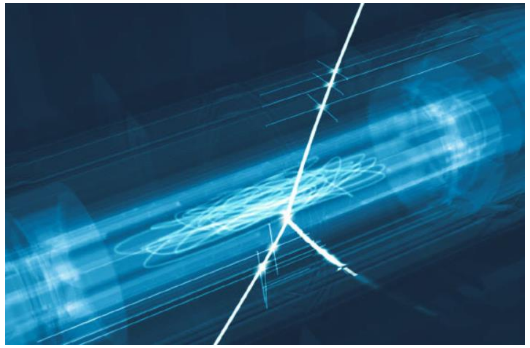
CERN Detector Seminar 2021/04/30

Experiments at the Antiproton Decelerator Facility of CERN

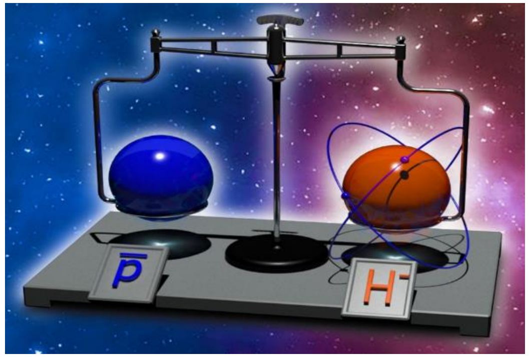
Stefan Ulmer

RIKEN

2021 / 04 / 30



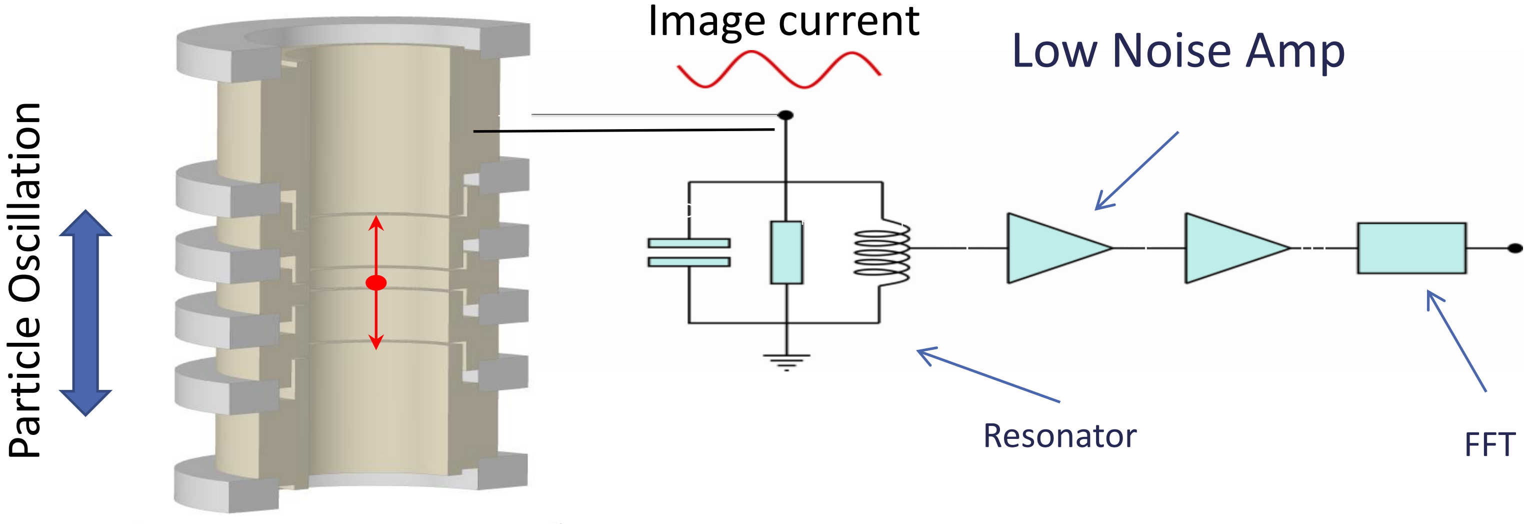
antihydrogen trap

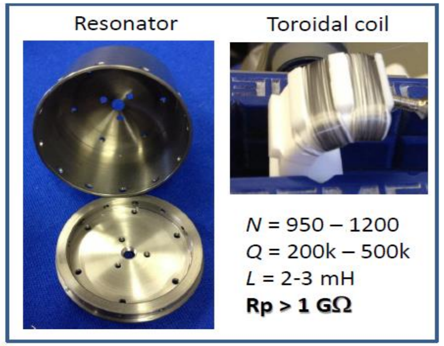


antiproton/proton balance

The Sound of Antimatter

- Concept of image current detection



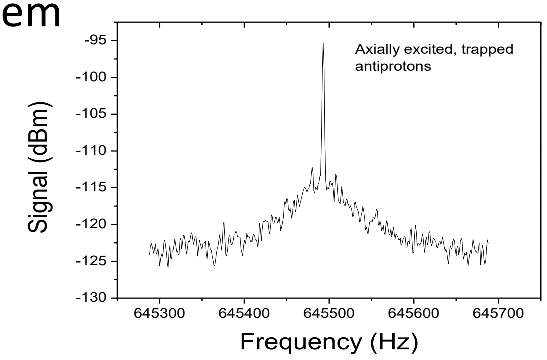


N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

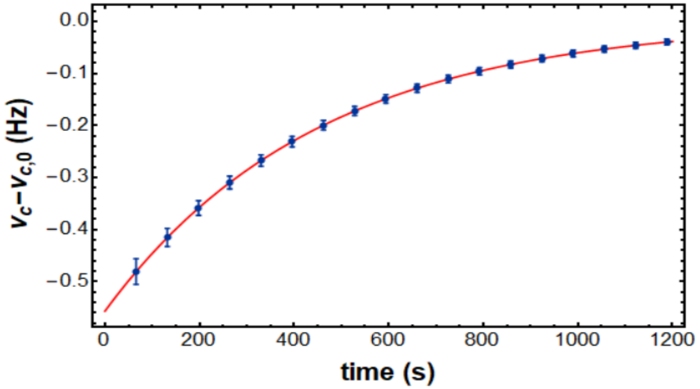
Inductor compensates system capacitance

$$I_{p,x} \sim \frac{q}{D_{eff}}(2\pi\nu_x)x$$

$$I_{p,x} \sim 0.1\ fA\ /(MHz\ \mu m)$$



- Special Relativity
  - Resistive cooling changes oscillation frequency



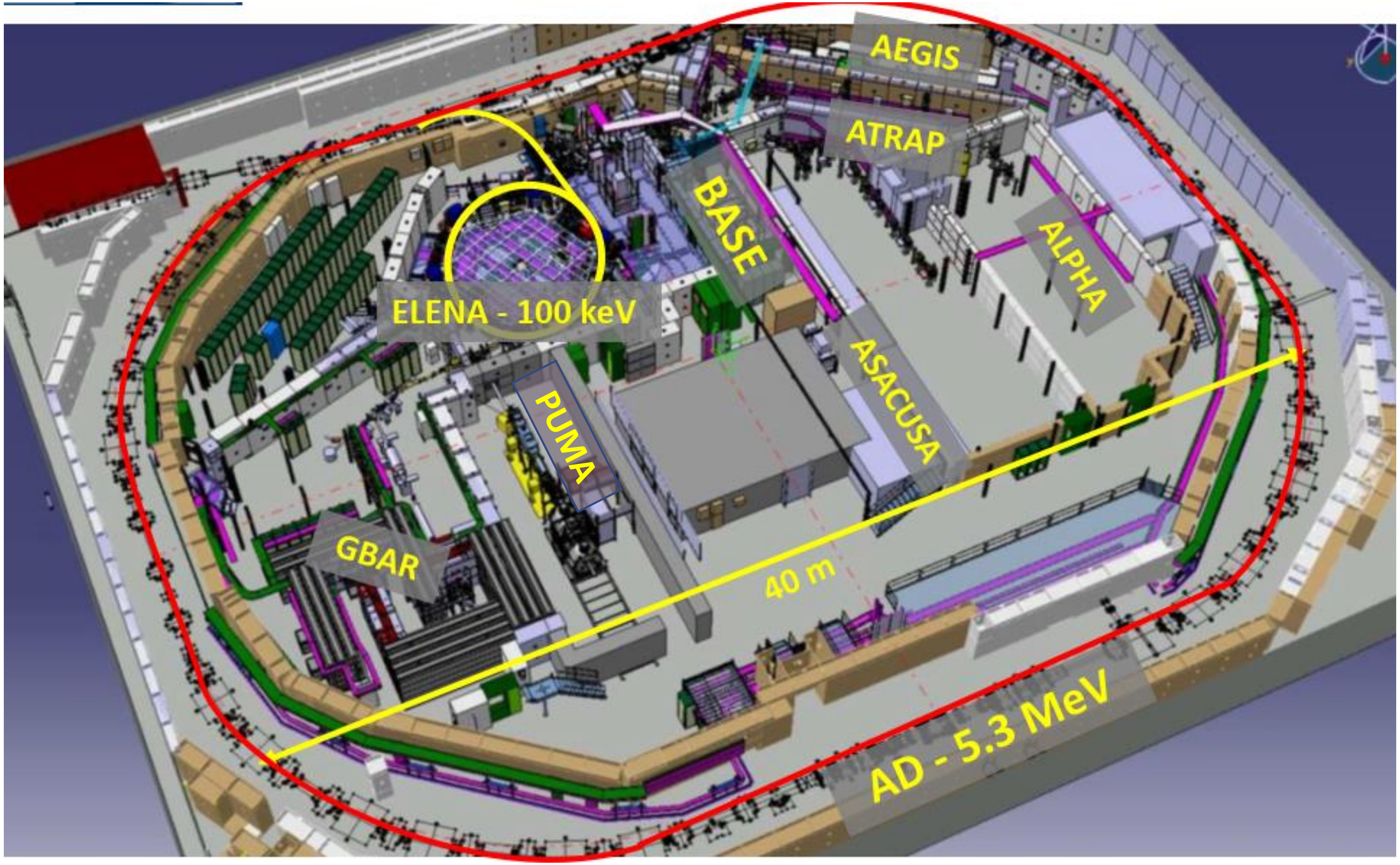
$$\nu_c = \frac{1}{2\pi}\left(\frac{q}{m}\sqrt{1-\left(\frac{v}{c}\right)^2}\,B_0\right)$$

  - Special relativity changes pitch

In the AD we are «listening» to the sound of extremely simple, well understandable Antimatter systems to detect exotic physics , **which appears as changes in pitch / frequency beating**

The AD/ELENA-Facility

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.



BASE,
Fundamental properties of the antiproton and test of clock WEP.

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

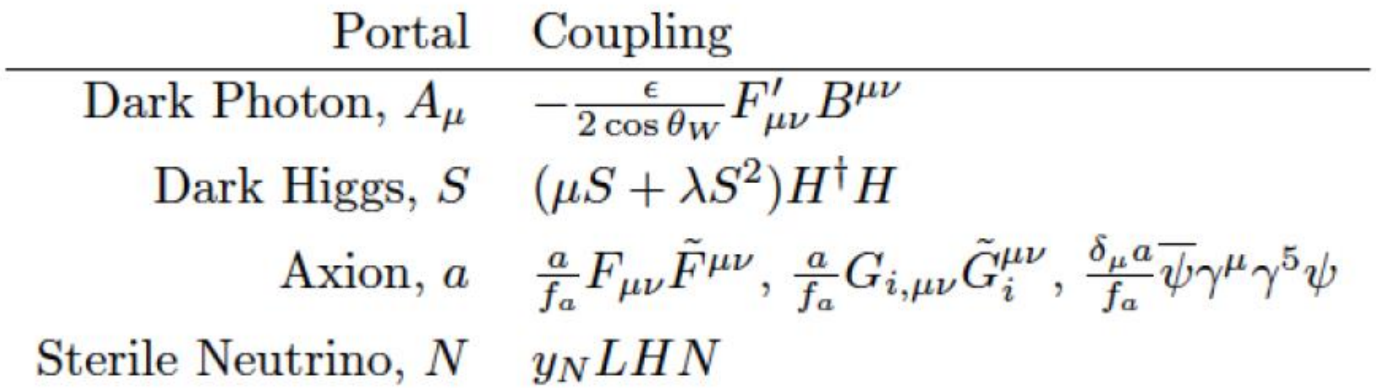
PUMA
Antiproton/nuclei scattering to study neutron skins

60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations

M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

Updated PBC Mandate

- The physics objectives also include projects aimed **at addressing fundamental particle physics questions using the experimental techniques** of nuclear, **atomic** and astroparticle-physics, as well as emerging technologies such as **quantum sensors**.



Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$
Dark Higgs, S	$(\mu S+\lambda S^2)H^\dagger H$
Axion, a	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\delta_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N LHN$

- **This talk: Present experiments which apply atomic physics and quantum metrology methods to study fundamental physics questions using simple antimatter systems at lowest energy and with highest resolution**

AE$\bar{g}$IS

ALPHA

BASE

GBAR

STE$\bar{p}$

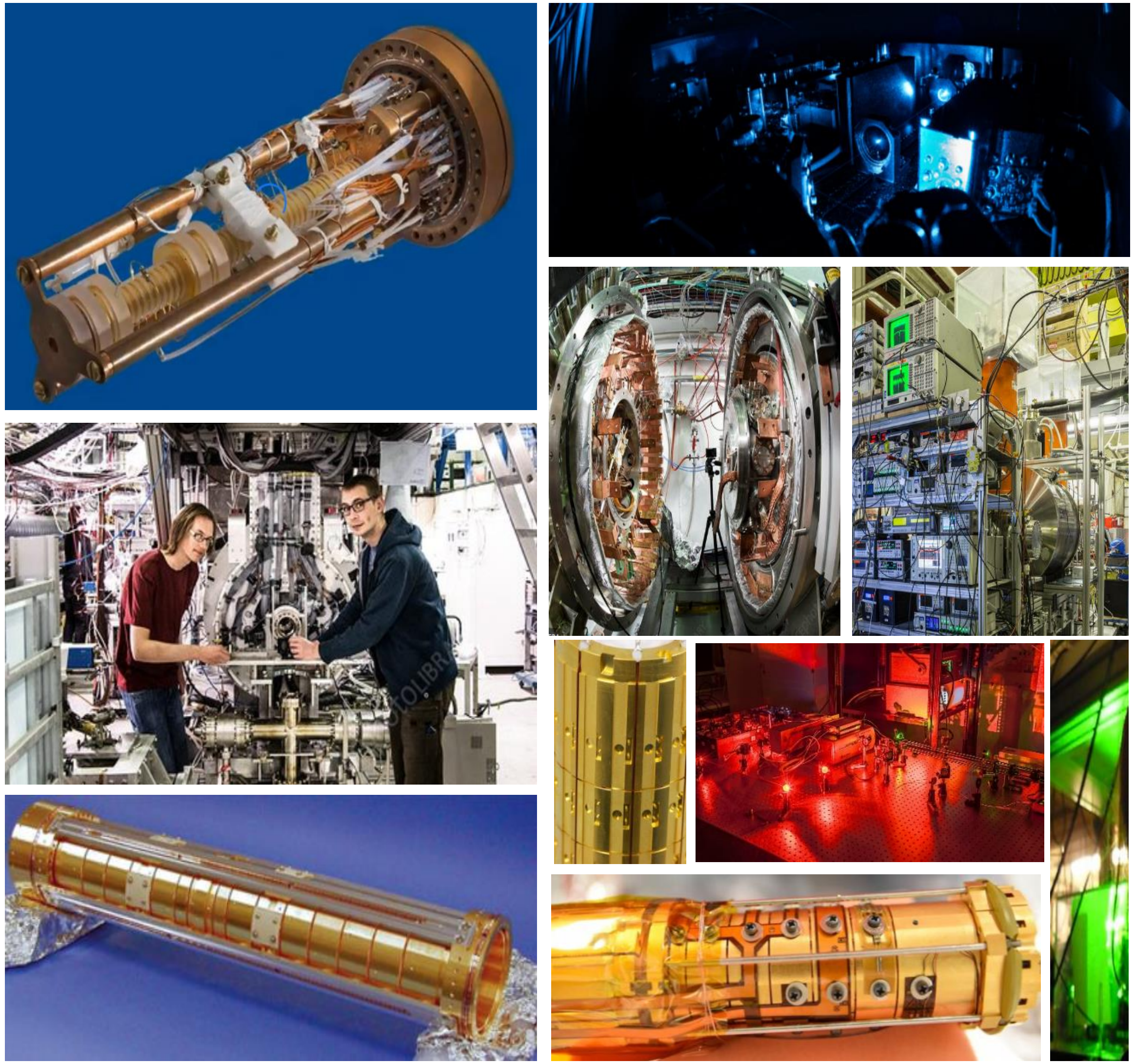
Methods and Achievements

- This community is performing measurements using quantum technologies at world leading precision…

Clocks

Traps

Lasers



Innovation and Technology

- Antihydrogen traps
- Advanced Multi Penning trap systems
- Ultra-stable ultra-high power lasers
- Transportable antimatter traps and reservoir traps
- Advanced magnetic shielding systems
- Quantum Logic Spectroscopy

matter sector 2016

proton lifetime (direct)	>1.67 e34 y
proton m	90 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2016

antiproton lifetime	>1.2 y
antiproton m	120 p.p.t.
antiproton m. moment	4.4 p.p.m.
antihydrogen 1S/2S	?
antihydrogen GSHFS	?

matter sector 2021

proton lifetime (direct)	>1.67 e34 y
proton m	**30 p.p.t.**
proton magn. moment	**0.3 p.p.b.**
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2021

antiproton lifetime	**>30 y**
antiproton m	**30 p.p.t.**
antiproton m. moment	**1.5 p.p.b.**
antihydrogen 1S/2S	**2 p.p.t.**
antihydrogen GSHFS	**400 p.p.m.**

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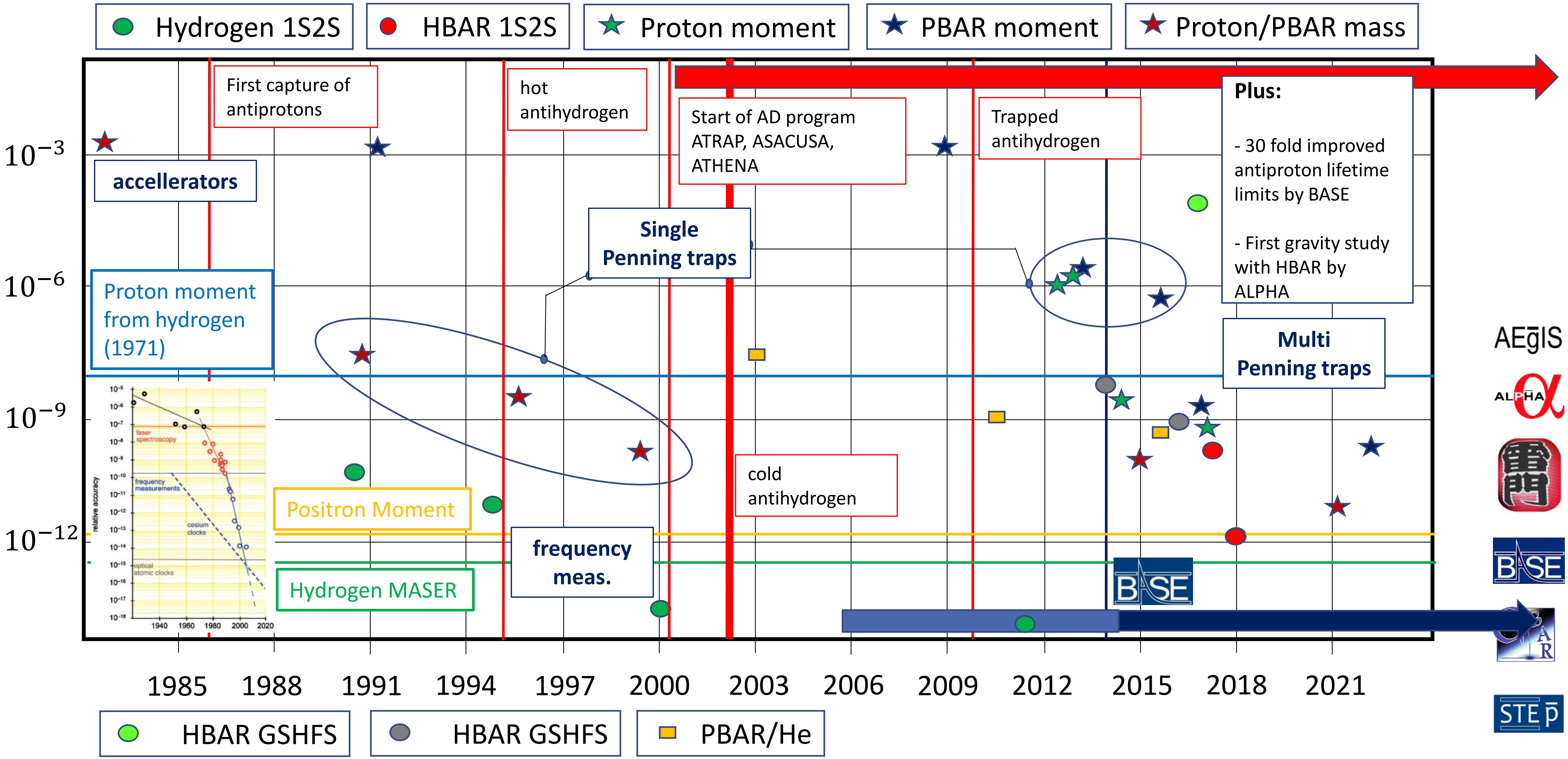
…and is a vital part of the low energy precision physics community…

Historical Milestones



Plus:

- 30 fold improved antiproton lifetime limits by BASE

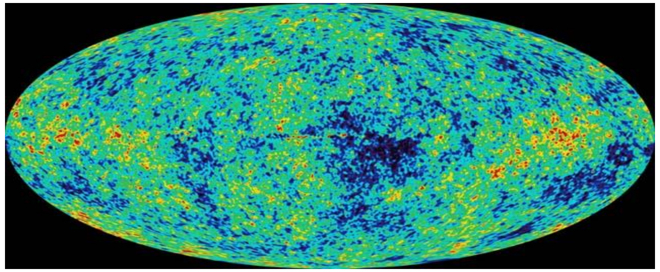
- First gravity study with HBAR by ALPHA

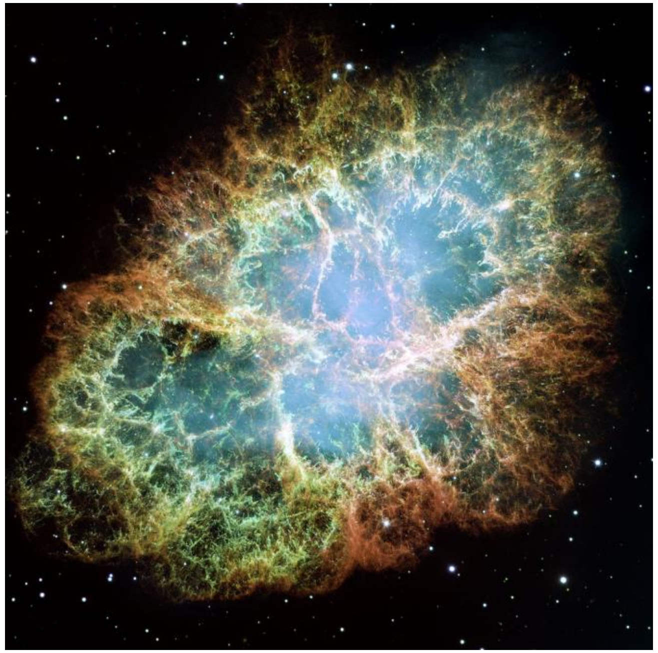
Matter / Antimatter Asymmetry

Combining the Λ-CDM model and the SM our predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

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

Observation	
Baryon/Photon Ratio	$0.6 * 10^{-9}$
Baryon/Antibaryon Ratio	10 000





Sakharov conditions

1.) B-violation (plausible)

2.) CP-violation (observed / too small)

3.) Arrow of time (less motivated)

Alternative Source: CPT violation – adjusts matter/antimatter asymmetry by natural inversion given the effective chemical potential.

