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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

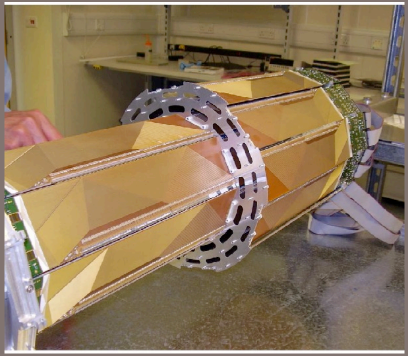
ALPHA Antihydrogen Experiment

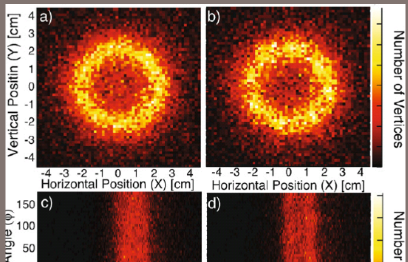
TRIUMF Science Week, July 13, 2017

Makoto C. Fujiwara

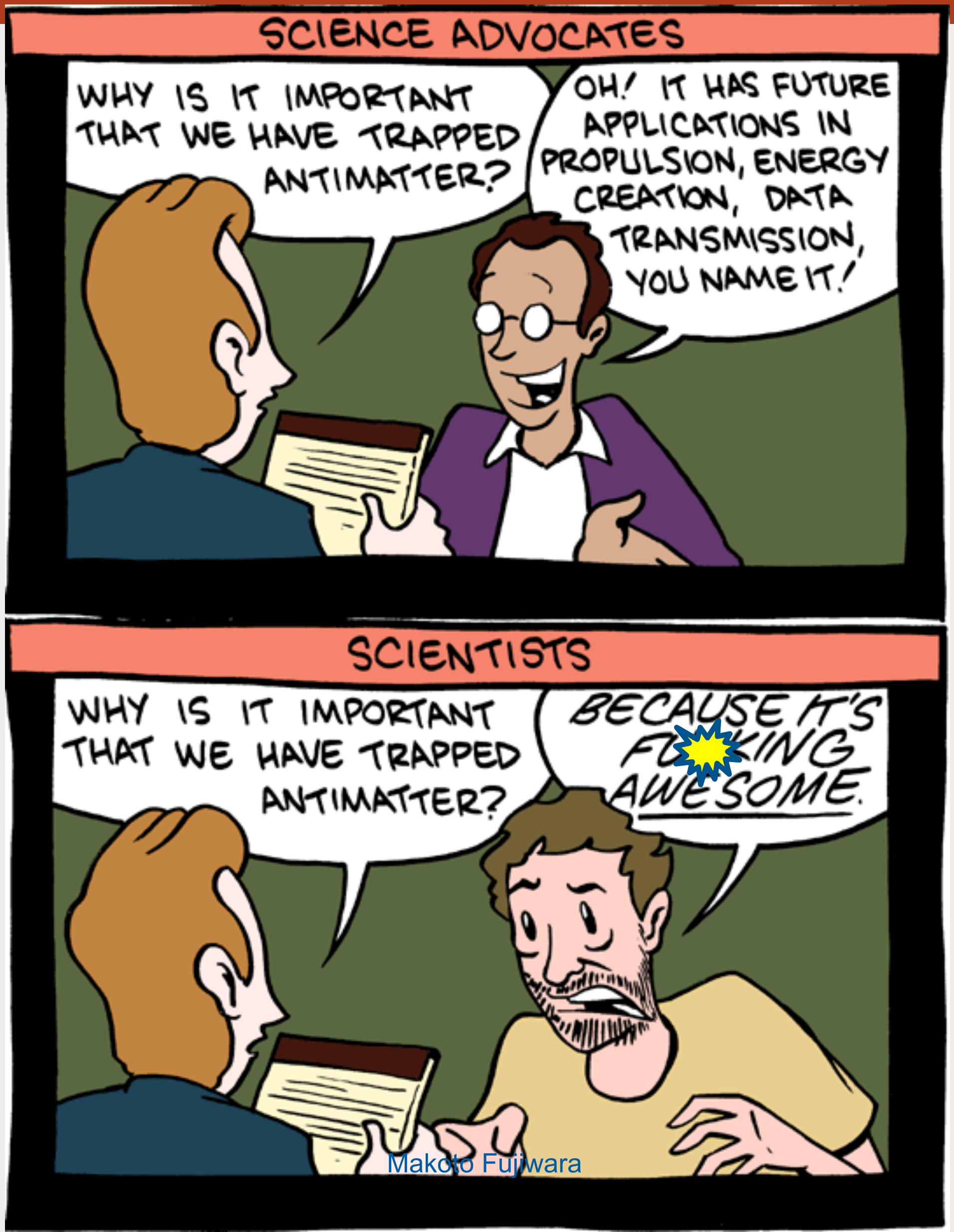
Senior Scientist & Head, Particle Physics
Deputy Associate Lab Director, Physical Sciences

TRIUMF – Canada's National Lab for Particle & Nuclear Physics





Confession



SCIENCE ADVOCATES
WHY IS IT IMPORTANT THAT WE HAVE TRAPPED ANTIMATTER?
OH! IT HAS FUTURE APPLICATIONS IN PROPULSION, ENERGY CREATION, DATA TRANSMISSION, YOU NAME IT!
SCIENTISTS
WHY IS IT IMPORTANT THAT WE HAVE TRAPPED ANTIMATTER?
BECAUSE IT'S FU KING AWESOME.

"Big Questions"

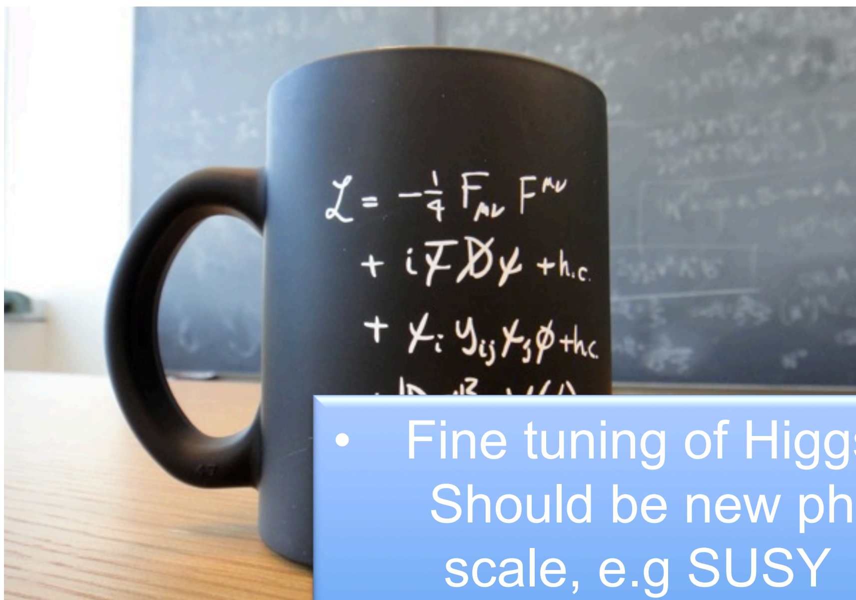
What is Particle Physics?

(e.g. Grossman)

$$\mathcal{L} = ?$$

"Simple Answer"

The Standard Model! is (technically) unnatural ...



- Fine tuning of Higgs mass
  Should be new physics at TeV scale, e.g SUSY
- Other issues
  - Cosmological constant
  - Dark matter
  - Flavor, CP
  - Charge quantization, etc.

Are we asking right question?

"L=?" really right question to ask?

Is Quantum Field Theory correct description of Nature?

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Motivations: Symmetries

Quantum Field Theory ⟷ CPT Symmetry ⟷ H & anti-H Spectra

- CPT: Fundamental property of QFT
  - Theorem: atomic spectra of H & anti-H identical
  - NB: QED tests limited by fundamental constants

General Relativity ⟷ Equival. Principle ⟷ H & anti-H Free fall

- Einstein's Equivalence Principle
  - Matter and Antimatter fall in same way

Any violation would force radical change in theory!

Where do you look when asking Big Questions?

ALPHA: Rare Isotope Physics!

$$ {}^{1}_{1}\mathrm{H} \longrightarrow {}^{-1}_{-1}\mathrm{H} $$

ALPHA Potential CPT Sensitivity (model dep't!)

Possible CPTV shift (Pospelov)

$$\Delta E \sim \frac{m^{n+1}}{\Lambda^n_{CPTV}}$$

Small absolute energy ΔE

→ probes high energy scale

For n=1, m=1 GeV,

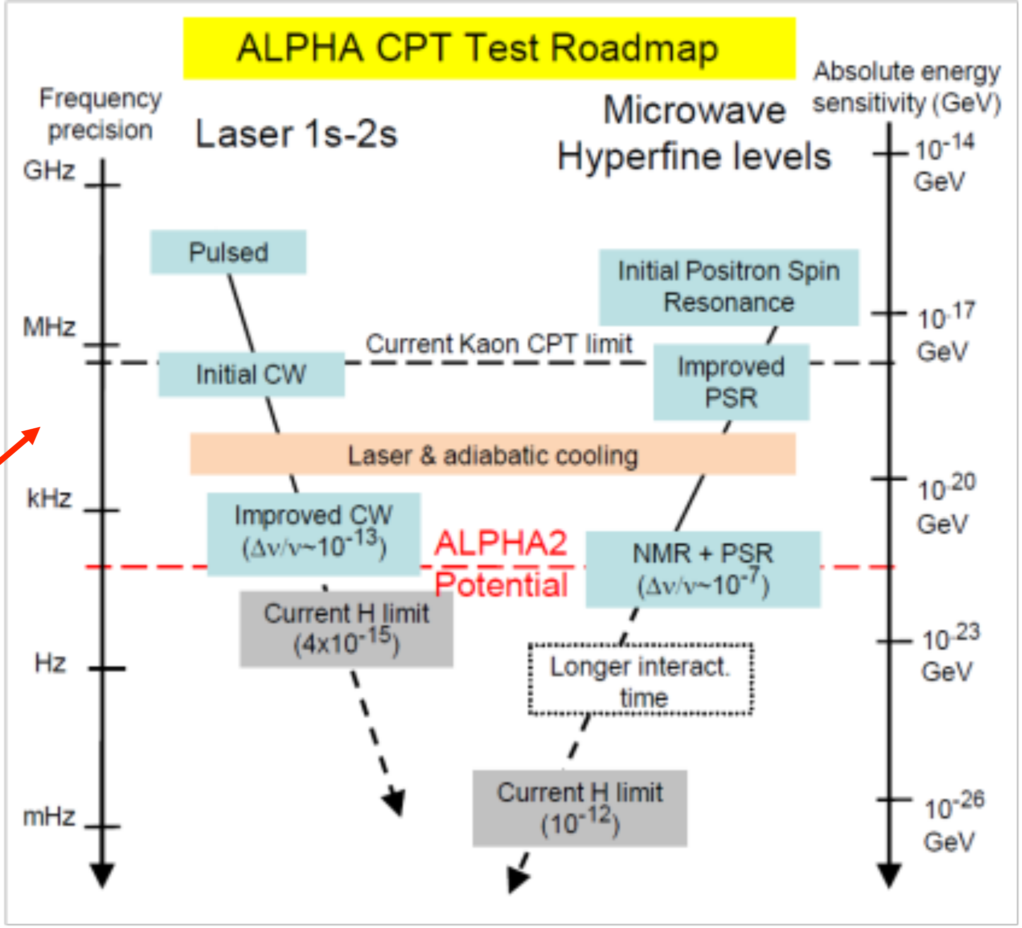
$\Lambda_{CPTV} = M^*_{Pl} \sim 10^{18}$ GeV

$\Delta E_{CPT} \sim 10^{-18}$ GeV

(~100 kHz in frequency)

Neutral Kaon test at few 100 kHz

Antihydrogen studies potentially sensitive to Planck-suppresed physics!



