Observation of gravitational free-fall of antimatter with ALPHA-g at CERN and future development with HAICU at TRIUMF

Andrea Capra
on behalf of the ALPHA Collaboration

2024 CAP Congress

Antihydrogen Experiments

- 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)

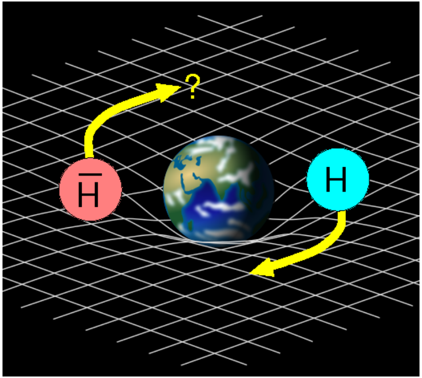
- Hydrogen-antihydrogen spectra comparison $\Rightarrow$ test CPT invariance violation

- Measurement of antihydrogen gravitational acceleration $\Rightarrow$ search for deviations from the Universality of Free-Fall (WEP)

  $\overline{\mathrm{H}}$ = antihydrogen

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

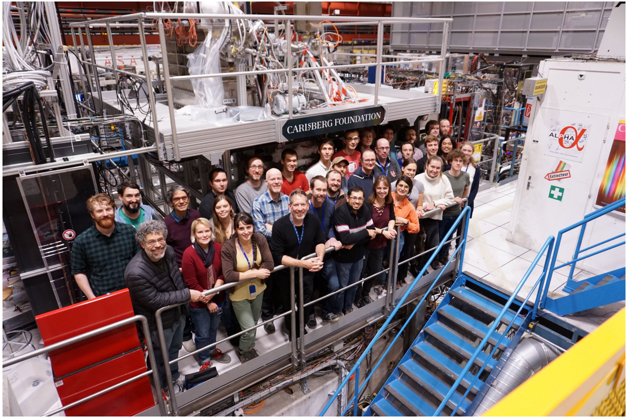
EEP = LLI + LPI + WEP Living Rev. Relativity, **17**, (2014)



- Group of coordinate transformation is the symmetry in GR
- Weak Equivalence Principle:
  All bodies (particles and *antiparticles* alike) 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

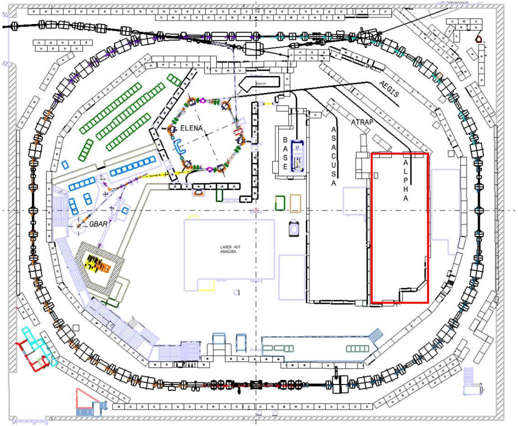
ALPHA Collaboration



~55 people from 18 institutions in 9 countries

https://alpha.web.cern.ch/

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



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

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

A view of ALPHA-2 and ALPHA-g

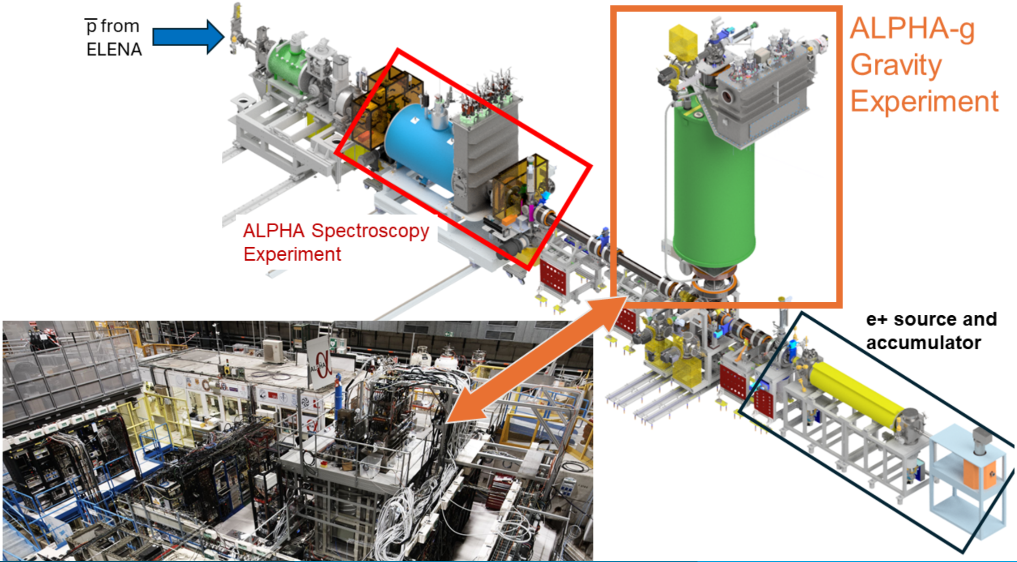
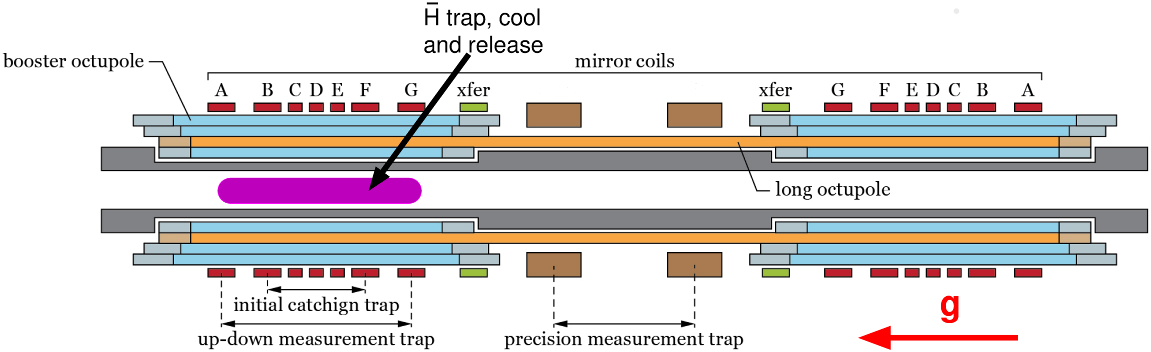


