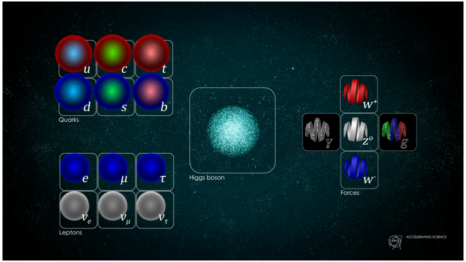
Recent Advancement in Laser Spectroscopy of Antihydrogen and the Progress towards the Measurement of its Gravitational Acceleration

Andrea Capra
on behalf of the ALPHA Collaboration

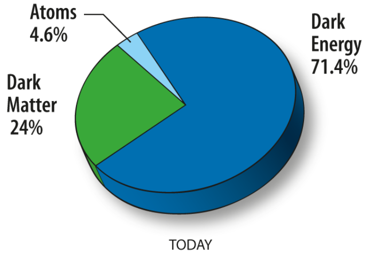
DISCRETE
7 November 2022

Outline

1. Fundamental Symmetries
   - CPT invariance
   - Universality of Free-fall
2. ALPHA-2: the Antihydrogen Spectroscopy Apparatus
   - Antihydrogen Synthesis and Confinement
   - Antihydrogen Detection
   - Antihydrogen Spectroscopy
3. ALPHA-g: the Antihydrogen Gravity Experiment



https://cds.cern.ch



http://www.nasa.gov

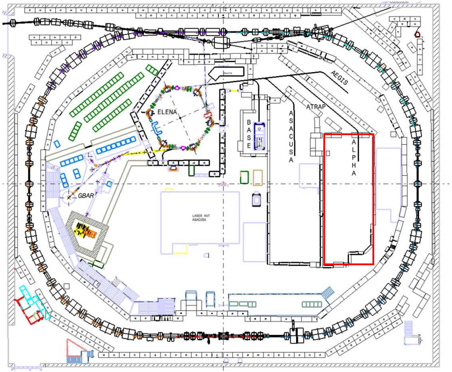
***Snowmass21** Letter of Interest RF3*

«[...] fundamental physics can also be uncovered via indirect effects at lower energies without necessarily exciting new degrees of freedom, but with the requirement of ultrahigh sensitivities.»

- Search for CPT invariance violation
  $\Rightarrow$ comparing matter and antimatter spectra

- Search for deviations from the Universality of Free-Fall (WEP)
  $\Rightarrow$ measuring $\overline{\mathrm{H}}$ gravitational acceleration

Antimatter Factory



https://espace.cern.ch/elena-project

Microwave Spectroscopy	ASACUSA, ALPHA
Laser Spectroscopy	ALPHA, GBAR
Gravity	AEGIS, GBAR, ALPHA-g

ELENA is the new decelerator: 100 keV $\bar{p}$

ALPHA Collaboration

- 50 people
- 17 institutions
- 8 countries

Hydrogen vs. Antihydrogen

- Hydrogen is the best known physical system

  both theoretically,

  e.g., H. A. Bethe and E. E. Salpeter, *Quantum mechanics of one and two-electron atoms* (1977)

  and experimentally,

  e.g., Atomic Data and Nuclear Data Tables **96**, 586-644 (2010)

- Natural linewidth of 1S-2S is $\sim$ 0.001ppt of central frequency $\Rightarrow$ Ideal for CPT tests!

- High-precision spectroscopy on hydrogen $\mathbf{4 \times 10^{-15}}$

  Phys. Rev. Lett. **107** 203001 (2011)

- Recent advancements in $\overline{\mathrm{H}}$ experiments are closing the gap
  - Beam-based experiments, like ASACUSA or AEGIS
  - Trap-based experiments, like ALPHA or GBAR
  - Laser-cooling of $\overline{\mathrm{H}}$ in ALPHA

  Nature **592** (2021)

CPT Invariance Theorem

In abstract: every theory with

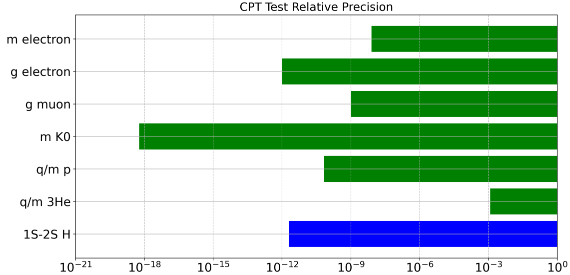
- an Hermitian Hamiltonian $\mathcal{H} = \mathcal{H}^\dagger$
- local operators $\mathcal{O} = \mathcal{O}(\mathbf{x}, t)$,
  constructed from spin zero, one-half and one fields
- usual connection between spin and statistics is valid,
  i.e., fermion fields anticommute $\{\psi_i, \psi_j\} = \delta_{ij}$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

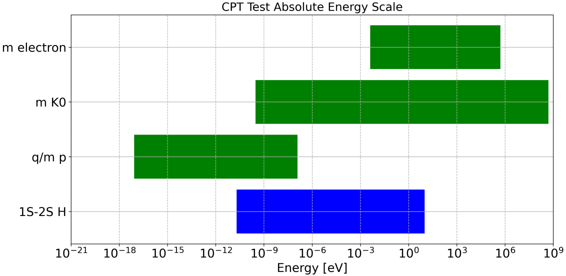
is **invariant** under the combined action of
parity reflection P, *time reversal* T and *charge conjugation* C

