BASE: Tests of fundamental symmetries by high precision comparisons of the fundamental properties of protons and antiprotons

Barbara Latacz, Stefan Ulmer, BASE Collaboration

CERN / RIKEN

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RIKEN

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What happened with antimatter?

Standard Model of Particle Physics

Naive Expectations	
Baryon/Photon Ratio	10^{-18}
Baryon/Antibaryon Ratio	1

Observations	
Baryon/Photon Ratio	0.6×10^{-9}
Baryon/Antibaryon Ratio	10 000

- A. Sakharov presented possible solutions in 1967 . According to his work, the matter-antimatter asymmetry could be explained by simultaneously occurring three conditions:
  - violation of baryon number;
  - C and CP symmetry violation;
  - lack of thermal equilibrium in the expanding Universe (=> direct CPT violation).

CPT violation? → **Ultra Precise Comparisons of fundamental properties of matter/antimatter conjugate system**

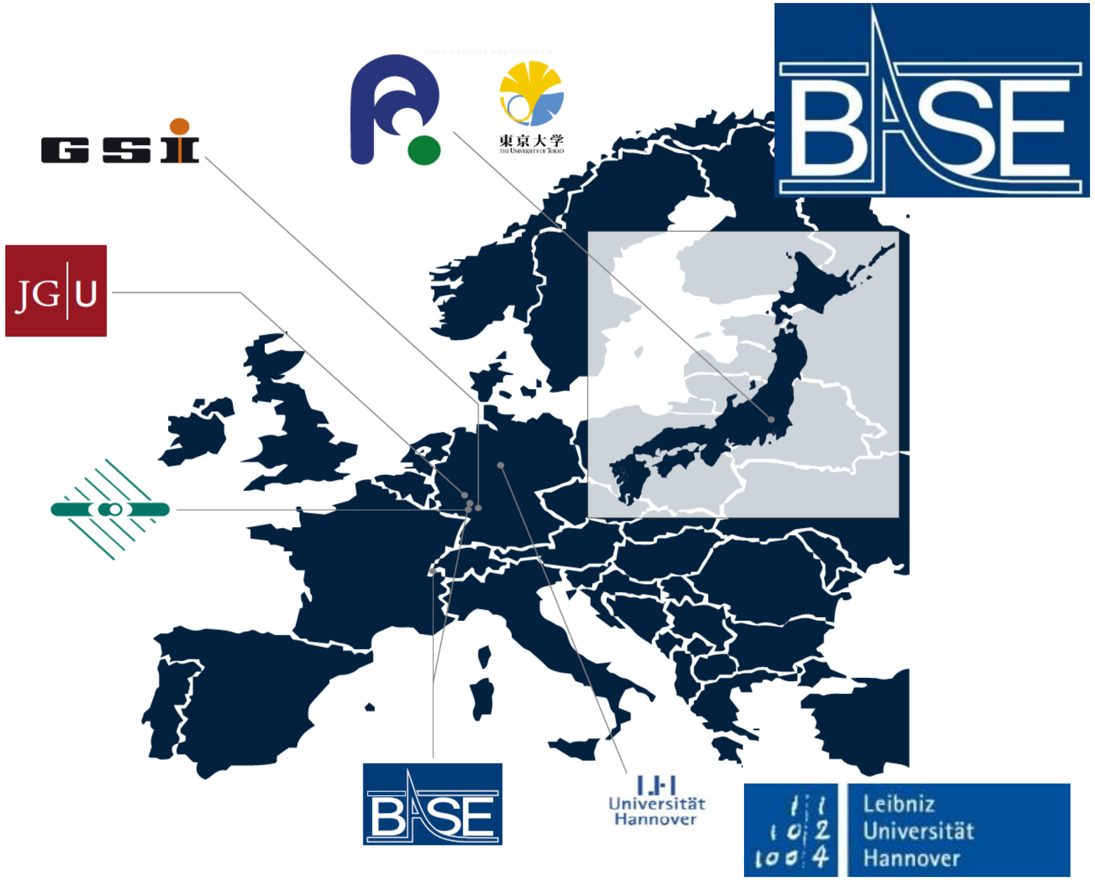
BASE Collaboration

- **CERN-AD:** Measurement of (RIKEN):
  - → **proton/antiproton q/m ratio**
  - → **magnetic moment of the antiproton**
  - → **cold dark matter searches**
- ○ Core members: **Stefan Ulmer**, Barbara Latacz, Elise Wursten, Bela Arndt, Benny Bayer, Stefan Erlewein, Markus Fleck, Julia Jaeger, Gilbertas Umbrazunas, Maylin Schiffelholz

- **Mainz:** Measurement of the magnetic moment of the proton, implementation of new technologies (RIKEN/MPG)
- ○ Core members: **Christian Smorra**, Peter Micke, Fatma Abbass, Matthew Bohman, Markus Wiesinger, Daniel Popper, Christian Will

- **Hannover/PTB:** QLEDS-laser cooling project, new technologies. (RIKEN/PTB/UH)
- ○ Group leader: **Christian Ospelkaus**

- K. Blaum, Y. Matsuda, W. Quint, A. Sótér, J. Walz, Y. Yamazaki

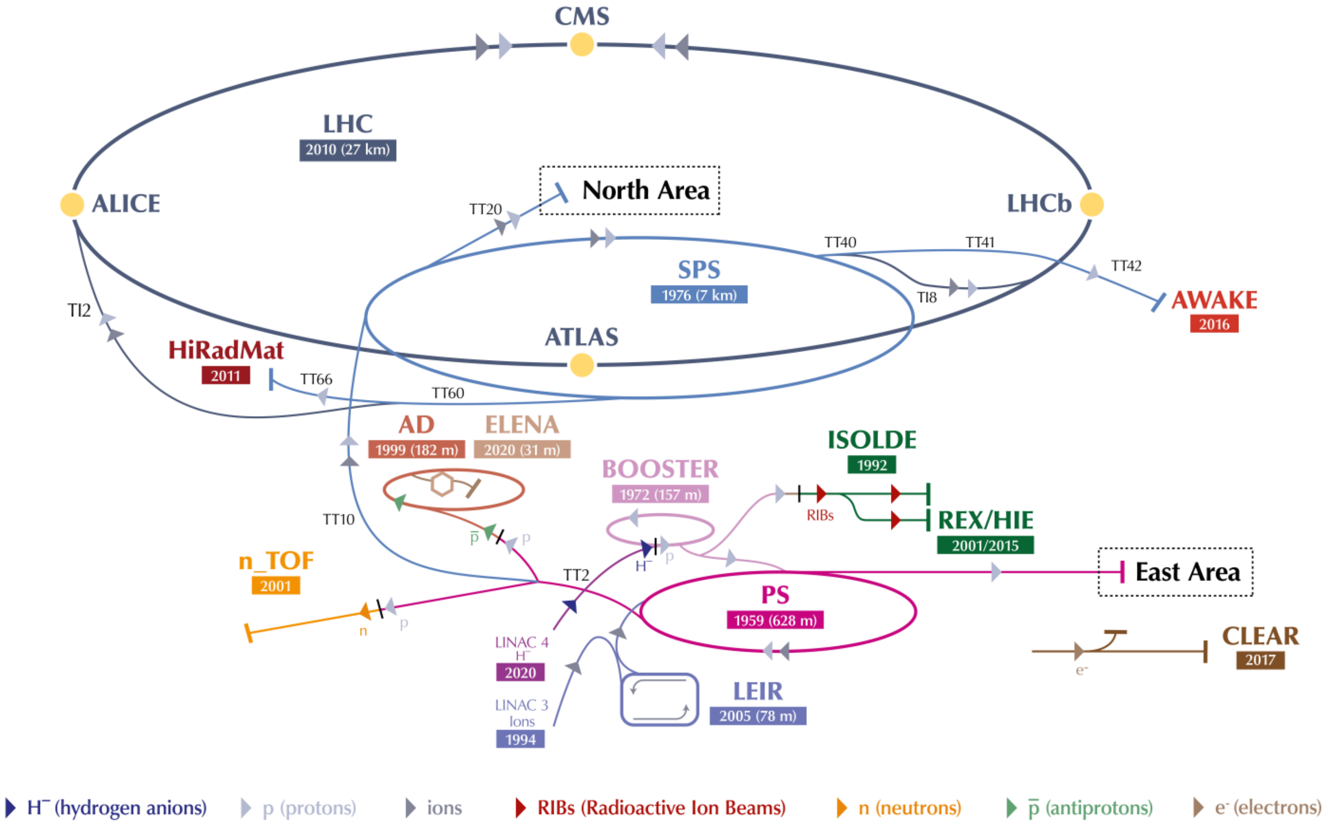


Institutes: RIKEN, MPIK, CERN, University of Mainz, Tokyo University, GSI Darmstadt, University of Hannover, PTB Braunschweig, ETH Zurich

Baryon/Antibaryon Symmetry Experiment

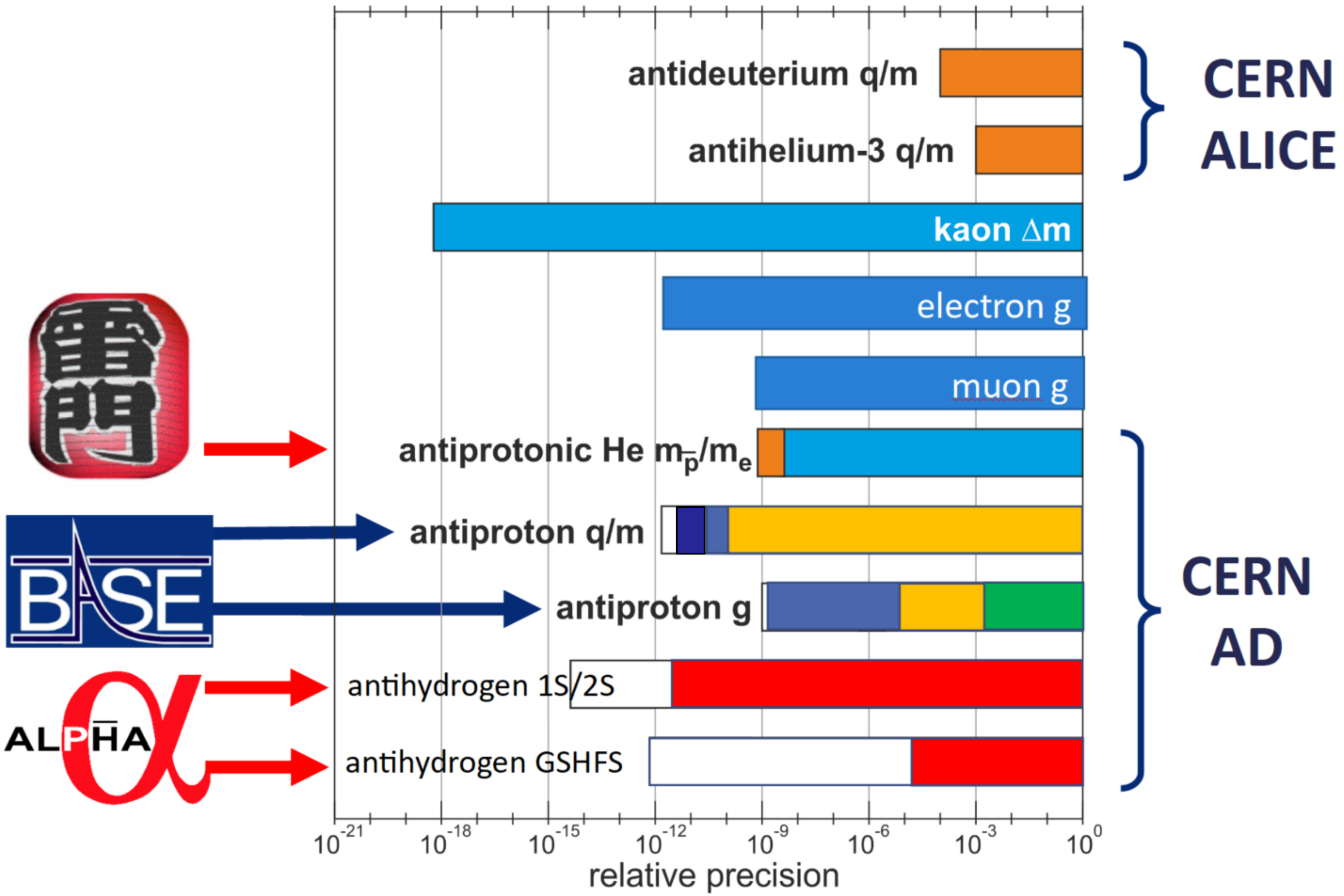
- CERN Antiproton Decelerator Facility is the only operating source of low energy antiprotons.
- Since 2021: ELENA – 100 keV antiproton beam with $5 \times 10^{7}\ \bar{p}$ in one pulse.

The CERN accelerator complex
Complexe des accélérateurs du CERN



LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

CPT with particle/antiparticle comparisons



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-> Absolute energy resolution normalized to m-scale.

Baryon/Antibaryon Symmetry Experiment

CPT violation?

Ultra Precise Comparisons of fundamental properties of protons and antiprotons

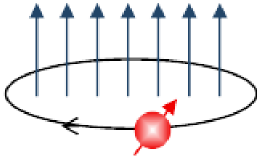
BASE

High precision mass spectroscopy of antiprotons and protons

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Cyclotron Motion

$$\omega_c = \frac{e}{m_p}B$$

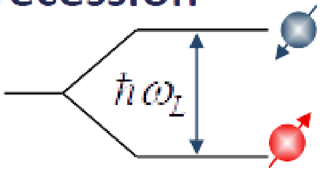


High precision magnetic moment measurements

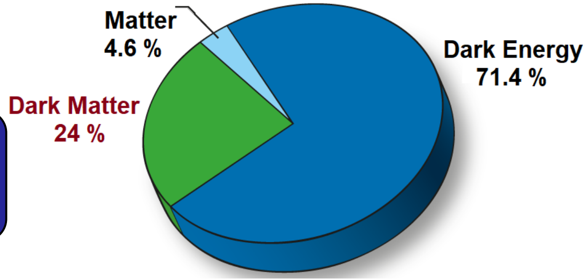
$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession

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



Dark Matter Searches



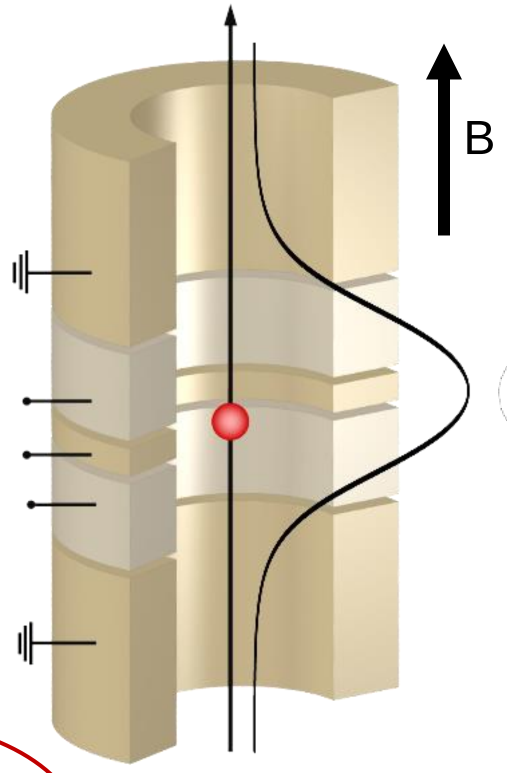
Penning trap

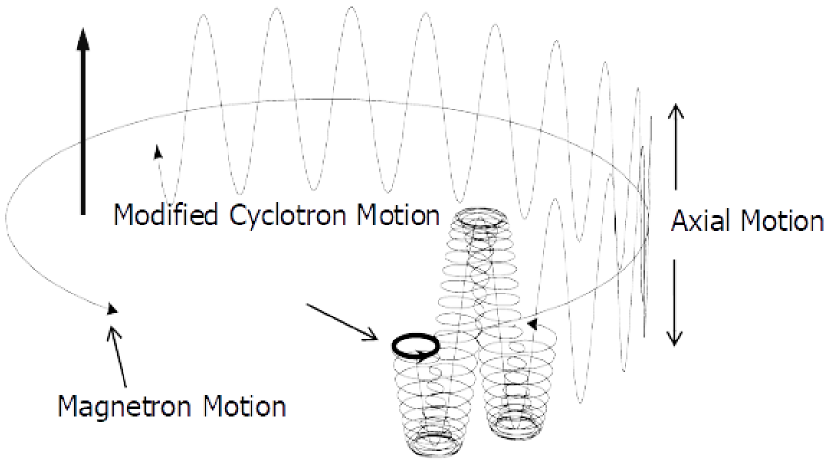
- **Penning trap with:**
  -> radial confinement: $\vec{B} = B_0 \hat{z}$
  -> axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

- **Invariance theorem:**
  Cyclotron frequency of a particle

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

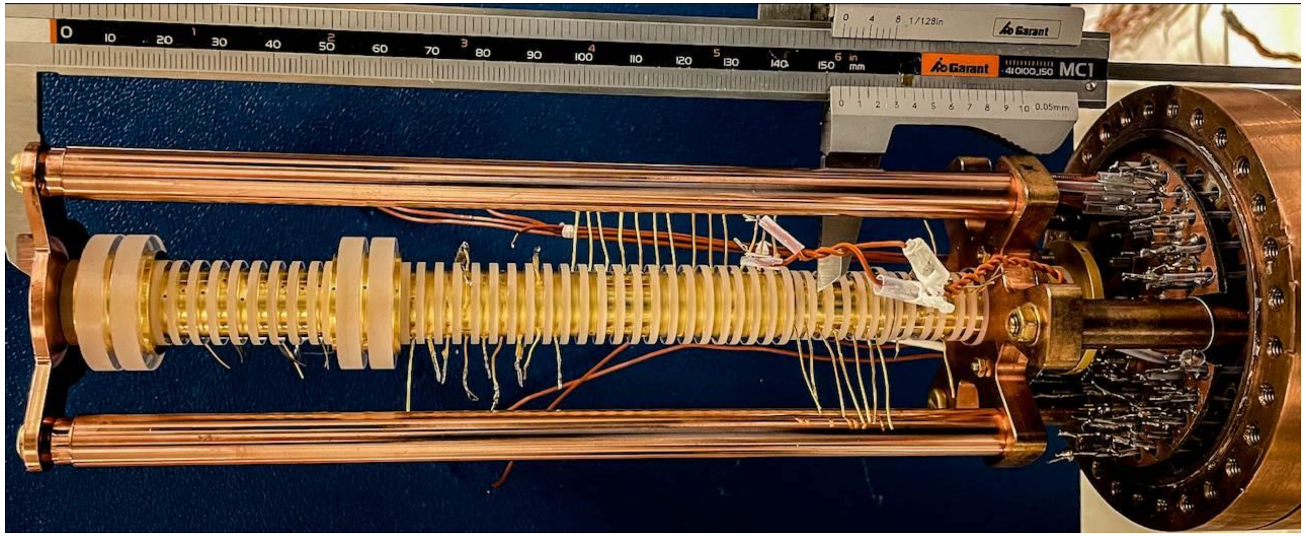
which is correct also for any small angle misalignment of the trap or quadratic imperfections of the field (G. Gabrielse)!