Experimental signatures sensitive to CPT violation can be derived from precise comparisons of the fundamental properties of simple matter / antimatter conjugate systems

Fundamentality of CPT Invariance

- **A relativistic theory which conserves CPT requires only five basic ingredients (Axioms):**

Lorentz and translation invariance

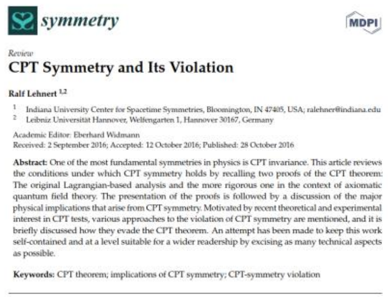
Energy Positivity

Micro Causality (Locality)

A stable vacuum ground state without momentum nor angular momentum

Unitary Field Operators Interpretation

READ: R. Lehnert, CPT Symmetry and its violation, *Symmetry* 8 (2016) 11, 114



symmetry

MDPI

Review

CPT Symmetry and Its Violation

Ralf Lehnert [1,2]

[1] Indiana University Center for Spacetime Symmetries, Bloomington, IN 47405, USA; ralehner@indiana.edu

[2] Leibniz Universität Hannover, Welfengarten 1, Hannover 30167, Germany

Academic Editor: Eberhard Widmann

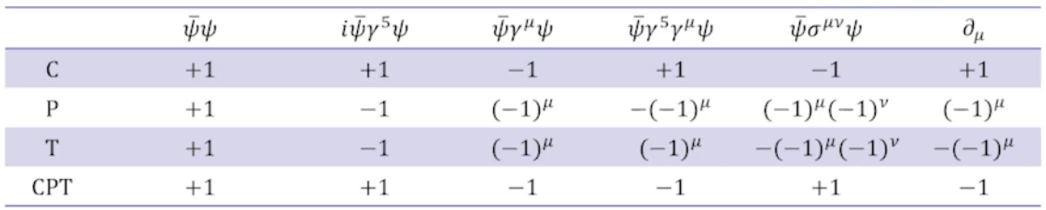
Received: 2 September 2016; Accepted: 12 October 2016; Published: 28 October 2016

Abstract: One of the most fundamental symmetries in physics is CPT invariance. This article reviews the conditions under which CPT symmetry holds by recalling two proofs of the CPT theorem: The original Lagrangian-based analysis and the more rigorous one in the context of axiomatic quantum field theory. The presentation of the proofs is followed by a discussion of the major physical implications that arise from CPT symmetry. Motivated by recent theoretical and experimental interest in CPT tests, various approaches to the violation of CPT symmetry are mentioned, and it is briefly discussed how they evade the CPT theorem. An attempt has been made to keep this work self-contained and at a level suitable for a wider readership by excising as many technical aspects as possible.

Keywords: CPT theorem; implications of CPT symmetry; CPT-symmetry violation

CPT

Parameterized in the Standard Model Extension



	$\bar{\psi}\psi$	$i\bar{\psi}\gamma^5\psi$	$\bar{\psi}\gamma^\mu\psi$	$\bar{\psi}\gamma^5\gamma^\mu\psi$	$\bar{\psi}\sigma^{\mu\nu}\psi$	∂_μ
C	$+1$	$+1$	-1	$+1$	-1	$+1$
P	$+1$	-1	$(-1)^\mu$	$-(-1)^\mu$	$(-1)^\mu(-1)^\nu$	$(-1)^\mu$
T	$+1$	-1	$(-1)^\mu$	$(-1)^\mu$	$-(-1)^\mu(-1)^\nu$	$-(-1)^\mu$
CPT	$+1$	$+1$	-1	-1	$+1$	-1

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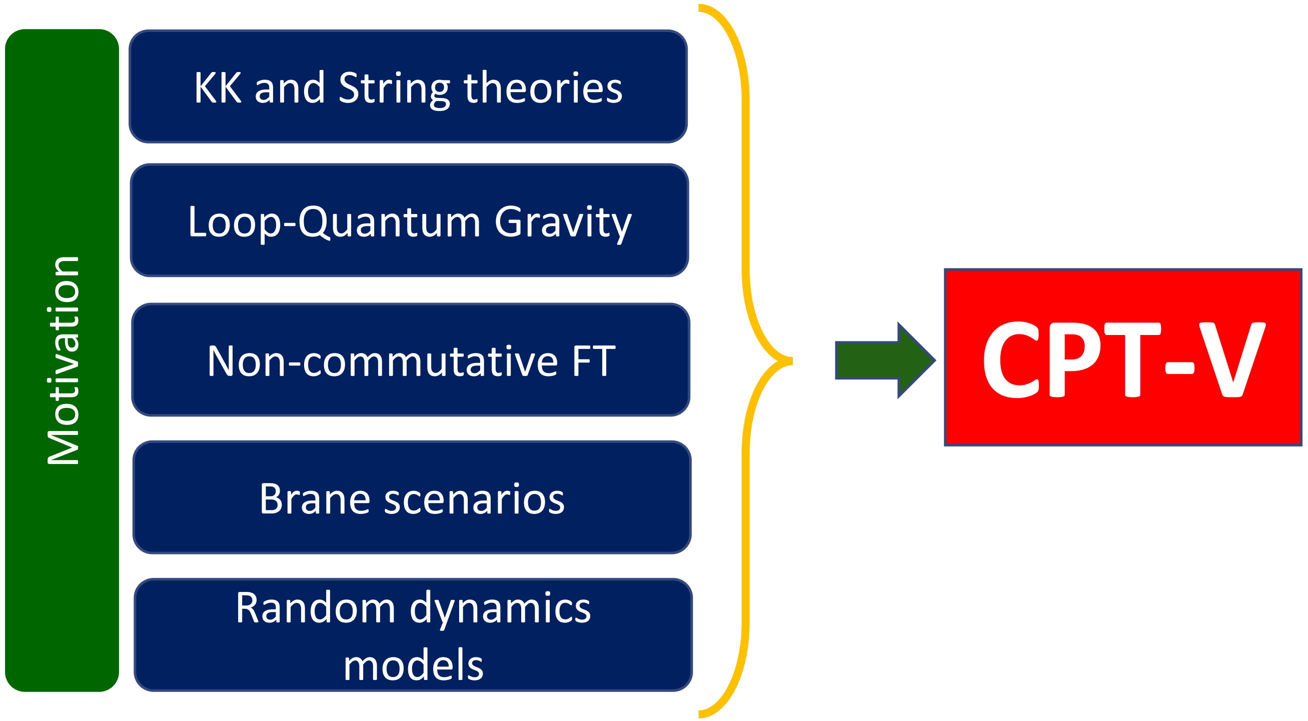
The Standard Model Extension



Motivation

KK and String theories

Loop-Quantum Gravity

Non-commutative FT

Brane scenarios

Random dynamics models

CPT-V

- SME contains the Standard Model and General Relativity, but adds CPT violation

Expectation value / Mass Scale / Coupling strength

$$\mathcal{L}' \supset \frac{\lambda}{M^k}\langle T\rangle \cdot \overline{\psi}\Gamma(i\partial)^k\psi + \text{h.c.}$$

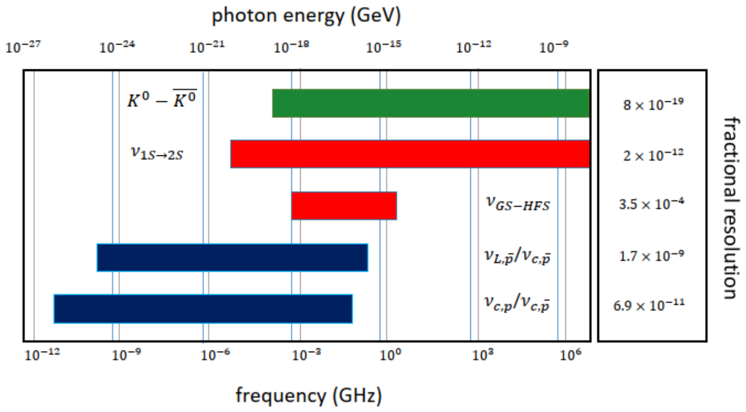
Lorentz bilinear

- E.g. k=2 produces attractive baryogenesis scenario

- Which type of **measureable** signatures of these «BSM» theories would be imprinted onto the structure of the vacuum-box of relativistic quantum field theories.

$$\mathcal{L} = ?$$

- Construct effective field theory which features:
  - microcausality
  - positivity of energy
  - energy and momentum conservation
  - standard quantization methods



Kostelecký, V. Alan; Samuel, Stuart (1989-01-15). "Spontaneous breaking of Lorentz symmetry in string theory". Physical Review D. ***39*** *(2): 683–685.*

Limits on Exotic Physics – ONE example

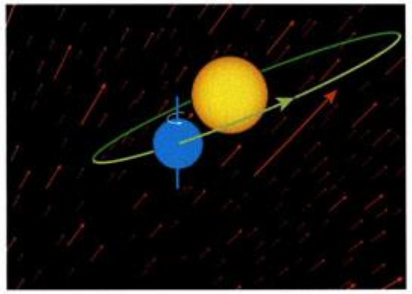
- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

$$\left(\boxed{i\gamma^{\mu}D_{\mu}-m}-\boxed{a_{\mu}\gamma^{\mu}-b_{\mu}\gamma_5\gamma^{\mu}}\right)\psi=0$$

Dirac equation CPT-odd modifications

$$\boldsymbol{H\,\psi=(H_0+\ V_{exotic})\,\psi}$$

$$\boldsymbol{\Delta E_{exotic}\ =\langle\psi|V_{exotic}|\psi\rangle}$$



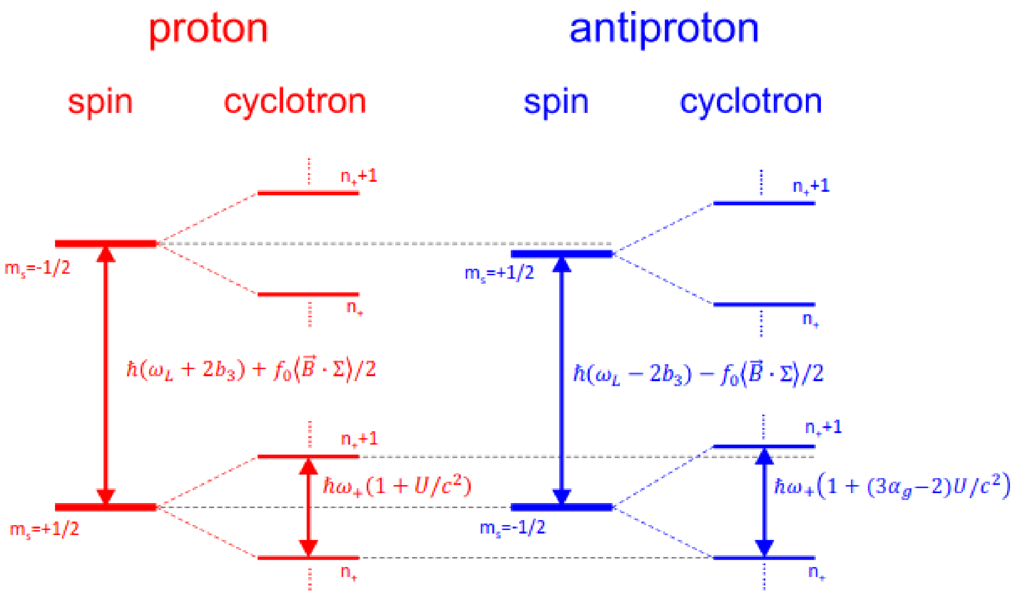
$$b_{\mu}\gamma_5\gamma^{\mu}\rightarrow b_x\begin{pmatrix}-\boldsymbol{\sigma_x} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_x}\end{pmatrix}+b_y\begin{pmatrix}-\boldsymbol{\sigma_y} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_y}\end{pmatrix}+b_z\begin{pmatrix}-\boldsymbol{\sigma_z} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_z}\end{pmatrix}$$

Pseudo-magnetic field, with different coupling to matter and antimatter, respectively

$$\Delta V_{int}=\widetilde{b_{z,D}}\begin{pmatrix}\boldsymbol{0} & \boldsymbol{0}\\ \boldsymbol{0} & \pm\boldsymbol{\sigma_z}\end{pmatrix}$$

V. A. Kostelecky, N. Russell, 0801.0287v10 (2017).

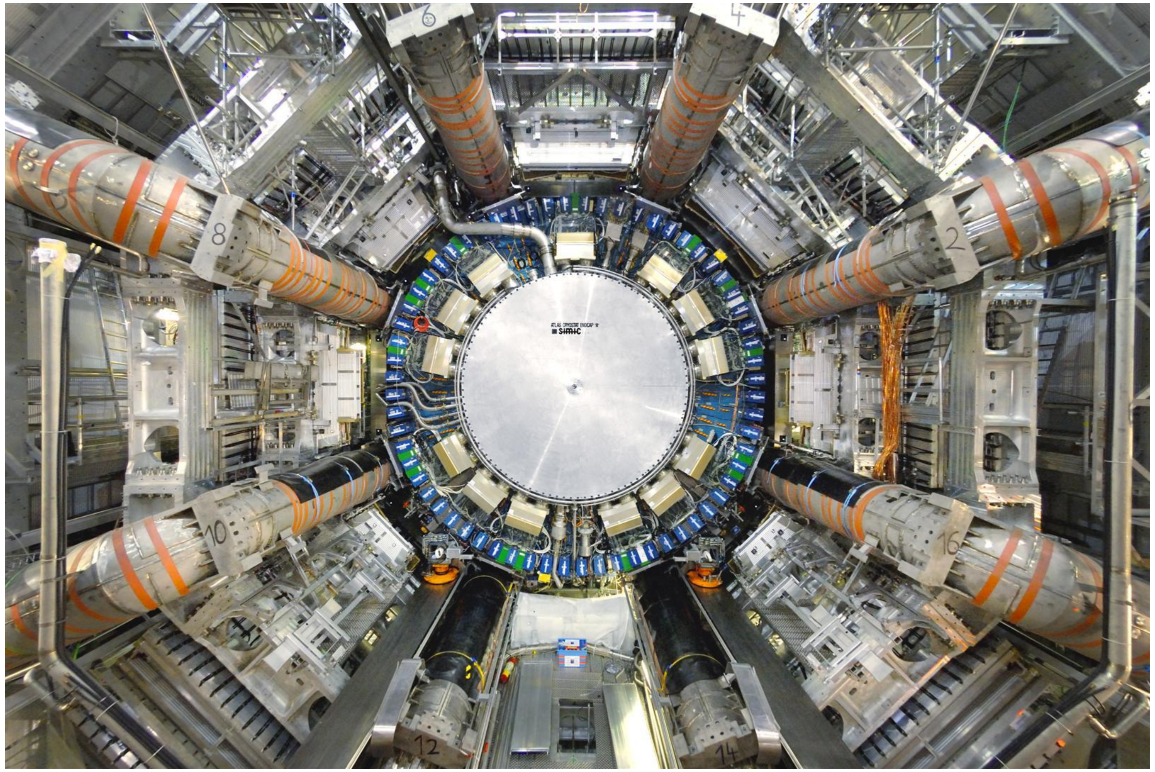
Would correspond to the discovery of a boson field which exclusively couples to antimatter.



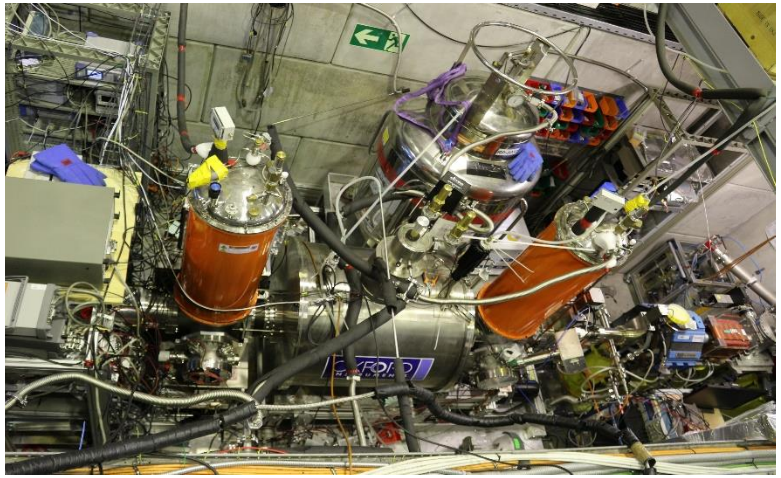
sensitive: comparisons of particle/antiparticle magnetic moments in traps

A Typical AD Detector…

- …is in essential aspects very different to a particle physics detector…



ALPHA



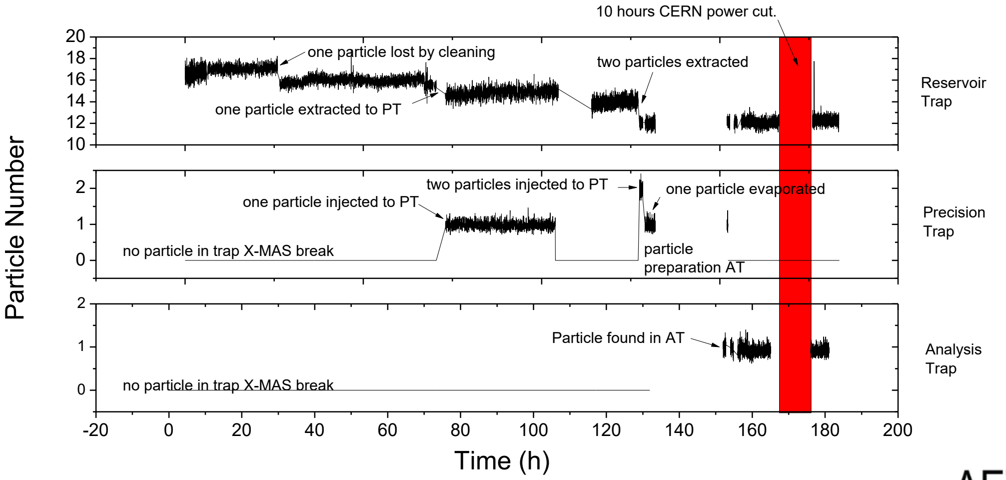
BASE

- destructive measurements at high lumiosity
- Non-destructive frequency measurements at highest frequency resolution

Example: the BASE trap

405 day of antiproton-cloud trapping demonstrated

- We have
  - A vacuum of 5e-19 mbars
    - best characterized vacuum on earth,
    - comparable to pressures in the interstellar medium
  - Antiproton storage times of several 10 years.
  - Not more than 5000 residual atoms in a vacuum volume of 1.2l
  - 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	**$5.9*10^8$**
Ratio Inversion	**$3.8*10^{12}$**

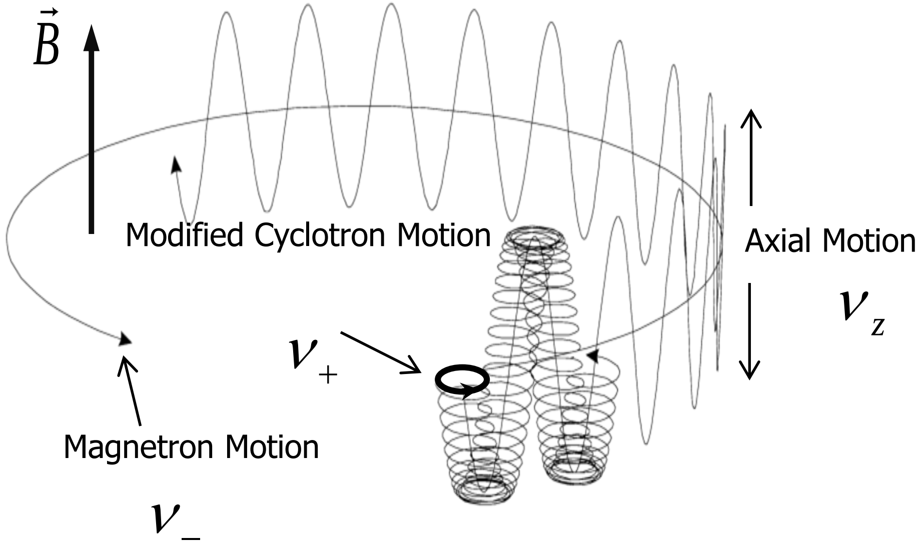
- **Pbar consumption (excl. steering and trap loading):**
  - Since 2014: 68 particles lost
  - Since 2014: 34 particles lost due to exp. mistakes
- Average loss rate is at 1 particle in 2.5 months.
- **Direct lifetime limits: t > 26.5a** (80-fold impr.)

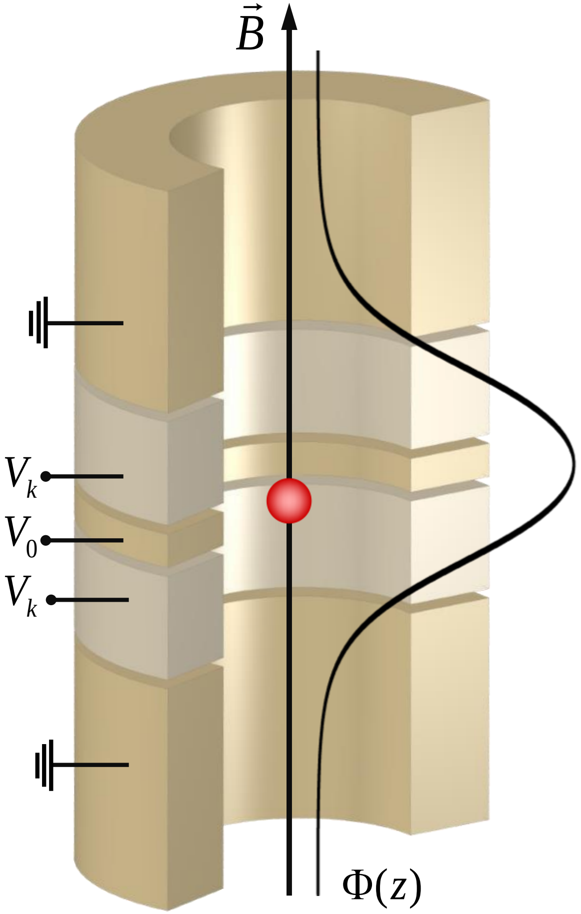
With this instrument: Investigate properties of antimatter very precisely

Main Tool: Penning Trap

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

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





$$\nu_z = \frac{1}{2\pi} \sqrt{\frac{2 C_2 q V_0}{m}}$$

$$\nu_+ = \frac{1}{2} \left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2} \right)$$

$$\nu_- = \frac{1}{2} \left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2} \right)$$

Axial	$\nu_z = 680\,\text{kHz}$
Magnetron	$\nu_- = 8\,\text{kHz}$
Modified Cyclotron	$\nu_+ = 28{,}9\,\text{MHz}$

Invariance Theorem

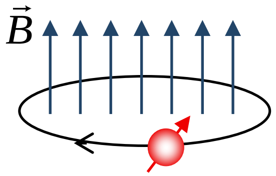
$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2}$$

Gives undisturbed access to cyclotron frequencies

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

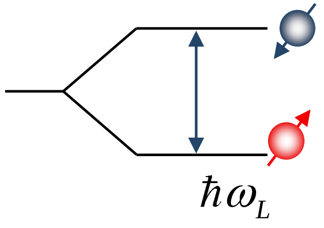
Measurements in Precision Penning traps

Cyclotron Motion



simple

Larmor Precession

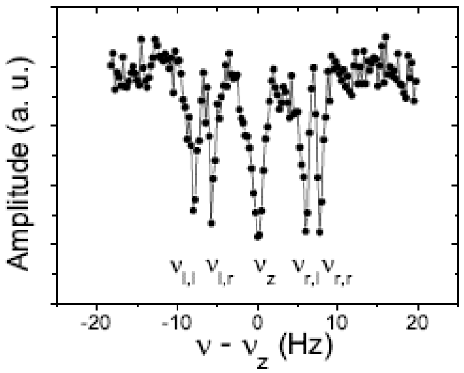


difficult

g: mag. Moment in units of nuclear magneton

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

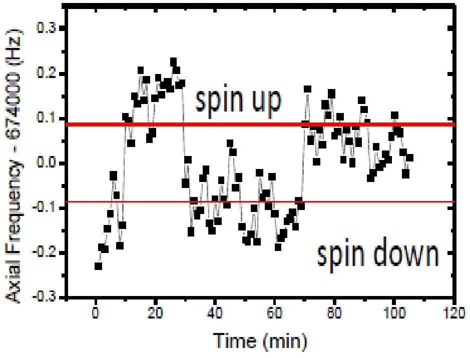
$$\omega_L = g \frac{e}{2m_p} B$$



S. Ulmer, A. Mooser *et al.* PRL 107, 103002 (2011)

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

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



S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

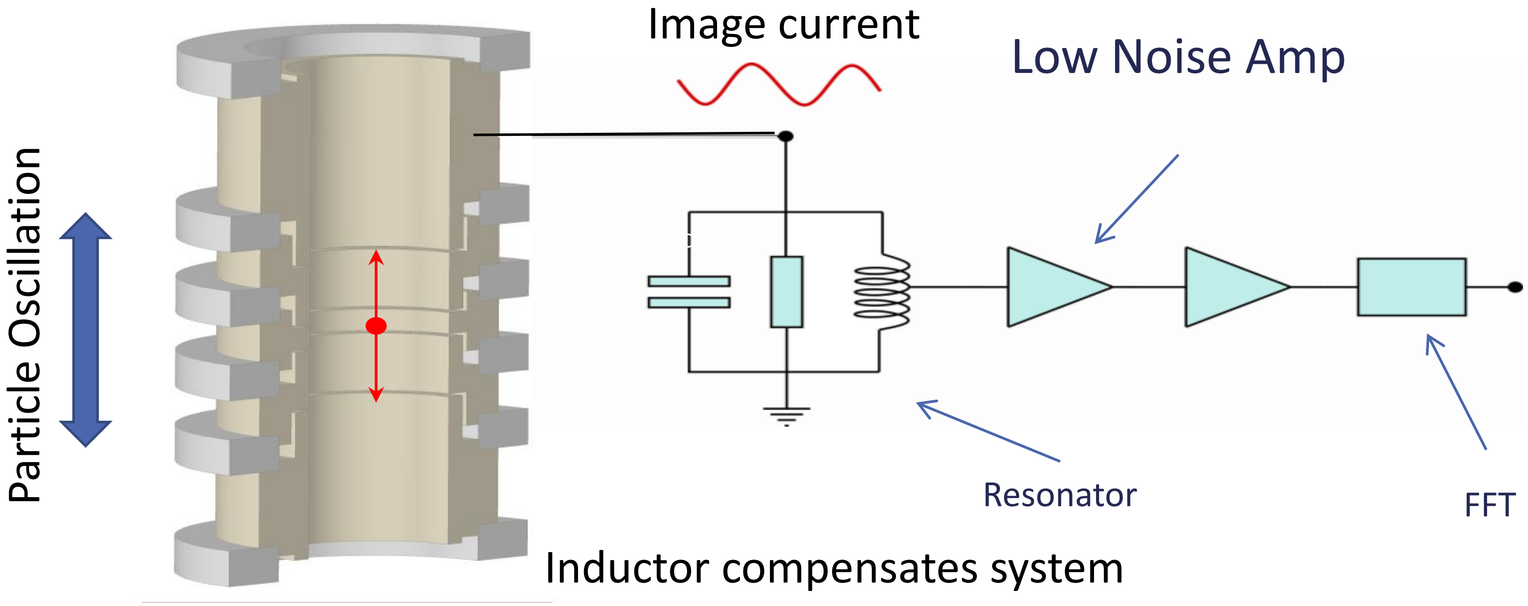
Determinations of the q/m ratio and g-factor reduce to measurements of frequency ratios -> in principle **very simple** experiments –> **full control, (almost) no theoretical corrections required.**

