# Antimatter in the lab

Lecture 2

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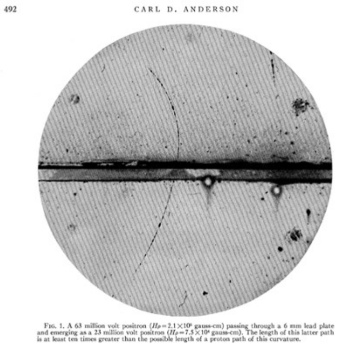
CERN

19/7/2022 10:25

# Recap

## Lecture 1

1. What is antimatter?



492 CARL D. ANDERSON

FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

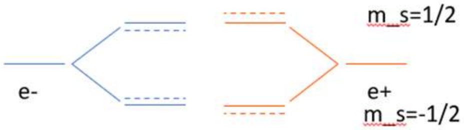
$$(i\gamma^\mu \partial_\mu - m)\,\Psi(\boldsymbol{x}, t) = 0$$

$$E = +E_p = +\sqrt{p^2 + m^2} \qquad E = -E_p = -\sqrt{p^2 + m^2}$$

$$\Psi_1 = A\begin{pmatrix} 1 \\ 0 \\ \frac{p}{m+E_p} \\ 0 \end{pmatrix} e^{-ip^\mu x_\mu} \qquad \Psi_3 = A\begin{pmatrix} \frac{-p}{E_p+m} \\ 0 \\ 1 \\ 0 \end{pmatrix} e^{-ip^\mu x_\mu}$$

$$\Psi_2 = A\begin{pmatrix} 0 \\ 1 \\ 0 \\ \frac{-p}{E_p+m} \end{pmatrix} e^{-ip^\mu x_\mu} \qquad \Psi_4 = A\begin{pmatrix} 0 \\ \frac{p}{E_p+m} \\ 0 \\ 1 \end{pmatrix} e^{-ip^\mu x_\mu}$$

2. Why study antimatter?



In a magnetic field

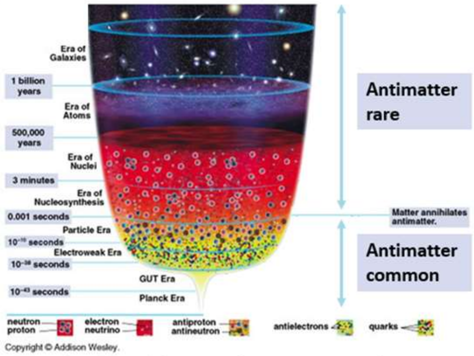


Figure adapted from "The Essential Cosmic Perspective", by Bennett, Voit, and Donahue

SHOULD NOT EXIST (according to known physics)

Problem: one billion times more matter left over than expected

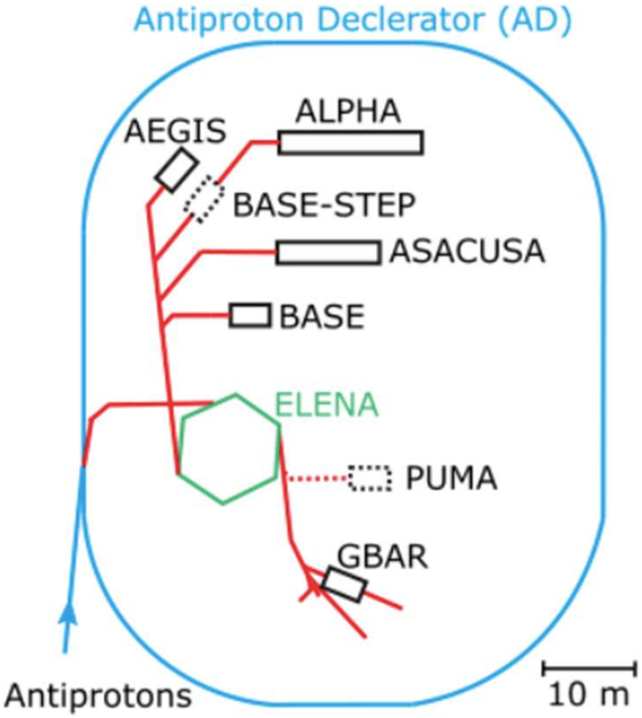
3. How do we make antimatter at CERN?

(Maximilien Brice/CERN)

# Overview

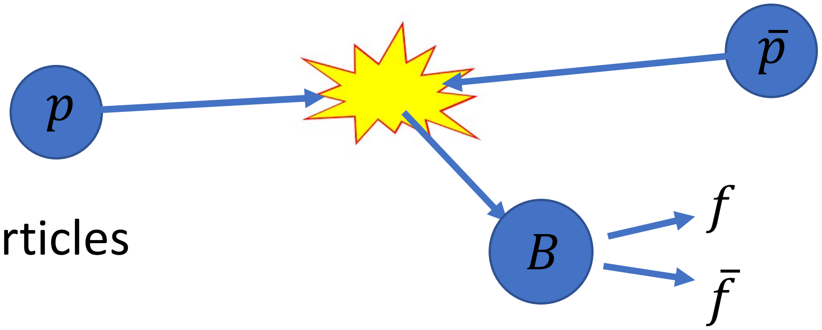
## Lecture 2:Experiments at the Antimatter Factory

1. Catching and storing antimatter
2. Measurements on antiprotons
3. Spectroscopy of anti-atoms
4. Gravity and antihydrogen
5. Taking antimatter out of the lab (and into another lab..)



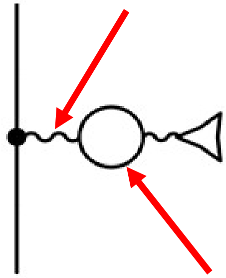
# Low energy physics

- High energy experiments (direct search)
  - Produce and detect new particles in high energy particle collisions
  - High energies needed to make non-virtual particles



- Precision experiments: (indirect search)

$$\frac{g_{electron}}{2} = 1 + a_{QED} + a_{\mu,\tau} + a_{weak} + a_{hadrons} + a_{New\ physics}$$



Any interacting boson

Any fermion/
antifermion pair

**So far, all low energy CPT tests have been consistent with no CPT breaking**

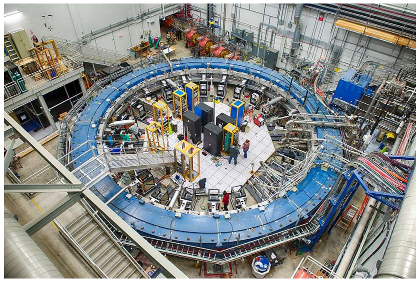
# Other efforts

Many groups studying antimatter. Some notable ones are:

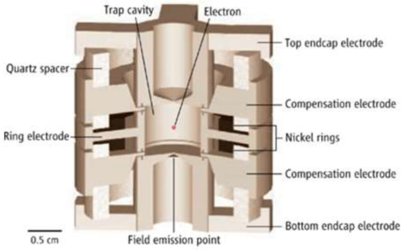
**Positron-electron magnetic moment** University of Washington/Harvard, new effort at Northwestern

Van Dyke& Dehmelt / Gabrielse

Gabrielse



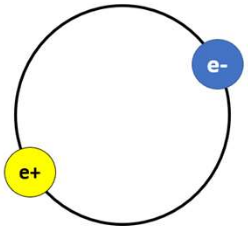
Reidar Hahn



Gabrielse /Harvard

**Muon-antimuon magnetic moment** Fermilab, formerly Brookhaven

**Positronium, muonium,** bound states of electrons/positron and antimuon+ electron: many groups



**Kaons, B mesons, other collider searches**

D. Hanneke et al. Phys. Rev. Lett. **100** (2008)
R.S. Van Dyke, Jr., P.B. Schwinberg, and H.G. Dehmelt, Phys. Rev. Lett. **59**, 26 (1987)
G.W. Bennett et al., Phys. Rev. Lett. **89**, 101804 (2002)
B. Abi et al. (Muon g−2 Collaboration) Phys. Rev. Lett. **126**, (2021)

