INTERNATIONAL MAX PLANCK RESEARCH SCHOOL
PTFS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

International Max Planck Research School
Quantum Dynamics
in Physics, Chemistry and Biology

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

High-Precision Measurement of the Deuteron's Atomic Mass

International Conference on Precision Physics and Fundamental Physical Constants

Sascha Rau

LION TRAP

What is LIONTRAP?

- acronym for **L**ight **ION TRAP**

- purpose-built high precision Penning-trap mass spectrometer for light ions, located in Mainz, follow up from Mainz *g*-factor experiment for highly charged ions (electron mass, strong field BS-QED Tests)

- first successful measurement campaign on proton mass with ${}^{\delta m}/_{m} = 32\ \mathrm{ppt}$ (parts per trillion, 10^{-12})
  (F. Heiße et al. PRL 119, 033001, 2017)

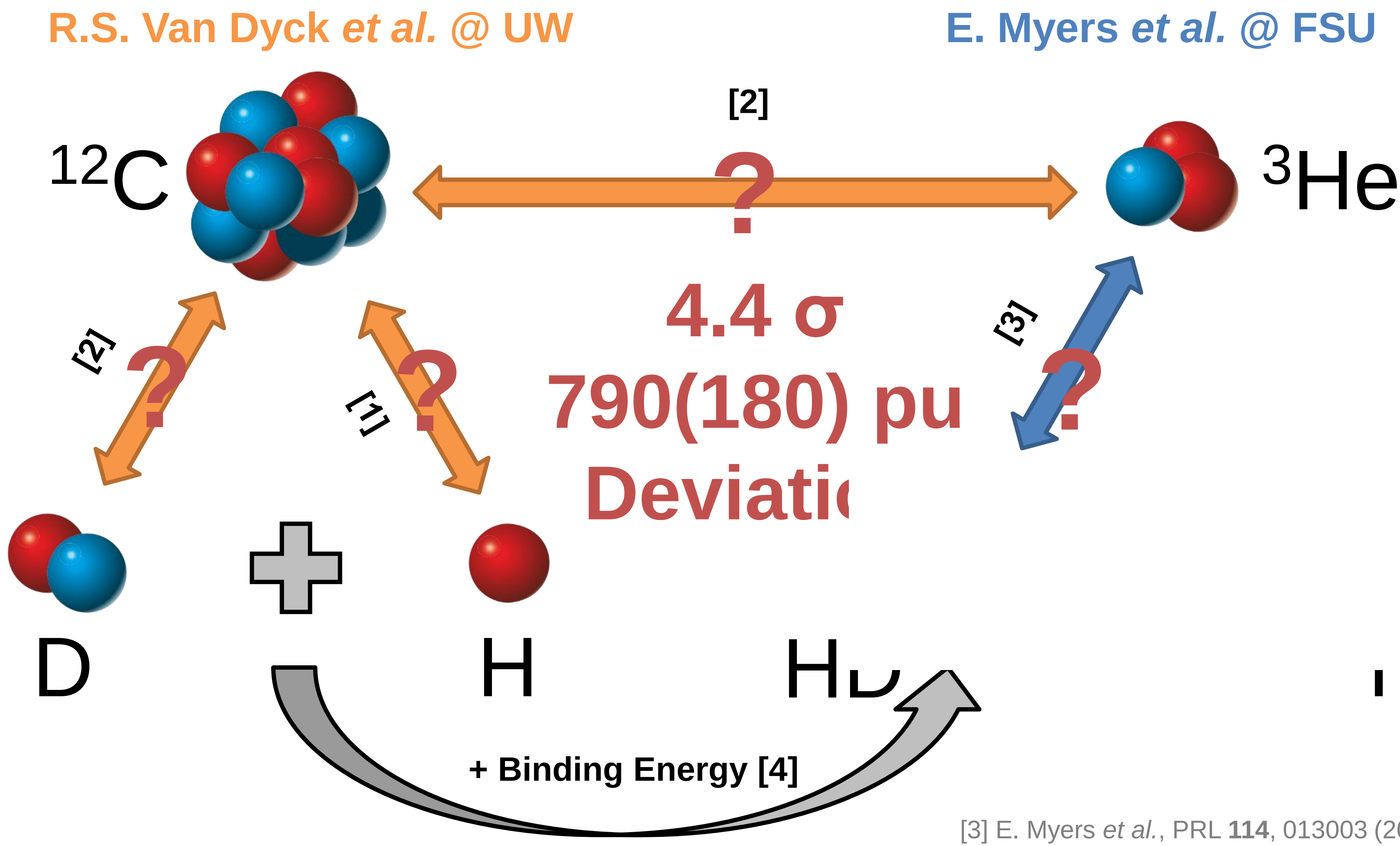
Why are mass measurements on light ions important?

- relevant for precision spectroscopy ($m_\mathrm{p}/m_\mathrm{e}$), tests of special relativity (m_d), KATRIN ($m_{^3\mathrm{He}} - m_\mathrm{t}$)

- inconsistency in literature calls for independent values

- difficult because of relatively small signals, high relativistic shifts

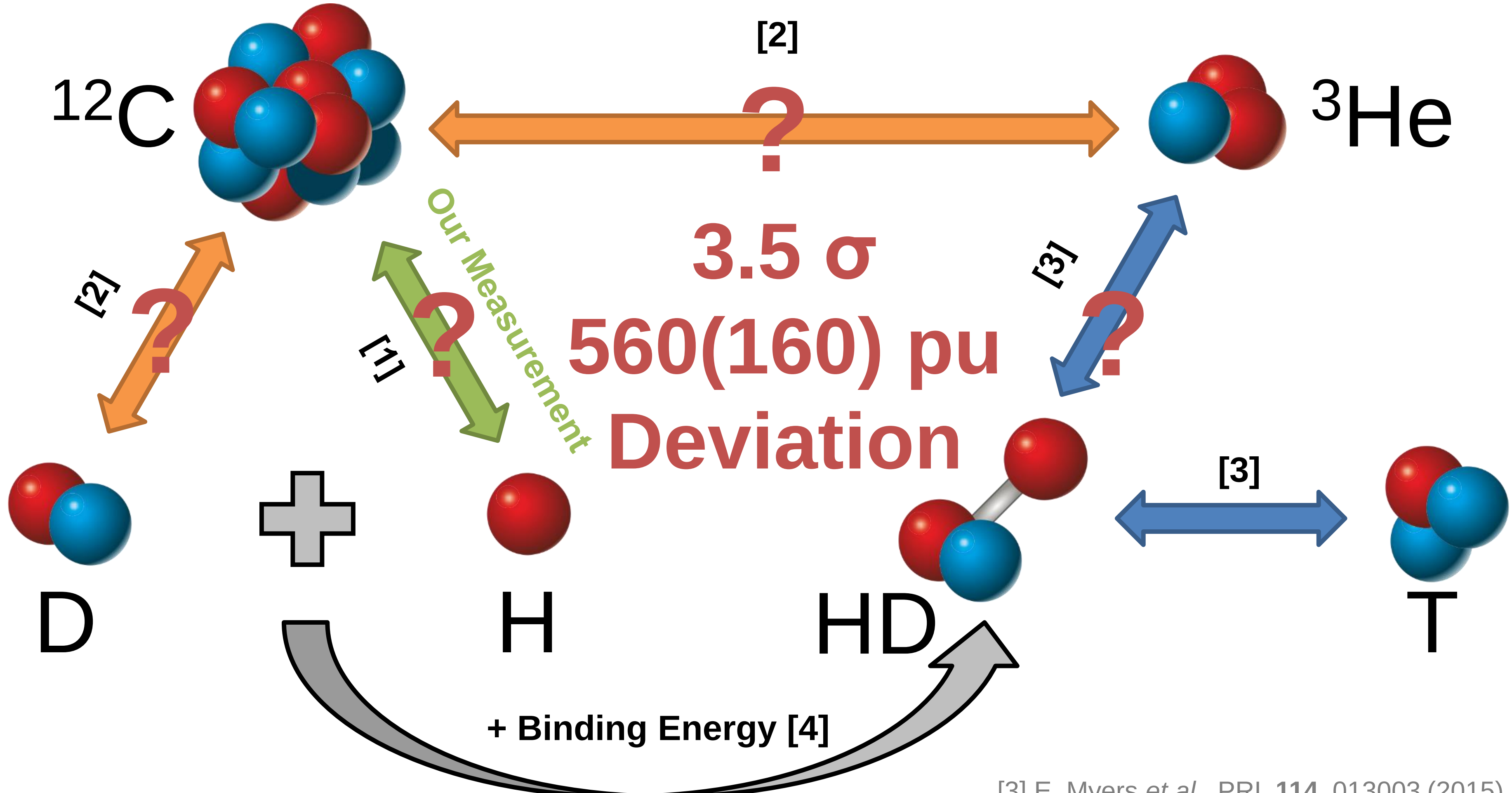
Puzzle of Light Atomic Masses



[3] E. Myers *et al.*, PRL **114**, 013003 (2015)
[4] Yan *et al.*, PRA **67**, 062504 (2003)
[1] R. S. Van Dyck Jr. *et al.*, AIP Conf. Proc. **457**, 101 (1999)
[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)

Puzzle of Light Atomic Masses

R.S. Van Dyck *et al.* @ UW — **E. Myers *et al.* @ FSU**



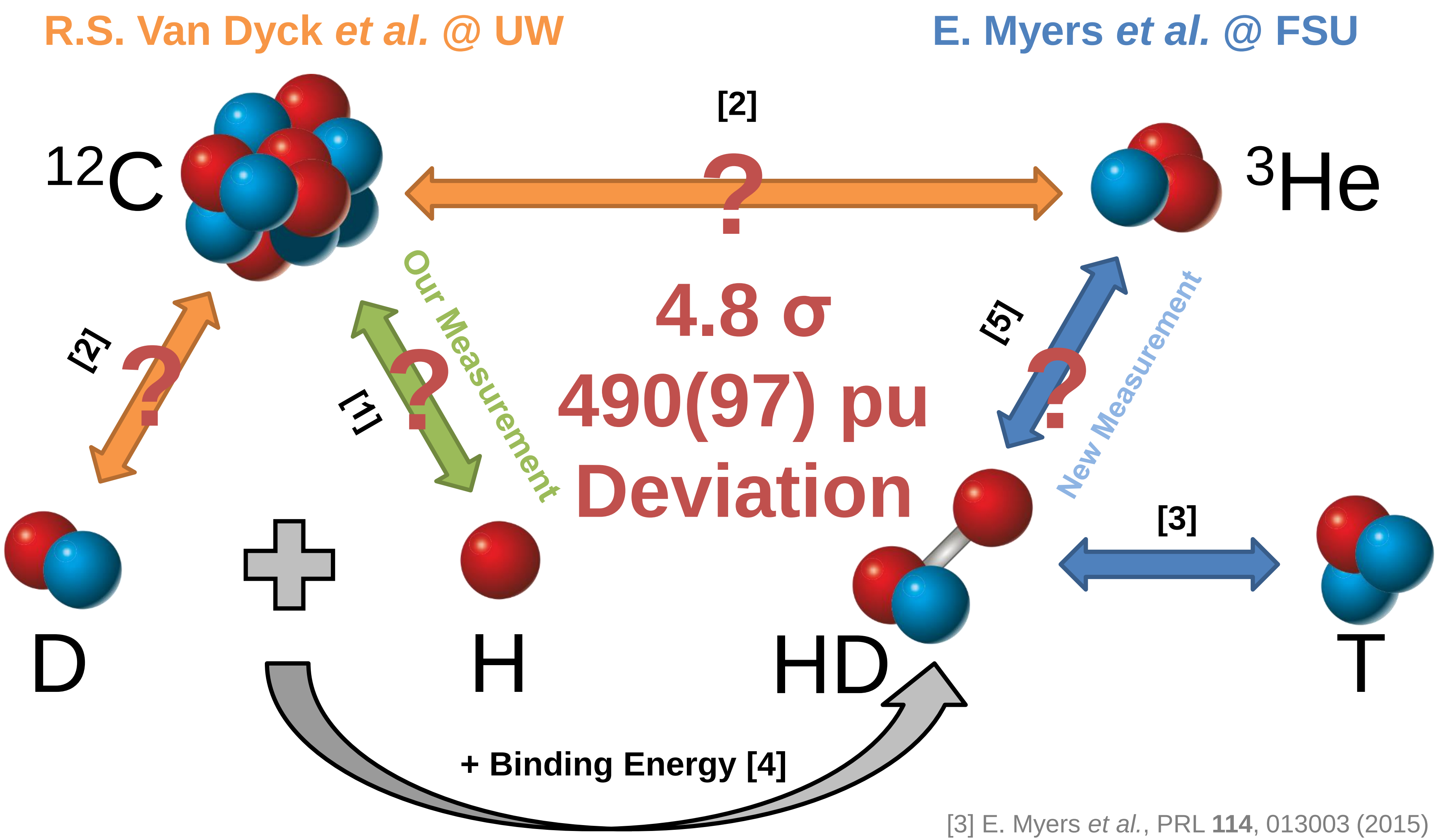
[1] F. Heiße *et al.*, PRL **119**, 033001 (2017)

[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)

[3] E. Myers *et al.*, PRL **114**, 013003 (2015)

[4] Yan *et al.*, PRA **67**, 062504 (2003)

Puzzle of Light Atomic Masses



[1] F. Heiße *et al.*, PRL **119**, 033001 (2017)
[2] S. L. Zafonte *et al.*, Metrologia **52**, 280 (2015)
[3] E. Myers *et al.*, PRL **114**, 013003 (2015)
[4] Korobov *et al.*, PRL. 118, 233001 (2017)
[5] S. Hamzeloui *et al*, PRA **96**, 060501 (2017)

Outline

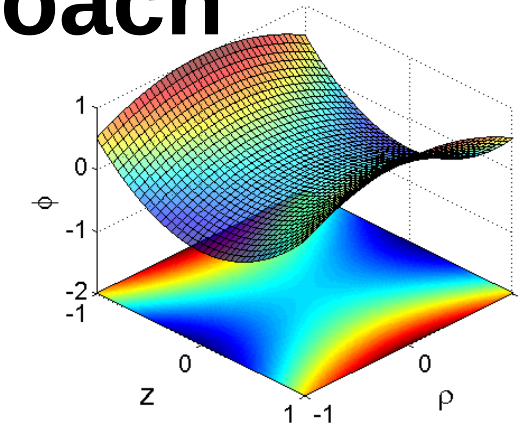
- **Setup and Experimental Techniques**
  - a new ultra-harmonic trap

- Proton's Atomic Mass
  F. Heiße *et al.*, PRL **119**, 033001 (2017)

