# *Precision Tests of Fundamental Interactions and Their Symmetries using Exotic Ions in Penning Traps*

- Basics of Penning-trap spectroscopy
- Atomic and nuclear mass measurements
- Precision *g*-factor measurements

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

MAX-PLANCK-INSTITUT
FÜR KERNPHYSIK

Bormio, Jan 22nd, 2024

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# Atomic/nuclear spectroscopy …

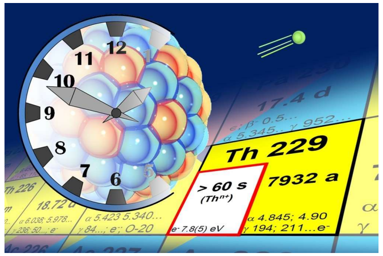
**… probes fundamental physics!**

**How heavy are the building blocks of matter?**

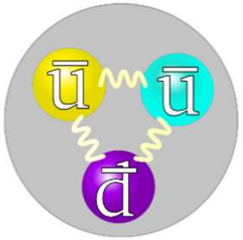
**What is the mass of a neutrino?**

**Why is there more matter than anti-matter?**

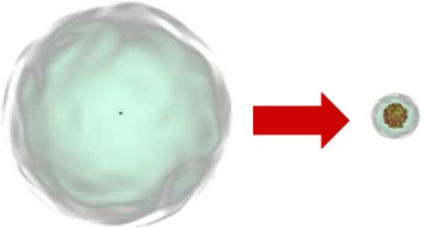
**Does QED fail in the strong field regime?**



