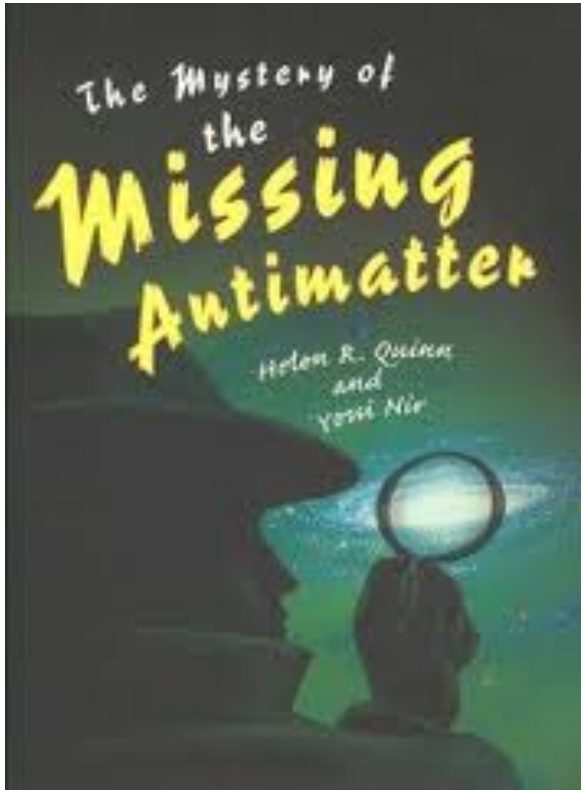
ALPHA-g Would an Anti-apple Fall Up?

Scott Menary

YORK U

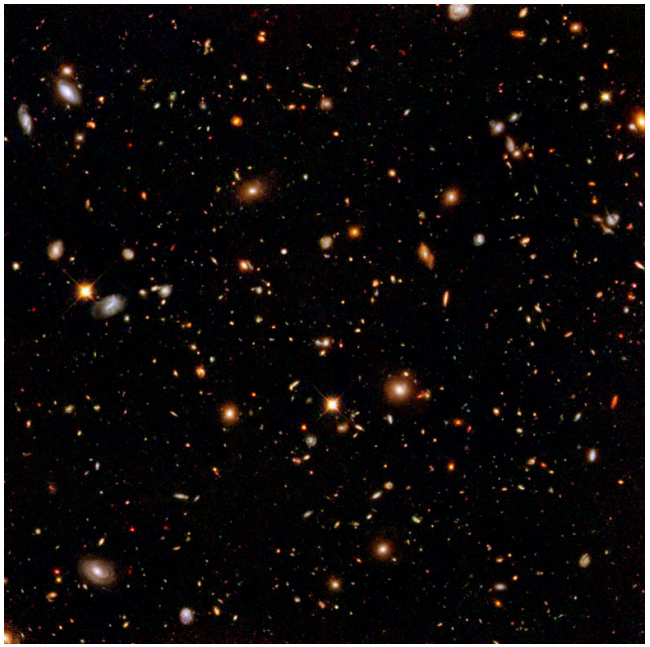
What if matter and antimatter repelled gravitationally?

Some Attractive Features of "Antigravity" :



- The "antimatter-matter asymmetry" in the universe would be solved because **there wouldn't be one!** Half the galaxies we see would be "anti-galaxies" and half matter galaxies. We wouldn't observe annihilations because the galaxies and anti-galaxies would repel each other. This could explain why the universe is expanding.

Can you tell an antigalaxy from a galaxy? Not from the light emitted. But you could using neutrinos! Stars emit neutrinos while antistars emit antineutrinos!



- We wouldn't see antimatter locally (as is observed) because our galaxy is repelling antimatter originating from outside the galaxy.

How Could Antimatter Be Different?

- **Setting $\bar{m}_I = -\bar{m}_G$ for antimatter doesn't destroy the structure of the classical picture. Only $m_I = m_G$ has been tested. That is, we would still have $F_I = \bar{m}_I a$ but now $F_{G,}$ when an antimatter particle is interacting with matter, is in the opposite direction to when the situation is matter interacting with matter. Further, the strength of the interaction still goes like $1/r^2$.**
- **Again, the situation for matter was articulated by Einstein with The Equivalence Principle:**

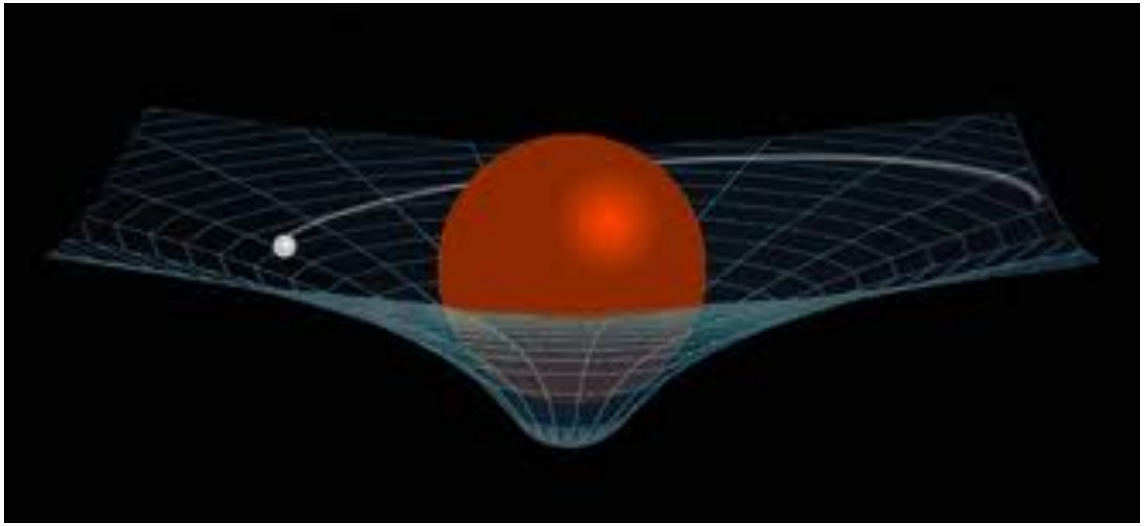
"A little reflection will show that the law of the equality of the inertial and gravitational mass is equivalent to the assertion that the acceleration imparted to a body by a gravitational field is independent of the nature of the body. For Newton's equation of motion in a gravitational field, written out in full, it is:

(Inertial mass) (Acceleration) = (Intensity of the gravitational field) (Gravitational mass).

It is only when there is numerical equality between the inertial and gravitational mass that the acceleration is independent of the nature of the body."

Albert Einstein

General Relativity and Antimatter



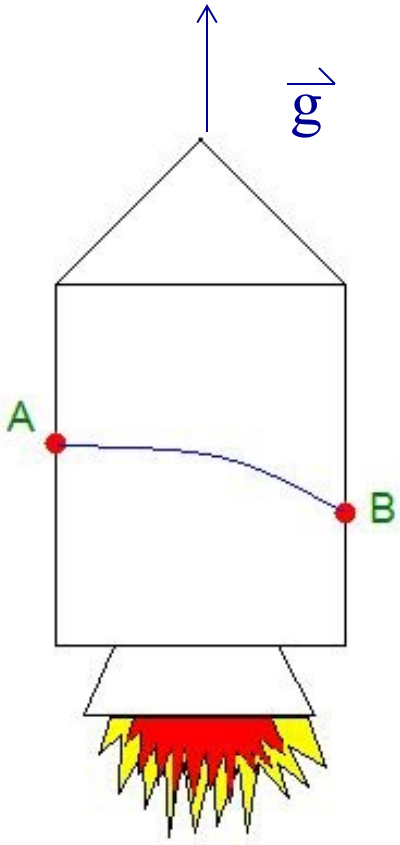
In 2011 Villata (arXiv:1103.4907) showed that if you explicitly keep the ratio of m_I/m_G in the geodesic equation then you can have an equation consistent with General Relativity:

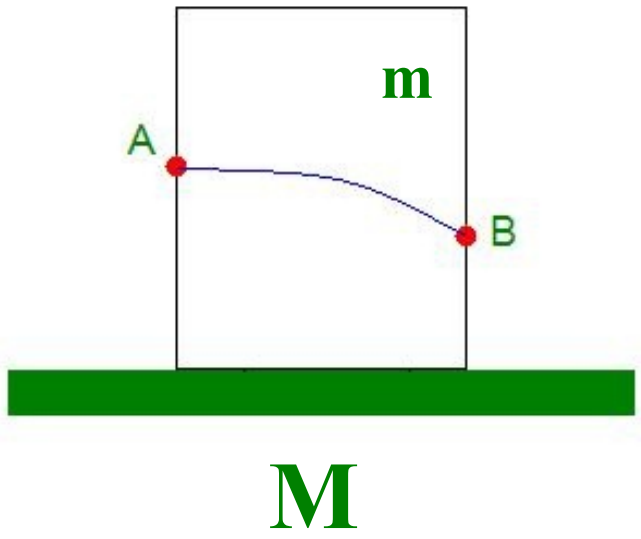
$$\frac{d^2x^\lambda}{d\tau^2} = -\frac{m_{(g)}}{m_{(i)}}\frac{dx^\mu}{d\tau}\Gamma_{\mu\nu}{}^{\lambda}\frac{dx^\nu}{d\tau}$$

"Matter tells space how to curve, and space tells matter how to move."

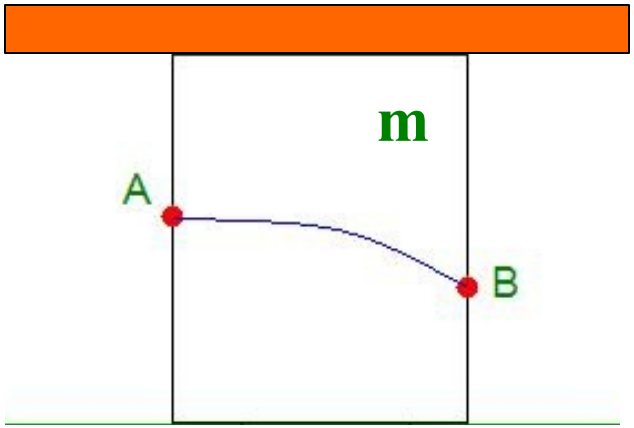
- J. Wheeler

Is this consistent with WEP?





