Antimatter Physics at the Antiproton Decelerator

Jeffrey S. Hangst – Aarhus University, Denmark
Spokesperson: the ALPHA antihydrogen collaboration

jeffrey.hangst@cern.ch

http://alpha-new.web.cern.ch/

"CERN People" on Google +
https://plus.google.com/104143331673460015980/posts

I will try to answer the following questions:

- What happens if time runs backwards?
- Is right better than left?
- Why is the universe made of matter instead of antimatter?
- Is there an anti-universe?
- Can we blow up the Vatican with antimatter?

- Something completely different - sometimes
- Sometimes
- Nobody knows.
- Nobody knows.
- We could, if we had enough. We never will.

Thanks for your attention, have a good day!

(Seriously, how cool is it to actually get paid to worry about this…)

ALPHA

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

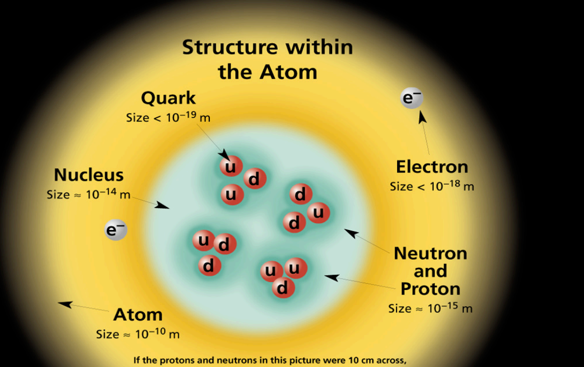
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$
Mesons are bosonic hadrons.
There are about 140 types of mesons.

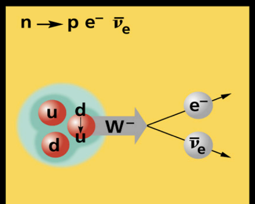
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

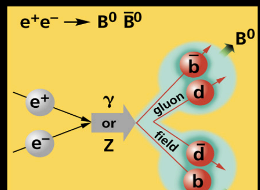
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

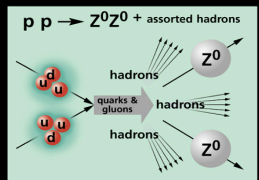
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

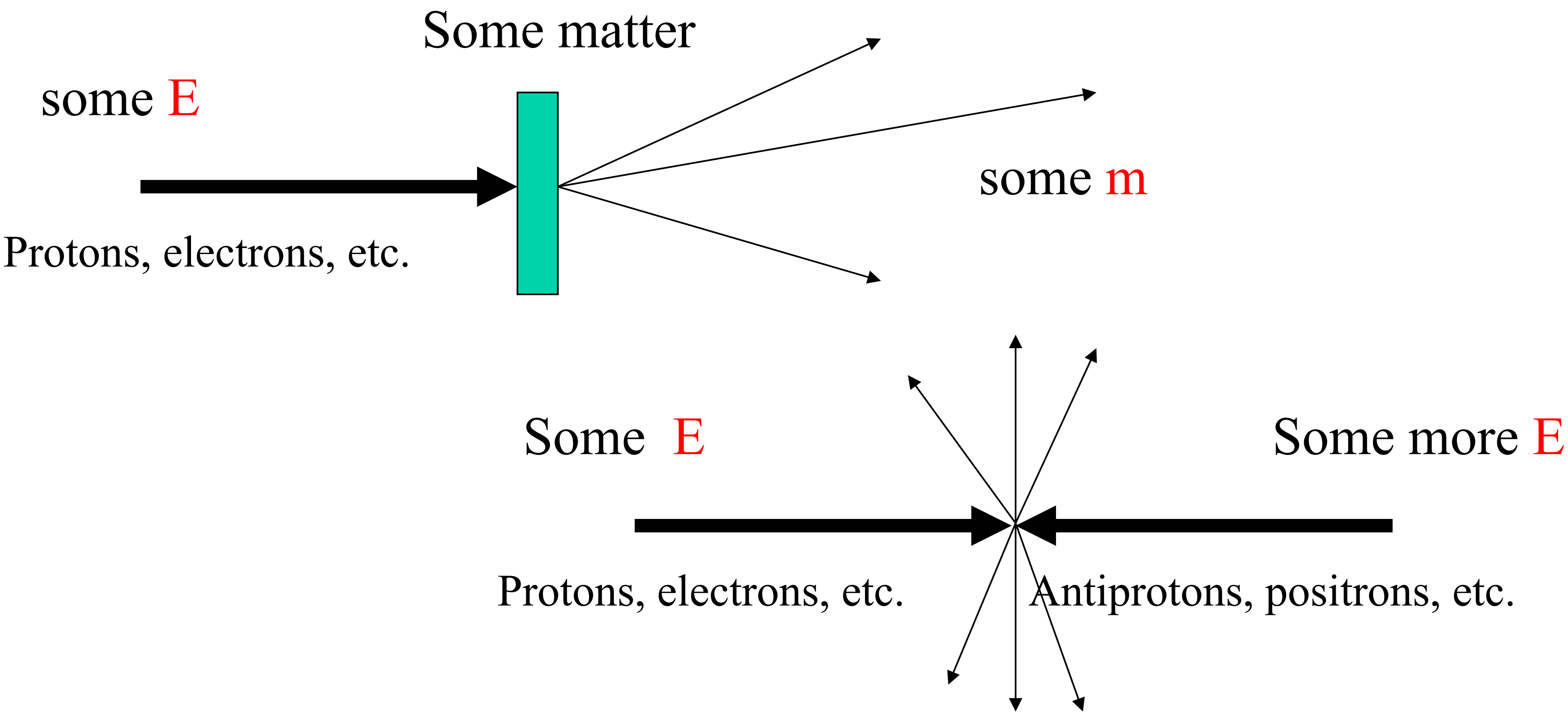
This chart has been made possible by the generous support of:

U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

How do we know all of that?

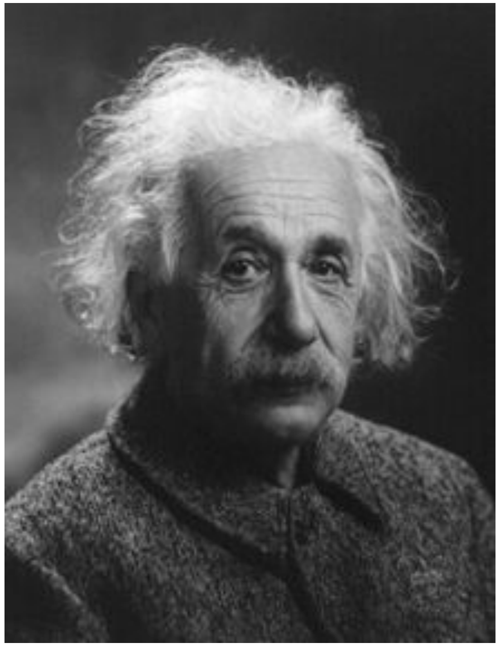
- **From *experiments* with $E=mc^2$**



Thinking outside the box - farmer Jensens paradox:

- **You need to fence in a field of 10000 m^2, with equal sides**
- **How long is each side?**
- **You know a little math, so you write an equation:**
  A = s × s = s^2
- **Easily solved! For *A* = 10000 m^2, *s* must be 100 m.**
- **Wait a minute, I can also solve that equation with s = -100 m**
- **Don't be an idiot, a length of -100 m is meaningless!**
- ***It's not physical.***

+



=

Physics of really small things (quantum mechanics)

Physics of really fast things (special relativity)

$$\left(c\boldsymbol{\alpha}\cdot\hat{\mathbf{p}}+\beta mc^2\right)\psi = i\hbar\frac{\partial\psi}{\partial t}$$

Antimatter !!!

- **Paul Adrian Maurice Dirac (1902-1984)**
- Theory implied antimatter (1928, 1929)
- Positron discovered (Anderson,1932)
- Nobel prize for Dirac (1933)
- *Doubled the universe*
- Ruined my life (circa 1983)

Antimatter in the laboratory

- **When we use $E=mc^2$ to create mass, we get equal amounts of matter and antimatter**

- **This is because quarks and leptons are Fermions (spin 1/2) and must be created pair-wise; baryon and lepton number are conserved – as far as we know…**

- **To create an antiproton, I must have enough energy to also create a proton**

- **Matter/antimatter pairs *annihilate* when they meet, destroying the Vatican**

  - **Enrico Fermi (1901-1954)**
  - **University of Chicago (USA)**
  - **Nobel prize 1938**
  - **Should have received 5 or 6 more**

Symmetry – it starts with a woman

- **Amelie ”Emmy” Noether (March 23, 1882 – April 14, 1935)**
  - Born in Germany
  - Doctoral degree in Erlangen 1907
  - Göttingen 1915; tenured 1919
  - Fled to the USA i 1933
  - Bryn Mawr College (only women)
    - According to Einstein: ”in the judgment of the most competent living mathematicians, [...] the most significant creative mathematical genius thus far produced since the higher education of women began."

Noether's Theorem (1918)

Every continuous symmetry leads to a conservation law.

- **A mathematical result in classical mechanics – pre-dates quantum mechanics**
- **Also valid in QM and quantum field theory**
- **Extremely important for how physicists regard the universe**

Noether's Theorem -examples

Symmetry

- **The description of a physical system is independent of time**
- **The description of a physical system is independent of position (translation symmetry)**
- **The description of a physical system is invariant under rotation about an axis**

Conserved Quantity

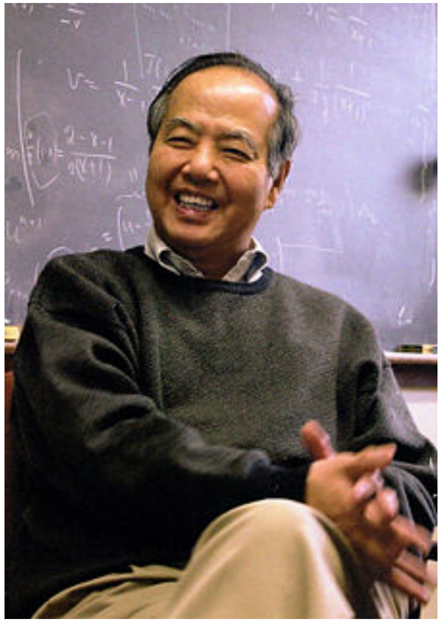
- **The total energy**
- **Linear momentum**
- **Angular momentum**

Discrete Symmetries

P - parity

- **The universe should look the same if we look at it in a mirror**
- **Or: Nature doesn’t know the difference between left and right (up and down, forward and back)**
- **A good symmetry? Before 1957, the answer was ’obviously!’ Left and right are human conventions; Nature could care less what we think.**

Parity Breaking



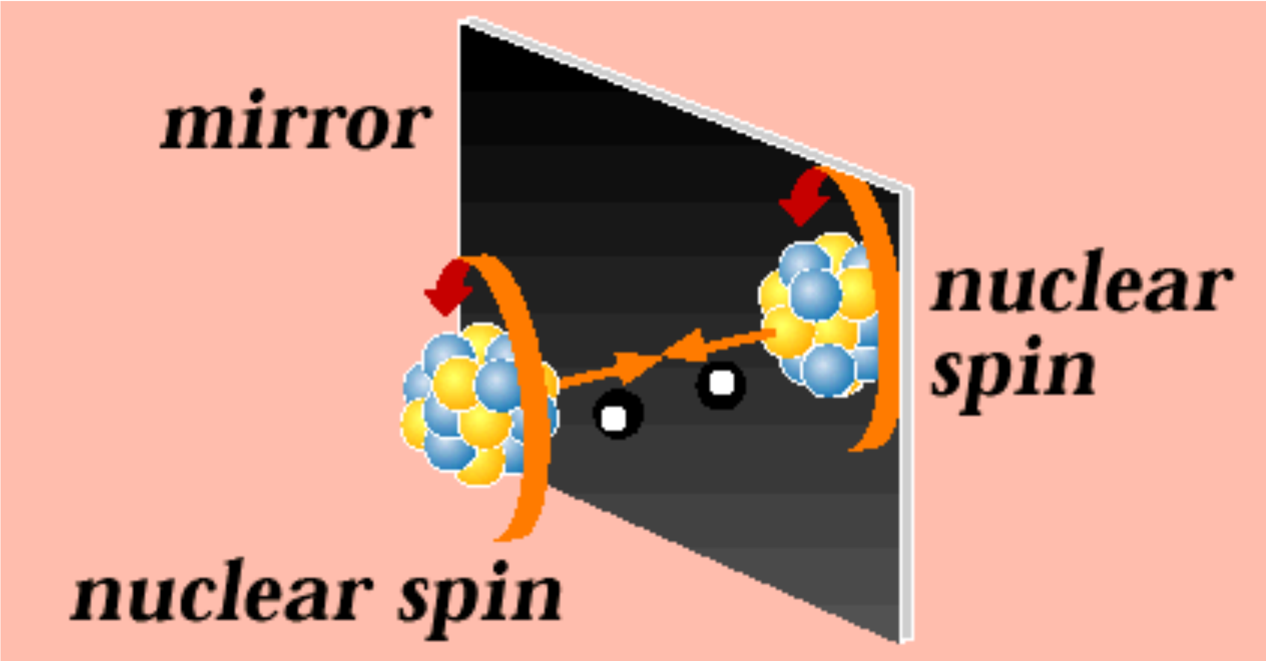
- **T.D. Lee -theory**
  - born 1926 i Shanghai
  - Columbia University (USA)
  - Nobel Prize 1957

- **C.N. Yang - theory**
  - born 1922
  - SUNY Stonybrook (USA)
  - Nobel Prize 1957

- **C.S. Wu - experiment**
  - 1912-1997 (born i Shanghai)
  - Columbia University (USA)
  - Confirmed the expectations of Lee and Yang
  - Didn’t win the Nobel Prize!

Madame Wu's Experiment

- An unstable nucleus emits a particle (electron or positron)
- The nucleus has it's spin in a given direction
- Mesure the distribution of emitted particles with respect to the spin direction
- If more particles come out in one direction (left or right) than the other; parity is broken
- The weak interaction is the culprit



C - charge conjugation

- **The physics of the universe should be the same if we change all of the particles into their respective antiparticles**

- **A good symmetry? For electromagnetism and the strong force - yes. Not for the weak interaction – e.g., neutrino chirality.**

Discrete Symmetries

T – time reversal invariance

What happens if time runs backwards?

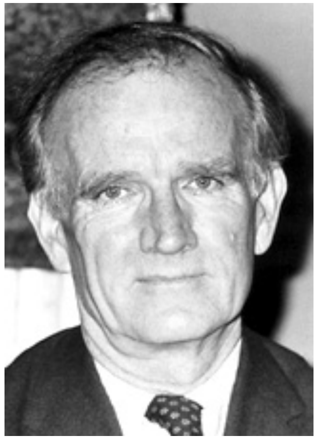
For example: make a movie of a physical process and run it backwards – can you see a difference

A good symmetry?

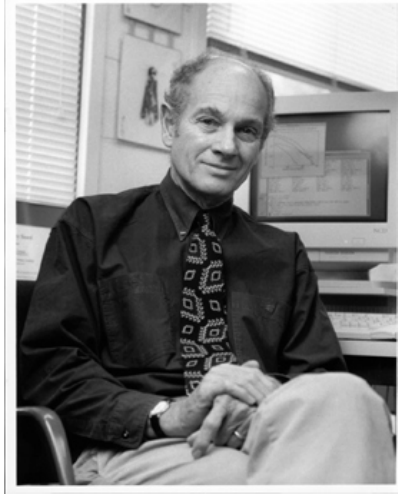
As usual, not for the weak force…

CP Bites the dust

- **Val Fitch**
  - Born 1923
  - Princeton University (USA)
  - Nobel prize 1980



- **James Cronin**
  - Født 1931
  - University of Chicago (USA)
  - Nobel prize 1980
  - Most famous for being a member of Jeff's PhD committee

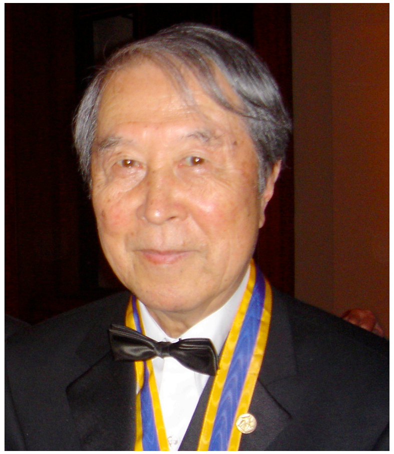


They discovered in 1964 that CP is not conserved in the decay of a K-meson – again a weak interaction effect. These "strange" particles can change back and forth between particle and antiparticle – all on their own. But the back and forth rates are different.

Two things that never should have happened

- Matter (or antimatter)
- Matter with mass (Higgs mechanism)

- **There must have been some *serious* symmetry breaking**



- **Yoichiro Nambu**
  - born Tokyo 1921
  - University of Chicago (USA)
  - Nobel prize 2008
  - Also a member of Jeff's PhD committee

What happened to the antimatter?

- **Andrei Sakharov (1921-1989)**
  - Three conditions for antimatter disappearence
    - Baryon number not conserved
    - CP- not conserved
    - Interactions out of equilibrium in early universe

- **But…**
  - Baryon number is conserved in the laboratory
  - CP-violation is way too little

Won Nobel Peace Prize!!!

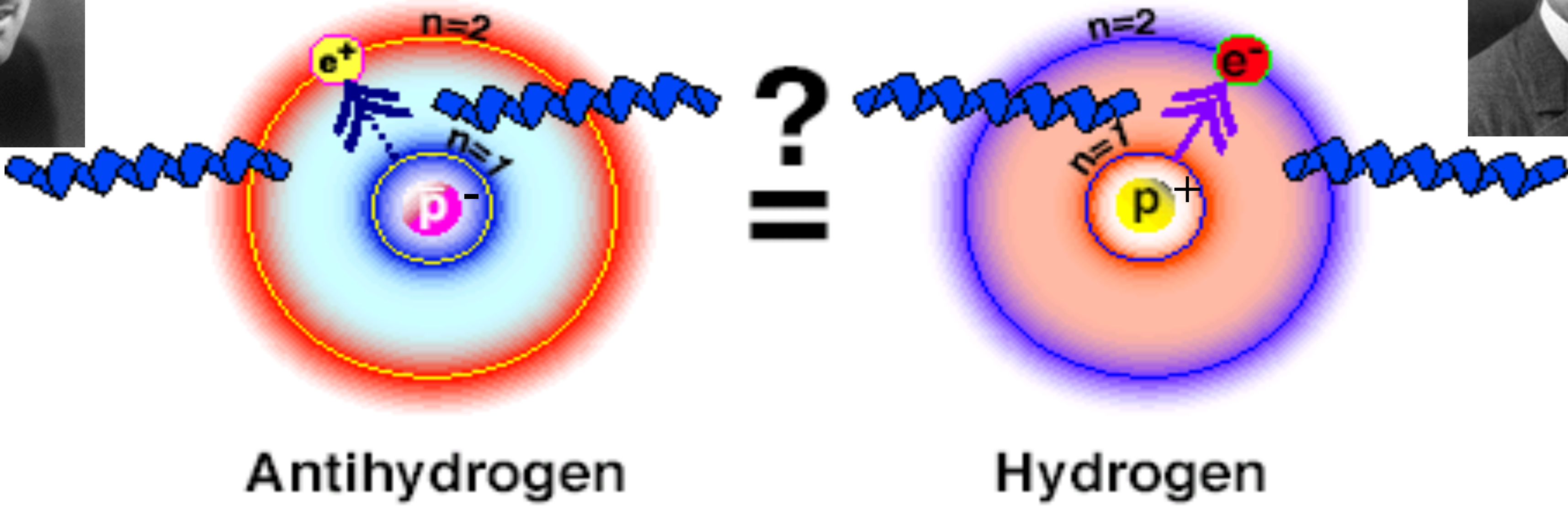
Discrete symmetries – what's left?

- Only CPT – the combination of all three – still seems to hold
- Most theorists believe this to be absolutely true – the CPT theorem
- They have *NEVER* been right in the past
- Antimatter provides a really cool way to check this out – particularly because we know that we don't know the whole story about antimatter

The Essential Question

Paul Dirac

Niels Bohr



How could you possibly work in Denmark and *not* want to know the answer to this?

ALPHA

THE ALPHA COLLABORATION

Aarhus University, Denmark

Auburn University, USA

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Liverpool, UK

University of Manchester, UK

NRCN - Nucl. Res. Center Negev, Israel

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

Motivations in Brief

- Tests of fundamental symmetries by applying ***precision*** atomic physics techniques to anti-atoms:
    - CPT violation?
    - Lorentz invariance violation?

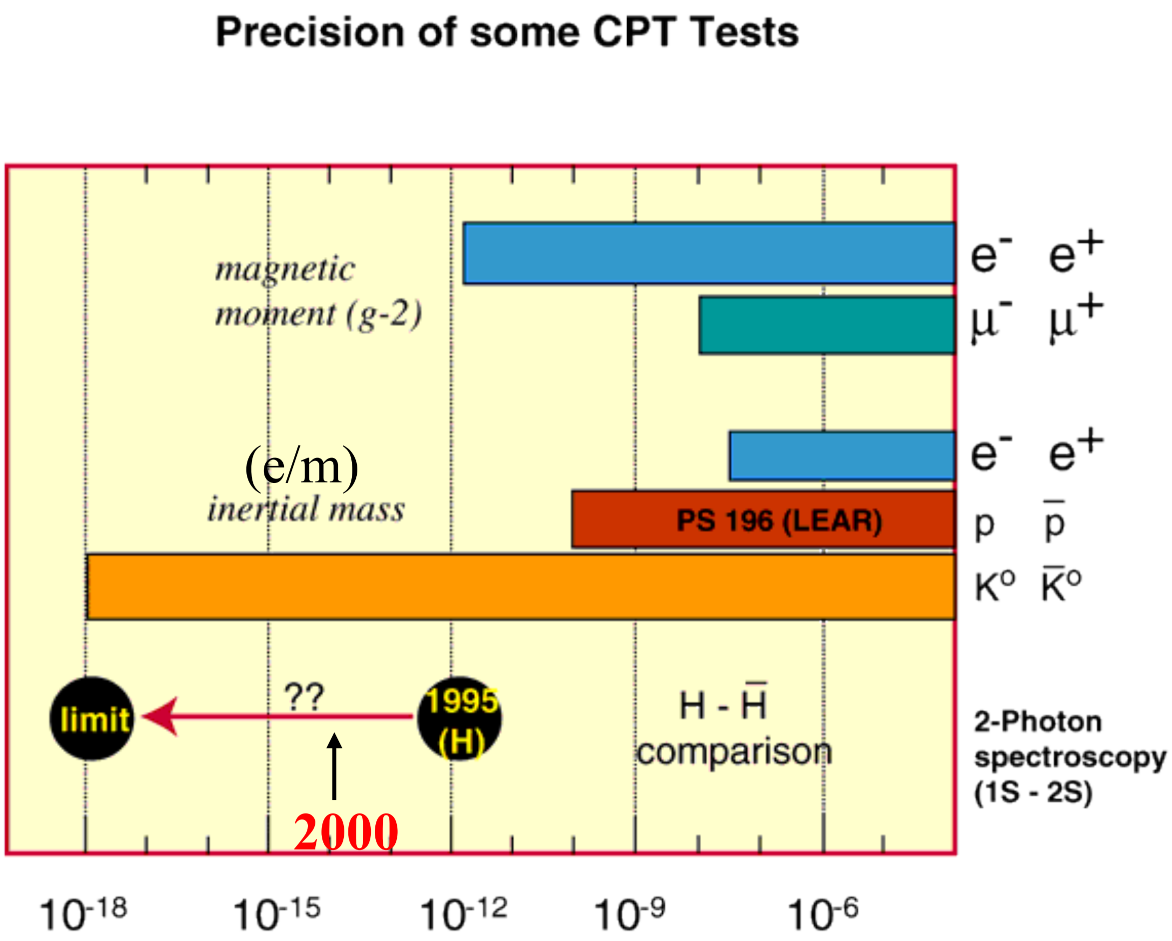
        Physics beyond the Standard Model?

