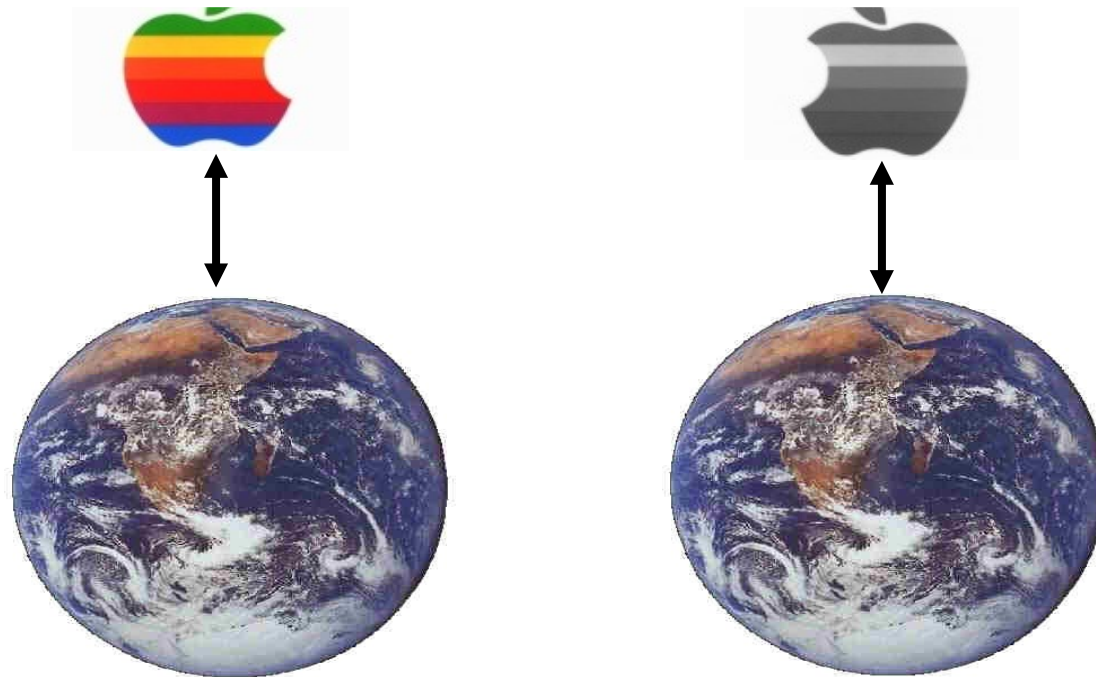


(Anti)Gravity Studies with the ALPHA Antihydrogen Trapping Experiment

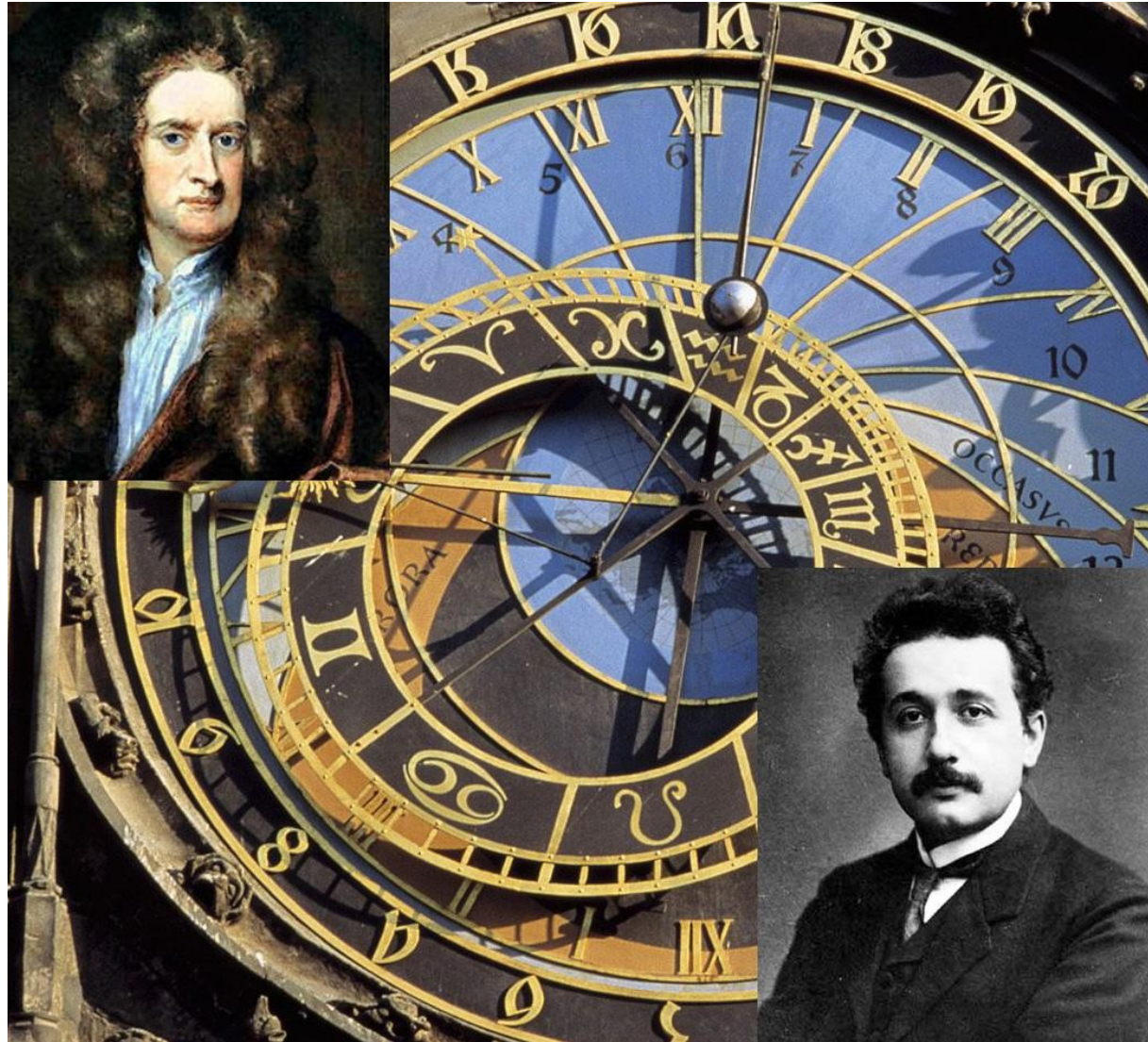


Scott Menary



Antimatter and Gravity

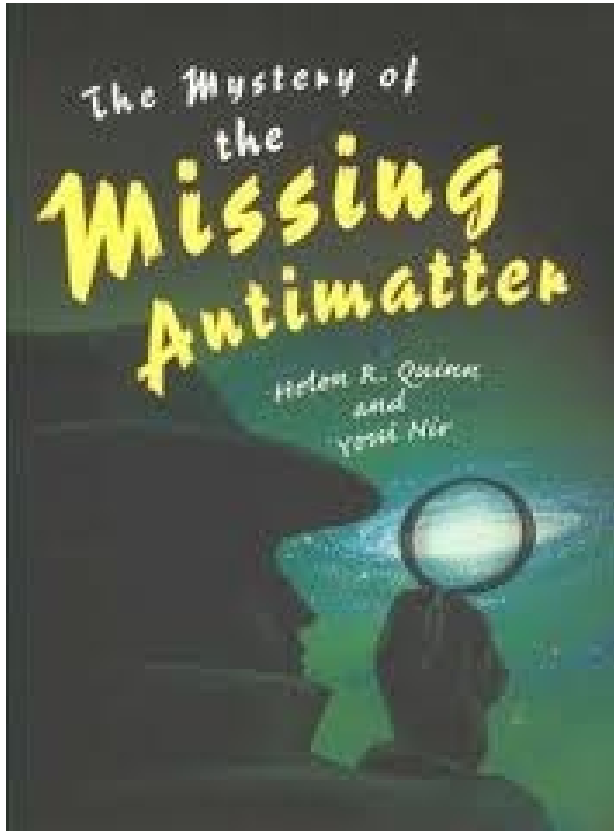
1. Antigravity - Does Antimatter Fall Up?
2. Are There Limits on Antigravity?
3. The ALPHA Antihydrogen Trapping Experiment
4. Future Antigravity Tests - ALPHAg



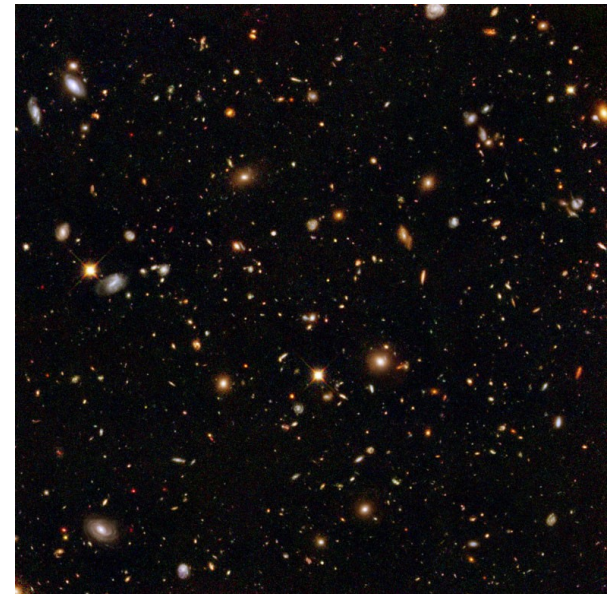
What if matter and antimatter repelled gravitationally?

gravitationally?

