Recent results from the BASE experiment

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Speaking on behalf of the BASE collaboration

Contents

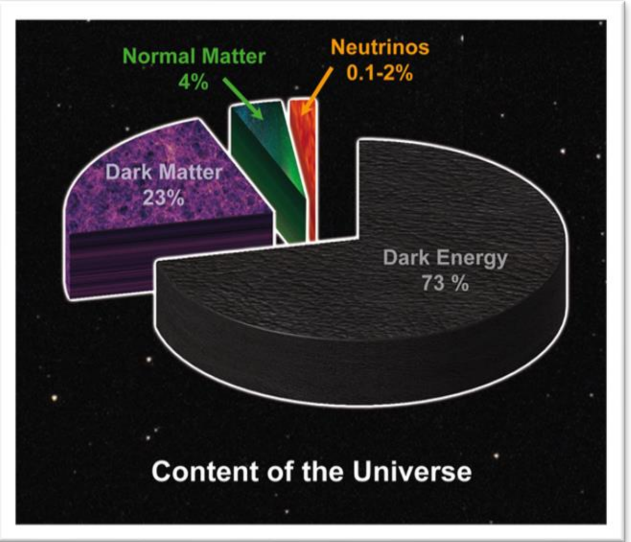
- Motivation & Goals
- The BASE experiment
- Results of the last antiproton campaign
  - Two detection methods to measure the charge-to-mass ratio
  - Weak Equivalence Principle for clocks
  - In the meantime, we have also used data to search for ALPs!
- Outlook on the next campaign

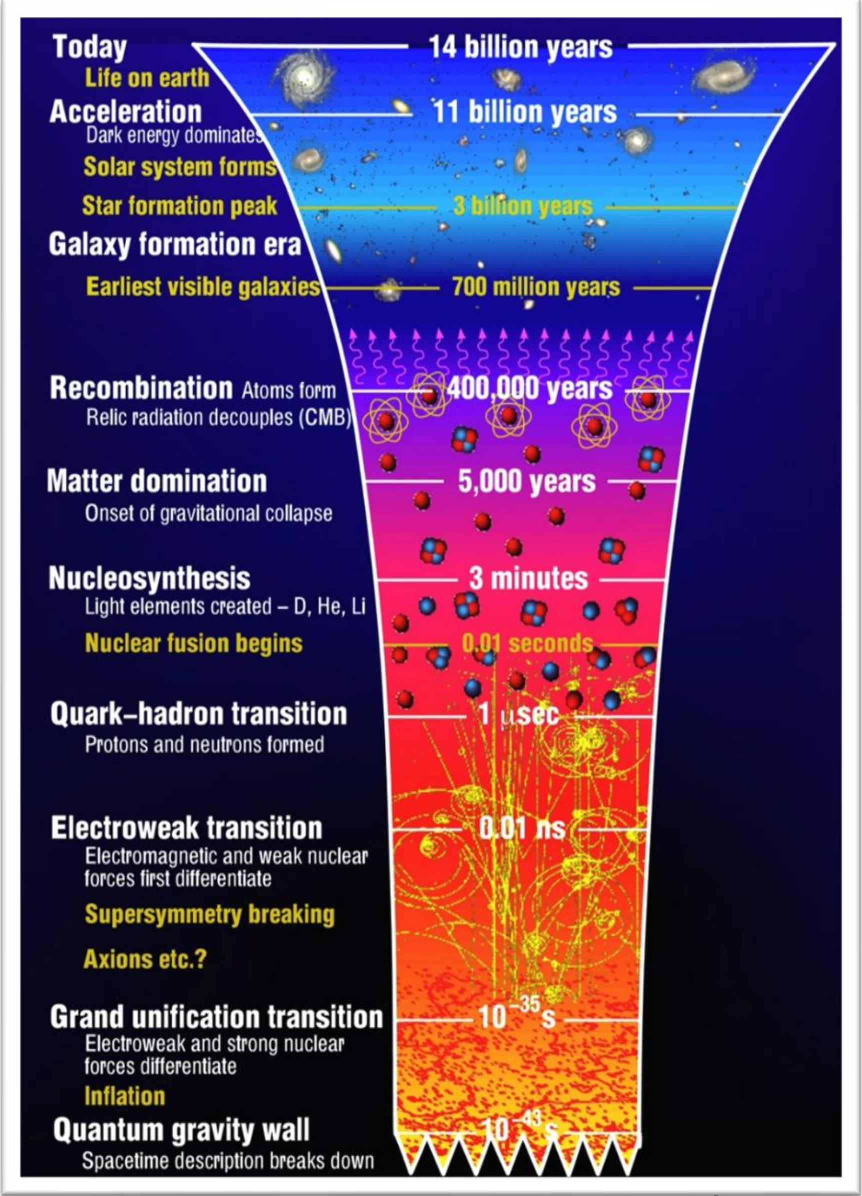
Motivation & Goals

The Standard Model of Particle Physics is very successful…

… but there are still some open issues:

- gravity
- dark matter
- dark energy
- **matter/antimatter asymmetry**
- …





Motivation & Goals

Why is there so much more matter than antimatter in the universe?
Baryon asymmetry parameter:

Observed: $$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Standard Model prediction: $$\sim 10^{-18}$$

BASE

Motivation & Goals

Why is there so much more matter than antimatter in the universe?
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Standard Model prediction: $$\sim 10^{-18}$$

Conditions for baryon asymmetry by Sakharov[1]:

- Baryon number violation
- C and CP violation
- Departure from local equilibrium or **CPT violation**

[1] A.D. Sakharov, JETP Lett 5, 24 (1967)

Motivation & Goals

CPT invariance implies for a particle and its antiparticle:

- Same mass m
- Same lifetime τ
- Opposite charge q
- Opposite magnetic moment μ

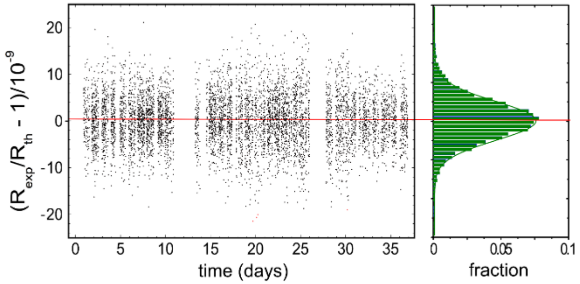
The Baryon Antibaryon Symmetry Experiment (BASE)

- Studies the fundamental properties (m, q, τ, μ) of **protons and antiprotons**

Motivation & Goals

Charge-to-mass ratio

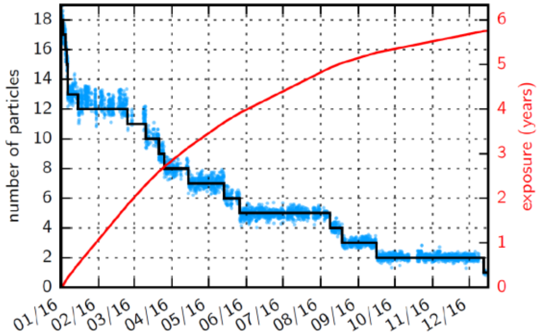
$$R_{\mathrm{exp}} = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$



$$\frac{(q/m)_{\bar{p}}}{(q/m)_{p}} + 1 = 1(69) \times 10^{-12}$$ **69ppt** [1]

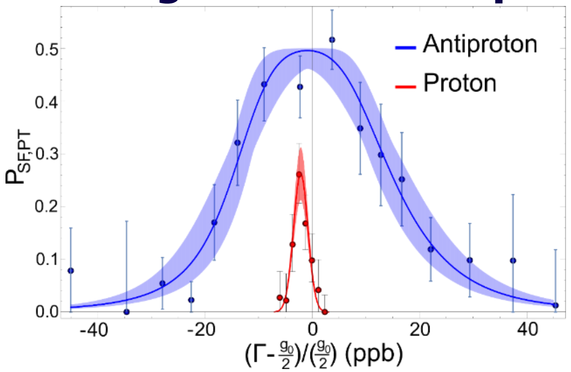
Lifetime τ

Antiprotons stored for longer than a year



$\tau_{\bar{p}} > 10.2a$ [2]

Magnetic moment μ



$\frac{g_p}{2} = +2.792\,847\,344\,62(82)$ **0.3ppb** [3]

$\frac{g_{\bar{p}}}{2} = -2.792\,847\,344\,1(42)$ **1.5ppb** [4]

The Baryon Antibaryon Symmetry Experiment (BASE)

- Studies the fundamental properties (m, q, τ, μ) of protons and antiprotons

[1] S. Ulmer *et al.*, Nature **524**, 196 (2015)
[2] S. Sellner *et al.*, NJP **19**, 083023 (2017)
[3] G. Schneider *et al.*, Science **358**, 1081 (2017)
[4] C. Smorra *et al.*, Nature **239**, 47 (2017)

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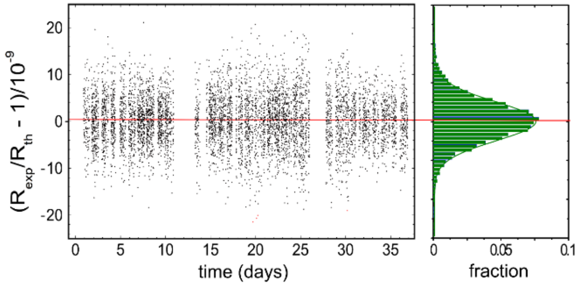