# Why many efforts?

Minimal Standard Model Extension (SME)

$$\mathcal{L}^{\mathrm{CPT-even}}_{\mathrm{lepton}} = \tfrac{1}{2}i(c_L)_{\mu\nu AB}\overline{L}_A\gamma^\mu \overleftrightarrow{D^\nu} L_B + \tfrac{1}{2}i(c_R)_{\mu\nu AB}\overline{R}_A\gamma^\mu \overleftrightarrow{D^\nu} R_B \quad , \qquad (9)$$

$$\mathcal{L}^{\mathrm{CPT-odd}}_{\mathrm{lepton}} = -(a_L)_{\mu AB}\overline{L}_A\gamma^\mu L_B - (a_R)_{\mu AB}\overline{R}_A\gamma^\mu R_B \quad , \qquad (10)$$

$$\mathcal{L}^{\mathrm{CPT-even}}_{\mathrm{quark}} = \tfrac{1}{2}i(c_Q)_{\mu\nu AB}\overline{Q}_A\gamma^\mu \overleftrightarrow{D^\nu} Q_B + \tfrac{1}{2}i(c_U)_{\mu\nu AB}\overline{U}_A\gamma^\mu \overleftrightarrow{D^\nu} U_B + \tfrac{1}{2}i(c_D)_{\mu\nu AB}\overline{D}_A\gamma^\mu \overleftrightarrow{D^\nu} D_B \quad , \qquad (11)$$

$$\mathcal{L}^{\mathrm{CPT-odd}}_{\mathrm{quark}} = -(a_Q)_{\mu AB}\overline{Q}_A\gamma^\mu Q_B - (a_U)_{\mu AB}\overline{U}_A\gamma^\mu U_B - (a_D)_{\mu AB}\overline{D}_A\gamma^\mu D_B \quad . \qquad (12)$$

$$\mathcal{L}^{\mathrm{CPT-even}}_{\mathrm{Yukawa}} = -\tfrac{1}{2}\left[(H_L)_{\mu\nu AB}\overline{L}_A\phi\sigma^{\mu\nu}R_B + (H_U)_{\mu\nu AB}\overline{Q}_A\phi^c\sigma^{\mu\nu}U_B + (H_D)_{\mu\nu AB}\overline{Q}_A\phi\sigma^{\mu\nu}D_B\right] + \mathrm{h.c.} \qquad (13)$$

$$\mathcal{L}^{\mathrm{CPT-even}}_{\mathrm{Higgs}} = \tfrac{1}{2}(k_{\phi\phi})^{\mu\nu}(D_\mu\phi)^\dagger D_\nu\phi + \mathrm{h.c.} - \tfrac{1}{2}(k_{\phi B})^{\mu\nu}\phi^\dagger\phi B_{\mu\nu} - \tfrac{1}{2}(k_{\phi W})^{\mu\nu}\phi^\dagger W_{\mu\nu}\phi \quad , \qquad (14)$$

$$\mathcal{L}^{\mathrm{CPT-odd}}_{\mathrm{Higgs}} = i(k_\phi)^\mu\phi^\dagger D_\mu\phi + \mathrm{h.c.} \quad . \qquad (15)$$

$$\mathcal{L}^{\mathrm{CPT-even}}_{\mathrm{gauge}} = -\tfrac{1}{2}(k_G)_{\kappa\lambda\mu\nu}\mathrm{Tr}(G^{\kappa\lambda}G^{\mu\nu}) - \tfrac{1}{2}(k_W)_{\kappa\lambda\mu\nu}\mathrm{Tr}(W^{\kappa\lambda}W^{\mu\nu}) - \tfrac{1}{4}(k_B)_{\kappa\lambda\mu\nu}B^{\kappa\lambda}B^{\mu\nu} \quad . \qquad (16)$$

$$\mathcal{L}^{\mathrm{CPT-odd}}_{\mathrm{gauge}} = (k_3)_\kappa\epsilon^{\kappa\lambda\mu\nu}\mathrm{Tr}(G_\lambda G_{\mu\nu} + \tfrac{2}{3}ig_3G_\lambda G_\mu G_\nu) + (k_2)_\kappa\epsilon^{\kappa\lambda\mu\nu}\mathrm{Tr}(W_\lambda W_{\mu\nu} + \tfrac{2}{3}igW_\lambda W_\mu W_\nu) + (k_1)_\kappa\epsilon^{\kappa\lambda\mu\nu}B_\lambda B_{\mu\nu} + (k_0)_\kappa B^\kappa \quad . \qquad (17)$$

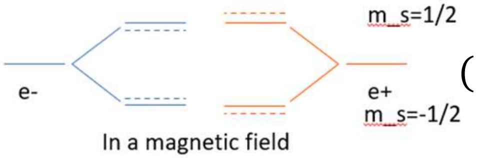
Non-minimal Standard Model Extension (SME)

18 pages to write down

**Don’t know a priori where to look!**

CPT breaking coefficients proportional to (energy)^(-order)

| Measurement | Energy scale | Fractional precision | Measurement in energy units |
|---|---|---|---|
| $K_0 - \bar{K}_0$ mass difference | Mass of two Kaons ~1 GeV | 4.8x$10^{-19}$ | 4.8x$10^{-19}$ GeV |
| $\bar{H}$ 1S-2S | ~2500 THz | 2x$10^{-12}$ | 2x$10^{-20}$ GeV |
| $\bar{p}$ magnetic moment | Larmor frequency ~81 MHz at 1.95 T | 1.5x$10^{-9}$ | 5x$10^{-25}$ GeV |



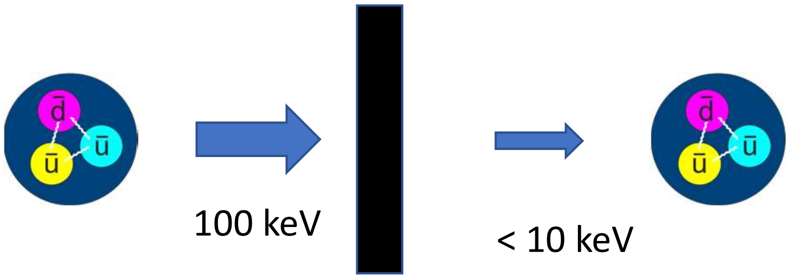
In a magnetic field

$$(i\gamma^\mu\partial_\mu - m + b^e_\mu\gamma_5\gamma^\mu)\,\Psi(\boldsymbol{x},t) = 0$$

# Catching and storing antimatter

# Final step of slowing

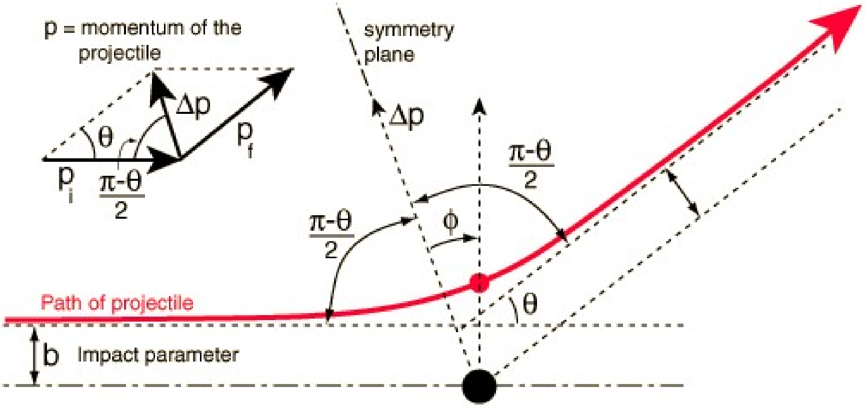
Final ELENA energy 100 keV, need a final step to reach trappable energies

