MAX-PLANCK-INSTITUT FÜR KERNPHYSIK

The ALPHATRAP *g*-factor experiment

α TRAP

International Conference on Precision Physics and Fundamental Physical Constants FFK 2019

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isoQuant SFB1225

HITRAP

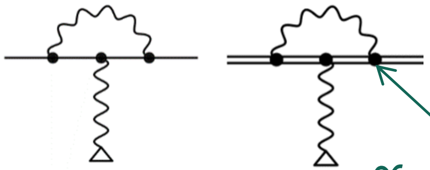
Quantum Electrodynamics (QED) In Strong Fields

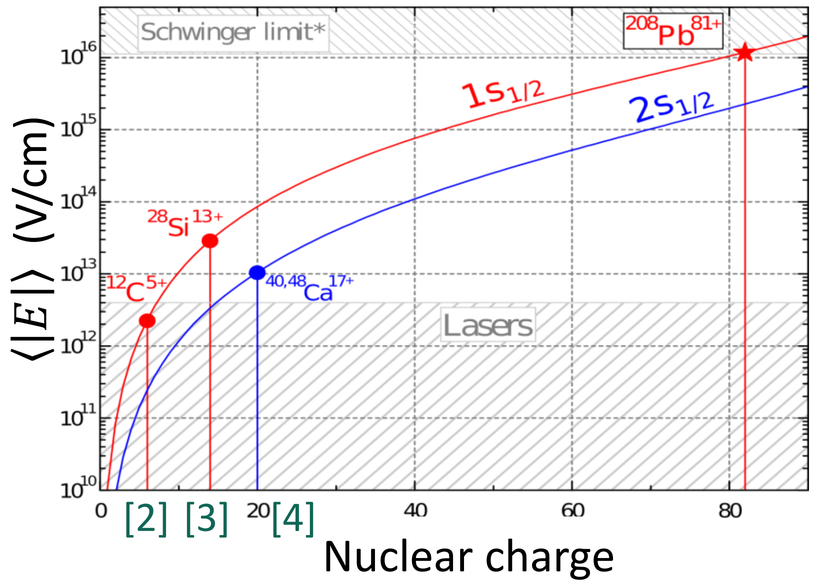
- QED describes interaction of light/photons and charged particles

- Impressive theory predictions and most precise experimental results, e.g. electron magnetic moments: g-2, g-factor in highly charged ions (HCI) [1]
  → Most stringently tested theory in weak fields

- Validity of QED in strong fields?
  Test of bound state QED (BS-QED) under extreme conditions in high electric and magnetic fields of heavy HCI
  - *g*-factor measurements in H or Li-like systems
  - Fine structure and hyperfine structure spectroscopy

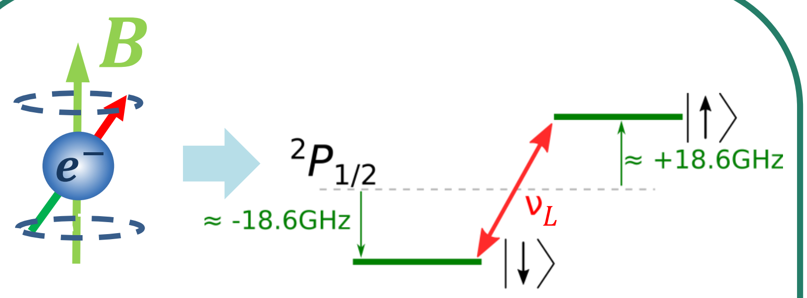
→ Combine strongest field and highest precision





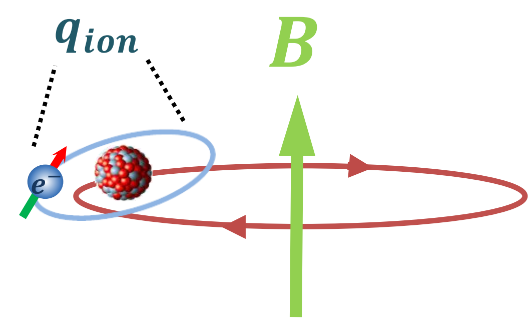
[1] H. Häffner, et al., Phys. Rev. Lett. 85, 5308 (2000)
J.Verdu, et al., Phys. Rev. Lett. 92, 093002 (2004)
[2] S. Sturm, et al., Nature 506, 7489 (2014)
[3] S. Sturm, et al., Phys. Rev. Lett. 107, 023002 (2011)
[4] F. Köhler, et al. Nat. Comm. 7, 10246 (2016)

Measurement principle



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

Measure the Larmor frequency
in a well-known magnetic field



$$\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}}B$$

Measure the free cyclotron frequency
to determine magnetic field

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

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

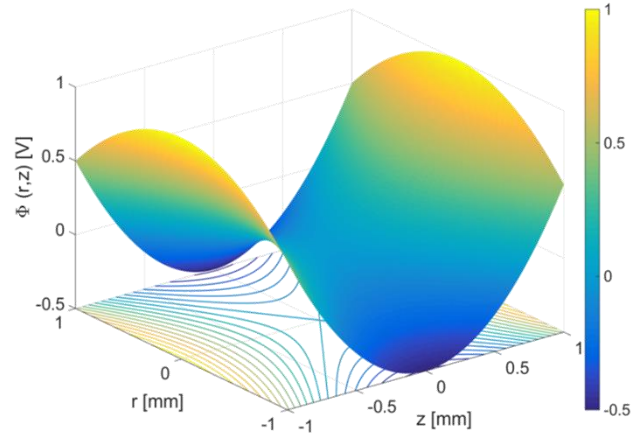
Independent precision experiments

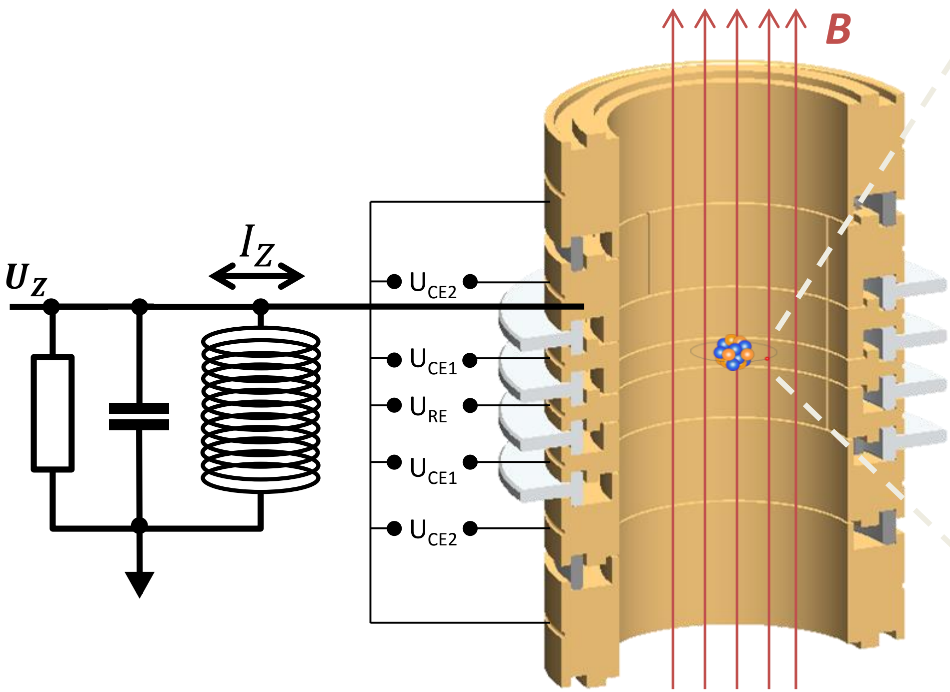
Penning Trap - Principle

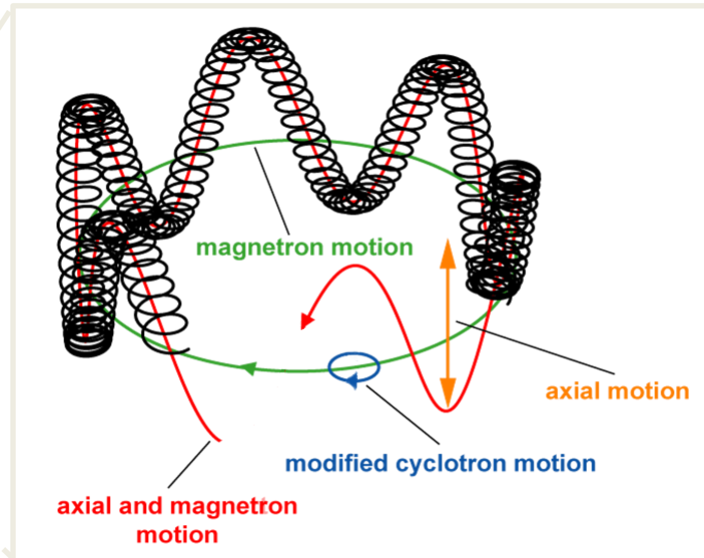
$$\Gamma = {}^{\nu_L}/_{\nu_c}$$

Experimental Conditions:

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





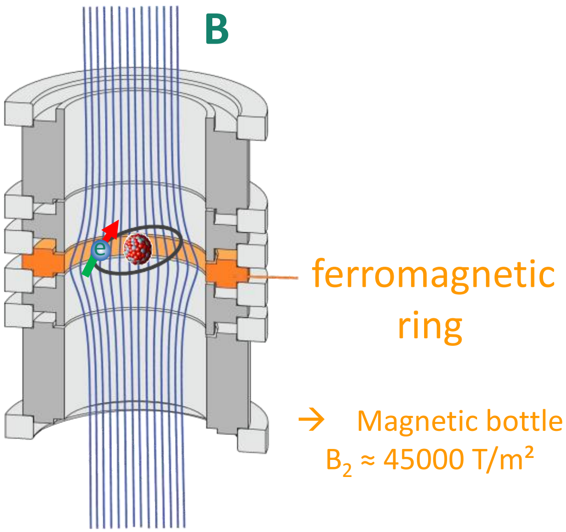


$$\nu_c = \frac{1}{2\pi}\frac{q_{ion}}{m_{ion}} B = \sqrt{\nu_z{}^2 + \nu_+{}^2 + \nu_-{}^2}$$

Spin state detection- Continuous Stern Gerlach Effect

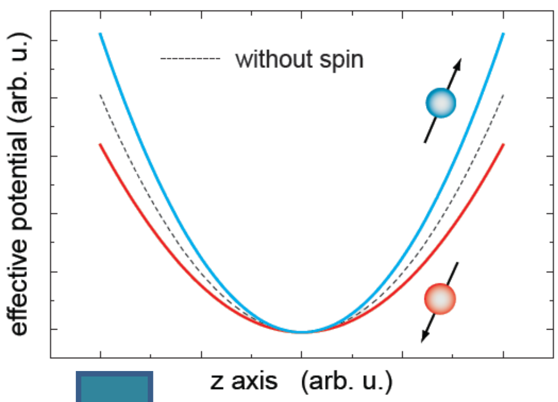
$$\Gamma = {\nu_L}/{\nu_c}$$

Introducing magnetic bottle inhomogeneity



additional potential:

