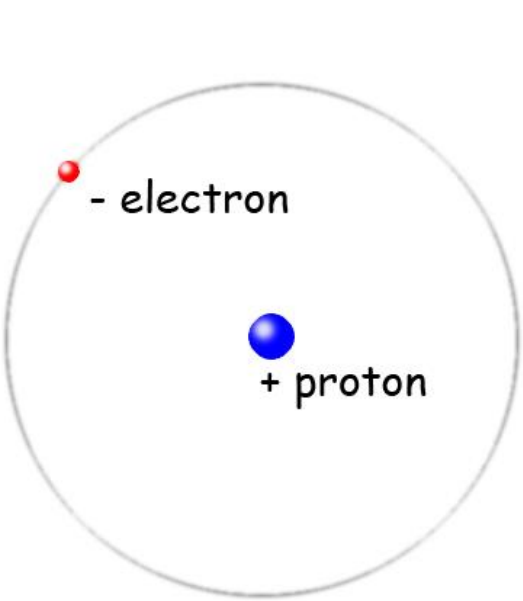
מחקרי אנטי מימן (ALPHA, CERN) יצירה, לכידה ותכונותיהם של אטומי אנטי חומר

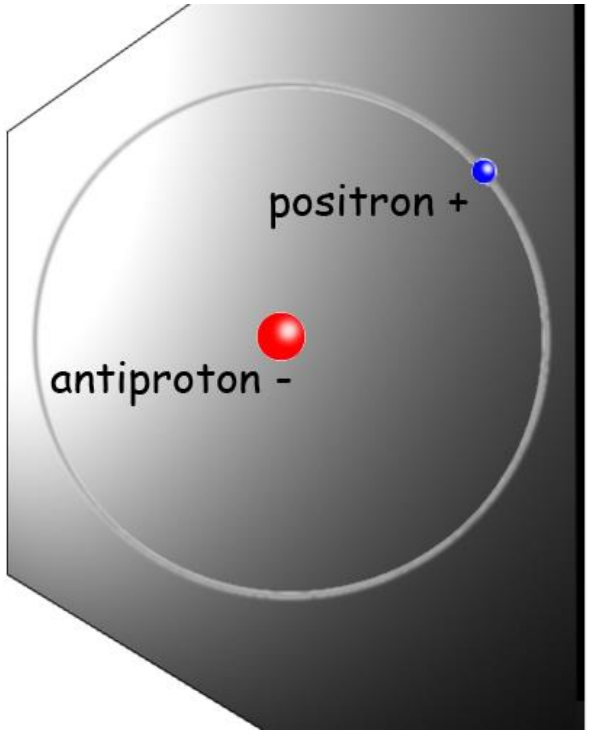
אלי שריד

ALPHA Collaboration, CERN +

מרכז מחקר גרעיני (ממ"ג), שורק, ישראל

אנטי מימן- דמות המראה שלאטום המימן





STAR TREK ENTERPRISE

FACT

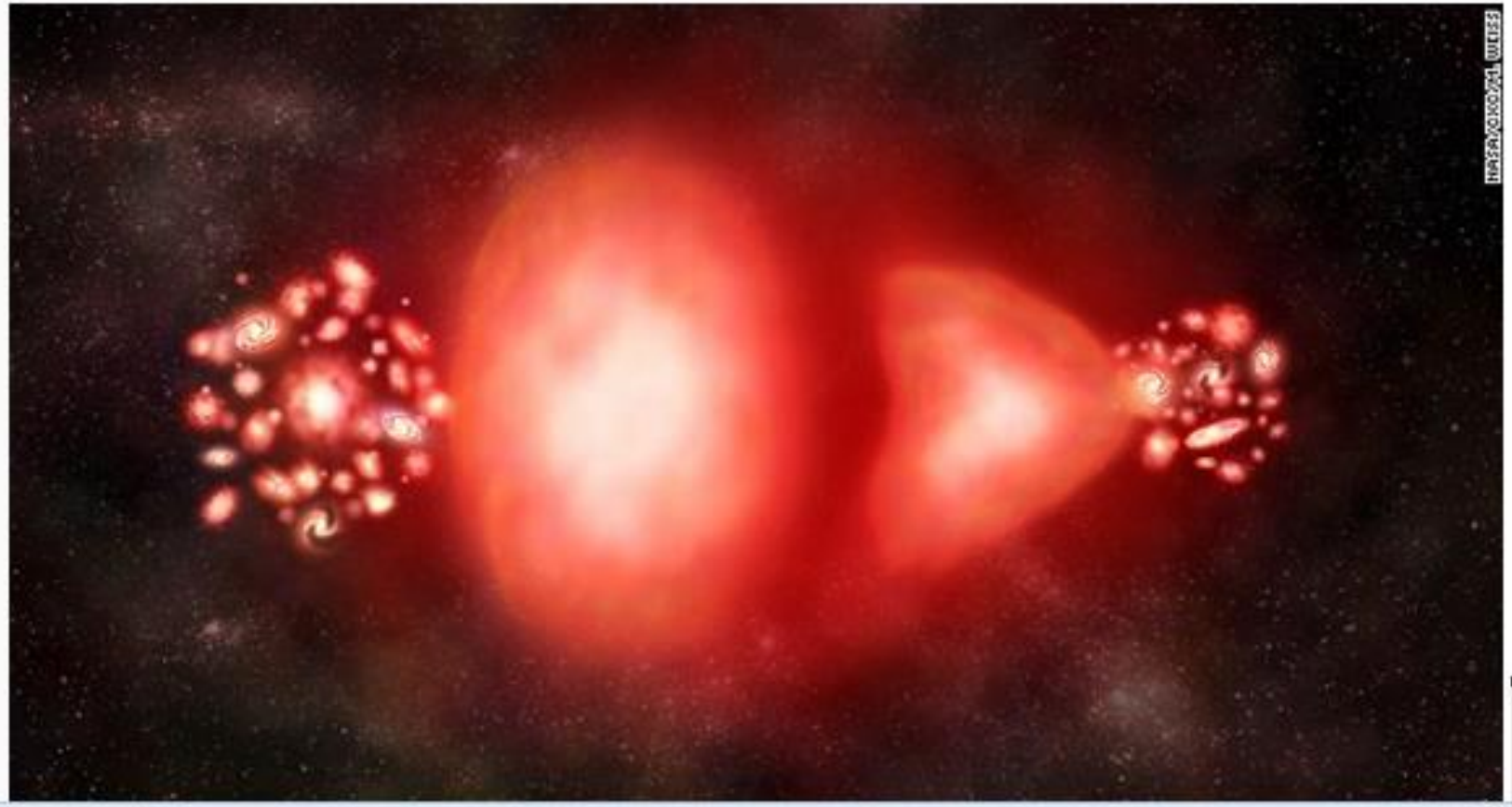
Until recently antimatter has been created in very small amounts. But CERN has now broken ground on its new Antiproton Decelerator- an advanced antimatter production facility that promises to create antimatter in much larger quantities.

Dan Brown , Angels and Demons (2000)

Antiproton Decelerator

What's the matter with antimatter? Scientists want to know

By **Ben Brumfield**, CNN
May 2, 2013 – Updated 1851 GMT (0251 HKT)



Dirac Equation (1928)

commemorative plaque for Paul Dirac, close to the one of Isaac Newton, Westminster Abbey, London

$$\begin{pmatrix} mc^2 & c\sigma\cdot p \\ c\sigma\cdot p & -mc^2 \end{pmatrix} \begin{pmatrix} \phi_+ \\ \phi_- \end{pmatrix} = i\hbar\frac{\partial}{\partial t}\begin{pmatrix} \phi_+ \\ \phi_- \end{pmatrix}.$$

DIRAC 1931

Quantised Singularities in the Electromagnetic Field.

By P. A. M. Dirac, F.R.S., St. John's College, Cambridge.

(Received May 29, 1931.)

"…it will be beyond the power of human intelligence to get the necessary new ideas by direct attempts to formulate the experimental data in mathematical terms… The theoretical worker. . have to proceed to employ the resources of pure mathematics in attempt to perfect and generalise mathematical formalisms.. And try to interpret the new mathematical features in terms of physical entities.

Discovery of the positron (1932)

The Apparent Existence of Easily Deflectable Positives
Author(s): Carl D. Anderson
Source: *Science*, New Series, Vol. 76, No. 1967 (Sep. 9, 1932), pp. 238-239

THE APPARENT EXISTENCE OF EASILY DEFLECTABLE POSITIVES

Up to the present a positive electron has always been found with an associated mass 1,850 times that associated with the negative electron. In measuring the energies of charged particles produced by cosmic rays some tracks have recently been found which seem to be produced by positive particles, but if so the masses of these particles must be small compared to the mass of the proton. The evidence for this statement is found in several photographs, three of which are discussed below.

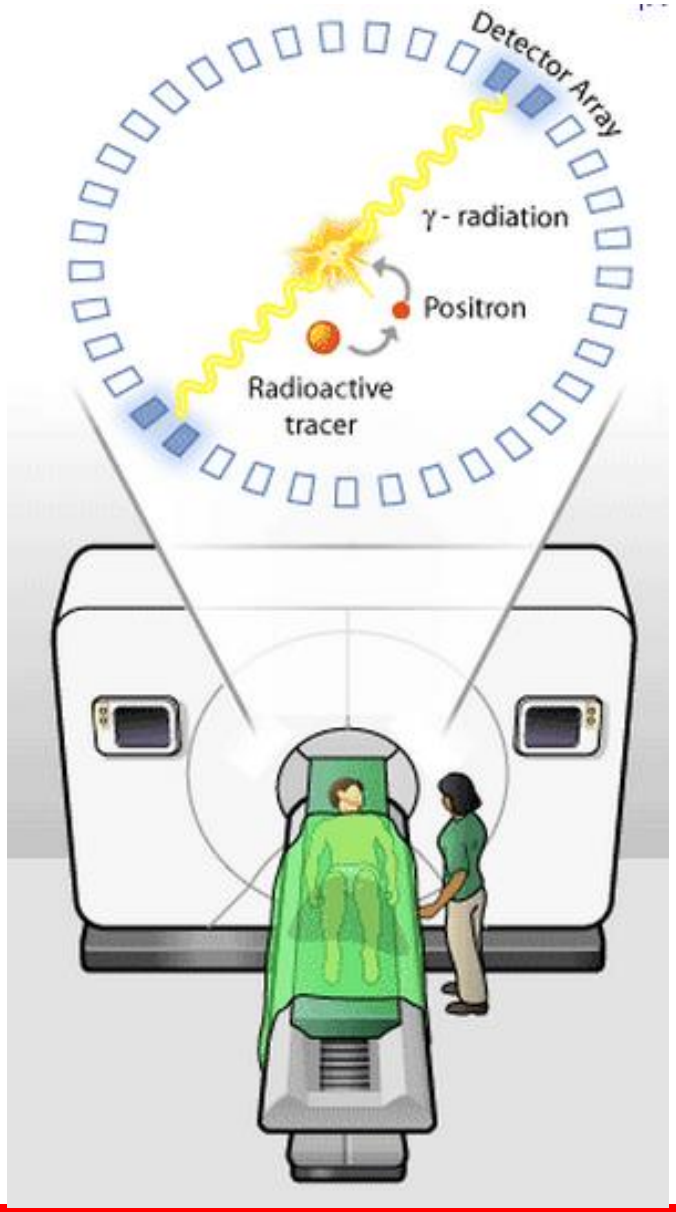
In one instance, in which a lead plate of 6 mm thickness was inserted in the cloud-chamber, tracks of a particle were observed above and below the lead. The curvature due to the magnetic field was measurable both above and below the lead. There are the

The interpretation of these tracks as due to protons, or other heavier nuclei, is ruled out on the basis of range and curvature. Protons or heavier nuclei of the observed curvatures could not have ranges as great as those observed. The specific-ionization is close to that for an electron of the same curvature, hence indicating a positively-charged particle comparable in mass and magnitude of charge with an electron.