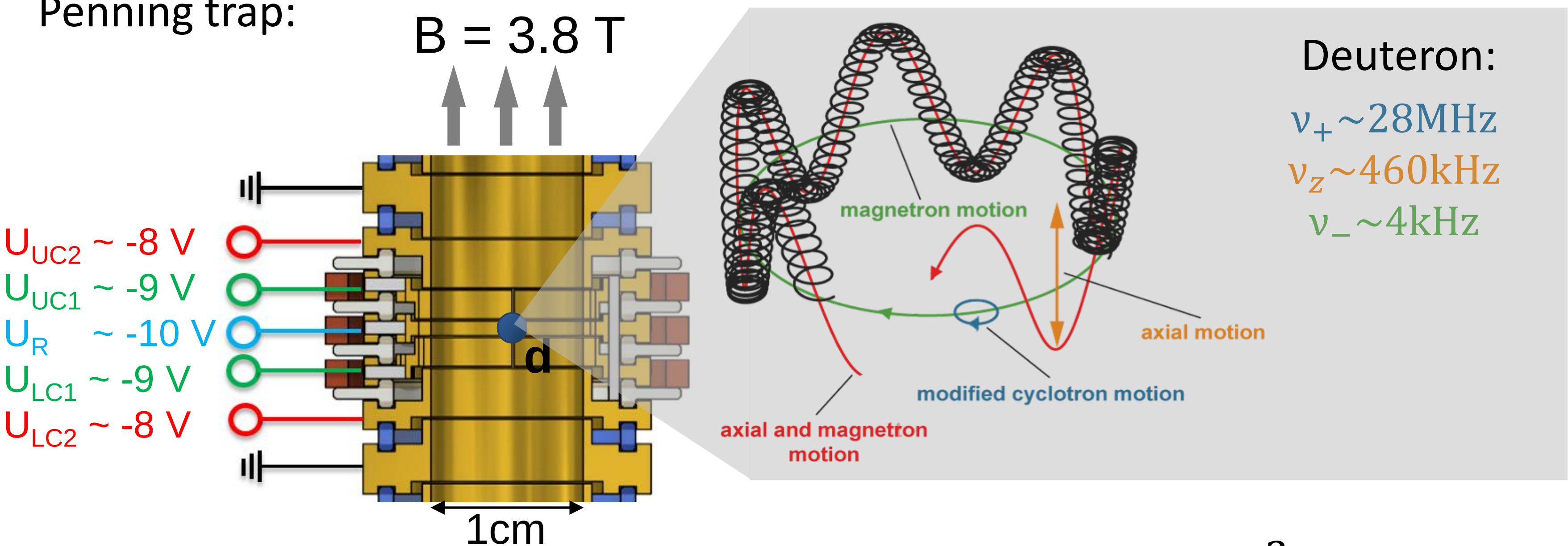
- Deuteron's Atomic Mass

Experimental Approach

- measurement of cyclotron frequency: $\nu_C = \frac{1}{2\pi}\frac{q}{m}B$
  → homogenous static magnetic field
  → electrostatic quadrupole potential for trapping



- Penning trap:



- cyclotron frequency via invariance theorem [1]:

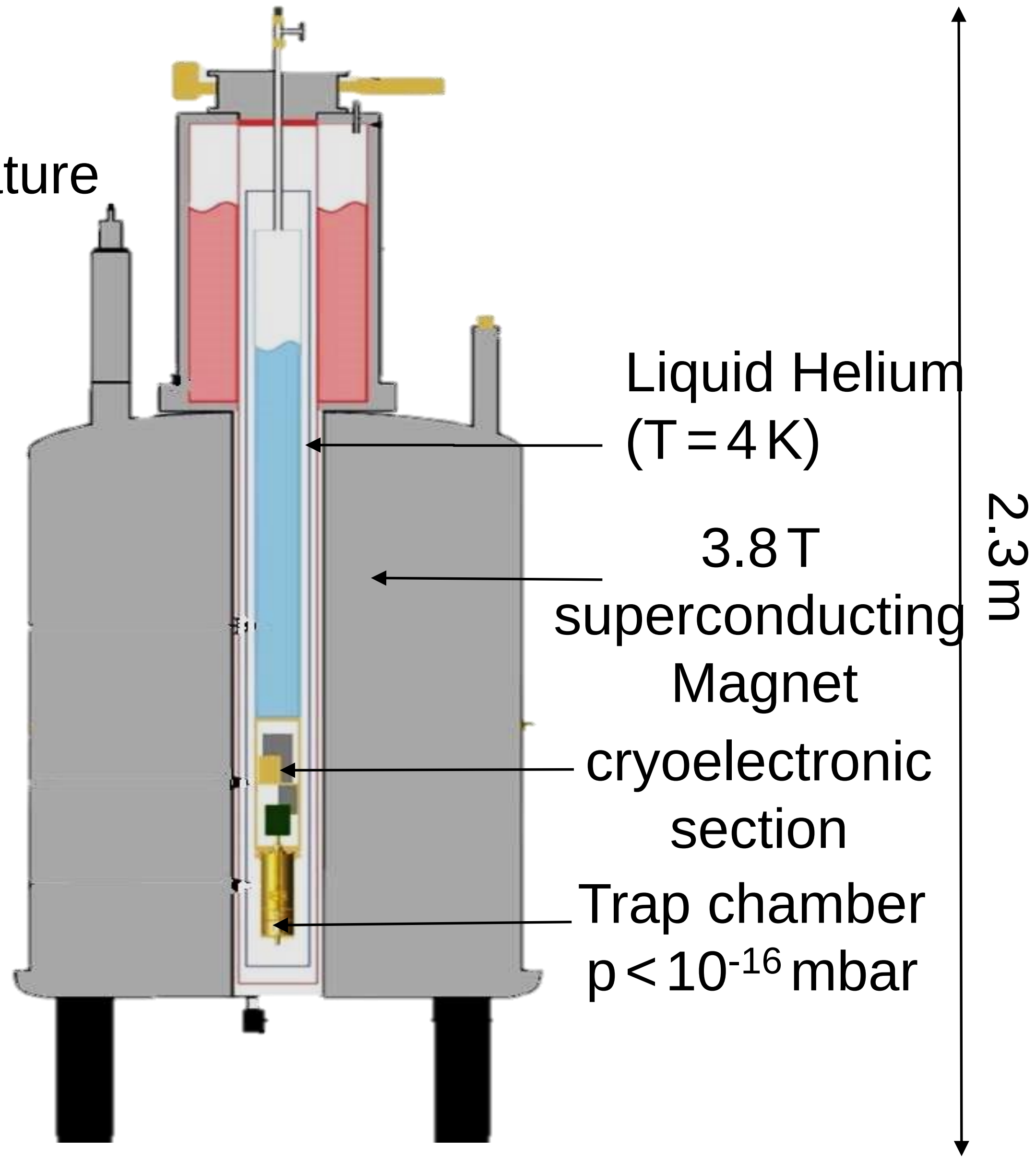
$$B = \frac{2\pi\, m}{q(^{12}C)}\nu_c(^{12}C)$$

$$\nu_c = \sqrt{\nu_+{}^2 + \nu_z{}^2 + \nu_-{}^2} = \frac{1}{2\pi}\frac{q}{m}B$$

[1] L.S. Brown & G. Gabrielse, PRA 25, 2423 (1982)

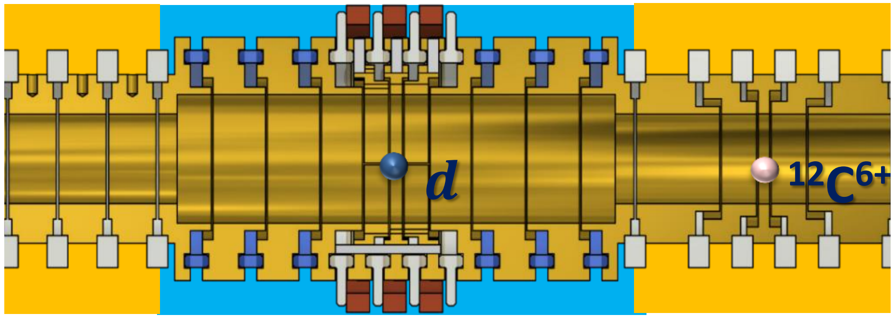
Setup

- offline Experiment
- liquid Helium temperature
- hermetically sealed trap chamber
- in situ ion creation using miniature EBIT/S



Measurement Procedure

$$\mathrm{m_d} = \frac{1}{6}\frac{\nu_c(^{12}\mathrm{C}^{6+})}{\nu_c(d)}\mathrm{m}(^{12}\mathrm{C}^{6+})$$



Storage trap 2 (ST2)

Precision trap (PT)

Storage trap 1 (ST1)

both ions at the same time within the trap chamber

(I) $\nu_c(d)$ in PT

(II) $\nu_c(^{12}C^{6+})$ in PT

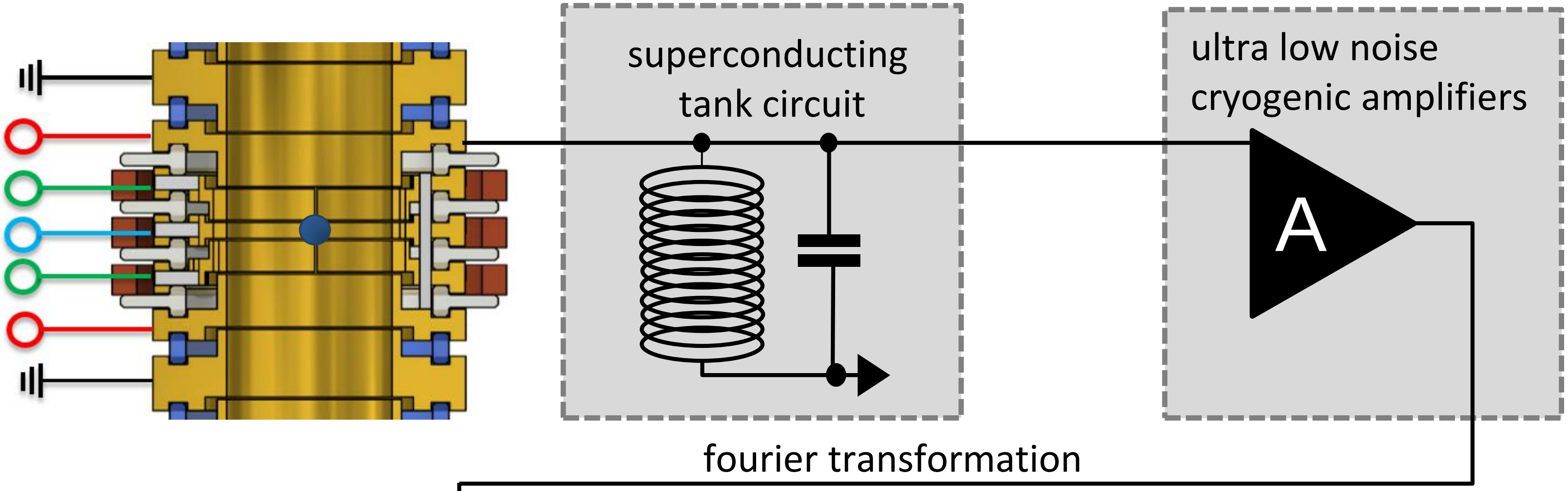
$$R \equiv \frac{\nu_c(^{12}\mathrm{C}^{6+})}{\nu_c(\mathrm{d})}$$

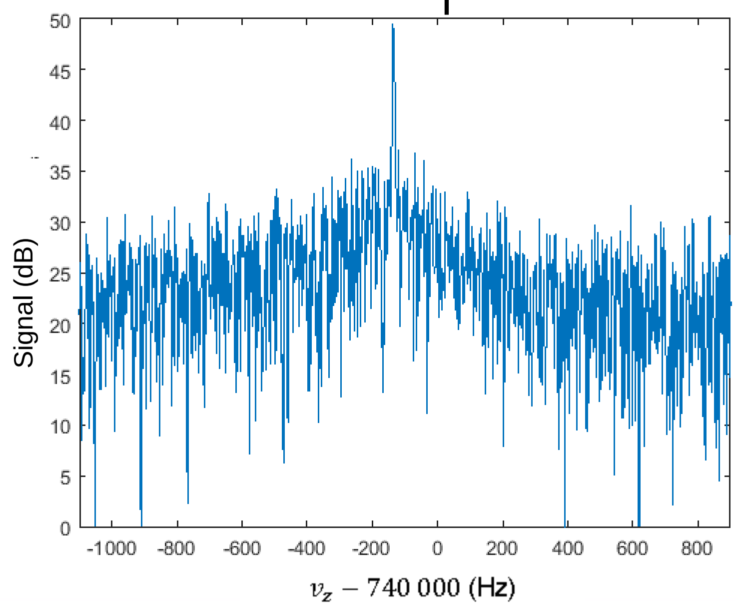
time between ν_+ measurements optimized

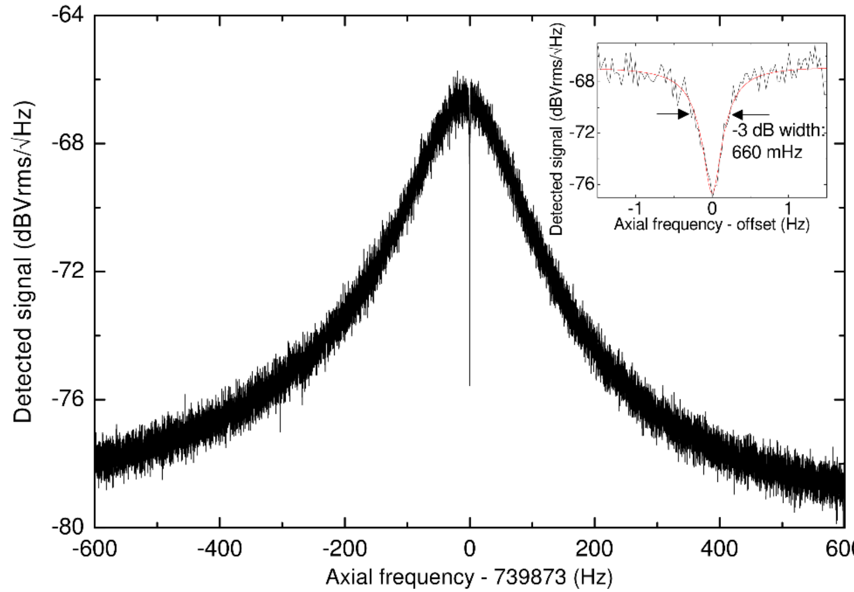
→ reduction of impact of magnetic field fluctuations compared to former measurements

Eigenfrequency Detection

- measurement of induced image currents (~fA) on trap electrodes



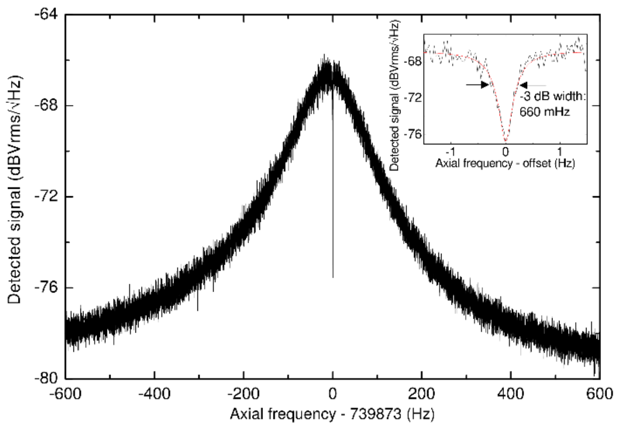




Eigenfrequency Measurement Techniques

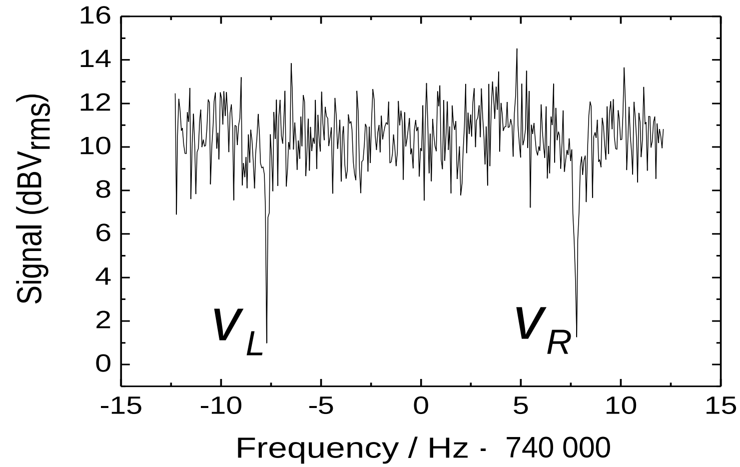
1. Dip Signal

$\mathbf{\nu_z}$ of thermalized ion (T_z=4.5 K) measured as narrow "dip"