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Cold Antihydrogen Brief History

- 1999: Antiproton Decelerator at CERN
- 2002: Production of cold anti-H (ATHENA) [*Nature*]
- 2004: ALPHA LOI
- 2006: ALPHA first beam
- 2010: Trapping of anti-H [*Nature*]
- 2011: Confinement for 1000 s [*Nature Phys.*]
- 2012: First spectroscopy via microwaves (10^{-3}) [*Nature*]
- 2012-14: Construction of ALPHA-2
- 2016: Charge neutrality of anti-H (10^{-9}) [*Nature*]
- 2017: First laser spectroscopy (10^{-10}) [*Nature*]
- 2017: x200 improved microwave [*Nature (in press)*]

Production of cold antihydrogen

(ATHENA, ATRAP 2002)

10^{-12}

AD

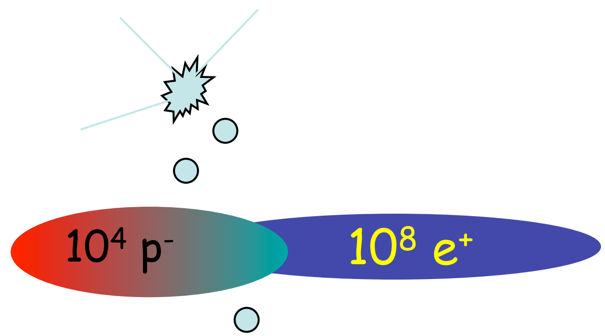
p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)

Gabrielse



10^{-9}

Na-22

e^+ Production (MeV)

Moderation

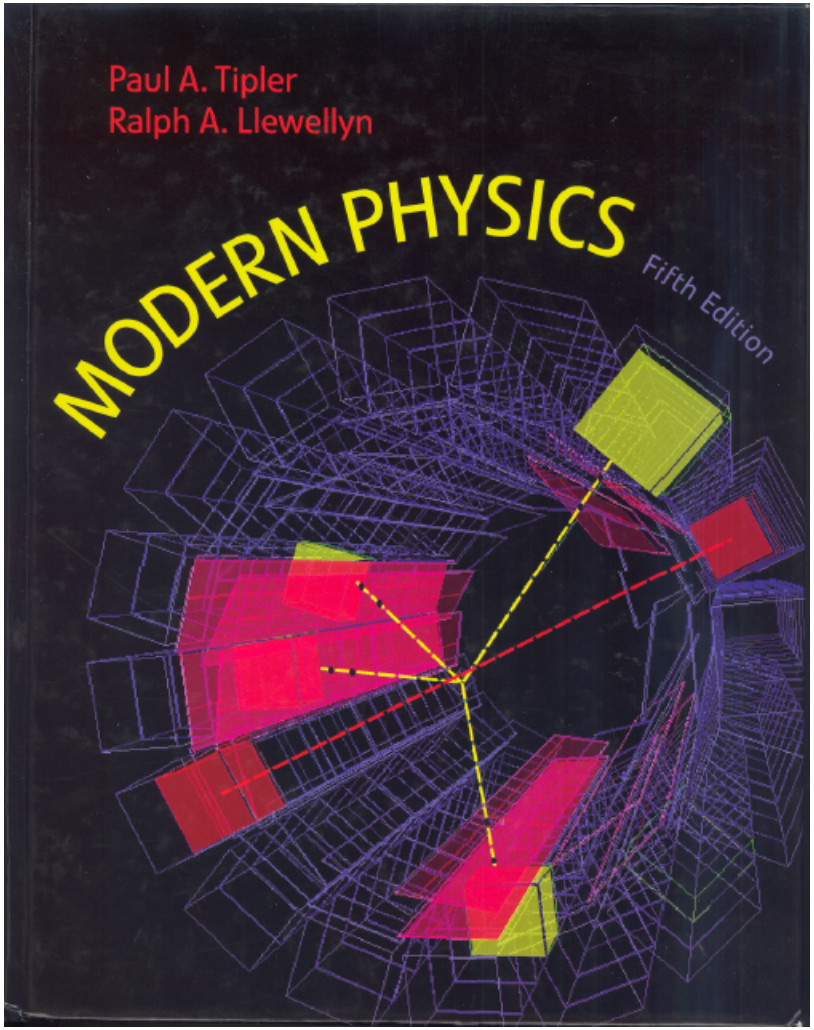
Accumulation (eV)

Cooling (~ meV)

Surko

Key features:
Particle detector

Cold Antihydrogen: ATHENA, ATRAP (2002)



- Anti-H annihilation event (Nature, 2002): now on the cover of textbook!

- $107.28 on Amazon.com

From ATHENA to ALPHA

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

~~**ALE**~~

~~Antihydrogen Laser Experiment~~

ALPHA

Antihydrogen Laser Physics Apparatus

Also Microwaves, Gravity, Charge…

ALPHA Collaboration

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

ALPHA

- 16 institutions
- ~40 physicists

ALPHA-Canada

- ~40% of ALPHA
- 11 Faculty/Scientists/Staff
- Several PDF/Students
- Particle detection, microwave spectroscopy, laser cooling

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Producing & Trapping Antihydrogen

10^{-12}

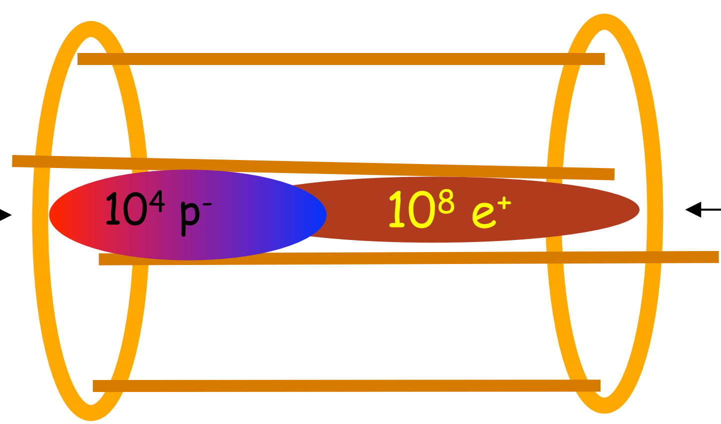
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (~ meV)



10^{-9}

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

Cooling (~ meV)

<u>Superimpose Magnetic Trap</u>

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

Anti-H Trapping Challenges

Characteristic energy scales:

- Plasma energy: space charge ($\propto e n_e r^2$) ≈ 10 eV
- Neutral trap depth:

  ($\mu \Delta B$) ≈ 50 μeV
- Need 10^{-5} control of plasmas to make cold enough anti-H

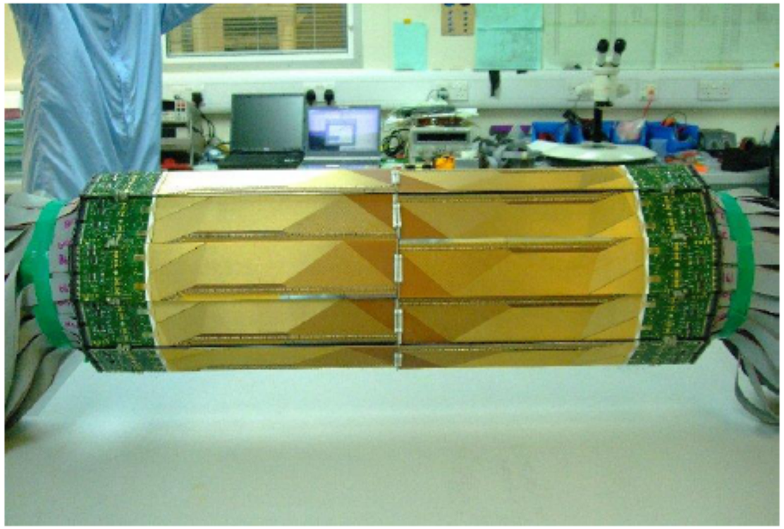
- ATHENA's anti-H production was much easier!

  Atomic energy scale: ($m_e \alpha^2$) 10 eV

  ≈ Plasma space charge 10 eV

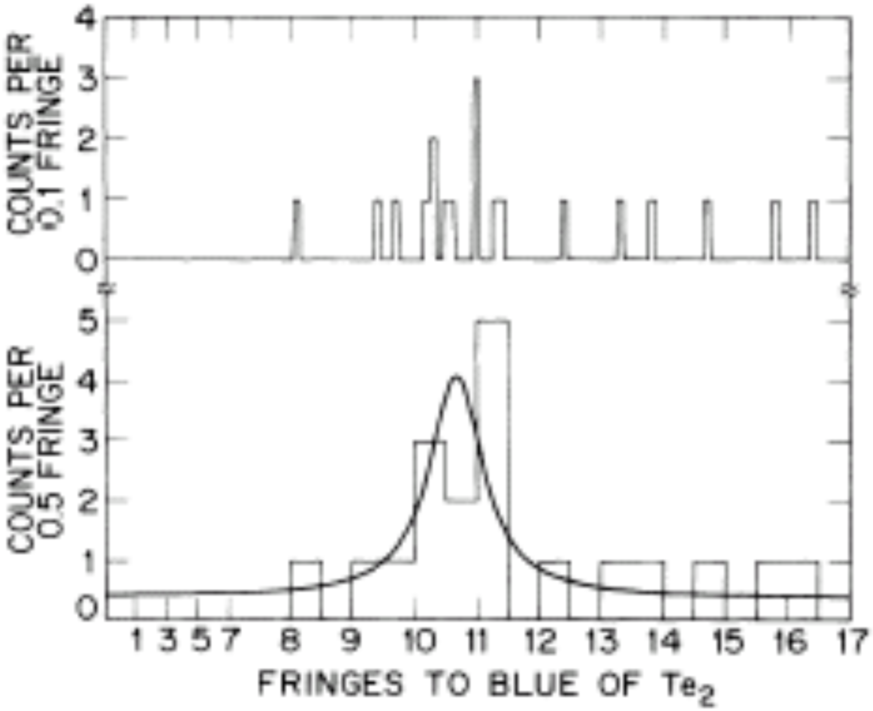
Detection of anti-H trapping

- Expected event rates very low
- Statistics & backgd limited



30,000 channel 3-layer Si strips
~0.8 m^2 active area
Liverpool + ALPHA Canada
Position Sensitivity Essential

Detecting Rare Events with Exotic Atoms

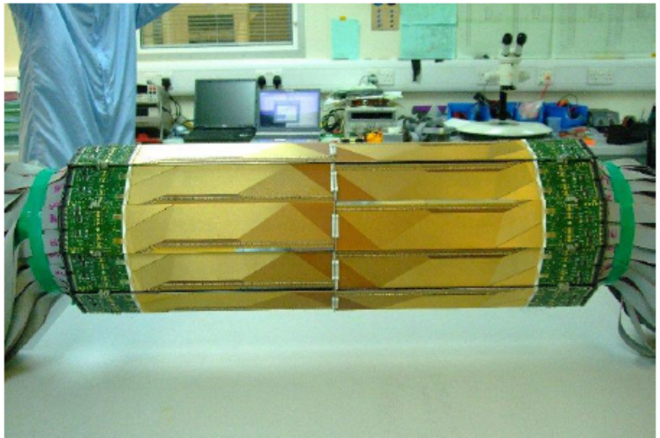


Muonium (μ+ e-)
1S-2S spectroscopy
Chu, Mills et al.
Phys. Rev. Lett. (1988)

~8 events!

