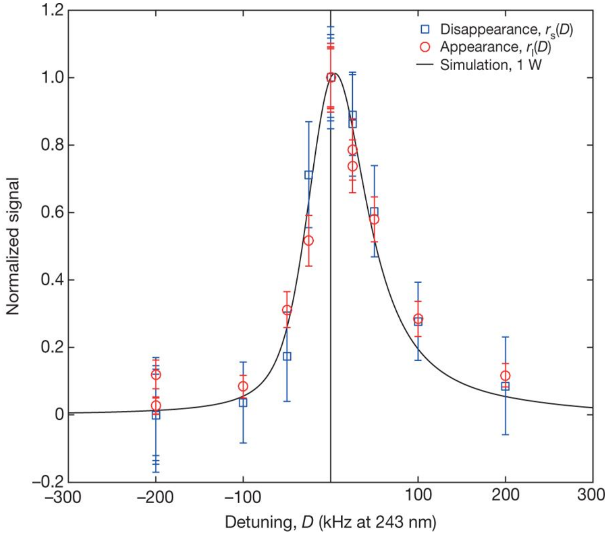
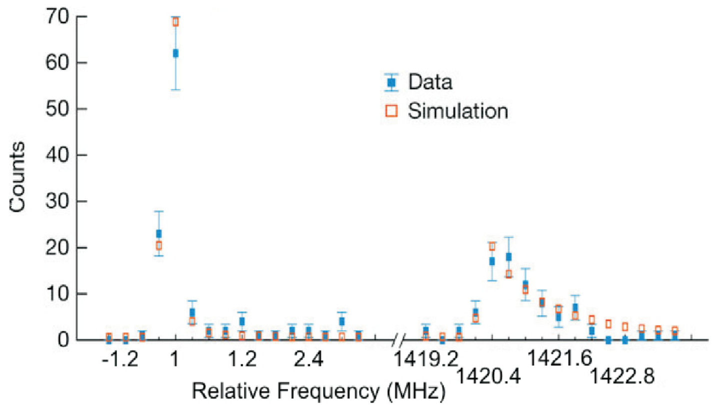
CPT Tests with Antimatter
Particles in Collision Symposium 2018
Bogota, Columbia
September 11-15

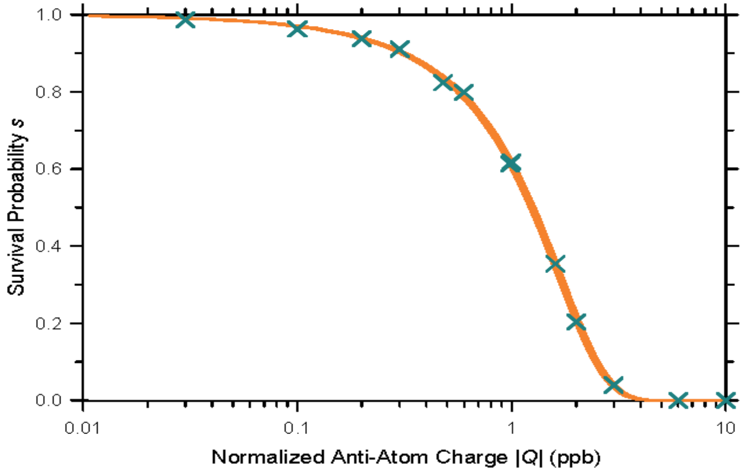
Jonathan Wurtele
U.C. Berkeley



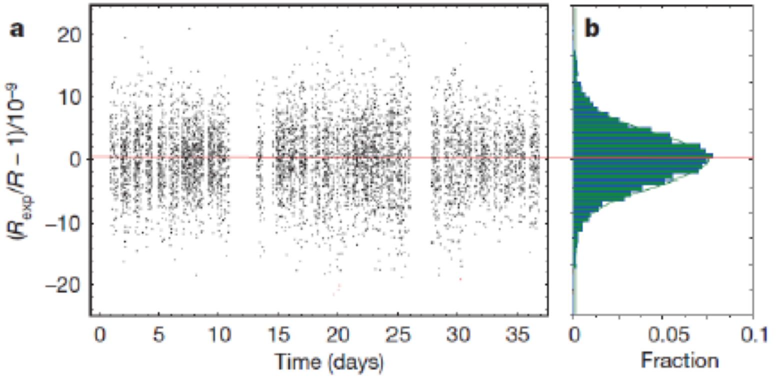
1S-2S Spectroscopy



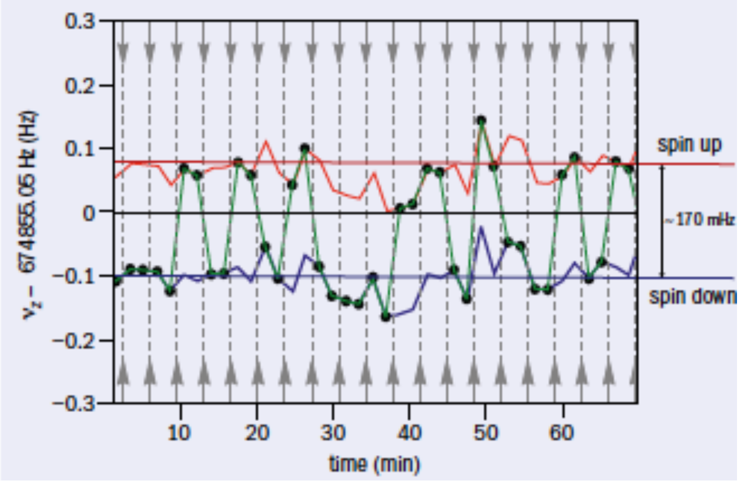
Hyperfine Spectroscopy



Antihydrogen Charge



Antiproton q/m



Antiproton Magnetic Moment

CPT Tests with Antimatter

The CPT Theorem states that the combined transformations of charge conjugation, spatial inversion and time reversal leave physical laws invariant. One consequence is that particles and antiparticles should have equal masses and lifetimes and equal magnitude charge and magnetic moments, and anti-atoms should have the identical spectra as atoms.

- Hints that CPT might not hold come from the Baryogenesis problem:
  - Why is there so little antimatter in the universe?
  - CPT violation could solve the Baryogenesis problem.
  - Dark matter…

This talk will focus on low energy high-precision measurements undertaken by ALPHA and BASE at the CERN AD.
Both groups have had major advances over the last two years.

Detailed review of low energy tests of CPT and other fundamental symmetries: Safronova et al., RPM 2018.
Detailed review of CERN AD physics program: (Ed. N. Madsen) Phil Trans. Royal Soc. A **376** Issue 2116 (2018)
Easier reading: CERN COURIER March 2018 articles by Hangst (ALPHA) and Ulmer (BASE).

CPT and WEP Tests with Antimatter

- Weak Equivalence Principle (WEP):
  - Does antimatter accelerate in the same fashion as normal matter (Is its inertial mass equal to its gravitational mass)?

- CPT requires that M, |Q|, τ, |μ| be identical
- CPT requires that atomic spectra be identical
- WEP requires that $M_I=M_G$ (inertial mass=gravitational mass)

Antiparticles:
Fundamental particle properties
Apparatus: Innovations on precision traps with long history of fundamental measurements

Antihydrogen:
Fundamental properties and antiparticle interactions
Apparatus: Novel 3 species traps
Requires antiproton, positron and electron plasmas to create antihydrogen

Model independent.
Extraordinarily precise…Experimentally: ~10^{-15} with 1S-2S H
Theoretically: ~10^{-18} with 1S-2S H

- Violation of CPT or WEP would revolutionize fundamental physics. To date all experiments are consistent with CPT and WEP.
  - Both CPT and WEP are *very likely* to hold, and yet…

Could CPT Be Violated?

- Physicists have been wrong before…
- P violation---Wolfgang Pauli:[1]

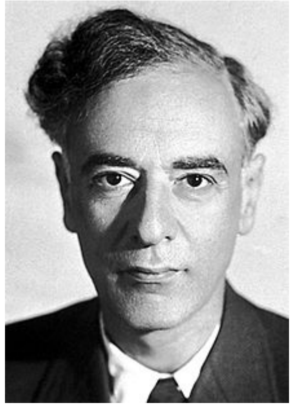
"I do not believe that the Lord is a weak left-hander, and I am ready to bet a very high sum that the experiments will give symmetric results."

- CP violation---Lev Landau:[2]

"If CP is violated, I will hang myself."

Wolfgang Pauli

All results to date are consistent with CPT.



Lev Landau

---

[1] Pauli in a letter to Victor Weisskopf, quoted in the Ambidextrous Universe, by Martin Gardner.

[2] Oral history, as related by Dima Budker.

The Antiproton Decelerator at CERN is the only source of low energy antiprotons

- CERN’s Antiproton Deaccelerator reduces antiproton energy to ~5MeV.

CPT Physics Collaborations and Goals at the CERN AD

Properties of the antiproton: ATRAP, BASE

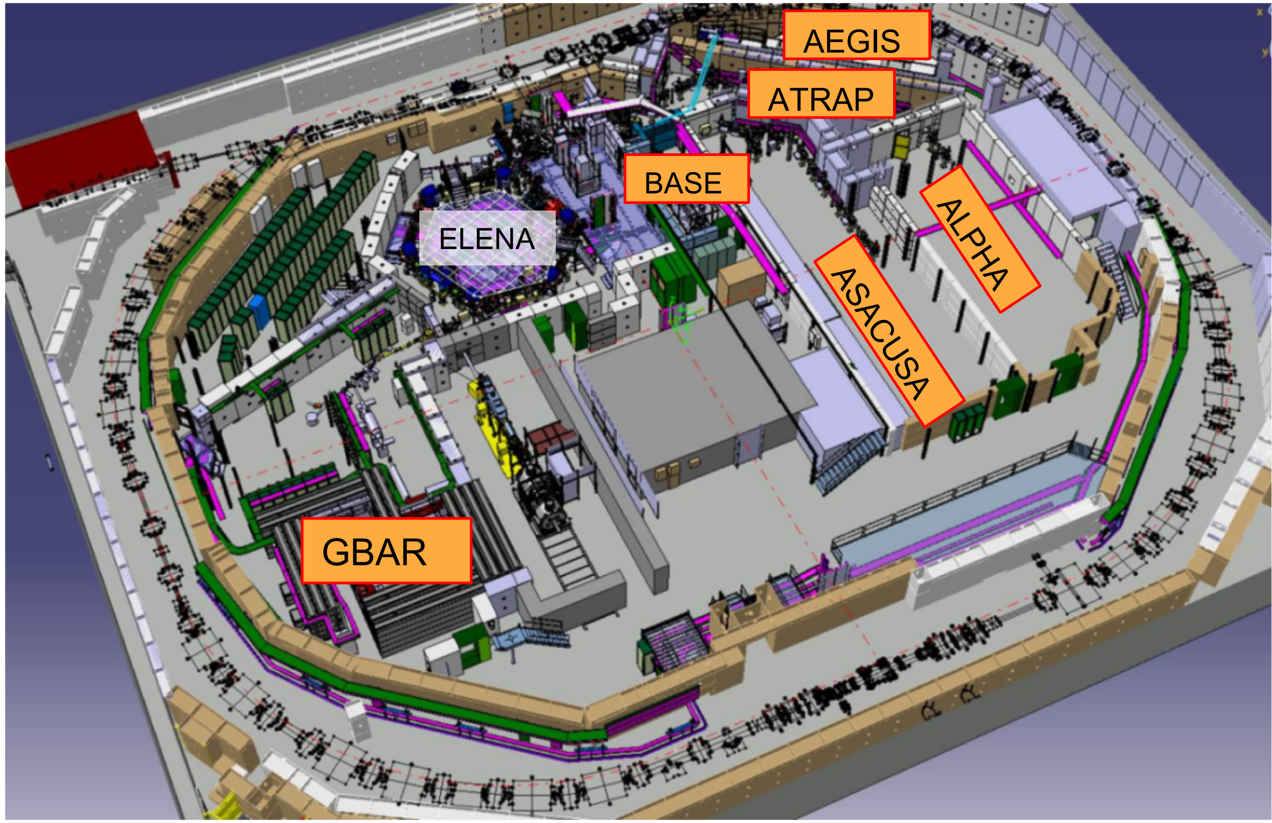
Antihydrogen spectroscopy (1S-2S, and more): ATRAP, ALPHA

Antihydrogen Hyperfine measurements: ALPHA, ASACUSA

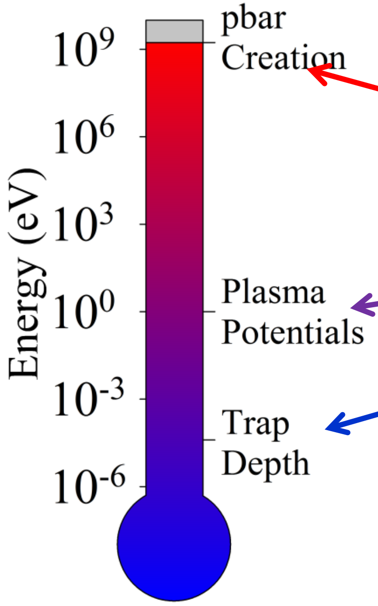
Charge neutrality of antihydrogen: ALPHA

Antiprotonic Helium spectroscopy: ASACUSA

Antihydrogen gravitation: ALPHA, GBAR, AEGIS



Energy Scales



Antiproton Creation Energy: 1.7GeV

Plasma Potential: 30mV-10V

Neutral Trap Depth: 0.5K or 40μeV

$$\frac{\text{Antiproton Creation Energy}}{\text{Trap Depth}} = 10^{14}$$

$$\frac{\text{LHC Energy Increase}}{\text{Free Protons on Creation}} = 10^{8}$$

$$\frac{\text{Collective Potential}}{\text{Neutral Trap Depth}} = 10^{3} - 10^{5}$$

AD Provides 5 MeV

Degrader to few keV
Electron cooling

Plasmas (ALPHA):
Evaporative coolng

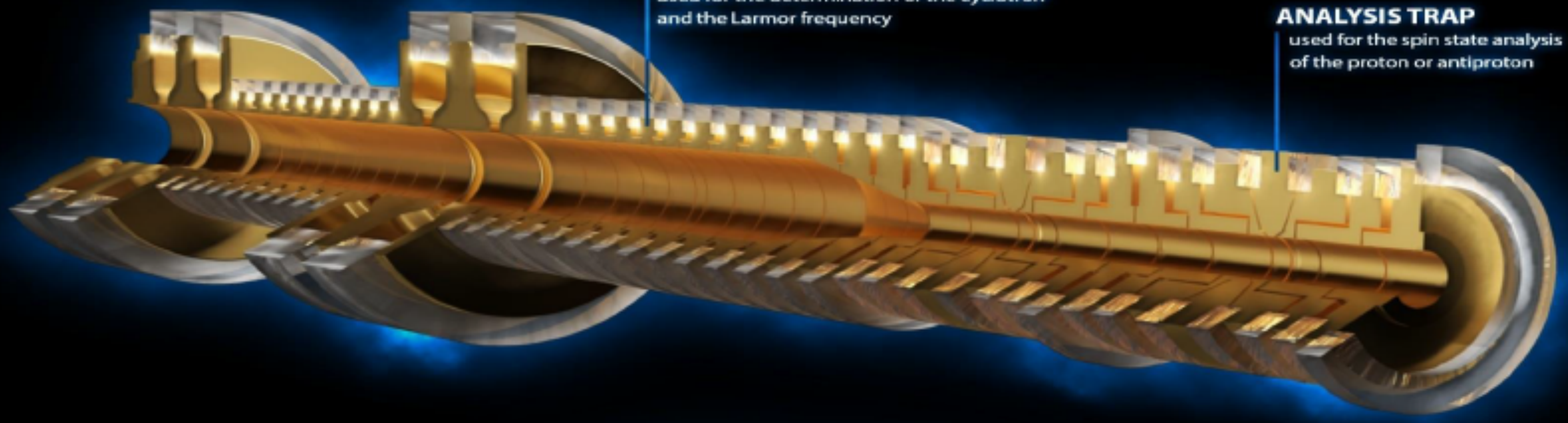
$4x10^4$ Anitprotons~100K
$2x10^6$ Positrons ~ 10-50K

Single particles (BASE)
Resistive cooling ~.1K

Nonneutral plasma physics is a key enabling science in the field of antiatom physics. Advances in are critical to antihydrogen synthesis from positrons and antiprotons.

THE BASE EXPERIMENT

dedicated to the highest level of precision! This innovative experiment can be operated with protons and/or antiprotons. It allows single particle control leading to the determination of the g-factor or the charge-to-mass ratio with outrageous sensitivity.



PRECISION TRAP
used for the determination of the cyclotron and the Larmor frequency

ANALYSIS TRAP
used for the spin state analysis of the proton or antiproton

Ulmer et al., Phil. Trans. R. Soc. A 376: 20170275 .

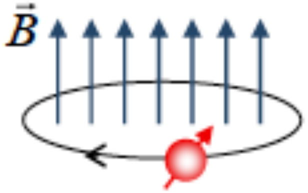
BASE
Antibaryon Baryon Symmetry Experiment

$$\frac{(q/m)_{\bar{p}}}{(q/m)_p}$$

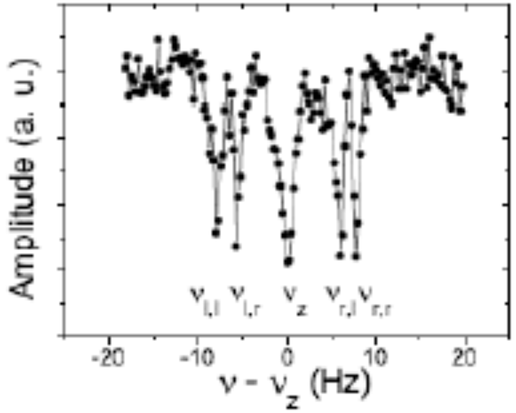
$$\frac{\mu_{\bar{p}}}{\mu_p}$$

Measurements require understanding of particle dynamics in the trap

Cyclotron Motion



simple



S. Ulmer *et al.* PRL **107**, 103002 (2011)

Slide: S. Ulmer

g: mag. Moment in units of nuclear magneton

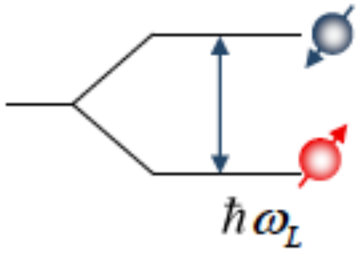
$$\boxed{\omega_c = \frac{e}{m_p} B}$$

$$\boxed{\omega_L = g \frac{e}{2m_p} B}$$

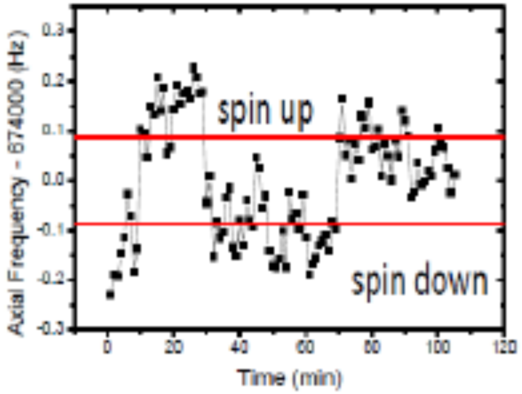
$$\frac{\mu_{\bar{p}}}{\mu_N} = \frac{g_{\bar{p}}}{2} \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p} = \frac{\nu_L}{\nu_c}$$

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Larmor Precession



difficult

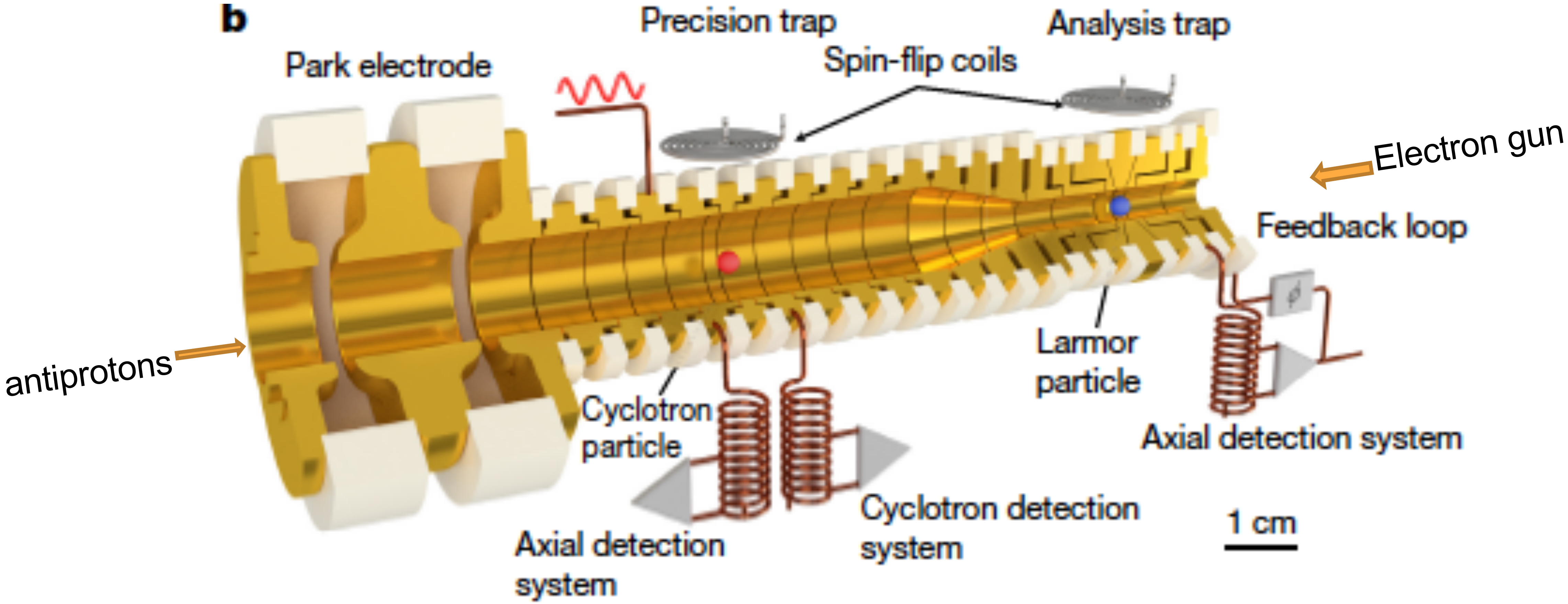


S. Ulmer *et al.*, PRL **106**, 253001 (2011)
A. Mooser *et al.*, PRL **110**, 140405 (2013)

Useful early reference for Leptons: Brown and Gabrielse, RMP 86

BASE Schematic

Double Penning Trap: Separate gradient trap for spin state analysis from precision trap for determining Larmor and cyclotron frequencies. Other innovations: fast particle manipulations (cooling); reservoir of antiprotons (not shown)



Larmor frequency measurement

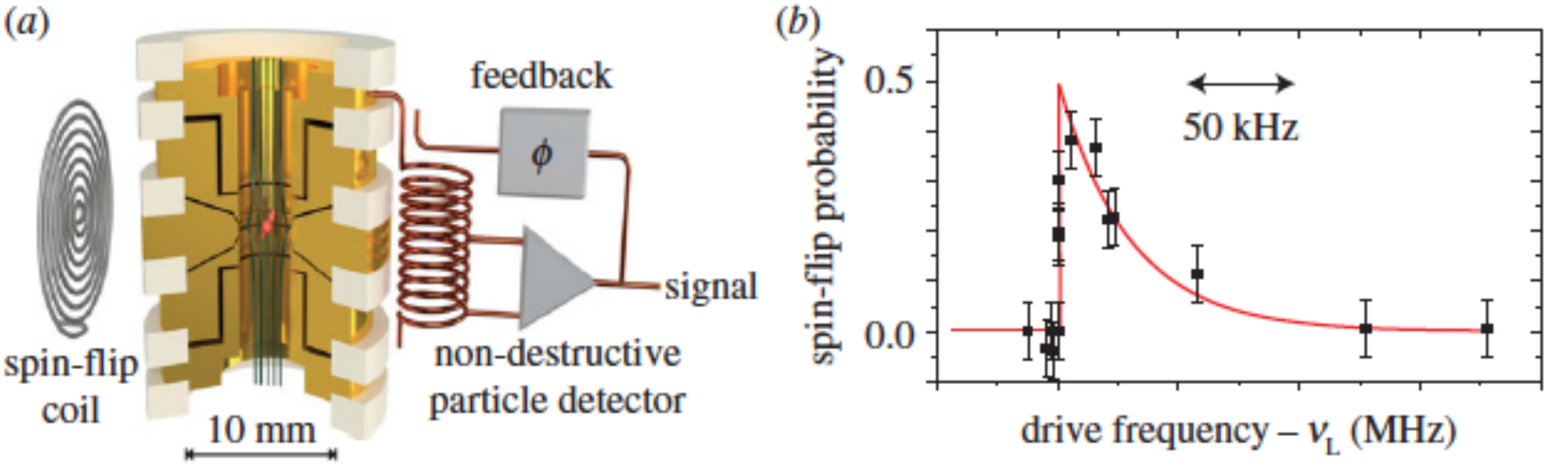


Figure 1. (*a*) Penning trap with a superimposed magnetic bottle for the detection of proton and antiproton spin quantum transitions. (*b*) Larmor resonance as measured in [18]. The steep slope represents the Larmor or spin precession frequency. (Online version in colour.)