2. Double-Dip Signal:

$\mathbf{\nu_+, \nu_-}$ coupled to axial motion via rf-sideband coupling



$$\nu_+ = \nu_{rf} - \nu_z + \nu_L + \nu_R \qquad \nu_- = \nu_{rf} + \nu_z - \nu_L - \nu_R$$

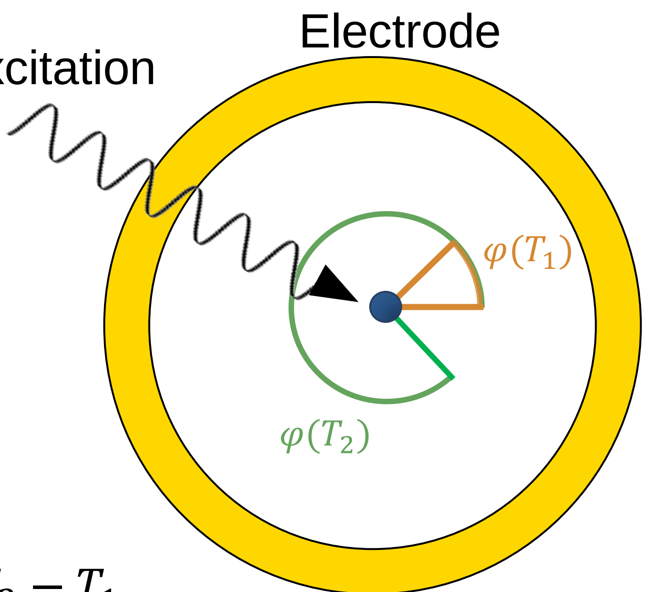
Advantages: - Thermal equilibrium during measurement
→ Small energy dependent systematic shifts

Disadvantages: - $\frac{\delta u_n}{u_n} \propto \frac{1}{\sqrt{t_m}}$ → "slow" (3 min) → impact of field fluctuations

- Lineshape dependent

Phase-Sensitive Detection Method

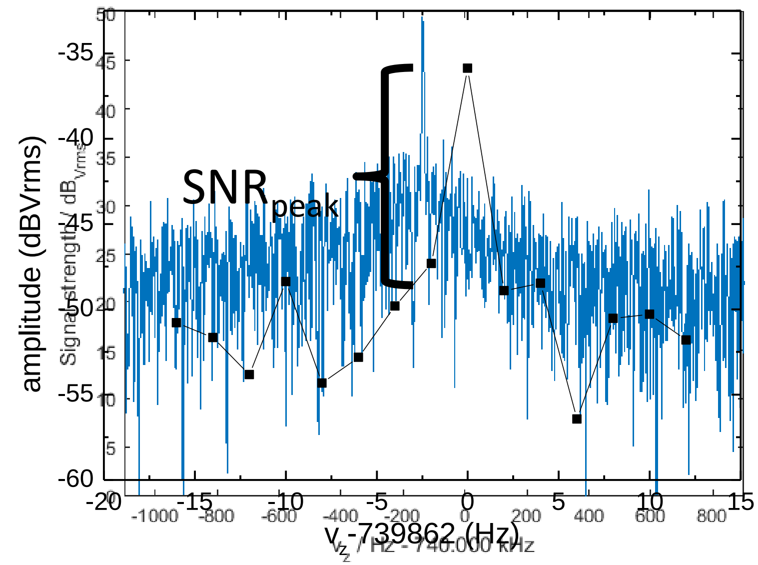
A phase sensitive measurement scheme allows **coherent detection.**
The complex Fourier spectrum provides besides the peak position in the Fourier spectrum also the instantaneous phase of the ion.



$$T_{\mathrm{evol}} = T_2 - T_1$$

$$\nu = \frac{\varphi(T_2) - \varphi(T_1)}{360° \cdot T_{\mathrm{evol}}}$$

Peak-signal of a single proton



Advantages:
-linear scaling with Measurement Time
-no lineshape model needed

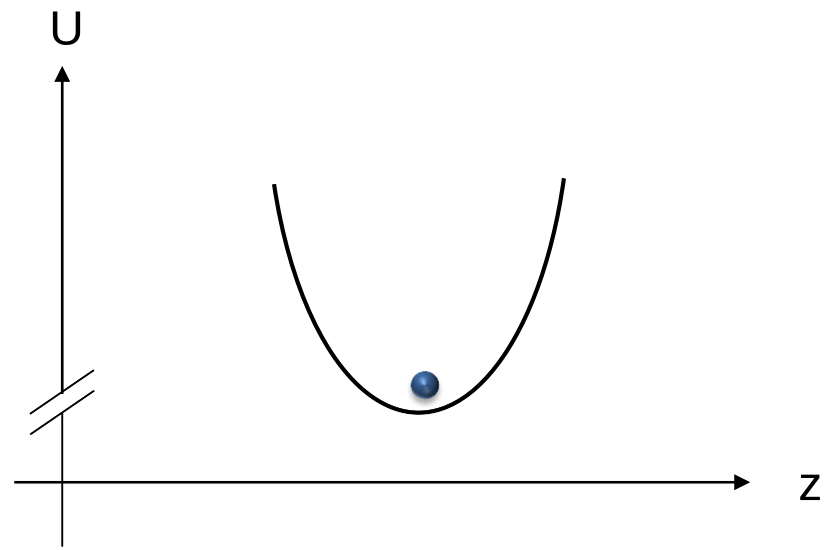
$$\frac{\delta\nu}{\nu} = \frac{\delta\varphi}{360° \cdot \nu \cdot T_{evol}}, \qquad \delta\varphi \triangleq \text{phase jitter}$$

A New Ultra-Harmonic Trap

Ideal world:

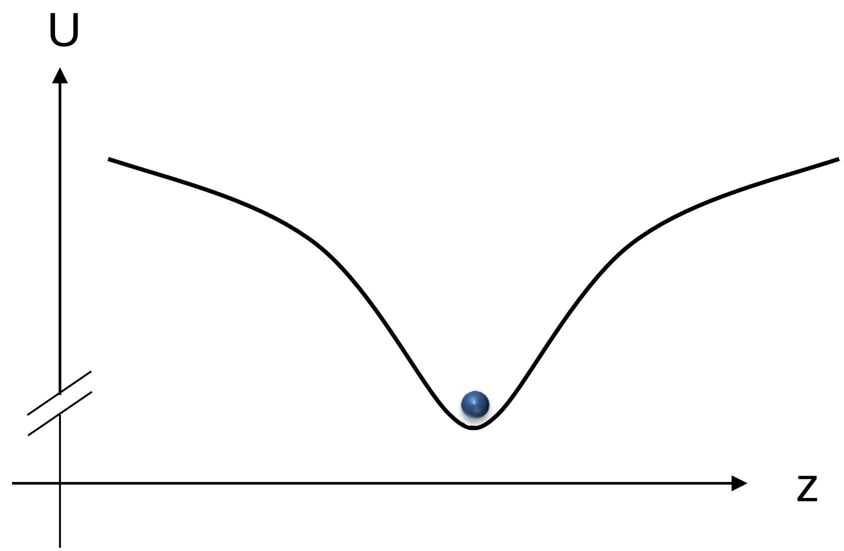
$$U(z) = \frac{1}{2} U_r \left(C_0 + C_2 \frac{z^2}{d_{char}^2} \right)$$

→ v_z independent of energy!



Real world:

→ v_z depends on energy!



A New Ultra-Harmonic Trap

Real world:

$$U(z) = \frac{1}{2}U_r\left(C_0 + C_2\frac{z^2}{d_{char}^2} + \cancel{C_4\frac{z^4}{d_{char}^4}} + \cancel{C_6\frac{z^6}{d_{char}^6}} + C_8\frac{z^8}{d_{char}^8} + C_{10}\frac{z^{10}}{d_{char}^{10}} + \cdots\right) = \frac{1}{2}U_r\sum_{i=0,2,\ldots}^{\infty} C_i\frac{z^i}{d_{char}^i}$$

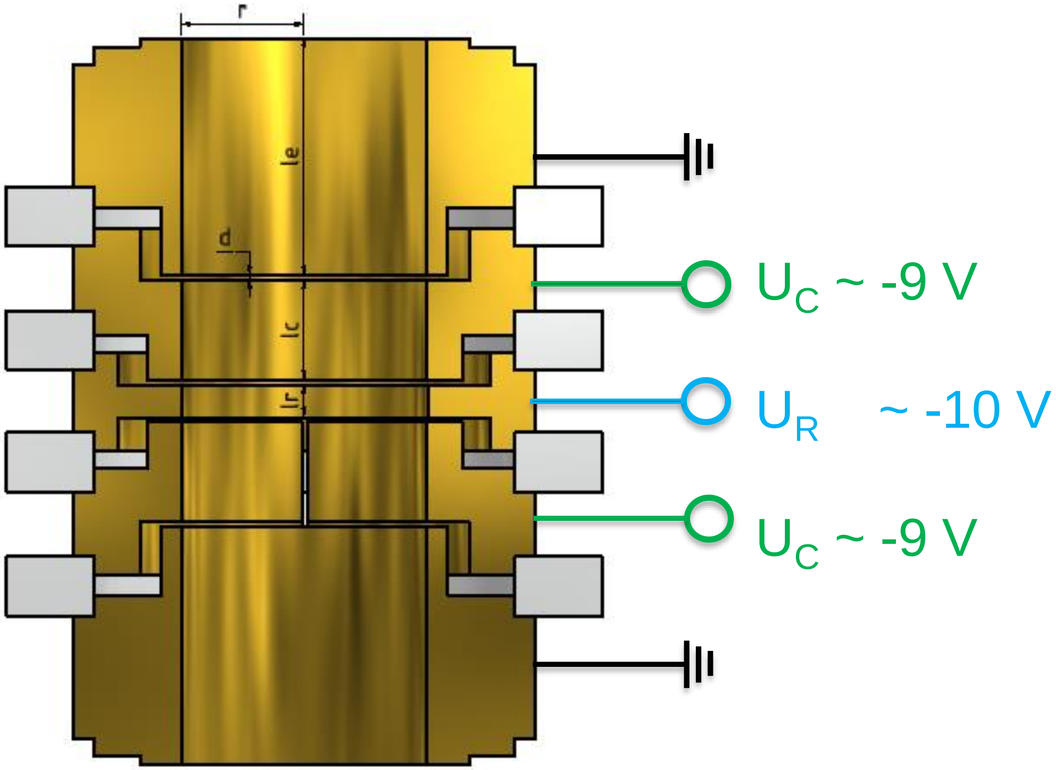
So far:

Use one pair of correction electrodes

Degrees of freedom: L_R, L_C, U_C

Optimized parameters:

$C_4 = C_6 = 0$ (compensated)



A New Ultra-Harmonic Trap

Real world:

$$U(z) = \frac{1}{2}U_r\left(C_0 + C_2\frac{z^2}{d_{char}^2} + \cancel{C_4\frac{z^4}{d_{char}^4}} + \cancel{C_6\frac{z^6}{d_{char}^6}} + \cancel{C_8\frac{z^8}{d_{char}^8}} + \cancel{C_{10}\frac{z^{10}}{d_{char}^{10}}} + \cdots\right) = \frac{1}{2}U_r\sum_{i=0,2,\ldots}^{\infty} C_i\frac{z^i}{d_{char}^i}$$

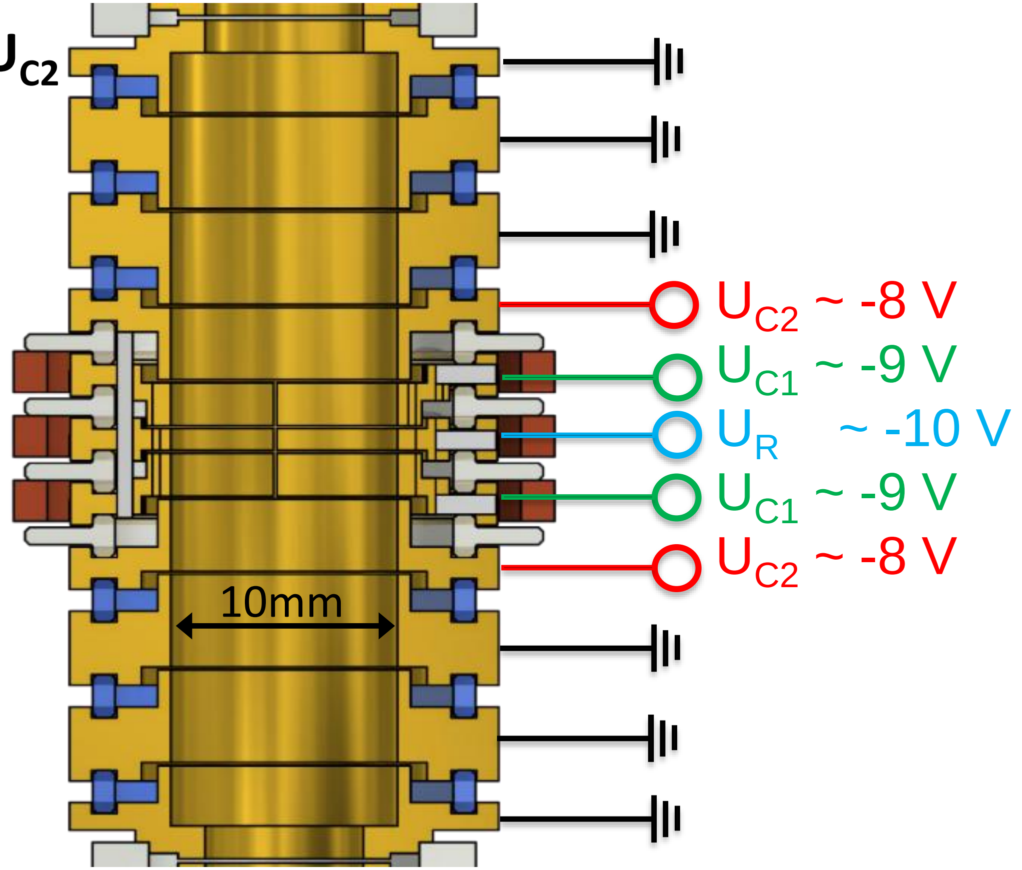
New trap **(additional pair of correction electrodes)**

