Physics Beyond Colliders Annual Workshop 2021/03/02

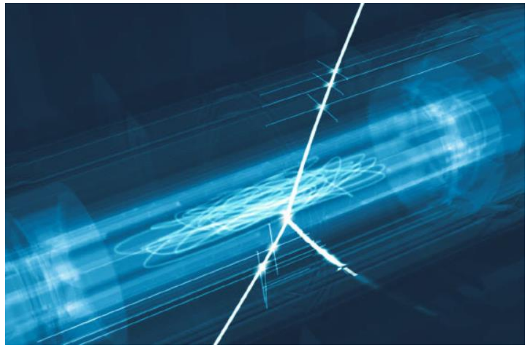
Experiments at the Antiproton Decelerator Facility of CERN

Review on Quantum Technologies applied in and FIP Sensitivity of AD experiments

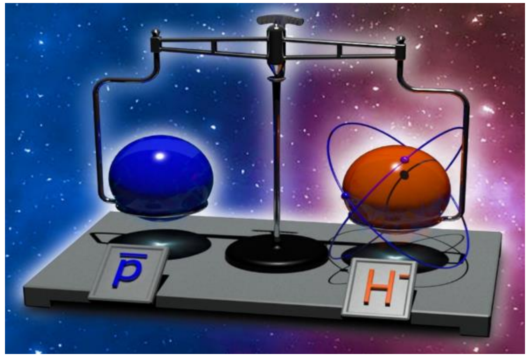
Stefan Ulmer

RIKEN

2021 / 03 / 02



antihydrogen trap



antiproton/proton balance

AEḡIS

ALPHA

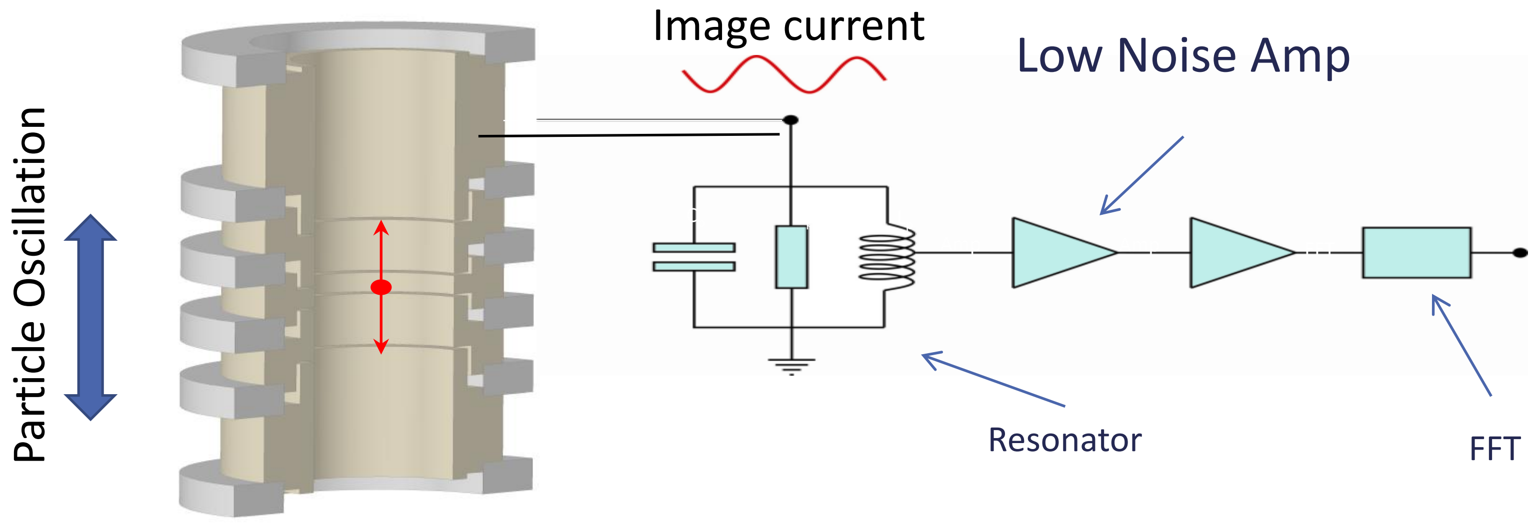
BASE

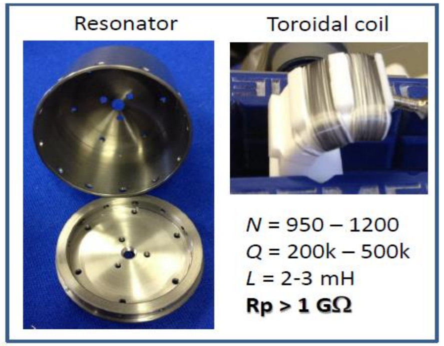
GBAR

STEp̄

The Sound of Antimatter

- Concept of image current detection



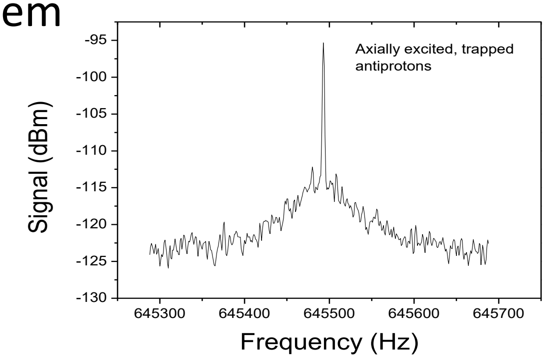


$N = 950 - 1200$
$Q = 200\text{k} - 500\text{k}$
$L = 2\text{-}3\ \text{mH}$
Rp > 1 GΩ

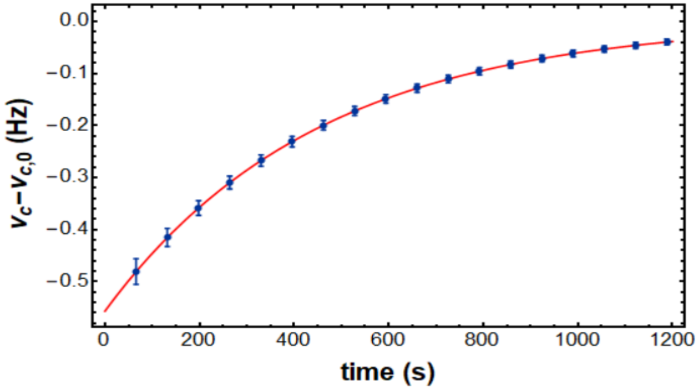
Inductor compensates system capacitance

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

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



- Special Relativity
  - Resistive cooling changes oscillation frequency



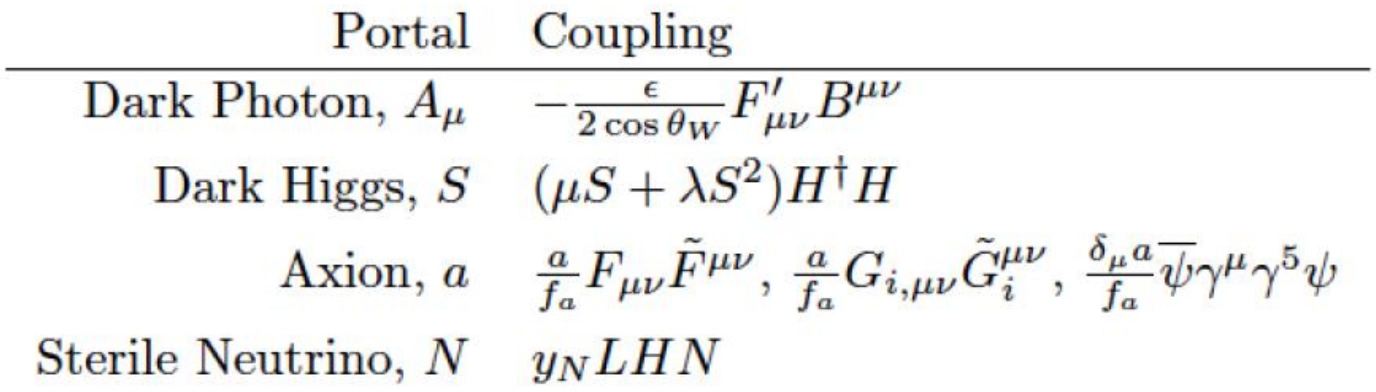
$$\nu_c = \frac{1}{2\pi}\left(\frac{q}{m}\sqrt{1-\left(\frac{v}{c}\right)^2} B_0\right)$$

  - 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**

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**

AEḡIS

ALPHA

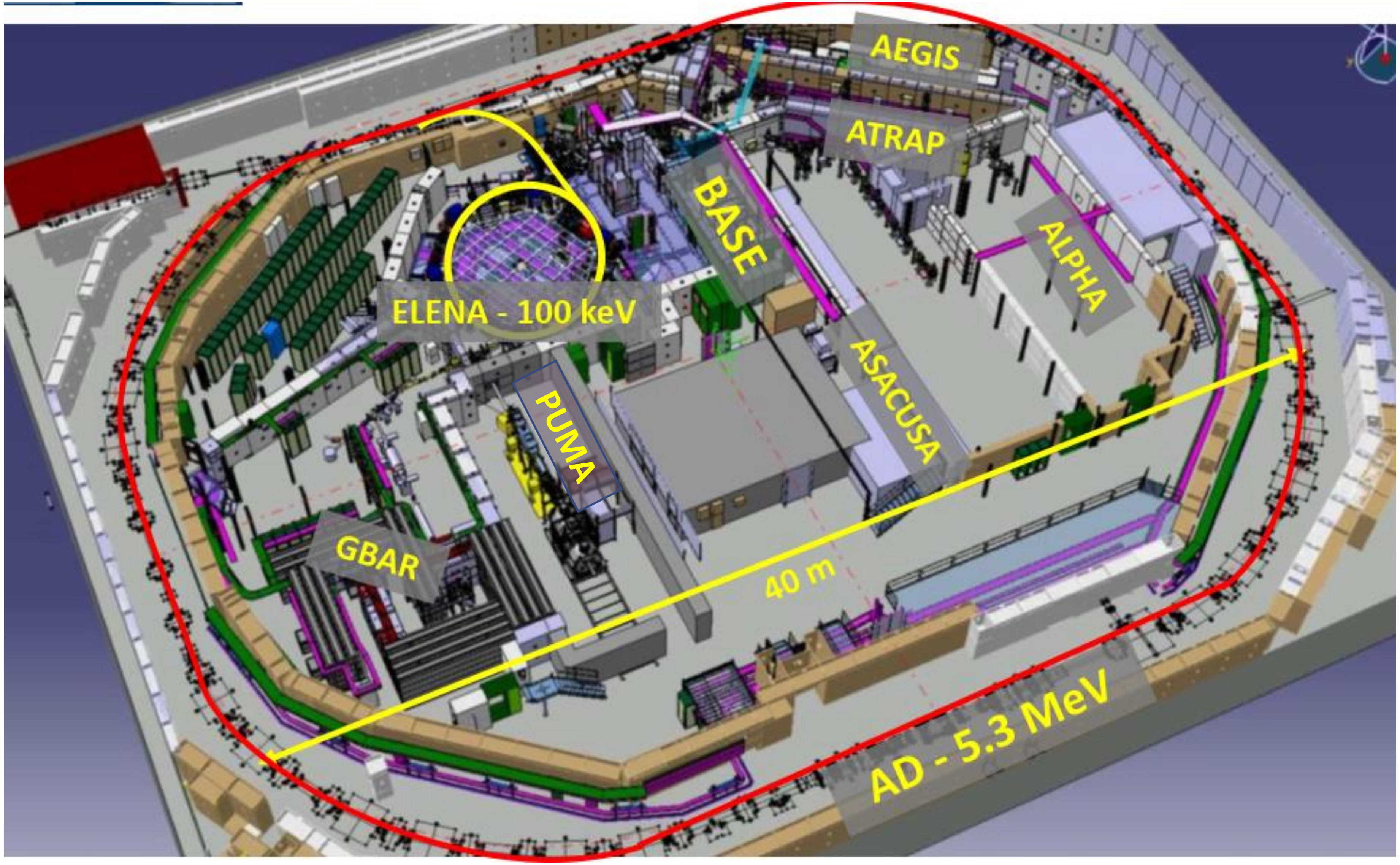
BASE

GBAR

STEp̄

The AD/ELENA-Facility

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



BASE,
Fundamental properties of the antiproton

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/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).