Some Attractive Features of “Antigravity” :



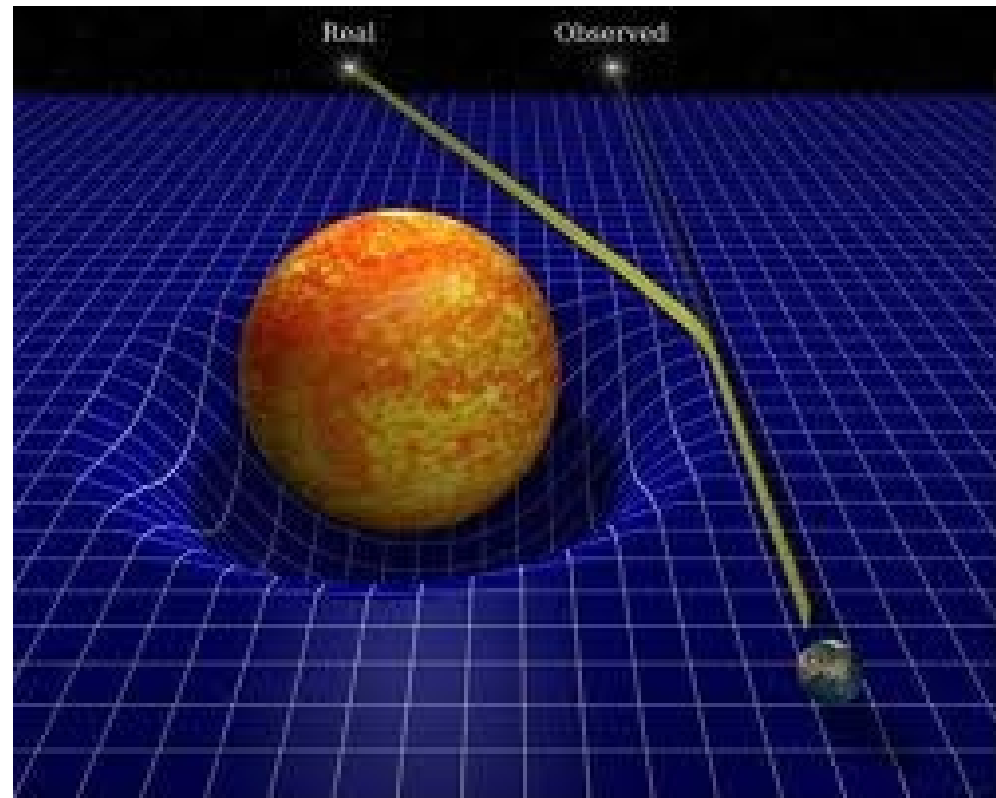
- The “antimatter-matter asymmetry” in the universe would be solved because **there wouldn’t be one!** Half the galaxies we see would be “anti-galaxies” and half matter galaxies. We wouldn’t observe annihilations because the galaxies and anti-galaxies would repel each other. This could explain why the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



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

Arguments against Repulsive Antigravity

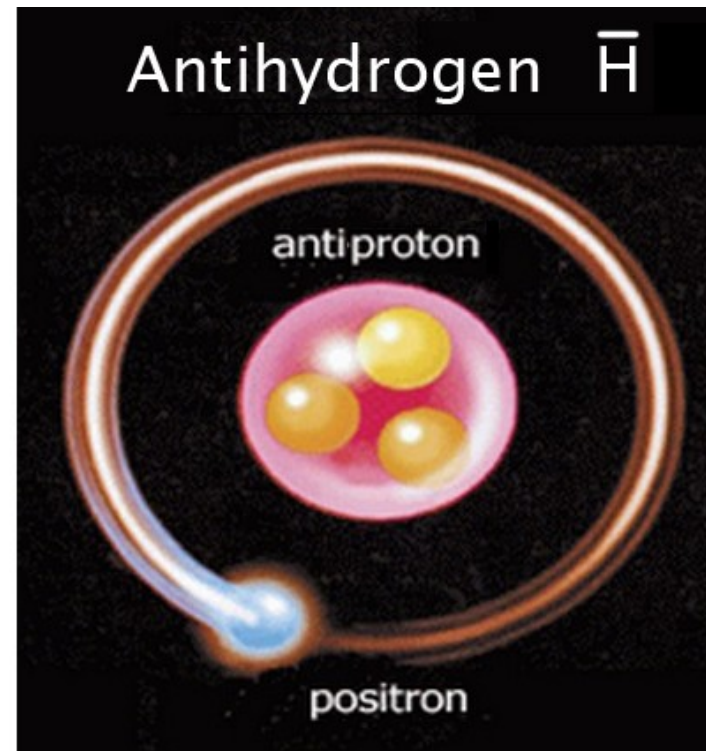
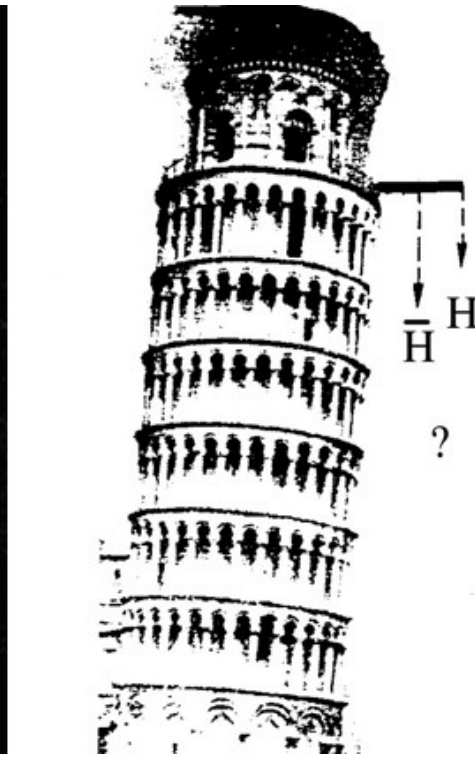
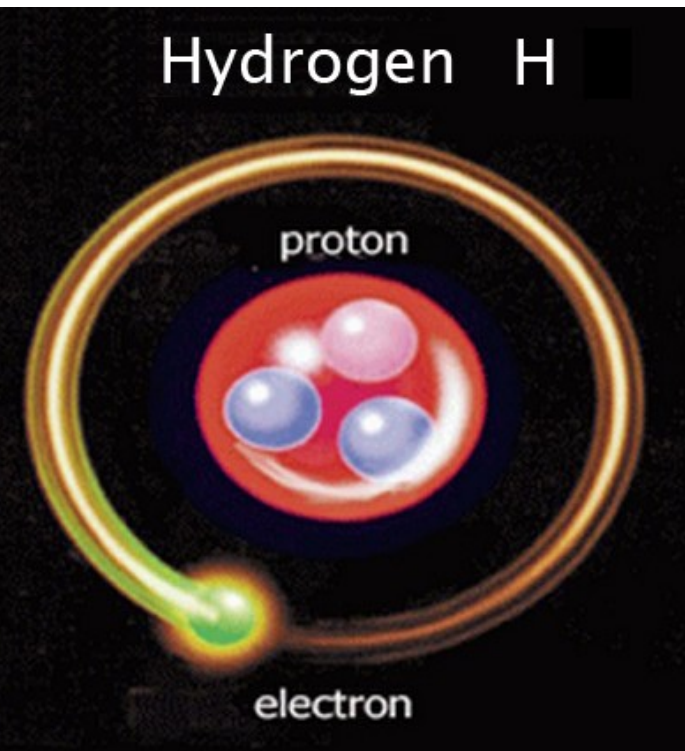
- Bending of light by the Sun (see Cross - arXiv:1108.5117 - for a general argument and Menary – arXiv:1207.7358 – for a more complete look at the data versus expectations from models.)
- A photon is its own antiparticle so it presumably wouldn't feel any effect from gravity if matter-antimatter repel.
- But light is clearly 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 \bar{g} of $<0.5\%$



