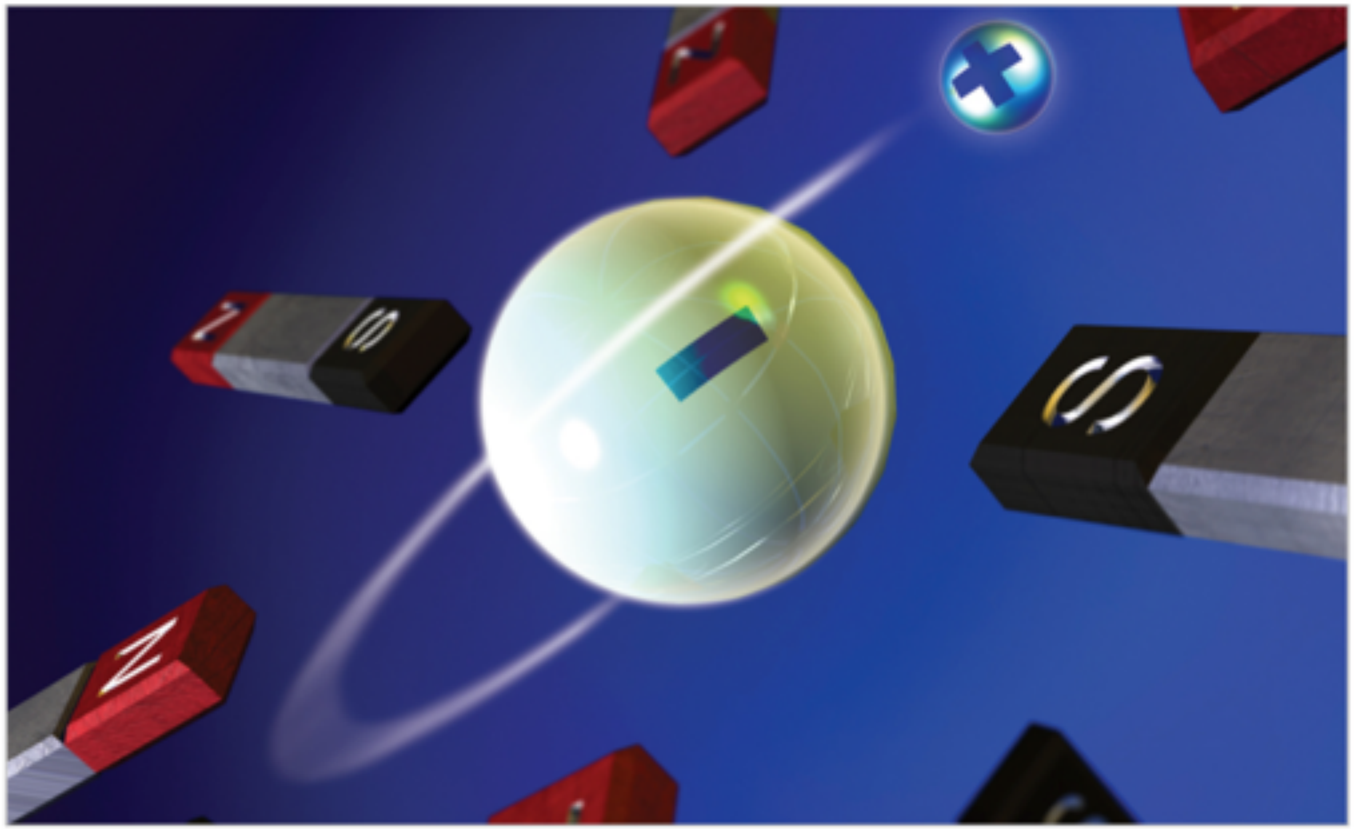
Precision tests with trapped antimatter:
A glimpse of the 1S - 2S transition in antihydrogen



Dr. Will Bertsche

The University of Manchester
The Cockcroft Institute

The University of Manchester

The Cockcroft Institute
of Accelerator Science and Technology

ALPHA Experiment @ CERN

- Precision measurements on antimatter using **Antihydrogen** atoms

What is Antimatter?

- Particles have twins with same mass, opposite charge

	Electron	Proton
Matter:	− e^-	+ P

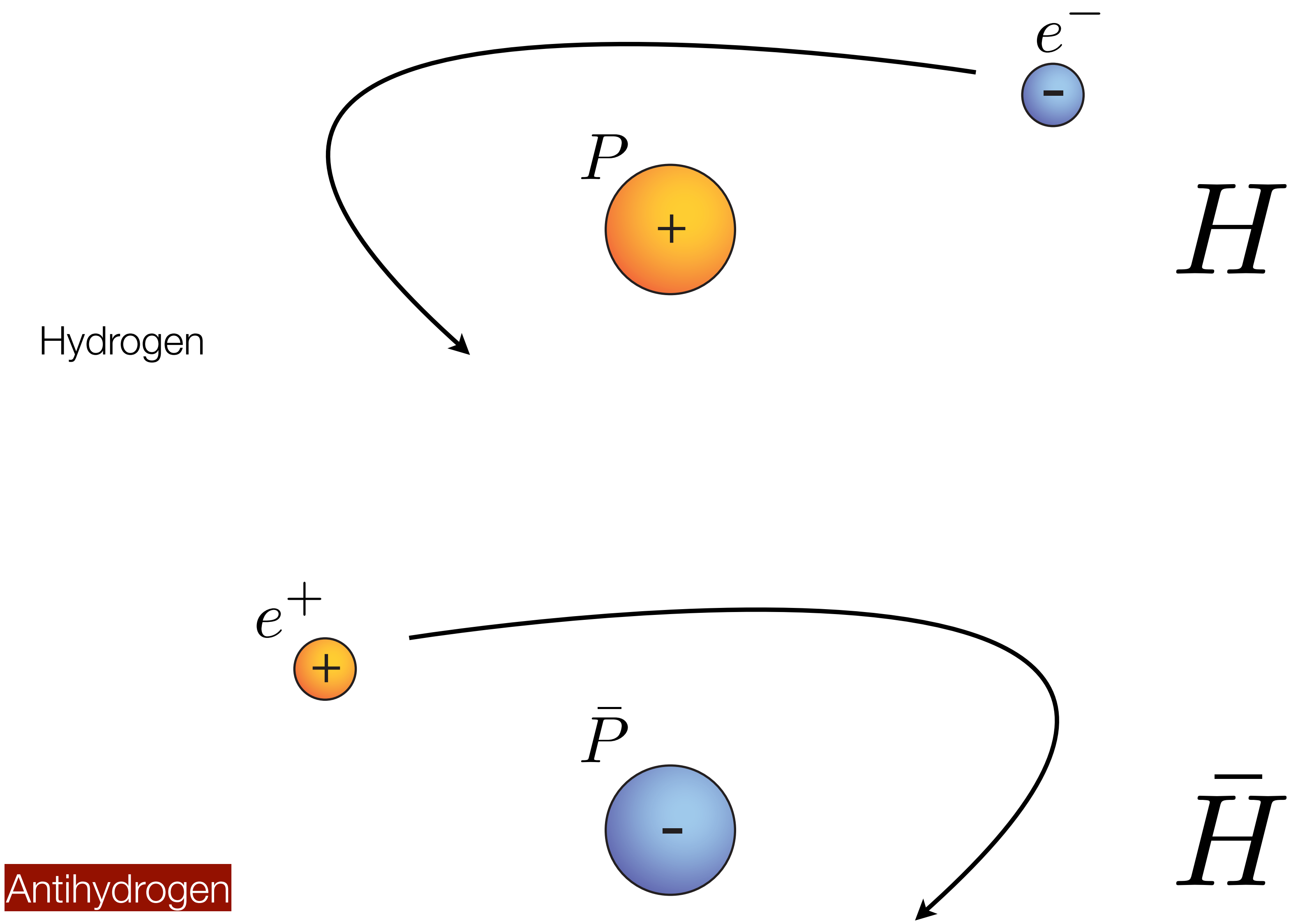
	Positron	Antiproton
Antimatter:	+ e^+	− $\bar{P}$

What is Antimatter?

- Atoms and antimatter atoms?

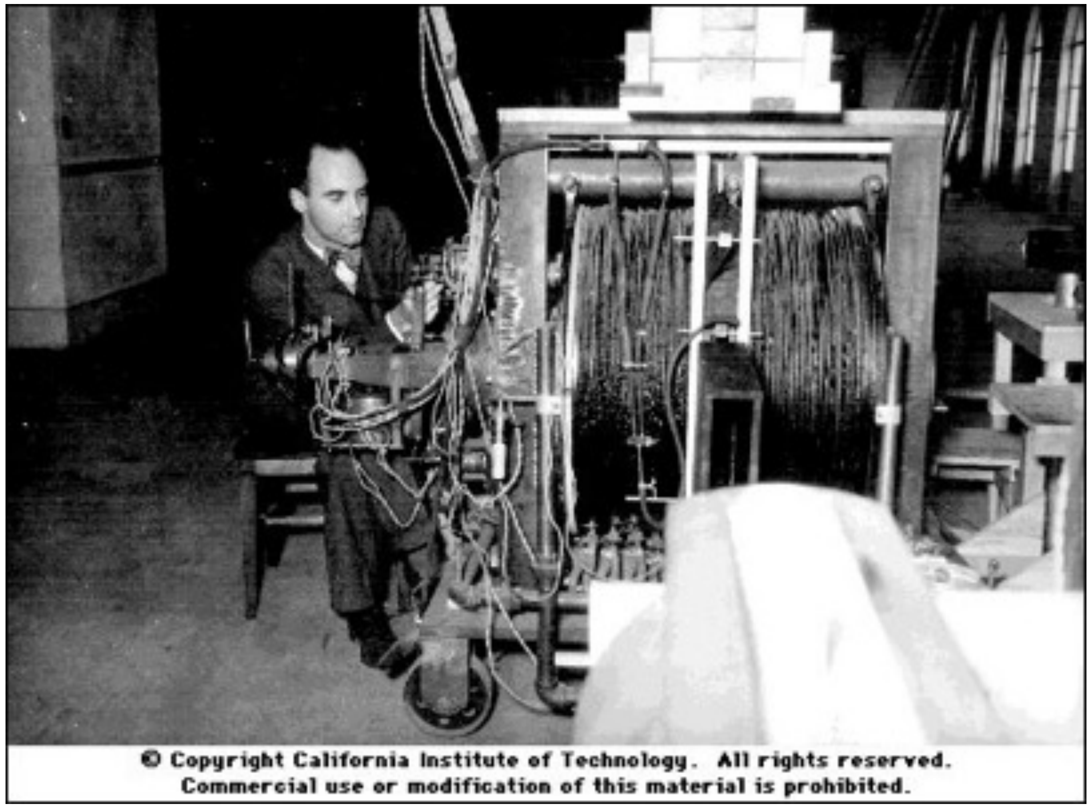
Matter:

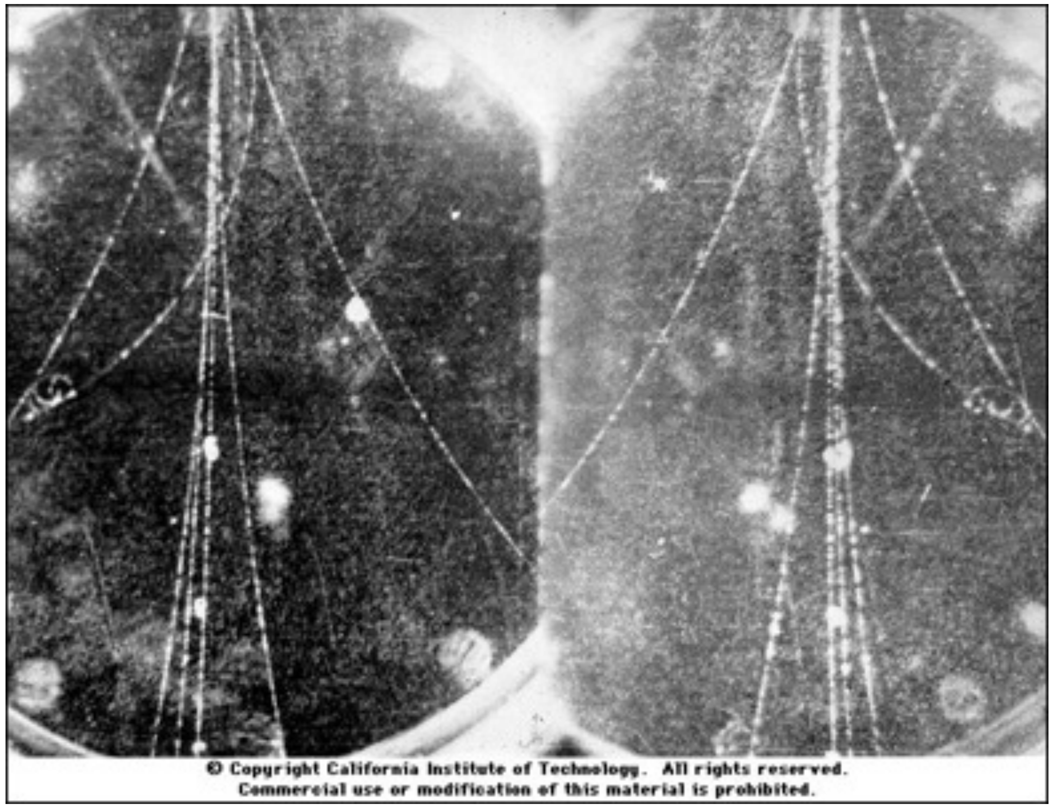
Antimatter:



First Observation: Positrons

- 1932: Carl Anderson follows up theory quickly:
  Positrons in Cosmic Rays





First Observation: Antiprotons

- 1955: Owen Chamberlain and Emilio Segrè Antiprotons from 1 GeV Protons on Cu Target

Bevatron,
Lawrence Berkeley National Lab

Chamberlain

Segrè

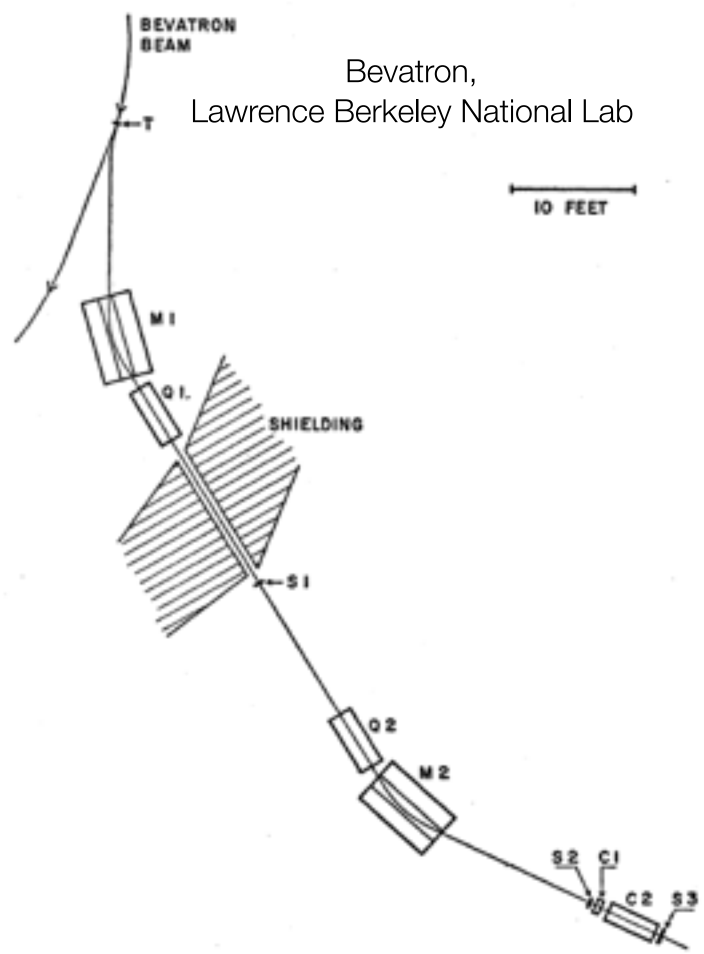
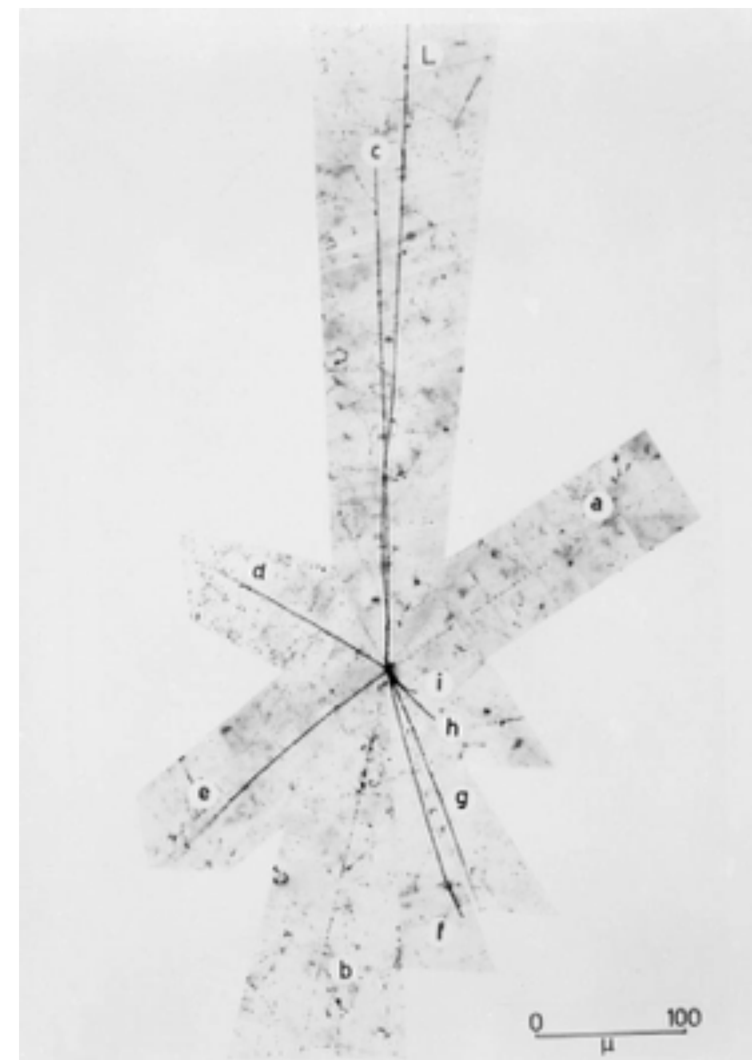
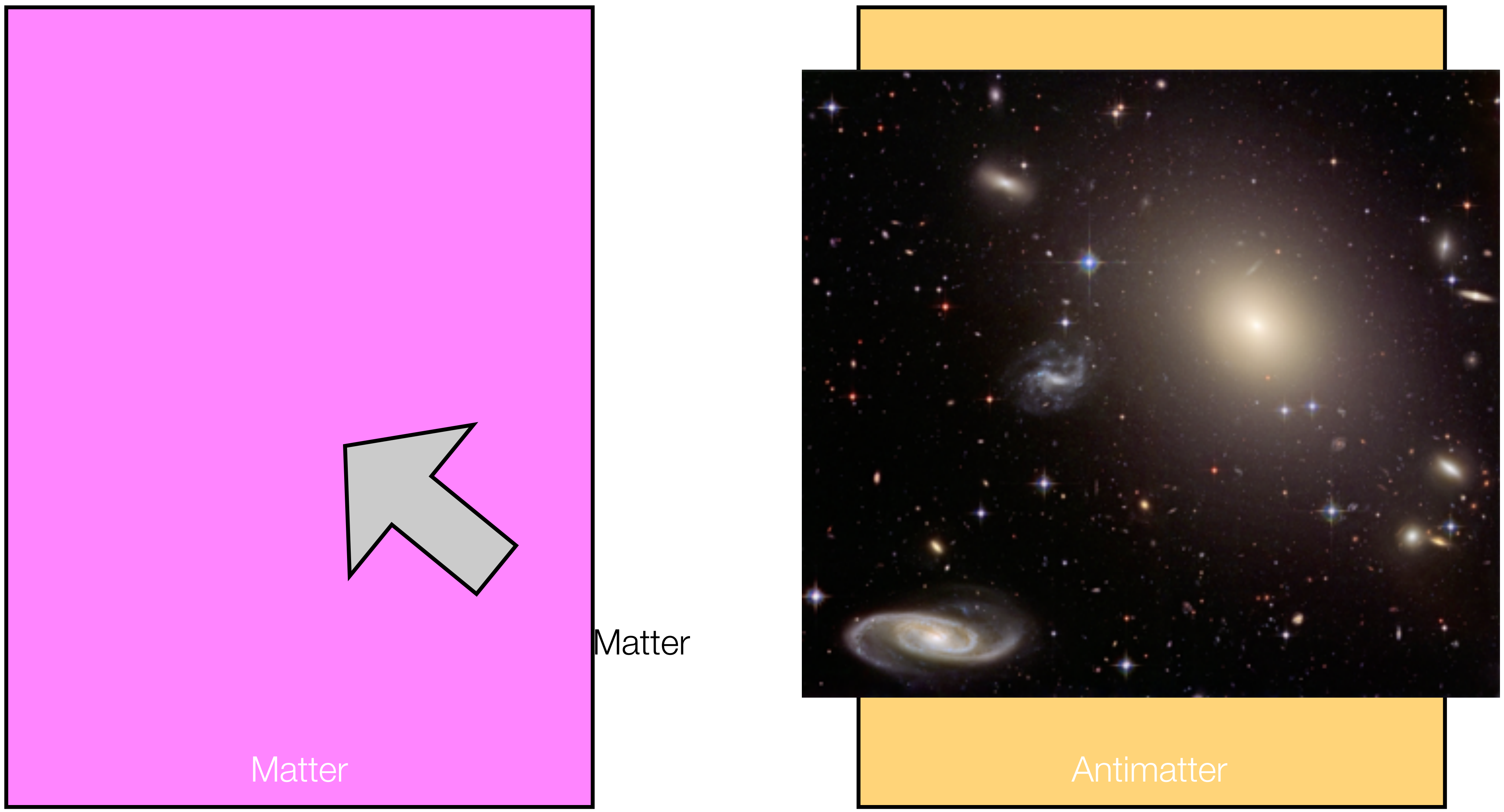


FIG. 1. Diagram of experimental arrangement. For details see Table I.