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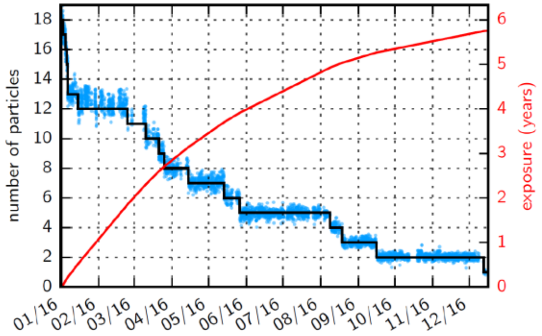

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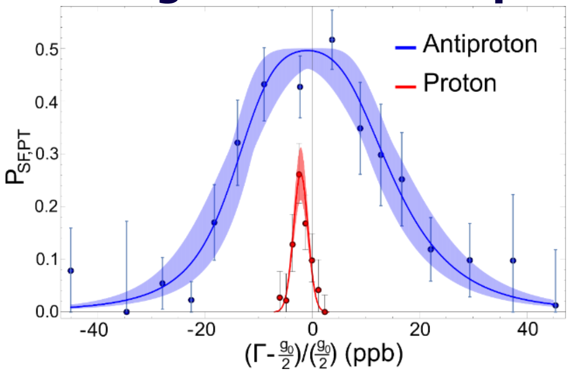

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The Baryon Antibaryon Symmetry Experiment (BASE)

- Studies the fundamental properties (m, q, τ, μ) of protons and antiprotons
- The last antiproton campaign measured the q/m ratio and will improve the limit by a factor 4
- The upcoming campaign will improve the antiproton magnetic moment

[1] S. Ulmer *et al.*, Nature **524**, 196 (2015)
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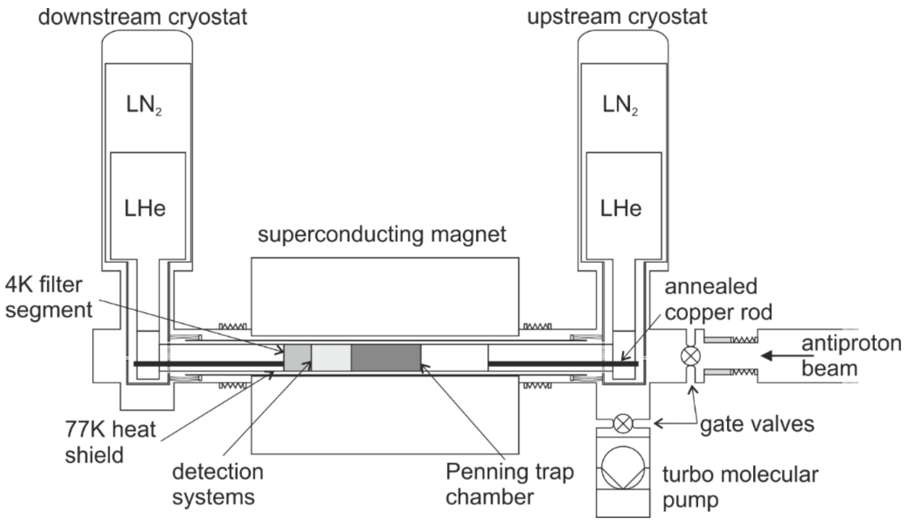
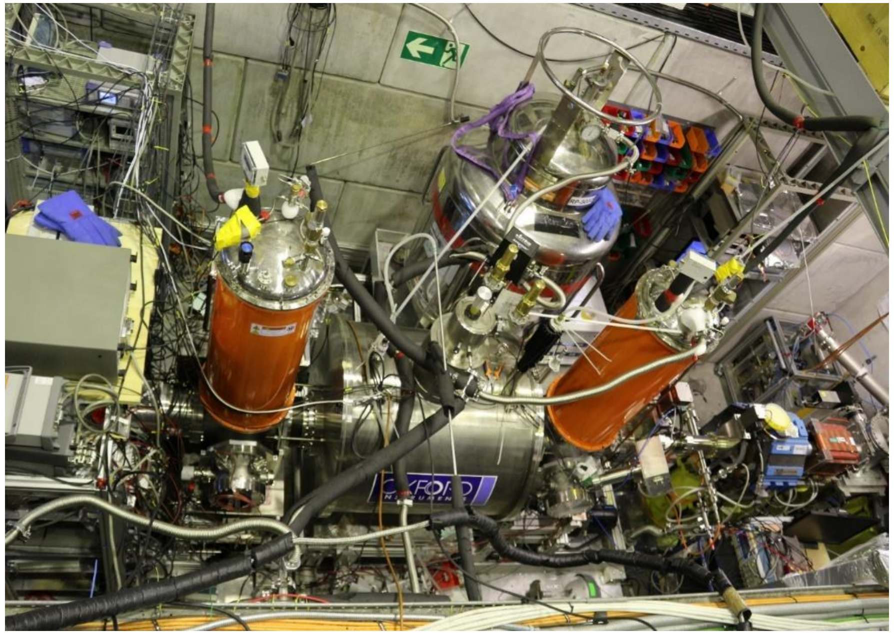
The BASE experiment

The BASE apparatus at CERN's Antiproton Decelerator is a system of cryogenic Penning traps



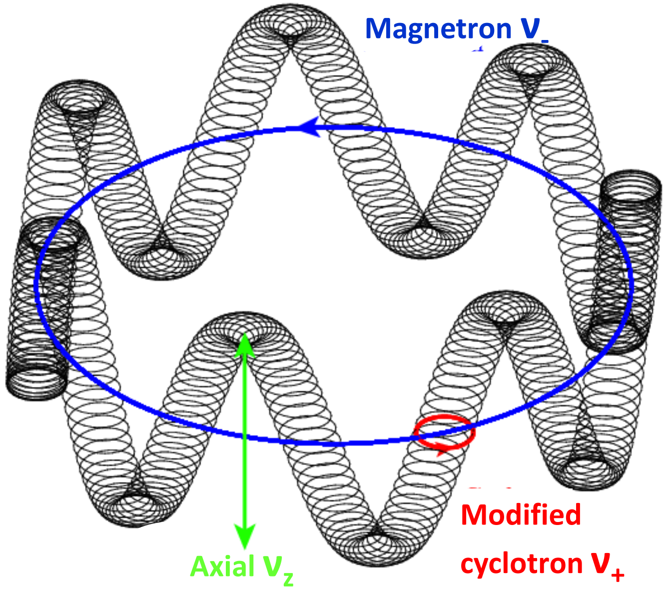


The BASE experiment

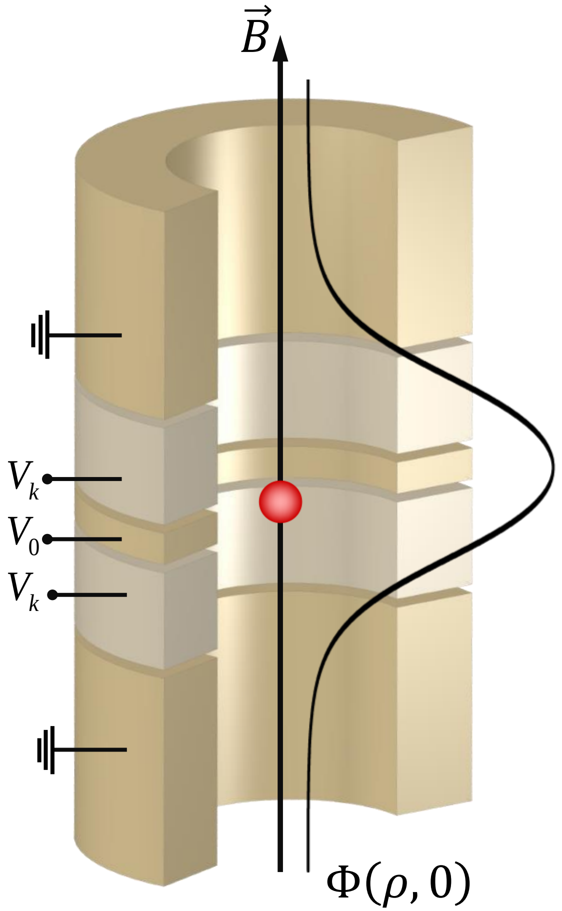
The core of the experiment is the Penning trap

Radial confinement: $\vec{B} = B_0 \hat{z}$

Axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$



Axial ν_z	640kHz
Magnetron ν_-	6kHz
Modified Cyclotron ν_+	23.9MHz



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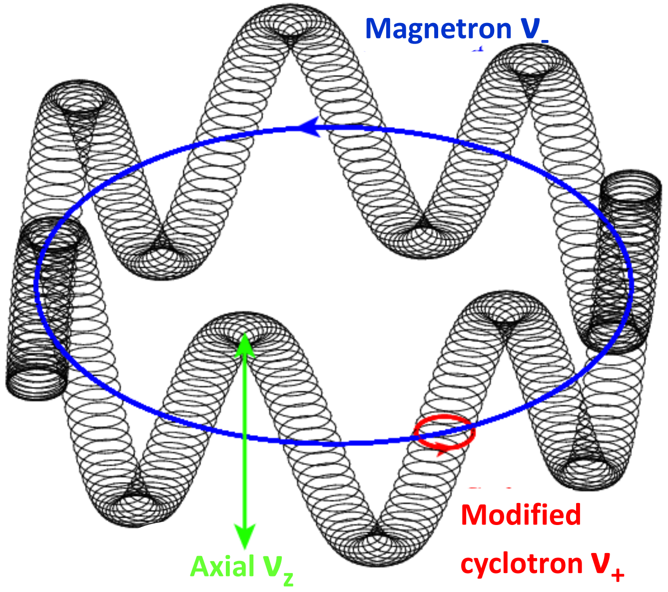