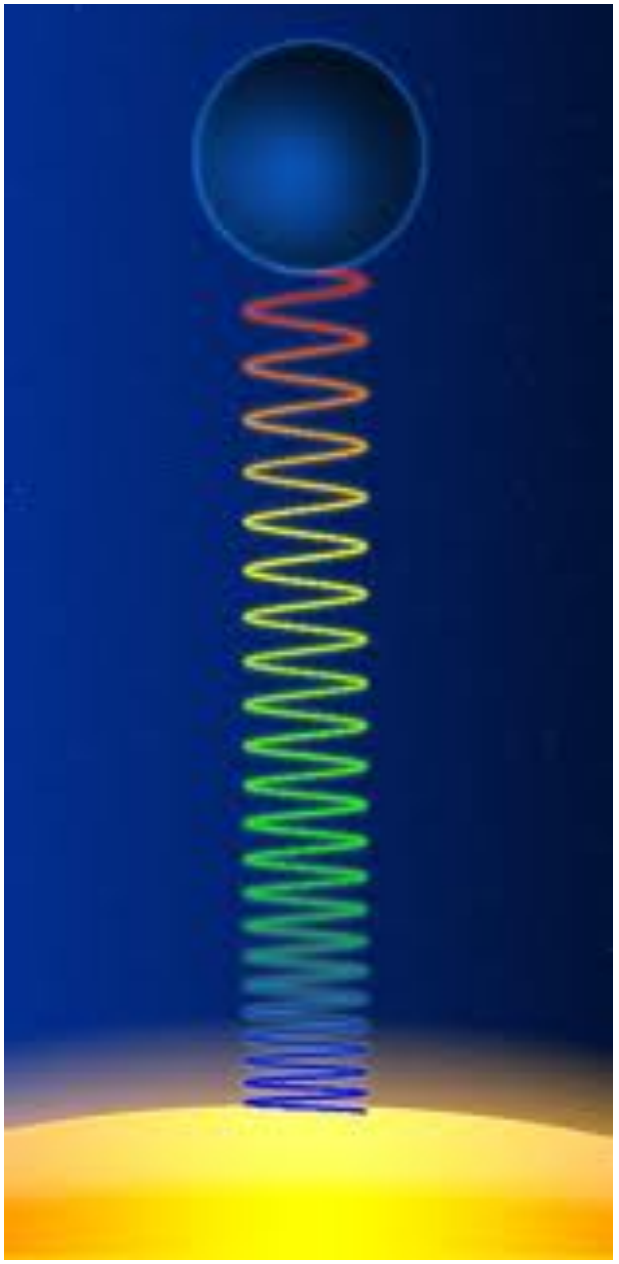
$M = \bar{M}$



To really test WEP with antimatter you want to drop two antimatter samples having different masses and test that they "fall" at the same rate.

Arguments against Antigravity

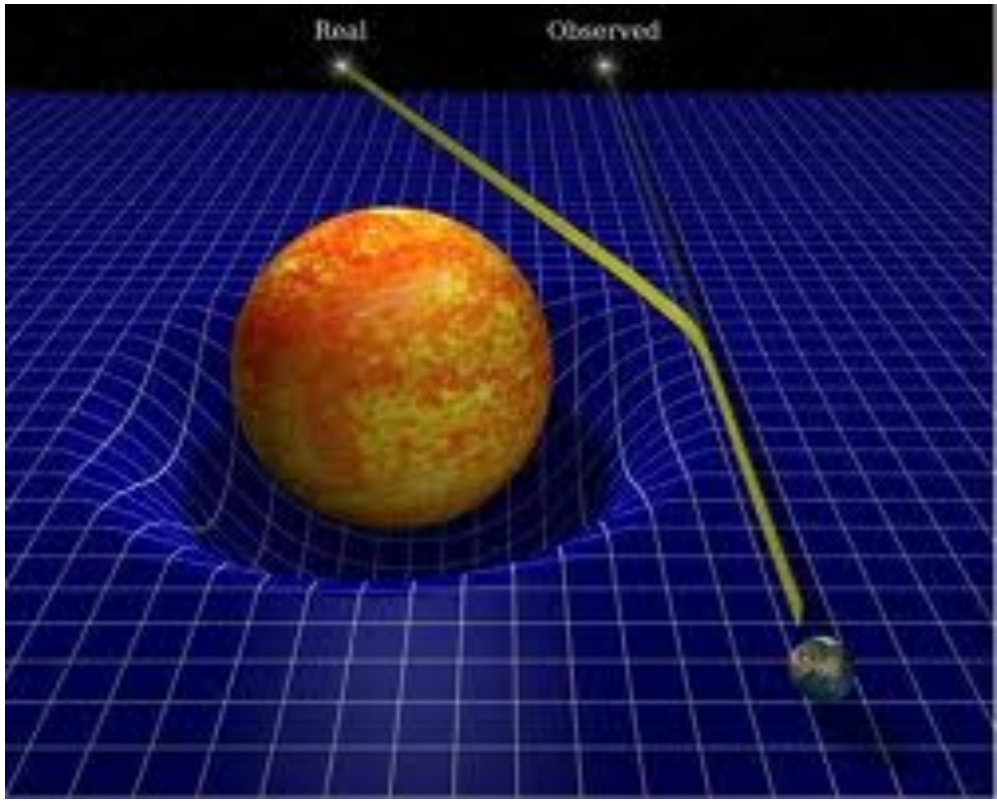
- It's not motivated by any fundamental principle (like The Equivalence Principle).
- The Morrison Argument leads to the claim that you get a Perpetual Motion Machine.
  - **Start with an electron-positron pair.**
  - **If matter and antimatter repel, then you can raise the pair to a greater height and not have done any work.**
  - **Let the pair annihilate and then use mirrors to reflect the annihilation photons back towards the Earth.**
  - **The photons gain energy in the gravitational field of the Earth and so they could at some lower height annihilate giving an electron and positron and energy.**
  - **Repeat.**
- Like most arguments against, this assumes photons act as in GR.



Arguments against Antigravity

- Bending of light by the Sun (see Cross - arXiv:1108.5117 - for a general argument and Menary – arXiv:1207.7358 – for a more complete look at the data versus expectations from models.)

- A photon is its own antiparticle (like positronium) so it presumably wouldn't feel any effect from gravity if matter-antimatter repel.
- But light is bent towards (i.e., attracted to) the Sun so clearly repulsion is not happening.
- Using actual observations allows to put limits on difference of g and $\overline{g}$ of <0.5%



➢ **Can get around this if test is done using antiprotons**

The ALPHA Collaboration

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THINKING OF THE WORLD

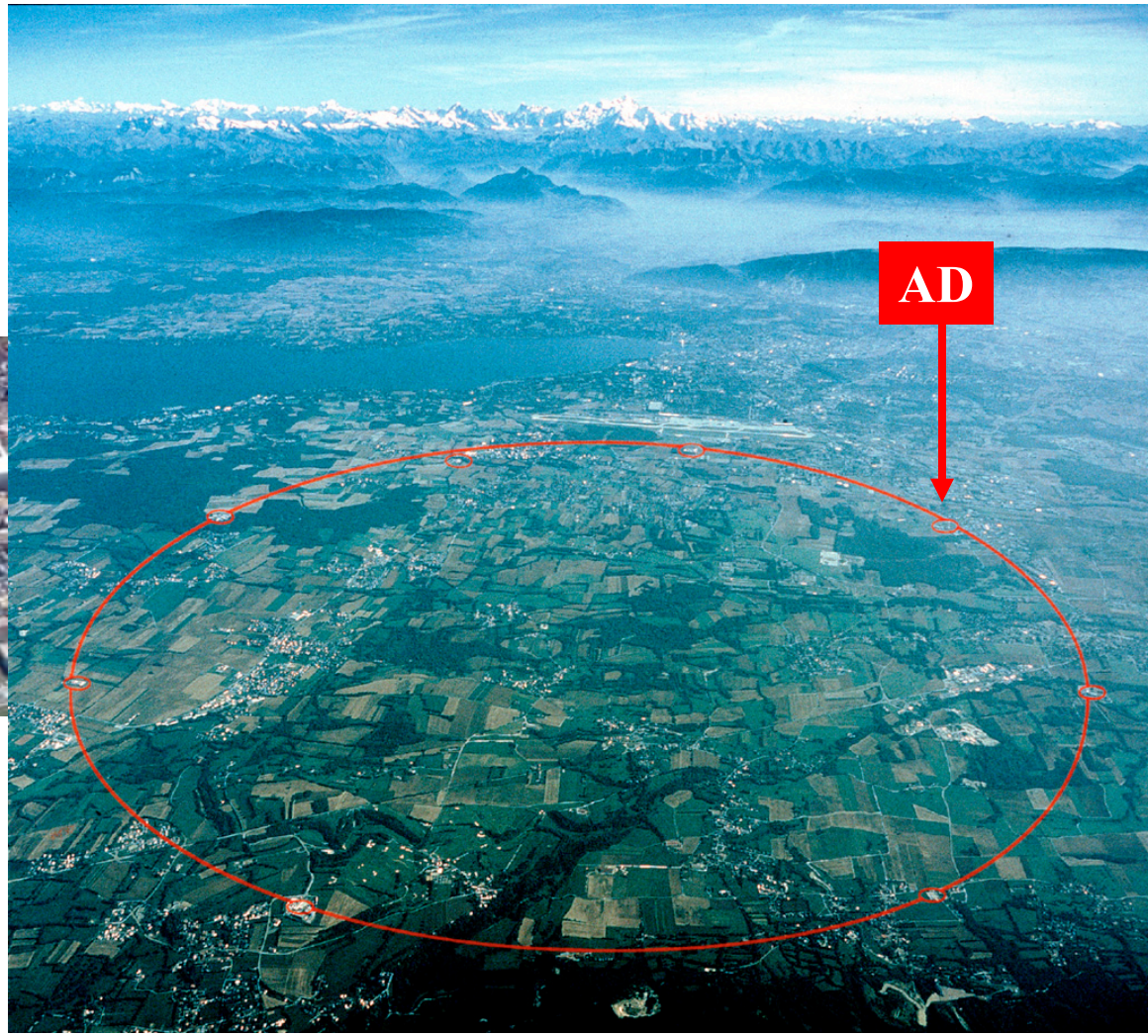
TRIUMF

Making Antihydrogen

Getting Antiprotons – the Antiproton Decelerator

We get antiprotons from CERN's Antiproton Decelerator (AD)

-generate high energy antiprotons using the CERN PS
- the AD reduces antiproton KE to 5.3 MeV
- 30 million antiprotons every ~100 seconds



