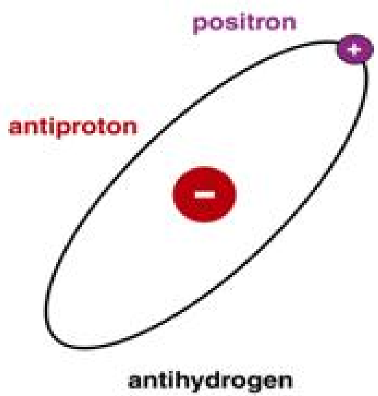
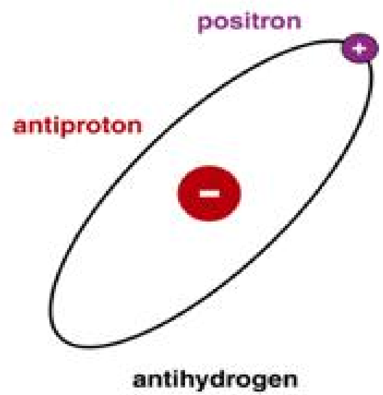
Cold Matter and Antimatter:
How Similar Are They?

Gerald Gabrielse

Leverett Professor of Physics, Harvard University
Spokesperson for CERN ATRAP Collaboration





Uppsala Popular Science Lecture

About Me

Professor at Harvard University since 1987
- research group of 10 to 12 PhD students
- 2 postdocs
- 6 undergraduates
- 1 visitor

Wife, 3 Children, 1 international daughter, 2 grandchildren

Like to ride my bicycle -- several years ago went 940 miles in 9 days

Like to backpack -- hoping to do 275 mile trip this summer

27 Year Antimatter Story

27 Years Ago - we trapped the first antiprotons

Now: CERN has an entire storage ring dedicated to trapping antiprotons → Antiproton Decelerator (AD)

5 large international collaborations of physicists are trapping antimatter using our methods

Antihydrogen atoms (atoms made entirely of antimatter) are now being routinely produced and confined

Soon: CERN's Antiproton Decelerator will be upgraded to make it possible to trap more antiprotons

My Research Group Specializes in Fundamental Particle Physics using Low-Energy Methods and High Precision

- Comparing q/m of the antiproton to 9 parts in 10^{11}
- Measuring the electron magnetic moment to 3 parts in 10^{13}
- Determining the fine structure constant to 4 parts in 10^{10}
- Measuring helium fine structure (100 Hz optical frequency meas.)
- Comparing the positron and electron magnetic moments
- Measuring the electron's electric dipole moment
- Comparing the antiproton and proton magnetic moments
- Making antihydrogen to compare hydrogen and antihydrogen

Supported by NSF and AFOSR

"High precision" rather than CERN's normal "high energy"

Scientists Invent Things

We do not worry much about applications (fundamental science)

Even then, scientists invent things

- atomic clocks → GPS
- nuclear magnetic resonance → MRI imaging
- transistor → computer, cell phone, …
- laser → CD players, communications, grocery store checkout, …
- internet
- self-shielding solenoid → better MRI imaging

Such Discoveries Allow Technological Development

Cold Matter and Antimatter: How Similar Are They?

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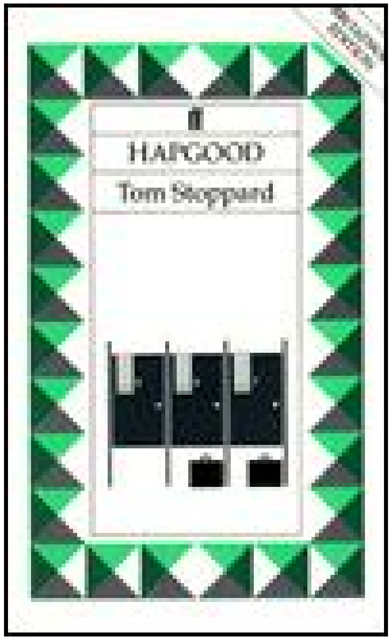
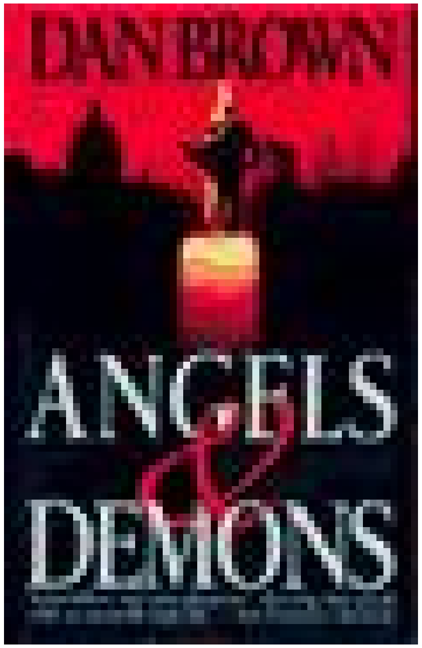
- Matter, Antimatter and Annihilation
- Great Unsolved Mystery
- Setting a Trap for Antimatter
- Capturing and Probing a Single Particle
- How Similar are Matter and Antimatter Particles?

Popular Culture "Explains" Some of Our Science



Serious Play: Hapgood
Author: Tom Stoppard



Fiction best seller,
recently a movie

Jim Carrey and Conan O'Brien Celebrate Our One-Electron Experiments

VOLUME 83, NUMBER 5 PHYSICAL REVIEW LETTERS 2 AUGUST 1999

Stochastic Phase Switching of a Parametrically Driven Electron in a Penning Trap

L. J. Lapidus, D. Enzer, and G. Gabrielse
Department of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 7 January 1999)

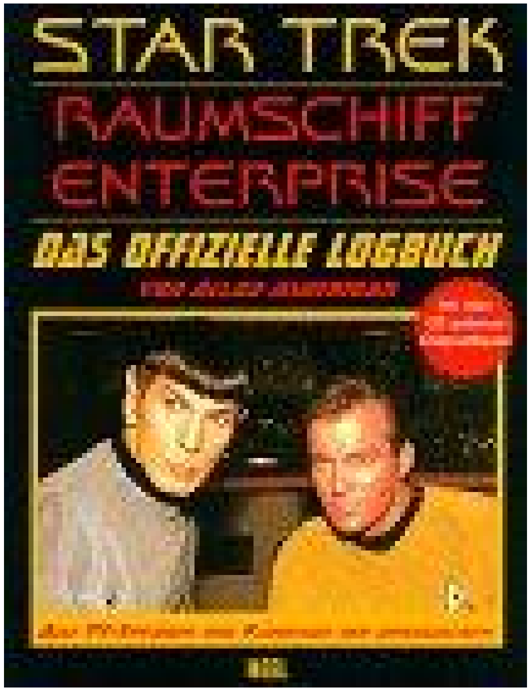
Fluctuation-induced switching of driven bistable systems, far from equilibrium, has been the focus of theoretical analysis and analog circuit computations. A parametrically driven electron in a Penning trap is shown to be a nearly ideal experimental realization. Noise applied to this dynamic double well system produces random switching between two steady-state oscillations which differ in the oscillation phase by 180°.

Jim Carrey

Conan O'Brien

What is Antimatter?

How Do You Know About Antimatter?



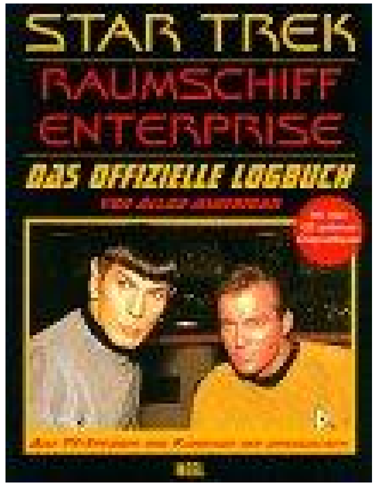
Dr. Spock "knew"

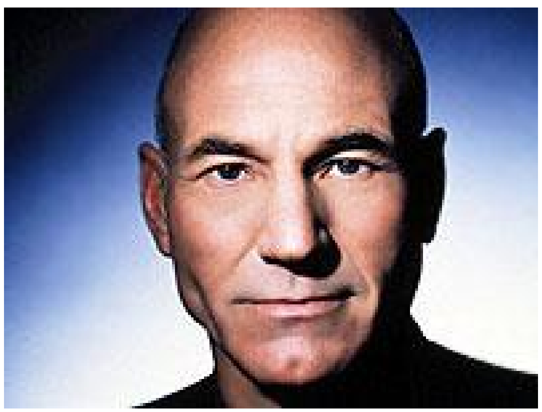
Antimatter annihilation → powered Star Trek space ship "Enterprise"

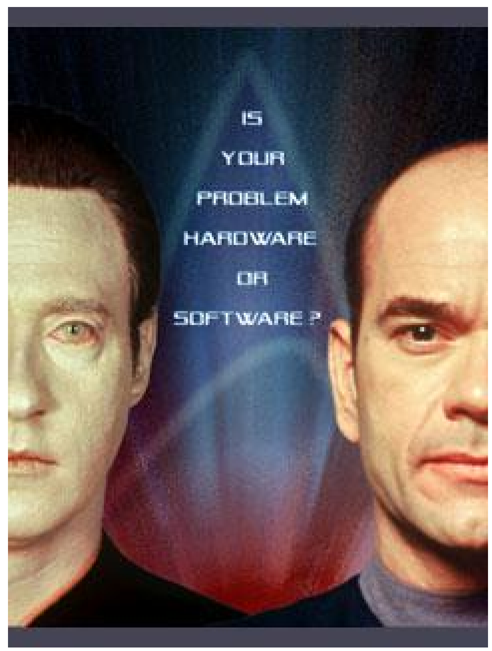
"going boldly where no one had gone before"

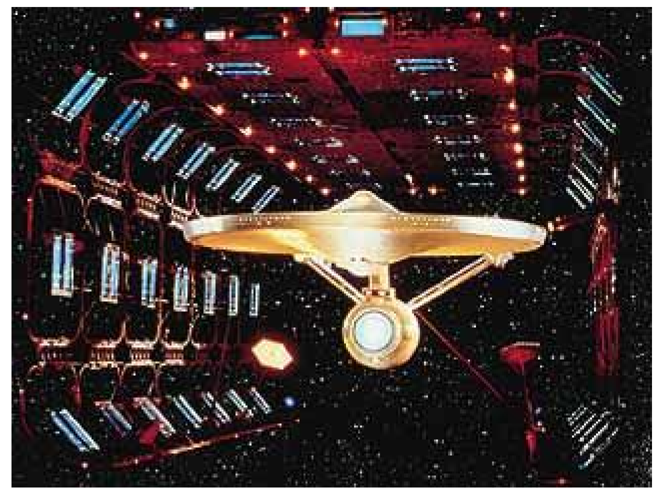
Gabrielse

Generations of Trekies









hardware: android

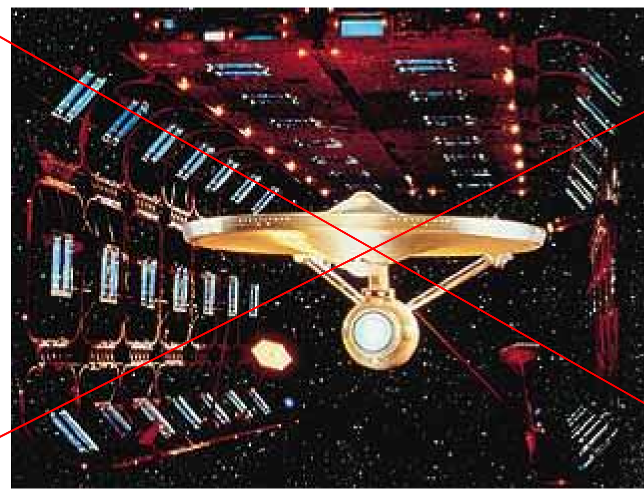
software: hologram

We study antimatter. How close are we to the Star Trek imagination?

What is Antimatter?

Gerald Gabrielse, ATRAP Spokesperson (CERN)

