Max-Planck-Institut für Kernphysik

Precision mass measurements for nuclear and neutrino physics studies

- ❖ Motivation and fields of applications
- ❖ Basics of Penning-trap mass spectrometry
- ❖ Recent results and future perspectives

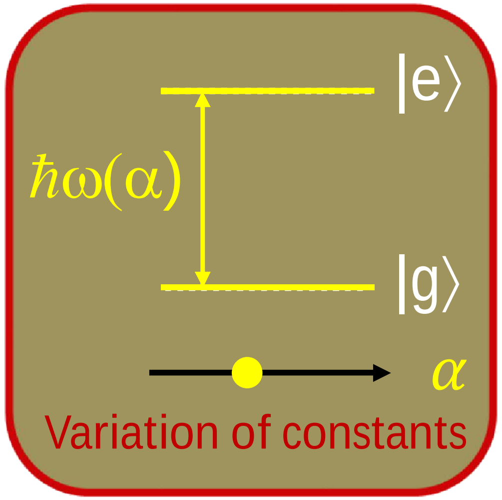
Klaus Blaum
Max-Planck-Institute for Nuclear Physics, Heidelberg

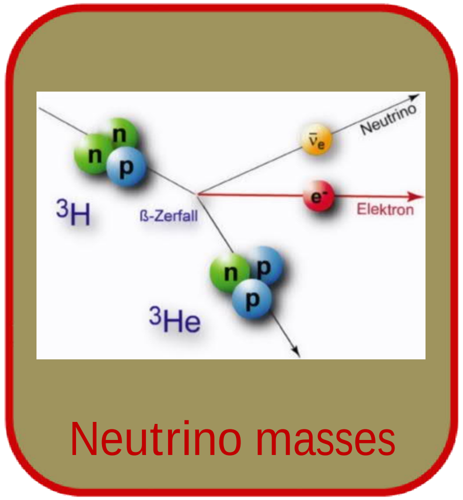
Max-Planck-Institut für Kernphysik

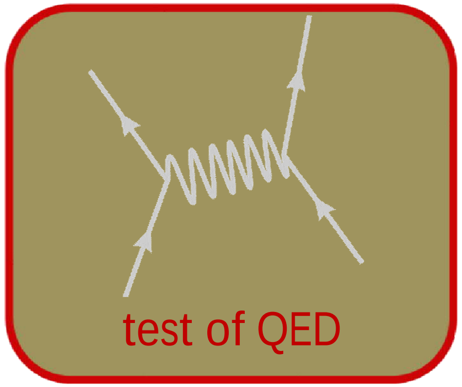
Cape Town, Feb 25th, 2020

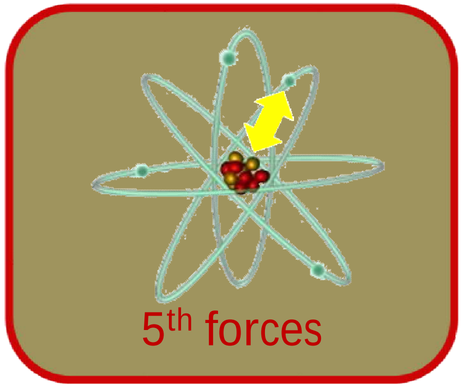
European Research Council
Established by the European Commission

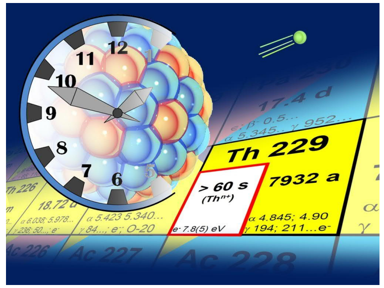
Exotic systems as sensitive probes



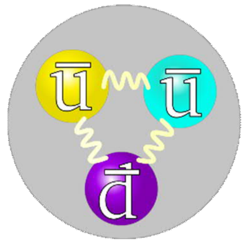




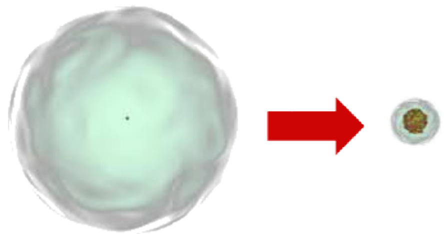




- radionuclides



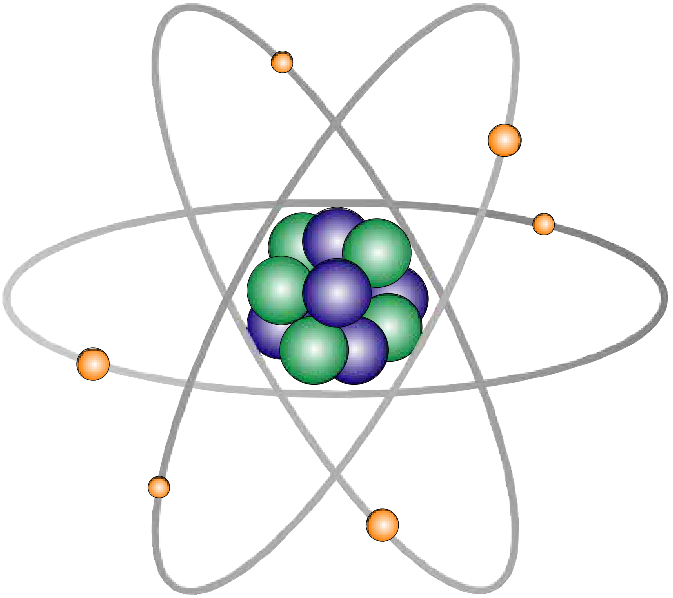
- antimatter

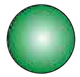
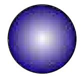
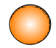


