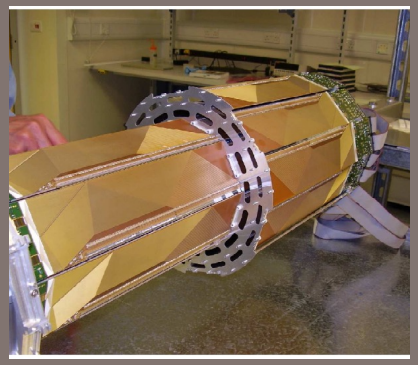
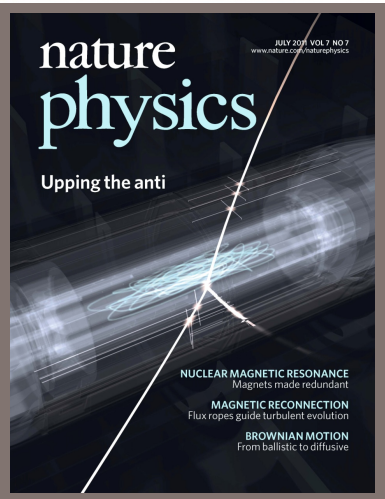
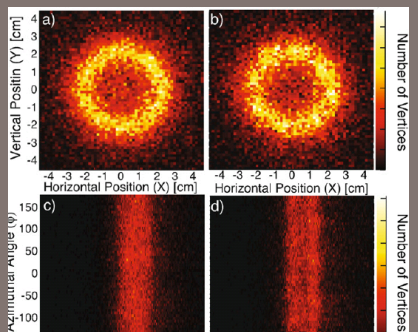
ALPHA Antihydrogen Symmetry Tests

IPP Town Hall Meeting, CAP Edmonton
June 14, 2015

Makoto C. Fujiwara
TRIUMF
For ALPHA-Canada







Forewords

- Many thanks to Mike, IPP, LRP committee
- In Canadian SAP context, we are a part of Fundamental Symmetries program within CINP (Chair: Gerald Gwinner)
  - Fun. Sym. ≈ Fundamental Physics with low energy tools
  - UCN, EDMs, TRINAT, TITAN, Moller etc
  - Many projects require continuous R&D
    - Cannot easily predict physics reach e.g. from (Luminosity) x (Cross section)
    - Excellent for HQP training
  - Interdisciplinary components
    - AMO, Plasma, Low Temperature, High Energy
    - This is a strength, not weakness!

Motivations

- Atomic hydrogen: 75% of known universe;
  Simplest atom; 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 $\sim 10^{-13}$
- Antihydrogen: stably confined by ALPHA (2010)
  →Comparison of H and anti-H: "Textbook" experiment
- Precision tests of CPT and gravity: confront fundamental assumptions in physics, QFT+GR; possibly probing the Planck scale:

$$\Delta E \sim \frac{m_p^2}{\Lambda_{Planck}} \sim 5 \times 10^{-19}\ \text{GeV} \sim 100\ \text{kHz}$$

HEP Landscape after LHC@8TeV

[Grojean]

Summary by Mangano@Aspen2014

My key message

- The days of "guaranteed" discoveries or of no-lose theorems in particle physics are over, at least for the time being ....
- .... but the big questions of our field remain wild open (hierarchy problem, flavour, neutrinos, DM, BAU, ...)
- This simply implies that, more than for the past 30 years, future HEP's progress is to be driven by experimental exploration, possibly renouncing/reviewing deeply rooted theoretical bias

- An approach that few years back would have raised eyebrows, but that today is legitimate and well motivated

ALPHA and ALPHA-Canada

University of Aarhus, Denmark

Auburn University, USA

University of British Columbia, Canada

University of California Berkel

University of Calgary, Canada

University of Liverpool, U.K.

NRCN - Nucl. Res. Center Negev, Israel

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

The Cockcroft Institute of Accelerator Science and Technology

ALPHA

- Since 2005
- 16 institutions
- ~40 physicists

ALPHA and ALPHA-Canada

U Calgary recently joined TRIUMF Consortium
(leading ALPHA-g CFI)

ALPHA

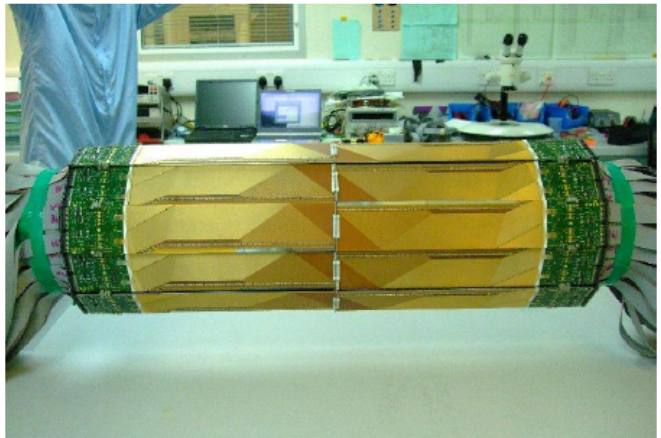
- Since 2005
- 16 institutions
- ~40 physicists

ALPHA-Canada

- >1/3 of ALPHA: largest group in ALPHA (largest Can. fraction offshore?)
- 10 Faculty/Scientists/Staff (8 grant eligible; 5.2 FTE↗)
- Excellent HQP training
- Leadership in particle detection, uWave spectr., laser cooling

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
  - Random Forest technique (variation of decision tree)
- Exotic atom physics
  - Canadian expertise: muonic, pionic, kaonic, antiprotonic atoms
  - Doing experiment with few atoms
- All this helps make us competitive! (so far)



Highlights of Recent ALPHA Results (briefly!)

2010: 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]

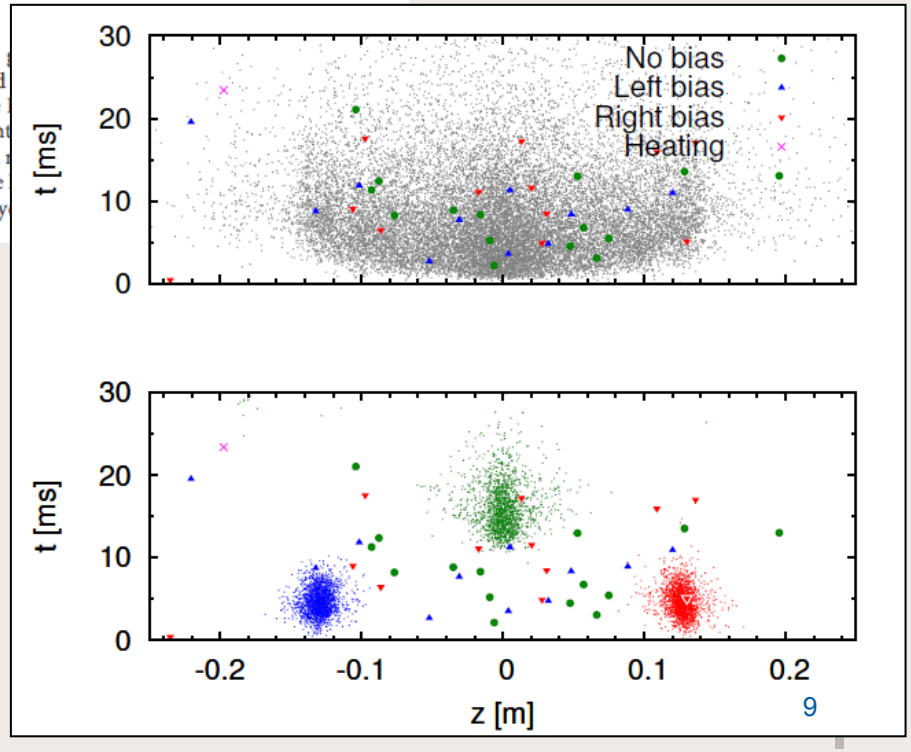
Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at 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
charged plasmas[9,10]. The liquid
cools the vacuum wall and the
measured to be at about 9 K. Ant
low enough kinetic energy can
rather than annihilating on the
can confine ground-state antihy

ALPHA-Canada

15 out of 42 authors (incl. 5 students)

R. Hydomako, Ph.D. thesis (Calgary)
DNP Thesis Award

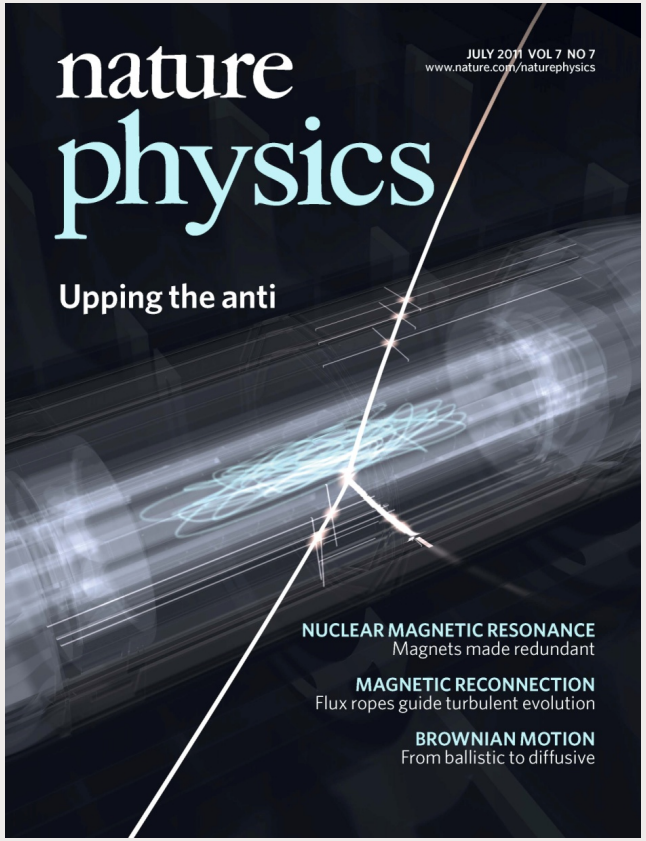


Detected annihilations of 38 anti-H released from the trap

- Position sensitive detection to discriminate against:
  - Cosmic background
  - Bare antiprotons

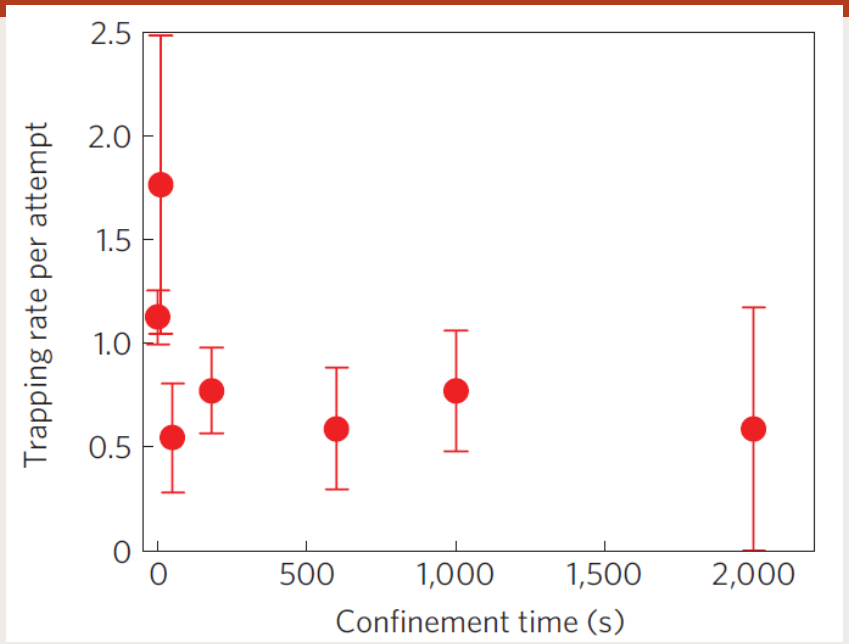
"#1 Breakthrough in 2010" *PhysicsWorld*

2011: Confinement of Antihydrogen for 1000 s



Cover, Nature Physics, July 2011 Issue

Principle author: Fujiwara



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

2012: First Spectroscopy on Antihydrogen Atoms

Canadian-Led Initiative:

Mike Hayden (SFU), Walter Hardy (UBC)

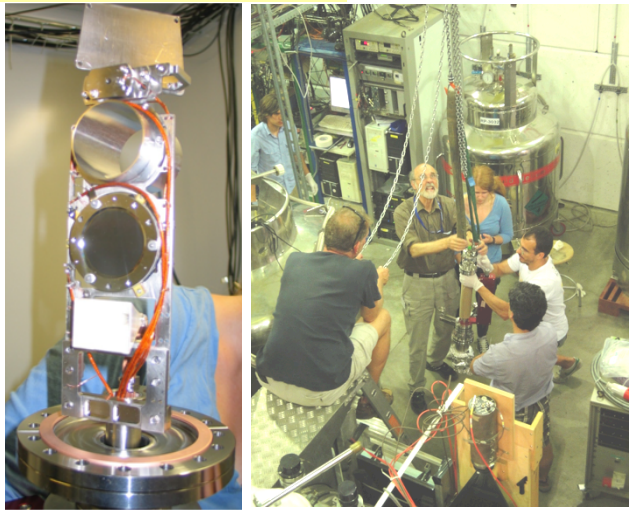
Art Olin, MCF (TRIUMF) et al.

