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

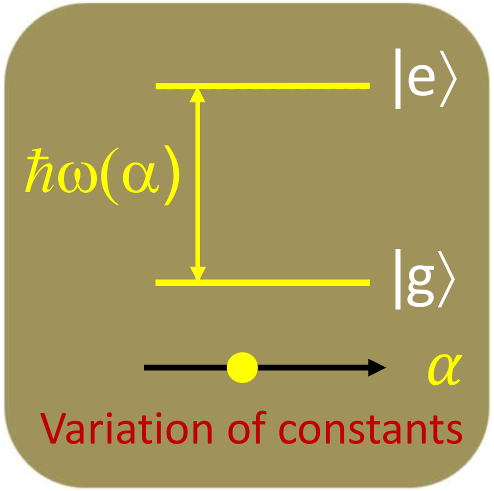
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

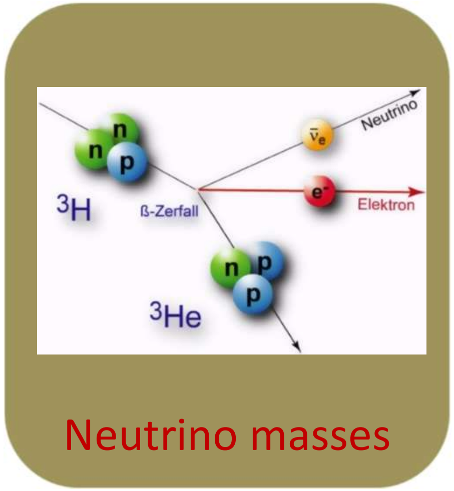
Heidelberg, April 26th, 2021

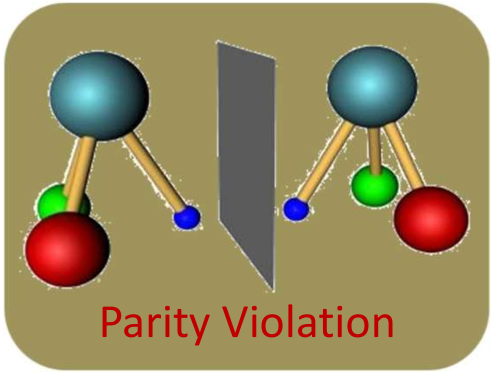
European Research Council
Established by the European Commission

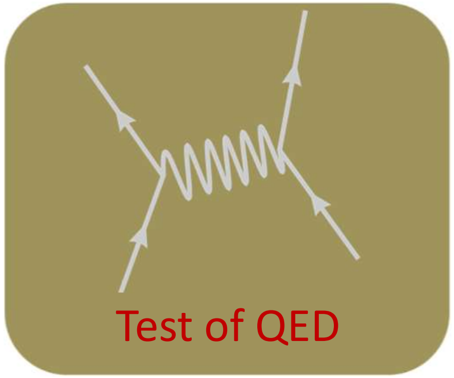
Atomic/nuclear spectroscopy …

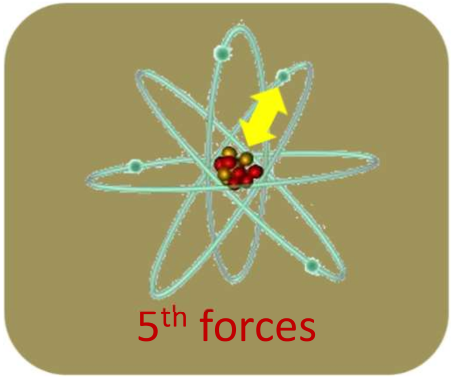
… probes fundamental physics!

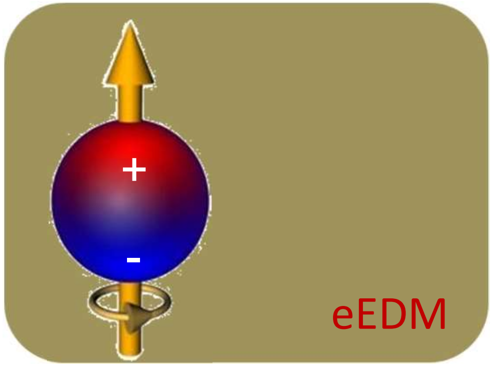






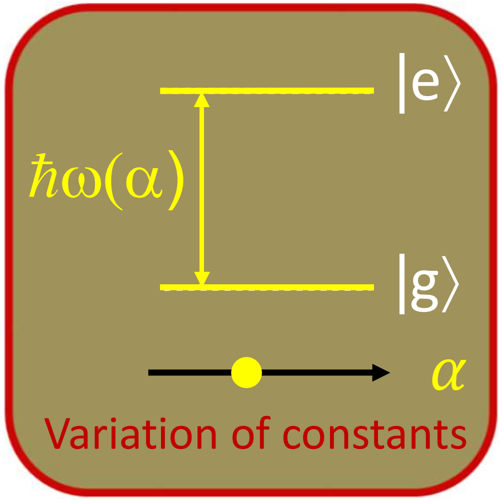


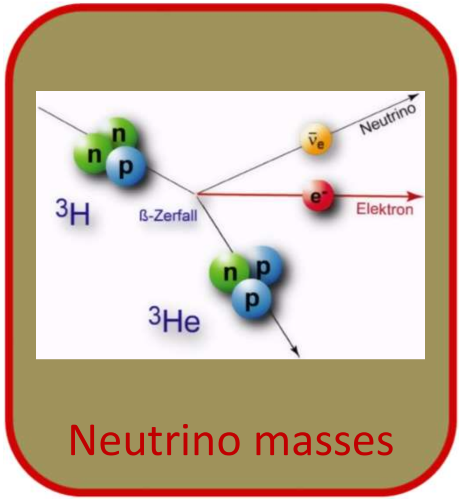


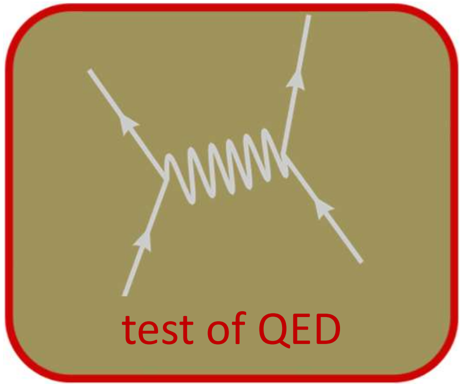


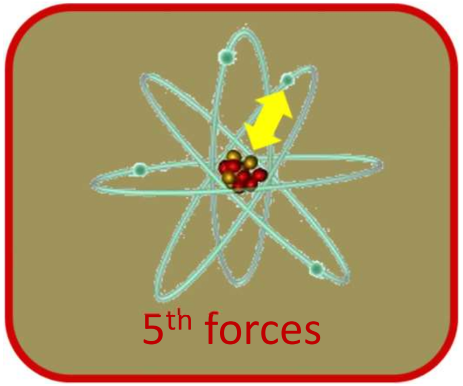
Safronova *et al.* Rev. Mod. Phys. **90**, 025008 (2018)

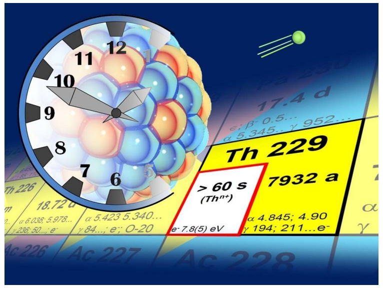
Exotic systems as sensitive probes



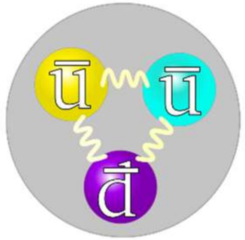




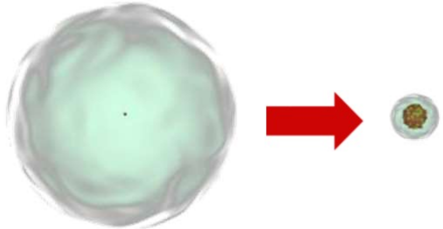




- radionuclides



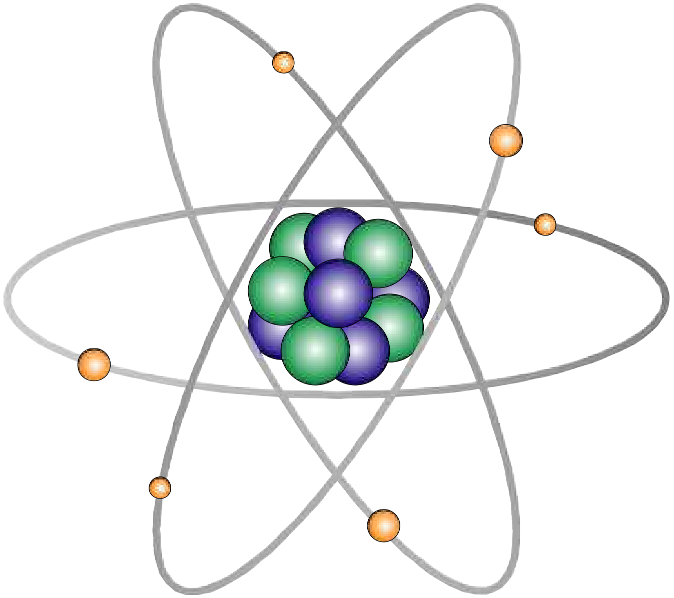
- antimatter

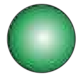
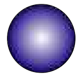