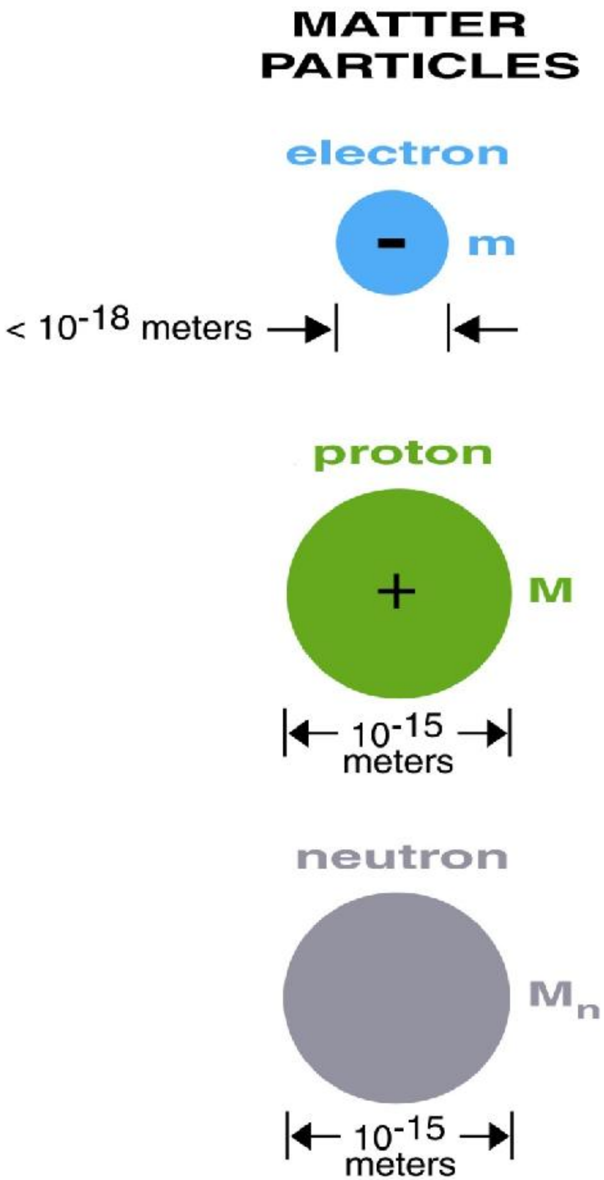
Leverett Professor of Physics, Harvard

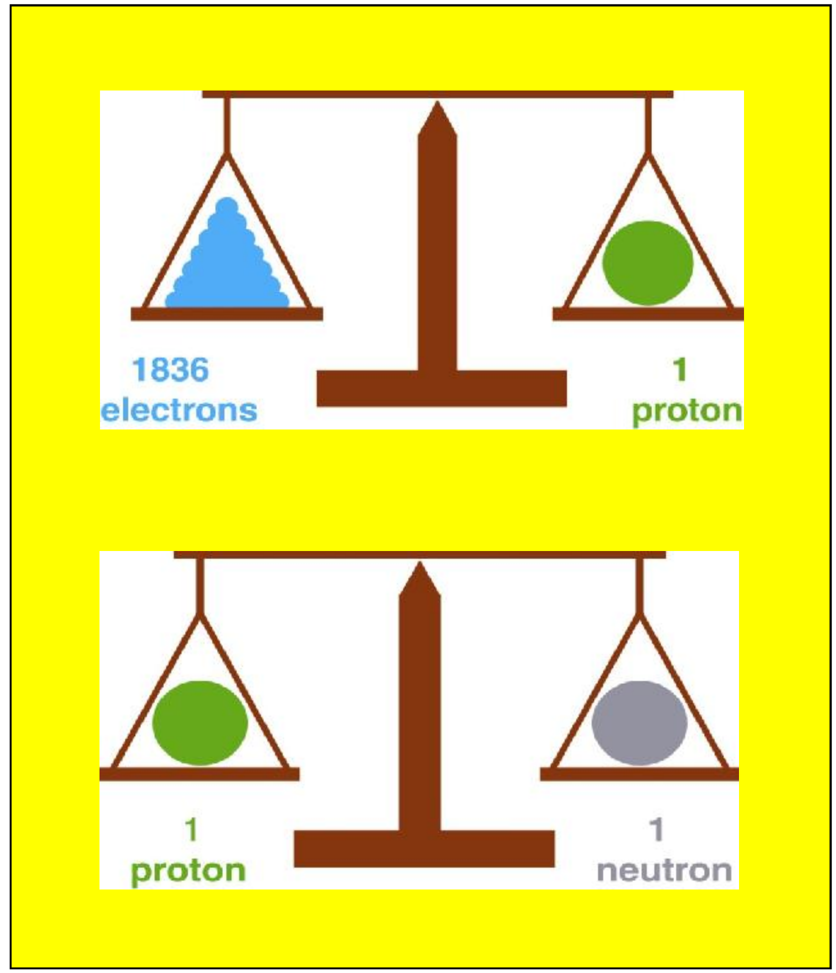


We actually do science, not science fiction

The Science Reality
Behind the Science Fiction Imagination

We Are Made of Matter

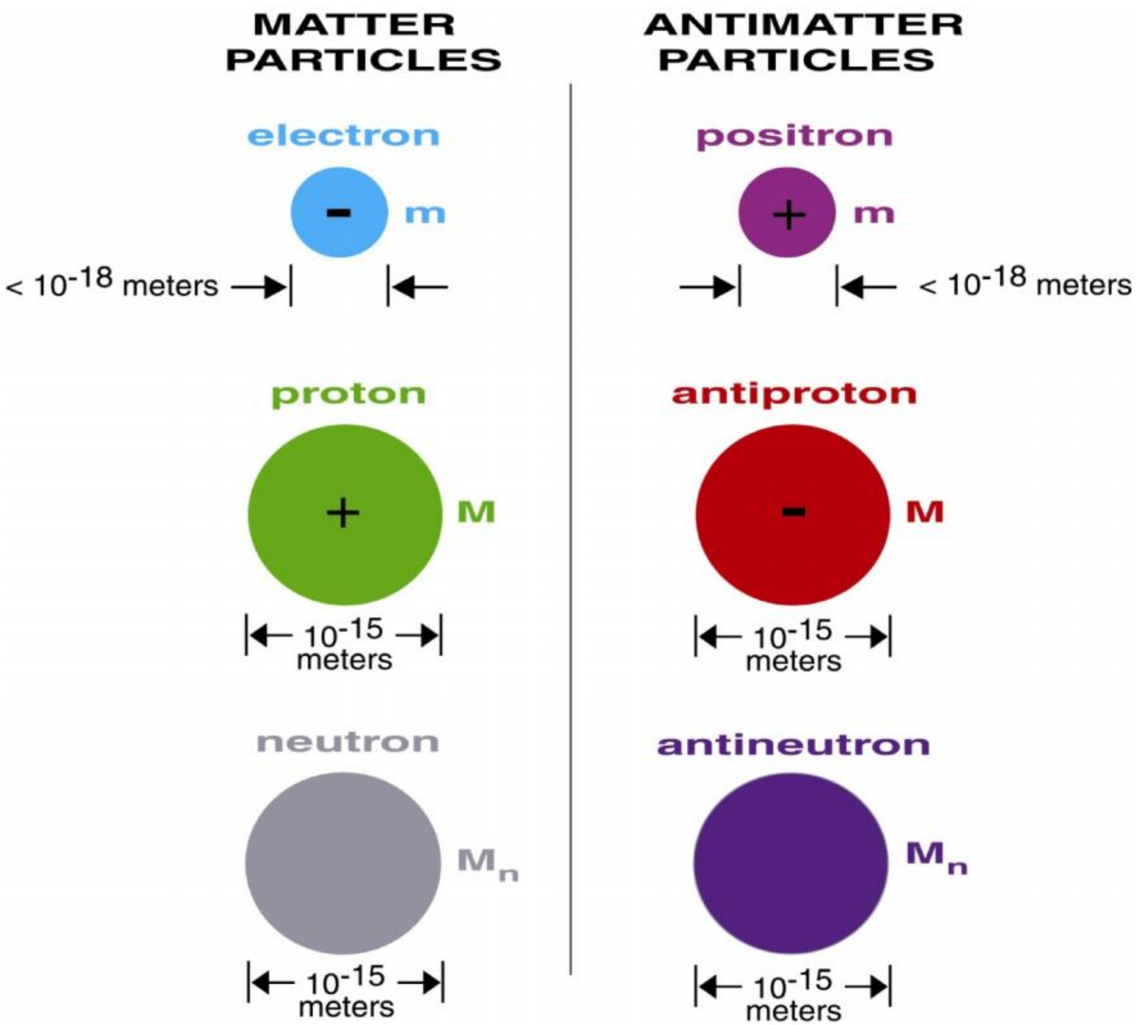




Particles of Matter and Antimatter: Opposite and Identical

charge

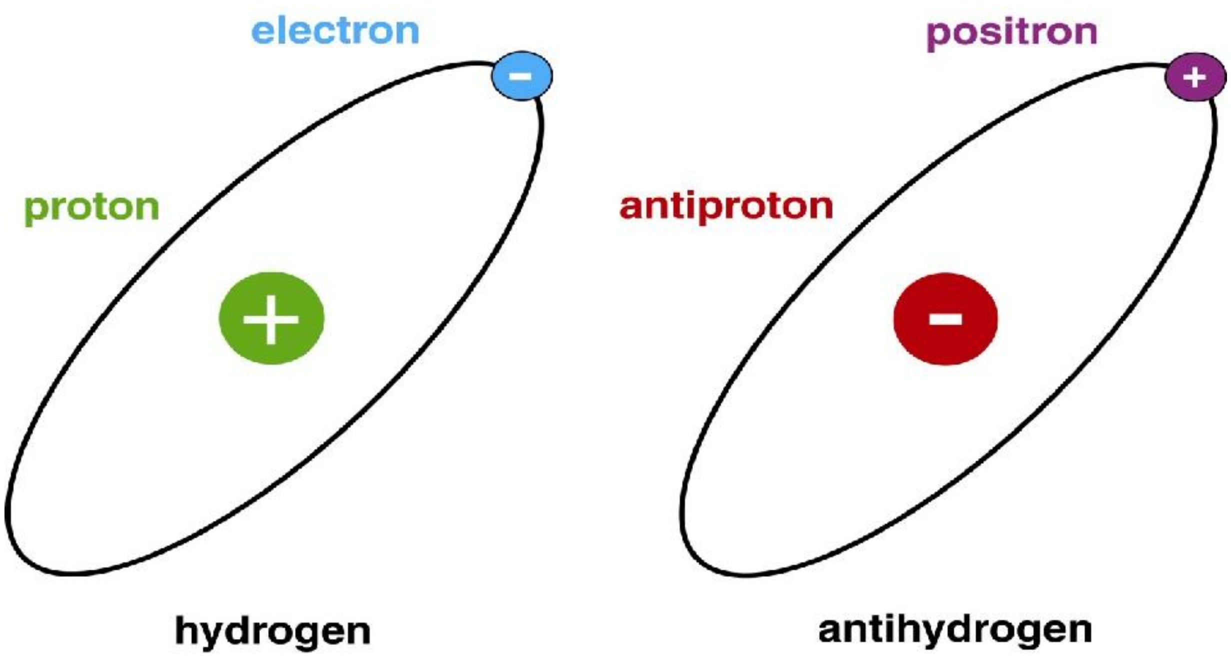
mass



ignore quarks

Only measurements tell how identical

Can Make Atoms Out of Matter and Antimatter



uncharged atom

uncharged anti-atom

My ATRAP team makes these atoms

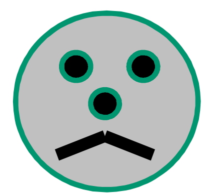
Would People Made Out of Antimatter Atoms Be Different Than People Made Out of Matter Atoms?

Gabrielse Made of Matter

Gabrielse Made of Antimatter

Would he be
- ~~smarter?~~
- ~~more handsome?~~
- ~~less massive?~~

Bad News: Modern physics predicts that Gabrielse and the Antimatter Gabrielse would be just the same



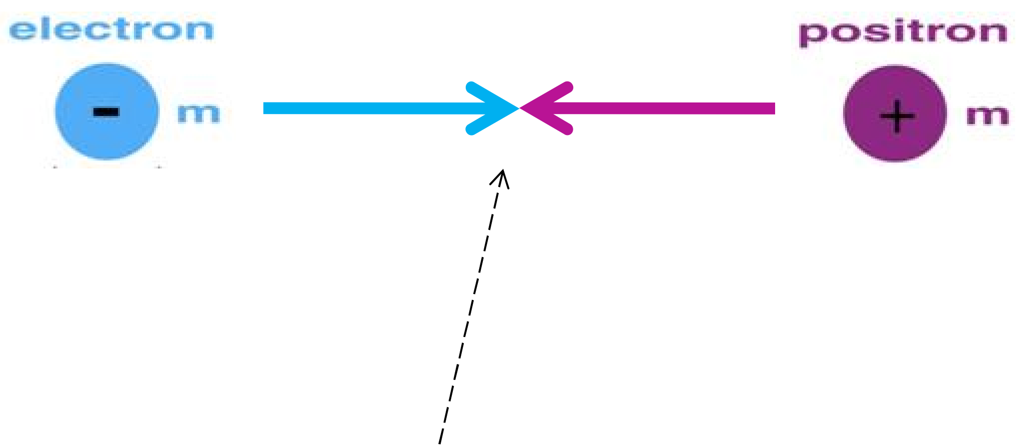
Could Make a Whole Universe Out of Antimatter

The properties would be the same – except for one tiny difference that would be very difficult to detect

Big mystery : **Why is the universe made out of matter rather than antimatter?**

We do not know the answer

Matter and Antimatter Annihilate Each Other

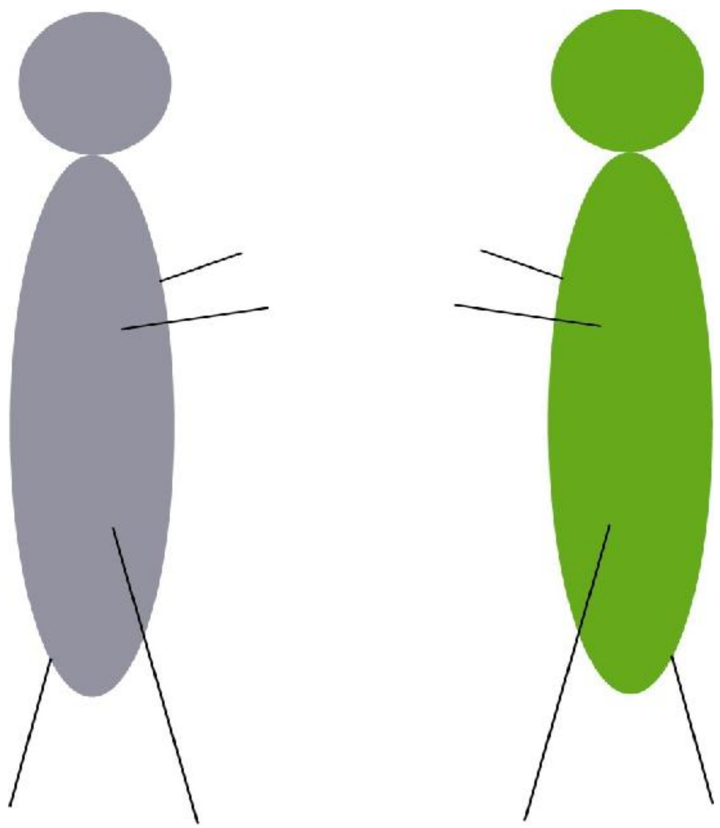


Both particles disappear (they "**annihilate**")

Energy is released $E = m\,c^2$
(as light in this example)

Einstein's famous formula

What Happens When Antimatter and Matter Gabrielse Meet?

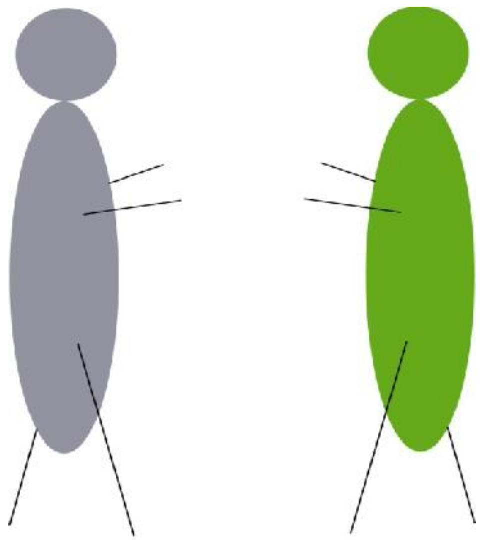


Anti-Gabrielse **Gabrielse**

About to shake hands

Huge Energy Release!