- radionuclides

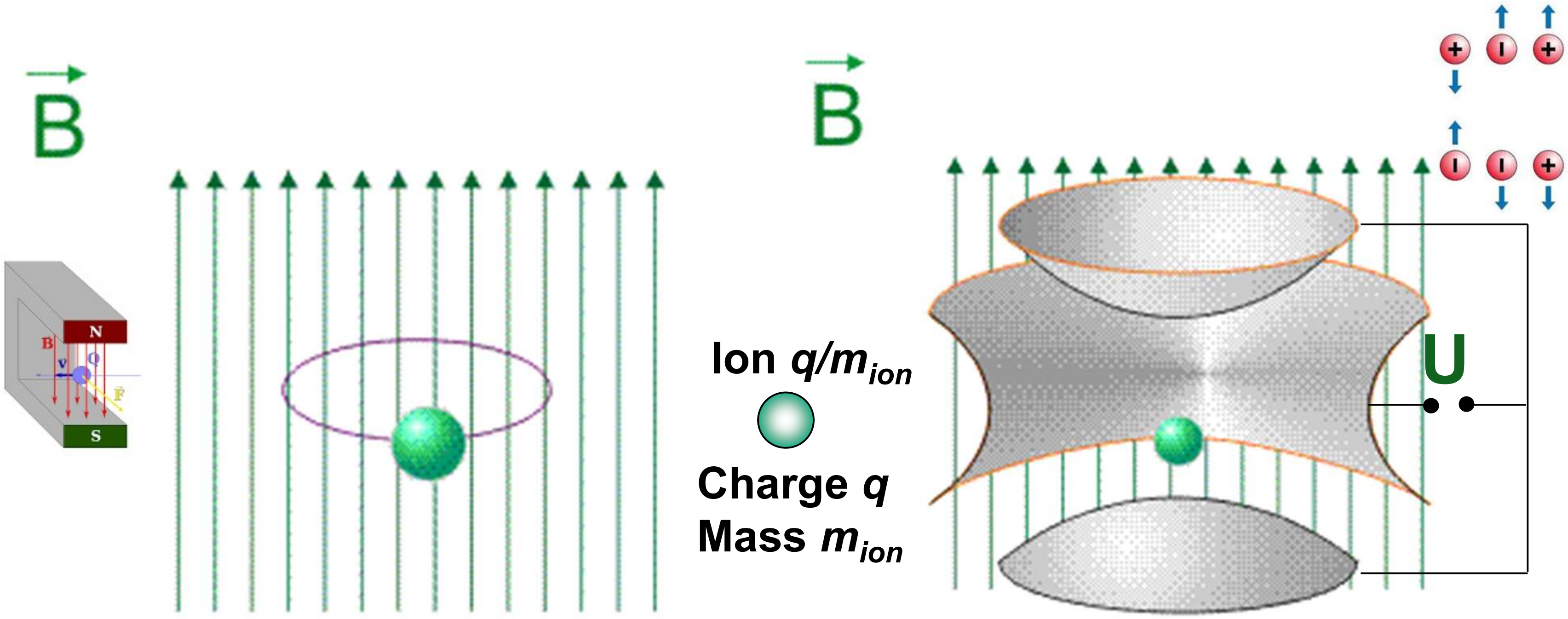


- antimatter



- highly charged ions

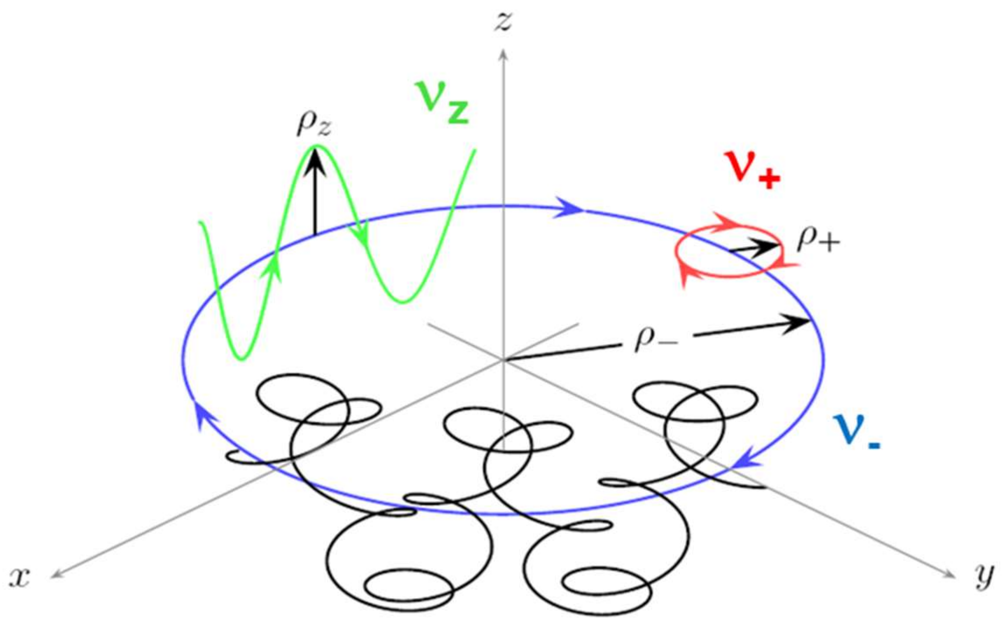
# Storage of ions in a Penning trap

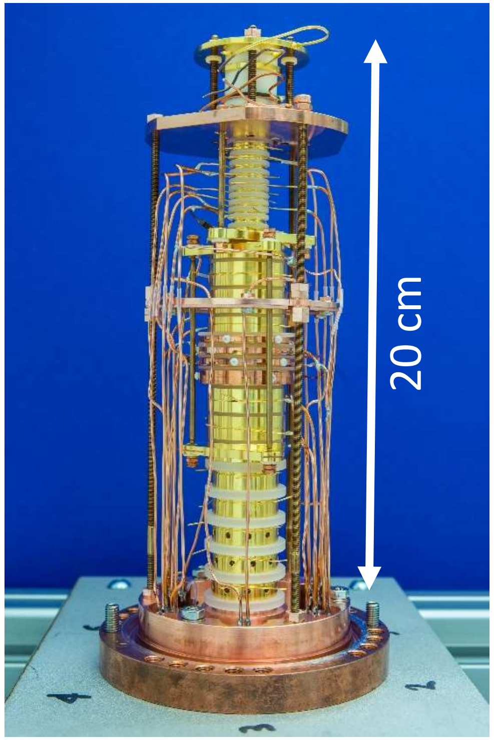


**Ion $q/m_{ion}$**

**Charge $q$**
**Mass $m_{ion}$**

# Storage of ions in a Penning trap





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

- Non-destructive FT-ICR detection technique

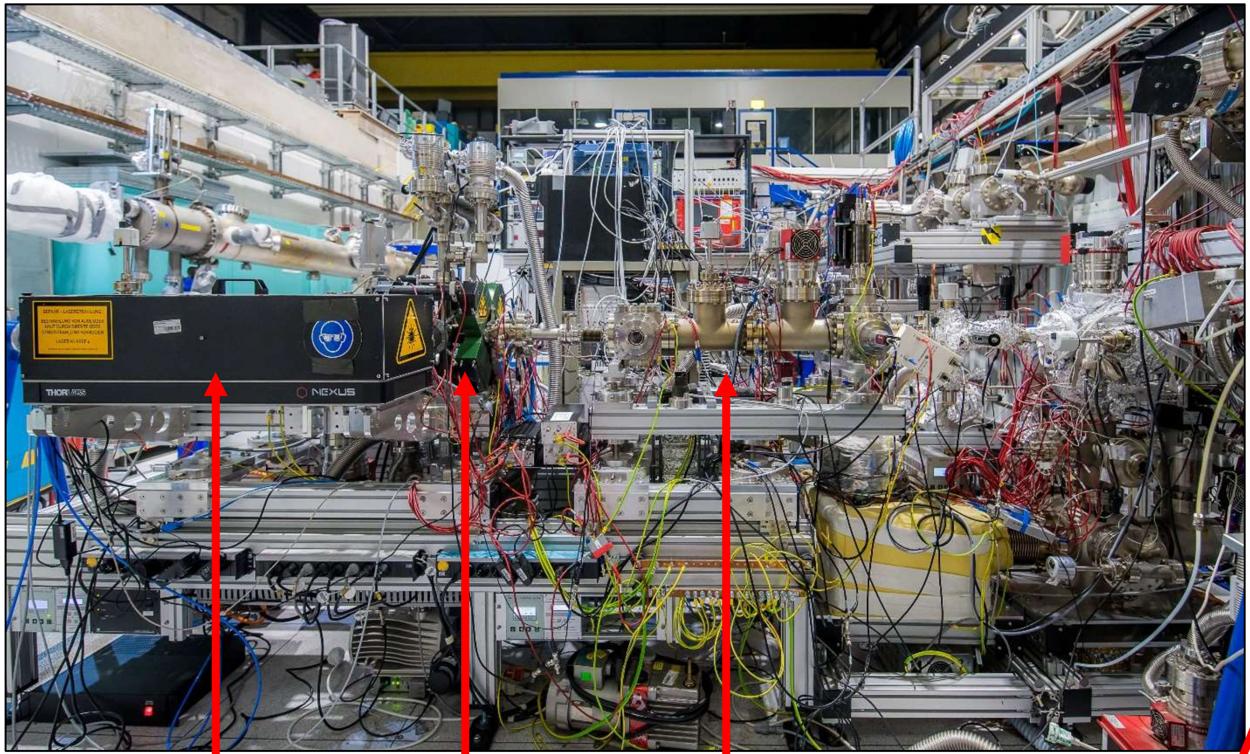
$$\nu_c = qB/(2\pi m_{ion})$$

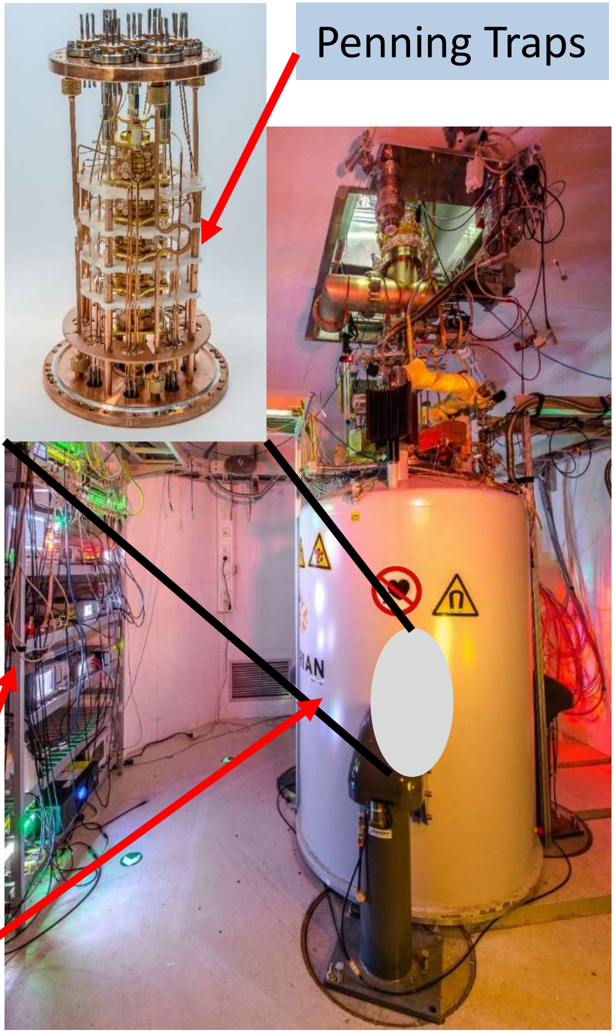
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

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

# PENTATRAP – A Penning-trap setup at MPIK

## A balance for highly charged ions.





Penning Traps

Laser Ion Source

EBIT

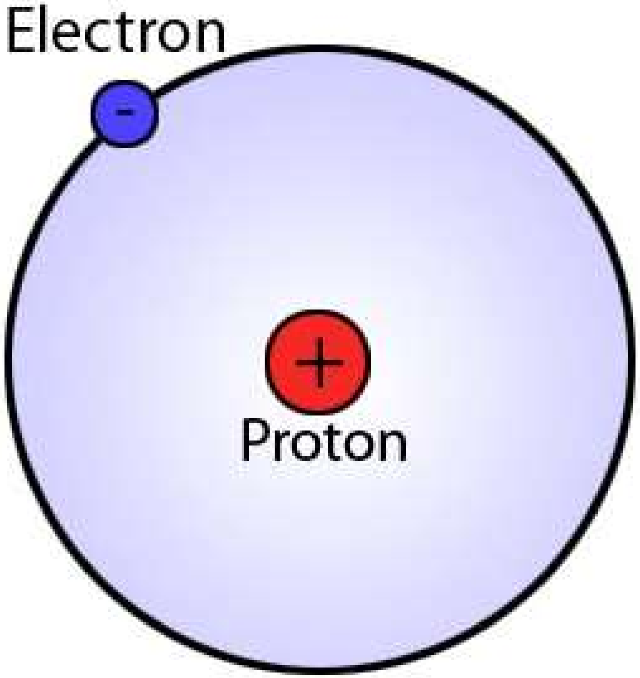
Transfer Beamline

Electronics

Superconducting Magnet

# Results I

**The masses of the building bocks of matter**

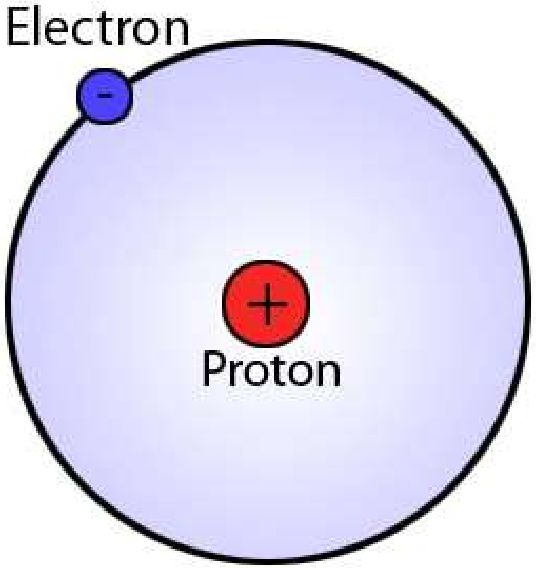


**LIONTRAP: MPIK, Uni Mainz, GSI**

# The building blocks of matter

The atomic mass of the proton and electron

**Hydrogen**



Electron: previous best value improved by a factor of 13

$m_e$ = 0.000 548 579 909 067(17) u

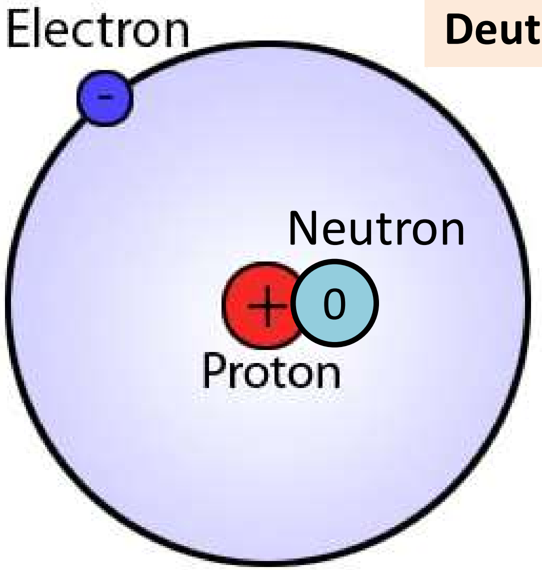
Nature **506** (2014) 467

Proton: previous best value improved by a factor of 3

$m_p$ = 1.007 276 466 583 (33) u

Phys. Rev. Lett. **119** (2017) 033001

# The atomic mass of the deuteron and HD$^+$



**Deuterium**

$$m_\mathrm{d} = \frac{1}{6}\frac{\nu_\mathrm{c}(^{12}\mathrm{C}^{6+})}{\nu_\mathrm{c}(\mathrm{d})}m(^{12}\mathrm{C}^{6+})$$

**A factor of ~3 improved value and 5 sigma deviation!**

$$m_\mathrm{d} = 2.013553212535(11)_\mathrm{stat}(13)_\mathrm{sys}(17)_\mathrm{tot}\ \mathrm{AMU} \qquad \frac{\delta m_\mathrm{d}}{m_\mathrm{d}} = 8.5\times10^{-12}$$