- highly charged ions

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 ·  + Z ·  + Z · 

– binding energy

Einstein $E = mc^2$

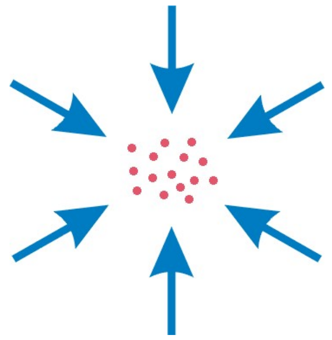
$$m_{\text{Atom}} = N \cdot m_{\text{neutron}} + Z \cdot m_{\text{proton}} + Z \cdot m_{\text{electron}}$$
$$- (B_{\text{atom}} + B_{\text{nucleus}})/c^2$$

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

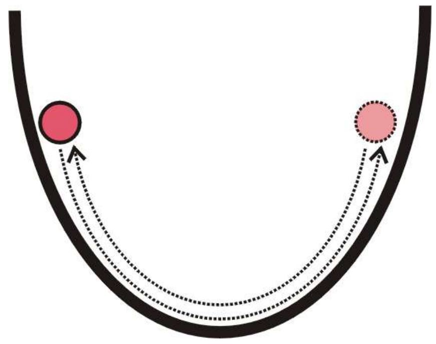
$\delta m/m = 10^{-6} – 10^{-8}$

Storage and cooling of ions

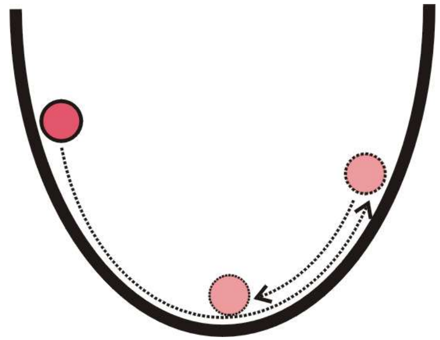
Radial force



Harmonic potential



Cooling



electric fields

magnetic fields

light fields

characteristic oscillation frequency

↓

pendulum clock

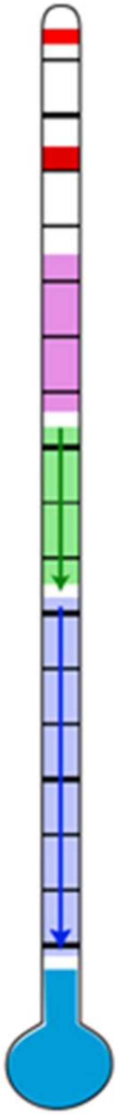
damping of oscillation amplitudes

minimization of imperfections

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

Energy and precision regimes

LHC



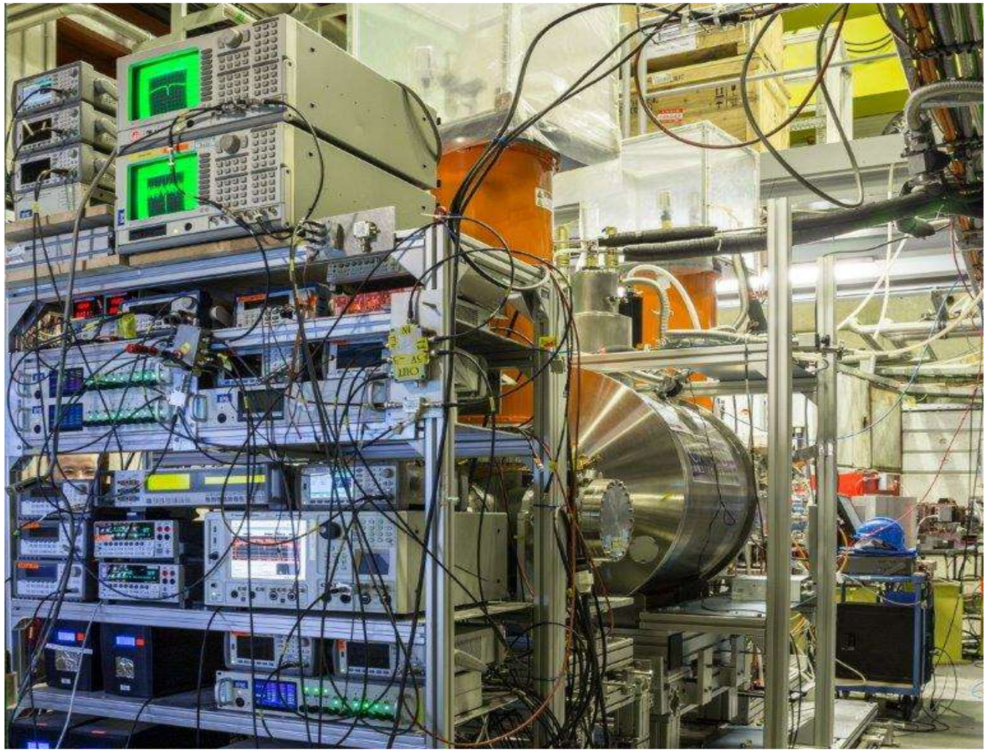
trap

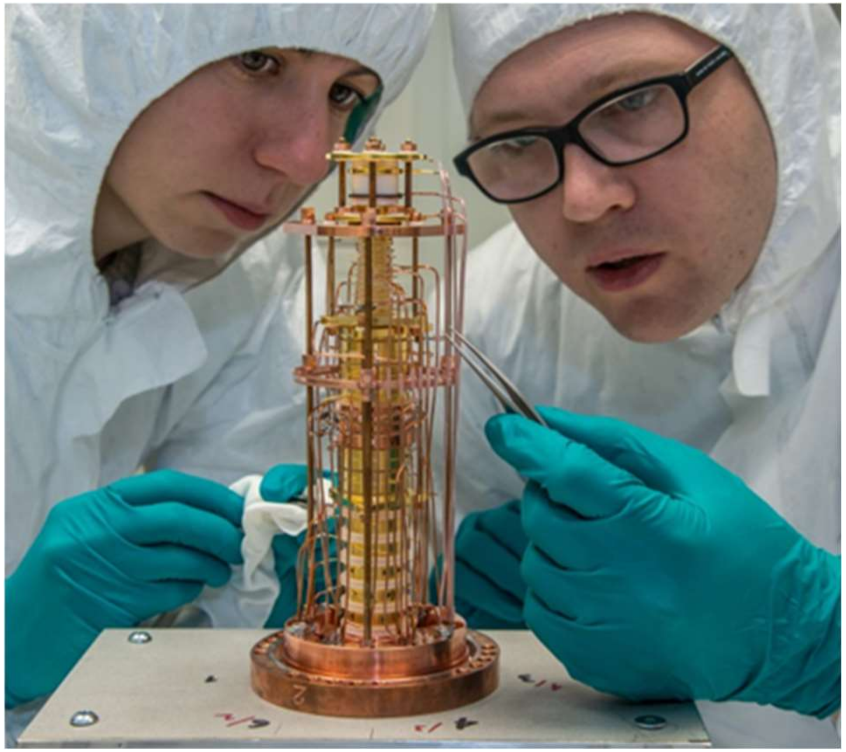
energy	temperature
1 TeV	10^{16} K
1 GeV	10^{13} K
1 MeV	10^{10} K
1 keV	10^{7} K
1 eV	10^{4} K
1 meV	10 K
1 μeV	0.01 K (ca. -273°C)

Energy frontier

Precision frontier

Storage of ions in a Penning trap





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

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

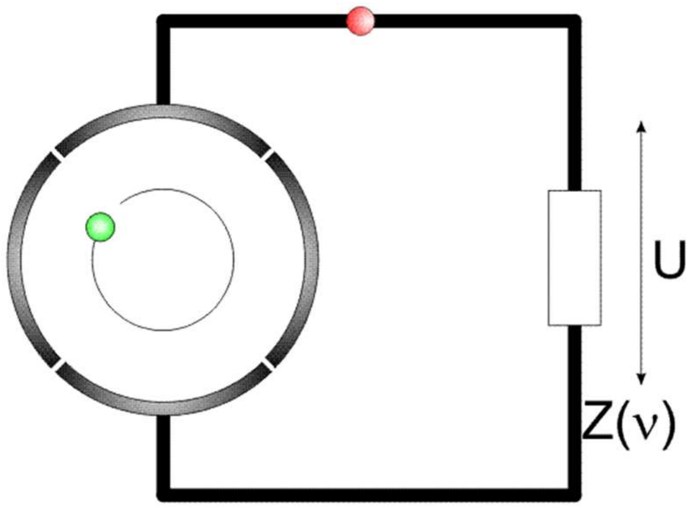
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