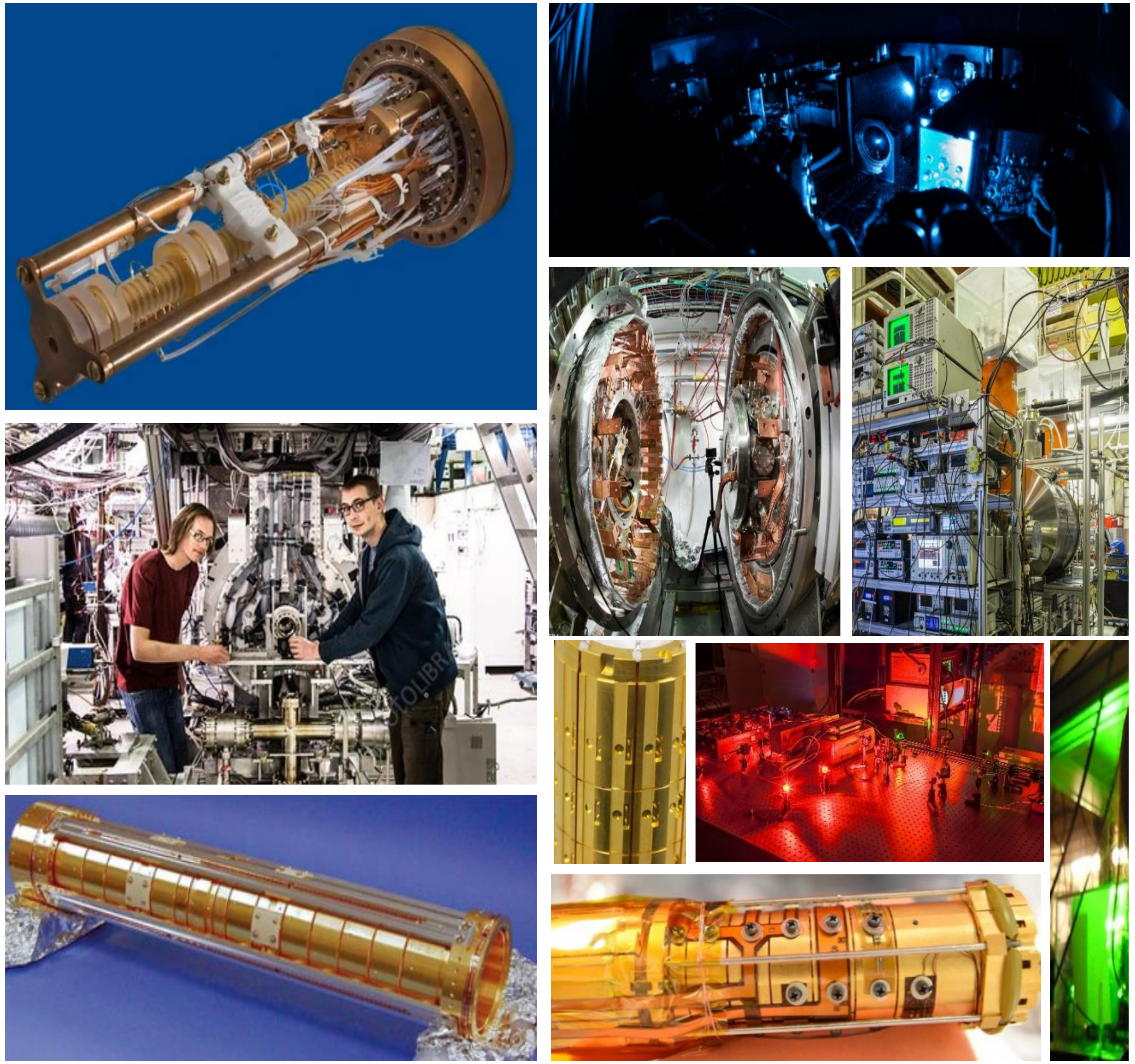
Methods and Achievements

- 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.**

AEḡIS

ALPHA

BASE

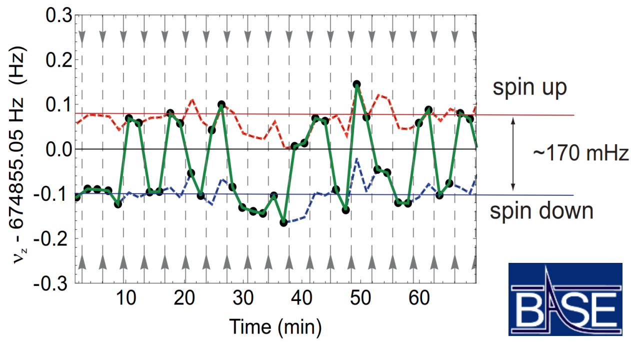
GBAR

STEp̄

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

Quantum Technologies

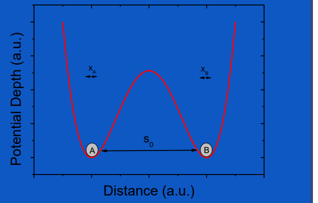
Non-destructive spin transition spectroscopy



Single spin spectroscopy in a Penning trap

Sympathetic Cooling

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



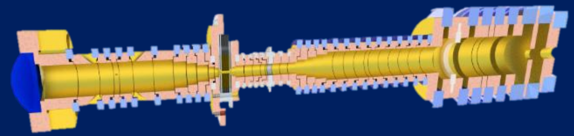
Improves

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

Quantum Logic Spectroscopy

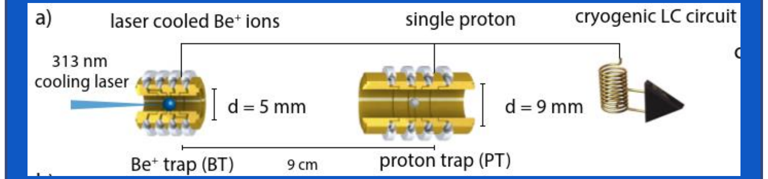
Use Wineland Al-clock quantum-logic algorithm to measure antiproton spin

$$|\psi\rangle_0 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L} \qquad |\psi\rangle_0 = |\downarrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$$
$$|\psi\rangle_1 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L} \qquad |\psi\rangle_1 = |\uparrow\rangle_p|1\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L}$$
$$|\psi\rangle_2 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L} \qquad |\psi\rangle_2 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|1\rangle_{m,L}$$
$$|\psi\rangle_3 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L} \qquad |\psi\rangle_3 = |\uparrow\rangle_p|0\rangle_{m,p}|\downarrow\rangle_L|0\rangle_{m,L}$$
$$|\psi\rangle_4 = |\uparrow\rangle_p|0\rangle_{m,p}|\uparrow\rangle_L|0\rangle_{m,L} \qquad |\psi\rangle_4 = |\uparrow\rangle_p|0\rangle_{m,p}|\downarrow\rangle_L|0\rangle_{m,L}$$



Laser Cooled Superconductors

coupled Penning traps with common SC-LC

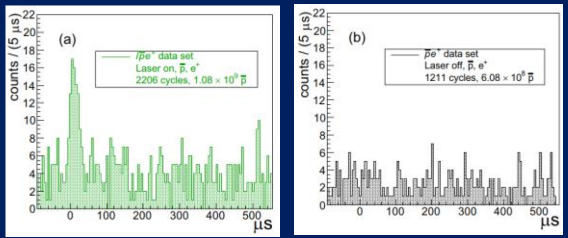


Demonstrated reduction of SC-LC circuit temperature to sub-1K level

Axion detection / precision frequency measurements

Production of Hbar via Charge Exchange with Laser Excited PS

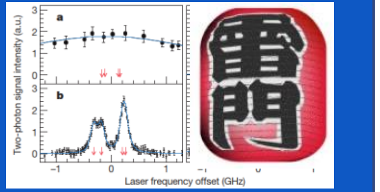
$$Ps^* + \bar{p} \rightarrow \bar{H}^* + e^-$$



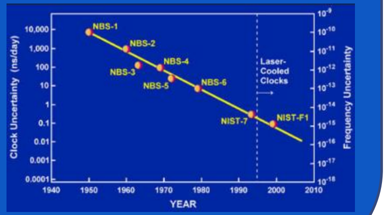
Similar methods to be applied for production of Hbar+-ion / H2+bar

