Cold Antihydrogen Future

Motivations – Clear and Long Term

Big Time-line Picture and Milestones

Status and Improvements: Antiproton and Positron Accumulation

Antihydrogen Production: Method I
Method II
Other Methods?

Quest for Useful Antihydrogen

- **Devising a method to measure the antihydrogen state**
- **Devising a method to measure the antihydrogen velocity**

Antihydrogen Trapping

Antihydrogen Spectroscopy

Thanks to CERN

The CERN AD is unique in the world,
and will continue to be so for the next decade or more.

Thanks to the SPSC

We are grateful for the time that you spend watching over the CERN antiproton program.

We know that you all do this as volunteers, in addition to your many regular responsibilities.

ATRAP

Harvard University

Prof. G. Gabrielse	Dr. T. Roach	J. Estrada
(Spokesperson)	Dr. J.N. Tan	P. Yesley
	Dr. C. Storry	P. Oxley
	Dr. J. Tan	N. Bowden
		M. Wessels
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Juelich Laboratory

Prof. W. Oelert	Dr. T. Sefzick	
	Dr. G. Schepers	
	Dr. D. Grzonka	

Max Planck Institute for Quantum Optics

Prof. T. Haensch		
Dr. J. Walz		H. Pittner

York University

Prof. E. Hessels		D. Comeau

Free University of Amsterdam

K. Eikema

Earlier contributions from Bonn, Vienna, FOM

2004 ATRAP Papers and Preprints

"Strongly Magnetized Antihydrogen and Its Field Ionization"
D. Vrinceanu, B.E. Granger, R. Parrott, H. R. Sadeghpour, L. Cederbaum, A. Mody, J. N. Tan and G. Gabrielse
Phys. Rev. Lett. **92**, 133402 (2004).

"G. Gabrielse, et al. reply" (A reply to a Comment discusses comparing our measured field ionization spectra to theory)
G. Gabrielse, *et al.*
Phys. Rev. Lett. **92**, 149304 (2004).

"Aperture Method to Determine the Density and Geometry of Anti-Particle Plasmas", P. Oxley, N. S.Bowden, R. Parrott, A. Speck, C. Storry, J.N. Tan, M. Wessels, G. Gabrielse, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, J. Walz, H. Pittner, T.W. Haensch and E. A. Hessels
Phys. Lett. B **595**, 60 (2004).

"First Measurement of the Velocity of Slow Antihydrogen Atoms",
G. Gabrielse, A. Speck and C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
Phys. Rev. Lett. **93**, 073401 (2004).

"First Evidence for Atoms of Antihydrogen Too Deeply Bound to be Guiding Center Atoms",
G. Gabrielse, A. Speck, C.H. Storry, D. Le Sage, N. Guise, D. Grzonka, W. Oelert, G. Schepers, T. Sefzick, H. Pittner, J. Walz, T.W. Haensch, D. Comeau, E.A. Hessels
To be published.

"Laser-Controlled Production of Rydberg Positronium"
A. Speck, C.H. Storry, E. Hessels and G. Gabrielse
Phys. Lett. B. **597**, 257 (2004).

"Single-Particle Self-excited Oscillator (includes proposed application to measuring antiproton spin flips)
B. D'Urso, R. Van Handel, B. Odom and G. Gabrielse
Submitted to PRL.

"First Laser-Controlled Antihdyrogen Production"
C.H. Storry, A. Speck, D. Le Sage, N. Guise, G. Gabrielse, D. Grozonka, W. Oelert, G. Scheppers, T. Sefzick, J. Walz, H. Pittner, M. Herrmann, T.W. Haensch, E.A. Hessels and D. Comeau
PRL (in press).

Motivations and Goals

Clear, Stable, Long Term

Highly accurate spectroscopic comparisons of antihydrogen atoms and hydrogen atoms.

- Clear before the AD was built
- Clear now
- Clear when the AD rests for one year
- Clear in the future

Why Cold Antihydrogen?

Goal: Highly Accurate Comparison – Antihydrogen and Hydrogen

No Hope with Hot Antihydrogen

- **too fast v ~ c**
- **little measurement time**
- **too few atoms**

1995 – CERN
1997 -- Fermilab

$\leq 4.2\,K$

Cold Hydrogen Aspirations Announced Long Ago

Goals

- **Produce cold antihydrogen**
- **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).

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

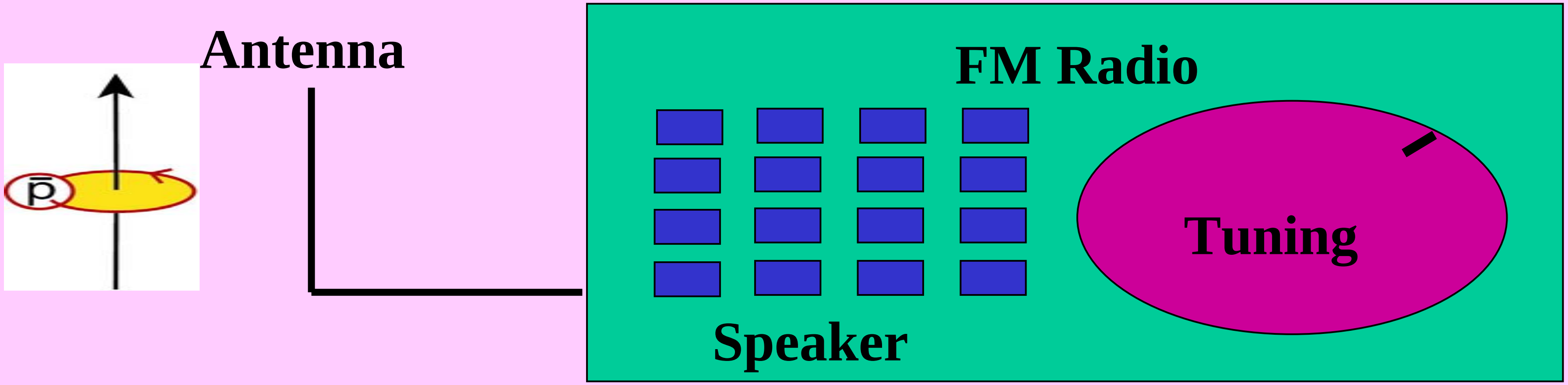
→ same structure

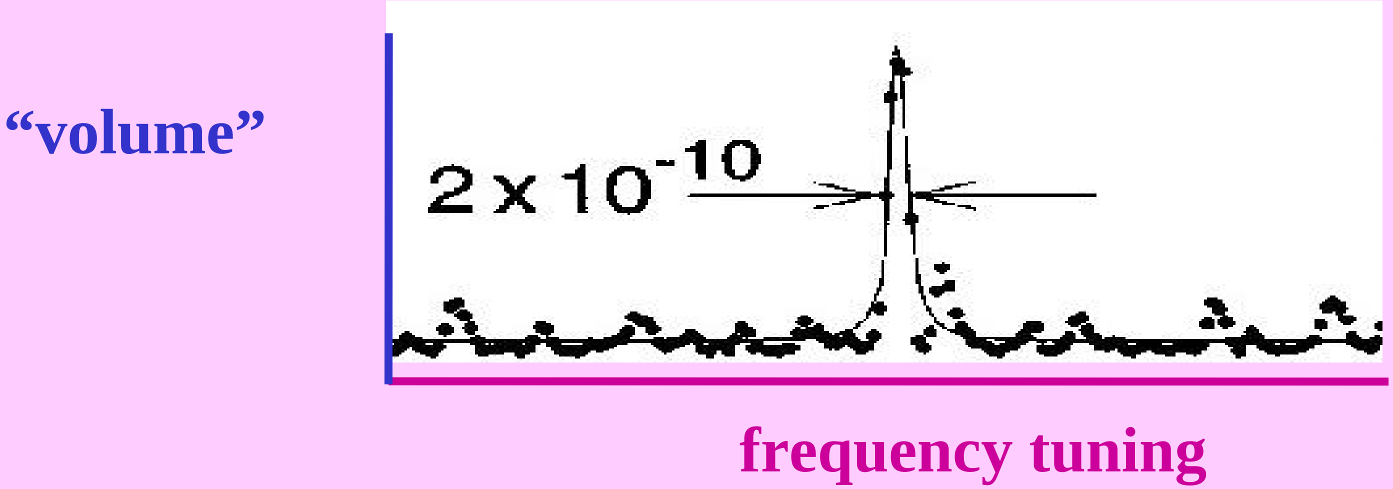
Looking for Surprises

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

So far, the best CPT test with baryons
was realized with CERN’s unique antiprotons

One-Antiproton Radio



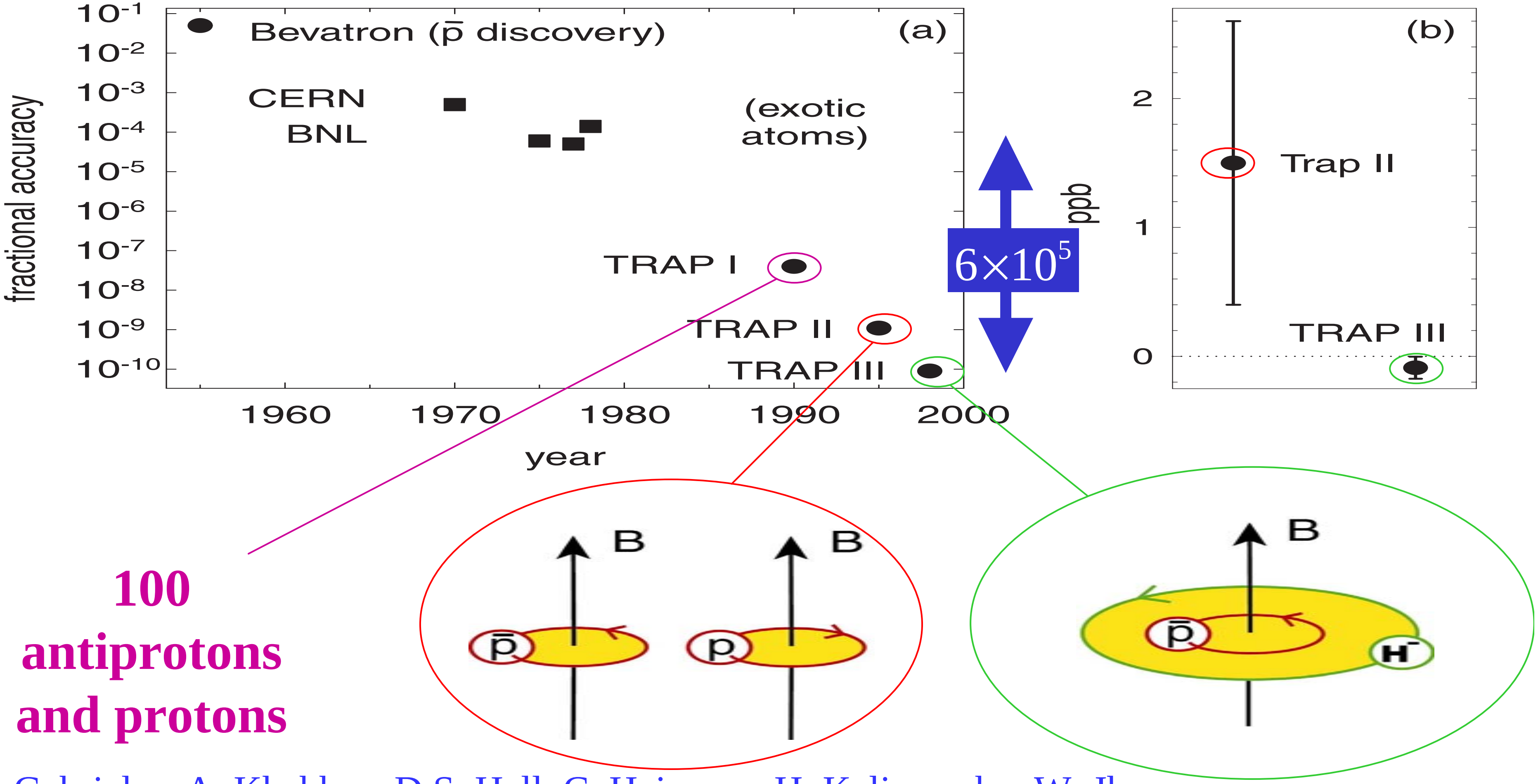


TRAP Improved the Comparison of Antiproton and Proton by ~ 10^6

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

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

best 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).

Comparing the CPT Tests

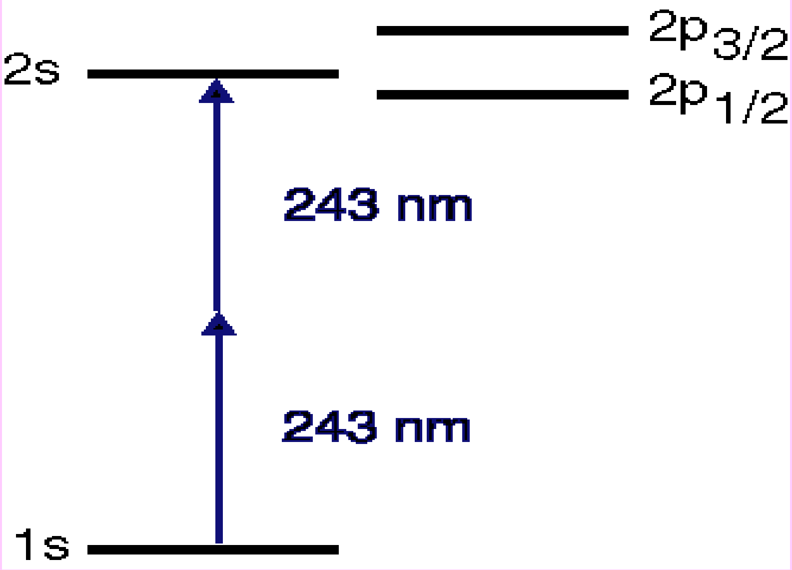
Warning – without CPT violation models it is hard to compare

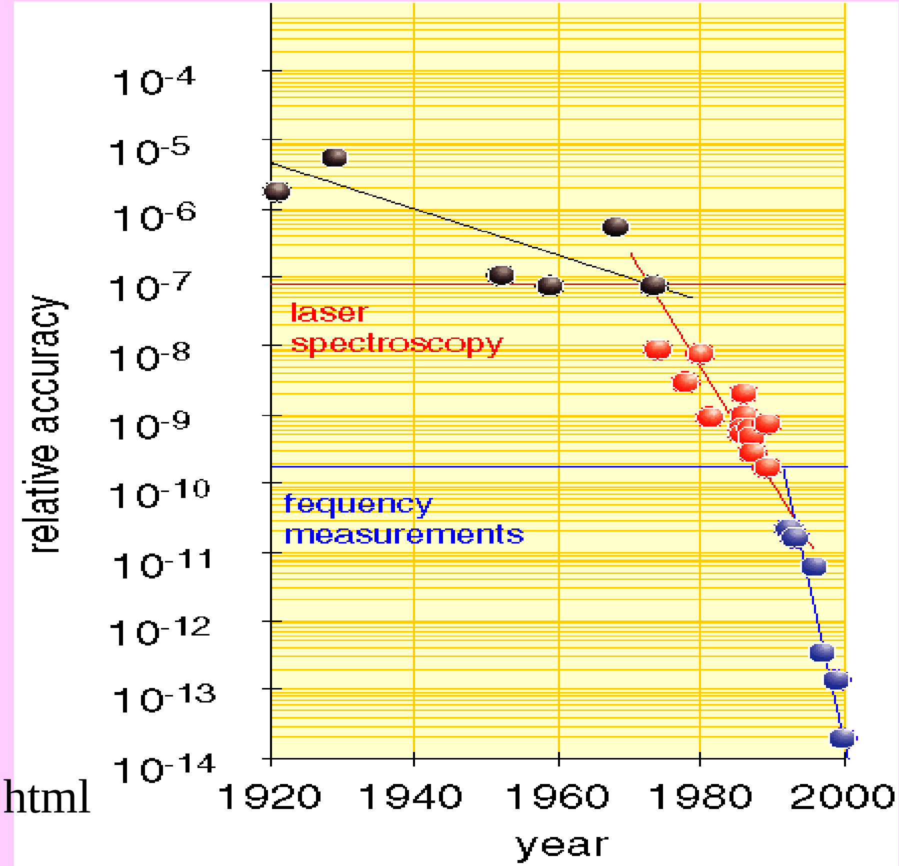
3 fundamentally different types of particles

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

improve with antihydrogen

Hydrogen 1s – 2s Spectroscopy

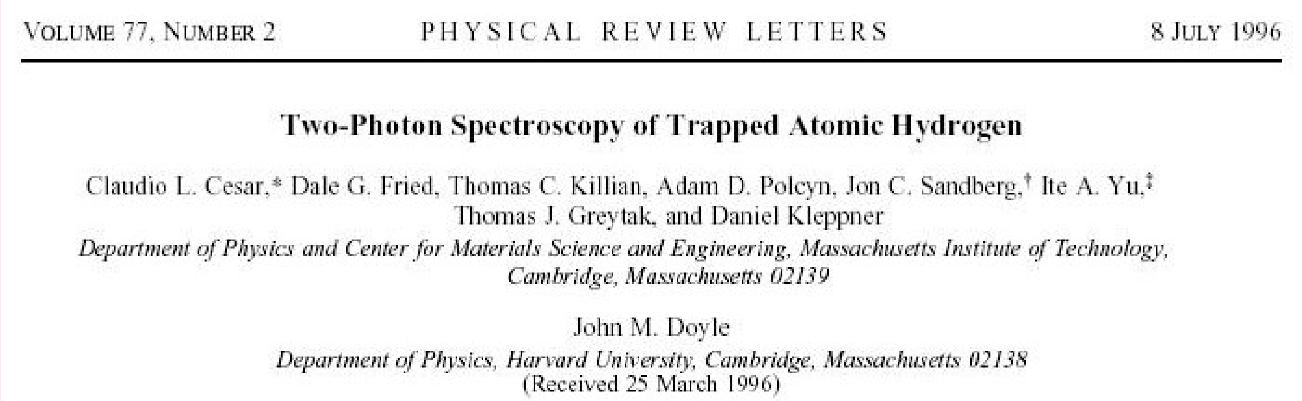




(Haensch, et al., Max Planck Soc., Garching)
http://www.mpq.mpg.de/~haensch/hydrogen/h.html

Many fewer antihydrogen atoms will likely be available

Not as Accurate Yet, but Similar Environment



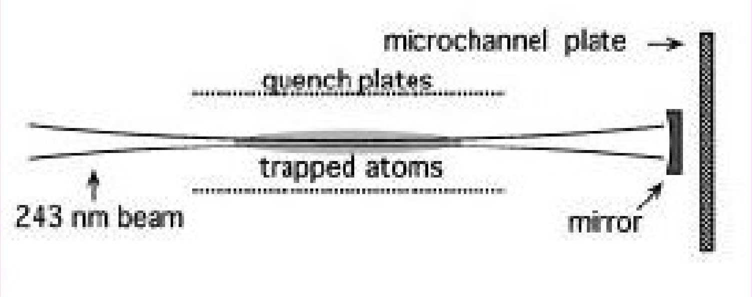
VOLUME 77, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1996

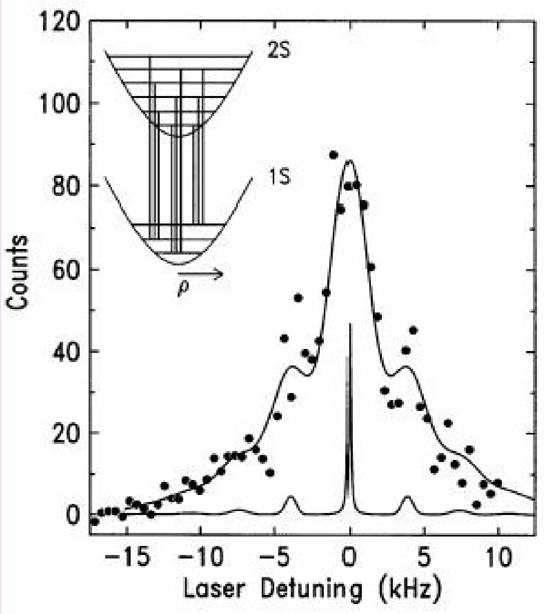
Two-Photon Spectroscopy of Trapped Atomic Hydrogen

Claudio L. Cesar,* Dale G. Fried, Thomas C. Killian, Adam D. Polcyn, Jon C. Sandberg,† Ite A. Yu,‡
Thomas J. Greytak, and Daniel Kleppner
Department of Physics and Center for Materials Science and Engineering, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

John M. Doyle
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

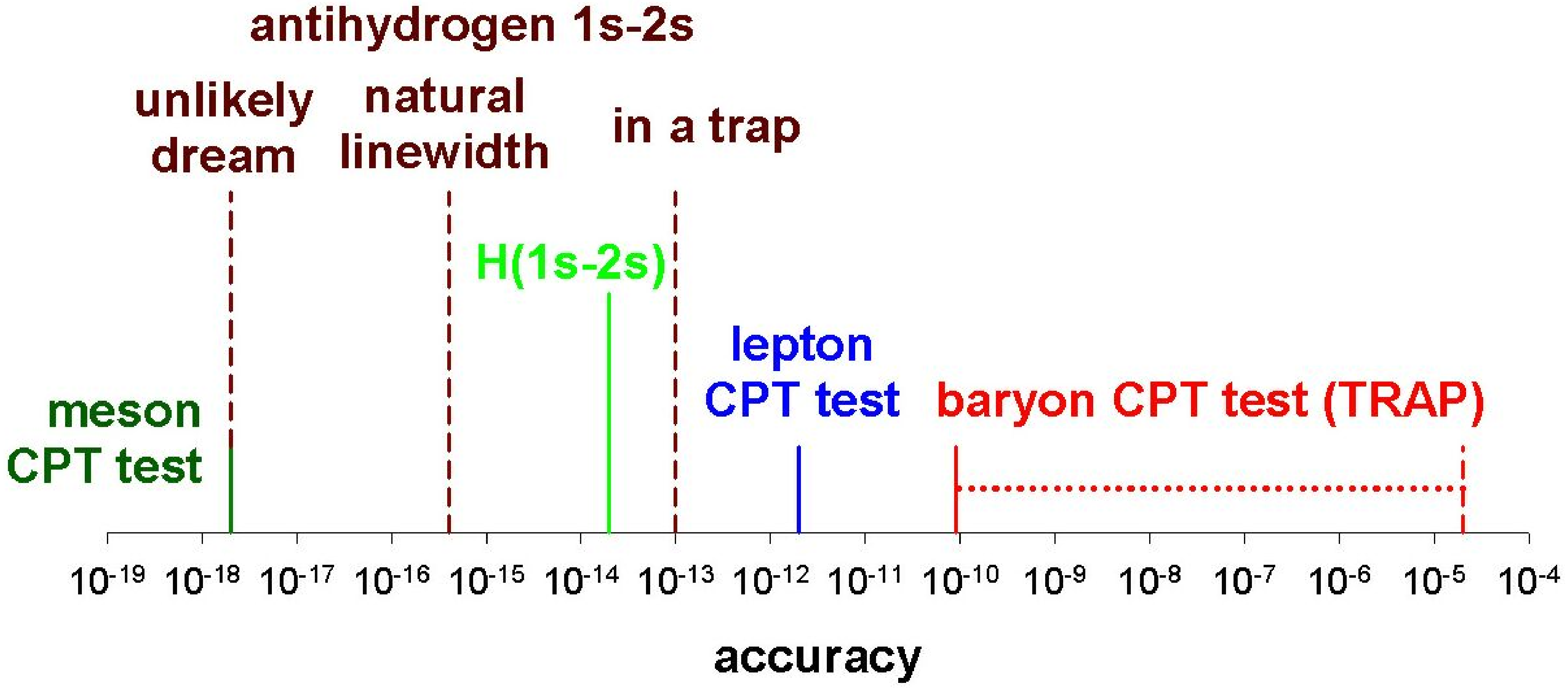
(Received 25 March 1996)





Still uses a lot more hydrogen atoms
than we expect to have antihydrogen atoms

Seek to Improve Lepton and Baryon CPT Tests



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

Quantum Field Theory → CPT Theorem

Kostelecky, et al. -- What extensions to the standard model arise if Lorentz invariance (alone) is not taken as a postulate of QFT?