(The initial physics goal of ALPHA was to TRAP antihydrogen atoms, so that they can be studied in detail.)

- (Anti)-Gravity - no current experimental effort in ALPHA, but success in ALPHA suggests possibilities for long-term work.

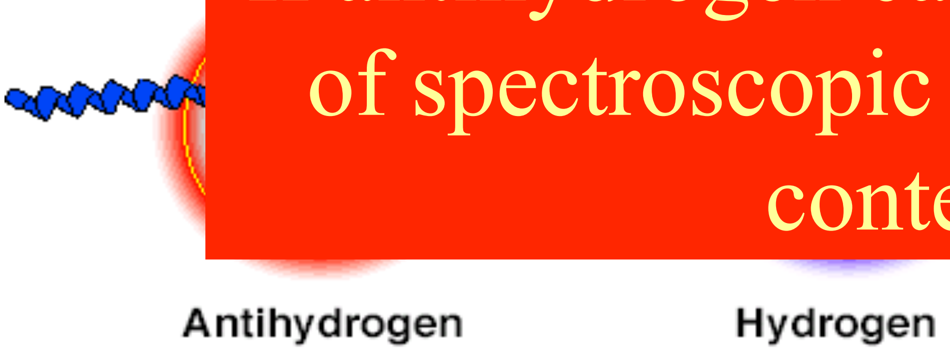
We're looking for evidence for NEW PHYSICS

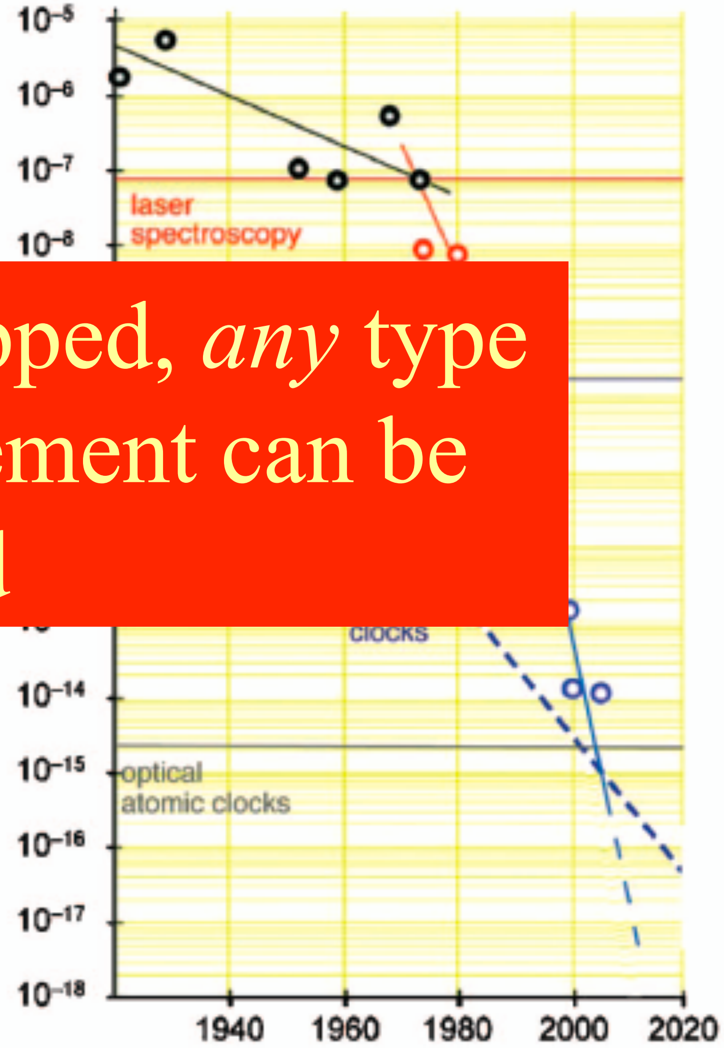
- **CPT violation? Why not?**
- **Has anyone looked?**



The dream - Antihydrogen Spectroscopy

1s-2s two-photon spectroscopy





If antihydrogen can be trapped, *any* type of spectroscopic measurement can be contemplated

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

f(1S-2S) = 2 466 061 413 187 035 (10) Hz - Hänsch group (2011)

A Brief History of Antihydrogen

- CERN (LEAR-TRAP Collaboration): pioneering work on trapping, cooling of antiprotons; proton/antiproton mass comparison (to 1996, LEAR closed)

- CERN (LEAR-PS210): Baur et al., 1996, gas-jet experiment in LEAR

$\bar{p} + Xe -> \bar{H} + e^- + Xe$ $\gamma = 2.3$ 11 atoms observed

- Fermilab (E862): Blanford et al., 1998, gas-jet experiment at FNAL Accumulator

$\bar{p} + H -> \bar{H} + e^- + H$ $\gamma = 9.5$ 57 atoms observed

- CERN (AD-1): Amoretti et al., Sept. 2002

ATHENA produces and observes first cold (< eV) antihydrogen atoms by mixing cold antiprotons and positrons in a Penning trap.

~50000 atoms produced

M. Amoretti et al., Nature 419, 456 (3 Oct 2002)

- CERN (AD-2): Gabrielse et al., Oct. 2002

ATRAP confirms observation of antihydrogen atoms, indirect detection.

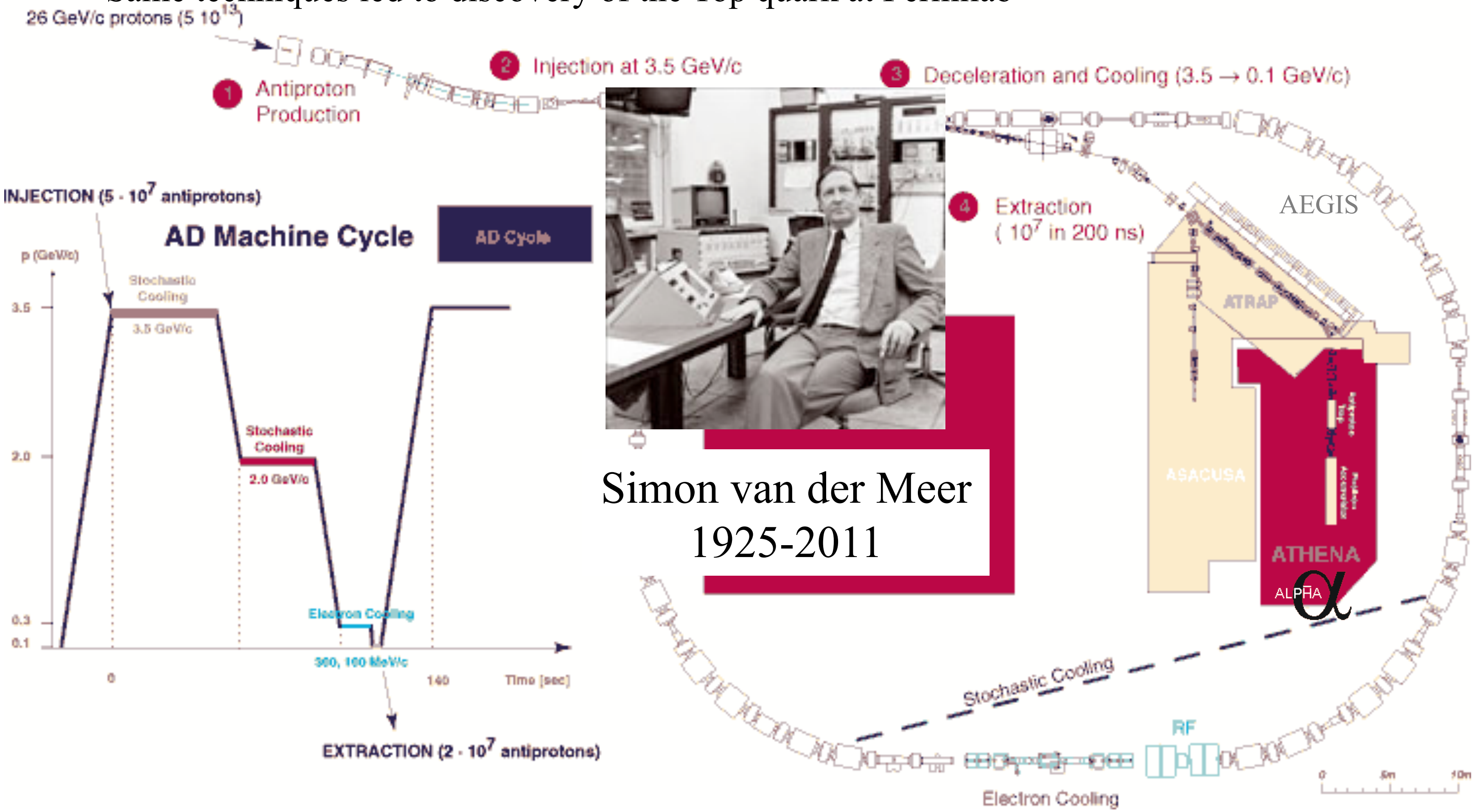
~170000 atoms produced

A Brief History of Antihydrogen II

- CERN closes AD for 1.5 years because of LHC construction: November 2004 (ATHENA dissolved and ATRAP I finishes operation)
- ALPHA proposed (former ATHENA groups + new partners): January 2005
- ALPHA approved by CERN: June 2005
- AD restarts, ALPHA operational: June 2006
- First ALPHA PRL: January 2007
- ALPHA first to trap antihydrogen: November 2010
- ALPHA confines antihydrogen for 1000 s: June 2011
- ALPHA demonstrates resonant interaction with antihydrogen: March 2012

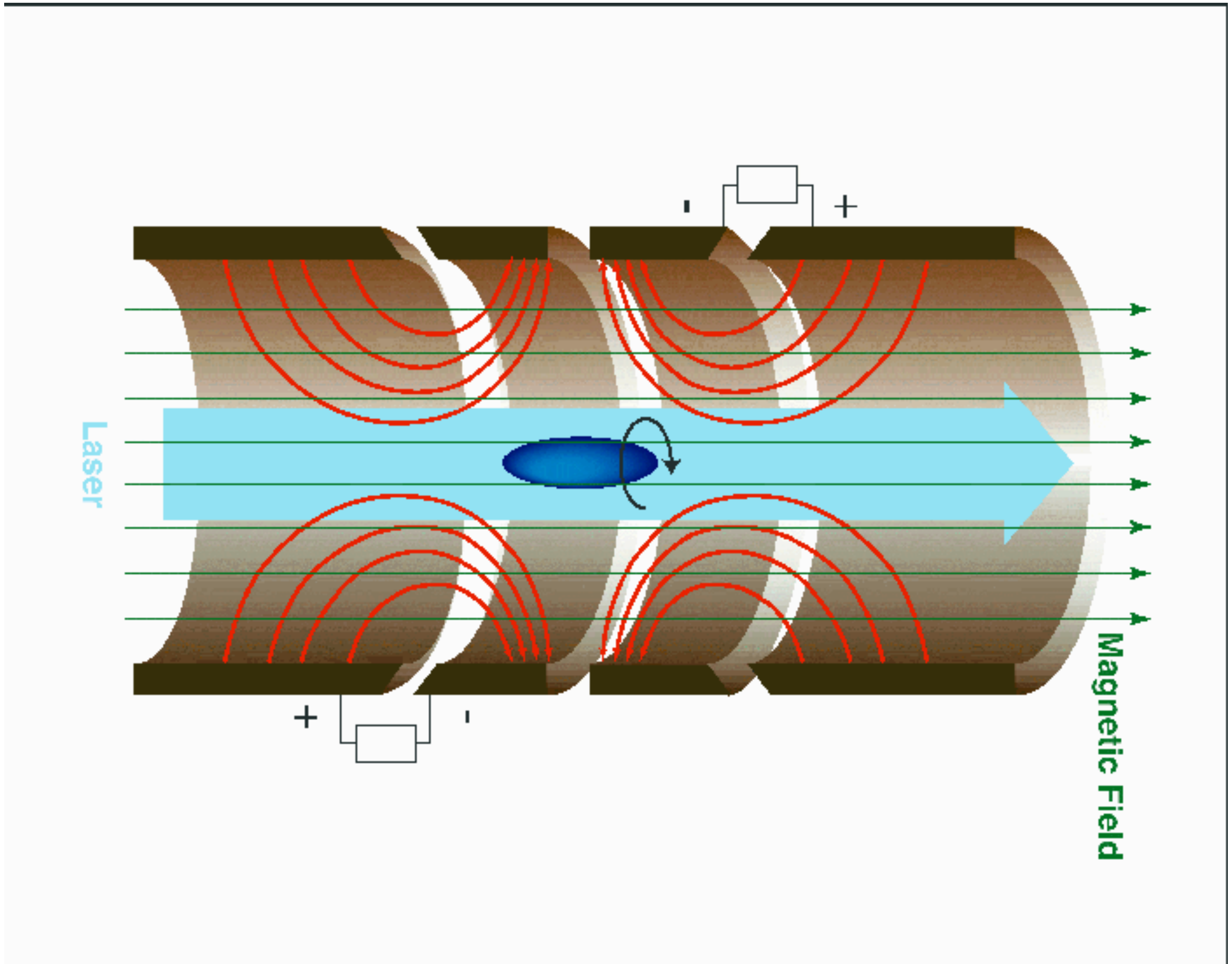
The CERN AD

- Antiproton technology developed for proton-antiproton collisions in SPS
- AD is descended from the AA (antiproton accumulator) and AC (antiproton collector)
- The AD is the most interesting machine at CERN…
- Nobel prize for van der Meer and Rubia (1984) for discovery of *W* and *Z* particles
- Same techniques led to discovery of the Top quark at Fermilab

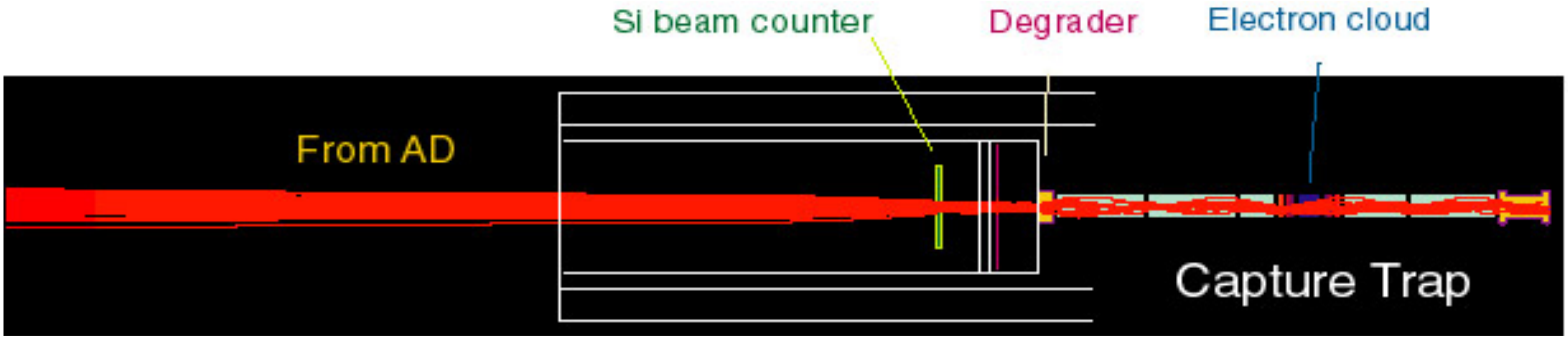


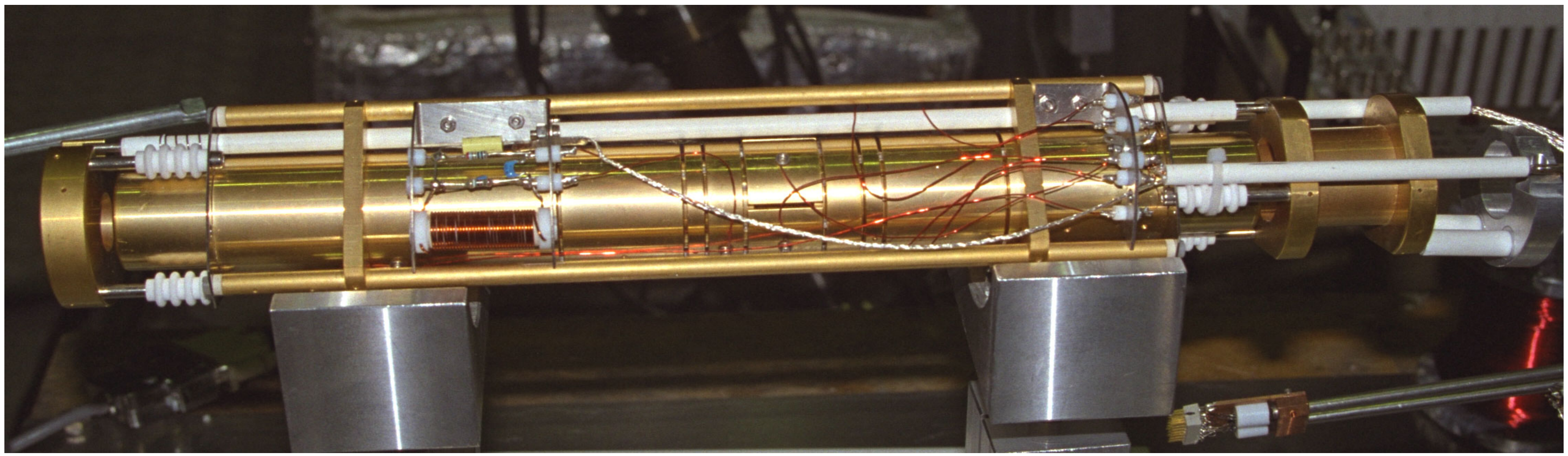
Simon van der Meer
1925-2011

Penning Trap



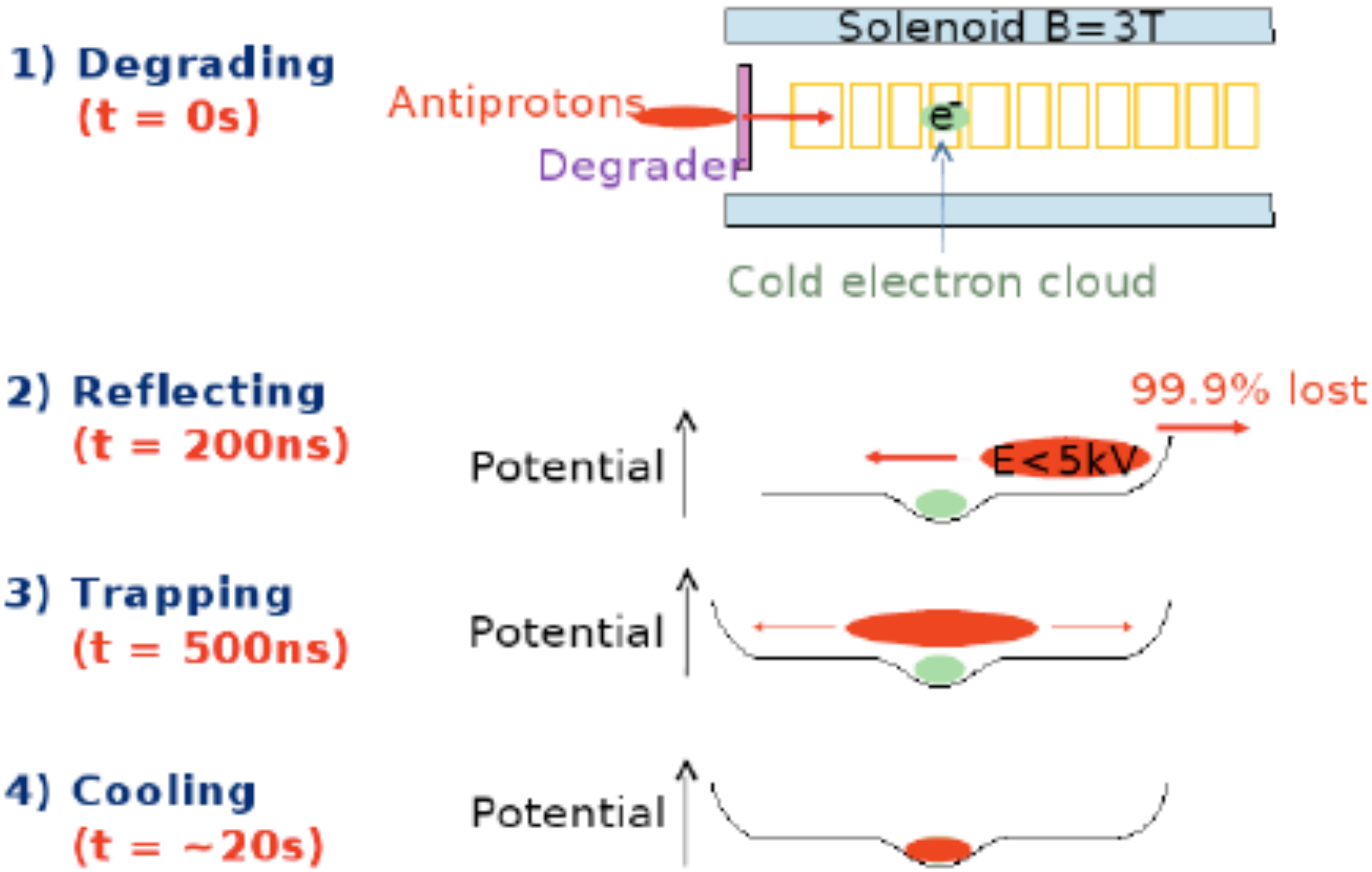
Antiproton Slowing and Catching





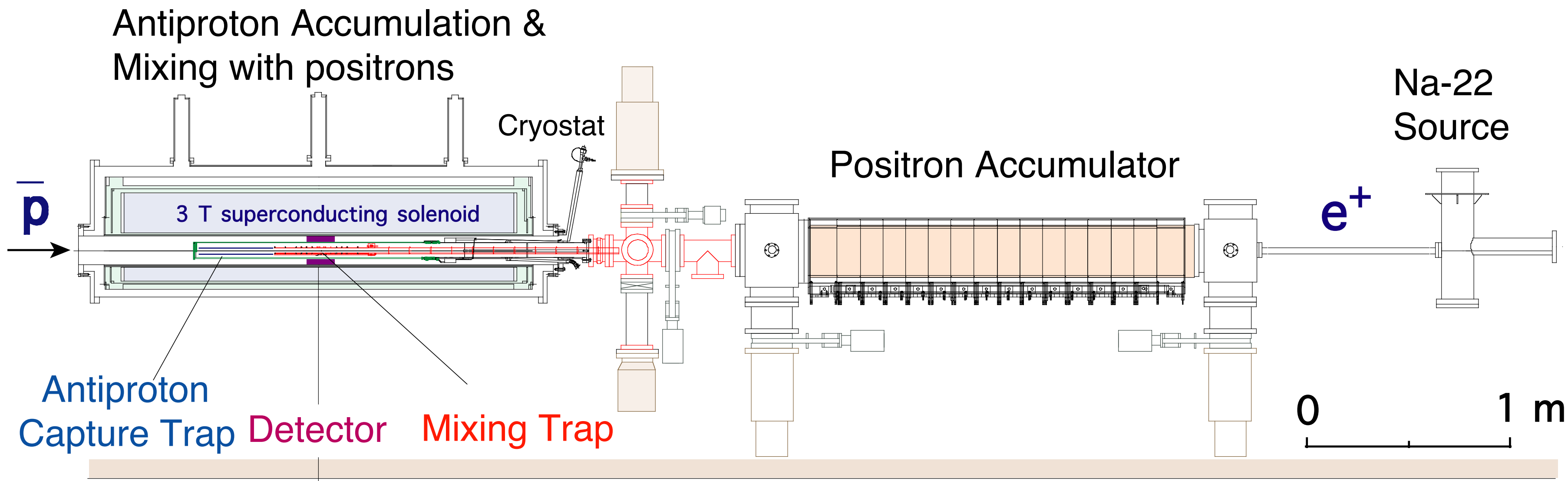
Ab **40000 (ALPHA)** protons are captured from an AD shot.

