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Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

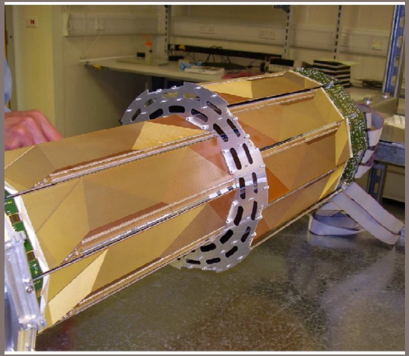
Gravity and CPT tests with ALPHA Antihydrogen Trap

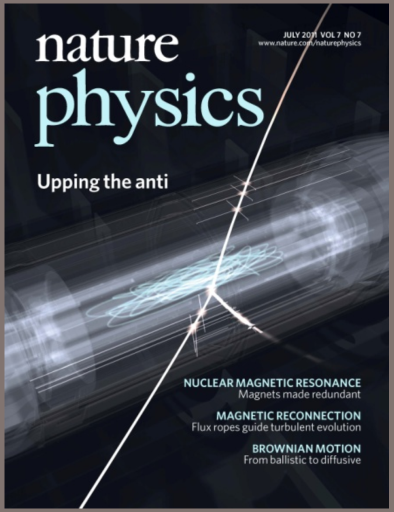
Testing Gravity 2015, SFU

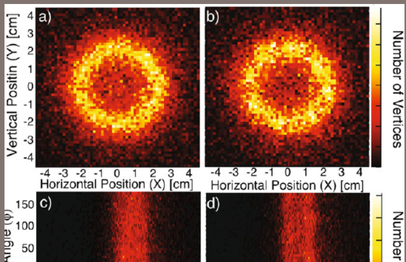
Makoto C. Fujiwara

TRIUMF – Canadian National Lab for Particle & Nuclear Physics, Vancouver

(Also University of Calgary)







TRIUMF, Vancouver, BC

Canada's National Laboratory for Particle and Nuclear Physics, located on UBC campus

"Tri-University Meson Facility"
Owned and operated by 18 Canadian Universities

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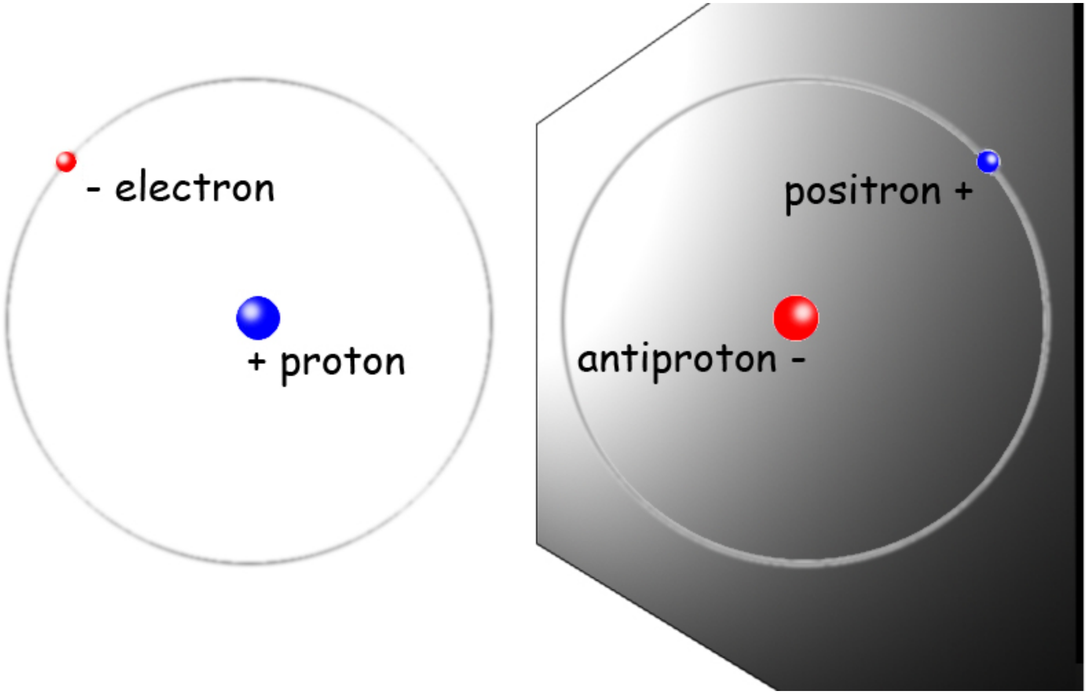
<u>On-site accelerator program</u>
- Radioactive Ion beams
- Muons, Pions

<u>Off-site program</u>
- ATLAS, ALPHA at CERN
- T2K in Japan

Antihydrogen Atom



Pbar = antiproton
Hbar = antihydrogen, anit-H
(bound state of pbar and e+)

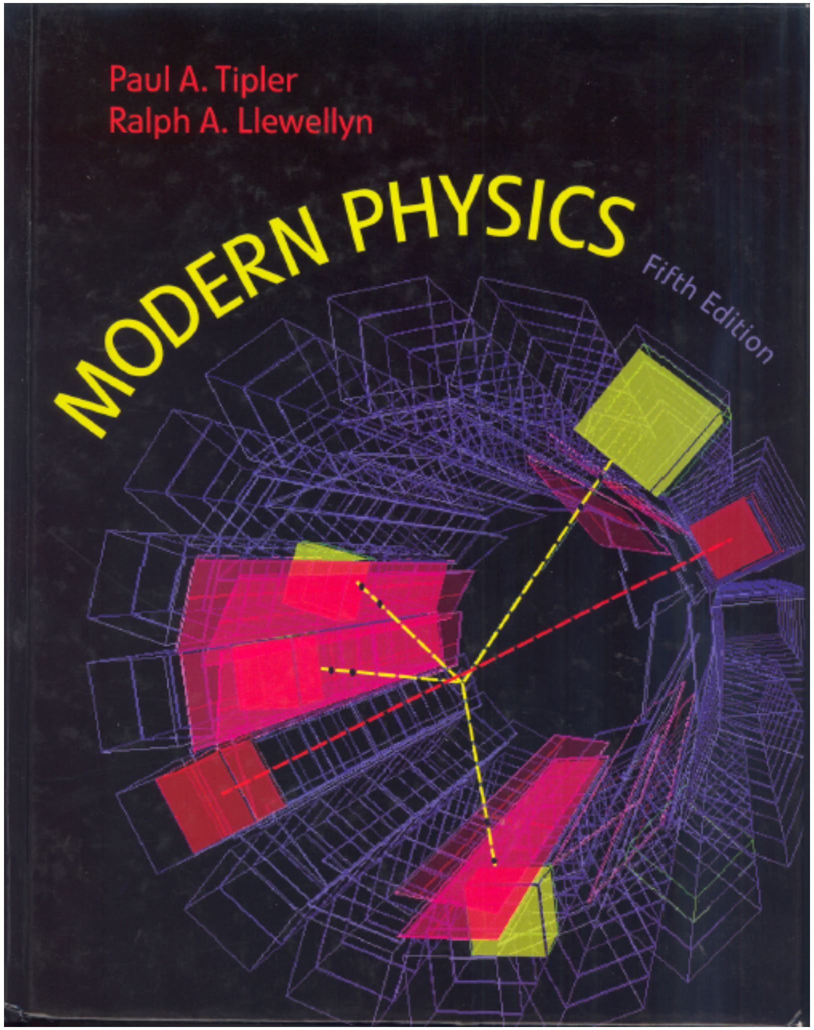
Outline

- Motivations: “Big Picture” (mostly on CPT)
  - MCF arXiv 2013
- Experiments at CERN’s Antiproton Decelerator
- ALPHA experiment
  - CPT
  - Gravity
- Summary & Prospects

Motivations (experimental)

- Atomic hydrogen: one of best studied systems
  - 1s-2s level: 2 466 061 413 187 035 (10) Hz $\Delta\nu/\nu \sim 10^{-15}$
  - Hyperfine splitting: 1 420 405 751.768 (1) Hz $\sim 10^{-12}$
- Antihydrogen (anti-H): produced in large quantities by ATHENA, ATRAP (2002)
- Comparison of H and anti-H: "Textbook" experiment!
  - Compelling regardless of theoretical motivations
- Gravitational force on Antimatter: never been measured directly:
  - c.f. very lose limit by ALPHA

Textbook Experiment



- ATHENA's anti-H annihilation event (Nature, 2002): now on the cover of textbook!
- $107.28 on Amazon.com

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Theoretical Motivations: "Big Picture"

- What is Particle Physics? (e.g. Grossman)

$$\boxed{\mathcal{L} = ?}$$

- "Simple answer": The Standard Model, including a Higgs, works extremely well!

Peter Higgs
July 4, 2012

Issues with the Standard Model

- Many open issues with SM, which motivated “New Physics” at the TeV scale
- “Naturalness” problem of Higgs mass very serious
  - Quantum corrections in SM require Higgs mass to be naturally heavy, like 10^{19} GeV
  - A “small” mass 125 GeV requires fine-tuning to O(30)
  - Motivation for Beyond SM theories (Susy, Extra Dim…)
- No new physics yet at LHC
  - Hopefully x2 energy, or precision expt’s will solve this!
  - Simple BSM models ruled out
  - Cosmological Constant even greater fine-tuning O(120)
  - Anthropic Principle our last resort?

“Pen standing without any balance”

is (technically) unnatural …

Motivations

Perhaps time to stop and think:

- "*L*=?" really the right question to ask?