Illustration by Sandbox Studio, Chicago with Steve Shanabruch

- Produce and trap $\overline{H}$
- Controlled release
- Detection of population (annihilation) vs. position

Goals:

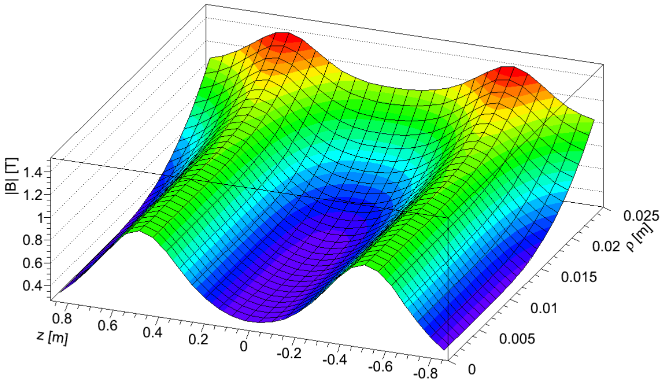
- Measure $\overline{H}$ gravitational acceleration to 1% precision



Credit: C. So

Vertical H̄ trap for gravity measurement

Double-ended design to minimize systematic



Confinement due to superposition of magnetic fields

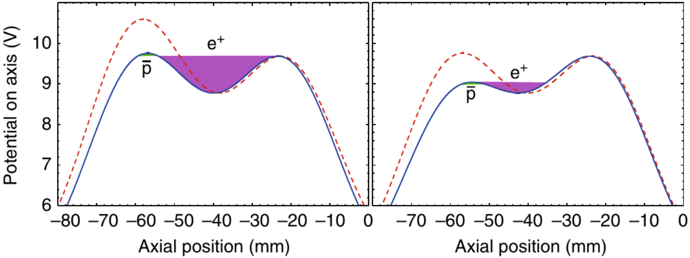
$\overline{\mathrm{H}}$ magnetic dipole moment
$|\boldsymbol{\mu}_{\overline{\mathrm{H}}}| \sim \mu_B \approx 6 \times 10^{-11}\,\mathrm{MeV\,T^{-1}}$.

Magnetic field gradient used to trap $\overline{\mathrm{H}}$: $\nabla B \sim \Delta B \approx 0.8\,\mathrm{T}$

Only "cold" $\overline{\mathrm{H}}$ can be trapped!
$\Delta U \sim \mu_B \Delta B \approx 0.5\,\mathrm{K} \approx 50\,\mu\mathrm{eV}$

Only $\boldsymbol{\mu}_{\overline{\mathrm{H}}}$ anti-parallel to $\boldsymbol{B}$ can be **confined** by U-minimum **low-field seeker**

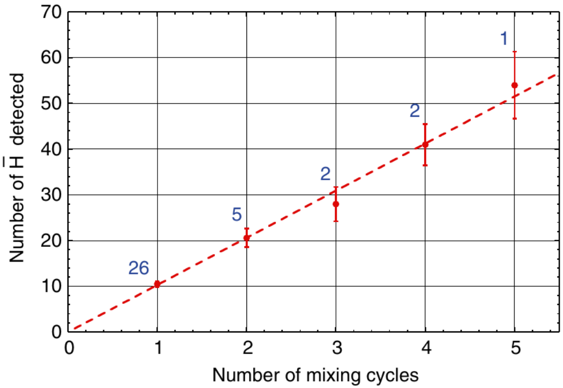
- e^+ and $\bar{p}$ confined in a Penning trap
- $\bar{H}$ formation in three-body recombination process: $e^+ + e^+ + \bar{p} \rightarrow \bar{H} + e^+$