Many papers

e.g. R. Bluhm, V.A.Kostelecky, N. Russell

Phys. Rev. D **57**, 3932 (1998)

CPT in String Theory

?????

No CPT theorem in general

Get CPT theorem if go to the limit of a quantum field theory

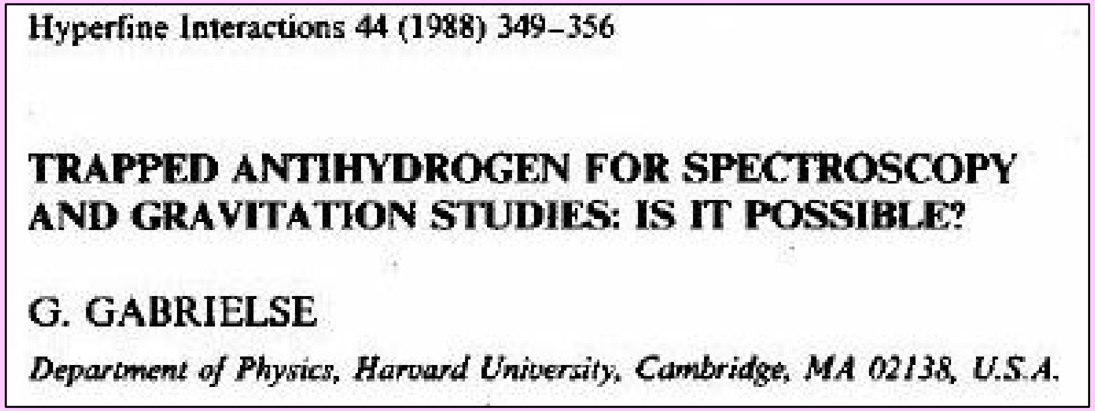
Baryon-Antibaryon Assymetry is Not Understood

Normal "Explanation"	**Alternate**
1. CP Violation	1. CPT violation
2. Violation of baryon number	2. Violation of baryon number
3. Thermodynamic non-equilibrium	3.

"CPT Violation and Baryogenesis"
Bertolami, Colladay, Kostelecky, Potting
Phys. Lett. B 395, 178 (1997)

Makes sense to investigate these fundamental symmetries in the few places that we can hope to do so very precisely.

Gravity and Antihydrogen

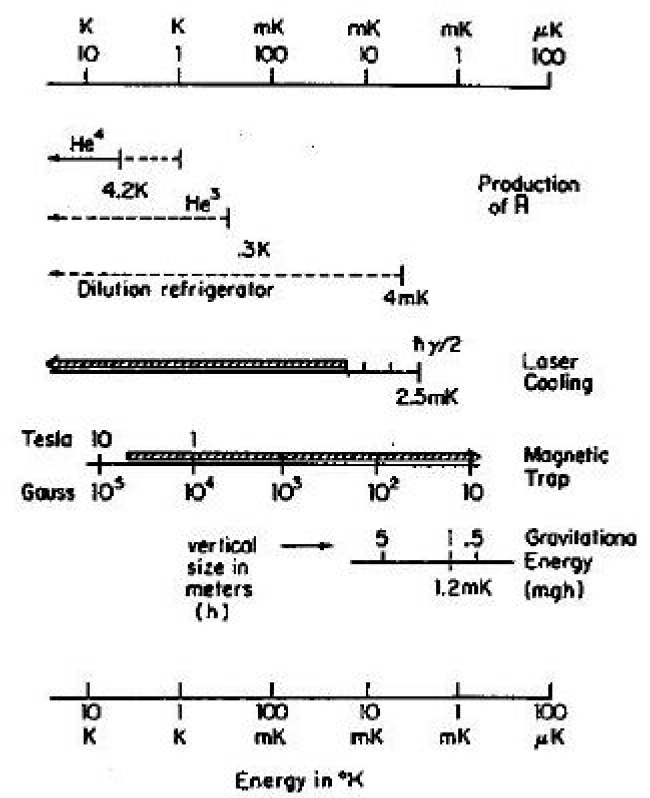


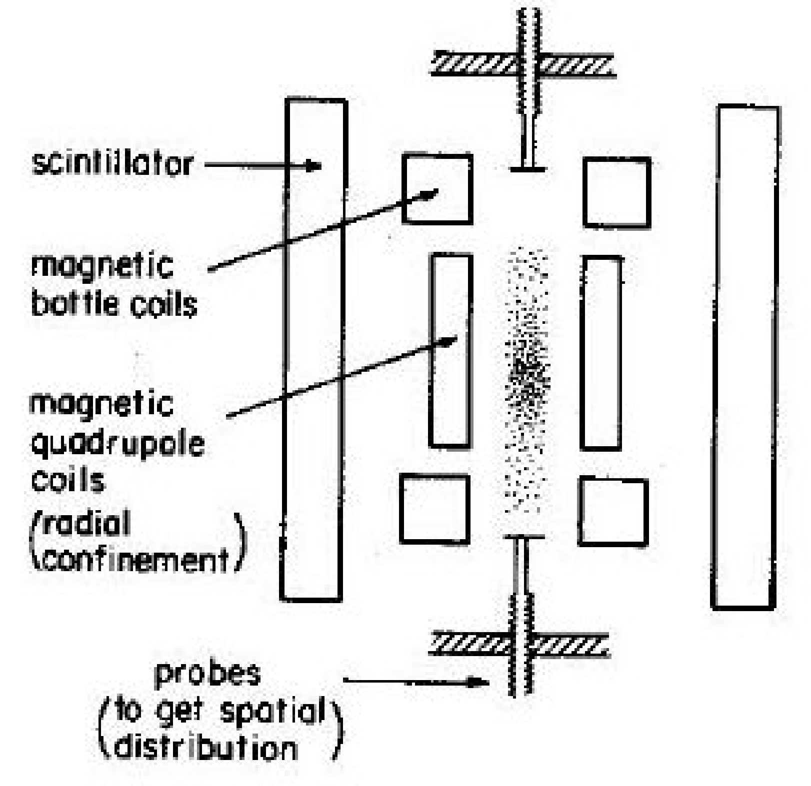
Hyperfine Interactions 44 (1988) 349–356

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

G. GABRIELSE

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





Experimental Milestones

- * **Need Antiprotons and Positrons**
  - **AD, Antiproton Accumulation, Positron Accumulation**
- * **Need to produce antihydrogen production:** **Method I** *
  - **Method II** *
  - **Other Methods?**
- **Need useful antihydrogen ← cold, ground state**
  - * **Devising a method to measure the antihydrogen velocity**
  - * **Devising a method to measure the antihydrogen state**
  - **Ground state antihydrogen**
  - **Antihydrogen cold enough to trap**
- **Need to trap antihydrogen**
  - * **Stability test for trapped particles in Ioffe field**
- **Need antihydrogen spectroscopy**
  - * **First continuous Lyman-alpha source**

Need Antiprotons and Positrons

Status
Challenges
Needed Improvements

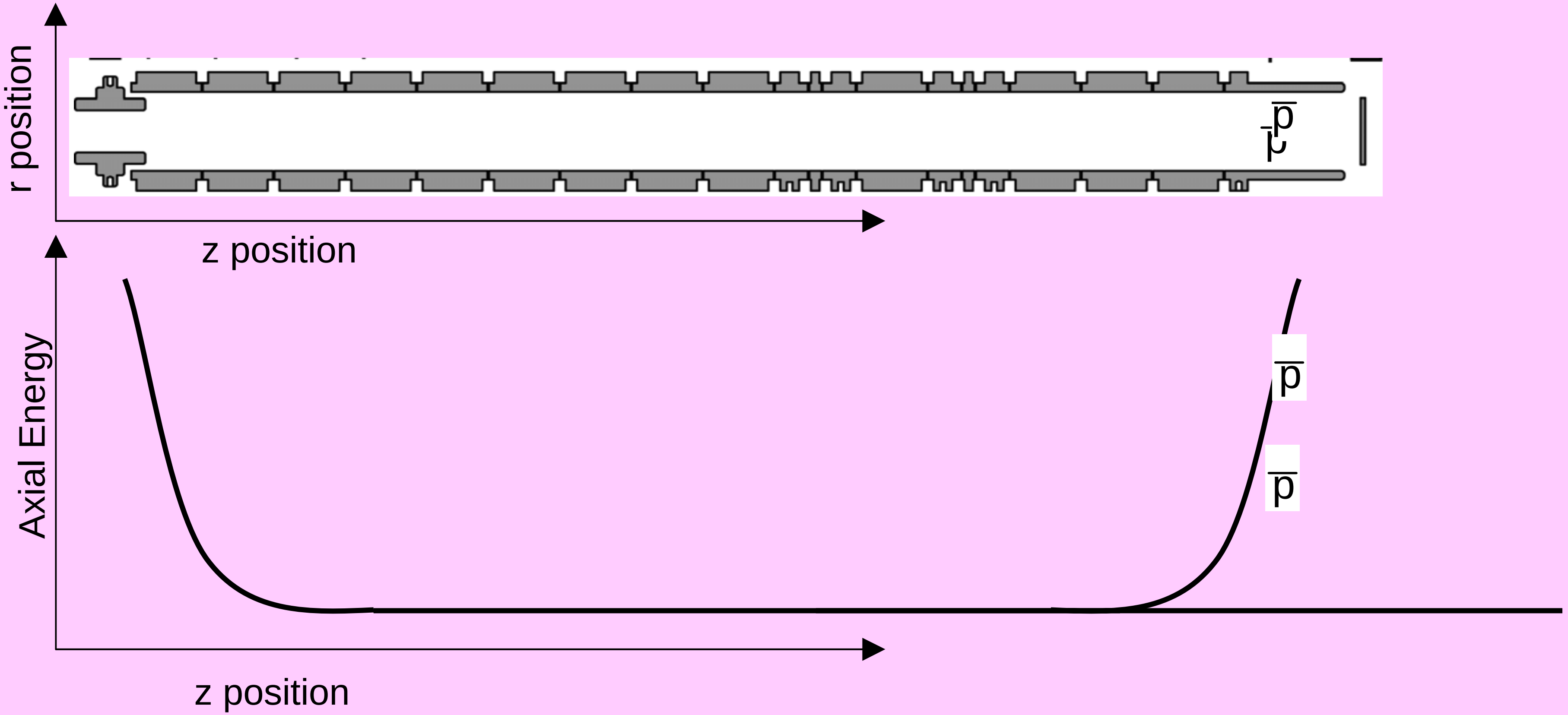
Accumulating Antiprotons – Basic Ideas

(Developed by Our TRAP Collaboration at CERN's LEAR: 1986 - 2000)

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

Used by 3 collaborations at the CERN AD
ATRAP, ATHENA and ASACUSA

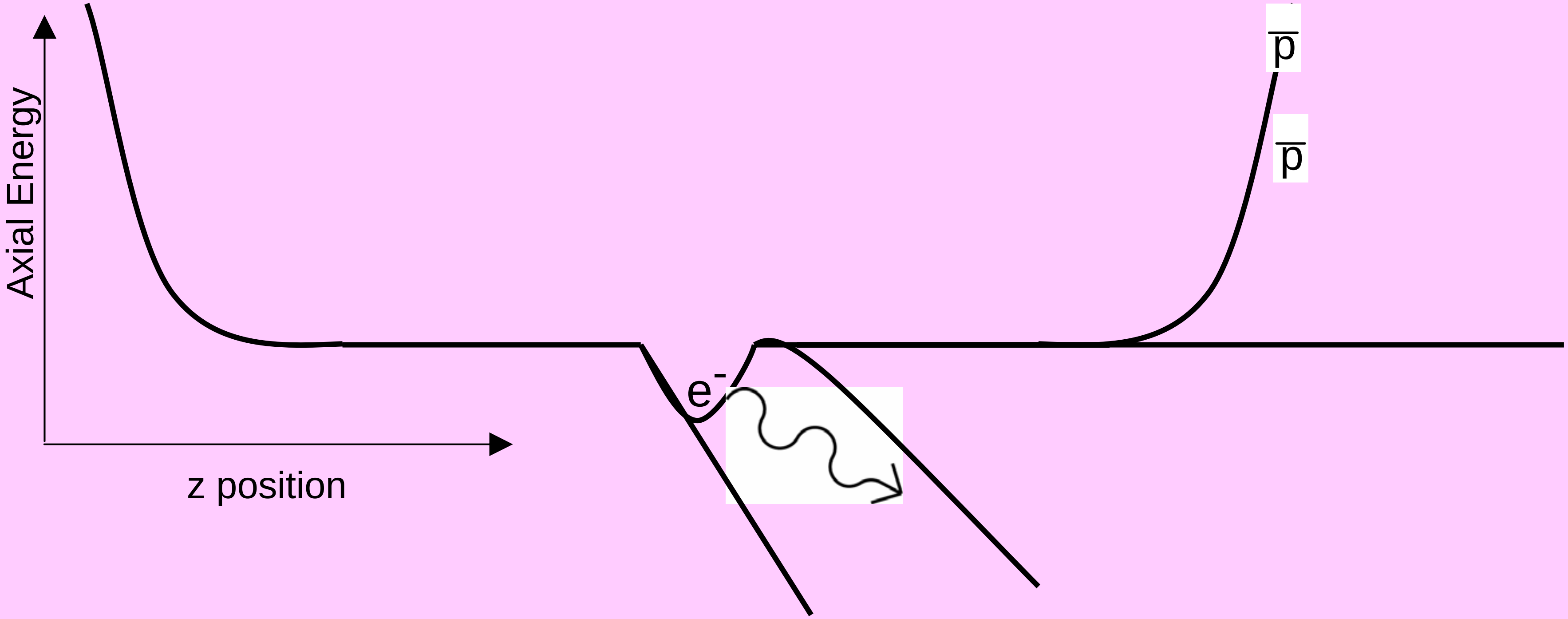
Antiproton Capture – the Movie



"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

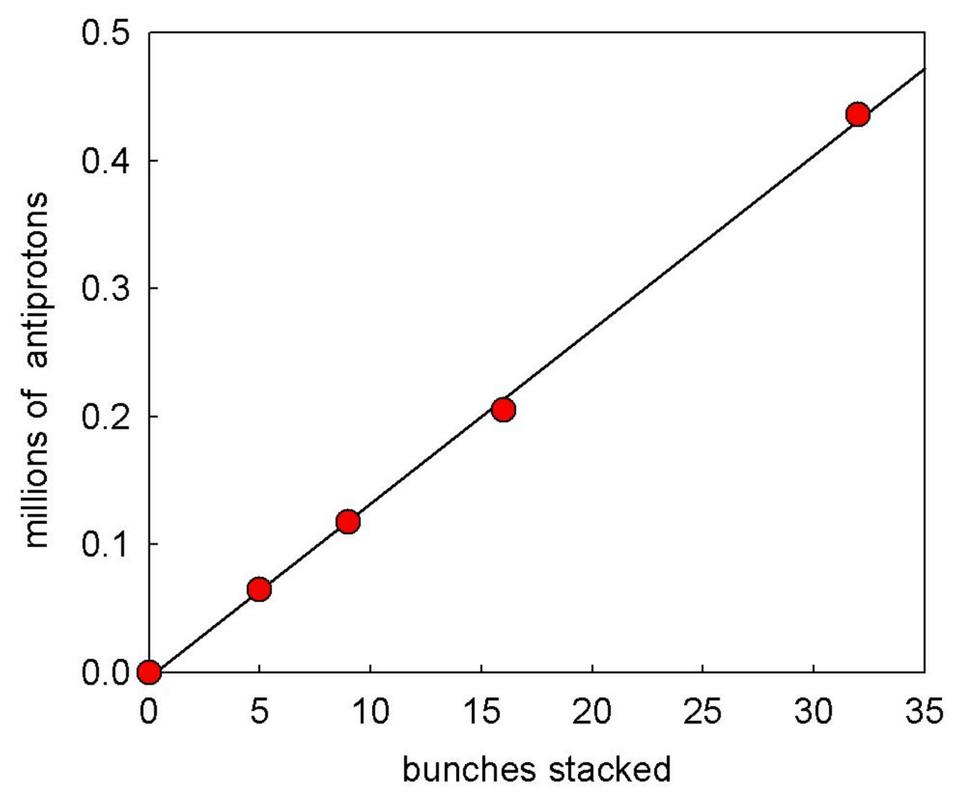
- Antiprotons cool via collisions with electrons
- Electrons radiate away excess energy



"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).

“Stacking”

Accumulating Antiprotons – just a matter of time



Can stack this number
in a single well, for more
need multiple wells

ATRAP’s good vacuum
$< 5 \times 10^{-17}$ Torr
allows such stacking
(ATHENA and ASACUSA
use stacking but with less
bunches)

First Demonstration – Antiprotons Stacked in a Trap
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells
Phys. Rev. Lett. 63, 1360 (1989)

“Stacking of Cold Antiprotons”
ATRAP
Phys. Lett. B **548,** 140 (2002)

Antiprotons – Needed Improvements

Status: 4.2 K antiprotons are routinely accumulated

Improvements?

- Needed: much lower temperatures
- Desired: more antiprotons to speed data accumulation
- Desired: more antiprotons to improve spectroscopy signal-to-noise

Decelerator?