What's the matter with Antimatter?

- Should be equal amounts produced at Big Bang...



Possible Explanations: Fundamental Flaw?

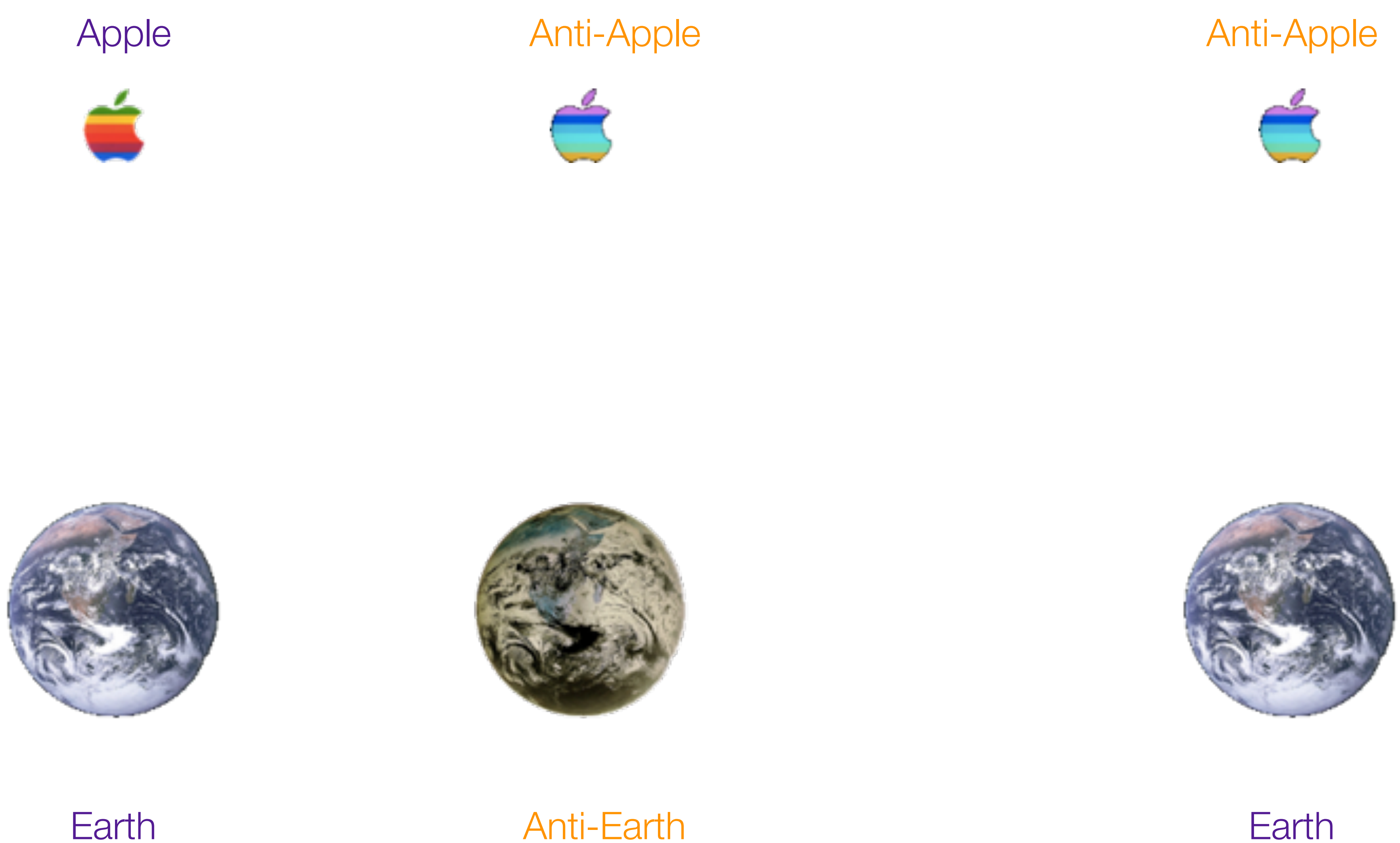
- C. P. T. Symmetry: Fundamental Feature of Universe

1. Take any experiment
2. Swap Charge, Parity, and run Time backwards
   "CPT Transformation"
3. Outcome should be the same

- CPT violation has never been observed
- It is an assumption in essentially all Physic
- Replacing matter with antimatter: a CPT Transformation
- CPT Test: Compare properties of Matter and Antimatter

Possible Explanations: Gravity?

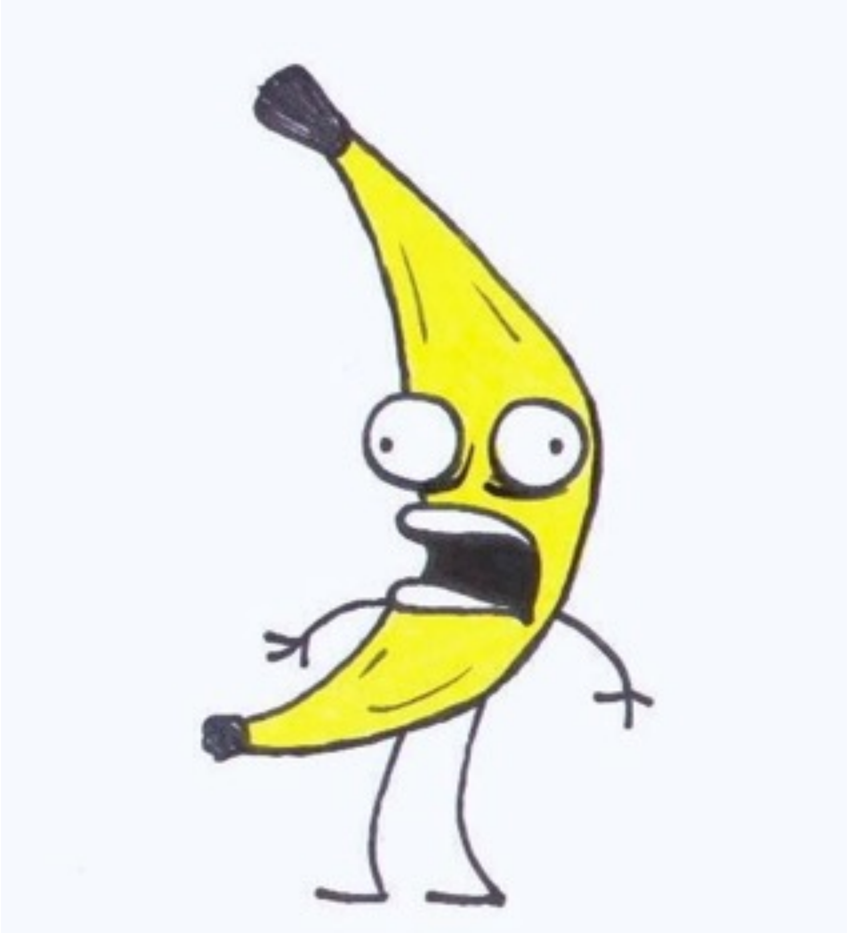
- Gravity?



Where do Positrons come from?

- Easy: Some radioactive isotopes
  - Naturally occurring Potassium-40 (in Bananas: ~ 15 Positrons / sec)
  - 'Manufactured' Sodium-22

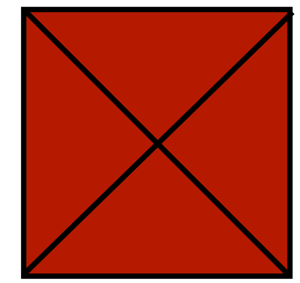
$$^{22}\mathrm{Na} \rightarrow {}^{22}\mathrm{Ne} + e^{+} + \nu_e + \gamma$$



"I am a banana!" Don Hertzfeld

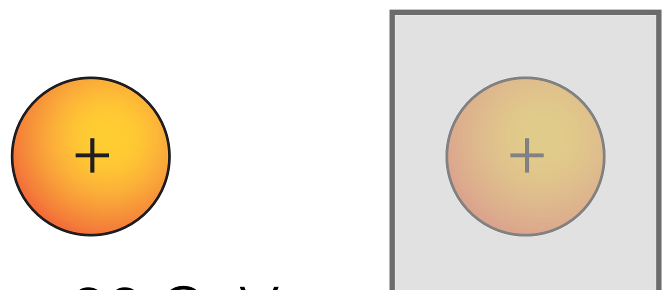
Where do Antiprotons come from?

1. Energetic proton creates Proton/Antiproton pair
2. Charge/Mass selected



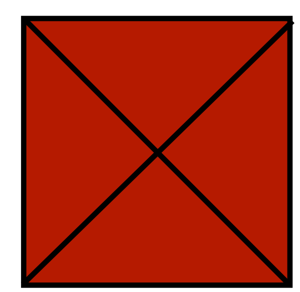
~3 GeV

Cern Proton Synchrotron



~26 GeV

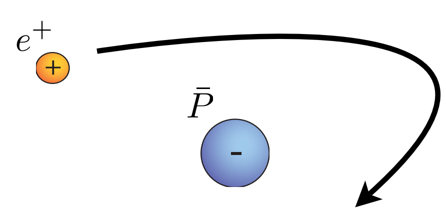
(and other stuff)



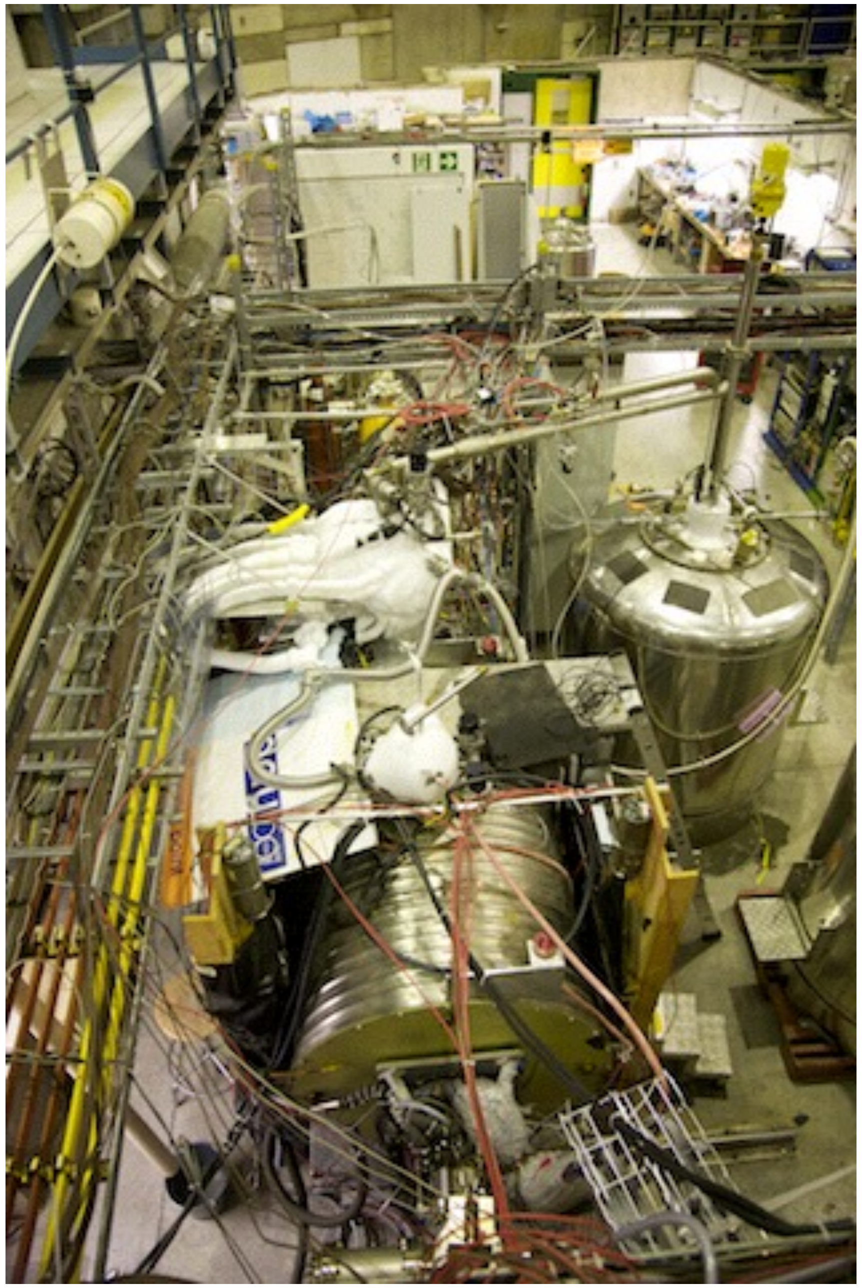
Recipe for Cold Antihydrogen

1. Trap ~10 Thousand antiprotons
2. Trap ~10 Million positrons
3. Chill ingredients to 10’s of Kelvin
4. Mix, while keeping species cold and confined
5. Bam!

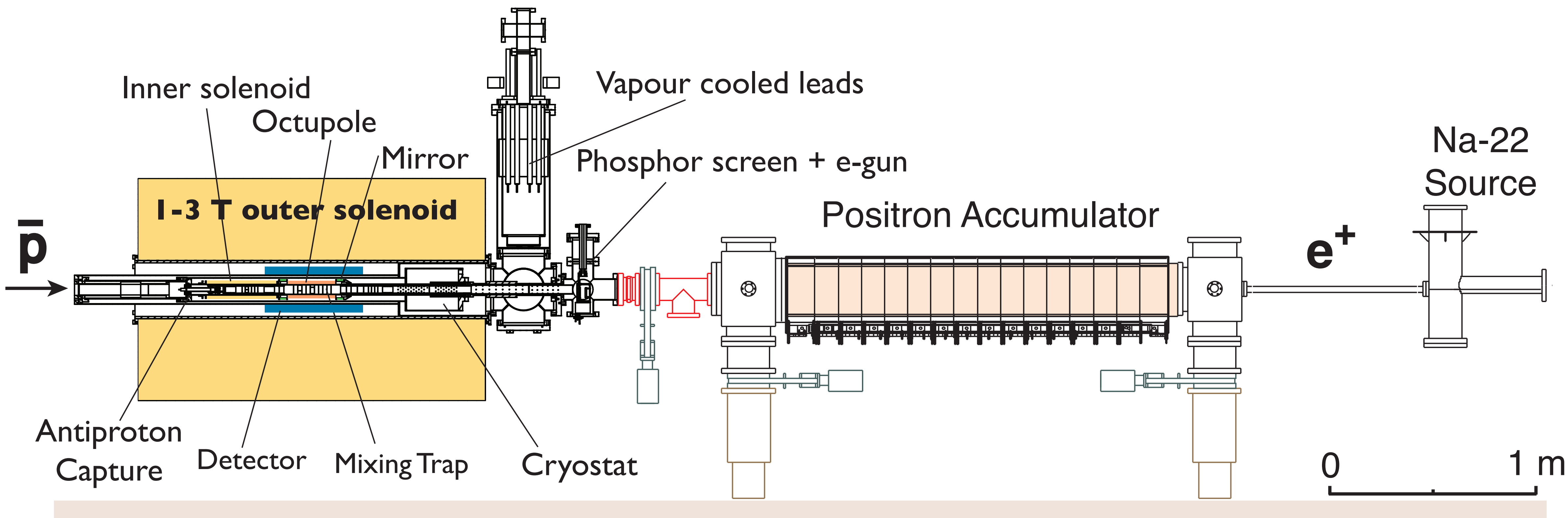
$\bar{H}$!



ALPHA Apparatus



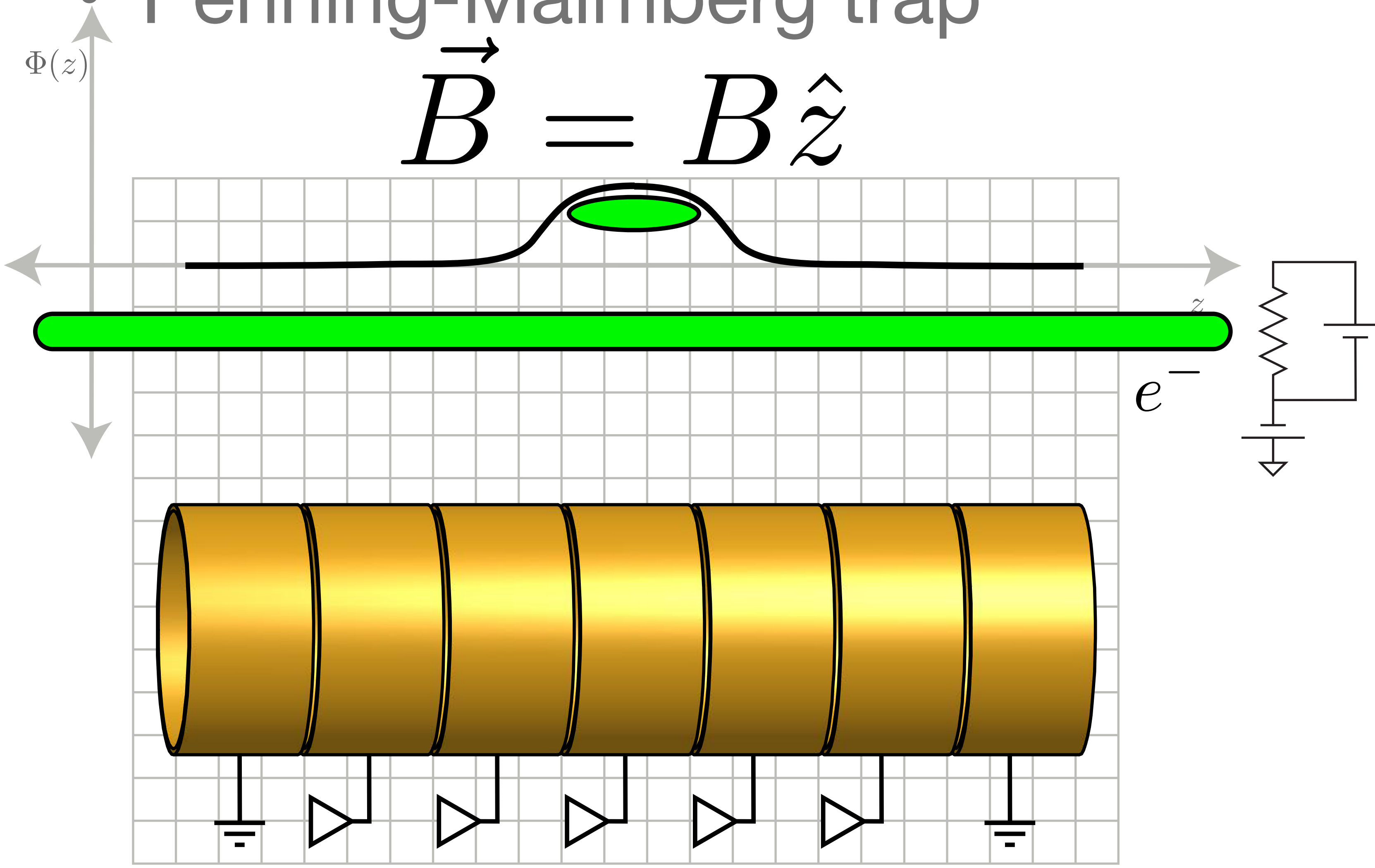
ALPHA Apparatus



Antimatter: Confinement

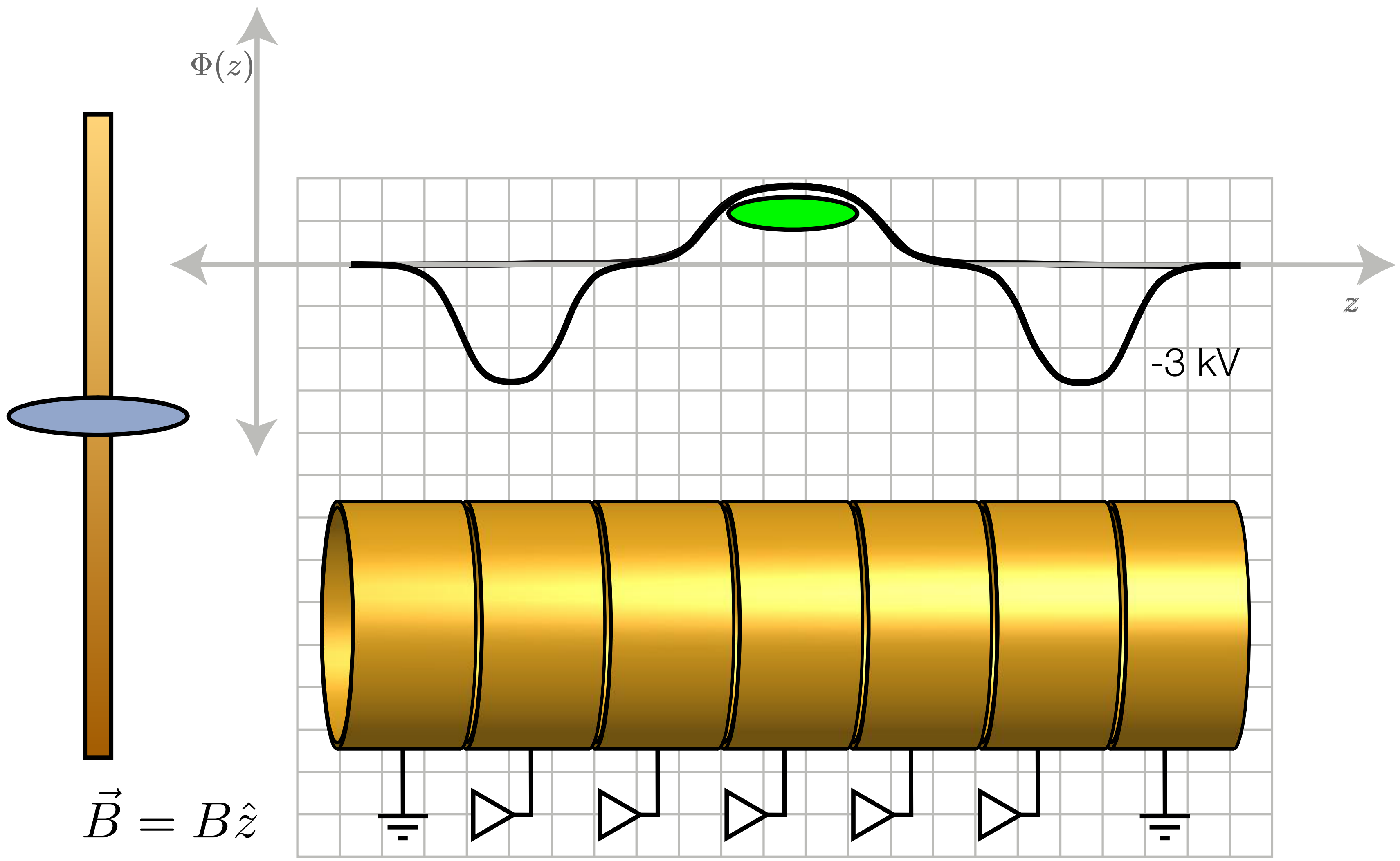
- Non-neutral plasmas: gas of single-charged particles
  - Pure ensembles of electrons, positrons, antiprotons, etc.
- Penning-Malmberg trap