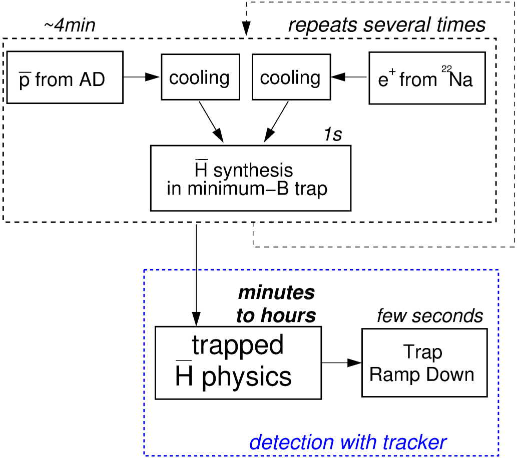
PhotoCredit: ALPHA

1. e^+ and $\bar{p}$ in nested well.
2. Align of potential wells [left]
3. e^+ -$\bar{p}$ mixing [right]

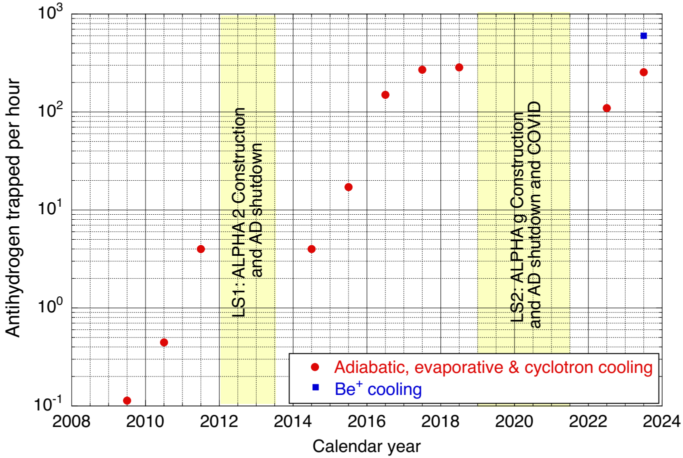
Phys. Rev. A **69** 010701 (2004)
Phys. Rev. A **70** 022510 (2004)
J. of Phys. B **41** 192001 (2008)



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

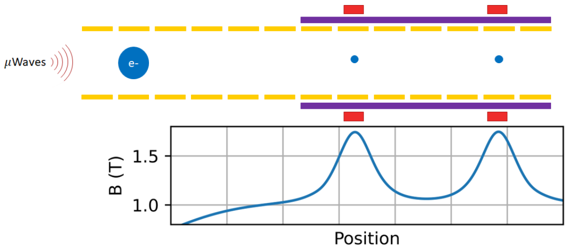


Recent Progress in Antihydrogen Trapping



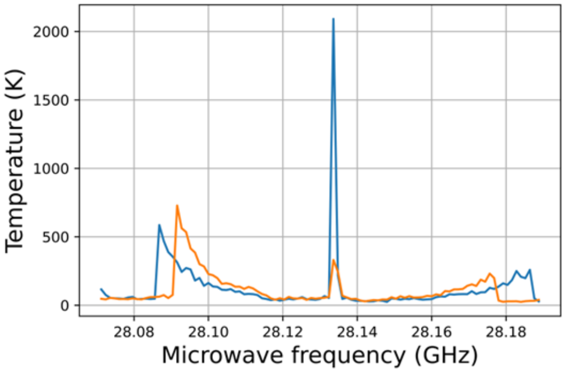
- Magnetic field measurement from response of e^- to microwave
- Temperature increase near cyclotron resonance $\frac{eB}{2\pi m_e}$

New J. Phys. **16**, 013037 (2014)



- B field map by rapid repetition of ECR

Phys. Plasmas **27**, 032106 (2020), Rev. Sci. Instrum. **91**, 103502 (2020)



- Precision related to peak width
- Broad, asymmetric sidebands from electrons axial motion

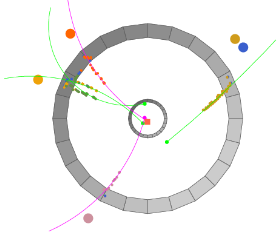
The ALPHA-g Detectors

- Position sensitive tracker detector ⇒ Time Projection Chamber
  - $\overline{\mathrm{H}}$ annihilation detection/reconstruction
  - *Radial* design to minimize the effect of the external solenoid fringing field
  - rTPC entirely built at TRIUMF JPS Conf. Proc. **18** (2017)

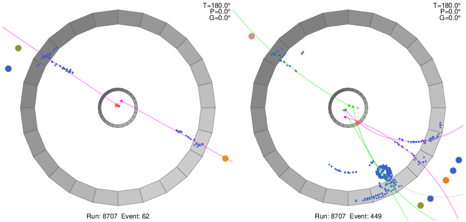
2.3 m active length, 180 litres of Ar-CO_2, 256 sensing wires, 18688 channels

