Art Olin for the ALPHA Collaboration

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Stockholm University, Sweden

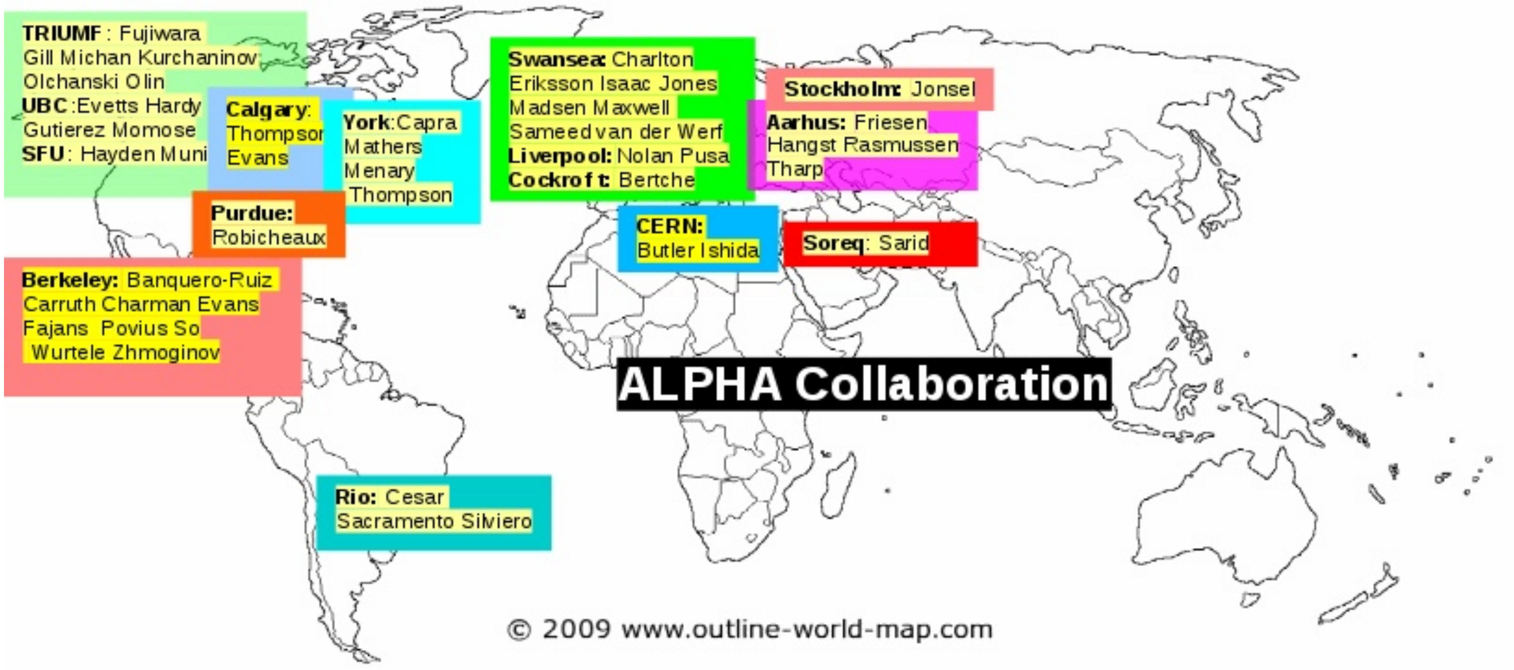
Simon Fraser University, Canada `

TRIUMF, Canada

Cockcroft Institute, UK

York University, Canada

ALPHA Cast of Characters



Physics Areas: Accelerator, Atomic, Condensed Matter, Particle, Plasma

Supported by:
CNPq, FINEP/RENAFAE (Brazil) ISF (Israel); JSPS PFRA (Japan)
FNU, Carlsberg Foundation (Denmark); VR (Sweden);
NSERC, NRC/TRIUMF, AIF, FQRNT (Canada); DOE, NSF (USA);
EPSRC, the Royal Society and the Leverhulme Trust (UK).

CPT Symmetry

CPT Theorem: Lüders, Pauli, Schwinger, Bell, Zumino. Follows from Lorentz invariance, locality, unitary Hamiltonian.
Quantum field theories have this symmetry.

- CPT predicts equality of particle and antiparticle masses, charges, and decay widths.
- Strings are non-local, and Lorentz invariance may be violated in extra dimension theories or quantum gravity.
- Tests of CPT symmetry determine the experimental limits on these fundamental assumptions.
- Experimental limits on CPTV observables in different systems are required.

Where's the Anti?

Sakharov conditions for matter- antimatter asymmetry:

- B violation
- C, CP violation
- out of equilibrium
- Known CP violation is not enough.

- With CPTV, the asymmetry can develop under equilibrium conditions.
- CPTV at $O(10^{-6})$ in t and $\bar{t}$ masses required.

A.D. Dolgov, Phys. Rep. 222, 309 (1992).

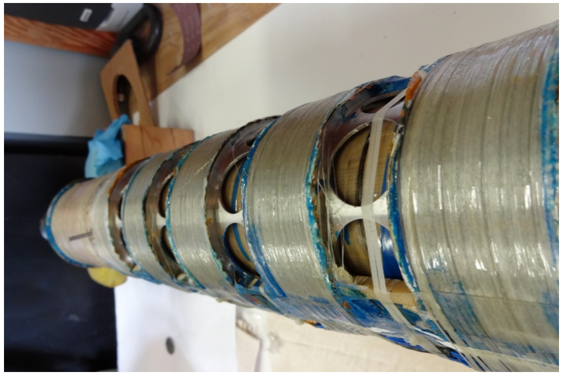
Gauge Invariance

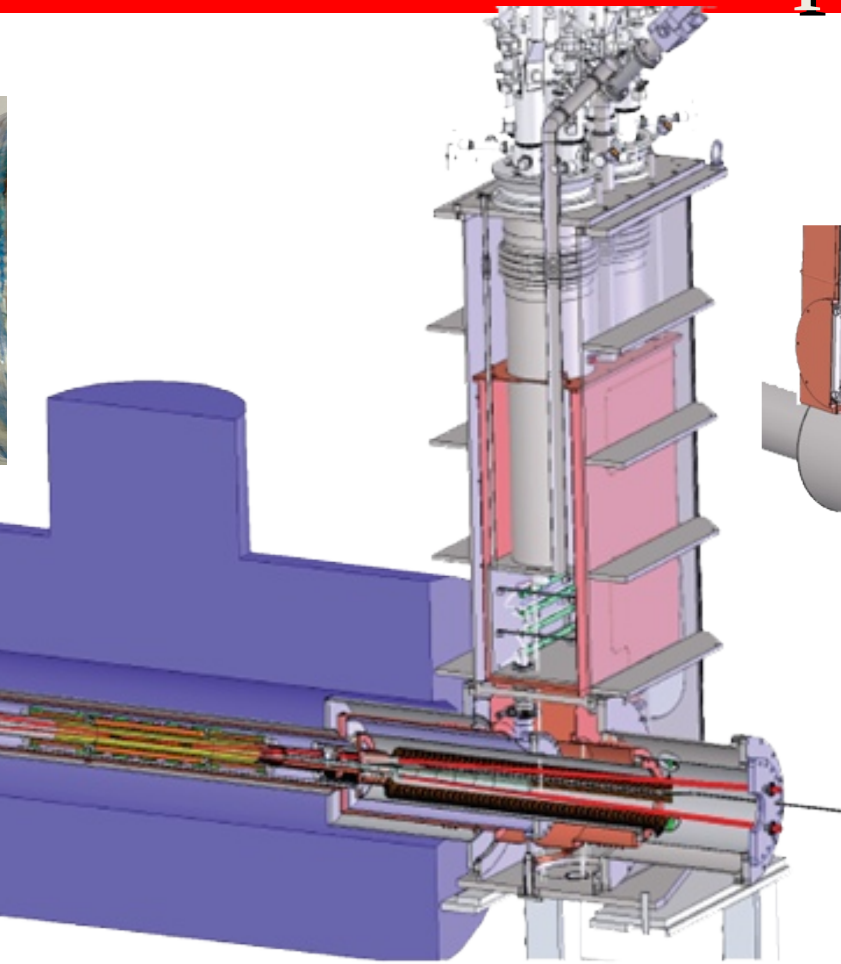
In the SM gauge invariance is broken if particle/antiparticle charges differ.

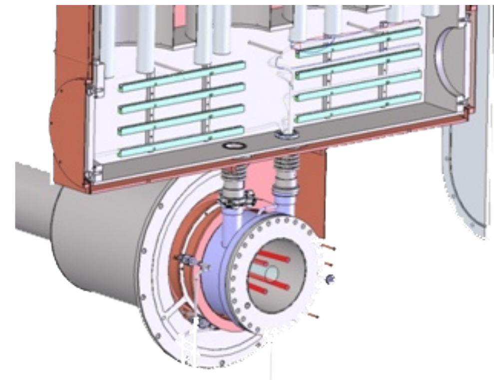
- Atomic neutrality and charge quantization may emerge from embedding SM in a GUT.
- Models with CP violation and topological magnetic monopoles can have small charge shifts.
- Models with photons having a small mass m_γ can result in a charge shift proportional to $m_\gamma/M_{cutoff.}$
- Models with U(1)B-L may have charge shifts. However these would result in neutral H, H and equal particle/antiparticle charges, with the shift manifest in small charges on the neutral fermions.
- Gauge invariance is very well tested in the matter sector.

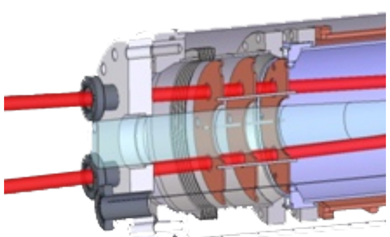
Ref Arvanitaki et al, PRL 100, 120407 (2008).