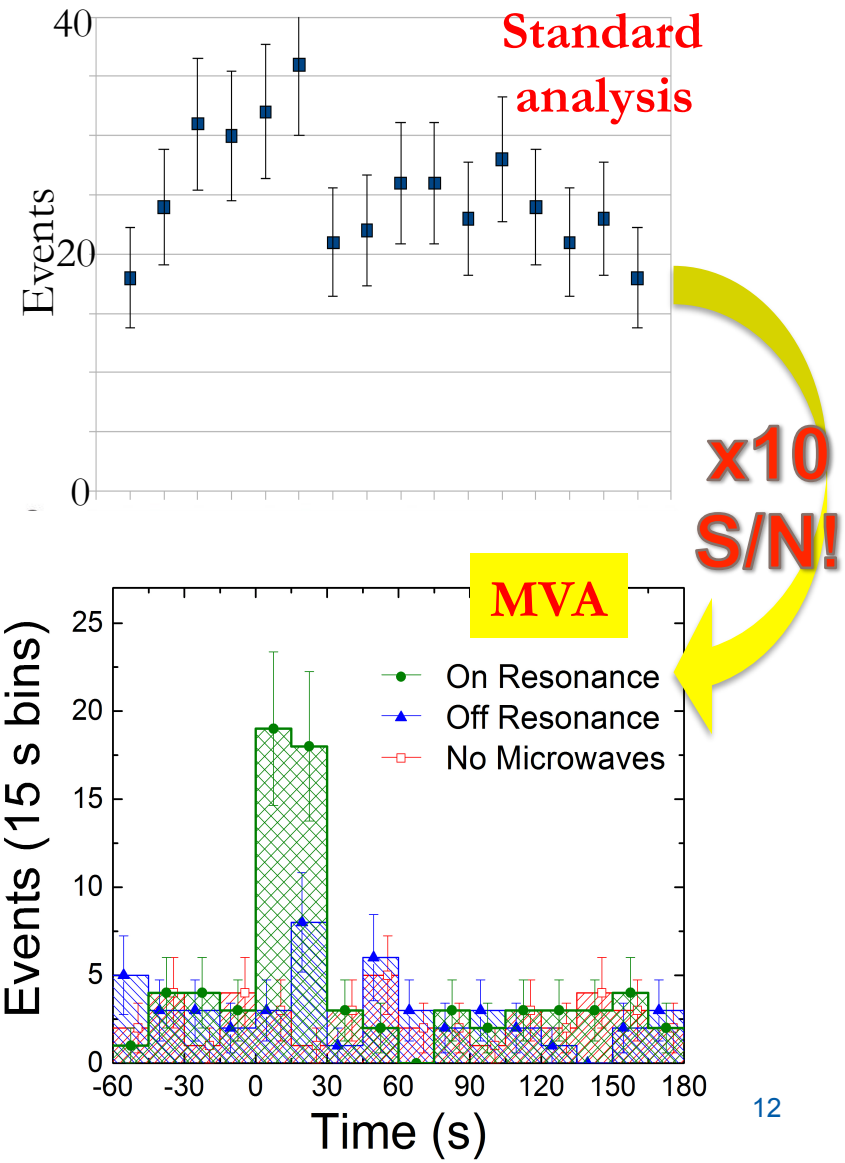
M. Ashkezari (SFU), T. Friesen (Calgary)

S. Stracka (TRIUMF)

2012: Microwave-induced Hyperfine Transition

Installation at CERN, July 2011





- 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

Finally!

Letter to Nature, March 2012
Principal author: Michael Hayden (SFU)

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NATURE | LETTER

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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

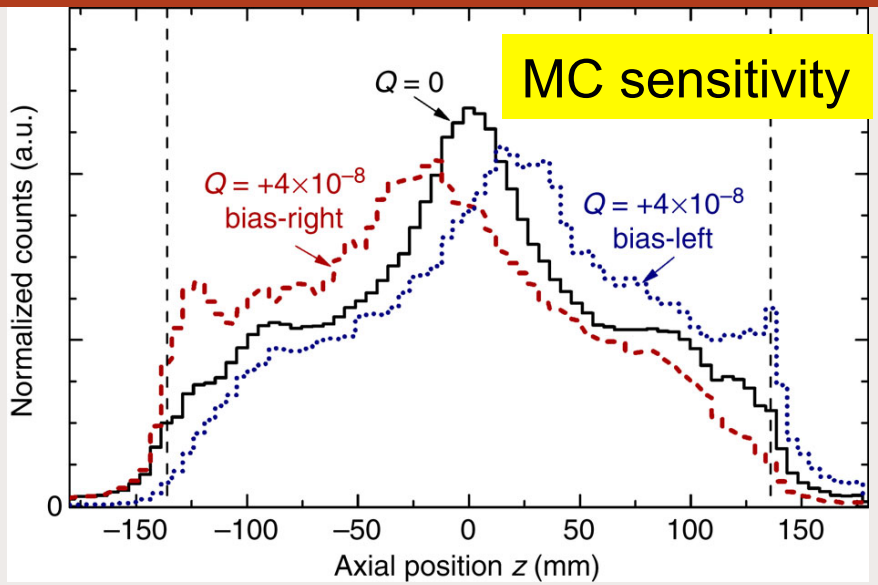
Nature **483**, 439–443 (22 March 2012) | doi:10.1038/nature10942
Received 09 January 2012 | Accepted 07 February 2012 | Published online 07 March 2012

First spectroscopic measurements on anti-H!

- Precision limited: $O(10^{-3})$
- Demonstration of spectroscopy on a single anti-atom at a time
- "Historic!" – *Nature Editor*
- Annihilation detection: key
- Major Canadian-led success

Latest result: Is Antimatter Neutral?
Nature Comm. 5, 3955 (2014)

- Why matter is neutral?
  - Anomaly cancellation, GUT?
  - Experimentally, proton + electron = neutral to 10^{-21}
- CPT test: Is antiproton + positron neutral?
  - "Hidden" Canadian proposal!
- Result (Berkeley, York Ph.D.):
  - Anti-H neutral to 1.3×10^{-8}
- New limit on e+ charge
  - ALPHA's first precision result!
  - X10 better from 2014 run?
  - Sensitivity to e+ mass?



PDG 2014

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

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 pol
$<1 \times 10^{-18}$	[9] MUELLER	92	THEO	Vacuum pol

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

NSERC John Polanyi Award, Feb 3, 2014

"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."

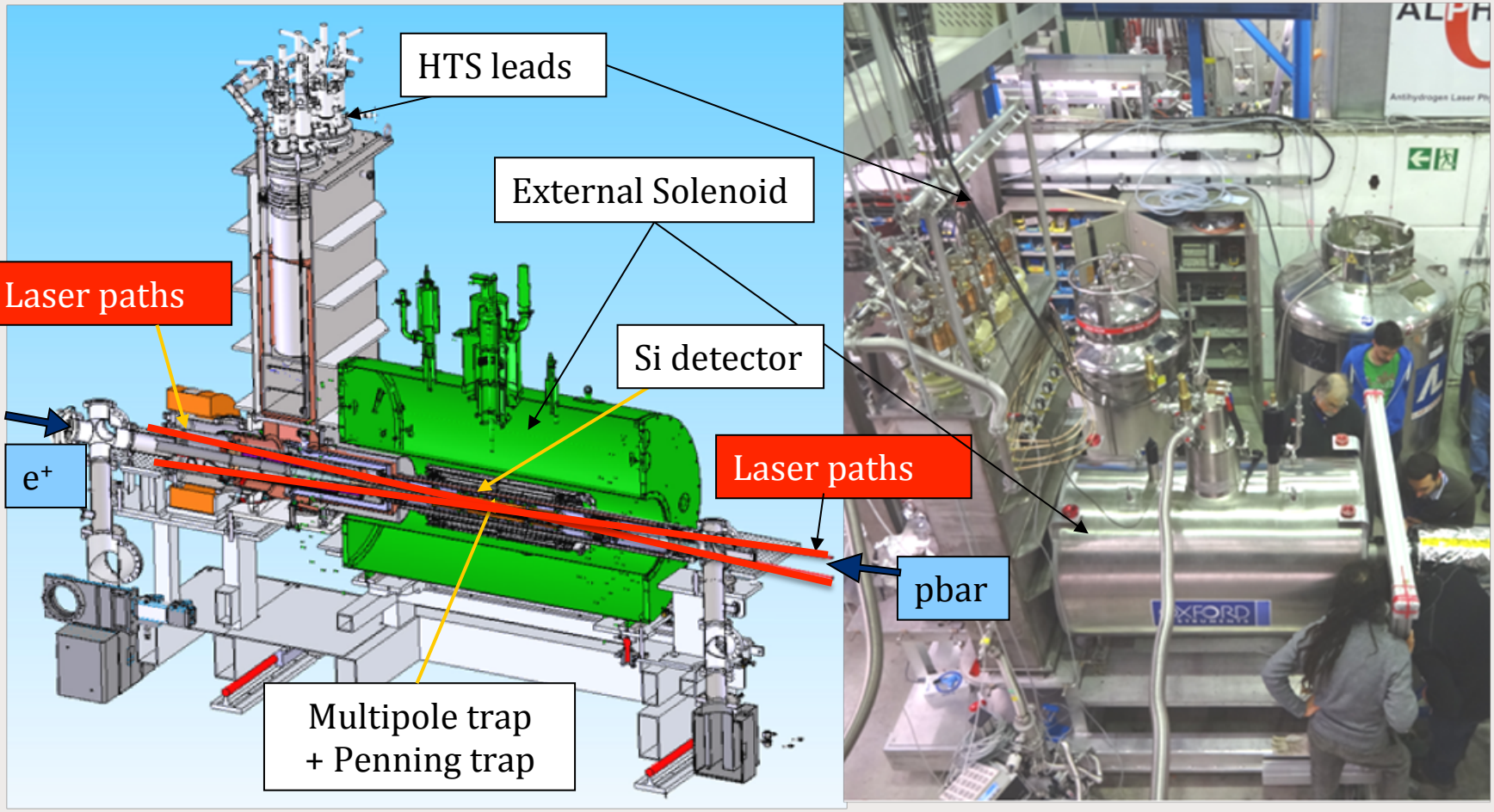
--- Message from Dr. John Polanyi to the ALPHA-Canada team

NSERC CRSNG

Also, 2011 APS John Dawson Award for Anti-H Trapping

Plan (1)
Precision Spectroscopy with ALPHA-2

ALPHA-2: Laser Spectroscopy

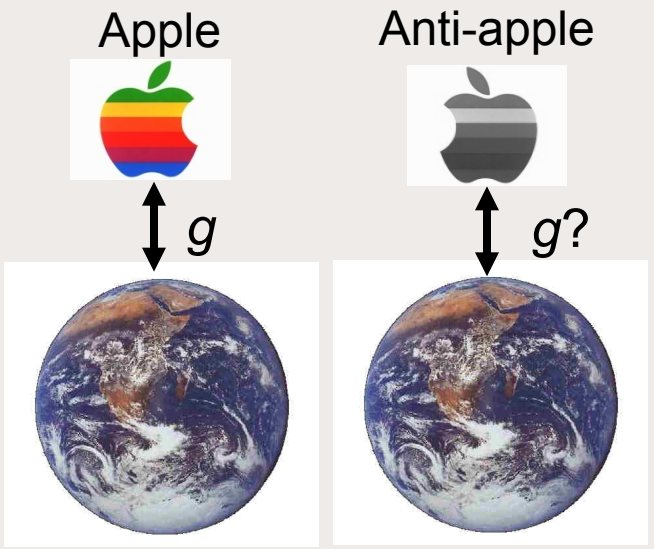


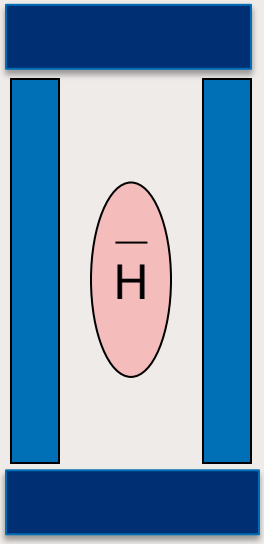
- Constructed w/ major Canadian contributions: RTI+TRIUMF&Calgary
- Commissioning successful Dec 2014: > x2 anti-H trapping rates
- New Canadian initiative: Lyman-alpha spectroscopy and cooling
- First physics run in July 2015; will run for several years

Plan (2)
Antimatter Gravity studies with ALPHA-g

ALPHA-*g*: Antimatter Gravity Experiment

- Does antimatter fall down with *g*?
  - Experimental question!
    (e.g. Lykken et al, arXiv:0808.3929)
  - Already 2 dedicated exp'ts at AD
  - We can do it better in a trap?
- Originally Canadian initiative now adopted by entire ALPHA
  - Laser cooling essential: UBC/Calgary
  - CPT test via uWaves: SFU/UBC
  - TPC tracker, cosmic veto: TRIUMF/York
- $6.9M approved (CFI + Ontario)
  - Waiting for other matching funds
  - Total Cdn contributions: >$12M cash