➤ Can get around this if test is done using antibaryons

Scott Menary – CAP 2014

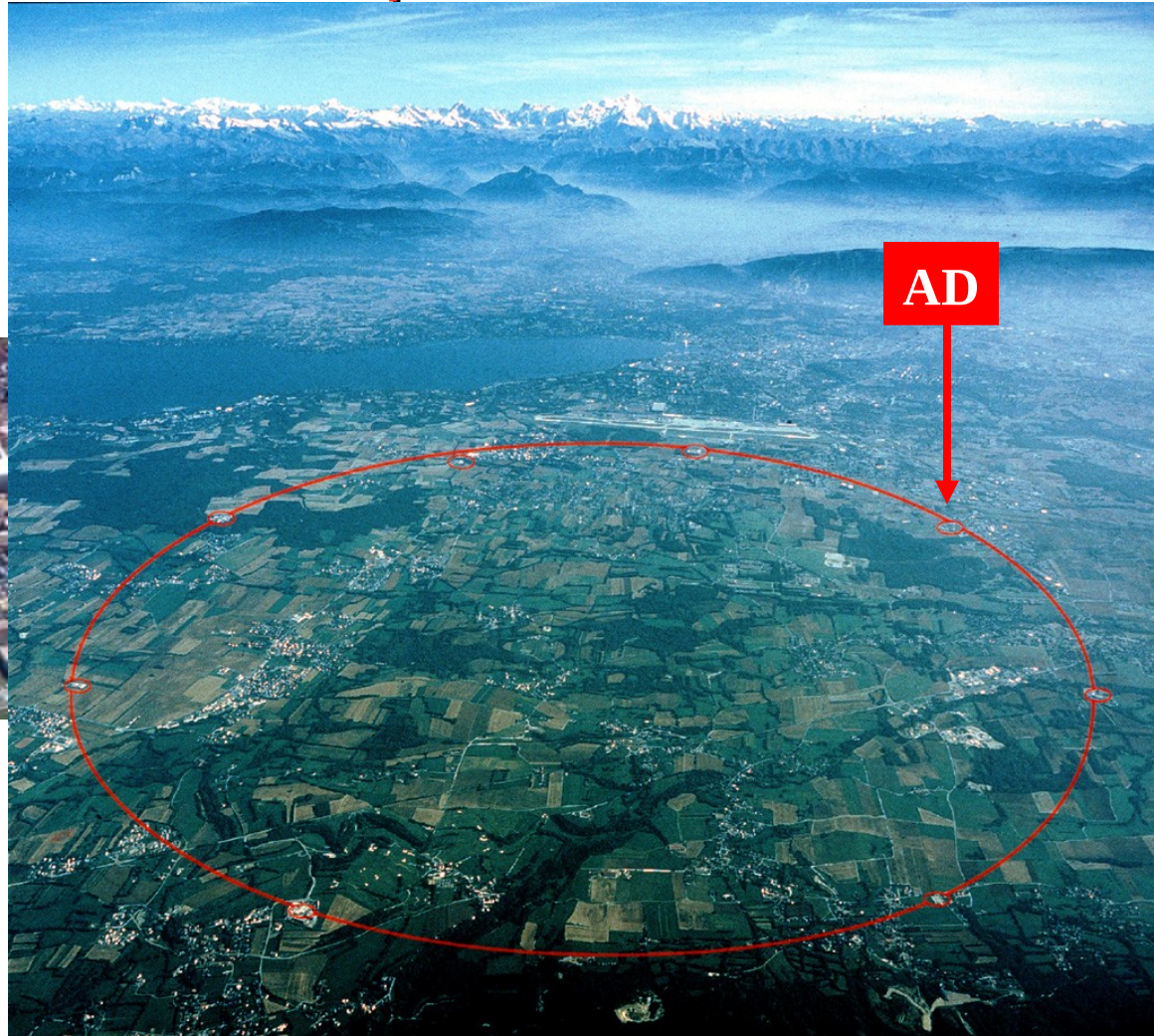
- We have trapped plenty of antiprotons so what is the problem?
- On a single charged particle (antiparticle) level the gravitational interaction is swamped by the tiniest electric or magnetic interactions.
- To mitigate the effect of stray electric and magnetic fields use an electrically neutral antibaryonic-system to test the antimatter-Earth gravitational interaction. Simplest antiatom is **antihydrogen**.



Making Antihydrogen

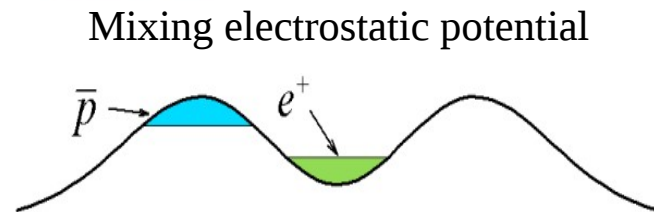
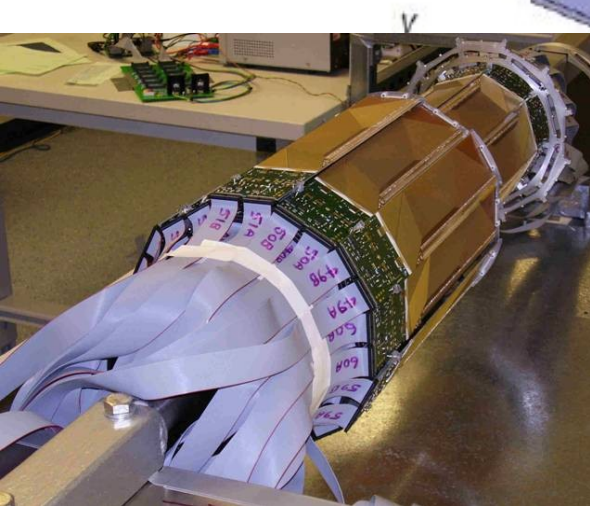
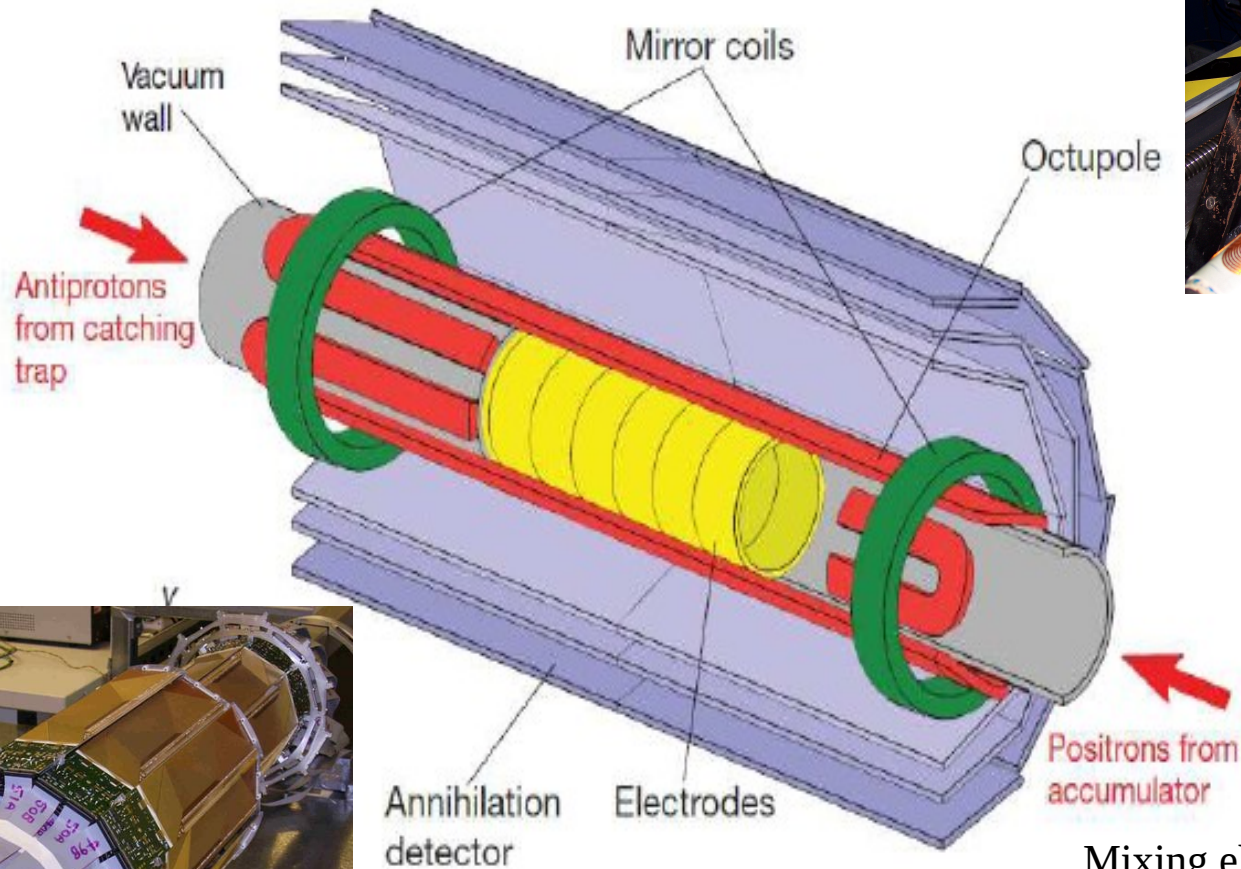
Getting Antiprotons – the Antiproton Decelerator

