680 Times Improved Measurement of the Antiproton Magnetic Moment

Gerald Gabrielse
Leverett Professor of Physics, Harvard University
Spokesperson of the CERN ATRAP Collaboration

Supported by NSF and AFOSR

- Antihydrogen
- Electron and Antiproton Magnetic Moments
- Does the Electron have and Electric Dipole Moment?

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Antihydrogen Update

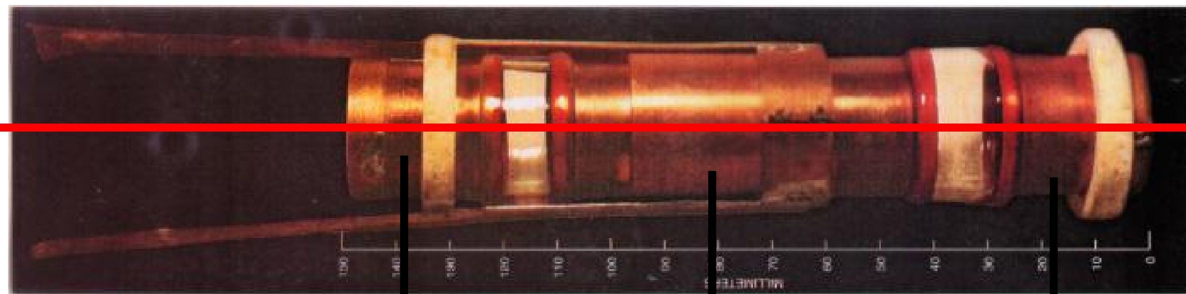
27 Years Since We First Trapped and Then Cooled Antiprotons

TRAP Collaboration
at CERN's LEAR

1 cm

magnetic field

21 MeV antiprotons



− + −

10^{-10} energy reduction

- **Slow antiprotons in matter**
- **Capture antiprotons in flight**
- **Electron cooling → 4.2 K**
- **5 x 10^{-17} Torr**

Now used by 5 collaborations at the CERN AD
ATRAP, ALPHA, ASACUSA, AEGIS, BLAZE

Proposal to Trap Cold Antihydrogen – 1986

- **Produce cold antihydrogen from cold antiprotons**

"When antihydrogen is formed in an ion trap, the neutral atoms will no longer be confined and will thus quickly strike the trap electrodes. Resulting annihilations of the positron and antiproton could be monitored. ..."

- **Trap cold antihydrogen**
- **Use accurate laser spectroscopy to compare antihydrogen and hydrogen**

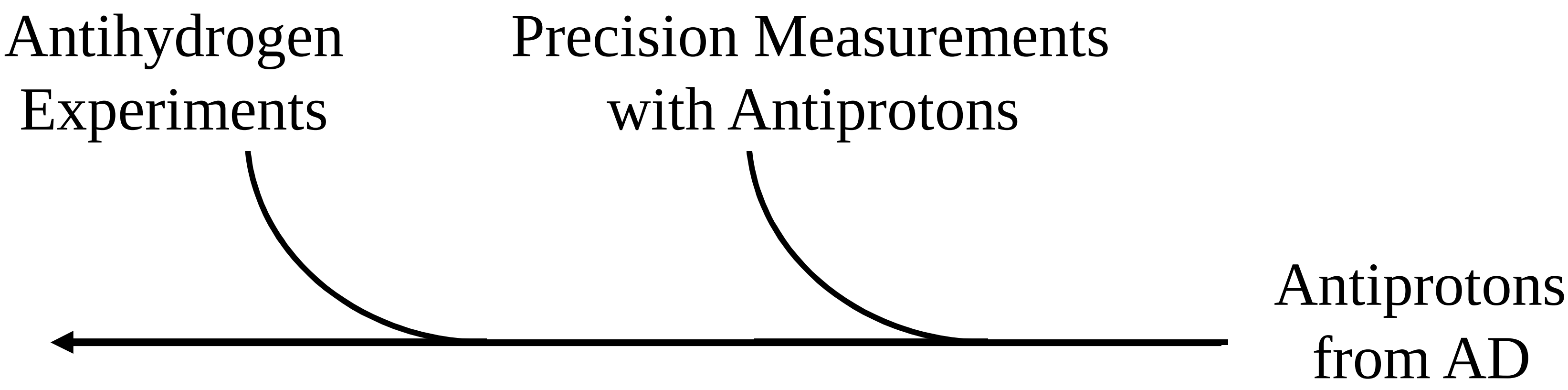
"For me, the most attractive way ... would be to capture the antihydrogen in a neutral particle trap ... The objective would be to then study the properties of a small number of [antihydrogen] atoms confined in the neutral trap for a long time."

Gerald Gabrielse, 1986 Erice Lecture (shortly after first pbar trapping)
In **Fundamental Symmetries**, (P.Bloch, P. Paulopoulos, and R. Klapisch, Eds.) p. 59, Plenum, New York (1987).

Use trapped antihydrogen to measure antimatter gravity

G. Gabrielse, Hyperfine Interact. 44, 349 (1988)

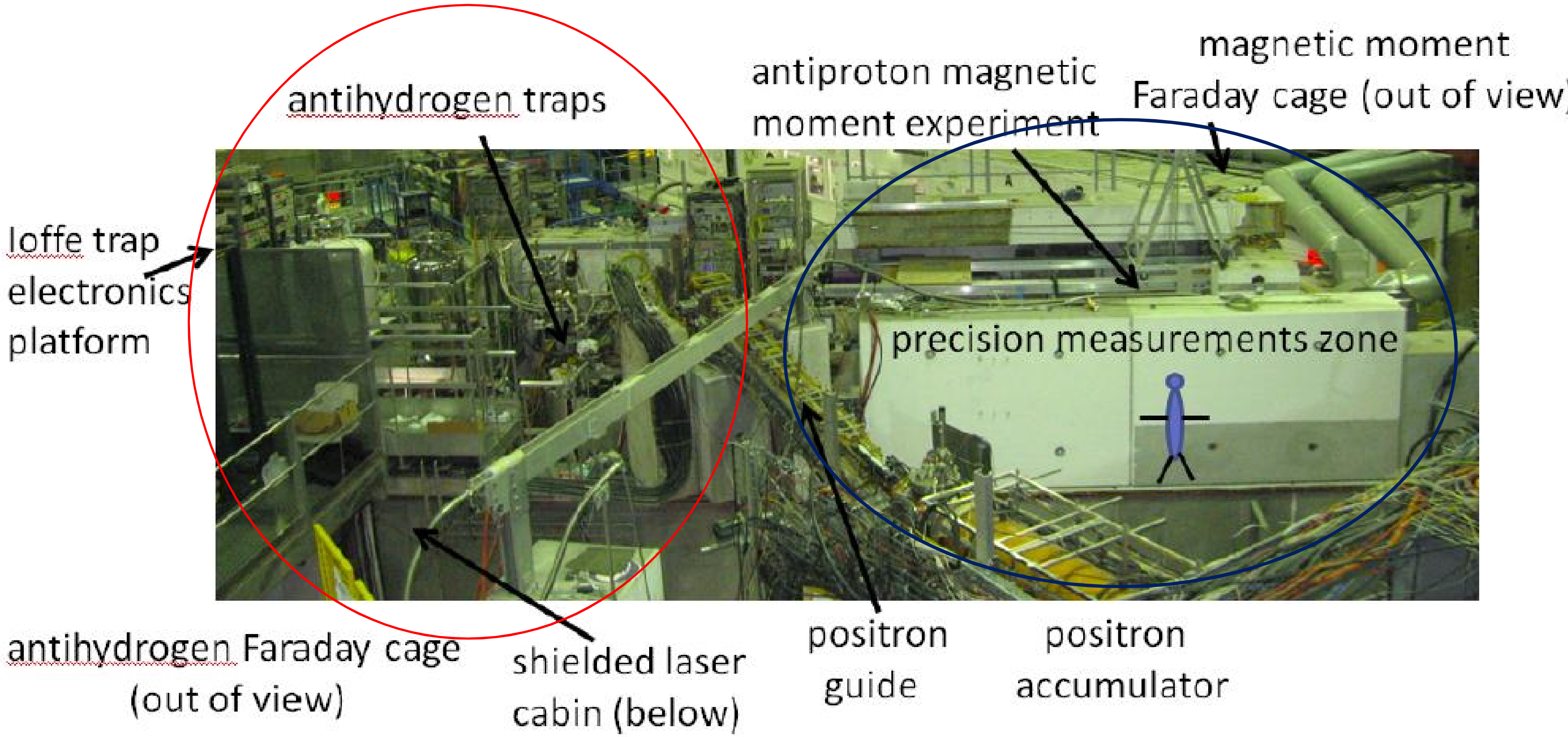
ATRAP Apparatus Built to do Two Types of Experiments Simultaneously



trapped antihydrogen in its ground state

680-fold improved measurement of the antiproton magnetic motion

Simultaneous Antihydrogen Experiments and Precision Measurements



ATRAP Experimental Area

ATRAP Collaboration

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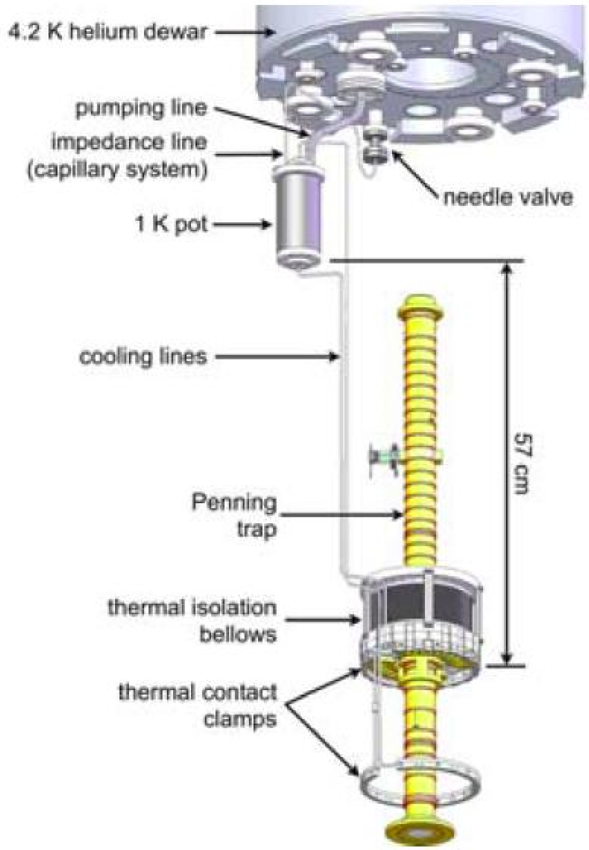
1.2 K Electrodes and Millions of Antiprotons



1.2 K Using
Pumped Helium

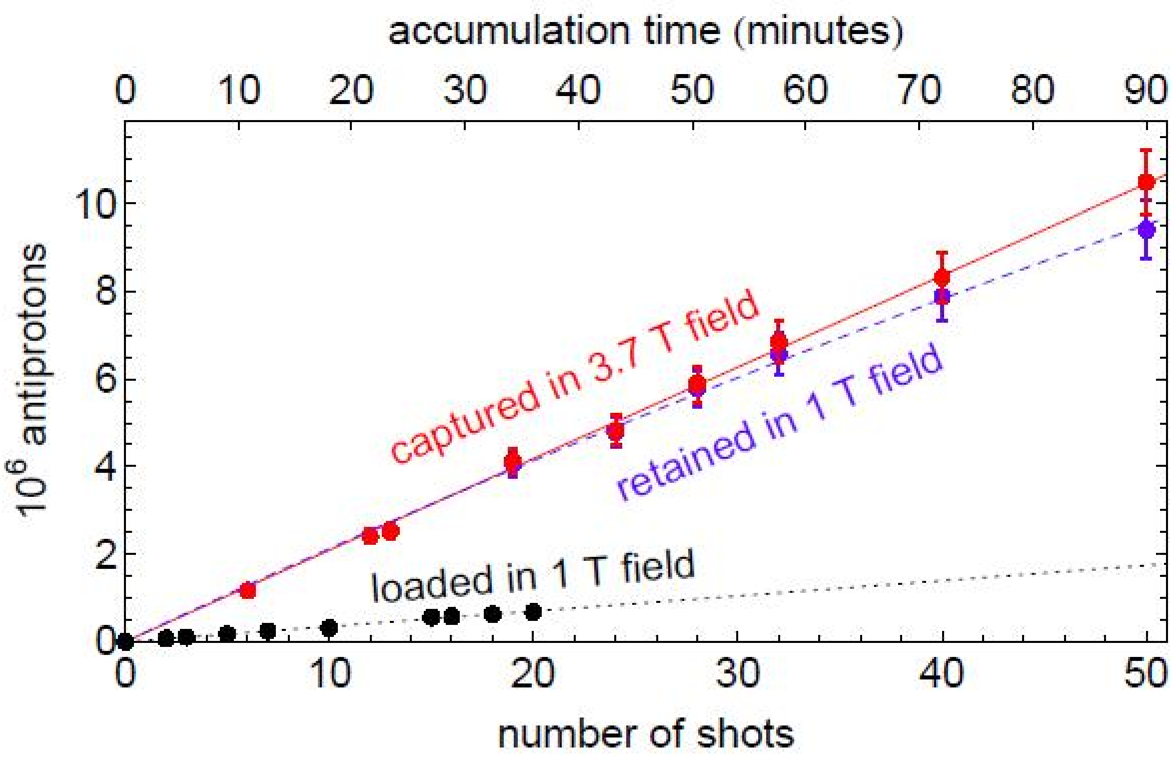
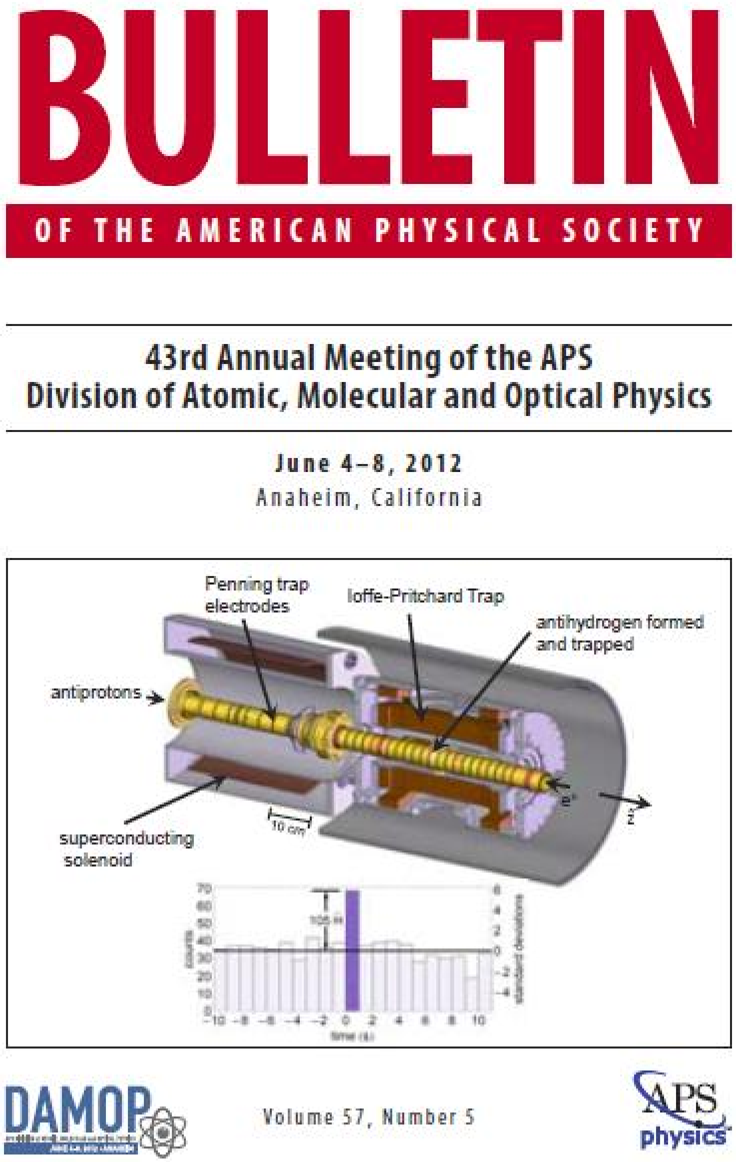


Figure 4: Accumulation of ten million $\overline{\mathrm{p}}$.

ELENA will make this much faster!

Trapped Antihydrogen in Its Ground State



Used larger antiproton and positron plasmas

→ Much more trapped antihydrogen per trial

→ still not nearly enough

5 +/- 1 ground state atoms simultaneously trapped

ATRAP, "Trapped Antihydrogen in Its Ground State", Phys. Rev. Lett. **108**, 113002 (2012)

Direct Comparison of Antimatter and Matter Gravity

Does antimatter and matter accelerate at the same rate in a gravitational field?

$$g_{antimatter} \overset{\copyright}{=} g_{matter}$$

acceleration due to gravity for antimatter

acceleration due to gravity for matter

The Most Precise Experimental Answer is "Yes" → to at lease a precision of 1 part per million

Gravitational red shift for a clock: $\Delta\mu / \mu = g\, h / c^2$

→ Antimatter and matter clocks run at different rates
if g is different for antimatter and matter

$$\frac{\Delta\mu_c}{\mu_c} = 3(© - 1)\frac{U}{c^2}$$

Hughes and Holzscheiter, Phys. Rev. Lett. 66, 854 (1991).

for tensor gravity
(would be 1 for scalar gravity)

grav. pot. rnergy difference
between empty flat space time
and inside of hypercluster of galaxies

Experiment: TRAP Collaboration, Phys. Rev. Lett. 82, 3198 (1999).

$$\frac{\Delta\mu_c}{\mu_{\partial c}} < 10^{-10} \quad --> \quad © = 1 \pm (< 10^{-6})$$

Why is this stringent direct comparison never quoted?