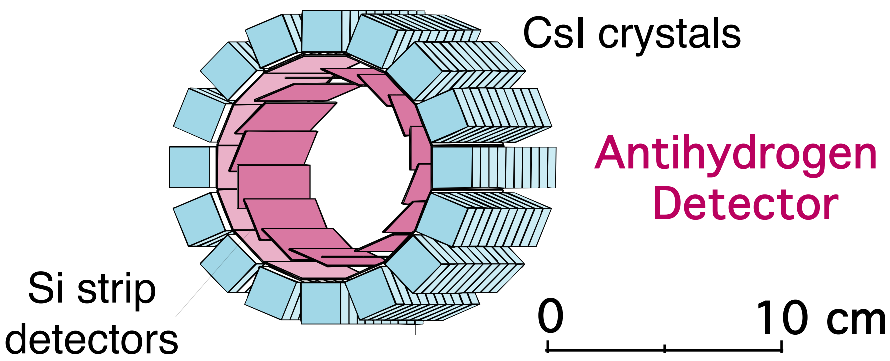
Capture and Cooling of Antiprotons

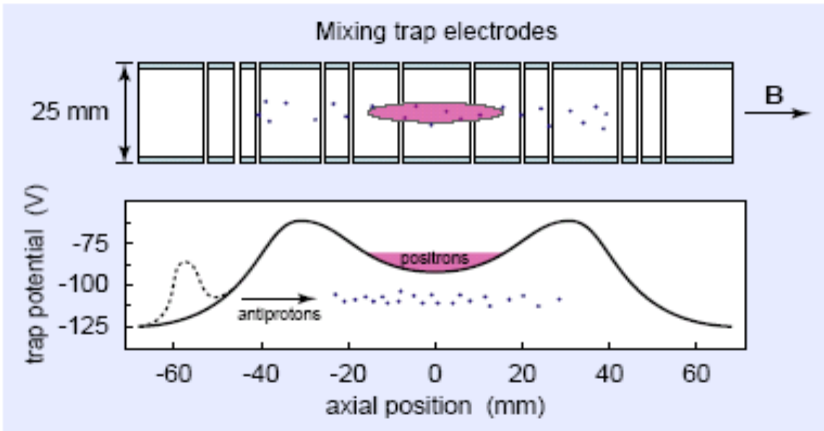


Technique developed by the TRAP collaboration.

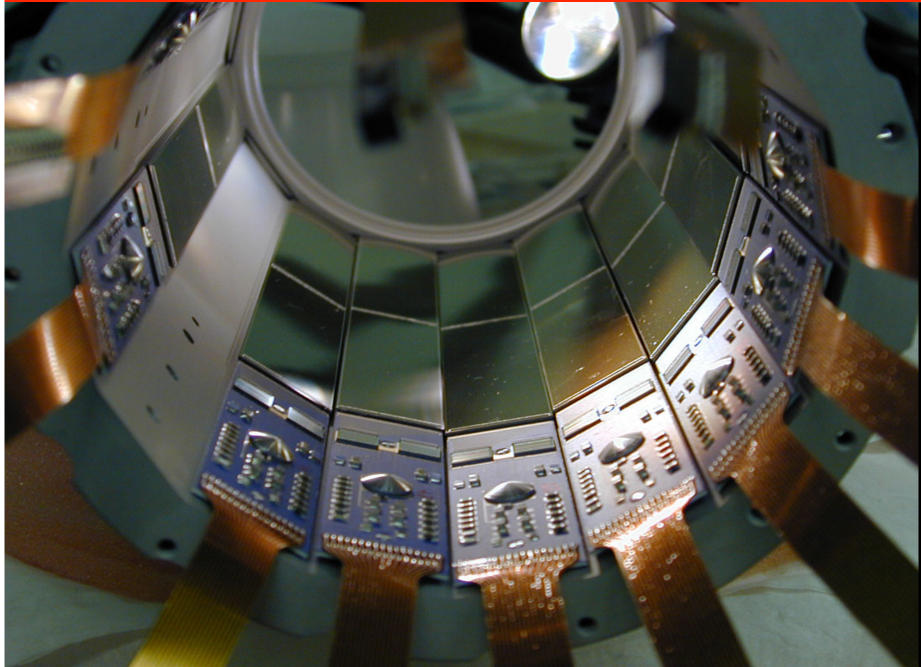
How do you make a lot of antihydrogen? : ATHENA 2002

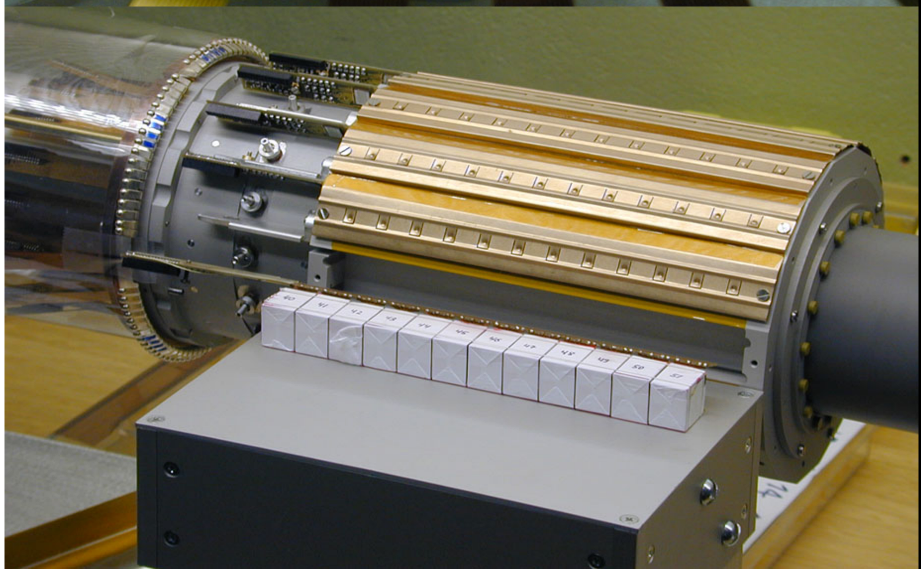


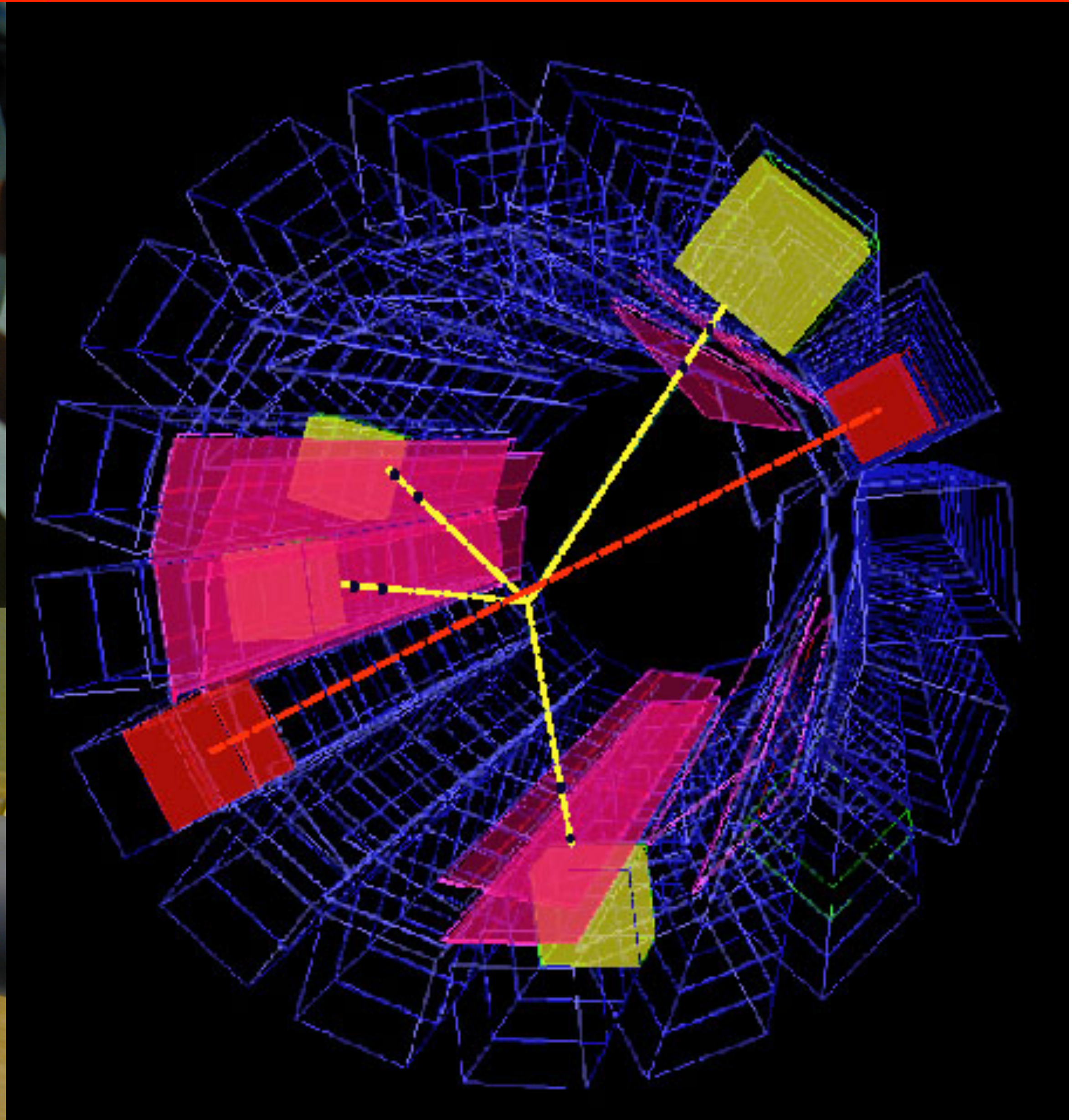


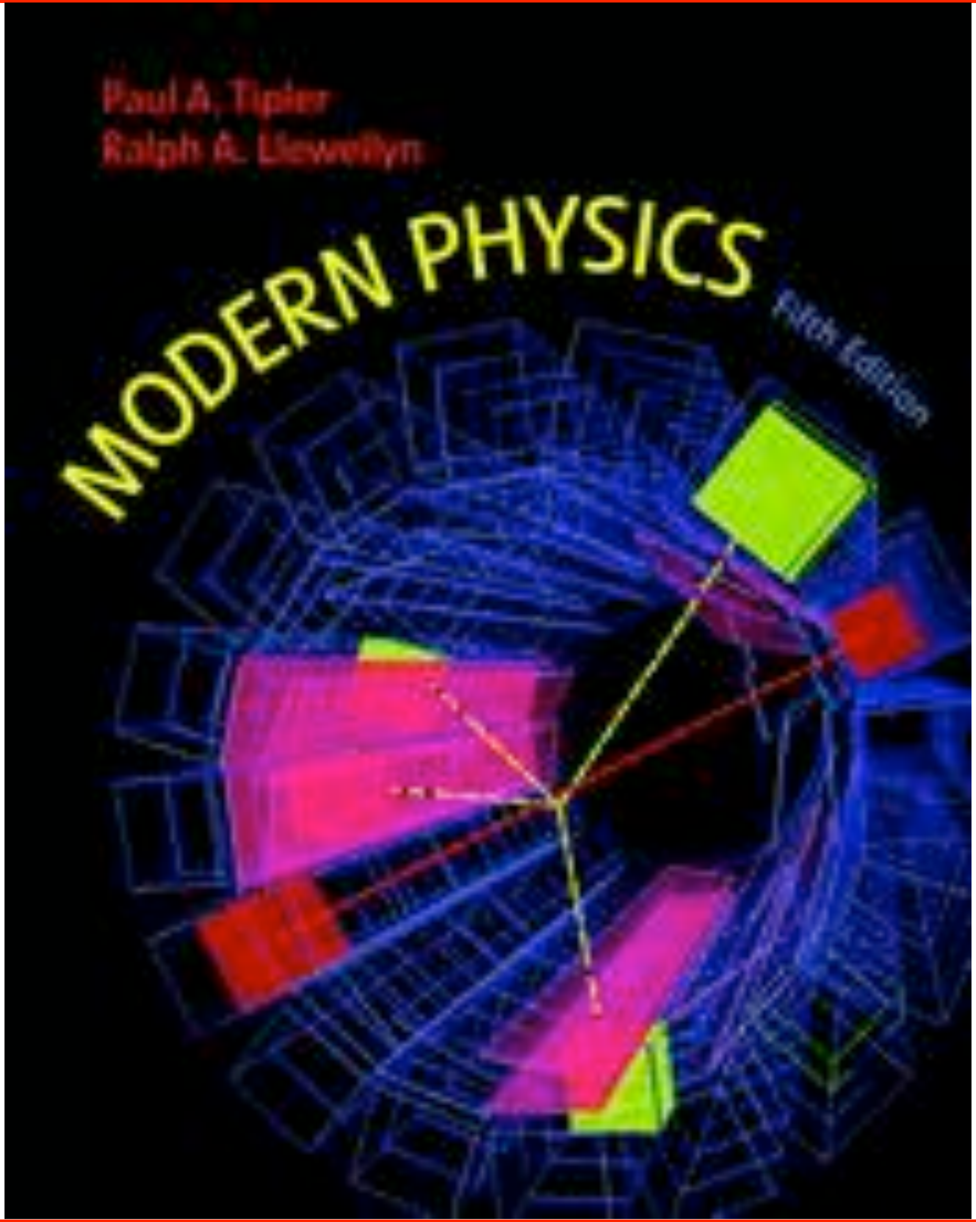


ATHENA Detector



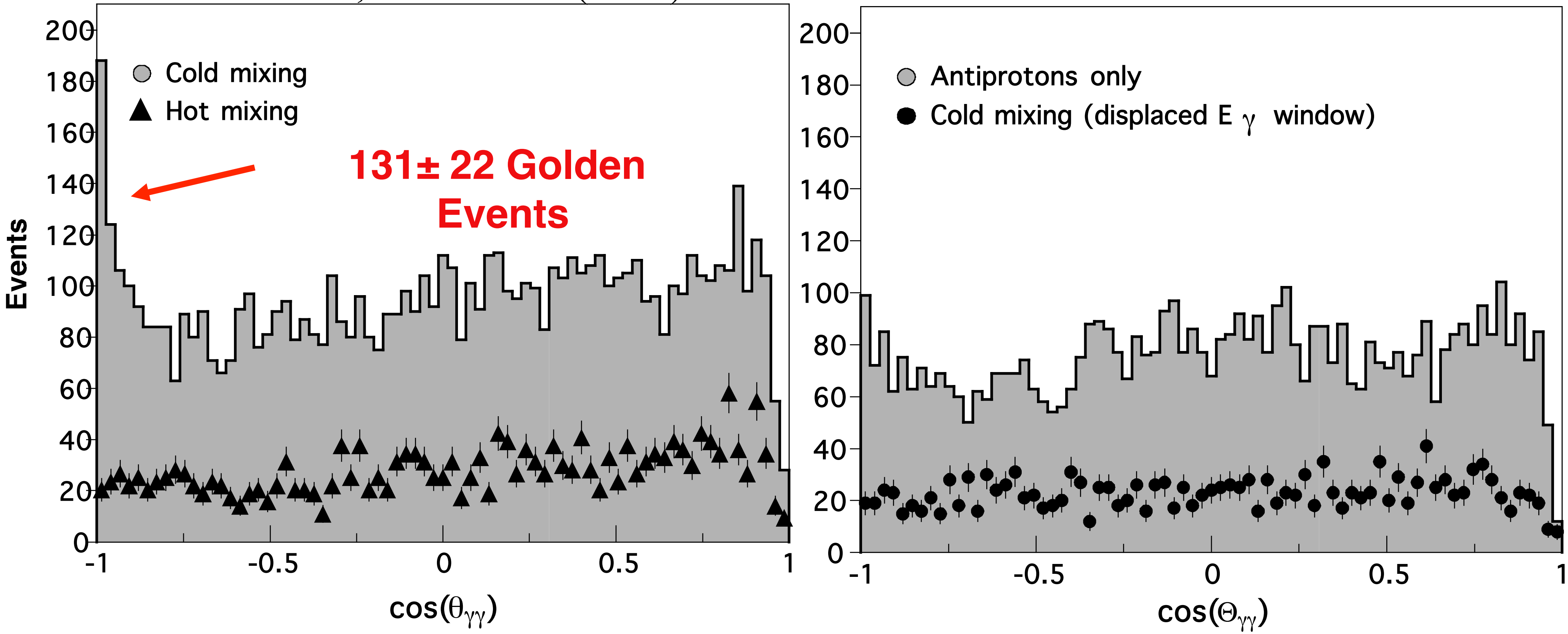





Paul A. Tipler
Ralph A. Llewellyn
MODERN PHYSICS
Fifth Edition

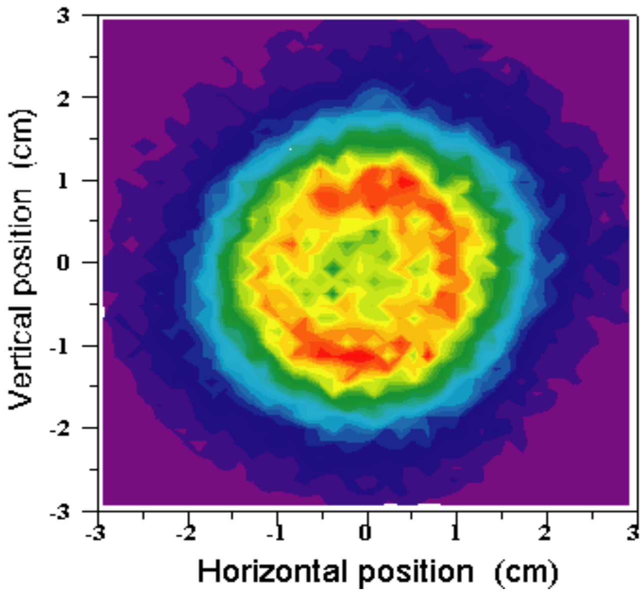
Antihydrogen Signal August 2002 *ATHENA*

Amoretti et al., ***Nature*** 419 (2002) 456

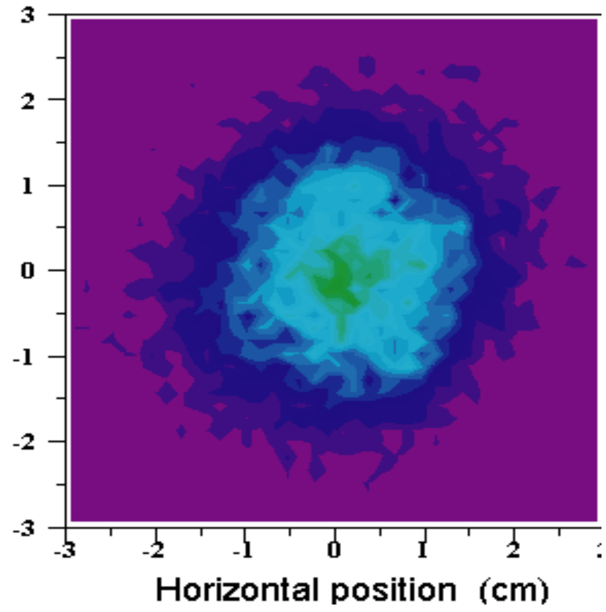


>50000 Cold Antihydrogen

Cold Antihydrogen Signal - Vertices



Cold Mix

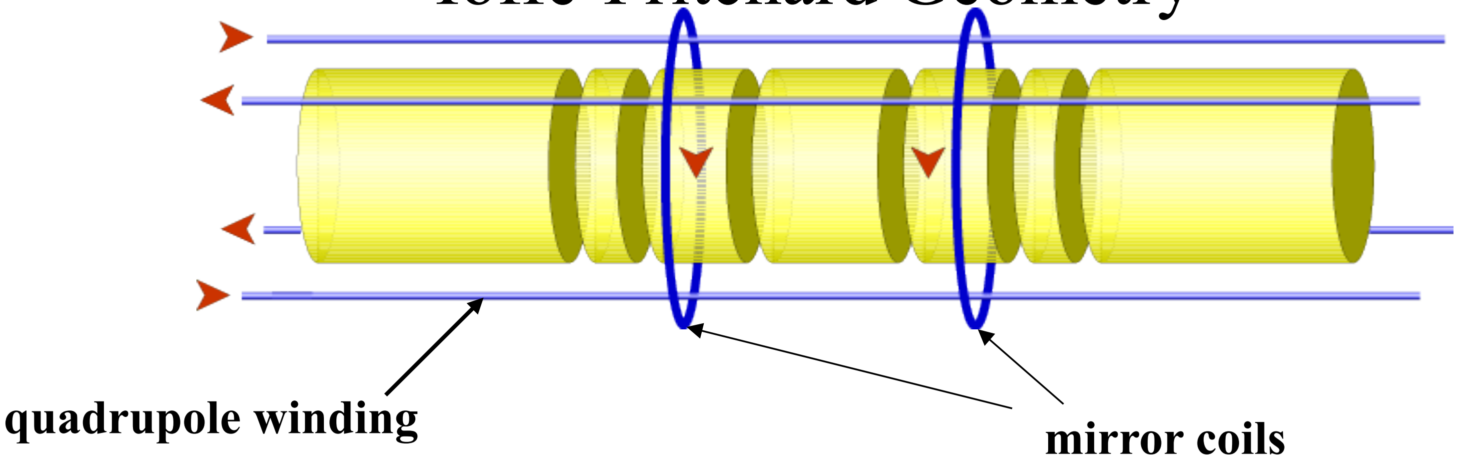


Hot Mix

Amoretti et al., ***Nature*** 419 (2002) 456

Trapping Neutral Anti-atoms?

Ioffe-Pritchard Geometry



$$U = -\overline{\mu} \cdot \overline{\mathbf{B}}$$

Aside: high n-states could have higher μ

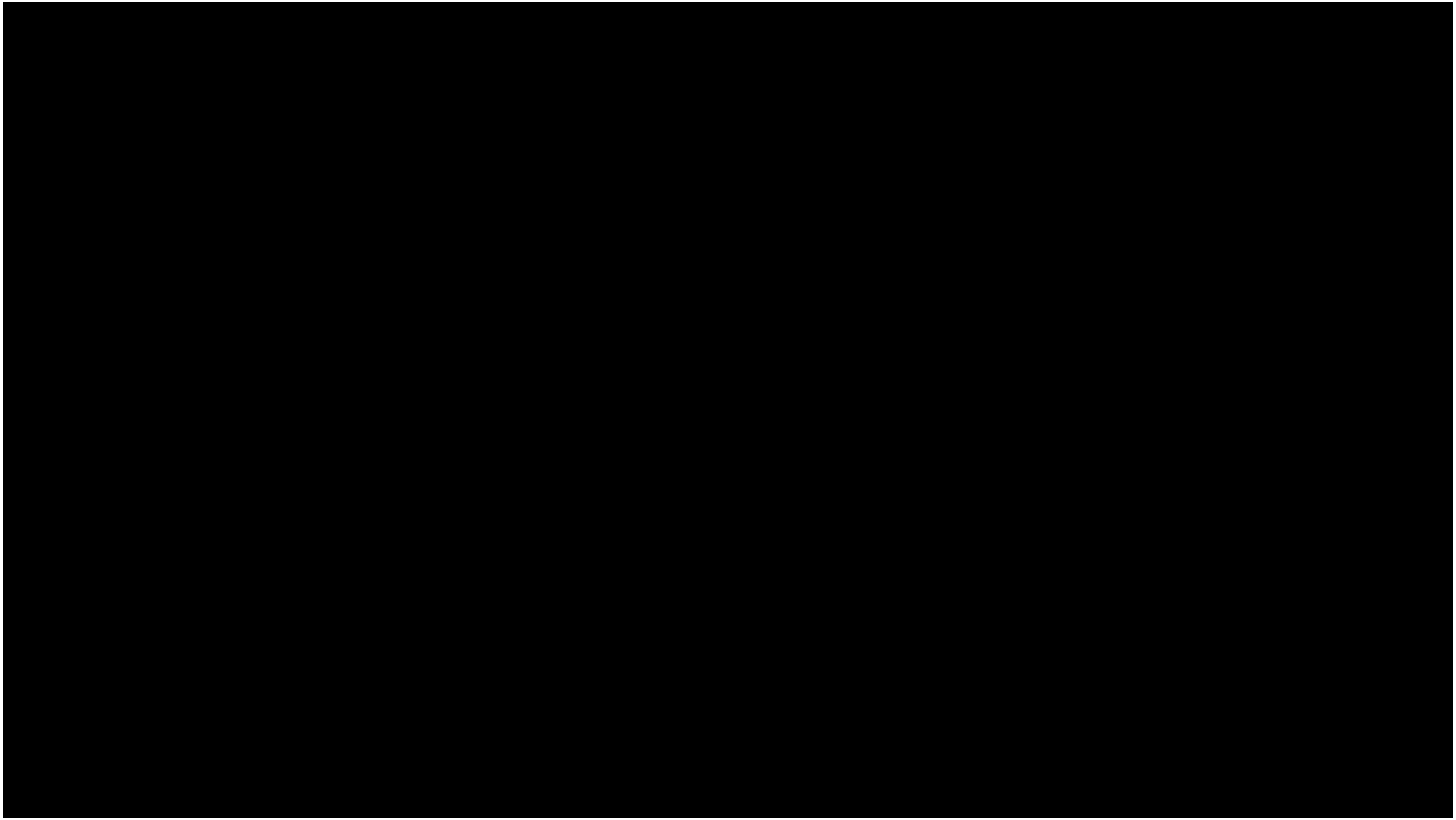
Solenoid field is the minimum in B

Broken rotational symmetry: Can we superpose this on a Penning trap?