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Brown-Gabrielse Invariance Theorem

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

Cyclotron Frequency

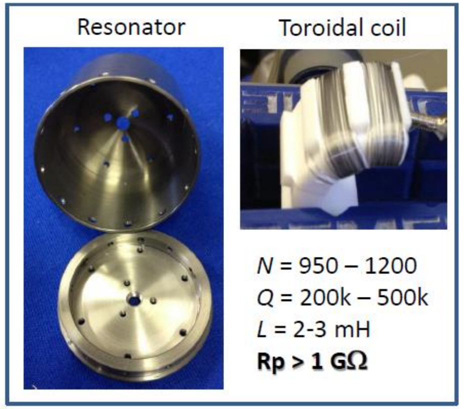
$$\nu_c = \frac{1}{2\pi} \frac{q}{m} B$$

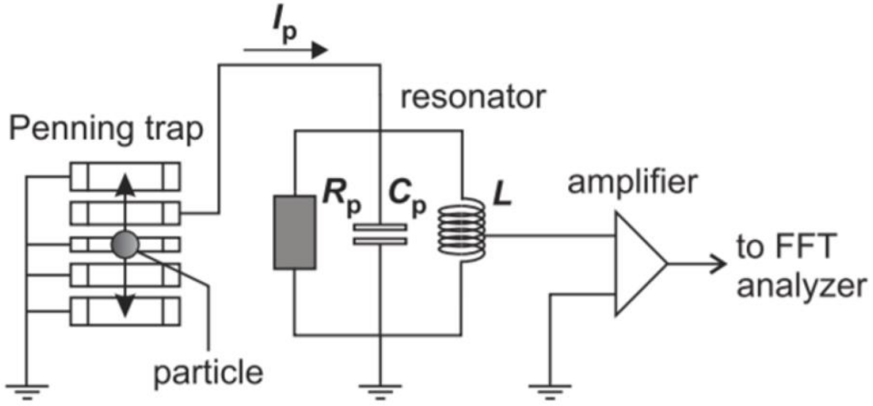
Brown, L. S., and G. Gabrielse, Phys. Rev. A **25**, 2423 (1982)

The BASE experiment

How do we measure the frequencies ν_z, ν_+ and ν_-?

- **axial motion ν_z** induces tiny image currents (1fA) in the trap electrodes, can be measured with an image current detector





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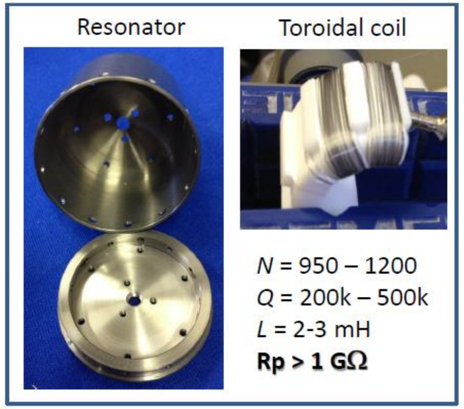

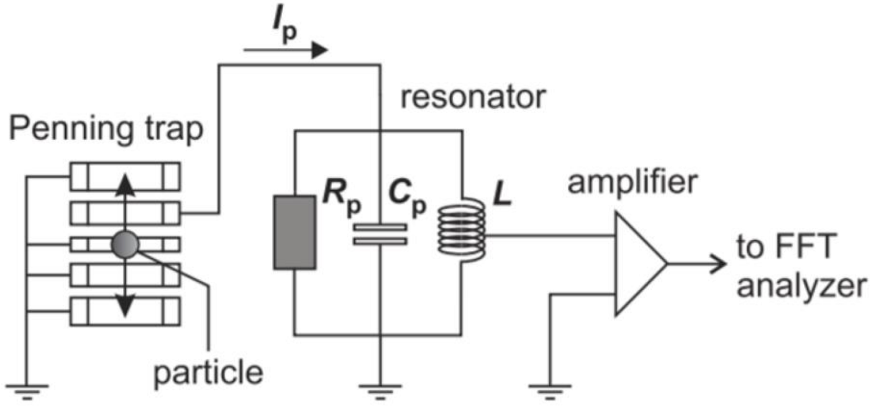

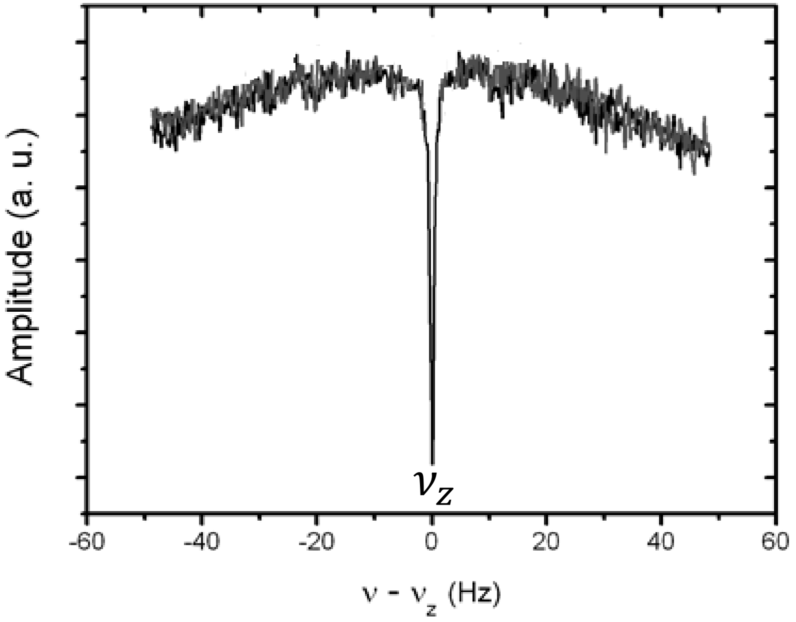

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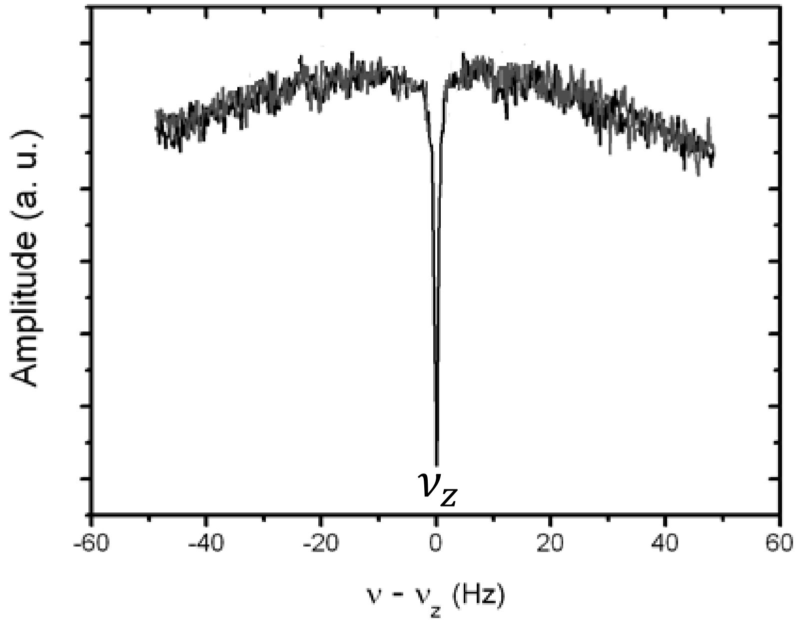
- **axial motion ν_z** induces tiny image currents (1fA) in the trap electrodes, can be measured with an image current detector
- **radial motions ν_+** and **ν_-** can be measured by inducing **Rabi oscillations** with the axial mode by applying the appropriate RF drive



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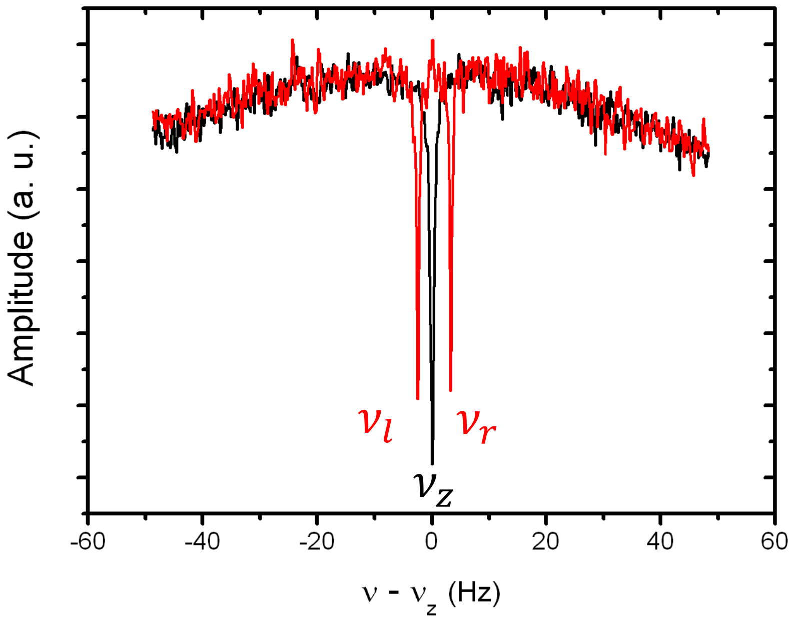
  $\nu_+ = \nu_{RF} + \nu_l + \nu_r - \nu_z$