High Precision Mass Spectrometry

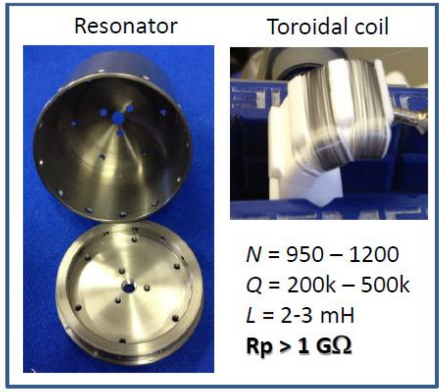
High Precision Magnetic Moment Measurements

Frequency Measurements in Penning Traps

- Concept of image current detection



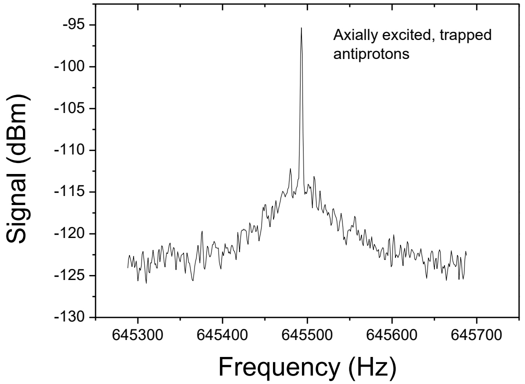
Inductor compensates system capacitance



N = 950 – 1200
Q = 200k – 500k
L = 2-3 mH
Rp > 1 GΩ

$$I_{p,x} \sim \frac{q}{D_{eff}}(2\pi\nu_x)x$$

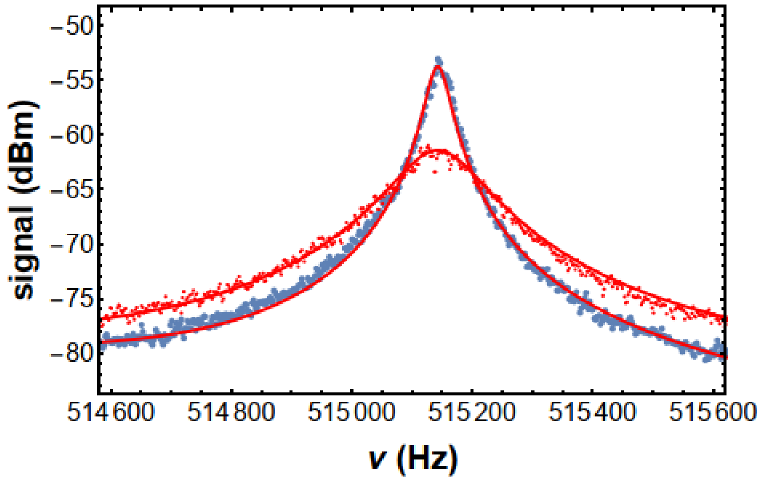
$$I_{p,x} \sim 0.1\ fA\ /(MHz\ \mu m)$$



- Resonant Detection

$$R_p = Q(2\pi\nu_x L)$$

$$R_p = 100\ M\Omega \text{ to } 500\ M\Omega$$



- Voltage drops of order

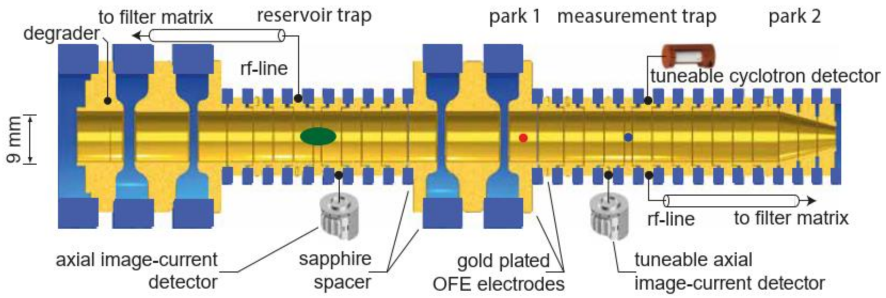
$$U_{p,x} \sim 10\ nV\ /(MHz\ \mu m)$$

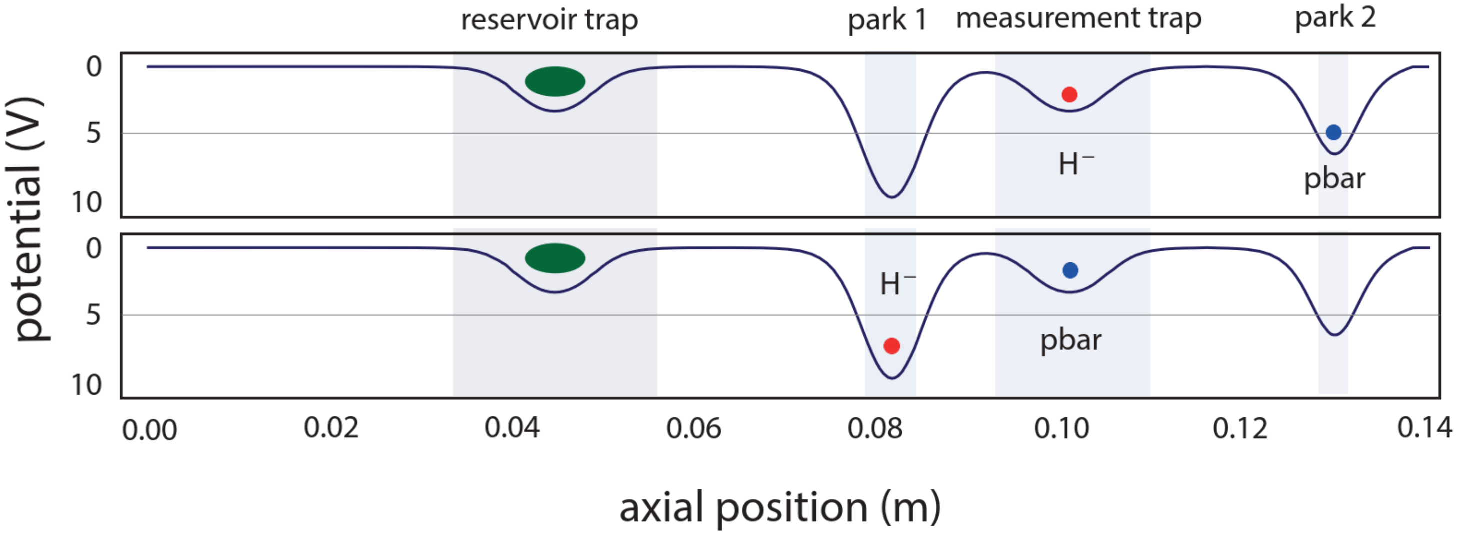
H. Nagahama, Rev. Sci. Instum. 87, 113305 (2016)

Charge-to-Mass Ratio Measurement

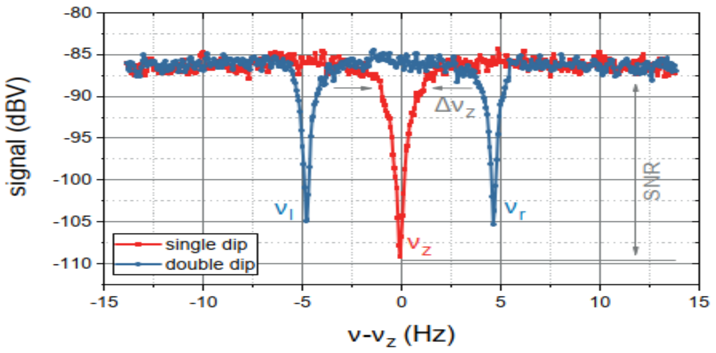
- In BASE one frequency ratio measurement takes 240 s, 50 times faster than in 1999 measurement

First Measurement: S. Ulmer, et al., **Nature 524, 196 (2015)**





- Sideband Method



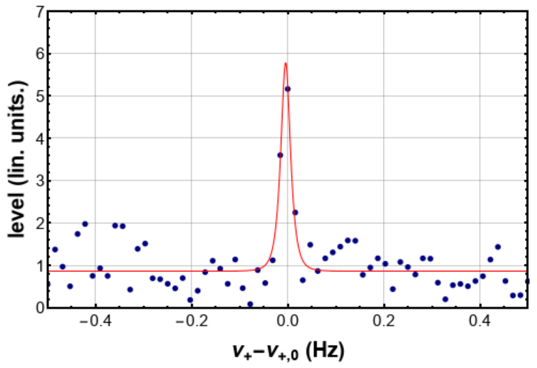
2.5 Hz linewidth

Limited by fit scatter

Thermal equilibrium measurement

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

- Peak Method



25 mHz linewidth

Limited by magnetic field scatter

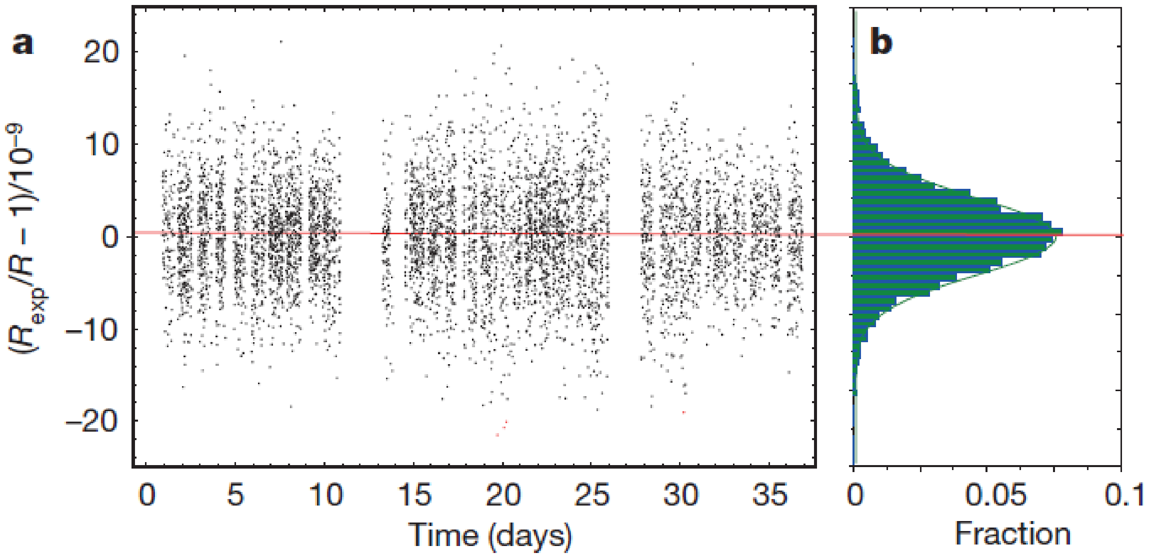
Excited measurement

Considerable systematic shifts

A. Mooser, et al., **Nature 509, 596 (2014) /** Cornell et al., **PRA (1991)**

In aspects similar to G. Gabrielse, et al.,**Phys. Rev. Lett. 82, 3198 (1999)**

BASE Measurements – Proton to Antiproton Q/M



Result of 6500 proton/antiproton Q/M comparisons:

$R_{\mathrm{exp,c}}$ = 1.001 089 218 755 (69)

$$\boxed{\frac{(q/m)_{\bar{\mathrm{p}}}}{(q/m)_{\mathrm{p}}}+1 = 1(69)\times 10^{-12}}$$

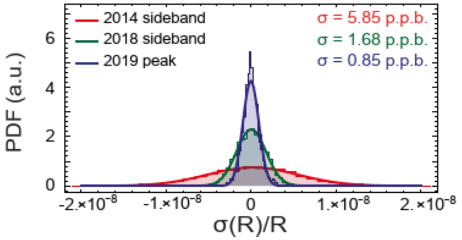
Stringent test of CPT invariance with Baryons.

Consistent with CPT invariance

S. Ulmer et al., *Nature* **524** 196 (2015)

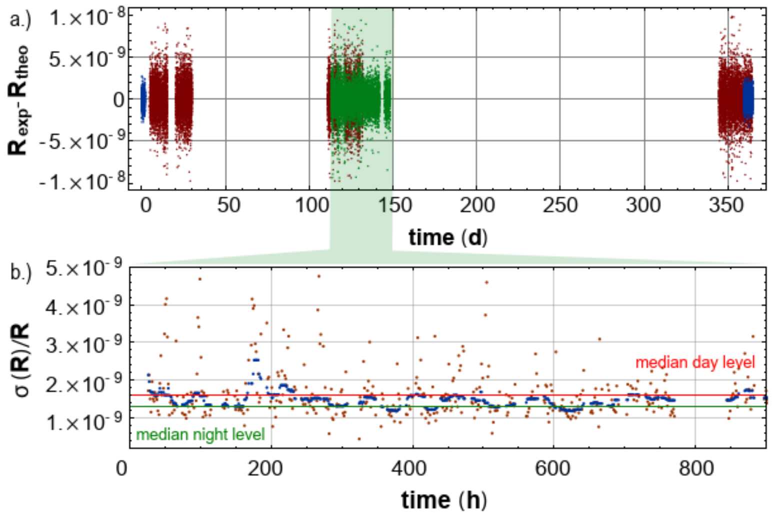
New measurement:

- Acquired 35000 frequency ratio measurements over 1.5 years, distributed over the sidereal year.
- Used two measurement methods, tunable axial detector to suppress systematics, and a rebuilt apparatus



$R_{\mathrm{exp,c,1}}$ = 1.001 089 218 763 (23)
$R_{\mathrm{exp,c,2}}$ = 1.001 089 218 7XX (2X)

Final data analysis is work in progress



BASE, *in preparation* (2021)

BASE Measurements – Proton to Antiproton Q/M

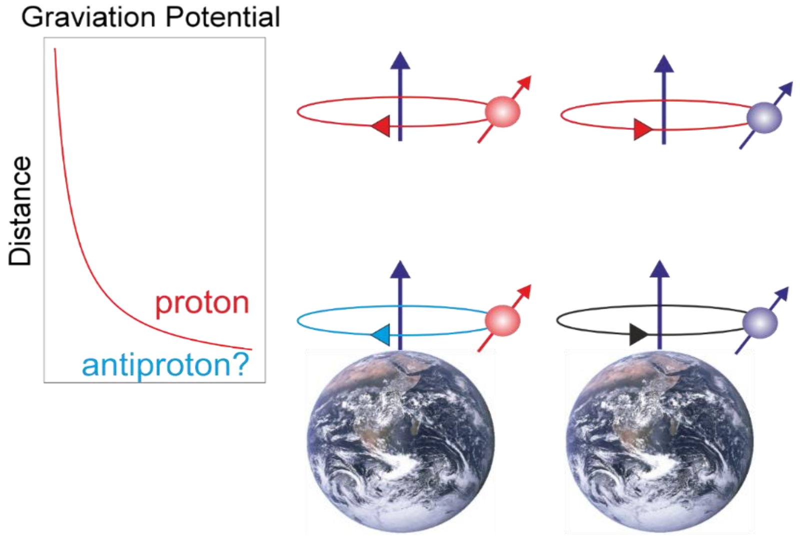
- Constrain of the gravitational anomaly for antiprotons:

$$\frac{\omega_{c,p}-\omega_{c,\bar{p}}}{\omega_{c,p}} = -3(\alpha_g - 1)\; U/c^2$$

Our recent result sets an upper limit of

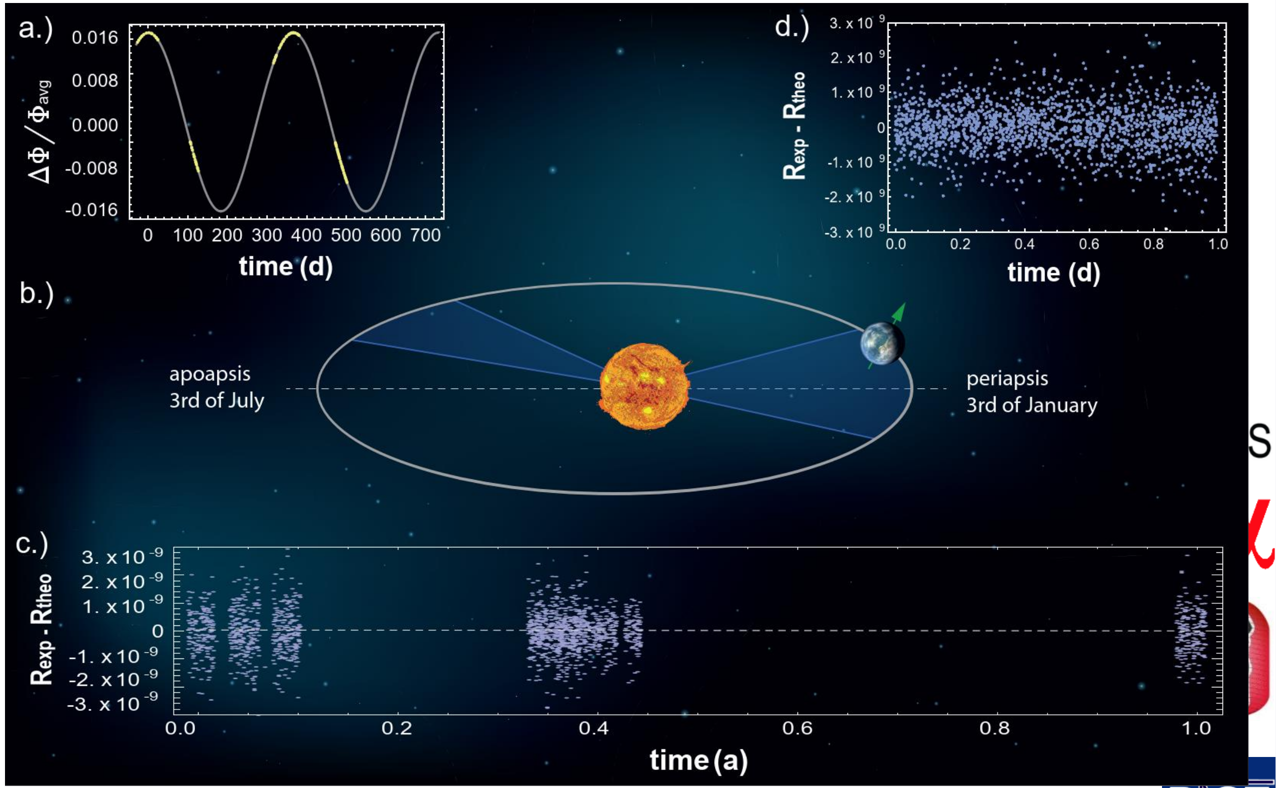
$$|\alpha_g - 1| < 1.9 \times 10^{-7}$$

tests WEPcc, in aspects (vectors) different to WEPff



- Direct experiments planned by Aegis, GBAR, ALPHA

- Planned Longer Term Measurements



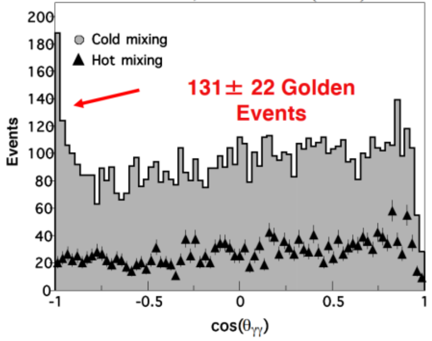
- Set differential constraints on the weak equivalence principle by measuring charge-to-mass ratio as a function of gravitational potential at surface of earth.
- Final data analysis is work in progress.

S. Ulmer et al., *Nature* **524** 196 (2015)

Antihydrogen Production and Trapping

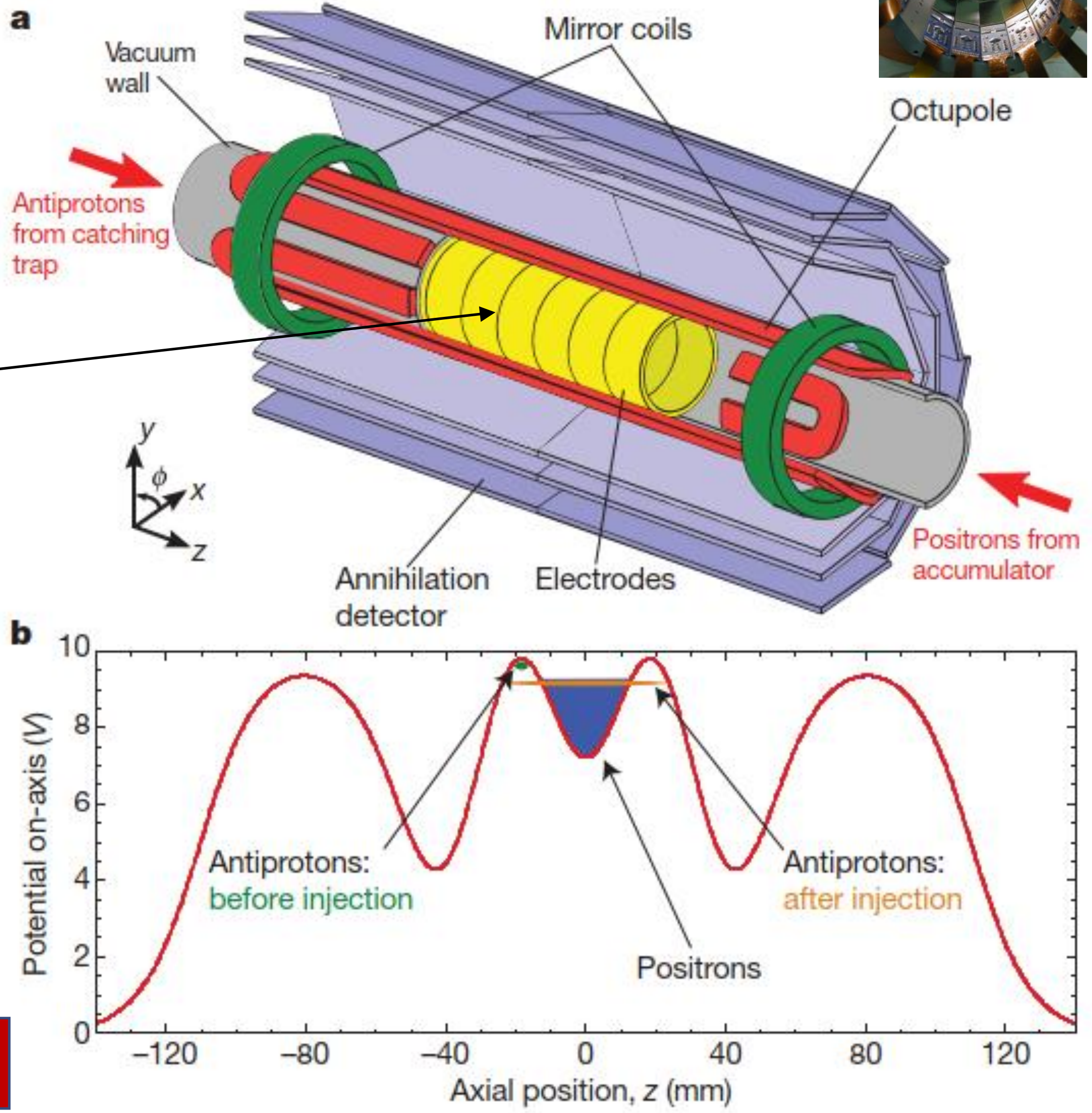
Cold antihydrogen

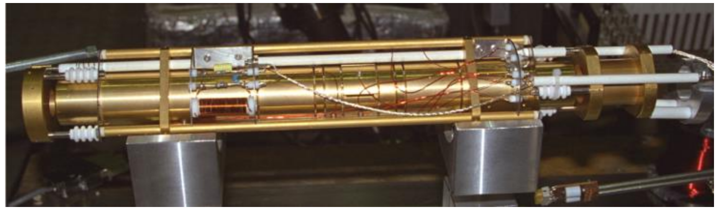
Amoretti et al., *Nature* 419 (2002) 456

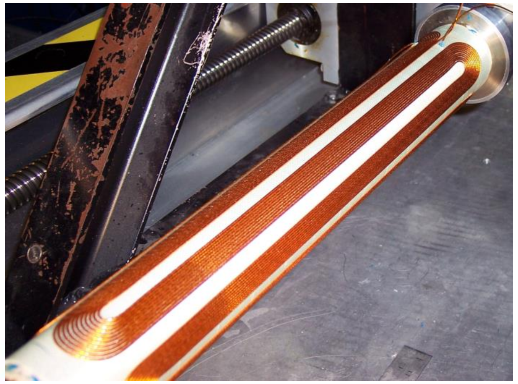


«simple»

trap electrodes







Nested Penning Trap with

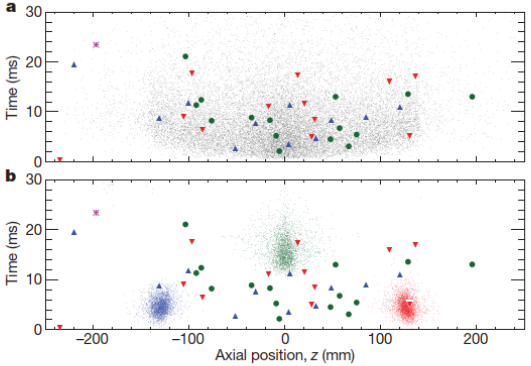
- Antiprotons and
- Positrons

trapped close to each other.

