First Several Slides are a Summary

ATRAP Progress and Aspirations

G. Gabrielse,[1,*] R. Kalra,[1] W.S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[2] M. Zielinski,[2] D.W. Fitzakerley,[3] M.C. George,[3] E.A. Hessels,[3] C.H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]
(ATRAP Collaboration)
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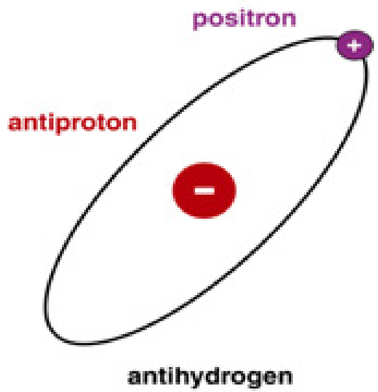
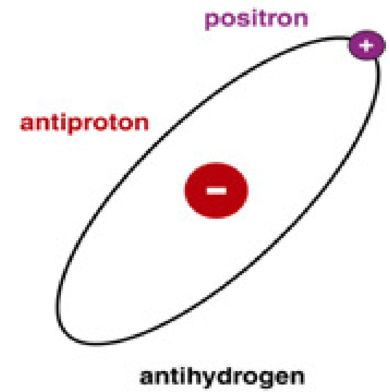
[2] *IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3] *York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
[4] *Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*



Support: USA: NSF and AFOSR.
Canada: NSERC, CRC and CFI
Germany: BMBF, DFG and DAAD



Gerald Gabrielse

Leverett Professor of Physics, Harvard University
ATRAP Spokesperson

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)

High Precision Tests of CPT Invariance

The Most Precise CPT Test with Baryons → by TRAP at CERN

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

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

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

(most precise result of CERN's antiproton program)

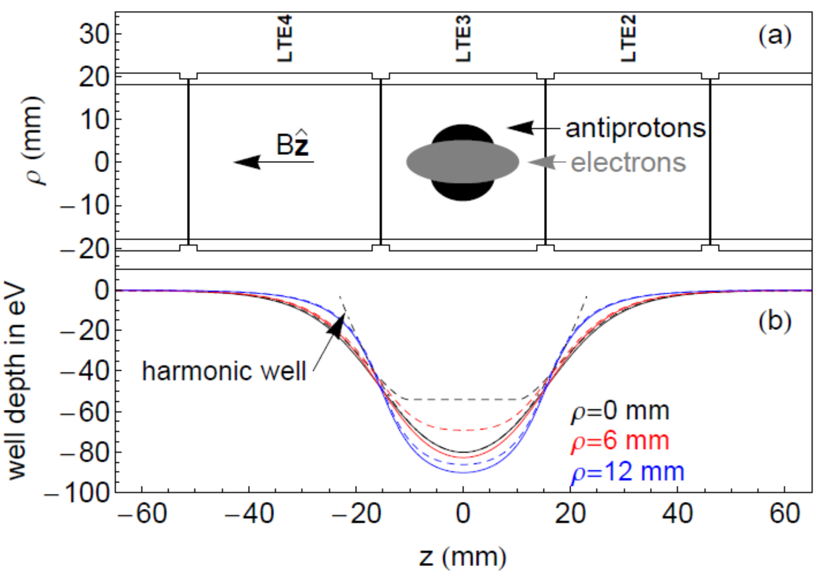
Goal at the AD: Make CPT test that approach exceed this precision

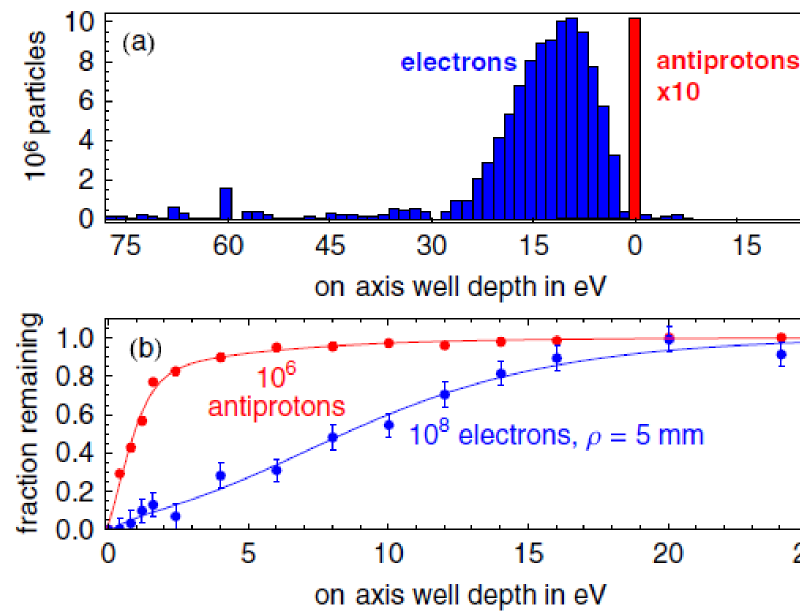
PRL **105,** 213002 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

ATRAP

Centrifugal Separation of Antiprotons and Electrons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] J. Wrubel,[1,†] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[3] M. Zielinski,[2] J. S. Borbely,[3] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] J. Walz,[4] and A. Speck[5]





- Important for arranging efficient overlap of antiprotons and a positron plasma
- Important for understanding the heating of antiprotons when electrons are ejected

1 million antiprotons,
100 million electrons

ATRAP

Adiabatic Cooling of Antiprotons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[1] T. Sefzick,[2] M. Zielinski,[2] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]

(ATRAP Collaboration)

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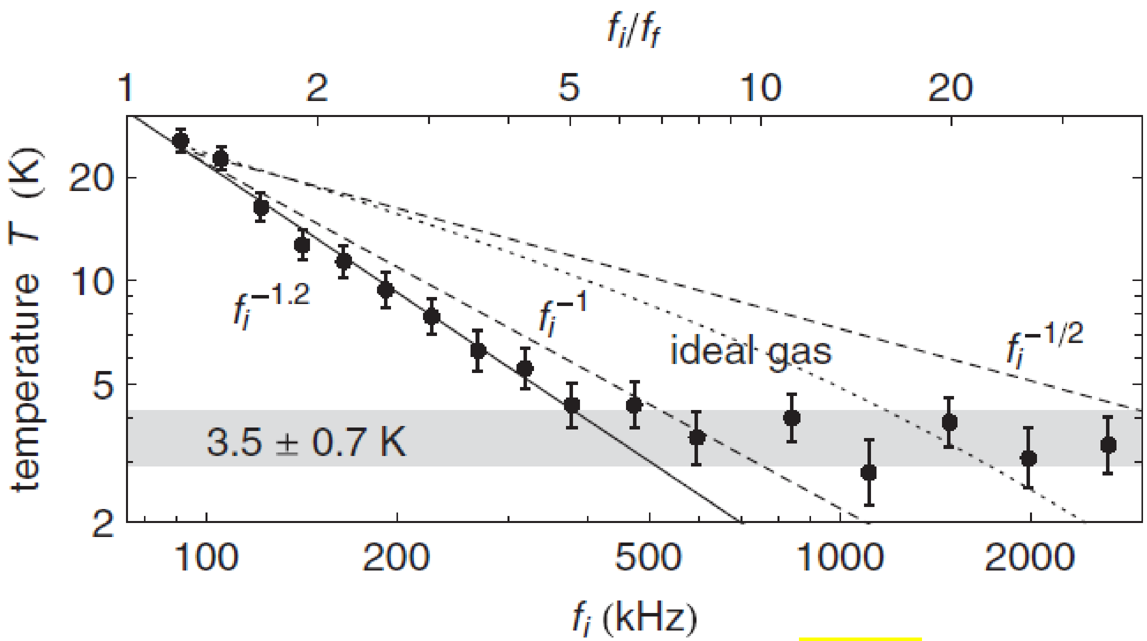
[4]*Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*
(Received 1 December 2010; published 15 February 2011)



0.4 K

Embedded electron cooling
(to 31 K or 17 K)

Followed by adiabatic cooling
(to 3.5 K or below)

ATRAP

Gabrielse

Trapped Antihydrogen in Its Ground State

G. Gabrielse,[1,*] R. Kalra,[1] W.S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[2] M. Zielinski,[2] D.W. Fitzakerley,[3] M.C. George,[3] E.A. Hessels,[3] C.H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]
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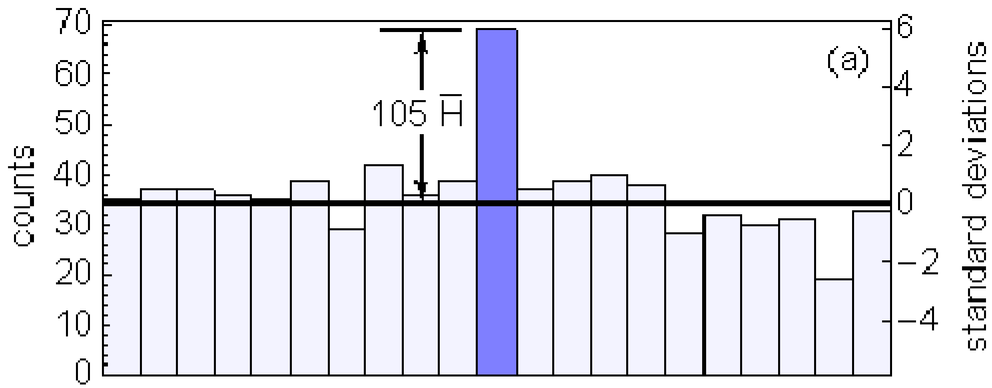
Antihydrogen atoms ($\overline{\mathrm{H}}$) are confined in an Ioffe trap for 15 to 1000 seconds – long enough to ensure that they reach their ground state. Though reproducibility challenges remain in making large numbers of cold antiprotons ($\overline{\mathrm{p}}$) and positrons (e^+) interact, 5 ± 1 simultaneously-confined ground state atoms are produced and observed on average, substantially more than previously reported. Increases in the number of simultaneously trapped $\overline{\mathrm{H}}$ are critical if laser-cooling of trapped $\overline{\mathrm{H}}$ is to be demonstrated, and spectroscopic studies at interesting levels of precision are to be carried out.



5 +/- 1 ground state atoms
simultaneously trapped

Still to be optimized

Crude Antigravity Limit

Gravity force on hydrogen: Mg

Gravity force on antihydrogen: $\kappa M g$

ATRAP 2011

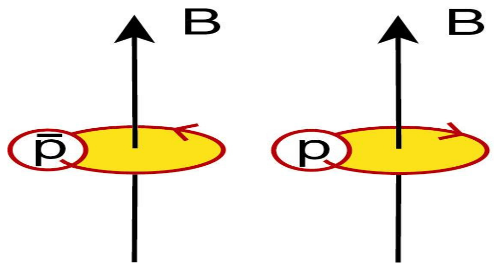
To have a trap: $|\kappa| \leq W/(Mgh) = 3 \times 10^3$

Since many antihydrogen atoms leave quickly: $|\kappa| < 2 \times 10^2$

(as trap goes from 375 mK to 350 mK)

Our earlier gravitational redshift limit is much more stringent

Antiproton and proton
clocks run at the same rate, $< 10^{-10}$



$|\kappa - 1| < 1 \times 10^{-6}$

Experiment

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

Theory

R. J. Hughes and M. H. Holzscheiter, Phys. Rev. Lett. **66**, 854 (1991).

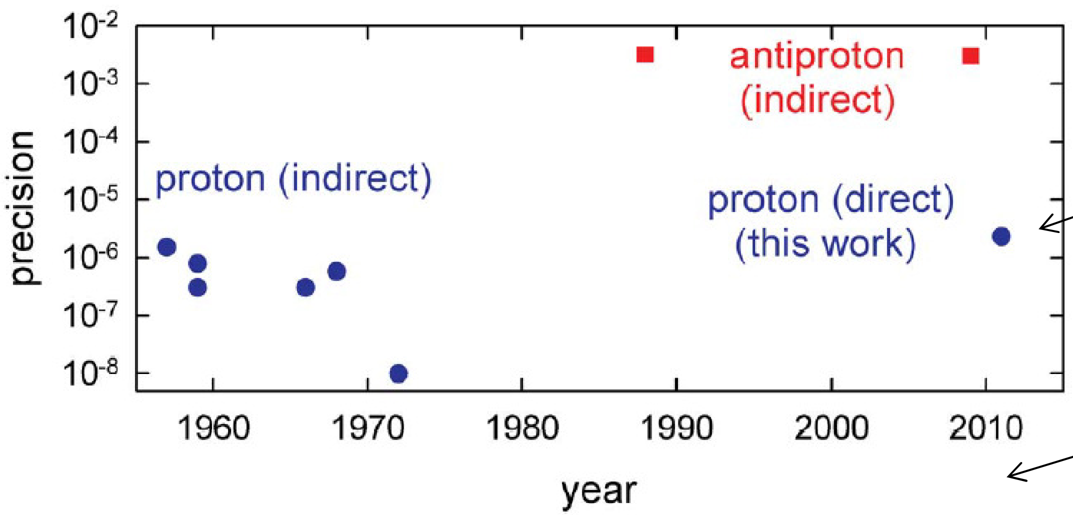
Direct Measurement of the Proton Magnetic Moment

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 ($\bar{\mathrm{p}}$) as with a proton (p). This opens the way to measuring the $\bar{\mathrm{p}}$ magnetic moment (whose uncertainty has essentially not been reduced for 20 years) at least 10^3 times more precisely.



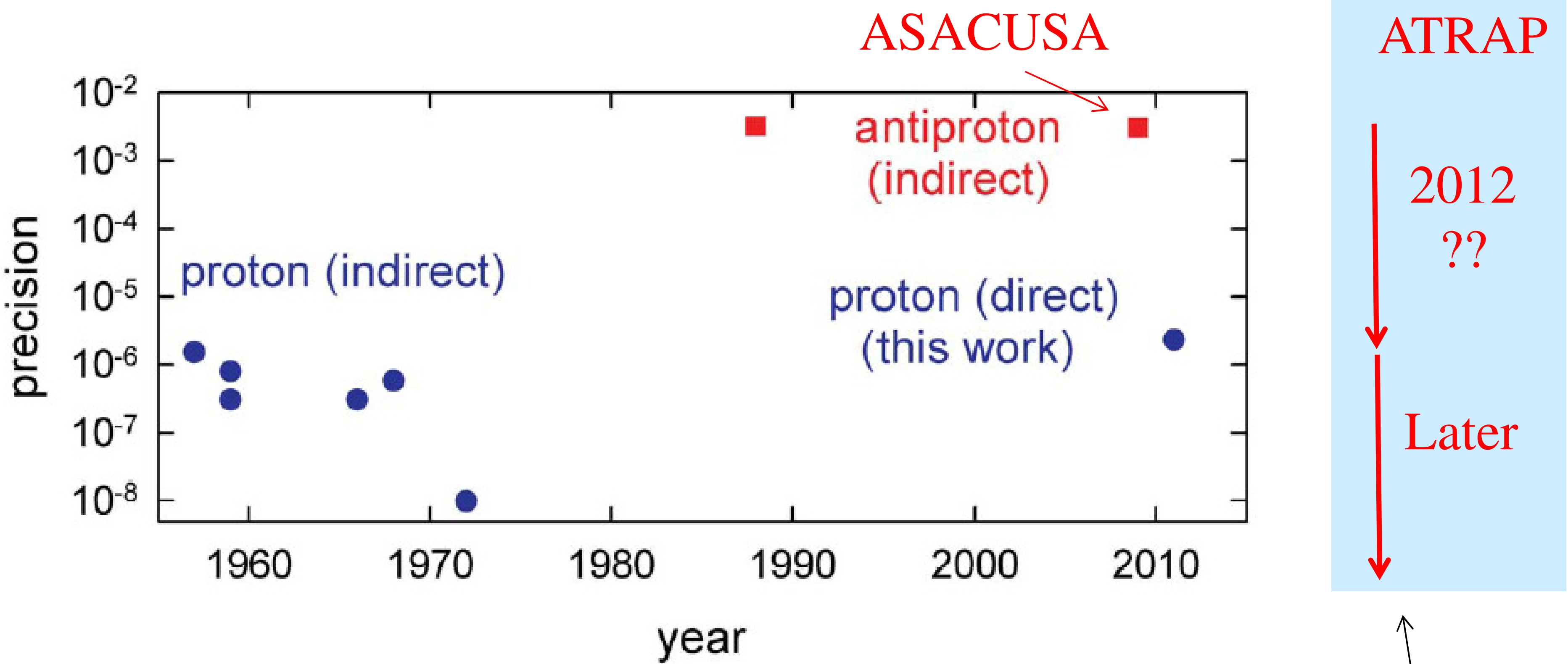
could do this with antiprotons now

eventually should get below this plot

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

Gabrielse

Could Now Realize 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 → currently under consideration

Expect to eventually be more precise than all proton measurements

Second Generation Ioffe Trap

Fully assembled, vacuum tested cold

Wiring finished this week

Cold testing at high current → soon

Intend to use from the beginning of the 2012 run

second generation Ioffe trap

ports for laser and microwaves

Slides Used for Talk

ATRAP Progress and Aspirations

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Gerald Gabrielse

Leverett Professor of Physics, Harvard University
ATRAP Spokesperson

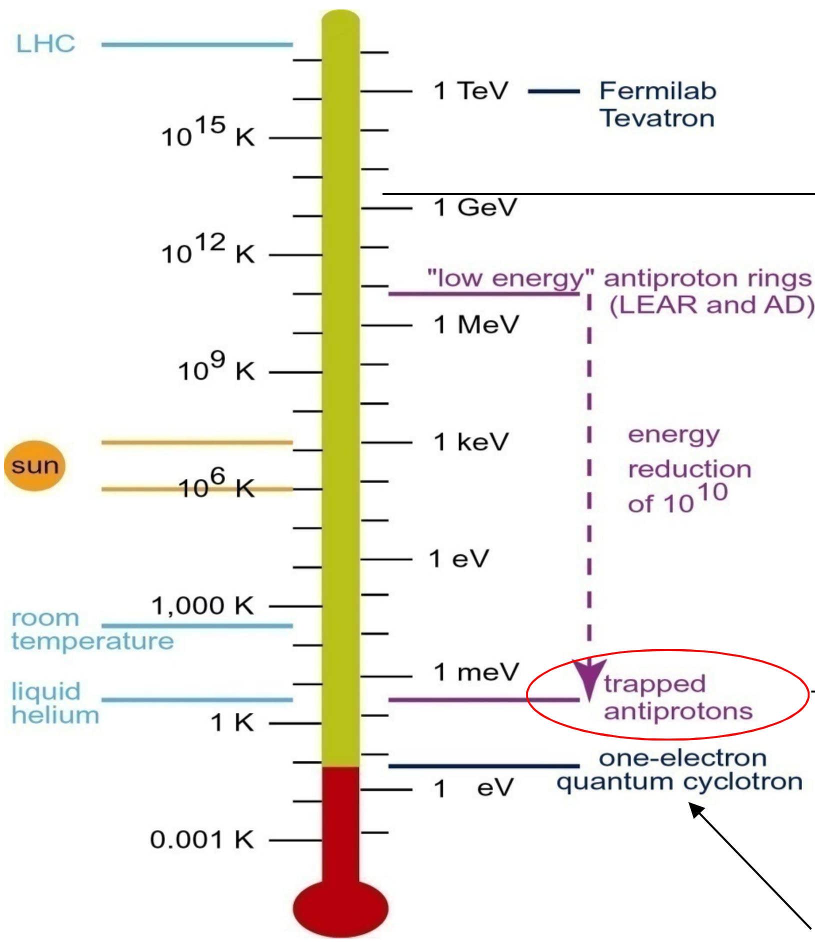
Low Energy Particle Physics

AMO Physics, Particle Physics, Plasma Physics

methods and funding

goals and facility

can't avoid



$2M_pc^2$

LEAR and AD

10^{10}

TRAP 4.2 K

0.3 meV

70 mK, lowest storage energy for any charged particles

Cold Antiprotons
and
Antihydrogen

High Precision Tests of CPT Invariance

The Most Precise CPT Test with Baryons → 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