More Quantum Methods

Deep UV two photon spectroscopy in antiprotonic helium

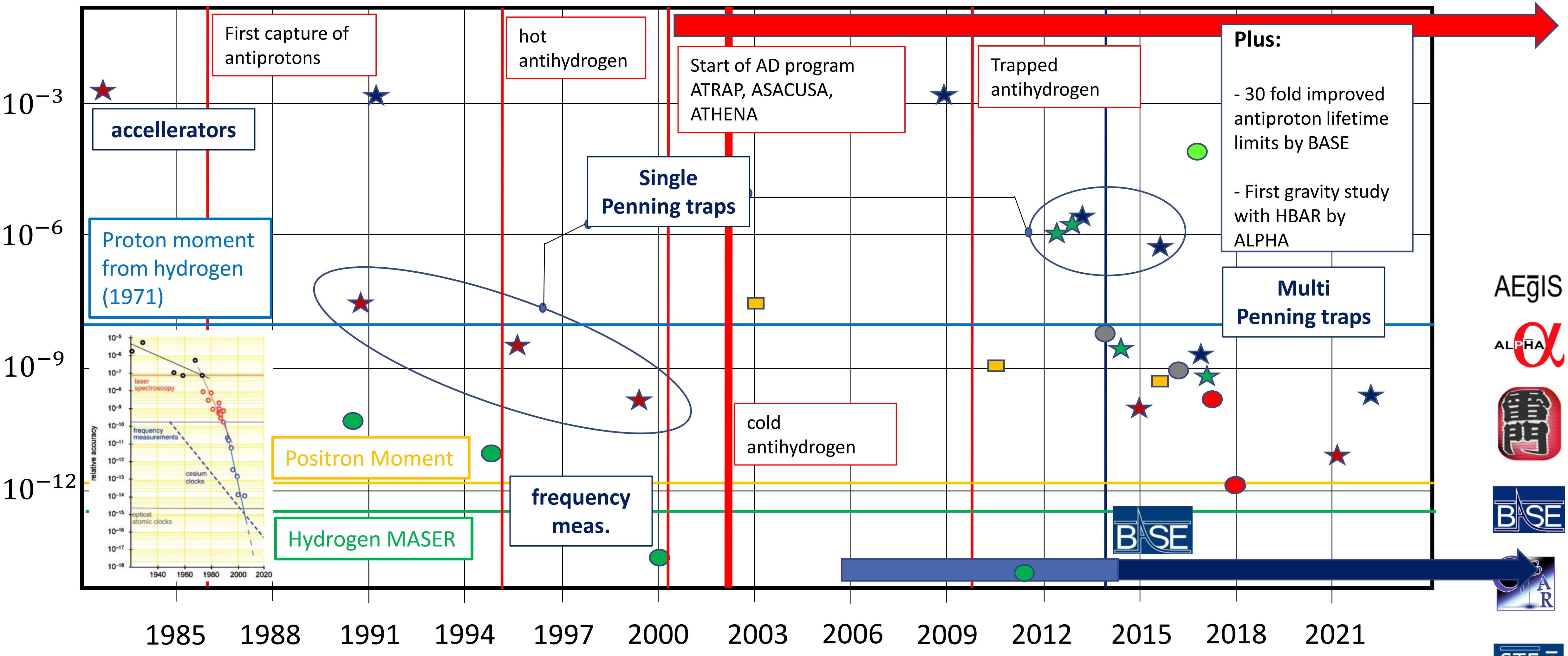


Atomic fountain microwave clocks



Historical Milestones

- 🟢 Hydrogen 1S2S
- 🔴 HBAR 1S2S
- ★ Proton moment
- ★ PBAR moment
- ★ Proton/PBAR mass



First capture of antiprotons

hot antihydrogen

Start of AD program ATRAP, ASACUSA, ATHENA

Trapped antihydrogen

Plus:

- 30 fold improved antiproton lifetime limits by BASE
- First gravity study with HBAR by ALPHA

accellerators

Single Penning traps

Multi Penning traps

Proton moment from hydrogen (1971)

Positron Moment

Hydrogen MASER

frequency meas.

cold antihydrogen

AEḡIS

ALPHA

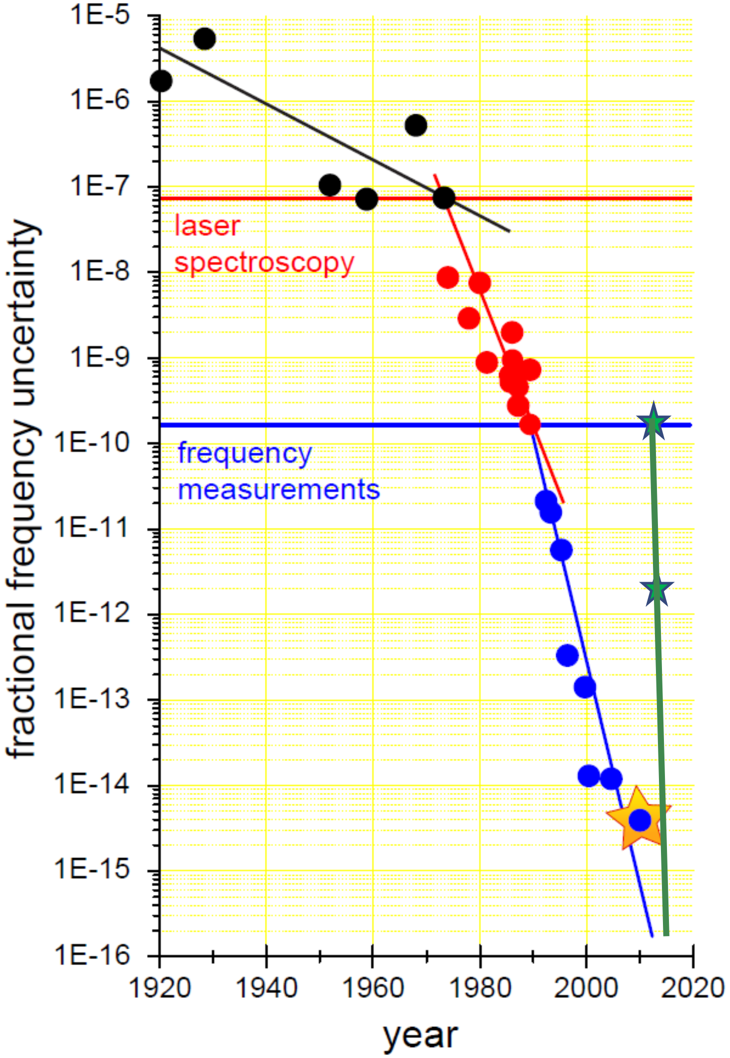
BASE

STEP p̄

- 🟢 HBAR GSHFS
- ⚫ HBAR GSHFS
- 🟨 PBAR/He

Precision Measurements – Some Highlights

- Antihydrogen Spectroscopy



Hydrogen
Hänsch Plot

Antihydrogen
Hangst Plot

- Magnetic Moment Measurements

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)

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

Antiproton to electron mass ratio

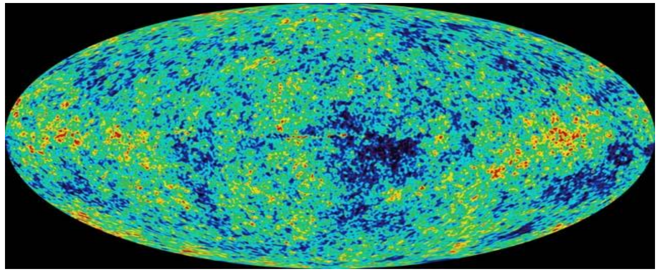
Production of antihydrogen in AEgIS

Production of an antihydrogen beam

AEḡIS
ALPHA
BASE
GBAR
STEp̄

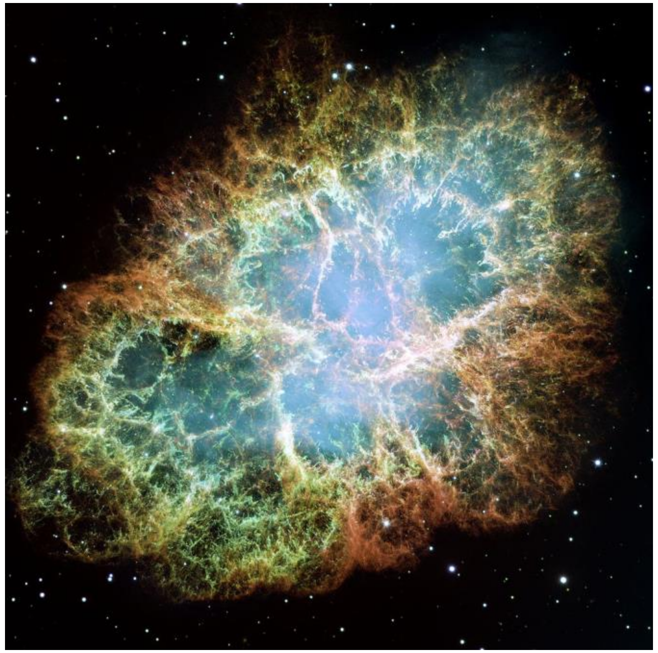
Matter / Antimatter Asymmetry

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)

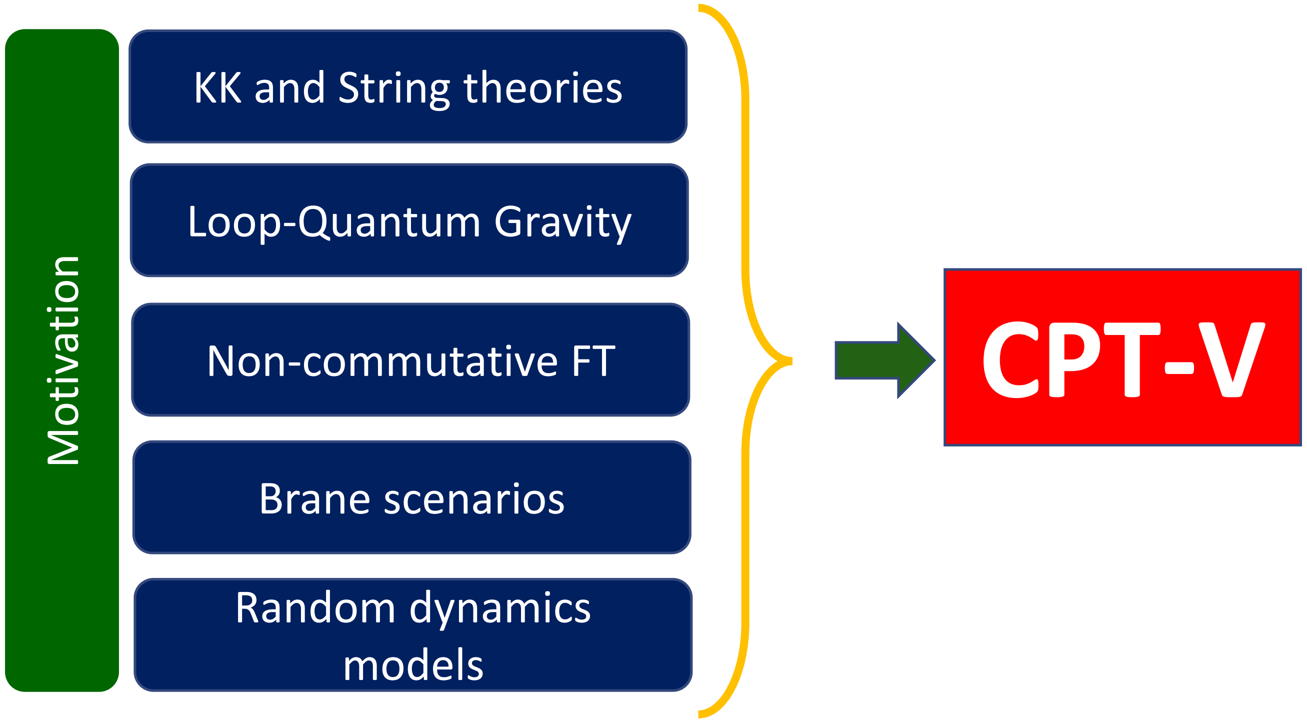
2.) CP-violation (observed / too small)

