14)
V_{ub} (B meson decay) = 0.0037(5)

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

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

Masses II

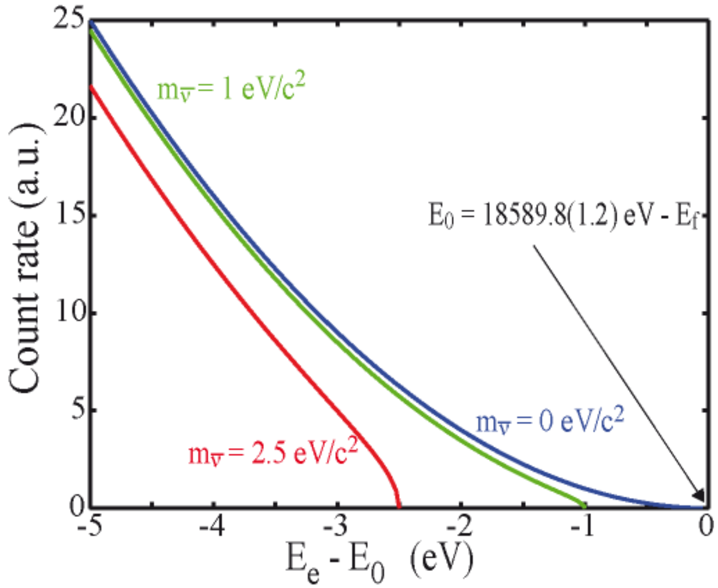
Neutrino physics applications



$m(\bar{\nu}_e) < 2$ 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
$\delta m/m = 7 \cdot 10^{-12}$

$\Delta T < 0.02$ 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 $\delta m/m = 1.4 \cdot 10^{-11}$ performed.

The ECHo (^{163}Ho) project

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

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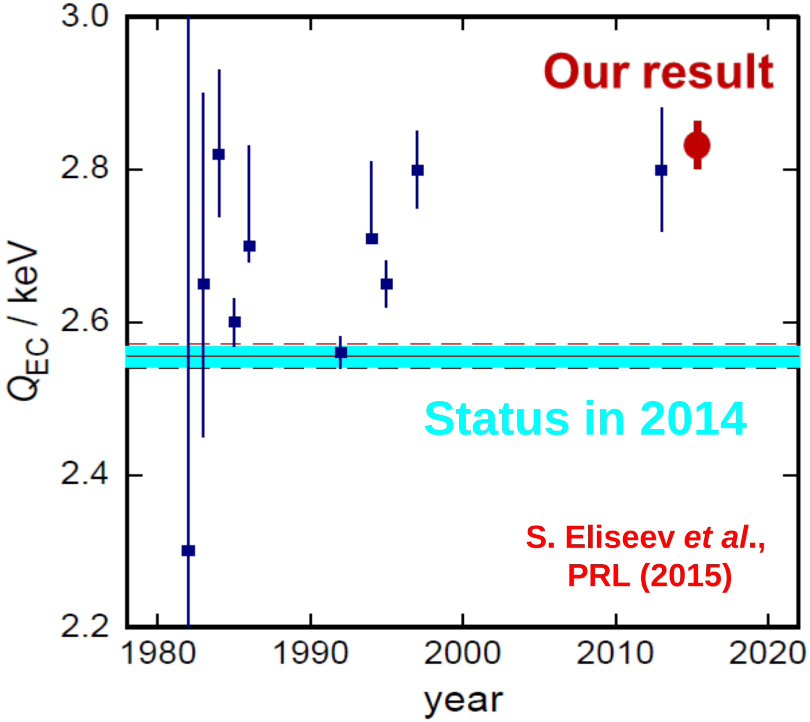
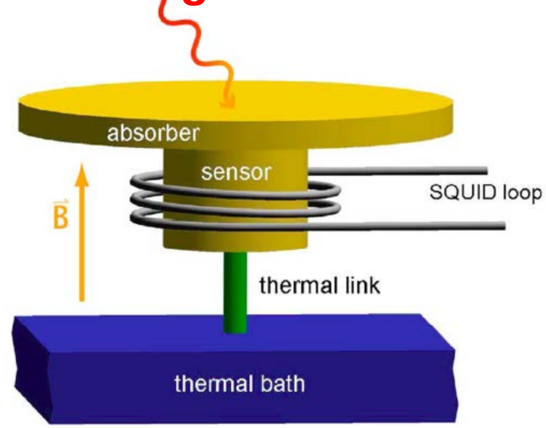
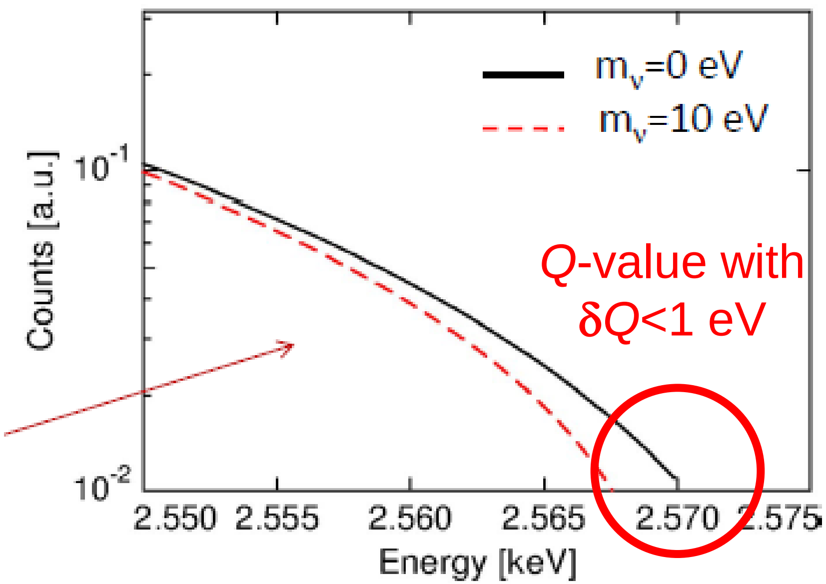
$$^{163}_{66}\mathrm{Dy}^* \rightarrow {}^{163}_{66}\mathrm{Dy} + E_C$$