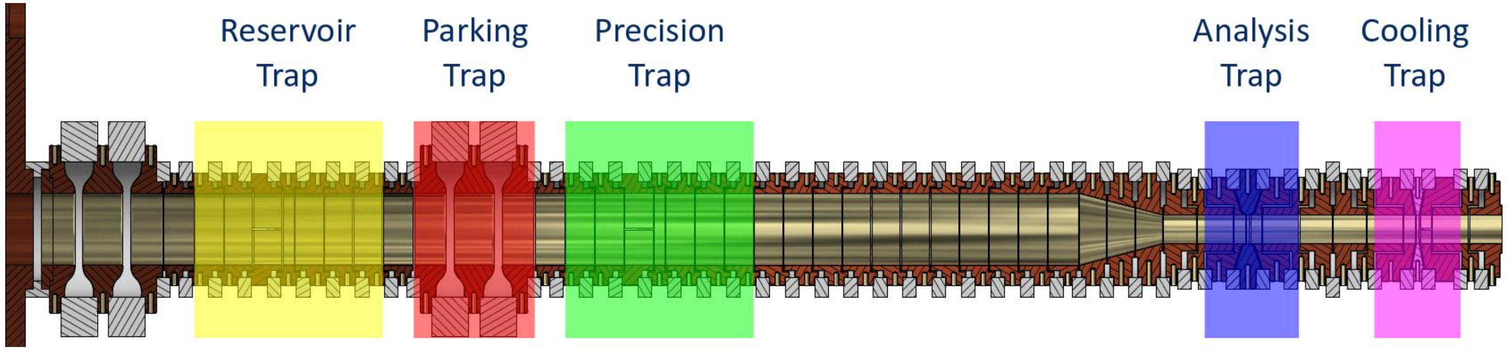




Axial	680 kHz	$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}$
Magnetron	8 kHz	$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
Modified Cyclotron	28.9 MHz	$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$

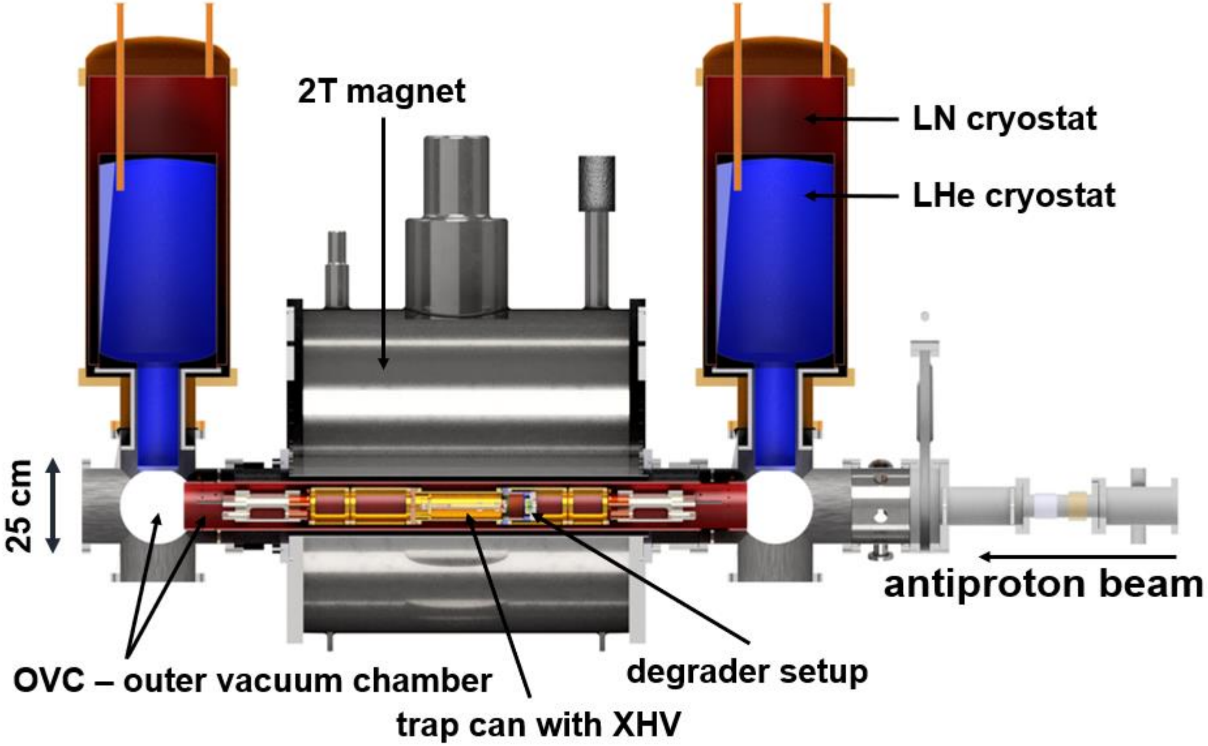
BASE Trap Stack 2022

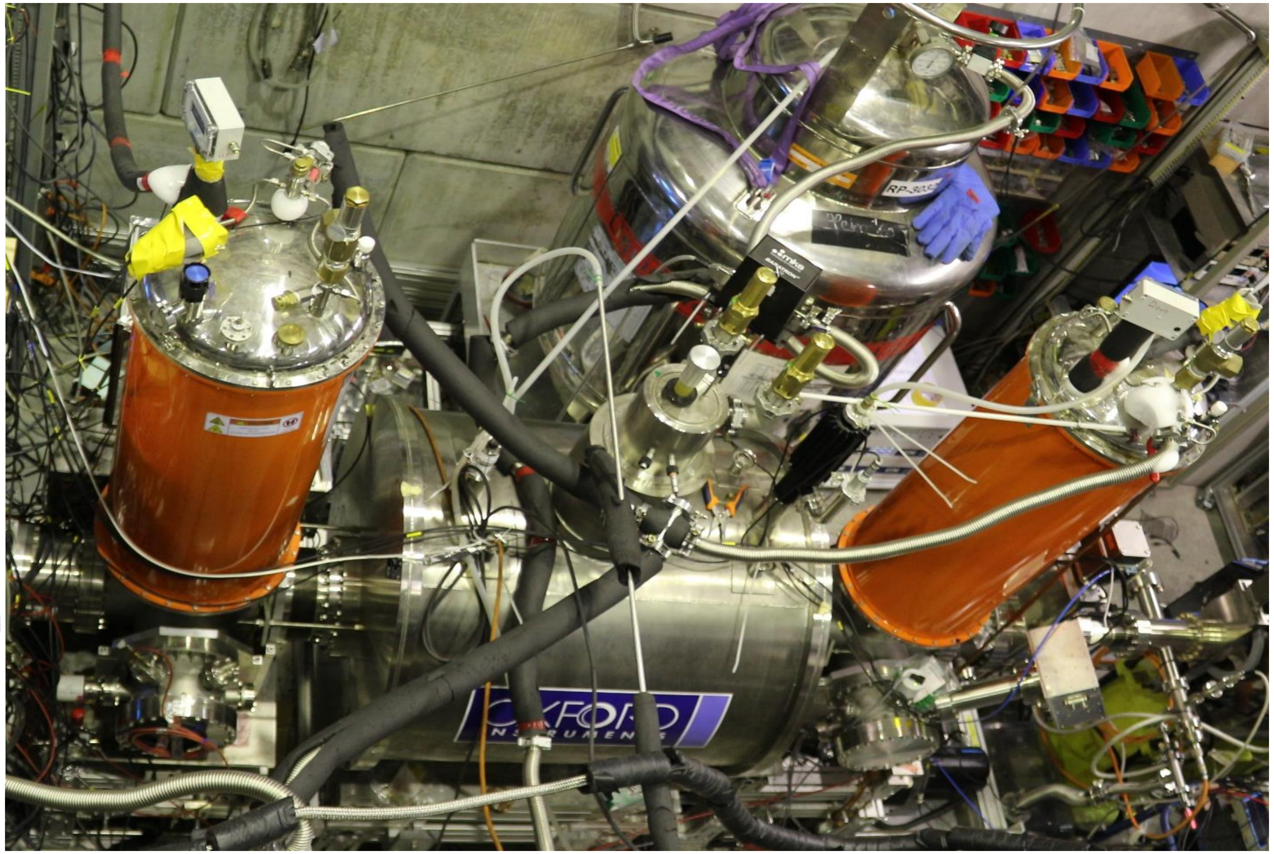




Reservoir Trap: Stores a cloud of antiprotons, suspends single antiprotons for measurements.
Precision Trap: **Homogeneous field for frequency measurements, $B_2 < 0.5\ \mu T / mm^2$.**
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, $B_2 = 300\ mT / mm^2$.
Cooling Trap: Fast cooling of the cyclotron motion.

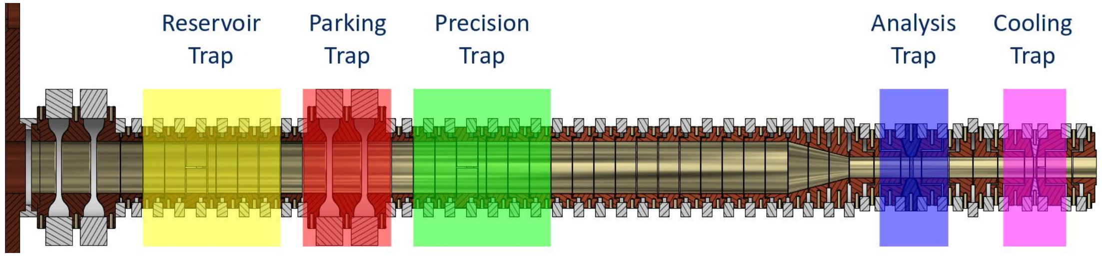
The experiment



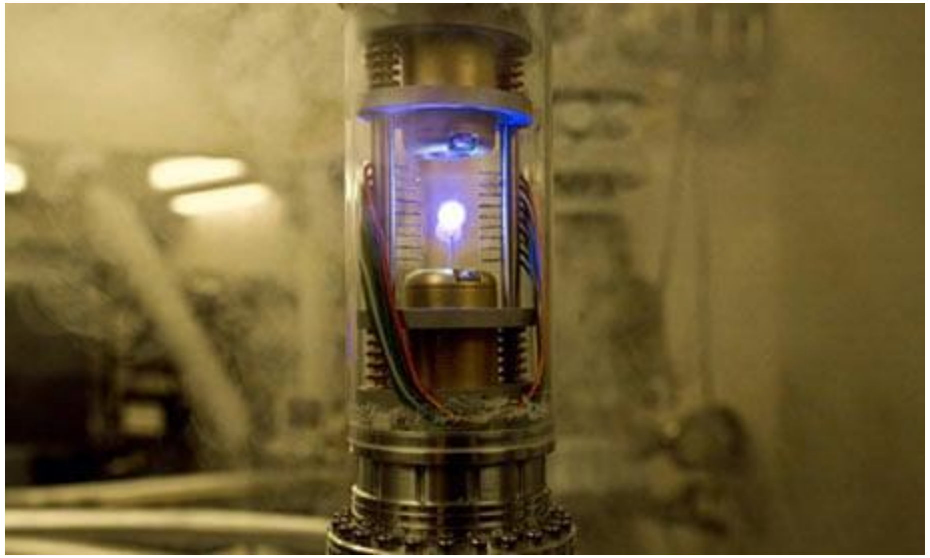


A special place (in the Universe?) – BASE Reservoir trap

- BASE Reservoir trap:
  - **Pressure:** $p_H < 0.46 \times 10^{-18}$ **mbar** and $p_{He} < 1.04 \times 10^{-18}$ **mbar**.
  - best characterized vacuum on Earth, comparable to pressures in the interstellar medium
  - Antiproton storage time is 10s of years -> 405 days.
  - Not more than 3000 atoms in a vacuum volume of 0.5 l
  - Order 100 to 1000 trapped antiprotons
  - A local inversion of the baryon asymmetry



BASE ANTIMATTER INVERSION	
local volume	0.0001^3 m^3
Baryons in local trap volume	$1.65*10^{-7}$
Antibaryon in local trap volume	100
Antibaryon/Baryon Ratio	**$5.9*10^8$**

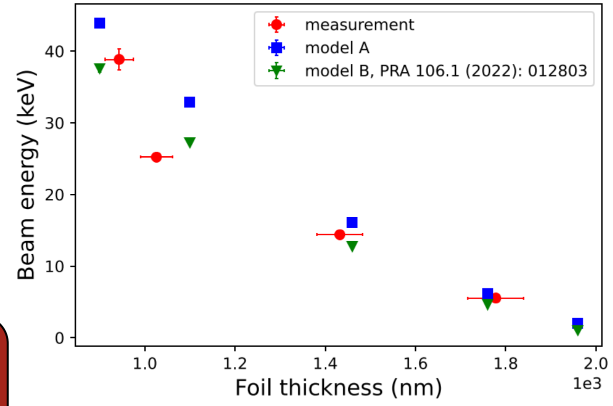


1760 nm thick vacuum window

BASE must have:

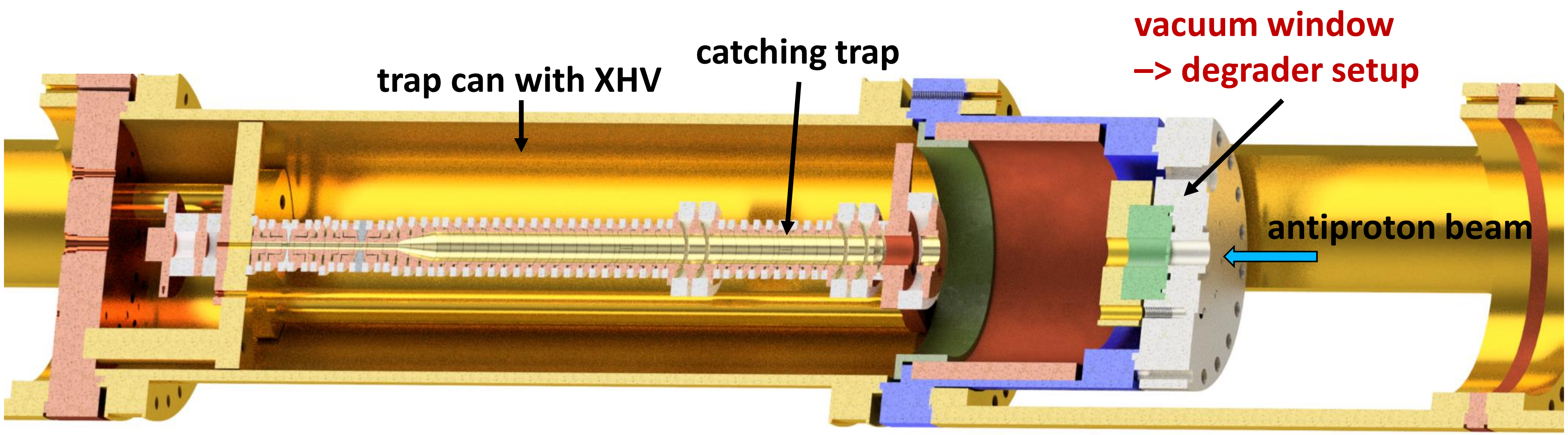
1. Trap system has to be permamentry closed in order to reach XHV with $p_H < 1.0 \times 10^{-17}$ **mbar** and $p_{He} < 1.0 \times 10^{-17}$ **mbar**.
2. We have to be able to transport to the trap center antiprotons and be able to catch them.

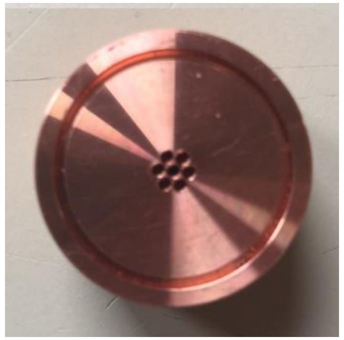
Beam source	Beam energy	Max window thickness
ELENA	100 keV	**1760 nm of Mylar**



Ultra Thin (1.76 µm - 2.16 µm) Polymer Foil Cryogenic Window

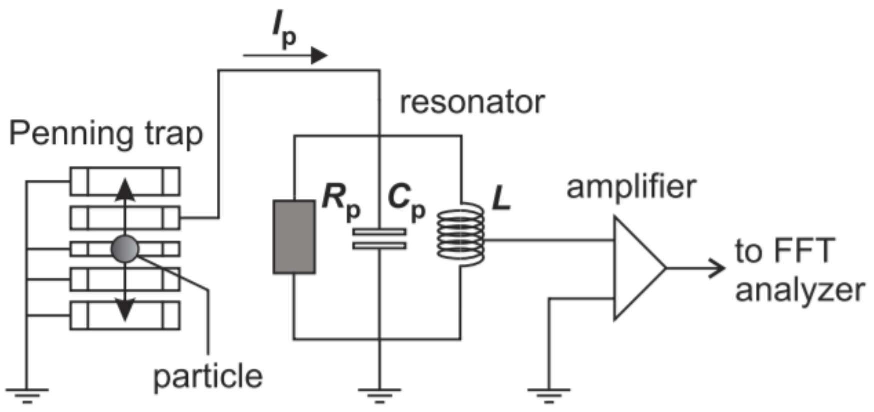
+ cryogenic
+ has to survive 1 bar pressure difference