100 kg
Anti-Gabrielse



100 kg
Gabrielse

energy released

mass that disappears

200 kg

$$E = mc^2$$

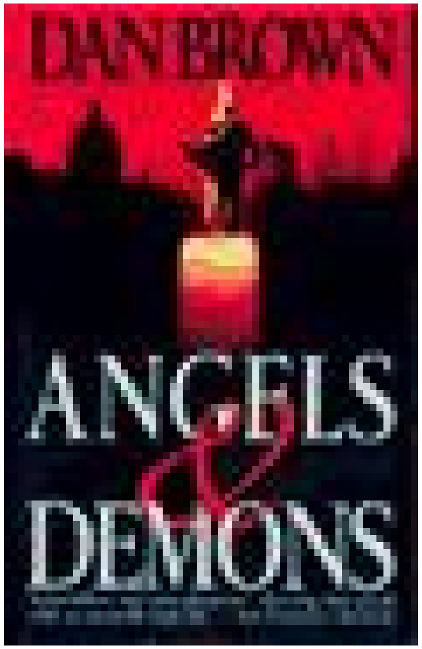
Einstein's famous formula

5,000,000,000,000 kilowatt-hours
Yearly output of 500 nuclear power plants
Energy from 4200 Megatons of TNT

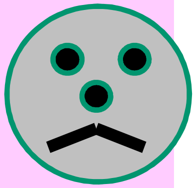
Fortunately It is NOT Possible to Make Very Much Antimatter

Cannot make enough to be dangerous

Cannot make enough to be useful



There is a book and movie that claim that much more antimatter can be made and stored



This is "based" upon my research work

What Dan Brown did for the Roman Catholic Church in the "Da Vinci Code" he did for my antimatter research in "Angels and Demons"

Why Study Antimatter

(i.e. Why Compare Matter and Antimatter?)

- Why is our universe made of matter and not of antimatter?
- Why does our universe exist at all?

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

CPT

→ Predicts that a particle and antiparticle have opposite charges and the same masses

Consequence of a Quantum Field Theory

Quantum field theories are very successful, but not universal (do not describe gravity)

How Is Antimatter Made?

Get Antiprotons at CERN

France

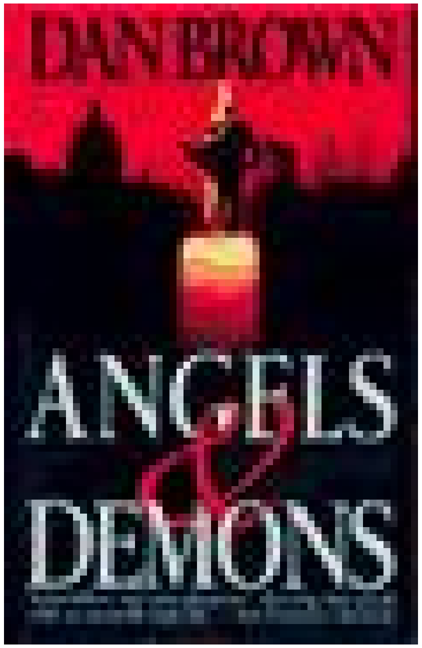
Switzerland
(Geneva)

Smash and Catch

Should the Cardinals Have Worried?

Missing detail: if all the antiprotons we have made
in the history of the world were annihilated
at the same time

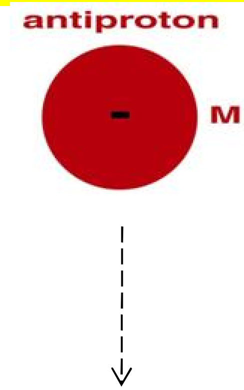
→ Not enough energy to boil a pot of tea



Clearly the cardinals should have studied more science

How is Antimatter Contained?

How Can We Store Antimatter?



Can we put it in a bottle?

No. Antiprotons will be annihilated when they hit protons in the bottle

Need a "bottle without walls"

particle trap

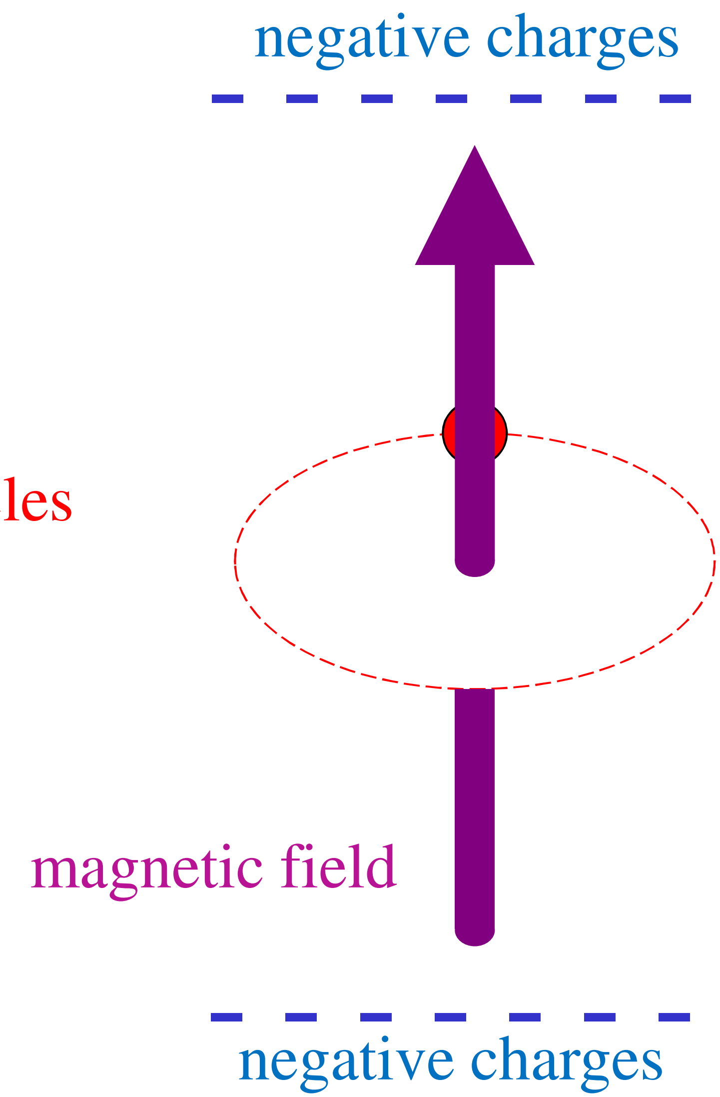
Particle Trap is a "Bottle Without Walls"

Use batteries and magnets

negative
charge

Physics you must know or learn

- charges near magnet go in circles
- opposite charges repel



Quiz question: which direction does
an antiproton orbit?

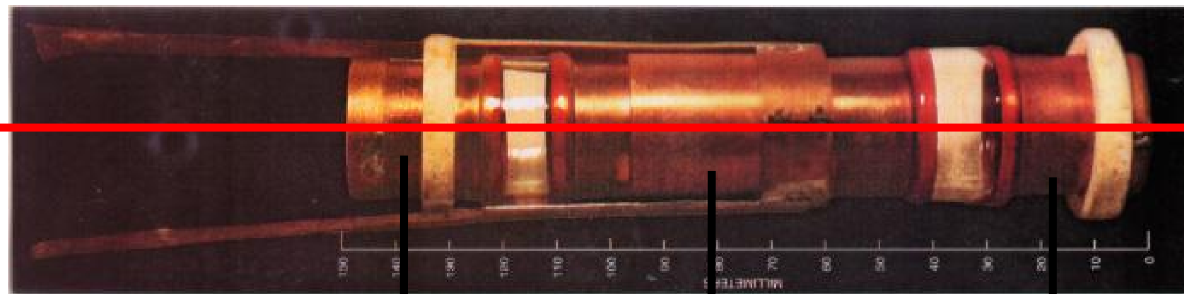
Accumulating Low Energy Antiprotons: Basic Ideas and Demonstrations (1986 – 2000)