Different antiproton/positron injection methods

!!! difficult !!!

Trapped Antihydrogen

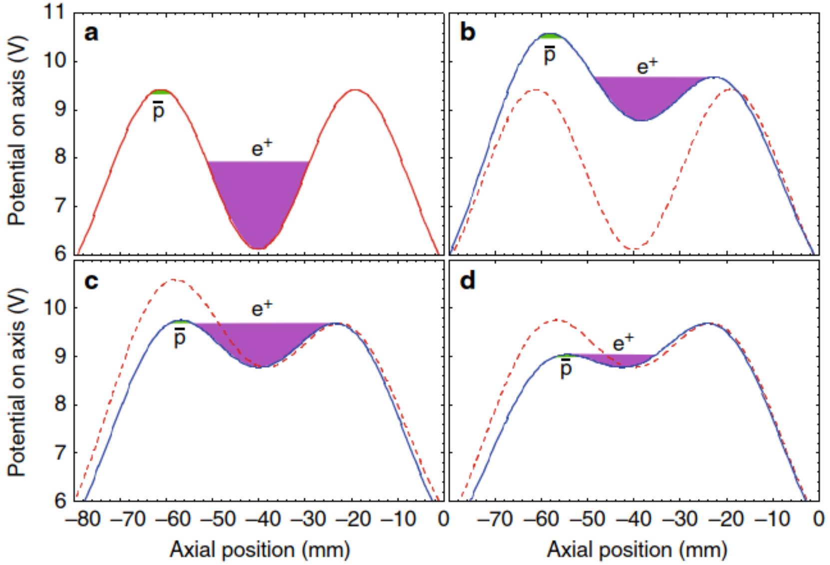


Initially: less than one atom per attempt

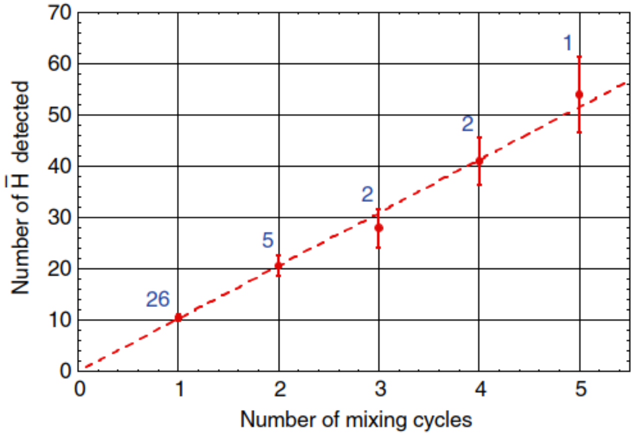
ALPHA collaboration: Nature **468**, 673 (2010)

Antihydrogen Trapping History

Improved mixing methods



even antihydrogen accumulation
was demonstrated by ALPHA



> 1000 atoms were accumulated

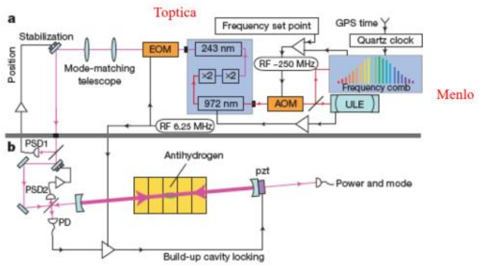
planned: improve antihydrogen production yield by sympathetic cooling of positrons, before the mixing

??? How to do spectroscopy with such a small amount of atoms ???

ALPHA Collaboration, Nature Communs. 8, 681 (2018)

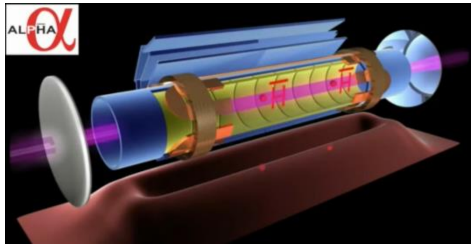
Antihydrogen Spectroscopy

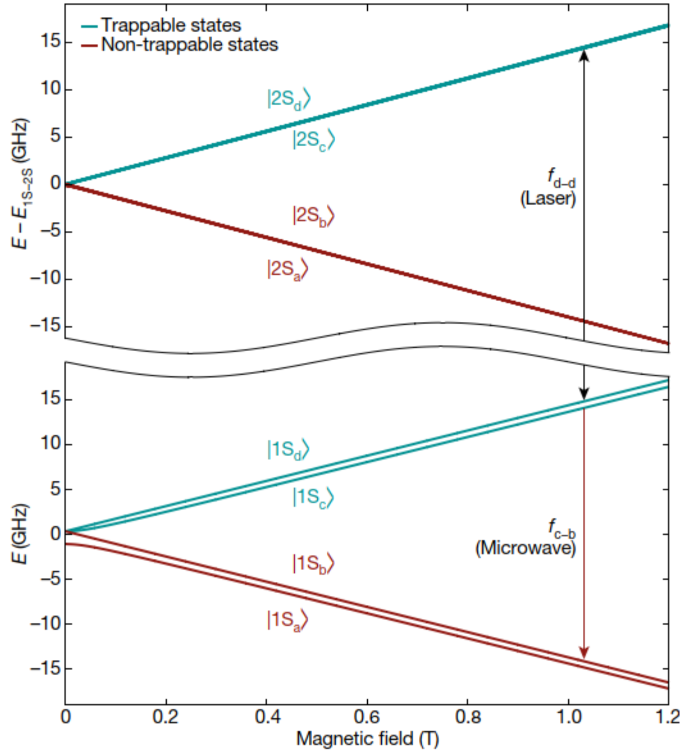
- 1S/2S Spectroscopy – dipole-forbidden very narrow transition.



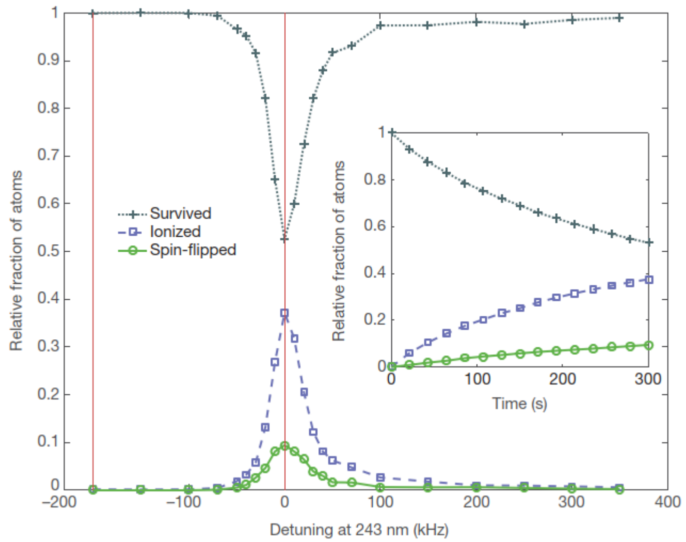
Trapped antihydrogen is by definition in low field seeking state

(positron moment in «down» state)





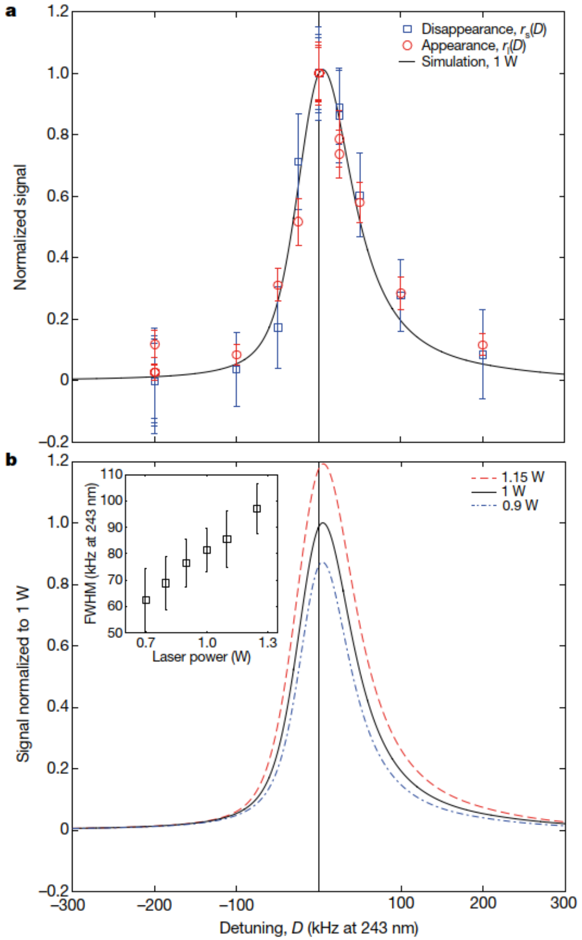
Resonant laser-field produces loss-mechanisms by resonant ionization and by inducing parasitic positron spin transitions



- Measure annihilation signal as a function of laser frequency (appearance and disappearance mode accessible)

ALPHA collaboration, Nature 557, 71 (2018)

The Result



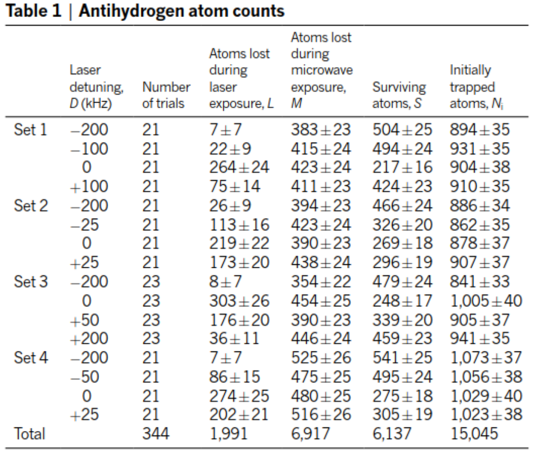
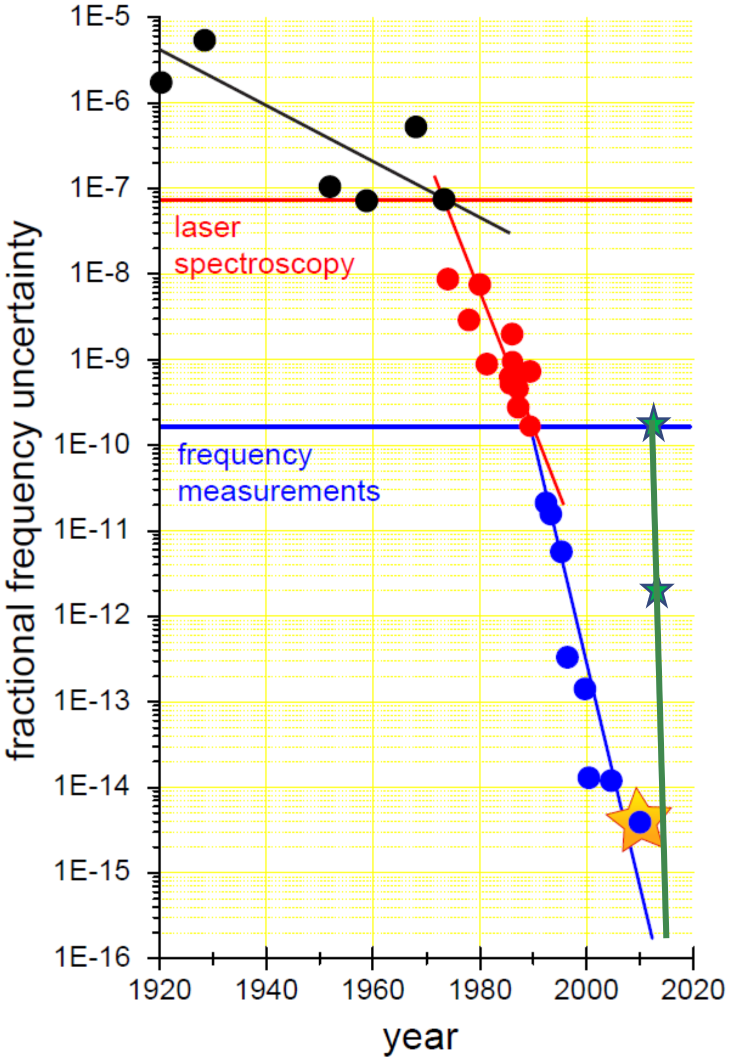


Table 1 | Antihydrogen atom counts

	Laser detuning, D (kHz)	Number of trials	Atoms lost during laser exposure, L	Atoms lost during microwave exposure, M	Surviving atoms, S	Initially trapped atoms, N_i
Set 1	−200	21	7±7	383±23	504±25	894±35
	−100	21	22±9	415±24	494±24	931±35
	0	21	264±24	423±24	217±16	904±38
	+100	21	75±14	411±23	424±23	910±35
Set 2	−200	21	26±9	394±23	466±24	886±34
	−25	21	113±16	423±24	326±20	862±35
	0	21	219±22	390±23	269±18	878±37
	+25	21	173±20	438±24	296±19	907±37
Set 3	−200	23	8±7	354±22	479±24	841±33
	0	23	303±26	454±25	248±17	1,005±40
	+50	23	176±20	390±23	339±20	905±37
	+200	23	36±11	446±24	459±23	941±35
Set 4	−200	21	7±7	525±26	541±25	1,073±37
	−50	21	86±15	475±25	495±24	1,056±38
	0	21	274±25	480±25	275±18	1,029±40
	+25	21	202±21	516±26	305±19	1,023±38
Total		344	1,991	6,917	6,137	15,045

$$f_{\mathrm{d-d}} = 2{,}466{,}061{,}103{,}080.3(0.6)\ \mathrm{kHz}$$



Hydrogen
Hänsch Plot

Antihydrogen
Hangst Plot

AEḡIS

ALPHA

BASE

GBAR

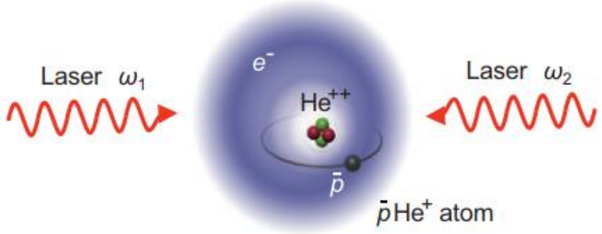
STEP

Tests hydrogen/antihydrogen CPT invariance with a fractional precision of 2 p.p.t.

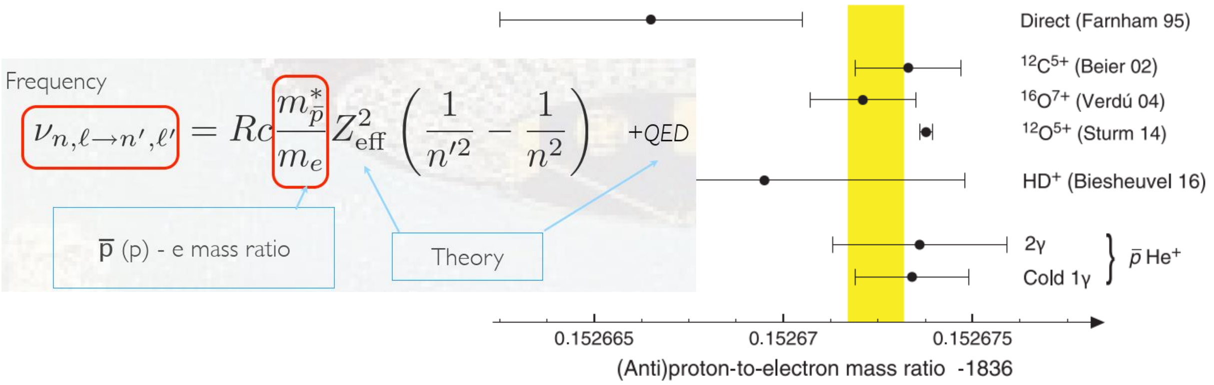
Future perspective: Laser cooling of antihydrogen just demonstrated

ALPHA collaboration, Nature 592, 35 (2021)

Antiprotonic Helium (ASACUSA)

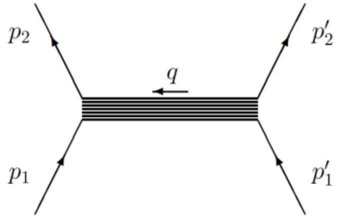


- Helium atom with one of the electrons replaced by an antiproton



$$\nu_{n,\ell\to n',\ell'} = Rc\frac{m^*_{\bar p}}{m_e}Z^2_{\text{eff}}\left(\frac{1}{n'^2}-\frac{1}{n^2}\right)$$

- Elegant and technically challenging experiments on circular states lead to measurements of the antiproton-to-electron mass ratio (0.6 p.p.b.)



- For exotic spin-1 bosons: general approach assuming rotational invariance -> 16 spin dependent interactions (**Moody-Wilczek-Dobrescu-Mocioiu formalism**)

$$V_2 = f_2^{e\bar p}\frac{\hbar c}{\pi}\left(\mathbf{s}_{\bar p}\cdot\mathbf{s}_e\right)\frac{e^{-r/\lambda}}{r},$$

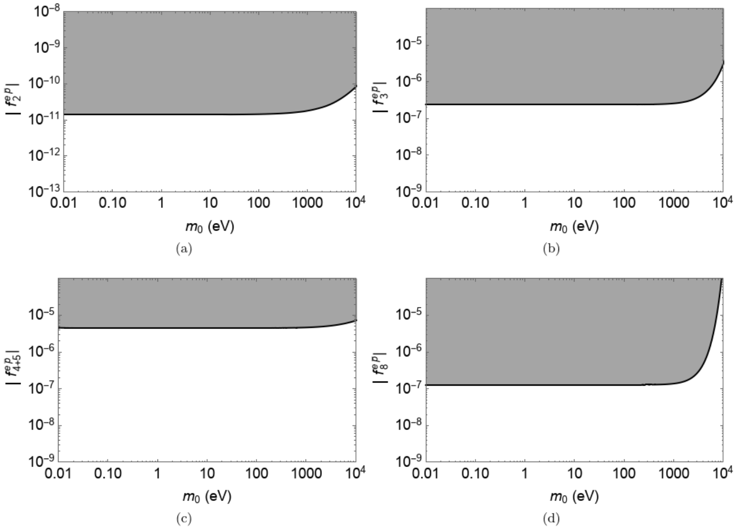
$$V_3 = f_3^{e\bar p}\frac{\hbar^3}{\pi m_e^2 c}\left[\mathbf{s}_{\bar p}\cdot\mathbf{s}_e\left(\frac{1}{\lambda r^2}+\frac{1}{r^3}+\frac{4\pi}{3}\delta^3(r)\right)-\left(\mathbf{s}_{\bar p}\cdot\mathbf{r}\right)\left(\mathbf{s}_e\cdot\mathbf{r}\right)\left(\frac{1}{\lambda^2 r^3}+\frac{3}{\lambda r^4}+\frac{3}{r^5}\right)\right]e^{-r/\lambda},$$

$$V_{4-5} = f_{4-5}^{e\bar p}\frac{i\hbar^3}{4m_e^2 c}\mathbf{s}_{\bar p}\cdot\left[\left(\frac{m_e}{m_{\bar p}+m_e}\nabla_{\bar p}-\frac{m_{\bar p}}{m_{\bar p}+m_e}\nabla_e\right)\times\mathbf{r},\left(\frac{1}{r^3}+\frac{1}{\lambda r^2}\right)e^{-r/\lambda}\right]_+,$$

$$V_{4+5} = f_{4+5}^{e\bar p}\frac{i\hbar^3}{4m_e^2 c}\mathbf{s}_e\cdot\left[\left(\frac{m_e}{m_{\bar p}+m_e}\nabla_{\bar p}-\frac{m_{\bar p}}{m_{\bar p}+m_e}\nabla_e\right)\times\mathbf{r},\left(\frac{1}{r^3}+\frac{1}{\lambda r^2}\right)e^{-r/\lambda}\right]_+,$$

$$V_8 = -f_8^{e\bar p}\frac{\hbar^3}{4\pi m_e^2 c}\left[\mathbf{s}_e\cdot\left(\frac{m_e}{m_{\bar p}+m_e}\nabla_{\bar p}-\frac{m_{\bar p}}{m_{\bar p}+m_e}\nabla_e\right),\left[\mathbf{s}_{\bar p}\cdot\left(\frac{m_e}{m_{\bar p}+m_e}\nabla_{\bar p}-\frac{m_{\bar p}}{m_{\bar p}+m_e}\nabla_e\right),\frac{e^{-r/\lambda}}{r}\right]_+\right]_+$$

Interactions would modify atomic potential and lead to shifts in wavelengths



(a)

(b)

(c)

(d)

AEḡIS

ALPHA

BASE

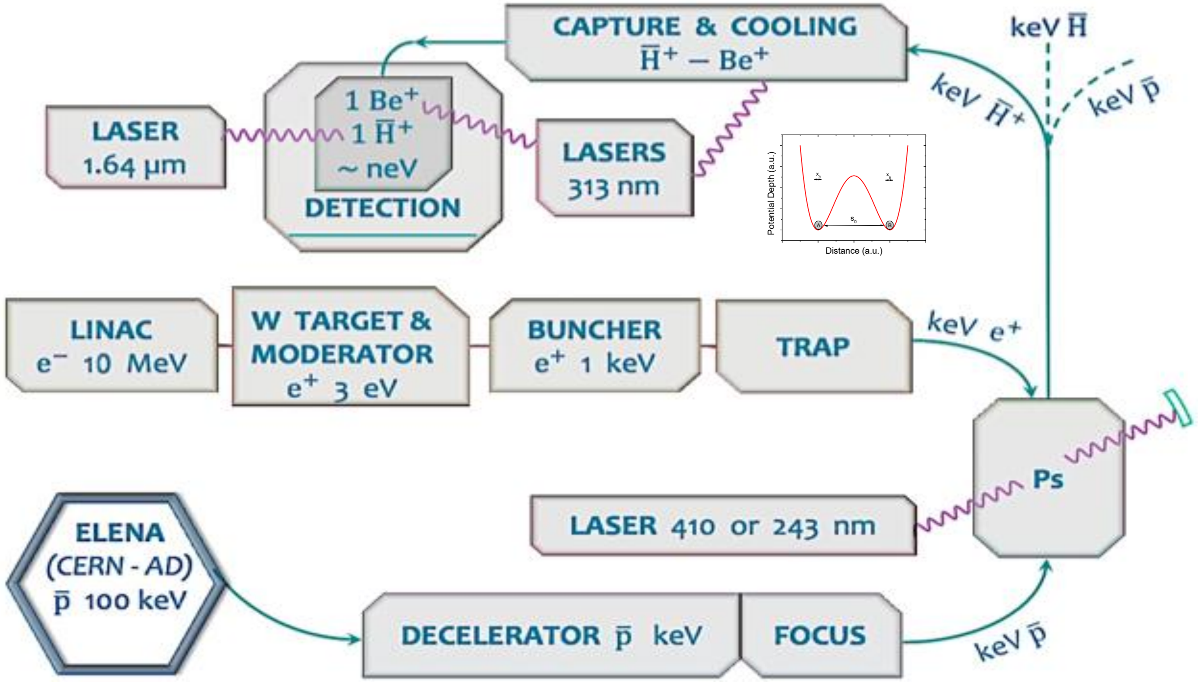
GBAR

STEp̄

- First limits on exotic antimatter/axion coupling derived

Gravity Experiments – GBAR/AEgIS/ALPHA-g

- Motivation: Test the weak equivalence principle by studying antihydrogen in the gravitational field of the earth.