Subatomic Physics Techniques/Expertise

- ALPHA optimized for particle detection
  - Distinctive feature among AD expt's
  - Position sensitive annihilation detection with 37,000 channel Si strips
- Software & analysis
  - DAQ & all software incl. tracking, MC
  - Introduced blind analysis
  - Machine learning techniques
- Exotic atom physics
  - Canadian expertise: muonic, pionic, kaonic, antiprotonic atoms
  - Doing experiment with very few atoms
- All this helps make us competitive! (so far)



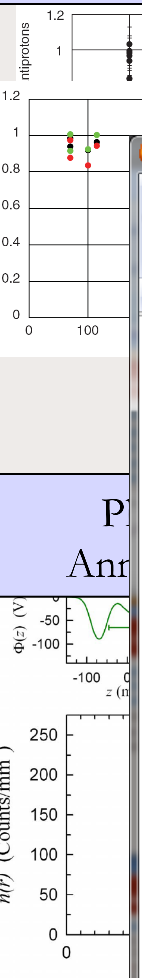
Progress since First Beam in 2006

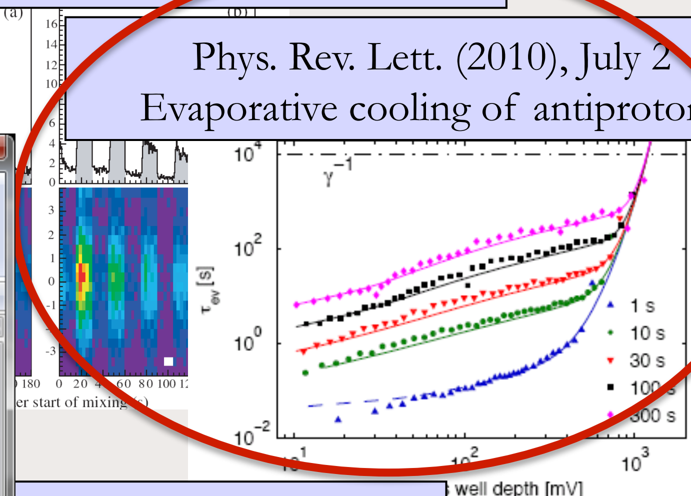
Phys. Rev. Lett. **98**, 023402 (2007)
Compatibility of Penning and Neutral traps

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

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

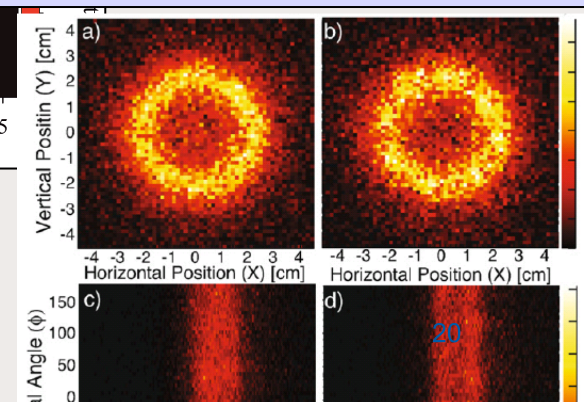
Phys. Rev. Lett. (2010), July 2
Evaporative cooling of antiprotons





…s **16**, 100702 (2009) New 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

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]

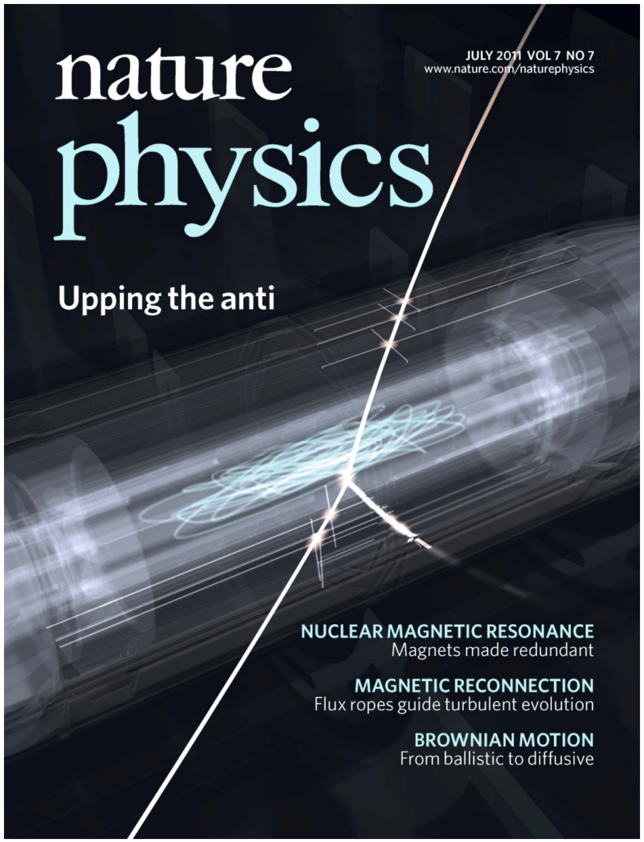
Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at 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 heliun
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 antihydroger

Among top news stories in 2010

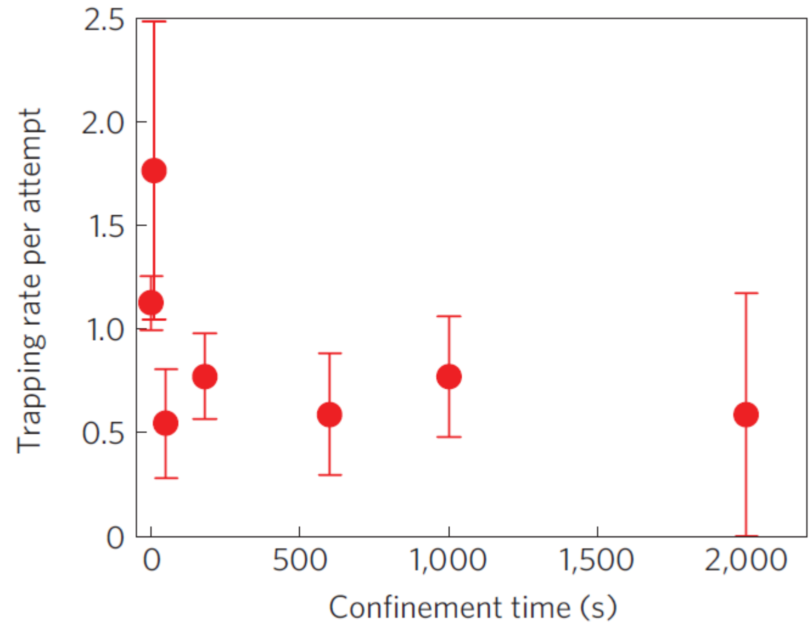
- #1 Physics Breakthrough: PhysicsWorld
- #1 Most read news: Nature
- #2 Science News: CBC National

Confinement of Antihydrogen for 1000 s



Cover, Nature Physics, July 2011 Issue

Principle author: MCF



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

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Canadian-led Success!

Letter to Nature, March 2012
Principle Author: Mike Hayden (SFU)

nature International weekly journal of science

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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
Show fewer authors

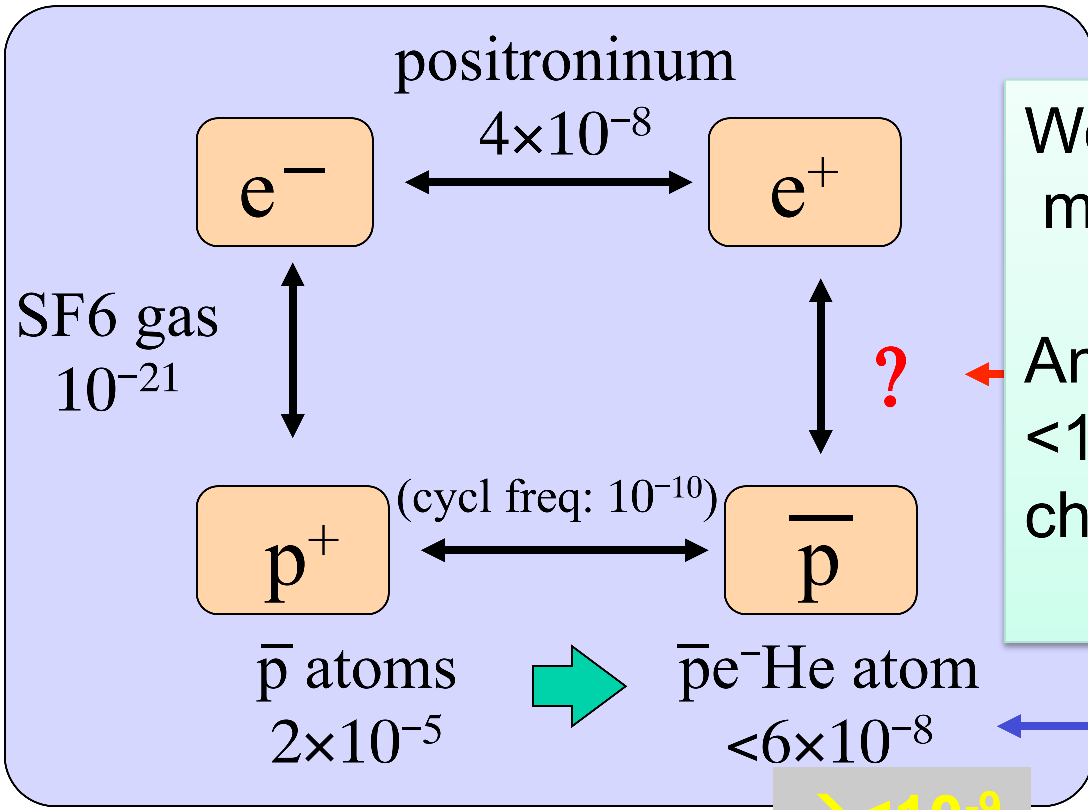
Affiliations | Contributions | Corresponding authors

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

Experimental Limits on $|\delta q/q|$

Slide from 2002!