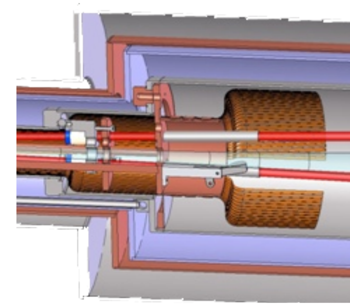
ALPHA-II Atom Trap



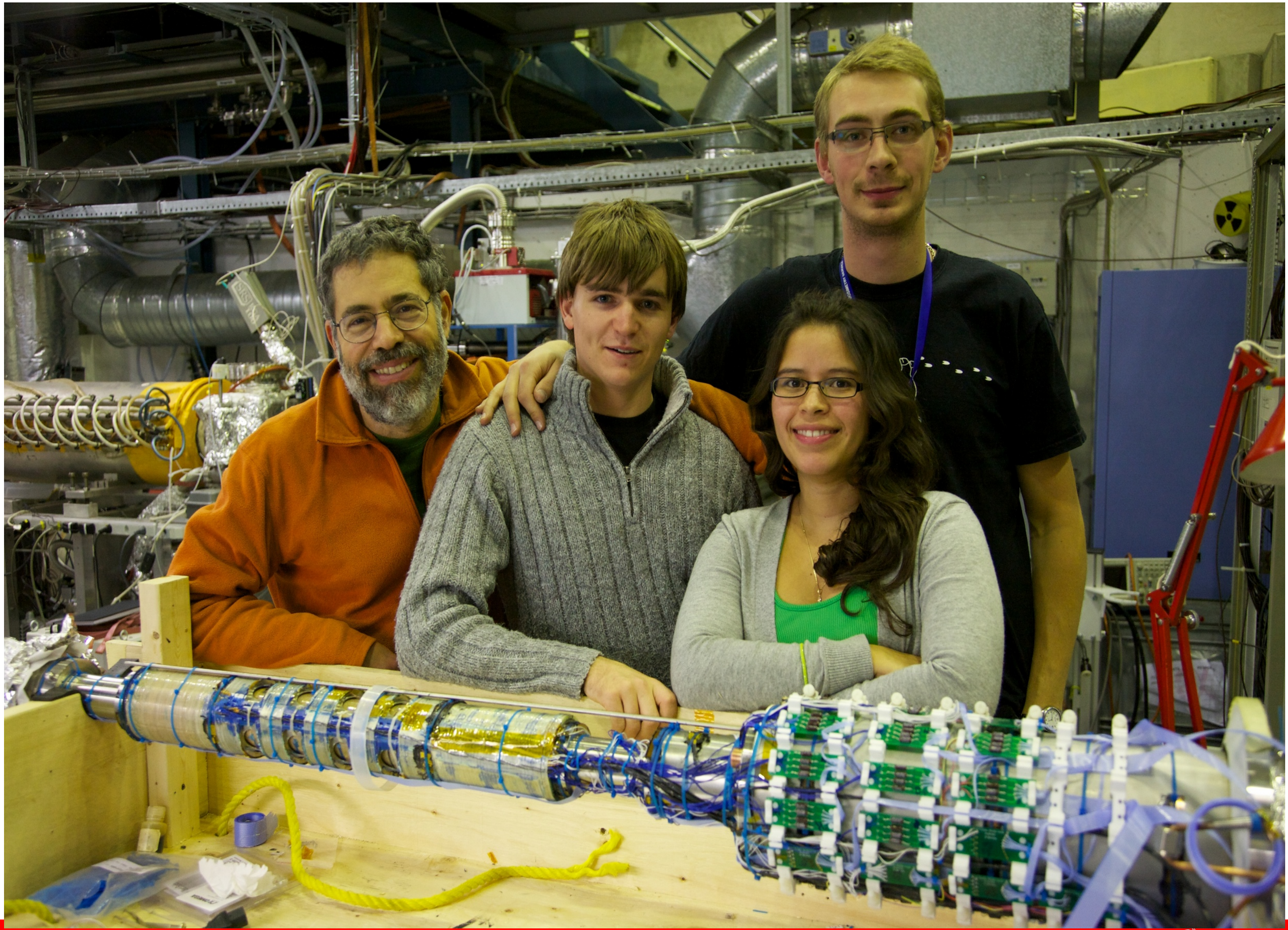




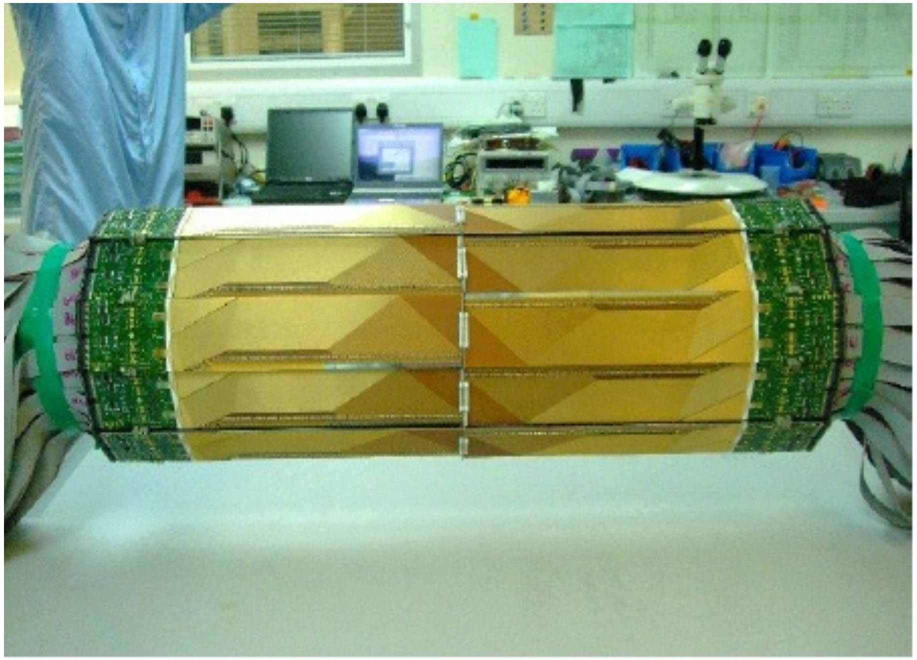




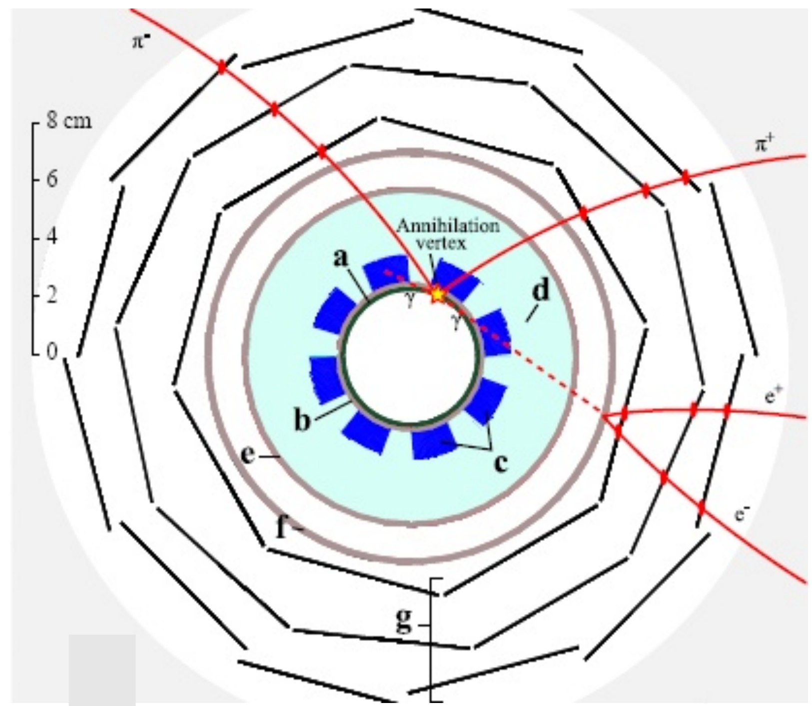
Multipole Ready for Insertion to Cryostat



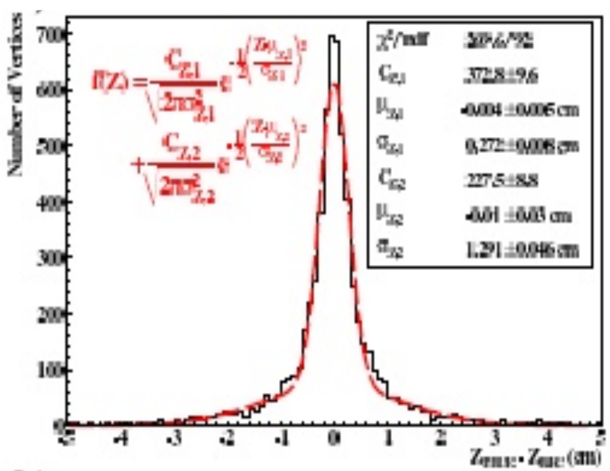
Si Vertex Detector



Double sided silicon strips
Vertex Resolution ~7mm
Hit Efficiency > 95%.
30,000 channel strips
~0.8 m^2 active area



Difference between simulated hits and reconstructed track hits.



ALPHA Challenges

Characteristic energy scales:

Antiprotons from AD: 5 MeV

Hydrogen atom binding energy: 13.6 eV

Plasma space charge energy: ≈ 10 eV

Neutral trap depth: 0.5K ≈ 50 μeV

Need 10^{-5} control of plasma to make cold enough $\bar{H}$

$\bar{H}$ production is much easier than trapping.

- Atomic energy scale 10 eV ≈ Plasma space charge

Only a few atoms will be cold enough to be trapped, so very efficient low background detection is needed.

ALPHA Status 2011

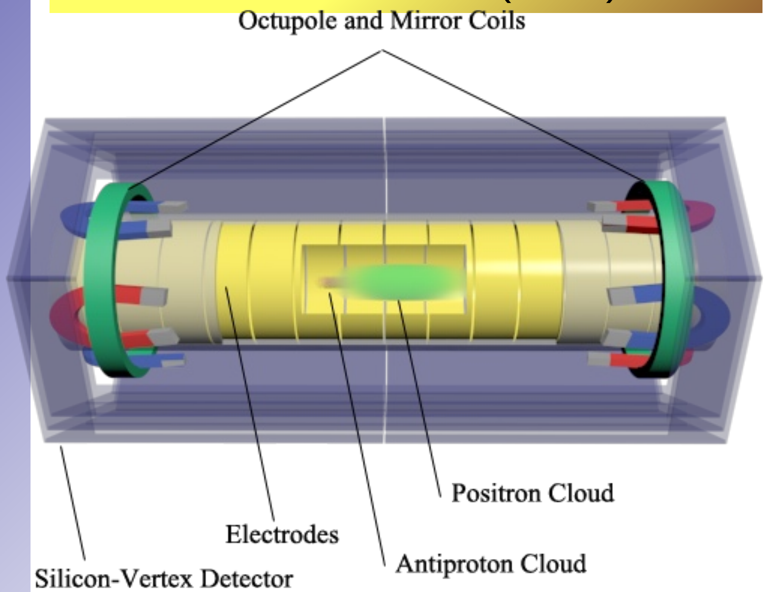
Succeeded in trapping antihydrogen.

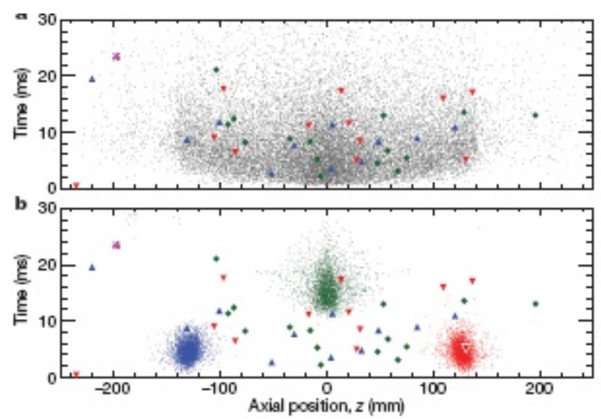
- Mix $\bar{p}$ and e^+ plasmas in trap for 1s. Most $\bar{H}$ escape ~5000 annihilations.
- Clear charged particles with E fields.
- Quench trap magnets.

Evidence of trapping based on time and spatial distribution of 38 $\bar{H}$ annihilations.