Q-value of EC in ^{163}Ho



Metallic Magnetic Calorimetry





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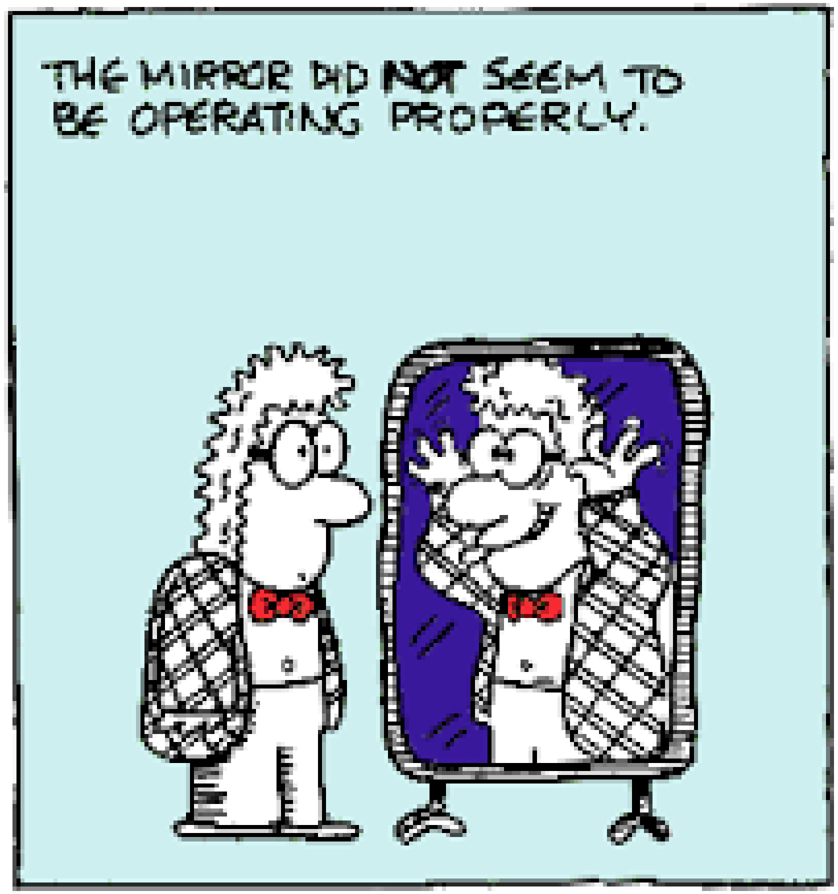
Atomic masses III

