Testing Fundamental Physics with Trapped Antihydrogen: Recent Results and Future Plans of the ALPHA Experiment at CERN

The Economist

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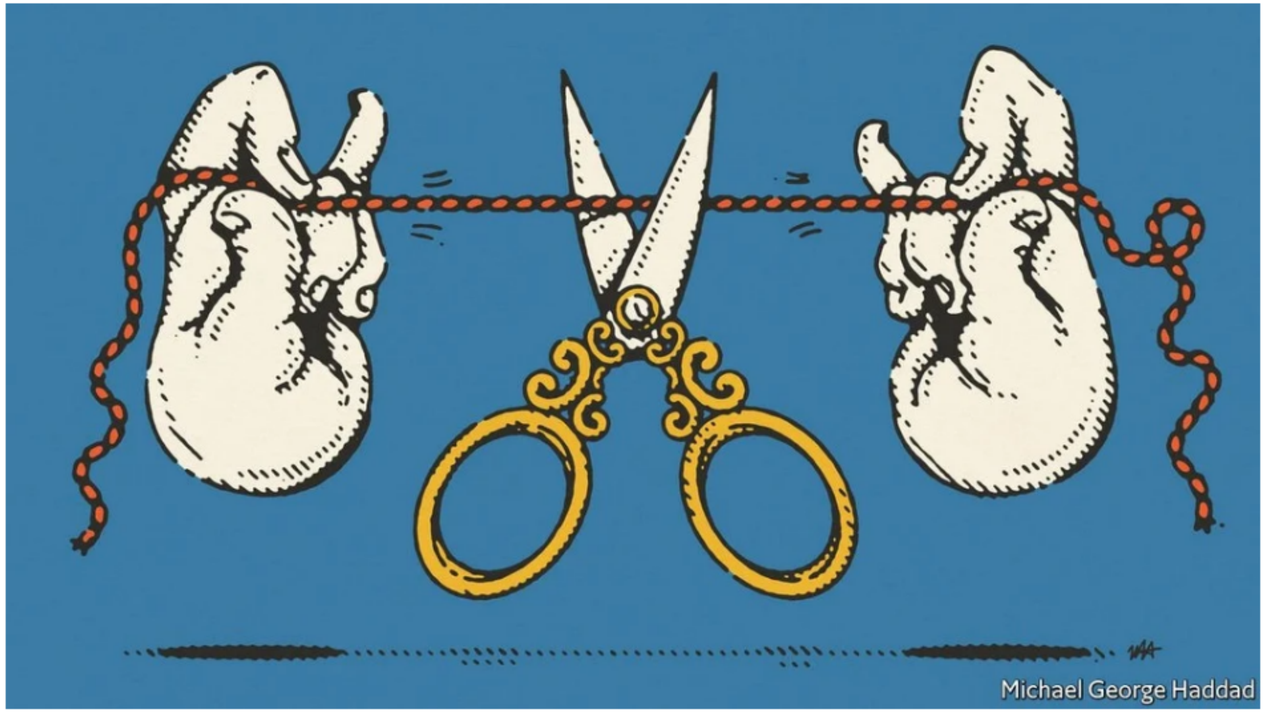
Leaders

Aug 28th 2021 edition ›

In praise of physics

Fundamental physics is humanity's most extraordinary achievement

It sees worlds in grains of sand and infinities in hours



Scott Menary

ALPHA

YORK U

Testing the **Foundations** of Physics with Trapped Antihydrogen

- Foundations of Physics
  - CPT Invariance - The Standard Model
- Making Trapped Antihydrogen
- Spectroscopy - ALPHA 2
- Foundations of Physics
  - Equivalence Principle - General Relativity
- Dropping Antihydrogen - ALPHA-g
- The Future

Invariance/Symmetry ⟷ Conservation Laws

$$\frac{d}{dt}\left(\sum_a \frac{\delta L}{\delta \frac{dq_a}{dt}}\,\delta q_a\right)=0$$

Invariante Variationsprobleme.

(F. Klein zum fünfzigjährigen Doktorjubiläum.)

Von

Emmy Noether in Göttingen.

Vorgelegt von F. Klein in der Sitzung vom 26. Juli 1918[1]).

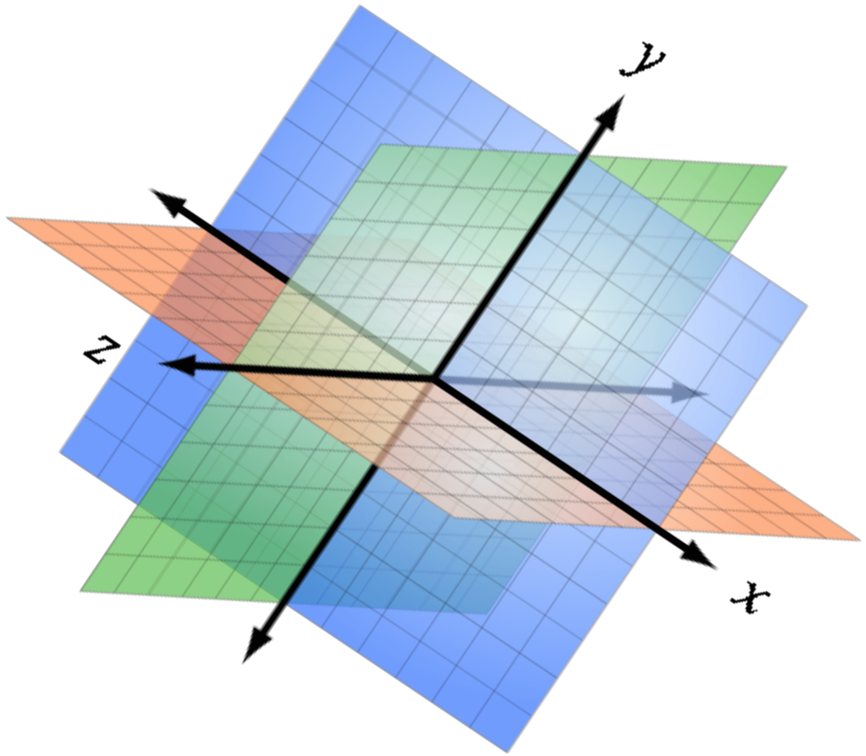
Es handelt sich um Variationsprobleme, die eine kontinuierliche Gruppe (im Lieschen Sinne) gestatten; die daraus sich ergebenden Folgerungen für die zugehörigen Differentialgleichungen finden ihren allgemeinsten Ausdruck in den in § 1 formulierten, in den folgenden Paragraphen bewiesenen Sätzen. Über diese aus Variationsproblemen entspringenden Differentialgleichungen lassen sich viel präzisere Aussagen machen als über beliebige, eine Gruppe gestattende Differentialgleichungen, die den Gegenstand der Lieschen Untersuchungen bilden. Das folgende beruht also auf einer Verbindung der Methoden der formalen Variationsrechnung mit denen der Lieschen Gruppentheorie. Für spezielle Gruppen und Variationsprobleme ist diese Verbindung der Methoden nicht neu; ich erwähne Hamel und Herglotz für spezielle endliche, Lorentz und seine Schüler (z. B. Fokker), Weyl und Klein für spezielle unendliche Gruppen[2]). Insbesondere sind die zweite Kleinsche Note und die vorliegenden Ausführungen gegenseitig durch einander beein-

1) Die endgiltige Fassung des Manuskriptes wurde erst Ende September eingereicht.

2) Hamel: Math. Ann. Bd. 59 und Zeitschrift f. Math. u. Phys. Bd. 50. Herglotz: Ann. d. Phys. (4) Bd. 36, bes. § 9, S. 511. Fokker, Verslag d. Amsterdamer Akad., 27./1. 1917. Für die weitere Litteratur vergl. die zweite Note von Klein: Göttinger Nachrichten 19. Juli 1918.

In einer eben erschienenen Arbeit von Kneser (Math. Zeitschrift Bd. 2) handelt es sich um Aufstellung von Invarianten nach ähnlicher Methode.

Invariance/Symmetry → Conservation Laws



- Time Zero 👉 Energy
- Position of origin 👉 Linear Momentum
- Angle of axes 👉 Angular Momentum

Discrete Symmetries $\longleftrightarrow$ Conserved Quantum Numbers

$$\vec{F} = \frac{1}{4\pi\varepsilon_0}\frac{qQ}{|\vec{r}|^2}\hat{r}$$

$\vec{F}$ is force on q due to Q

- **C**harge conjugation (particle to antiparticle) $\quad qQ \Longrightarrow (-q)(-Q) = qQ$

- **P**arity Inversion $\quad \vec{r} \Longrightarrow -\vec{r} \quad |-\vec{r}|^2 = |\vec{r}|^2$

$$\hat{r} \Longrightarrow -\hat{r}$$

- **T**ime Reversal $\quad \sigma(AB \to CD) = \sigma(CD \to AB)$

CPT Invariance and The Standard Model

Every theory with

- an Hermitian Hamiltonian $\mathcal{H} = \mathcal{H}^\dagger$
- local operators $\mathcal{O} = \mathcal{O}(\mathbf{x}, t)$,
  constructed from spin zero, one-half and one fields
- usual connection between spin and statics is valid,
  i.e., fermion fields anticommute $\{\psi_i, \psi_j\} = \delta_{ij}$
- products are normally ordered, i.e., $\psi_1^\dagger \psi_2^\dagger \psi_1 \psi_2$

is invariant under the combined action of **C**, **P**, and **T** (G.Lüders, Annals Phys. **2**, 1957). The Standard Model is such a theory.

CPT Invariance requires particles and their antiparticles have the same mass and magnetic moment as well as equal and opposite electric charge.
Also atoms and anti-atoms have the exact same energy levels.

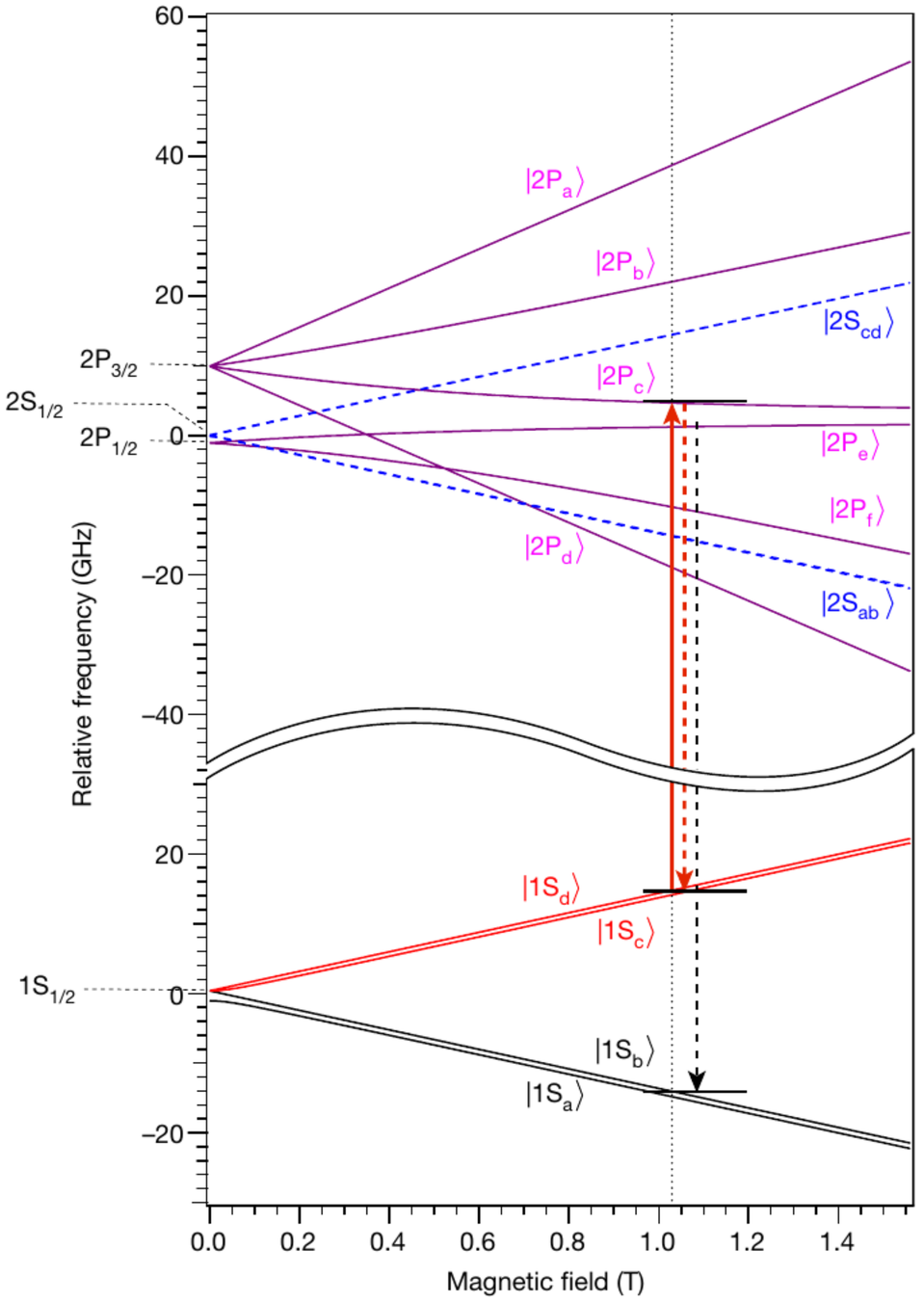
The most precisely measured system in physics is the hydrogen atom.

In particular, the 1S-2S transition frequency is measured to be:

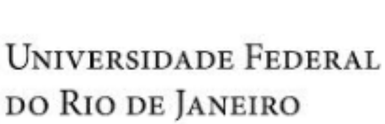
$$f = 2{,}466{,}061{,}413{,}187{,}035\ (10)\ \text{Hz}$$

Phys. Rev Lett. 107 203001 (2011)

Measuring the same quantity for antihydrogen would then constitute a very powerful test of CPT Invariance of the Standard Model.

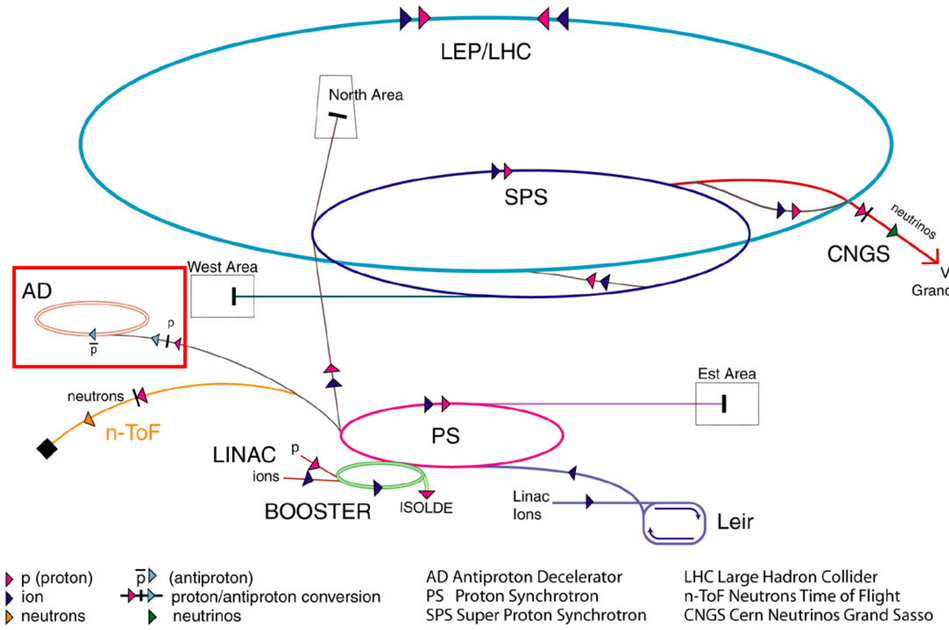


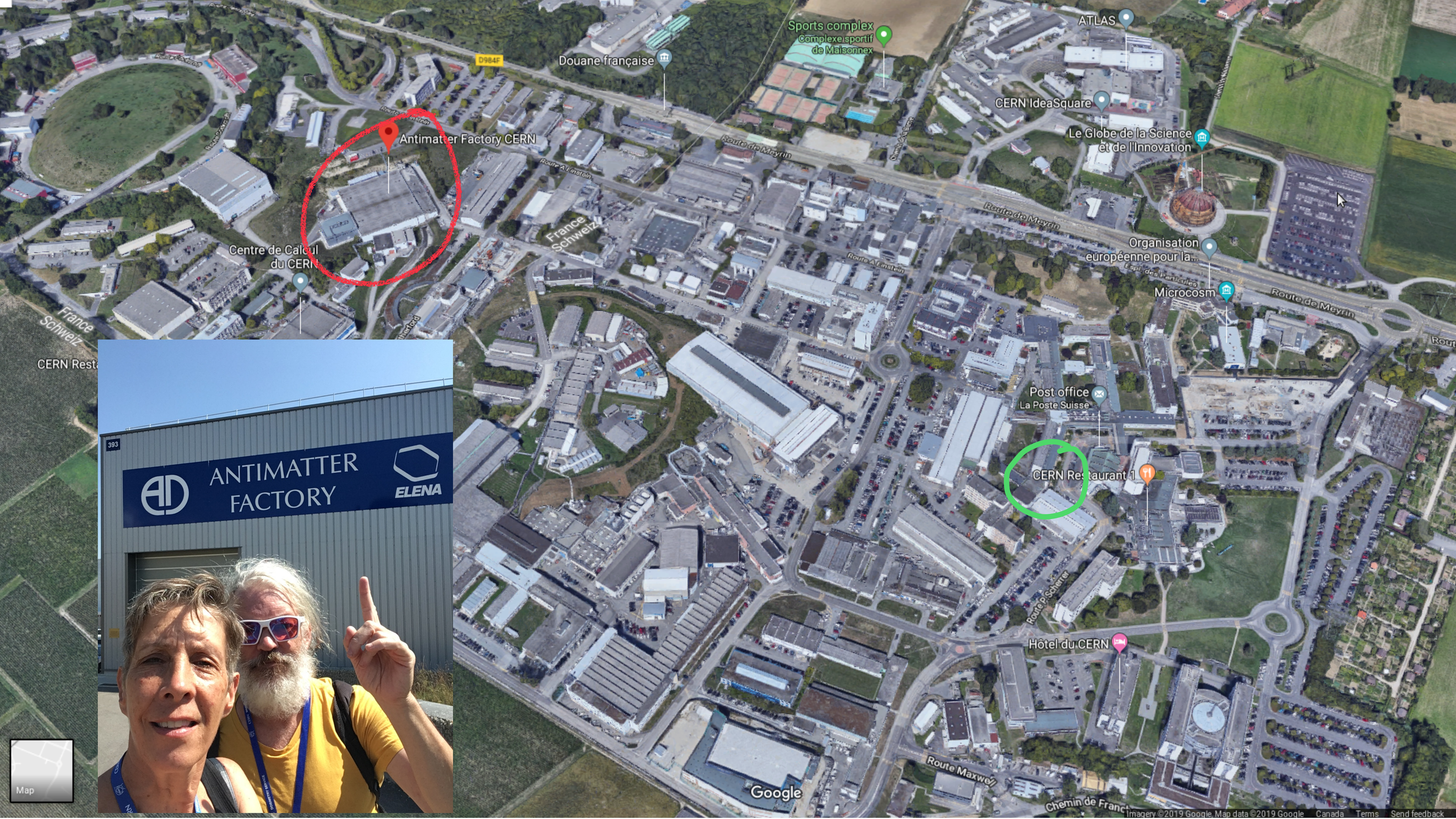
The ALPHA Collaboration ~ 55 physicists from 17 institutions