- Additional cosmic ray rejection ⇒ Barrell SCintillator (topic for another meeting)
- More on rTPC and annihilation reconstruction by A. Ferreira

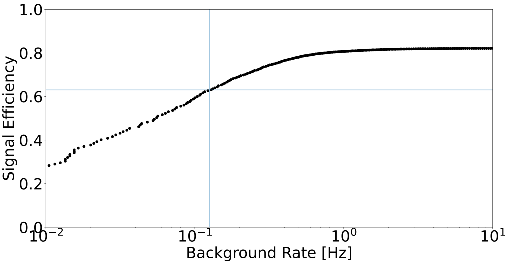
p̄ annihilation



Cosmic rays



- Major source of background: cosmic rays $\sim 70\,\mathrm{Hz}$
- Boosted Decision Tree [TMVA arXiv:physics/0703039]



Credit: L. Golino and J.T. McKenna

ALPHA TRIUMF

Article

Observation of the effect of gravity on the motion of antimatter

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CBC | MENU

NEWS Sections

Science

Scientists drop antimatter to see if it falls

Antimatter is influenced by gravity just like matter, ALPHA-g experiment finds

Le Monde Se connecter

SCIENCES · PHYSIQUE

Des chercheurs démontrent que l'antimatière ne « tombe » pas vers le haut

Une équipe internationale a observé, pour la première fois, le comportement d'antiatomes en chute libre. La gravité, connue pour attirer les masses de matière ordinaire entre elles, n'est pas répulsive pour l'antimatière.

Par David Larousserie

ALJAZEERA

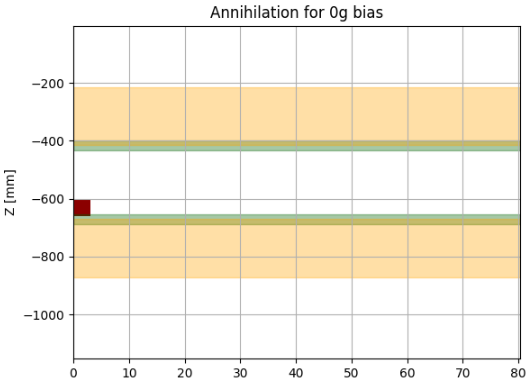
EXPLAINER

Features | Science and Technology

Gravity test: Antimatter falls down, but where did it all go?

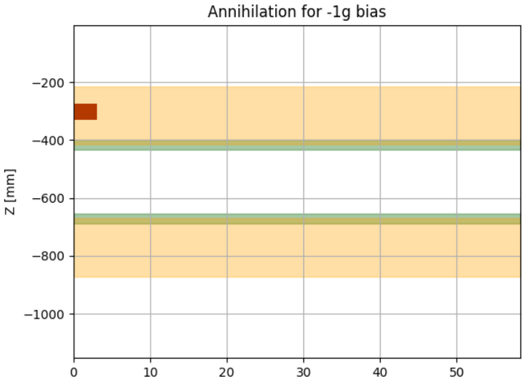
From Star Trek to PET scans, antimatter has thrilled

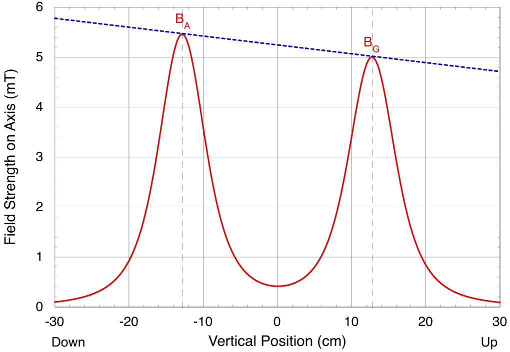
Typical Antihydrogen Release Experiment



1. $\overline{H}$ accumulation for 4 hours resulting in about 100 trapped atoms
2. Long Octupole rampdown
3. Measurement of the on-axis field (with Electron Cyclotron Resonance technique)
4. Mirror coil linear rampdown in 20 s
5. Measurement of the on-axis field (ECR)

