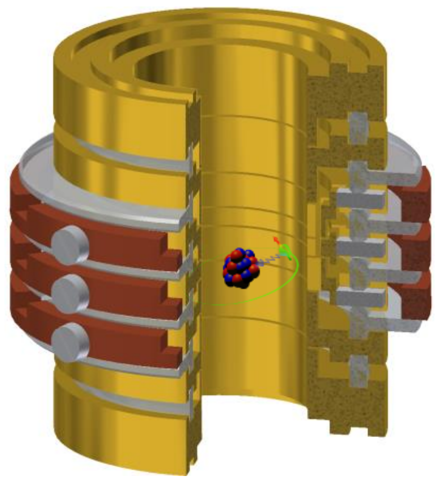
QED Tests in Strong Fields and Fundamental Constants from Precision Measurements on Highly Charged Ions



Sven Sturm

MPIK Heidelberg

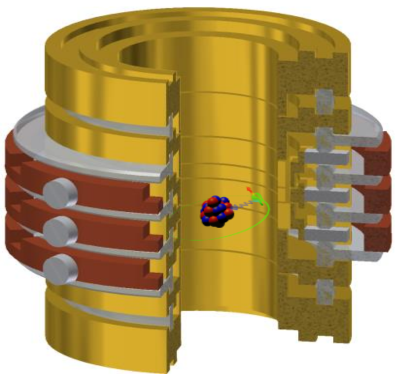
PSI 2019

LION TRAP

α TRAP

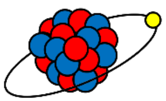
The best of two worlds

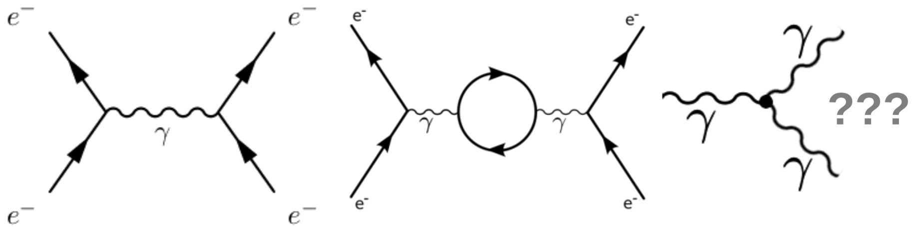
Penning traps



- Single ion in free space – **perfect spectroscopy conditions**
  - Solely static fields
- **Access to many properties** of the ion:
  - Mass (via cyclotron frequency)
  - Magnetic moments (via Larmor frequency)
  - Excitation energies
  - …

Quantum Electrodynamics (QED) in simple systems

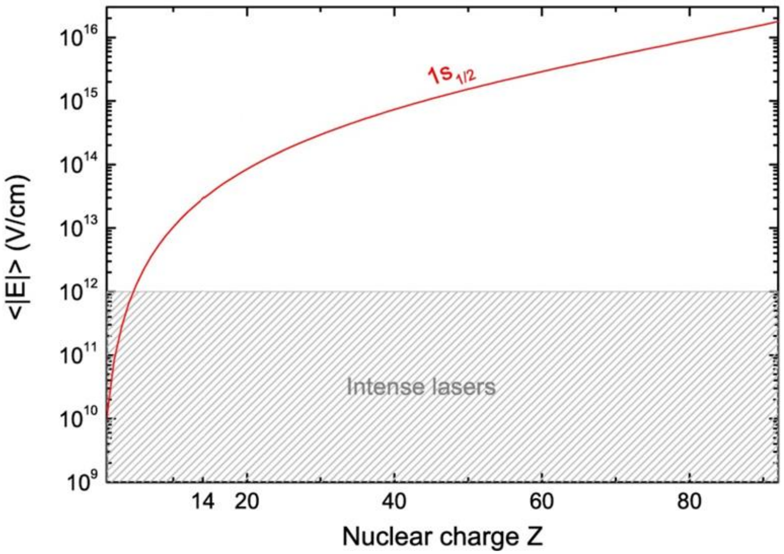


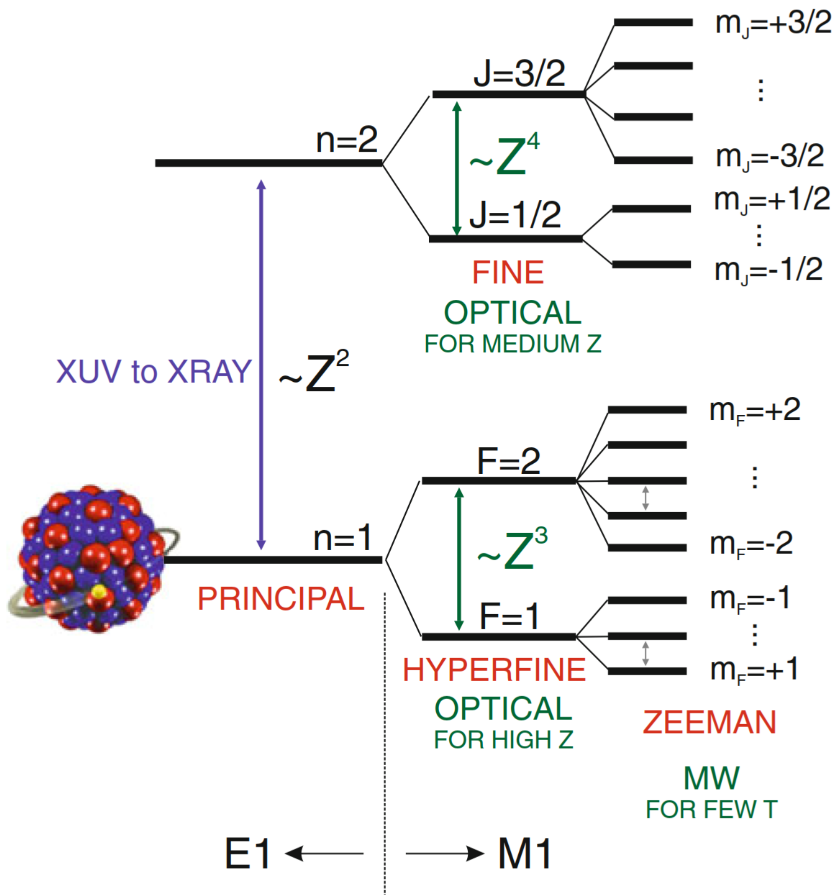


- QED enables **extremely** precise predictions:
  - (hydrogen) spectrum
  - (Hyper-)fine structure
  - magnetic moments
  - …
  - ➢ "the jewel of physics" (Feynman)

Perfect match for testing fundamental physics

How strong can it get ?





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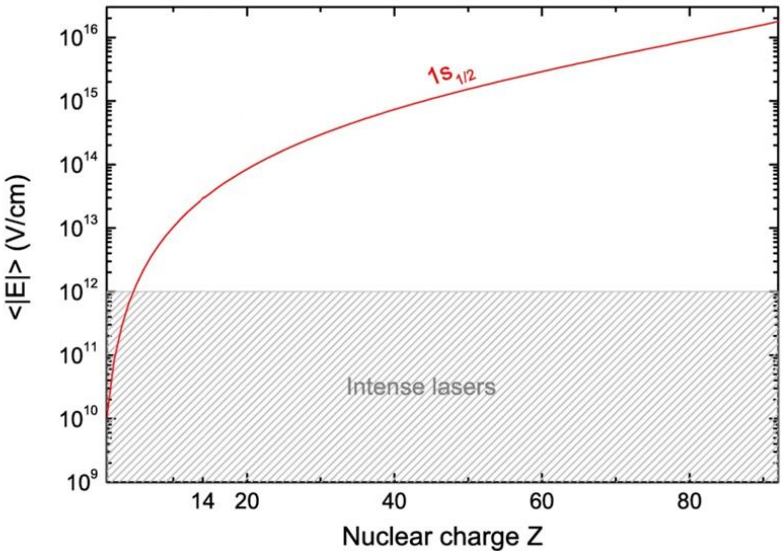
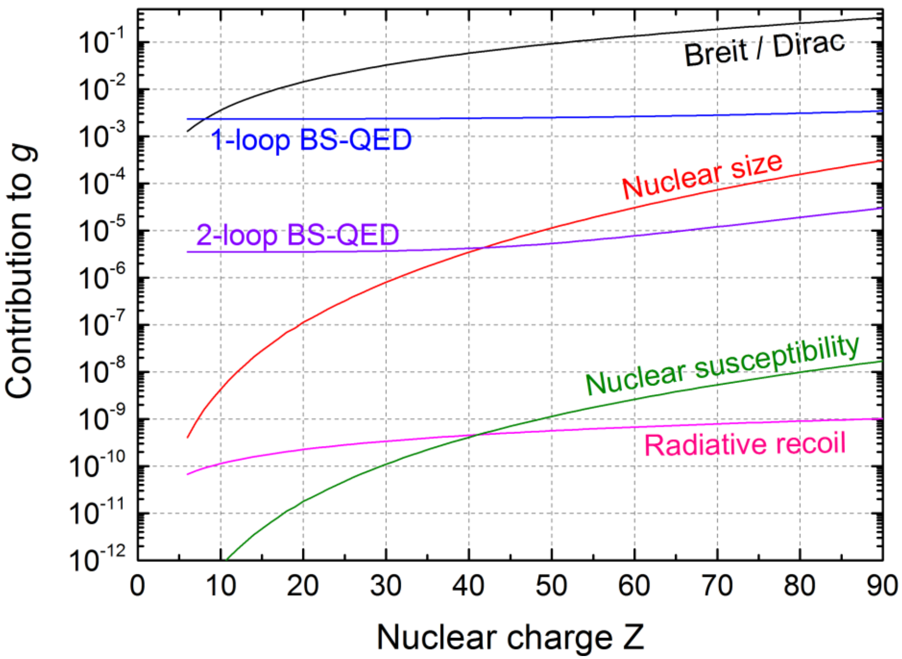
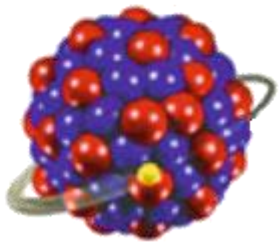


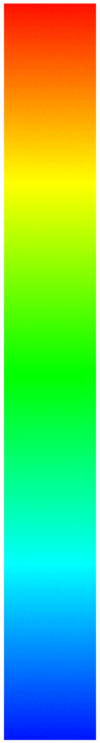


Nothing comes without a price…

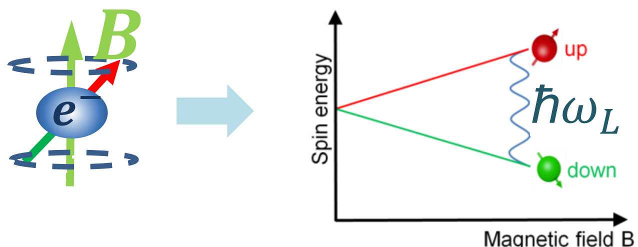


Typical energy scales are **very diverse**:

- **Ionisation** energy ($^{208}Pb^{81+}$): up to 100 keV
- During **creation** (EBIT): ~ Megakelvin (500eV)
- After **trapping and cooling**: mK-K (40μeV)