ALPHA Strategy: Demonstrating Trapped Antihydrogen (from 2005)

- Produce cold antihydrogen at the minimum of a multipolar, minimum-B trap
- Get rid of any remaining charged particles
- Shut off the atom trap as quickly as possible to release any trapped antihydrogen
- Detect the antiproton annihilation from released antihydrogen with a *position sensitive annihilation detector*
- Use event topology to reject cosmic rays

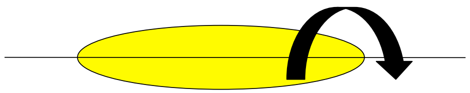
ALPHA



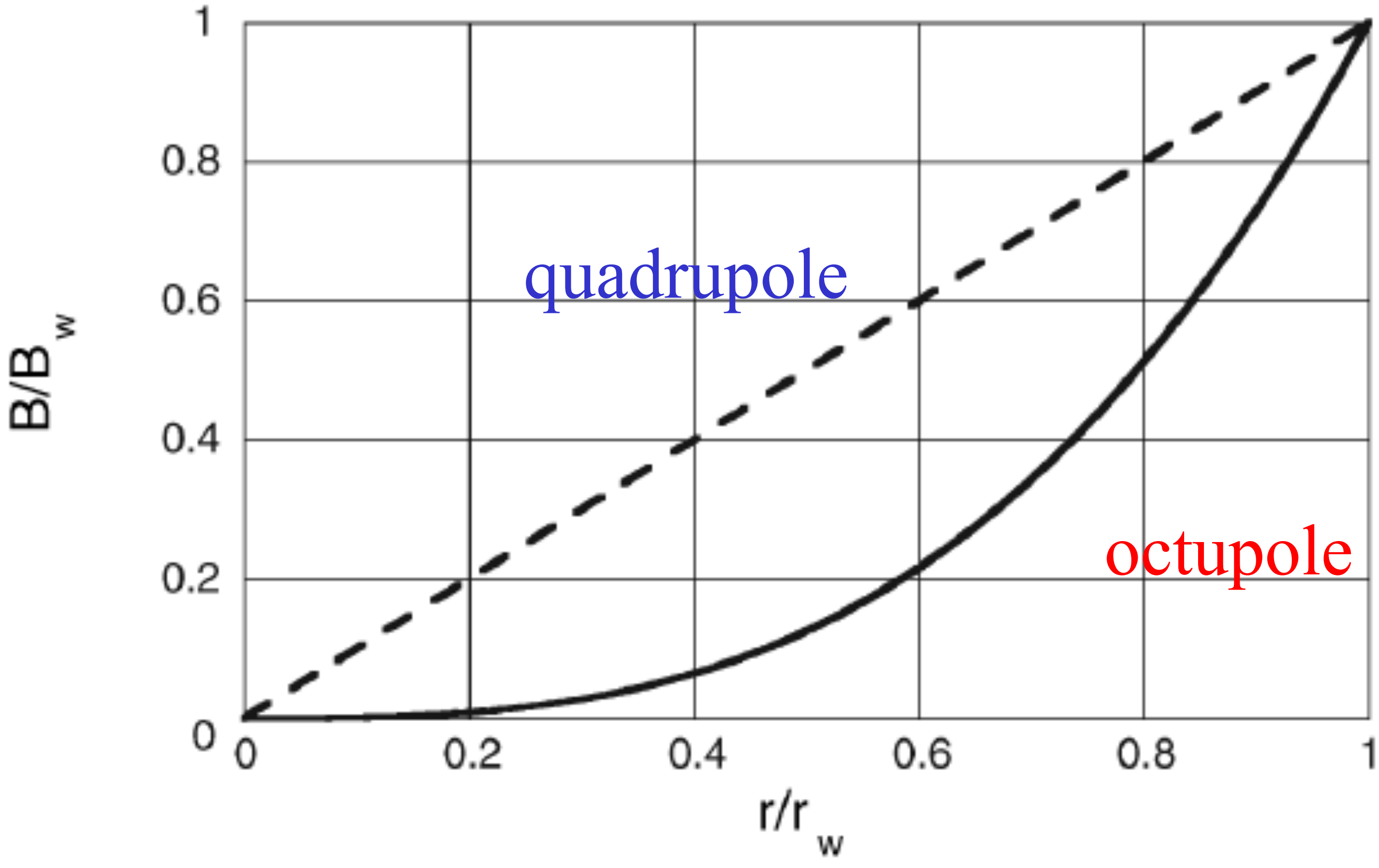
Why is this difficult?

- Keep in mind: 1eV of kinetic energy is about *12000 K*
- The antiprotons are captured at 5 keV
- Typical spacecharge energies of plasmas are a few eV
- The trap for neutral antihydrogen is *0.5 K deep*
- Need large B-fields for catching pbars, cooling, etc. – but need a large delta-B for trapping

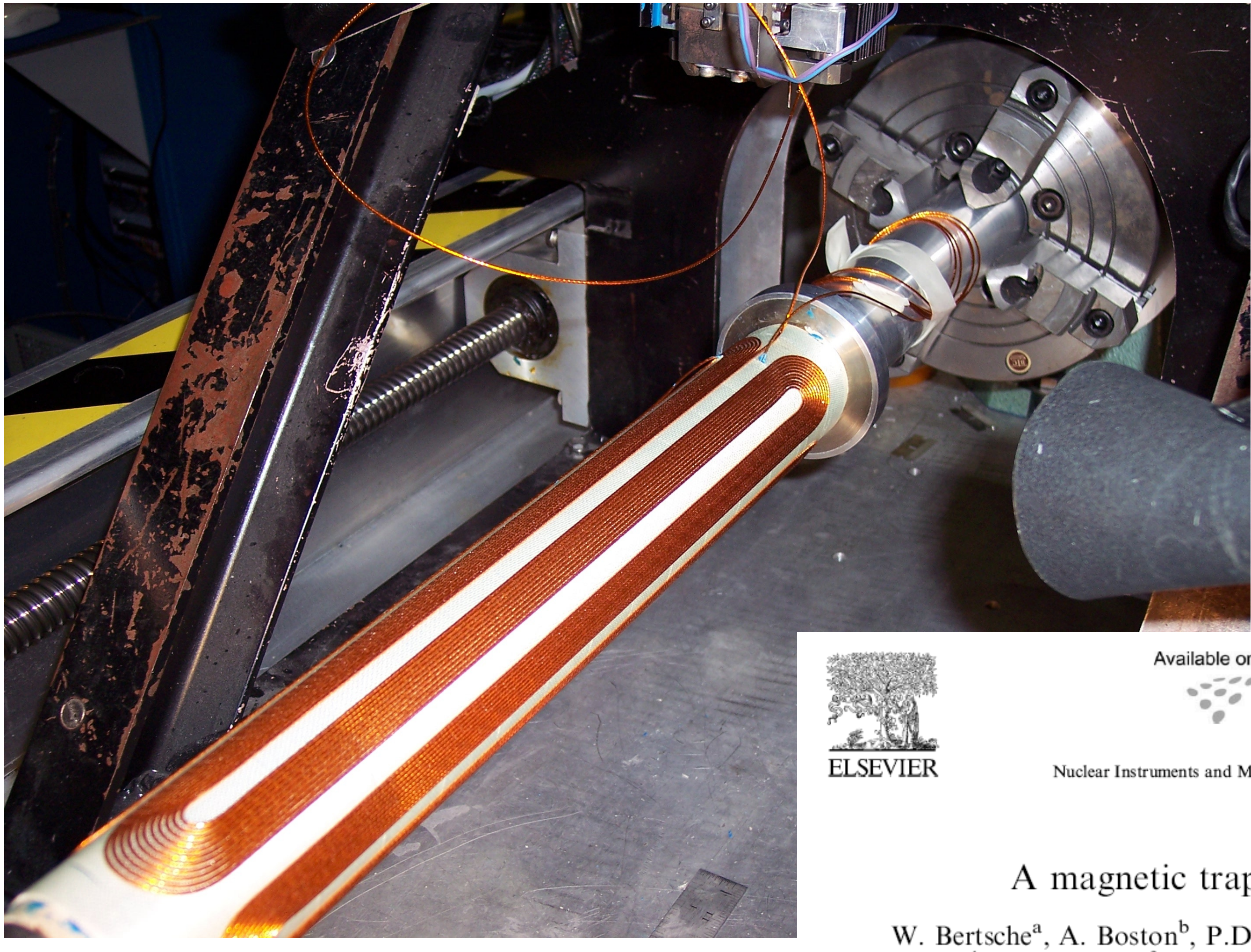
One-component plasmas in equilibrium rotate at a constant angular frequency. The velocities associated with this rotation are of just as much concern as thermal velocities, as far as trapping is concerned. **Not obvious that high positron number and density are desirable - sometimes less is more.**



The ALPHA Approach: higher-order multipole



Octupole Fabrication at BNL



- Magnets wound directly on vacuum chamber (1.25 mm wall)
- No metals in support structure: epoxy/fiber
- High SC/copper ratio cable

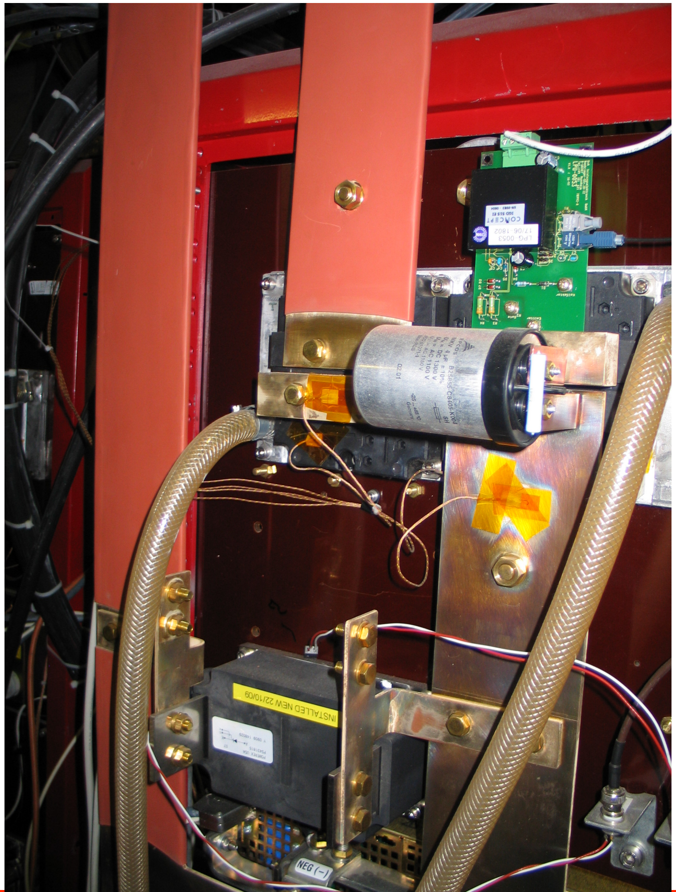
ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 566 (2006) 746–756
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

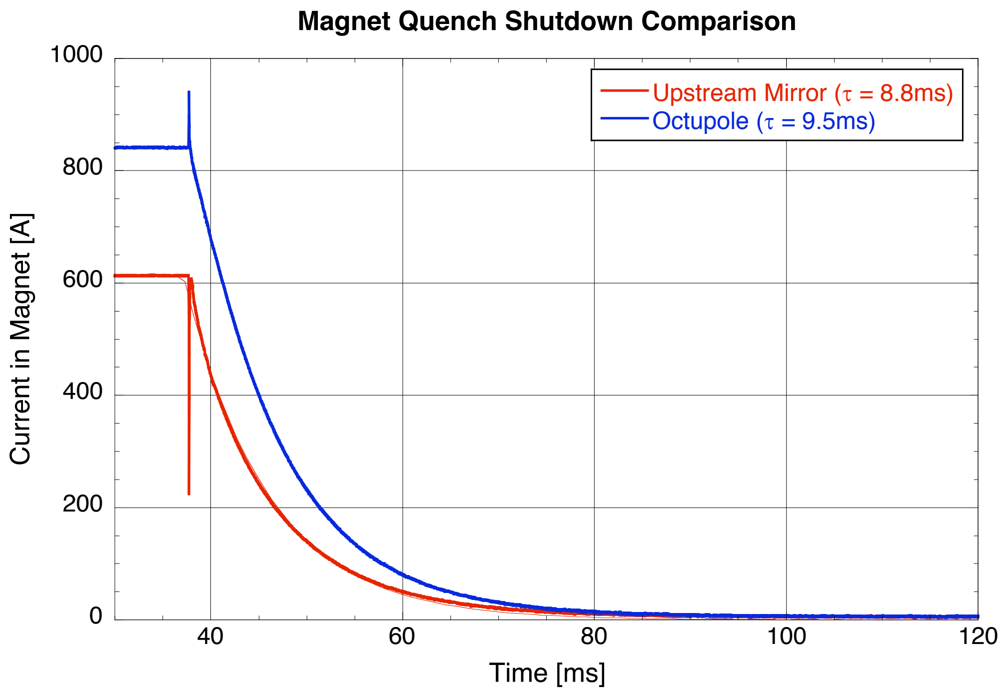
A magnetic trap for antihydrogen confinement

W. Bertsche[a], A. Boston[b], P.D. Bowe[c], C.L. Cesar[d], S. Chapman[a], M. Charlton[e], M. Chartier[b], A. Deutsch[a,f], J. Fajans[a,f], M.C. Fujiwara[g], R. Funakoshi[h], K. Gomberoff[a,f], J.S. Hangst[c], R.S. Hayano[h], M.J. Jenkins[e], L.V. Jørgensen[e], P. Ko[a], N. Madsen[e], P. Nolan[b], R.D. Page[b], L.G.C. Posada[h], A. Povilus[a], E. Sarid[i], D.M. Silveira[d], D.P. van der Werf[e,*], Y. Yamazaki[j] (ALPHA Collaboration) , B.Parker[k], J.Escallier[k], A.Ghosh[k]

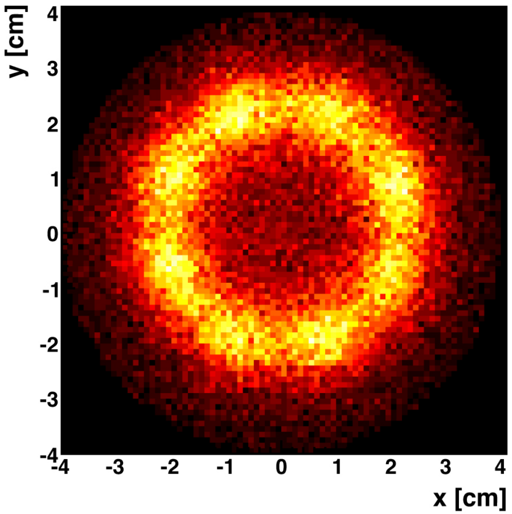
Detection of trapped antihydrogen: Rapid Shutdown

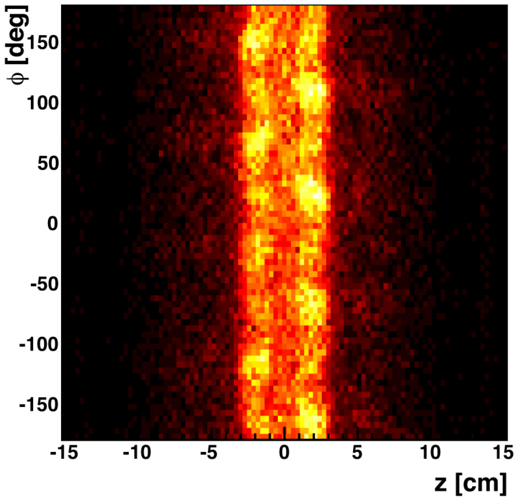
- Hardware patterned after G. Ganetis – IGBT switch to dump resistors
- Signal conditioning hardware from CERN LHC test chain
- Home-made FPGA QPS
- Taps on magnets, vapor cooled leads, and SC leads
- Magnets quench when shutting down – have survived several 10^3 cycles of this





ALPHA Silicon Vertex Detector



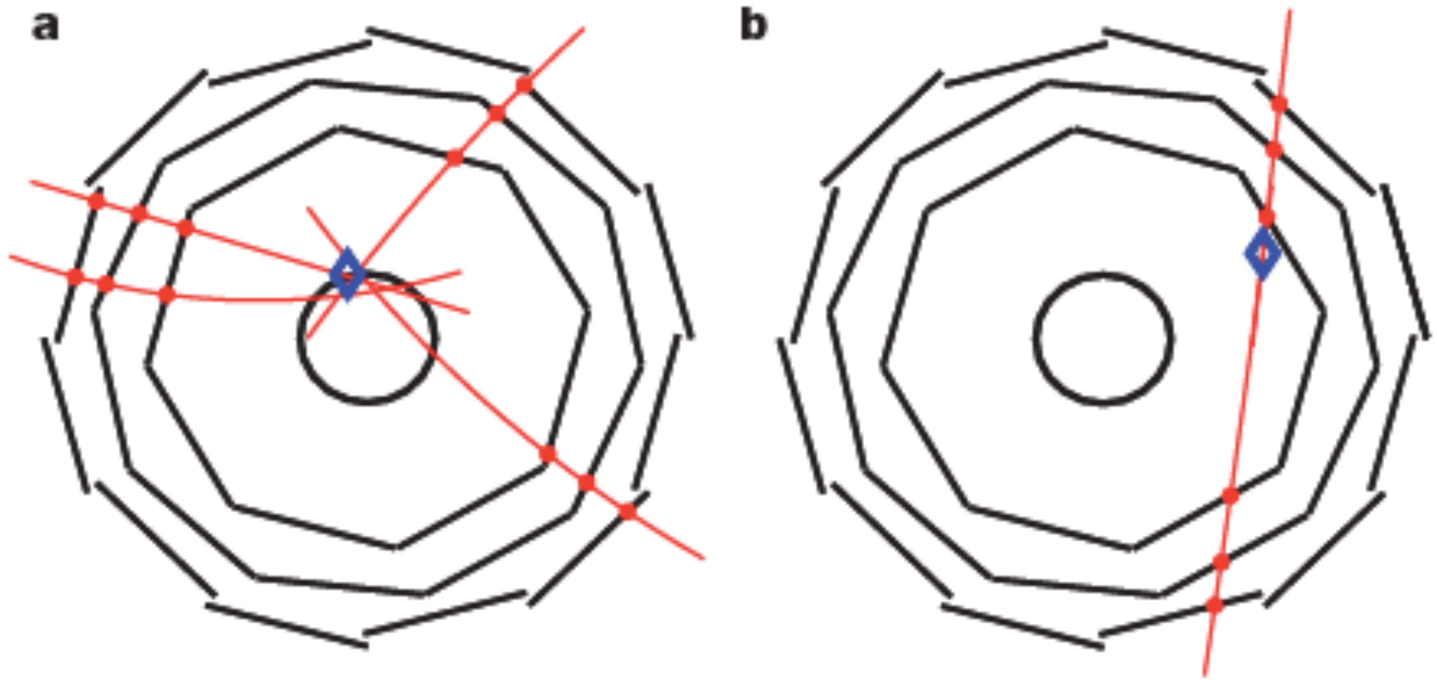


3-layer, double-sided modules
Detect antiproton anihilation (not e^{+})
Fabricated by U. Liverpool