- would give the much larger antiproton rate desired
- small ring would fit in AD hall
- new beam lines would be needed
- magnetic fields from experimental apparatus
- substantial cost

Positron Accumulation

Status: Two methods routinely accumulate positrons
Enough positrons are available, all independent of CERN

Ionizing Rydberg positronium – compact, high field, high vacuum, lower accumulation rate

Gas slowing – larger, outside of high field, lower vacuum, higher accumulation rate

Another possibility: **Electron plasma slowing ??**

Improvements? Likely need much lower temperatures

Two Ways to Produce Slow Antihydrogen

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

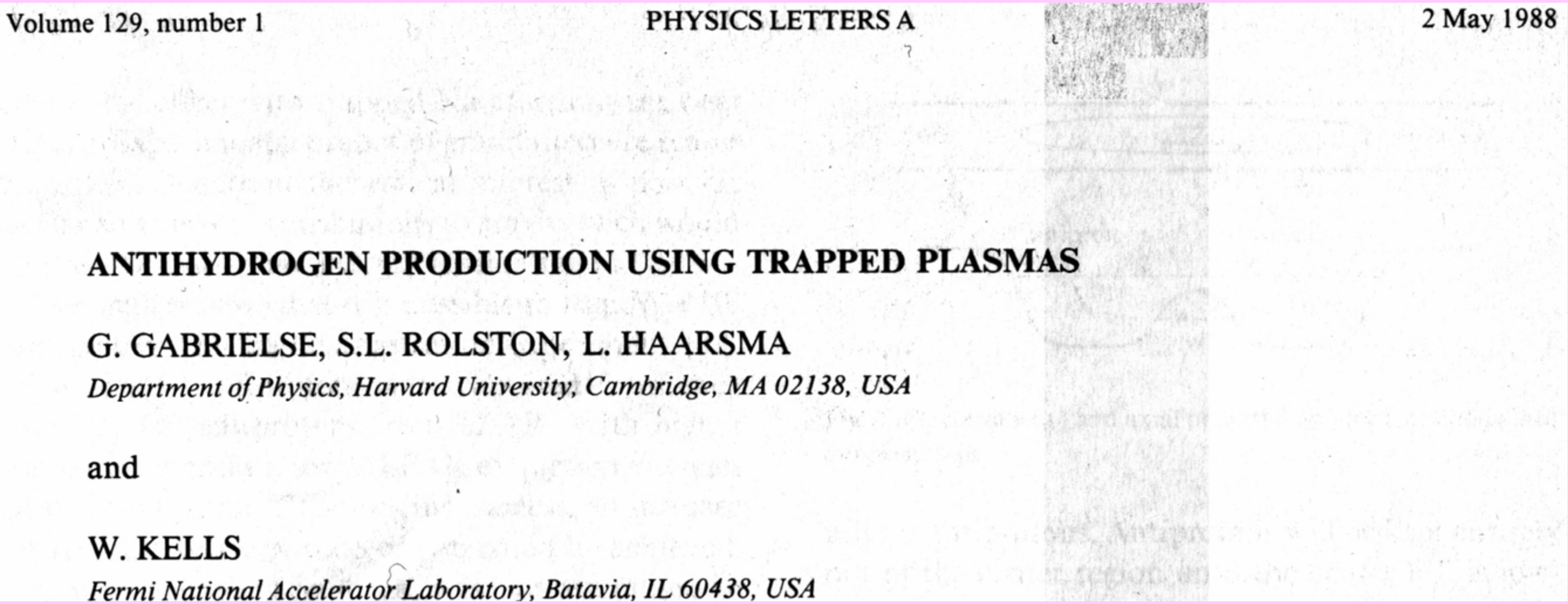
   Device and technique – ATRAP
   Used to produce slow antihydrogen – ATHENA and ATRAP

2. Laser-controlled resonant charge exchange

   ATRAP

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

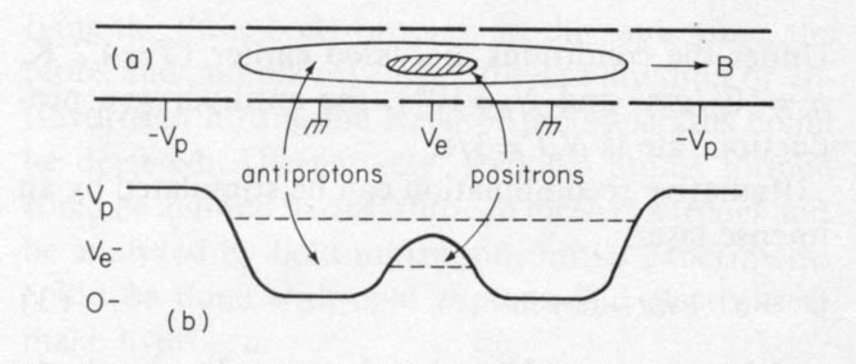
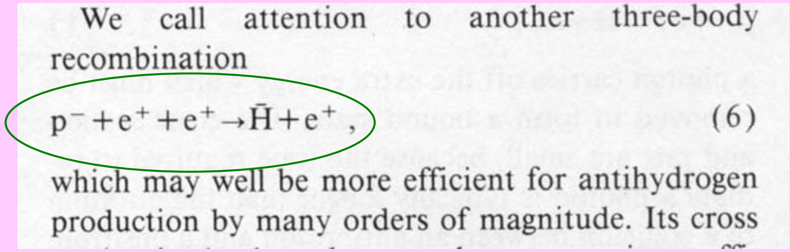


Fig. 1. Electrodes (a) and axial potential (b) for a nested pair of Penning traps.

Nested Penning Trap



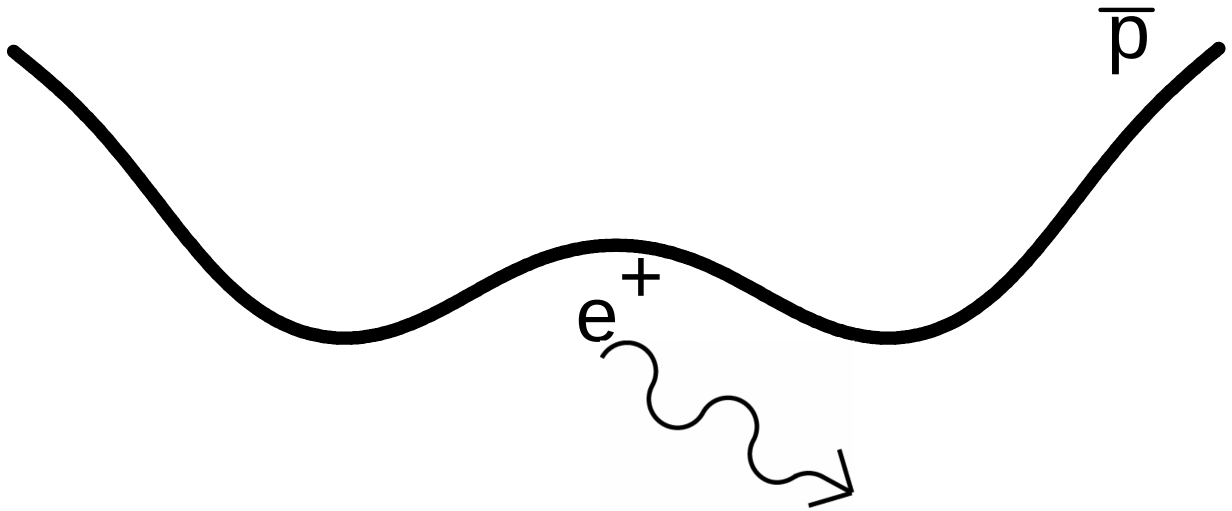
We call attention to another three-body recombination

$$p^- + e^+ + e^+ \rightarrow \bar{H} + e^+ , \quad (6)$$

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

3-Body “Recombination”

Method I: Positron Cooling of Antiprotons in a Nested Penning Trap



TRAP/ATRAP Develops the Nested Penning Trap

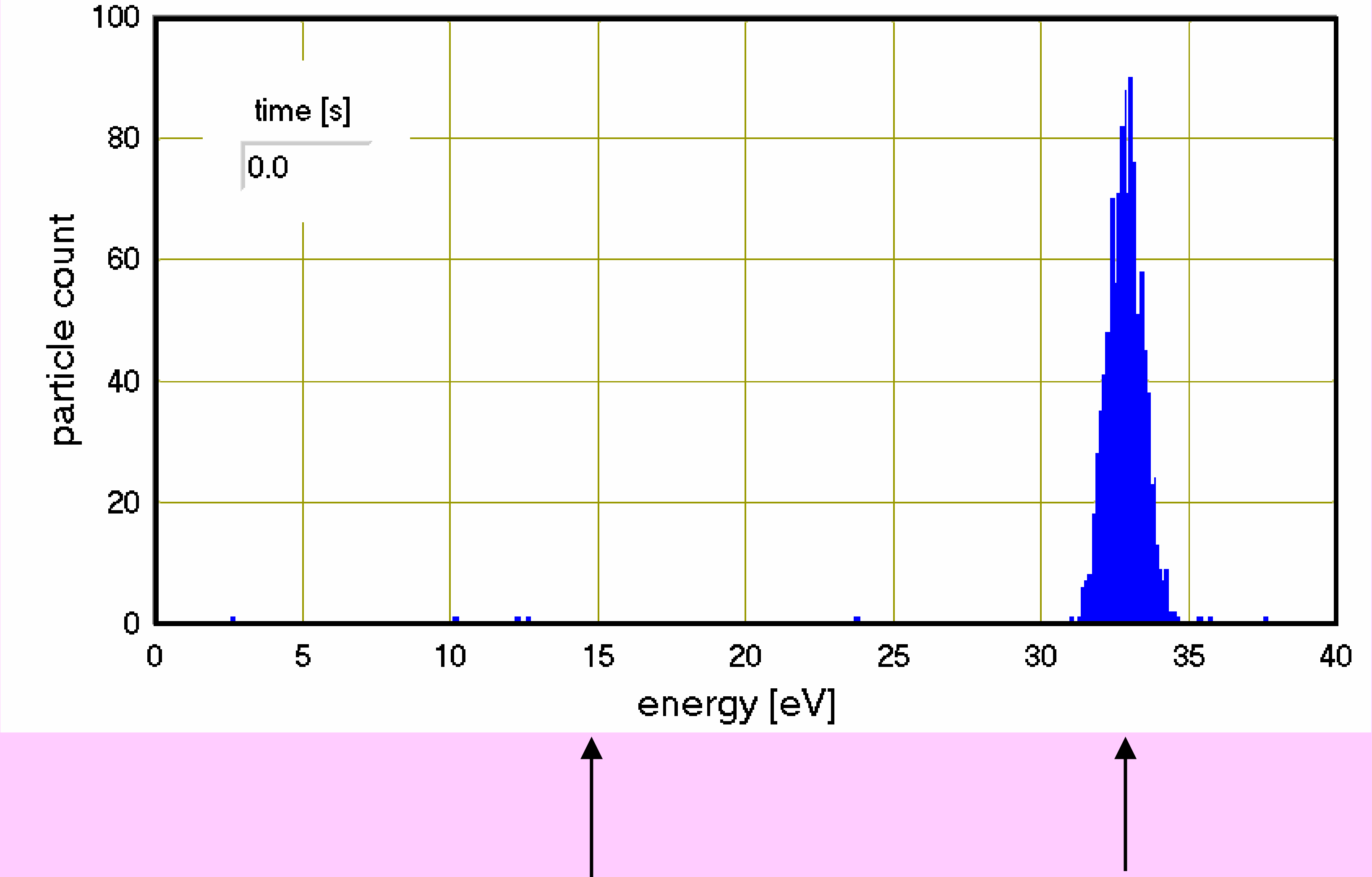
Proposed nested trap as a way to make antihydrogen

"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)

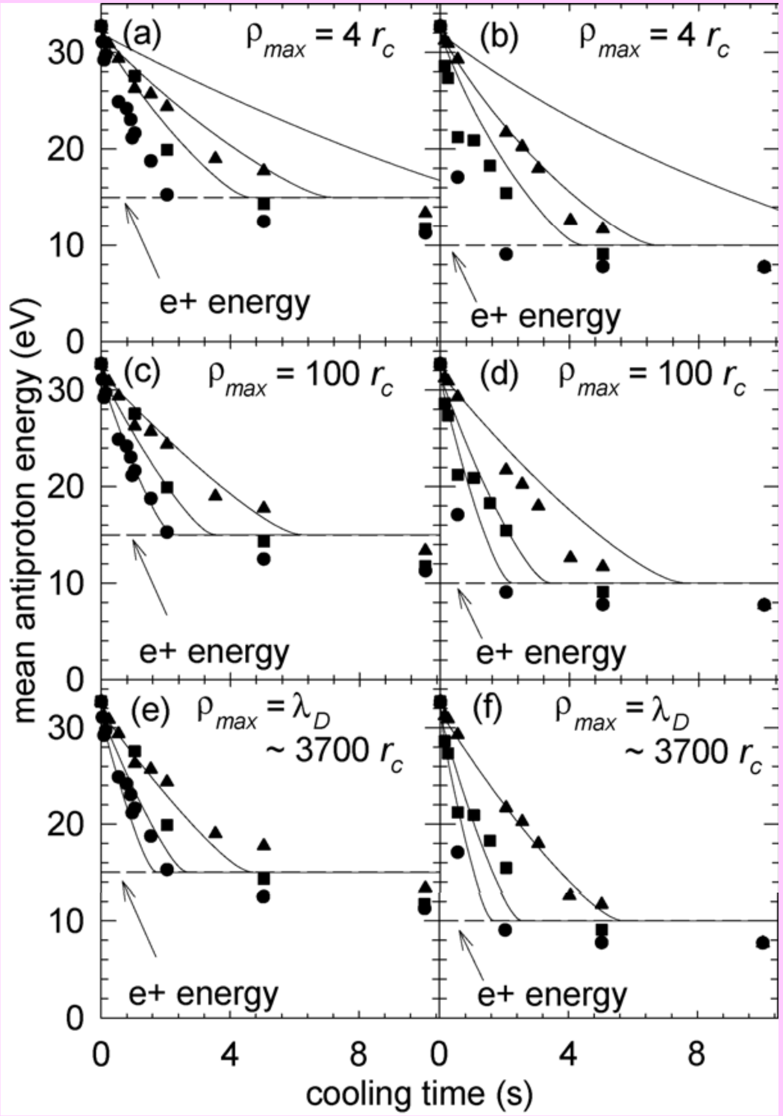
Positron Cooling of Antiprotons



positrons

initial antiproton
energy

Quantitative Understanding of Positron Cooling



Big change in view
of positron cooling of antiprotons

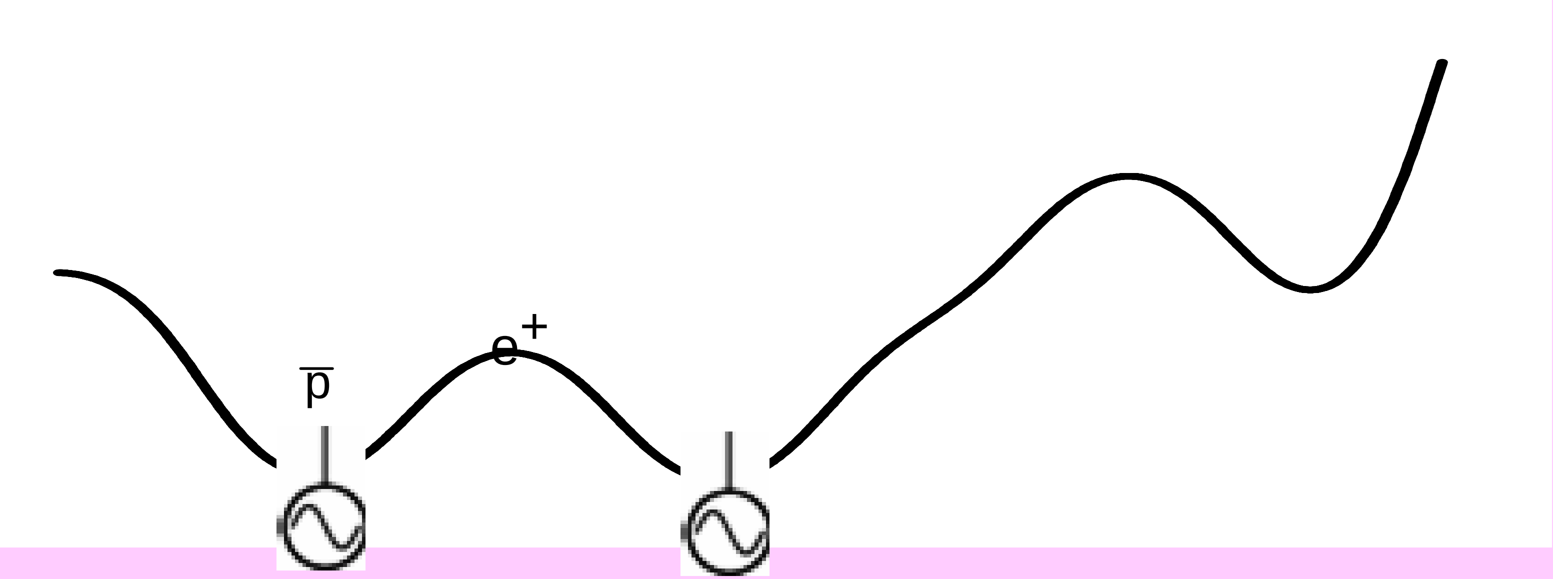
3 numbers of positrons:
70000
125000
200000

Two well depths

Experiment required big change
in cutoff parameter

Driven Antihydrogen Production → Higher Rate

- Antiprotons cool below the positrons – interaction stops
- Drive axial motion of antiprotons repeatedly to “drive” interaction



Advantages

- higher antihydrogen production rate
- colder antihydrogen atoms (still to be proven)

Two Detection Methods

Athena – correlated loss of positrons and antiprotons within
5 microseconds and +/- 8 mm of each other
(now using mostly antiproton annihilations, 4 mm resolution)

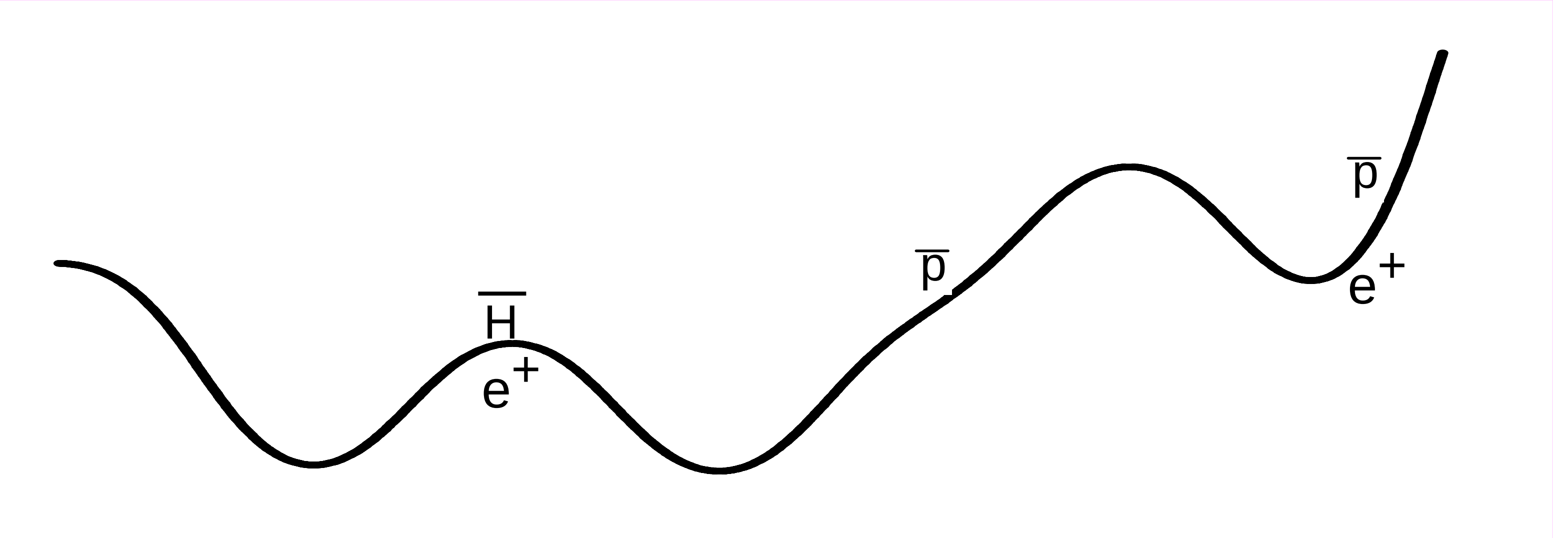
Good: Detects antihydrogen whatever is velocity and state
Not as good: Insensitive to antihydrogen velocity and state

ATRAP – field ionization detection

Good: No background
Probes internal state of the antihydrogen
Can measure antihydrogen velocity
Not as good: Can only detect states that can be field ionized
(Hope to use lasers to excite lower states to states
that can be field ionized)

ATRAP’s Field Ionization Method

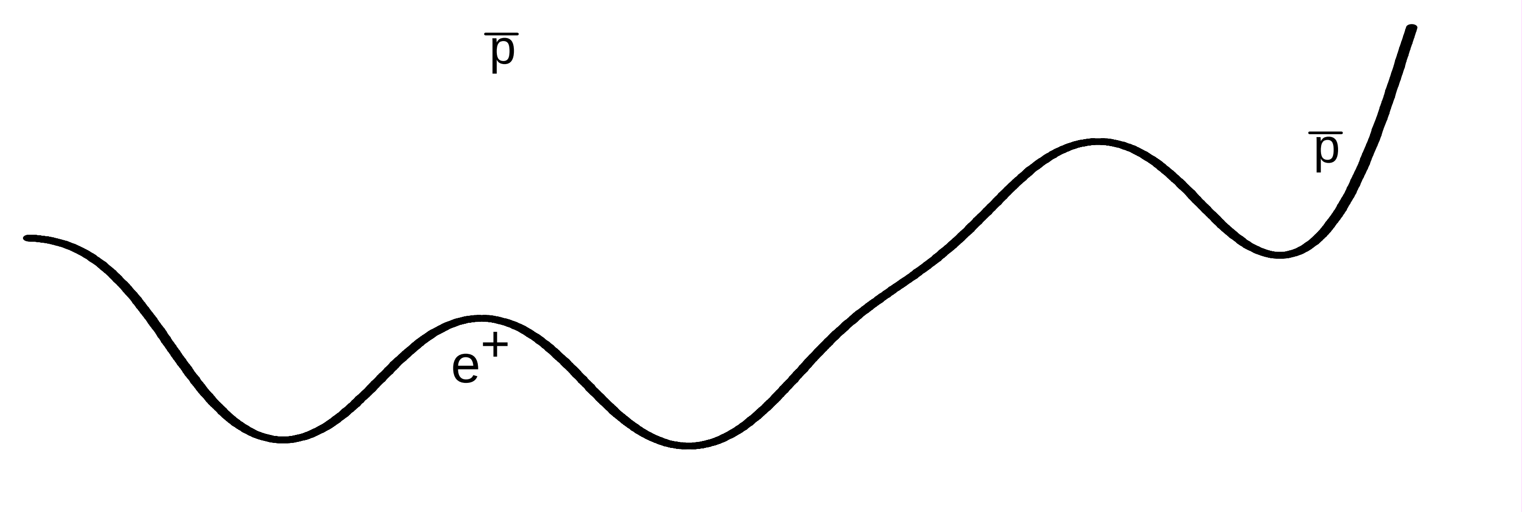
- Use Field-Ionization – strip positron and store antiproton



- Dump stripping well after experiment
  - Dump other particles before looking in stripping well
  - Ramp quickly compared to cosmic background count rate (ramp in 20ms, get one cosmic/second)
  - Essentially no background for this measurement!