Example of Field Configuration



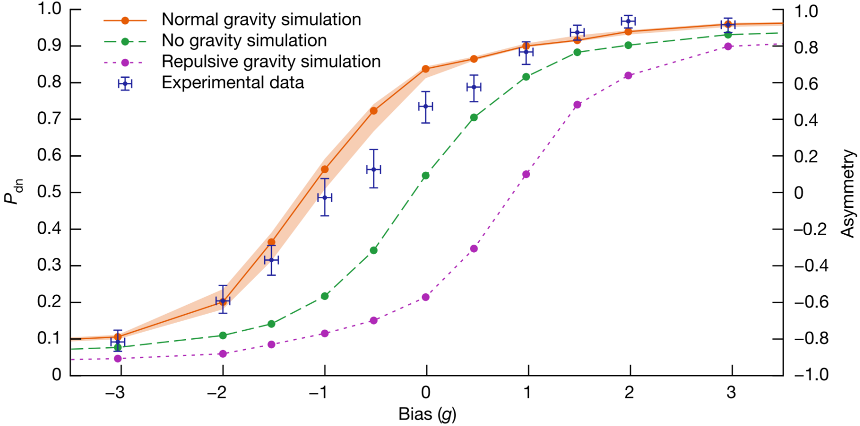


$$B_A - B_G = 4.53 \cdot 10^{-4}\ \mathrm{T} \rightarrow 1g$$

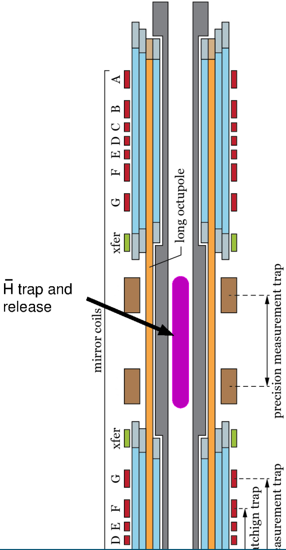
E.g., cancel the effect of gravity

Escape Curve

$P_{dn} = \frac{DW}{UP+DW}$ Asymmetry$= \frac{UP-DW}{UP+DW}$ Bias$= \frac{\mu_B(B_G - B_A)}{m_H(z_G - z_A)}$ Nature **621** 716-722 (2023)

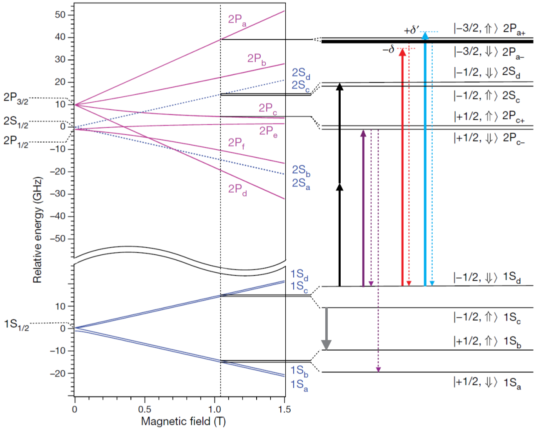


$$a = (-0.75 \pm 0.13\ \text{(stat.+sys.)} \pm 0.16\ \text{(model)})\ g$$

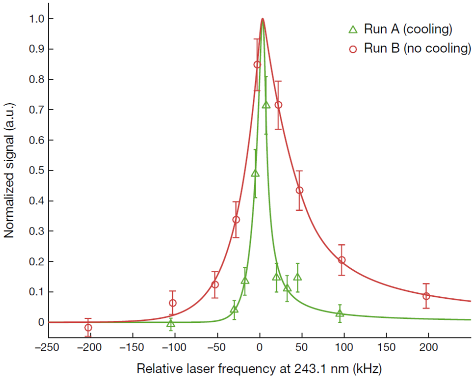


- Improve knowledge of magnetic field to 10^{-6} T
- More magnetometry to reduce systematics
- $\overline{H}$ cooling to increase sensitivity (escape-curve slope)
- Slower $\overline{H}$ release (slower coils ramp down)

Doppler cooling on $|1S,d\rangle \rightarrow |2P_a+\rangle$



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



Nature **592** (2021)

The HAICU experiment at TRIUMF

Hydrogen-**A**ntihydrogen **I**nfrastructure of **C**anadian **U**niversities

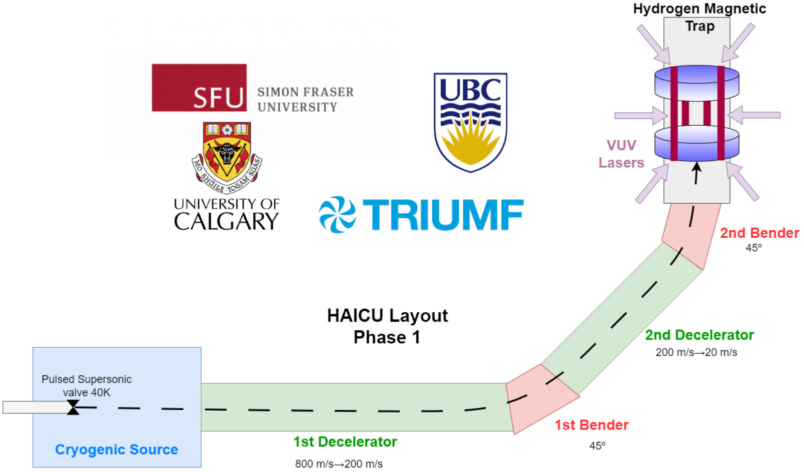
- Platform to develop atomic manipulation techniques on H to apply to $\overline{\mathrm{H}}$