Degrees of freedom: L_R, L_{C1}, U_{C1}, $\mathbf{L_{C2}}$, $\mathbf{U_{C2}}$

Optimized parameters:

$C_4=C_6=C_8=C_{10}=0$

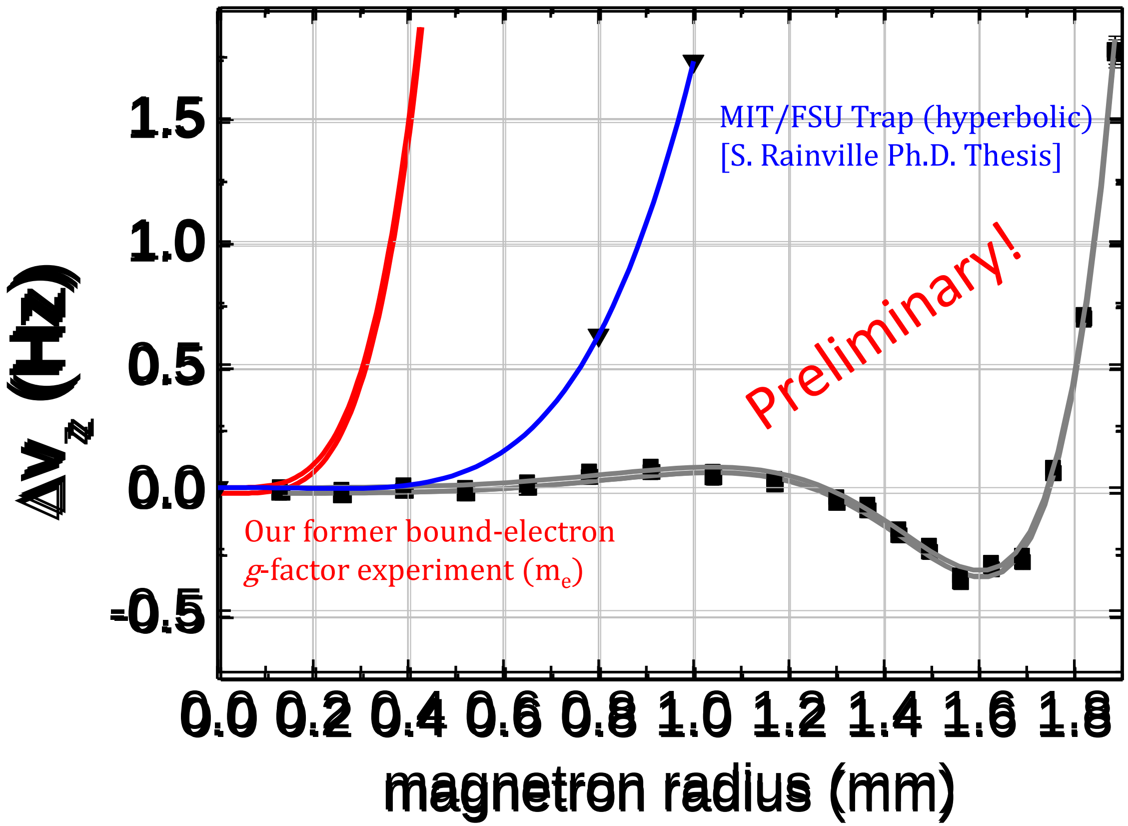
(doubly compensated)



A New Ultra-Harmonic Trap - Performance

Study shifts of axial freq. due to magnetron bursts:

$$\frac{\Delta\nu_z}{\nu_z} = -\frac{3}{2}\frac{C_4}{d_{char}^2 C_2} r_-^2 + \frac{15}{8}\frac{C_6}{d_{char}^4 C_2} r_-^4 - \frac{35}{8}\frac{C_8}{d_{char}^6 C_2} r_-^6 + \cdots$$



F. Heiße *et al.*, PRA, accepted

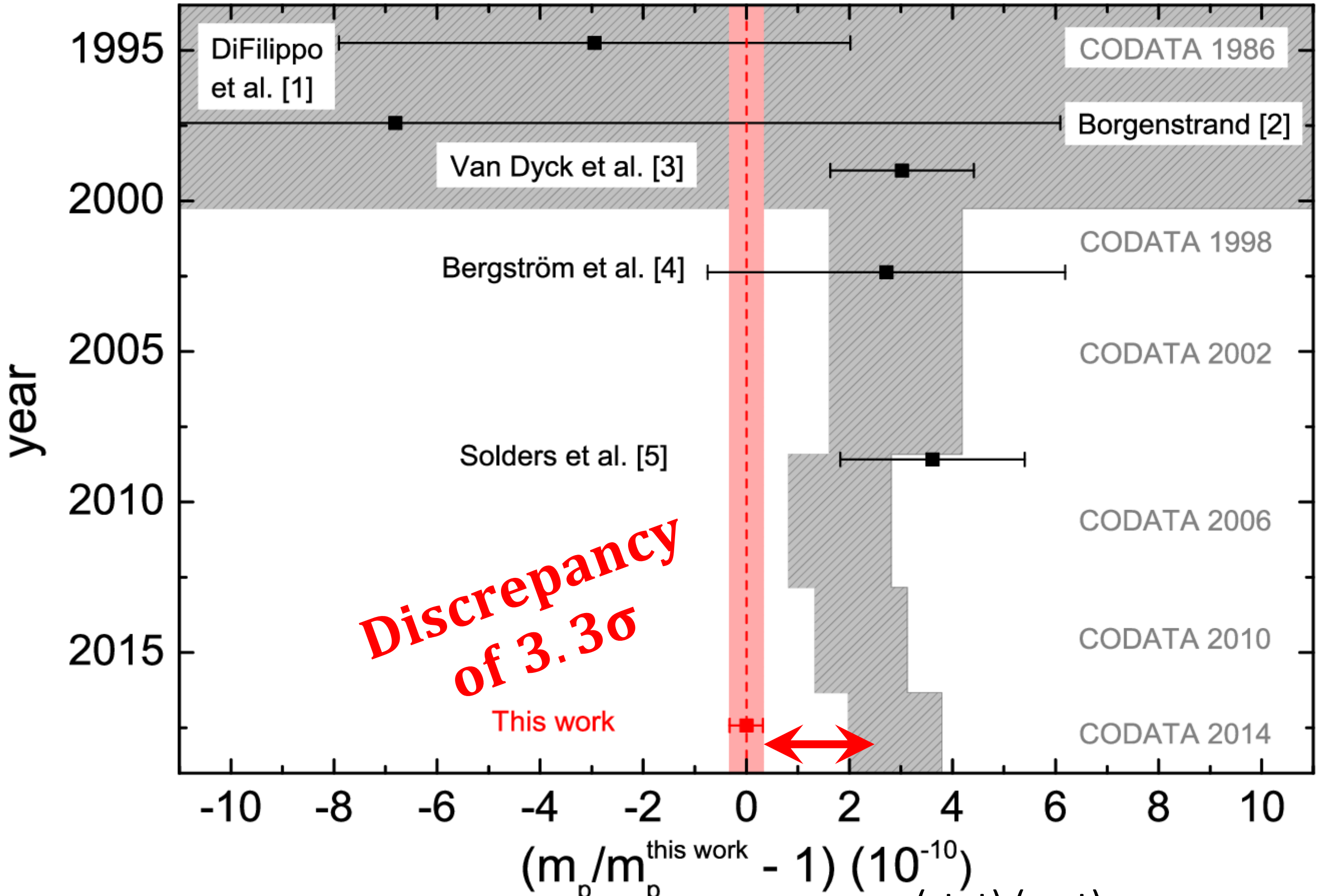
Outline

- Setup and Experimental Techniques
  - a new ultra-harmonic trap

- **Proton's Atomic Mass**
  F. Heiße *et al.*, PRL **119**, 033001 (2017)

- Deuteron's Atomic Mass

Results



(stat) (syst)

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

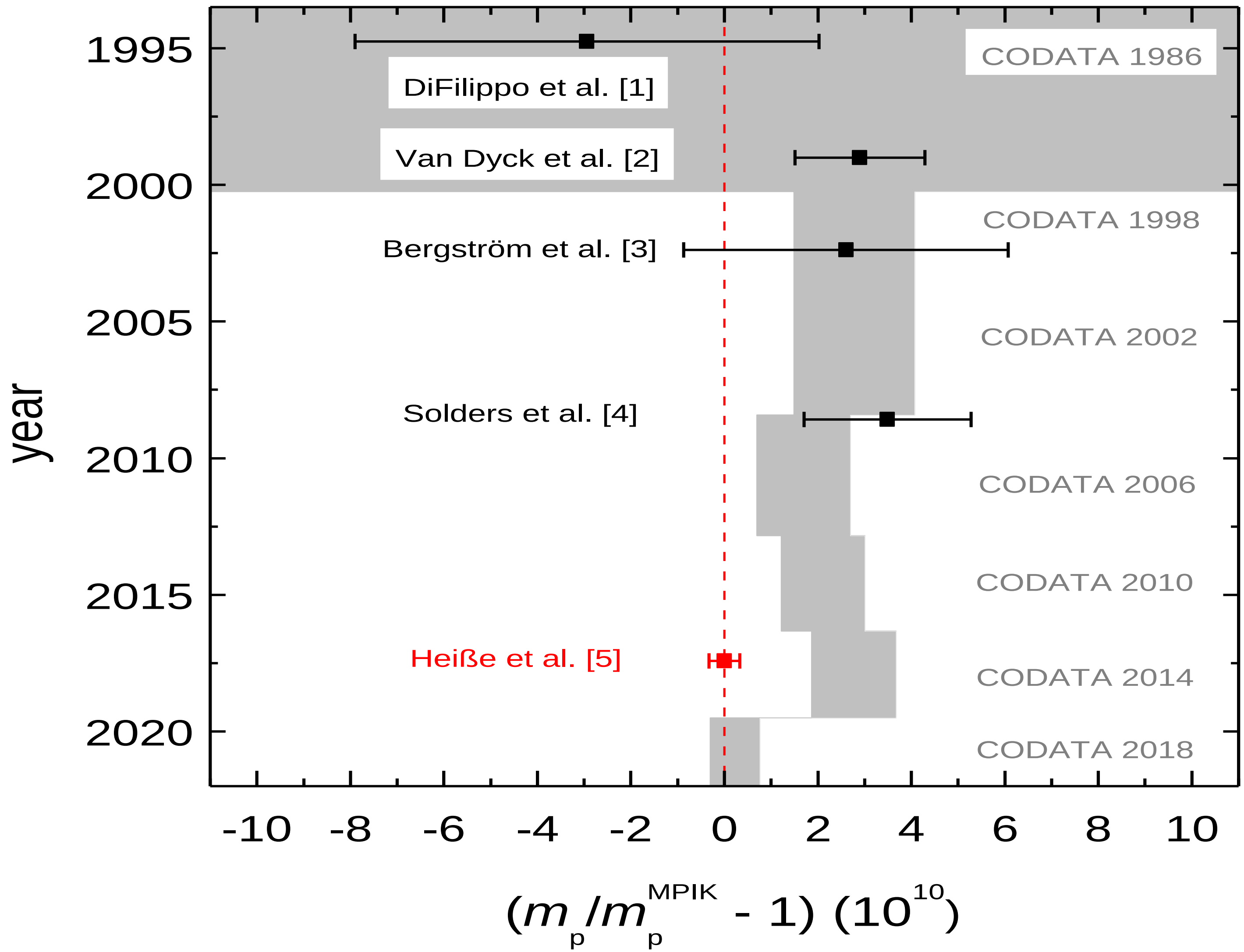
$$\frac{\delta m_p}{m_p} = 3.2 \cdot 10^{-11}$$

$\longrightarrow$ **Improvement by a factor of 3**

[1] PRL **73**, 1481 (1994). [2] Ph.D. thesis, Stockholm University (1997).
[3] AIP Conf. Proc. **457**, 101 (1999). [4] Phys. Scr. **66**, 201 (2002). [5] PRA **78**, 2514 (2008).

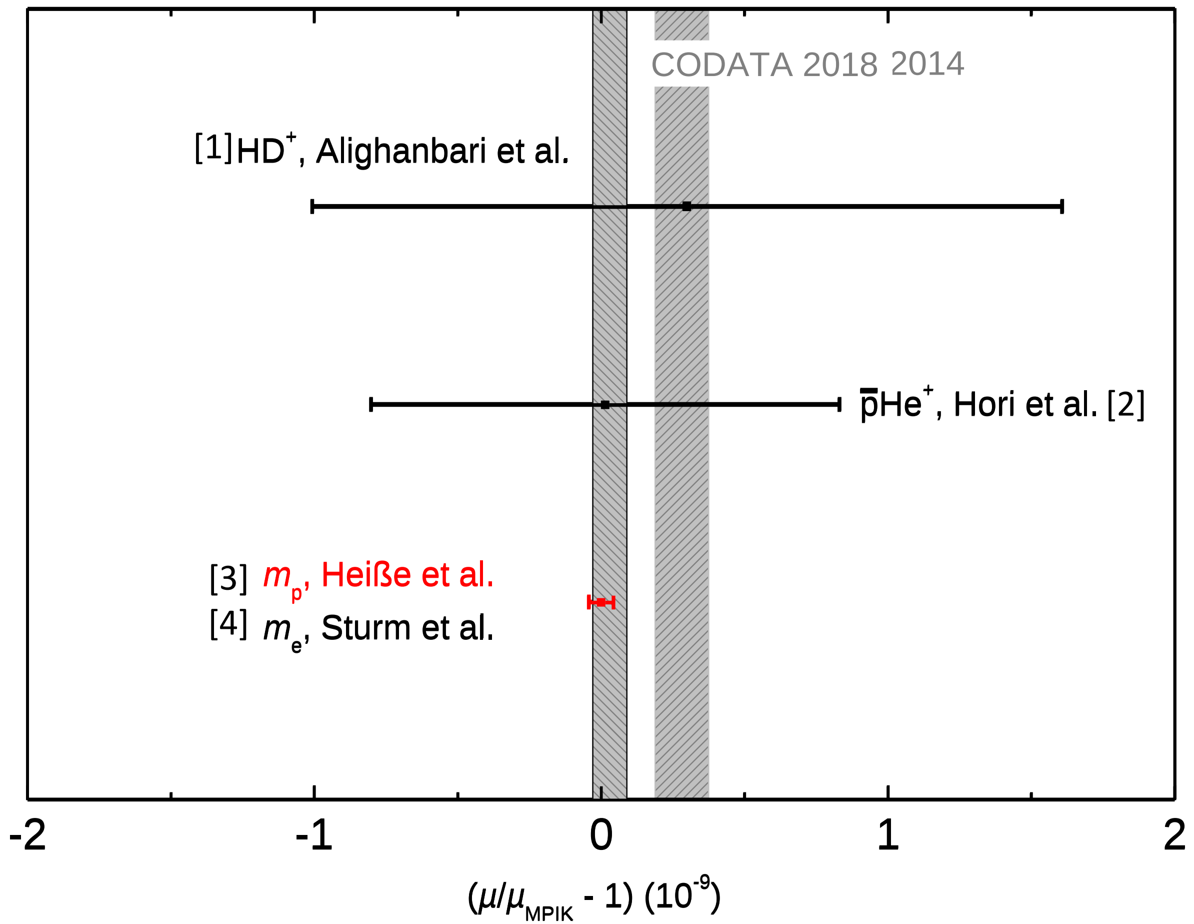
[PRL **119**, 033001 (2017)]

