FIPS 2022

Oct 18, 2022

Antimatter Experiments and its (Possible) Connections to FIPs

Makoto C. Fujiwara

TRIUMF
Vancouver, Canada

UBC
UNIVERSITY OF CALGARY
SFU SIMON FRASER UNIVERSITY
YORK U UNIVERSITÉ UNIVERSITY
TRIUMF

Disclaimer

This is my personal view, and does not represent that of the Antimatter Community!

(unlike Lindley's talk, yesterday)

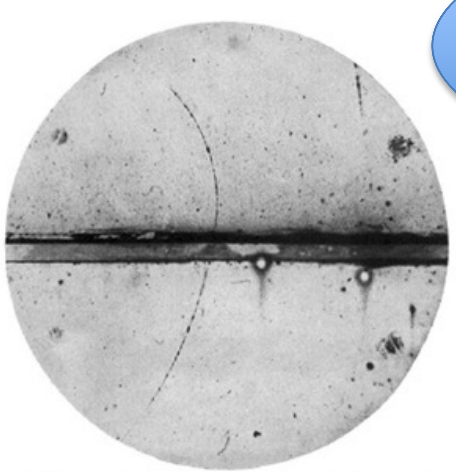
Shameless self-promotion alert!

Thanks to S. Ulmer, M. Hori, M. Doser for slides/input

Antimatter and FIPs

Primary objective

To test fundamental symmetries between matter and antimatter at the highest precision possible



Technology driven field

We have been at this for 90 years!
(Positron discovered in Aug 6, 1932)

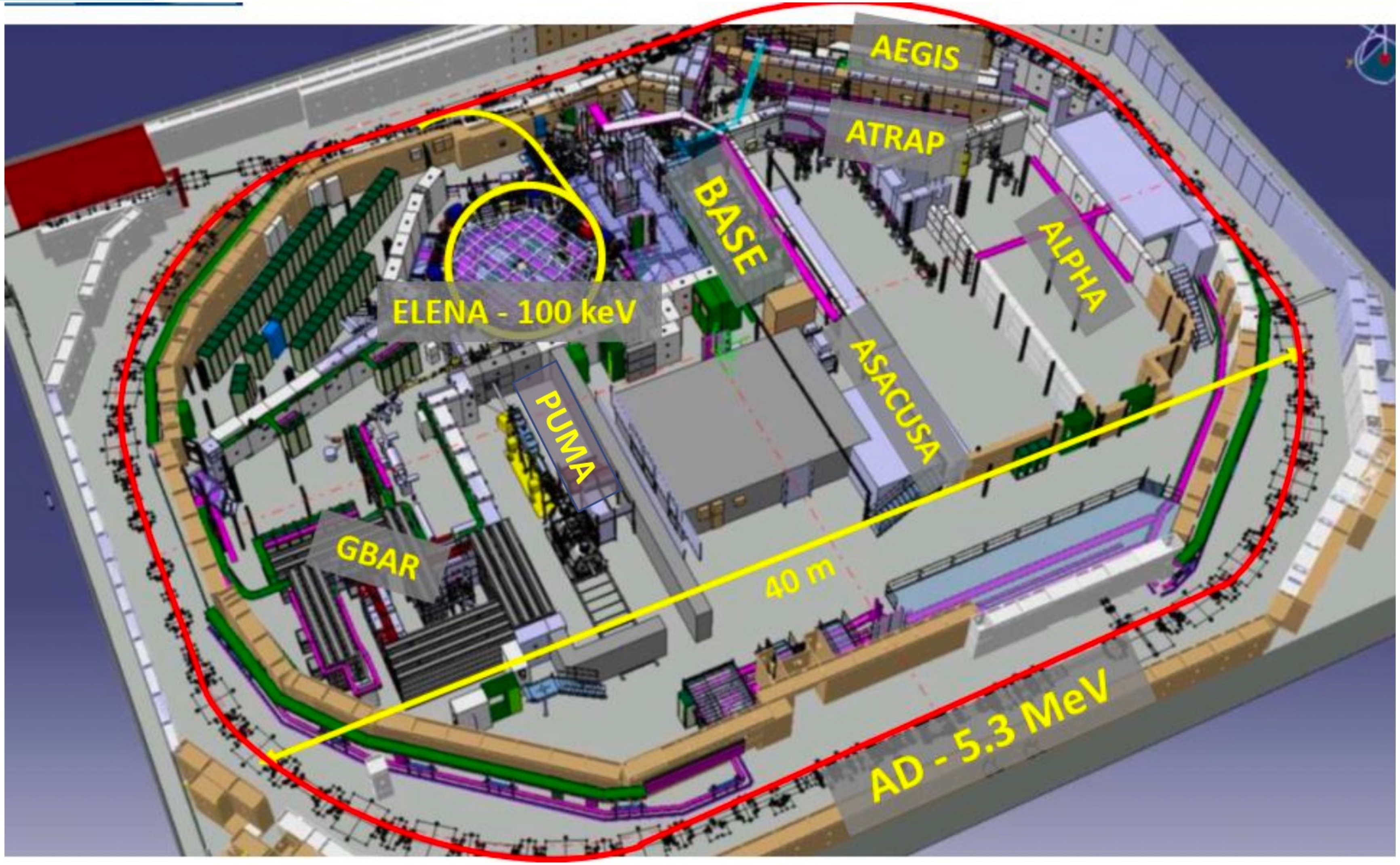
Take Home

Technologies developed for antimatter studies can be applied to other areas such as FIPs searches

CERN's Antiproton Facility (Stefan Ulmer, AD Users Chair)

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

Categorizing physics via the interactions

	Lorentz even	Lorentz odd
CPT even		
CPT odd		

Each sector addresses different questions

Different Questions

	Lorentz even	Lorentz odd
CPT even	SM Most of BSM, FIPs	
CPT odd		

Typical questions asked (at low energies)

- Is there new CPV?
- How is neutrino mass generated?
- Does proton decay?
- What is dark matter?
- Are there FIPs in Nature?

Overriding Question:

$$L = ?$$

What is the fundamental Lagrangian of Nature?

Different Questions

	Lorentz even	Lorentz odd
CPT even	SM Most of BSM	LV EFT (e.g. SM Extension)
CPT odd		LV EFT (e.g. SM Extension)

Is there a preferred direction (or coordinate) in Nature?

LV EFT (Kostelecky, Pospelov etc), a popular framework

Well tested with matter-only expts; antimatter expts sensitive to fine-tuned scenarios

Different Questions

	Lorentz even	Lorentz odd
CPT even	SM Most of BSM	LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT	LV EFT (e.g. SM Extension)

Is “L = ?” the right question to ask?

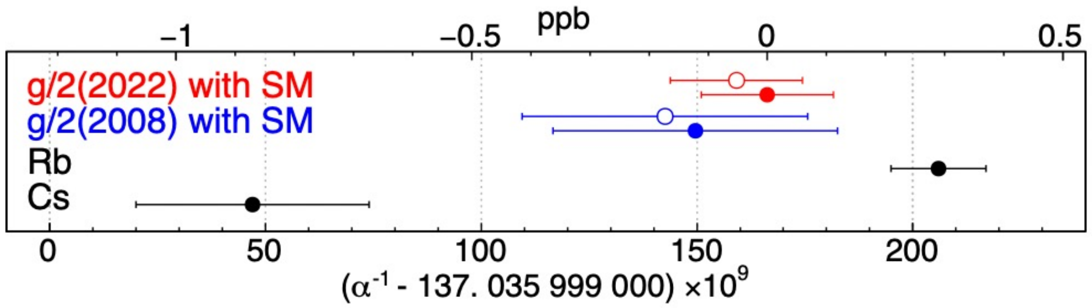
Is local QFT a correct description of Nature?

Lorentz even, CPT odd interactions cannot happen in local QFT (Greenberg 2002)

Testing Quantum Field Theory

- What's the most precise test of QFT?
- At low energies, electron g-2?
- QED test limited to 10^{-10} level
  - Need a measurement of α

    [talk by P. Claude]



New measurement of electron g-2
arXiv:2209.13084

- Hydrogen atom spectroscopy at 4×10^{-15}
- Comparison with QED hindered by proton radius
- Antimatter-matter comparison could test aspects of QFT at higher precisions
  - BASE: antiproton-proton q/m comparison: 1.6×10^{-11}
  - ALPHA: 1s-2s in anti-H: 2×10^{-12}

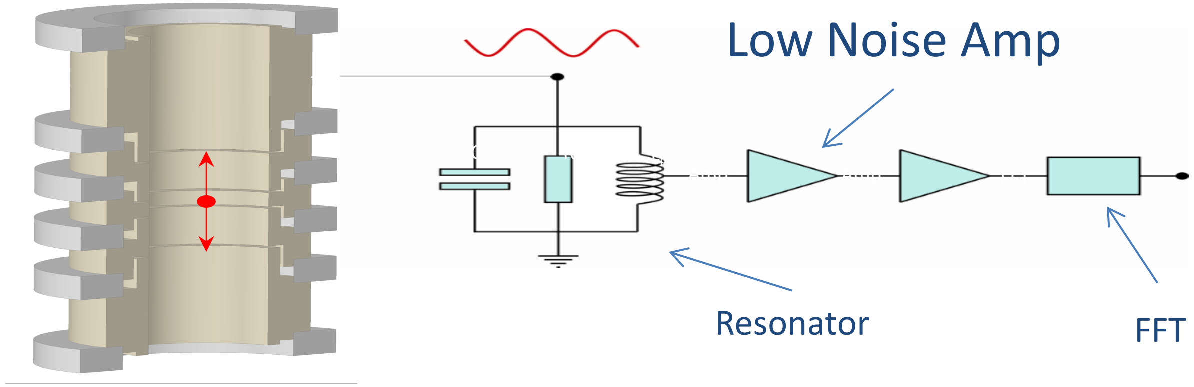
Experiments at CERN Antimatter Facility
(Selected Examples)

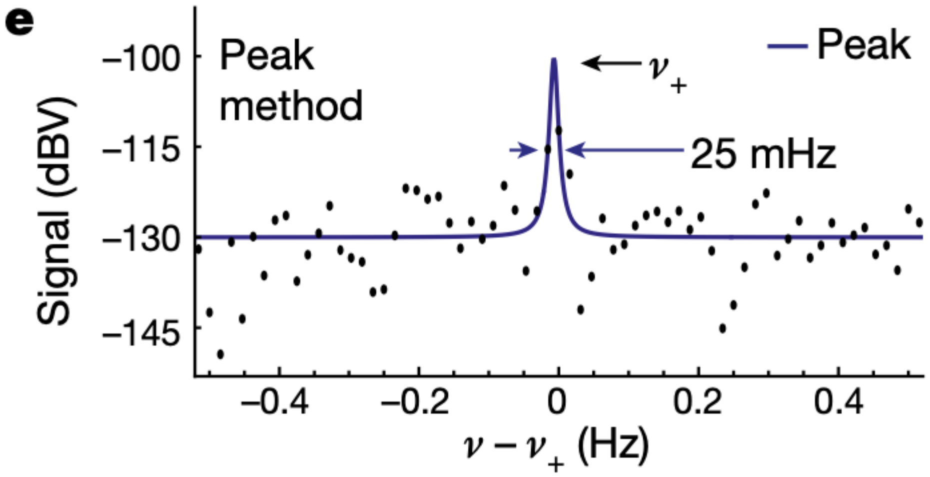
AD experiments: Examples

	Lorentz even	Lorentz odd
CPT even	SM Most of BSM, FIPs	LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT → BASE	LV EFT (e.g. SM Extension)

BASE: Antiproton charge-to-mass ratio

Nature 601, 53 (2022)





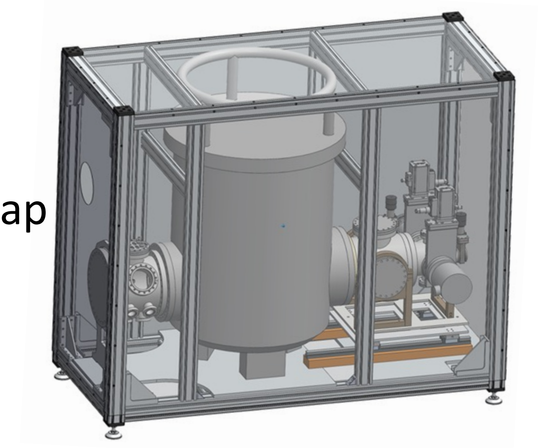
q/m ratio between anti-p and p: 1.000000000003(16)

1.6 x 10^{-11} precision (Δf ~ 400 μHz) !!!

- Trap single antiproton
- Cyclotron freq via image currents with sensitive detector
- >24,000 measurements over 1.5 yr: using only 5 pbars!
- AD environment limiting factor

→ Portable trap to transport pbars to a more quite labl!

BASE-STEP:
Transportable pbar trap

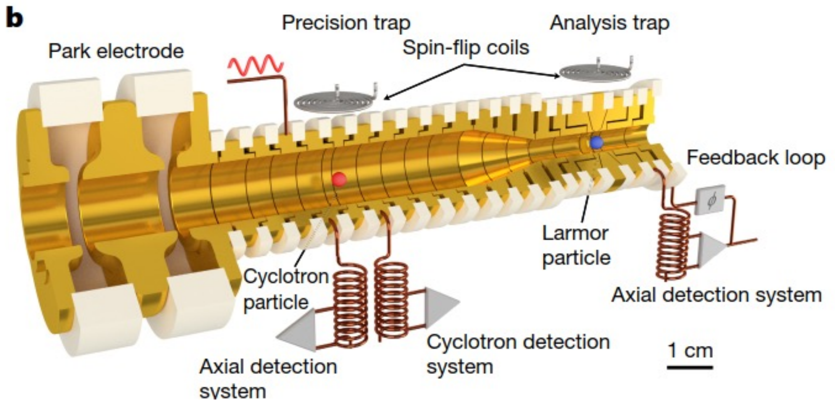


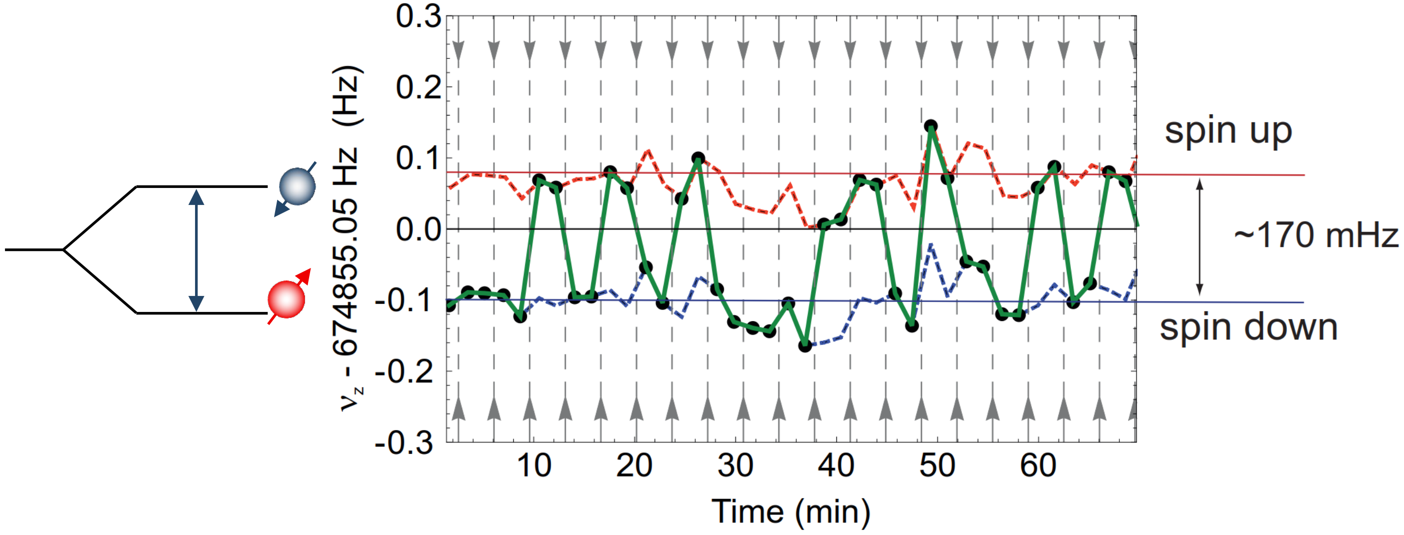
→ Factor 5–10 imprv't in near future?