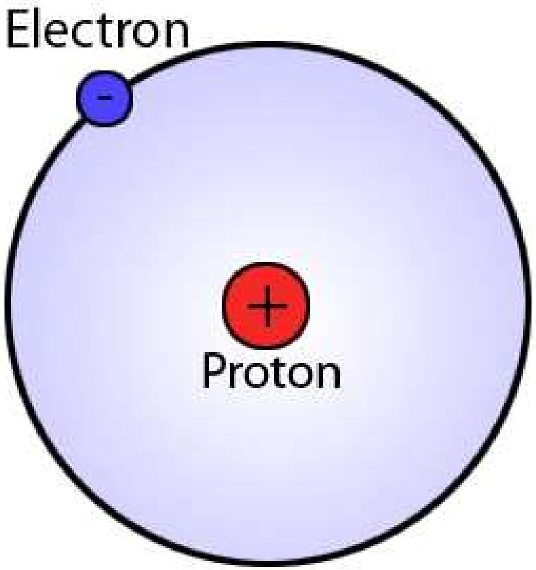
**→ Provides access to the mass of the neutron**

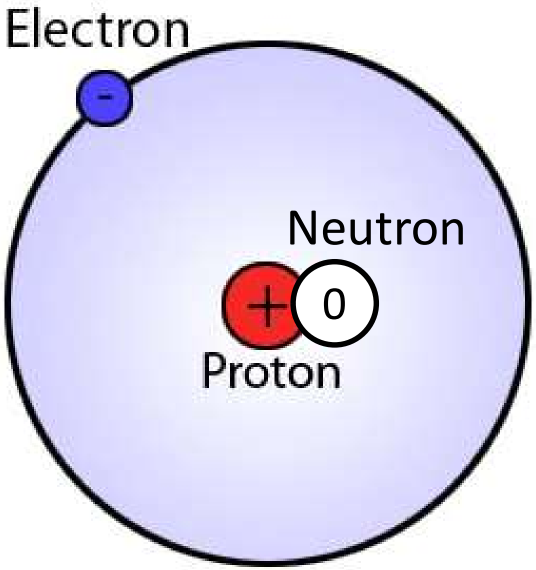
S. Rau *et al.*, Nature **585** (2020) 43

# The building blocks of matter

The atomic masses of the proton and electron and neutron. ☺

**Hydrogen**





**Deuterium**

Electron: previous best value improved by a factor of 13

$m_e = 0.000\,548\,579\,909\,067(17)$ u

Nature **506** (2014) 467

Proton: previous best value improved by a factor of 3

$m_p = 1.007\,276\,466\,583\,(33)$ u

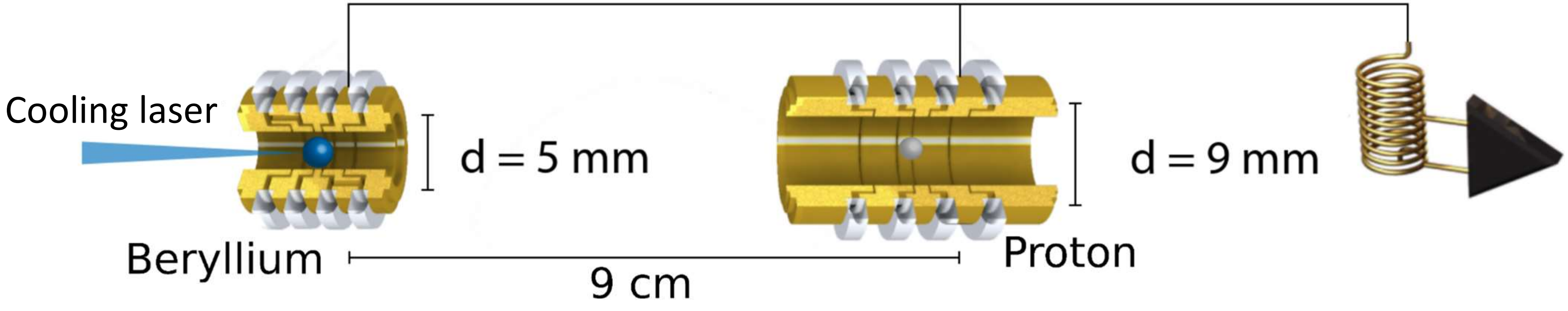
Phys. Rev. Lett. **119** (2017) 033001

Deuteron: previous best value improved by a factor of ~3

$m_d = 2.013\,553\,212\,535\,(17)$ u

Nature **585** (2020) 43

# Sympathetic laser cooling of a proton



M.Bohman *et al.*, Nature **596** (2021) 514

B. Tu *et al.*, AQT **210009** (2021) 1

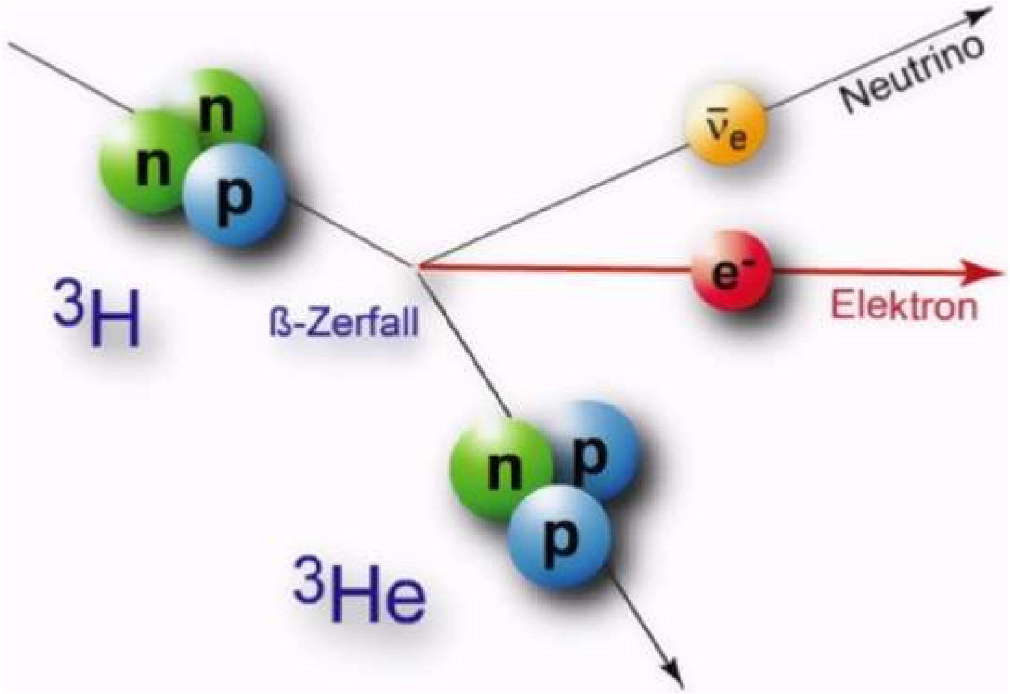
**Proton axial temperature of ~ 100 mK demonstrated!**

# Results II

## Nuclear masses for neutrino physics

**_Q_-values:**

$^{3}T \rightarrow {}^{3}He$
$^{163}Ho \rightarrow {}^{163}Dy$
$^{187}Re \rightarrow {}^{187}Os$



**$\beta^-$ -decay of $^{187}$Re**

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

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

# Measurement principle at PENTATRAP

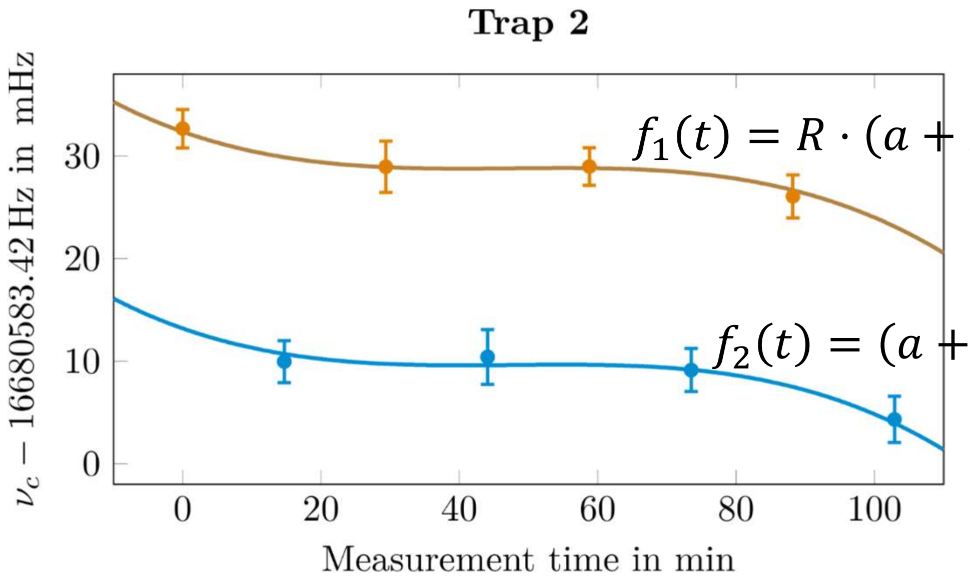
## Mass Ratio determination – Polynomial Method

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

Magnetic field not known!