Results



[1] PRL **73**, 1481 (1994). [2] AIP Conf. Proc. **457**, 101 (1999).
[3] Phys. Scr. **66**, 201 (2002). [4] PRA **78**, 2514 (2008).
[5] PRL **119**, 033001 (2017)

Proton/Electron Mass Ratio



[1] S. Alighanbari *et al.* Nat. Phys. **14**, 555 (2018)
[2] M. Hori *et al.* Science **354**, 610 (2016)
[3] F. Heiße *et al.*, Phys. Rev. Lett. **119**, 033001 (2017)
[4] S. Sturm *et al.* Nature **506**, 467 (2014)

Systematic Uncertainties

Effect	Relative Uncertainty (10^{-12})
Residual Magnetostatic Inhomogeneity	27.5
Special Relativity	7.1
Image Charge	4.6
Quadratic Sum	≈29

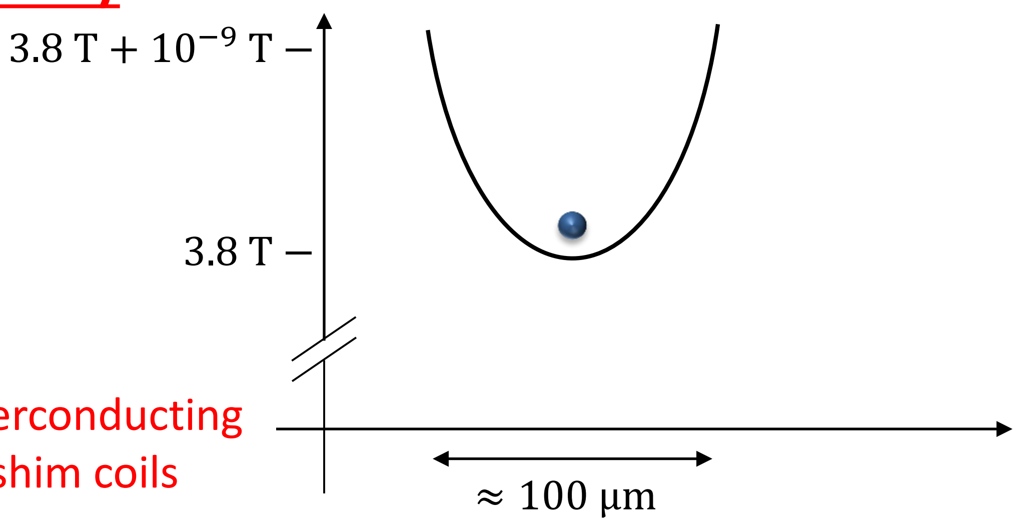
Magnetic inhomogeneity:

$B(z)=B_0+B_1z+B_2z^2+\ldots$

$\langle B\rangle=B_0+\mathbf{B_2\langle z_0^2\rangle/2}$

B_2=-0.27(2)T/m²
B_1=0.92(1)mT/m

→ Superconducting B1/B2-shim coils



Outline

- Setup and Experimental Techniques
  - a new ultra-harmonic trap

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  F. Heiße *et al.*, PRL **119**, 033001 (2017)

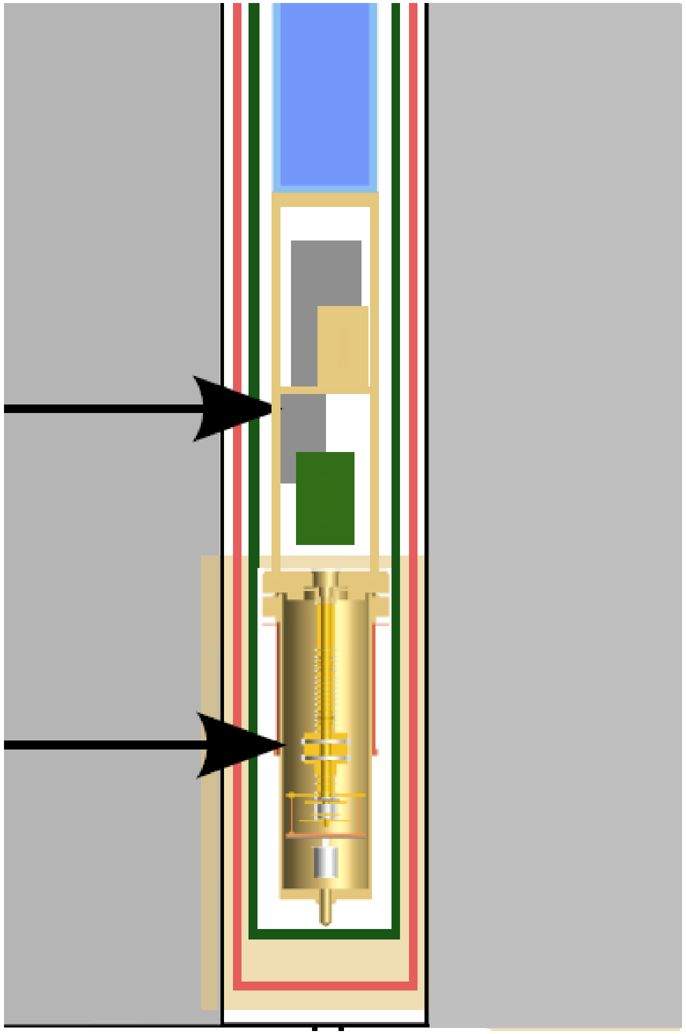
- **Deuteron's Atomic Mass**

Solenoidal Superconducting B_2 Shim Coil

- placed around trap chamber:

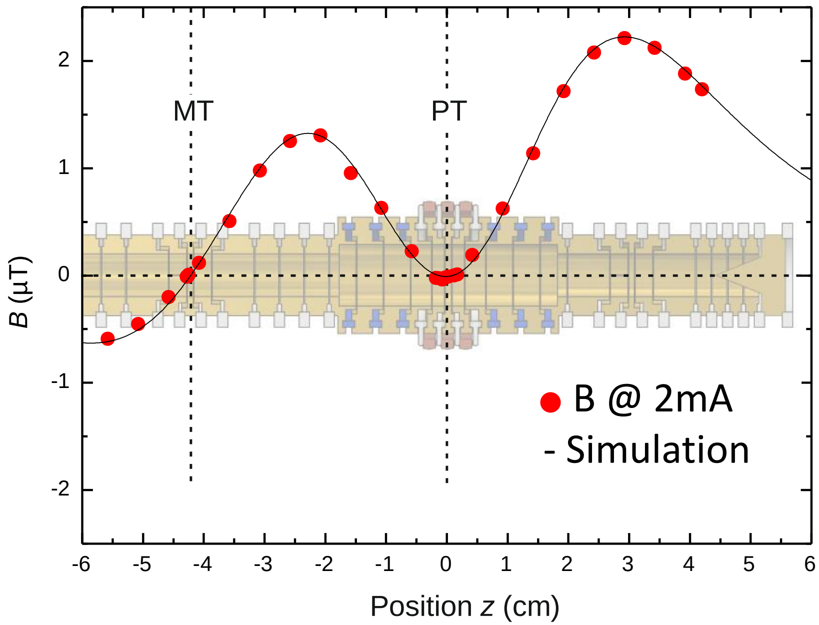
cryogenic electronic section

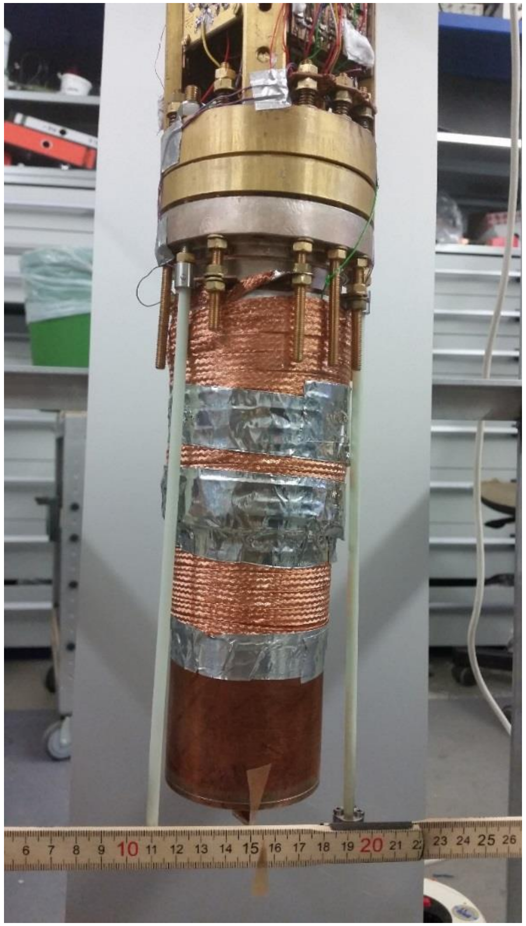
trap chamber



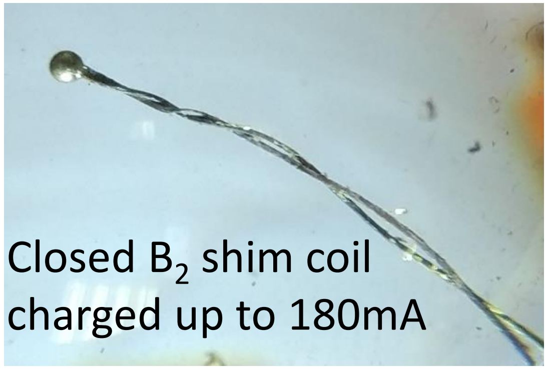
Solenoidal Superconducting B_2 Shim Coil

measurement in a testsetup



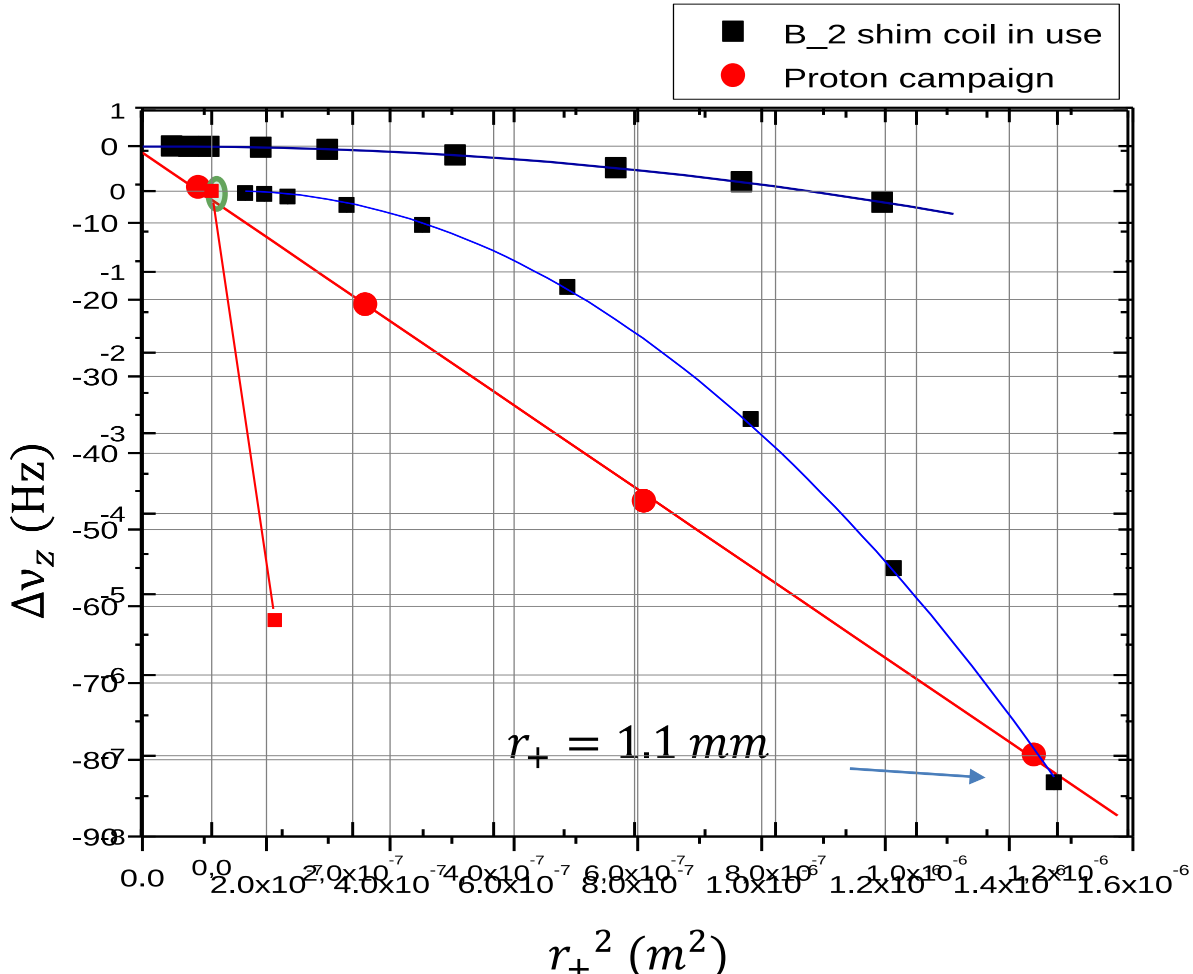


Superconducting Connection:



B_2 Shim Coil Performance

axial frequency shift as function of energy in ν_+-mode $\sim {r_+}^2$



Proton mass campaign: B_2=−0.27(2) $^{\mu T}/_{mm^2}$

now: B_2=−0.00127(40) $^{\mu T}/_{mm^2}$

⇒Factor 200 improvement

Estimated Error Budget Deuteron

Effect	Rel. Unc. (10^{-12}) Pmass	Rel. Unc. (10^{-12}) Deuteron (predicted)
Residual Magnetostatic Inhomogeneity	**27.5**	**0.2**
Special Relativity	**7.1**	**2.9**
Image Charge	**4.6**	**4.1**
Quadratic Sum	**≈29**	**≈5.0**