G. Lüders, Annals Phys. **2** 1-15 (1957)

$\Rightarrow$ Test of essential features of the Standard Model

CPT Tests

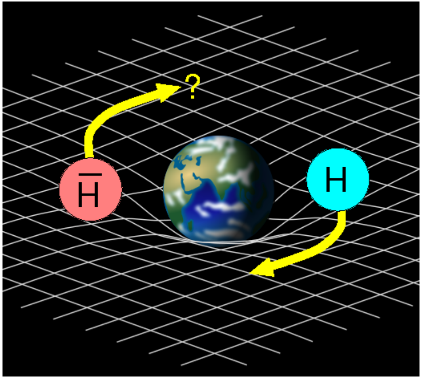




Phys. Rev. D **98** 030001 (2018)
ALPHA collab. Nature **557** 71 (2018)

The Einstein's Equivalence Principle underpins the idea *curved spacetime*

EEP = LLI + LPI + WEP Living Rev. Relativity, **17**, (2014)



- Group of coordinate transformation is the symmetry in GR
- Weak Equivalence Principle:
  All bodies (particles and *antiparticles*) fall with the same acceleration in a terrestrial laboratory.
- Quantum gravity and Grand-Unification models suggest that EEP is violated at some level.

arxiv:gr-qc/0103067v1 arxiv:1006.4106v2

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2. ALPHA-2: the Antihydrogen Spectroscopy Apparatus
   - Antihydrogen Synthesis and Confinement
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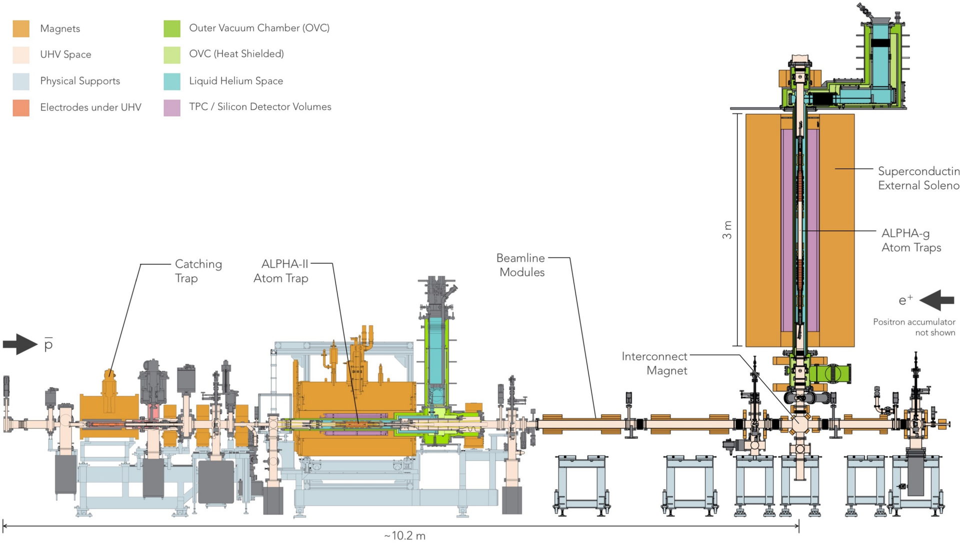
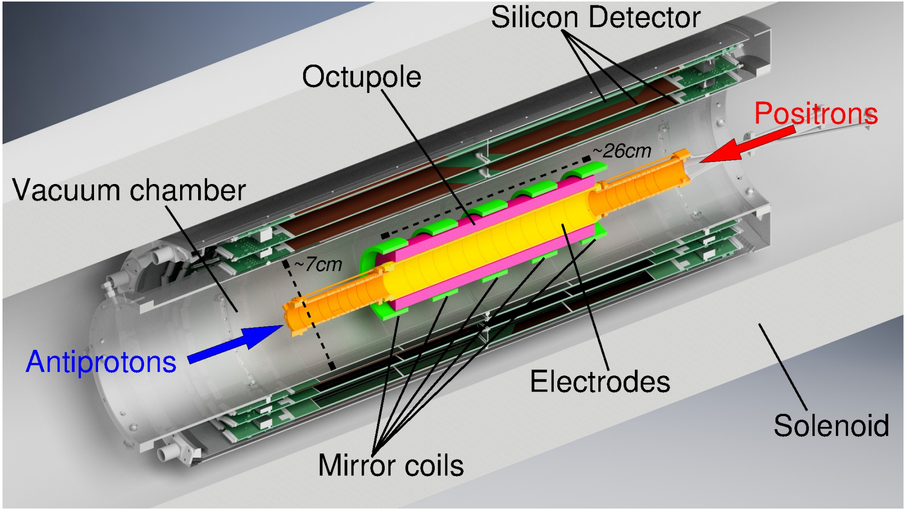
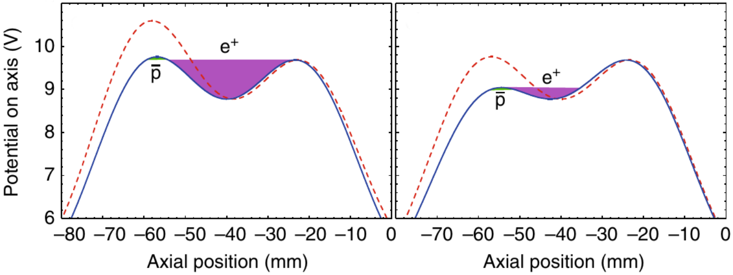
A view of ALPHA-2 and ALPHA-g



The ALPHA Apparatus



see “The ALPHA antihydrogen trapping apparatus”, NIMA (2014)



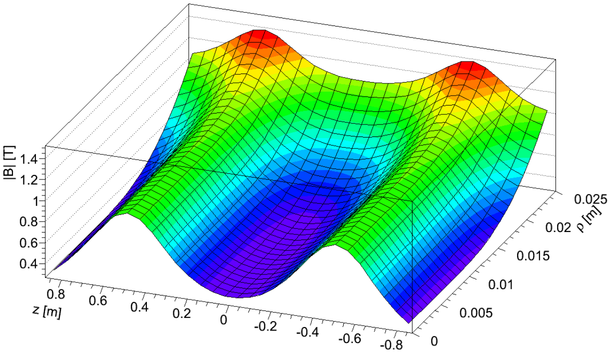
PhotoCredit: ALPHA

- a e^+ and $\bar{p}$ in nested well.
- b e^+ EVC
- c Align of potential wells
- d e^+-$\bar{p}$ mixing

$$e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+$$

Three-body recombination

Phys. Rev. A **69** 010701 (2004)
Phys. Rev. A **70** 022510 (2004)
J. of Phys. B **41** 192001 (2008)



$\overline{\mathrm{H}}$ has a *magnetic dipole moment* - $\boldsymbol{\mu}_{\overline{\mathrm{H}}}$.