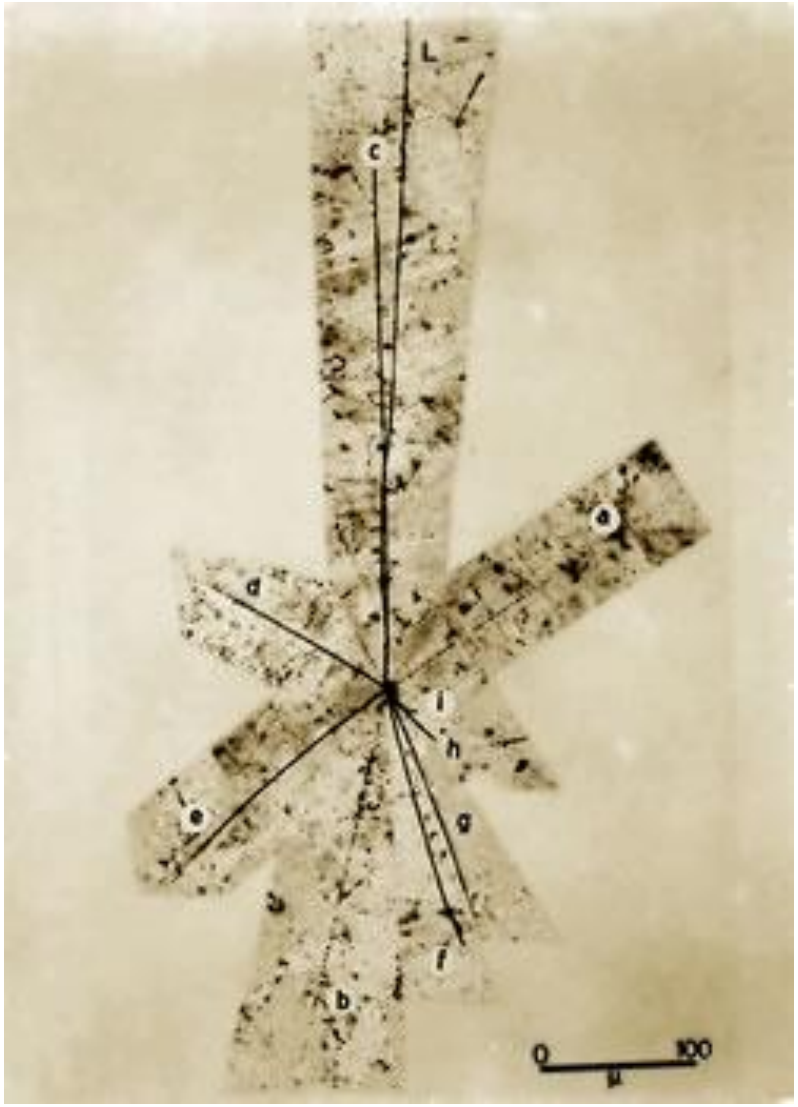
Carl D. Anderson

California Institute
of Technology,
September 1, 1932

PET scan



Antiproton discovered- 1955



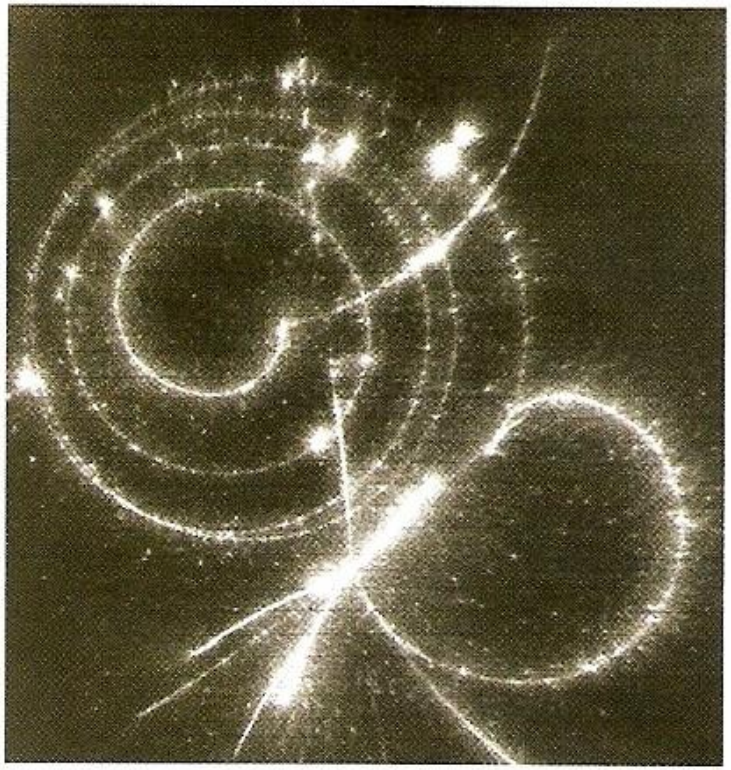
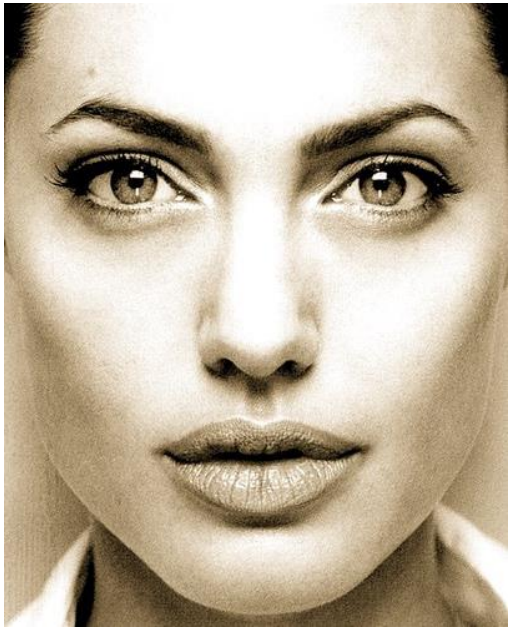
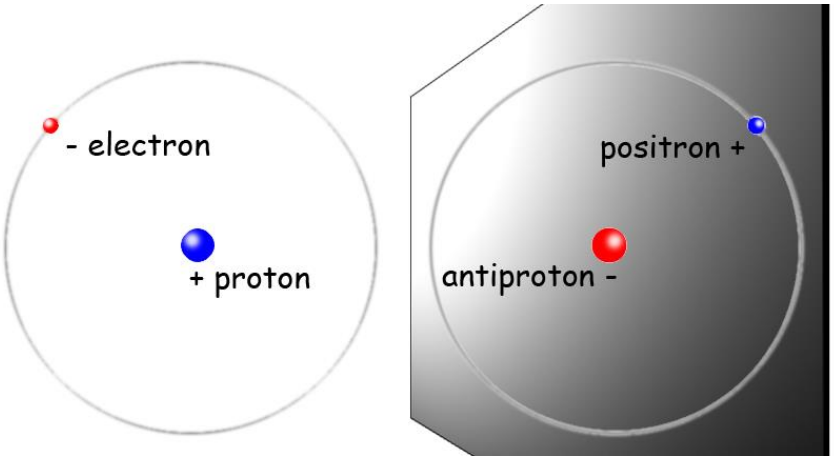


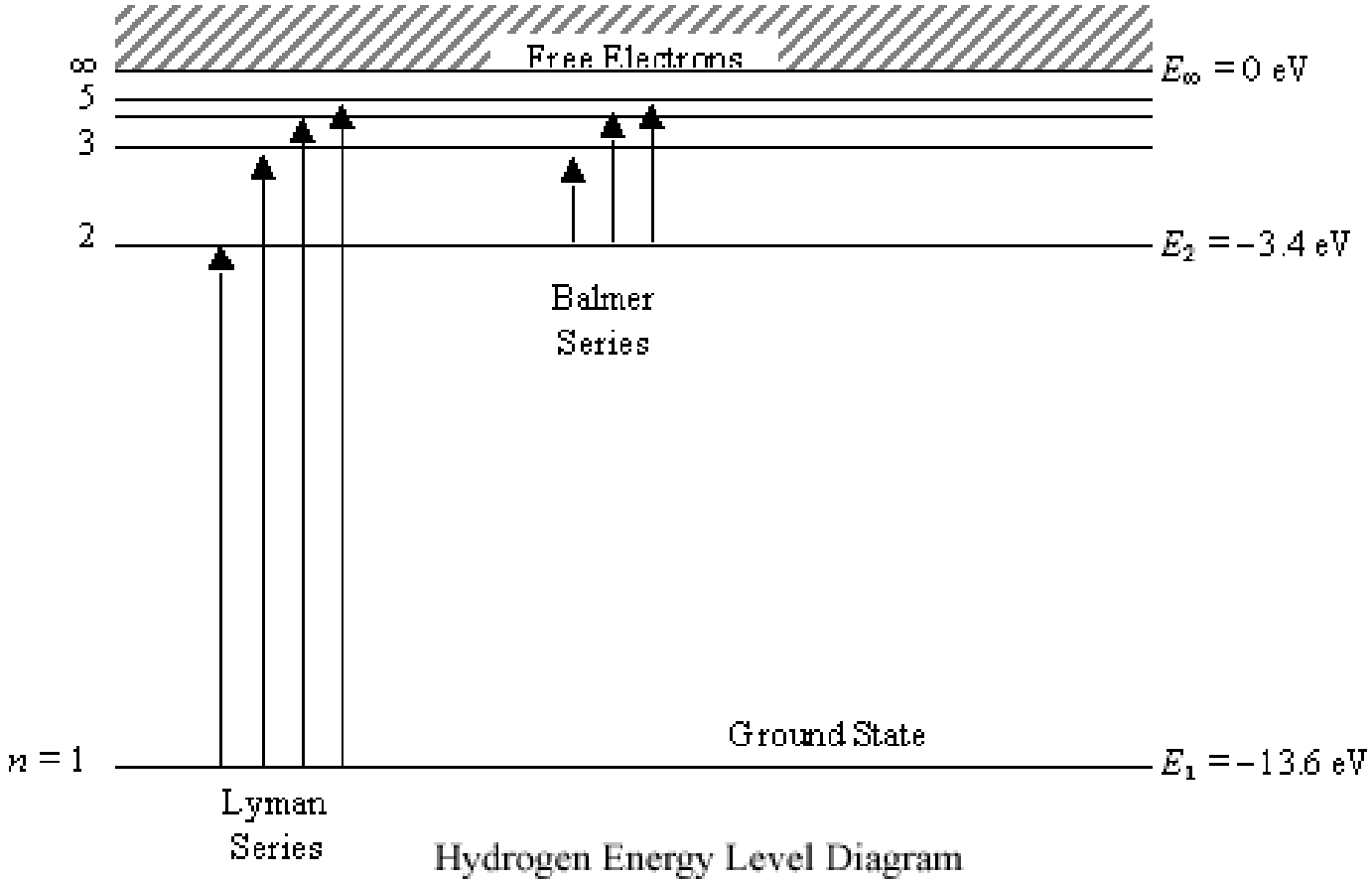
Figure 1 *Creation and decay of a π meson. The short spiral track is a π^+ meson created when an antiproton from the bottom edge annihilates a proton. The π^+ meson decays into an antimuon that spirals and decays into a positron.*

עד כמה מושלמת הסימטריה חומר- אנטי חומר?





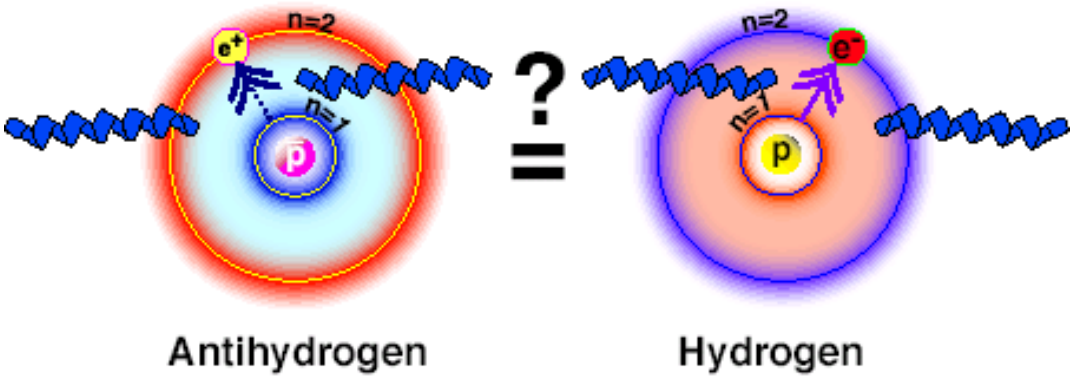
האם יש "שבירה" של הסימטריה?



Hydrogen Energy Level Diagram

The dream - Antihydrogen Spectroscopy

1s-2s two-photon spectroscopy



- **Doppler effect cancels**
- **High precision in matter sector**
- **test of CPT theorem**

f(1S-2S) = 2 466 061 102 474 851(34) Hz - Hänsch group

למה ביקום יש חומר ו(כמעט) לא אנטיחומר?