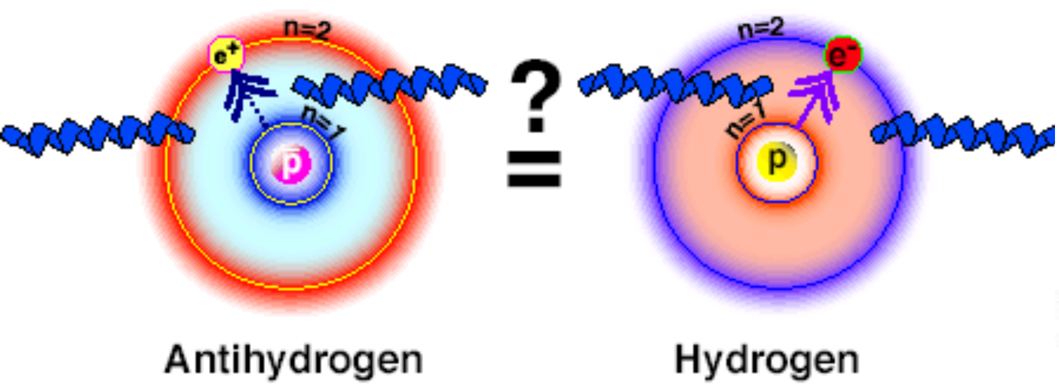
Is (effective) Quantum Field Theory the correct description of Nature?

CPT and Gravity tests with Antihydrogen

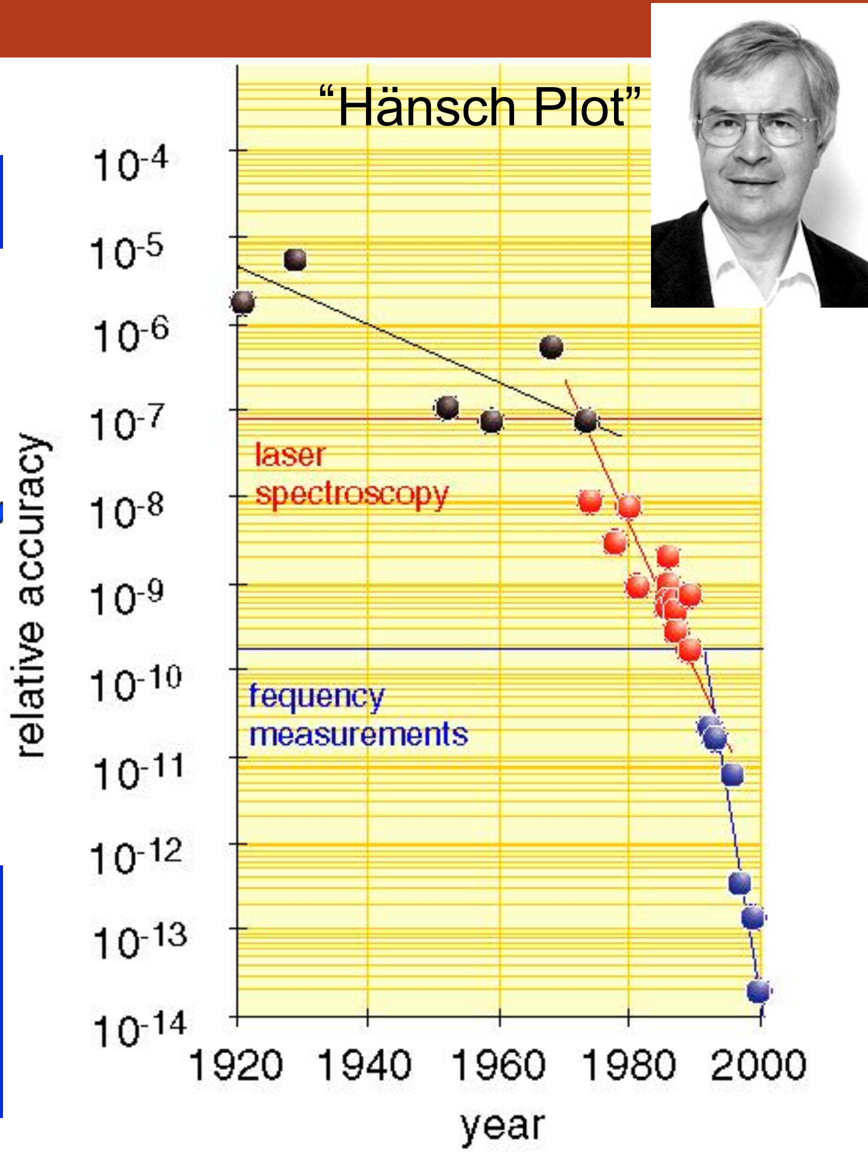
- Test of Charge-Parity-Time Reversal
  - CPT is a fundamental property of local, relativistic Quantum Field Theory
  - Assuming: Unitarity, Spin Statistics, Lorentz Invariance etc., CPT theorem demands atomic spectrum of H and Anti-H be identical
  - Violation of CPT would force fundamental change in theory, incl. validity of QFT
- Test of Gravity (not in the SM) in regimes previously untested
- Anti-H probes fundamental framework of physics (QFT+GR), rather than specific models within it
  - Unlike other SM tests, e.g. EDM
  - No guarantee anything shows up in anti-H tests

Anti-H long term goal: Precision spectroscopy

1s-2s two-photon spectroscopy



- Doppler effect cancels
- High precision in matter sector
- "Lamp post"



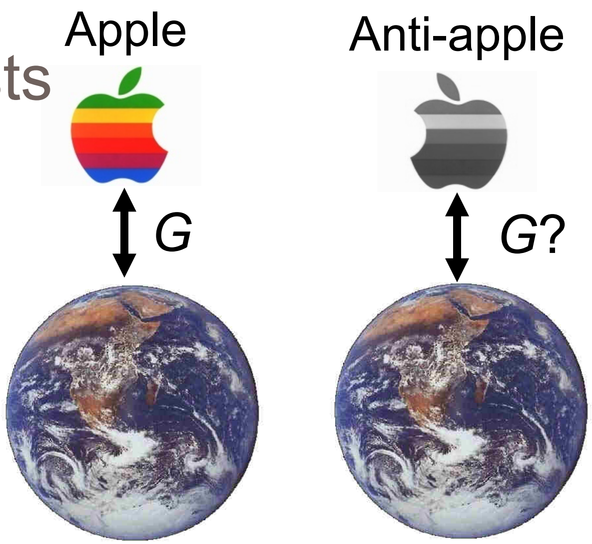
Gravity with Antihydrogen

- Does antimatter fall down with G?
  - Many indirect constraints incl. WEP tests
    - E.g. Eric Adelberger
    - ~99% of mass of hadron: gluons

      →"Adelberger" factor
    - Strong limit on vector coupling
  - Experimental question!

    (e.g. Lykken et al, arXiv:0808.3929)

  "gravitational asymmetry at 1% level is NOT ruled out"
    - Jason Tasson
  - Two expt's approved at CERN with a goal of 1% measurement
  - NB: Cold atom tests of gravity: $<10^{-10}$



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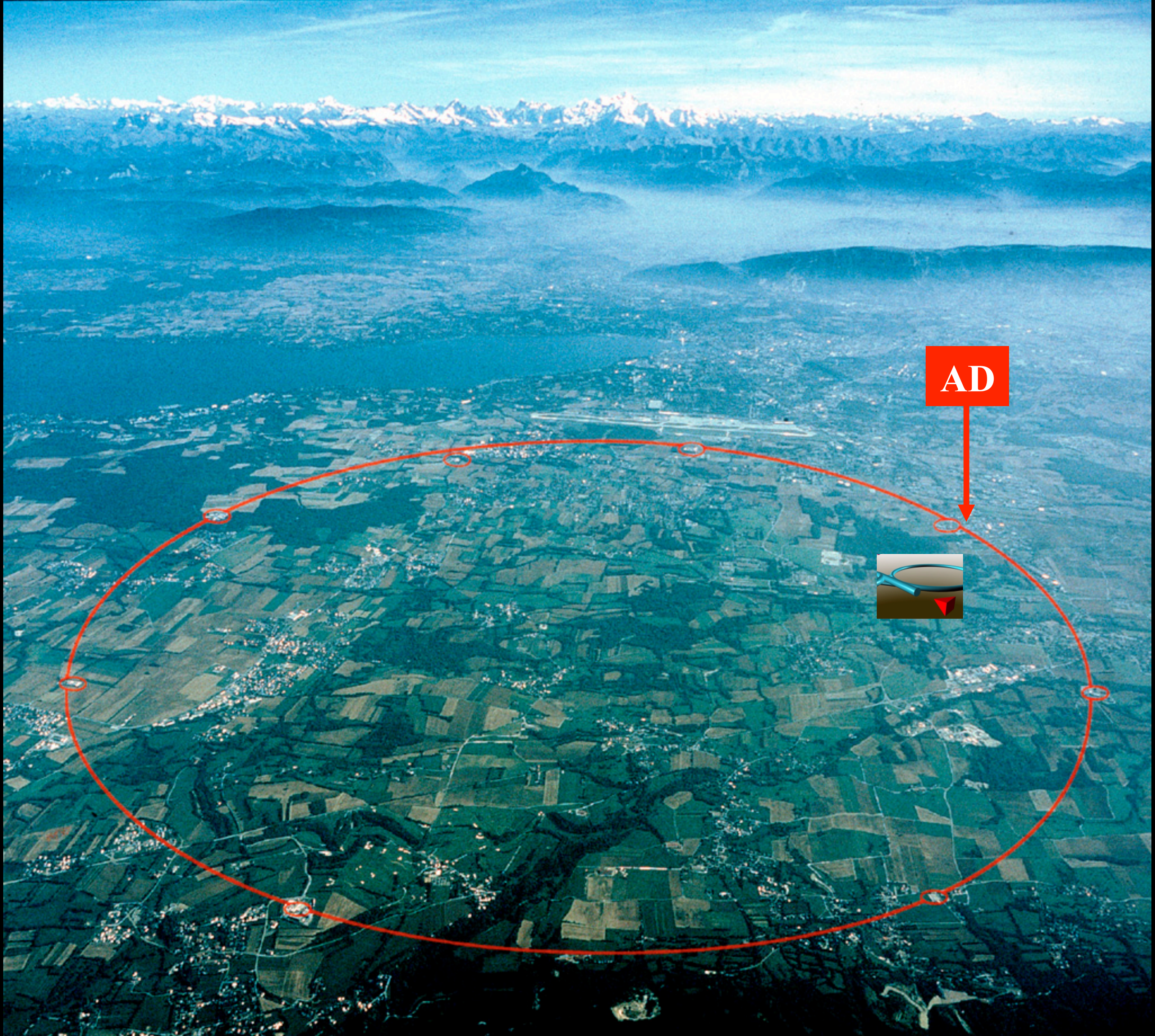
Experiments at CERN/AD


