# *g*-factor of Boronlike Argon $^{40}Ar^{13+}$ at ALPHATRAP

PSI 2019

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MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

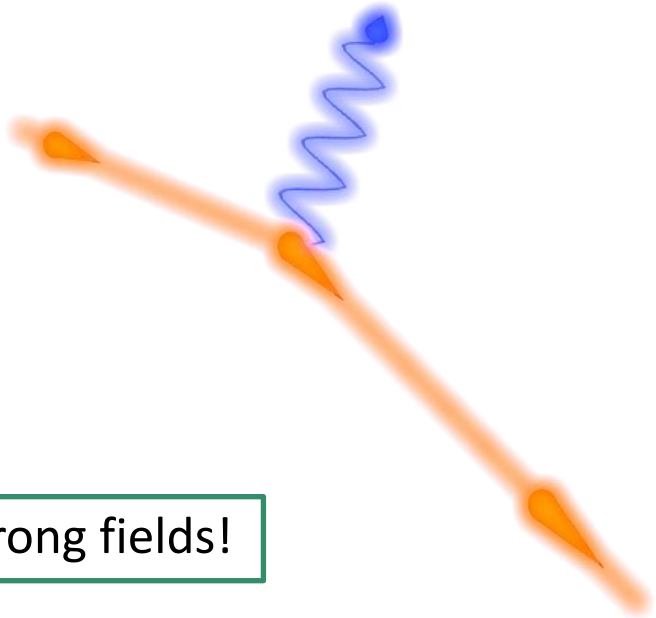
# Quantum Electrodynamics (QED)

***Quantum Electrodynamics (QED), the theory of light and matter, is tested and proven in the lab***

Richard P. Feynman

- Most successful theory in the Standard Model
- Prediction of physical observables
- All accessible field scales
- Experiments consistent with theory
- Non-linear QED processes?

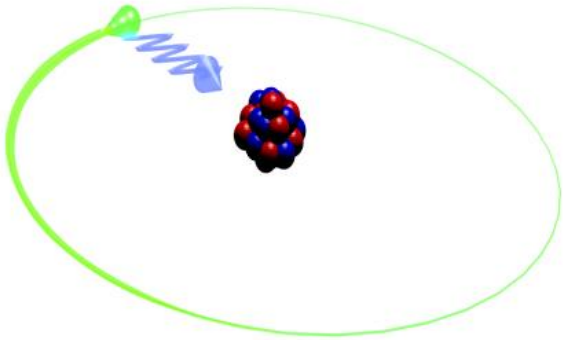
  Photon-photon interaction

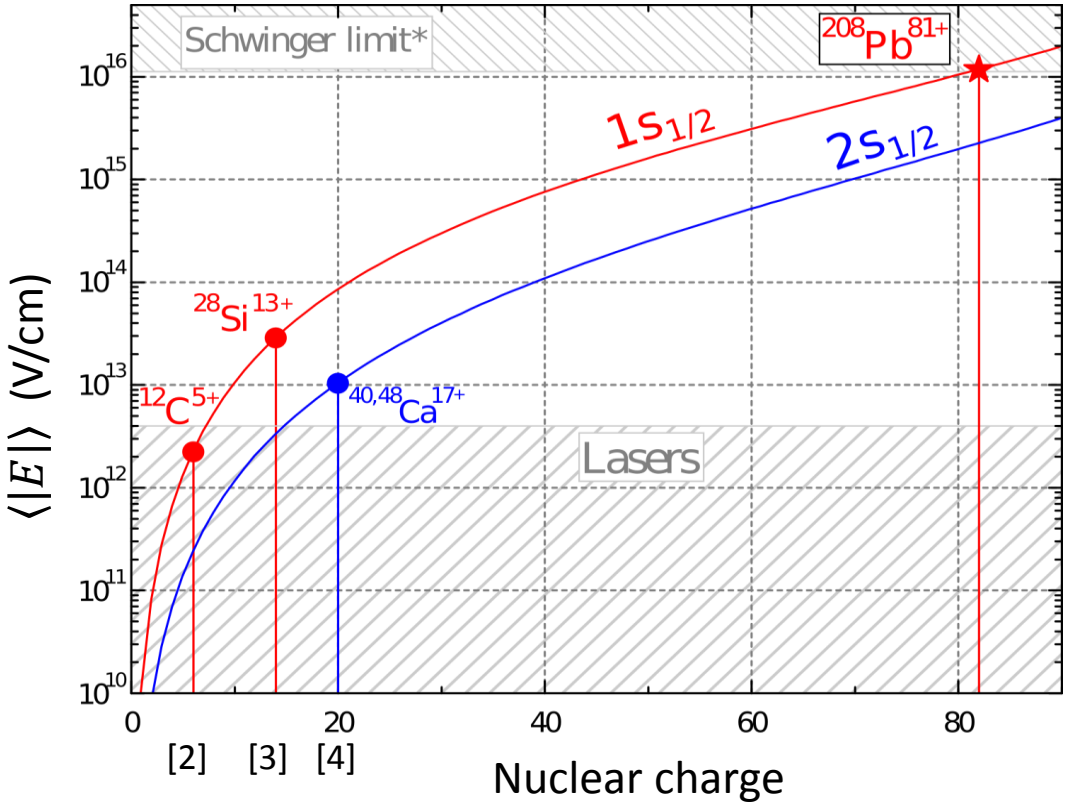


ALPHATRAP: Combine high precision & strong fields!

# Testing the Standard Model with ALPHATRAP

$$\vec{\mu} = -g\mu_B \frac{\vec{s}}{h}$$







[1] H. Häffner, et al., *Phys. Rev. Lett*. 85, 5308 (2000)
J.Verdu, et al., *Phys. Rev. Lett*. 92, 093002 (2004)
[2] S. Sturm, et al., *Nature* 506, 7489 (2014)
[3] S. Sturm, et al., *Phys. Rev. Lett*. 107, 023002 (2011)
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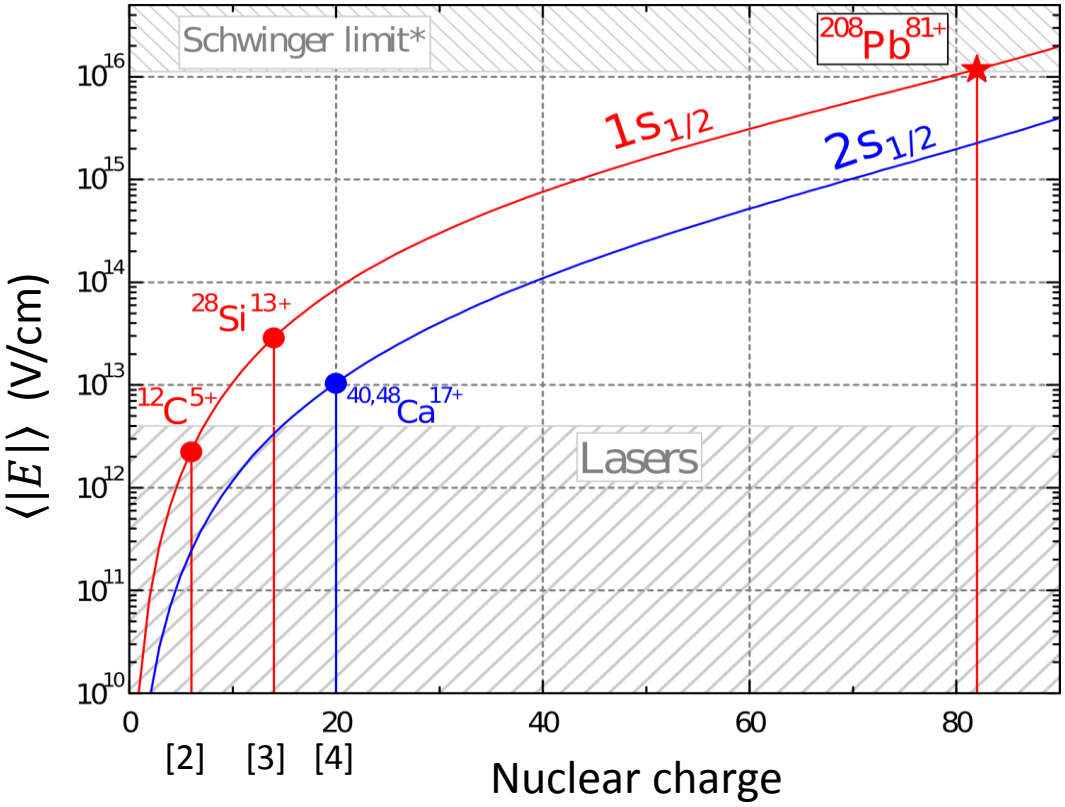
- Follow-up experiment of the Mainz *g*-factor experiment
- High-precision test of BS-QED in strong fields, up to $^{208}Pb^{81+}$
- Strongest *E*-fields achievable in high Z nuclei
- Determination of fundamental constants:
  e.g. electron mass [1]
  fine structure constant $\alpha$