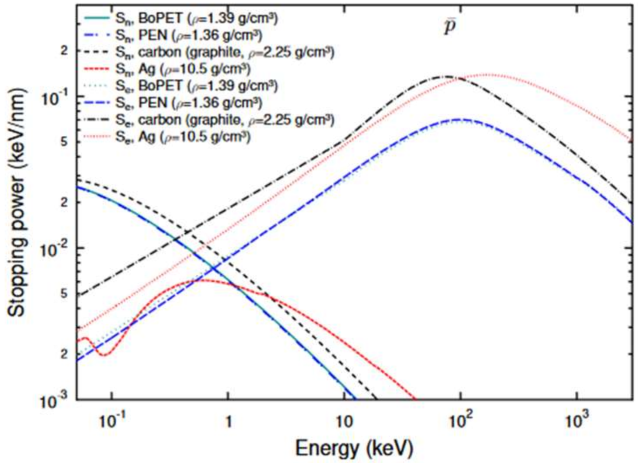


Degrader foil

100 keV

< 10 keV





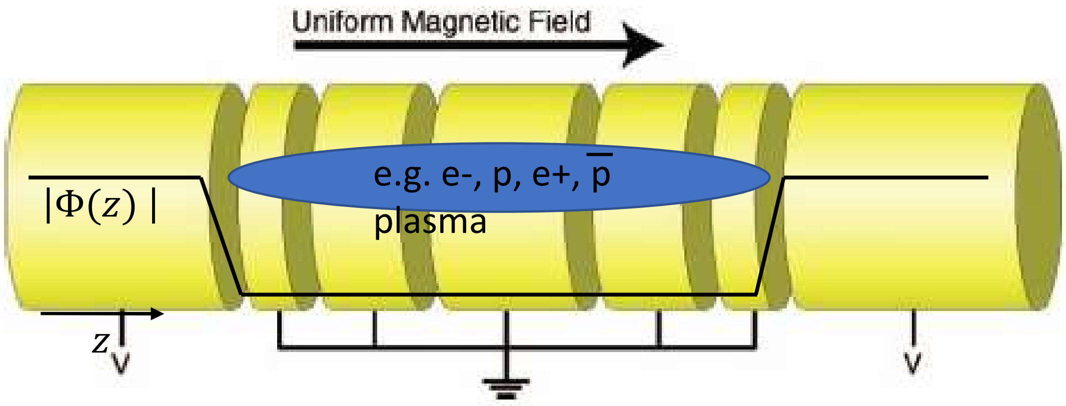
Sum of scattering from electrons and Rutherford scattering from nuclei

Up to ~50% antiprotons transmitted

J.F. Ziegler, J. Appl. Phys. **85**, 1249-1272 (1999). *(Author of SRIM)*
K. Nordlund et al., Phys. Rev. A **106** (2022)

# Catching antiprotons

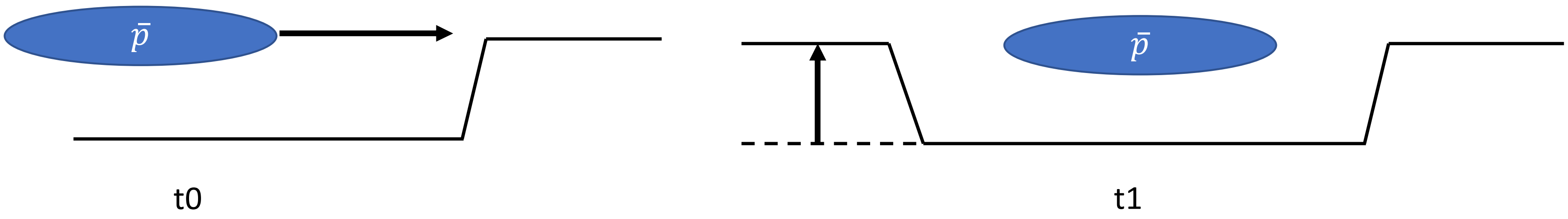
## Strong magnetic and moderate electric fields used



Penning-Malberg trap

Radial confinement from Lorentz force on charged particles in 1-2 T magnetic field

Axial confinement from voltages applied to electrodes

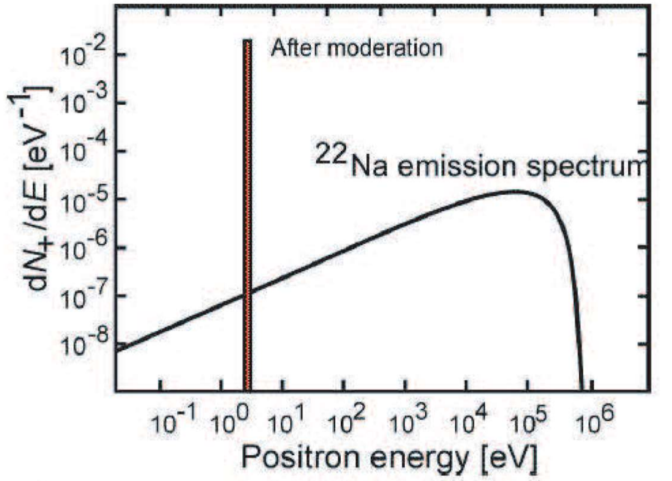


Can co-trap with electrons and use these to sympathetically cool

# What about the positrons?

- Need positrons to make antihydrogen

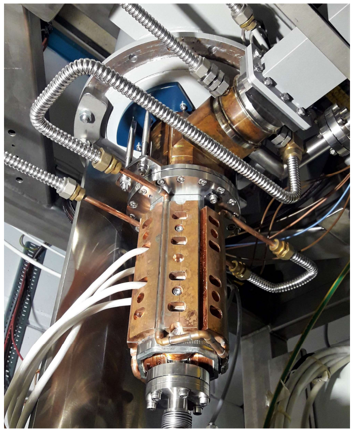
ALPHA, AEGIS, ASACUSA
Radioactive source and moderation with frozen noble gas



(CERN/ALPHA)

~ 5 million slow e+ per second

GBAR



(CERN/GBAR/Comini)

e- accelerated 10 MeV onto a water-cooled tungsten target to form positrons by pair production, moderated by tungsten mesh

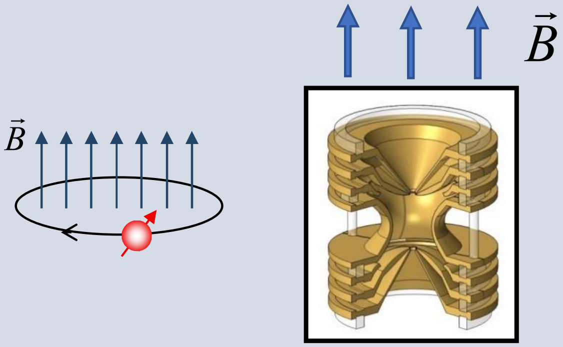
~ 40 million slow e+ per second

# Measurements on antiprotons

# Properties

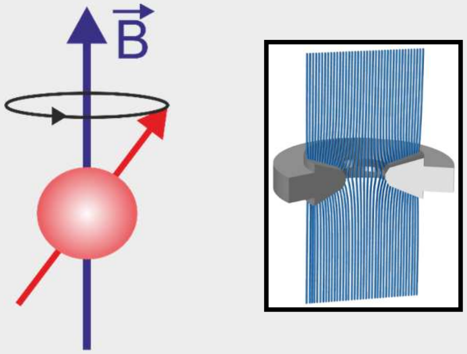
Measurements

**Cyclotron Frequency**



$$\omega_c = \frac{q}{m} B$$

**Larmor Frequency**



$$\omega_L = g \frac{e}{2m_p} B$$

**Trap loss rate**

CPT Tests

$$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}} = \frac{q_{\bar{p}}/m_{\bar{p}}}{q_p/m_p}$$ Charge to mass comparison

