Ultra-low heating rates for high precision measurements on antiprotons

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BASE RIKEN MAX-PLANCK-GESELLSCHAFT JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ 東京大学 THE UNIVERSITY OF TOKYO PTB Leibniz Universität Hannover GSI

BASE – high precision measurements on antiprotons

Baryon **A**ntibaryon **S**ymmetry **E**xperiment
Stringent tests of the CPT theorem
High-precision comparisions of the fundamental properties of protons and antiprotons
Cryogenic Penning trap system

$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Cyclotron frequency: Measurement by using image currents
In a Penning trap the electrical field modifies ν_c to ν_+.

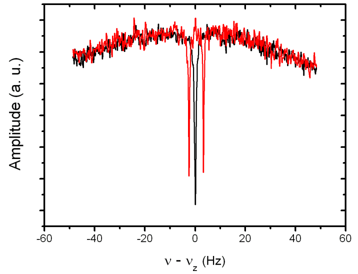
$$\nu_L = \frac{1}{2\pi}\frac{q}{m}\frac{g_{\bar{p}}}{2}B$$

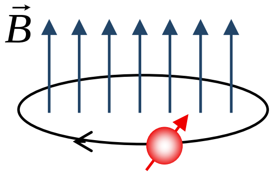
Larmor frequency: Spin precession in an applied magnetic field
Measurement based on the continous Stern Gerlach effect

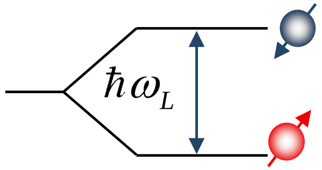
$$g_{\bar{p}} = 2\frac{\nu_L}{\nu_c}$$

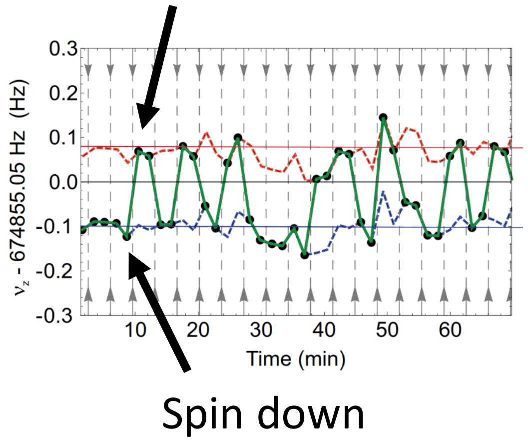
C. Smorra et al., EPJ-ST **224**, 16, pp 3055-3108

State of the art







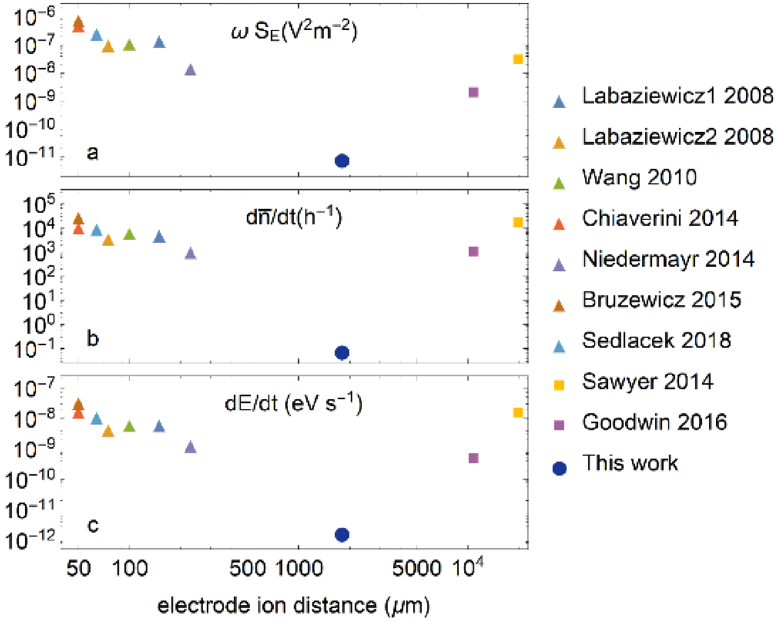


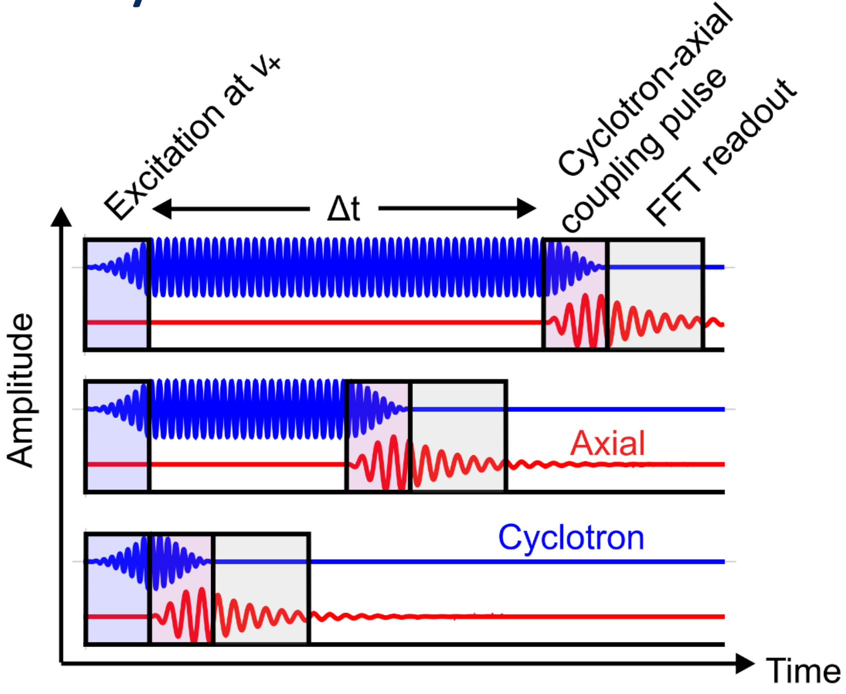
Pioneering work with protons

For further information also see the talks 72, by James Harrington (Monday), talk 92 by Markus Wiesinger, (Wednesday) and talk 78 by Stefan Erlewein (Thursday)

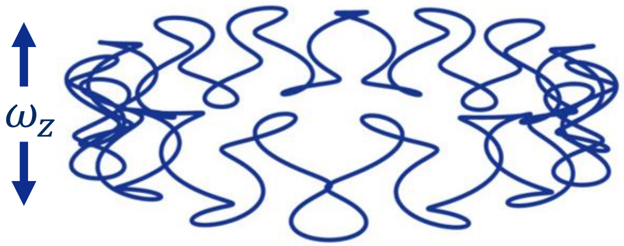
Outline

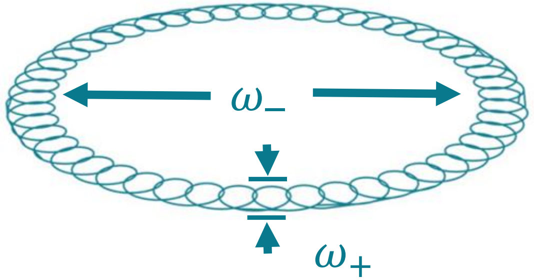
1. Brief introduction
2. Ultra-low heating rates & high precision measurement of the antiproton magnetic moment
3. Phase sensitive methods for measurements of the (anti-)proton cyclotron frequency





Cyclotron frequency measurements in a Penning trap





Three harmonic eigenmotions in a Penning trap

$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

1. Modified cyclotron frequency ω_+
2. Electrostatic axial frequency ω_z
3. Magnetron motion ω_-

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

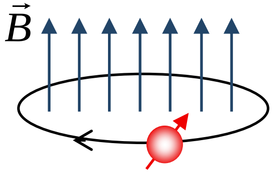
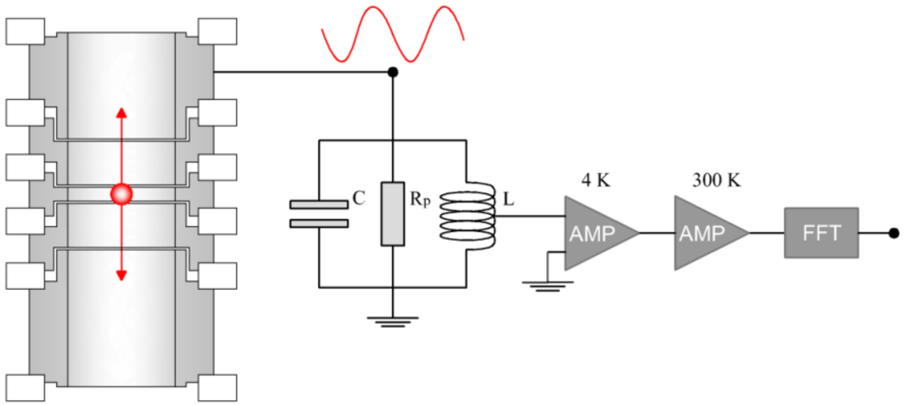
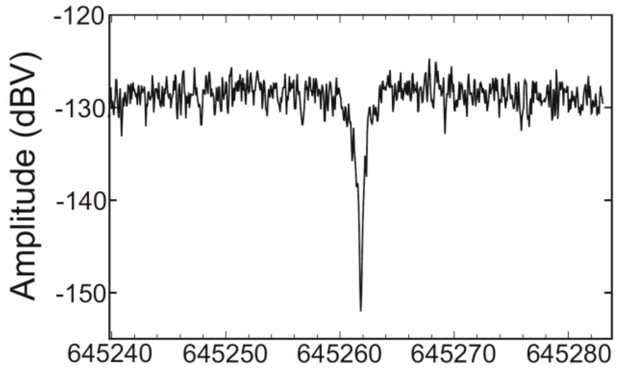