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

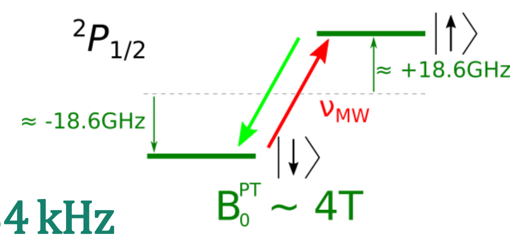


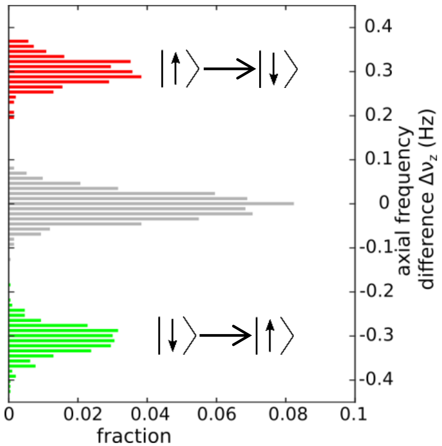
Continuous Stern-Gerlach effect:

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

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

@ $\nu_z \approx 334$ kHz

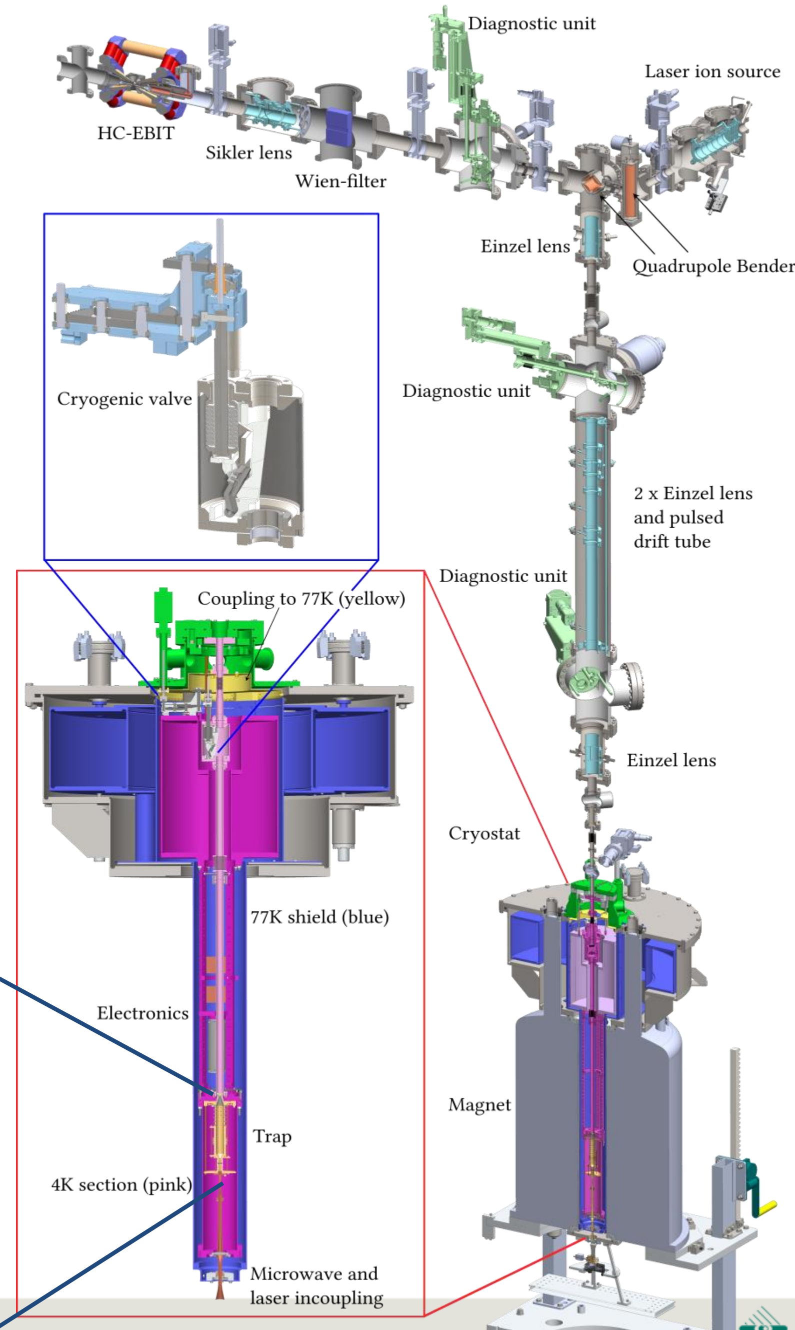


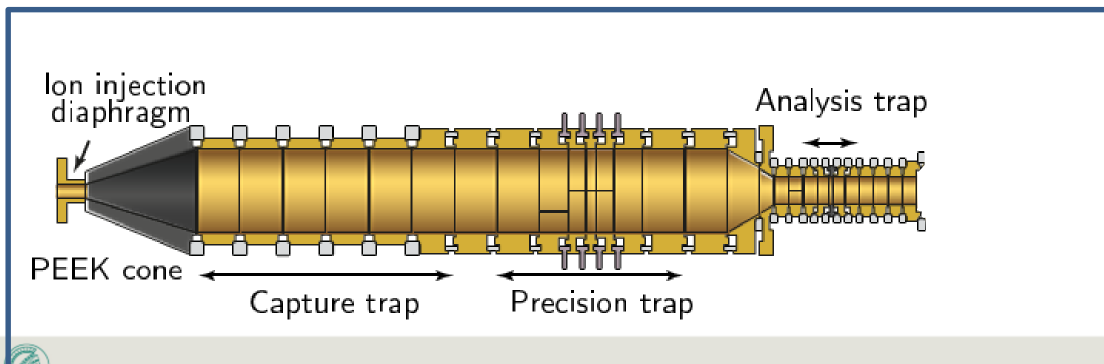


	$^{12}C^{5+}$	$^{28}Si^{13+}$	$^{40}Ar^{13+}$	$^{208}Pb^{81+}$
$\Delta\nu_z$	3.1 Hz	1.3 Hz	312 mHz	156 mHz

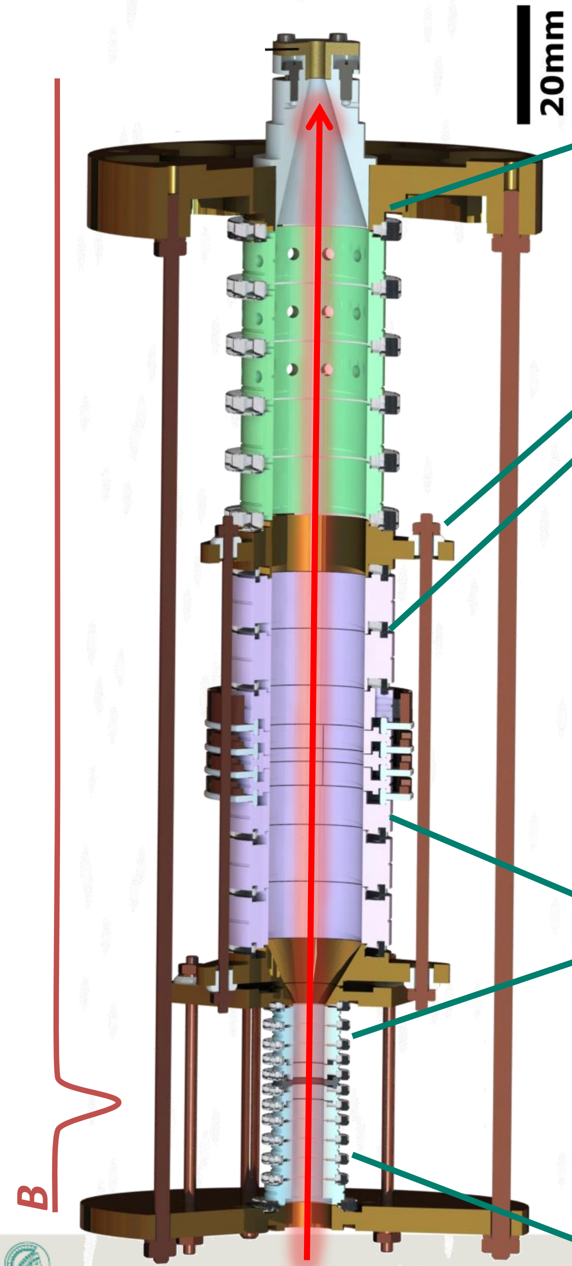
The ALPHATRAP setup

- Access to externally produced ions
  - Laser ion source (Be^{+})
  - HC-EBIT
  - HD-EBIT (commissioning phase)
- Transport through room-temperature beamline into 4K section
- Separated by cryogenic valve





Double Trap System



Capture section

-dynamic ion capturing

-storage of ions (months)

Precision Trap (PT)

-homogeneous B

$B_1 = 2.638(24)\ ^{\mathrm{mT}}/_{\mathrm{m}}$

$B_2 = 0.0643(32)\ ^{\mathrm{T}}/_{\mathrm{m^2}}$

-**measurement of ν_c**

-spin flips induction ν_L

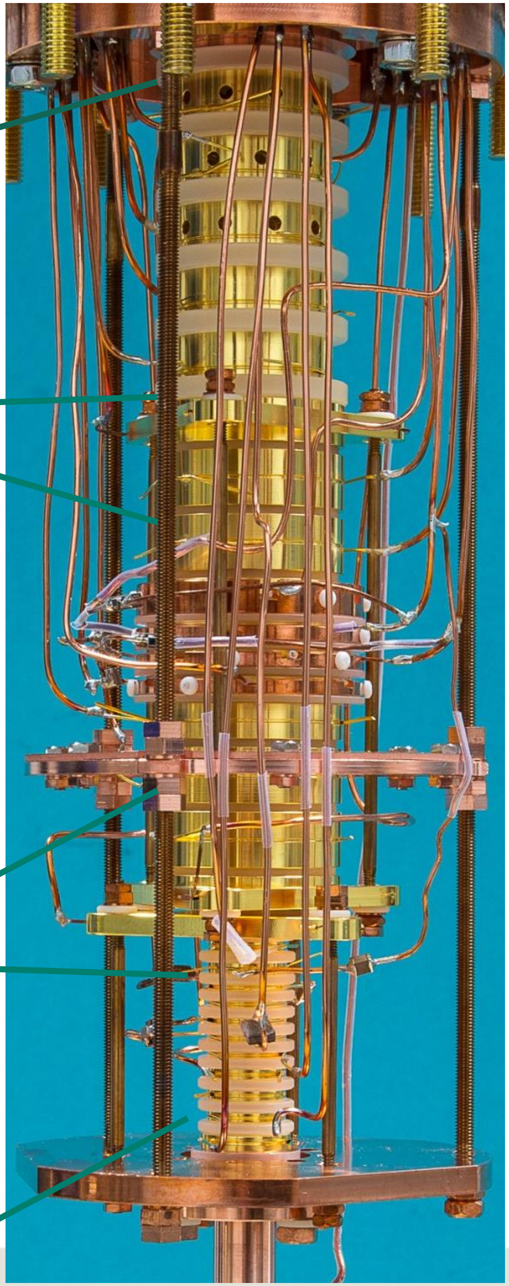
$\left.\right\} \frac{\nu_L}{\nu_c} = \Gamma$