Making Antihydrogen

Getting Antiprotons – the Antiproton Decelerator

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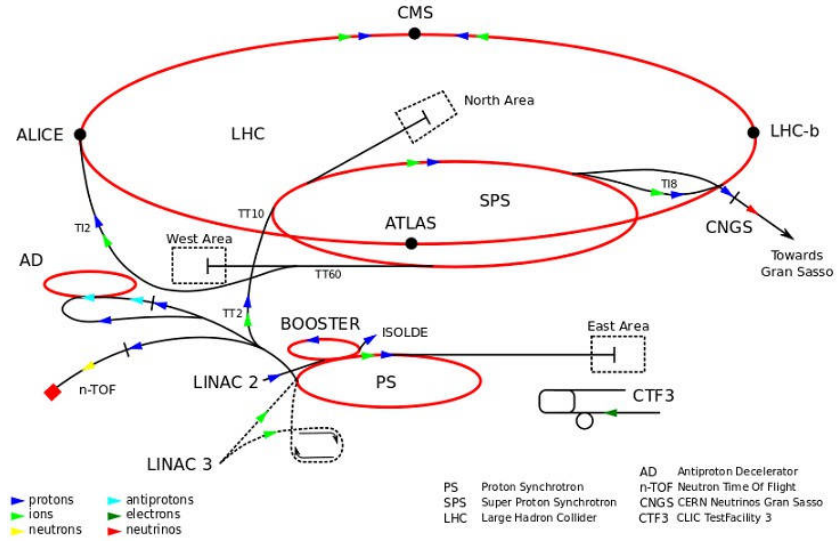
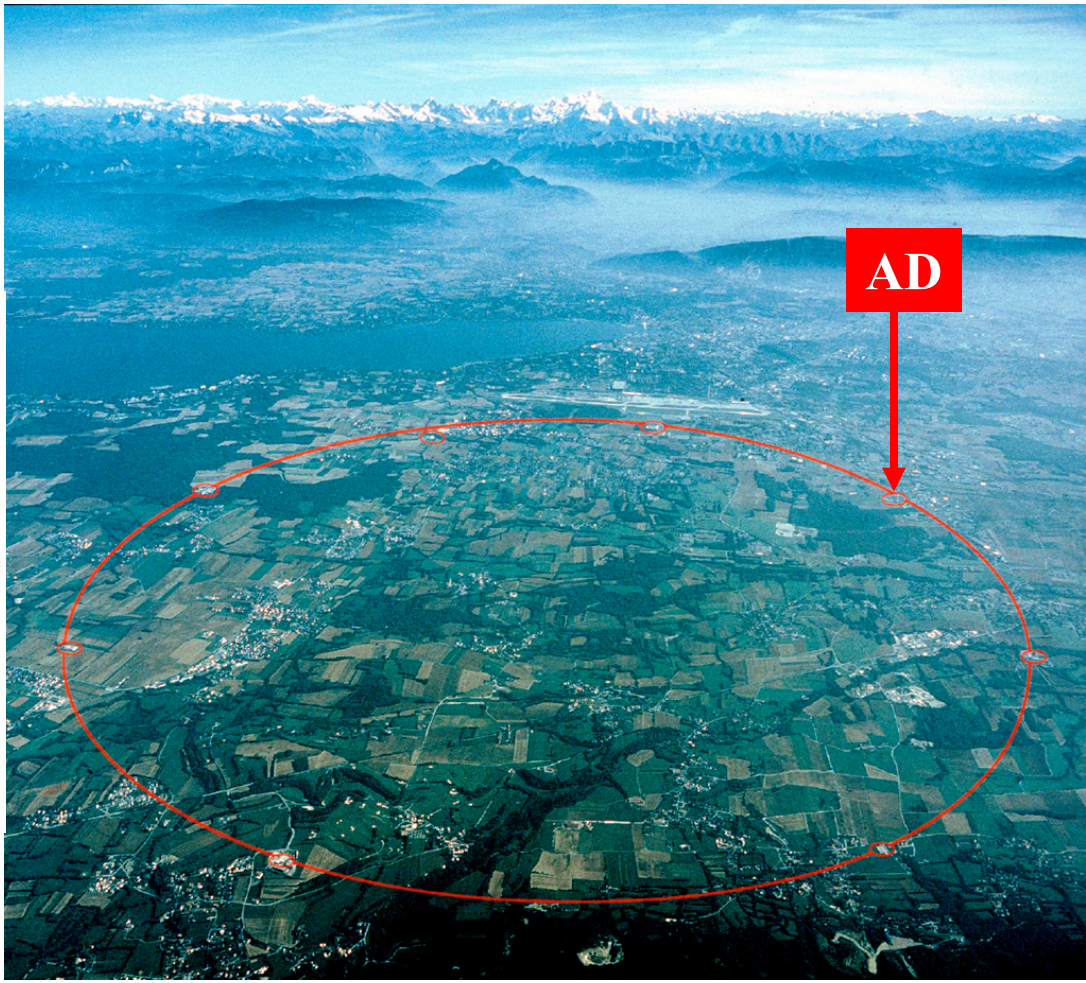


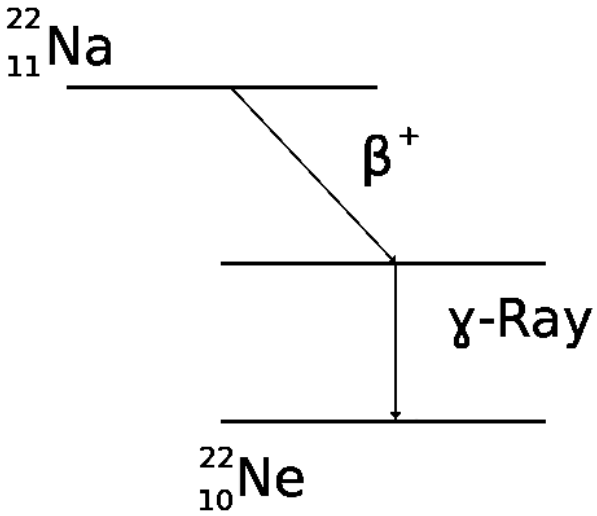


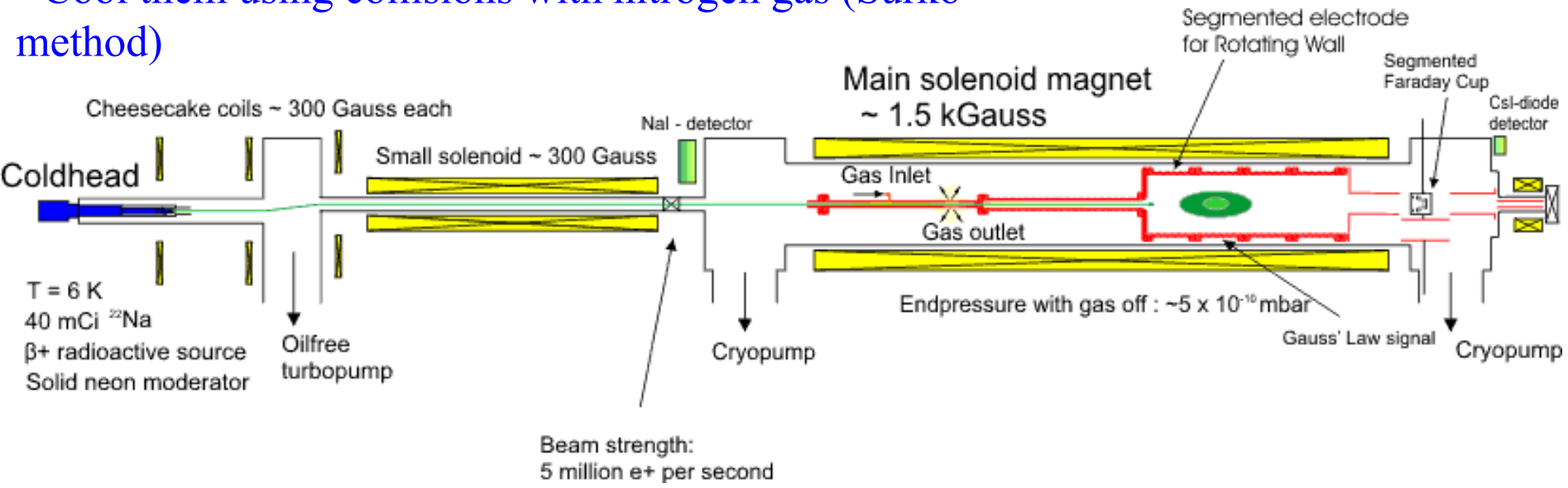
- generate high energy antiprotons using the CERN PS
- the AD reduces antiproton Kinetic Energy to 5.3 MeV
- 30 million antiprotons every ~100 seconds

Making Antihydrogen

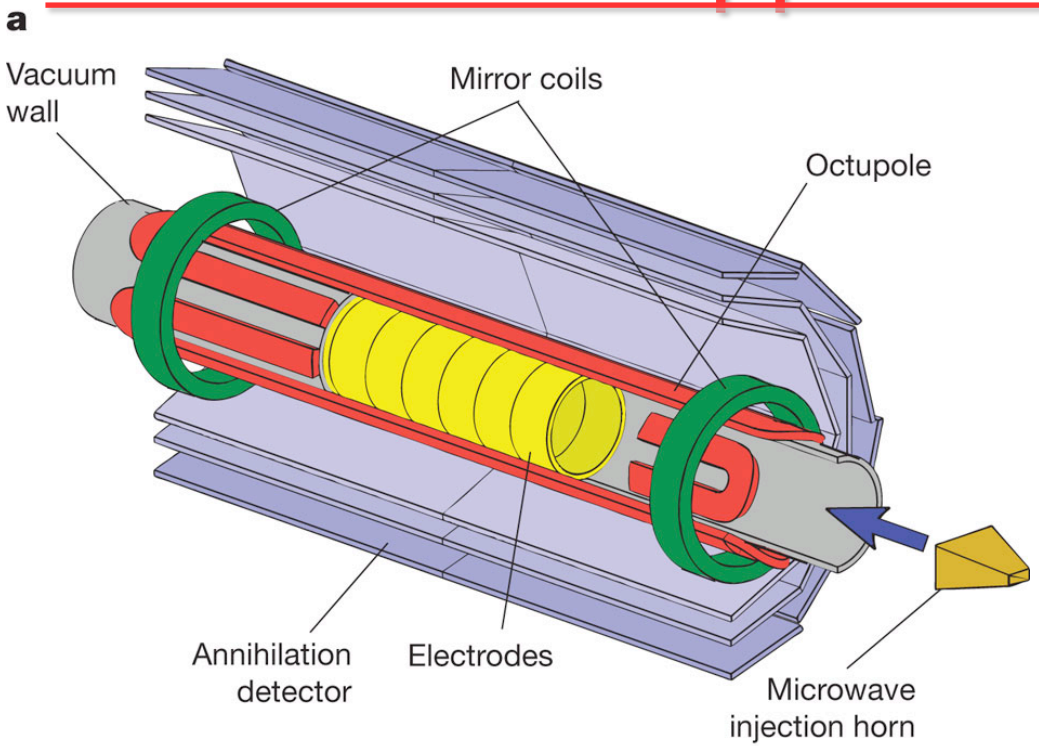
Getting Positrons – the Positron Accumulator