We don’t know why matter is neutral

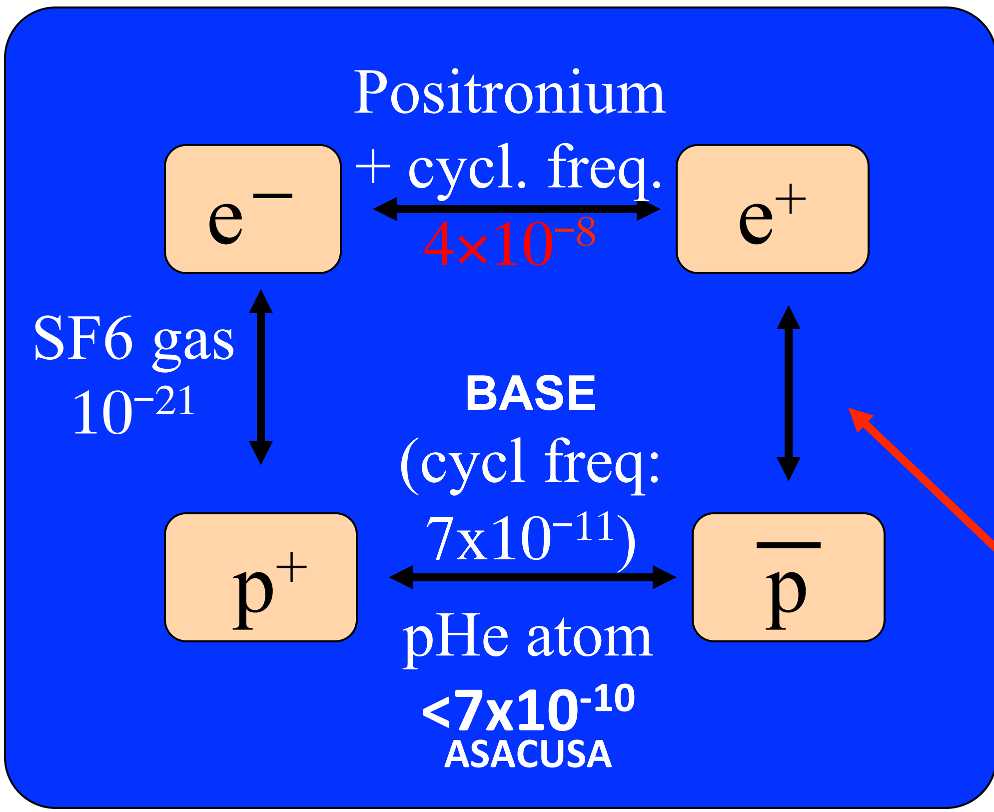
Anti-H neutrality meas. $<10^{-8}$ would improve e+ charge

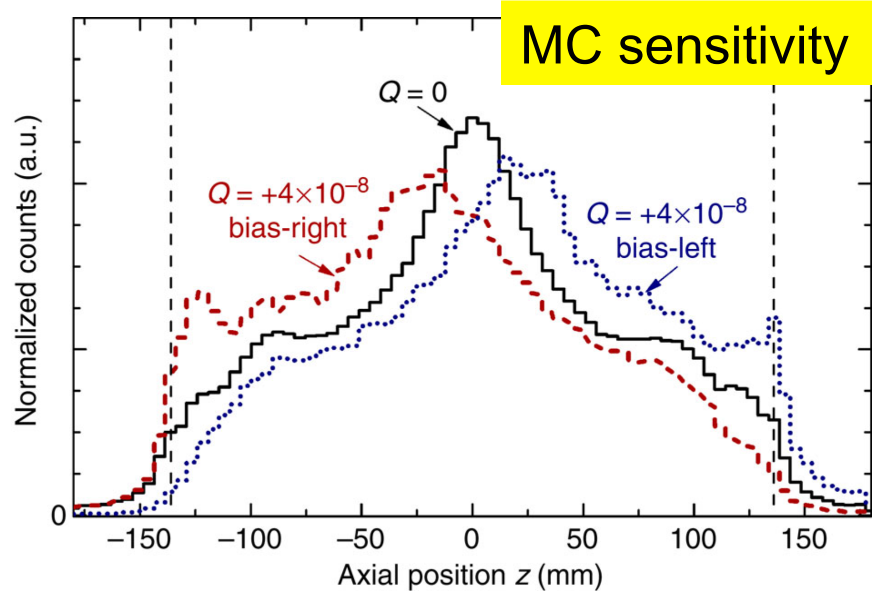
3 body calc. needed

→ $<10^{-9}$ in 2014

Experimental Limits on $|\delta Q/Q|$

(Nature Comm. 2014, Nature 2016)





Anti-H neutrality tests:

2014 (ALPHA-1): Q<~10^{-8}

2016 (ALPHA-2): Q<0.7×10^{-9}

New e+ charge limit ~10^{-9}

(40 fold improv't over PDG)

What about e+ mass?

PDG 2014 $< 8 \times 10^{-9}$

$(m_{e^+} - m_{e^-}) / m_{\text{average}}$

A test of *CPT* invariance.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8 \times 10^{-9}$	90	[6] FEE	93	CNTR	Positronium spectroscopy
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<4 \times 10^{-23}$	90	[7] DOLGOV	14		From photon mass limit
$<4 \times 10^{-8}$	90	CHU	84	CNTR	Positronium spectroscopy

[6] FEE 93 value is obtained under the assumption that the positronium Rydberg constant is exactly half the hydrogen one.

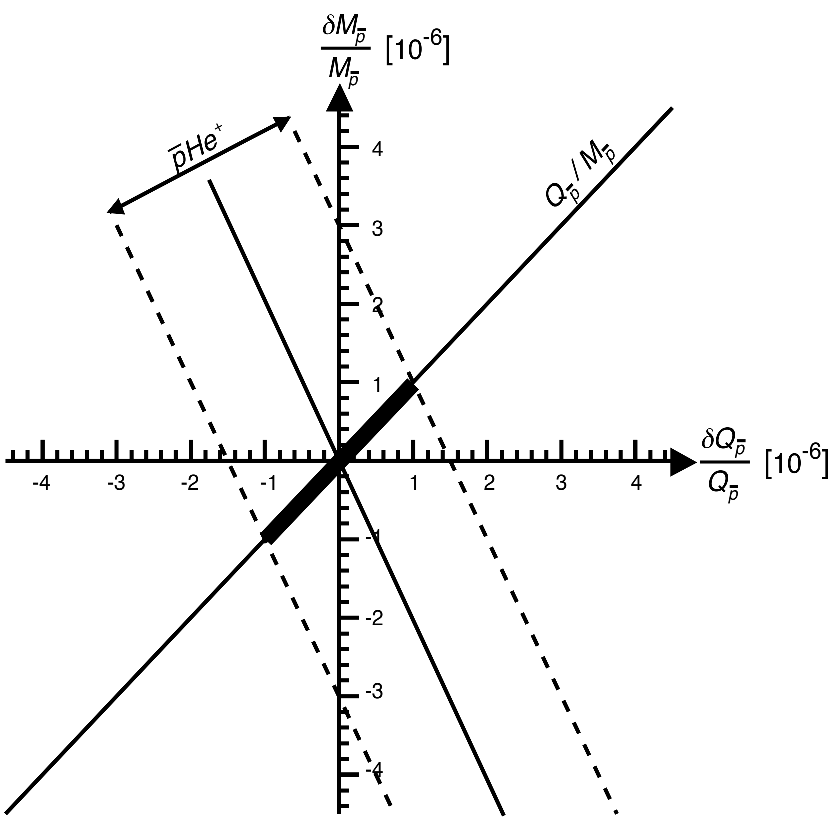
[7] DOLGOV 14 result is obtained under the assumption that any mass difference between electron and positron would lead to a non-zero photon mass. The PDG 12 limit of 1×10^{-18} eV on the photon mass is in turn used to derive the value quoted here.

I have issues with PDG and Fee, Chu et al.!

1. PDG "assumption that the Ps Rydberg is exactly half of the hydrogen one" does not make sense
2. It seems FEE93 assumed incorrect sensitivity between Δfreq(1s-2s) and $\Delta m_{e+}/m_e$
3. e+ mass & charge should be treated independently
4. Not clear if the limit is 90% CL rather than 1σ

Pbar mass & charge from ASACUSA pbar-He

T. Yamazaki et al. / Physics Reports 366 (2002) 183–329



Toshi et al: pbar mass & charge should be treated independently

Since 2000, PDG has done so!

PDG2000

$|m_p - m_{\bar{p}}| / m_p$

A test of *CPT* invariance. Note that the $\bar{p}/p$ charge-to-mass ratio, given below, is much better determined.

VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<5 × 10^{-7}	[3] TORII	99	SPEC	$\bar{p}e^-$He atom

[3] TORII 99 uses the more-precisely-known constraint on the $\bar{p}$ charge-to-mass rati GABRIELSE 95 (see below) to get this result. This is not independent of the TORI value for $|q_p + q_{\bar{p}}|/e$, below.

$|q_p + q_{\bar{p}}| / e$

A test of *CPT* invariance. Note that the $\bar{p}/p$ charge-to-mass ratio, gi above, is much better determined. See also a similar test involving electron.

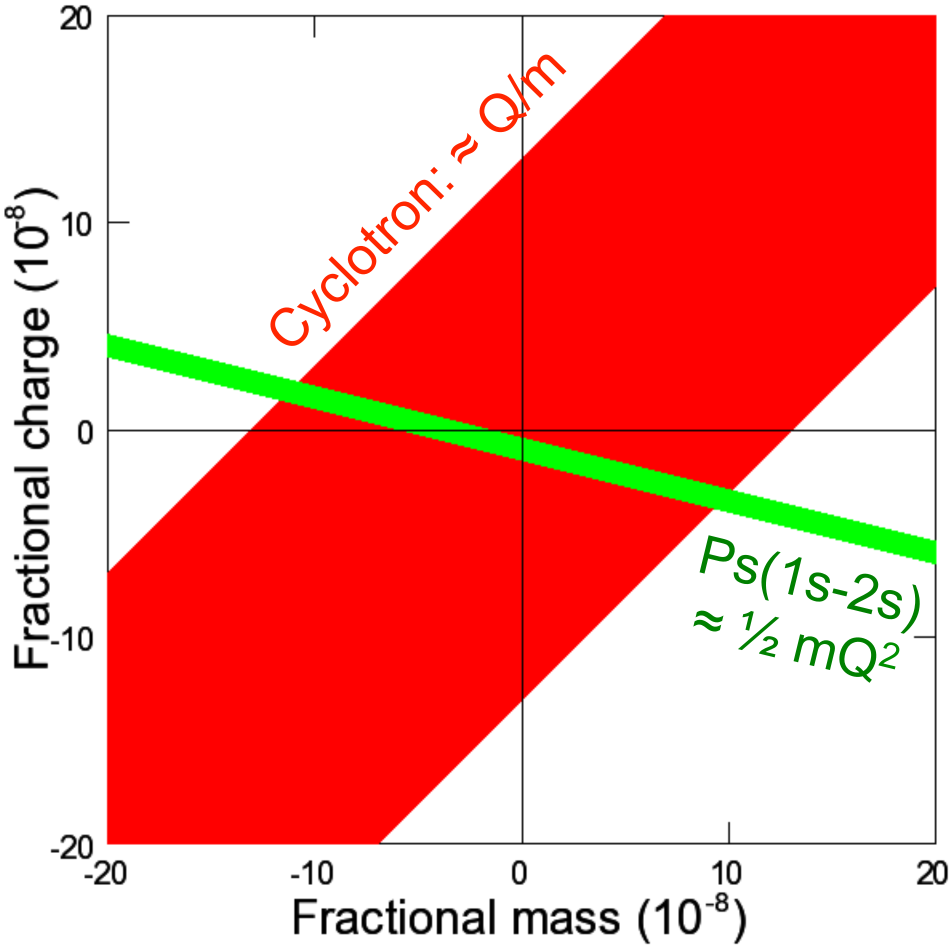
VALUE	*DOCUMENT ID*		*TECN*	*COMMENT*
<5 × 10^{-7}	[6] TORII	99	SPEC	$\bar{p}e^-$He atom
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<2 \times 10^{-5}$	[7] HUGHES	92	RVUE	

[6] TORII 99 uses the more-precisely-known constraint on the $\bar{p}$ charge-to-m GABRIELSE 95 (see above) to get this result. This is not independent of t value for $|m_p - m_{\bar{p}}|/m_p$, above.

[7] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-f tios.