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



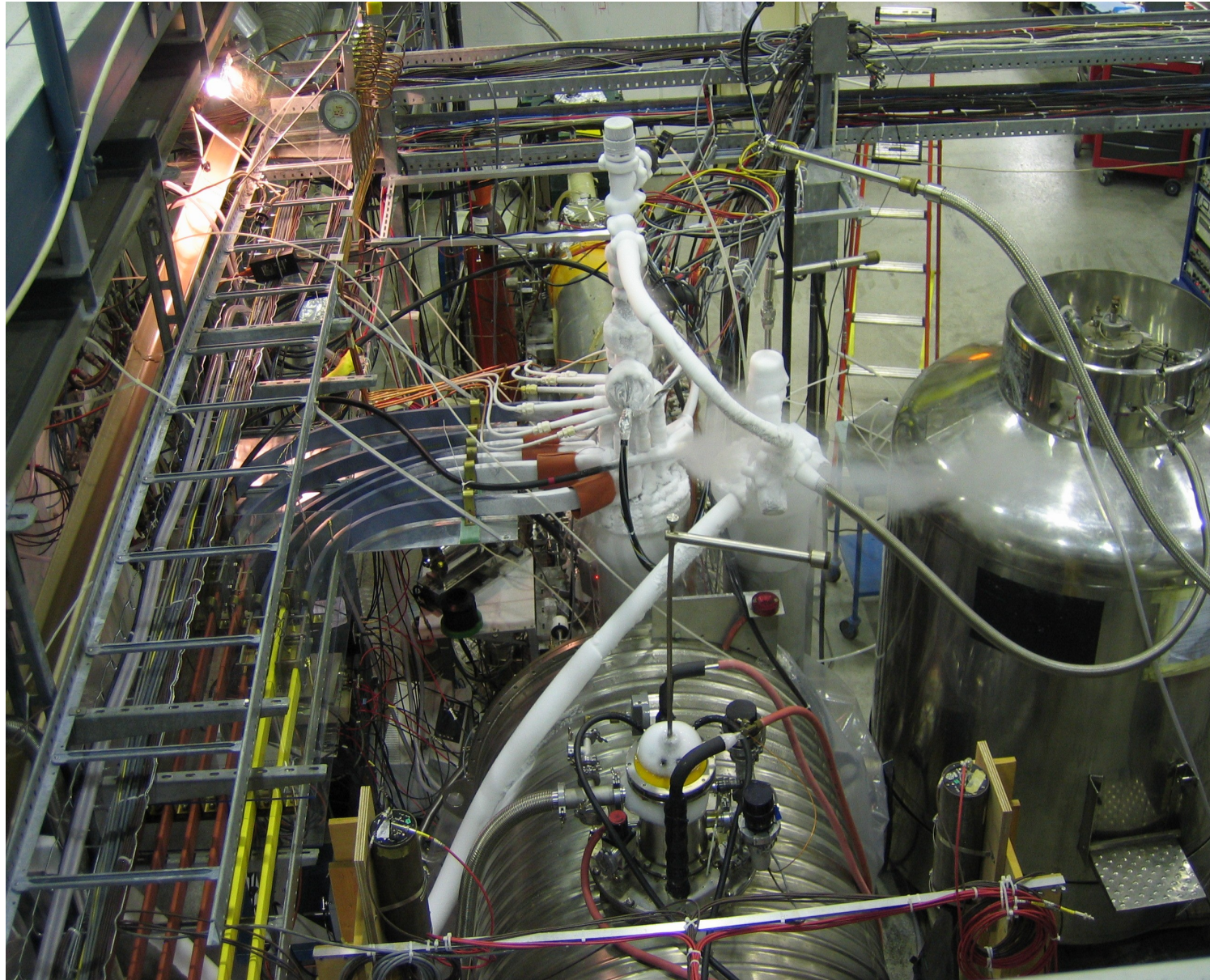
- generate high energy antiprotons using the CERN PS
- the AD reduces antiproton KE to 5.3 MeV
- 30 million antiprotons every ~100 seconds

The ALPHA Apparatus



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

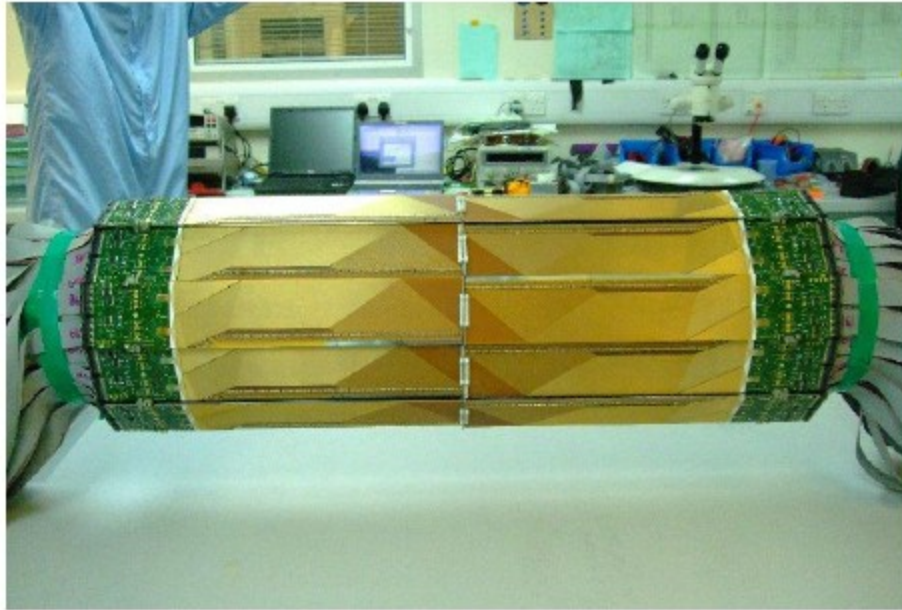
The ALPHA Experiment in the AD Hall



Scott Menary – CAP 2014

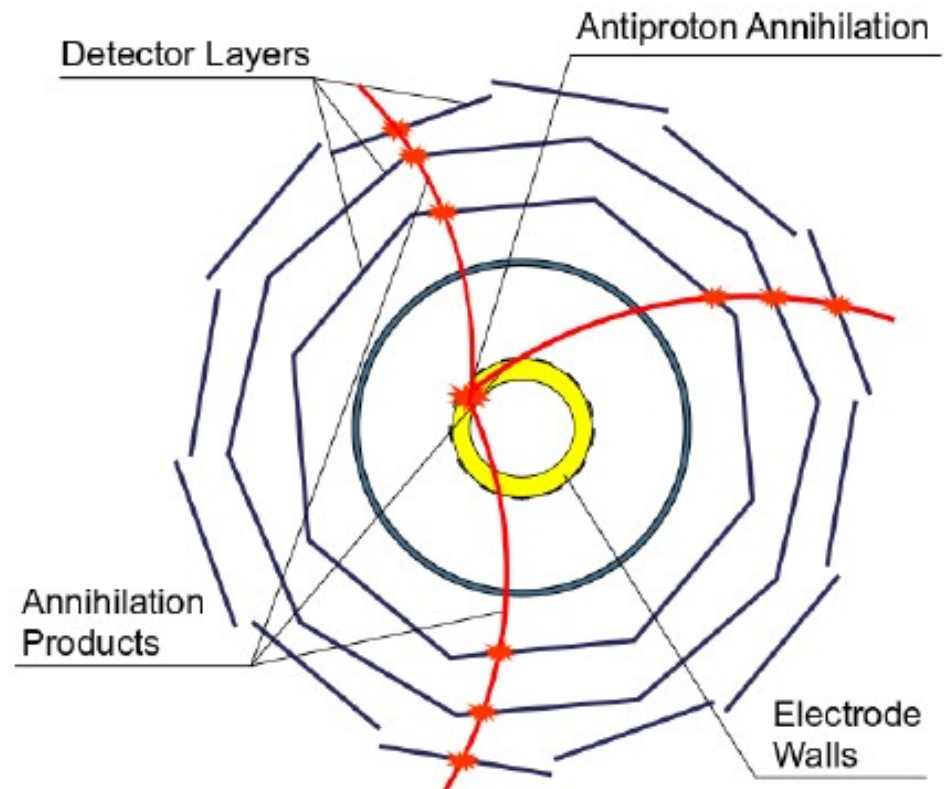
ALPHA: Si Vertex Detector

30,000 channel strips
~0.8 m² active area



Liverpool: Sensors & hybrid

ALPHA-Canada: Readout,
DAQ, Software, Analysis



Important ALPHA Results for Antigravity Tests

LETTER

doi:10.1038/nature09610

Trapped antihydrogen

G. B. Andresen¹, M. D. Ashkezari², M. Baquero-Ruiz³, W. Bertsche⁴, P. D. Bowe¹, E. Butler⁴, C. L. Cesar⁵, S. Chapman³, M. Charlton⁴, A. Deller⁴, S. Eriksson⁴, J. Fajans^{3,6}, T. Friesen⁷, M. C. Fujiwara^{8,9}, D. R. Gill⁸, A. Gutierrez⁹, J. S. Hangst¹, W. N. Hardy⁸, M. E. Hayden², A. J. Humphries⁴, R. Hydomako⁷, M. J. Jenkins⁴, S. Jonsell¹⁰, L. V. Jørgensen⁴, L. Kurchaninov⁸, N. Madsen⁴, S. Menary¹¹, P. Nolan¹², K. Olchanski⁸, A. Olin⁸, A. Povilus³, P. Pusa¹², F. Robicheaux¹³, E. Sarid¹⁴, S. Seif el Nasr⁹, D. M. Silveira¹⁵, C. So³, L. W. Storey⁸, R. L. Thompson⁷, D. P. van der Werf⁴, J. S. Wurtele^{3,6} & Y. Yamazaki^{15,16}