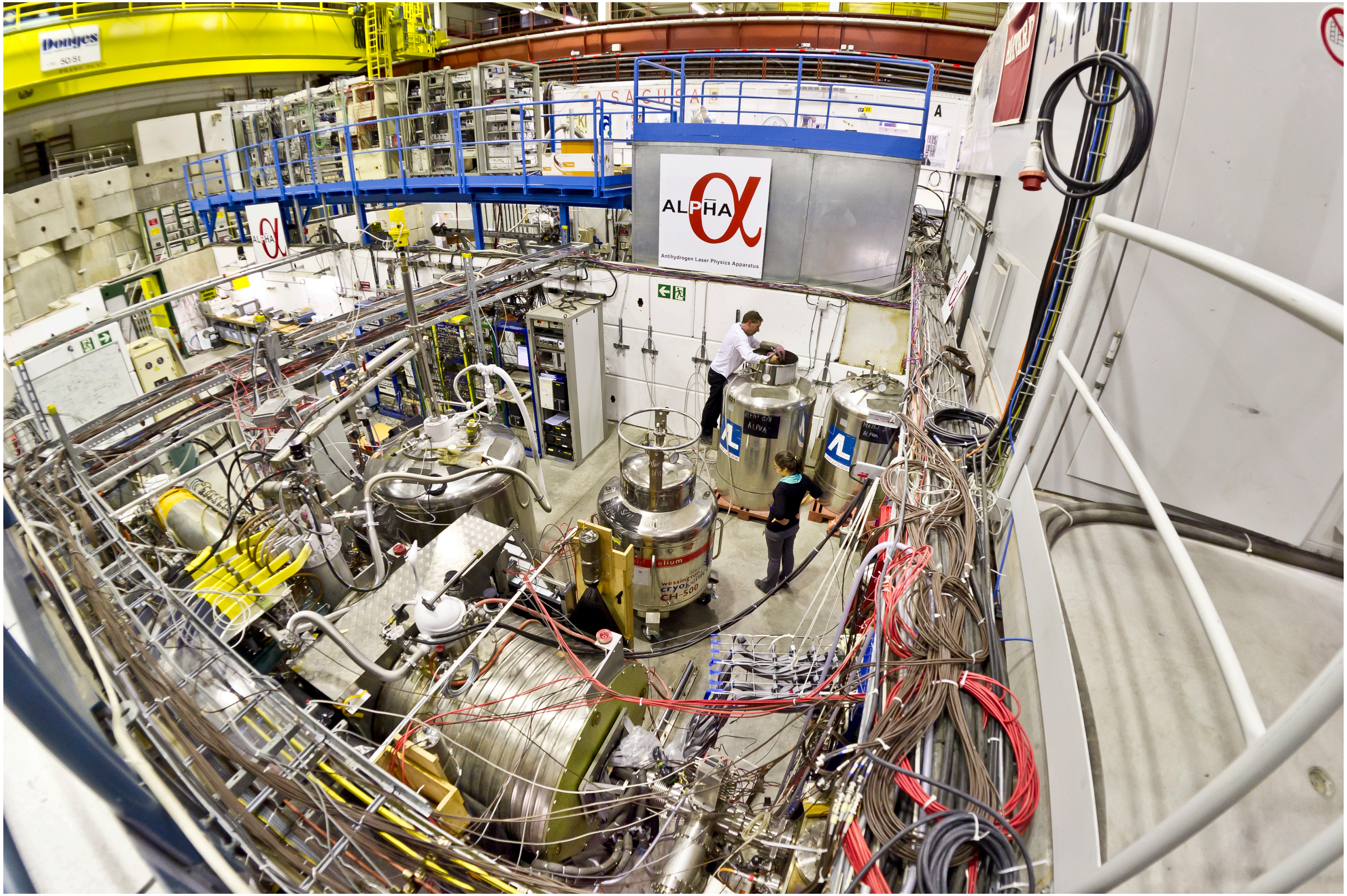
Topology

Typical antiproton annihilation

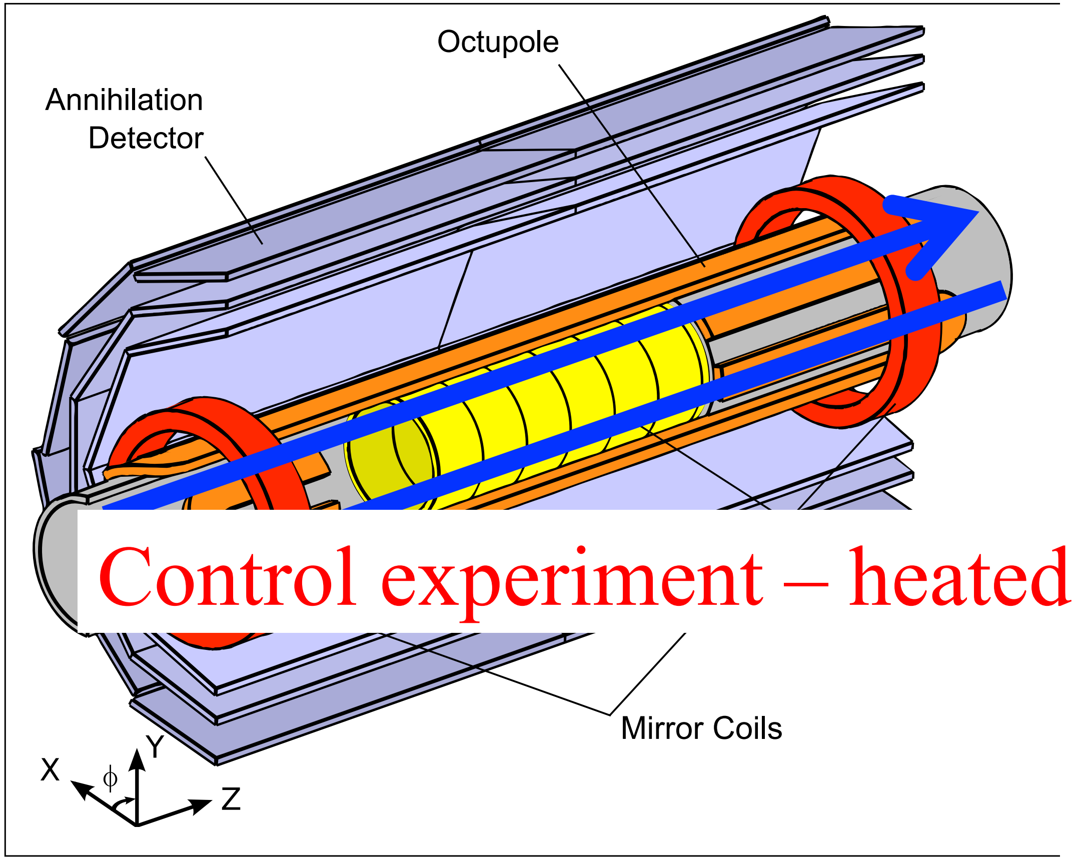
Typical cosmic ray

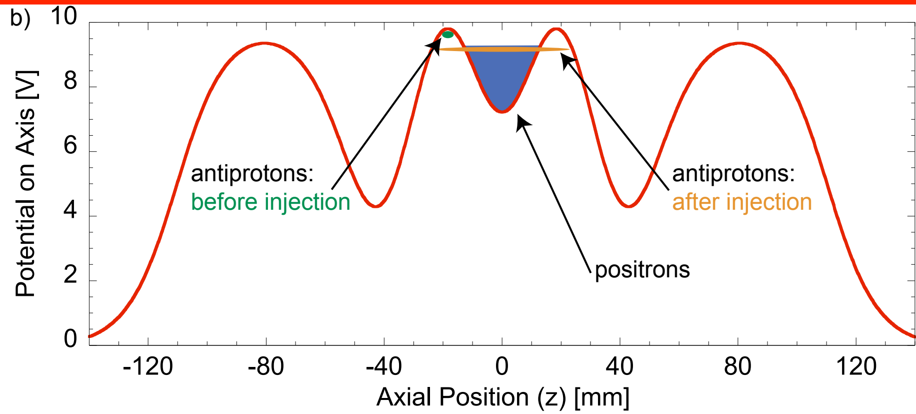


… not much going on here


ALPHA
Antihydrogen Laser Physics Apparatus

The Experiment -2010



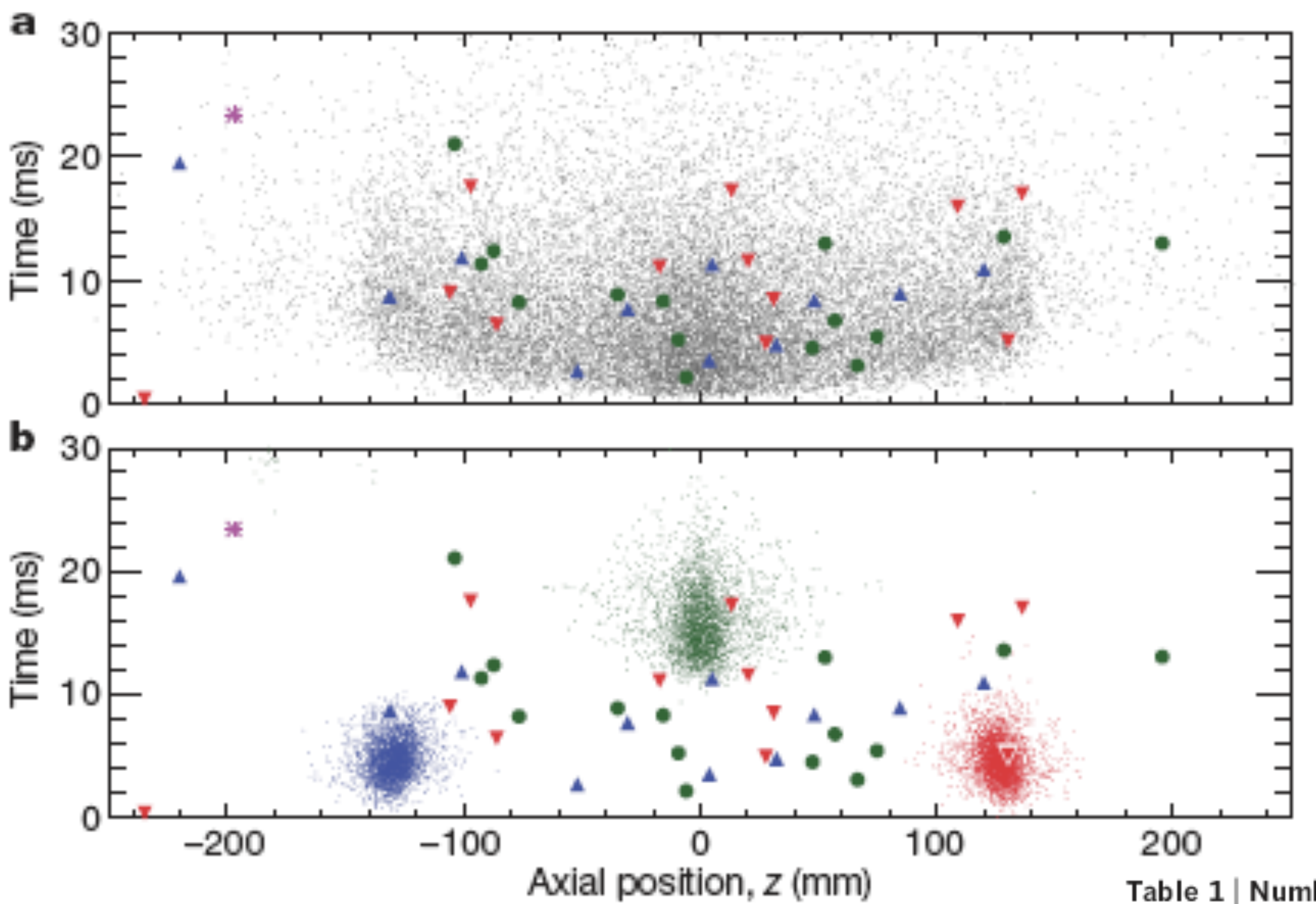


Control experiment – heated positrons (ATHENA)

Trap antihydrogen in magnetic minimum trap
Trap depth ~ 0.5 K

- 30000 antiprotons at 200 K
- 2 M positrons at 40 K, evaporatively
- Mix for 1 s
- Eject trapped charged particles
- Pulsed fields to clear any mirror-trapped pbars
- Fast shutdown of trap magnets (9 ms)
- Look for annihilating pbar from hbar
- Was it really a neutral? Apply bias electric fields during shutdown.

The Result



HBAR simulation

left bias
right bias
no bias

PBAR simulations

1 event with heated positrons

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

Conclusion from 2010 Run

38 annihilations in 335 attempts

Total background 1.4±1.4 events, including cosmic of 0.46±0.01 events – heated positrons

Bias fields prove that the annihilations are not mirror trapped pbars

Trapped antihydrogen for at least 172 ms.


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]

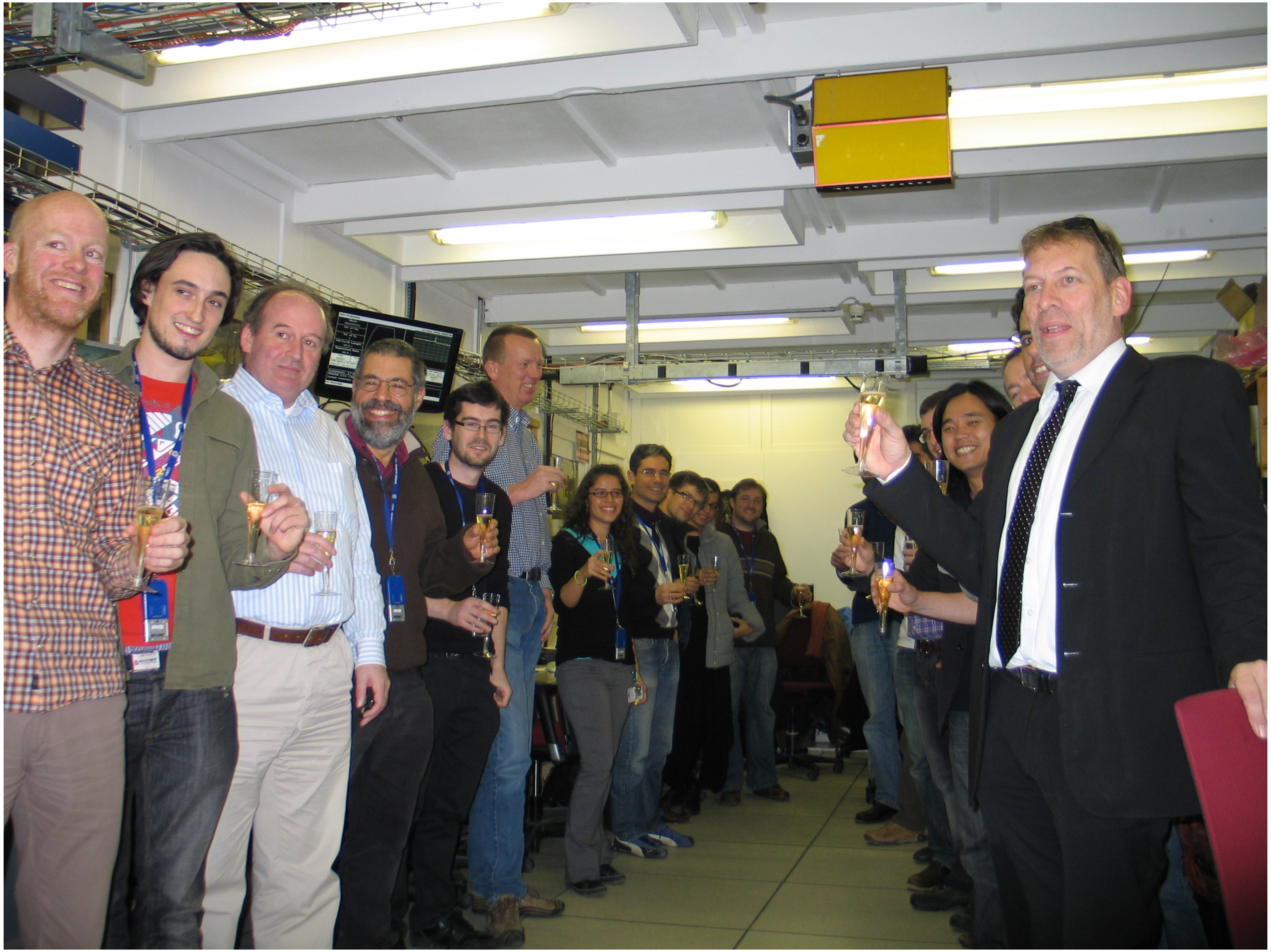
Published online in *Nature*, 17 November 2010

Physics Breakthrough of the Year (with Yamazaki group!) , 2010 *Physics World* (UK)

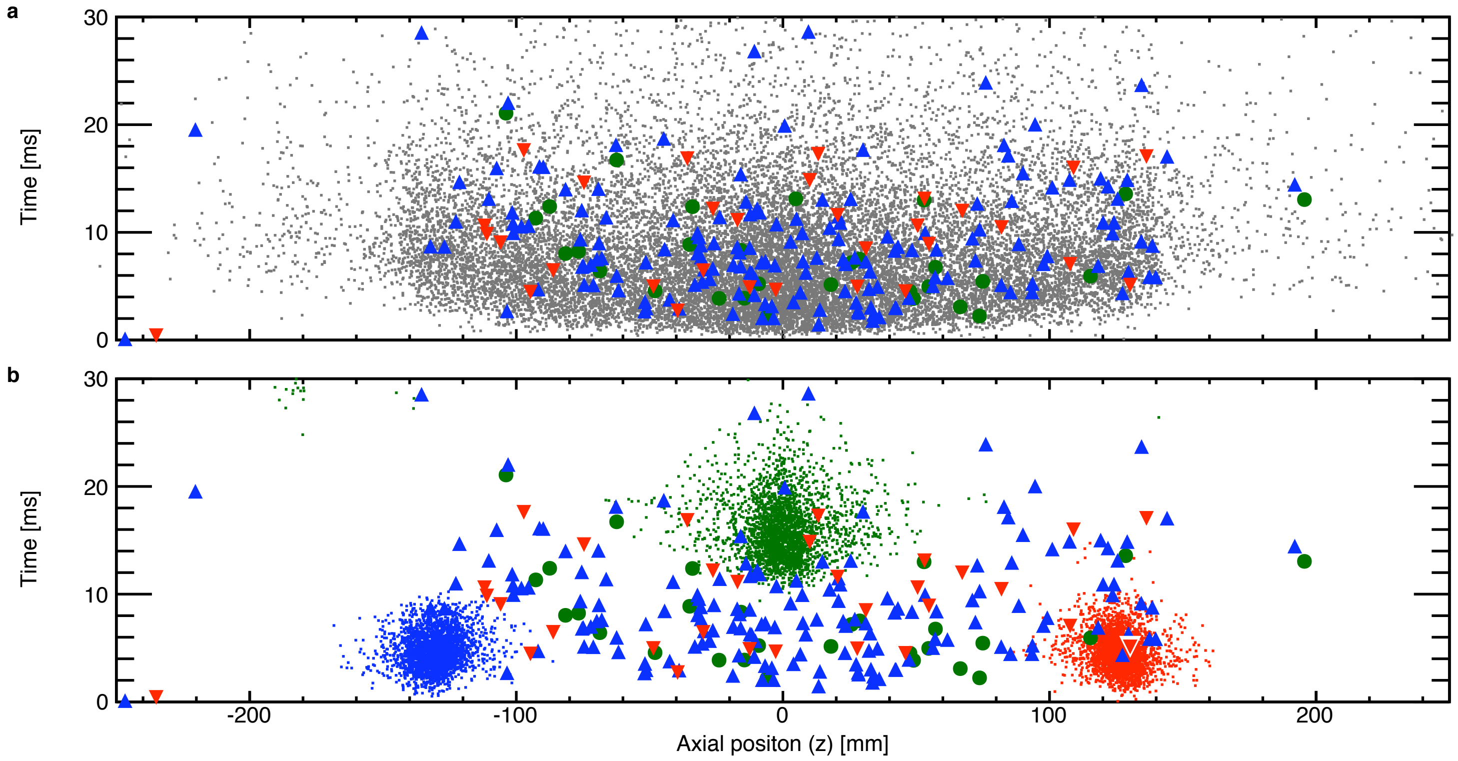
One of the top ten physics stories of 2010 - American Institute of Physics

Most clicked-on story on *Nature* website for all of 2010

"The very fact of a proof-of-principle demonstration of wall-free confinement of even a small number of antimatter atoms has an intrinsic philosophical value."

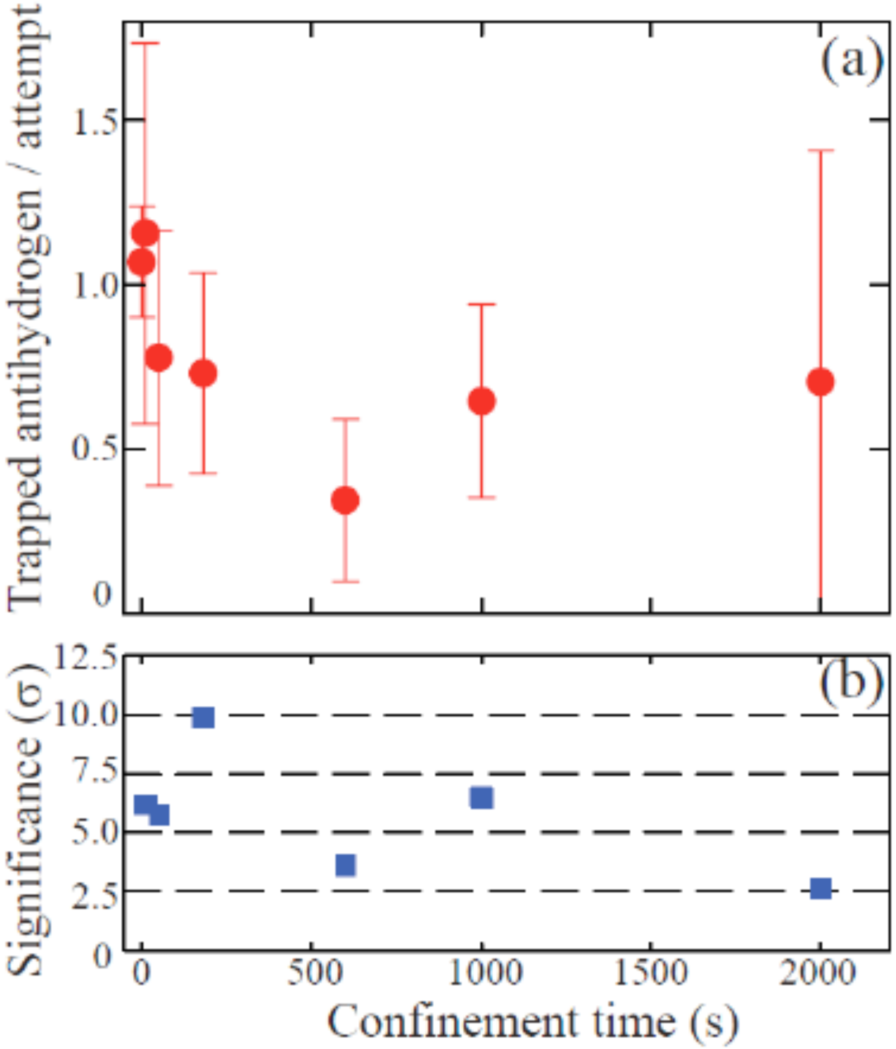


TOTAL SAMPLE – 2010 – you can tweak 38



(300+ annihilation events)

Next published result: ANTIHYDROGEN STORAGE TIME



Confinement Time (s)	0	10	50	180	600	1000	2000
Number of attempts	119	7	13	32	12	16	3
Detected events (counts)	60	4	4	11	2	5	1
Estimated back-ground (counts)	0.16	0.01	0.02	0.04	0.02	0.02	0.004
Statistical significance (σ)	24	6.2	5.8	9.9	3.6	6.5	2.6
Trapping rate per attempt	1.1 ±0.17	1.2 ±0.6	0.78 ±0.39	0.73 ±0.30	0.34 ±0.25	0.65 ±0.29	0.70 ±0.70

Nature Physics, 5 June 2011

ALPHA

nature physics

ARTICLES

PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

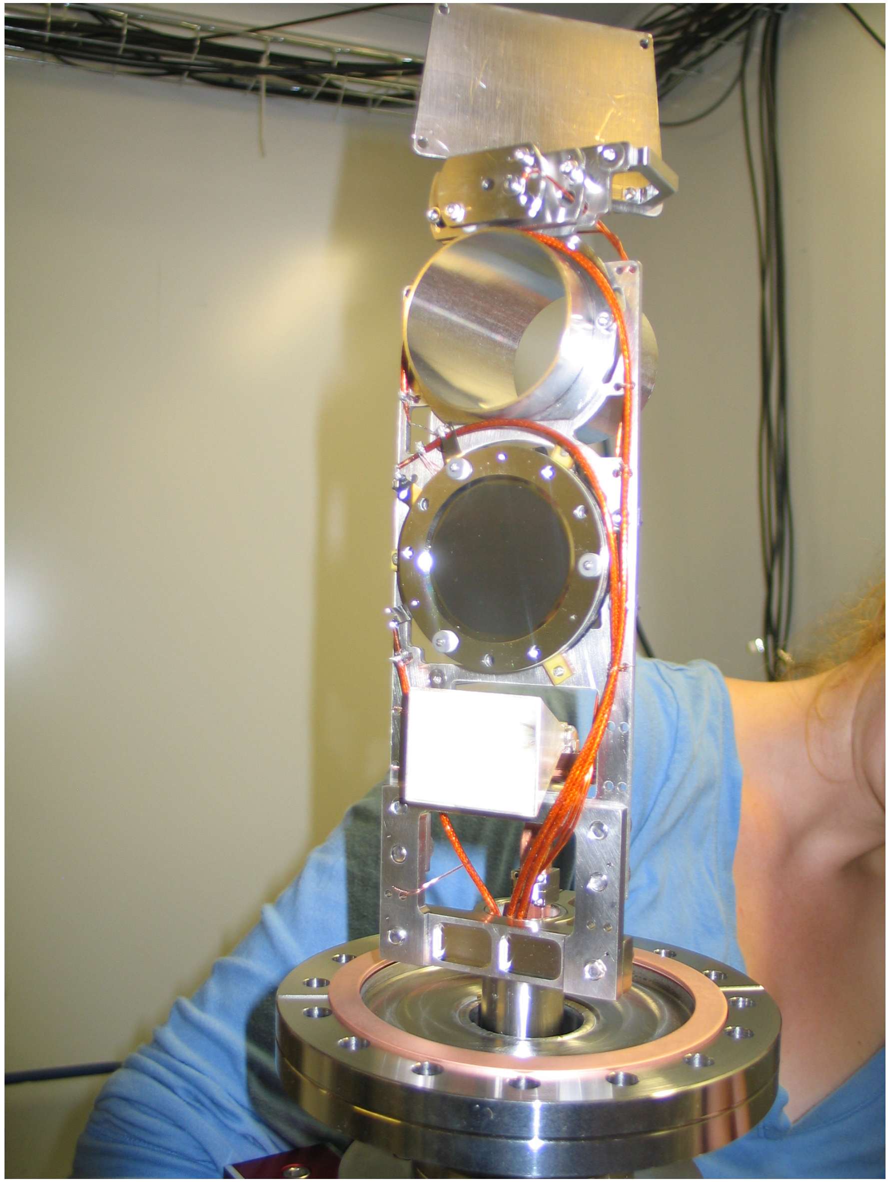
The ALPHA Collaboration*

Atoms made of a particle and an antiparticle are unstable, usually surviving less than a microsecond. Antihydrogen, made entirely of antiparticles, is believed to be stable, and it is this longevity that holds the promise of precision studies of matter–antimatter symmetry. We have recently demonstrated trapping of antihydrogen atoms by releasing them after a confinement time of 172 ms. A critical question for future studies is: how long can anti-atoms be trapped? Here we report the observation of anti-atom confinement for 1,000 s, extending our earlier results by nearly four orders of magnitude. Our calculations indicate that most of the trapped anti-atoms reach the ground state. Further, we report the first measurement of the energy distribution of trapped antihydrogen, which, coupled with detailed comparisons with simulations, provides a key tool for the systematic investigation of trapping dynamics. These advances open up a range of experimental possibilities, including precision studies of charge–parity–time reversal symmetry and cooling to temperatures where gravitational effects could become apparent.