Ulmer et al., Phil. Trans. R. Soc. A 376: 20170275 .

CPT Tests with Antiprotons by BASE Collaboration

q/m RATIO COMPARISON

$$\frac{\left[\frac{q}{m}\right]_{\bar{p}}}{\left[\frac{q}{m}\right]_{p}} + 1 = 1\,(69)\,\mathrm{x}10^{-12}$$

LIFETIME

21.7 years (status Feb. 2018)

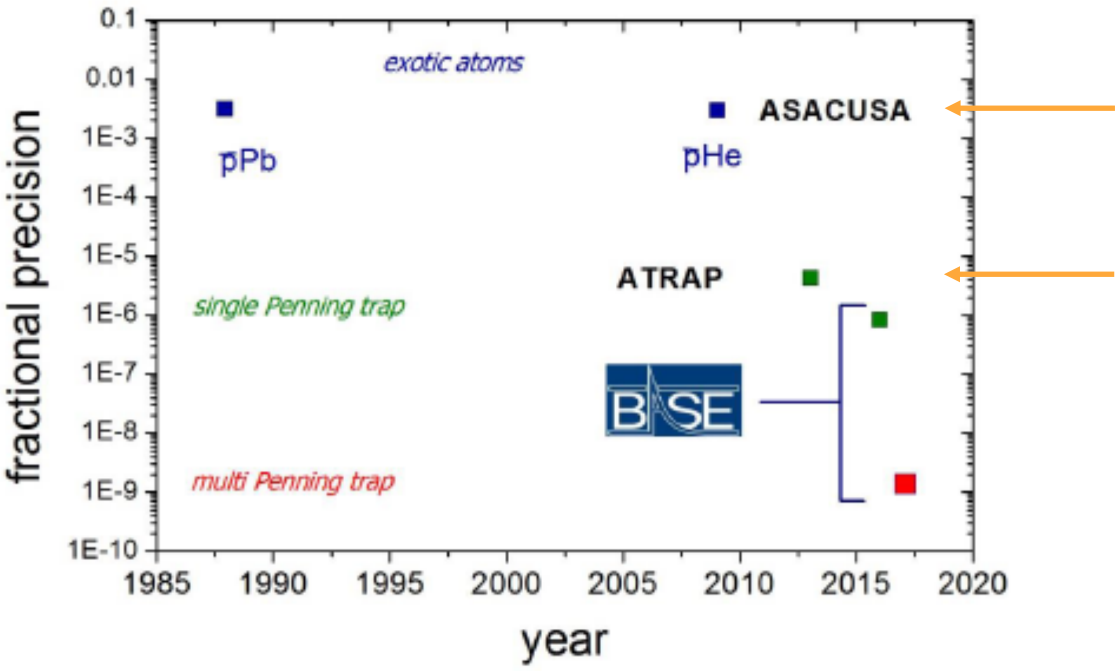
Antiprotons were continuously trapped in a reservoir for 400 days

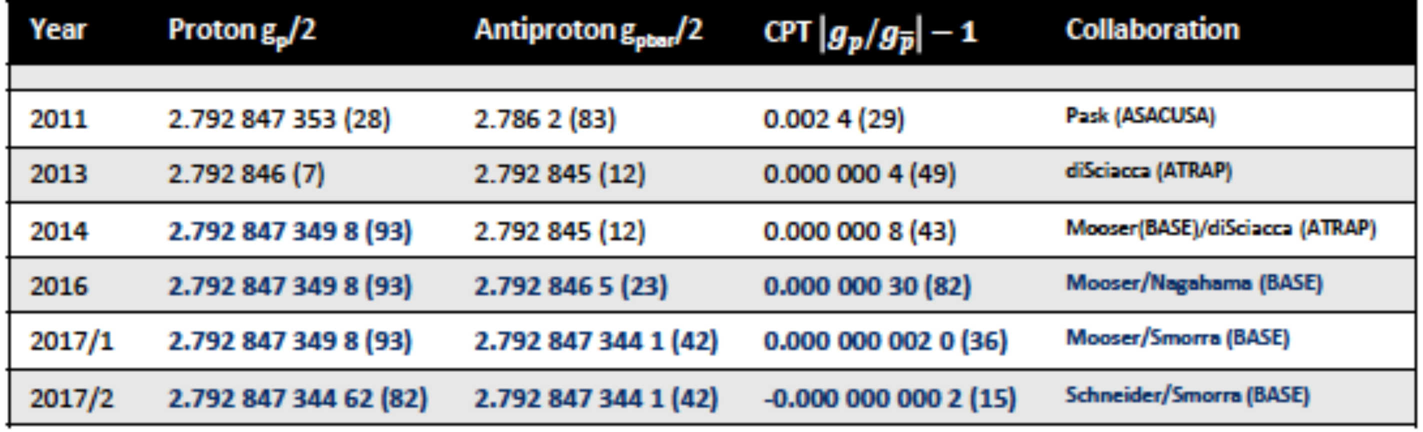
MAGNETIC MOMENT

$$\frac{\delta g_{\bar{p}}}{g_{\bar{p}}} = 2.6 \times 10^{-9}$$

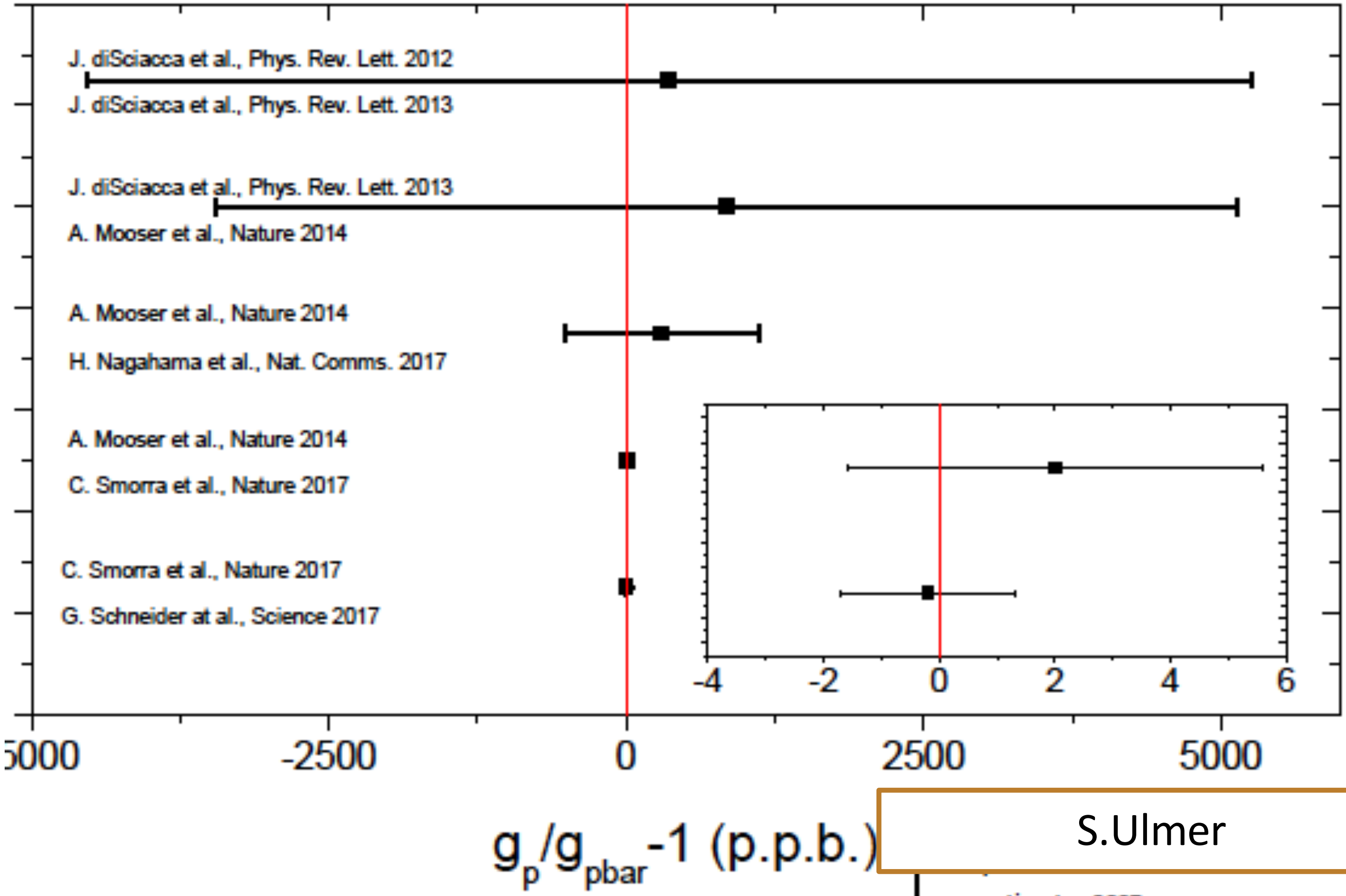
μ_p= 2.792 847 344 62 (82) μ_N

BASE 2017: $\mu_{\bar{p}}$= -2.792 847 344 1 (42) μ_{nucl}





Year	Proton $g_p/2$	Antiproton $g_{pbar}/2$	CPT $\lvert g_p/g_{\bar{p}}\rvert - 1$	Collaboration
2011	2.792 847 353 (28)	2.786 2 (83)	0.002 4 (29)	Pask (ASACUSA)
2013	2.792 846 (7)	2.792 845 (12)	0.000 000 4 (49)	diSciacca (ATRAP)
2014	2.792 847 349 8 (93)	2.792 845 (12)	0.000 000 8 (43)	Mooser(BASE)/diSciacca (ATRAP)
2016	2.792 847 349 8 (93)	2.792 846 5 (23)	0.000 000 30 (82)	Mooser/Nagahama (BASE)
2017/1	2.792 847 349 8 (93)	2.792 847 344 1 (42)	0.000 000 002 0 (36)	Mooser/Smorra (BASE)
2017/2	2.792 847 344 62 (82)	2.792 847 344 1 (42)	-0.000 000 000 2 (15)	Schneider/Smorra (BASE)



S.Ulmer

SME Model Constraints from the BASE Experiment

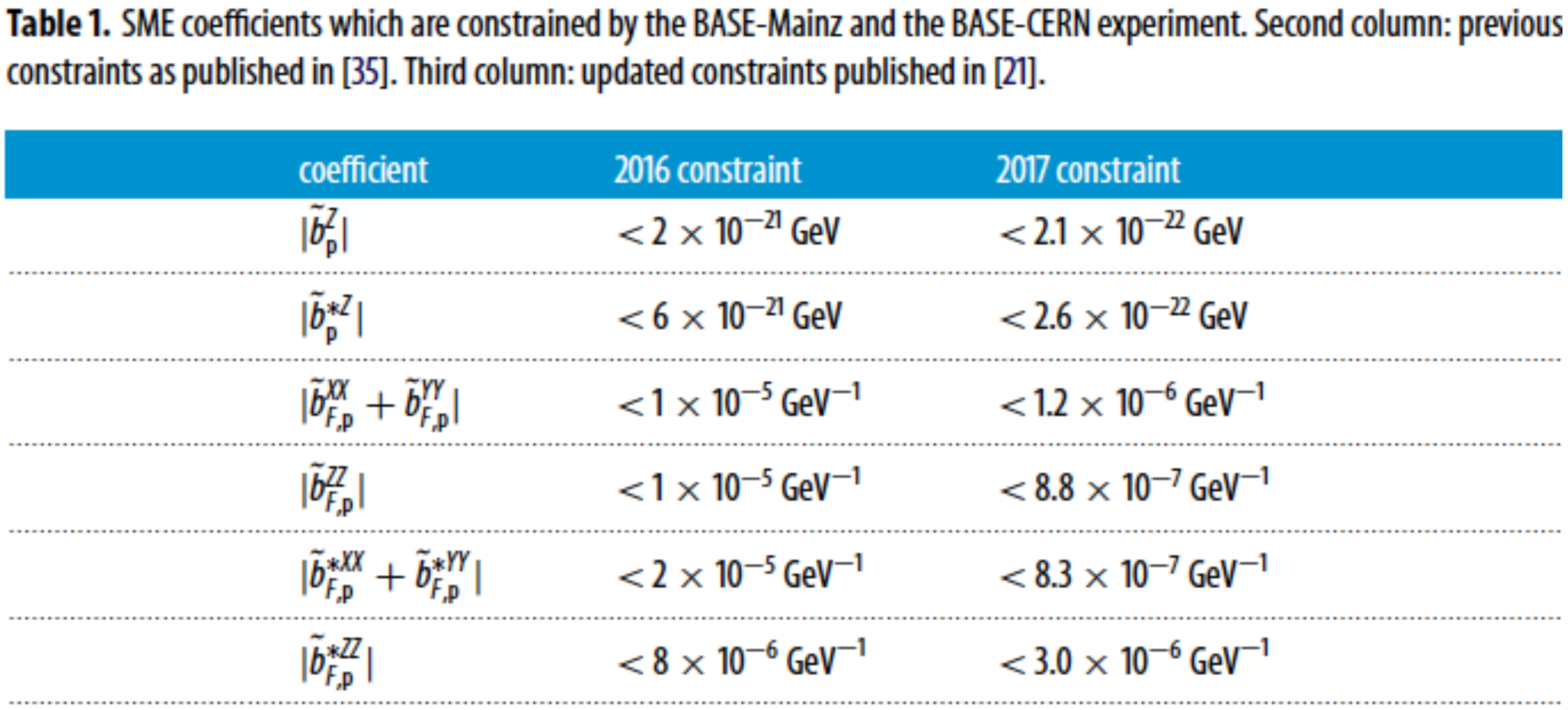


Table 1. SME coefficients which are constrained by the BASE-Mainz and the BASE-CERN experiment. Second column: previous constraints as published in [35]. Third column: updated constraints published in [21].

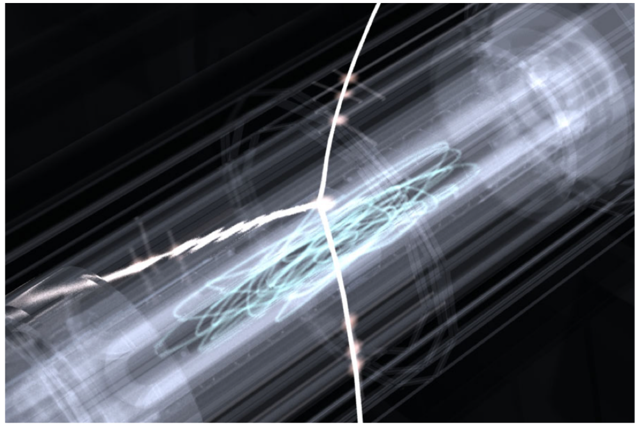
coefficient	2016 constraint	2017 constraint
$\lvert\tilde{b}_{p}^{Z}\rvert$	$< 2 \times 10^{-21}$ GeV	$< 2.1 \times 10^{-22}$ GeV
$\lvert\tilde{b}_{p}^{*Z}\rvert$	$< 6 \times 10^{-21}$ GeV	$< 2.6 \times 10^{-22}$ GeV
$\lvert\tilde{b}_{F,p}^{XX} + \tilde{b}_{F,p}^{YY}\rvert$	$< 1 \times 10^{-5}$ GeV^{-1}	$< 1.2 \times 10^{-6}$ GeV^{-1}
$\lvert\tilde{b}_{F,p}^{ZZ}\rvert$	$< 1 \times 10^{-5}$ GeV^{-1}	$< 8.8 \times 10^{-7}$ GeV^{-1}
$\lvert\tilde{b}_{F,p}^{*XX} + \tilde{b}_{F,p}^{*YY}\rvert$	$< 2 \times 10^{-5}$ GeV^{-1}	$< 8.3 \times 10^{-7}$ GeV^{-1}
$\lvert\tilde{b}_{F,p}^{*ZZ}\rvert$	$< 8 \times 10^{-6}$ GeV^{-1}	$< 3.0 \times 10^{-6}$ GeV^{-1}

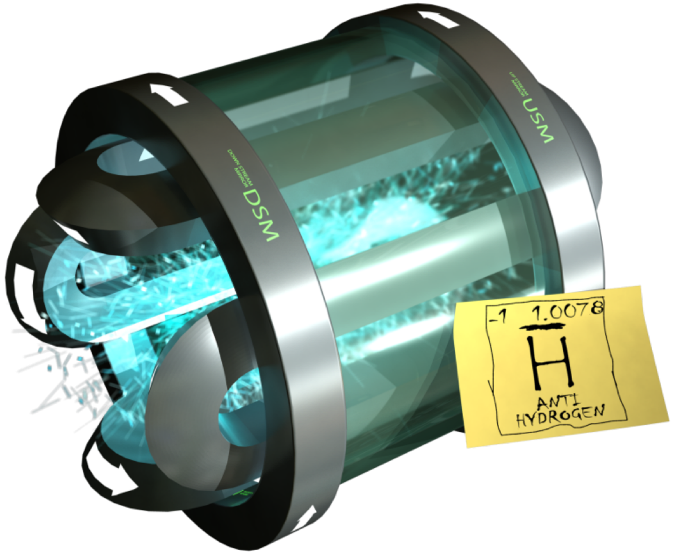
SME: Kostelecky et al.