$\frac{\omega_{c,\bar{p}}}{\omega_{c,p}}(\text{Year})$ Gravity, clock comparison

$$\frac{\omega_L}{\omega_c} = \frac{g}{2} = \frac{\mu}{\mu_N}$$

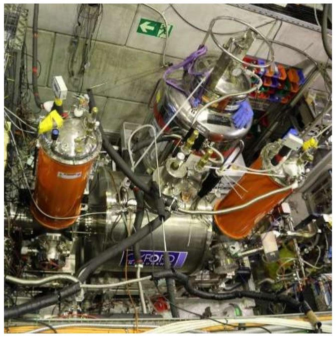
Magnetic moment

$t_{\bar{p}}$

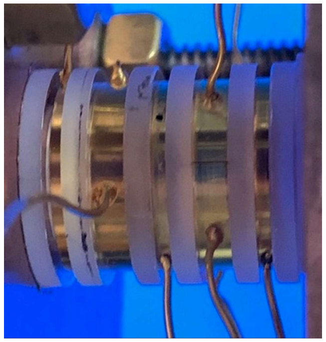
Lifetime

# Frequency measurements in a Penning trap

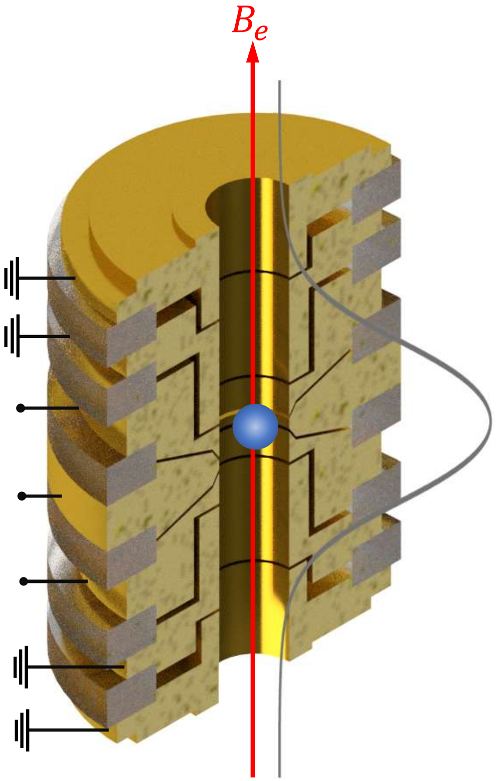
1.95 T B field from solenoid



Voltages applied to ring-shaped electrodes



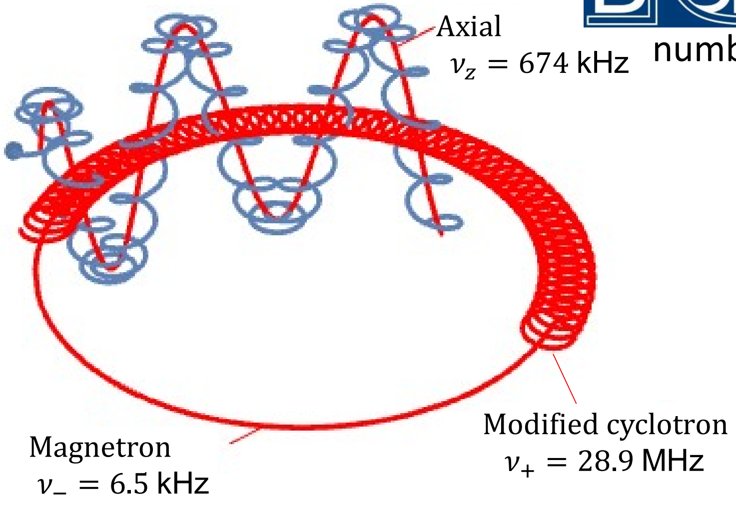
A Penning trap



$$\Phi(0,z)$$

$$\Phi(\rho,z) = V_0 C_2 (z^2 - \frac{\rho^2}{2})$$

numbers



$$\sqrt{\nu_z^2 + \nu_+^2 + \nu_-^2} = \nu_c = \frac{q}{2\pi m} B_e$$

Orbit is sum of three normal modes

Measure frequencies and get access to charge-to-mass ratio and magnetic field

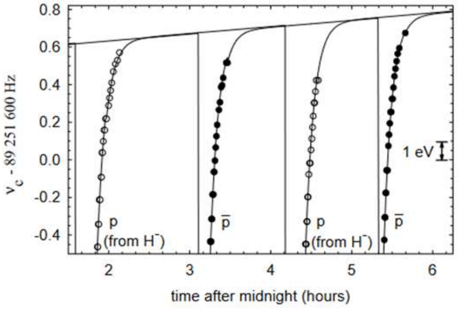
# Charge-to-mass ratio comparisons

$$R = \frac{\nu_{c,\bar{p}}}{\nu_{c,H^-}} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}} \text{ x } \frac{B/2\pi}{B/2\pi} = \frac{(q/m)_{\bar{p}}}{(q/m)_{H^-}}$$

$$m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{E_b}{m_p} - \frac{E_a}{m_p} + \frac{\alpha_{pol,H^-} B_0^2}{m_p}\right)$$

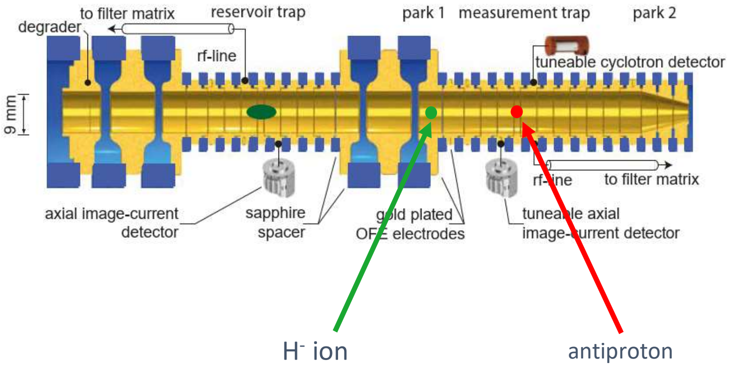
$R_{theo}$ = 1.001 089 218 754 2(2)

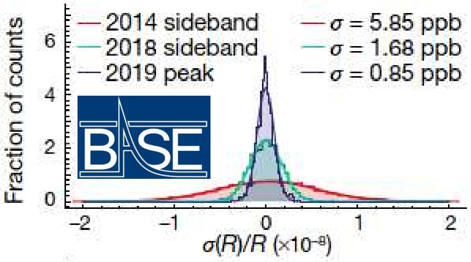
Multiyear campaign performed by G. Gabrielse and collaborators at CERN's LEAR Decelerator 1990's



Single trap, 2 hrs to exchange particles, 90 ppt reached

2 measurements by BASE at CERN's AD





Multi trap, 2 minutes to exchange particles,

$$-\frac{(q/m)_{\bar{p}}}{(q/m)_p} = 1.000000000003(16)$$

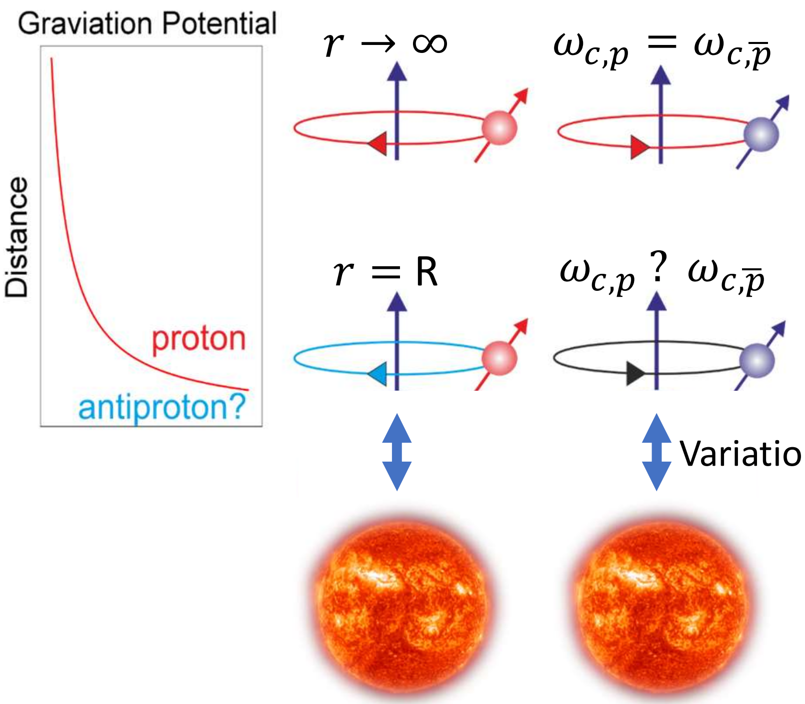
16 ppt reached

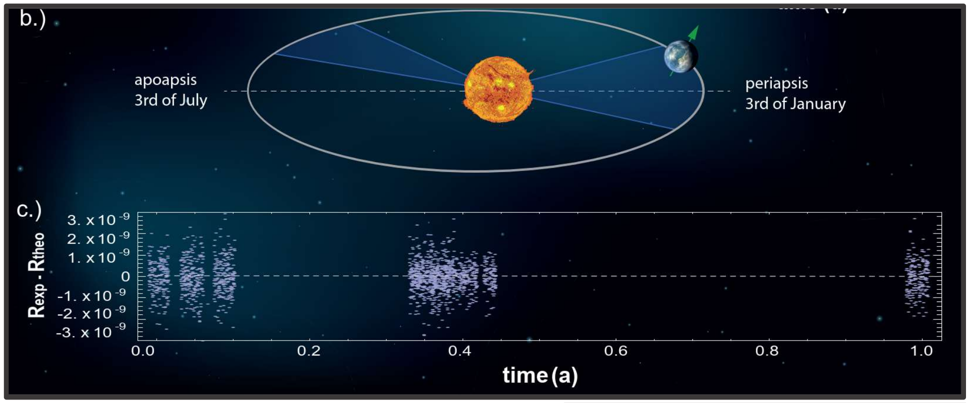
G. Gabrielse et al., Phys. Rev. Lett. **82** (1999)
M Borchert et al., Nature **601** (2022)