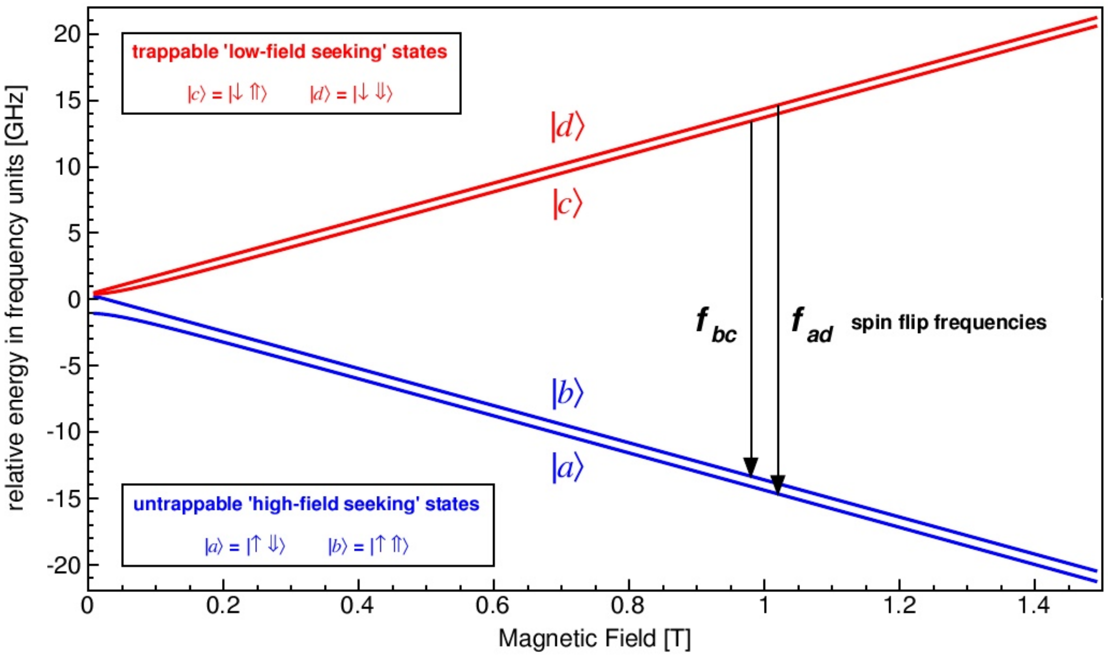
- Position and time of these annihilations reveals the trapping dynamics.
- Observation that some $\bar{H}$ remain trapped for 1000 seconds. Presently in ALPHA2 we measure a mean loss time of >1200 s.
- Enables long laser and microwave interrogation times.

Trapped Antihydrogen
Nature 468, 673(2010)





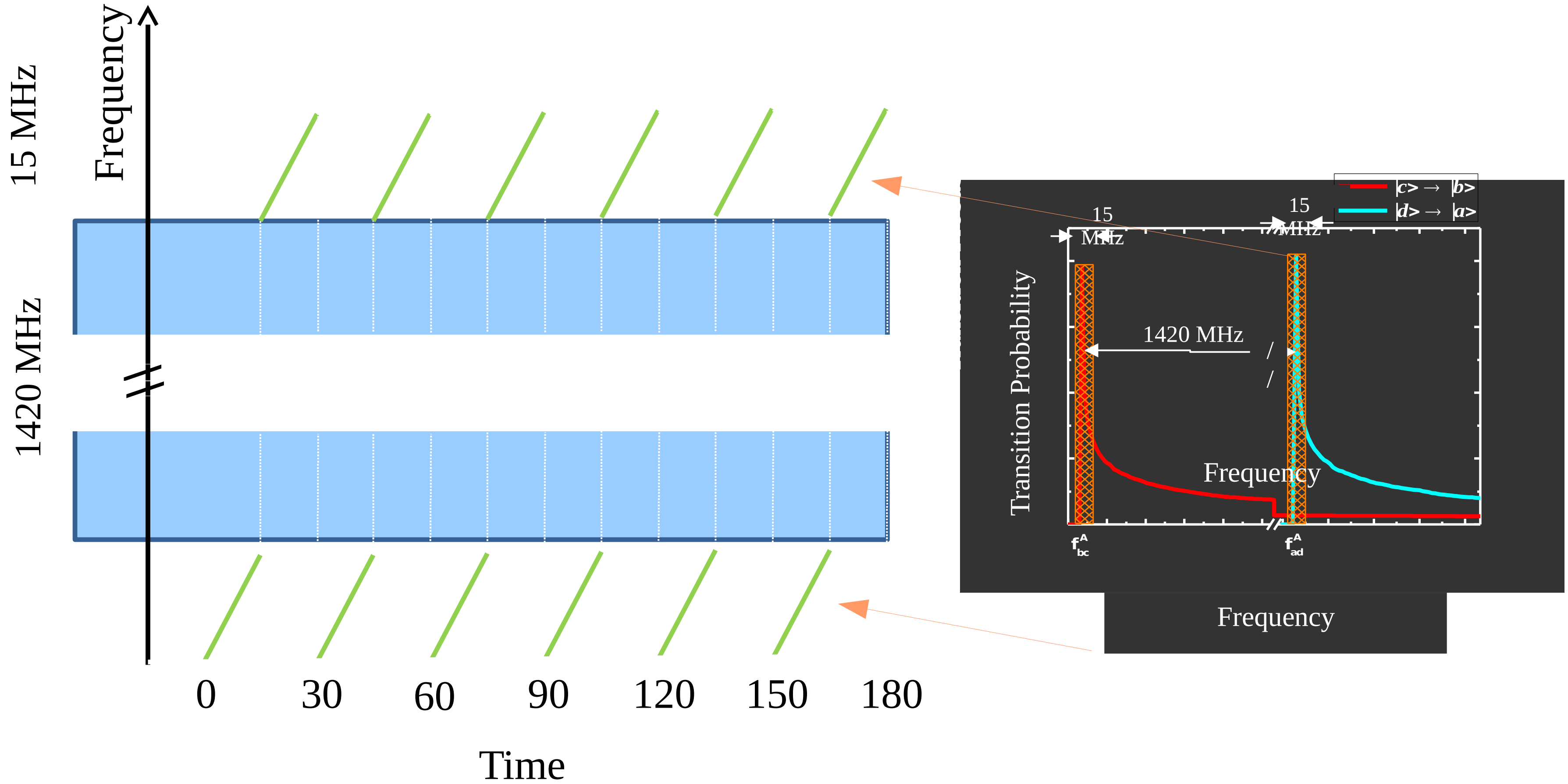
Antihydrogen Hyperfine Energy Levels



- Hyperfine interval in hydrogen, $\boldsymbol{f}_{ad}$ - $\boldsymbol{f}_{bc}$, is measured to $\sim 10^{-12}$.
- A measurement in antihydrogen at this precision is a significant CPT test.
- Driving $\boldsymbol{f}_{bc}$ or $\boldsymbol{f}_{ad}$ expels $\overline{\text{H}}$ from trap.

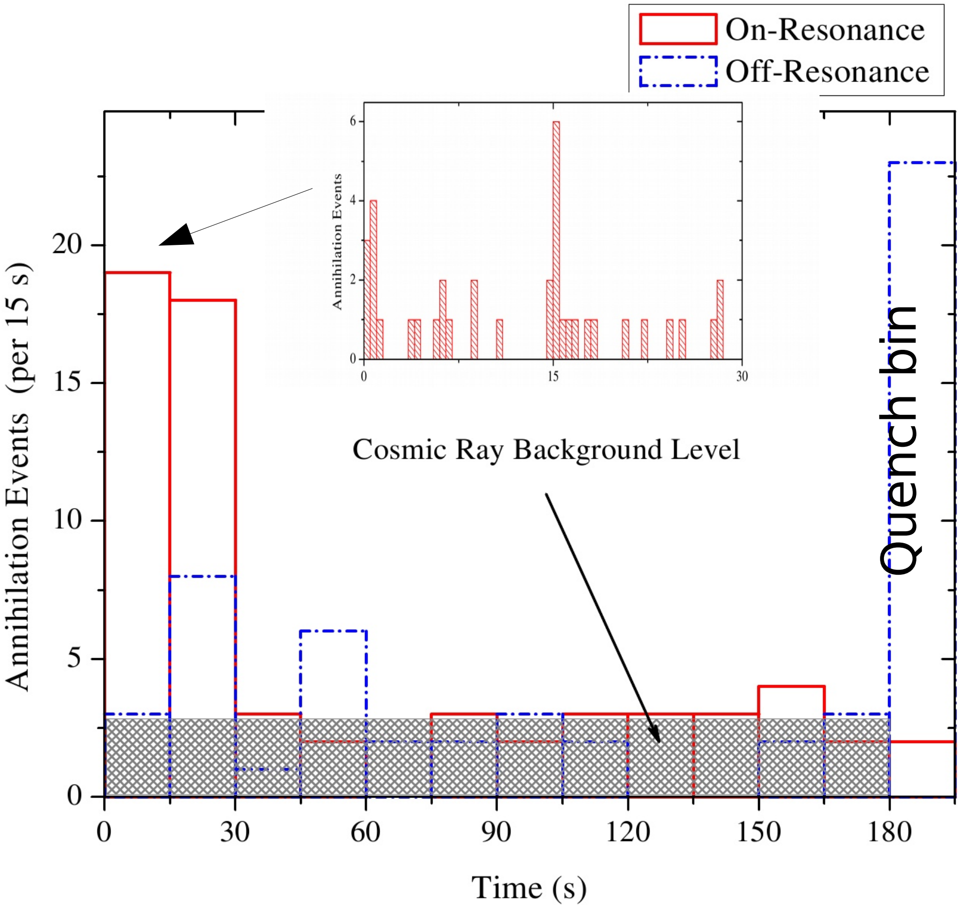
The Breit–Rabi diagram, showing the relative hyperfine energy levels of the ground state of the hydrogen (and antihydrogen, assuming CPT invariance) atom in a magnetic field. In the state vectors shown (for the high-field limit), the single arrow refers to the positron spin and the double arrow refers to the antiproton spin.

Microwave Sweep Sequence

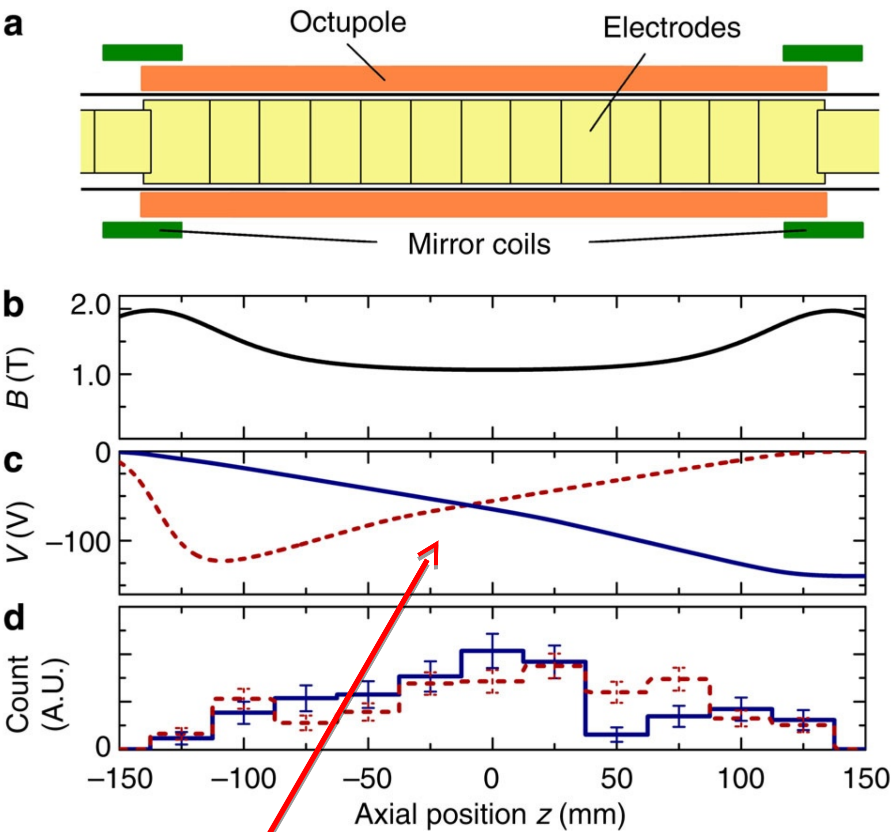


2012: Microwave-Correlated Transitions Observed

Consistent with hydrogen transitions to 4 10^{-3}.
Hyperfine splitting 1420 ±85 MHz.