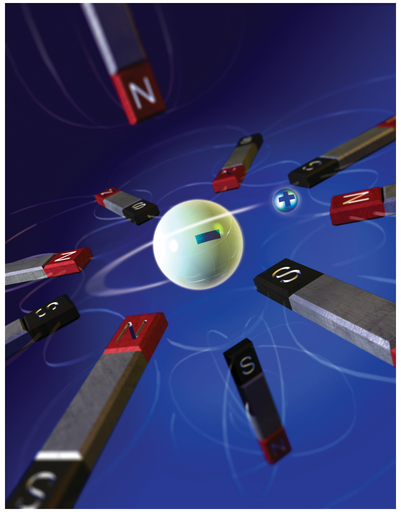
Ulmer, et al. Proc. Roy Phil. Soc. 2018

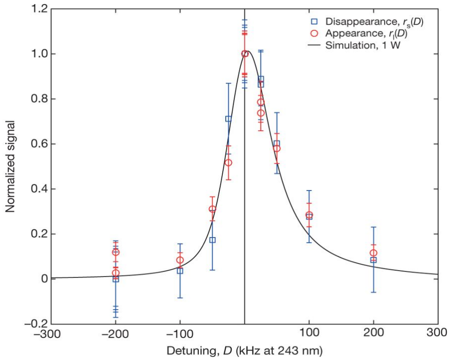
Fundamental Symmetry Tests with Antihydrogen

All antihydrogen work as part of the ALPHA Collaboration

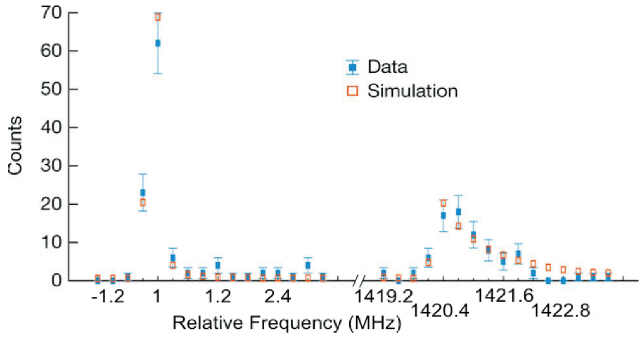




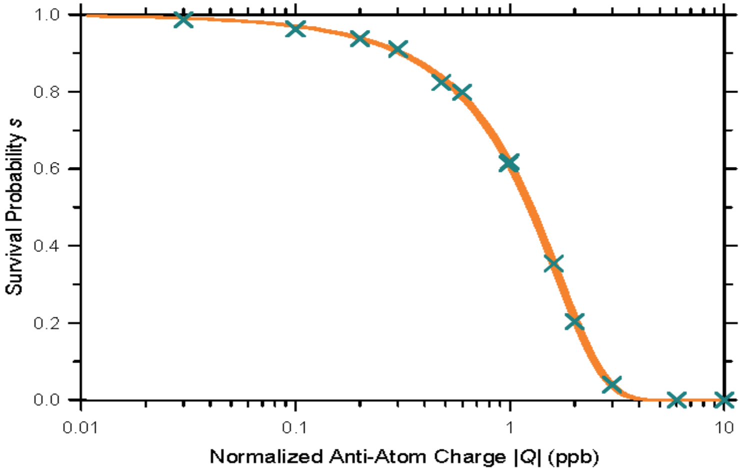




1S-2S Spectroscopy



Hyperfine Spectroscopy

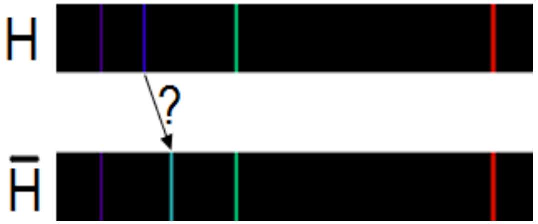


Antihydrogen Charge

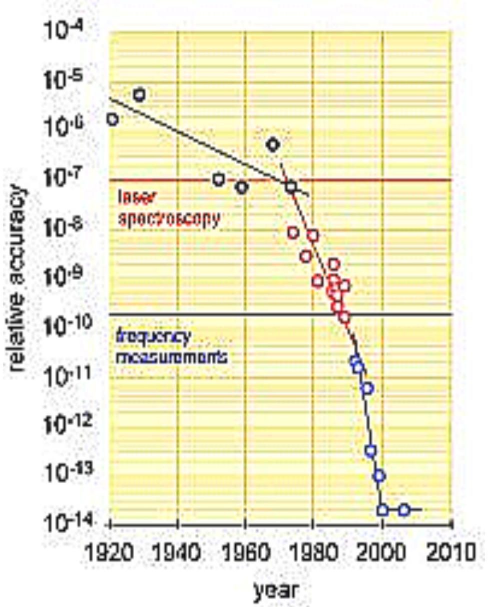
Why Study CPT With Antihydrogen?

- CPT predicts that the spectra of hydrogen and antihydrogen are identical.

- Why look for CPT violations with antihydrogen?
- Because we can…
- CPT tests can be made:
  - Model independent.
  - Extraordinarily precise…
    - Experimentally: ~10^{-15} with 1S-2S H
    - Theoretically: ~10^{-18} with 1S-2S H



Spectral differences between hydrogen and antihydrogen.



Progress in fractional accuracy in H 1s-2s spectroscopy.
http://www.mpq.mpg.de/~ajh/iontraps/index.php/Research/Helium

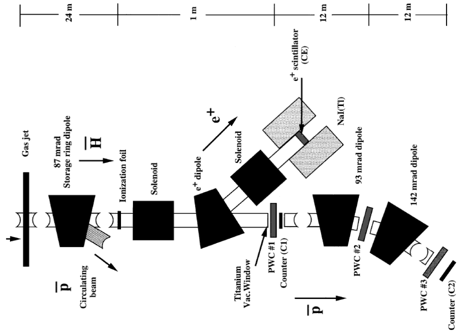
Parthey et al, Improved measurement of the hydrogen 1S-2S transition frequency, Phys. Rev Lett, **107** 203001 (2011).

Antihydrogen Research History

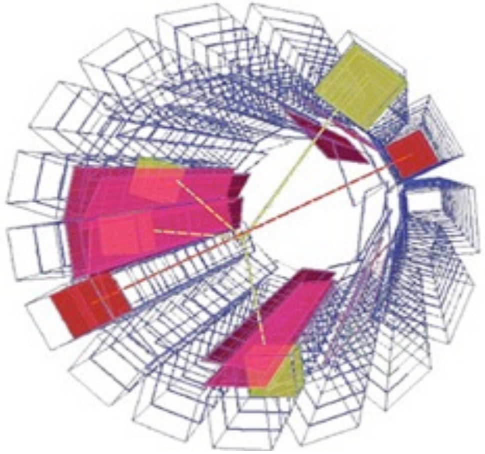
- 1996: Antihydrogen atoms were produced at accelerator scale energies at CERN and at Fermilab (1998).
  - This antihydrogen was too energetic to be used to measure its physics properties.

- 2000: Antiprotons were decelerated to 5.3MeV at CERN's then new Antiproton Decelerator (AD) facility.

- 2002: Low energy (eV scale) antihydrogen was produced by the ATHENA and ATRAP collaborations at CERN.
  - Hundreds of millions of antiatoms have been made to date.
  - The antihydrogen atoms were untrapped, and lived for a few milliseconds before annihilating on the apparatus walls.
  - Many researchers believe that antiatoms are best studied when trapped, not transitory.



Fermilab Experiment

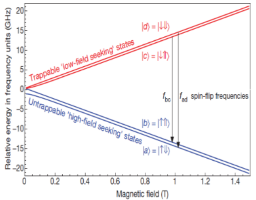


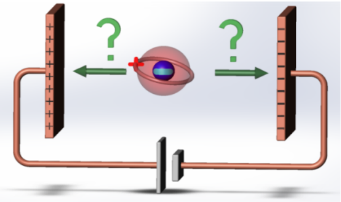
ATHENA Antihydrogen Event

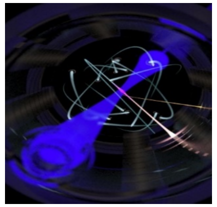
G. Baur, et al, Production of antihydrogen, Phys. Lett. B, **368**, 251 (1996).
G. Blanford, D. C. Christian, K. Gollwitzer, M. Mandelkern, C. T. Munger, J. Schultz, and G. Zioulas, Observation of Atomic Antihydrogen, Phys. Rev. Lett. **80**, 3037 (1998).
ATHENA, Production and detection of cold antihydrogen atoms, Nature **419**, 456 (2002).
ATRAP, Background-free observation of cold antihydrogen with field-ionization analysis of its states, Phys. Rev. Lett. **89**, 213401 (2002).

Antihydrogen Research History

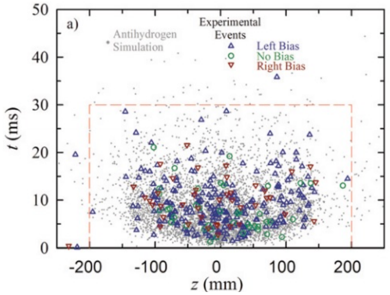
- 2010: ALPHA trapped 38 antihydrogen atoms.
  - Progress has been rapid since 2010.
    - In 2011, we trapped approximately 500 antiatoms, and held some for as long as 1000s.
    - ALPHA now can trap about 50 antiatoms in twenty minutes, as opposed to the 38 antiatoms total in 2010.
    - Last year we trapped approximately 7000 antiatoms.
- ALPHA has made several significant physics measurements on antihydrogen.
  - 2012: Measurement of the microwave spin flip frequency to 0.1%: a CPT test, and a start to measuring the antiproton radius.
  - 2013: Crude direct measurement of the antimatter *g* to within a factor of 100: a WEP test.
  - 2014 and 2016: Bounded the charge of antihydrogen to 1ppb: a CPT and charge anomaly test, and sets a new bound on the positron charge.
  - 2016: Measured the 1s-2s transition of antihydrogen to about 200ppt





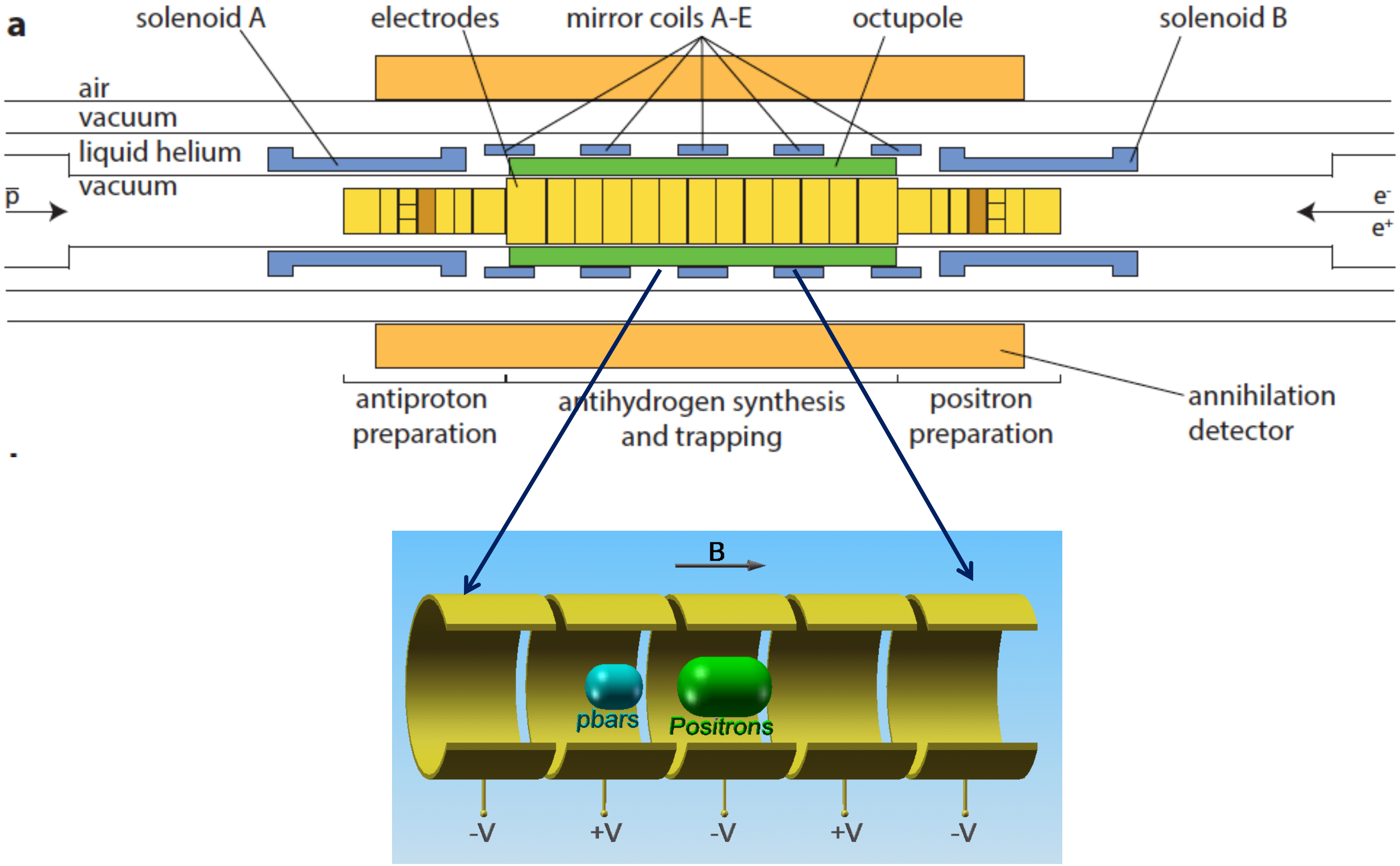


ALPHA, Trapped Antihydrogen, Nature **468,** 673 (2010).
ALPHA, Confinement of antihydrogen for 1000s, Nature Physics **7,** 558 (2011).
ALPHA, Resonant quantum transition in trapped antihydrogen atoms, Nature **483,** 439 (2012).
ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm **4**, 1785 (2013).
A I Zhmoginov, A E Charman, R Shalloo, J Fajans, J S Wurtele, Nonlinear dynamics of anti-hydrogen in magnetostatic traps: implications for gravitational measurements, Class. and Quantum Grav., **30** 205014 (2013).
ALPHA, An experimental limit on the charge of antihydrogen, Nature Comm, **5**, 3955 (2014).
M. Baquero-Ruiz, A. E. Charman, J. Fajans, A. Little , A. Povilus, F. Robicheaux, J.S. Wurtele and A. I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, (2014).
ALPHA, An improved limit on the charge of antihydrogen from stochastic acceleration, Nature, **529**, 373 (2016).
ALPHA, Observation of the 1S–2S transition in trapped antihydrogen, Nature (2016), doi:10.1038/nature21040.



Annihilation Locations of Previously Trapped Antihydrogen Atoms After Release

ALPHA

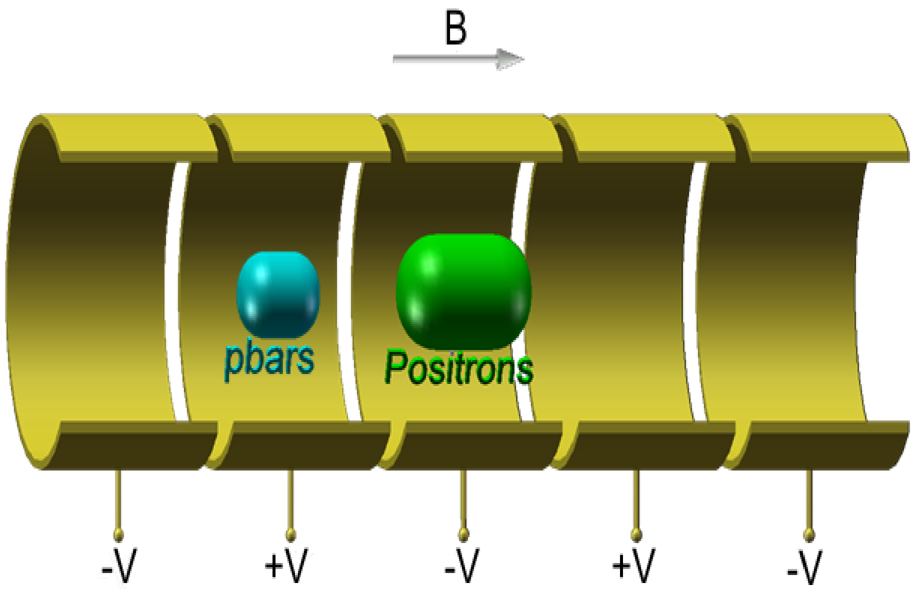


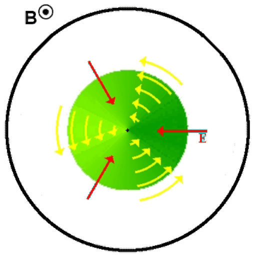
Penning-Malmberg Plasma Trap

Plasma Physics of Antihydrogen Synthesis

Antihydrogen is synthesized by mixing antiproton and positron plasmas in a Penning-Malmberg trap.

- A strong axial magnetic field provides radial confinement.
- Potentials applied to electrically-isolated electrodes provides axial confinement.
- The plasmas E×B spin in the external magnetic and the self-consistent electric fields.

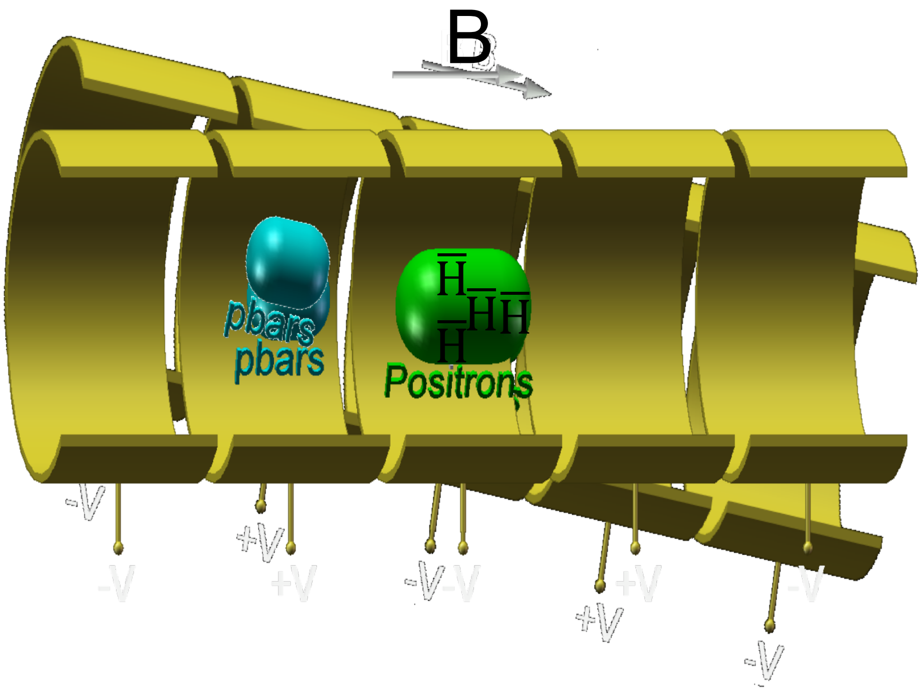




Connection to Plasma Physics

Antihydrogen is synthesized by mixing antiproton and positron plasmas in a Penning-Malmberg trap.

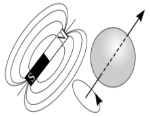
- The positrons come from a Surko-style positron accumulator.
  - Positron plasma parameters:
    - N = 20M
    - r <= 1mm
    - L = 10mm
    - n = 10^8 cm^{-3}
    - T = 10K



- The antiprotons come from the AD at CERN.
  - Antiproton plasma parameters:
    - N = 20k
    - r = 1mm
    - T = 100K
- Once these plasmas are made, they are mixed together, and antihydrogen forms by three-body recombination.
- Antihydrogen is charge neutral, so it is not trapped by the Penning-Malmberg trap fields, and would annihilate on the trap wall without additional magnetic fields.

Plasma and Neutral Traps

Antihydrogen Trapping

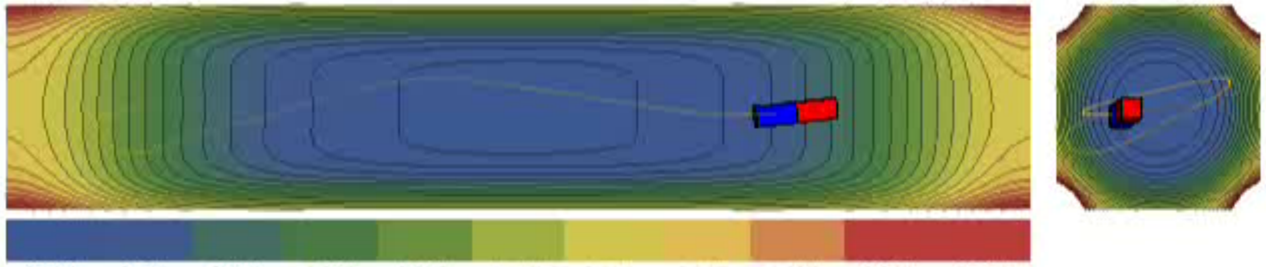


tihydrogen has a magnetic moment.

- Consequently, antihydrogen can be confined in a magnetic minimum.
  - Mirror coils can be used to create an axial minimum.
  - Multipole (quadrupole, octupole etc.) coils can be used to create a radial minimum.
- ***These magnetic fields impact plasma confinement. Good for one particle may be bad for plasma.***
  - The art to trapping antiatoms is to keep the plasmas cold and dense in the presence of the octupole.