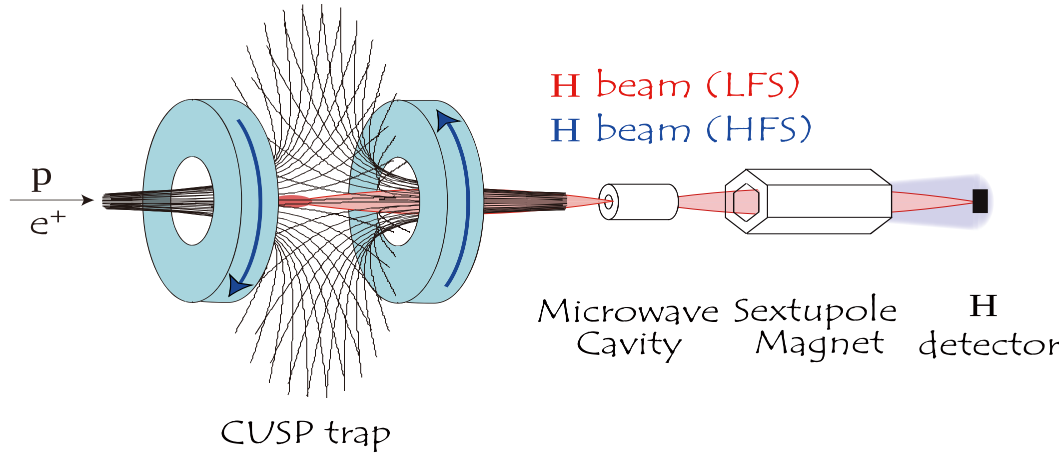
- Ingredients
  - Production of $\bar{\mathbf{H}}^+$
  - Sympathetic cooling of this charged system by coupling it to laser-cooled Be ions
  - Resonant stripping
  - Drop and annihilate

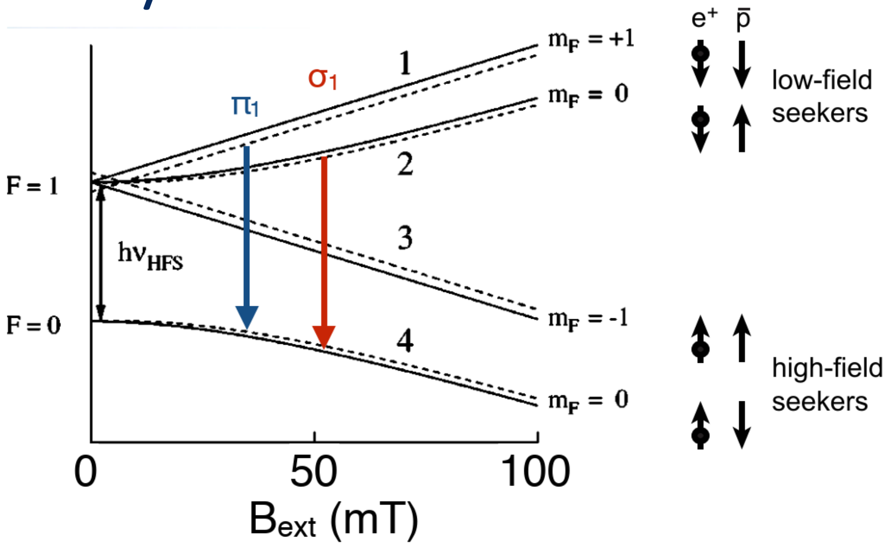
Goal: Measurement of g to 0.1% level

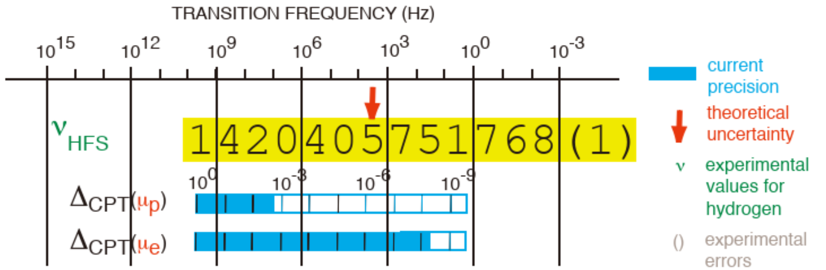
Production of $\bar{\mathbf{H}}^+$ opens bright perspective for future precision experiments

GSHFS of Antihydrogen: ALPHA/ASACUSA CUSP

- Measure the ground state hyperfine splitting using a Rabi beam experiment.







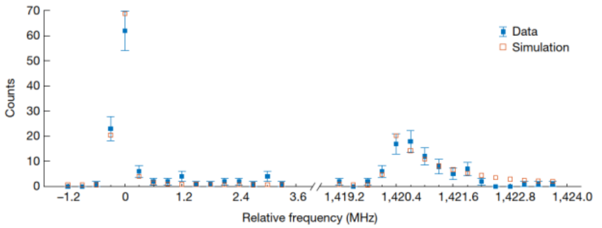
Hydrogen: $\nu_{HF} = 1{,}420{,}405{,}748.4(3.4)$

- Demonstrated with hydrogen with 2.7 p.p.b. precision ASACUSA collaboration, Nature Comms. 8, 15749 (2017)
- Successful production of first beam of antihydrogen atoms

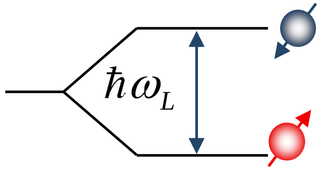
ASACUSA collaboration, Nature Comms. 5, 3089 (2014)

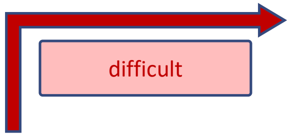
Antihydrogen:

1.420 4(5)GHz



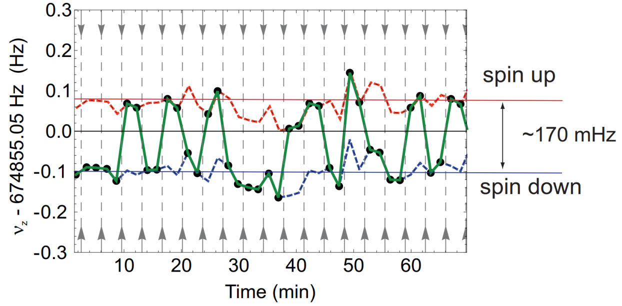
ALPHA collaboration, Nature 548, 66 (2017)




difficult

Continuous Stern Gerlach Effect

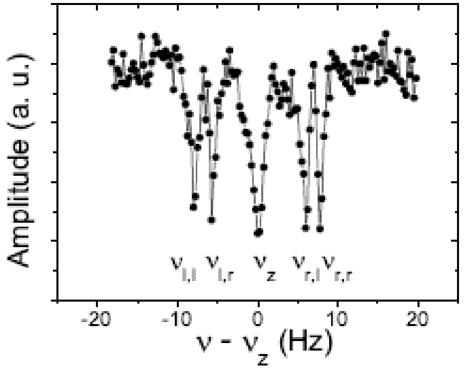
C. Smorra *et al.*, Phys. Lett. B 769, 1 (2017)



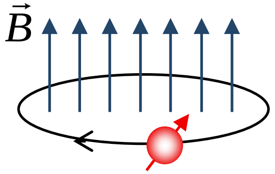
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2}\,\frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$


straight forward

Image Current Measurements



S. Ulmer *et al.*, PRL 107, 103002 (2011)



AEḡIS

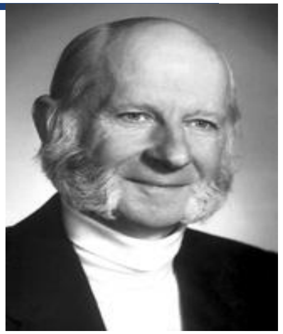
ALPHA

BASE

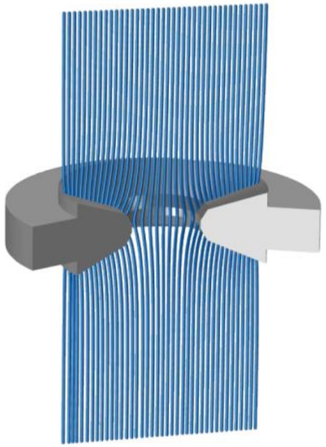
GBAR

STEp̄

Larmor Frequency – extremely hard



Measurement based on continuous Stern Gerlach effect.



Energy of magnetic dipole in magnetic field $\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$

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
-> Axial frequency becomes a function of the spin state

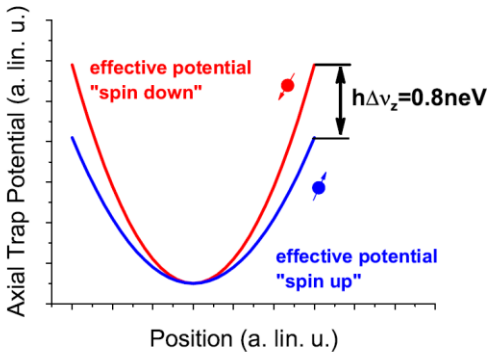
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p \frac{B_2}{\nu_z}$$

- Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

- Most extreme magnetic conditions ever applied to single particle.

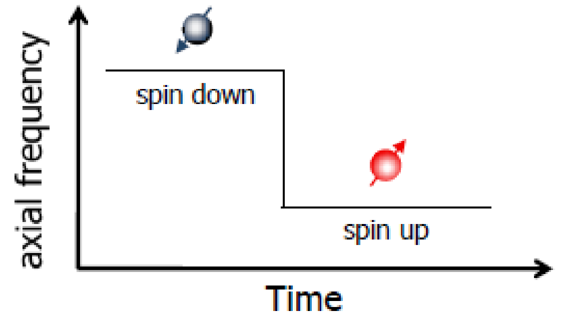
$$\Delta\nu_z \sim 170\ mHz$$

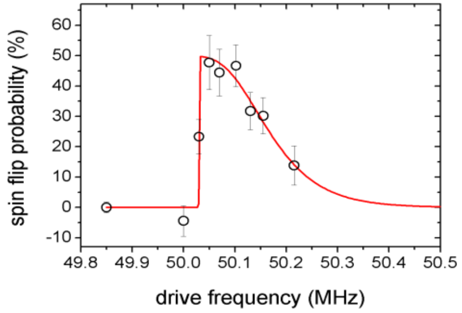


Single Penning trap method is limited to the p.p.m. level

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

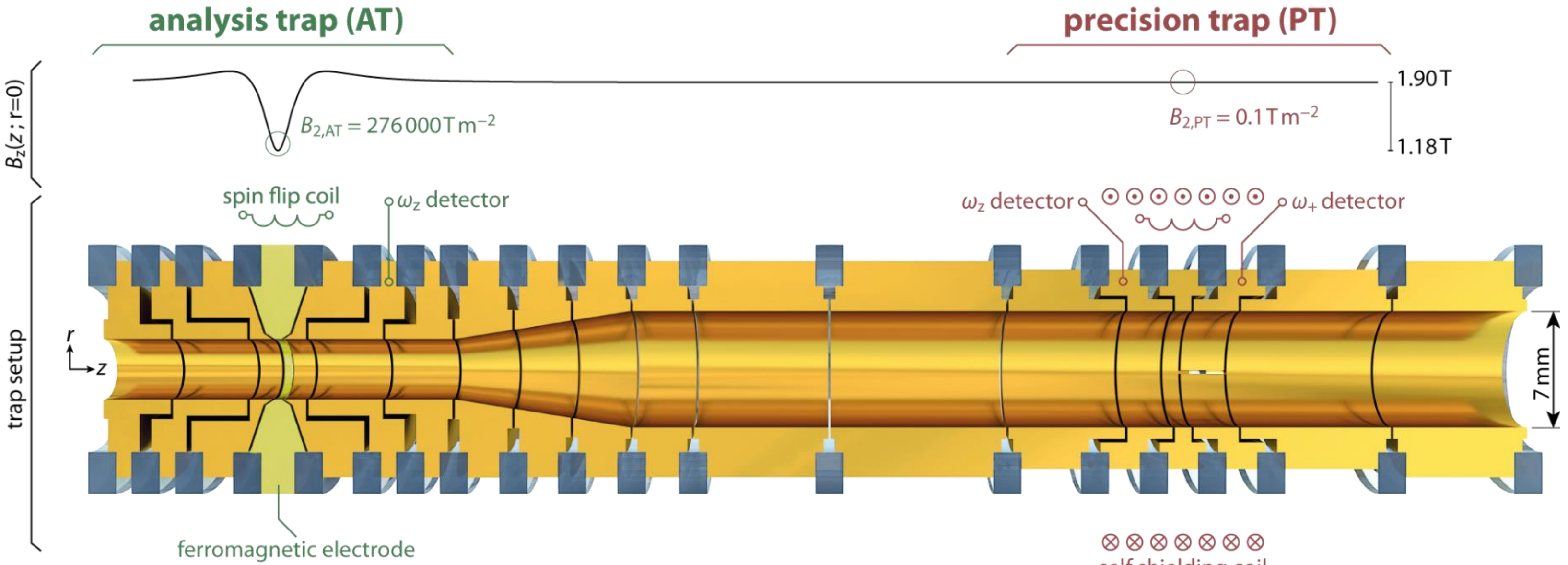


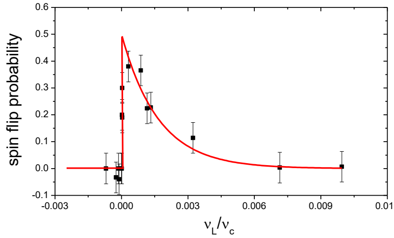


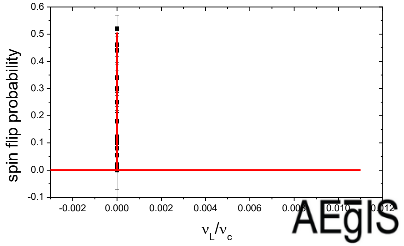
S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

The Mainz Double Penning-Trap Method

Invented by **H. Haeffner**, in group of **G. Werth** also highly relevant in electron mass measurements and tests of BS QED (Blaum / Sturm et al.)







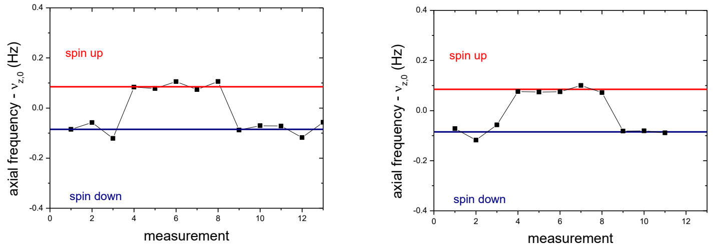
Initialize the spin state

particle transport

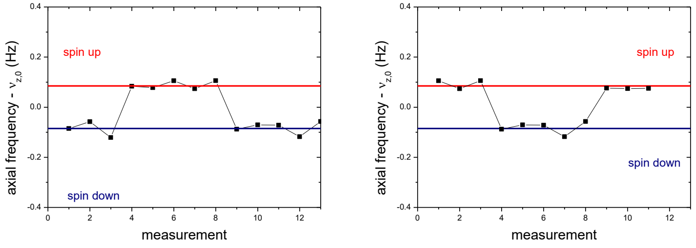
1.) measure cyclotron ν_c

2.) drive spin transition at ν_{rf}

analyze the spin state



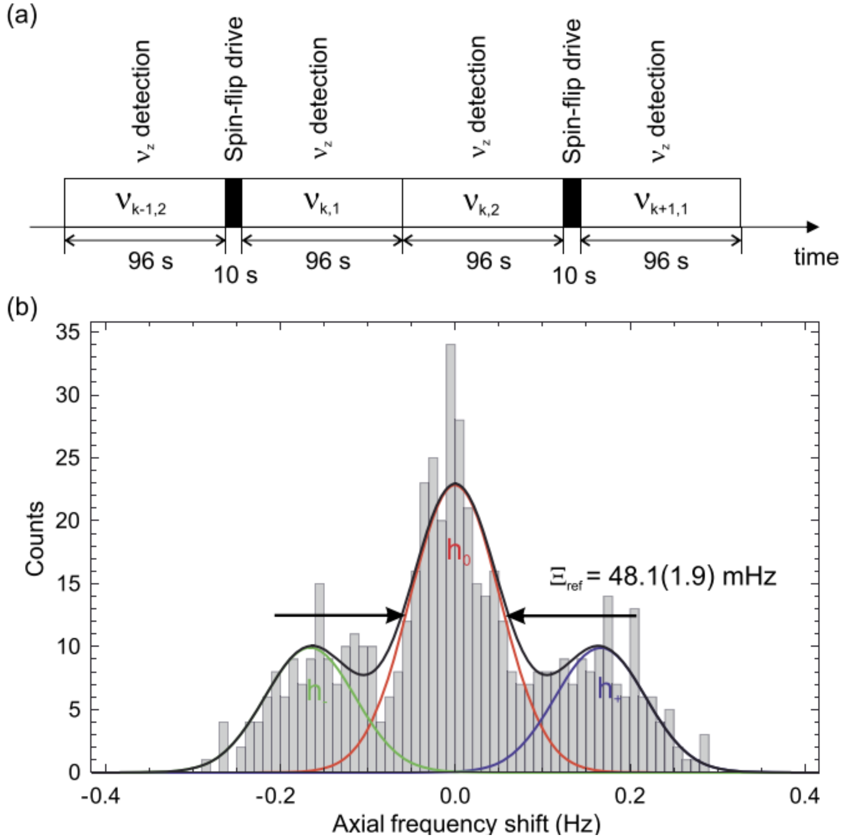
no spin-flip in PT

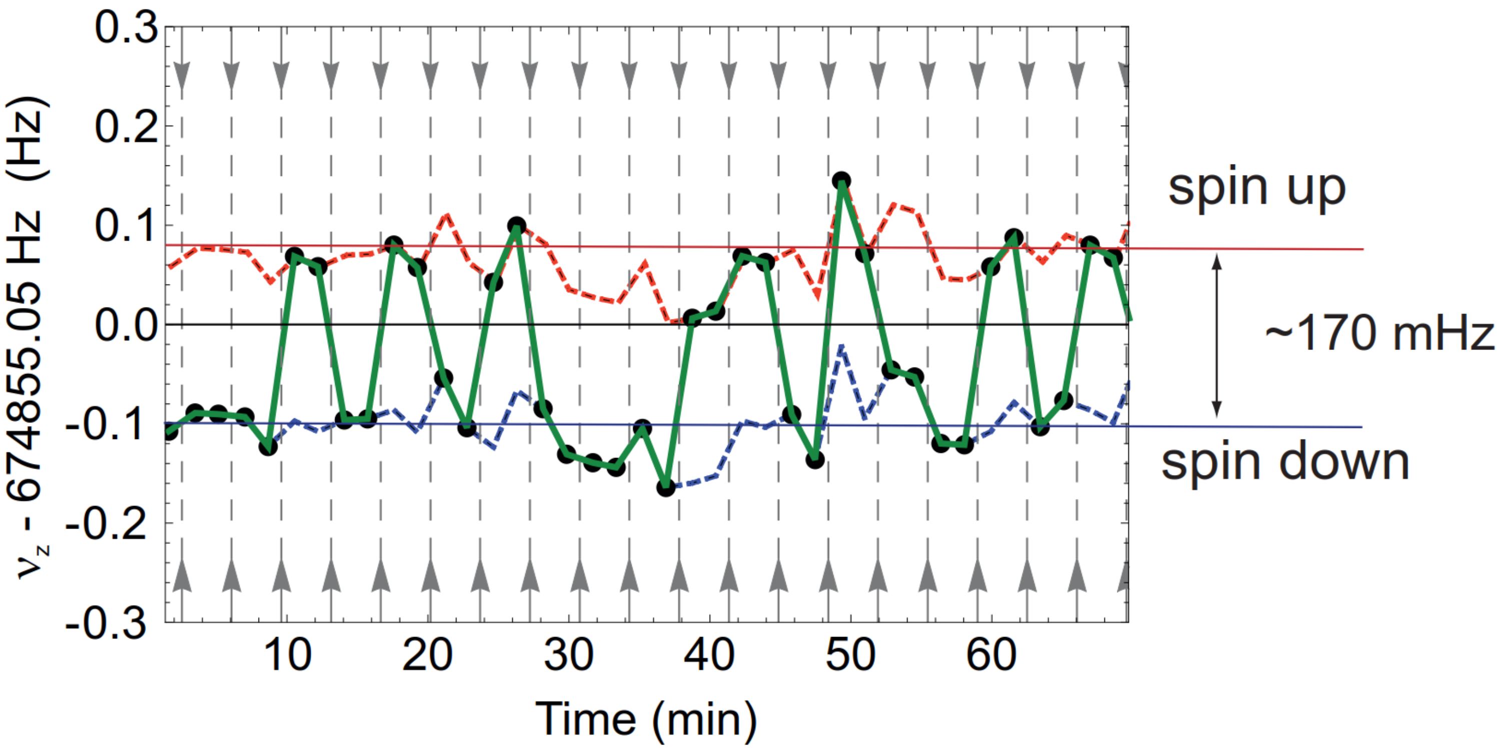


spin flipped in PT

measures spin flip probability as a function of the drive frequency in the homogeneous magnetic field of the precision trap

The «holy-grail»: single antiproton spin flips



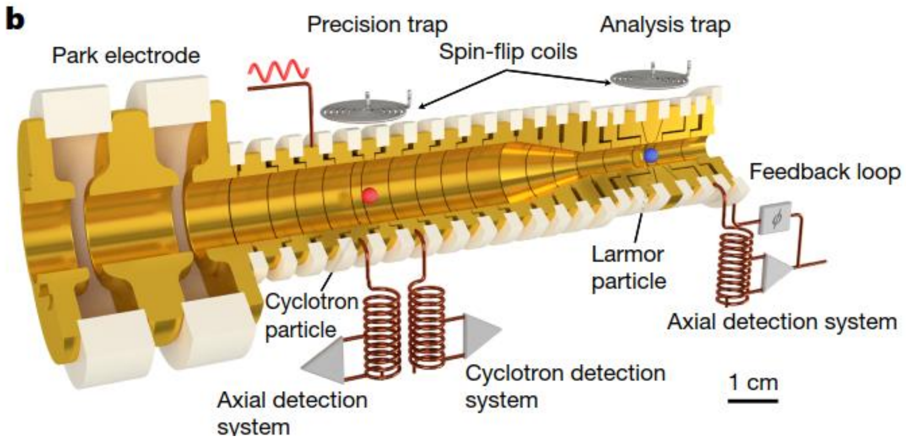


C. Smorra *et al.,* Phys. Lett. B 769, 1 (2017)

- First non-destructive observation of single-antiproton spin-quantum transitions.
- **Double trap method ultimately requires single spin-flip resolution with high fidelity.**