# Gravity

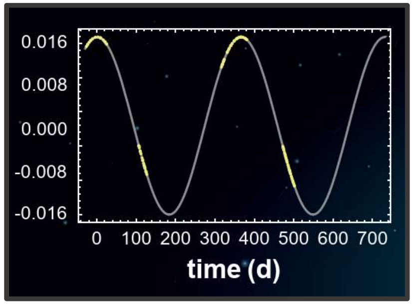
Clock comparison between matter and antimatter clocks in a gravitational potential

Relies on assumptions about CPT





Variation in distance modulates effect

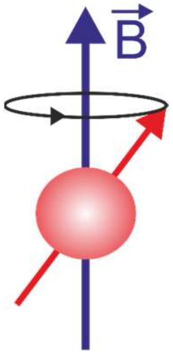


$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{sun}}}{c^2}(\alpha_{g,D}-1)\left(\frac{1}{O(t)}-\frac{1}{O(t_0)}\right)$$

| Property | Limit |
|---|---|
| $\alpha_g - 1$ | $< 1.8 * 10^{-7}$ |
| $\alpha_{g,D} - 1$ | $< 0.03$ |

M Borchert et al., Nature **601** (2022)

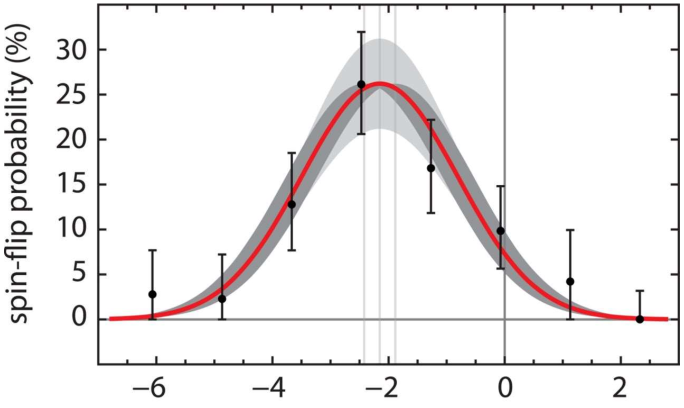
# Measuring the magnetic moment



$$\omega_L = g\frac{e}{2m_p}B$$

$$\frac{g}{2} = \frac{\mu}{\mu_N} = \frac{\omega_L}{\omega_c}$$

How to measure the Larmor frequency $\omega_L$?



$$\omega_{rf}\frac{2}{g_{\mathrm{CODATA}}\,\omega_c} - 1\ (\mathrm{ppb})$$

Weak radiofrequency magnetic field most likely to flip antiproton spin at $\omega_L$

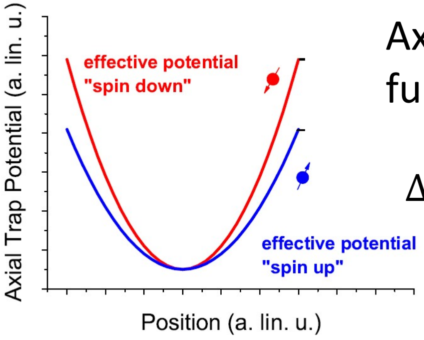
**How to measure spin?**

Continuous Stern-Gerlach effect

$$\mathrm{H}_M = -(\overrightarrow{\mu_p}\cdot\vec{B})$$

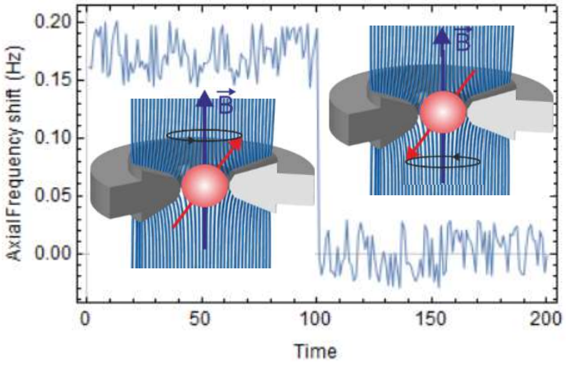
Energy of magnetic dipole in magnetic field

$$B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$$



Axial frequency becomes function of spin state

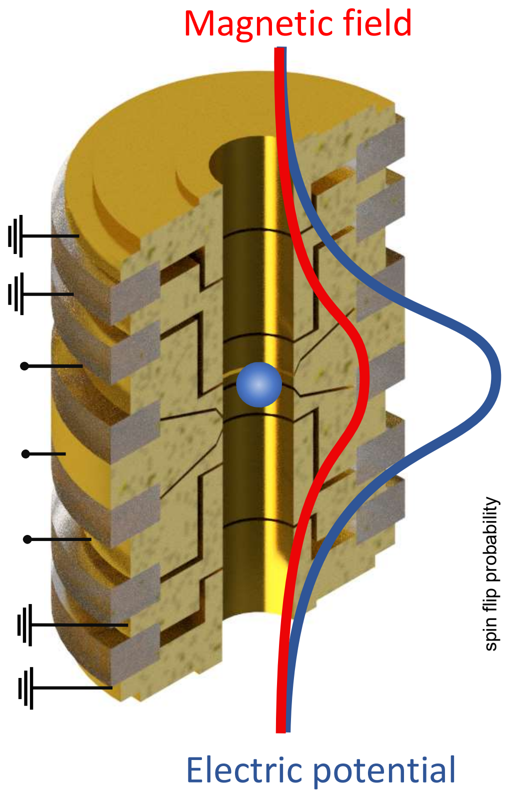
$$\Delta\nu_z \sim \frac{\mu_p B_2}{m_p \nu_z} := \alpha_p\frac{B_2}{\nu_z}$$



G. Schneider et al., Science. **358** 6366 (2017)

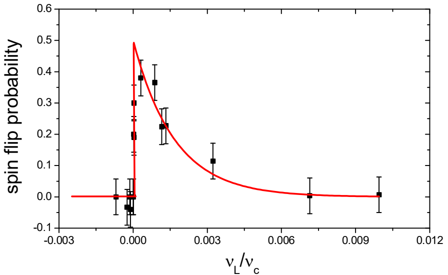
# Method

**Single trap method**



Measure $\omega_L$ and $\omega_c$ and spin states in the same trap

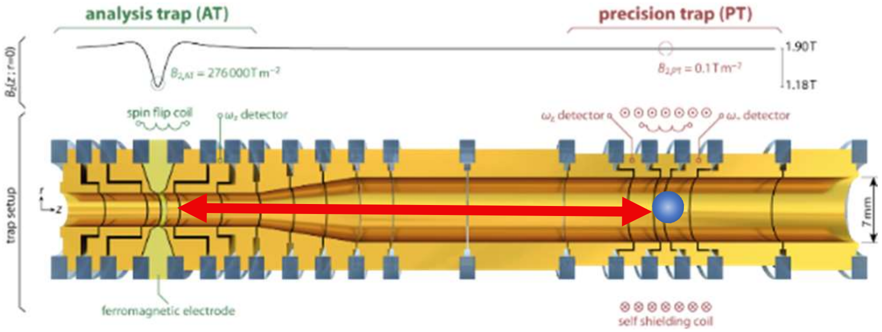
Works well for electrons, but large quadratic B field adds temperature broadening, limits measurements