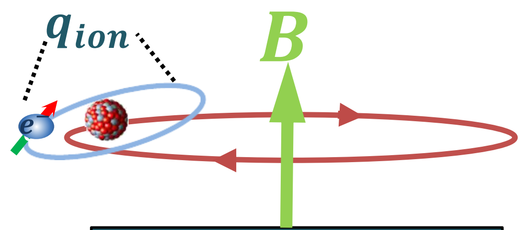


g – factor measurement in a Penning trap



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

Determine the Larmor frequency
in a well-known magnetic field



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

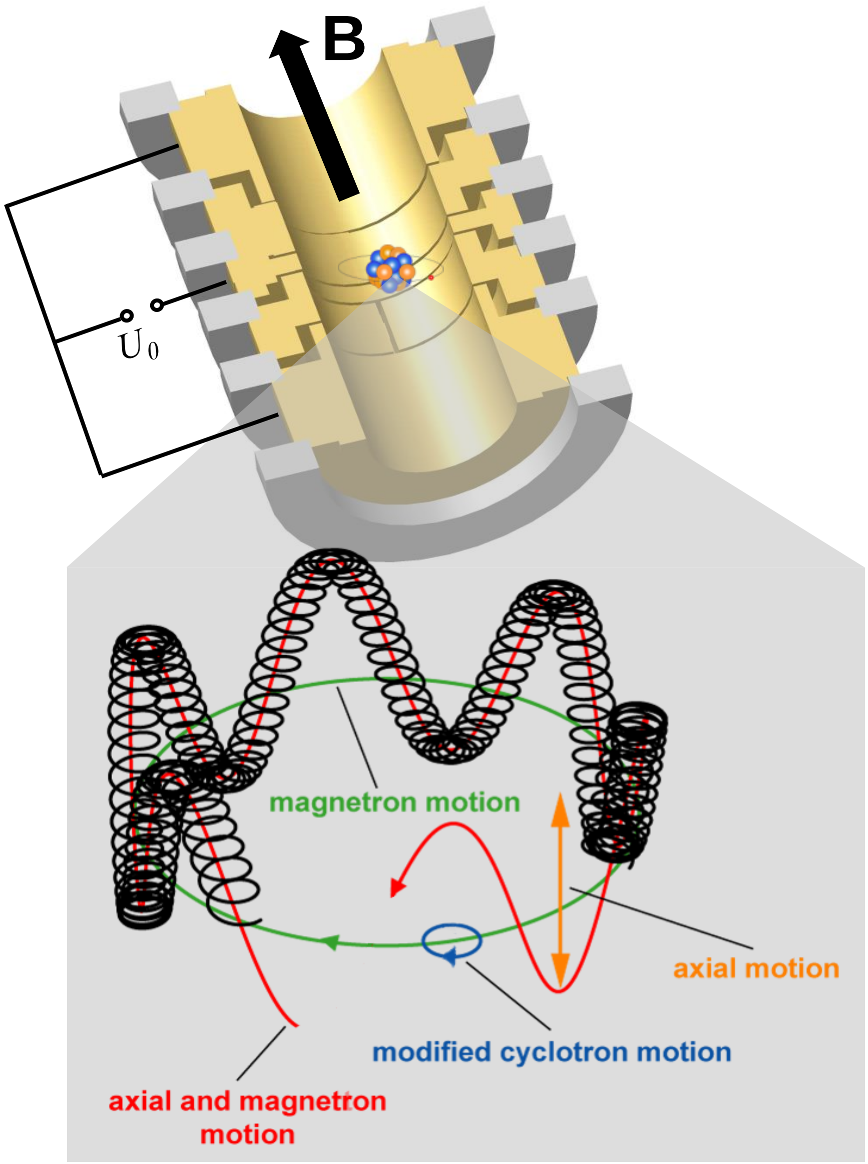
Measure the free cyclotron frequency
to determine the magnetic field

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

to be measured
$\Gamma = {}^{\omega_L}/_{\omega_c}$

Independent precision experiments

Our measurement tool - the Penning trap



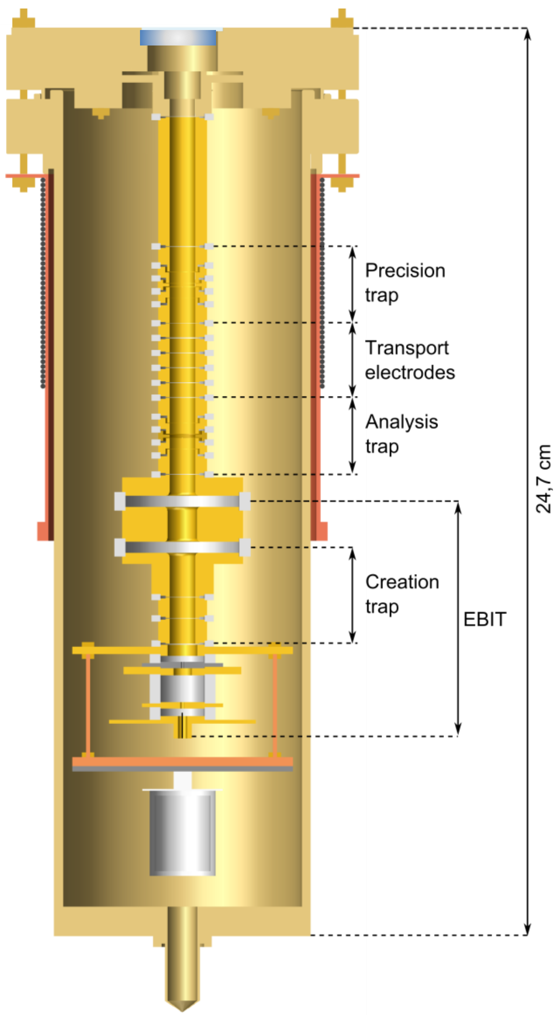
Trap eigenfrequencies

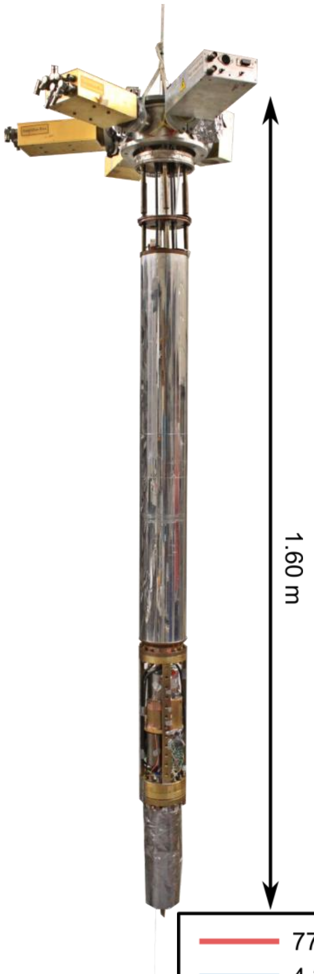
- Reduced cyclotron frequency: $\sim 2\pi\cdot$ 27 MHz
- Magnetron drift frequency: $\sim 2\pi\cdot$ 9 kHz
- Axial frequency: $\sim 2\pi\cdot$ 700 kHz
- Larmor frequency: $\sim 2\pi\cdot$ 110 GHz

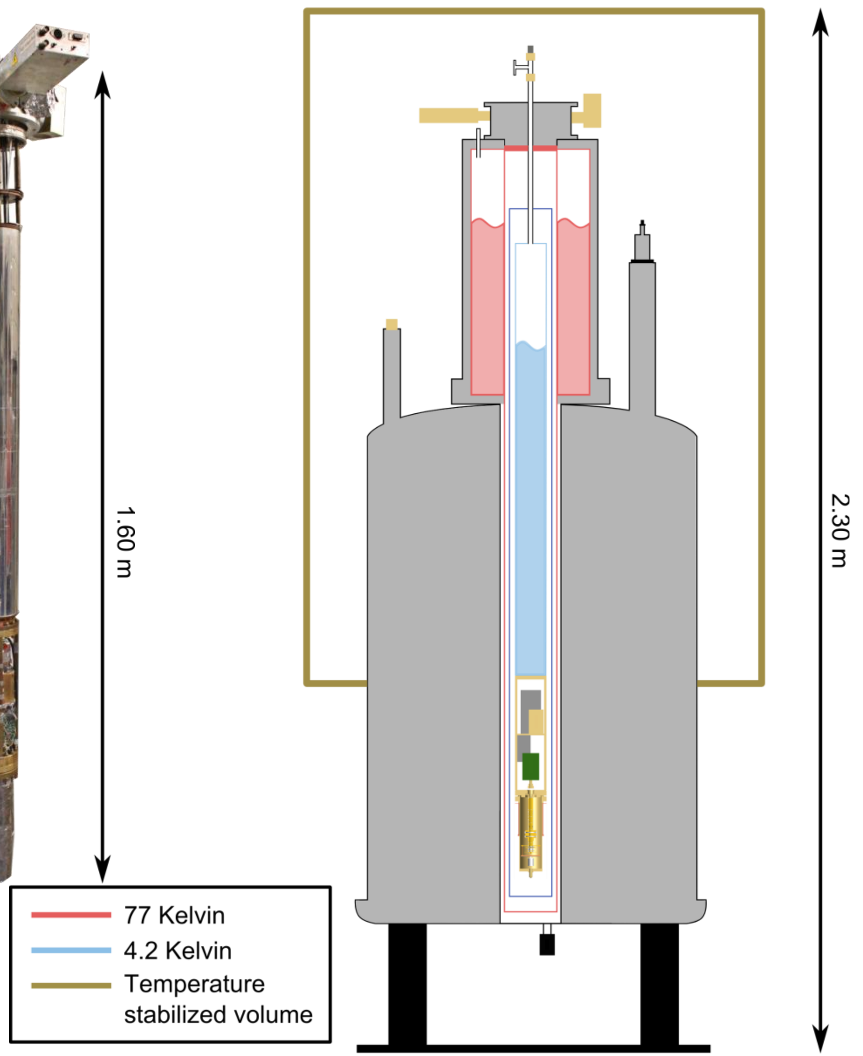
➢ Free cyclotron frequency $\omega_c^2 = \omega_+^2 + \omega_-^2 + \omega_z^2$

(Brown-Gabrielse invariance theorem)

Experimental setup

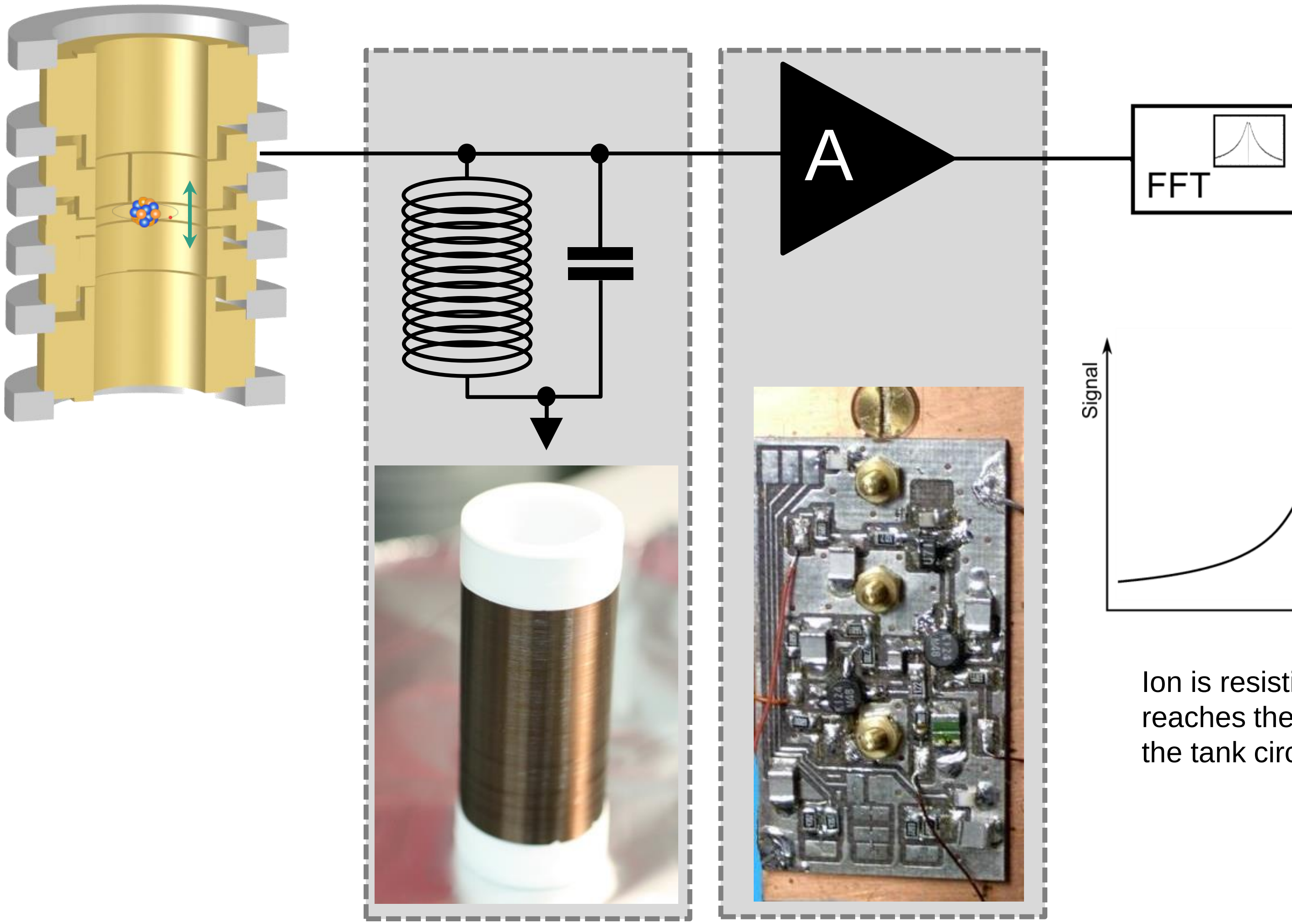


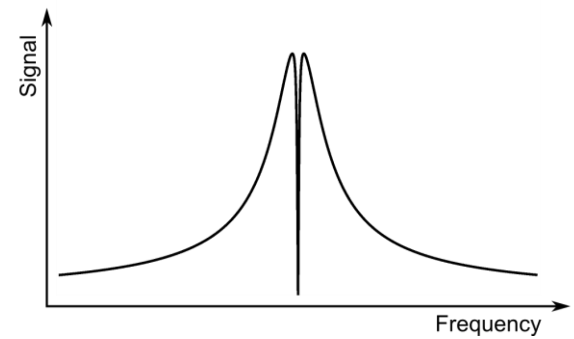




- ✓ Cryogenic temperatures (**4.2K**)
- ✓ Vacuum better than **10^{-17} mbar**
  - ➢ basically no rest gas