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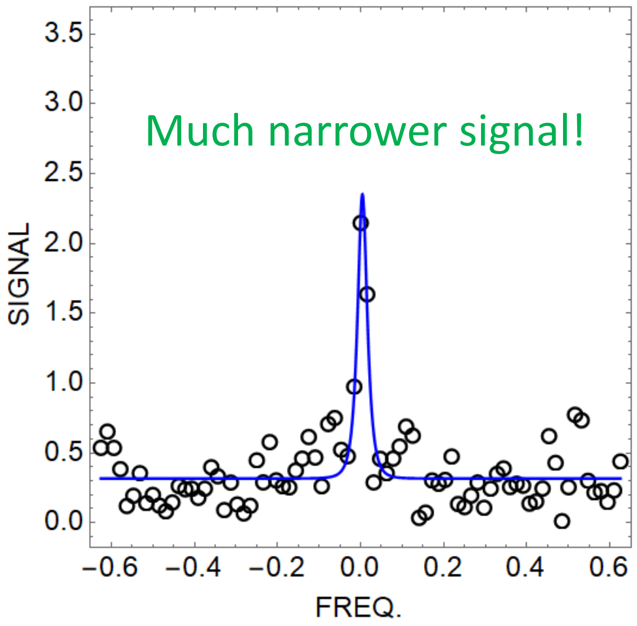
- **axial motion ν_z** induces tiny image currents (1fA) in the trap electrodes, can be measured with an image current detector
- **radial motions ν_+** and **ν_-** can be measured by inducing **Rabi oscillations** with the axial mode by applying the appropriate RF drive
  $\nu_+ = \nu_{RF} + \nu_l + \nu_r - \nu_z$
- **ν_+** can also be detected by the Peak method: excitation makes **ν_+** visible directly on a cyclotron detector

helical coil

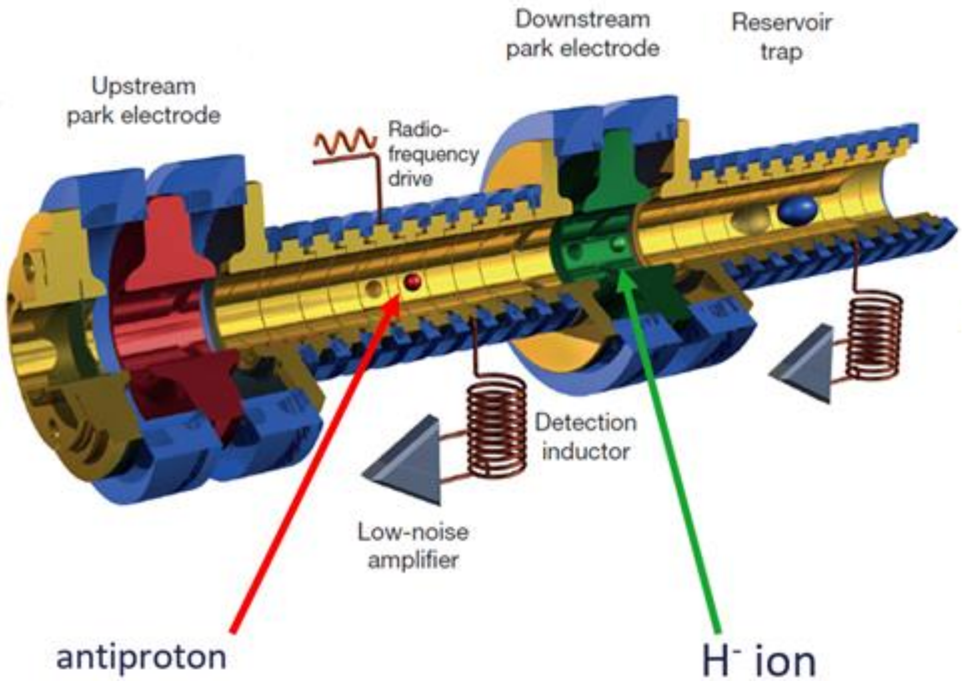
22 mm



More systematics related to excitation energy

Results of the last antiproton campaign

Extract an antiproton and an H^- ion from the reservoir and alternatingly measure the cyclotron frequency of the antiproton and the H^- ion



$$R = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \text{x} \frac{B/2\pi}{B/2\pi}$$

Magnetic field cancels out!

The theoretical ratio is then

R_{theo} = 1.001 089 218 754 2(2) because

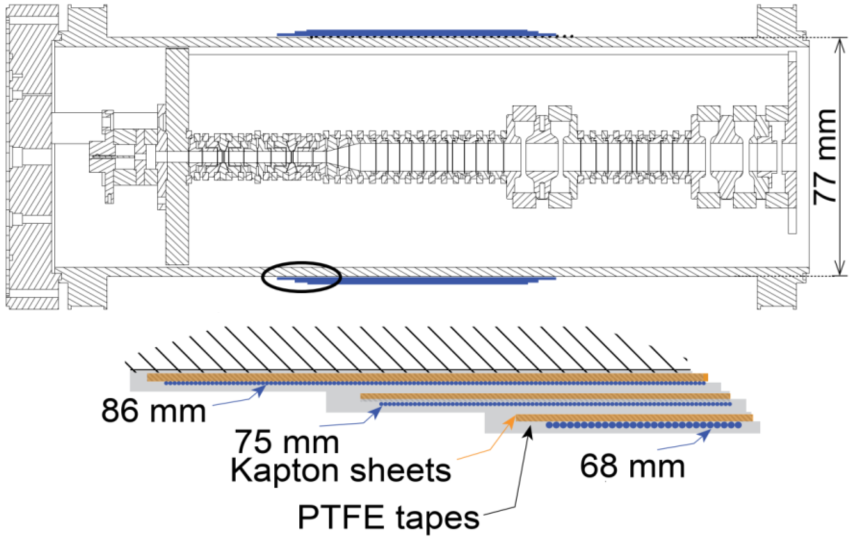
$$m_{H^-} = m_p(1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p})$$

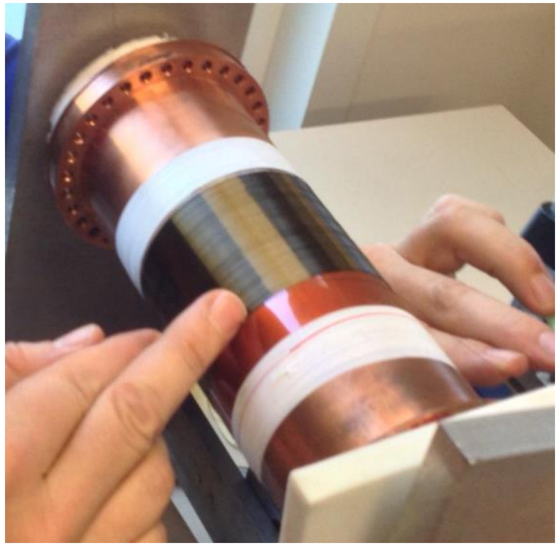
Inspired by work of TRAP collaboration
(G. Gabrielse et al., PRL **82**, 3199(1999).)

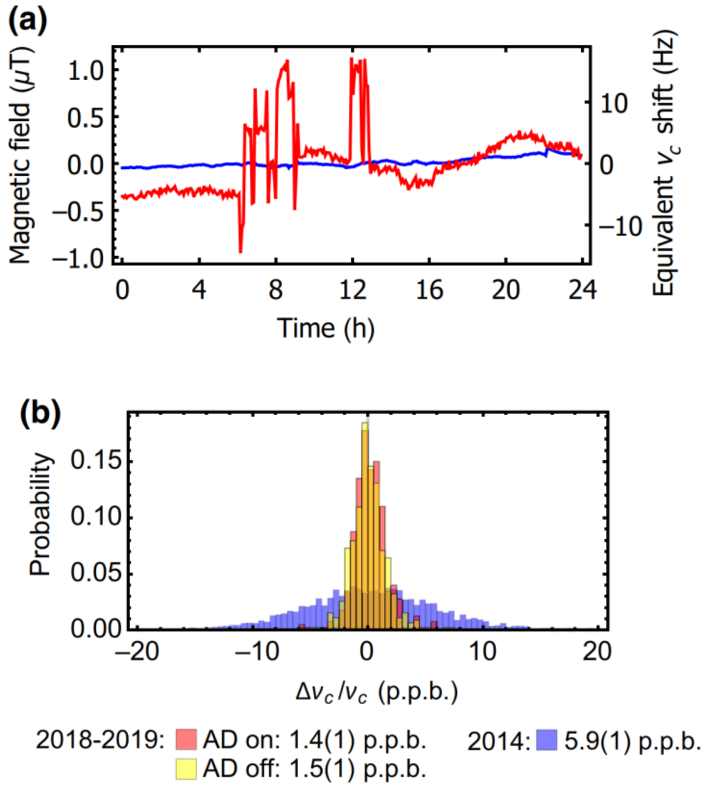
Results of the last antiproton campaign

Improvements compared to the run of 2015

- **Stability**: The apparatus was rebuilt to improve the magnetic field stability, a system of superconducting self-shielding coils[1] was installed to shield external magnetic field changes