TRAP Collaboration
at CERN's LEAR

1 cm

magnetic
field

21 MeV
antiprotons



–
+
–

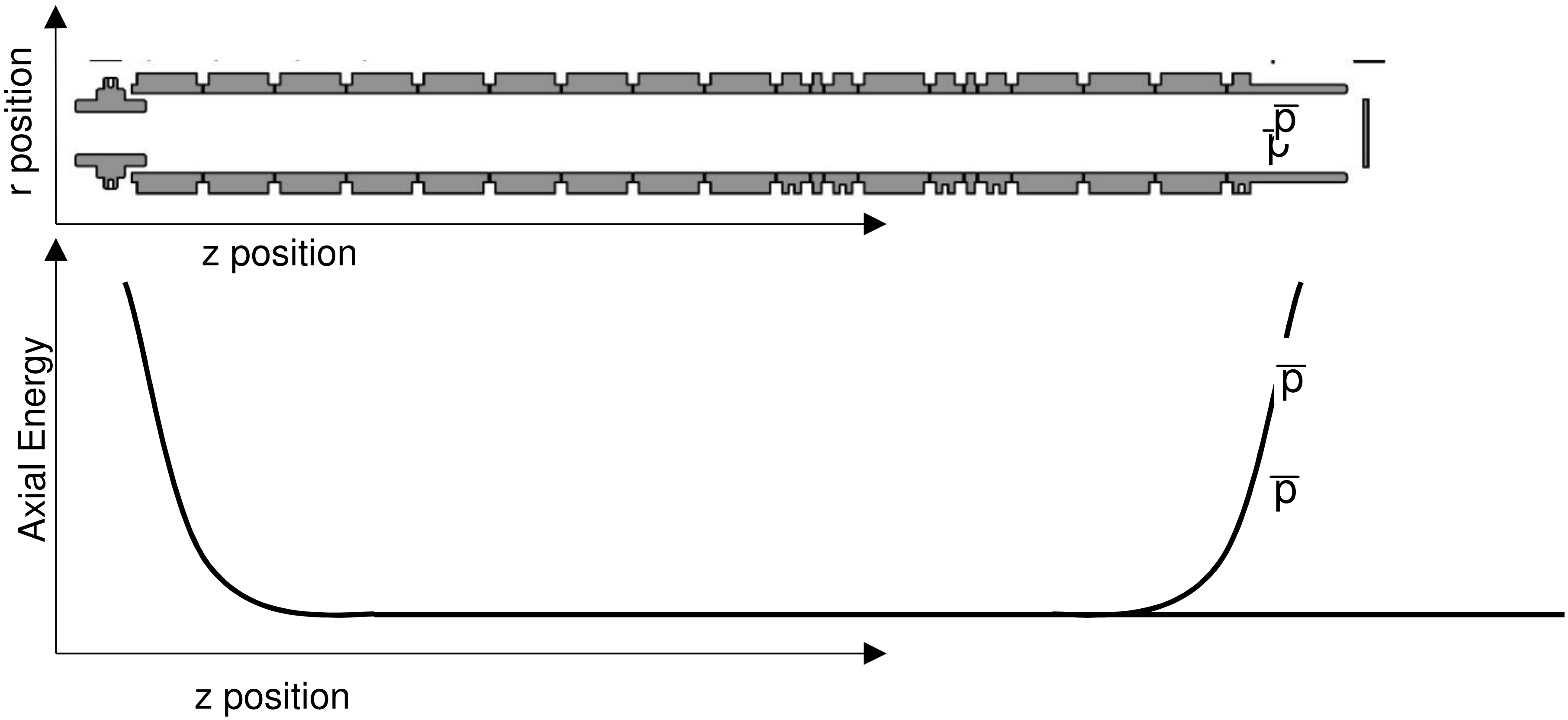
10^{-10}
energy
reduction

- **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 NSF and AFOSR

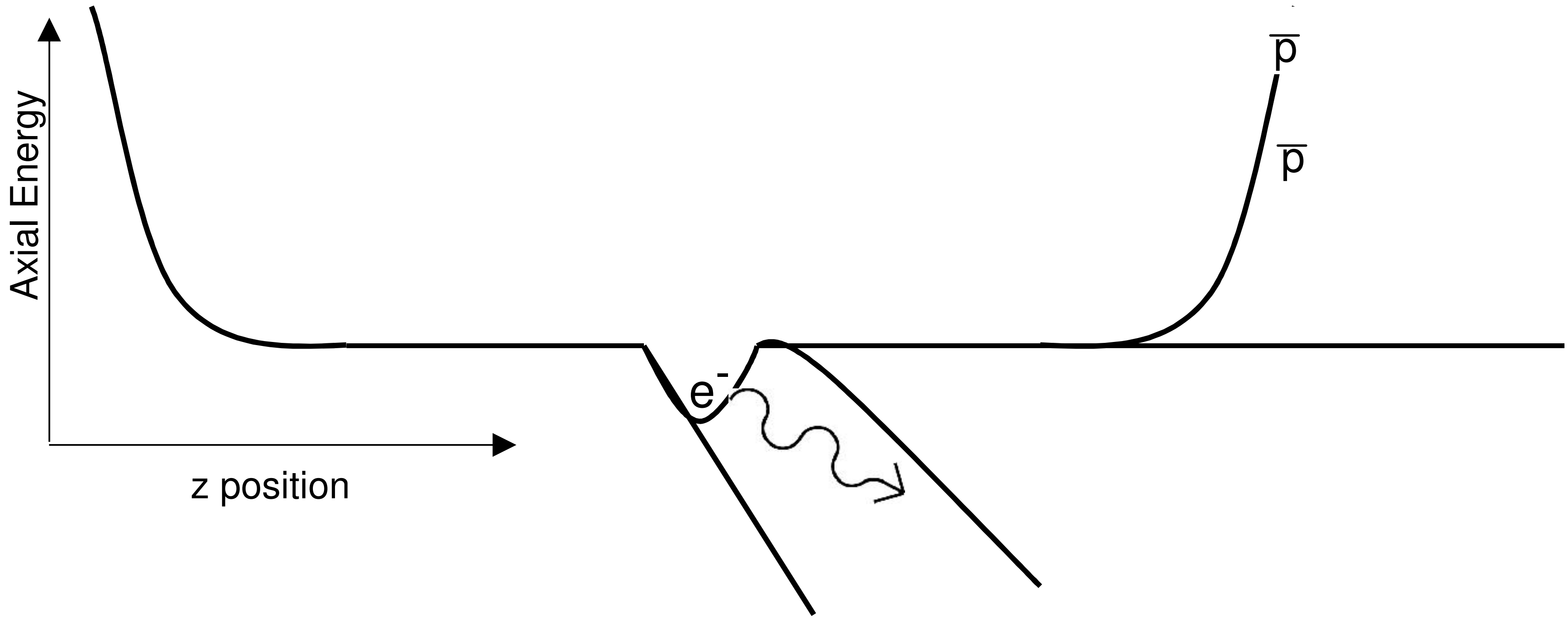
Antiproton Capture – the Movie



"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

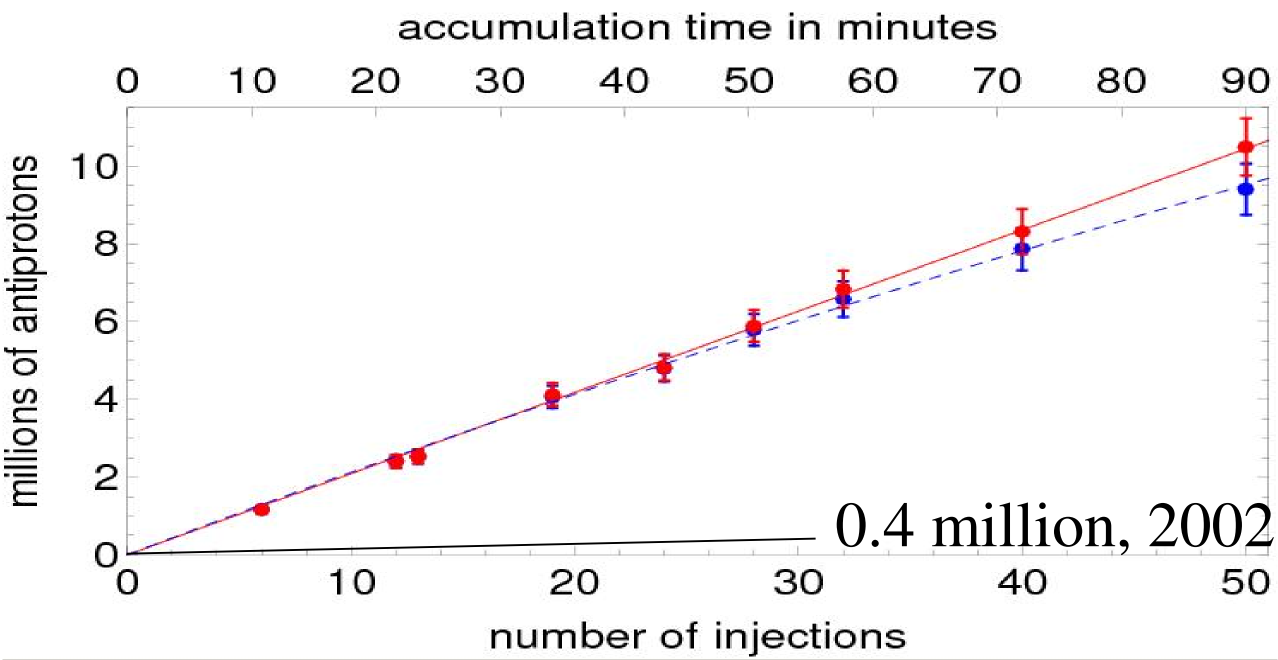


"Cooling and Slowing of Trapped Antiprotons Below 100 meV",
G. Gabrielse, X. Fei, L.A. Orozco, R. Tjoelker, J. Haas, H. Kalinowsky, T.A. Trainor, W. Kells;
Phys. Rev. Lett. 63, 1360 (1989).