Eigenfrequency Detection





Ion is resistively cooled until it reaches thermal equilibrium with the tank circuit

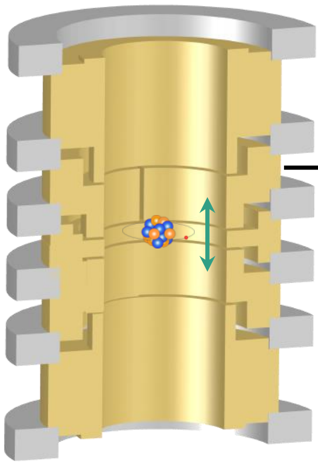
Oscillating ion induces image charges in trap electrodes

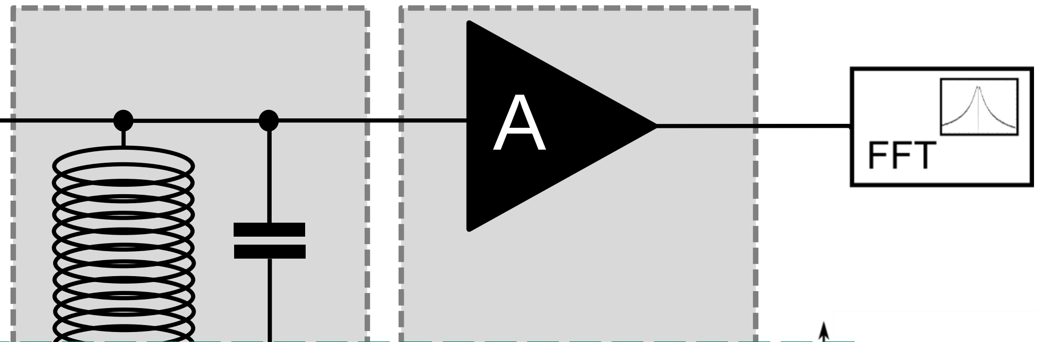
Tank circuit with high impedance
R_p = 50 MΩ
Q = 3200

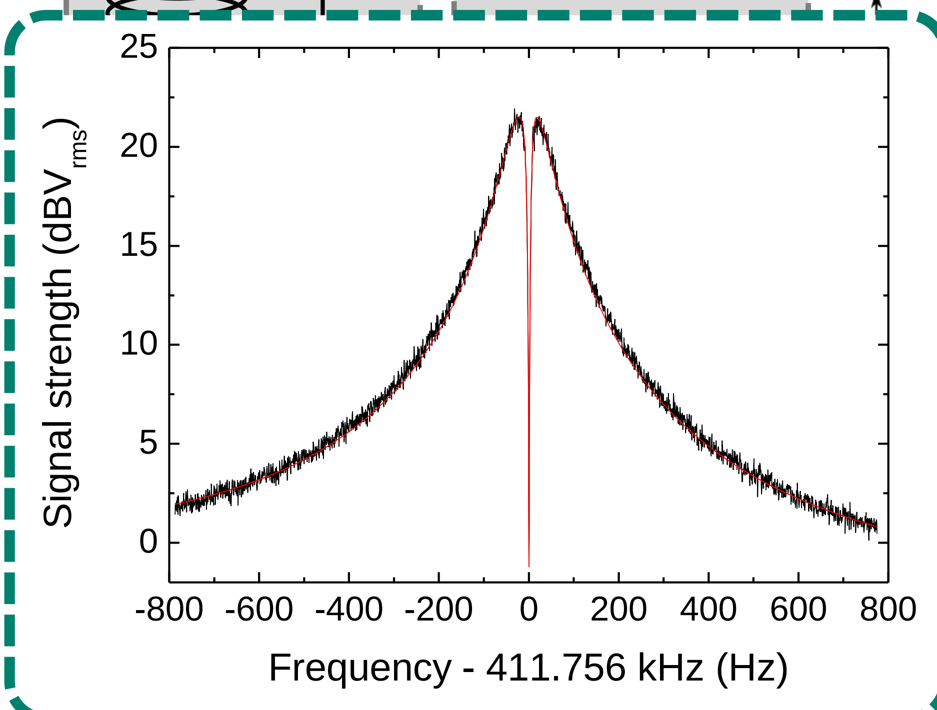
Cryogenic ultra low-noise amplifier
e_n = 400pV/ √Hz
i_n ≤ 10fA/ √Hz

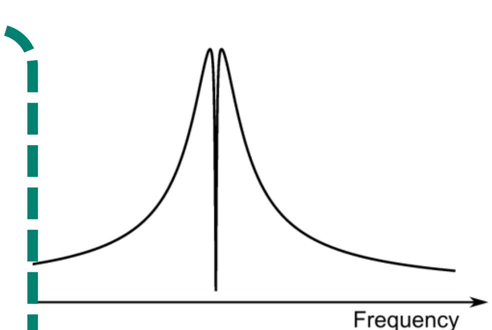
Fast Fourier Transformation to obtain the frequency information

Eigenfrequency Detection









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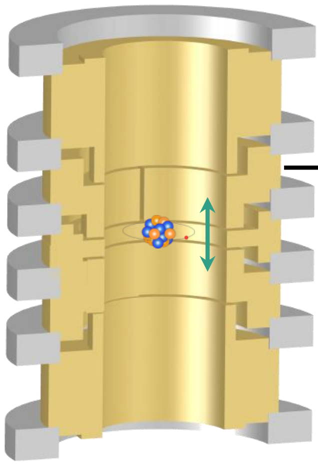

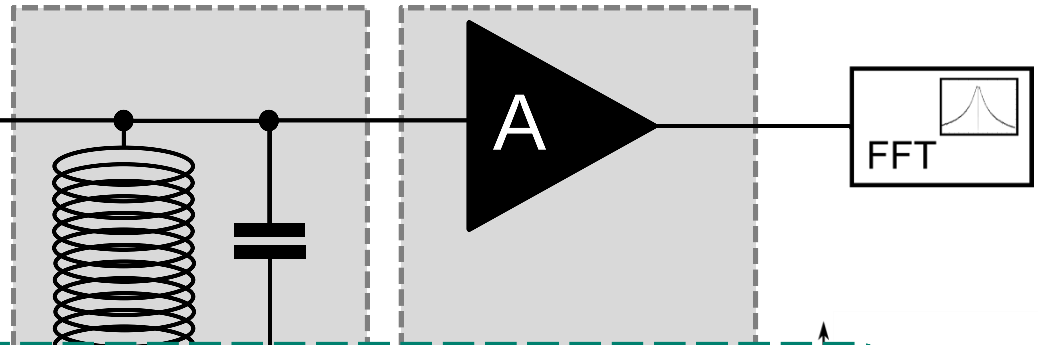

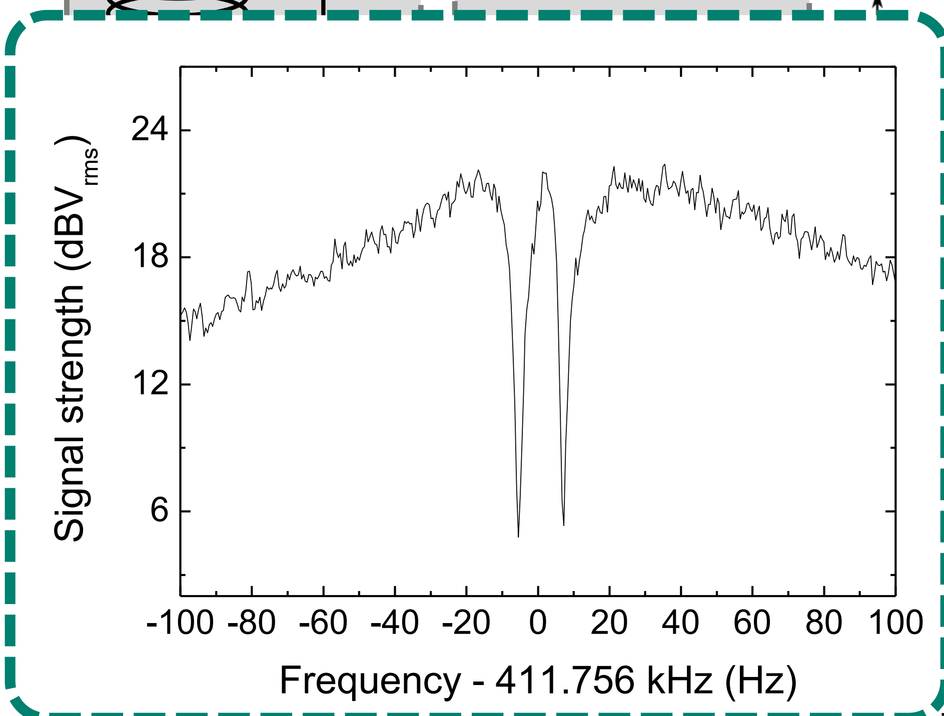

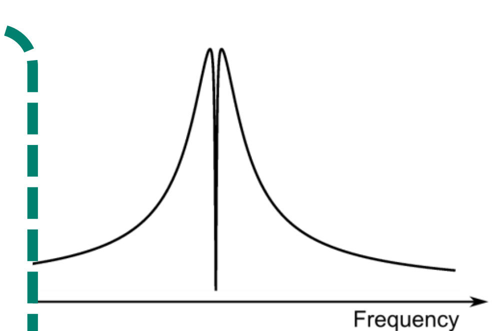

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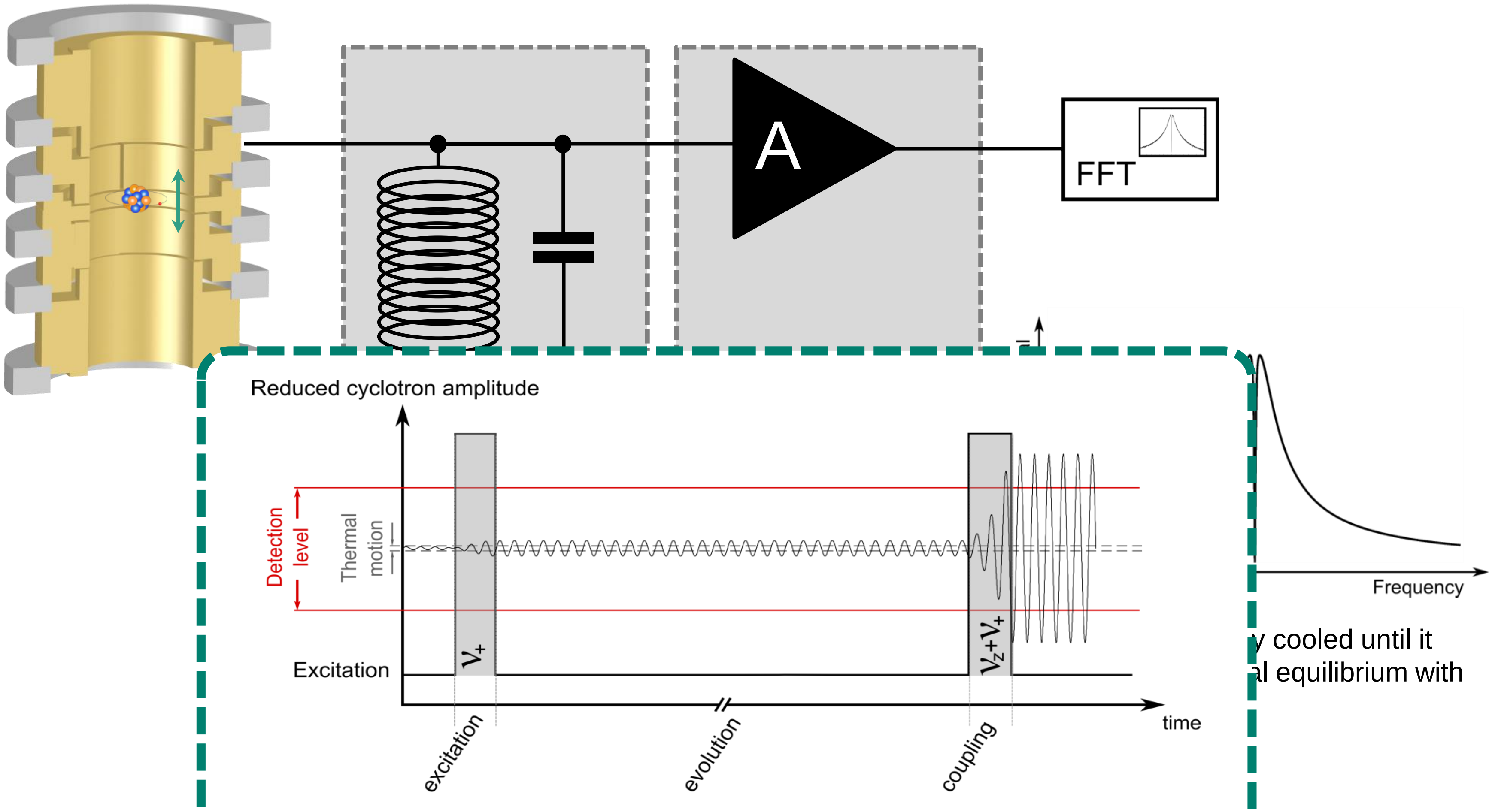