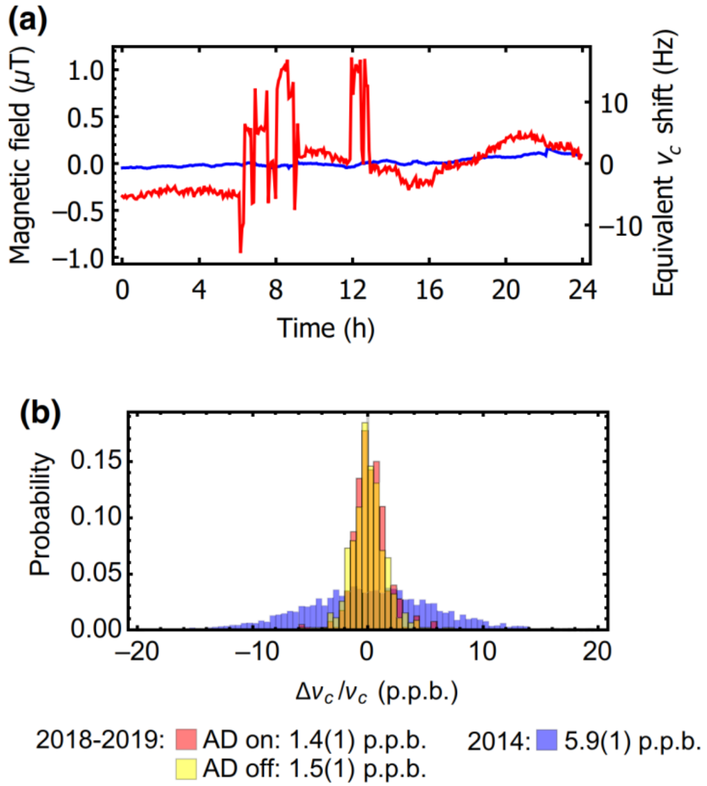
Results of the last antiproton campaign

Improvements compared to the run of 2015

- **Stability**: The apparatus was rebuilt to improve the magnetic field stability, a system of superconducting self-shielding coils[1] was installed to shield external magnetic field changes
- **Systematics**: Tuneable detectors reduce the dominant systematic correction of 2014, no longer need to adjust the trapping voltage to accommodate the mass difference!

Resulting in a factor 4 improvement of $\frac{(q/m)_{\bar{p}}}{(q/m)_p}$!

(to be published soon)



Results of the last antiproton campaign

The cyclotron frequency acquires a **redshift** in the gravitational potential[1]:

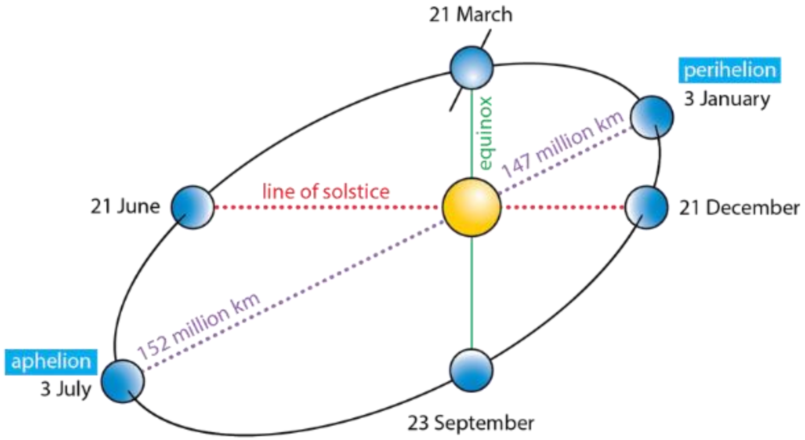
$$U = \frac{GM}{r}$$

It could be that antimatter feels a different gravitational coupling and sees a slightly different potential αU. This would imply a **cyclotron frequency difference**:

$$\frac{\overline{\omega}_c - \omega_c}{\omega_c} = 3(\alpha_g - 1)\, U/c^2$$

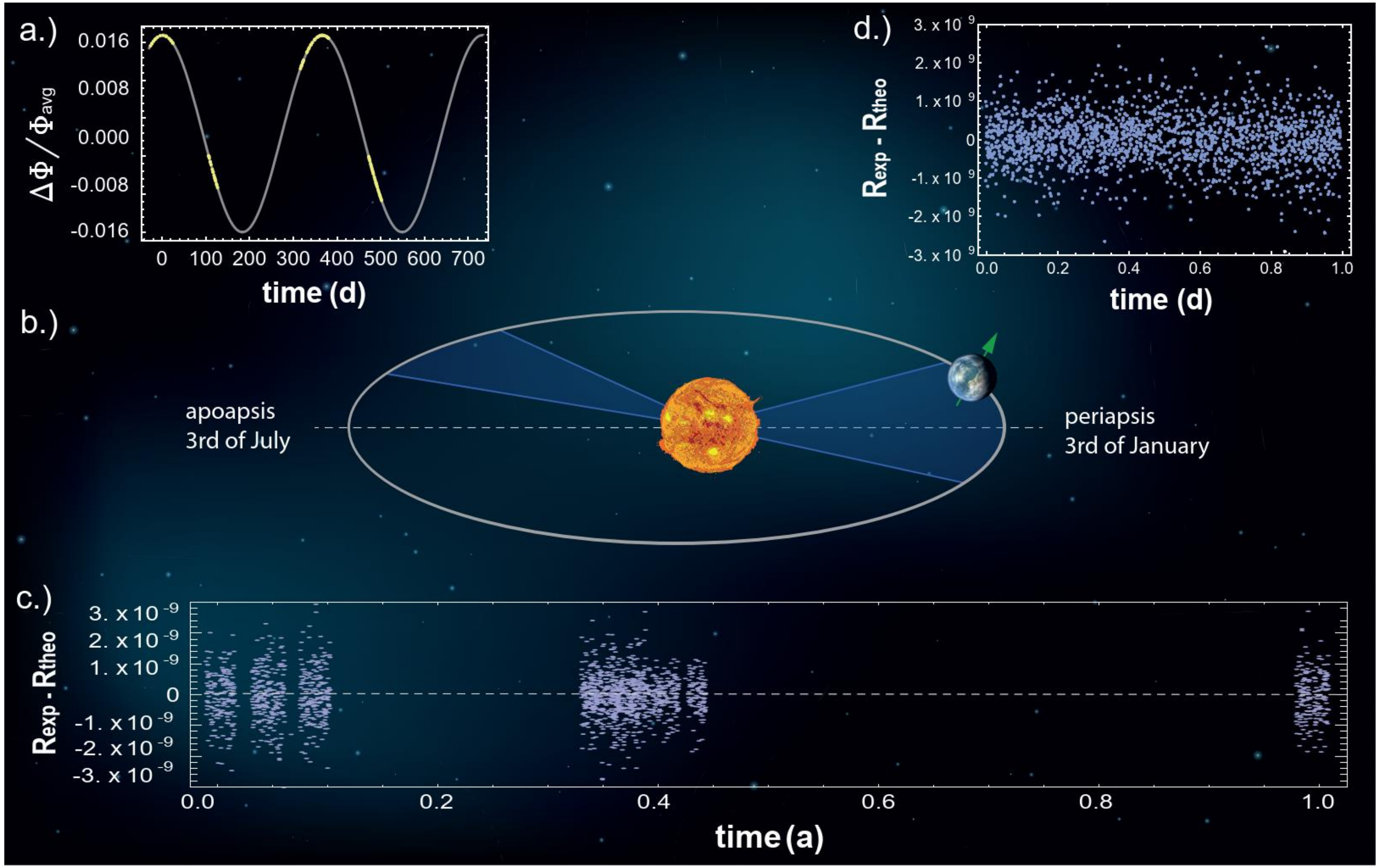
Value for U at the Earth's surface ($U/c^2 = 3 \times 10^{-5}$) still critically debated in the scientific community

Differential measurement!



$$\frac{\Delta U}{c^2} = 3 \times 10^{-10} \text{ during orbit}$$

Results of the last antiproton campaign



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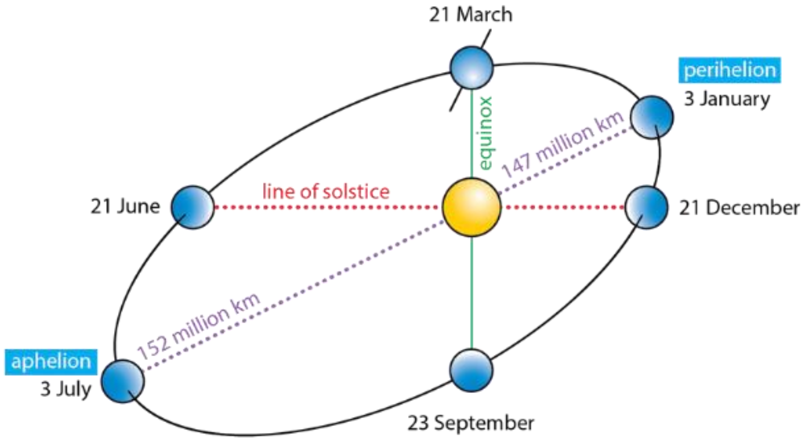


$$\frac{\Delta U}{c^2} = 3 \times 10^{-10} \text{ during orbit}$$

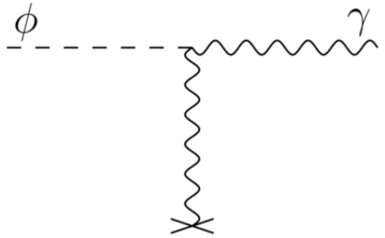
Constrains α_g to a few %!
(to be published soon)