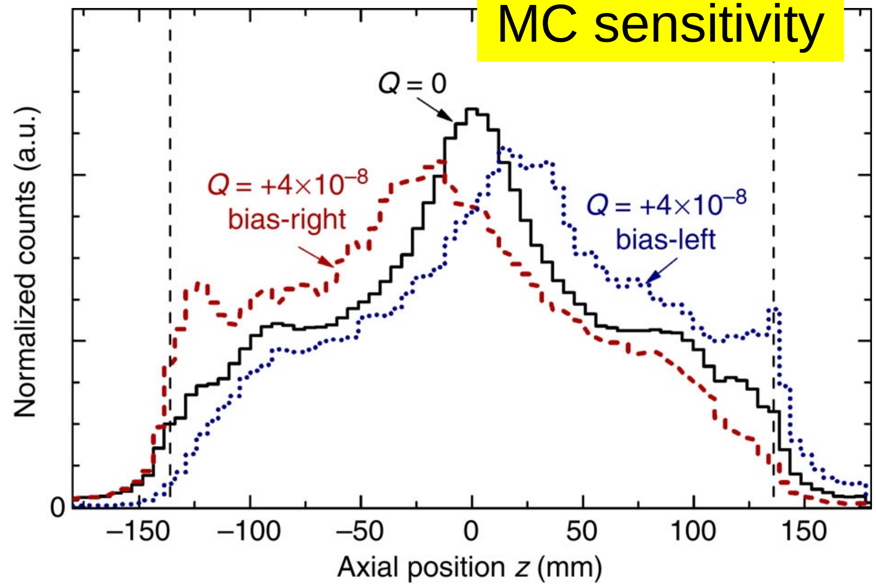
Charge Neutrality 2014



Biasing E field

$\langle z\rangle_R - \langle z\rangle_L = 8.2 \pm 6.2$ mm

MC sensitivity



Result (M. Baquero, Ph.D.):
$Q=(-1.3\pm1.1\pm0.4)\times10^{-8}$
An experimental limit on the charge of antihydrogen.
Nature Comm. 5: 395(2014).

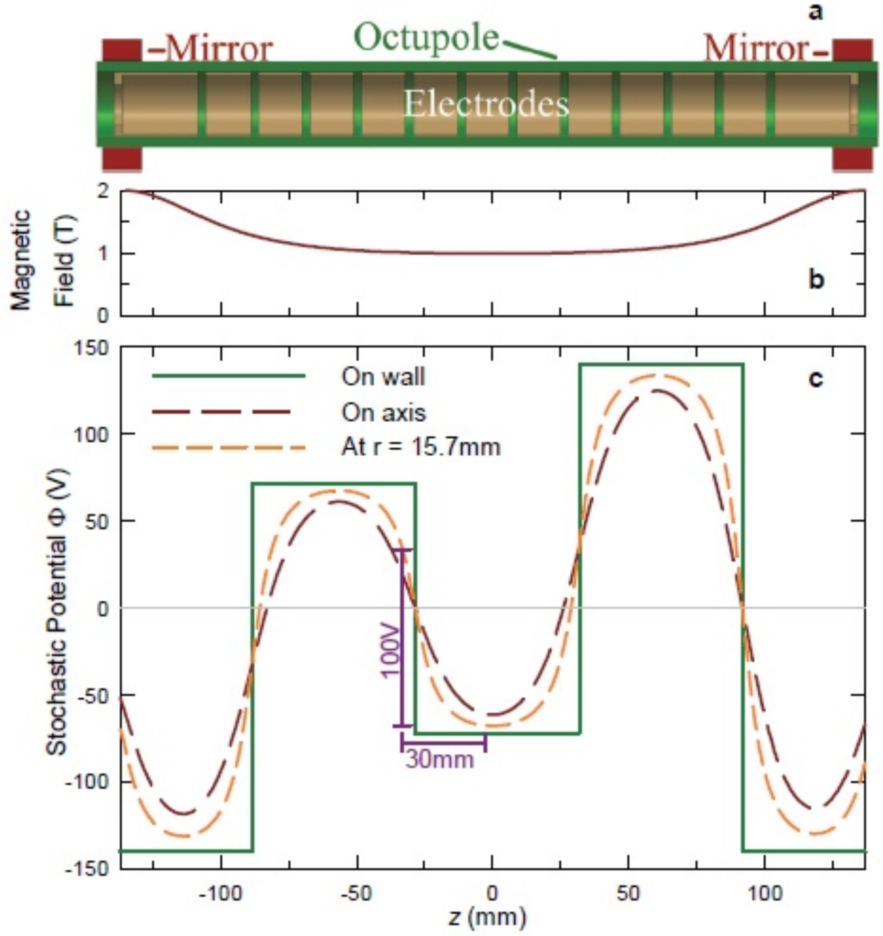
Stochastic Heating Basics

- $\overline{H}$ held in magnetic well μ•B
- Transition gives a random kick ΔΦ to each charge Q.
- Ejected from the 0.5K well unless

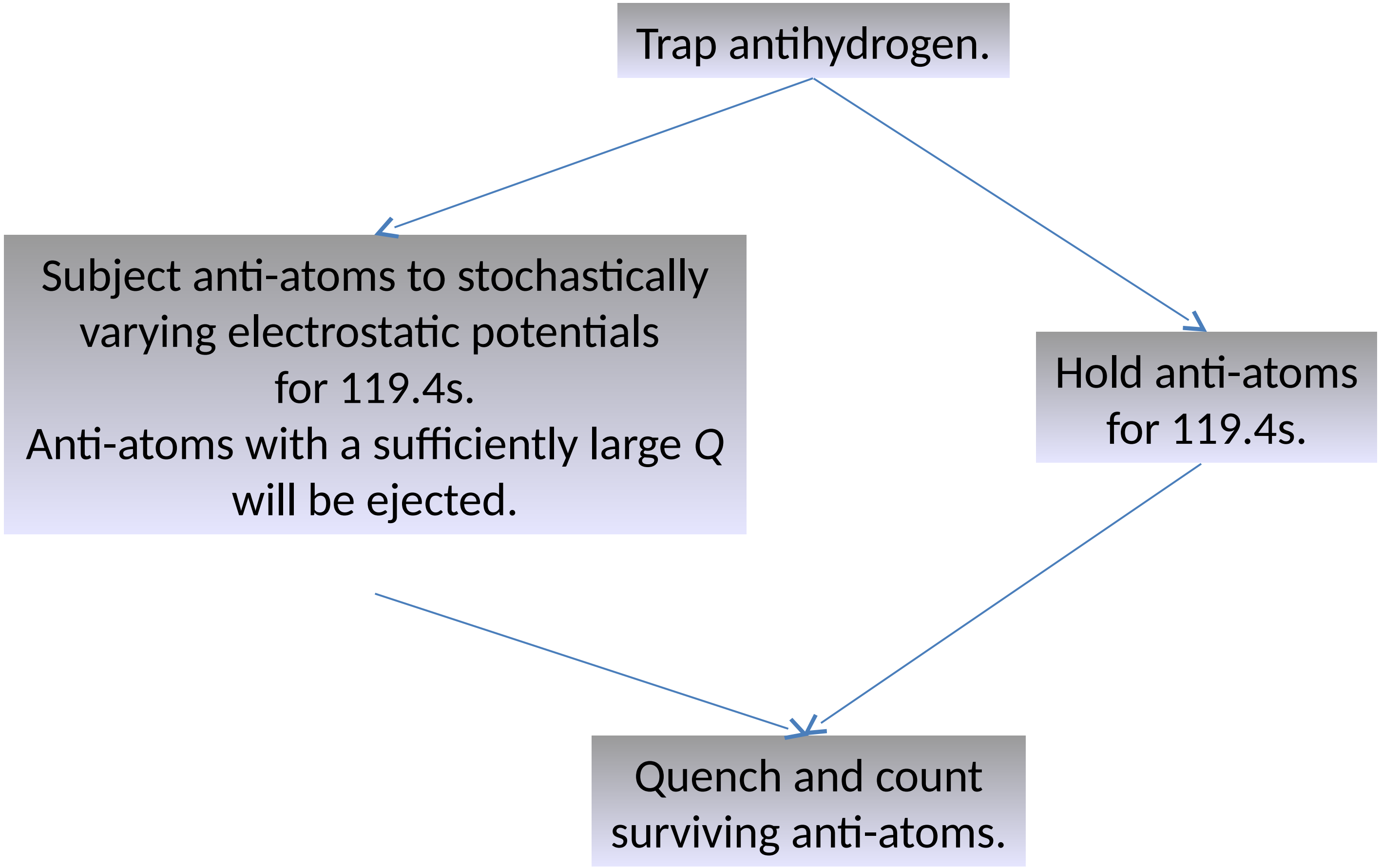
$$|Q|e\,\Delta\Phi\,\sqrt{N} < E_{well}$$

$$N=84900; \quad \Delta\Phi\simeq 100V$$

With these parameters
|Q|≤1.6 ppb
≤0.9 ppb taking account mean energy of the $\overline{H}$s in the trap.



Experimental Cycle



M. Baquero-Ruiz, et al, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, 2014, doi:10.1088/1367-2630/16/8/083013

Bayesian Statistics Calculation

•Simulation of $\bar{H}$ trajectories with detailed trap fields and stochastic potentials.

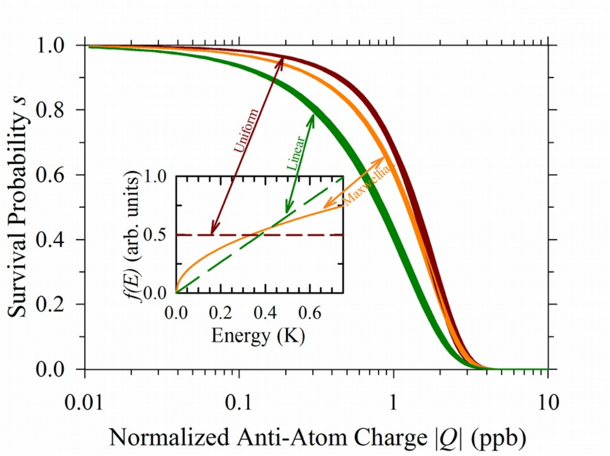
•1000 $\bar{H}$ trials for each Q.

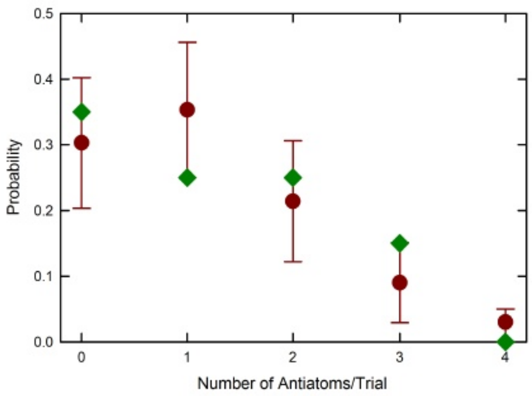
•1σ error band for survival probability.