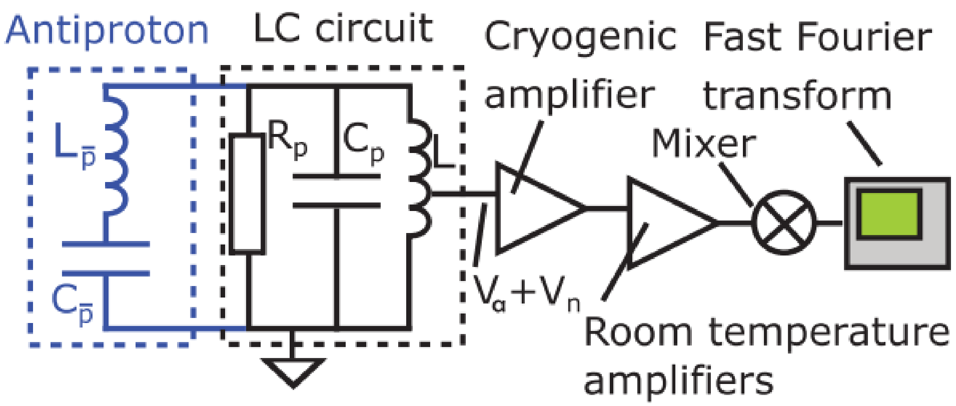




Frequency Measurements

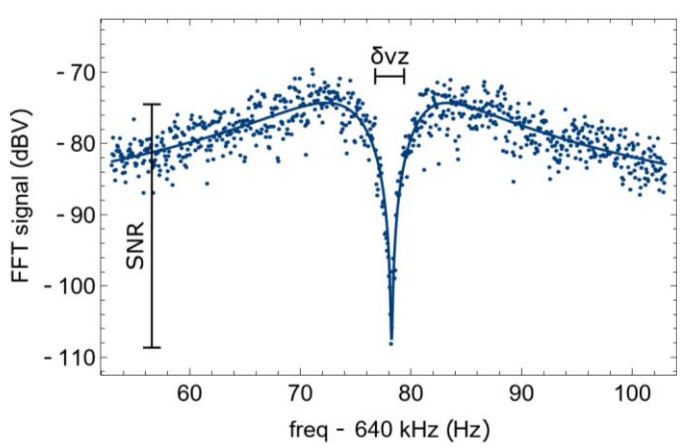
- Measurement of fA image currents induced in trap electrodes

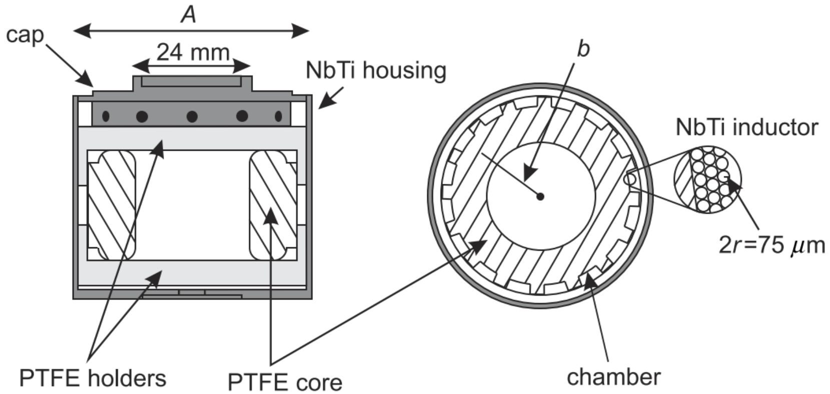




- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip -> number of particles

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$





Cyclotron frequency

Axial	680 kHz
Magnetron	8 kHz
Modified Cyclotron	28.9 MHz

- **„Simple” measurement, with main systematics coming from magnetic field stability**

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

- **Sideband method (5.5 ppb in 2016 scatter):**
  -> axial dip spectrum: v_z
  -> sideband radio-frequency drive at $v_{rf} \approx v_+ - v_z$
  -> double dip spectrum: $v_+ = v_{rf} + v_l + v_r - v_z$
  -> megnetron mode: $v_- \approx v_z^2/(2v_+)$

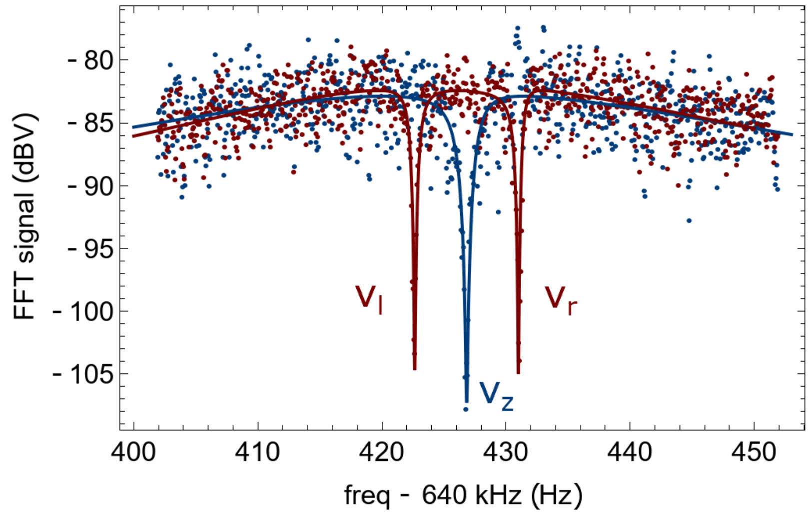
Main uncertaintity: spectrum shift.

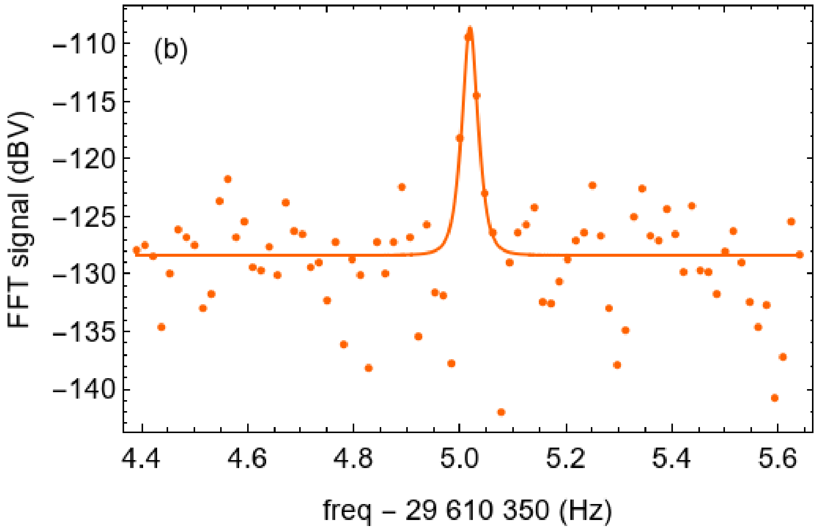
- **Peak method:**

-> direct detection of the modified cyclotron frequency using specially designed cyclotron detector

$$\Delta\nu_{+,z} = \nu^*_{+,z} - \nu_{+,z} = \mathcal{M}_{+,z}(B_2, C_4, \mathrm{SR}) \times E_+$$

Main uncertaintity: magnetic field stability.





Antiproton-to-proton charge to mass ratio measurement

- Inspired by earlier work of TRAP collaboration (G. Gabrielse et al., PRL 82, 3199(1999)).
- Charge to mass ratio:

$$R = \frac{(q/m)_{\bar{p}}}{(q/m)_{p}} = \frac{\upsilon_{c,\bar{p}}}{\upsilon_{c,p}} = a_{corr}\frac{\upsilon_{c,\bar{p}}}{\upsilon_{c,H^-}}$$

with H^- as a perfect proxy of a proton

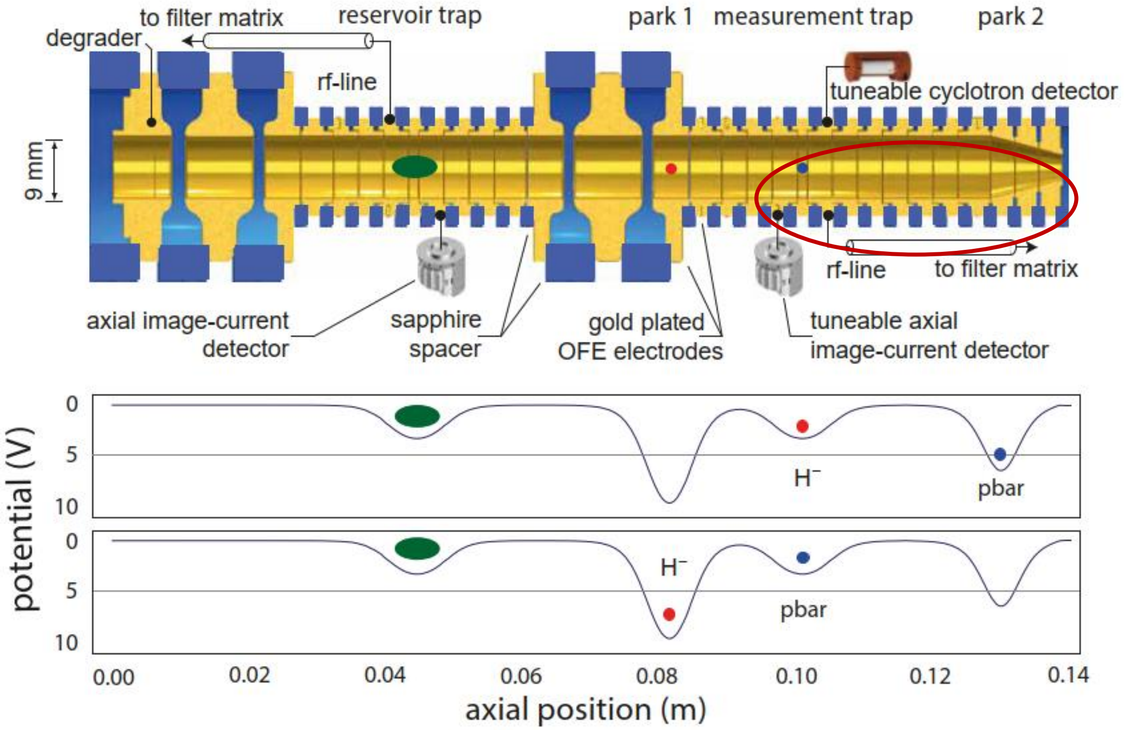
$$m_{\mathrm{H}^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{B_e}{m_p} - \frac{A_e}{m_p} + \alpha_{\mathrm{H}^-}\frac{B^2}{m_p}\right)$$

B_e - binding energy of an electron in hydrogen

A_e - afinity energy of a second electron

Effect	Magnitude	
m_e/m_p	0.001 089 234 042 95 (5)	MPIK/HHU-D
$-B_e/m_p$	0.000 000 014 493 061 …	MPQ
$-A_e/m_p$	0.000 000 000 803 81 (2)	Lykke

- Pioneered by BASE shuttling measurement method:



- In BASE one frequency ratio measurement takes 240 s, 50 times faster than in 1999.

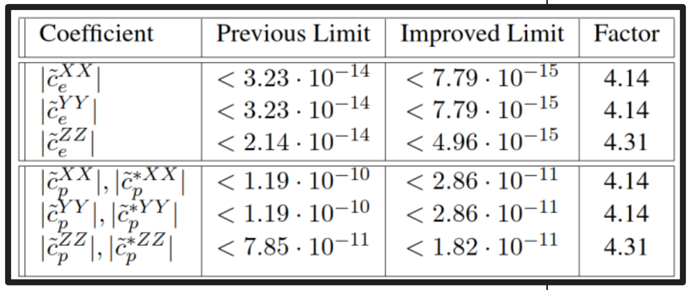
Most precise test of CPT invariance in the baryon sector

- 24 000 data points acquired in 4 measurment campaigns over 1.5 years. All in accelerator experimental hall!

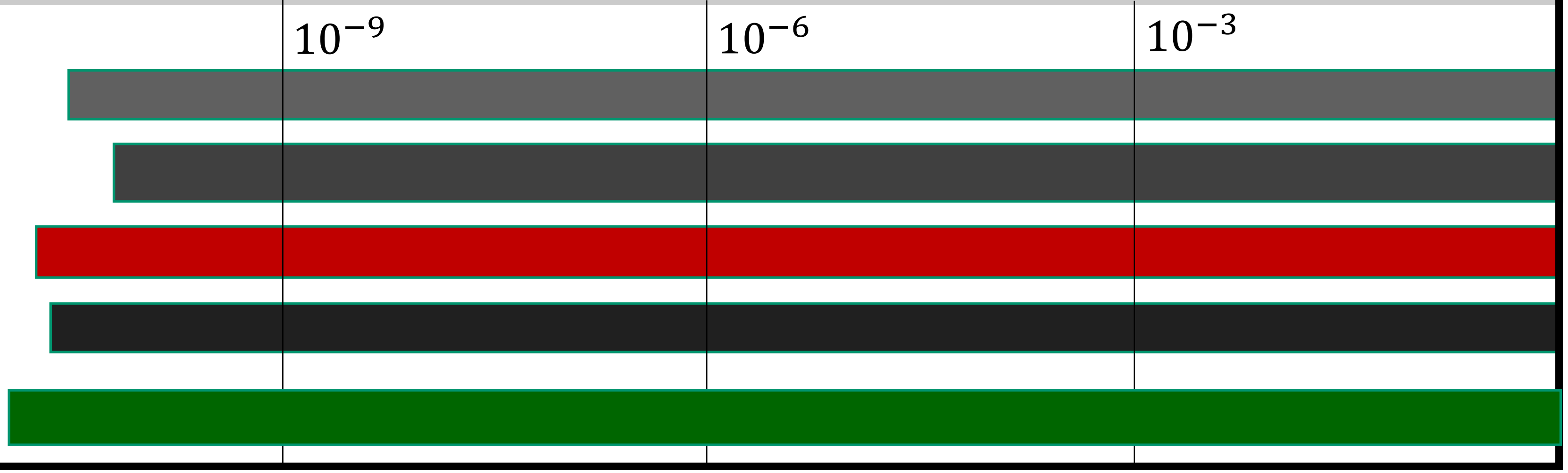
Campaign	R_{exp}	$\sigma(R)_{stat}$	$\sigma(R)_{sys}$
2018-1-SB	1.001089218748	$27 * 10^{-12}$	$27 * 10^{-12}$
2018-2-SB	1.001089218727	$47 * 10^{-12}$	$49 * 10^{-12}$
2018-3-PK	1.001089218748	$19 * 10^{-12}$	$14 * 10^{-12}$
2018-1-SB	1.001089218781	$19 * 10^{-12}$	$23 * 10^{-12}$
Result	$R_{exp,p,\bar{p}} = -1.000000000008(16)$		

SME Limits

$$|\delta\omega_c^{\bar{p}} - R_{\bar{p},p,\mathrm{exp}}\delta\omega_c^{p} - 2R_{\bar{p},p,\mathrm{exp}}\delta\omega_c^{e^-}| < 1.96\times10^{-27}\ \mathrm{GeV}$$



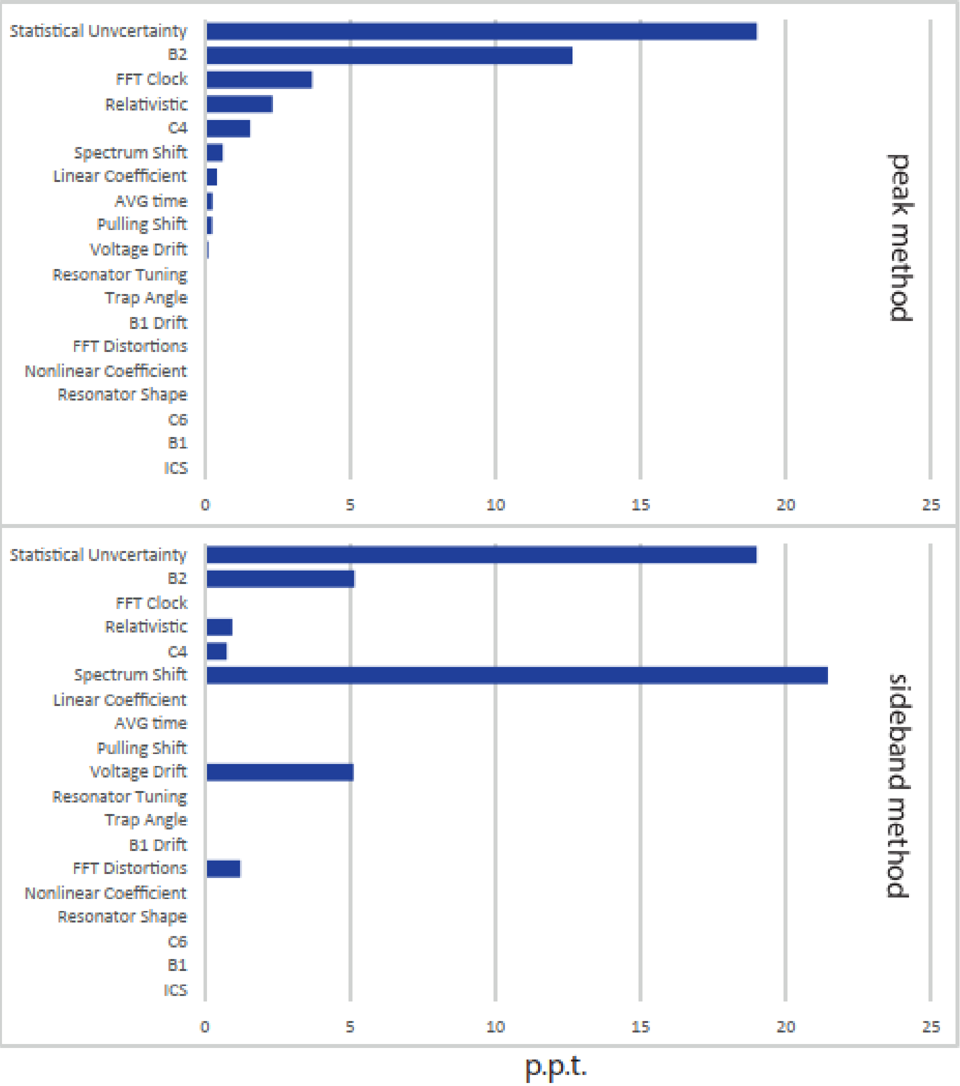
Coefficient	Previous Limit	Improved Limit	Factor
$\lvert\tilde{c}_e^{XX}\rvert$	$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}_e^{YY}\rvert$	$< 3.23\cdot10^{-14}$	$< 7.79\cdot10^{-15}$	4.14
$\lvert\tilde{c}_e^{ZZ}\rvert$	$< 2.14\cdot10^{-14}$	$< 4.96\cdot10^{-15}$	4.31
$\lvert\tilde{c}_p^{XX}\rvert, \lvert\tilde{c}_p^{*XX}\rvert$	$< 1.19\cdot10^{-10}$	$< 2.86\cdot10^{-11}$	4.14
$\lvert\tilde{c}_p^{YY}\rvert, \lvert\tilde{c}_p^{*YY}\rvert$	$< 1.19\cdot10^{-10}$	$< 2.86\cdot10^{-11}$	4.14
$\lvert\tilde{c}_p^{ZZ}\rvert, \lvert\tilde{c}_p^{*ZZ}\rvert$	$< 7.85\cdot10^{-11}$	$< 1.82\cdot10^{-11}$	4.31



2015 (*Nature* 524 196 (2015))	**2022 (Nature 601.7891 (2022): 53-57)**
$R_{exp,p,\bar{p}}$= -1.000 000 000 001 (69)	−1.000000000008(16)