$$\vec{B} = B\hat{z}$$



Capturing Antiprotons

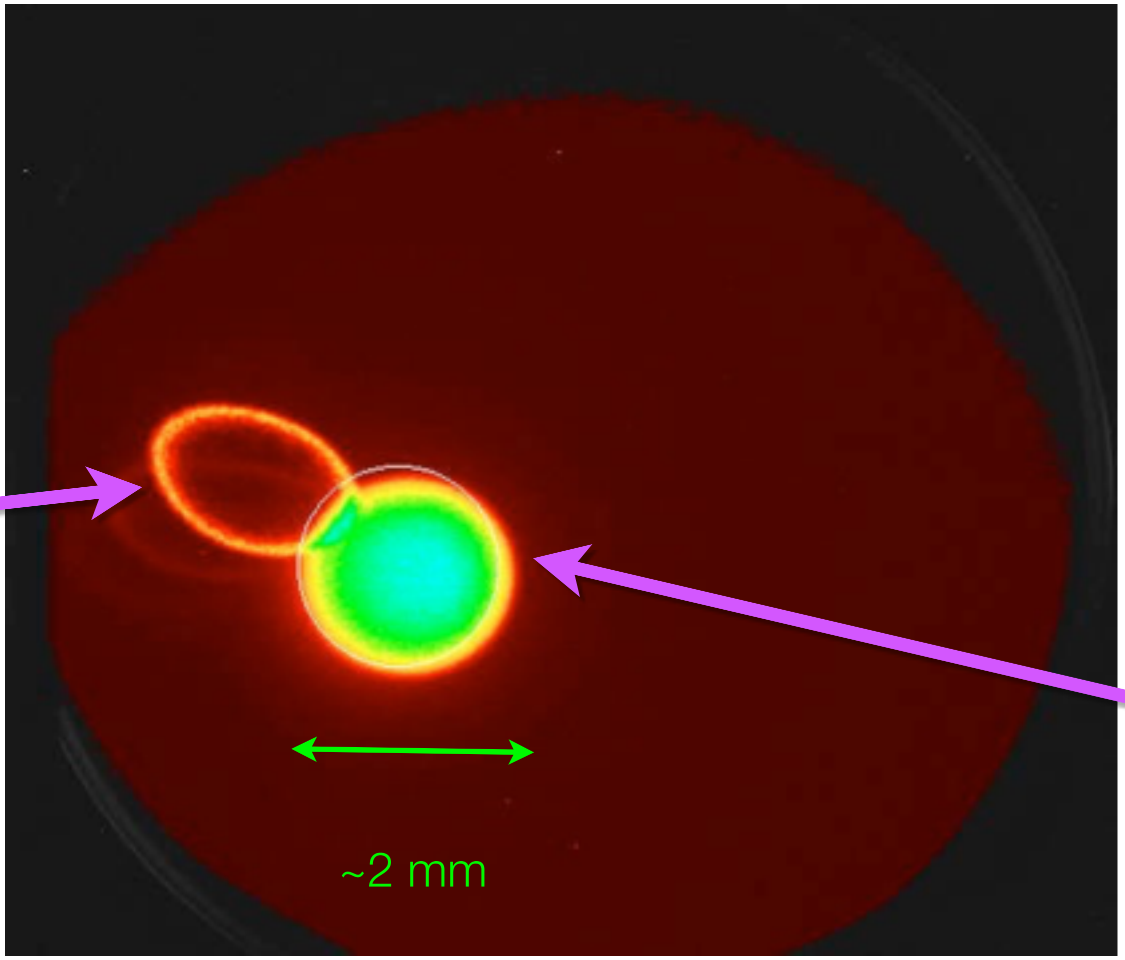
- Degrade antiprotons - 5 Million Volts is still a lot...
- Antiprotons equilibrate with electrons



Antiproton / Electron Plasma

- Image the equilibrium Antiproton / Electron plasma

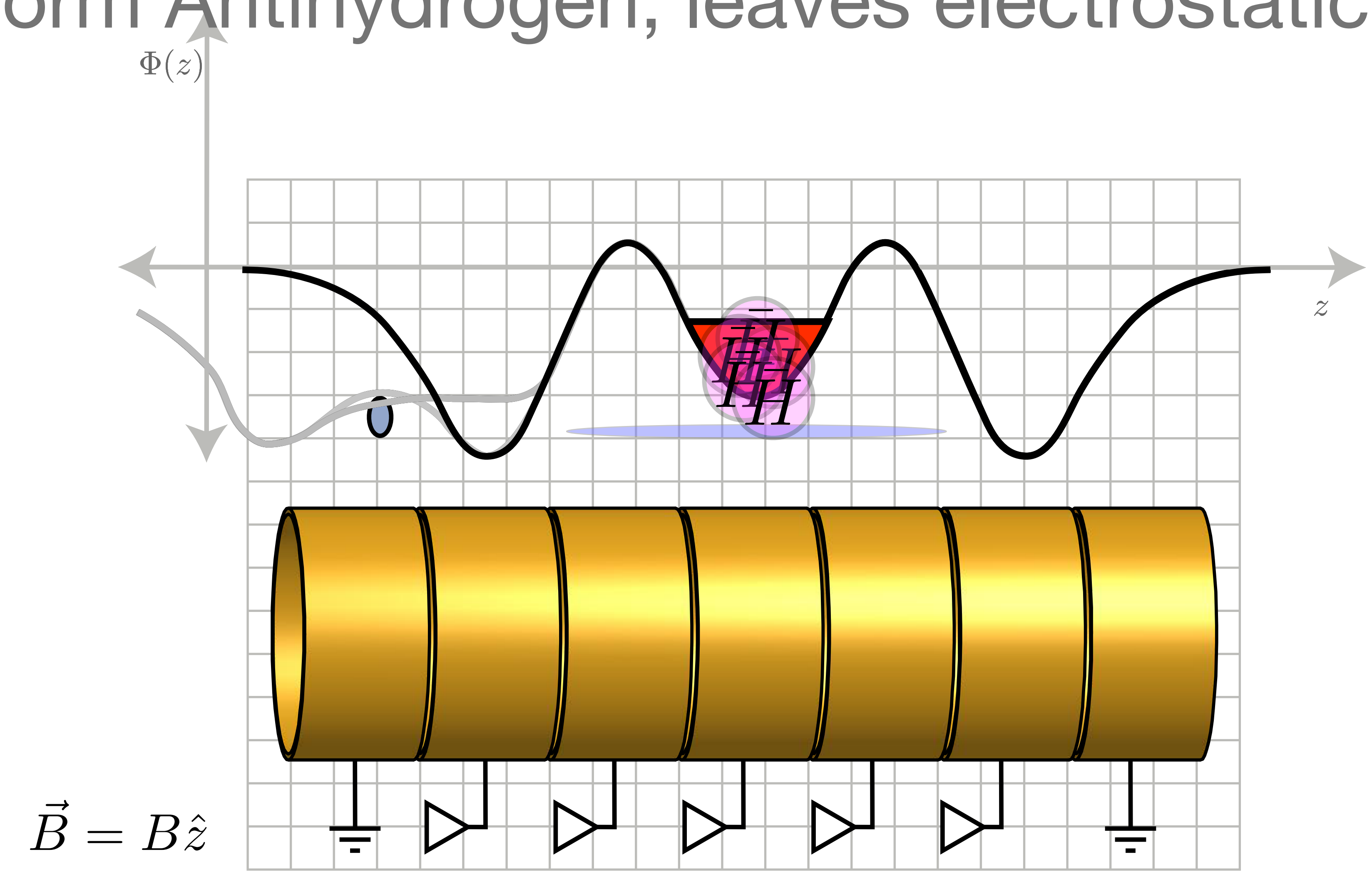
antiprotons



electrons

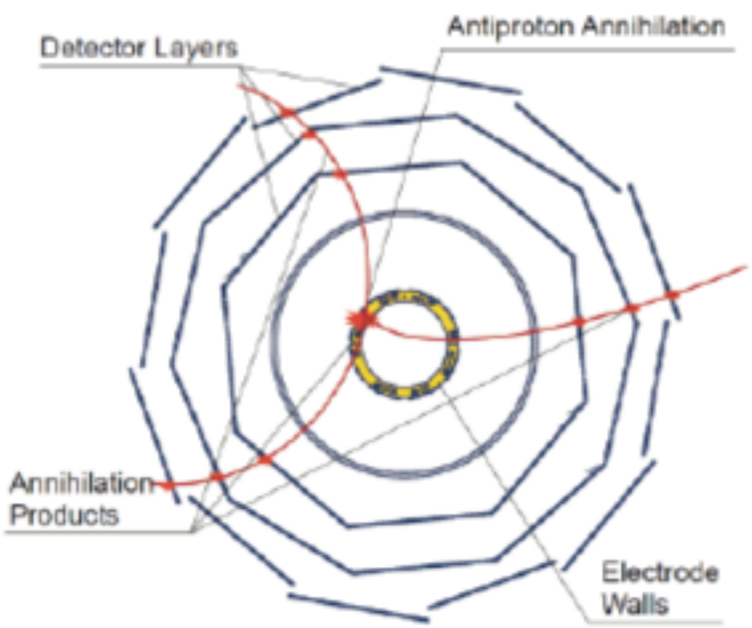
Antihydrogen Formation: Mixing Antiprotons and Positrons

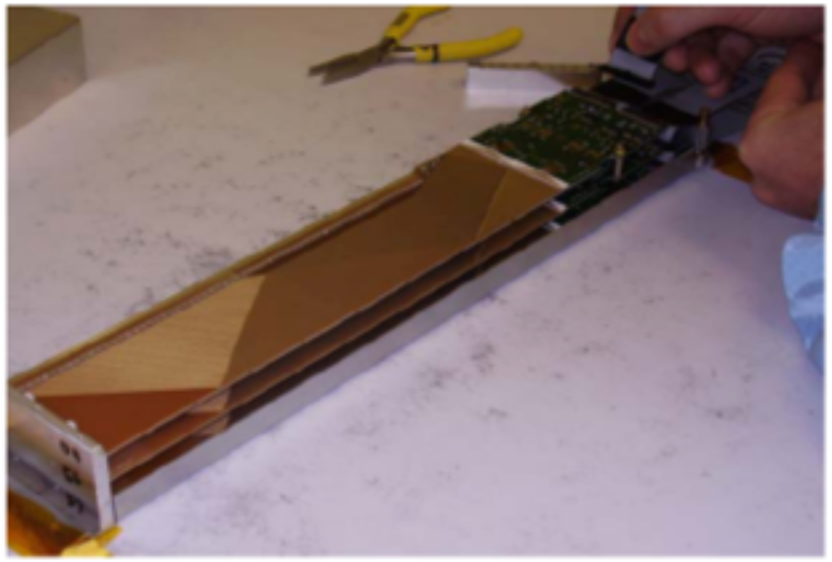
1. Antiprotons injected into 'Nested Potential'
2. Antiprotons lose energy by collisions with Positrons
3. Form Antihydrogen, leaves electrostatic trap

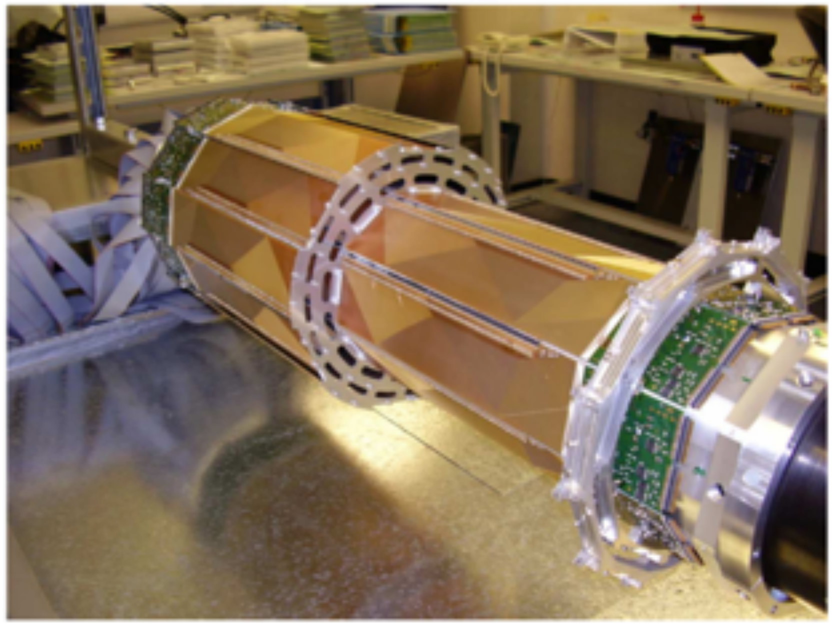


Antihydrogen Detection

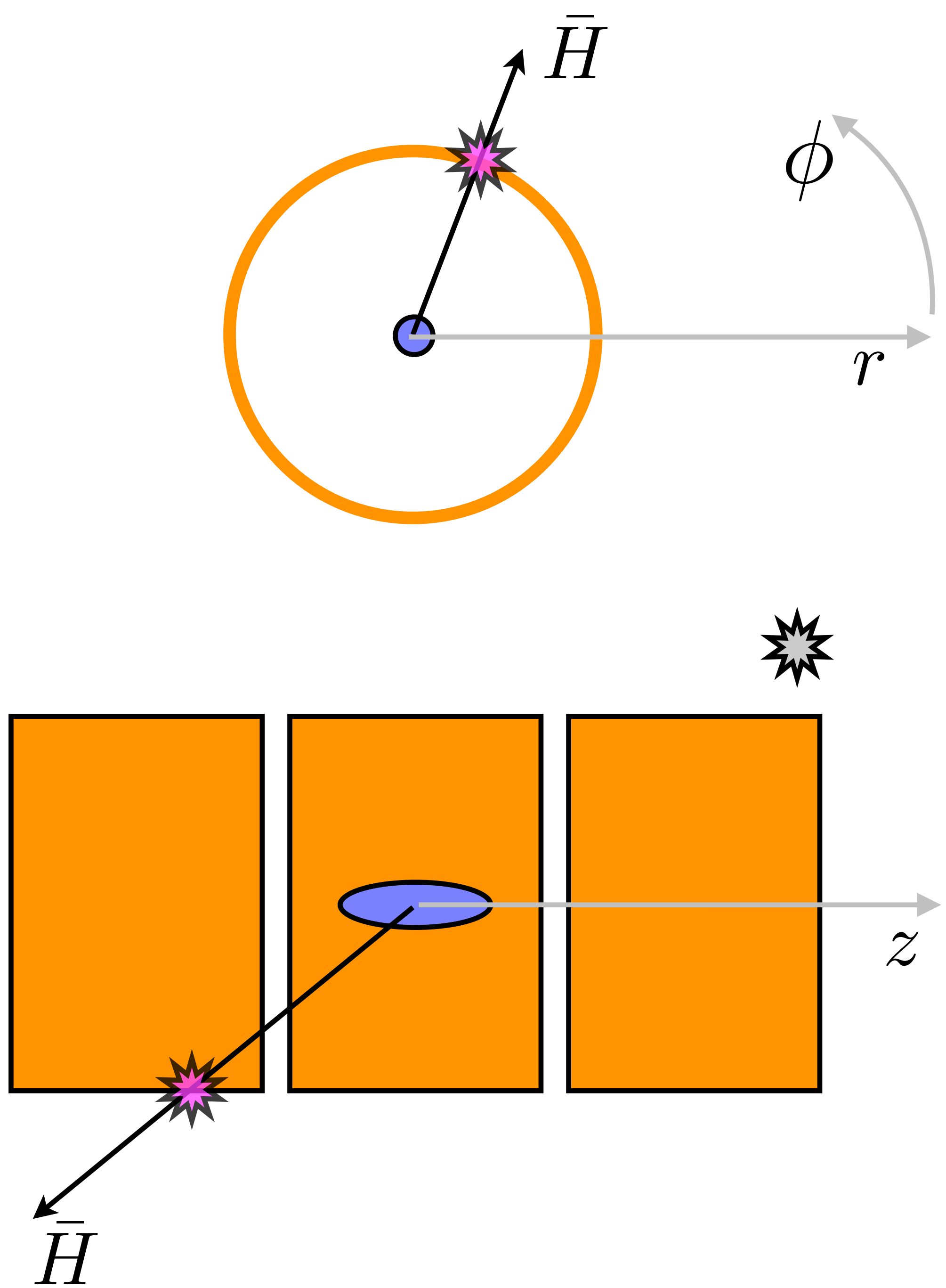
- Silicon-strip detector
- 3D 'Digital Camera'
  - Particle tracks point to vertex
- Vertex resolution ~ 3mm
- > 50% efficiency for annihilations