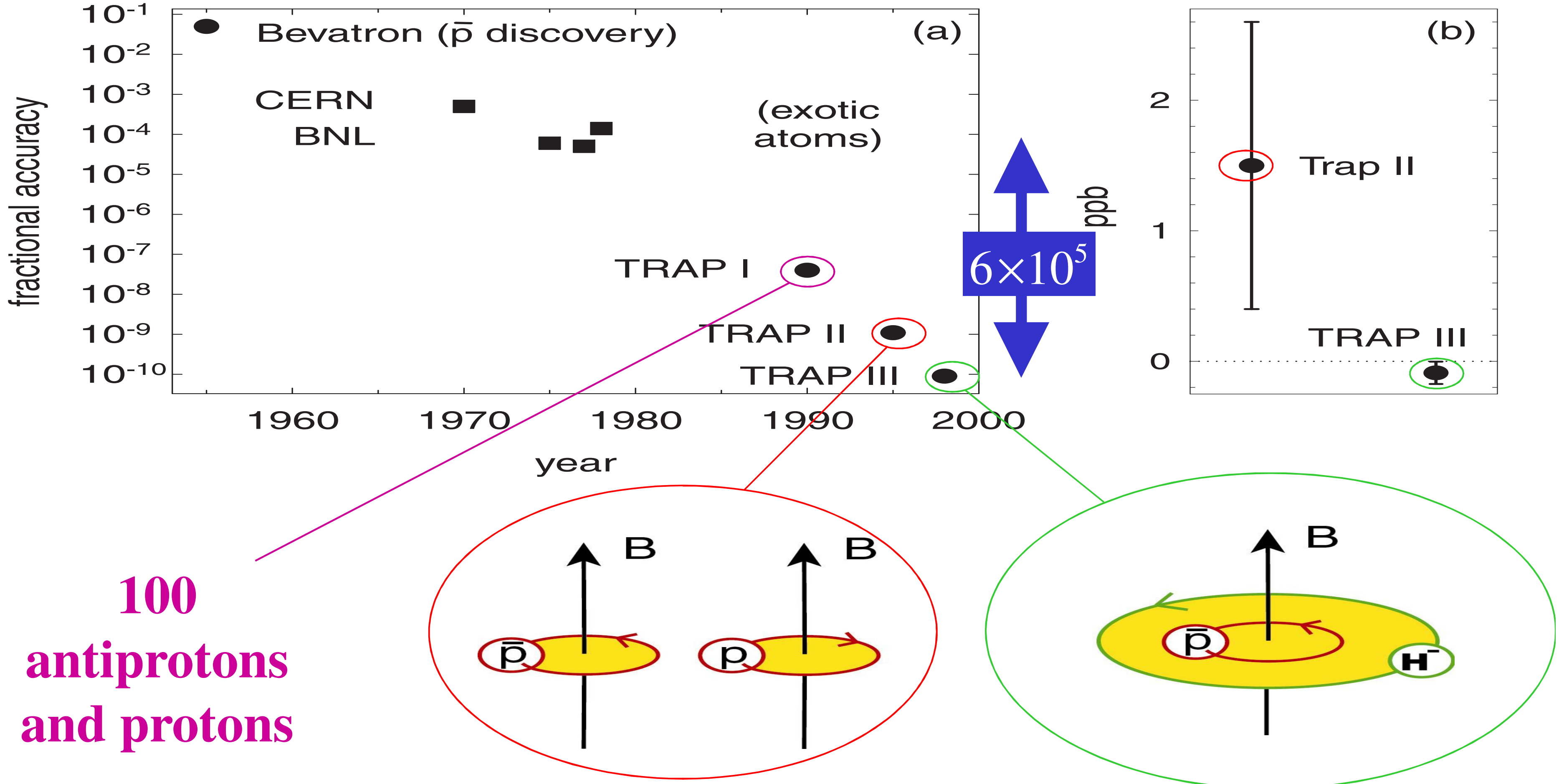
Gabrielse

TRAP 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).

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

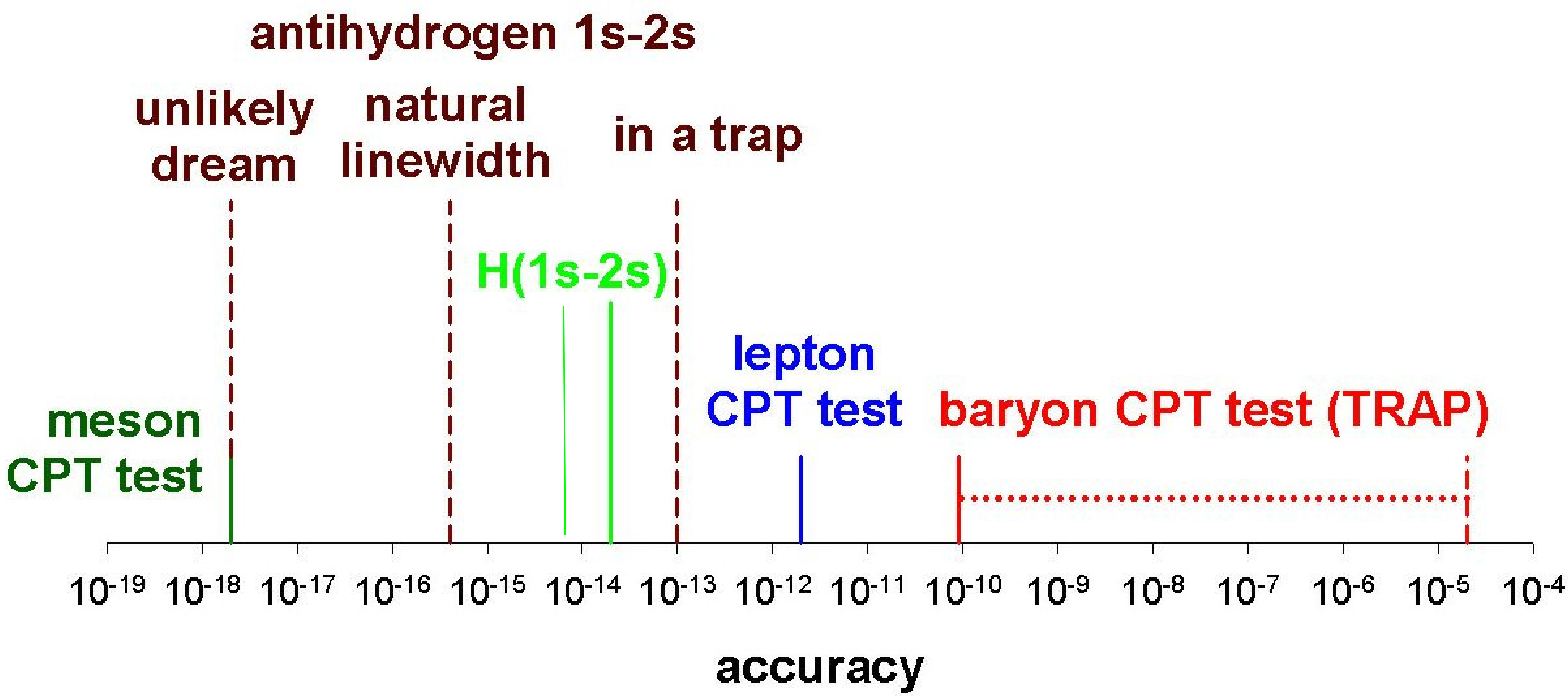
3 fundamentally different types of particles

	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

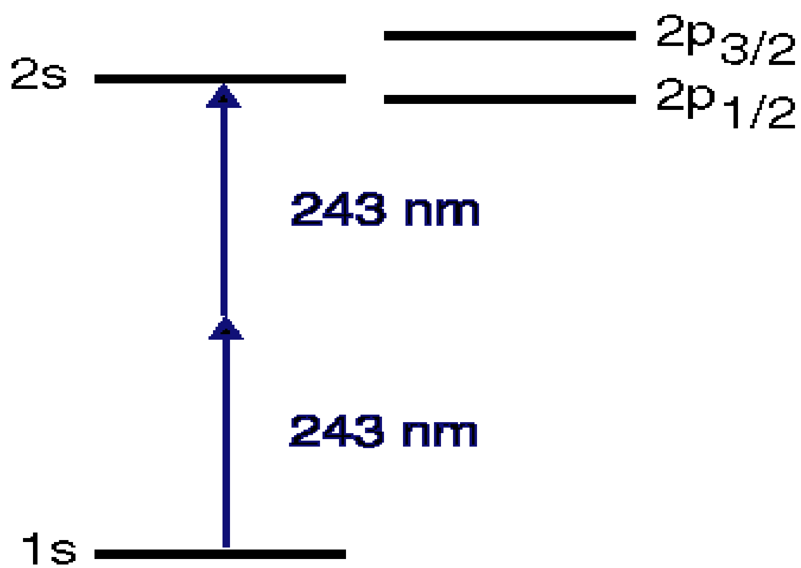
Gabrielse

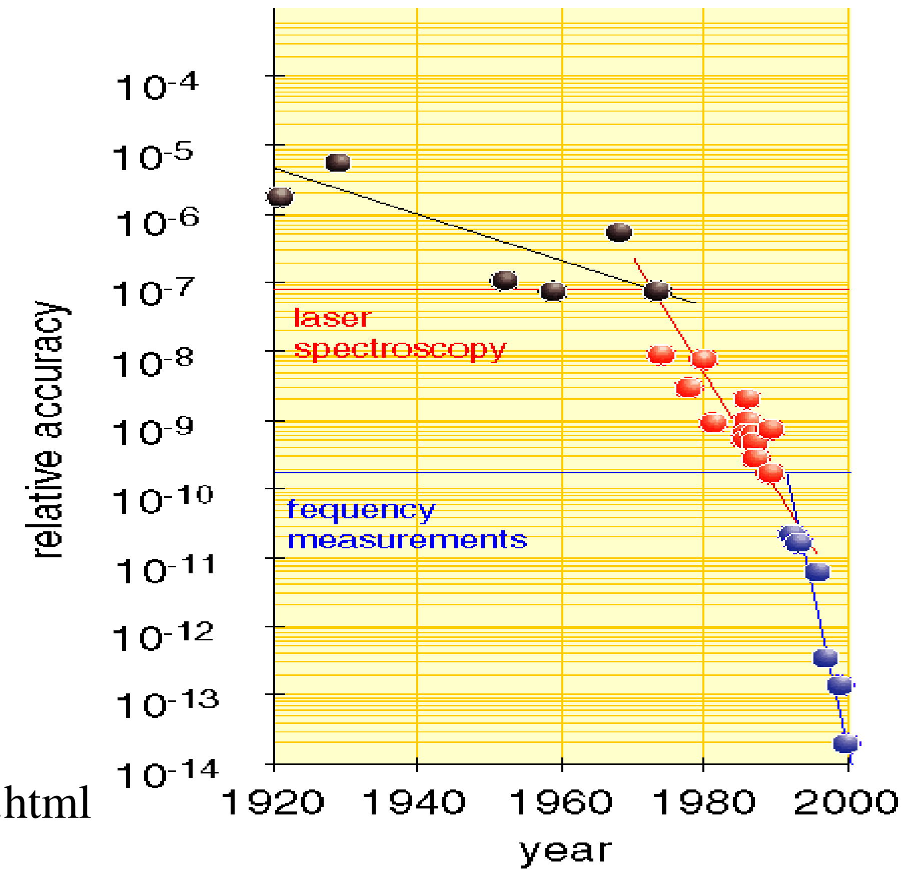
Seek to Improve Lepton and Baryon CPT Tests



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

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 likely be available

Cold Antiproton Physics is Now Routine
Cold Antihydrogen is Routinely Made

Only Accessible Antiprotons are at CERN

France

Switzerland (Geneva)

- Unusual for AMO experiment to be done over an ocean
- Must conform to accelerator schedule
- Environment not very amenable to precise AMO methods
- No AMO funding source for facility upgrades
- Data rate is very slow

Gabrielse

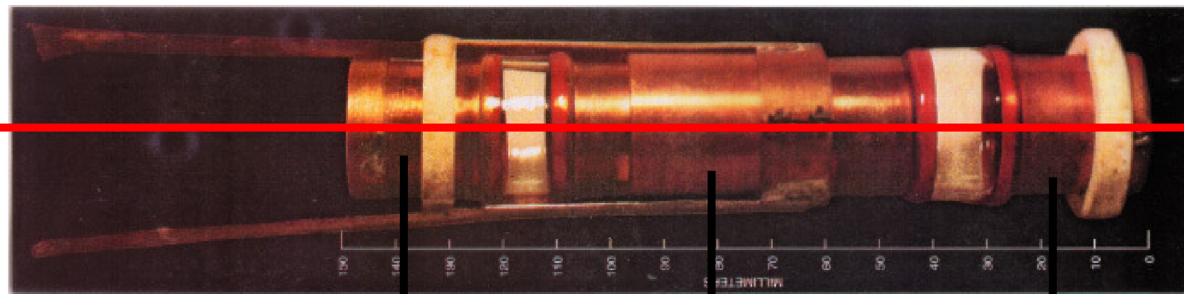
Accumulating Low Energy Antiprotons: Basic Ideas and Demonstrations (1986 – 2000)

TRAP Collaboration
at CERN's LEAR

1 cm

magnetic
field

21 MeV
antiprotons



–

+

–

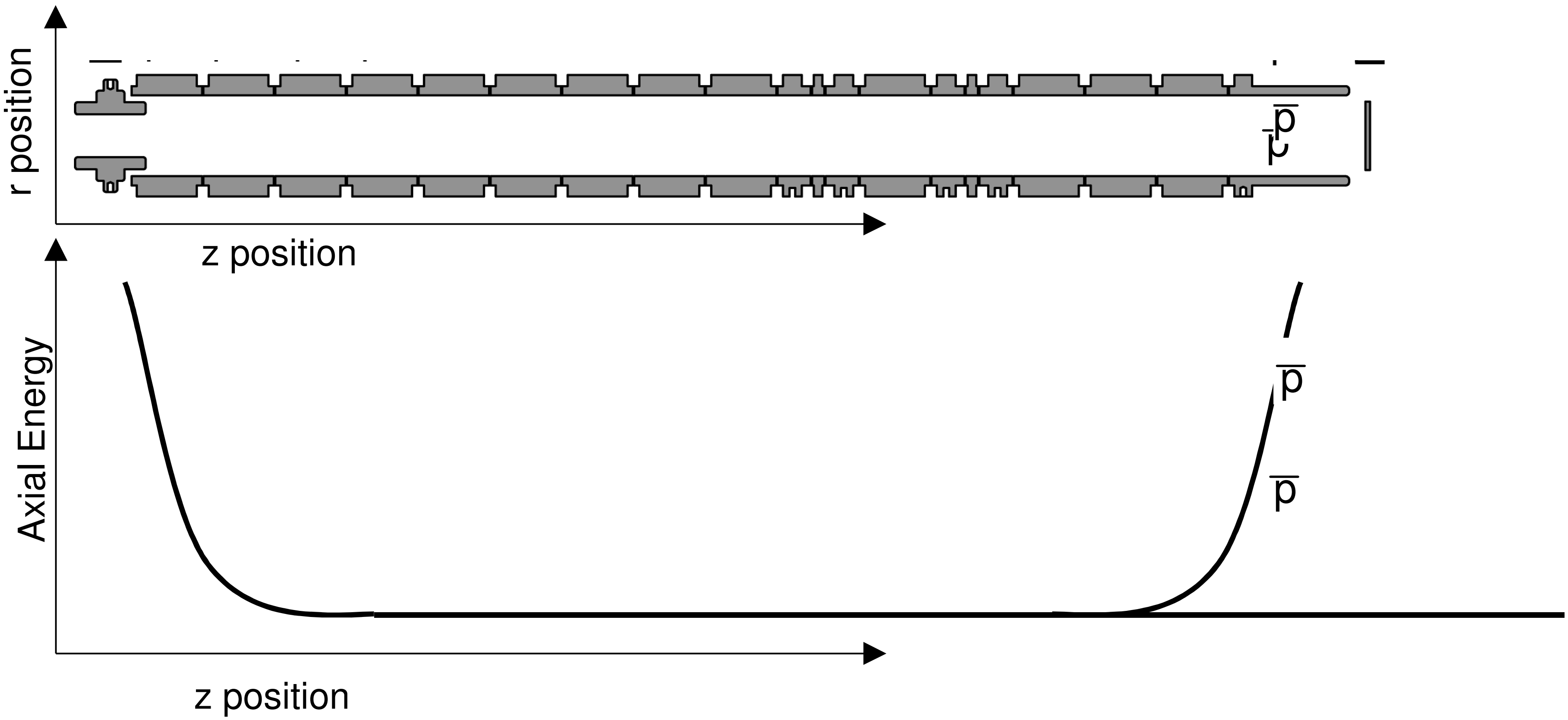
10^{-10}
energy
reduction

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

Now used by 3 collaborations
at the CERN AD
ATRAP, ALPHA and ASACUSA

Supported by AFOSR

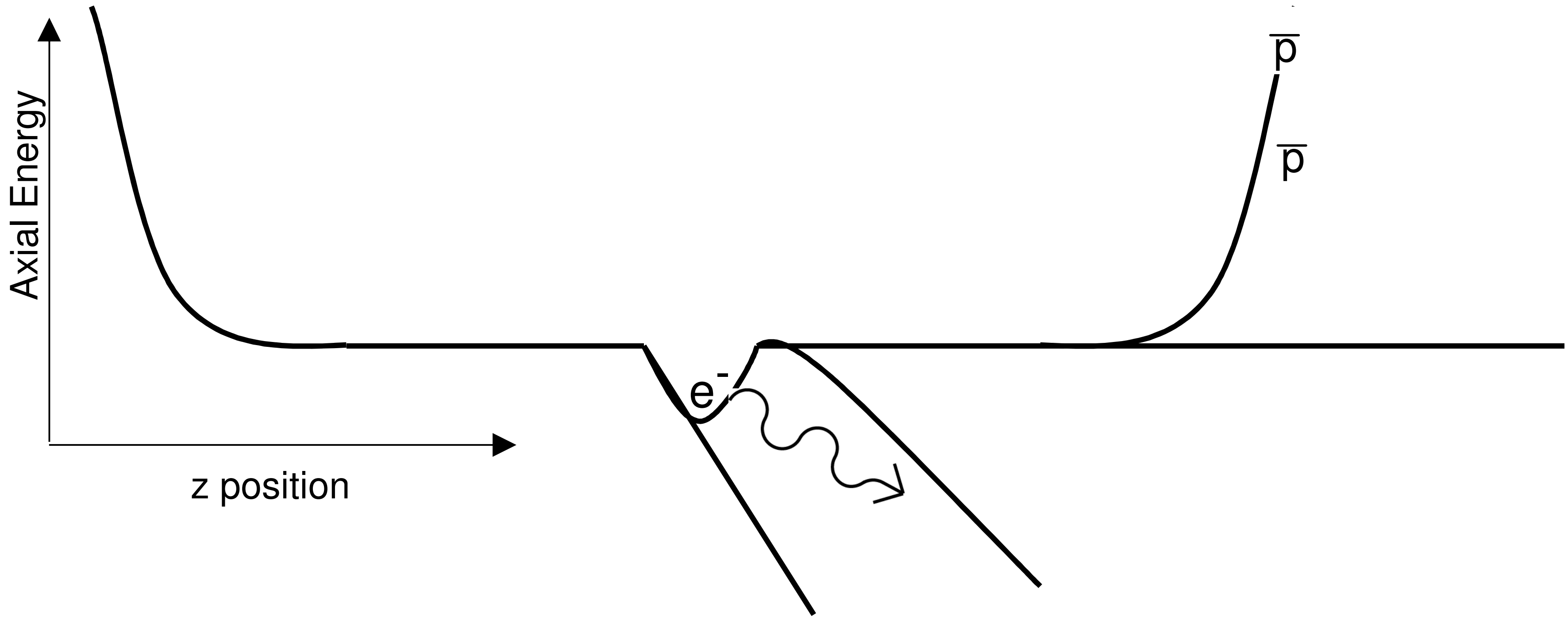
Antiproton Capture – the Movie



"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).