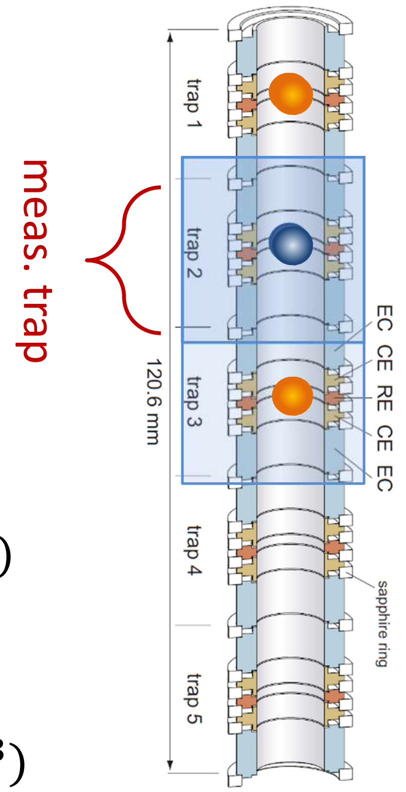
Second ion:

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



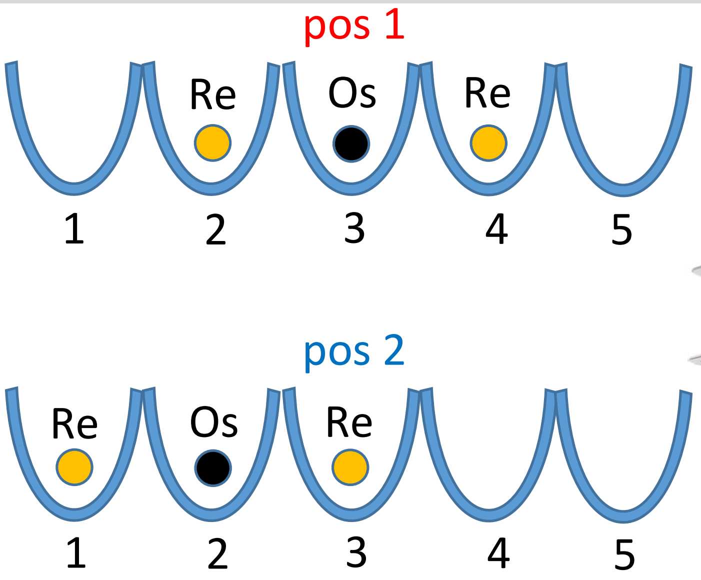
$$f_1(t) = R \cdot (a + b \cdot t + c \cdot t^2 + d \cdot t^3)$$

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



A. Rischka *et al.*, Phys. Rev. Lett. **124** (2020) 113001

# $Q$-value of $^{187}$Re-$^{187}$Os for neutrino physics



- ❖ Change position every 30 min
- ❖ Measurement of $\nu_+$, $\nu_z$, $\nu_-$
- ❖ Phase detection method
- ❖ Storage time of days

P. Filianin *et al.*, Phys. Rev. Lett. **127** (2021) 072502

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

**BUT**

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

$$R_1 = 1.000000013886(15)$$

$$R_2 = 1.000000015024(12)$$

# Weighing of different electron config.

Ground-state configuration of Re$^{29+}$ and Os$^{30+}$: $[_{36}\mathrm{Kr}]\,4d^{10}$

Metastable state $[_{36}\mathrm{Kr}]\,4d^{9}\,4f^{1}$ with $E_{\mathrm{exc}} \approx 200$ eV in Re$^{29+}$

Similar state in Os$^{30+}$ expected!

## Re$^{29+}$

metastable state

$B_{\text{PENTATRAP}} = 202.2(17)$ eV

$B_{\text{Harman}} = 202.2(5)$ eV

$B_{\text{Indelicato}} = 202.1\,(27)$ eV

$B_{\text{Haverkort}} = 202.8(4)$ eV

ground state

## Os$^{30+}$

metastable state

$B_{\text{PENTATRAP}} = 207(3)$ eV

$B_{\text{Haverkort}} = 209(2)$ eV

$B_{\text{Indelicato}} = 207(3)$ eV

ground state

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

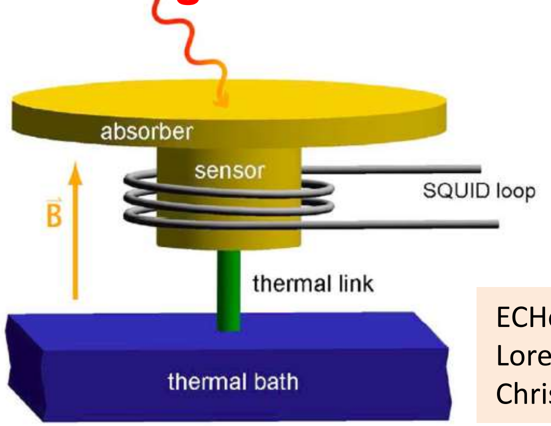
**Possible application: search for suitable clock transitions**

# The ECHo ($^{163}$Ho) project

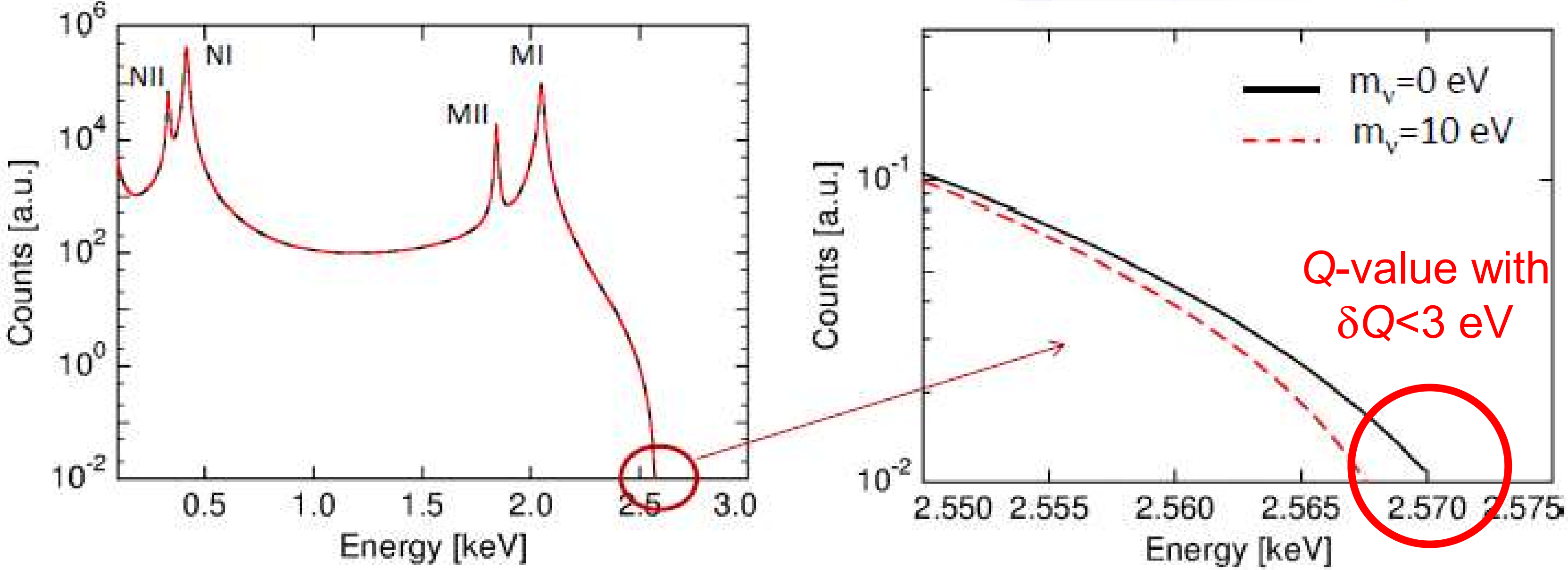
$$^{163}_{67}\mathrm{Ho} + e^{-} \rightarrow {}^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