- highly charged ions

Blaum, Dilling, Nörtershäuser, Phys. Scr. T152, 014017 (2013)
Kozlov, Safronova, Crespo, Schmidt, Rev. Mod. Phys 90, 045005 (2018)

The mass of an atom/nucleus



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

– binding energy

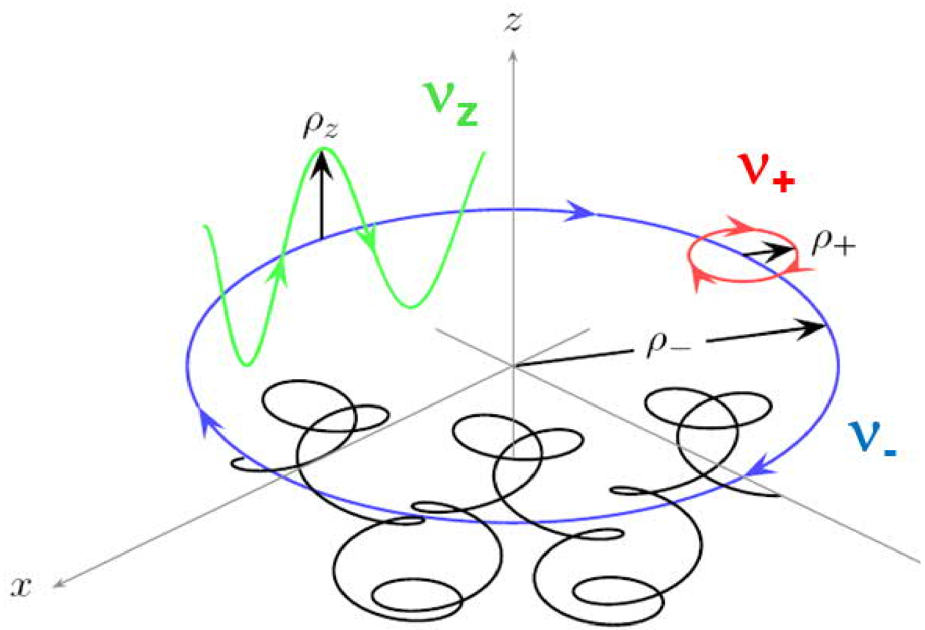
Einstein $E = mc^2$

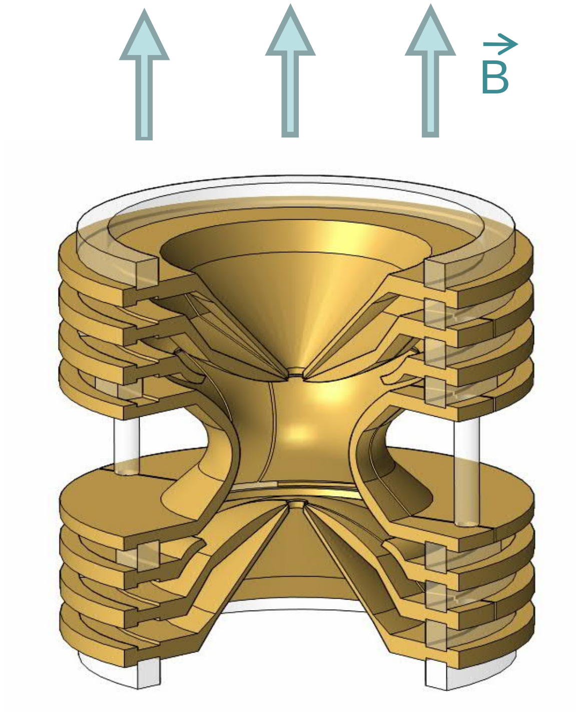
$$m_{\mathrm{Atom}} = N \bullet m_{\mathrm{neutron}} + Z \bullet m_{\mathrm{proton}} + Z \bullet m_{\mathrm{electron}} - (B_{\mathrm{atom}} + B_{\mathrm{nucleus}})/c^2$$