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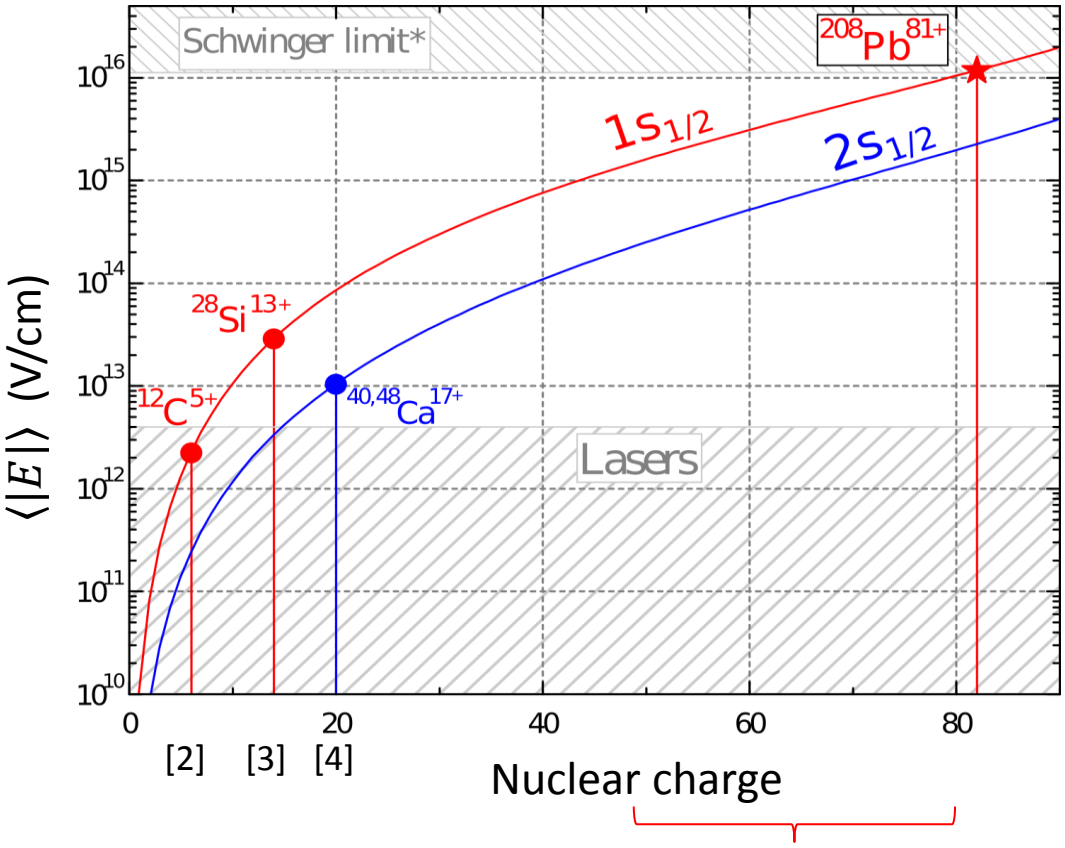


**Heidelberg-EBIT @ MPIK/**
**HITRAP @ GSI Darmstadt**


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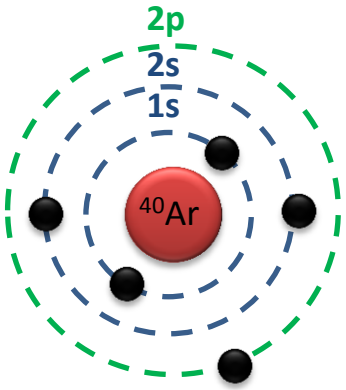
# *g*-factor of $^{40}Ar^{13+}$

$$\vec{\mu} = -g\mu_B \frac{\vec{s}}{h}$$

$$g = g_{\mathrm{Dirac}} + \Delta g_{\mathrm{QED}} + \Delta g_{\mathrm{nucl}} + \Delta g_{\mathrm{int}} + \cdots$$