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

**Metallic Magnetic Calorimetry**



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss



*Q*-value with
δ*Q*<3 eV

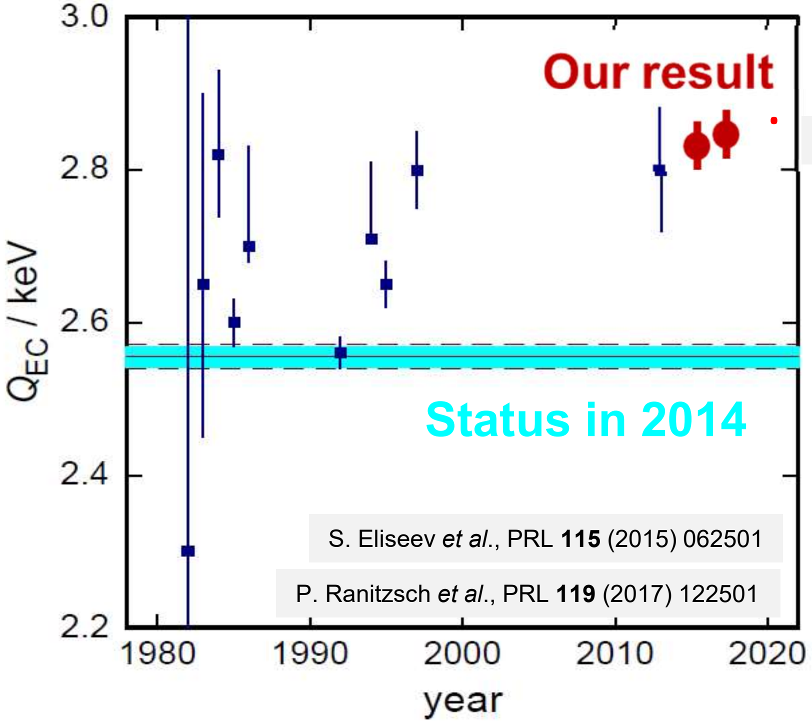
# The ECHo ($^{163}$Ho) project

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

NEUTRONS FOR SCIENCE

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

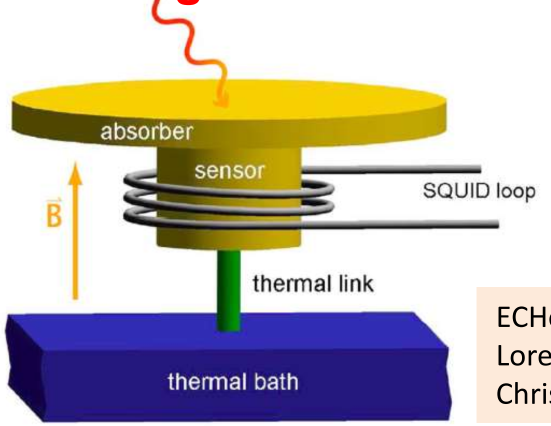
## *Q*-value of EC in $^{163}$Ho



S. Eliseev *et al.*, PRL **115** (2015) 062501

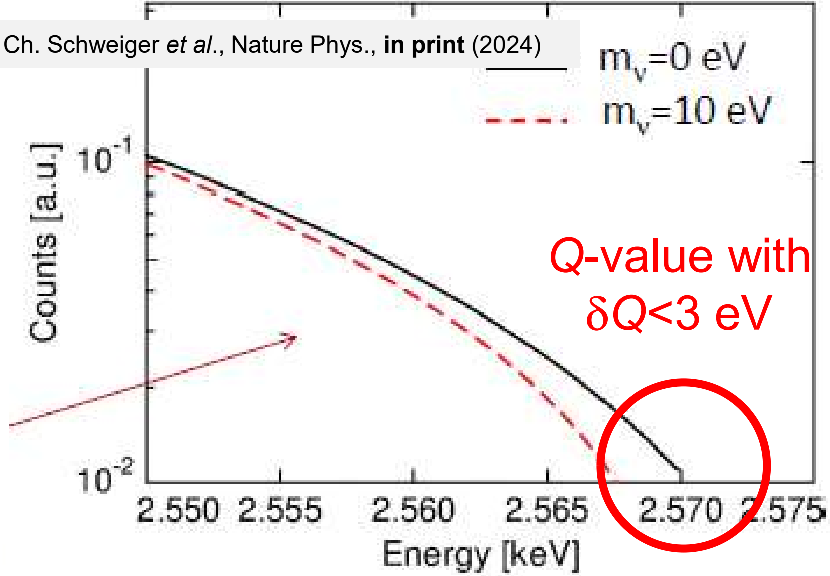
P. Ranitzsch *et al.*, PRL **119** (2017) 122501

## Metallic Magnetic Calorimetry



ECHo-Collaboration:
Loredana Gastaldo
Christian Enss

**$\delta Q$=0.6 eV**

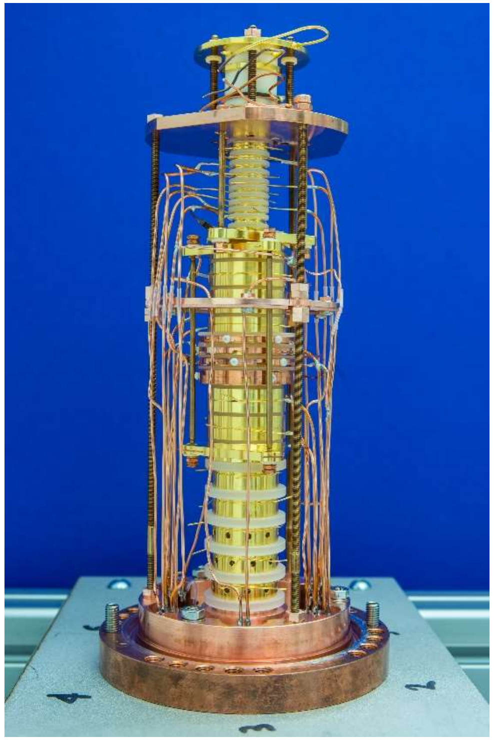


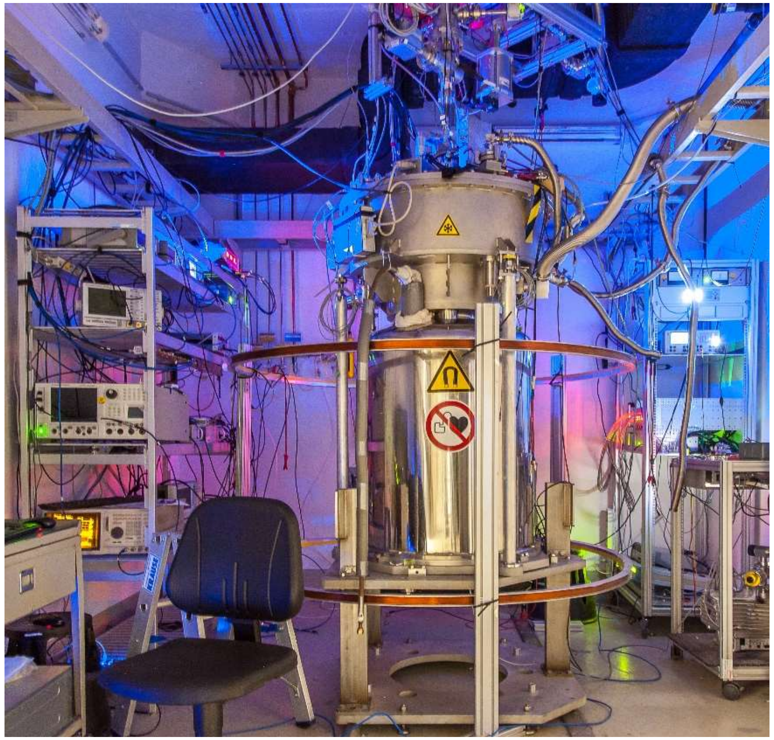
Ch. Schweiger *et al.*, Nature Phys., **in print** (2024)

*Q*-value with $\delta Q$<3 eV

# Results III

## Tests of fundamental interactions and their symmetries

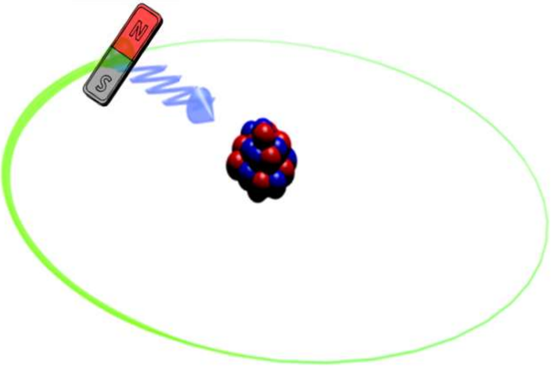




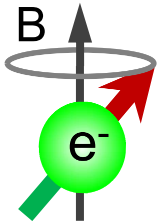
**ALPHATRAP, BASE, PENTATRAP: MPIK, PTB, RIKEN**

# The *g*-factor of the bound electron

Study one electron bound to the nucleus, e.g. $^{12}C^{5+}$ (highly charged ions)



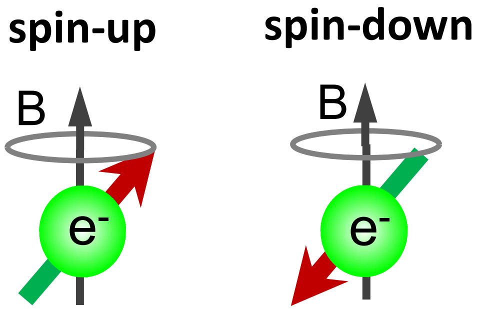
*g*-factor: measure for the magnetic strength of the bound electron



Electron acts like a spinning top in the magnetic field with frequency $\omega_L$

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

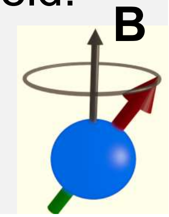
Electron can be in spin-up or spin-down state with transition frequency $\omega_L$



# Measurement principle

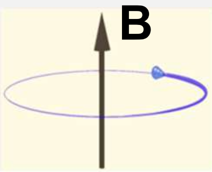
Measurement of the Larmor frequency in a well-known magnetic field:

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



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

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

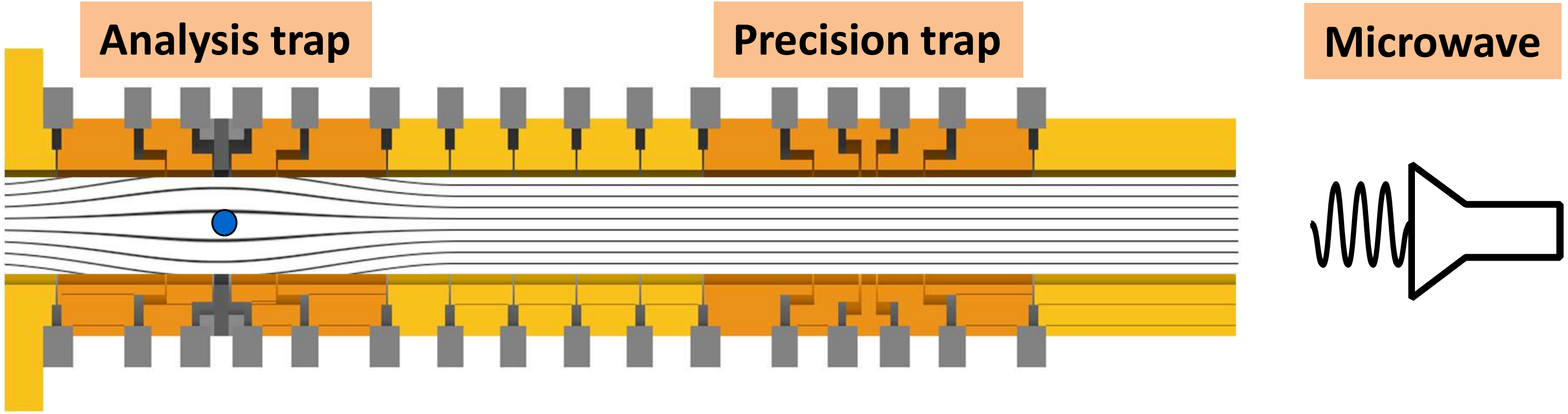


$$g = 2\frac{\omega_L}{\omega_c}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e} = 2\Gamma\frac{q_{ion}}{m_{ion}}\frac{m_e}{e}$$

has to be determined

Measured by independent precision experiments

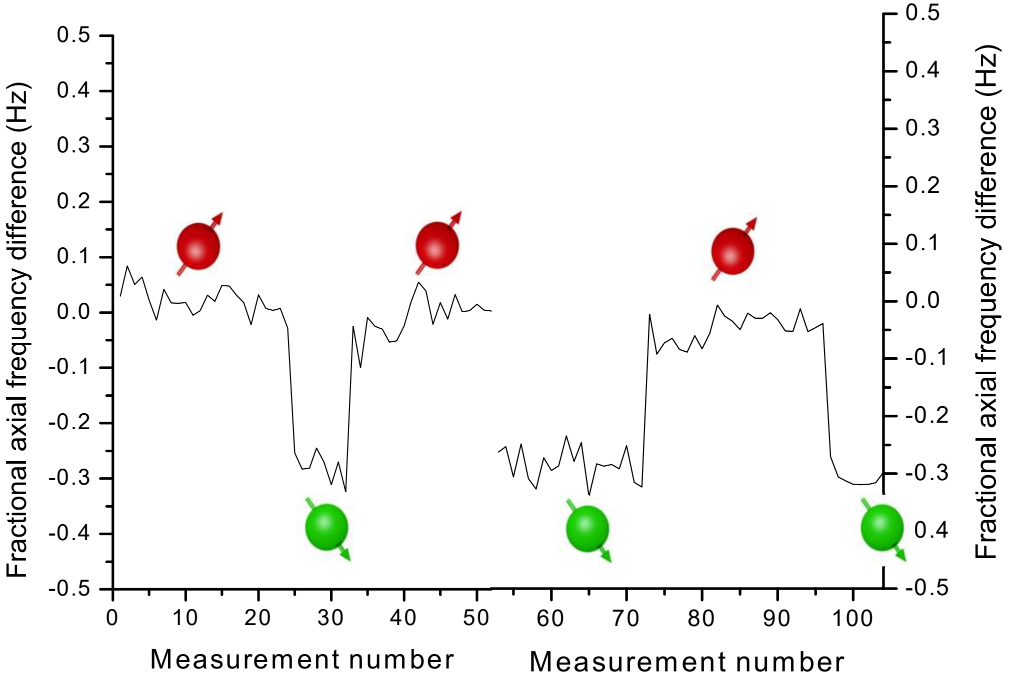
# *g*-factor measurement process



**Analysis trap**

**Precision trap**

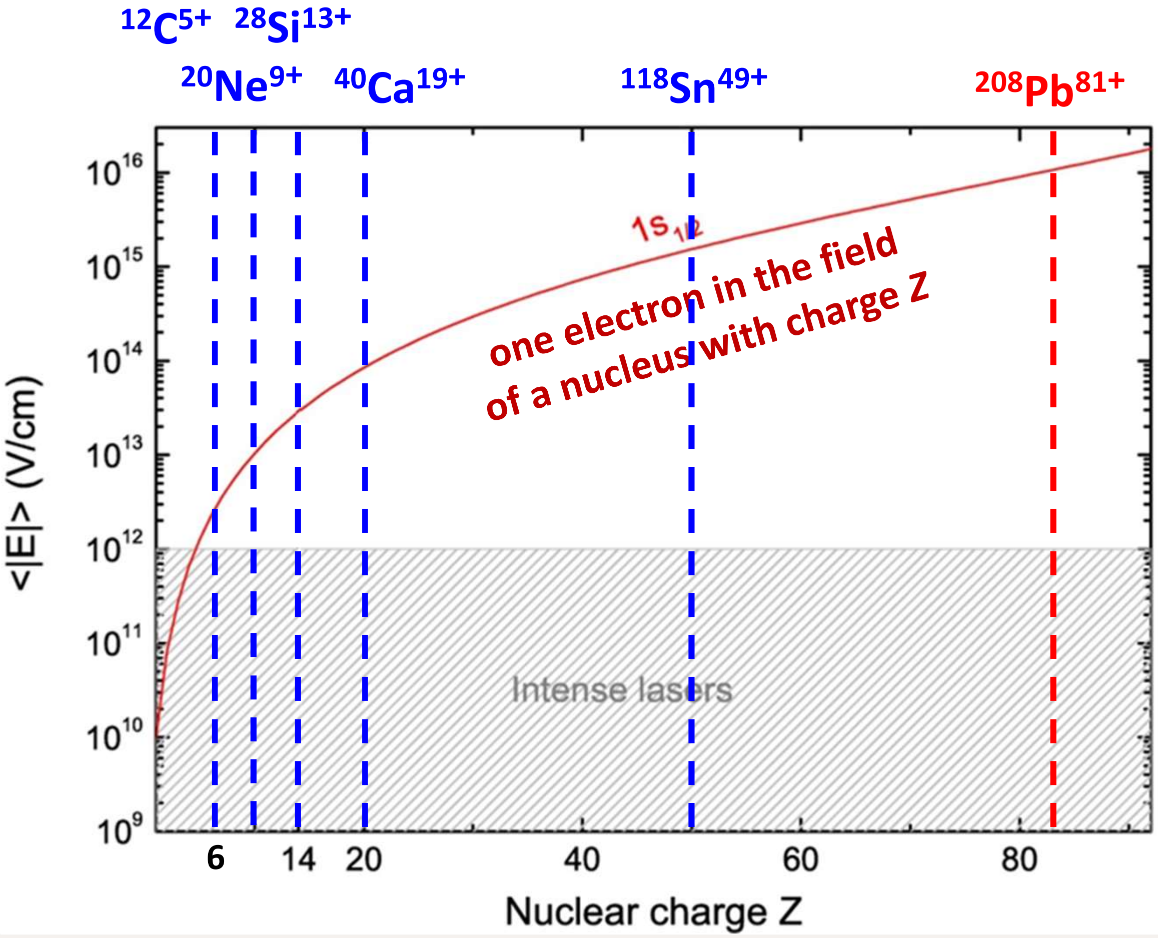
**Microwave**



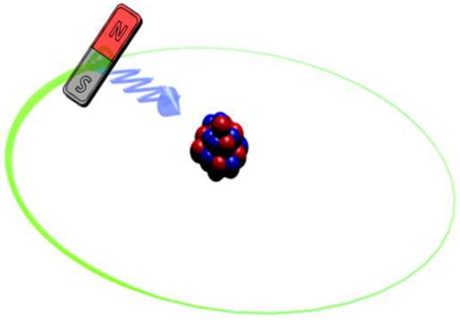
| Measurement cycle | time |
|---|---|
| Detection of spin-state | 2-3min |
| Transport | 20s |
| $\nu_c$ measurement and microwave irradiation | 10min |
| Transport | 20s |
| Detection of spin-state | |