Precision improvement ~ factor 10

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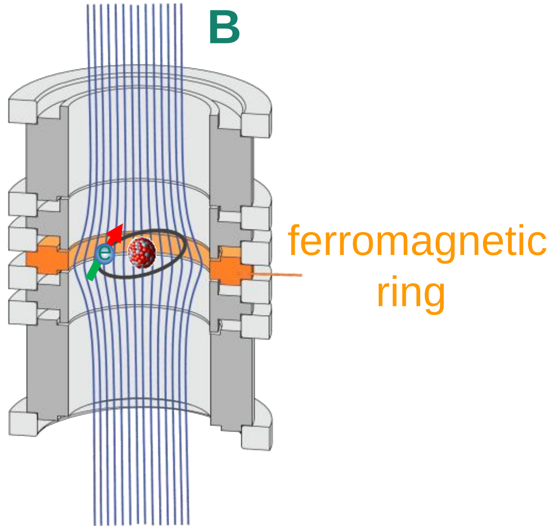
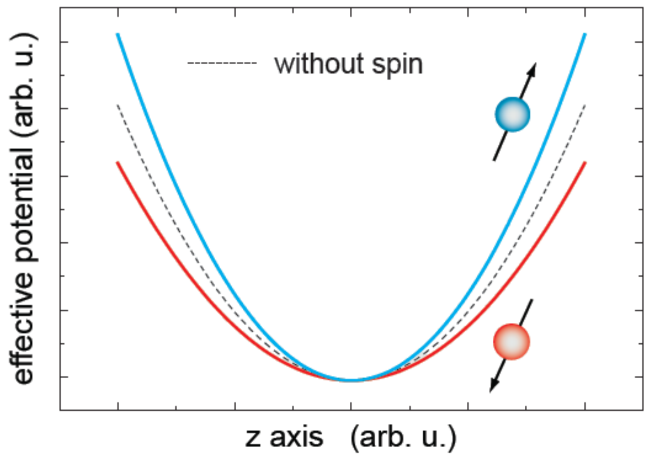
Fast Fourier Transformation to obtain the frequency information

The continuous Stern-Gerlach Effect



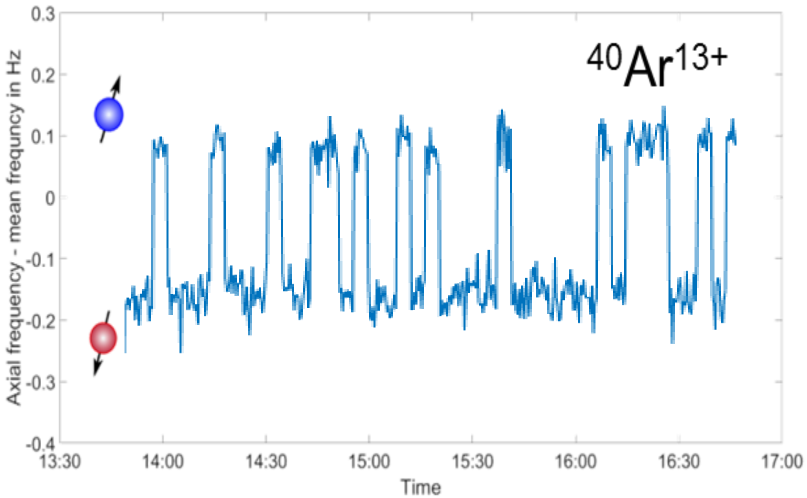


Continuous Stern-Gerlach effect:

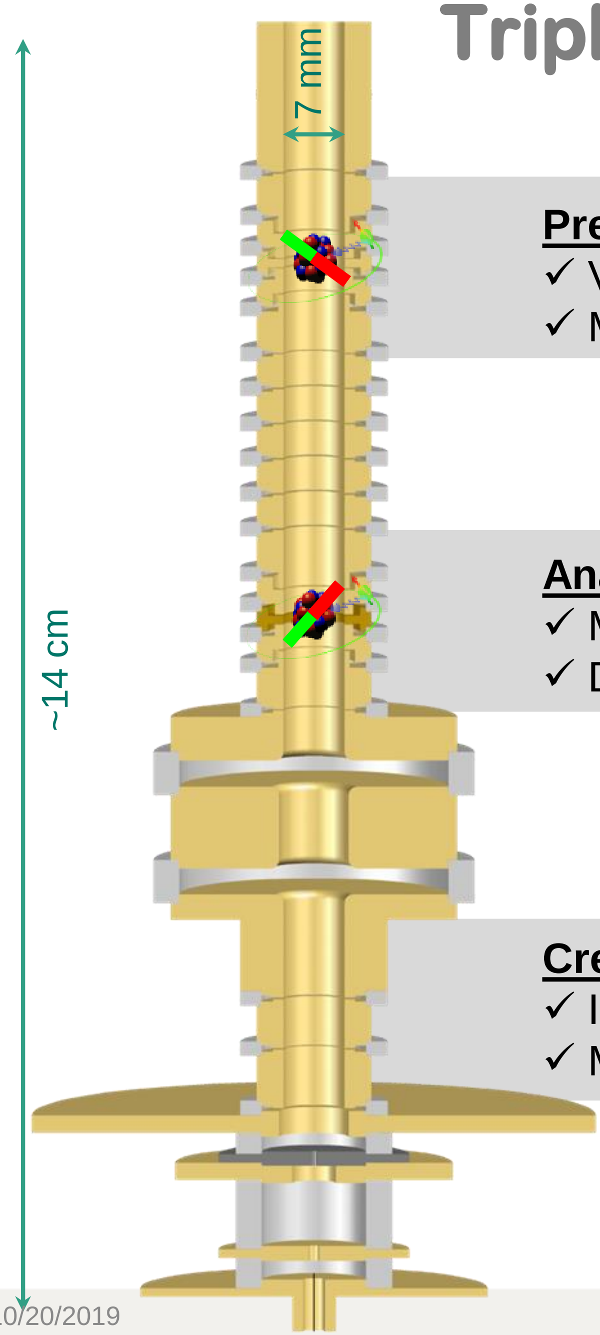
axial frequency offset between "up" and "down" spin orientation

$$\boxed{\Delta\nu_z \approx \frac{B_2 g \mu_B}{4\pi^2 m_{ion} \nu_z}}$$

	$^{12}C^{5+}$	$^{28}Si^{13+}$	$^{40}Ar^{13+}$	$^{208}Pb^{81+}$
$\Delta\nu_z$	3.1 Hz	1.3 Hz	312 mHz	156 mHz



Triple Penning trap system

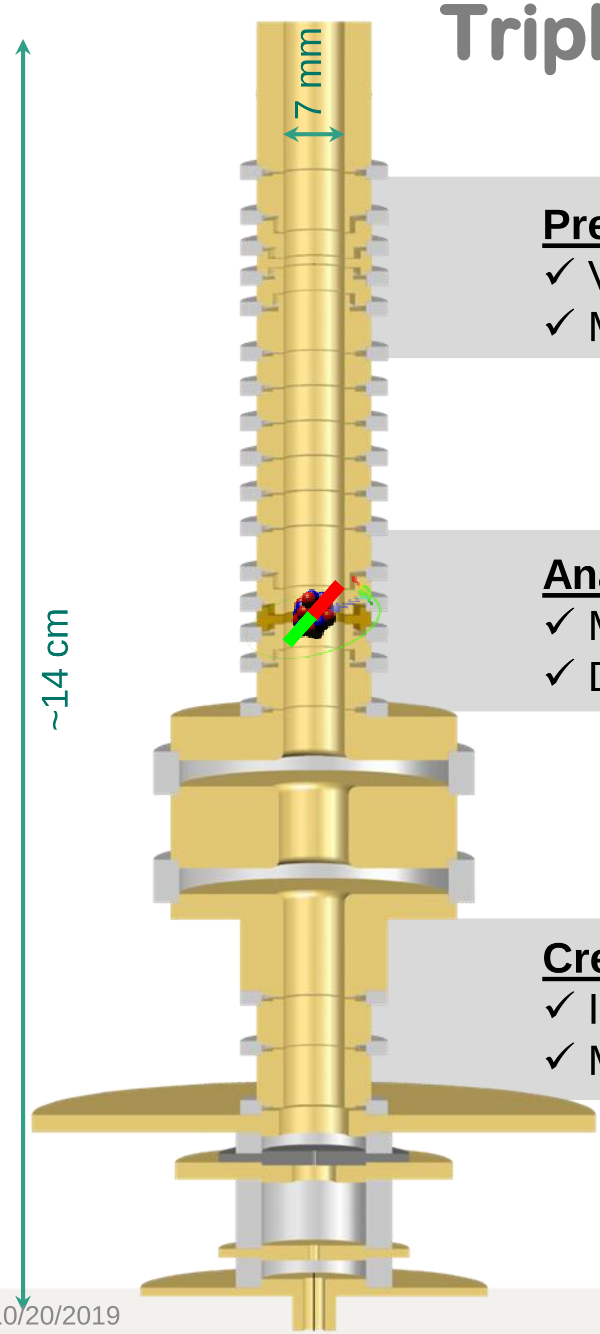


Precision trap
- ✓ Very homogeneous magnetic field
- ✓ Measurement of the frequency ratio Γ

Analysis trap
- ✓ Magnetic inhomogeneity
- ✓ Detection of spin direction

Creation trap
- ✓ In-trap ion creation of highly-charged ions
- ✓ Miniature EBIT/S

Triple Penning trap system



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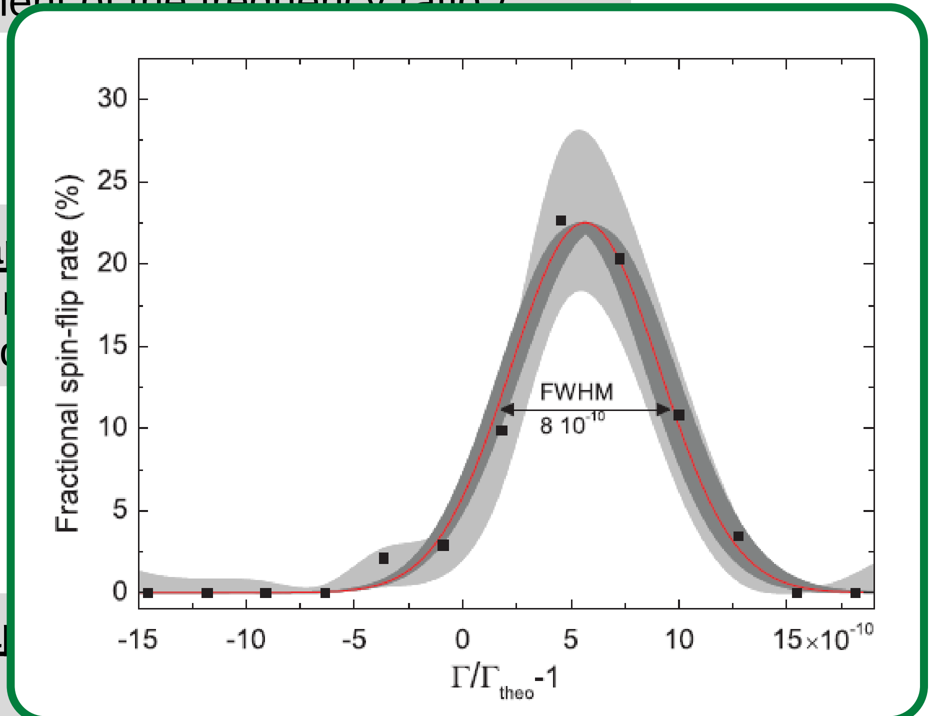
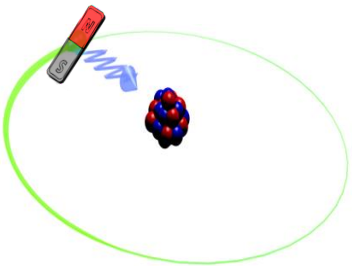