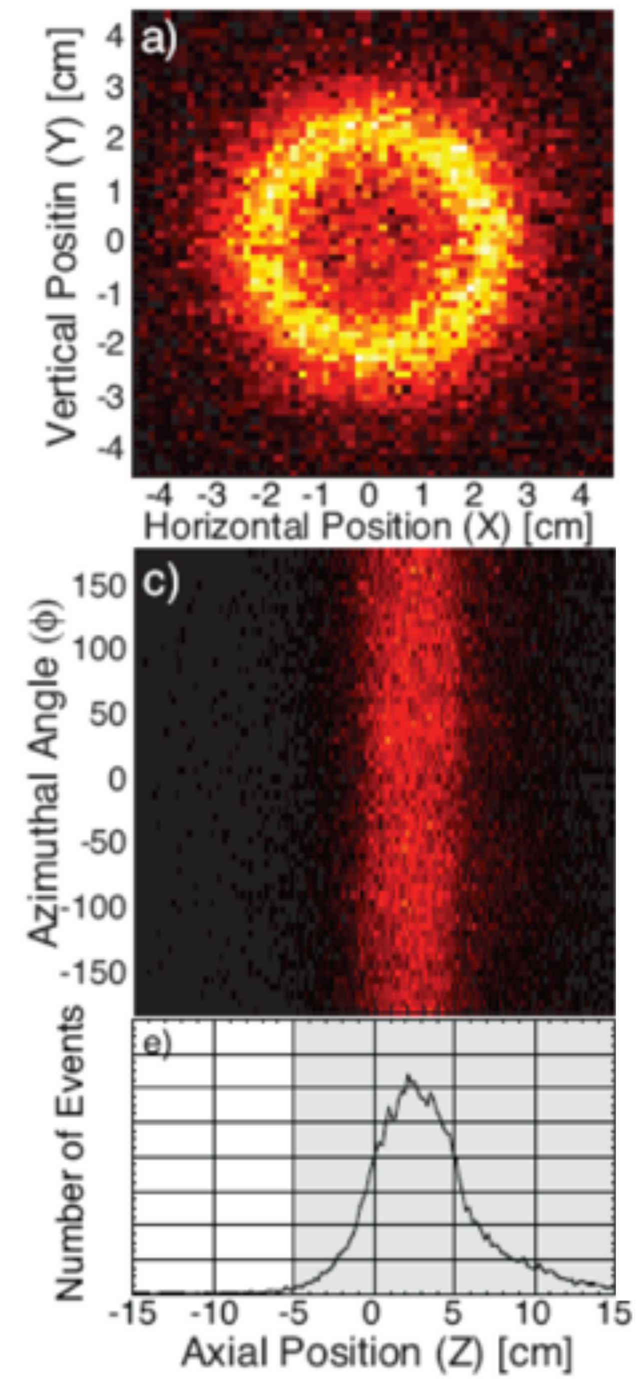






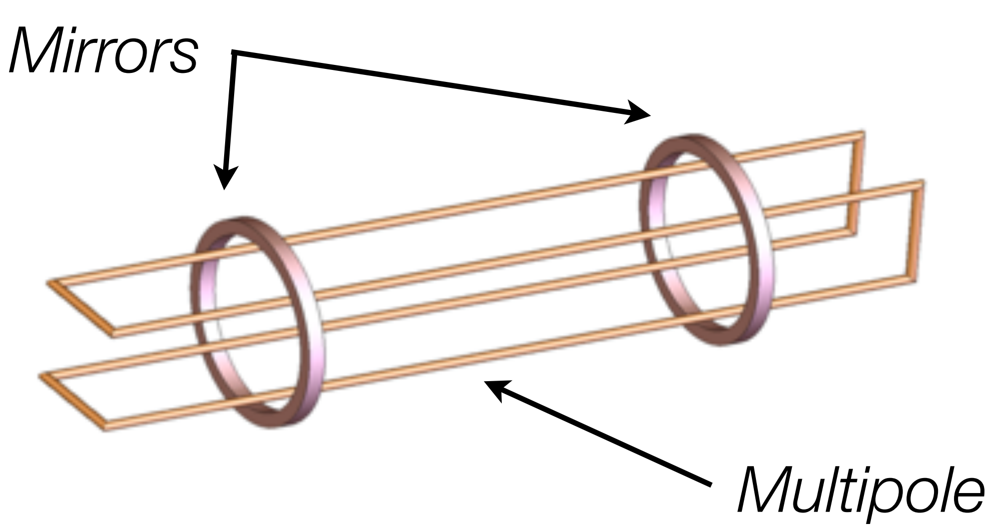
Antihydrogen Detection During Mixing

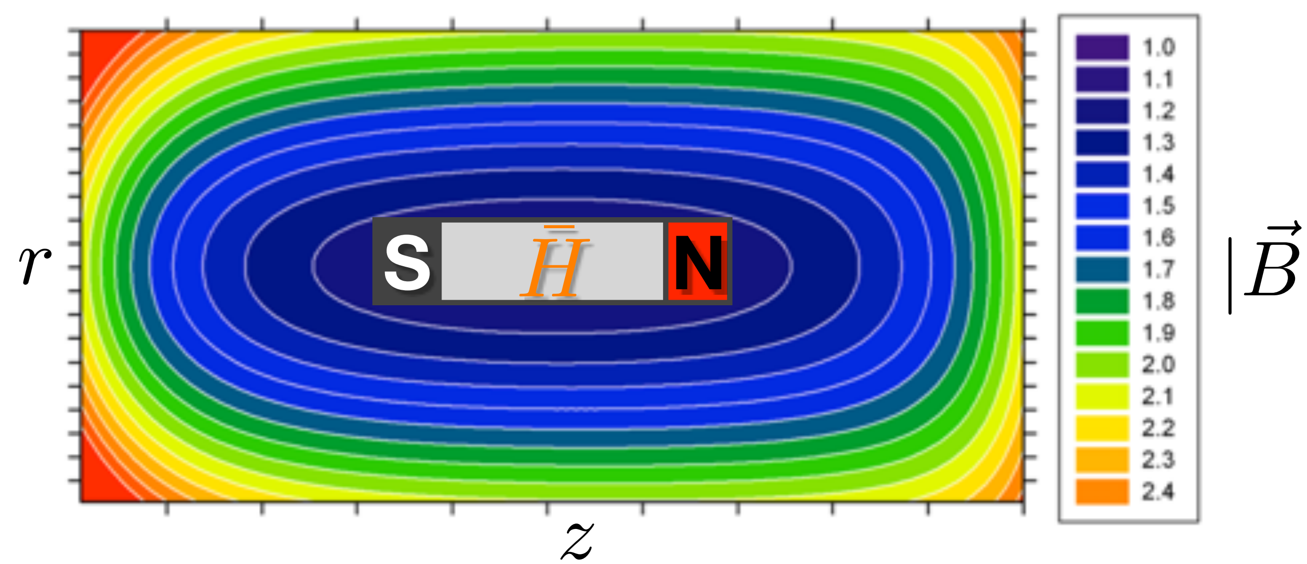




Trapping Antihydrogen

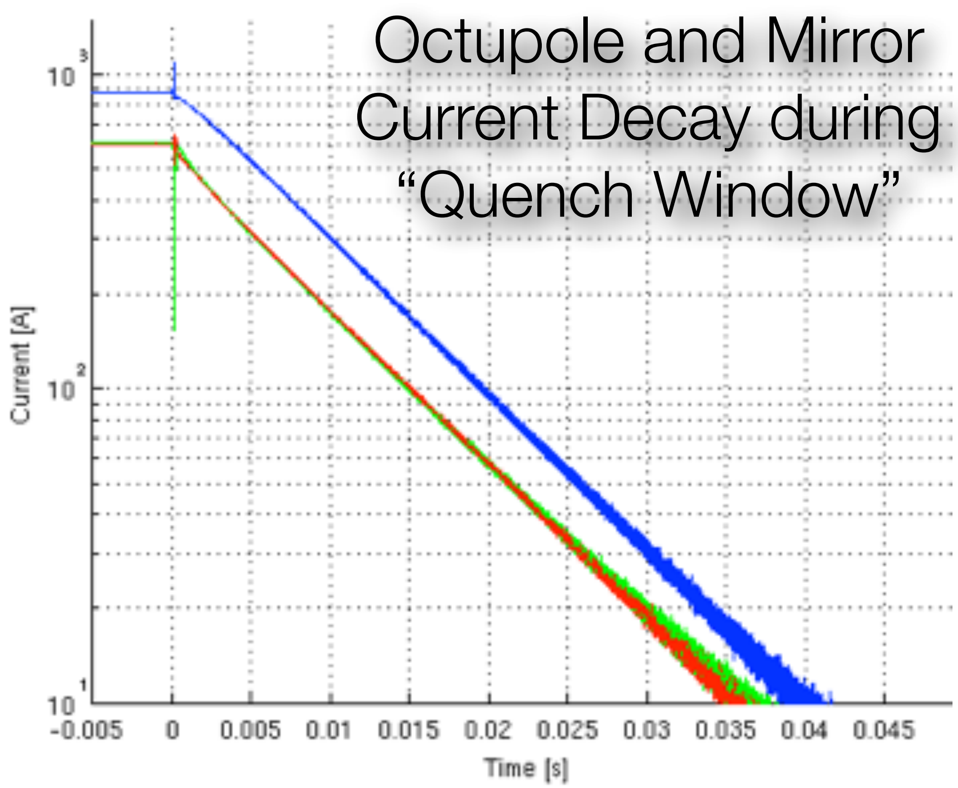
- Atoms are neutral: Not confined by penning traps
- Antihydrogen has a small magnetic moment
  - Like a little refrigerator magnet
- Can use a magnetic minimum trap (superconducting)
- Orientation matters (solenoid keeps alignment)
- Makes a shallow 'Bathtub' for T < 0.5 K (-272.65 C)

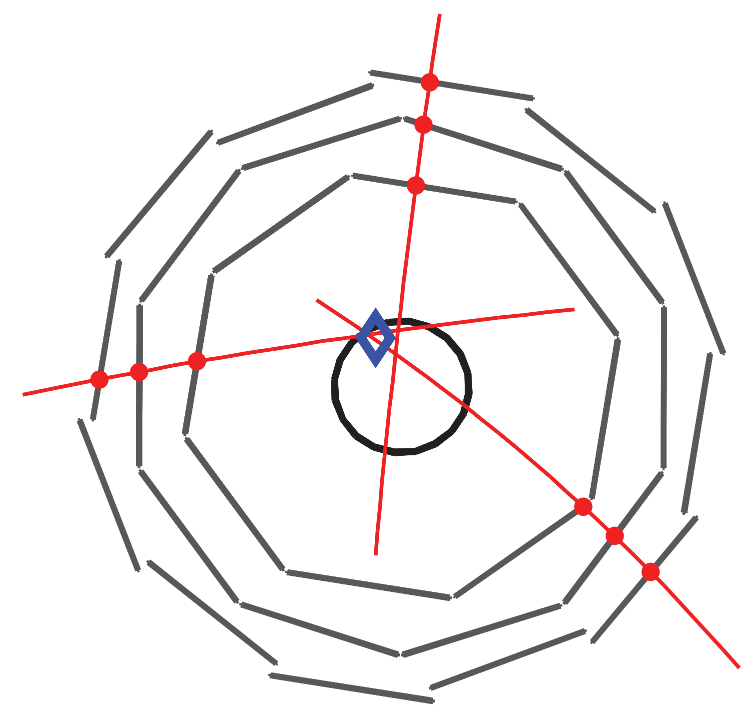




Trapping Antihydrogen: Search

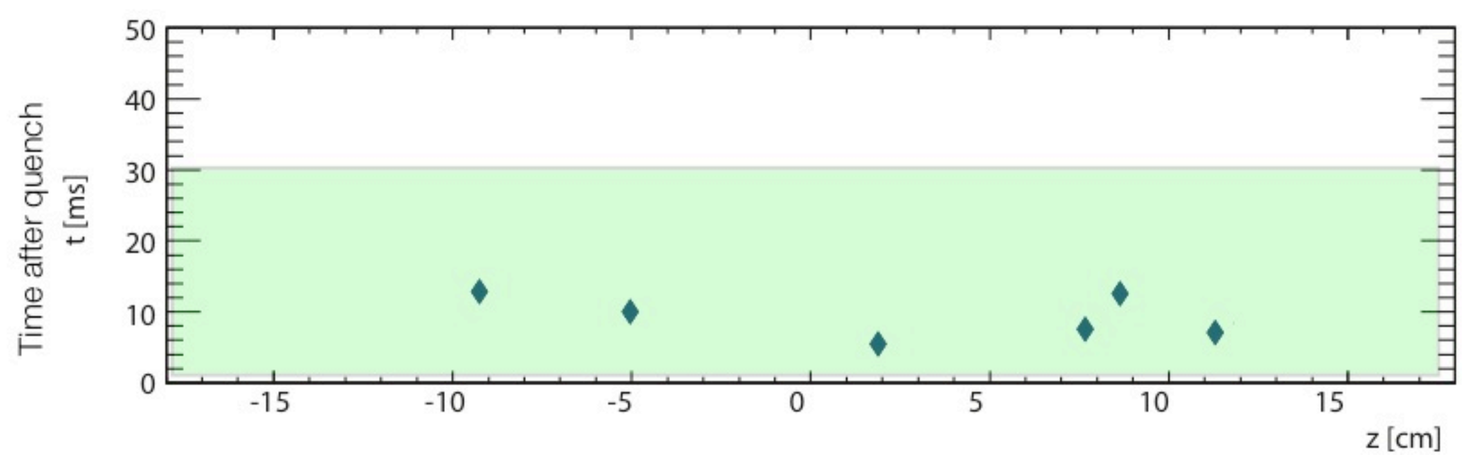
1. Turn on magnetic trap
2. Mix and Form Antihydrogen
3. Eject remaining charged particles
4. Rapidly (< 30 ms) shut off trap ("Quench")
5. Detect annihilations





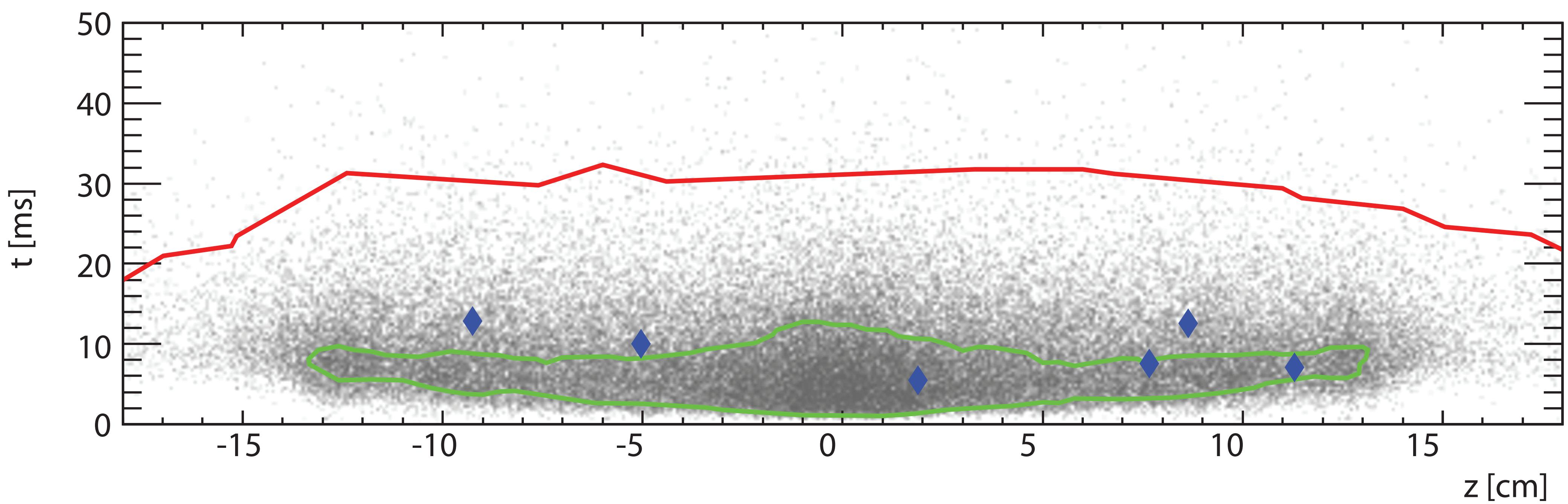
Trapped Antihydrogen Detection

- Pattern / Time / Spatial Information from Detector
- Reject cosmic rays
- Detect antiproton annihilations
- Only look at events during the quench (time)
- Bias electric field (space)
  - Antihydrogen stays in the “middle”!



Antihydrogen Expectation?

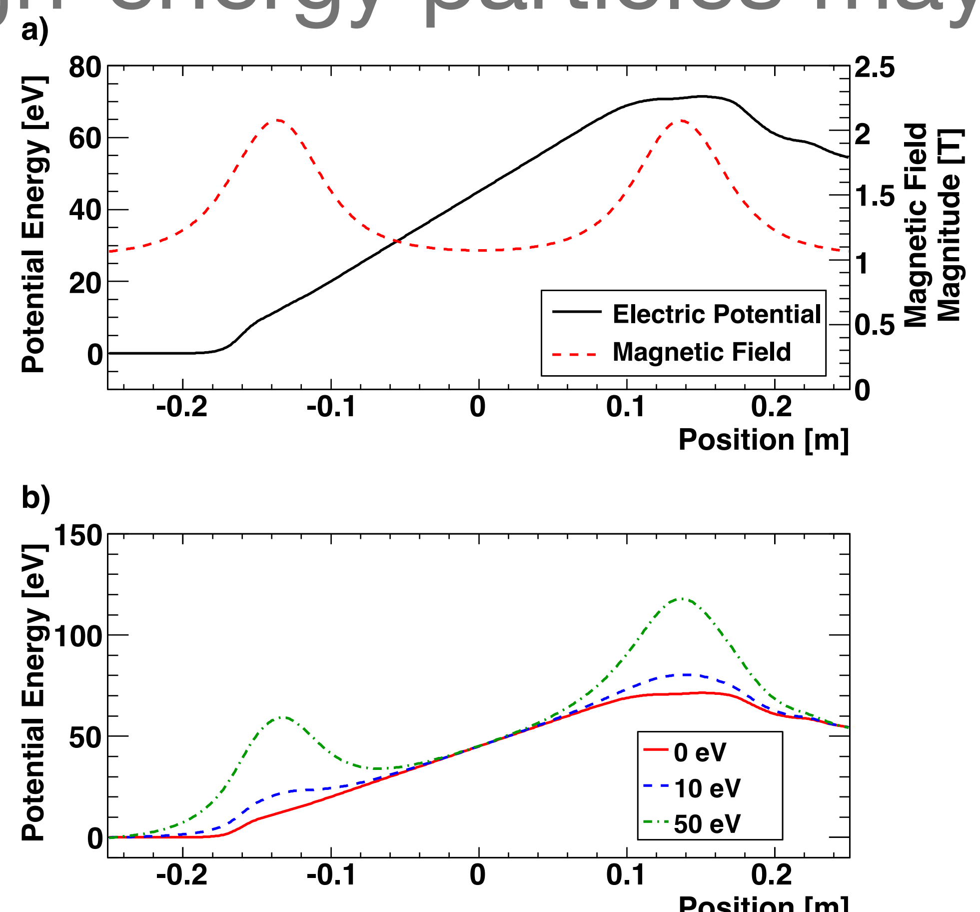
- Simulate Antihydrogen atoms in trap
- Accounts for effects like adiabatic cooling in quench

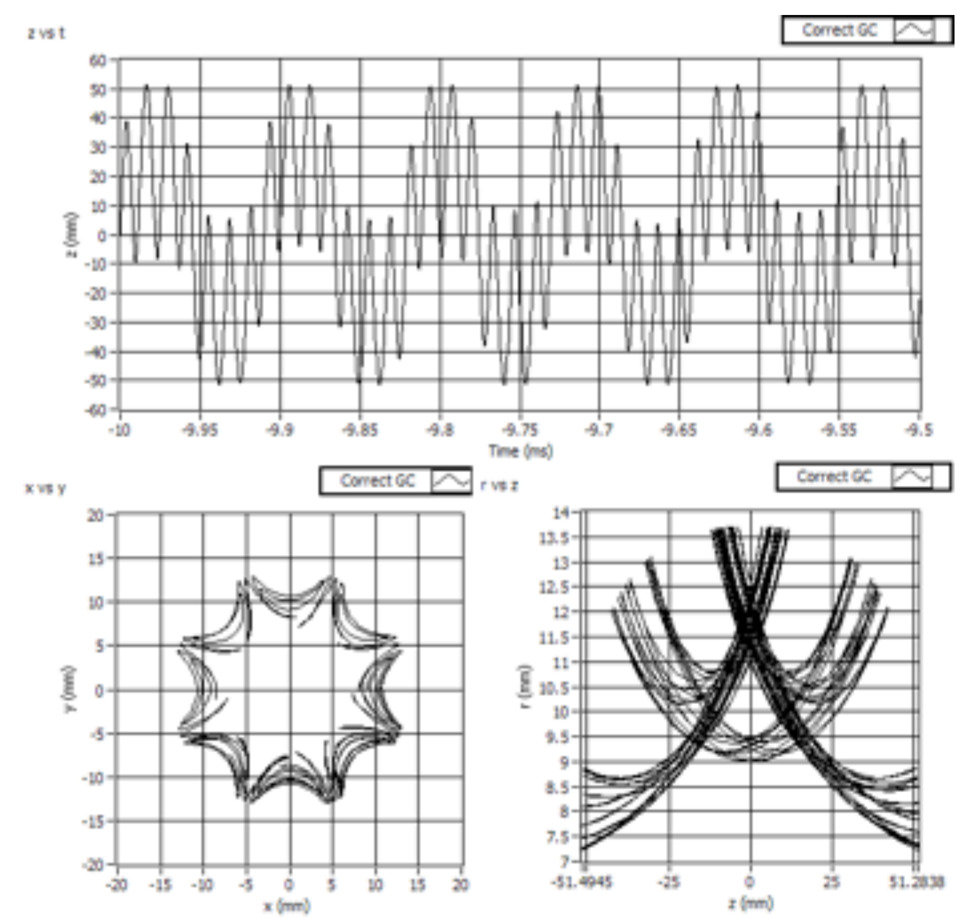


- Looks good! Is it enough?

High $E_\perp$, Mirror-Trapped Antiprotons Background?

- Charged particles follow field-lines, preserve flux.
- Off-axis, ExB dynamics complicate picture
- High-energy particles maybe not conserve adiabatics

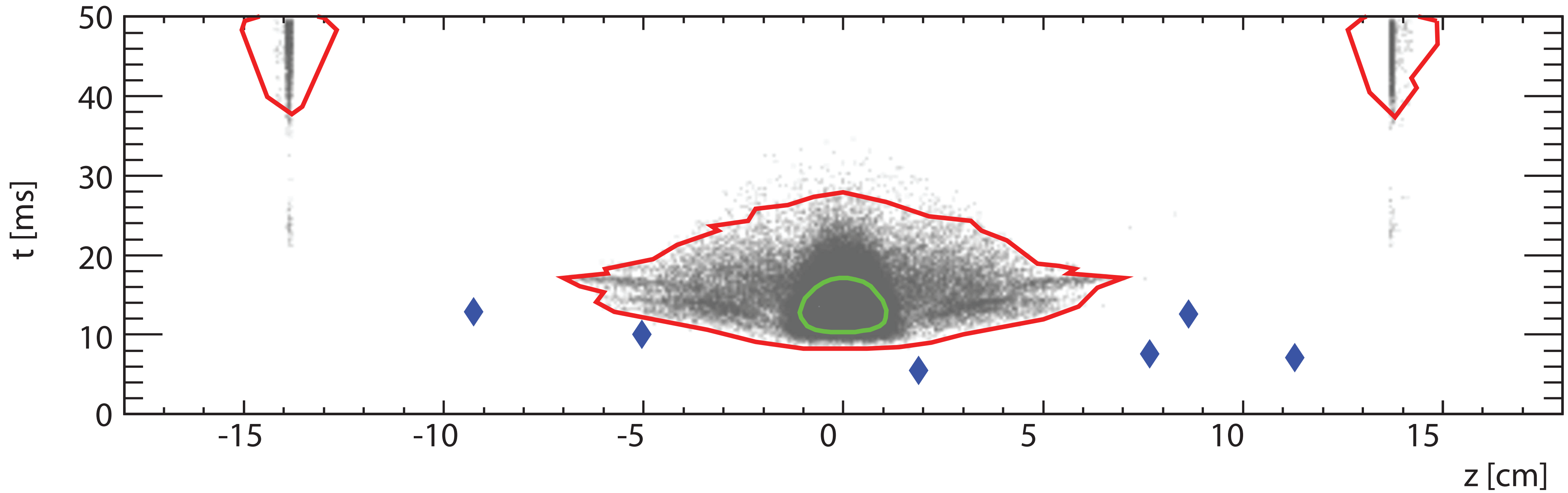




$$U_{\mathrm{tot}}(z, r=0) = q(\phi - \phi_0) + E_\perp \frac{B_\parallel - B_0}{B_0}$$

Are events Mirror-Trapped Antiprotons?