➢ Non-destructive FT-ICR detection technique

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

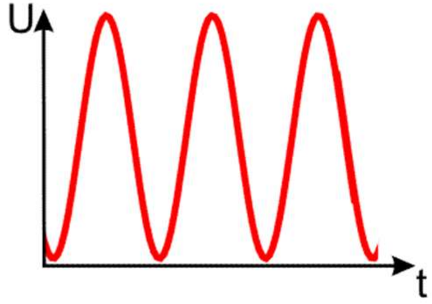
Non-destructive detection technique

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



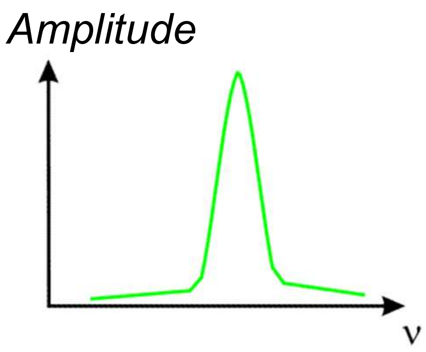
S. Sturm *et al.*, Phys. Rev. Lett. 107, 143003 (2011)

ion signal

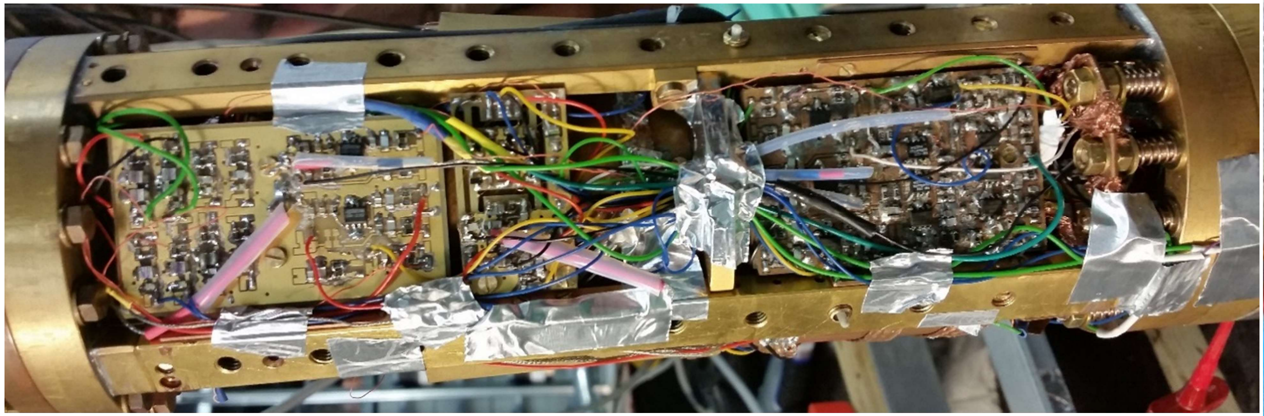


very small signal ~fA

mass/frequency spectrum



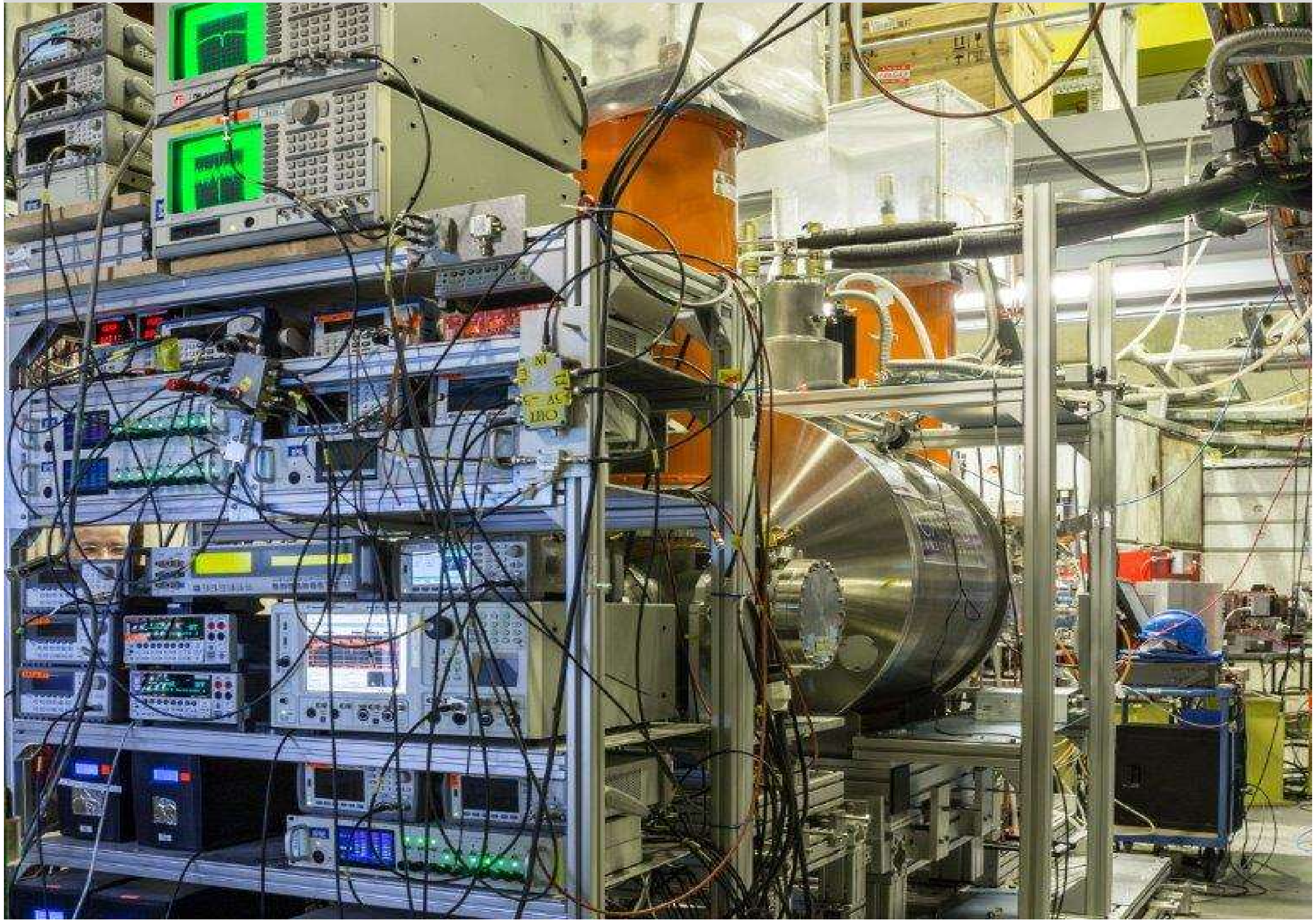
Fourier transformation



30 cm

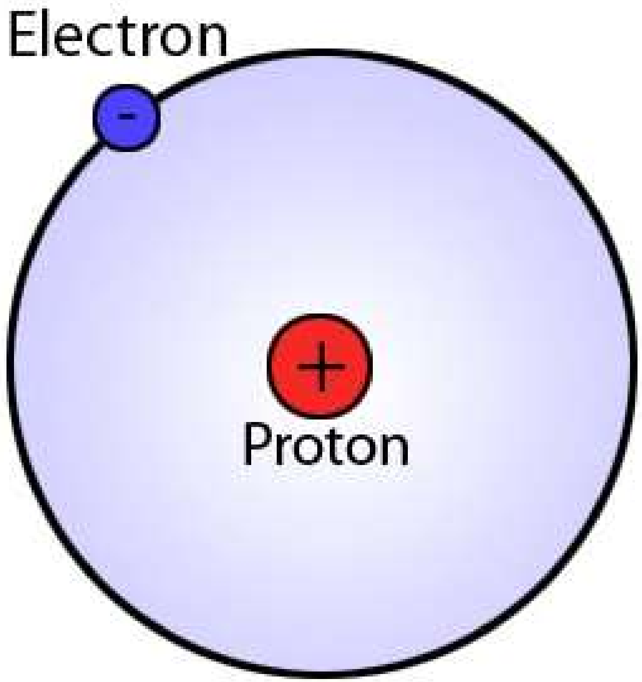
BASE – A Penning-trap setup at CERN

A balance for protons and antiprotons.