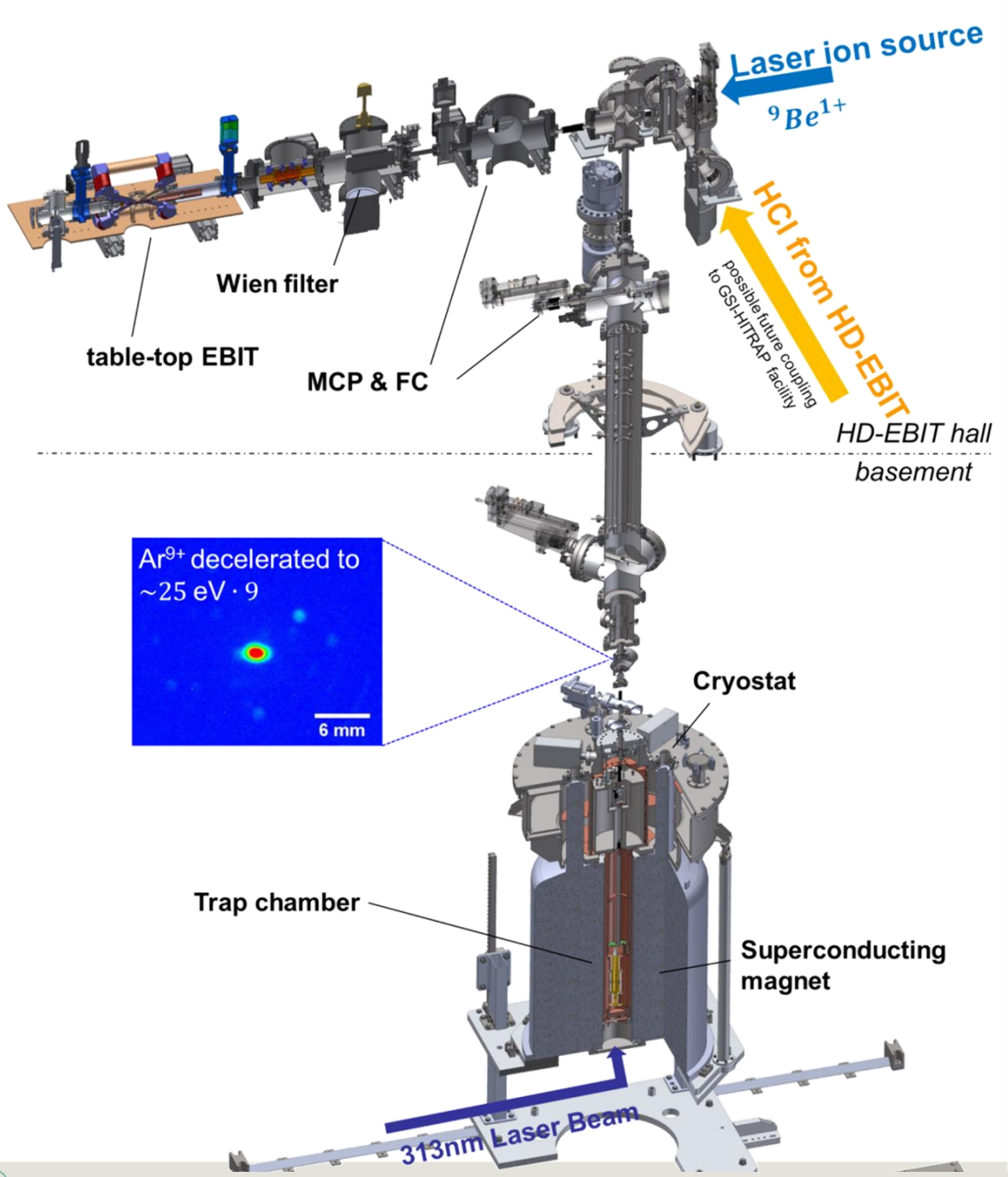



**First high-precision *g*-factor measurement of 5-electron HCI**

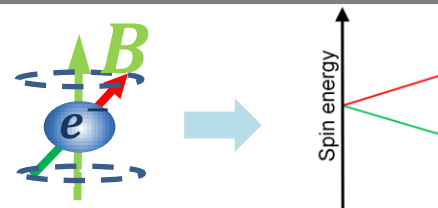
- Bound electron spin-orbital coupling
- Many-electron QED contribution($\Delta g_{\mathrm{int}}$)
- Higher order (cubic) Zeeman effect [1]
- *g*-factor difference between B- and H-like ions [2]
  - Reduced nuclear-structure effect
  - Fine structure constant α determination

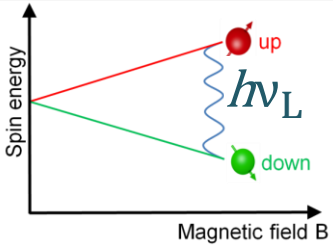

[1] D. von Lindenfel et al., *Phys. Rev. A* 87, 023412 (2013)
[2] V. Shabaev et al., *Phys. Rev. Lett*. 96, 253002 (2006)

# Experimental Setup



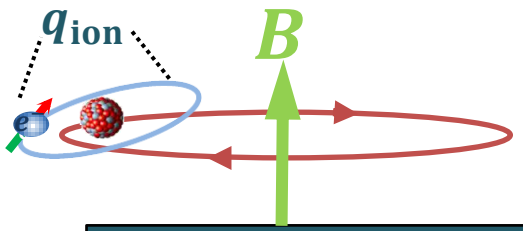
# *g*-factor determination




$$\nu_L = \frac{g}{4\pi}\frac{e}{m_e}B$$

**Determine the Larmor frequency**
in a well-known magnetic field




$$\nu_c = \frac{q_{ion}}{2\pi m_{ion}}B$$

**Measure the free cyclotron frequency**
to determine the magnetic field

$$g = 2\frac{\nu_L}{\nu_c}\frac{q_{ion}}{m_{ion}}\frac{m_e}{e}$$

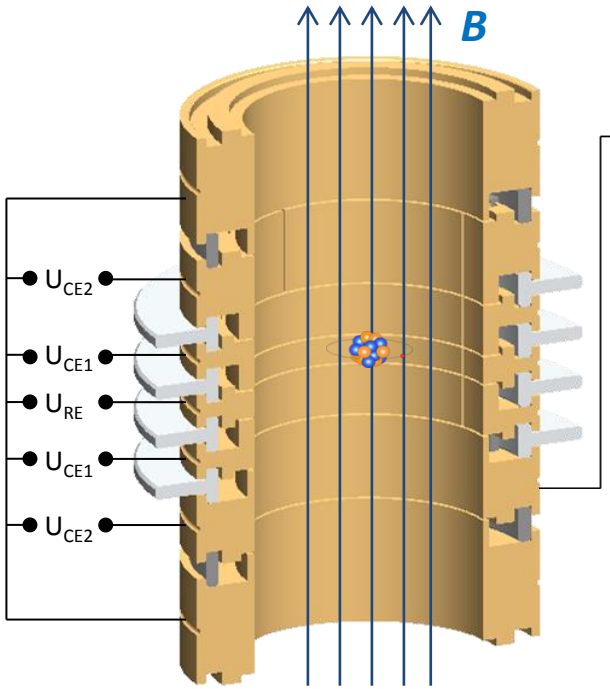
**to be measured**
$\Gamma = {}^{\nu_L}/_{\nu_c}$

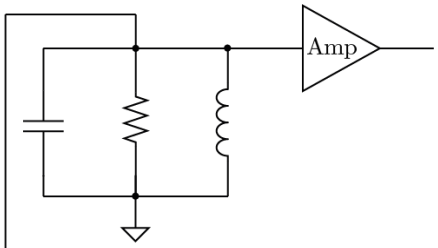
**Independent precision experiments**

# Penning trap

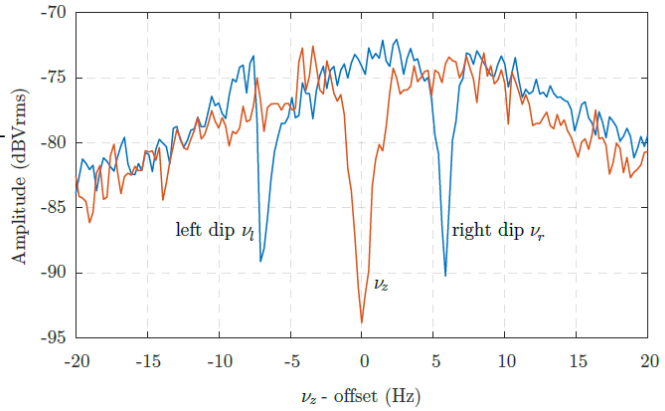
**Requirements:**

- Single, cold ion
- Homogeneous magnetic field: ~ **4 T**
- Cryogenic temperature: ~ **4.2 K**
- Long storage times: ~ **months**
- Extremely high vacuum: ~ **$10^{-17}$ mbar**