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

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

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

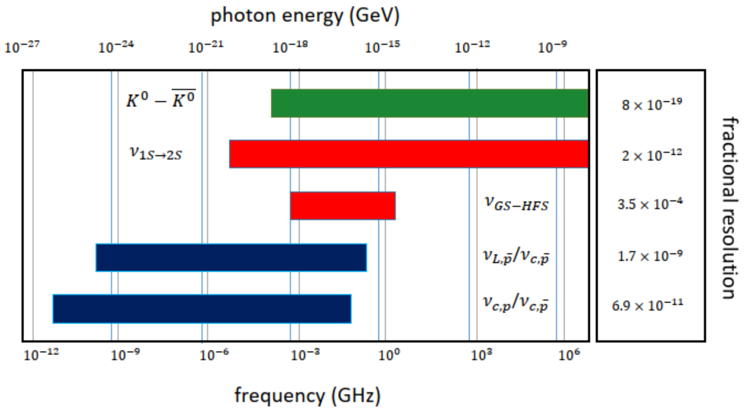
Lorentz bilinear

- 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.

$$\boxed{\mathcal{L} = ?}$$

- 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

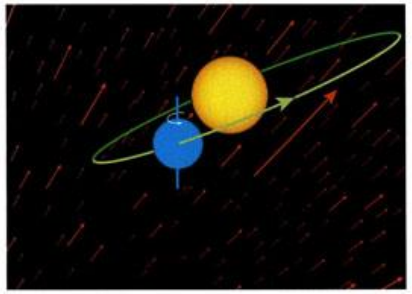
- Test the Standard Model (CPT invariance) by comparing the fundamental properties of protons and antiprotons with high precision

$$\left(\boxed{i\gamma^{\mu}D_{\mu} - m} - \boxed{a_{\mu}\gamma^{\mu} - b_{\mu}\gamma_{5}\gamma^{\mu}}\right)\psi = 0$$

Dirac equation CPT-odd modifications

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

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



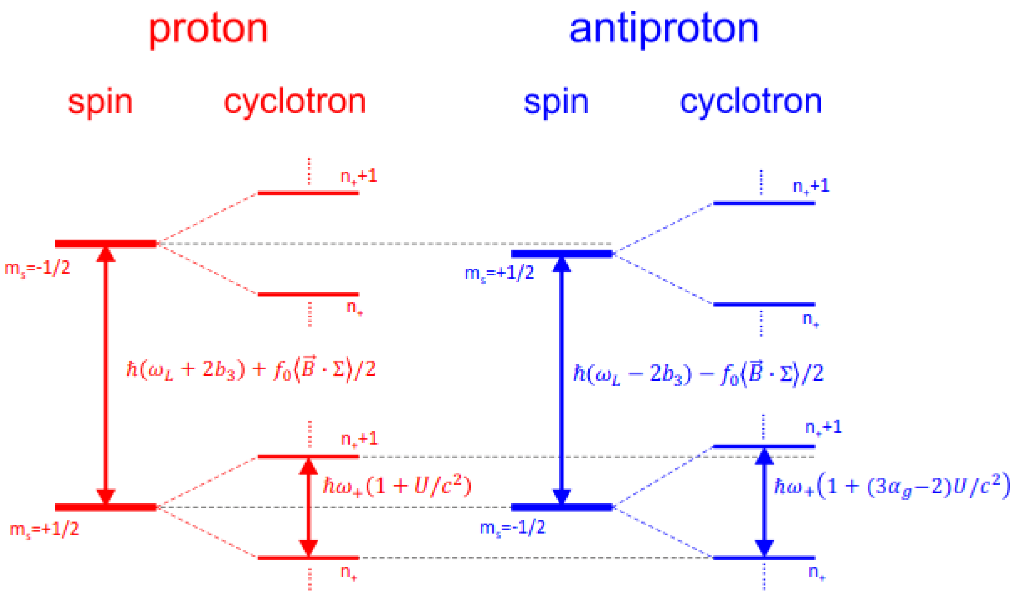
$$b_{\mu}\gamma_{5}\gamma^{\mu} \rightarrow b_x\begin{pmatrix}-\boldsymbol{\sigma_x} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_x}\end{pmatrix} + b_y\begin{pmatrix}-\boldsymbol{\sigma_y} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_y}\end{pmatrix} + b_z\begin{pmatrix}-\boldsymbol{\sigma_z} & \boldsymbol{0}\\ \boldsymbol{0} & \boldsymbol{\sigma_z}\end{pmatrix}$$

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

$$\Delta V_{int} = \tilde{b}_{z,D}\begin{pmatrix}\boldsymbol{0} & \boldsymbol{0}\\ \boldsymbol{0} & \pm\boldsymbol{\sigma_z}\end{pmatrix}$$

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

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

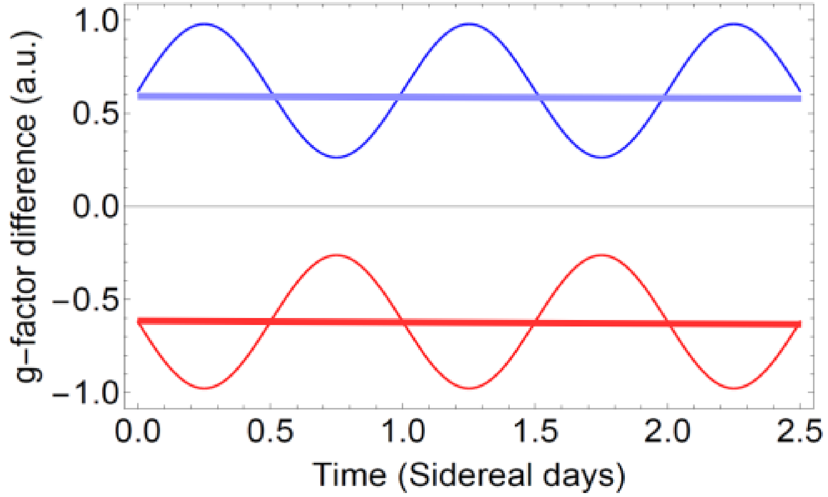


sensitive: comparisons of particle/antiparticle magnetic moments in traps

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

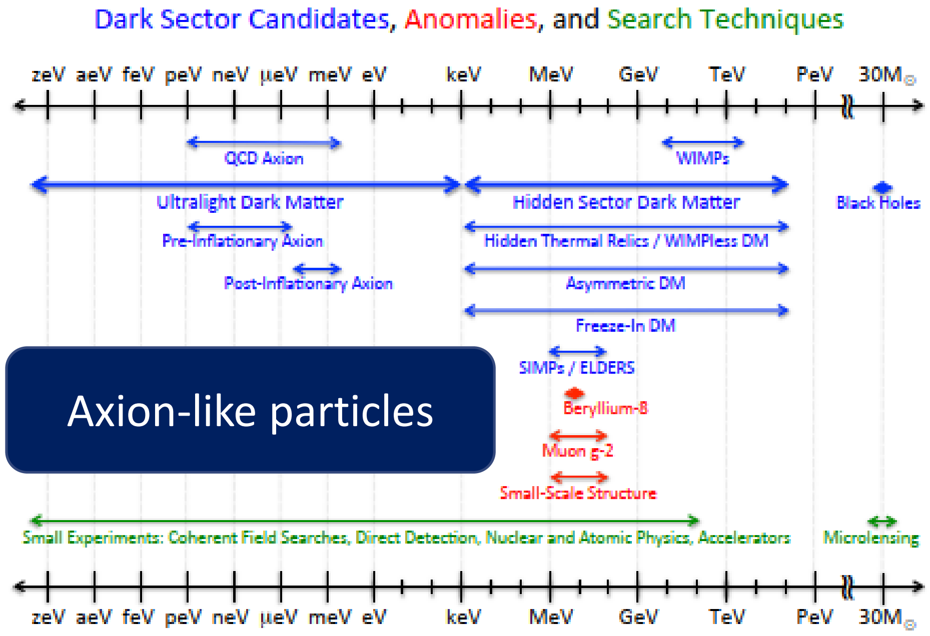
Spontaneous breaking of any continuous symmetry leads to the existence of (almost) massless NG-bosons

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

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

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

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


Dark Sector Candidates, Anomalies, and Search Techniques

Axion-like particles

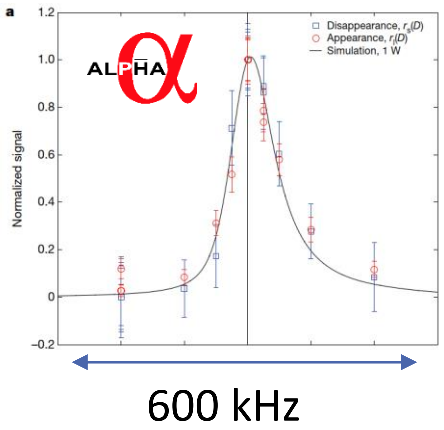
Possible Signatures

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

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

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

(Anti-)Atomic Transition Frequencies

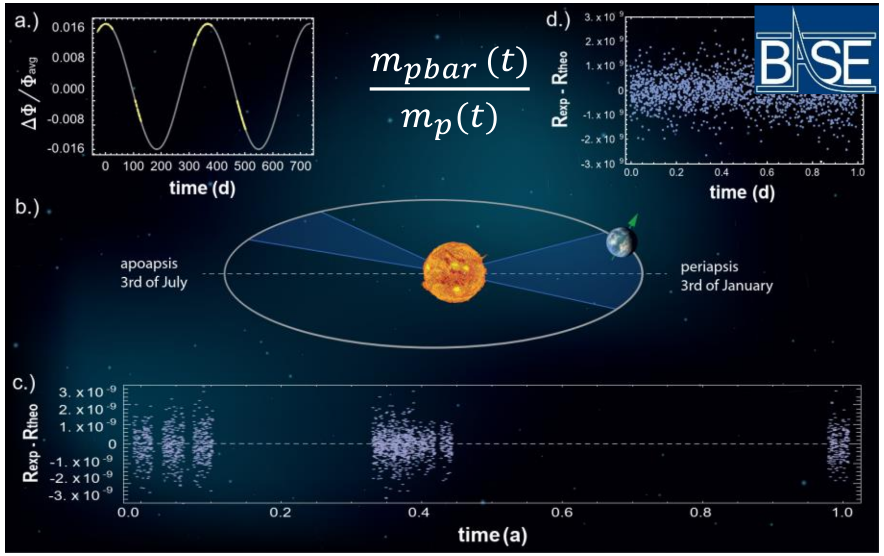


$$\frac{\delta(\nu_{atom} - \nu_{Laser})}{\nu_{atom}} = \left(2\,g_\gamma + \frac{g_e}{m_{e,0}}\right)\left(\frac{\sqrt{2\rho_{DM}}}{m_\phi}\right) \text{ for } \nu < \nu_{c,r}$$