# Extreme conditions in highly charged ions

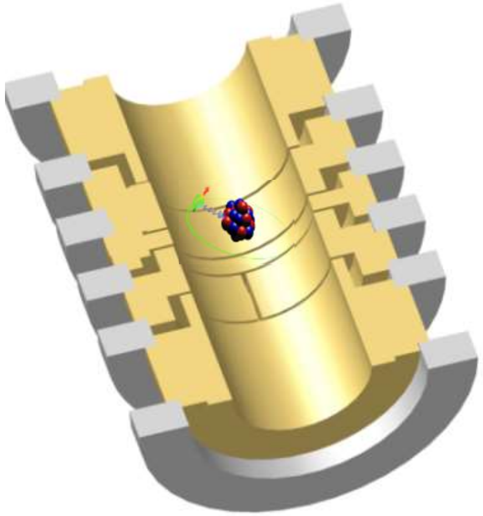
- QED is the best tested quantum field theory
  (see *g*-2 of the electron; Dehmelt, Gabrielse)
- we would like to test QED in ultra strong fields



***Highly charged ions***



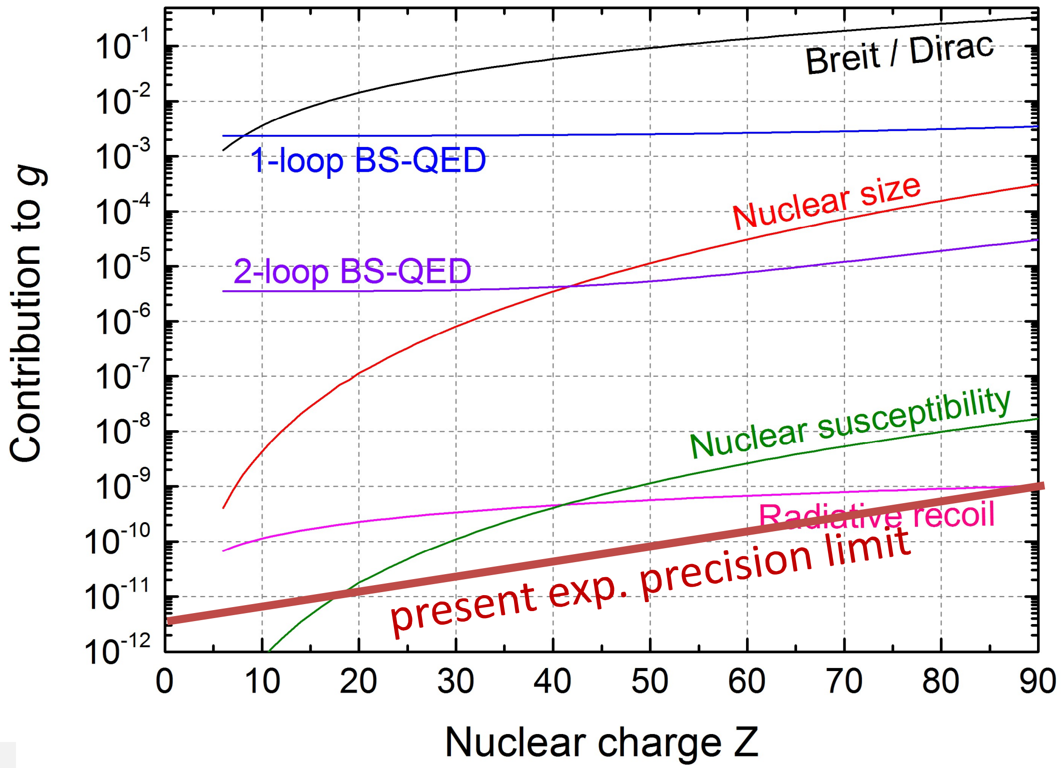
***Penning trap***



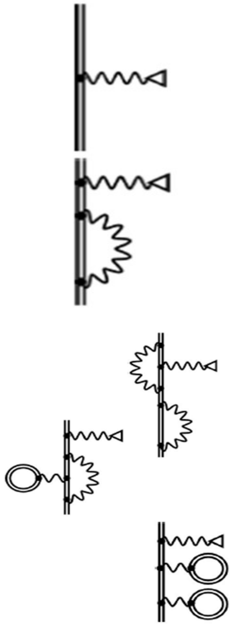
# The *g*-factor of a bound electron

Theory can calculate the *g*-factor extremely well!

$$g = 2(1 + a_{Breit} + a_{1loop} + a_{NuclearSize} + a_{2loop} + a_{recoil} + \ldots)$$

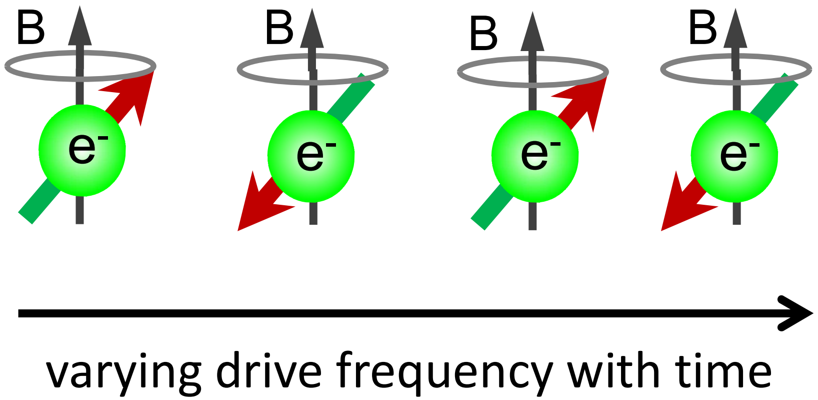


Z. Harman *et al.*, 2016

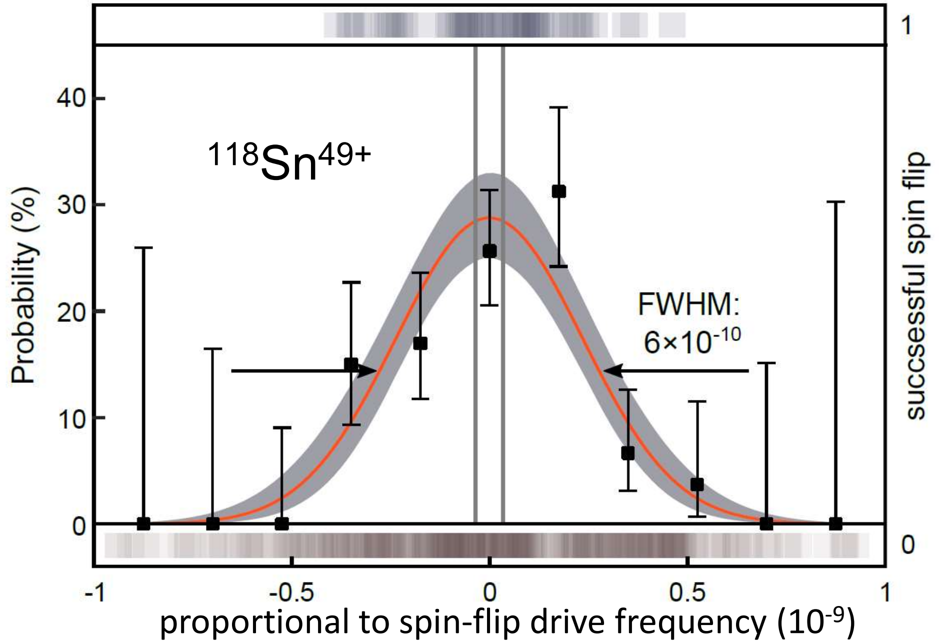


K. Pachucki *et al.*,
Phys. Rev. A 72, 022108 (2005)

# Test of QED in strong fields



varying drive frequency with time



$^{20}$Ne$^{9+}$

$g_{exp}$ = 1.998 767 276 93 (16)
$g_{theo}$ = 1.998 767 277 11 (12)

$^{118}$Sn$^{49+}$

$g_{exp}$ = 1.910 562 058 (1)
$g_{theo}$ = 1.910 561 821 (299)