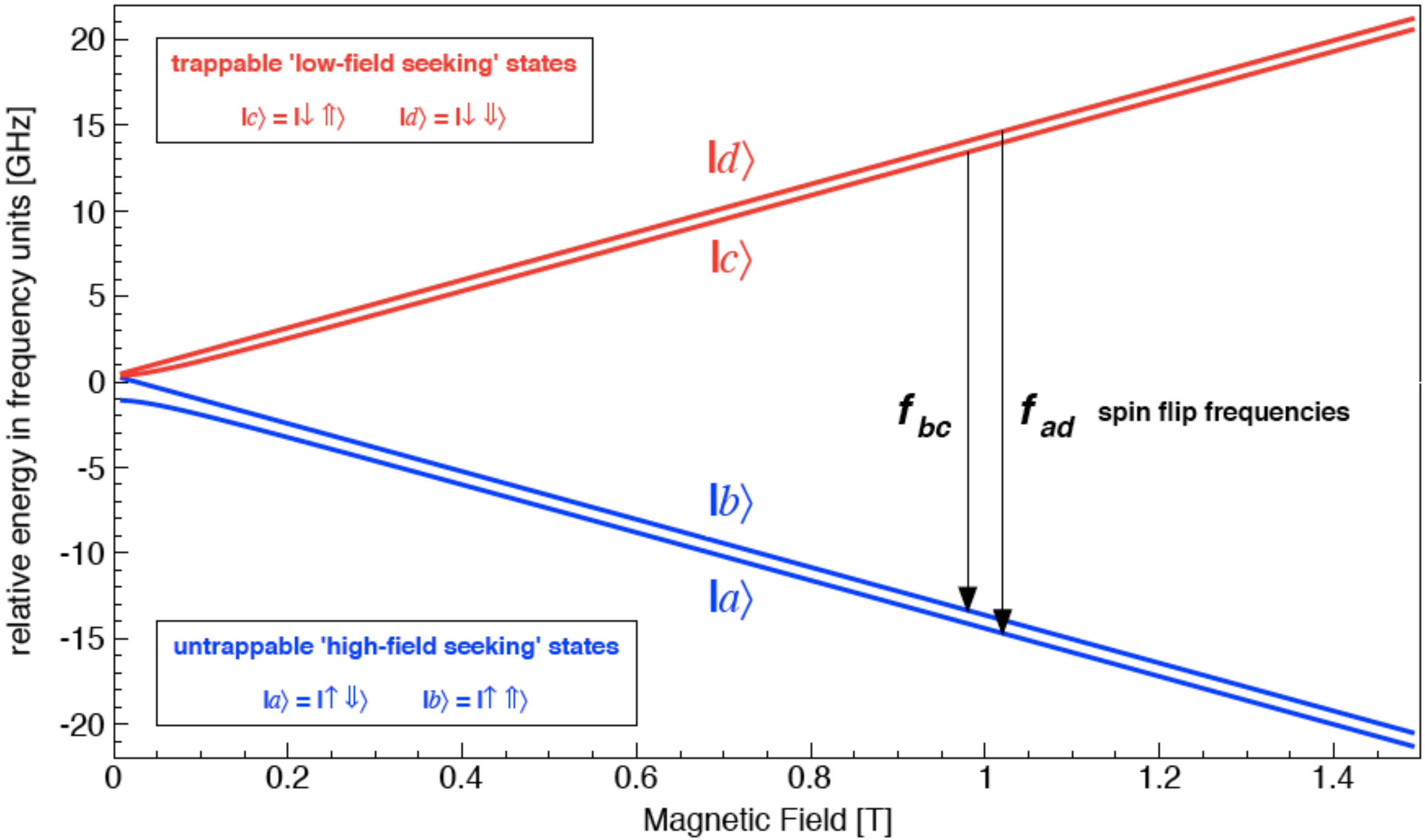
- Published online 5 June 2011
- First ***ground state*** antihydrogen
- Important implications for future spectroscopy and gravitational studies, laser cooling?
- More press circus…

Cover of Nature Physics – July 2011

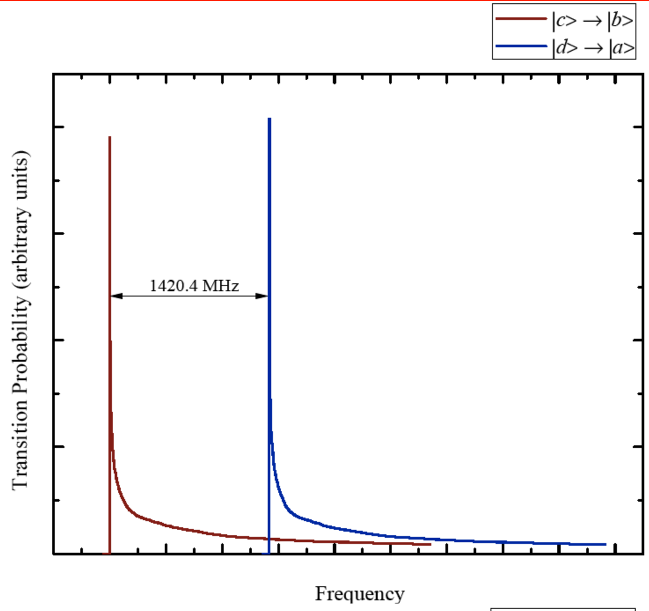
Add Microwaves

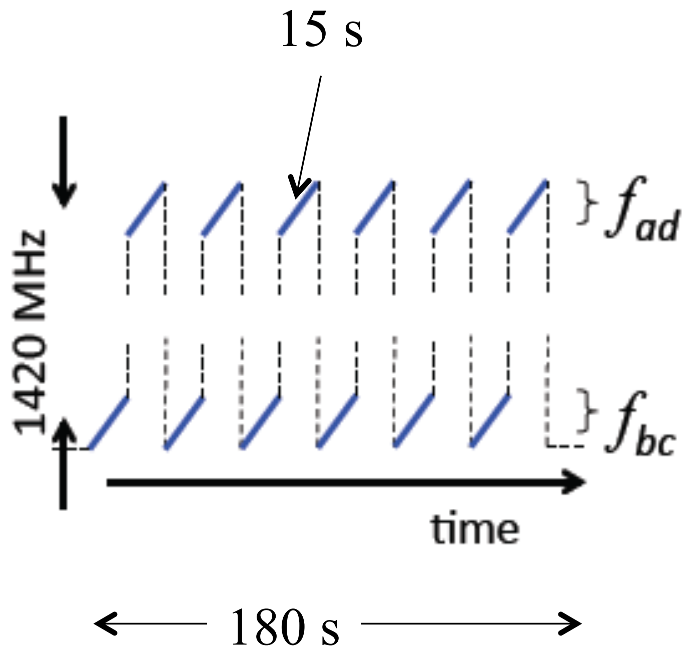


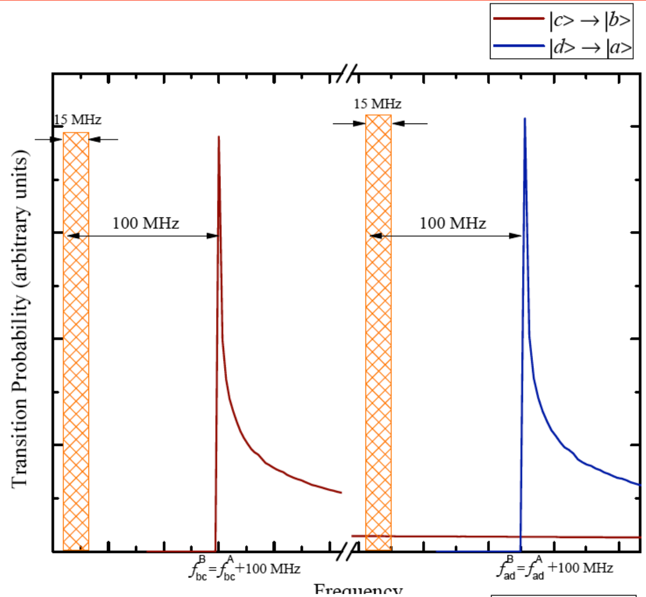
Breit-Rabi Diagram

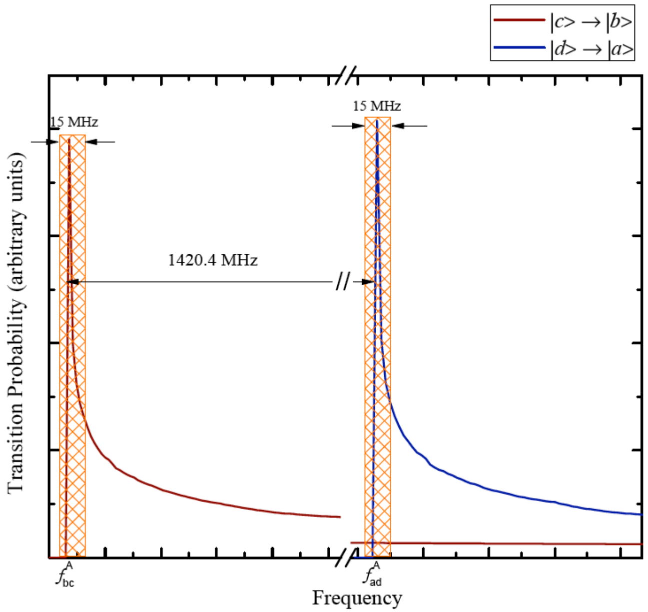


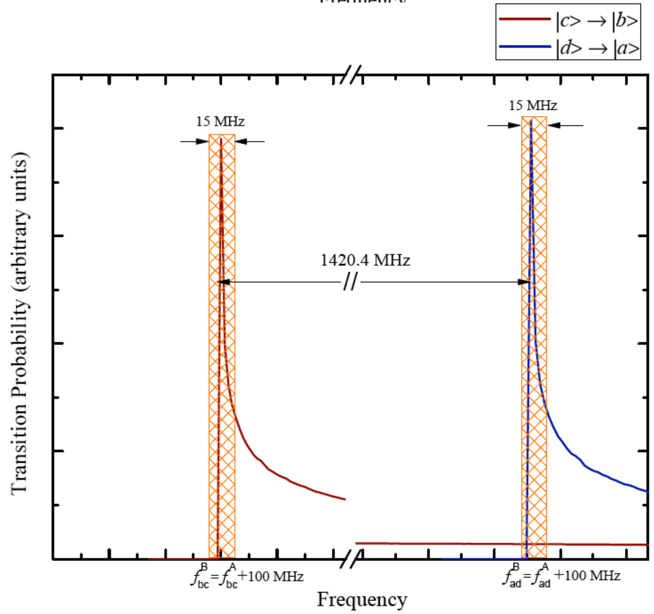
Microwave Configurations



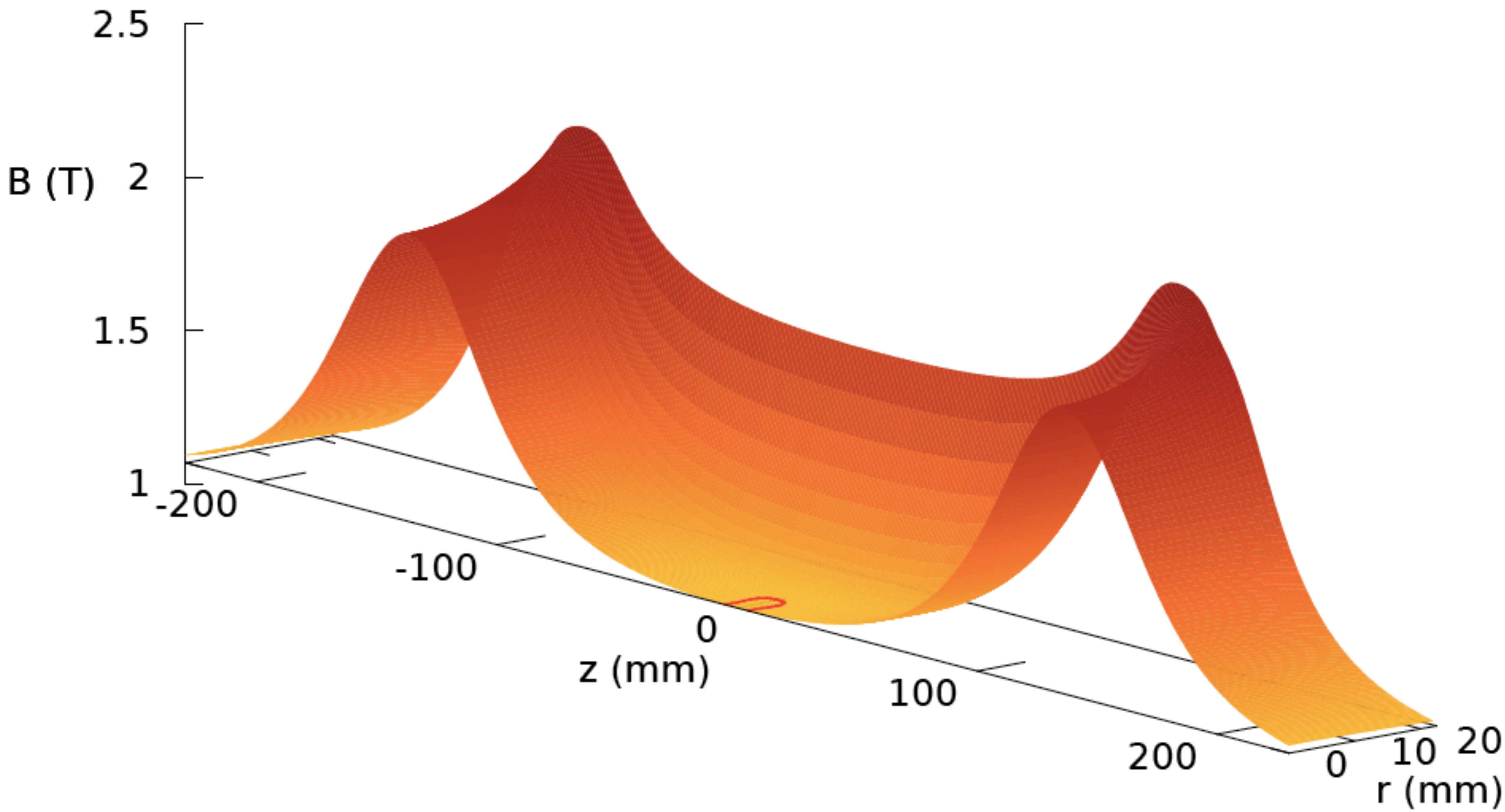








Field Map – Not an Ideal Environment for Microwave Spectroscopy



Microwave Procedure

1) Mix antiprotons and positrons for 1 s in the atom trap to produce antihydrogen.
2) Execute the normal procedures for removing any remaining charged particles from the trap.
3) During the next 60 s, any trapped antihydrogen atoms are held. During the first second of this, the mirror coil currents can be adjusted to change the resonance condition; if changed, the field can then stabilise for 59 s.
4) The trapped atoms are then held for an additional 180 s, during which microwaves can be introduced - either on- or off- resonance; or no microwaves are introduced in order to make a control measurement.
5) After the total 240s storage time, the atom trap is rapidly shut down, and any remaining trapped atoms released and detected by the ALPHA silicon detector.

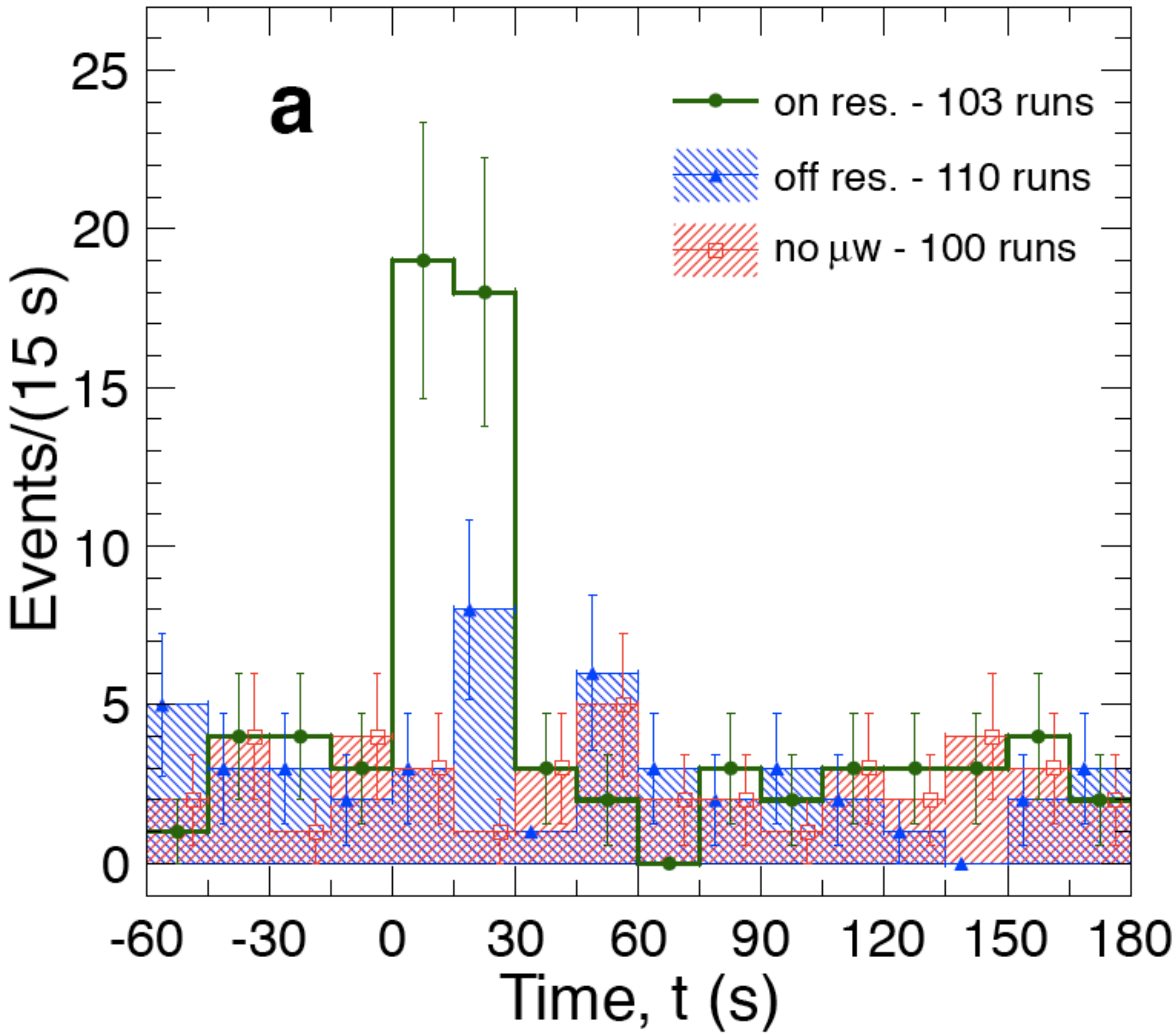
Compare survival rate for on-resonance, off-resonance and no-microwave attempts: “Disappearance Mode”

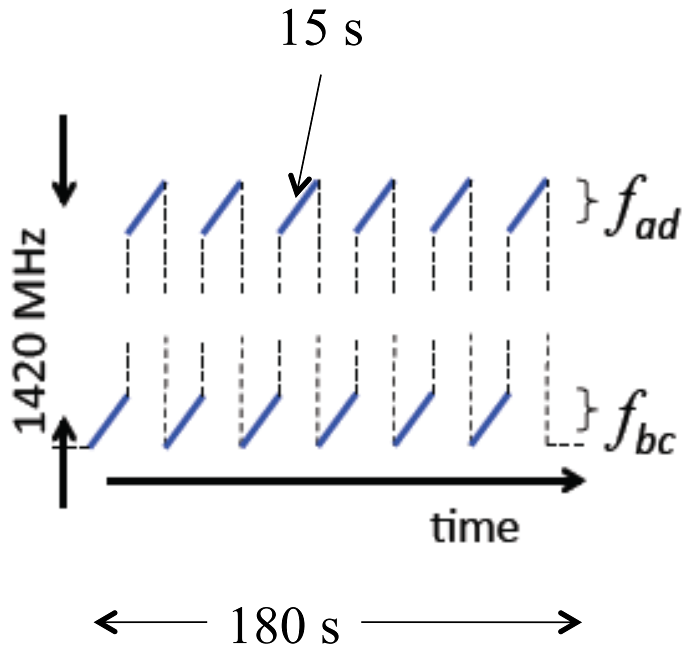
'Disappearance Mode'

Table 2: Totals for all 'disappearance mode' series.