Only Detect Ionized Antihydrogen

- Field-Ionization is very robust – only antihydrogen can get antiprotons into the stripping well



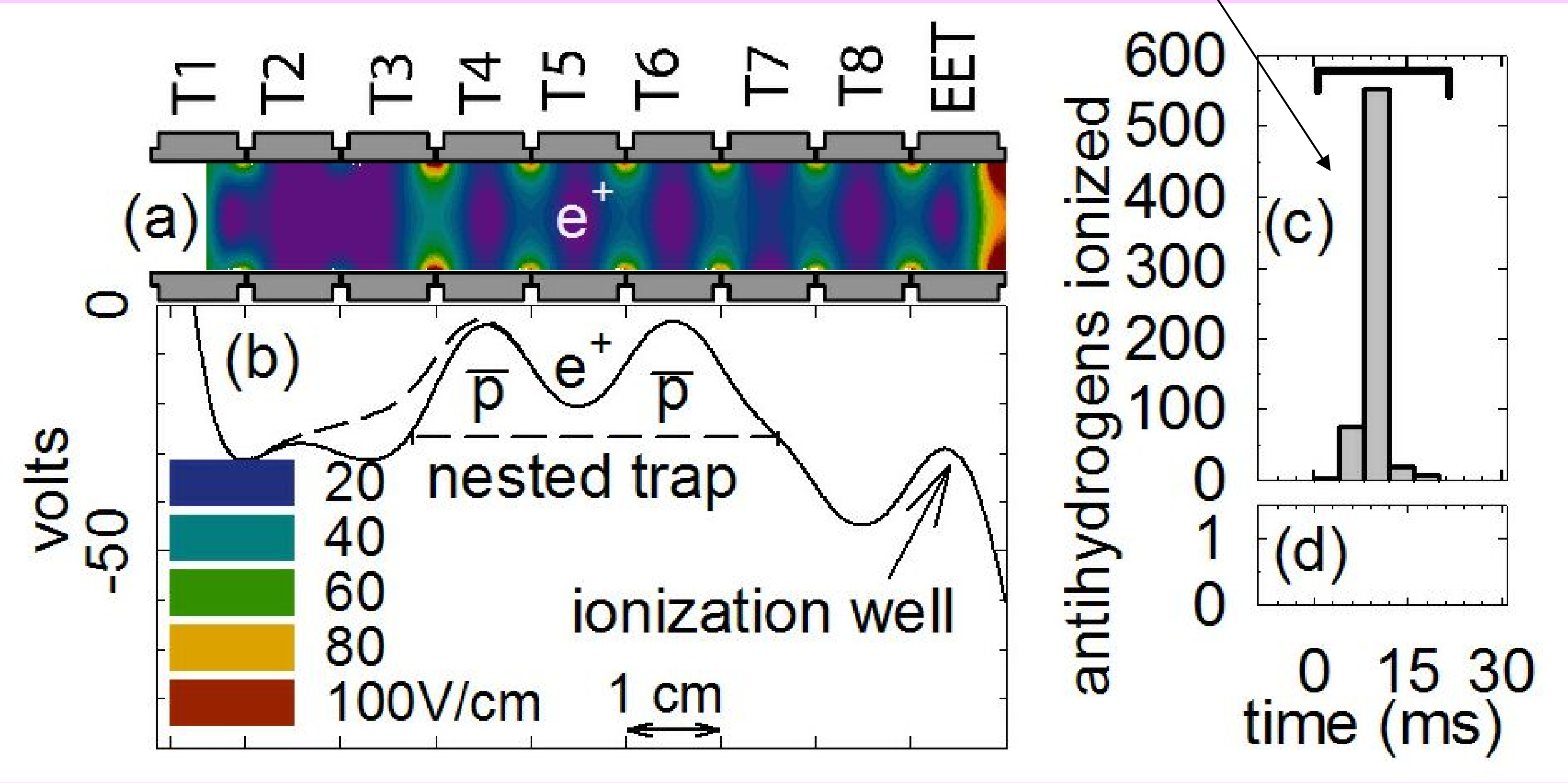
- Antiprotons knocked out of well leave to the left

- Even if an antiproton has enough energy to get to the ionization well, it can not get into the well

Early example – background-free detection

Here: 657 + 780 + …

Reported: 9 + 90 + 131



Background-free → no background counts observed

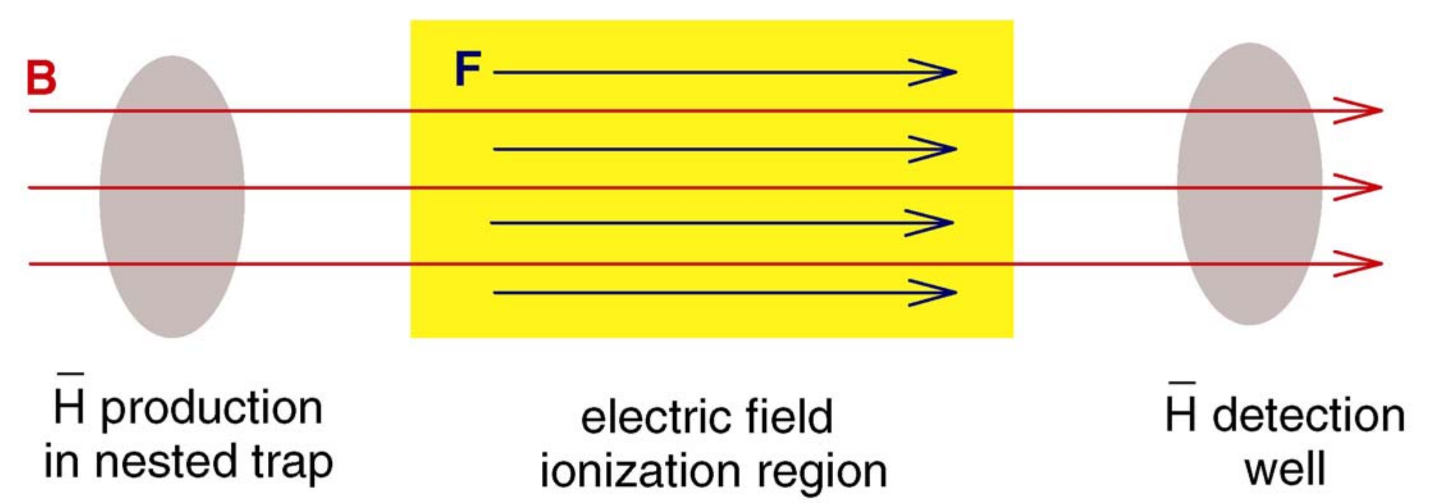
Useful Antihydrogen

- Cold enough to trap
- Ground state

How Close to Useful Antihydrogen?

How close to the ground state?

ATRAP’s field ionization method is only probe so far

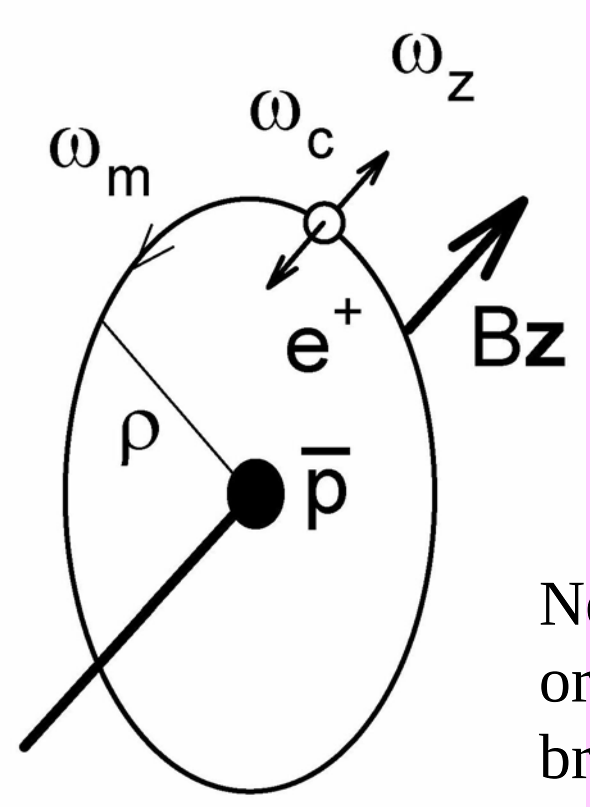


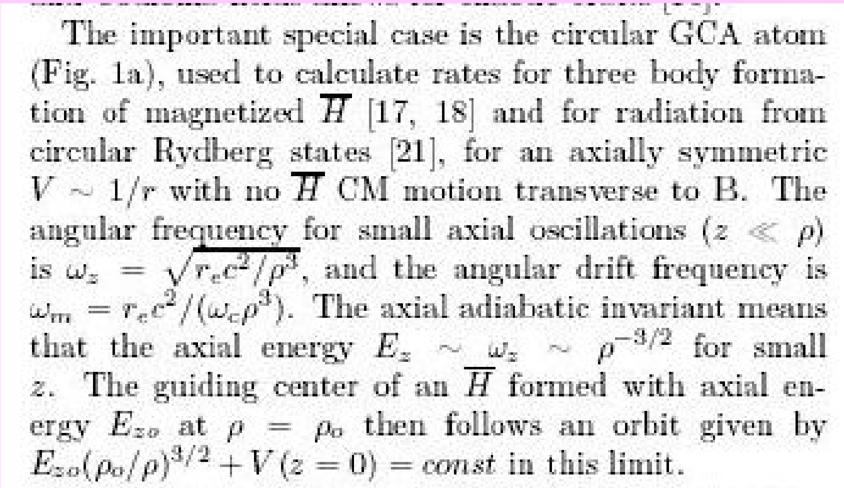
How cold?

Vary ionization field F in time to find out.
Fast atoms make it through while field is at a low value.

Identified Atoms are Mostly Guiding Center Atoms

- for small amplitude oscillations
- like a particle in a Penning trap

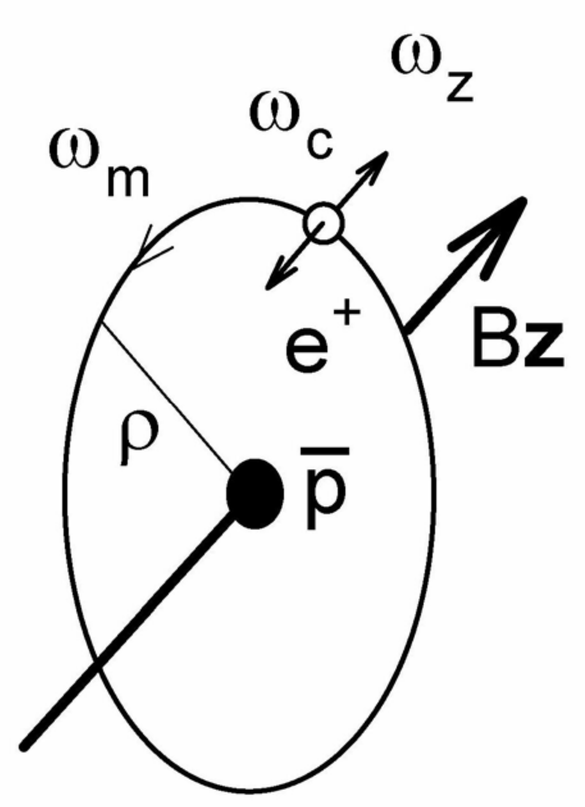



The important special case is the circular GCA atom (Fig. 1a), used to calculate rates for three body formation of magnetized $\overline{H}$ [17, 18] and for radiation from circular Rydberg states [21], for an axially symmetric $V \sim 1/r$ with no $\overline{H}$ CM motion transverse to B. The angular frequency for small axial oscillations ($z \ll \rho$) is $\omega_z = \sqrt{r_e c^2/\rho^3}$, and the angular drift frequency is $\omega_m = r_e c^2/(\omega_c \rho^3)$. The axial adiabatic invariant means that the axial energy $E_z \sim \omega_z \sim \rho^{-3/2}$ for small z. The guiding center of an $\overline{H}$ formed with axial energy E_{zo} at $\rho = \rho_o$ then follows an orbit given by $E_{zo}(\rho_o/\rho)^{3/2} + V(z=0) = const$ in this limit.

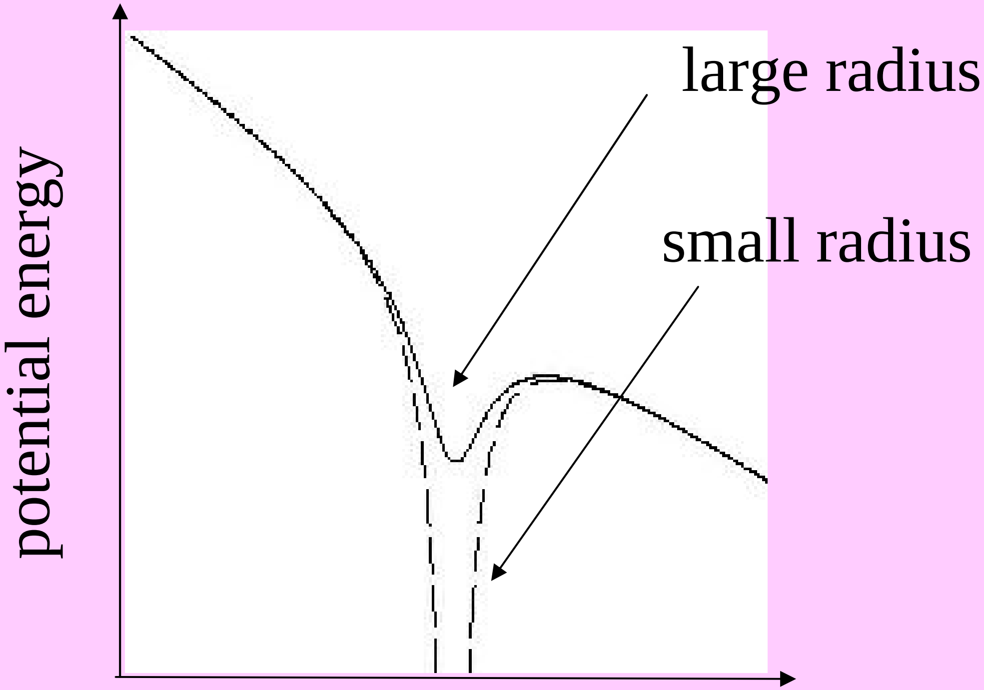
Need: cyc. freq >> magnetron freq
or the guiding center approximation (GCA)
breaks down

$$\rho > 0.25\,\mu m$$

Guiding Center Antihydrogen Atoms

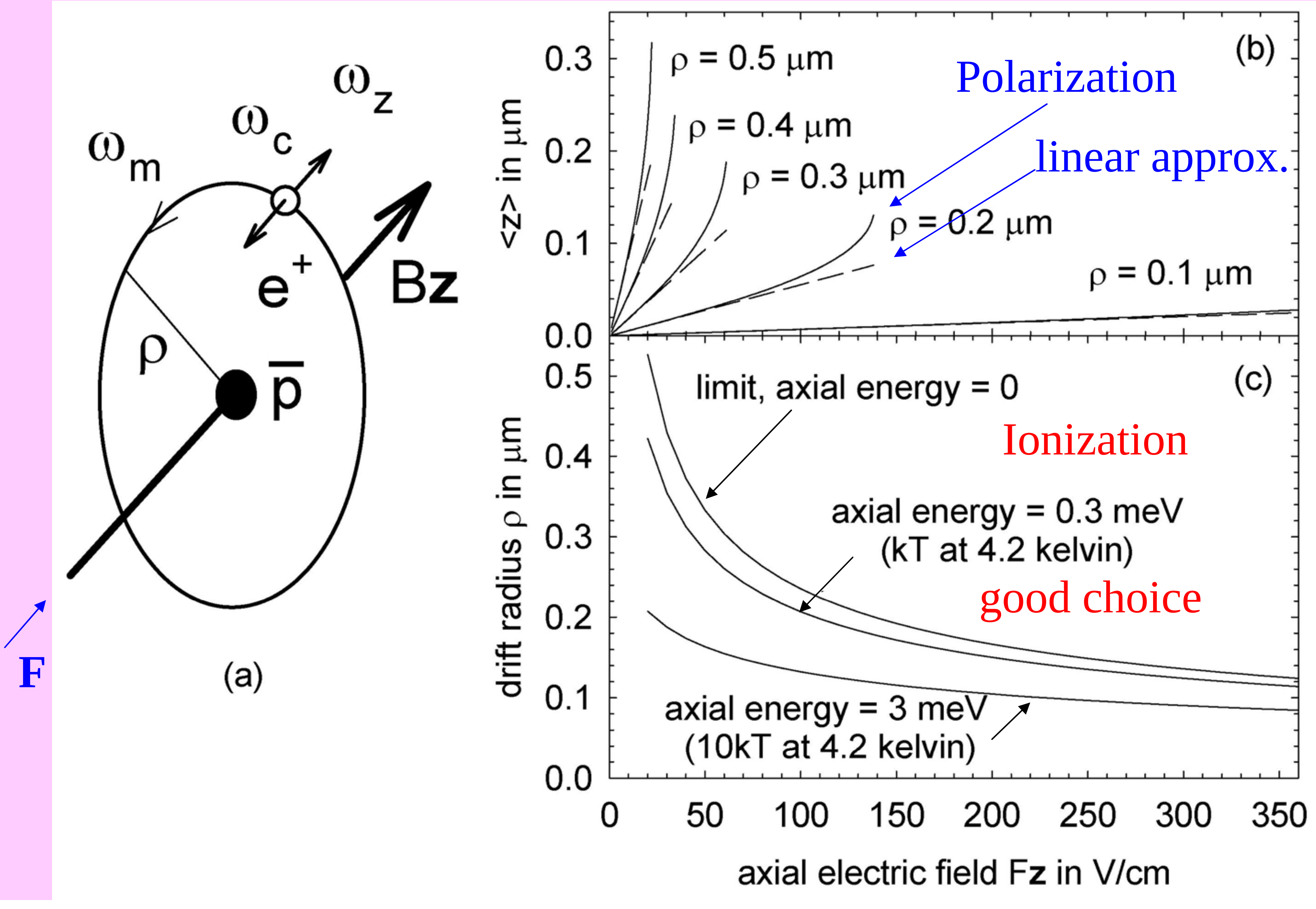


In an axial electric field



distance to positron from antiproton

Guiding Center Atom



F

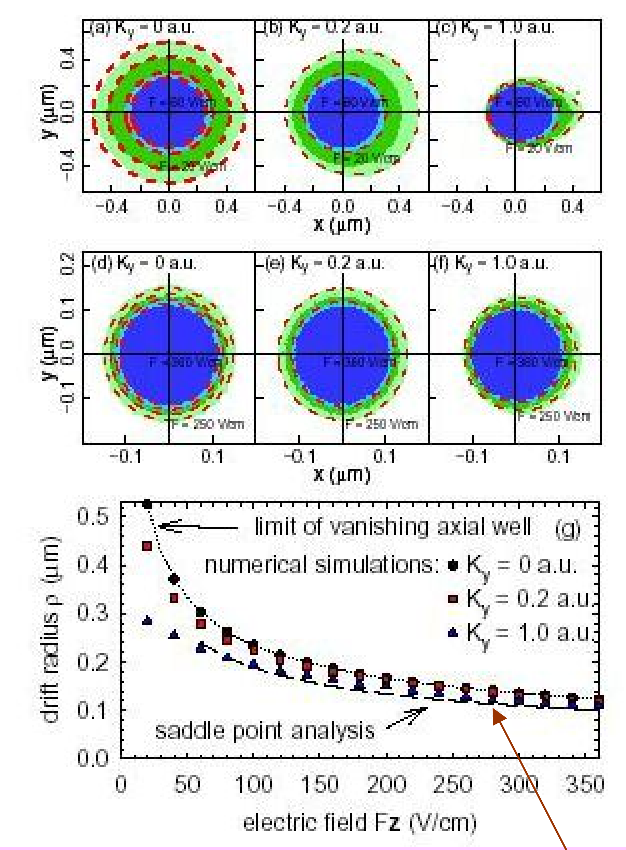
Polarization

linear approx.