•Q bounds are obtained from a Bayesian determination of the range of survival probability corresponding to a 1σ variation of our data.

•Dominant systematic is energy distribution in the trap.

•Consistent with assumption that trapped $\bar{H}$ distribution is Poisson.





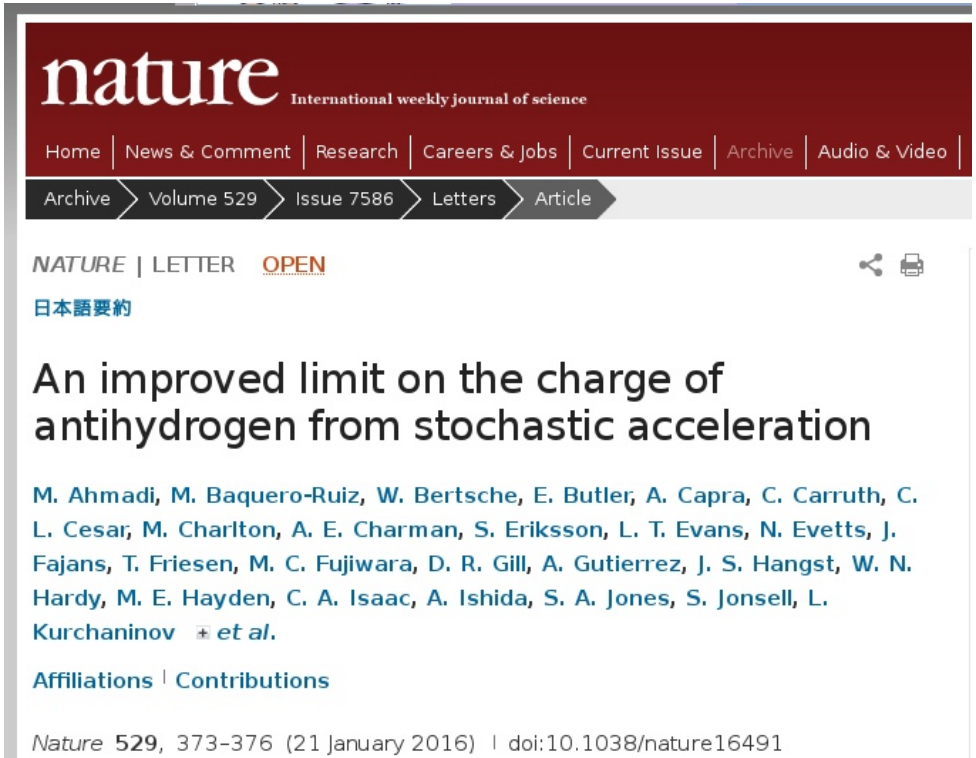
Principal Observations and Conclusions

	Number of Trials	Observed Antiatoms Surviving	Observed Antiatoms During 119s Heating
Stochastic Trials	10	12	**6**
Null Trials	10	12	**11**

Predicted cosmic ray background in heating period: 6.9 counts.

$|Q_{\bar{H}}|/e < 0.7\ 10^{-9}$ (1σ)

Improvement of 20x from our measurement with ALPHA1.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NATURE | LETTER OPEN

日本語要約

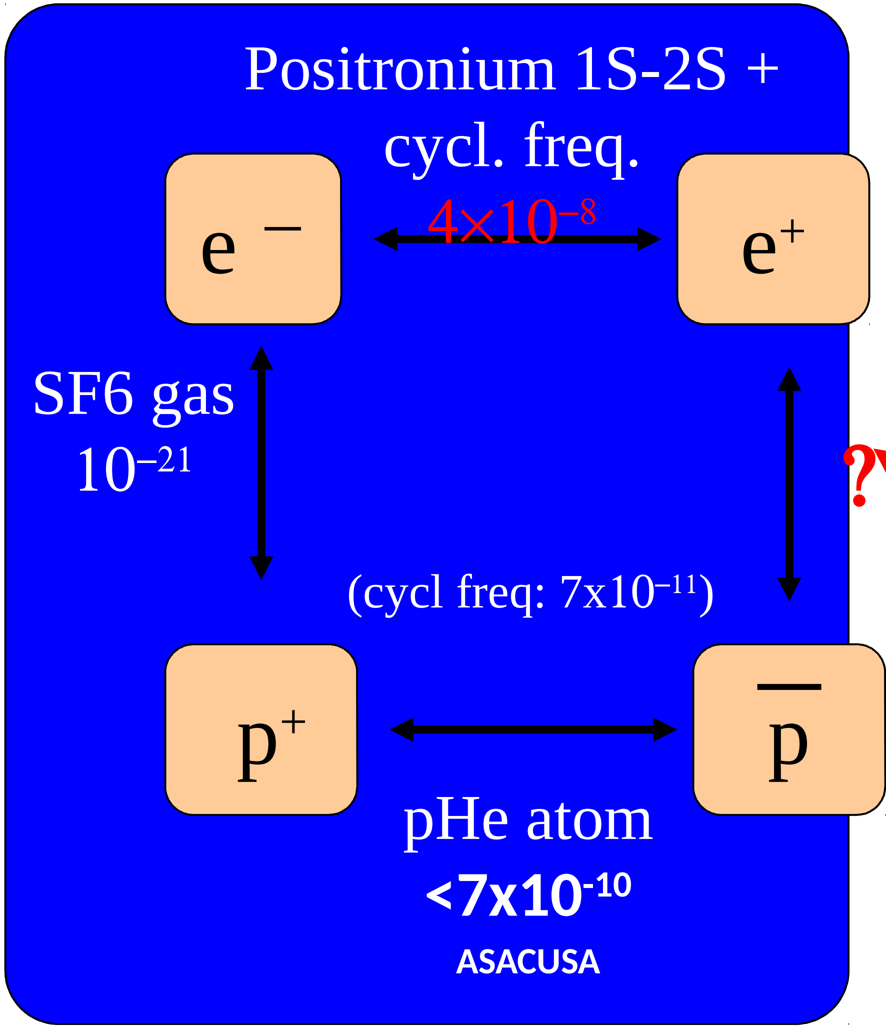
An improved limit on the charge of antihydrogen from stochastic acceleration

M. Ahmadi, M. Baquero-Ruiz, W. Bertsche, E. Butler, A. Capra, C. Carruth, C. L. Cesar, M. Charlton, A. E. Charman, S. Eriksson, L. T. 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, S. A. Jones, S. Jonsell, L. Kurchaninov + *et al.*

Affiliations | Contributions

Nature **529**, 373–376 (21 January 2016) | doi:10.1038/nature16491

Experimental limits on anomalous charge



PDG 2014

"Weak link": e+ charge

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

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

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

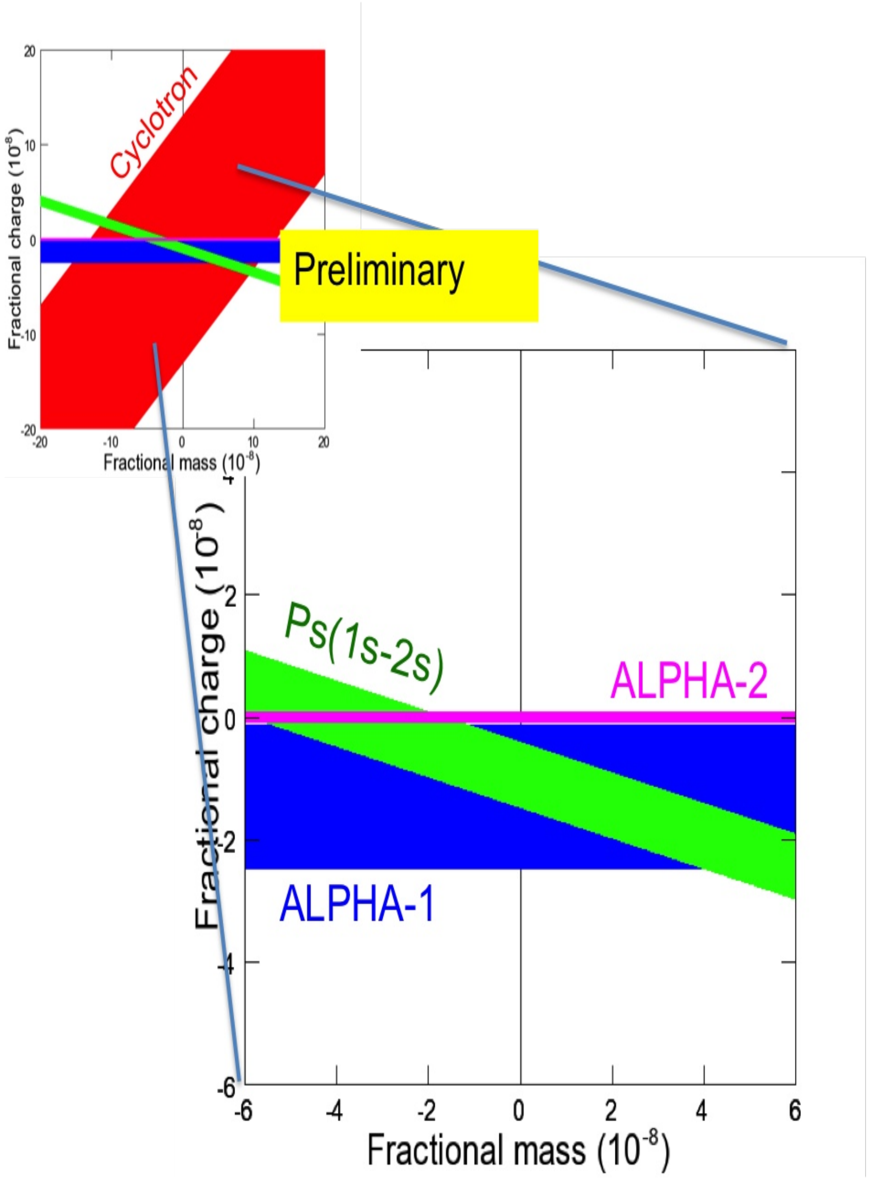
[8] HUGHES 92 uses recent measurements of Rydberg-energy and cyclotron-frequency ratios.
[9] SCHAEFER 95 removes model dependency of MUELLER 92.
[10] MUELLER 92 argues that an inequality of the charge magnitudes would, through higher-order vacuum polarization, contribute to the net charge of atoms.