אם בהתחלה היו

על כל	1000000001	חלקיקי חומר
רק	1000000000	חלקיקי אנטיחומר-

התוצאה מה שאנחנו רואים היום- כולנו חומר

The ALPHA Collaboration

University of Aarhus, Denmark

Auburn University, USA

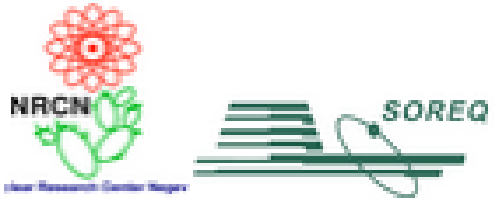
University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

THE UNIVERSITY of LIVERPOOL

University of Liverpool, UK



SNRC+ NRCN - Nucl. Res. Center, Israel

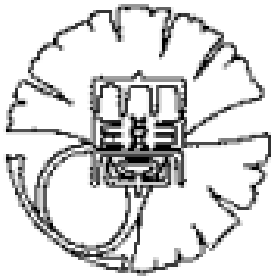
RIKEN, Japan

Federal University of Rio de Janeiro, Brazil

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK



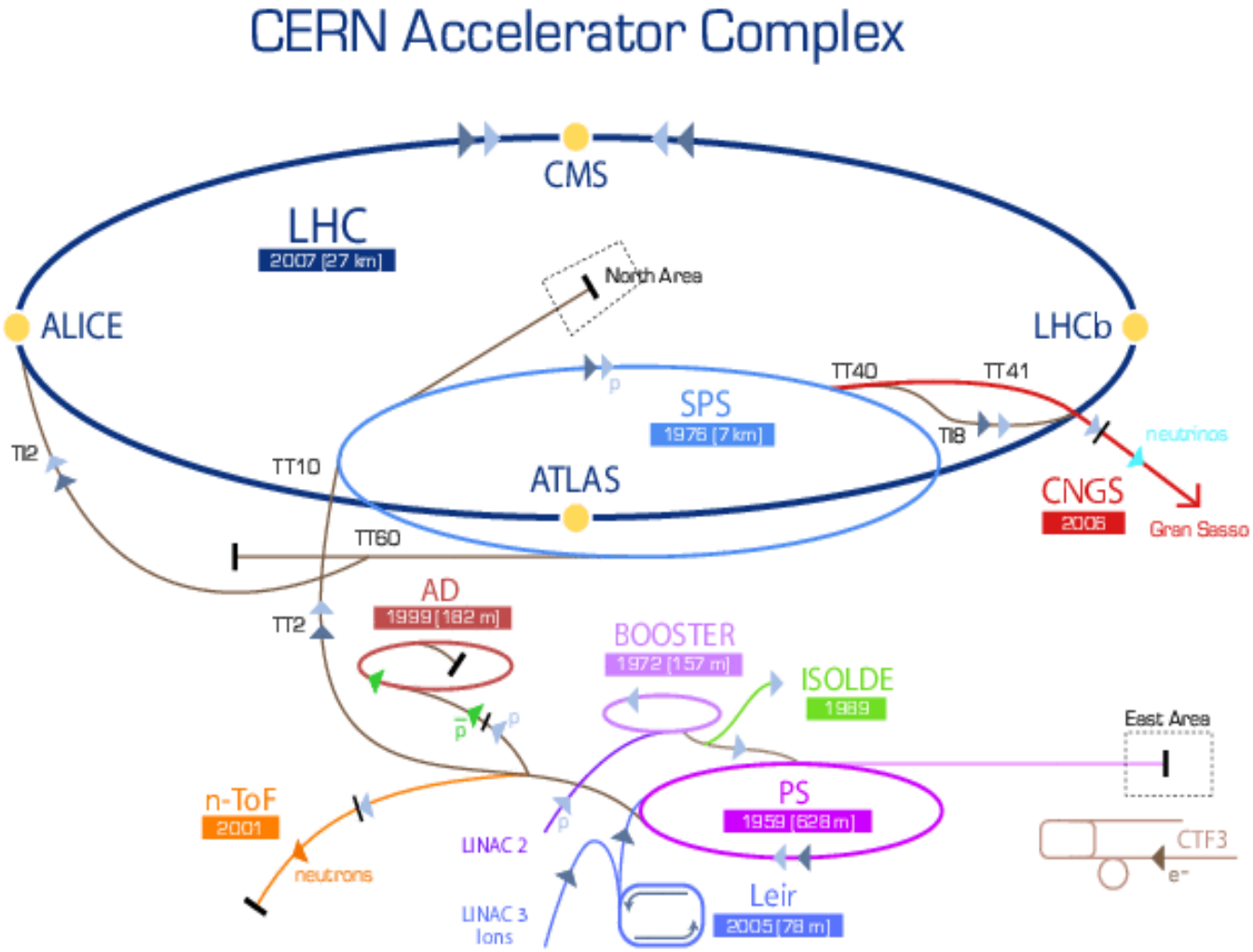
University of Tokyo, Japan

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

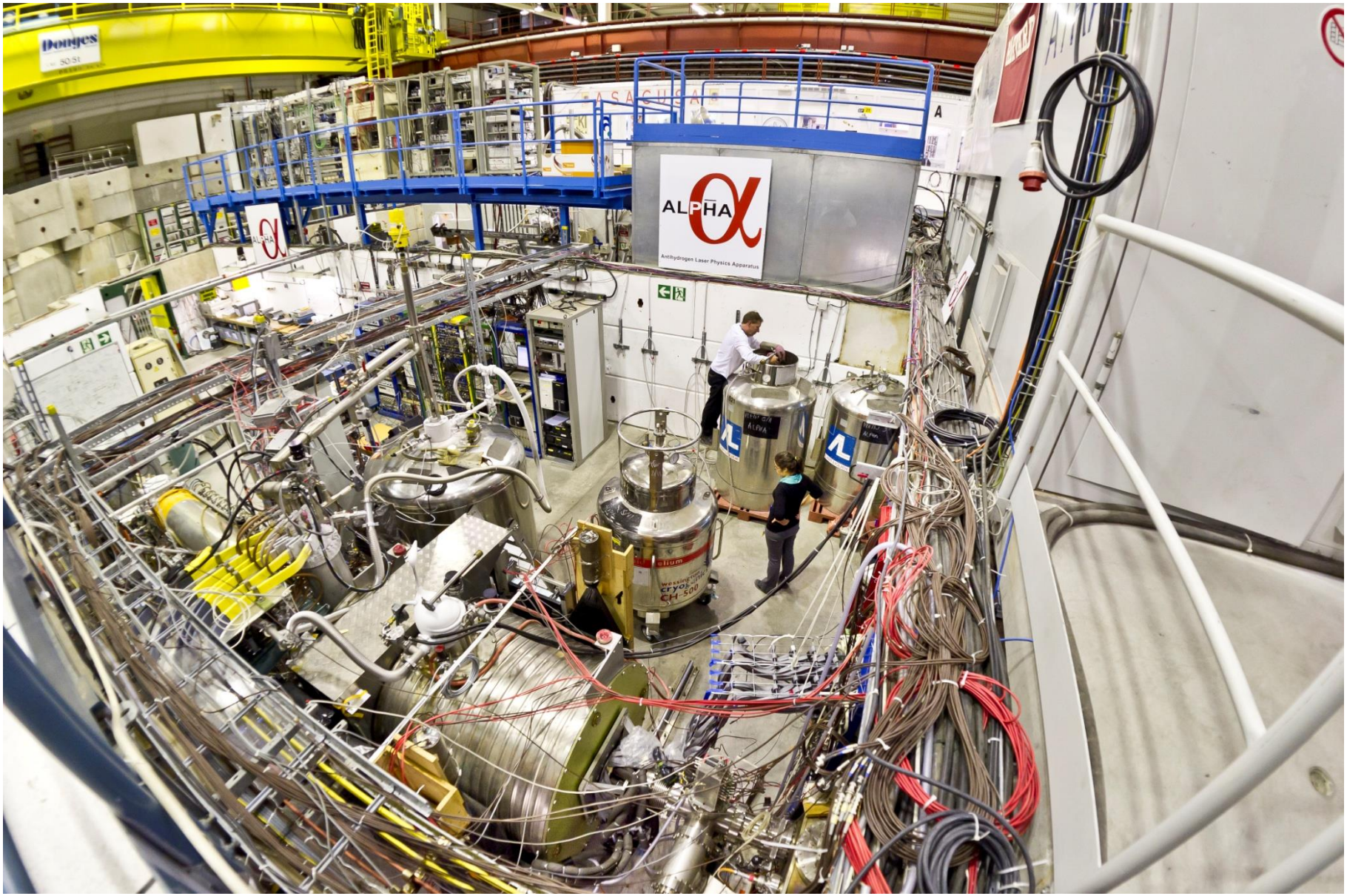
Supported by:
CNPq, FINEP/RENAFAE (Brazil)
ISF (Israel); MEXT (Japan)
FNU (Denmark); VR (Sweden);
NSERC, NRC/TRIUMF, AIF, FQRNT (Canada); DOE, NSF (USA);
EPSRC, the Royal Society and the Leverhulme Trust (UK).

We are not LHC (No Higgs in this talk…)

- Duoplasmatron= Sou
  ➒ 90 keV (kinetic ene
- LINAC2= Linear accelerator ➒ 50 Me
- PSBooster= Proton Synchrotron Booster
  ➒ 1.4 GeV
- PS= Proton Synchrot
  ➒ 25 GeV
- SPS= Super Proton Synchrotron ➒ 450 G
- LHC= Large Hadron Collider ➒ 7 TeV



ALPHA EXPERIMENT



Questions ALPHA asks about antimatter

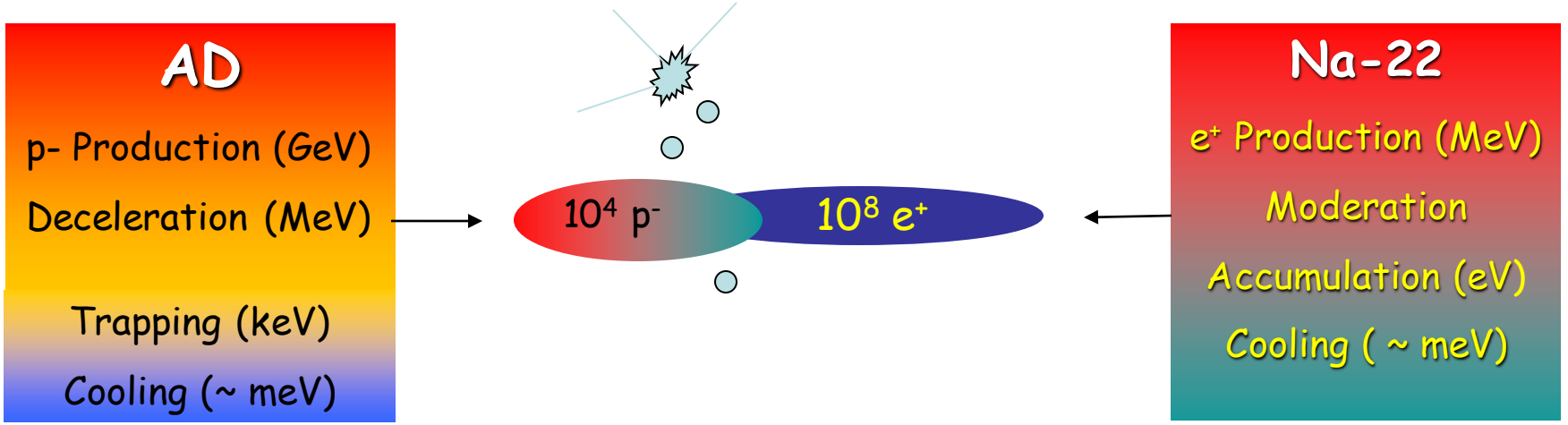
1. Are the **atomic levels** of antihydrogen exactly like those of normal hydrogen (CPT theorem)?

2. Is the antihydrogen atoms perfectly neutral? (equality of the size of the opposite **electrical charges** of positron and antiproton)

3. Does antimatter behave **gravitation**ally exactly like those of normal matter?

And what we all ask: how come we are here (small inequality of big bang matter and antimatter)