Vertical trap

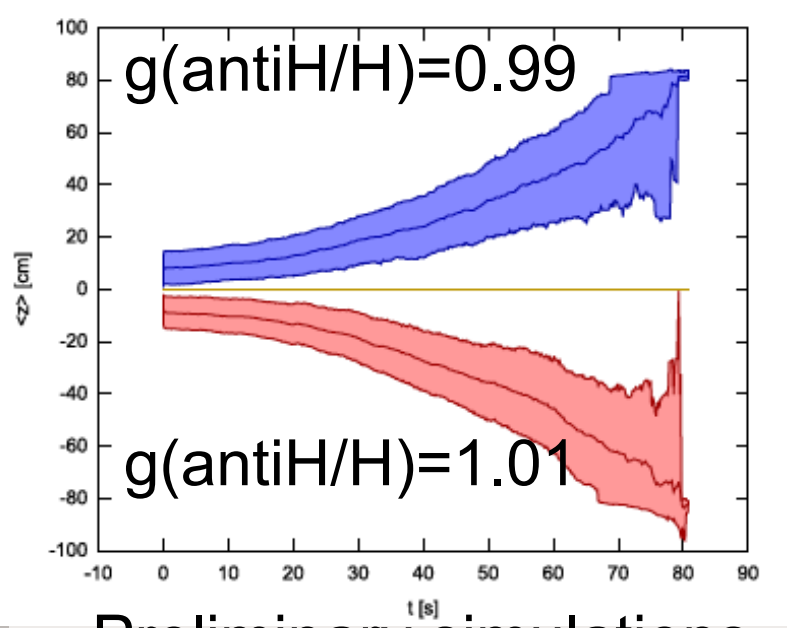
ALPHA-g Staged Approach

Stage 1: Sign of g

- Should be “immediate” once ALPHA-g is commissioned

State 2: ~1% meas. of g

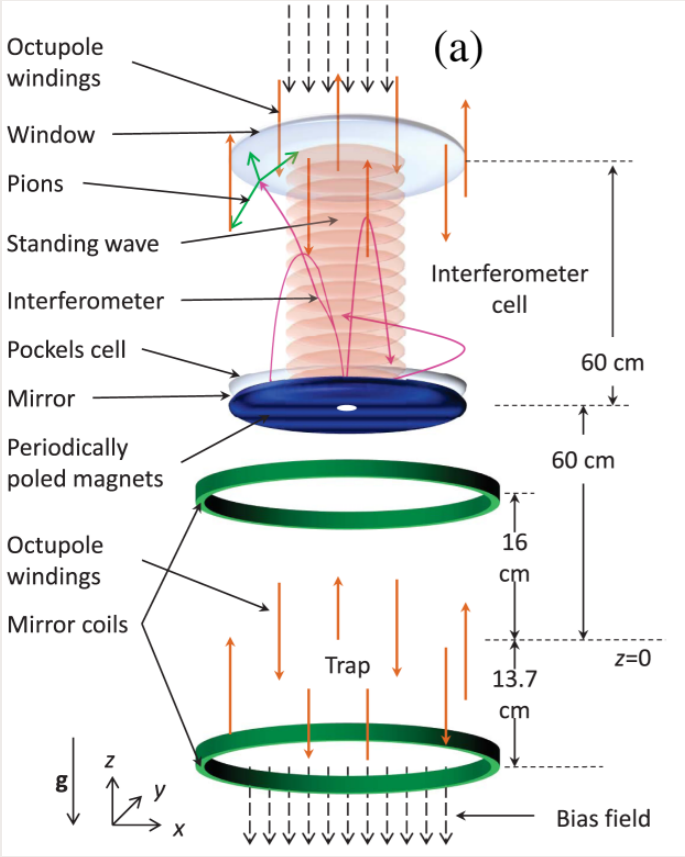
- Laser cooled anti-H
- Also uWave CPT



Preliminary simulations

Stage 3: Anti-atom fountain & Interferometer

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



Faculty FTE commitment as of 2015

Name	Institution	FTE	Main contributions
Makoto Fujiwara	TRIUMF	100%	Detectors, Analysis, Traps
David Gill	TRIUMF	50%	Detectors, Analysis
Walter Hardy	UBC	70%	Microwaves, Cryogenics
Michael Hayden	SFU	30%	Microwaves, Cryogenics
Scott Menary	York	80%	Detectors, Analysis
Takamasa Momose	UBC	30%	Lasers, Cooling
Art Olin	TRIUMF/UVic	85%	Detectors, Software, Cryo
Robert Thompson	Calgary	75%	Lasers, Traps
	Total Grant-Eligible FTE	5.2	(Not including expected hires)

- Anticipated new hires
  - CRC-2 Chair, U. Calgary
  - Replacement for Art Olin, Andy Miller, TRIUMF

Resources

Funding source/grants	Amount	Comments
CFI-related		
CFI Innovation Fund 2015	$6.13M	Announced
AB, BC, ON provincial matching	$6.13M	In review
CFI Infrastructure Operating Fund	$368K/yr	Only after infrastructure completion
NSERC		
Operating grant	$1.4M/yr	Optimum
Operating grant	$800K/yr	Minimum
Capital	$150K/yr	Minor upgrades at level of RTI1

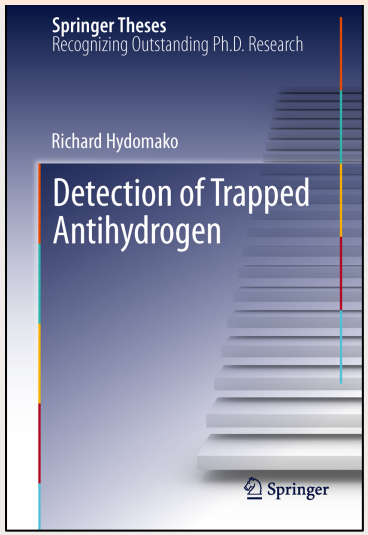
Assume ~7FTE

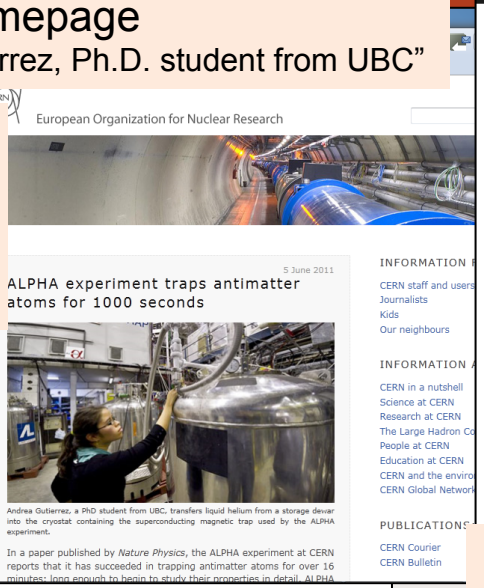
- Doing research in Geneva/CERN is expensive! Common fund!
- Development & operation of 2 complex devices
- $200K/FTE comparable with other successful SAP projects

Our Hard-working HQPs

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.)





CBC News

CBC News

Finnish paper

Calgary Sun

CBC News

CBC TV

HQP: Excellent Training Ground

- Small experiment
  - Large responsibility for students

    e.g. A student in charge of Si vertex reconstruction
  - Fast turn around
  - Diverse skill training: Vacuum, cryostat, magnets, laser, microwaves, computing, electronics, detector
- Completed & Current 14 grad, 4 PDF, ~5 undergrad
  - Including: 1 IPP summer student

Request

- 5 PDF
- 10 grad student (one per faculty)
- 5 man-term/yr undergrad
- Development & operation of 2 complex devices

Other Info

- Support from TRIUMF
  - TPC tracker
  - SiPM based cosmic veto
- Technical & Physics Synergies
  - Detector (TPC, SiPM), DAQ, Laser, Microwaves, Traps, Cryogenics
  - Simulations, Analysis (MVA)
- CERN committed >50M CHF on AD and ELENA: electron cooling ring
  - Increasing number of experiments at AD

Summary

- ALPHA has made significant progress since its inception in 2005, and in 2011-16 period
  - Strong Canadian leadership in SAP and spectroscopy
  - Expect more breakthroughs before 2016!
- We have ambitious, exciting program for next decade, with ALPHA-2 and ALPHA-g
- CERN is committed to antiproton physics
  - ELENA ring + AD upgrade: >50M CHF
- Great public interest; please make use of it!

Thank you!
Merci!

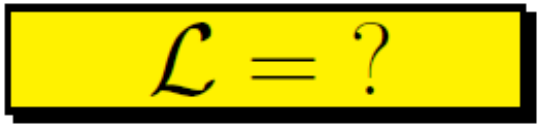
Backup Slides

ALLPHA Motivations (experimental)

- Atomic hydrogen: 75% of known universe;
  Simplest atom; 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 $\sim 10^{-13}$
- Antihydrogen: stably confined by ALPHA (2010)
  →Comparison of H and anti-H: "Textbook" experiment
- Many experimental challenges in production, trapping, spectroscopy, detection of anti-H → continuous R&D
- Subatomic physics technique: a key in all of ALPHA physics; advantage in competitive field

Big Picture: Fundamental Physics

- What is Fundamental (Particle) Physics? (Grossman)



- "Simple answer": The SM, including Higgs, works extremely well!
- Many open (recently exacerbated) issues, in particular:
  - Naturalness of Higgs mass & Cosmological constant
  - Require fine-tuning by O(30), O(120)? Multiverse?
  - Hopefully, LHC & precision expt's will solve them soon!
- But, "*L*=?" really the right question to ask?

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

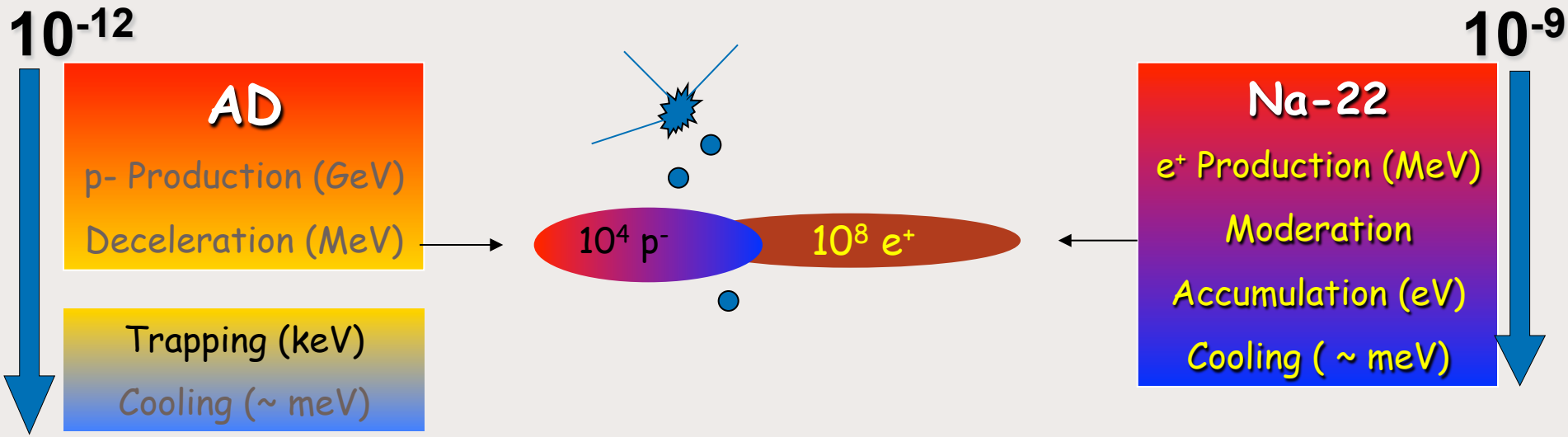
CPT and Gravity tests with Antihydrogen

- Test of CPT
  - CPT: a fundamental property of local, relativistic QFT
  - CPT theorem demands H & Anti-H spectra be identical
  - Violation of CPT would force fundamental change in theory, incl. validity of QFT
- Test of Gravity (not in SM) in regimes previously untested
- Anti-H probes fundamental framework of physics (QFT+GR), rather than specific models within it
  - Probability for finding violation is low!
  - Expt's are hard and competitive!
- High risk business!

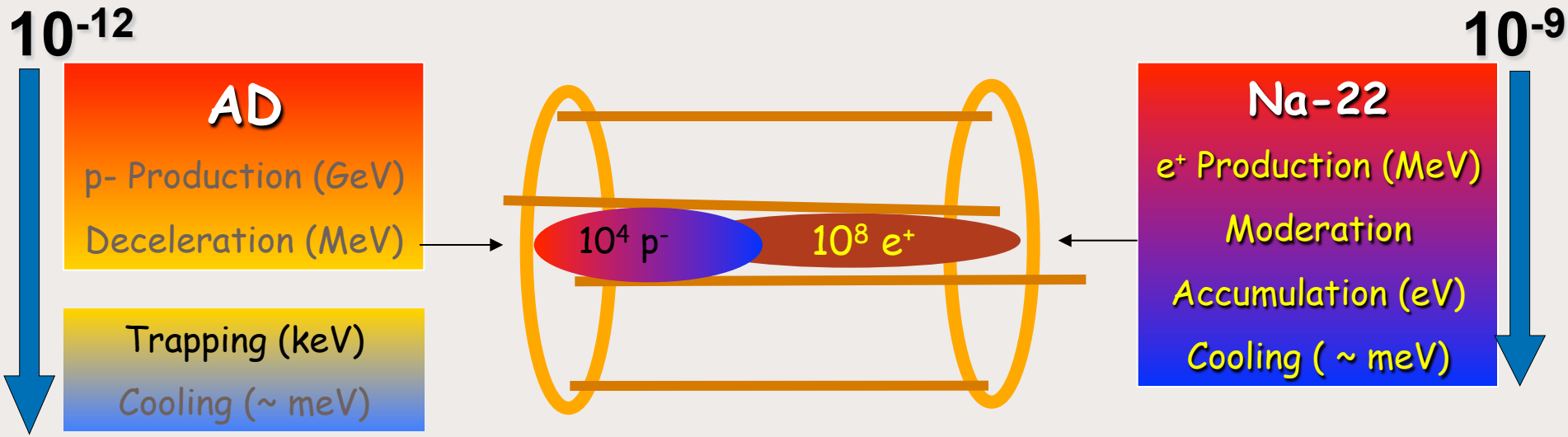
Where do you look when asking Big Questions?