A **magnetic field gradient** is used to trap $\overline{\mathrm{H}}$.

$$\boldsymbol{F} = \mu_{\overline{\mathrm{H}}} \nabla B \,,$$

Superposition of magnetic fields, creating **axial and radial confinement**:

- the axial gradient is provided by the *mirror coils* and
- the radial gradient is provided by the *octupole*.

$\boldsymbol{\mu}_{\overline{\mathrm{H}}}$ for ground-state $\overline{\mathrm{H}}$ is dominated by the e $^{+}$ spin: $|\boldsymbol{\mu}_{\overline{\mathrm{H}}}| \sim \mu_B \approx 6 \times 10^{-11}\,\mathrm{MeV\,T^{-1}}$

Magnetic field gradient in ALPHA: $\boldsymbol{\nabla} B \sim \Delta B \approx 0.8\,\mathrm{T}$,

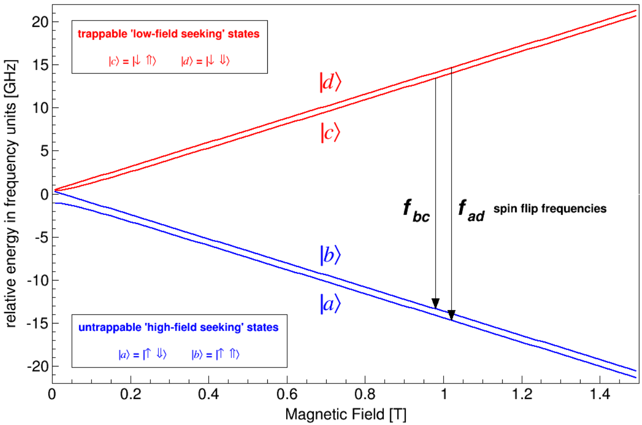
The typical trap depth is therefore $\Delta U \sim \mu_B \Delta B \approx 0.5\,\mathrm{K} \approx 50\,\mu\mathrm{eV}$

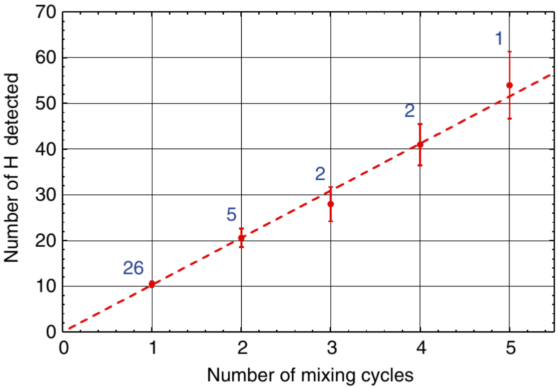
Only “cold” $\overline{\mathrm{H}}$ can be trapped!

$$U = -\mu_{\overline{\mathrm{H}}} \cdot \boldsymbol{U} =$$
$$= -|\mu_{\overline{\mathrm{H}}}||\boldsymbol{B}| \cos(\widehat{\mu_{\overline{\mathrm{H}}}\boldsymbol{B}})$$

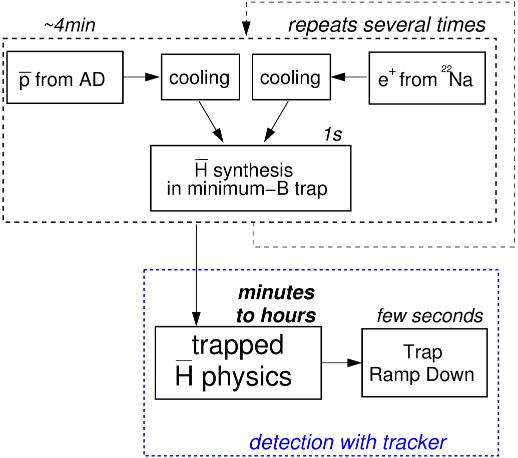
In addition, if $\cos(\widehat{\mu_{\overline{\mathrm{H}}}\boldsymbol{B}}) < 0$

- $\mu_{\overline{\mathrm{H}}}$ is anti-parallel to $\boldsymbol{B}$
- $\overline{\mathrm{H}}$ is called *low-field seeker*
- $\overline{\mathrm{H}}$ is **confined** by the U-minimum



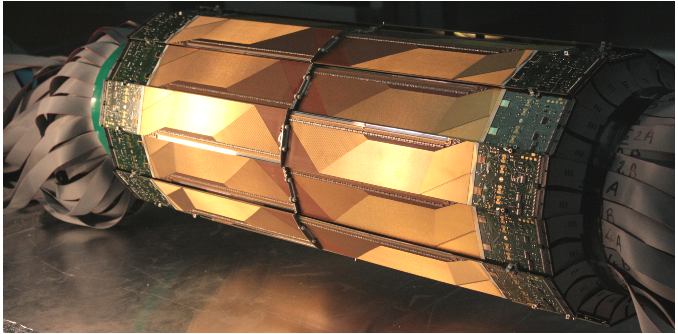


Nat. Comm. **8** 681 (2017)



The ALPHA tracker the *Silicon Vertex Detector* is used to:

- monitor $\overline{\mathrm{H}}$ production
- perform physics measurements
  - Spectroscopic signal comes from $\overline{\mathrm{H}}$ annihilation upon iteraction with radiation
  - Typically the transition from a *trappable* state to an *un-trappable* one



$\overline{\mathrm{H}}$ annihilation with Penning trap electrode

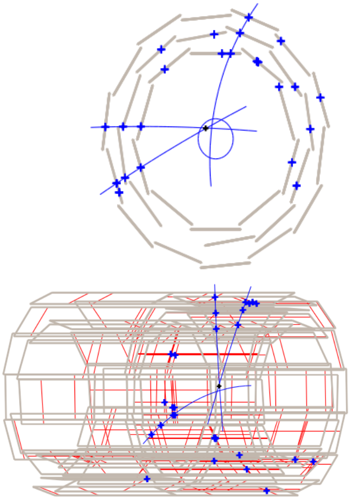
$$\overline{\mathrm{H}} + \mathrm{A} \rightarrow n_+\pi^+ + n_-\pi^- + m\pi^0 + 2\gamma$$

$\pi^\pm$ from $\overline{\mathrm{p}}$ annihilation are detected by the

- **Silicon Vertex Detector**
  - double-sided microstrip tracker

$\overline{\mathrm{H}}$ annihilation position $\Longleftrightarrow$ the *vertex*:

1. hits position from clusters of strip,
2. reconstruction of *tracks* from hits,
3. tracks selection, $\pi^\pm$ -like,
4. determine the point where the tracks pass closest to each other.



Events **unrelated** to $\overline{\text{H}}$ annihilation are background:

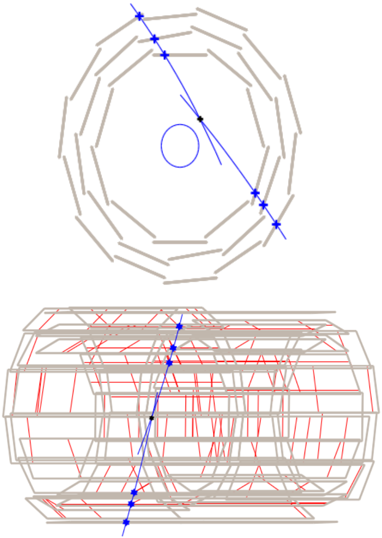
- Un-bound $\overline{\text{p}}$, since e $^{+}$ annihilation is not detected.
- Cosmic rays, mainly $\mu^{\pm}$, occur at all times.

Two methods used for cosmic ray rejection

- Cuts on reconstructed vertex radius and on "straightness" of tracks
  - Efficiency: 68%
  - False-positive rate: 47mHz

    Nucl. Instrum. Meth. **A684** 73 (2012)
- Machine Learning - *Boosted Decision Tree*
  - Efficiency: 40%
  - False-positive rate: 4mHz

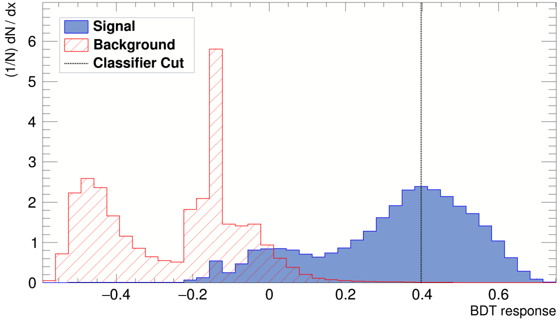
    J. of Phys. **1085** 042007 (2018)

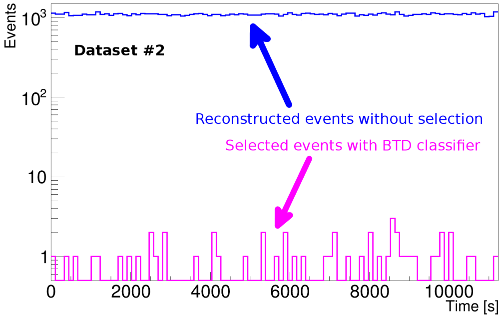


Application of ML to Antihydrogen Detection

Lifetime of Trapped $\overline{\mathrm{H}}$: $>$ **66 hours** Hyper. Int. **240** (2019)

- more than 7 hours of $\overline{\mathrm{H}}$ confinement
- more than 1000 $\overline{\mathrm{H}}$ trapped
- stacking more than 100 $\overline{\mathrm{H}}$ synthesis

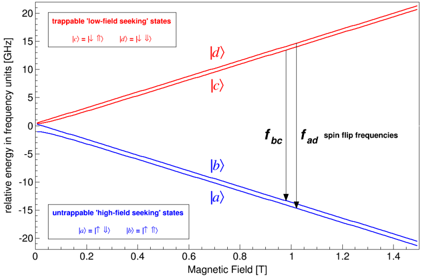


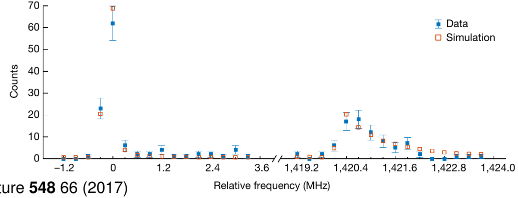


Spectroscopy

- Ground State Hyperfine Splitting
- Two-photons 1S-2S
- Lyman-α 1S-2P

Spectroscopy GS HFS





Nature **548** 66 (2017)

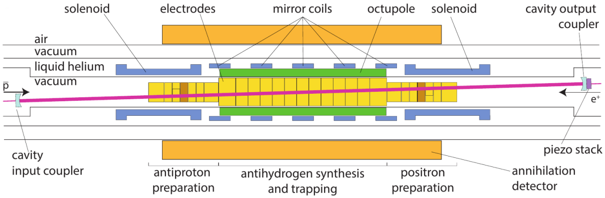
- **Resonant** e^+ spin flip: transition from trapped to un-trapped states