Test of CPT symmetry

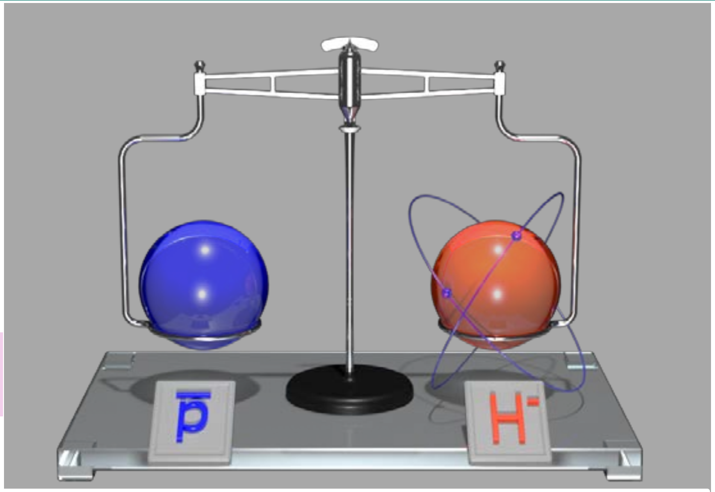


Most stringent baryonic CPT test

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!

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

Atomic masses IV

The mass of the electron –
A fundamental constant

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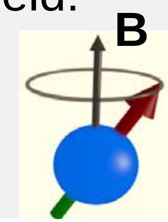
Measurement principle

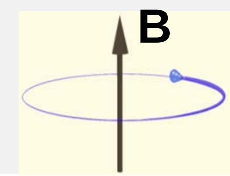
Measurement of the Larmor frequency in a well-known magnetic field:

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



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

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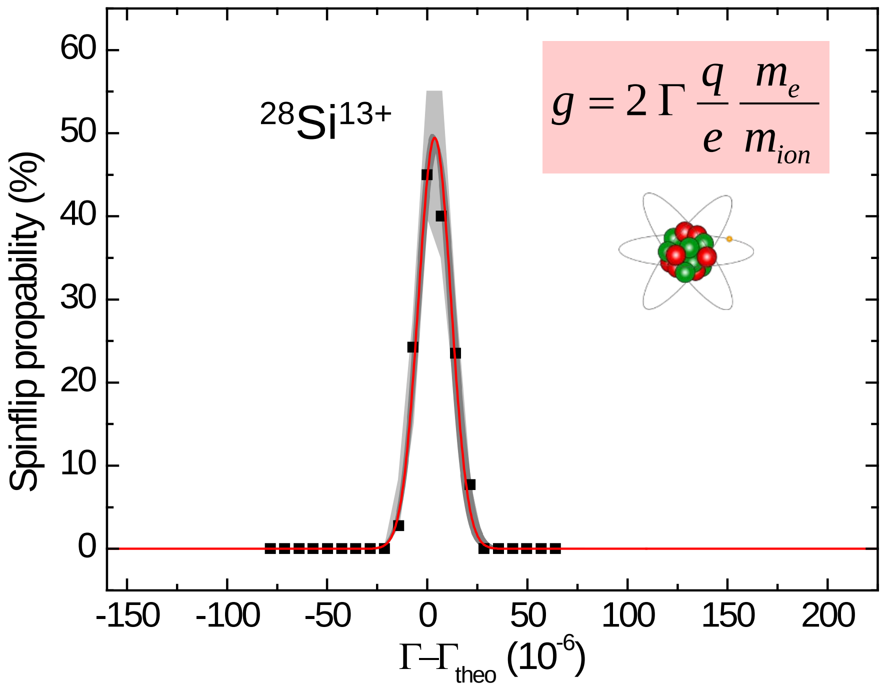
g-factor resonance of a single $^{28}Si^{13+}$ ion