Where do you look when asking Big Questions?

Producing & Trapping Antihydrogen



Producing & Trapping Antihydrogen



Superimpose Magnetic Trap

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

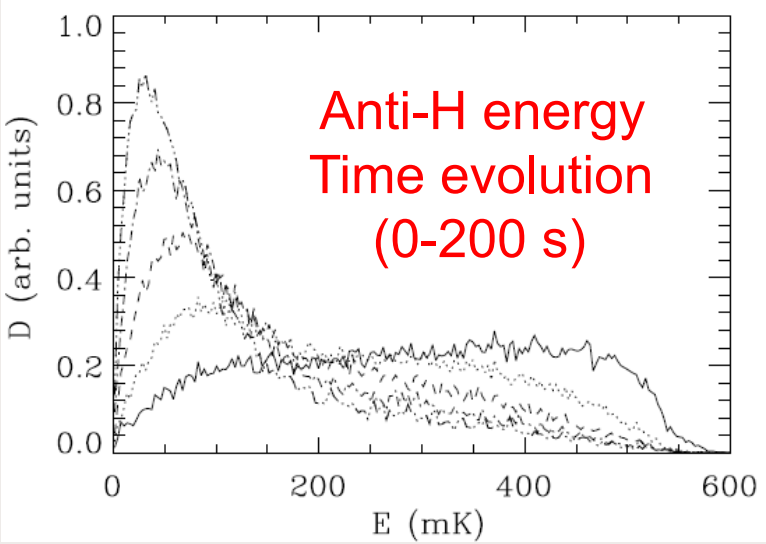
Challenge: Antihydrogen $kT >> \mu \Delta B$ (trap depth)

ALPHA-g

Laser cooling

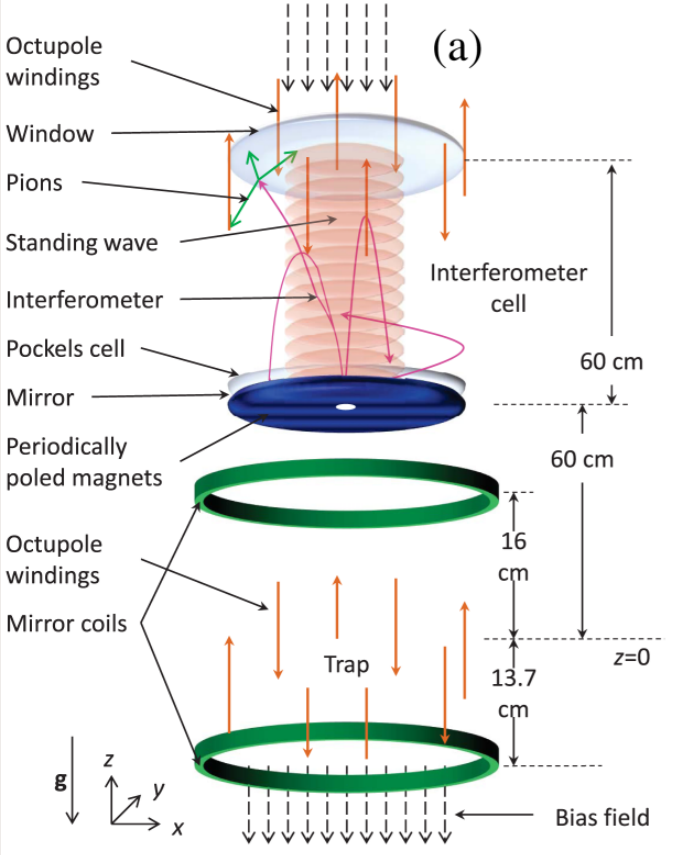
[Donnan, MCF, Robicheaux, J. Phys. B. 46, 205302 (2013)]

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

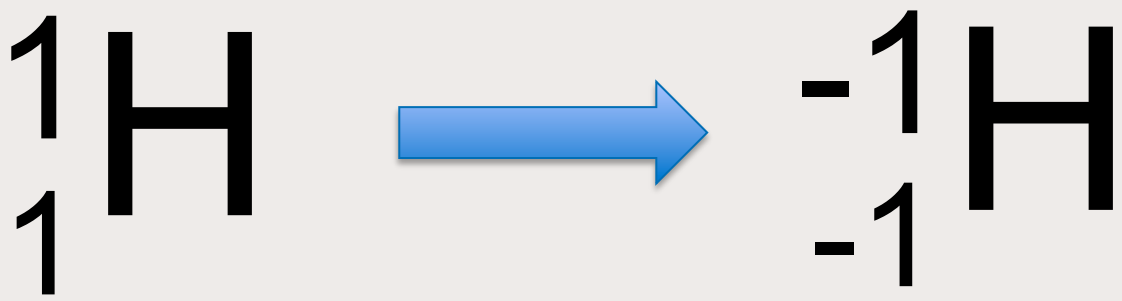


Anti-atomic fountain & Anti-atom interferometer

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



Rare Isotope Physics!



Probing Antiproton Structure with anti-H

- Recall proton radius puzzle: 7 sigma effect
- Atomic H 1s-2s (Laser)
  - r_p shift at ~1 MHz
- Hyperfine splitting (uWaves)
  - Proton structure shift (Zemach) at 60 kHz

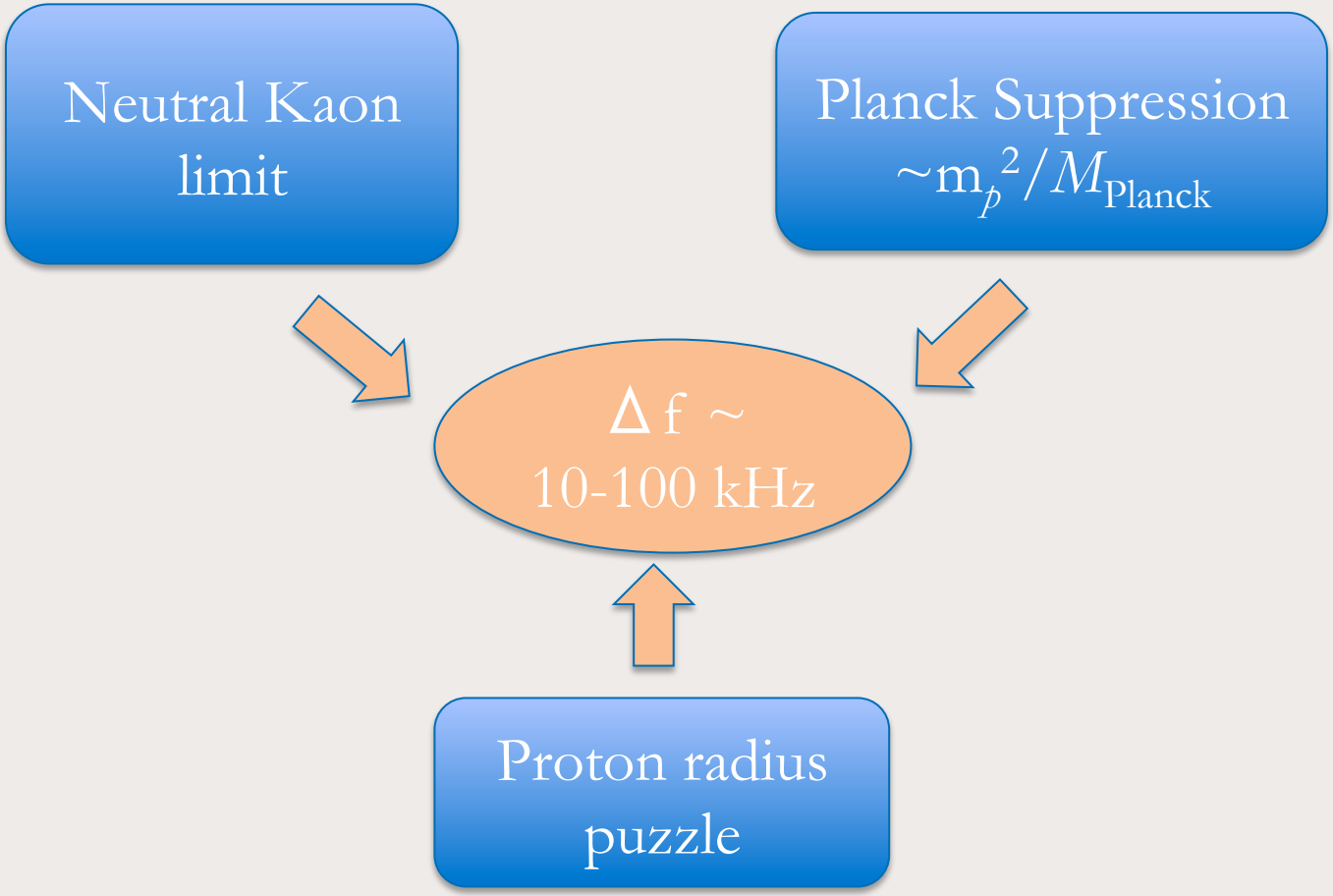
- ALPHA initial goals
  - 1s-2s: 100 kHz
  - HFS: 1 kHz

→ Already sensitive to antiproton internal structure

Thank you!
Merci!

4004 Wesbrook Mall | Vancouver BC | Canada V6T 2A3 | Tel 604.222.1047 | Fax 604.222.1074 | www.triumf.ca

CPT test benchmark



http://www.cern.ch

(June 2011)

5 June 2011

ALPHA experiment traps antimatter atoms for 1000 seconds

Andrea Gutierrez, a PhD student from UBC, transfers liquid helium from a storage dewar into the cryostat containing the superconducting magnetic trap used by the ALPHA experiment.

In a paper published by *Nature Physics*, the ALPHA experiment at CERN reports that it has succeeded in trapping antimatter atoms for over 16 minutes: long enough to begin to study their properties in detail. ALPHA

INFORMATION FOR:

CERN staff and users
Journalists
Kids
Our neighbours

INFORMATION ABOUT:

CERN in a nutshell
Science at CERN
Research at CERN
The Large Hadron Collider (LHC)
People at CERN
Education at CERN
CERN and the environment
CERN Global Network

PUBLICATIONS:

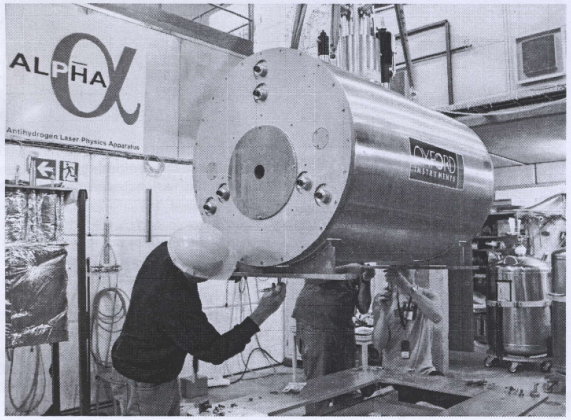
CERN Courier
CERN Bulletin

CERN Bulletin November, 2012

CERN Bulletin

Nos 47-48 | 19 & 26 November 2012
More articles available at:
http://bulletin.cern.ch

ALPHA-2: the sequel



A Large Angle Veto detector in place in the NA62 decay volume.

While many experiments are methodically planning for intense works over the long shutdown, there is one experiment that is already working at full steam: ALPHA-2. Its final components arrived last month and will completely replace the previous ALPHA set-up. Unlike its predecessor, this next generation experiment has been specifically designed to measure the properties of antimatter.

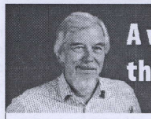
The ALPHA collaboration is working at full speed to complete the ALPHA-2 set-up for mid-November – this will give them a few weeks of running before the AD shutdown on 17 December. "We really want to get some experience with this device this year so that, if we need to make any changes, we will have time during the long shutdown in which to make them," says Jeffrey Hangst, ALPHA spokesperson. "Rather than starting the 2014 run in the commissioning stage, we will be up and running from the get go."

The first piece to arrive was the ALPHA-2 cryostat from the TRIUMF laboratory in Canada. This cryostat will hold 16 LHC current leads to power the eight superconducting magnets in the new ALPHA-2 atom trap.

The leads will allow the ALPHA-2 set-up to use less liquid helium. "These leads were provided by CERN, and use special technology developed specifically for the LHC," explains Jeffrey. "As a small collaboration, we could never have afforded this technology on our own."

Meanwhile, the final piece of the ALPHA-2 puzzle – the superconducting solenoid

(Continued on page 3)



A word from the DG

Our top priority

After three years of LHC running, we are still at the beginning of a long research programme with our flagship facility, and hopefully 4 July 2012 will go down in history as the date of one of many landmark discoveries spanning several years. CERN's top priority for the next decade and more is the full exploitation of the LHC. With speculation about potential future facilities mounting in the light of the discovery of a new Higgs-like particle, it's important to state that most clearly. Of course, this will rely on continued global collaboration, and it's important that CERN engage constructively with other regions.