How?

Proposal to Trap Cold Antihydrogen – 1986

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  "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**
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  "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."

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Use trapped antihydrogen to measure antimatter gravity

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

Two Methods Produce Slow Antihydrogen

1. In a nested Penning trap, during positron cooling of antiprotons

   Device and technique – ATRAP
   Used to produce slow antihydrogen – ATHENA and ATRAP

   Variations: Basic (ATRAP initially, ATHENA-ALPHA)
   Driven (ATRAP before 2007)
   Adiabatic well depth change (ATRAP 2007)

2. Laser-controlled resonant charge exchange

   ATRAP

Anti-H Method 1: Nested Penning Trap
3-Body "Recombination"

Volume 129, number 1 PHYSICS LETTERS A 2 May 1988

ANTIHYDROGEN PRODUCTION USING TRAPPED PLASMAS

G. GABRIELSE, S.L. ROLSTON, L. HAARSMA
Department of Physics, Harvard University, Cambridge, MA 02138, USA

and

W. KELLS
Fermi National Accelerator Laboratory, Batavia, IL 60438, USA

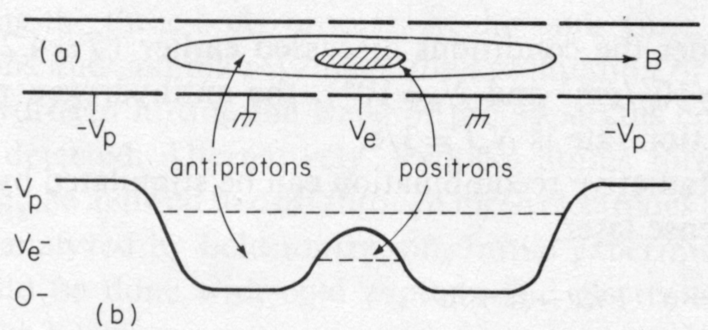


Fig. 1. Electrodes (a) and axial potential (b) for a nested pair of Penning traps.

Nested Penning Trap

We call attention to another three-body recombination

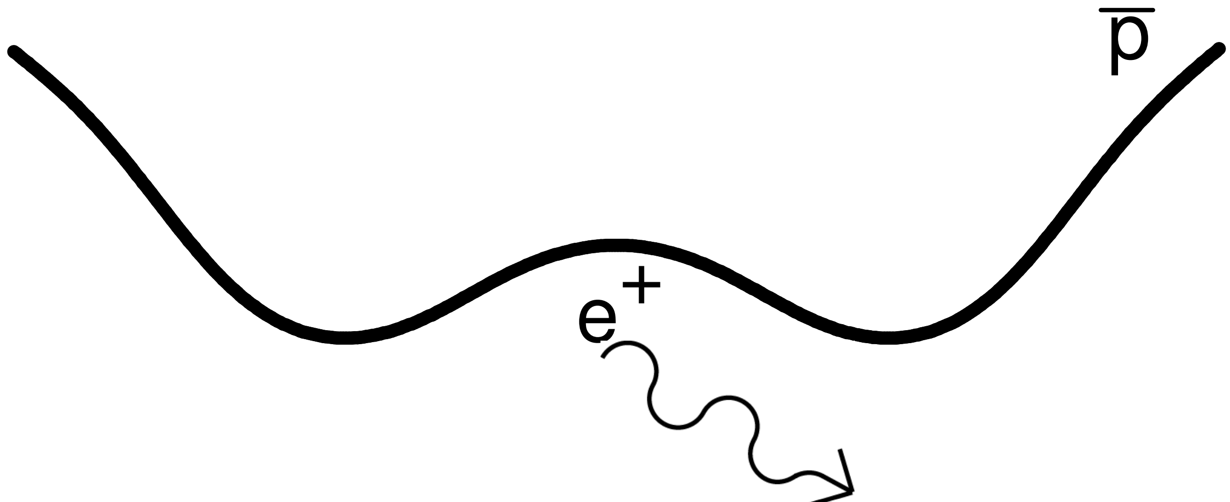
$$p^- + e^+ + e^+ \to \bar{H} + e^+ , \qquad (6)$$

which may well be more efficient for antihydrogen production by many orders of magnitude. Its cross

3-Body "Recombination"

Positron Cooling of Antiprotons in a Nested Penning Trap

Gabrielse



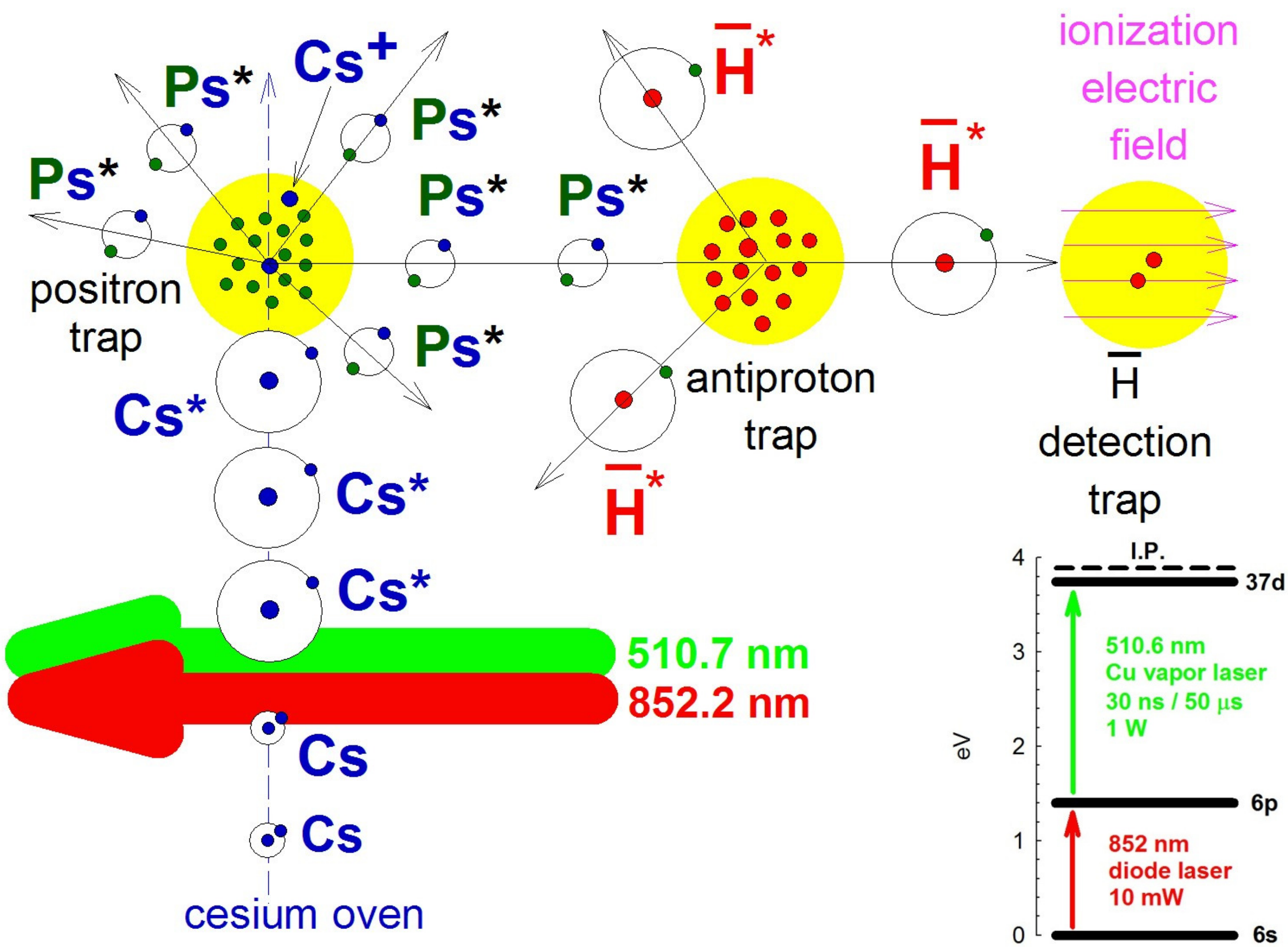
TRAP/ATRAP Develops the Nested Penning Trap

Proposed nested trap as a way to make antihydrogen
"Antihydrogen Production Using Trapped Plasmas"
G. Gabrielse, L. Haarsma, S. Rolston and W. Kells
Physics Letters A 129, 38 (1988)

"Electron-Cooling of Protons in a Nested Penning Trap"
D.S. Hall, G. Gabrielse
Phys. Rev. Lett. 77, 1962 (1996)

"First Positron Cooling of Antiprotons"
ATRAP
Phys. Lett. B 507, 1 (2001)

Anti-H Method II: Antihydrogen Via Laser-Controlled Resonant Charge Exchange



ATRAP, Phys. Rev. Lett. **93**, 263401 (2004)

What is Happening Now

Gabrielse

1986 → 2012

1 Collaboration → 4 Collaborations

Following the 1986 plan:

cold antiprotons

↓

cold antihydrogen → colder antihydrogen

↓

trap antihydrogen → extract from trap

↓

precise laser spectroscopy

Variations

extract from trap → laser spectroscopy

colder antihydrogen → interferometry

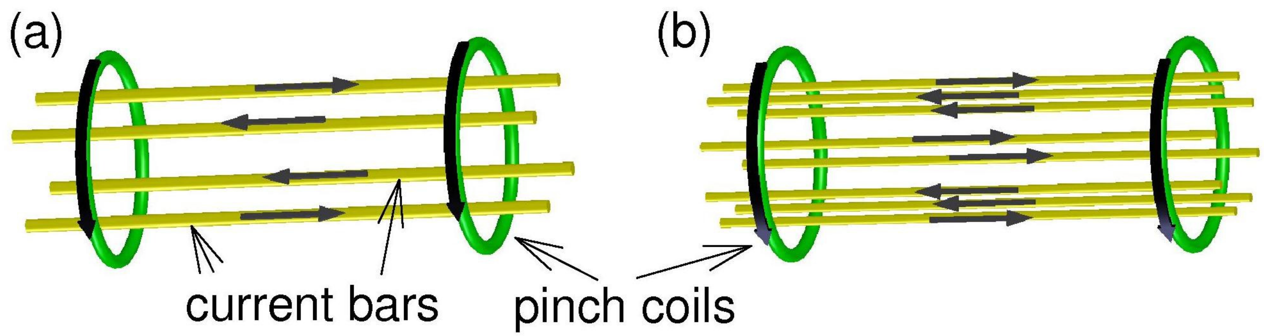
ATRAP and **ALPHA**

ASACUSA

AEGIS

Gabrielse

Variations of Magnetic Traps



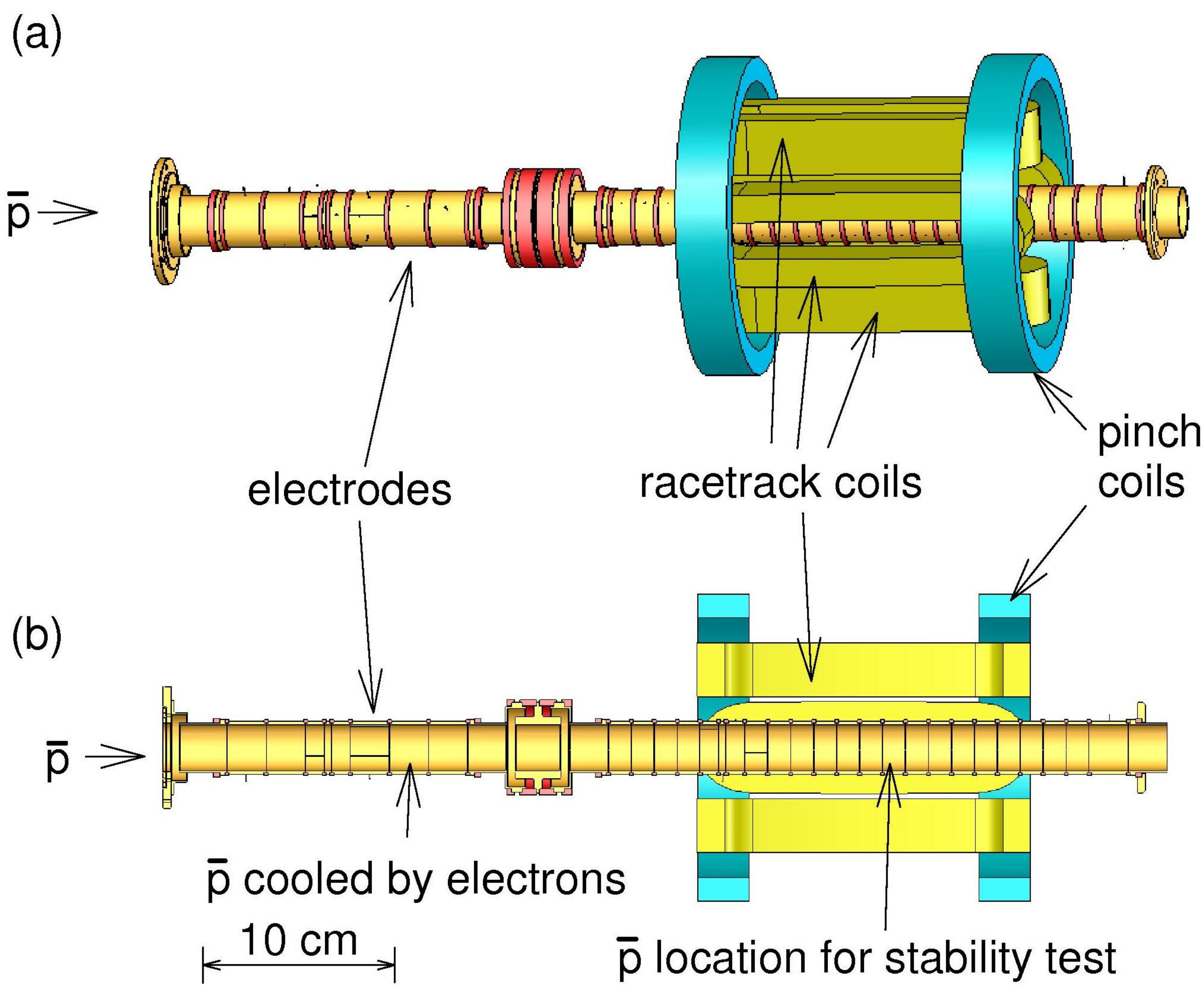
quadrupole-Ioffe trap addition

higher order Ioffe trap

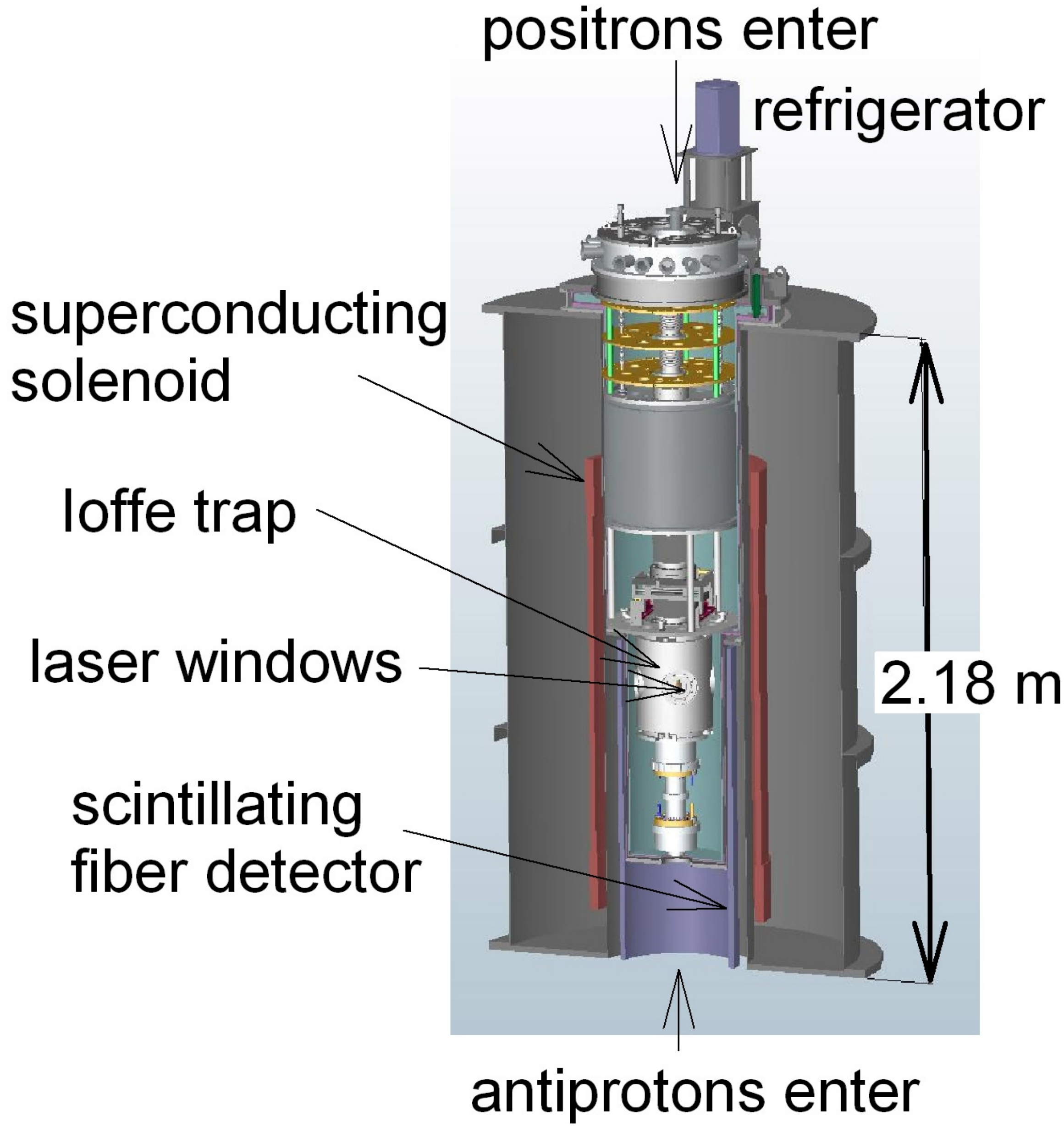
- Deeper antihydrogen well within trap electrodes (in principle)
- Tighter confinement of antihydrogen
- Easier radial access for cooling and spectroscopy lasers