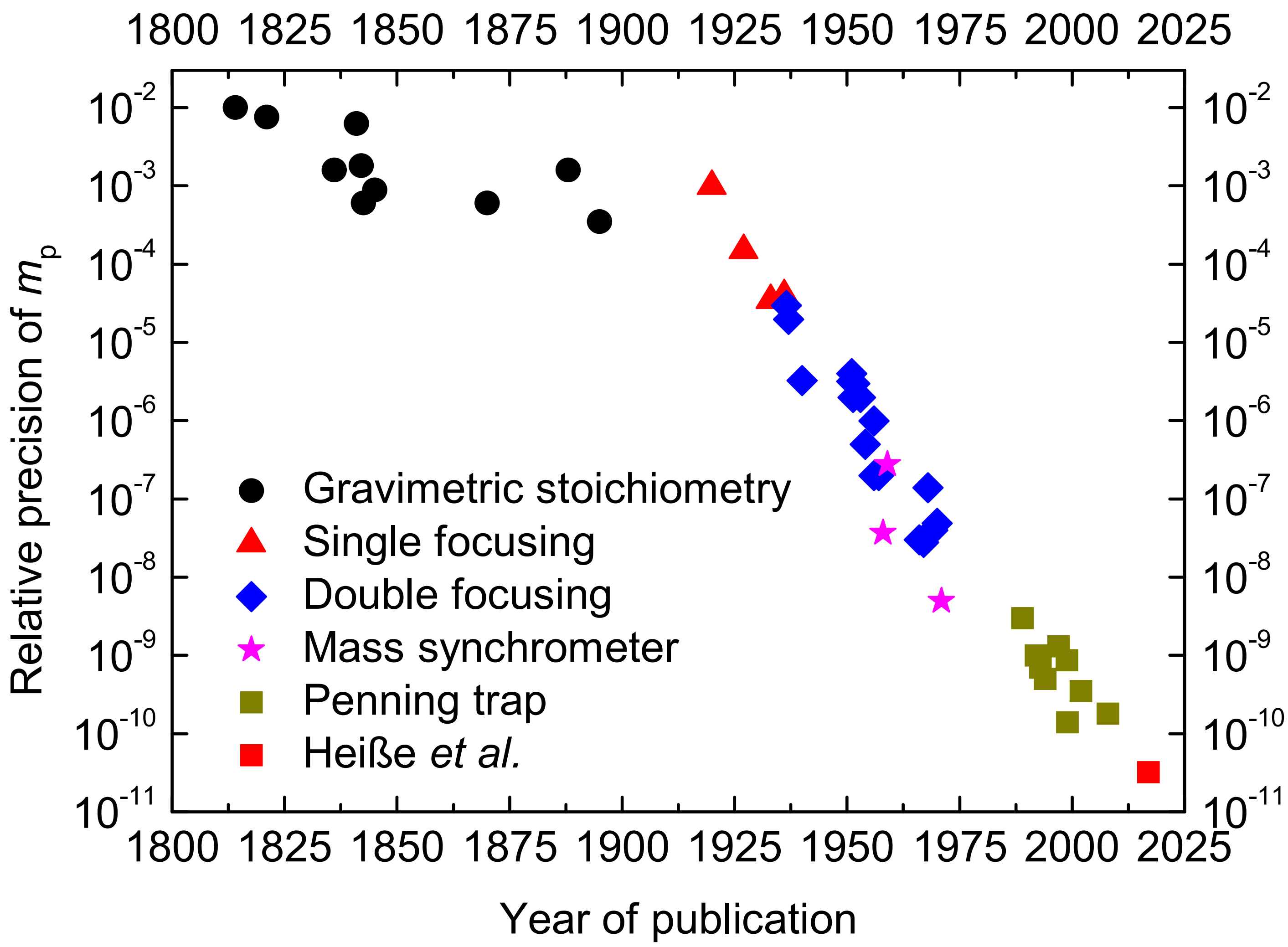
Results I

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



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

The atomic mass of the proton



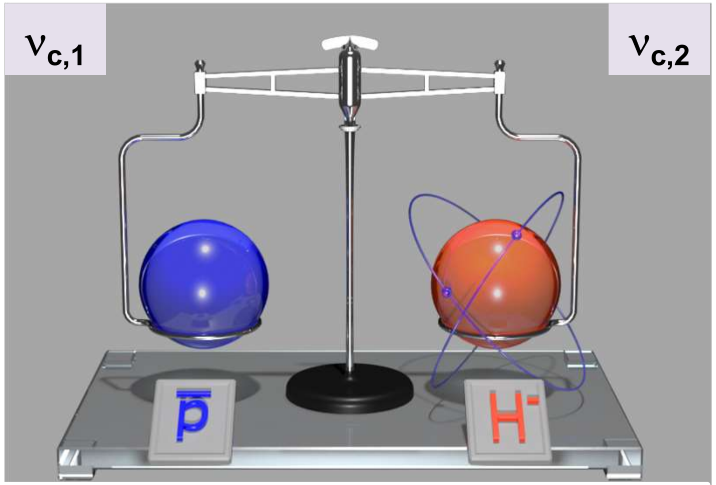
F. Heiße *et al.*, Phys. Rev. Lett. 119, 033001 (2017)

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)



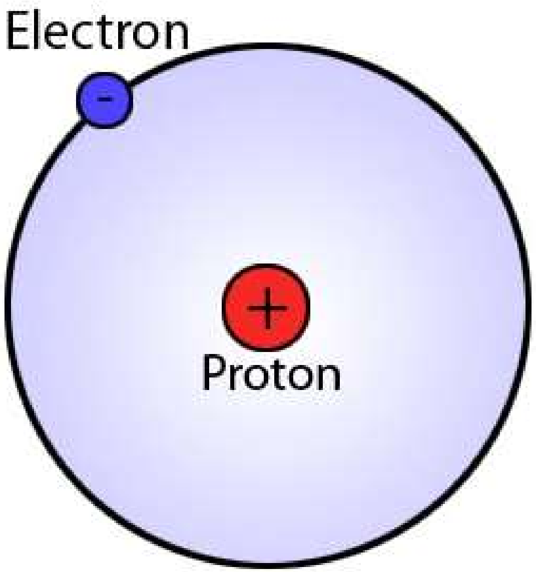
It is not that easy!

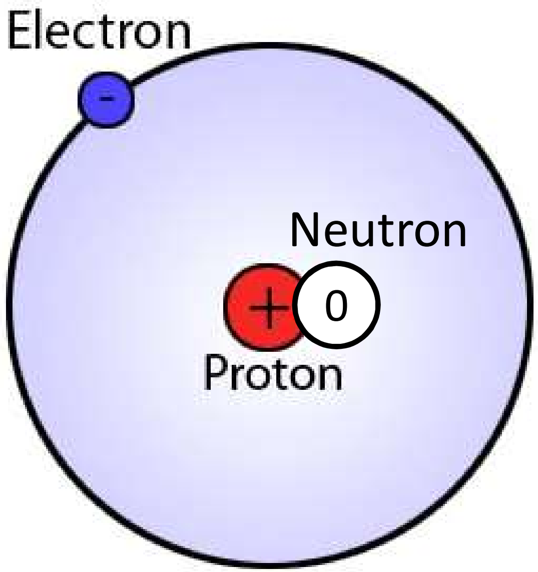
$$m_{H^-} = m_p \left(1 + 2\frac{m_e}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} \right)$$