BASE: Antiproton magnetic moment (Holy Grail)

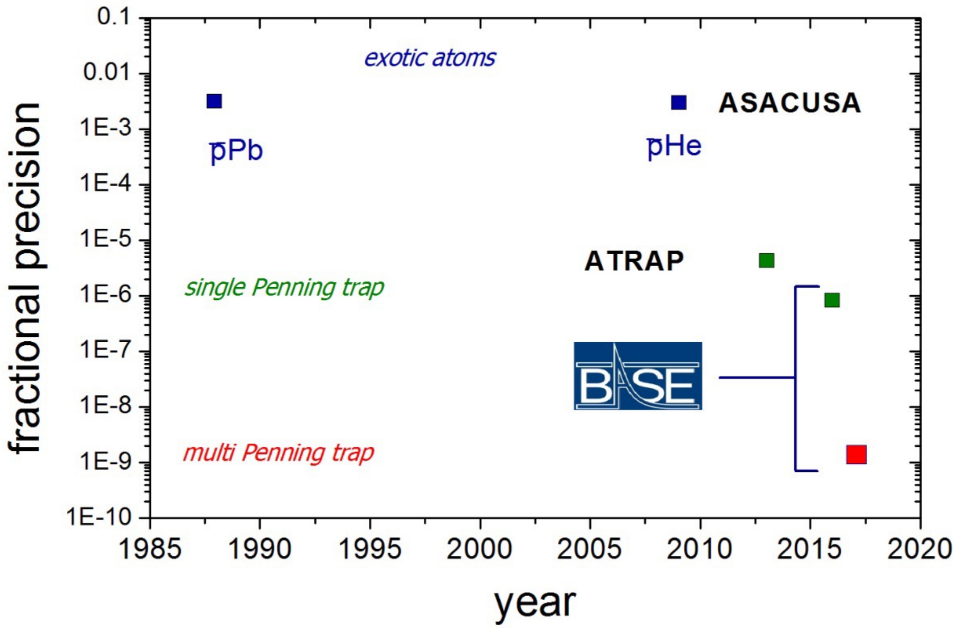
Nature 550, 317 (2017)

- Antiproton g-factor
  - Requires quantum spin flip detection
  - Very hard; pbar g-factor 1/660 of e-
  - New double trap method





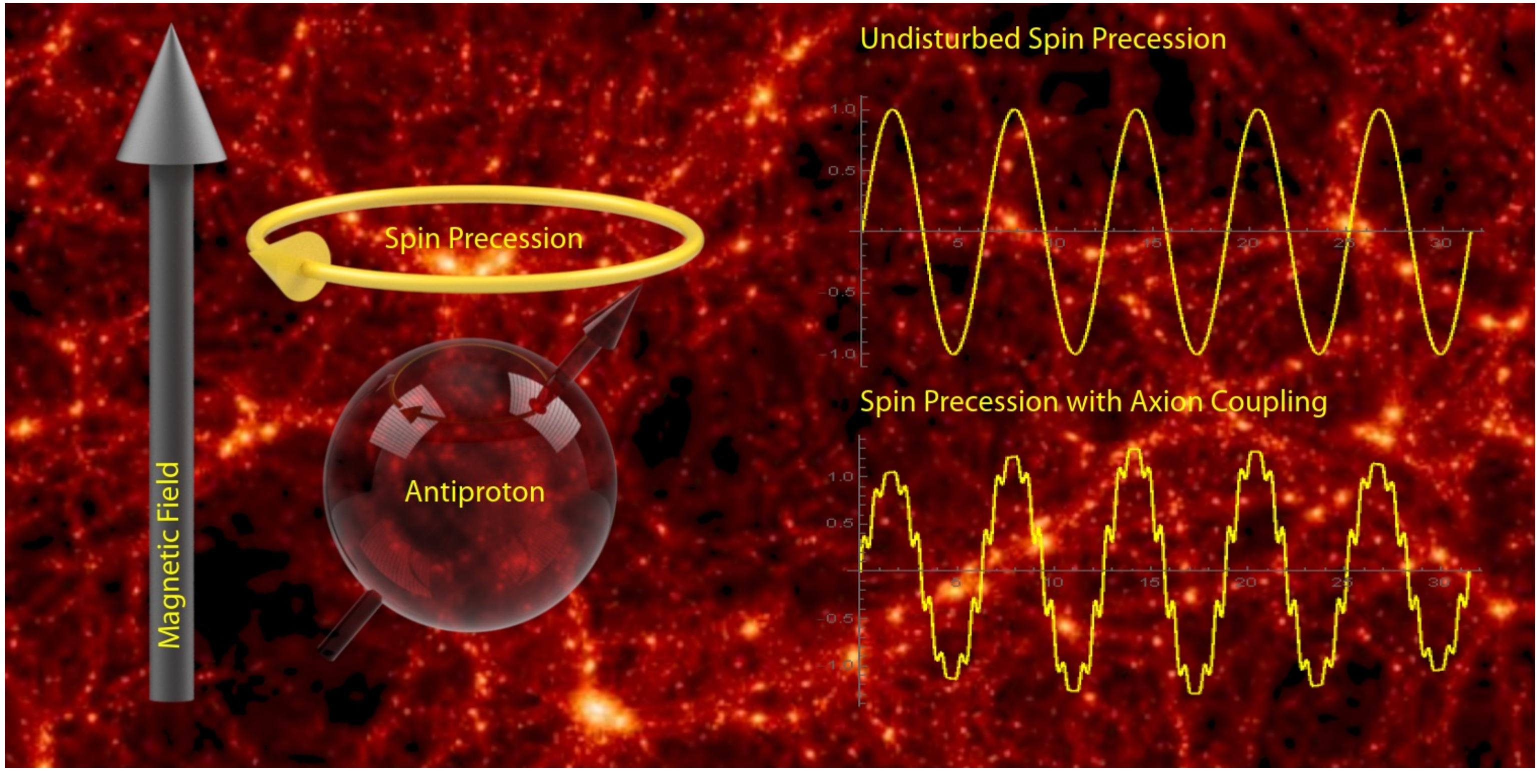
BASE 2017: $\mu_{\bar{p}}$ = -2.792 847 344 1 (42) μ_{nucl}



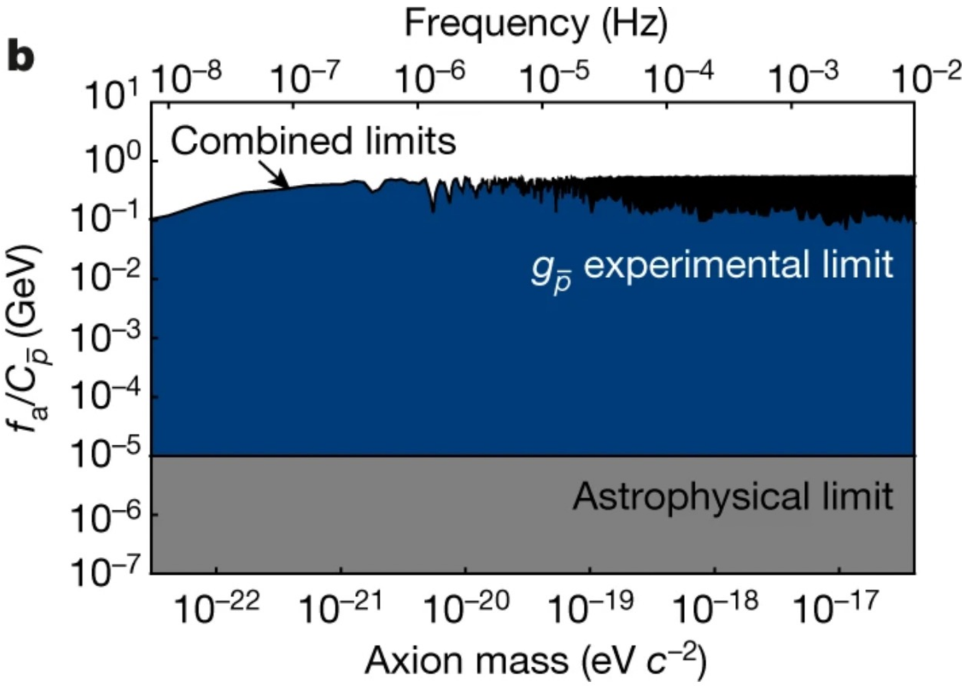
1.5 x 10^{-9} precision!→ Factor 5–10 imprv't in near future?

BASE: (CPT violating) ALP Dark Matter– Antiproton coupling

Nature 575, 31 (2019)



Look for modulations of pbar spin precession from interaction of axion field and pbar spin vector

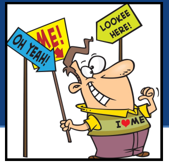


Limit on CPT violating DM!

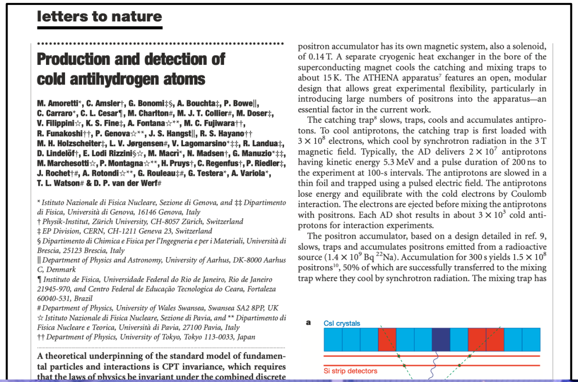
Categorizing via the interactions

	Lorentz even	Lorentz odd
CPT even	SM Most of BSM, FIPs	LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT → BASE → ALPHA	LV EFT (e.g. SM Extension)

20 Years of Cold Antihydrogen



Production of cold antihydrogen, Oct 3, 2002



letters to nature

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe‖, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst‖, R. S. Hayano†† M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macrì*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#**

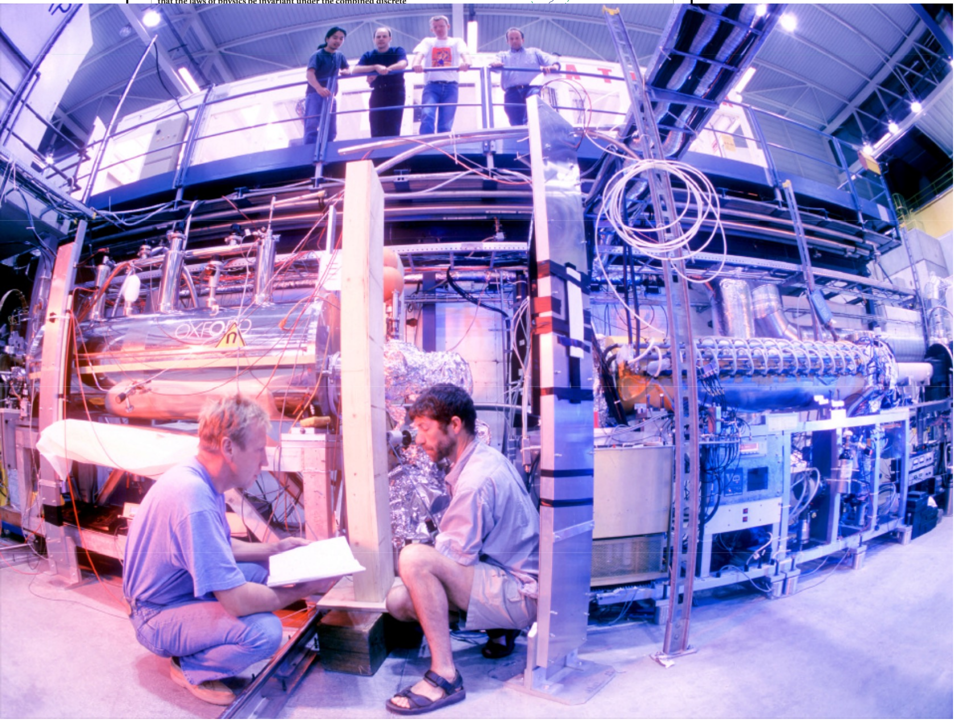
** Istituto Nazionale di Fisica Nucleare, Sezione di Genova, and ‡‡ Dipartimento di Fisica, Università di Genova, 16146 Genova, Italy*
† Physik-Institut, Zürich University, CH-8057 Zürich, Switzerland
‡ EP Division, CERN, CH-1211 Geneva 23, Switzerland
§ Dipartimento di Chimica e Fisica per l'Ingegneria e per i Materiali, Università di Brescia, 25123 Brescia, Italy
‖ Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark
¶ Instituto de Fisica, Universidade Federal do Rio de Janeiro, Rio de Janeiro 21945-970, and Centro Federal de Educação Tecnologica do Ceara, Fortaleza 60040-531, Brazil
 # Department of Physics, University of Wales Swansea, Swansea SA2 8PP, UK
*☆ Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, and ** Dipartimento di Fisica Nucleare e Teorica, Università di Pavia, 27100 Pavia, Italy*
†† Department of Physics, University of Tokyo, Tokyo 113-0033, Japan

A theoretical underpinning of the standard model of fundamental particles and interactions is CPT invariance, which requires that the laws of physics be invariant under the combined discrete

positron accumulator has its own magnetic system, also a solenoid, of 0.14 T. A separate cryogenic heat exchanger in the bore of the superconducting magnet cools the catching and mixing traps to about 15 K. The ATHENA apparatus[7] features an open, modular design that allows great experimental flexibility, particularly in introducing large numbers of positrons into the apparatus—an essential factor in the current work.

The catching trap[8] slows, traps, cools and accumulates antiprotons. To cool antiprotons, the catching trap is first loaded with 3×10^8 electrons, which cool by synchrotron radiation in the 3 T magnetic field. Typically, the AD delivers 2×10^7 antiprotons having kinetic energy 5.3 MeV and a pulse duration of 200 ns to the experiment at 100-s intervals. The antiprotons are slowed in a thin foil and trapped using a pulsed electric field. The antiprotons lose energy and equilibrate with the cold electrons by Coulomb interaction. The electrons are ejected before mixing the antiprotons with positrons. Each AD shot results in about 3×10^3 cold antiprotons for interaction experiments.

The positron accumulator, based on a design detailed in ref. 9, slows, traps and accumulates positrons emitted from a radioactive source (1.4×10^9 Bq ^{22}Na). Accumulation for 300 s yields 1.5×10^8 positrons[10], 50% of which are successfully transferred to the mixing trap where they cool by synchrotron radiation. The mixing trap has



ATHENA at CERN AD

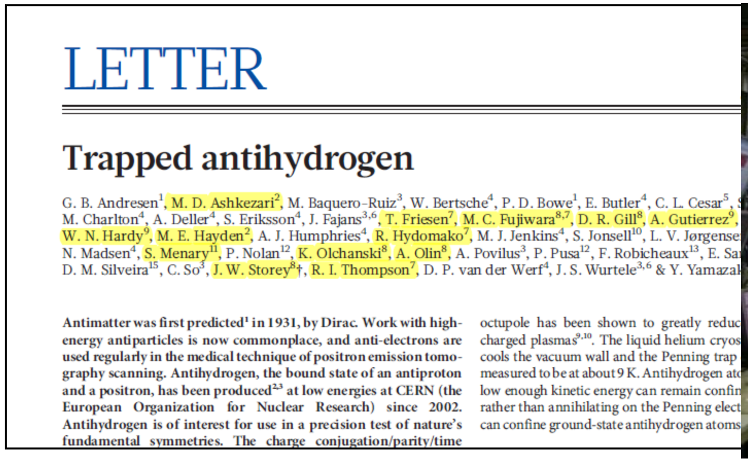
- ATHENA finished in 2004
- Developed new experiment to trap

anti-H for precision measurements in 2005

- ~~ALE —Antihydrogen Laser Experiment~~

- ALPHA: Antihydrogen Laser Physics Apparatus
  (now confusing with Wilczek's axion experiment!)