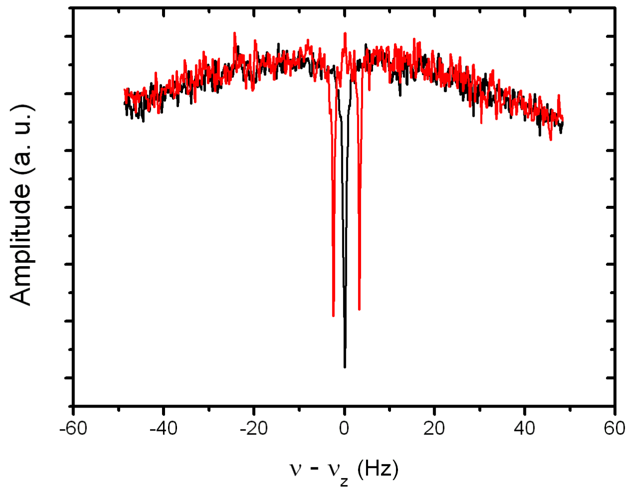
Image current detection





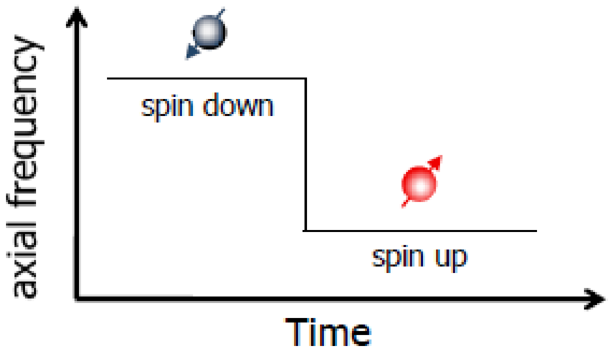
The axial motion of the particle shorts the thermal noise of the detector

Coupling cyclotron to axial via $\nu_{rf} = \nu_+ - \nu_z$



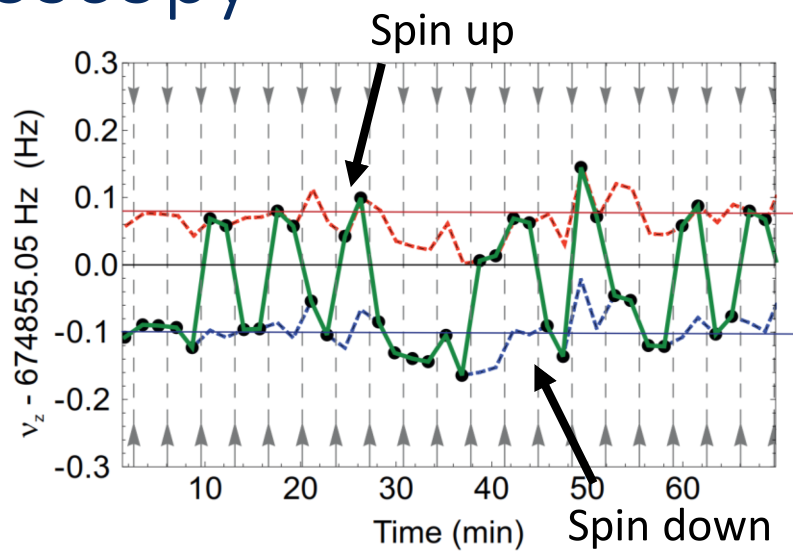
$$\nu_+ = \nu_l + \nu_r - \nu_z + \nu_{rf}$$

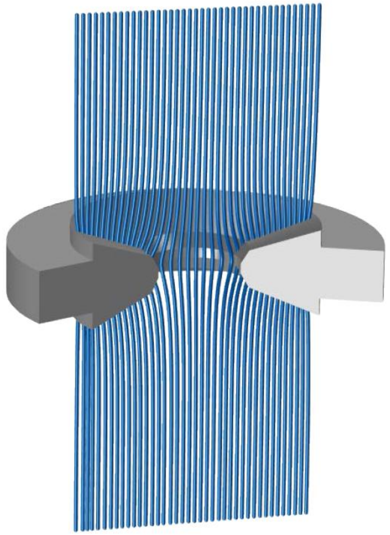
Larmor frequency: Spin state spectroscopy



The Larmor frequency is not associated with image currents and cannot be measured directly

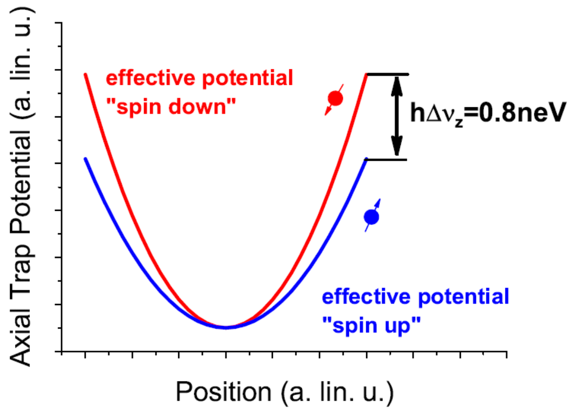
The spin state is translated into an axial frequency shift by means of the continuous Stern-Gerlach effect





$$\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$$

$$B_z = B_0 + B_2 \cdot (z^2 - \rho^2/2)$$



Magnetic bottle $B_2 \approx 300\ \mathrm{kT/m^2}$

BASE demonstrated the resolution of proton and antiproton spin transitions for the first time

➔ Enables direct measurements of the proton/antiproton magnetic moment

➔ Spin state identification required for high precision measurements

S. Ulmer et al., PRL **106** (2011), A. Mooser et al., PRL **110** (2013), C. Smorra et al., PLB **769**(C) (2017), see also J. DiSciacca et al., PRL **108** (2012) and J. DiSciacca et al., PRL **110** (2013)

The main challenge: heating rates

Change of ∓ 1	$\Delta\nu_z$
m_s	172 mHz
n_+	64 mHz
n_-	40 μHz

Spin state detection:
➔ Coupling $\overrightarrow{\mu_{\bar{p}}}$ to ν_z

Challenge ➔

$\overrightarrow{\mu_{\bar{p}}} = \overrightarrow{\mu_+} + \overrightarrow{\mu_-} + \overrightarrow{\mu_S}$
→ Sum of radial and spin moment

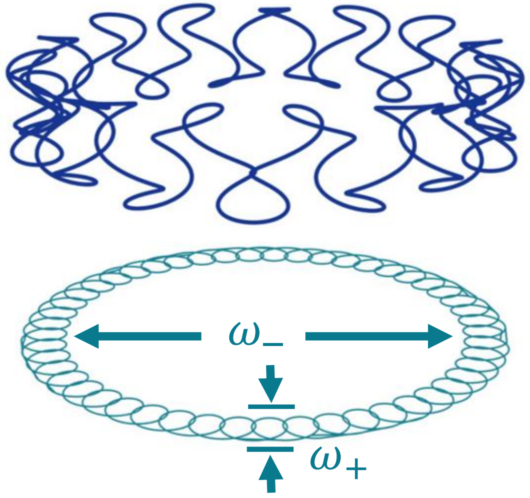
$$\Phi_M = -(\overrightarrow{\mu_{\bar{p}}} \cdot \vec{B})$$

$$\Delta\omega_z \approx |\overrightarrow{\mu_+} + \overrightarrow{\mu_-} + \overrightarrow{\mu_S}| \cdot \frac{B_2}{2\pi\, m_{\bar{p}}\omega_z} \approx \frac{\hbar\omega_+}{m_{\bar{p}}\omega_z}\frac{B_2}{B_0}\left(\left(n_+ + \frac{1}{2}\right) + \frac{\omega_-}{\omega_+}\left(n_- + \frac{1}{2}\right) + \frac{g_{\bar{p}} m_s}{2}\right)$$

Cyclotron motion ω_+

Spin precession ω_L

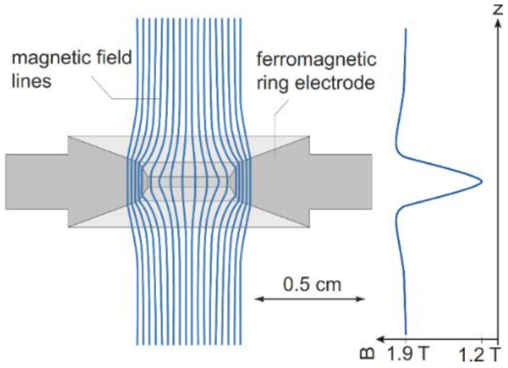
Magnetron motion ω_-



$$\boxed{\zeta_+ = \frac{q^2 n_+}{2 m_{\bar{p}} \hbar\omega_+} S_E(\omega_+)}$$

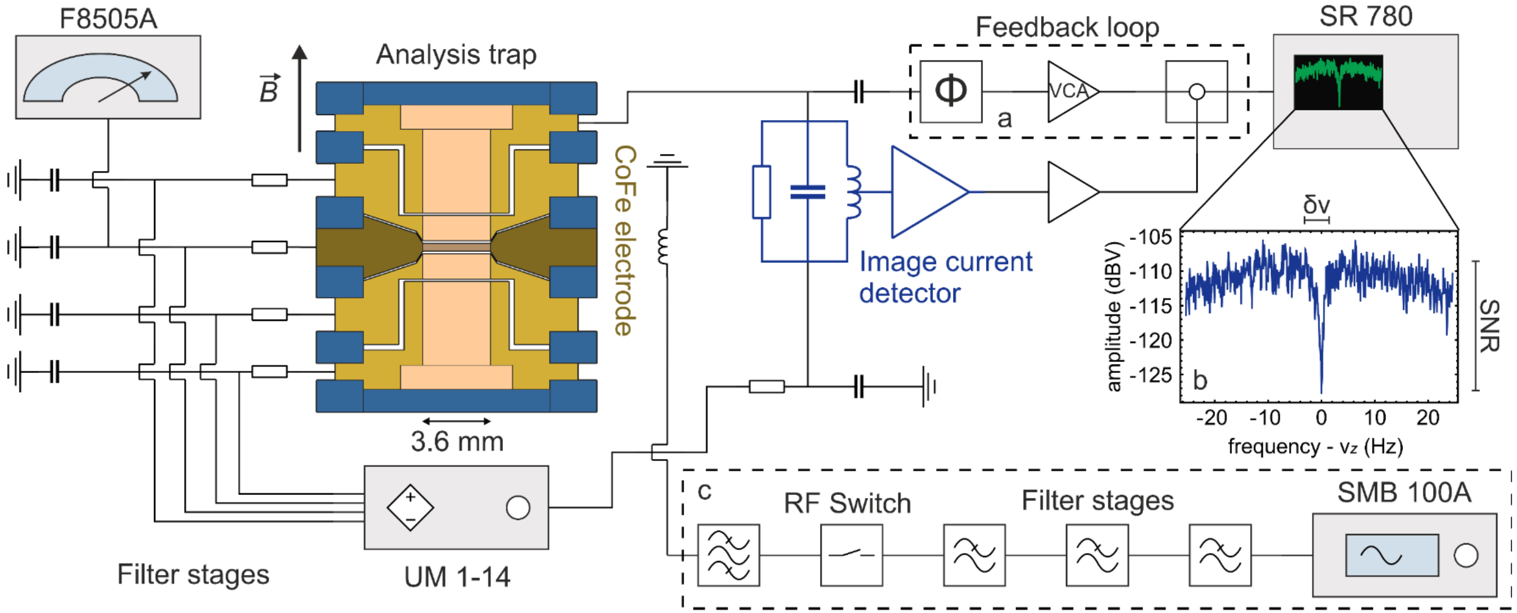
3 cyclotron quantum jumps shift ν_z similar to a spin flip!