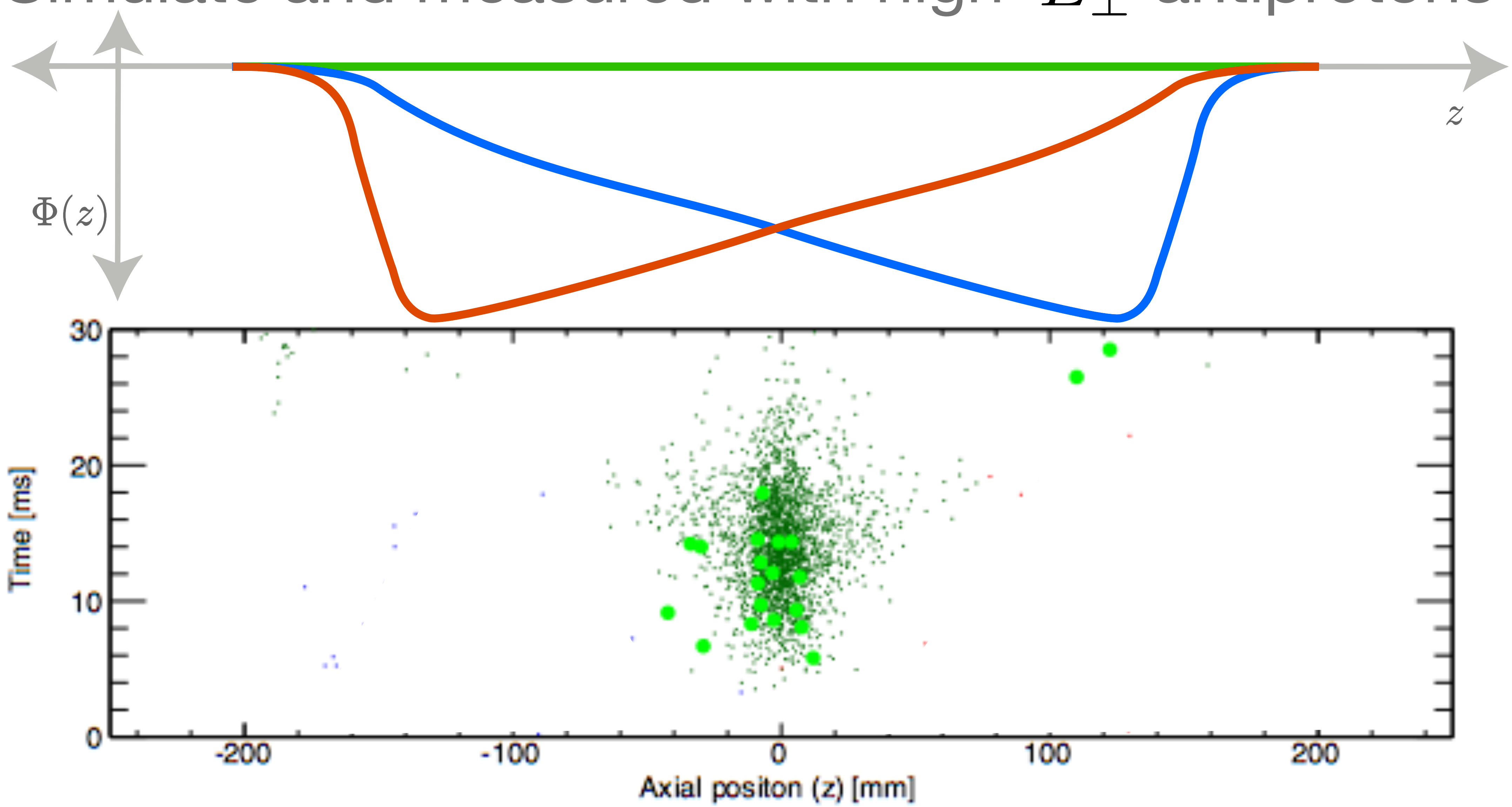
- Simulate mirror-trapped antiprotons in quench



- Enough?
- “Consistent” with trapped Antihydrogen
- No validation of code, no test for systematic errors

Quench With Bias Electric Field

- E *Fields should deflect charged particles, not atoms*
- Simulate and measured with high $E_\perp$ antiprotons

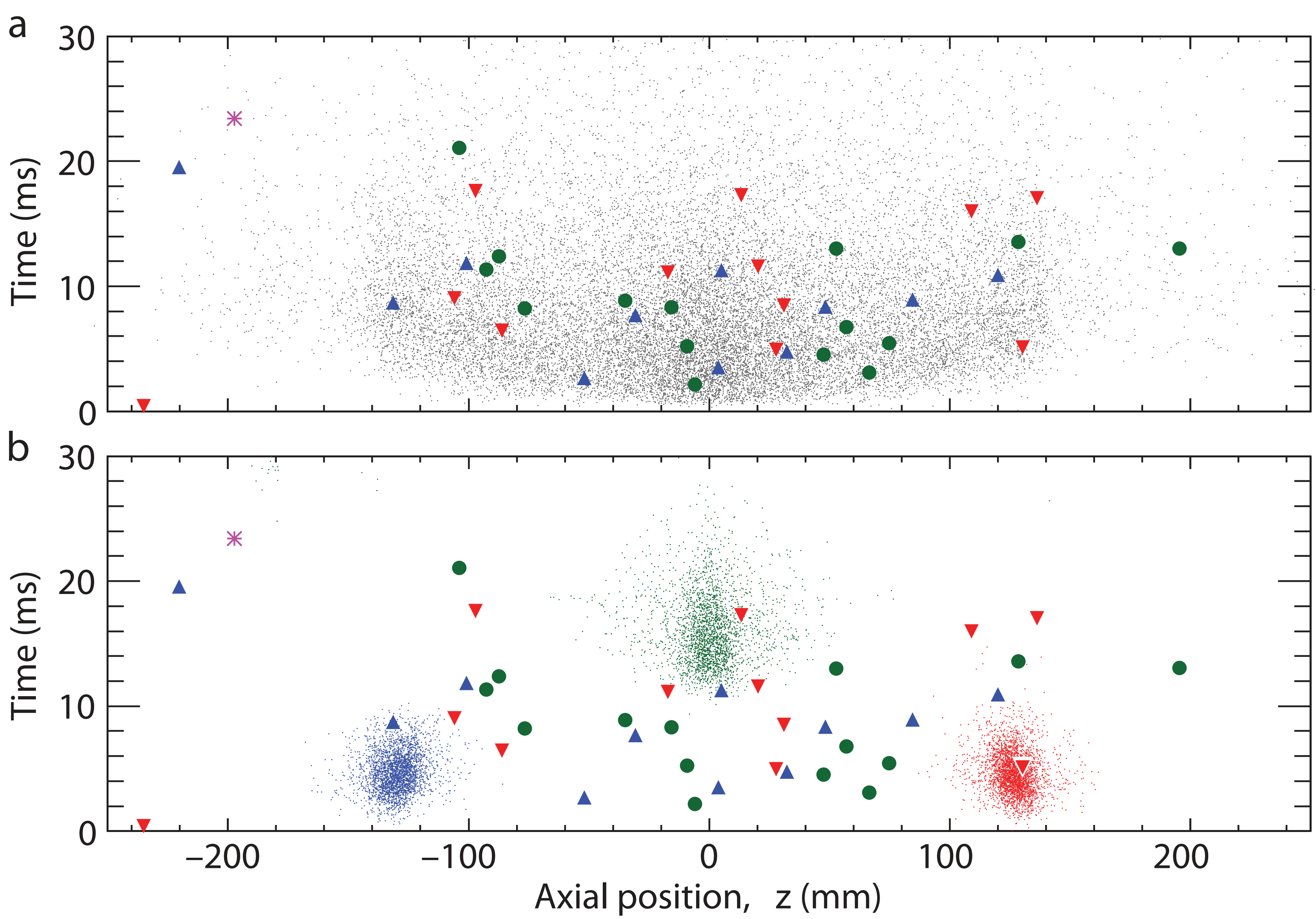


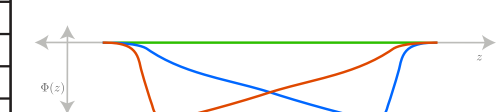
Antihydrogen Search with Bias Fields

- No spatial bias in signal

$\bar{H}$ Simulation

$\bar{P}$ Simulation





No Bias
Left Bias
Right Bias
(* Heating)

Trapped Antihydrogen!

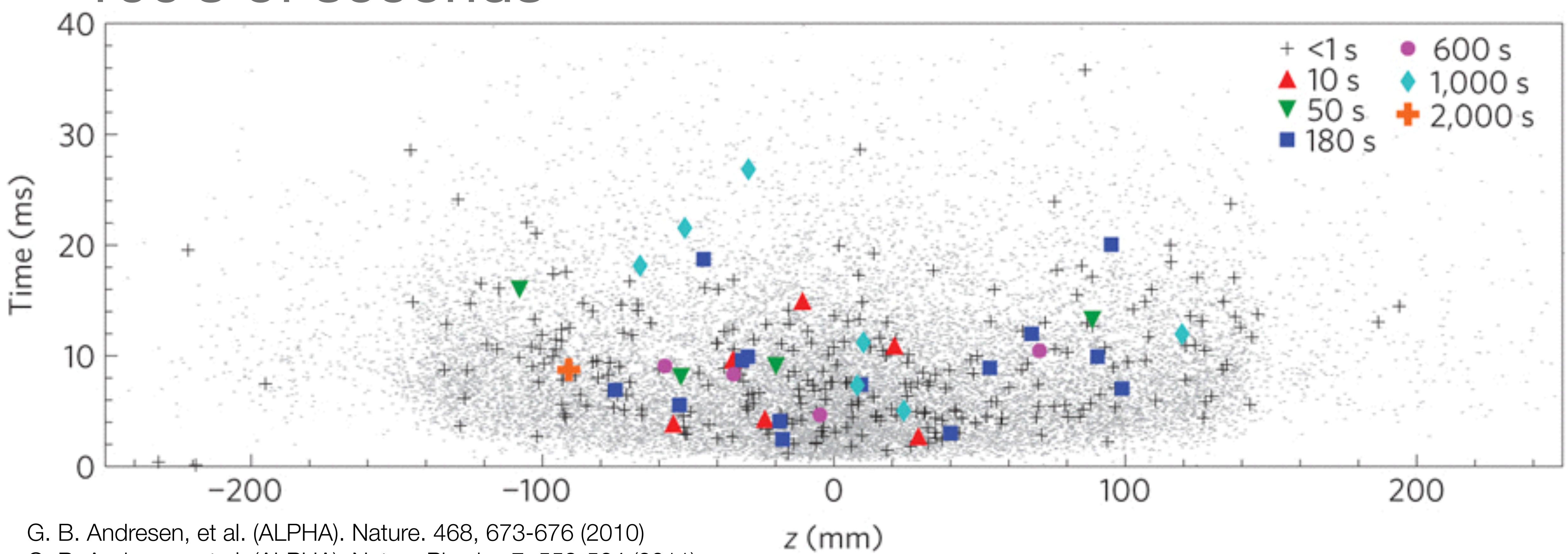
- Antihydrogen trapped.
  - 1 atom / 15 minutes.
- 100‘s of atoms for 100’s of seconds


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]



G. B. Andresen, et al. (ALPHA). Nature. 468, 673-676 (2010)
G. B. Andresen, et al. (ALPHA). Nature Physics 7, 558-564 (2011)
G. Gabrielse, et al. (ATRAP) Phys Rev. Lett. 108, 113002 (2012)

What sorts of measurements can we do?

- What if the E-fields did deflect the atoms?
- Antihydrogen "charge anomaly"

$$\bar{H} \text{ charge} = Qe$$

- Magnetic atom trap + bias field potential:

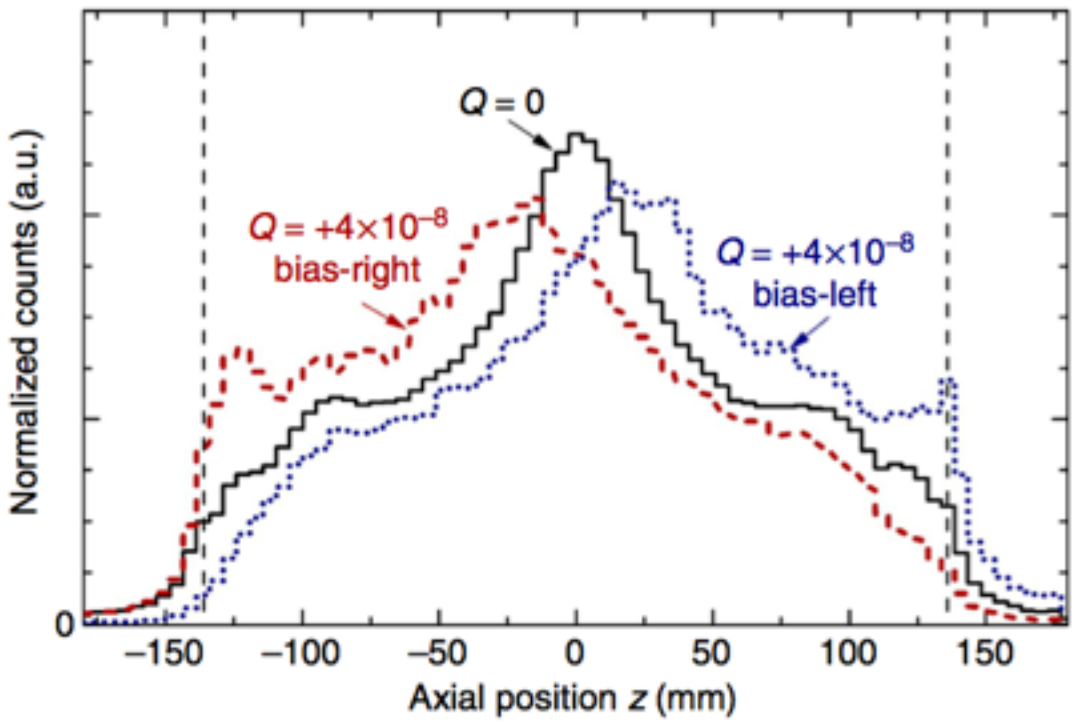
$$U(z) = \mu_{\bar{H}} B(z) - \frac{QeE}{k_B} z$$

- Measure the distribution spatial bias for left/right bias:

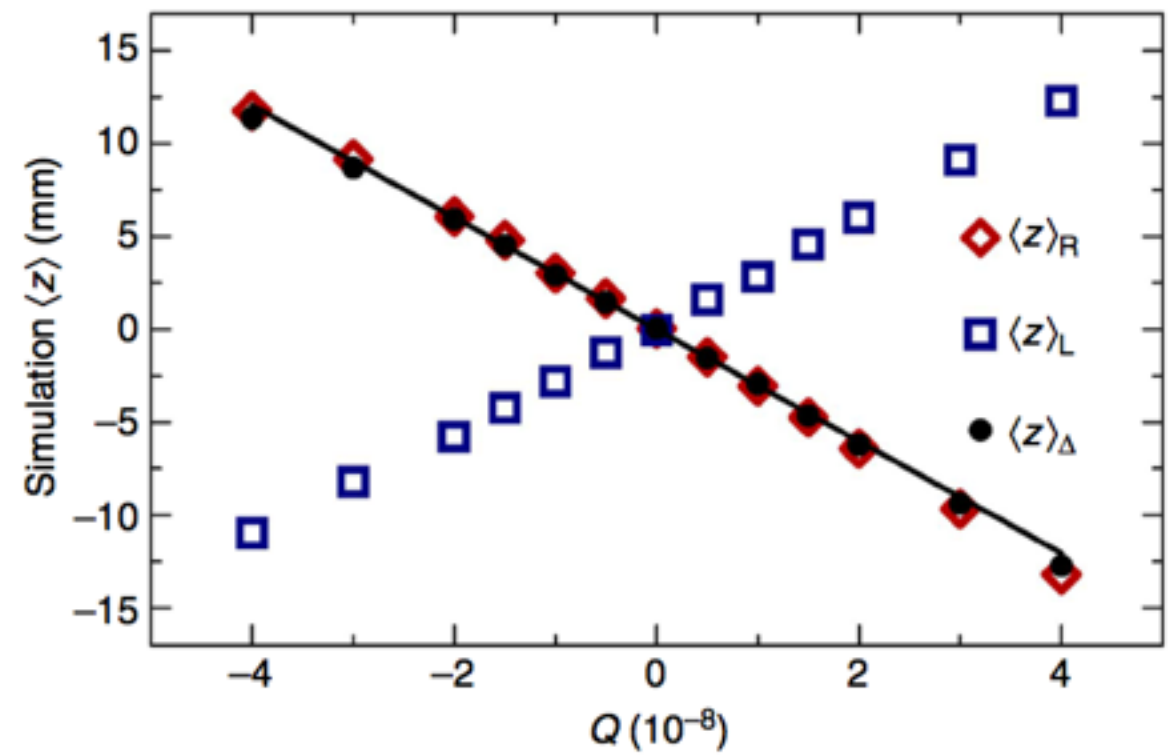
$$Q = \frac{4\mu_{\bar{H}} \beta k_B}{e\left(E_R - E_L\right)} \langle z \rangle_{\Delta}$$

Charge neutrality

Simulate Hbar Annihilations



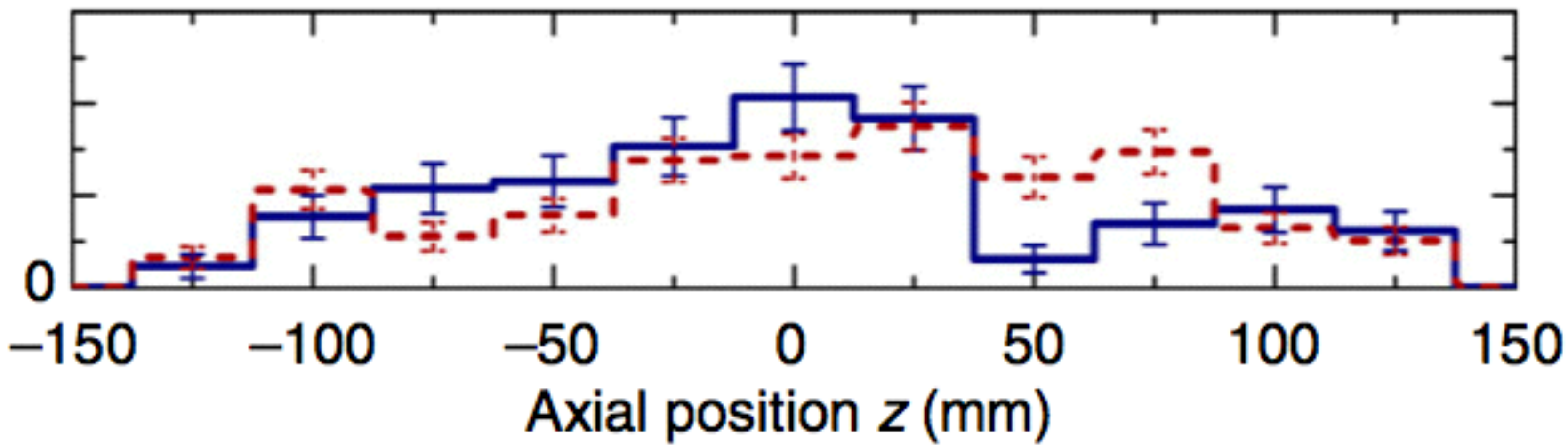
Relate $\langle z \rangle_\Delta \longleftrightarrow Q$



$$Q = \frac{4\mu_{\bar{H}}\beta k_B}{e\left(E_R - E_L\right)} \langle z \rangle_\Delta$$

Charge neutrality: Measure

Measure $\langle z \rangle_\Delta$



$$\langle z \rangle_\Delta = 4.1 \pm 3.4\,\mathrm{mm}$$

$$Q = (-1.3 \pm 1.1 \pm 0.4) \times 10^{-8}$$

*At 90% confidence, statistical error is: $\pm 1.8 \times 10^{-8}$
(covers zero… Whew!)