Force on a magnet moment from a magnetic gradient:

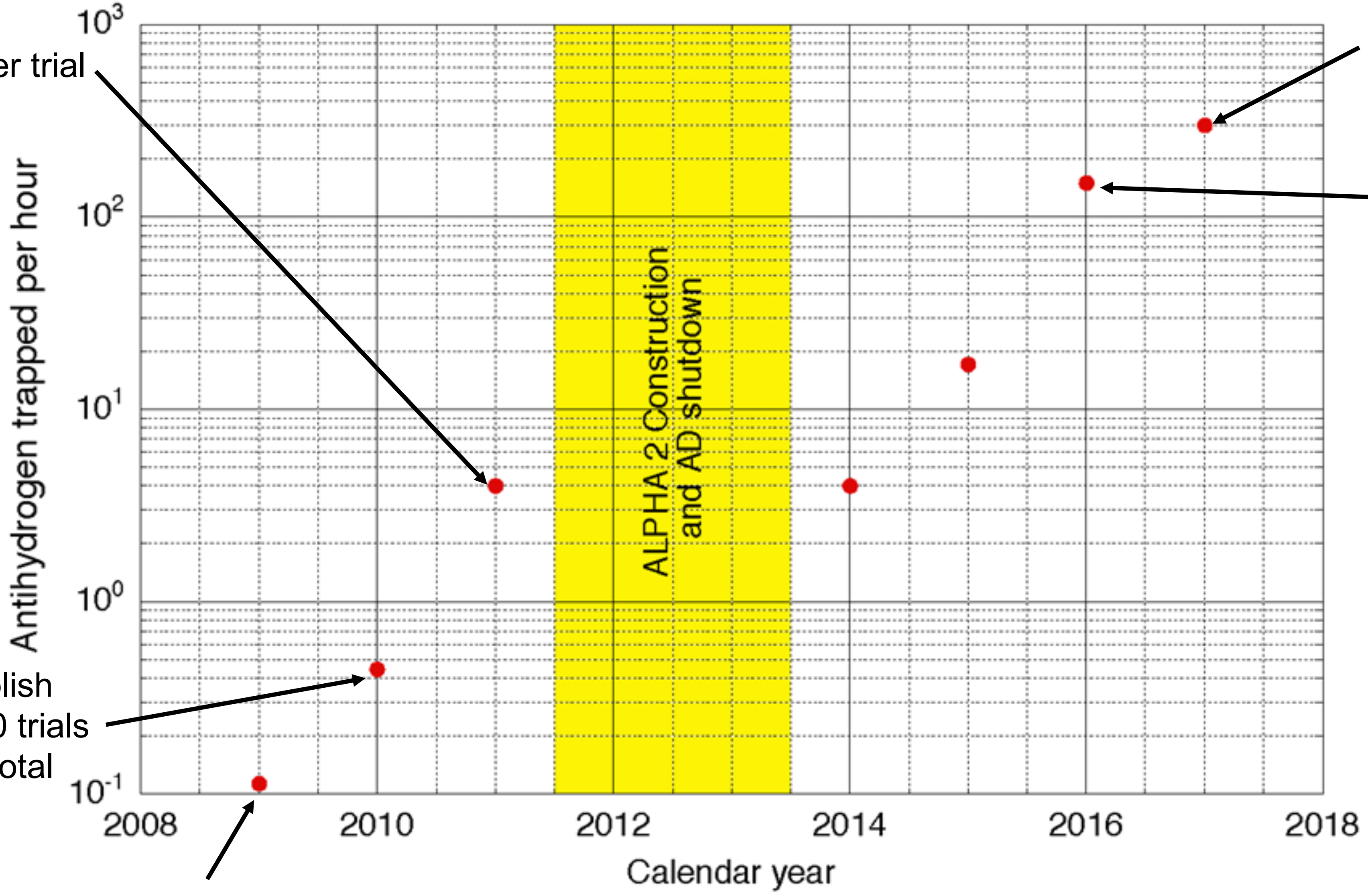
$$\mathbf{F}=\nabla(\mu\cdot\mathbf{B})$$



Chukman So / Berkeley

Magnetic Field Magnitude

Milestones in Antihydrogen Trapping



1 per trial

>1000 trapped
simultaneously
>70 000 total

20 per trial
Stacking
~100 simultaneously

Publish
1 in 10 trials
38 total

1 in 35 trials
6 total

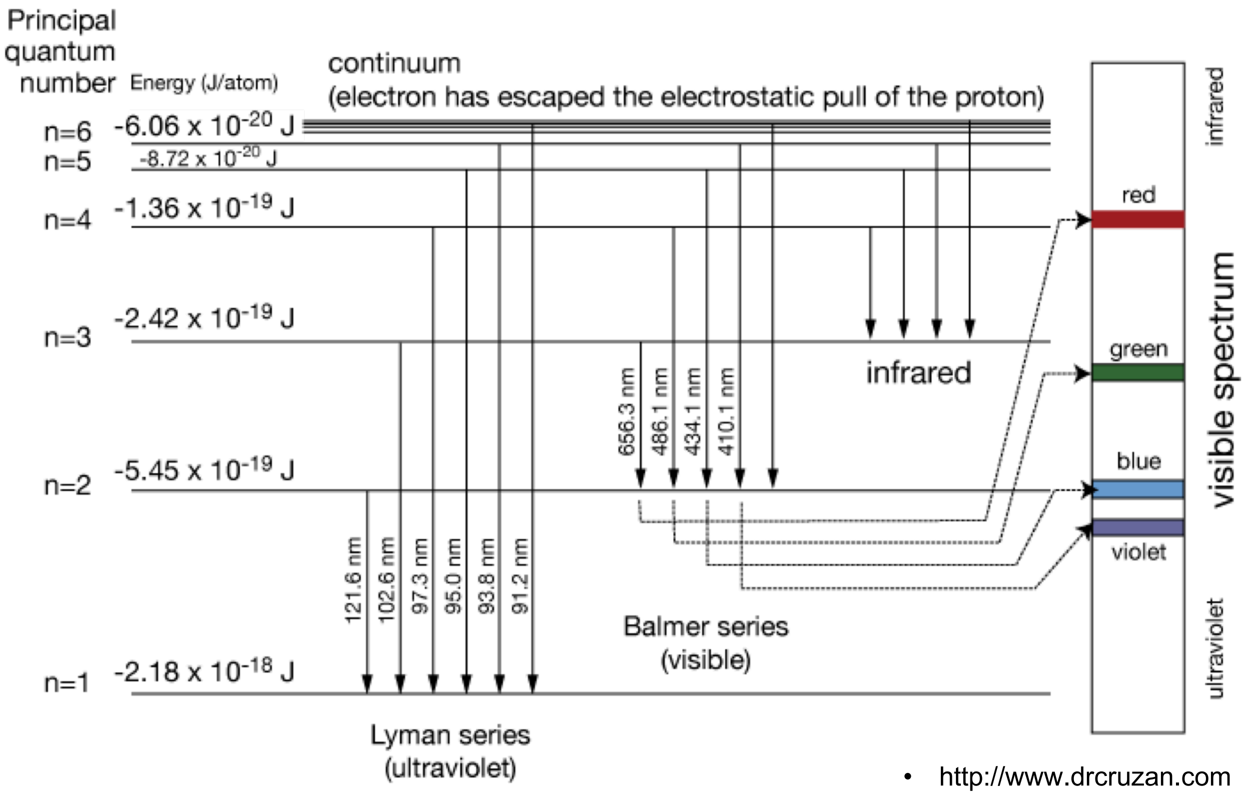
Plasma Techniques:
- Octupole trap
- Radial compression
- Electron kickout
- Autoresonance mixing
- Evaporative cooling
- Ion cleanout
- Faster plasma cycles
- SDREVC
- Smerge mixing
- Adiabatic expansion cooling
- Stacking

ALPHA, Antihydrogen accumulation for fundamental symmetry tests, *Nat. Commun.*, **8**, 681, (2017).

Laser Spectroscopy of Antihydrogen

Antihydrogen spectroscopy is complicated because the Lyman series is in the ultraviolet.

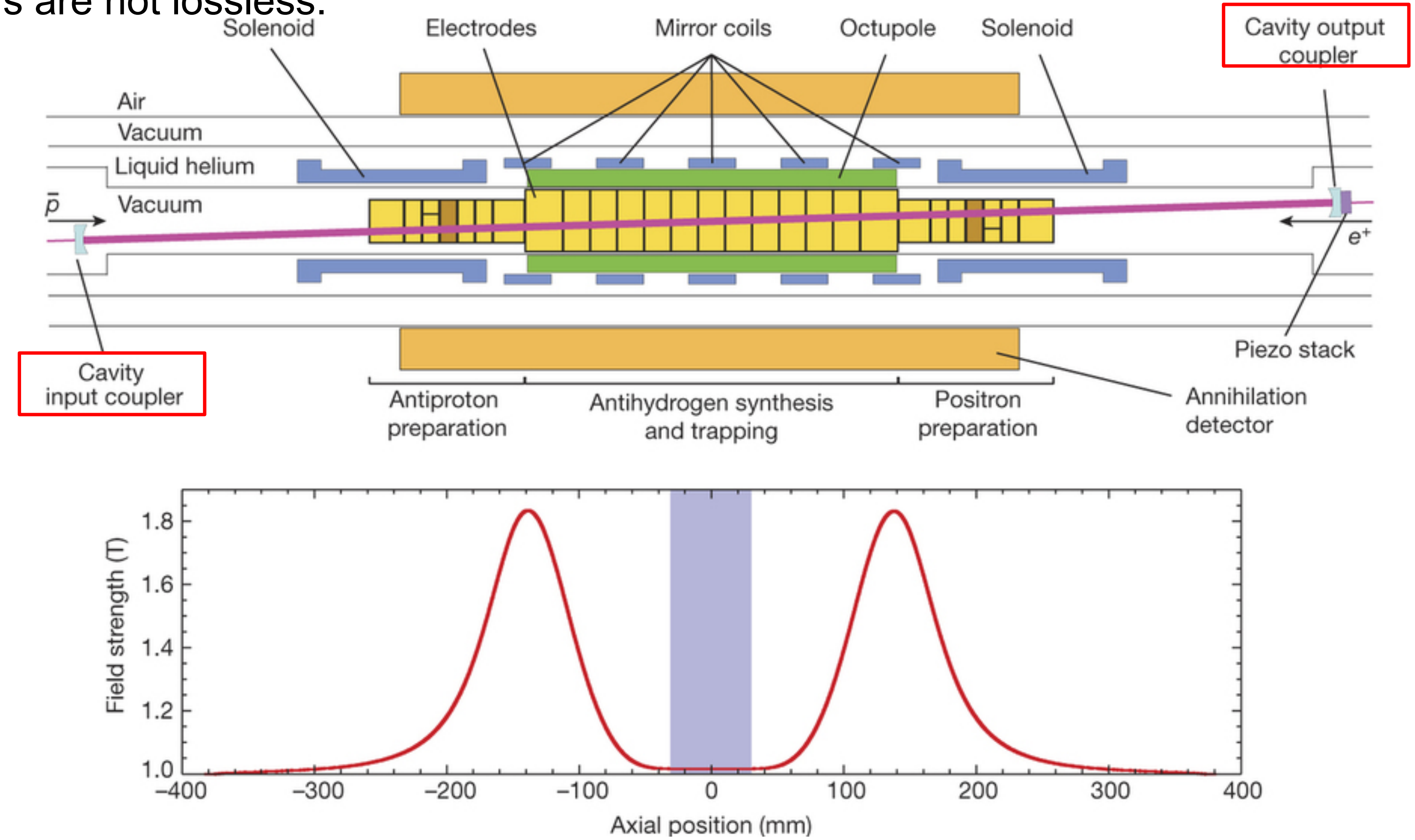
- The least energetic spectral line is the 1S-2S transition at 121.6nm.
  - This is a forbidden transition, but can be excited by two 243nm photons.
    - This two photon transition can be Doppler free.
  - As a two photon process, the excitation requires high laser power.



- http://www.drcruzan.com

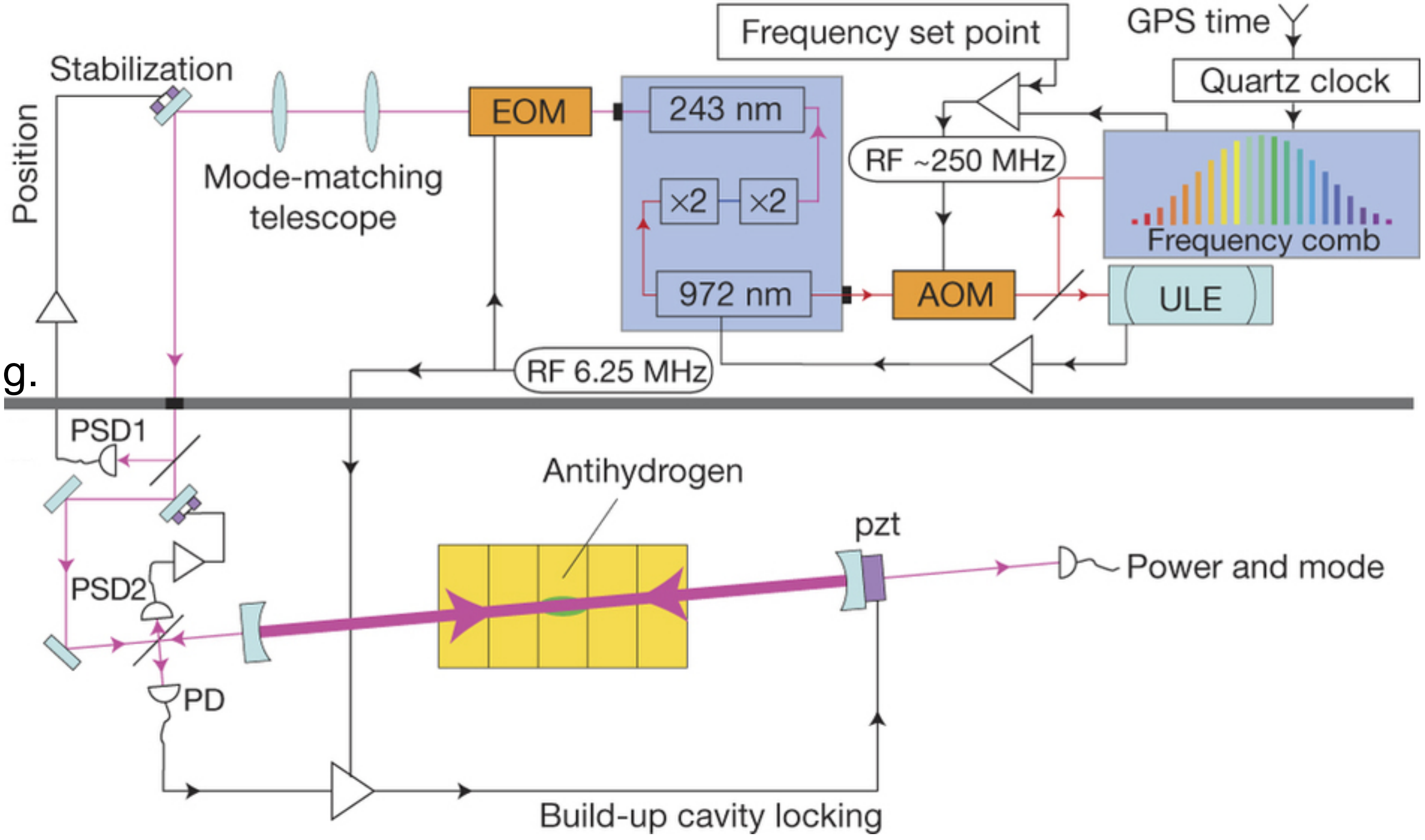
Precision Spectroscopy Inside a Cryogenic Trap.

- A laser cavity is required to get to high intensity.
  - Mirrors are not on an optical table.
  - Mirrors spaced by over 90cm.
  - Mirrors are at cryogenic temperatures.
  - Mirrors are in vacuum, limiting material choice.
  - 243nm mirrors are not lossless.



Laser and Laser Cavity System

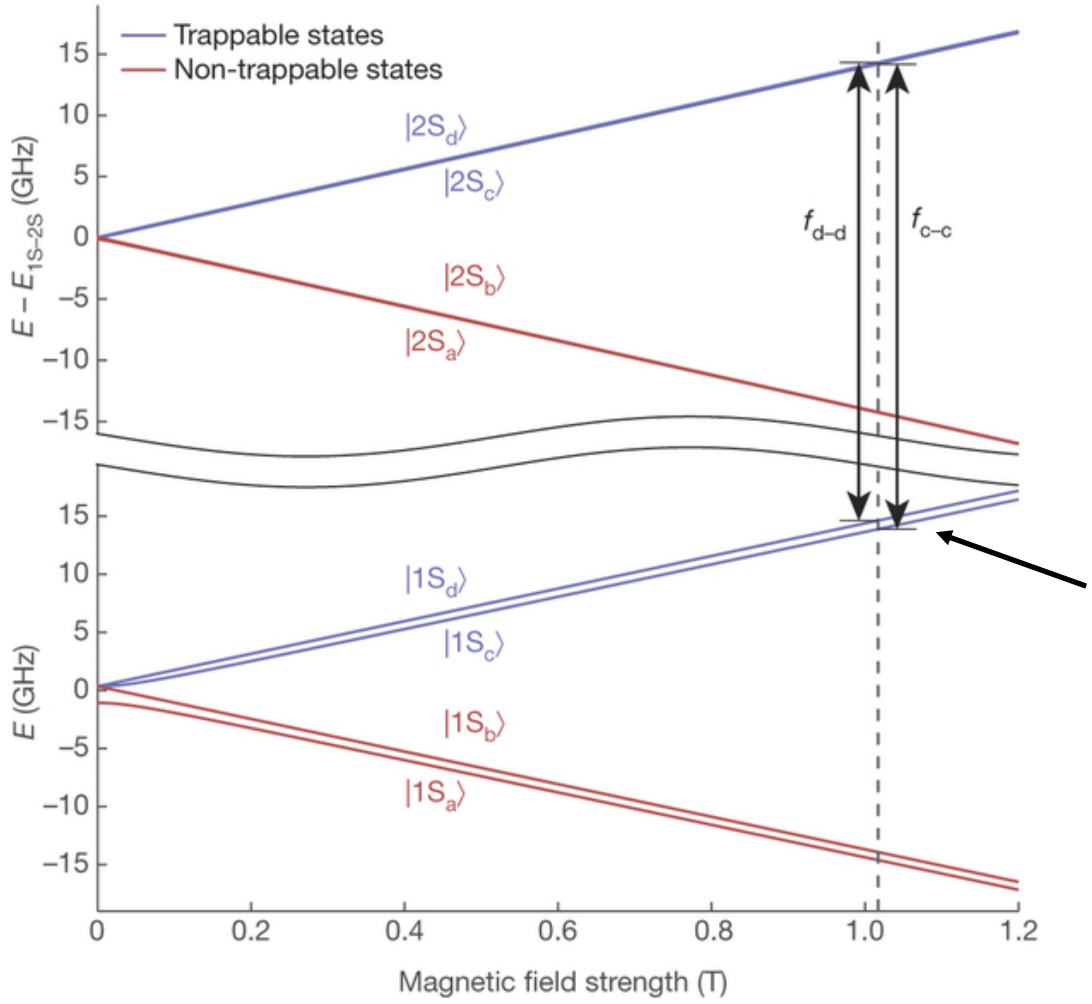
- Laser:
  - Toptica.
  - 2.5W at 972nm.
  - 150mW at 243nm.
- Cavity:
  - Design finesse 417.
  - Achieved finesse >200.
  - Pound Drever Hall (PDH) locking.
  - Circulating power >1W.
- Wavelength Stabilization:
  - Menlo frequency comb.
  - GPS disciplined.
  - Linewidth <10kHz (short-term).



Precision Antihydrogen Spectroscopy

Trapped antiatoms can be in one of two S states depending on the antiproton spin: the c or the d state.

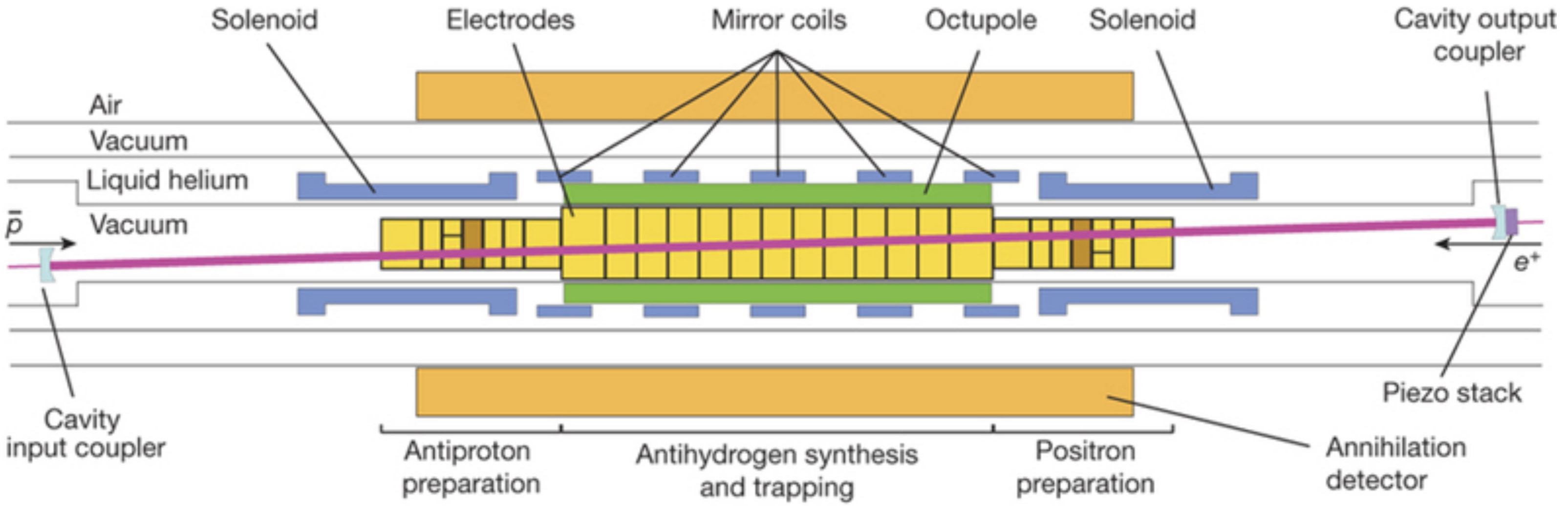
- Accurate magnetometry allows us to do precision spectrometry in the presence of 10GHz field induced shifts.



Split by ~600MHz

Failure of Conventional Spectroscopy Techniques

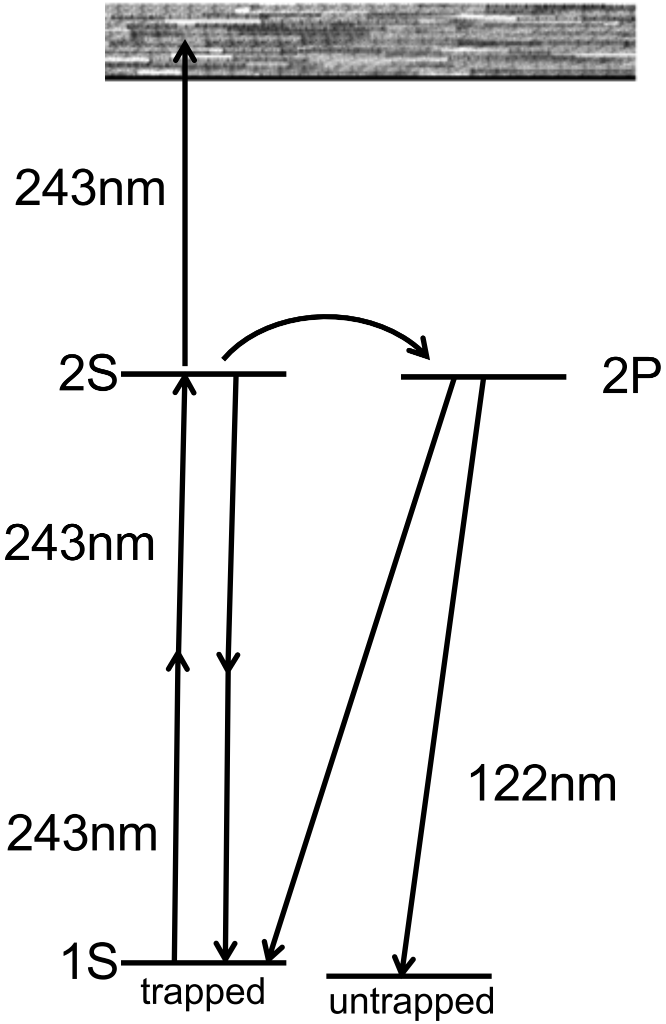
- It is futile to look for emitted photons:



- The nearest detectors would be no nearer than 0.5m.
- Only a few photons would be emitted over the 600s exposure.
- Conceivably, some of the photons could come from hydrogen, not antihydrogen.