Systematic Effects and Result

Effect	2018-1-SB	2018-2-SB	2018-3-PK	2019-1-SB
B_1-shift	0.03(2)	0.01(2)	< (0.01)	< (0.01)
B_2-shift	20.27(14.86)	8.38(14.86)	10.79(12.66)	3.75 (5.16)
C_4-shift	(1.12)	(1.13)	(1.54)	(0.76)
C_6-shift	< (0.01)	< (0.01)	< (0.01)	< (0.01)
Relativistic	1.20(92)	0.47(90)	1.90(2.32)	0.65(94)
Image charge shift	0.05(0)	0.05(0)	0.05(0)	0.05(0)
Trap misalignment	0.06(0)	0.06(0)	0.05(0)	0.05(0)
Voltage Drifts	−3.35(5.12)	−3.77(5.12)	−0.11(11)	−5.03(5.12)
Spectrum Shift	0.37(20.65)	16.89(46.49)	0.74(61)	−8.61(21.45)
FFT-Distortions	(1.57)	(3.48)	(0.03)	(1.23)
Resonator-Shape	0.02(3)	0.02(2)	< (0.01)	0.01(2)
B_1-drift offset	< (0.11)	< (0.11)	< (0.04)	< (0.04)
Resonator Tuning	< (0.16)	< (0.16)	< (0.06)	< (0.06)
Averaging Time	–	–	−2.87(25)	–
FFT Clock	–	–	(3.69)	–
Pulling Shift	–	–	2.86(24)	–
Linear Coefficient Shift	–	–	0.16(40)	–
Nonlinear Shift	–	–	0.03(2)	–
Systematic Shift	18.65(26.04)	22.11(49.22)	13.60(13.50)	−9.13(22.71)
$R_{exp} - R_{theo}$	13.02(27.12)	−5.04(46.57)	7.99(18.57)	18.34(18.89)
$R_{exp,c} - R_{theo}$	−5.63(37.60)	−27.15(67.76)	−5.61(22.66)	27.47(29.54)



Future perspective

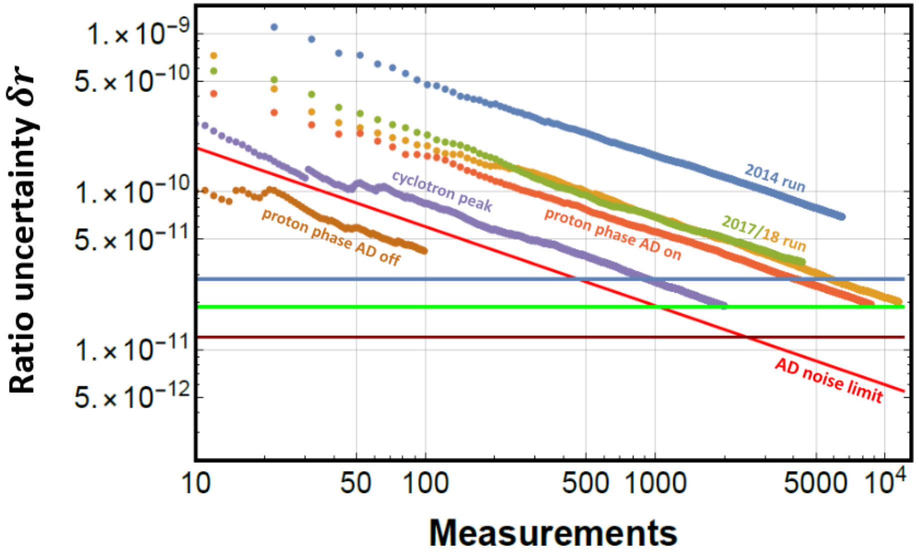
1. Cyclotron frequency measurement with phase sensitive methods - **20 p.p.t. / 24h , but only possible during accelerator shutdown.**

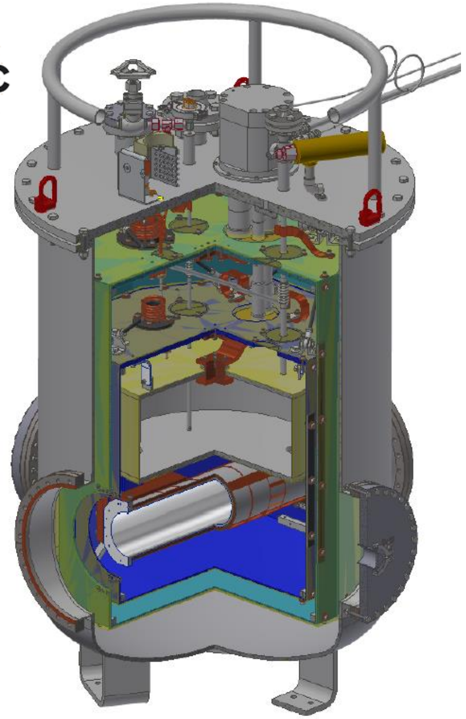
2. Two particle method:
   - Moderately „simple” for mass measurements
   - Difficult for antiproton nuclear magnetic moment (for antiproton it is 658 times smaller then for electron!!!)

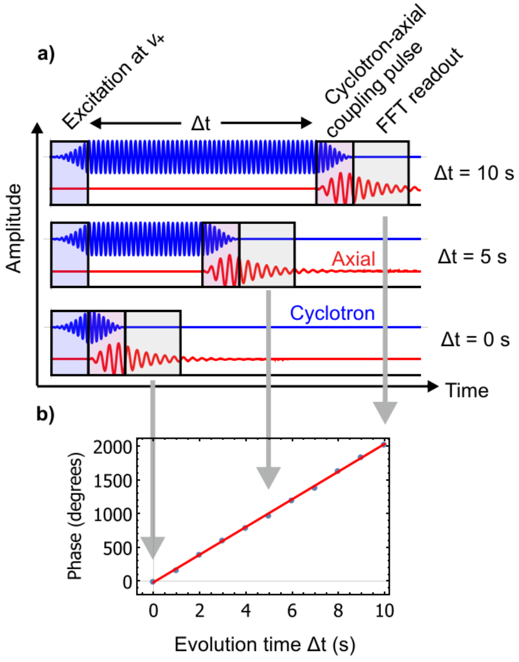
3. Magnetic noise in the accelerator hall:

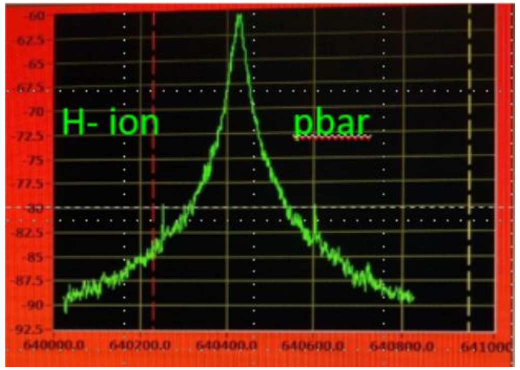
If you can not switch off the accelerator...

Transport yourself out of the accelerator hall.









Weak Equivalence Principle Tests

- Single particle in a Penning trap -> **A cyclotron frequency clock**.
- Hughes and Holzscheiter

(PRL 66, 854 (1991)):

$$\frac{\nu_{c,\bar{\mathrm{p}}} - \nu_{c,\mathrm{p}}}{\nu_{c,\mathrm{avg}}} = \frac{3\Phi}{c^2}(\alpha_g - 1)$$

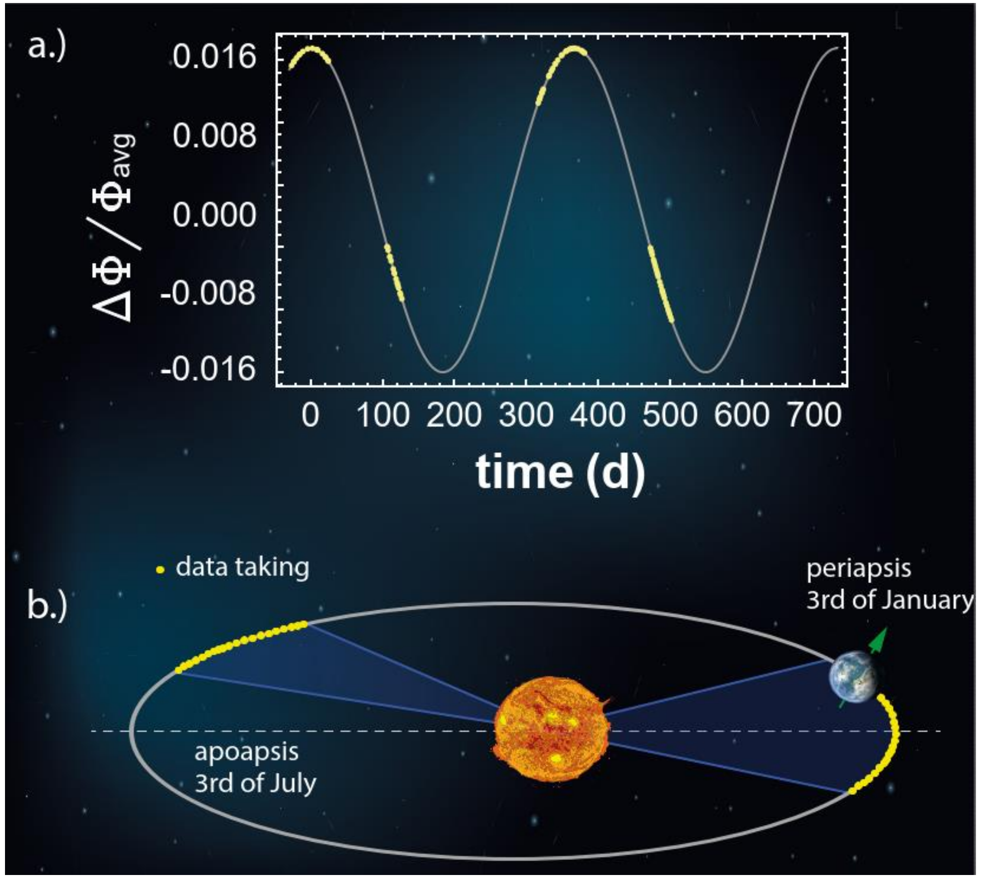
where $\frac{\phi}{c^2} = \frac{GM}{rc^2} = 2.99 \times 10^{-5}$ is a potential of the local supergalactic cluster.
Then

$$\boldsymbol{\alpha_g < 1.8 \times 10^{-7}}.$$

- Differential analysis: $O(t) = D_p(1-\varepsilon^2)/[1+\varepsilon\cos\left(\left(\frac{2\pi}{t_{sid}}\right)t\right)$

$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3\gamma M_{\mathrm{sun}}}{c^2}(\alpha_{g,D} - 1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right)$$

$$\boxed{\boldsymbol{\alpha_{g,D} < 0.0301}.}$$



- Dedicated Antihydrogen Free Fall Experiments (ALPHAg, AEgIS, GBAR): first anticipated precision at up to 1 %.

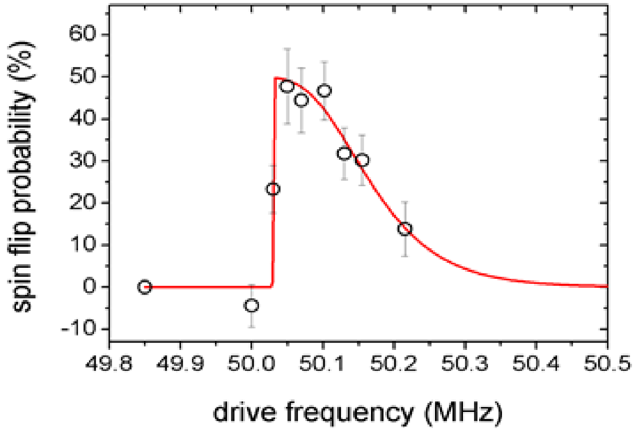
g factor

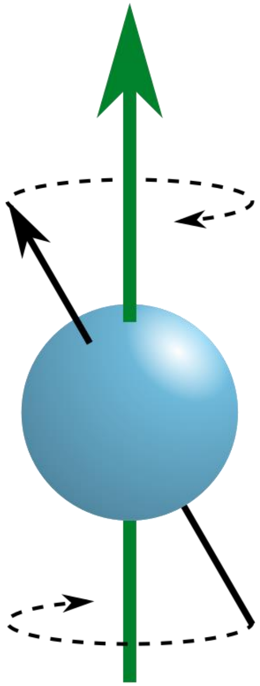
- **Magnetic moment and a spin of a particle are related through a dimentionless parameter called g-factor:**

$$\boldsymbol{\mu} = g\frac{q}{2m}\mathbf{S} \quad\Rightarrow\quad \mu = \frac{g}{2}\mu_{\mathrm{N}}$$

- **(Anti)Proton / electron spin S = ½**
- **Larmor frequency – spin precession in a given magnetic field:**

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

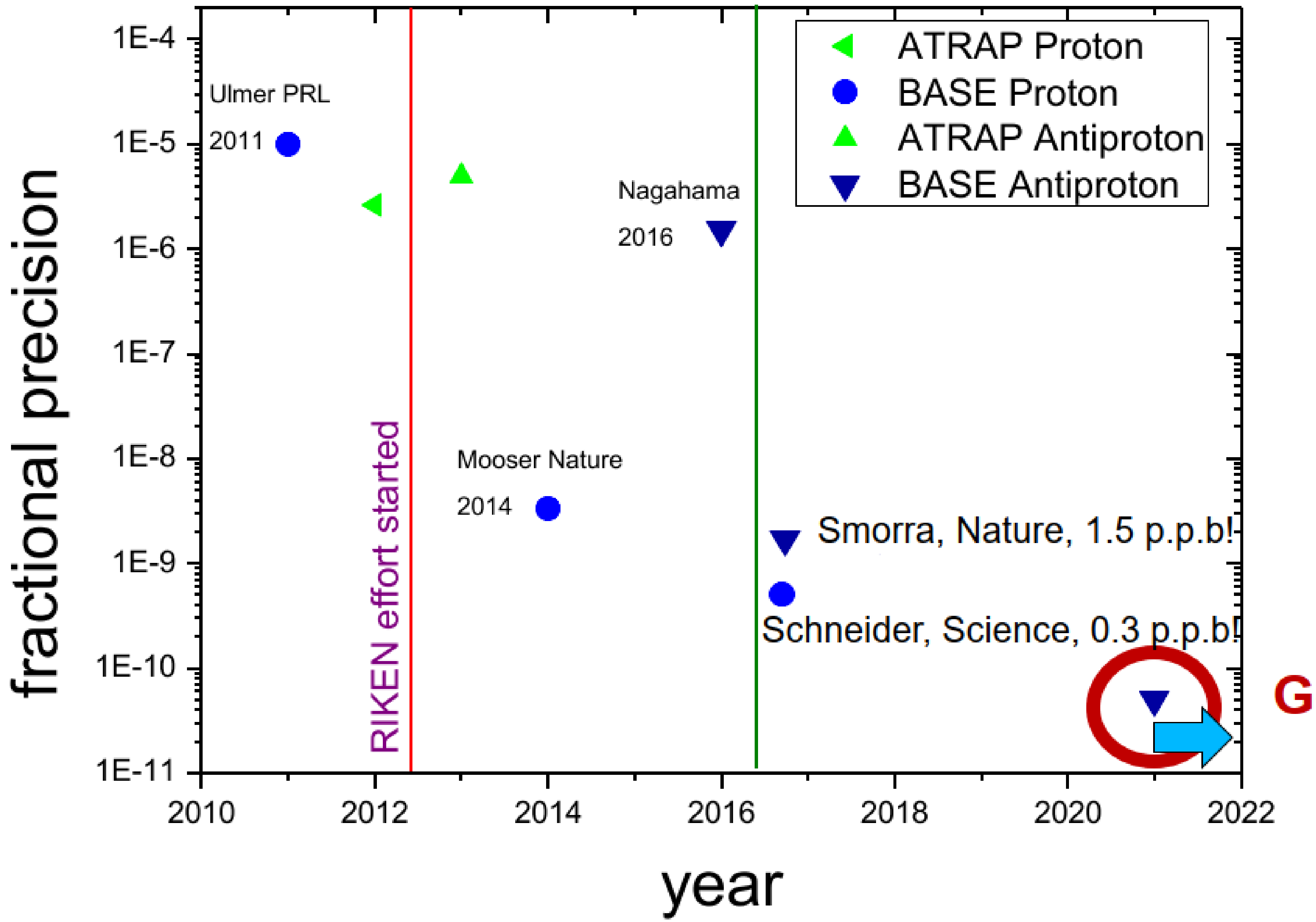




- **g factors:**

Particle	g-factor	Relative standard uncertaintity
Electron	−2.00231930436256(35)	1.7×10^{-13}
Muon – (experiment-world-average-2021)	−2.002 331 84121(82)	4.1×10^{-10}
Proton	5.5856946893(16)	$\mathbf{2.9 \times 10^{-10}}$
Antiproton	5.5856946906(60)	$\mathbf{1.5 \times 10^{-9}}$

Goal – 10-fold improved measurement of the pbar moment



Goal of this run

Spin flip detection

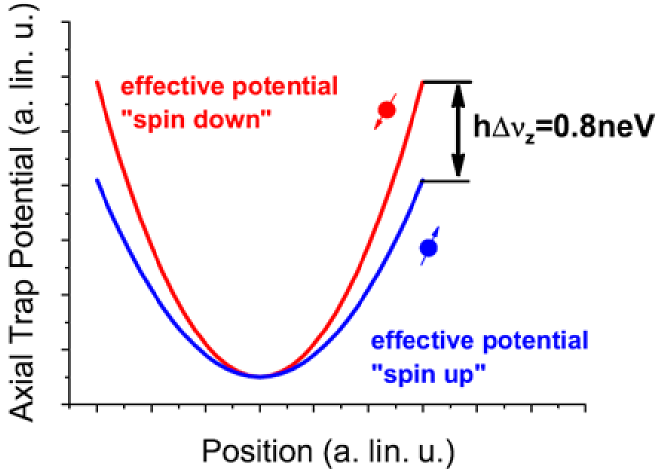
- Measurement based on continuos Stern Gerlach effect.
- Energy of magnetic dipole in magnetic field: $\Phi_M = -(\overrightarrow{\mu_p} \cdot \vec{B})$
- Leading order magnetic field correction: $B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$
- This term adds a spin dependent quadratic axial potential so **the Axial frequency becomes function of spin state**

$$\Delta\nu_z = |\vec{\mu}_+ + \vec{\mu}_- + \vec{\mu}_S| \times \frac{B_2}{4\pi^2 m_{\bar{p}} \nu_z}$$

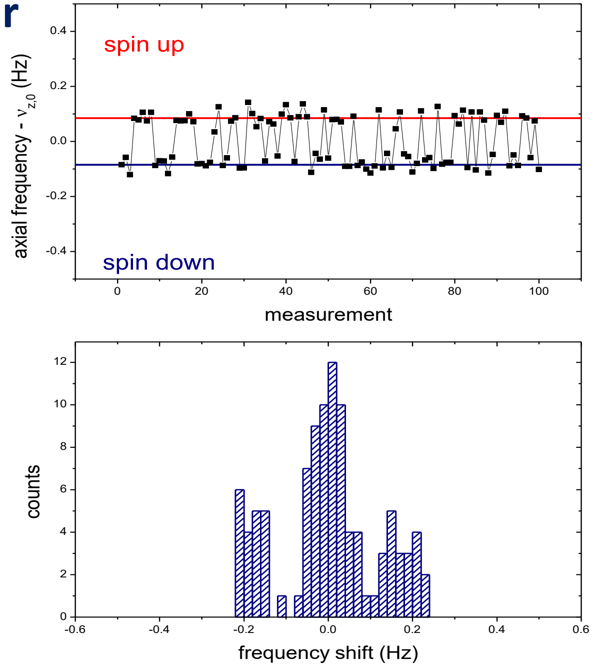
- The proton/antiproton magnetic moment it is **658 times smaller** than for electron ($\boldsymbol{\mu} = g\frac{q}{2m}\boldsymbol{S}$)!!! In order to resolve the change of the spin state we need extremly high B2 (axial frequency about 700 kHz):

$$B_2 \sim 300000\, T/m^2 \Rightarrow \Delta\nu_{z,\mathrm{SF}} = \frac{\hbar\omega_L}{4\pi^2 m_{\bar{p}}\nu_z}\frac{B_2}{B_0} = 172(8)\,\mathrm{mHz}$$

- **Most extreme magnetic conditions ever applied to single particle**.
- One cyclotron quantum jump induce about ~70mHz (70 neV) shift, while spin flip ~170 mHz.