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

These type of studies are possible within ALPHA and ASACUSA

Antypas et al., arXiv:2012.01519



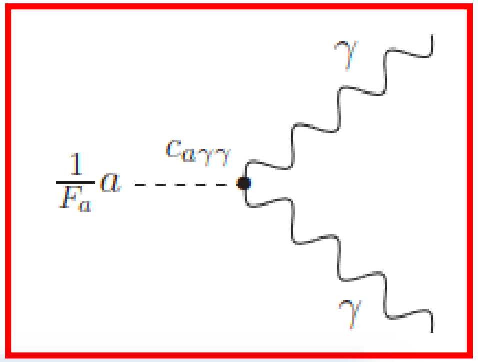
$$\frac{m_{pbar}(t)}{m_p(t)}$$

Axion Wind Model

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

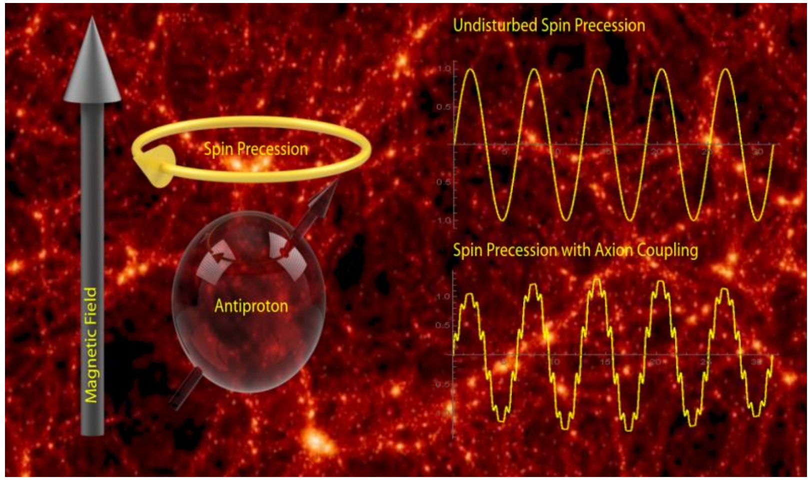
J. Kim, G. Carosi, https://arxiv.org/pdf/0807.3125.pdf

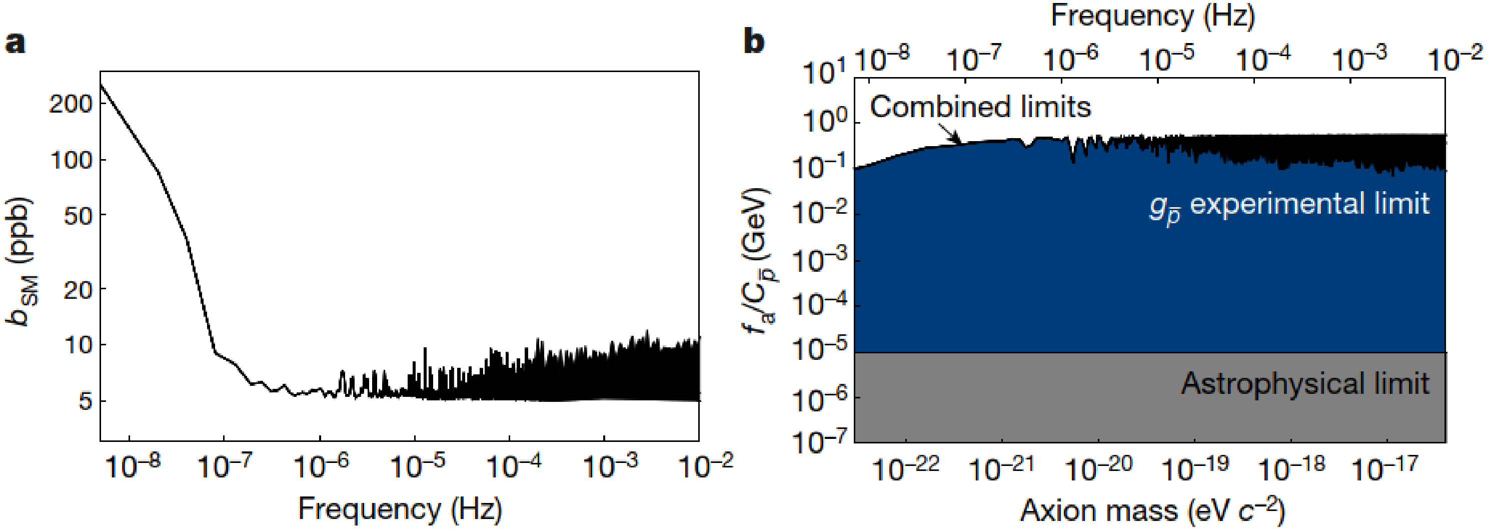
$$\begin{aligned}\mathcal{L}_\theta = {}& \frac{1}{2} f_S^2 \partial^\mu\theta\partial_\mu\theta - \frac{1}{4g_c^2} G^a_{\mu\nu} G^{a\,\mu\nu} + (\bar{q}_L i\not{D} q_L + \bar{q}_R i\not{D} q_R) \\ & + c_1 (\partial_\mu\theta)\bar{q}\gamma^\mu\gamma_5 q - \left(\bar{q}_L\ m\ q_R e^{ic_2\theta} + \text{h.c.}\right)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



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

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





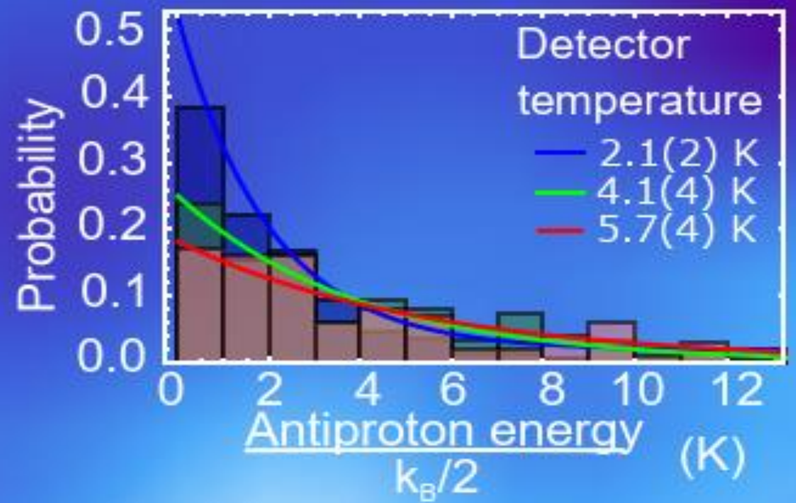
Improves previous antiproton/axion limits by 5 orders of magnitude

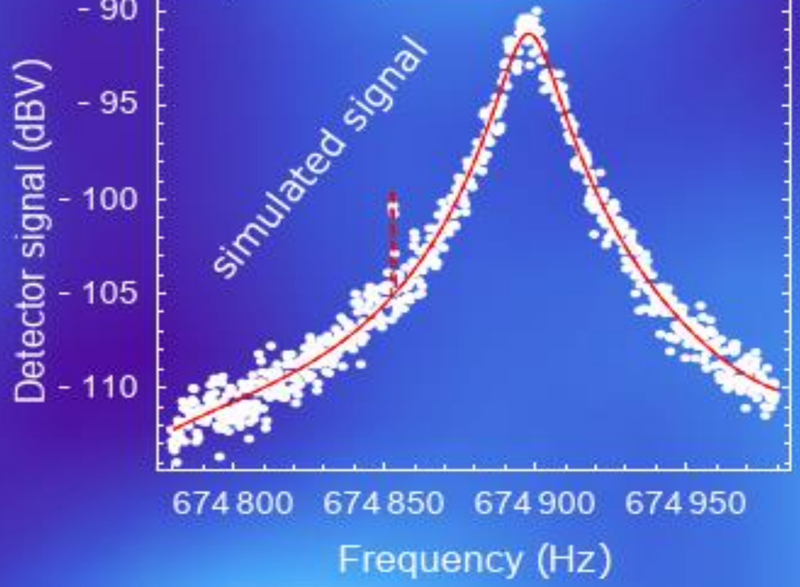
By 4 o.o.m. less stringent than current best matter limits

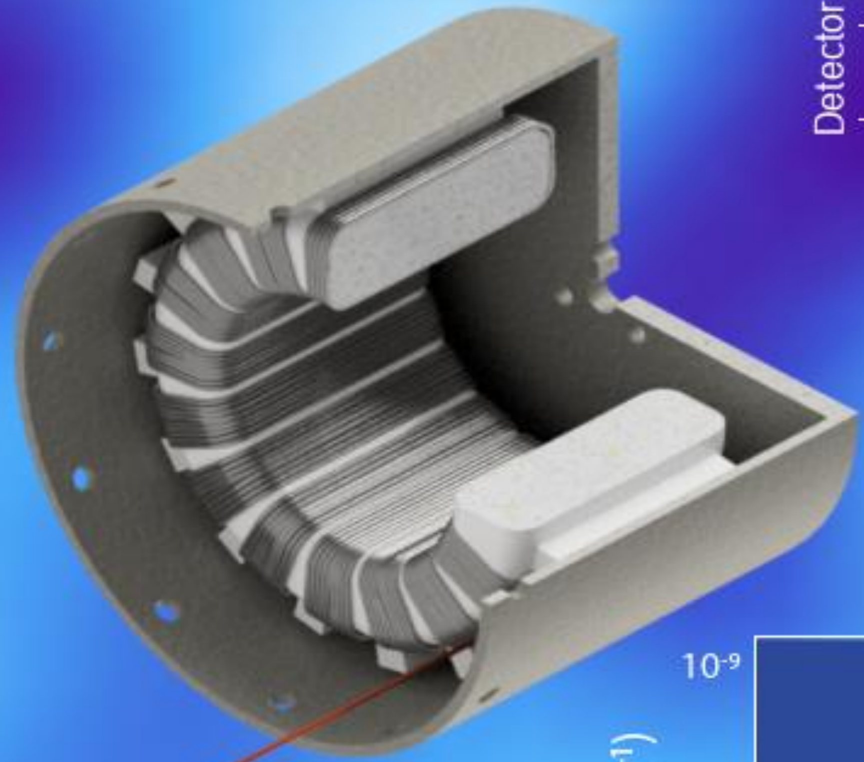
C. Smorra, Y. Stadnik, Nature **(575)**, 310 (2019)