Trapped antihydrogen, Nov. 17, 2010



LETTER

Trapped antihydrogen

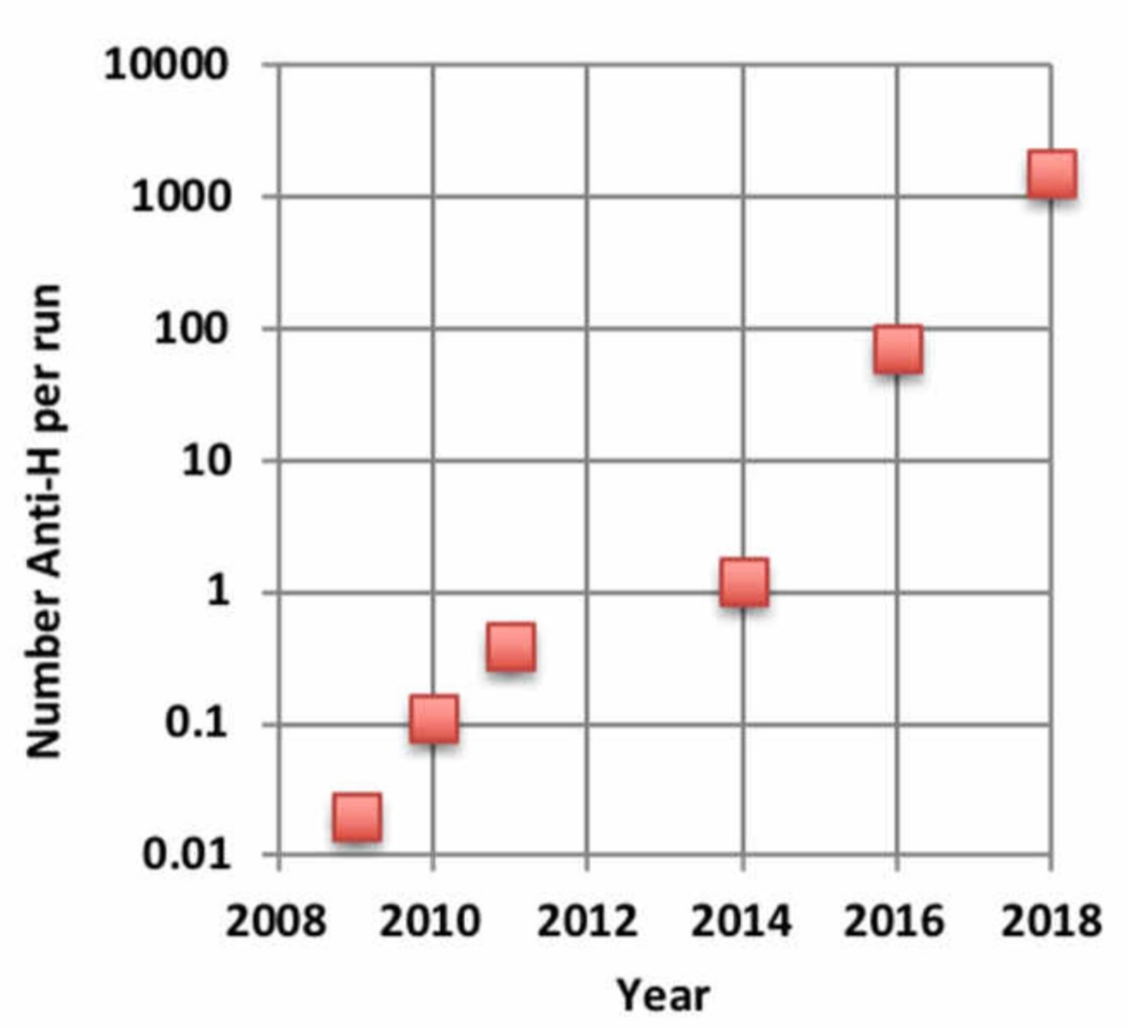
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgense N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sa D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazak

Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at low energies at CERN (the European Organization for Nuclear Research) since 2002. Antihydrogen is of interest for use in a precision test of nature's fundamental symmetries. The charge conjugation/parity/time

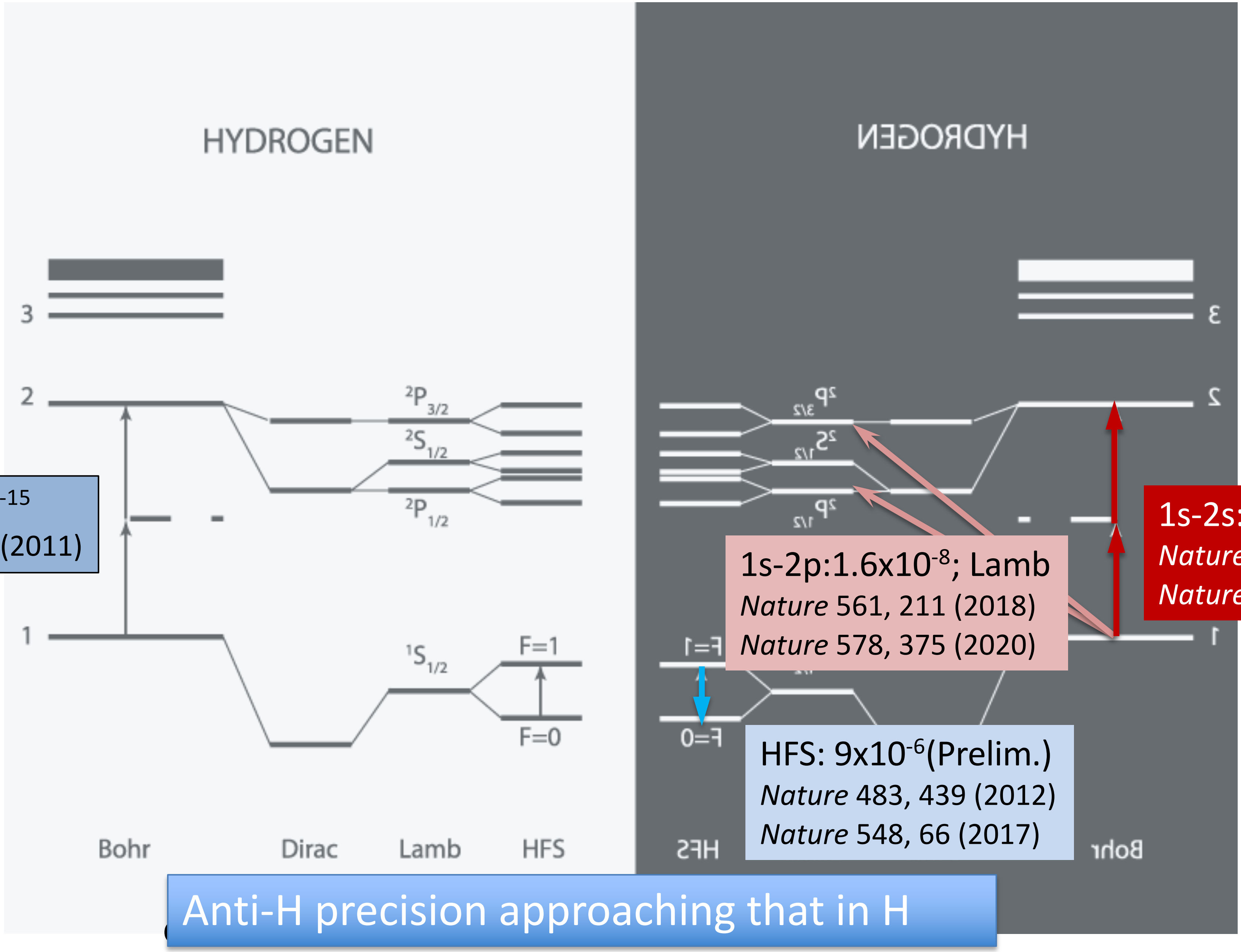
octupole has been shown to greatly reduc charged plasmas[9,10]. The liquid helium cryos cools the vacuum wall and the Penning trap measured to be at about 9 K. Antihydrogen at low enough kinetic energy can remain confin rather than annihilating on the Penning elect can confine ground-state antihydrogen atoms

Technical developments over past 20 years (one example)

Improvements in trapping rates; now routinely accumulate >1000 anti-H, by repeated leading, or “stacking”



Antihydrogen Spectroscopy with ALPHA at CERN



1s-2s: $4\text{x}10^{-15}$
PRL 107, 203001 (2011)

1s-2p:$1.6\text{x}10^{-8}$; Lamb
Nature 561, 211 (2018)
Nature 578, 375 (2020)

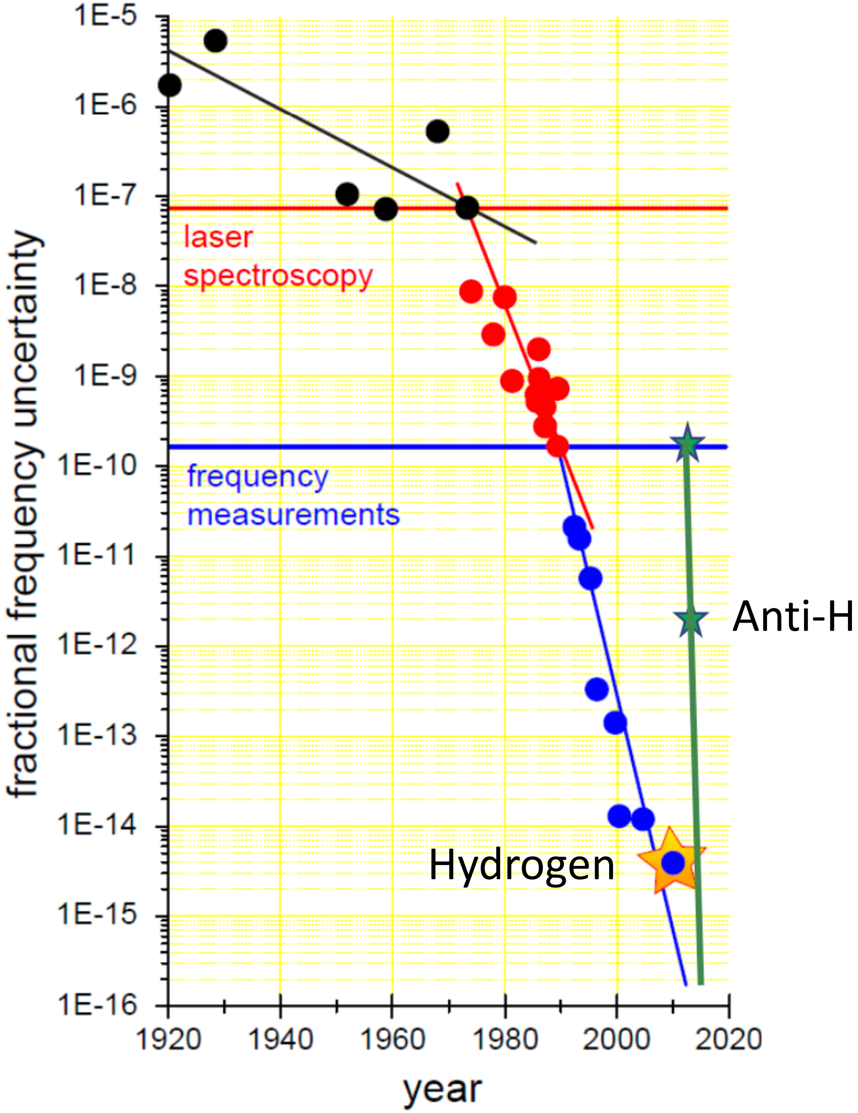
1s-2s: $2\text{x}10^{-12}$
Nature 541, 506 (2017)
Nature 557, 71 (2018)

HFS: $9\text{x}10^{-6}$(Prelim.)
Nature 483, 439 (2012)
Nature 548, 66 (2017)

Charge neutrality
Nature 539, 373 (2016)
Gravity (ongoing)

Anti-H precision approaching that in H

Anti-H spectroscopy precision approaching hydrogen!

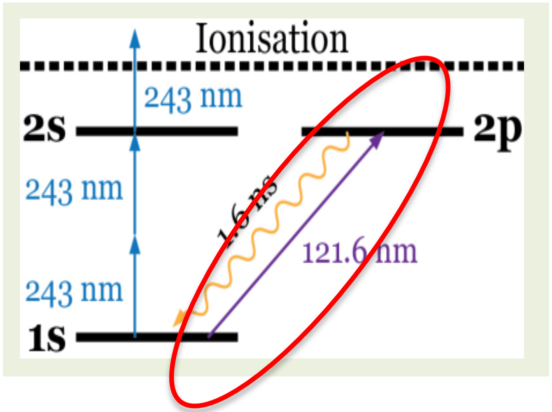


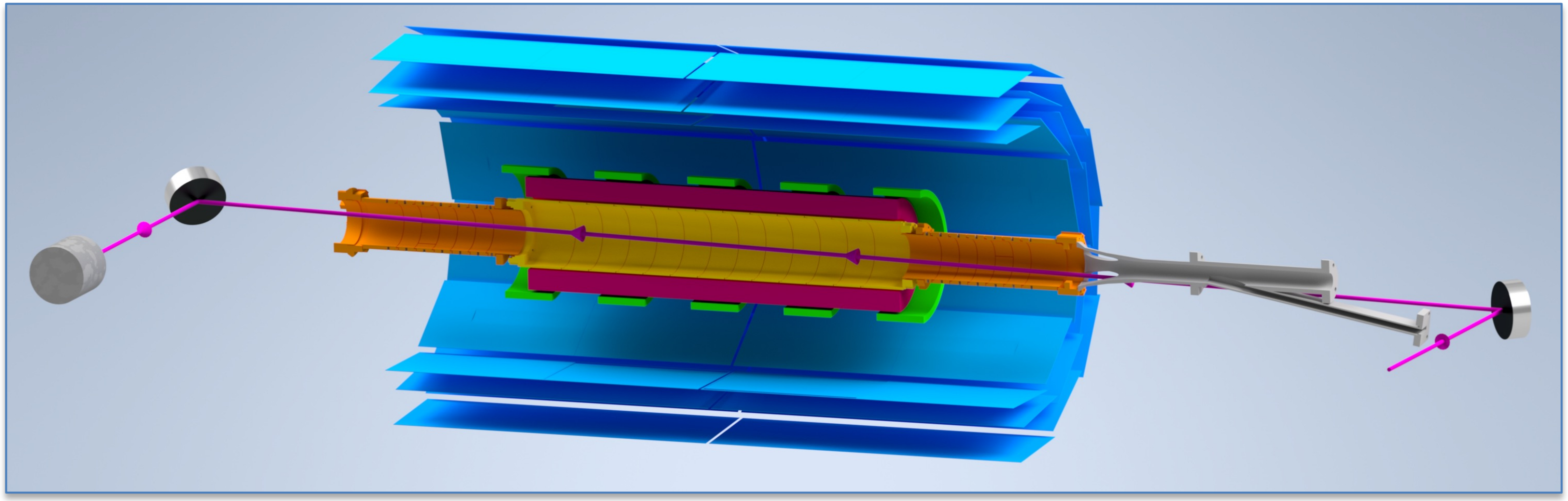
Hydrogen: 4 x 10^{-15}

Antihydrogen: 2 x 10^{-12}

Within a factor of 500!