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ARTICLES

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

Confinement of antihydrogen for 1,000 seconds

The ALPHA Collaboration*

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



nature
COMMUNICATIONS

The Most Important Recent ALPHA Result – The Charge of the Antihydrogen

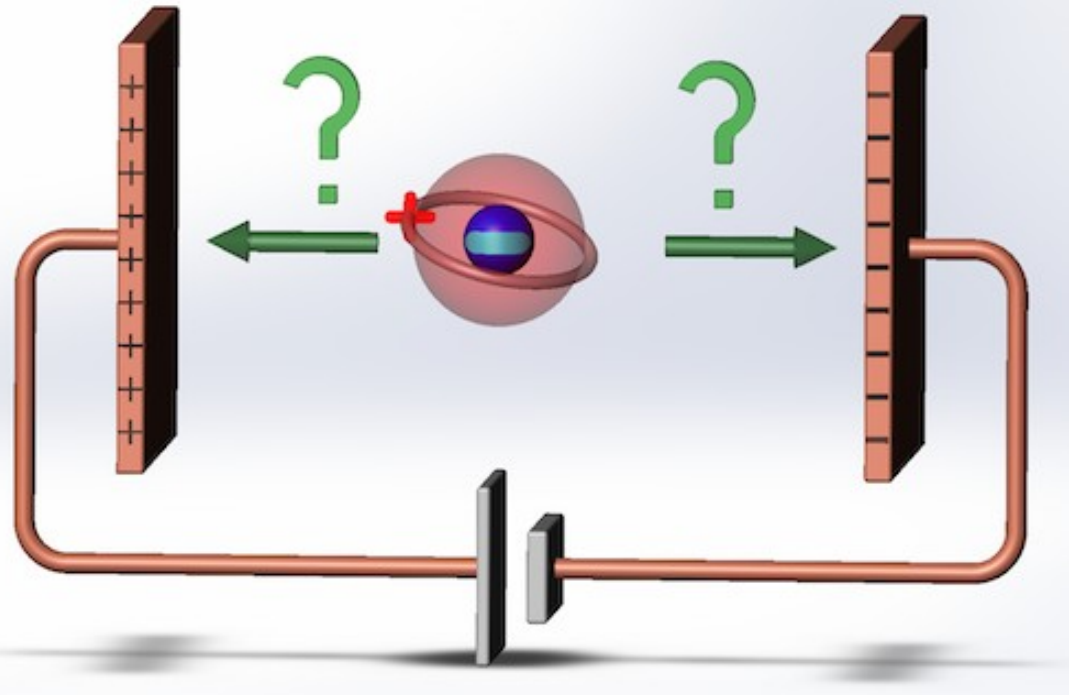


Nature Communications 5 – June 3, 2014

Article number: 3955 doi:10.1038/ncomms4955

An experimental limit on the charge of antihydrogen
ALPHA Collaboration

“A retrospective analysis of the influence of electric fields on antihydrogen atoms released from the ALPHA trap finds a mean axial deflection of 4.1 ± 3.4 mm for an average axial electric field of 0.51 ... this measurement leads to a bound on the charge Q_e of antihydrogen of $Q = (-1.3 \pm 1.1 \pm 0.4) \times 10^{-8}$ ”



Antimatter Gravity Measurement

- Relevant energy/length scales:
 - Considering one dimension

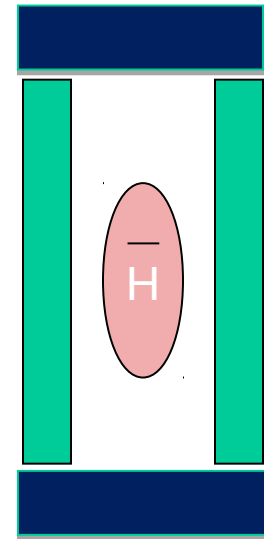
$$1/2kT = mgh$$

$$h(m) \sim 420 \times T (K)$$

If $T \sim 3$ mK, $h \sim 1.3$ m

equivalent magnetic energy at:

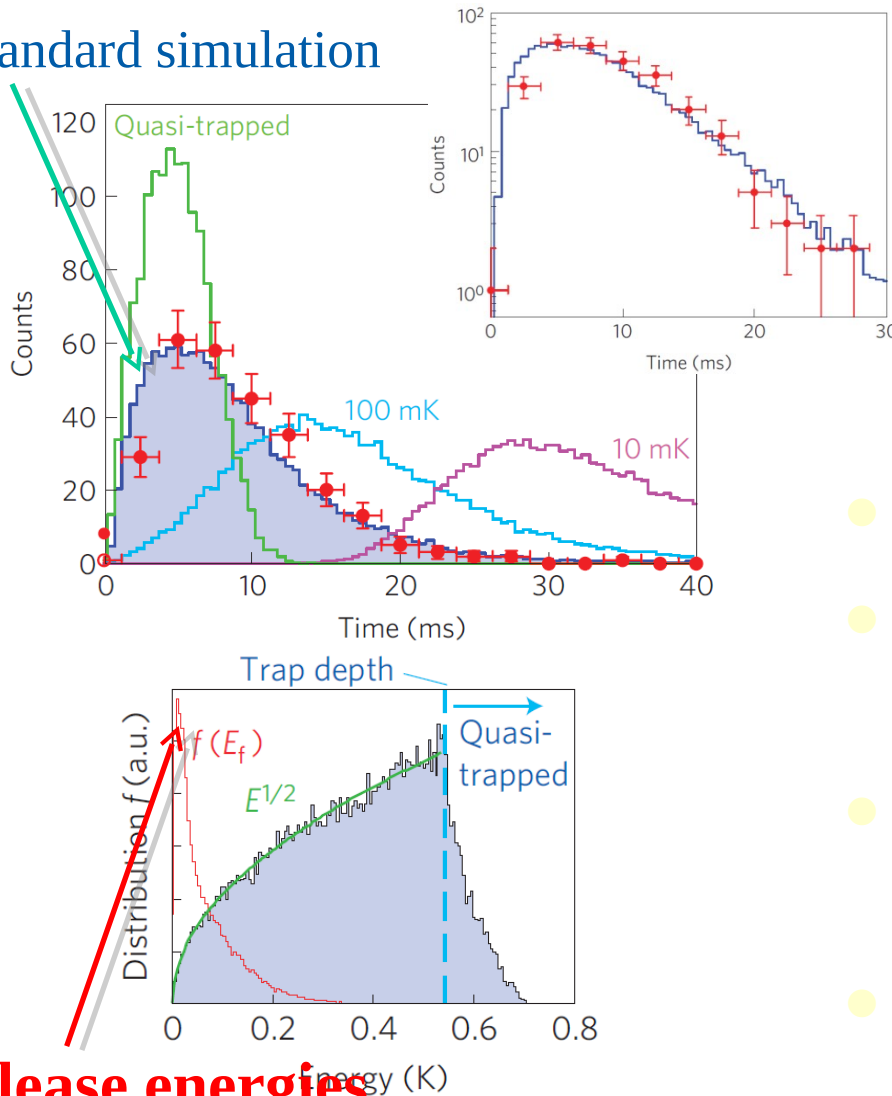
$$\Delta B \sim 1/2 \cdot kT/\mu \sim 20 \text{ Gauss}$$



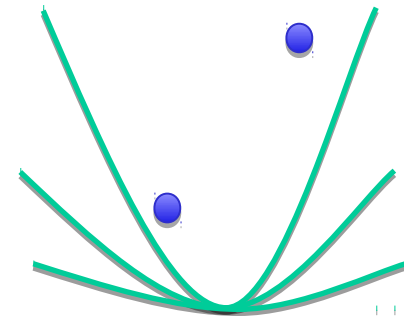
Kinetic energy of trapped Hbars:

Nature Phys. 2011

Standard simulation



Release of trapped Hbar at $t=0$

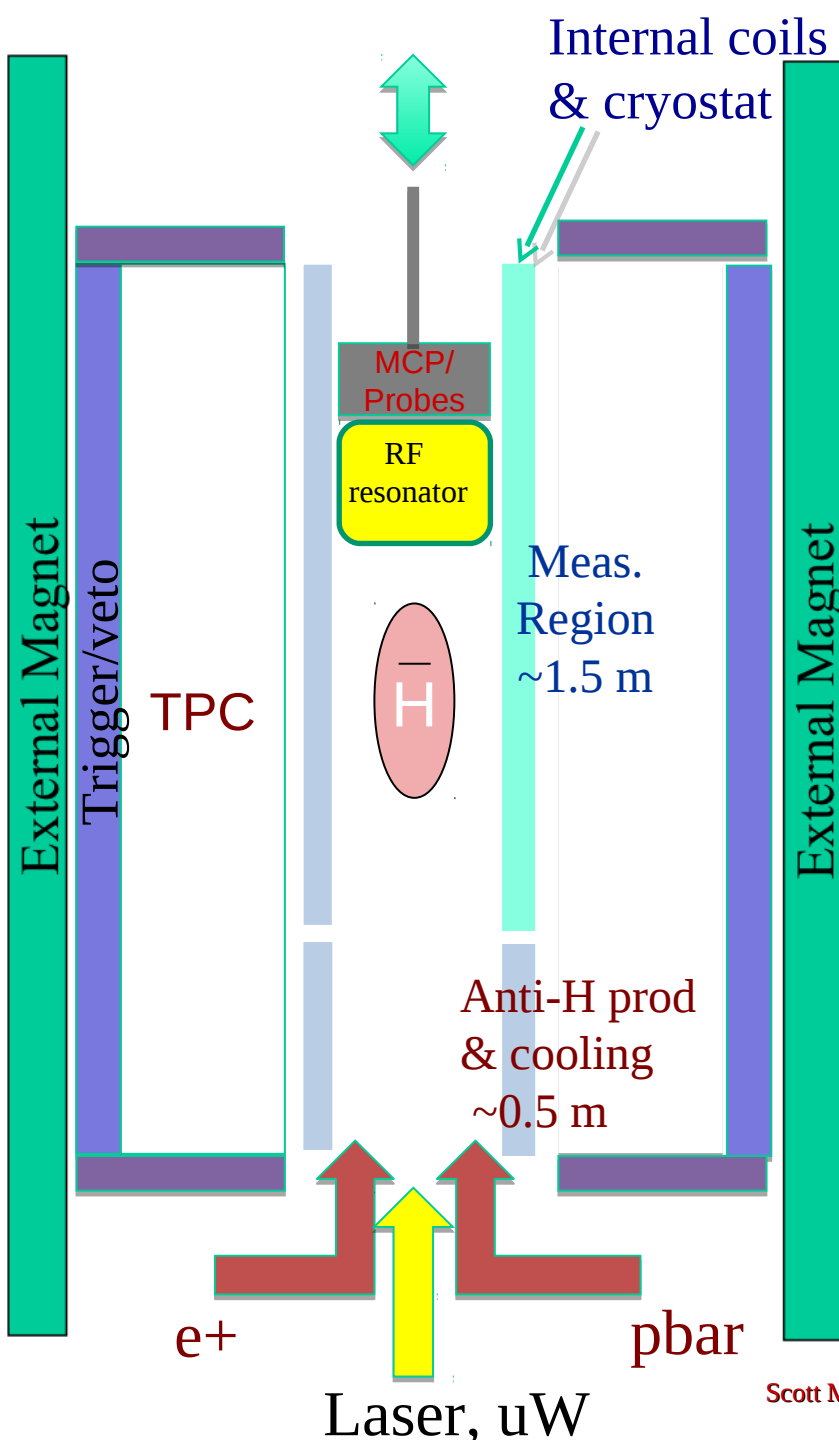


- Colder Hbars come out later
- Data agree with simulated energy distribution
- Temperature diagnosis for future cooling studies
- Released energies very cold:
 - Claiming the potential hill; adiabatic cooling