Selected *g*-factor Results

Hydrogenlike $^{28}Si^{13+}$

[S. Sturm et al., PRL 107, 2 (2011)]
[S. Sturm et al., PRA 87, 030501(R) (2013)]

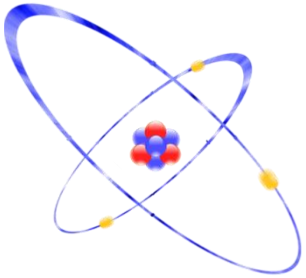
Most stringent test of QED in strong fields



Lithiumlike $^{28}Si^{11+}$

[A. Wagner *et al.*, PRL **110**, 033003 (2013)]

Most stringent test of relativistic 3 electron interactions



Hydrogenlike $^{12}C^{5+}$

[S. Sturm *et al.*, Nature **506**, 467-470 (2014)]

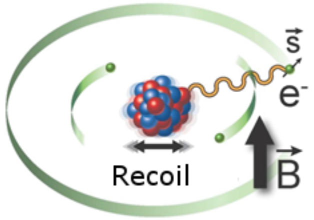
Electron mass

Lithiumlike
$^{48}Ca^{17+}$ / $^{40}Ca^{17+}$

[F. Koehler-Langes *et al.*, Nature Comm. **10246** (2016)]

Relativistic recoil

$^{40}Ca^{17+}$/ $^{48}Ca^{17+}$



The electron's mass

Electron mass from ultra-high precision *g*-factor of **hydrogenlike carbon:**

Theory (Pachucki et. al) x 10^{-12}

$$m_e = \frac{g_{theo}}{2}\frac{\omega_c}{\omega_L}\frac{e}{q_{ion}}m_{ion}$$

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

Experiment

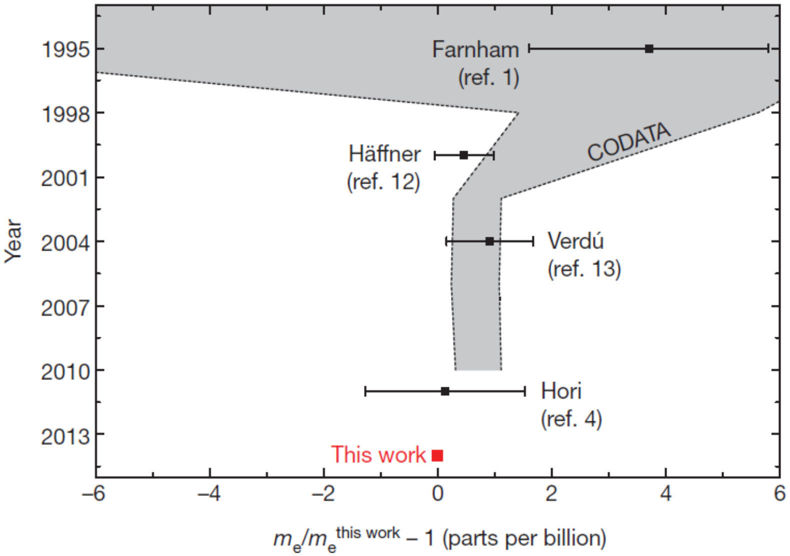
The electron's mass

Electron mass from ultra-high precision *g*-factor of **hydrogenlike carbon:**

$$m_e = \frac{g_{theo}}{2}\frac{\omega_c}{\omega_L}\frac{e}{q_{ion}}m_{ion}$$

m_e=0.000 548 579 909 067(16) u

Order of magnitude improved value !



Nature 506, 467-470, 2014

History of our experiments on HCI

~ 1995: Project start in Mainz
(Werth, Kluge, Quint *et al*)

1999/2000: First g-factor measurements on HCI in Mainz

Redesign / upgrade

2011-2014: up to $^{28}Si^{13+}$, $^{40,48}Ca^{17+}$: Stringent tests of BS-QED and **electron mass**

2013: Start of ALPHATRAP @ MPIK Heidelberg

2015: Redesign of the Mainz experiment → LIONTRAP

2018/2019: First online *g*-factor and laser spectroscopy with HCI

2017: **proton mass**

LIONTRAP

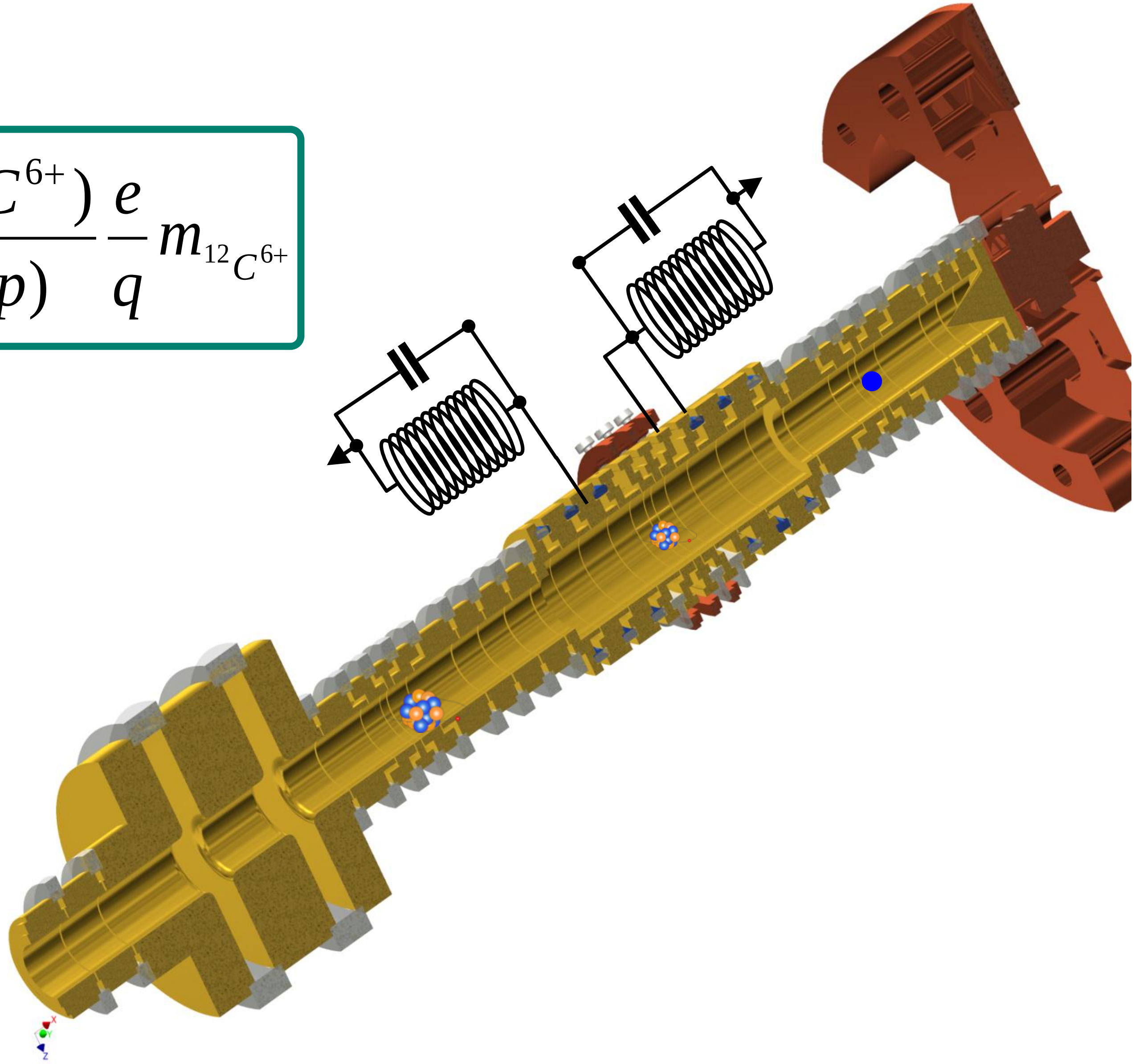
Mass measurements on light ions (proton, deuteron, …)

αTRAP

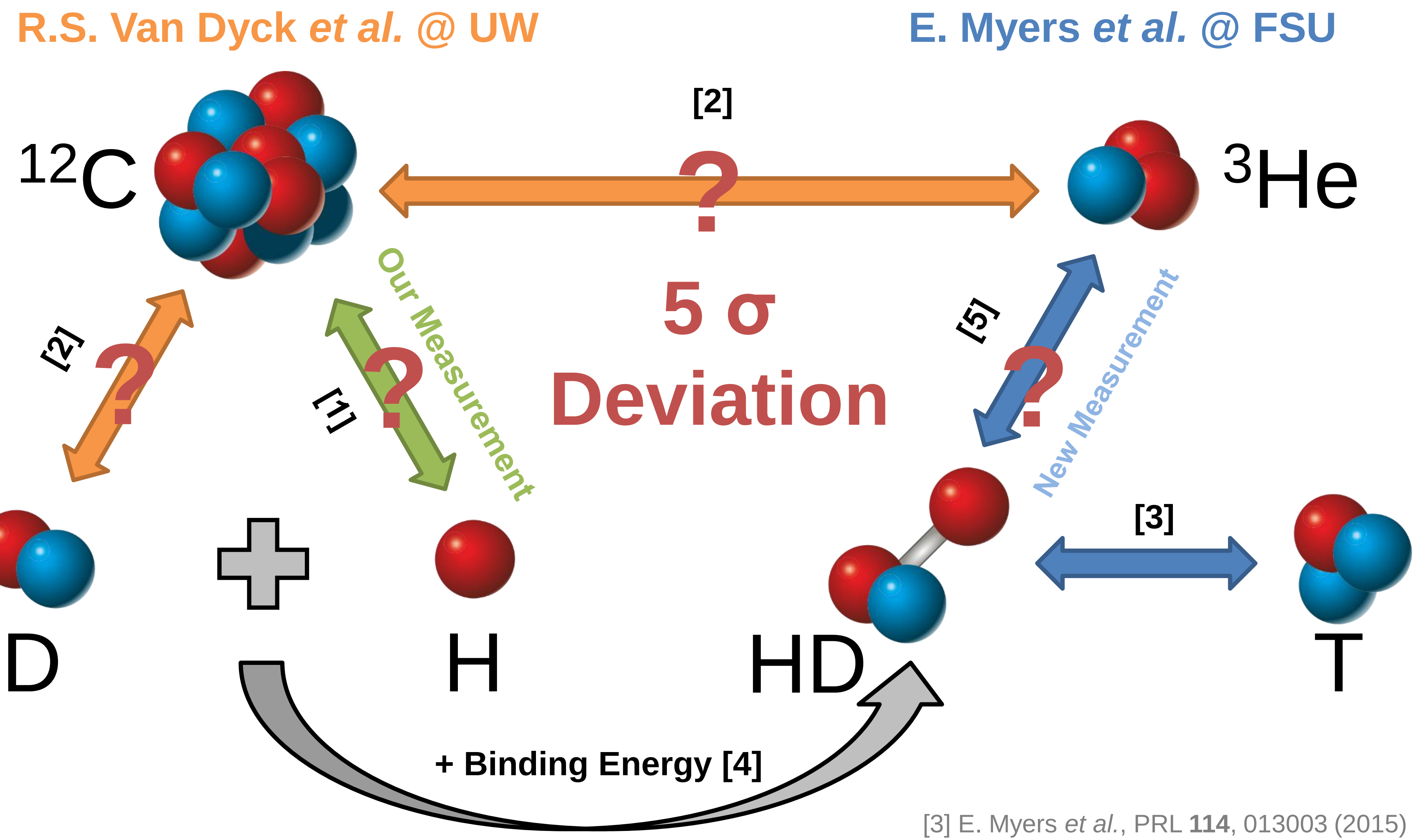
***g*-factor measurements in heavy HCI**

Ultra-precise q/m measurements

$$\boxed{m_p = \frac{f_c(^{12}C^{6+})}{f_c(p)} \frac{e}{q} m_{^{12}C^{6+}}}$$



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] Yan *et al.*, PRA **67**, 062504 (2003)
[5] S. Hamzeloui *et al*, PRA **96**, 060501 (2017)