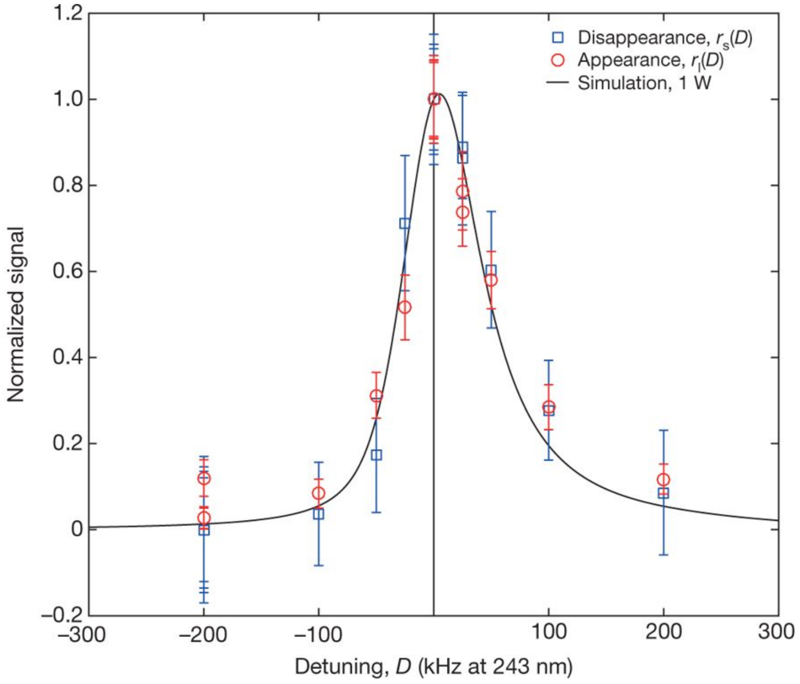
Detecting the Transitions Using Annihilation

- There are three routes a 2S antiatom can take, two of which lead to annihilation of the antiatom.
  - *Route 1: $\boldsymbol{v}\times\boldsymbol{B}$ electric field mixing of 2S and 2P states, followed by 1 photon emission from 2P to an untrapped 1S state.*
  - *Route 2: Ionization by photon absorption while in 2S state.*
  - *Route 3: The 2S and 2P states can also decay back to the trapped 1S state.*
- Simulations suggest that, while all three routes occur, ionization events dominate.
- The resulting antiatoms negative ions (i.e. antiprotons) do not last long in our trap, and almost immediately annihilate.



1S-2S Measurements and Simulation

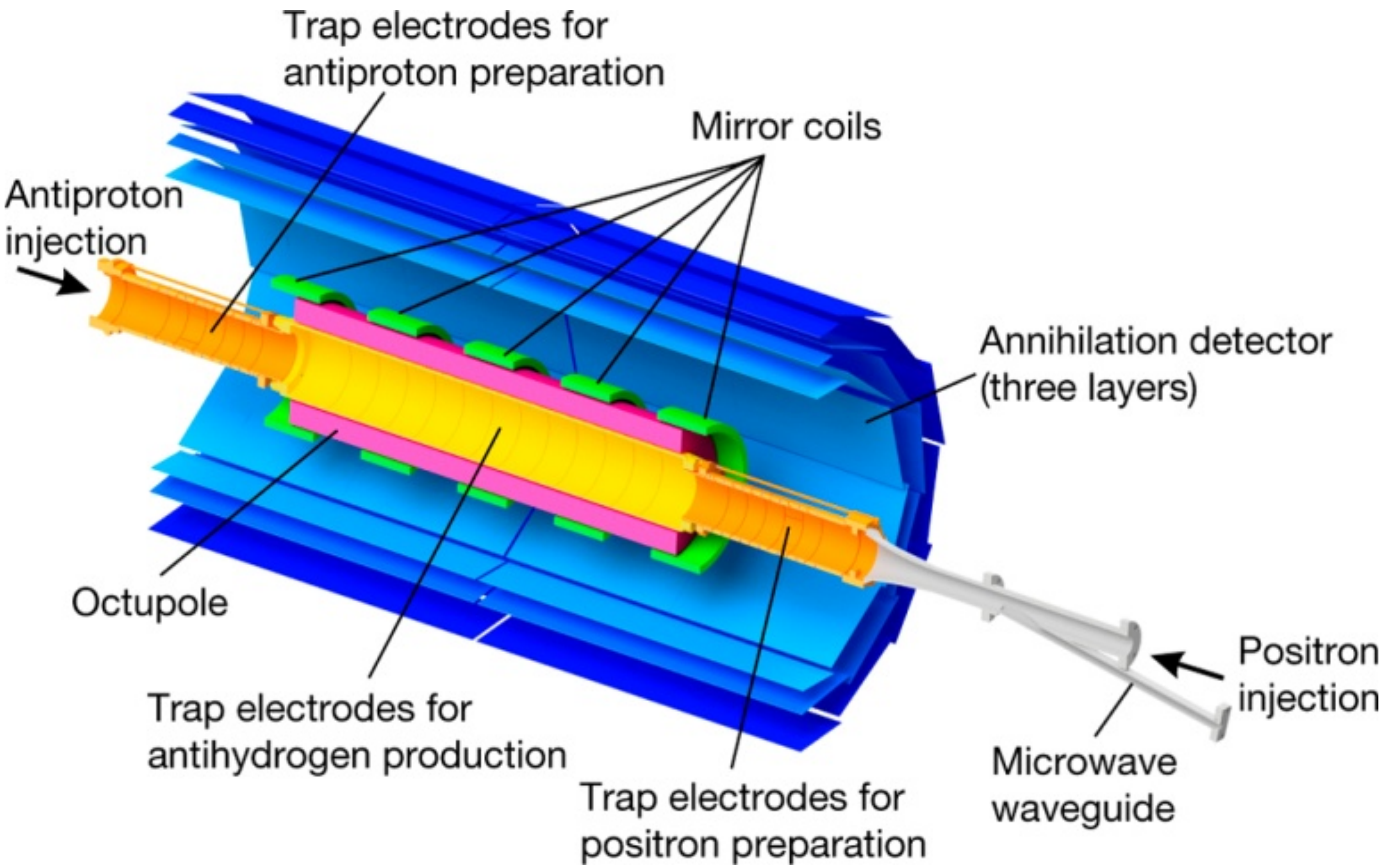
- In early 2017, we published an on-off resonance measurement of the 1S-2S line.
  - This measurement was accurate to 200ppt.
- In 2018, we published the full lineshape of the 1S-2S transition.
  - The line center is accurate to 2ppt.



1S-2S Spectrum of Antihydrogen

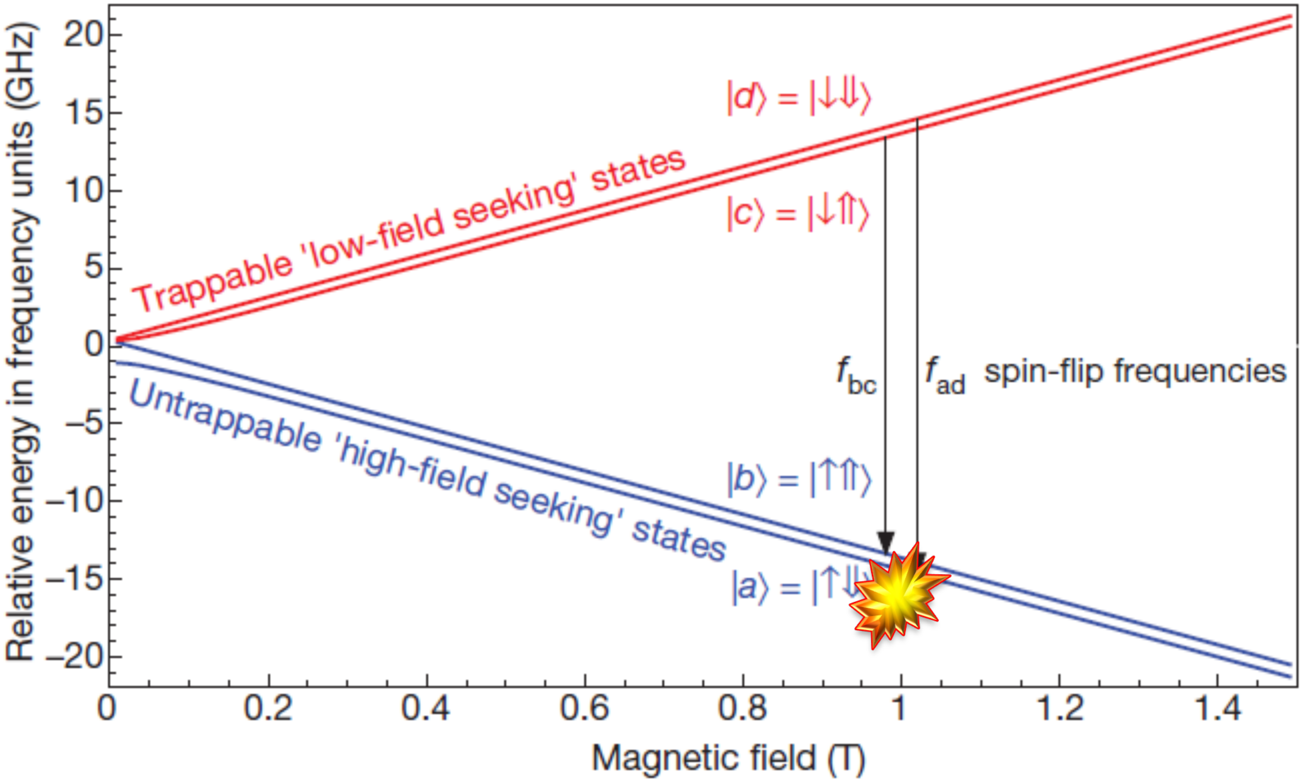
ALPHA, Observation of the 1S–2S transition in trapped antihydrogen, *Nature*, **541**, 506 (2017).
ALPHA, Characterization of the 1S–2S transition in antihydrogen, *Nature* **557**, 71 (2018).

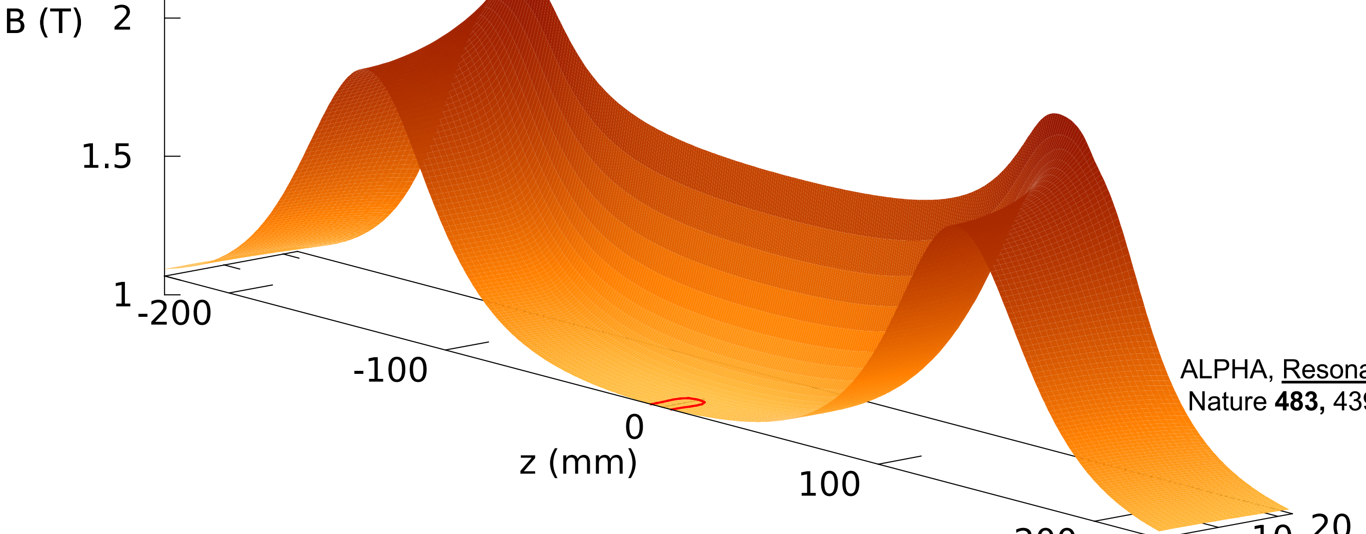
ALPHA Hyperfine Measurements



M Ahmadi *et al.* *Nature* **548,** 66–69 (2017) doi:10.1038/nature23446

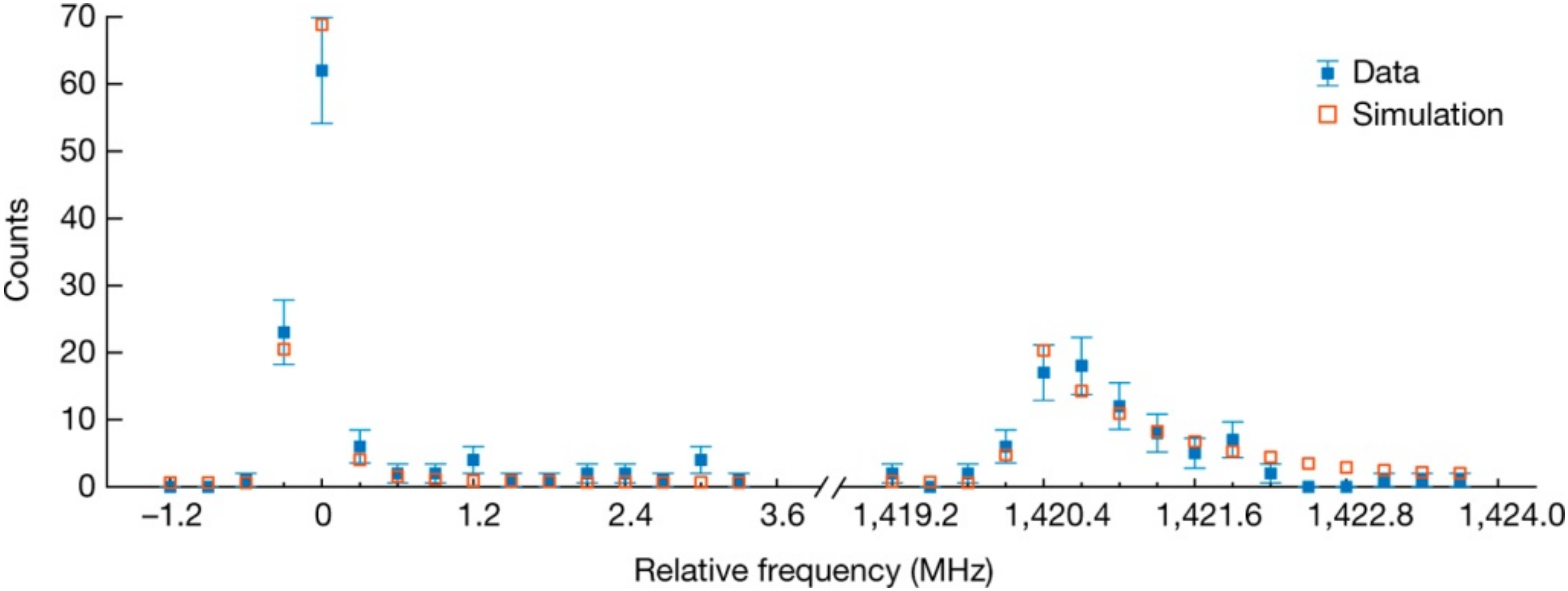
Microwave Spin Flip: Breit-Rabi Diagram





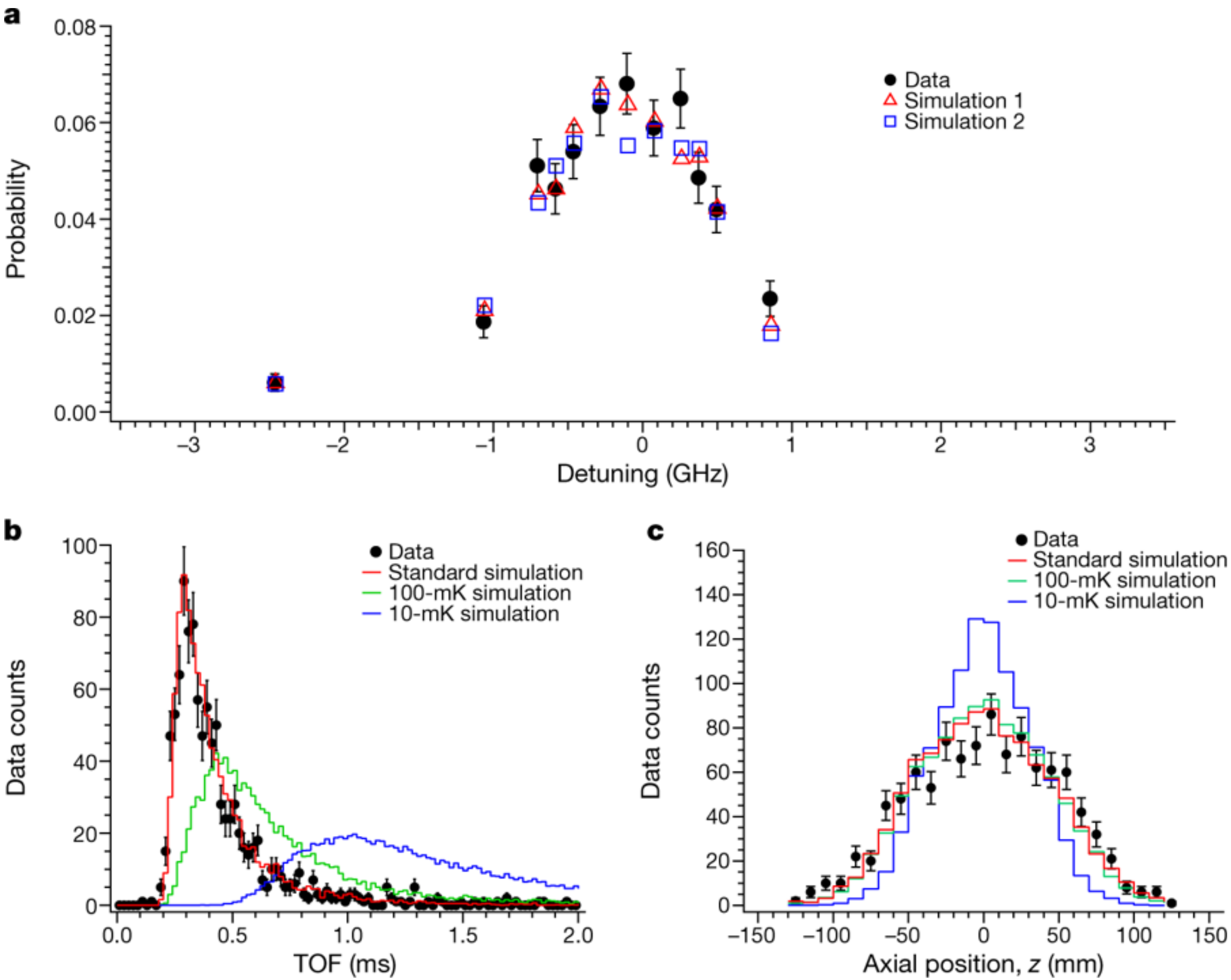
ALPHA, Resonant quantum transition in trapped antihydrogen atoms, Nature **483,** 439 (2012).

Hyperfine Splitting: Data and Simulation



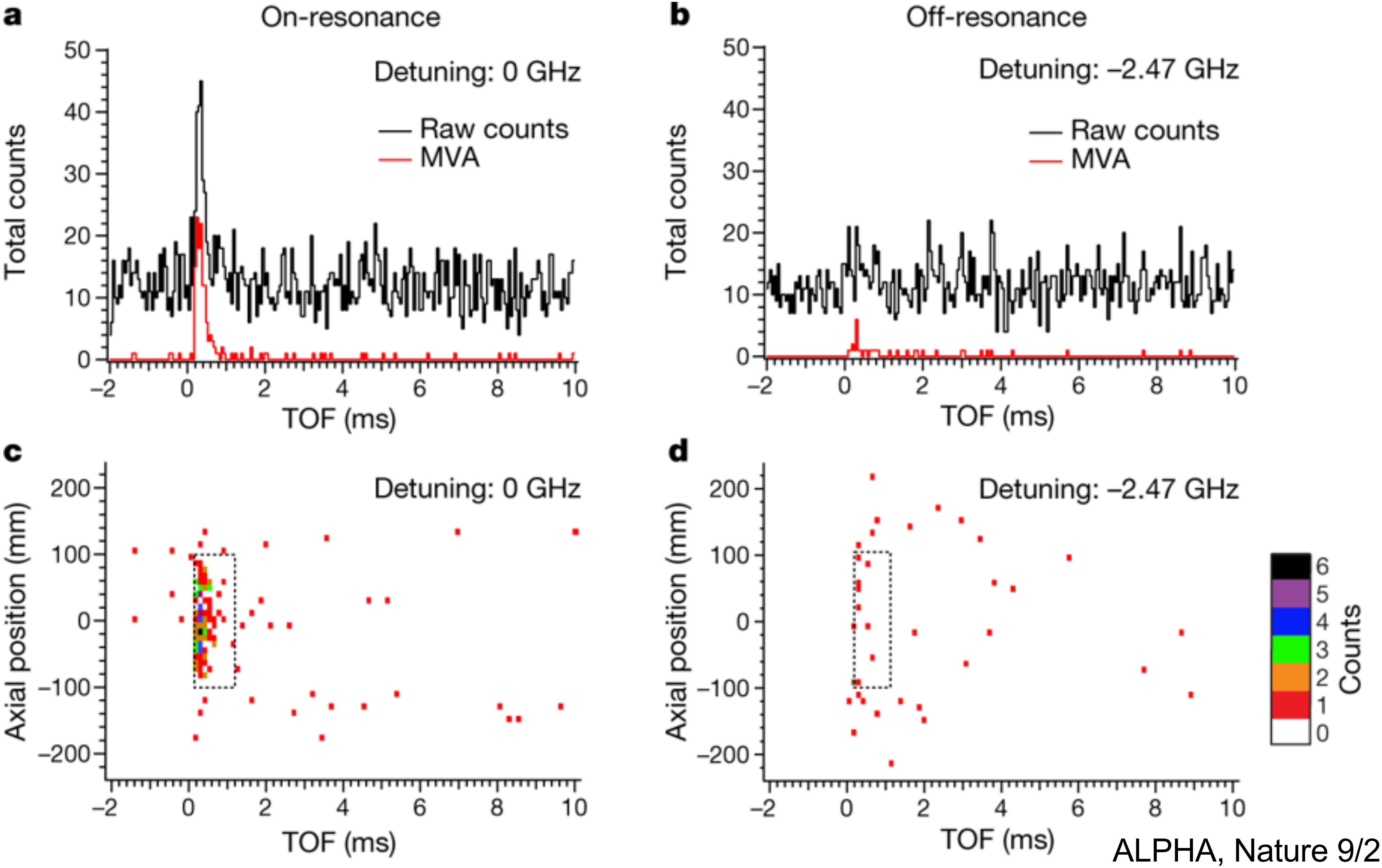
M Ahmadi *et al. Nature* **548,** 66–69 (2017)

Laser Spectroscopy of Antihydrogen: Data and Simulation for Lyman-α



ALPHA, Nature 9/2018

Theory: Rasmussen, Madsen, & Robicheaux, J. Phys. B 50, 184002 (2017).