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

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

Storage of ions in a Penning trap





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

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

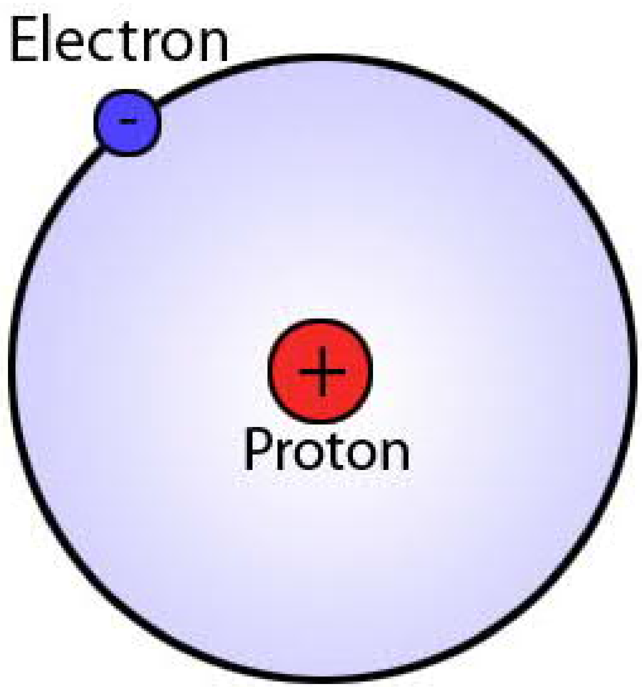
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

- Non-destructive FT-ICR detection technique

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

Results I

The masses of the building bocks of (anti-)matter



BASE and LIONTRAP: CERN, MPIK, RIKEN, Uni Mainz

The atomic mass of the proton

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

A factor of 3 improved value !

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

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

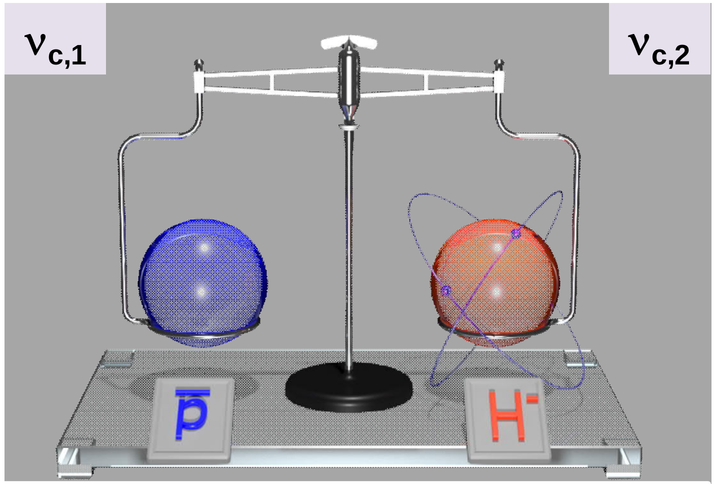
F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

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)

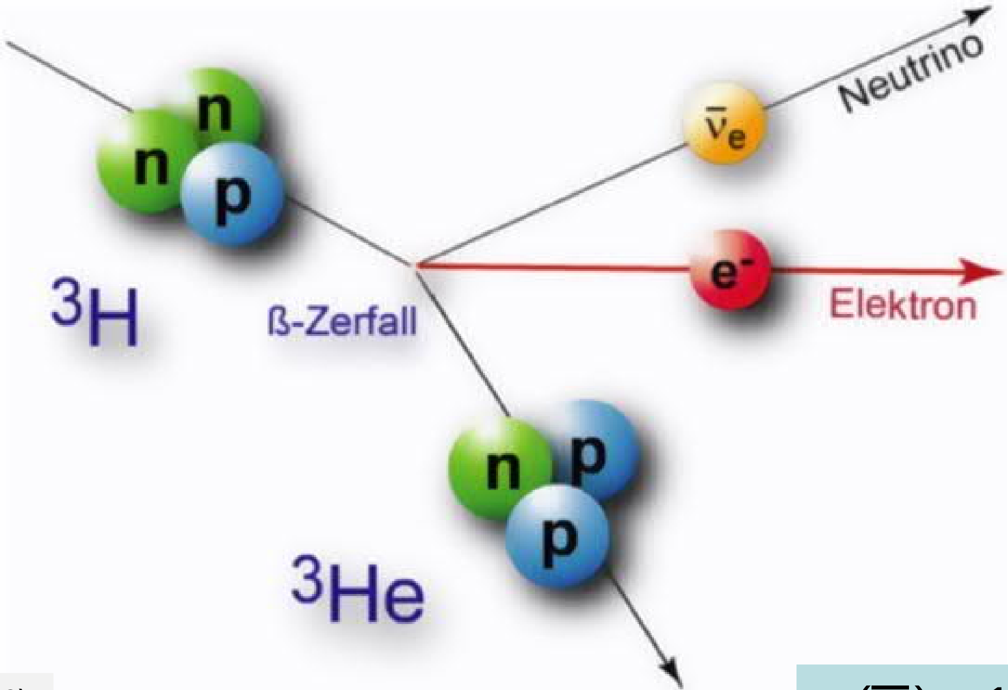


It is not that easy!