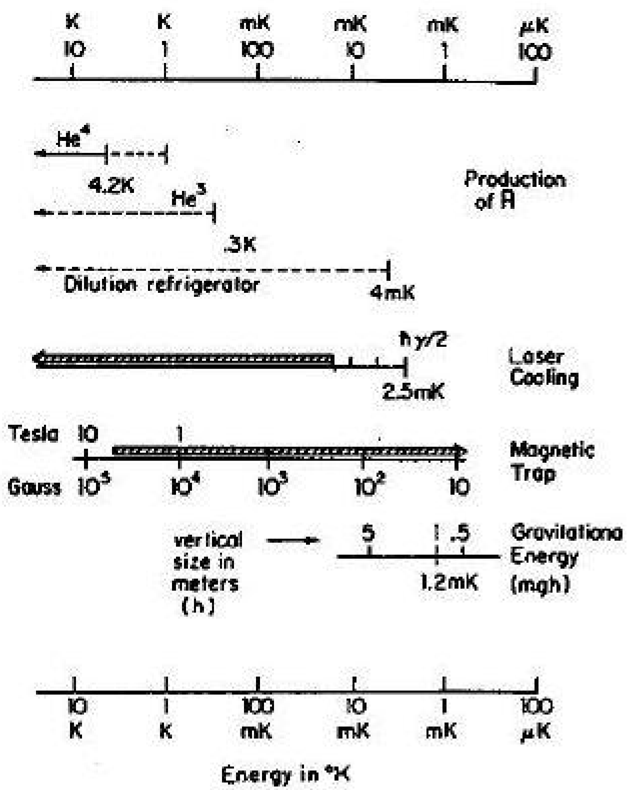
Gravity and Antihydrogen

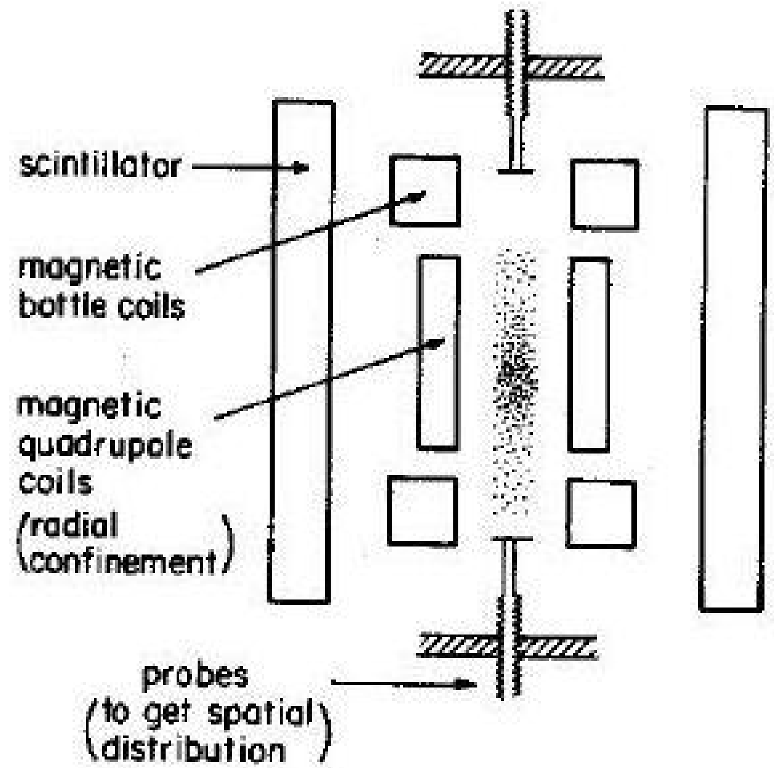
Hyperfine Interactions 44 (1988) 349–356

TRAPPED ANTIHYDROGEN FOR SPECTROSCOPY AND GRAVITATION STUDIES: IS IT POSSIBLE?

G. GABRIELSE

Department of Physics, Harvard University, Cambridge, MA 02138, U.S.A.





Hard to Get the Part per Million Precision of the Redshift Limit with Antihydrogen and Hydrogen

$$g_{antimatter} = \copyright\, g_{matter}$$

Gravitational redshift: $\frac{\Delta\mu_c}{\mu_{\partial c}} < 10^{-10}$ $\quad --> \quad$ $\copyright = 1 \pm (< 10^{-6})$

ATRAP trapped antihydrogen released (2012): $\copyright <$ ~~200~~
(intended to illustrate that a stringent limit was not at all possible so far)

too optimistic, should have released axially

~~(Assumed radial and axial energy would exchange in 10^6 oscillations.)~~

ALPHA trapped antihydrogen released (2013): $\copyright < 110$

Can AEGIS and GBAR get a part per million?

Why Compare Matter and Antimatter

Start general

Embarrassing, Unsolved Mystery: How did our Matter Universe Survive Cooling After the Big Bang?

Big bang → equal amounts of matter and antimatter created during hot time

As universe cools → antimatter and matter annihilate

Big Questions:

- **How did any matter survive?**
- **How is it that we exist?**

Our experiments are looking for evidence of any way that antiparticles and particles may differ

Our "Explanations" are Not so Satisfactory

Baryon-Antibaryon Asymmetry in Universe is Not Understood

Standard "Explanation"
- CP violation
- Violation of baryon number
- Thermodynamic non-equilibrium

Alternate
- CPT violation
- Violation of baryon number
- Thermo. equilib.

Bertolami, Colladay, Kostelecky, Potting
Phys. Lett. B 395, 178 (1997)

Why did a universe made of matter survive the big bang?
Makes sense look for answers to such fundamental questions in the few places that we can hope to do so very precisely.

Bigger problem: don't understand dark energy within 120 orders of magnitude

Why Compare H and $\bar{H}$ (or P and $\bar{P}$)?

Reality is Invariant – symmetry transformations

~~P~~ parity
~~CP~~ charge conjugation, parity
CPT charge conjugation, parity, and time reversal

CPT Symmetry

→ Particles and antiparticles have

- same mass
- opposite charge
- same magnetic moment
- same mean life

→ Atom and anti-atom have

→ same structure

Looking for Surprises

- simple systems
- extremely high accuracy
- comparisons will be convincing
- reasonable effort
- FUN

Comparing the CPT Tests

Warning – without CPT violation models it is hard to compare

3 fundamentally different types of particles

	CPT Test Accuracy	Measurement Accuracy	Free Gift
$K_0 \bar{K}_0$ Mesons	2×10^{-18}	2×10^{-3}	10^{15}
$e^+ e^-$ Leptons	2×10^{-12}	2×10^{-9}	10^{3}
$P \bar{P}$ baryons	9×10^{-11}	9×10^{-11}	1

improve with antihydrogen

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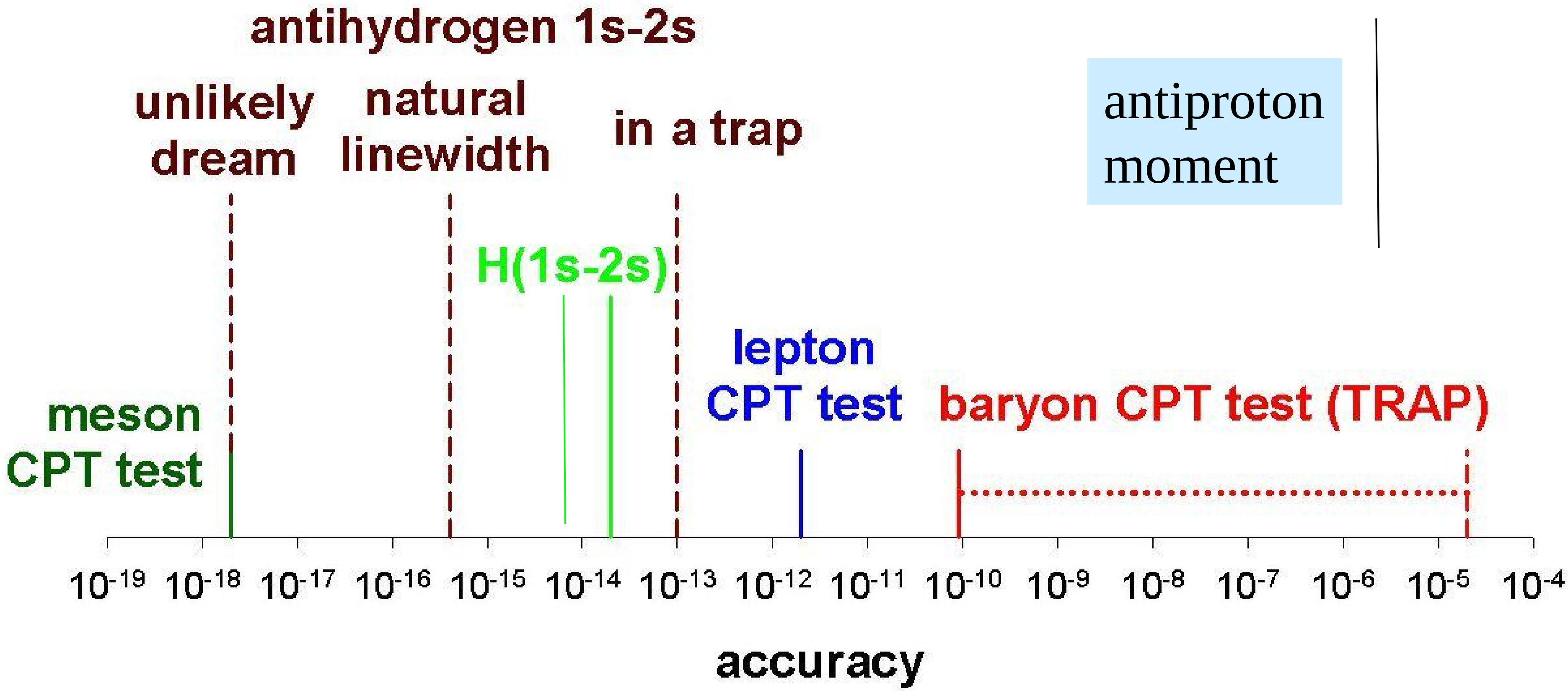
Seek to Improve Lepton and Baryon CPT Tests



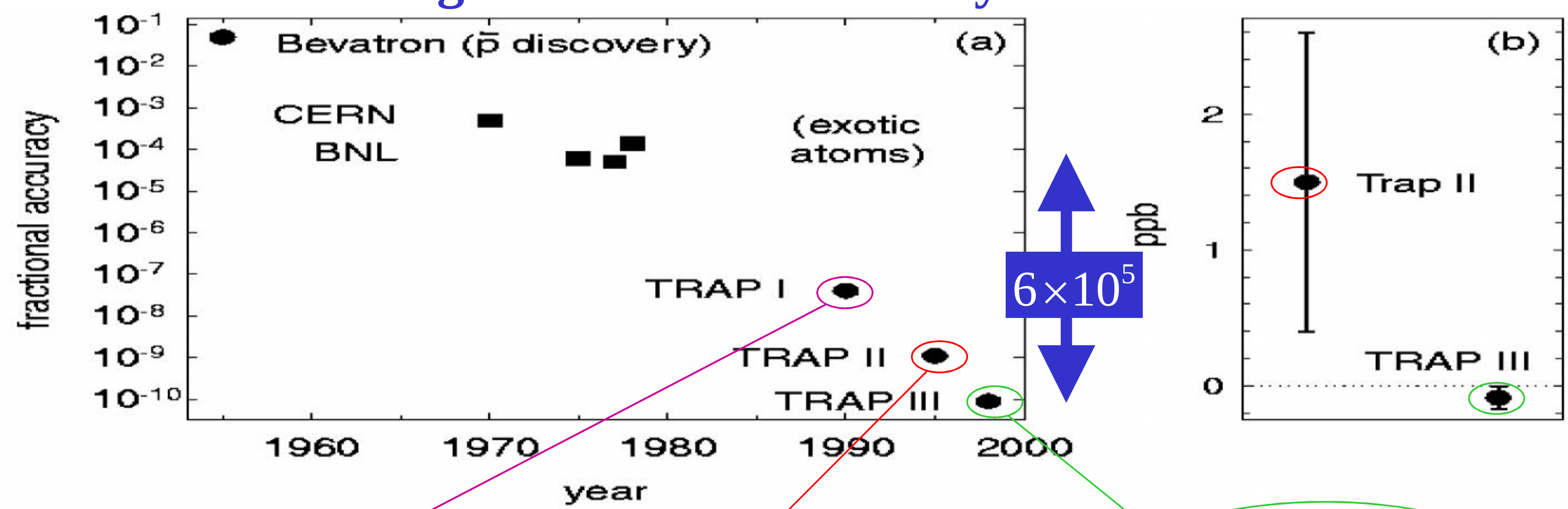
$$\frac{R_\infty[\overline{\mathrm{H}}]}{R_\infty[\mathrm{H}]} = \frac{m[e^+]}{m[e^-]} \left(\frac{q[e^+]}{q[e^-]}\right)^2 \left(\frac{q[\overline{p}]}{q[p]}\right)^2 \frac{1 + m[e^-]/M[p]}{1 + m[e^+]/M[\overline{p}]}$$

We Improved the Comparison of Antiproton and Proton by ~10^6

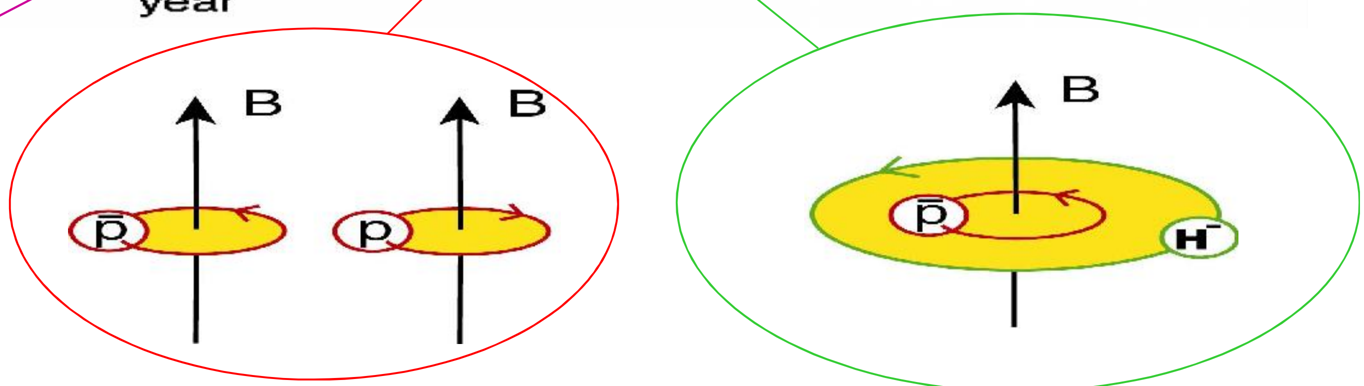
$$\frac{q/m \ \text{(antiproton)}}{q/m \ \text{(proton)}} = -0.99999999991(9)$$

$$9\times10^{-11} = 90\,\text{ppt}$$

most stringent CPT test with baryons



100 antiprotons and protons



G. Gabrielse, A. Khabbaz, D.S. Hall, C. Heimann, H. Kalinowsky, W. Jhe;
Phys. Rev. Lett. **82**, 3198 (1999).

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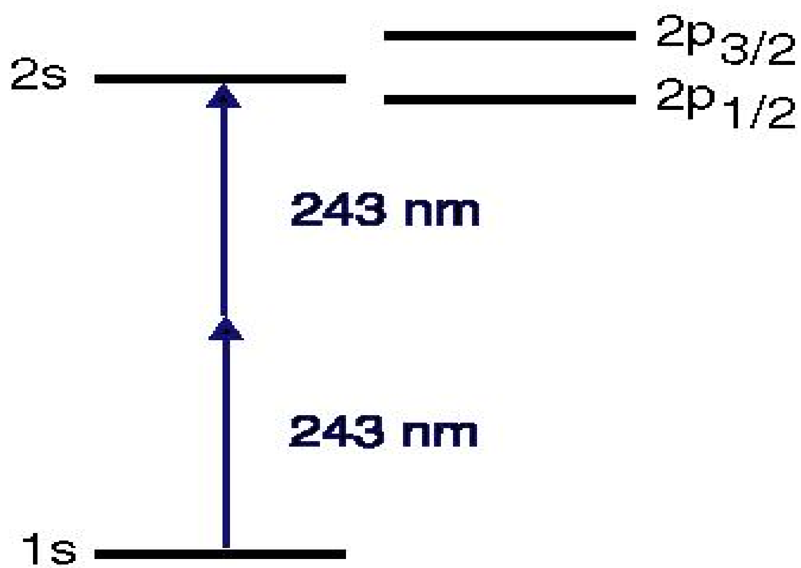
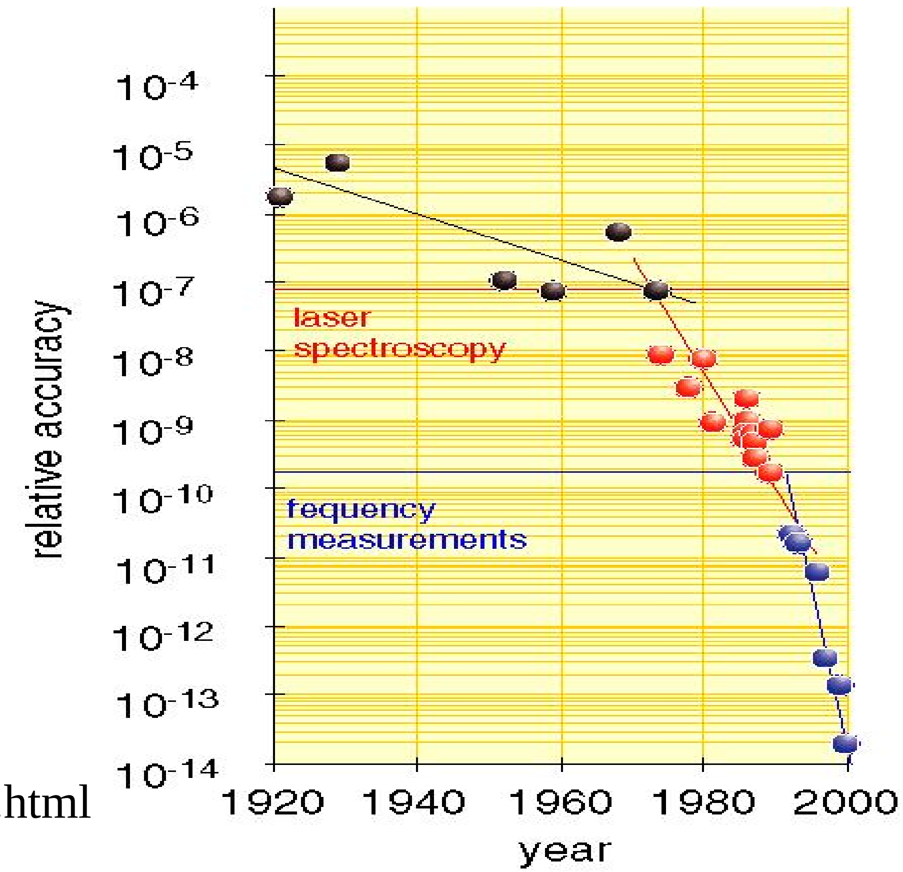
Ultimate Goal: Hydrogen 1s – 2s Spectroscopy