BASE CDM

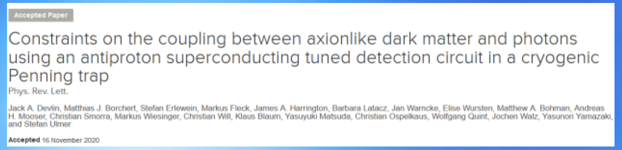
AXION SEARCH







calibrated with a trapped antiproton



Accepted Paper

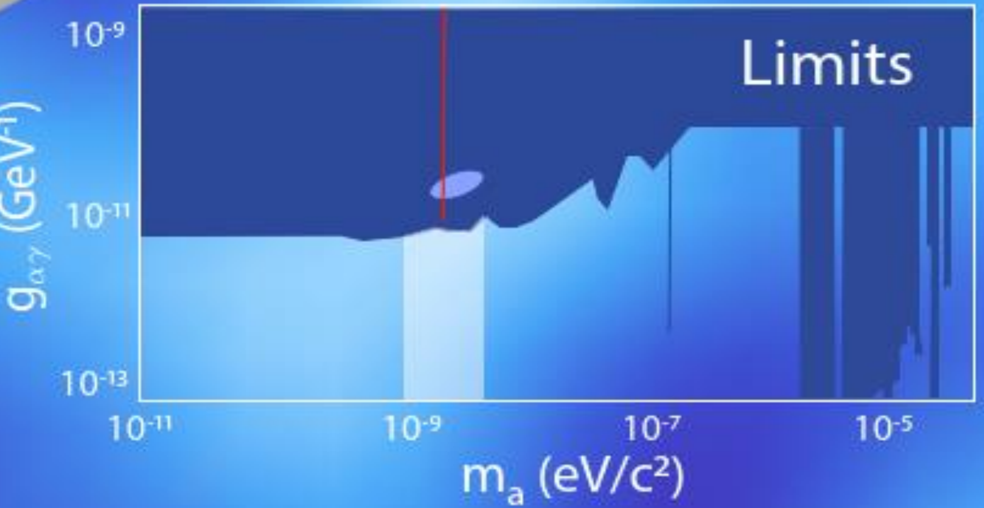
Constraints on the coupling between axionlike dark matter and photons using an antiproton superconducting tuned detection circuit in a cryogenic Penning trap

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



Future Projection

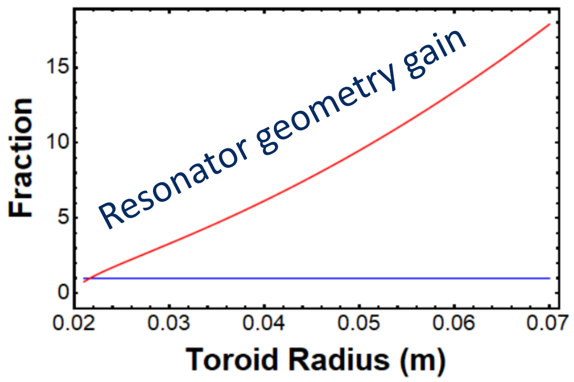
- With a purpose-built experiment we should be able to improve sensitivity considerably

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

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)

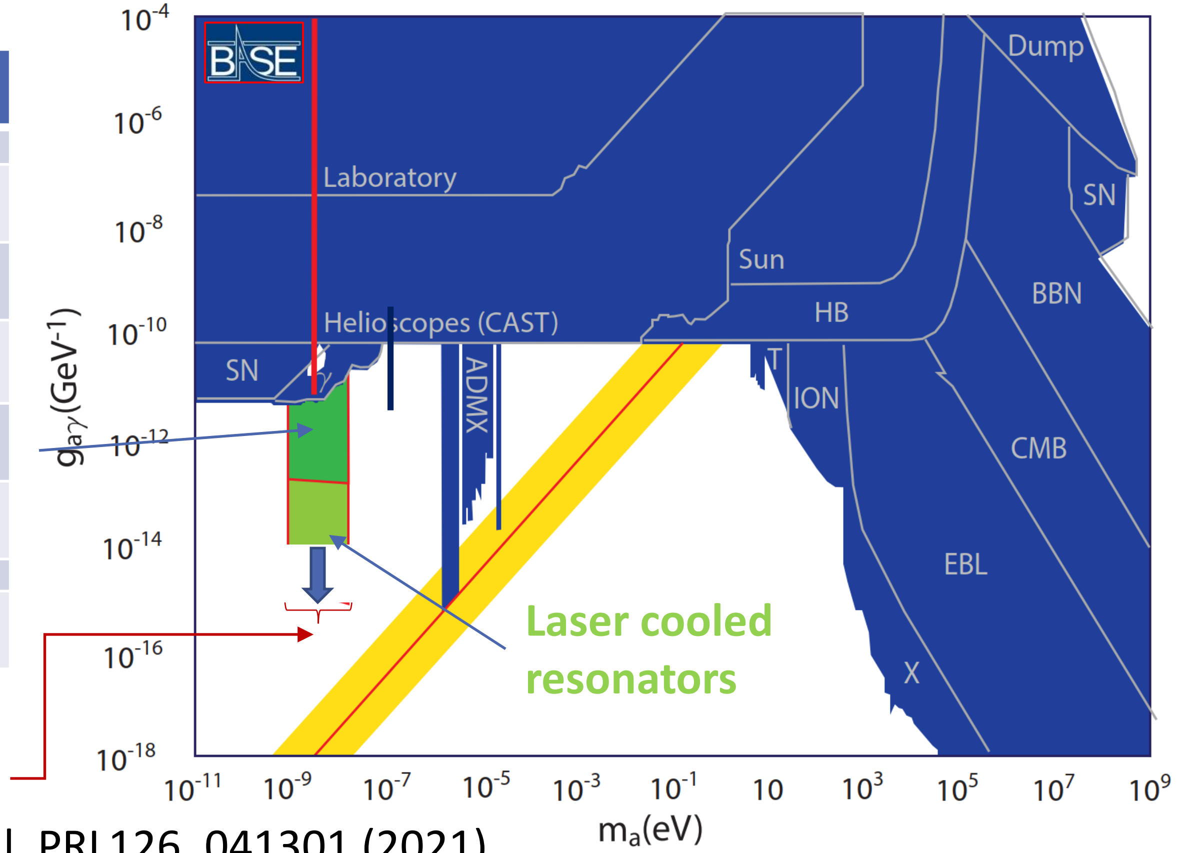
Recent lab result: 600 kHz tunability achieved (x 3000)



Technology available in BASE

No specific relation to antimatter

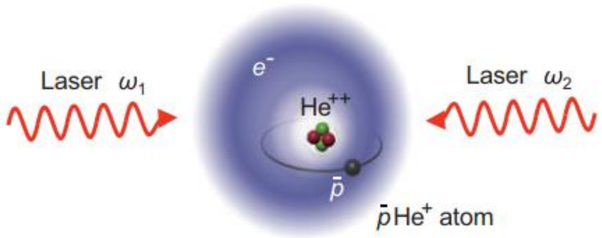
Sensitivity comparable to ADMX / ADMX SLIC



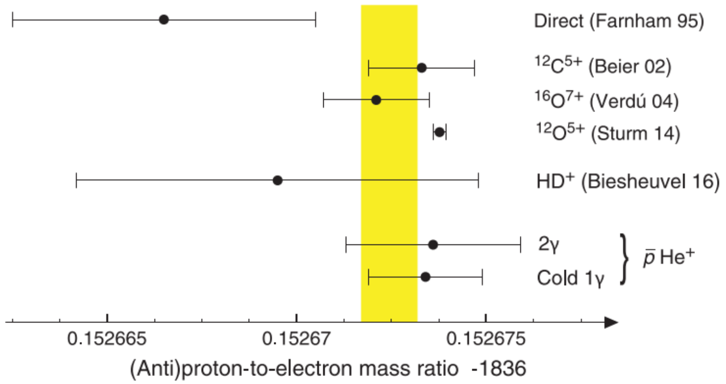
Devlin et al, PRL126, 041301 (2021)

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

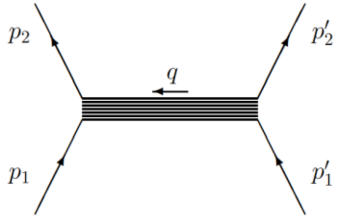
Antiprotonic Helium (ASACUSA)



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



- 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**)

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

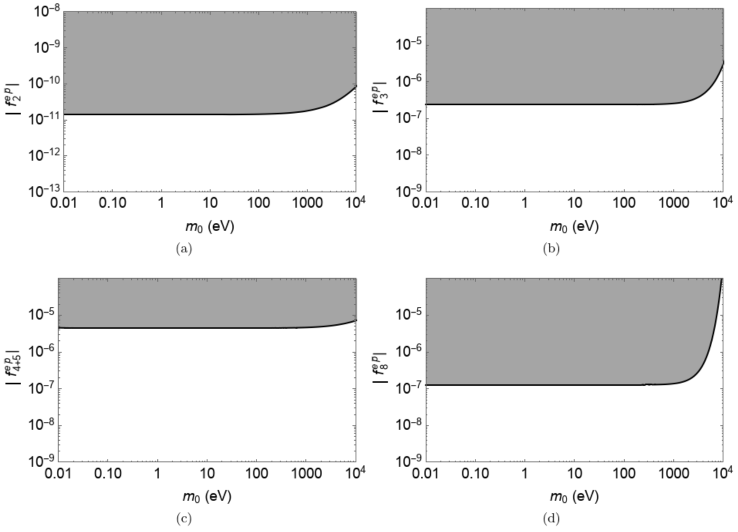
$$V_3 = f_3^{e\bar{p}} \frac{\hbar^3}{\pi m_e^2 c} \left[\mathbf{s}_{\bar{p}} \cdot \mathbf{s}_e \left(\frac{1}{\bar{\lambda} r^2} + \frac{1}{r^3} + \frac{4\pi}{3} \delta^3(r) \right) - (\mathbf{s}_{\bar{p}} \cdot \mathbf{r}) (\mathbf{s}_e \cdot \mathbf{r}) \left(\frac{1}{\bar{\lambda}^2 r^3} + \frac{3}{\bar{\lambda}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