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

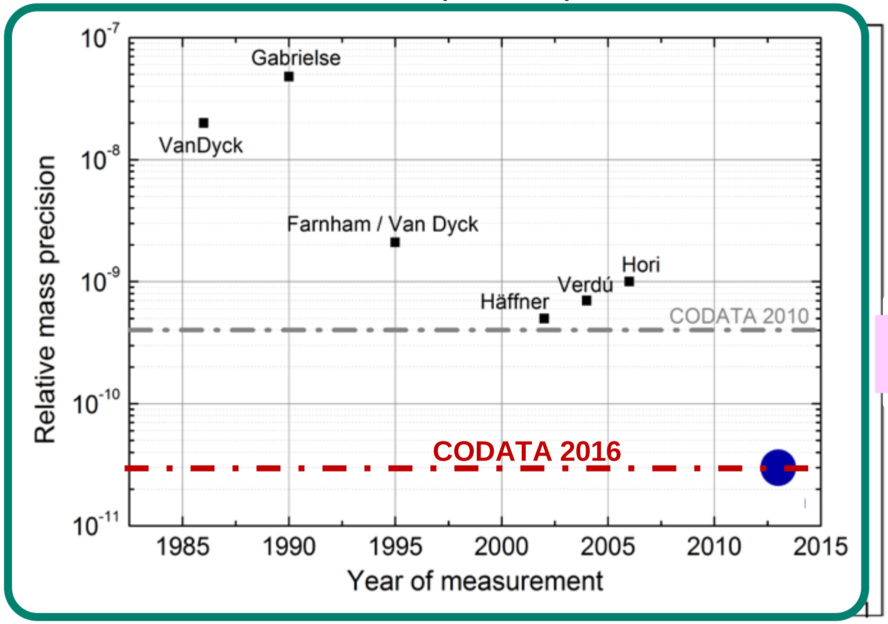
S. Sturm *et al.*, Phys. Rev. Lett. 107, 023002 (2011)
A. Wagner *et al.*, Phys. Rev. Lett. 110, 133003 (2013)