Invented: BASE Two-Particle Method

Idea: divide measurement to two particles

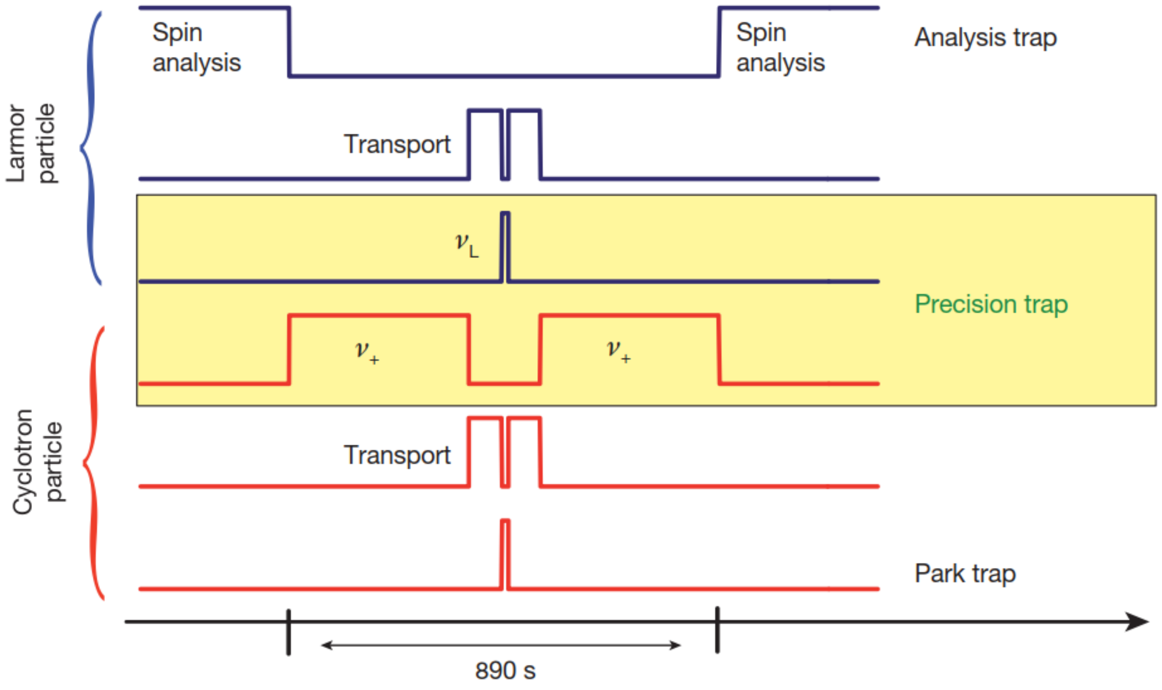


«hot» cyclotron particle which probes the magnetic field in the precision trap

«cold» cyclotron particle to flip and analyze the spin-eigenstate

pay: measure with two particles at different mode energies

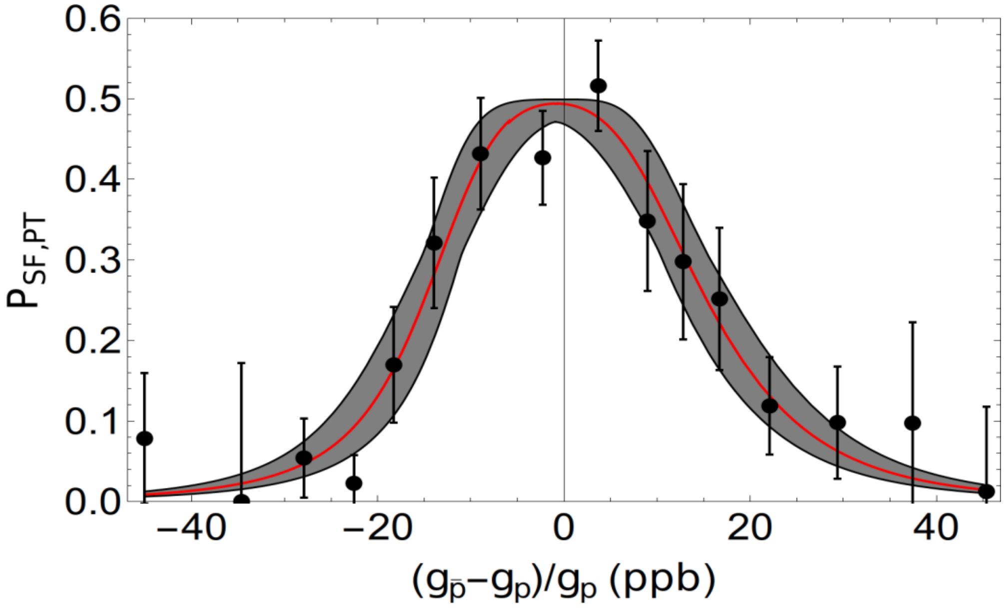
win: 60% of time usually used for sub-thermal cooling useable for measurements



challenges:

- transport without heating
- more challenging systematics

The Magnetic Moment of the Antiproton



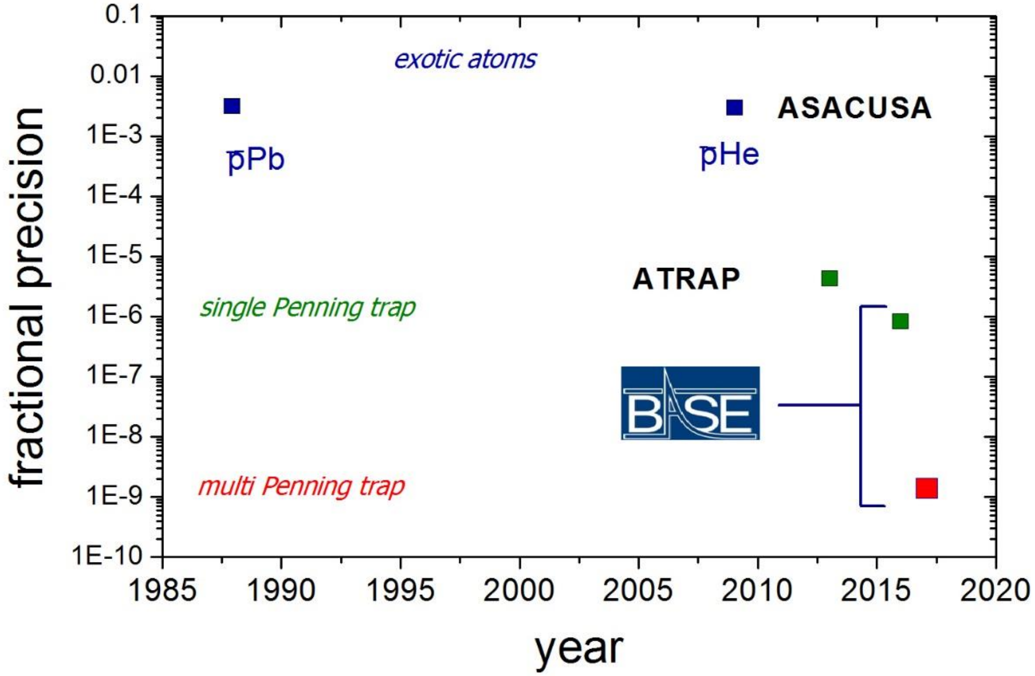
A. Mooser *et al.*, Nature **509**, 596 (2014)

$$\frac{g_p}{2} = 2.792\,847\,350\ (9)$$

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

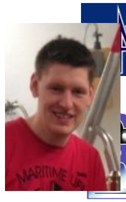
C. Smorra *et al.*, Nature **550**, 371 (2017)

BASE 2017: $\mu_{\bar{p}}$ = -2.792 847 344 1 (42) μ_{nucl}



first measurement more precise for antimatter than for matter...

$$\frac{g_p}{2} = 2.792\,847\,344\,62\ (82)$$



G. Schneider *et al.*, Science **358**, 1081 (2017)

RIKEN

MAX-PLANCK-GESELLSCHAFT

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

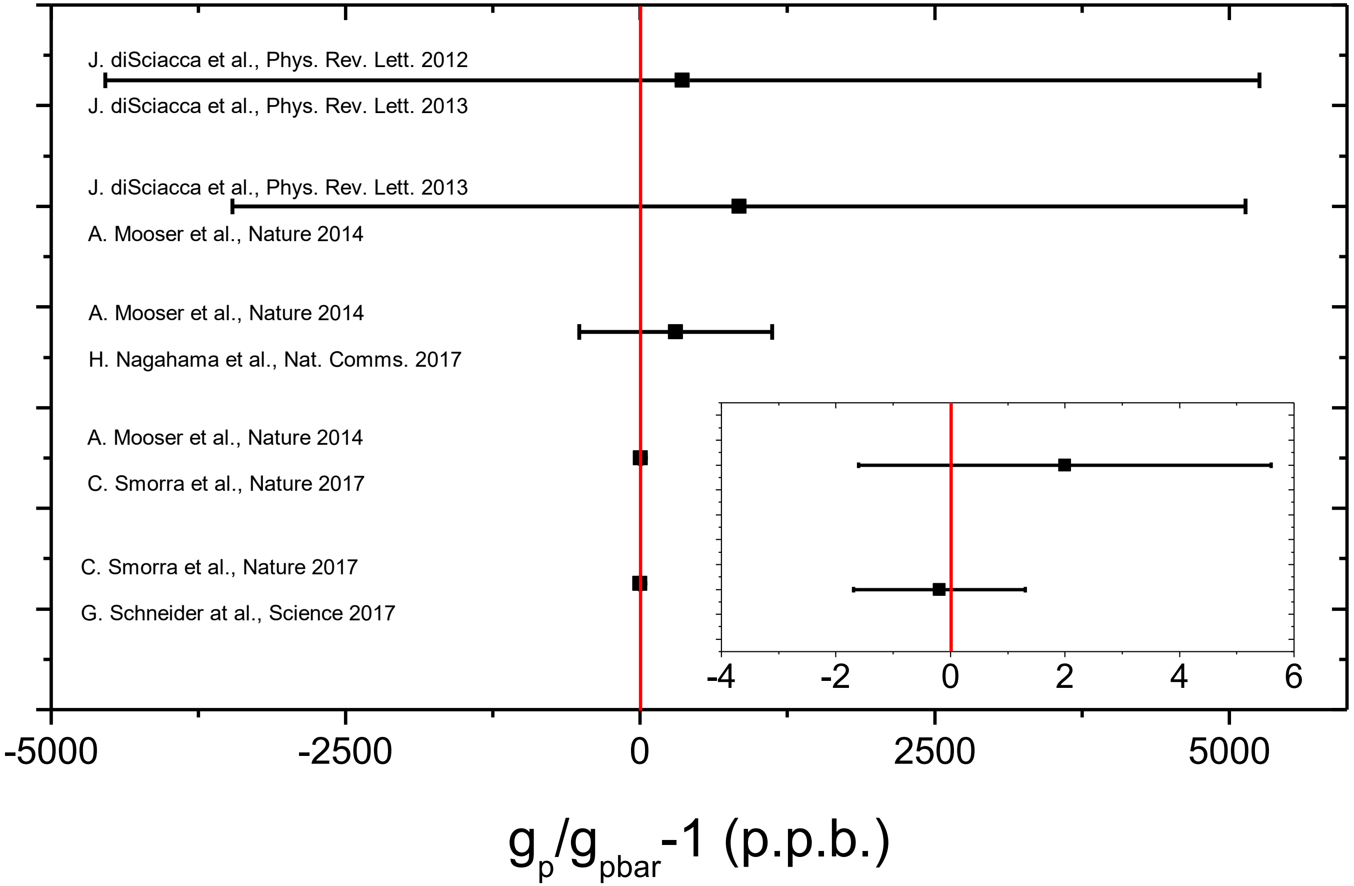
東京大学 THE UNIVERSITY OF TOKYO

GSI

Leibniz Universität Hannover

PTB

Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	CPT $\lvert g_p/g_{\bar{p}}\rvert - 1$	Collaboration
2011	2.792 847 353 (28)	2.786 2 (83)	0.002 4 (29)	Pask (ASACUSA)
2013	2.792 846 (7)	2.792 845 (12)	0.000 000 4 (49)	diSciacca (ATRAP)
2014	**2.792 847 349 8 (93)**	2.792 845 (12)	0.000 000 8 (43)	**Mooser(BASE)/**diSciacca (ATRAP)
2016	**2.792 847 349 8 (93)**	**2.792 846 5 (23)**	**0.000 000 30 (82)**	**Mooser/Nagahama (BASE)**
2017/1	**2.792 847 349 8 (93)**	**2.792 847 344 1 (42)**	**0.000 000 002 0 (36)**	**Mooser/Smorra (BASE)**
2017/2	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**-0.000 000 000 2 (15)**	**Schneider/Smorra (BASE)**



2013

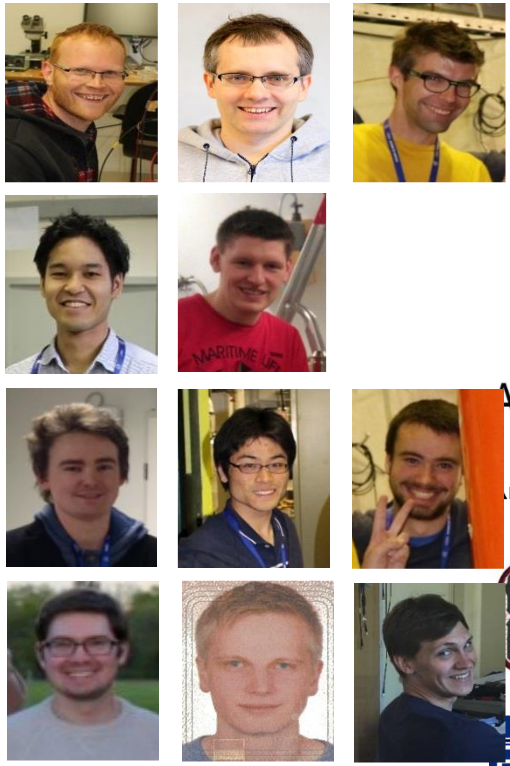
2014

2016

2017

2018

K. Blaum, Y. Yamazaki
J. Walz, W. Quint,
Y. Matsuda, C. Ospelkaus



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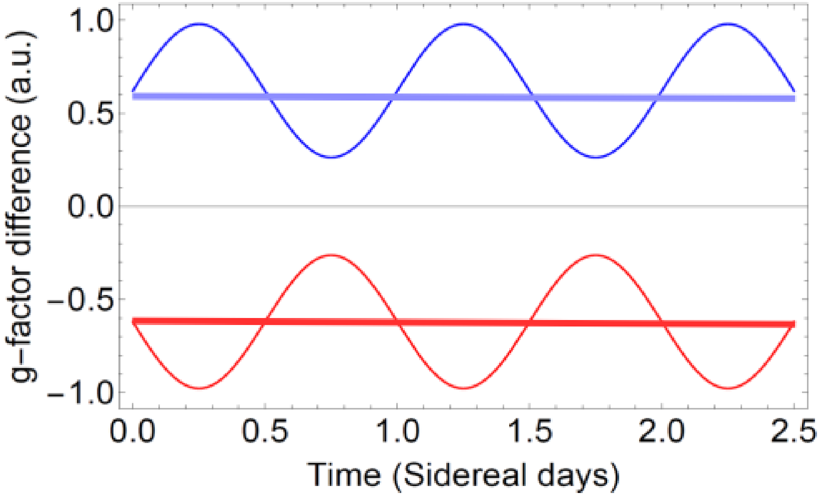
$$\frac{g_p}{g_{\bar{p}}} - 1 = -0.000\,000\,000\,2\,(15)$$

STEp

Physics – SME limits

$$\frac{g_{\bar{p}}}{2} = 2.792\,847\,344\,3\,(46)$$

$$\frac{g_{p}}{2} = 2.792\,847\,344\,62\,(83)$$



$$\left|\frac{g_p}{2} - \frac{g_{\bar{p}}}{2}\right| = 0.3\,(8.3)\,10^{-9}\ \text{GeV}$$

3000-fold improved limits on CPT-odd interactions in the baryon sector

Coefficient	Limit
$\tilde{b}_p^{Z}$	$8.1 * 10^{-25}$GeV
$\tilde{b}_p^{ZZ}$	$3.3 * 10^{-9}$ GeV^{-1}
$\tilde{b}_{F,p}^{XX}+\tilde{b}_{F,p}^{YY}$	$4.6 * 10^{-9}$ GeV^{-1}
$\tilde{b}_{F,p}^{*Z}$	$1.5 * 10^{-24}$ GeV
$\tilde{b}_{F,p}^{*ZZ}$	$1.1 * 10^{-8}$ GeV^{-1}
$\tilde{b}_{F,p}^{*XX}+\tilde{b}_{F,p}^{*YY}$	$3.1 * 10^{-9}$ GeV^{-1}
f_p^0	4.5 10^{-12} μ_B

Time Dependence of Fundamental Constants

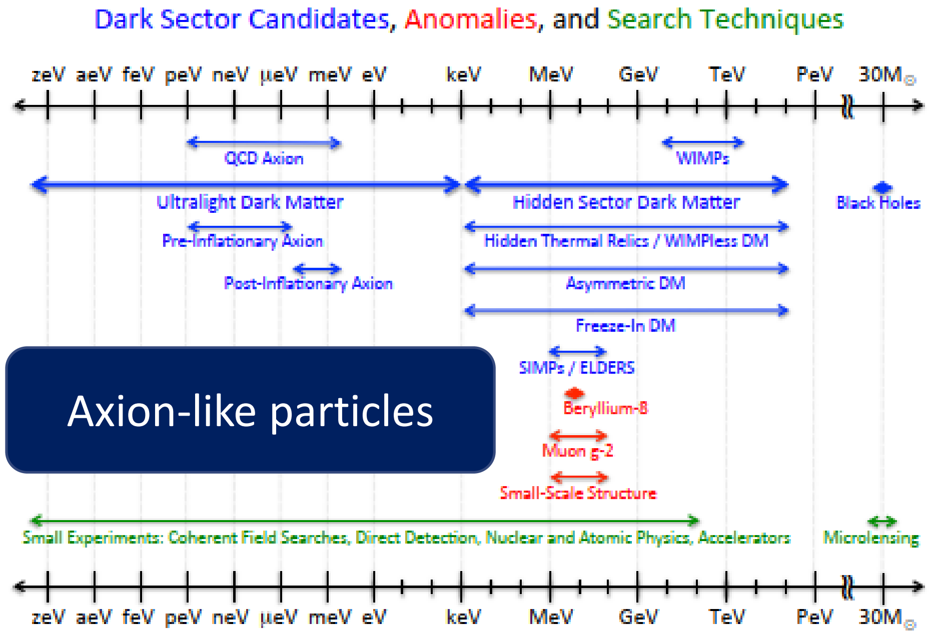
Spontaneous breaking of any continuous symmetry leads to the existence of (almost) massless NG-bosons

$$\boldsymbol{\phi(\vec{r},t) \approx \frac{\sqrt{2\rho_{DM}}}{m_\phi}\sin(m_\phi t)}$$

$$\boldsymbol{\rho_{DM} = 0.4\ GeV/cm^3}$$

$$\boldsymbol{Q = 6 \cdot 10^6}$$

$$\boldsymbol{\nu_\phi = m_\phi c^2/h}$$



Axion-like particles

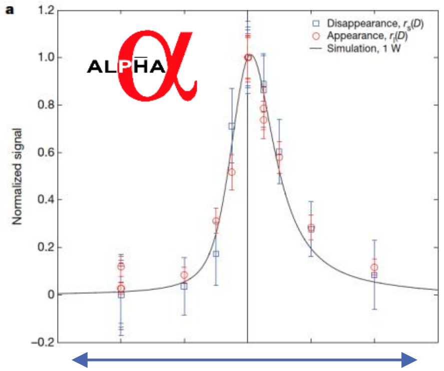
Possible Signatures

$$\alpha(t) = \alpha_0(1 + g_\gamma \phi(\vec{r},t))$$

$$m_e(t) = m_{e,0}\left(1 + \frac{g_e}{m_{e,0}}\phi(\vec{r},t)\right)$$

$$m_p(t) = m_{p,0}\left(1 + \frac{g_p}{m_{p,0}}\phi(\vec{r},t)\right)$$

(Anti-)Atomic Transition Frequencies

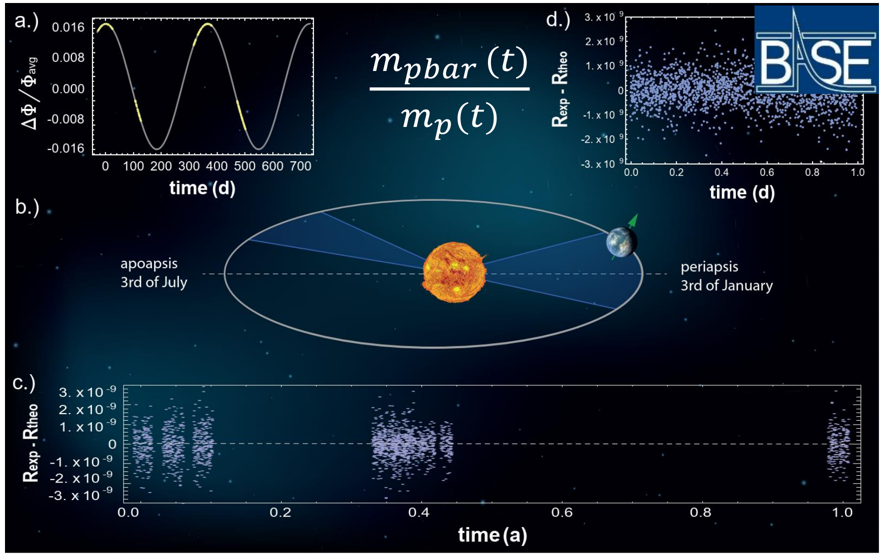


600 kHz

$$\frac{\delta(\nu_{atom} - \nu_{Laser})}{\nu_{atom}} = \left(2\ g_\gamma + \frac{g_e}{m_{e,0}}\right)\left(\frac{\sqrt{2\rho_{DM}}}{m_\phi}\right) \text{ for } \nu < \nu_{c,r}$$

$$\frac{\delta(\nu_{atom} - \nu_{Laser})}{\nu_{atom}} = \left(2\ g_\gamma + \frac{g_e}{m_{e,0}}\right)\left(\frac{\sqrt{2\rho_{DM}}}{m_\phi}\right) h_{atom}(t) \text{ for } \nu > \nu_{c,r}$$

These type of studies are possible within ALPHA and ASACUSA



Antypas et al., arXiv:2012.01519

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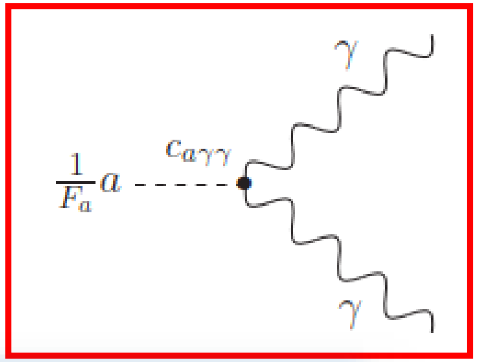
Axion Wind Model

- Frist of all: a quick comment on axion fermion coupling

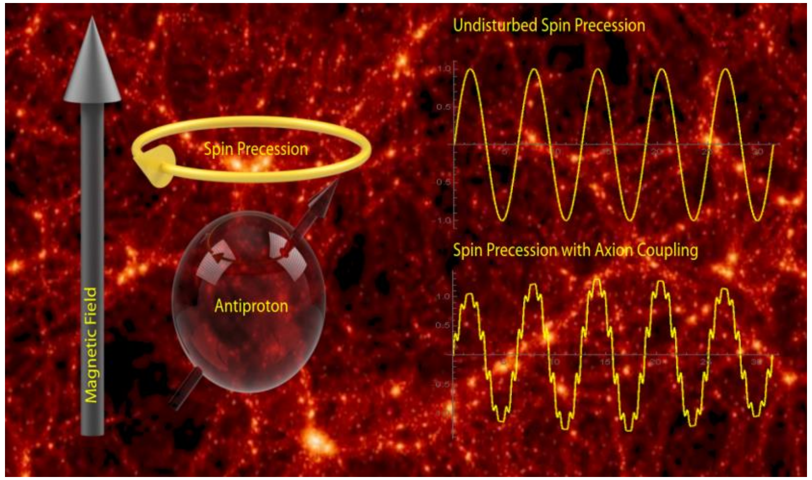
J. Kim, G. Carosi, https://arxiv.org/pdf/0807.3125.pdf