Swansea University
Prifysgol Abertawe

Accelerator chain of CERN (operating or approved projects)




Sports complex
Complexe sportif de Maisonnex
ATLAS
Douane française
D984F
CERN IdeaSquare
Le Globe de la Science et de l'Innovation
Antimatter Factory CERN
Route de Meyrin
Route A. Einstein
France Schweiz
Centre de Calcul du CERN
Organisation européenne pour la...
Microcosm
Post office
La Poste Suisse
CERN Restaurant 1
Hôtel du CERN
Route Maxwell
Google
393
ANTIMATTER FACTORY
ELENA
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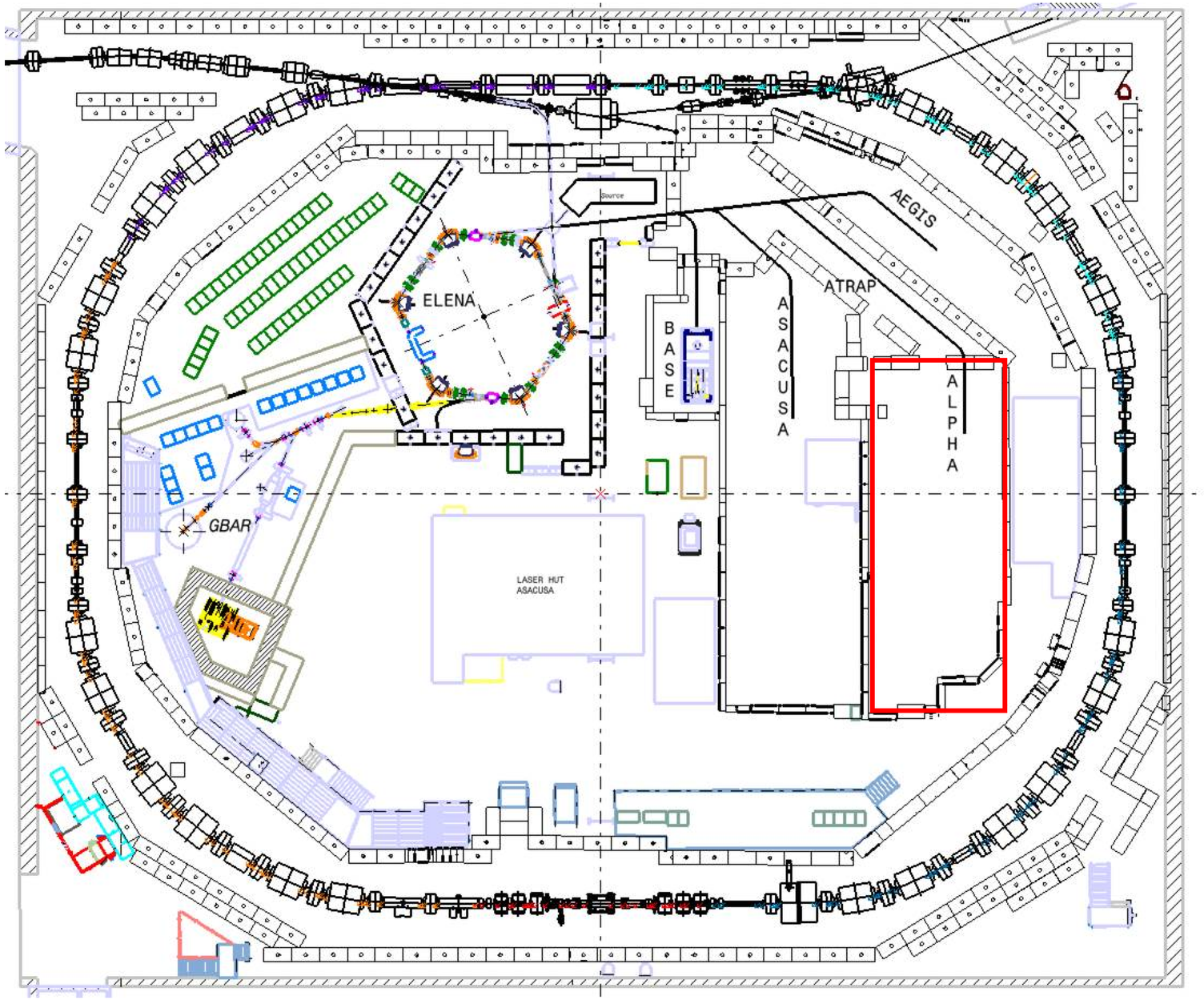
Antiprotons for ALPHA

<2021 - Antiproton Decelerator

- ~30 million antiprotons every ~2 minutes
- KE of 5.3 MeV
- 8 hours of beam per day

2021 - ELENA

- ~7.5 million antiprotons every ~2 minutes
- KE of 100 keV
- Beam delivered 24/7

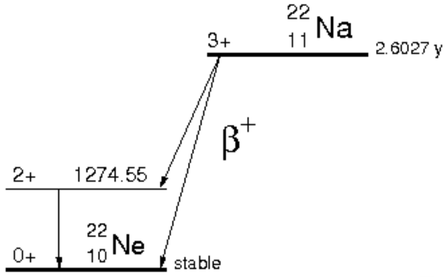


$\bar{P}$

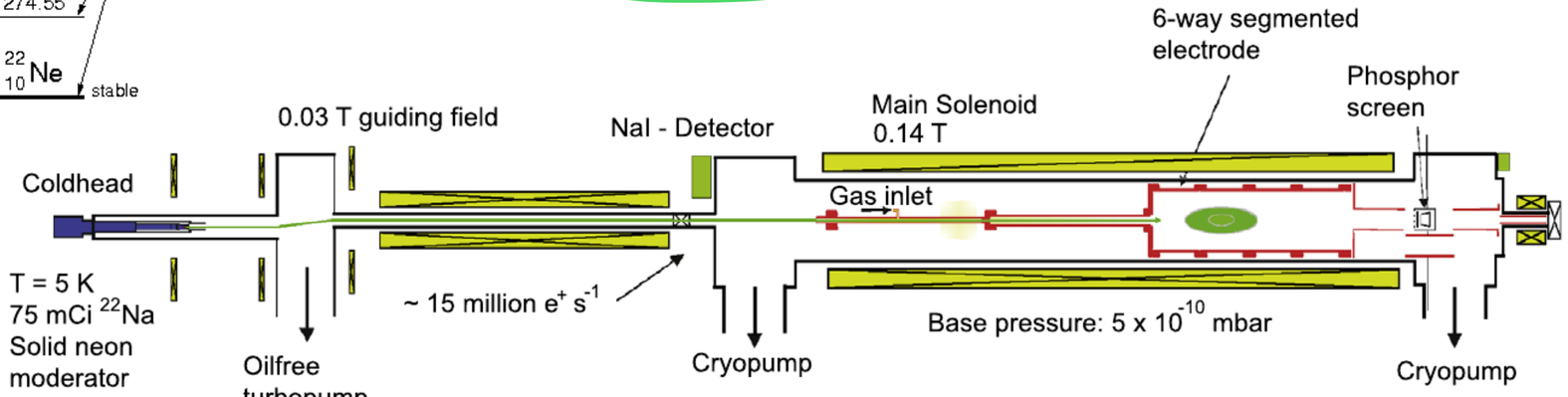
Catching Trap

ALPHA 2

ALPHA-g

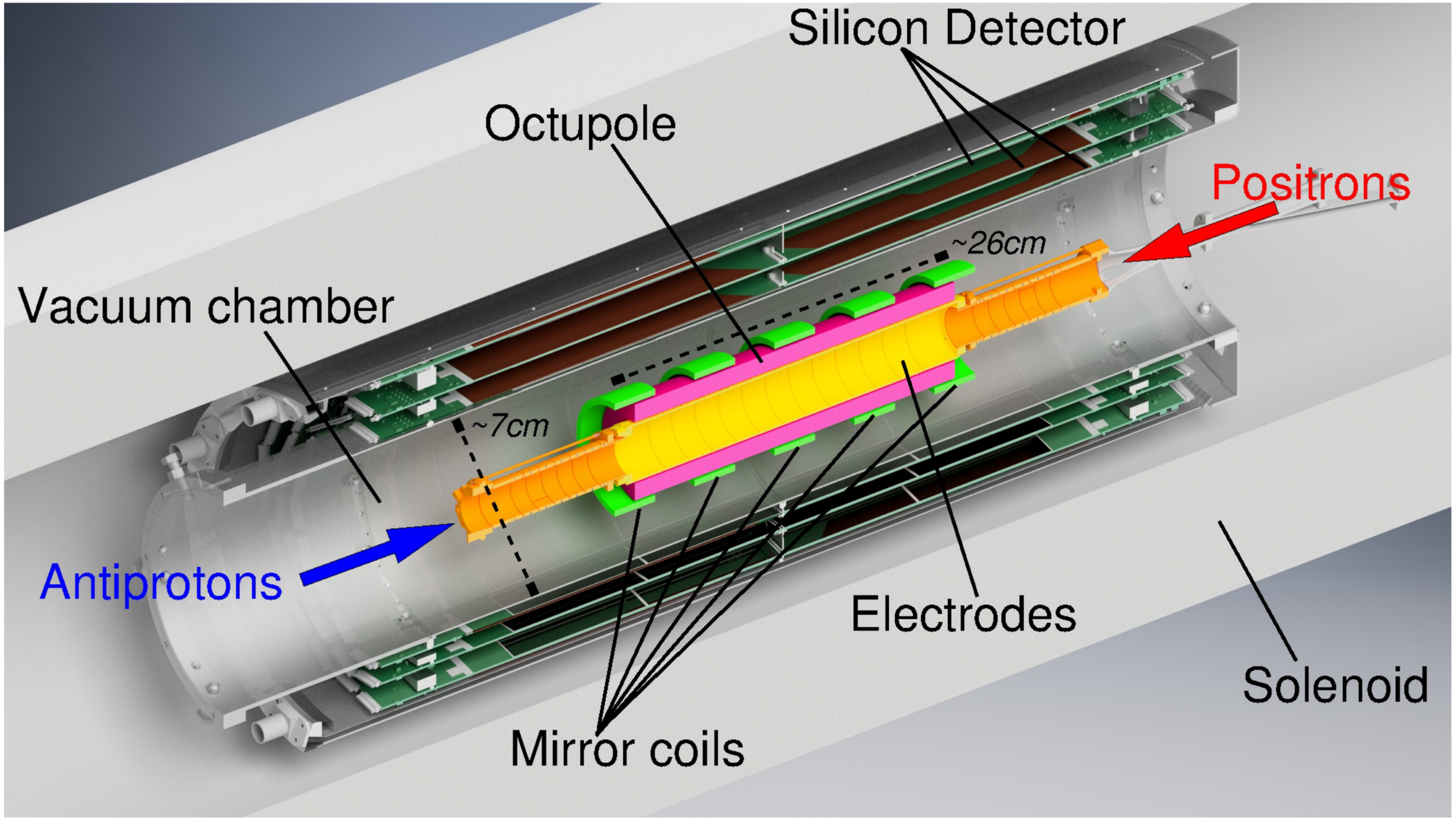


Positron Accumulator



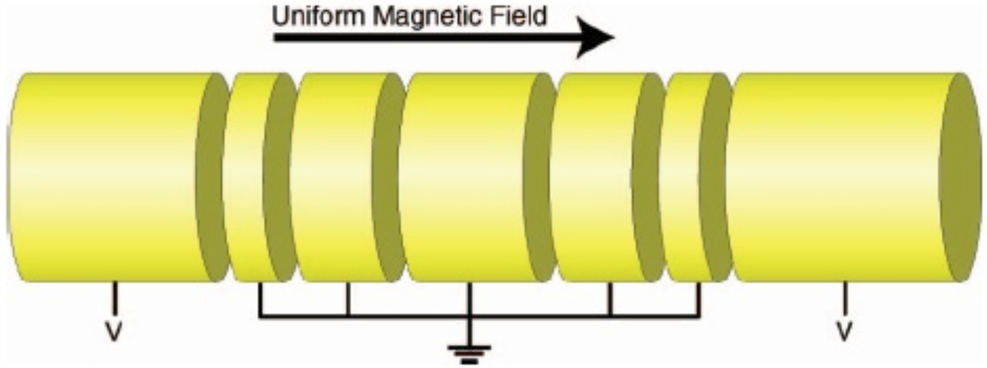

antiproton
catching trap
antihydrogen formation
and trapping

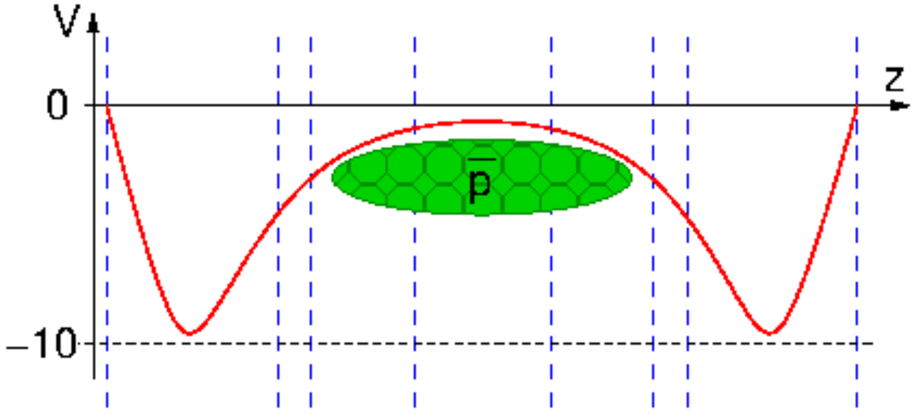
Catching
Trap
ALPHA-II
Atom Trap
Beamline
Modules
Interconnect
Magnet
Superconductin
External Soleno
ALPHA-g
Atom Traps
3 m
e+
Positron accumulator
not shown
p̄
~10.2 m


Silicon Detector
Octupole
Positrons
~26cm
Vacuum chamber
~7cm
Antiprotons
Electrodes
Solenoid
Mirror coils