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

Results II

Nuclear masses for neutrino physics



Aker et al., PRL 123, 221802 (2019)

$m(\overline{\nu}_e) < 1.1$ eV/c^2 (90% CL)

ECHo, LIONTRAP, PENTATRAP: MPIK, Uni Heidelberg, Uni Mainz

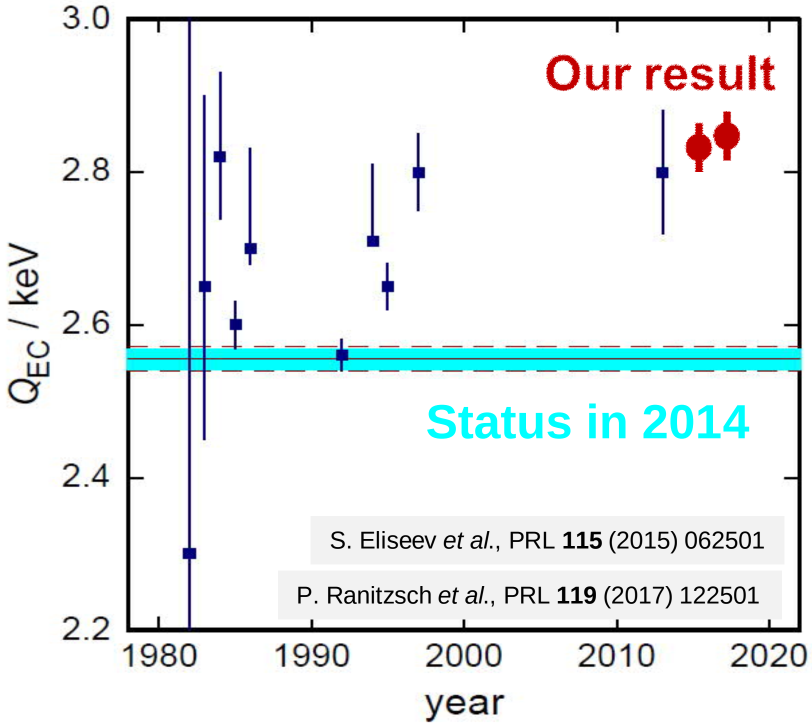
The ECHo (^{163}Ho) project

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

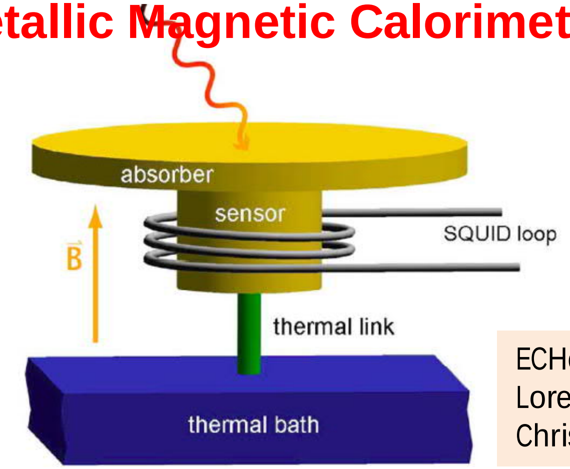
NEUTRONS FOR SCIENCE

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

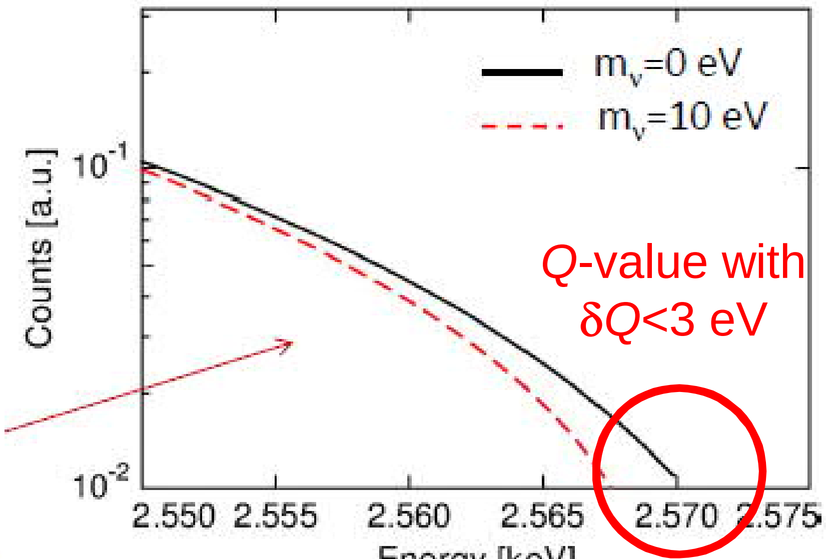
Q-value of EC in ^{163}Ho



Metallic Magnetic Calorimetry



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss



Measurement principle at PENTATRAP

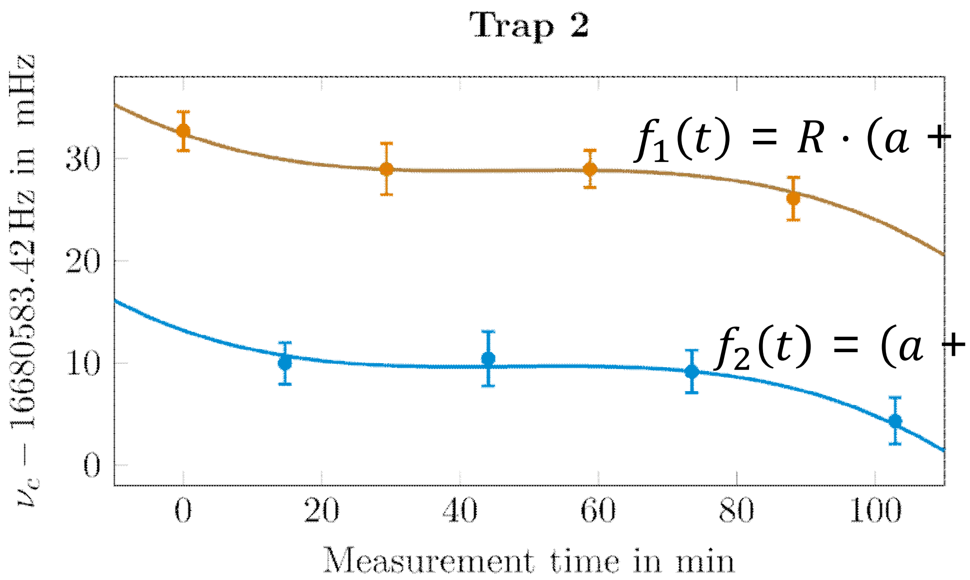
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