AD

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Experiments at CERN AD

ALPHA Antihydrogen Experiment

Makoto Fujiwara

From ATHENA to ALPHA

- ATHENA: produced first cold Hbars (2002)
    (They were not trapped)
  Completed data taking in 2004
- Developed into new experiments (2005)
  – Trapping and Spectroscopy of Hbars

~~**ALE**~~

~~Antihydrogen Laser Experiment~~

ALPHA

Antihydrogen Laser Physics Apparatus

ALPHA Collaboration

ALPHA

16 institutions, ~40-50 physicists

University of Aarhus, Denmark

Auburn University, USA

University of British Columbia, Canada

University of California Berkeley,

University of Calgary, Canada

University of Liverpool, U.K.

NRCN - Nucl. Res. Center Negev, Israel

CERN

Federal University of Rio de Janeiro, Brazil

Simon Fraser University, Canada

Stockholm University, Sweden

Swansea University, U.K.

Stockholm University

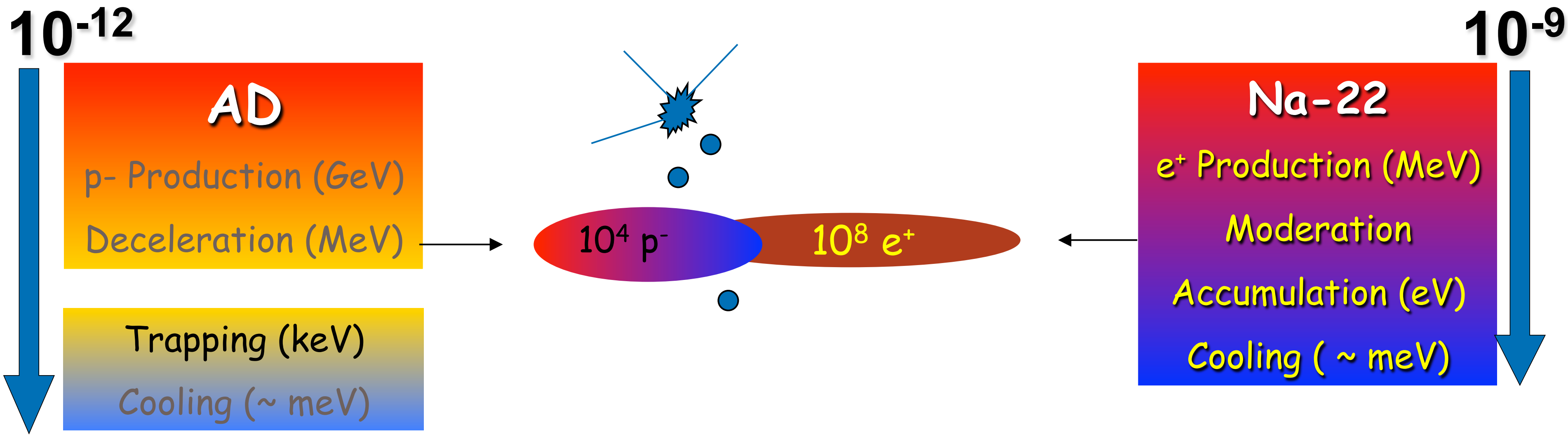
TRIUMF, Canada

York University, Canada

MANCHESTER 1824

The Cockcroft Institute of Accelerator Science and Technology

Producing & Trapping Antihydrogen



Producing & Trapping Antihydrogen

10^{-12}

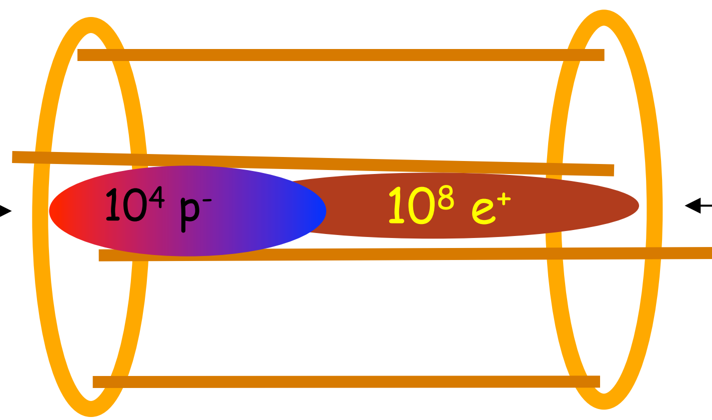
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



10^{-9}

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

Cooling (~ meV)

Superimpose Magnetic Trap

$$U = -\vec{\mu} \cdot \vec{B}$$

Challenge: Antihydrogen $kT >> \mu\, \Delta B$ (trap depth)

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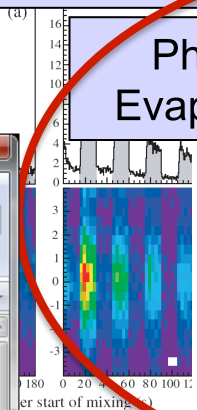
Progress since First Beam in 2006

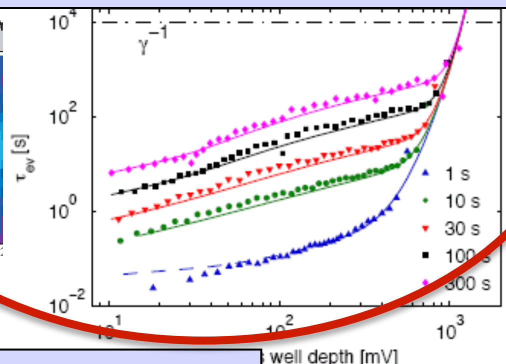
Phys. Rev. Lett. **98**, 023402 (2007)
Compatibility of Penning and Neutral traps

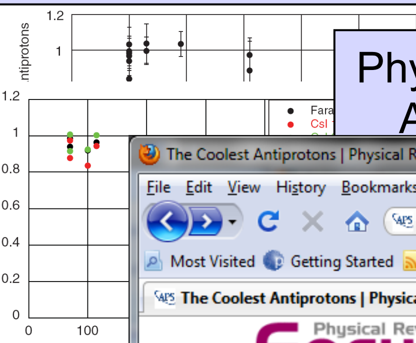
Phys. Rev. Lett. **101**, 053401 (2008)
Pulsed source of antihydrogen (ATHENA)