The building blocks of matter

The atomic mass of the proton and electron and neutron ☺

Hydrogen



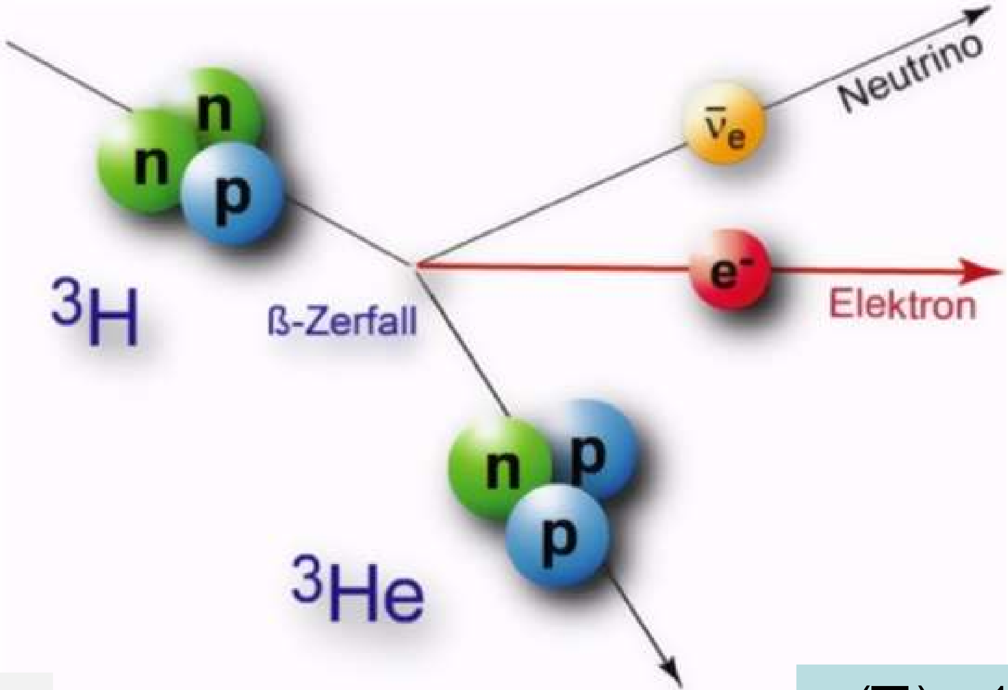


Deuterium

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

Results II

Nuclear masses for neutrino physics

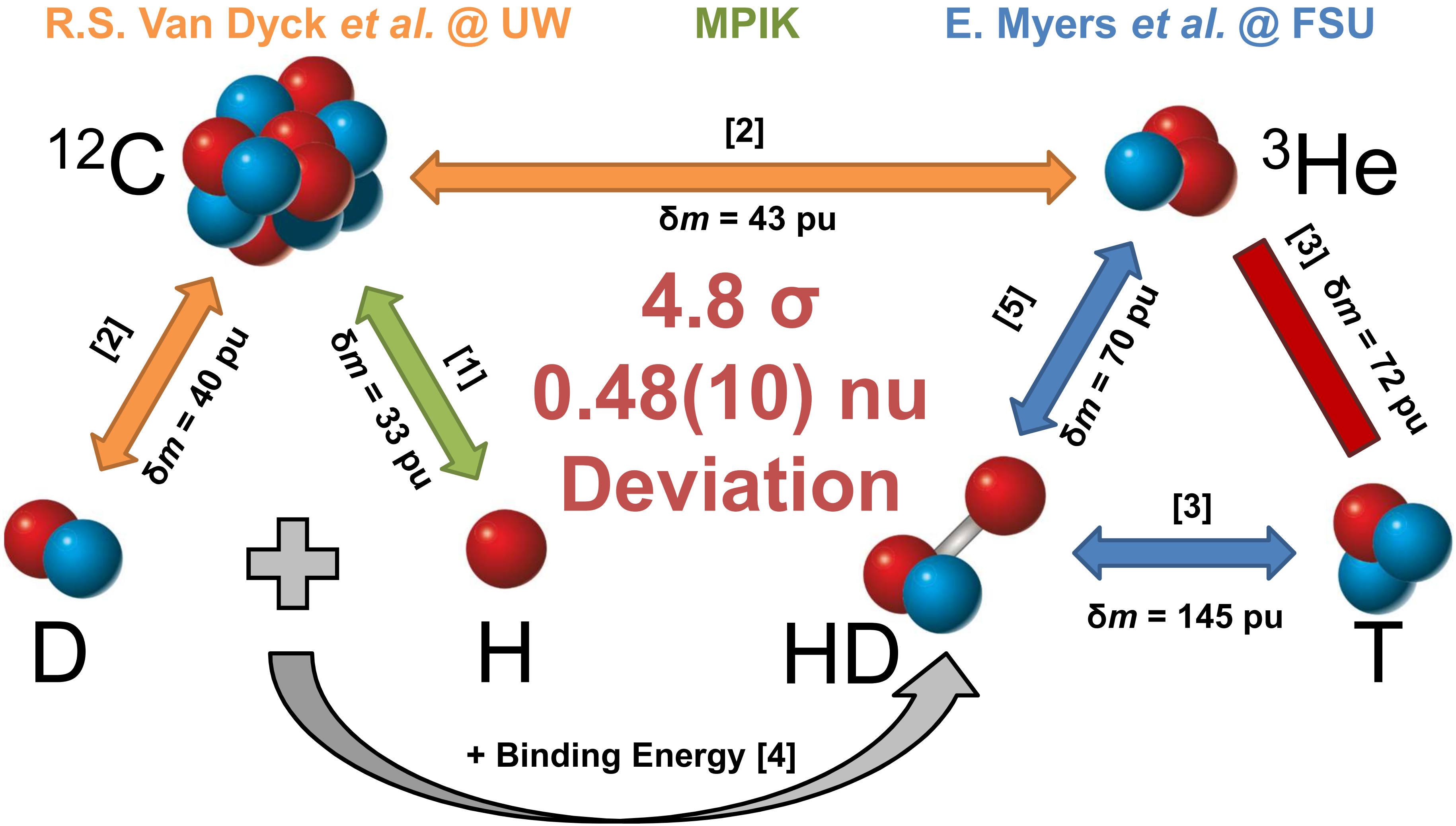


Aker *et al.*, PRL **123**, 221802 (2019)

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

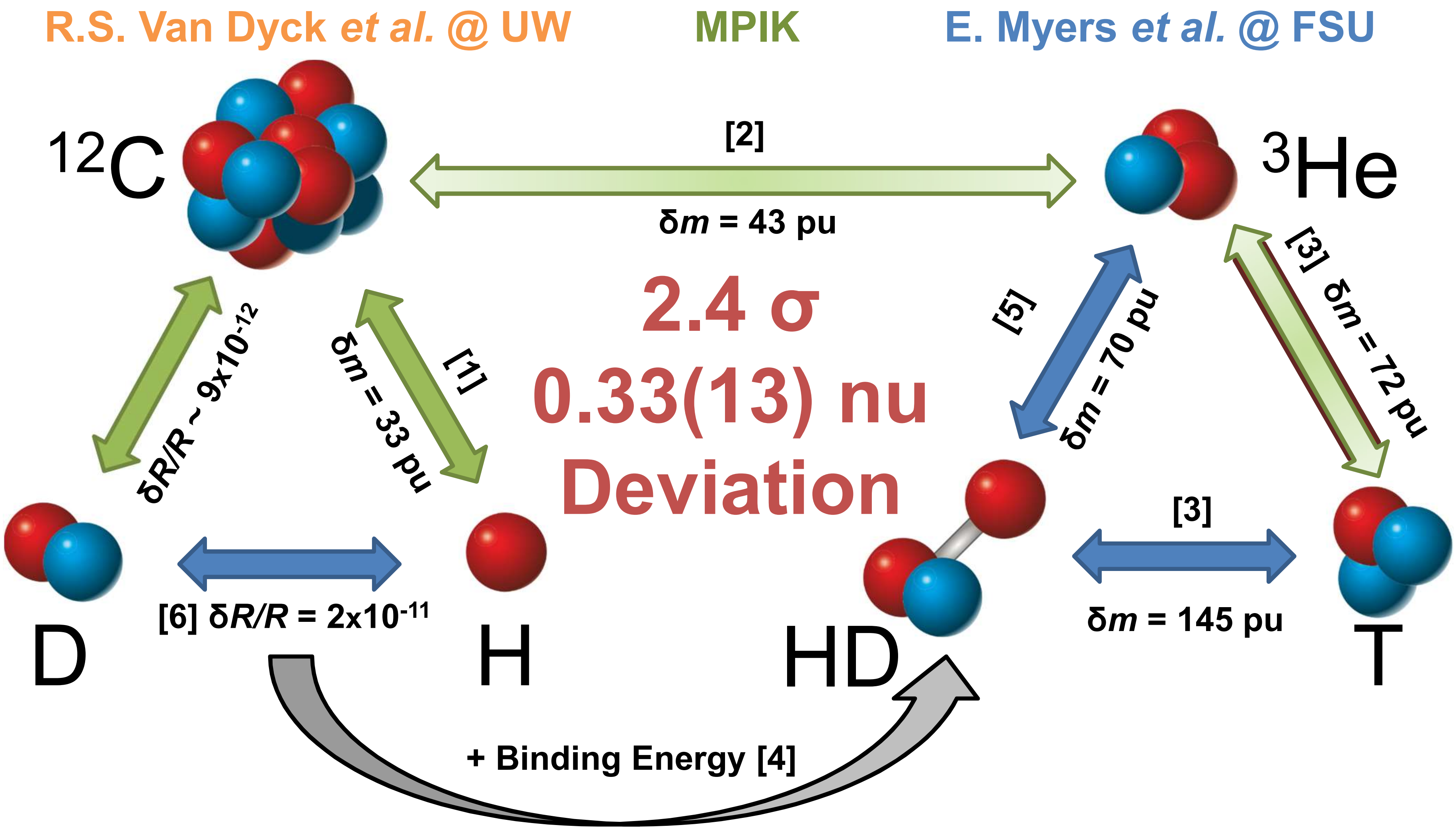
ECHo, LIONTRAP, PENTATRAP: MPIK, Uni Heidelberg, Uni Mainz

The puzzle of light atomic masses



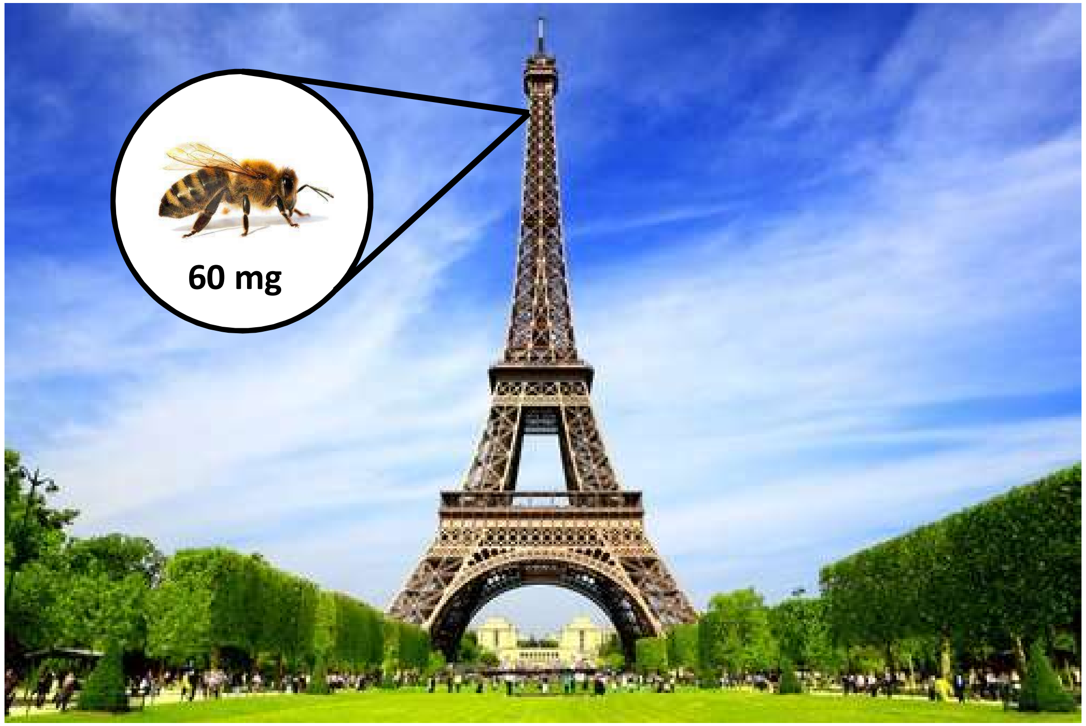
[1] Heiße *et al.*, Phys. Rev. Lett. **119**, 033001 (2017)
[2] Zafonte *et al.*, Metrologia **52**, 280 (2015)
[3] Myers *et al.*, Phys. Rev. Lett **114**, 013003 (2015)
[4] Korobov *et al.*, Phys. Rev. Lett. **118**, 233001 (2017)
[5] Hamzeloui *et al*, Phys. Rev. A **96**, 060501 (2017)

The puzzle of light atomic masses



[1] Heiße *et al.*, Phys. Rev. Lett. **119**, 033001 (2017)
[2] Zafonte *et al.*, Metrologia **52**, 280 (2015)
[3] Myers *et al.*, Phys. Rev. Lett **114**, 013003 (2015)
[4] Korobov *et al.*, Phys. Rev. Lett. **118**, 233001 (2017)
[5] Hamzeloui *et al*, Phys. Rev. A **96**, 060501 (2017)
[6] Fink *et al.*, Phys. Rev. Lett. **124**, 013001 (2020)

