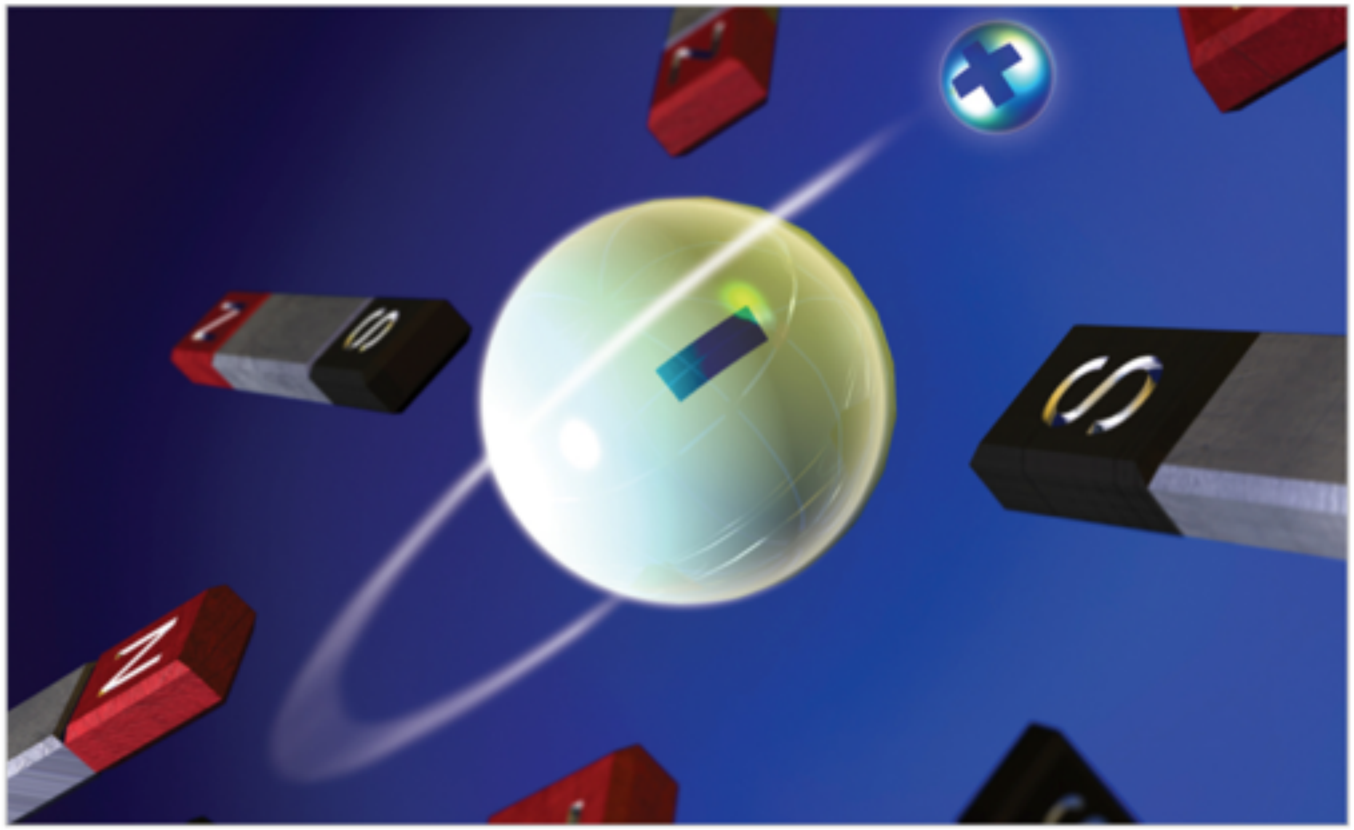
Precision tests with trapped antimatter: A glimpse of the 1S - 2S transition in antihydrogen



Dr. Will Bertsche
The University of Manchester
The Cockcroft Institute

The University of Manchester

The Cockcroft Institute of Accelerator Science and Technology

ALPHA

ALPHA Experiment @ CERN

- Precision measurements on antimatter using Antihydrogen atoms

What is Antimatter?

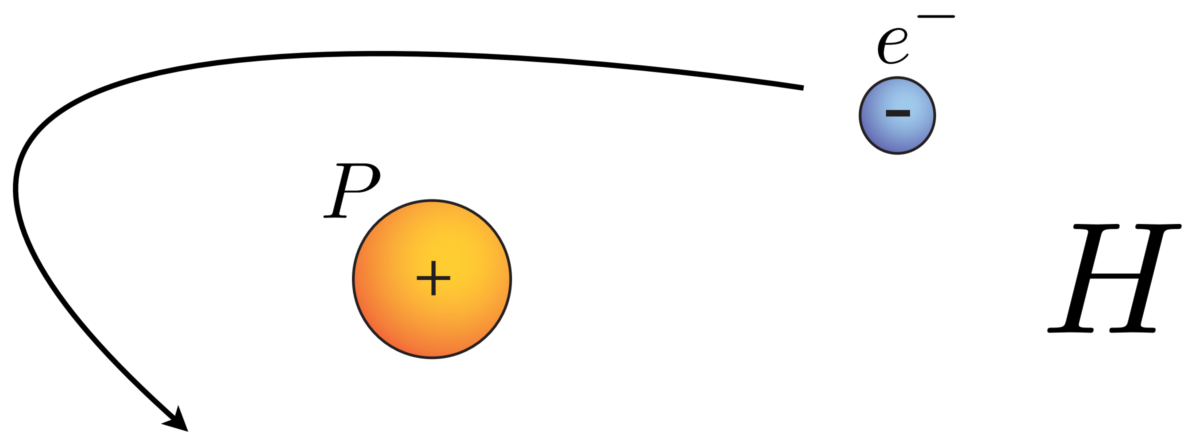
- Particles have twins with same mass, opposite charge

	Electron	Proton
Matter:	e^{-}	P
Antimatter:	Positron e^{+}	Antiproton $\bar{P}$

What is Antimatter?

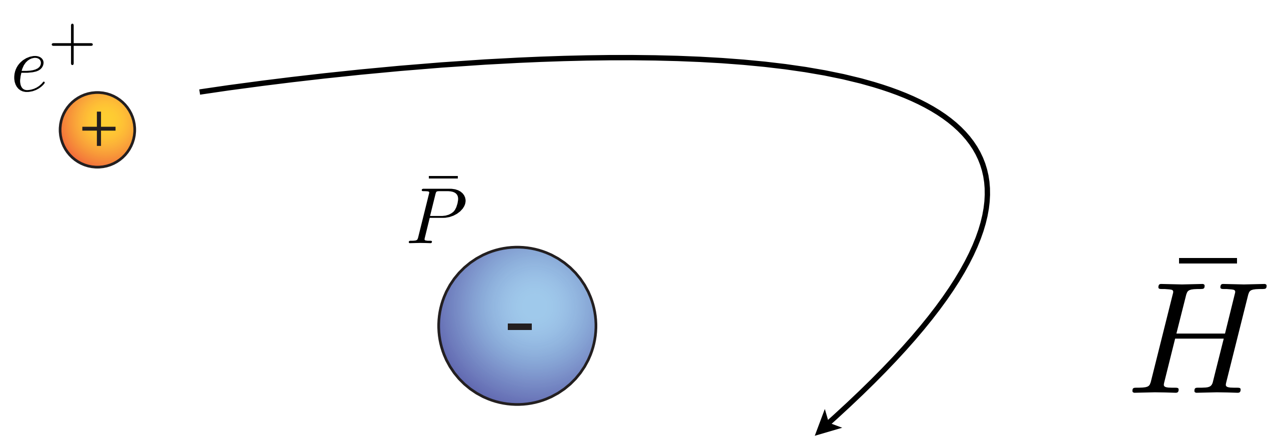
- Atoms and antimatter atoms?

Matter:



Hydrogen

Antimatter:



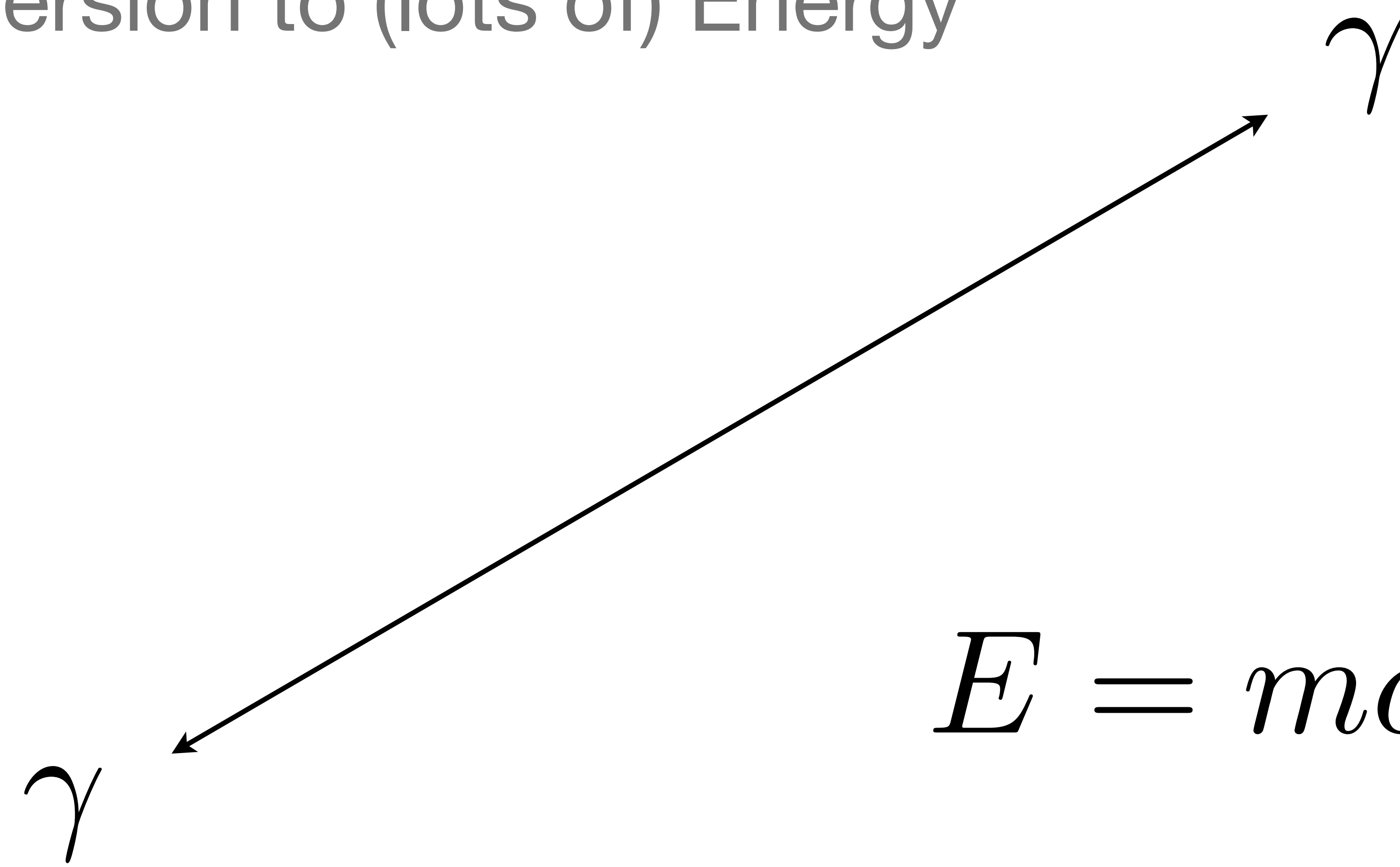
Antihydrogen

What is Antimatter?

- Watch out when they meet their twin!

What is Antimatter?

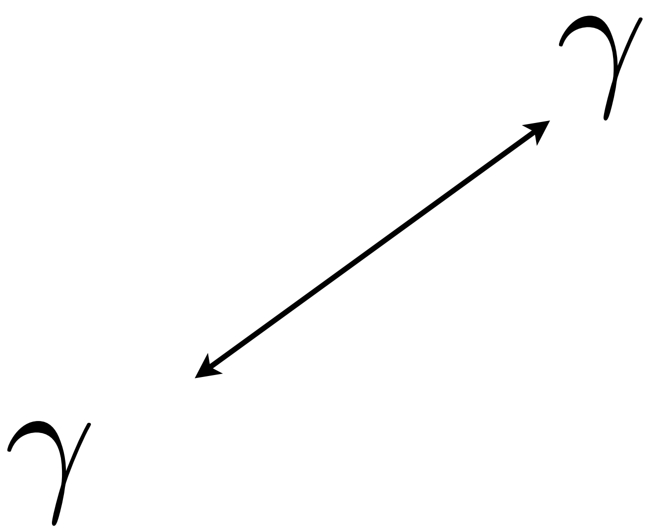
- Annihilation!
- Conversion to (lots of) Energy



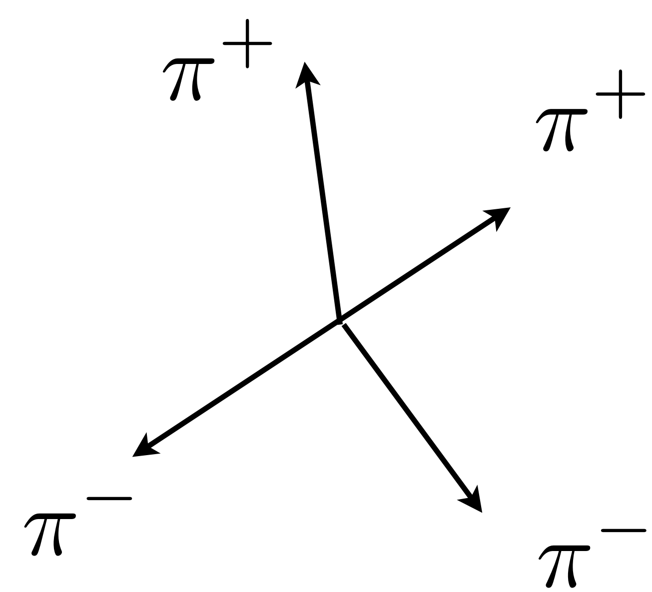
$$E = mc^2$$

Annihilations

- Positron / Electron: photons (511 keV)
- Antiproton / Proton: Many possibilities - Pions, etc.