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

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

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

Interactions would modify atomic potential and lead to shifts in wavelengths



AEḡIS

ALPHA

BASE

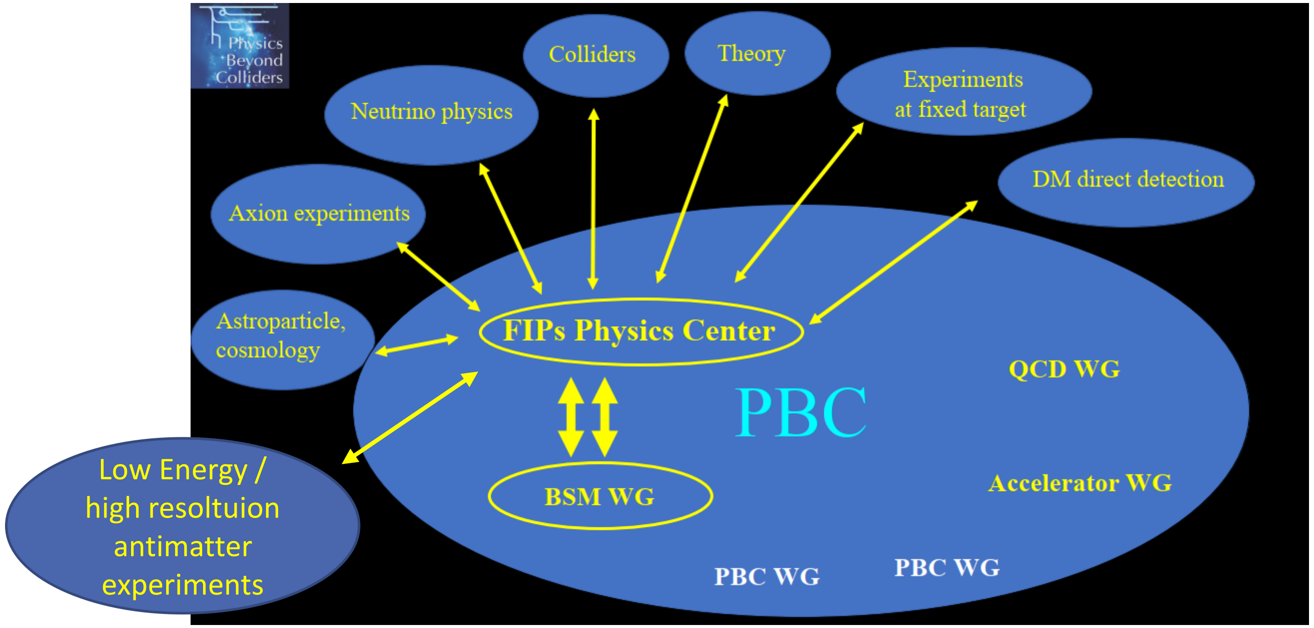
GBAR

STEp̄

- First limits on exotic antimatter/axion coupling derived

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**


Physics Beyond Colliders

Colliders

Theory

Neutrino physics

Experiments at fixed target

DM direct detection

Axion experiments

Astroparticle, cosmology

FIPs Physics Center

PBC

QCD WG

BSM WG

Accelerator WG

PBC WG

PBC WG

Low Energy / high resoltuion antimatter experiments

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.**

AEḡIS

ALPHA

BASE

GBAR

STE p̄

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

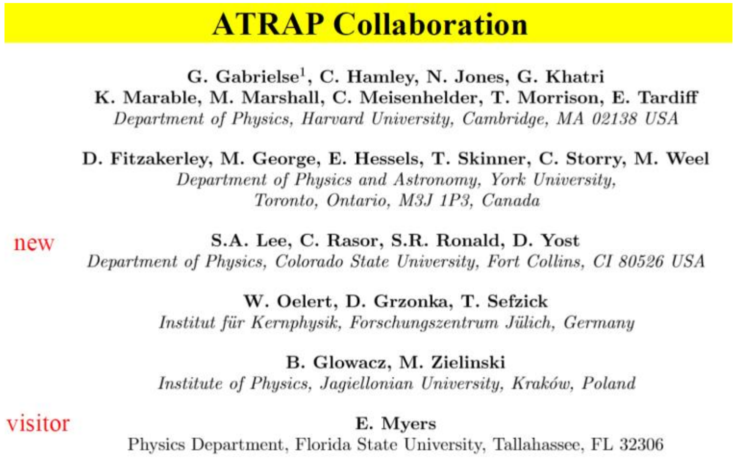
Simon Fraser University, Canada

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

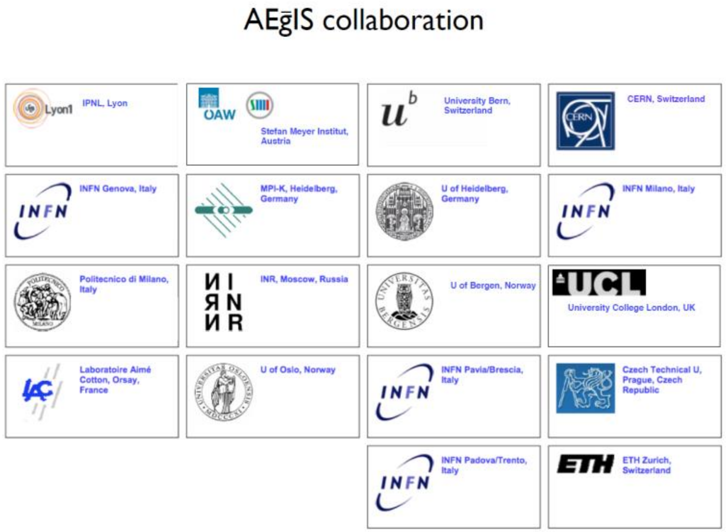
D. Fitzakerley, M. George, E. Hessels, T. Skinner, C. Storry, M. Weel
Department of Physics and Astronomy, York University,
Toronto, Ontario, M3J 1P3, Canada

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

Thanks very much for your attention

Fundamentality of CPT Invariance

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

Lorentz and translation invariance

Energy Positivity

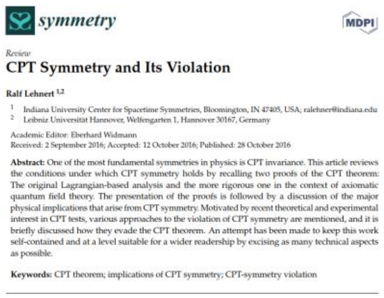
Micro Causality (Locality)

A stable vacuum ground state without momentum nor angular momentum

Unitary Field Operators Interpretation

CPT

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]

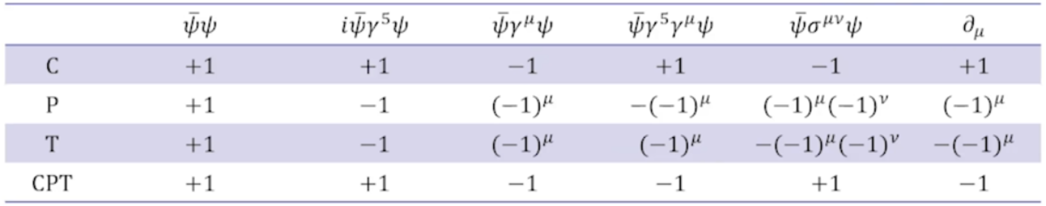
[1] Indiana University Center for Spacetime Symmetries, Bloomington, IN 47405, USA; ralehner@indiana.edu
[2] Leibniz Universität Hannover, Welfengarten 1, Hannover 30167, Germany

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

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

Quantum Logic Spectroscopy

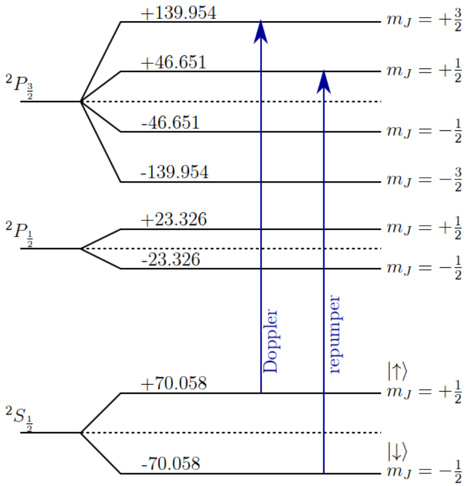
Initial state of coulomb coupled particles in a Paul-trap which share a phonon mode

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

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

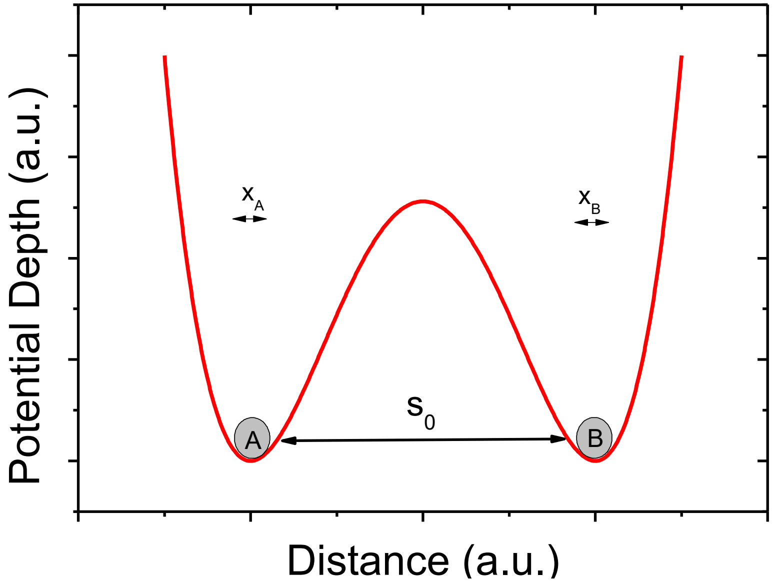
$$|\psi\rangle_{final} = |{\downarrow}\rangle_S (\alpha|{\downarrow}\rangle_L + \beta|{\uparrow}\rangle_L)|0\rangle_m$$

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.



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

$$\approx \frac{1}{4\pi\varepsilon_0}\frac{q_a q_b}{s_0}\Bigg(\underbrace{1 + \frac{x_a - x_b}{s_0} + \frac{x_a^2}{s_0^2} + \frac{x_b^2}{s_0^2}}_{\text{Static}} - \underbrace{\frac{2x_a x_b}{s_0^2}}_{\text{Dynamic}}\Bigg)$$

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

Resonant Coupling:

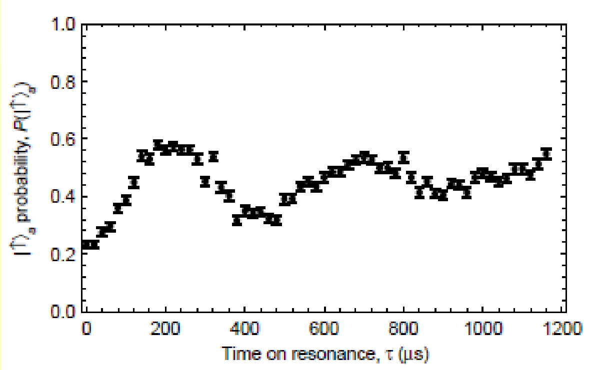
$$a^\dagger(t) = \exp(i\omega_0 t)(a^\dagger(0)\cos(\Omega_{\mathrm{ex}}t) - ib^\dagger(0)\sin(\Omega_{\mathrm{ex}}t))$$

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

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).