(Continued on page 2)

In this issue

News

VISIT the CLIC Test Facility CTF3!

CERN Internal Communication is organising a visit to the CTF3 facility for CERN access-card holders. More details available on page 4.

To participate, send an email to **bulletin-editors@cern.ch.**

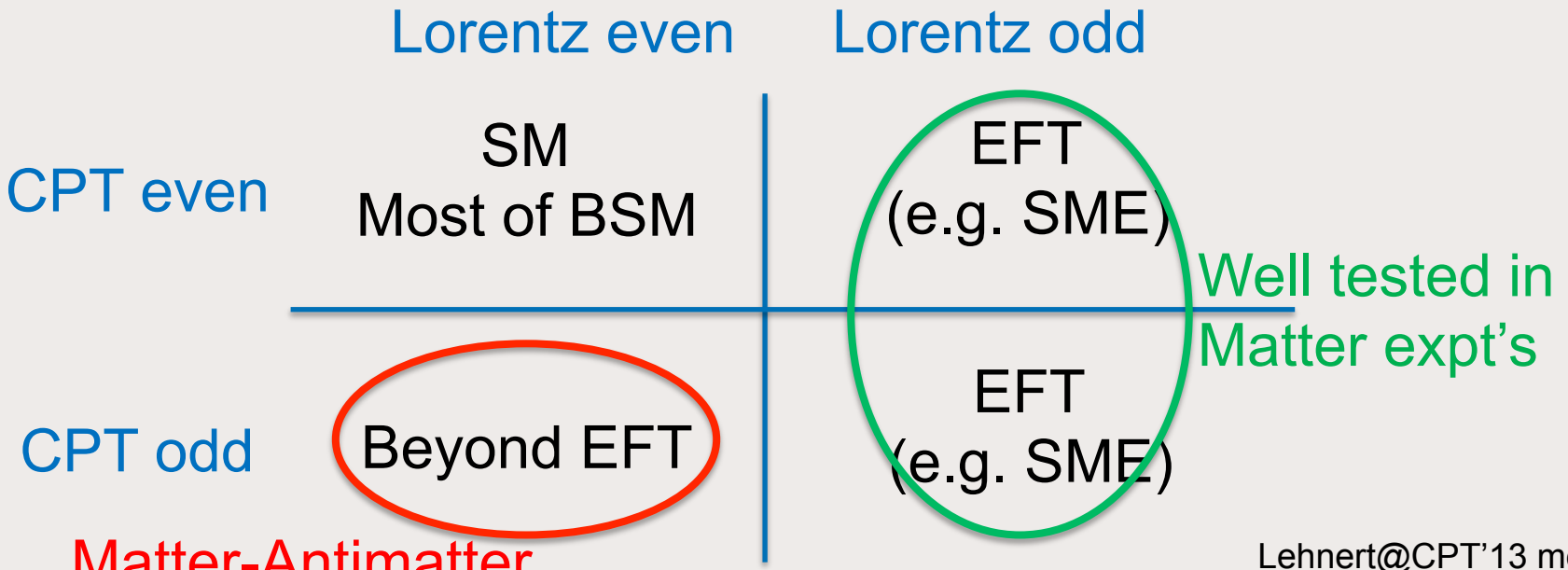
Published by:
CERN-1211 Geneva 23, Switzerland
Tel. + 41 22 767 35 86 Printed by: CERN Printshop

The first piece to arrive was the ALPHA-2 cryostat from the TRIUMF laboratory in Canada. This cryostat will hold 16 LHC current leads to power the eight superconducting magnets in the new ALPHA-2 atom trap.

Canadian contribution recognized!

Antimatter and Standard Model Extension (SME)

- SME: Effective Field Theory by Kostelecky et al.
  - Pospelov, Myers, Moore etc.
- "Anti-CPT theorem" Greenberg 2002
  - In local field theories, CPT violation does not happen without Lorentz violation



Lehnert@CPT'13 meeting

ALPHA Potential CPT Sensitivity (model dep't!)

Possible CPTV shift (Pospelov)

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

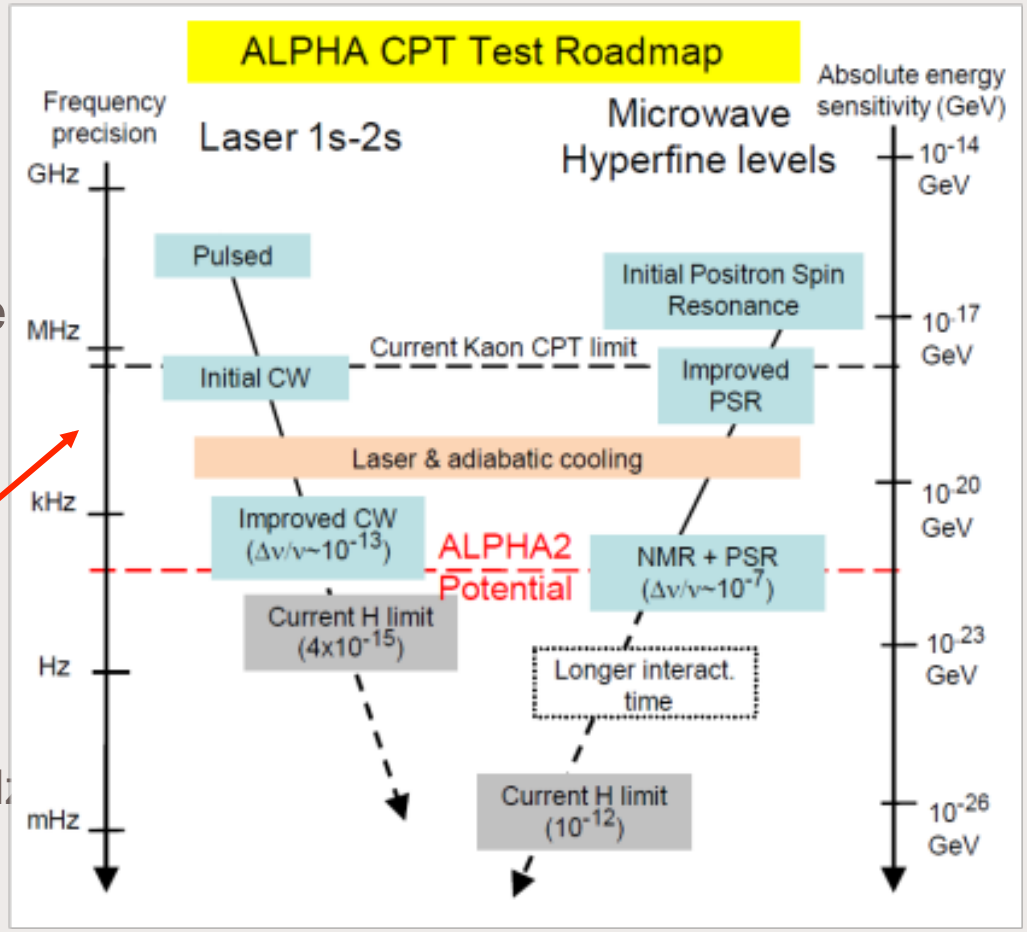
Small absolute energy ΔE
→ probes high energy scale

For n=1, m=1 GeV,
$\Lambda_{CPTV} = M_{Pl} \sim 10^{19}$ GeV

$\Delta E_{CPT} \sim 10^{-19}$ GeV
(~10 kHz in frequency)

Neutral Kaon test at few 100 kH

Antihydrogen studies potentially sensitive to Planck scale physics!



TRIUMF

Progress 2006-2010

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

Phys
Annih

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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http://focus.aps.org/story/v26/st1

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Previous Story / Volume 26 archive

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

2 July 2010

The Coolest Antiprotons

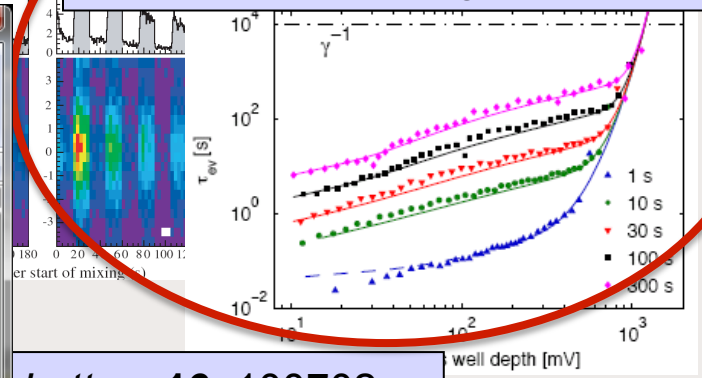
A new record low temperature for a cloud of antiprotons was measured at CERN in Geneva, announces a report in the 2 July *Physical Review Letters*. Researchers cooled a cloud of about 4,000 antiprotons down to 9 kelvin using a standard approach for cooling atoms that has never been used with charged 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.

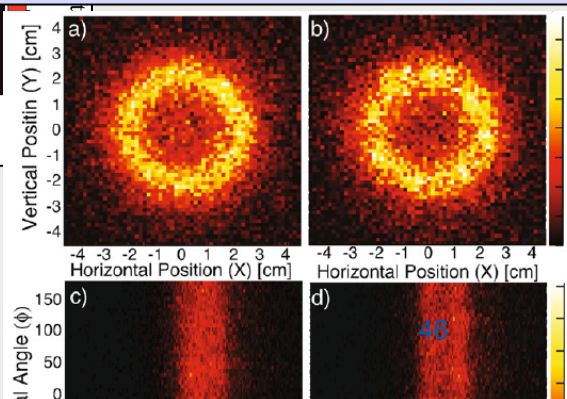
Antihydrogen, the antimatter counterpart of hydrogen, is composed of one antiproton and one positron (anti-electron). According to the CPT (charge-parity-time) theorem, a fundamental pillar of the standard model of particle physics, hydrogen and antihydrogen should share many basic traits, like mass