An easy image of our precision regime

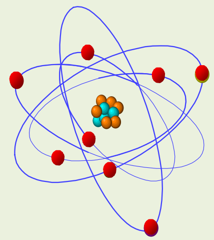


$m_{bee} \approx 60$ mg

$$\frac{m_{bee}}{m_{Eiffel}} \approx 8 \cdot 10^{-12}$$

m_{Eiffel} = 7300 T = 7.300.000.000.000 mg = $7.3 \cdot 10^{12}$ mg

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



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

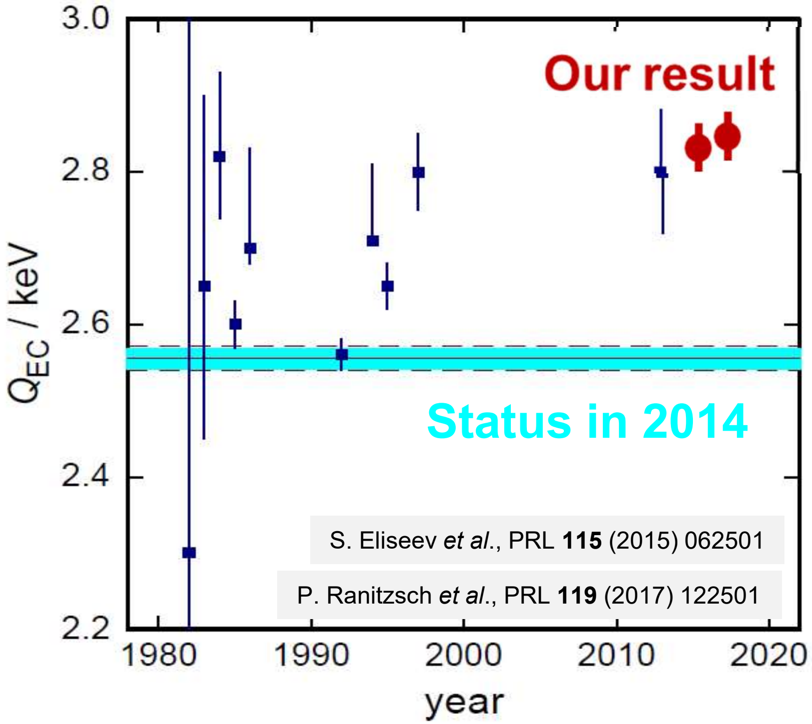
The ECHo (^{163}Ho) project

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

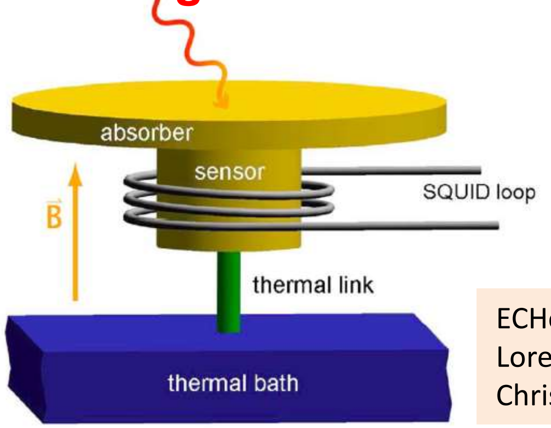
NEUTRONS FOR SCIENCE

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

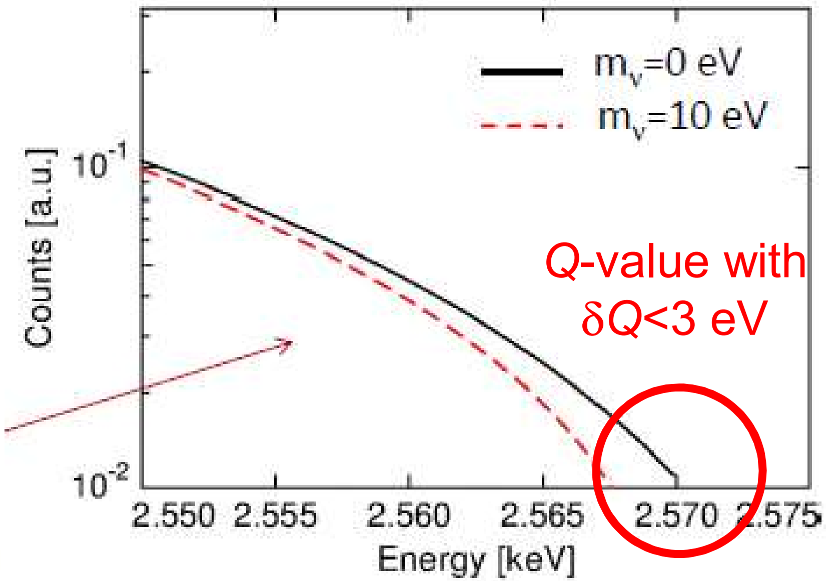
Q-value of EC in ^{163}Ho



Metallic Magnetic Calorimetry



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss



Measurement principle at PENTATRAP

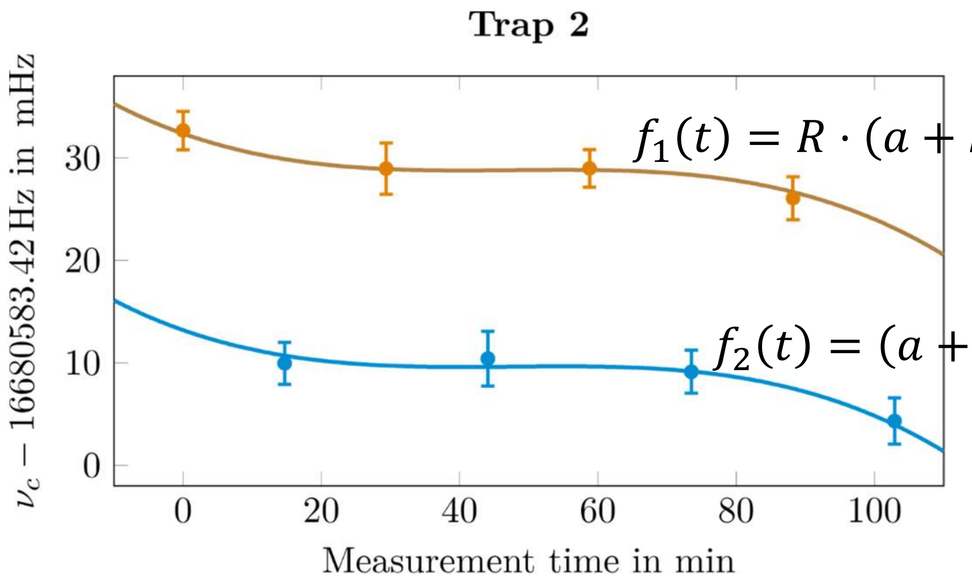
Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

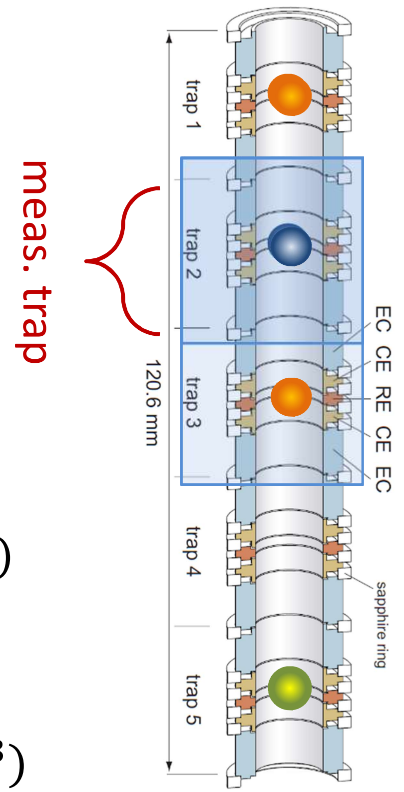
Second ion:

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



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

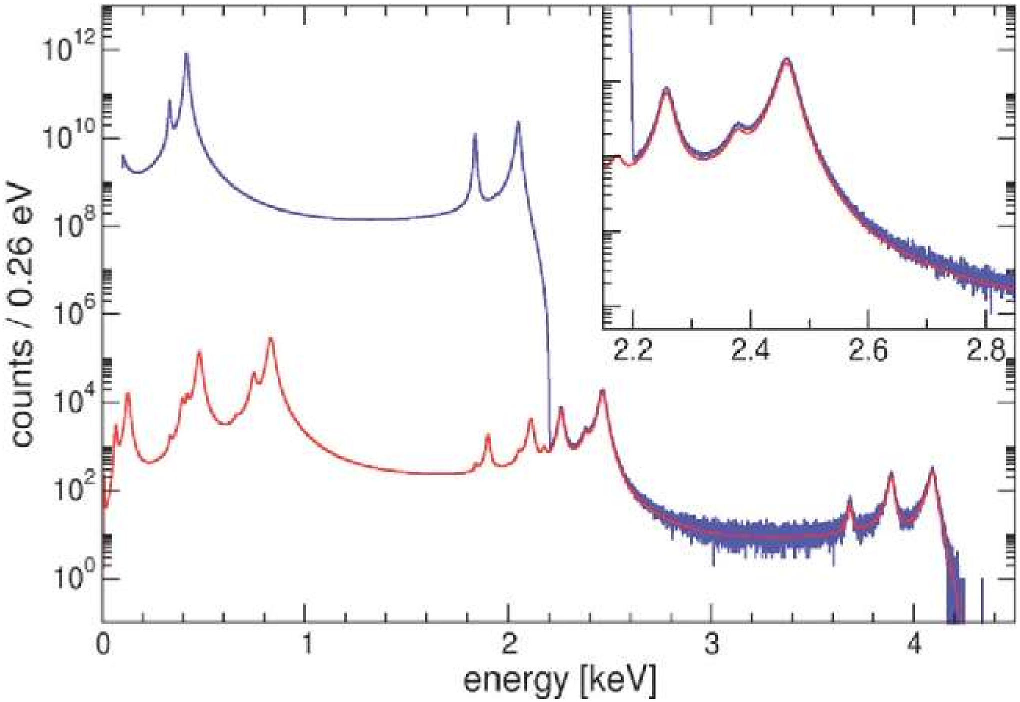
$$f_2(t) = (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$