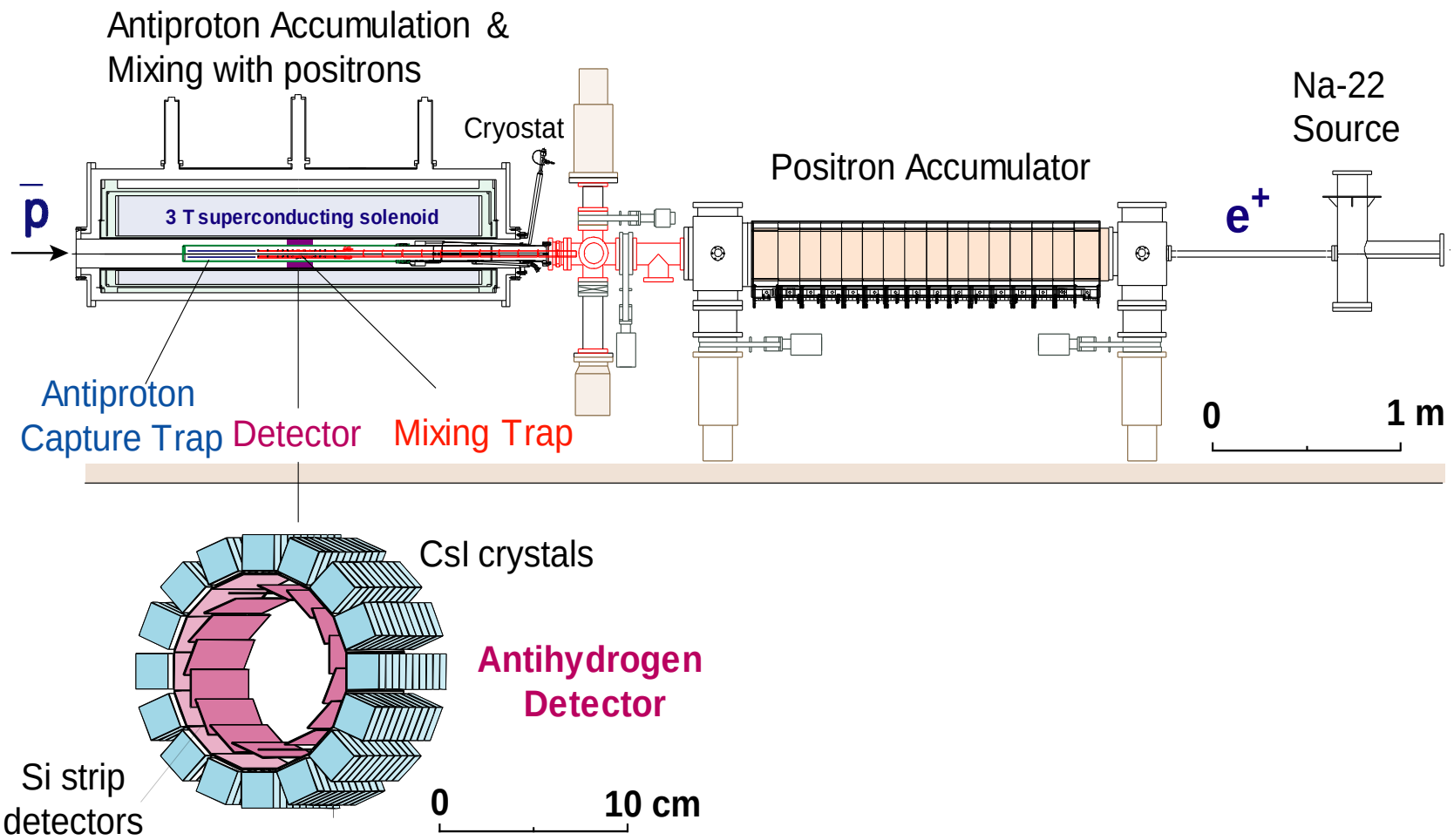
Antihydrogen Production



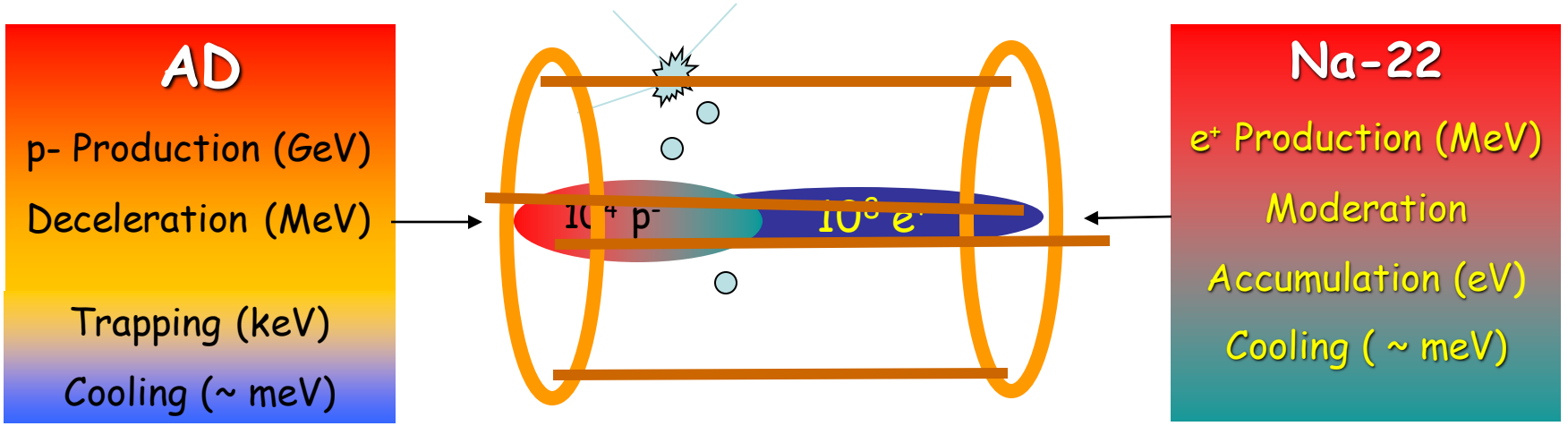
Hbar Formation mechanism:

- Radiative recombination
  - Binding E. deep; Formation rates low, $\sim T^{-0.6}$
- Three-body recombination
  - Binding E. shallow; Formation rate high, $\sim T^{-4.5}$

ATHENA- 2002


Antiproton Accumulation &
Mixing with positrons
Cryostat
Positron Accumulator
Na-22
Source
$\bar{p}$
3 T superconducting solenoid
e^+
Antiproton
Capture Trap
Detector
Mixing Trap
0
1 m
CsI crystals
Antihydrogen
Detector
Si strip
detectors
0
10 cm

Antihydrogen Trapping

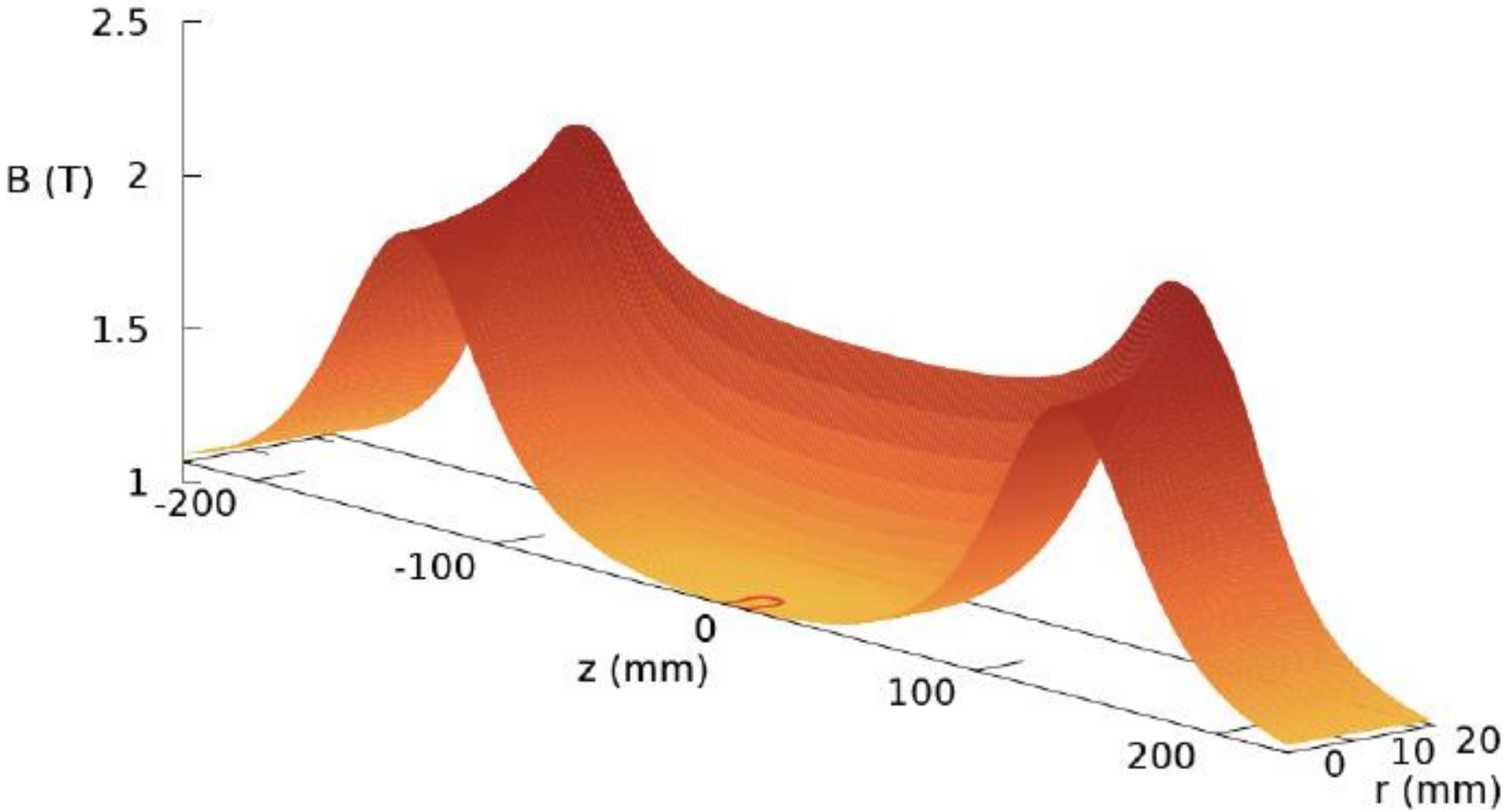


Superimpose Magnetic Trap

$U=-\mu B$

0.7 K/T per Bohr magneton

Magnetic Trap



ALPHA

LETTER

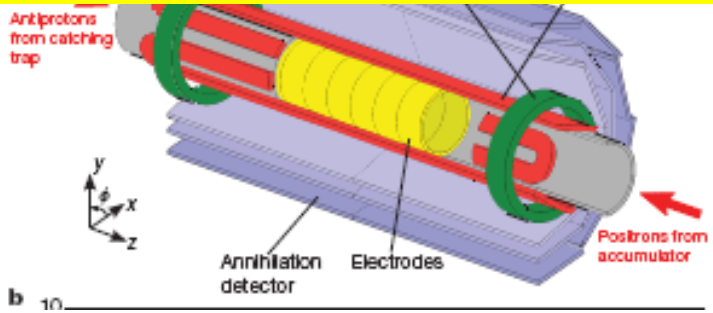
doi:10.1038/nature09610

Trapped antihydrogen

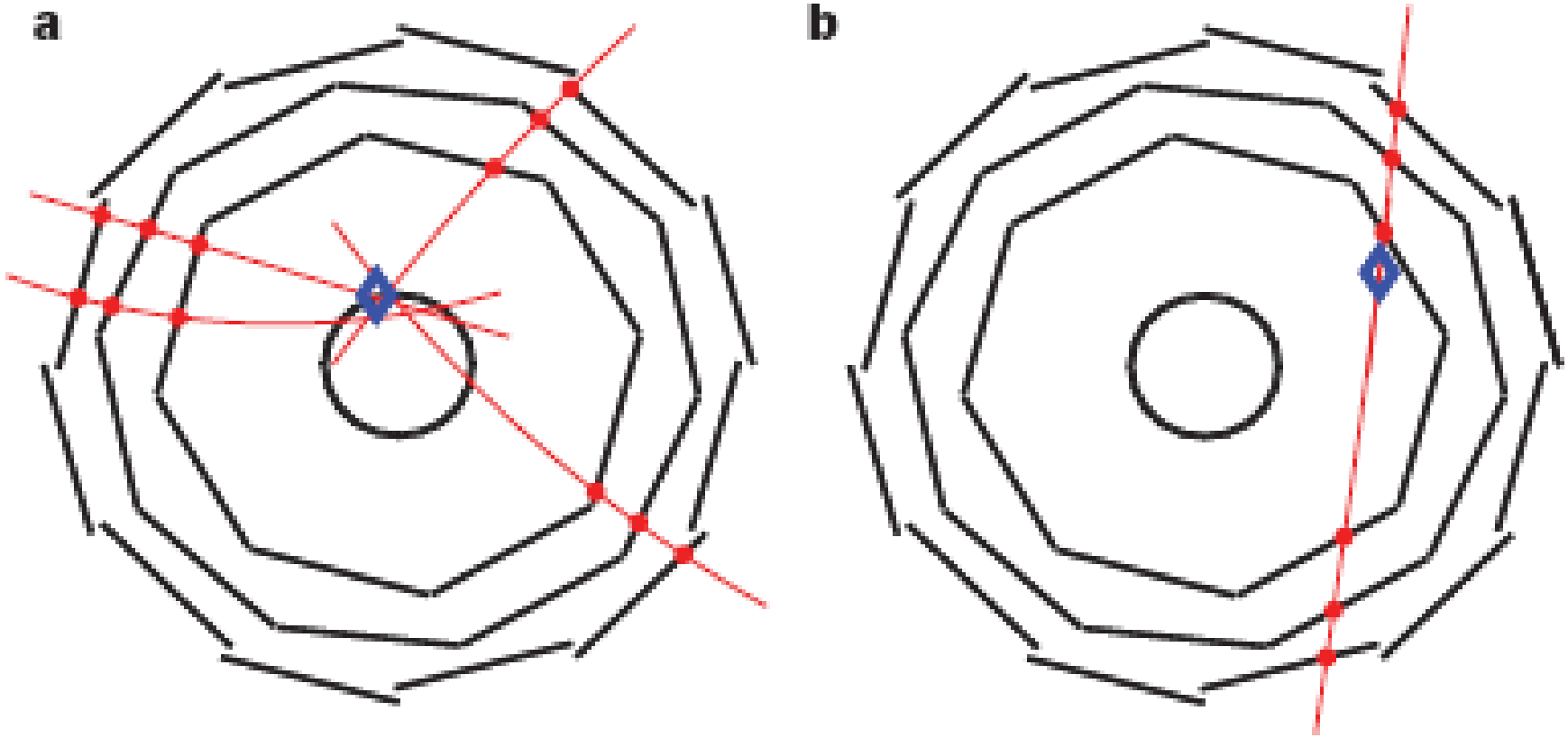
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M.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