Superconducting tank circuit:
$f = 650\,\mathrm{kHz}$
$Q = 40000$




$$\nu_c^2 = \nu_z^2 + \nu_+^2 + \nu_-^2$$

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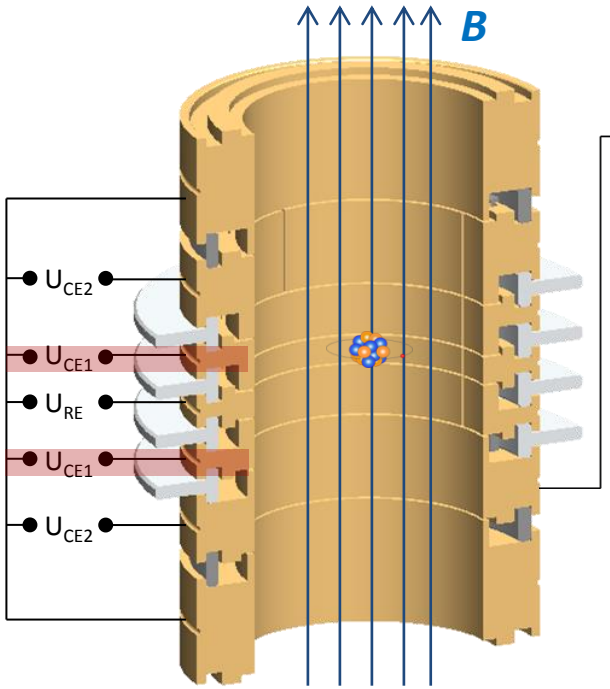


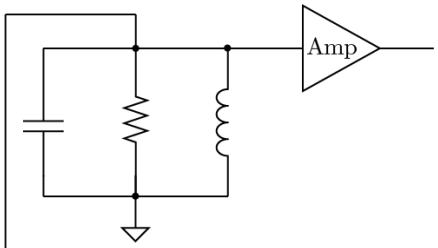


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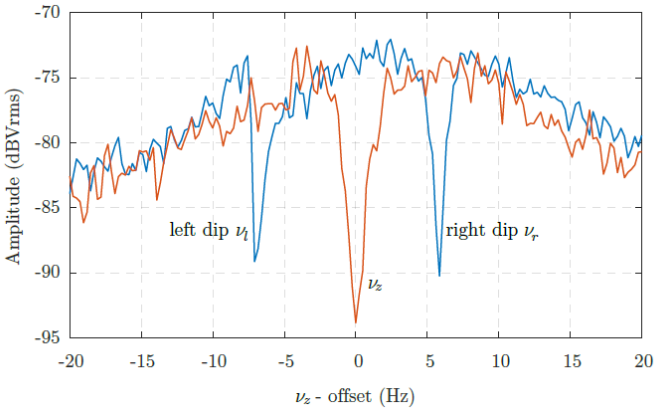


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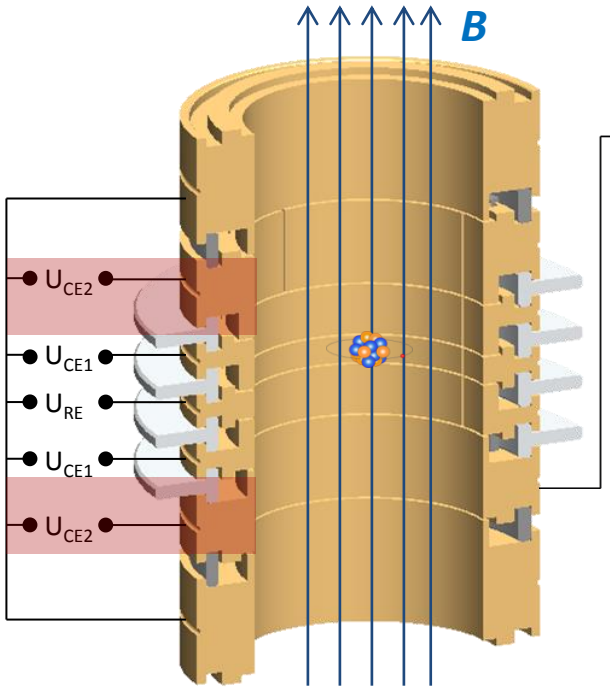


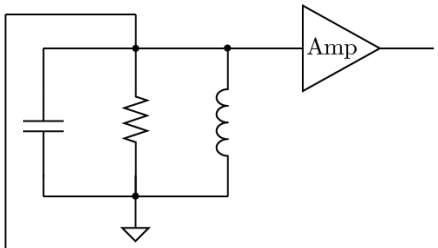


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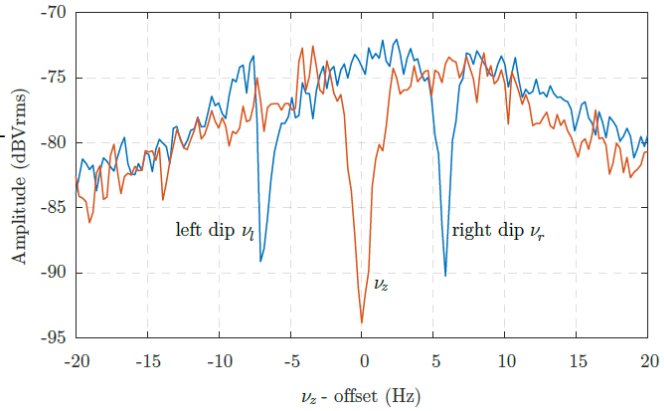


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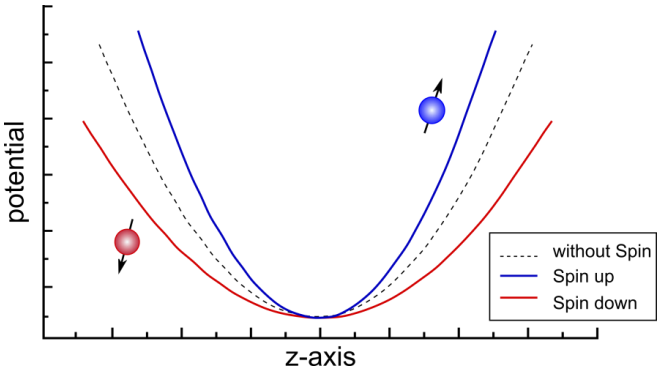
# Penning trap – spin state detection

***Continuous Stern-Gerlach effect:***

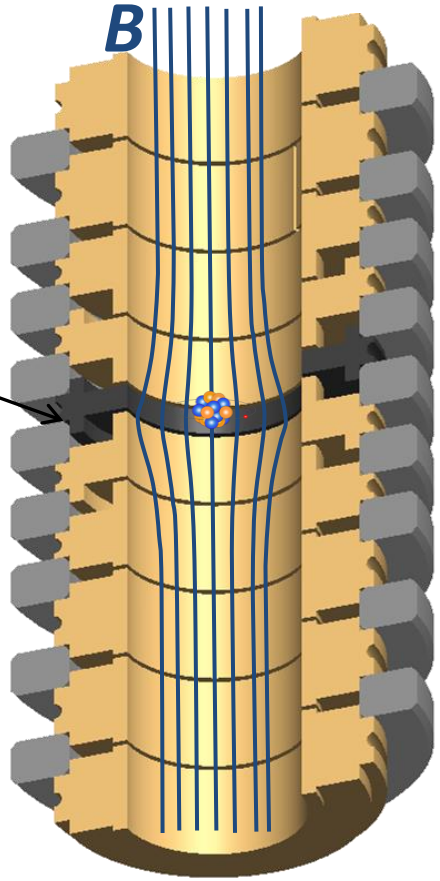
axial frequency difference between “up” and “down” spin orientation




$$\Phi_z^{mag} = \pm \mu_z \left[ B_0 + B_2 \left( z^2 - \frac{\rho^2}{2} \right) \right]$$