-Laser spectroscopy

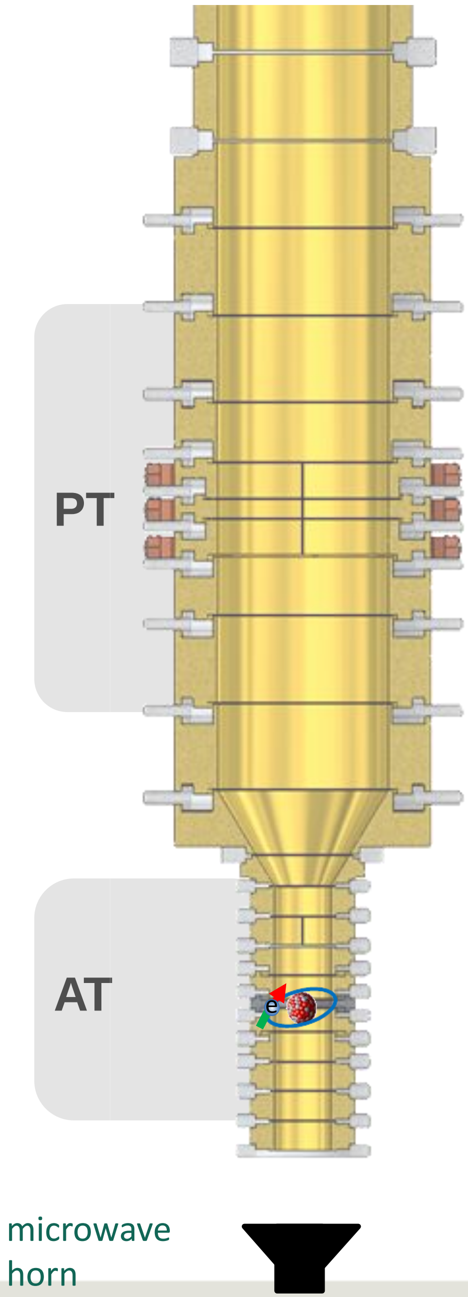
Analysis Trap (AT)

-strong B_2 $(44\ k\mathrm{T}/\mathrm{m}^2)$

-Spin state **detection** and **preparation**



Measurement cycle



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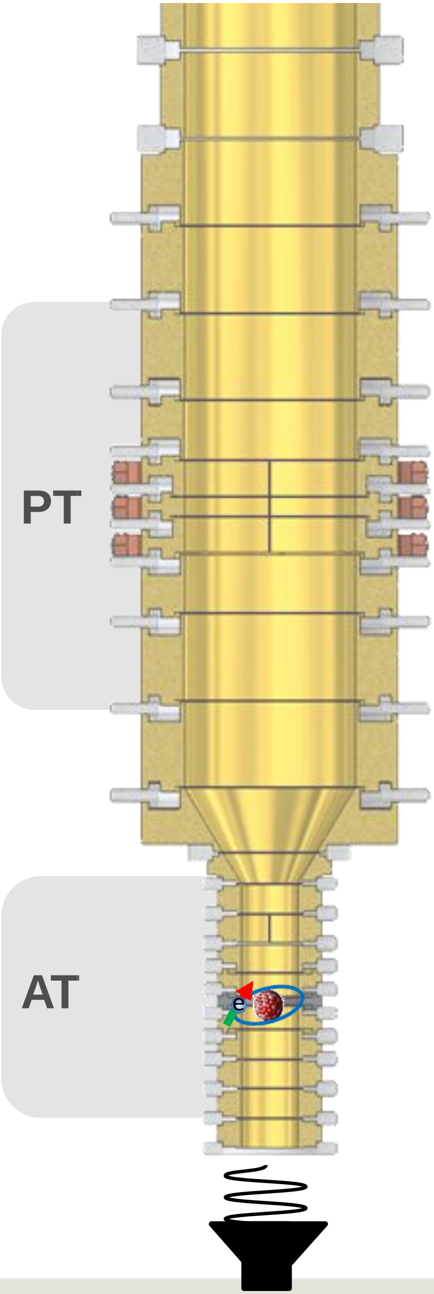
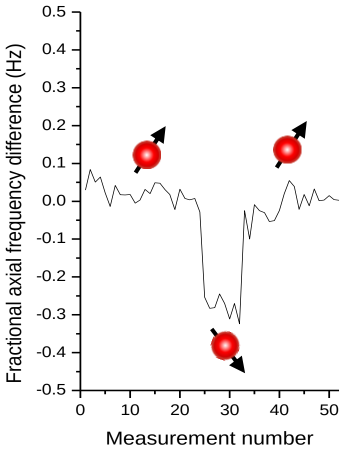


AT: Detection and preparation of spin orientation



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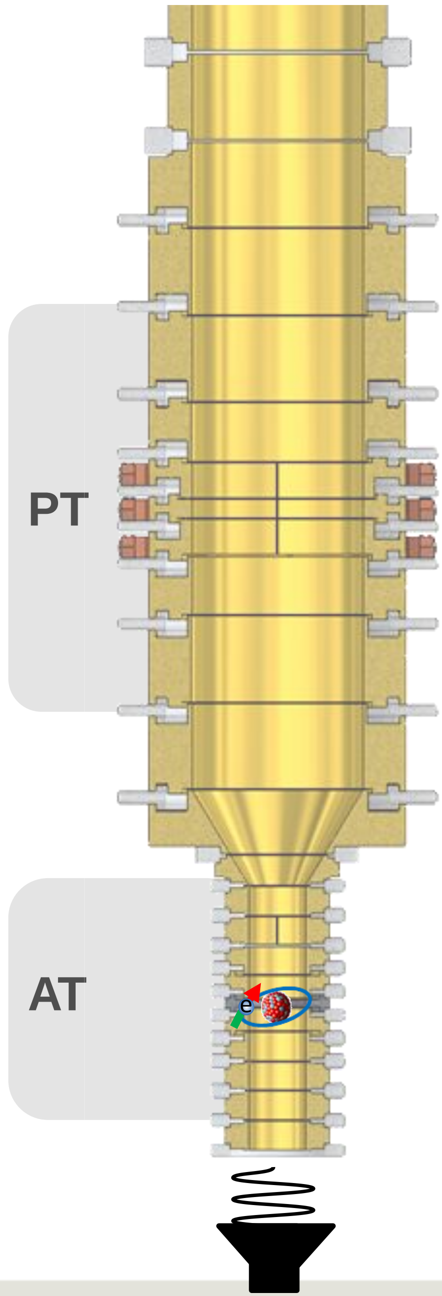
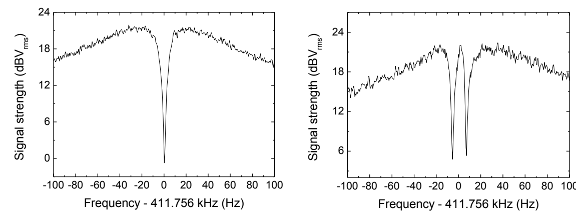
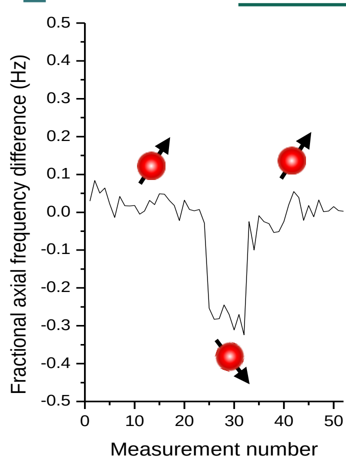


PT: Measurement of motional frequencies and probe with spectroscopy frequency

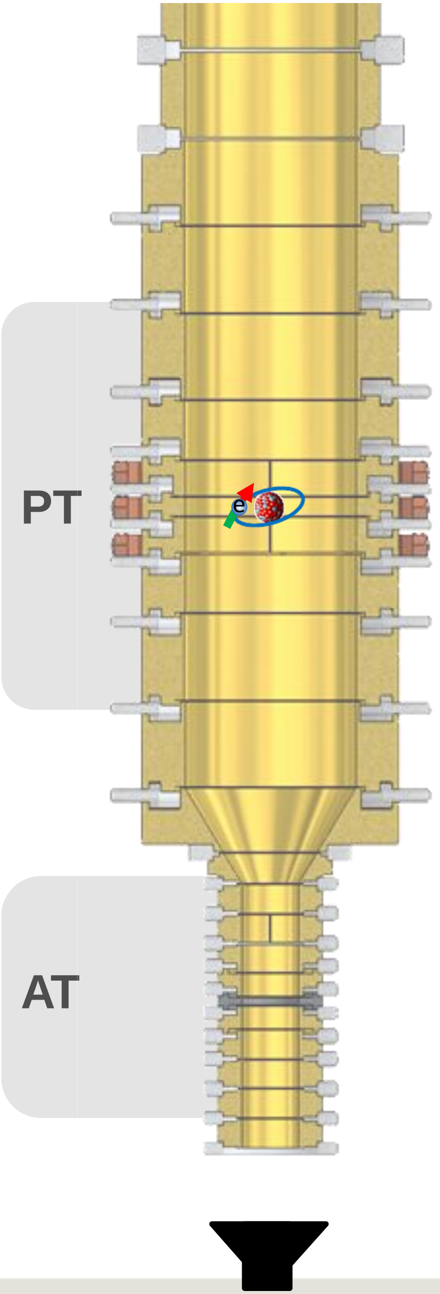


$$\nu_z^2 + \nu_+^2 + \nu_-^2 = \nu_c^2$$

AT: Detection and preparation of spin orientation



Measurement cycle



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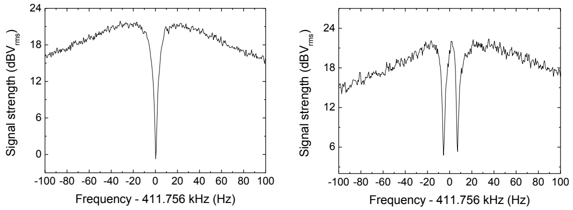

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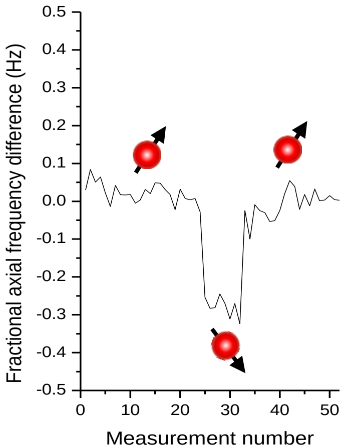
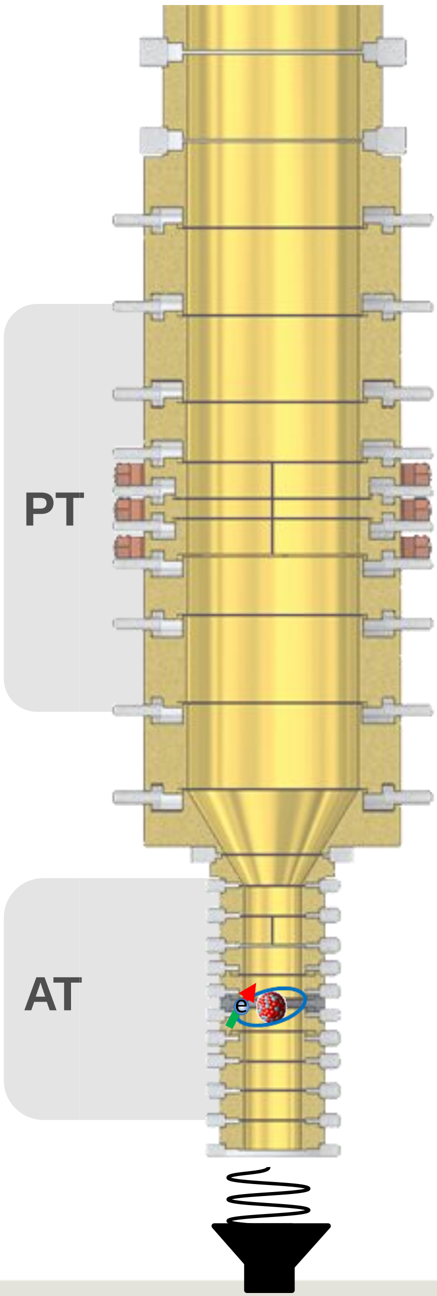