Ionization

good choice

Ionization in the General Case



An antihydrogen atom that survives an ionization field **F** ~ **B** has a radial size

$$\rho \le \frac{a}{\sqrt{F}}\sqrt{\frac{e}{4\pi\varepsilon_o}}$$

1 atomic unit

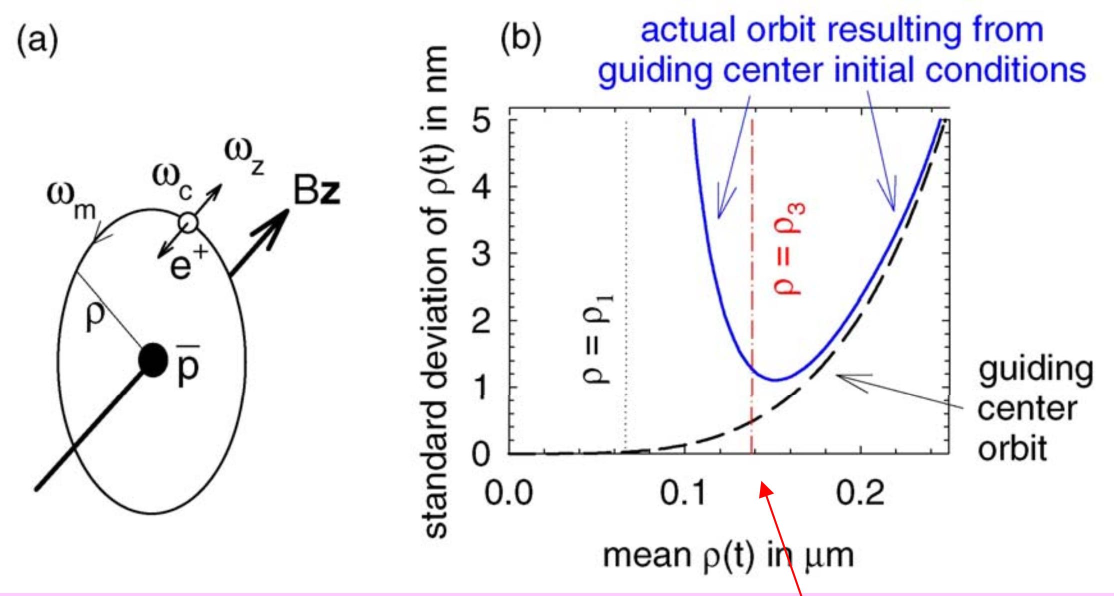
$$= 3.795\,\mu m\sqrt{\frac{V}{cm}}$$

a = $(4/27)^{1/4}$ = 0.62 (vanishing well limit)

good choice

a = ½ ← not so far from 4 K as well

GCA Breakdown



GCA freq.
not well def.
here

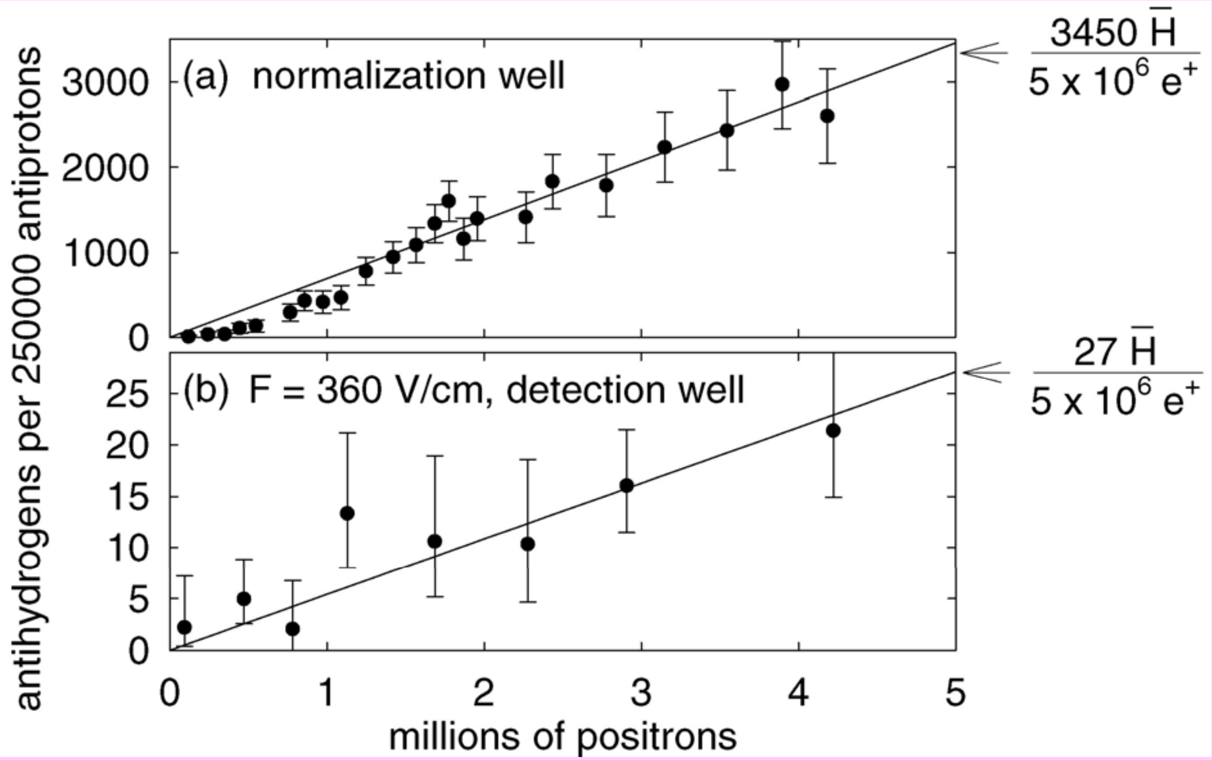
For GCA to be valid: $Need : \omega_m \ll \omega_z \ll \omega_c$

$$\omega_m = \omega_z = \omega_c : \qquad \rightarrow \rho < 0.07\,\mu m$$

$$\omega_m < \frac{1}{3}\omega_z \;\; and \;\; \omega_z < \frac{1}{3}\omega_c : \qquad \rightarrow \rho < 0.14\,\mu m$$

Chaotic?

ATRAP Observation of Deeply Bound States

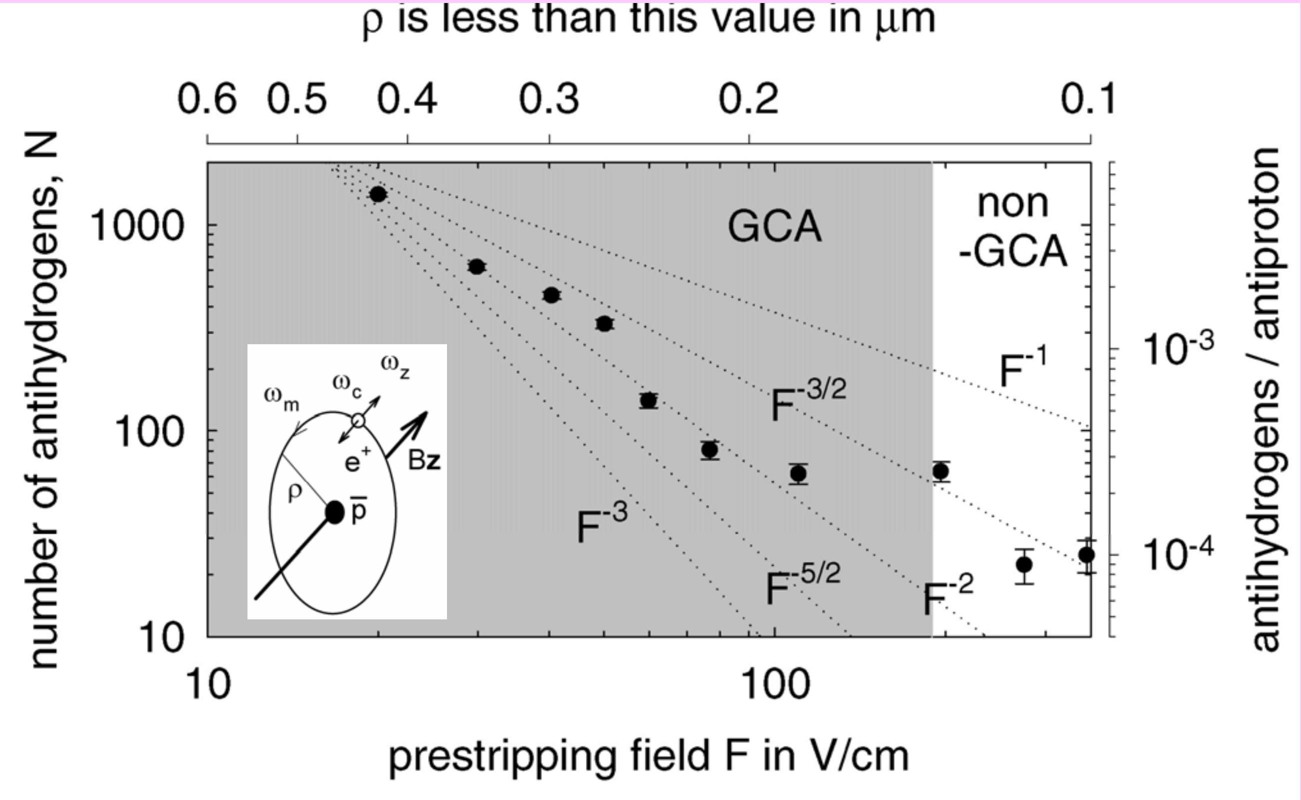


How deeply bound?

Radius: < 0.1 μm

GCA no longer valid

More Deeply Bound Antihydrogen – Chaotic?



Breakdown of the GCA picture
→ chaotic motion?

Recent Theoretical Papers

B. Zygelman, “Recombination of antiprotons with positrons at low temperatures‘”,
J. Phys. B: At. Mol. Opt. Phys. **36**, L31-L37 (2003).

D. Vrincenu, B.E. Granger, R. Parrott, H.R. Saddghpour, L. Cederbaum, A. Mody, J. Tan and G. Gabrielse, “Strongly Magnetized Antihydrogen and Its Field Ionization",
Phys. Rev. Lett. (in press).

F. Robicheaux and J.D. Hanson, “Three body recombination for protons moving in a strong magnetic field”, Phys. Rev. A (in press).

F. Driscoll, “Comment on Driven Production of Cold Antihydrogen and the First Measured Distribution of Antihydrogen States", (submitted to Phys. Rev. Lett.).

ATRAP, “ATRAP Responds”, (submitted to Phys. Rev. Lett.).

S.G.\ Kruzmin and T.M. O'Neil, “Polarization and Trapping of Weakly Bound Atoms in Penning Traps Fields” (submitted for publication).

S.G. Kuzmin, T.M. O'Neil and M.E. Glinsky, “Guiding Center Drift Atoms”
(submitted for publication).

F. Robicheaux, “Simulations of Anti-Hydrogen Formation”, (submitted for publication).

E.M. Bass and D.H.E. Dubin, “Energy Loss Rate for Guiding Center Antihydrogen Atoms”,
(submitted for publication).

More Theory Papers

S. Jonsell, P. Froelich, S. Eriksson, K. Strasburger,
“On the Strong Nuclear Force in Cold Antihydrogen-Helium Collisions”,
(submitted for publication)

B. Zygelman, A. Saenz, P. Froelich, S. Jonsell,
“Cold Collisions of Atomic Hydrogen with Antihydrogen Atoms: An optical potential approach”,
(submitted for publication).

S. Jonsell, A. Saenz, P. Froelich, B. Zygelman, A. Dalgarno,
“Stability of Hydrogen-Antihydrogen Mixtures at Low Energies”,
Phys. Rev. A (in press).

E.M Bass and D.H. Dubin,
“Energy Loss Rate for Guiding-Center Antihydrogen Atoms”,
Phys. Plas. 11, 1240 (2004).

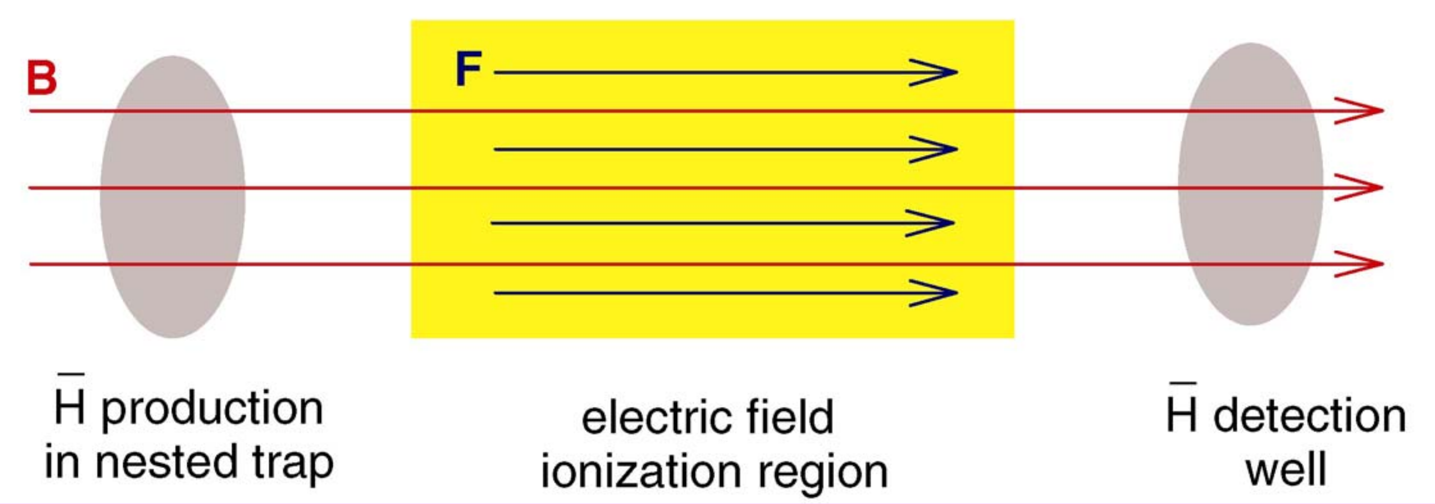
E.A.G. Armour, C.W Chamberlain, Y. Yiu and G.D.R. Martin
“Collisions Between Low-Energy Antihydrogen And Atoms”
Nuc. Inst. Meth. B xx, xxx (2004)

How Cold is “Cold” Antihydrogen?

"First Measurement of the Velocity of Slow Antihydrogen Atoms",
ATRAP
Phys. Rev. Lett. **93**, 073401 (2004).

How To Measure Antihydrogen Velocity

Variation on ATRAP’s field ionization method

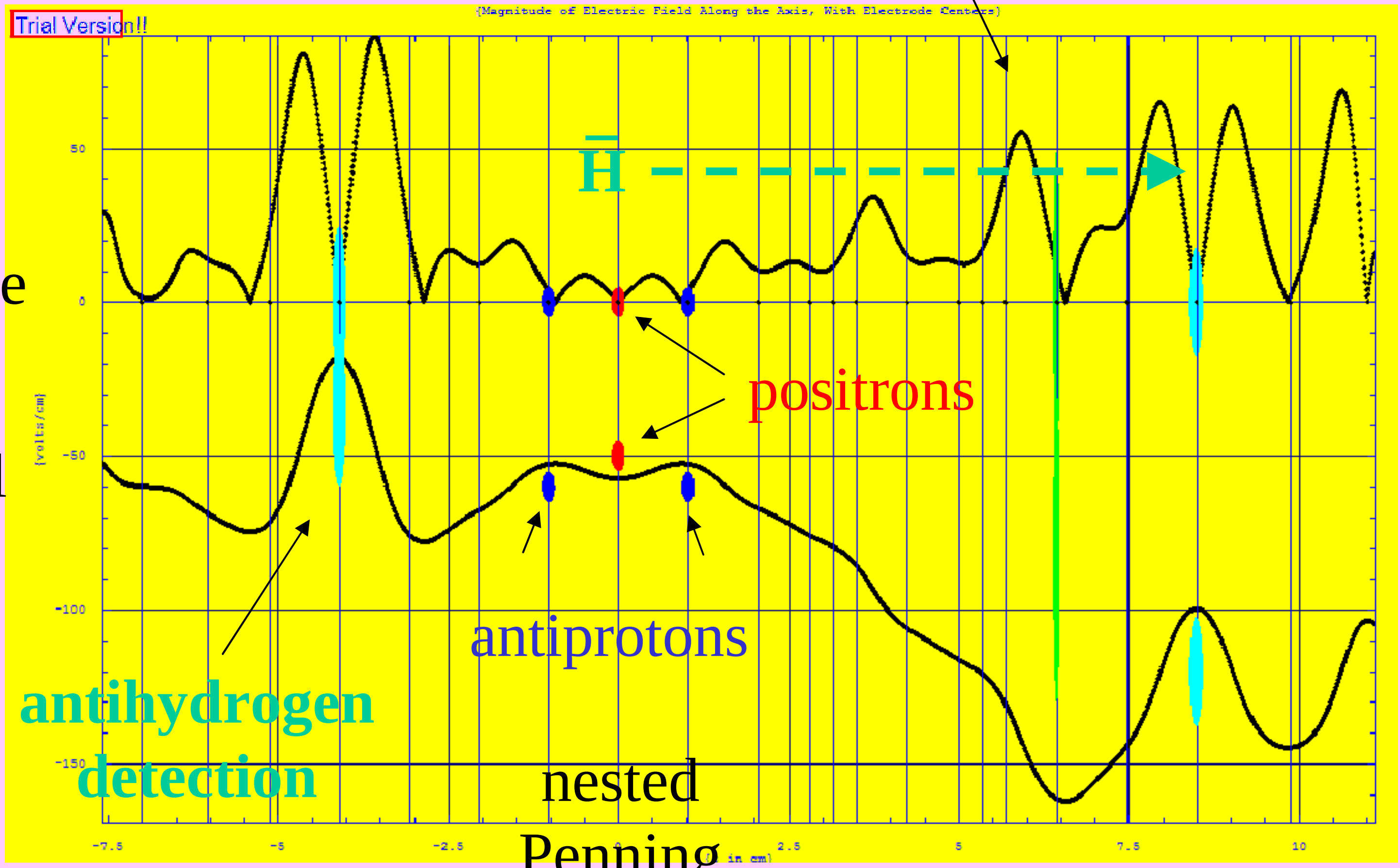


~ Cos(ωt)

- Fast atoms get through when the electric field is low
- Slow atoms always get ionized

First Measurement of an Antihydrogen Velocity

→ oscillate the prestripping field



electric field magnitude

potential

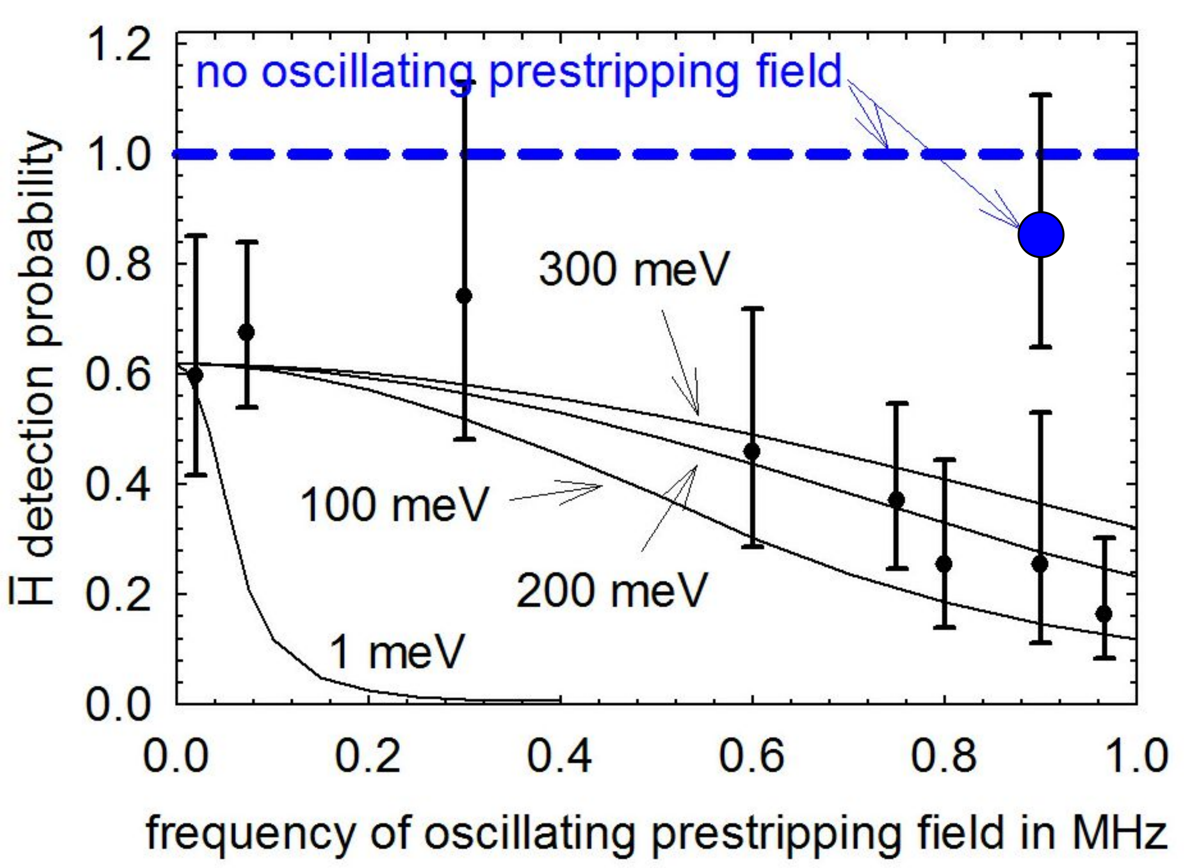
positrons

antiprotons

antihydrogen detection

nested Penning trap

First Measurement of an Antihydrogen Velocity



$$\frac{v}{v_{thermal}} \approx 20$$

200 meV

- This is for the most weakly bound antihydrogen states
- More deeply bound states may be going more slowly

Other Implications

Three-formation of high speed antihydrogen
is a likely alternative interpretation of the ATHENA
dependence of antihydrogen production upon temperature.