Positron charge & mass before ALPHA

(MCF at LEAP 2016)



Before ALPHA

- $\Delta m_{e+}/m_{e+} \sim 10^{-7}$
- $\Delta Q_{e+}/Q_{e+} \sim 3\text{x}10^{-8}$

(Pbar mass, charge anomaly negligible)

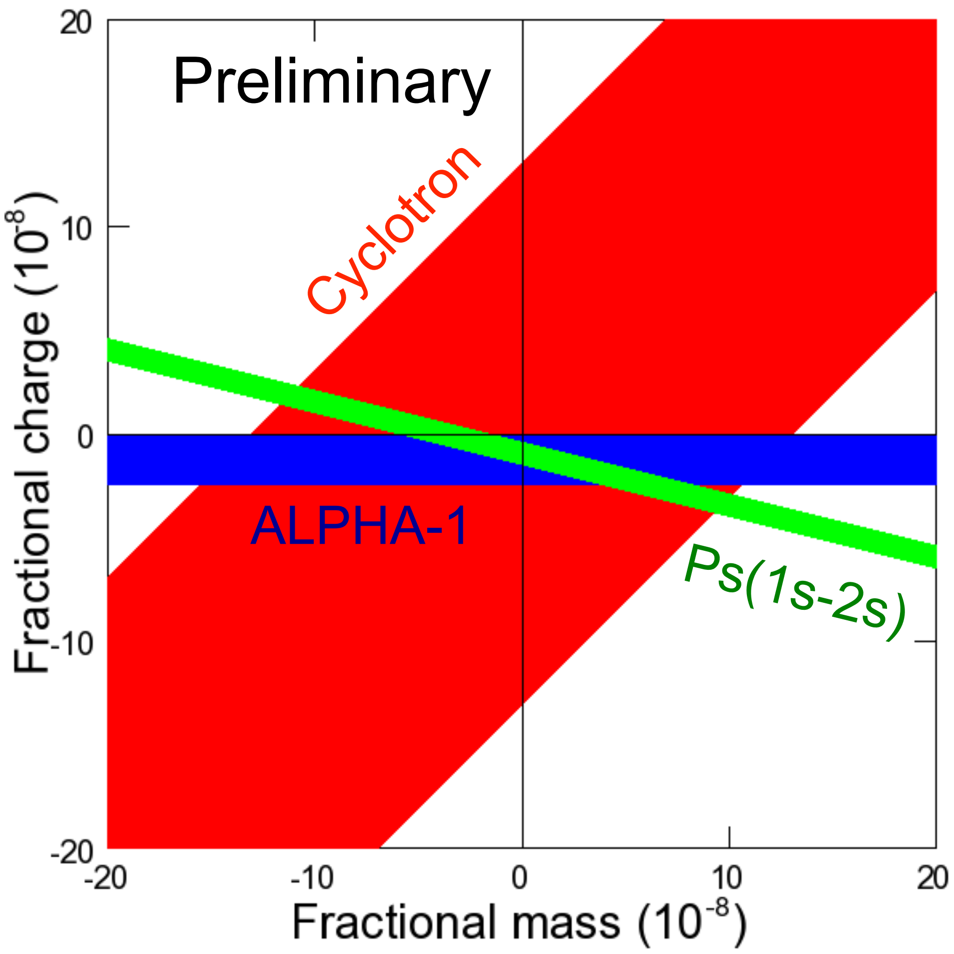
Cf: PDG 2014

- $\Delta m_{e+}/m_{e+}$: 8 x10^{-9}

(x 10 overestimate of precision!)

- $\Delta Q_{e+}/Q_{e+}$: 4 x 10^{-8}

Positron Charge & Mass after ALPHA-1



- After ALPHA-1
  - Both $\Delta m_{e+}/m_{e+}$ and $\Delta Q_{e+}/Q_{e+}$ improved marginally ~ x2

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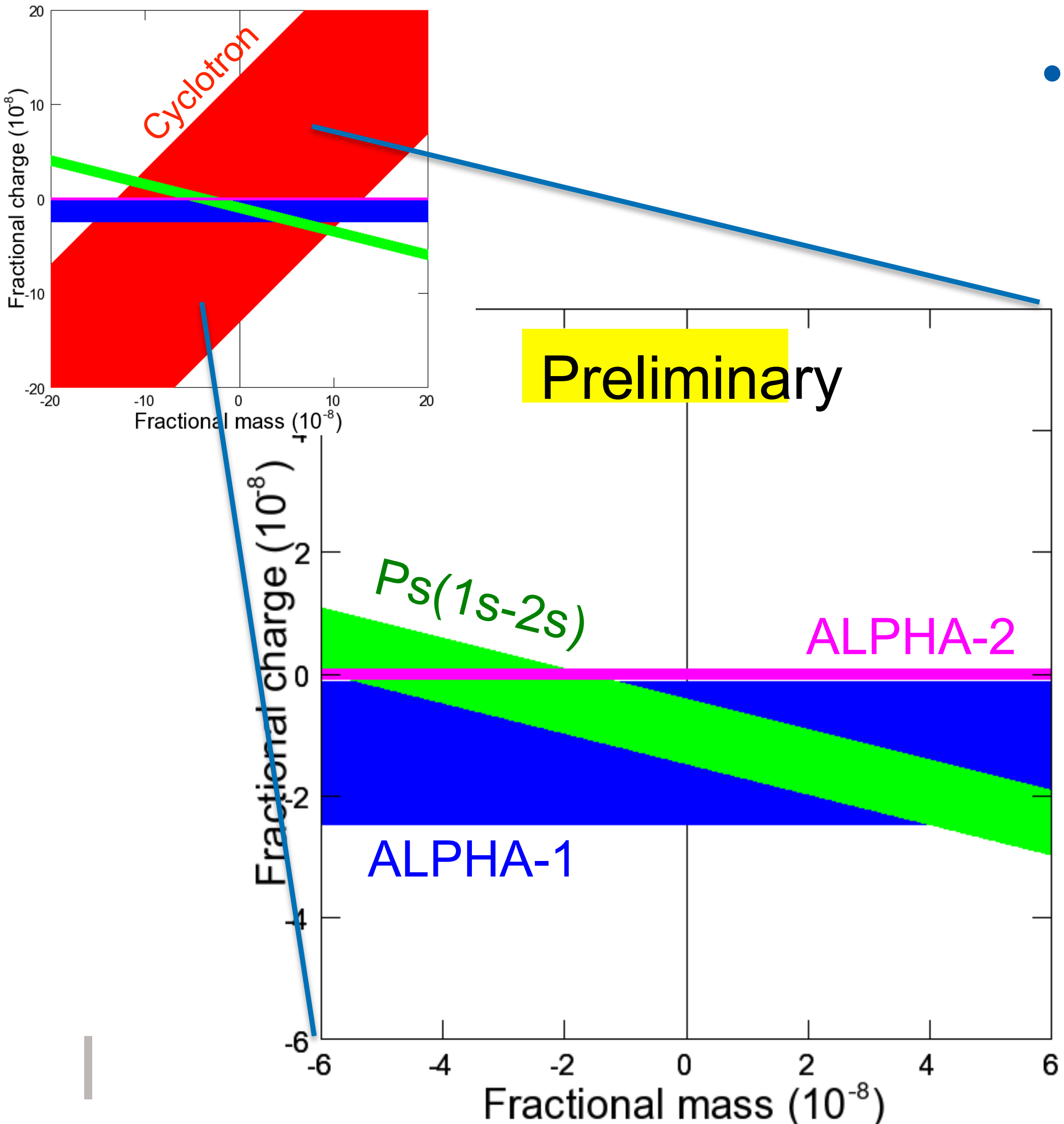
Positron Charge & Mass after ALPHA-2



- After ALPHA-2
  - Ignore pbar charge & mass anomaly (4×10^{-10})
  - $\Delta Q_{e+}/Q_{e+} \sim 7\times10^{-10}$ (1σ), 40-fold improvement over pre-ALPHA
  - $\Delta m_{e+}/m_{e+} \sim \pm2\times10^{-8}$, ~5 fold improvement
  - But central value shifted due to disagreement between theory and exp in Ps(1s-2)

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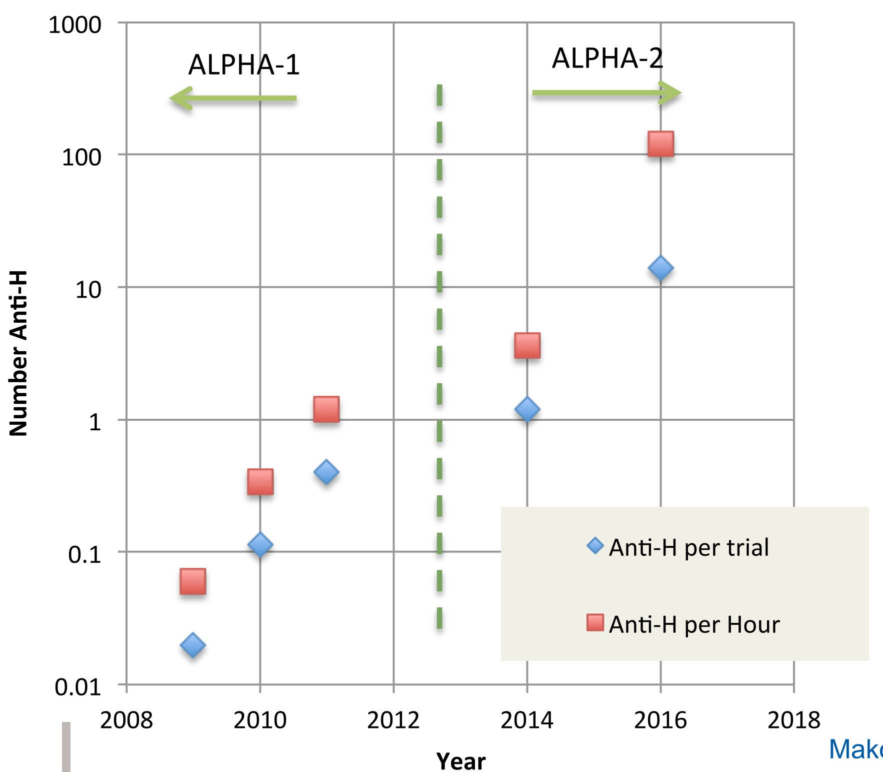
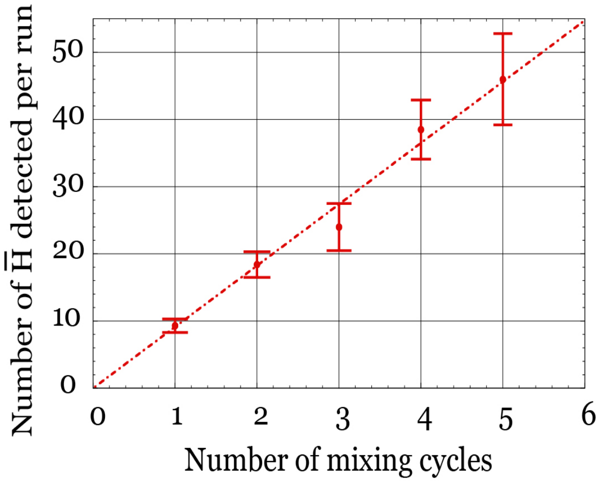
- 2017: First laser spectroscopy (10^{-10}) [*Nature*]
- 2017: x200 improved microwave [*Nature (in press)*]

Breakthroughs: increased anti-H trapping rates

- Trapping improvements
  - Improved ALPHA-2 cryostat
  - Improvements in # per trial and duty cycle
  - Detection improvements