Gabrielse

10 Million Cold Pbar/Trial at ATRAP

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



3.7 Tesla

1 Tesla

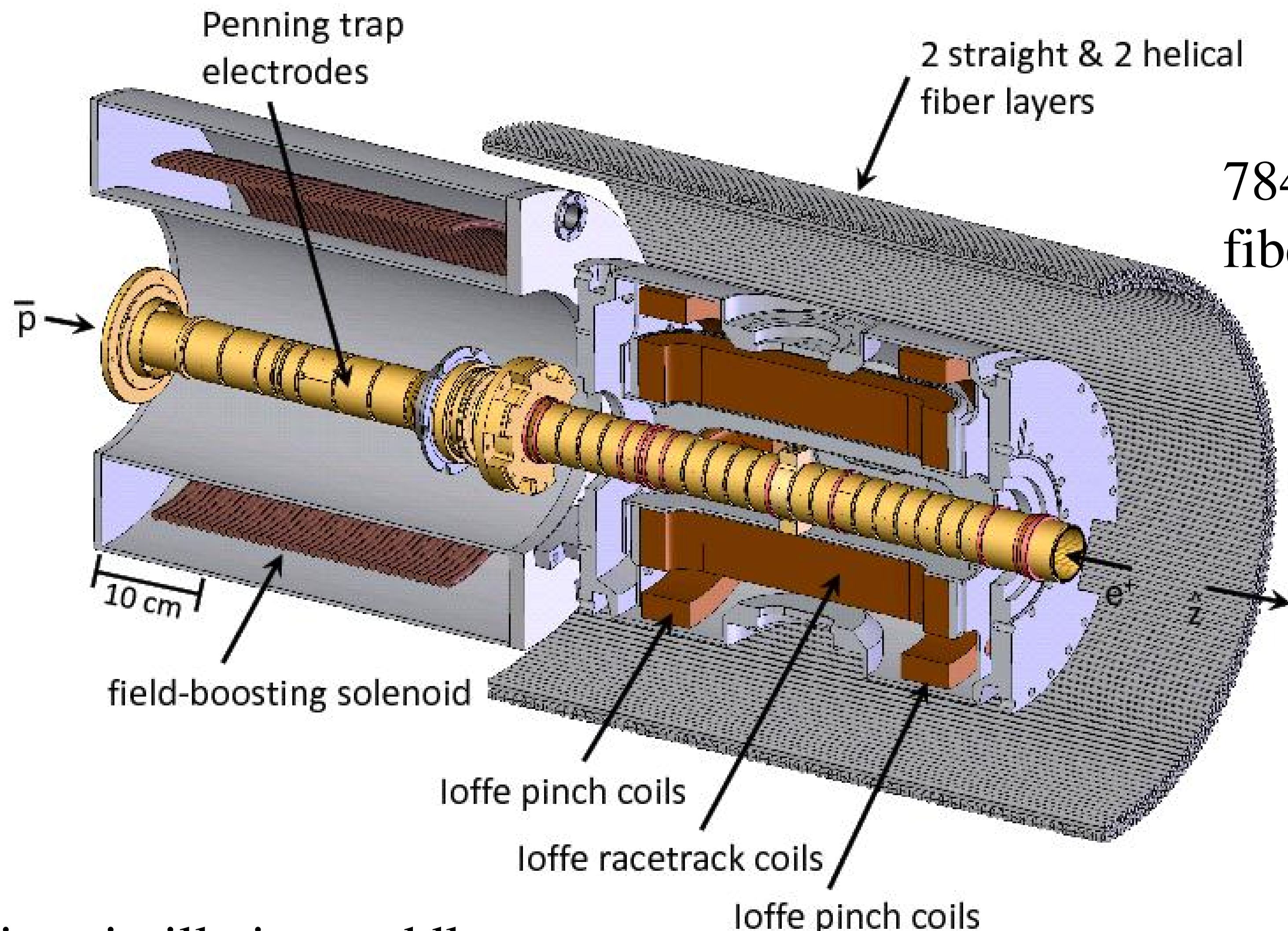
↑ better cooling

Methods to Detect Trapped Antimatter

Destructive methods

Non-destructive methods

Detecting Trapped Antihydrogen

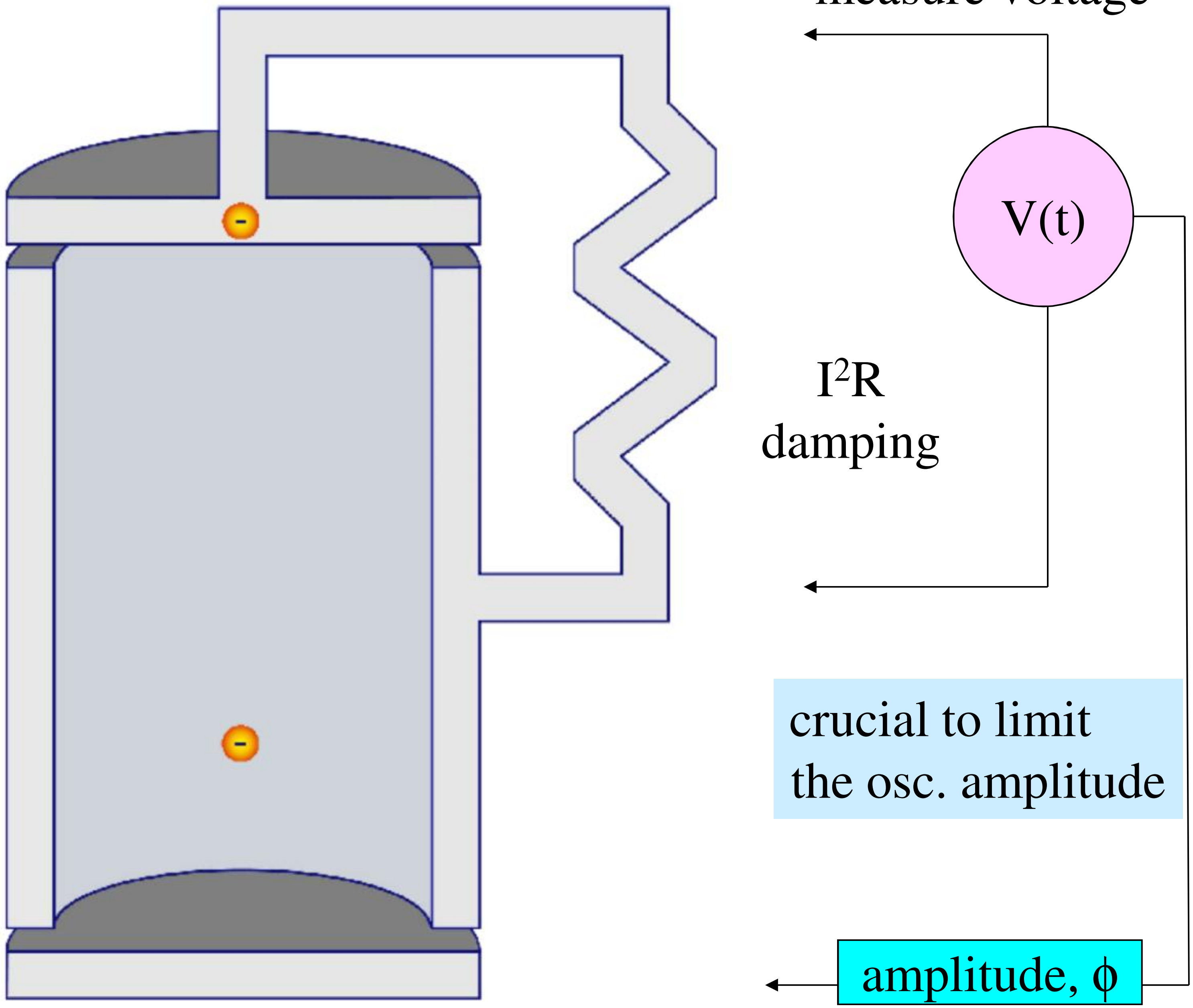


784 scintillating fibers

big scintillating paddles surround the solenoid dewar

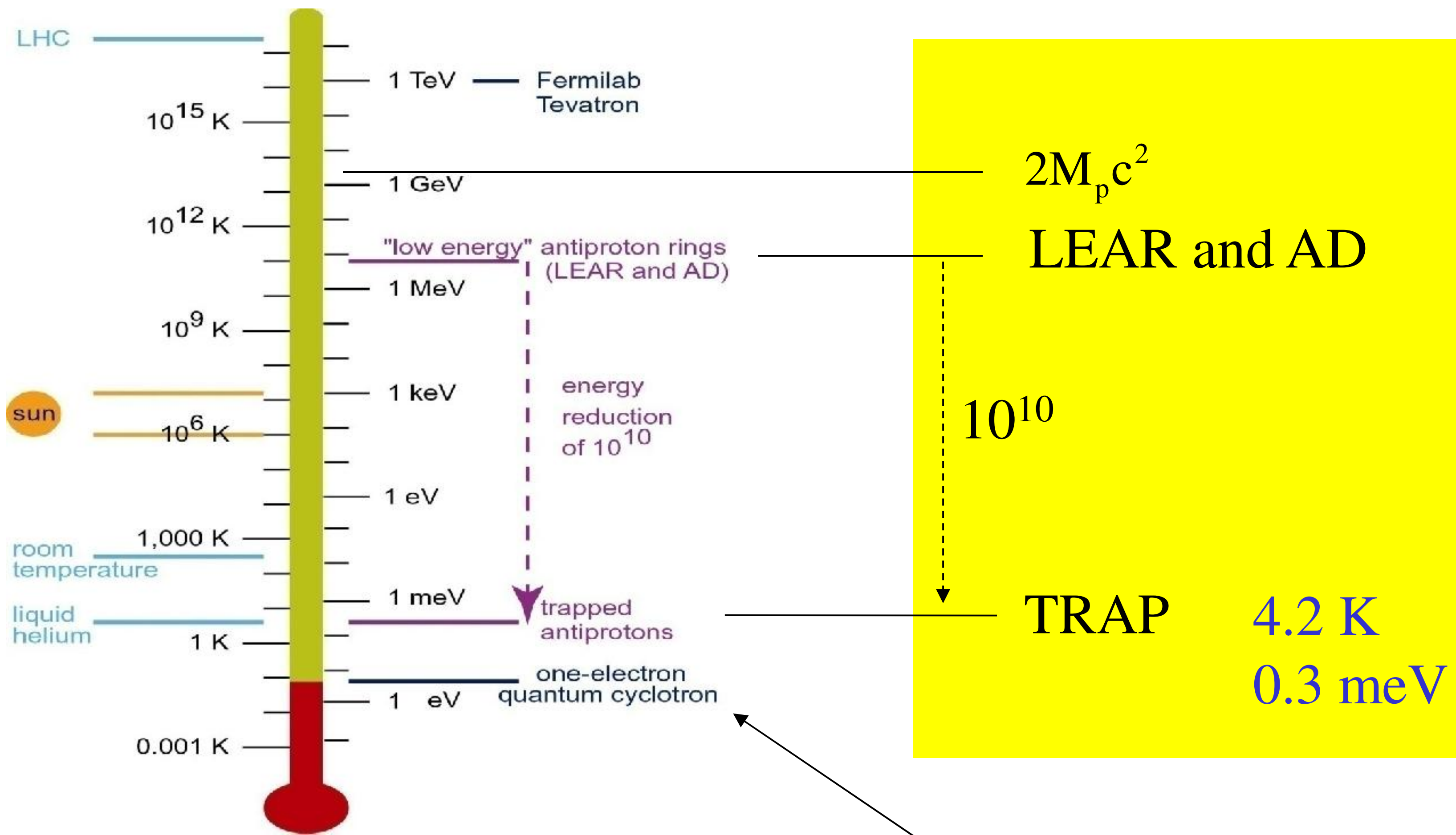
Detecting One Particle

axial motion
200 MHz
of
trapped
electron



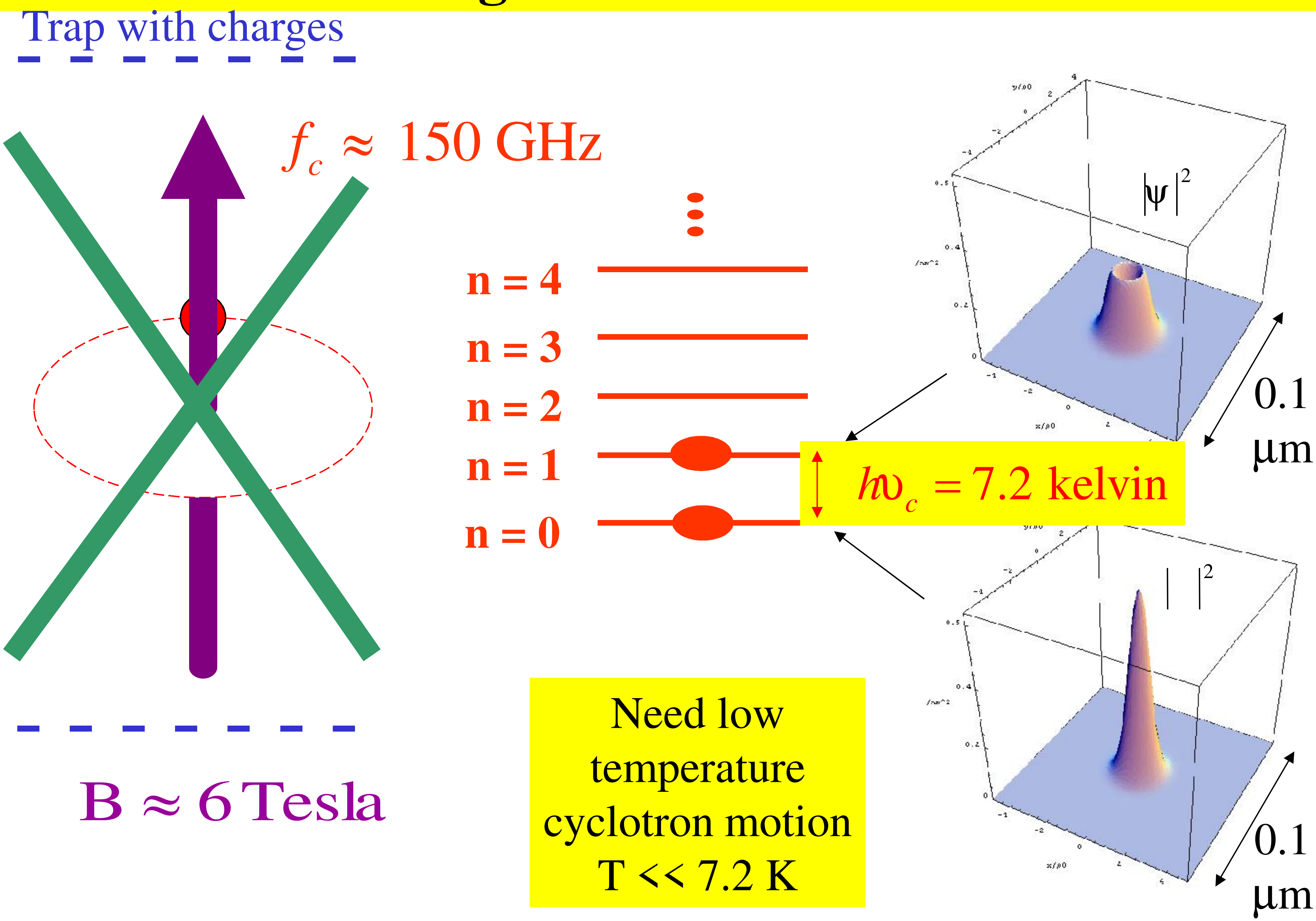
One Trapped Particle, Very Cold, Allows Some of the Most Precise Measurements

A Very Cold Electron



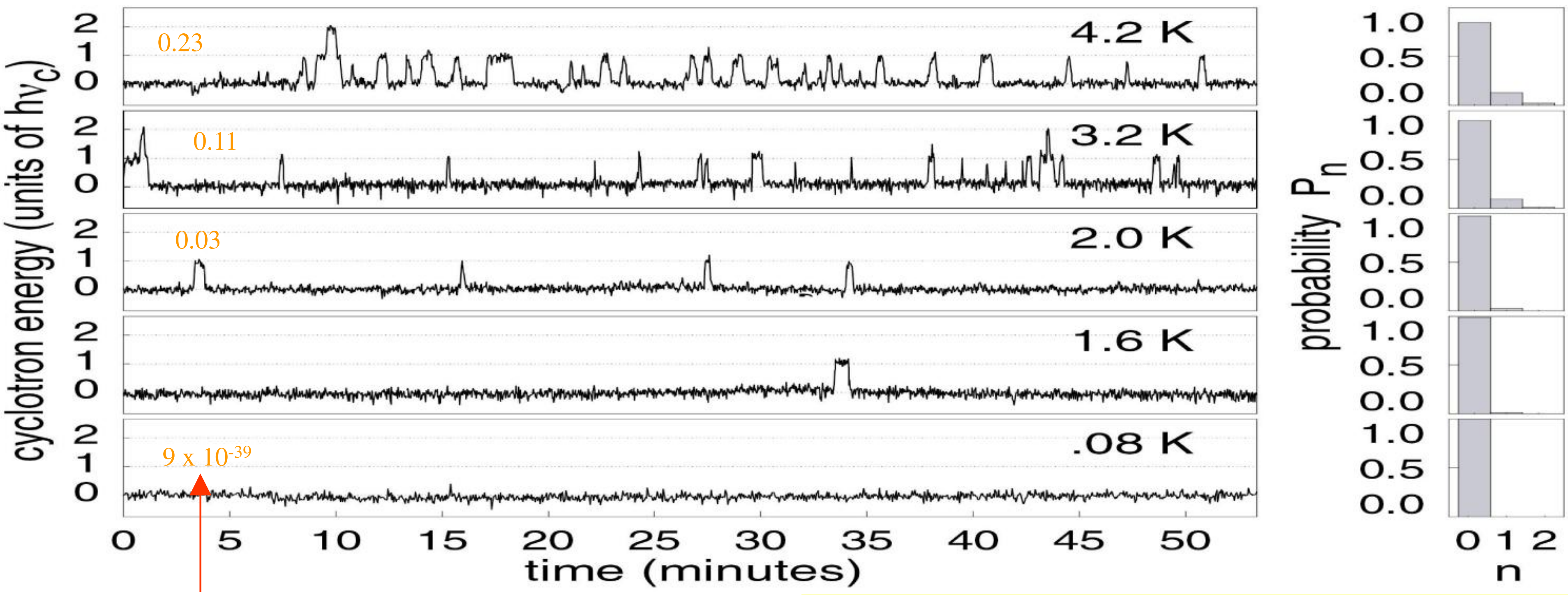
70 mK, lowest storage energy for any charged particles

Making an Artificial Atom



Electron in Cyclotron Ground State

QND Measurement of Cyclotron Energy vs. Time



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

S. Peil and G. Gabrielse, Phys. Rev. Lett. **83**, 1287 (1999).

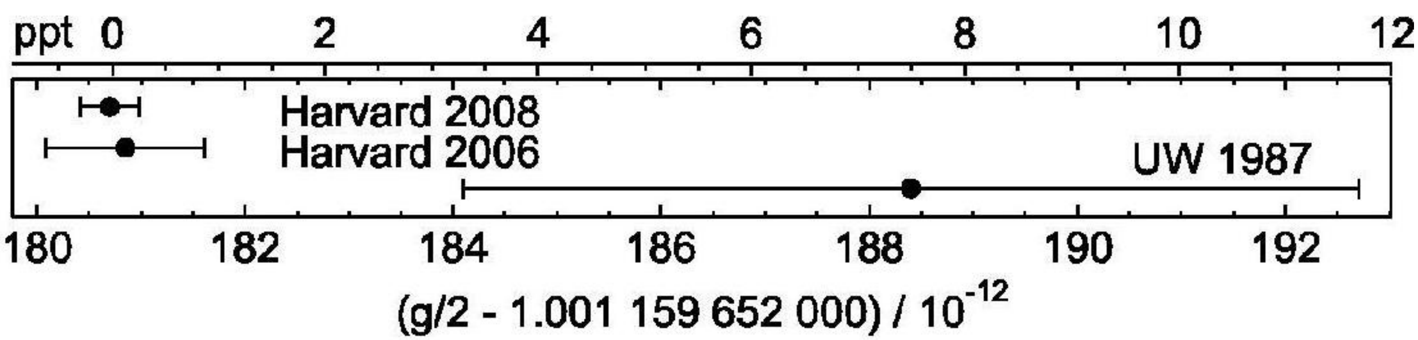
Measurement of "Magnet in the Electron"

magnetic moment $\vec{\mu} = g\,\mu_B \frac{\vec{S}}{\hbar}$ ← spin

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

$$g/2 = 1.001\,159\,652\,180\,73$$

$$\pm 0.000\,000\,000\,000\,28 \qquad 2.8\times10^{-13}$$



D. Hanneke, S. Fogwell and G. Gabrielse

- First improved measurements (2006, 2008) since 1987
- 15 times smaller uncertainty
- 1.7 standard deviation shift
- 2500 times smaller uncertainty than muon g

Standard Model of Particle Physics

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\text{hadronic}} + a_{\text{weak}}$$

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

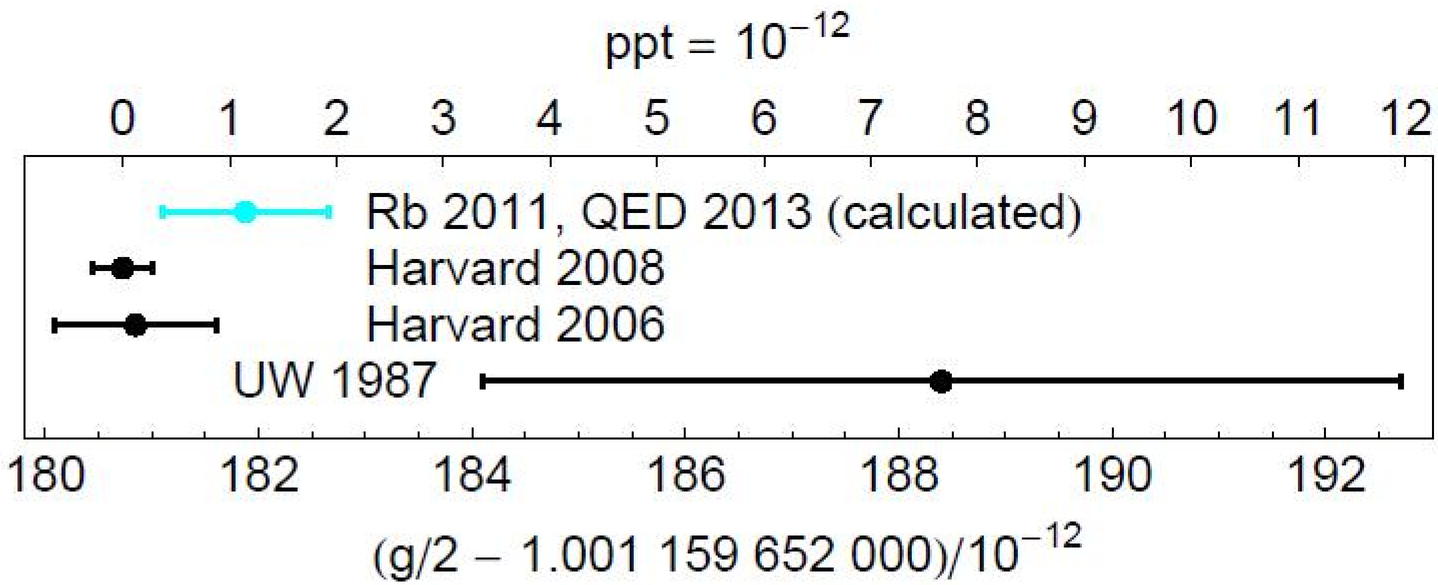
$$a_e^{\text{hadronic}} = 1.677(16) \times 10^{-12}$$

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)



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

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

From Freeman Dyson – One Inventor of QED

Dear Jerry,

... I love your way of doing experiments, and I am happy to congratulate you for this latest triumph. Thank you for sending the two papers.

Your statement, that QED is tested far more stringently than its inventors could ever have envisioned, is correct. As one of the inventors, I remember that we thought of QED in 1949 as a temporary and jerry-built structure, with mathematical inconsistencies and renormalized infinities swept under the rug. We did not expect it to last more than ten years before some more solidly built theory would replace it. We expected and hoped that some new experiments would reveal discrepancies that would point the way to a better theory. And now, 57 years have gone by and that ramshackle structure still stands. The theorists … have kept pace with your experiments, pushing their calculations to higher accuracy than we ever imagined. And you still did not find the discrepancy that we hoped for. To me it remains perpetually amazing that Nature dances to the tune that we scribbled so carelessly 57 years ago. And it is amazing that you can measure her dance to one part per trillion and find her still following our beat.

With congratulations and good wishes for more such beautiful experiments, yours ever, Freeman.

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).