ALPHA, Nature 9/2018

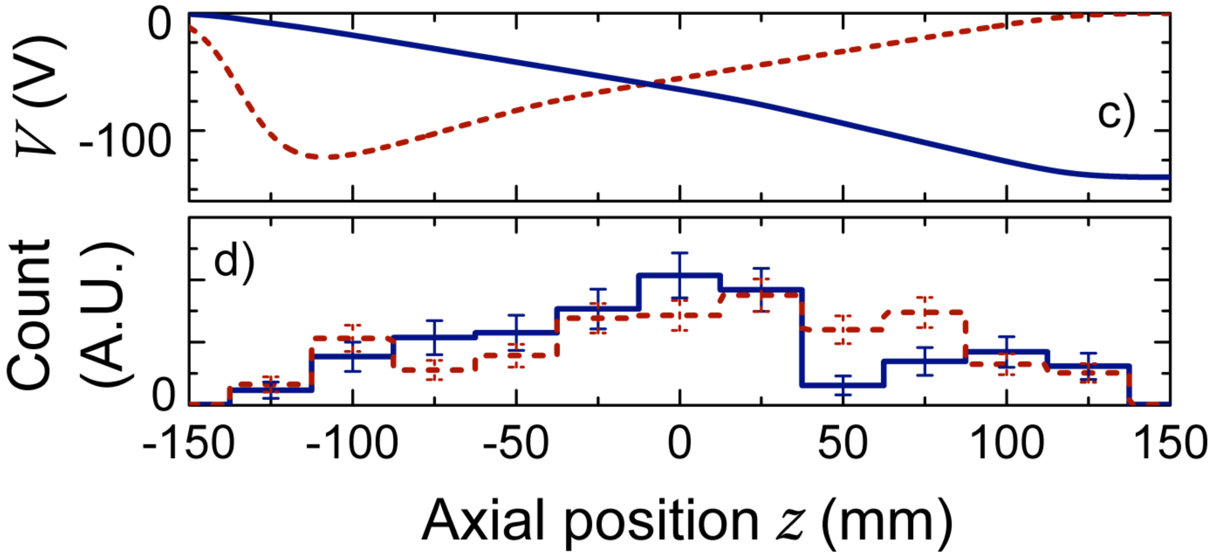
Antihydrogen Charge

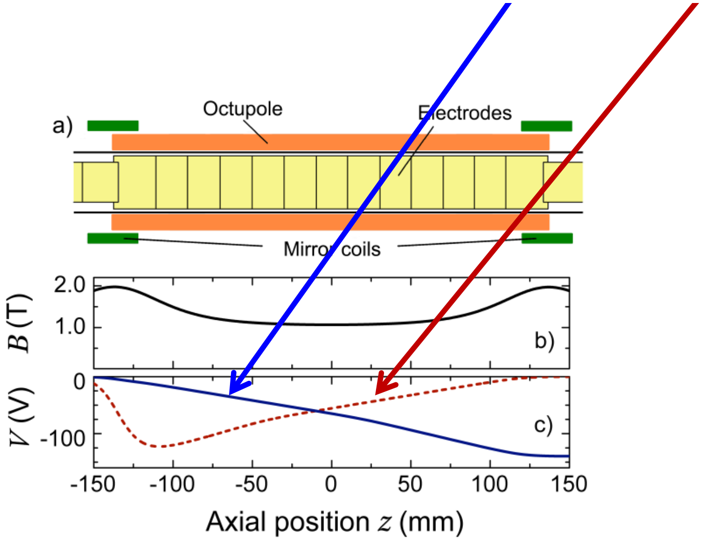
- Normal matter atoms are known to be charge neutral to remarkable precision: on the order of $10^{-21}e$.
- CPT and quantum anomaly cancellation demand that antihydrogen be charge neutral to a similar level.
- How well is the charge of antihydrogen known?
    - Techniques used for normal matter atoms are inapplicable.
    - Only prior limits on antihydrogen at the $10^{-2}e$ level.
    - Using superposition:
        - Charge of the antiproton is known to $710^{-10}e$.
        - Charge of the positron is known to $2.510^{-8}e$.
        - *Can we be sure that superposition is valid? Almost surely…*

- A search for the charge of antihydrogen is a novel and potentially interesting test of fundamental physics.

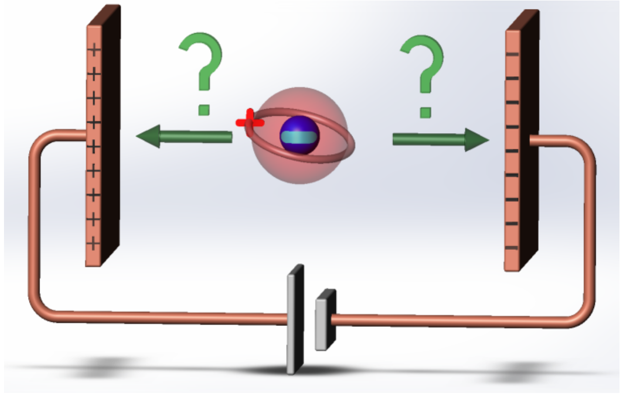
Bressi, G. et al. Testing the neutrality of matter by acoustic means in a spherical resonator. Phys. Rev. A **83**, 052101 (2011).
Greenland, P. T. Antimatter, Contemporary Physics **38**, 181 (1997).
Olive, K. A. *et al*. Review of particle physics. *Chinese Phys. C* **38**, 090001 (2014).
Fee, M. S. *et al*. Measurement of the positronium $1\ {}^3S_1$–$2\ {}^3S_1$ interval by continuous-wave two-photon excitation. *Phys. Rev. A* **48**, 192 (1993).
Hori, M. *et al*. Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio. *Nature* **475**, 484 (2011).
Hughes, R. J. & Deutch, B. I. Electric charges of positrons and antiprotons. *Phys. Rev. Lett.* **69**, 578 (1992).

2014 ALPHA charge bound (unplanned): $<\sim 2\ 10^{-8}e$.



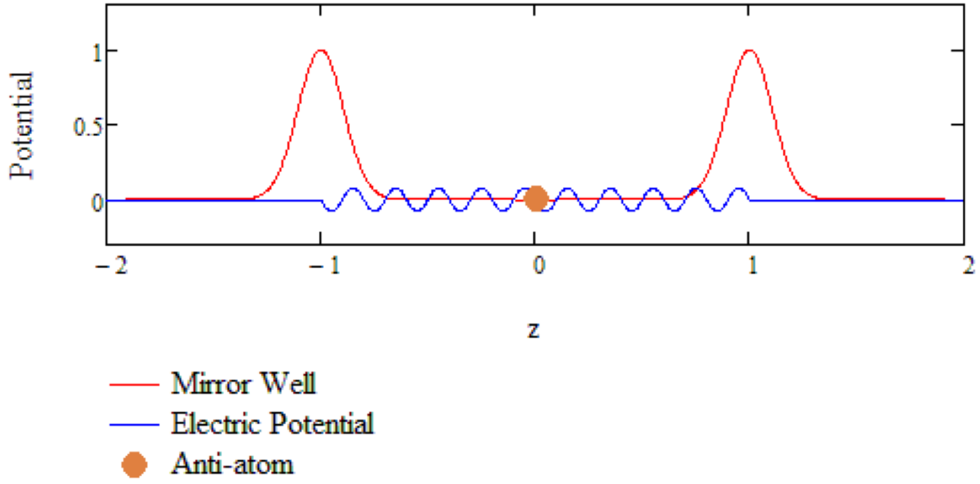


ALPHA, Nat. Comm. 2014



Improved Antihydrogen Charge Bound Using Stochastic Fields

- Stochastic acceleration (Fermi acceleration) can eject charged anti-atoms from the trap.



- Using stochastic acceleration, we expect that we can determine the charge to the $10^{-12}e$ level.

$$\Delta E_{\bar{H}} \sim Qe\Delta\Phi_{kick} N_{kick}^{1/2}$$

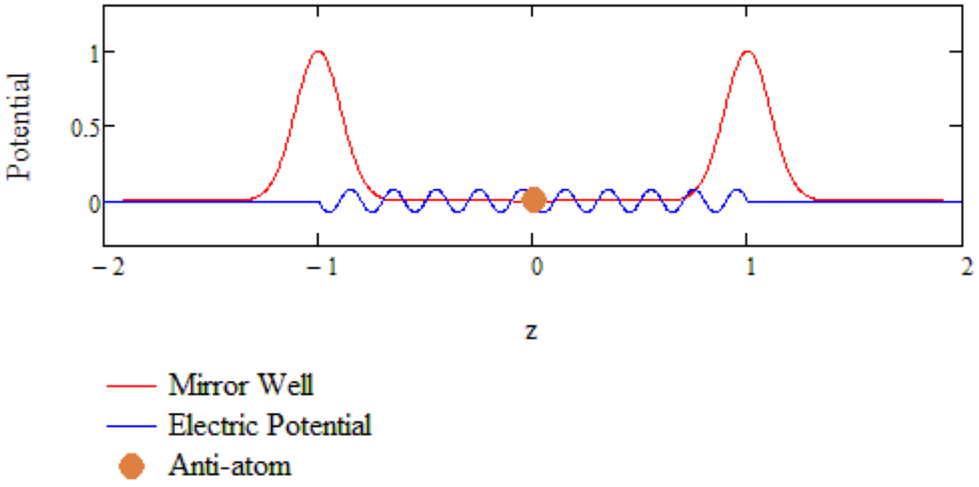
$$\Delta E_{\bar{H}} \leq U_{trap}$$

$$Q \leq \frac{U_{trap}}{e\Delta\Phi}\sqrt{\frac{1}{N}}$$

M. Baquero-Ruiz, Studies on the neutrality of antihydrogen. Ph.D. thesis, University of California, Berkeley, 2013.
M. Baquero-Ruiz and A. E. Charman and J. Fajans and A. Little and A. Povilus and F. Robicheaux and J.S. Wurtele and A. I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, (2014).

Antihydrogen Charge Bound Using Stochastic Acceleration

- Stochastic acceleration (Fermi acceleration) can eject putatively charged antiatoms from the trap.
  - Stochastic acceleration: the acceleration of a charged particle by randomly time-varying electric fields.
    - This is a "textbook" problem in nonlinear dynamics.



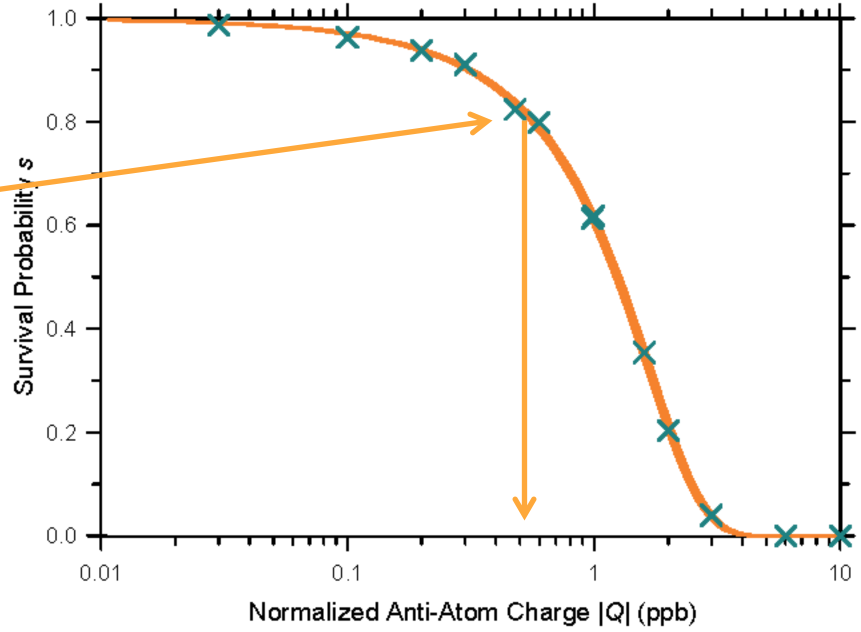
M. Baquero-Ruiz, Studies on the neutrality of antihydrogen. Ph.D. thesis, University of California, Berkeley, 2013.
M. Baquero-Ruiz and A. E. Charman and J. Fajans and A. Little and A. Povilus and F. Robicheaux and J.S. Wurtele and A. I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, (2014).

Stochastic Acceleration Experimental Results

	Number of Trials	Observed Antiatoms
Stochastic Trials	10	12
Null Trials	10	12

Cosmic background is negligible.

- Clearly, most antiatoms survive.
  - Appropriate survival cutoff is significantly greater than 50%.
- After much Bayesian statistical analysis…
  $Q < 0.59$ ppb (one sigma).
- After much systematic analysis…
  $Q < 0.71$ppb (one sigma).
- Using superposition, this sets a limit on the positron charge anomaly of $|q_{\text{pos}} - e|/e < 1\text{ppb},$ an improvement by a factor of 25.



ALPHA, An improved limit on the charge of antihydrogen from stochastic acceleration, Nature, **529**, 373 (2016).
Capra, A. Testing CPT and antigravity with trapped antihydrogen at ALPHA, Ph.D. Thesis, York University (2015).
L. Evans, Phenomenology of creation of antihydrogen and measurement of antihydrogen properties, Ph.D. thesis, Berkeley (2016).

Gravity

- Average energy of the antiatoms (current parameters: ~300mK).
- Typical velocity: ~90m/s.
- Equivalent height: ~400m.
  - Fountain is impossible at this energy.
    - Gbar collaboration intends to trap antihydrogen$^+$ ions, cool and strip the ions, and make a fountain.

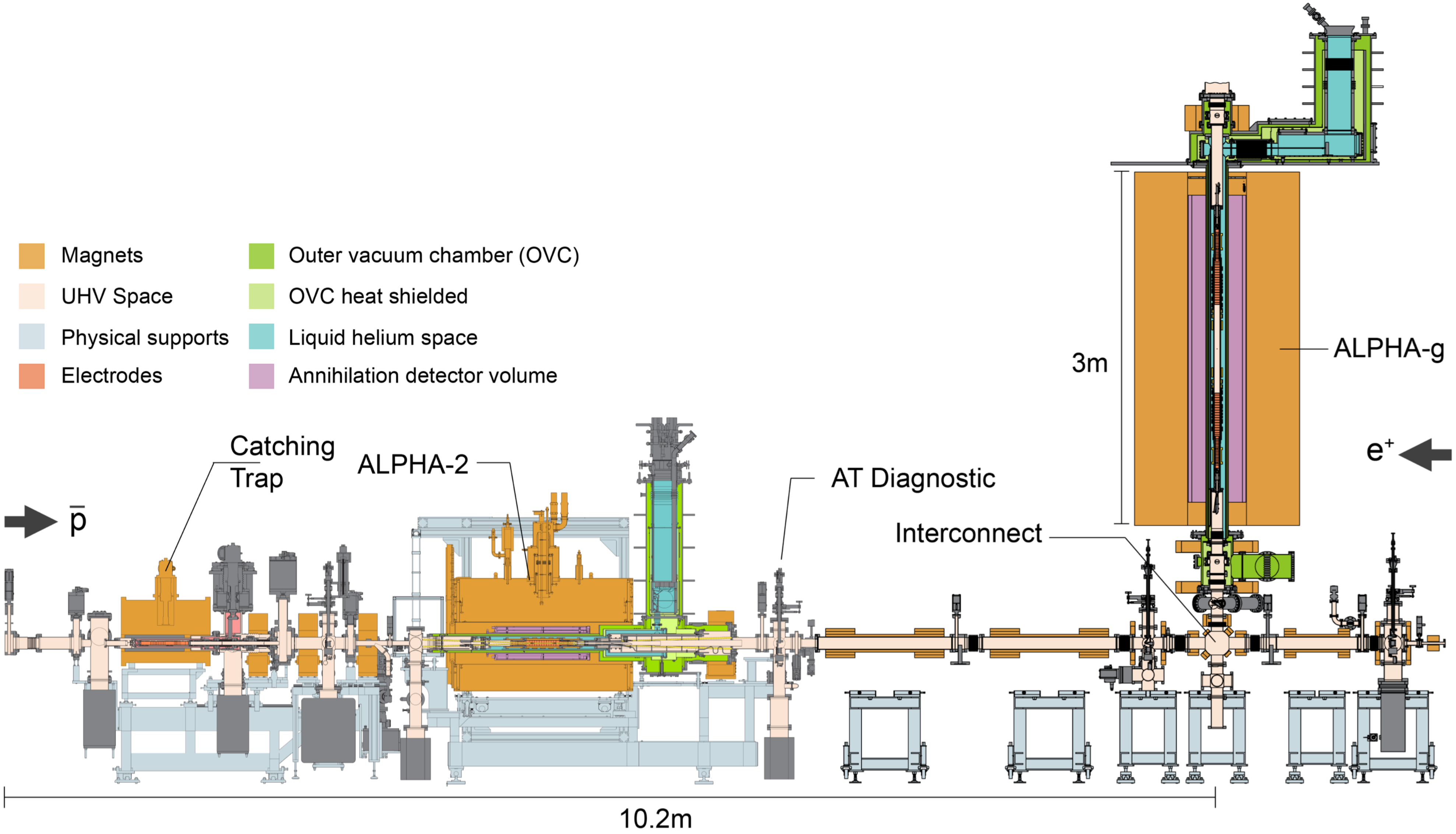
- Downward deflection in 1m: 0.6mm (“falling” beam)
  - A deflection measurement is possible, but difficult.
    - AEGIS collaboration intends to make a much lower energy antihydrogen beam.

- Laser cooling + adiabatic cooling will improve ALPHA precision
- Magnetic confinement force is strong (G is small)

→in situ knowledge of B is vital

We expect to reach a precision of ~1% with this apparatus

ALPHA g Schematic



- 🟧 Magnets
- ⬜ UHV Space
- ⬜ Physical supports
- 🟥 Electrodes
- 🟩 Outer vacuum chamber (OVC)
- 🟩 OVC heat shielded
- 🟦 Liquid helium space
- 🟪 Annihilation detector volume

Limits on gravity from other experiments

Experiments with matter

Larmor frequency measurements on antiprotons.

GR measurements (bent light, Shapiro effect).

Synchrotron radiation for positron limit.

These indirect measurements set limit less than ~10^{-7} g for antigravity on antihydrogen. Current experiments are expected to reach 10^{-2} but we have (preliminary) ideas (antihydrogen interferometer, e.g., PRL 2014) that approach 10^{-6} g.

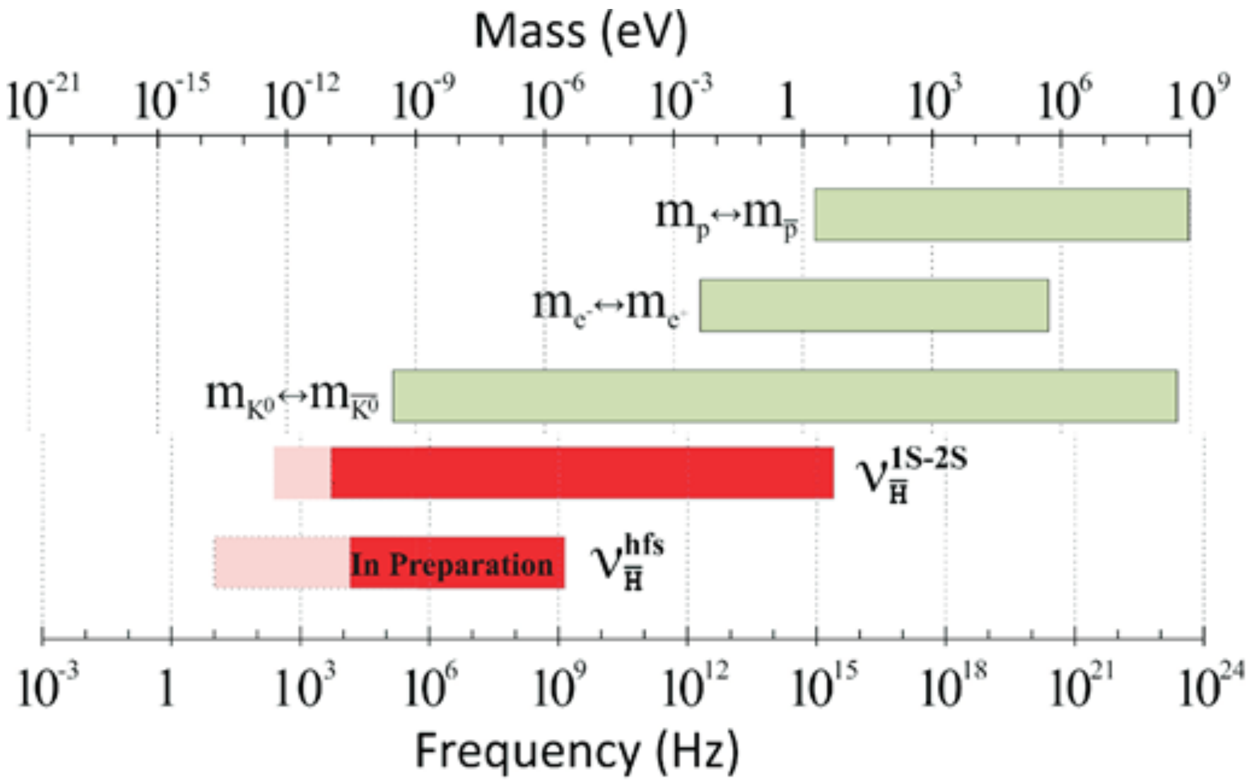
Precision neutral antimatter science is in its infancy.