iStockphoto/Thomas_EyeDesign

Antiproton steam. A standard method for

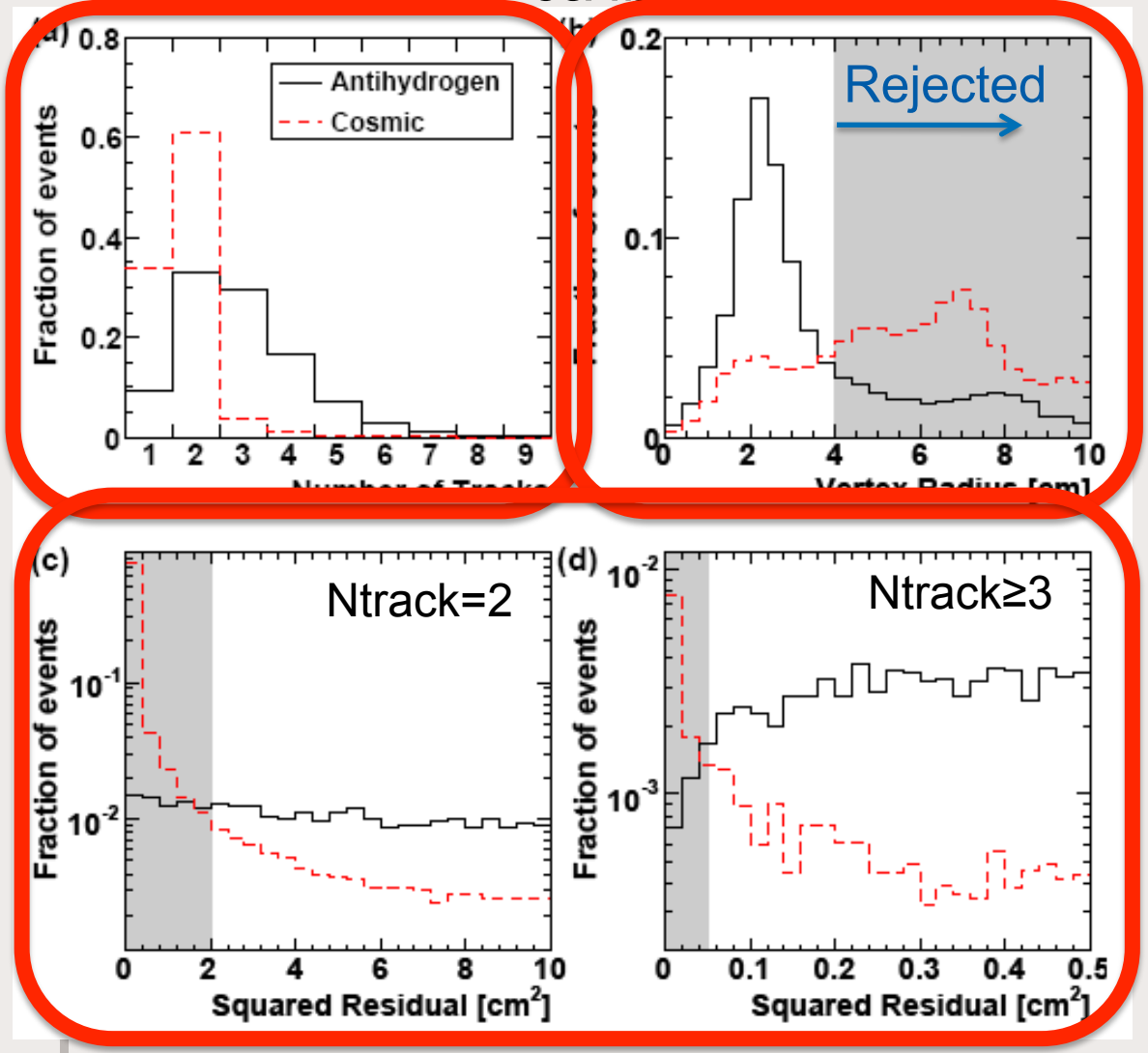
Done





Trapped anti-H: Event Selection Criteria

Distributions of calibration samples



Main cut variables

1. Number of tracks
2. Vertex radius
3. Linear fit residuals

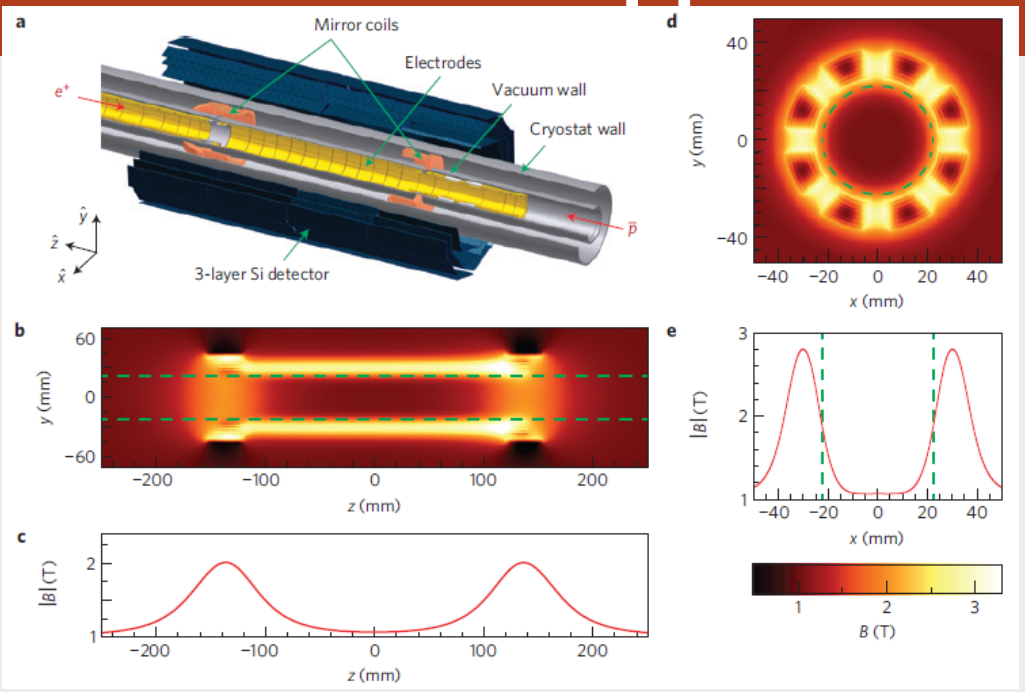
Cuts optimized for *expected* significance (p-value)

Cosmic rejection: 99.5%

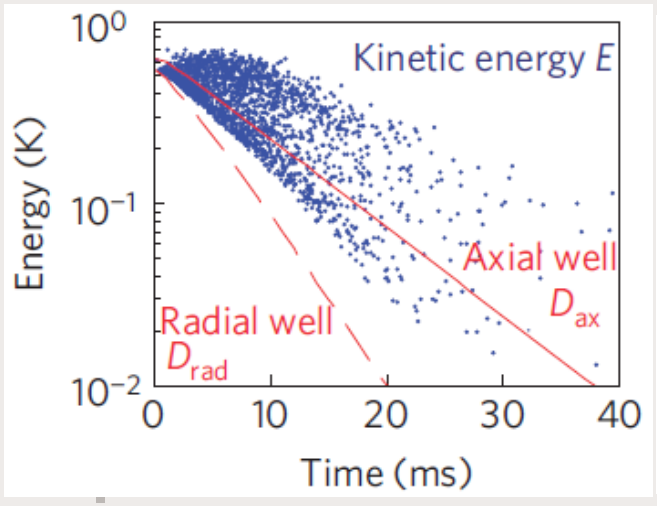
Signal acceptance: 65%

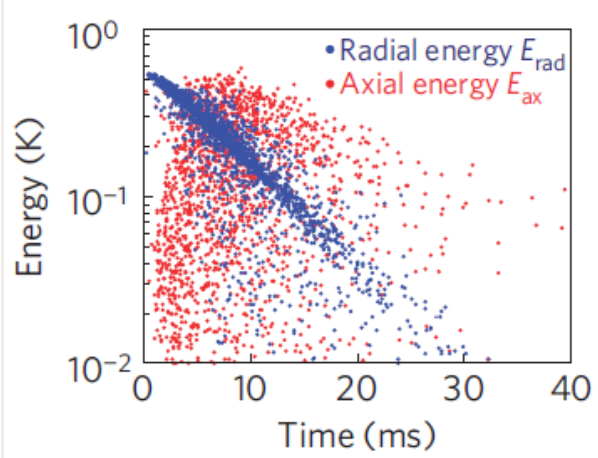
All this studied without Looking at the data

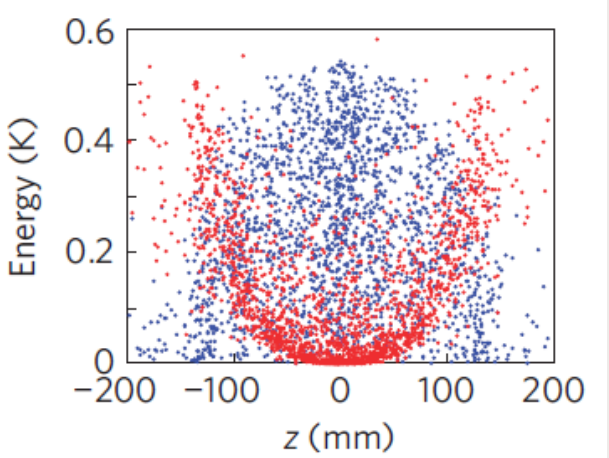
Nature Phys. 2011
Trapped antihydrogen dynamics



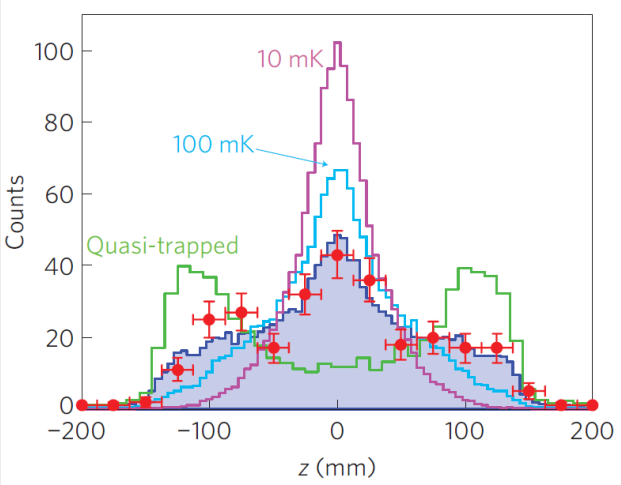
- Radial & axial deg. freedom largely decoupled
- Radial well decays faster than axial in trap shutdown
  → Hbar escapes radially
- *t* correlated with radial energy; *z* with axial energies: Orthogonal

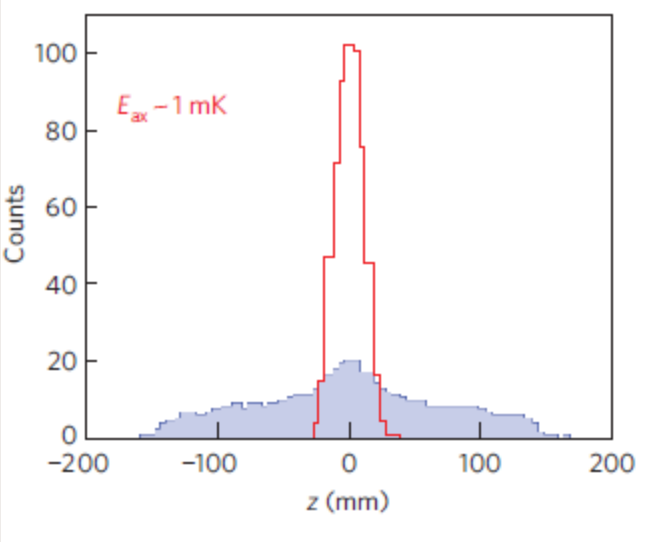






Nature Phys. 2011
Annihilation position distribution





- Sensitivity to direction dependent (anisotropic) energy distribution
- Erad ~ 0.5 K, Eax ~ 1 mK (could be possible by one dimensional cooling)
- Position sensitive detection (feature of anti-atoms), giving unexpected information!

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

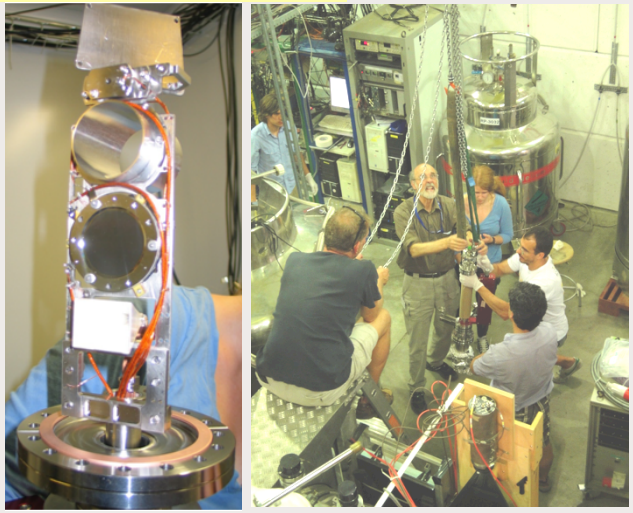
Confinement of antihydrogen for 1,000 seconds

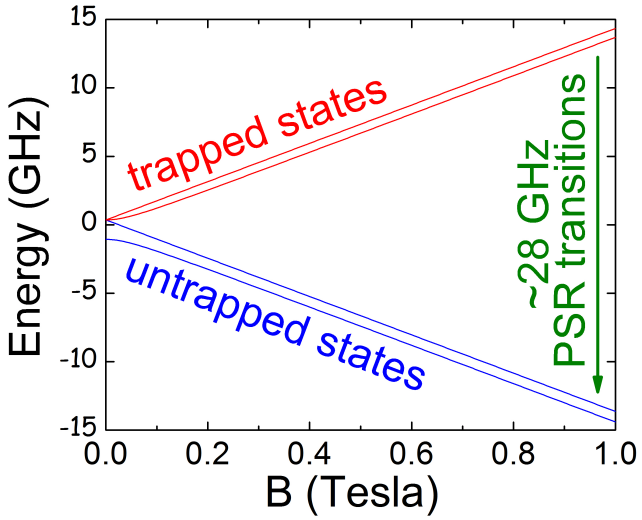
The ALPHA Collaboration*

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.

Microwave-induced Positron Spin Resonance (PSR)

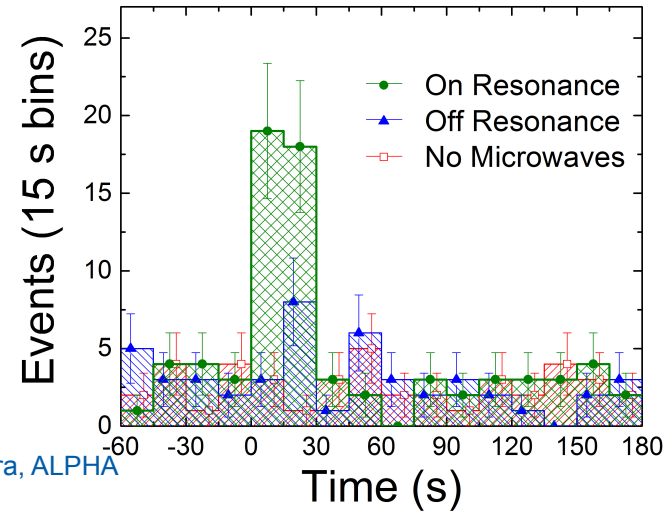
Installation at CERN, July 2011





- Developed at SFU/UBC
- Trap ~1 Anti-H/20 min
- Irradiate with μW
  - Drive transition:

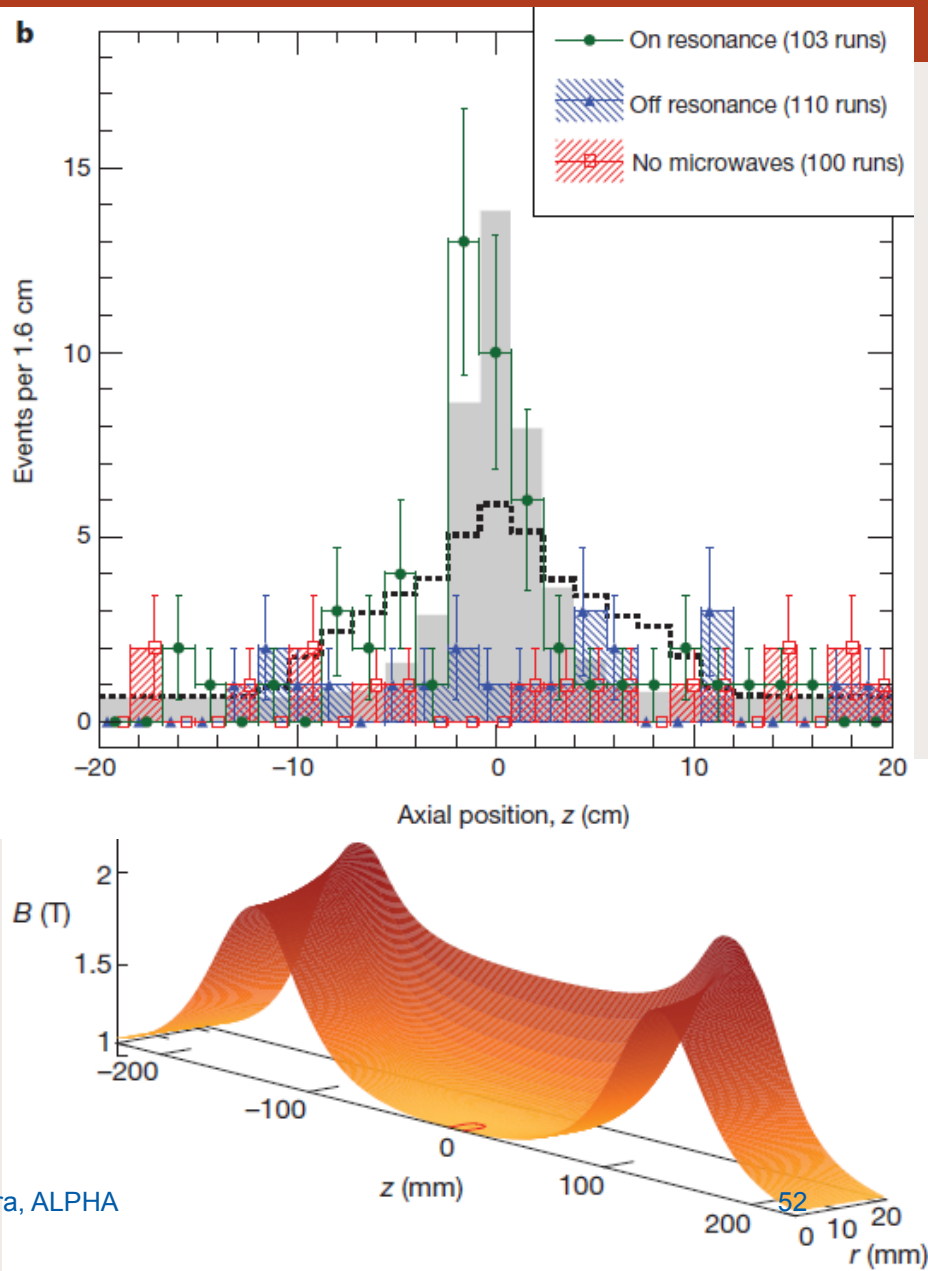
    trapped → un-trapped
  - Look for annihilations
- Multivariate (blind) analysis
  - improved S/N by x10



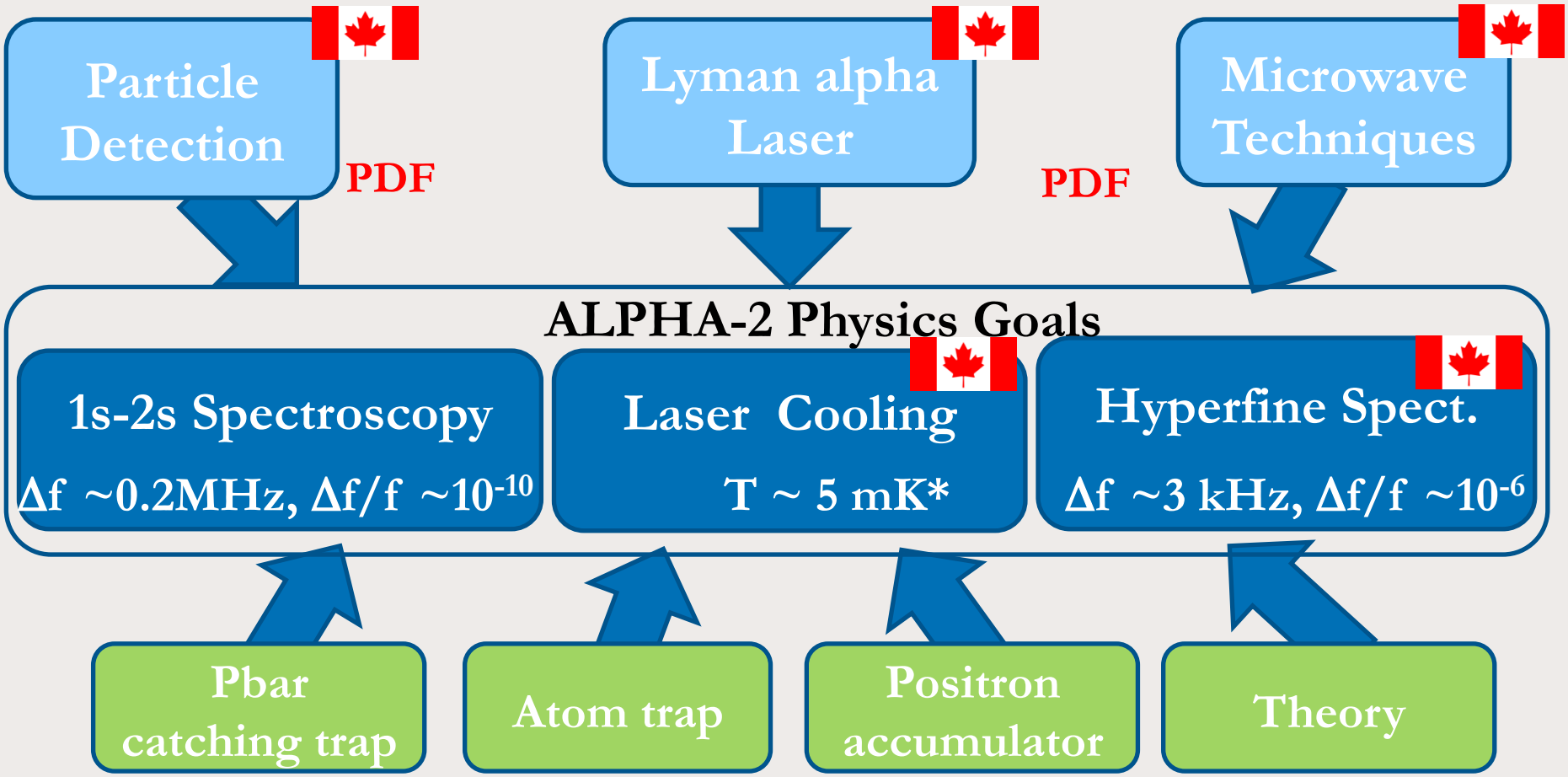
Microwave Results: Nature 2012

Careful Cross checks & Controls: e.g.

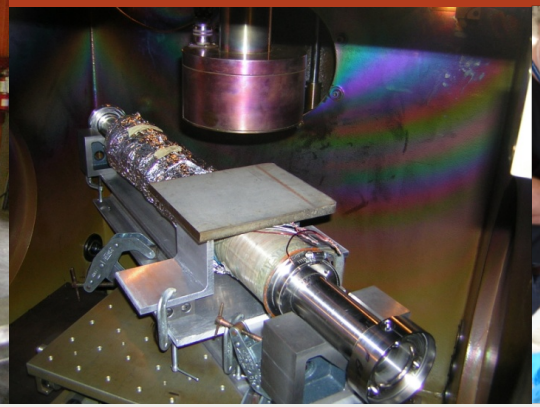
- Blind analysis
- "Decision tree" analysis to reject cosmic backgd
- Annihilation positions
- Different uWave powers
- Background studies, esp annihilations on residual gas

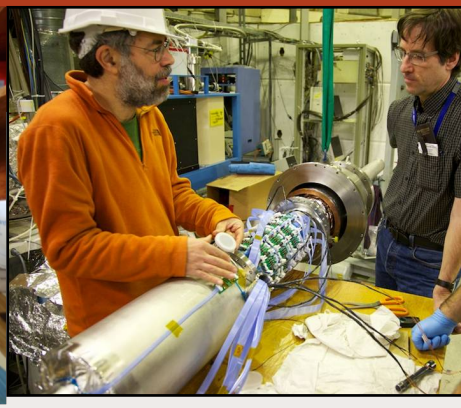


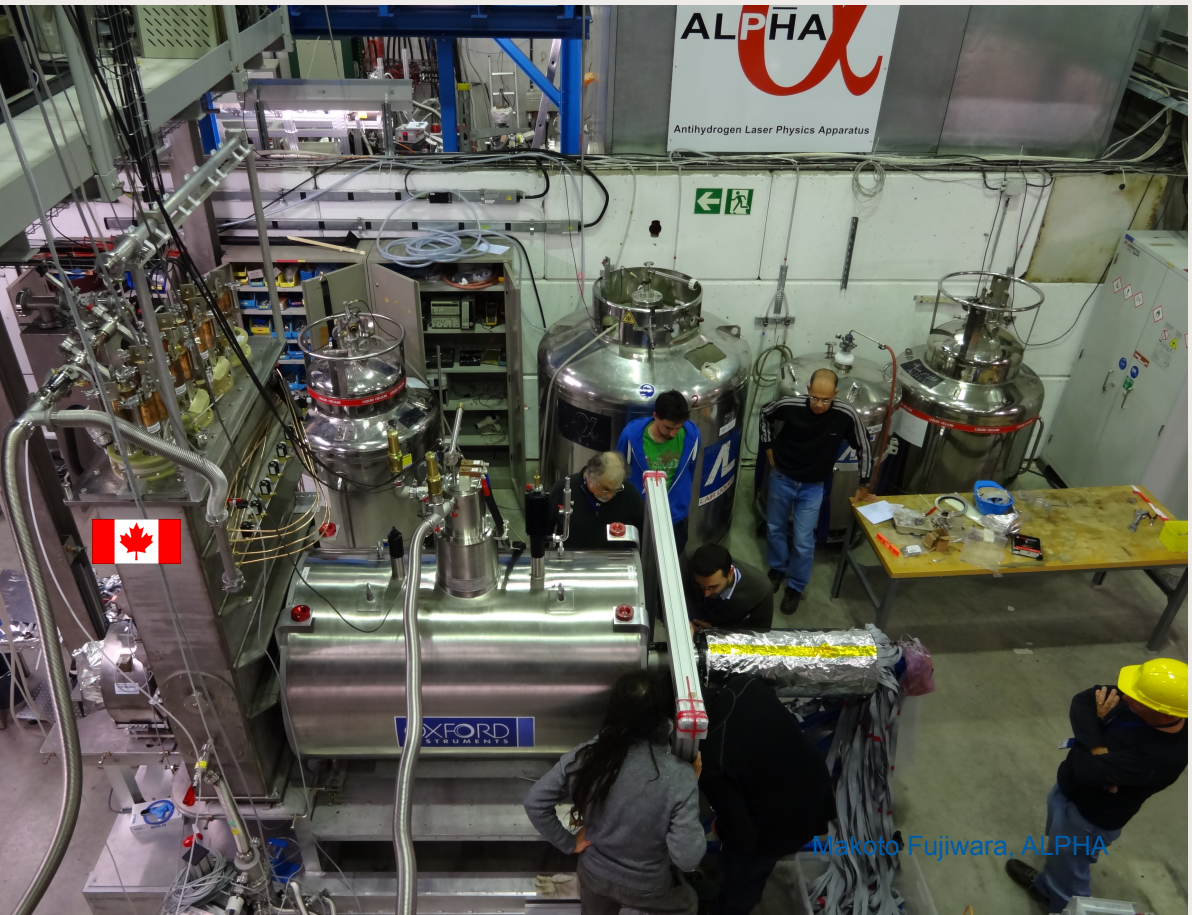
Focused Canadian Contributions: Overview



2012: ALPHA-2 Construction







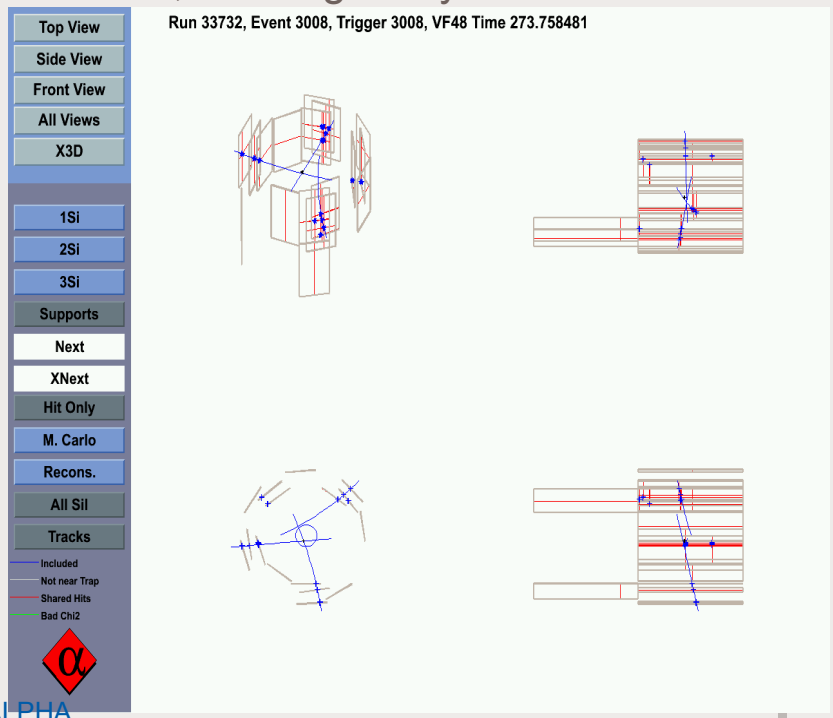
Makoto Fujiwara, ALPHA

- New apparatus for laser and microwave spectroscopy
- Very complex design & construction job for cryostat
- Unique Canadian contributions
  - Cryo-engineering
  - Precision welding
  - Canadian industry (PAVAC)
  - >3000 hours of machining at TRIUMF and Calgary