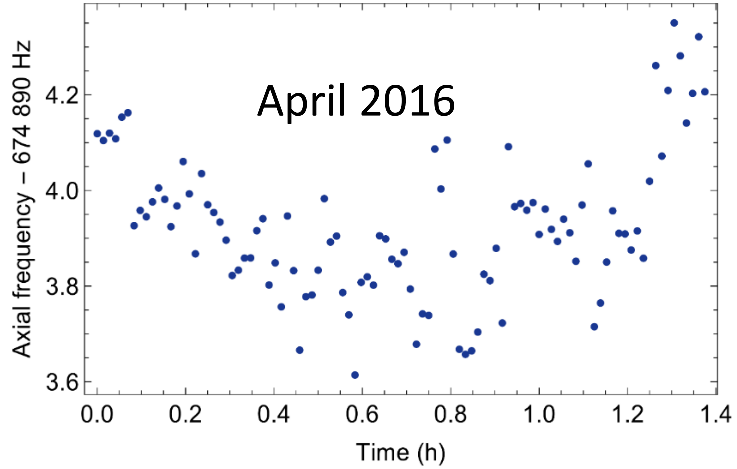
➔ Extremely low cyclotron transition rate ζ_+ below a few quanta per 10 minutes is required!
➔ Parasitic electric field noise with PSD $S_E(\omega_+)$ needs to be very highly suppressed!



Magnetic bottle
$B_2 \approx 300\ \mathrm{kT/m^2}$

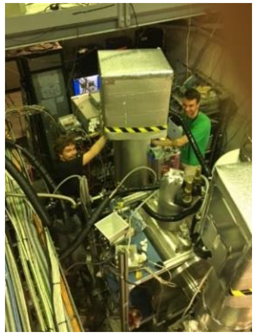
Stabilizing the BASE apparatus

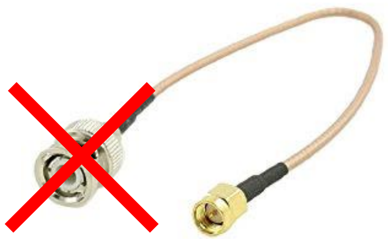


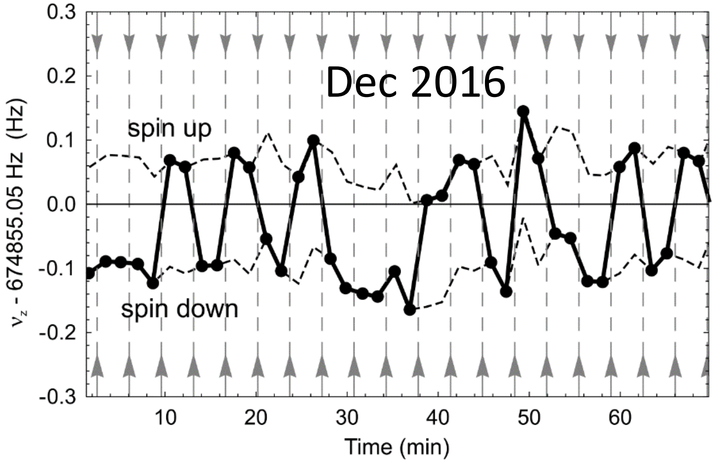


How to minimize $S(\omega)$?

- Ground loops
- High-order filter-stages
- Careful RF design
- Decoupling from turbulent airflow
- …





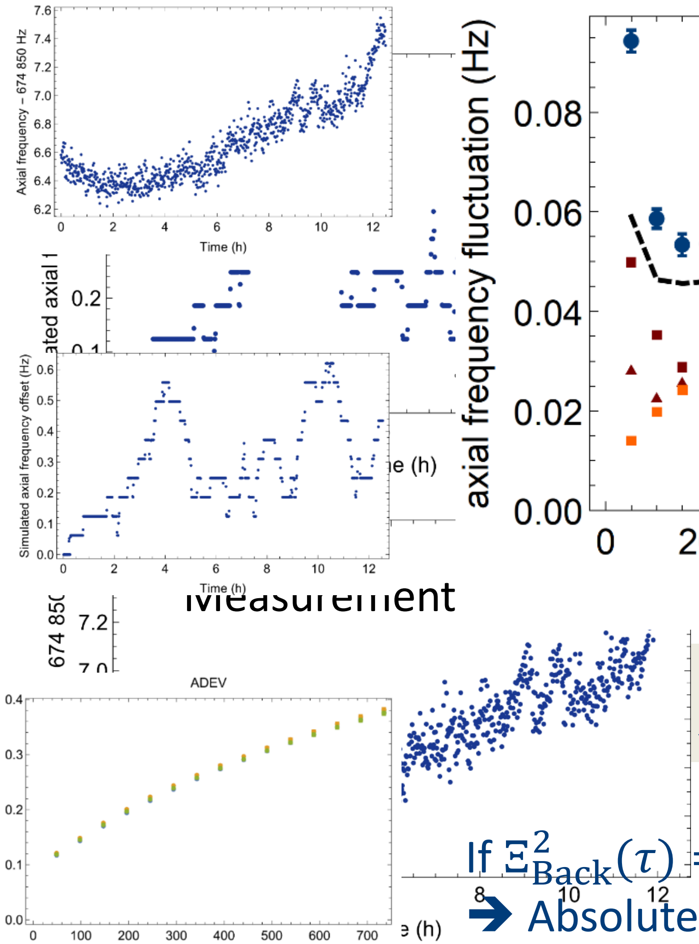


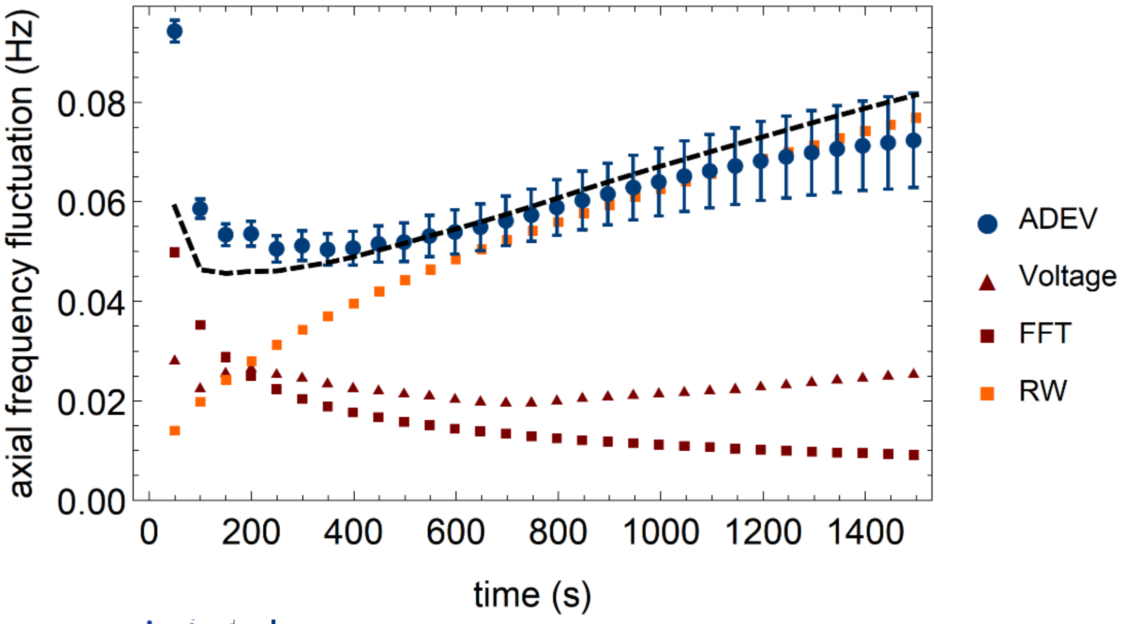
➔ 10 mHz improvement ➔ 20 mHz improvement

C. Smorra et al., *Phys. Lett. B* **769**, 1-6 (2017)

How big are the transition rates really?