(Haensch, et al., Max Planck Soc., Garching)
http://www.mpq.mpg.de/~haensch/hydrogen/h.html

Many fewer antihydrogen atoms will be available

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CPT for Antiprotons and Antihydrogen

Compare Antiproton and Proton

q/m	TRAP (direct)
q and m separately	TRAP + ASACUSA (indirect, not nearly as precise)
μ	ATRAP

Compare antihydrogen and hydrogen structure

Despite all the publicity → no interesting comparisions of antihydrogen and hydrogen have yet been possible

Highest Precision Test of Baryon CPT Invariance

→ by TRAP at CERN

G. Gabrielse, A. Khabbaz, D. S. Hall, C. Heimann, H. Kalinowsky, and W. Jhe, Phys. Rev. Lett. **82**, 3198 (1999).

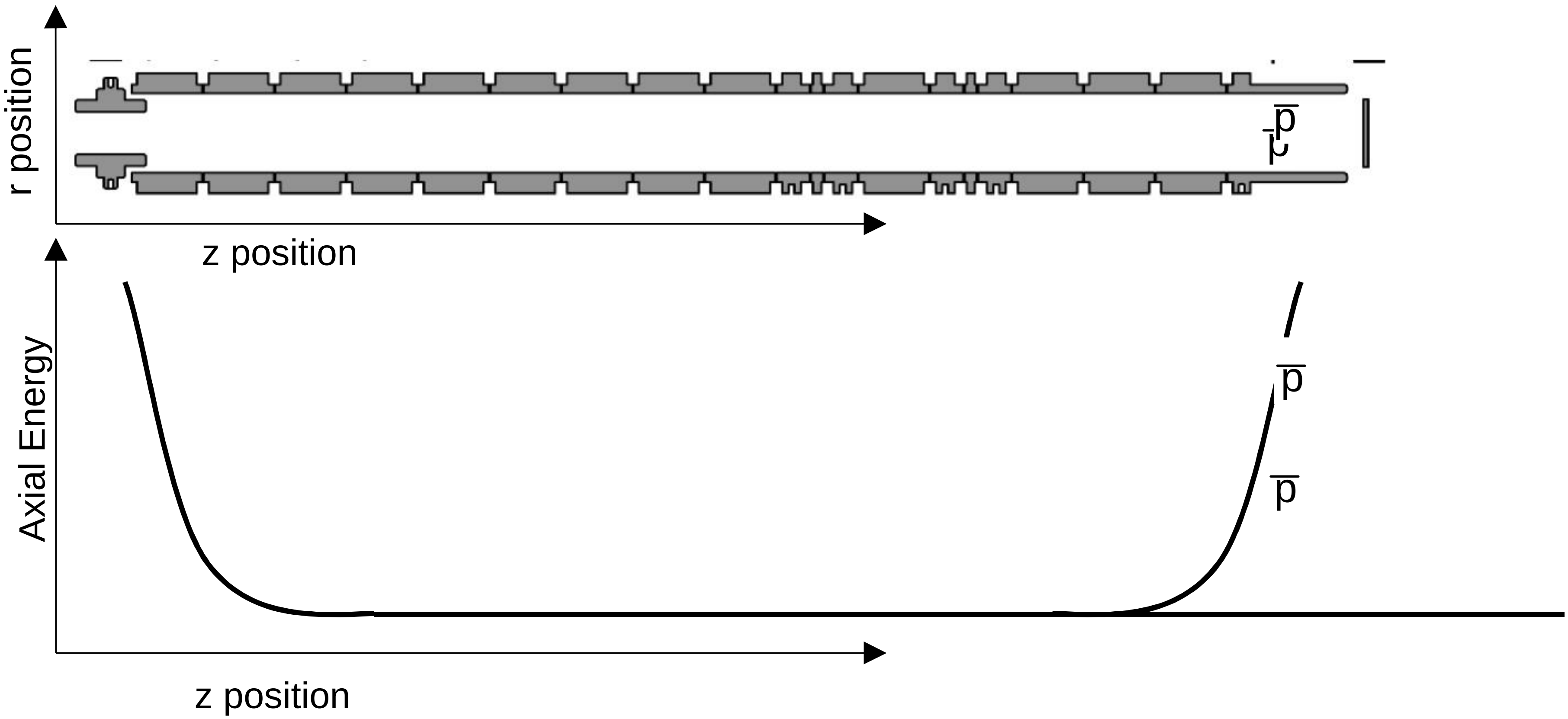
$$\frac{q/m \ \text{(antiproton)}}{q/m \ \text{(proton)}} = -0.999\,999\,999\,91(9)$$

$9\times 10^{-11} = 90\,\text{ppt}$

(most precise result of CERN's antiproton program)

Goal at the AD: Make CPT test that approach exceed this precision

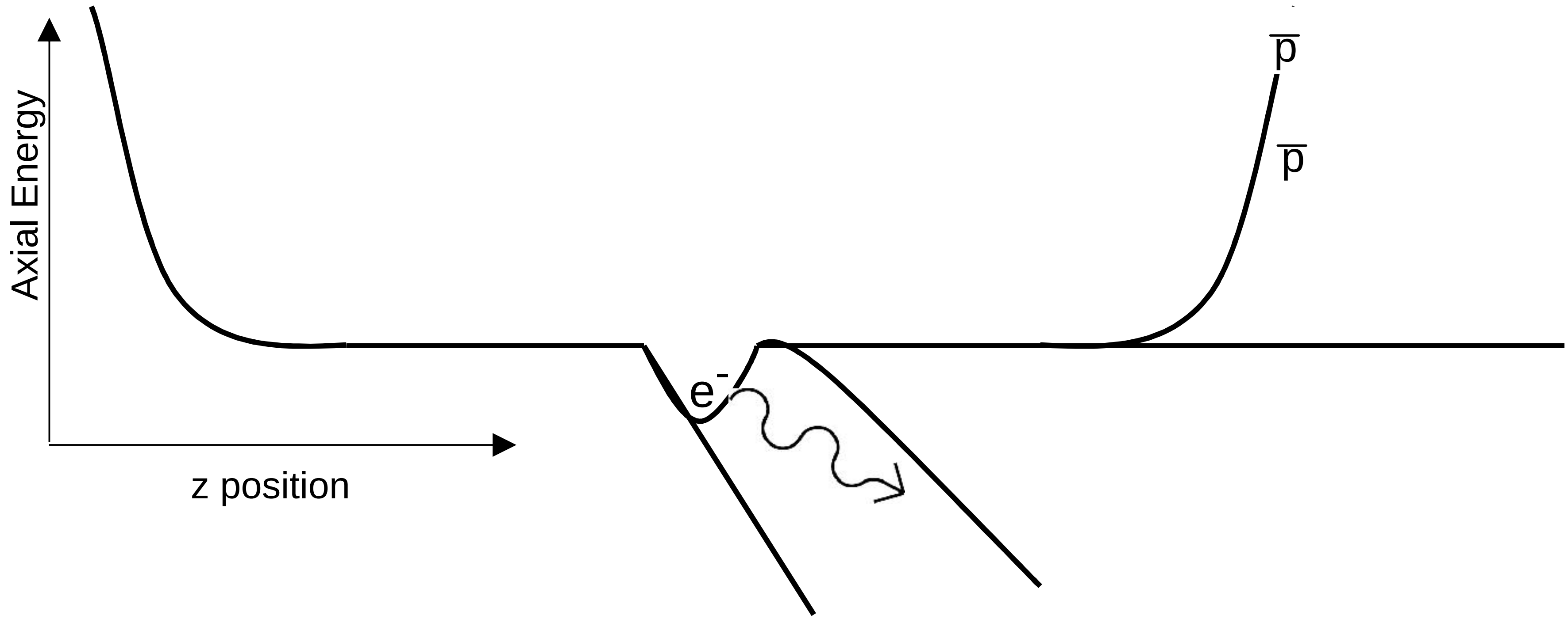
Antiproton Capture – the Movie



"First Capture of Antiprotons in a Penning Trap: A KeV Source",
G. Gabrielse, X. Fei, K. Helmerson, S.L. Rolston, R. Tjoelker, T.A. Trainor, H. Kalinowsky, J. Haas, and W. Kells;
Phys. Rev. Lett. 57, 2504 (1986).

Electron-Cooling of Antiprotons – in a Trap

- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy



"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells;
Phys. Rev. Lett. 63, 1360 (1989).

ATRAP's Principle Focus in 2012
→ First Direct Comparison of the Antiproton and Proton Magnetic Moments

Magnetic Moments
Can be Measured Very Precisely

e.g. Electron magnetic moment is the most precisely measured property of an elementary particle

Electron Magnetic Moment

electron magnetic moment $\vec{\mu} = -g\mu_B \frac{\vec{L}}{\hbar}$ ← angular momentum

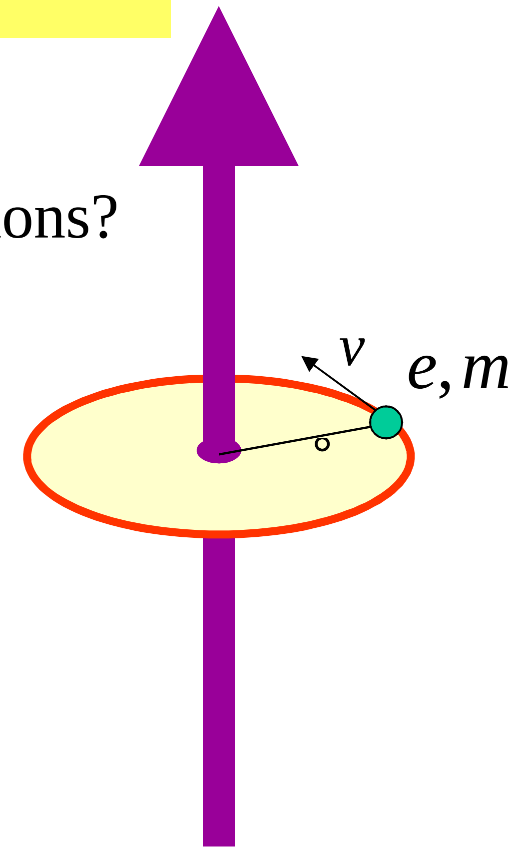
↑ Bohr magneton $\frac{e\hbar}{2m}$

e.g. What is g for identical charge and mass distributions?

$$\mu = IA = \frac{-e}{\left(\frac{2\pi\rho}{v}\right)}(\pi\rho^2) = -\frac{ev\rho}{2}\frac{L}{mv\rho} = -\frac{e}{2m}L = -\frac{e\hbar}{2m}\frac{L}{\hbar}$$

↑ μ_B

$$\rightarrow \quad g = 1$$



Electron Magnetic Moment

magnetic moment $$\vec{\mu} = -\frac{g}{2}\mu_B \frac{\vec{S}}{\hbar/2}$$

$\vec{S}$ ← angular momentum

μ_B ← Bohr magneton $\frac{e\hbar}{2m}$

g/2 = magnetic moment in Bohr magnetons for spin 1/2

$g = 1$ mechanical model with identical charge and mass distribution

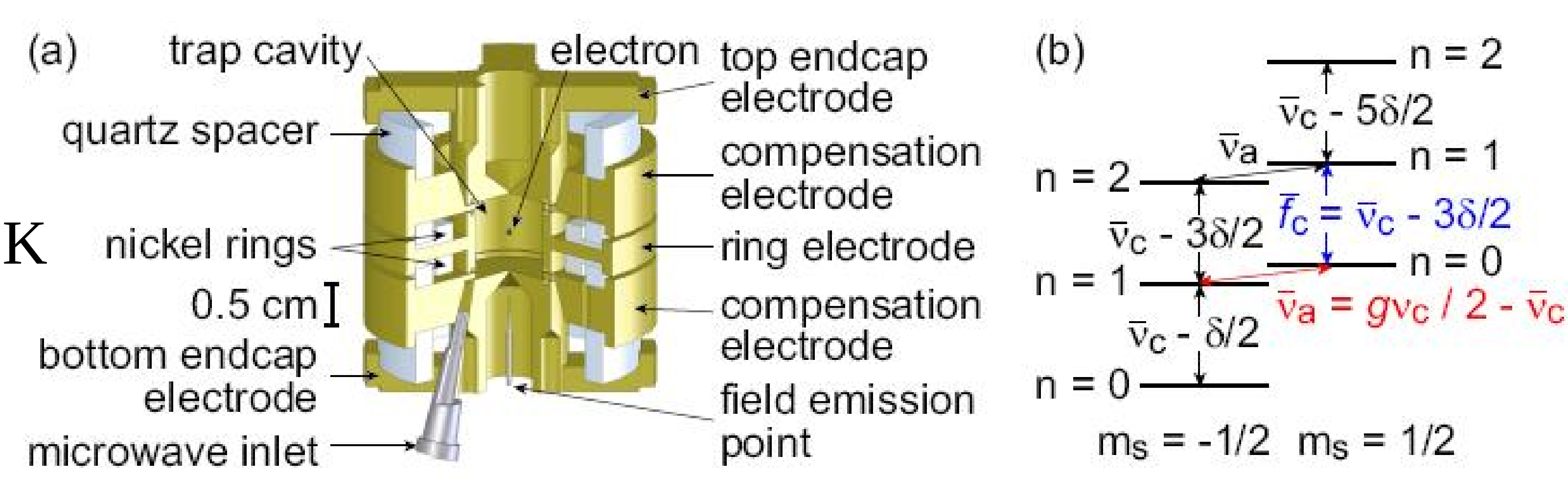
$g = 2$ spin for simple Dirac point particle

$g = 2.002\ 319\ 304\ ...$ simplest Dirac spin, plus QED

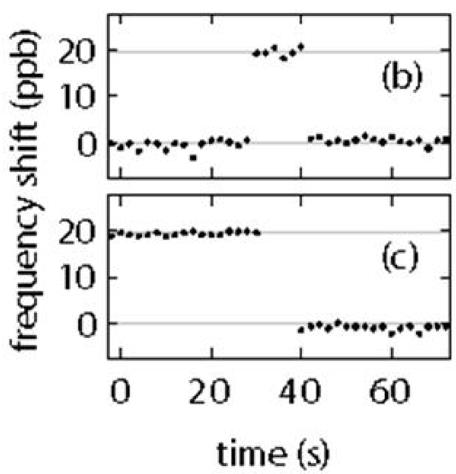
(if electron g is different → electron has substructure)

One Electron: Resolve One-Quantum Excitation

0.1 K



QND observations
of one-quantum
transitions



one quantum cyclotron excitation

spin flip

"Single-Particle Self-excited Oscillator“,
B. D'Urso, R. Van Handel, B. Odom and G. Gabrielse
Phys. Rev. Lett. **94**, 113002 (2005).