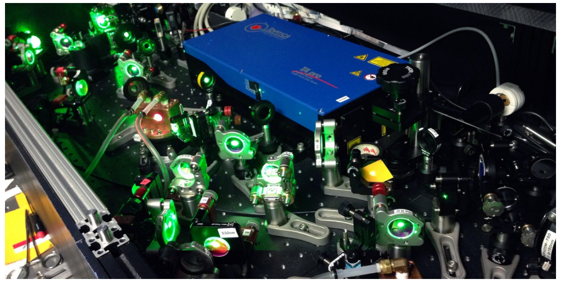
Demonstration of Laser Cooling

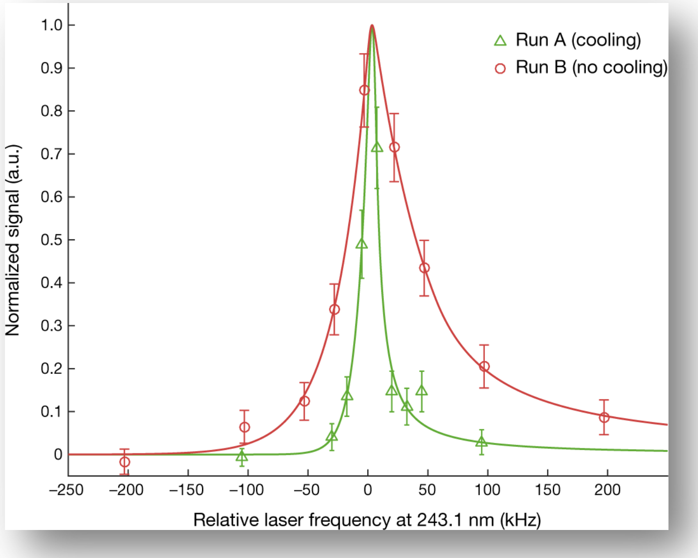




Laser cooling (anti)hydrogen is hard

- 121 nm: vacuum ultraviolet
- Challenging laser built at UBC, Canada
- Cooling takes hours (rather than msec)



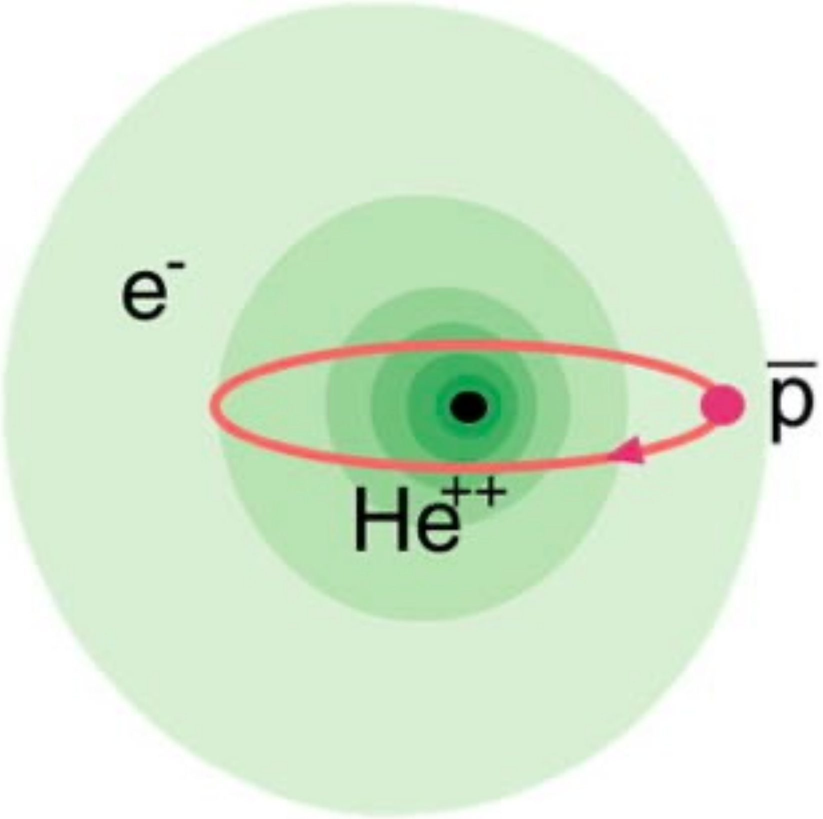


Laser cooling a likely game changer in anti-H and H studies

	Lorentz even	Lorentz odd
CPT even	→ ASACUSA SM Most of BSM, FIPs	LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT → BASE → ALPHA	LV EFT (e.g. SM Extension)

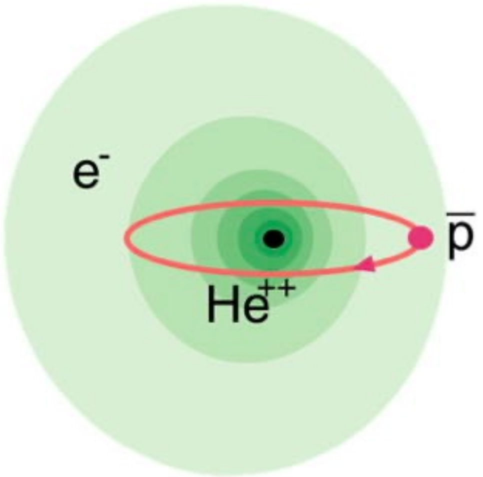
Antimatter techniques can be applied to FIPs searches

Electron-pbar interactions: ASACUSA

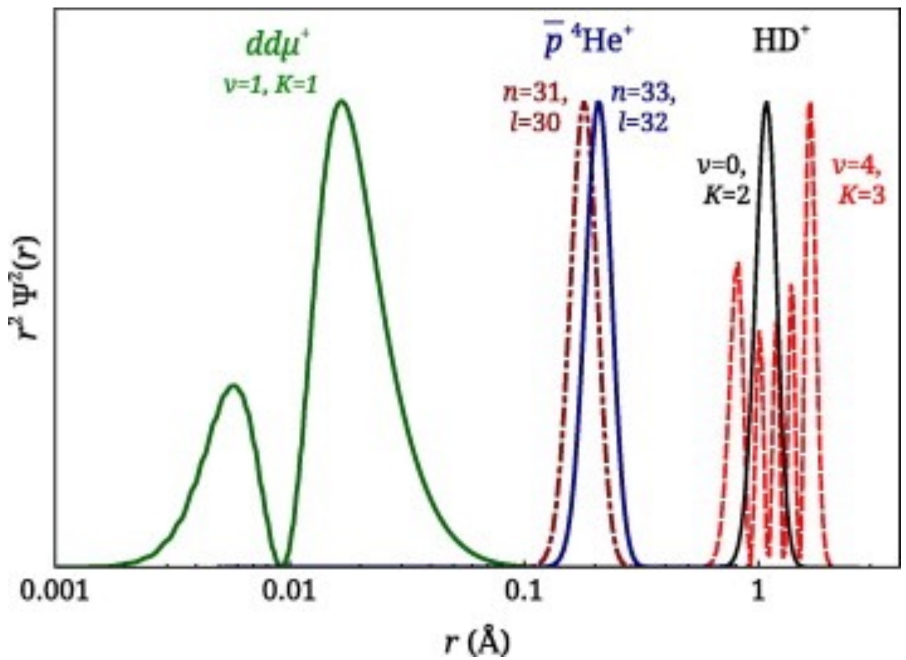


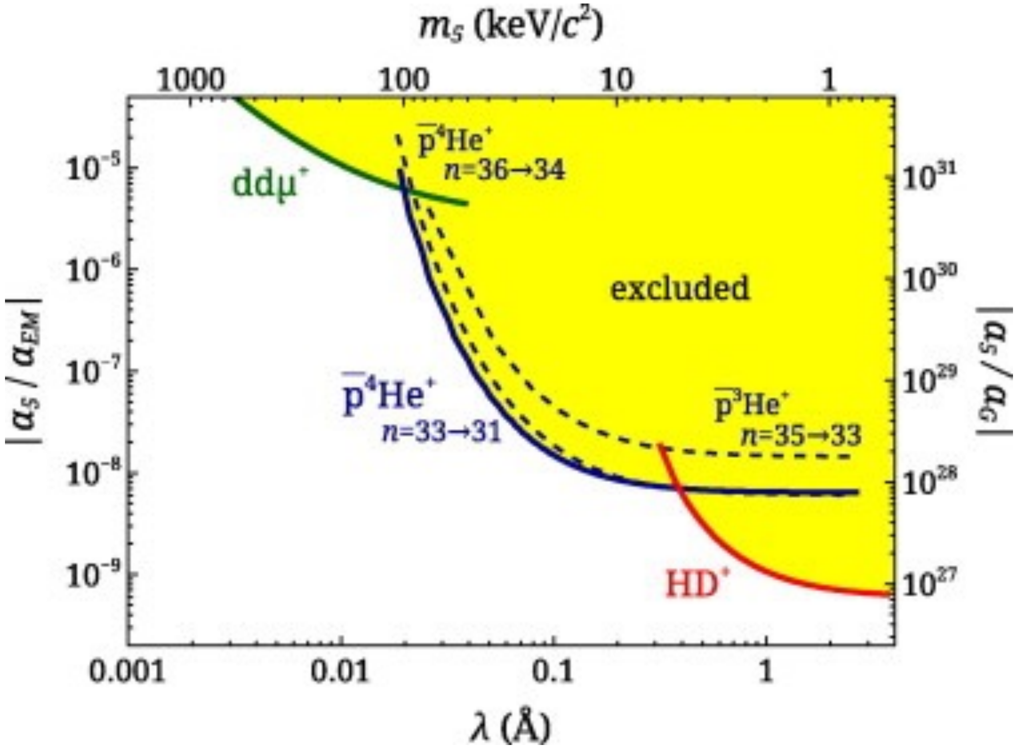
- The exotic atom, containing anti-p, e-, He nucleus (long-lived)
- Precision laser spectroscopy compared to QED 3-body calculations
- Any deviations could be interpreted as a new force between the constituents
  - Helium nucleus - Antiproton
  - Electron – Antiproton

5th force between Helium nucleus and Pbar: ASACUSA



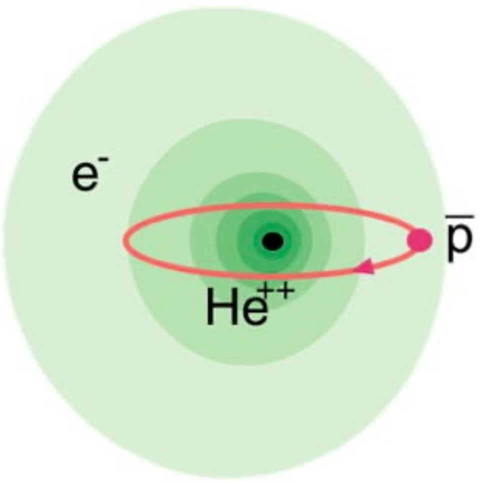
- Search for a new Yukawa coupling at short distance scales [Salubides, Ubachs, Korobov, 2014]



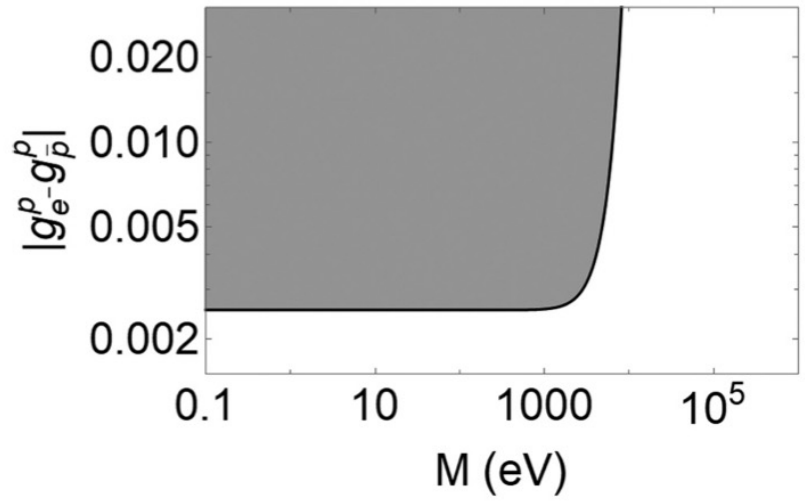


NB: astrophysical constraints; See also Murata 2005, German et al. 2021

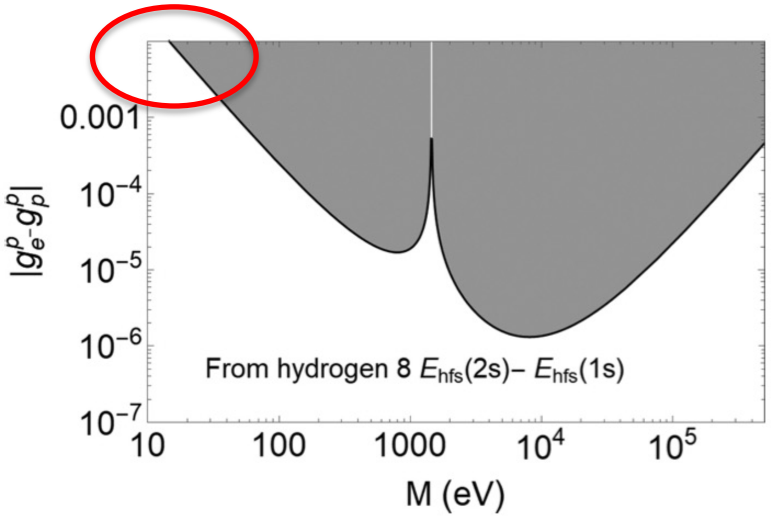
Electron-Antiproton interactions: ASACUSA



- New spin dependent couplings between e- and antiproton [Flambaum, Stadnik, Budker etc, PRL 2018, PRA 2022]
- Some parameter space already excluded if CPT assumed
- In other regions, e – pbar coupling is more strongly constrained than e – p (pseudoscalar example below)



electron – antiproton
(from antiprotonic He)



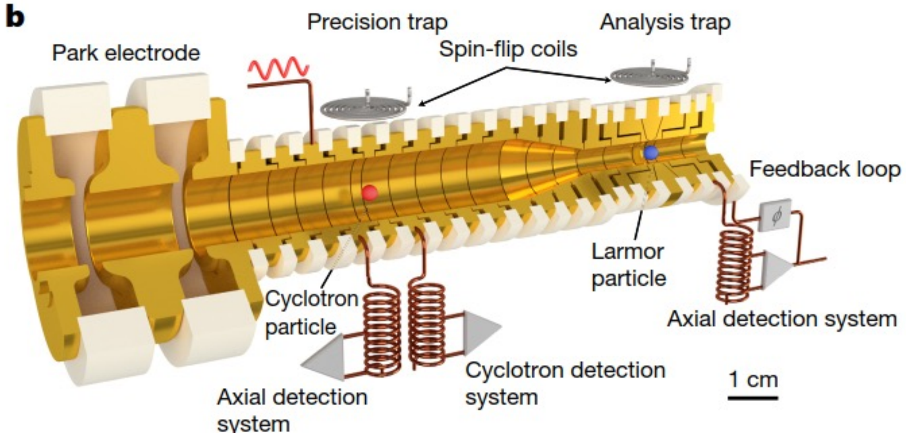
Electron – proton
(from hydrogen)

ASACUSA aims at improving the precision by 100 in coming years (M. Hori)

	Lorentz even	Lorentz odd
CPT even	→ ASACUSA → BASE SM Most of BSM, FIPs	LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT → BASE → ALPHA	LV EFT (e.g. SM Extension)

Antimatter techniques can be applied to FIPs searches

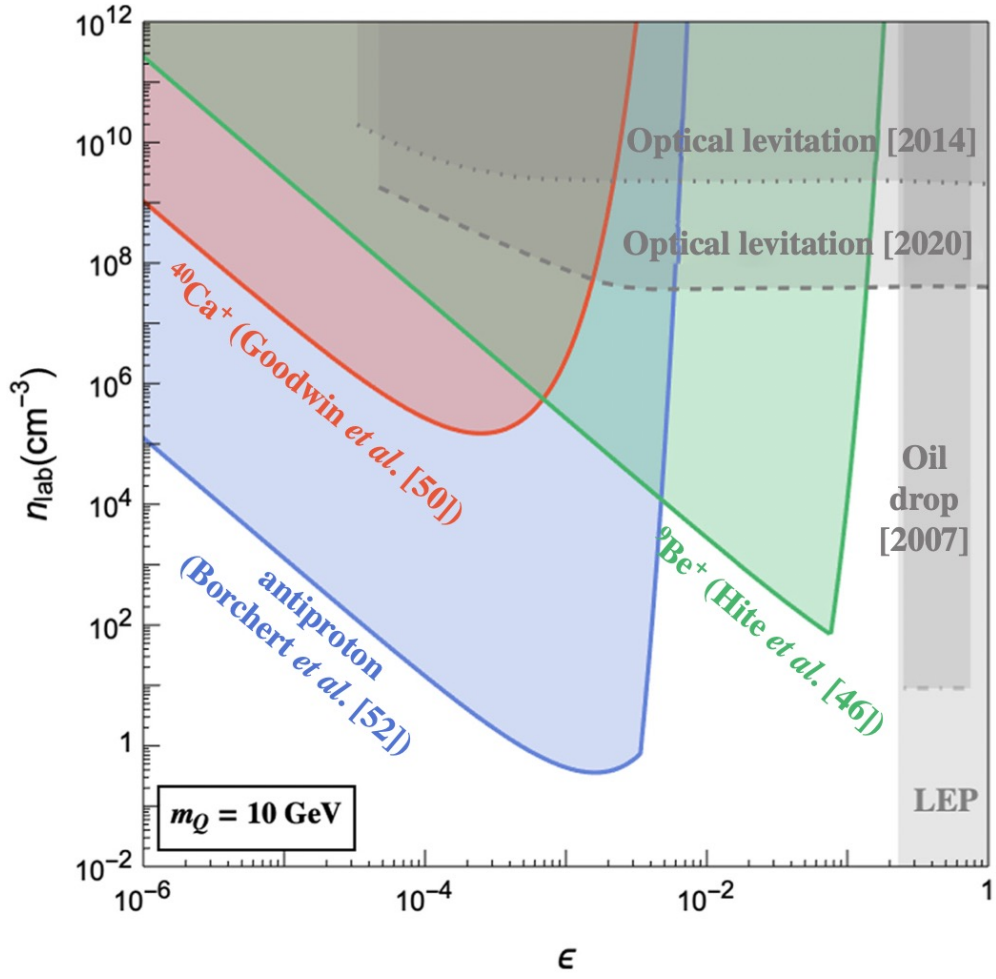
BASE: milli-charged particles



- BASE Penning trap: lowest noise trap

  [Phys. Rev. Lett. 122, 043201]
- Could search for anomalous heating from very low energy collisions, e.g. from milli-charged particles