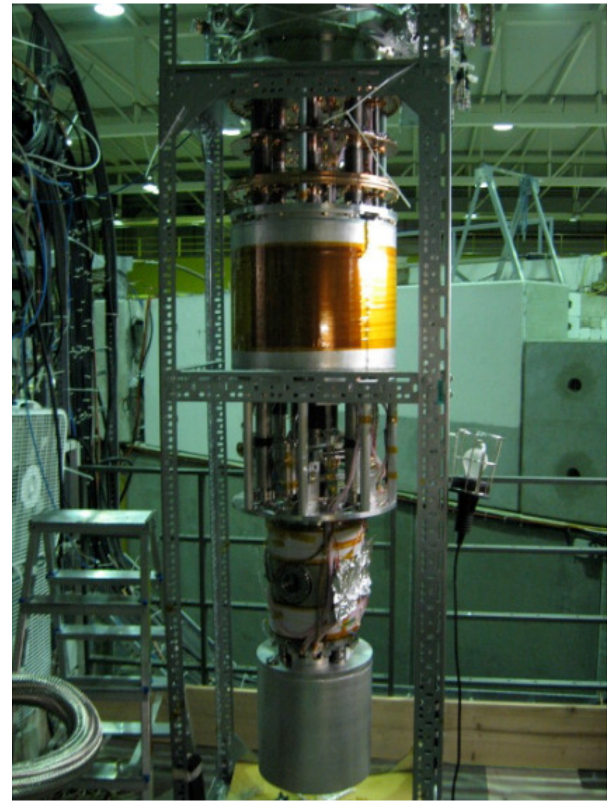
- Less magnetic gradient gives longer charged particle storage
- Less magnetic gradient gives make it easier to produce antihydrogen

ATRAP’s Most Recent Antihydrogen Trap



ATRAP II Trap Apparatus





quick study

Slow antihydrogen

Gerald Gabrielse

The quest to precisely compare cold antihydrogen and hydrogen atoms should enable physicists to test our understanding of one of reality's fundamental symmetries.

Gerald Gabrielse is the Leverett Professor of Physics at Harvard University in Cambridge, Massachusetts and is the spokesperson for the ATRAP collaboration at CERN in Geneva.

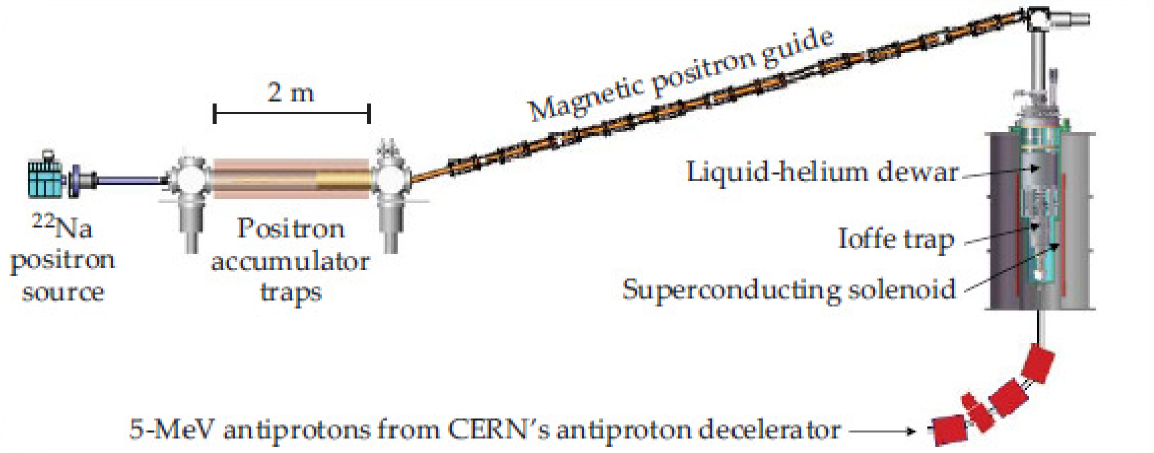


Figure 1. Key components of the ATRAP apparatus that accepts antiprotons from the antiproton decelerator at CERN and slows positrons from a sodium-22 source. The goal of the experiment is to trap and study cold antihydrogen atoms in the specially designed magnetic fields of the Ioffe trap.

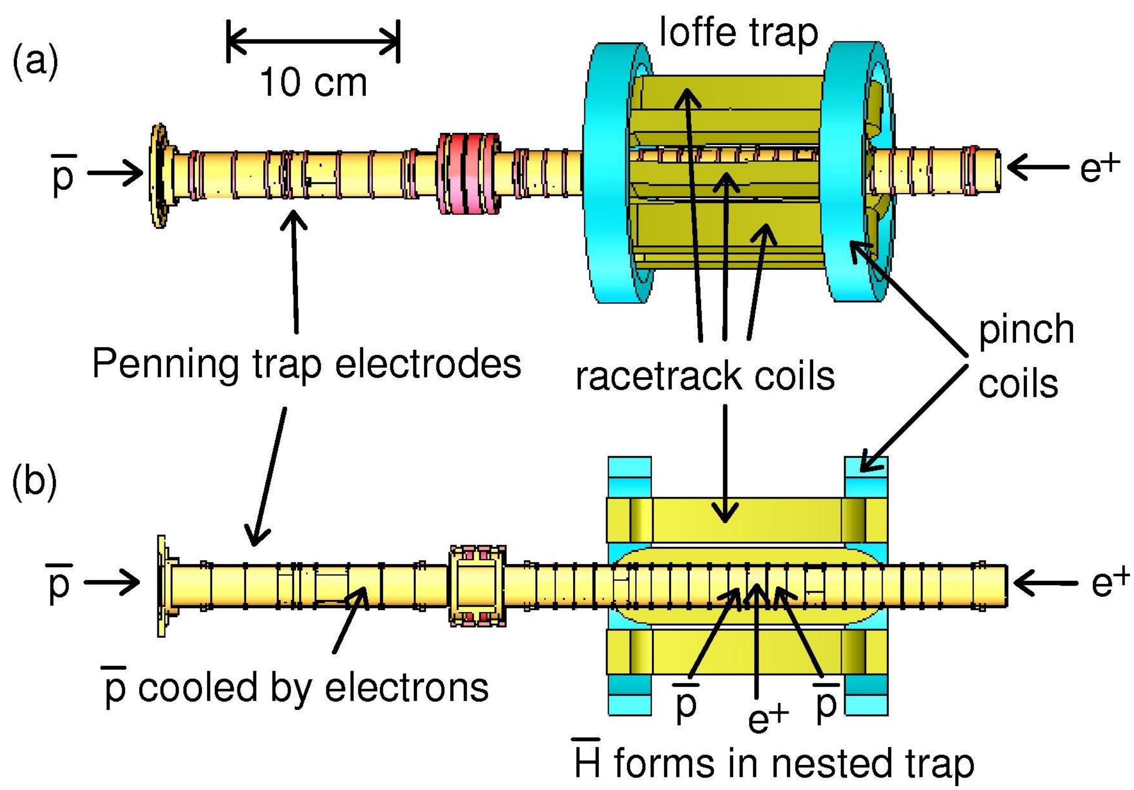
PRL 2008

Gabrielse

First Antihydrogen Production within a Penning-Ioffe Trap

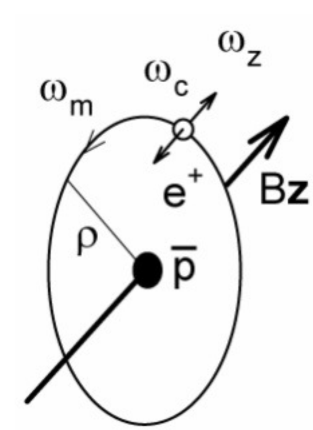
G. Gabrielse,[1,*] P. Larochelle,[1] D. Le Sage,[1] B. Levitt,[1] W.S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] J. Wrubel,[1] A. Speck,[2] M.C. George,[3,4] D. Grzonka,[3] W. Oelert,[3] T. Sefzick,[3] Z. Zhang,[3] A. Carew,[4] D. Comeau,[4] E.A. Hessels,[4] C.H. Storry,[4] M. Weel,[4] and J. Walz[5]
(ATRAP Collaboration)

[1]*Dept. of Physics, Harvard University, Cambridge, MA 02138*
[2]*Rowland Inst. at Harvard, Harvard University, Cambridge, MA 02142*
[3]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[4]*York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
[5]*Institut fur Physik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany*



No antihydrogen trapped yet

- not cold enough
- not in ground state



ATRAP – observed the first production of antihydrogen atoms in the fields of a Ioffe trap (PRL 2008)

Less than **20 atoms** were being trapped per trial

ALPHA – did similar production the following year

two directions

ATRAP
Try to make more atoms

5 +/- 1 per trial

ALPHA
Try to detect fewer atoms

0.7 +/- 0.3 per trial

ATRAP → More Antiprotons, Much Colder, More Simultaneously Trapped Atoms

- Lowered electrode temperature to 1.2 K
- Started measuring antiproton temperatures
- Developed new pbar cooling methods

First antiprotons cold enough to centrifugally separate from the electrons that cool them

Phys. Rev. Lett. **105**, 213002 (2010).

Two new cooling methods for antiprotons

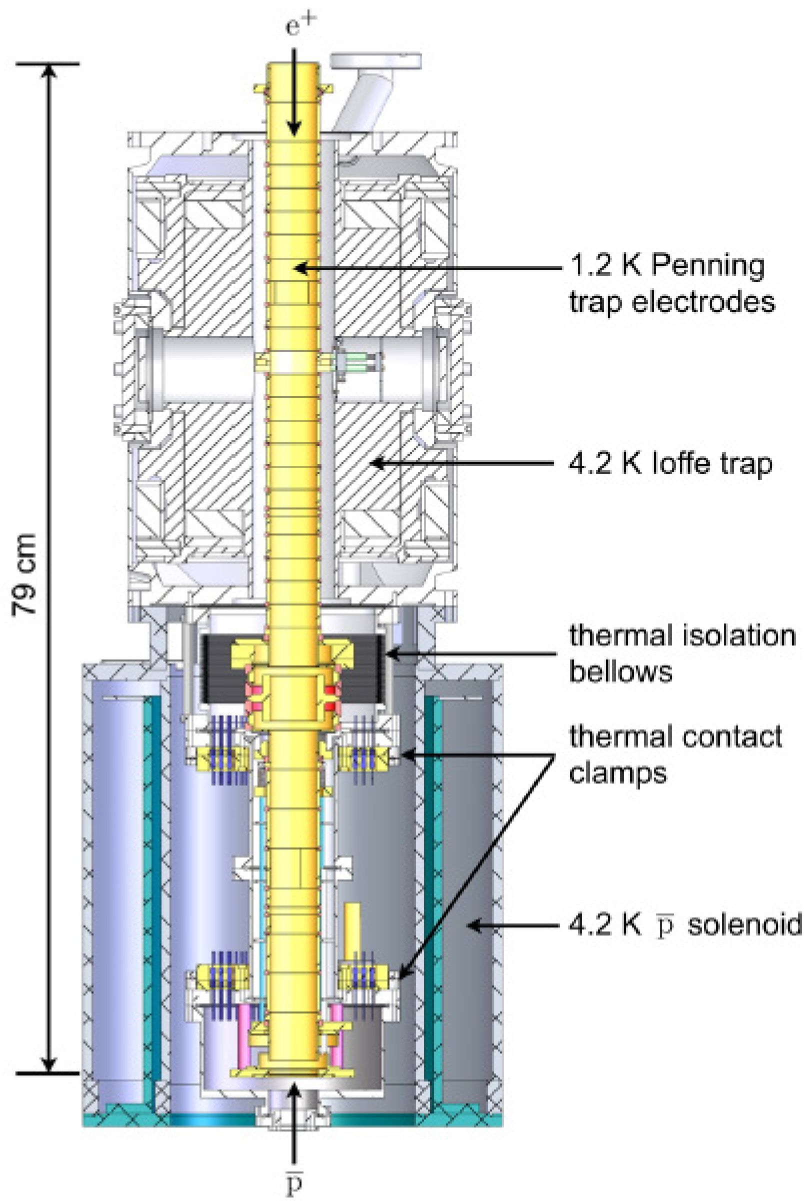
-- embedded electron cooling

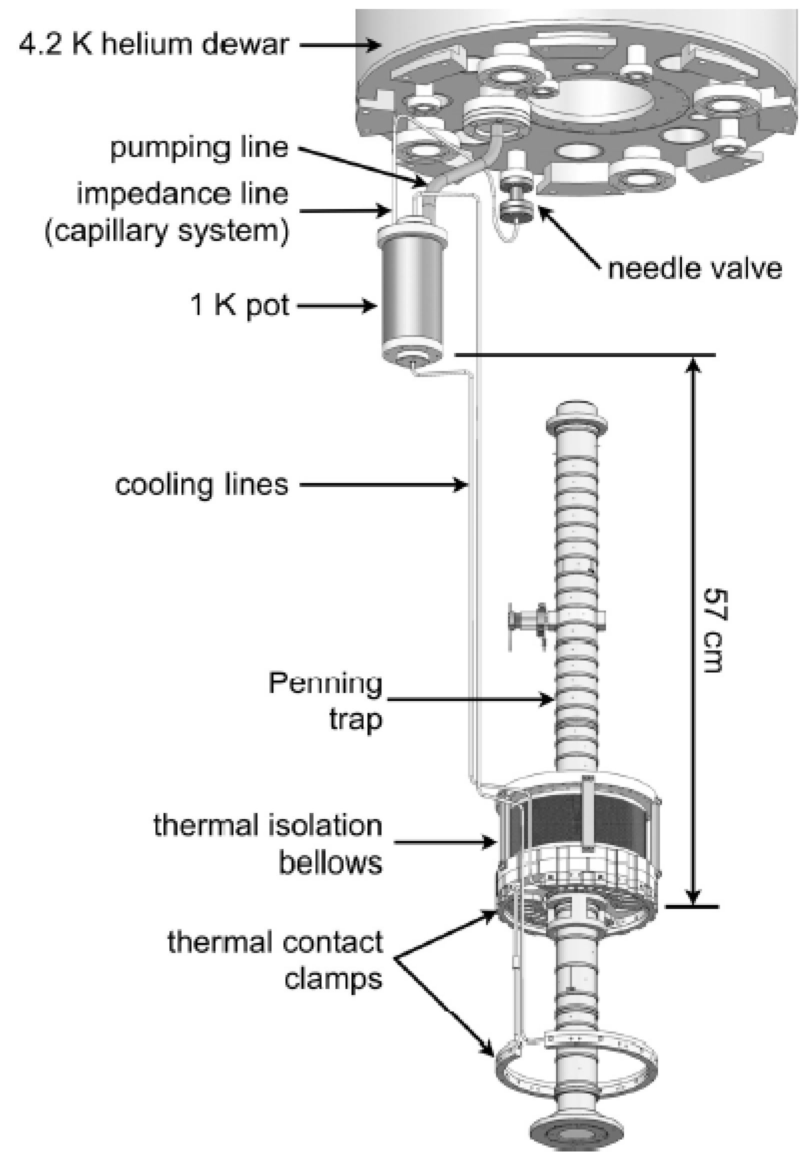
-- adiabatic cooling

Phys. Rev. Lett. **106**, 073002 (2011).