Penning Trap

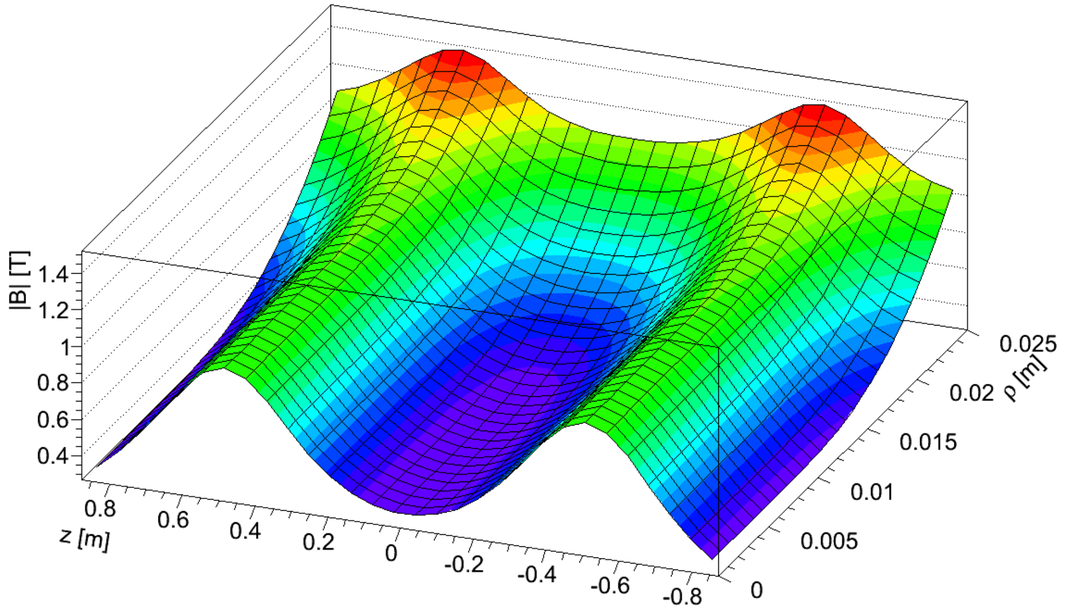
- Varying electric field for axial confinement
- Solenoidal magnetic field for radial confinement





Atom Trap

- Octupole for magnetic gradient



- Potential energy of magnetic dipole in B field

$$U = -\vec{\mu}_{\bar{H}} \cdot \vec{B}$$

- Antihydrogen is confined to minimum U

$\mu_{\bar{H}}$ for ground state $\bar{H}$ is dominated by positron

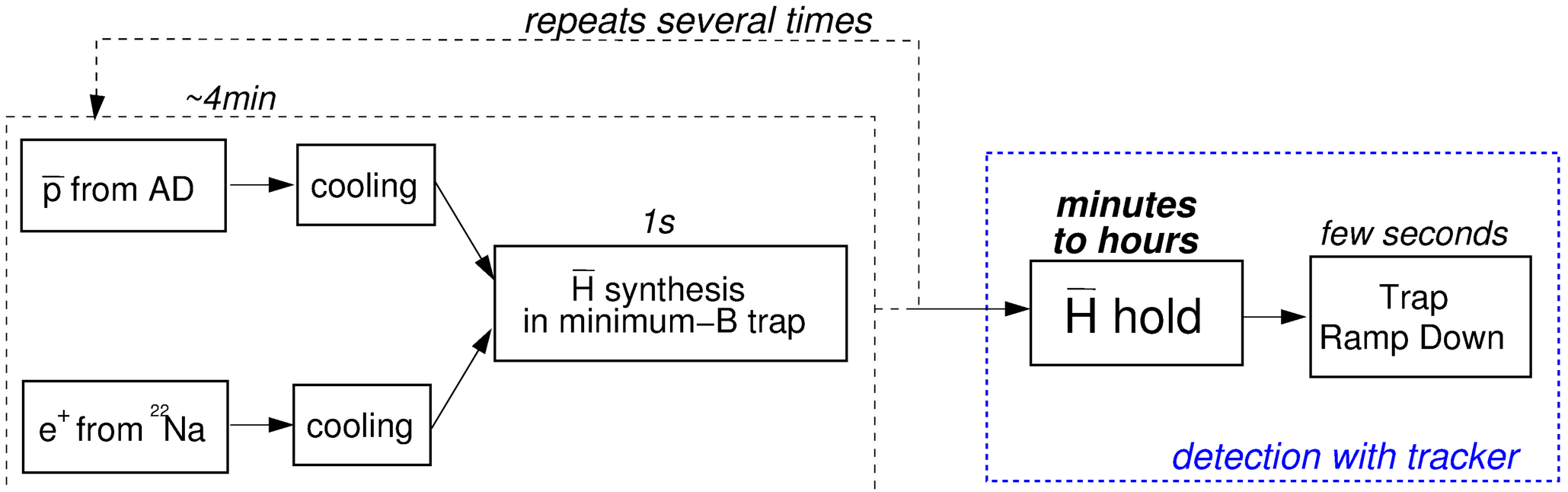
Hence $\mu_{\bar{H}} \approx \mu_B \sim 6 \times 10^{-11}$ MeV/T

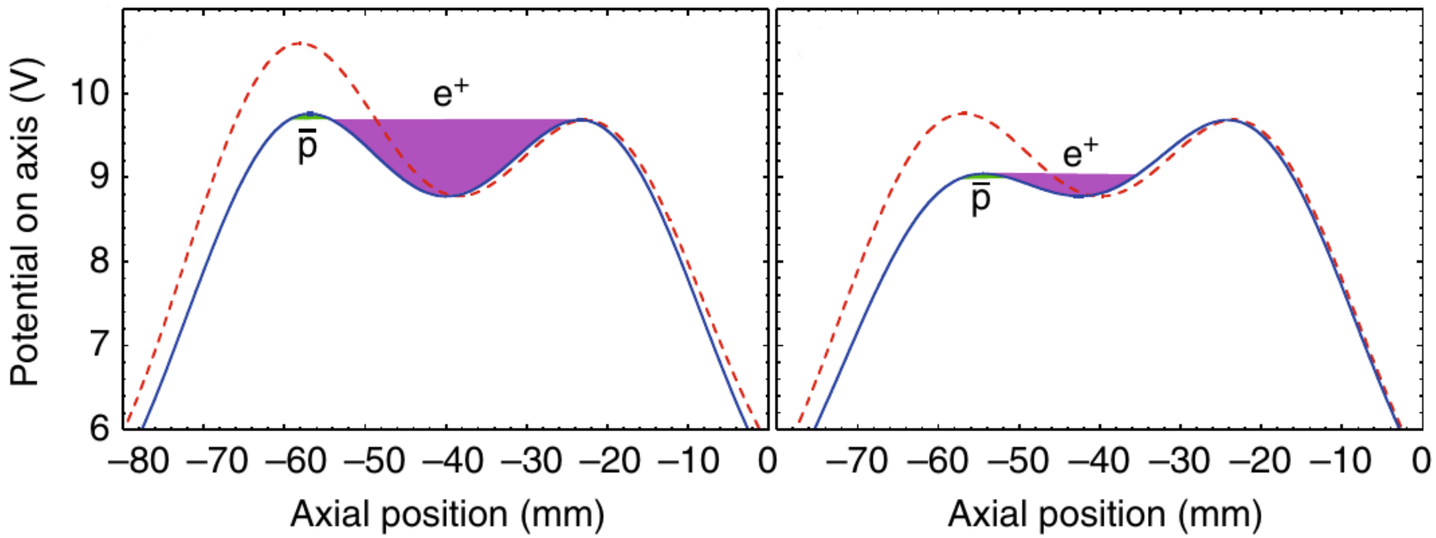
The magnetic field gradient in ALPHA is $\Delta B \approx 0.8$ T

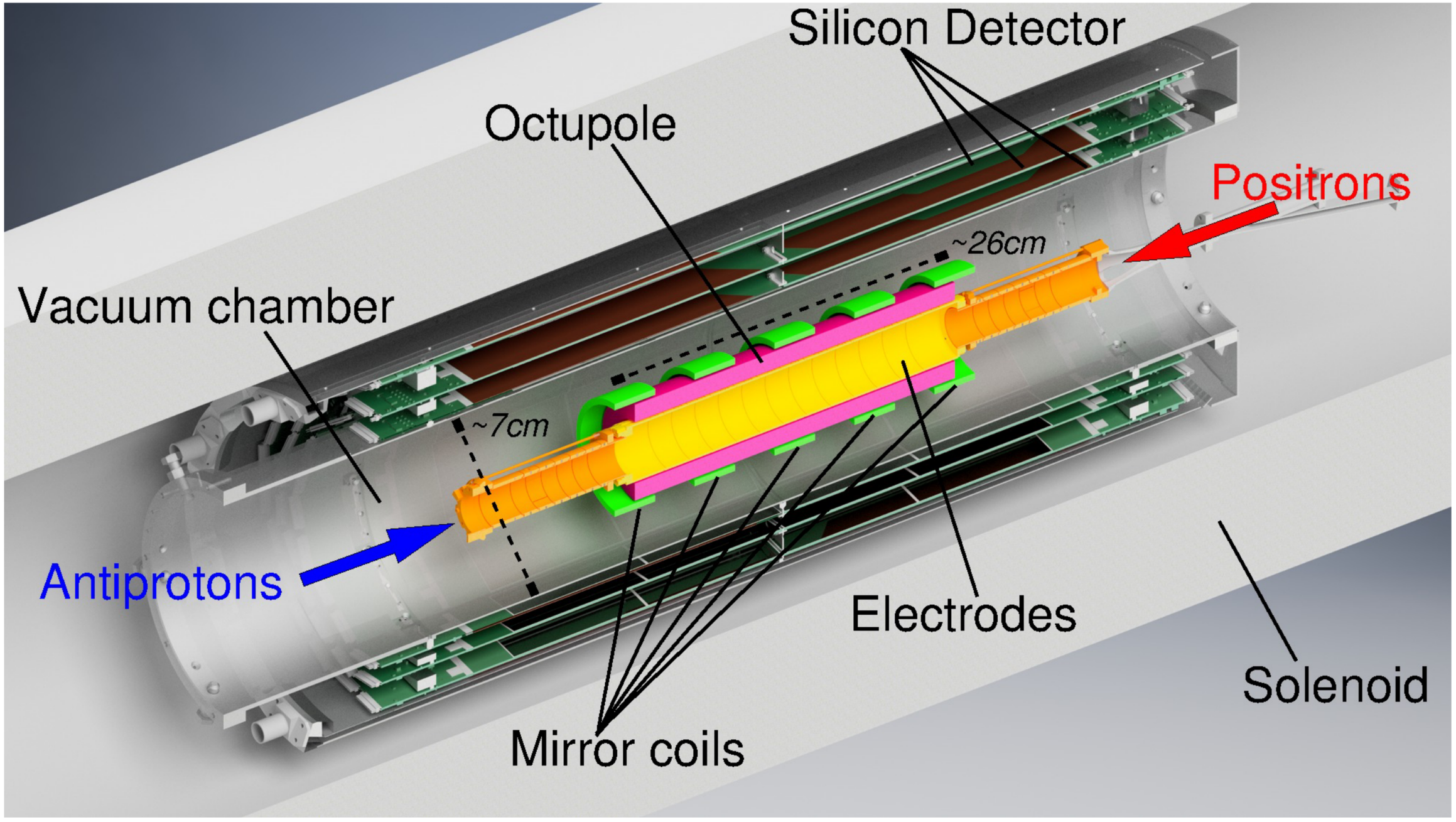
The trap depth is therefore on the order of $\Delta U \sim \mu_B \Delta B \approx 50$ μeV (0.5 ˚K)

Only ultra cold antihydrogen can be trapped

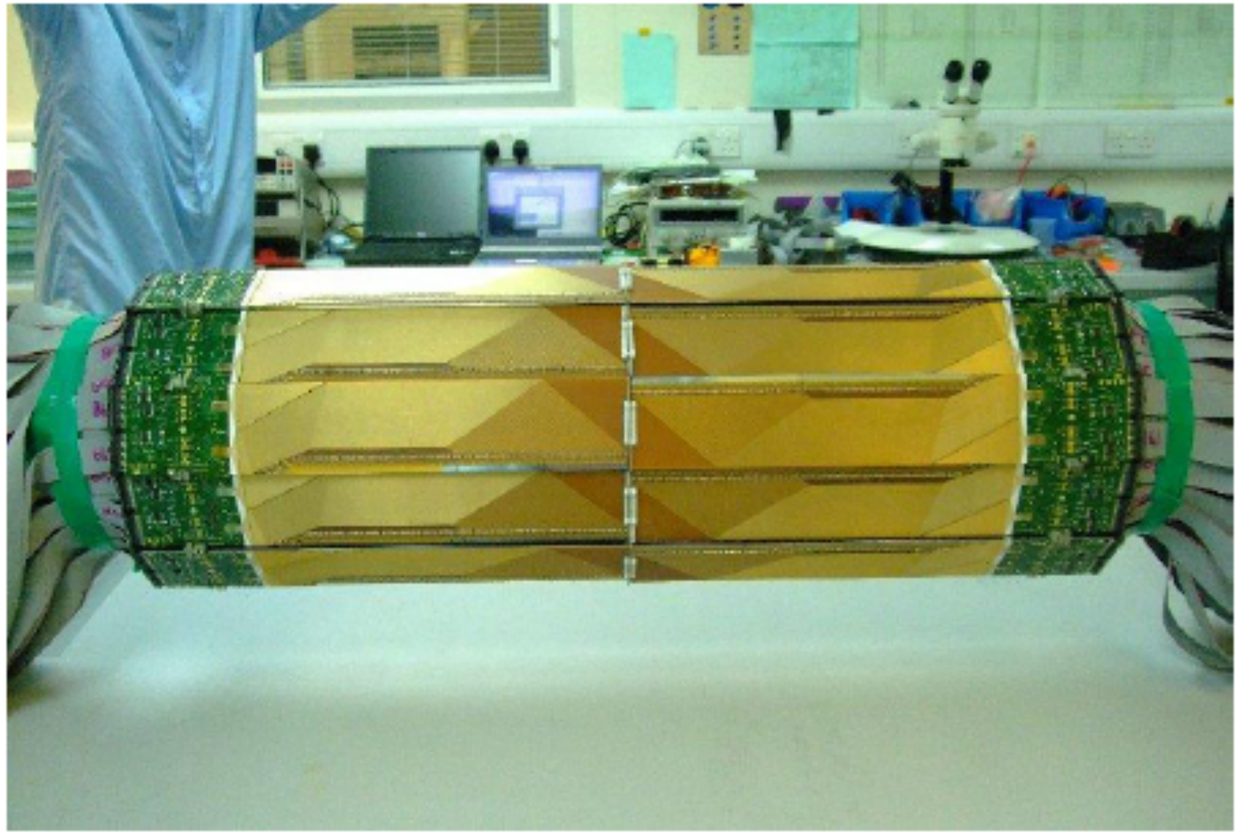
Need to do lots of cooling at all stages of antihydrogen production



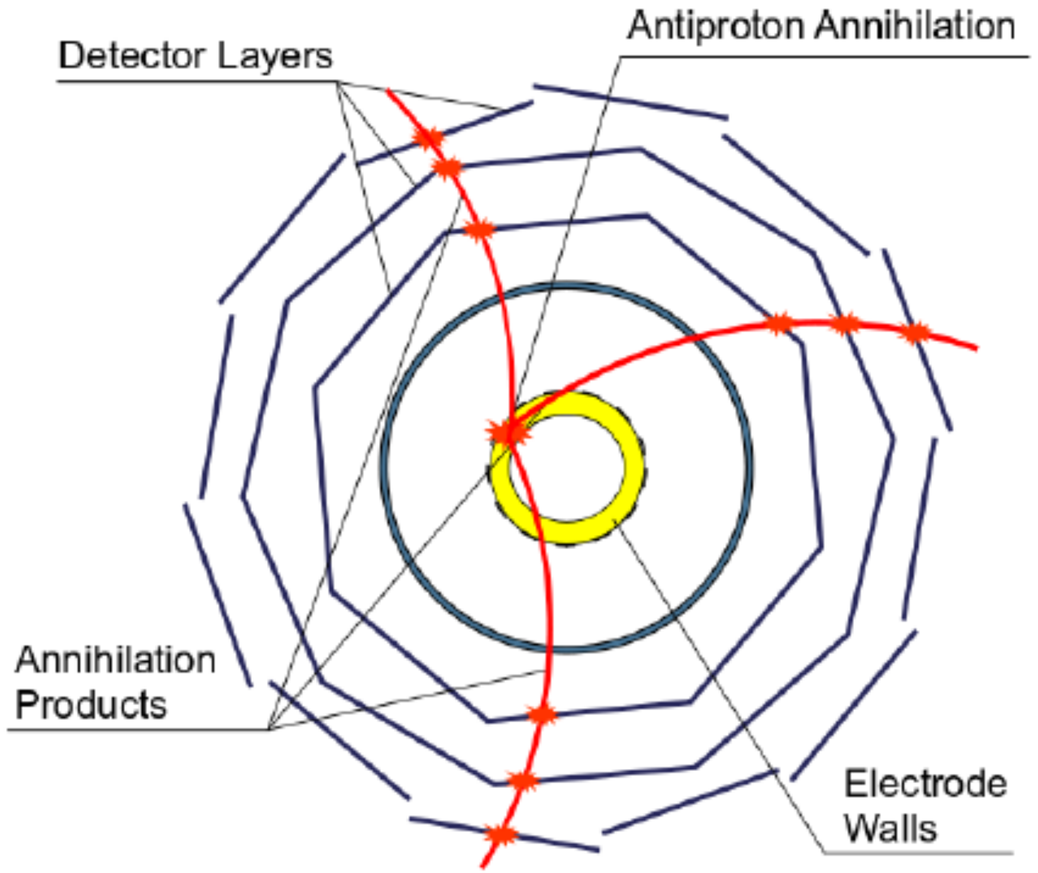



Silicon Detector
Octupole
Positrons
~26cm
Vacuum chamber
~7cm
Antiprotons
Electrodes
Solenoid
Mirror coils