Most precisely measured property of an elementary particle

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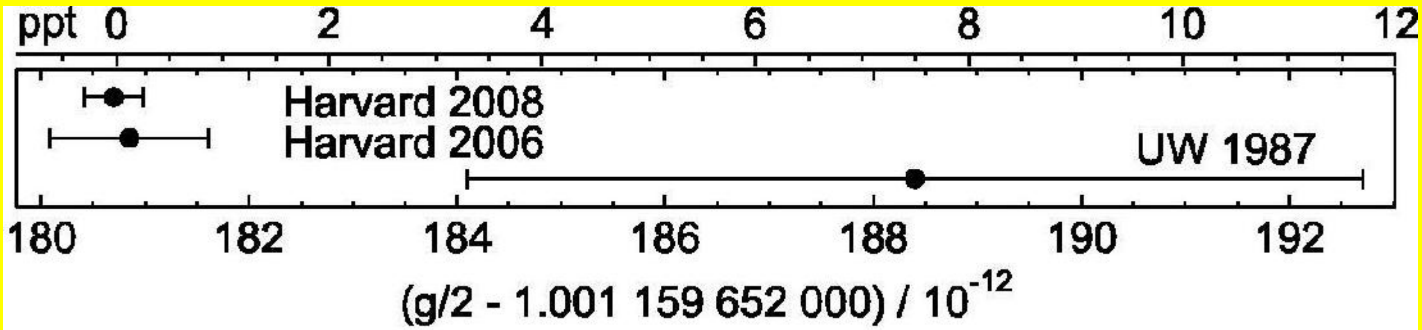
Electron Magnetic Moment Measured to 3 x 10^{-13}

2.8×10^{-13}



(improved measurement is currently underway)

electron magnetic moment in Bohr magnetons

trying to do as well with a as with an electron

"New Measurement of the Electron Magnetic Moment and the Fine Structure Constant"
D. Hanneke, S. Fogwell and G. Gabrielse,
Phys. Rev. Lett. **100**, 120801 (2008) and arXiv:0801.1134v1 [physics.atom-ph].

"Cavity Control of a Single-Electron Quantum Cyclotron: Measuring the Electron Magnetic Moment"
D. Hanneke, S. Fogwell Hoogerheide and G. Gabrielse,
Phys. Rev. A **83**, 052122 (2011).

Standard Model → Relates g/2 and alpha

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4$$

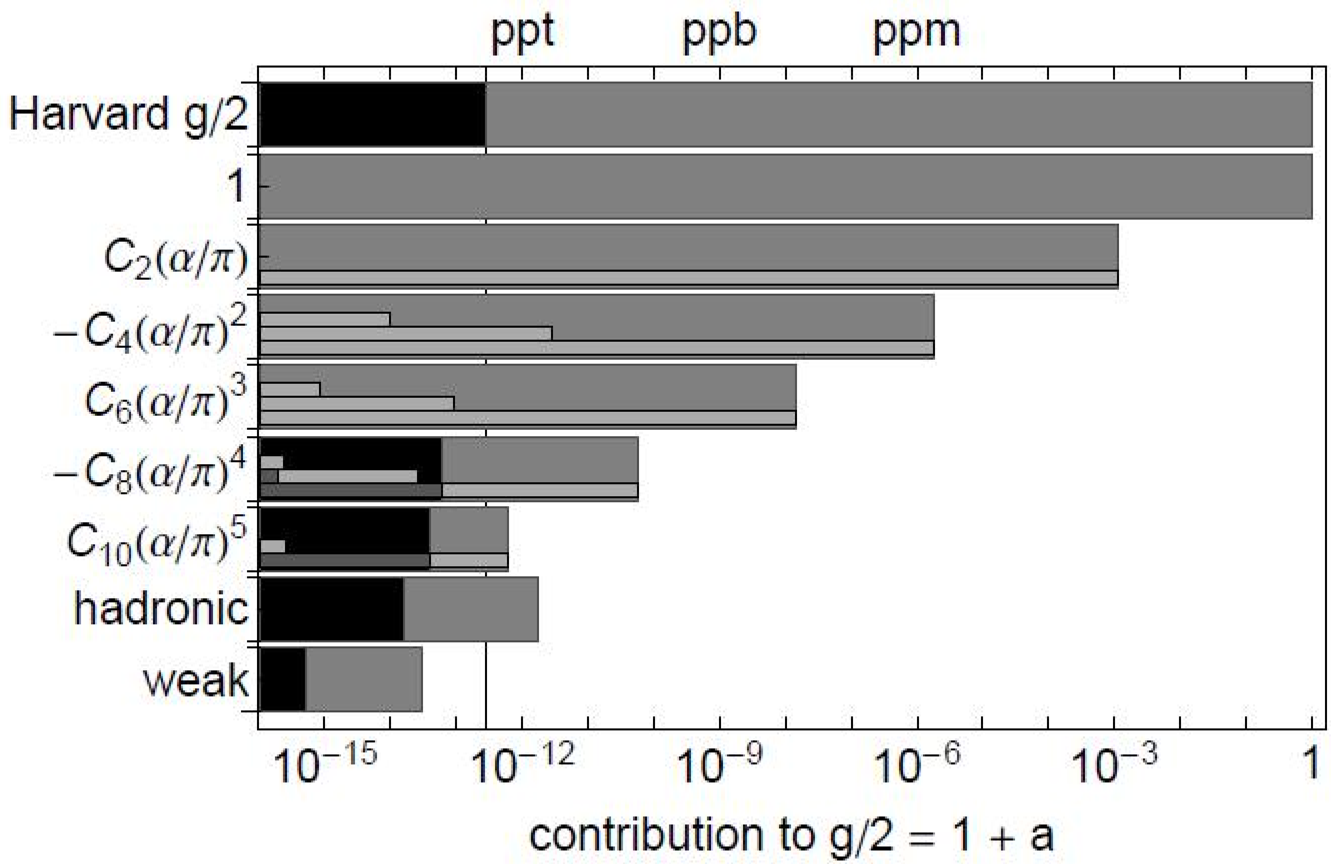
$$+ C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\text{hadronic}} + a_{\text{weak}}$$

$$\begin{aligned}
C_2 &= \quad 0.500\,000\,000\,000\,00 \text{ (exact)} \\
C_4 &= -\,0.328\,478\,444\,002\,55\,(33) \\
C_6 &= \quad 1.181\,234\,016\,815\,(11) \\
C_8 &= -\,1.909\,7\,(20) \\
C_{10} &= \quad 9.16\,(0.57).
\end{aligned}$$

Essentially exact
-- depend weakly on
mass ratios

$$a_e^{\text{hadronic}} = 1.677(16) \times 10^{-12}$$

Standard Model Contributions

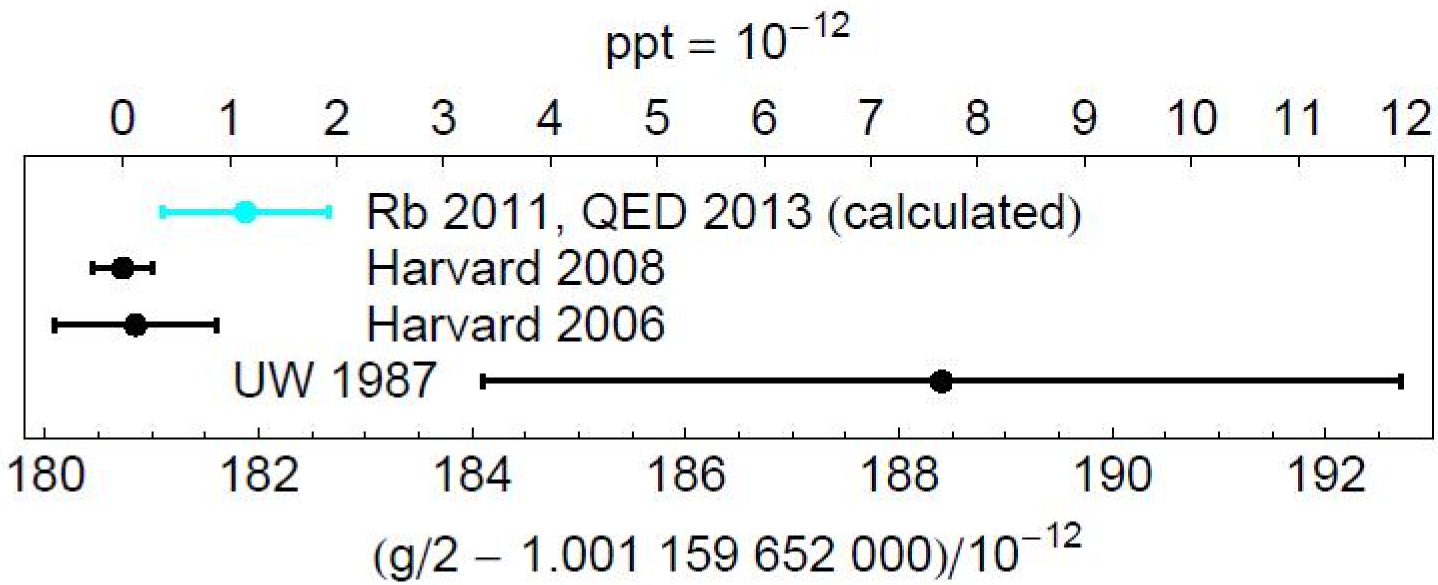


(Greatest?) Triumph of the Standard Model

Measured: $\mu/\mu_B = -g/2 = -1.001\,159\,652\,180\,73\,(28) \quad [0.28 \text{ ppt}].$

"Calculated": $\mu/\mu_B = -g/2 = -1.001\;159\;652\;181\;88\;(78)\;[0.77\;\;\text{ppt}]$

(Uncertainty from measured fine structure constant)

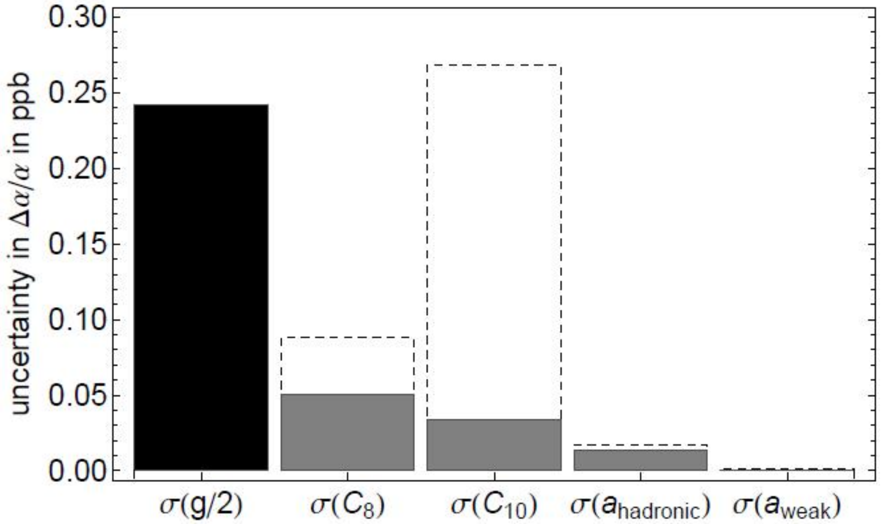


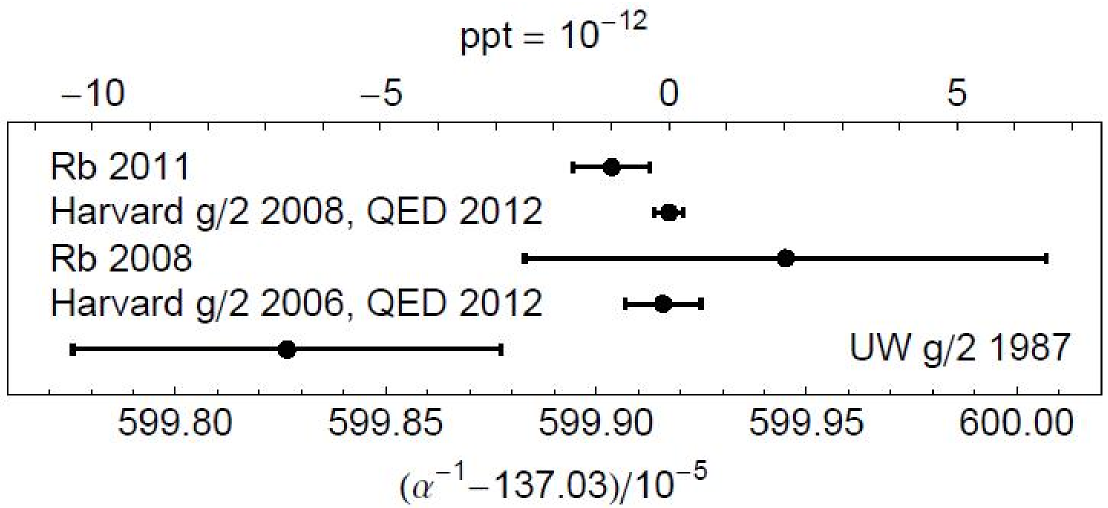
$$\frac{\mu - \mu(SM)}{\mu} = 0.000\,000\,000\,000\,15\;(82)\;[0.82\;\;\text{ppt}],$$

$$= 1.5\;(0.8) \times 10^{-12}\;[0.8\;\;\text{ppt}].$$

Determine Fine Structure Constant

$$\alpha^{-1} = 137.035\,999\,173\,(33)\,(8) \quad [0.24 \text{ ppb}]\,[0.06 \text{ ppb}]$$
$$= 137.035\,999\,173\,(34) \qquad [0.25 \text{ ppb}],$$





Proton and Antiproton Magnetic Moments are Much Smaller

Harder: nuclear magneton rather than Bohr magneton

$$\mu_N/\mu_B = m_e/m_p \sim 1/2000$$

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Precise Proton Magnetic Moment Measurement
→ Most precise so far (0.01 ppm)
→ Cannot be Used with Antiprotons

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{\mu_e}{\mu_B}\frac{m_p}{m_e}\frac{\mu_p(H)}{\mu_e(H)}\frac{\mu_e(H)}{\mu_e}\frac{\mu_p}{\mu_p(H)}$$

theory corrections
1 ppb

free electron magnetic moment

0.0003 ppb

Harvard

10 ppb

hydrogen maser

MIT

2 ppb or 0.7 ppb

UW

direct

bound electron magnetic moment

Mainz

ppb = 10^{-9}

Exotic Atom Measurements

→ **Very low precision (3000 ppm)**

→ **Works only with an antiproton**

Single Particle Measurements Have Three Big Advantages

Can be done with antiparticles

Can reach a much higher precision

Direct measurement → same measurement and apparatus is used with a particle and antiparticle

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Antiproton Magnetic Moment

$$\boldsymbol{\mu}_{\overline{\mathrm{p}}} = \mu_{\overline{\mathrm{p}}} \boldsymbol{S}/(\hbar/2)$$

Single particle method: Measure two frequencies

current challenge

$$\frac{\mu_{\overline{\mathrm{p}}}}{\mu_N} \equiv \frac{g_{\overline{\mathrm{p}}}}{2} \frac{q_{\overline{\mathrm{p}}}/m_{\overline{\mathrm{p}}}}{q_p/m_p} \approx -\frac{g_{\overline{\mathrm{p}}}}{2} = -\frac{f_s}{f_c}$$

nuclear magneton

we measured to $< 9 \times 10^{-11}$

-1 we measured to be to 9 parts in 10^{11}

Phys. Rev. Lett. 180, 153001 (2012)

Direct Measurement of the Proton Magnetic Moment

J. DiSciacca[1] and G. Gabrielse[1,*]

[1] *Dept. of Physics, Harvard University, Cambridge, MA 02138*

(Dated: January 14, 2012)

The proton magnetic moment in nuclear magnetons is measured to be $\mu_p/\mu_N \equiv g/2 = 2.792\,846 \pm 0.000\,007$, a 2.5 ppm (parts per million) uncertainty. The direct determination, using a single proton in a Penning trap, demonstrates the first method that should work as well with an antiproton ($\overline{\mathrm{p}}$) as with a proton (p). This opens the way to measuring the $\overline{\mathrm{p}}$ magnetic moment (whose uncertainty has essentially not been reduced for 20 years) at least 10^3 times more precisely.

Earlier contributions

[12] N. Guise, J. DiSciacca, and G. Gabrielse, Phys. Rev. Lett. **104**, 143001 (2010).

[14] S. Ulmer, C. C. Rodegheri, K. Blaum, H. Kracke, A. Mooser, W. Quint, and J. Walz, Phys. Rev. Lett. **106**, 253001 (2011).

Later measurement with similar methods

C. C. Rodegheri, K. Blaum, H. Kracke, S. Kreim, A. Mooser, W. Quint, S. Ulmer, and J. Walz, New J. Physics **14**, 063011 (2012).