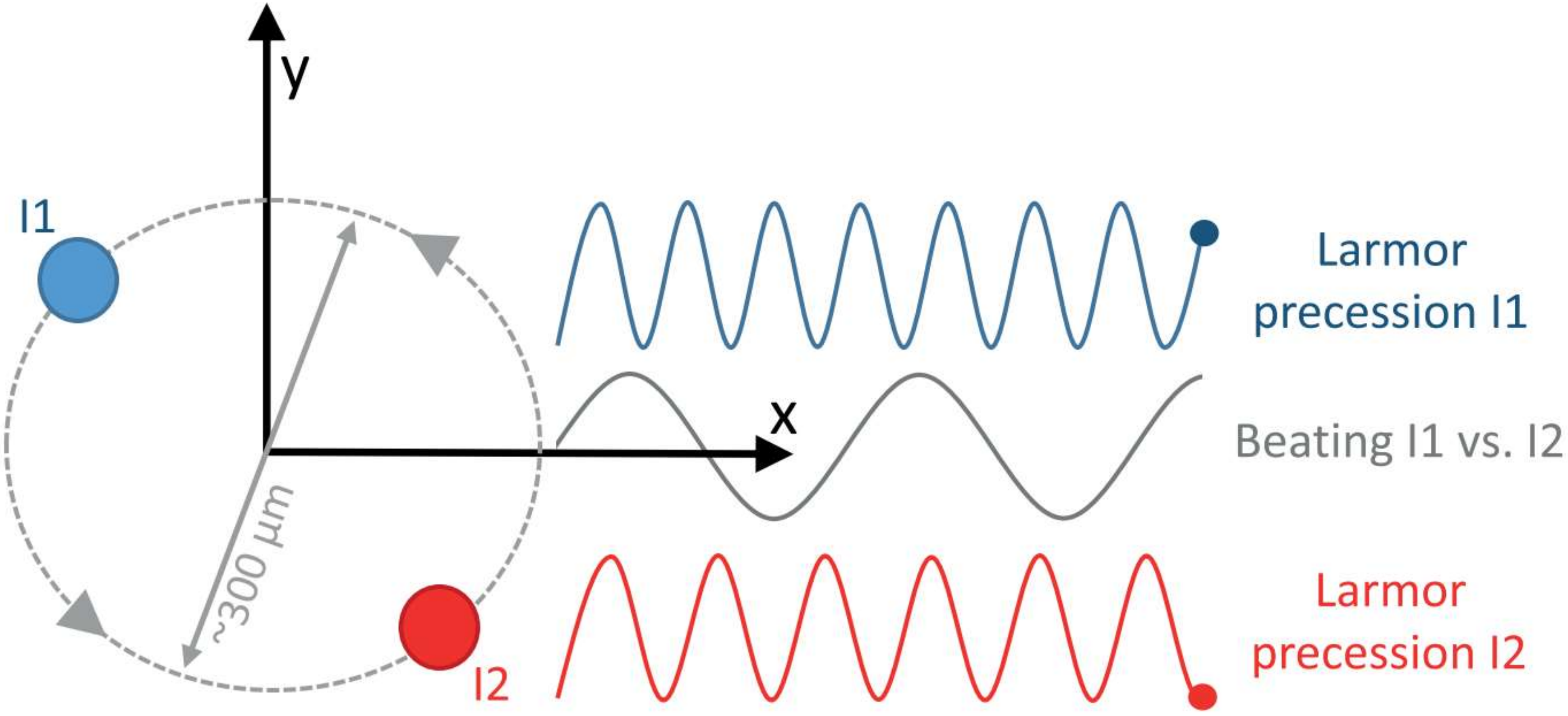
Stringent test of bound-state QED in strong fields!

**Theory colleagues: Harman, Keitel, Oreshkina, Yerokhin**

T. Sailer *et al.*, Nature **606**, 479 (2022)
F. Heiße *et al.*, Phys. Rev. Lett., **in print** (2023)
J. Morgner *et al.*, Nature **622**, 53 (2023)

# Bound *g*-factor difference in coupled ions

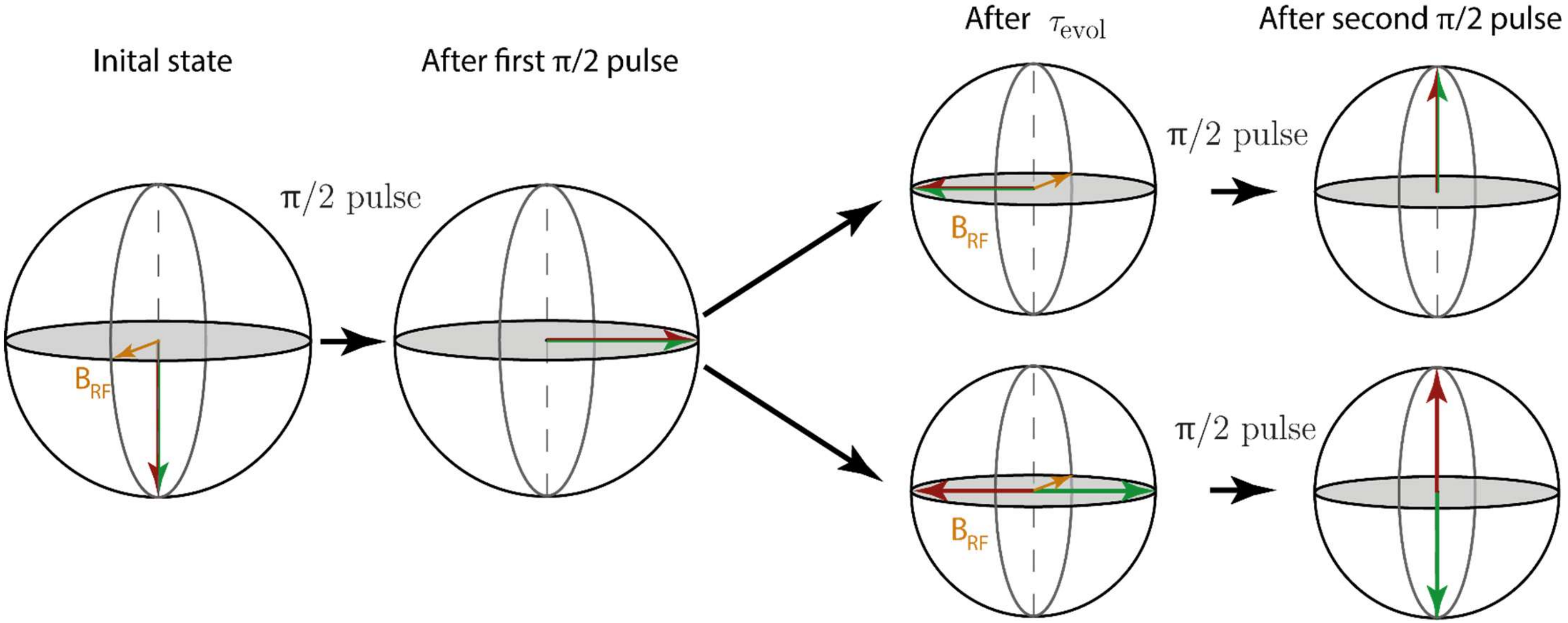
Delta-*g* measurement in $^{20,22}\mathrm{Ne}^{9+}$: how to get $\nu_L$



# Bound *g*-factor difference in coupled ions

Delta-*g* measurement in $^{20,22}\mathrm{Ne}^{9+}$: how to get $\nu_L$

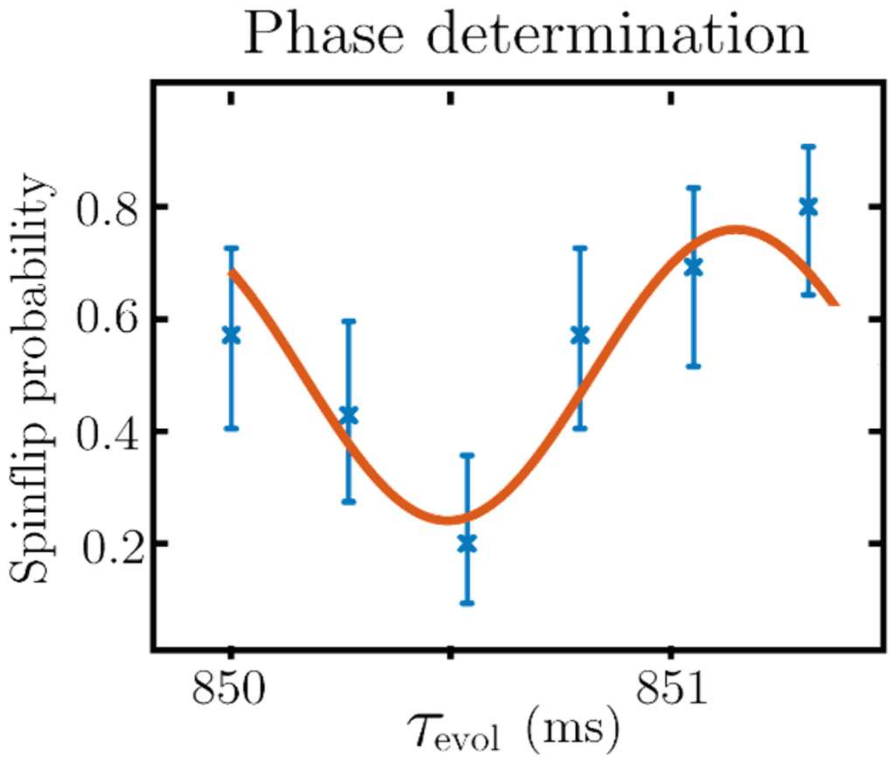
Probability of common spin behavior modulated by beat frequency!



# Bound $g$-factor difference in coupled ions

## Delta-$g$ measurement in $^{20,22}\mathrm{Ne}^{9+}$: how to get $\nu_L$

Probability of common spin behavior modulated by beat frequency!



Relative precision of $5\cdot10^{-13}$ achieved, most stringent BS-QED test!

T. Sailer *et al.*,
Nature **606** (2022) 479

# Summary

*Precision Penning-trap spectroscopy has reached an amazing precision even on exotic systems and has opened up many new fields of research!*

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