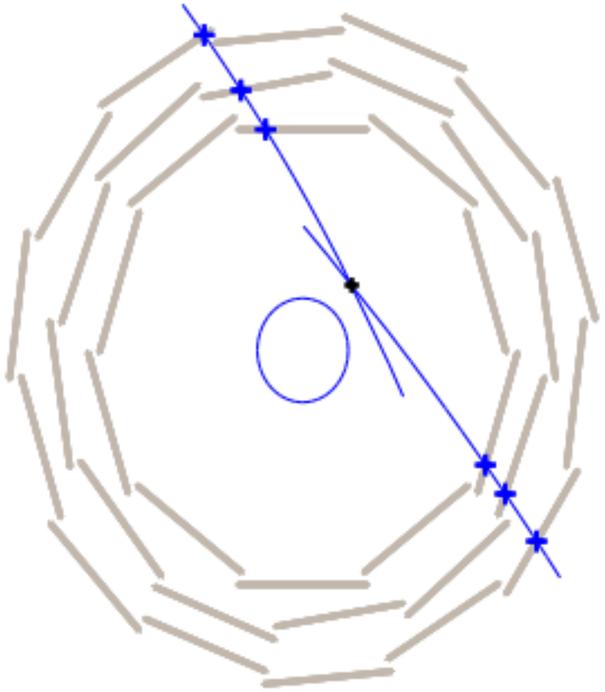
The Double-Sided Silicon Vertex Detector

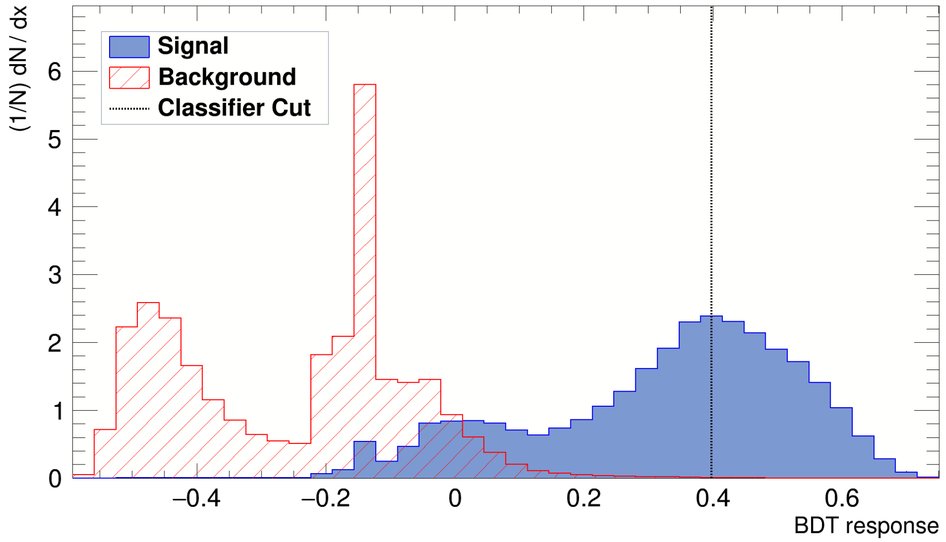


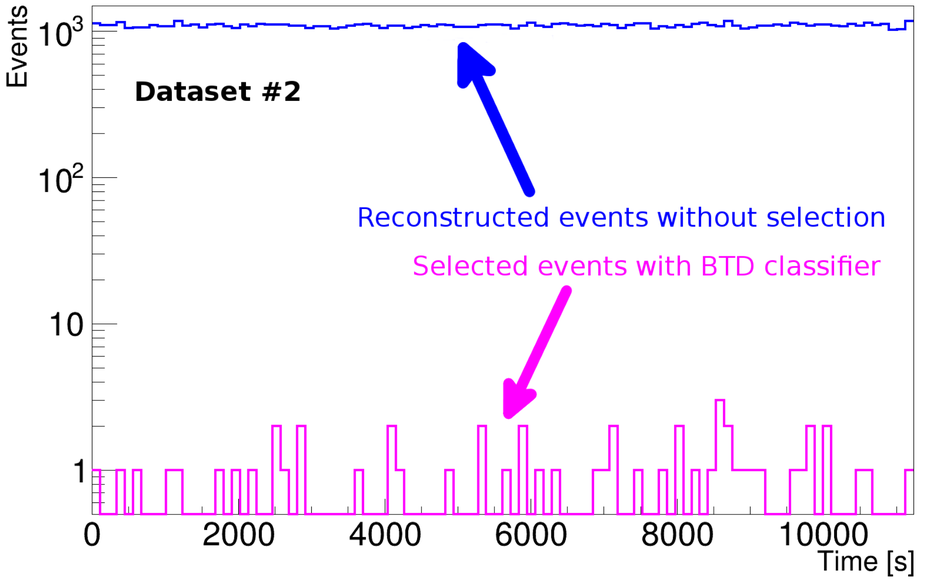
30,000 channel strips
~0.8 m^2 active area



Major background is cosmic rays





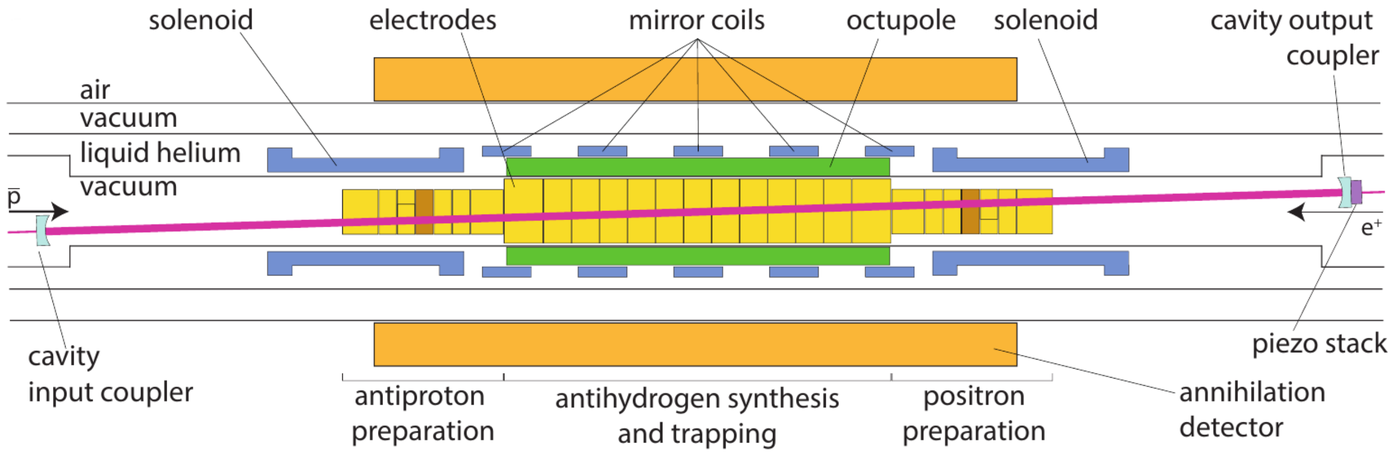


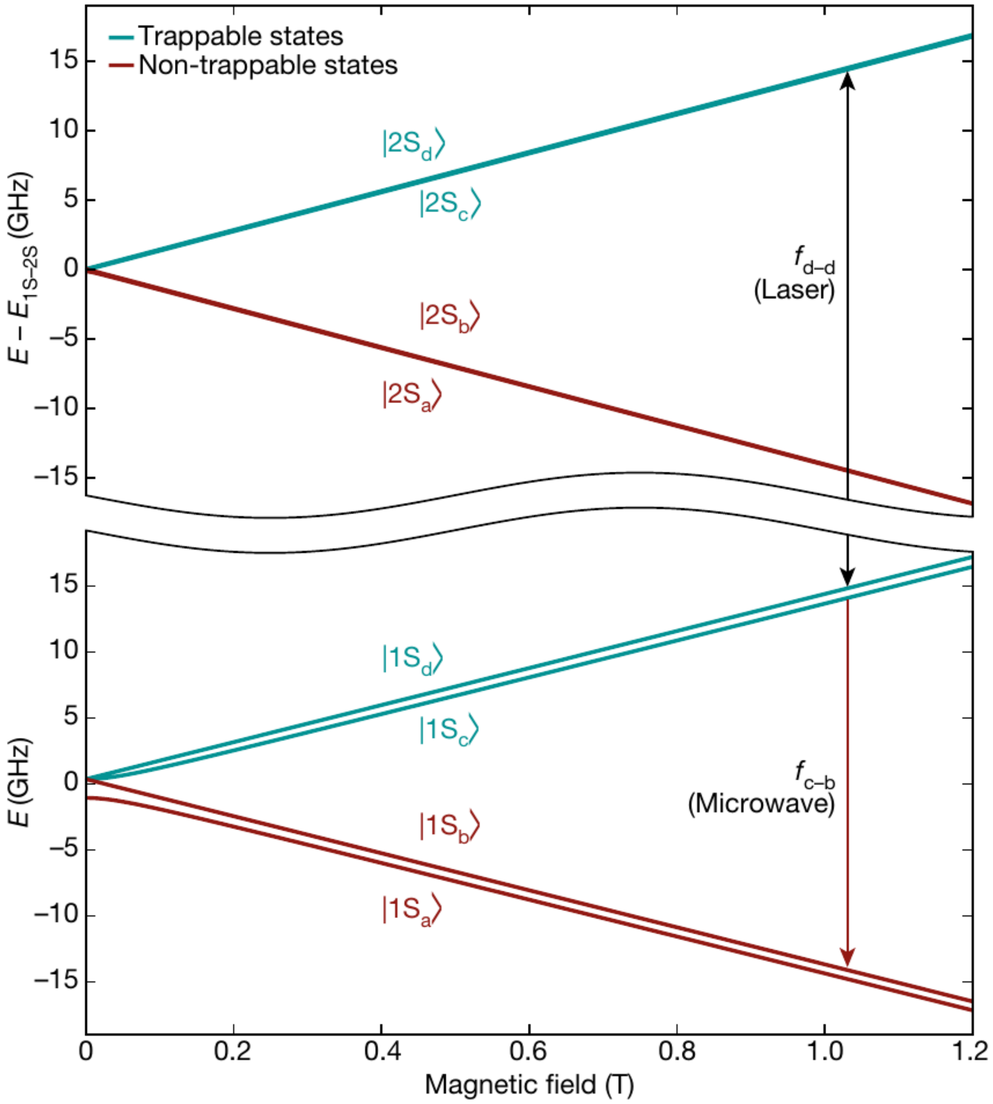
Two methods for cosmic ray rejection

- Cuts on reconstructed vertex position and “straightness” of combined track - Efficiency ~68% with false-positive rate of 47 MHz

- Machine Learning: Boosted Decision Trees - Efficiency ~40% with false positive rate of 4 MHz

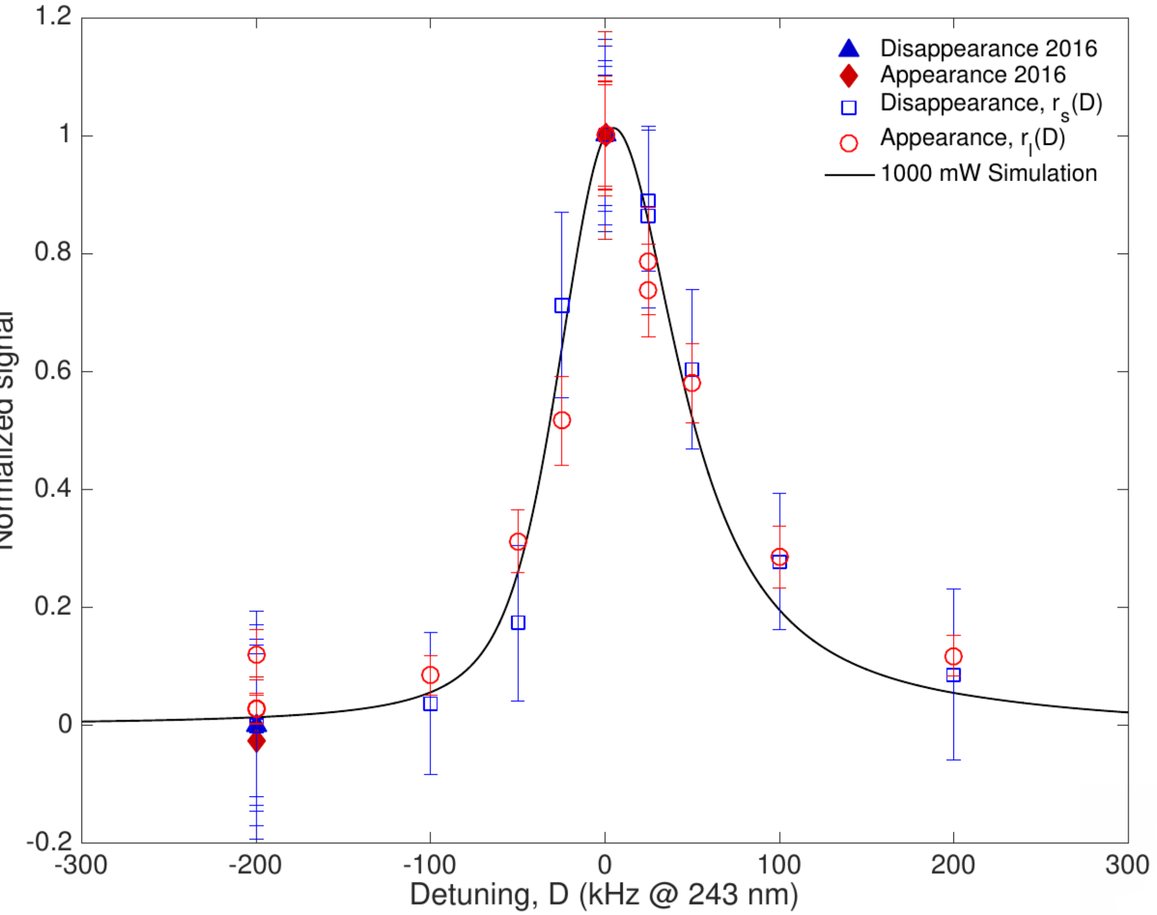
Spectroscopy with Antihydrogen





- Trap antihydrogen (3 mixing cycles, ~40 atoms)
- Clear out any remaining charged particles
- 300s laser exposure at frequencies near the |1S,d> to |2S,d> transition
- 32s microwave sweep to eject |1S,c>
- Ramp down magnets to detect remaining Hbars

CPT Test



- **Appearance** - 1991 antihydrogen detected during laser illumination
- **Disappearance** - 6137 antihydrogen detected during trap shutdown

$$\geq 15000\ \bar{\mathrm{H}}\ \text{trapped}$$

Our result for antihydrogen:

$$f = 2{,}466{,}061{,}103{,}079.4\ (5.4)\ \mathrm{kHz}$$

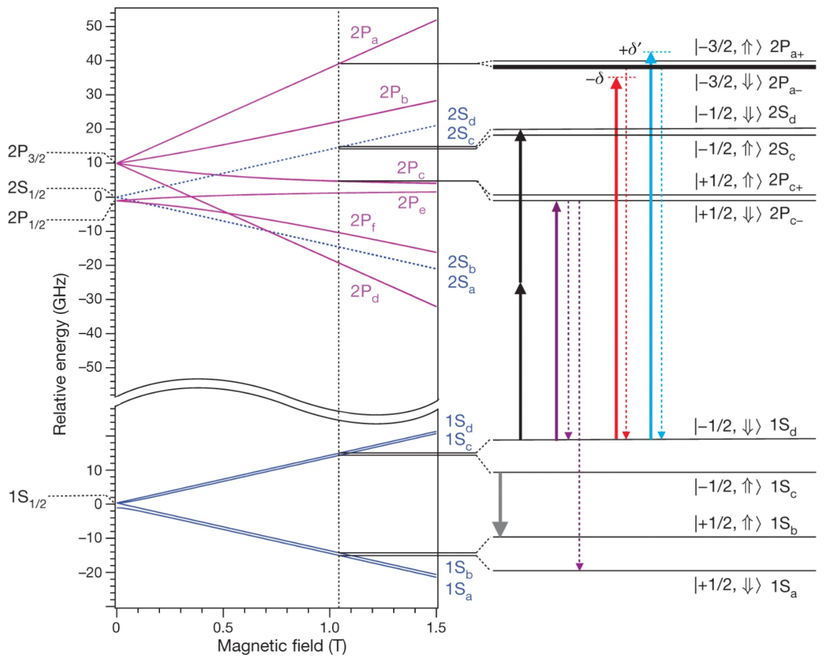
The value for hydrogen at the same field:

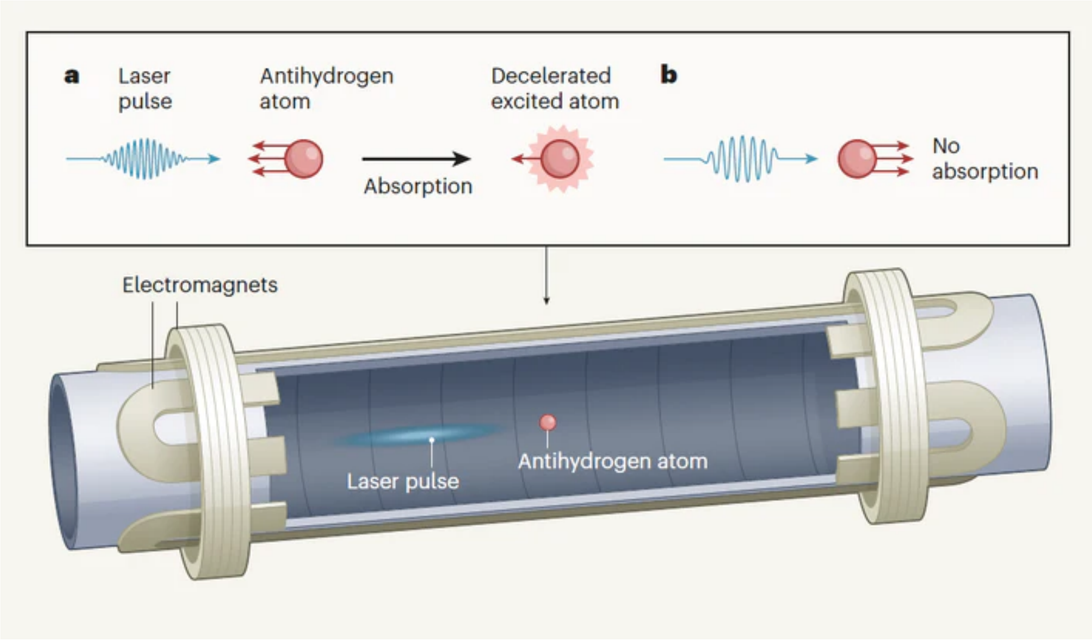
$$f = 2{,}466{,}061{,}103{,}080.3\ (0.6)\ \mathrm{kHz}$$

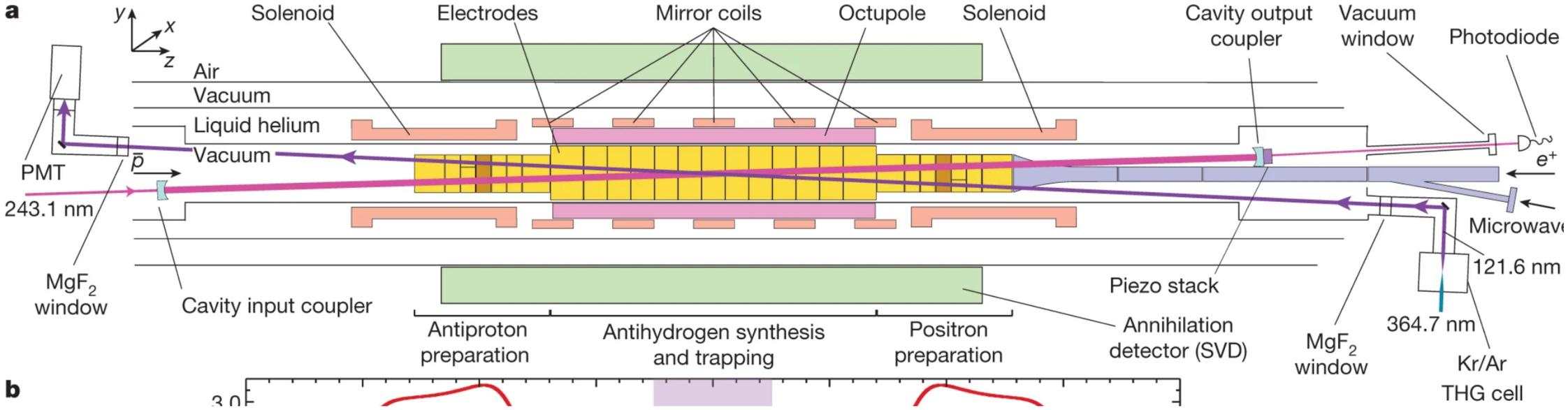
$$\Delta f = 0.9 \pm 5.4\ \mathrm{kHz} \quad < \sim 2 \times 10^{-20}\ \mathrm{GeV}$$

They agree to a part in 10^{12}

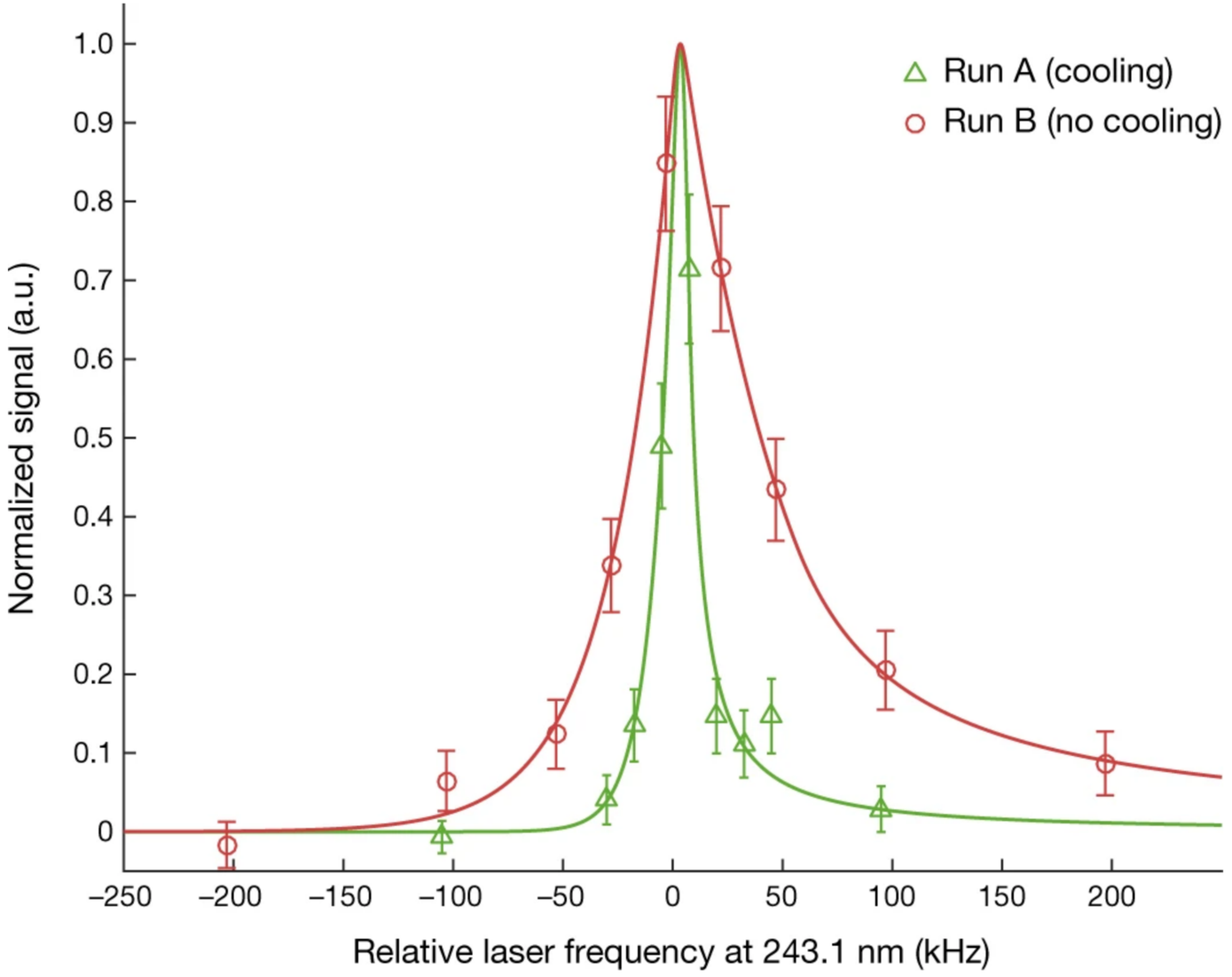
Laser Cooling of Antihydrogen





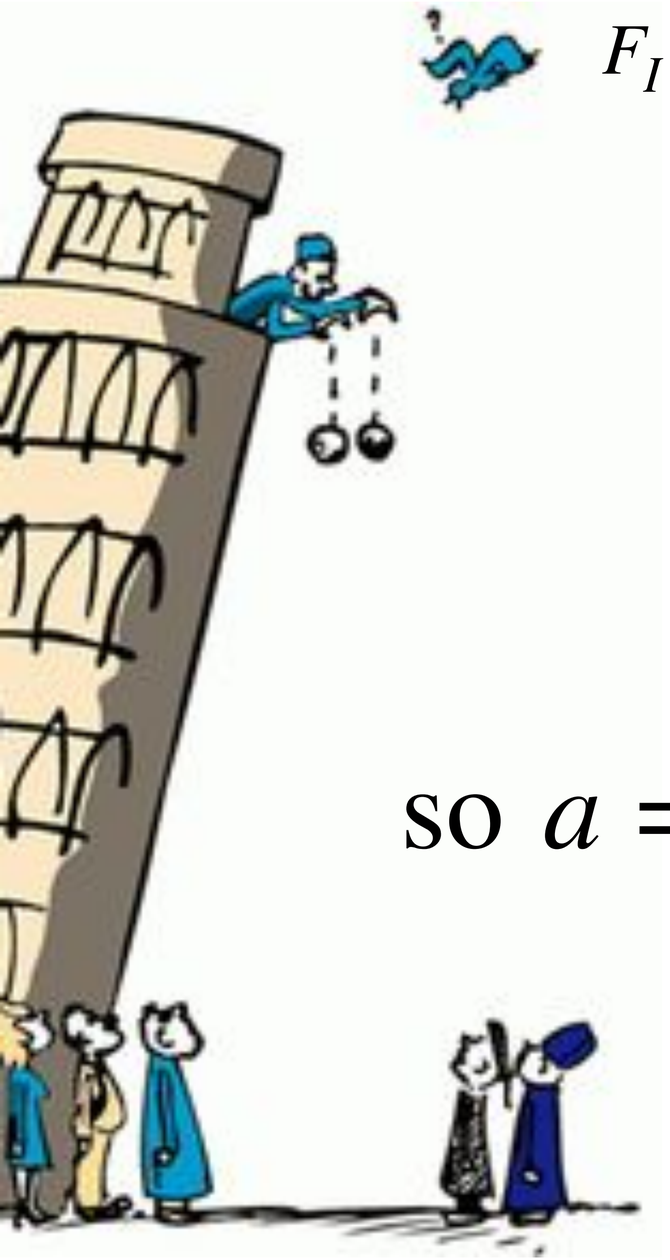


Laser Cooling of Antihydrogen Achieved!



Testing the Equivalence Principle using Antihydrogen

The Equivalence Principle



$$F_I = m_I a \qquad F_G = G\frac{m_G M_E}{R_E^2}$$

$$F_I = F_G$$

$$m_I a = G\frac{m_G M_E}{R_E^2}$$

$$a = \left(\frac{m_G}{m_I}\right) g$$

$$\text{so } a = g \text{ if } m_G = m_I$$

- Newton compared the period of a pendulum for a number of bob materials (gold, sand, wood, water, wheat!) and found it to be equal to a part in a thousand

$$T = 2\pi\sqrt{\frac{m_I \ell}{m_G g}}$$

PROPOSITION VI. THEOREM VI.

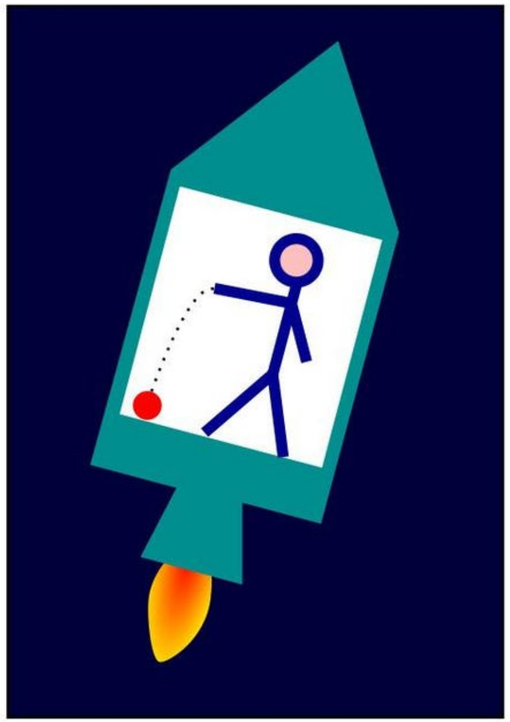
That all bodies gravitate towards every planet; and that the weights of bodies towards any the same *planet, at equal distances from the centre of the planet, are proportional to the quantities of matter which they severally contain.*

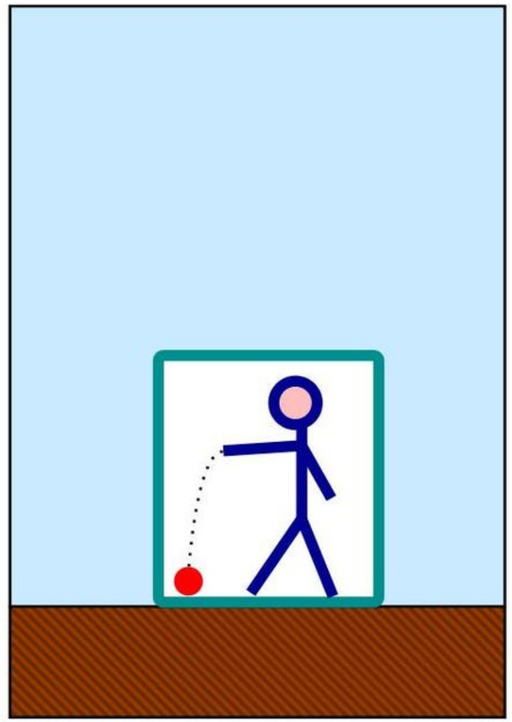
It has been, now of a long time, observed by others, that all sorts of heavy bodies (allowance being made for the inequality of retardation which they suffer from a small power of resistance in the air) descend to the earth *from equal heights* in equal times; and that equality of times we may distinguish to a great accuracy, by the help of pendulums. I tried the thing in gold, silver, lead, glass, sand, common salt, wood, water, and wheat. I provided two wooden boxes, round and equal: I filled the one with wood, and suspended an equal weight of gold (as exactly as I could) in the centre of oscillation of the other. The boxes hanging by equal threads of 11 feet made a couple of pendulums perfectly equal in weight and figure, and equally receiving the resistance of the air. And, placing the one by the other, I observed them to play together forward and backward, for a long time, with equal vibrations. And therefore the quantity of matter in the gold (by Cor. 1 and 6, Prop. XXIV, Book II) was to the quantity of matter in the wood as the action of the motive force (or *vis motrix*) upon all the gold to the action of the same upon all the wood; that is, as the weight of the one to the weight of the other: and the like happened in the other bodies. By these experiments, in bodies of the same weight, I could manifestly have discovered a difference of matter less than the thousandth part of the whole, had any such been. But, without all doubt, the nature of gravity towards the planets is the same as towards the earth. For, should we imagine our terrestrial

The Equivalence Principle and General Relativity

I was sitting in a chair in the patent office at Bern when all of sudden a thought occurred to me: "If a person falls freely he will not feel his own weight." I was startled. This simple thought made a deep impression on me. It impelled me toward a theory of gravitation.