Any spectroscopy of high speed antihydrogen will have a broad spectral linewidth

First Laser-Controlled Antihydrogen Production

Very Different Method II to Produce Slow Antihydrogen

Use positronium – Deutch, …
Use Rydberg positronium – Charlton, …
Use charge exchange to produce the positronium – Hessels, …

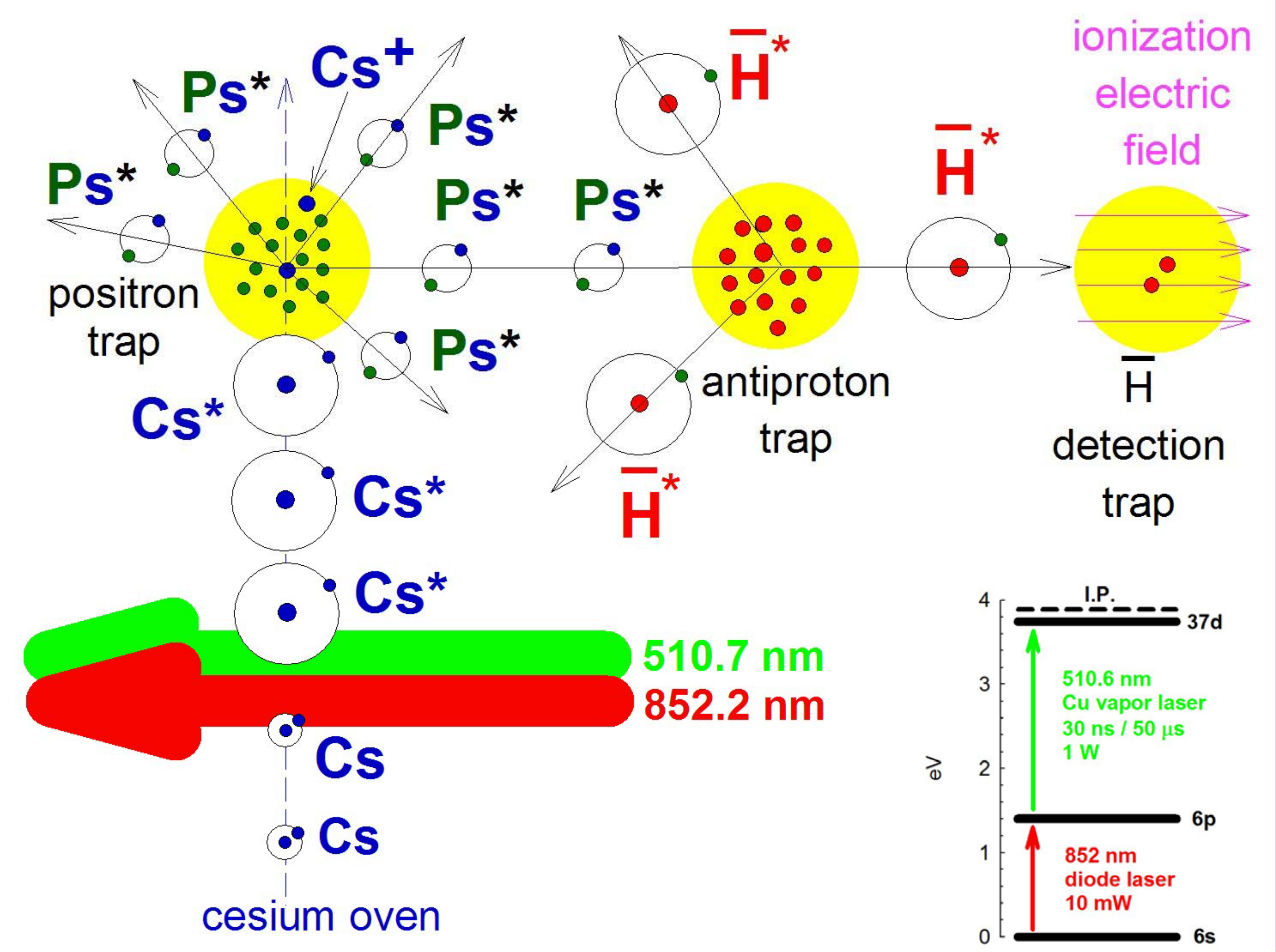
Calculation (no B field): E.A. Hessels, D.M. Homan, M.J. Cavagnero, Phys. Rev. A **57**, 1668 (1998).

Observe Rydberg Cs and Rydberg Positronium (at Harvard)

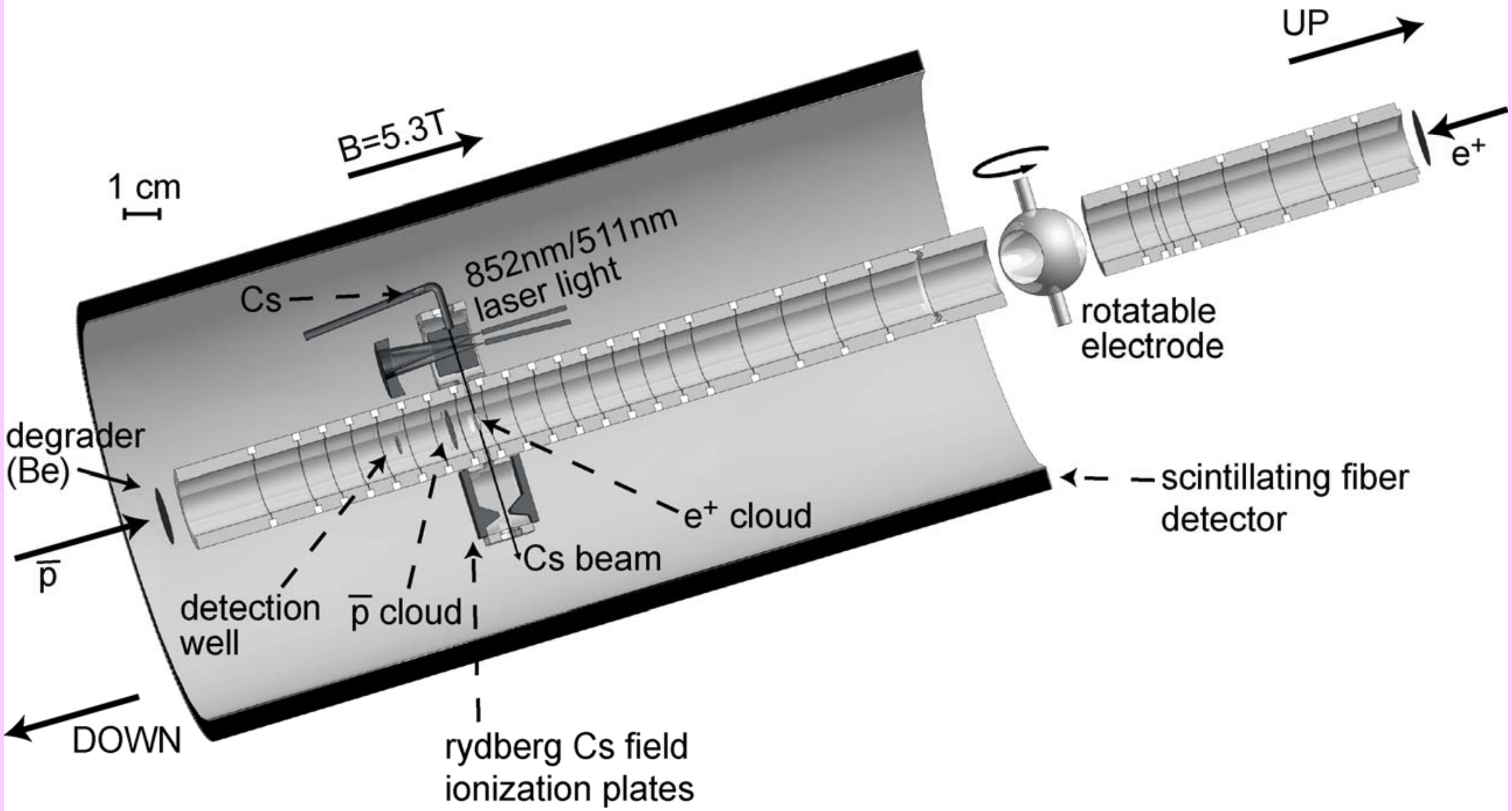
Observe Antihydrogen n~37 this year (at CERN)

→ State-selected antihydrogen, should be very cold
→ hope to de-excite with a laser (not easy)

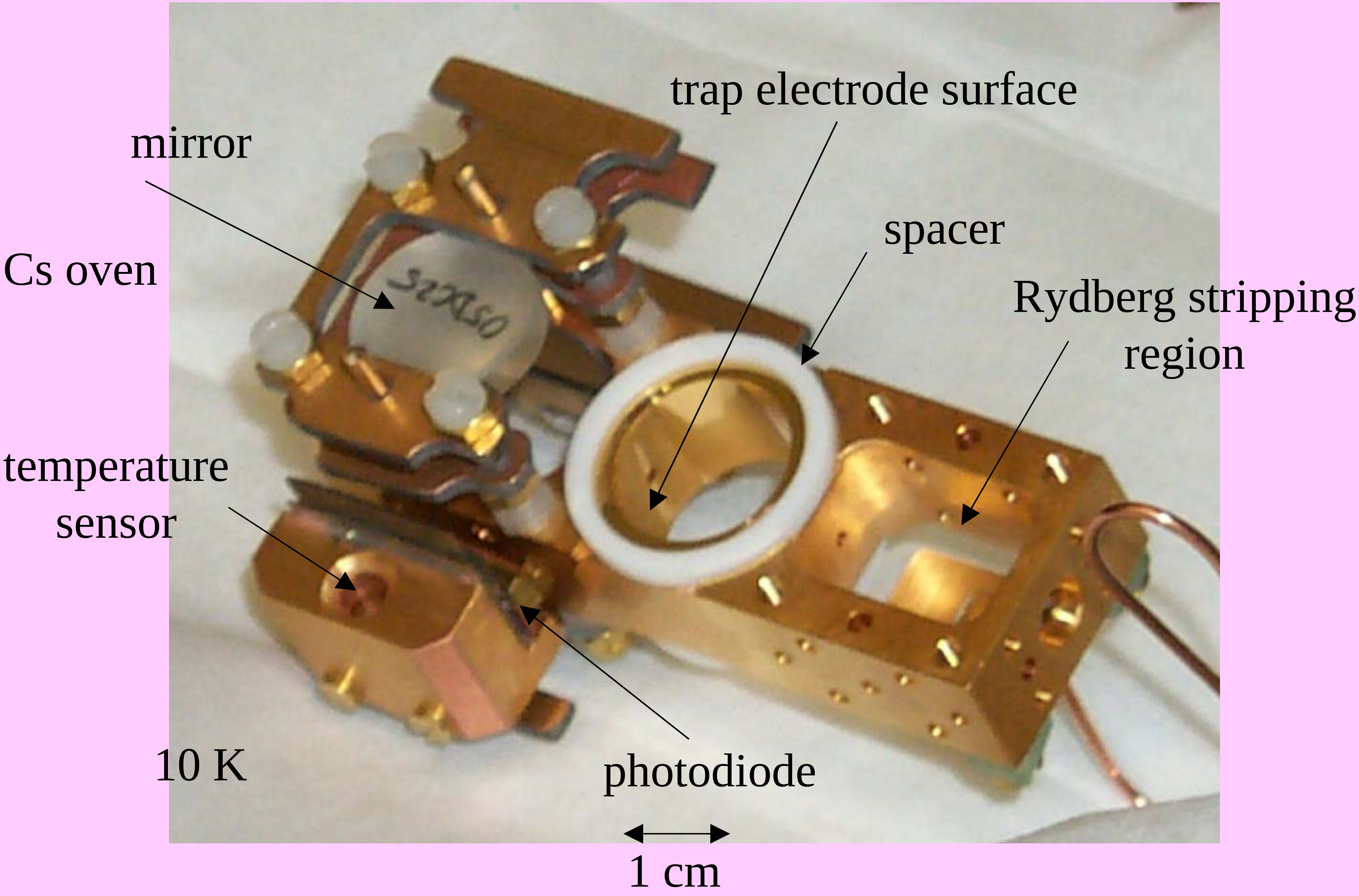
Antihydrogen Via Laser-Controlled Resonant Charge Exchange



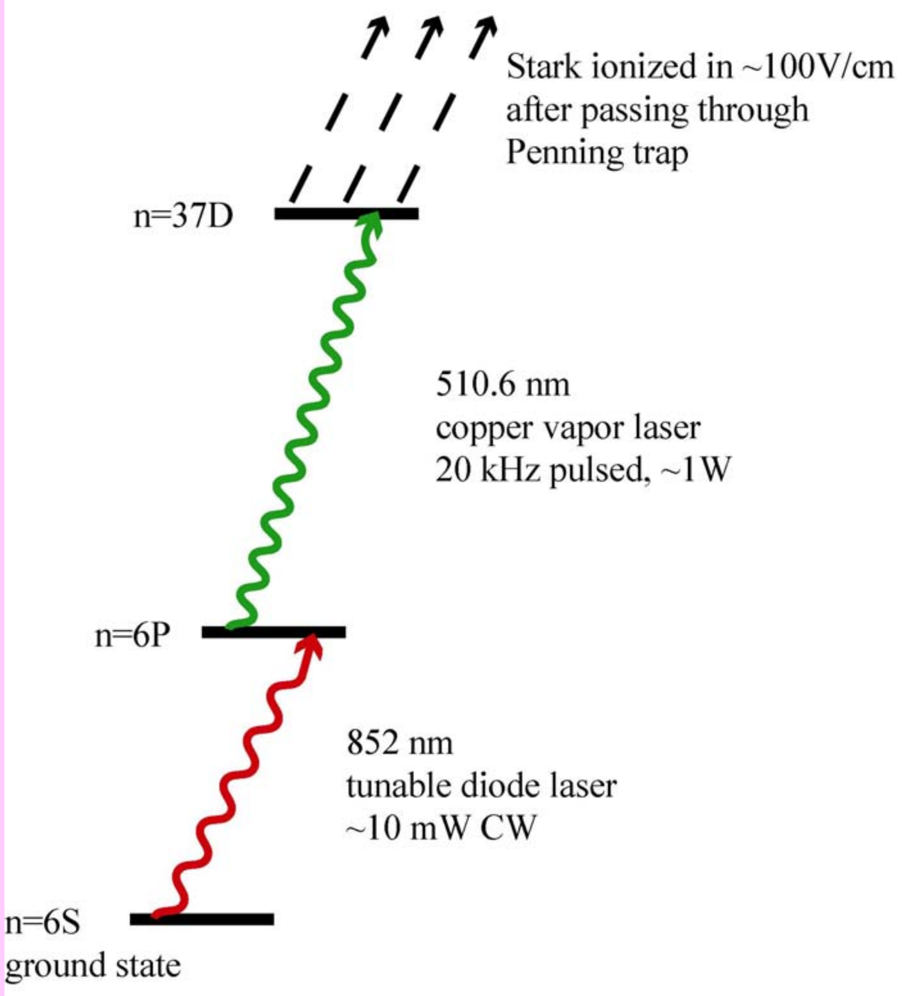
Trap

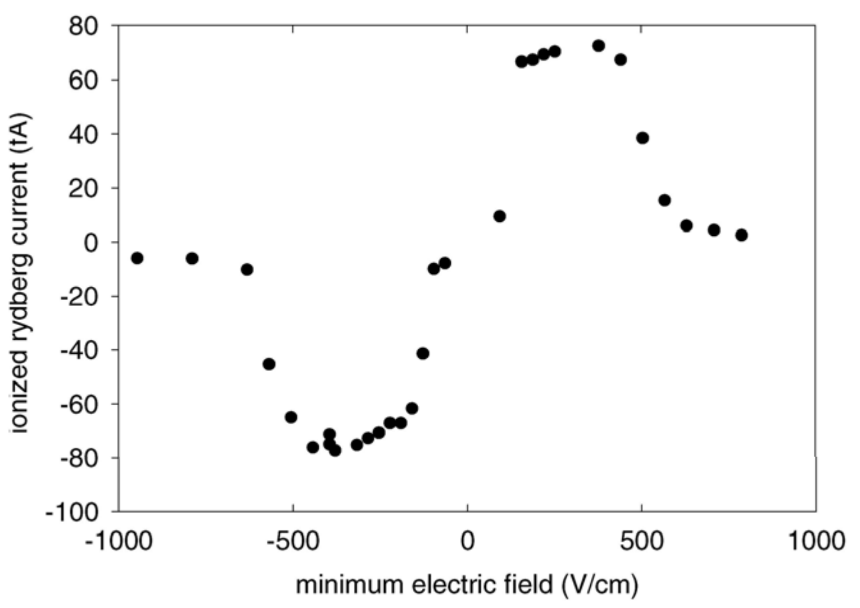

UP
B=5.3T
1 cm
852nm/511nm
laser light
Cs
e^+
rotatable
electrode
degrader
(Be)
scintillating fiber
detector
e^+ cloud
Cs beam
$\overline{p}$
detection
well
$\overline{p}$ cloud
DOWN
rydberg Cs field
ionization plates

One Trap Electrode

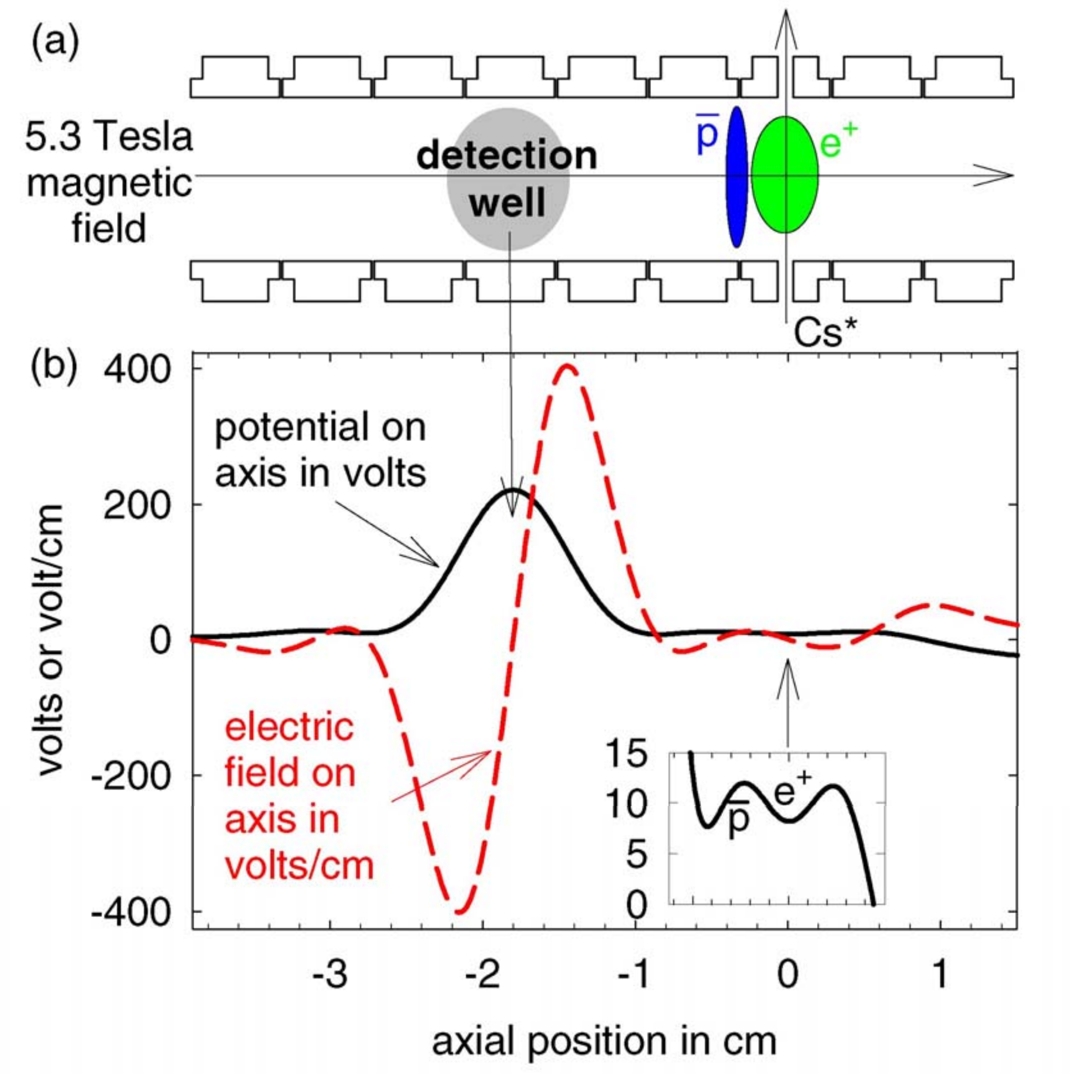


Excite Rydberg Cesium States (n = 37)

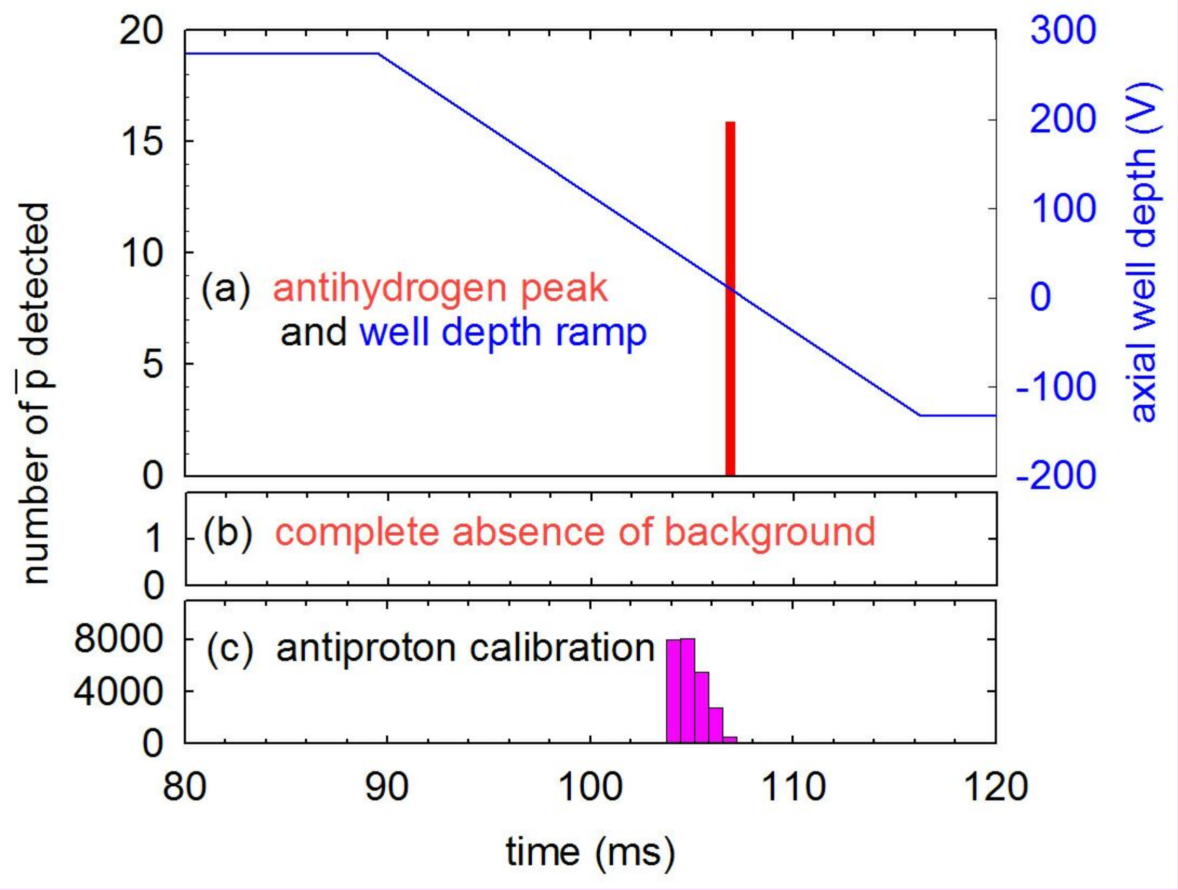




Trap And Potentials



Method II: Antihydrogen Via Laser-Controlled, Resonant Charge Exchange



Second method to make slow antihydrogen → should be as cold as the antiprotons

Is There a Better Method III ?