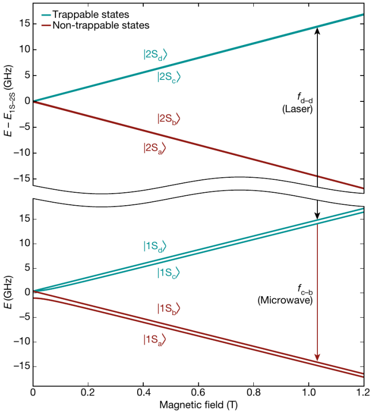
  Nature **483** 439 (2012)

  $|c\rangle \to |b\rangle$ and $|d\rangle \to |a\rangle \sim 29\,\text{GHz}$ @ 1 T

- Ground State Hyperfine Splitting: $1420.4 \pm 0.5\,\text{MHz}$
- CPT test at 10^{-4} level

Outline of Spectroscopy 1S-2S

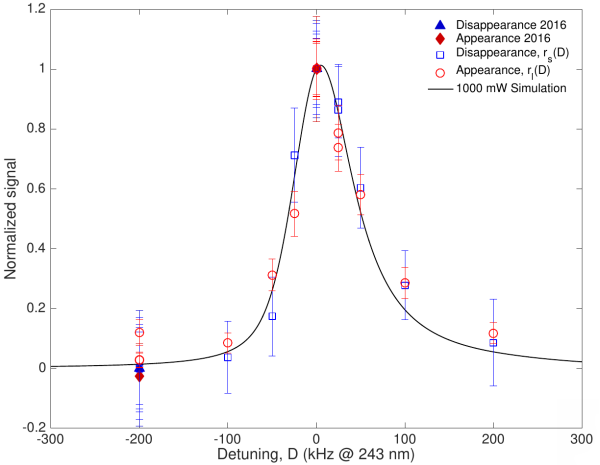




Nature **557** 71 (2018)

1. Trap antihydrogen (3 mixing cycles, $\sim$40 atoms)
2. Clear out any remaining charged particles
3. 300s laser exposure at fixed frequency near $|1S,d\rangle \rightarrow |2S,d\rangle$ transition
4. 32s microwave sweep to eject $|1S,c\rangle$
5. Ramp down magnets to detect remaining atoms

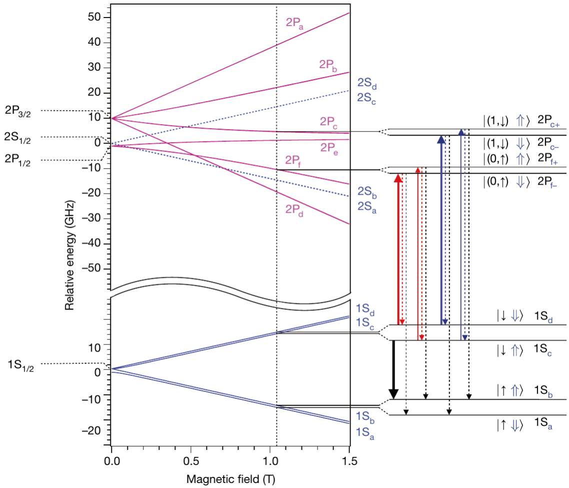
Result of Spectroscopy 1S-2S



$$f_{d-d} = 2466061103079.4(5.4) \text{ kHz}$$

Consistent with CPT at 2×10^{-12}

- The $|1S,c\rangle \rightarrow |2S,c\rangle$ has a larger Zeeman brodening and was not considered in this measurement
- Two "counting" channels:
  Appearance Spin-flip and ionization.
  Disappearance Surviving $\overline{H}$.
- The main contribution to the linewidth is the *transit time broadening*.



- Many hours of irradiation with 121.6 nm light (0.5 nJ per 12 ns pulse)
- 1S-2P at 1T with precision of 16ppb
- Fine-structure ($2P_{1/2}$-$2P_{3/2}$ splitting) measurement: (10.88 ± 0.19)GHz
- Combined with the 1S-2S measurement, the Lamb shift ($2S_{1/2}$-$2P_{1/2}$ splitting) is consistent with theory to 11%

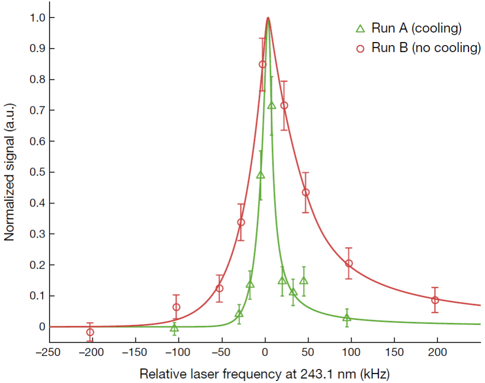
Nature **578** (2020)

1. Stacking 500-1000 $\overline{\text{H}}$ (10 orders of magnitude less than H experiments)
2. Sample polarization with Microwave
3. Doppler cooling/heating on $|1S,d\rangle \rightarrow |2P_{a-}\rangle$ transition (2 to 4 hours)
4. Probing on $|1S,d\rangle \rightarrow |2P_{c-}\rangle$
   - TOF is used to determine perpendicular energy.
   - Median energy reduced by a order of magnitude, 15 to 1.3 μeV.