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

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

(most precise result of CERN's antiproton program)

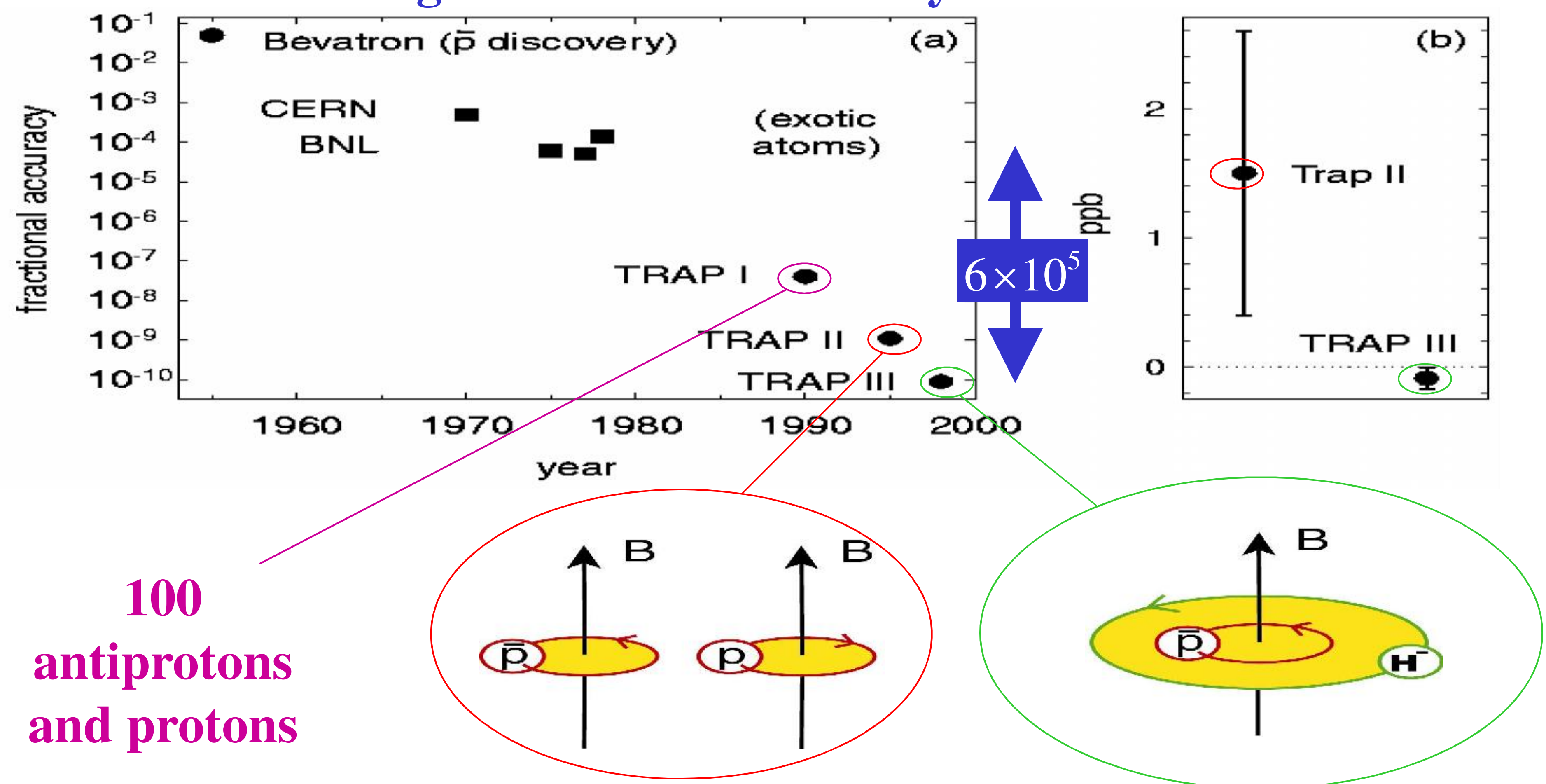
Gabrielse

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



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

(Announced earlier this year)

Gabrielse

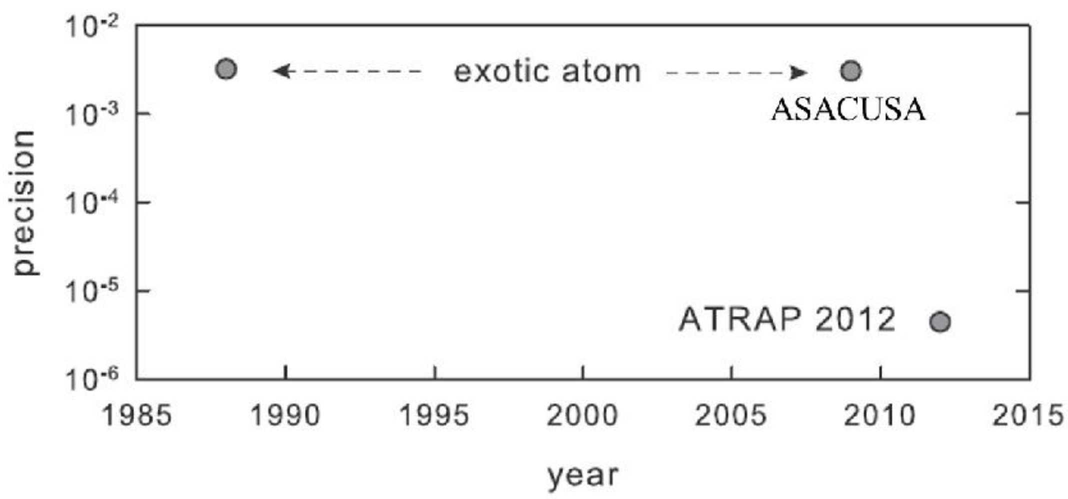
680 Times Improved Precision for the "Magnetic in the Antiproton"

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

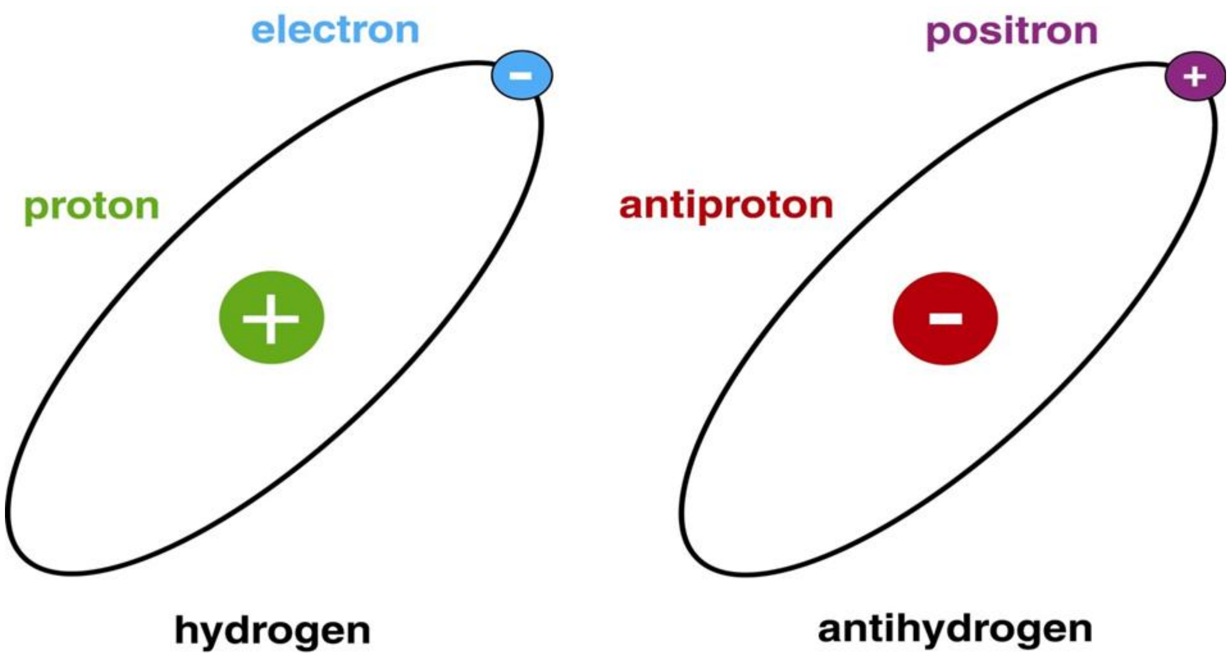
$$\mu_{\overline{p}}/\mu_p = -1.000\,000 \pm 0.000\,005 \qquad [5.0\ \text{ppm}]$$

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

680 times lower than previous



Producing and Trapping Antihydrogen



uncharged atom

uncharged anti-atom

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)

Gabrielse

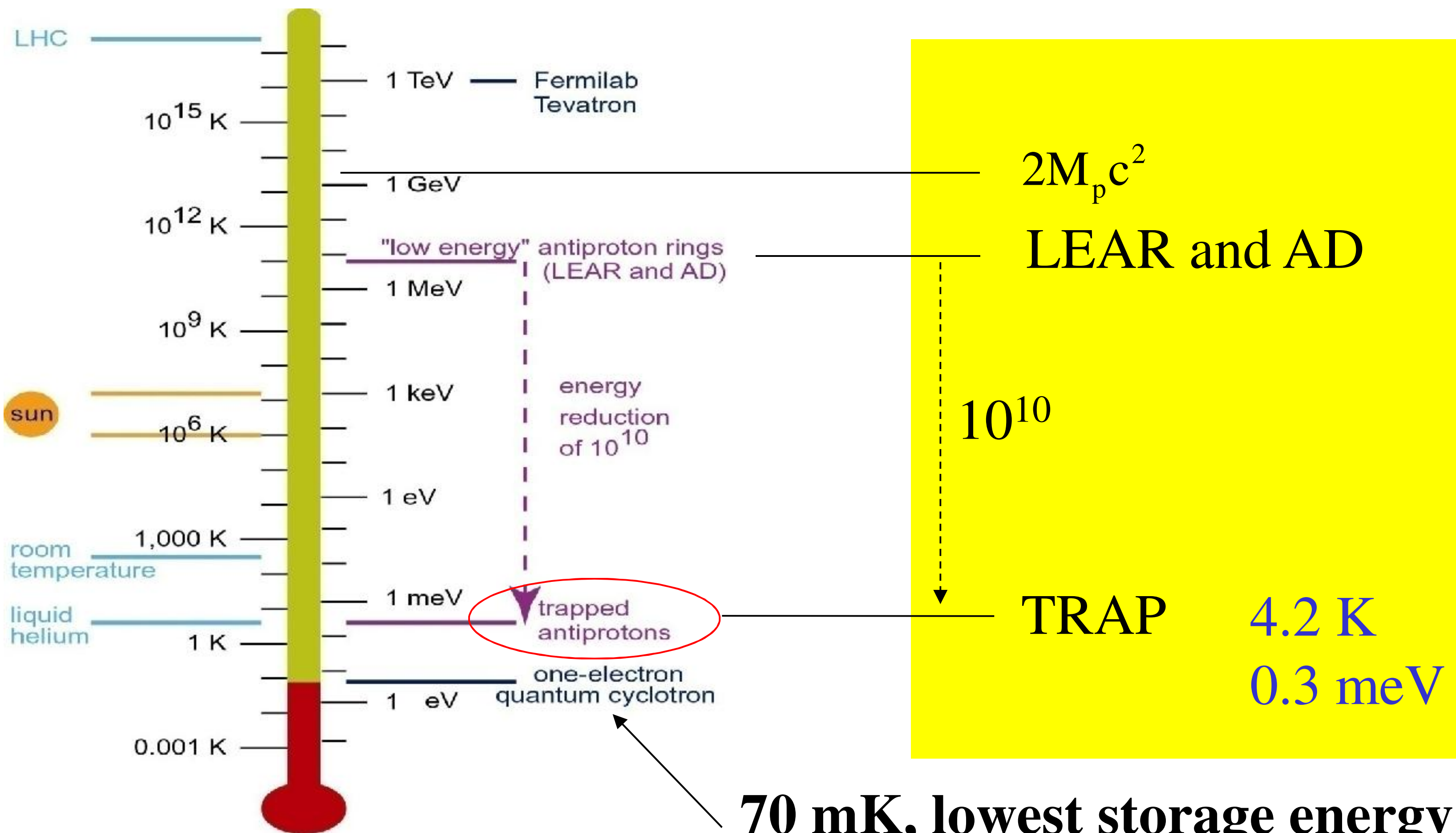
Need Low Temperatures

AMO Physics, Particle Physics, Plasma Physics

methods and funding → AMO Physics

goals and facility → Particle Physics

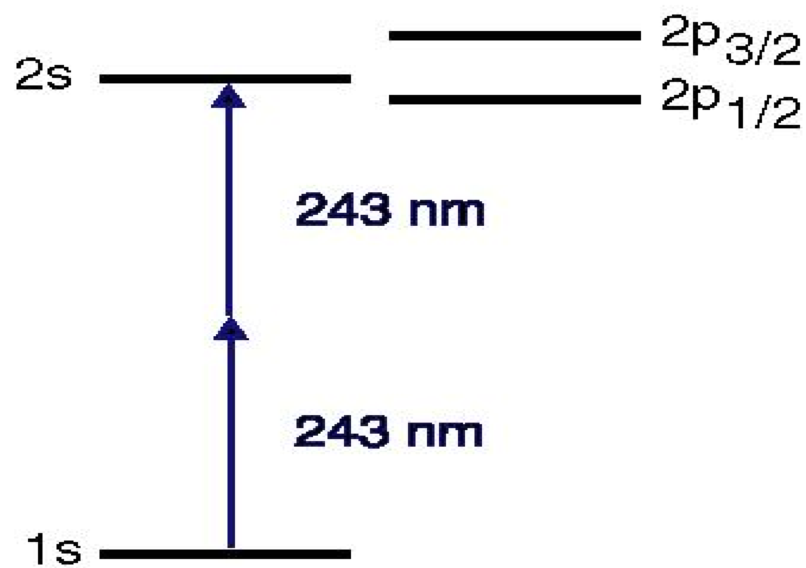
can't avoid → Plasma Physics



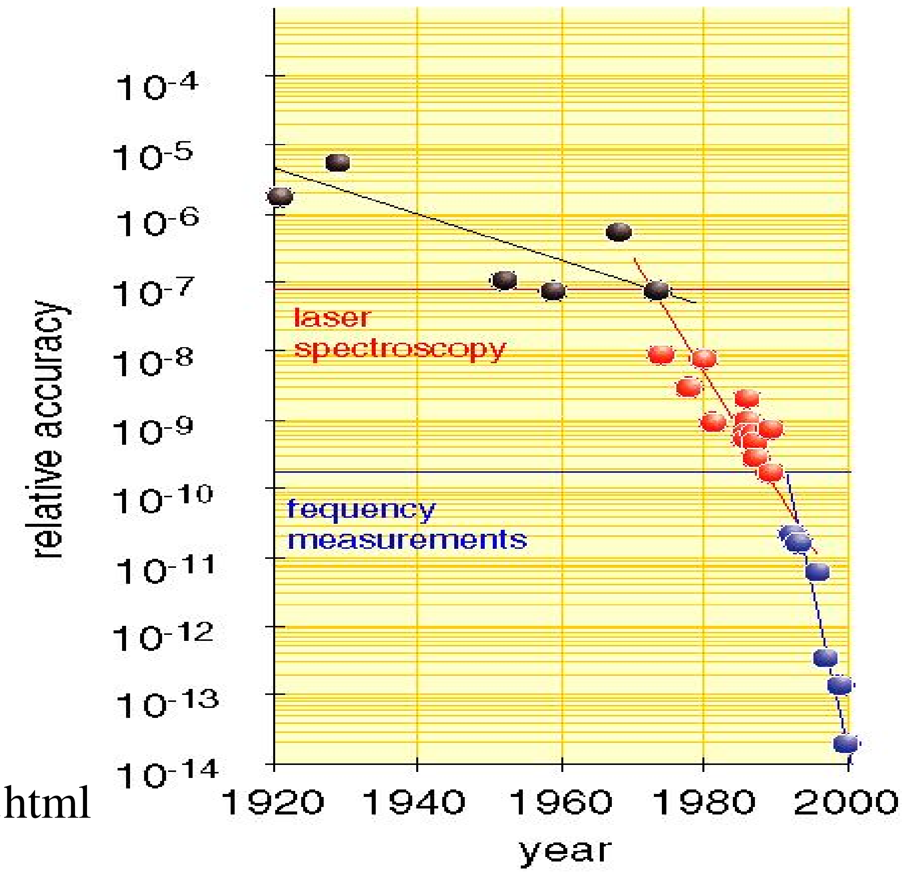
70 mK, lowest storage energy for any charged particles