Ferromagnetic ring

- Magnetic bottle
- $B_2$ ~ 44000 T/m²




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

| | $^{12}C^{5+}$ | $^{28}Si^{13+}$ | $^{40}Ca^{19+}$ | $^{40}Ar^{13+}$ | $^{208}Pb^{81+}$ | $^{208}Pb^{77+}$ |
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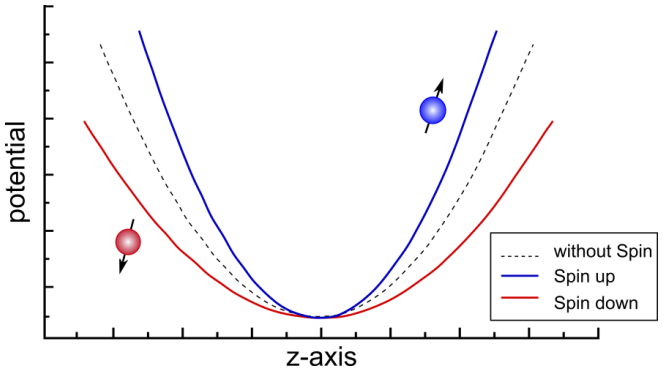


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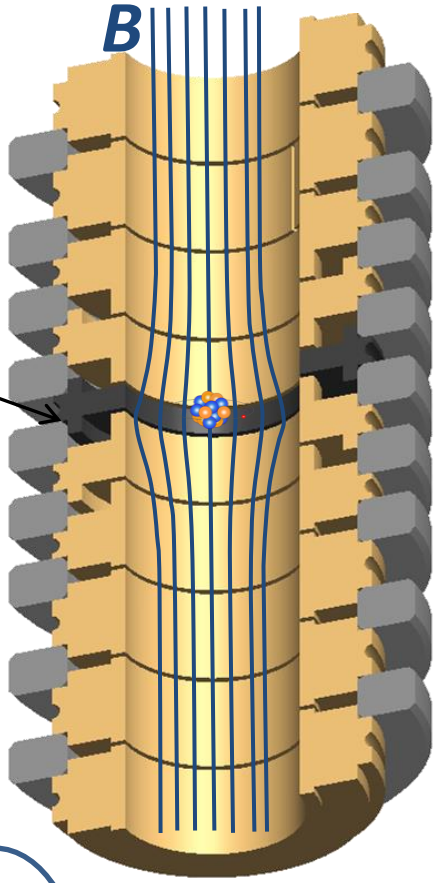


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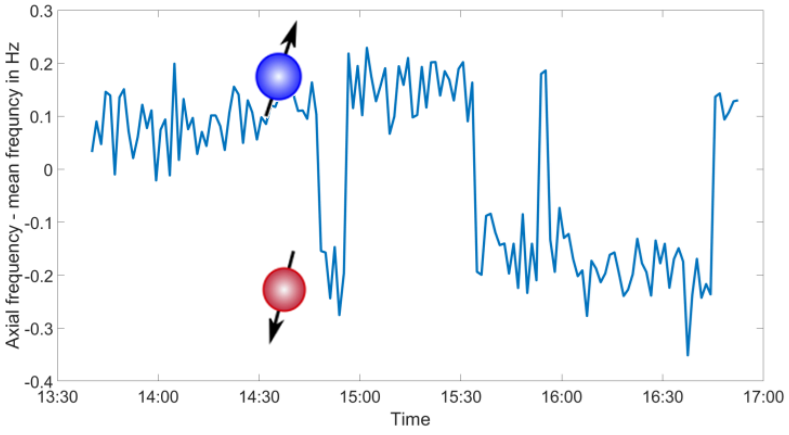


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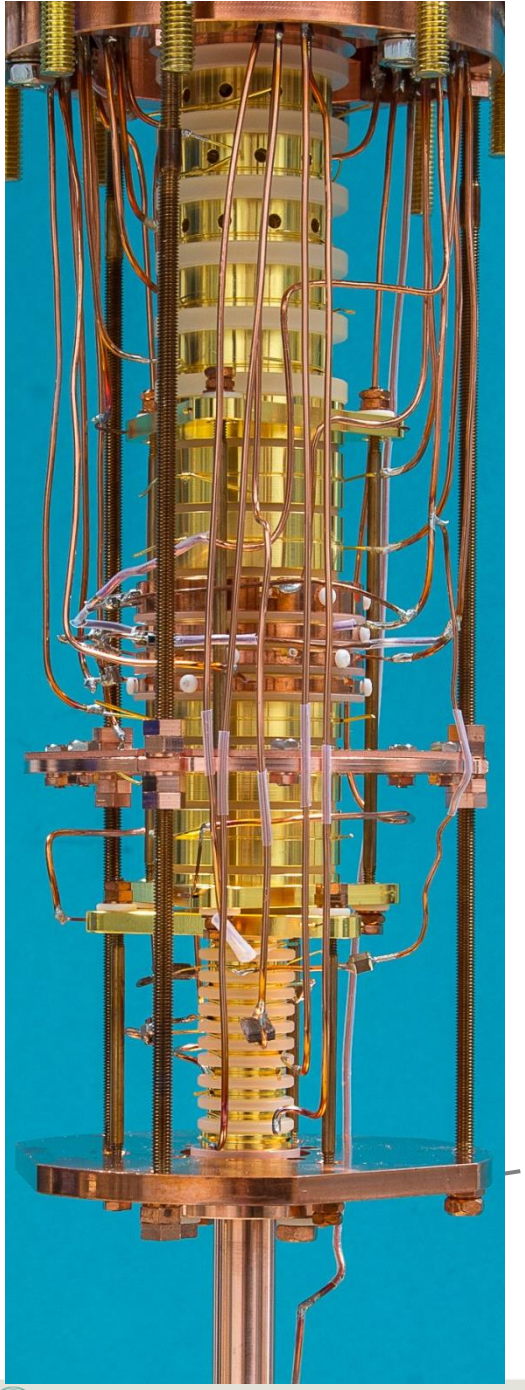
# Double Penning trap