Measurement cycle



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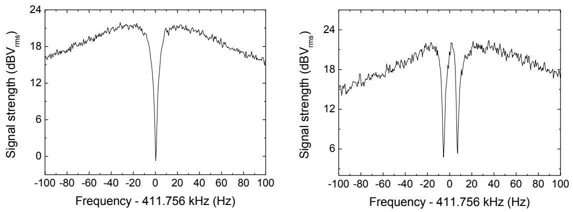

$$\nu_z^2 + \nu_+^2 + \nu_-^2 = \nu_c^2$$

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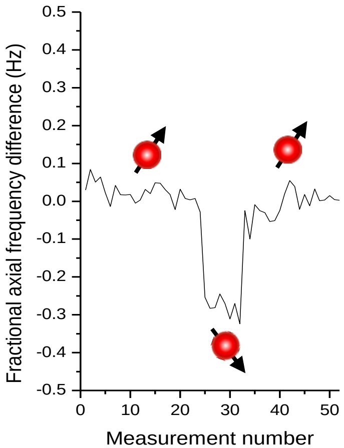
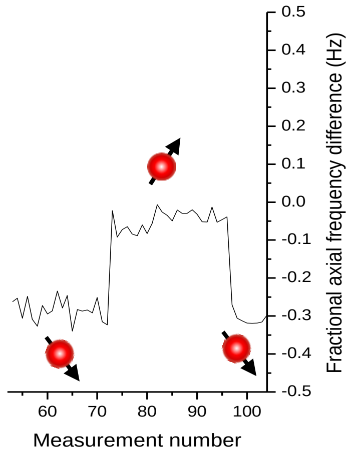


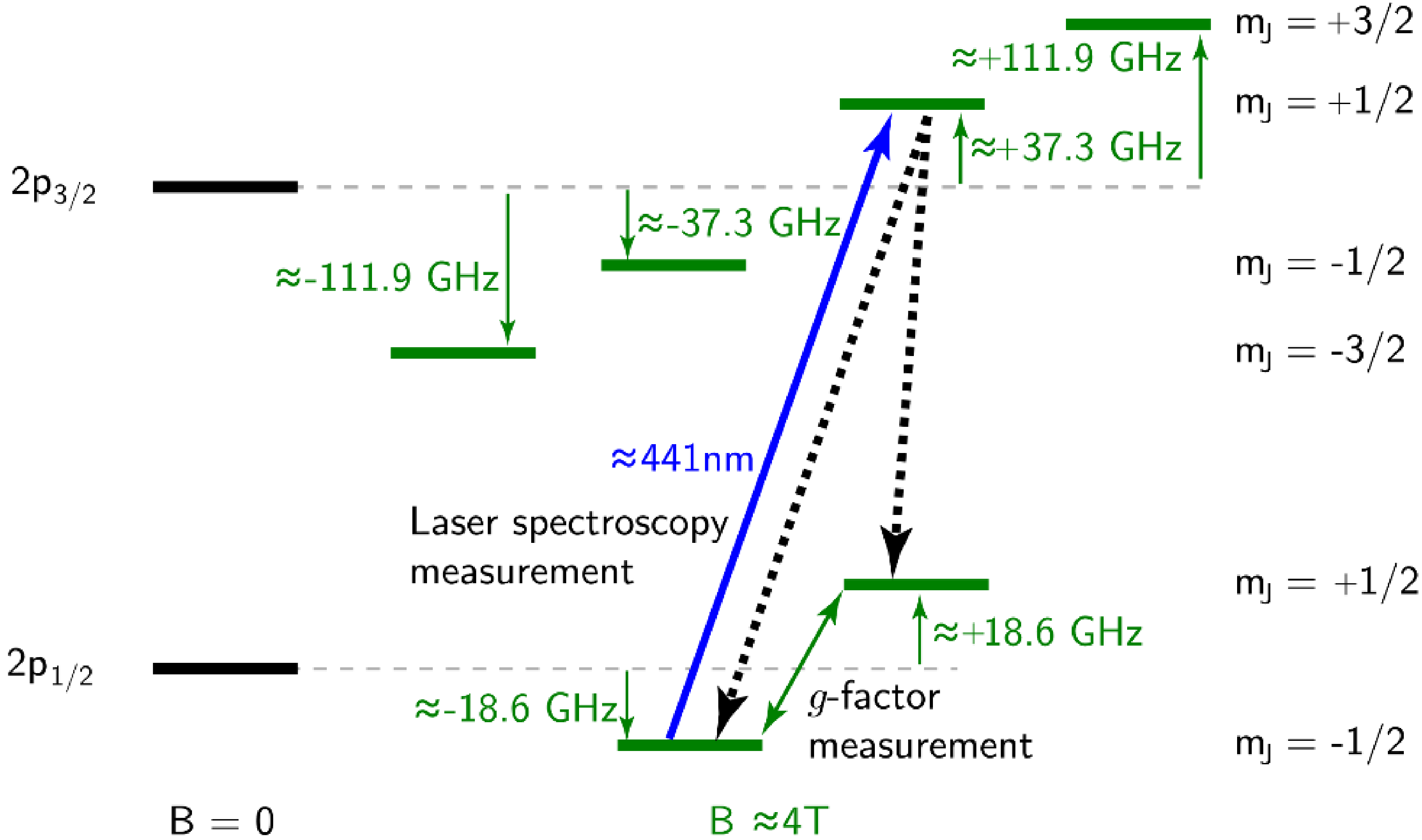
Compare

spin state



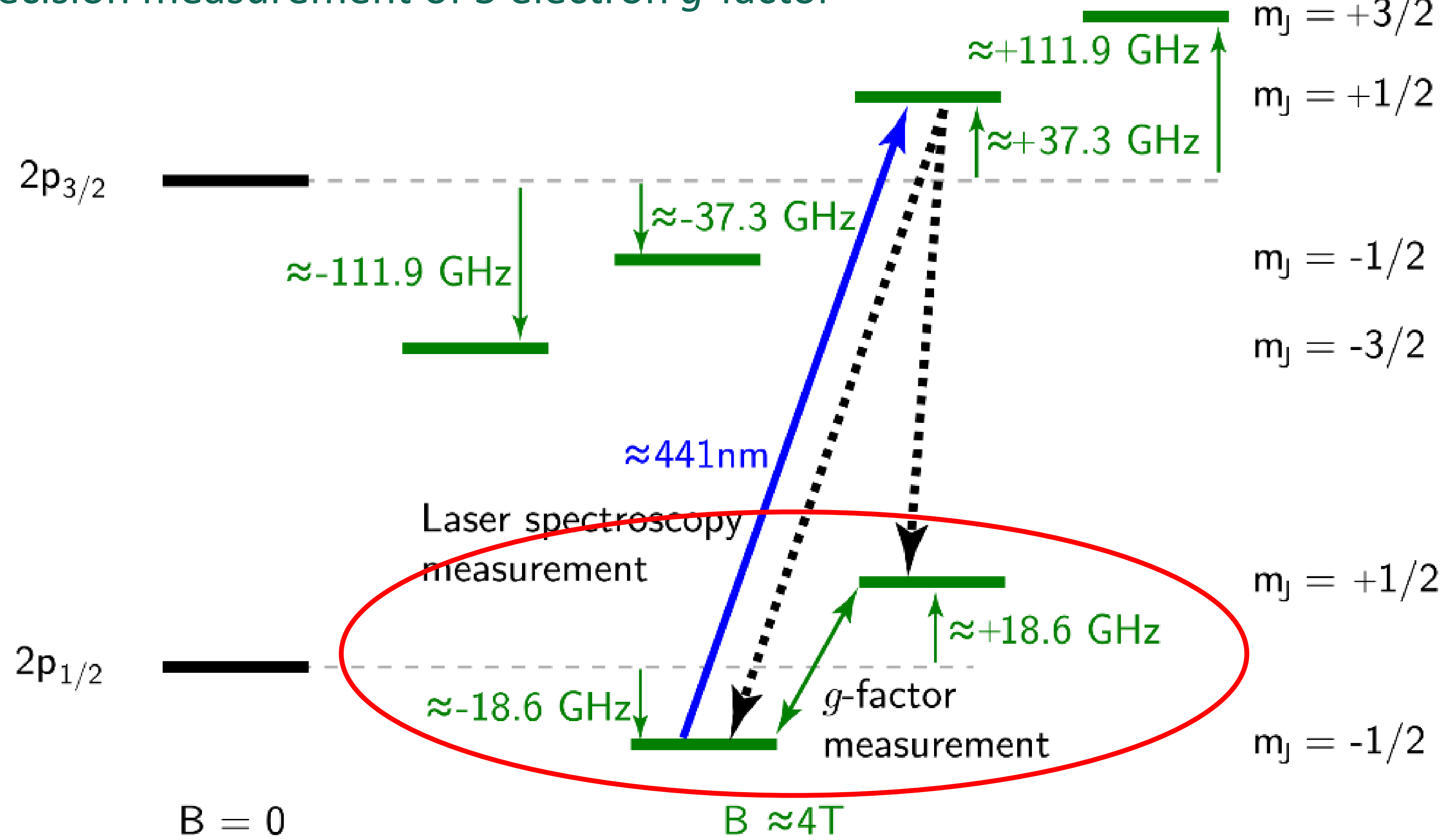
Measurements so far

$^{40}Ar^{13+}$ measurements



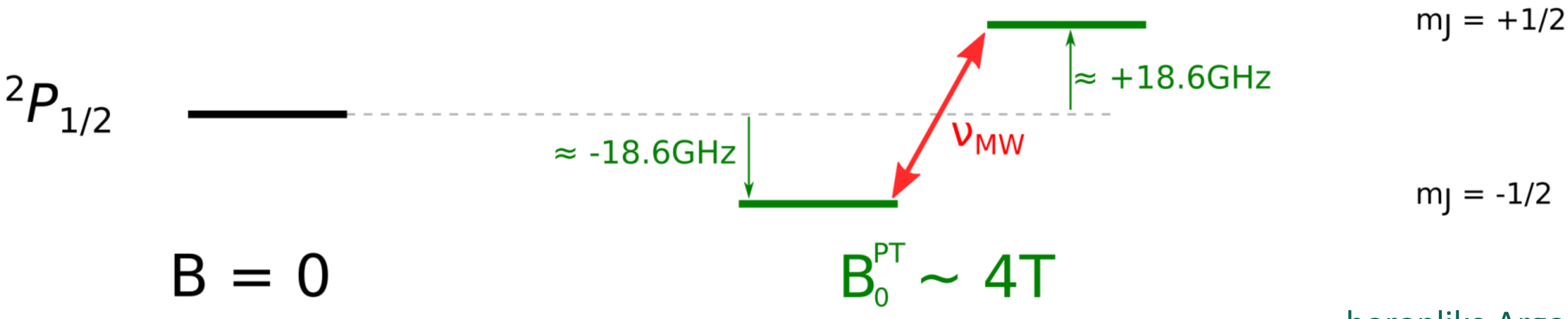
Measurements so far

$^{40}Ar^{13+}$ measurement of *g*-factor:
first high precision measurement of 5 electron *g*-factor