→ 3 million antiprotons at 3.5 K

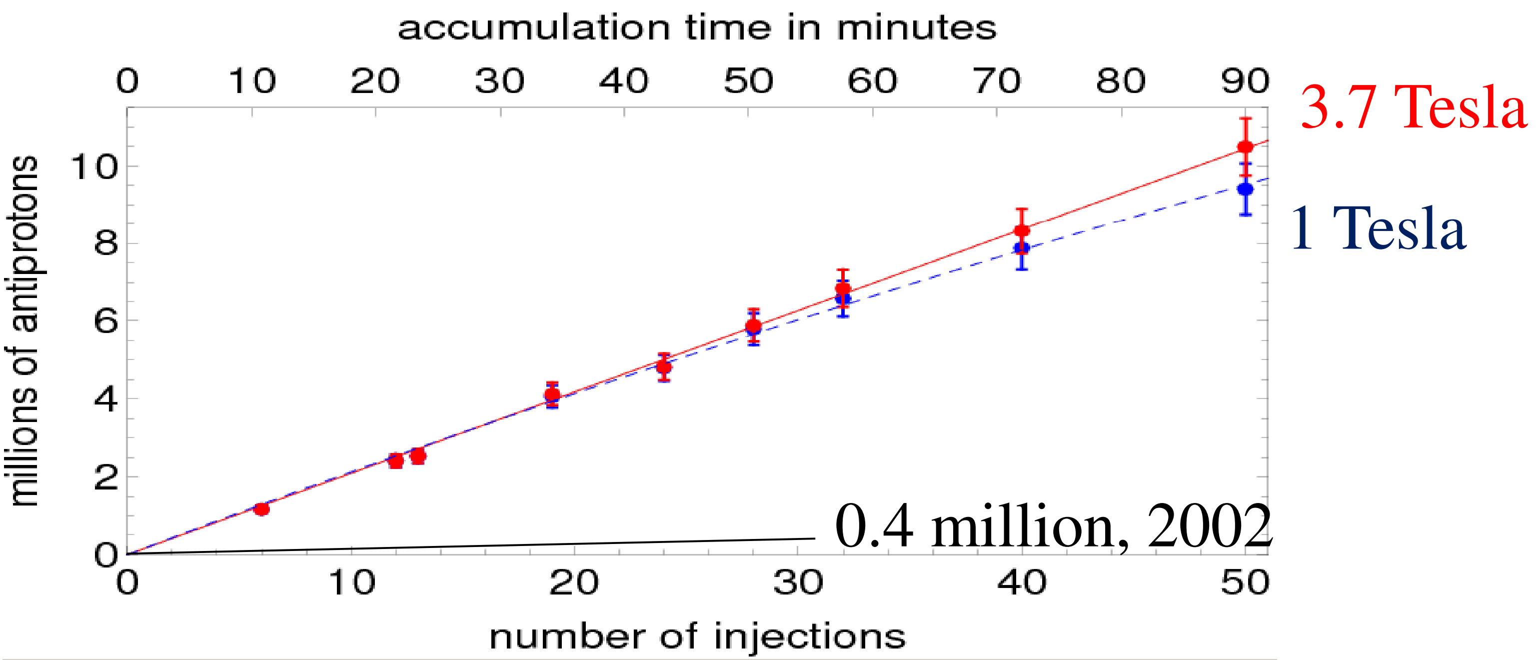
Colder Electrodes: 4.2 K → 1.2 K





10 Million Cold Pbar/Trial at ATRAP

0.4 million → 10 million
(5.4 Tesla) (1 Tesla)



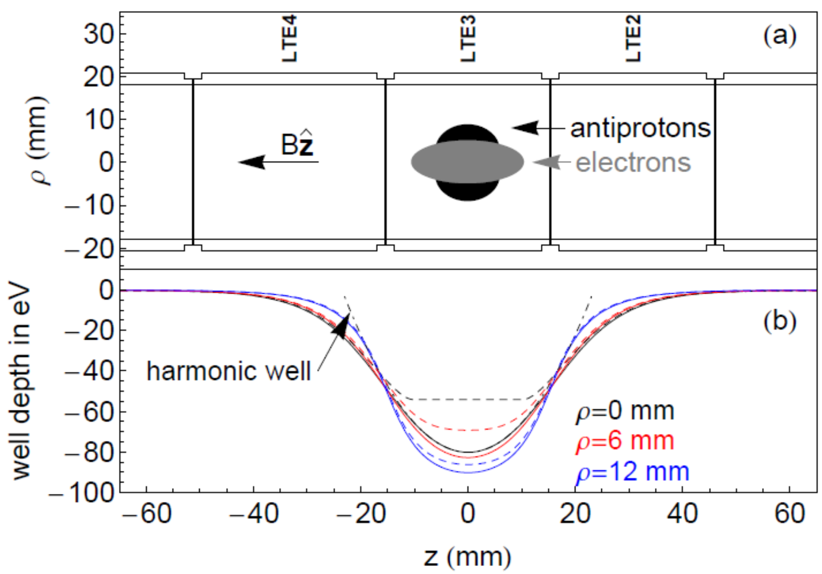
↑ better cooling

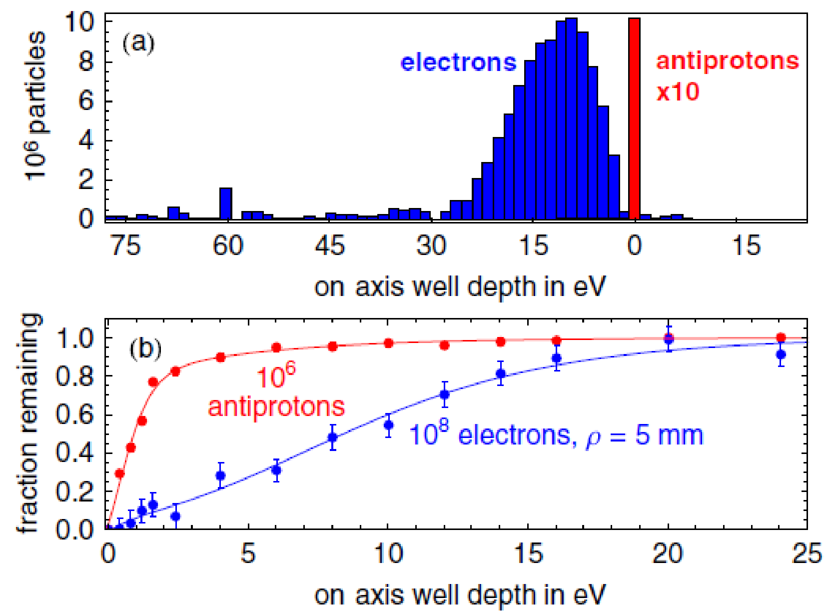
PRL 105, 213002 (2010) PHYSICAL REVIEW LETTERS week ending 19 NOVEMBER 2010

ATRAP

Centrifugal Separation of Antiprotons and Electrons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] J. Wrubel,[1,†] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[3] M. Zielinski,[2] J. S. Borbely,[3] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] J. Walz,[4] and A. Speck[5]





- Important for arranging efficient overlap of antiprotons and a positron plasma
- Important for understanding the heating of antiprotons when electrons are ejected

1 million antiprotons,
100 million electrons

ATRAP

Adiabatic Cooling of Antiprotons

G. Gabrielse,[1,*] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] R. Kalra,[1] E. Novitski,[1] D. Grzonka,[2] W. Oelert,[1] T. Sefzick,[2] M. Zielinski,[2] D. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]

(ATRAP Collaboration)

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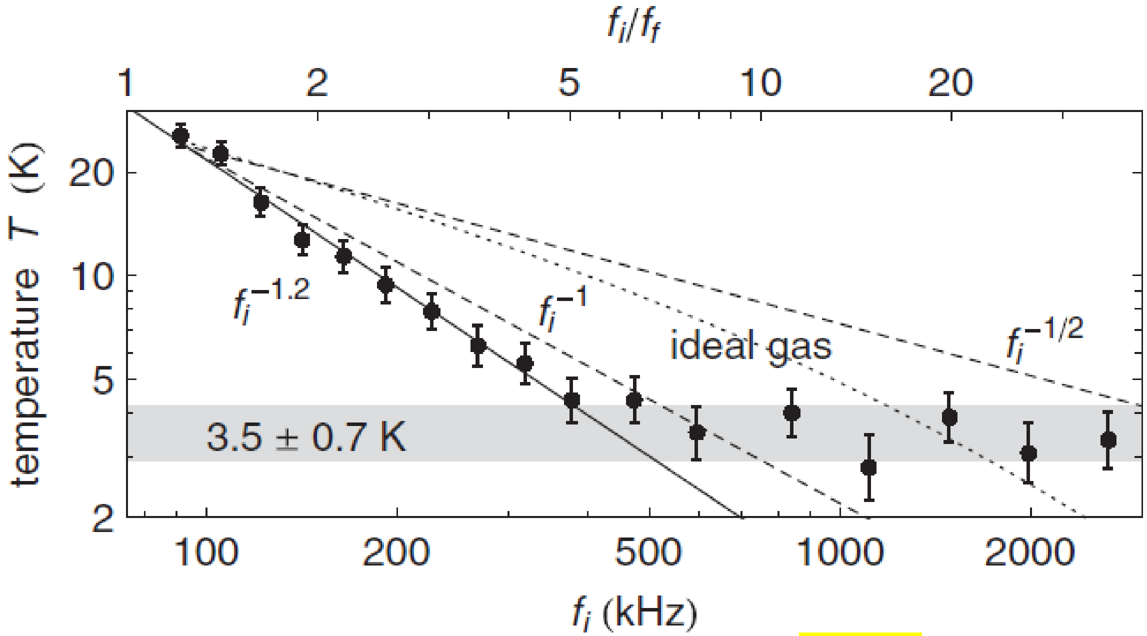
[2]*IKP, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*
[3]*Department of Physics and Astronomy, York University, Toronto, Ontario M3J 1P3, Canada*
[4]*Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*
(Received 1 December 2010; published 15 February 2011)



0.4 K

Embedded electron cooling
(to 31 K or 17 K)

Followed by adiabatic cooling
(to 3.5 K or below)

Gabrielse

Trapped Antihydrogen in Its Ground State

G. Gabrielse,[1,*] R. Kalra,[1] W.S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[2] M. Zielinski,[2] D.W. Fitzakerley,[3] M.C. George,[3] E.A. Hessels,[3] C.H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]

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[1] *Dept. of Physics, Harvard University, Cambridge, MA 02138*
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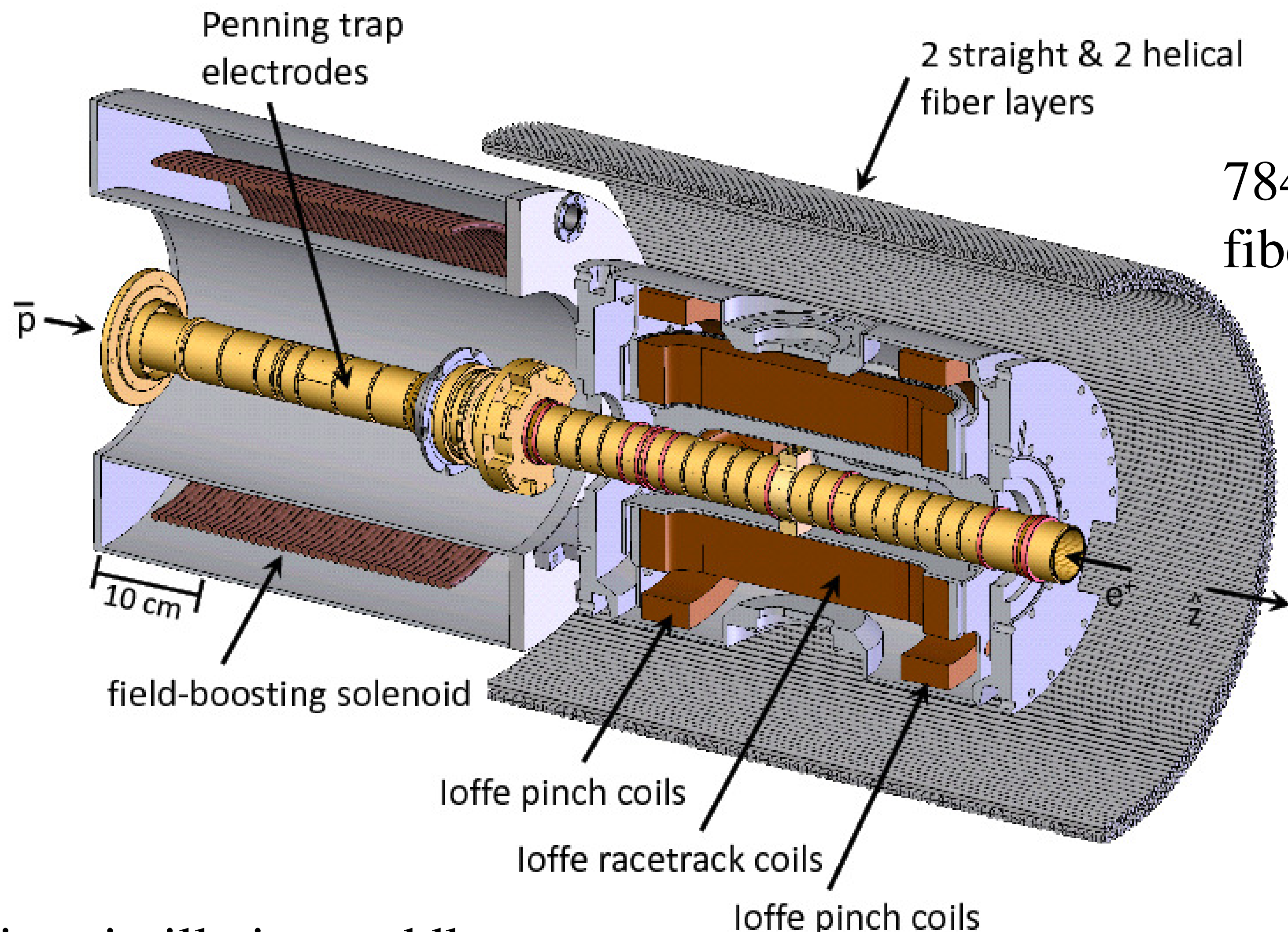
[3] *York University, Department of Physics and Astronomy, Toronto, Ontario M3J 1P3, Canada*
[4] *Institut für Physik, Johannes Gutenberg Universität and Helmholtz Institut Mainz, D-55099 Mainz, Germany*

Antihydrogen atoms ($\overline{\mathrm{H}}$) are confined in an Ioffe trap for 15 to 1000 seconds – long enough to ensure that they reach their ground state. Though reproducibility challenges remain in making large numbers of cold antiprotons ($\overline{\mathrm{p}}$) and positrons (e^+) interact, 5 ± 1 simultaneously-confined ground state atoms are produced and observed on average, substantially more than previously reported. Increases in the number of simultaneously trapped $\overline{\mathrm{H}}$ are critical if laser-cooling of trapped $\overline{\mathrm{H}}$ is to be demonstrated, and spectroscopic studies at interesting levels of precision are to be carried out.

Gabrielse

Detecting Trapped Antihydrogen



784 scintillating fibers

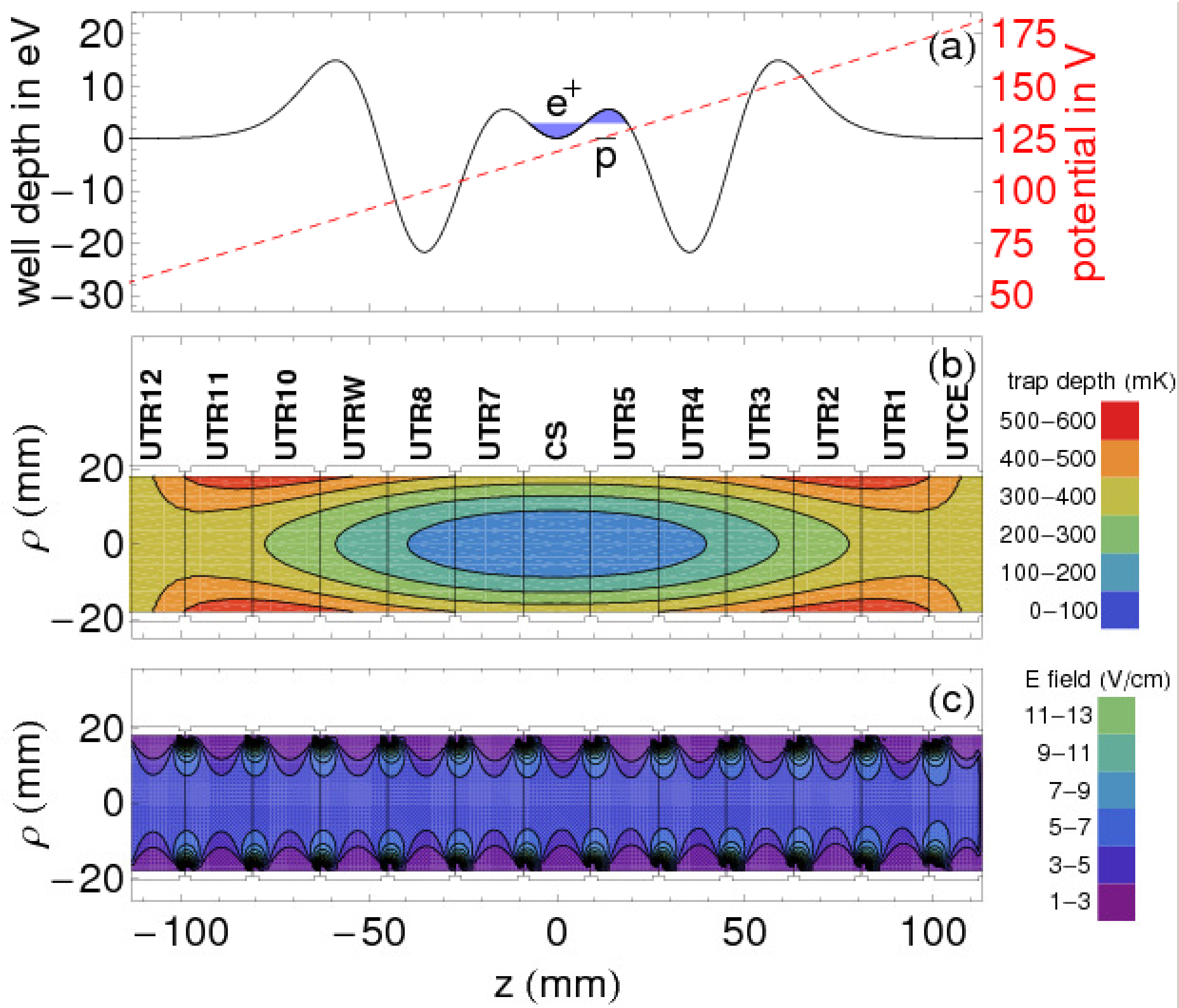
big scintillating paddles
surround the solenoid dewar

Penning-Ioffe Trap

Penning traps
(for charged particles)

Ioffe trap
(for g.s. antihydrogen)

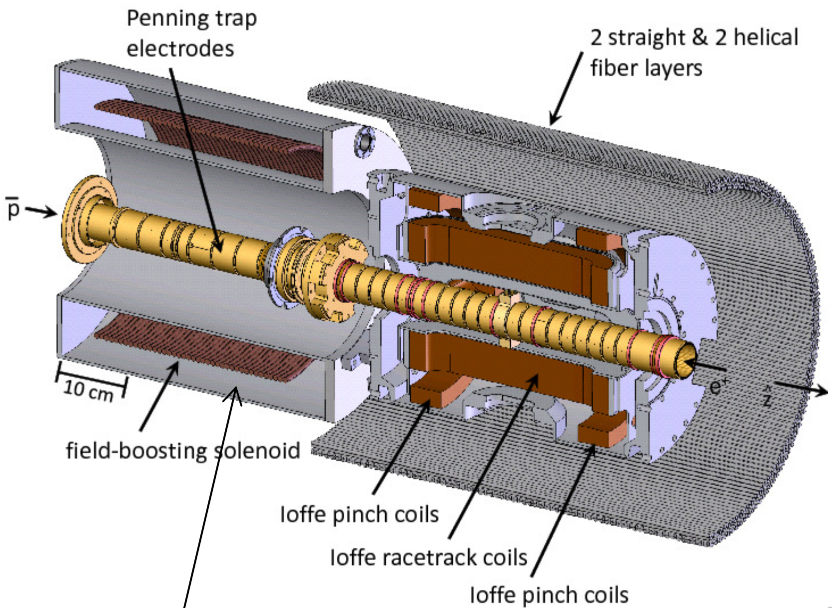
Clearing electric field
(get rid of all antiprotons)



After 15 to 1000 s, Turn Off theTrap → Quench

Record antihydrogen annihilation signal in time short compared to time between cosmic ray events.