Phys. Rev. Lett. **100**, 203401 (2008)
Antiproton plasma manipulation

Phys. Rev. Lett. (2010), July 2
Evaporative cooling of antiprotons







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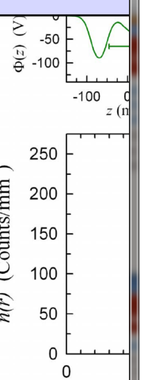
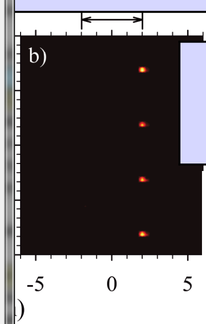
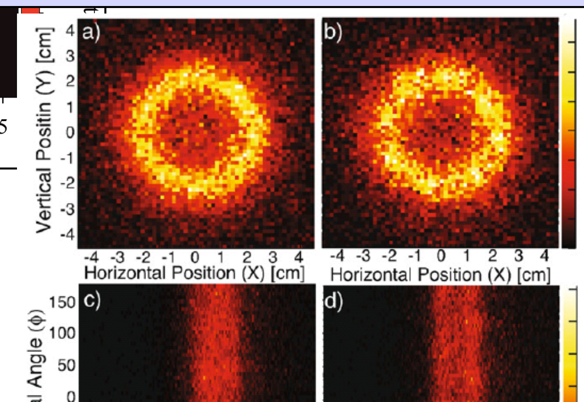
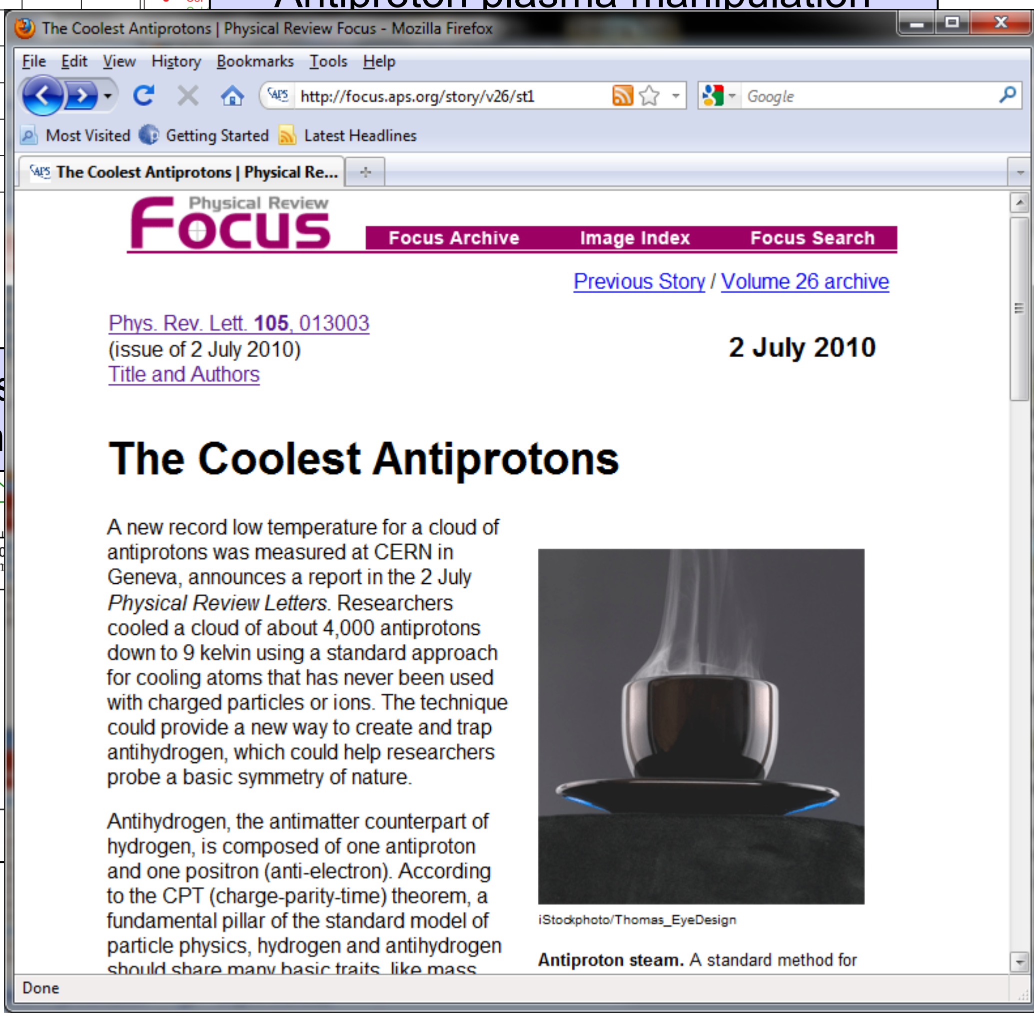


...Letters **16**, 100702
...asma resonances



Phys. Lett. B **685**, 141 (2010)
Anti-H production in atom trap





The Coolest Antiprotons | Physical Review Focus - Mozilla Firefox

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Phys. Rev. Lett. **105**, 013003
(issue of 2 July 2010)
Title and Authors

2 July 2010

The Coolest Antiprotons

A new record low temperature for a cloud of antiprotons was measured at CERN in Geneva, announces a report in the 2 July *Physical Review Letters*. Researchers cooled a cloud of about 4,000 antiprotons down to 9 kelvin using a standard approach for cooling atoms that has never been used with charged particles or ions. The technique could provide a new way to create and trap antihydrogen, which could help researchers probe a basic symmetry of nature.

Antihydrogen, the antimatter counterpart of hydrogen, is composed of one antiproton and one positron (anti-electron). According to the CPT (charge-parity-time) theorem, a fundamental pillar of the standard model of particle physics, hydrogen and antihydrogen should share many basic traits, like mass

iStockphoto/Thomas_EyeDesign

Antiproton steam. A standard method for

Done

Trapping Antihydrogen

Antihydrogen Trapped (for 172 ms)

Letter to Nature, Nov. 17, 2010

LETTER

doi:10.1038/nature09610

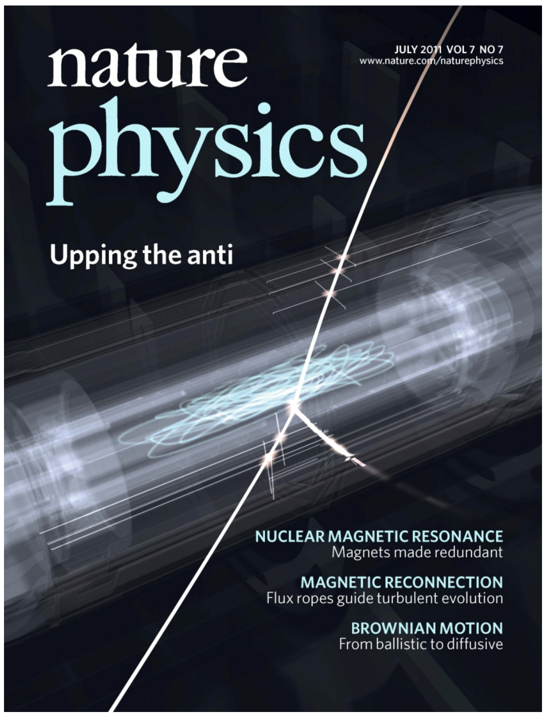
Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]

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

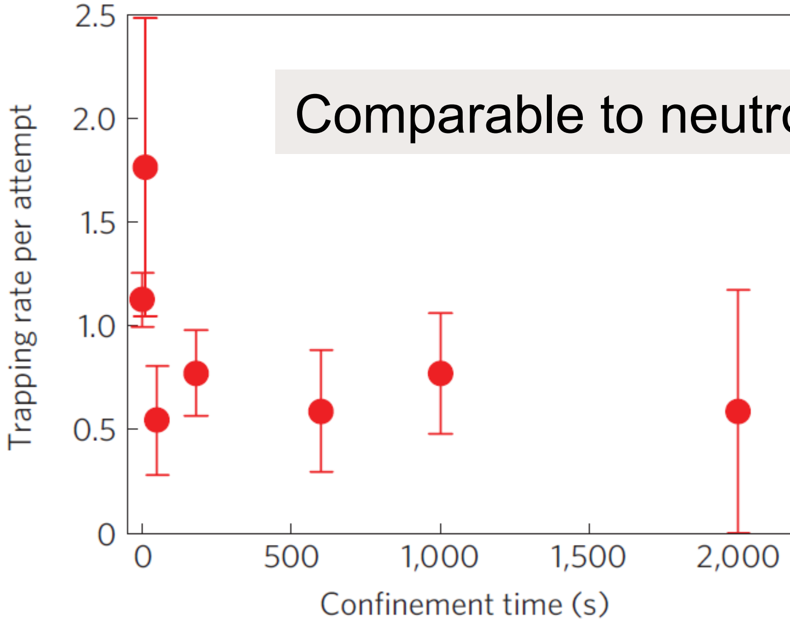
octupole has been shown to greatly
charged plasmas[9,10]. The liquid helium
cools the vacuum wall and the Pennin
measured to be at about 9 K. Antihydro
low enough kinetic energy can remain
rather than annihilating on the Pennin
can confine ground-state antihydrogen

Confinement of Antihydrogen for 1000 s



Nature Physics, July 2011 Issue

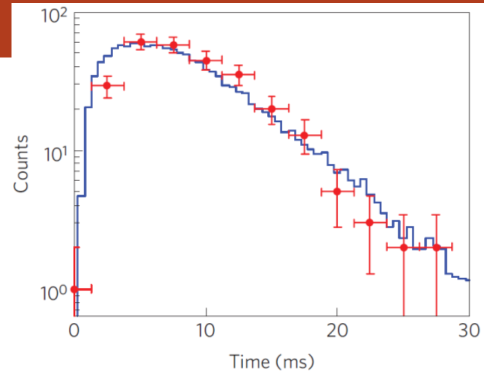
Principle author: Fujiwara



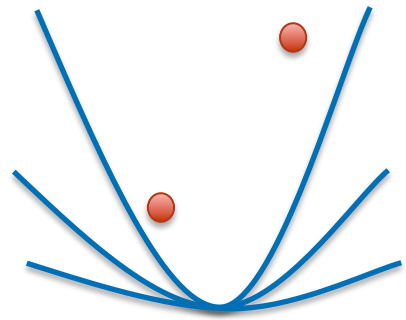
Comparable to neutron!

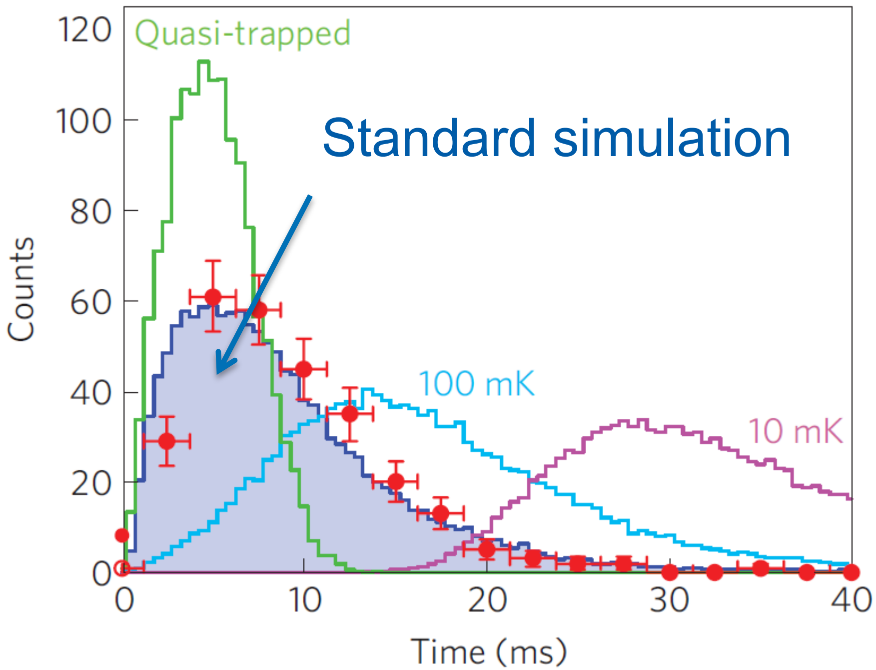
- Increased trapping rates by x5 (hard to tweak zero)
- Trapping time increased by x5000
- "Game changer"
  - Opens up many possibilities
- Detailed studies of dynamics