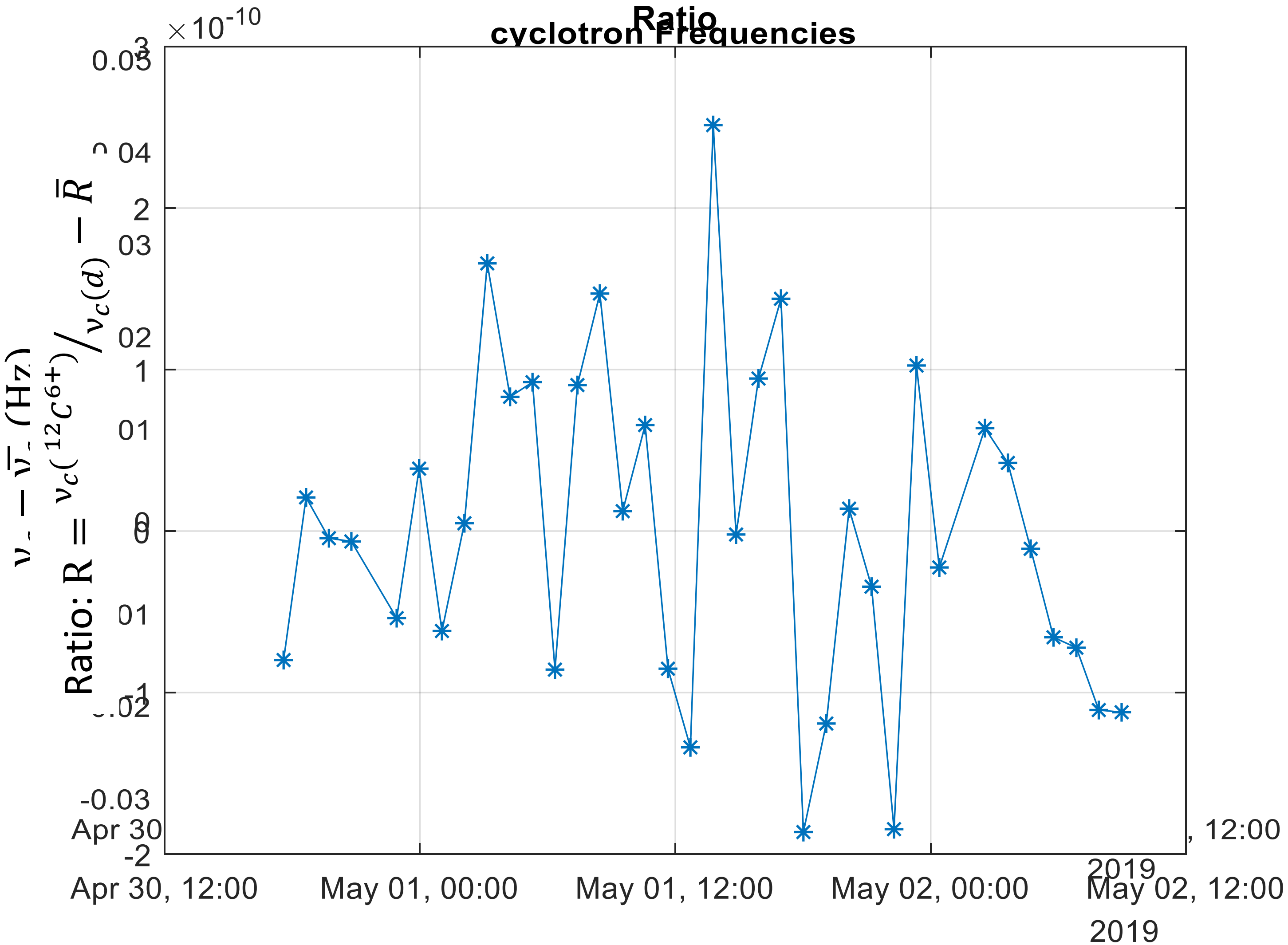
Schuh *et al.*, PRA, accepted

- current best value for the deuteron's atomic mass:
  $^{\delta m}/_{m} = 20 \times 10^{-12}$
  S. L. Zafonte and R. S. Van Dyck Jr., Metrologia 52, 280 (2015)

- current best mass ratio: R=m($^{29}Si^{+}$)/m($^{28}SiH^{+}$)
  $^{\delta R}/_{R} = 6.5 \times 10^{-12}$
  S. Rainville et al., Nature 438, 1096 (2005)

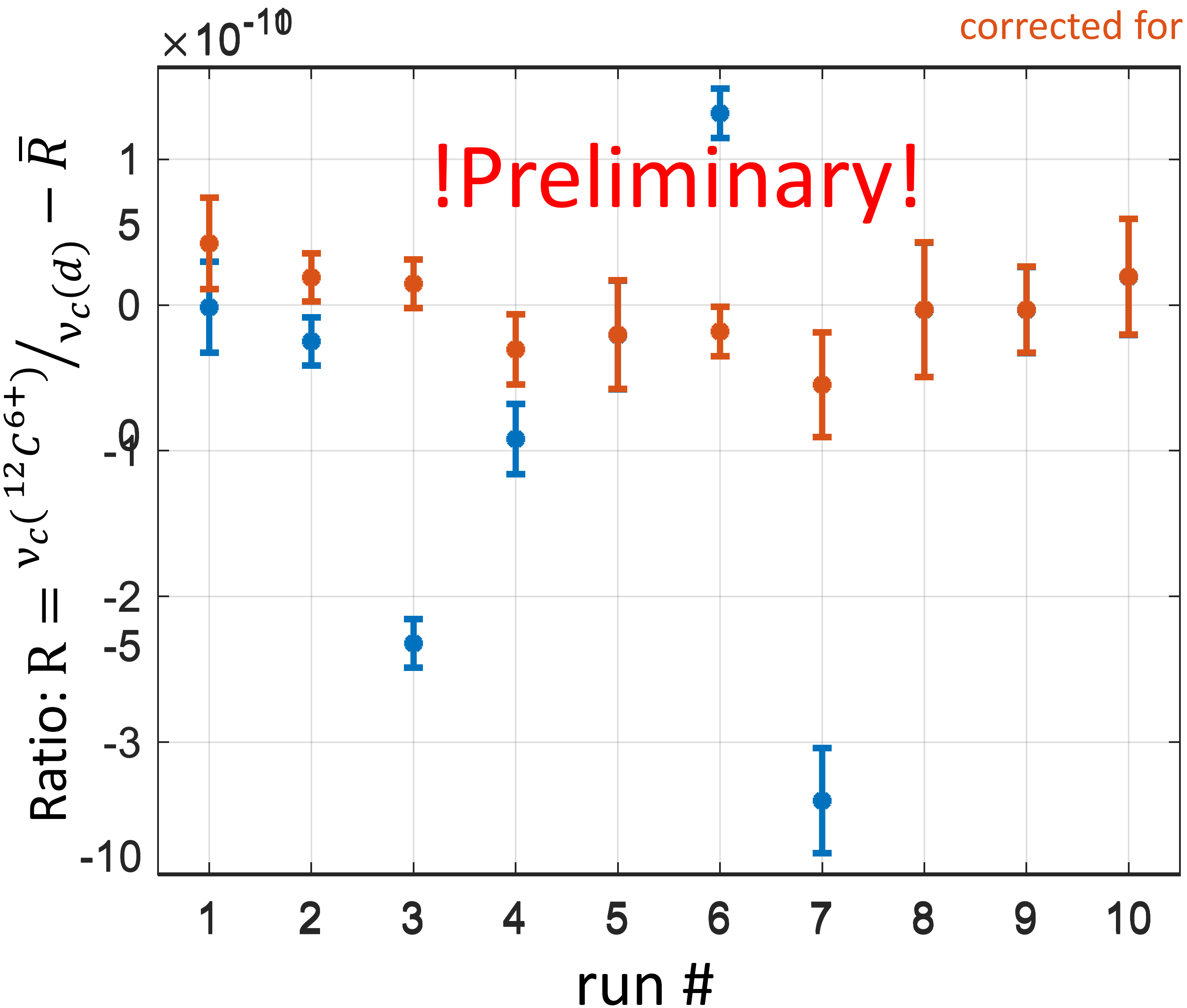
Preliminary Results

example run from 30.04.2019 to 02.05.2019



Preliminary Results

corrected for PnA Energy

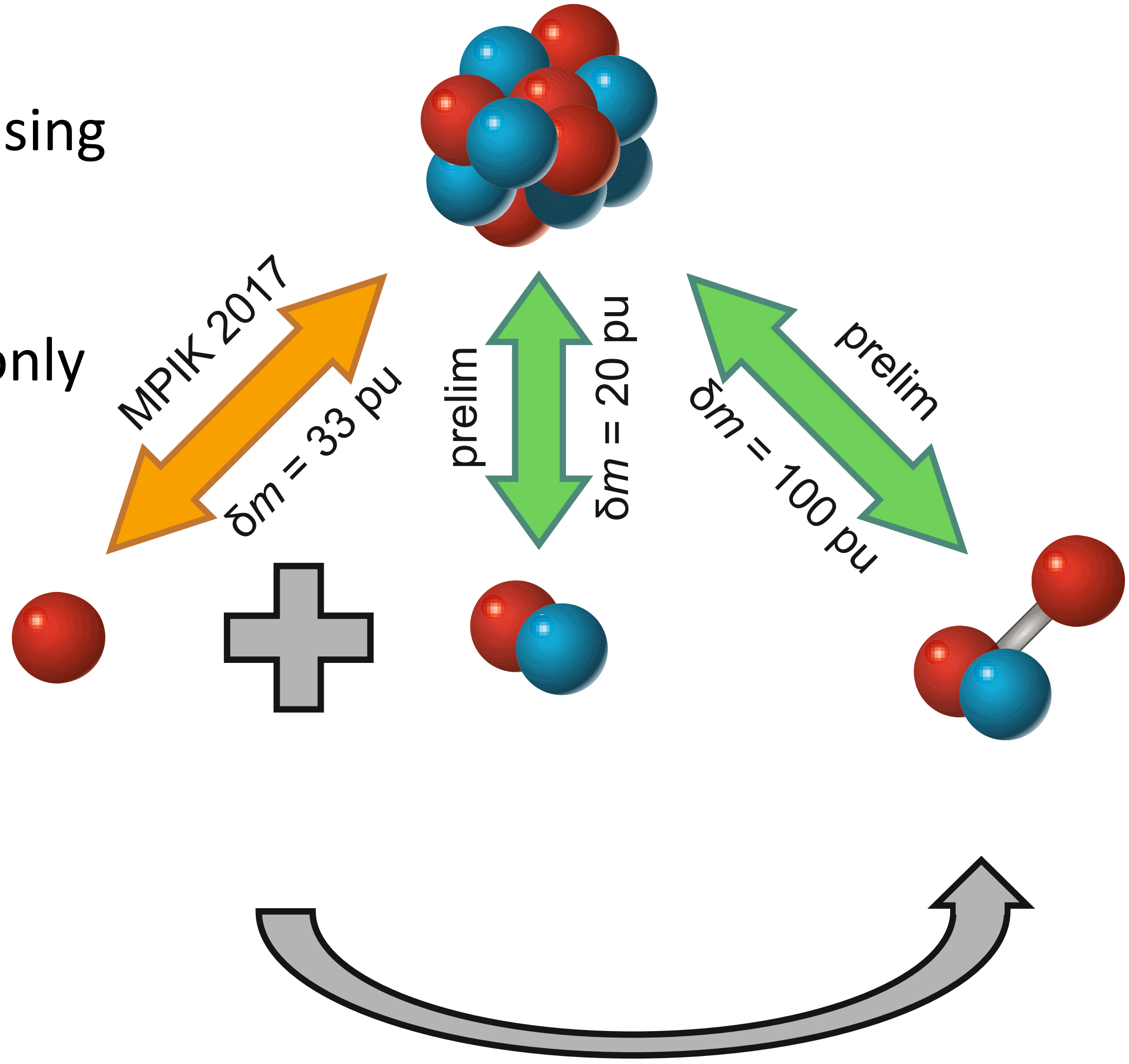


Zafonte and Van Dyck Jr., Metrologia 52, 280 (2015)

The mass of HD^+

- consistency check using HD^+

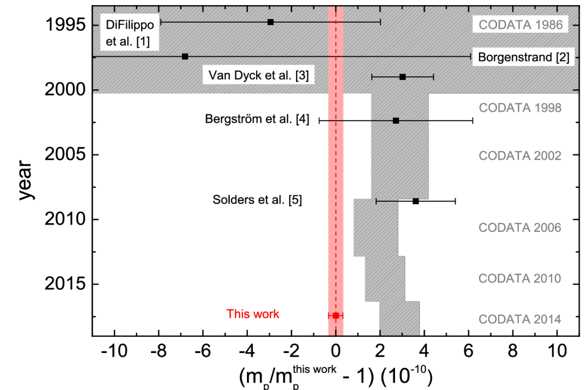
- closed circle using only our values

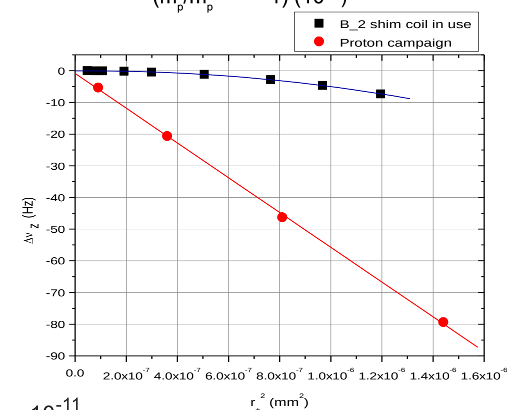


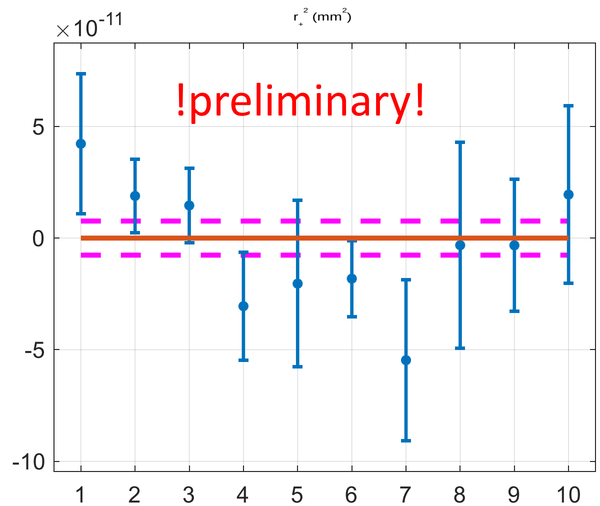
HD atomic & molecular Binding Energy:
Korobov et al., Phys. Rev. Lett. 118, 233001 (2017)

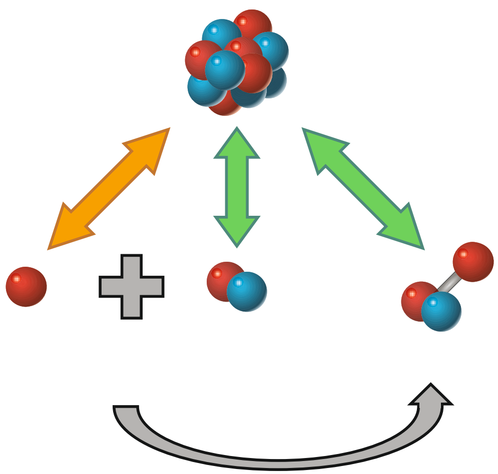
Summary

- proton mass with 33 ppt precision
- leading order systematic effect made negligible with B_2 shim coil
- estimated systematic uncertainty for deuteron to be around 5×10^{-12}
- ongoing measurement, statistical error around 8×10^{-12}
- strong consistency check using HD^+









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Collaboration: Sascha Rau, Fabian Heiße[1,2], Florian Köhler-Langes[1], Wolfgang Quint[2], Sven Sturm[1] and Klaus Blaum[1]

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

GSI

Target: Raphael Haas[2,3,4], Dennis Renisch[3,4] and Christoph Düllmann[2,3,4]

[3]*Institut for nuclear chemistry at JGU, Mainz*

[4]*Helmholtz Institute Mainz*

JG|U

HIM Helmholtz-Institut Mainz

Funding:

MAX-PLANCK-GESELLSCHAFT

INTERNATIONAL MAX PLANCK RESEARCH SCHOOL PT FS FOR PRECISION TESTS OF FUNDAMENTAL SYMMETRIES

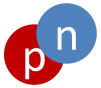
International Max Planck Research School Quantum Dynamics in Physics, Chemistry and Biology

Why deuteron?