Gabrielse

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

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

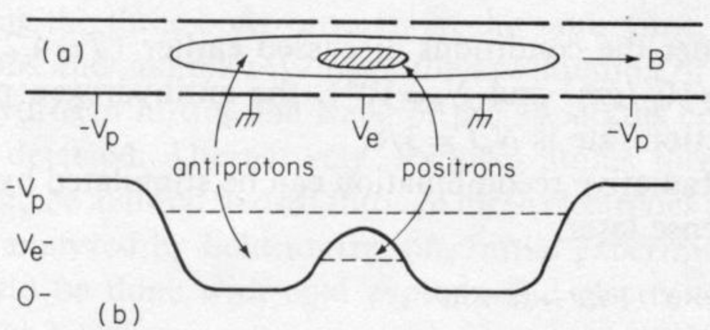


Fig. 1. Electrodes (a) and axial potential (b) for a nested pair of Penning traps.

Nested Penning Trap

We call attention to another three-body recombination

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

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

3-Body "Recombination"

From the Beginning ATRAP was Built to do Two Types of Experiments Simultaneously

Antihydrogen Experiments

Precision Measurements with Antiprotons

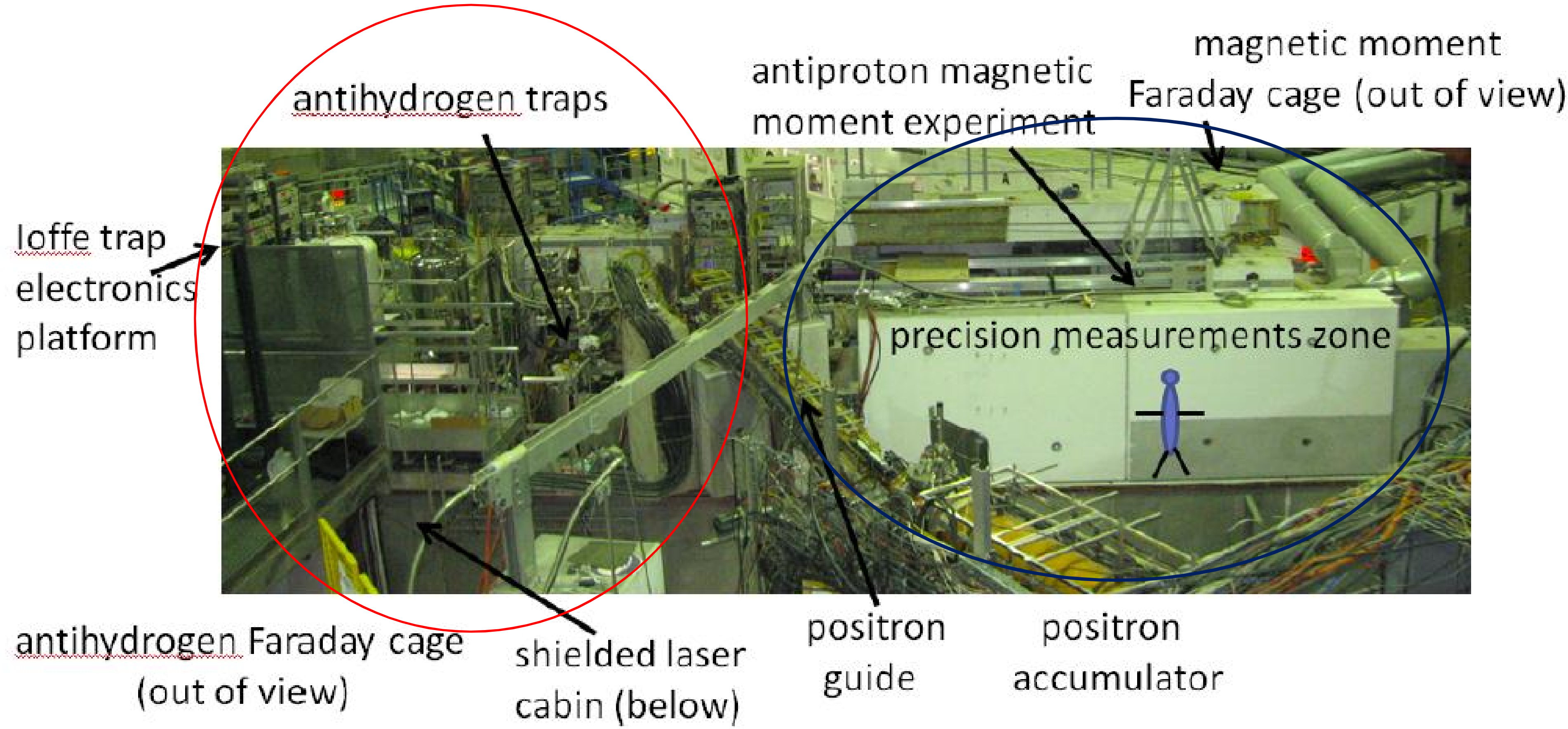
Antiprotons from AD

SPSC has heard a lot from us about antihydrogen

SPSC has heard less from us about the precision measurements

- Preparations taking place off site
- Brief report each annual report

Simultaneous Antihydrogen Experiments and Precision Measurements



ATRAP Experimental Area

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.

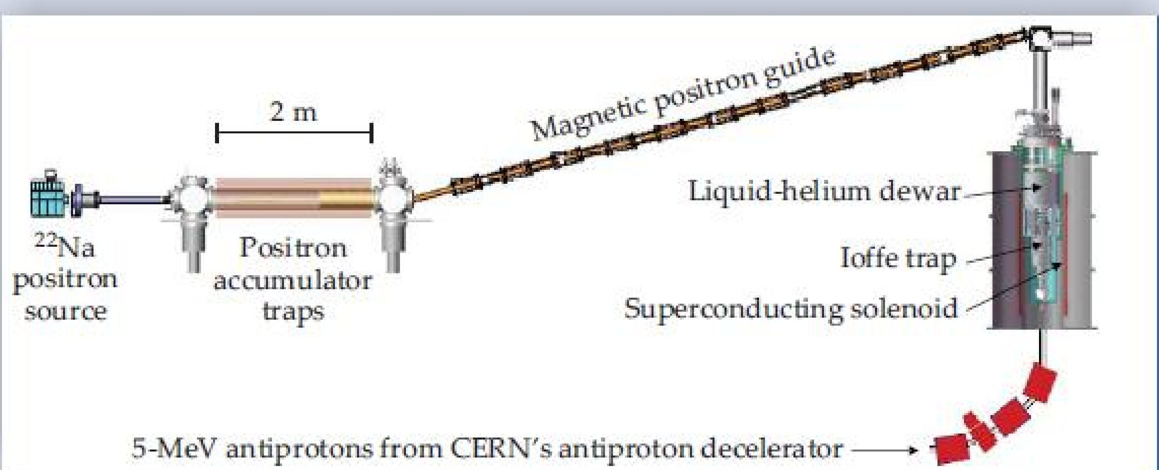
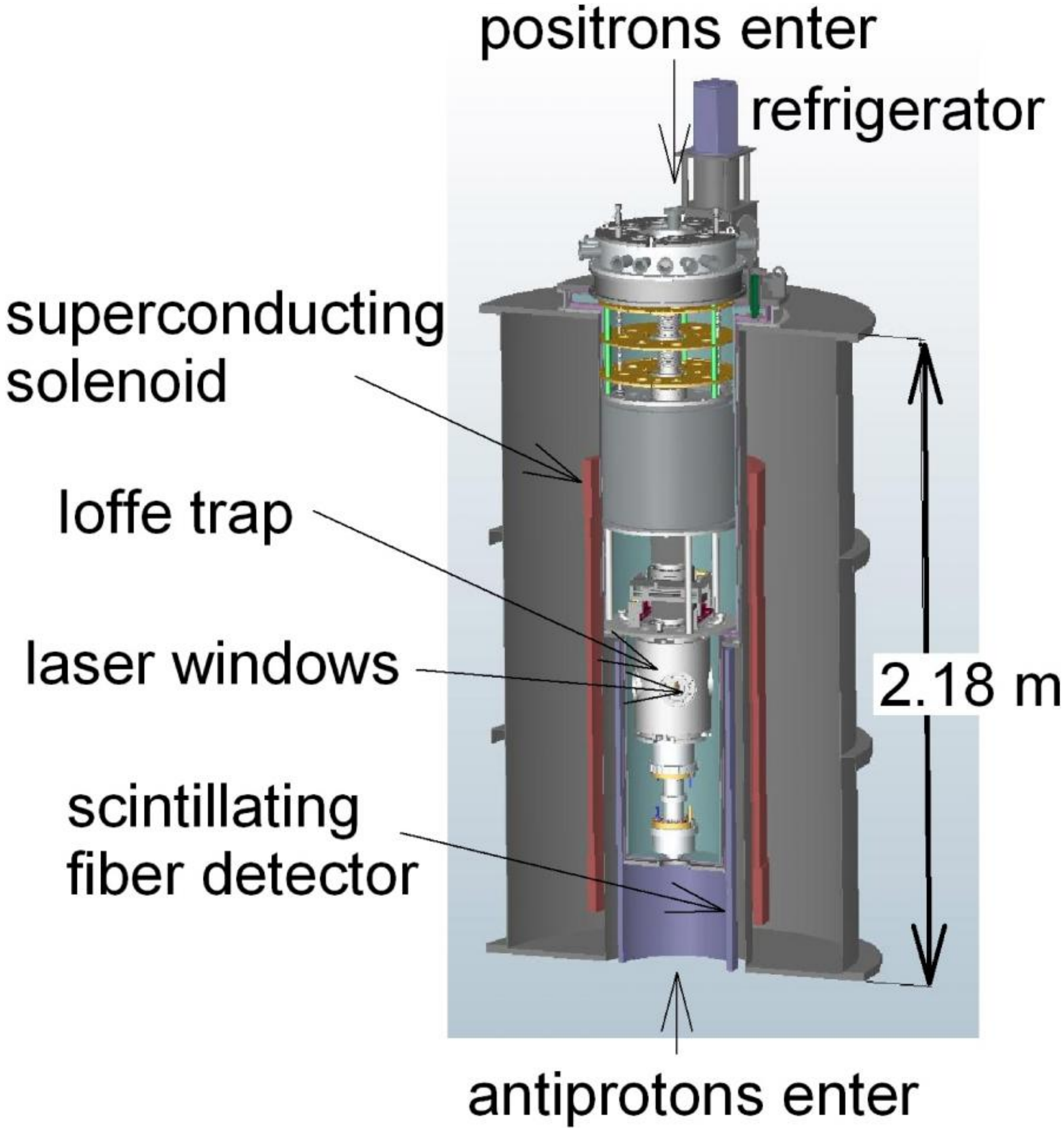
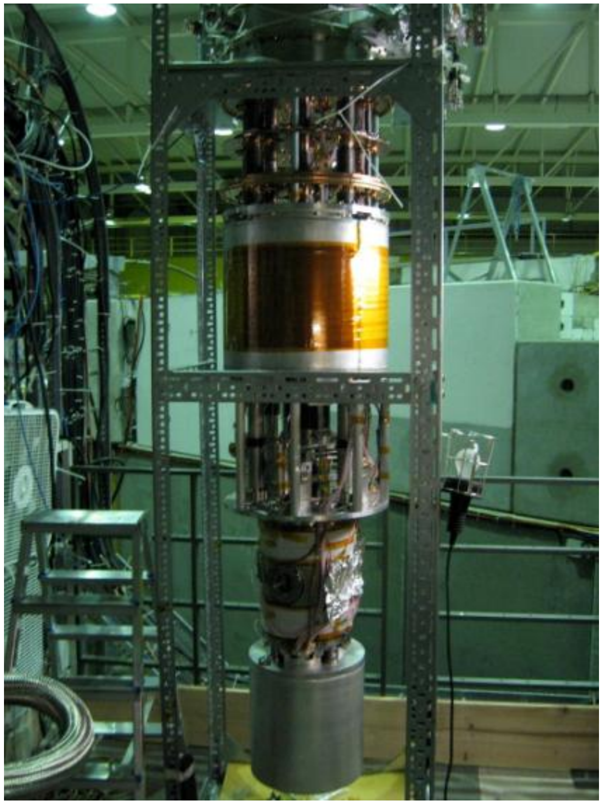


Figure 1. Key components of the ATRAP apparatus that accepts antiprotons from the antiproton decelerator at CERN and slows positrons from a sodium-22 source. The goal of the experiment is to trap and study cold antihydrogen atoms in the specially designed magnetic fields of the Ioffe trap.