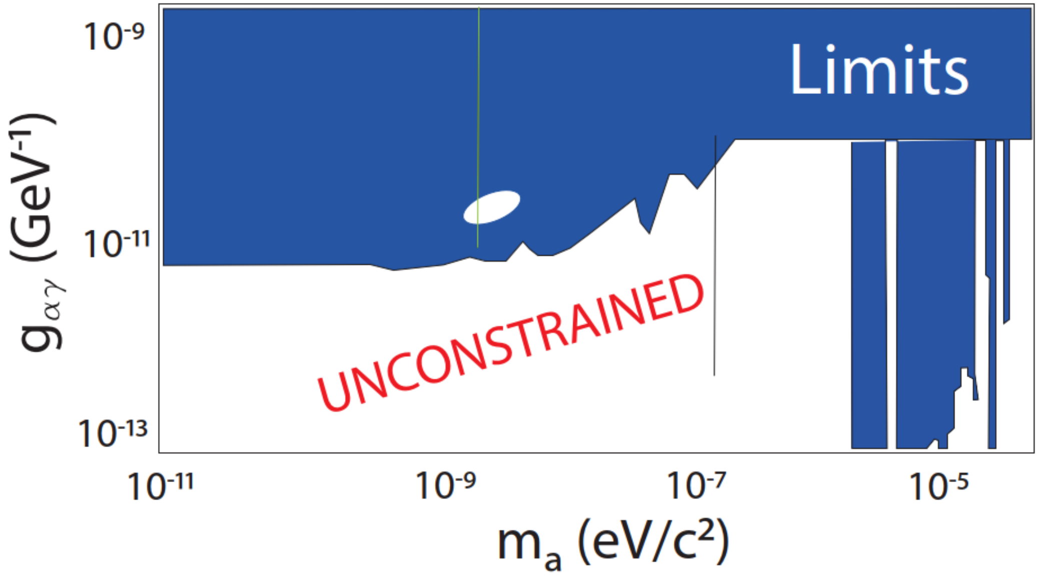
Results of the last antiproton campaign

We have very sensitive detectors at BASE, so why not use it also to search for dark matter[1]…

Axion-like Particles (ALPs):

- Pseudoscalar bosons weakly interacting with matter motivated by many beyond the Standard Model theories
- Coupling to photons by derivative interactions $g_{\alpha\gamma}$ through e.g. inverse Primakoff Effect
- Mass $\mathrm{m_a} \ll 1eV$





Results of the last antiproton campaign

- Any low mass ALP would form a classical field oscillating with frequency:

$$\nu_a \approx m_a c^2/h$$

- Coupling ALP field to **E** and **B** fields:

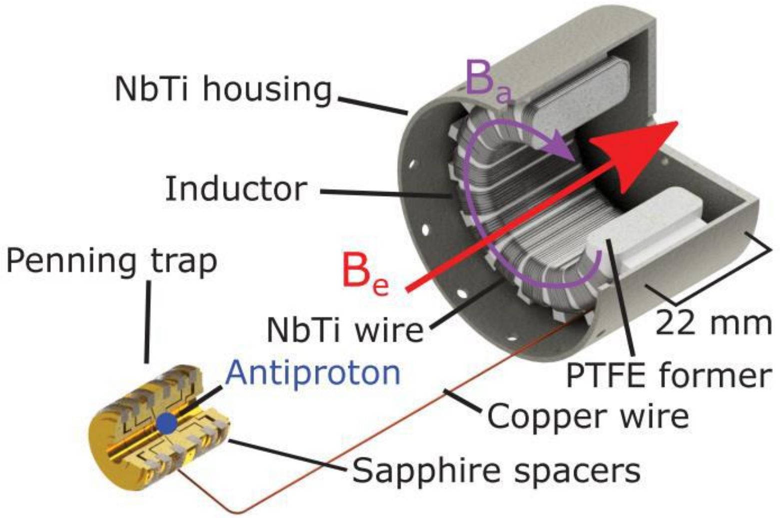
$$L_{a\gamma} = -g_{a\gamma} a(x)\mathbf{E}(x)\cdot\mathbf{B}(x)$$

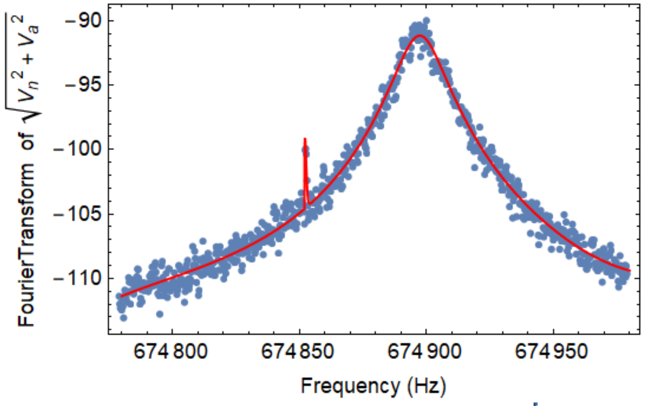
- The oscillating ALP field sources an oscillating magnetic field:

$$\nabla\times\mathbf{B} - \mu\frac{\partial\mathbf{E}}{\partial t} = -g_{a\gamma}\mathbf{B}_e\frac{\partial a}{\partial t}$$

$$\mathbf{B}_a = -\frac{1}{2}g_{a\gamma} r\sqrt{\rho_a\hbar c}B_e\hat{\phi}$$

where $\rho_a\hbar c$ is the local ALP energy density, r is the radial distance from the axis of the toroid





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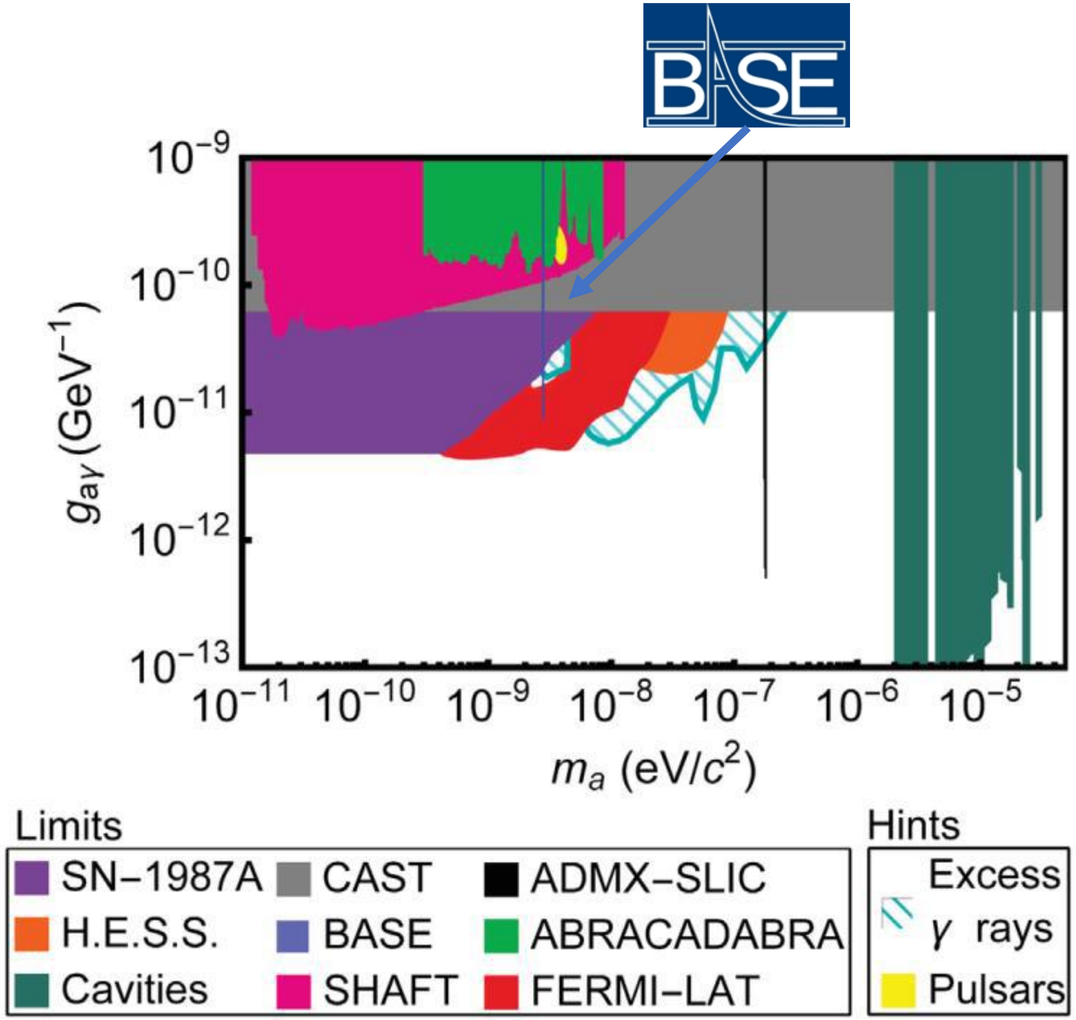