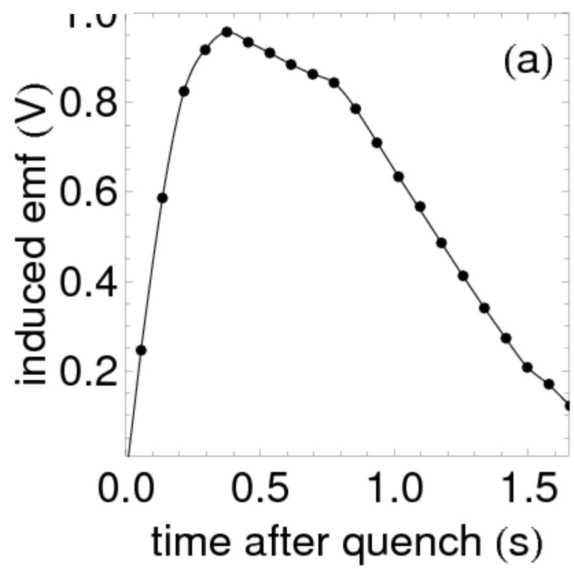
Show precisely when trapped Antihydrogen should annihilate

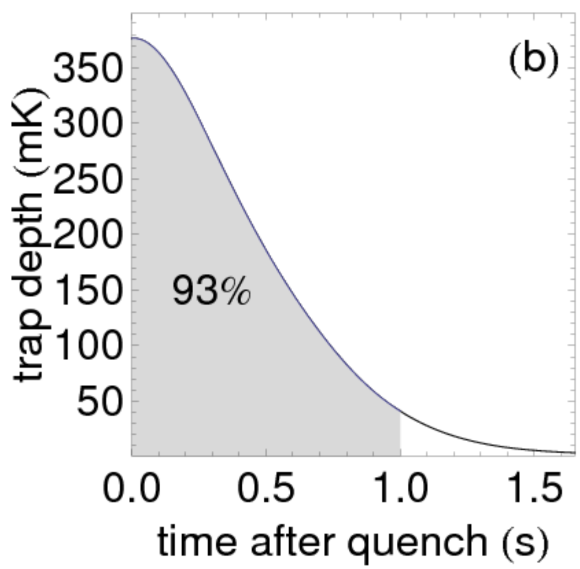


use solenoid as change-of-flux detector

measure flux change

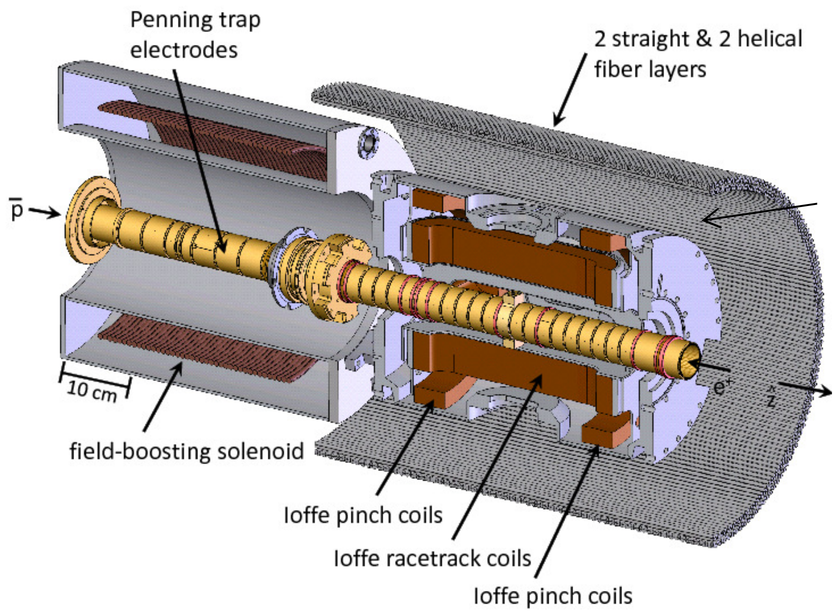
integrate to get B(t)





Detection of Trapped Antihydrogen

784 BICRON BCF-12 scintillating fibers
- 435 nm peak emission
- 2.7 m attenuation length



large plastic scintillator paddles
- 1 m high
- outside picture

Coincidence – no cuts (MHz)
- 54% efficiency for pbar ann.
- 41 Hz cosmic ray background

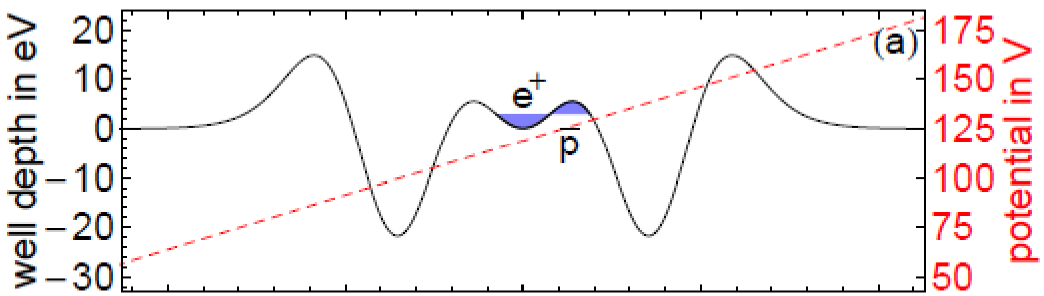
Time-stamped events (kHz rate)
- radially spilled antiprotons
- cosmic rays
- evaluate 4096 detector combinations

Best signal-to-noise
- 33% detection efficiency
- 1.7 Hz cosmic ray background

Goal for 2011 Was to Obtain a Lot More Simultaneously Trapped Antihydrogen Atoms

→ Enough to see trapped antihydrogen every trial

Tried a variety of methods to make the antiprotons and positron interact



- 2 ms coherent drive
- 15 minute noise -broadened drive

Did not see (yet) the clear signal for every trial → averaged all trials together

- not what one wants to do on the long term
- see if antihydrogen is being made
- averaged over the different methods → 5 +/- 1 trapped antihydrogens per trial

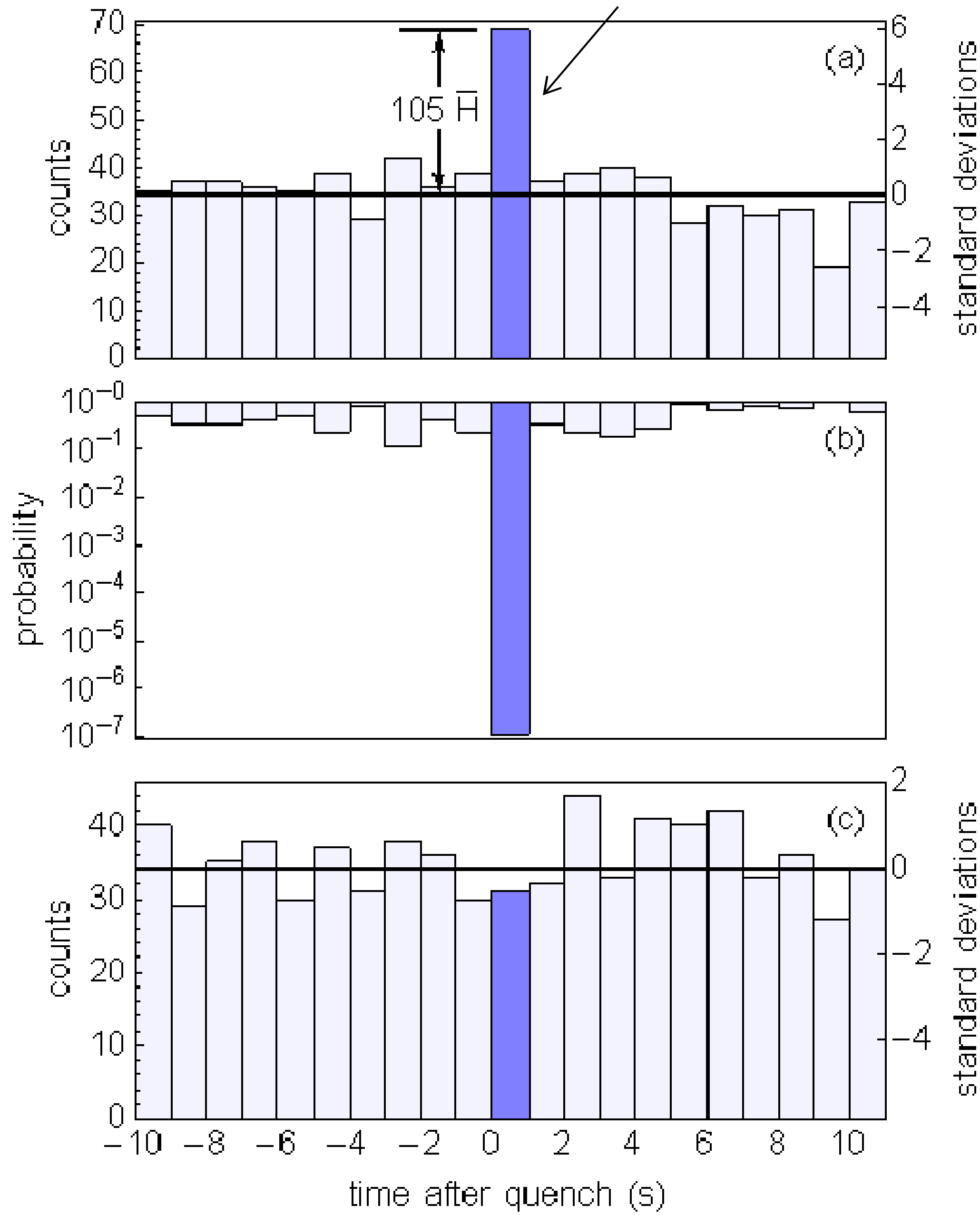
Detector Counts During Quench (1 second)

Signal is during the 1 second quench window
(20 trials averaged together)

1 chance in 10^7 that such a signal comes from the cosmic ray background

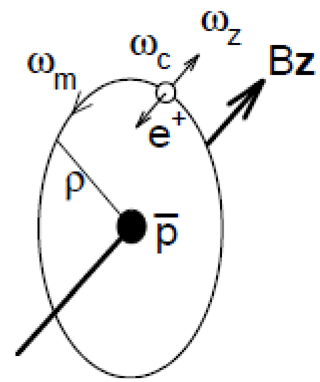
All 1 sec. bins before and after the quench bin are statistical

Control trial: quench without particles (to see if flux change makes fake signal)

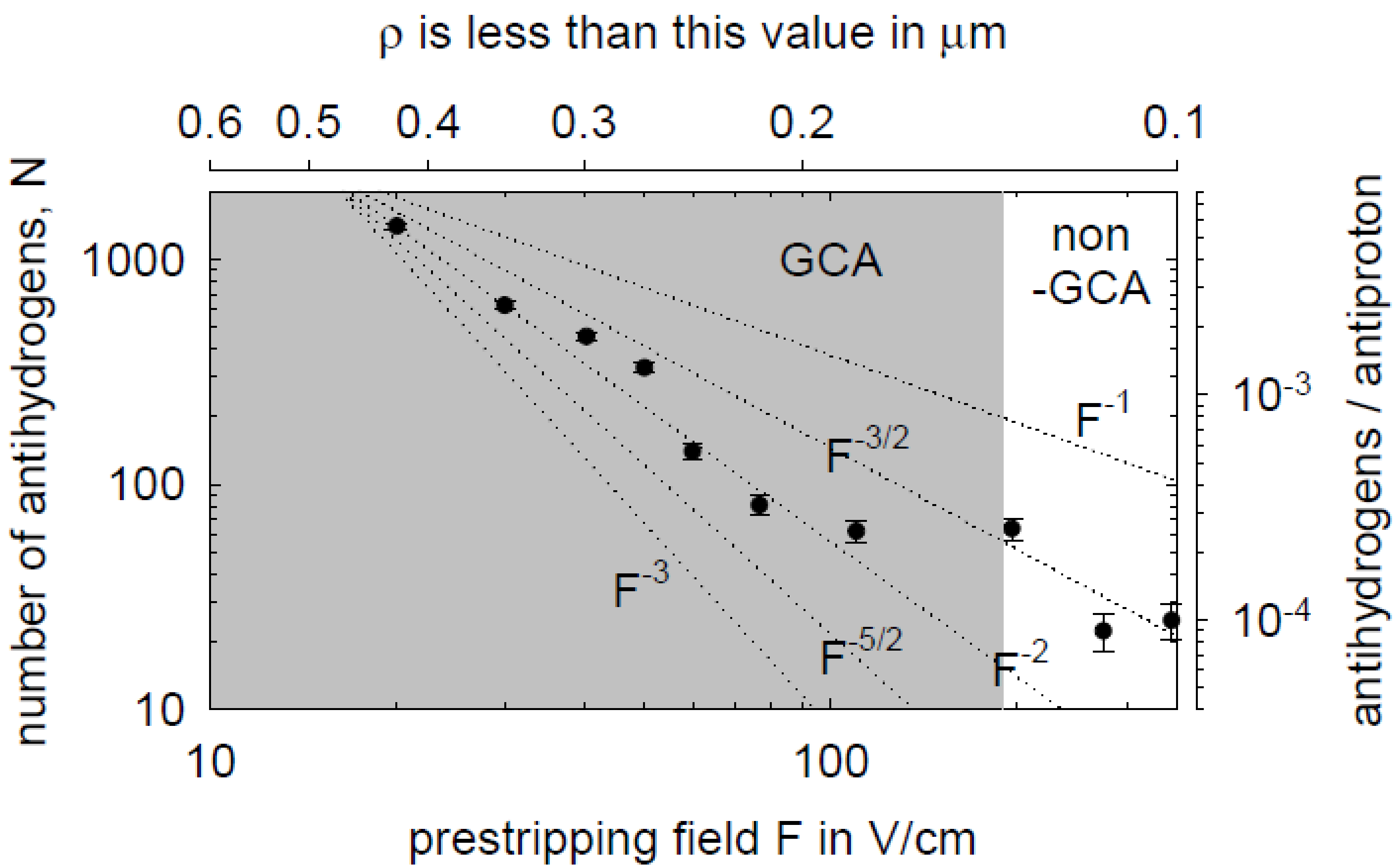


What Kind of Antihydrogen Atoms Are These?

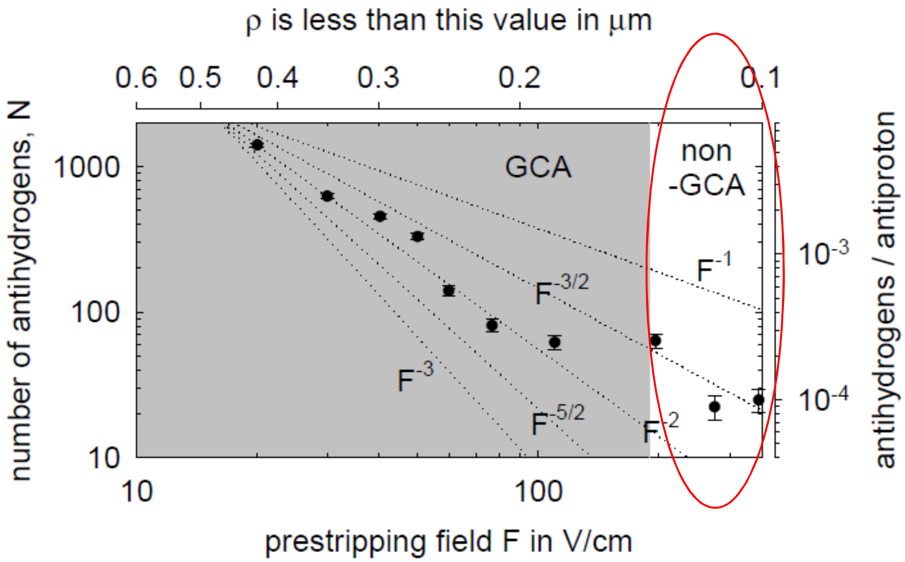
Most of the antihydrogen atoms in the strong magnetic field
→ **Guiding Center Atoms**



strong field seekers not trapped in a magnetic minimum



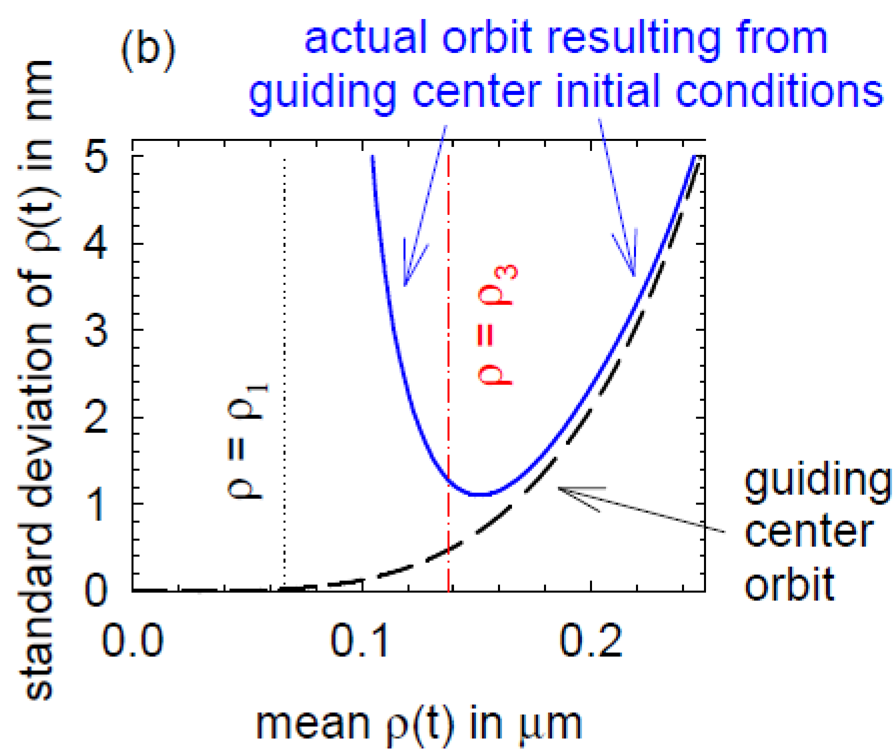
A few Atoms Are Have Chaotic Dynamics



Coulomb attraction and magnetic forces are comparable

→ chaotic positron motion

n ~ 50
(if n was a good q.n.)