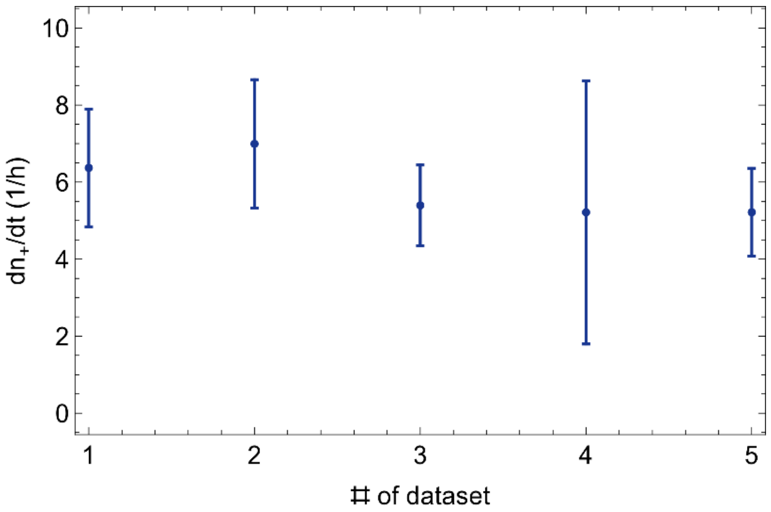
Measuring transition rates ζ_+





$$\sigma_y^2(\tau) = \langle(\bar{y}_m - \bar{y}_{m+1})^2\rangle$$

Allan variance $\sigma_y^2(\tau)$ is the variance of fractional averages of a quantity y



$\Delta\nu_z \approx 1$ Hz

$\Delta n_+ \approx 17$

$$\sqrt{\sigma_V(\tau)^2 + \sigma_{\mathrm{FFT}}(\tau)^2 + \tau(\Delta_+^2\zeta_+)}$$

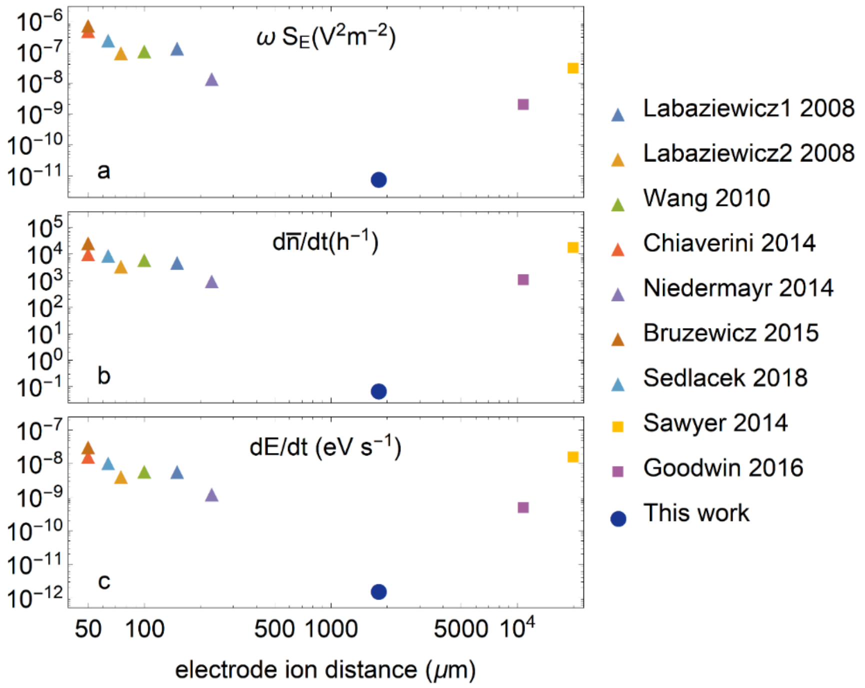
If $\Xi^2_{\mathrm{Back}}(\tau) = \sqrt{\sigma_V(\tau)^2 + \sigma_{FFT}(\tau)^2}$ is sufficiently small,

➔ Absolute heating rates can be extracted.

Stabilized a single antiproton to $\zeta_+ < 10 \cdot \mathrm{h}^{-1}$ for several days!

Achieving such low transition rates is the key prerequisite for a high precision multi-trap g-factor measurement!

Heating rates and electric field noise PSD



Why is the BASE scaled electric field noise so low?

- Triangles: cryogenic RF trap measurements with small electrode-ion distances
- Squares: room temperature Penning trap measurements
- FIRST heating rate measurement in a cryogenic Penning trap
- The measurement of the antiproton magnetic moment requires extremely low noise conditions due to its small value (and also due to the small mass)
- ν_+ is comparably high

$$dn_+/dt = \zeta_+ \times 1/(2n_+)$$

For $n_+ \gg 1$, transition rate ζ_+ and heating rate dn_+/dt are not identical!

$$\zeta_+ = \frac{q^2 n_+}{2m_{\bar{p}}\hbar\omega_+} S_E(\omega_+)$$

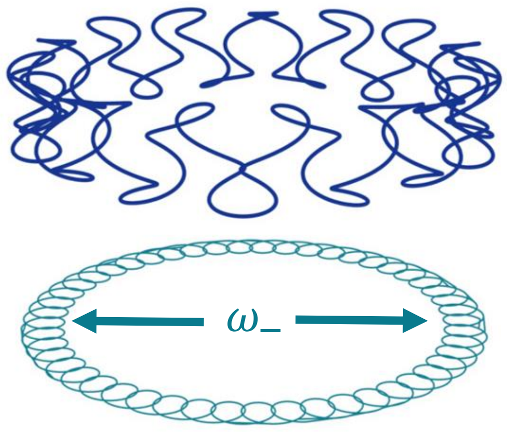
Scaled electric field noise is by a factor of 230 lower than the most low-noise Penning traps (Goodwin et al, Imperial) Factor of 1800 for Paul traps (Niedermayr, Innsbruck)

PHYSICAL REVIEW LETTERS 122, 043201 (2019)

Measurement of Ultralow Heating Rates of a Single Antiproton in a Cryogenic Penning Trap

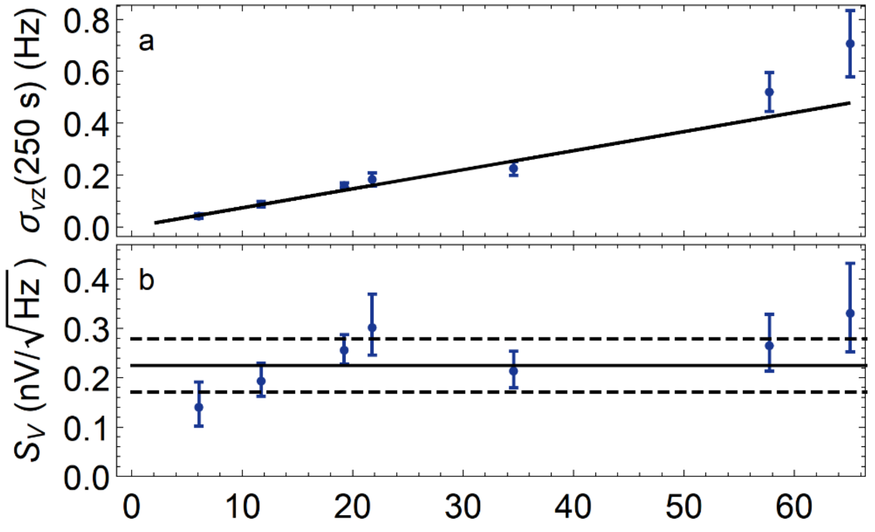
M. J. Borchert,[1,2,*] P. E. Blessing,[1,3] J. A. Devlin,[1] J. A. Harrington,[1,4] T. Higuchi,[1,5] J. Morgner,[1,2] C. Smorra,[1] E. Wursten,[1,7] M. Bohman,[1,4] M. Wiesinger,[1,4] A. Mooser,[1] K. Blaum,[4] Y. Matsuda,[5] C. Ospelkaus,[2,8] W. Quint,[3,9] J. Walz,[6,10] Y. Yamazaki,[11] and S. Ulmer[1]

Where does the noise come from?

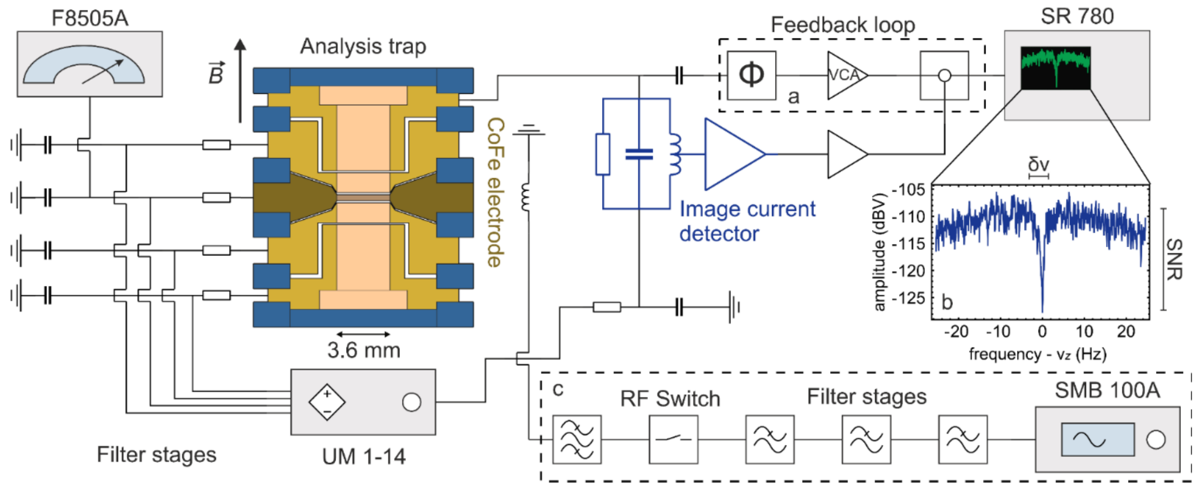


Varying the magnetron radius ρ_-

- Electrode ion distance d remains the same ($d \approx 1.8$ mm, $\rho_- < 70$ µm)
- Particle position in the trapping potential is changed
- Transition rate scaling is related to trapping voltage fluctuations
- This has to be discriminated from the d^{-4} behaviour observed in Paul traps



Observed S_V	$225(54)$ pV $\mathrm{Hz}^{-1/2}$
Axial detection system	1.5 pV $\mathrm{Hz}^{-1/2}$
Low-pass filter stages	< 1 pV $\mathrm{Hz}^{-1/2}$
Electrode Johnson noise	$\sim 3 \times 10^{-3}$ pV $\mathrm{Hz}^{-1/2}$
Blackbody radiation	$\omega_+ \times S_E(\omega_+) \sim 6 \times 10^{-14}\ \mathrm{V}^2\,\mathrm{m}^{-2}$
Background pressure	$\zeta_+ < 4 \times 10^{-9}\ \mathrm{s}^{-1}$