Future: Monitoring trap

Atomic physics isn‘t that easy

Atomic mass differences and ν-physics



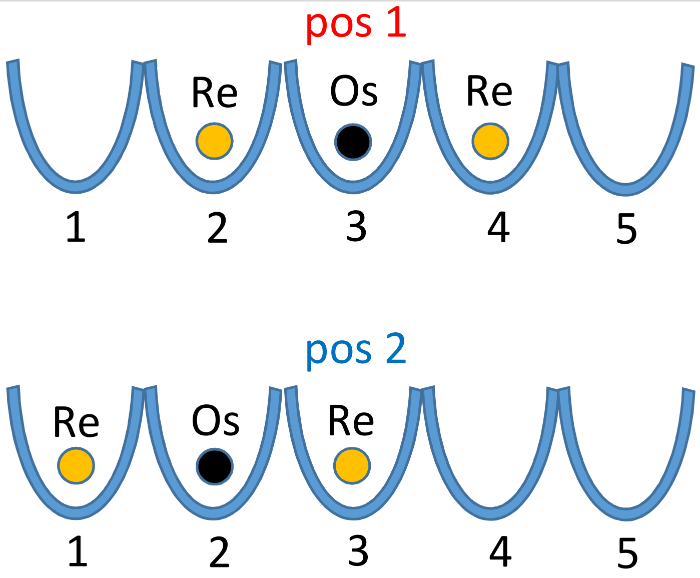
Gomes *et al.*, IEEE **23** (2013)

β^--decay of ^{187}Re

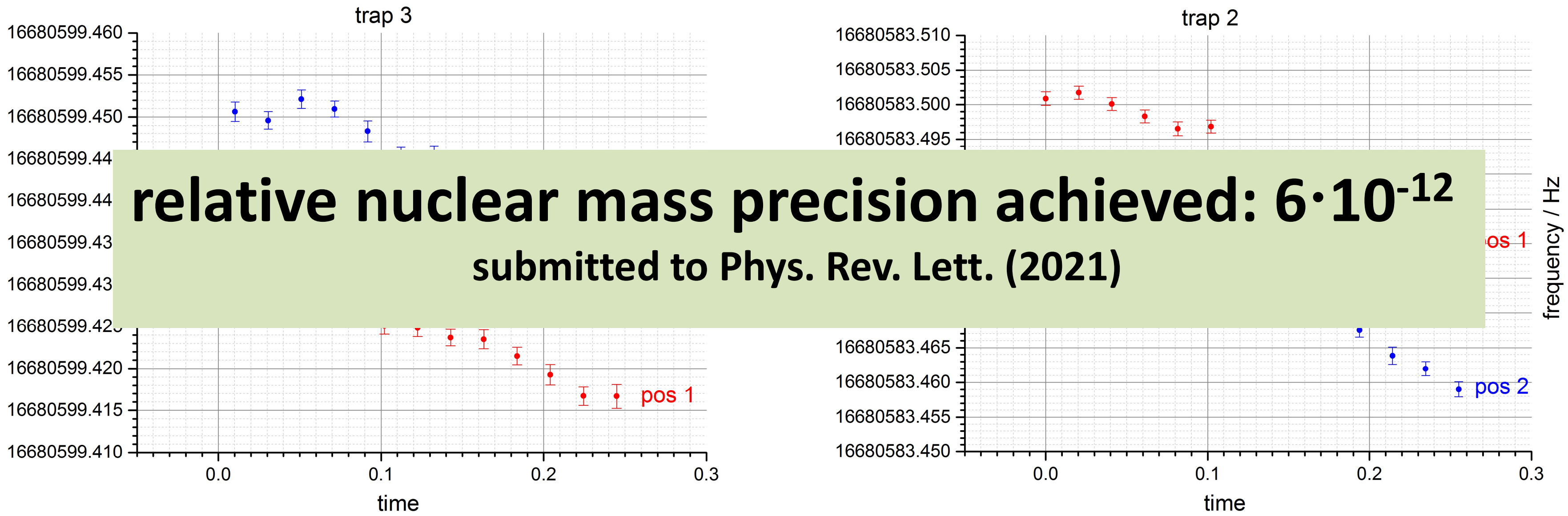
$$R = \frac{\nu_c(^{187}\mathrm{Os}^{29+})}{\nu_c(^{187}\mathrm{Re}^{29+})}$$

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

Highly charged Re and Os ions



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



relative nuclear mass precision achieved: $6 \cdot 10^{-12}$

submitted to Phys. Rev. Lett. (2021)

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 $1+1.14 \cdot 10^{-9}$.

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.
(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

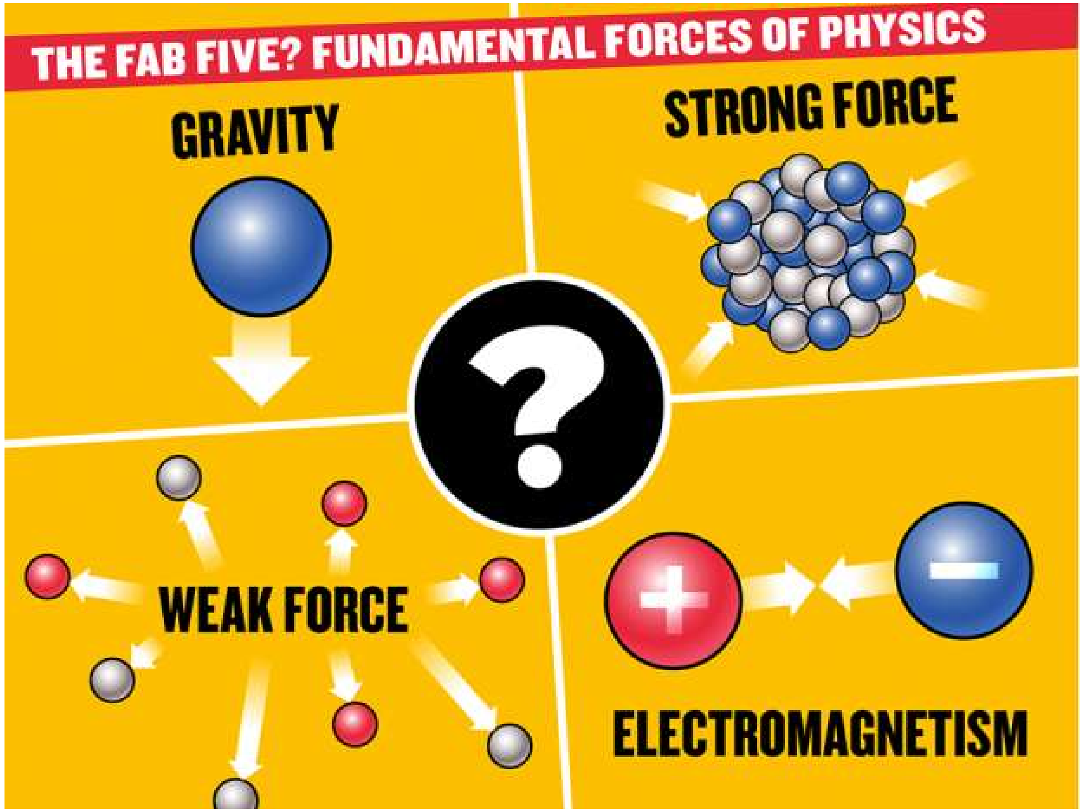
ground state

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

Possible application: search for suitable clock transitions

Results III

Nuclear masses for fifth force search



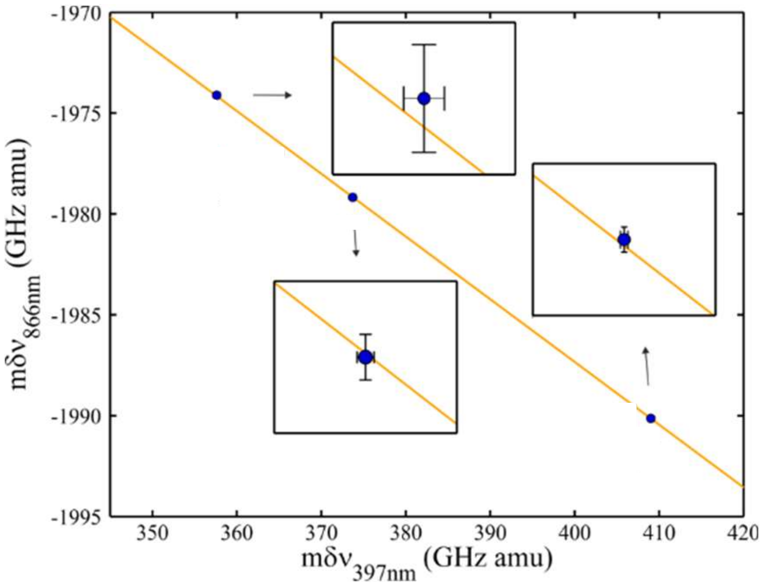
PENTATRAP: MPIK, RIKEN, CERN

www.freedomsphoenix.com/

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 $\delta\langle r^2\rangle_{A,A'}$