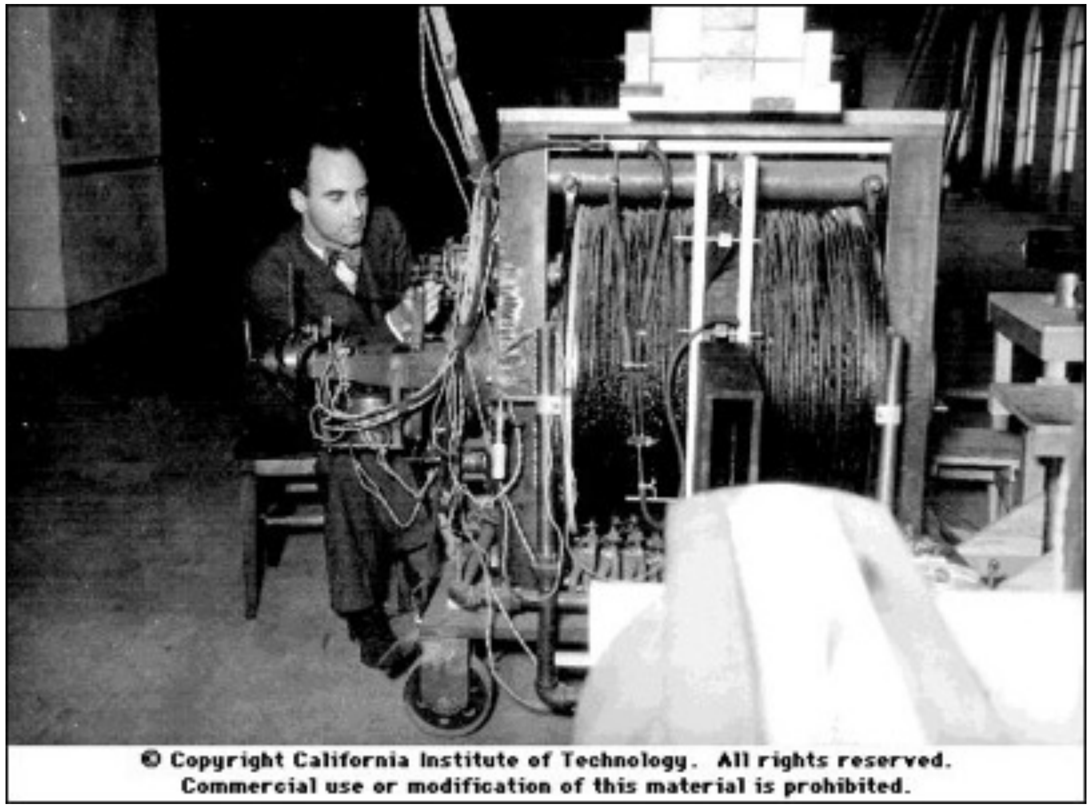
positron / electron
Annihilation

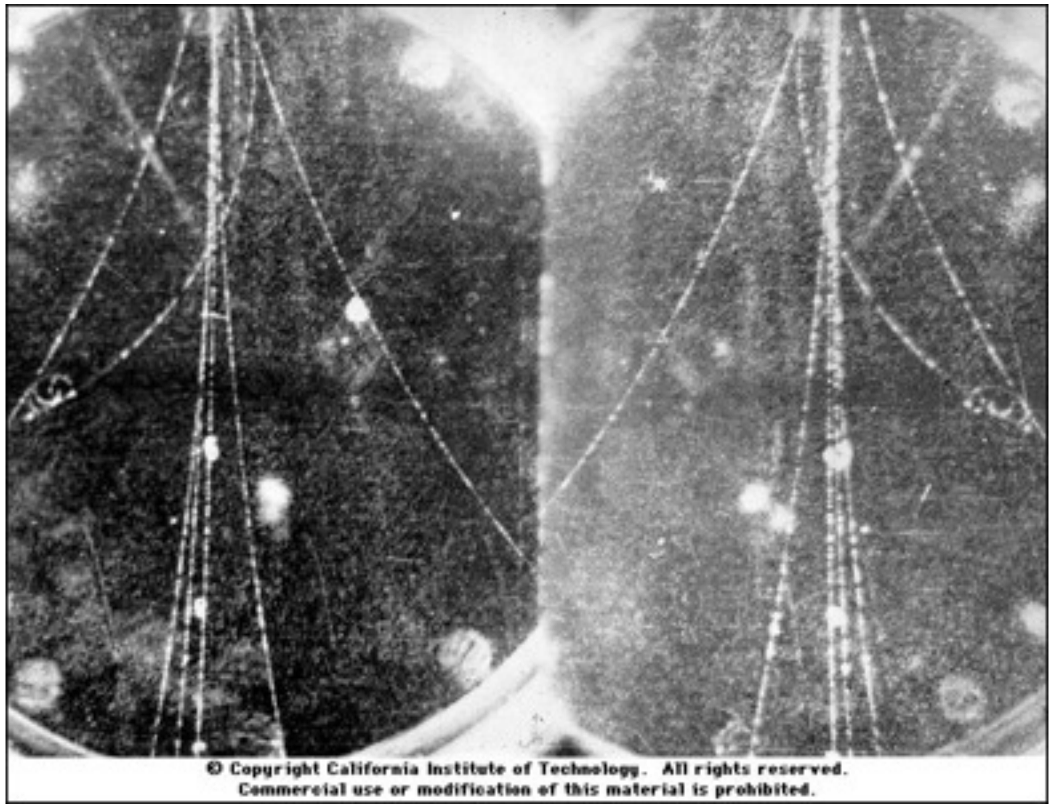


proton / antiproton
Annihilation

First Observation: Positrons

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



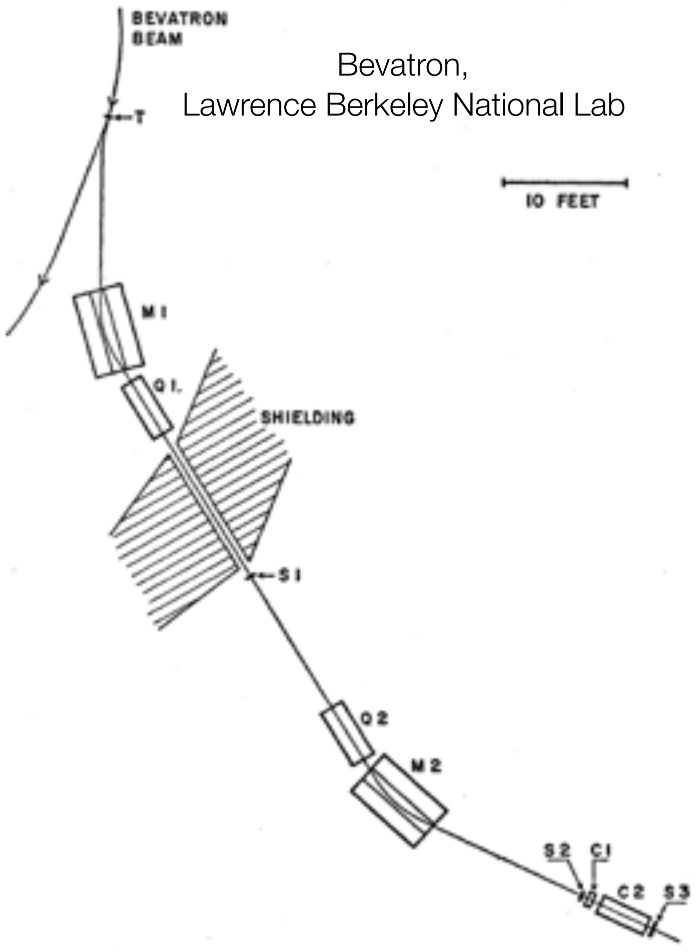


First Observation: Antiprotons

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

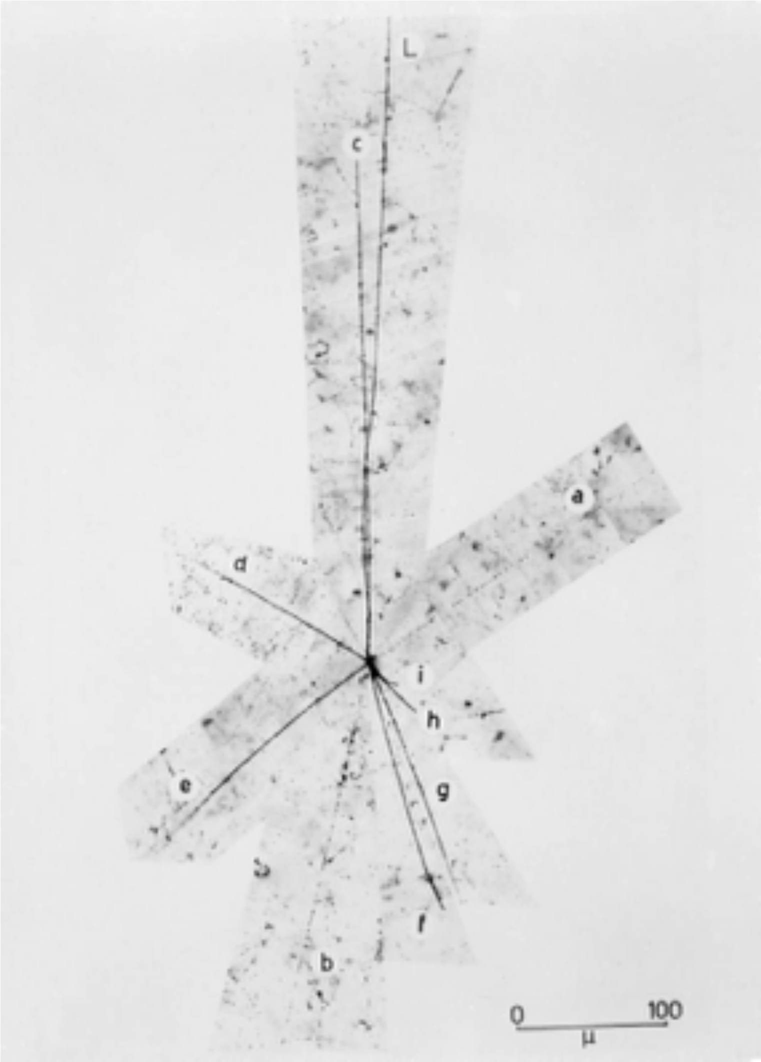
Chamberlain

Segrè



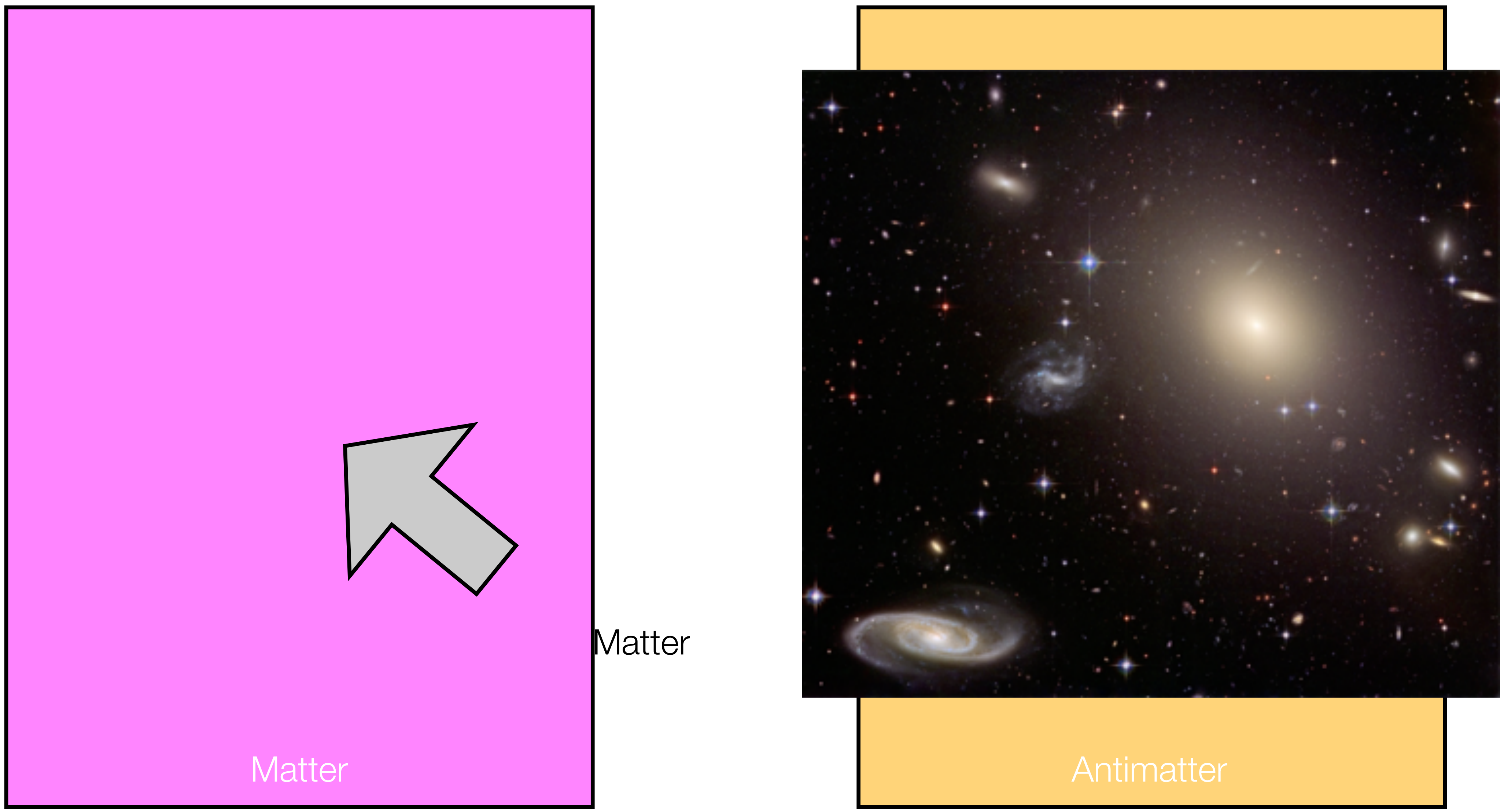
Bevatron,
Lawrence Berkeley National Lab

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?

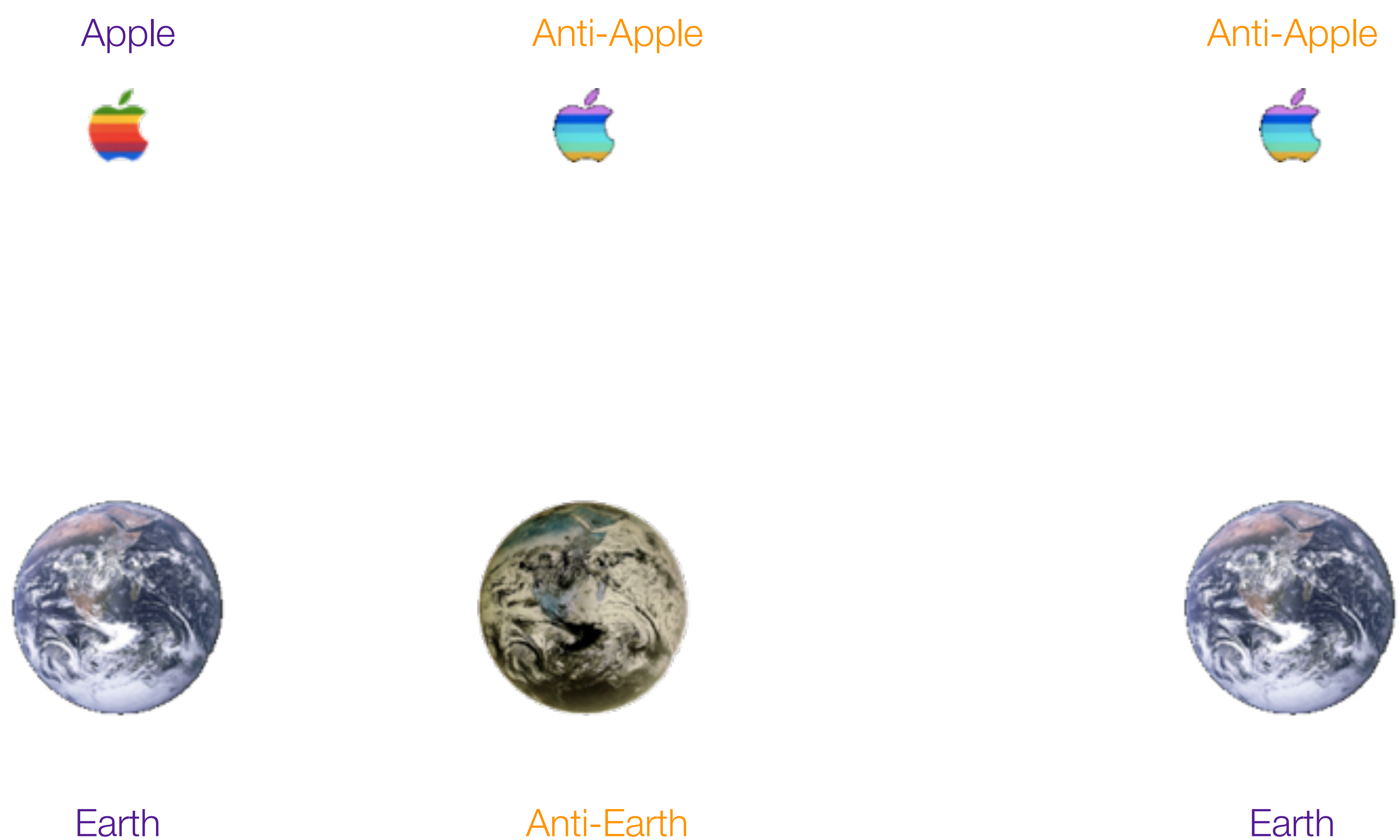
- C. P. T. Symmetry: Fundamental Feature of Universe

  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?

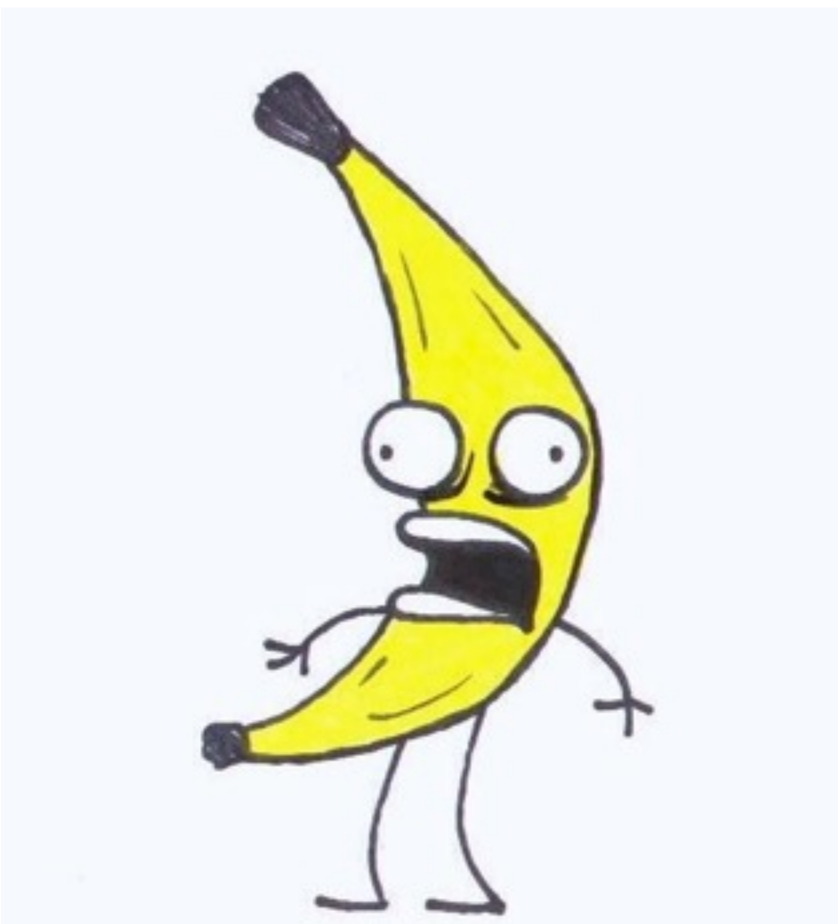
- Gravity?



Where do Positrons come from?

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

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

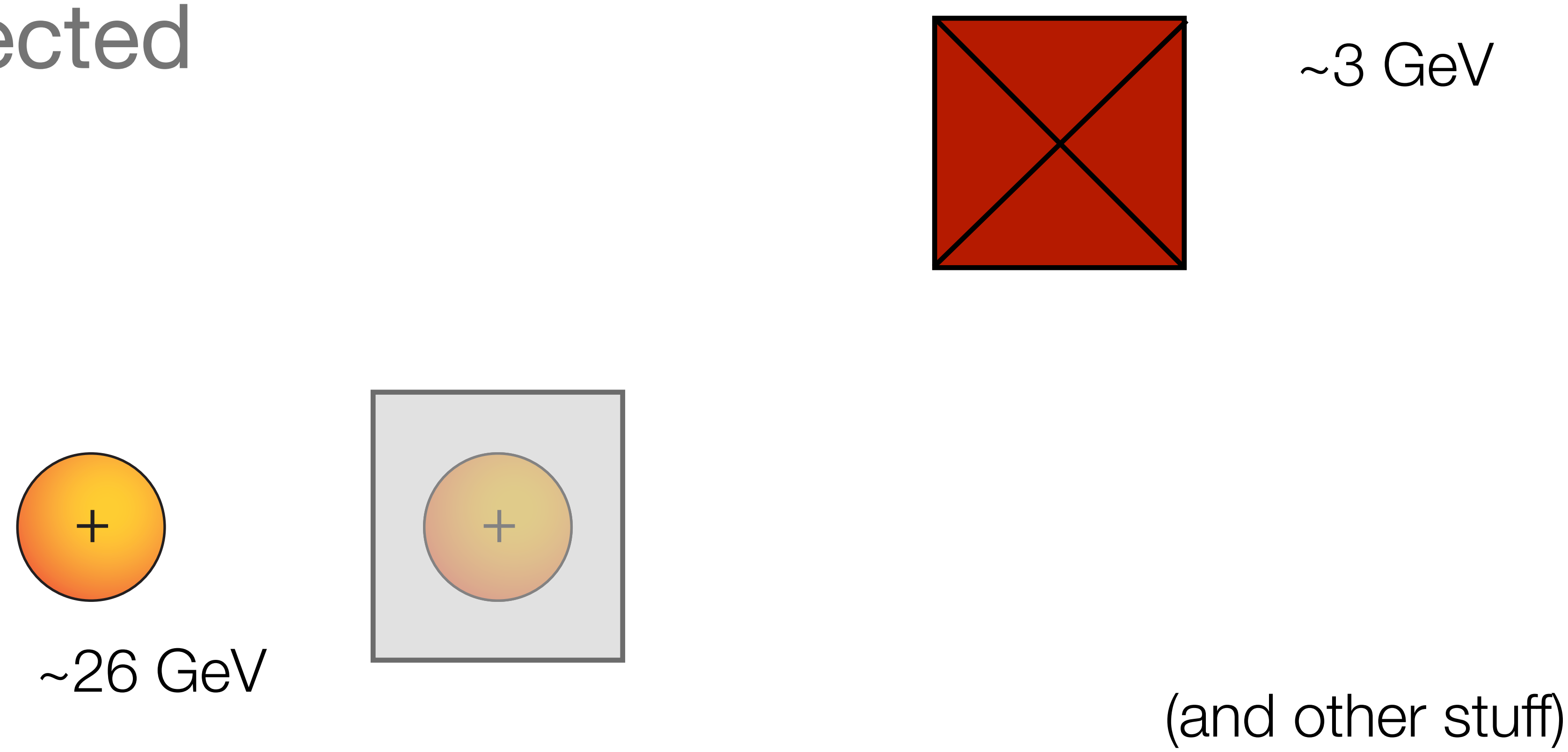


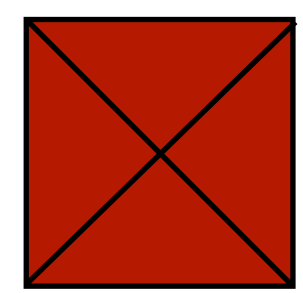
“I am a banana!” Don Hertzfeld

Where do Antiprotons come from?