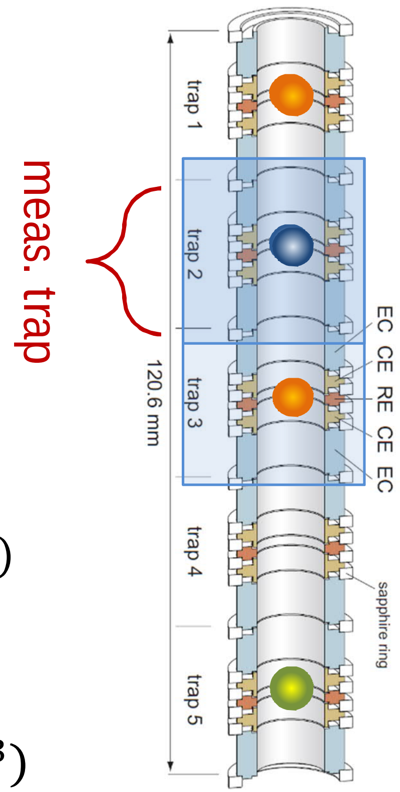
Second ion:

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



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

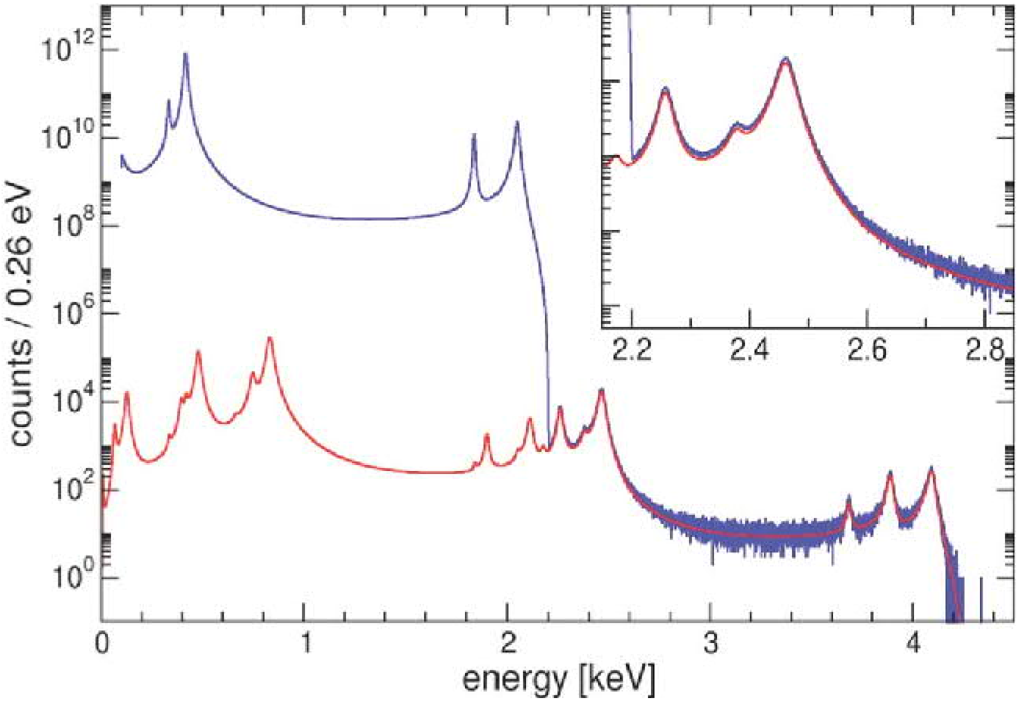
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