**Capture electrodes**

- Potential switching
- Dynamic ion capture/storage

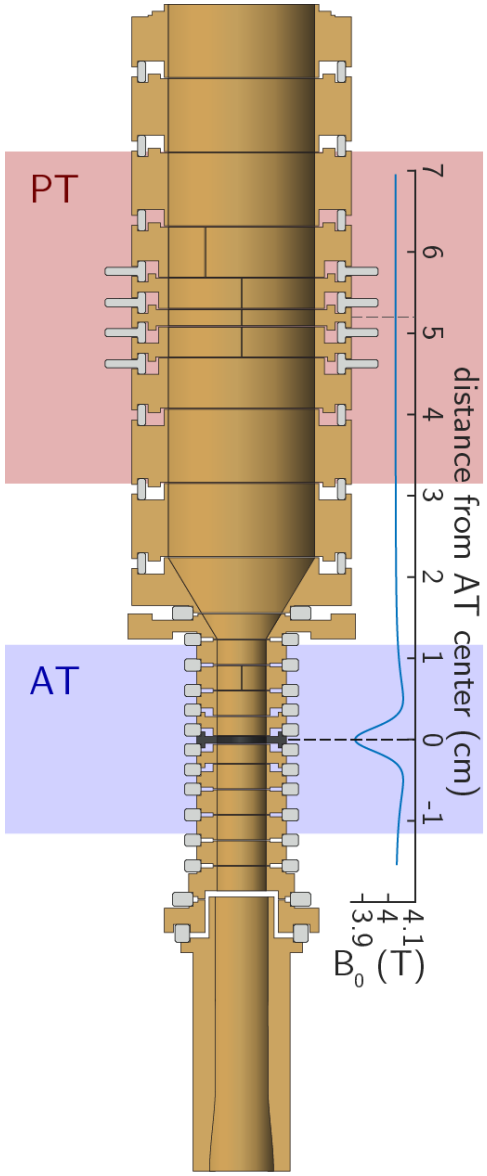
**Precision trap**

- 18mm diameter
- Homogeneous *B*-field: measure $\boldsymbol{\Gamma = \nu_L/\nu_c}$
- Compensation ring for PT: improved *B*-field homogeneity

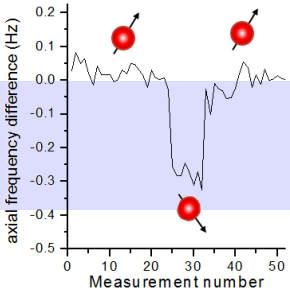
**Analysis trap**

- 6mm diameter
- Ferromagnetic ring electrode: spin detection
- $B_2$ ~ 44000 T/m$^2$

# *g*-factor measurement cycle




Spin state detection



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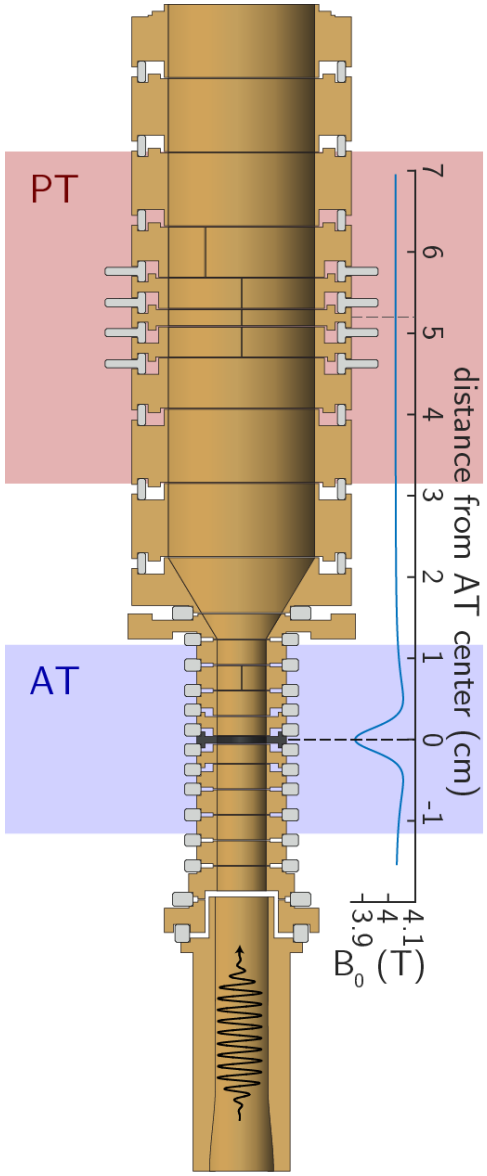


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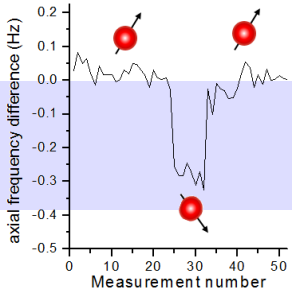
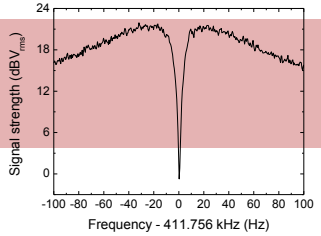
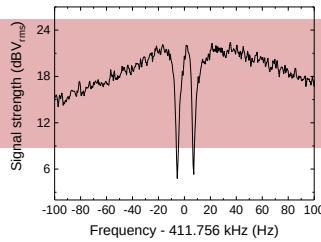



$\Gamma = \nu_L / \nu_c$ determination:
$\nu_c$ & mm-wave injection

Single dip $\nu_z$




Double dip $\nu_+$



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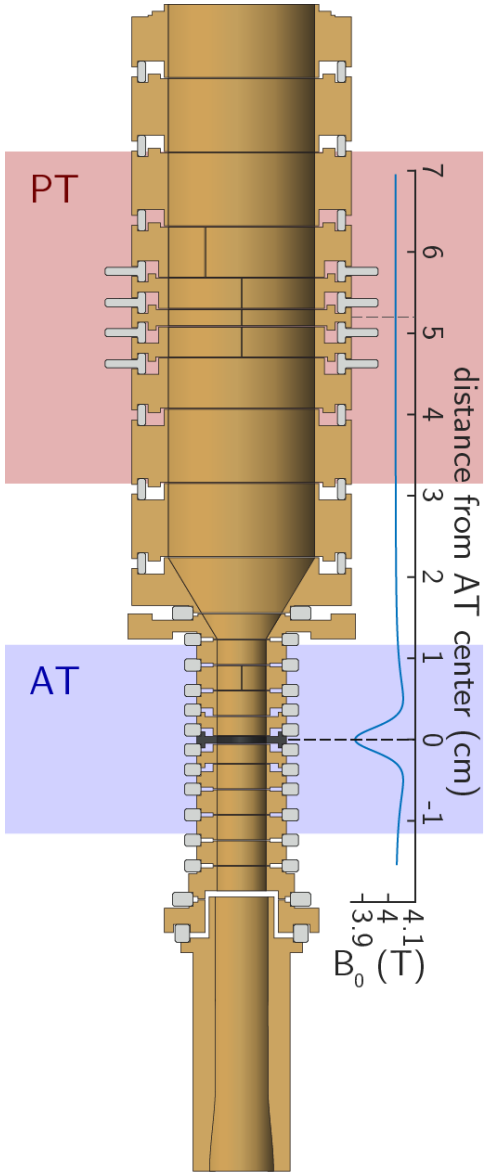


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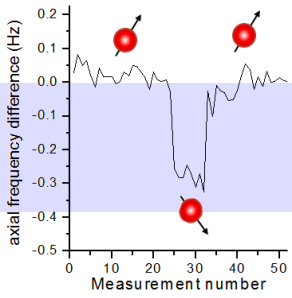


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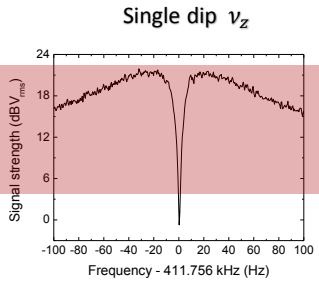