Measurement of the g-factor of $^{40}Ar^{13+}$

(preliminary results)



boronlike Argon: g ≈ 2/3

- 3 different theoretical values:
- 120 σ deviation between first 2

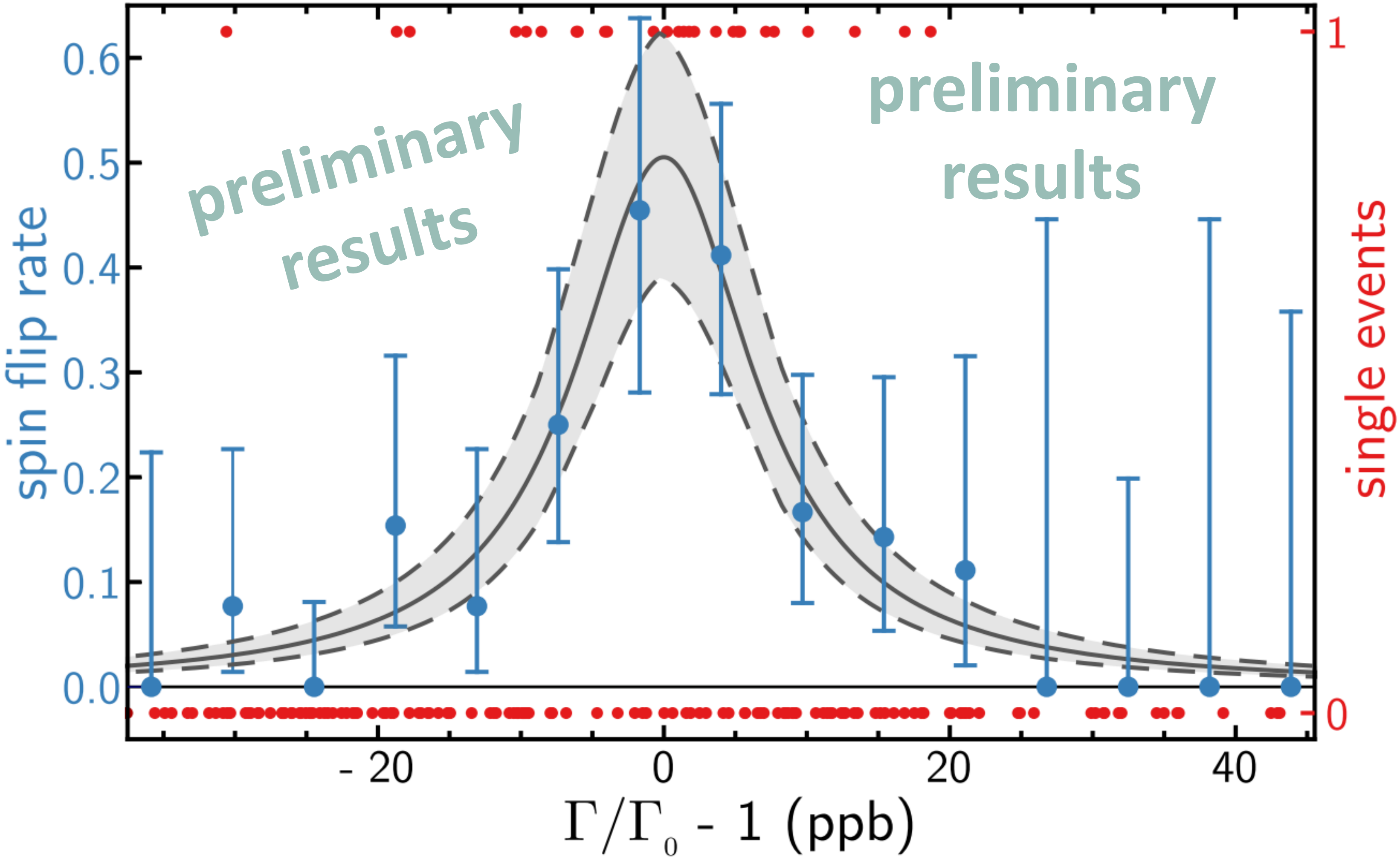
J. P. Marques et al. [1]	**0.663899(2)**
Glazov/Agababaev et al. [2]	**0.6636488(12)**
Shchepetnov et al. [3]	**0.6636477(7)**
S. Verdebout et al. [4]	0.663728 (-)

- Measured 2 resonances

[1] Physical Review A 94, 042504 (2016)
[2] HCI 2018 Conference Talk, Group of Volotka, Shabaev et al.
[3] J. Phys. Conf. Ser. 583 012001
[4] At. Data Nucl. Data Tables 100, 1111 (2014); no error given

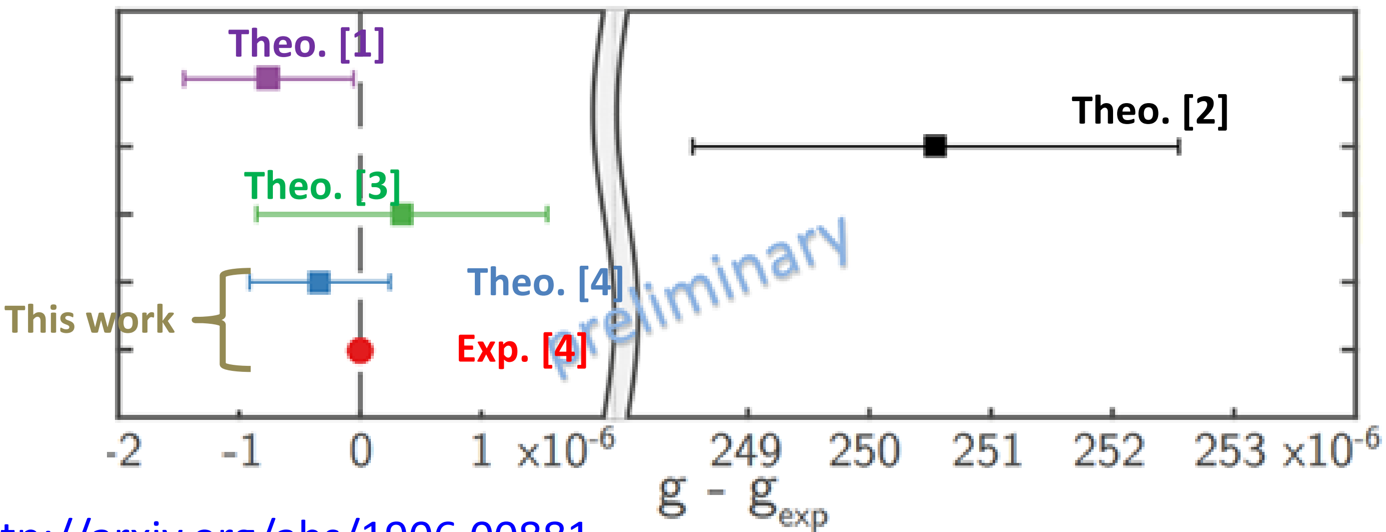
Measurement of the *g*-factor of $^{40}Ar^{13+}$

(preliminary results)



Gaussian fitted by maximum likelihood estimation (binned data only for representation)

Comparison with Current Theory



http://arxiv.org/abs/1906.00881

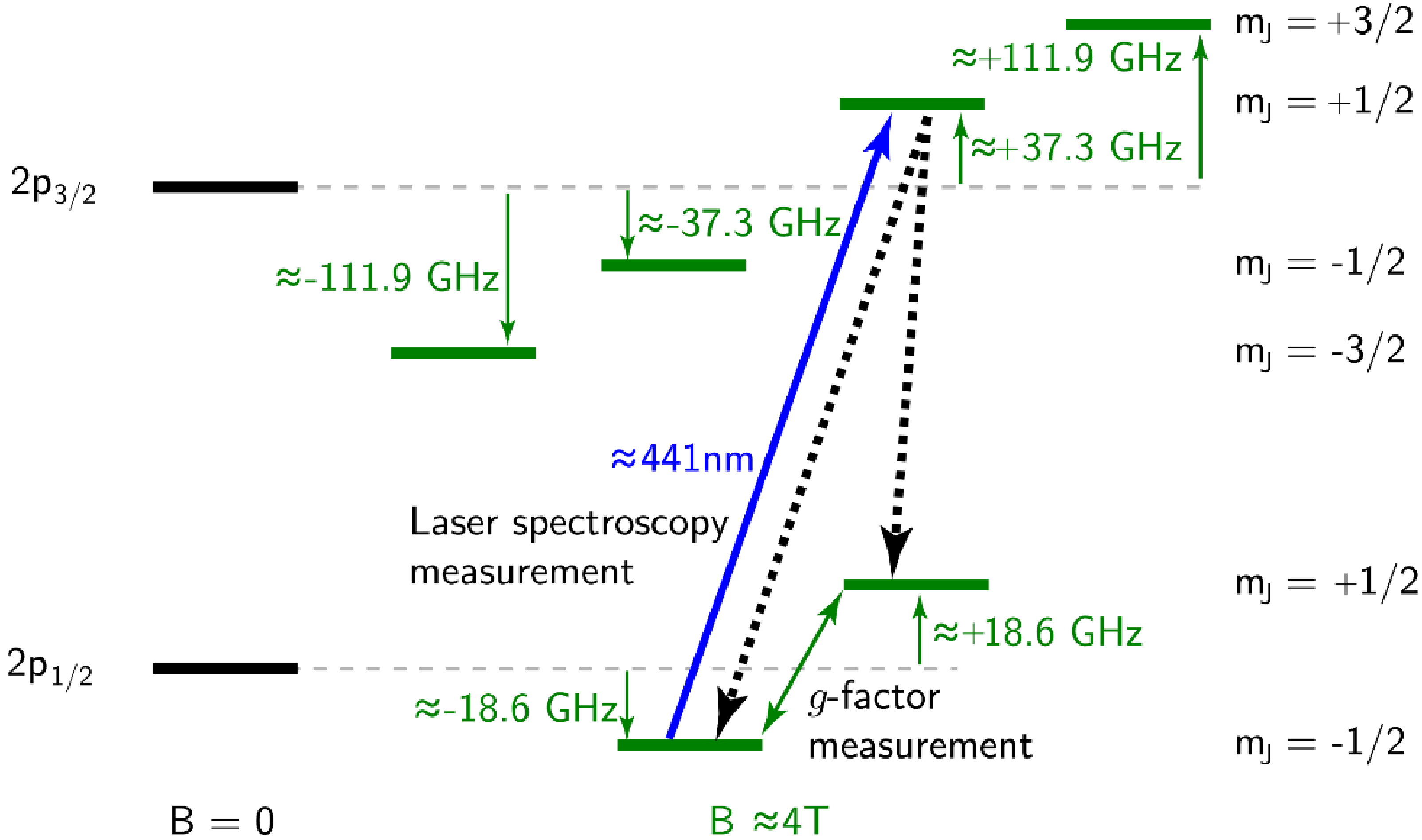
Shchepetnov *et al.* [1]	**0.663 647 7(7)**
J. P. Marques et al. [2]	**0.663 899(2)**
Glazov/Agababaev et al. [3]	**0.663 648 8(12)**

- A maximum of 120σ deviation comparing the existing theoretical predictions
- Our experimental result shows the agreement with the current theory at 10^{-7} level. (**Experiment precision at 10^{-9}**)