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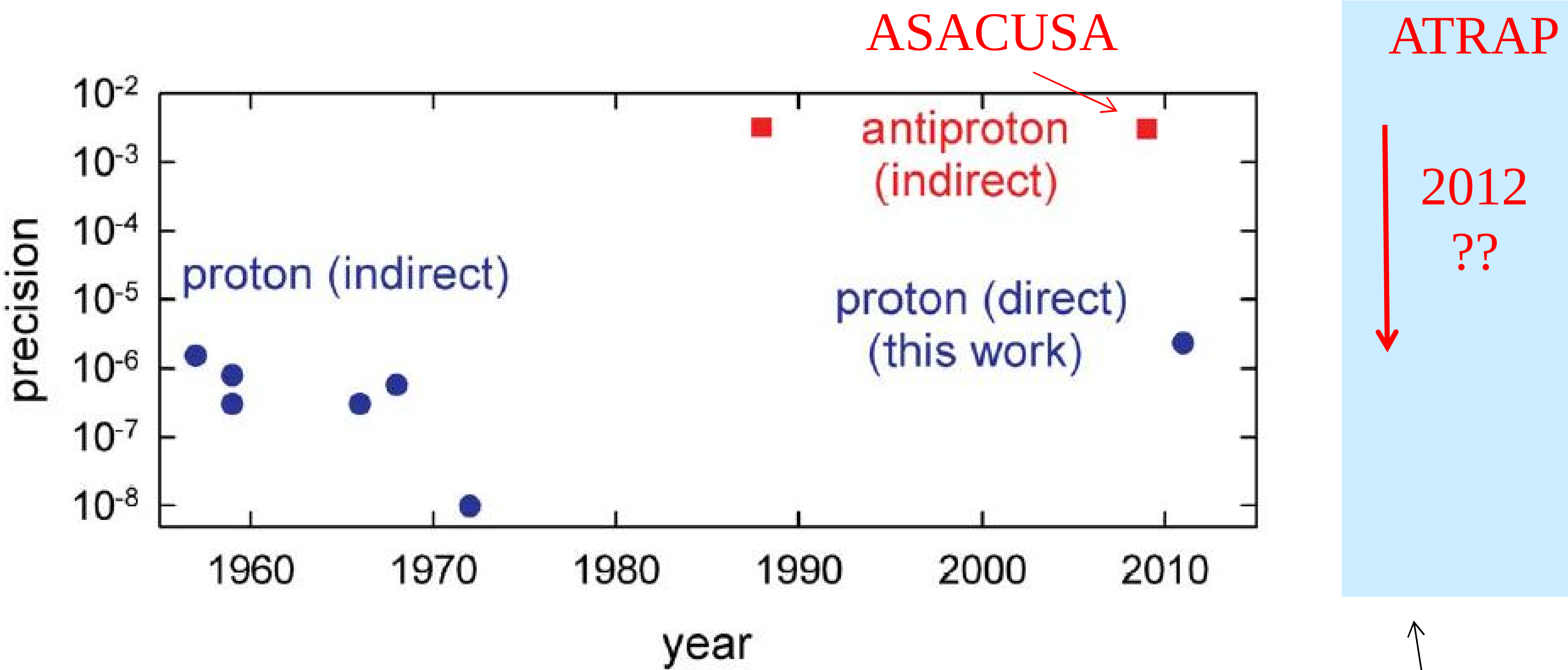
Suggested Possibility of a Thousand-fold Improved Measurement of the Antiproton Moment



If everything went exactly right it would be possible to do this with antiprotons in 2012

Expect to eventually be more precise than all proton measurements

Could We Adapt the Apparatus, Move to CERN, and Make the -- all in 2012?

Decided to take the risk:

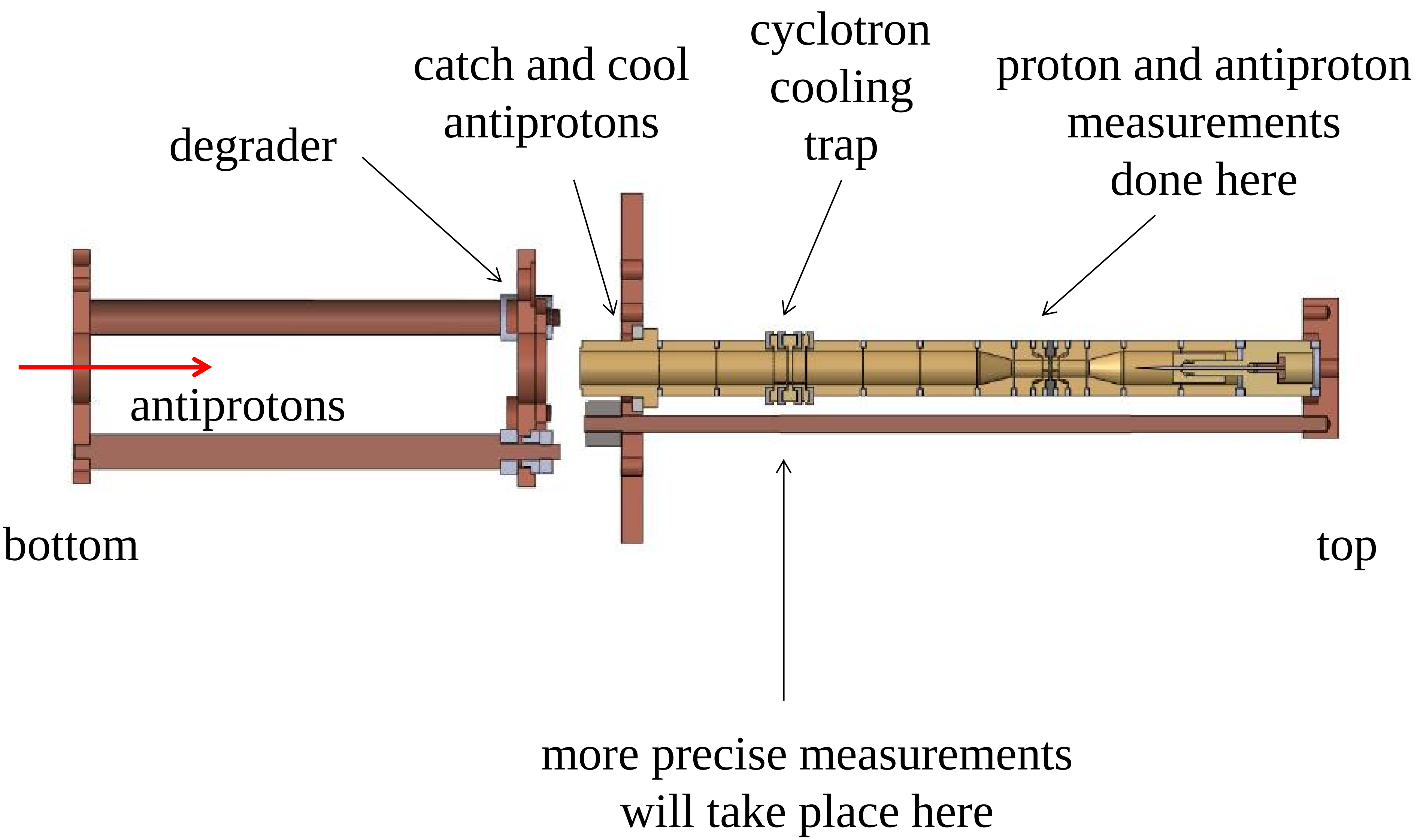
-- even if we failed, we would learn what to work on over the long shutdown

-- we were not anticipating any major scientific accomplishments at the ATRAP or the AD in 2012

-- perhaps we could succeed

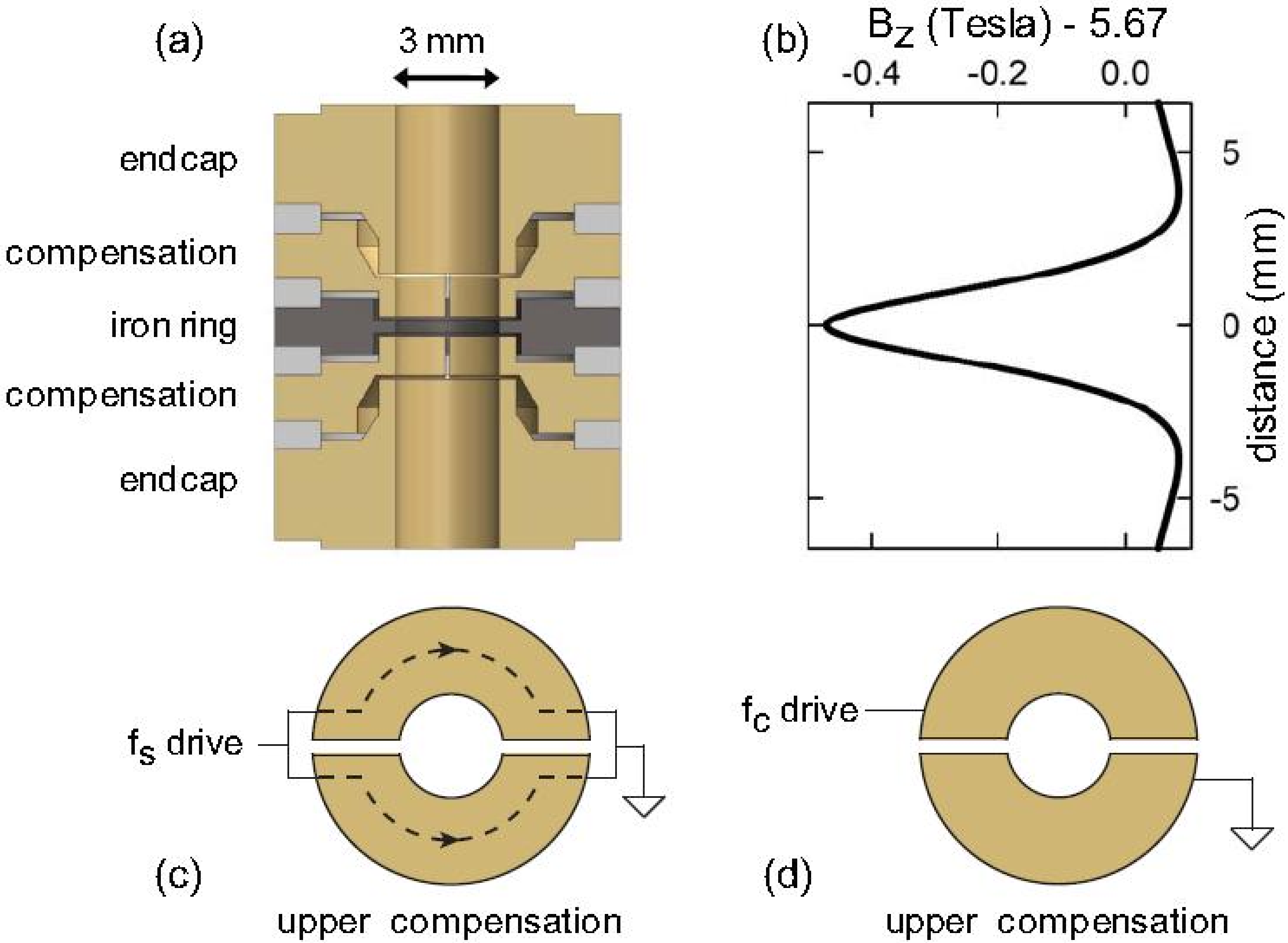
Antiproton Magnetic Moment Apparatus

For Magnetic Moments: Three Antiproton Traps



Huge Magnetic Bottle Gradient

190 times larger than used for electron



One-Particle Method

With one proton or antiproton suspended in a trap, measure spin and cyclotron frequencies

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

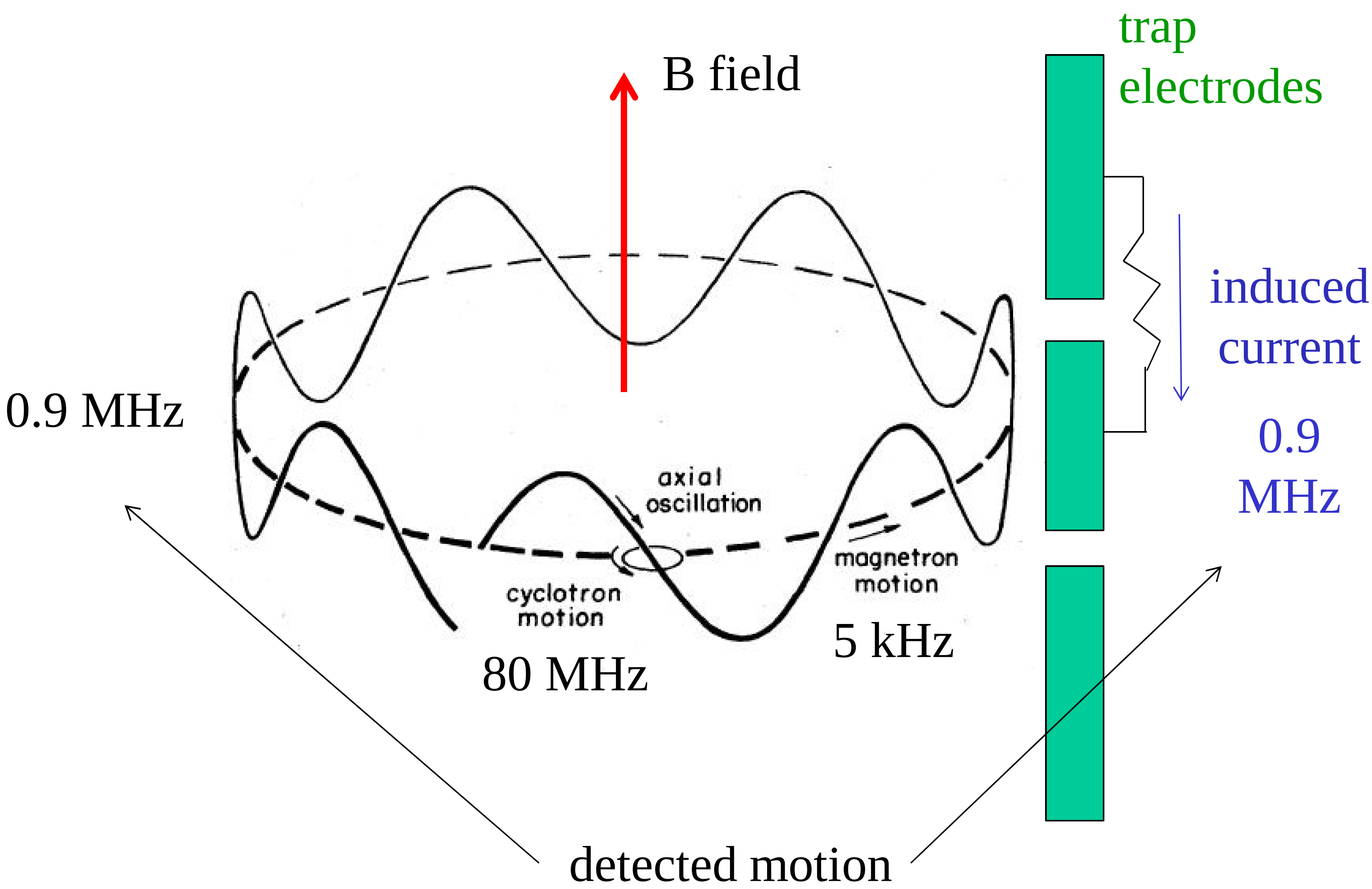
current challenge (f_s)

we measured to $< 9 \times 10^{-11}$ back at LEAR (f_c)

no previous method has been devised to measure antiproton and proton moments in the same way