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

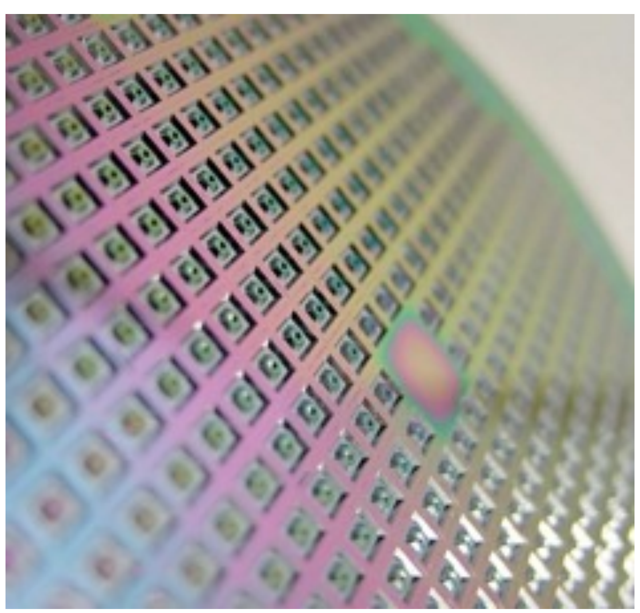
Cern Proton Synchrotron

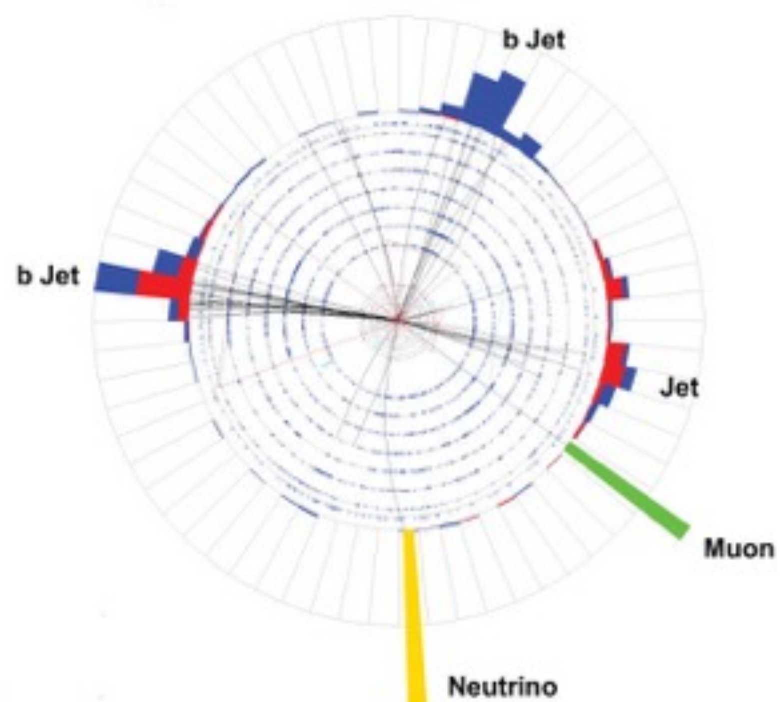




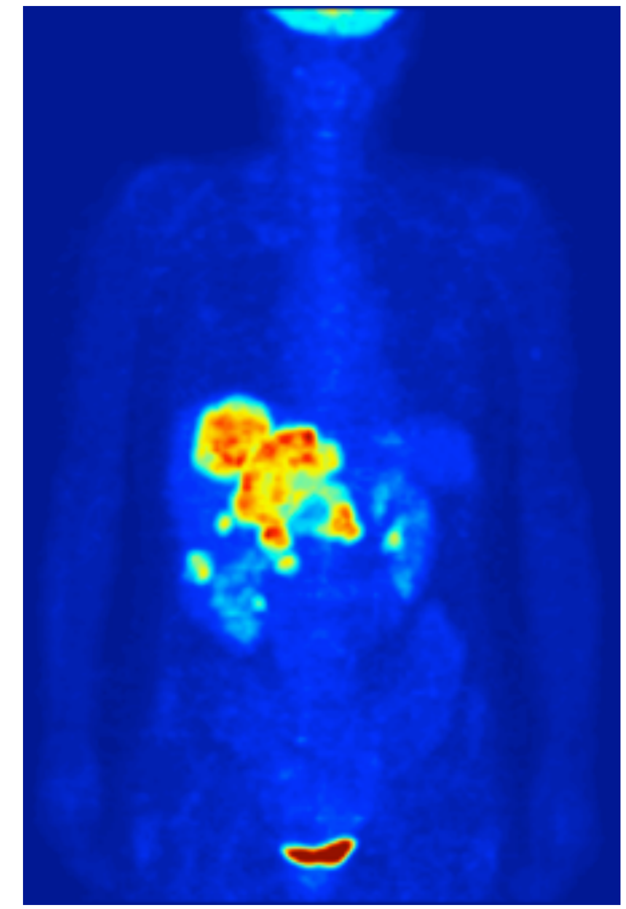
Antimatter: What's it good for?

- Material Characterization (positrons)
- Medical imaging: PET scans
  - Positron Emission Spectroscopy
- High energy physics (antiprotons)



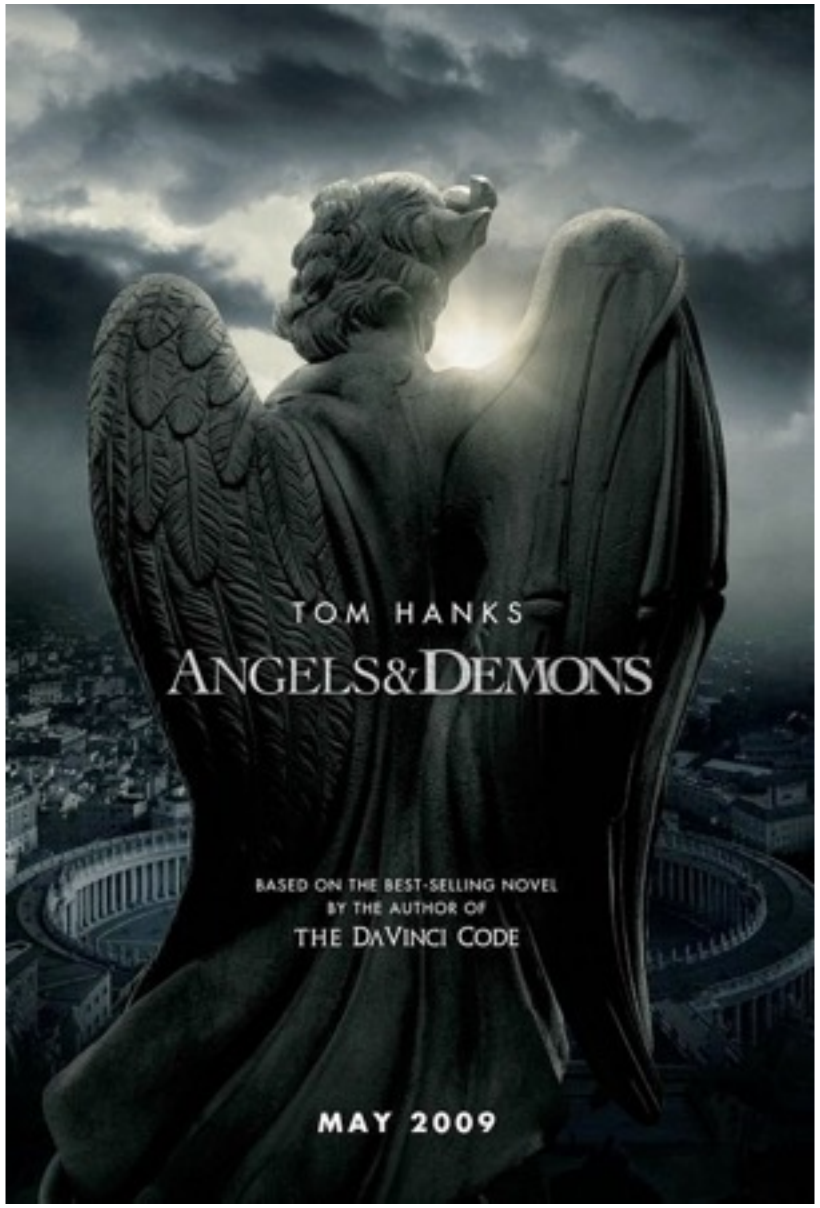


Single Top-Quark Candidate Event.
D-Zero collaboration



Antimatter: What's it good for?

Hollywood has some suggestions...



a surprisingly timely movie...

Wouldn't that make a good bomb?

Dan Brown writes a novel: "Angels and Demons"

- About researchers from CERN ...
- ... trapping 1/4 gram of antimatter ...
- ... that is stolen by the Illuminati ...
- ... who threaten to blow up the Vatican.

...amidst scandal on the eve of a new Pope

Antimatter Bombs

- Start with antiprotons: (more bang for the buck)
- Mass conversion efficiency is a fundamental limit.

$$\mathrm{P} \rightarrow \sim 10^{-6}\bar{\mathrm{P}} \text{ at } \sim 20 \text{ GeV}/c$$

- Ignoring practicalities of storage...
- CERN could produce this 1/4 gram in ...
  ... about 1 Million years

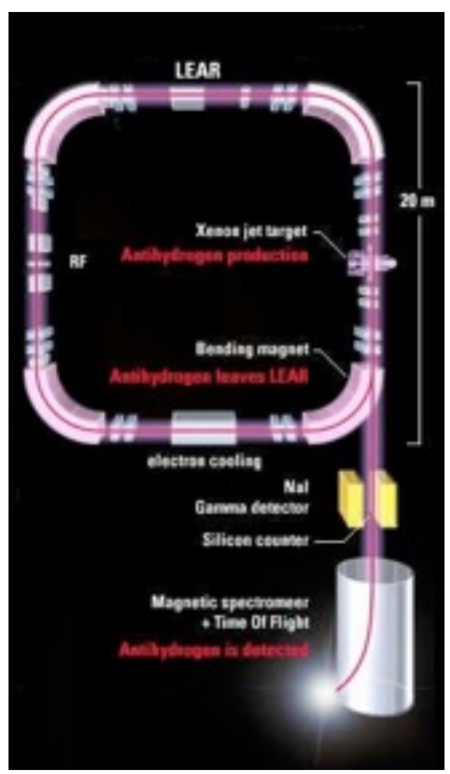
<u>No bombs</u>. Economics don't make sense.

But surely...

Original: Zach Weiner, SMBC-Comics.com

History: Forming Antihydrogen

- 1980’s - Antiprotons at CERN / Fermilab
- ‘Fixed Target’ - smack antiprotons into Xenon
- 9 atoms at CERN (1995), 99 at Fermilab (1996)
- Momenta way too high!



PS210: Baur *et al.* Phys. Lett. B 368, 251 (1996)

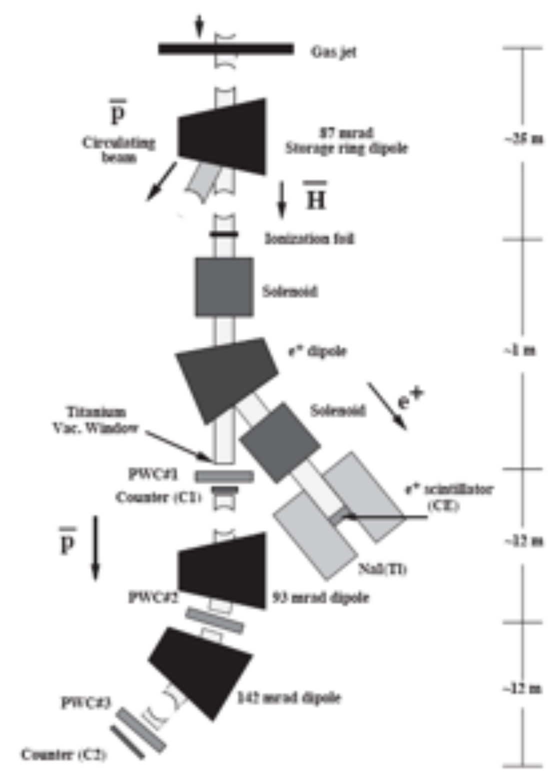
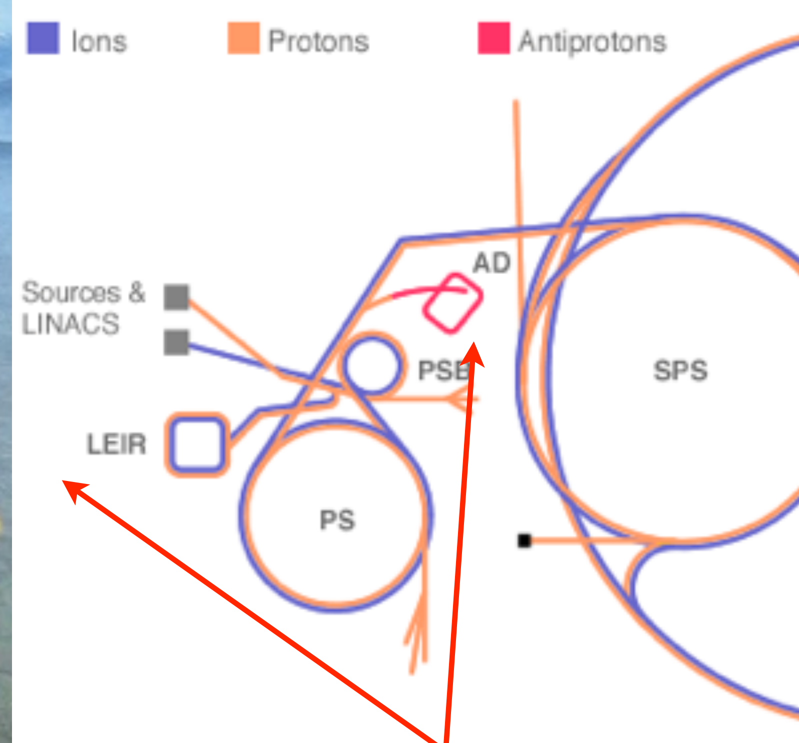


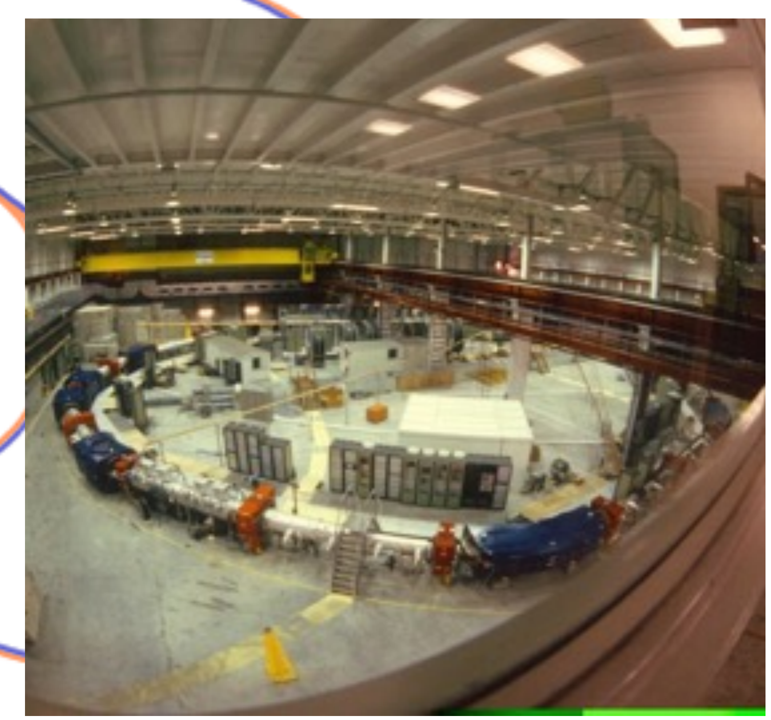
FIG. 1. Experimental Apparatus

E862: Blanford *et al.* Phys. Rev. Lett. 80, 3037 (1998)

History: Forming COLD Antihydrogen

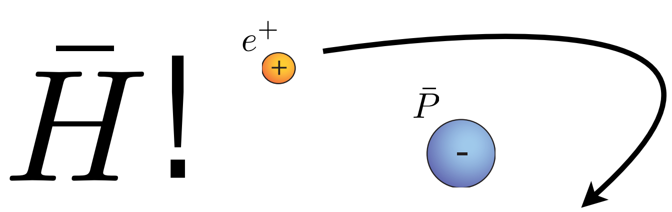
- CERN Antiproton Decelerator (1999)
- AD: 10,000,000 antiprotons / 2 minutes
  - "Low Energy" = 5 Million Volts!
- First 'Cold' antihydrogen: ATHENA and ATRAP (2002)
- 100's of millions produced since