SFU SIMON FRASER UNIVERSITY

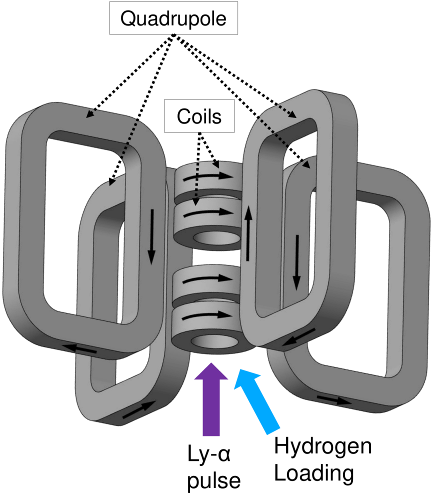
UNIVERSITY OF CALGARY

UBC

TRIUMF



The HAICU Hydrogen Trap at TRIUMF



- Ioffe-Pritchard Trap (same as ALPHA but with quadrupole)
- Normal conducting magnets
  - Bitter coils (current flows through sheets of conductors)
- |B| = 0.15 T at trap centre
- Max |B| = 0.376 T
- See talk G. Wankling later in this session

HAICU Program

- Current status:
  - Optimization of H source at UBC
  - Decelerator is being built at UBC
  - Bitter coils prototyping at TRIUMF
  - Quadrupole assembly at TRIUMF

- Short terms goals:
  - Wall-free trapping of hydrogen
  - Laser cooling in 3D

- Long term goals:
  - Sample in metastable 2S state
  - Raman spectroscopy
  - Hydrogen fountain
  - Ramsey-Bordé Interferometry
  - ...

Summary

- $\overline{\mathrm{H}}$ is a well-established tool for testing fundamental symmetries, i.e., CPT invariance and Weak Equivalence Principle (WEP)
- The ALPHA experiment at CERN/AD is leading way to precision $\overline{\mathrm{H}}$ test
- First successful gravity experiment with ALPHA-g at CERN/AD
- New hydrogen experiment - HAICU - in preparation at TRIUMF

Additional Material

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

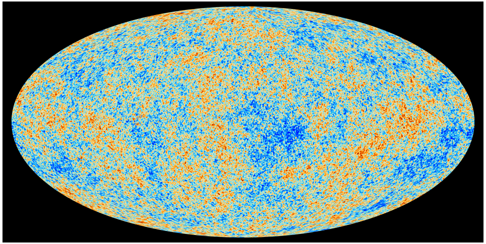
SM prediction:

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

Observation:

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

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



Many orders of magnitude discrepancy!

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)

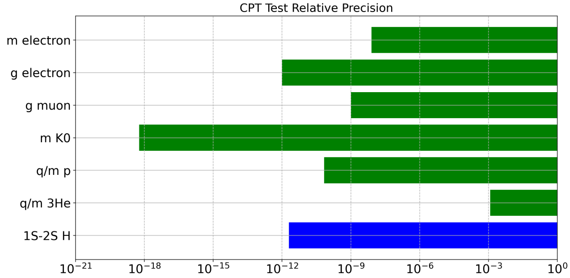
$\Rightarrow$ Test of essential features of the Standard Model

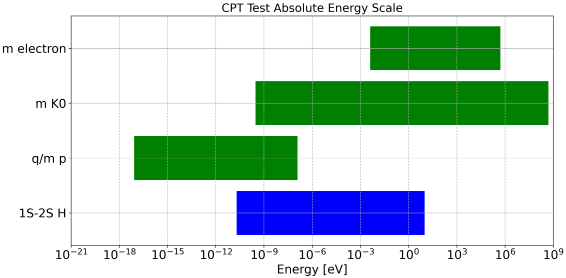
Hydrogen vs. Antihydrogen

- 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)

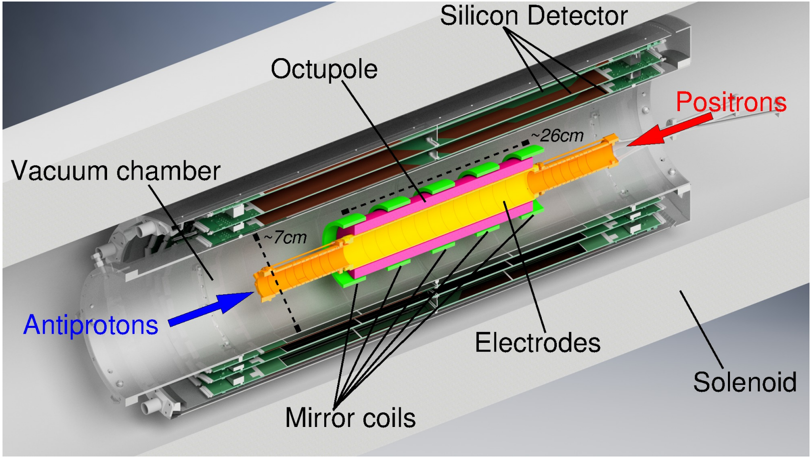
CPT Tests





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

The ALPHA Apparatus



see "The ALPHA antihydrogen trapping apparatus", NIMA (2014)