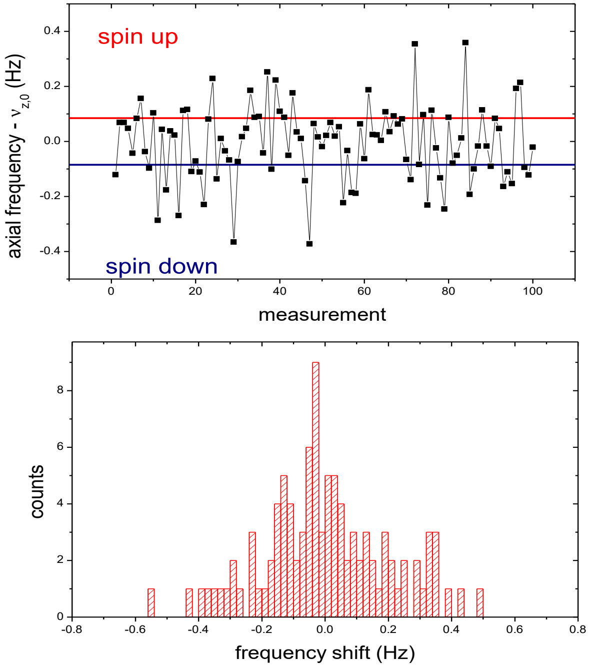


cold particle (50mK)



high-fidelity spin state resolution

hot particle (1K)



fidelity at 65%, not useful for measurements

Antiproton magnetic moment measurement

- Larmor frequency measurement:

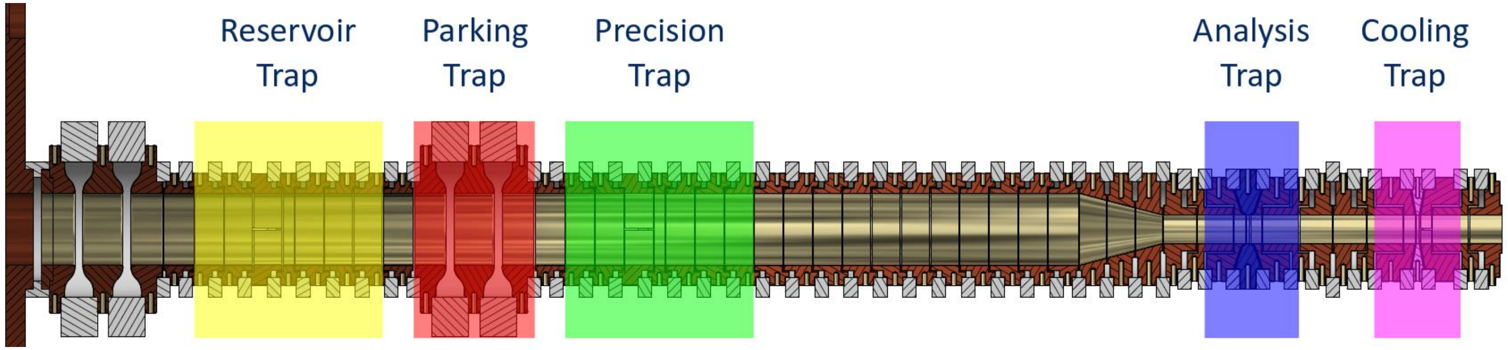
Analysis Trap - high B2 / Cold →

Precision Trap - low B2 / Hot →

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

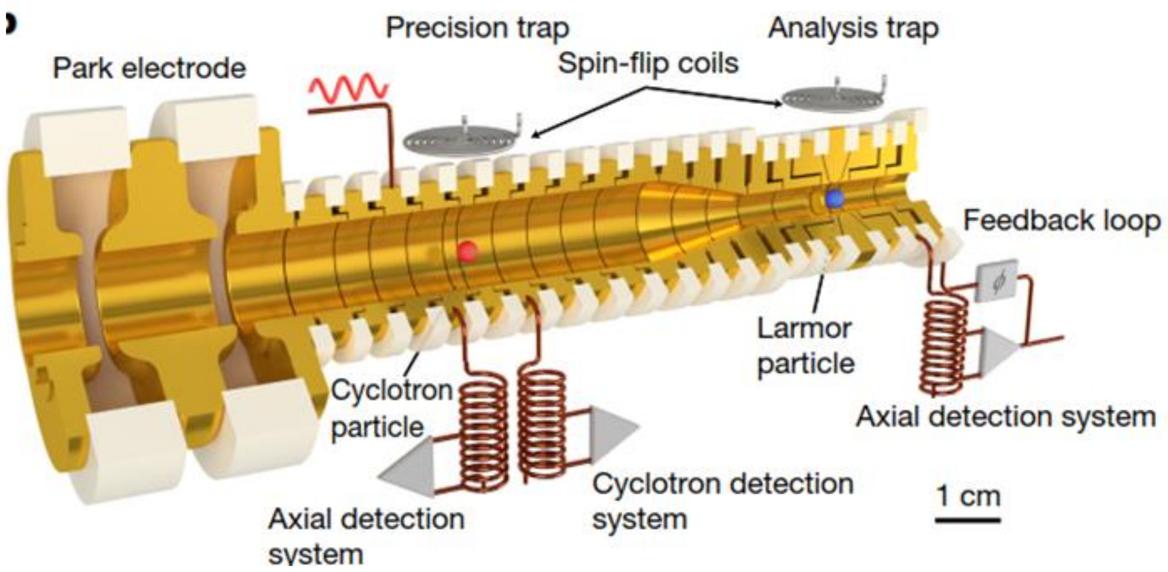
High B2? Low B2? How???

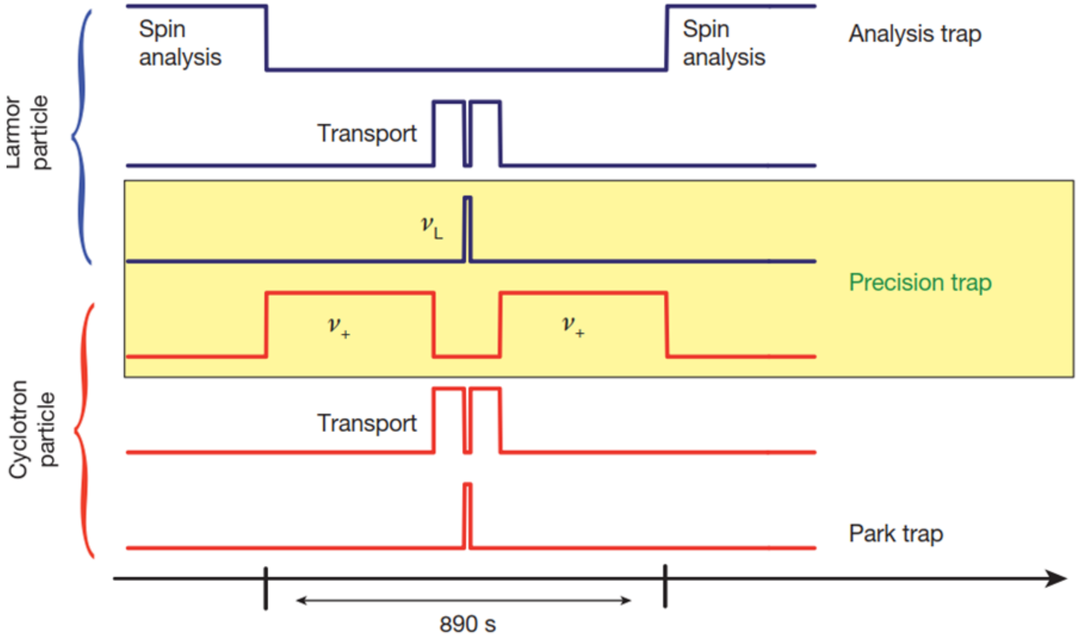
How can we cool antiprotons < 200 mK???



1.5 p.p.b. Antiproton magnetic moment measurement (2017)

- C. Smorra, Nature 550, 371-374 (2017)





Main systematic effects:

- different temperatures of particles proble different magnetic field

Goal: make more homogenous magnetic field and

go back to a measurement with one particle (cooling!)

Improve this measurement by at least a factor of 10.

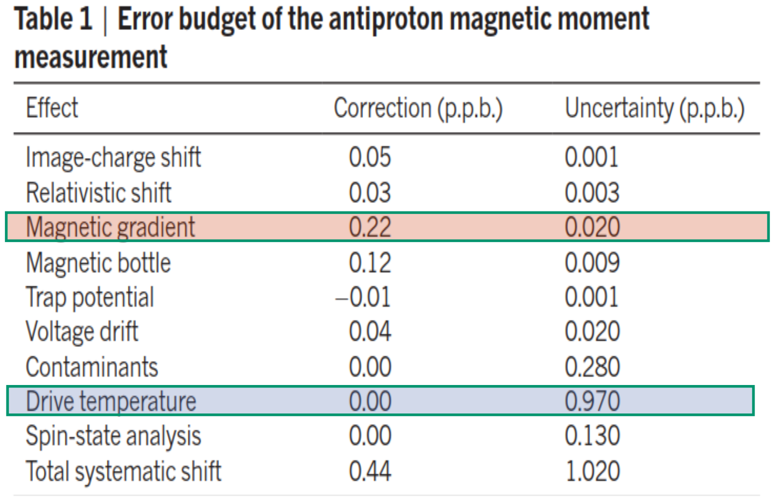
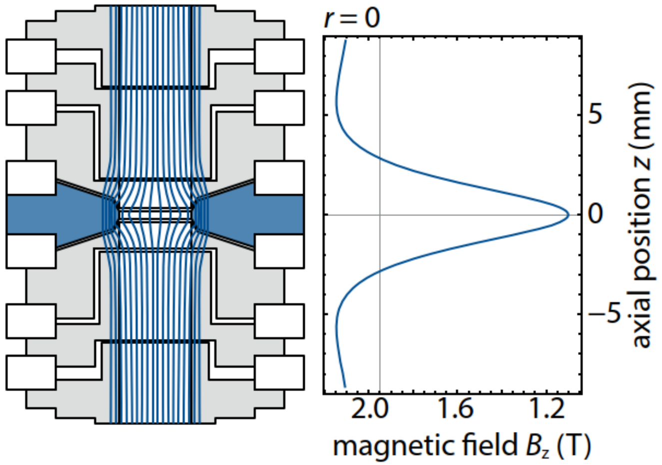


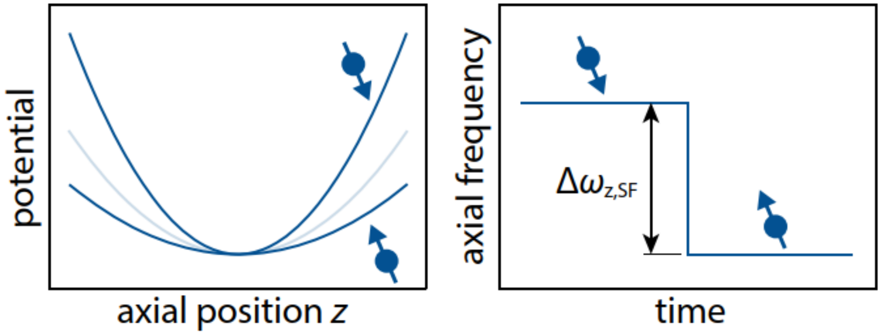
Table 1 | Error budget of the antiproton magnetic moment measurement

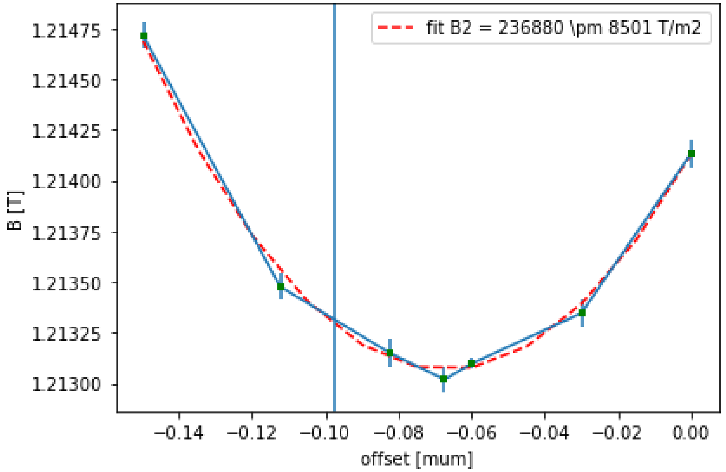
Effect	Correction (p.p.b.)	Uncertainty (p.p.b.)
Image-charge shift	0.05	0.001
Relativistic shift	0.03	0.003
Magnetic gradient	0.22	0.020
Magnetic bottle	0.12	0.009
Trap potential	−0.01	0.001
Voltage drift	0.04	0.020
Contaminants	0.00	0.280
Drive temperature	0.00	0.970
Spin-state analysis	0.00	0.130
Total systematic shift	0.44	1.020

High B2 -Analysis Trap - frequency stability 2022

- Ferromagnetic ring electrode:

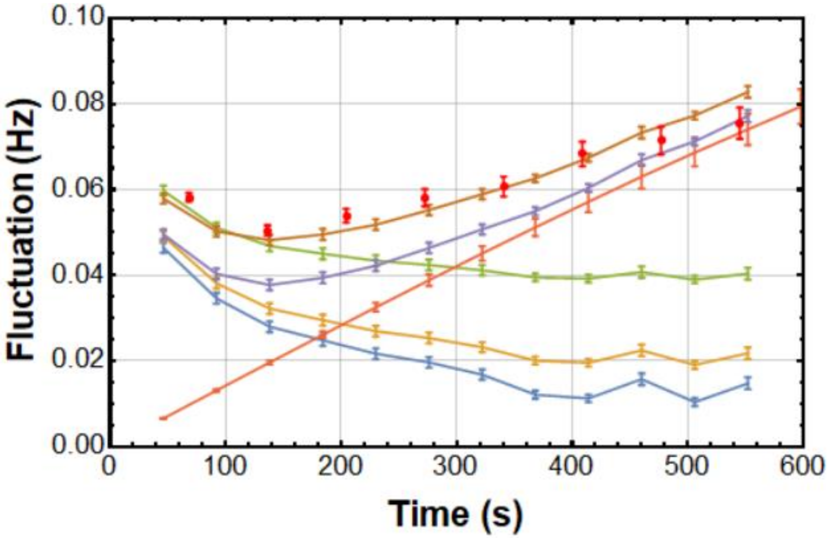






$$\omega_{z,SF} = \omega_z \pm \frac{\Delta\omega_{z,SF}}{2}$$

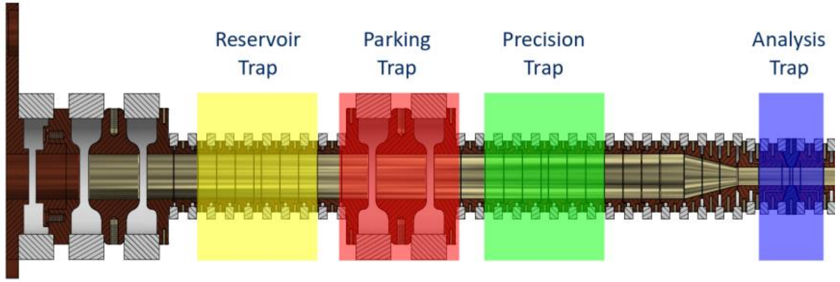
- Optimum frequency stability is at 45mHz, which corresponds to $650\ \mu\mathrm{K}$ or $60\ \mathrm{neV}$ energy resolution.