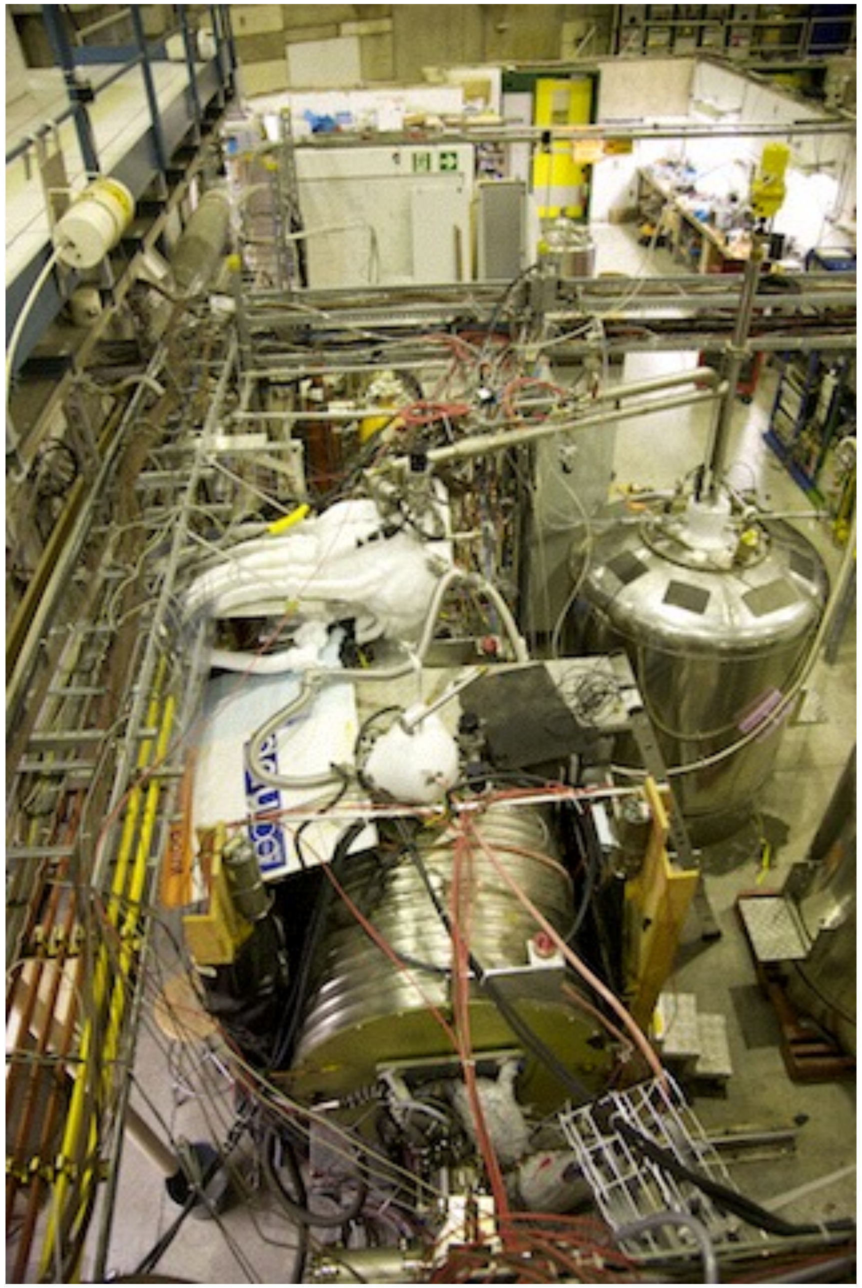


Recipe for Cold Antihydrogen

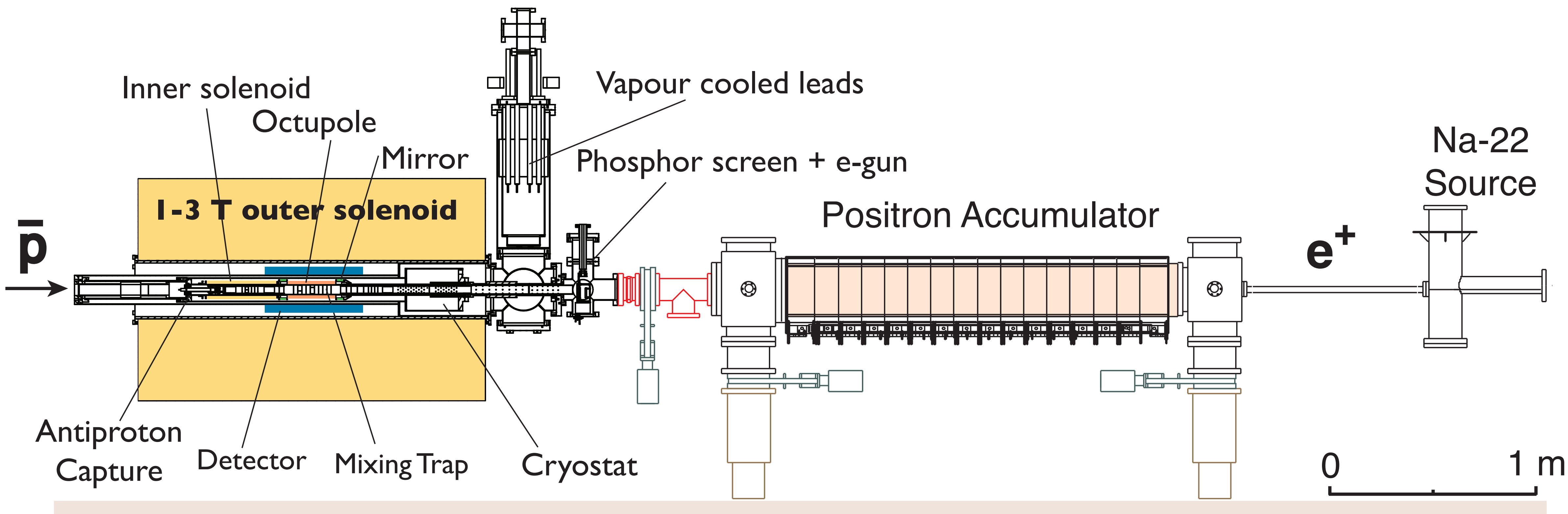
1. Trap ~10 Thousand antiprotons
2. Trap ~10 Million positrons
3. Chill ingredients to 10’s of Kelvin
4. Mix, while keeping species cold and confined
5. Bam!