Forty-two physicists from 15 institutions around the world contributed to the research, including 13 from Canada. Other participating countries were Brazil, Denmark, Israel, Japan, Sweden, the U.K., and the United States. (CBC, Canada, 17.11.10)

gen atom (about two parts in $10^{\cdot\cdot}$ for the frequency of the 1s-to-2s transition[4]), subjecting antihydrogen to rigorous spectroscopic examination would constitute a compelling, model-independent test of CPT. Antihydrogen could also be used to study the gravitational behaviour of antimatter[5]. However, so far experiments have produced antihydrogen that is not confined, precluding detailed study of its structure. Here we demonstrate trapping of antihydrogen atoms. From the interaction of about 10^7 antiprotons and 7×10^8 positrons, we observed 38 annihilation events consistent with the controlled release of trapped antihydrogen from our magnetic trap; the measured background is 1.4 ± 1.4 events. This result



Cosmic rays vs. antiprotons



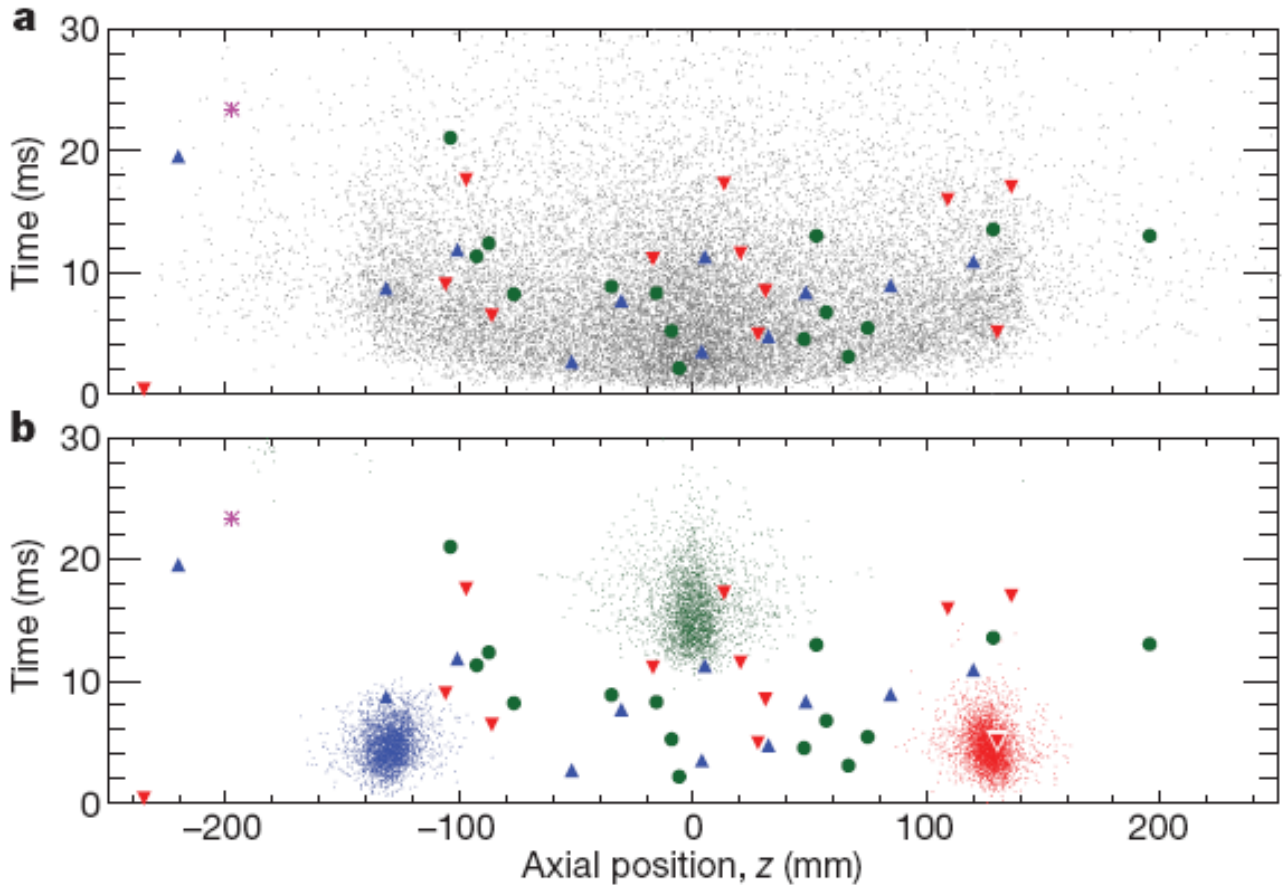
Nature 38 events

Table 1 | Number of annihilations identified in the 30 ms following the trap shutdown

Type of attempt	Number of attempts	Antiproton annihilation events
No bias	137	15
Left bias	101	11
Right bias	97	12
No bias, heated positrons	132	1
Left bias, heated positrons	60	0
Right bias, heated positrons	54	0

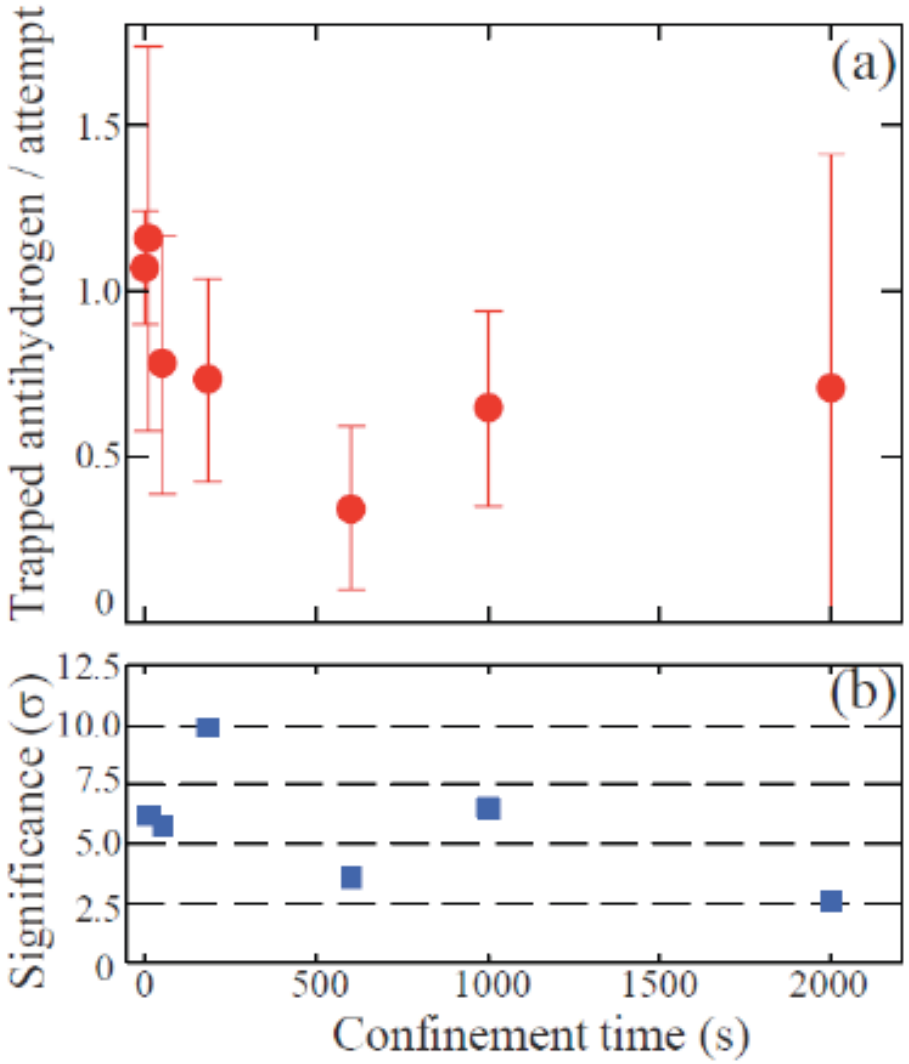
38 annihilations in 335 attempts, only 1 in 246 with heated positrons
Total background 1.4±1.4 events, including cosmic of 0.46±0.01 events
Trapped antihydrogen for at least 172 ms.

Nature 38 events vs. simulation (with the effect of bias electric fields)



Bias fields prove that the annihilations are not mirror trapped pbars

ANTIHYDROGEN CONFINEMENT FOR 1000S



nature physics
ARTICLES
PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

- Published online 5 June 2011
- First ***ground state*** antihydrogen
- Important implications for future spectroscopy and gravitational studies, laser cooling?

ALPHA

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17 November 2010 Last updated at 18:07 GMT

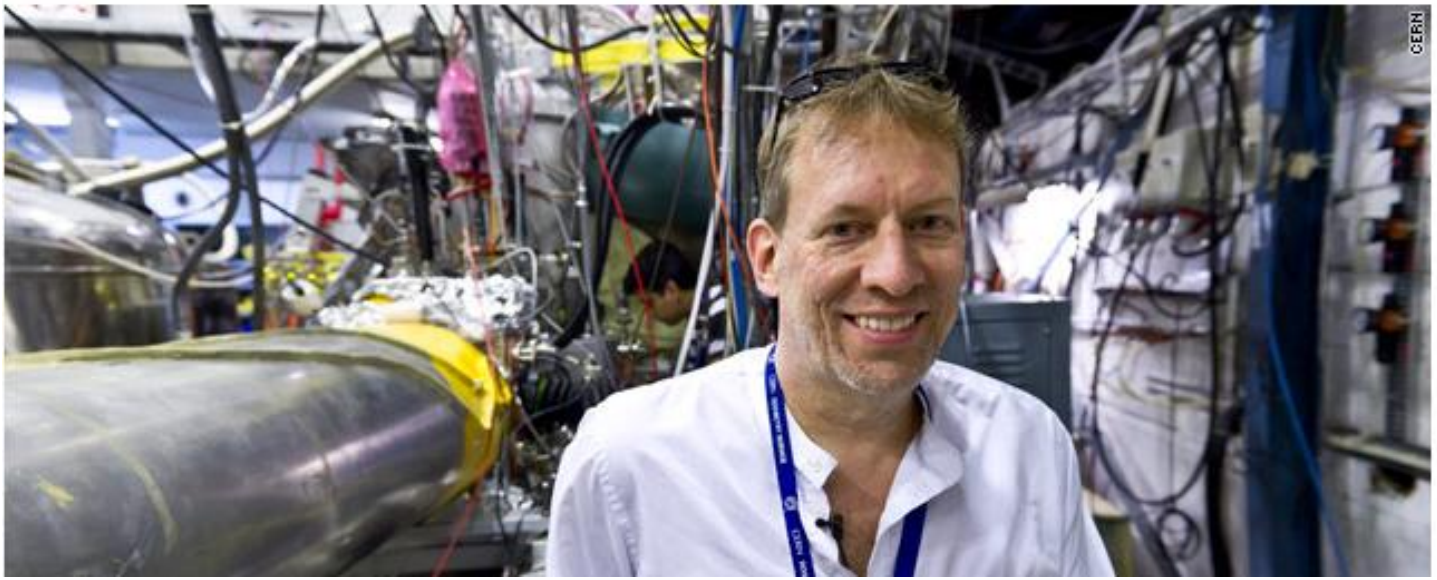
Antimatter atom trapped for first time, say scientists

By Jason Palmer
Science and technology reporter, BBC News

Antimatter atoms have been trapped for the first time, scientists say.

Scientists capture antimatter atoms in particle breakthrough

By Thair Shaikh, CNN
November 18, 2010 -- Updated 1721 GMT (0121 HKT)



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Physicists capture antimatter

Swiss-based institute creates and, for the first time, traps antimatter atoms, one of the bigge science.