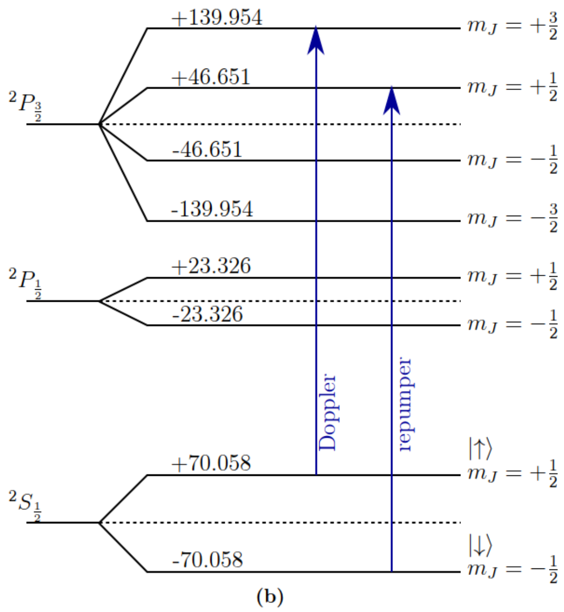
See also: M. Harlander, R. Lechner, M. Brownnutt, R. Blatt, W. Hänsel, Nature **471**, 200 (2011).

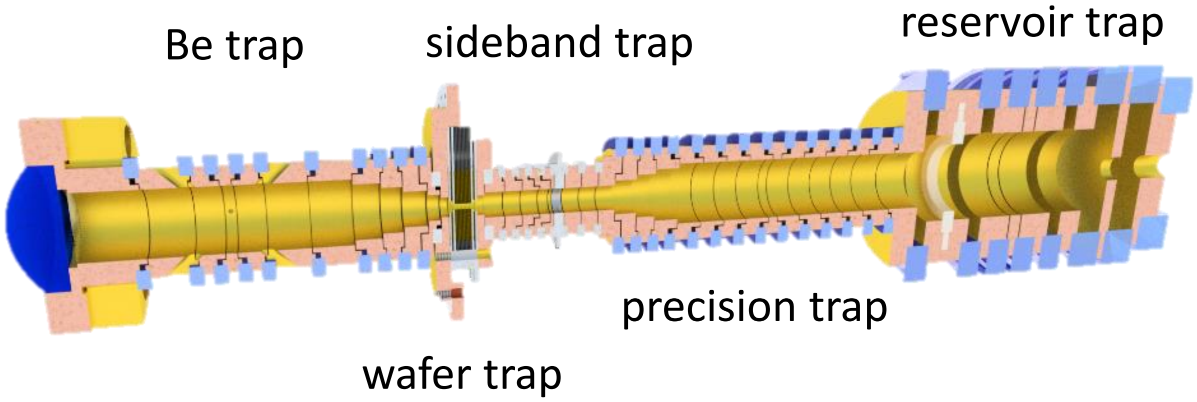
QLS with Antiproton Spins

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

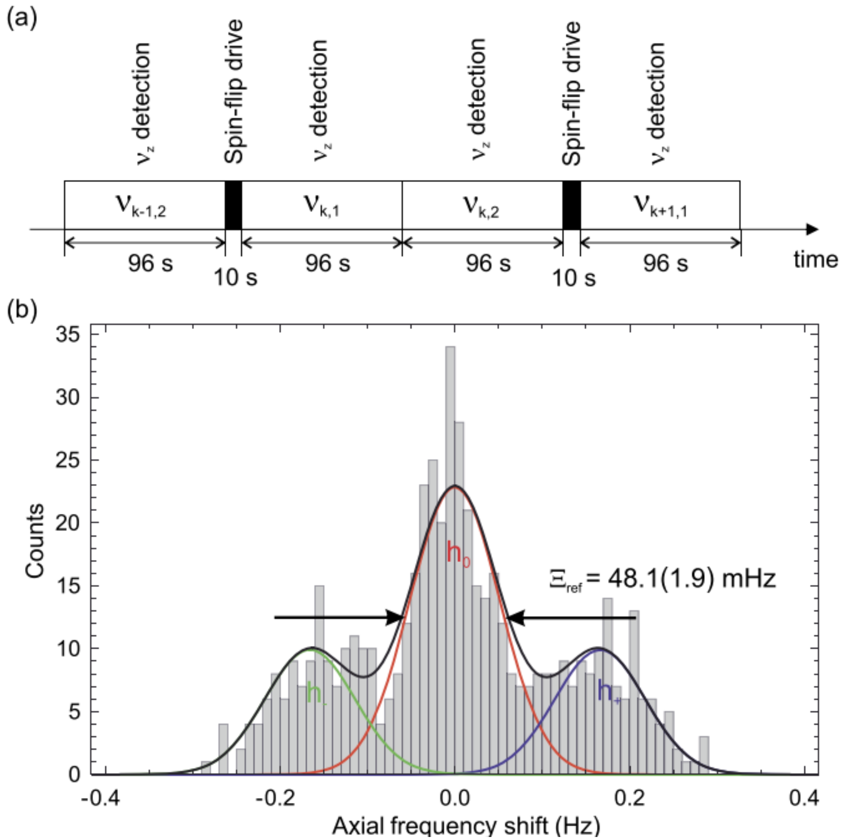
Initial conditions of experiment	$\|\psi\rangle_0 = \|\uparrow\rangle_p \|0\rangle_{m,p} \|\uparrow\rangle_L \|0\rangle_{m,L}$	$\|\psi\rangle_0 = \|\downarrow\rangle_p \|0\rangle_{m,p} \|\uparrow\rangle_L \|0\rangle_{m,L}$
Magnetic SWAP gate in sideband trap	$\|\psi\rangle_1 = \|\uparrow\rangle_p \|0\rangle_{m,p}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

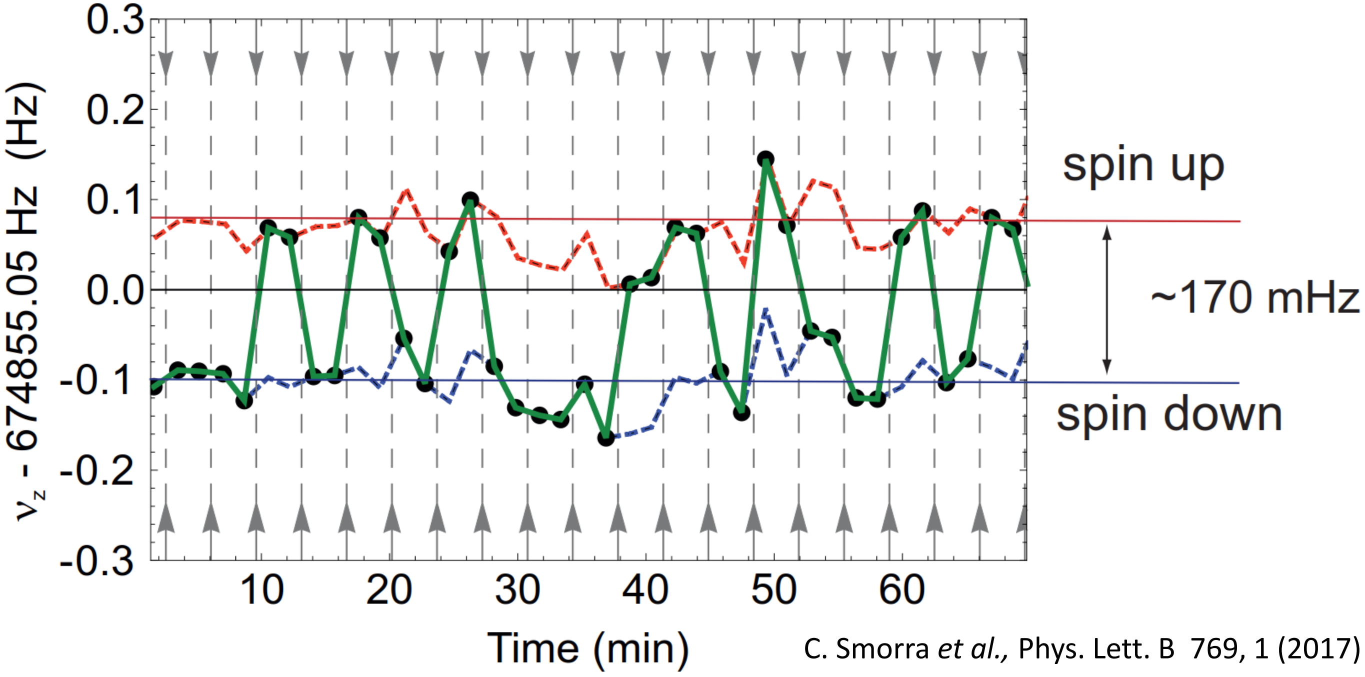
Be+ level scheme





Quantum Spectroscopy at CERN





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

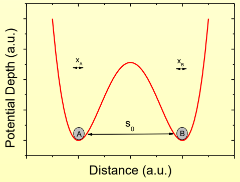
- First non-destructive observation of single-antiproton spin-quantum transitions.
- **Double trap method ultimately requires single spin-flip resolution with high fidelity.**

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

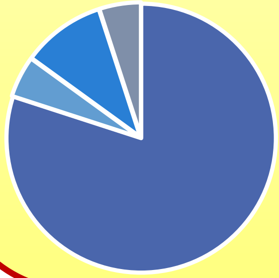
Couple protons/antiprotons sympathetically to laser cooled $^9Be^+$ ions and imprint Doppler temperatures to the antiproton



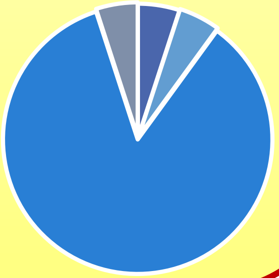
Publication: K. R. Brown, C. Ospelkaus, Y. Colombe, A. C. Wilson, D. Leibfried, D. J. Wineland, Nature **471**, 196 (2011).

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

Current Time Budget

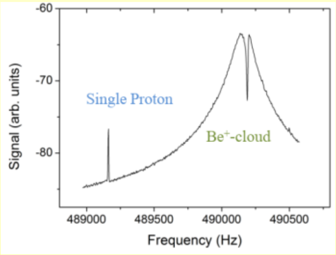


Laser Time Budget



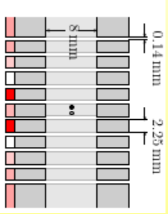
Effort at University of Mainz

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

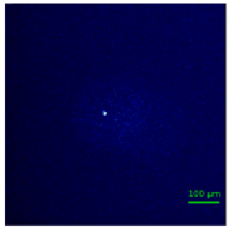


C. Smorra, M. Bohman, M. Wiesinger, C. Will, et al.

Effort at University of Hannover and PTB

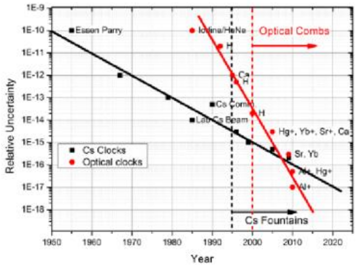


Recent dramatic progress:
Detection of a single laser cooled $^9Be^+$ ion, in a Penning trap system which is fully compatible with the BASE trap system at CERN



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