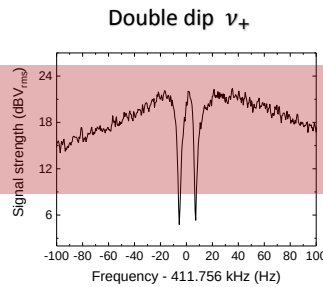


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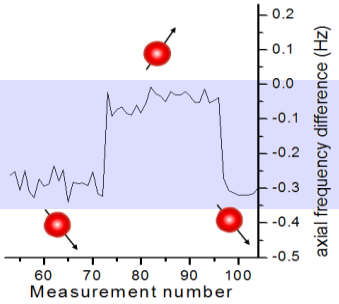

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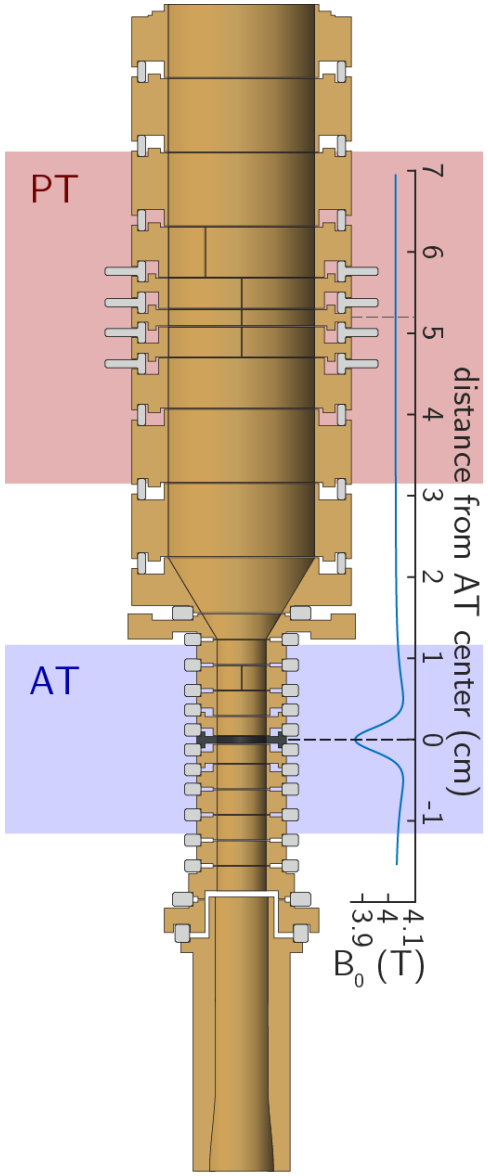


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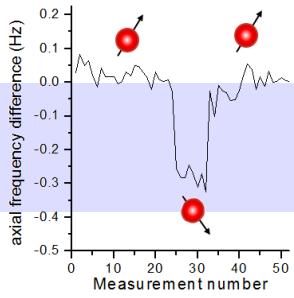


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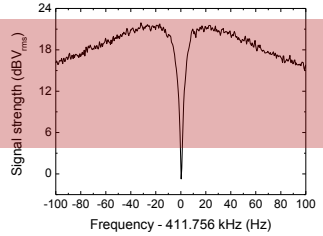


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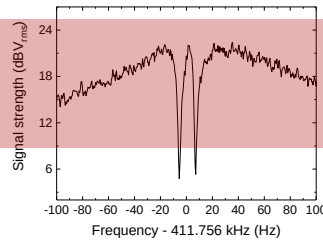
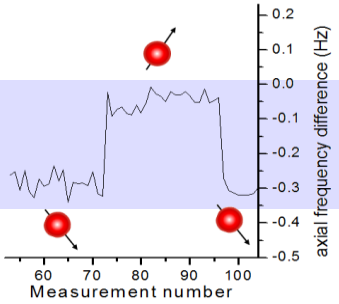
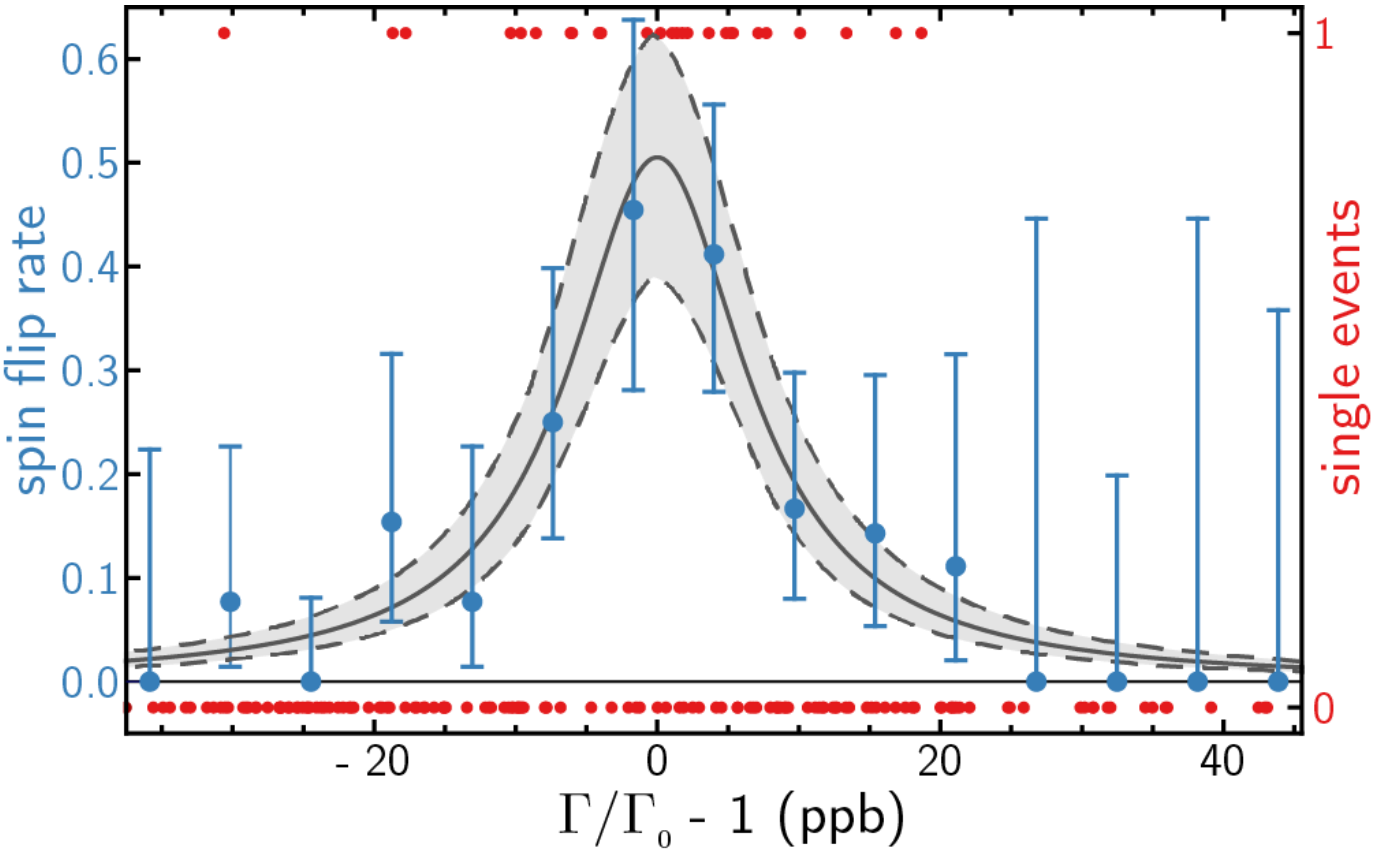