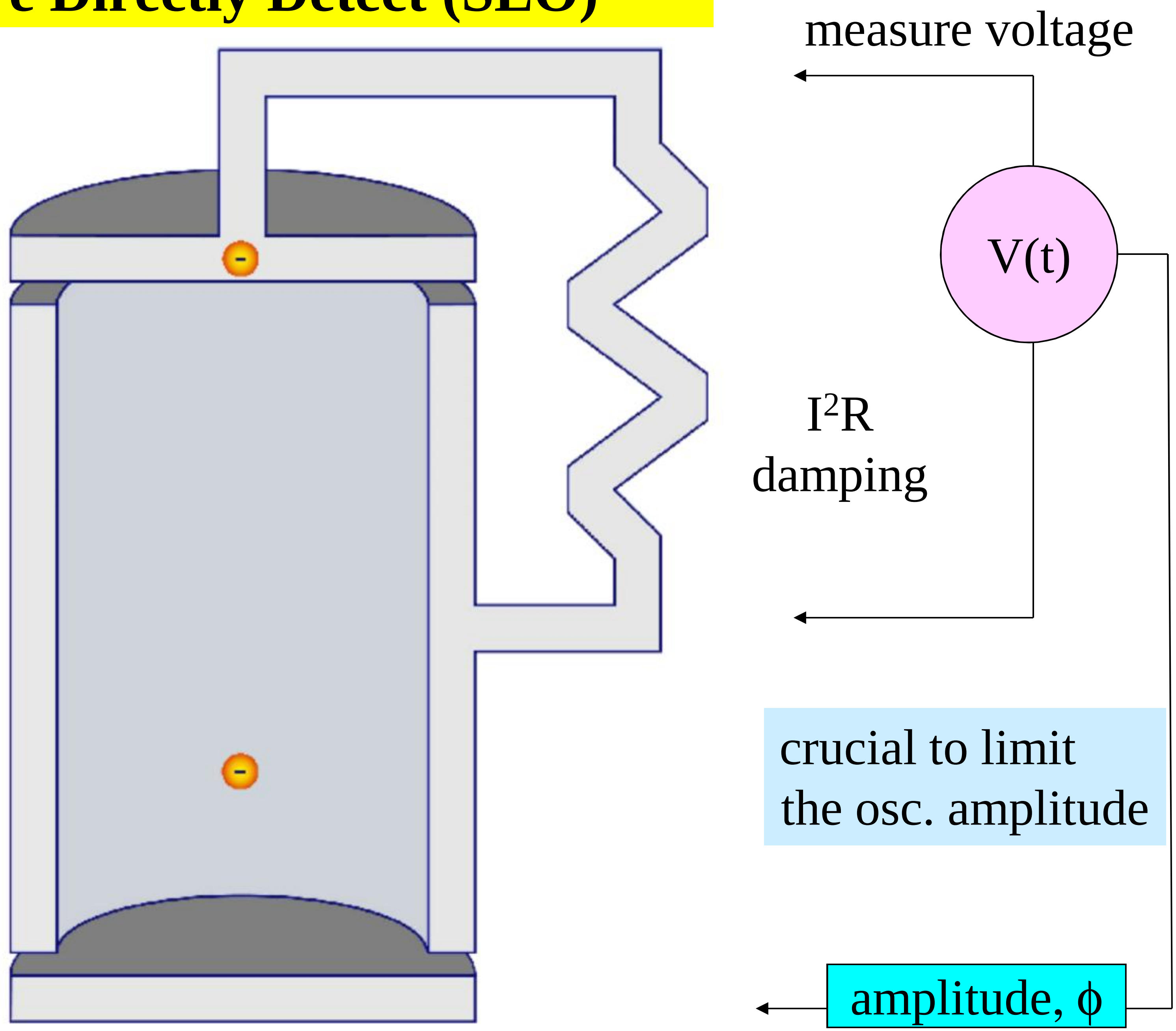
Gabrielse

Antiproton Orbits in a Penning Trap

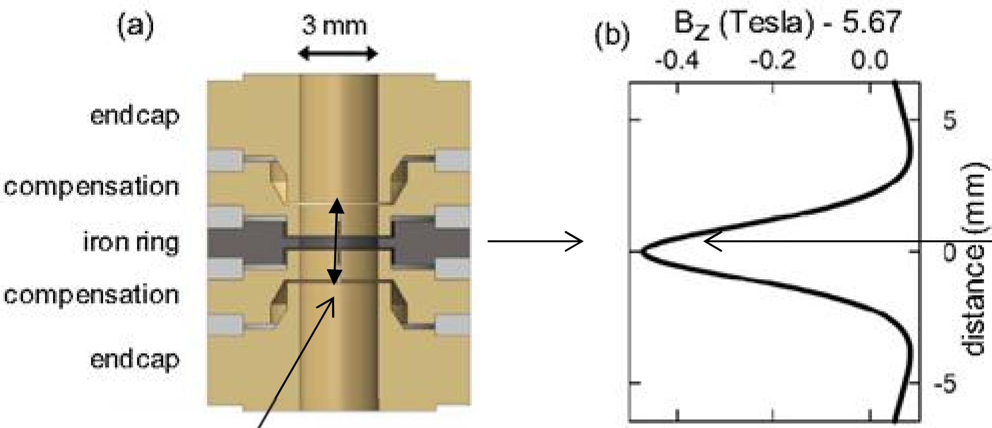


What We Directly Detect (SEO)

axial motion
1 MHz
of
trapped
electron



Detecting the Antiproton Magnetic Moment



$$\Delta \mathbf{B} = \beta_2 [(z^2 - \rho^2/2)\hat{\mathbf{z}} - z\rho\hat{\boldsymbol{\rho}}]$$

magnetic moment

$$\Delta H \sim -\mu\, \Delta B \sim \mu\, z^2$$

Harmonic oscillator

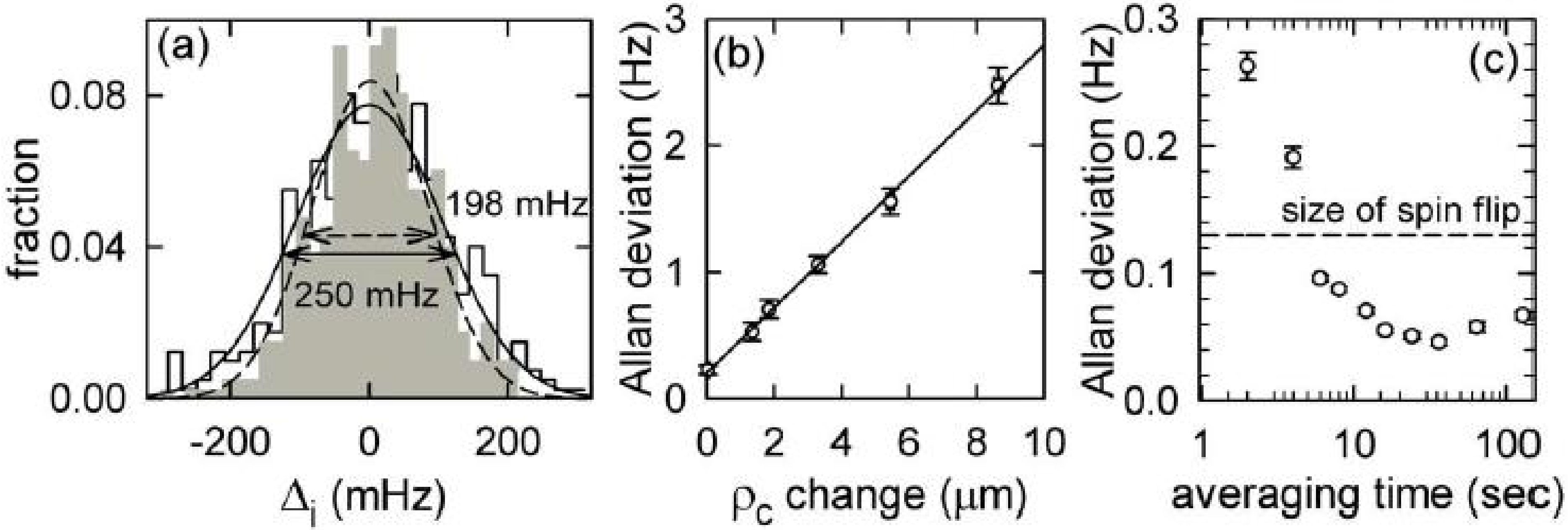
$$H \sim f^2 z^2$$

oscillation frequency

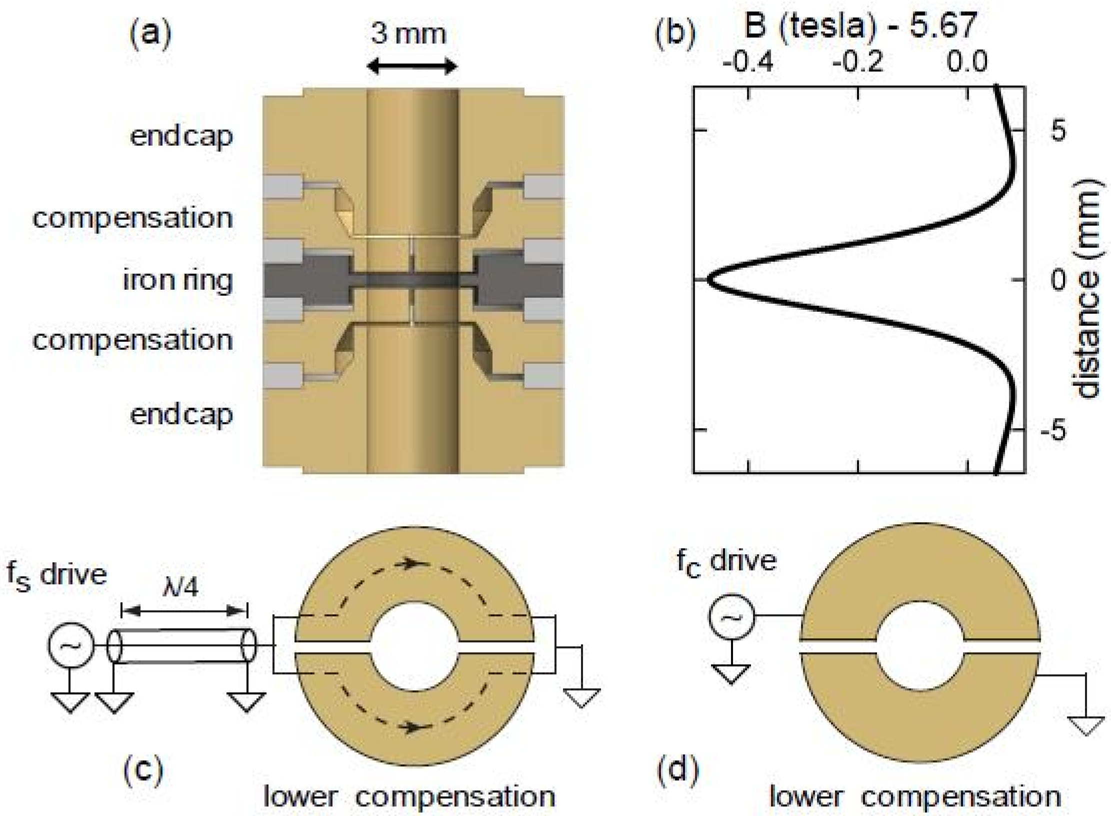
$$\Delta f \sim \mu$$

shift in oscillation frequency

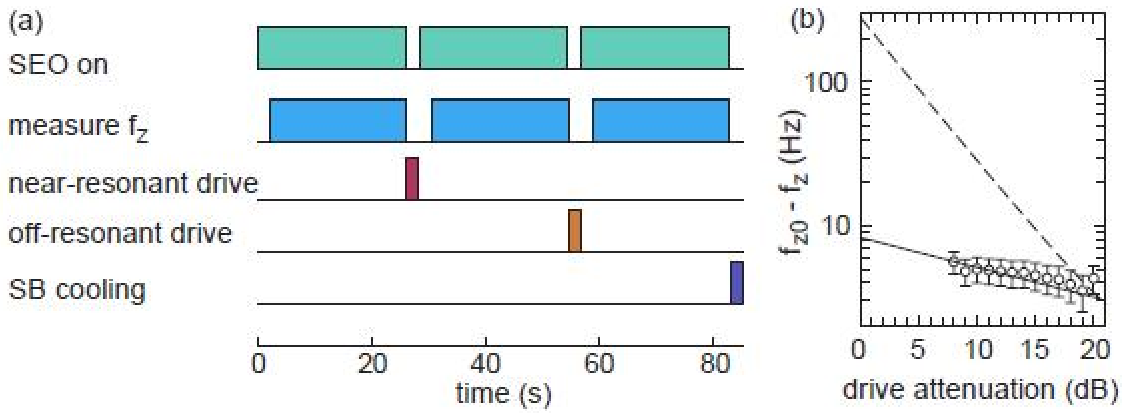
Spin-Flips Increase Allan Deviation



Slightly Improved Apparatus



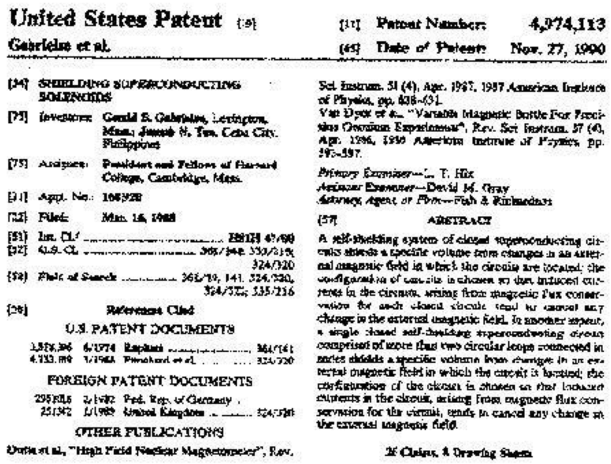
Measurement Sequence – for Spin Measurement



Self-Shielding Solenoid

Flux conservation → Field conservation

Reduces field fluctuations by about a factor > 150



United States Patent [19]

Gabrielse et al.

[11] Patent Number: 4,974,113

[45] Date of Patent: Nov. 27, 1990

[54] SHIELDING SUPERCONDUCTING SOLENOIDS

[75] Inventors: Gerald S. Gabrielse, Lexington, Mass.; Joseph N. Tan, Cebu City, Philippines

[73] Assignee: President and Fellows of Harvard College, Cambridge, Mass.

[21] Appl. No.: 168928

[22] Filed: Mar. 16, 1988

[51] Int. Cl. ... H01H 47/00

[52] U.S. Cl. ... 361/141; 335/216; 324/320

[58] Field of Search ... 361/19, 141; 324/320; 324/322; 335/216

[56] References Cited

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FOREIGN PATENT DOCUMENTS

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Sci. Instrum. 58 (4), Apr. 1987, 1987 American Institute of Physics, pp. 628–631.

Van Dyck et al., "Variable Magnetic Bottle For Precision Geonium Experiments", Rev. Sci. Instrum. 57 (4), Apr. 1986, 1986 American Institute of Physics, pp. 593–597.

Primary Examiner—L. T. Hix

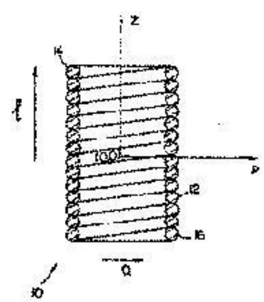
Assistant Examiner—David M. Gray

Attorney, Agent, or Firm—Fish & Richardson

[57] ABSTRACT

A self-shielding system of closed superconducting circuits shields a specific volume from changes in an external magnetic field in which the circuits are located; the configuration of circuits is chosen so that induced currents in the circuits, arising from magnetic flux conservation for each closed circuit, tend to cancel any change in the external magnetic field. In another aspect, a single closed self-shielding superconducting circuit comprised of more than two circular loops connected in series shields a specific volume from changes in an external magnetic field in which the circuit is located; the configuration of the circuit is chosen so that induced currents in the circuit, arising from magnetic flux conservation for the circuit, tends to cancel any change in the external magnetic field.

26 Claims, 8 Drawing Sheets



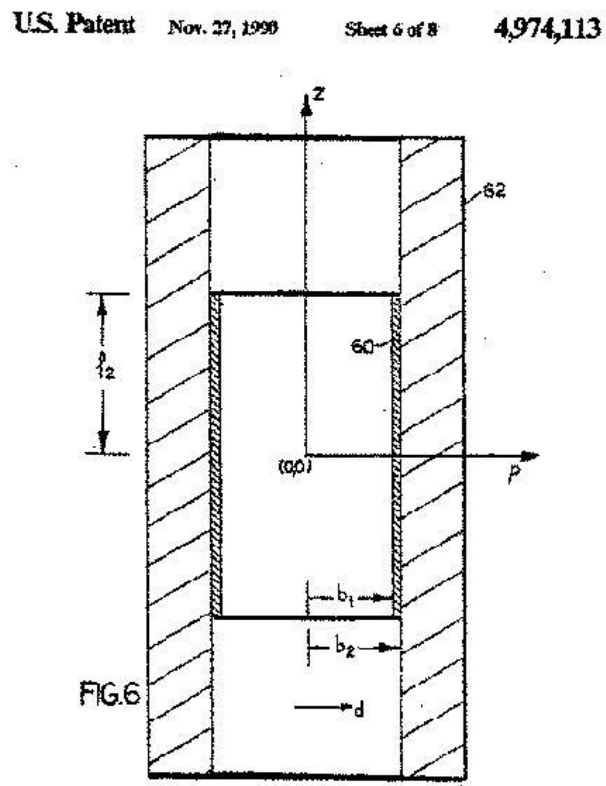


FIG.6

"Self-shielding Superconducting Solenoid Systems",
G. Gabrielse and J. Tan, J. Appl. Phys. **63**, 5143 (1988)

Resonance Lines to Determine the "Two" Frequencies

square of extra width

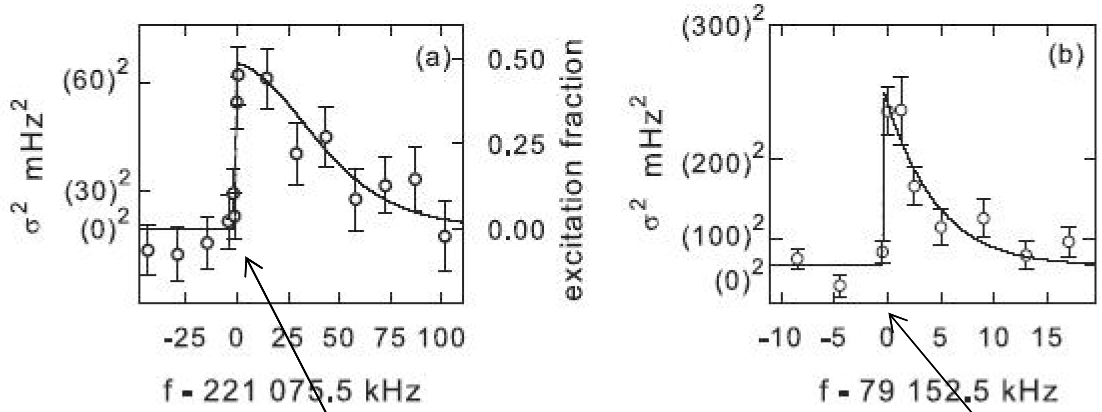


FIG. 4. (a) The spin line. (b)The cyclotron line.