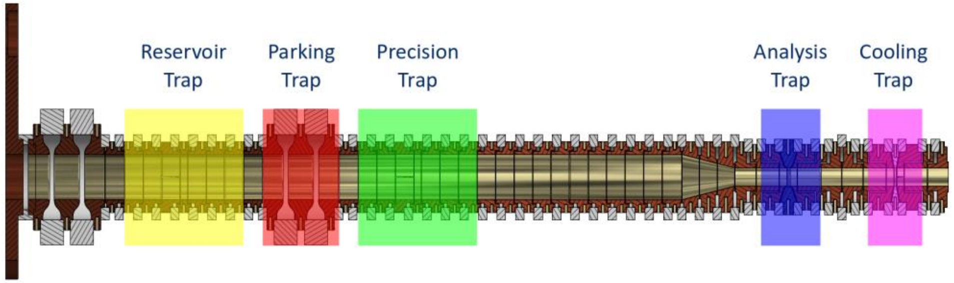
Low B2 - More homogenous magnetic field in the Precision Trap

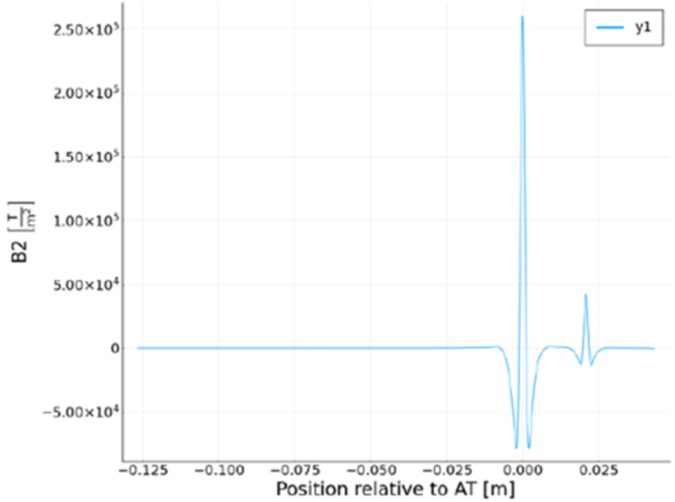
- New trap with increased distance between the Precision (homegenious B) and Analysis trap (spin flip trap)

2017:



2021:





Precision Trap: Homogeneous field for frequency measurements, $B_2 < 0.5$ / m^2 **(10 x improved)**.
Analysis Trap: Inhomogeneous field for the detection of antiproton spin flips, B_2 = 300 mT / mm^2

- Residual magnetic field in the PT originating from AT magnetic bottle:

	2017	2021 residual
B1 (linear)	0.0712(4) T/m	0.0270(7) T/m
B2 (quadratic)	2.7(3) T/m^2	0.1298(8) T/m^2

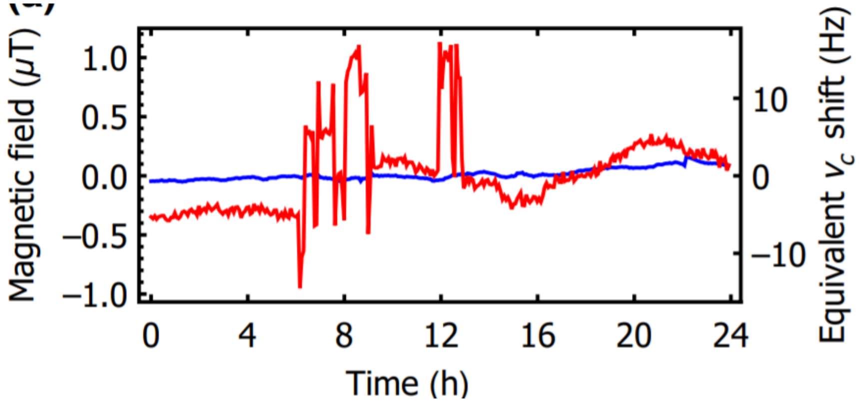
Reduces the dominant systematic shift of the 2017 measurement by a factor of 20 !

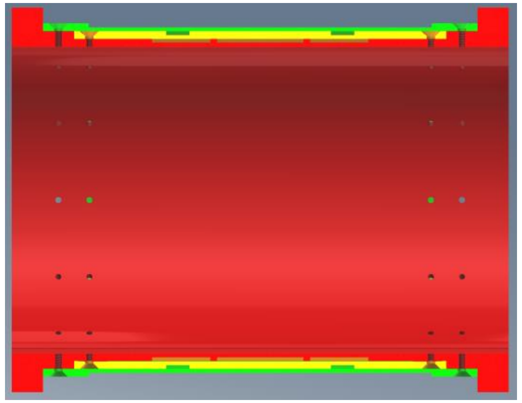
Low B2 - More homogenous magnetic field in the Precision Trap

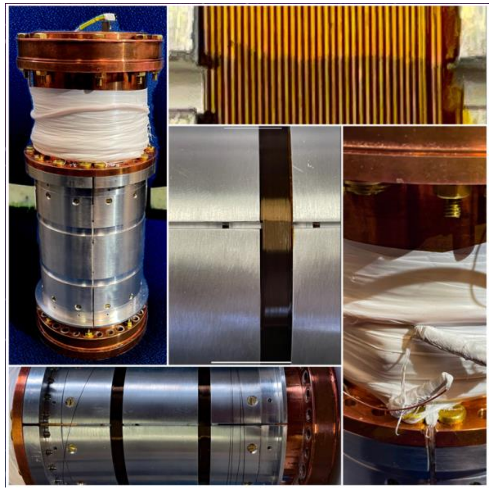
- Idea:
  - **Magnetic shielding** -> necessary to decrease fluctuations caused by the Antiproton Decelerator and other experiments.
  - In 2018 it supressed the magnetic field flactuations by up to 225(16).
  - **Magnetic shimming**
    - a system of superconducting coils to compensate residual B2 and B1:
    - B0 coil to be able to change B2 and B1 without changing ν_+.

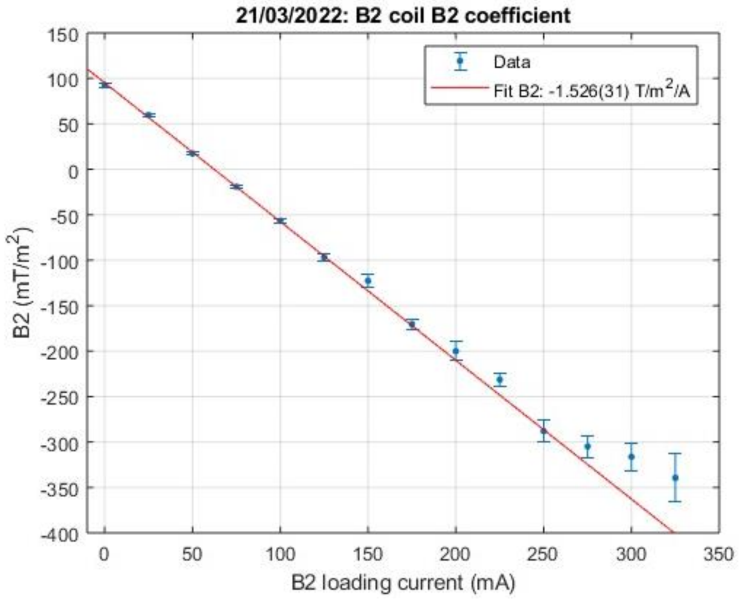
	2017	**2021 residual**	**2022 *tunning**
B1 (linear)	0.0712(4) T/m	0.0270(7) T/m	0.016 T/m
B2 (quadratic)	2.7(3) T/m^2	0.1298(8) T/m^2	0 (0.0003) T/m^2

Completely eliminates systematic shift of 2017 measurement!









Single antiproton cooling - Cooling Trap

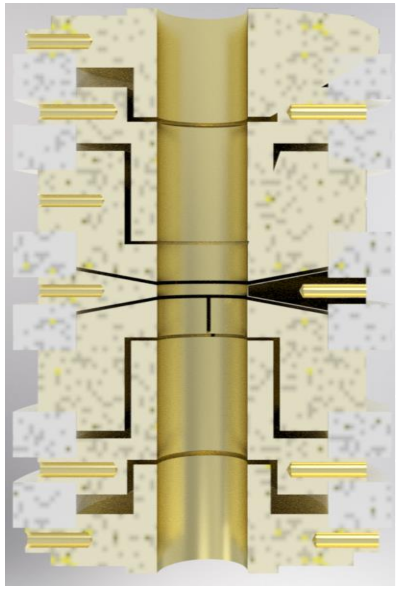
- **Resistive, subthermal cooling** – coupling of a particle to the dedicated cyclotron detector.

It’s a stochastic process in which you probe the Boltzman distribution with a temperature corresponding to the temperature of the detector.

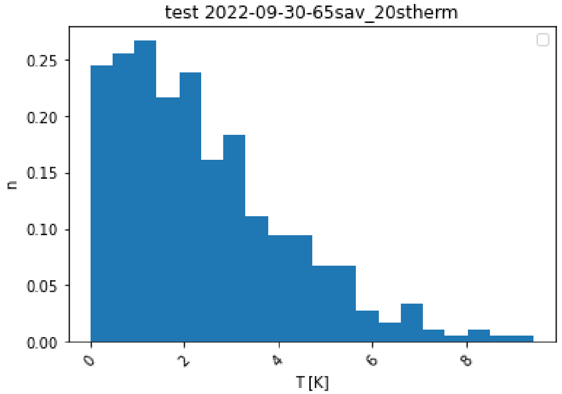
- Thermalisation constant:

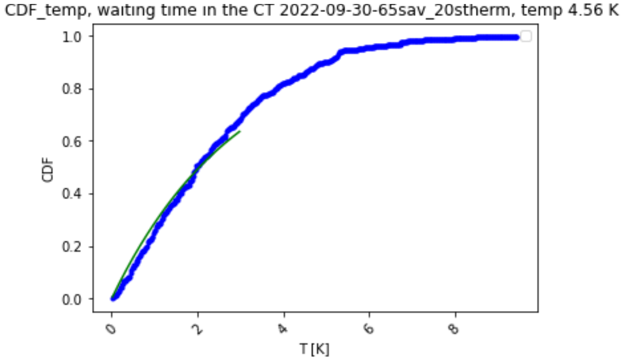
$$\tau = \frac{m}{R_p} * \left(\frac{D_{eff}}{q}\right)^2$$

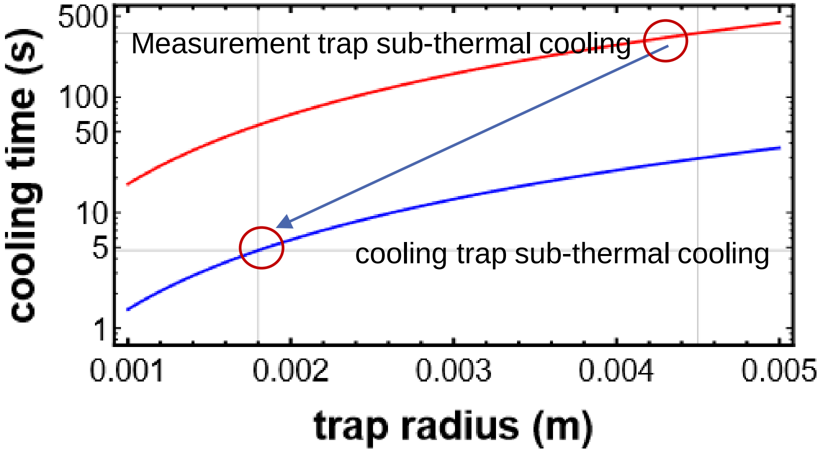
- **Implementation of a dedicated cooling trap with strong particle detector coupling, reduced detector temperature, high-performance detection resistor.**
- Optimize transport and readout time in single-particle temperature measurements.



Parameter	2016 measurement (PT)	2022 measurement (CT)
detector temperature	**12.8 K**	**4.2 K**
detection Q	450	1250
R_p	75.000 Ω	360.000 Ω
pickup length (D_{eff})	21.5 mm	4.8 mm
thermalization time τ	370 s	4.2 s
Transport time	2 x 78 s	2 x 4.6 s
Readout time	64 s	16 s

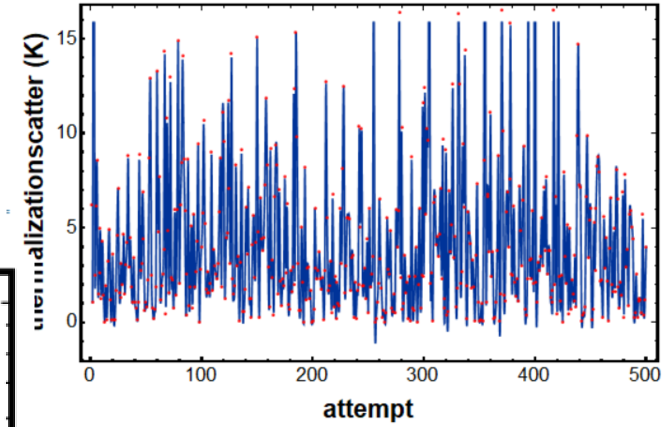


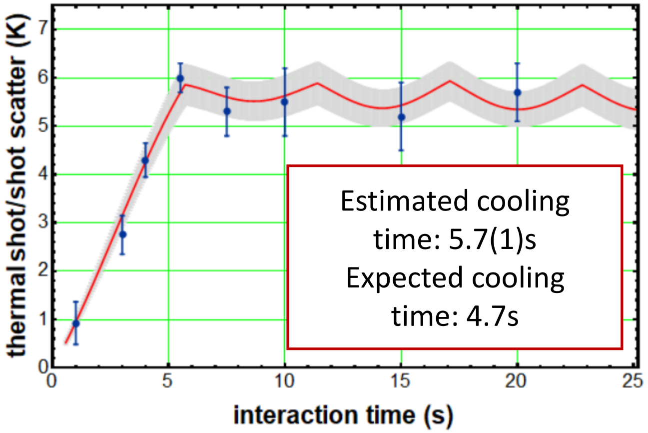




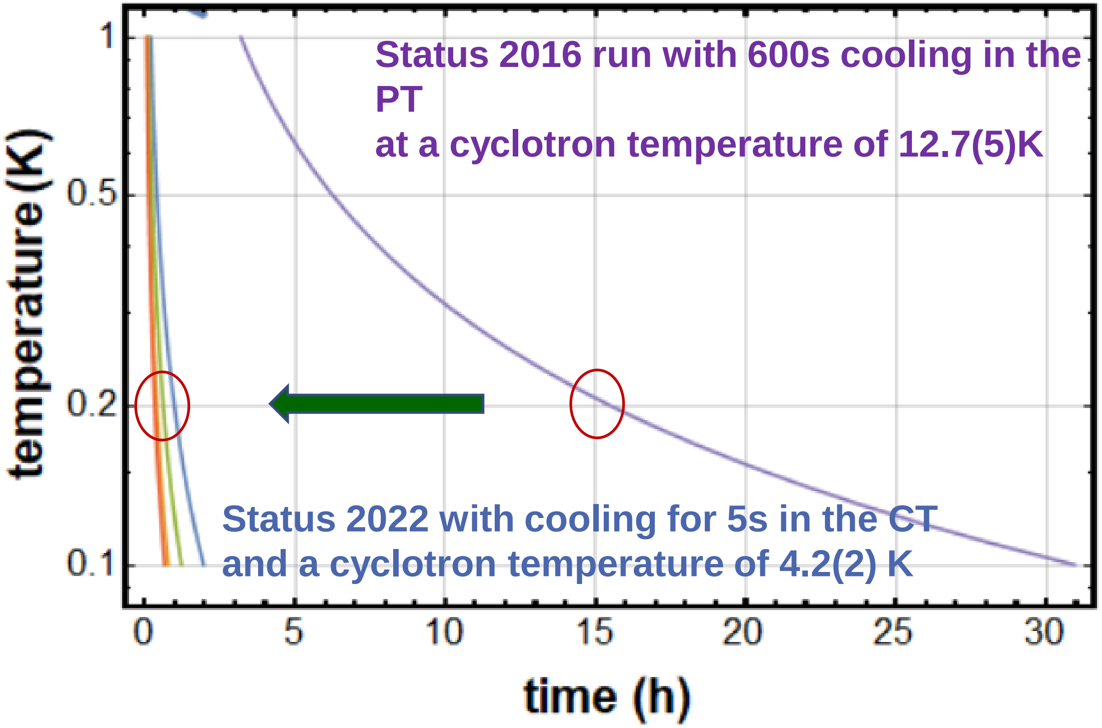
Thermalization Time Optimization

- Use correlation estimates to determine optimum particle / detector coupling time.
  - Measure frequency scatter as a function of particle / detector interaction time





Estimated cooling time: 5.7(1)s
Expected cooling time: 4.7s



Status 2016 run with 600s cooling in the PT
at a cyclotron temperature of 12.7(5)K

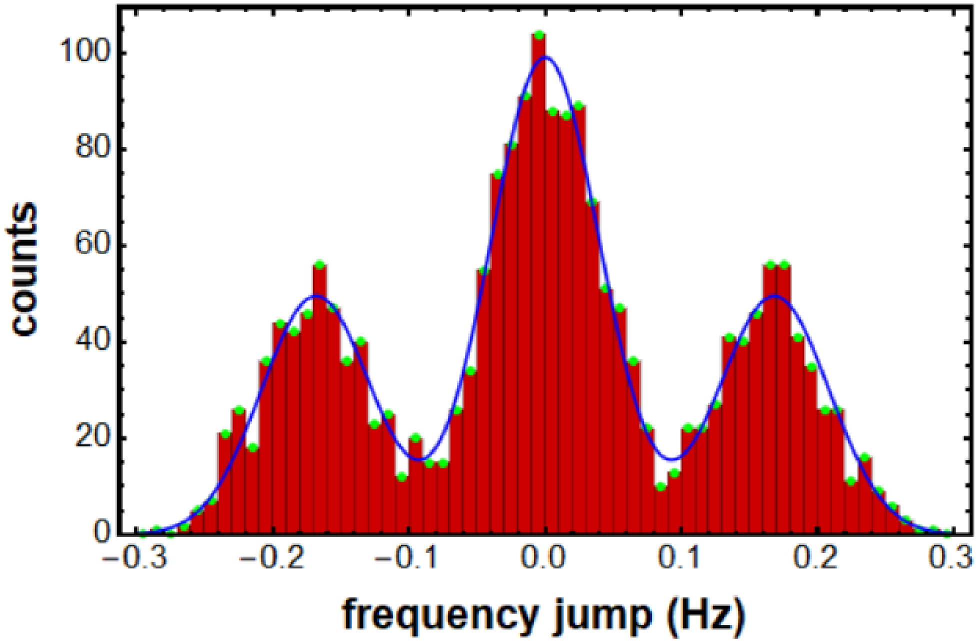
Status 2022 with cooling for 5s in the CT
and a cyclotron temperature of 4.2(2) K

Item	2016	2022
Spec AVG	64s	16s
TP from AT	78 s	5 s
Thermalize	600 s	5 s
TP To AT	78 s	5 s
Single Cycle	820 s	31 s
Improvement Factor: 26		

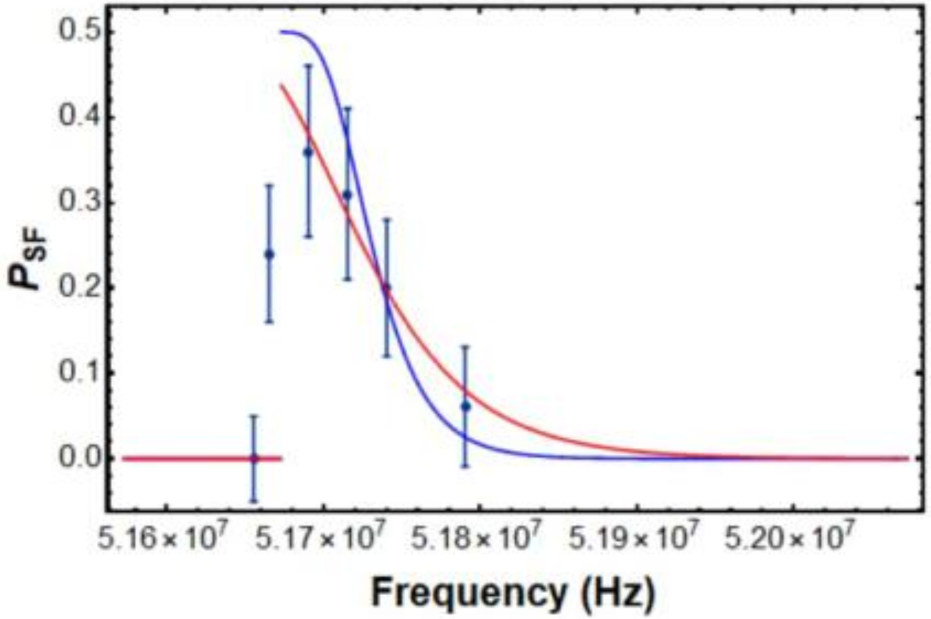
- Three-fold temperature reduction gives additional factor of three in time reduction for particle preparation at given threshold.
- **Explicitly demonstrated:** robust 200mK particle preparation in 8 minutes.
- **Reduces particle preparation time from 15h to 8 minutes!!!**