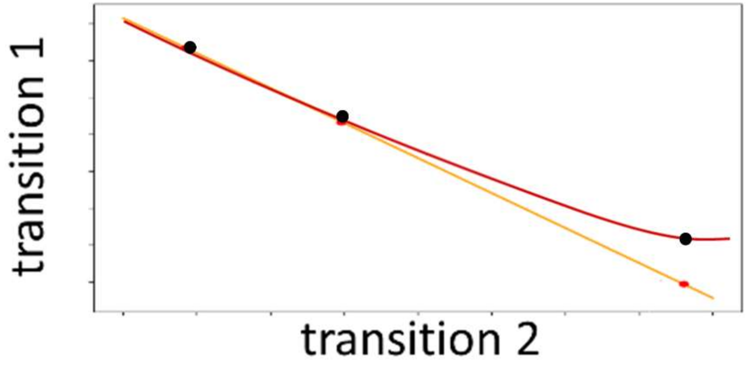


- new force mediated through scalar field with mass $m_\phi \rightarrow X_i$
- coupling to neutrons: y_n
- coupling to electrons: y_e

➔ 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)

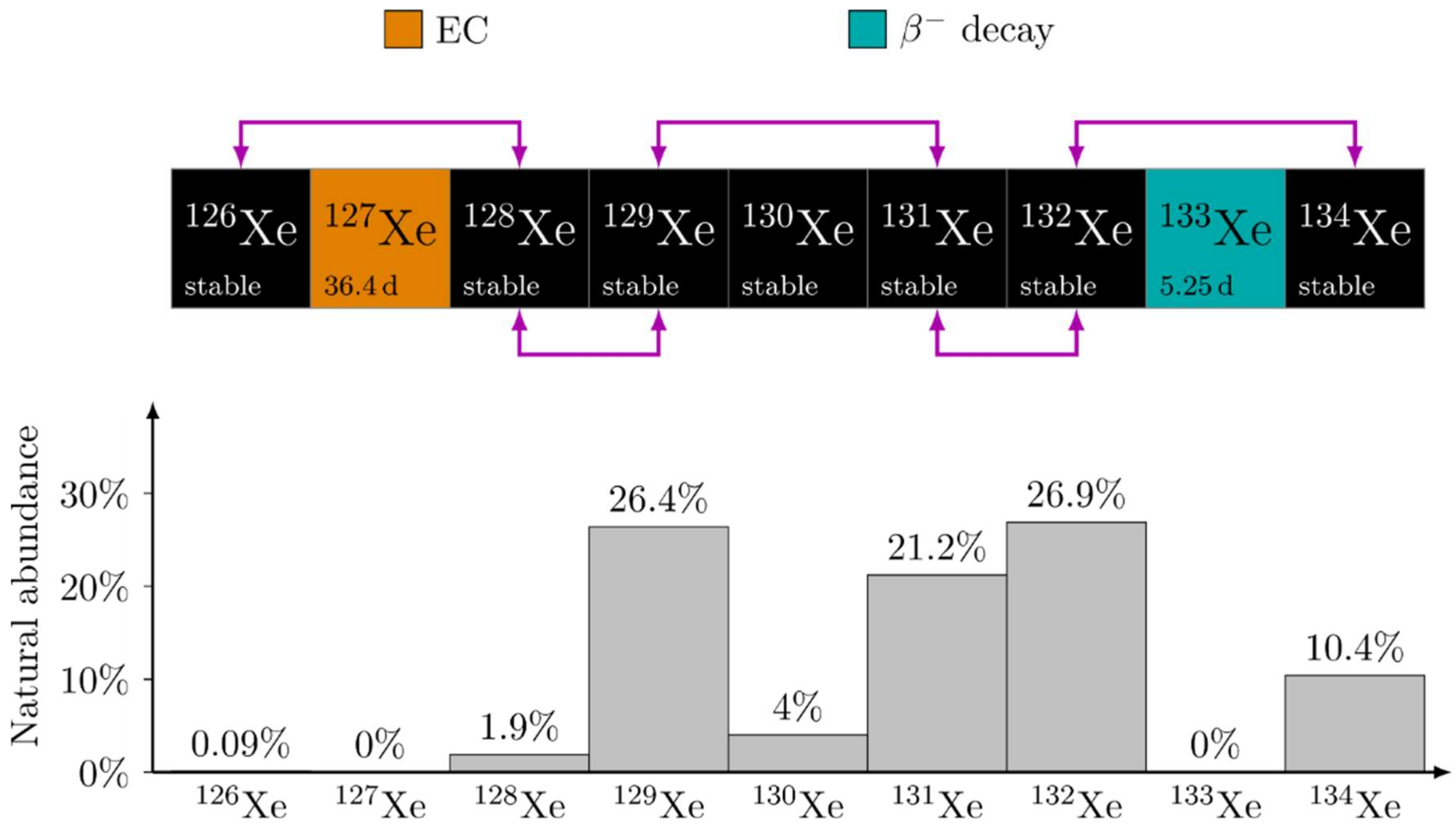


High-precision atomic and nuclear spectroscopy measurements needed!

Xe mass-ratio measurements

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

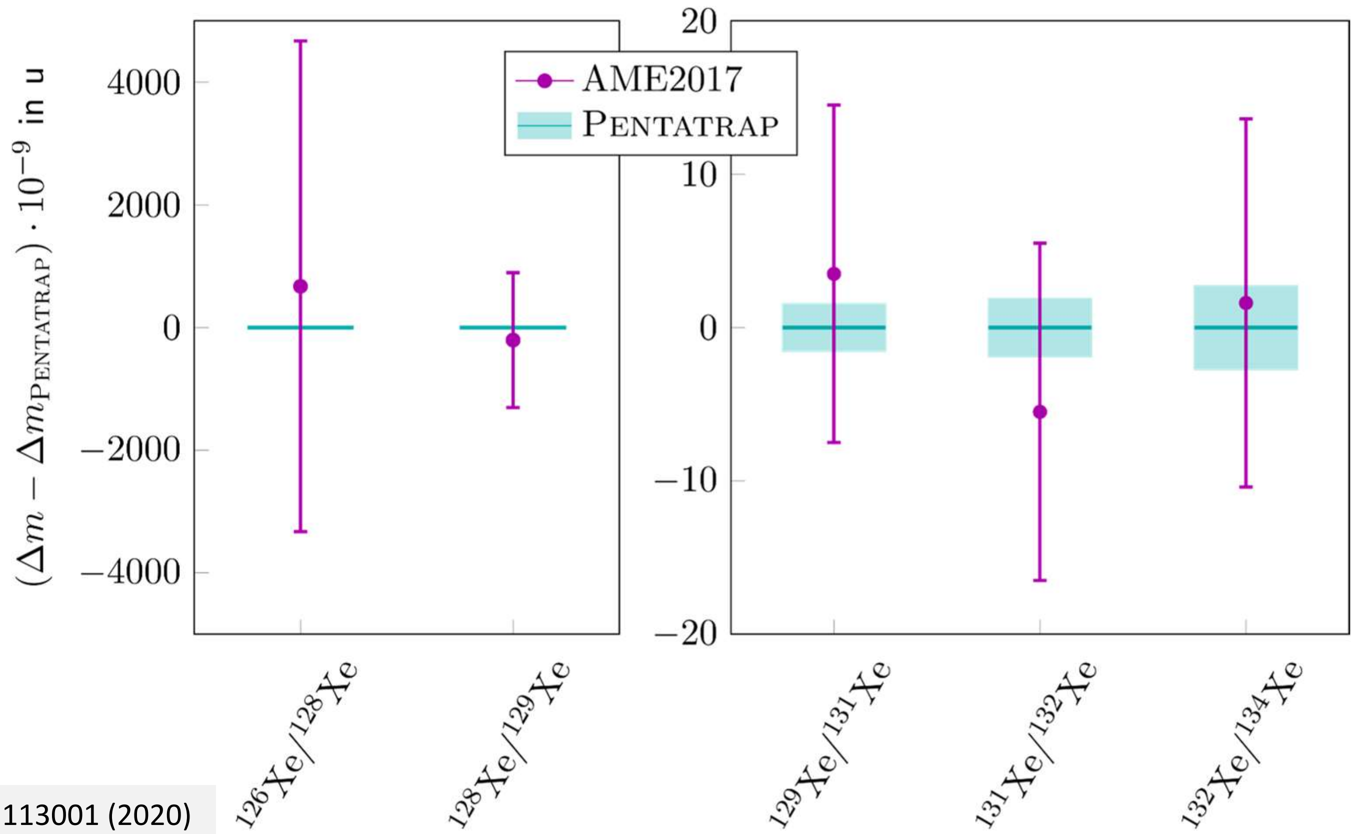
Mass-ratio uncertainties of 10^{-11} and below required!



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!



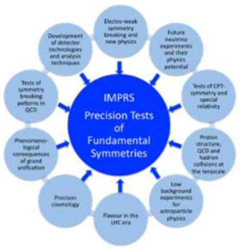
Rischka *et al.*, PRL **124**, 113001 (2020)

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

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***