Release energies

Simulated kinetic energy distribution

Dedicated Gravity Experiment "ALPHA-g"



• A long (~ 2m) vertical trap

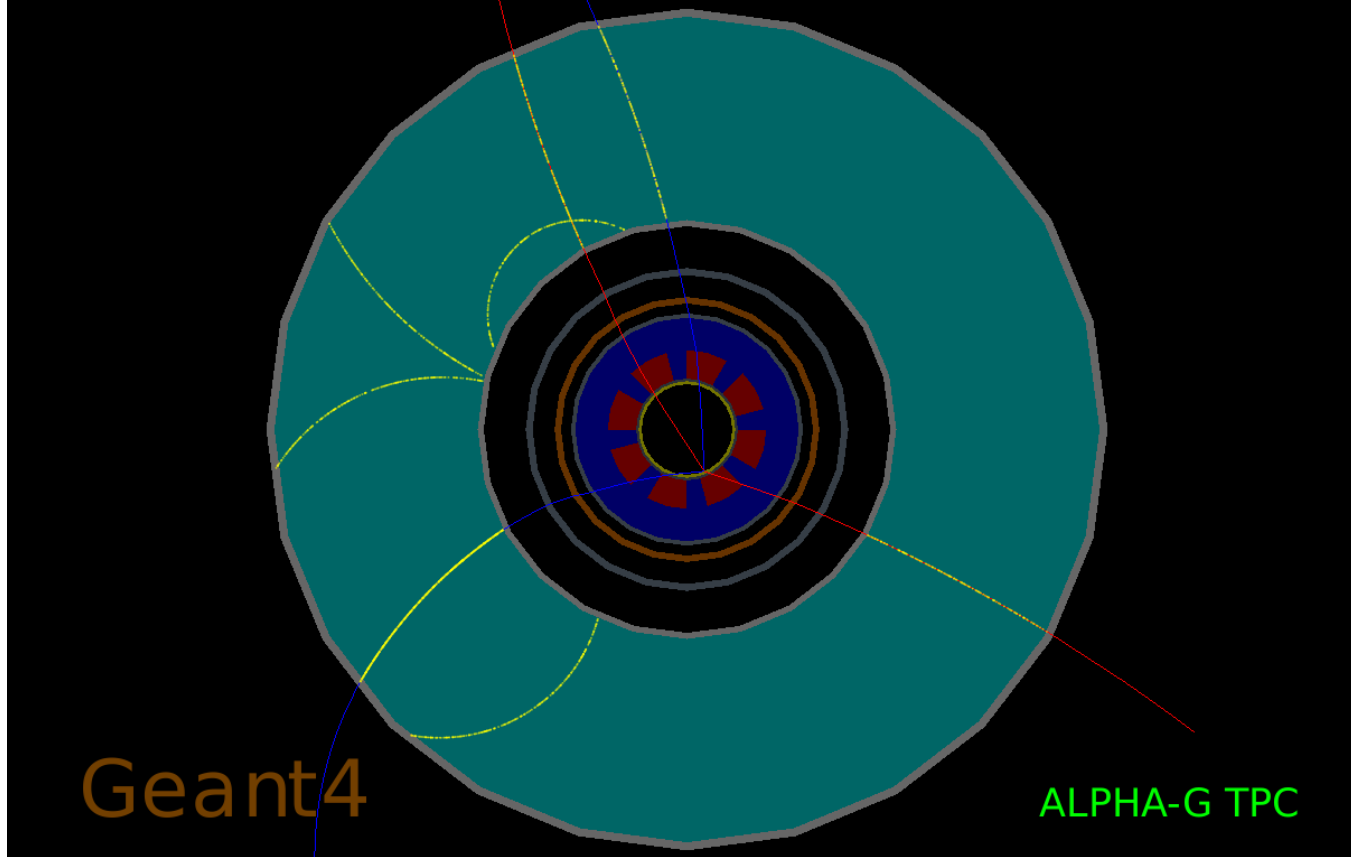
- Anti-H production region
Production, trapping, & cooling
- Measurement region
 - Sagging of anti-H "gas"
 - Anti-atomic "fountain"
 - Anti-atomic interferometry
 - uW spectroscopy

• Some key components

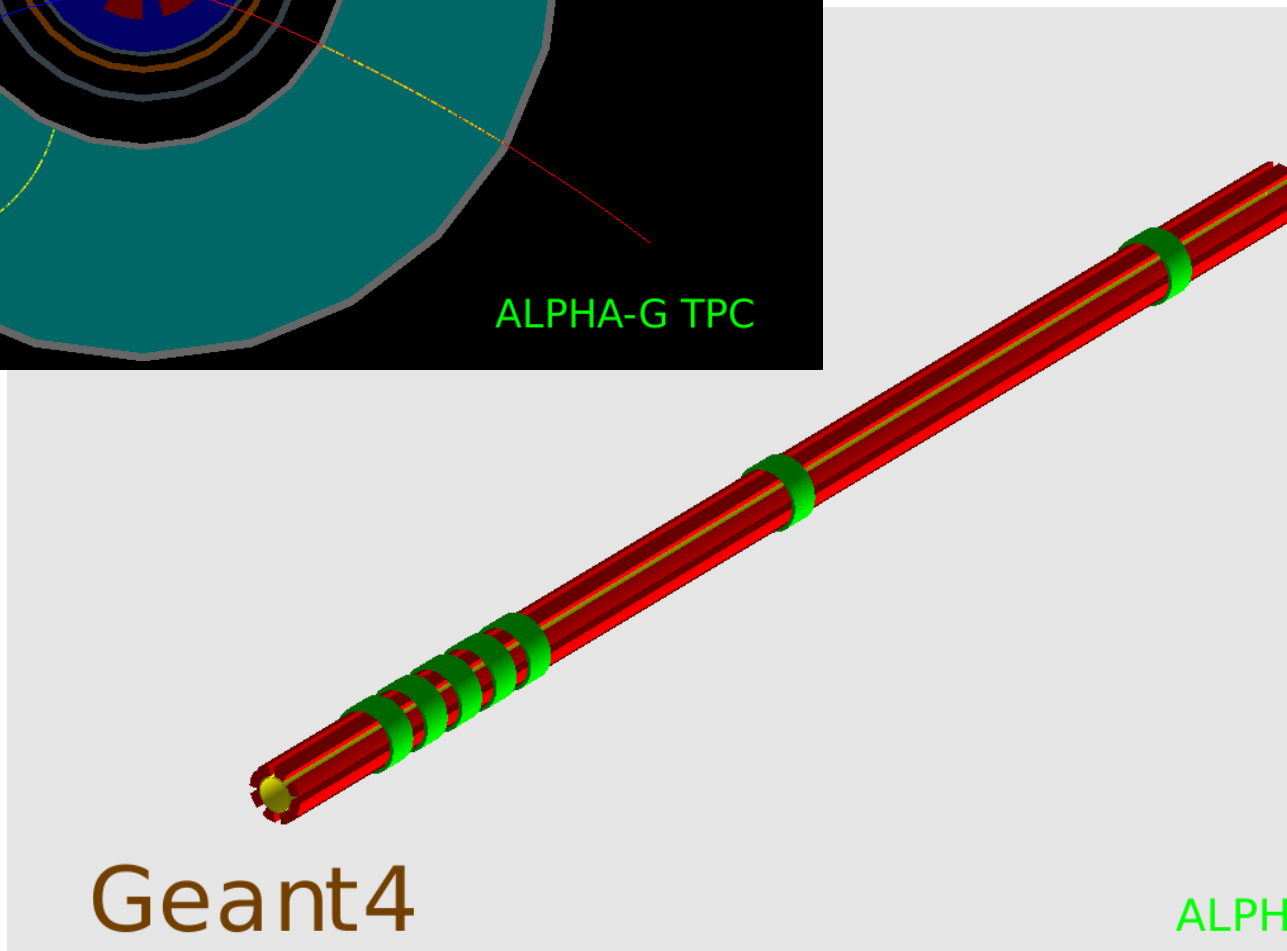
- Magnets & Cryostat
- Beam lines
- Tracking detector
- Cooling laser
- Magnetometry