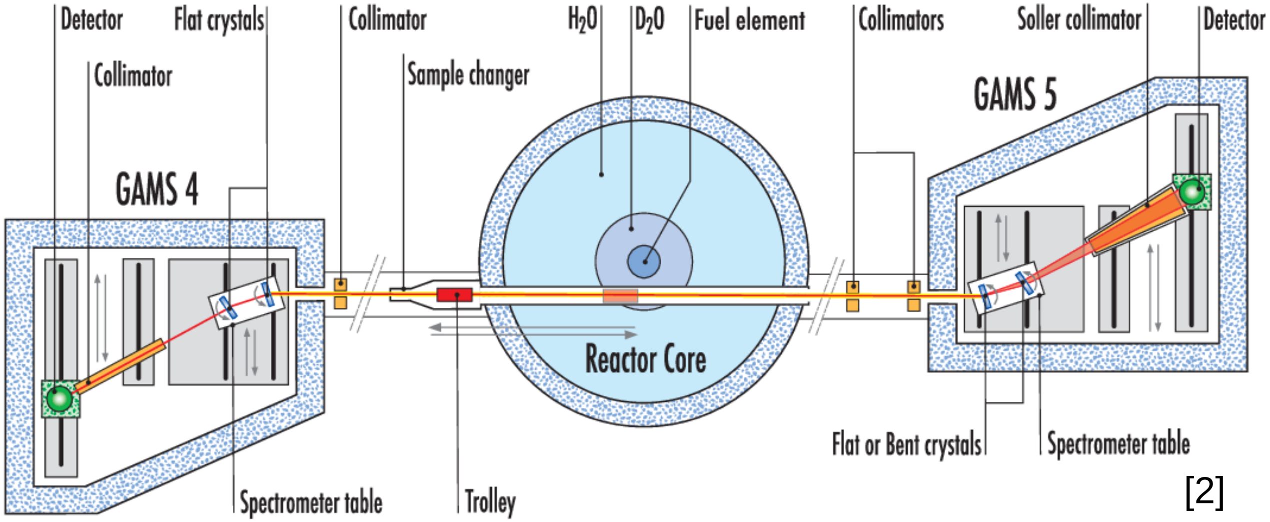
- Deuteron mass might help with puzzle of light ion masses
- allows for easier measurement of the Image Charge Shift (q/m doublet)
- one can extract the neutron mass

$$m_{\mathrm{n}} = m_{\mathrm{d}} - m_{\mathrm{p}} + E_{\gamma}/c^2$$

$$E_{\gamma}/c^2 = 2.388\,169\,96\,(42) \times 10^{-3}\mathrm{u} \ \ [1]$$



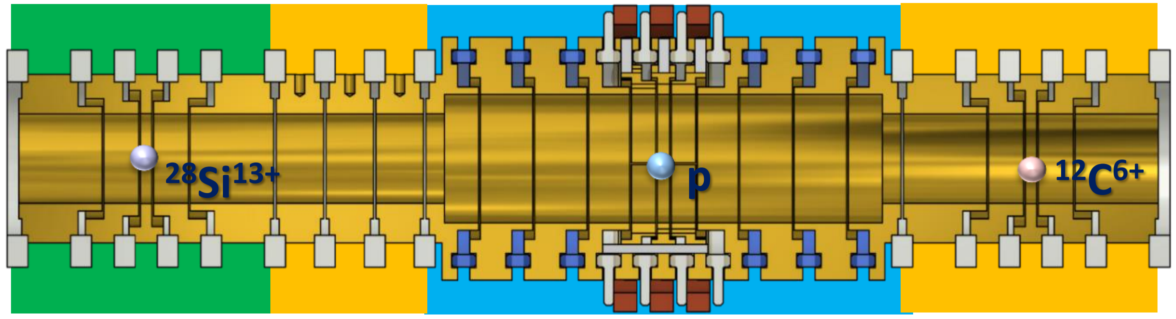
- improved binding energy needed, currently measured at the ILL in France



[2]

[1] M.S. Dewey et al. Physical Review C 73, 044303 (2006)
[2] https://www.ill.eu/instruments-support/ „PN3-GAMS“

Reference Trap



Simultaneous comparison of cyclotron frequencies to reference ion

(I) $\nu_c(^{28}\mathrm{Si}^{13+})$ and $\nu_c(\mathrm{p})$ $\quad R_1 = \dfrac{\nu_c(\mathrm{p})}{\nu_c(^{28}\mathrm{Si}^{13+})}$

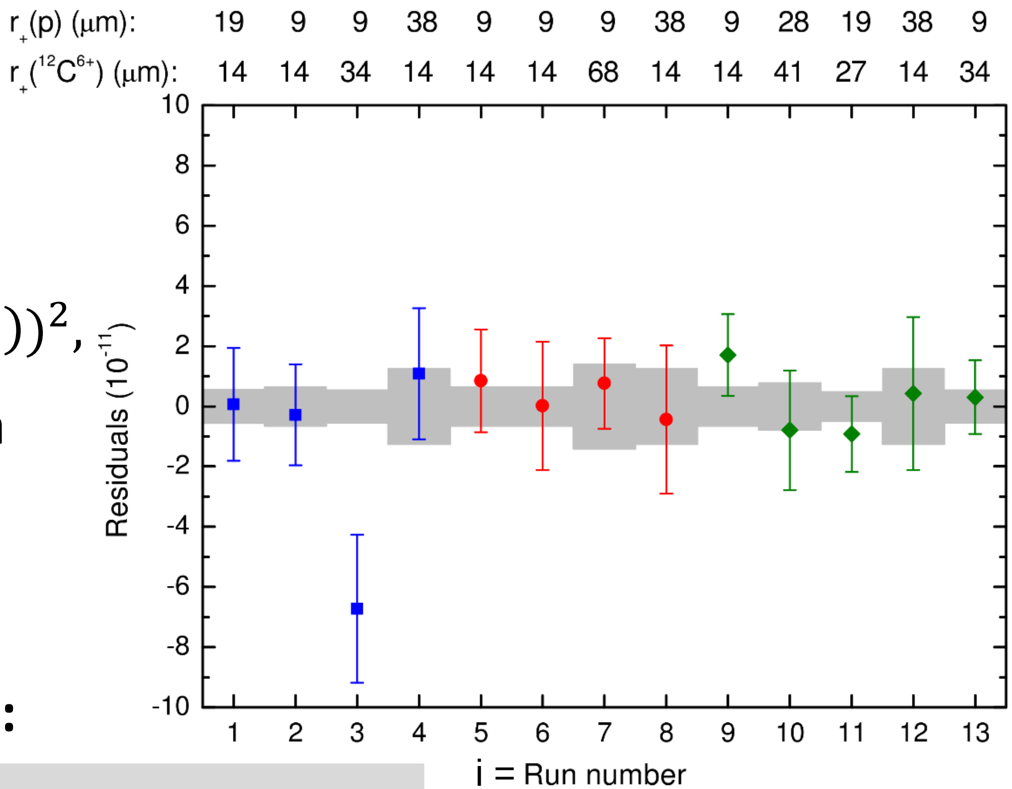
(II) $\nu_c(^{28}\mathrm{Si}^{13+})$ and $\nu_c(^{12}\mathrm{C}^{6+})$ $\quad R_2 = \dfrac{\nu_c(^{12}\mathrm{C}^{6+})}{\nu_c(^{28}\mathrm{Si}^{13+})}$

$$\boxed{\frac{R_1}{R_2} = \frac{\nu_c(\mathrm{p})}{\nu_c(^{12}\mathrm{C}^{6+})}}$$

→ **cancel impact of common mode magnetic field fluctuations**

Data

- **Several 100's of measurement cycles have been performed with:**
  - three different p / $^{12}C^{6+}$ pairs
  - at different $r_+(p) = \kappa \cdot A(p)$ and $r_+(^{12}C^{6+}) = \kappa' \cdot A(^{12}C^{6+})$.



- **Apply a golbal planar fit:**

$$R_i = R_0 + a\,(A_i(p))^2 + b\,(A_i(^{12}C^{6+}))^2,$$

where i is the run number and R_0, a and b are fit parameters.

- **Extrapolated frequency ratio R_0:**

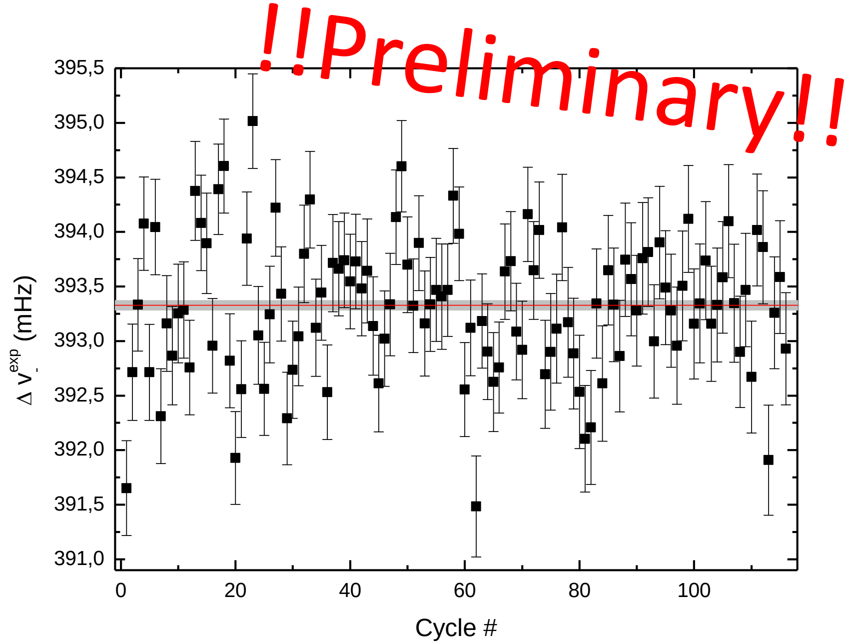
$$\boldsymbol{R_0 = R_{\text{stat}} = \frac{\nu_c(^{12}C^{6+})}{\nu_c(p)} = 0.503\,776\,367\,634\,1\,(77).}$$

$$\boldsymbol{\frac{\delta R_0}{R_0} = 1.5 \cdot 10^{-11}}$$

The Image Charge Shift

$\Delta\nu_- = \nu_-(\text{Proton}) - \nu_-({}^{12}\text{C}^{6+})$

Effect	Shifts $\Delta\nu_-$ [mHz]
ICS	2.394
B_2	0.076
Tilt	0.162
q/m missmatch	390.714
Total	393.346



BUT:

- Tilt between magnetic and electric field (0.5 °)

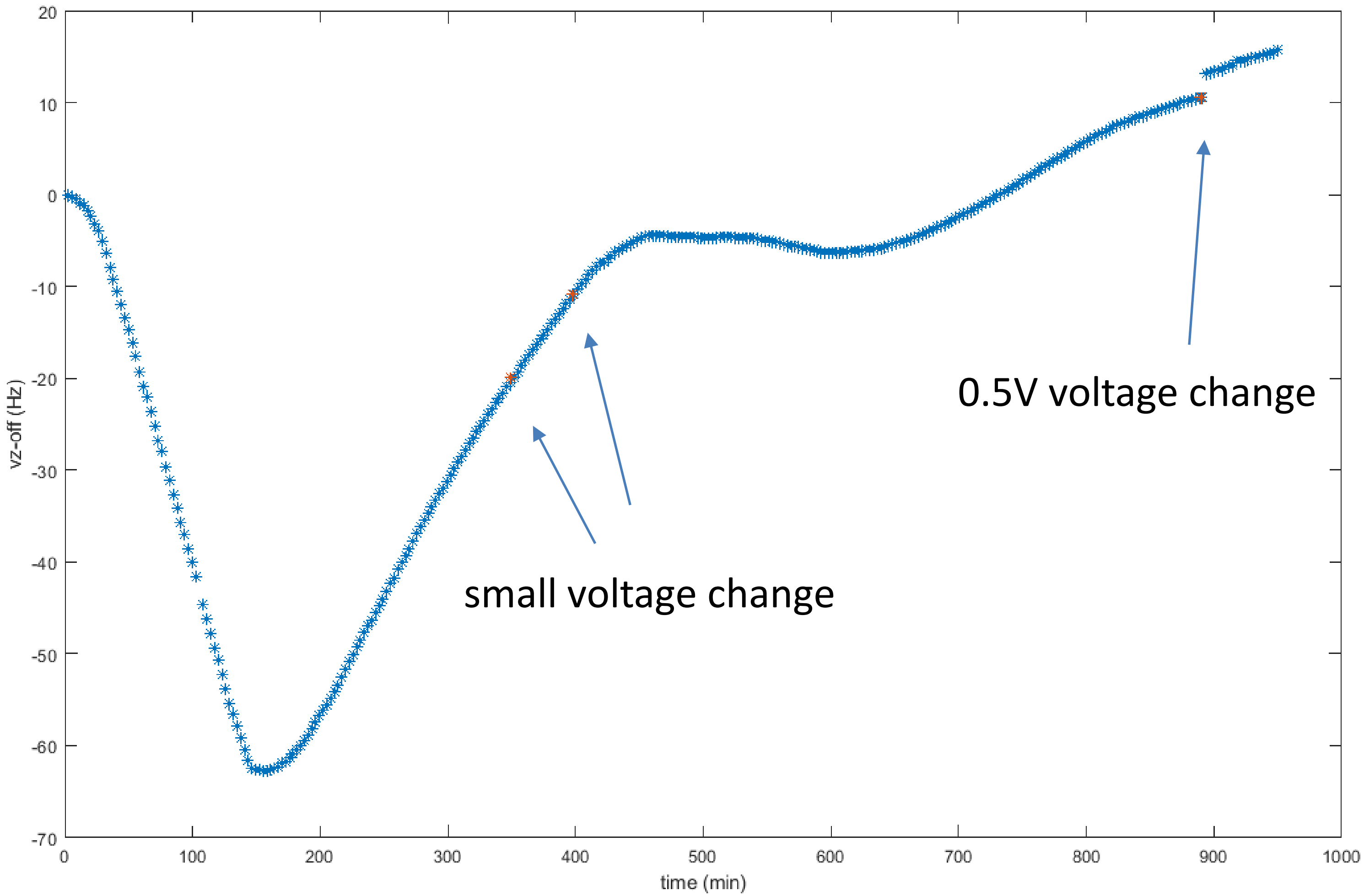
- Variations of this tilt are in the axial mode indistinguishable from voltage fluctuations

$$\delta\nu_-^{\text{tilt fluc.}}(p) \approx 1.4 \cdot 10^{-5} \cdot \delta\nu_z^{\text{tilt fluc.}}(p)$$
$$\delta\nu_-^{\text{volt. fluc.}}(p) \approx 1.3 \cdot 10^{-2} \cdot \delta\nu_z^{\text{volt. fluc.}}(p)$$

- Fit gives δ (Δ v_) = 43 μHz with Red chi² = 2

⇒ confirmation limited to 5% level (120 μHz)