Charge neutrality: Precision

- Parasitic 'precision' $Q = (-1.3 \pm 1.1 \pm 0.4) \times 10^{-8}$

ARTICLE

Received 12 Jan 2014 | Accepted 24 Apr 2014 | Published 3 Jun 2014 DOI: 10.1038/ncomms4955 OPEN

An experimental limit on the charge of antihydrogen

C. Amole[1], M.D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4,5], E. Butler[6,7], A. Capra[1], C.L. Cesar[8], M. Charlton[9], S. Eriksson[9], J. Fajans[3,10], T. Friesen[11], M.C. Fujiwara[12], D.R. Gill[12], A. Gutierrez[13], J.S. Hangst[7,14], W.N. Hardy[13,15], M.E. Hayden[2], C.A. Isaac[9], S. Jonsell[16], L. Kurchaninov[12], A. Little[3], N. Madsen[9], J.T.K. McKenna[17], S. Menary[1], S.C. Napoli[9], P. Nolan[17], K. Olchanski[12], A. Olin[12], A. Povilus[3], P. Pusa[17], C.Ø. Rasmussen[14], F. Robicheaux[18], E. Sarid[19], D.M. Silveira[8], C. So[3], T.D. Tharp[3], R.I. Thompson[11], D.P. van der Werf[9], Z. Vendeiro[3], J.S. Wurtele[3,10], A.I. Zhmoginov[3,10] & A.E. Charman[3]

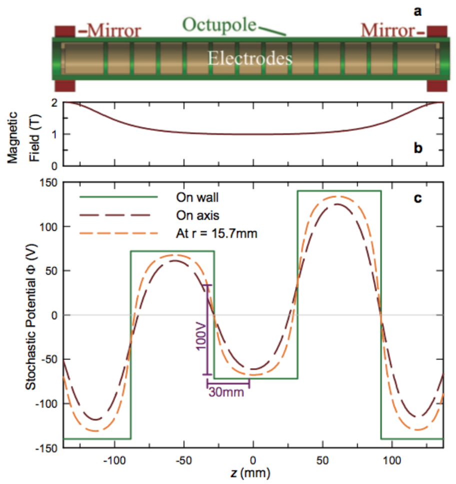
- Paranoia: Charge Superposition?
- Actually improves the positron charge anomaly limit

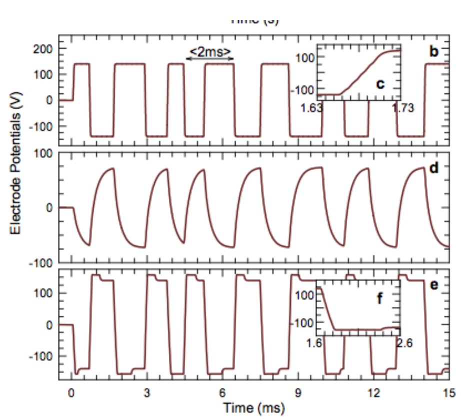
$$\left| \frac{(q_{e^+} - e)}{e} \right| < 2.5 \times 10^{-8} \qquad \left| \frac{|q_{\bar{p}}| - e)}{e} \right| < 7 \times 10^{-10}$$

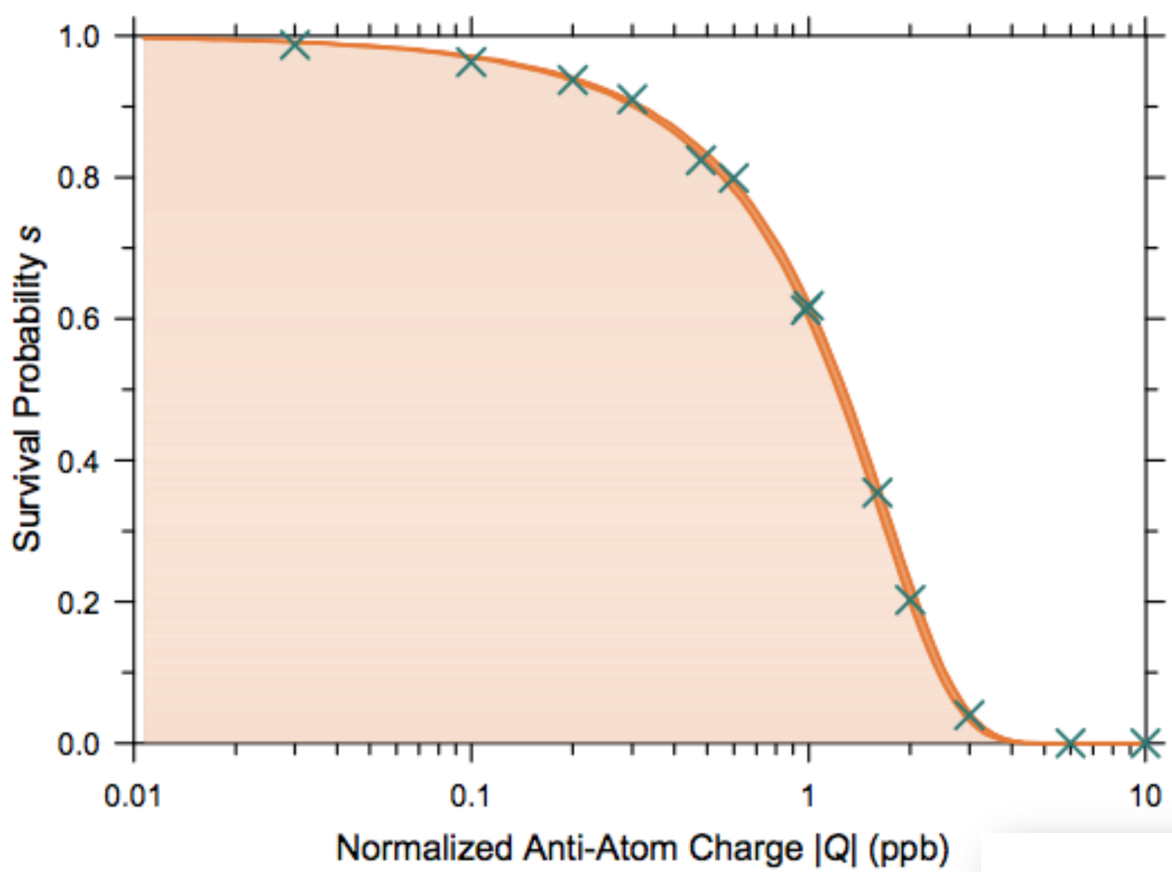
Hughes, R. J. & Deutch, B. I. Phys. Rev. Lett. 69, 578–581 (1992).

More Charge Neutrality

- Can improve precisions through electrostatic drive: Stochastic Heating







$$|Q| < 0.71 \cdot 10^{-9}$$

LETTER

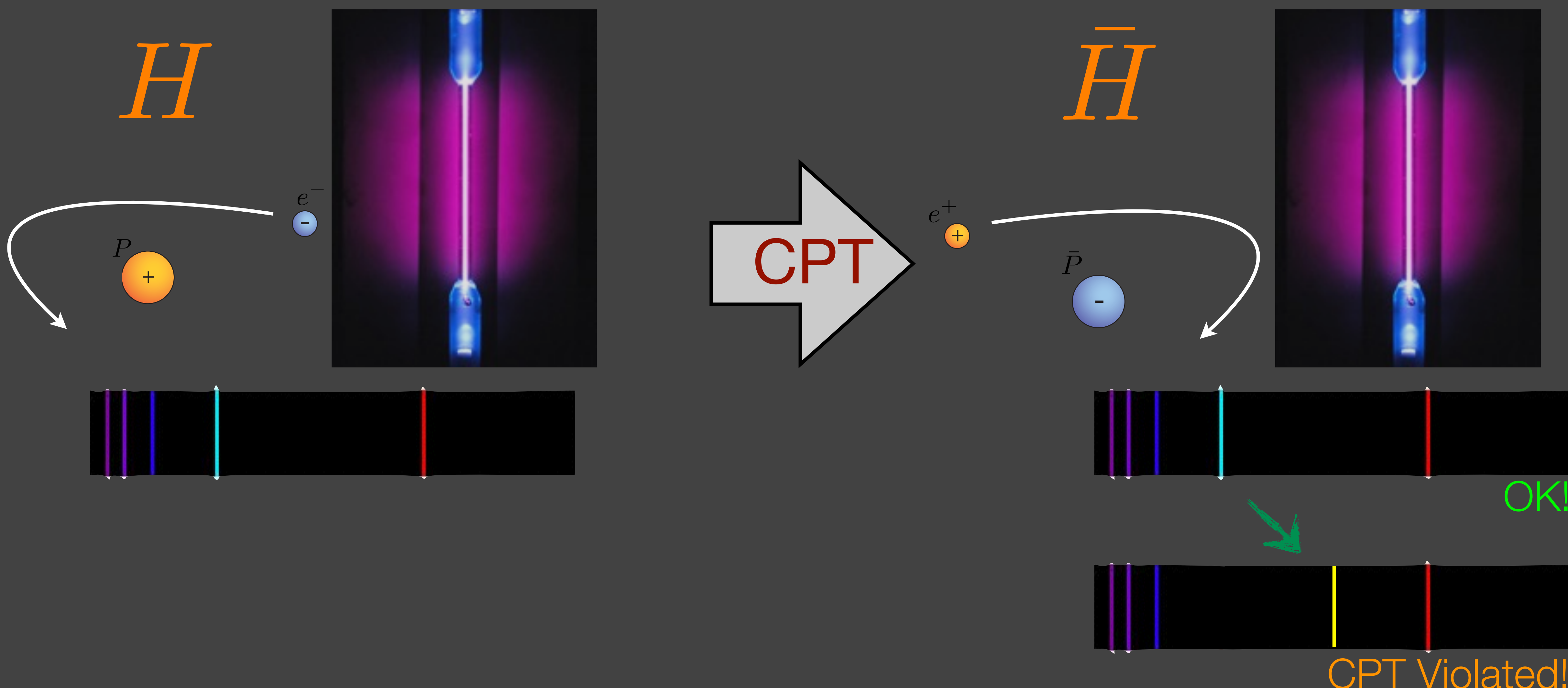
OPEN

doi:10.1038/nature16491

An improved limit on the charge of antihydrogen from stochastic acceleration

Atomic Spectra and CPT

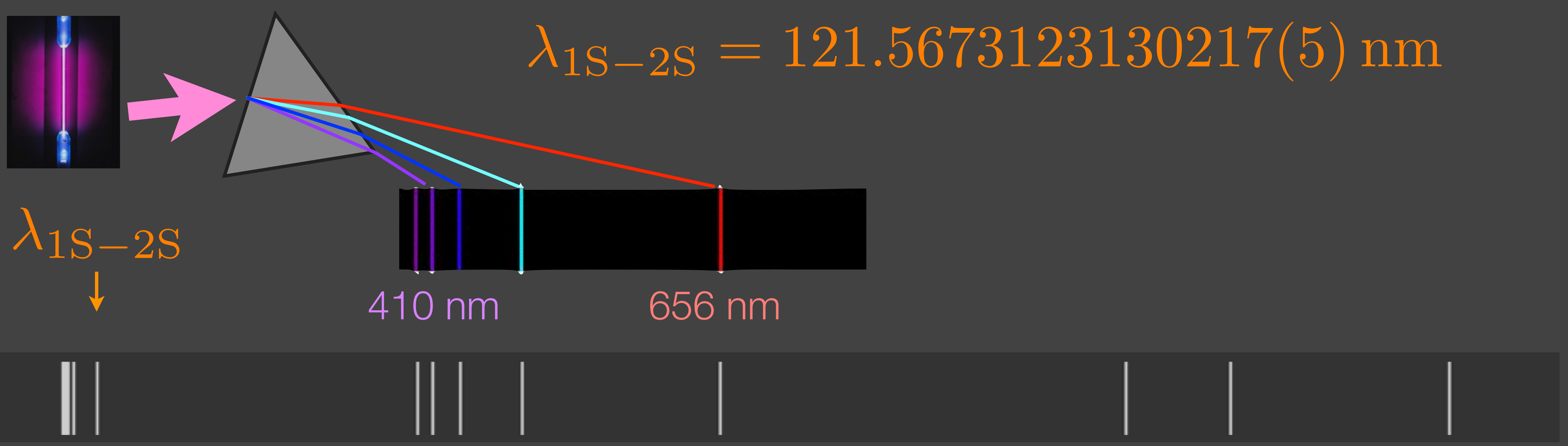
- Antihydrogen spectrum should be the same under CPT
- Verify by swapping in Antihydrogen and measuring



Goal: Precisely test CPT by comparing Hydrogen and Antihydrogen spectrum

- Hydrogen spectrum: accurately measured and predicted
  - Ground-state (1S) to first excited state (2S)

$$\lambda_{1S-2S} = 121.5673123130217(5)\ \mathrm{nm}$$



C. Parthey, et al. Phys. Rev. Lett. 107, 203001 (2011)

Challenges with Antihydrogen Spectroscopy

- Ultimate goal in ALPHA: Measure 1S - 2S transition

Problem: Few trapped atoms

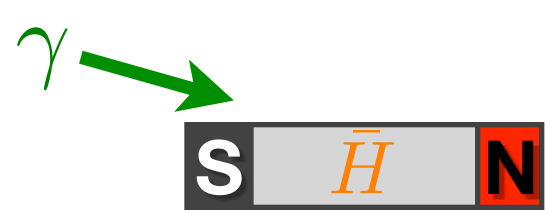
- Direct detection of absorbed or radiated photons is presently futile

Solution:

- Drive antihydrogen from a trapped to untrapped state
  - “Flip the magnetic moment”
- Efficiently detect annihilation

- Hyperfine Transition

$$\lambda_{\mathrm{hf}} = 21.1061140541791(13)\,\mathrm{cm}$$



Trapped State

Un-trapped State

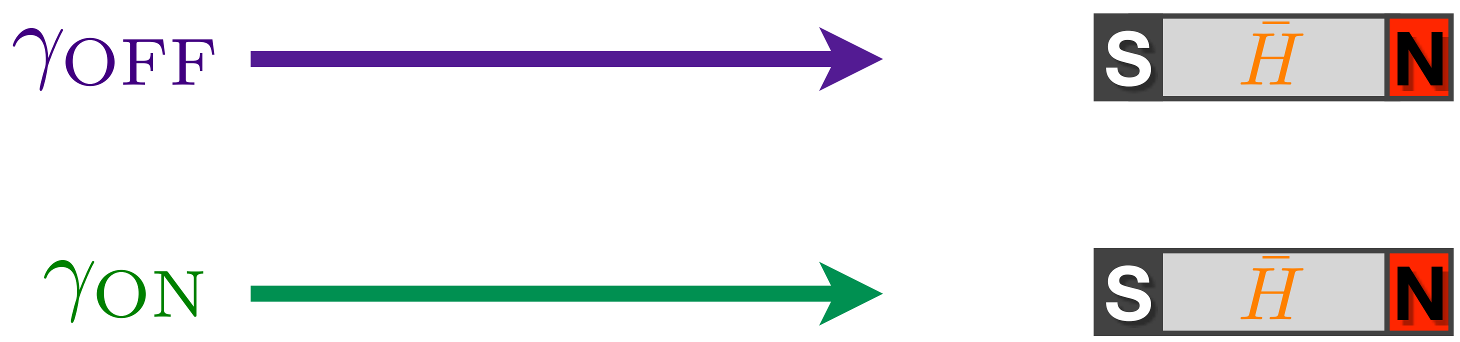
M. Niering, et al. Phys. Rev. Lett. 84, 5496 (2000)

Microwave Spectroscopy in ALPHA

- Illuminate Trapped Antihydrogen with Microwaves

- OFF-Resonance Frequency (wavelength)
  - Nothing happens

- ON-Resonance Frequency (wavelength)
  - Spin flips… Antihydrogen escapes… Annihilation



Spin Flipping Experiments

1. Produce and Trap Antihydrogen
2. Choose appropriate Magnetic Field
   Selects if the microwaves are ON or OFF resonance
3. Apply (or not) Microwave radiation for 180 seconds
4. Quench magnets / Detect annihilations

Two Measurements:

- Disappearance Mode:
  - Count the remaining antihydrogen atoms
  - ON resonance should deplete antihydrogen: lower the count
- Appearance Mode:
  - Count the ejected atoms during microwave injection
  - ON resonance should make annihilations appear when applied

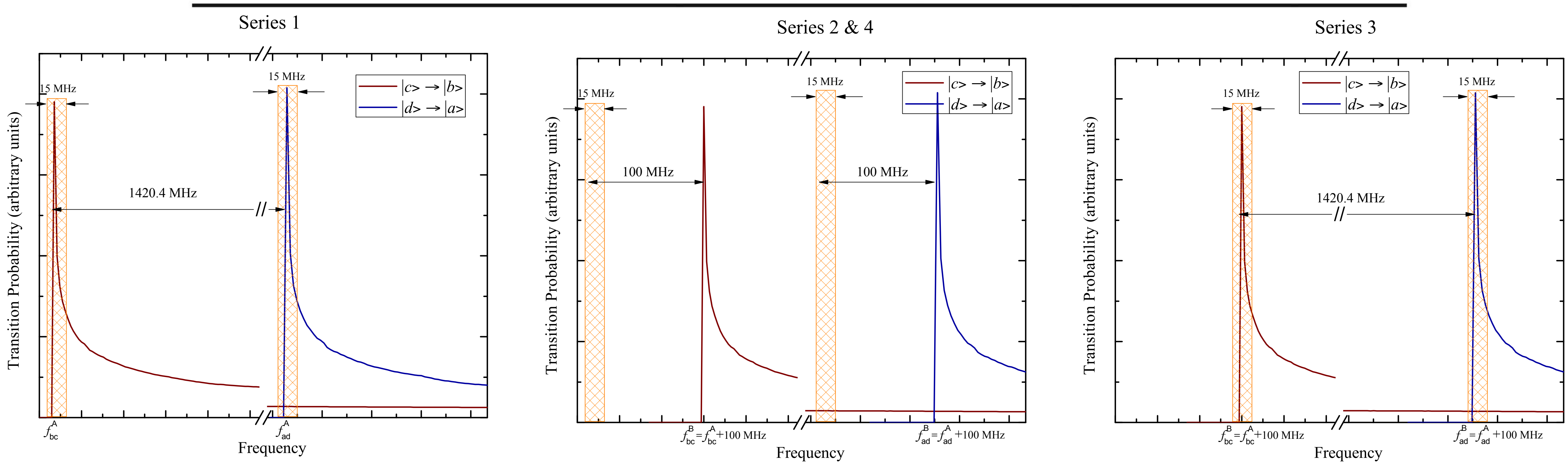
Disappearance Summary

ON: No Antihydrogen

OFF: Antihydrogen

Totals for all ‘disappearance mode’ series

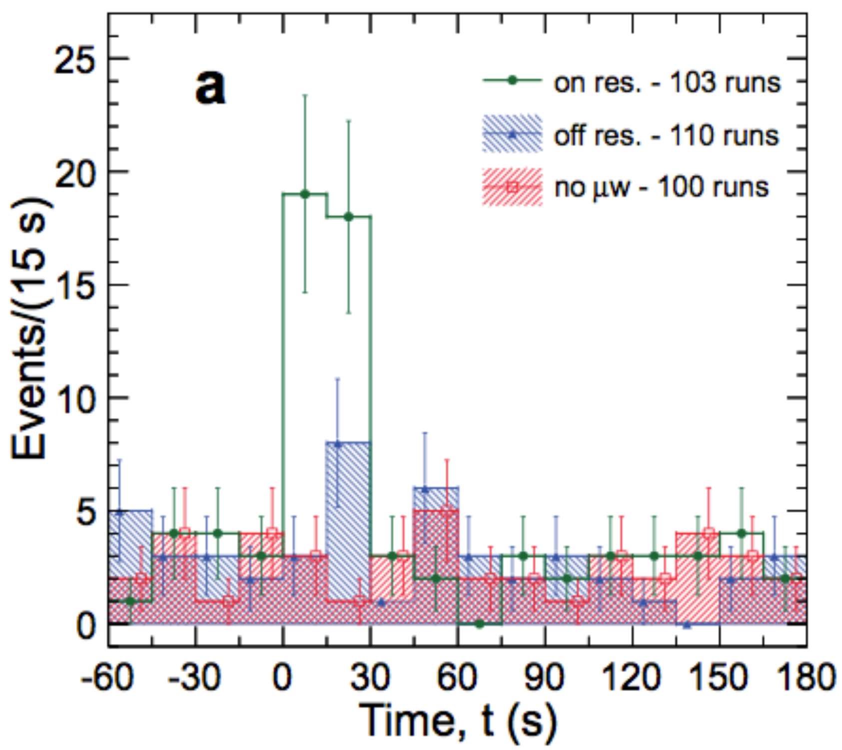
	Number of attempts	Detected antihydrogen	Rate
On resonance (1 + 3)	103	2	0.02 ± 0.01
Off resonance (2 + 4)	110	23	0.21 ± 0.04
No microwaves (5 + 6)	100	40	0.40 ± 0.06



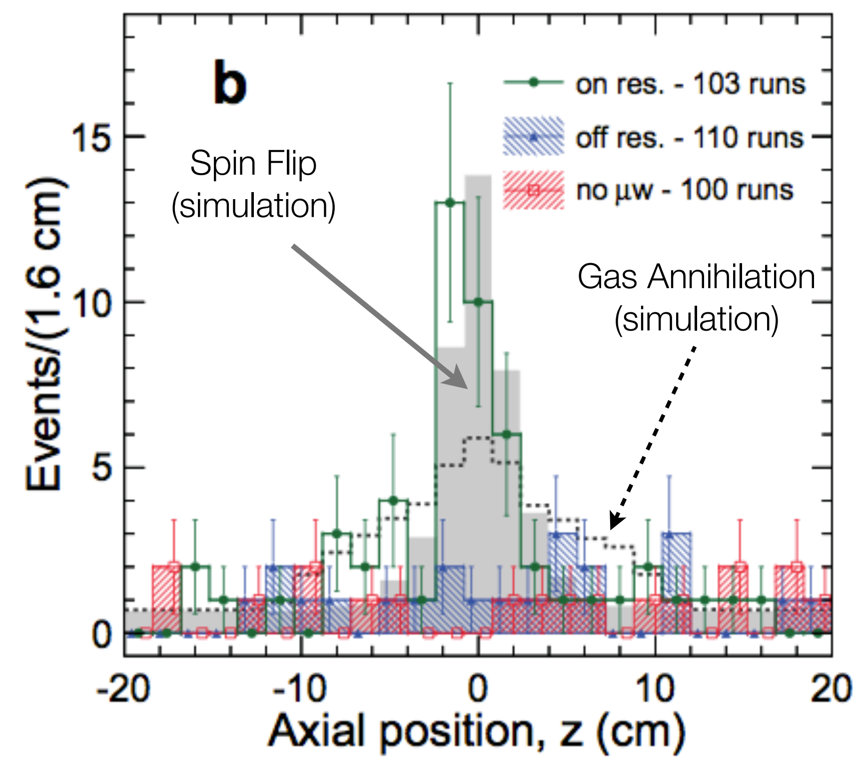
Appearance Summary

ON: Antihydrogen Annihilation ‘Appears’

OFF: No Antihydrogen Annihilation



Time history of events
during microwave injection



Annihilation positions for
events in $0 < t < 30$ s

Driving resonant transitions in ALPHA

- We have driven the first quantum transitions in Antihydrogen (Or any pure antimatter system)
- Early measurements: precision is < 0.5%
- Importantly, this is a scheme which can allow measuring the 1S-2S transition even with few atoms
- Perform a spin flip that only drives atoms that have made the 1S - 2S transition