Simulations

Pion track reconstruction in the TPC



All materials included in the GEANT4 simulation



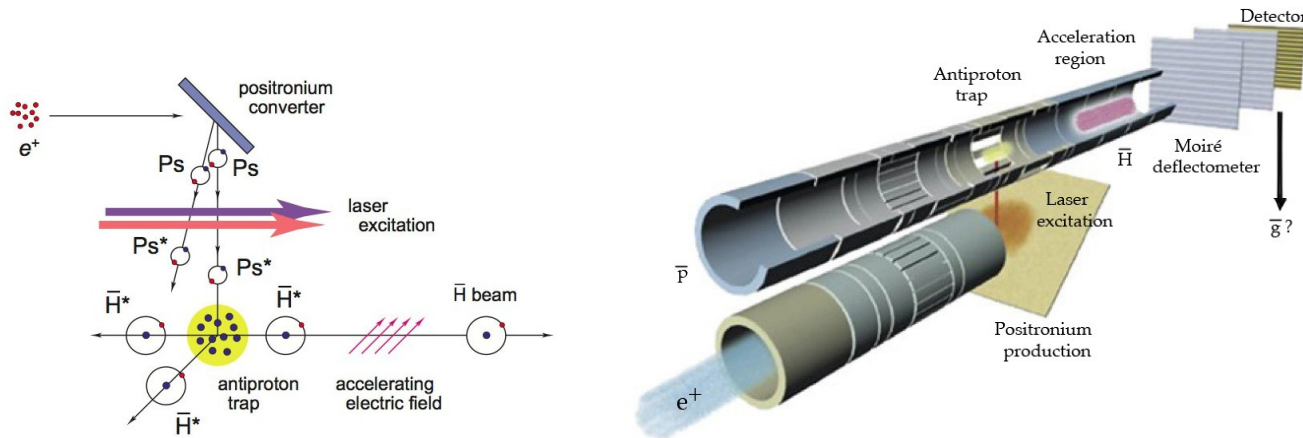
Physics: staged approach

- **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} ?)**

Other Dedicated Antihydrogen Gravity Experiments at the AD

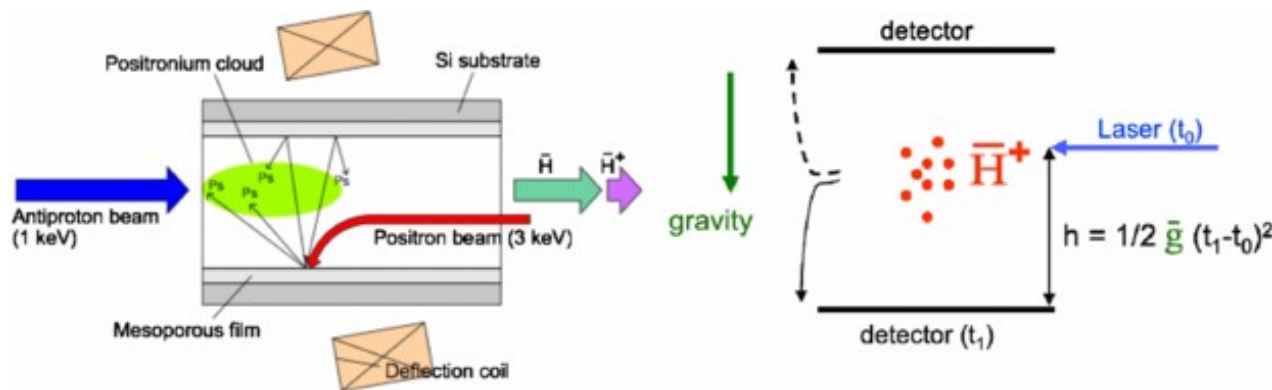


Antihydrogen Experiment: Gravity, Interferometry, Spectroscopy



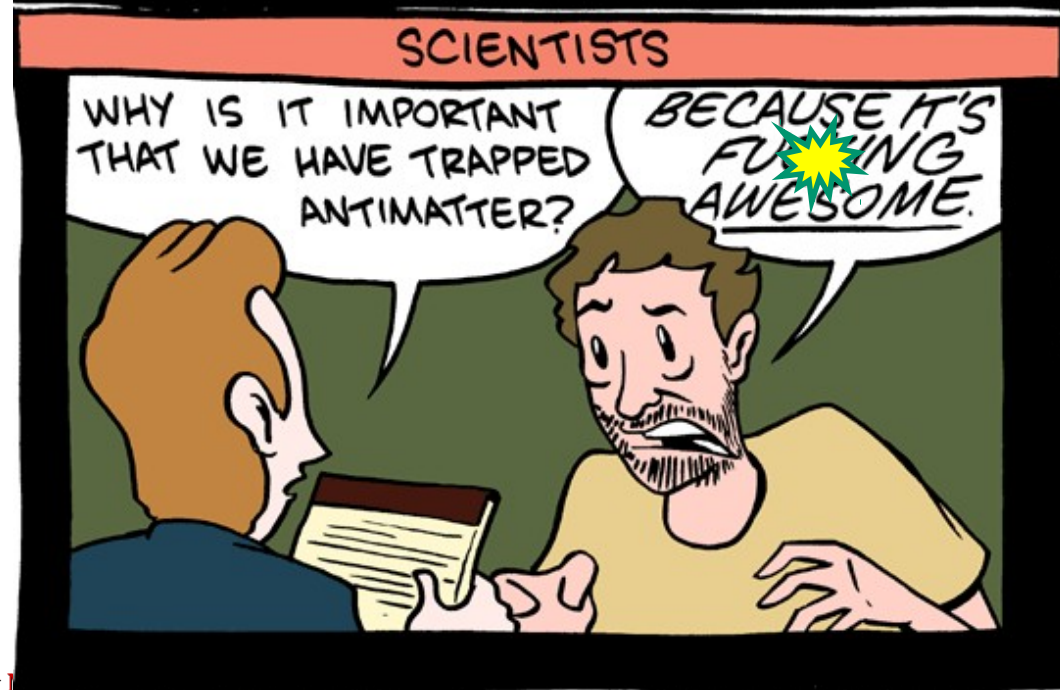
The goal of both experiments is to measure the gravitational acceleration of antihydrogen to the 1% level

GBAR - Gravitational Behaviour of Antihydrogen at Rest



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 probe this issue – including ALPHA-g.
- Because of the weakness of the gravitational attraction this is very demanding technically ...
but fun!



Backup Slides

First Ever Spectroscopic Measurement on Antihydrogen

nature

International weekly journal of science

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Resonant quantum transitions in trapped antihydrogen atoms

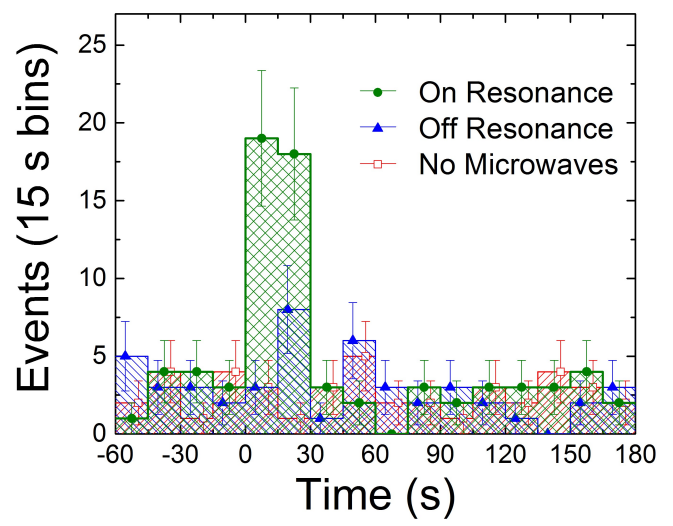
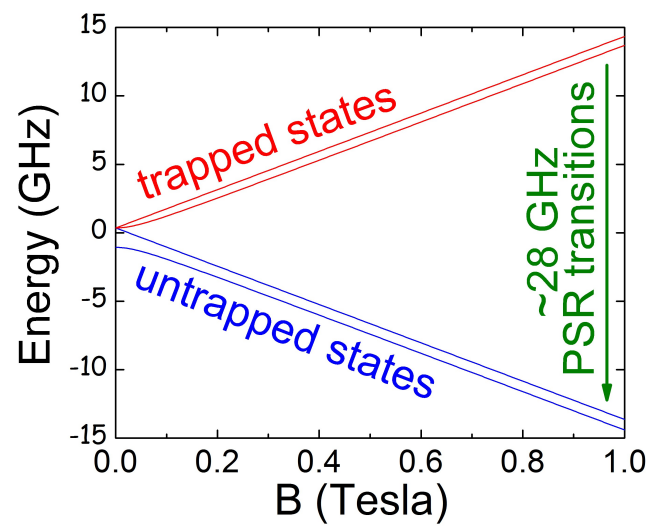
C. Amole, M. D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, P. D. Bowe, E. Butler, A. Capra, C. L. Cesar, M. Charlton, A. Deller, P. H. Donnan, S. Eriksson, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, A. J. Humphries, C. A. Isaac, S. Jonsell, 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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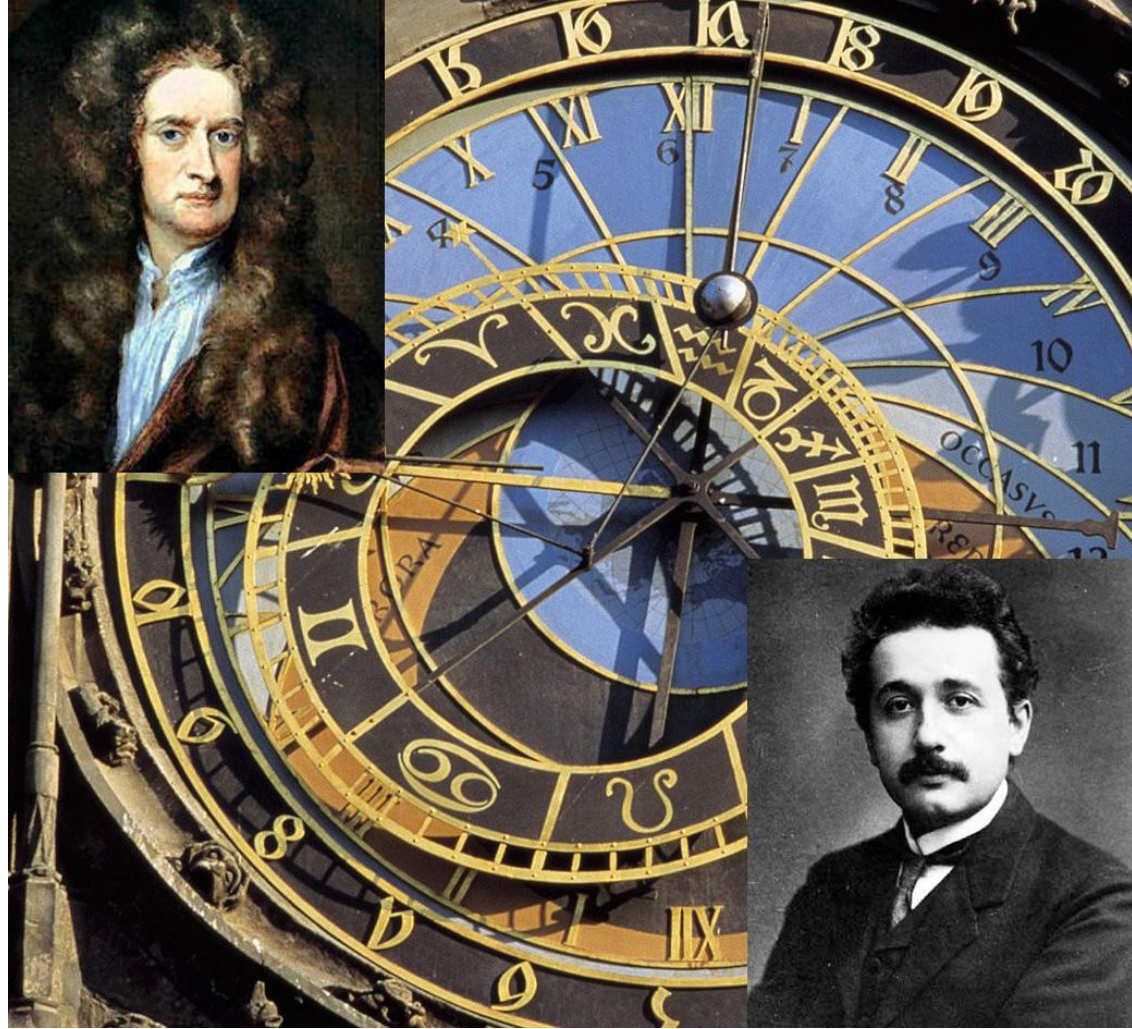
Inertial Versus Gravitational Mass