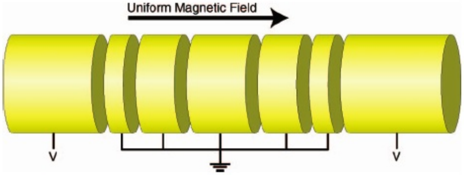
Antiprotons Preparation

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

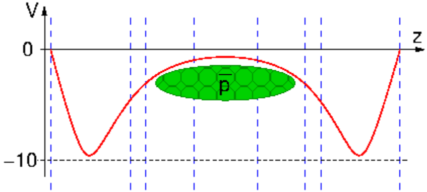
$\bar{p}$ are slowed down through a *degrader* and cooled in a Penning trap by means of:

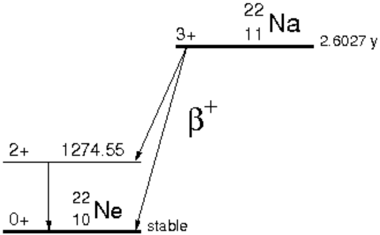
- *electron cooling*
- *evaporative cooling* Phys. Rev. Lett. **105** 013003 (2010)

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



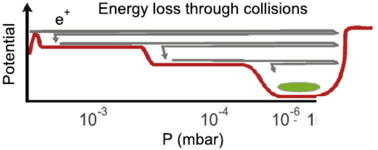
PhotoCredit: ALPHA





- 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 N_2.

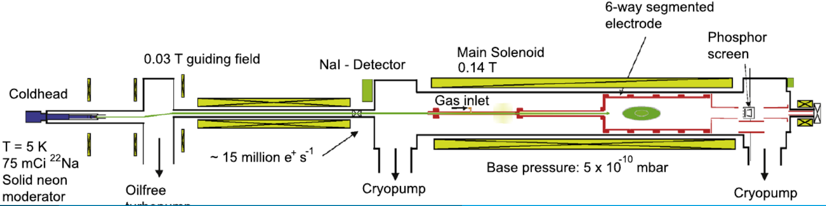
Phys. Rev. A **46** 5696 (1992)



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

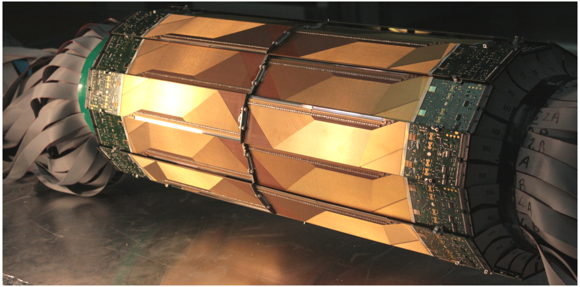
Phys. Rev. Lett. **120** 025001 (2018)

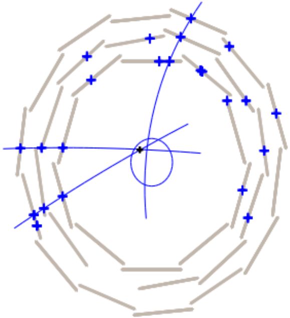
PhotoCredit: ALPHA



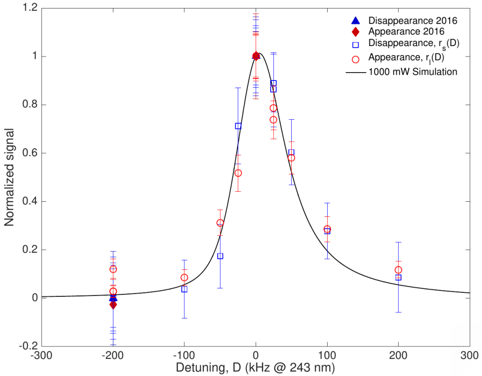
The ALPHA tracker the *Silicon Vertex Detector* is used to:

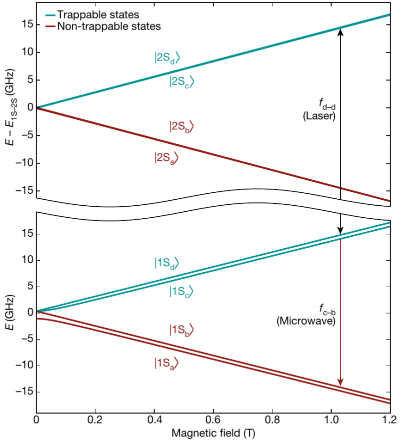
- monitor $\overline{\mathrm{H}}$ production
- perform physics measurements
  - Spectroscopic signal comes from $\overline{\mathrm{H}}$ annihilation upon iteraction with radiation
  - Typically the transition from a *trappable* state to an *un-trappable* one





1S-2S Spectroscopy





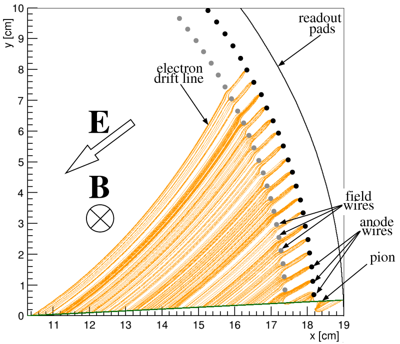
f_{d-d} = 2 466 061 103 079.4(5.4) kHz
Consistent with CPT at 2×10^{-12}