Nature **592** (2021)

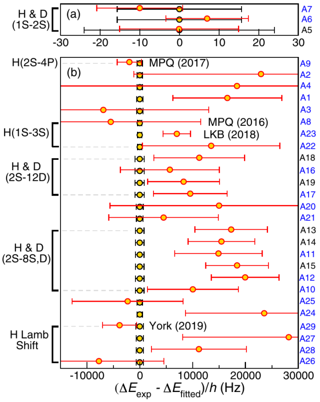
Stacking while cooling (9h) and additional cooling (6h), then spectroscopy (2h)

Dramatic effect on 1S-2S linewidth



Outlook

- Improve precision of 1S-2S frequency measurement
  - ALPHA current measurement is outside panel (a).
  - Measurement at different low magnetic fields to infer zero-field transition frequency.
- Measurement of $\bar{p}$ charge radius
  - Two-photons 1S-3S transition at 205nm
- Measurement of the Lamb shift
  - Microwave transition 2S-2P, following 2S states preparation
  - $2S_d - 2P_f$ is 24GHz @ 1T
  - Precision limited by 2P lifetime
  - Challenging background (Lyman-α detection helps)



Rev. Mod. Phys. **93** (2021)

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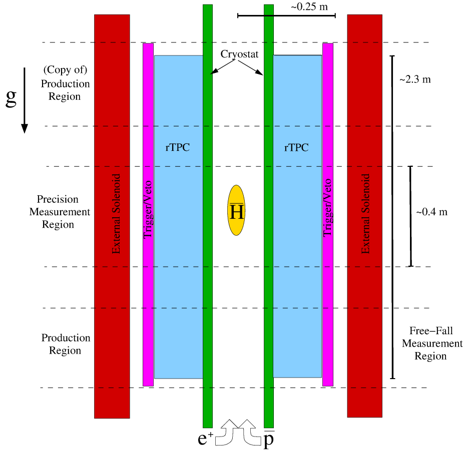
The ALPHA-g Apparatus

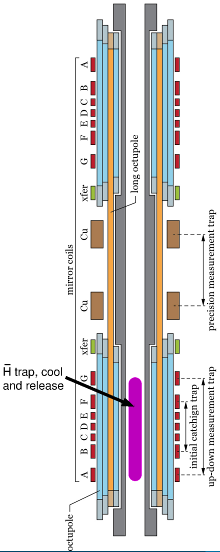


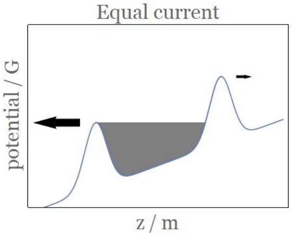
- Vertical $\overline{\mathrm{H}}$ trap for gravity measurement
- Double-ended design to minimize systematics
- Trap (and cool) $\overline{\mathrm{H}} \Rightarrow$ controlled release
- Detection of population vs. z

Goals:

- Unambiguous observation of $\overline{\mathrm{H}}$ free-fall
- Measurement of $\overline{\mathrm{H}}$ gravitational acceleration to 1%

Free-Fall of Antihydrogen

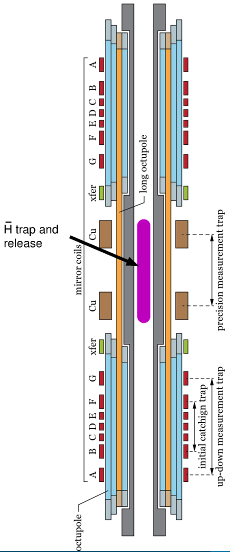


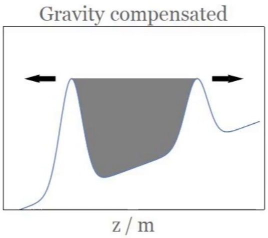


Credit: C. So

- Equal current in mirror coils A and G $\Rightarrow$ larger fraction of bottom $\overline{\mathrm{H}}$ annihilation

The Gravitational Acceleration of Antihydrogen

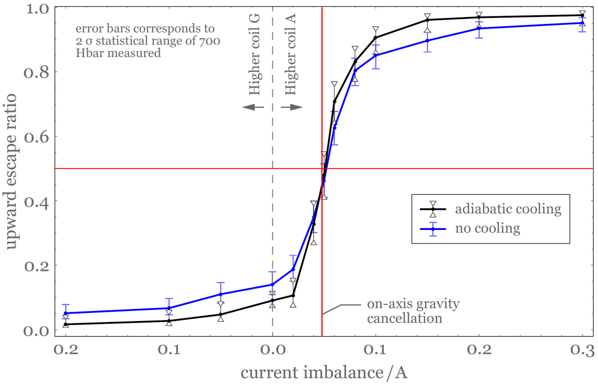




Credit: C. So

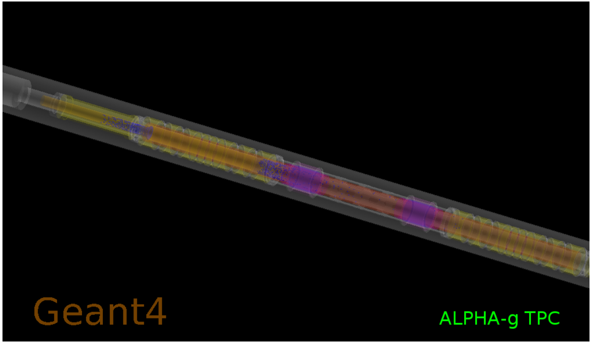
- Gravity compenseted current in mirror coils A and G $\Rightarrow$ equal fraction of $\overline{\mathrm{H}}$ annihilation

Scan of currents in coils A and G $\Rightarrow$ gravity compesation

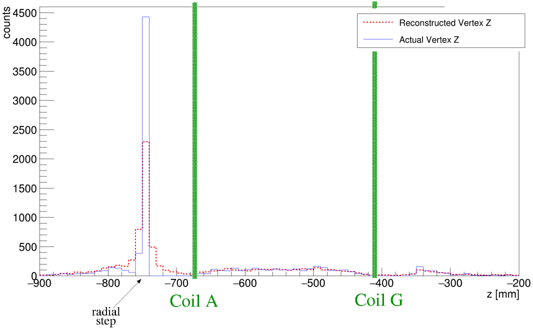


- Knowledge of magnetic field to 10^{-6} T
- Magnetometry to detemine systematics
- $\overline{\mathrm{H}}$ cooling to increase sensitivity (slope)
- Monitor rTPC efficiency
- Slow coils ramp down
- Control cosmic ray background