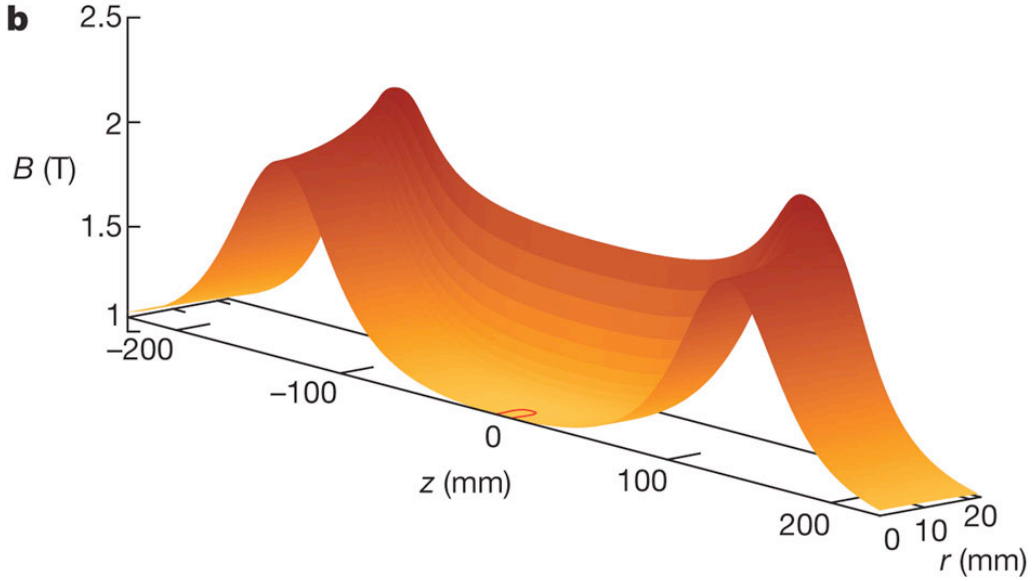
- Use 2 GBq (~75 mCi) ^{22}Na β^+ source (τ = 2.6y)
- Unfortunately they have a range of energies and the beam is continuous - need to cool and collect them
- This is done by the Positron Accumulator
- Stop the positrons in a moderator – solid neon (5 – 6 K)
- 5 million positrons per second escape from moderator surface (about 3-4% of total) and are directed to a trapping region
- Cool them using collisions with nitrogen gas (Surko method)