Results 4: kinetic energy of trapped Hbars



Release of trapped Hbar at *t*=0





- Colder Hbars come out later
- Data agree with simulated energy distribution
- Consistent with theory assuming Hbar produced at thermalized with e+ (~50 K)
- Source of very cold Hbars

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First “Spectroscopy” on Antihydrogen Atoms

March 2012

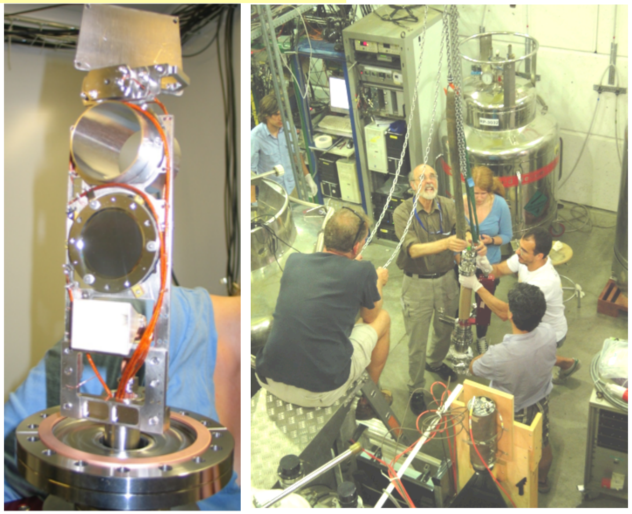
Ph.D. theses for

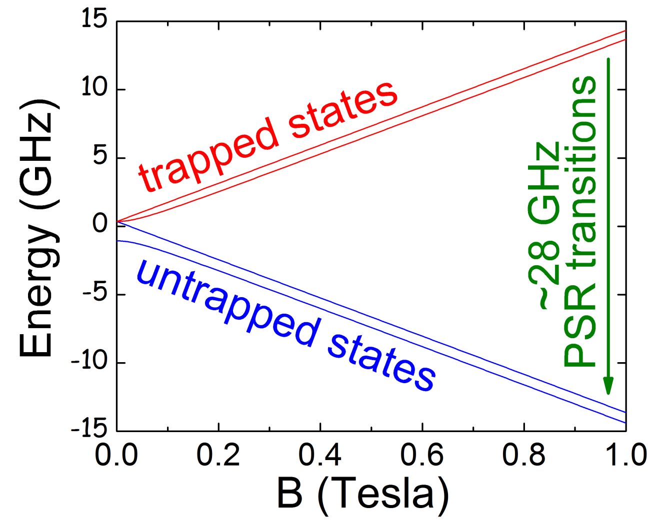
M. Ashkezari (Simon Fraser U)

T. Friesen (U Calgary)

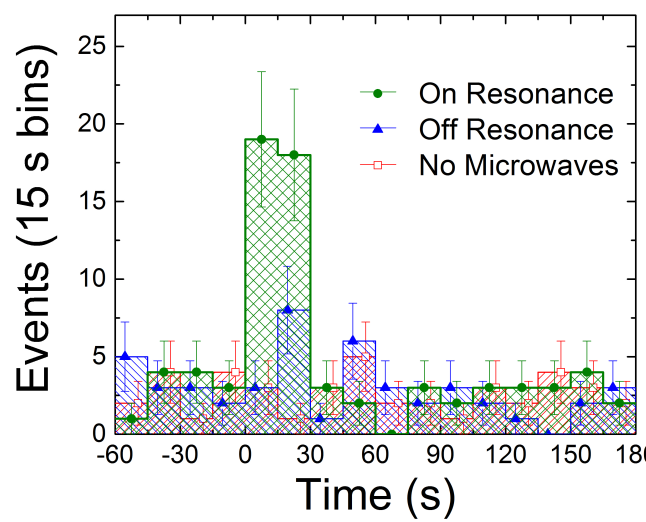
Microwave-induced Positron Spin Resonance (PSR)

Installation at CERN, July 2011





- μW system Developed at SFU/UBC
- Trap ~1 Anti-H/20 min
- Irradiate with μW
  - Drive transition:
    trapped → un-trapped
  - Look for annihilations
- Multivariate & blind analysis
  - improved S/N by x10



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Finally!

Letter to Nature, March 2012

nature International weekly journal of science

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Archive > Volume 483 > Issue 7390 > Letters > Article

ARTICLE PREVIEW

view full access options

NATURE | LETTER

previous article next article

Resonant quantum transitions in trapped antihydrogen atoms

C. Amole, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, A. Capra, C. L. Cesar, M. Charlton, A. Deller, P. H. Donnan, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, C. A. Isaac, S. Jonsell, L. Kurchaninov, A. Little, N. Madsen, J. T. K. McKenna, S. Menary, S. C. Napoli, P. Nolan, K. Olchanski, A. Olin, P. Pusa, C. Ø. Rasmussen, F. Robicheaux, E. Sarid, C. R. Shields, D. M. Silveira, S. Stracka, C. So, R. I. Thompson, D. P. van der Werf & J. S. Wurtele

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Affiliations | Contributions | Corresponding authors

Nature **483**, 439–443 (22 March 2012) | doi:10.1038/nature10942
Received 09 January 2012 | Accepted 07 February 2012 | Published online 07 March 2012

- First spectroscopic measurements on anti-H!!!
  - Limited precision: $O(10^{-3})$
  - Demonstrates it's possible to do spectroscopy on a single anti-atom at a time
  - "Historic!" – Nature Editor
  - Annihilation detection: key

Latest Result: June, 2014

Charge Neutrality of Antihydrogen

Is Antihydrogen Neutral?
Nature Comm. 5, 3955 (2014)

- We don't know why matter is neutral
  - Anomaly cancellation, GUT?
  - Experimentally, proton + electron = neutral to $<10^{-21}$
- Is antihydrogen neutral?
- CPT test: Is antiproton + positron neutral?
- "Weak link": positron charge

PDG 2012

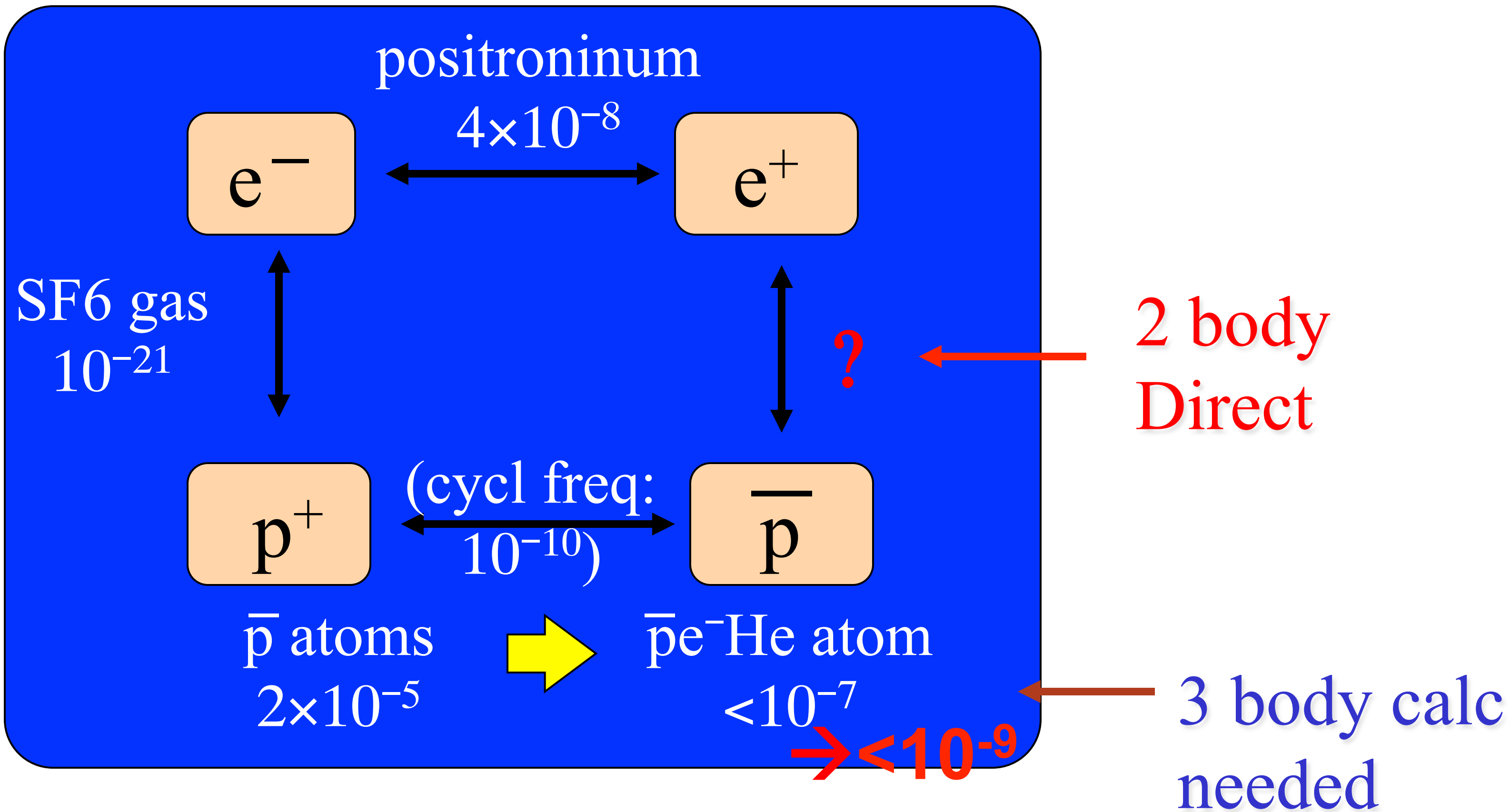
$|q_{e^+} + q_{e^-}|/e$

A test of *CPT* invariance. See also similar tests involving the proton.