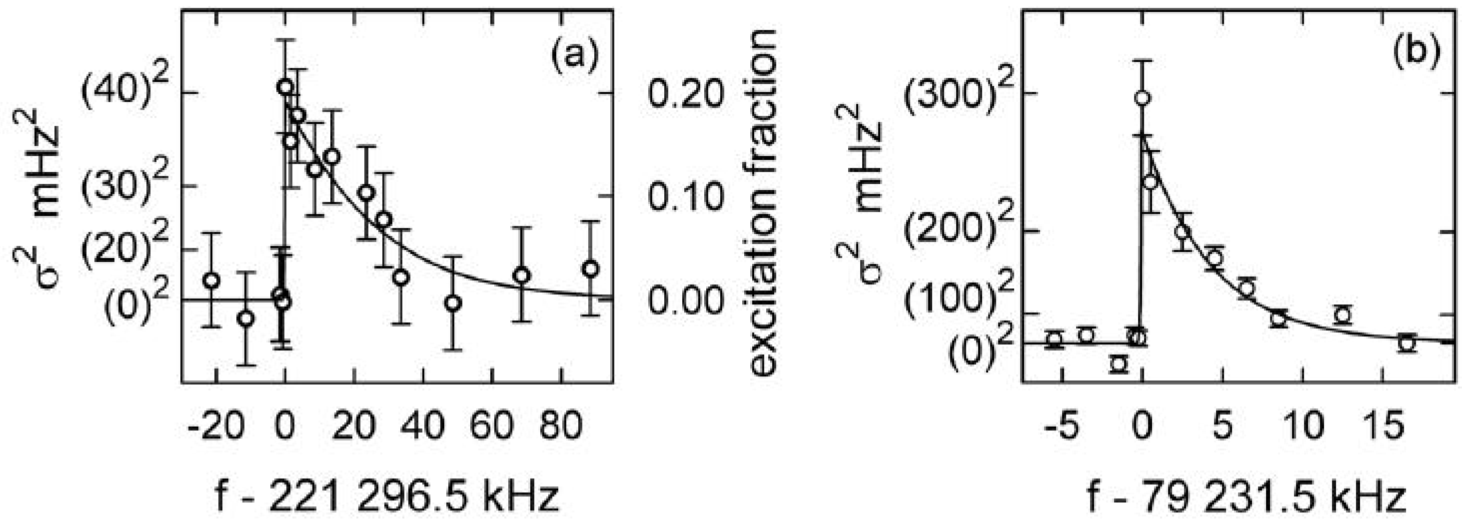
$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$

$$f_c^2 = f_+^2 + f_z^2 + f_-^2$$

Brown-Gabrielse Invariance Theorem

Direct Measurement of the Proton Mag. Moment

$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$



$$\frac{\mu_p}{\mu_N} = \frac{g}{2} = 2.792\,846 \pm 0.000\,007 \qquad [2.5\ \text{ppm}]$$

Harvard:	g/2 =	5.585 692	+/-	0.000 007	2 506.4 ppb
CODATA:	g/2 =	5.585 694 713	+/-	0.000 000 023	8.24 ppb

Selected for a Viewpoint in *Physics*
PRL **110,** 130801 (2013) PHYSICAL REVIEW LETTERS week ending 29 MARCH 2013

One-Particle Measurement of the Antiproton Magnetic Moment

J. DiSciacca,[1] M. Marshall,[1] K. Marable,[1] G. Gabrielse,[1,*] S. Ettenauer,[1] E. Tardiff,[1] R. Kalra,[1] D. W. Fitzakerley,[2] M. C. George,[2] E. A. Hessels,[2] C. H. Storry,[2] M. Weel,[2] D. Grzonka,[3] W. Oelert,[3,4] and T. Sefzick[3]

(ATRAP Collaboration)

[1]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[3]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[4]*Institut für Physik, Johannes Gutenberg Universität Mainz, D-5509 Mainz, Germany*
(Received 21 January 2013; published 25 March 2013)

For the first time a single trapped antiproton ($\bar{p}$) is used to measure the $\bar{p}$ magnetic moment $\boldsymbol{\mu}_{\bar{p}}$. The moment $\boldsymbol{\mu}_{\bar{p}} = \mu_{\bar{p}} \boldsymbol{S}/(\hbar/2)$ is given in terms of its spin $\boldsymbol{S}$ and the nuclear magneton (μ_N) by $\mu_{\bar{p}}/\mu_N = -2.792\,845 \pm 0.000\,012$. The 4.4 parts per million (ppm) uncertainty is 680 times smaller than previously realized. Comparing to the proton moment measured using the same method and trap electrodes gives $\mu_{\bar{p}}/\mu_p = -1.000\,000 \pm 0.000\,005$ to 5 ppm, for a proton moment $\boldsymbol{\mu}_p = \mu_p \boldsymbol{S}/(\hbar/2)$, consistent with the prediction of the *CPT* theorem.

Gabrielse

First One-Particle Measurement of the Antiproton Magnetic moment

$$\mu_{\overline{p}}/\mu_N = -2.792\,845 \pm 0.000\,012 \qquad [4.4 \text{ ppm}].$$

$$\mu_{\overline{p}}/\mu_p = -1.000\,000 \pm 0.000\,005 \qquad [5.0 \text{ ppm}]$$
$$\mu_{\overline{p}}/\mu_p = -0.999\,999\,2 \pm 0.000\,004\,4 \quad [4.4 \text{ ppm}].$$

680 times lower than previous

Resonance	Source	ppm
spin	resonance frequency	2.7
spin	magnetron broadening	1.3
cyclotron	resonance frequency	3.2
cyclotron	magnetron broadening	0.7
total		4.4

TABLE I. Significant uncertainties in ppm.

680 – Fold Improved Precision

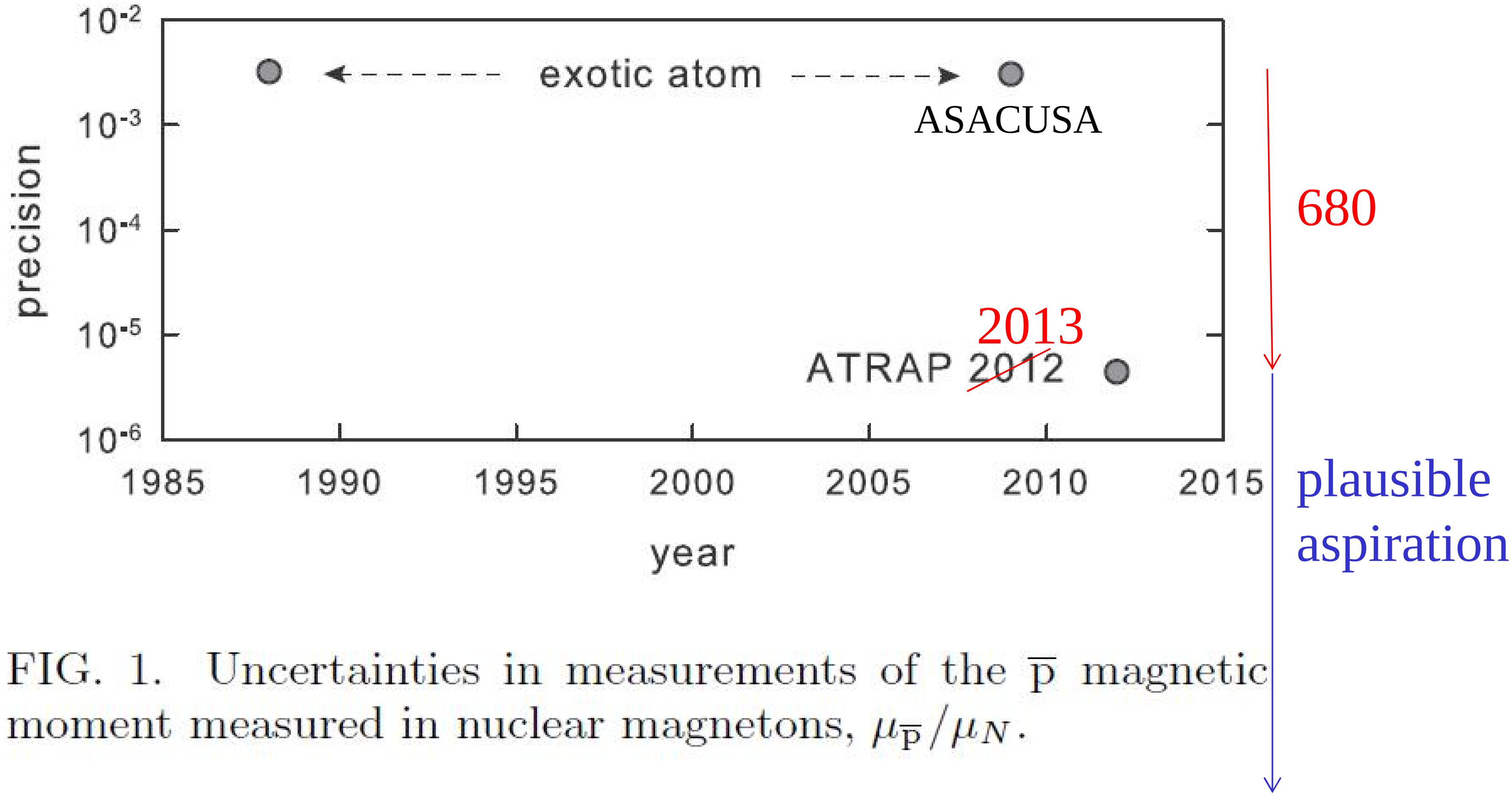
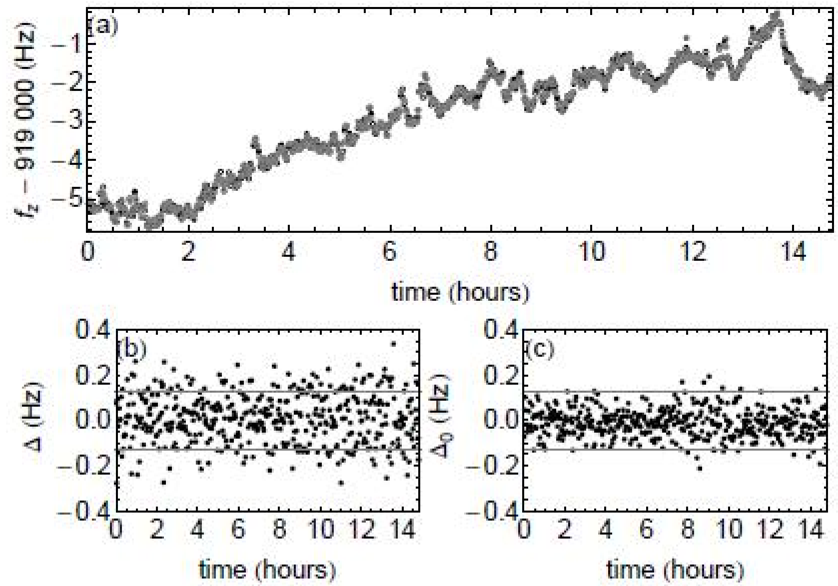


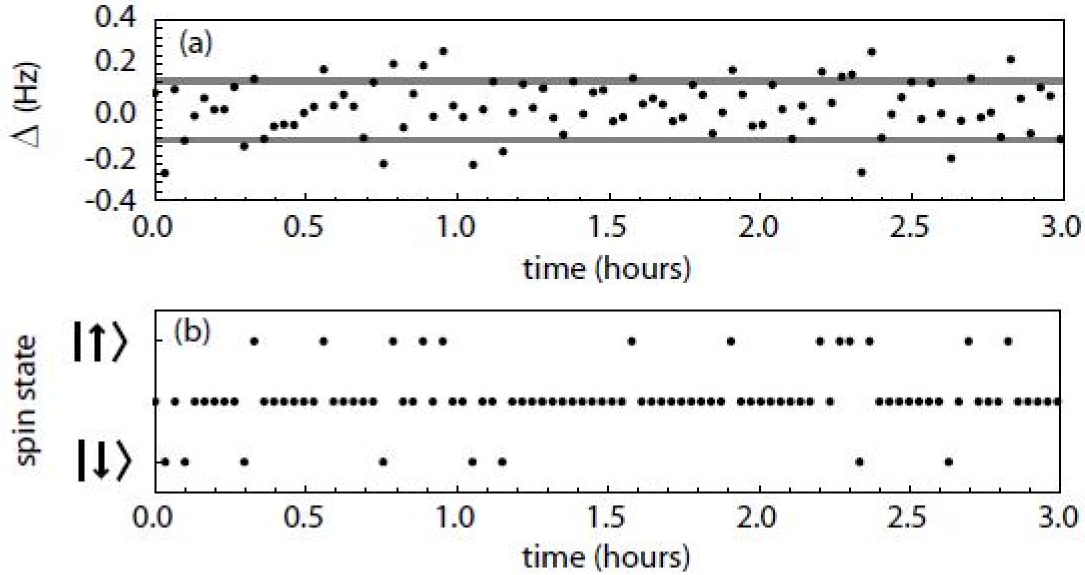
FIG. 1. Uncertainties in measurements of the $\overline{\mathrm{p}}$ magnetic moment measured in nuclear magnetons, $\mu_{\overline{\mathrm{p}}}/\mu_N$.

ATRAP, Phys. Rev. Lett. (2013).

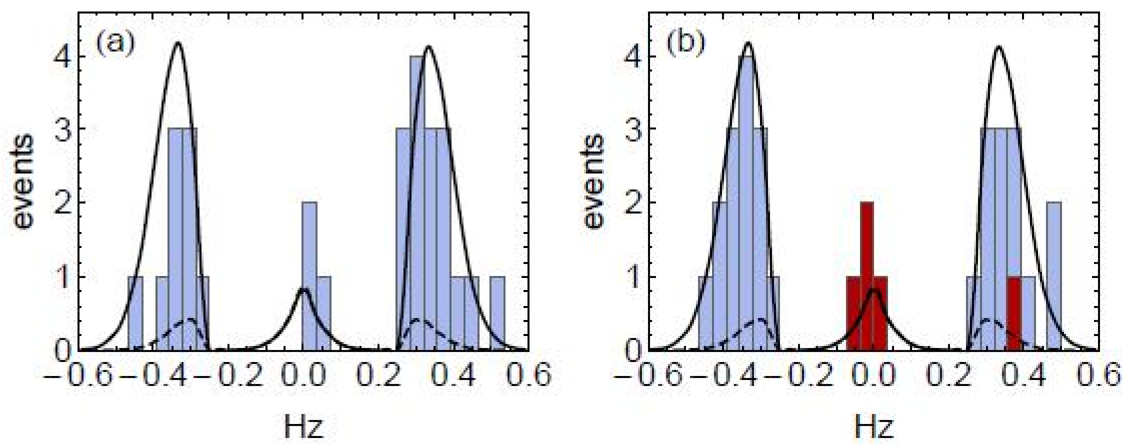
For the Future A 1000 to 10000-fold Improved Precision May be Possible



Single Proton Spin Flips Resolved



Spin Down to Up must follow Spin Up to Down: Correlation Function



Proton Spin Flip Report

PRL **110,** 140406 (2013) PHYSICAL REVIEW LETTERS week ending 5 APRIL 2013

Resolving an Individual One-Proton Spin Flip to Determine a Proton Spin State

J. DiSciacca, M. Marshall, K. Marable, and G. Gabrielse*
Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
(Received 21 February 2013; published 4 April 2013)

Previous measurements with a single trapped proton (p) or antiproton ($\bar{p}$) detected spin resonance from the increased scatter of frequency measurements caused by many spin flips. Here a measured correlation confirms that individual spin transitions and states are rapidly detected instead. The 96% fidelity and an efficiency expected to approach unity suggests that it may be possible to use quantum jump spectroscopy to measure the p and $\bar{p}$ magnetic moments much more precisely.

DOI: 10.1103/PhysRevLett.110.140406 PACS numbers: 13.40.Em, 14.20.Dh, 37.10.Ty

Similar proton result from Mainz group in same issue

Does the Electron Also Have an Electric Dipole Moments

Particle EDM Requires Both P and T Violation

Magnetic moment:

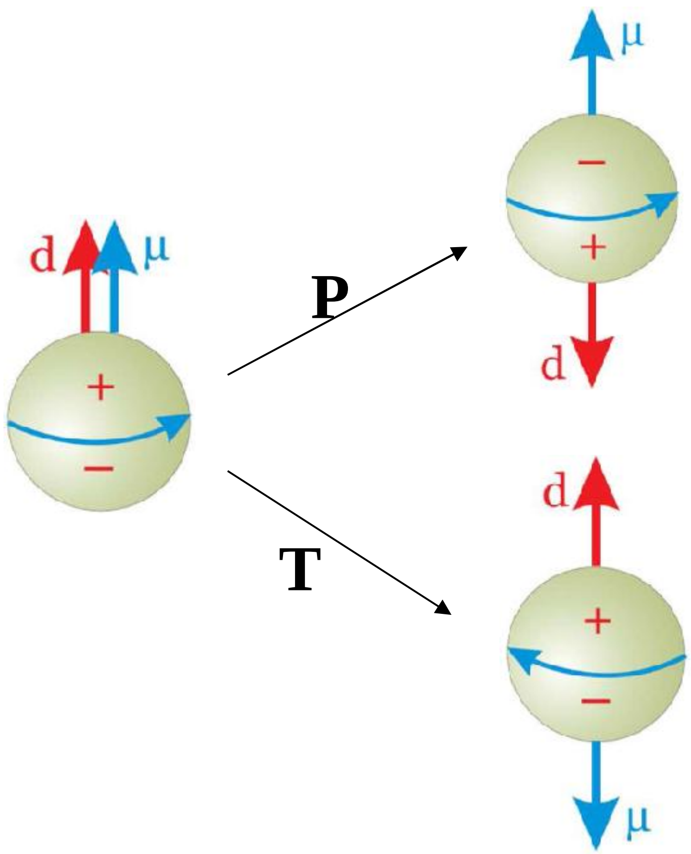
$$\vec{«} = -« \frac{\vec{S}}{\hbar / 2}$$

(exists and well-measured)

Electric dipole Moment:

$$\vec{d} = -d \frac{\vec{S}}{\hbar / 2}$$

(d is extremely small)



If reality is invariant under parity transformations **P**

→ **d = 0**

If reality is invariant under time reversal transformations **T**

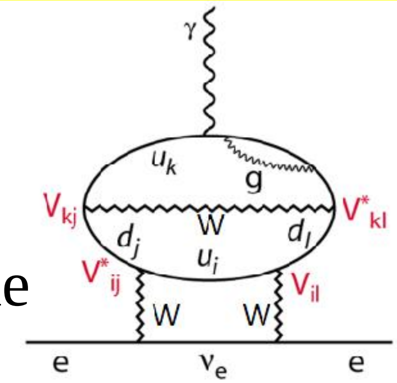
→ **d = 0**

Standard Model of Particle Physics → Currently Predicts a Non-zero Electron EDM

Standard model: d ~ 10^{-38} e-cm

Too small to measure by orders of magnitude

best measurement: d ~ 2 x 10^{-27} e-cm



four-loop level in perturbati theory

M. Pospelov and I. B. Khriplovich, "Electric dipole moment of the W boson and the electron in the Kobayashi-Maskawa model," Sov. J. Nucl. Phys. **53**, 638–640 (1991).