Single Spin Flips in the Analysis Trap 2022

- **Single Spin Flip resolution!!!**



- **First Larmor frequnecy resonance in the AT this year:**

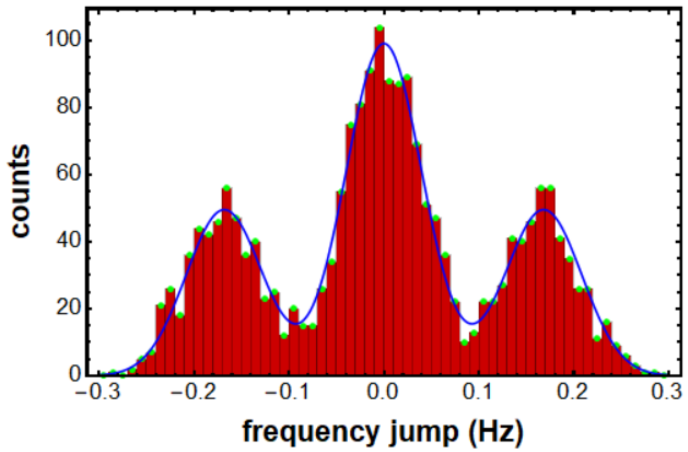


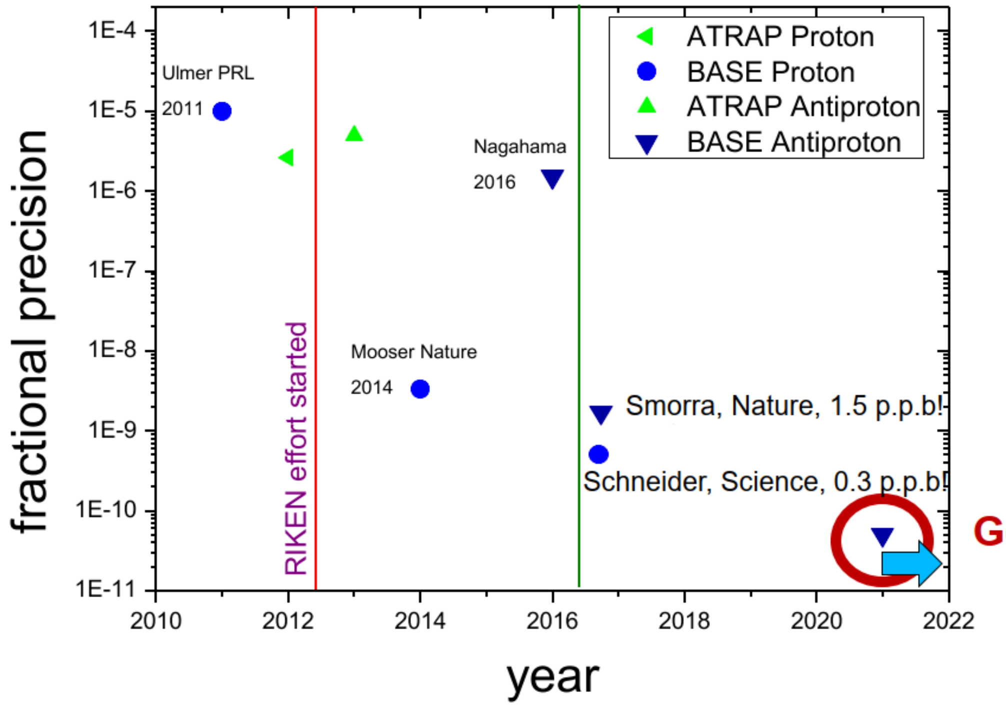
Status and Summary

- Working 1760 nm thick vacuum window which allows for catching 100 keV antiproton beam.
- Eliminated systematic error due to magnetic field inhomogenity in Precision Trap.
- Improved cooling time from 15 h to 8 min
- Transport scatter between traps < 20 quanta per transport.

- Reached 45 mHz background frequency scatter.
- Detected single spin flips!

Ready to commission planned <100ppt proton and antiproton magnetic moment measurements…!!!

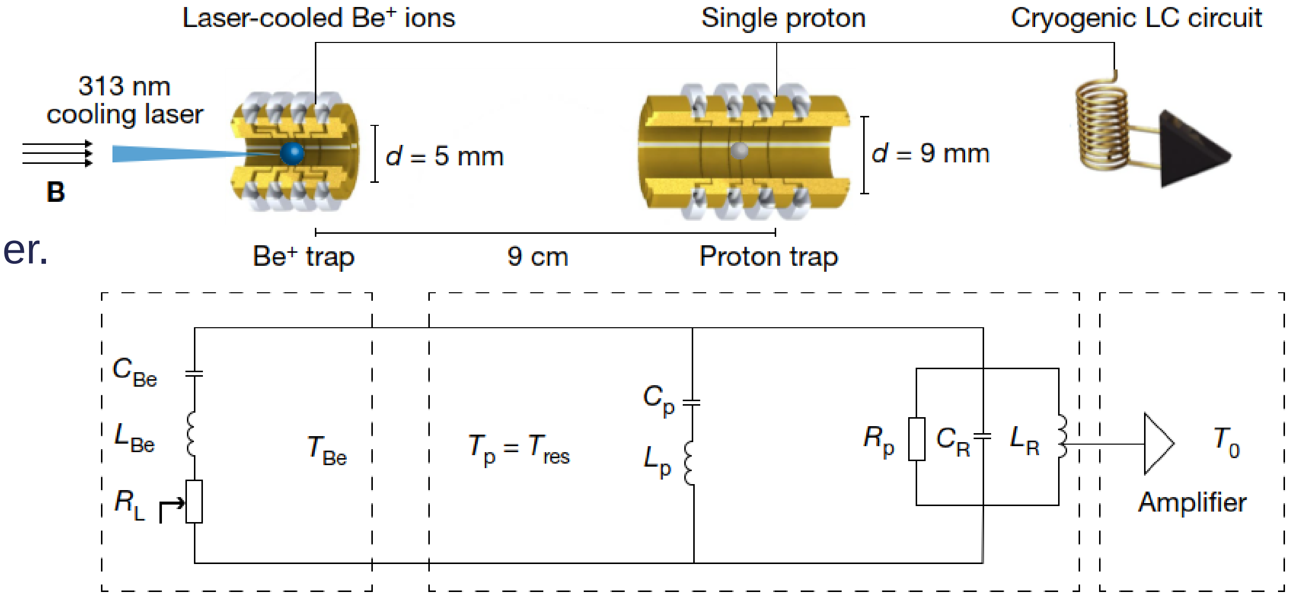


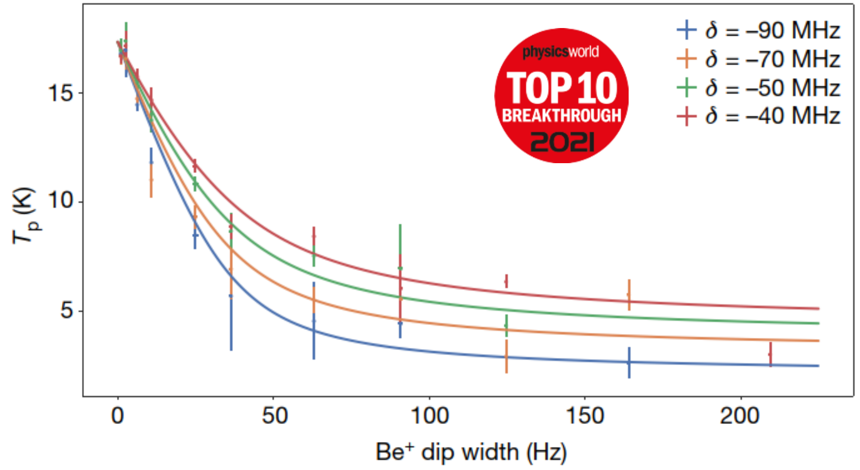


Goal of this run

Recent Achievements for the Future – Sympathetic Cooling

- Magnetic moment measurements are limited by particle temperature and would be considerably accelerated by inventing a method beyond resistive cooling.
- Method proposed by Wineland and Heinzen: Couple particles in different traps via image currents.
- Transfer particle temperatures from one trap to the other.
- **First proof of principle demonstration successful!!!** M. Bohman et al., Nature **596**, 514 (2021)
- **Demonstrated proton temperature reduction by about a factor of 8.**
- New trap geometries under development for more efficient cooling.
- Simulations show that optimised procedures will enable **20 mK temperatures in 10 s**.





Summary

- **New measurement of the antiproton-to-proton charge–mass ratio:**

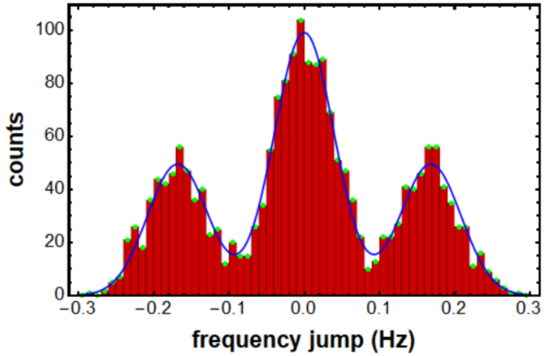
2015 (*Nature* 524 196 (2015))	2022 (Nature 601.7891 (2022): 53-57)
$R_{exp,p,\bar{p}}$= -1.000 000 000 001 (69)	−1.000000000008(16)

Factor of 4.3 improvement!!!

- **Now: New antiproton magnetic moment measurement with 10 times higher precision.**
- Main improvements:
  - New magnetic shielding and shimming system.

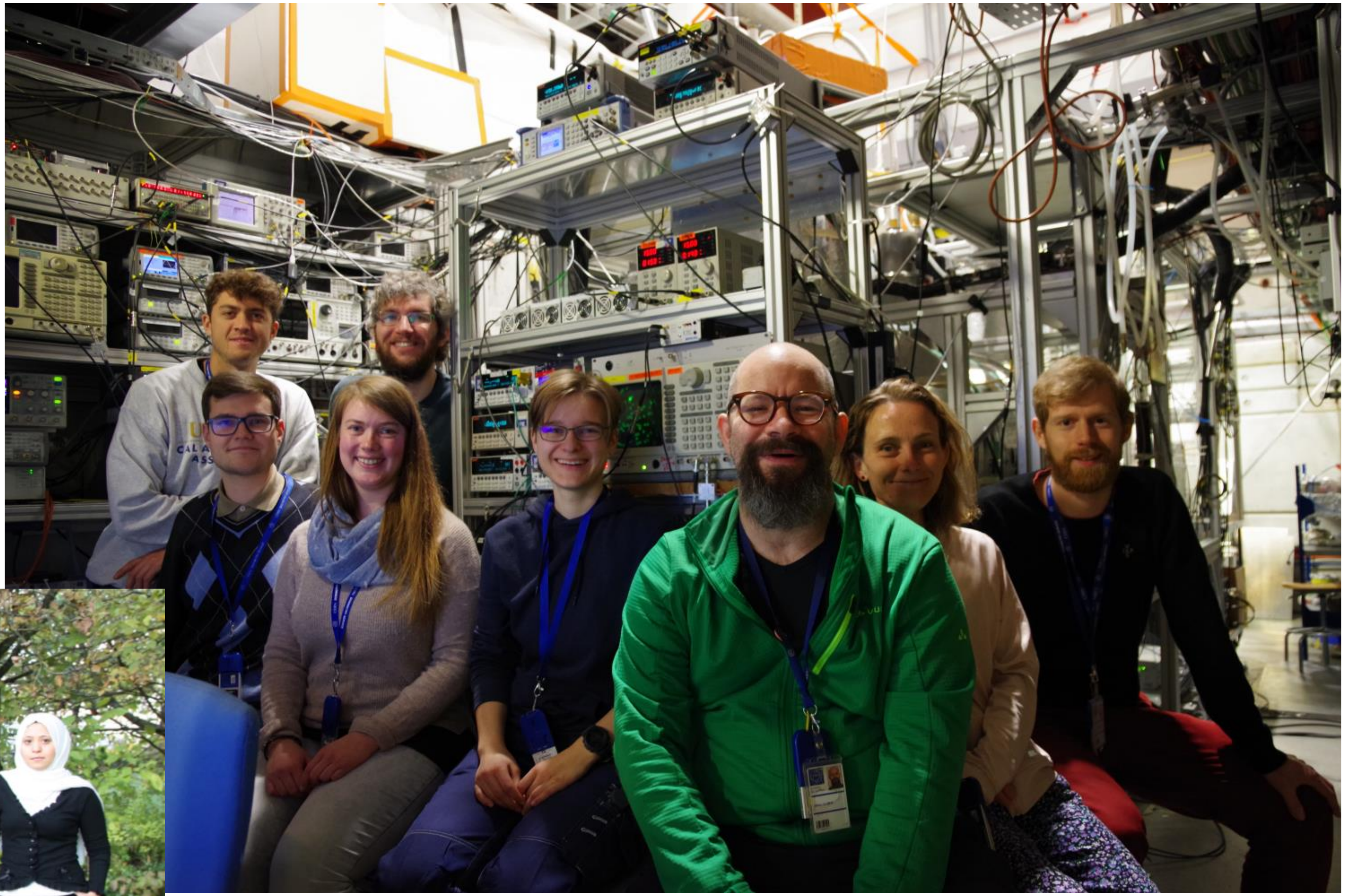
	2017	2021 residual	2022 *tunning
B1 (linear)	0.0712(4) T/m	0.0270(7) T/m	0.016 T/m
B2 (quadratic)	2.7(3) T/m^2	0.1298(8) T/m^2	0 (0.0003) T/m^2

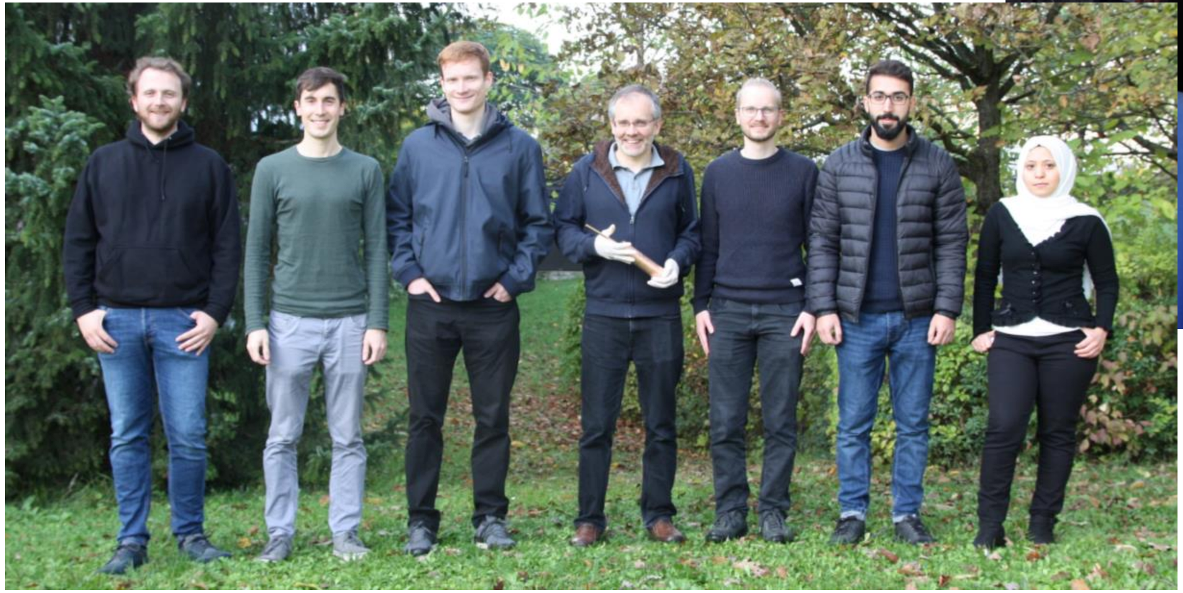
  - Dedicated cooling trap with <200 mK particle preparation time of 8 min (factor of 110 faster!!!)
  - New vacuum system.
  - 45 mHz frequency stability!!!



- Long term improvements:
  - **Sympathetic cooling of protons/antiprotons.**
  - **BASE STEP – transporting antiprotons outside the highly unstable antiproton decelerator hall.**
- **BASE CDM (Cold Dark Matter) – a competitive and compact solution for ALP searches.**

Thank you for your attention!





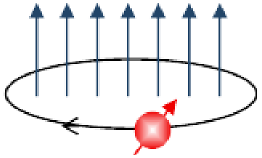
Main Measurements at BASE

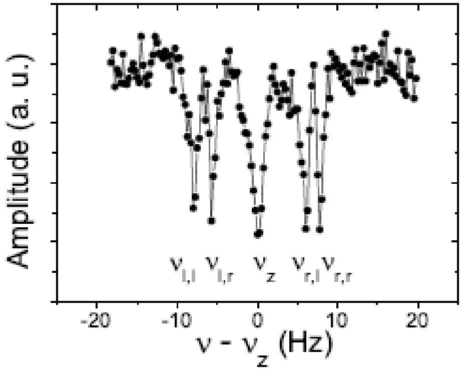
High precision mass spectroscopy

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Cyclotron Motion

$$\omega_c = \frac{e}{m_p} B$$





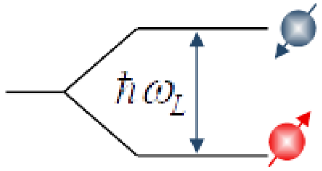
- **A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio,** Nature 601.7891 (2022): 53-57.