$\overline{H}$ neutrality test

Using the Horie et al constraint on $||Q_{\bar{p}}| - |Q_p||$ we obtain a new limit on the positron charge anomaly

$|Q_{e+} - e|/e < 10^{-9}$ (1σ)

Positron charge & mass after ALPHA-2

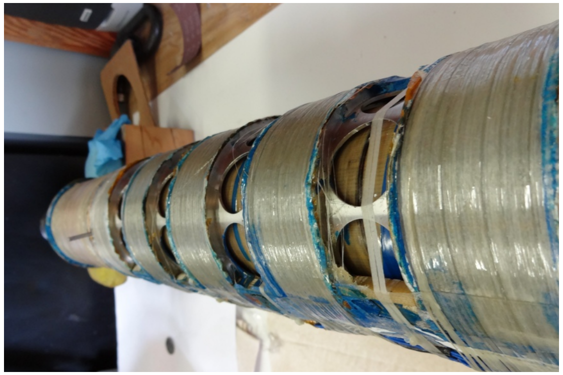


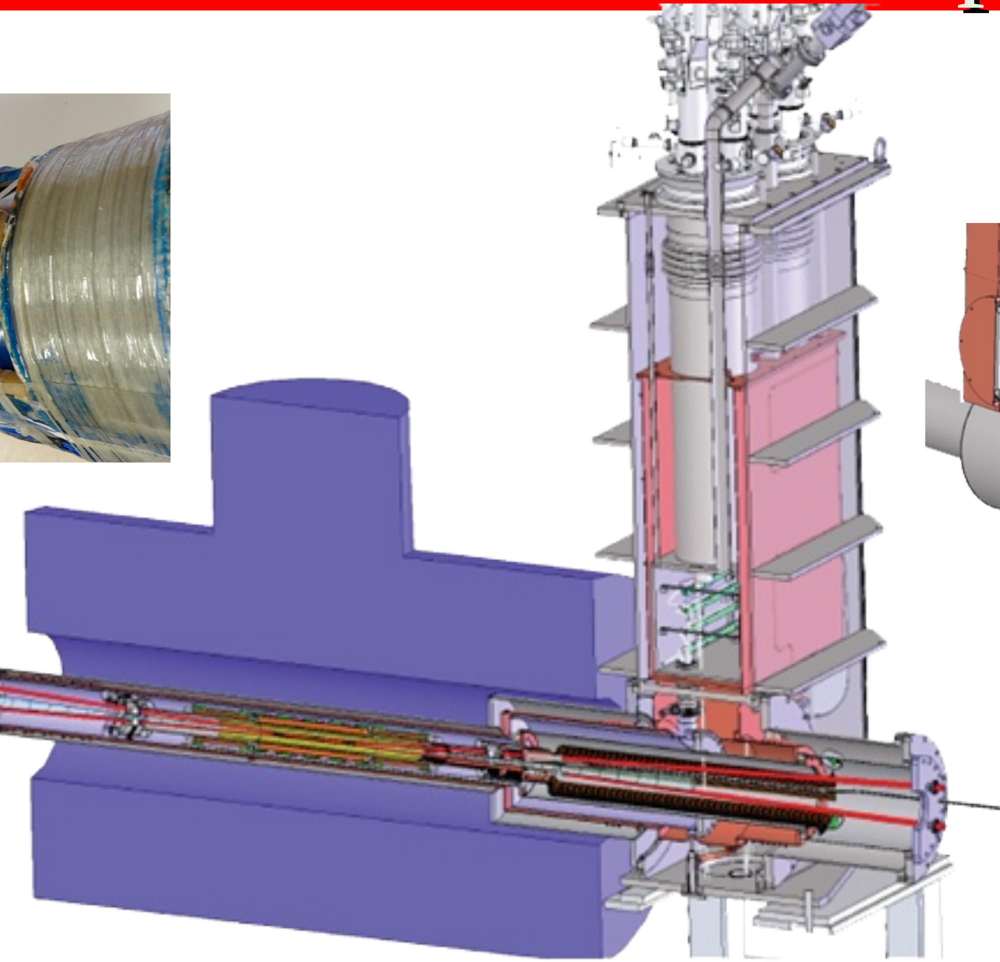
- After ALPHA-2

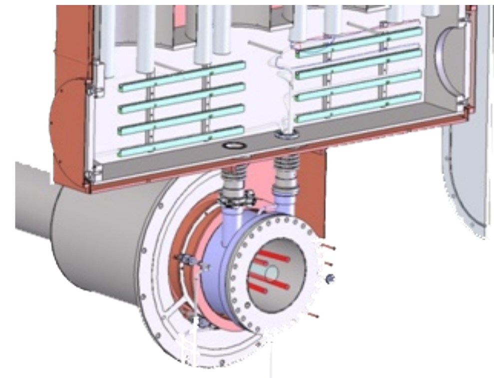
  (Nature, January 2016)
  - $\Delta Q_{e+}/e \sim 7\times10^{-10}$ (1σ), 40-fold improvement over pre-ALPHA
  - $\Delta m_{e+}/m_{e+} \sim \pm 2\times10^{-8}$, ~5 fold improvement