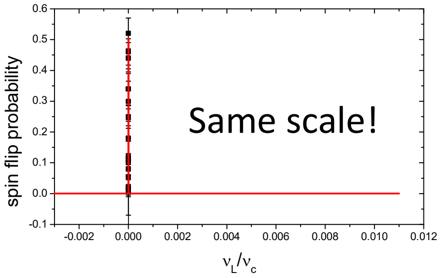


Proton: 2.5 ppm
Antiproton: 0.8 ppm
Electron: 0.28 **ppt**
Positron: 4.3 **ppt**

**Double trap method**

Separate spin state identification from measuring $\omega_L$ and $\omega_c$



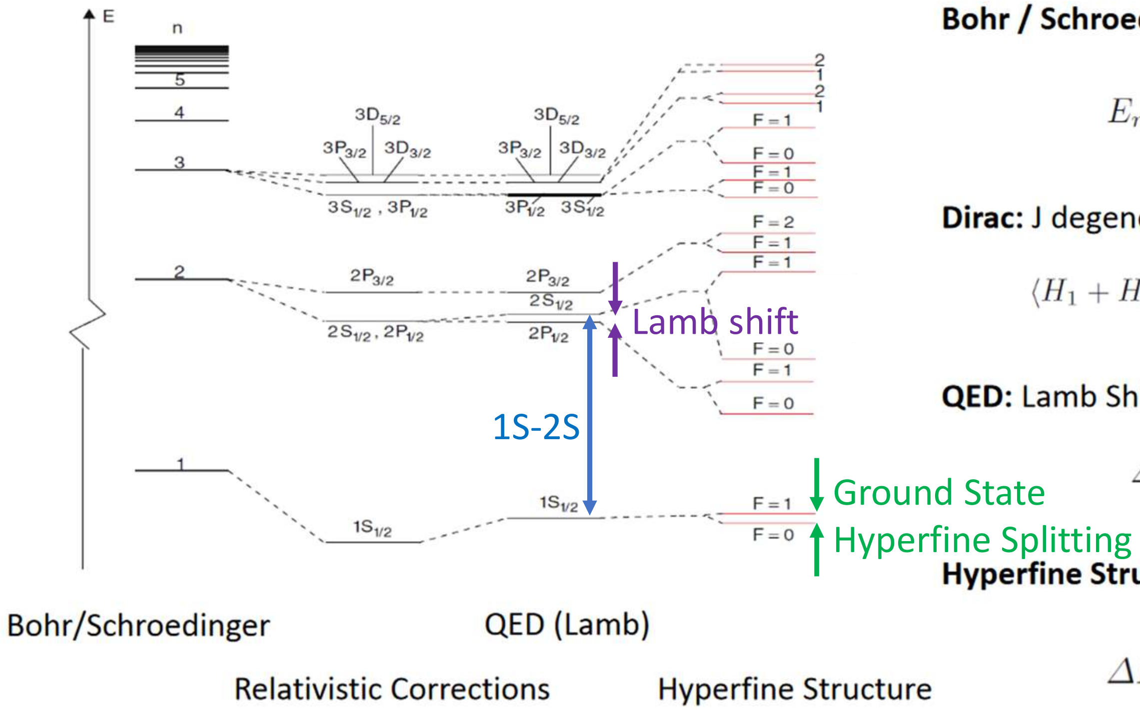


Proton: 0.3 **ppb**
Antiproton: 1.2 **ppb**

H Häffner et al., The European Physical Journal D **22** 2 (2003)
DiSciacca, J. & Gabrielse, G. *Phys. Rev. Lett.* **108**, 153001 (2012)
H. Nagahama et al. Nature Communications **8** (2017)
Hanneke et al., Phys. Rev. Lett. **100** (2008)
Van Dyck, R.S., Jr.; Schwinberg, P.B.; Dehmelt, H.G. Phys. Rev. Lett. **59** (1987)

# Spectroscopy of anti-atoms

# (anti)hydrogen



**Bohr / Schroedinger:** L degeneracy

$$E_n = -\frac{mZ^2e_0^4}{2\hbar^2 n^2} = -\frac{(Ze_0)^2}{2an^2} = -\frac{mc^2}{2}\alpha^2\frac{Z^2}{n^2}$$

**Dirac:** J degeneracy

$$\langle H_1 + H_2\rangle_{n,j=l\pm1/2,l} = \frac{mc^2(Z\alpha)^2}{2n^2}\frac{(Z\alpha)^2}{n^2}\left\{\frac{3}{4} - \frac{n}{j+1/2}\right\}$$

**QED:** Lamb Shift

$$\Delta E_{\mathrm{Lamb}} \approx \frac{4}{3\pi}\frac{mc^2Z^4\alpha^5}{n^3}\log\frac{1}{\alpha Z}\,\delta_{l,0}$$

**Hyperfine Structure:**

$$\Delta E^{\mathrm{Hyp}}_{n,1/2,0} = \frac{4}{3}\,g_{\mathrm{K}}\frac{m}{M_{\mathrm{K}}}(Z\alpha)^4\frac{mc^2}{n^3}\frac{(2I+1)}{2}$$

Analytically calculable energy levels, high precision hydrogen measurements (4.5 ppt for 1S-2S) to compare to antihydrogen

C. G. Parthey, et al. Phys. Rev. Lett. 107, 203001 (2011)

# Producing antihydrogen

1) Recombination $\bar{p} + e^+ \rightarrow \bar{H} + \text{UV photon}$

2) Three body recombination $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$

rate 2)>> rate 1) typically

ATRAP

ASACUSA

ALPHA: 2.6 ± 0.2 detected $\bar{H}$
trapped per minute

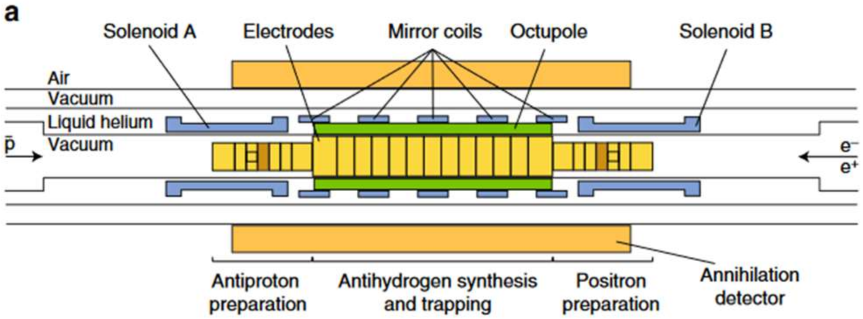
3) Charge transfer $\bar{p} + \text{positronium} \rightarrow \bar{H} + e^-$

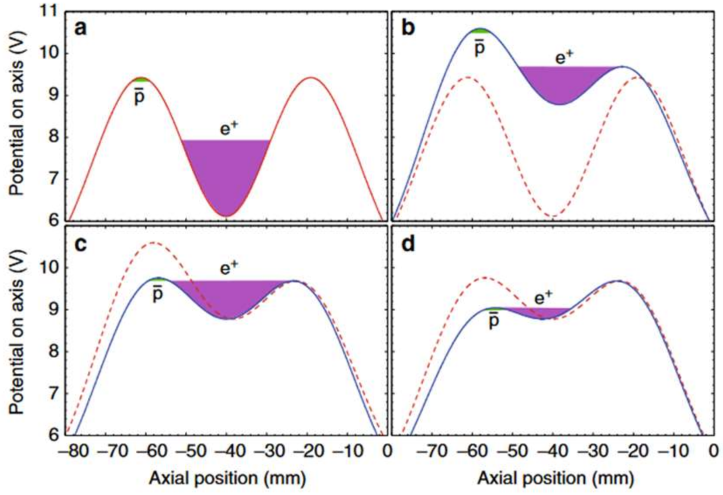
AEGIS: 0.021(5) $\bar{H}$ per attempt,
~15 minutes per attempt

M. Ahmadi, Nature Communications **8** (2017)
C. Amsler et al., Nature Communications Physics **4** (2021)
F Robicheaux J. Phys. B: At. Mol. Opt. Phys. **41** (2008)