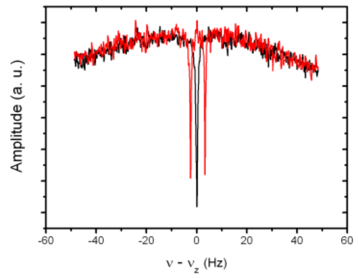


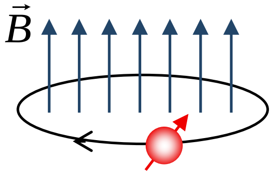
➔ Noise source is not clearly determined

➔ Electric field noise level in the analysis trap is extremely low

➔ Improvements might be possible by filtering the spin flip line

Magnetic moment measurement



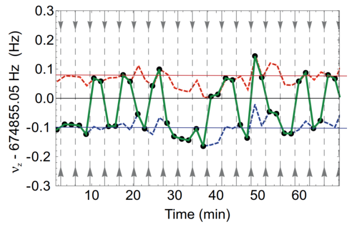


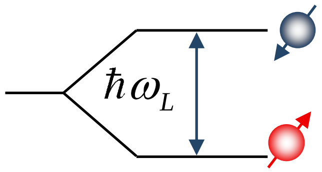
$$\nu_c = \frac{1}{2\pi}\frac{q}{m}B$$

Cyclotron frequency:
Image current based measurement
Cyclotron motion is coupled to axial via
$\nu_{rf} = \nu_+ - \nu_z$

$$\nu_+ = \nu_l + \nu_r - \nu_z + \nu_{rf}$$

$$g_{\bar{p}} = 2\frac{\nu_L}{\nu_c}$$





$$\nu_L = \frac{1}{2\pi}\frac{q}{m}\frac{g_{\bar{p}}}{2}B$$

Larmor frequency:
Measurement based on the continous
Stern Gerlach effect

$$\Delta\omega_z \approx \frac{\hbar\omega_+}{m_{\bar{p}}\omega_z}\frac{B_2}{B_0}\left(\frac{g_{\bar{p}}m_s}{2}\right)$$

A Larmor frequency measurement is only possible at low cyclotron transition rate ζ_+

$$\boxed{\zeta_+ = n_+ \cdot \frac{q^2}{2m_{\bar{p}}\hbar\omega_+}S_E(\omega_+)}$$

➔ Ultra-low electric field noise $S_E(\omega_+)$ needed
➔ Subthermal cooling required for achieving low n_+

Spin state resolution required for high precision measurements!

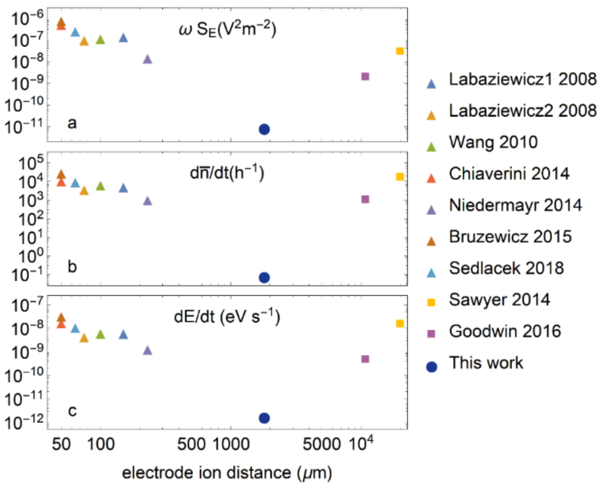
Single spin flip resolution

$$\zeta_+ = n_+ \cdot \frac{q^2}{2 m_{\bar{p}} \hbar \omega_+} S_E(\omega_+)$$

Spin state identification required for high precision g-factor measurements

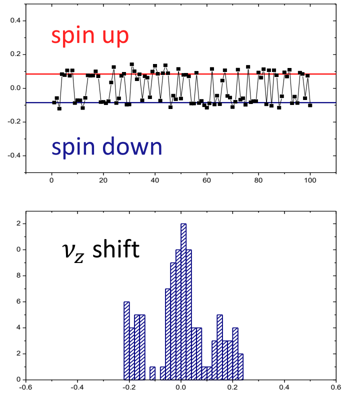
Low $S_E(\omega_+)$ & low n_+ ➔ Single spin transition are resolved and spin states identified

1. Low $S_E(\omega_+)$ ➔ Achieved



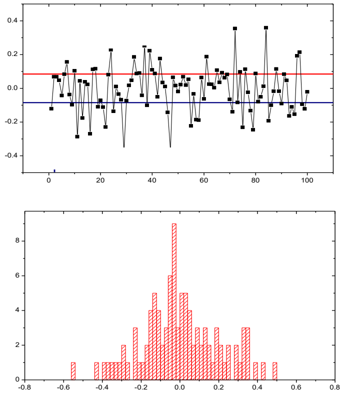
2. Low n_+ ➔ Subthermal cooling

cold particle (50mK)

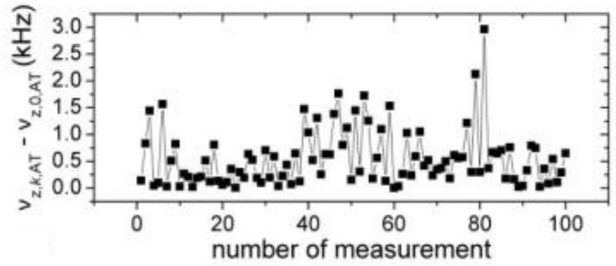


high-fidelity spin state resolution

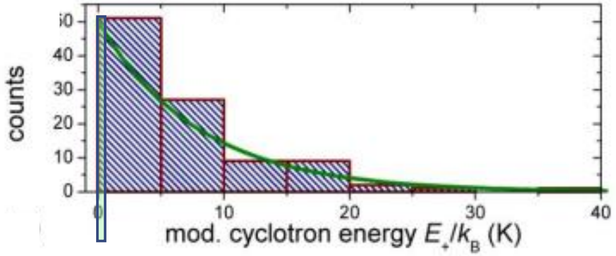
hot particle (1K)



fidelity at 65%, not useful for measurements



Mode preparation by resistive cooling with the detector at 12.8 K



particles with single spin-flip resolution are in this temperature range

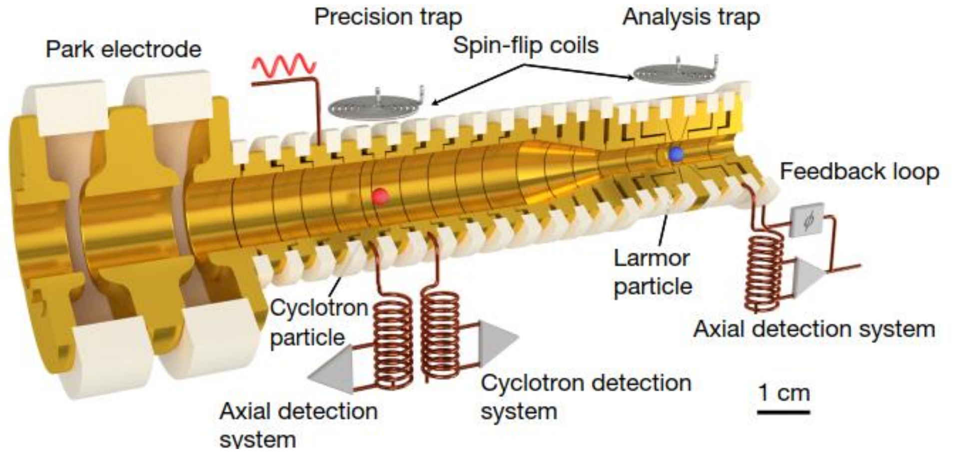
$E_+/k_B = 0.1\text{K}$

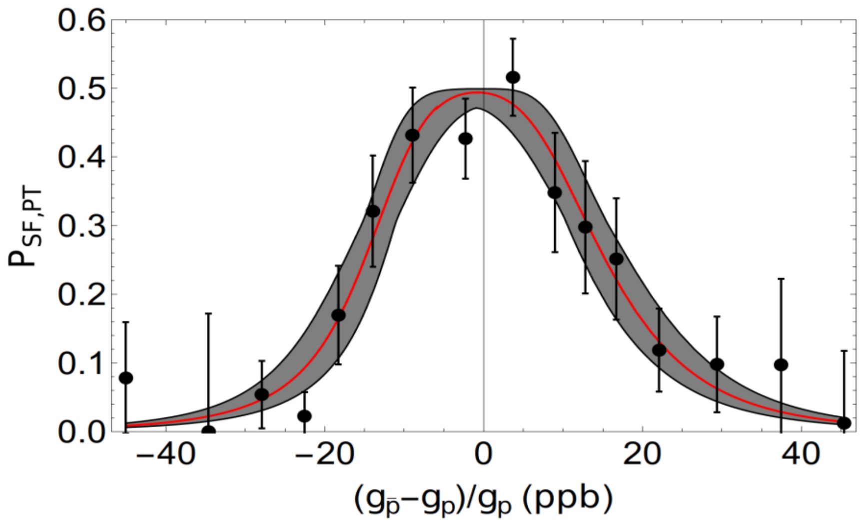
→ 90 % spin state detection fidelity

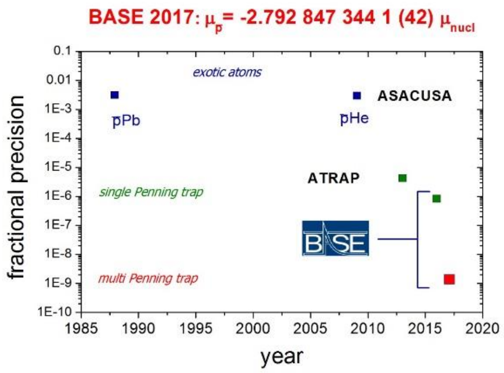
Challenge: Cyclotron frequency measurement with sidebands heats the cyclotron mode to about 300 K

Preparation time for a single antiproton: About 10 hrs!