Albert Einstein recalling the "happiest thought of my life," 1922





$$m_I \frac{d^2 x^\lambda}{d\tau^2} = - m_G \frac{dx^\mu}{d\tau} \Gamma^\lambda_{\mu\nu} \frac{dx^\nu}{d\tau}$$

Present Limit on Violation of the Equivalence Principle

General Relativity and Quantum Cosmology

[Submitted on 23 Sep 2019]

Space test of the Equivalence Principle: first results of the MICROSCOPE mission

Pierre Touboul, Gilles Métris, Manuel Rodrigues, Yves André, Quentin Baghi, Joel Bergé, Damien Boulanger, Stefanie Bremer, Ratana Chhun, Bruno Christophe, Valerio Cipolla, Thibault Damour, Pascale Danto, Hansjoerg Dittus, Pierre Fayet, Bernard Foulon, Pierre-Yves Guidotti, Emilie Hardy, Phuong-Anh Huynh, Claus Lämmerzahl, Vincent Lebat, Françoise Liorzou, Meike List, Isabelle Panet, Sandrine Pires, Benjamin Pouilloux, Pascal Prieur, Serge Reynaud, Benny Rievers, Alain Robert, Hanns Selig, Laura Serron, Timothy Sumner, Pieter Visser

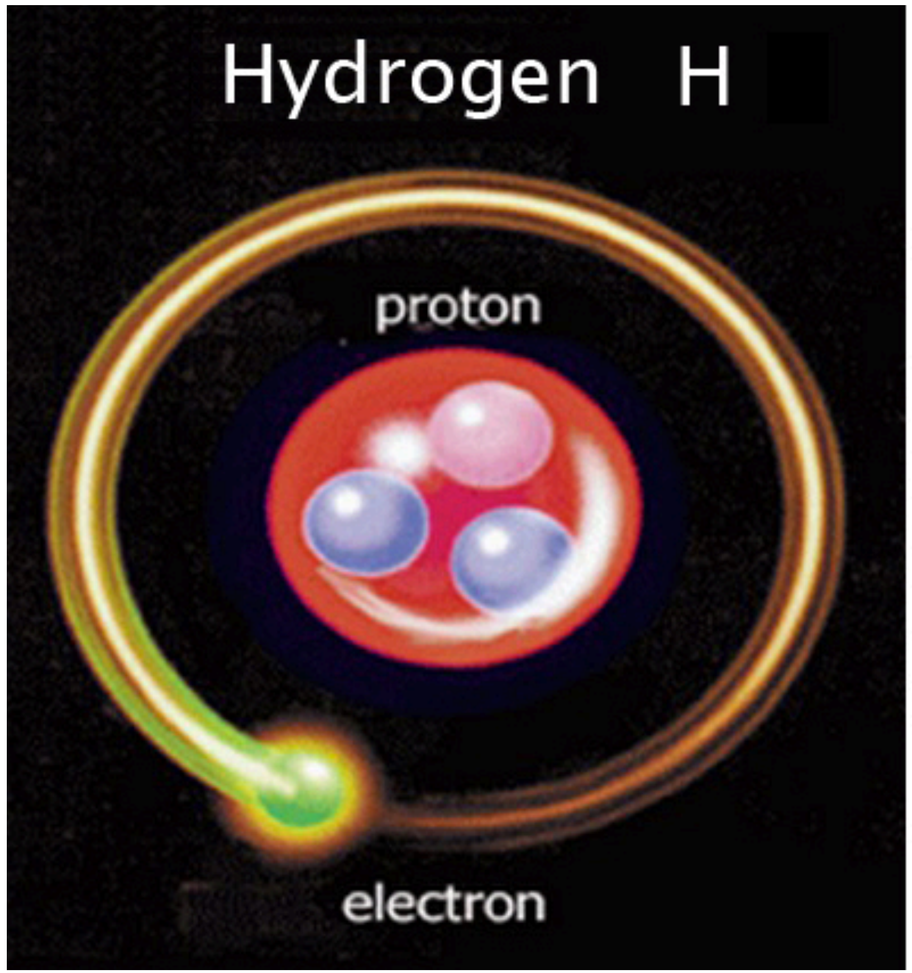
The Weak Equivalence Principle (WEP), stating that two bodies of different compositions and/or mass fall at the same rate in a gravitational field (universality of free fall), is at the very foundation of General Relativity. The MICROSCOPE mission aims to test its validity to a precision of 10^{-15}, two orders of magnitude better than current on-ground tests, by using two masses of different compositions (titanium and platinum alloys) on a quasi-circular trajectory around the Earth. This is realised by measuring the accelerations inferred from the forces required to maintain the two masses exactly in the same orbit. Any significant difference between the measured accelerations, occurring at a defined frequency, would correspond to the detection of a violation of the WEP, or to the discovery of a tiny new type of force added to gravity. MICROSCOPE's first results show no hint for such a difference, expressed in terms of Eötvös parameter $\delta(Ti, Pt) = [-1 \pm 9(\mathrm{stat}) \pm 9(\mathrm{syst})] \times 10^{-15}$ (both 1σ uncertainties) for a titanium and platinum pair of materials. This result was obtained on a session with 120 orbital revolutions representing 7\% of the current available data acquired during the whole mission. The quadratic combination of 1σ uncertainties leads to a current limit on δ of about 1.3×10^{-14}.

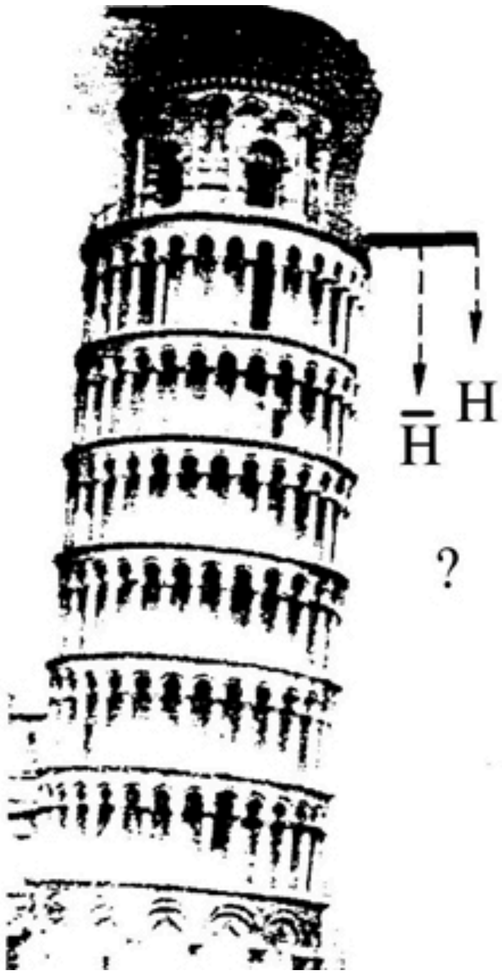
$$1.3 \times 10^{-14}$$

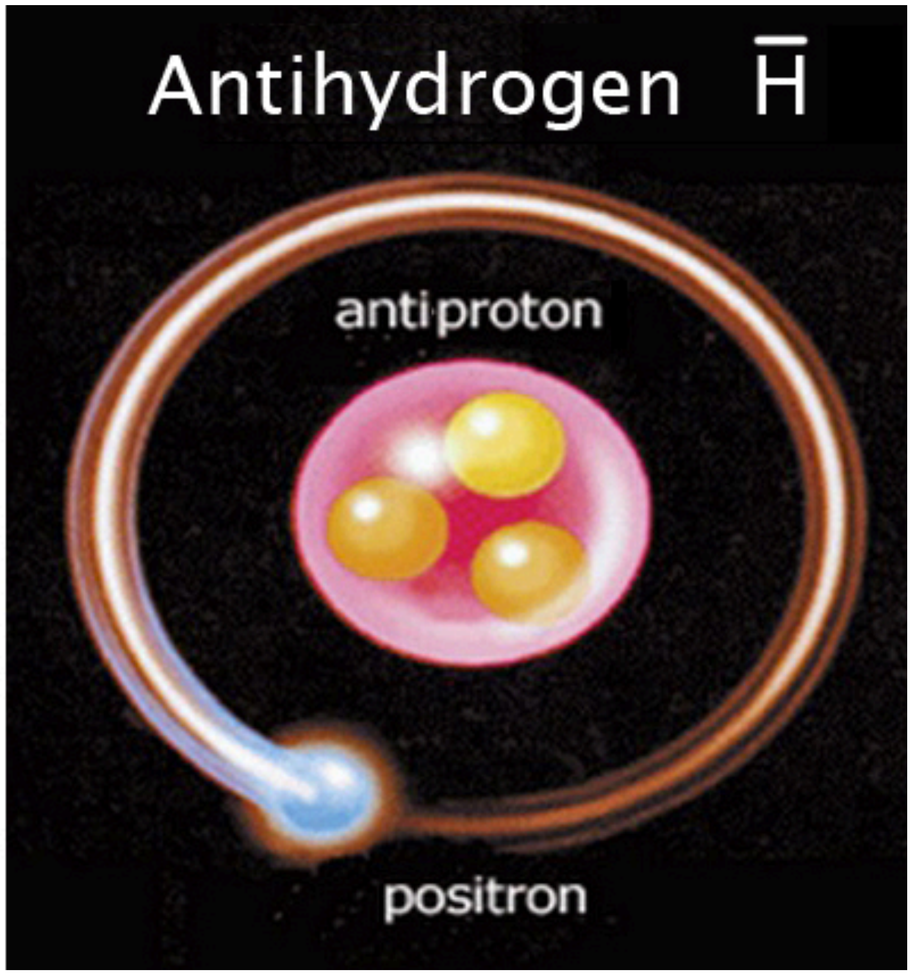
The Equivalence Principle has never been tested with antimatter.

Difficult to do with charged antiparticles (e.g., positrons)

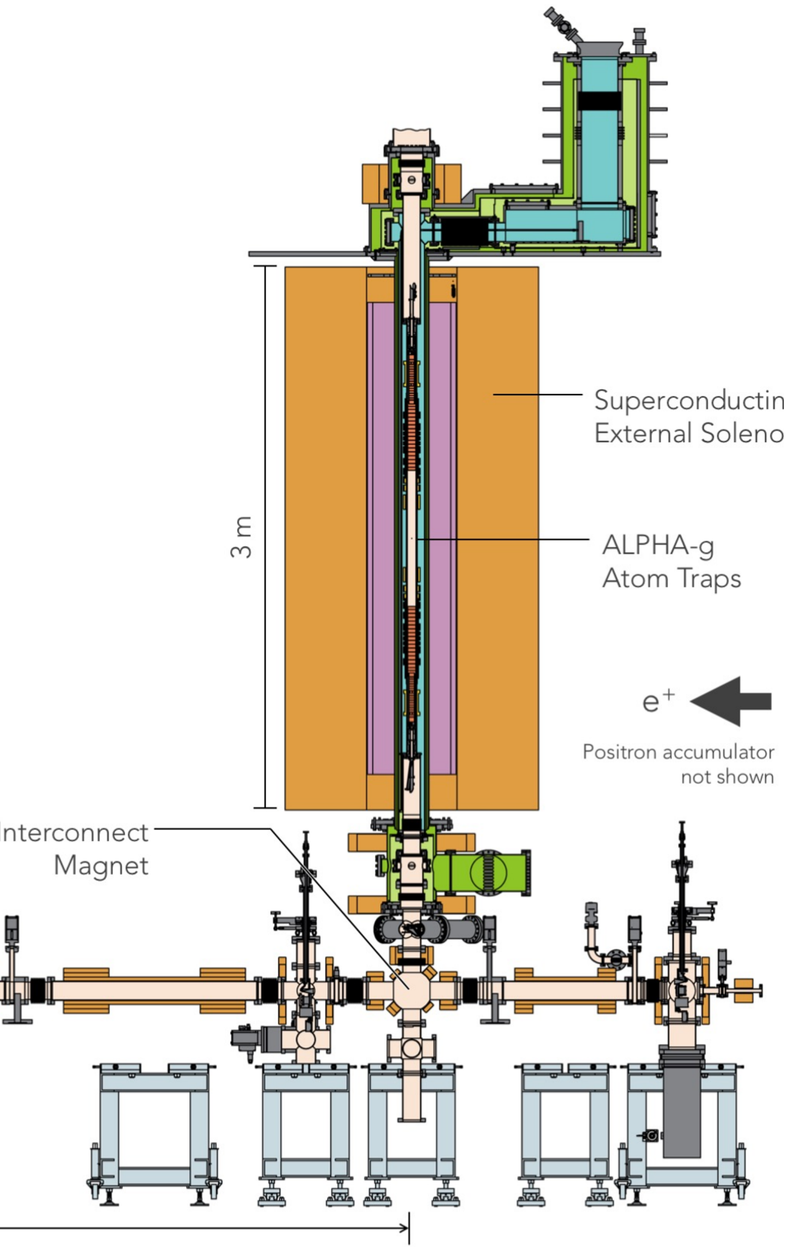
→ antiatoms

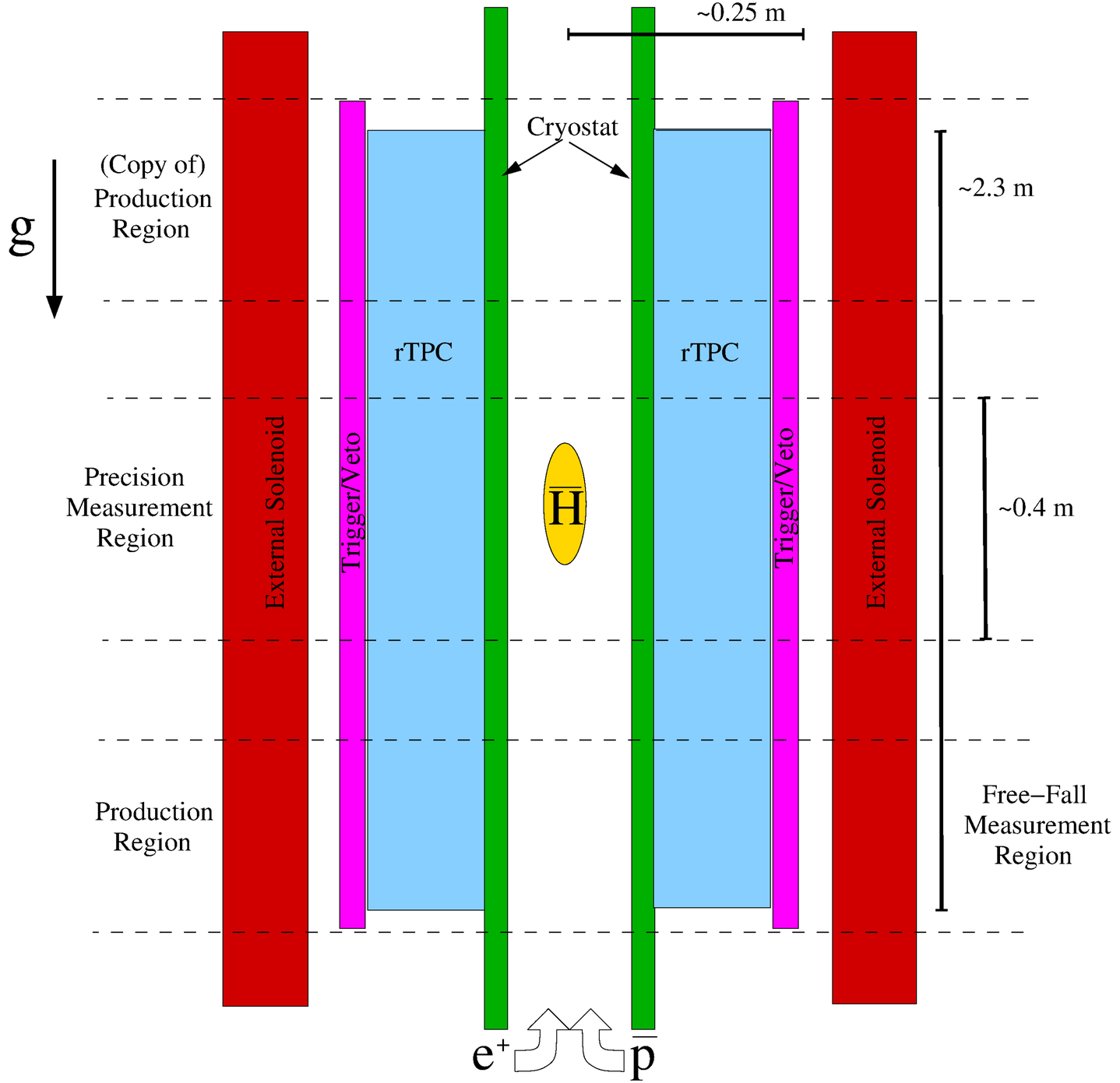




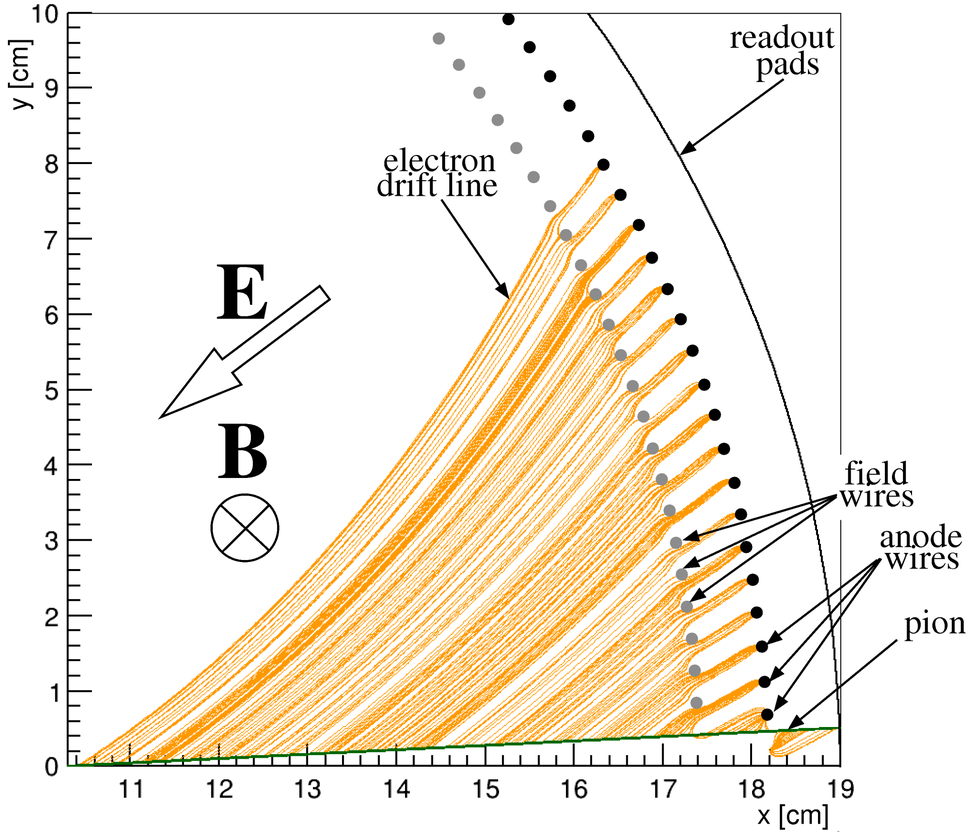


ALPHA-g

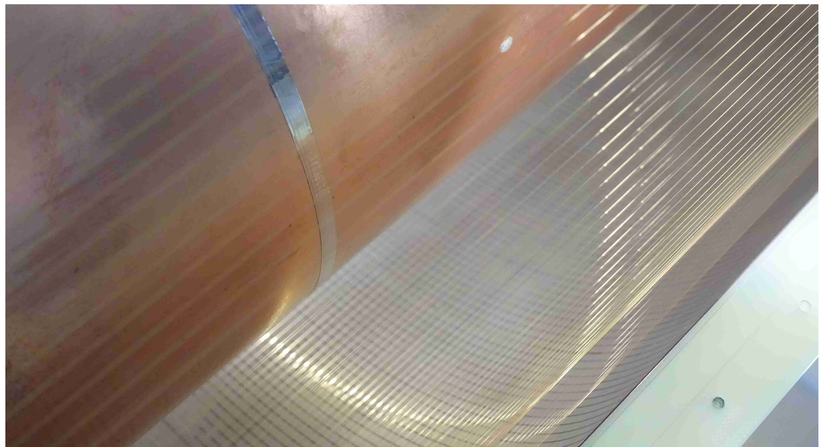

Superconductin
External Soleno
3 m
ALPHA-g
Atom Traps
e+
Positron accumulator
not shown
Interconnect
Magnet