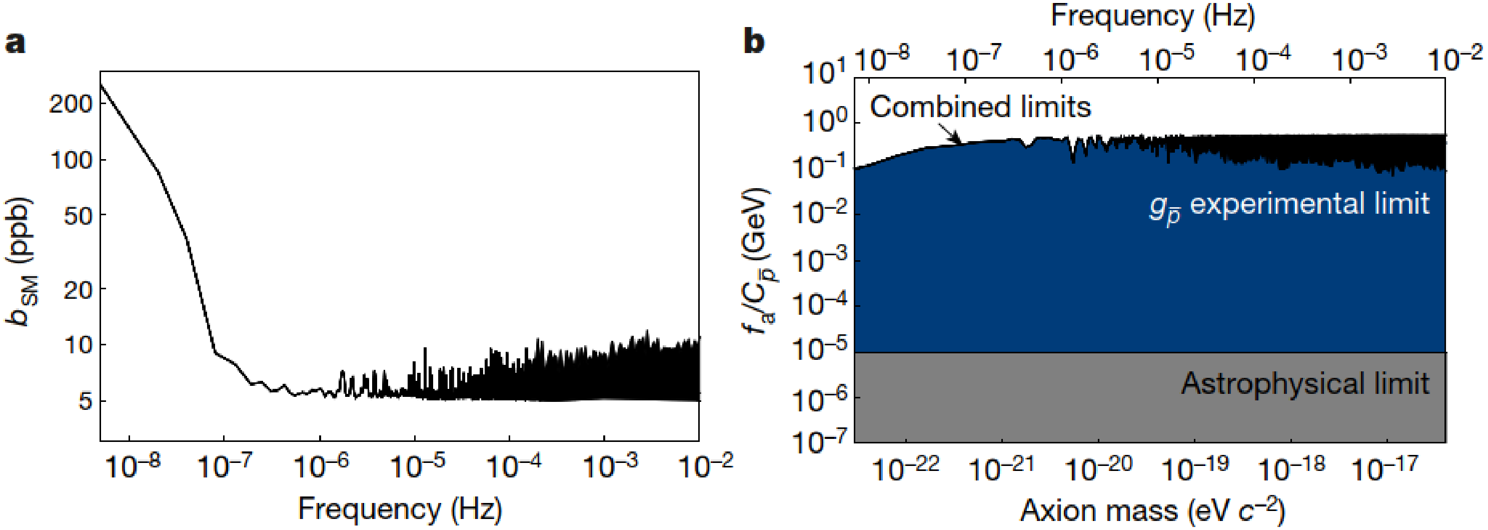
$$\begin{aligned}\mathcal{L}_\theta = &\frac{1}{2} f_S^2 \partial^\mu \theta \partial_\mu \theta - \frac{1}{4g_c^2} G^a_{\mu\nu} G^{a\,\mu\nu} + (\bar{q}_L i \not{D} q_L + \bar{q}_R i \not{D} q_R) \\ &+ c_1 (\partial_\mu \theta) \bar{q} \gamma^\mu \gamma_5 q - \left(\bar{q}_L \; m \; q_R e^{ic_2\theta} + \text{h.c.}\right) \\ &+ c_3 \frac{\theta}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\,\mu\nu} \;(\text{or } \mathcal{L}_{\text{det}}) \qquad\qquad (19) \\ &+ c_{\theta\gamma\gamma} \frac{\theta}{32\pi^2} F^i_{\text{em},\mu\nu} \tilde{F}^{i\,\mu\nu}_{\text{em}} + \mathcal{L}_{\text{leptons},\theta}\end{aligned}$$



this "derivative interaction" would induce a pseudo magnetic field and a modulation of the antiproton spin transition frequency

$$\delta\omega_{[}^{\bar{p}}(t) \approx \frac{C_{\bar{p}} m_{\text{a}} a_0 |\mathbf{v}_{\text{a}}|}{f_{\text{a}}} [A \cos(\Omega_{\text{sid}} t + \alpha) + B] \sin(\omega_{\text{a}} t)$$





Improves previous antiproton/axion limits by 5 orders of magnitude

By 4 o.o.m. less stringent than current best matter limits

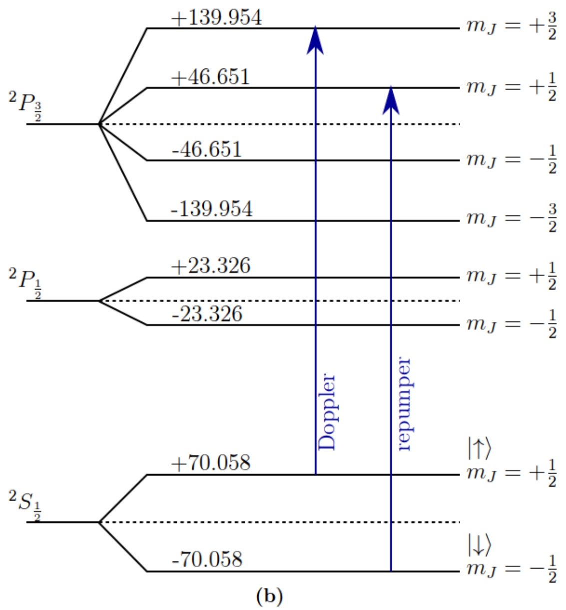
C. Smorra, Y. Stadnik, Nature **(575)**, 310 (2019)

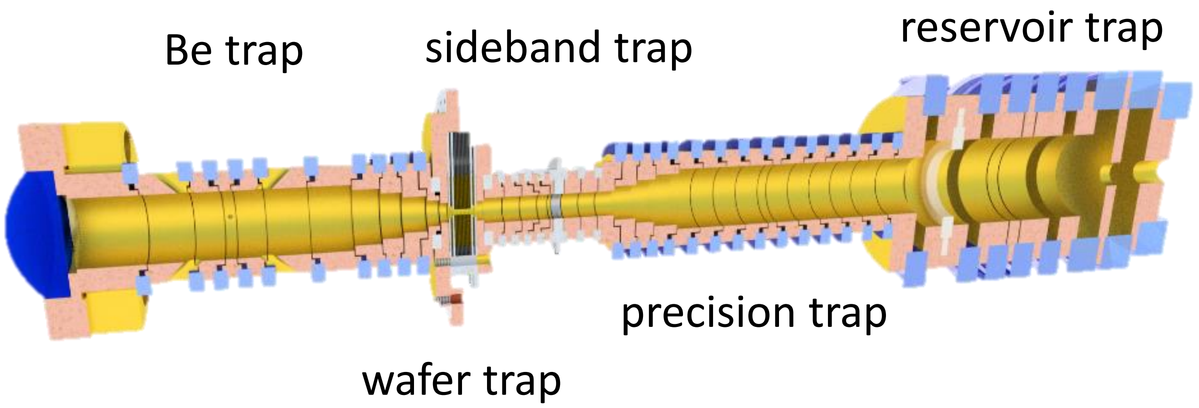
QLS with Antiproton Spins

- Apply the very same method to read-out the antiproton spin state

Initial conditions of experiment	$\lvert\psi\rangle_0 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$	$\lvert\psi\rangle_0 = \lvert\downarrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$
Magnetic SWAP gate in sideband trap	$\lvert\psi\rangle_1 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$	$\lvert\psi\rangle_1 = \lvert\uparrow\rangle_p \lvert 1\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$
Phonon SWAP gate in wafer trap	$\lvert\psi\rangle_2 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$	$\lvert\psi\rangle_2 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 1\rangle_{m,L}$
Phonon/Spin coupling in Be trap	$\lvert\psi\rangle_3 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$	$\lvert\psi\rangle_3 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\downarrow\rangle_L \lvert 0\rangle_{m,L}$
Readout	$\lvert\psi\rangle_4 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\uparrow\rangle_L \lvert 0\rangle_{m,L}$	$\lvert\psi\rangle_4 = \lvert\uparrow\rangle_p \lvert 0\rangle_{m,p} \lvert\downarrow\rangle_L \lvert 0\rangle_{m,L}$
	fluorescence	dark state

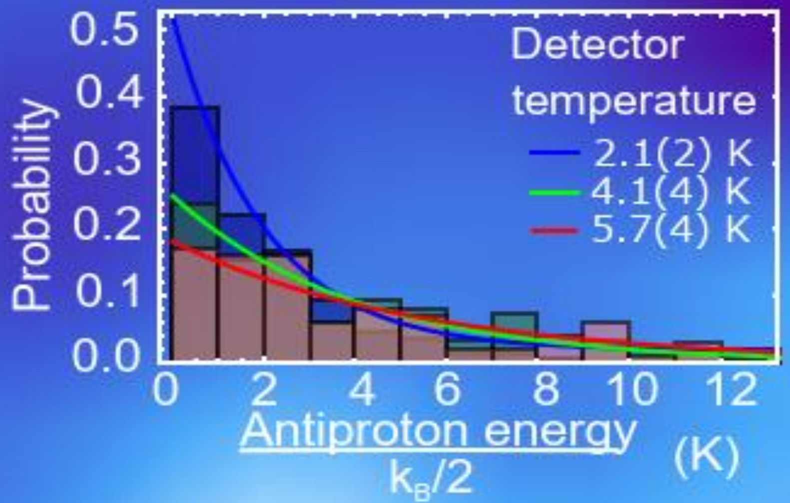
Be+ level scheme

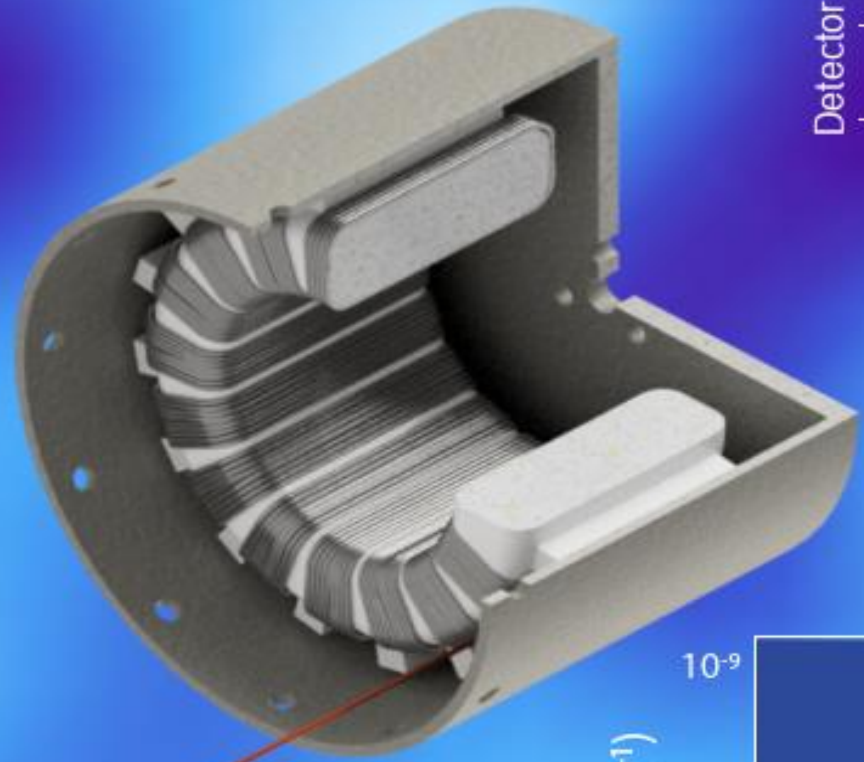




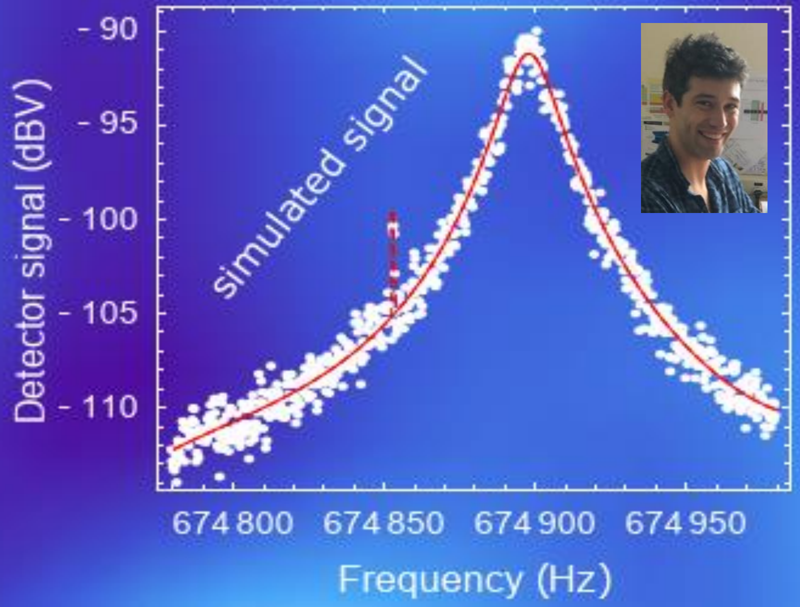
BASE CDM

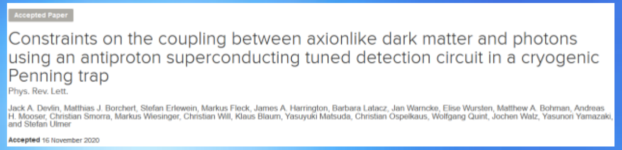
AXION SEARCH





calibrated with a trapped antiproton





Accepted Paper

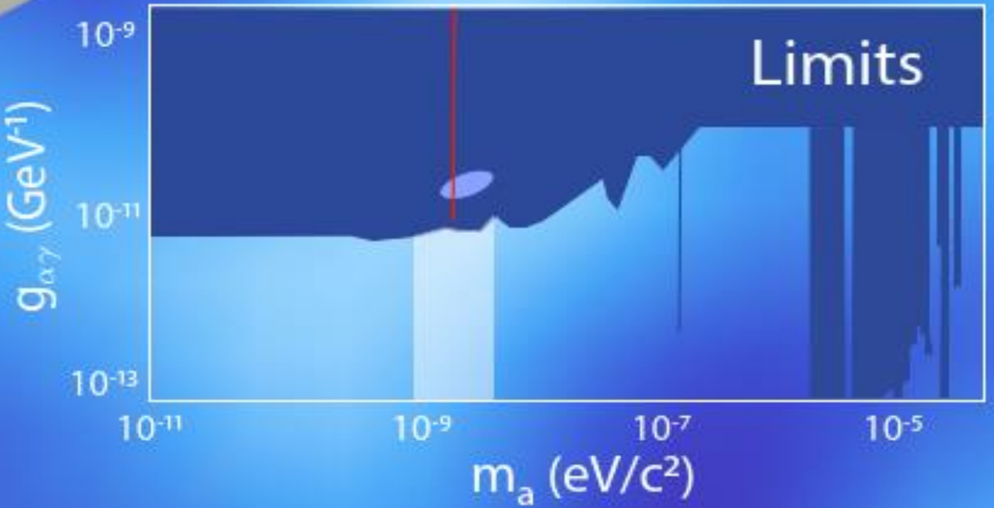
Constraints on the coupling between axionlike dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap

Phys. Rev. Lett.

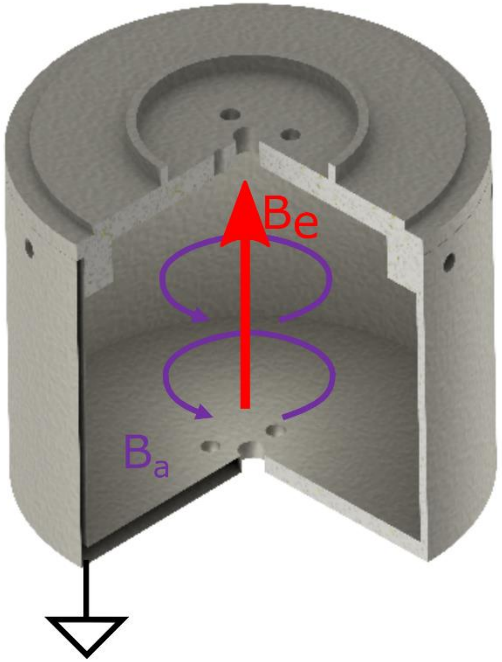
Jack A. Devlin, Matthias J. Borchert, Stefan Erlewein, Markus Fleck, James A. Harrington, Barbara Latacz, Jan Warncke, Elise Wursten, Matthew A. Bohman, Andreas H. Mooser, Christian Smorra, Markus Wiesinger, Christian Will, Klaus Blaum, Yasuyuki Matsuda, Christian Ospelkaus, Wolfgang Quint, Jochen Walz, Yasunori Yamazaki, and Stefan Ulmer

Accepted 16 November 2020

https://journals.aps.org/prl/accepted/15071Y2dJe514a63281b1498fe4274156d3788acc



Conversion of Axion-like particles into photons in the detector



Axions can couple to photons via the interaction term $\mathcal{L}_{\text{int}} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$

This modifies Maxwell's equations

$$\nabla \cdot \vec{E} = \rho - g_{a\gamma}\, \vec{B} \cdot \nabla a$$
$$\nabla \times \vec{B} - \partial_t \vec{E} = \vec{J} + g_{a\gamma}(\vec{B}\partial_t a - \vec{E} \times \nabla a)$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla \times \vec{E} + \partial_t \vec{B} = 0$$

Inside the resonator housing, $d \ll \lambda_a$, and where there is a strong field B_e, the axions source a magnetic field

$$|\vec{B}_a| = \frac{1}{2} r g_{a\gamma} |\vec{B}_0| \sqrt{\rho_a \hbar c}$$

Sikivie et al. PRL **112**, 131301 (2014); Y. Kim et al. Phys. Dark Universe **26**, 100362 (2019).

Future Projection

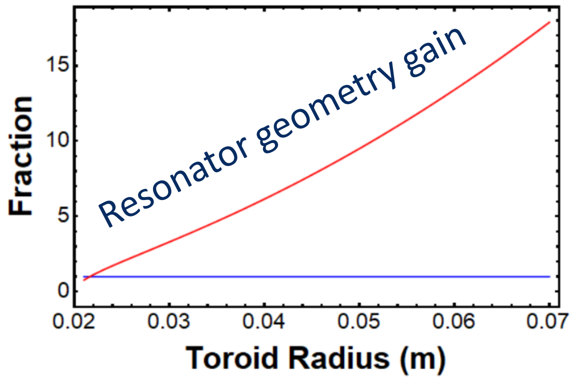
- With a purpose-built experiment we should be able to improve sensitivity considerably

$$\frac{V_a}{V_n} \propto \frac{\pi}{2} g_{a\gamma}\sqrt{\nu_a \rho_a \hbar c_0} * \sqrt{\frac{f(Q)}{4k_B g(T_z)}}\sqrt{(r_2 - r_1)}(r_2 + r_1)^{3/2} B_e$$

Parameter	Current	New	Factor
Temperature	$5.5\,K$	$0.05K - 0.1K$	> 3
Q	$40\,k$	$160\,k$	> 1.4
e_n	$1\,nV/\sqrt{Hz}$	$0.1\,nV/\sqrt{Hz}$	> 3
B_0	$1.8\,T$	$7.0\,T$	3.9
Geometry	**1**	**16**	**16**
Peak Sens.	1		> 260

Bandwidth-gain currently under development (F. Voelksen)

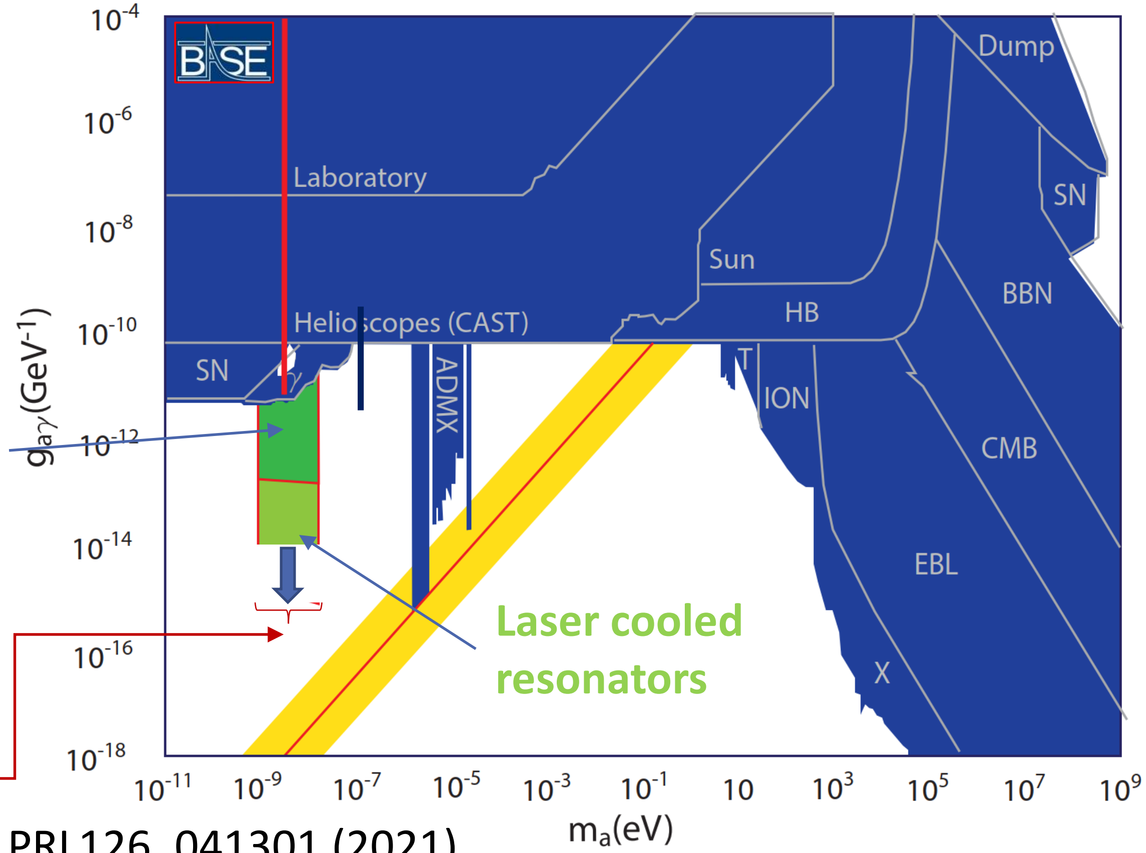
Recent lab result: 600 kHz tunability achieved (x 3000)



Technology available in BASE

No specific relation to antimatter

Sensitivity comparable to ADMX / ADMX SLIC



Laser cooled resonators

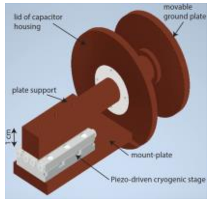
Devlin et al, PRL126, 041301 (2021)

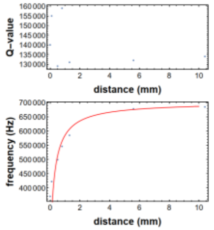
Technologies available to build such an experiment / discussion with IAXO started