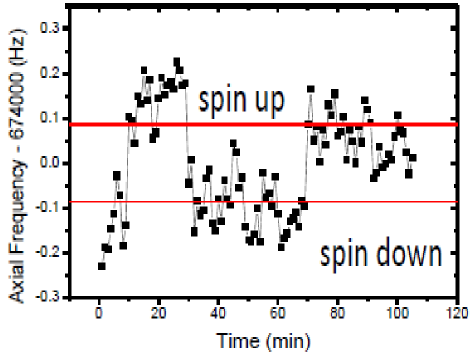
High precision magnetic moment measurements

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession

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



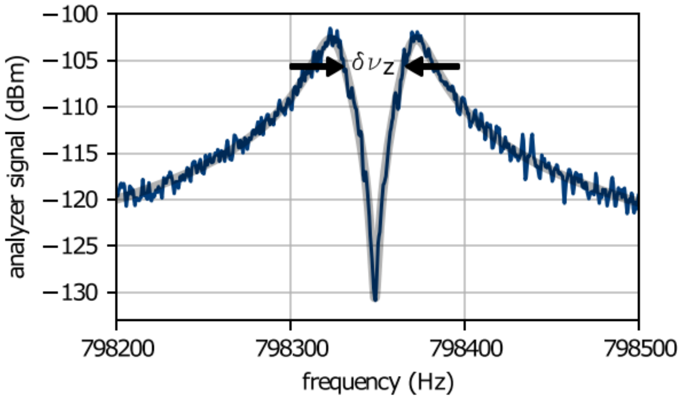


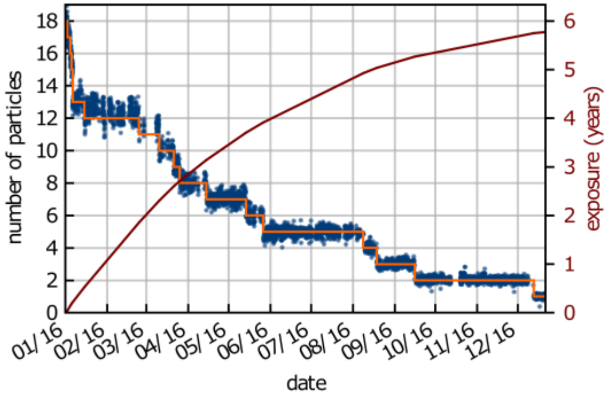
- **1.5 p.p.b. Measurement of antiproton magnetic moment,** Nature 550, 371-374 (2017)

Antiproton Storage

- **Reservoir trap** – a dedicated trap to store a cloud of antiprotons.
- We continuously record the number of particles trapped in the reservoid trap:

$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$



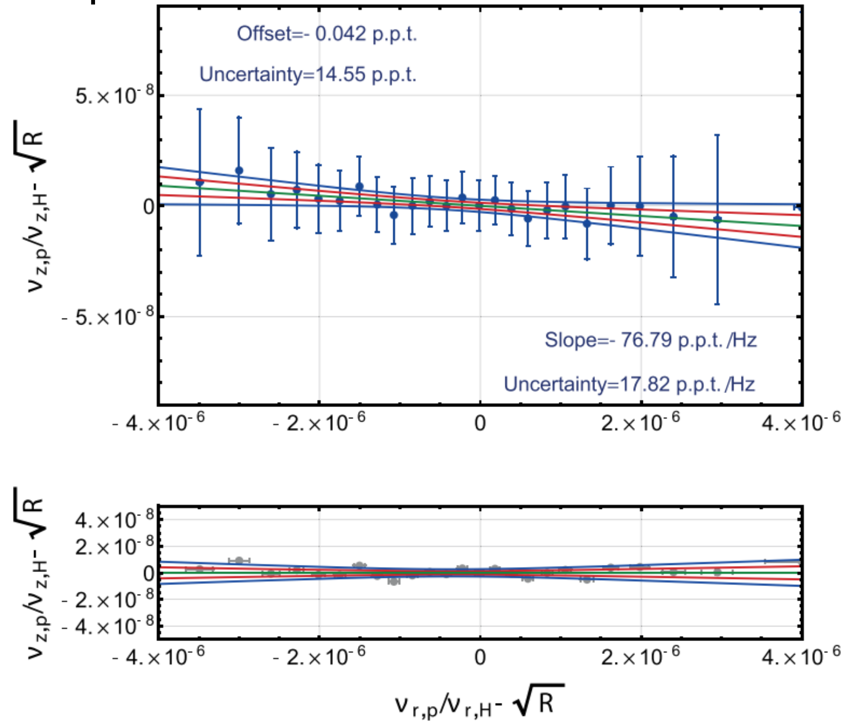


- **The record for storing of antimatter (antiprotons): 405 days.**
- S. Sellner, et al. Improved limit on the directly measured antiproton lifetime. New Journal of Physics,19(8):083023, August 2017.

$$\tau_{\mathrm{lower},\bar{p}} = 26.15\,\mathrm{a}$$

Dominant Systematic Limitations

- Lineshape Shift

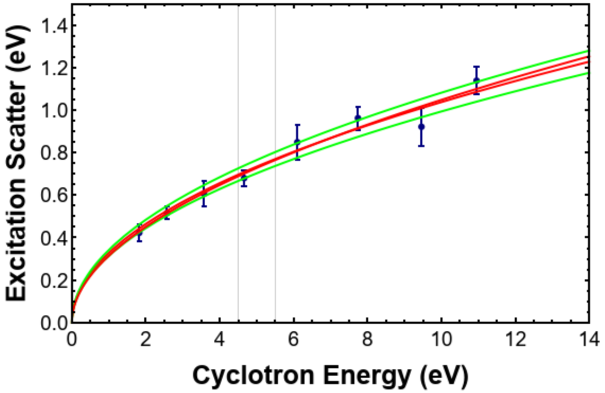


- Scaling of particle frequency with respect to frequency center of the detection resonator leads to frequency dependent shift of the measured frequency ratio.

- Temperature Shifts

$$\frac{\Delta\nu_c}{\nu_c} = \frac{\nu_+}{\nu_c^2}\Delta\nu +_{+} \frac{\nu_z}{\nu_c^2}\Delta\nu_z \approx \frac{1}{4\pi^2 m_0 \nu_z^2}\frac{B_2}{B_0}k_B T_z = -23.5(1.5)\frac{\text{p.p.t.}}{\text{K}},$$

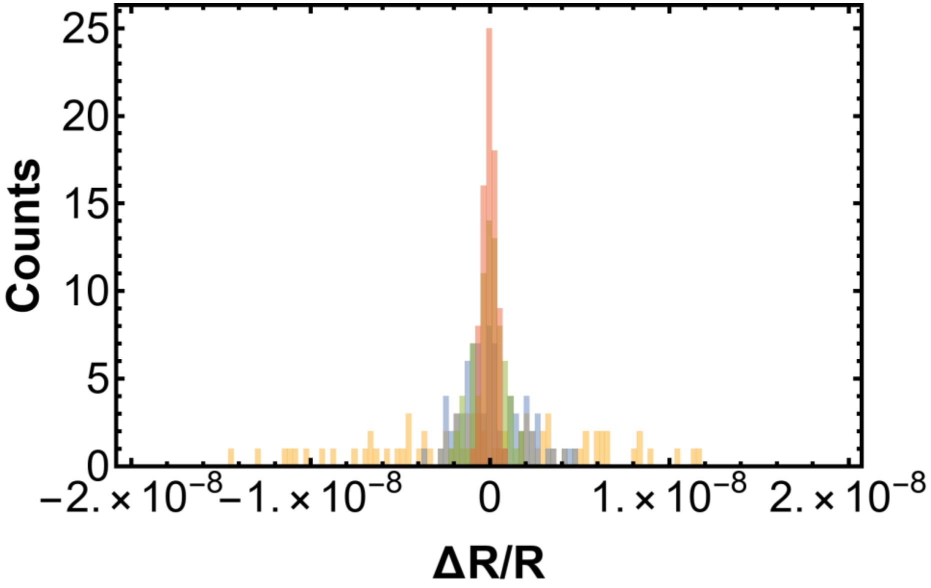
$$E(t) = \left(\frac{1}{2}\frac{qE_0}{m} * t + \rho_{0,th}\right)^2 = E_{exc} + 2\sqrt{E_{th}}\sqrt{E_{exc}} + E_{th}$$

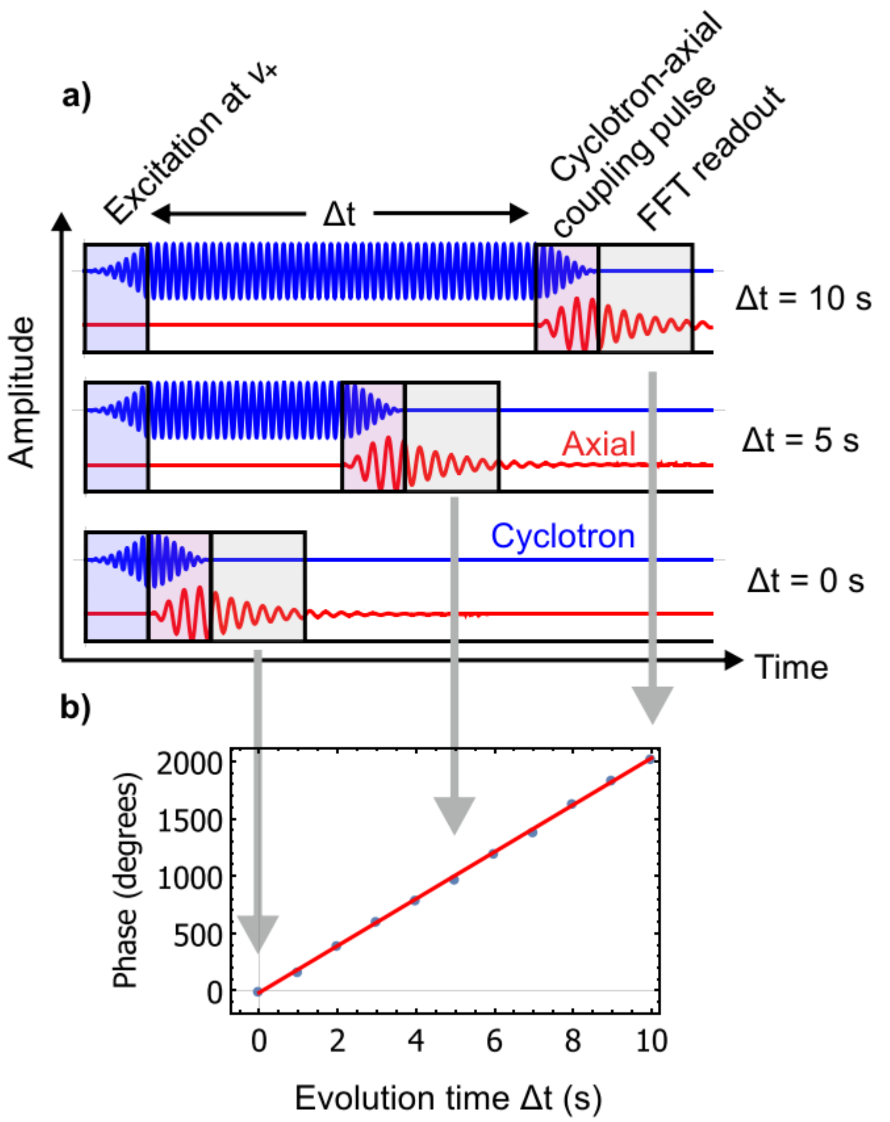


- Main improvements for 2018/2019 measurement campaigns:
  - Improved magnetic field homoheneity
  - Improved magnetic shielding
  - Tuneable superconducting detector - measurements at constant trapping potential for different masses

Cyclotron frequency measurement

- **In 2019, we implemented a new phase method** with which we reached even the frequency scatters for protons on the order of 280(20) p.p.t. at a shot-to-shot sampling rate of 1/(265 s)
- **20 p.p.t. / 24h , but only possible during accelerator shutdown**
- Eric A. Cornell, et al. PRL, 63(16):1674–1677, 1989.
  Sven Sturm, et al. PRL, 107(14):143003, September 2011.



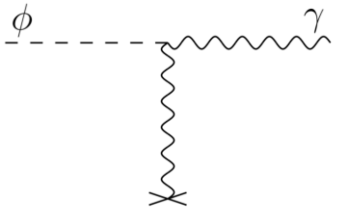


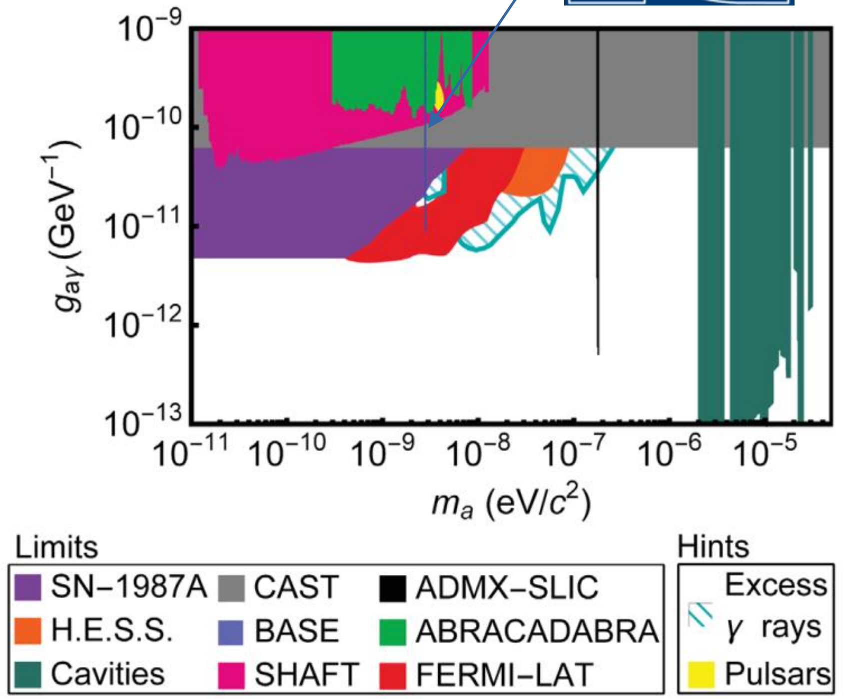
New Axion-like particle detection method

- **Axion Like Particles - ALPs:**

→ pseudoscalar bosons weakly interacting with matter motivated by many beyond the standard model theories

→ coupling to photons by derivative interactions $g_{a\gamma}$ through e.g. inverse Primakoff Effect.





Mass m_a << 1 eV (e− mass = 0.5 MeV!)

- **J. A. Devlin** et al. (BASE Collaboration), PRL 126, 041301 (2021).
- Any low mass ALP would form a classical field oscillating with frequency:

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

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

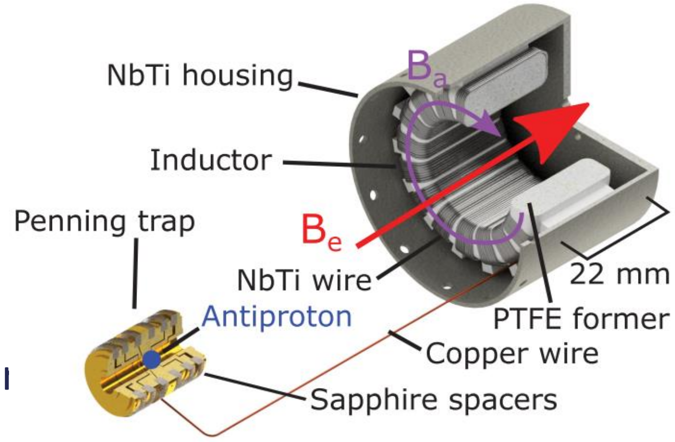
$$L_{a\gamma} = -g_{a\gamma} a(x) \mathbf{E}(x) \cdot \mathbf{B}(x)$$

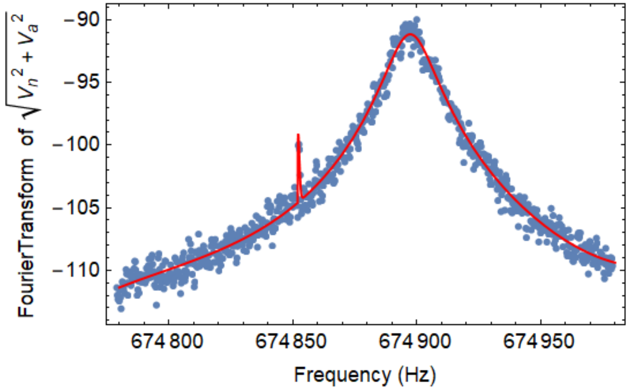
- The oscillating ALP field source oscillating magnetic

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

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

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





Upgraded ALPs detection sensitivity

- Dedicated ALPs detection experiment:

→ improved sensitivity

Magnetic field

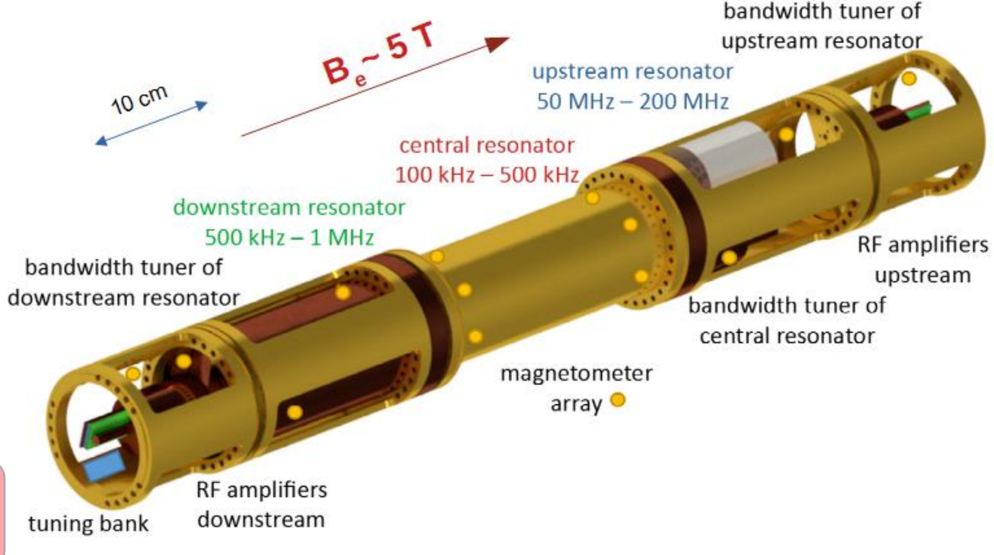
Temperature and **Quality factor** of the detector

Measurement averaging time

$$Limit\left(g_{a\gamma}\right) \sim \frac{1}{B_e}\cdot\frac{1}{V}\cdot\sqrt{\frac{T}{Q}\cdot\frac{e_n}{\kappa}\cdot\frac{1}{N_{av}}}$$

Volume of the detector

Amplifier noise contribution which defines the strength of the signal with respect to the noise of the amplifier



→ increased bandwidth between 500 kHz and 200 MHz with a tunable capacitance of the resonator (which does not decrease Q value!).

- Prototype - bachelor thesis of F. Voelksen