ALPHA Apparatus

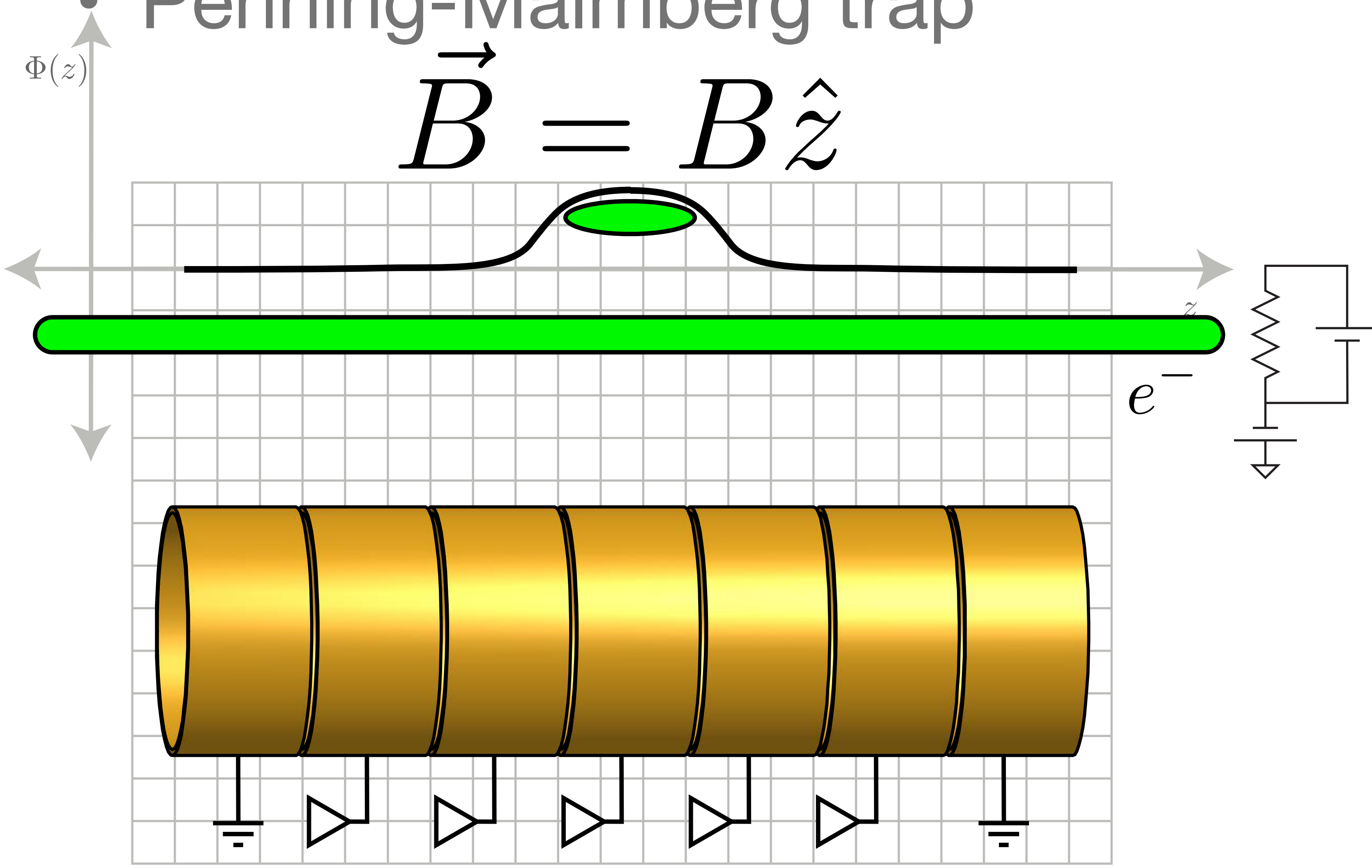


ALPHA Apparatus



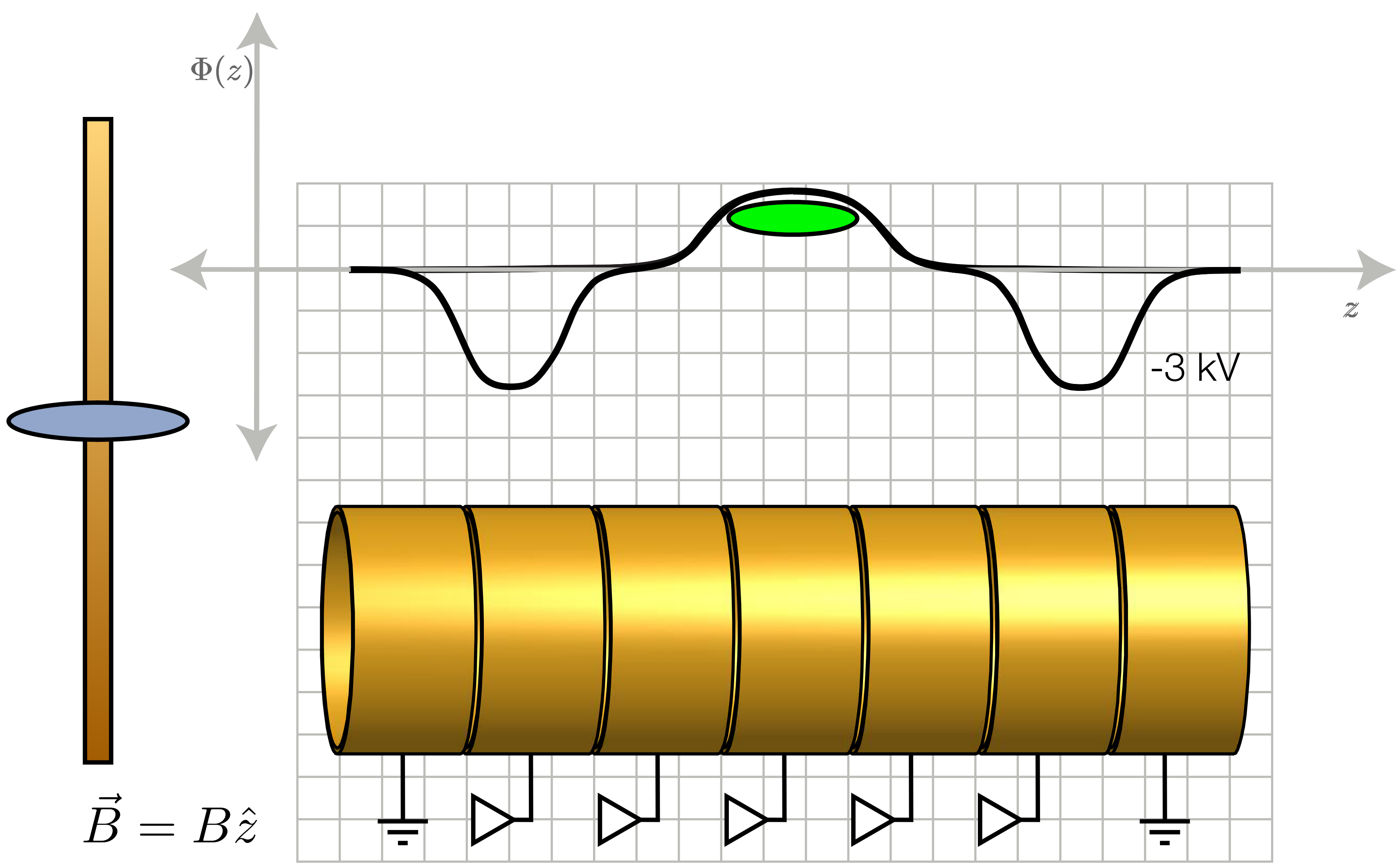
Antimatter: Confinement

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



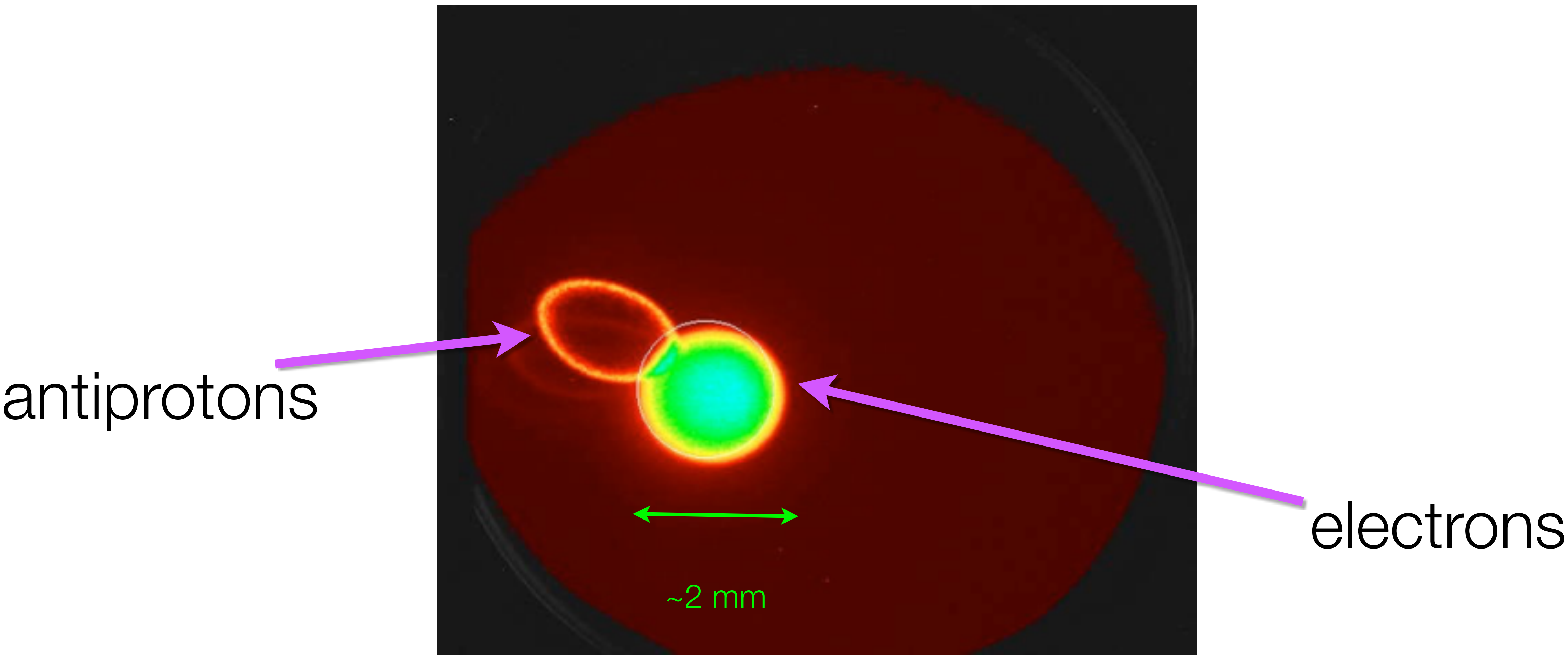
Capturing Antiprotons

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



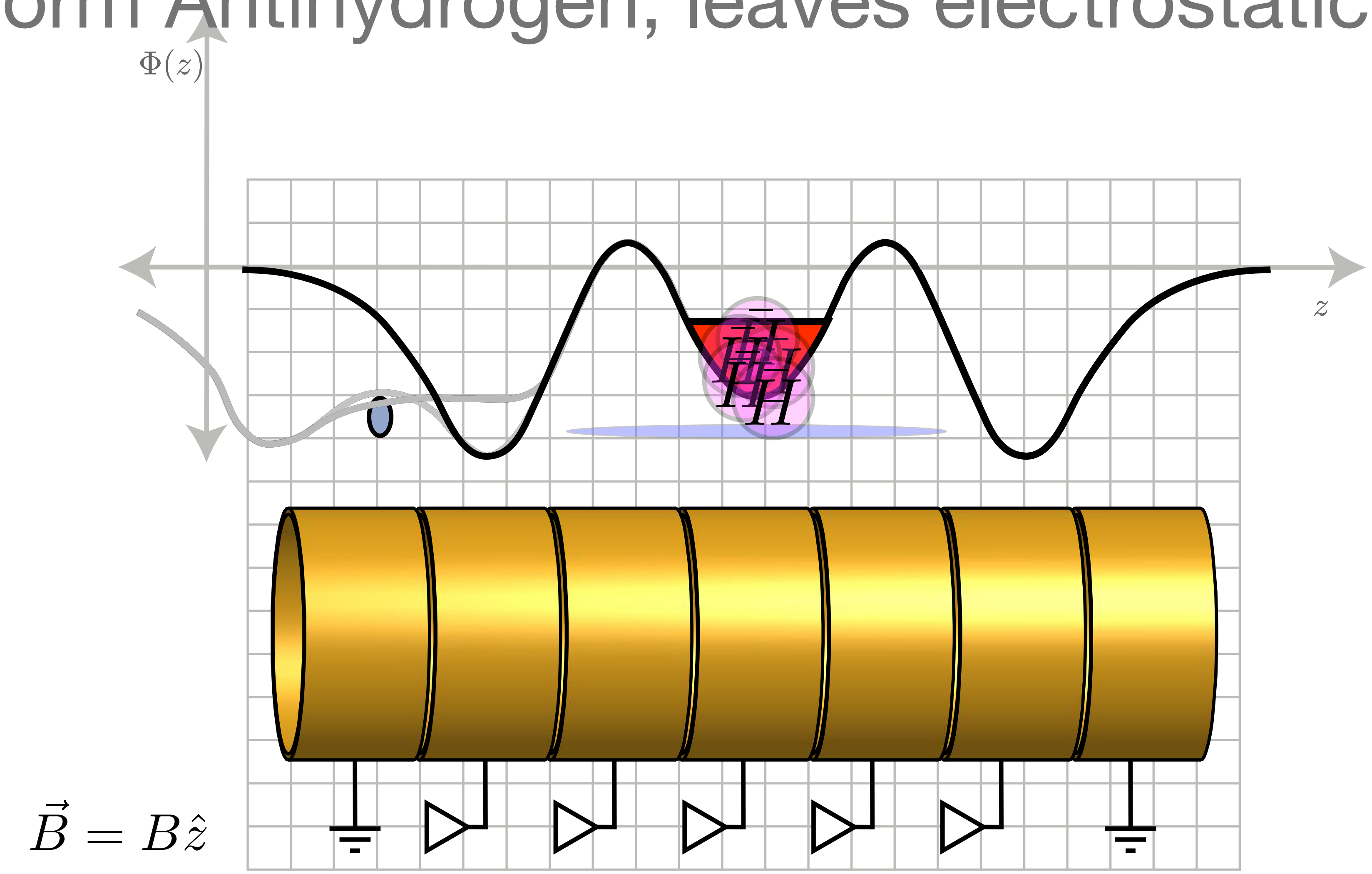
Antiproton / Electron Plasma

- Image the equilibrium Antiproton / Electron plasma



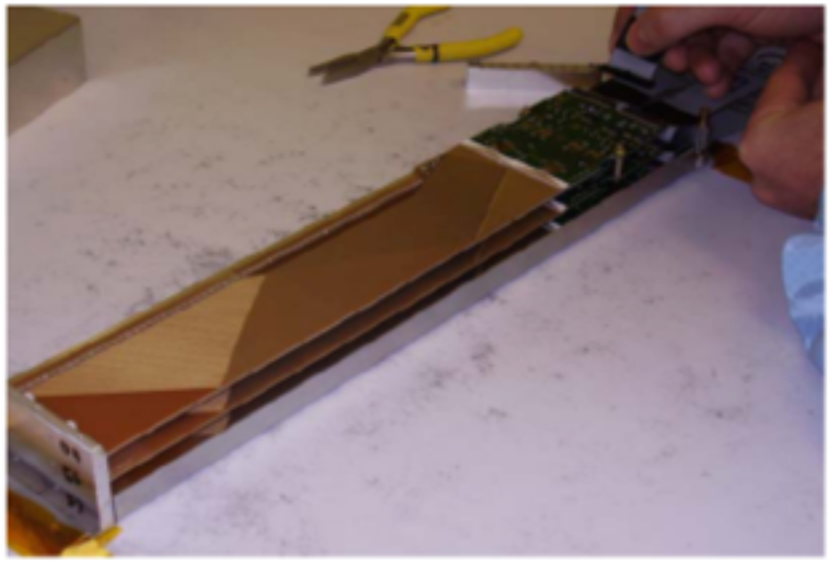
Antihydrogen Formation:
Mixing Antiprotons and Positrons

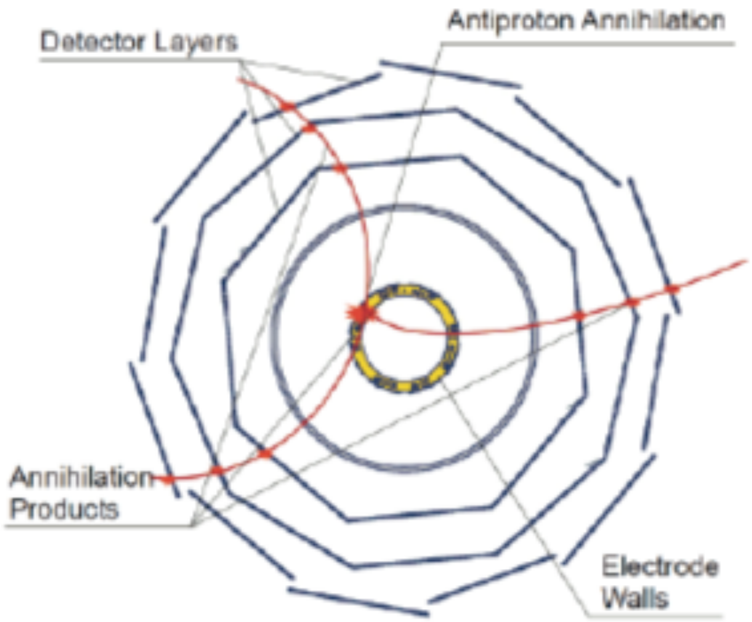
1. Antiprotons injected into ‘Nested Potential’
2. Antiprotons lose energy by collisions with Positrons
3. Form Antihydrogen, leaves electrostatic trap

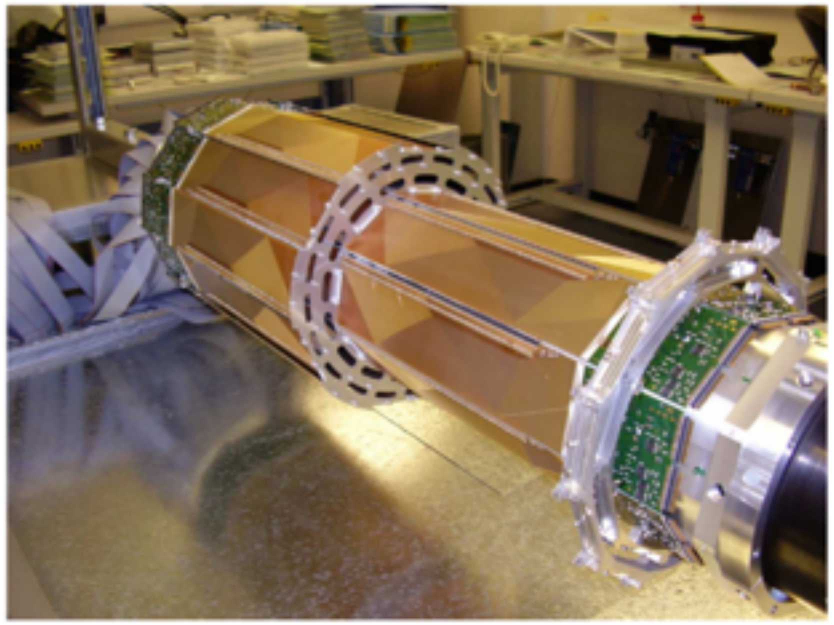


Antihydrogen Detection

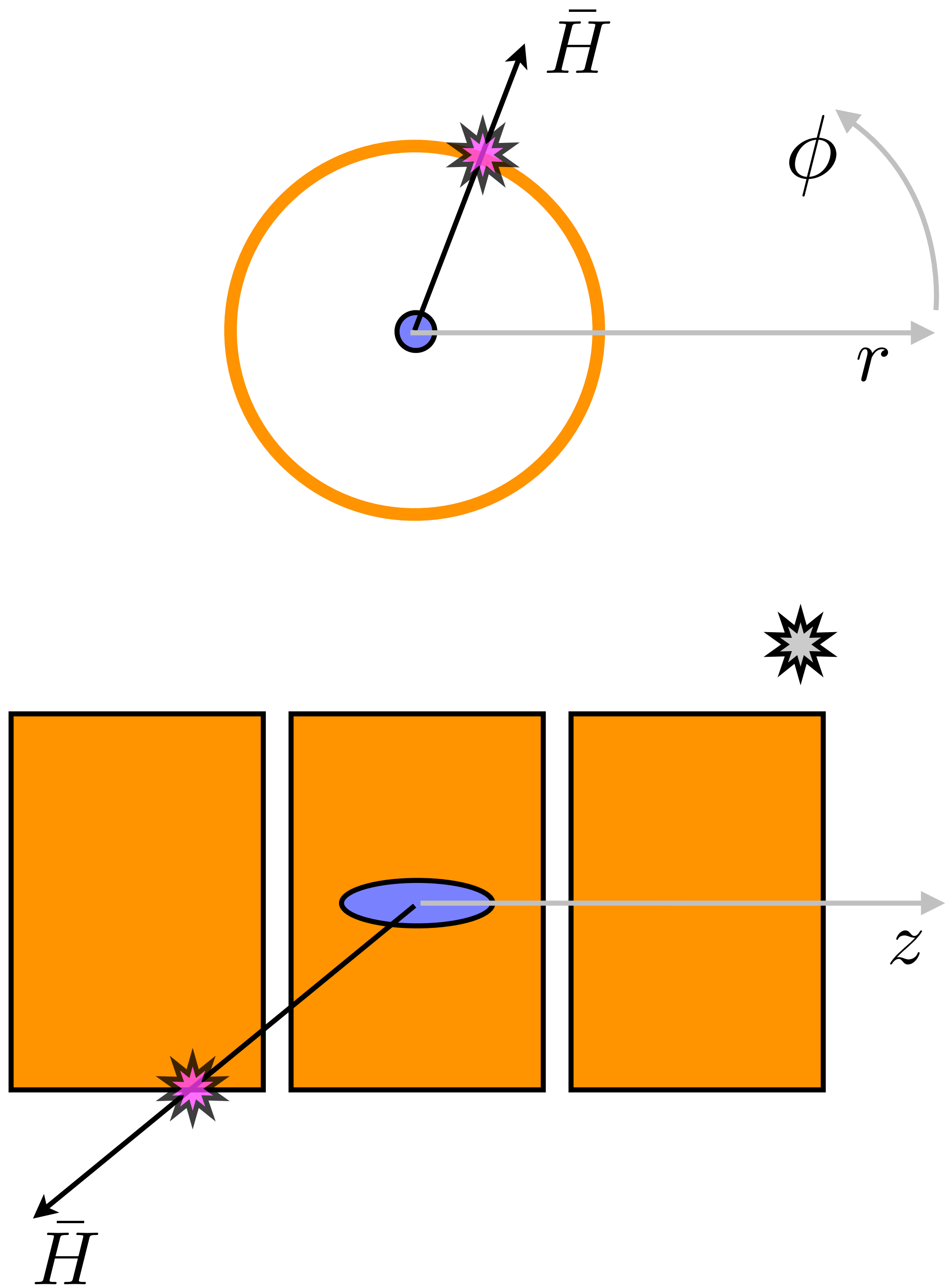
- Silicon-strip detector
- 3D 'Digital Camera'
  - Particle tracks point to vertex
- Vertex resolution ~ 3mm
- > 50% efficiency for annihilations

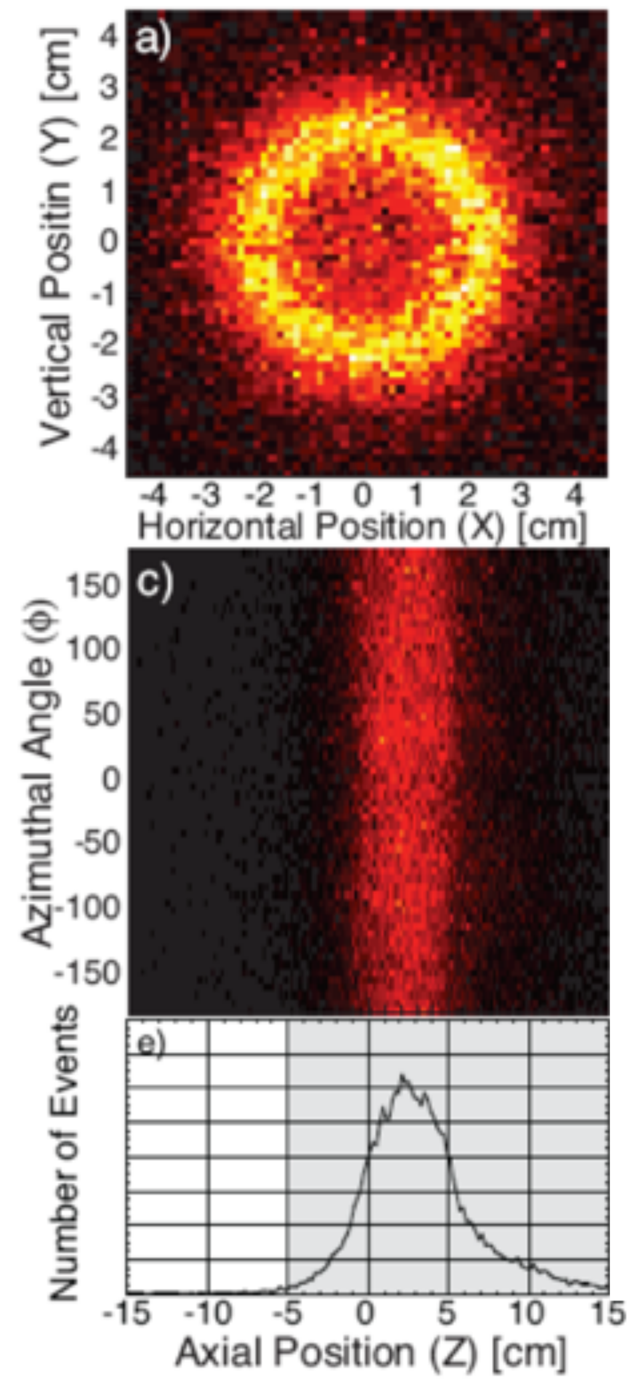






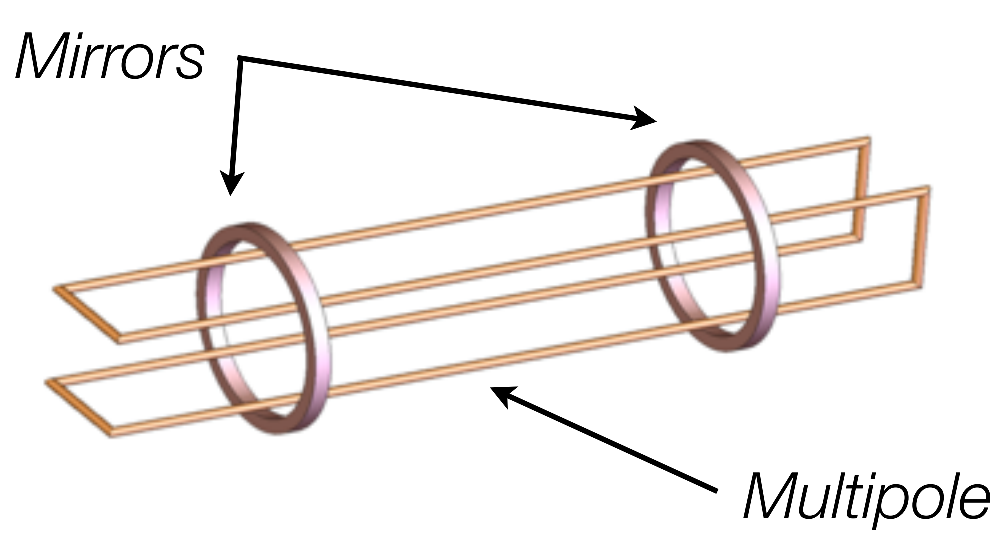
Antihydrogen Detection During Mixing

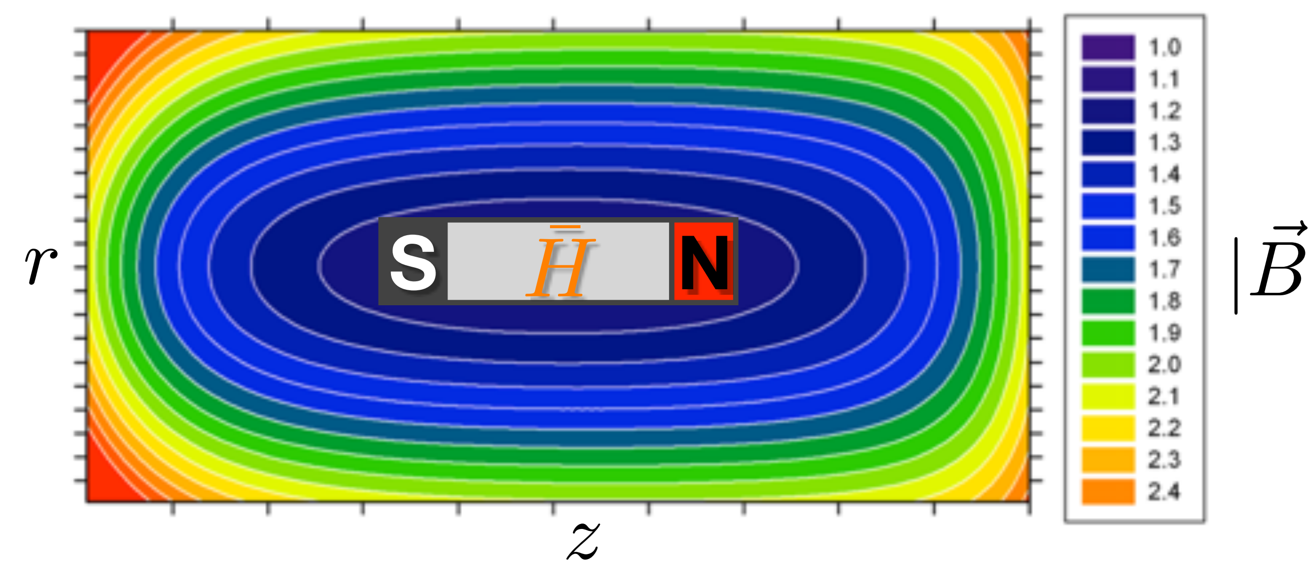




Trapping Antihydrogen

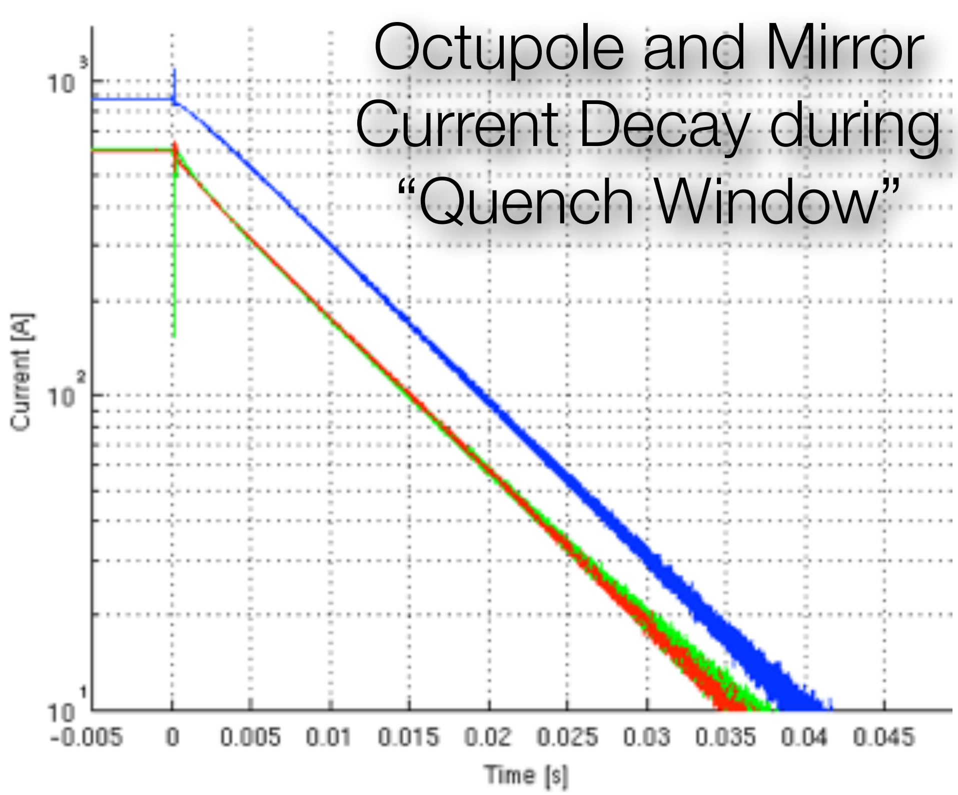
- Atoms are neutral: Not confined by penning traps
- Antihydrogen has a small magnetic moment
  - Like a little refrigerator magnet
- Can use a magnetic minimum trap (superconducting)
- Orientation matters (solenoid keeps alignment)
- Makes a shallow 'Bathtub' for T < 0.5 K (-272.65 C)