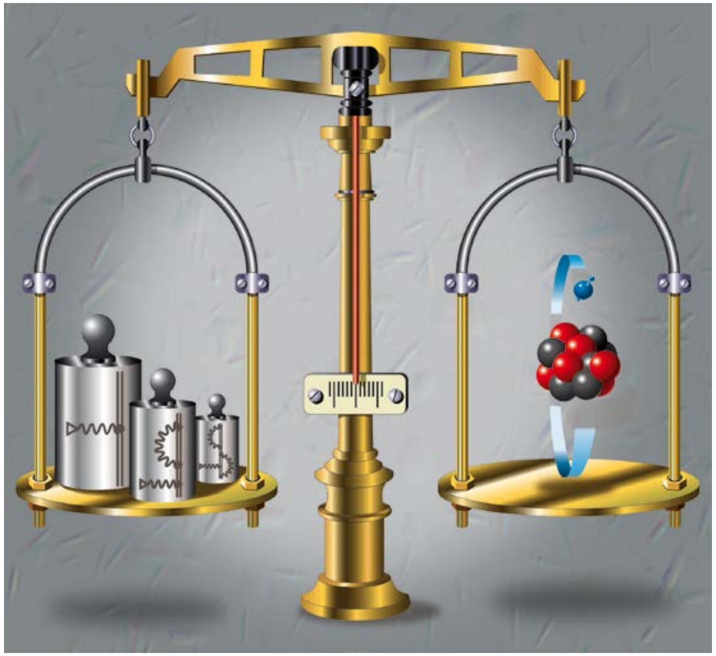
A 13-fold improved electron mass

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



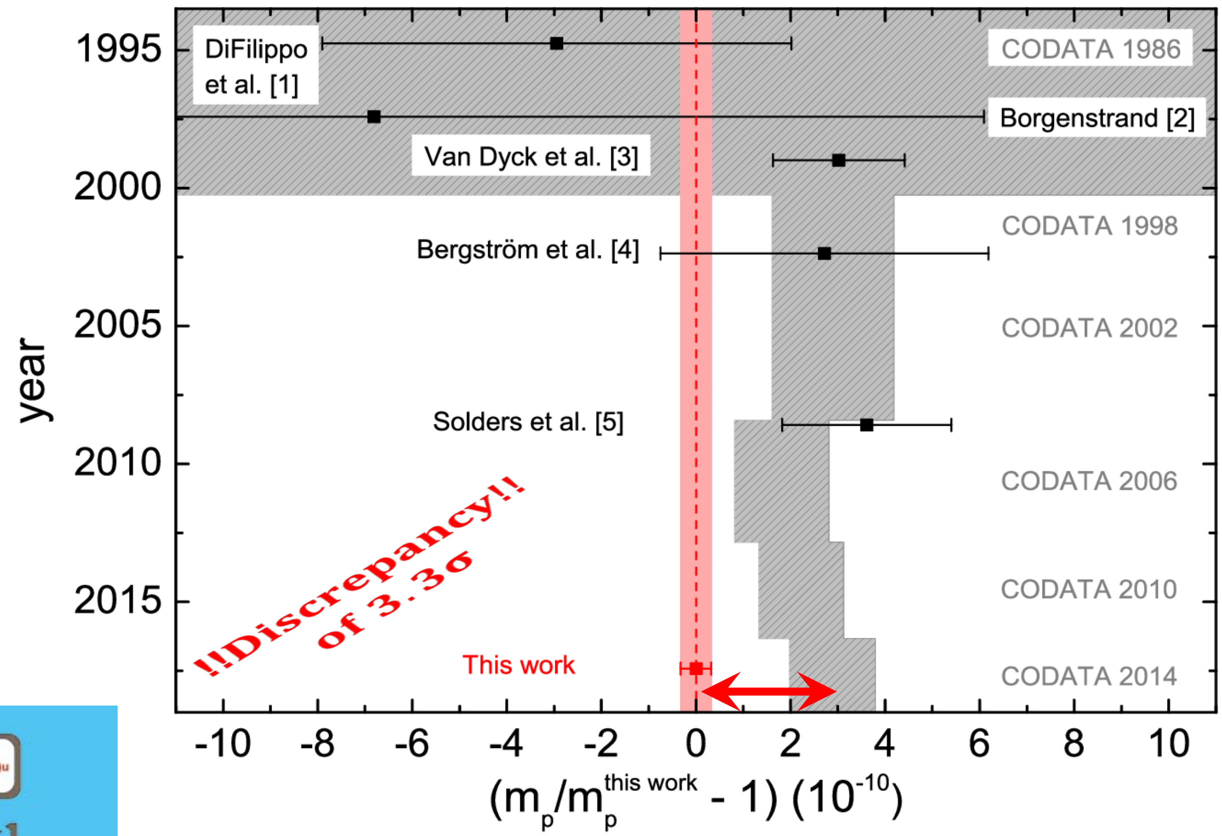


$m_e = 0.000548\,579\,909\,067(14)(9)(2)\mathrm{u}$

A factor of 13 improved value !