VALUE	DOCUMENT ID		TECN	COMMENT
$<4 \times 10^{-8}$	[7] HUGHES	92	RVUE	
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-18}$	[8] SCHAEFER	95	THEO	Vacuum polarization
$<1 \times 10^{-18}$	[9] MUELLER	92	THEO	Vacuum polarization

[7] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.
[8] SCHAEFER 95 removes model dependency of MUELLER 92.
[9] MUELLER 92 argues that an inequality of the charge magnitudes would, through higher-order vacuum polarization, contribute to the net charge of atoms.

Experimental Limits on |δ*q*/*q*|



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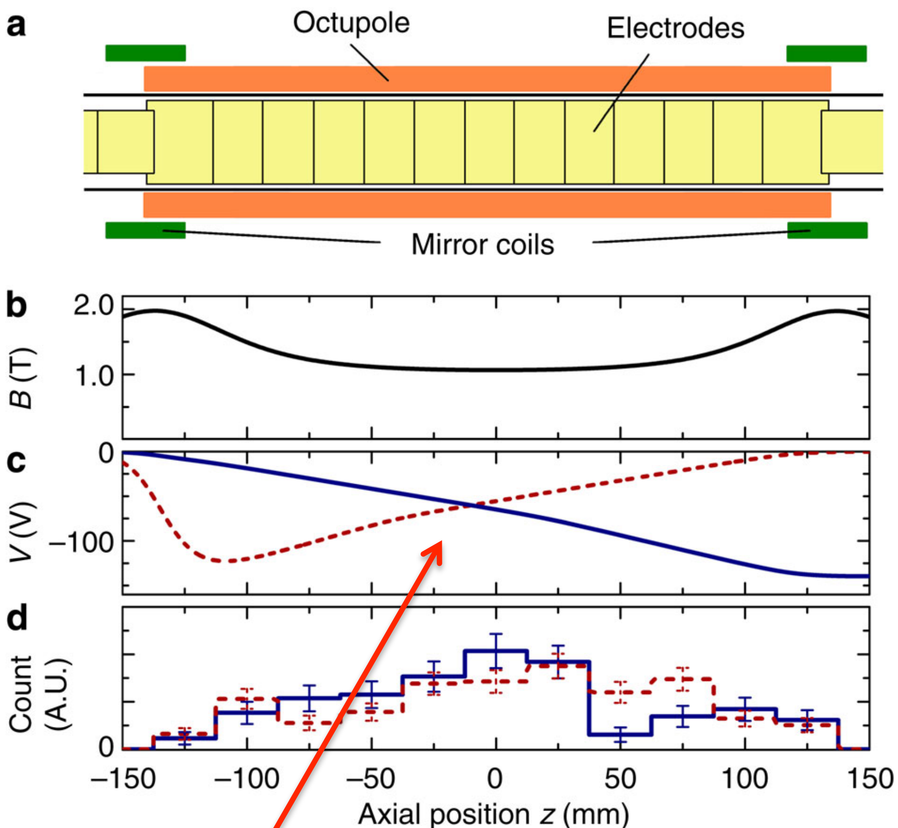
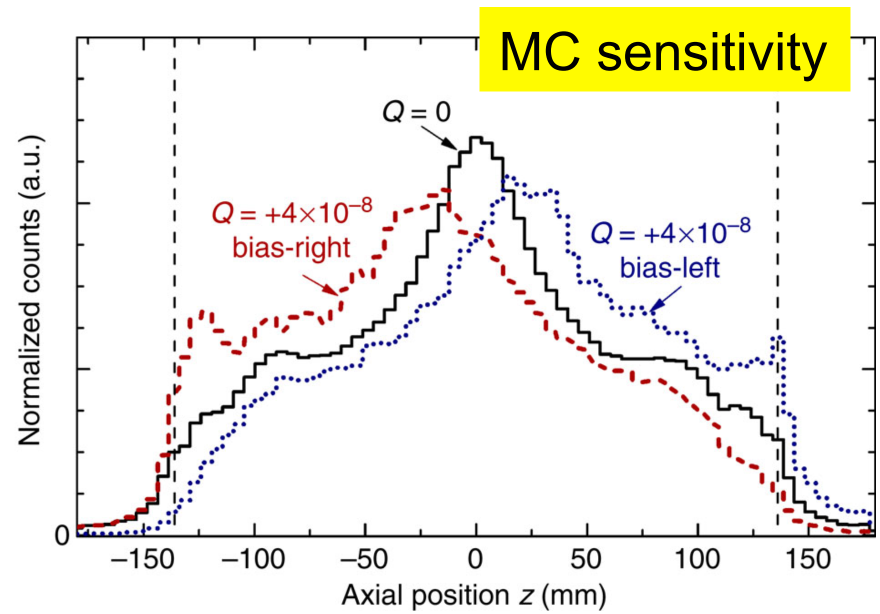
Charge Neutrality





Biasing E field, occasionally swapped (secretly)

Result (M. Baquero, Ph.D.):

$Q=(-1.3\pm1.1\pm0.4) \times 10^{-8}$

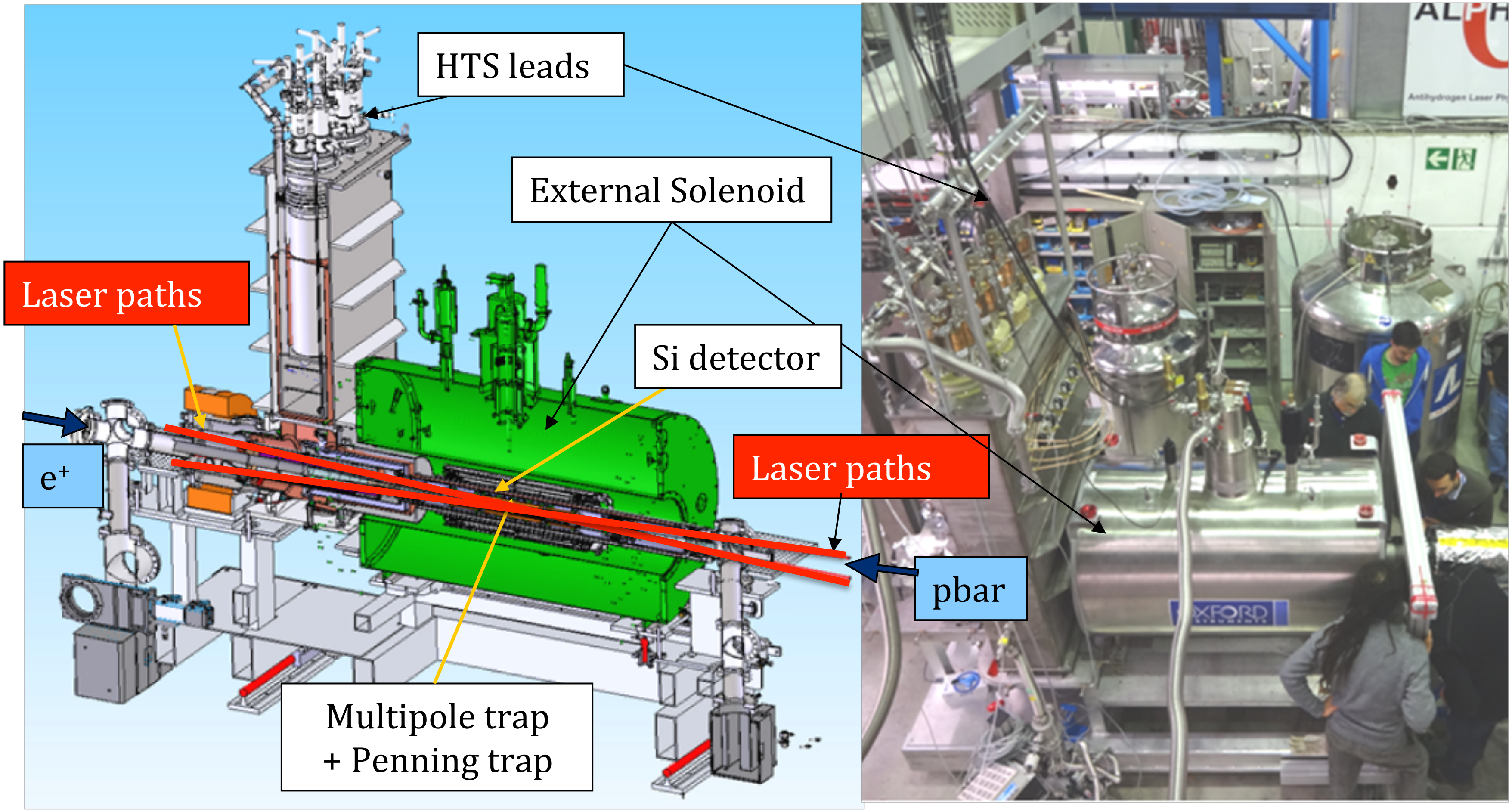
New limit on e+ charge

ALPHA's first precision result!