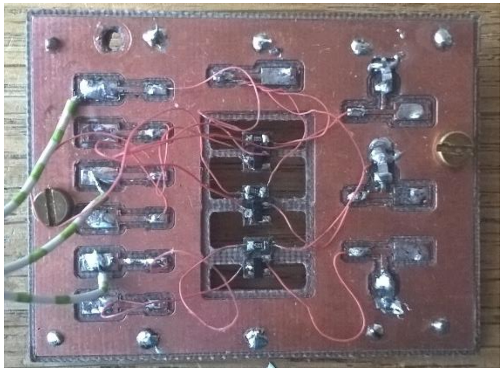
Improving axial stability



- leakage currents in the order of a few fA, resistance to ground $\sim 10^{15}\Omega$
- transistors DC resistance at least in same magnitude, acts as very small capacity (17fF)

Improving axial stability

- improve voltage stability by using a filter with a switchable time constant
- use „freeze-out“ of silicon transistor (BF545) happening at $\sim 20\ K$:



Characteristics:

Conducting at: 13 mW for 20 s
Freezing out: 3 min
R_{cold} > 500 GΩ

- Fluctuations in angle lead to instabilities:

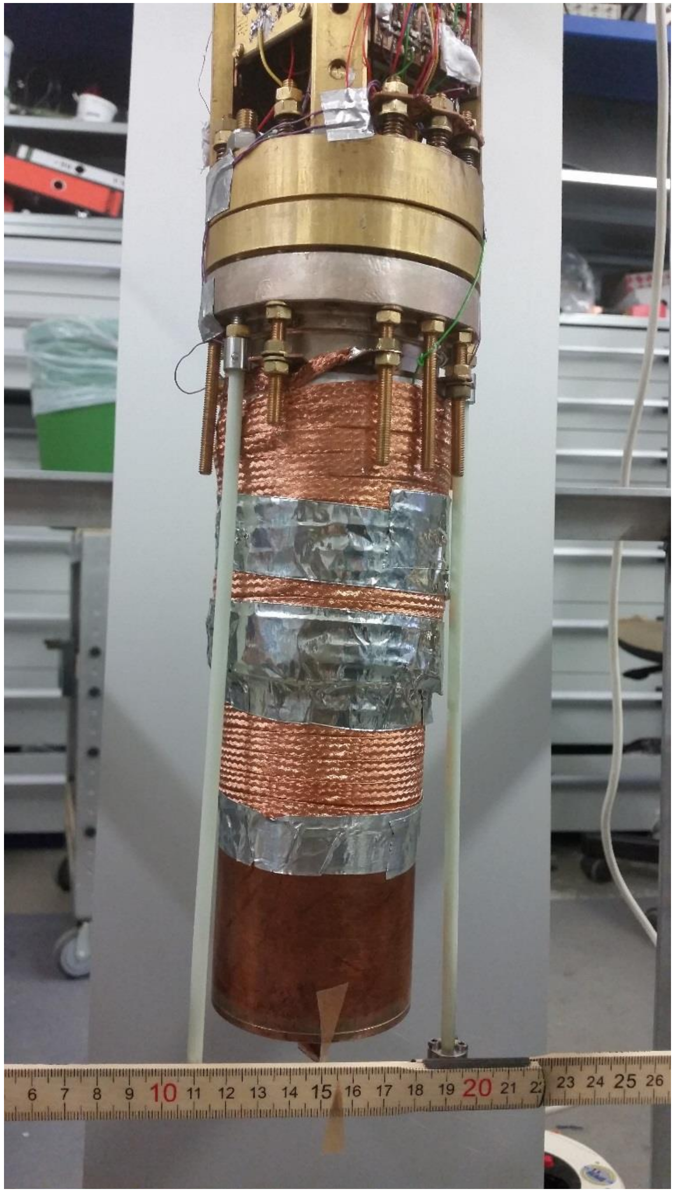
$$\bar{\nu_z} \approx \nu_z \sqrt{1 - \frac{3}{2}\sin^2\theta}$$

$$\theta = \theta_0 + \delta\theta$$

$$\delta\bar{\nu_z} \approx -\frac{3}{2}\nu_z\theta_0\delta\theta$$

⇒ Mechanical Feedthrough to adjust angle to zero in situ

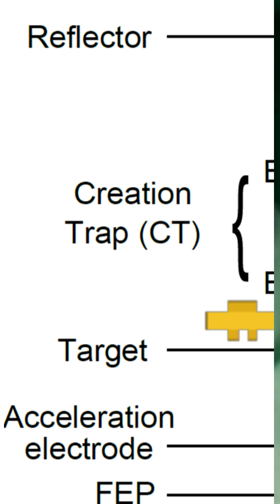
Mechanical Feedthrough

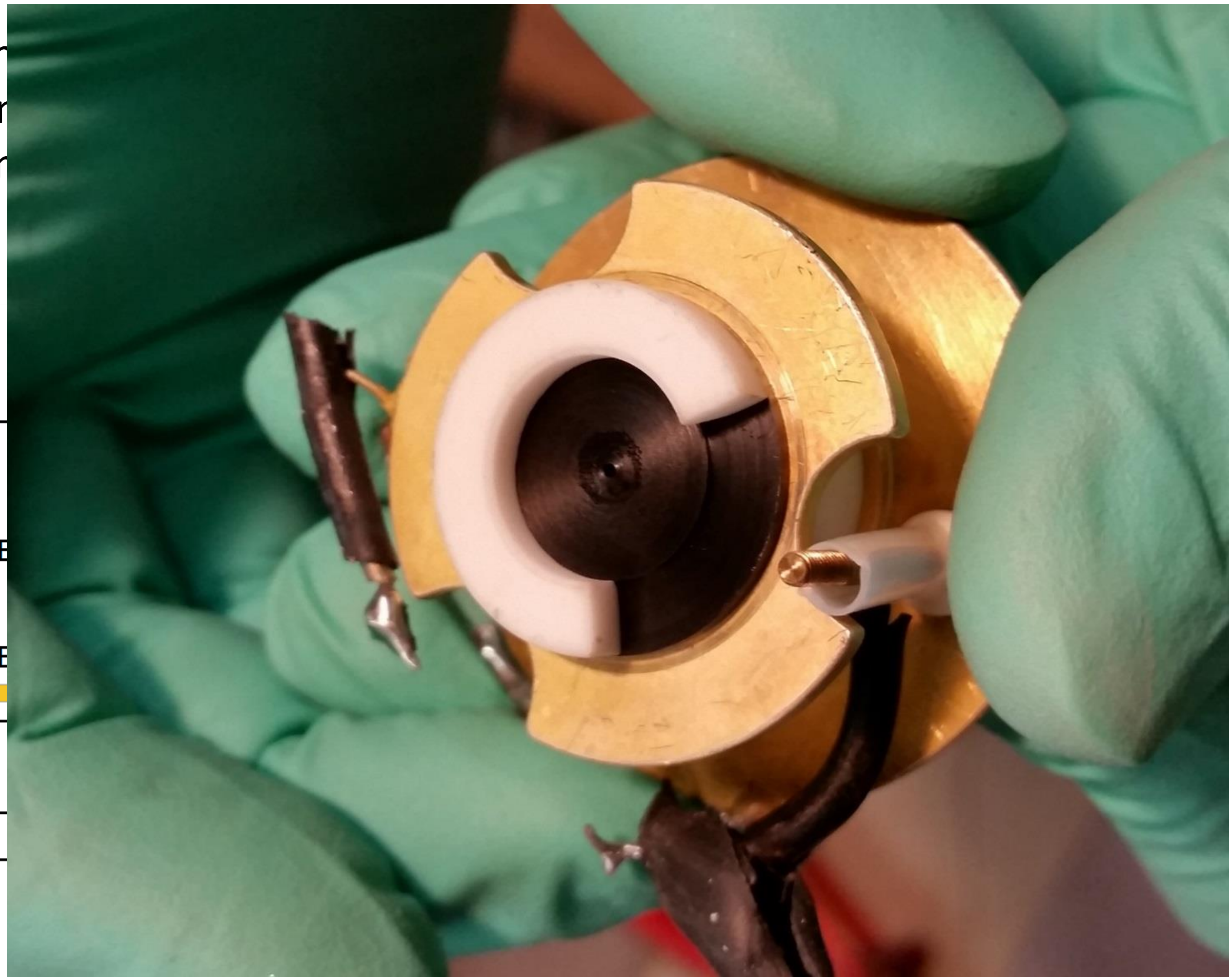


Target Preparation

- use target printer to apply deuterated molecules (Thymidine-α,α,α,6-d_4) to surface of standard mEBIS target *R. Haas et al., Nucl. Instr. Meth. Phys. Res. A 874*

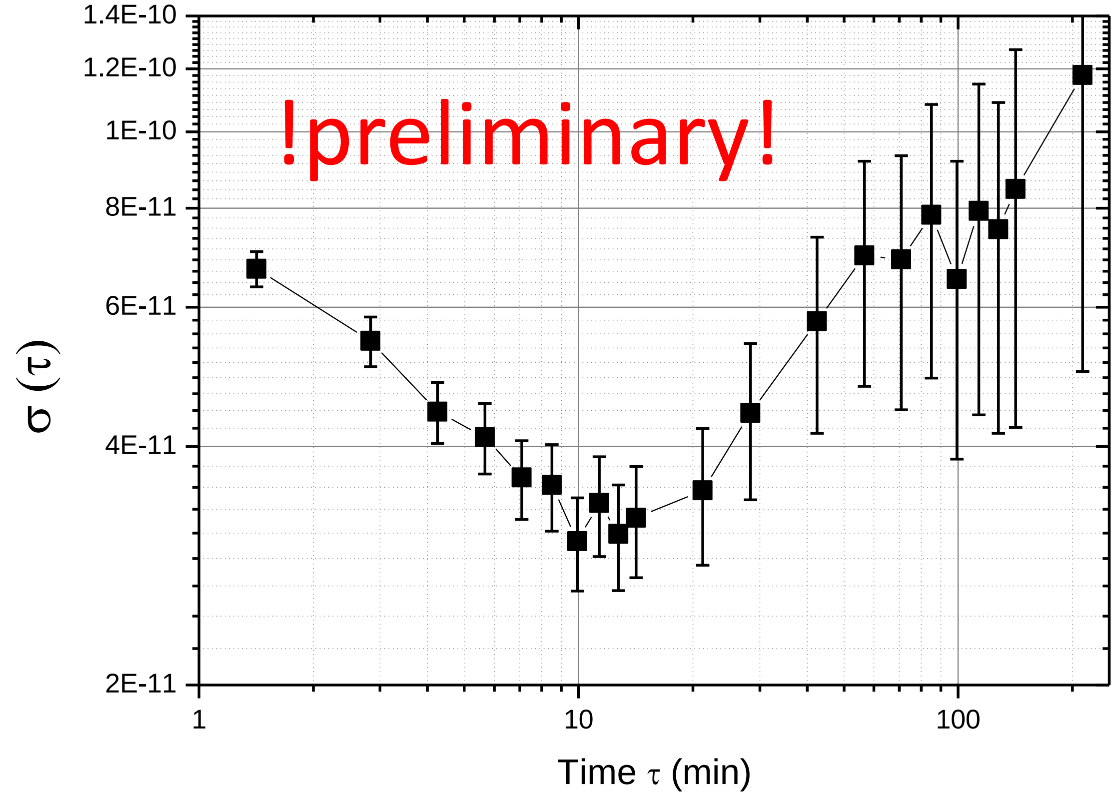
- small r
while r
vacuur





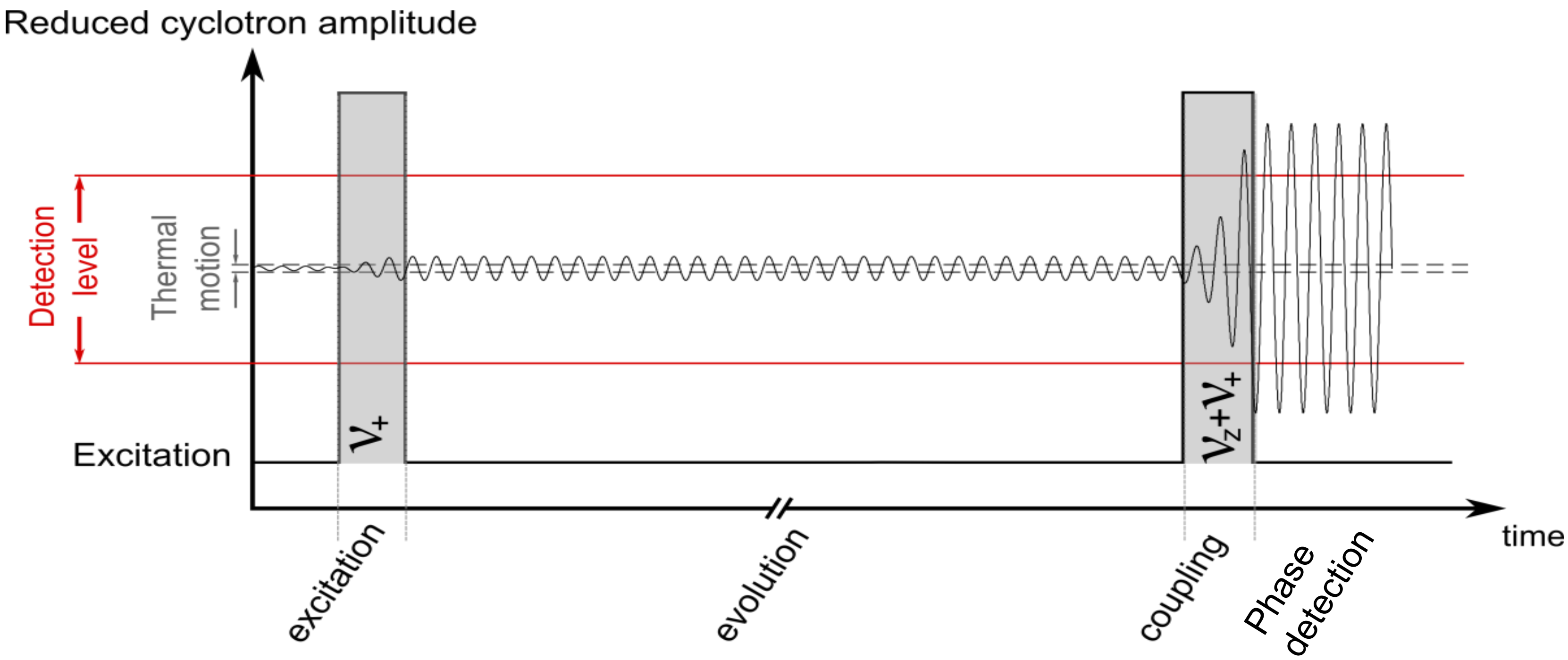
Improved Statistics

- implemented pressure and temperature stabilization
- Allan deviation with consecutive ν_+ measurements with a single deuteron promises statistics in the few 10^{-11} per cycle



Pulse and Amplification – Method

- Phase sensitive detection method for ν_+



- Rapid measurement time (~ 10 s instead of ~ 3 min for Double-Dip)
  → **Reduction of impact of B-field fluctuations**
- Small radial kinetic energies during phase evolution
  → **Small magnetic and relativistic shifts**

S. Sturm *et al.*, PRL 107, 143003 (2011)