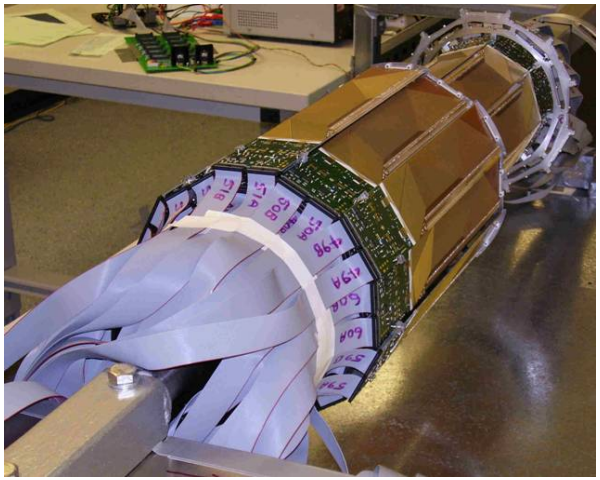




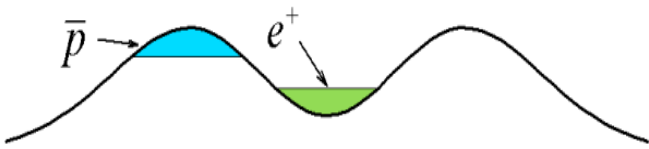
The ALPHA Apparatus

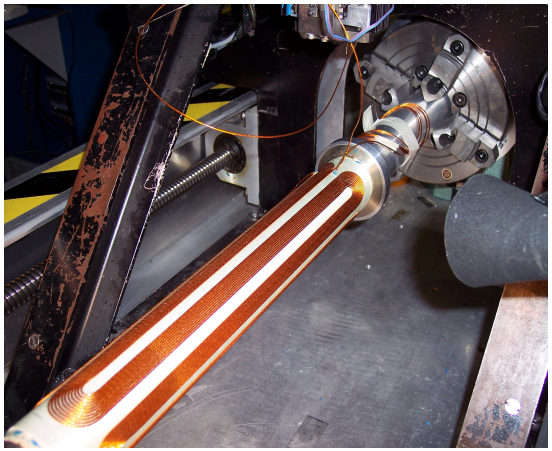






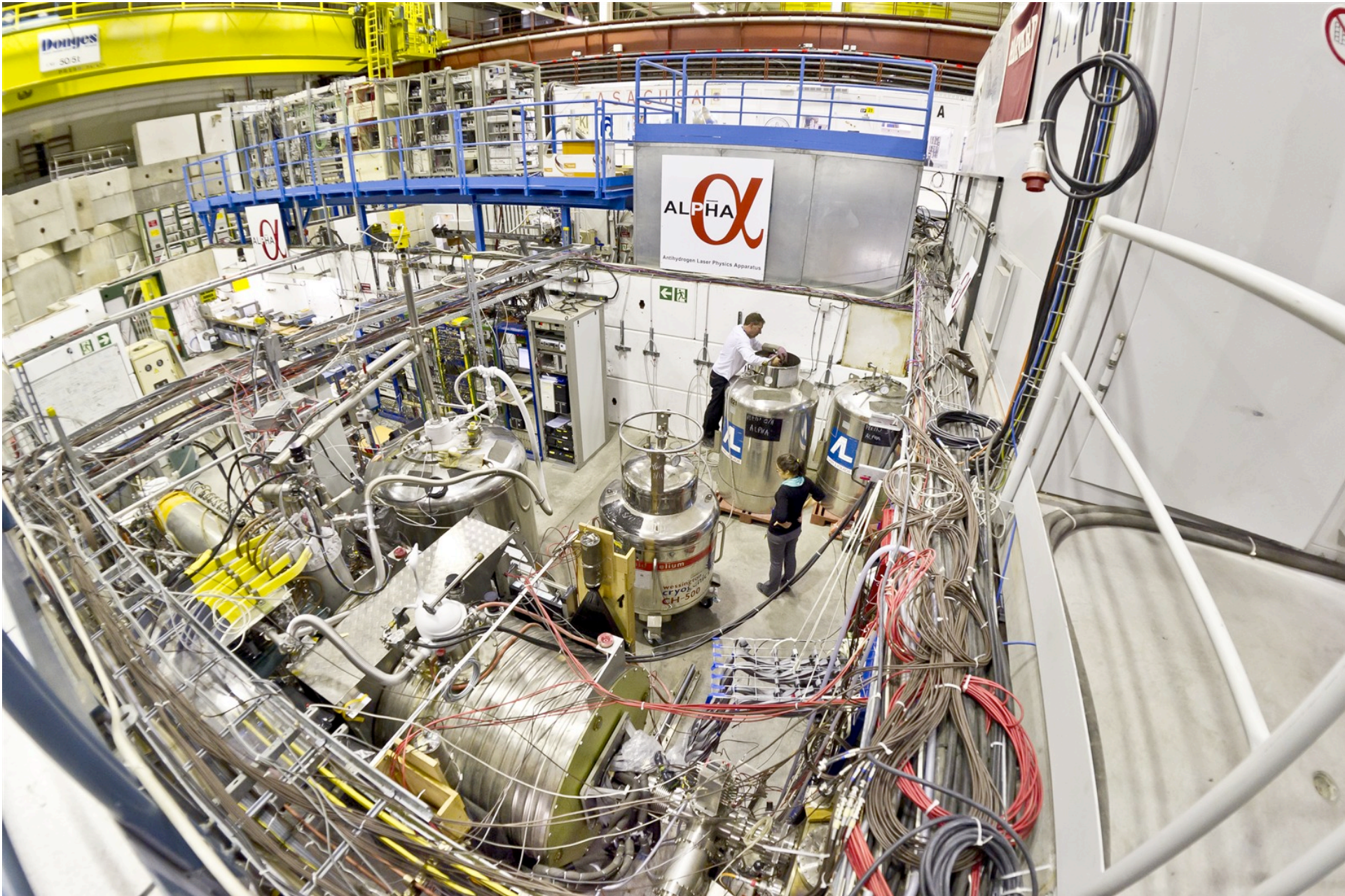
Mixing electrostatic potential



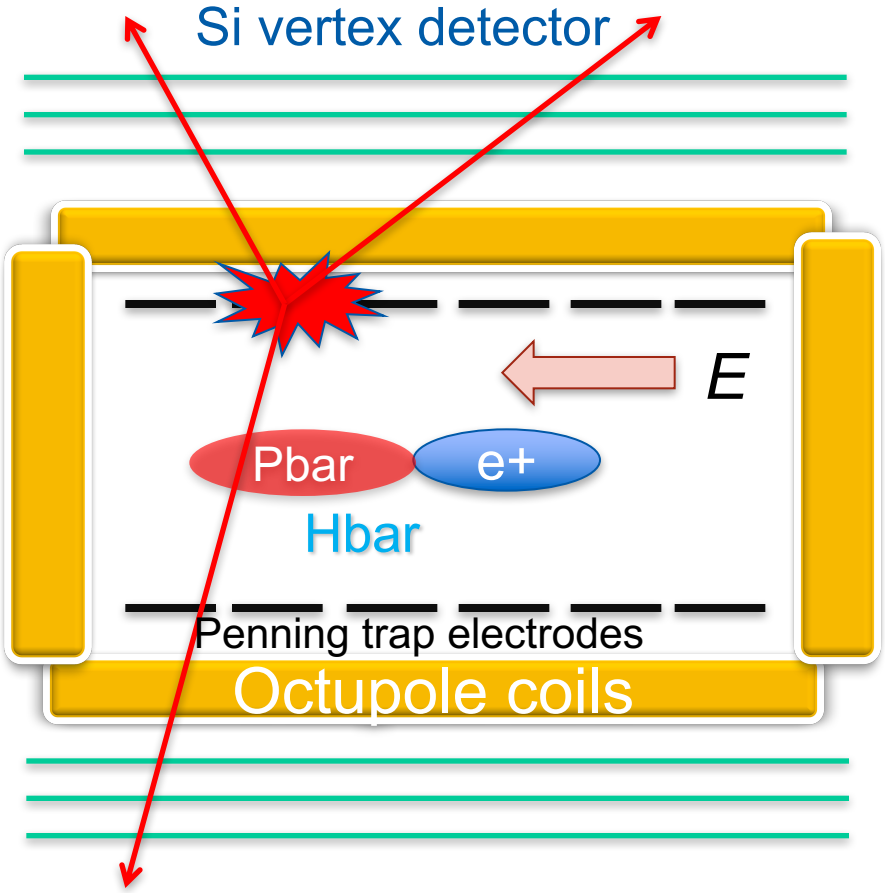


$$U_B = -\vec{\mu} \cdot \vec{B}$$

The ALPHA Experiment in the AD Hall

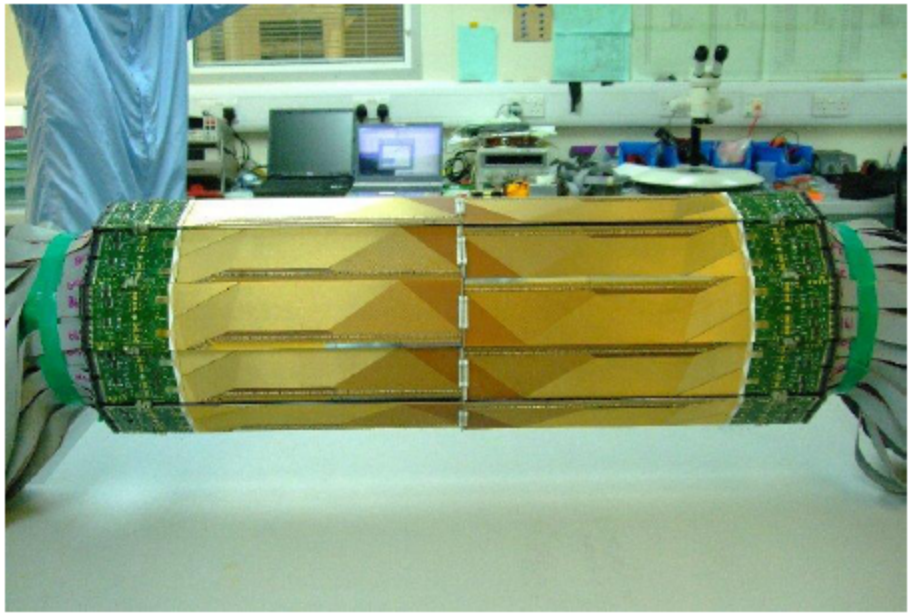


Trapping Antihydrogen

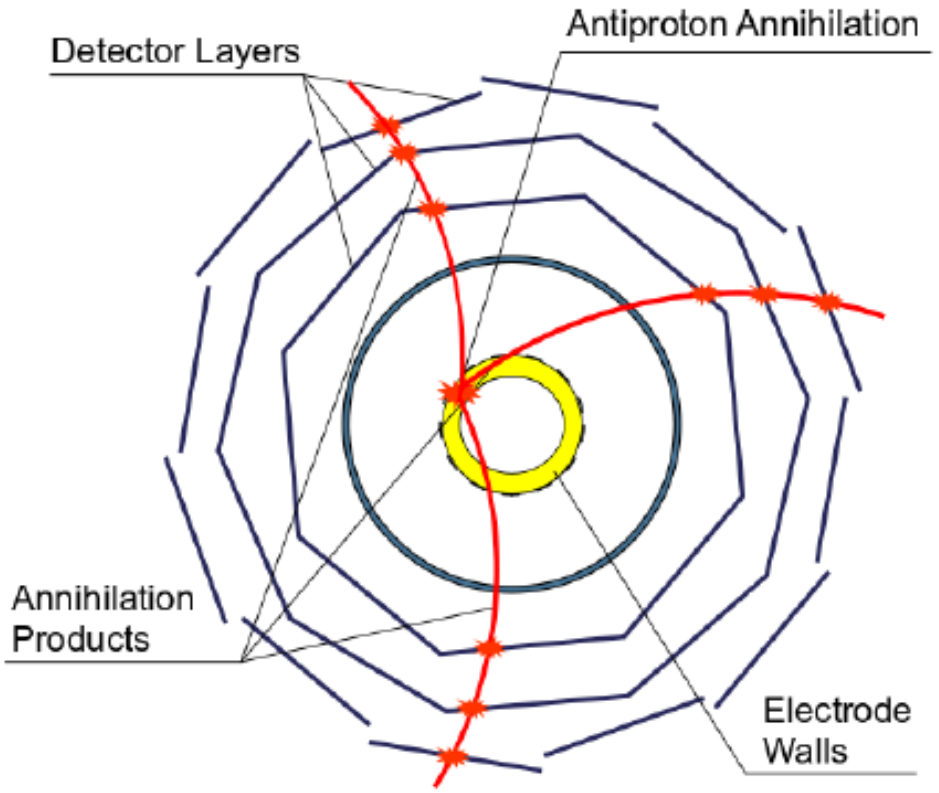


1. Prepare $3x10^4$ pbars (200K; after cooling, compression, transfer)
2. $4x10^7$ e+ evaporatively cooled to 40K – left with $2x10^6$
3. Energize magnetic trap
4. Gently mix pbars and e+ for 1 s
5. Hbar < 0.6 K (50 μeV) will be trapped
6. Clear the charged particles by E field (minimum of 172 ms)
7. Anything remain trapped should be neutral anti-H
8. Dump magnetic trap in ~30 msec by quenching magents
9. Released anti-H hit the walls
10. Search for annihilation signatures in Si detector

ALPHA: Si Vertex Detector



30,000 channel strips
~0.8 m^2 active area



Important ALPHA Results for Antigravity Tests

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]

nature physics

ARTICLES

PUBLISHED ONLINE: 5 JUNE 2011 | DOI: 10.1038/NPHYS2025

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

nature COMMUNICATIONS

Nature Communications **4** – April 30, 2013

Article number: 1785 doi:10.1038/ncomms2787

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

The Charge of the Antihydrogen Atom

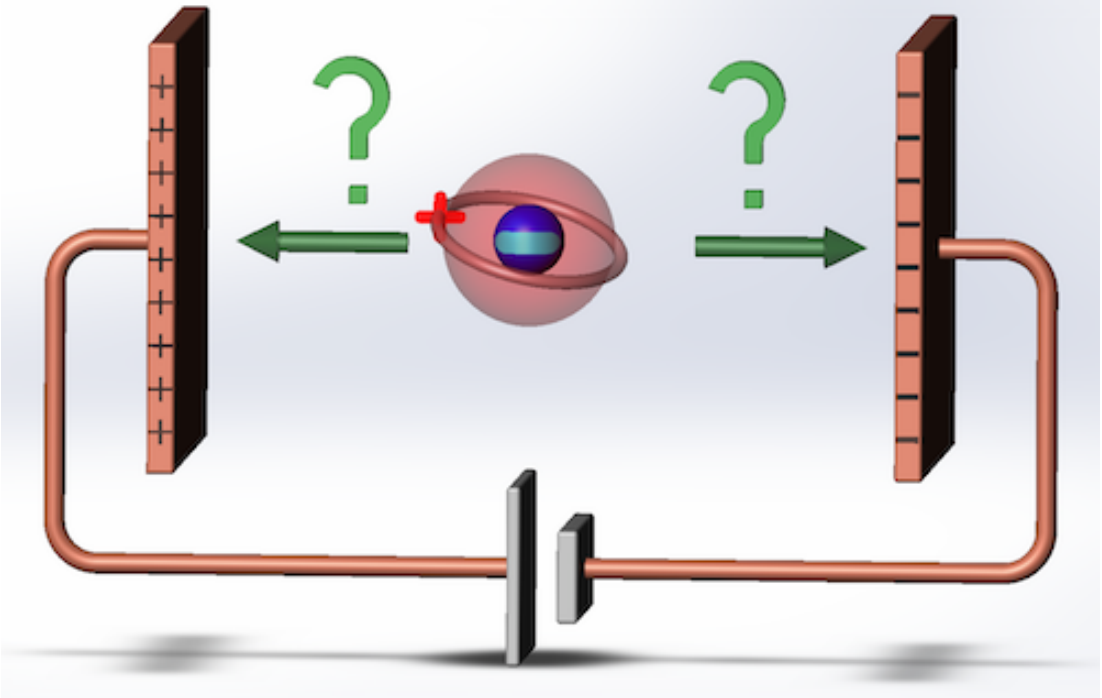
Nature Volume **529 – January 21, 2016**

http://www.nature.com/nature/journal/v529/n7586/full/nature16491.html

An improved limit on the charge of antihydrogen from stochastic acceleration

ALPHA Collaboration

"By applying stochastic acceleration to trapped antihydrogen atoms we determine an experimental bound on the antihydrogen charge, Qe, of $|Q|<0.71$ parts per billion (one standard deviation), in which e is the elementary charge. "



Antihydrogen Trapped!

ALPHA-Canada

15 out of 42 authors (incl. 5 students)

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

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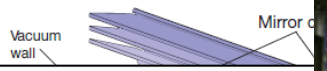
Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at low energies at CERN (the European Organization for Nuclear Research) since 2002. Antihydrogen is of interest for use in a precision test of nature's fundamental symmetries. The charge conjugation/parity/time reversal (CPT) theorem, a crucial part of the foundation of the standard model of elementary particles and interactions, demands that hydrogen and antihydrogen have the same spectrum. Given

octupole has been shown to greatly reduce the perturbations on charged plasmas[9,10]. The liquid helium cryostat for the magnets also cools the vacuum wall and the Penning trap electrodes; the latter are measured to be at about 9 K. Antihydrogen atoms that are formed with low enough kinetic energy can remain confined in the magnetic trap, rather than annihilating on the Penning
can confine ground-state antihydrogen at

a



5 June 2011

ALPHA experiment traps antimatter atoms for 1000 seconds

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The Large Hadron Collider (LHC)
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First Ever Spectroscopic Measurement on Antihydrogen

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Archive > Volume 483 > Issue 7390 > Letters > Article

NATURE | LETTER

previous article next article

Resonant quantum transitions in trapped antihydrogen atoms

C. Amole, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, A. Capra, C. L. Cesar, M. Charlton, A. Deller, P. H. Donnan, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, C. A. Isaac, S. Jonsell, L. Kurchaninov, A. Little, N. Madsen, J. T. K. McKenna, S. Menary, S. C. Napoli, P. Nolan, K. Olchanski, A. Olin, P. Pusa, C. Ø. Rasmussen, F. Robicheaux, E. Sarid, C. R. Shields, D. M. Silveira, S. Stracka, C. So, R. I. Thompson, D. P. van der Werf & J. S. Wurtele