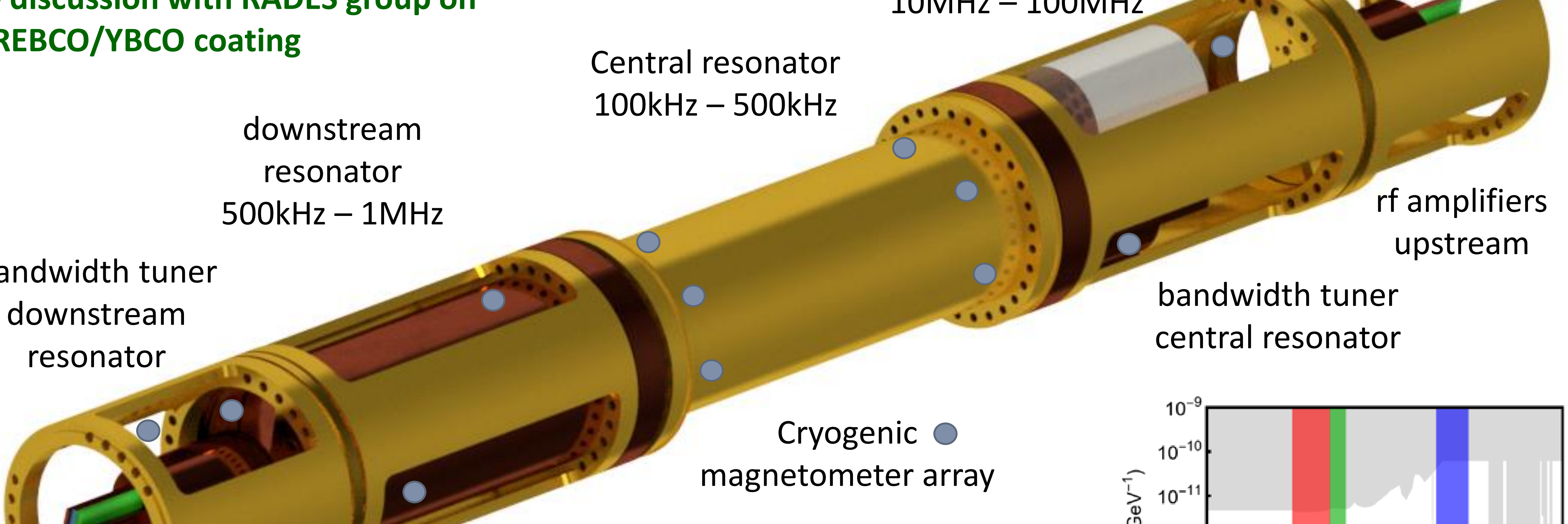
BASE-CDM – Under Development

Under development, Jack Devlin, Barbara Latacz, Stefan Ulmer

Some discussion with RADES group on HTS/REBCO/YBCO coating







bandwidth tuner central resonator

upstream resonator 10MHz – 100MHz

Central resonator 100kHz – 500kHz

downstream resonator 500kHz – 1MHz

bandwidth tuner downstream resonator

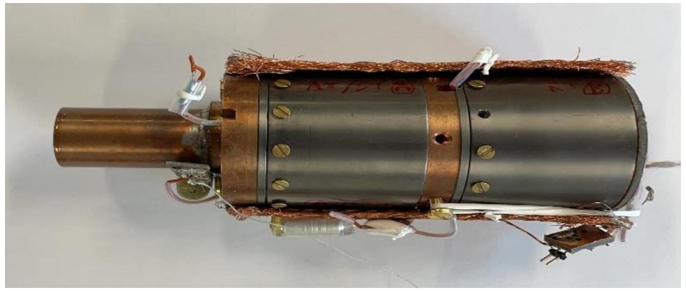
rf amplifiers upstream

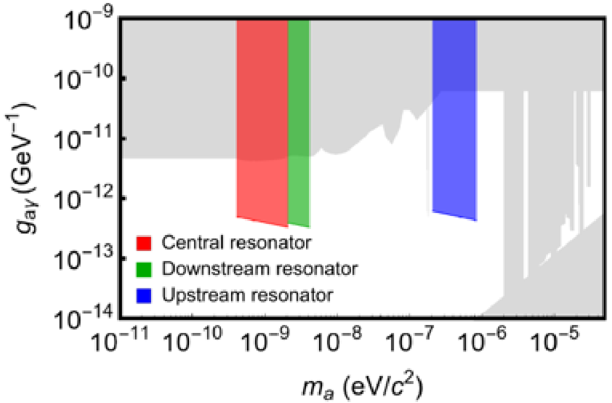
bandwidth tuner central resonator

Cryogenic ● magnetometer array

Tuning bank

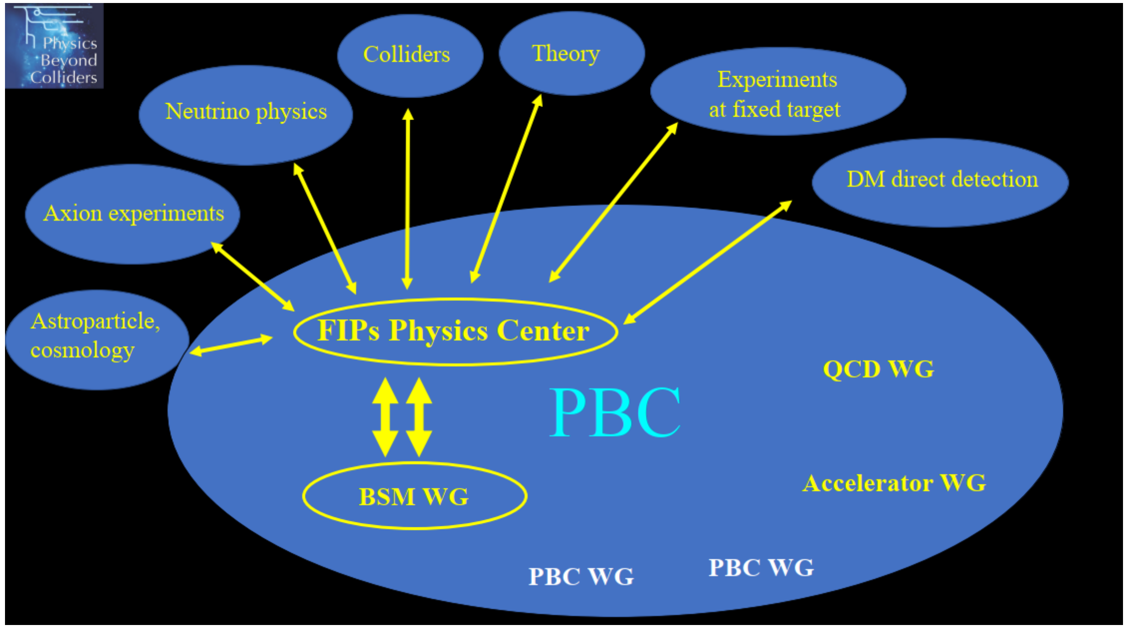
rf amplifiers downstream





Summary

- The physics community at the antiproton decelerator of CERN uses methods of **low energy / high precision atomic physics and quantum spectroscopy** to study simple antimatter systems with ultra high resolution, sensitive to signals imposed by exotic physics.
- A lot of creative potential and (quantum) expertise is available in this community at CERN.
- Tremendous progress produced in recent years.
- Bright future perspective for considerably improved precision measurements, **thanks to the very strong support of CERN**



matter sector 2016

proton lifetime (direct)	>1.67 e34 y
proton m	90 p.p.t.
proton magn. moment	3.3 p.p.b.
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2016

antiproton lifetime	>1.2 y
antiproton m	120 p.p.t.
antiproton m. moment	4.4 p.p.m.
antihydrogen 1S/2S	?
antihydrogen GSHFS	?

matter sector 2021

proton lifetime (direct)	>1.67 e34 y
proton m	**30 p.p.t.**
proton magn. moment	**0.3 p.p.b.**
hydrogen 1S/2S	0.004 p.p.t.
hydrogen GSHFS	0.7 p.p.t.

antimatter sector 2021

antiproton lifetime	**>30 y**
antiproton m	**30 p.p.t.**
antiproton m. moment	**1.5 p.p.b.**
antihydrogen 1S/2S	**2 p.p.t.**
antihydrogen GSHFS	**400 p.p.m.**

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ALPHA
BASE
GBAR
STEp

Thanks very much for your attention

THE ALPHA COLLABORATION

Aarhus University, Denmark

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

Imperial College London

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, West Lafayette, USA

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

ATRAP Collaboration

G. Gabrielse[1], C. Hamley, N. Jones, G. Khatri
K. Marable, M. Marshall, C. Meisenhelder, T. Morrison, E. Tardiff
Department of Physics, Harvard University, Cambridge, MA 02138 USA

D. Fitzakerley, M. George, E. Hessels, T. Skinner, C. Storry, M. Weel
Department of Physics and Astronomy, York University,
Toronto, Ontario, M3J 1P3, Canada

new

S.A. Lee, C. Rasor, S.R. Ronald, D. Yost
Department of Physics, Colorado State University, Fort Collins, CI 80526 USA

W. Oelert, D. Grzonka, T. Sefzick
Institut für Kernphysik, Forschungszentrum Jülich, Germany

B. Glowacz, M. Zielinski
Institute of Physics, Jagiellonian University, Kraków, Poland

visitor

E. Myers
Physics Department, Florida State University, Tallahassee, FL 32306

AEḡIS collaboration

IPNL, Lyon

Stefan Meyer Institut, Austria

University Bern, Switzerland

CERN, Switzerland

INFN Genova, Italy

MPI-K, Heidelberg, Germany

U of Heidelberg, Germany

INFN Milano, Italy

Politecnico di Milano, Italy

INR, Moscow, Russia

U of Bergen, Norway

University College London, UK

Laboratoire Aimé Cotton, Orsay, France

U of Oslo, Norway

INFN Pavia/Brescia, Italy

Czech Technical U, Prague, Czech Republic

INFN Padova/Trento, Italy

ETH Zurich, Switzerland

K. Blaum, Y. Matsuda,
C. Ospelkaus, W. Quint,
J. Walz, Y. Yamazaki

60 Research Institutes/Universities – 339 Researchers – 6 Collaborations

Quantum Logic Spectroscopy

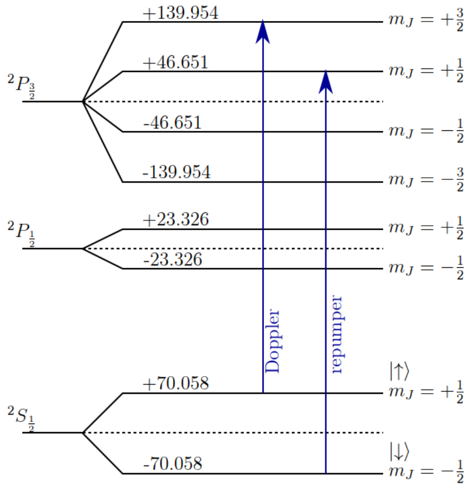
Initial state of coulomb coupled particles in a Paul-trap which share a phonon mode

$$|\psi\rangle_0 = |\downarrow\rangle_S |\downarrow\rangle_L |0\rangle_m$$

Laser pulse which excites the spectroscopy particle

$$|\psi\rangle_1 = (\alpha|\downarrow\rangle_S + \beta|\uparrow\rangle_S)\,|\downarrow\rangle_L |0\rangle_m$$

$$|\psi\rangle_1 = (\alpha|\downarrow\rangle_S|0\rangle_m + \beta|\uparrow\rangle_S|0\rangle_m)\,|\downarrow\rangle_L$$



(b)

The important quantum-logic pulse

Red sideband which deexcites the spectrosopy particle and puts one motional quantum in the phonon mode.

$$|\psi\rangle_2 = (\alpha|\downarrow\rangle_S|0\rangle_m + \beta|\downarrow\rangle_S|1\rangle_m)\,|\downarrow\rangle_L$$

Translates the internal excited state to a coupled phonon state

Red sideband pulse, which removes the phonon and excites the logic ion

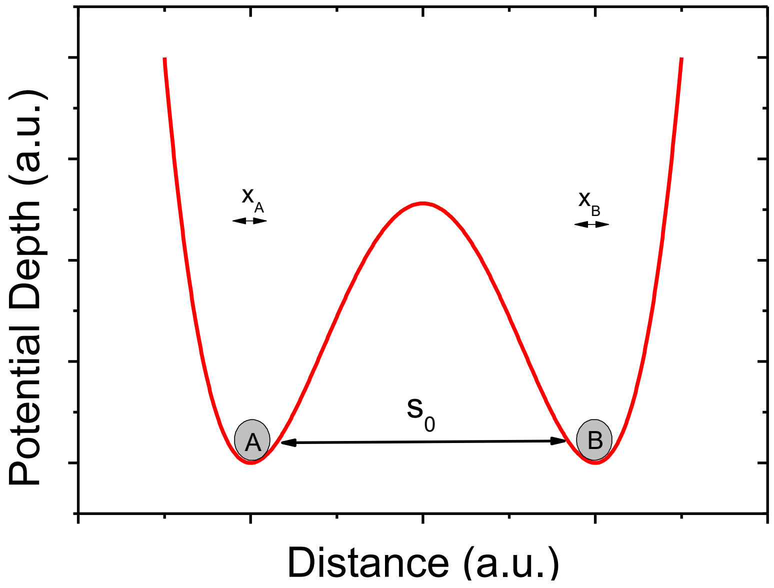
$$|\psi\rangle_{final} = |\downarrow\rangle_S(\alpha|\downarrow\rangle_L + \beta|\uparrow\rangle_L)|0\rangle_m$$

This algorithm translates the properties of the narrow transition of a spectroscopy ion onto the properties of the easily controlable logic ion.

Meanwhile routinely applied in NIST $^1S_0 \rightarrow {}^3P_0$ of $27Al^+$ clock, which reaches precision better 10^{-18}.

Sympathetic Cooling of Antiprotons

Two charged particles trapped in direct vicinity interact via coulomb interaction.



$$U(x_a,x_b) = \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0 - x_a + x_b}$$

$$\approx \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0}\left(1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2} - \frac{2x_a x_b}{s_0^2}\right)$$

Static

Dynamic

$$\frac{-q_a q_b}{2\pi\varepsilon_0 s_0^3}(x'_a x'_b) = -\hbar\Omega_{\mathrm{ex}}(a+a^\dagger)(b+b^\dagger) \approx -\hbar\Omega_{\mathrm{ex}}(ab^\dagger + a^\dagger b) \longrightarrow \Omega_{\mathrm{ex}} \equiv \frac{q_a q_b}{4\pi\varepsilon_0 s_0^3\sqrt{m_a m_b}\sqrt{\omega_{0a}\omega_{0b}}}$$

Resonant Coupling:

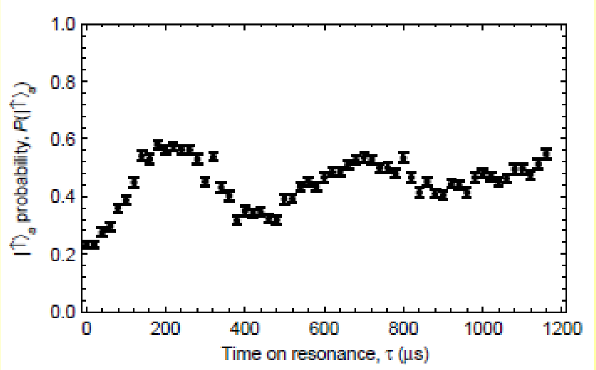
$$a^\dagger(t) = \exp(i\omega_0 t)(a^\dagger(0)\cos(\Omega_{\mathrm{ex}}t) - ib^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

$$b^\dagger(t) = \exp(i\omega_0 t)(b^\dagger(0)\cos(\Omega_{\mathrm{ex}}t) - ia^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

Effective Energy Exchange

Phonon Exchange

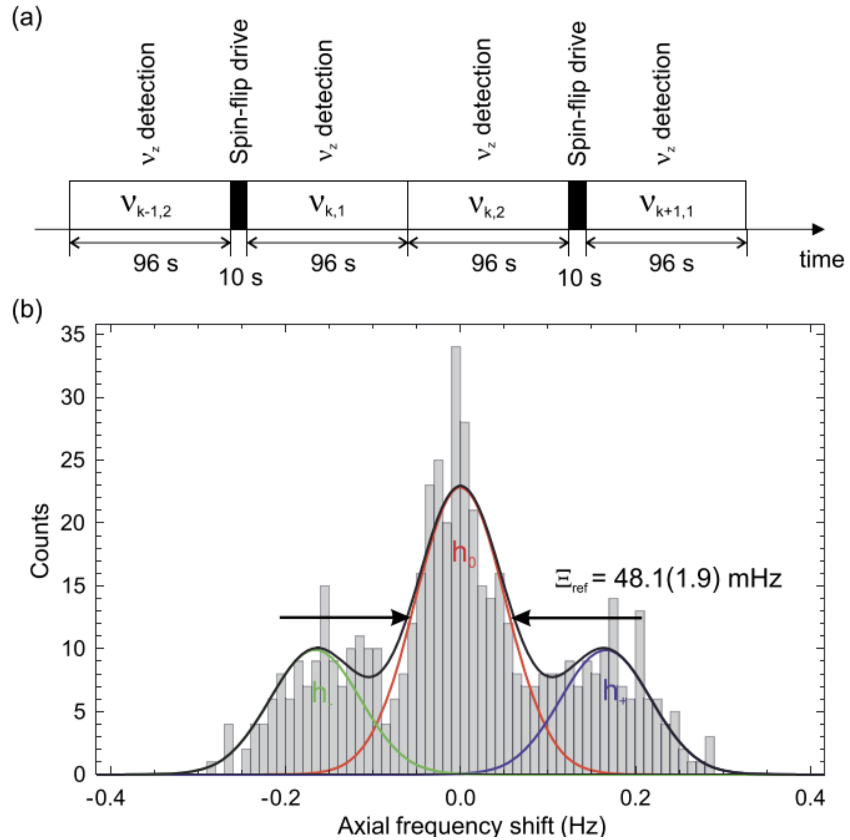
Successfully demonstrated in Paul trap with Be ions

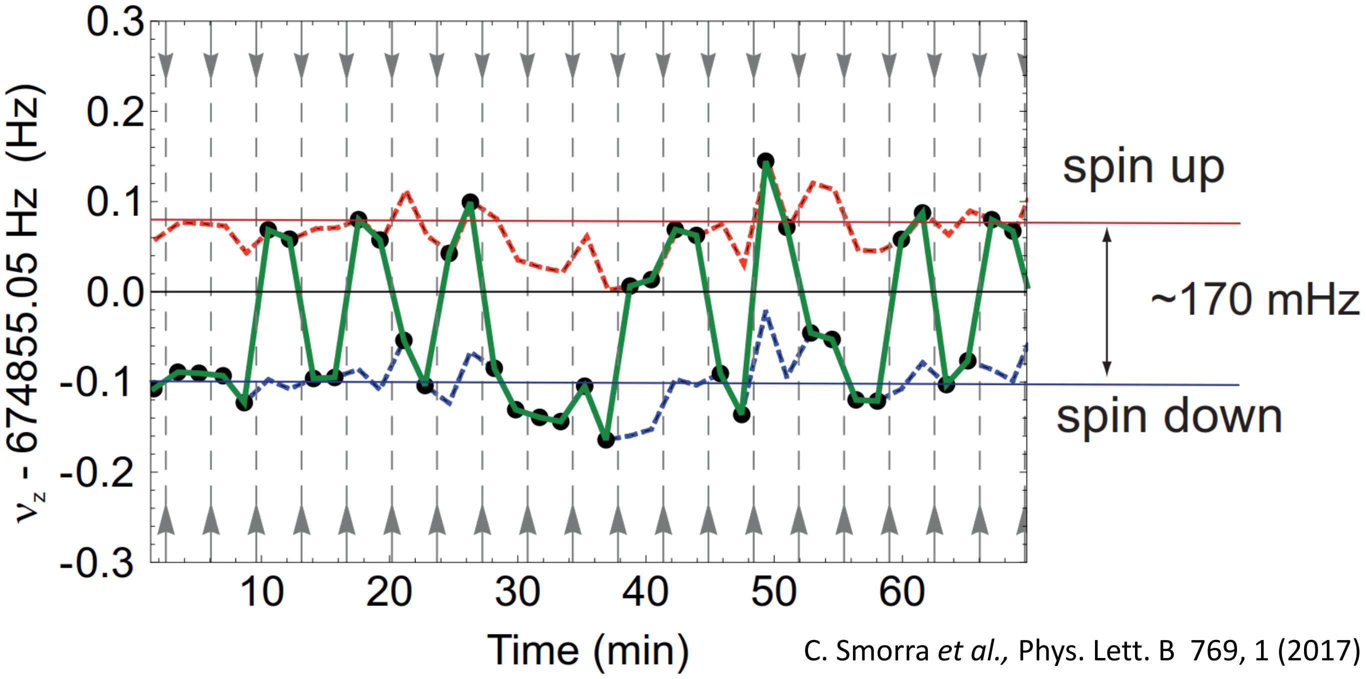


Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

Quantum Spectroscopy at CERN





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

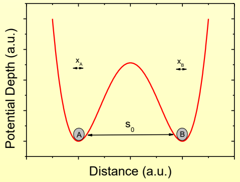
- First non-destructive observation of single-antiproton spin-quantum transitions.
- **Double trap method ultimately requires single spin-flip resolution with high fidelity.**

Future – Sympathetic Cooling of Antiprotons

- Current antiproton magnetic moment measurements are limited by particle preparation time and particle mode temperature
- Expect: With traditional methods another 50-fold improvement is possible, **afterwards: limit of traditional methods will be reached!**

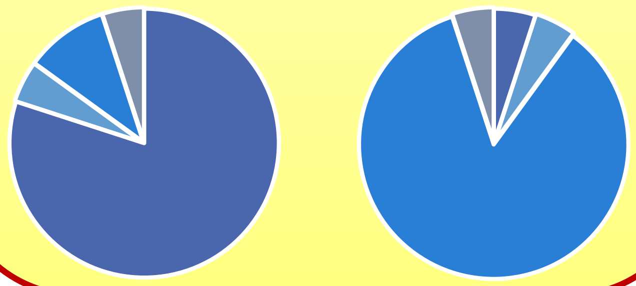
New Method

Couple protons/antiprotons sympathetically to laser cooled ^{9}Be$^+$ ions and imprint Doppler temperatures to the antiproton



Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

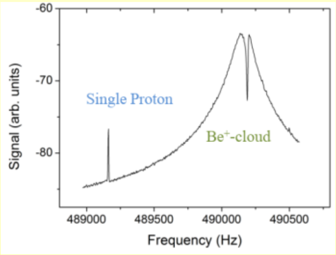
Was demonstrated for ^{9}Be$^+$ ions in Paul traps – implement same in Penning traps


Current Time Budget

Laser Time Budget

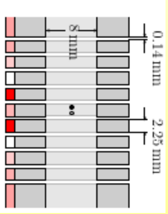
Effort at University of Mainz

5 trap design implemented and simultaneous detection of ^{9}Be$^+$ ion and proton in common endcap trap was demonstrated.

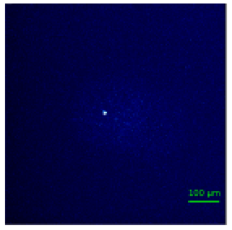


C. Smorra, M. Bohman, M. Wiesinger, C. Will, et al.

Effort at University of Hannover and PTB

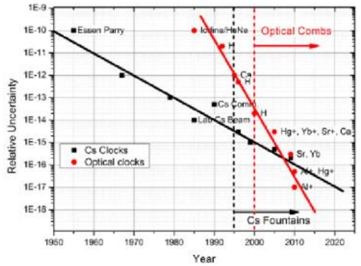


Recent dramatic progress:
Detection of a single laser cooled ^{9}Be$^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN



J. M. Cornejo, M. Niemann, T. Meiners, J. Mielke **C. Ospelkaus** et al.

The Vision

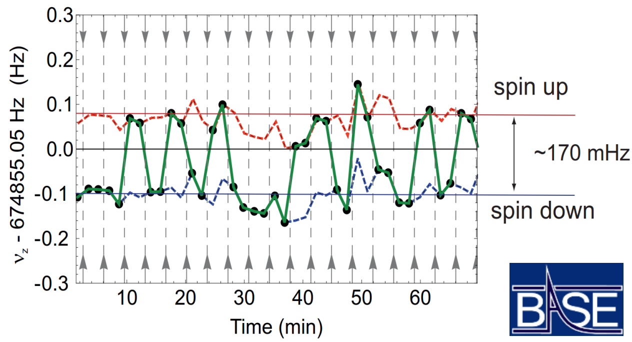


>100-fold improved antiproton cooling time seems to be in reach

Implement hypefine clock for magnet stabilization

Quantum Technologies

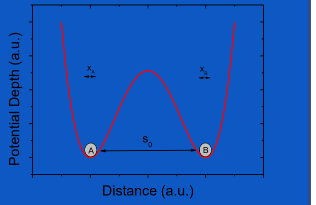
Non-destructive spin transition spectroscopy



Single spin spectroscopy in a Penning trap

Sympathetic Cooling

Quantum logic inspired sympathetic cooling of antiprotons, Hbar +, and positrons to laser-cooled Be+ ions



Improves

- spin detection fidelity
- Anihydrogen yield
- Resolution in test of WEP

Quantum Logic Spectroscopy

Use Wineland Al-clock quantum-logic algorithm to measure antiproton spin

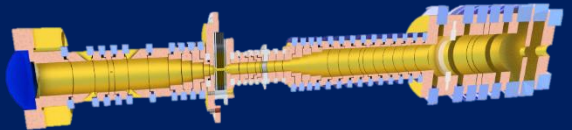
$$|\psi\rangle_0 = |\uparrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L} \qquad |\psi\rangle_0 = |\downarrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L}$$

$$|\psi\rangle_1 = |\uparrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L} \qquad |\psi\rangle_1 = |\uparrow\rangle_p |1\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L}$$

$$|\psi\rangle_2 = |\uparrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L} \qquad |\psi\rangle_2 = |\uparrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |1\rangle_{m,L}$$

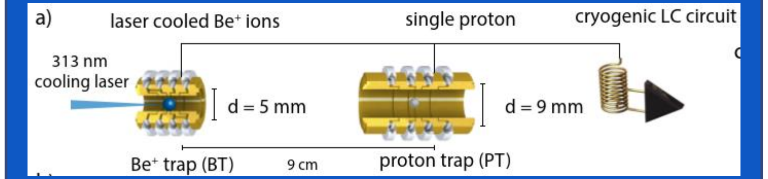
$$|\psi\rangle_3 = |\uparrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L} \qquad |\psi\rangle_3 = |\uparrow\rangle_p |0\rangle_{m,p} |\downarrow\rangle_L |0\rangle_{m,L}$$

$$|\psi\rangle_4 = |\uparrow\rangle_p |0\rangle_{m,p} |\uparrow\rangle_L |0\rangle_{m,L} \qquad |\psi\rangle_4 = |\uparrow\rangle_p |0\rangle_{m,p} |\downarrow\rangle_L |0\rangle_{m,L}$$



Laser Cooled Superconductors

coupled Penning traps with common SC-LC

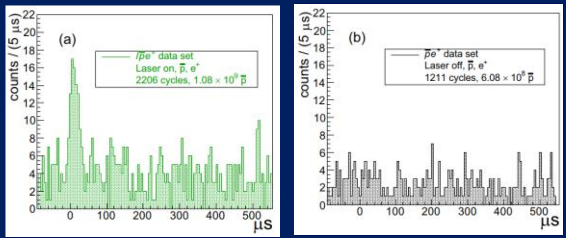


Demonstrated reduction of SC-LC circuit temperature to sub-1K level

Axion detection / precision frequency measurements

Production of Hbar via Charge Exchange with Laser Excited PS

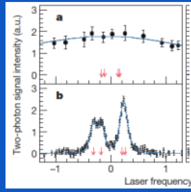
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



Similar methods to be applied for production of Hbar+-ion / H2+bar

More Quantum Methods

Deep UV two photon spectroscopy in antiprotonic helium



Atomic fountain microwave clocks