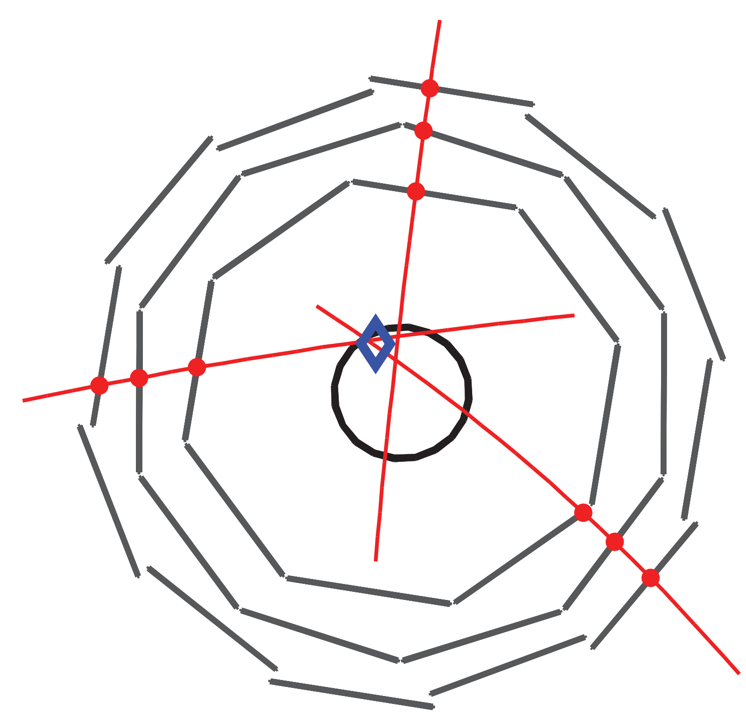




Trapping Antihydrogen: Search

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



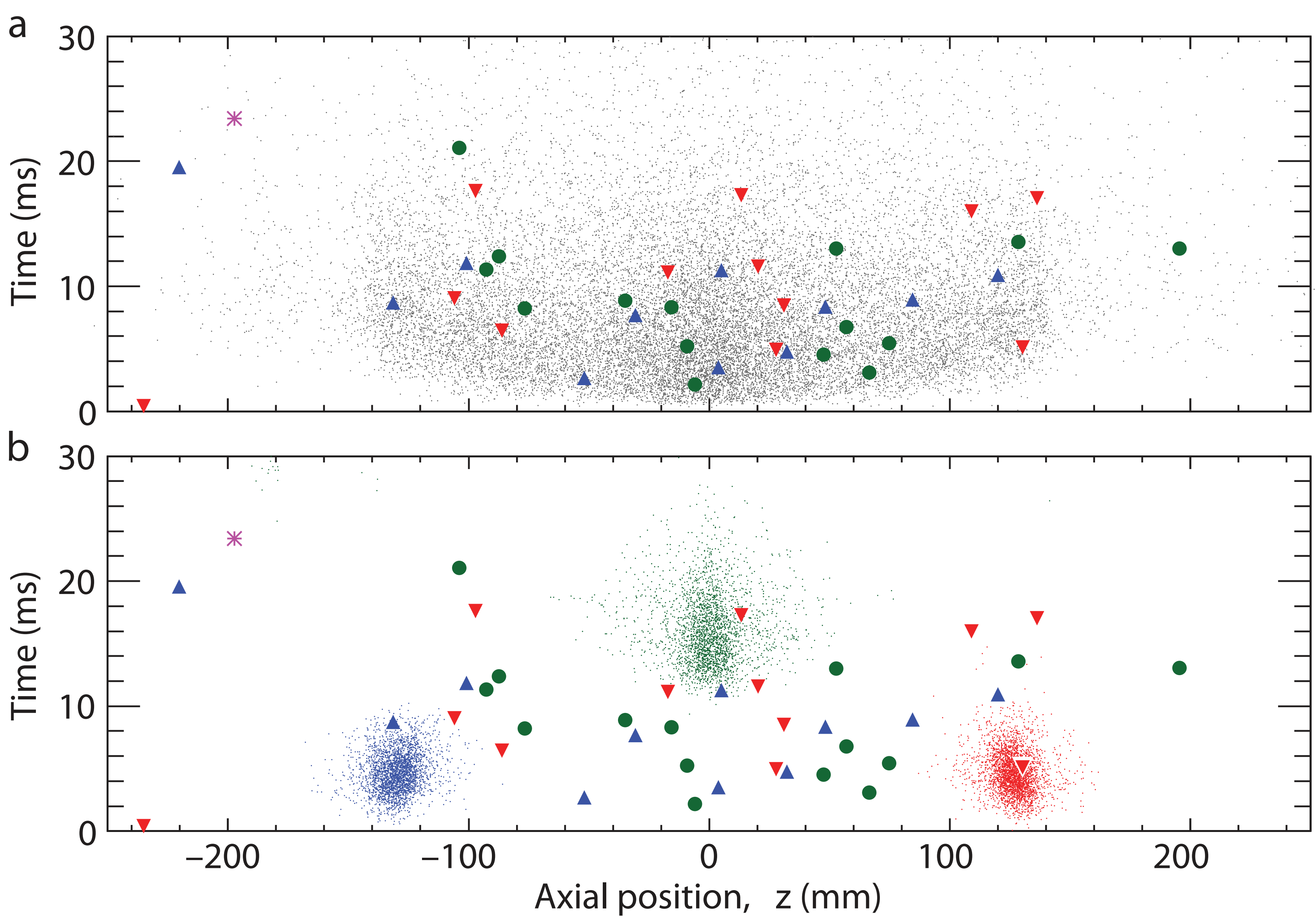


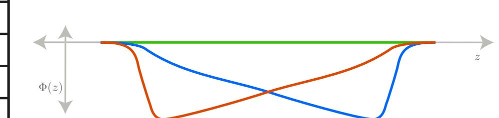
Antihydrogen Search with Bias Fields

- No spatial bias in signal

$\bar{H}$ Simulation

$\bar{P}$ Simulation





No Bias
Left Bias
Right Bias
(* Heating)

Trapped Antihydrogen!

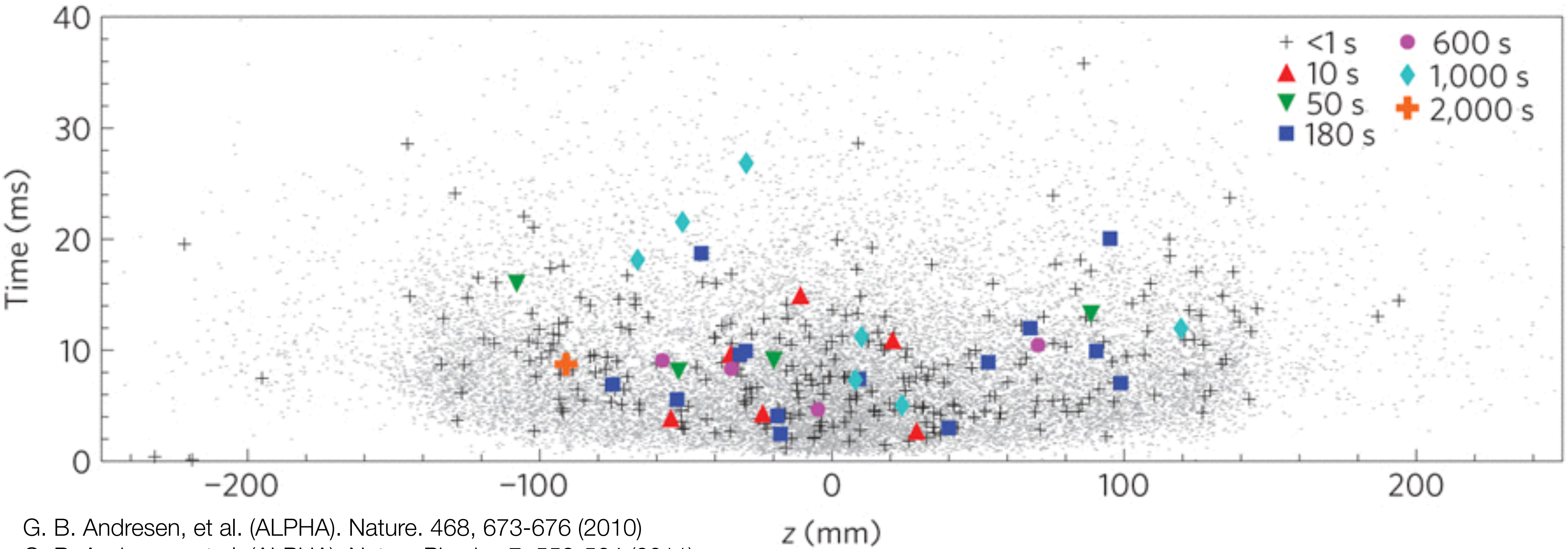
- Antihydrogen trapped.
  - 1 atom / 15 minutes.
- 100‘s of atoms for 100’s of seconds


LETTER

doi:10.1038/nature09610

Trapped antihydrogen

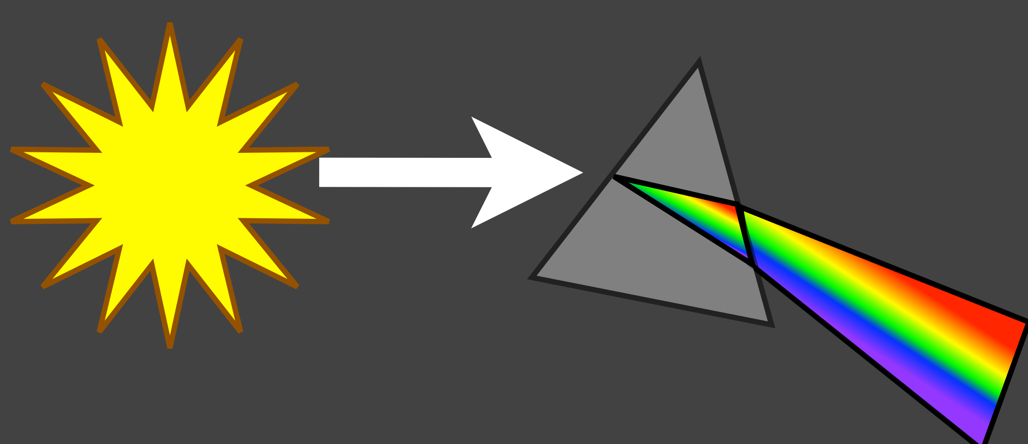
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. 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]

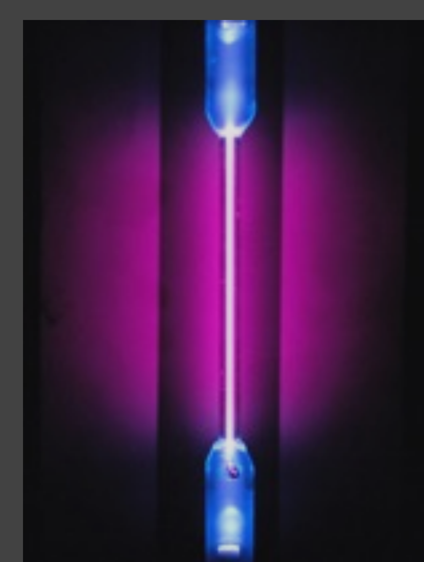


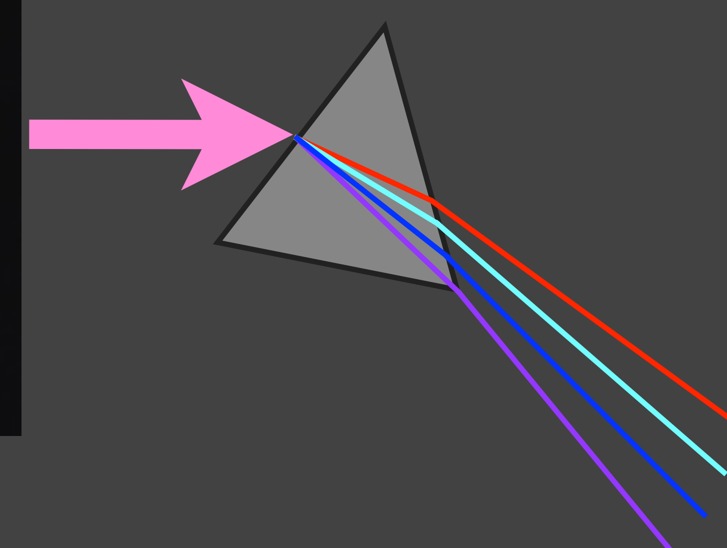
G. B. Andresen, et al. (ALPHA). Nature. 468, 673-676 (2010)
G. B. Andresen, et al. (ALPHA). Nature Physics 7, 558-564 (2011)
G. Gabrielse, et al. (ATRAP) Phys Rev. Lett. 108, 113002 (2012)

Comparing Matter and Antimatter: Color

- Color is a property of Light
- Light is composed of ‘Photons’
  - Electromagnetic waves - color from wavelength and frequency
- White light from the sun is composed of many colors
  - Use a prism to separate the different types of photons
- What color is Hydrogen?



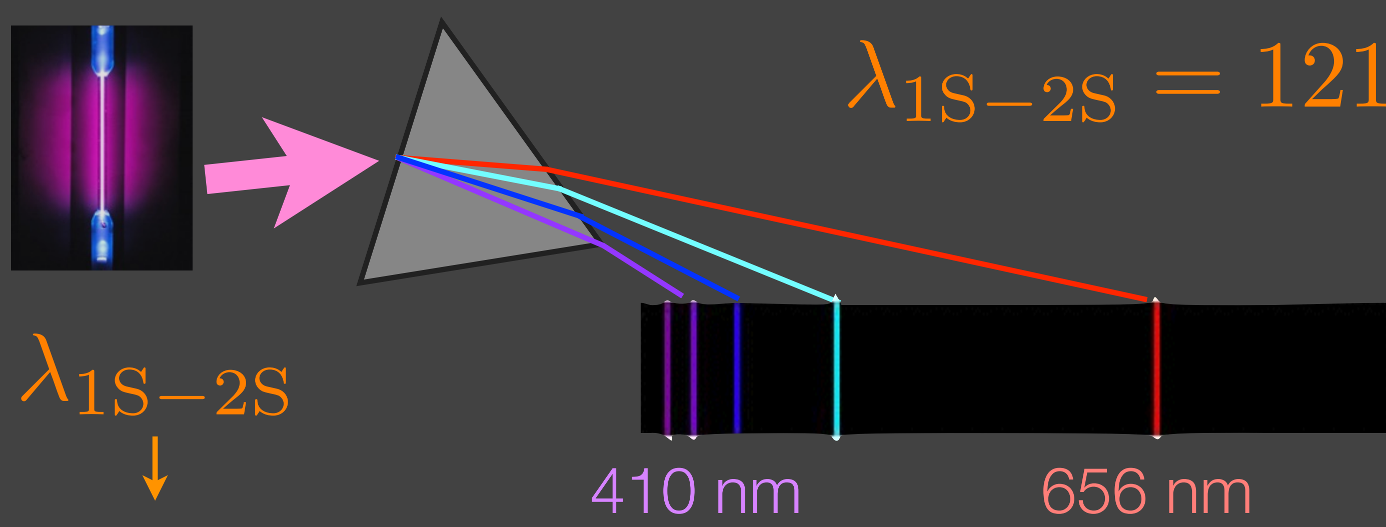




Hydrogen Spectroscopy

- Excited atoms emit discrete wavelengths
- Spectroscopy is the measurement of these photons
- Hydrogen spectrum: well- measured and predicted
  - Ground-state (1S) to first excited state (2S)