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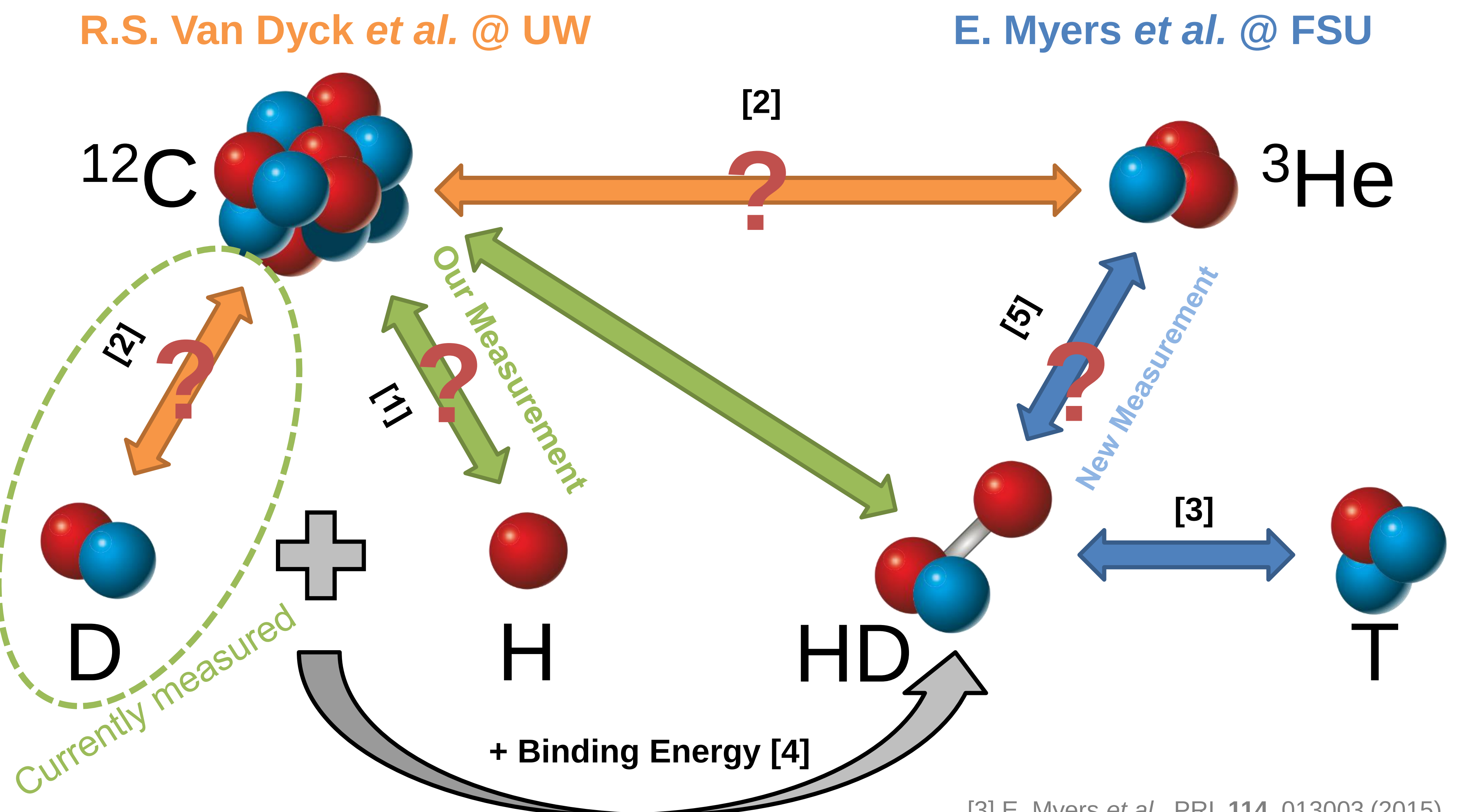

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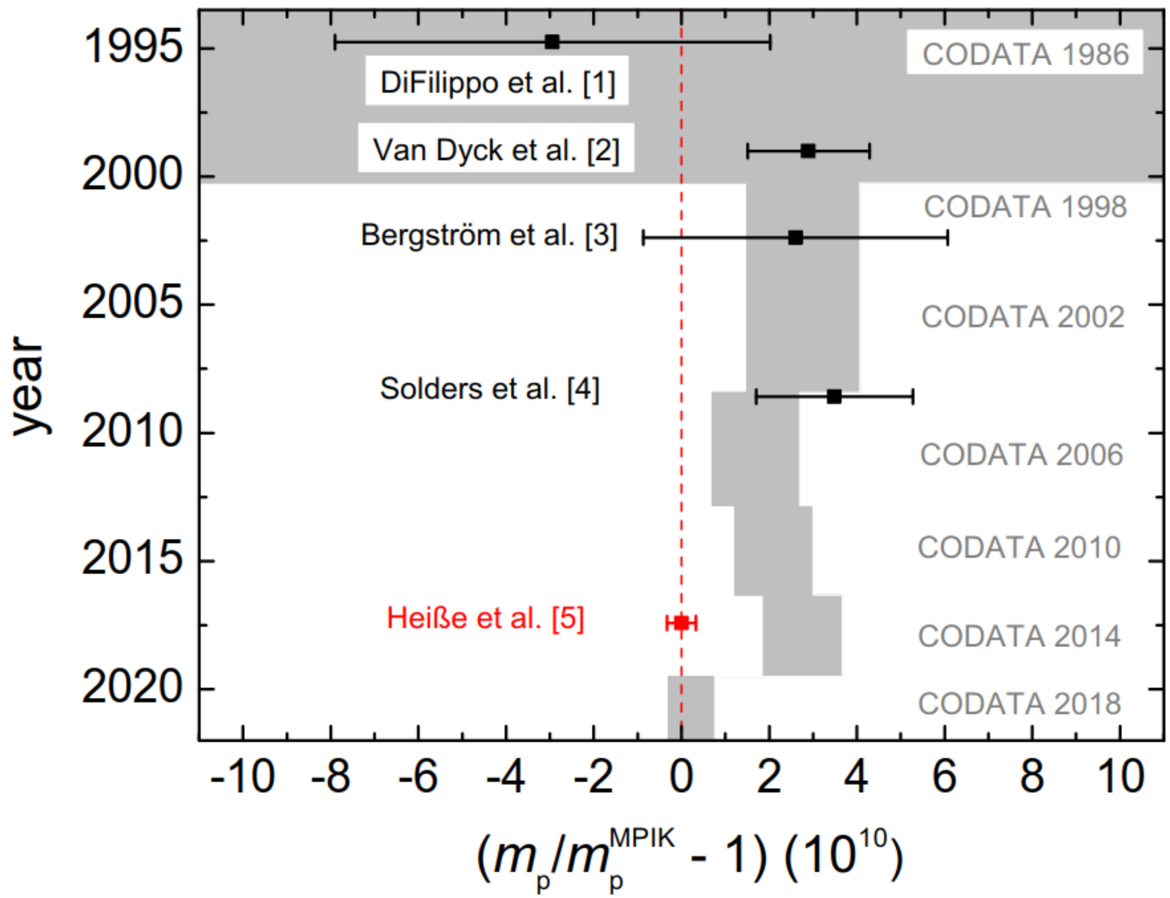
Results (see talk by Fabian Heisse (Tue))



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

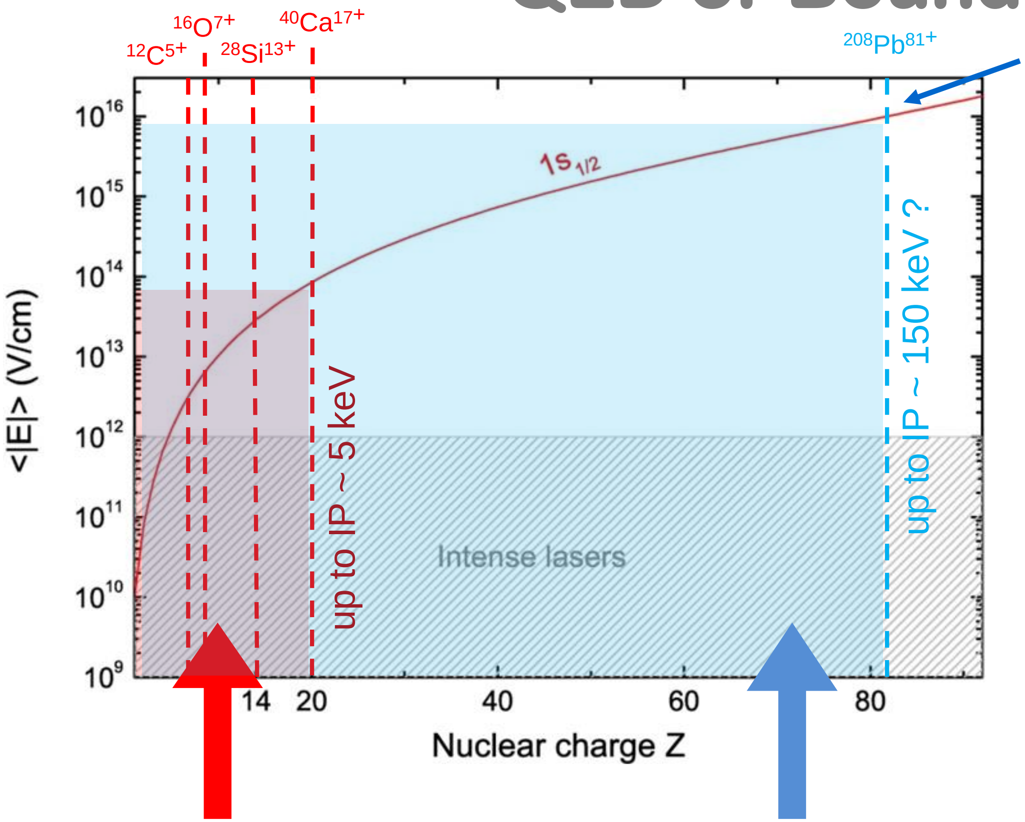
[PRL **119**, 033001 (2017)]

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

[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).

Back to *g* - factors …

QED of Bound States



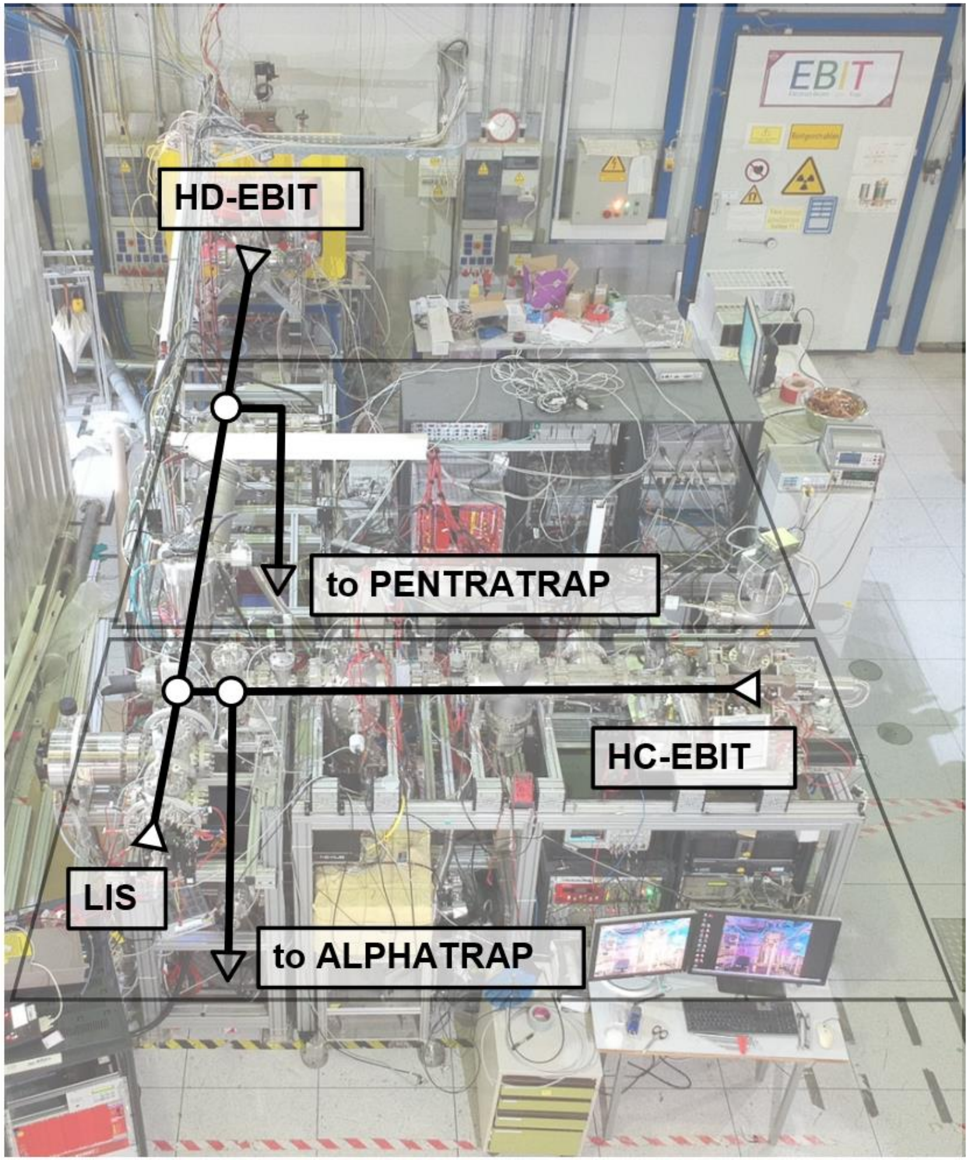
Range accessible in the Mainz HCI experiment