  [Graham, Ramani, Budker, Ulmer etc. 2022]



PRX Quantum 3, 010330 (2022)

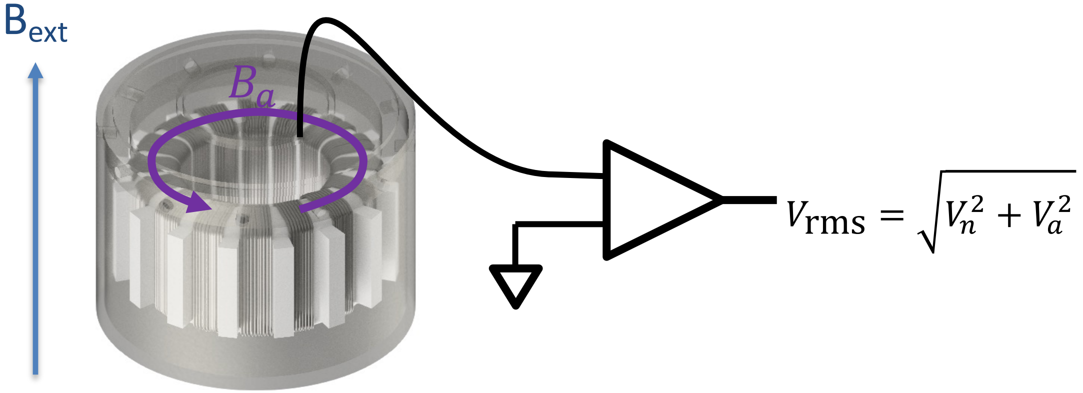
Also ALPHA limit on anti-H neutrality at 10^{-9}[Nature 2016]

BASE: Axion-Photon Coupling

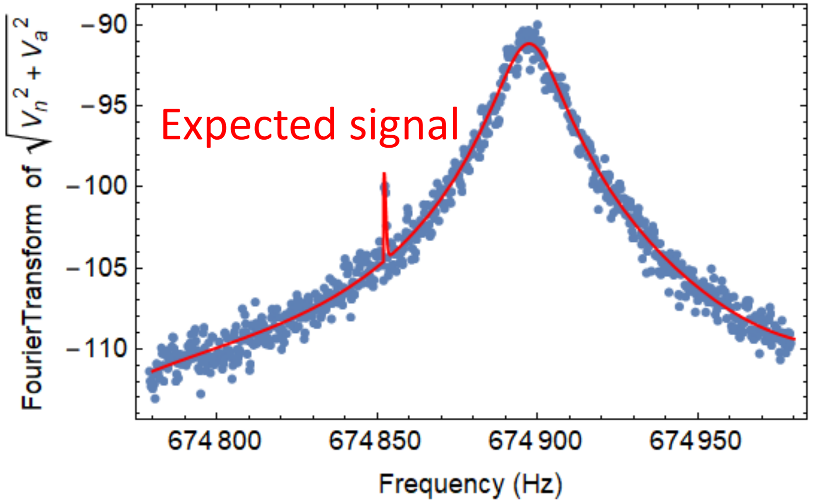
- Axion detection via LC circuits

[Sikivie et al. Phys. Rev. Lett. 112, 131301 (2014)]

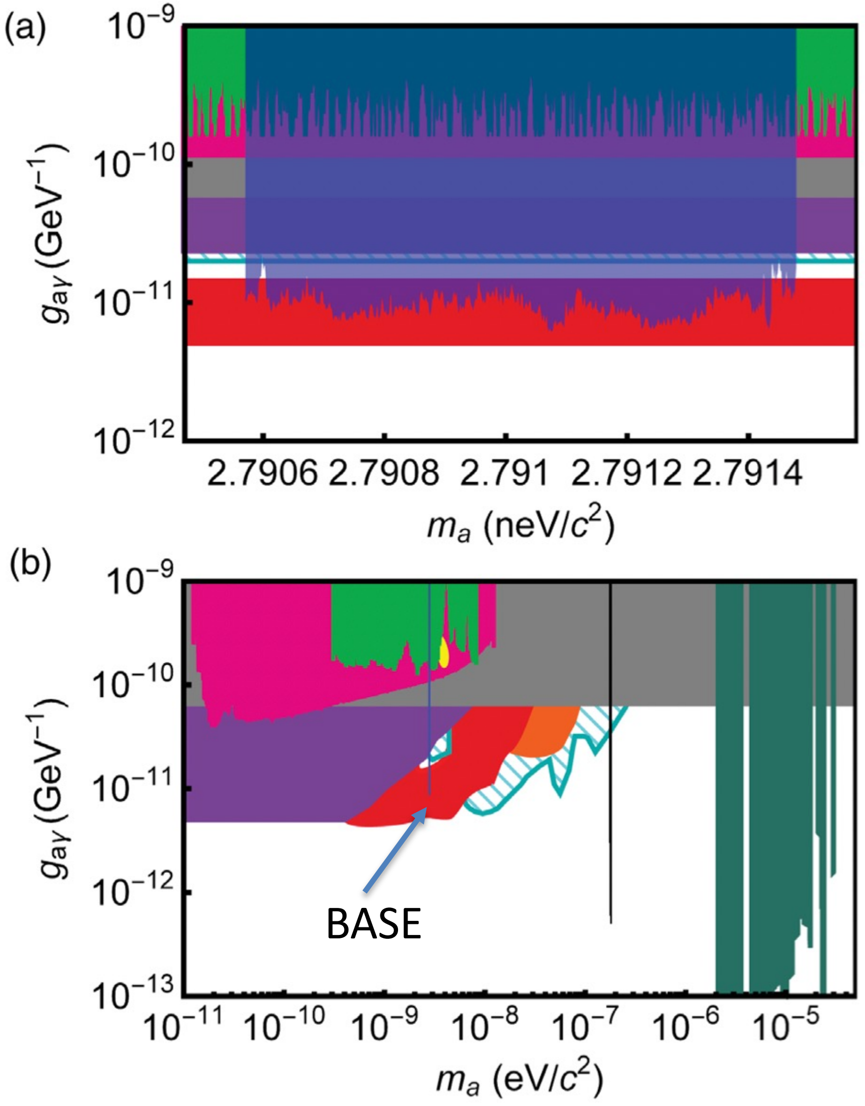
Axion in a strong B_{ext} field can source a small magnetic field B_a, which can be detected by BASE's sensitive detector



$$V_{\text{rms}} = \sqrt{V_n^2 + V_a^2}$$



Phys. Rev. Lett. 126, 041301 (2021)



Trapped pbar used to characterize the detector

Slide from Stefan Ulmer

Future potential

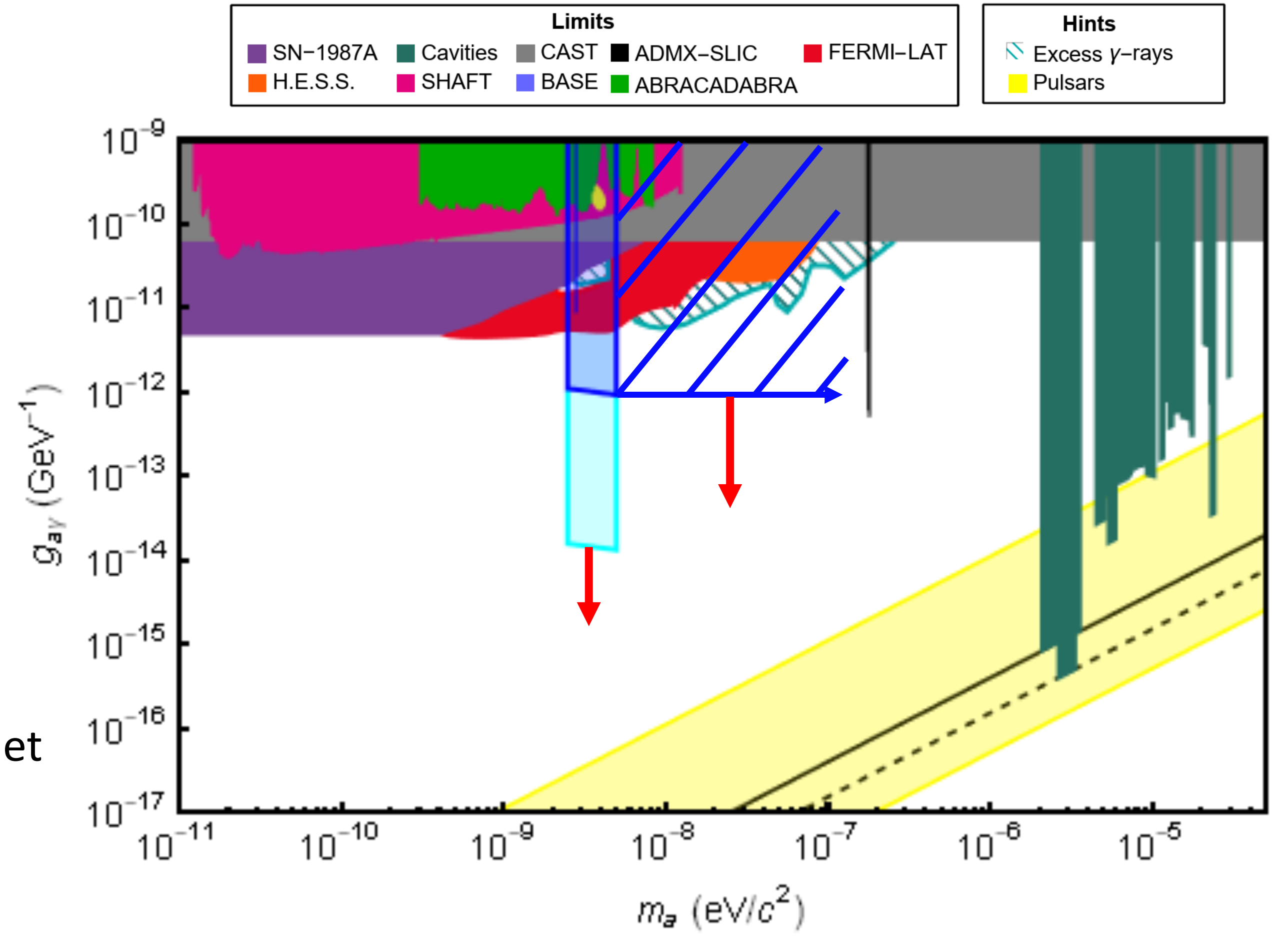
Small detector(s): 5 cm long, 5 cm diameter

🟦 **Immediately realizable with BASE technology today**, 6-9 months assembly time
($\frac{e_n}{\kappa} = 2.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, 7 T, 1 year acquisition)

▨ Possible in the short term with detector RnD work using BASE know-how
($\frac{e_n}{\kappa} = 2.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, 7 T, 1 year acquisition, use multiple higher frequency coils without excessive Q-loss)

Large detector: 80 cm long, 14 cm diameter

□ Optimistic projection, “normal” Penning trap magnet
($\frac{e_n}{\kappa} = 2.4\ \mathrm{nV}/\sqrt{\mathrm{Hz}}$, 7 T, 1 year acquisition, 10 mK, Q=200,000)



Pushing the sensitivity further

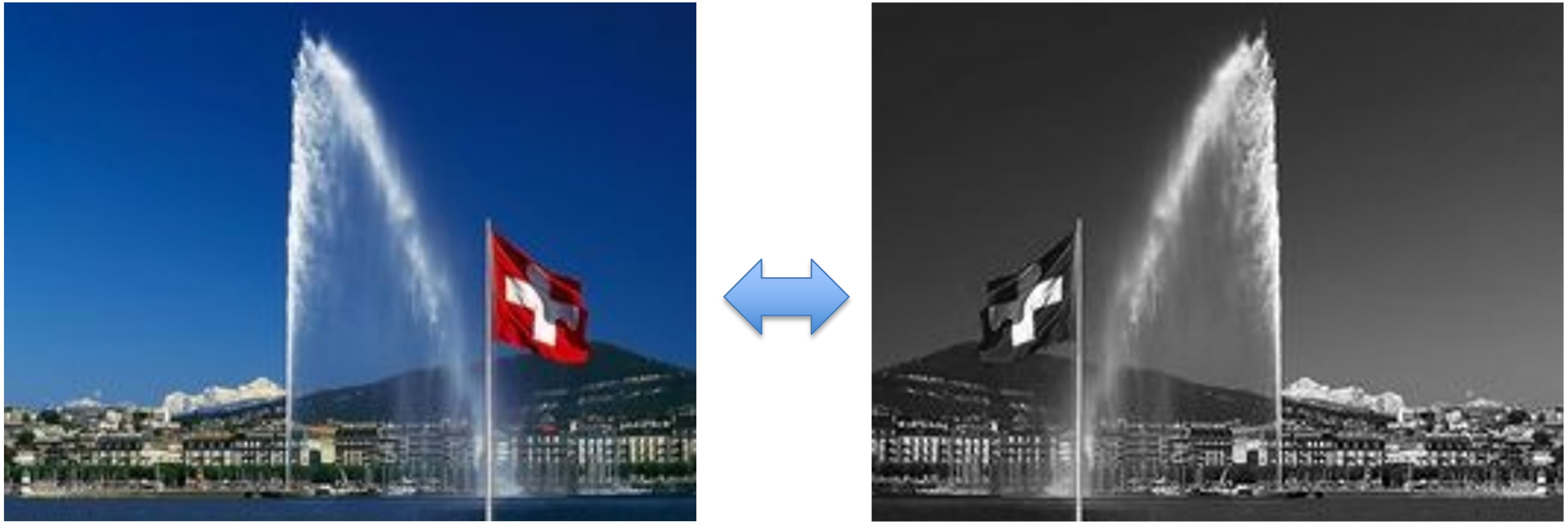
↓
- Much large detector volumes- **in discussion with RADES/babyIAXO**
- Colder detectors- **laser cooled resonators?**
- Lower noise amplifiers – particle assisted readout?

	Lorentz even	Lorentz odd
CPT even	→ ASACUSA → BASE → Hydrogen SM Most of BSM, FIPs	LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT → BASE → ALPHA	LV EFT (e.g. SM Extension)

Pushing precision of Hydrogen experiments with new techniques

→ Could set limits on new bosons, e.g. Jones, Potvliege, Sapnnowsky 2020

Example: (anti)hydrogen fountain!