[1] A. A. Shchepetno *et al.*, *J. Phys. Conf. Ser.* 583 012001
[2] J. P. Marques *et al.*, *PHYSICAL REVIEW A* 94, 042504 (2016)
[3] V. A. Agababaev *et al.*, *HCI 2018 Conference Talk*, Group of Volotka, Shabaev *et al.*
[4] I. Arapoglou *et al., Phy. Rev. Lett* accepted, http://arxiv.org/abs/1906.00881

Measurements so far

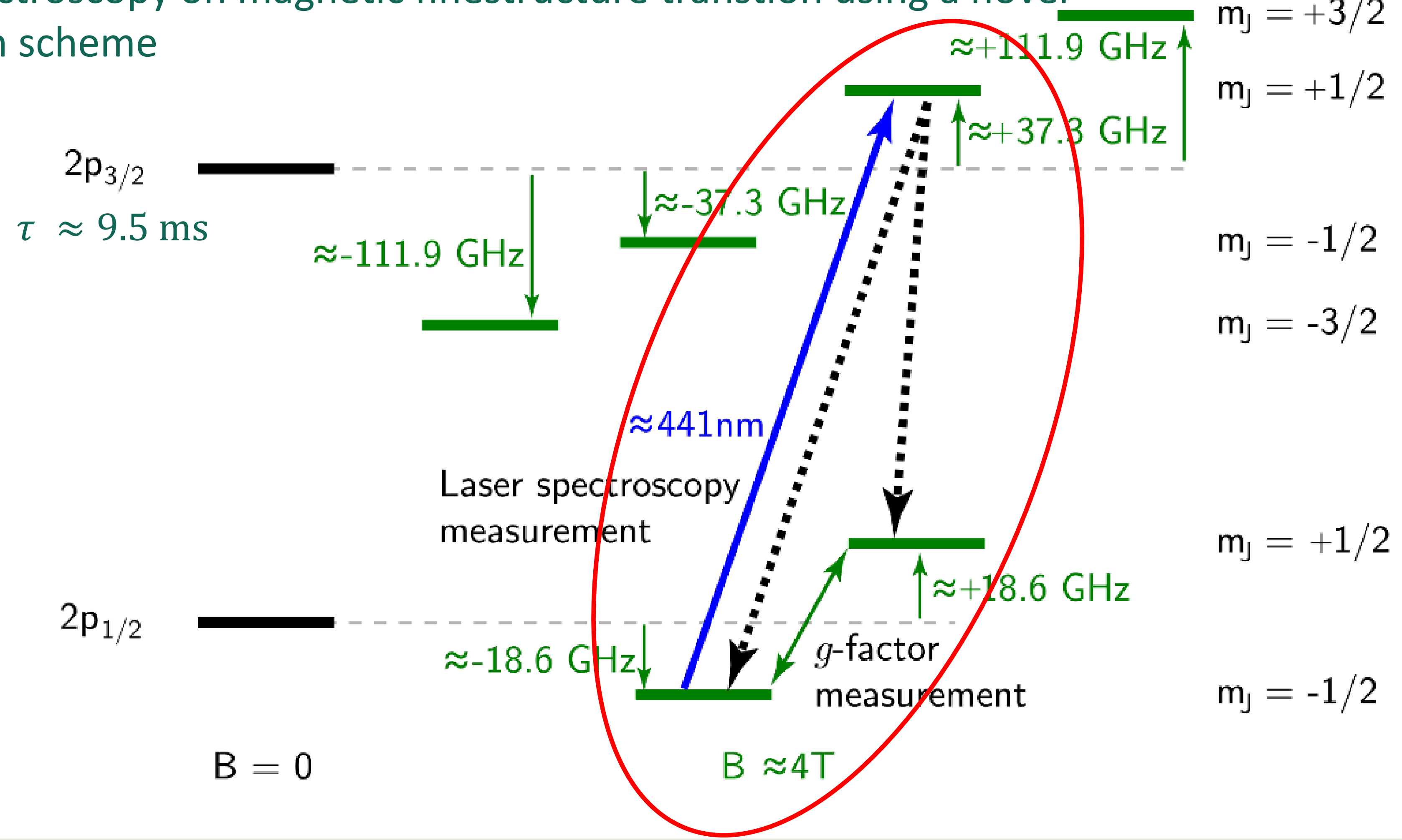
$^{40}Ar^{13+}$ measurements



Measurements so far

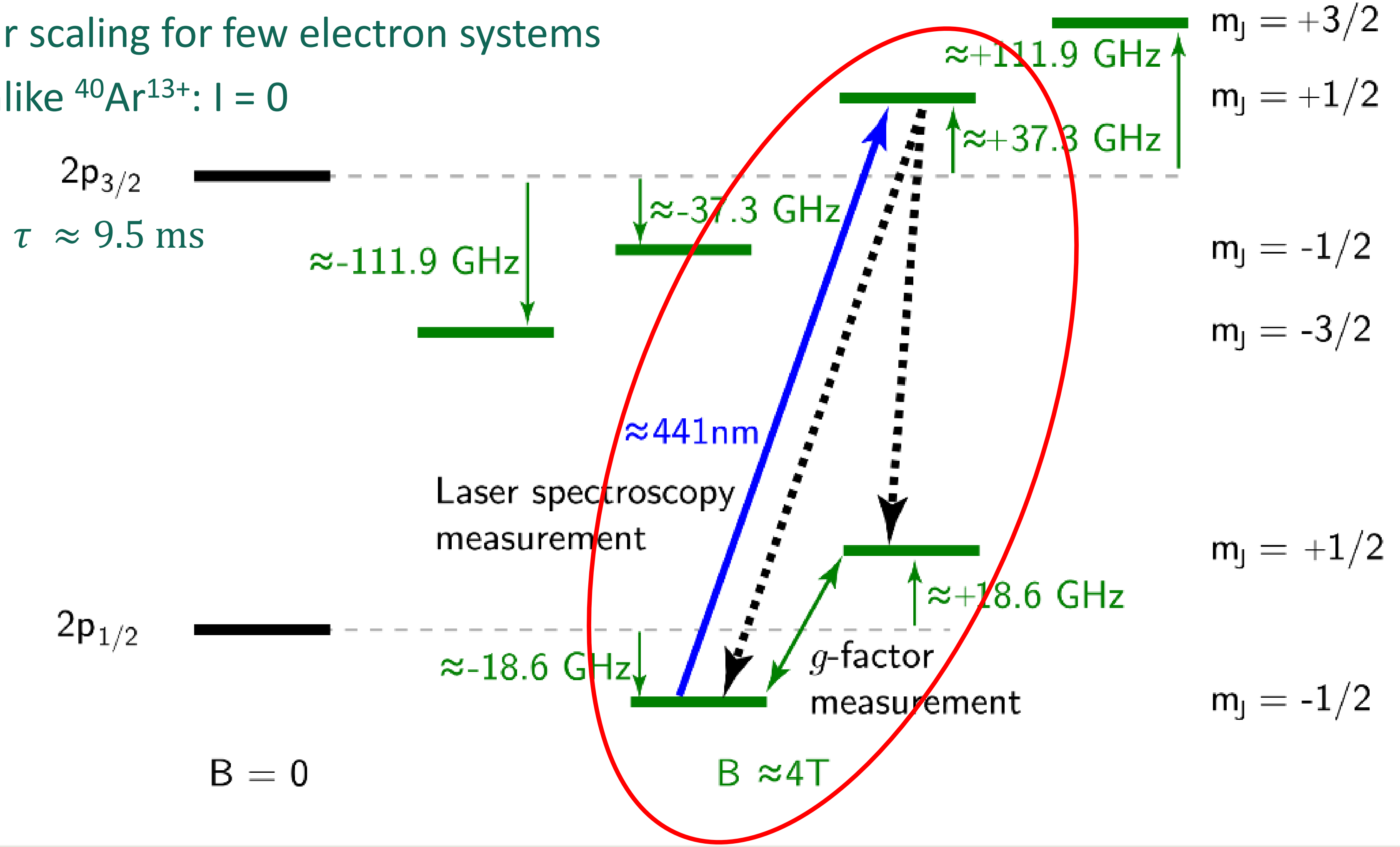
$^{40}Ar^{13+}$ measurement of finestructure transition:

laser spectroscopy on magnetic finestructure transtion using a novel detection scheme



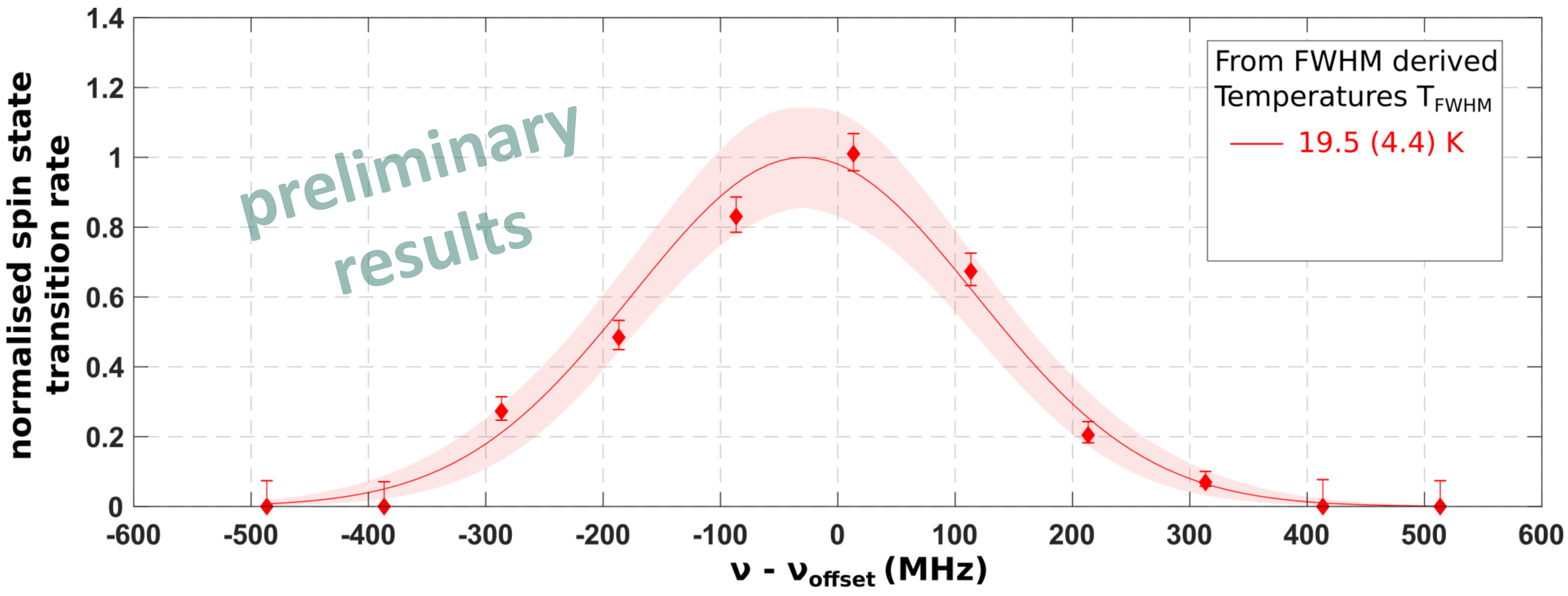
Measurements so far

- For hydrogenlike ions transition energy scaling: $\propto Z^2$ for principal, $\propto Z^3$ for HFS, $\propto Z^4$ for FS
- Similar scaling for few electron systems
- boronlike $^{40}Ar^{13+}$: I = 0