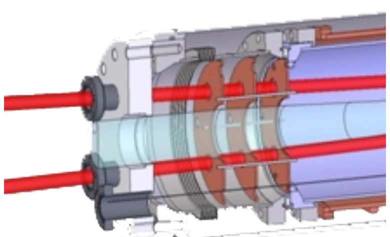
ALPHA's first precision result

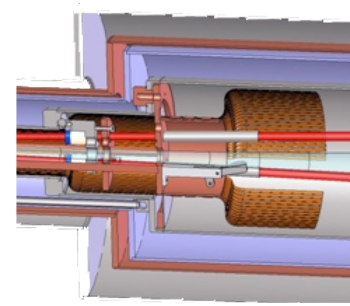
ALPHA-II Atom Trap



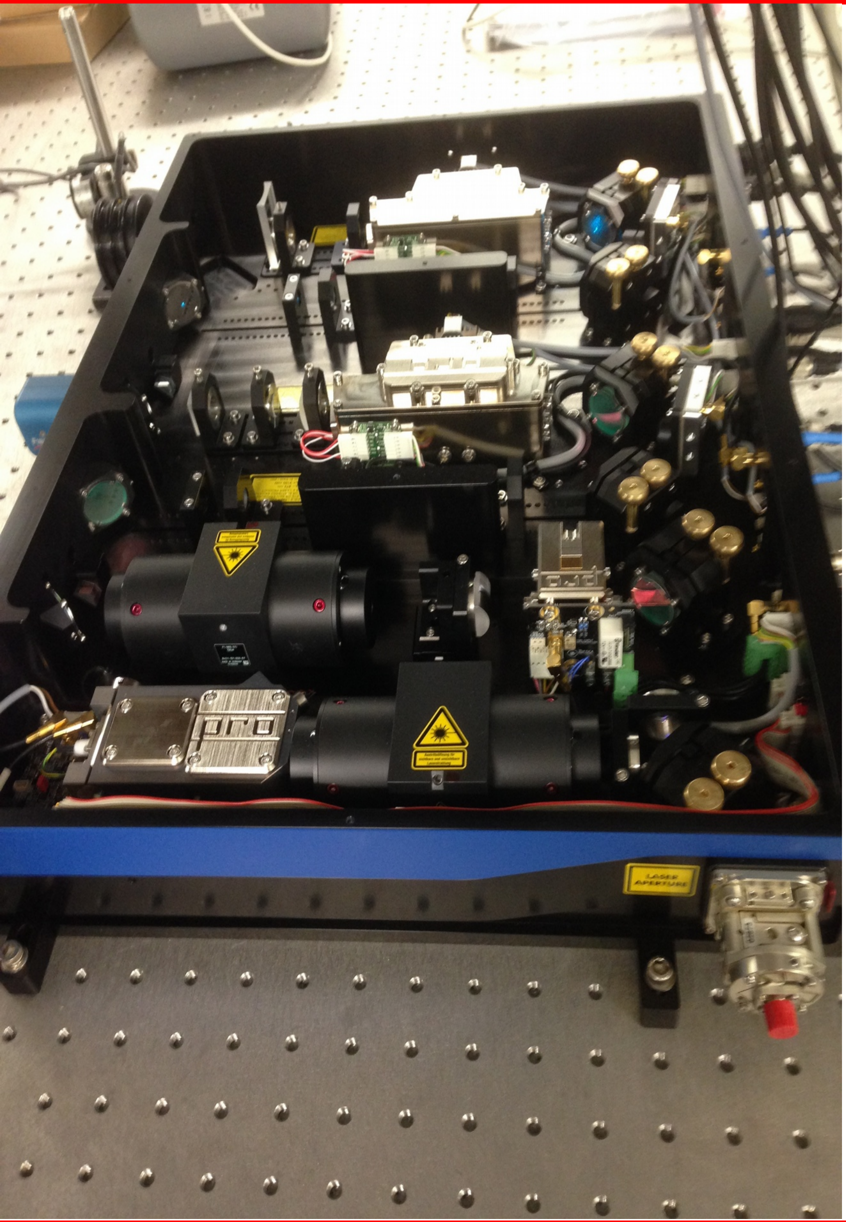


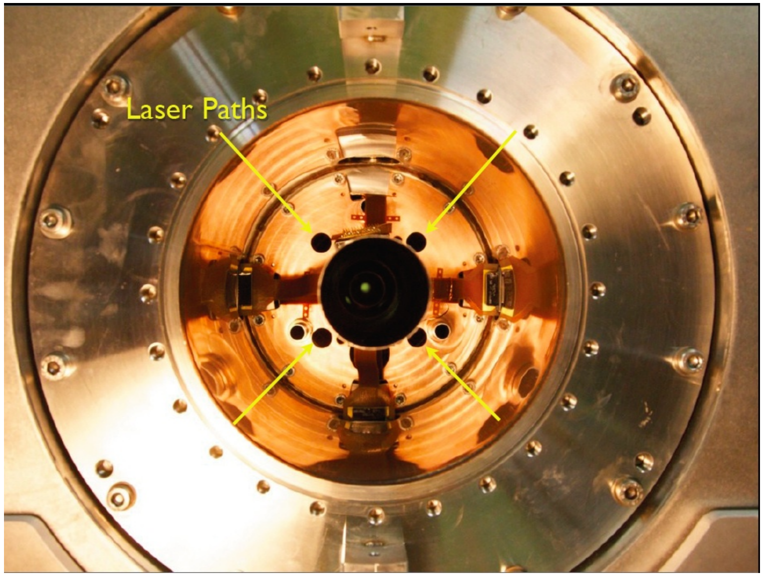






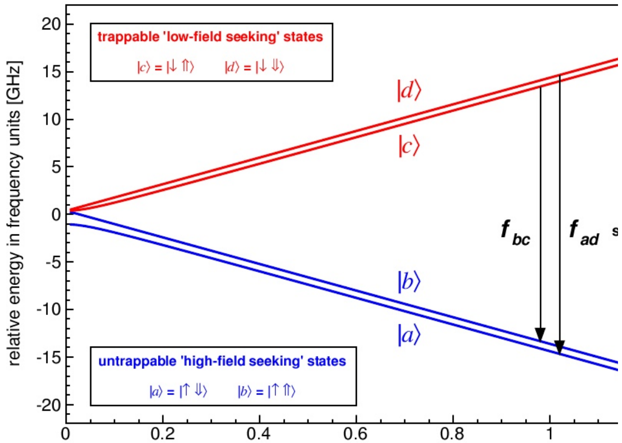
243 nm laser

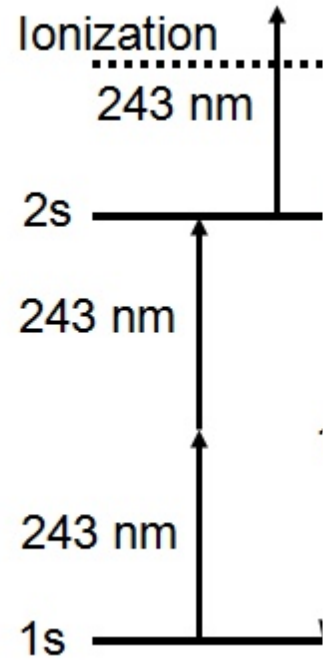


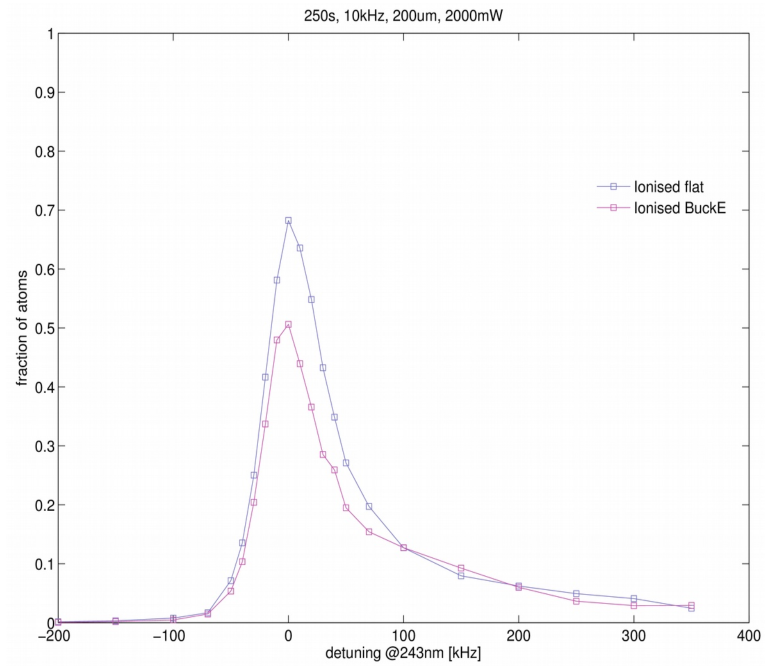


- All solid state, fourth harmonic generation
- > 50 mW indefinitely; easily makes 200 mW
- Limited by UV damage to optical elements
- Manufactured by Toptica
- Financed by ERC Advanced Grant

1S-2S Spectroscopy

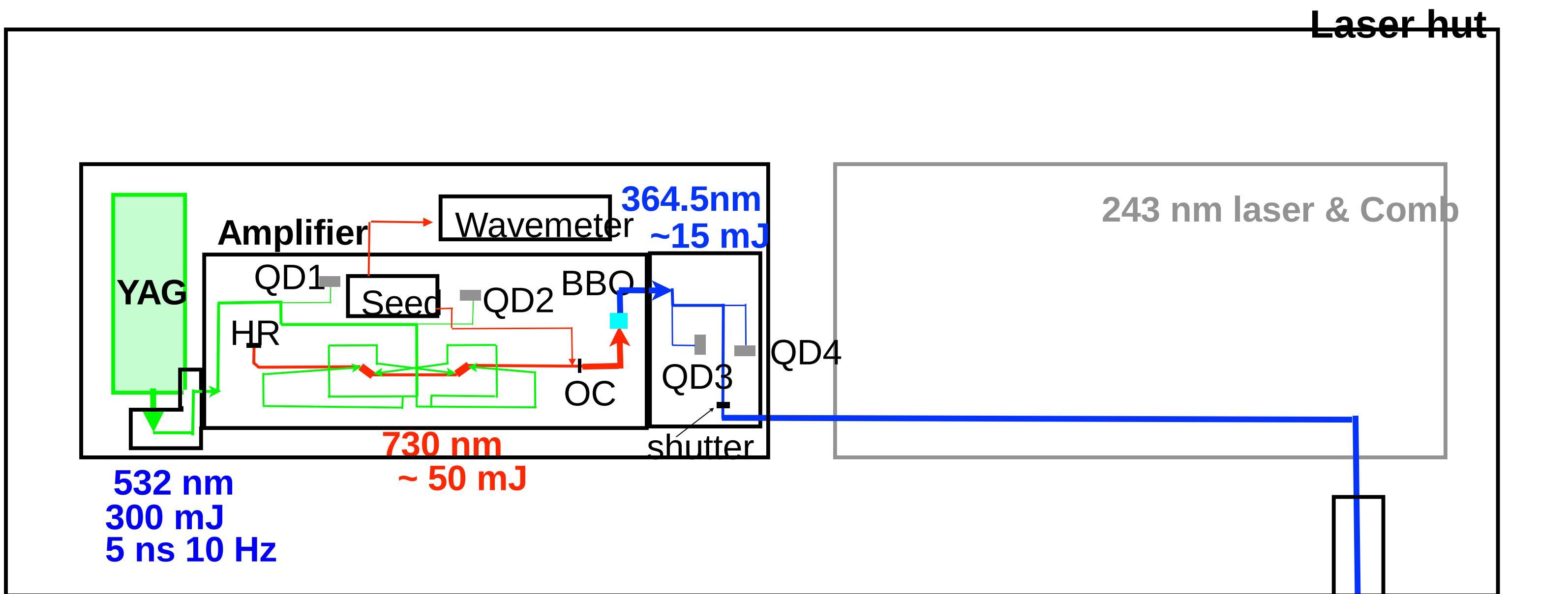




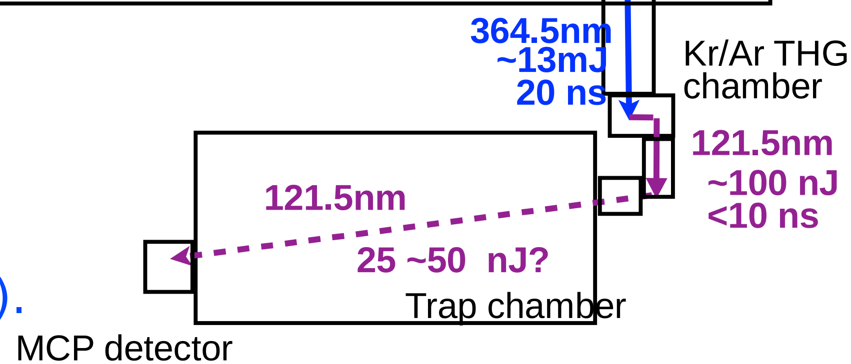


- 1S |c> and |d> hyperfine states are trapped.
- Excite the 2S state (still trapped) and ionize it.
- Clear the $\bar{p}$ ions and ramp down the trap magnets.
- Observe $\bar{H}$ annihilations in the vertex detector.
- Compare annihilation rates on resonance, detuned by 200kHz, and with laser off.

Lyman-α Laser Setup



An average flip time of <1 min is expected for the 1s 2p spectroscopy.
Enables $\bar{H}$ spectroscopy and laser cooling (at higher power).



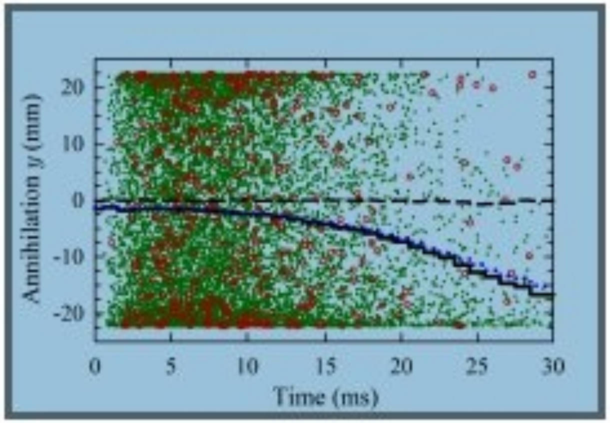
Antigravity Limits 2013

Effect of gravity on the $\bar{H}$ trajectories as the magnetic field is ramped down.

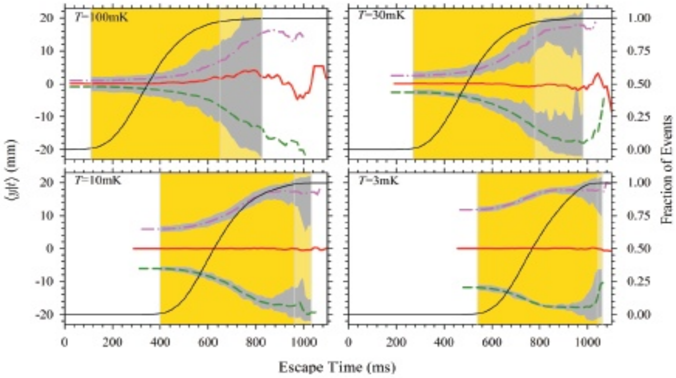
- First direct free-fall experimental test with antimatter.
- Sensitivity arises from very low $\bar{H}$ velocity when released.

$$|M_g(\bar{H})/M(H)| < 110 \text{ (90\%CL)}$$

- Sensitivity would be improved by slowing the trap shutdown and by cooling the $\bar{H}$.

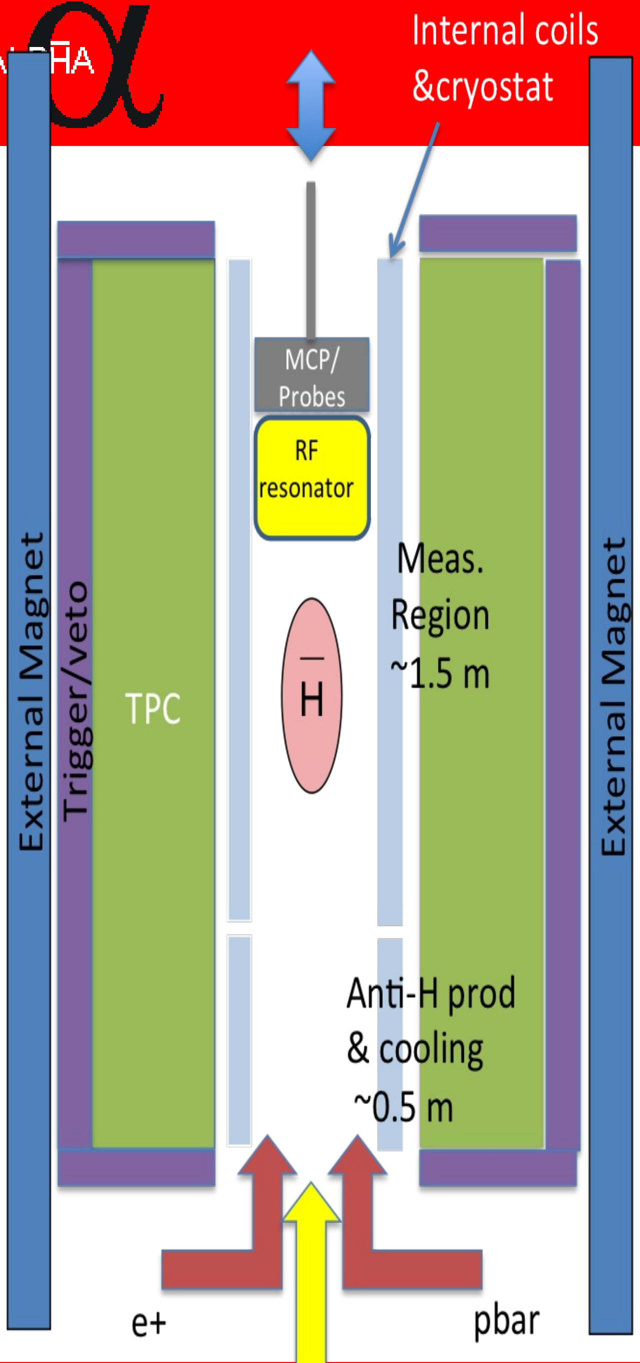


Annihilation locations: The red circles are the annihilation times and y-locations for 434 real anti-atoms, as measured by our particle detector. The green dots are from a simulation of $\bar{H}$ with 100X the H mass. Black solid line is <y>.