Current Status:
Precision Spectroscopy with ALPHA-2

Towards1s-2s laser spectroscopy &
Improved hyperfine spectroscopy

ALPHA-2: new precision physics machine



Laser access, improved magnetic fields
Improved cryostat
Separate antiproton trap

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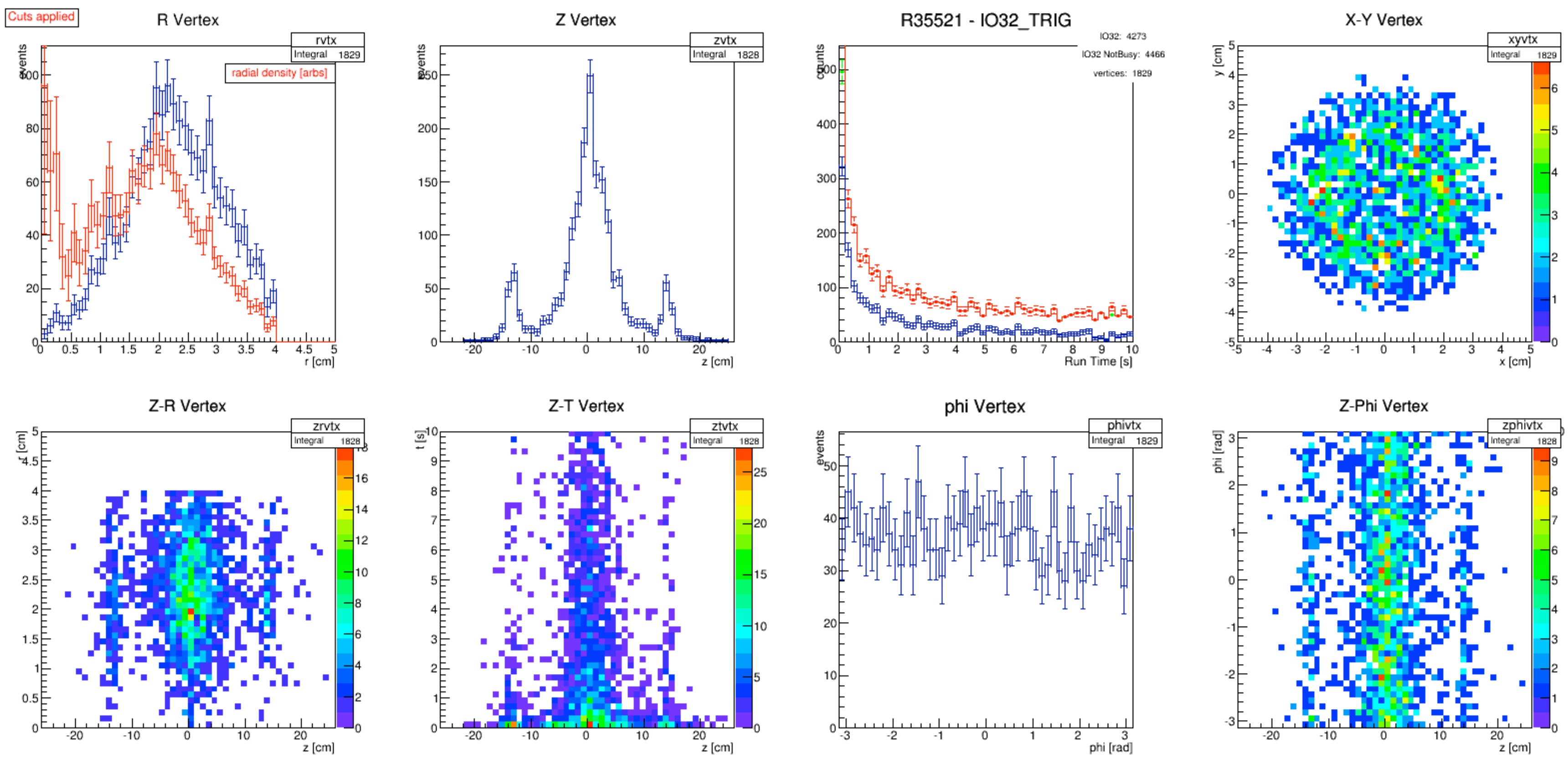
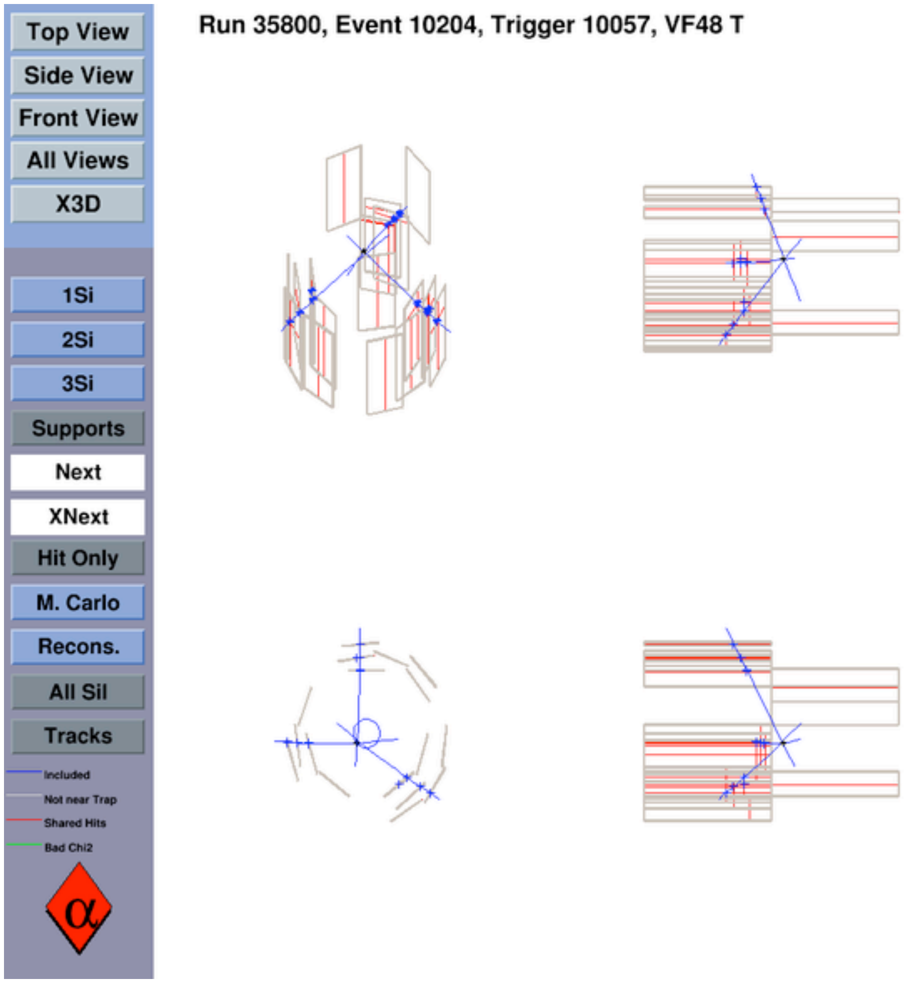
ALPHA-2 Status (Preliminary)

- Sep, 2014: AD beam resumed after 2 yr stop
- 4:00 am, Nov, 4th: mixing of pbar & e+
  - Produced antihydrogen "ATHENA style"



ALPHA-2 Status (Preliminary)

- 9:21 am, Nov 10^{th}, Evidence for trapped anti-H!



ALPHA-2 Status

- ALPHA-2 apparatus is successfully commissioned
- ALPHA-2 is ready for physics in 2015!
  - 1s-2s 243nm transition
  - 1s-2p 122nm transition and cooling
  - NMR microwave spectroscopy
  - Improved neutrality test
  - Towards gravity measurement

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Towards Measurement of Gravity on Antimatter

Makoto Fujiwara

Antimatter Gravity Measurement

- Gravity
  - Never measured with antimatter
  - Test of Weak Equivalence Principle
  - Very difficult experiment since gravity is so weak
- Now plausible due to long confinement time

nature physics ARTICLES
PUBLISHED ONLINE: 5 JUNE 2011 | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

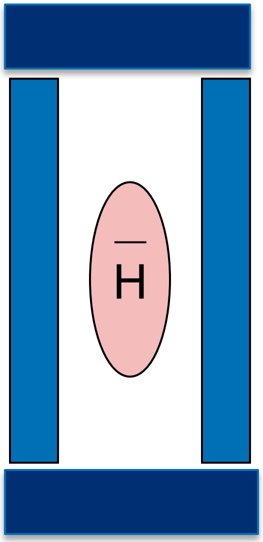
Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter–antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here, we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge–parity–time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.