Results – Resonance for |1/2,-1/2> ↔ |3/2,+1/2> (= $|J,m_j>$)

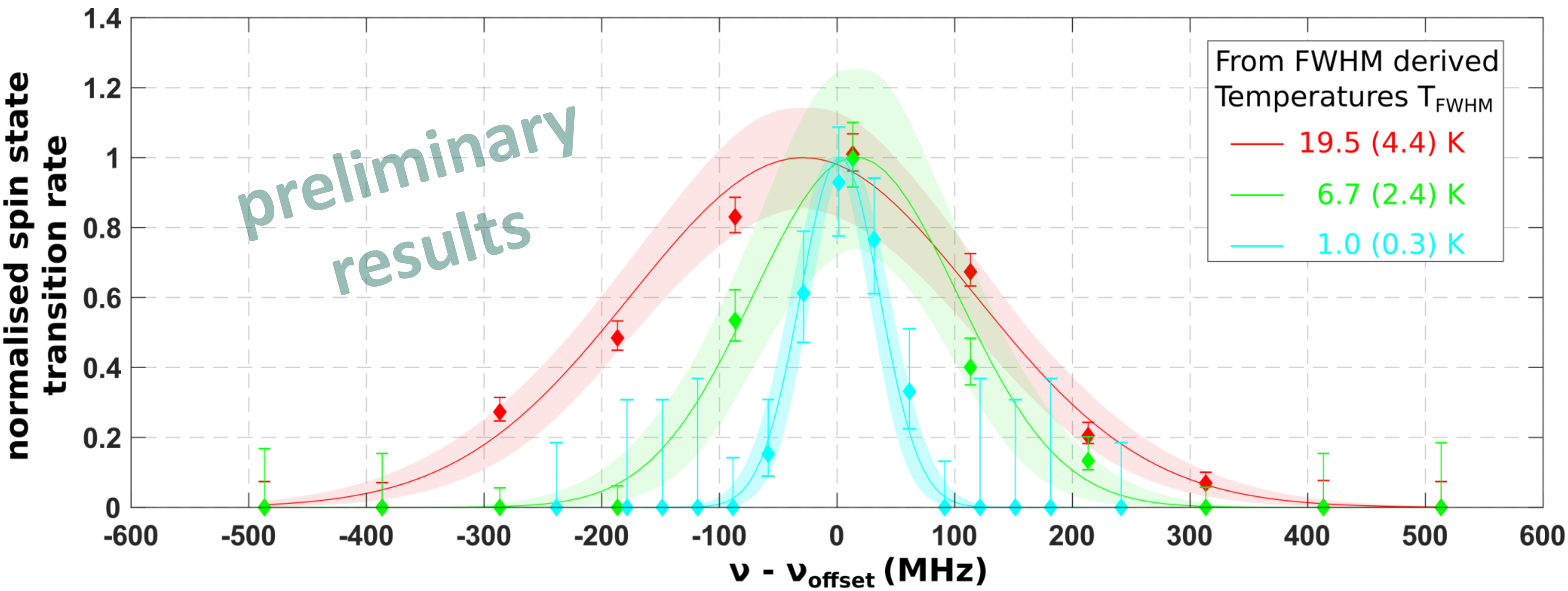
- Derived temperature from FWHM → 19.5 ± 4.4 K



Results – Resonance for |1/2,-1/2> ↔ |3/2,+1/2> (= |J,m_j>)

- Derived temperature from FWHM → 1.0 ± 0.3 K

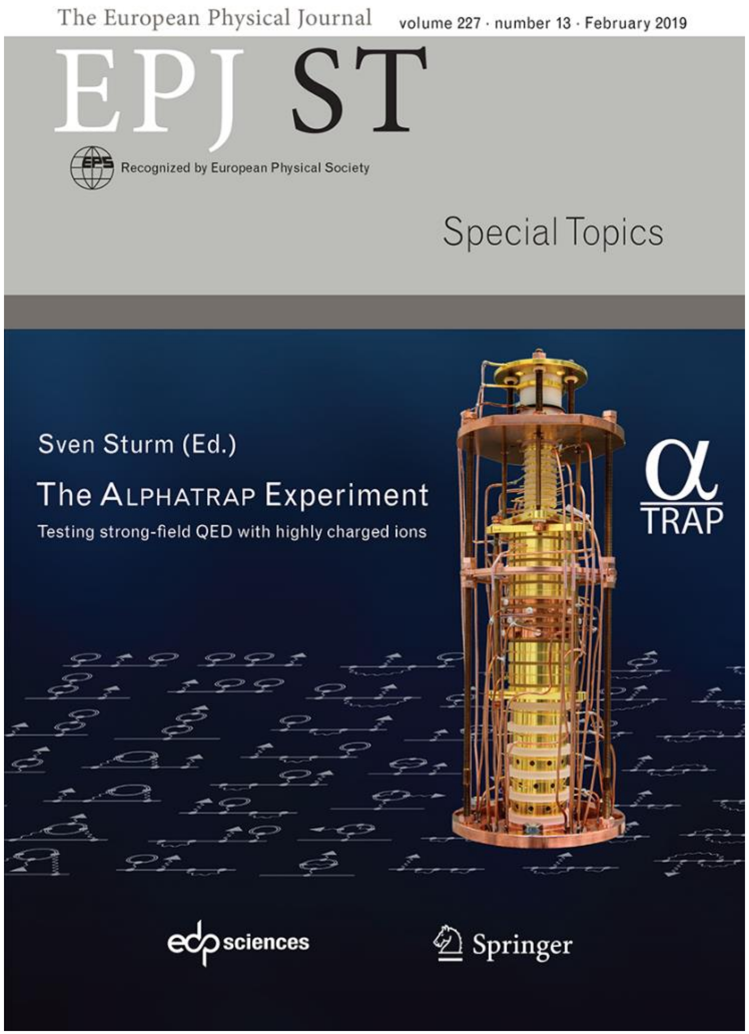
- Negative electronic feedback applied, expected lower temperature of factor ≈ 3
- Adiabatic cooling by lowering of trapping potential depth by factor of 3.8
  → lowered temperature by ≈ 3×3.8 = 11.4



Summary & Perspectives

- First high precision measurement of boronlike g-factor
- Fine structure spectroscopy without fluourescence detection
- ALPHATRAP: access to heavy HCI via HD-EBIT:
  - control over single ion states and preparation
  - long storage times
  - low energy
- QED tests of heavy HCI e.g. HFS splitting in hydrogen- and lithiumlike $^{209}Bi^{82+,80+}$
- Isotope shift measurement for g-factor in HCI → high sensitivity to nuclear effects

Sturm, Sven, et al. "The ALPHATRAP experiment." The European Physical Journal Special Topics 227.13 (2019): 1425-1491.



Thank you for your attention

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

α TRAP

The ALPHATRAP Team:

Klaus Blaum

Sven Sturm

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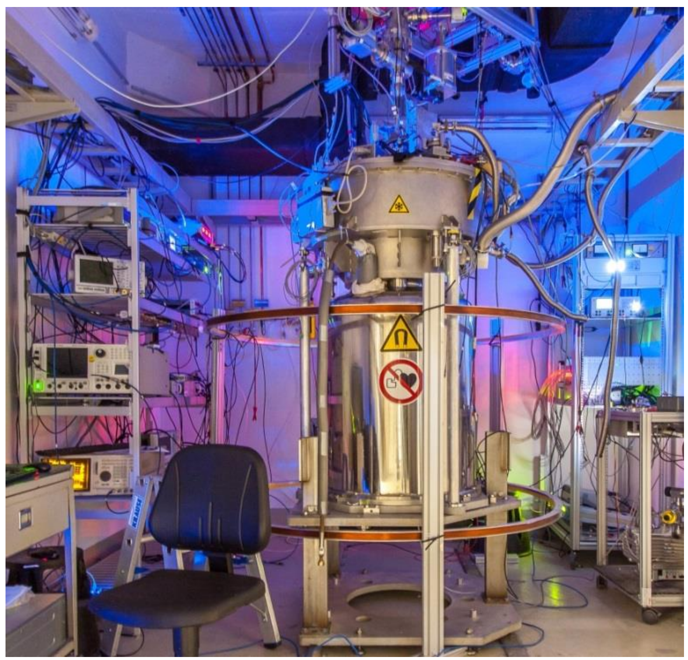
Ioanna Arapoglou

Alexander Egl

Tim Sailer

& …



+ for Ar^{13+} FS Laser spectroscopy:

W. Nörtershäuser[1], K. König[1], T. Ratajczyk[1]

[1] IKP, TU Darmstadt

+ for Ar^{13+} *g*-factor measurement:

H. Cakir[1], V. A. Yerokhin[1,2], N. S. Oreshkina[1], V. A. Agababaev[3,4], A. V. Volotka[3,5,6], D. V. Zinenko[3], D. A. Glazov[3], Z. Harman[1], C.H. Keitel[1]

[1] MPIK
[2] Peter the Great St. Petersburg University
[3] St Petersburg State University
[4] St Petersburg Electrotechnical University
[5] Helmholtz-Institut Jena
[6] GSI Darmstadt

Considerations for line shape

- Ion bound in a harmonic potential
  - Axial motion: $z(t) = z_0 \cos[\omega_z t]$
  - Doppler shift: $\omega_{Lab} = \omega_0 + k_L v_{ion}$