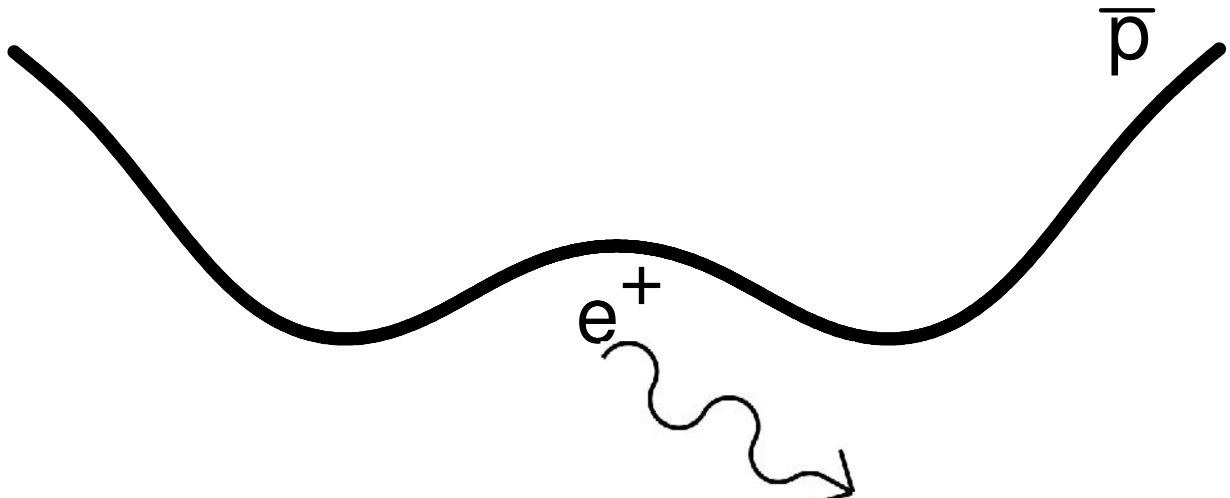
ATRAP II Trap Apparatus





Positron Cooling of Antiprotons in a Nested Penning Trap

Gabrielse



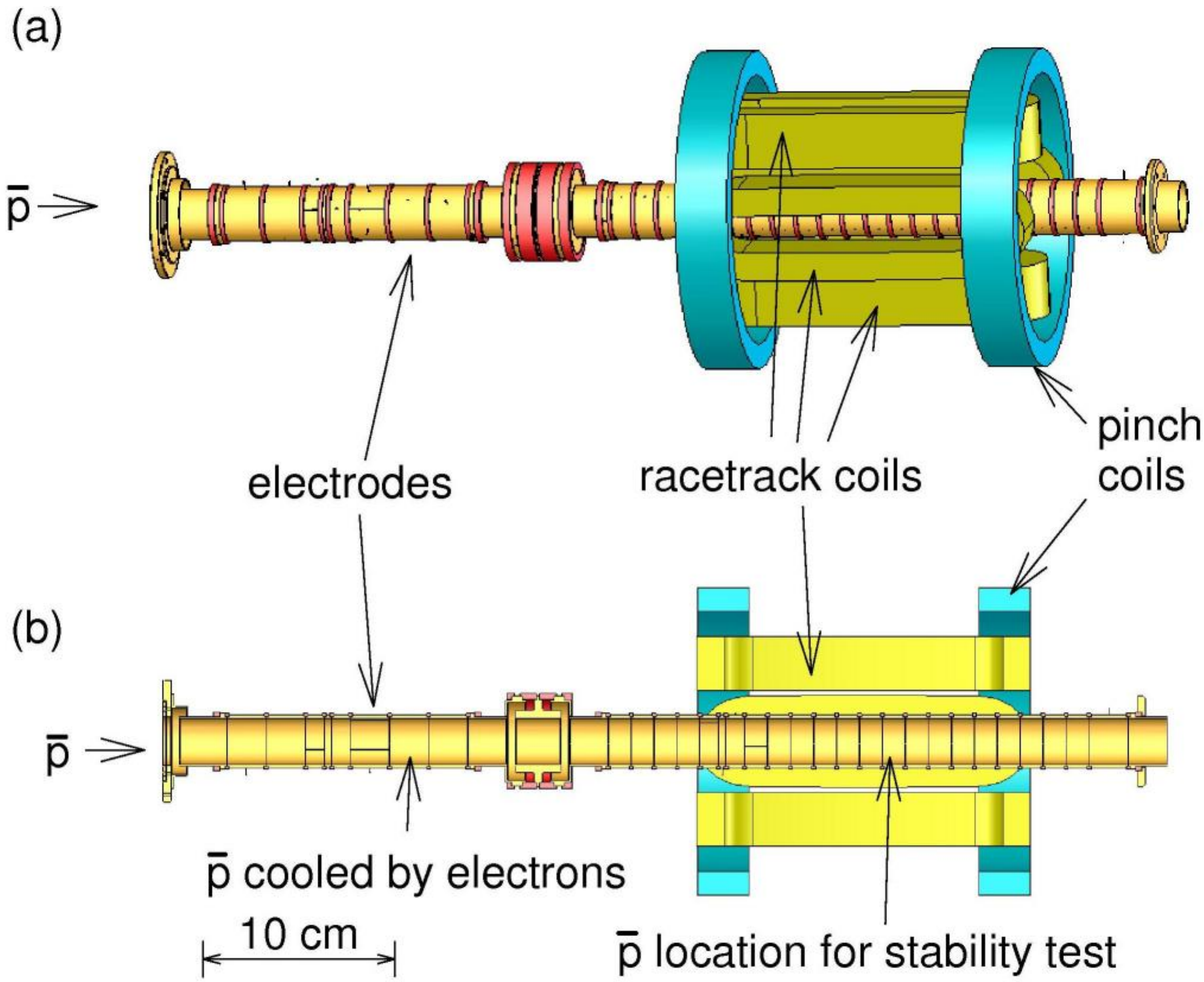
TRAP/ATRAP Develops the Nested Penning Trap

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)

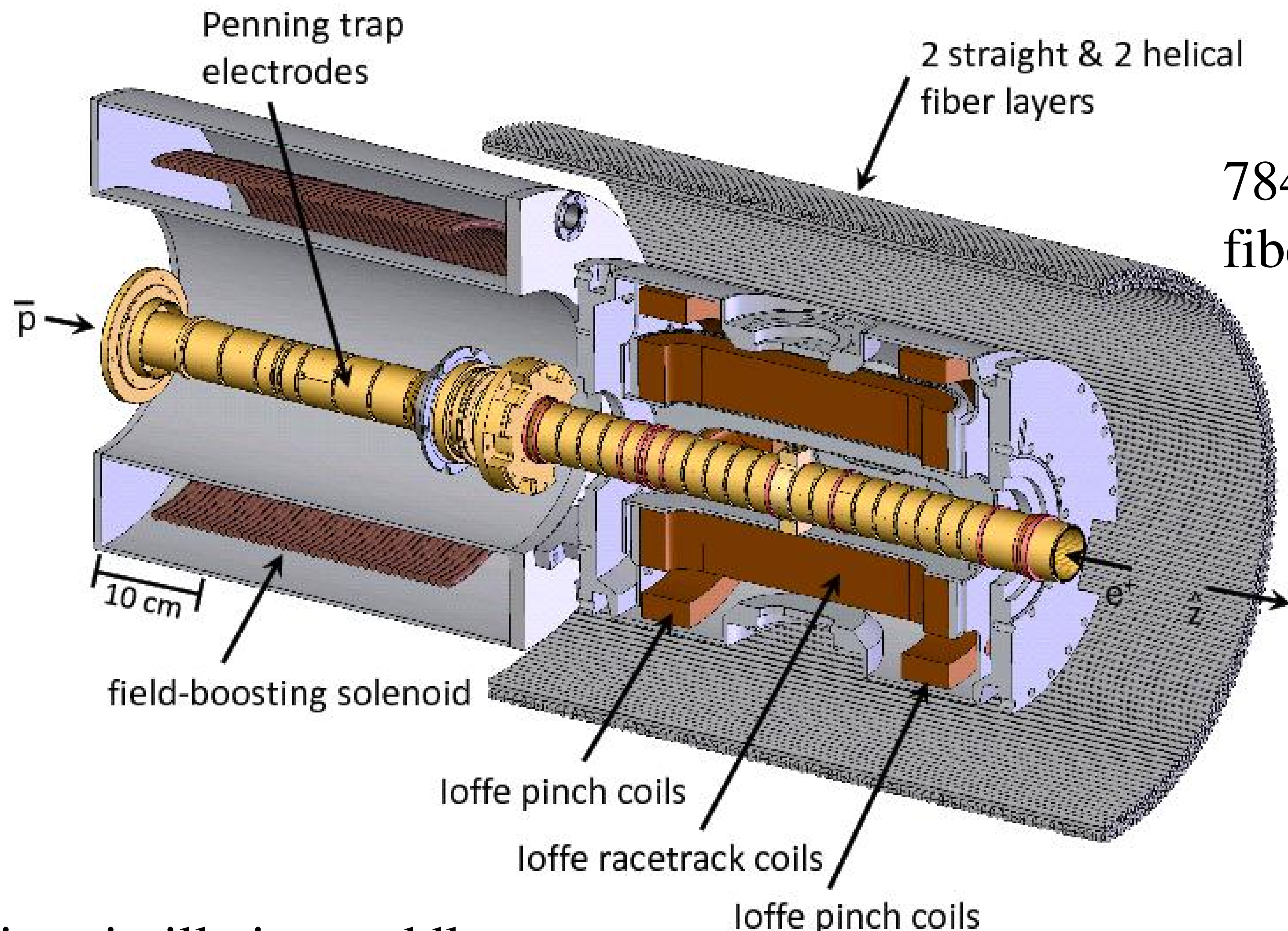
"Electron-Cooling of Protons in a Nested Penning Trap"
D.S. Hall, G. Gabrielse
Phys. Rev. Lett. 77, 1962 (1996)

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

Antihydrogen Trap



Detecting Trapped Antihydrogen



784 scintillating fibers

big scintillating paddles
surround the solenoid dewar

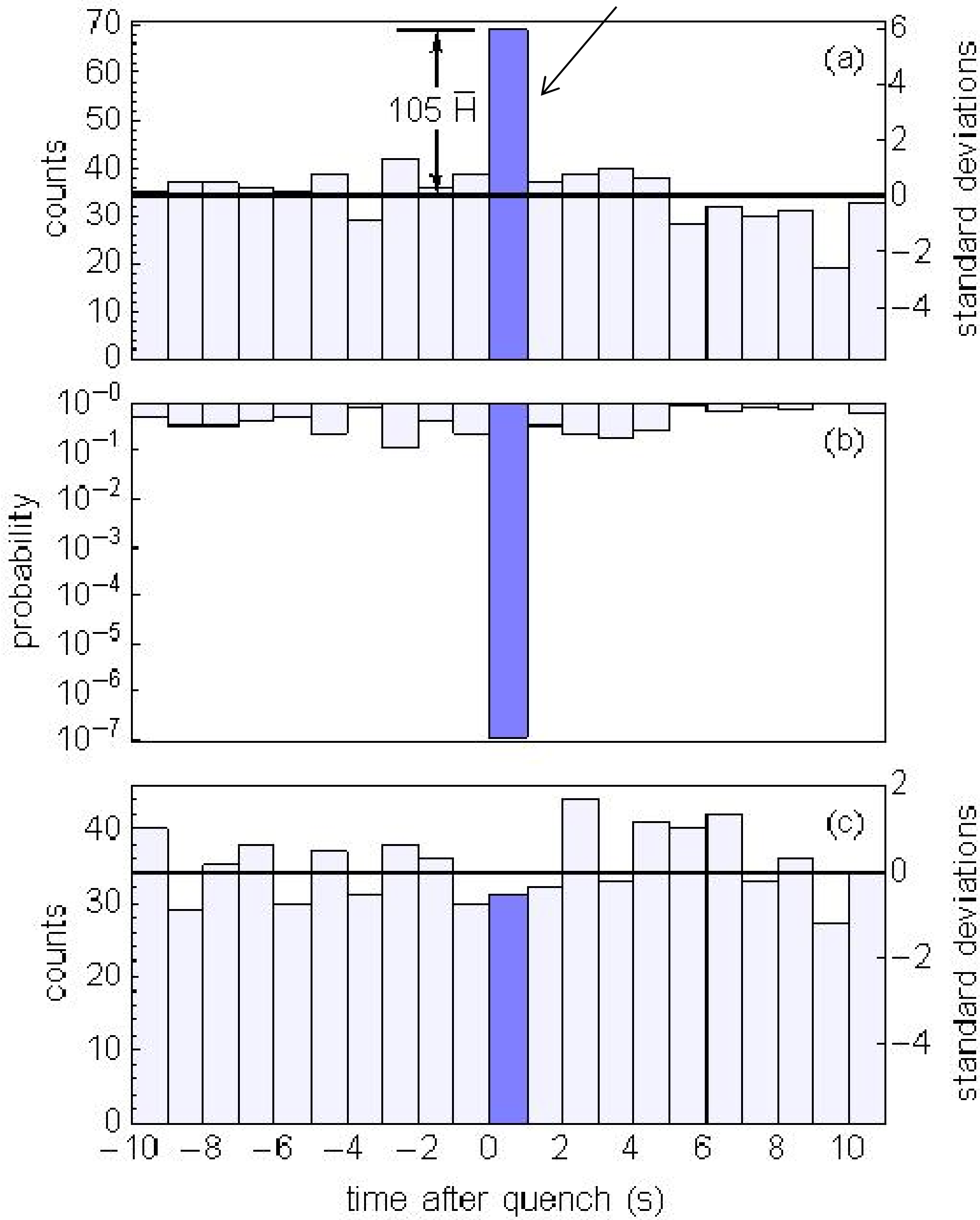
Detector Counts During Quench (1 second)

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)



1986 2012 Gabrielse

1 Collaboration → 4 Collaborations

Following the 1986 plan:

cold antiprotons
↓
cold antihydrogen → colder antihydrogen
↓
trap antihydrogen → extract from trap
↓
precise laser spectroscopy

Variations

colder antihydrogen
↓
interferometry

extract from trap
↓
laser spectroscopy

ATRAP and **ALPHA**

ASACUSA

AEGIS

Conclusion

So far, the most precise measurements of particle and antiparticle properties show them to be "exactly opposite"

- Opposite sign of charge
- Same charge magnitude
- Same mass
- Opposite direction magnets
- Same magnet strength

However, we will soon be able to probe for even smaller differences → we shall see