Objective: to make precision hydrogen–antihydrogen comparison

in the same apparatus

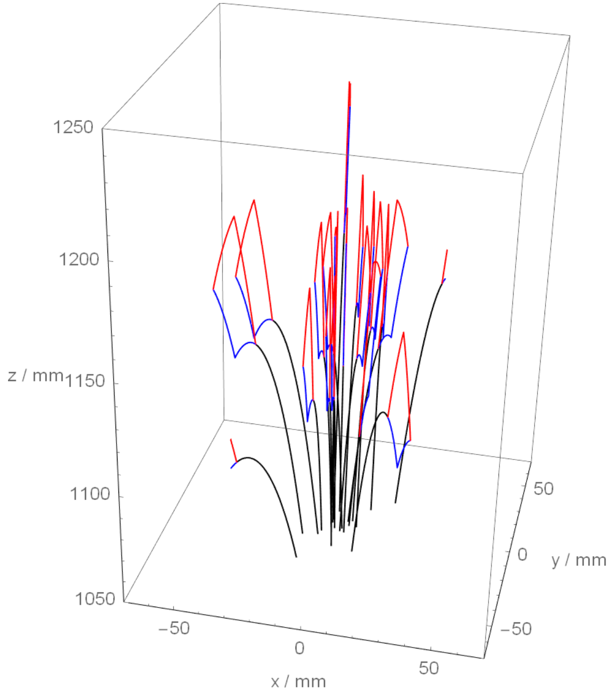
→ Need to improve both anti-H and H techniques!

New project at TRIUMF

HAICU(俳句): **H**ydrogen-**A**ntihydrogen **I**nfrastructure at **C**anadian **U**niversities

- R&D platform for development for “quantum sensing” techniques for anti-H
- Use H (and other cold atoms) as proxy
  - (Anti)atomic fountain
  - (Anti)Matter-wave interferometer
    With H. Mueller
  - Ramsey hyperfine spectroscopy
  - Optical trapping
  - Antimatter molecules
- Hydrogen difficult to handle
  - 1s-2p transition at 121 nm
  - Difficult to trap & detect
  - No fountain made with H

(Anti)Hydrogen Interferometer Simulation



- Techniques needed for anti-H could be useful to improve H measurements

TRIUMF

Summary of Examples (Not) Discussed

	Lorentz even	Lorentz odd
CPT even	→ ASACUSA → BASE → Hydrogen SM Most of BSM, FIPs	→ ASACUSA LV EFT (e.g. SM Extension)
CPT odd	Beyond local QFT → BASE → ALPHA →ASACUSA, AEGIS, Gbar	LV EFT (e.g. SM Extension) → BASE → ALPHA

Also, Weak Equivalence Principle tests by

- AEGIS
- Gbar
- ALPHA-g

Antimatter and FIPs: Take home

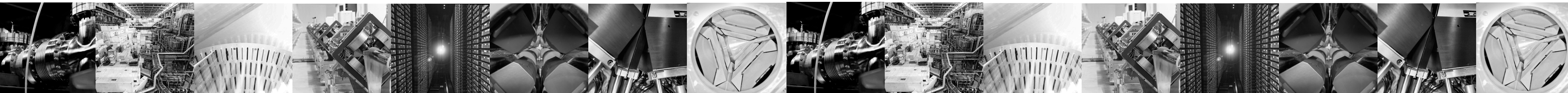
Experiments at CERN’s antimatter facility has been making tremendous progress in the past 20 years; Precision approaching, or surpassing, matter expts

Technologies developed can be applied to FIPs and other fundamental studies

Looking forward to fruitful collaborations!

Thank you, Merci!

Back up slides

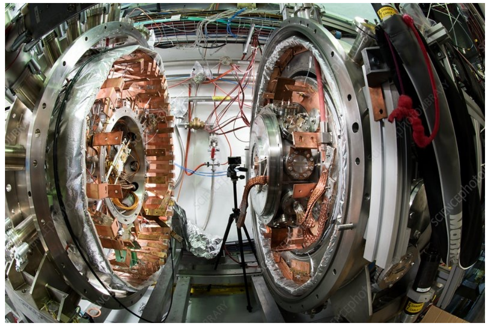


Gravity: Weak Equivalence Principle

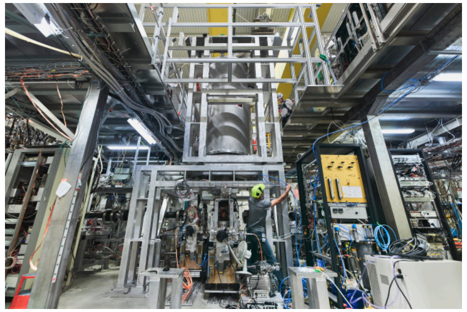
- Strong indirect evidence against matter-antimatter asymmetry (in QFT framework)
- No *direct* observational evidence below 1% [Lykken et al. arXiv:0808.3929]

- Gravitational Free fall
  - Dropping antimatter in the Earth's gravitational field
- 3 Expts ongoing at CERN
  - AEIGS, Gbar, ALPHA-g
  - Initial precision goal: 1%
    This is really hard!

- Clock comparison
  - Gravitational red shift
- Need antimatter & matter clocks
  - BASE: Pbar, P cyclotron frequency
    2×10^{-7} [Nature 2022]
  - ALPHA: 1s-2s transition frequency


AEGIS


Gbar


ALPHA-g

Limits on SME Coefficients: BASE

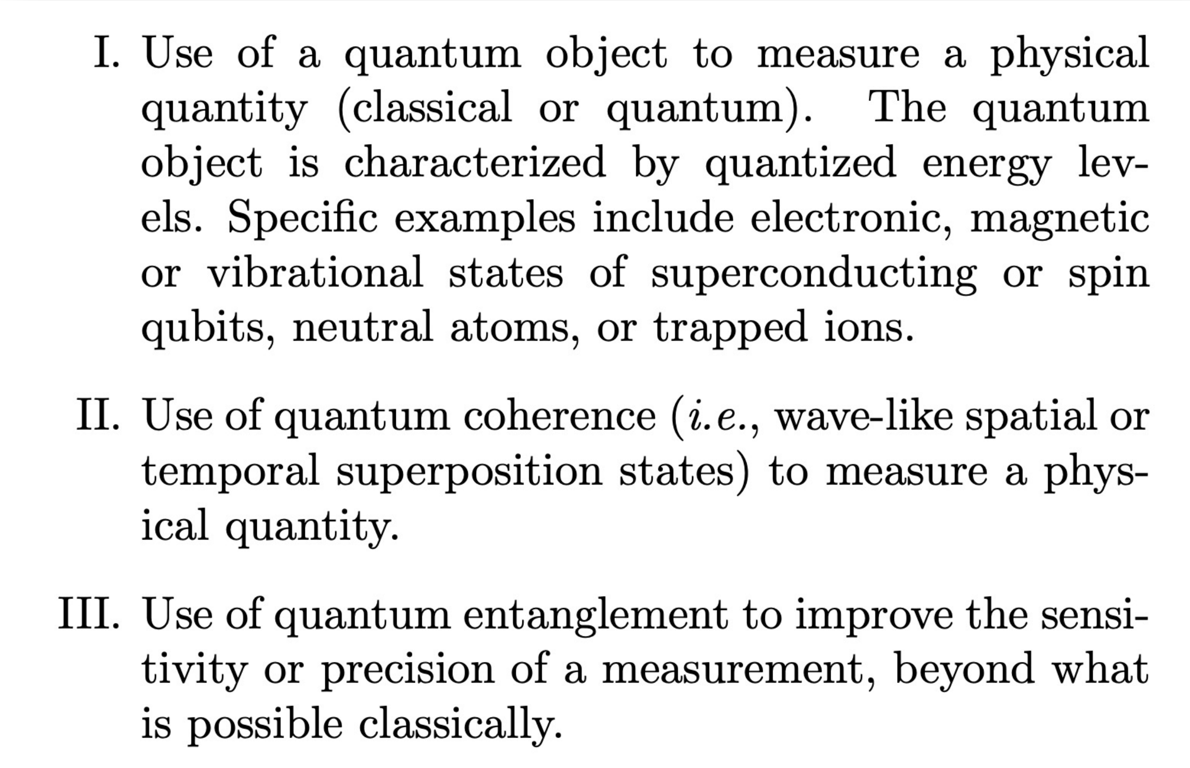
- The time-base analysis to constrain for the first time six coefficients of the Standard model extension with high precision

Coefficient	**Limit (CL 0.95)**
$\widetilde{b_p^{*X}}$	$9.7\times10^{-25}\ GeV$
$\widetilde{b_p^{*Y}}$	$9.7\times10^{-25}\ GeV$
$\widetilde{b_{F,p}^{*XX}} - \widetilde{b_{F,p}^{*XY}}$	$5.4\times10^{-9}\ GeV^{-1}$
$\widetilde{b_{F,p}^{*XZ}}$	$3.7\times10^{-9}\ GeV^{-1}$
$\widetilde{b_{F,p}^{*YZ}}$	$3.7\times10^{-9}\ GeV^{-1}$
$\widetilde{b_{F,p}^{*XY}}$	$2.7\times10^{-9}\ GeV^{-1}$

Antimatter as a Quantum Sensor

- Definition of "Quantum sensing"

Degen, Reinhard, Cappellaro, Rev. Mod. Phys. 89, 035002 (2017)



I. Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.

II. Use of quantum coherence (*i.e.*, wave-like spatial or temporal superposition states) to measure a physical quantity.

III. Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.

Quantum Sensing with Antimater

← We are here with ALPHA

← We want to go there with HAICU

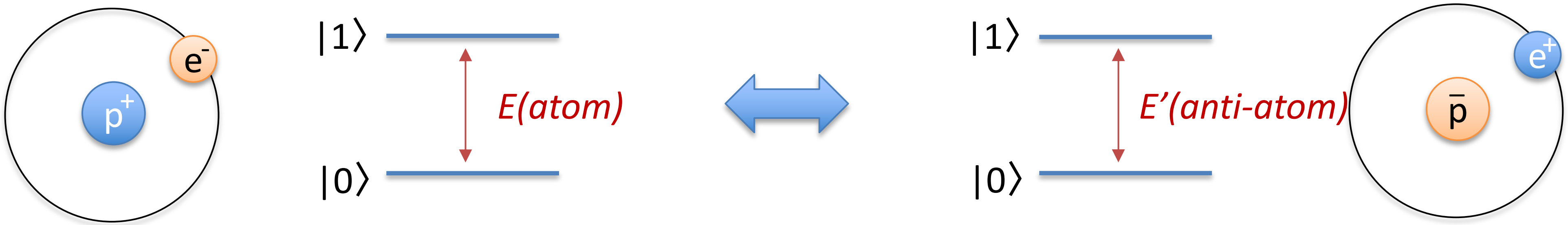
← This is our ultimate dream

(Anti)Atom or Ion as a Quantum Sensor

Atomic quantum sensor

Rev. Mod. Phys. 89, 035002 (2017)

Anti-atomic quantum sensor



$$E(\text{atom}) = E_0 + \Delta E_{ext} + \Delta E_{NP} \; (\equiv E_{QFT})$$

$E_0 \sim m_e \alpha^2 + \ldots \text{fn}\{Q_e, Q_p, m_e, m_p, r_p, \mu_e \ldots\}$

ΔE_{ext} : due to Ext field, e.g. *E*, *B*, Gravity

ΔE_{NP} : due to New Physics, e.g. DM, 5th force …

(could vary in time)

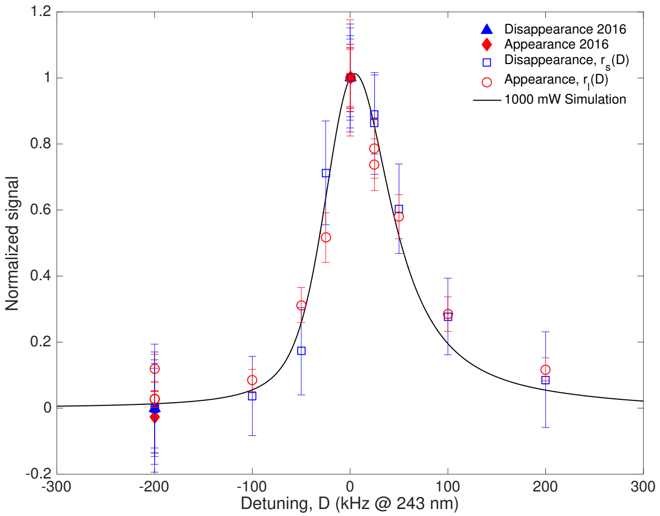
$$E'(\text{anti-atom}) = E_{QFT} + \Delta E_{CPTV}$$

E_{CPTV} : Shift due to CPT violation;

Beyond Quantum Field Theory!

CPT theorem requires $E = E'$ (i.e. $\Delta E_{CPTV} = 0$) in any local relativistic QFTs

Statistical Sensitivity of Anti-H Spectroscopy

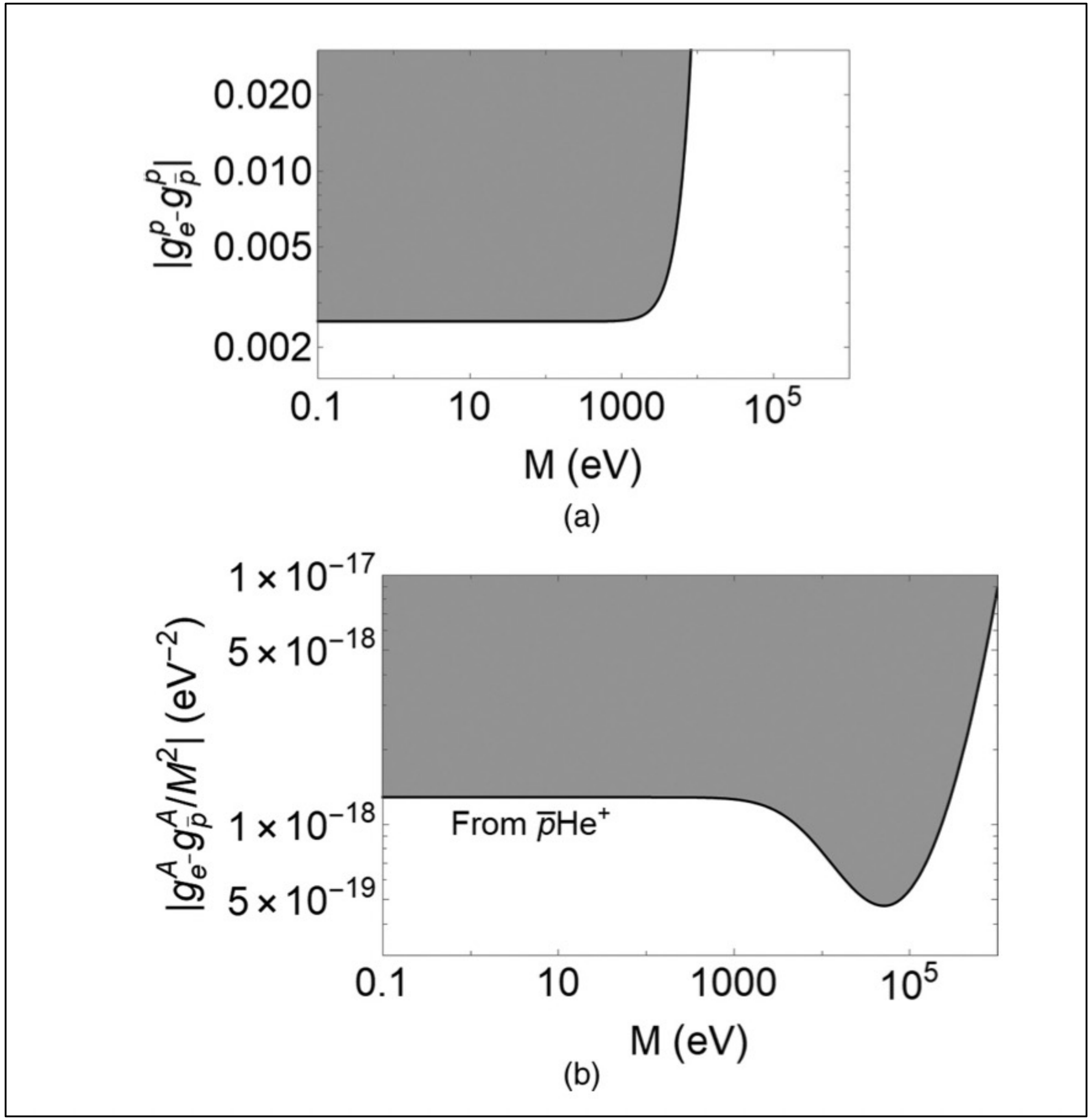


Ant-H 1s-2s resonance
[Nature 2018]

$$\Delta f \sim \frac{1}{W_{line} \cdot \sqrt{\varepsilon_{det} \cdot N_{atom}} \cdot P_{trans}}$$