(Gabrielse, 2005)

These are Ground State Antihdyrogen Atoms

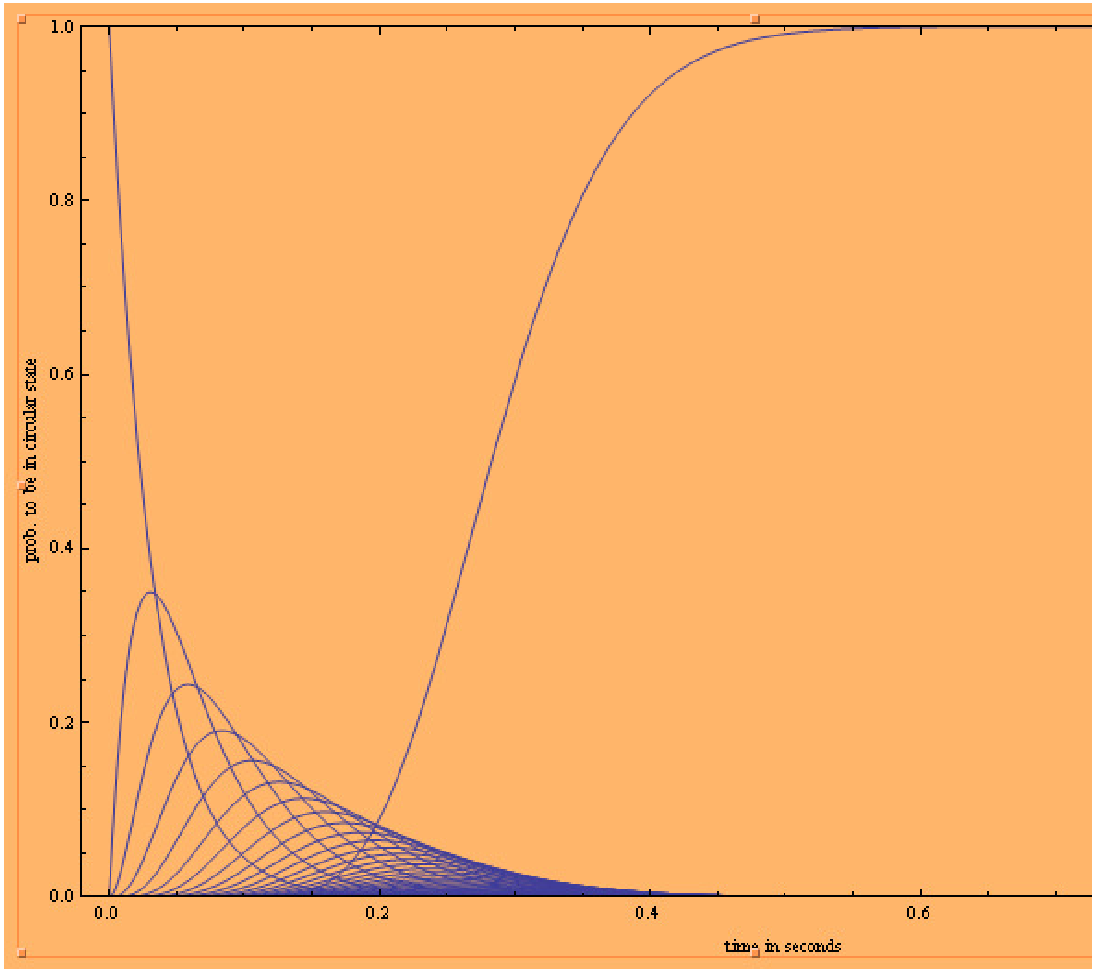
Conservative lifetime limit: Circular states decay most slowly (m = l = n-1)

Start: n = 50 circular state, lifetime = 30 ms ~ $1/n^5$

Cascade to ground state takes 0.5 s

In with collisions and field the decay must be much faster

Antihydrogen atoms are in trap for 15 to 1000 s)



Gravity

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

Crude Antigravity Limit

Gravity force on hydrogen: Mg

Gravity force on antihydrogen: κMg

ATRAP 2011

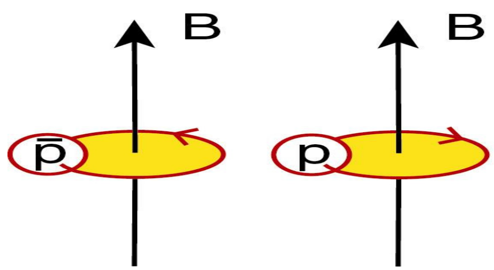
To have a trap: $|\kappa| \leq W/(Mgh) = 3 \times 10^3$

Since many antihydrogen atoms leave quickly: $|\kappa| < 2 \times 10^2$
(as trap goes from 375 mK to 350 mK)

Our earlier gravitational redshift limit is much more stringent

Antiproton and proton
clocks run at the same rate, $< 10^{-10}$

$|\kappa - 1| < 1 \times 10^{-6}$



Experiment

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

Theory

R. J. Hughes and M. H. Holzscheiter, Phys. Rev. Lett. **66**, 854 (1991).

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.

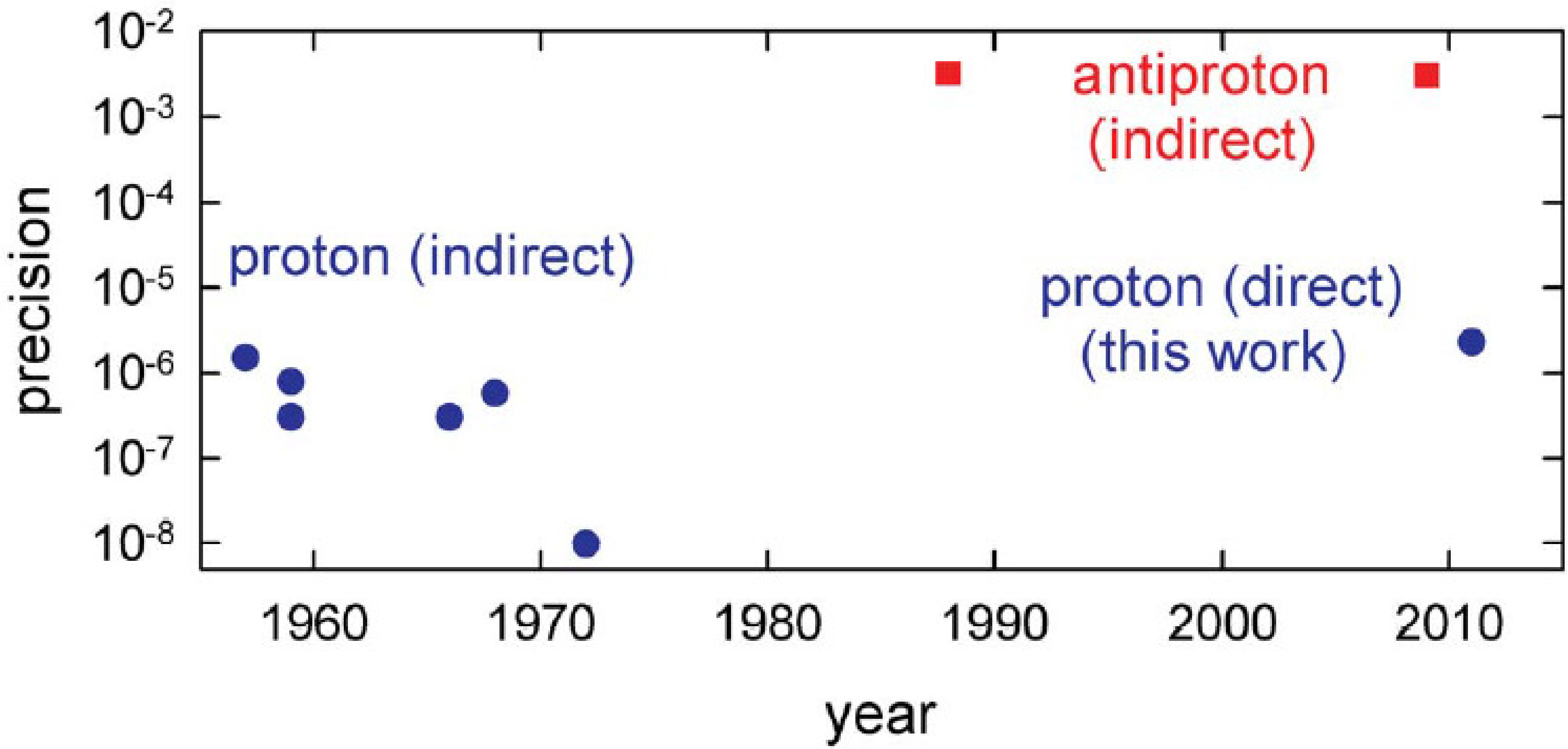
Earlier contributions

[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).

Why Measure the Antiproton Magnetic Moment

CPT test – compare with proton moment



Proton Magnetic Moment Measurements

(method cannot be applied to 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

10 ppb

hydrogen
maser

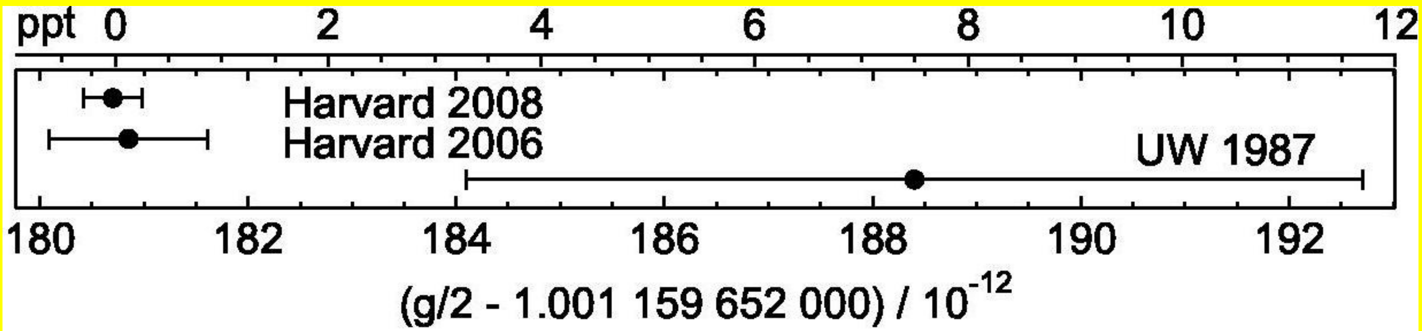
2 ppb or 0.7 ppb

bound electron
magnetic
moment

ppb = 10^{-9}

Insiration: Electron (Positron) Magnetic Moment Measurements to 3 x 10^{-13}

2.8×10^{-13}



(improved measurement is currently underway)

electron magnetic moment in Bohr magnetons

Can do as well with positron as with electron to compare

Can We Do A Similar Measurement with Antiprotons?

Harder: nuclear magneton rather than Bohr magneton

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

One-Particle Method

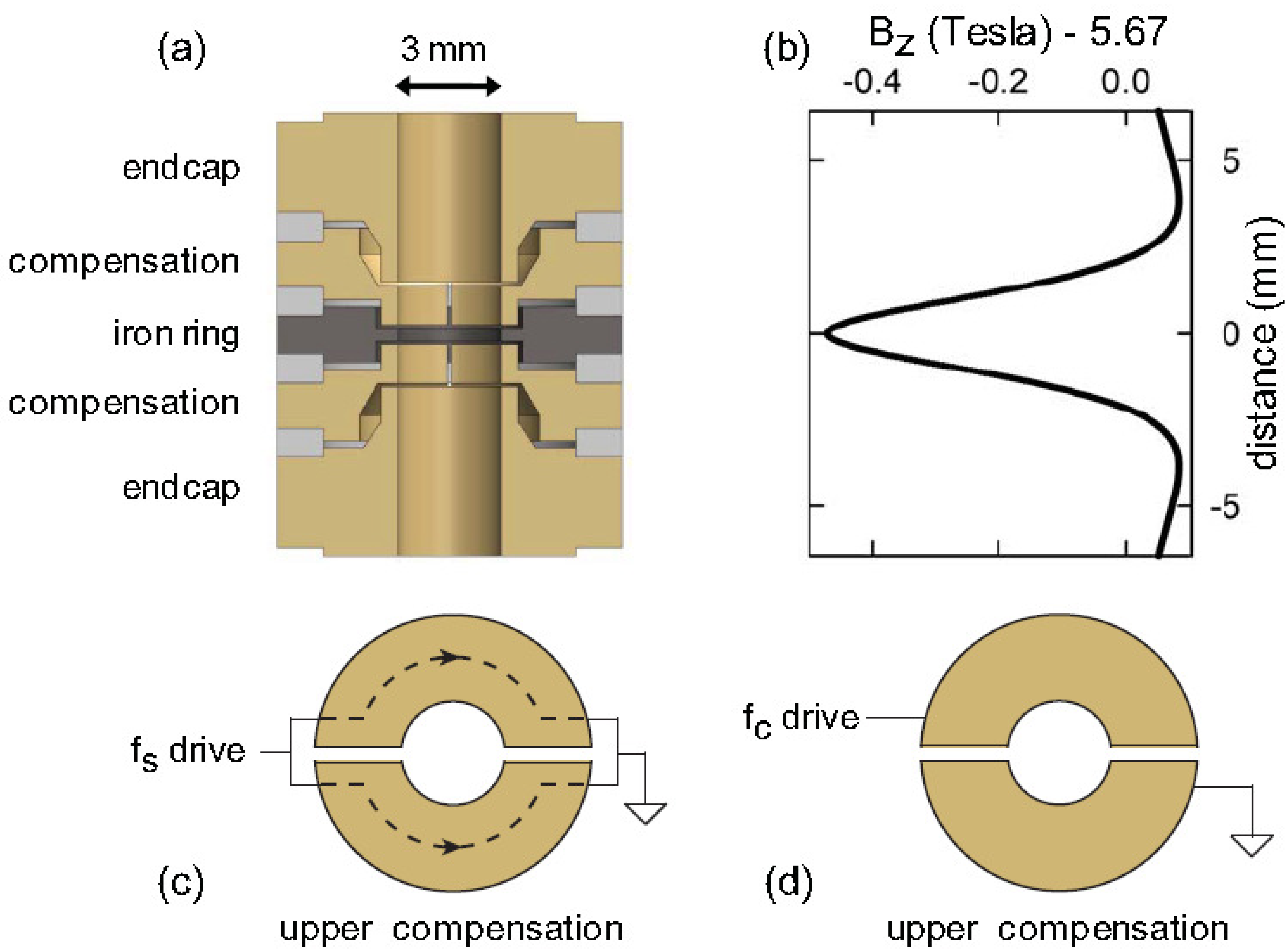
With one proton or antiproton suspended in a trap, measure spin and cyclotron frequencies

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

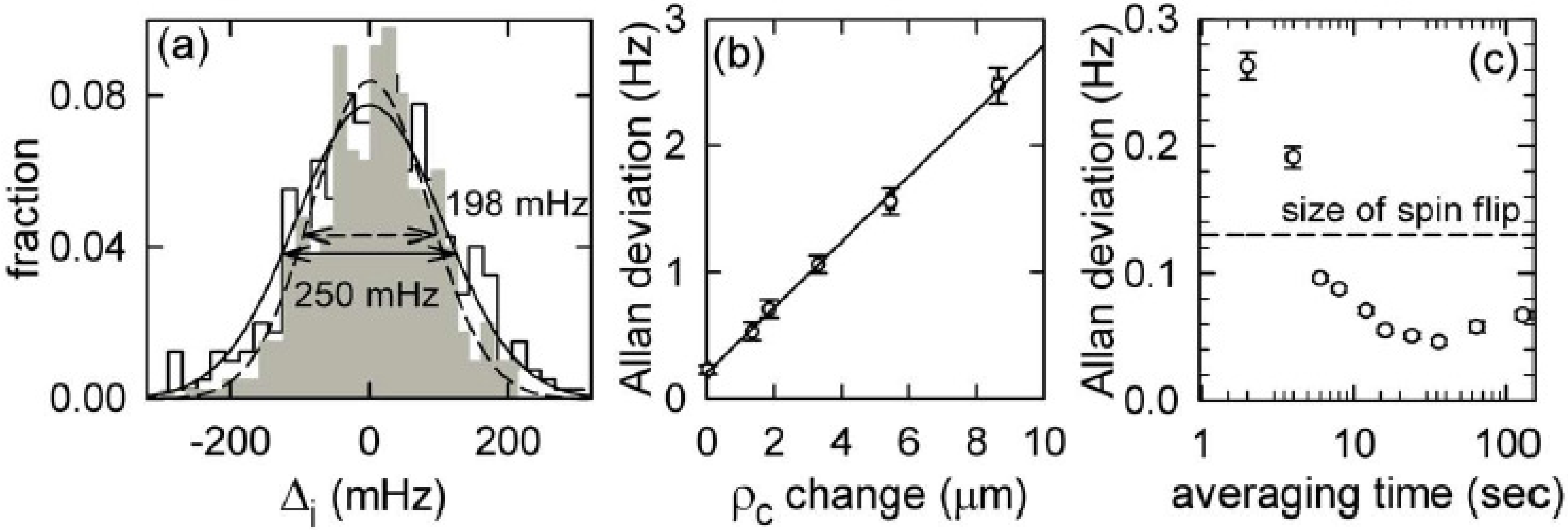
No previous method has been devised to measure antiproton and proton moments in the same way