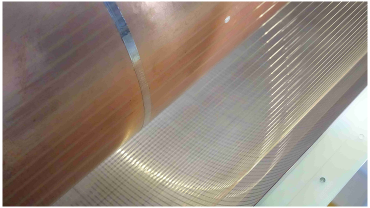
Nature **557** 71 (2018)

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

Since h and c are exact in the revised SI

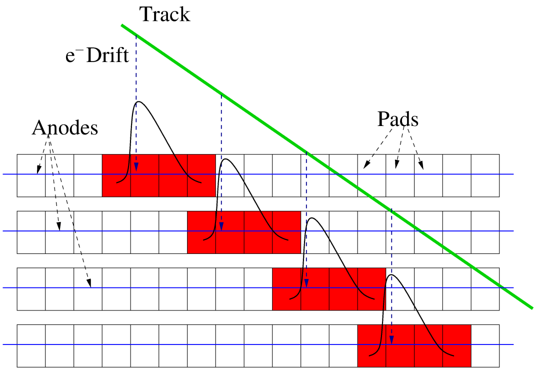
- Measurement of 2 lines determines, e.g., R_∞, α, and constrains m_e
- Alternatively, measuring all three constants confirms the validity of the identity.



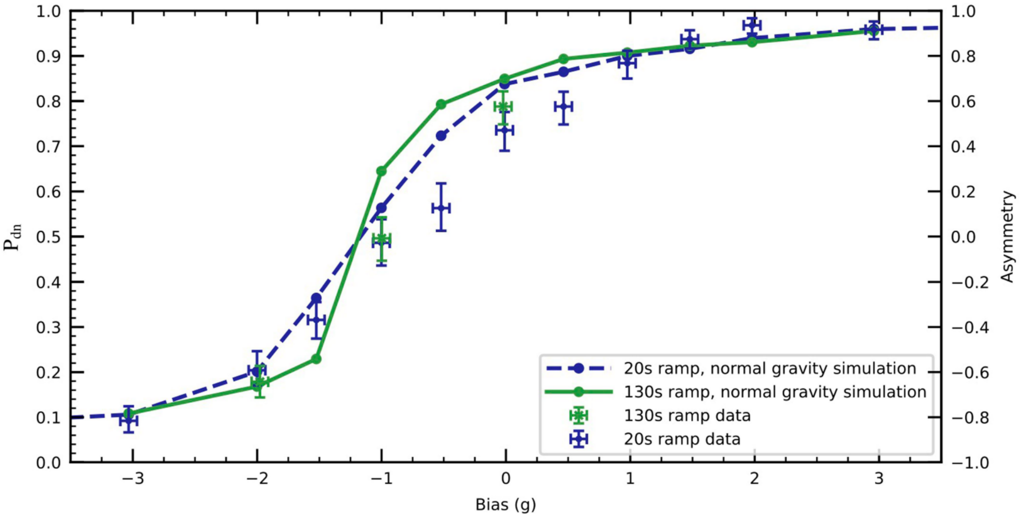


Spacepoints Reconstruction:

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



Escape Curve: 130s



Uncertainties in the bias determination and in the determination of $a_{\bar{g}}$

"x-axis" uncertainty

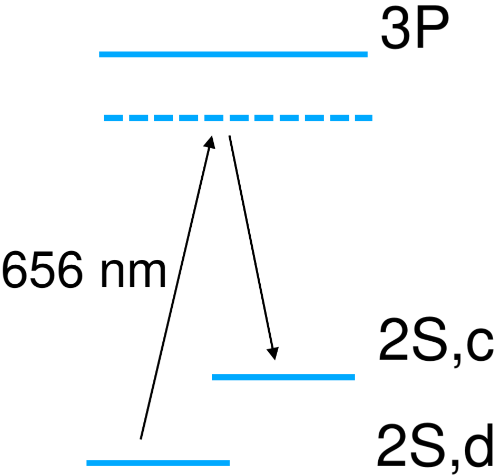
Uncertainty	Magnitude (g)
ECR spectrum width	0.07
Repeatability of ($B_G - B_A$)	0.014
Peak field size and z-location fit	0.009
Field decay asymmetry (A to G) after ramp	0.02
Bias variation in time	0.02
Field modelling	0.05

Summary of the uncertainties in the derived bias values, expressed in units of the local acceleration of gravity for matter (9.81 m s^{-2}).

"y-axis" uncertainty

	Uncertainty	Magnitude (g)
Statistical and systematic	Finite data size	0.06
	Calibration of the detector efficiencies in the up and down regions	0.12
	Other minor sources	0.01
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16
	Antihydrogen initial energy distribution	0.03

Estimated uncertainty associated with the simulation includes the potential impact of various unmeasured quantities, such as magnet winding misalignment, off-axis persistent magnetic fields, and uncertainty in the energy distributions (longitudinal and transverse) of the trapped $\overline{\mathrm{H}}$ atoms.


3P
656 nm
2S,c
2S,d