Field assisted antihydrogen formation – we could not make work.

Using a CO2 laser to stimulate n = 10

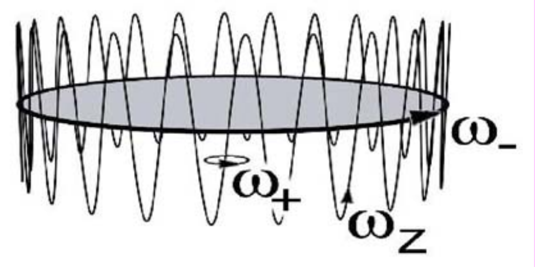
G. Gabrielse, S. L. Rolston, L. Haarsma and W. Kells,
"Antihydrogren production using trapped plasmas",
Phys. Lett. A **129**, 38 (1988).

A. Wolf,
"Laser-Stimulated Formation and Stabilization of Antihydrogen Atoms"
Hyper. Interact. 76, 189 (1993).

Can Antihydrogen and Its Ingredients be Trapped?

e.g. Penning – Ioffe – Pritchard Trap

Can We Trap Antihydrogen and Its Ingredients?



Penning trap

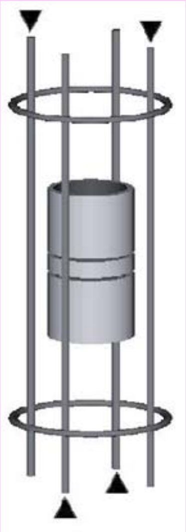
-- axial symmetry

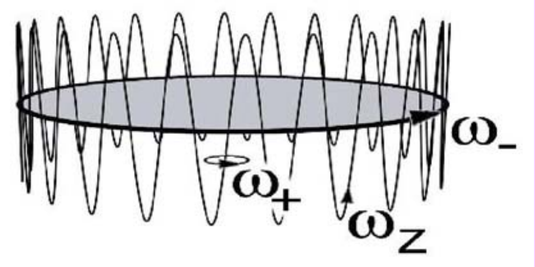
-- confinement theorem (O'Neil)

T. Squires, P. Yesley, G. Gabrielse,
"Stability of a Charged Particle in a Combined Penning-Ioffe Trap"
Phys. Rev. Lett. **86**, 5266 (2001)

(supported by ONR, NSF and AFOSR)

Can We Trap Antihydrogen and Its Ingredients?





Penning trap

-- axial symmetry

-- confinement theorem (O'Neil)

Add radial Ioffe field

-- destroy axial symmetry

-- no confinement theorem

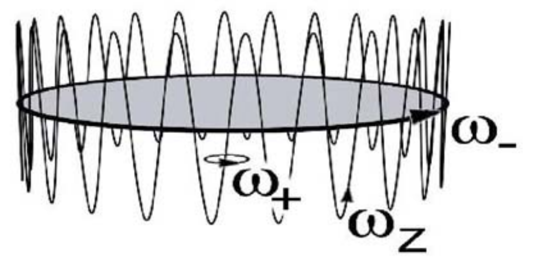
Are there stable orbits?

Can We Trap Antihydrogen and Its Ingredients?

Penning trap

-- axial symmetry

-- confinement theorem (O'Neil)



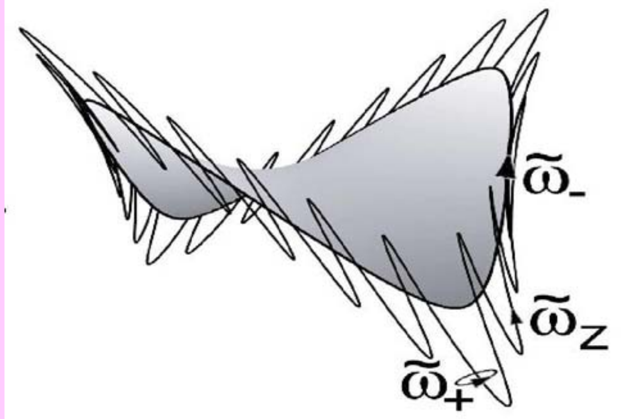
Add radial Ioffe field

-- destroy axial symmetry

-- no confinement theorem

Are there stable orbits?

Yes →



T. Squires, P. Yesley, G. Gabrielse,
"Stability of a Charged Particle in a Combined Penning-Ioffe Trap"
Phys. Rev. Lett. **86**, 5266 (2001)

(supported by ONR, NSF and AFOSR)

Our Conclusion

Charged particles should remain trapped when a radial Ioffe field is added at least for low enough particle densities

How low?

T. Squires, P. Yesley, G. Gabrielse,
"Stability of a Charged Particle in a Combined Penning-Ioffe Trap"
Phys. Rev. Lett. **86**, 5266 (2001)

Contrary Point of View

Charged particles will not remain trapped long enough to make antihydrogen under ATRAP conditions

E. P. Gilson and J. Fajans
"Quadrupole-Induced Resonant-Particle Transport in a Pure Electron Plasma"
Phys. Rev. Lett. 80, 015001 (2003).

Big Extrapolations are Involved

ATRAP Conditions

- Penning trap
- $n\lambda_D^3 = 0.25$
- Temperature: 4.2 K
- High magnetic field

Berkeley Conditions

- Malmberg trap
- $n\lambda_D^3 = 46000$
- Temperature: 12000 K
- Low magnetic field

These seems like very different conditions to me

ATRAP Added Radial Ioffe Fields Using Permanent Magnets

(Radial Ioffe field apparatus built at Juelich Laboratory)

Trapped electrons are very stable ~ hours at 3 Tesla. We have more parameter space to investigate.

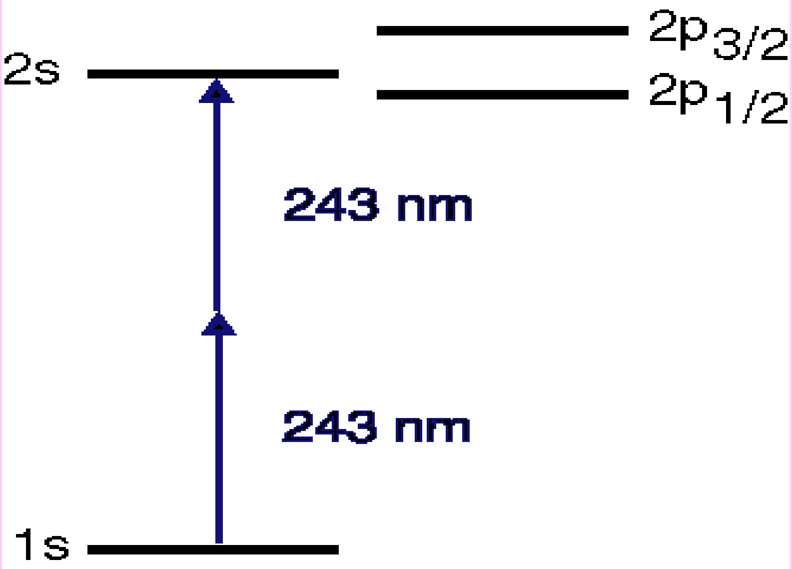
Summary:

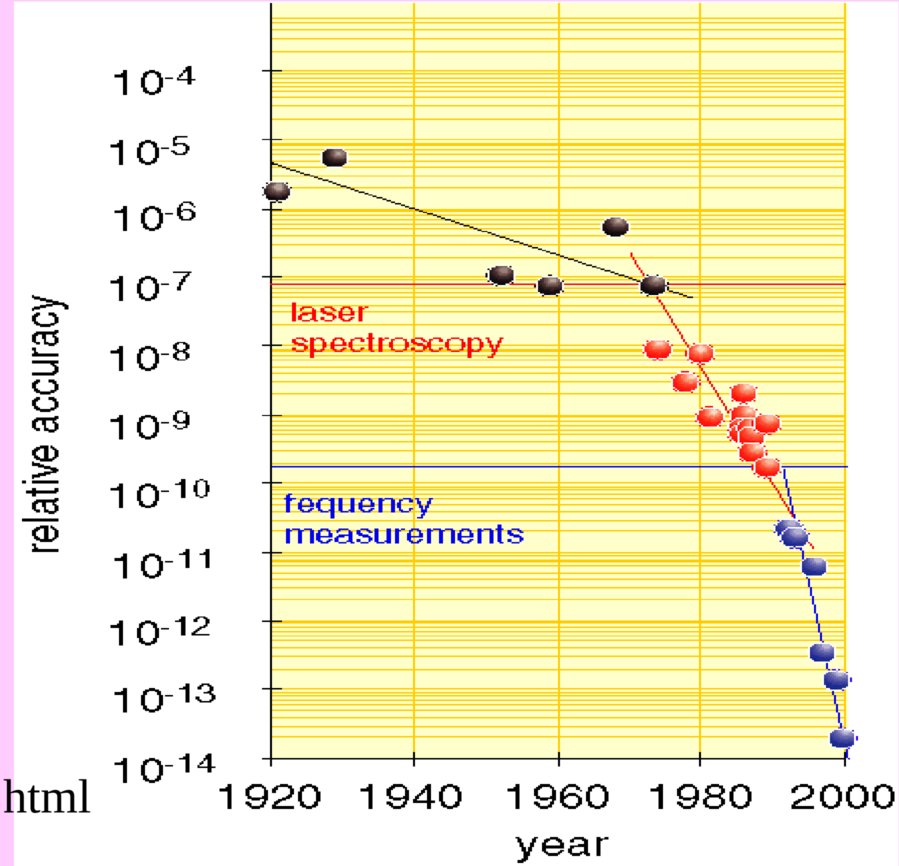
- There are still many open questions here
- Fortunately they can (and will) be answered with electrons and protons

Spectroscopy and Cooling Preparations with Hydrogen

- Hydrogen spectroscopy has been going on for many years
- Trapped hydrogen spectroscopy has been demonstrated
- First continuous, tunable,coherent source
  of Lyman-alpha radiation (in the UV, at 121.5 nm)
- Spectroscopy demonstration: hydrogen 1s – 2p

Hydrogen 1s – 2s Spectroscopy

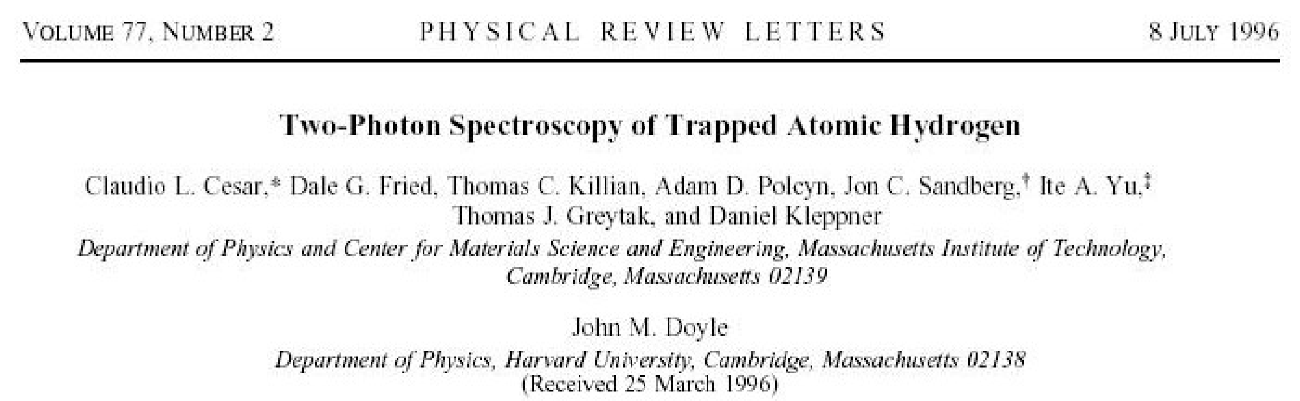




(Haensch, et al., Max Planck Soc., Garching)
http://www.mpq.mpg.de/~haensch/hydrogen/h.html

Many fewer antihydrogen atoms will likely be available

Hydrogen Spectroscopy in a Trap



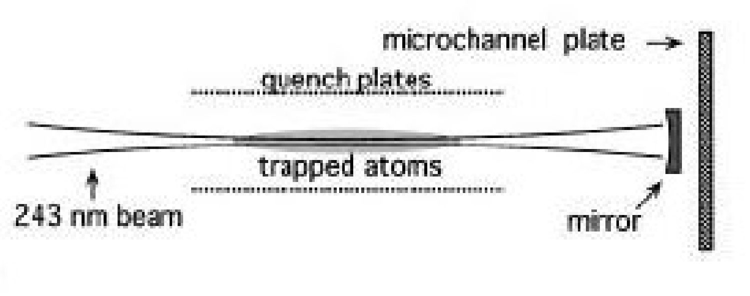
VOLUME 77, NUMBER 2 PHYSICAL REVIEW LETTERS 8 JULY 1996

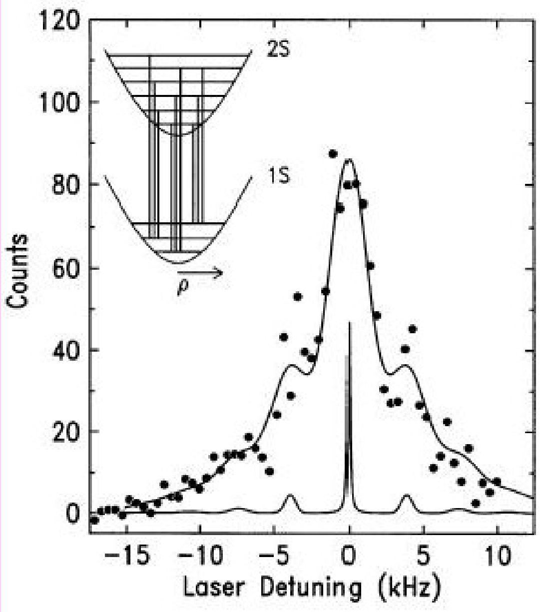
Two-Photon Spectroscopy of Trapped Atomic Hydrogen

Claudio L. Cesar,* Dale G. Fried, Thomas C. Killian, Adam D. Polcyn, Jon C. Sandberg,† Ite A. Yu,‡
Thomas J. Greytak, and Daniel Kleppner
Department of Physics and Center for Materials Science and Engineering, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

John M. Doyle
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

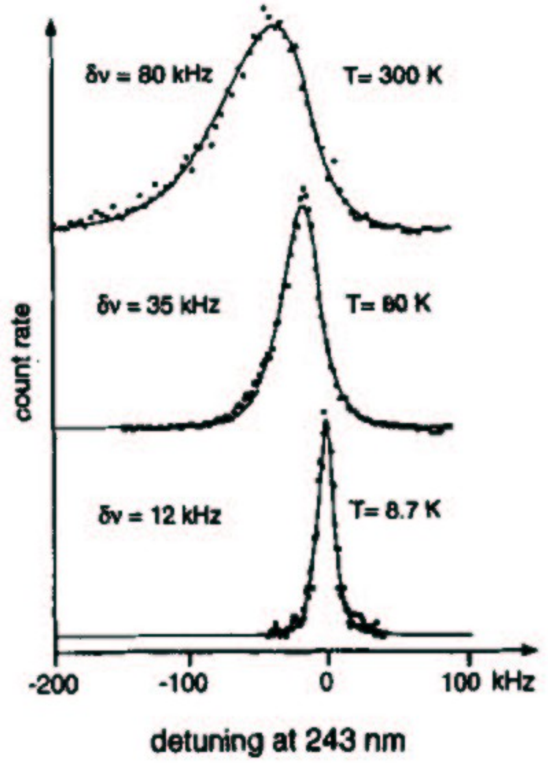
(Received 25 March 1996)





Still uses a lot more hydrogen atoms
than we expect to have antihydrogen atoms

Clear for Some Time that Low Temperatures are Essential

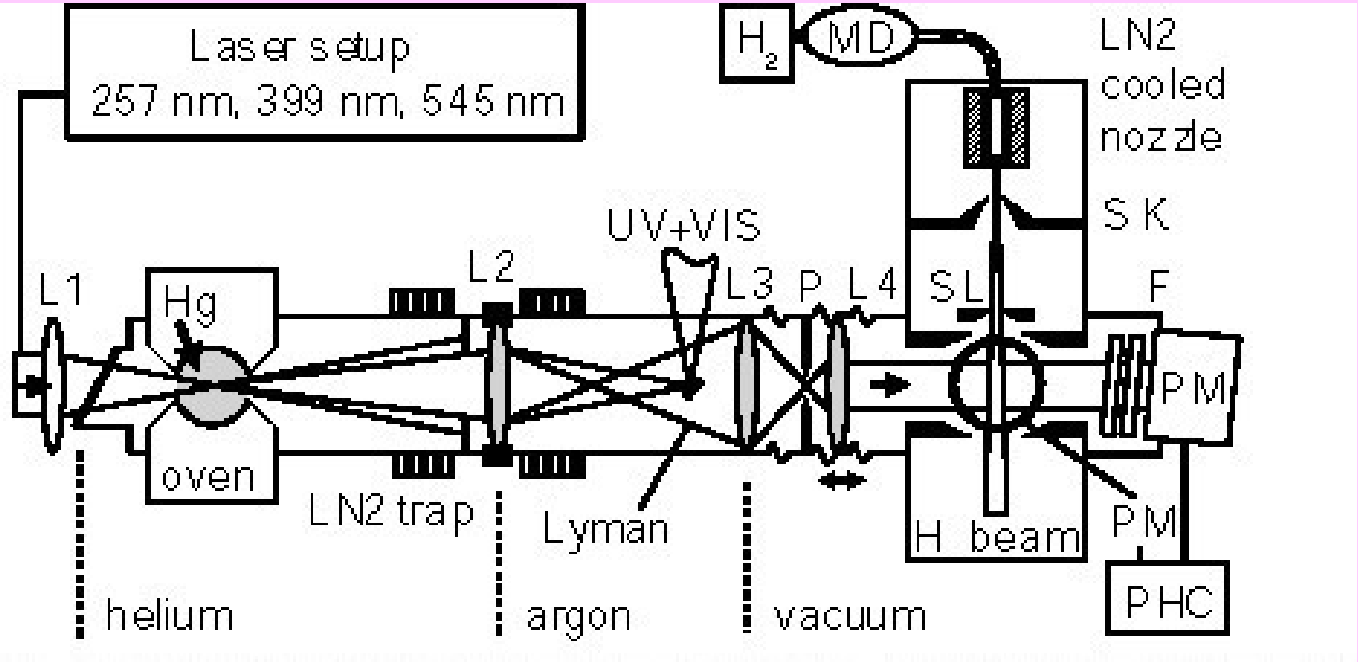


T. Haensch and C. Zimmerman,
Laser Spectroscopy of Hydrogen and Antihydrogen,
Hyper. Int. 76, 47 (1993).

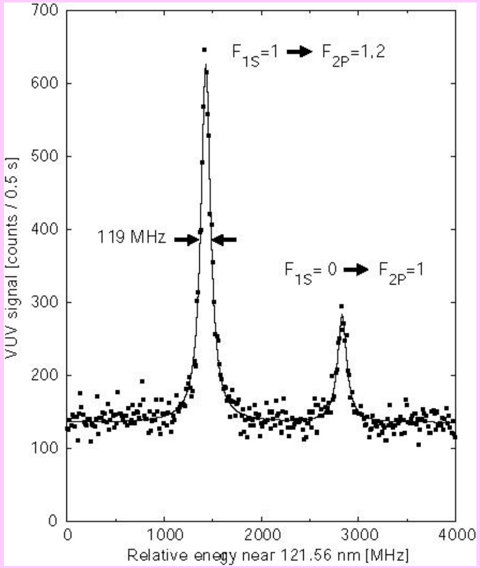
Big Challenge

Many fewer antihydrogen atoms will be available
than have been used for accurate hydrogen spectroscopy.