Antimatter Gravity Experiment

- Very cold anti-H in a vertical trap
  - Anti-H "gas" will sag due to gravity
  - Need anti-H cooling to ~mK

    $1/2kT = mgh$

    $\text{Vertical trap}: h \sim 1\ m$
  - Position sensitive detection via annihilations
- Challenges
  - Only a few anti-atoms at a time
  - (anti)hydrogen inconvenient
    - Light mass
    - Transitions in Extreme UV
- Laser cooling essential step: development at UBC
- Conceptual design of experiment & detector in progress
  - NB: Cold atom tests of gravity: ~10^{-10}



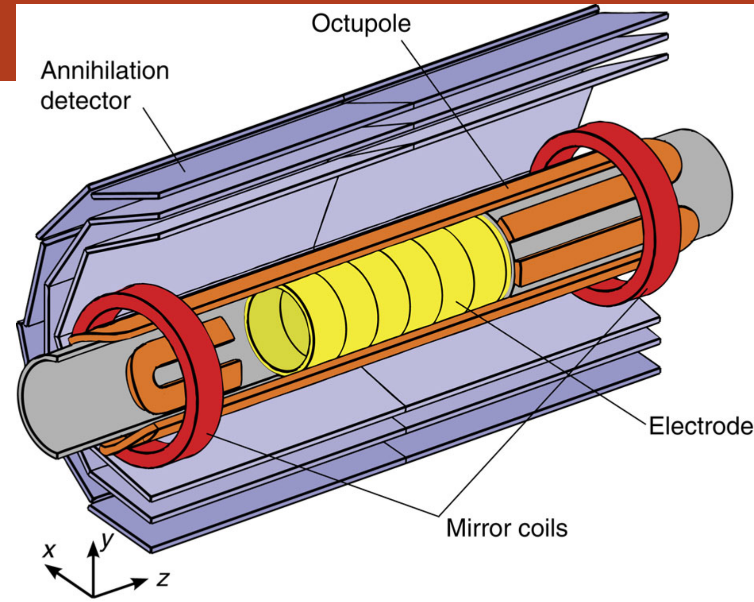
Vertical trap

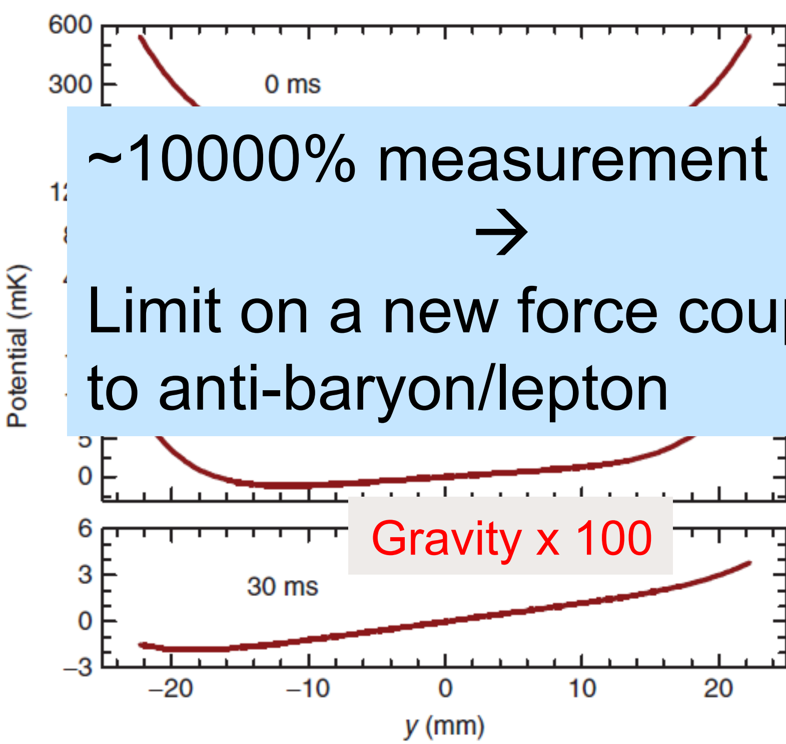
Towards gravity measurement

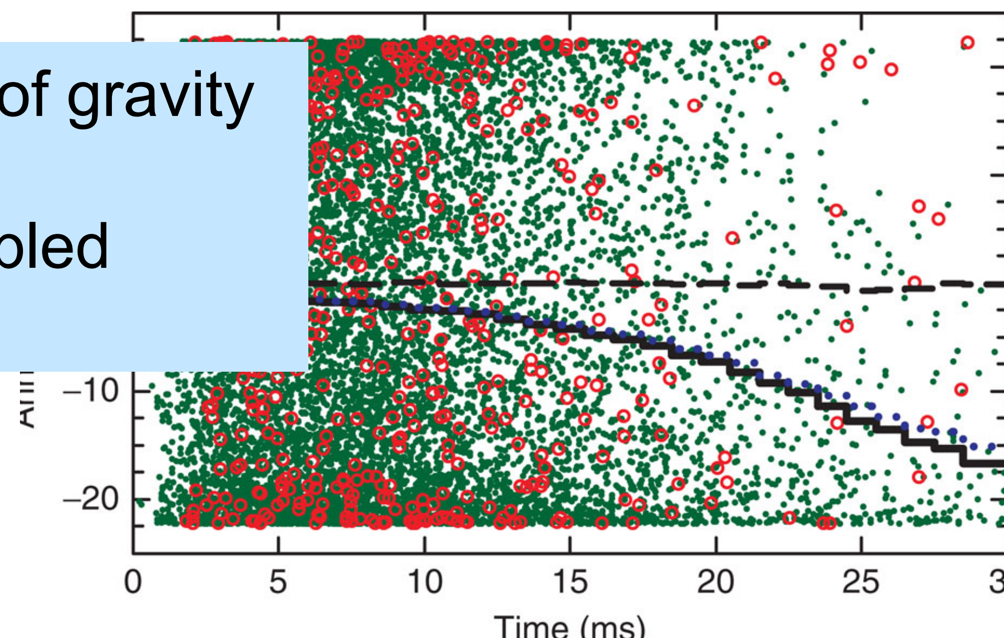
Possible gravity technique

[ALPHA, Nature Comm., 4, 1785 (2013)]

- Anti-H released by ramping down magnetic trap
- Late time events: colder, more sensitive to (anomalous)







~10000% measurement of gravity

→

Limit on a new force coupled to anti-baryon/lepton

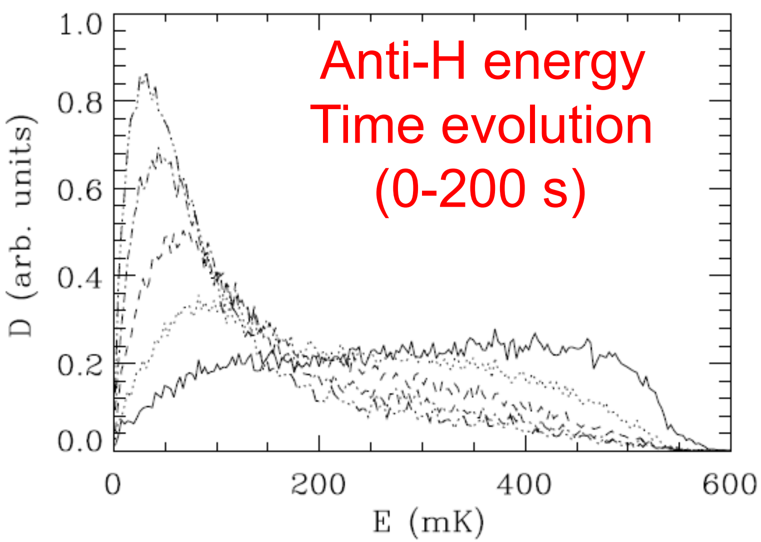
Gravity x 100

Proposals for Novel Techniques

Laser cooling

[Donnan, MCF, Robicheaux, J. Phys. B. 46, 205302 (2013)]

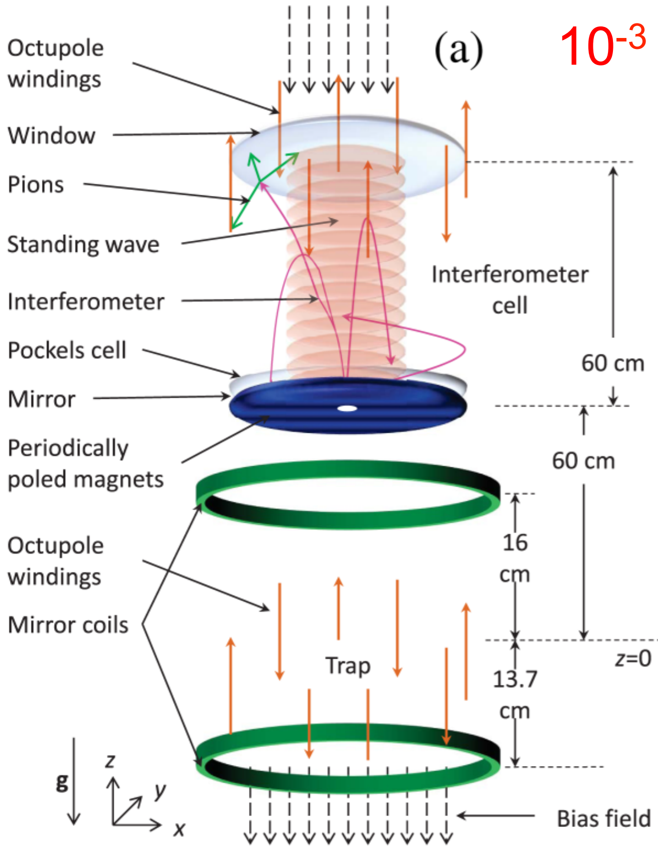
- Cooling on 1 dimension
- Use coupling of degrees of freedom for 3-D cooling
- Cooling from 500 mK to 20 mK
- Laser development at UBC



Anti-atom fountain & Anti-interferometer with 1 atom!

[Hamilton et al, Phys. Rev. Lett. (2014)]

10^{-3} to 10^{-6}?



Summary

- Antihydrogen CPT and Gravity Tests address fundamental questions in the LHC era
- Number of exciting expt's on AD floor at CERN
- In ALPHA, we have:
  - Trapped antihydrogen atoms (2010)
  - Confined them for 1000 s (2011)
  - First spectroscopy measurement (2012)
  - Method for gravitational test (2013)
  - Charge neutrality (2014)
  - Constructed ALPHA-2 for laser spectroscopy & cooling (2015)
  - Designing a dedicated gravity experiment: ALPHA-g
- ELENA in 2017
- Exciting future ahead!
- Excellent students graduating → photos

TRIUMF Our Hard-working Students Recognized

CERN Homepage
"Andrea Gutierrez, Ph.D. student from UBC"

Hydomako Thesis (Calgary) **published** as book: Springer "Best of Best" Thesis Series (20 downloads, since Jan.)

Finnish paper

CBC News

CBC News

CBC TV

Calgary Sun

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