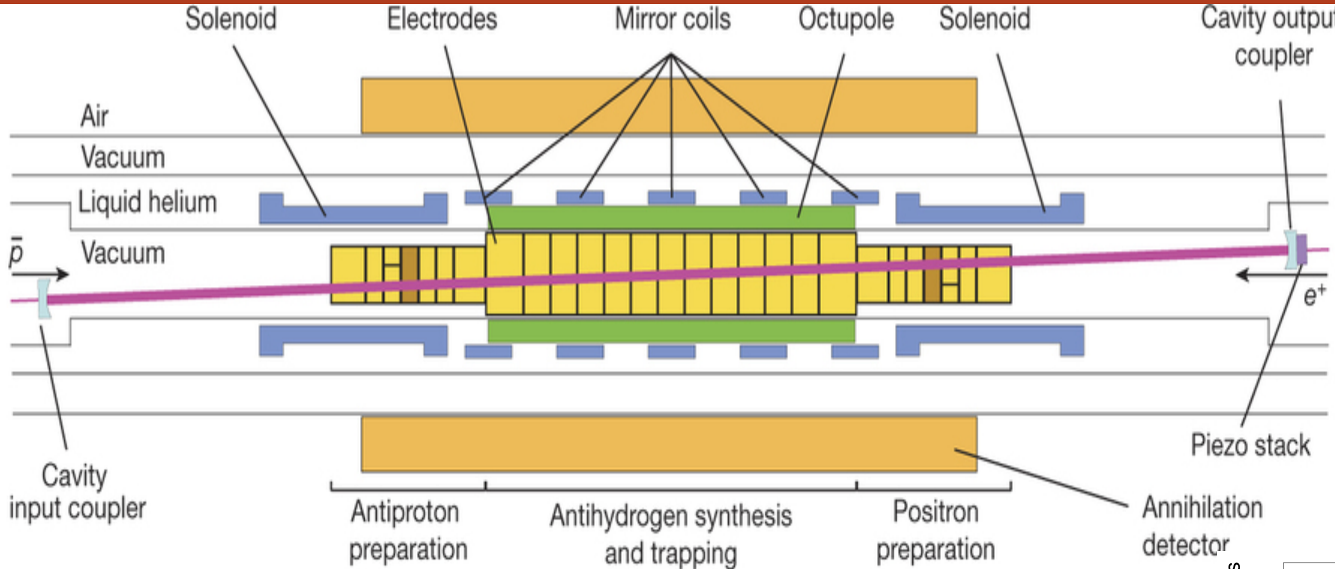


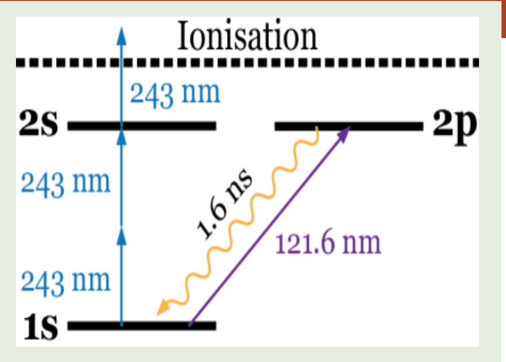
- "Stacking"
  - Repeated loading of anti-H in trap
  - Each cycle ~ 200 sec;
    (anti-H lifetime > 1000 sec)



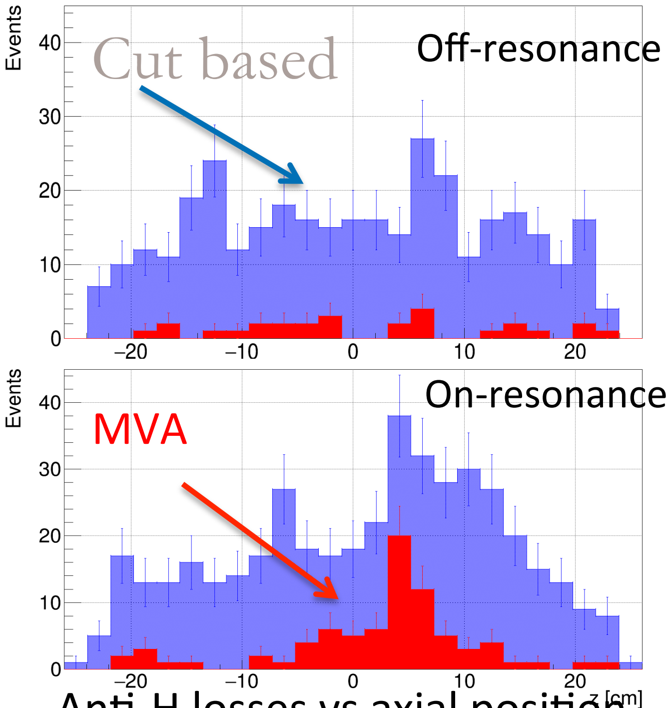
On June 7, 2017, >100 anti-H trapped (online, preliminary!)

First Laser Spectroscopy (Nature 2017)





Analysis by PDF McKenna



Anti-H losses vs axial position

- Trap ~14 anti-H per cycle
- Inject laser for 600 sec:
  1. on-resonance, or
  2. off-resonance
- If on-resonance, anti-H is destroyed
- Observe annihilations with Si vertex detector

Annihilation detection: Key

TRIUMF

Observation of 1s-2s transition in trapped anti-H

- First laser spectroscopy on anti-H

Nature 541, 506 (2017)

"A dream come true for entire field!" – M. Hori

nature International weekly journal of science

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NATURE | LETTER OPEN

日本語要約

Observation of the 1S–2S transition in trapped antihydrogen

M. Ahmadi, B. X. R. Alves, C. J. Baker, W. Bertsche, E. Butler, A. Capra, C. Carruth, C. L. Cesar, M. Charlton, S. Cohen, R. Collister, S. Eriksson, A. Evans, N. Evetts, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, C. A. Isaac, A. Ishida, M. A. Johnson, S. A. Jones, S. Jonsell, L. Kurchaninov, N. Madsen, M. Mathers, D. Maxwell, J. T. K. McKenna, S. Menary, J. M. Michan, T. Momose, J. J. Munich, P. Nolan, K. Olchanski, A. Olin, P. Pusa, C. Ø. Rasmussen, F. Robicheaux, R. L. Sacramento, M. Sameed, E. Sarid, D. M. Silveira, S. Stracka, G. Stutter, C. So, T. D. Tharp, J. E. Thompson, R. I. Thompson, D. P. van der Werf & J. S. Wurtele

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Affiliations | Contributions | Corresponding author

$f\,(1s_c\text{-}2s_c)$ = 2,466,061,707.1 (4) MHz

$f\,(1s_d\text{-}2s_d)$ = 2,466,061,103.0 (4) MHz

- 1st demonstration:
  - Precision already $2\text{x}10^{-10}$;
    $\Delta f \sim 400$ kHz
  - Among most precise measurements with antiparticles
  - Sensitive to antiproton internal structure at 20% level
    $\Delta E \sim 1.1\, r_p^2$ (MHz)
- Next steps in 2017
  - Resonant lineshape
    50 – 100 kHz benchmark
  - Laser cooling
    Lyman-alpha laser developed at UBC
  - New HFS spectroscopy

TRIUMF

Antiproton Mass & Charge

- Analysis so far assumed:

  $\delta m_{pbar}/m_{pbar}, \delta Q_{pbar}/Q_{pbar} << \delta m_{e+}/m_{e+}, \delta Q_{e+}/Q_{e+}$
- Next generation Anti-H exp'ts can no longer assume this.
- In general, need 4 independent measurements to determine m_{pbar}, Q_{pbar}, m_{e+}, Q_{e+}. Possibilities:

Measurement	Leading order dependence	Current precision (1σ)	Near future prospects
Pbar/p cyclotron	Q_{pbar} / m_{pbar}	7×10^{-11}	Base: 10^{-11} ?
Pbar He	$m_{pbar} Q_{pbar}^2$	4×10^{-10}	ASACUSA: 10^{-10} ?
e+/e- cyclotron	Q_{e+}/m_{e+}	1.3×10^{-7}	Harvard ?
Ps(1s-2s)	$(m_{e+}/2)\ Q_{e+}^2$	5×10^{-9}	ETH: 5×10^{-10} ?
Anti-H (charge)	$Q_{pbar} + Q_{e+}$	**7×10^{-10}**	ALPHA: 10^{-12} ?
Anti-H (1s-2s)	$m_{e+} Q_{pbar}^2 Q_{e+}^2$	**$2\text{x}10^{-10}$**	ALPHA: 10^{-12} ?

Anti-H studies entering precision era!

ALPHA-g:
Gravitational force on antimatter

Antimatter Gravity Measurement

- Gravity
  - Never measured with antimatter
- 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.

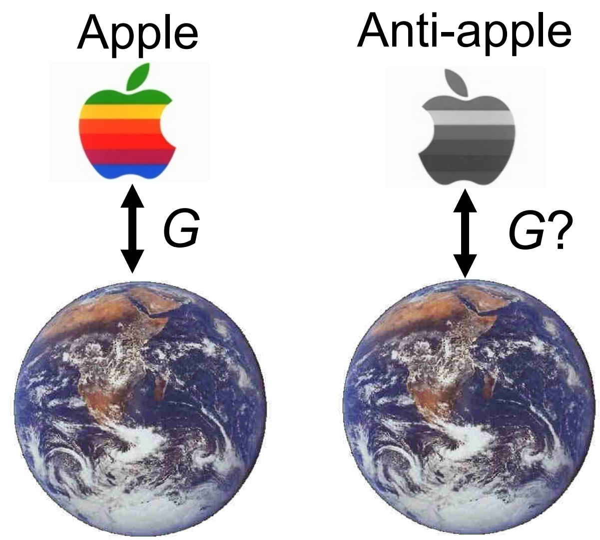
Antimatter Gravity Experiment

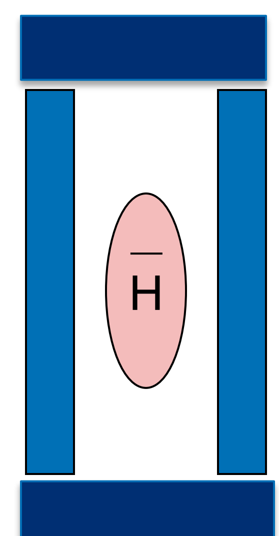
- Does antimatter fall down?
  - Many indirect constraints incl. EP tests
  - Experimental question!
    (e.g. Lykken et al, arXiv:0808.3929)
  - Anti-H "gas" will sag due to gravity
  - Need anti-H cooling to ~mK