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

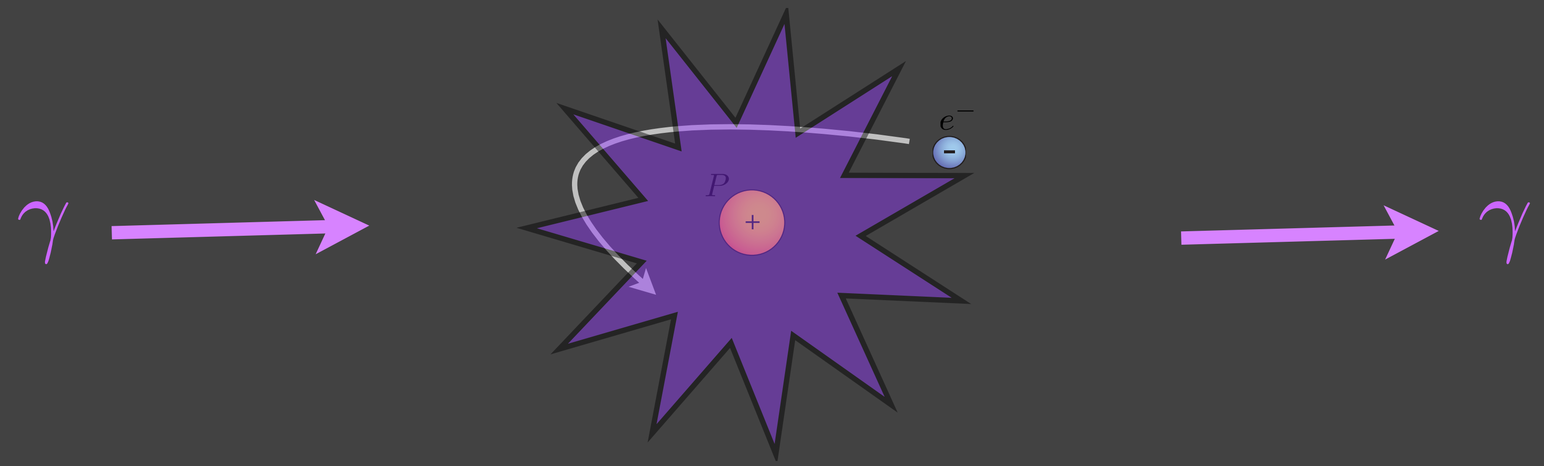


λ_{1S-2S} ↓

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

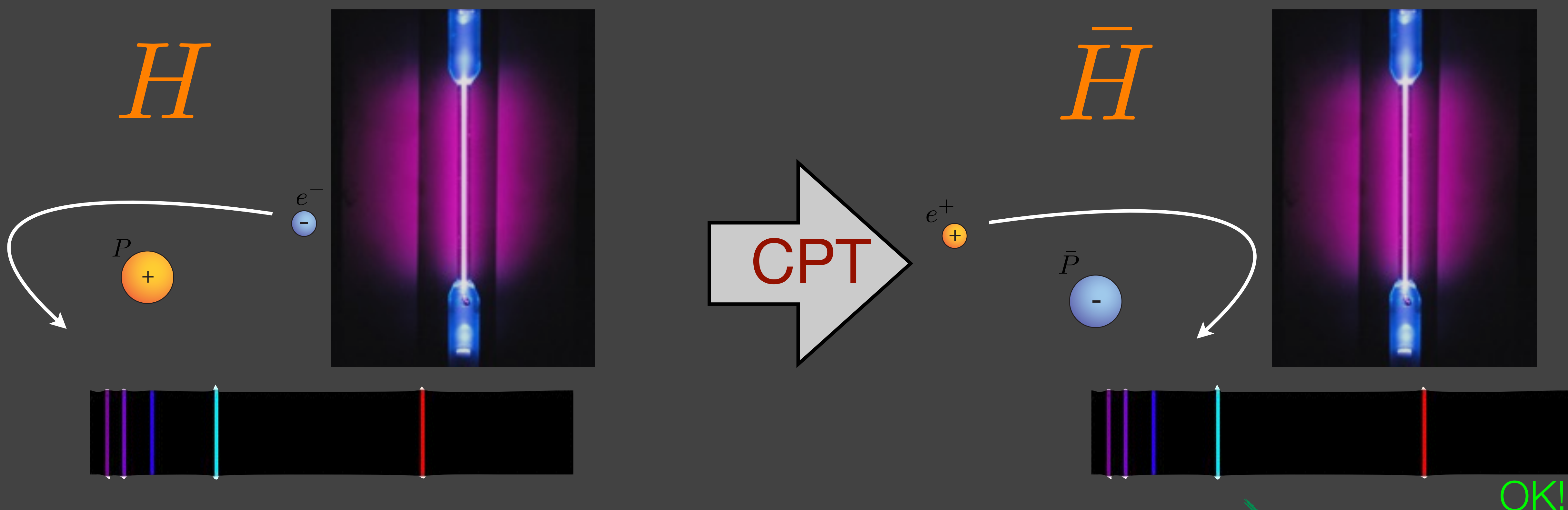
Atomic States

- Atoms can exist in many discrete (quantum) states
- Different states have different energies
  - Lowest energy: ‘Ground state’
  - Highest energy: Unbound (no longer an atom)
- Atoms transition between states by absorbing or emitting photons
- ‘Color’ of the photon relates to the energy differences

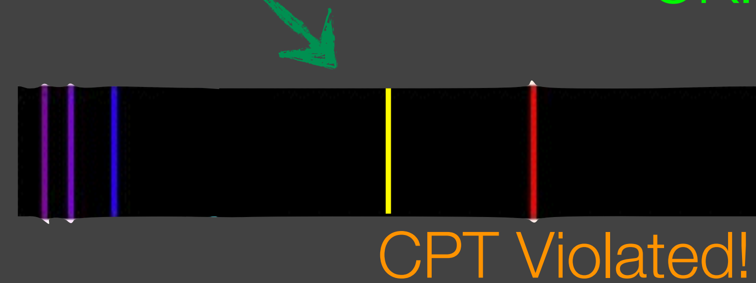


Atomic Spectra and CPT

- Atomic spectra should transform directly by CPT
- Accomplished by swapping in Antihydrogen

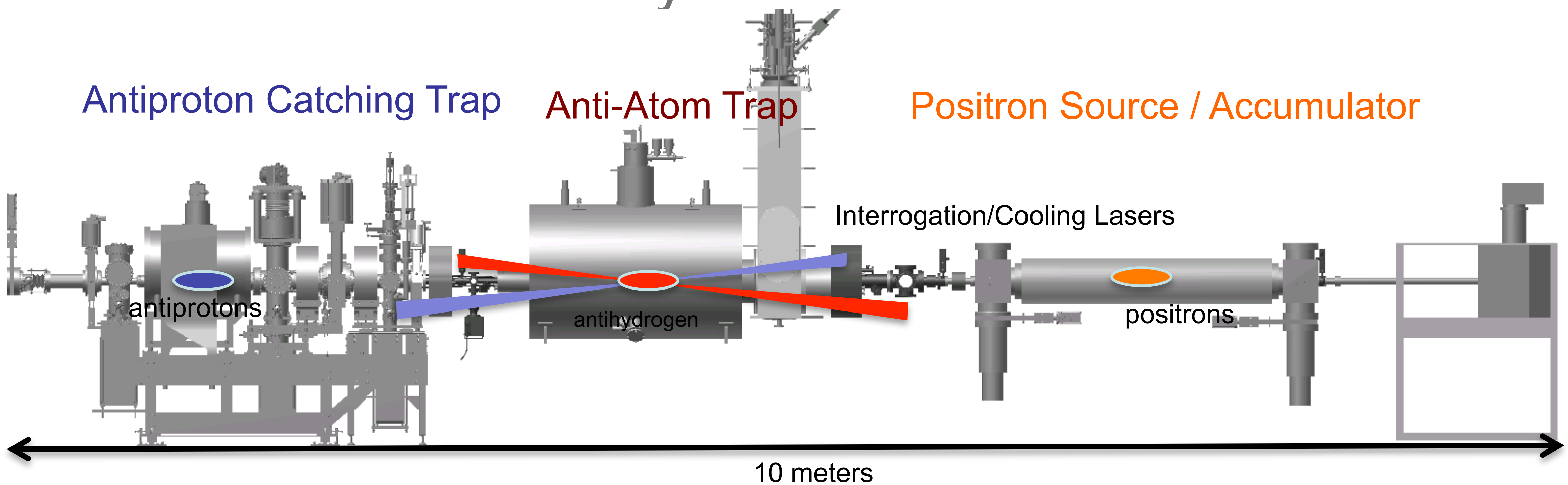


Goal: Precisely test CPT by comparing Hydrogen and Antihydrogen spectrum



ALPHA-2: Laser Access Required!

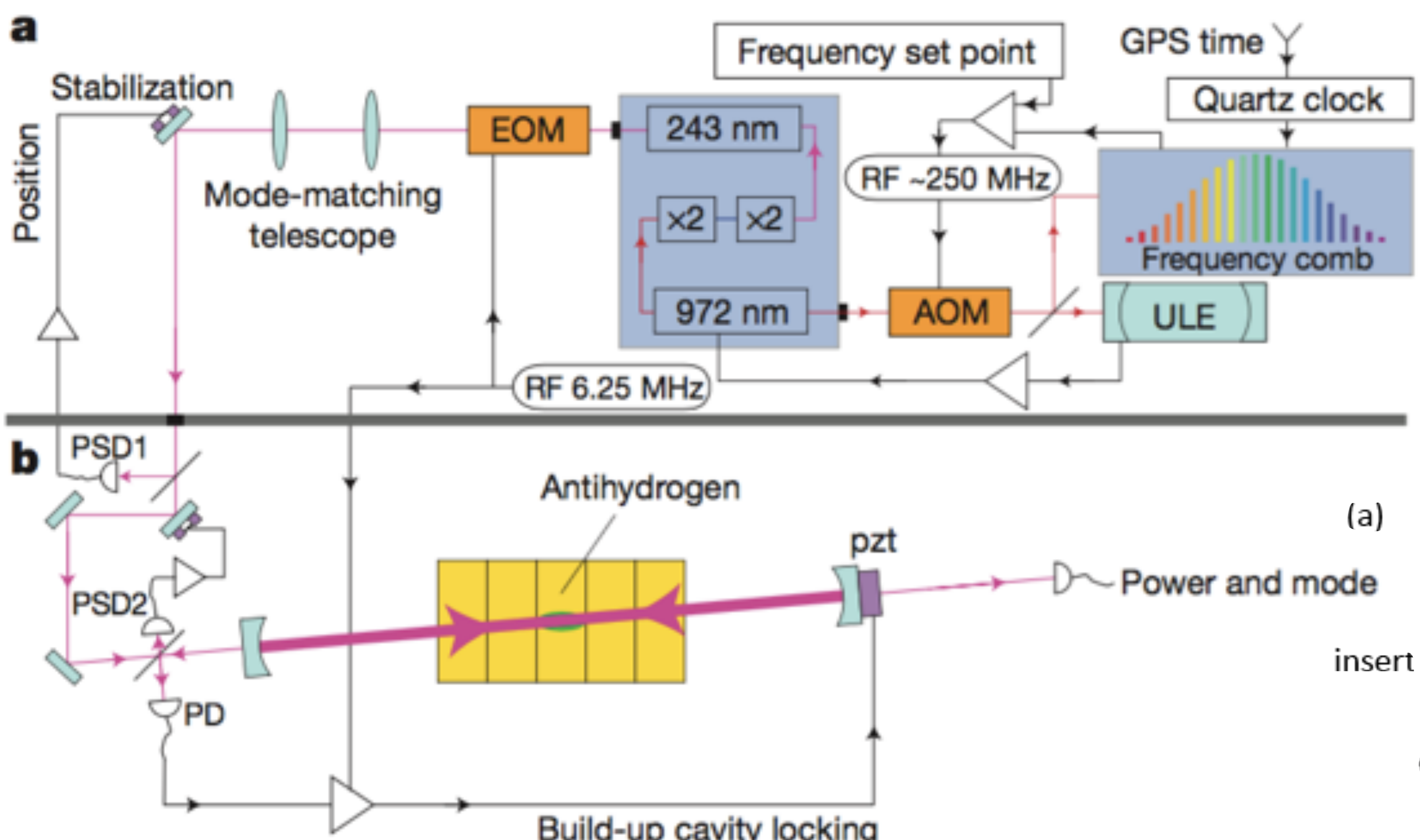
- Modularity for interfacing with CERN/ELENA upgrade
  - More antiprotons
- Increase antihydrogen trapping rate
- Lasers for Spectroscopy and Cooling
  - 243 nm 2-photon spectroscopy, 121 nm Lyman-alpha laser cooling
- Built from 2012 - today

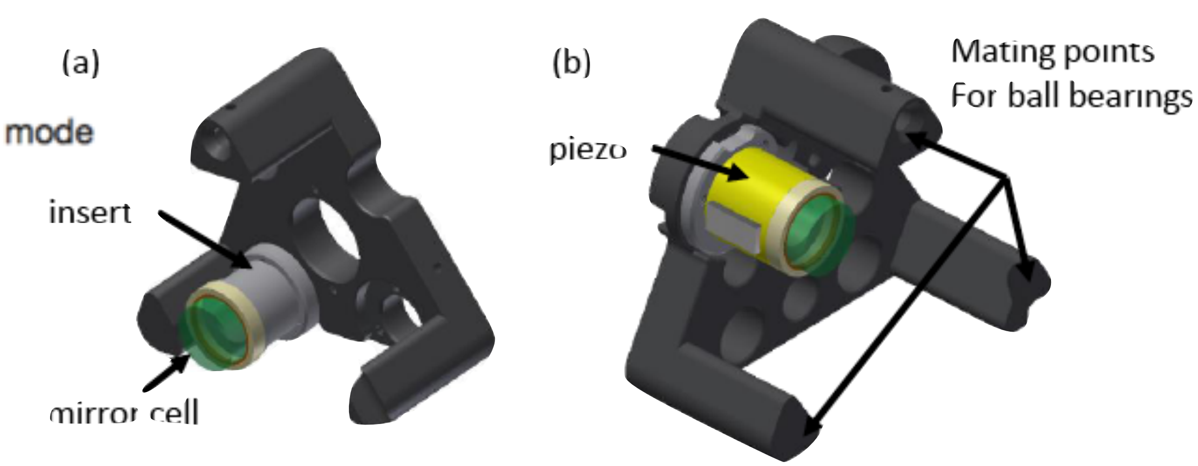


ALPHA-2: After LS1 (September 2014)

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)





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

- Efficiently detect annihilation

Untrapping Antihydrogen

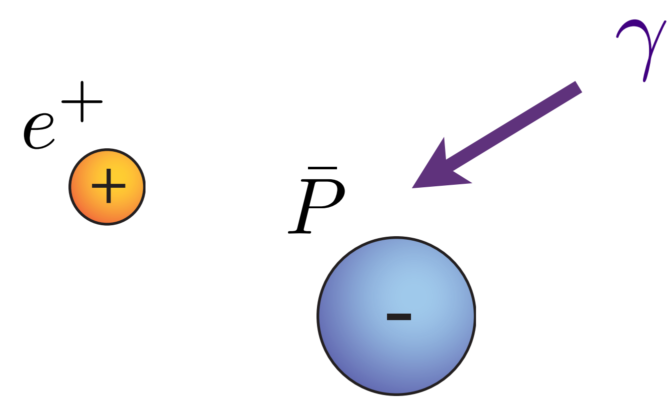
- Example: Hyperfine Transition (spin-flip)

Trapped State

Un-trapped State

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

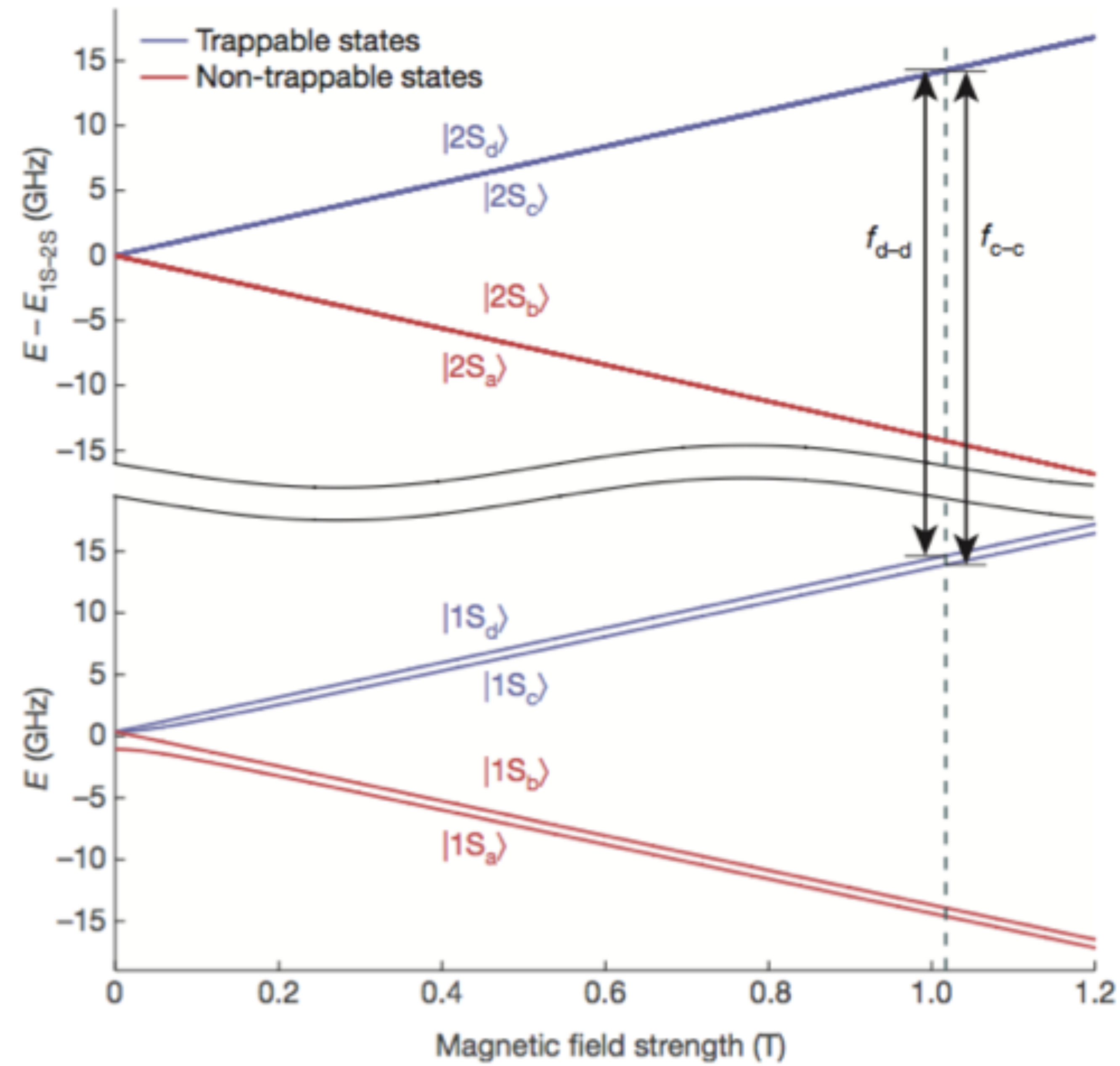
- Example: Ionization with ultraviolet light