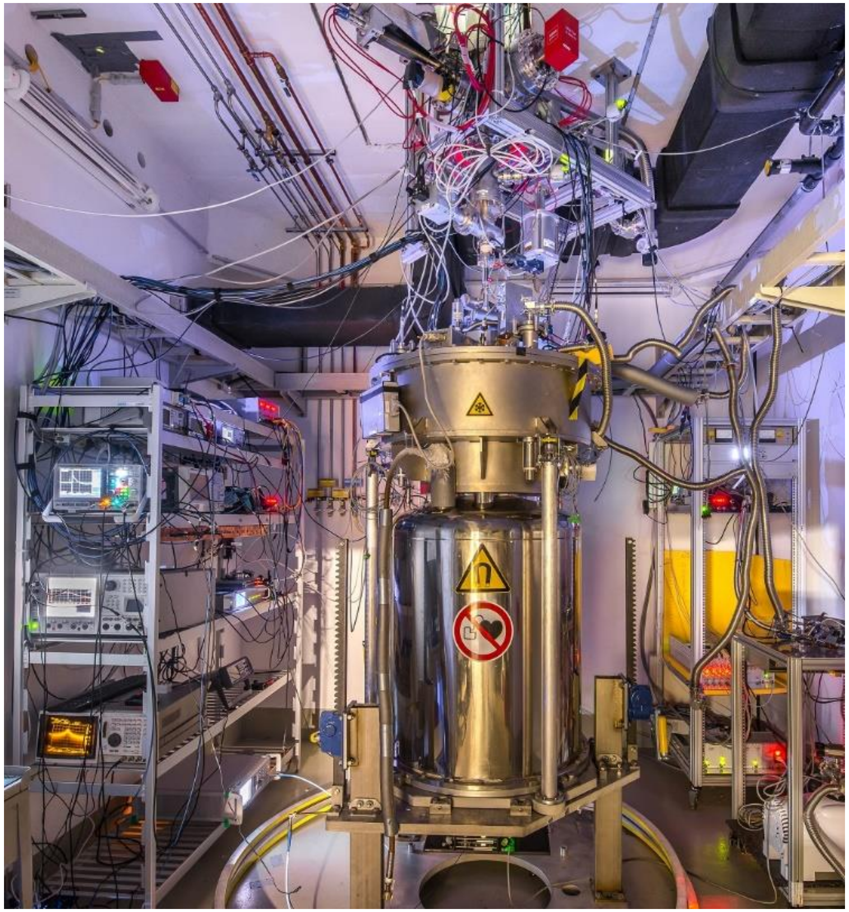
Range accessible by ALPHATRAP

α TRAP

- Probe validity of QED in the **strongest fields**
  - Precision experiment with heavy, highly charged ions
  - **Strongly coupled (Zα≈1)** electron, *beyond the Furry picture*
  - Extract nuclear structure information

Experimental Setup





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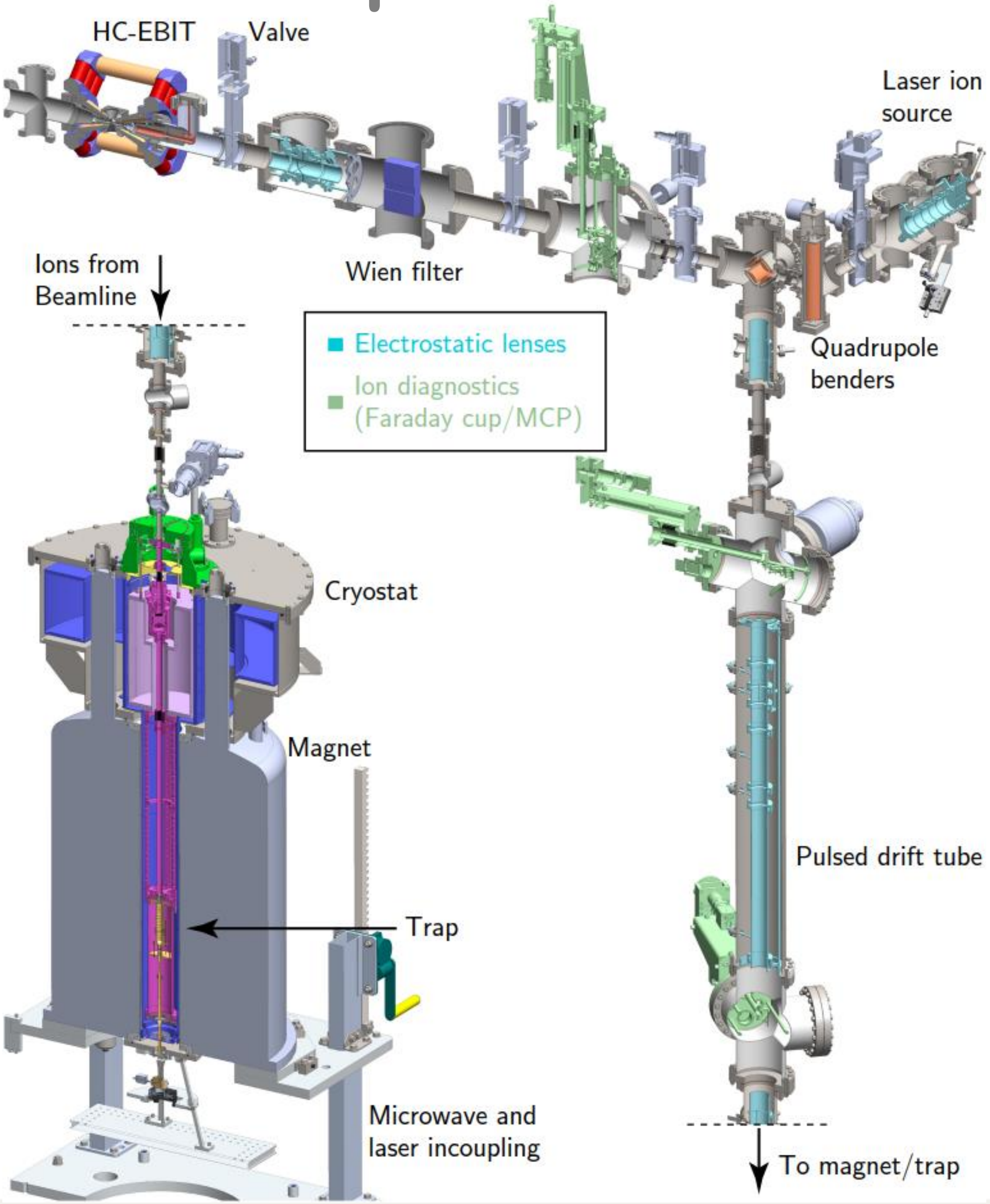
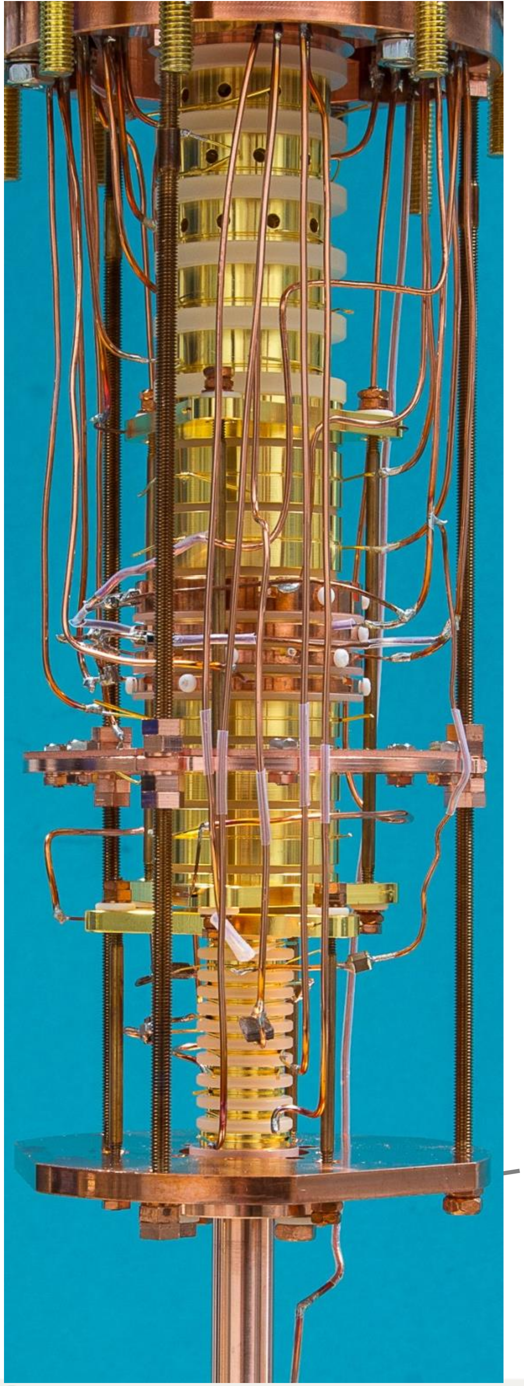




Double Penning trap

Capture electrodes
- Potential switching
- Dynamic ion capture/storage

Precision trap
- 18mm diameter
- Homogeneous *B*-field: measure $\Gamma = \omega_L/\omega_c$
- Compensation ring for PT: improved *B*-field homogeneity

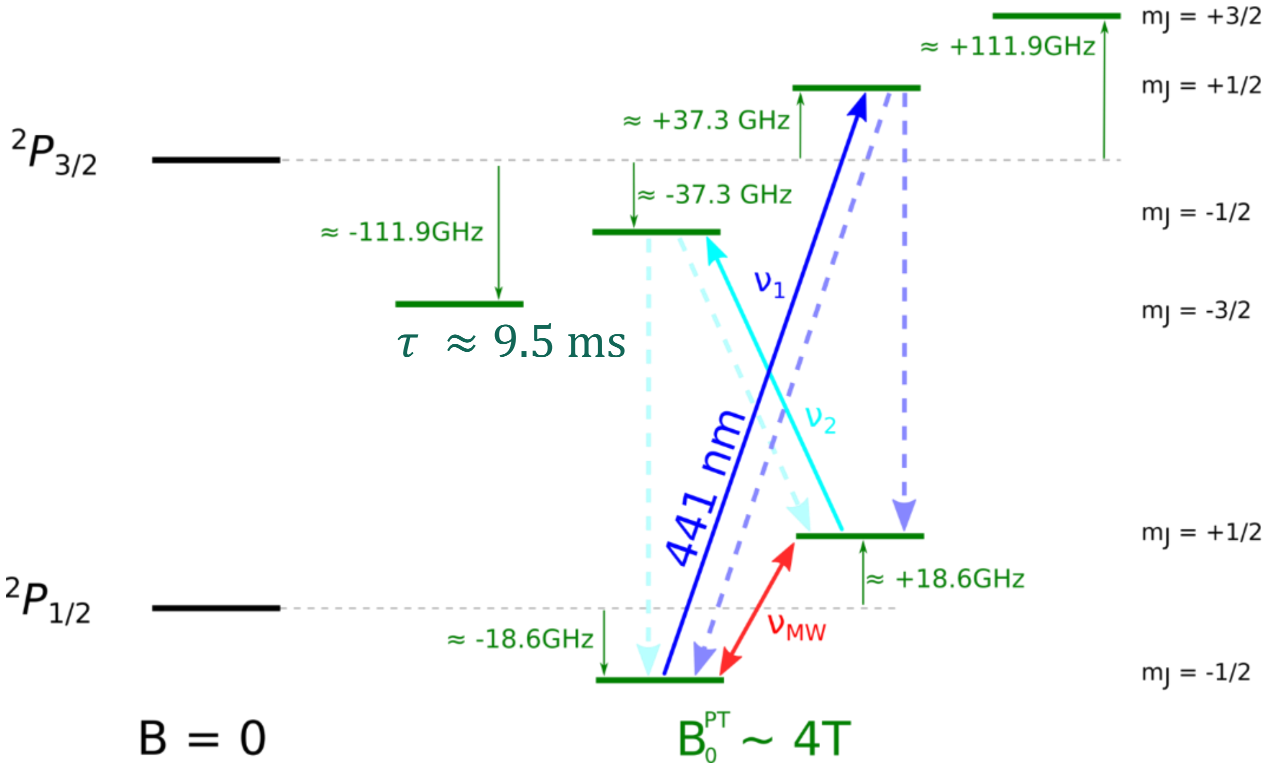
Analysis trap
- 6mm diameter
- Ferromagnetic ring electrode: spin detection