Future: Monitoring trap

Atomic physics isn't that easy

Atomic mass differences and ν-physics



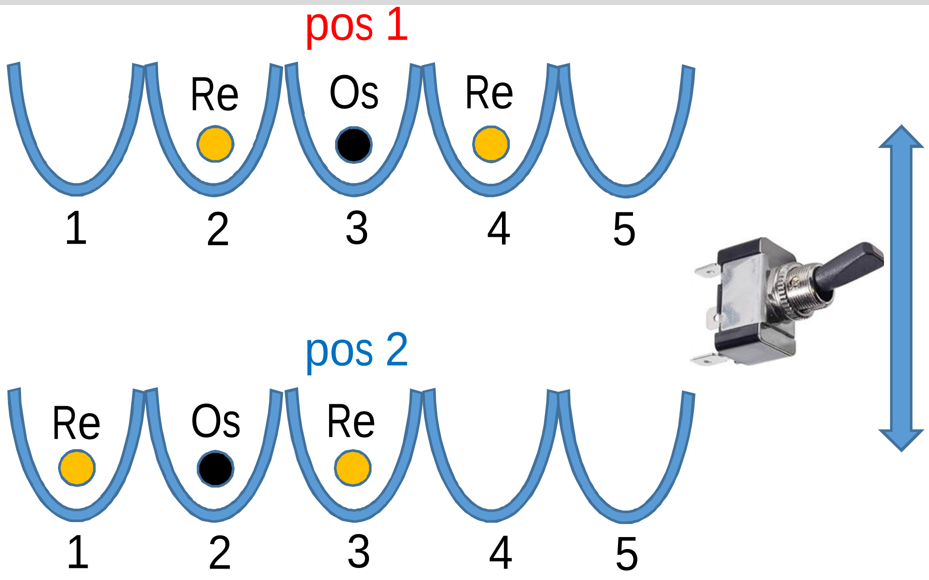
Gomes et al., IEEE 23 (2013)

β^- -decay of ^{187}Re

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

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

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

For Re^{29+} (Z = 75) vs. Os^{29+} (Z = 76) we measure two ratios with a 50/50 probability:

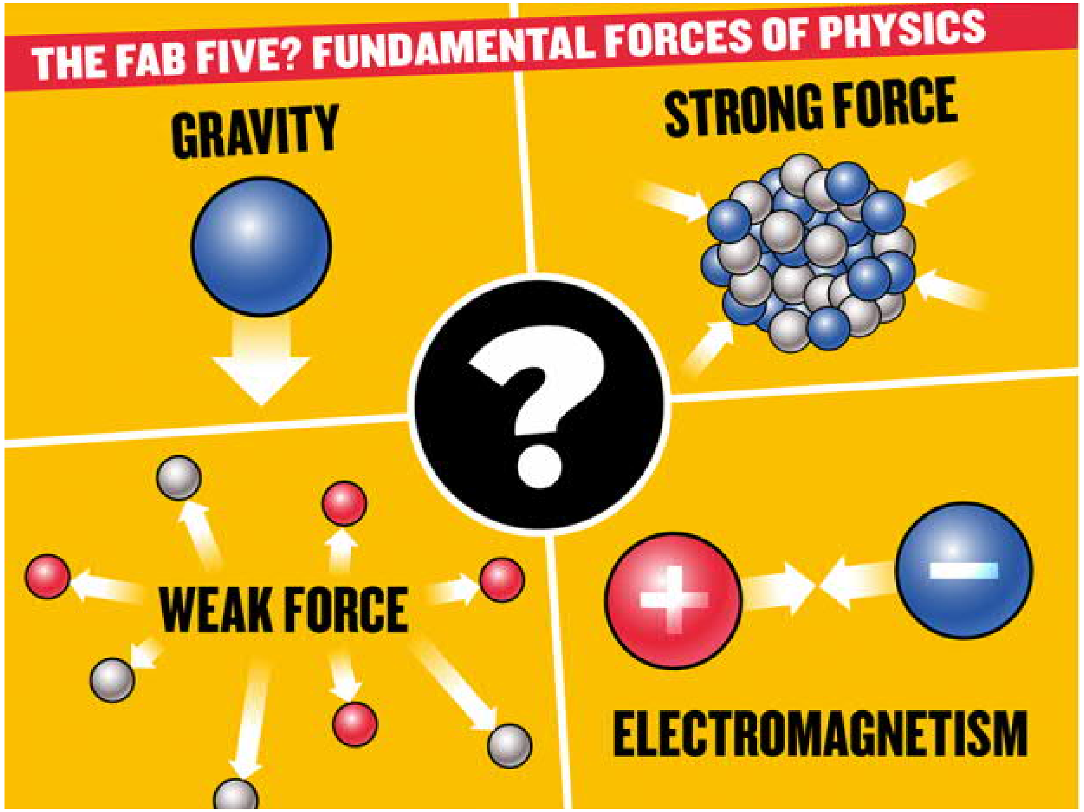
$$R_1 = 1.000000013886(15)$$

$$R_2 = 1.000000015024(12)$$

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

Results III

Nuclear masses for fifth force search



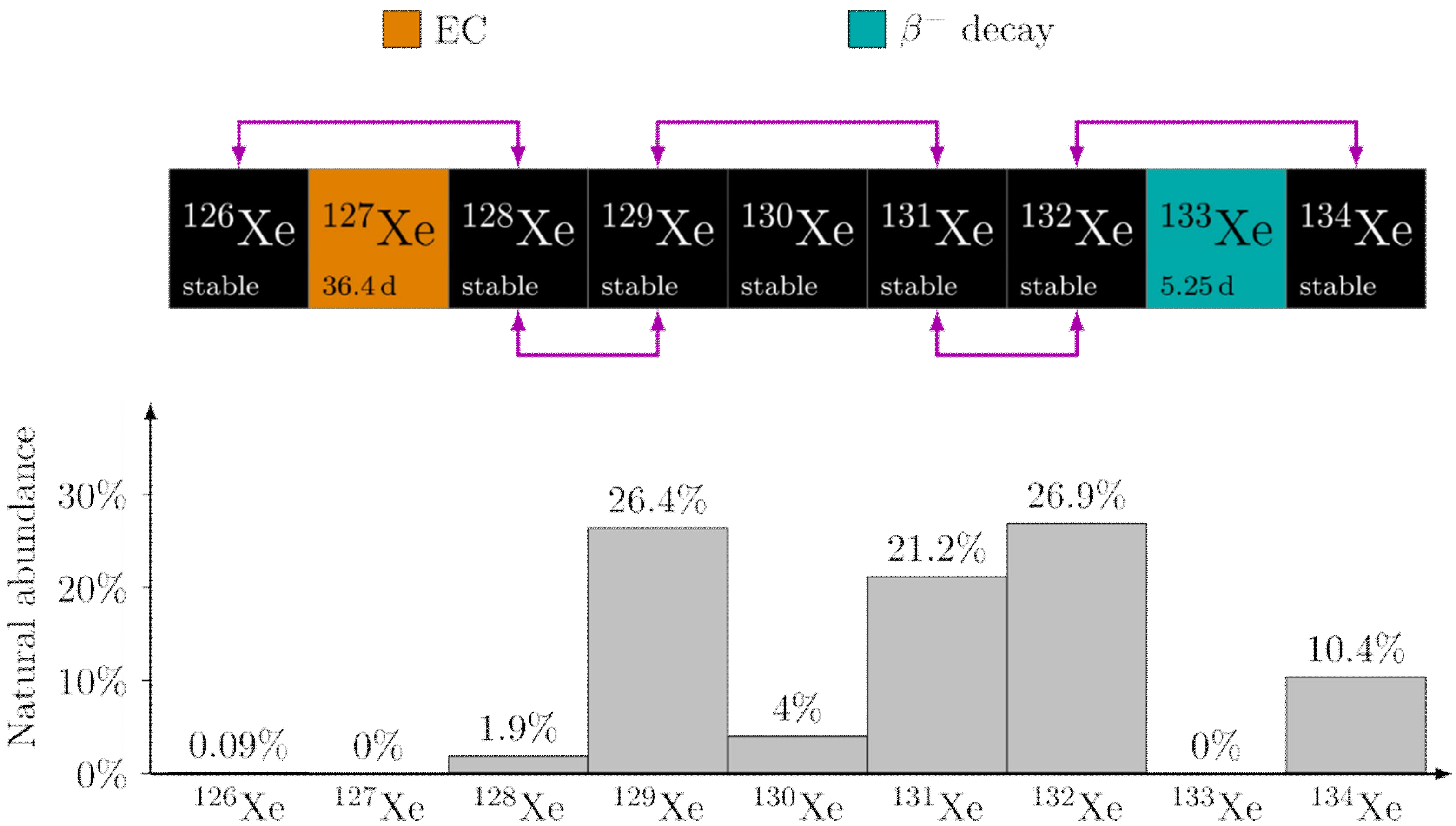
PENTATRAP: MPIK, RIKEN

www.freedomsphoenix.com/

Xe mass-ratio measurements

Motivation: Dark Matter search using King-plot analysis in Ca, Sr, Yb

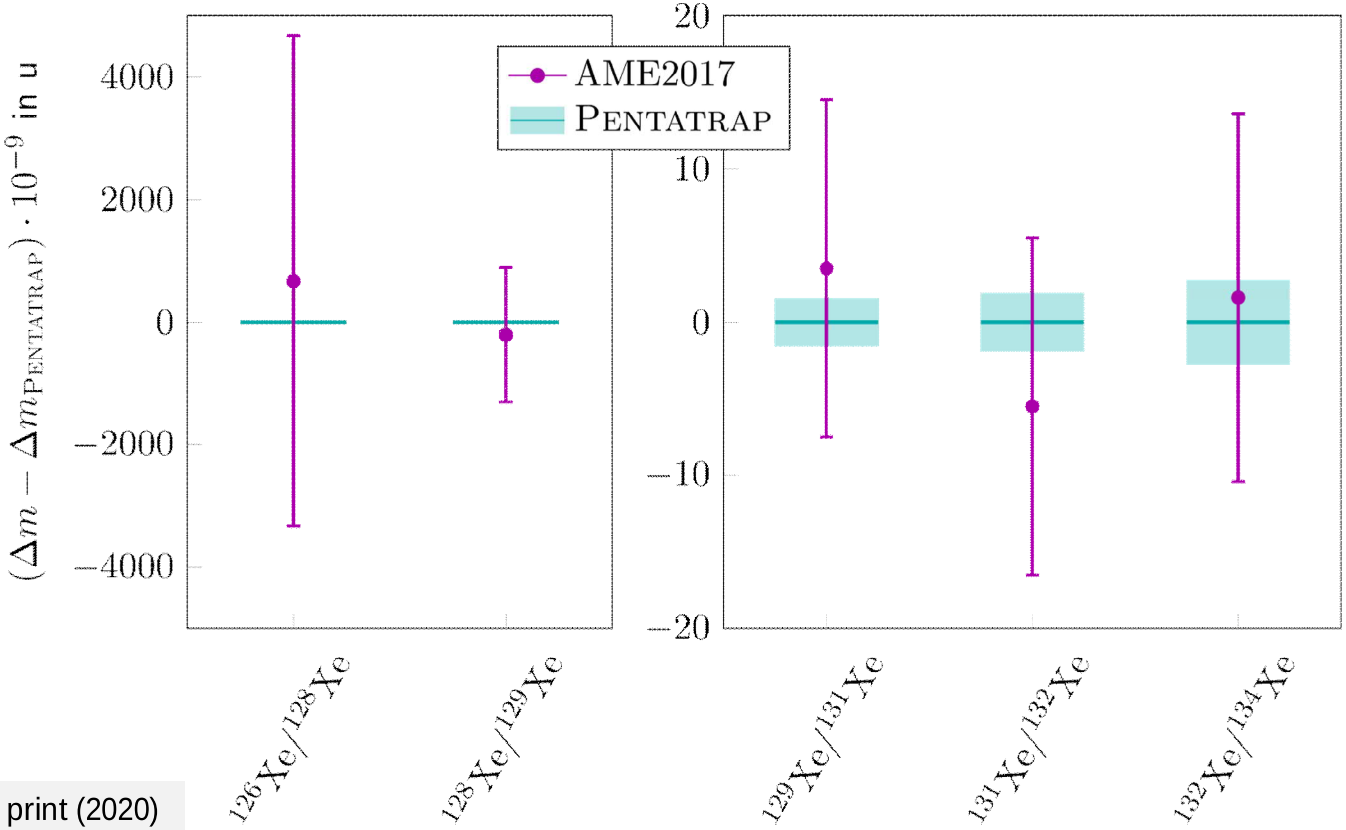
Mass-ratio uncertainties of 10^{-11} and below required!