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

A 3-fold improved proton mass



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

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

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

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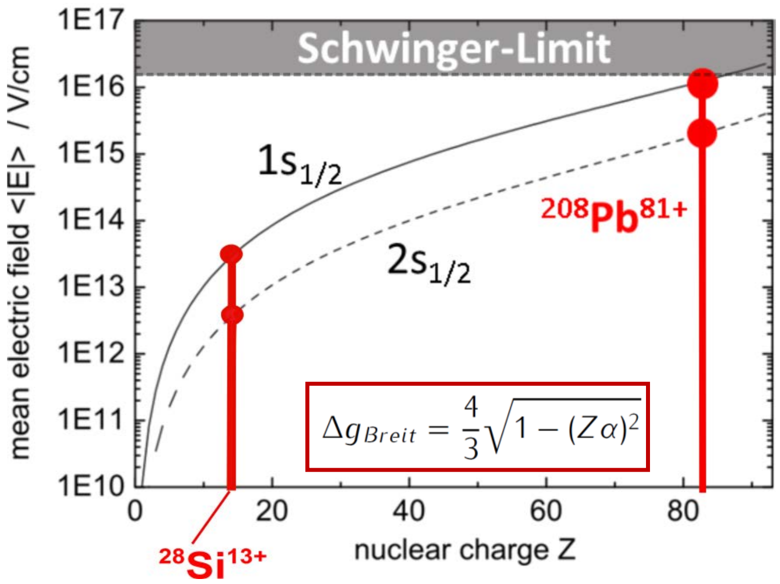
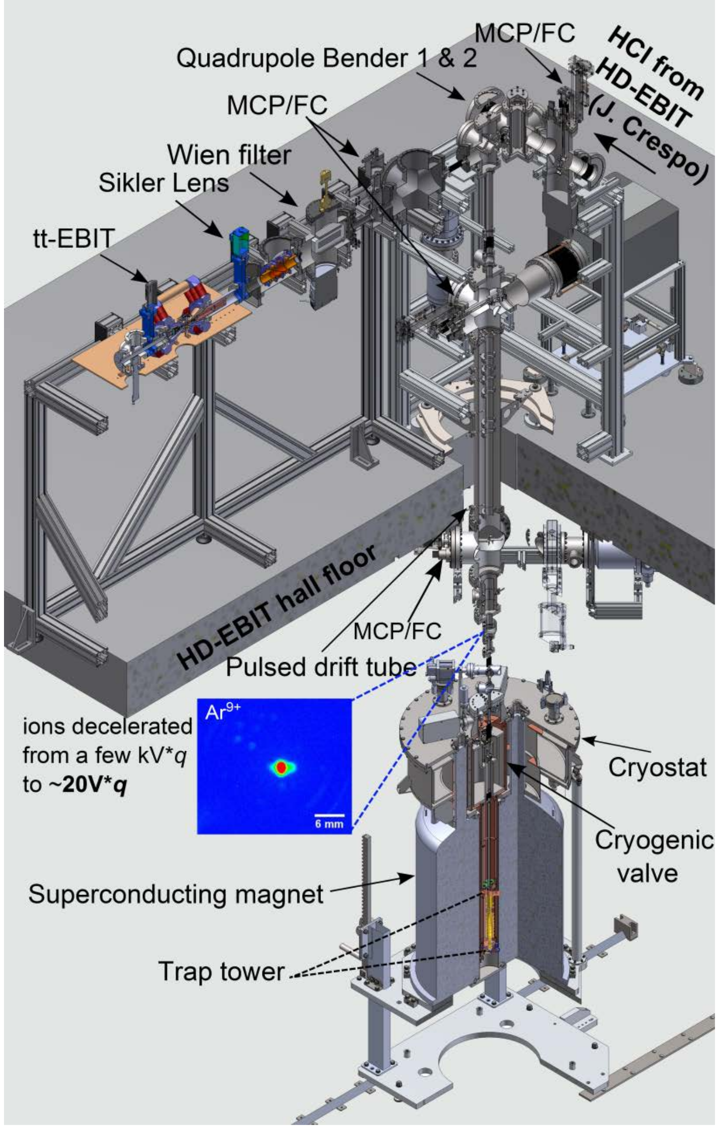
What comes next? α

- ALPHATRAP: A high-precision Penning-trap setup at MPIK & HITRAP
  - Production of HCI $^{208}Pb^{77+,81+}$
  - Larmor-to-cyclotron frequency ratio measurement in a double Penning trap yields $\delta g/g \approx 10^{-12}$
  - Experiment and theory provide stringent test of BS-QED and FSC α





Conclusion

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

Presently running experiments:

10-fold improved n mass
10-fold improved *E*=*mc*² test
1000-fold improved anti-p *g*-factor

Thanks a lot for the invitation and your attention!

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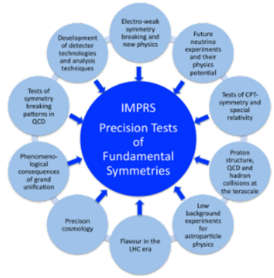

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