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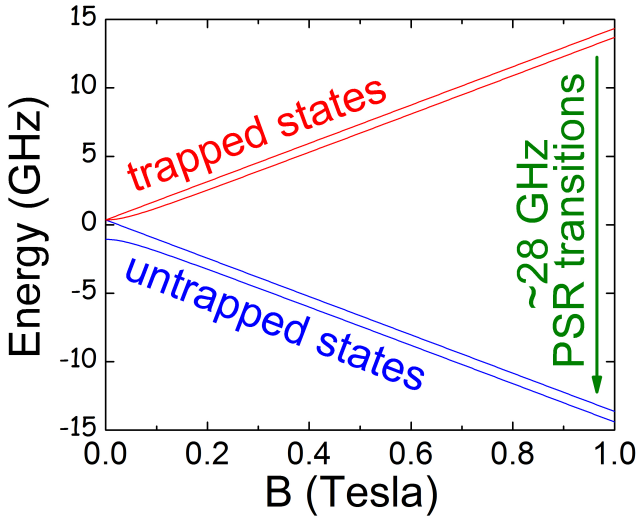
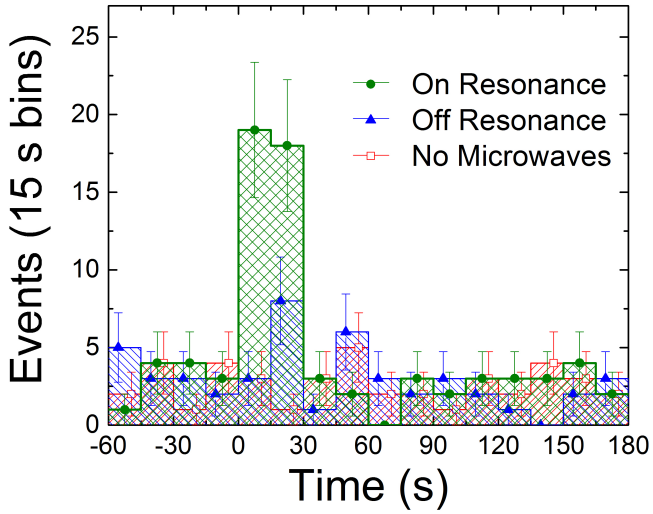




Antimatter Gravity Measurement

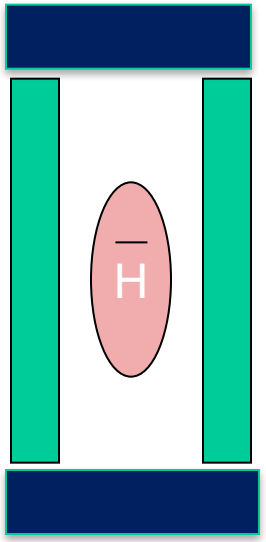
- **Relevant energy/length scales:**
  - **Considering one dimension**

    $1/2kT=mgh$

    $h \sim 420(\mathrm{m}) \times T\,(K)$

    If T ~ 3 mK, h ~ 1.3 m

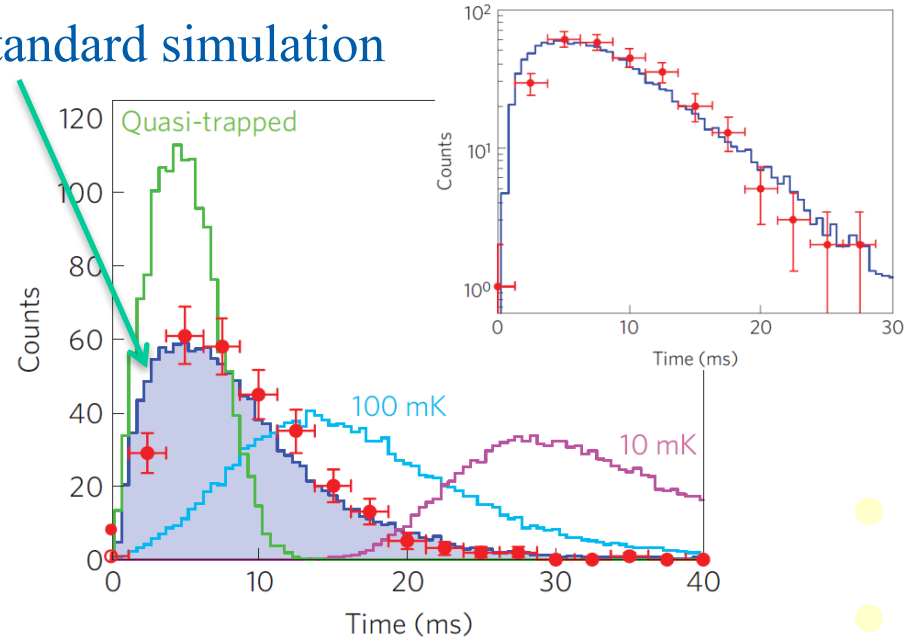
    equivalent magnetic energy at:
    $\Delta B \sim 1/2 \cdot kT/\mu \sim$ 20 Gauss

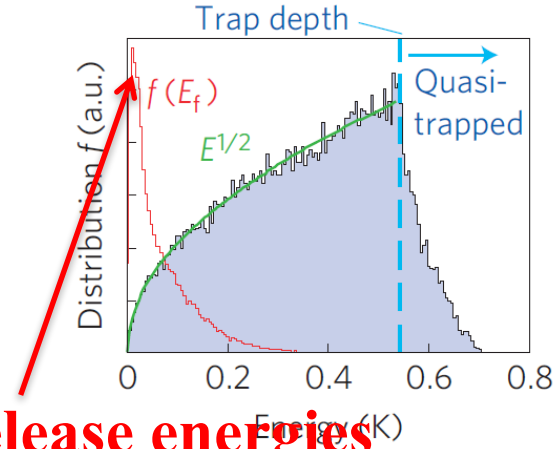


Kinetic energy of trapped Hbars:

Nature Phys. 2011

Standard simulation

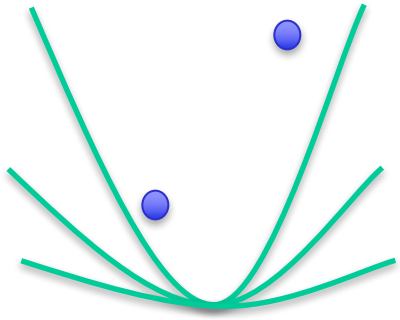




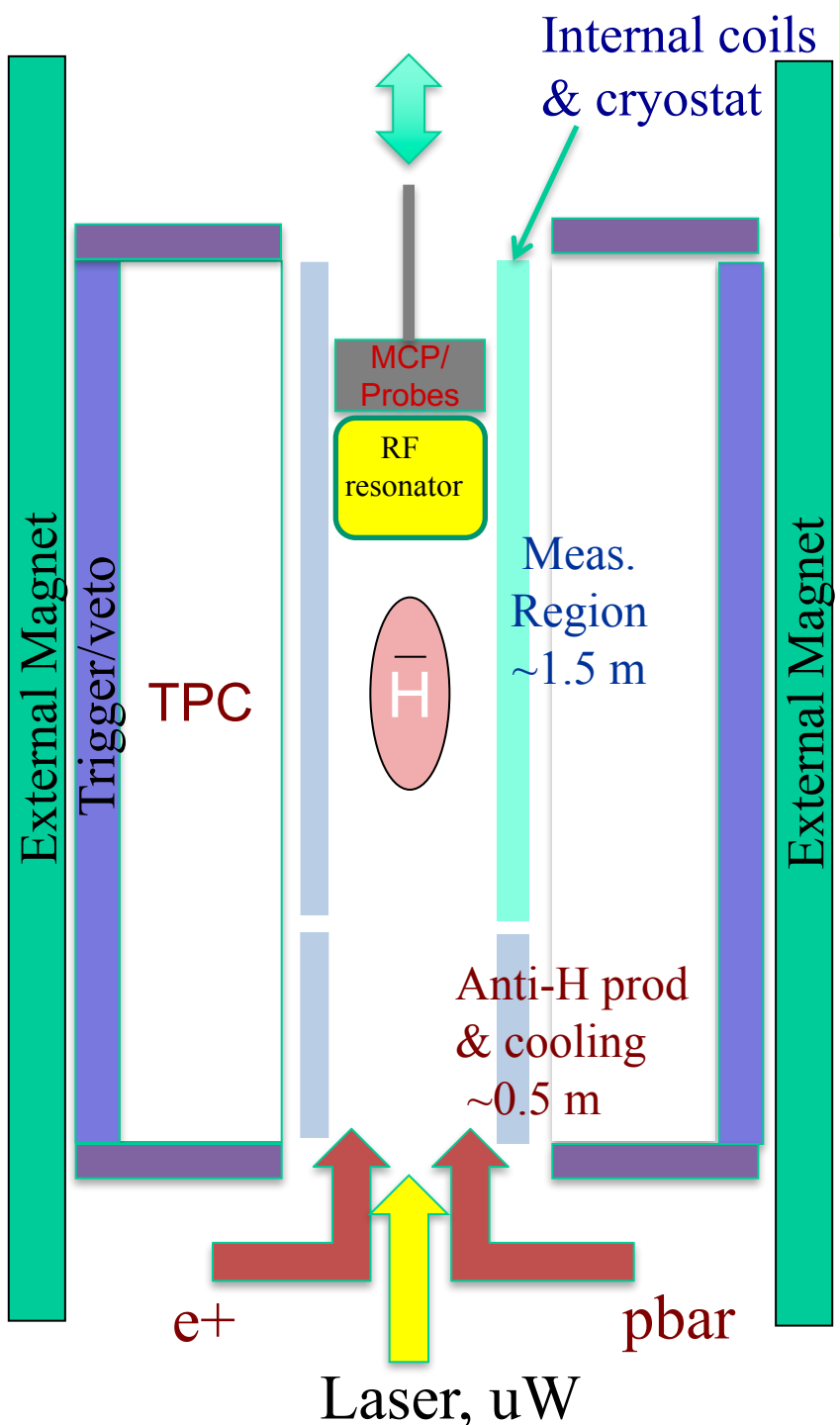
Release energies

Simulated kinetic energy distribution

Release of trapped Hbar at t=0



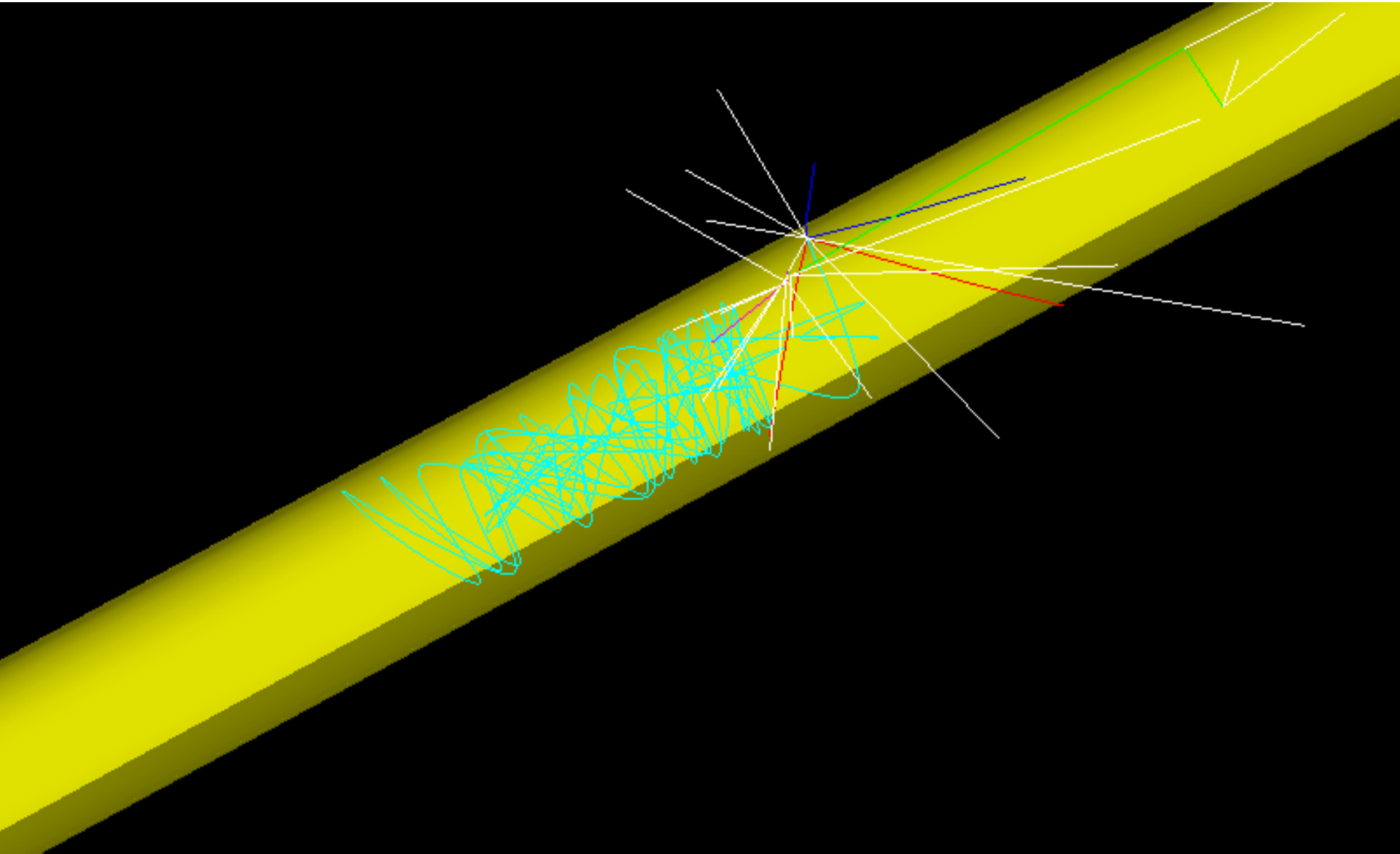
- **Colder Hbars come out later**
- **Data agree with simulated energy distribution**
- **Temperature diagnosis for future cooling studies**
- **Released energies very cold:**
  - **Claiming the potential hill; adiabatic cooling**



Dedicated Gravity Experiment "ALPHA-g"

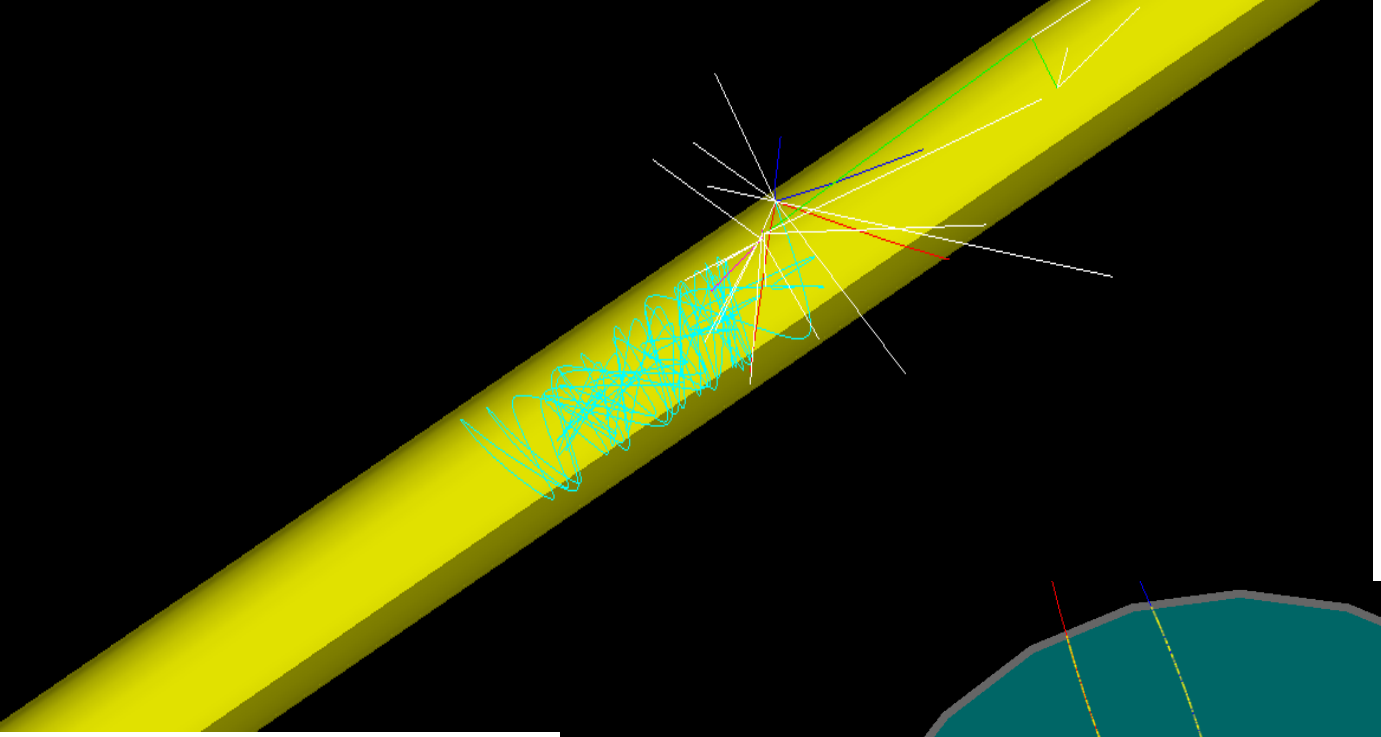
- **A long (~ 2m) vertical trap**
  - **Anti-H production region**
    Production, trapping, & cooling
  - **Measurement region**
    - **Sagging of anti-H "gas"**
    - **Anti-atomic "fountain"**
    - **Anti-atomic interferometry**
    - **uW spectroscopy**
- **Some key components**
  - **Magnets & Cryostat**
  - **Beam lines**
  - **Tracking detector**
  - **Cooling laser**
  - **Magnetometry**

Simulations are starting for possible “ALPHA-g”