Last Modified: 18 Nov 2010 06:14 GMT

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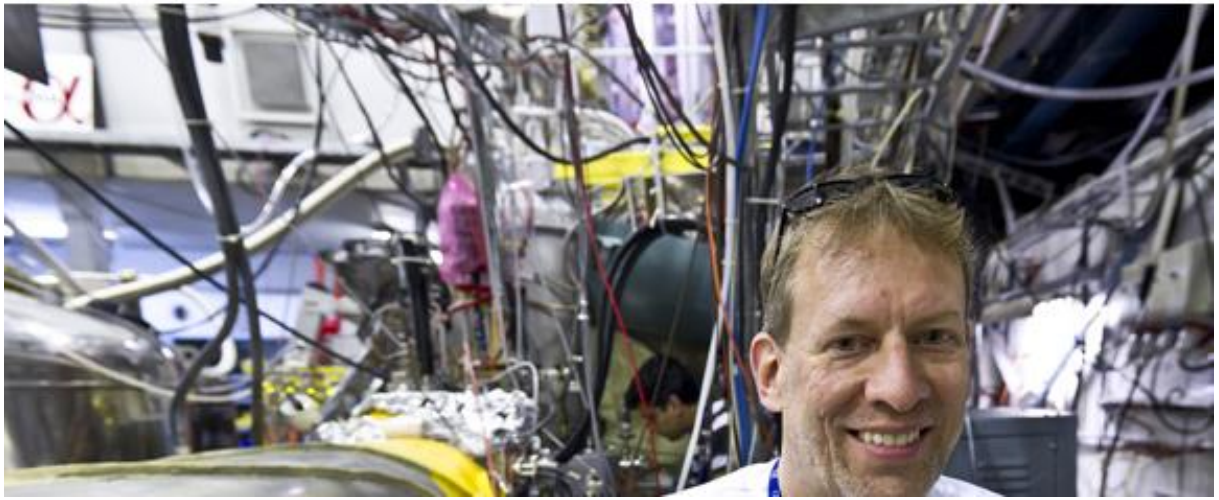
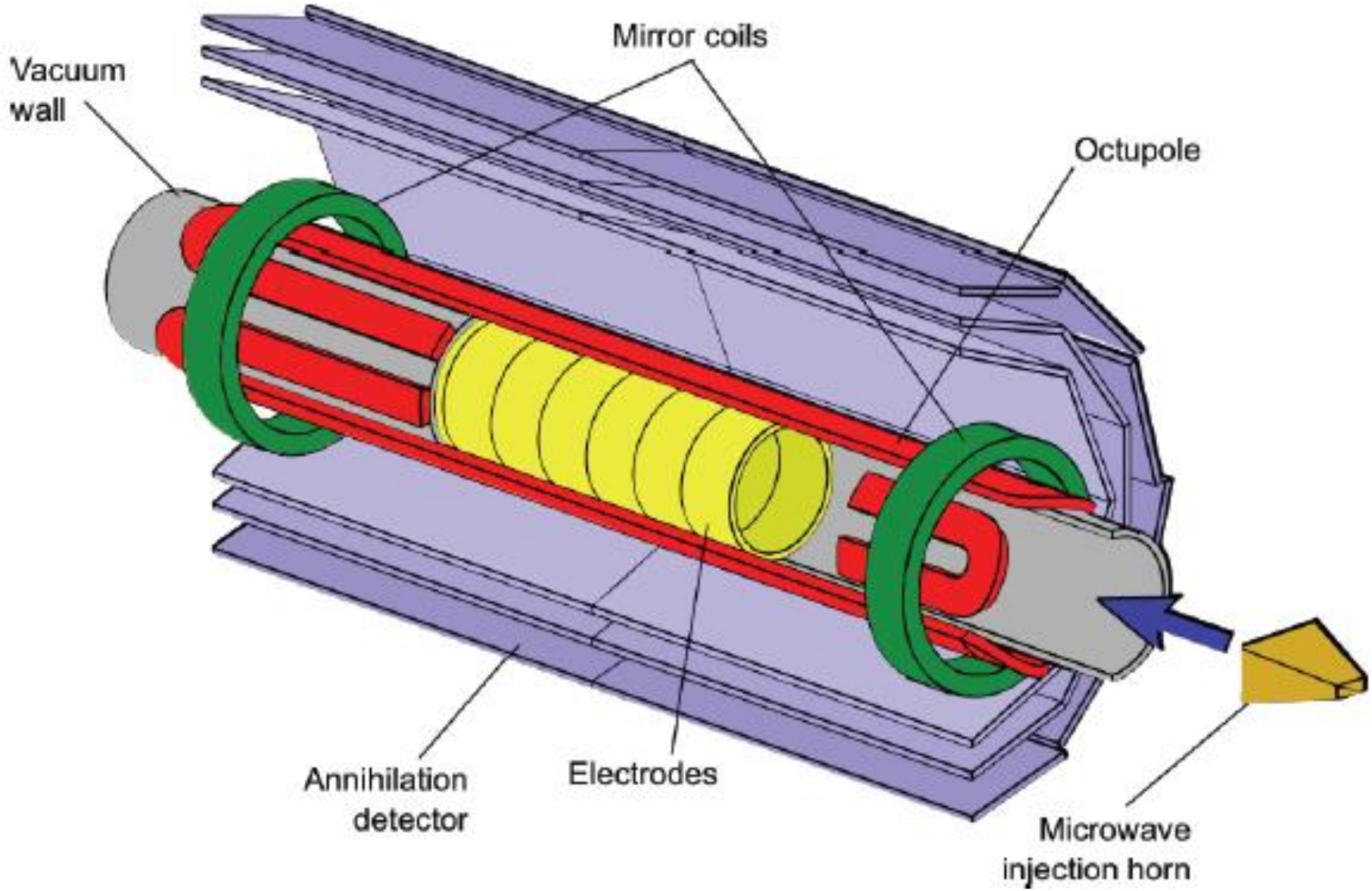


Physics World reveals its top 10 breakthroughs for 2010

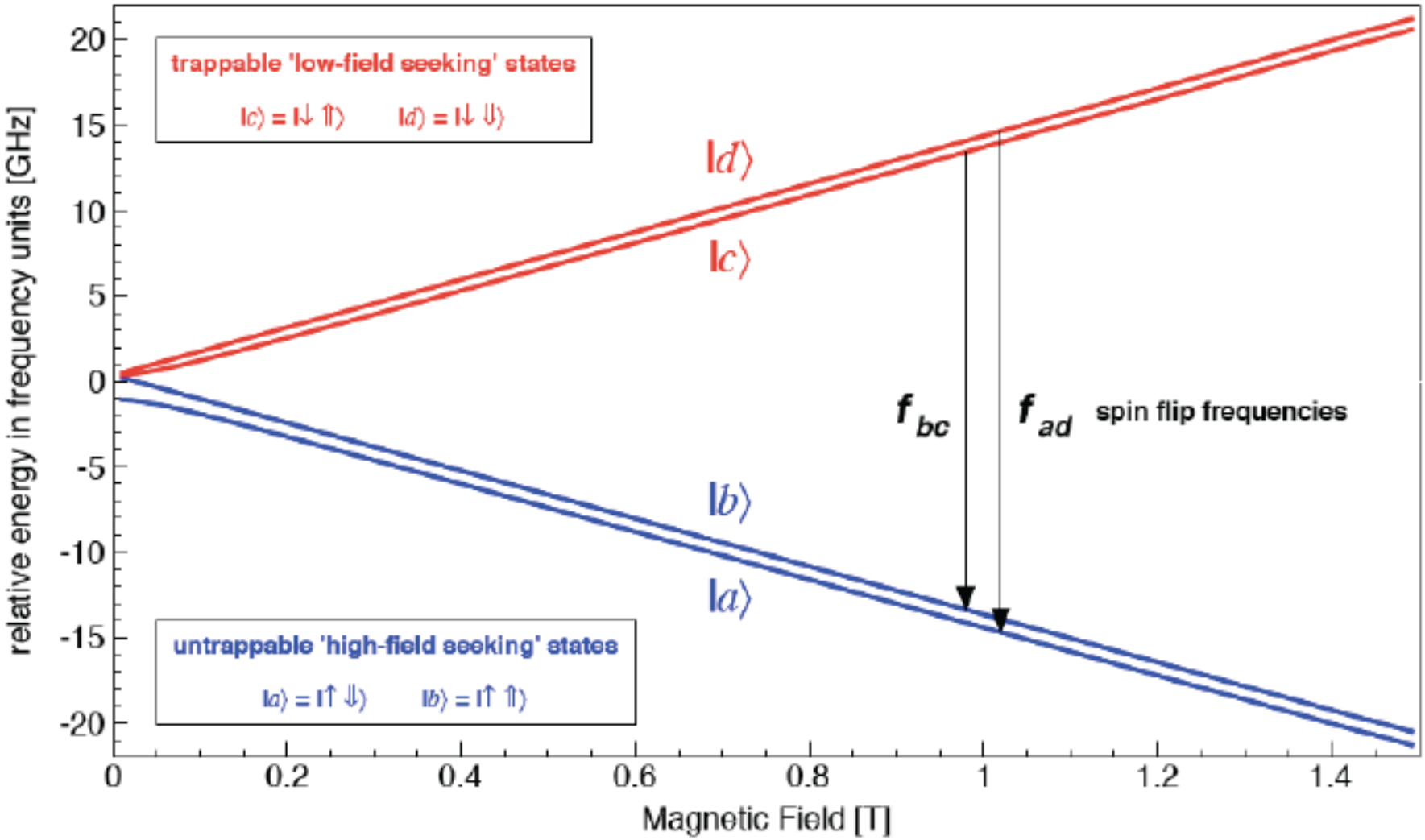
Dec 20, 2010 25 comments

It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the *Physics World* 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

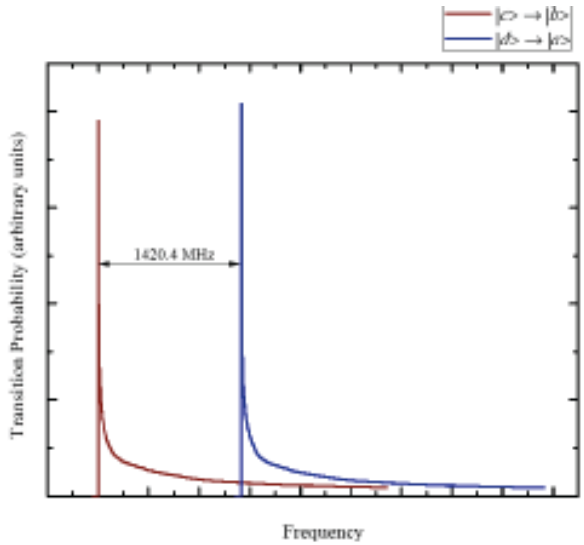
Talk in anti-matter language (2011)

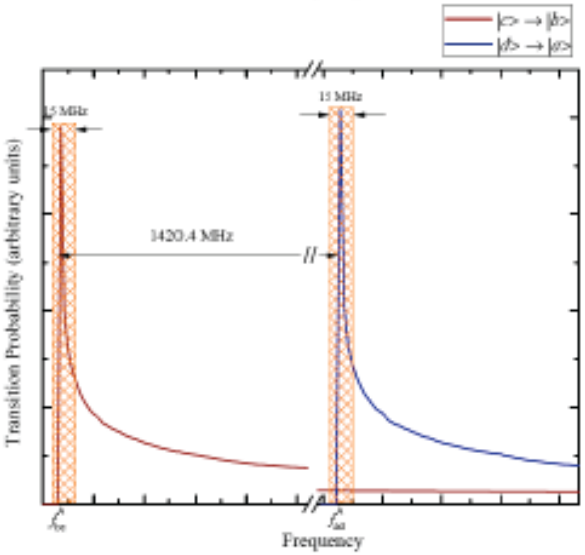


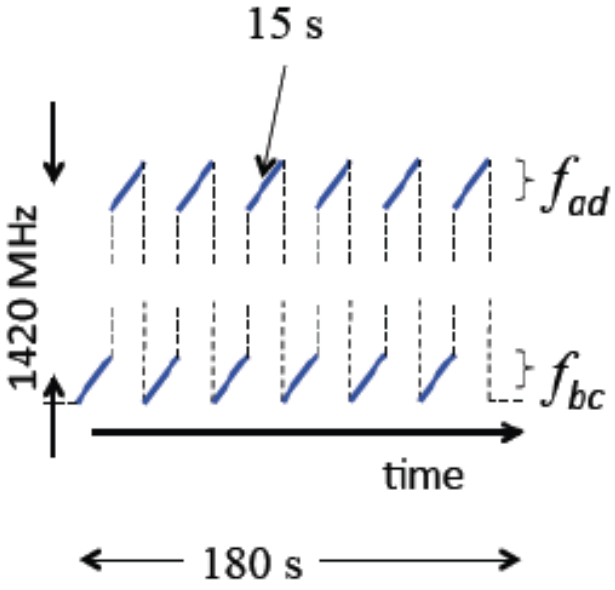
Breit-Rabi level diagram

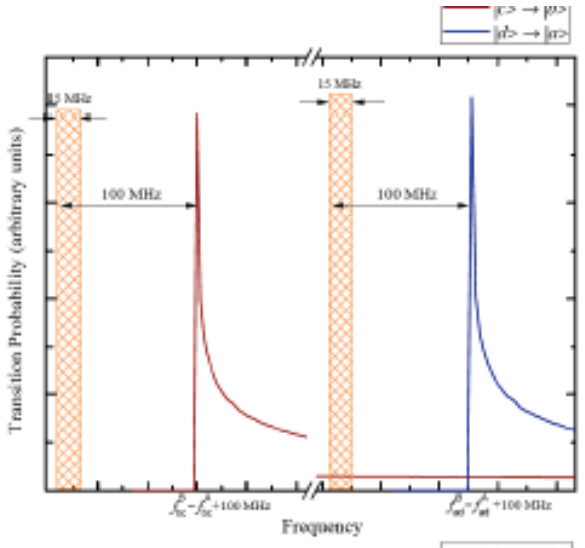


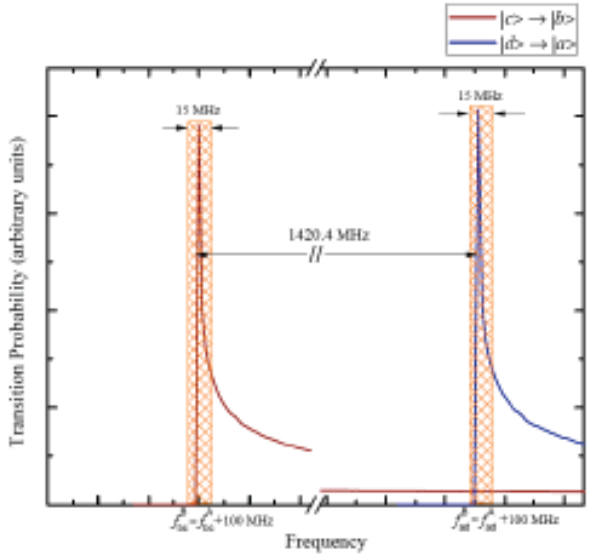
Microwave on-resonance , off-resonance excitatios