$$1/2kT=mgh$$

$$\text{Vertical trap}: h\sim 1\ m$$

  - Position sensitive detection via annihilations

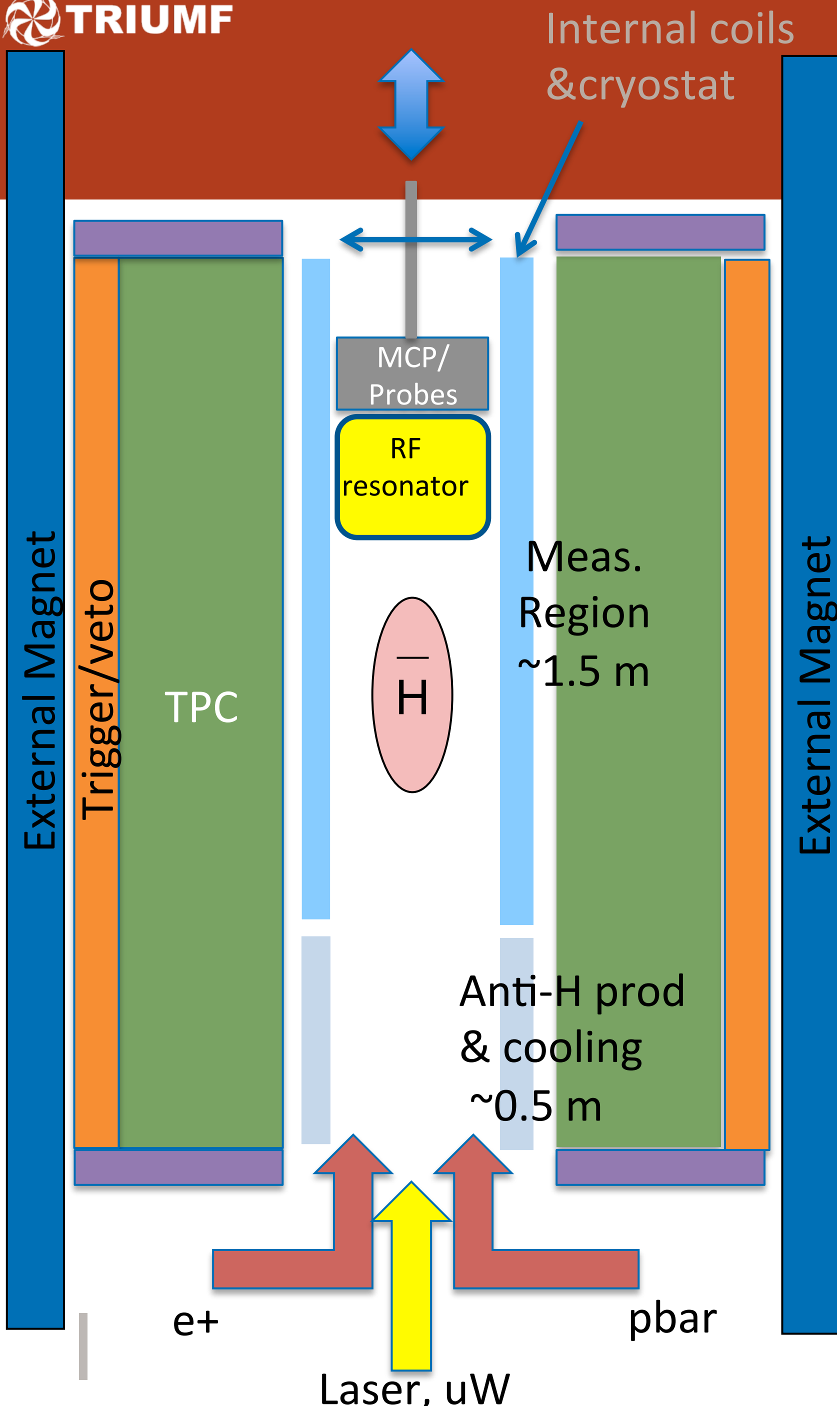




Vertical trap

- Laser cooling essential step: development at UBC
  - NB: Cold atom tests of gravity: $\sim10^{-10}$

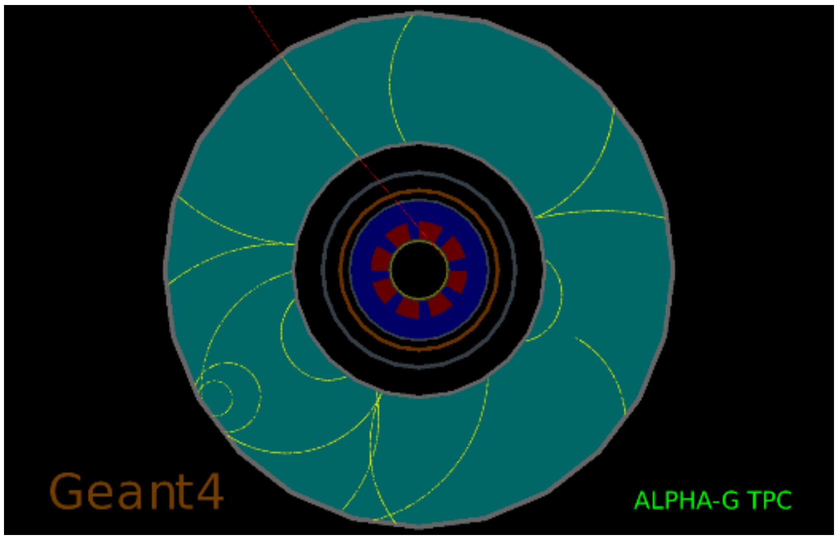
ALPHA-g Experimental Concept



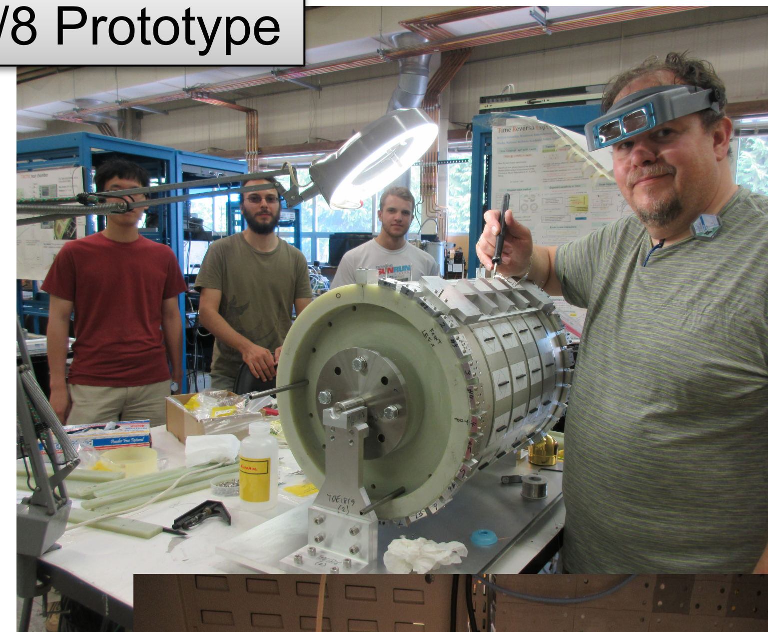
- A long (~ 2m) vertical trap
  - Anti-H production region
    Production, trapping, & cooling
  - Measurement region
    - Sagging of anti-H "gas"
    - Anti-atomic "fountain"
    - Anti-atomic interferometry
    - uW spectroscopy
- Major Canadian funding

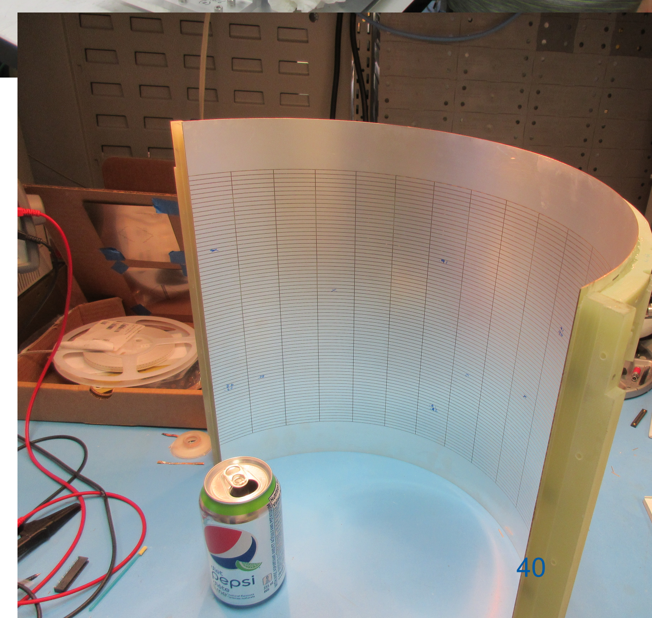
Radial TPC Construction at TRIUMF

GEANT simulation



1/8 Prototype

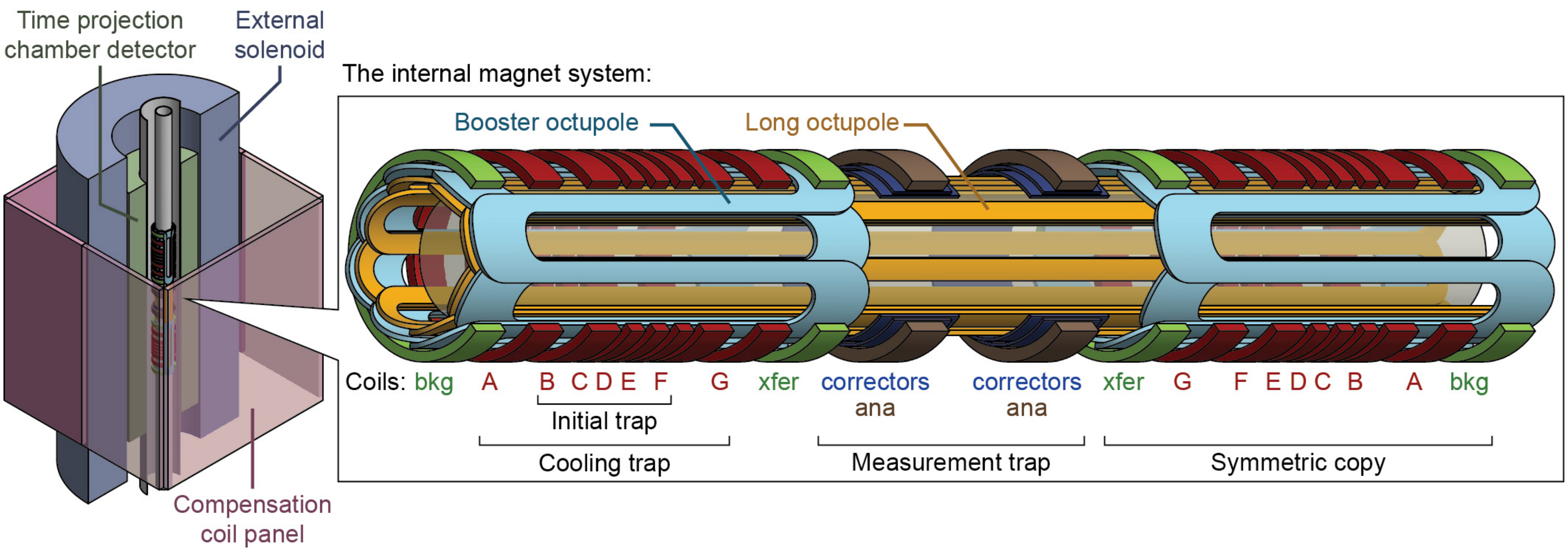




2.3 m long, Radial thickness:10 cm
→ Radial drift Time Projection Chamber

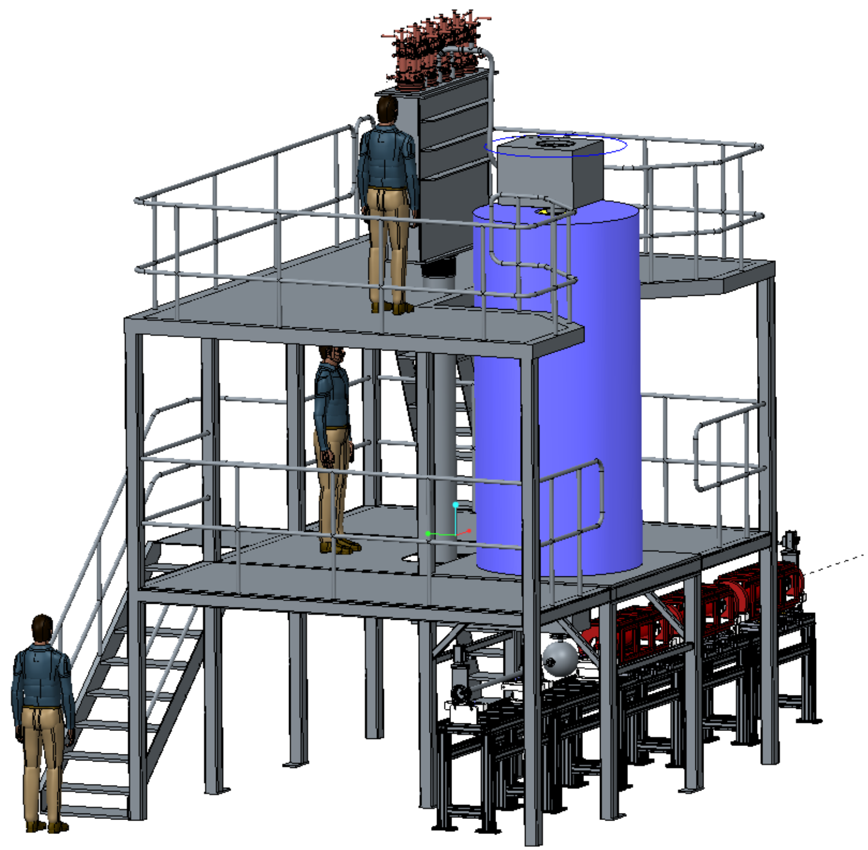
Excellent track recognition!
(~90% reconstruction efficiency)