- ALPHA (2011) could NOT make a 1S - 2S measurement
  - No access for lasers

LETTER

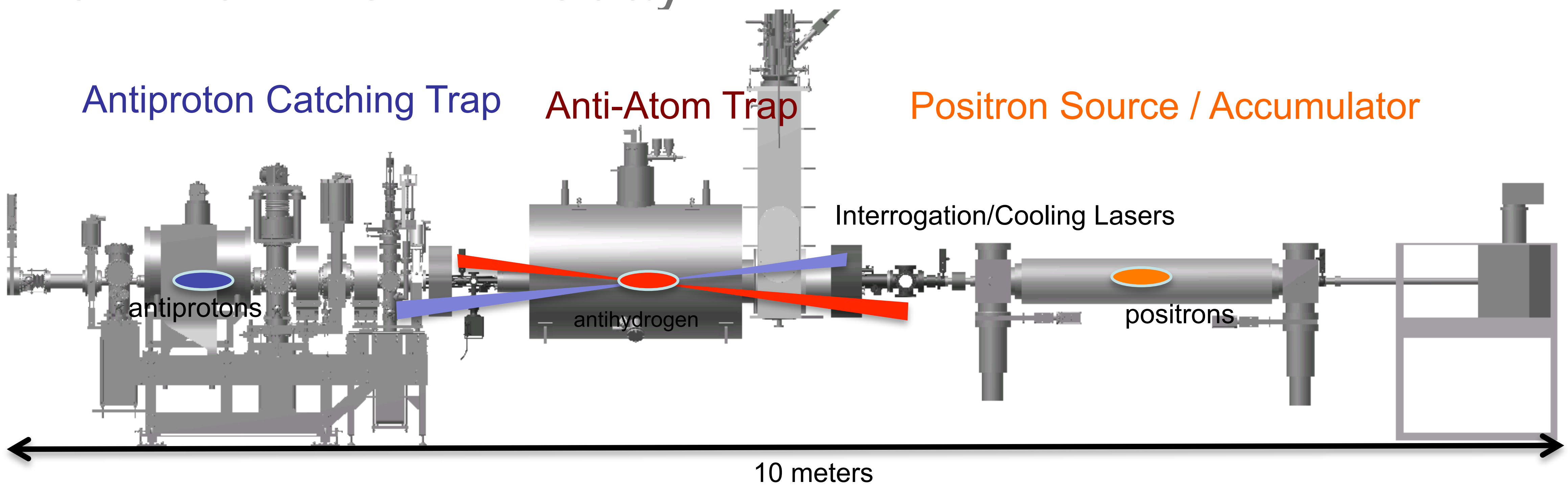
doi:10.1038/nature10942

Resonant quantum transitions in trapped antihydrogen atoms

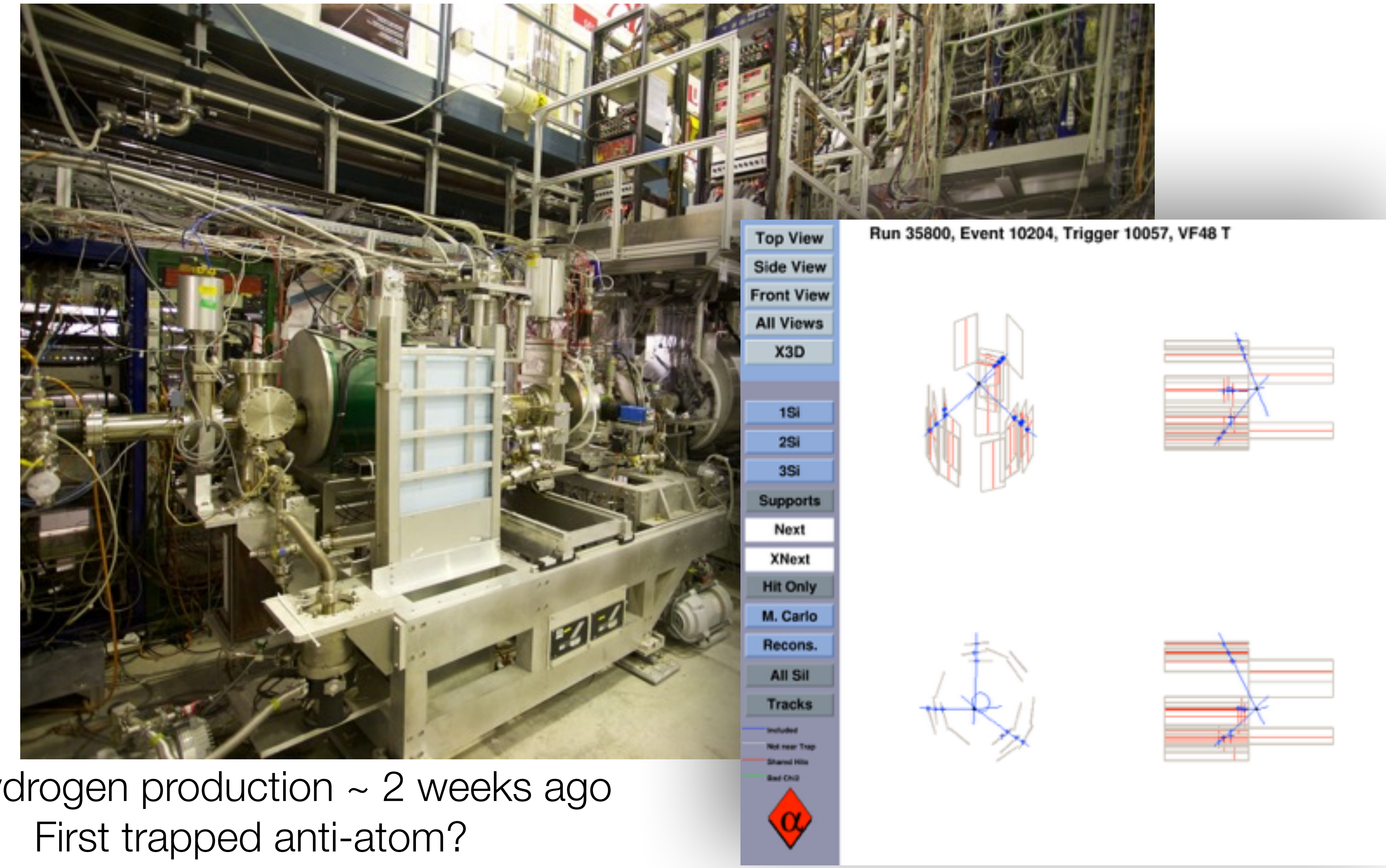
C. Amole[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4,5,6], P. D. Bowe[7], E. Butler[8], A. Capra[1], C. L. Cesar[9], M. Charlton[4], A. Deller[4], P. H. Donnan[10], S. Eriksson[4], J. Fajans[3,11], T. Friesen[12], M. C. Fujiwara[12,13], D. R. Gill[13], A. Gutierrez[14], J. S. Hangst[7], W. N. Hardy[14,15], M. E. Hayden[2], A. J. Humphries[4], C. A. Isaac[4], S. Jonsell[16], L. Kurchaninov[13], A. Little[3], N. Madsen[4], J. T. K. McKenna[17], S. Menary[1], S. C. Napoli[4], P. Nolan[17], K. Olchanski[13], A. Olin[13,18], P. Pusa[17], C. Ø. Rasmussen[7], F. Robicheaux[10], E. Sarid[19], C. R. Shields[4], D. M. Silveira[20]†, S. Stracka[13], C. So[3], R. I. Thompson[12], D. P. van der Werf[4] & J. S. Wurtele[3,11]

ALPHA-2: Laser Access Required!

- Modularity for interfacing with CERN/ELENA upgrade
  - More antiprotons
- Increase antihydrogen trapping rate
- Lasers for Spectroscopy and Cooling
  - 243 nm 2-photon spectroscopy, 121 nm Lyman-alpha laser cooling
- Built from 2012 - today



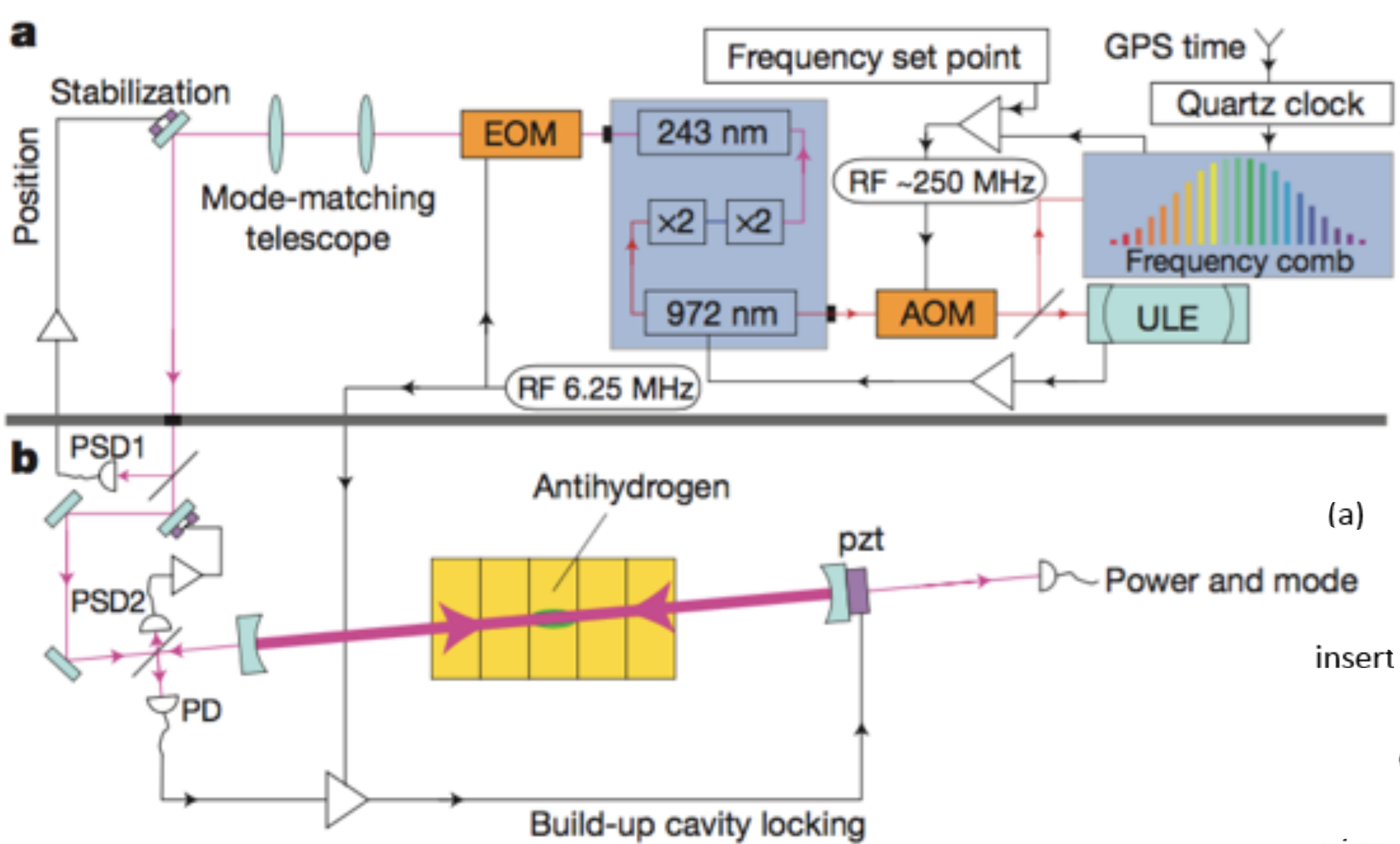
ALPHA-2: After LS1 (September 2014)

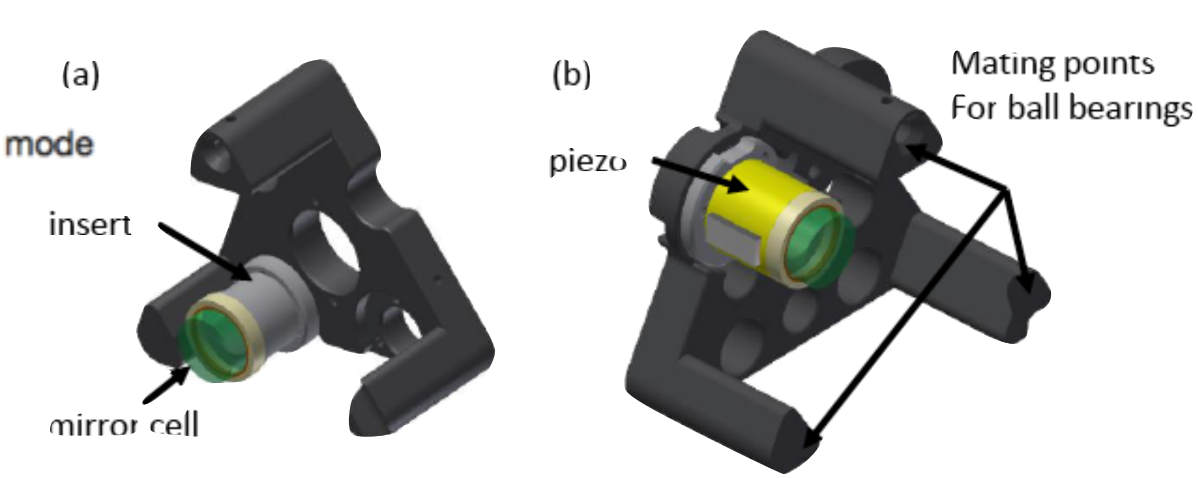


Antihydrogen production ~ 2 weeks ago
First trapped anti-atom?

1S - 2S Laser System

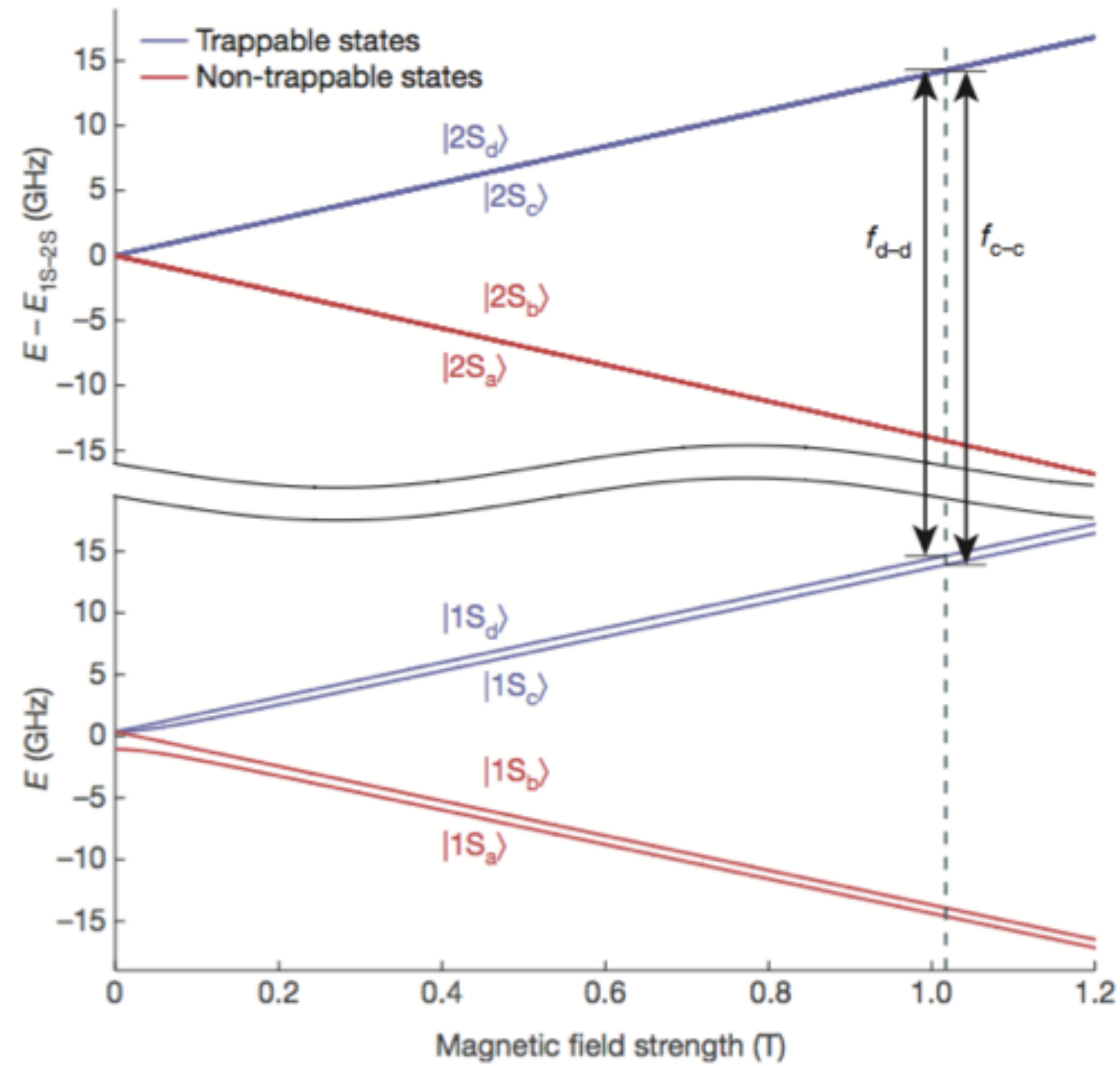
- GPS-reference Menlo Systems Frequency Comb locked to ULE cavity
- 243 nm Toptica laser (~ 100 mW) locked to ULE
- *In-situ* PDH-locked cryogen build-up cavity (~ 1 W)





1S - 2S Transition in (anti) hydrogen

- 2 - photon Doppler-free spectroscopy (243 nm)
- Drive between trapped hyperfine states

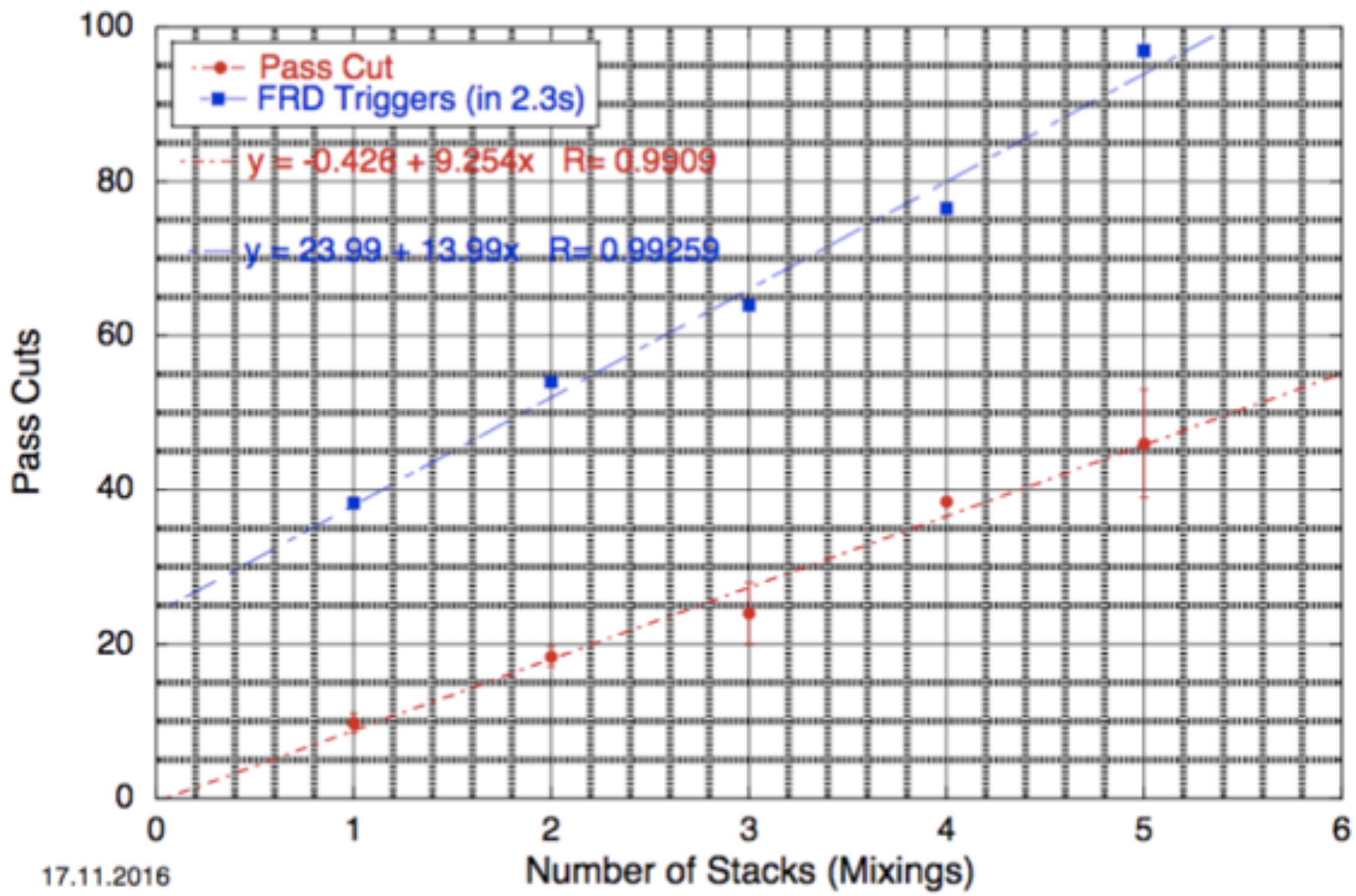


1S - 2S Experiment

- Produce and trap antihydrogen
- Illuminate experiment (or not) for 600 seconds
  - **On-Resonance**
    - Drive f_{cc} and f_{dd} (300 seconds each)
  - **Off-Resonance**
    - Detune each by 200 kHz
  - **No-laser**
- Fast magnet ramp-down
  - Look for disappearance
- Also look for appearance
  - Multivariate Analysis…