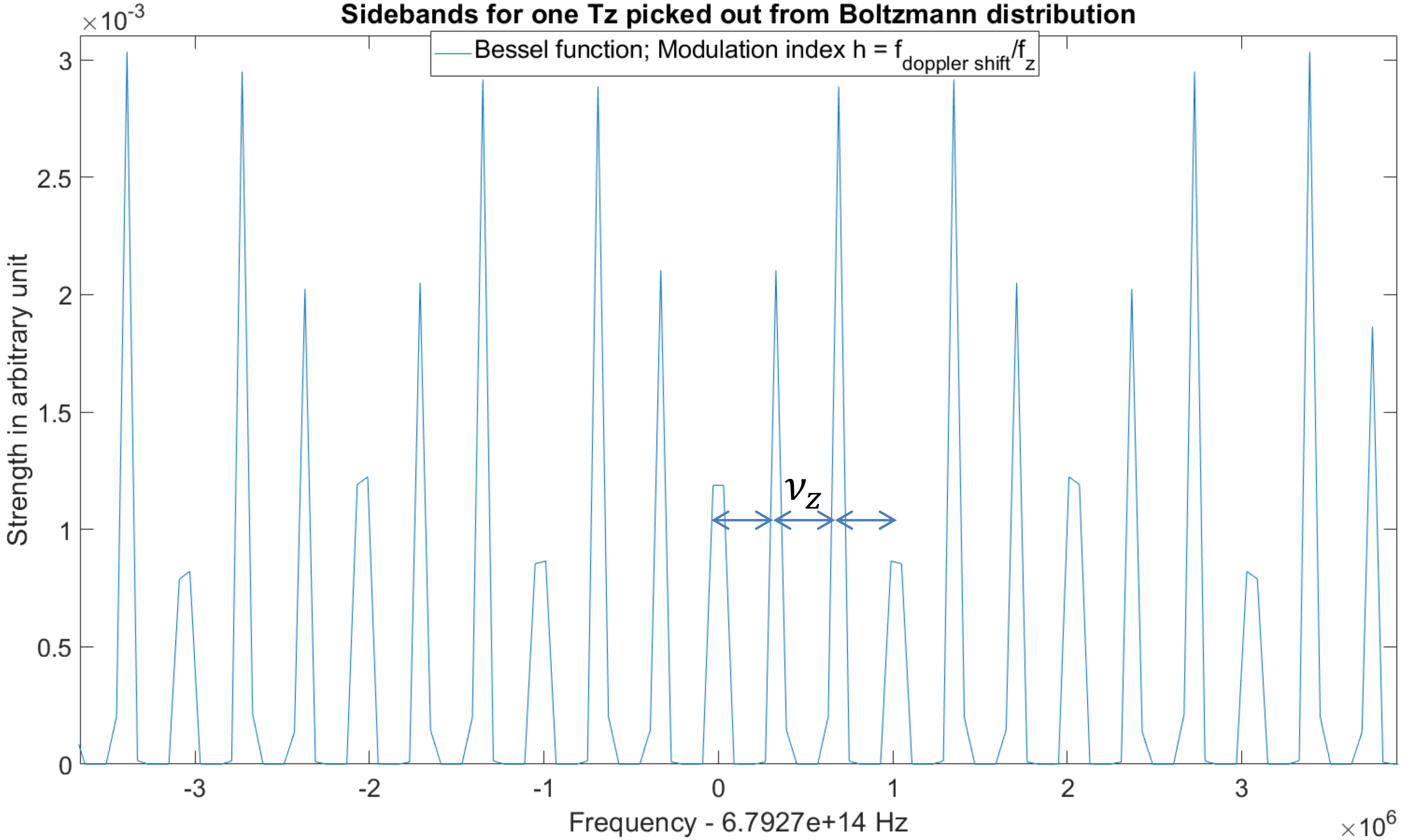
⇩

  - $E(t) = E_0 \exp\left[(i \int_0^t \omega_0 t - k_L \omega_z z_0 \sin(\omega_z t')\, dt'\right]$
  - $\mathcal{F}\{E(t)\} = E(\omega) = \cdots = E_0 \sum_{\alpha=-\infty}^{+\infty} i^\alpha J_\alpha(\eta)$
  - $I(\omega) \propto I_0 \sum_{\alpha=-\infty}^{+\infty} |J_\alpha(\eta)|^2$

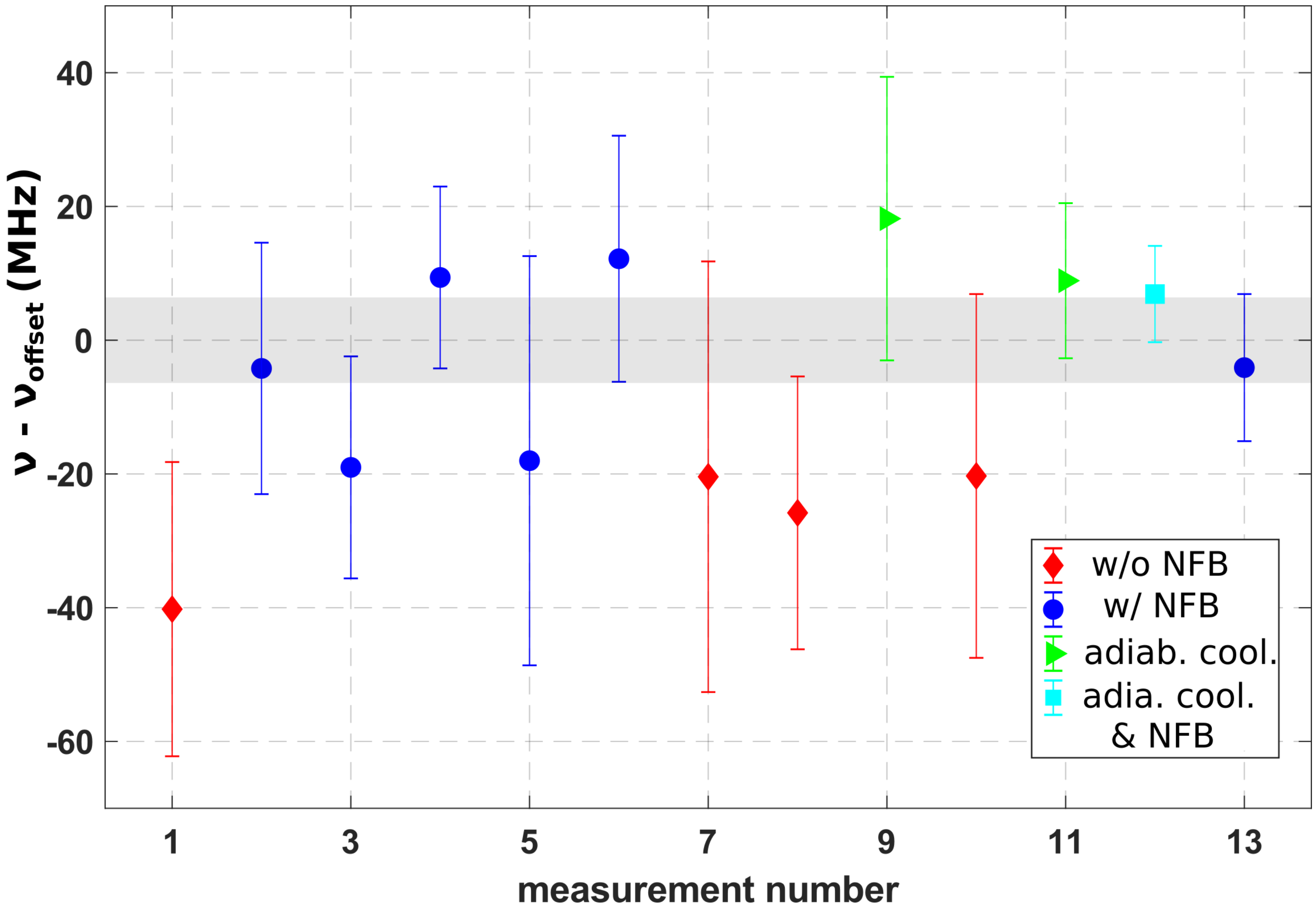
- modulation index η indicates by how much the modulated variable varies around its unmodulated level. It relates to variations in the carrier frequency. The Bessel function gives then the strength of the α^{th} sideband

Simulations

- Sideband spectrum for one specific temperature picked out of this distribution



Center of resonances



Outlook

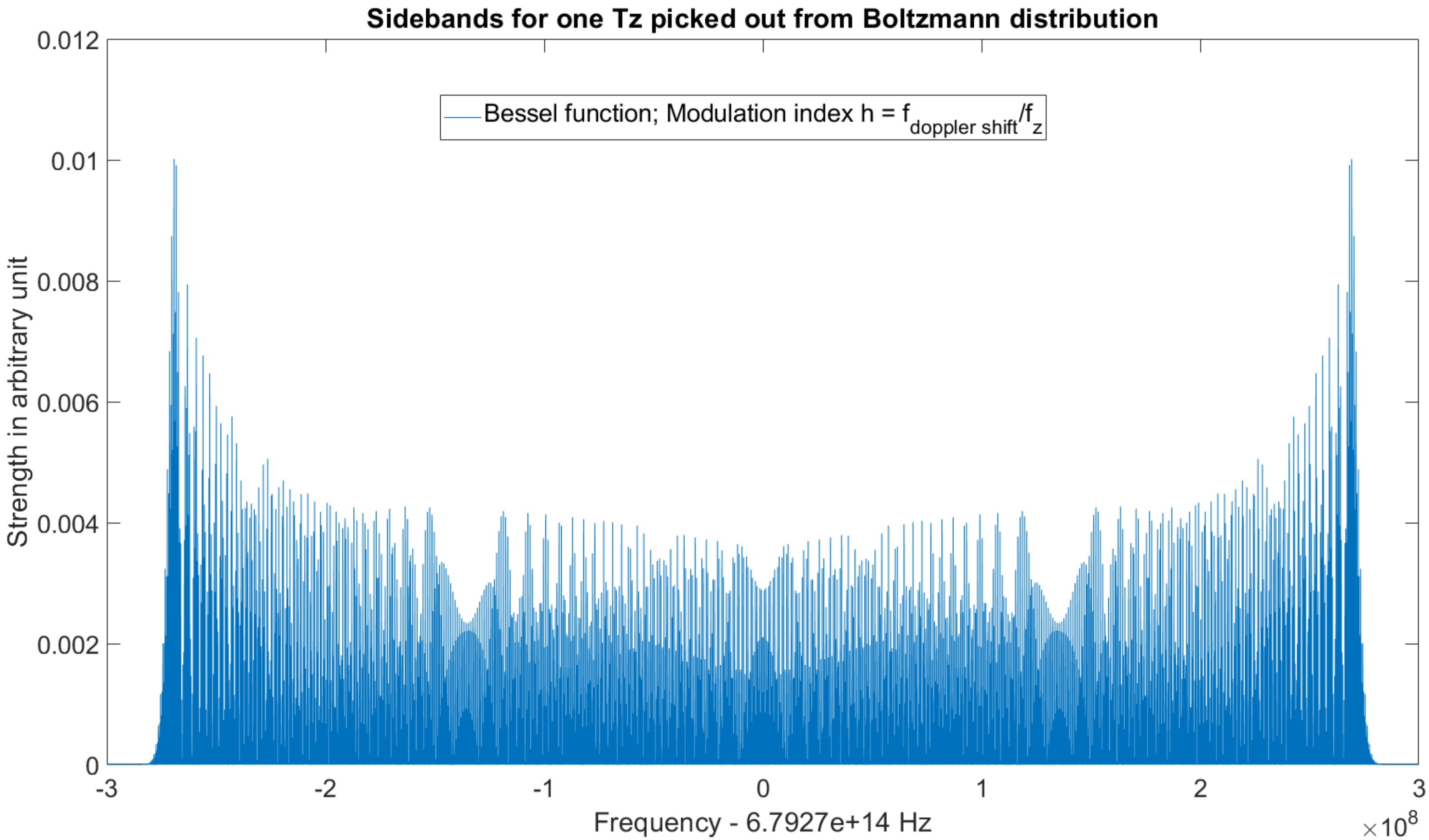
- Isotope shift measurement for g-factor in HCI
- Ground state g-factor of HCI
- Precision increased by sympathetical laser cooling, development of cooling scheme for HCI ↔ Be^+ ions
- Improved laser system: line width narrowing e.g. ULE cavities, absolute frequency determination via frequency comb
- Spectrocsopy, e.g. of Li-like and H-like Bismuth

Laser Cooling for ALPHATRAP

- Increase precision by
  - **Sympathetic Cooling** of a highly-charged ion
  - Phase Sensitive Detection Methods benefit from small radial kinetic energies during the phase evolution time → **smaller magnetic and relativistic shifts**
- **Facilitation of the Spin-Flip measurement** in the AT
- Open up new type of measurements: **Coulomb Crystals** in Penning traps (crystal made of a single Be^{1+} ion and a single HCI) → measurements of $\Delta \boldsymbol{g}$ → α

Considerations for line shape

- Sideband spectrum for one specific energy out of the thermal Boltzmann distribution



Considerations for line shape

$$\Delta f_{FWHM} = f_0 \sqrt{\frac{8k_BT\ln(2)}{m_{ion}c^2}}$$

- Smoothing and comparison of the Gaussian lineshape (Doppler broadening)