Experimental methodology for measuring the gravitational to inertial mass ratio of antihydrogen
Nature Comm 4,1785(2013)

ALPHA-g: Gravity on Antimatter



- Does antimatter fall with *g*?
  - Experimental question! (e.g. Lykken arXiv:0808.3929)
  - Already 2 dedicated exp’ts at AD
  - Can we do better in a trap? We think so!
- Very cold anti-H in a vertical trap
  - “Drop” anti-H atom inside the trap
  - Position sensitive detection via annihilations
- Challenges
  - Only few anti-atoms at a time
  - (anti)hydrogen inconvenient
    - Light mass; Transitions in deep UV
  - Magnetic fields
    - $\mu \Delta B = mgh$; $\Delta B \sim 20$ Gauss for h=1 m

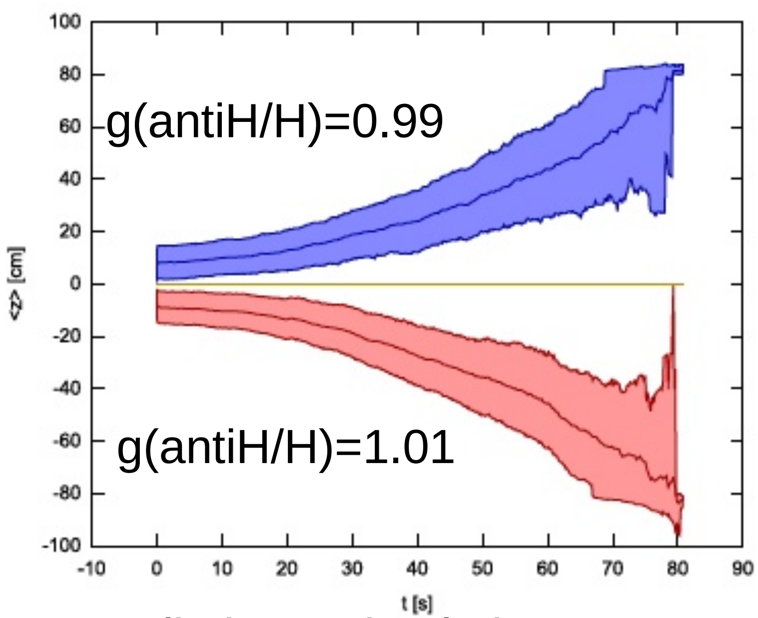
ALPHA-g Staged Approach

Stage 1: Sign of *g*

- Should be "immediate" once ALPHA-g is commissioned

State 2: ~1% meas. of *g*

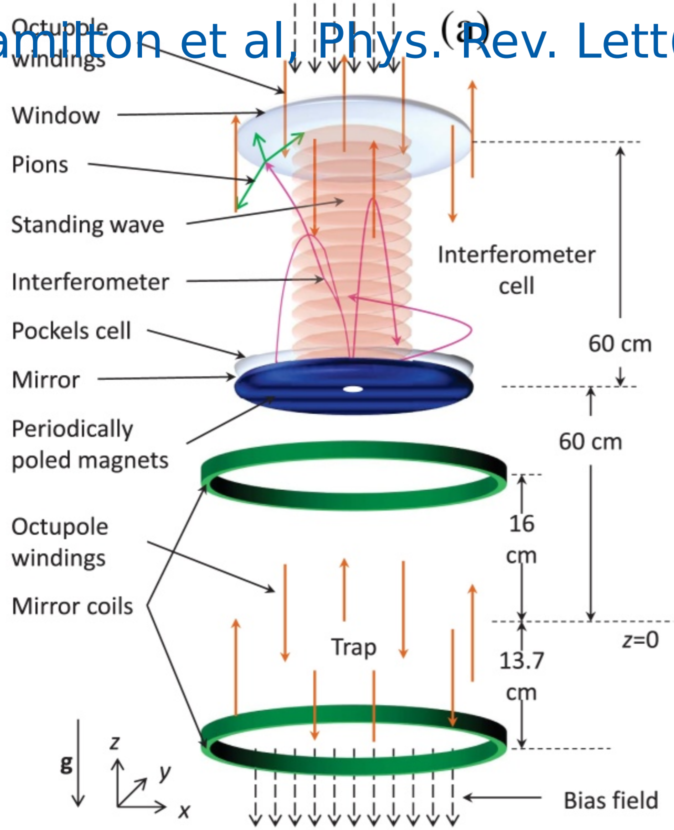
- Laser cooled anti-H



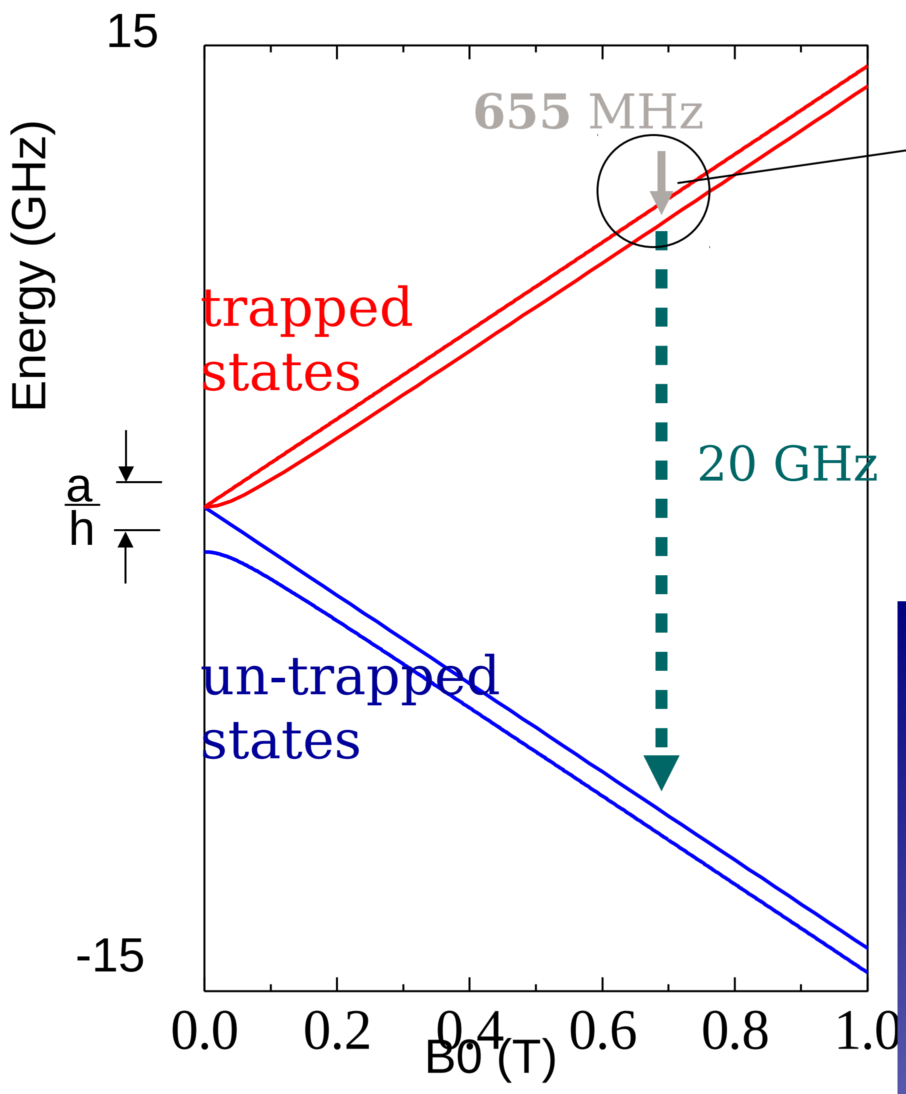
Preliminary simulation

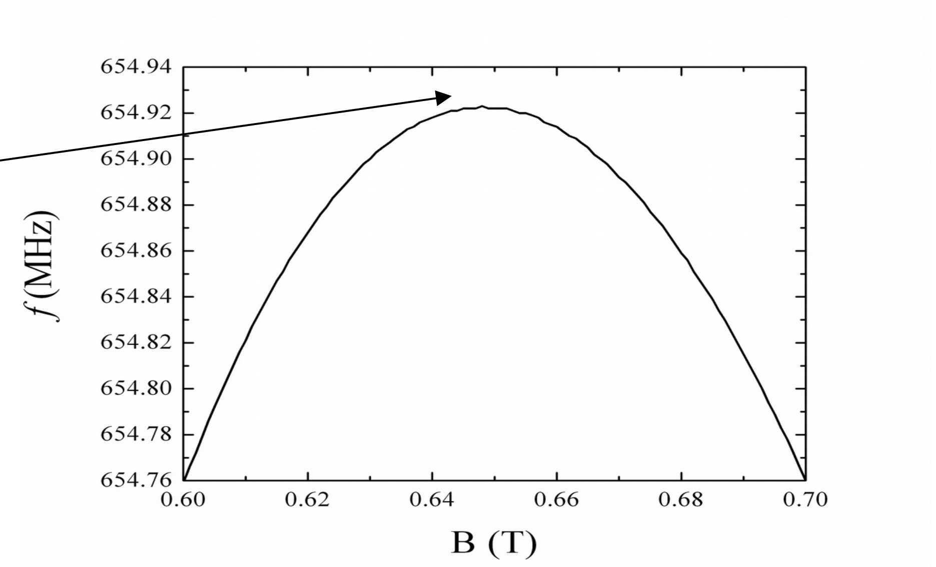
Stage 3: Anti-atom fountain & Interferometer

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



Road to Precision Hyperfine Spectroscopy





NMR (pbar spin flip)

655 MHz at magic 0.65T turning point: insensitive to 1st order B inhomogeneity

- Double resonance w/ PSR
- ~10^{-7} possible with large number of $\overline{\text{H}}$ (like Asacusa)

Summary

- ALPHA searches for a matter – antimatter asymmetry via precision antihydrogen atomic spectroscopy.
- Sophisticated techniques have been developed to create, cool and mix $\bar{p}$ and e^+ plasmas and magnetically trap the antihydrogen and measure their properties.
- We have driven hyperfine transitions in ground state $\bar{H}$.
- We have improved the measurement of the $\bar{H}$ charge and also the limit on the positron charge anomaly – a test of CPT.
- The limit on a CPT violating mass difference between the electron and positron has also been improved.

Outlook

- A new apparatus to enable higher precision laser and microwave spectroscopy has been commissioned.
- Trapping at a rate of 20 $\bar{H}$/shift is now routine.
- We have developed the difficult lasers required for $\bar{H}$ spectroscopy. Measurements of the 1S-2S and 1S-2P transitions in progress.
- We have performed the first very crude free fall measurement of its gravitational mass. An experiment to make a much more precise measurement, ALPHA-g, is in preparation.

Thank You!

Back up slides

What about e+ mass? (MCF presentation at LEAP 2016)

Some inconsistencies in PDG and FEE 93:

1. "assumption that the Ps Rydberg is exactly half of the hydrogen one" does not make sense
2. FEE93 assumed incorrect sensitivity between Δfreq(1s-2s) and $\Delta m_{e+}/m_e$
3. e+ mass & charge should be treated independently (PDG has done so for Pbar mass and charge since 2000)
4. Not clear if the limit is 90% CL rather than 1σ

PDG 2014

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

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

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.