# Antihydrogen production in ALPHA

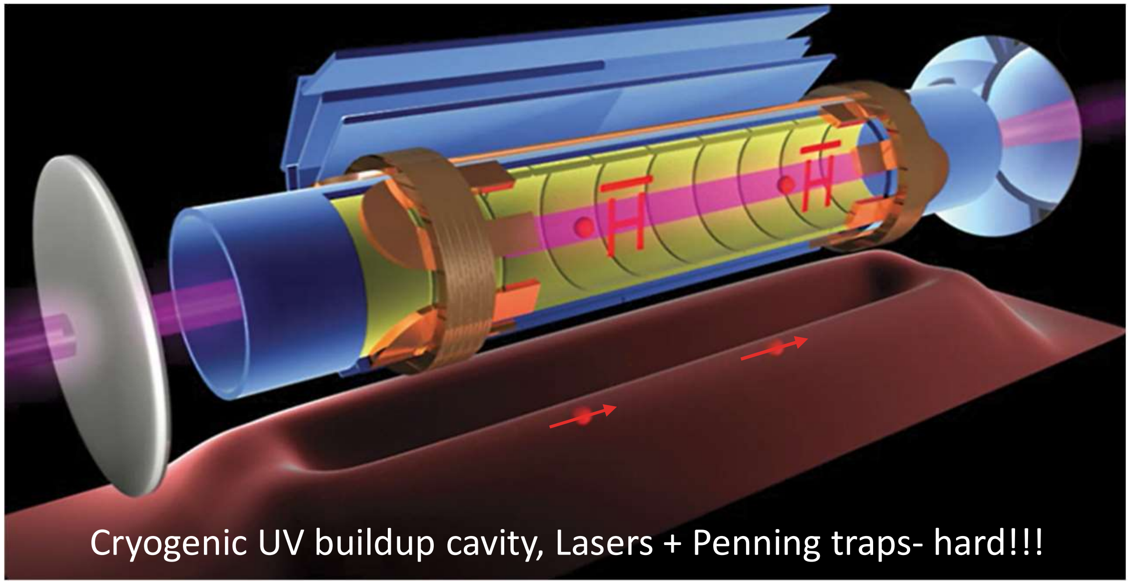
Careful control of antiproton and positron temperatures and densities





M. Ahmadi, Nature Communications **8** (2017)

# Laser spectroscopy of Antihydrogen 1S-2S



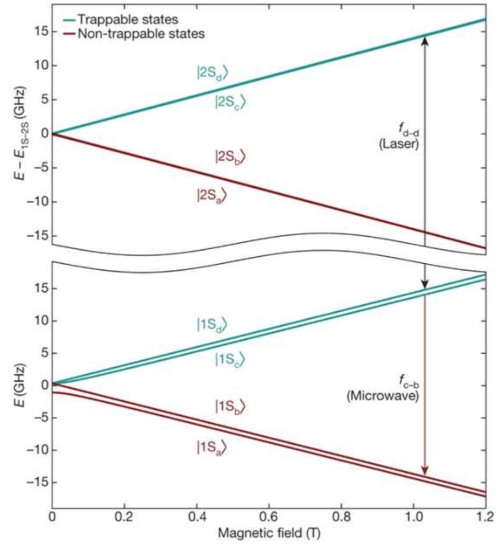
Cryogenic UV buildup cavity, Lasers + Penning traps- hard!!!

ALPHA collaboration

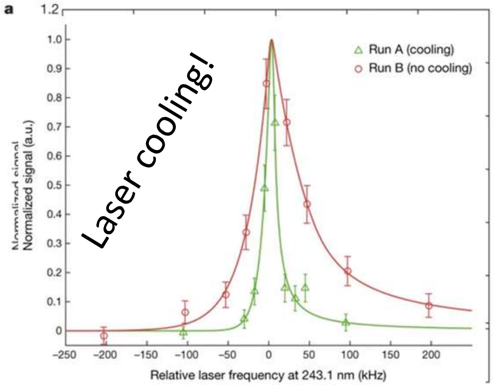
60 hr antihydrogen storage

$$f_{d-d} = 2,466,061,103,079.4(5.4)\ \text{kHz (measured)}$$
$$f_{d-d} = 2,466,061,103,080.3(0.6)\ \text{kHz (predicted)}$$

2 ppt



2 photons at 243 nm cancels Doppler shift

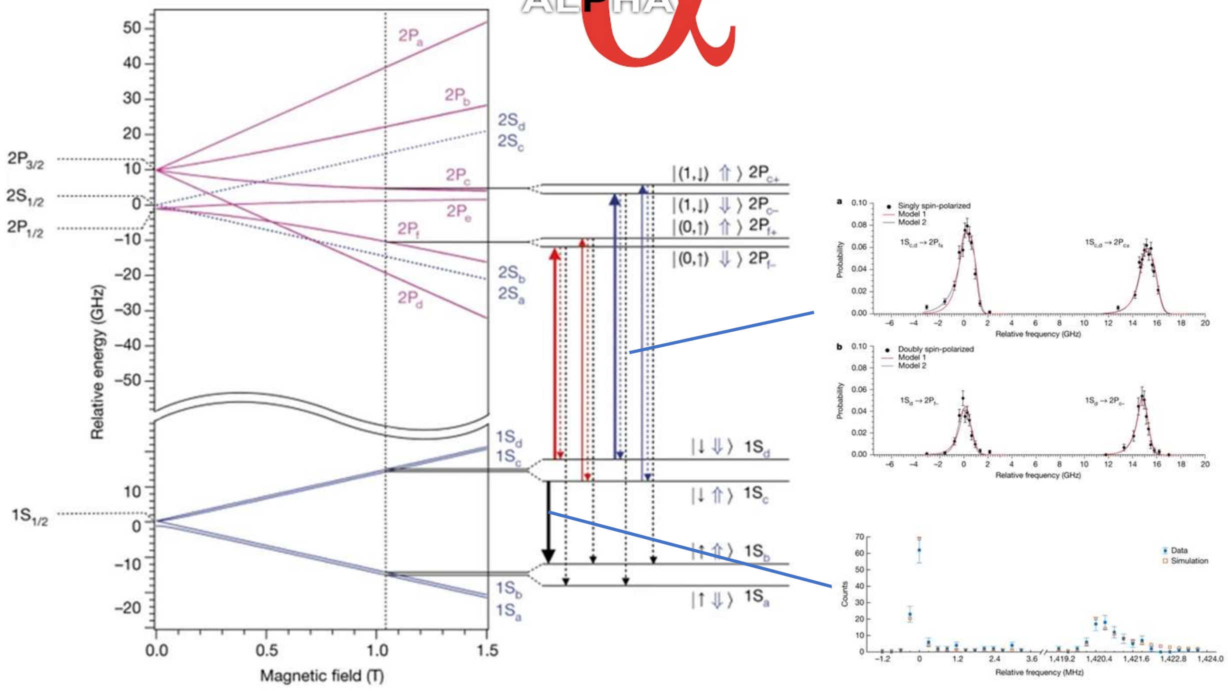


Laser cooling!

M. Ahmadi, Nature **557**, 71-75 (2018) C. J Baker, Nature **592**, 35–42 (2021)

# RF spectroscopy hyperfine splitting

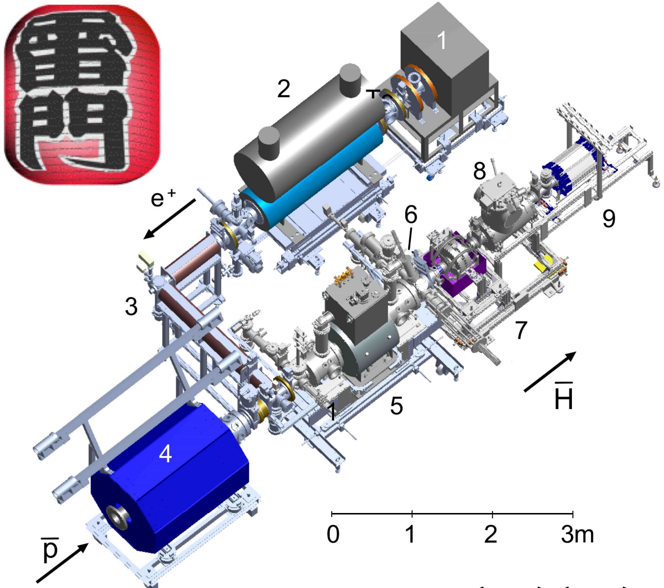
## ALPHA



Lamb shift $2S_{1/2} - 2P_{1/2}$ $\bar{H}$ 0.99 ± 0.11 GHz, H 0.9098717(32) GHz

Ground state splitting: $\bar{H}$ 1,420.4 ± 0.5 MHz, H 1 420 405.751 766 7(9)

## ASACUSA



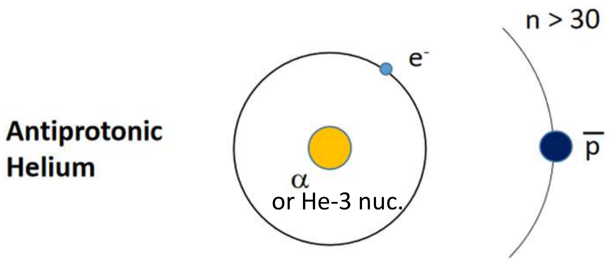
$$\Delta\nu = 1420405748.4(3.4)(1.6)\ \text{Hz}$$