For detailed reviews of antimatter gravity and many references see:

Blas, Proc. Trans. Roy. Soc. A **376** 20170277

Kashenboim, J. Phys. B: At. Mol. Opt. Phys. **49** (2016) 144001

CPT Tests



CPT Tests

- ALPHA 1S-2S and hyperfine measurements are now more precise, on an *absolute* energy scale, than the kaon system test, which is commonly regarded as the “best” CPT test.
- Our tests are model independent tests.
- CAVEAT: The BASE result on the antiproton magnetic moment is not readily plotted on these axes and is not included in the graph.

Future AD Physics

Ed. N. Madsen, Phil Trans. Royal Soc. A **376** Issue 2116 (2018), Special Issue: Antiproton Physics in the ELENA Era

CERN is upgrading the antiproton source with the new ELENA ring. We will have antiprotons ‘on demand’ and at lower energy.

ALPHA: Improve trapping, develop laser and adiabatic cooling techniques
Access higher level transitions such as 2S-2P, 2S-4S.
Measure (anti)Lamb shift, (anti)Rydber $\bar{p}He^{+}$ nt, antiproton radius,…

BASE: Deploy and develop existing (new) ideas for x10-100 improved precision.

ASACUSA: High precision spectroscopy on using electron cooler

AEGIS: Antihydrogen beam for gravity measurements; beam spectroscopy

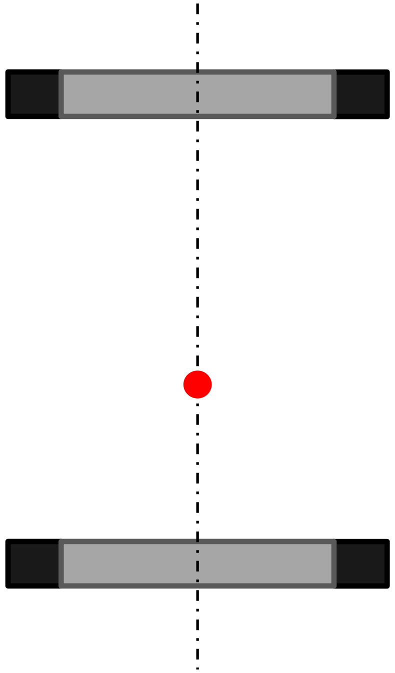
ATRAP: Improved antiproton measurements and antihydrogen measurements?

Gbar: Antihydrogen fountain.

extras

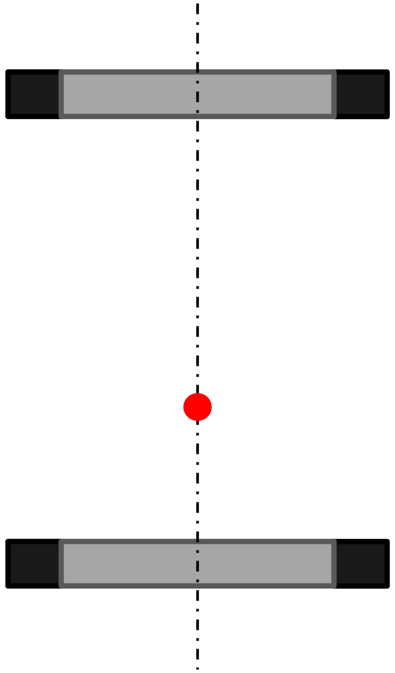
Gravitational Attraction of Antihydrogen to the Earth

- ALPHA traps antiatoms between mirror magnets.
- B_{mir}=1T



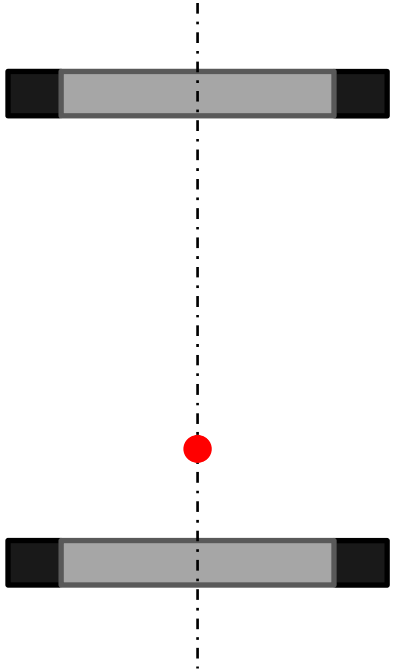
Gravity

- ALPHA traps antiatoms between mirror magnets.
- We can let that antiatoms escape by slowly lowering the field.
- B_{mir}=0.9T.



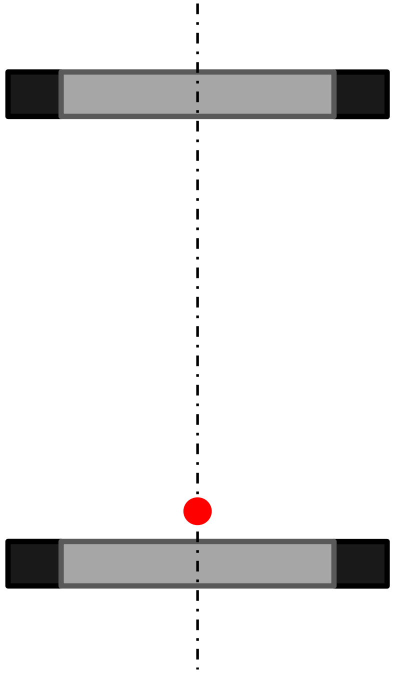
Gravity

- ALPHA traps antiatoms between mirror magnets.
- We can let that antiatoms escape by slowly lowering the field.
- B_{mir}=0.8T.



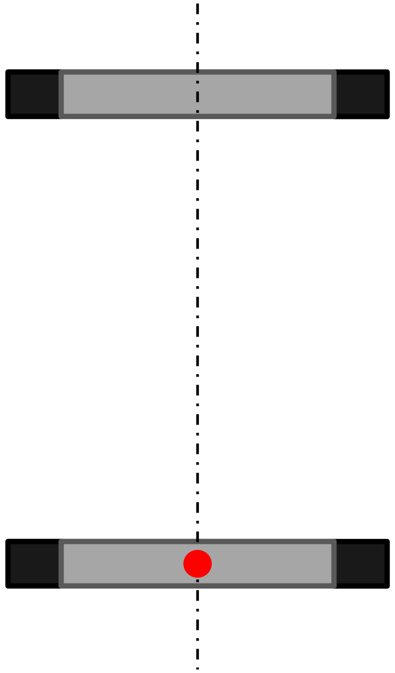
Gravity

- ALPHA traps antiatoms between mirror magnets.
- We can let that antiatoms escape by slowly lowering the field.
- B_{mir}=0.7T.



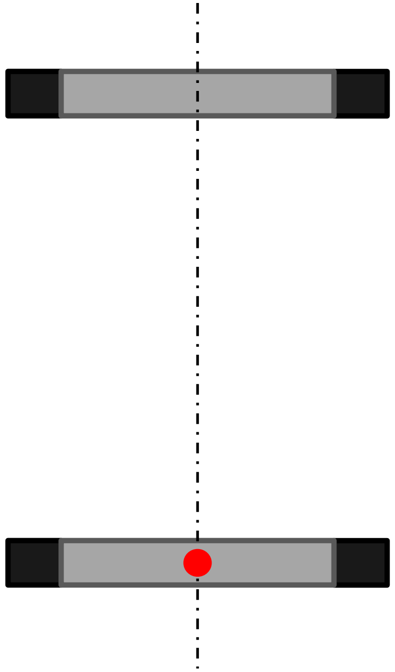
Gravity

- ALPHA traps antiatoms between mirror magnets.
- We can let that antiatoms escape by slowly lowering the field.
- B_{mir}=0.6T.



Gravity

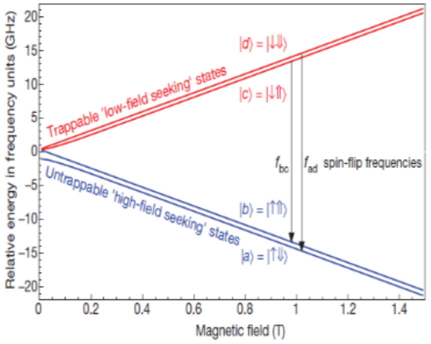
- ALPHA traps antiatoms between mirror magnets.
- We can let that antiatoms escape by slowly lowering the field.
- B_{mir}=0.59T.
- Because the antiatoms are barely escaping over the magnetic wells, the top and bottom well heights are affected by the gravitational potential energy differential.
  - "Normal" gravity would cause the antiatoms to escape downwards.
- By determining if the antiatoms fall out the top or bottom of the trap, we can measure the sign of gravity.
  - In 2013, we made a crude measurement using this technique, and determined that the antimatter *g* was constrained by $\pm 100g$.
    - While there are many indirect tests of antimatter gravity, this was the first "Leaning Tower of Pisa" measurement.
  - We are building a new experiment with the sensitivity to measure the sign of *g*.
    - By employing a gradient magnetic field, we can do a balance experiment and hope to measure *g* to $\pm 0.01g$.
    - This will require control to the 0.1G level in a 1T background.

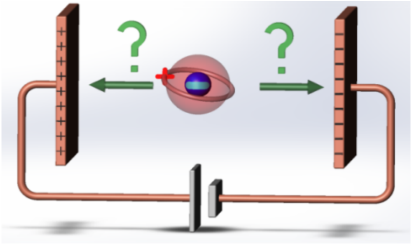


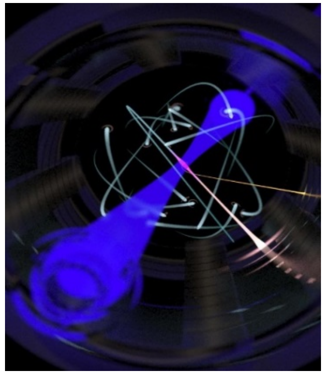
ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm **4**, 1785 (2013).
A I Zhmoginov, A E Charman, R Shalloo, J Fajans, J S Wurtele, Nonlinear dynamics of anti-hydrogen in magnetostatic traps: implications for gravitational measurements, Class. and Quantum Grav., **30** 205014 (2013).

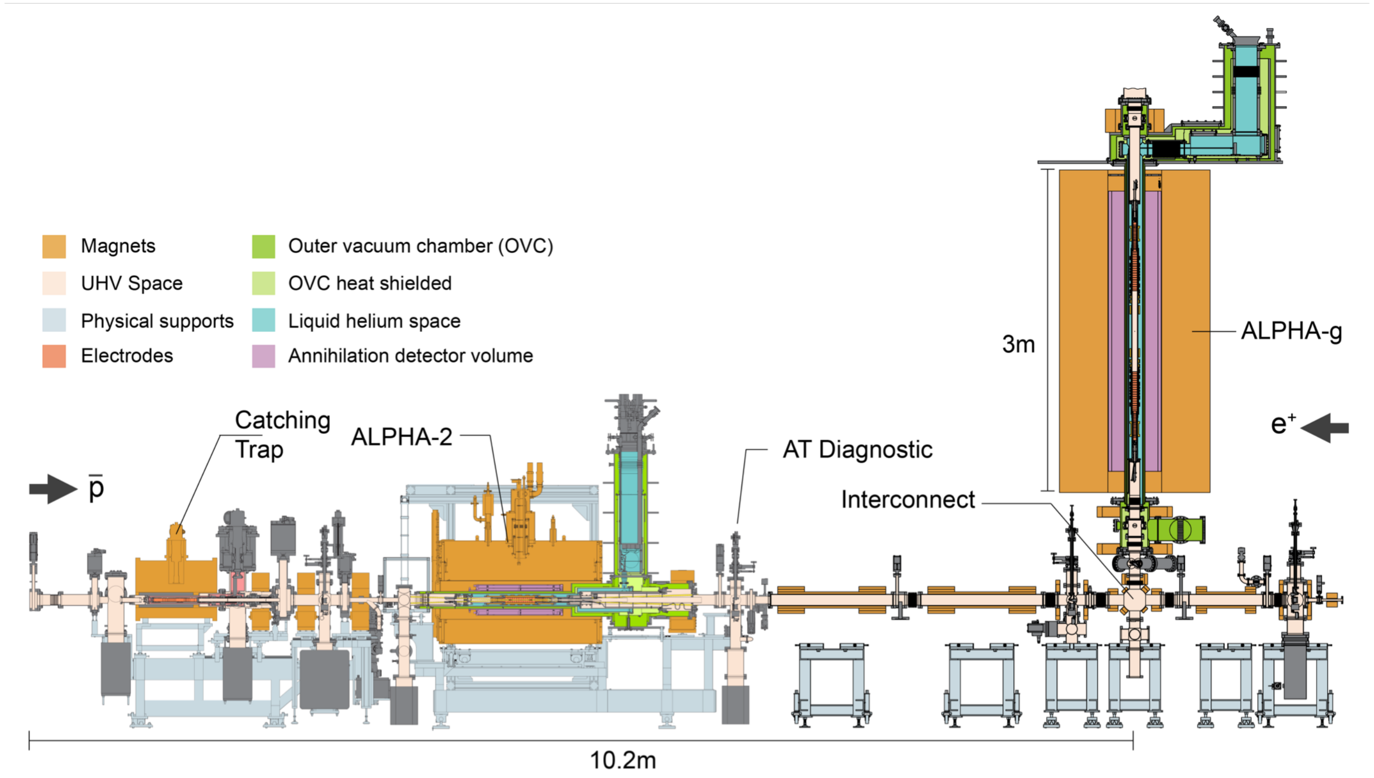
Conclusions

- Based on advances in plasma physics, ALPHA can routinely trap ~1000 antiatoms/day.
  - We have made measurements of the microwave spectrum of antihydrogen...
  - Very crudely, the antimatter *g* ($\pm 100g$). Next 5 years hope for 1% measurement
  - The charge of antihydrogen.
  - The 1S-2S spectrum of antihydrogen.
  - The hyperfine spectrum of antihydrogen.
  - None of the precision antimatter CPT test have detected any CPT symmetry violations

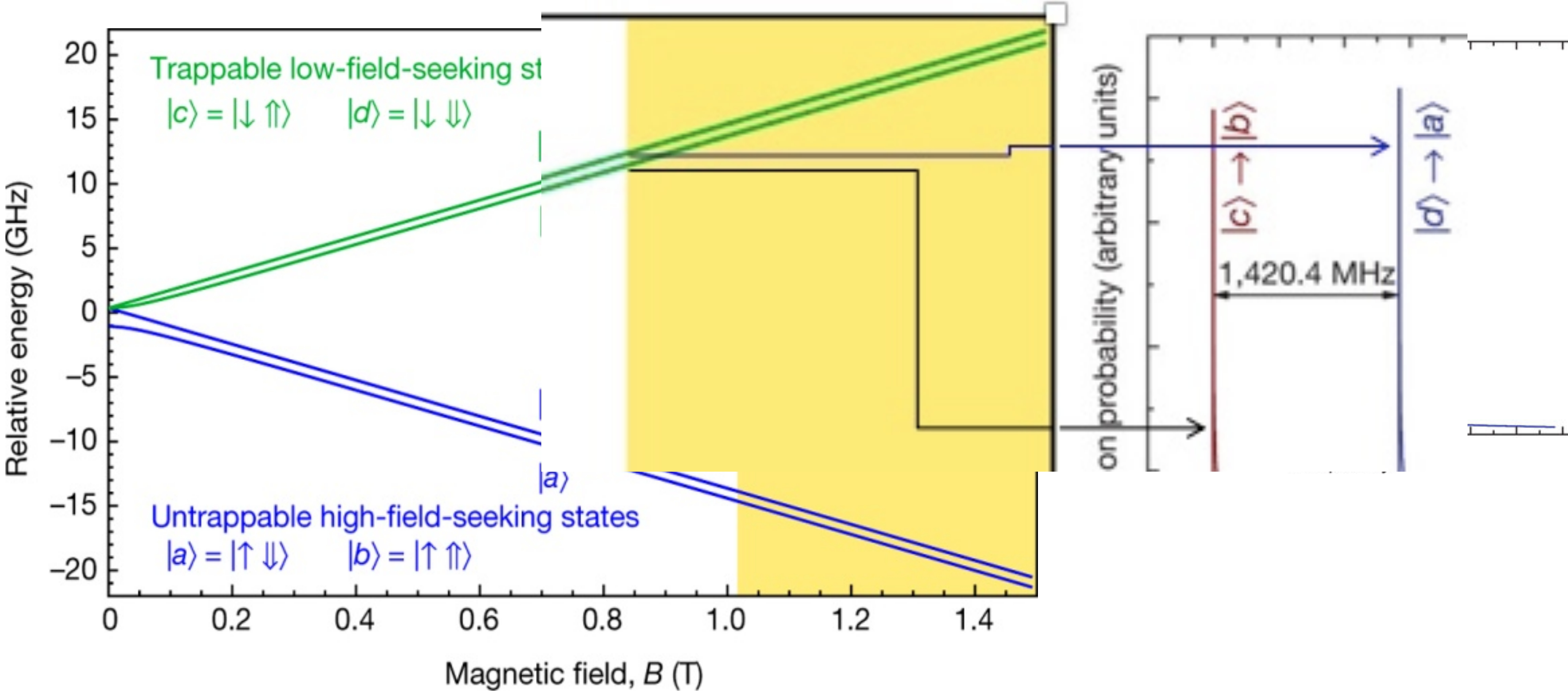








Ground-state hyperfine energy levels

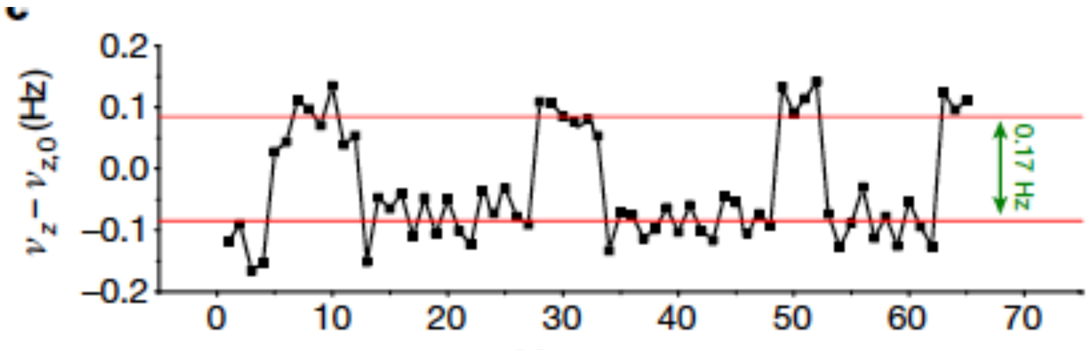


M Ahmadi *et al.* *Nature* **548,** 66–69 (2017) doi:10.1038/nature23446

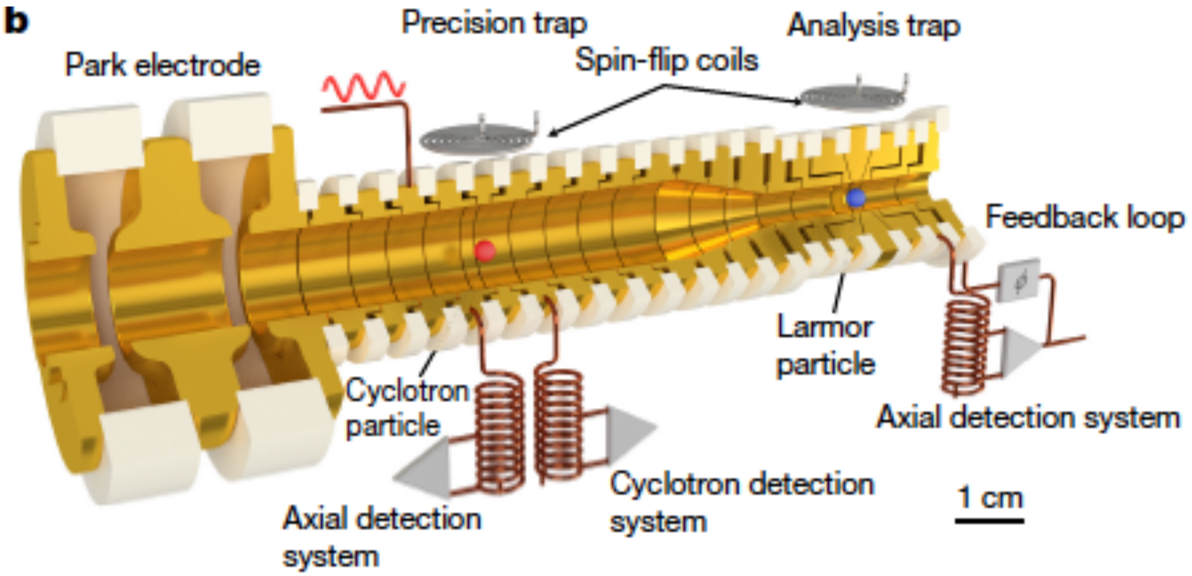
BASE CPT Measurements

$\overline{K}_0/K_0$ $\Delta m/m<10^{-18}$

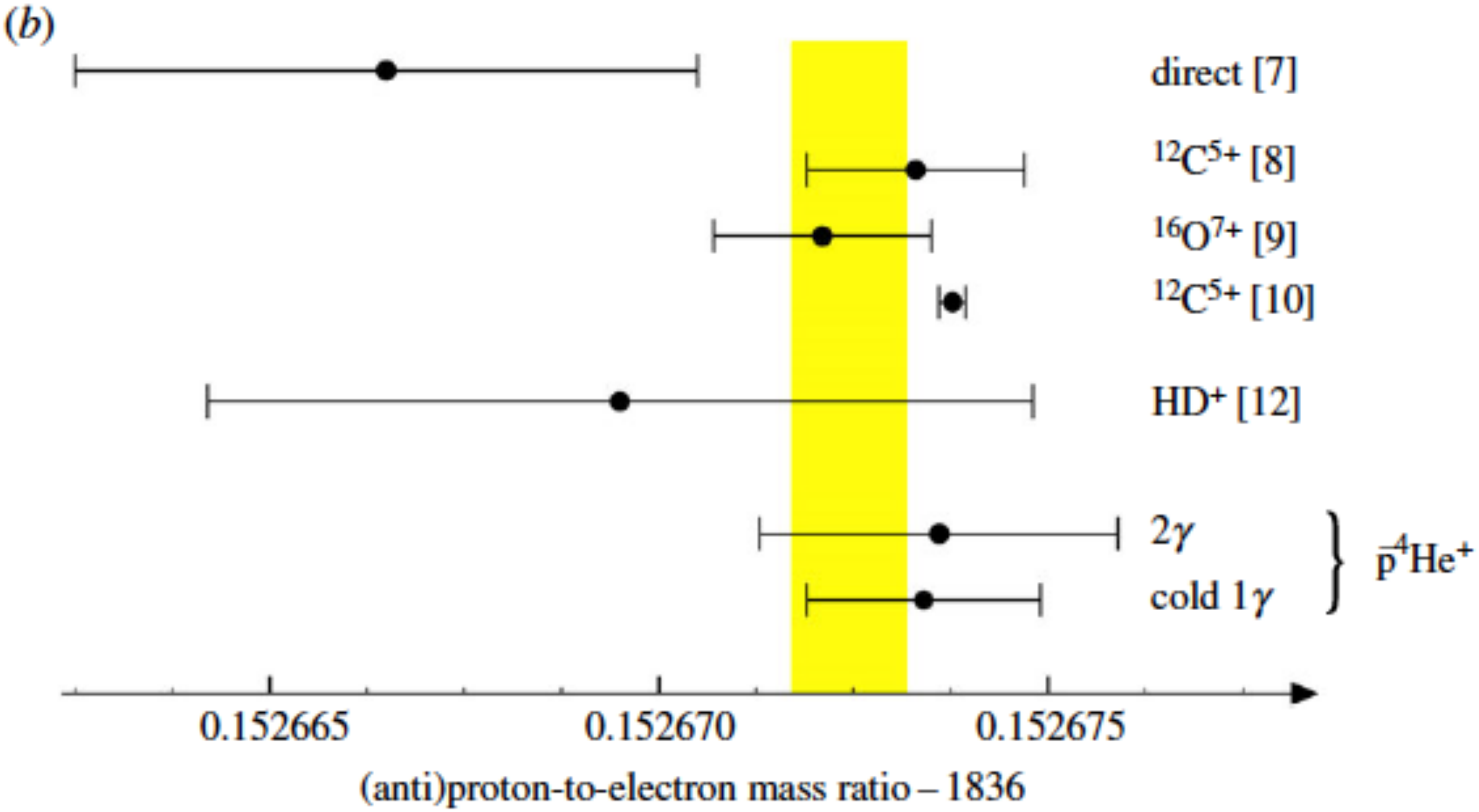
$\frac{g_{\mathrm{positron}}}{g_{\mathrm{electron}}}$ $<4\times10^{-12}$