Spin state detection



# *g*-factor of $^{40}Ar^{13+}$

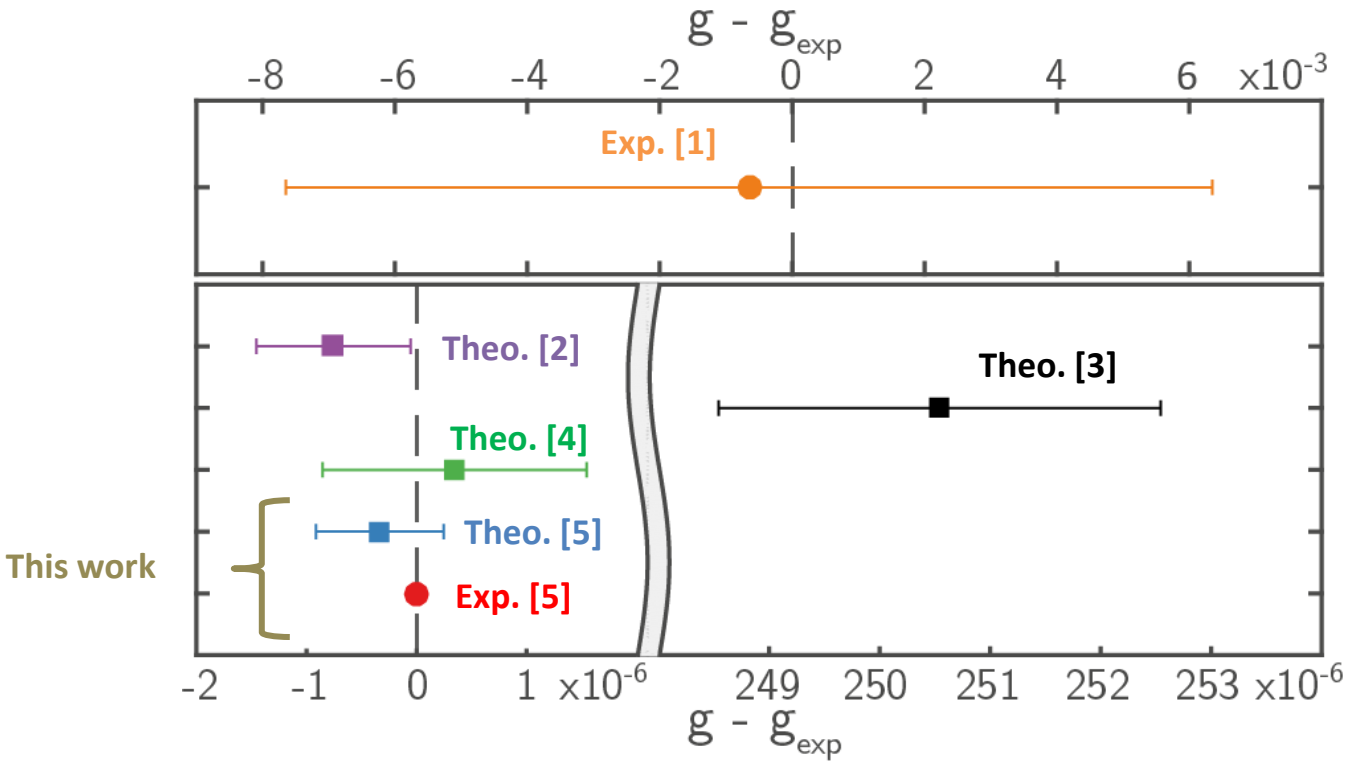



$$g = 2\Gamma_0 \frac{q_{ion}}{m_{ion}} \frac{m_e}{e}, \text{ where } \Gamma_0 = \nu_{L0}/\nu_c$$

$$g = 0.663\,648\,455\,32\,(83)(42)(5)$$

[I. Arapoglou *et al., Phys. Rev. Lett*. 122, 253001 (2019)]

# Comparison with theory




| | |
|---|---|
| Soria Orts *et al.* [1] | 0.663 (7) |
| Shchepetnov *et al.* [2] | 0.663 647 7 (7) |
| J. P. Marques *et al.* [3] | 0.663 899 (2) |
| Agababaev *et al.* [4] | 0.663 648 8 (12) |
| This work [5] | 0.663 648 12 (58) |
| | 0.663 648 455 32 (93) |

- Agreement with the **current theory** at $10^{-7}$ [5]
- Experimental fractional uncertainty **$1.4\times10^{-9}$**


[1] R. Soria Orts et al., *Phys. Rev. A* 76, 052501 (2007).
[2] A. A. Shchepetnov *et al.*, *J. Phys. Conf. Ser.* 583 012001 (2015).
[3] J. P. Marques *et al.*, *Phys. Rev. A* 94, 042504 (2016).
[4] V. A. Agababaev *et al.*, *J. Phys. Conf. Ser.* 1138.1(2018).
[5] I. Arapoglou *et al.*, *Phys. Rev. Lett*. 122, 253001 (2019).

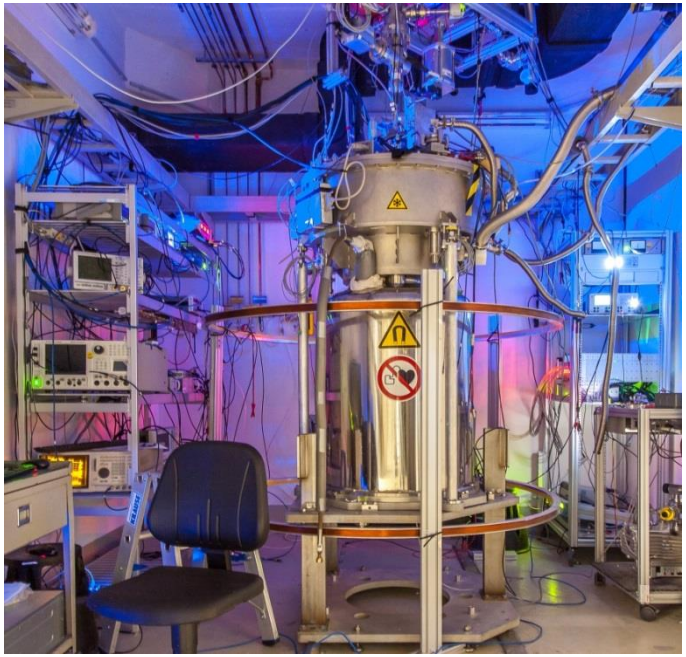
# Outlook

- g-factor measurements of highly charged high-Z ions
  - Testing QED in strong fields
  - α determination

- Isotope shift measurement and QED effect in the nuclear recoil ($^{40}Ca^{19+}$ & $^{48}Ca^{19+}$)

- Sympathetic laser cooling
  - Higher precision
  - Coulomb crystalization

# Thank you for your attention!



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