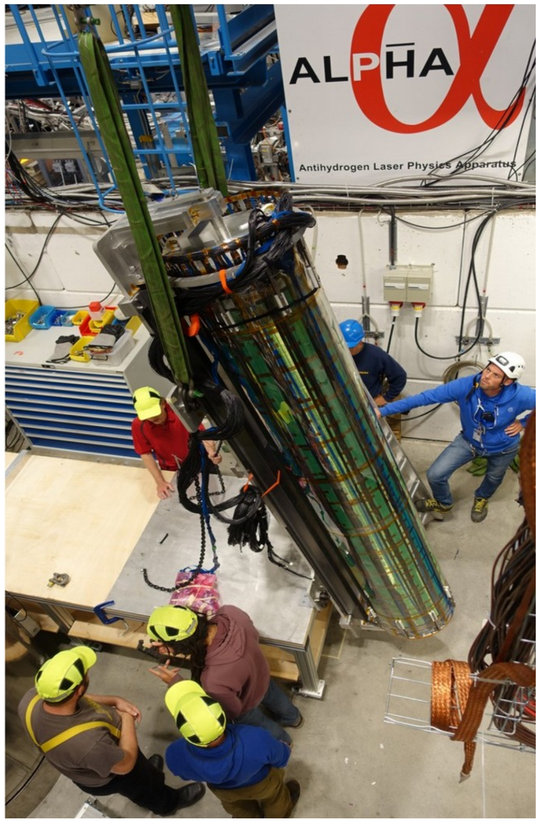

~0.25 m
Cryostat
g
(Copy of)
Production
Region
rTPC
rTPC
~2.3 m
Precision
Measurement
Region
External Solenoid
Trigger/Veto
H̄
Trigger/Veto
External Solenoid
~0.4 m
Production
Region
Free–Fall
Measurement
Region
e+
p̄

The radial Time Projection Chamber (rTPC)

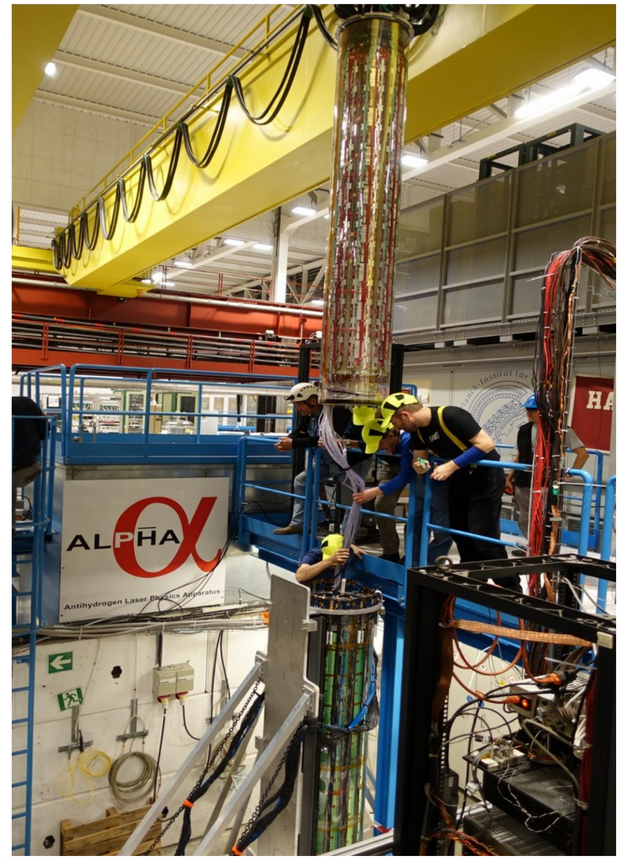


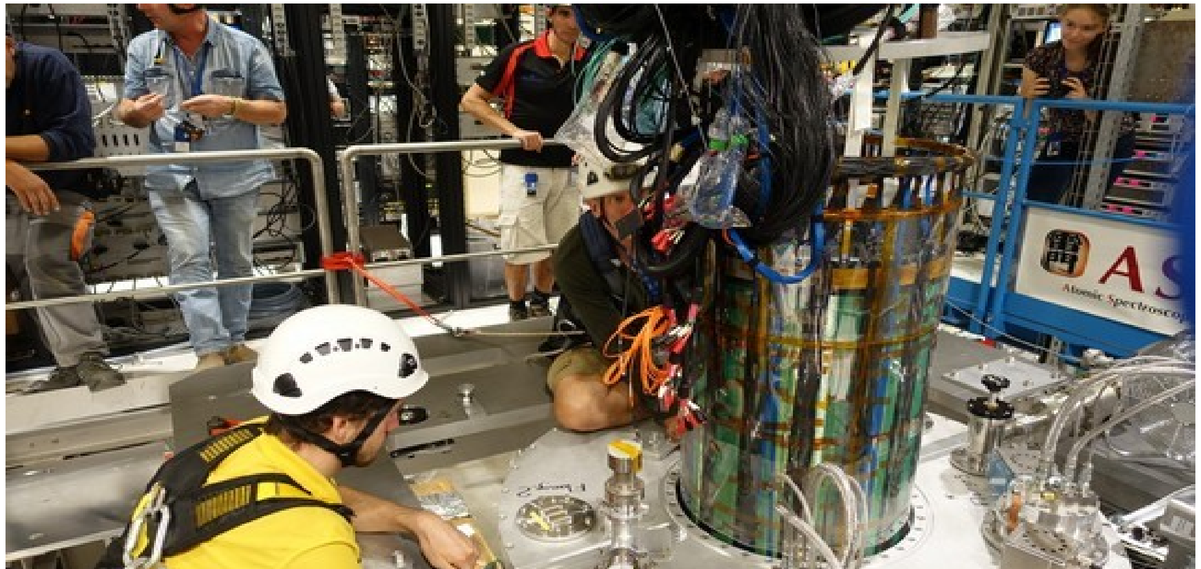
- 2.3 m long, 20 cm inner diameter, 40 cm outer diameter
- 256 wires, 18,432 pads
- Resolutions:
  - ~ 5 mm in z
  - ~ 9 mm in r
  - $\sim 18^{\circ}$ in azimuth



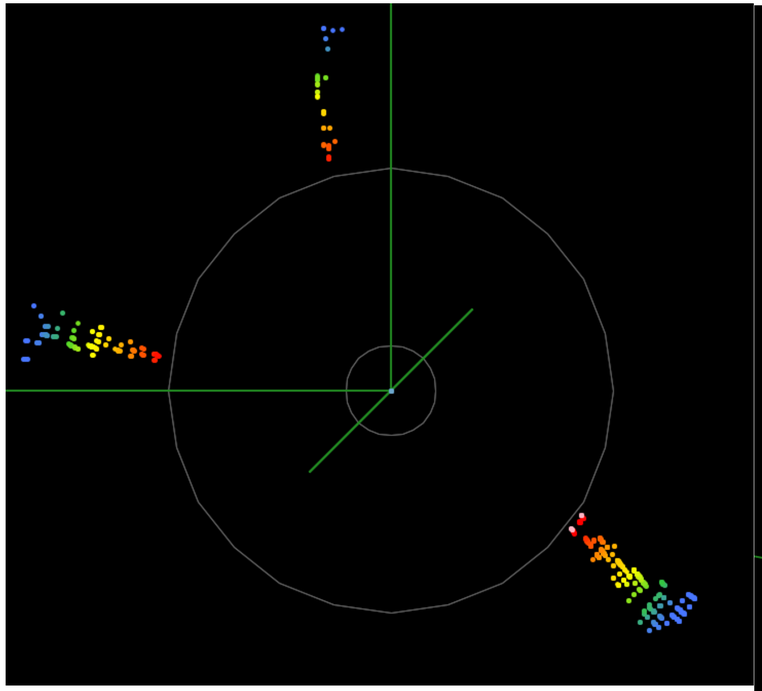

ALPHA
Antihydrogen Laser Physics Apparatus

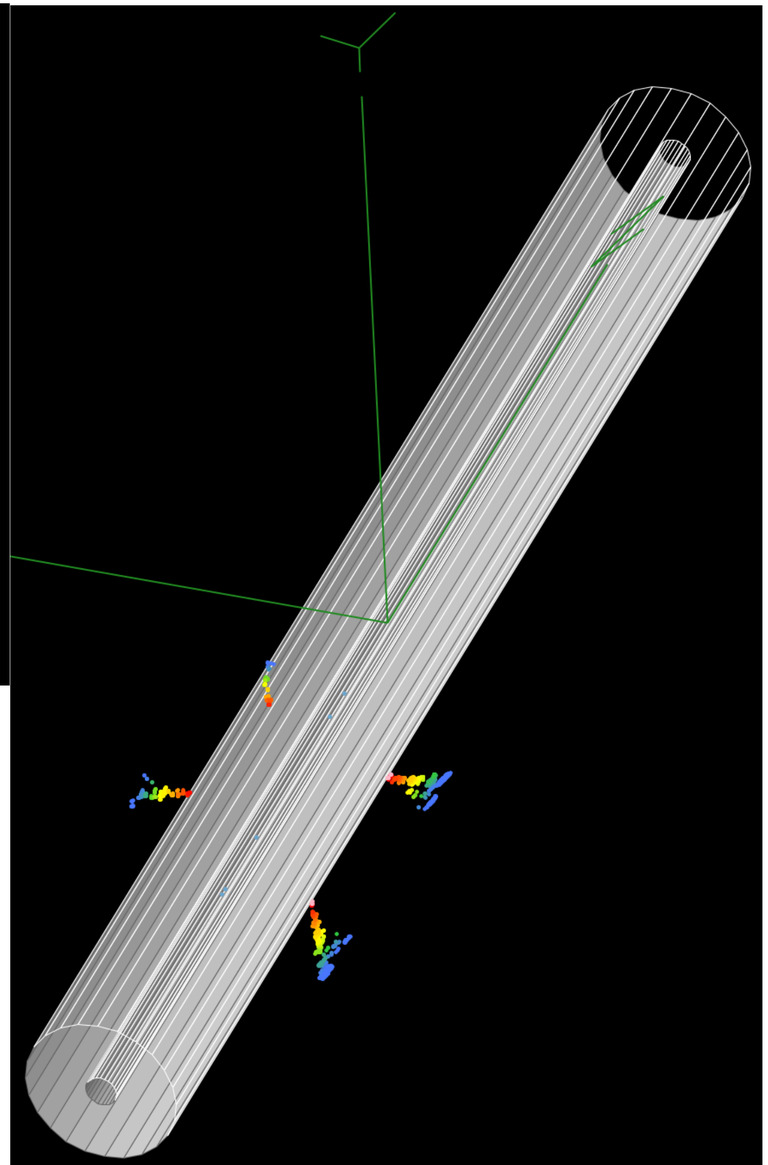

DANGER
LASER

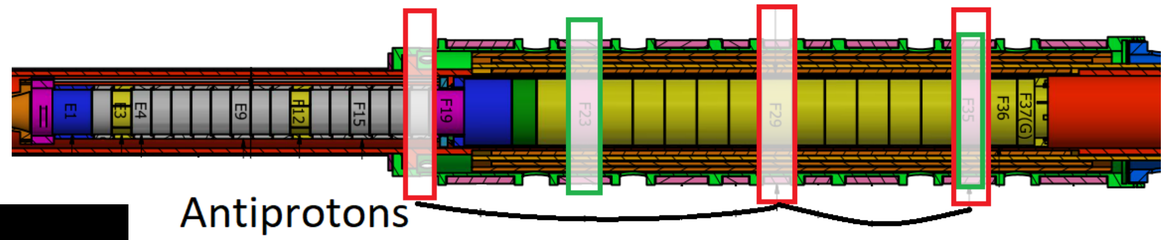

ALPHA
Antihydrogen Laser Physics Apparatus

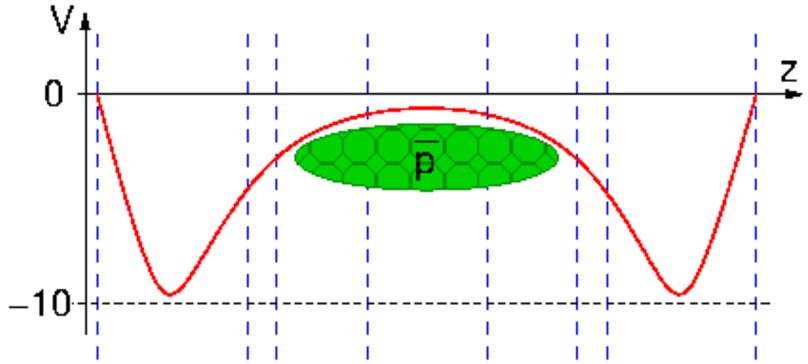


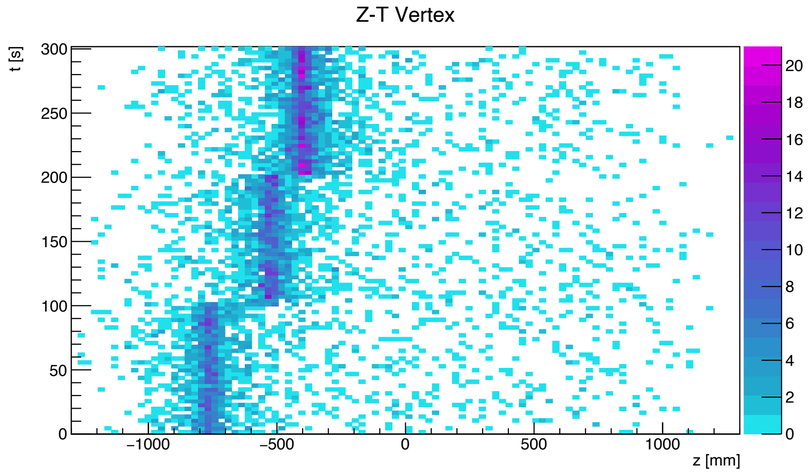
It Worked!