Most precise measurement of the antiproton magnetic moment







Overcome long preparation times: Divide and conquer!

C. Smorra *et al.*, Nature **550**, 371 (2017)

Hot cyclotron particle

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

Magnetic field measurement

Cold Larmor particle

$$\omega_L = \frac{q}{m}\frac{g_{\bar{p}}}{2} B$$

Spectroscopy of ω_L by spin state analysis

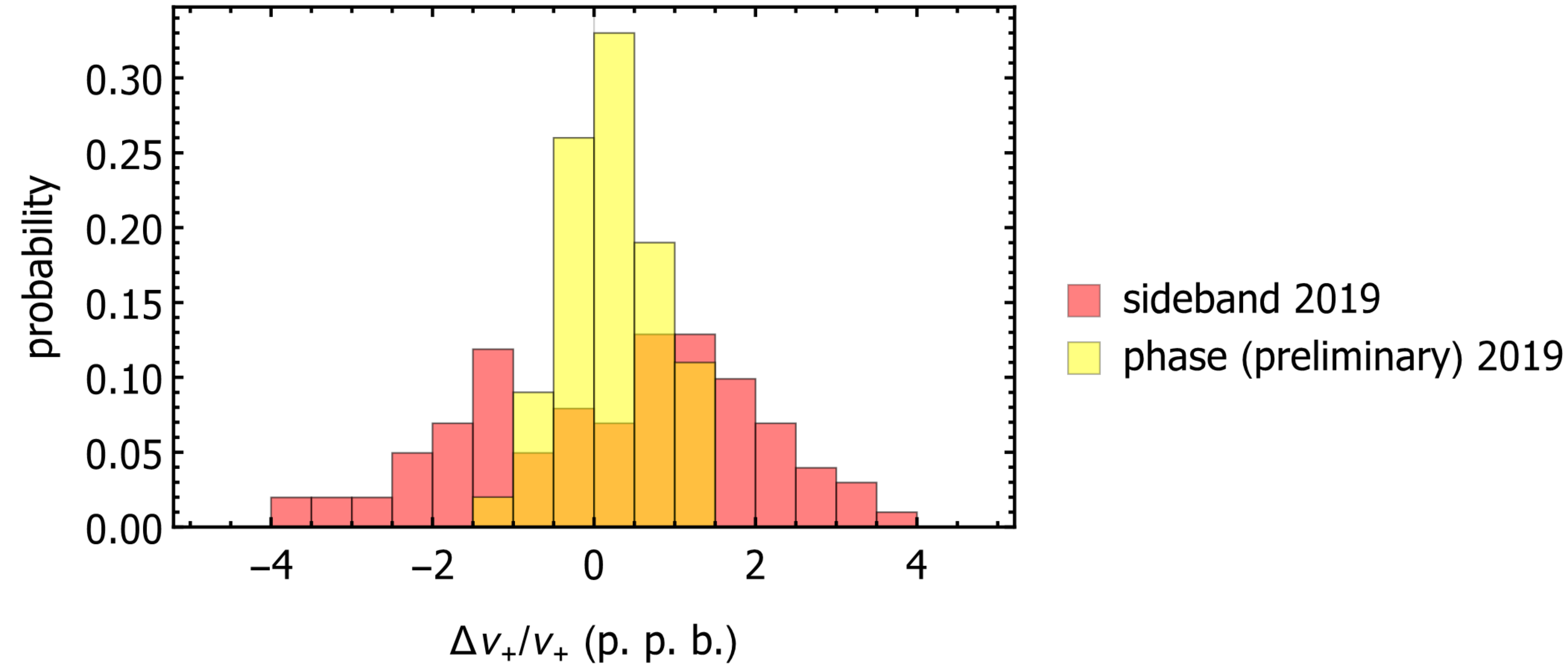
$$\boxed{g_{\bar{p}}/2 = 2.792\,847\,344\,1\,(42)}$$

Benefit: Fast sampling, no need to perform subthermal cooling to 100 mK
Disadvantage: Complicated systematics due to different particle energies $E_{c,+}$, $E_{L,+}$

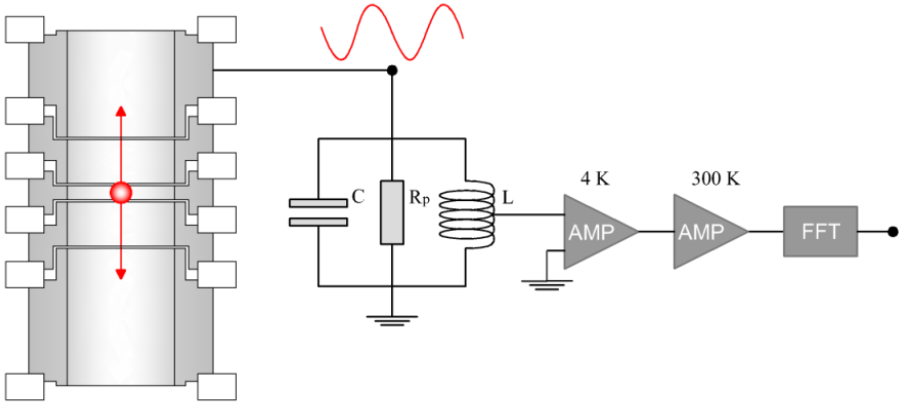
BASE improved the precision of $g_{\bar{p}}$ by a factor of > 3000!

For more details: See talk 78 by Stefan Erlewein (Thursday)

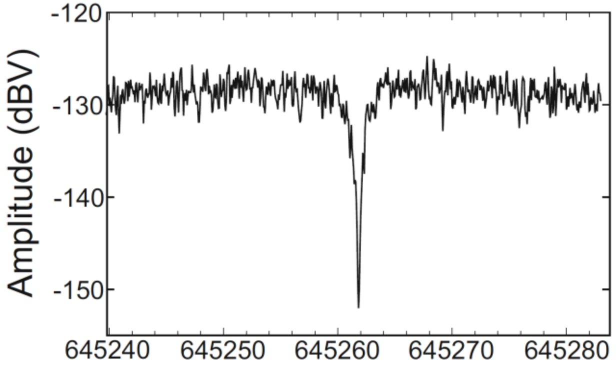
Part II – Phase measurements



Recap: Image current detection methods

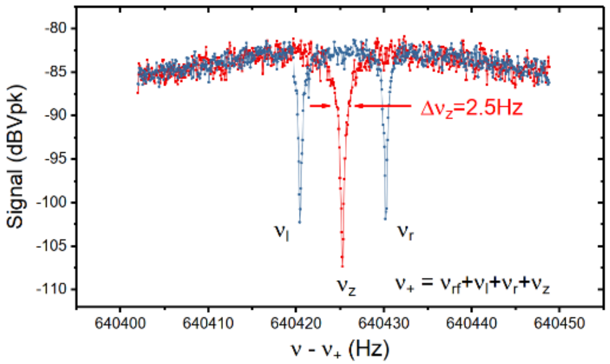


1. Axial motion shorts the thermal detector noise



2. Coupling cyclotron motion to axial by $\nu_{rf} = \nu_+ - \nu_z$

$$\nu_+ = \nu_l + \nu_r - \nu_z + \nu_{rf}$$



3. Summing up the three eigenfrequencies yields the cyclotron frequency

$$\omega_c^2 = \omega_+^2 + \omega_z^2 + \omega_-^2$$

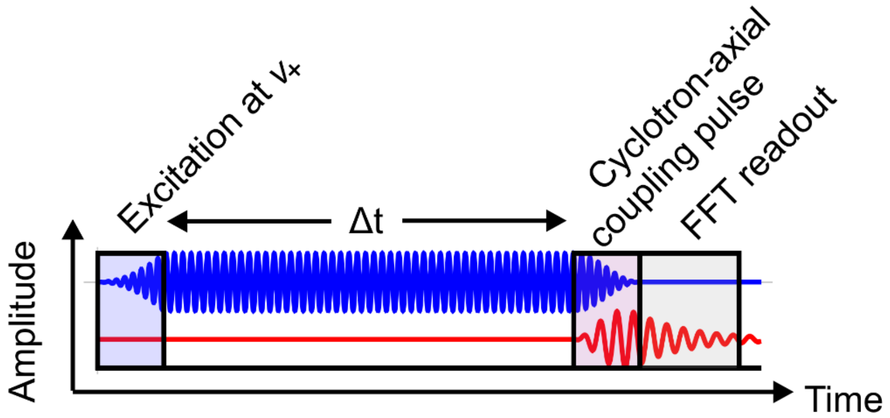
Shot-to-shot scatter: ~ 1.5 ppb
Resolution: ~20 ppt

Limited by voltage stability

Requires FFT averaging for about 60 s per spectrum

BUT: Superconducting magnets can be much more stable than the best voltage sources!