Weak interaction couples quark pairs (generations) $\begin{pmatrix} u \\ d' \end{pmatrix}, \begin{pmatrix} c \\ s' \end{pmatrix}, \begin{pmatrix} t \\ b' \end{pmatrix}$

CKM matrix relates to d, s, b quarks
(Cabibbo-Kabayashi-Maskawa matrix)

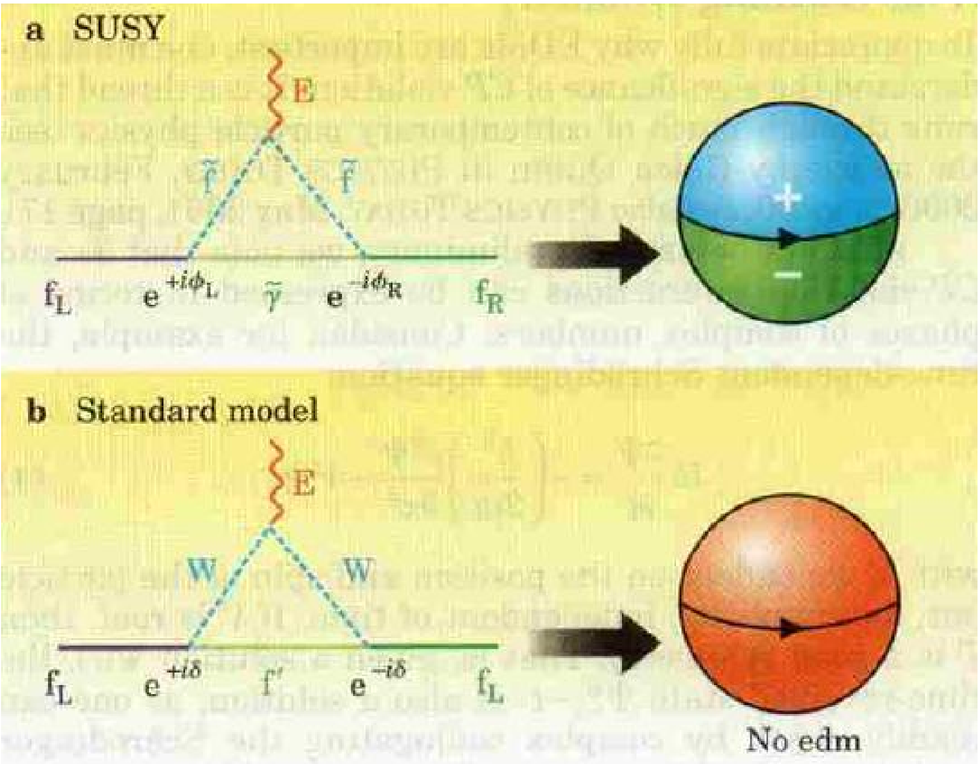
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

almost the unit matrix

$$\begin{pmatrix} 0.974 & 0.227 & 0.004 \\ 0.227 & 0.973 & 0.042 \\ 0.008 & 0.042 & 0.999 \end{pmatrix}$$

Extensions to the Standard Model → Measureable Electron EDM

An example

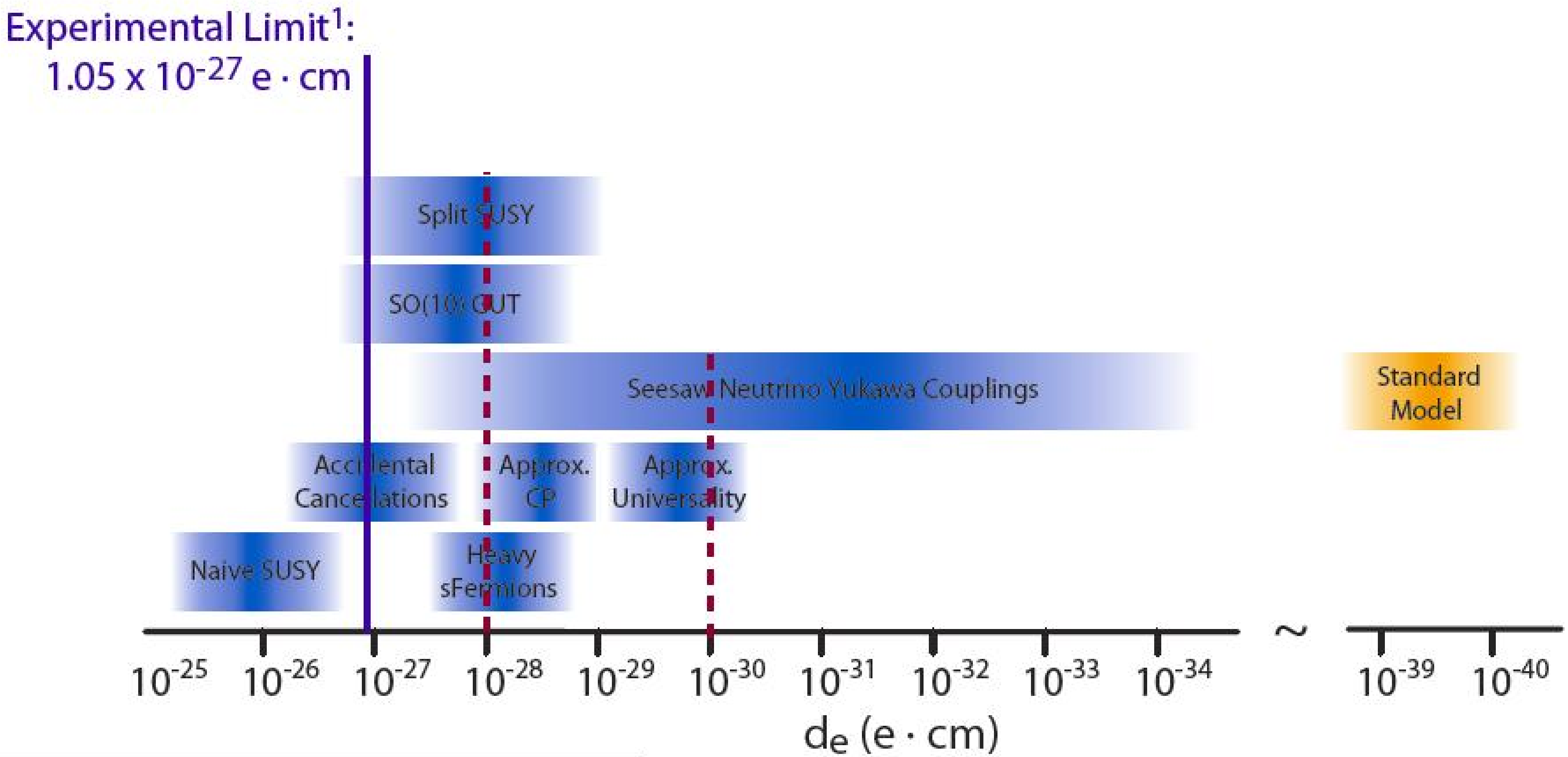


Low order contribution
→ larger moment

Low order contribution
→ vanishes

From Fortson, Sandars and Barr, Physics Today, 33 (June 2003)

EDM Predictions



[1] J. J. Hudson et al, Nature 473, 493-496 (2011)

No Particle EDM Has Yet Been Detected

Electron EDM limit $|d_e| \leq 1.6 \times 10^{-27} e$ cm

Commins, …
PRL **88**, 071805 (2002)

1.0 Hinds, 2011

Neutron EDM limit $|d_n| < 2.9 \times 10^{-26} e$ cm

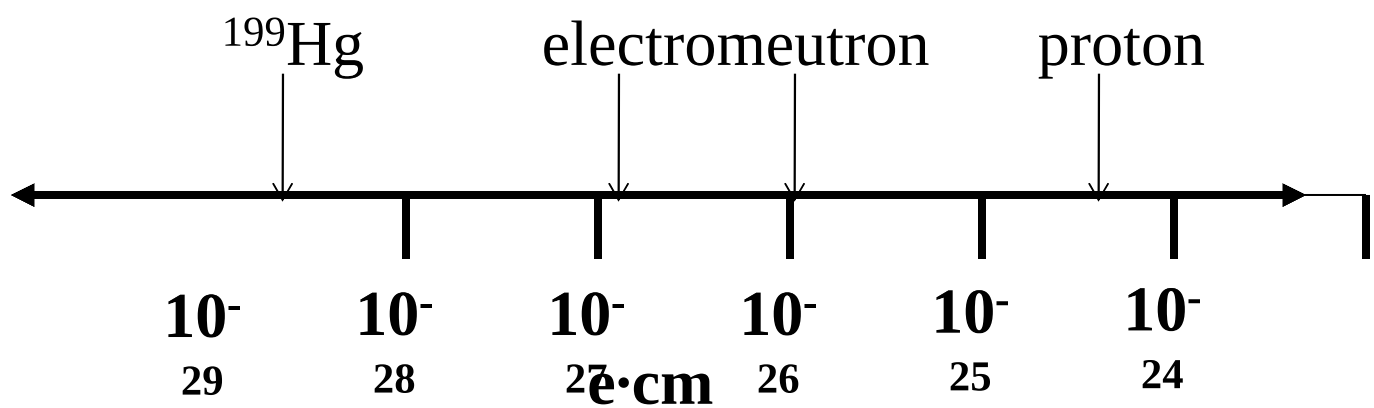
IIL Grenoble,
PRL **97**, 131801 (2006)

Proton EDM limit $|d_p| < 7.9 \times 10^{-25}\ e$ cm

Heckel, Fortson, …
PRL **102**, 101601 (2009)

from $|d(^{199}\mathrm{Hg})| < 3.1 \times 10^{-29}\ e$ cm

also sets $|d_n| < 5.8 \times 10^{-26}\ e$ cm



Does the Electron Also Have an Electric Dipole Moment?

Magnetic moment: $\vec{\mu} = -\mu \dfrac{\vec{S}}{\hbar / 2}$

(exists and well-measured)

Electric dipole moment: $\vec{d} = -d \dfrac{\vec{S}}{\hbar / 2}$

(d is extremely small)

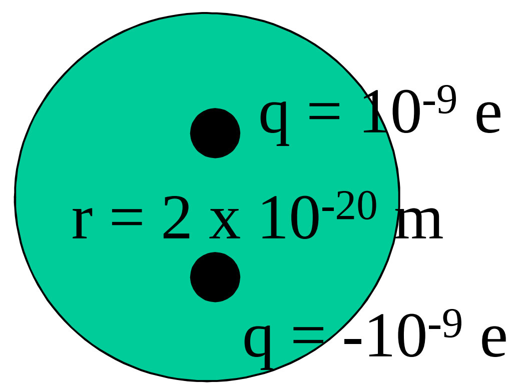
No Electron EDM Detected so Far

Commins limit (2002)

$|d_e| \leq 1.6 \times 10^{-27} e \text{ cm}$

Tl

Regan, Commins, Schmidt, DeMille,
Phys. Rev. Lett. **88**, 071805 (2002)



Imperial College (2011)

$|d_e| < 10.5 \times 10^{-28} e \text{ cm}$

YbF

Hudson, Kara, Smallman, Sauer, Tarbutt, Hinds,
Nature **473**, 493 (2011)

Advanced Cold-Molecule Electron EDM

ACME

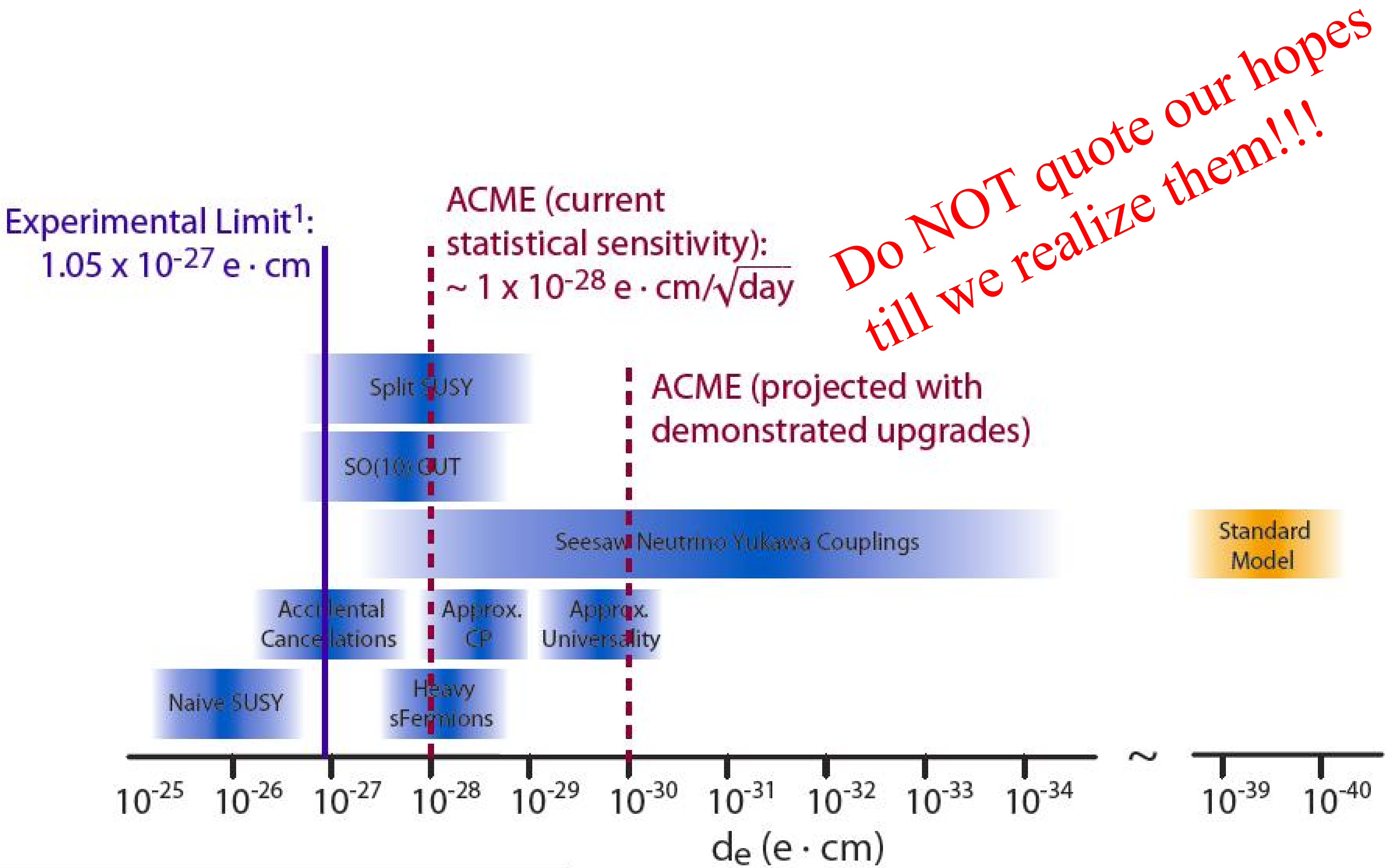
Harvard University
John Doyle Group
Gerald Gabrielse Group

Yale University
David DeMille Group

Nearing publication of a new result for the electron EDM

Funding from NSF

New Electron EDM Measurement Close



[1] J. J. Hudson et al, Nature 473, 493-496 (2011)

Relationship to LHC Physics

The LHC is exciting and important but EDMs also play a role

- should get an improved electron EDM on the LHC time scale
- If the LHC sees new particles, is CP violation involved?
- If the LHC sees nothing, EDM game is the only one in town

Main point for this conference

- It is easy to speak about making new EDM measurements

- It is much harder to get measurements within orders of magnitude of the precision in current measurements (especially with charged particles)

Summary

Antiproton magnetic moment

4.4 ppm (factor of 680 improvement)

Not so often that one gets to make such a step

Aspire to get 1000 to 10000 times better

Then will have a second extremely precise test of CPT with baryon/antibaryon system