Beryllium trap
- Be ions storage & detection

Microwave horn
- mm – wave coupling
- Laser access

The $^{40}Ar^{13+}$ ground-state system

- $2p_{1/2}$ ground state is split into the 2 Zeeman substates at 4T
- Energy : $\propto Z^2$ for principal transitions ,$\propto Z^3$ for HFS transitions $\propto Z^4$ for FS transitions
  - In Ar^{13+} the fine structure reaches the optical regime



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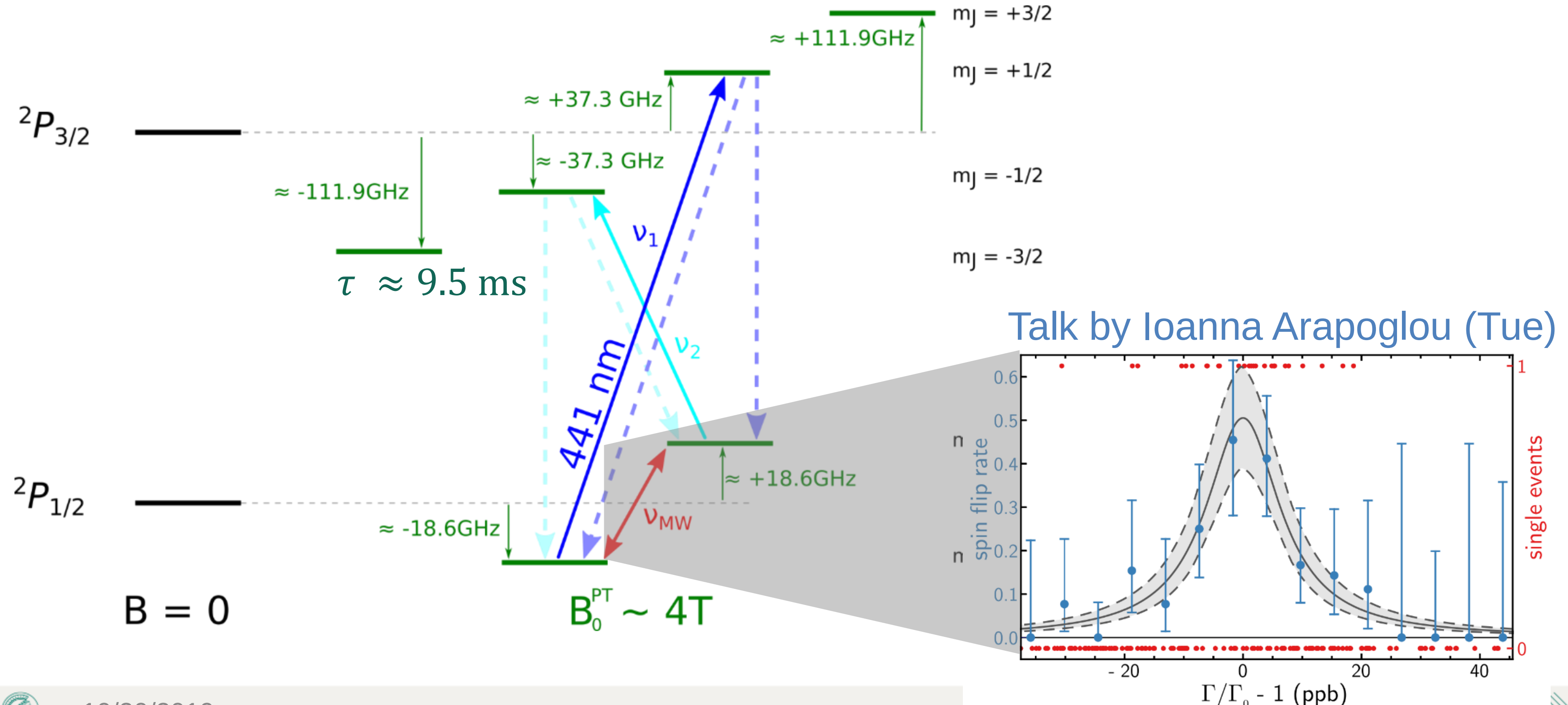

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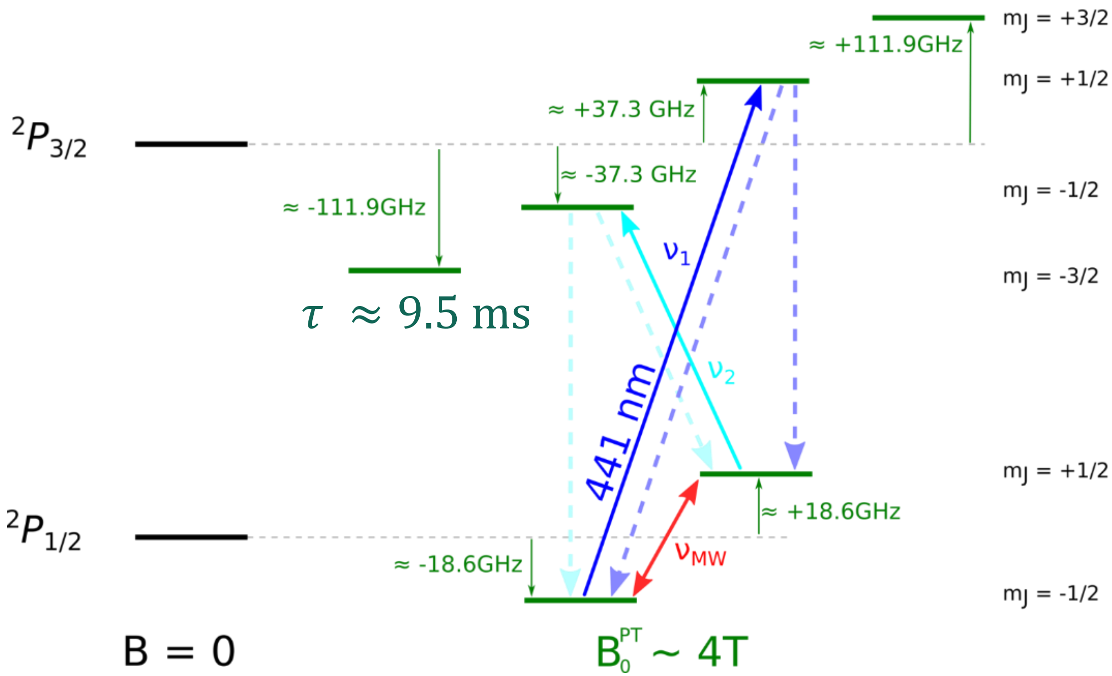

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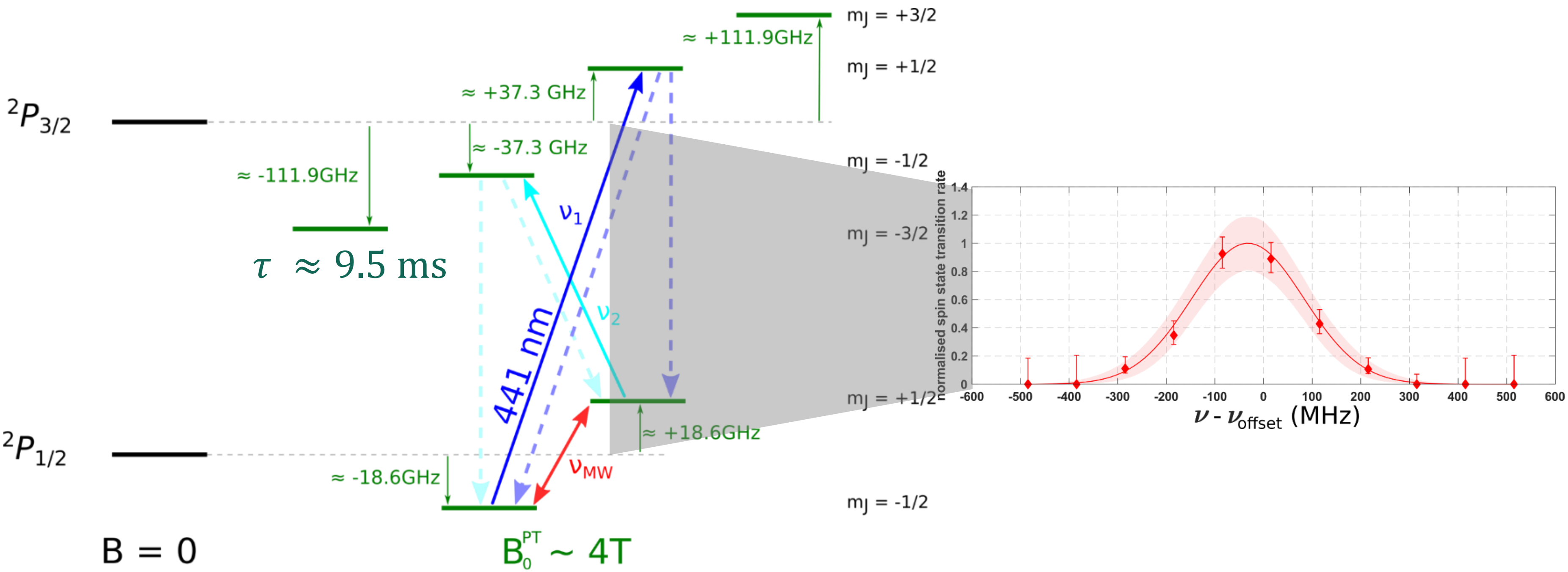
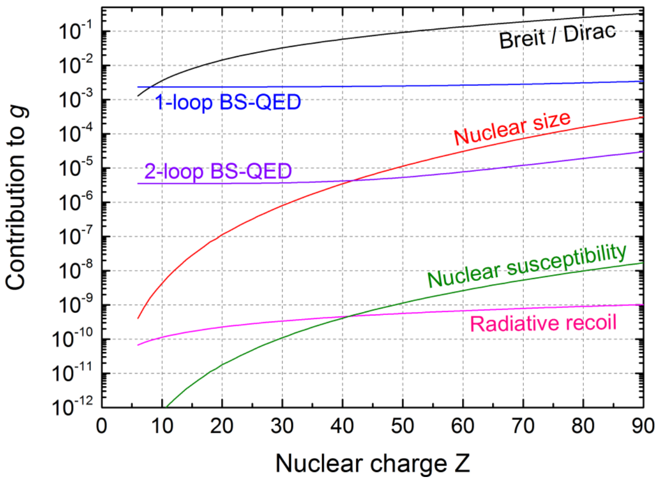
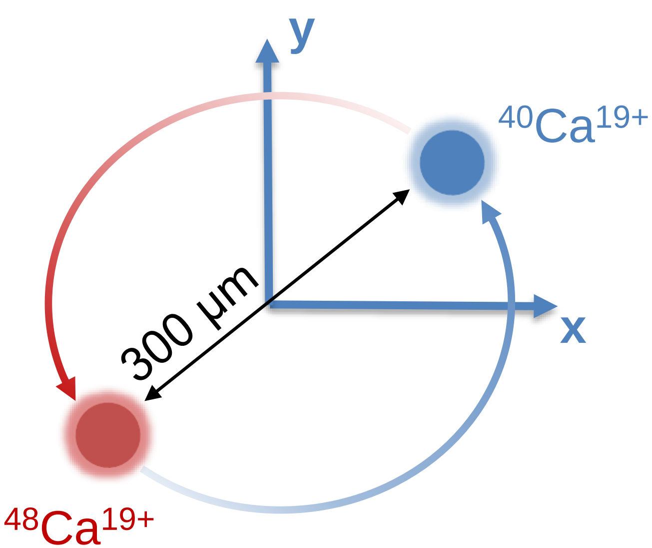
- Energy : $\propto Z^2$ for principal transitions ,$\propto Z^3$ for HFS transitions $\propto Z^4$ for FS transitions
  - In Ar^{13+} the fine structure reaches the optical regime



The next leap in precision – coherent differences

- Goal: directly address individual (small) *g*-factor contributions
  - Isotope shifts $\delta g/g \sim 10^{-7}$
  - Similar *Z* elements $\delta g/g \sim 10^{-3}$
- Magnetic field fluctuations **drop out** in the correlation





Magnetic field fluctuations **drop out** in the correlation

$$P(|\downarrow\rangle|\downarrow\rangle \rightarrow |\downarrow\rangle|\uparrow\rangle + |\uparrow\rangle|\downarrow\rangle \sim \cos((\omega_1-\omega_2)t) + \ldots$$

- *Potentially* achievable precision (related to the total g-factor) **$\delta g/g < 10^{-14}$**

Summary

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- ***g*-factor determinations with HCI have allowed rigorous tests of most QED contributions**
- **Fundamental constants such as the electron and proton masses have been determined, α is targeted**
- **ALPHATRAP can eventually provide and measure the initially envisaged heavy HCI**