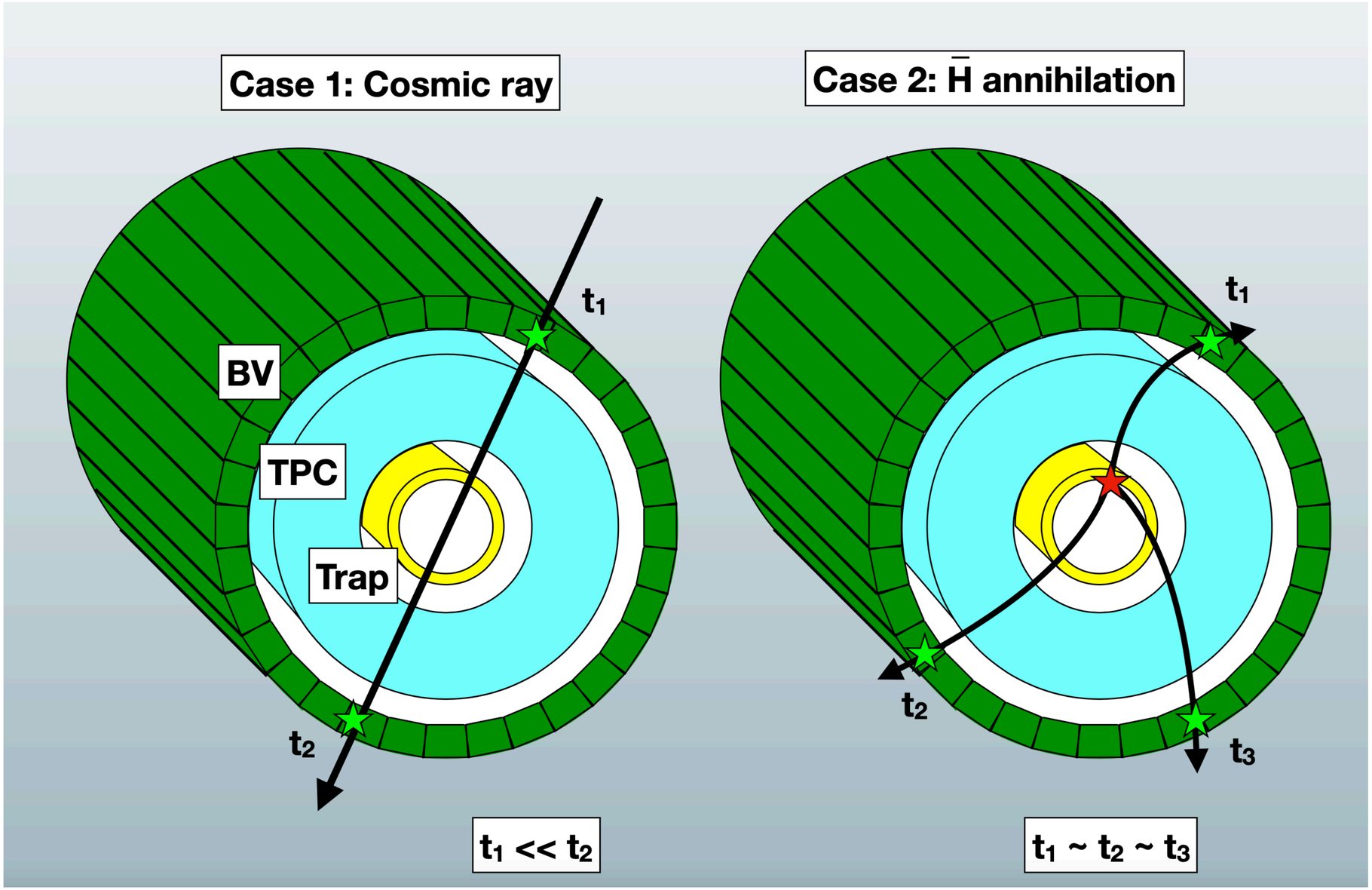


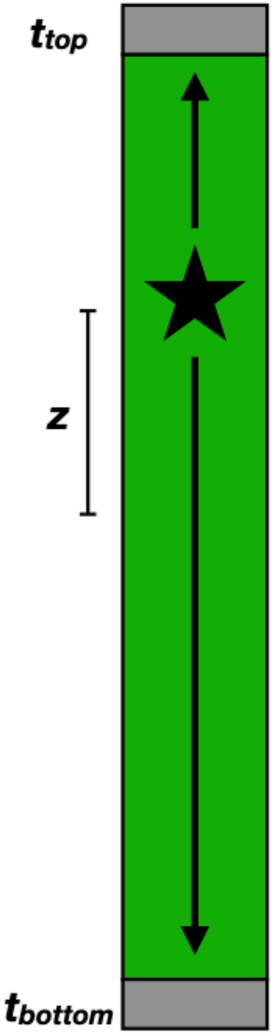

E1
E3
E4
E9
E12
E15
F19
F23
F29
F35
F36
F37(G)
Antiprotons


V
0
z
$\bar{p}$
−10


Z-T Vertex
t [s]
300
250
200
150
100
50
0
−1000
−500
0
500
1000
z [mm]
20
18
16
14
12
10
8
6
4
2
0

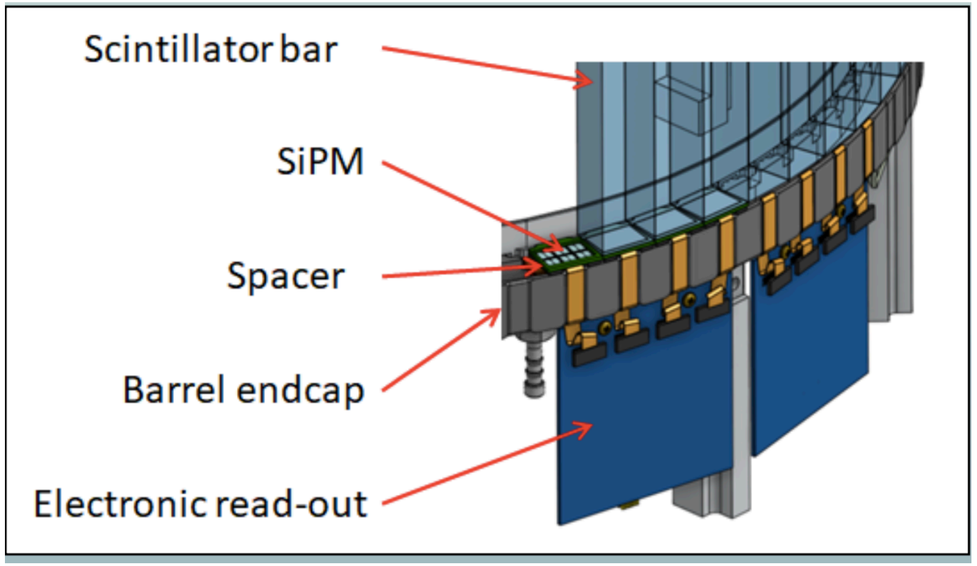
More Cosmic Ray Rejection





The Barrel Cosmic-ray Veto Detector

- 64 scintillator bars running the length of the rTPC
- Time resolution of <300 ps
- Will further reduce the cosmic rate to ~7 Hz



“Dropping” Antihydrogen

For an antihydrogen atom in the trap at vertical location *z* the potential is:

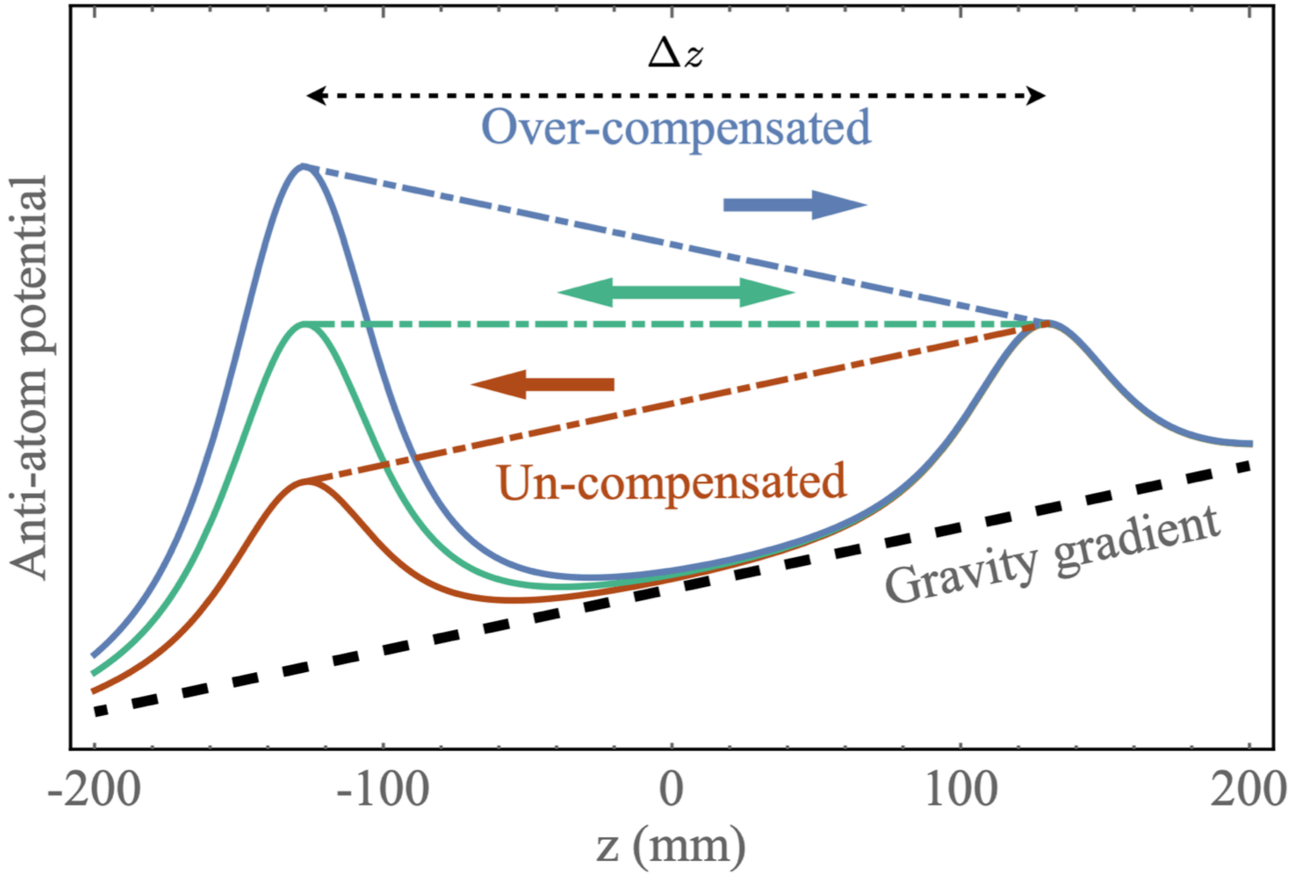
$$U(z) = \mu_B B(z) - m_{\bar{H}} \bar{g} z$$

For $\Delta z = 40$ cm $\rightarrow \Delta U_G \approx 4 \times 10^{-8}$ eV

This corresponds to a magnetic field of

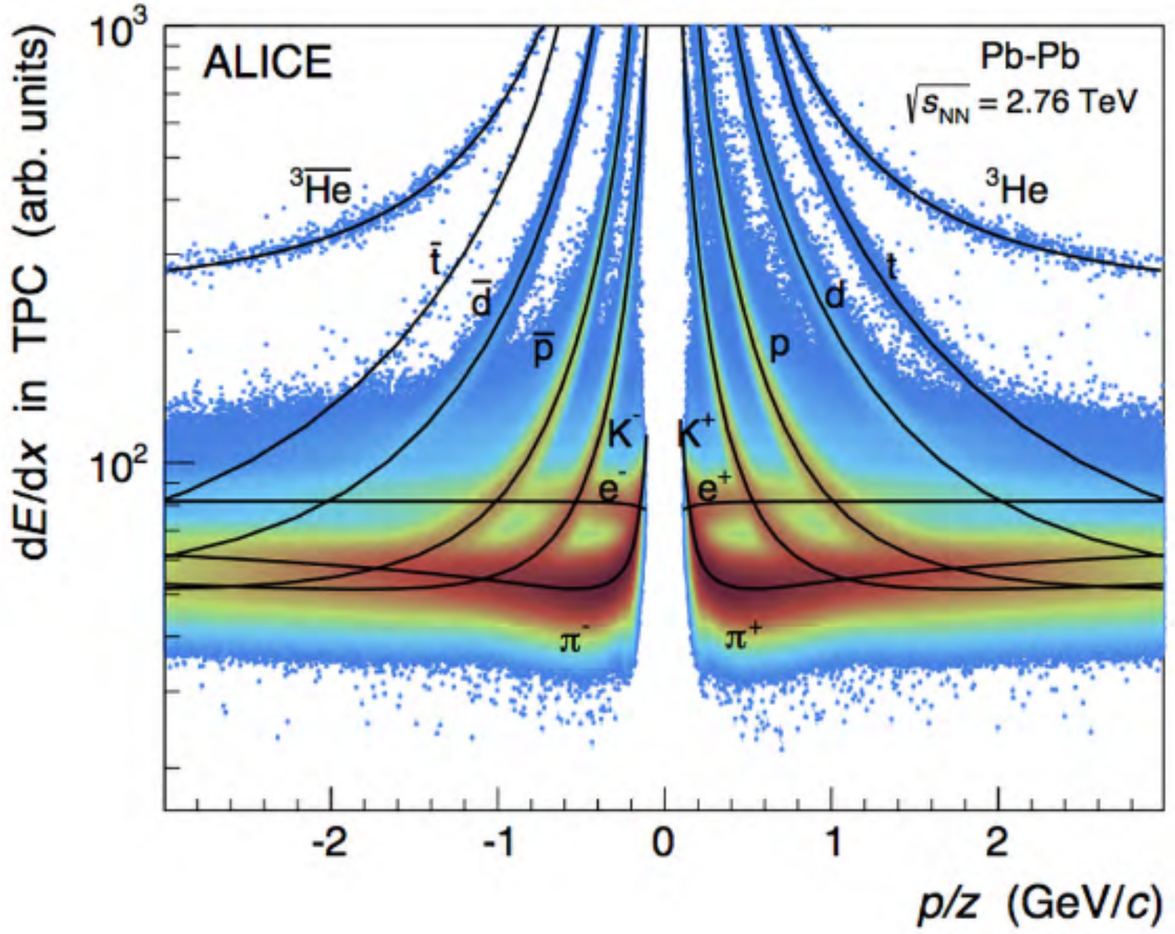
$$\frac{\Delta U_G}{\mu_B} \approx 0.7 \text{ mT}$$

For a 1% measurement must control the magnetic environment to 10^-6 T



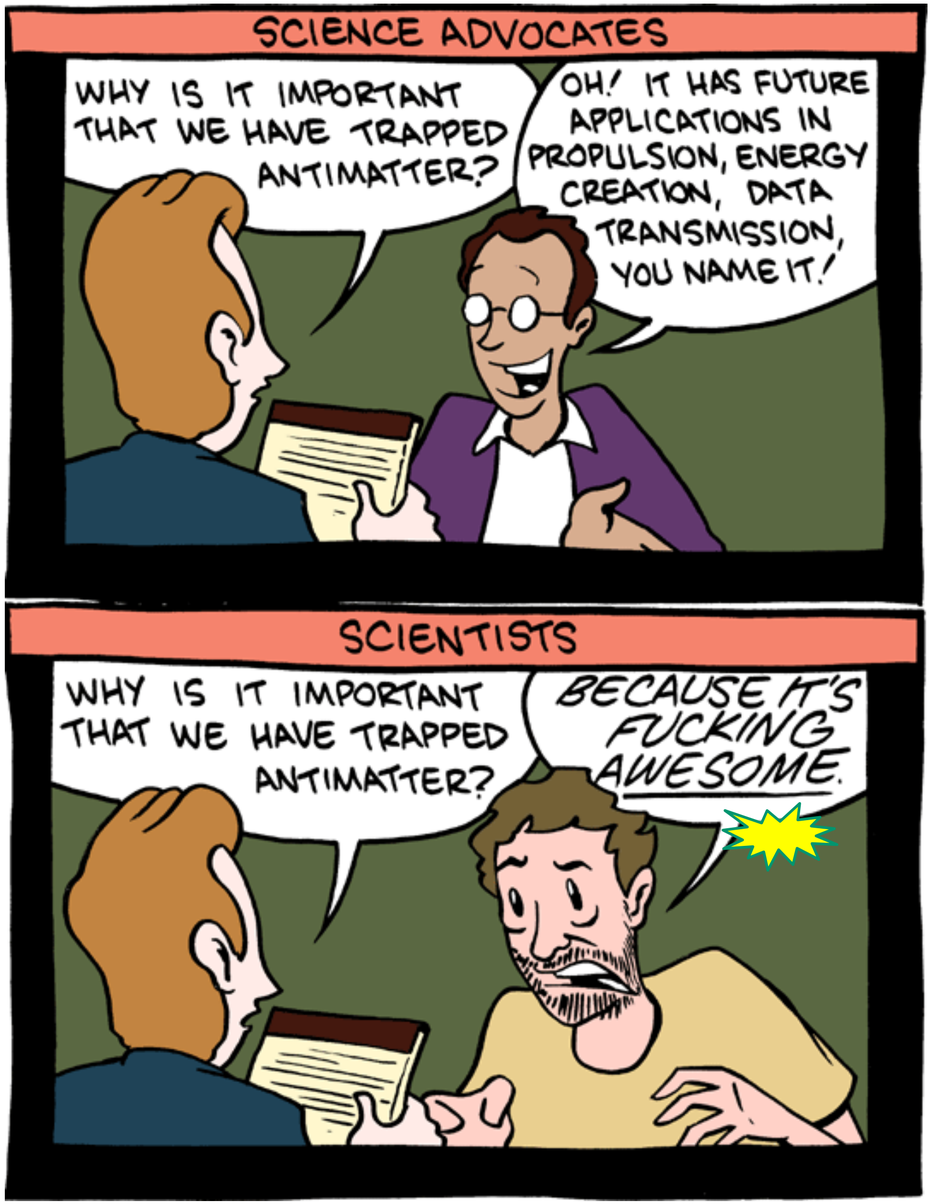
Some Future Plans (Dreams?)

- Antihydrogen Fountain - HAICU
- Antihydrogen Molecule
- Spectroscopy and Gravity test with Deuterium



Conclusions

- ALPHA has made huge gains in learning how to trap 100's of antihydrogen atoms for many hours.
- We have tested CPT Invariance to a part in 10^{12} through measurements of the 1S-2S transition frequency.
- We have demonstrated laser cooling which will allow an improvement of several orders of magnitude on this measurement.
- We are installing ALPHA-g now with the intent to make an "up-down" measurement this year and a 1% test of WEP by 2024.



More information at www.york.ca/menary/experiments/research.html