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

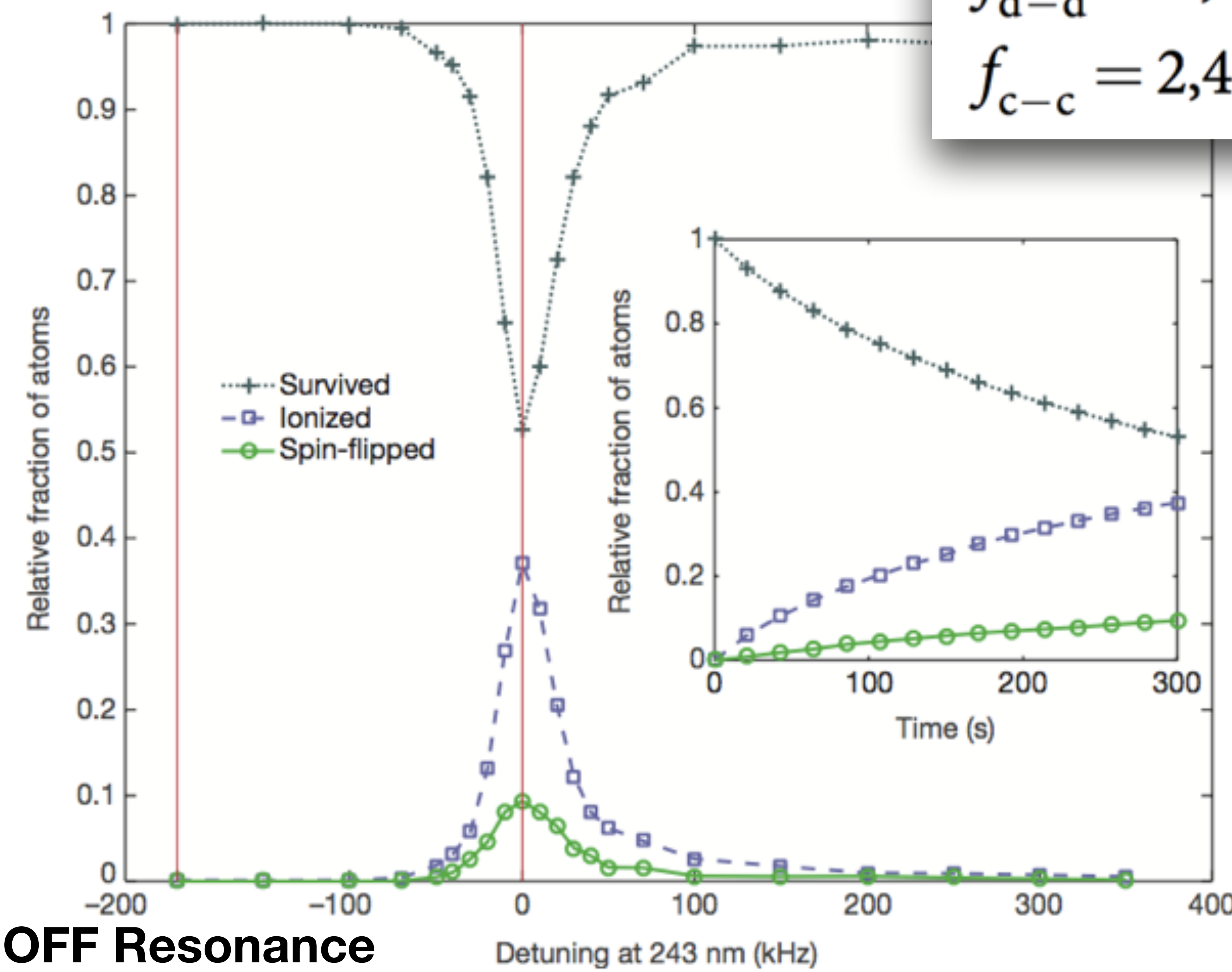
1S - 2S Transition in (anti) hydrogen

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



1S - 2S possible outcomes

ON Resonance



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

OFF resonance:
200 kHz detuned

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

OFF Resonance

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…

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

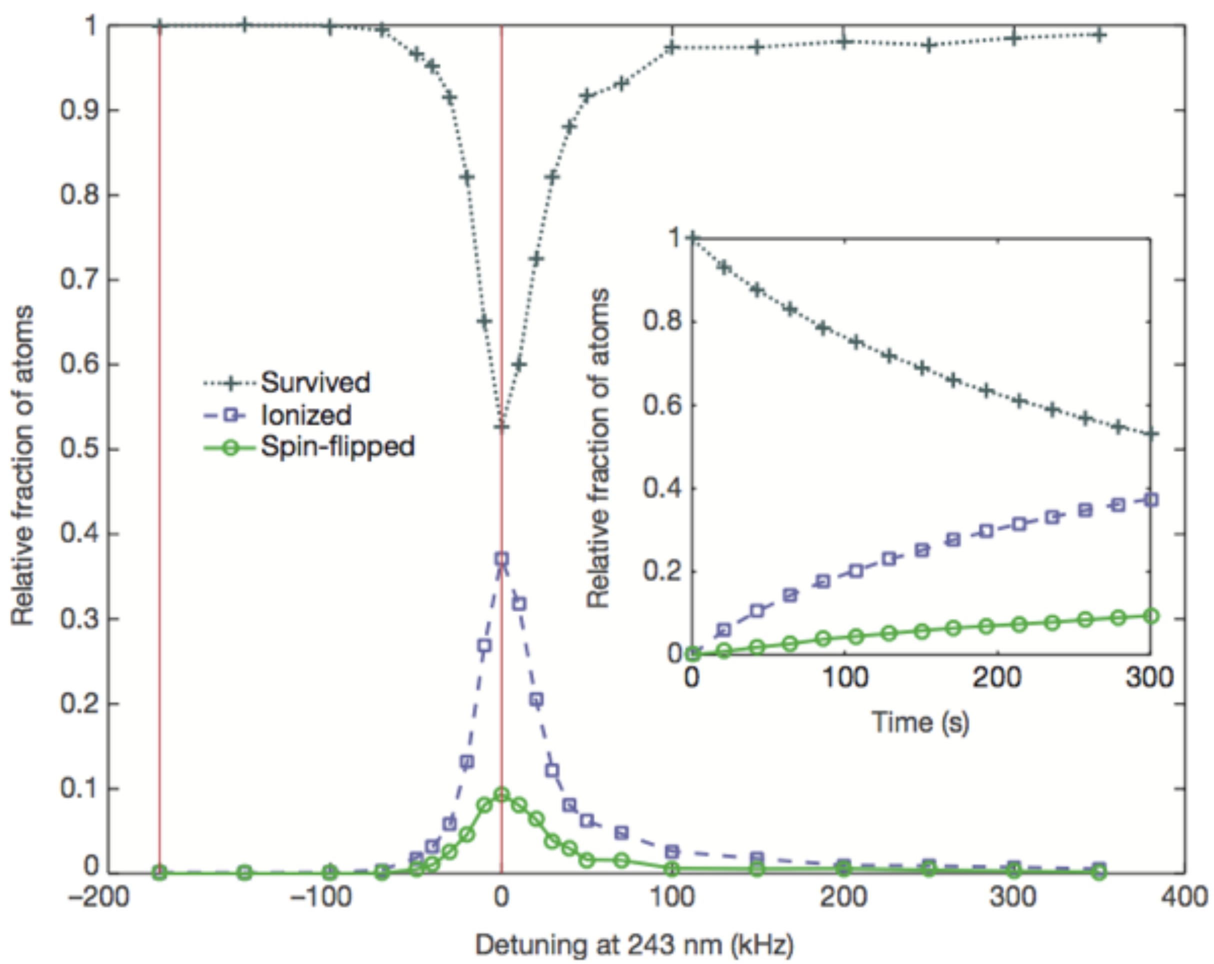
doi:10.1038/nature21040

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)



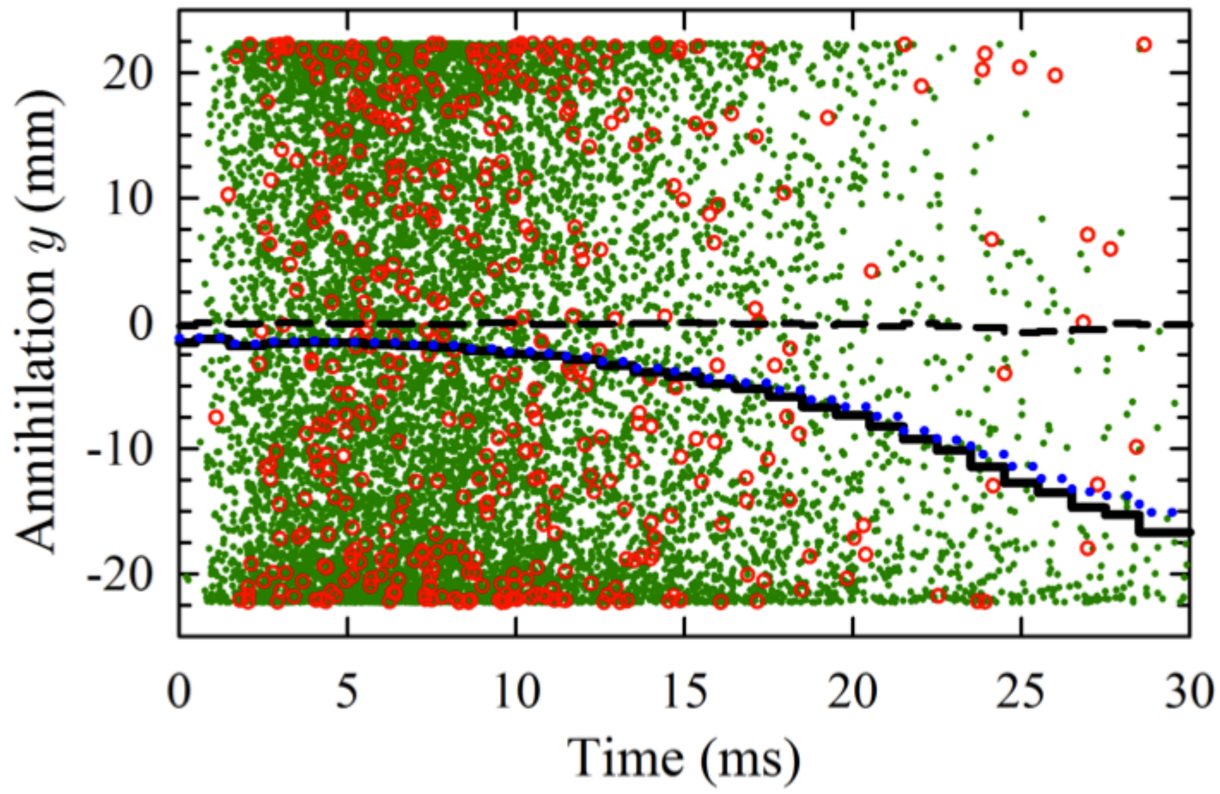
Precision gravity?

- Do atoms and anti-atoms gravitate differently?

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

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

Simulation for F = 100

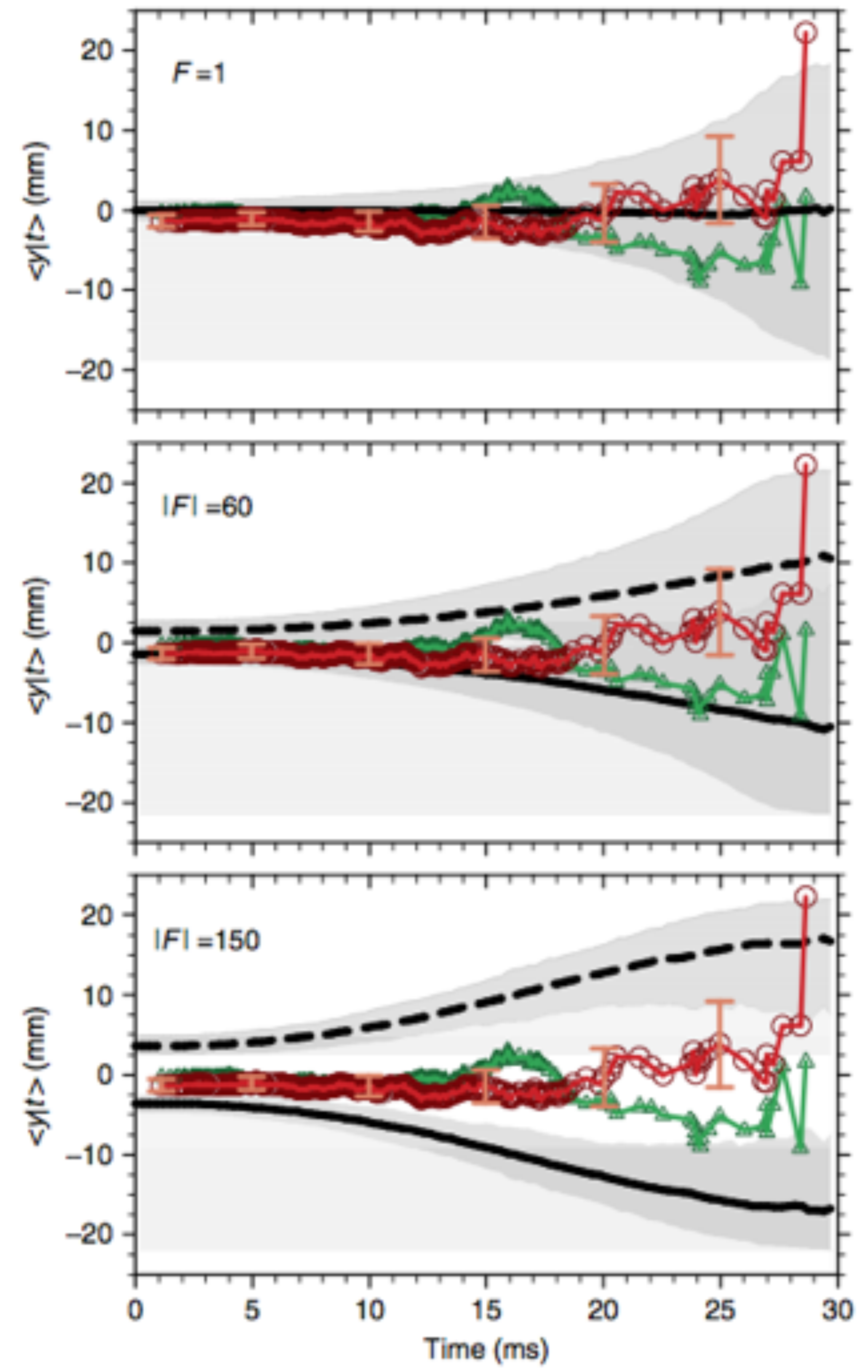


Gravitational Deflection: Precision?

- Simulate various F, test exclusion of RCA during quench

$$-65 < F < 110$$

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



ARTICLE

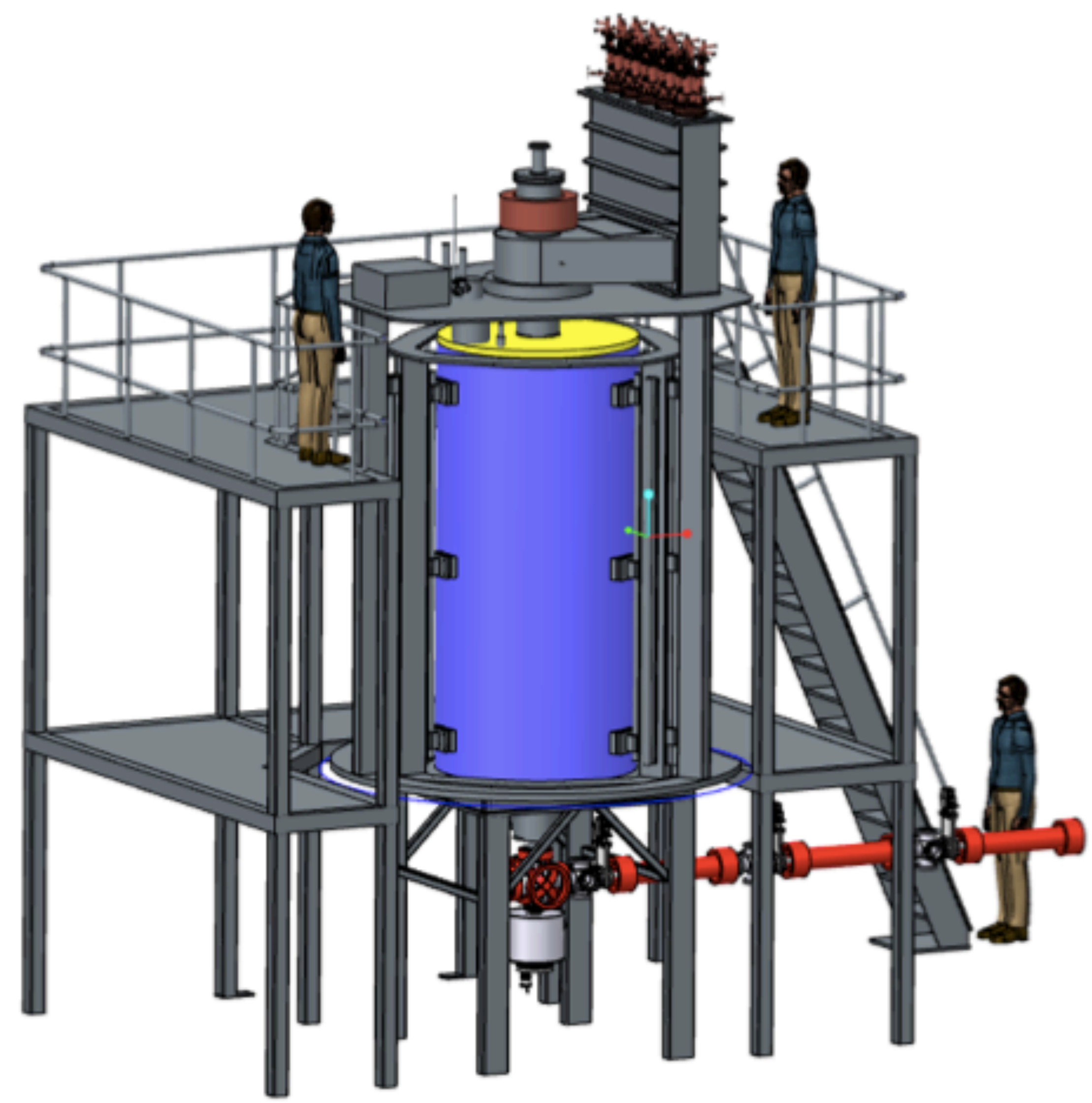
Description and first application of a new technique to measure the gravitational mass of antihydrogen

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

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

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, performing preliminary measurements on trapped antihydrogen.
- 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!