End-to-End Simulation



Monte Carlo starting from simulation of $\overline{\mathrm{H}}$ dynamics with gravity



Compatible at 97.8% level

Summary

- $\overline{\text{H}}$ is a portal to search for new fundamental physics by testing the CPT symmetry and the Weak Equivalence Principle
- The ALPHA experiment has developed the technology to test $\overline{\text{H}}$
- 1S-2S spectroscopy provides current best CPT invariance test at 2ppt level
- Demonstration of laser cooling is a milestone
- Gravity Experiment is underway at the CERN AD

Additional Material

Cosmological model:
Standard Big Bang with Hubble law confirmed by, e.g., CMB measurement

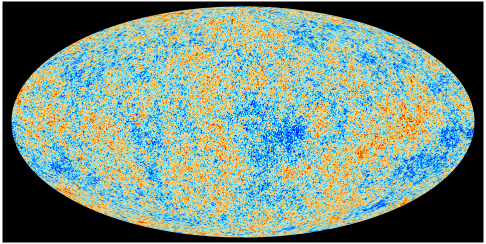
SM prediction:

$$\frac{\text{Baryon}}{\text{Photon}} \sim 10^{-18} \qquad \frac{\text{Baryon}}{\text{Antibaryon}} \sim 1$$

Observation:

$$\frac{\text{Baryon}}{\text{Photon}} \sim 6 \times 10^{-10} \qquad \frac{\text{Baryon}}{\text{Antibaryon}} \sim 10^{4}$$

Planck 2018 results, arXiv:1807.06209v4
WMAP 9 Years, arXiv:1212.5225v3



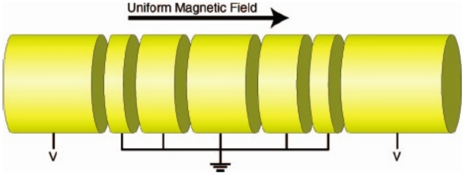
Many orders of magnitude discrepancy!

A **Penning trap** combines electric and magnetic fields to hold charged particles.

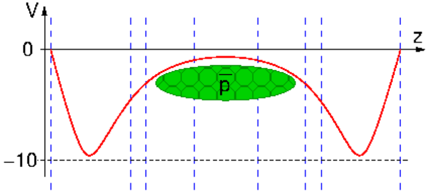
$\bar{p}$ are slowed down through a *degrader* and cooled in a Penning trap by means of:

- *electron cooling*
- *evaporative cooling* Phys. Rev. Lett. **105** 013003 (2010)

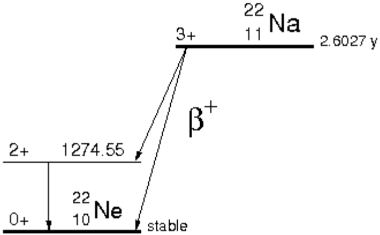
$\bar{p}$ are compressed (radially) to minimize losses and maximize chances to recombine with e^+ : the *rotating wall* technique Phys. Rev. Lett. **100** 203401 (2008)



PhotoCredit: ALPHA

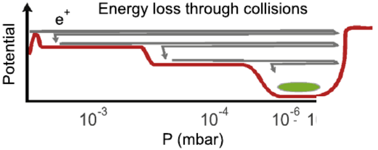


Positrons Preparation



- e^+ are emitted by a $^{22}\mathrm{Na}$ radioactive source.
- e^+ are slowed down by a solid Ne moderator.
- e^+ are cooled by collisions with $\mathrm{N_2}$.

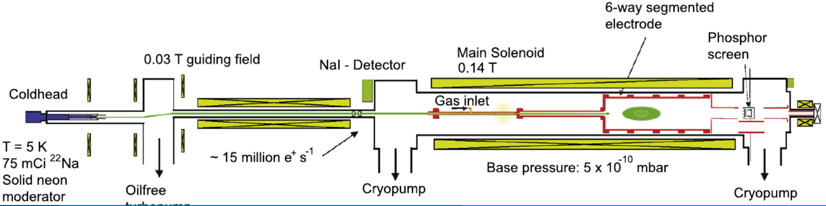
Phys. Rev. A **46** 5696 (1992)



e^+ are prepared using SDREVC technique:
evaporative cooling combined with *rotating wall*

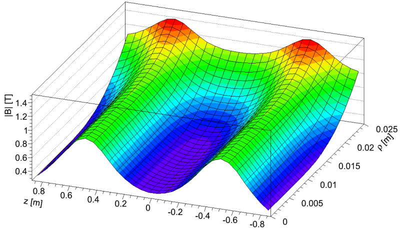
Phys. Rev. Lett. **120** 025001 (2018)

PhotoCredit: ALPHA

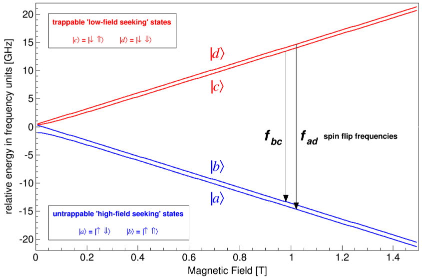


Antihydrogen Traps - ALPHA

$$\boldsymbol{F} = \mu_{\overline{\text{H}}} \cdot \nabla \boldsymbol{B}$$



$\nabla \boldsymbol{B}$



ALPHA confines $\overline{\text{H}}$ by means of superconducting magnets:

- axial confinement $\Leftarrow$ *mirror coils*
- radial confinement $\Leftarrow$ *octupole*

- $\mu_{\overline{\text{H}}}$ is anti-parallel to $\boldsymbol{B}$
- $\overline{\text{H}}$ is called *low-field seeker*
- $\overline{\text{H}}$ is confined in the potential minimum

Metrology:

$$2R_\infty hc = \alpha^2 m_e c^2$$

Since h and c are exact in the revised SI

- Measurement of 2 lines determines, e.g., R_∞, α, and constrains m_e
- Alternatively, measuring all three constants confirms the validity of the equation.