Microwave experiments

‘Disappearance Mode’ measurements in 2011:

Microwave on-resonance: Attempts: 103

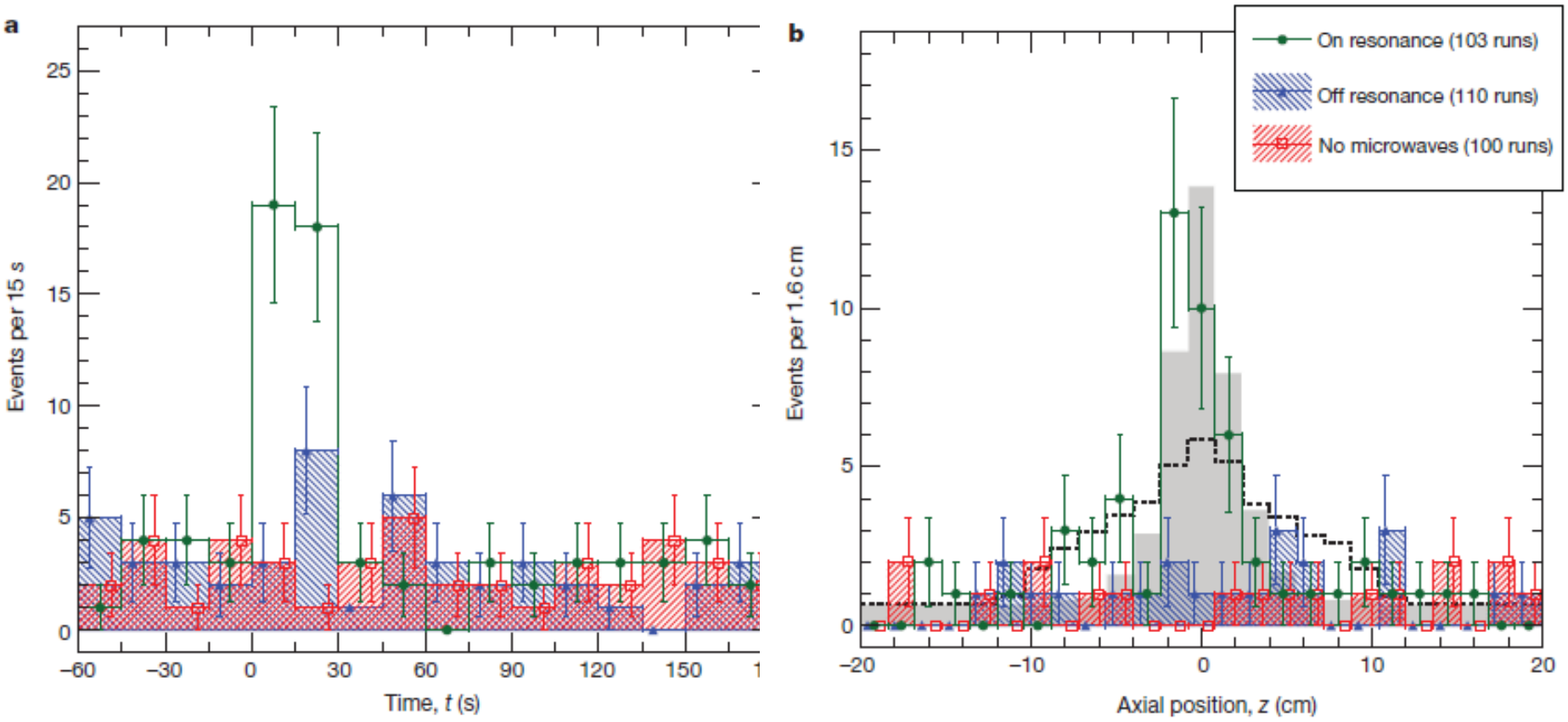
Microwave off-resonance: Attempts: 110

No microwaves: Attempts: 100

Appearance Mode:

Using the same runs, can also look for hbar annihilations above background in on-resonance case.

Microwave Appearance mode data



Nature, volume 483, p.439 (22 March 2012)

Microwave Disppearance mode

RESEARCH LETTER

Table 2 | 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

Nature, volume 483, p.439 (22 March 2012)

ALPHA
nature COMMUNICATIONS

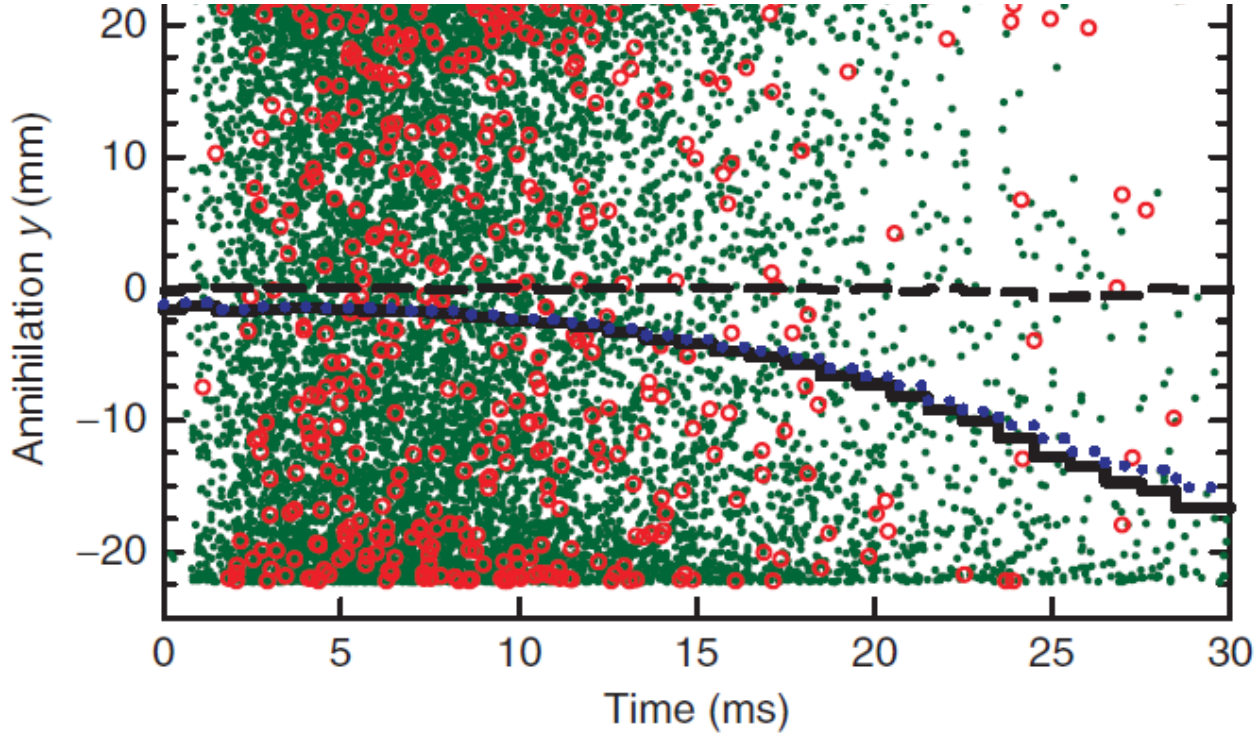
ARTICLE

Received 14 Jan 2013 | Accepted 22 Mar 2013 | Published 30 Apr 2013

DOI: 10.1038/ncomms2787 OPEN

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

The ALPHA Collaboration* & A.E. Charman[1]



30 April 2013 Last updated at 17:38 GMT

Antigravity gets first test at Cern's Alpha experiment

By Jason Palmer
Science and technology reporter, BBC News

The Alpha experiment's antimatter chamber uses magnetic fields to sequester antihydrogen atoms

Would an antimatter apple fall upward from the earth?

Los Angeles Times - Apr 30, 2013

That's where **ALPHA** comes in. The experiment uses strong magnets to trap **antihydrogen** atoms, which are formed by combining an antiproton and a positron. (For a great primer on how ATLAS works, check out this article by former Times staffer Thomas H.

Crazy world: Antimatter might just fall up

CBS News - May 1, 2013

Fajans and his colleagues at the **Alpha** experiment at Switzerland's CERN physics lab made the first experimental measurements of the gravitational mass of **antihydrogen** -- the antimatter equivalent of hydrogen, made of an antiproton and a

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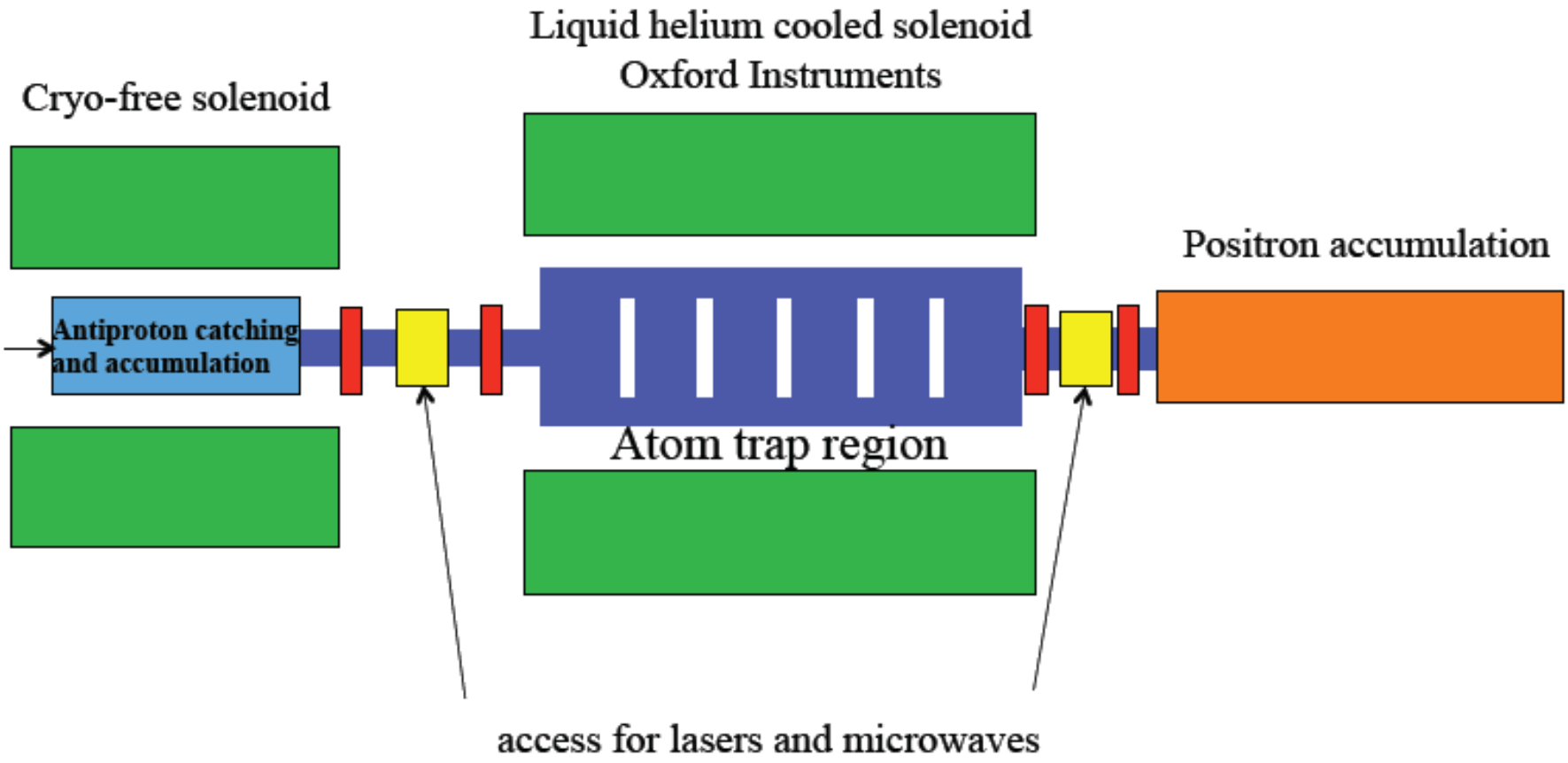
Scientists Trying to Determine If Anti-Matter Falls Up Against Gravity