ALPHA-2 Si Vertex Detector

- Annihilation imaging
  - Key for single atom sensitivity
- Expanded & Improved for ALPHA-2
  - TRIUMF/York responsible for readout, DAQ, tracking/analysis software

Canadian students in Liverpool Si Clean Room

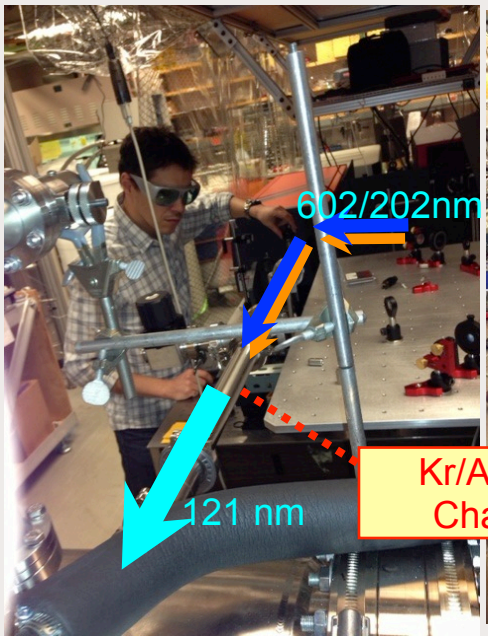


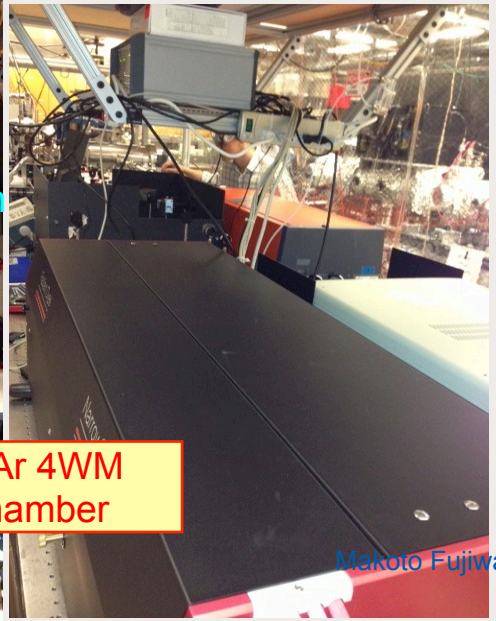
Annihilation of trapped pbar in ALPHA-2, Dec 2012

Lyman-alpha spectroscopy & cooling

M. Michan (Ph.D.), T. Momose, UBC

- Laser cooling
  - Provides cold, high density, spatially confined sample
  - Needed for gravity experiments
- Pulsed Lyman-alpha spectroscopy
  - Candidate for 1st laser exp.



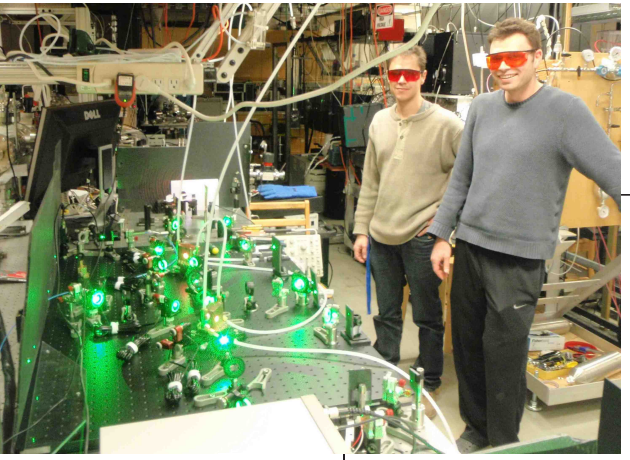


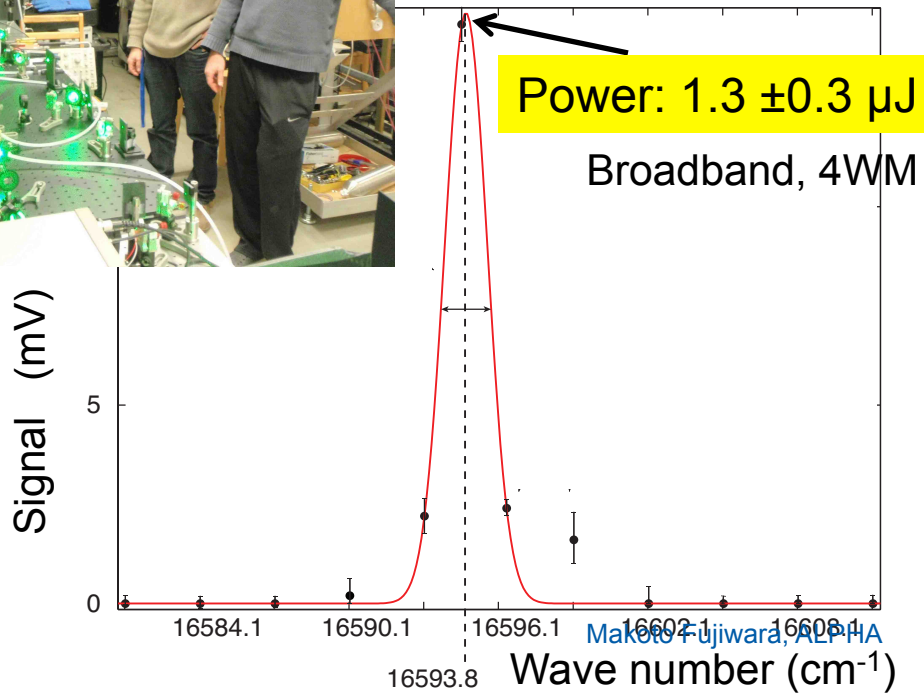
- Lyman-alpha source (122 nm)
  - Requires 4 Wave Mixing (4WM) or 3rd Harmonic Generation in gas
- UBC Development
  - Broad band (~6 GHz) source demonstrated (Summer 2012)!!!
  - 0.15 μJ per pulse (measured via H absorption): Sufficient for initial exp.
- Narrowband (<200 MHz) source being developed
  - 1st spectroscopy at 10^{-7} level
  - Allows cooling from 0.5 K to 20 mK [Simulations: J. Phys. B. 2013]

Pulsed Ly-alpha spectroscopy and cooling

M. Michan (UBC), G. Polovy (UBC):
T. Momose, R. Thompson, M. Fujiwara

- Ly-α laser: spectroscopy on atomic-H demonstrated @ UBC!
- Sufficient power obtained for 1st optical probing of anti-H





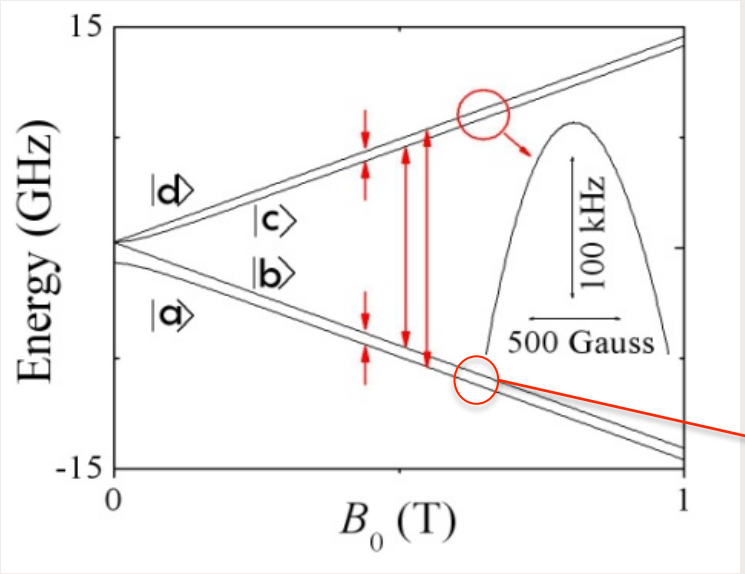
- Further optimizations
  - 4WM → THG ✔
  - Narrowing
  - Laser will be shipped to CERN, June, 2014
- Light transport & control system at under construction at CERN

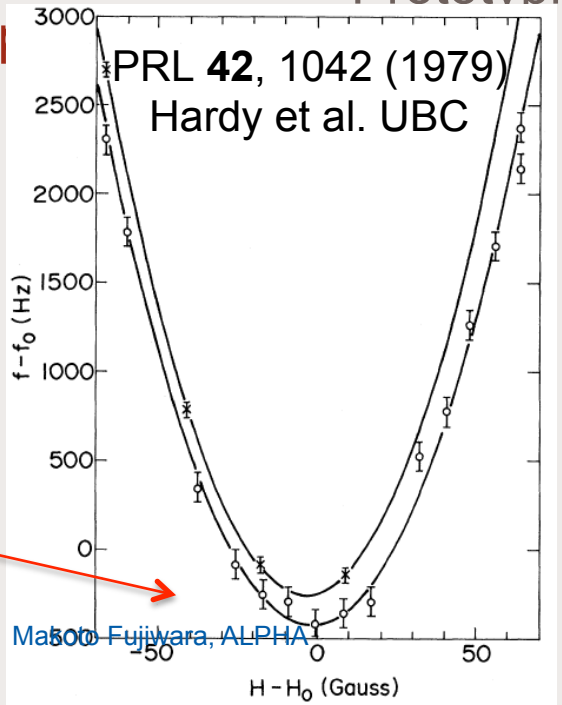
High Precision NMR of Antihydrogen

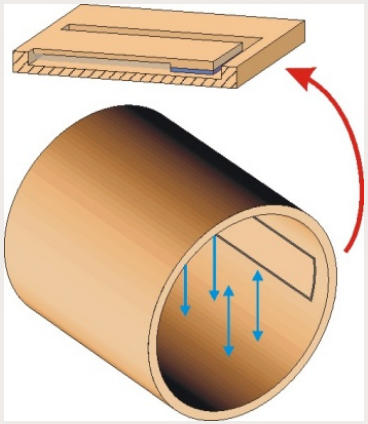
Ashkezari, Dunlop (SFU), Friesen (Calgary), Evetts (UBC): Hayden, Hardy

- Nuclear Magnetic Resonance
  - Antiproton spin flip
  - Broad maximum at 0.65 T
  - **Insensitive B field homogeneity!**
  - Initially at 10 kHz (10^{-5})
    → <100 Hz (10^{-7})
  - Complementary to laser exp

- 655 MHz Resonator development (Dunlop, Evetts)
  - Challenge: compatibility with trap/plasma requirements
  - Simulations with Laxdal, TRIUMF
  - Prototyping at SFU/UBC







Resonator Prototype at SFU (Q ~ 300)

Makoto Fujiwara, ALPHA

High Precision NMR of Antihydrogen

HPQ: Ashkezari (SFU), Friesen (Calgary), Capra (York), Evetts (UBC): Hayden, Hardy, Thompson, Olin, Fujiwara

Nuclear Magnetic Resonance

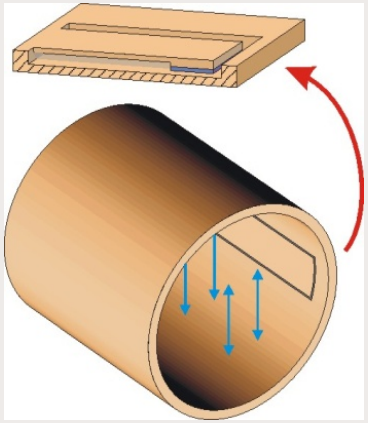
- **Insensitive to B field inhomogeneity at magic field 0.65 T!**
- Design criteria for ALPHA-2
- Probe internal structure of anti-nucleon
- Measured for H by Hardy+ at UBC

RF Resonator needed

- Challenge: compatibility with trap/plasma requirements
- Simulations with TRIUMF RF
- Prototyping at SFU/UBC

Systematic effects from simulations

Effects	Initial stage	With cooling
Transit time: transverse	2×10^{-6}	1×10^{-7}
Transit time: axial	2×10^{-7}	5×10^{-8}
Doppler broadening	1×10^{-7}	1×10^{-8}
Resonator stability	8×10^{-8}	6×10^{-9}
Octupole field reproducibility	2×10^{-9}	1×10^{-10}
Mirror fields reproducibility	1×10^{-10}	1×10^{-10}
Solenoidal field reproducibility	1×10^{-10}	1×10^{-10}



Resonator Prototype at SFU (Q ~ 300)