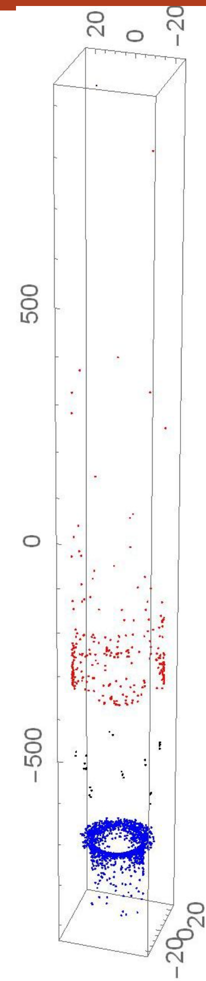
ALPHA-g Trap Design: C. So

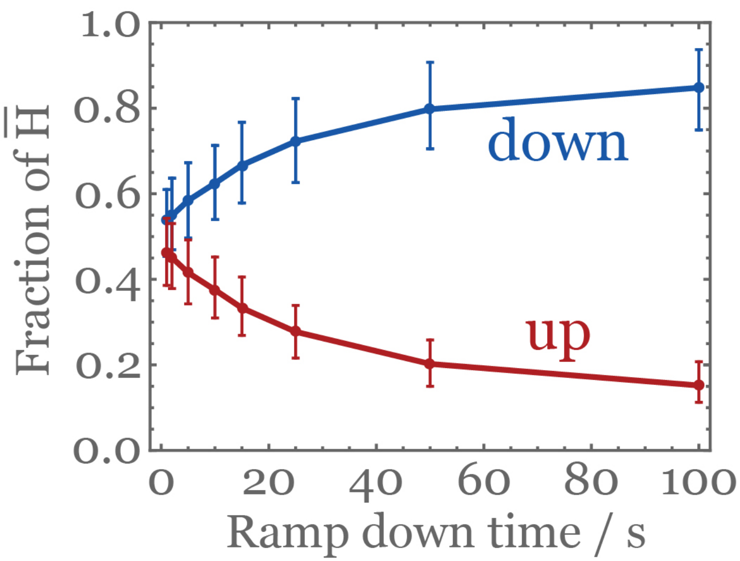


24 superconducting magnets!

ALPHA-g design & simulations







Anti-H free fall simulations

Aiming for measurement in 2018!

ALPHA Future Prospects

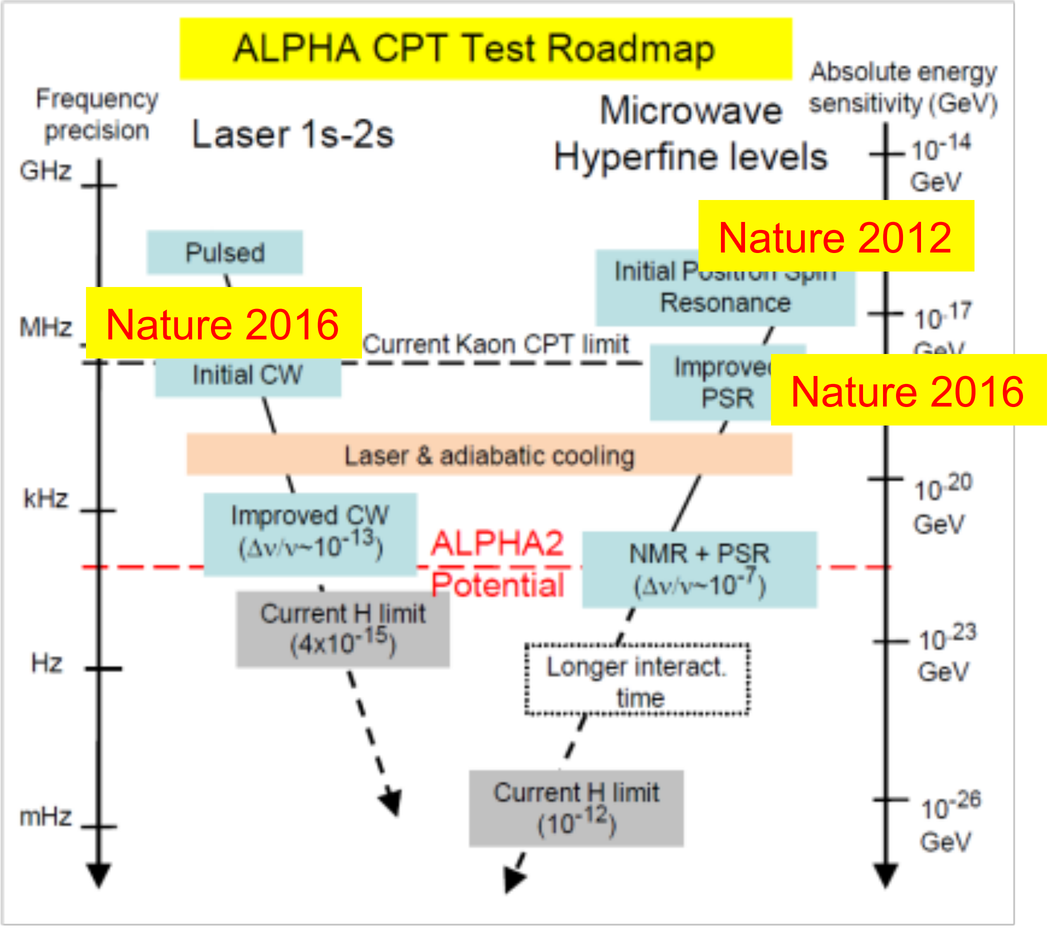
Challenge

"we congratulate NSERC for bravely recognizing the best and most basic research, and we applaud our prizewinners for adding an important milestone to the history of science." --- Message from Dr. John Polanyi to the ALPHA-Canada team

NSERC Polanyi Award, Feb 3, 2014

NSERC CRSNG

ALPHA CPT Road Map



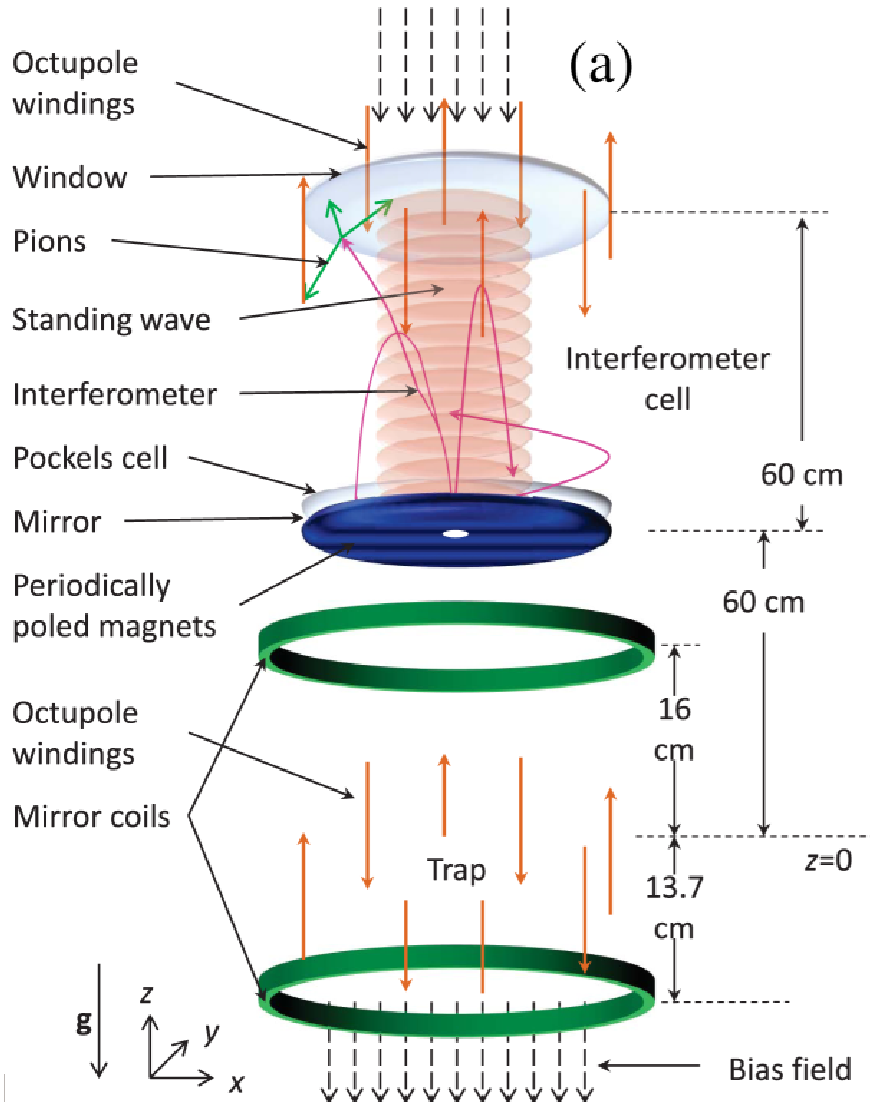
- Charge
- Lamb shift
- 2s-4s

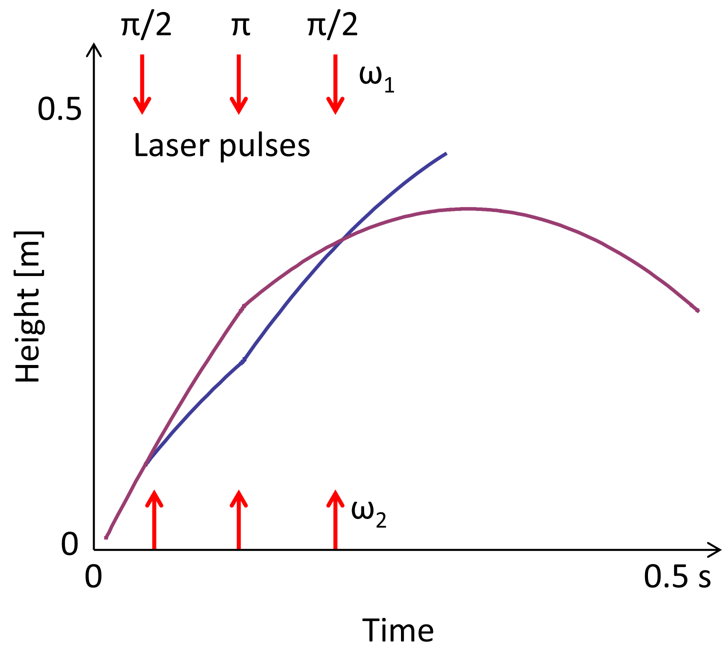
- Anti-H+ ion
- Molecule
- BEC?

Future?

Future: Anti-atomic fountain & interforometry

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





$$\Delta\varphi = (k_{eff}\cdot g)\,T^2$$

Summary

- Anti-H addresses fundamental questions
- 18 years since the start of Antiproton Decelerator at CERN, we entered the precision physics era
  - Laser spectroscopy at 10^{-10} level
  - Microwave, charge neutrality at 10^{-9} etc.
- Developing gravity measurement: ALPHA-g
- ELENA, upgrade to AD, under construction
- Exciting future ahead for 2020-25 and beyond!
- Excellent students → photos

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 TV

Calgary Sun

CBC News

CBC News

CBC News