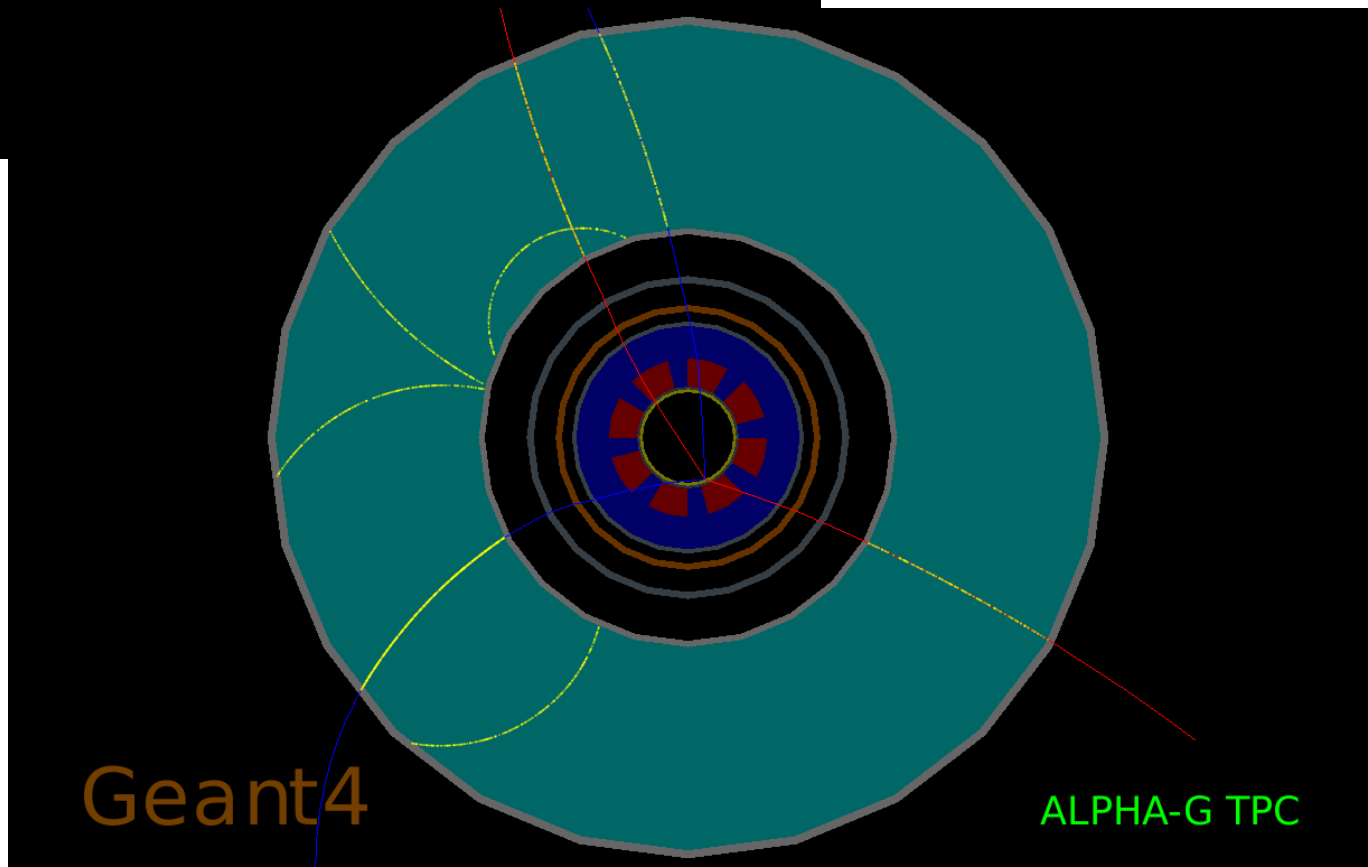


ALPHA-g Tracking

Reconstruction of trajectories of annihilation products in the TPC

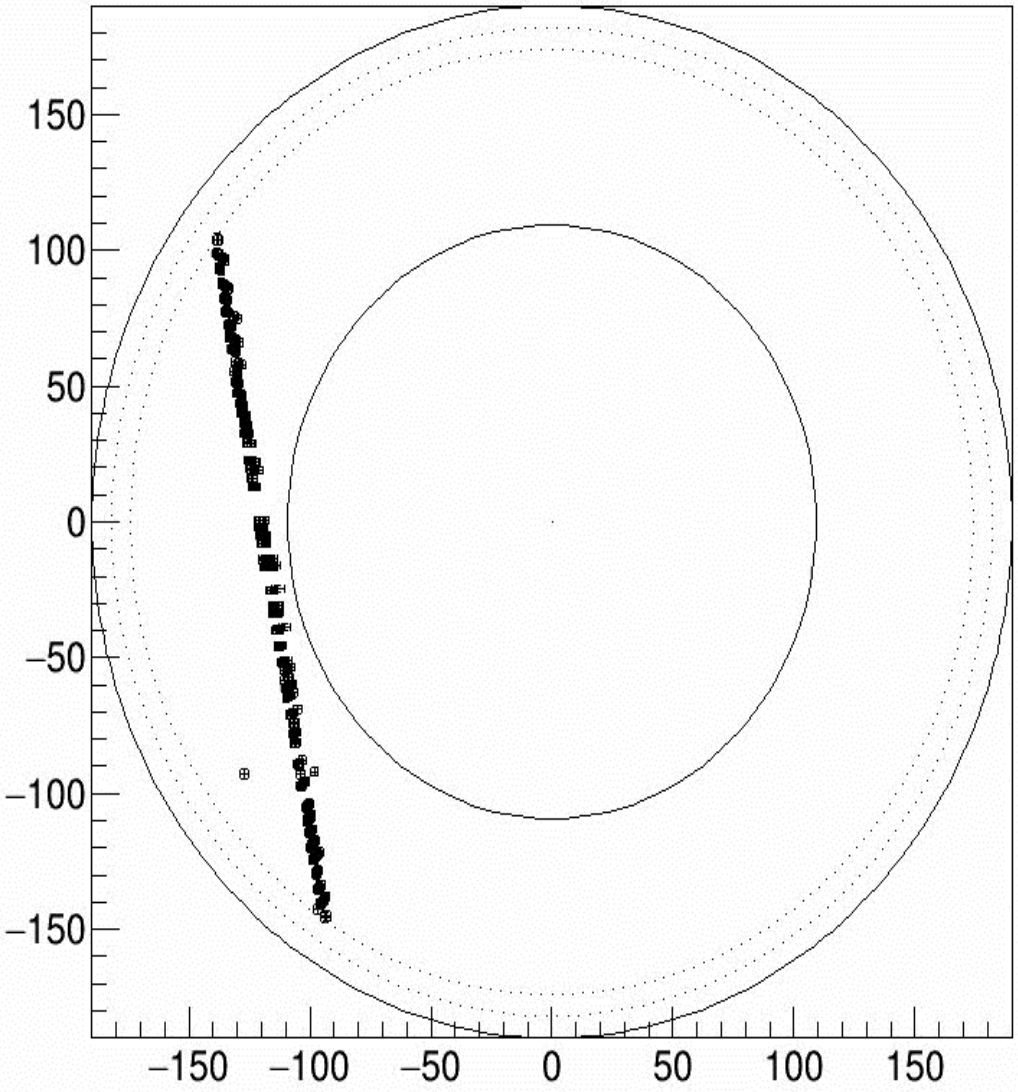


All materials included in the "GEANT4" simulation

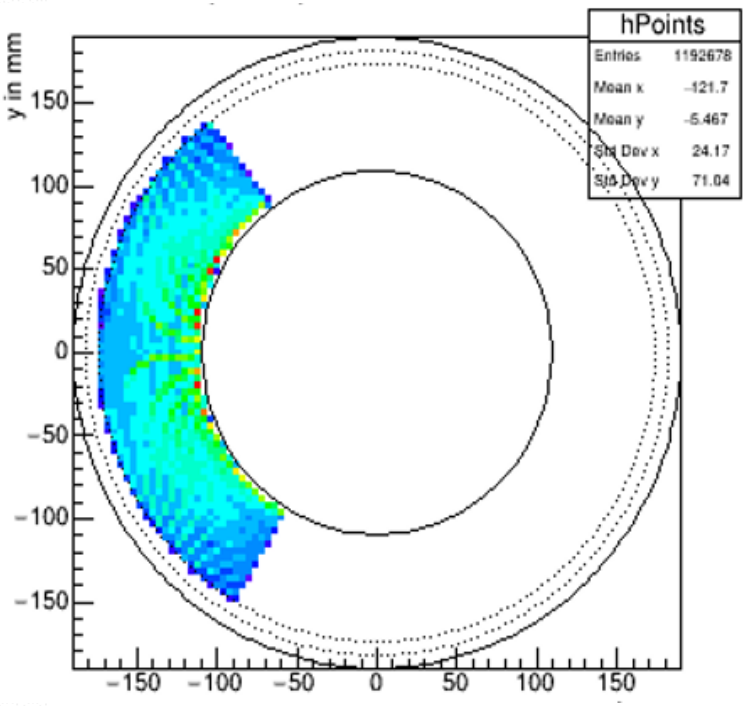


Prototype rTPC at TRIUMF

S1


150
100
50
0
−50
−100
−150
−150
−100
−50
0
50
100
150

S2


hPoints
Entries 1192678
Mean x -121.7
Mean y -5.467
Std Dev x 24.17
Std Dev y 71.04
y in mm
150
100
50
0
−50
−100
−150
−150
−100
−50
0
50
100
150

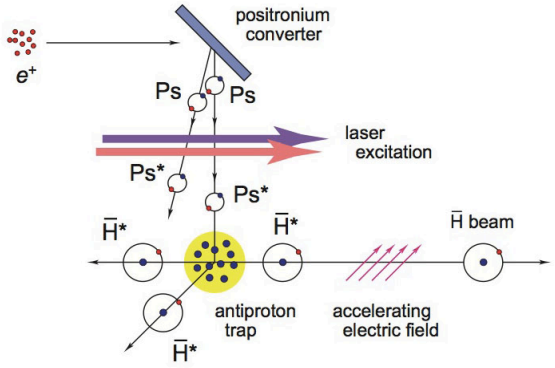
Physics: staged approach

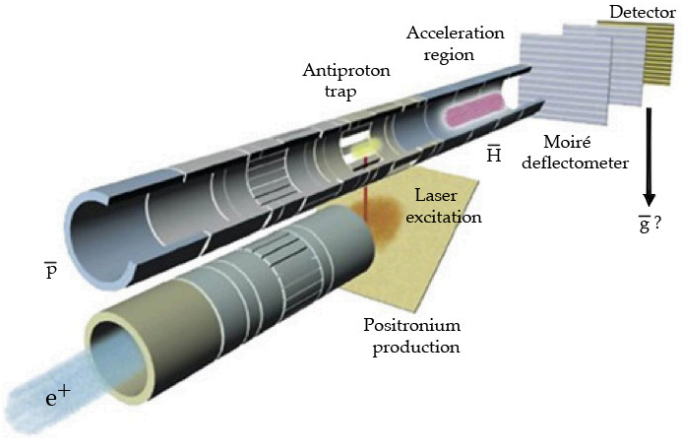
- **Stage 0: Fall 2016, start commissioning of apparatus**
- **Stage 1: Measurement of sign of *g***
  - **Should be immediate once anti-H is trapped**
- **Stage 2: Free fall of laser cooled anti-H**
  - **Few % measurement**
  - **Will allow microwave spectroscopy**
- **Stage 3: Antimatter-wave interferometry**
  - **PRL 112, 121102 (2014) (featured in *Physics*)**
  - **0.1% measurement (eventually 10^{-6}?)**

Dedicated Antihydrogen Gravity Experiments at the AD

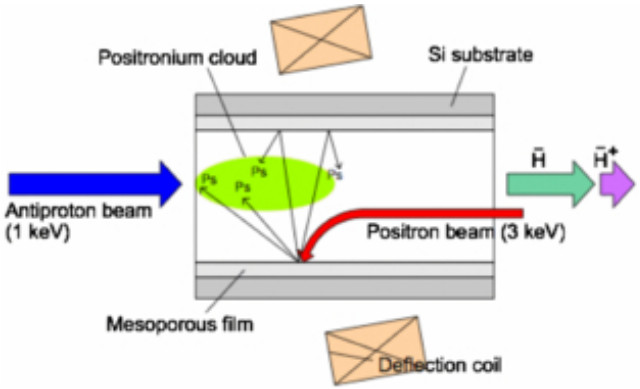
AEgIS

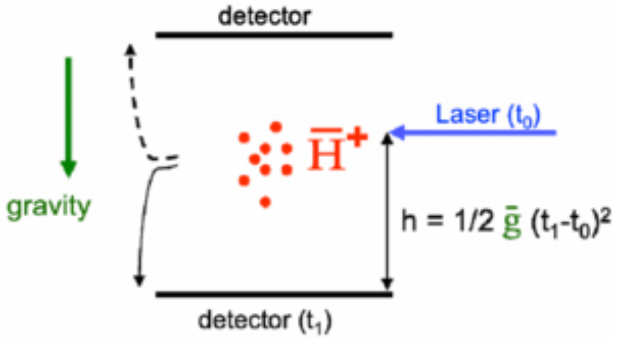
Antihydrogen **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy





GBAR - **G**ravitational **B**ehaviour of **A**ntihydrogen at **R**est





The goal of both experiments is to measure the gravitational acceleration of antihydrogen to the 1% level

Conclusions

- Whether matter and antimatter attract or repel is still an open question although whatever evidence there is seems to point towards attraction.
- A number of groups are investigating using antihydrogen to experimentally probe this issue.
- Because of the weakness of the gravitational attraction this is very demanding technically … but, of course, huge fun!