Huge Magnetic Bottle Gradient

190 times larger than used for electron

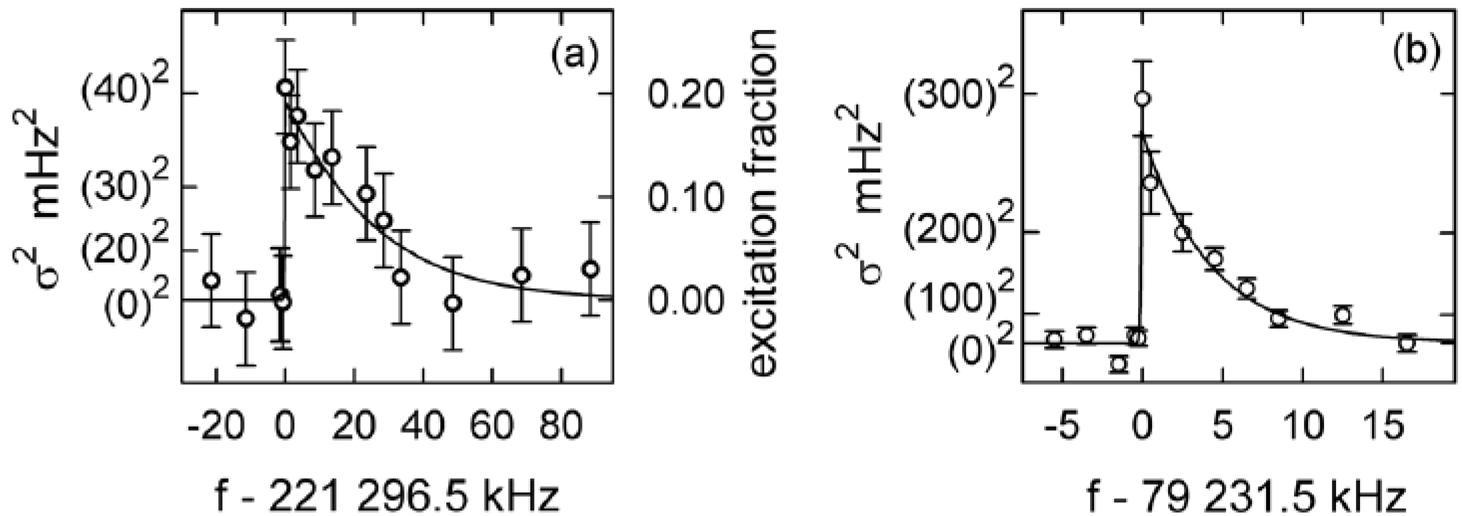


Spin-Flips Increase Allan Deviation



Direct Measurement of the Proton Mag. Moment

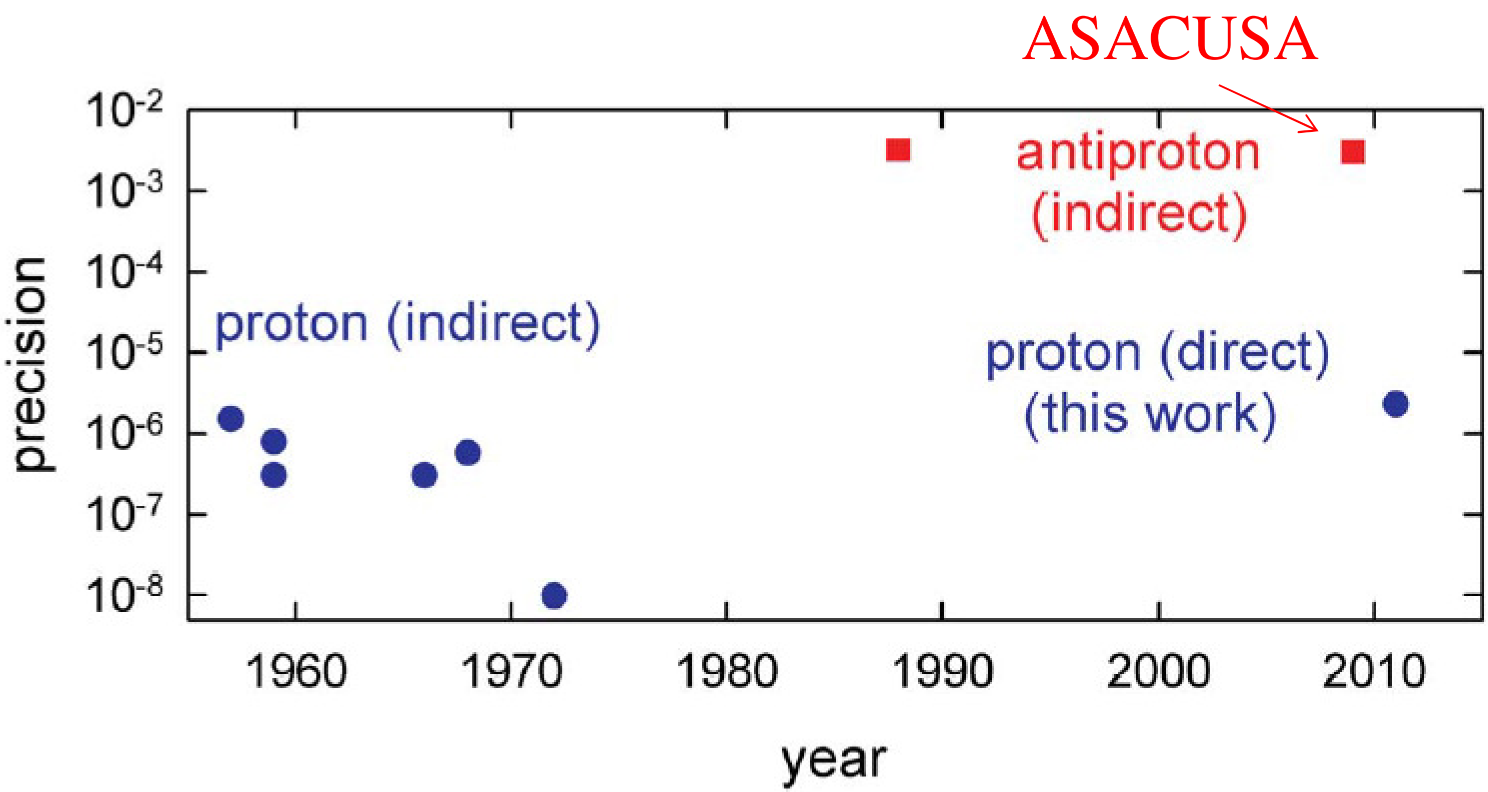
$$\frac{\mu_p}{\mu_N} \equiv \frac{g_p}{2} = \frac{f_s}{f_c}$$



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

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

Could Now Realize a Thousand-fold Improved Measurement of the Antiproton Moment



ATRAP

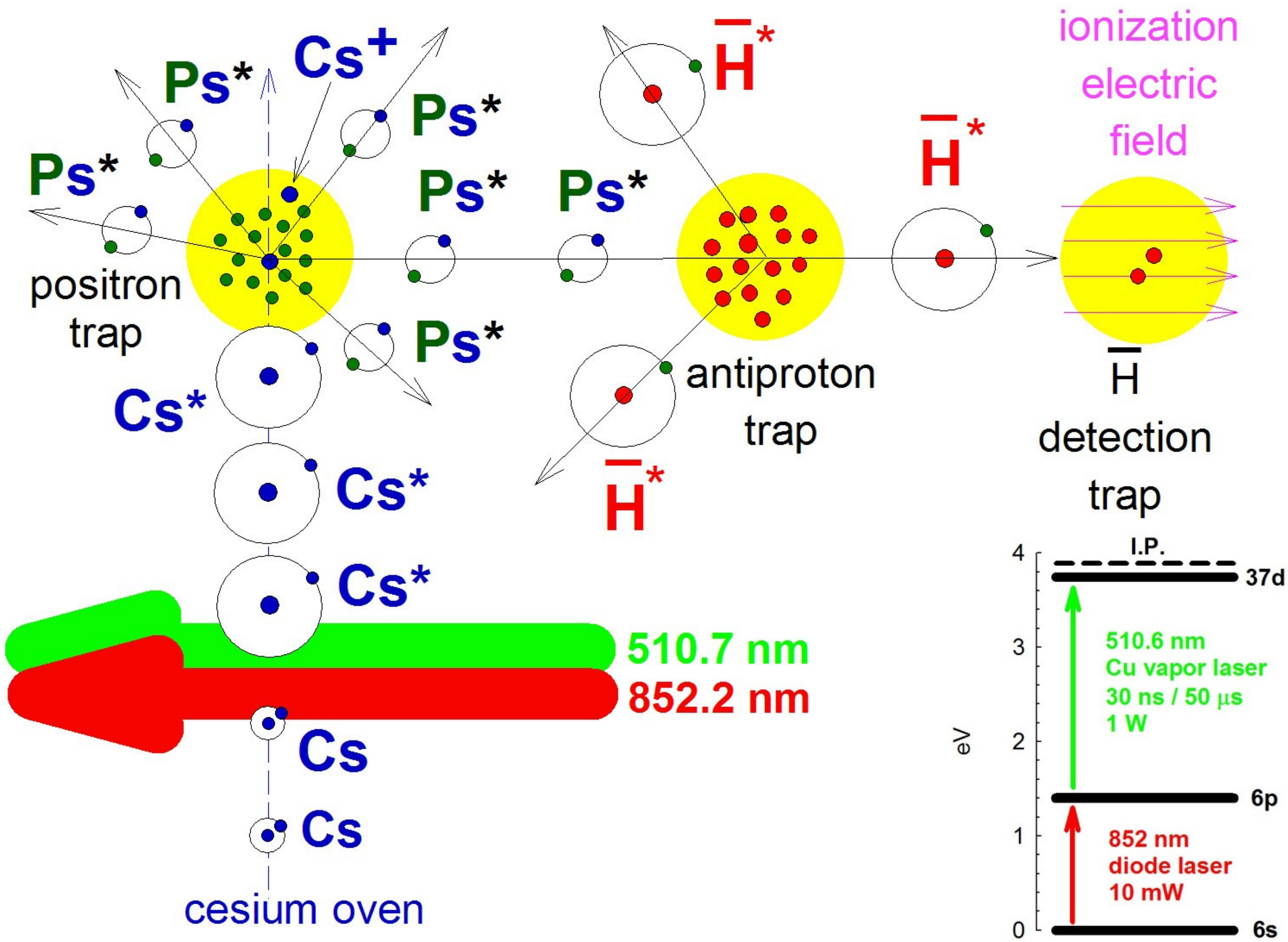
2012
??

Later

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

Expect to eventually be more precise than all proton measurements

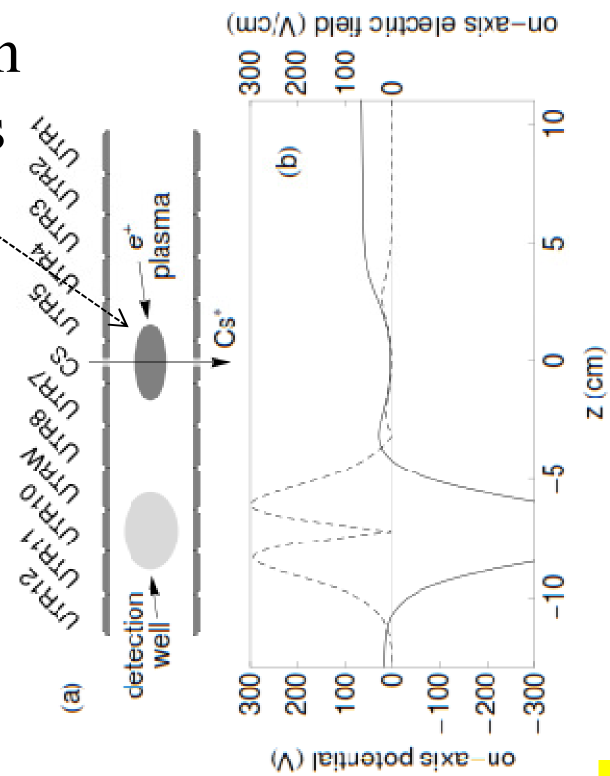
Method II: Antihydrogen Via Laser-Controlled Resonant Charge Exchange



ATRAP, Phys. Rev. Lett. **93**, 263401 (2004) -- demo with a few atoms

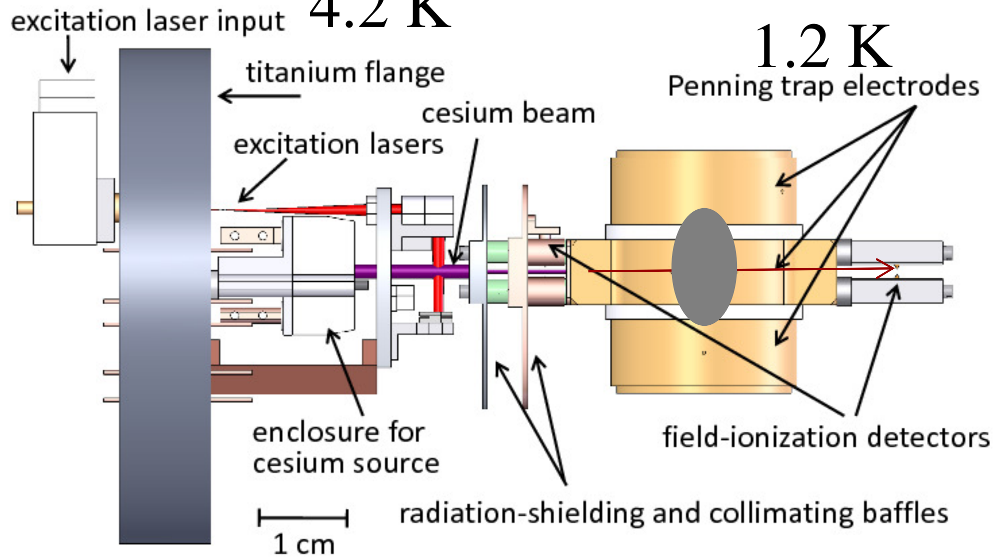
Gabrielse

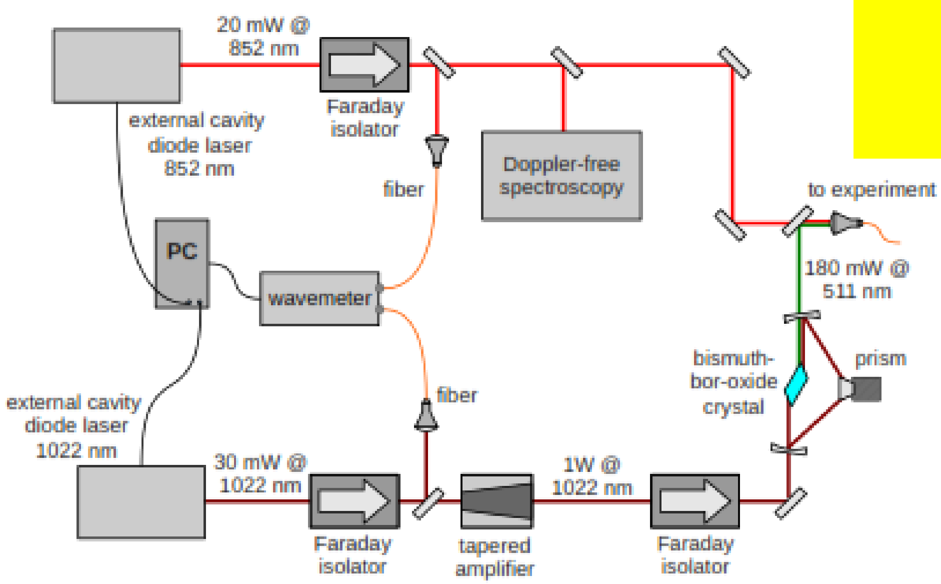
30 million positrons



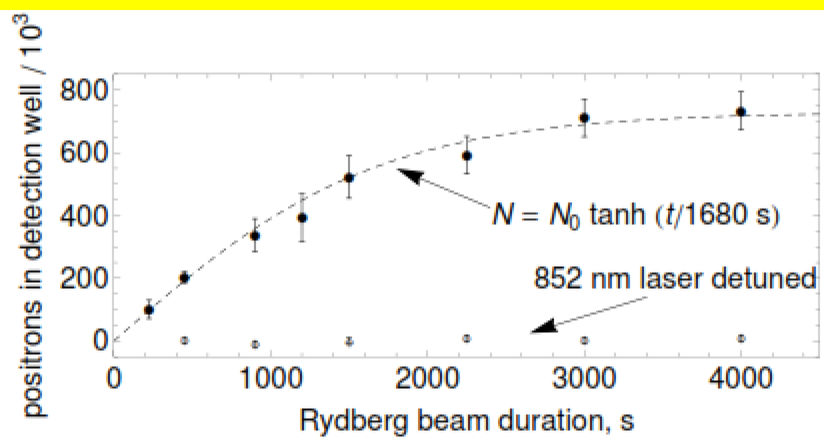
4.2 K

1.2 K





92 +/- 5 % of trapped positrons form Ps
- 520 time more Ps than in demo
- 3.5 higher efficiency per positron

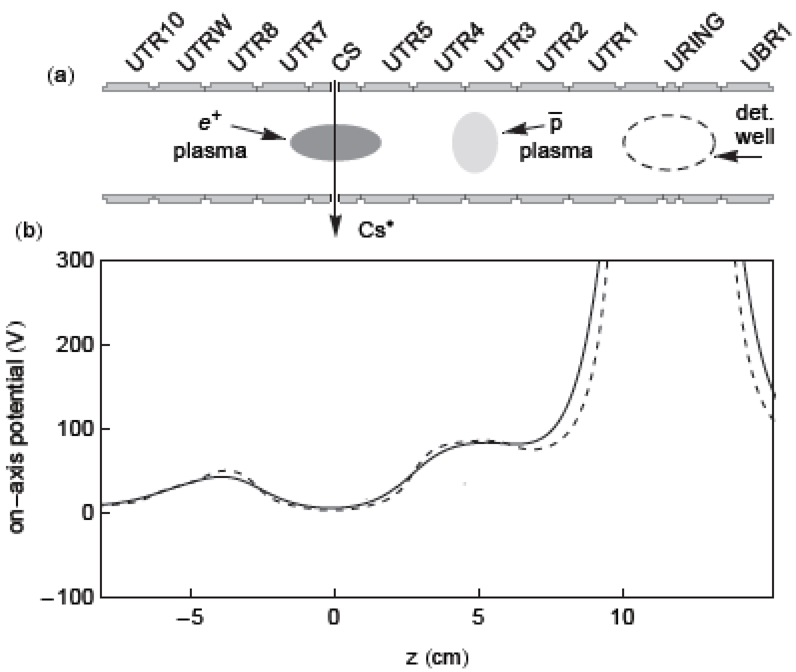


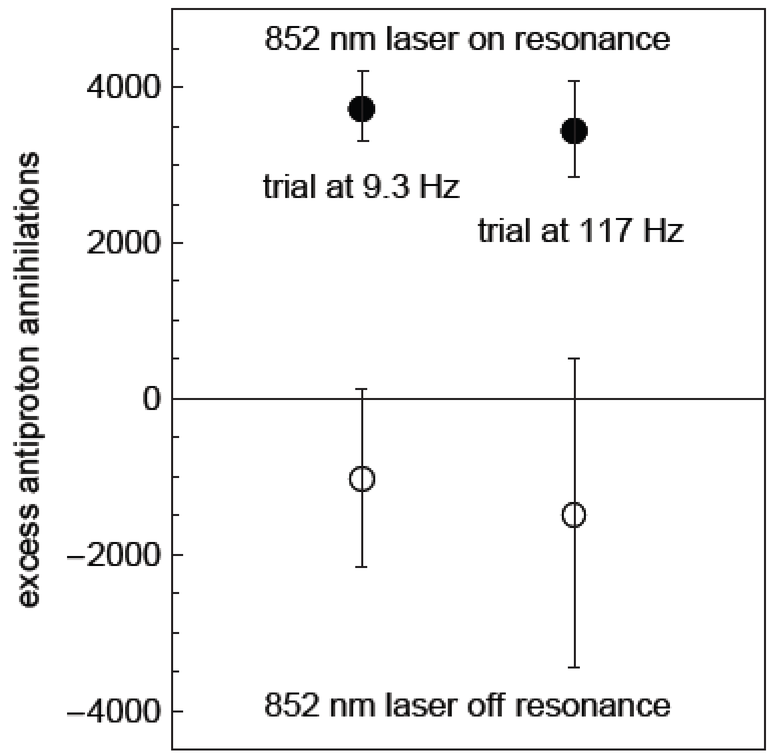
200 Times More Antihydrogen Made Per Trial

(compared to proof-of-principle demonstration)

Antiprotons: 5 million
Positrons: 300 million

$3600 \pm 610\ \overline{\mathrm{H}}$





Remains to see if this can be done in a Ioffe field

Progress in 2011

Repeated results of previous year → will now publish

Started to use adiabatically-cooled antiprotons

Started to do in presence of the Ioffe trap fields

Plan for 2012

Second Generation Ioffe Trap

Glued together vacuum system

- rapid switch off
- laser ports
- very challenging (company failed)

Fully assembled, vacuum tested cold (many cycles)

Wiring finished this week

Cold testing at high current → soon

Intend to use from the beginning of the 2012 run

second generation Ioffe trap

ports for laser and microwaves

Plan for 2012

Use second generation Ioffe trap
- expect some learning curve but testing this spring
- expect more trapped antihydrogen
- expect to turn off the trap repeatedly during a shift
- investigate energy distribution of antihydrogen in trap (preparation for laser cooling)

tempting to start but …

Try to trap antihydrogen made by laser-controlled charge exchange
- profit from adiabatic cooling
- profit from second generation Ioffe trap

Parasitic operation to measure antiproton magnetic moment

Summary

- Control of bigger and colder antiproton and positron plasmas
- New cooling methods
- More antihydrogen from laser-controlled charge exchange
- Trapped antihydrogen with
  → prospects for much more in 2012 (new Ioffe trap)
- New antiproton magnetic moment measurement
  → 1000 – fold improved comparison of antiproton and proton magnetic moments "soon"