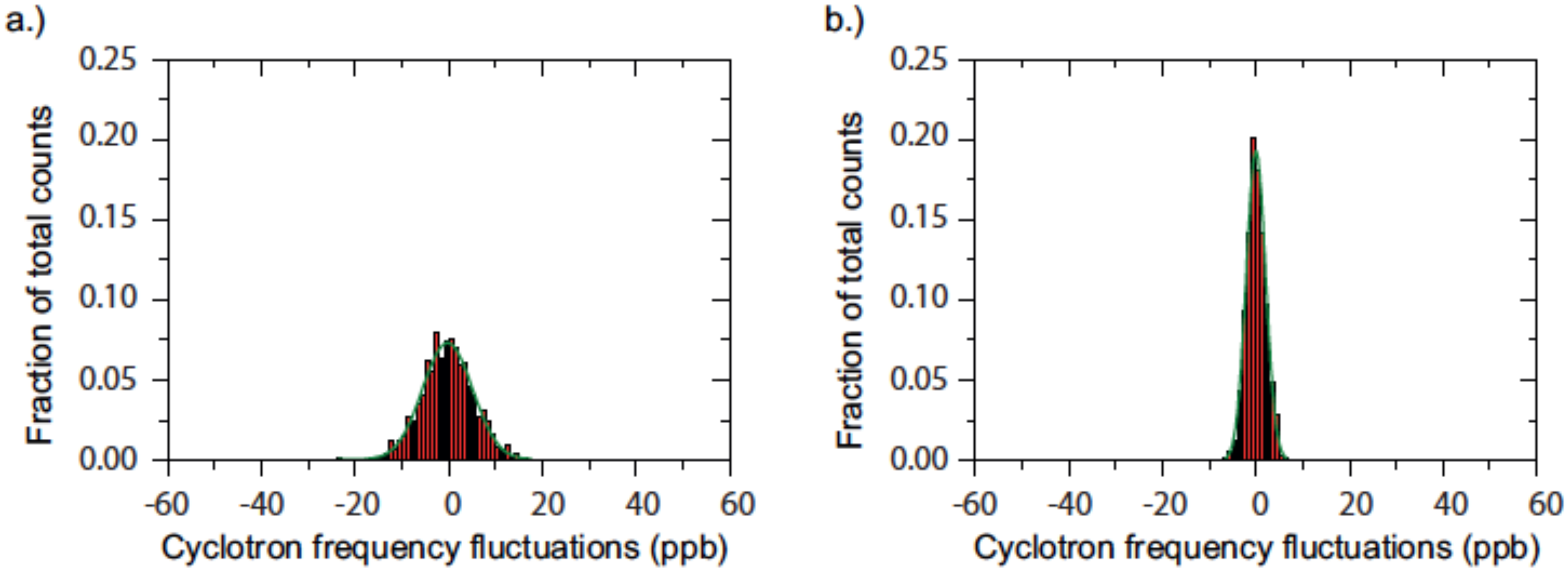
$$(\mathrm{CPT})_\mu = \left|\frac{(g/2)_{\bar{\mathrm{p}}}}{(g/2)_{\mathrm{p}}}\right| = 0.999\,999\,70\,(82)$$



ASACUSA

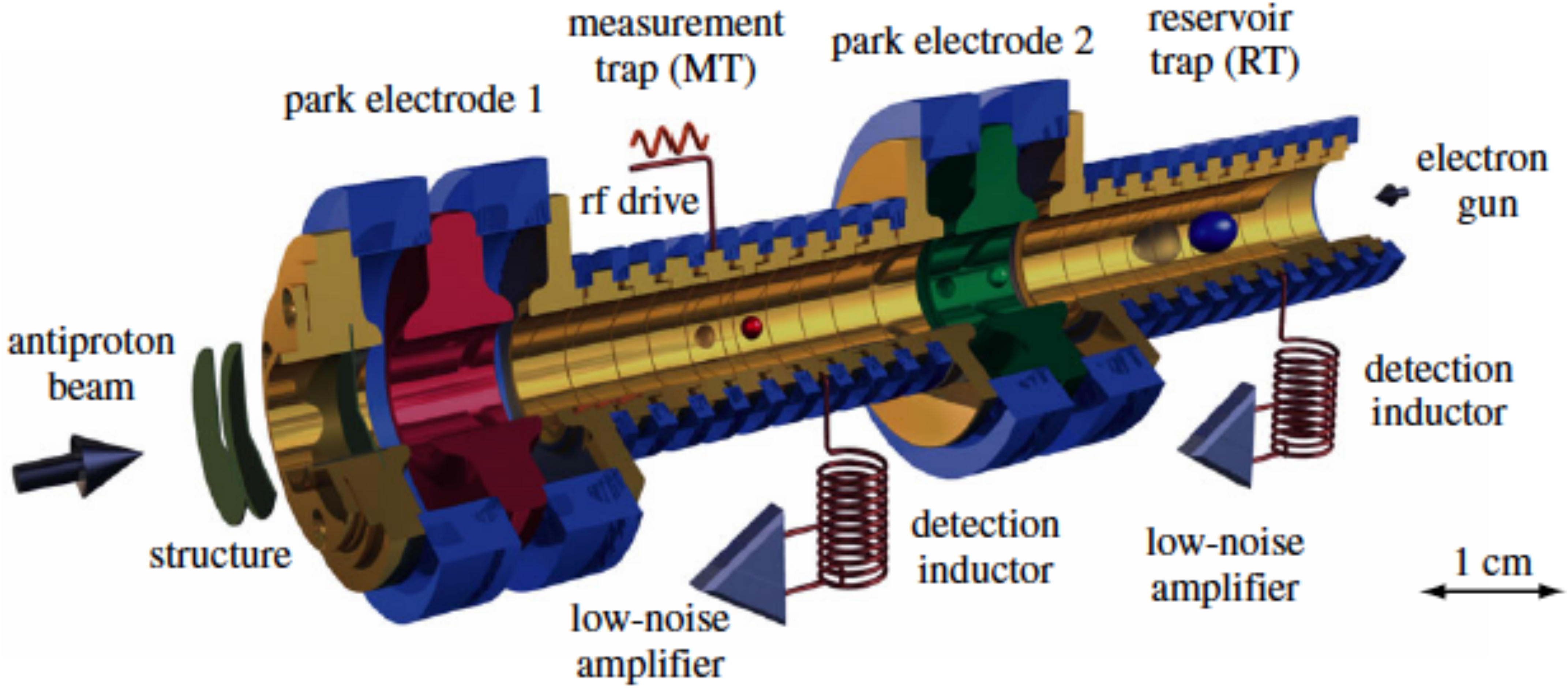

(b)
direct [7]
12C5+ [8]
16O7+ [9]
12C5+ [10]
HD+ [12]
2γ
cold 1γ
p̄4He+
0.152665
0.152670
0.152675
(anti)proton-to-electron mass ratio – 1836

BASE Cyclotron frequency measurements

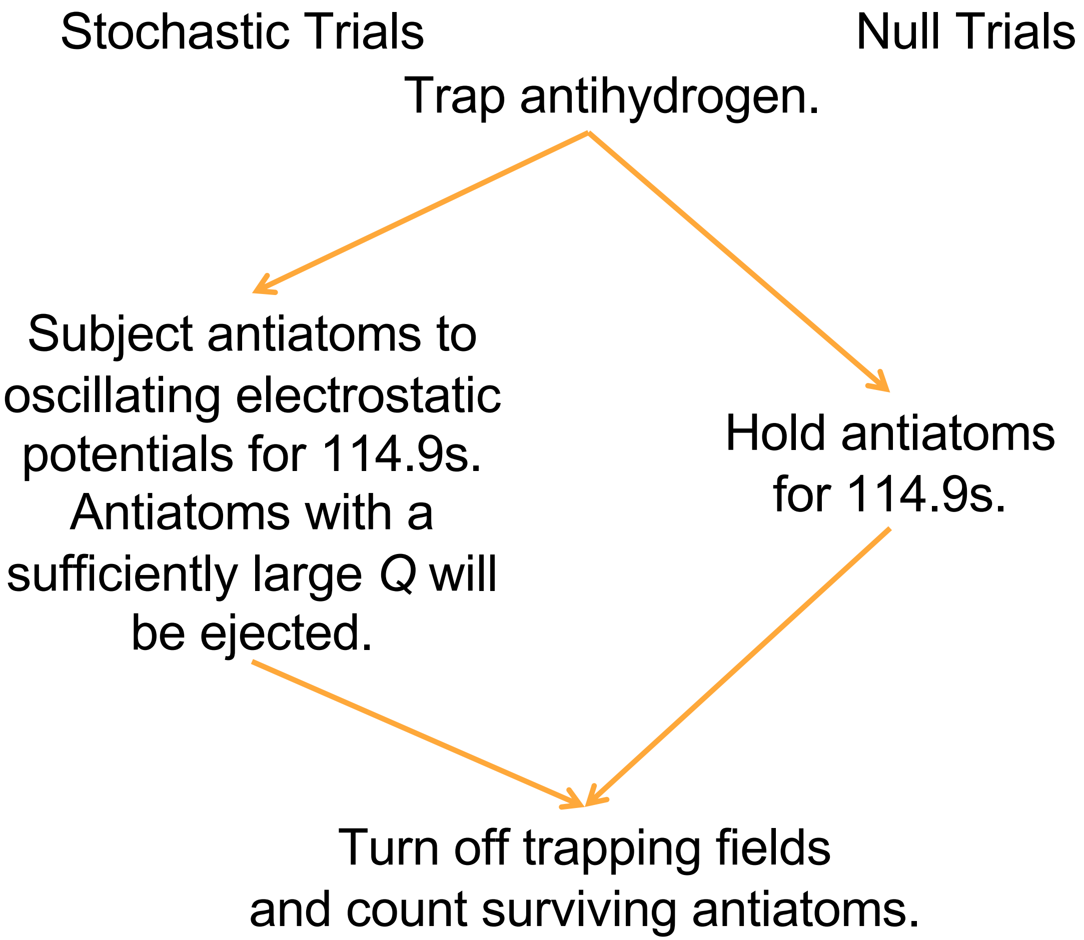


JPS Conf. Proc. 18, 011019 (2017

BASE Schematic



Stochastic Acceleration Experimental Cycle



Stochastic Trials

Null Trials

Trap antihydrogen.

Subject antiatoms to oscillating electrostatic potentials for 114.9s. Antiatoms with a sufficiently large *Q* will be ejected.

Hold antiatoms for 114.9s.

Turn off trapping fields and count surviving antiatoms.

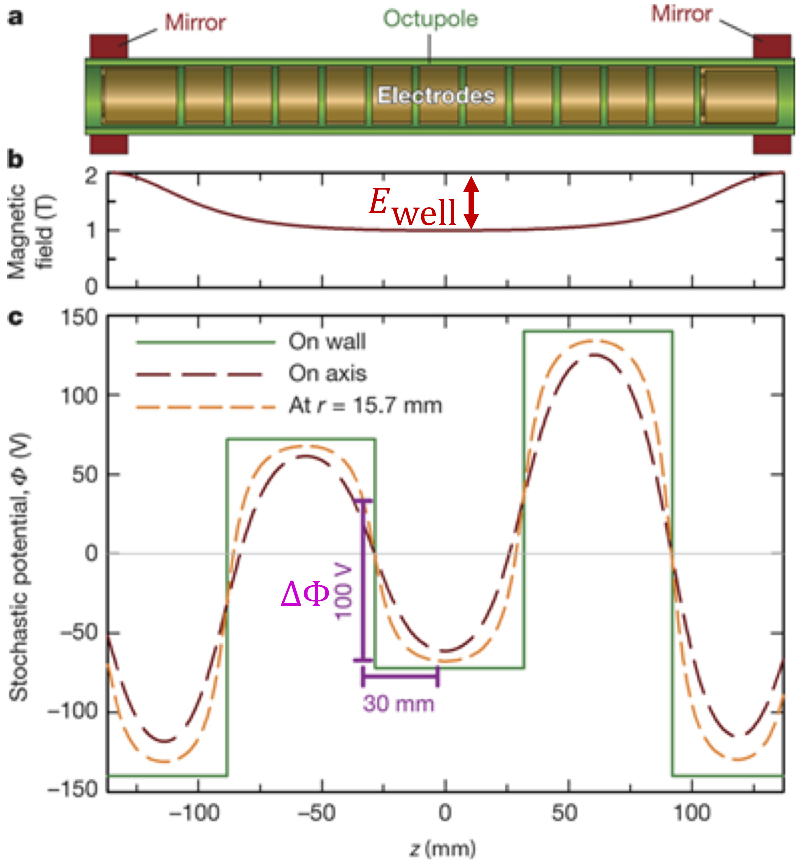
M. Baquero-Ruiz and A. E. Charman and J. Fajans and A. Little and A. Povilus and F. Robicheaux and J.S. Wurtele and A. I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, (2014).
ALPHA, An improved limit on the charge of antihydrogen from stochastic acceleration, Nature, **529**, 373 (2016).

Stochastic Acceleration Scaling

- Stochastic acceleration follows standard random walk scaling.
    - An antiatom with charge Qe will escape a trap if:

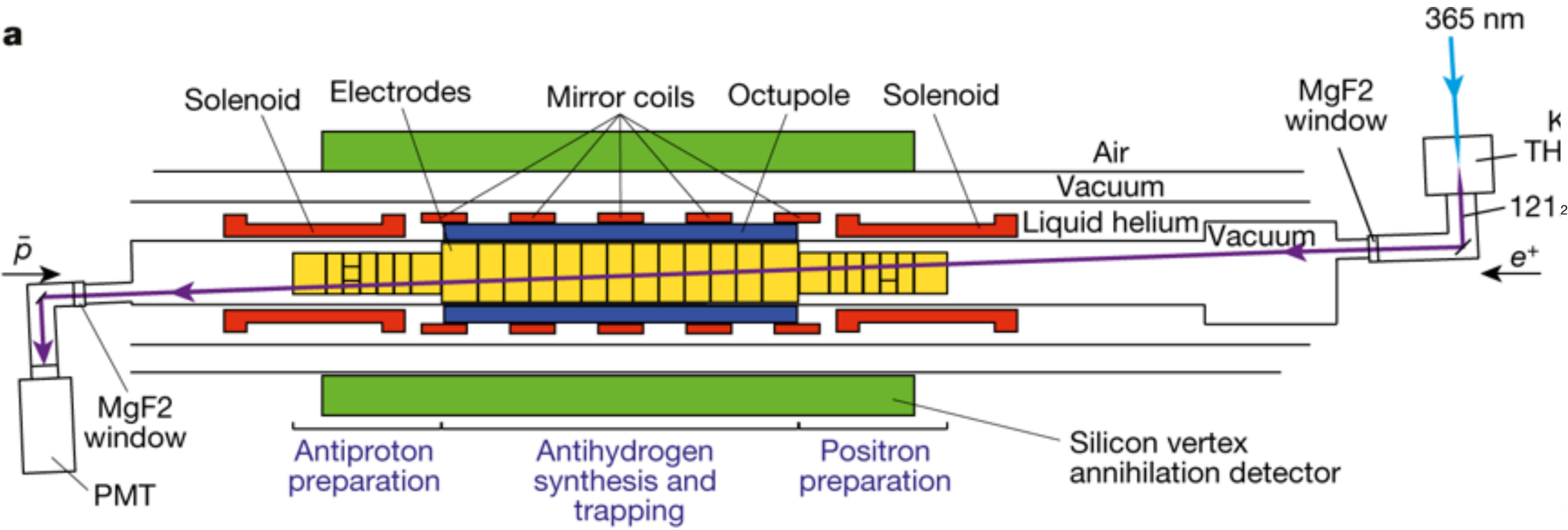
$$Q > \frac{E_{\mathrm{well}}}{e\Delta\Phi\sqrt{N}}$$

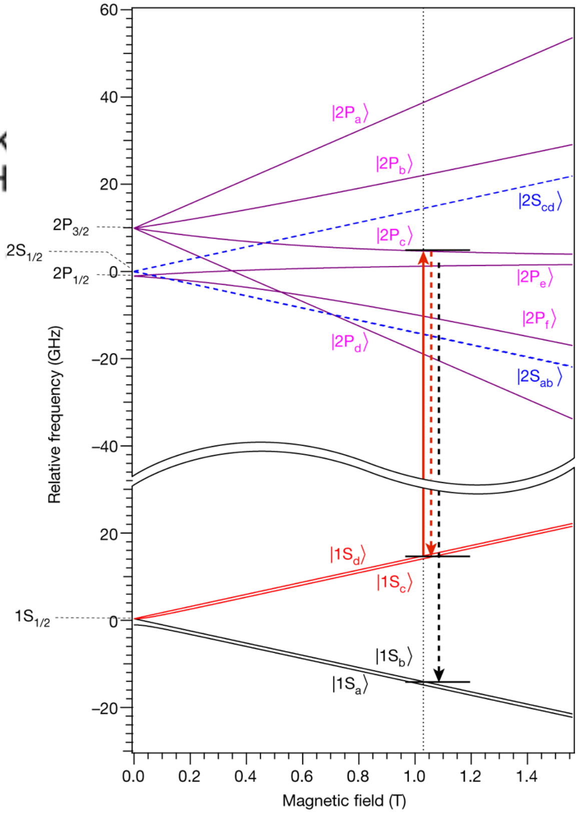
where N is the number of potential oscillations.



M. Baquero-Ruiz and A. E. Charman and J. Fajans and A. Little and A. Povilus and F. Robicheaux and J.S. Wurtele and A. I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, (2014).
ALPHA, An improved limit on the charge of antihydrogen from stochastic acceleration, Nature, **529**, 373 (2016).

Lyman-α





ALPHA, Nature 9/2018

Plasma Manipulations

- Preparing the antiproton and positron plasmas for antihydrogen trapping takes five to ten minutes.
- Hundreds of individually planned “gross” potential changes are required.
- These gross changes result in tens of millions of potential change commands.
- The currents of nine high-field magnets are manipulated.

atm Editor: Pbars\20141125\ARtrapping1.02_PbarAndPositronEVC.atm

AR injection, EVC everything,
trap and QWP right
ALPHA1 style, baby

P - use pbars
U - EVC Pbars 15.3V
A - AR injection
C - cold dump pre-mixing
E: EVC positrons

Pbars\20141125\ARtrapping1.02_PbarAndPositronEVC.atm

Ramp Steps 42558

Inst 7 m 0
State 9012 6.451034350
Macro Level 0
Repeat 1
Utilities\Magnets\Oct-MirA-MirE-On-Wait.atm
Ramp up all magnets
Macro Suppressed by Conditional Flags

Inst 8 m 2.000000m
State 9012 6.451034350
Macro Level 0
Repeat 1
Utilities\MidasTriggers\StartInjection.atm

Inst 9 10.000000m
State 9013 6.453034350
Macro Level 0
Ramp Steps 1000
morph to 2011 mixing well

Inst 10 m 100.000000m
State 10013 6.463034350
Macro Level 0
Repeat 1
Positrons\20141108\raise to pre-EVC.atm
Ramp Steps 1000

Inst 11 m 500.010000m
State 11013 6.563034350
Macro Level 0
Repeat 1
Positrons\20141109\PositronEVC_500ms_100_percent.atm
Ramp Steps 20000

Copy State Begin 0
Copy State End 1
Total Time 22.6495
Total # Instructions 36
Total # States 42615
Total # State Lines 91
Total Analog Triggers 42558
Link 100

The ALPHA Sequencer