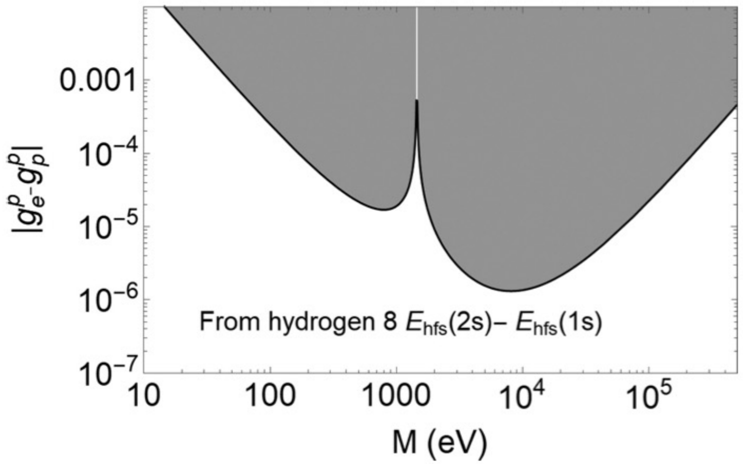
Factors		Example of technologies
# trapped atoms	→	Trap & plasma techniques
Transition probability	→	laser, microwaves
Spectral linewidth	→	Laser cooling (Note 1/linear scaling!)
Detection efficiency	→	Si vertex detector, radial TPC

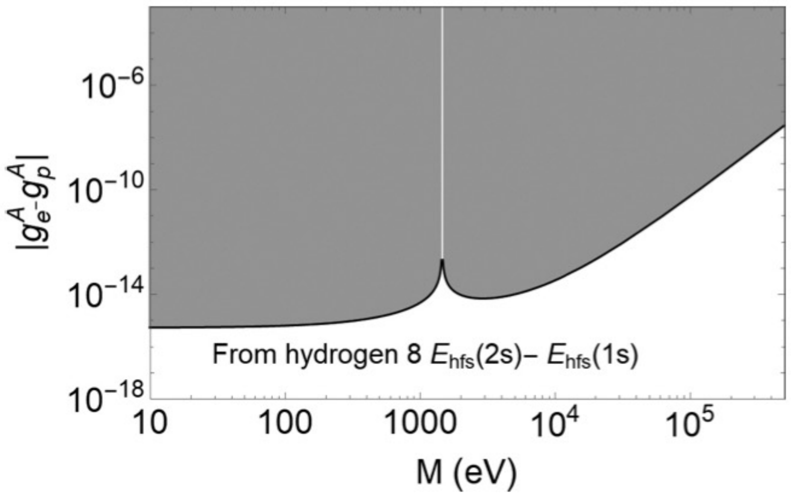
Feels crazy to talk about “sensitivity”…


0.020
0.010
0.005
0.002
$|g_e^p g_{\bar{p}}^p|$
0.1
10
1000
10^5
M (eV)
1×10^{-17}
5×10^{-18}
1×10^{-18}
5×10^{-19}
$|g_e^A g_{\bar{p}}^A/M^2|$ (eV^{-2})
From $\bar{p}$He$^+$
0.1
10
1000
10^5
M (eV)

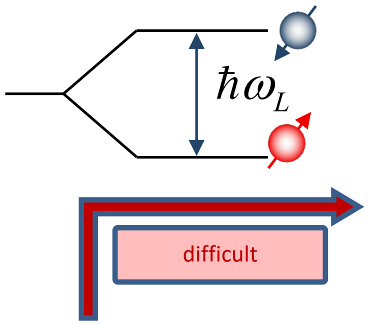
(a)

(b)


0.001
10^{-4}
10^{-5}
10^{-6}
10^{-7}
$|g_e^p g_p^p|$
From hydrogen 8 $E_{\rm hfs}(2s) - E_{\rm hfs}(1s)$
10
100
1000
10^4
10^5
M (eV)

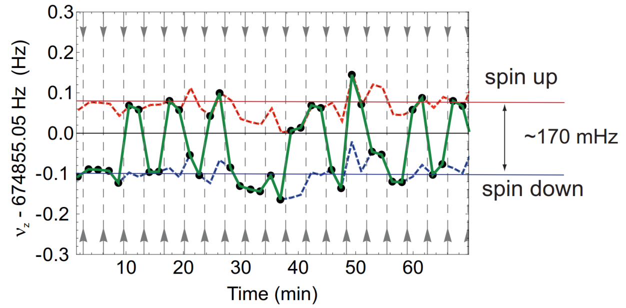

10^{-6}
10^{-10}
10^{-14}
10^{-18}
$|g_e^A g_p^A|$
From hydrogen 8 $E_{\rm hfs}(2s) - E_{\rm hfs}(1s)$
10
100
1000
10^4
10^5
M (eV)

BASE: Magnetic Moment Measurements



Continuous Stern Gerlach Effect

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



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

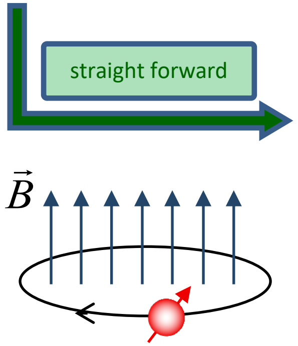
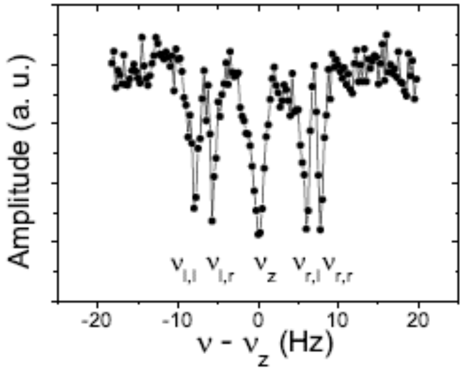
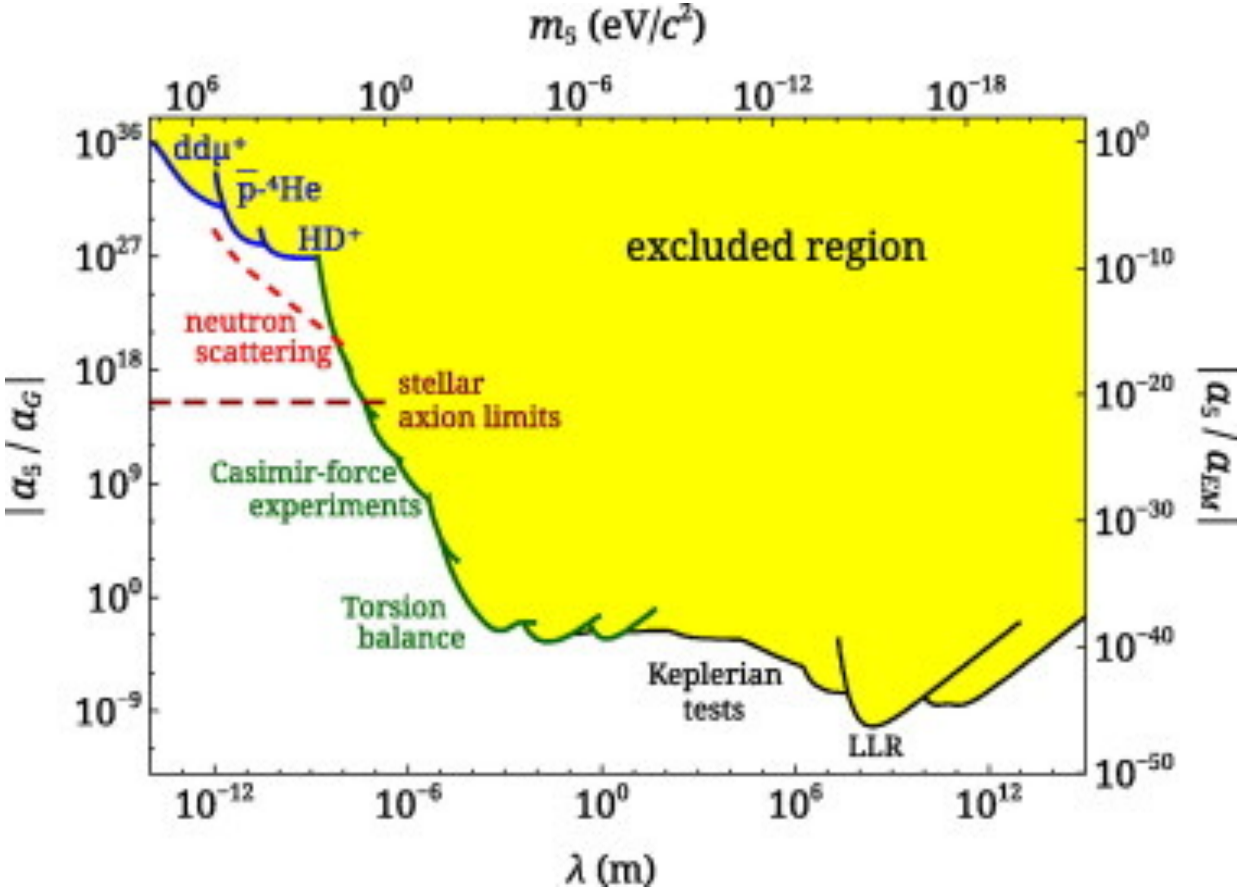
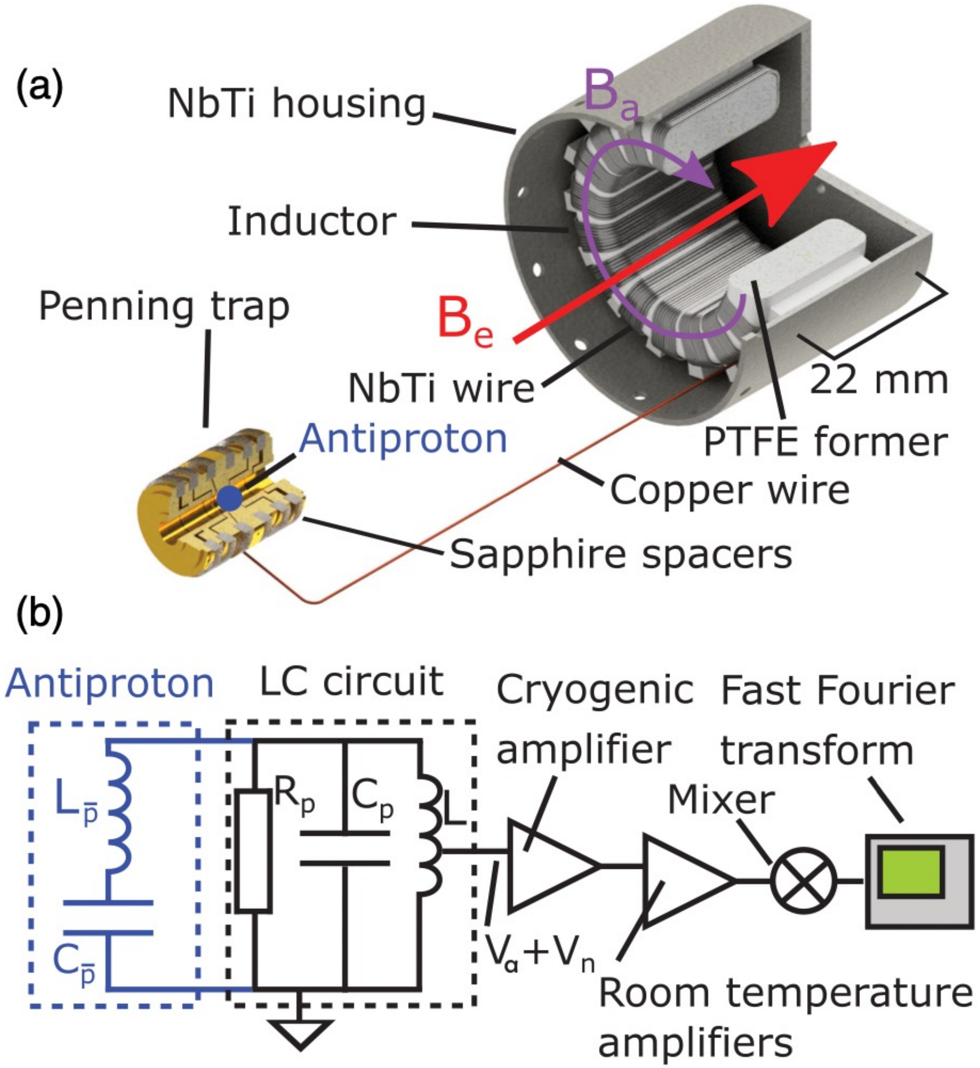


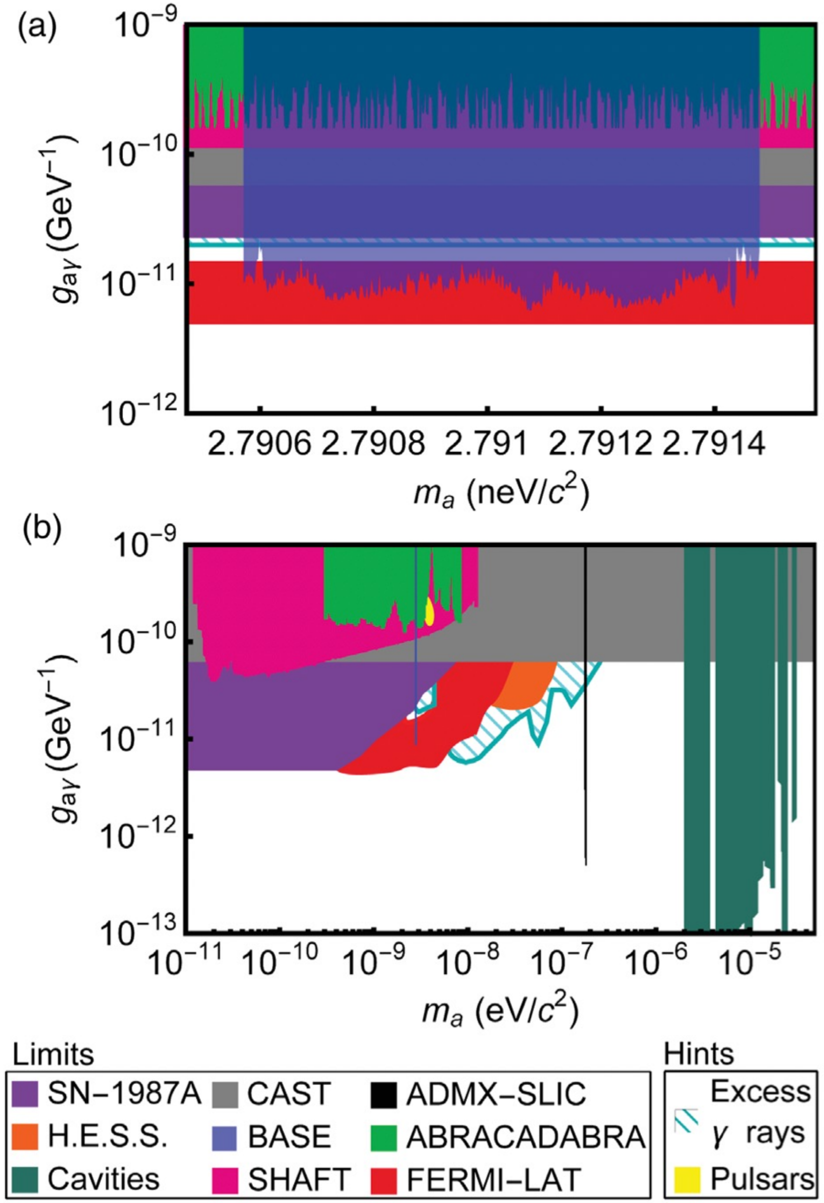
Image Current Measurements



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


m_5 (eV/c^2)
10^6
10^0
10^{-6}
10^{-12}
10^{-18}
10^{36}
10^{27}
10^{18}
10^9
10^0
10^{-9}
$|\alpha_5 / \alpha_G|$
10^0
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
$|\alpha_5 / \alpha_{EM}|$
ddμ⁺
$\bar{p}$-⁴He
HD⁺
excluded region
neutron
scattering
stellar
axion limits
Casimir-force
experiments
Torsion
balance
Keplerian
tests
LLR
10^{-12}
10^{-6}
10^0
10^6
10^{12}
λ (m)