Back to basics (i.e.,
Newton):

- $F = m_I a$
- $F = G m_G M / r^2$

where the I and G refer
to Inertial and
Gravitational mass.

It has always been
assumed that $m_I = m_G$ but
recall that even Galileo
and Newton thought that
this equivalence of m_I
and m_G should be tested.



How Could Antimatter Be Different?

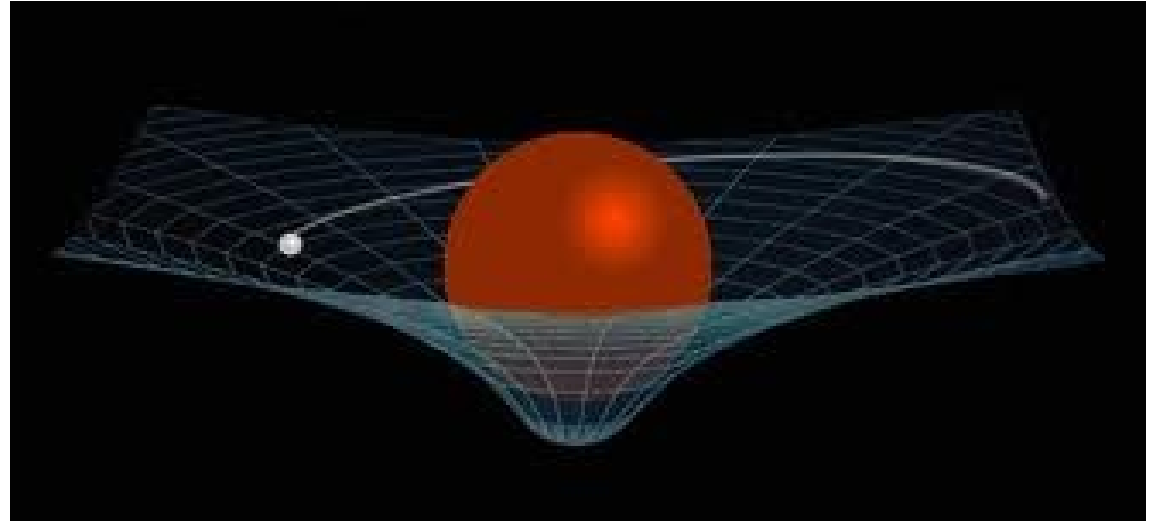
- Setting $\bar{m}_I = -\bar{m}_G$ for antimatter doesn't destroy the structure of the classical picture. Only $m_I = m_G$ was tested by Newton and others. That is, we still have $F_I = \bar{m}_I a$ but now F_G when an antimatter particle is interacting with matter is in the opposite direction to when the situation is matter interacting with matter. Further, the strength of the interaction still goes like $1/r^2$.
- 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.”

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:

“Matter tells space how to curve, and space tells matter how to move.”

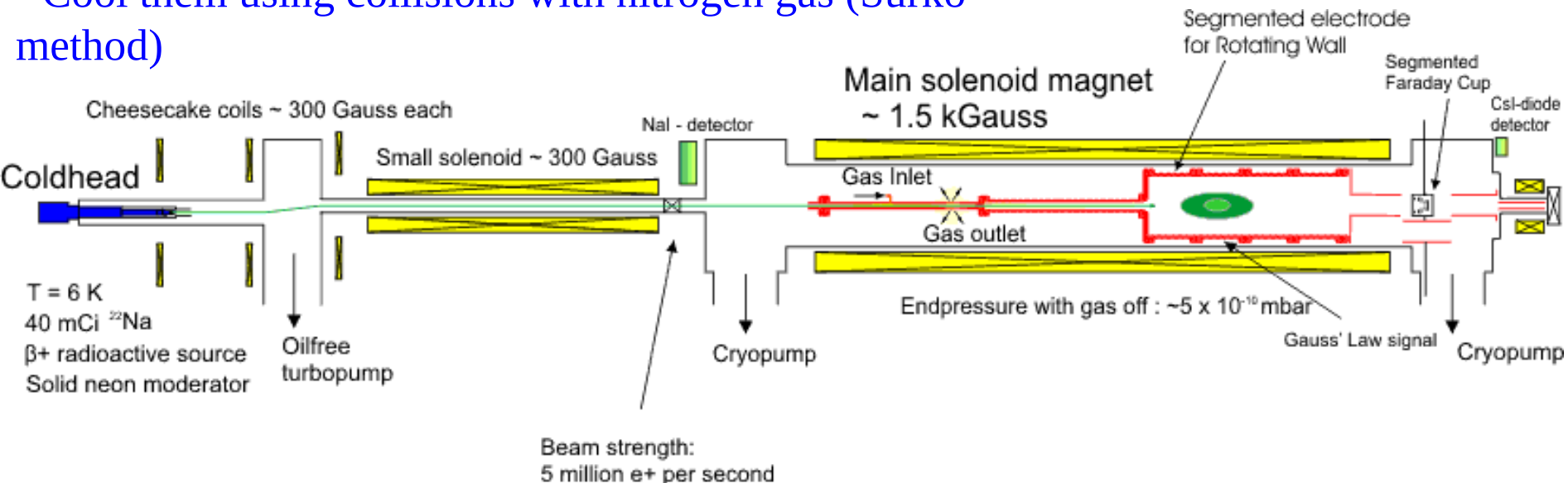
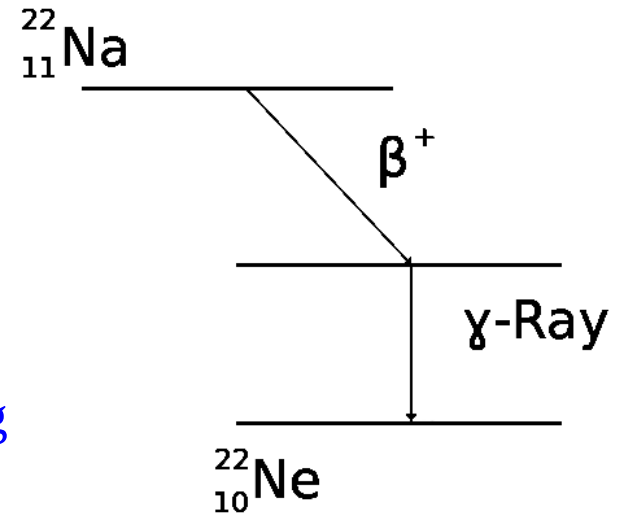
- J. Wheeler

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

Making Antihydrogen

Getting Positrons – the Positron Accumulator

- Use 2 GBq (~ 75 mCi) ^{22}Na β^+ source ($\tau = 2.6\text{y}$)
- 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)



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.