	Number of cycles	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 Mode’ – *t*-distribution

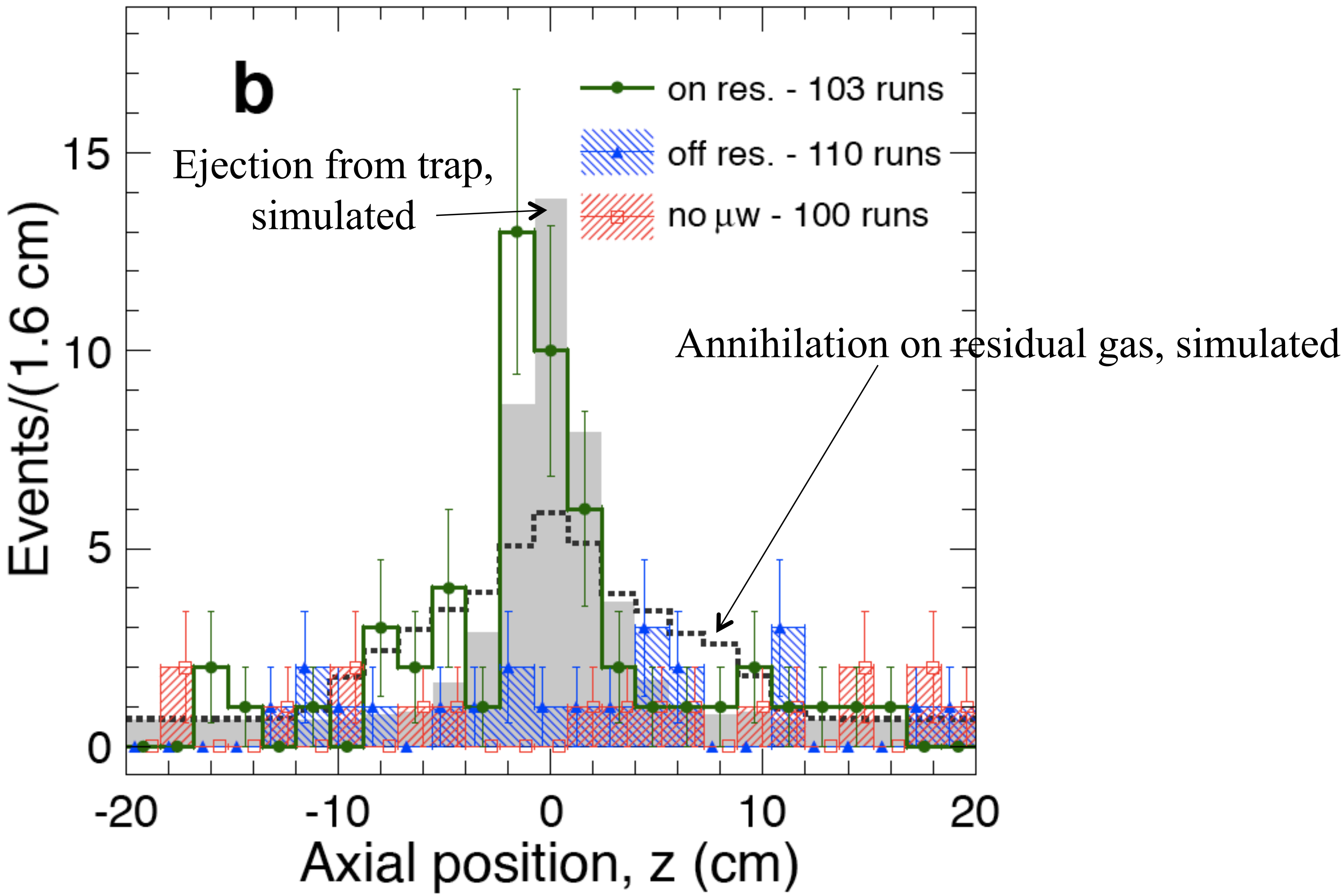




On- vs. off-resonance
P=2.8x10^{-5}

Off-resonance vs. no microwaves
P=5.6x10^{-2}

‘Appearance Mode’ – *z*-distribution



LETTER

doi:10.1038/nature10942

Resonant quantum transitions in trapped antihydrogen atoms

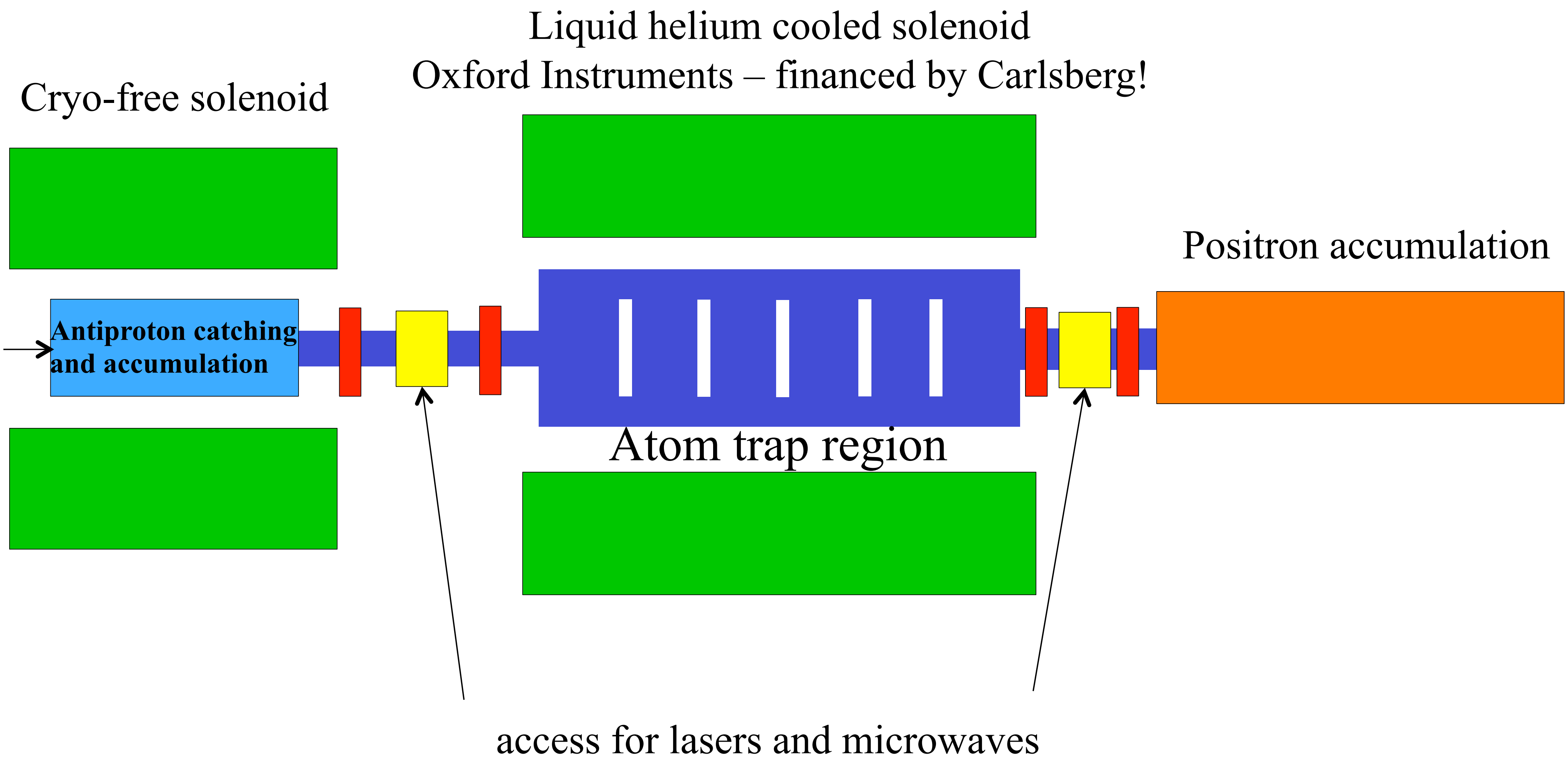
C. Amole[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4,5,6], P. D. Bowe[7], E. Butler[8], A. Capra[1], C. L. Cesar[9], M. Charlton[4], A. Deller[4], P. H. Donnan[10], S. Eriksson[4], J. Fajans[3,11], T. Friesen[12], M. C. Fujiwara[12,13], D. R. Gill[13], A. Gutierrez[14], J. S. Hangst[7], 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]

- Published in *nature* online 7 March, 2012
- First measurement on an antimatter atom
- Shows that it is possible to do physics with few atoms
- … but we'd like to have more

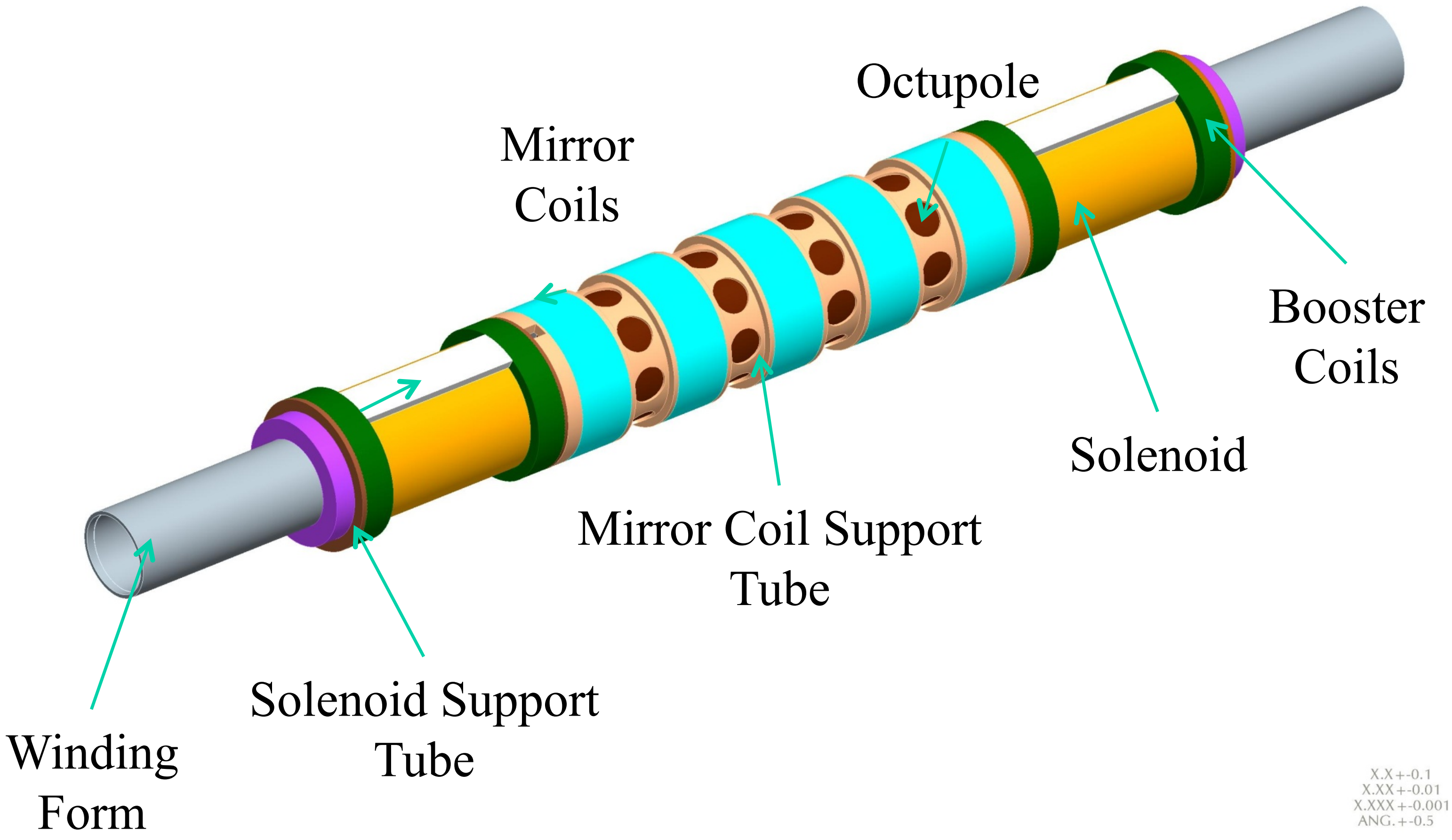
What to do with a device that works so well?

ALPHA has left the building…

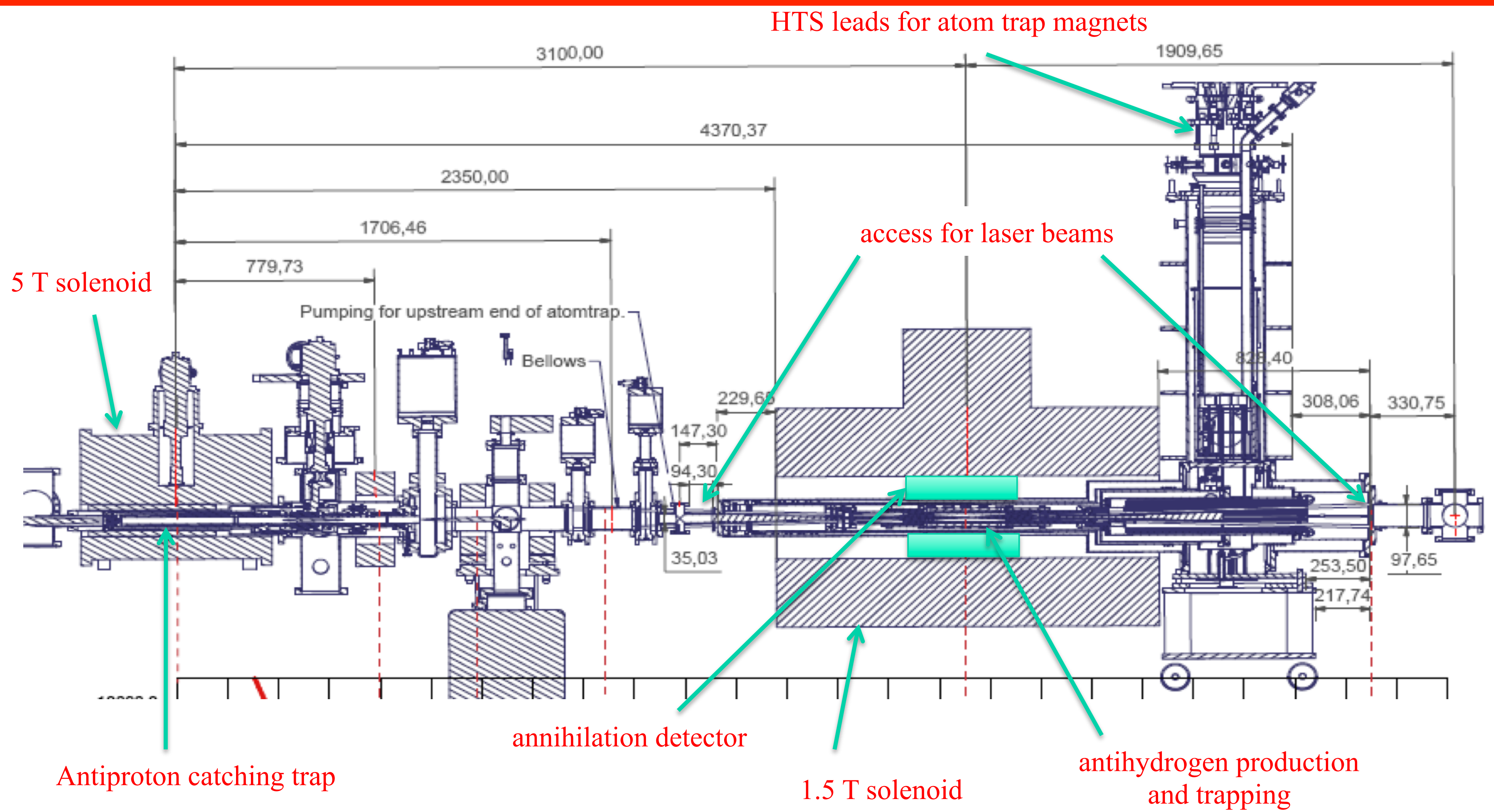
ALPHA-2 : separation of functions

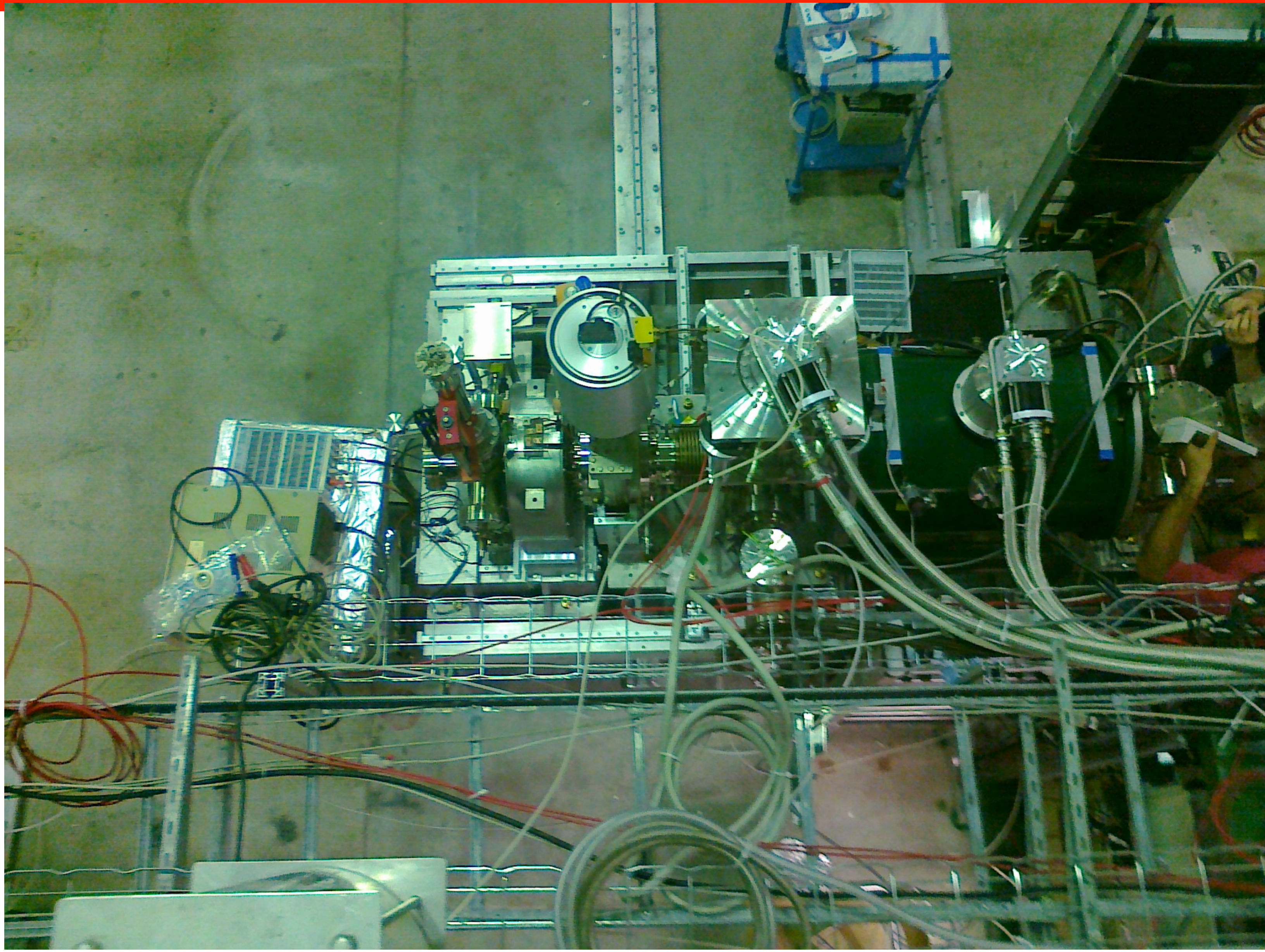


The ALPHA-2 Atom Trap

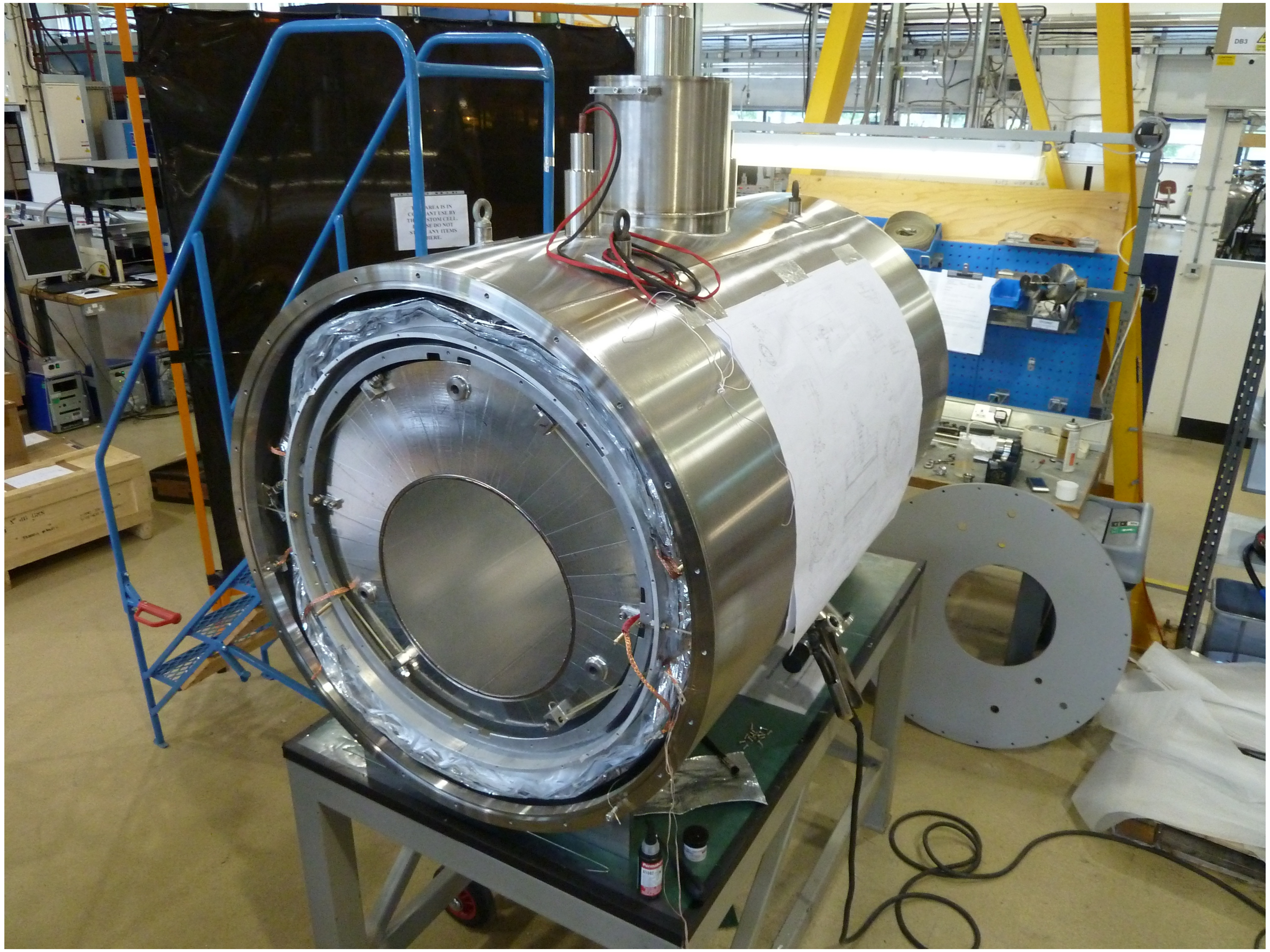


ALPHA-2


HTS leads for atom trap magnets
3100,00
1909,65
4370,37
2350,00
1706,46
779,73
access for laser beams
5 T solenoid
Pumping for upstream end of atomtrap.
Bellows
828,40
229,65
308,06
330,75
147,30
94,30
35,03
253,50
97,65
217,74
annihilation detector
Antiproton catching trap
1.5 T solenoid
antihydrogen production
and trapping

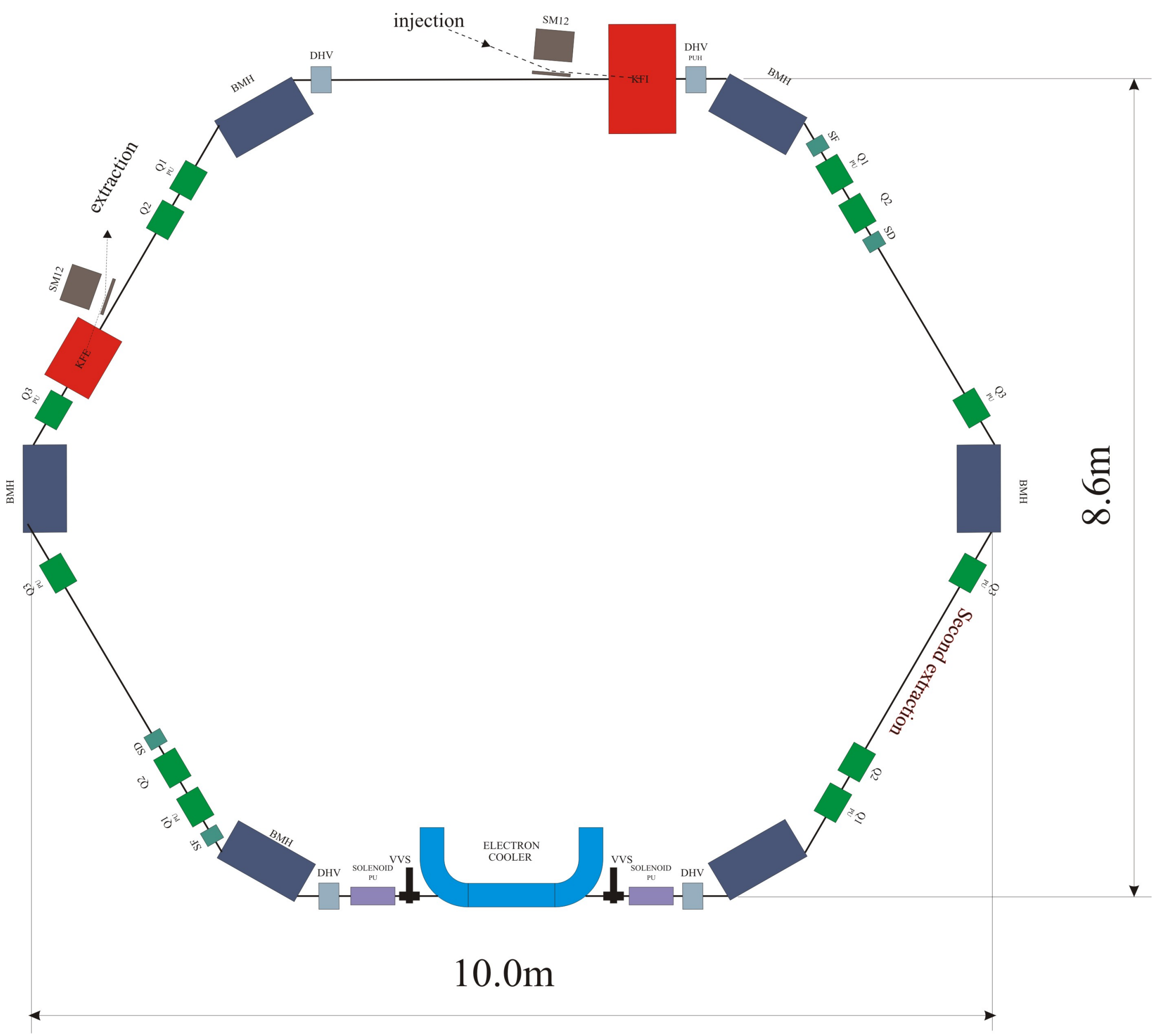


Oxford Magnet



- 350 mm warm bore, 1.5 m long
- 1.5 T
- 10 ppm uniformity over 30 cm (z) x 1 cm (r)
- 10 s ramp from 1 T to 0.65 T
- 480,000 €
- Financed by the Carlsberg foundation