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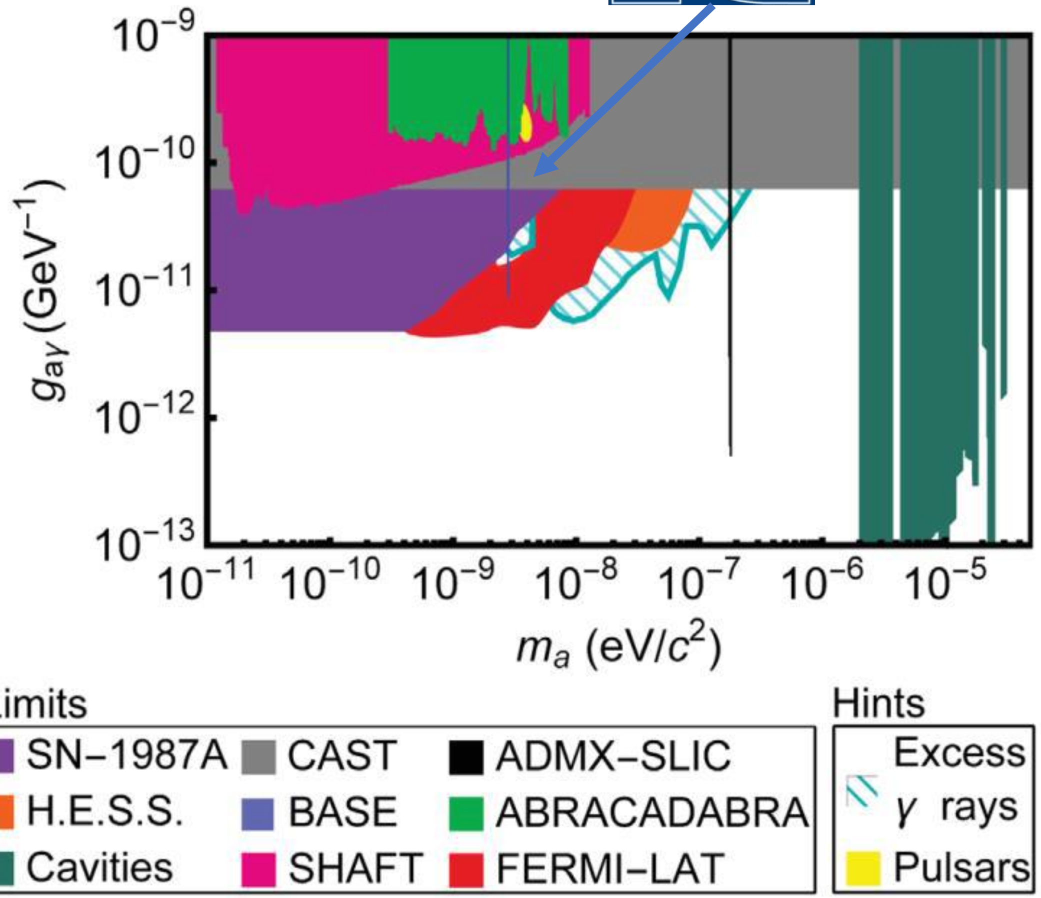
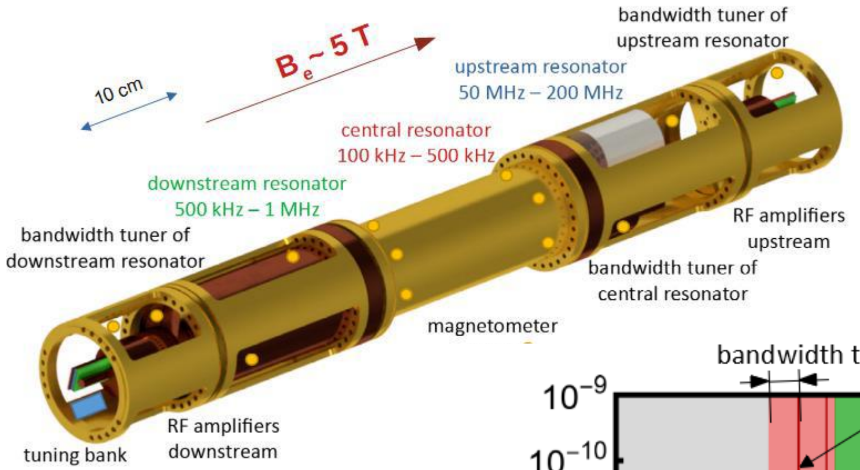
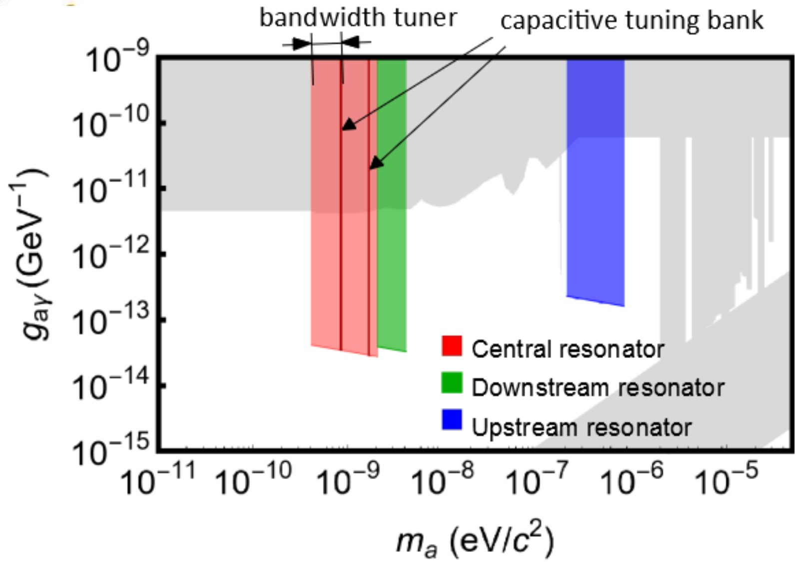
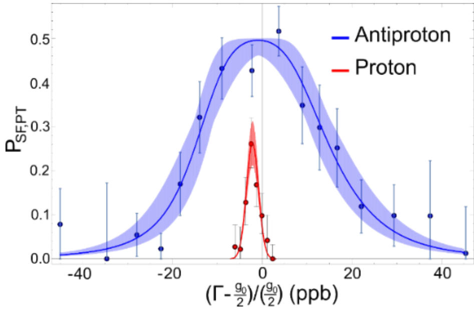


Plans for a dedicated ALP experiment



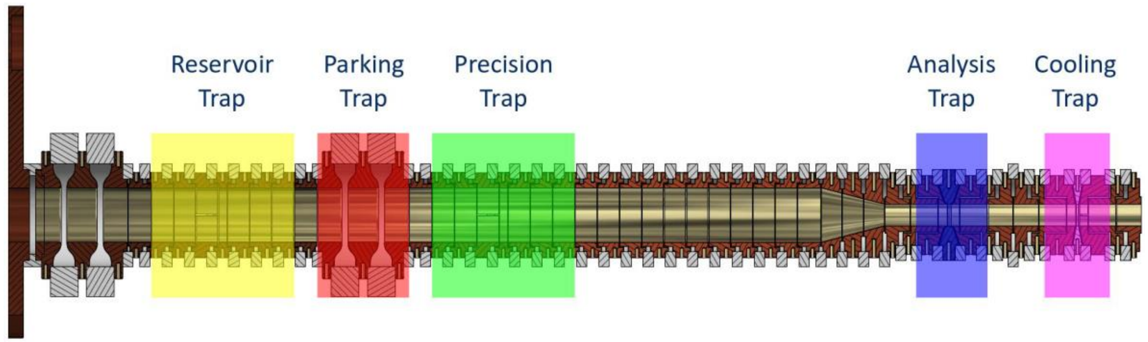


Outlook on the next antiproton campaign

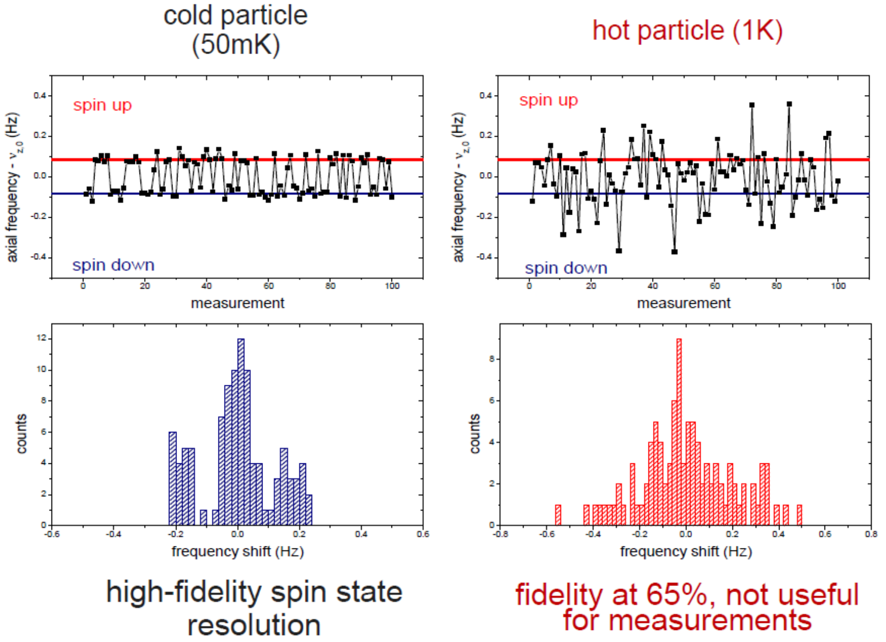


We are developing a new antiproton magnetic moment experiment:

- Especially designed cooling trap to cool the cyclotron mode



Precision Trap: Homogeneous field for frequency measurements, B2< 0.5 mT / mm2.
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, B2= 300 mT / mm2.
Cooling Trap: Fast cooling of the cyclotron motion.
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.