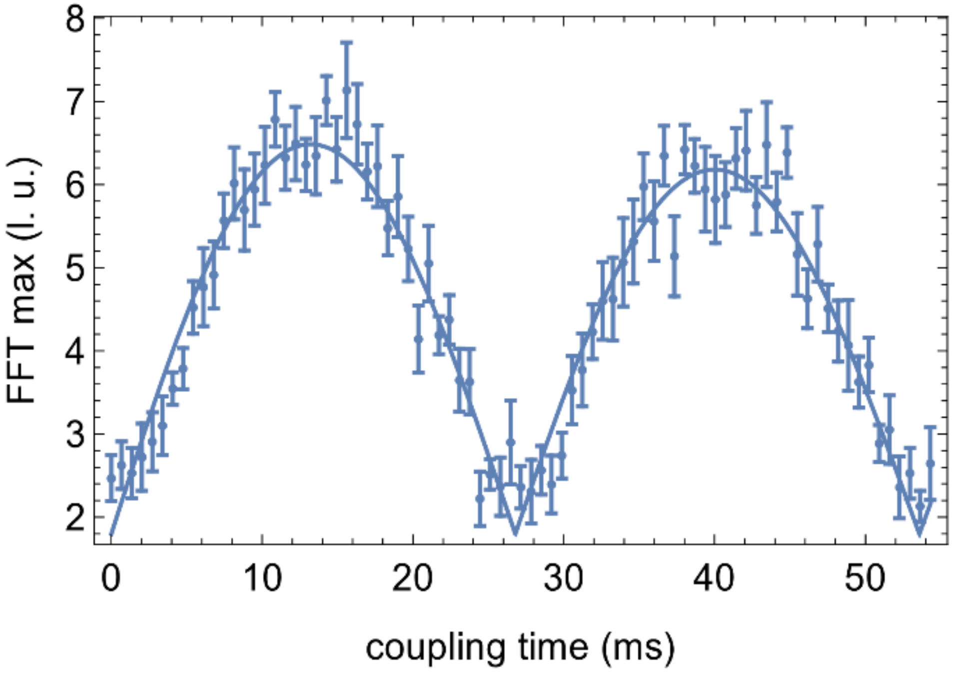
Classical Rabi oscillations



1. Excite cyclotron

2. Apply sideband $\nu_{rf} = \nu_+ - \nu_z$ for variable time

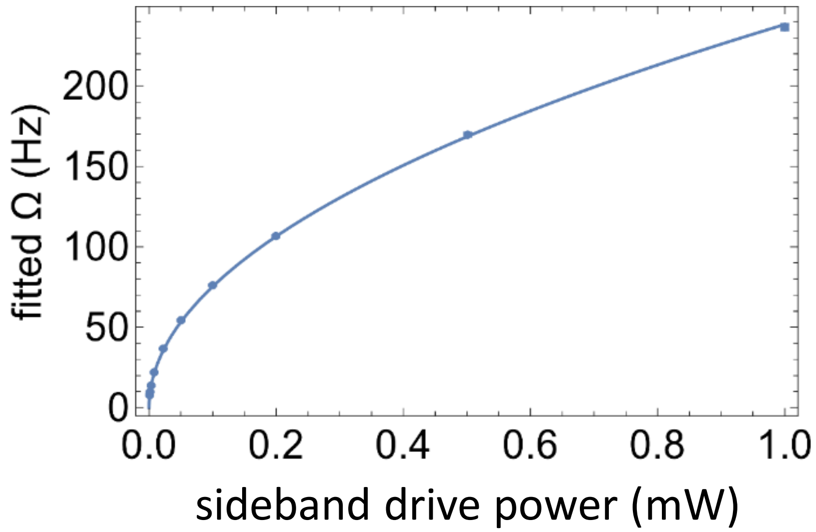
3. Read out axial amplitude



Periodic exchange of energy with frequency

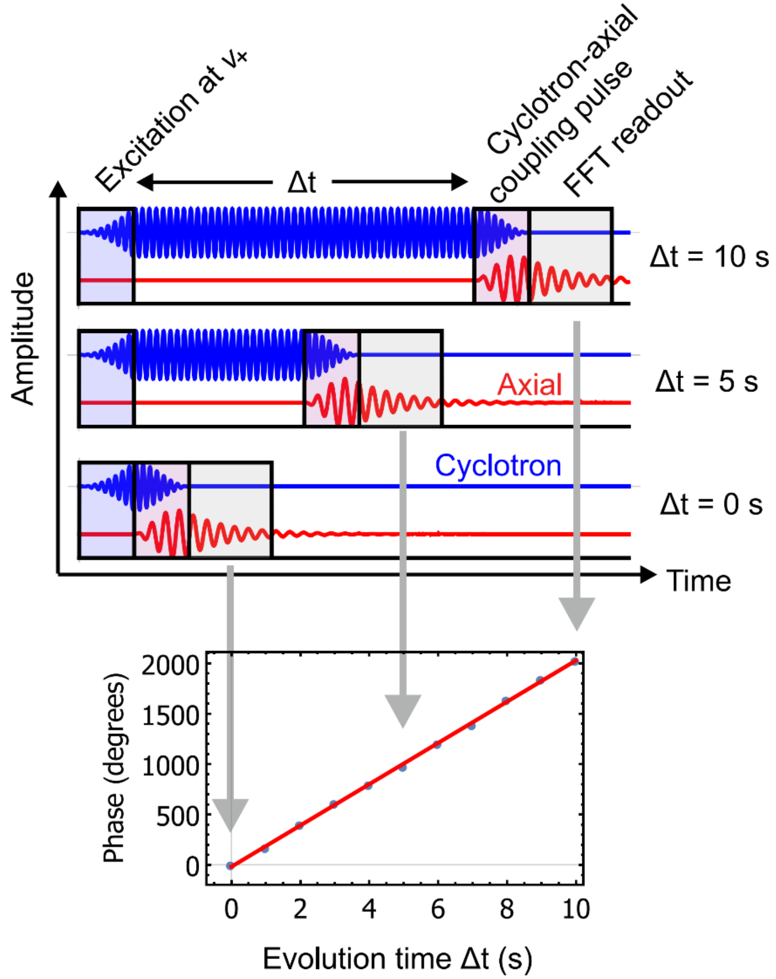
$$\Omega = \frac{qE_0}{2m\sqrt{\omega_+\omega_z}}$$

At a π-pulse (Ω=1/2), we observe a full transfer of energy and phase between both mode



The phase transfer between both modes can be used for high precision frequency measurements!

Phase sensitive detection



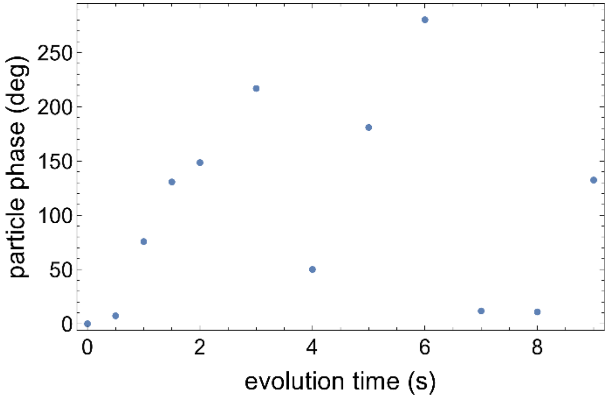
1. Excite cyclotron

2. Phase evolution

3. π-pulse at $\nu_{rf} = \nu_{+} - \nu_{z}$

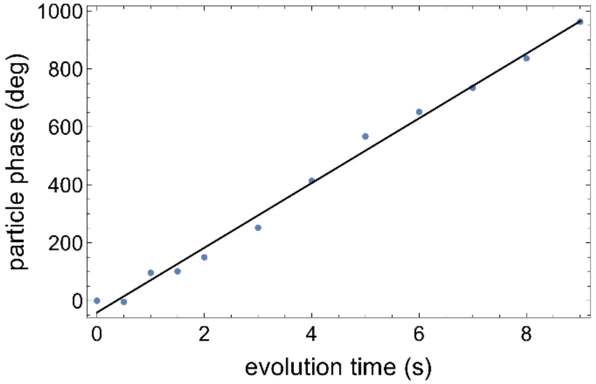
4. Phase readout

Raw data



Phase unwrapping

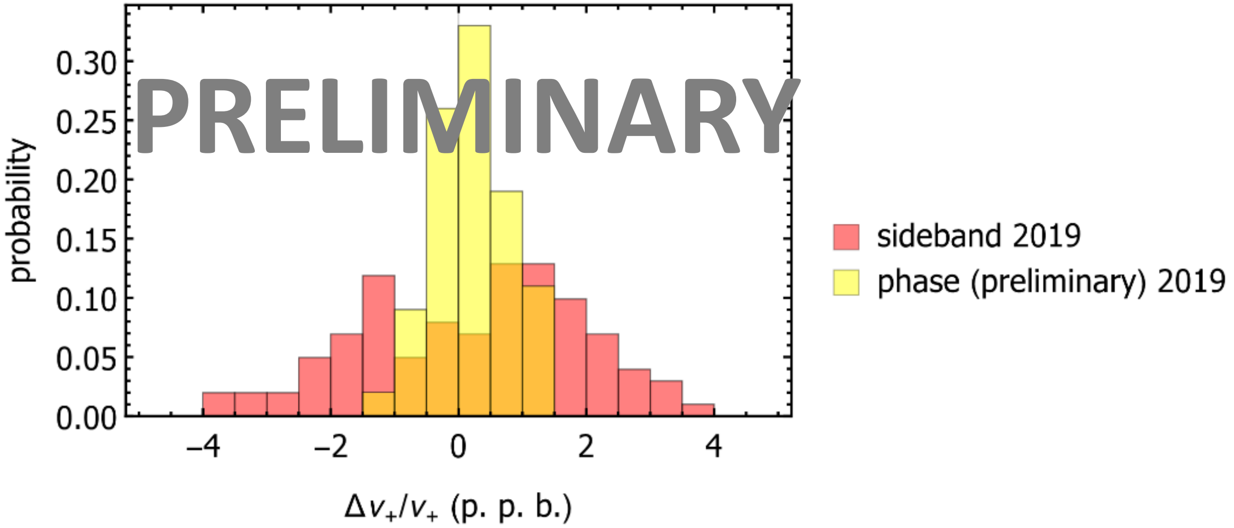
Unwrapped data

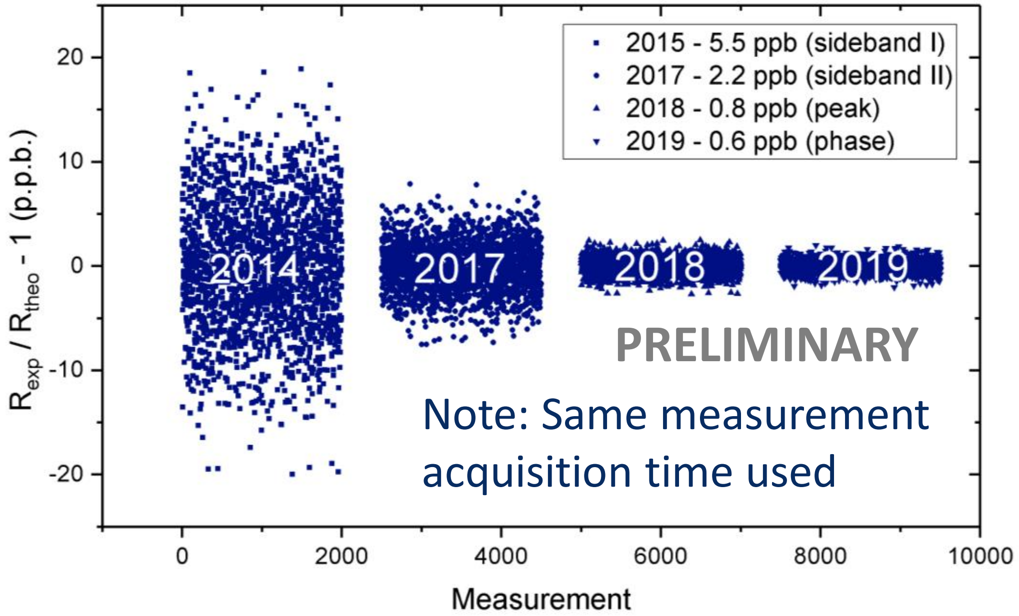


The gradient gives the cyclotron frequency minus a known offset frequency

Frequency stability

First thing to do:
Compared the old and the new measurement method:





Note: Same measurement acquisition time used

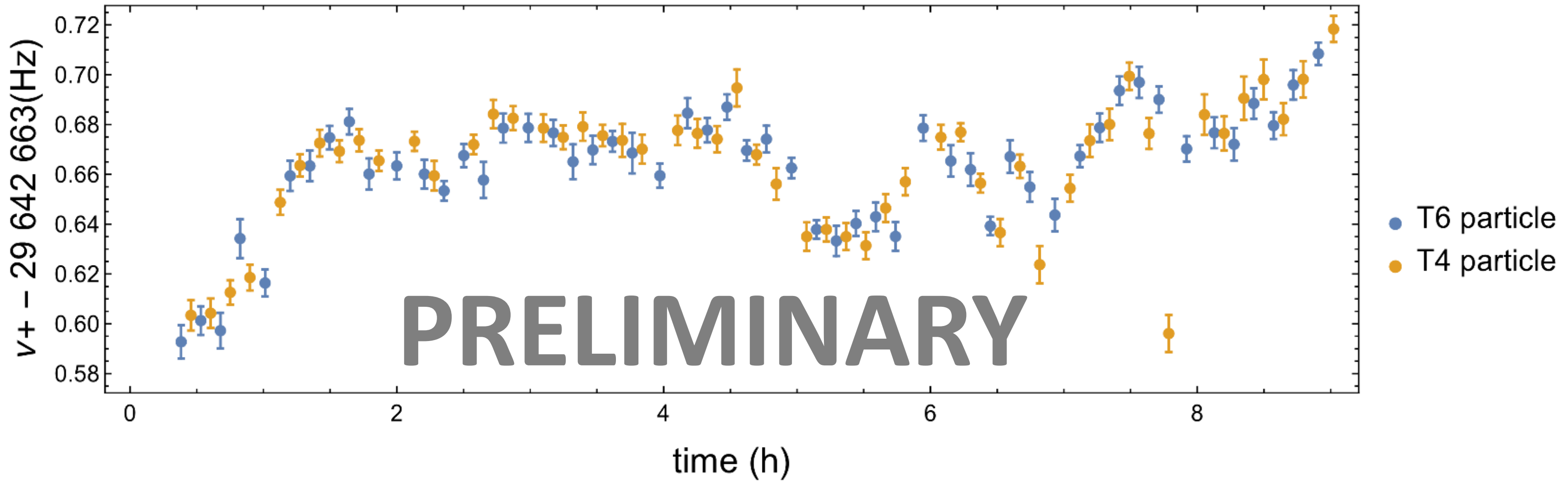
$\sigma \sim \sqrt{1/T_{avg}}$ for peak and sideband method
$\sigma \sim 1/T_{avg}$ for phase methods!

Advantages compared to the peak method

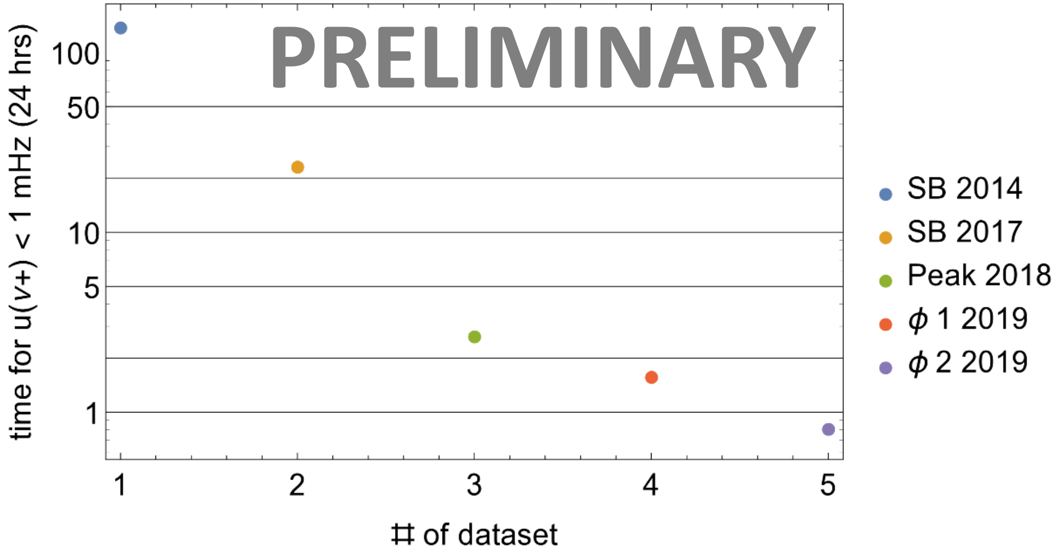
- Much lower excitation energies needed compared to the peak method (-> better systematics)
- Peak method based on dissipating energy during the measurement -> frequency changes during the measurement
- For a stable magnetic field, arbitrary long evolution times can be reached (in principle)

➔ Aiming for long evolution times and low excitation energies

Frequency resolution



Achieved a peak-to-peak stability of about 100 mHz over 9 hours:
➔ Good conditions for long evolution times



Measurement “days” for 1 mHz frequency resolution

As the standard error is $\sigma/\sqrt{N}$, a linear improvement in stability decreases the required measurement time quadratically

DISCLAIMER: Presented data show frequency resolution, BUT systematic studies are ongoing

During the past 5 years:
Cyclotron scatter improved by a factor of >10
➔ Required measurement time decreased by >100

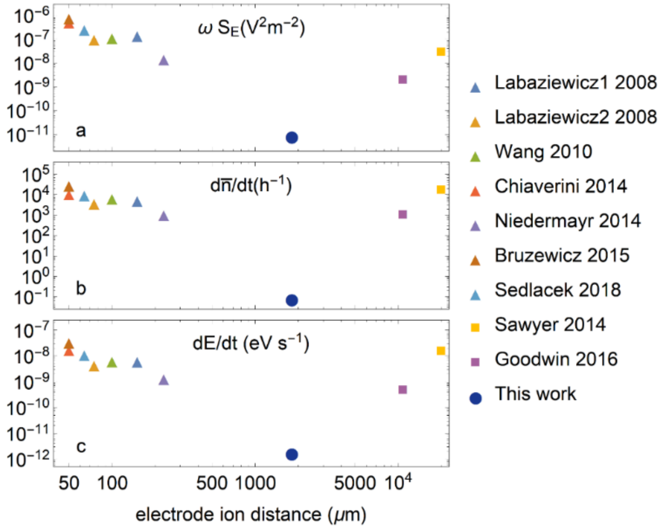
Summary

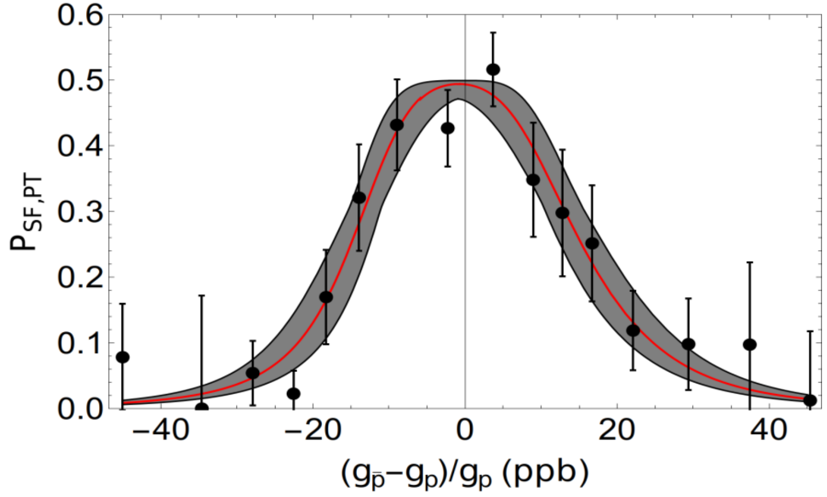
1. Ultra-low heating rates in a cryogenic Penning trap

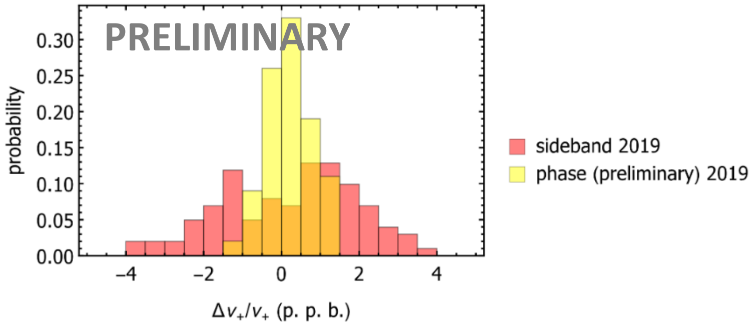
   Enabled

2. The most precise measurement of the antiproton magnetic moment

3. Phase sensitive methods demonstrated in the BASE apparatus







Backup slides

Phase measurements setup