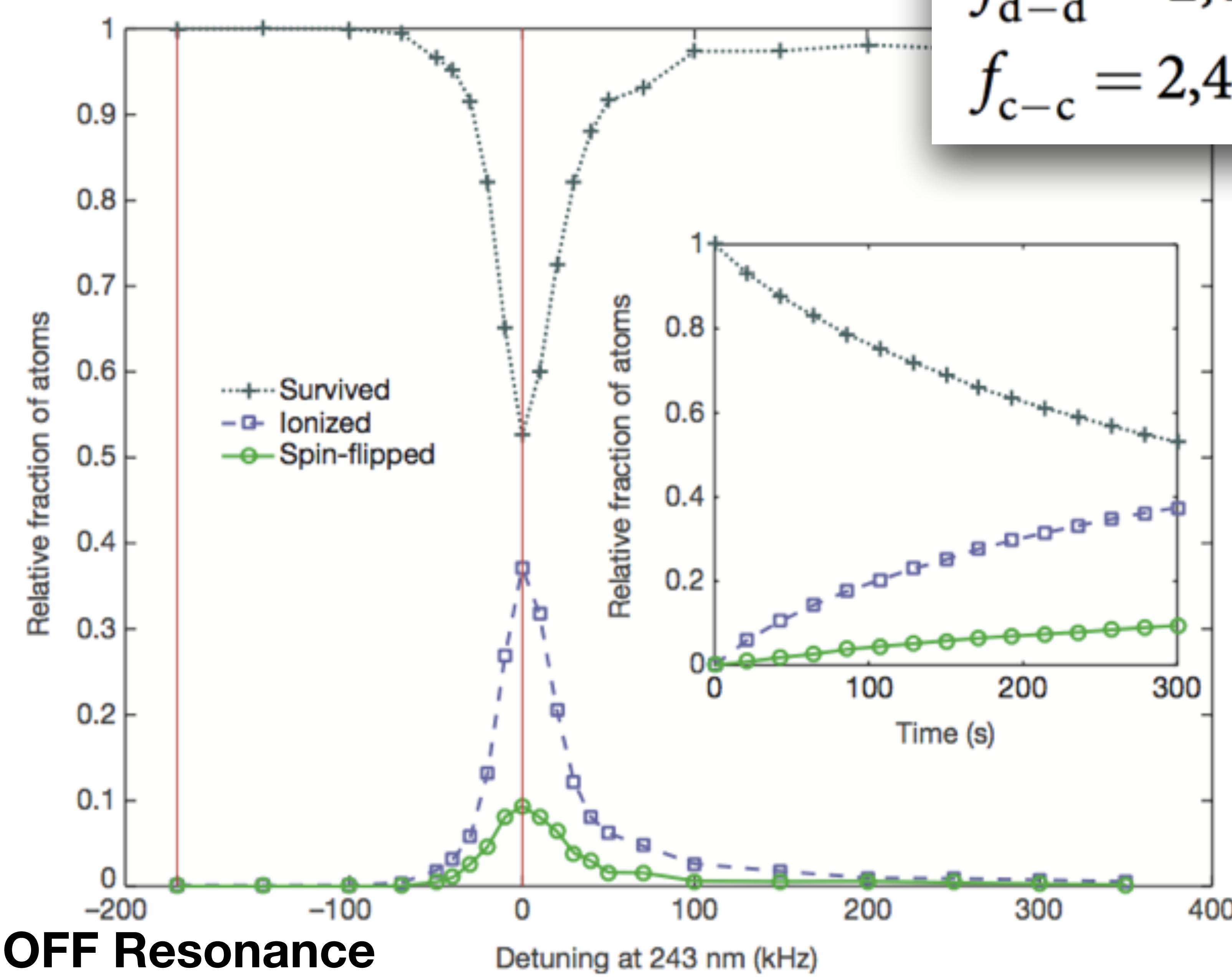
Antihydrogen stacking

- Plasma techniques improved (improved trapping rate)
- Anithydrogen stacked! (improved statistics)



1S - 2S possible outcomes

ON Resonance



OFF Resonance

$$f_{d-d} = 2{,}466{,}061{,}103{,}064(2)\ \text{kHz}$$
$$f_{c-c} = 2{,}466{,}061{,}707{,}104(2)\ \text{kHz}$$

OFF resonance:
200 kHz detuned

ON resonance:
47% Removal
(1 Watt circulating power)

1S - 2S Disappearance

- ON-Resonace de-populates the trap

Type	Number of detected events	Background	Uncertainty
Off resonance	159	0.7	13
On resonance	67	0.7	8.2
No laser	142	0.7	12

- ON and OFF resonance trials differ by 92 ± 15 counts
  - (Detector efficiency here is 0.376)
- (58 ± 6)% of atoms removed

1S - 2S Appearance

- Tune MVA for appearance mode

Type	Number of detected events	Expected Background	Uncertainty
d–d off resonance	15	14.2	3.9
d–d on resonance	39	14.2	6.2
No laser	22	14.2	4.7
c–c off resonance	12	14.2	3.5
c–c on resonance	40	14.2	6.3
No laser	8	14.2	2.8
d–d + c–c off resonance	27	28.4	5.2
d–d + c–c on resonance	79	28.4	8.9
No laser (sum)	30	28.4	5.5

- Difference (ON - OFF) resonance totals is 52 ± 10
  - (Detector efficiency here is 0.376)

Annihilations in disappearance	92 / 0.688	134
Annihilations in appearance	52 / 0.376	138

1S - 2S Summary

LETTER

OPEN

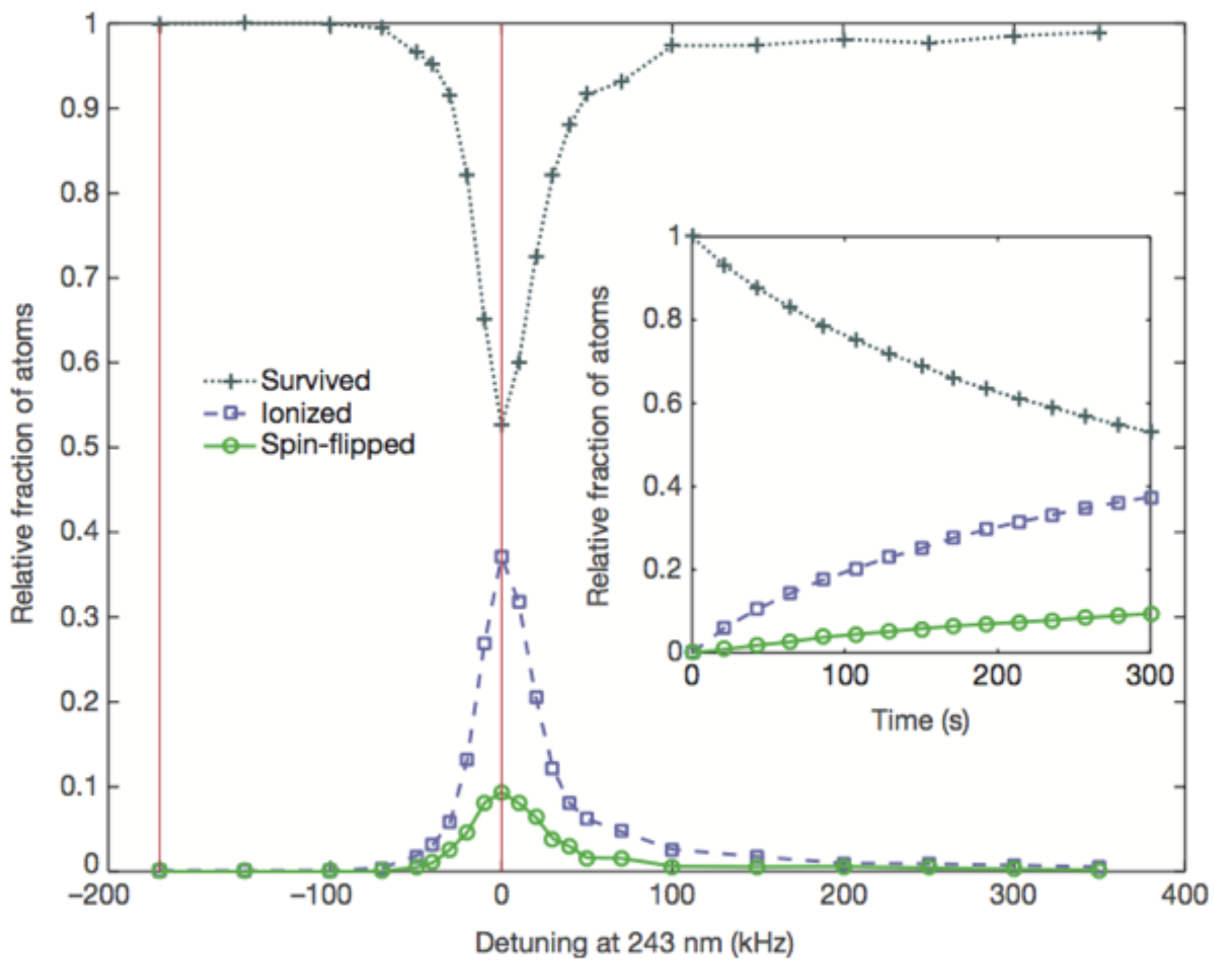
doi:10.1038/nature21040

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

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], E. Butler[6], A. Capra[7], C. Carruth[8], C. L. Cesar[9], M. Charlton[3], S. Cohen[10], R. Collister[7], S. Eriksson[3], A. Evans[11], N. Evetts[12], J. Fajans[8], T. Friesen[2], M. C. Fujiwara[7], D. R. Gill[7], A. Gutierrez[13], J. S. Hangst[2], W. N. Hardy[12], M. E. Hayden[14], C. A. Isaac[3], A. Ishida[15], M. A. Johnson[4,5], S. A. Jones[3], S. Jonsell[16], L. Kurchaninov[7], N. Madsen[3], M. Mathers[17], D. Maxwell[3], J. T. K. McKenna[7], S. Menary[17], J. M. Michan[7,18], T. Momose[12], J. J. Munich[14], P. Nolan[1], K. Olchanski[7], A. Olin[7,19], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[20], R. L. Sacramento[9], M. Sameed[3], E. Sarid[21], D. M. Silveira[9], S. Stracka[22], G. Stutter[2], C. So[11], T. D. Tharp[23], J. E. Thompson[17], R. I. Thompson[11], D. P. van der Werf[3,24] & J. S. Wurtele[8]

1S - 2S Prospects

- The transition has been found (100's kHz level)
- Measurement of lineshape limited by end of beamtime
- Precision at the 10's kHz level is possible
- ~10^{-10} (Hydrogen)



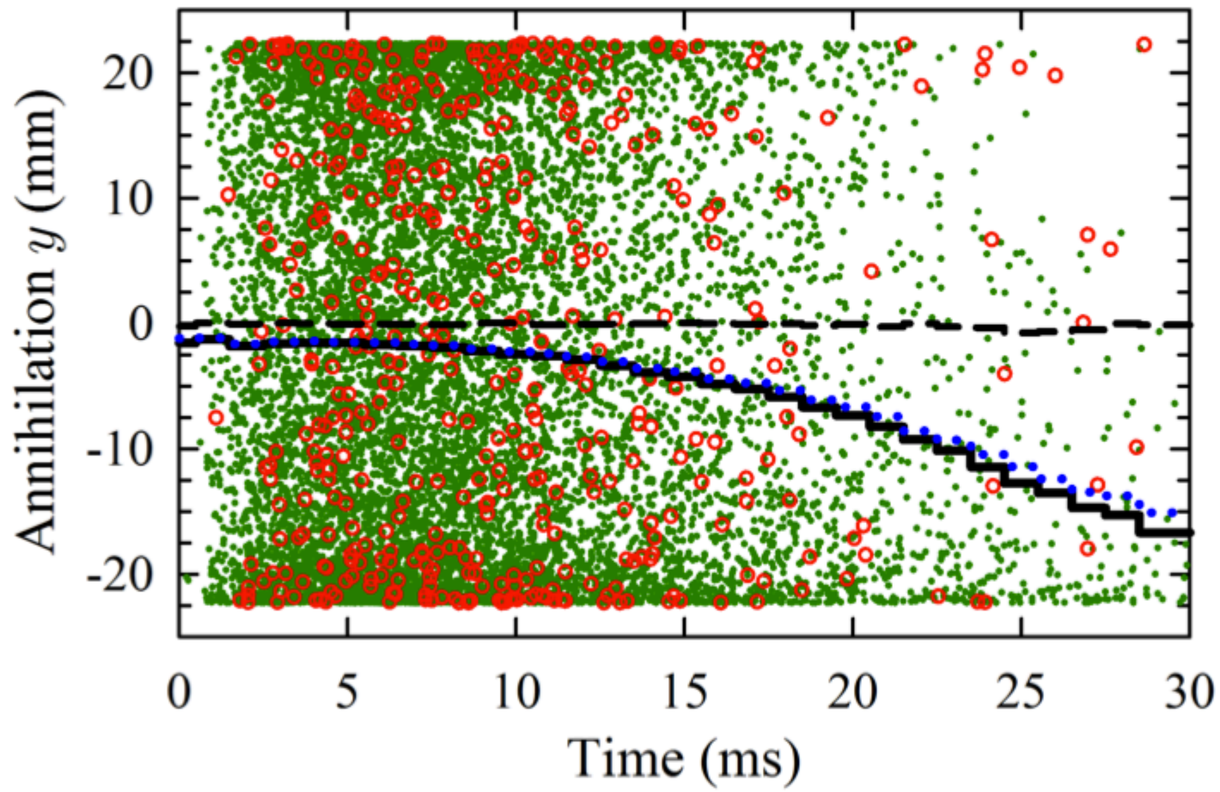
Precision gravity?

- Do atoms and anti-atoms gravitate differently?

$$F_{\text{antimatter}} = F \cdot mg$$

- Antihydrogen will fall out the bottom (or top) of the trap

Simulation for F = 100

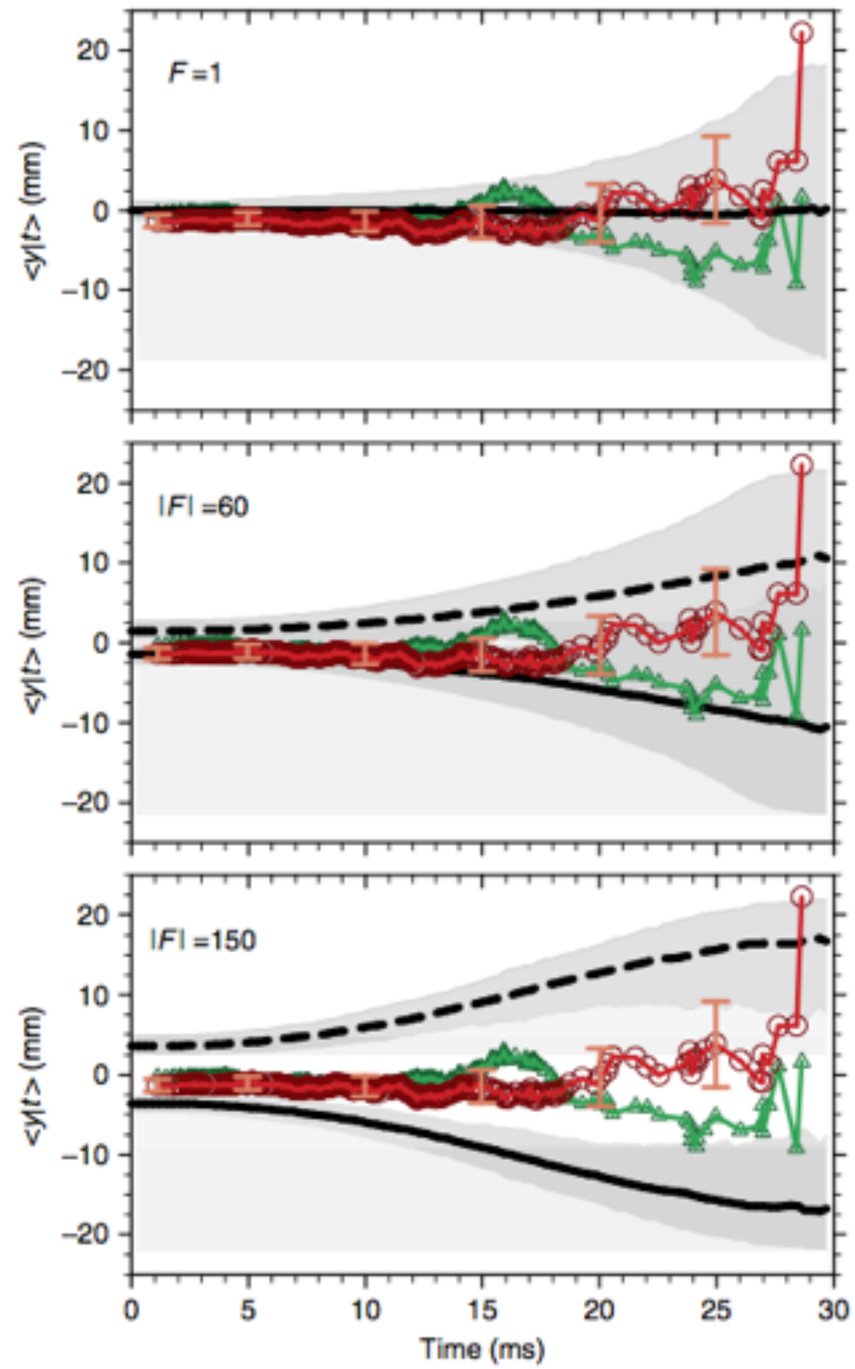


Gravitational Deflection: Precision?

- Simulate various F, test exclusion of RCA during quench

$$-65 < F < 110$$

- Not very precise:
  - Poor statistics, hot population, short distance
- Charge neutrality important



$$F = 1 \sim Q < 10^{-12}$$


ARTICLE

Description and first application of a new technique to measure the gravitational mass of antihydrogen

NATURE COMMUNICATIONS | 4:1785 | DOI: 10.1038/ncomms2787 | www.nature.com/naturecommunications

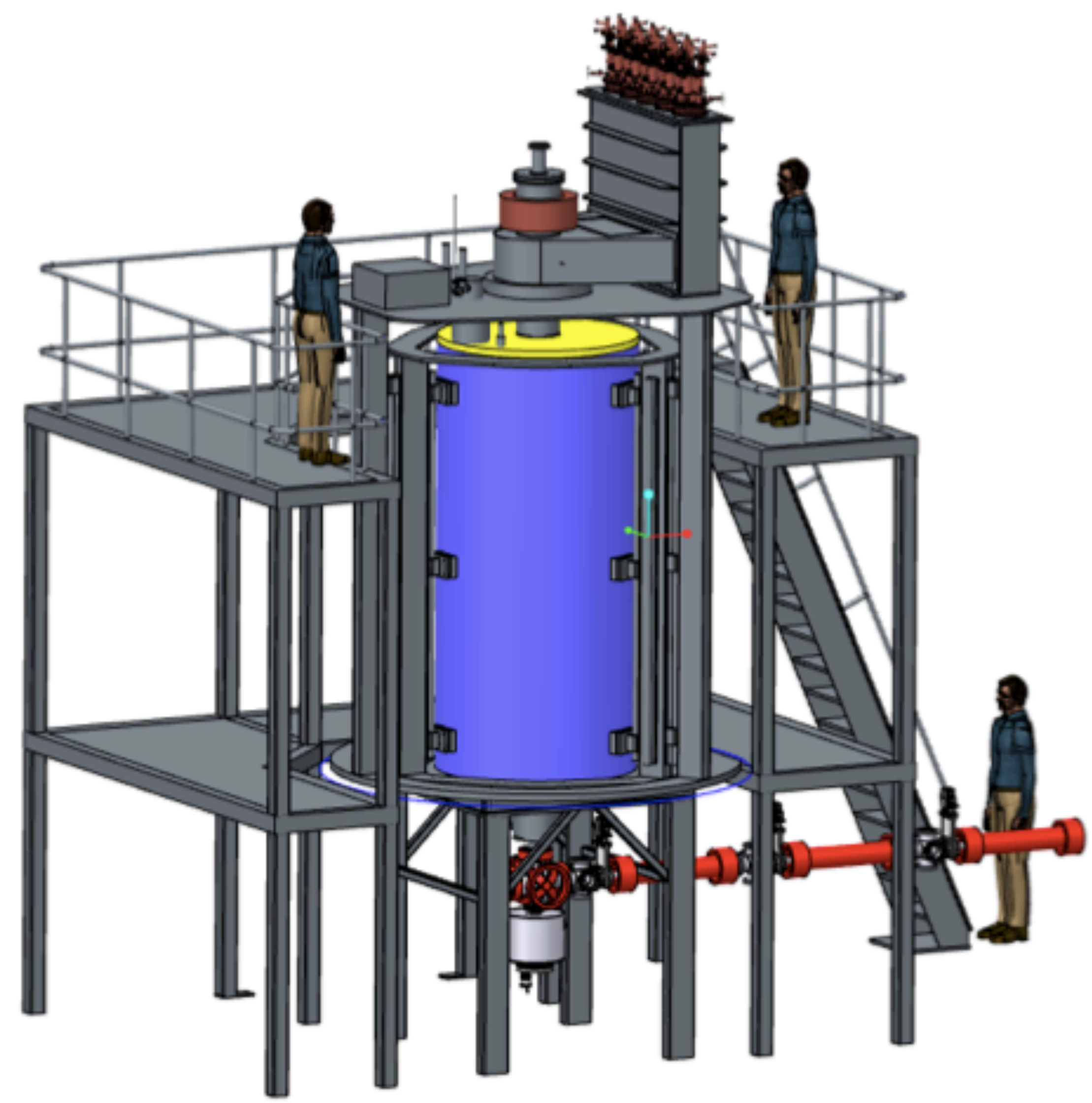
MANCHESTER 1824 The University of Manchester

The Cockcroft Institute of Accelerator Science and Technology

ALPHA

ALPHA-g: Precision gravitational measurements with antihydrogen

- ~ 2 m tall antihydrogen trap
- Release + detect falling Hbar
- Measure sign of gbar
  - ~ 1 year
- Measure gbar a ~ 1%
  - 4 - 5 years



Summary

- Understanding the differences between matter and antimatter is a Grand Challenge of physics

- ALPHA has taken the first steps towards this goal by trapping antihydrogen, driving resonant transitions, measure Charge neutrality
- ALPHA-2: Recently demonstrated driving the 1S - 2S transition
  - Line shape measurements in the near future!
- ALPHA-g: Future effort on gravity underway!

Thanks!

... Many things you can do with antimatter in a can!