Xe mass-ratio measurements

Motivation: Dark Matter search using King-plot analysis in Ca, Sr, Yb

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



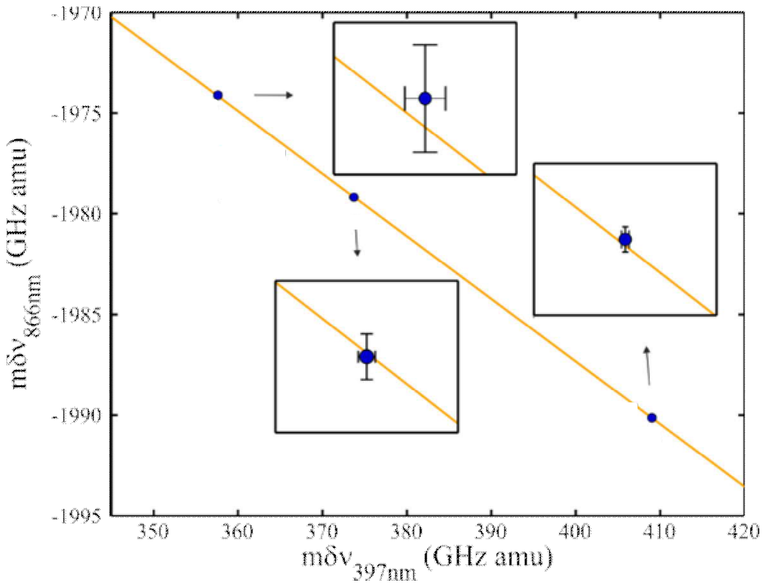
Rischka et al., PRL, in print (2020)

Improvement factor:	1700	740	7	6	4

Probe for new force carriers

Isotope shift spectroscopy: 5th force?

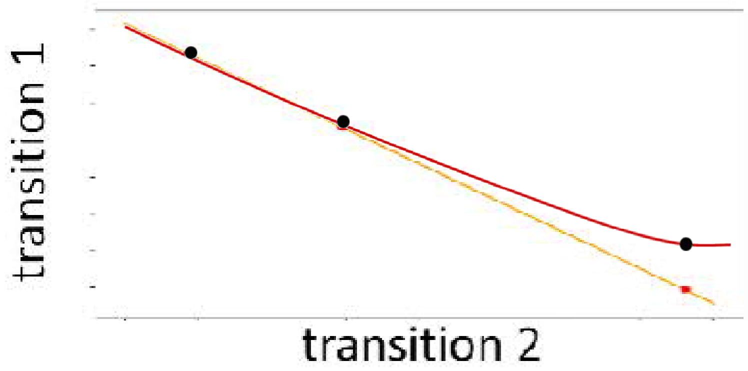
- $\delta\nu_i^{A,A'} = F_i \delta\langle r^2\rangle_{A,A'} + k_i \frac{A-A'}{AA'}$
- use 2 transitions i, j
  ➔ eliminate $\delta\langle r^2\rangle_{A,A'}$



- 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:

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



Berengut et al., PRL 120, 091801 (2018)

High-precision atomic and nuclear spectroscopy measurements needed!

Summary

Precision Penning-trap mass spectrometry has reached an amazing precision even on exotic systems and has opened up many new fields of research in neutrino and nuclear physics!

Thanks a lot for the invitation and your attention!

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