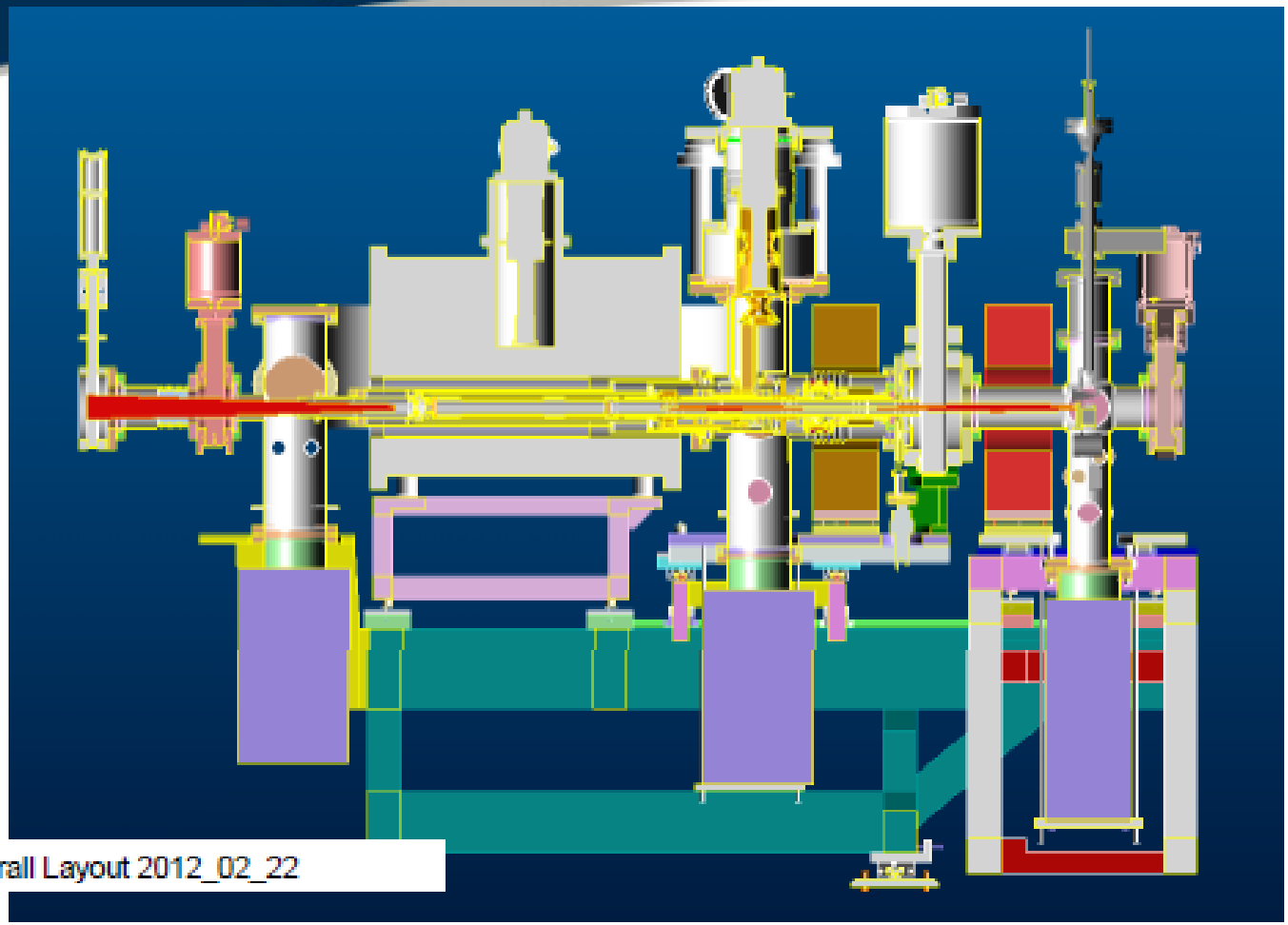
What to do with a device that works so well?

ALPHA 2- the Next Generation



Science & Technology Facilities Council

Alpha-2



Overall Layout 2012_02_22

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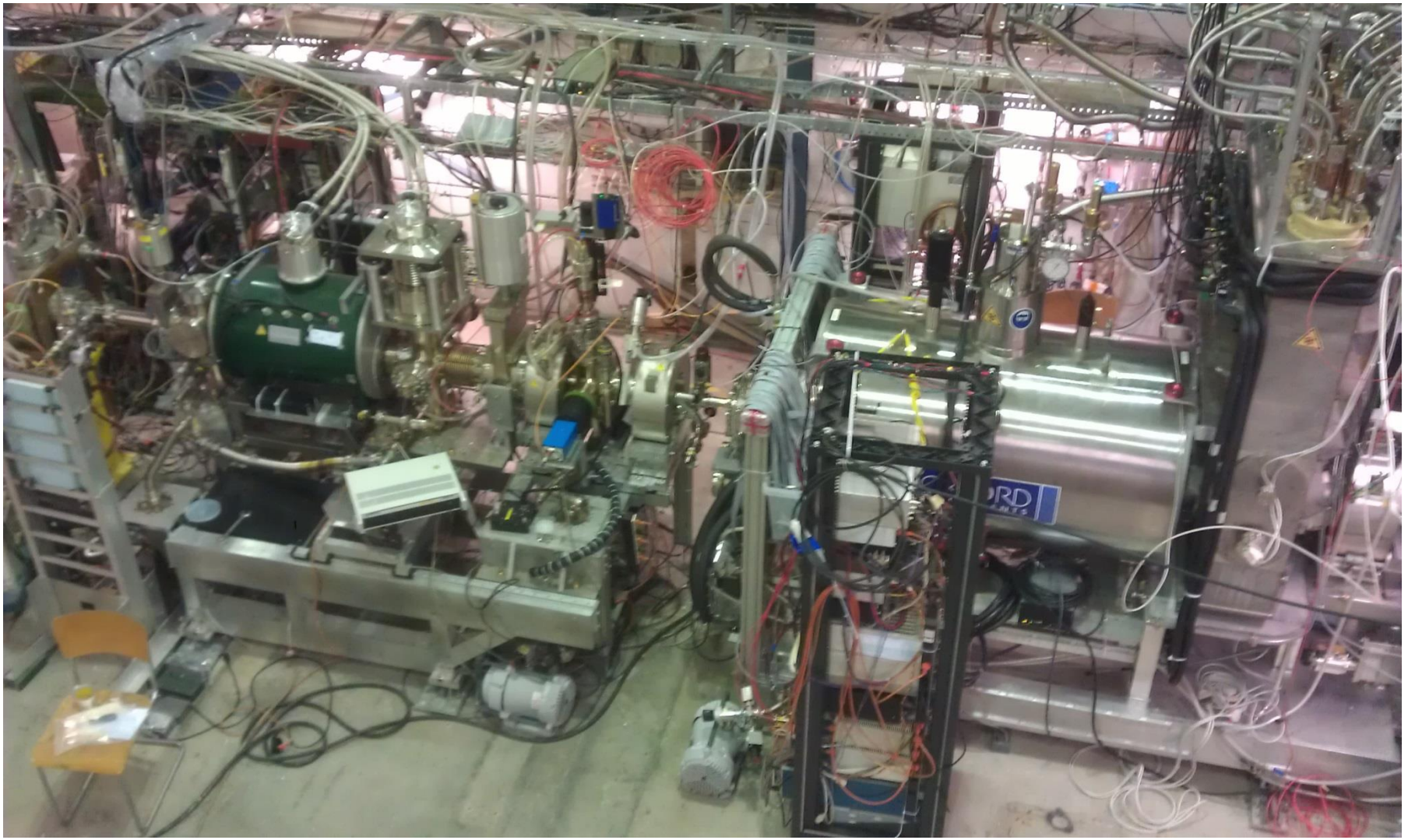
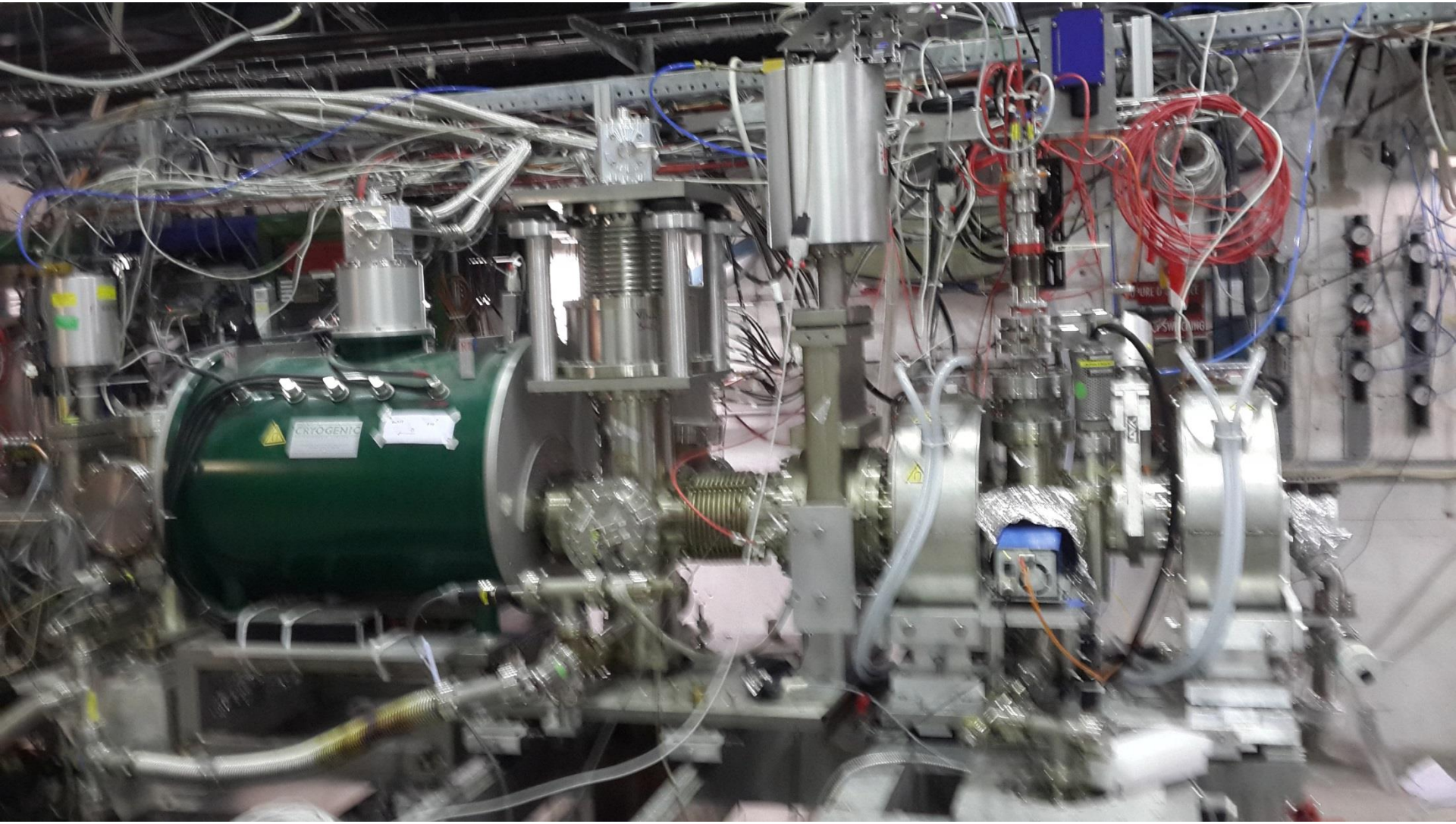
ALPHA 2- the Next Generation



ALPHA 2 antiproton catching trap



PROBABLY THE BEST ANTIMATTER EXPERIMENT IN THE WORLD

What do Carlsberg, Star Trek, and Angels and Demons have in common? Antimatter, of course! Antimatter – the evil twin or mirror-image of the normal matter that builds the universe – is not just a science fiction fuel or explosive. It's the main actor in modern, boundary-breaking research in physics.

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Professor Miri Amit
Ben Gurion University
Eilat Campus

Geneva, 12 November 2013

Israeli collaboration has been an important part of our success in ALPHA, and it was thus quite fitting for Dr. Sarid to organise a meeting for us. Needless to say, having a meeting in the beautiful and dramatic setting of Eilat was quite conducive to cooperation within the collaboration - I can't remember a meeting where spirits have been so high.

We all wish you the best of luck as you lead the development of the Eilat campus. If we can ever be of any professional assistance, don't hesitate to contact me. My colleagues are already asking when the next Eilat meeting will be.