Spectroscopy and Cooling Preparations with Hydrogen



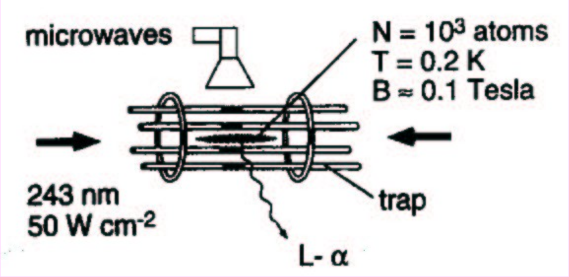
20 nW, enough
for cooling
and spectroscopy

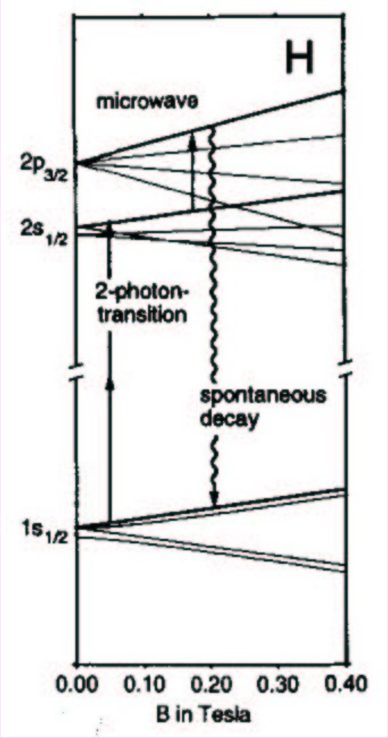


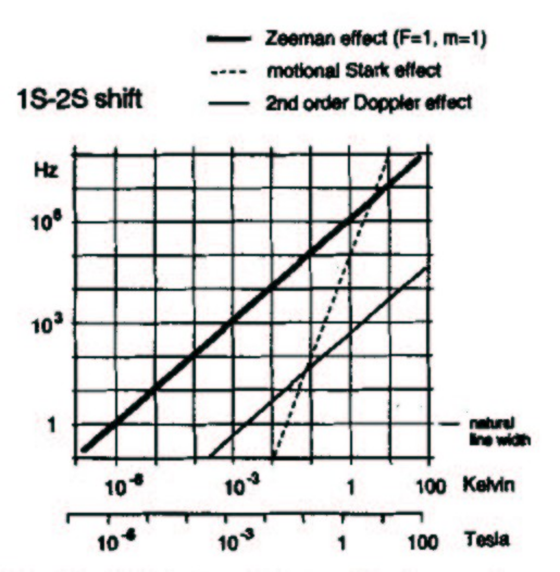
K. S. E. Eikema and J. Walz and T. W. Haensch,
“Continuous Wave Coherent Lyman-alpha Radiation”,
Phys. Rev. Lett. 83, 3828 (1999).

K. S. E. Eikema and J. Walz and T. W. Haensch,
“Continuous Coherent Lyman-alpha Excitation of Atomic Hydrogen,
Phys. Rev. Lett. 86, 5679 (2001).

Spectroscopy on 1000 or Fewer Atoms Seems Possible → 1 part in 10^{12} estimated







T. Haensch and C. Zimmerman,
Laser Spectroscopy of Hydrogen and Antihydrogen,
Hyper. Int. 76, 47 (1993).

Conclusions

Crucial Experimental Milestones Have Been Reached

* **Need Antiprotons and Positrons**

AD, Antiproton Accumulation, Positron Accumulation

* **Need to produce antihydrogen production:** **Method I** *

Method II *

Other Methods?

Need useful antihydrogen ← cold, ground state

- * **Devising a method to measure the antihydrogen velocity**
- * **Devising a method to measure the antihydrogen state**
- **Ground state antihydrogen**
- **Antihydrogen cold enough to trap**

Need to trap antihydrogen

- * **Stability test for trapped particles in Ioffe field**

Need antihydrogen spectroscopy

- * **First continuous Lyman-alpha source**

I Hope That I Have Persuaded You That …

1. Cold antihydrogen studies provide a unique opportunity for studies of high scientific importance – studies that are only possible at CERN.

2. These studies are proving to be just as challenging as was anticipated when the long-term AD program was established, given the need to develop and demonstrated many new techniques.

3. Important recent milestones signal great progress
   → Slow antihydrogen atoms can now be produced using two entirely different methods.
   → A method has been devised to measure the speed of antihydrogen atoms
   → A method has been devised to measure the antihydrogen excitation state
   I hope the SPSC is encouraged by the rapid progress and commends it.

4. For highly accurate spectroscopy experiments, ground state atoms that can be trapped are needed. The atoms whose internal states have been probed are still highly excited, and the atoms whose velocity has been measured are moving to rapidly to trap. I hope that the SPSC strongly encourages a proper current emphasis upon
   - → speed of antihydrogen atoms (measuring and slowing)
   - → state of antihydrogen atoms (measuring and deexciting)

I Hope That I Have Persuaded You That …

5. As long as steady progress is reported, I hope that the SPSC will strongly support the ongoing antihydrogen research program.

6. I hope that the committee will note with great interest the studies suggesting that the number of antiprotons that could be made available for antihydrogen experiments (and other users) could be dramatically increased by approximately a factor of 100 if a small decelerator ring could be added at the AD facility.

A New Direction – With Negligible Antiproton Use

Next you will hear of another exciting possibility – to measure the antiproton magnetic moment. The proof of principle can first be demonstrated with protons. The antiproton measurement could be carried out parasitically, with negligible use of antiproton

Thanks for the Opportunity to Make the Case

* **Need Antiprotons and Positrons**

AD, Antiproton Accumulation, Positron Accumulation

* **Need to produce antihydrogen production:** **Method I** *

Method II *

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- * **Stability test for trapped particles in Ioffe field**

Need antihydrogen spectroscopy

- * **First continuous Lyman-alpha source**

End

First Fully Quantum Measurement of the Electron Magnetic Moment

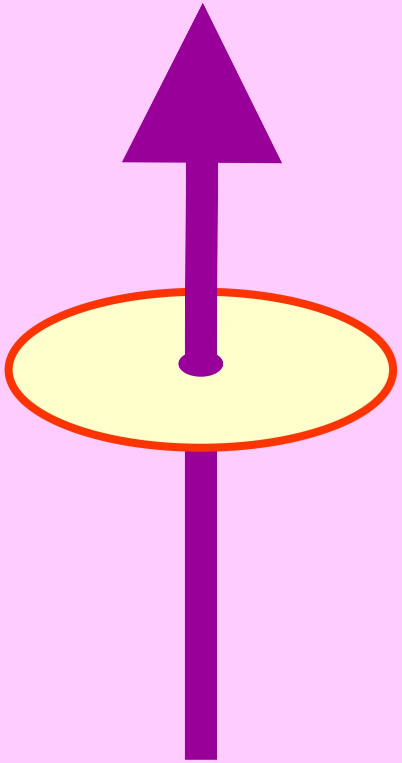
Brian Odom, David Hanneke, Gerald Gabrielse
Harvard University

Goals: 15-fold improved electron magnetic moment measurement
Improvement in fine structure constant by this factor
Similar improvement in positron mag. moment → CPT
Improved proton to electron mass ratio

N$F

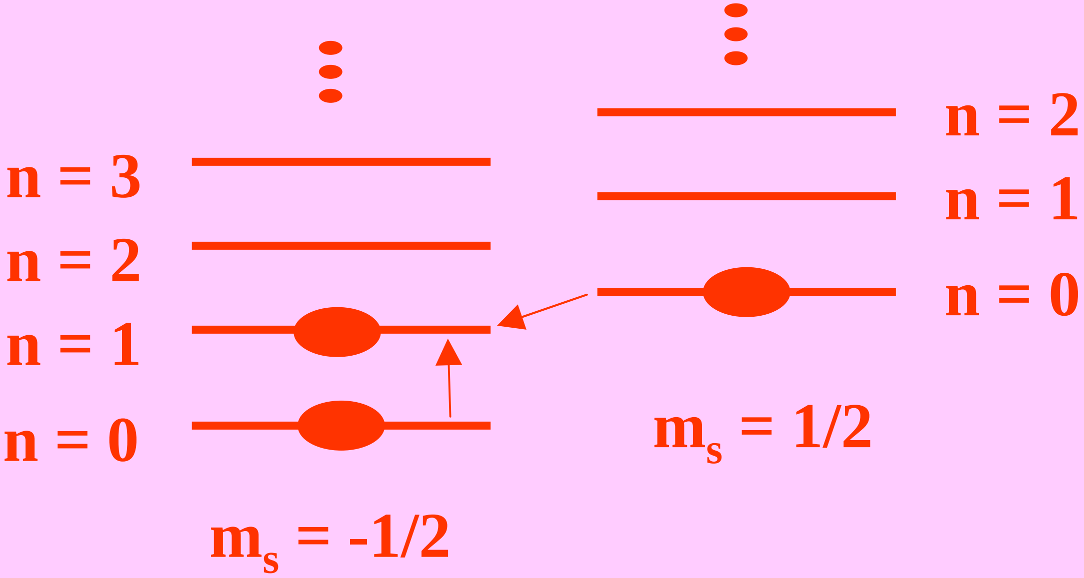
Fully Quantum Measurement of the Electron Magnetic Moment

$$\mu = g \frac{e\hbar}{2m} \frac{S}{\hbar}$$



B ≈ 6 Tesla

υ_c ≈ 150 GHz



n = 3

n = 2

n = 1

n = 0

m_s = -1/2

n = 2

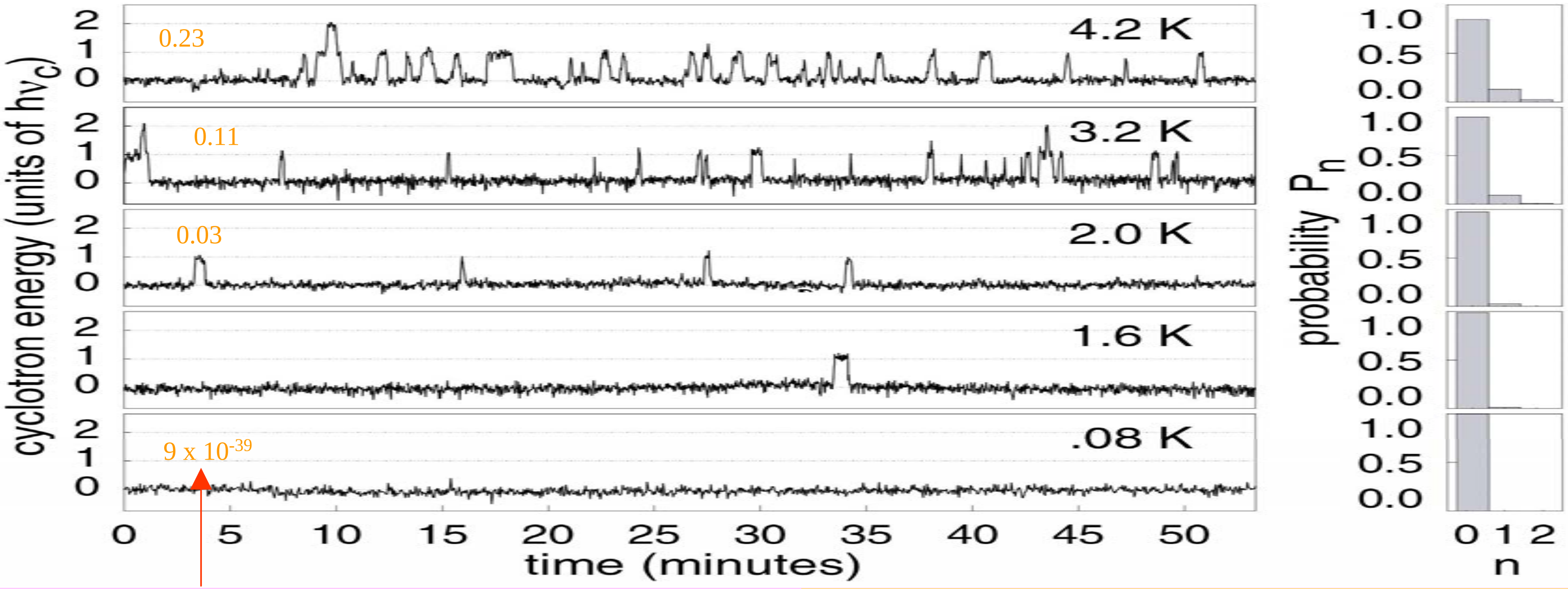
n = 1

n = 0

m_s = 1/2

Quantum Jumps as a Function of Temperature

- one electron
- Fock states of a cyclotron oscillators
- due to blackbody photons



average number of blackbody photons in the cavity

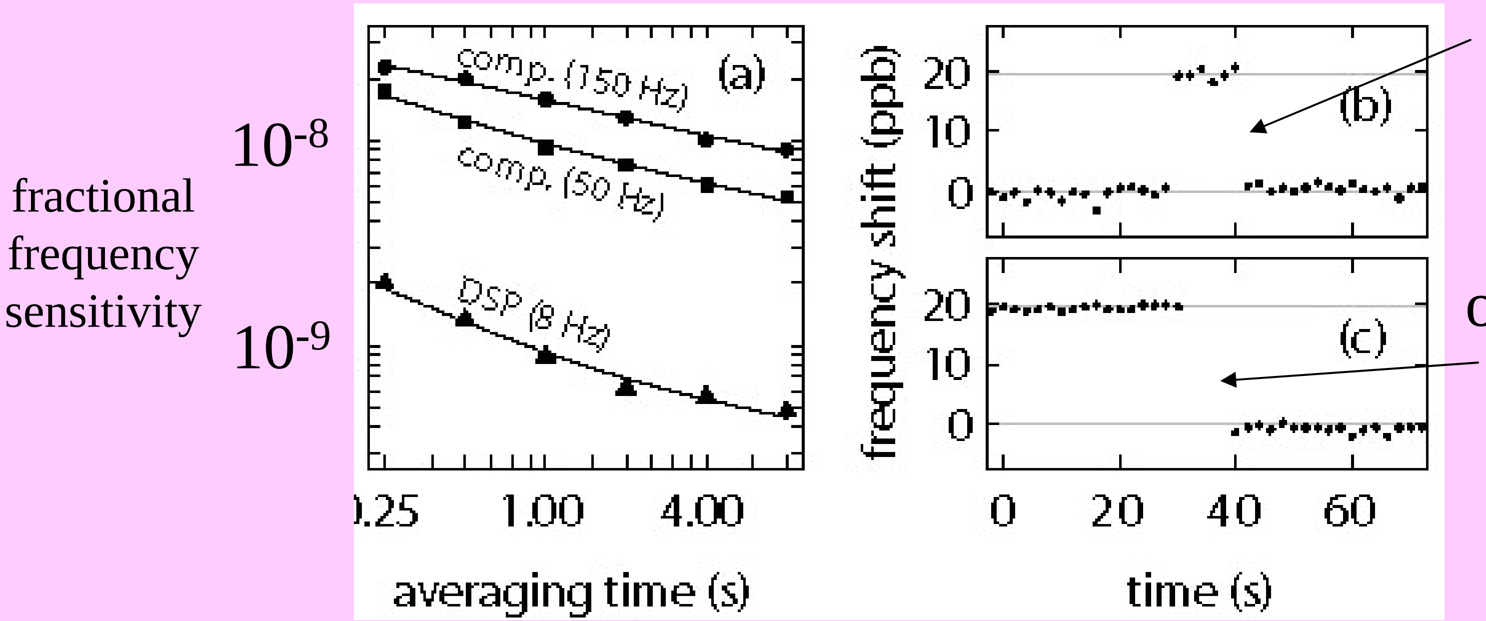
On a short time scale

→ in one Fock state or another

Averaged over hours

→ in a thermal state

One-Particle Self-Excited Oscillator



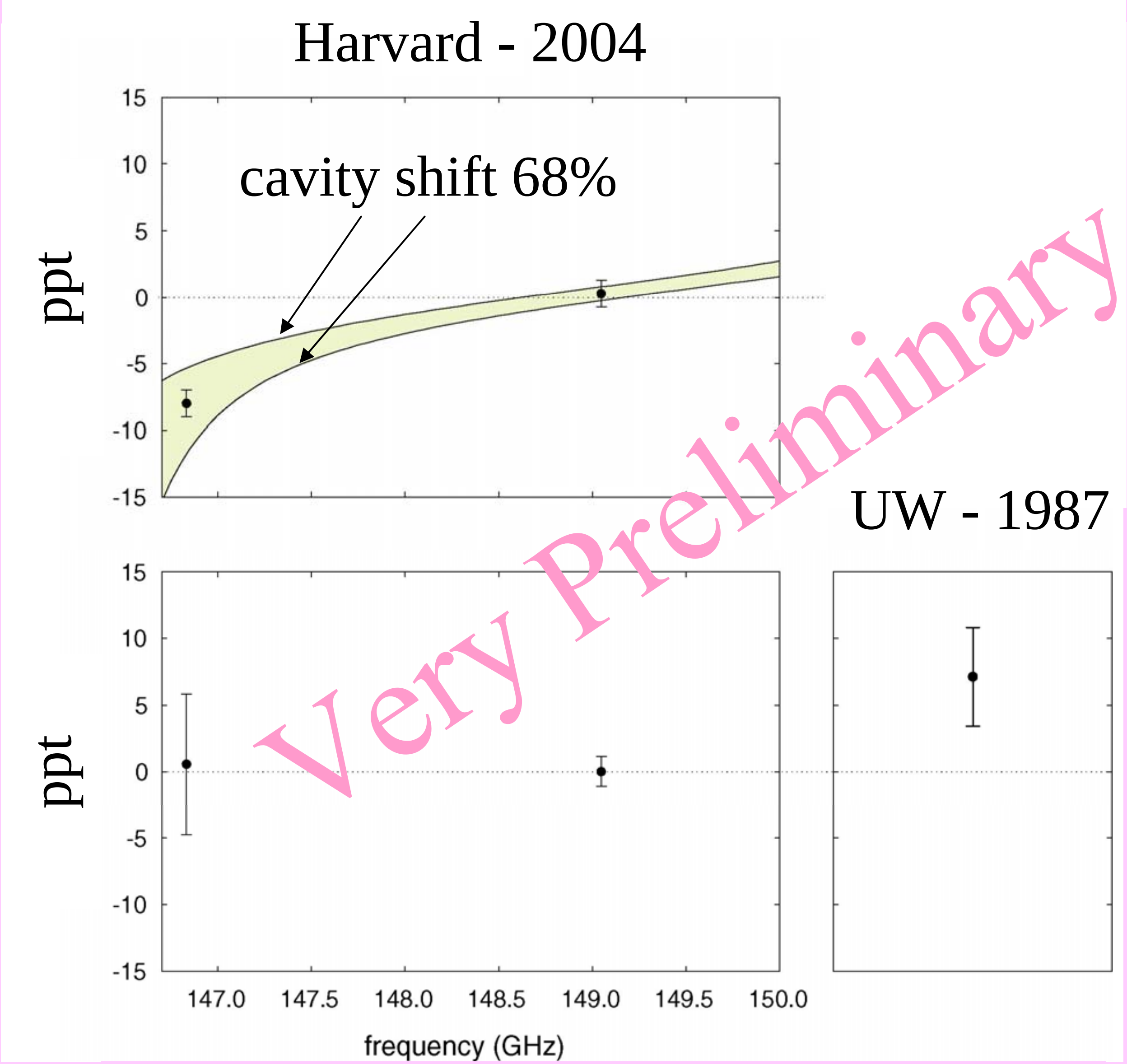
one-electron
one-quantum
cyclotron
excitation

one-electron
spin flip

Gives great sensitivity to small frequency shifts, such as those that would reveal an antiproton spin flip.

B. D'Urso, R. Van Handel, B. Odom, D. Hanneke, G. Gabrielse,
“Single-Particle Self-Excited Oscillator” (submitted for publication).

Fully Quantum Measurement of the Electron Magnetic Moment



electron magnetic
moment
(as shifted by cavity)

electron magnetic
moment
(corrected)

Future: It Now Seems Feasible to Attempt to Measure the Antiproton Magnetic Moment

Goal: Improve accuracy by a factor of a million or more

Challenge: Nondestructive detection of a proton/antiproton spin flip