(a)
NbTi housing
B_a
Inductor
Penning trap
B_e
NbTi wire
Antiproton
22 mm
PTFE former
Copper wire
Sapphire spacers
(b)
Antiproton
LC circuit
Cryogenic amplifier
Fast Fourier transform
$L_{\bar{p}}$
$C_{\bar{p}}$
R_p
C_p
L
Mixer
$V_\alpha+V_n$
Room temperature amplifiers


(a)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
$g_{a\gamma}\,(\mathrm{GeV}^{-1})$
2.7906
2.7908
2.791
2.7912
2.7914
$m_a\ (\mathrm{neV}/c^2)$
(b)
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
$g_{a\gamma}\,(\mathrm{GeV}^{-1})$
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
$m_a\ (\mathrm{eV}/c^2)$
Limits
SN−1987A
CAST
ADMX−SLIC
H.E.S.S.
BASE
ABRACADABRA
Cavities
SHAFT
FERMI−LAT
Hints
Excess γ rays
Pulsars

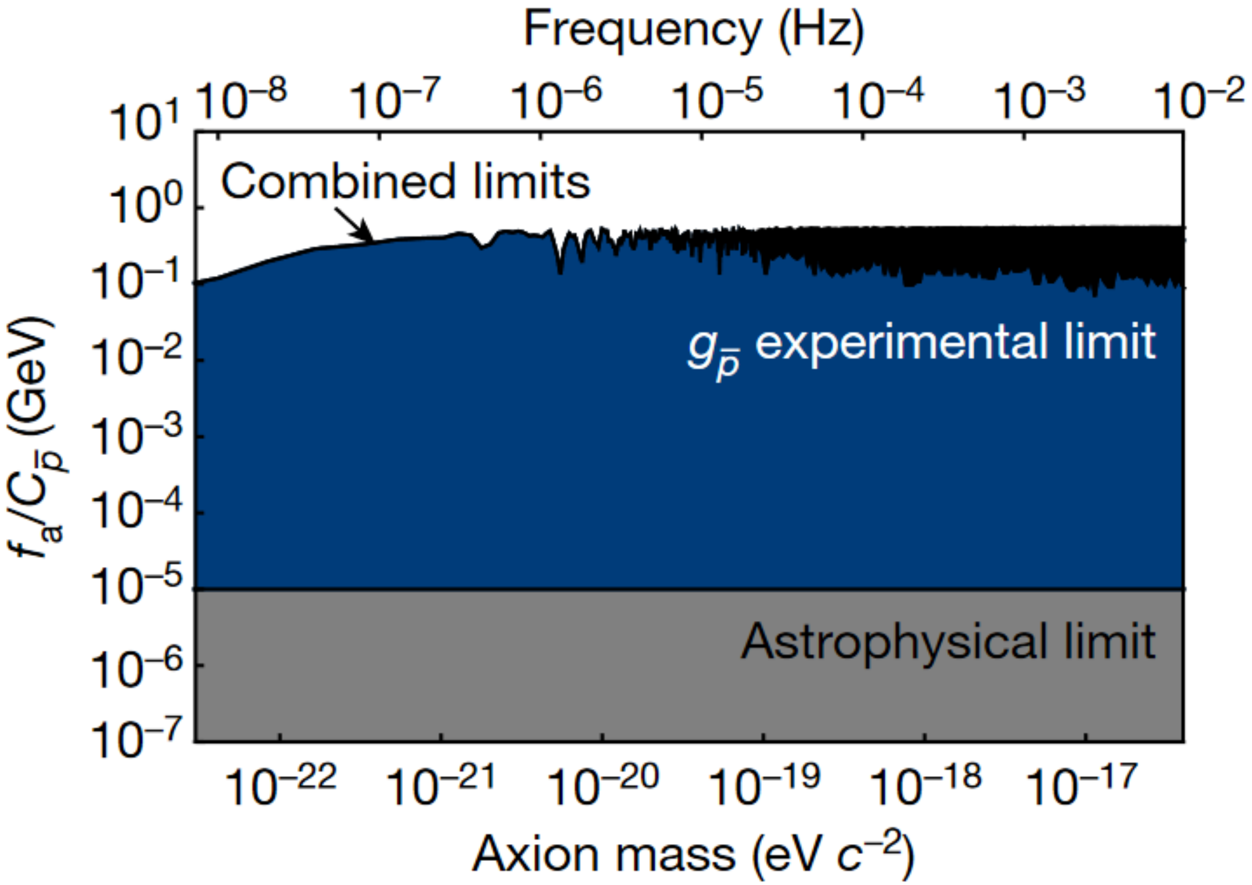
Couplings between dark matter and antiprotons

Measure the coupling $\mathcal{L}_{\text{int}} = -\frac{\partial a}{f_a}\bar{\psi}\gamma^{\mu}\gamma^{5}\,\psi$ between ultralight, pseudoscalar ALP relic dark matter and $\bar{p}$

Interaction

$$H_{\text{int}} = -\frac{C_{\bar{p}}a_0}{2f_a}\sin(\omega_a t)\,\vec{\sigma}_{\bar{p}}\cdot\vec{p}_a$$

between the momentum of the axion field $\vec{p}_a$ and the antiproton spin vector $\vec{\sigma}_{\bar{p}}$ oscillating at the axion Compton frequency $\omega_a = m_a c^2/\hbar$

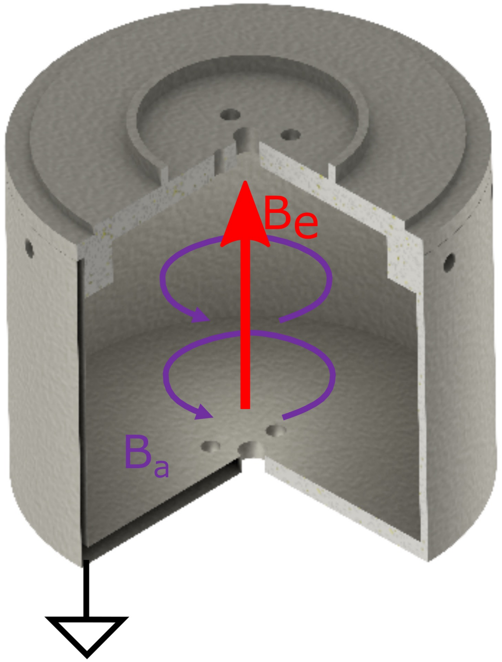


Should cause characteristic time dependent variation in ν_L, by constraining the size of this a-$\bar{p}$ coupling limits extracted

a- $\bar{p}$ coupling limits a natural bi-product of precision CPT tests

C. Smorra *et al.*, Nature **575**, 310 (2019).

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

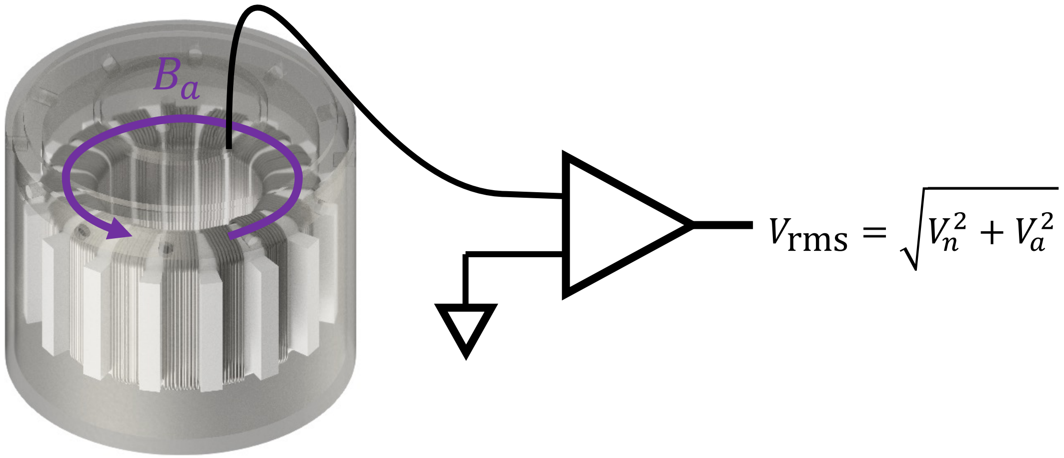
$$\nabla \cdot \vec{E} = \rho - g_{a\gamma}\, \vec{B} \cdot \nabla a$$
$$\nabla\times\vec{B} - \partial_t\vec{E} = \vec{J} + g_{a\gamma}(\vec{B}\partial_t a - \vec{E}\times\nabla a)$$
$$\nabla \cdot \vec{B} = 0$$
$$\nabla\times\vec{E} + \partial_t\vec{B} = 0$$

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

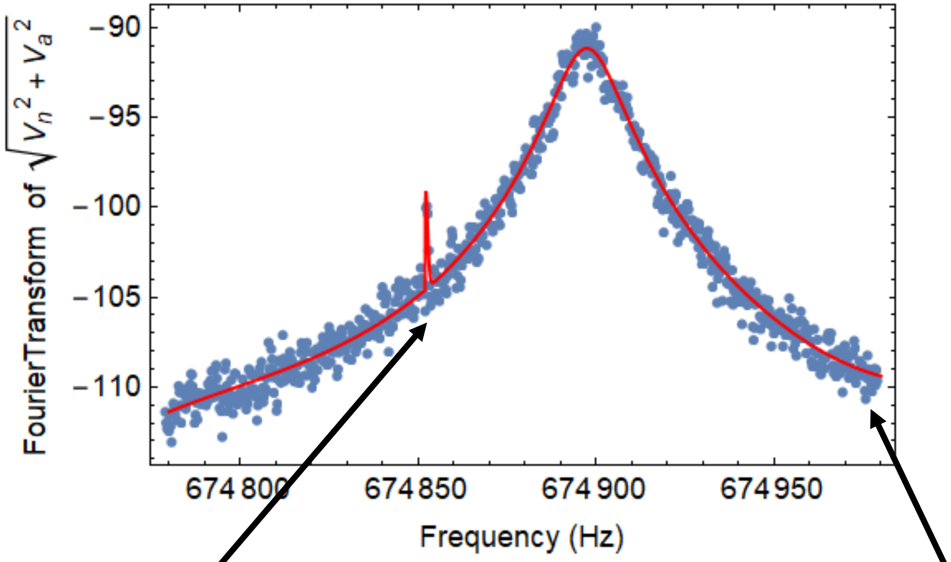
$$\left|\vec{B}_a\right| = \frac{1}{2} r g_{a\gamma} \left|\vec{B}_0\right| \sqrt{\rho_a \hbar c}$$

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

Expected signal



$$V_{\mathrm{rms}} = \sqrt{V_n^2 + V_a^2}$$



The axion signal

$$V_a = \frac{\pi}{2} Q \sqrt{f(\nu, Q, \mathbf{q})}\, \kappa \nu_a l N_{\mathrm{T}} (r_2^2 - r_1^2) g_{a\gamma} ||\mathbf{B}_e|| \sqrt{\rho_a \hbar c}\,.$$

The resonator background

$$V_n = \sqrt{e_n^2 \Delta\nu + \kappa^2 4 k_B T_z \Delta\nu R_p f(\nu, Q, \mathbf{q})}$$

f(ν,Q,**q**) is a lorentzian line-shape function proportional to Re{Z}
e_n is the equivalent input noise of the amplifier
κ is the coupling constant
Q is the resonator Q-factor
N_T is the number of turns
l is the length of the toriod along the magnet B field

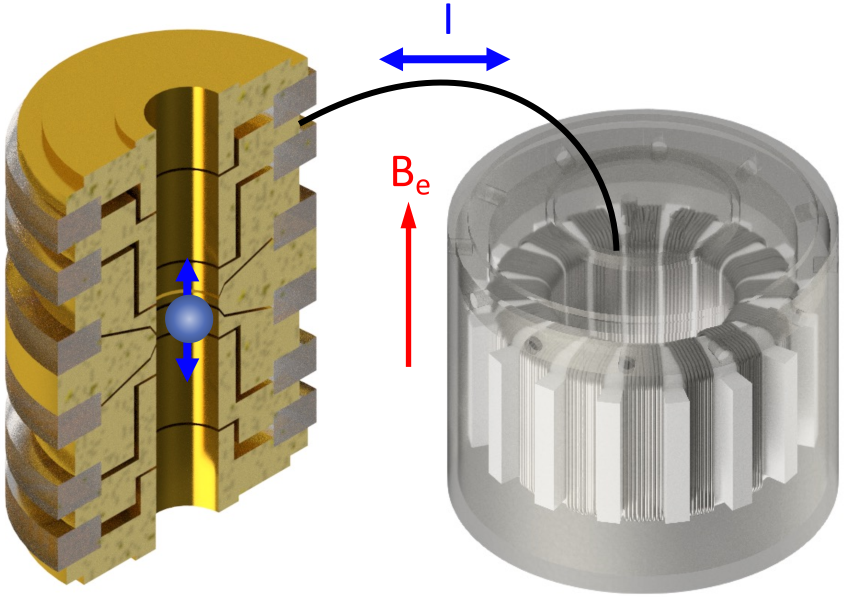
r_1 is the inner radius of the toroid
r_2 is the outer radius
$g_{a\gamma}$ is the coupling constant
B is the static magnetic field
ρ_a is the dark matter density

How to measure T_z?

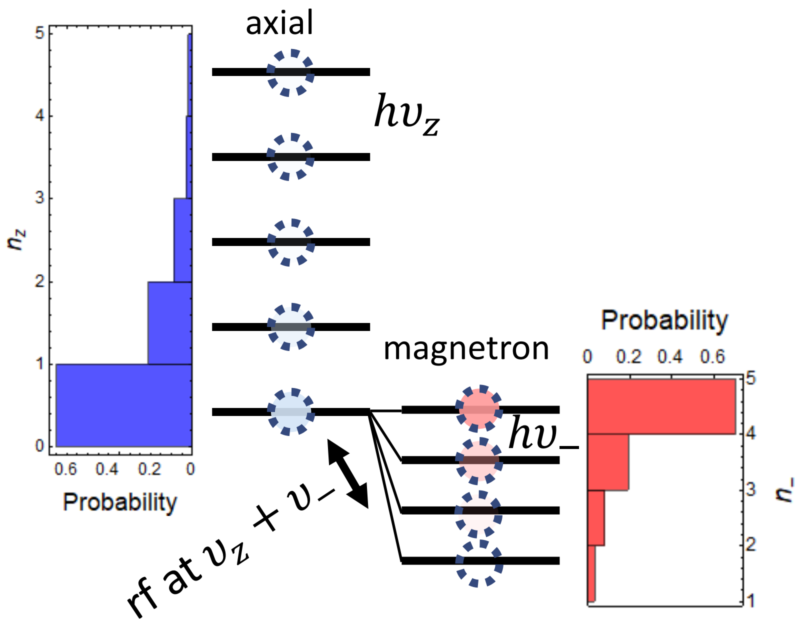
J. A. Devlin et al., Phys. Rev. Lett. **126**, 041301 (2021).

A quantum “Boltzmann” thermometer

1.



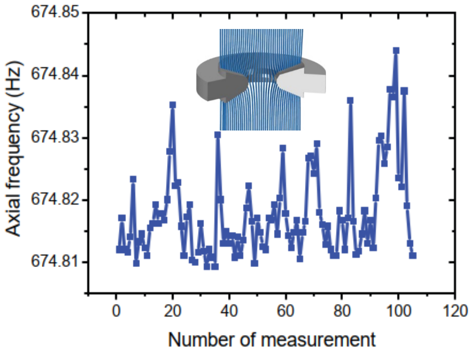
2.



Trapped antiproton’s axial motion reaches thermal equilibrium with the detector- can use it as a “quantum” sensor

3.

Magnetic inhomogneity gives axial frequency shift proportional to $\mu \propto n_-$



Knowing strength of inhomogeneity, can determine T_z