ELENA

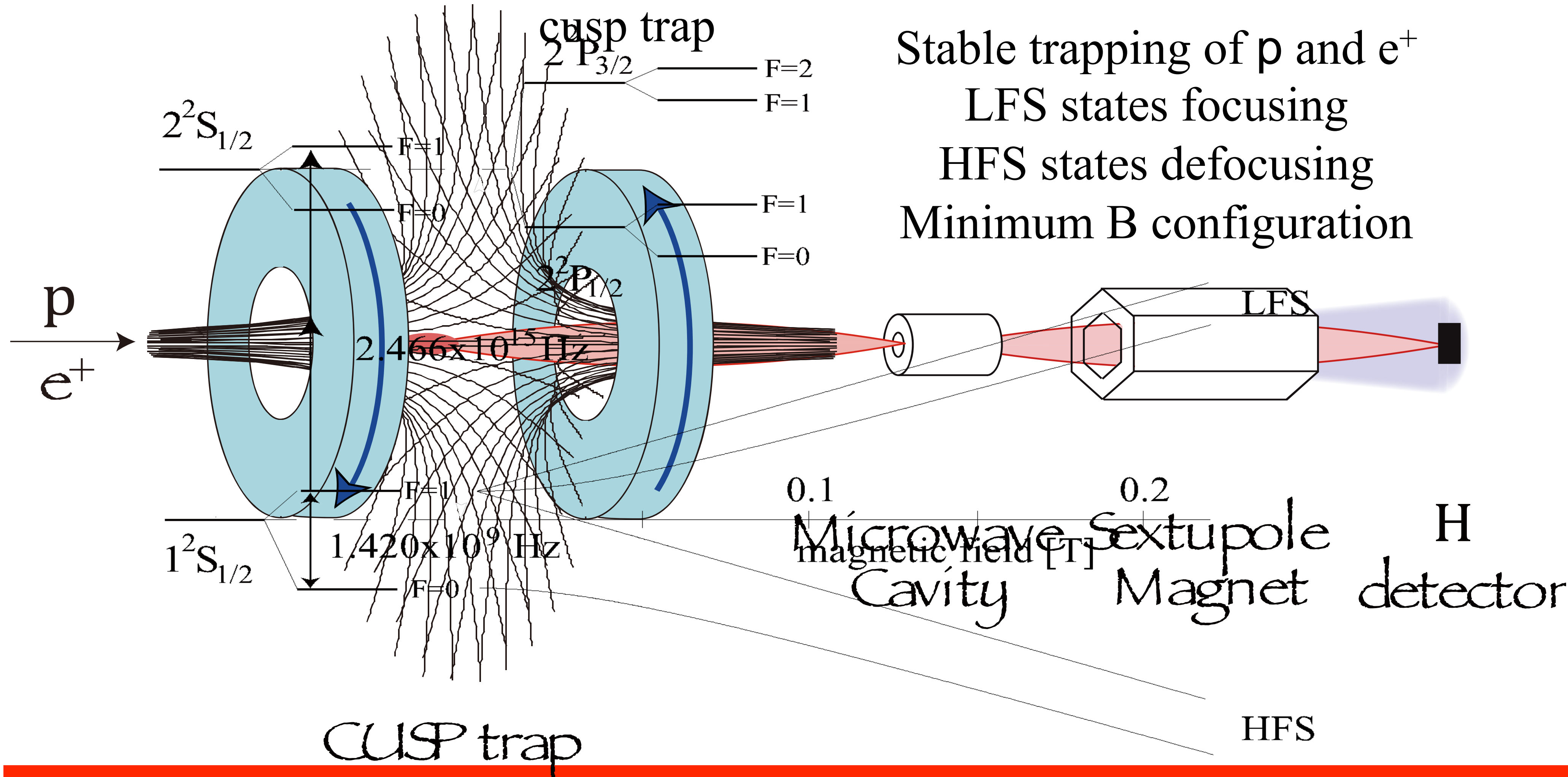


- Extra Low ENergy Antiproton ring
- Decelerate from 5 MeV to 100 keV
- Can trap up to 100 times more pbars
- Possible 24 hour operation for all users
- CERN approval directly linked to success in ALPHA

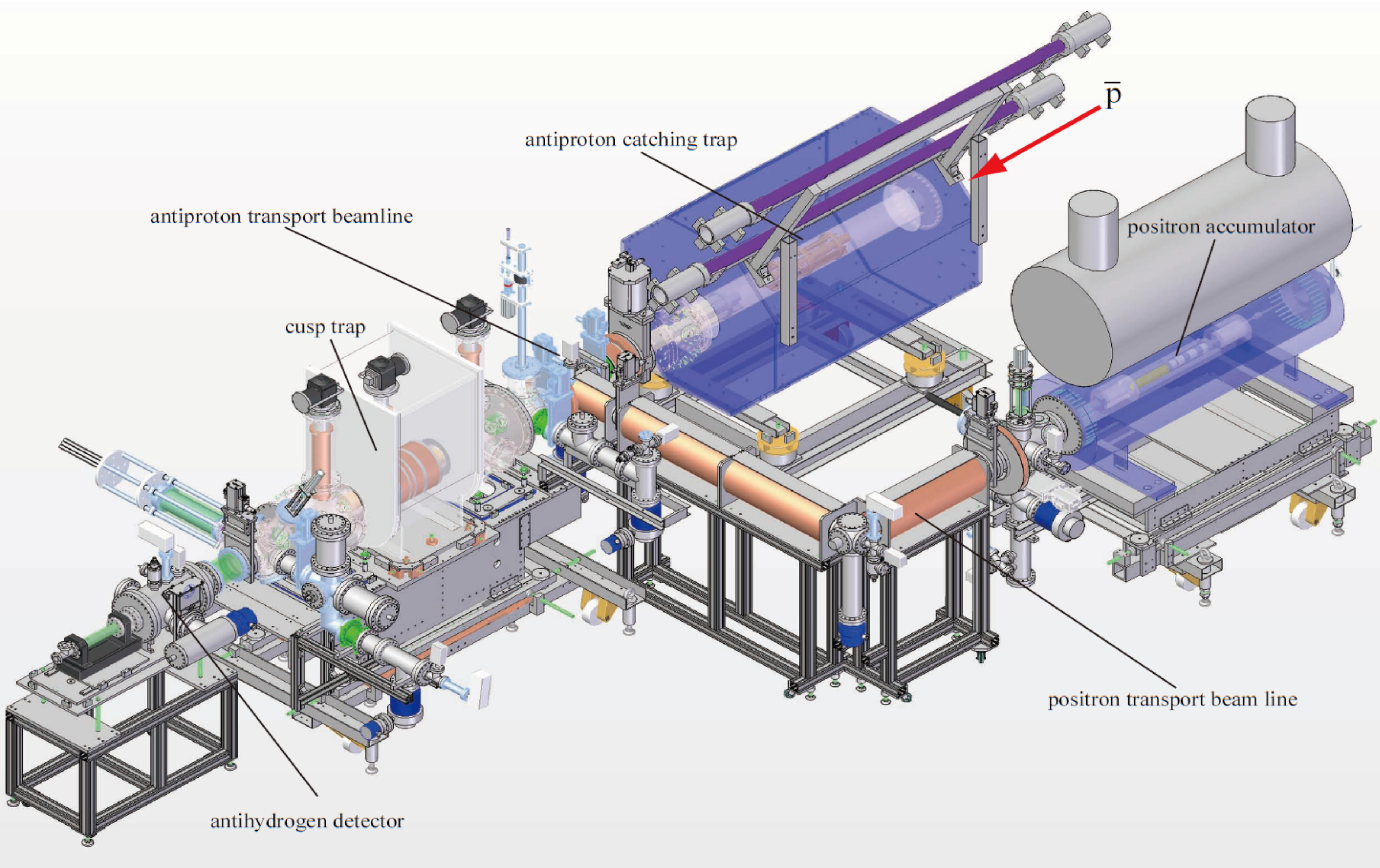
ASACUSA Cusp trap scheme: Hbar beam

Hyperfine Transition microwave spectroscopy →
H extraction in a field-free region →

Stable trapping of p and e^+
LFS states focusing
HFS states defocusing
Minimum B configuration



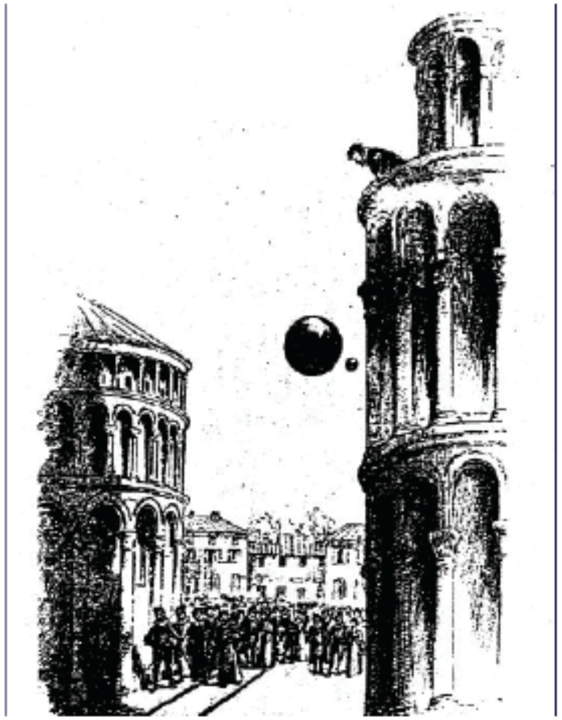
ASACUSA Cusp trap scheme: Hbar beam

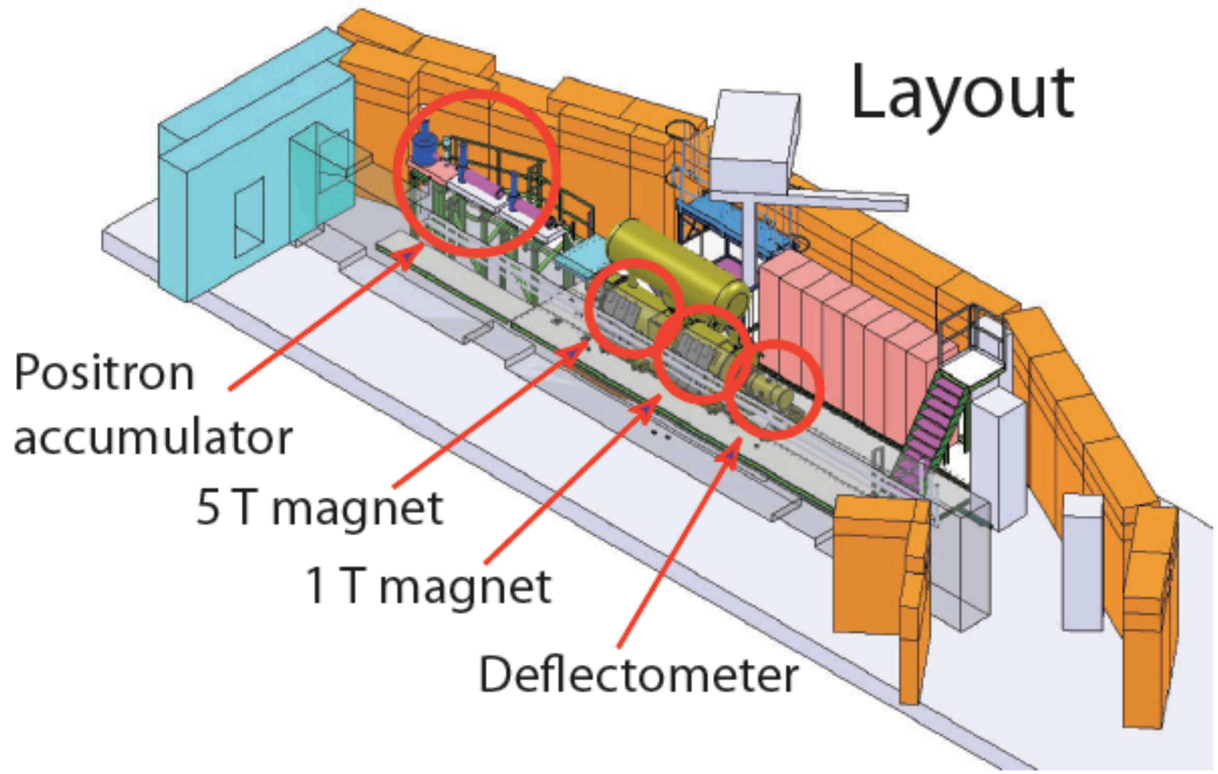


ALPHA

AEḡIS: Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy

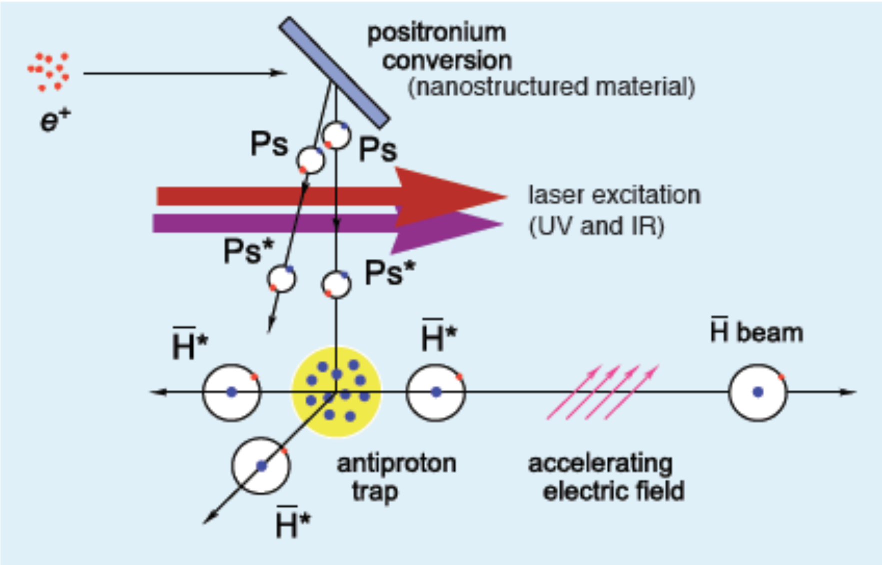
(atomic physics with antimatter)





AEGIS

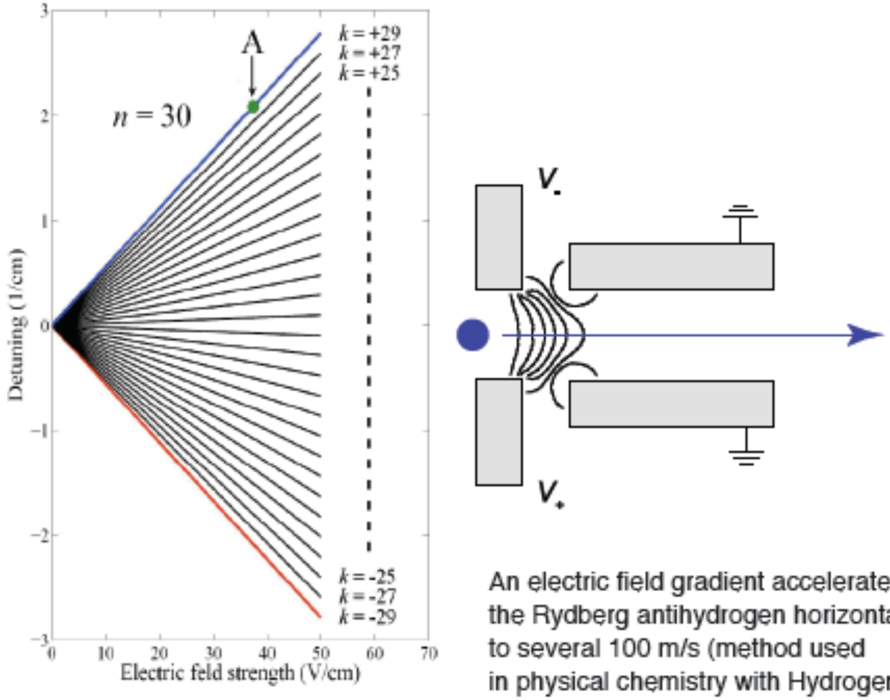
Antihydrogen formation



$$Ps^* + \bar{p} \longrightarrow \bar{H}^* + e^-$$

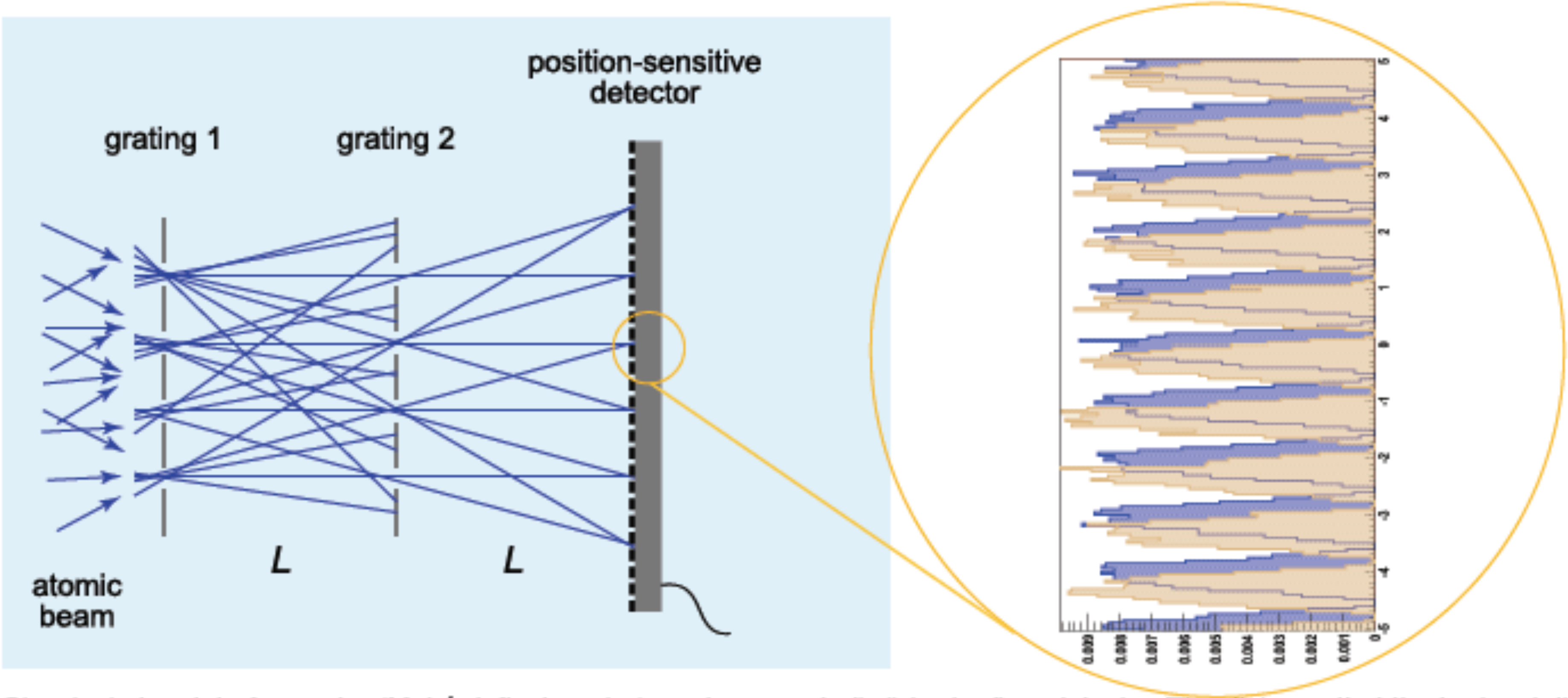
Antihydrogen atoms are produced in a burst by colliding laser-excited Positronium with ultra-cold (<1K) antiprotons; the resulting atoms are highy excited (Rydberg atoms)

Antihydrogen beam



An electric field gradient accelerates the Rydberg antihydrogen horizontally to several 100 m/s (method used in physical chemistry with Hydrogen)

Gravity measurement



Classical atom interferometer (Moiré deflectometer) produces periodic “shadow” on detector. The distance that the horizontally flying antihydrogen falls depends on the time of flight: the slower atoms will fall more. This drop is measured for different anti-hydrogen velocities, from which one can determine the strength of the gravitational force.

Other AD experiments:

•ACE – studies effect of antiprotons on live cells for possible cancer therapy
•ATRAP – antihydrogen trapping and spectroscopy
•Gbar – another gravitational experiment, just approved in 2012, operation in 2017

Antihydrogen Summary

•Trapped neutral antimatter in 2010 – lots of fun, great relief

•More than 20 years of effort – finally measuring something - first precision spectroscopy of antihydrogen in ~ 5 years

•I have been telling funding agencies this for ~ 15 years

•One front-page story in the *New York Times*, one best-selling novel, one hit movie (what's the impact factor?), physics story of the year twice (various outlets); live on *Al Jazeera,* ongoing documentary film…

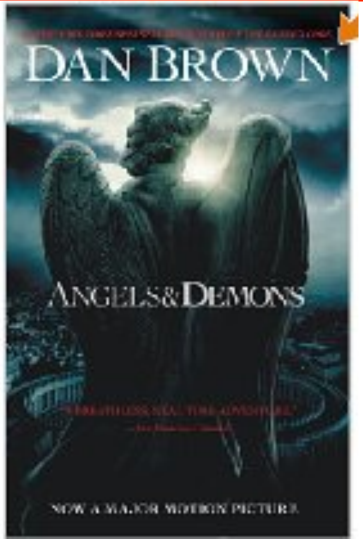
•No matter what Dan Brown, Hollywood (or CERN, or Fermilab, etc.) may tell you, the trapped antimatter at CERN is at the Antiproton Decelerator, and has *nothing at all* to do with the LHC

•New device – ALPHA-2 - under construction to allow for laser and improved microwave spectroscopy as early as 2012

•Gravitational studies in ALPHA? Preliminary thoughts about this.

•With the upcoming construction of ELENA, new experiments coming online – bright times ahead

Angels and Demons – Can I Destroy the Vatican?



Conclusion: antimatter makes for a poor weapons strategy

Discovery Channel producer: "Antimatter physicist recommends nuking Vatican!"

•Claim: the only conceivable *portable* antimatter with a mass of ¼ gram would be *neutral antihydrogen*

•Charged plasma densities about 10^9 cm^{-3}; 10^{23} particles would need a volume of 10^{14} cm^3 or 10^8 m^3

•Hydrogen BEC density about 10^{15} cm^{-3}; transition about 50 μK – need liquid *antihelium* and evaporative cooling

•ALPHA captures about 10^5 antiprotons every 100 s

•Assuming all of these could be converted to antihydrogen *and* trapped, it would take about 10^{20} seconds to get ¼ gram; This is $3\text{x}10^{12}$ years.

•The ¼ gram of antimatter would have an explosive power of about 50 kilotons of TNT, comparable to the Hiroshima bomb

•How would you safely contain this?

•The most unbelievable part of the film is that anyone with a PhD in physics would go anywhere near ¼ gram of antimatter contained by a device built by someone with a PhD in physics…

And now a word from my sponsor:

ALPHA + Carlsberg

Probably the best antihydrogen experiment in the world…

Have a nice, thirsty summer!