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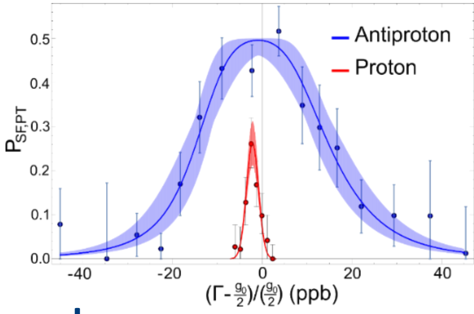

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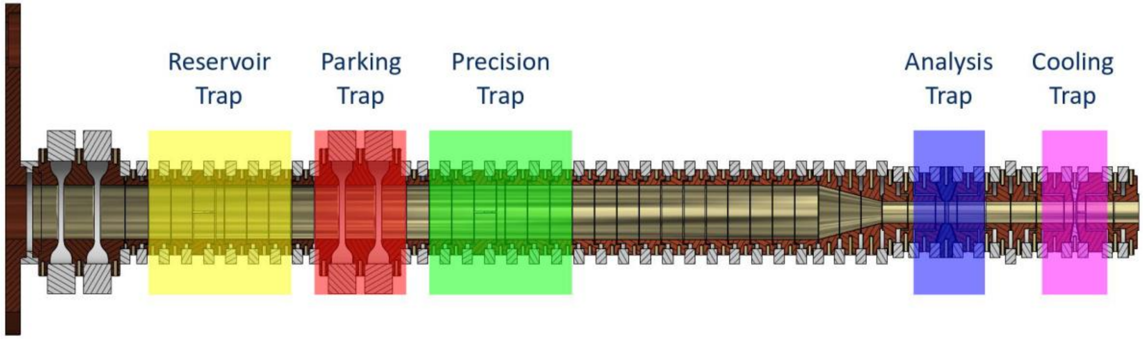
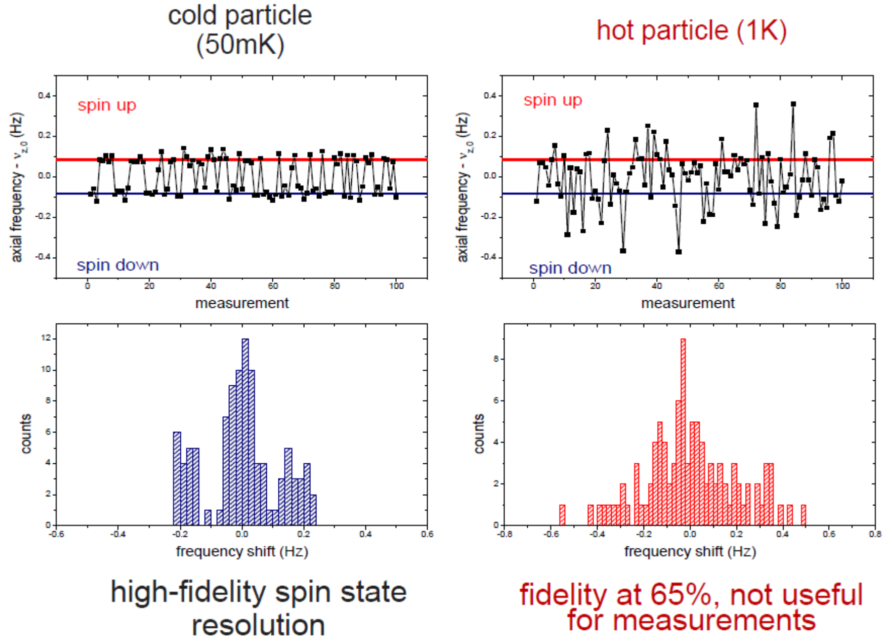
- Especially designed cooling trap to cool the cyclotron mode
- Magnetic shimming coils developed to homogenise the magnetic field in the precision trap to reduce systematics
- New degrader to connect to ELENA





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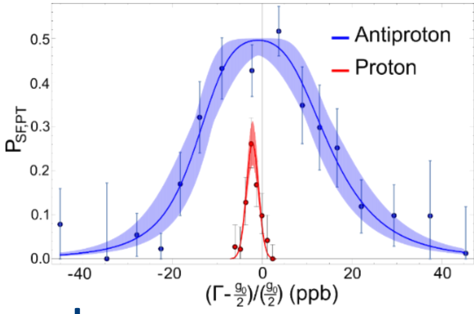

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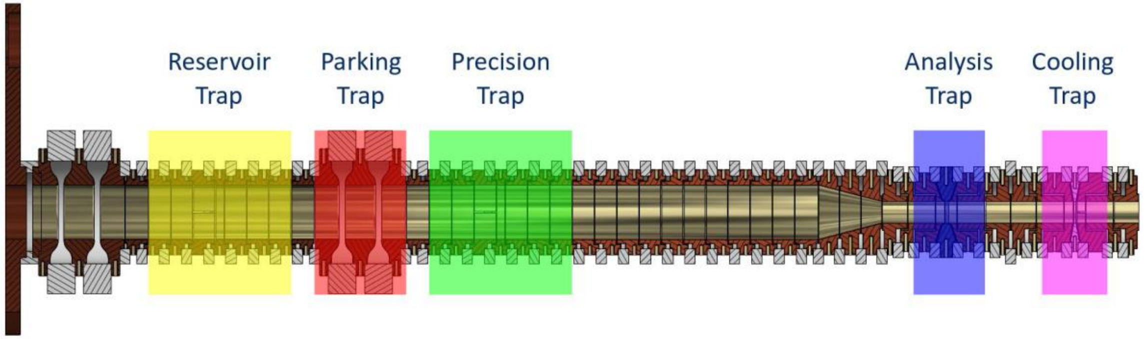

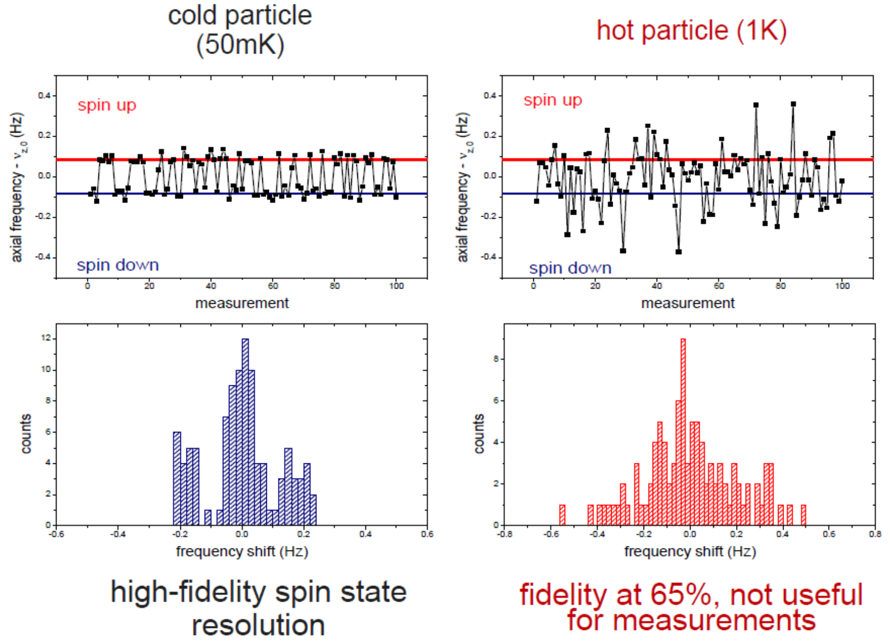

Precision Trap: Homogeneous field for frequency measurements, B2< 0.5 mT / mm2.
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, B2= 300 mT / mm2.
Cooling Trap: Fast cooling of the cyclotron motion.
Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.

Outlook on the next antiproton campaign

We are developing a new antiproton magnetic moment experiment

- Especially designed cooling trap to cool the cyclotron mode
- Magnetic shimming coils developed to homogenise the magnetic field in the precision trap to reduce systematics
- New degrader to connect to ELENA

We are planning to take beam this week!

Conclusions

Last campaign:

- We have improved our antiproton-to-proton charge-to-mass ratio measurement by a factor four
- We have tested the Weak Equivalence Principle for clocks
- Results will be published soon
- We have done a search for ALPs coupling to photons

New campaign:

- We are ready to take beam to start a new magnetic moment measurement with a goal of improving to better than 0.3ppb
- Simultaneous development of dedicated ALP experiment