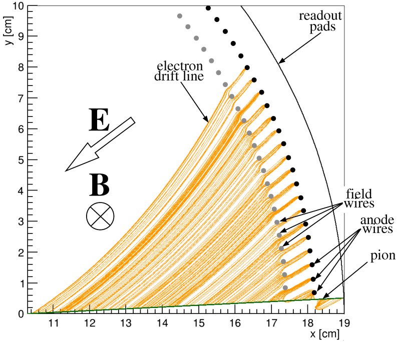
New Challenge from ALPHA-2 to ALPHA-g:

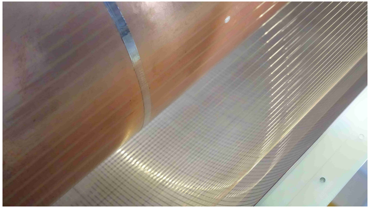
- $3\times$ the number of $\overline{\mathrm{H}}$ traps $\Rightarrow$ $3\times$ the active volume
- Position sensitivity $\Rightarrow$ tracker
- Gas detector for a uniform coverage of trapping regions $\Rightarrow$ Time Projection Chamber
- *Radial* design to minimize the effect of the external solenoid fringing field
- Help cosmic ray rejection with additional detector $\Rightarrow$ Scintillator bars (barrell)

Gas detector to track charged particles produced by $\overline{\mathrm{H}}$ annihilation.
rTPC was entirely built at TRIUMF JPS Conf. Proc. **18** (2017)

- 2.3 m active length
- 8 cm drift path
- 180 litres of Ar-CO_2 70:30
- 256 anodes (sensing wires)
- 576×32 pads
- cathode -4 kV, anodes 3.2 kV

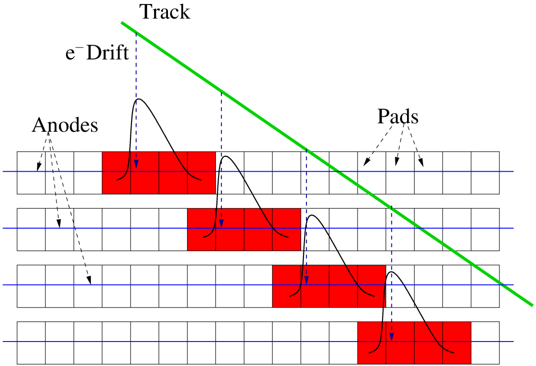
Reconstruction of rTPC



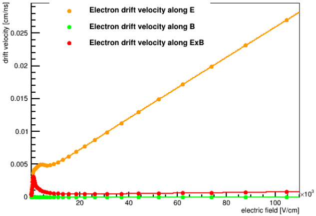


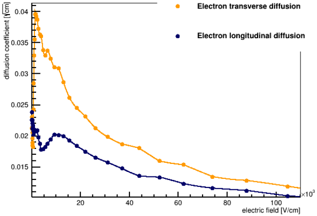
Spacepoints Reconstruction:

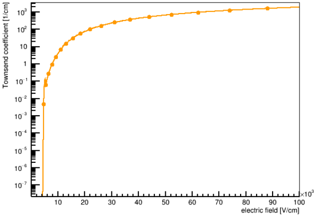
- e^- *drift time* ⇒ Radial coordinate
- Anode position ⇒ Azimuthal coordinate
- Charge induced on pads ⇒ Axial coordinate

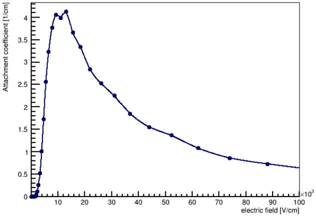


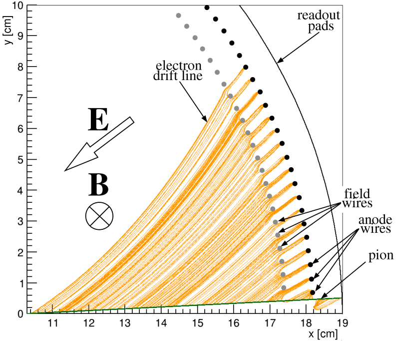
The design of the detector (2014-2016) required lots of simulations



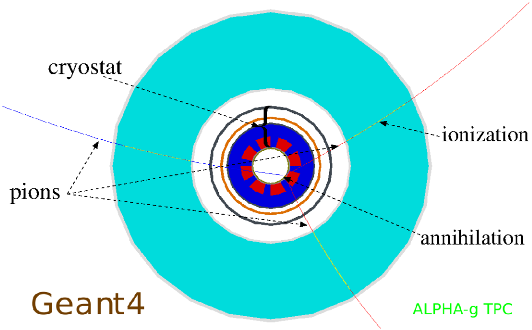


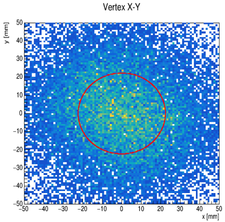


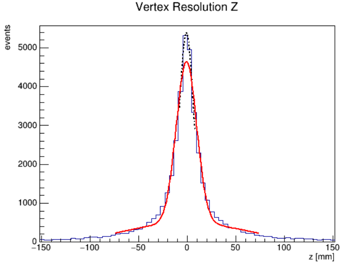




Performance evaluation with Monte Carlo







$z : (7.7 \pm 0.2)$ mm