- 2.7 ppb in Hydrogen

M. Ahmadi, Nature **548**, 66-69 (2017)
M. Ahmadi, Nature **578**, 375–380 (2020)
ASACUSA Collaboration. Report No. SPSC-P-307 Add. 1 CERN-SPSC-2005-002 (2005)
N. Ramsey, Hyp. Interactions **81** (1993)

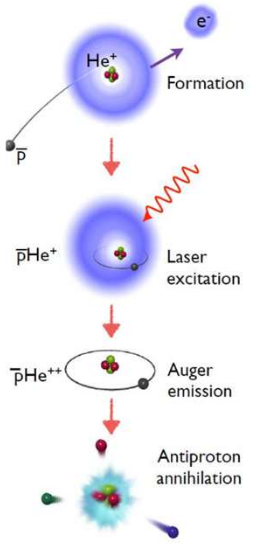
# Antiprotonic helium

ASACUSA

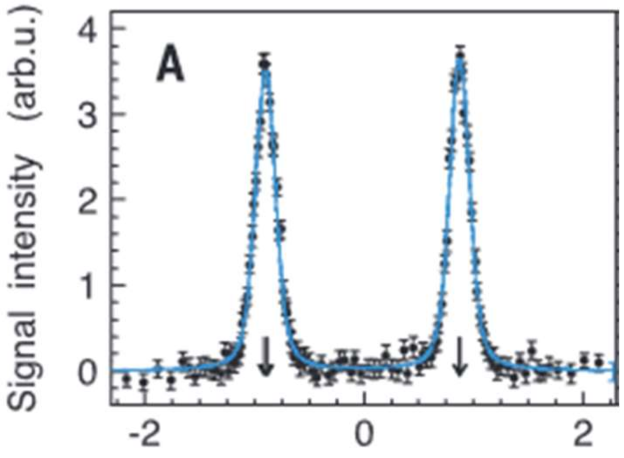


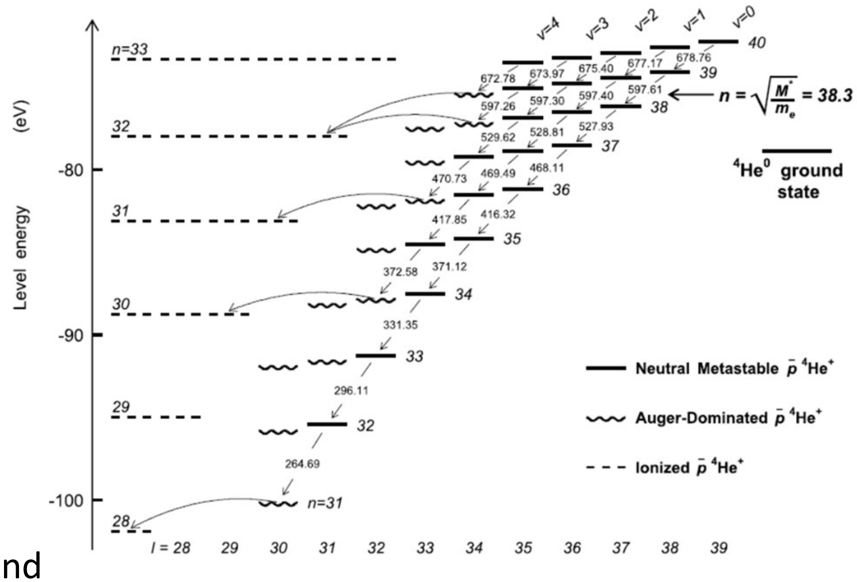
$$E_n = -hcR\frac{Z^2}{n^2} \qquad R = R_\infty \frac{m_{\bar{p}}}{m_e}\frac{1}{\left(\frac{m_{\bar{p}}}{m_e}+1\right)}$$

Measure energy levels, determine $\frac{m_{\bar{p}}}{m_e}$



Ground state lifetime: 100 ns
Lifetime n~38 ~1-2 us or ~ns



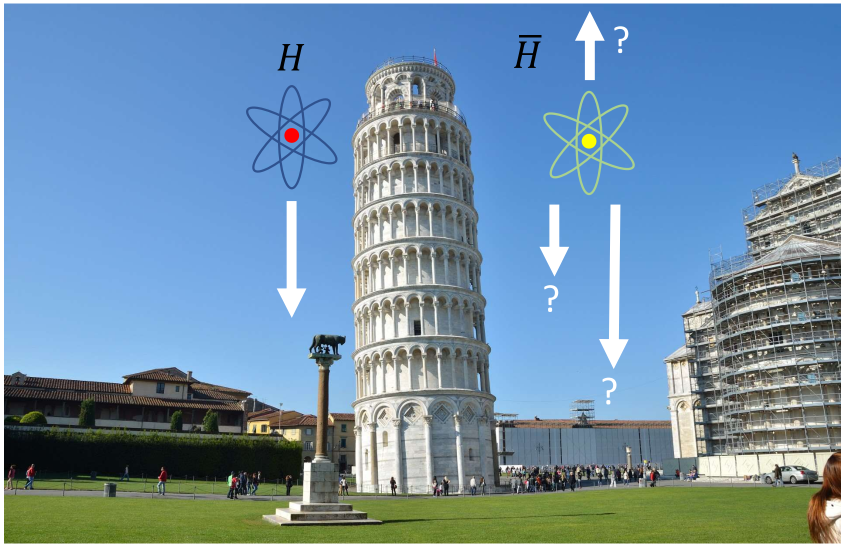


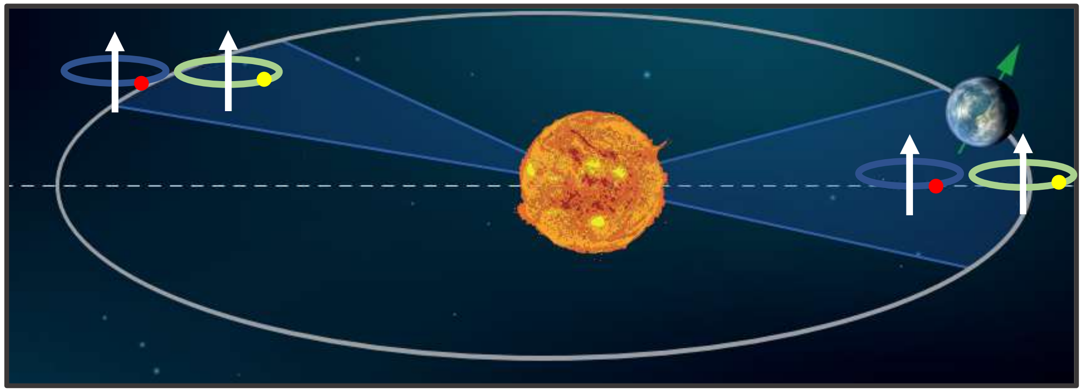
Laser resonance leads to electron ejection and rapid $\bar{p}\mathrm{He}^{2+}$decay emitting pions, detected via Cherenkov detectors

M. Hori et al., Science 354, 610 (2016)

# Effect of gravity on antihydrogen

# Types of measurement



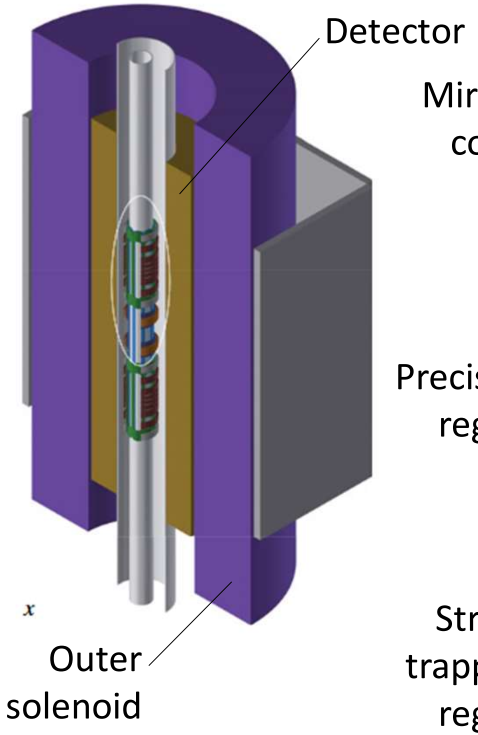


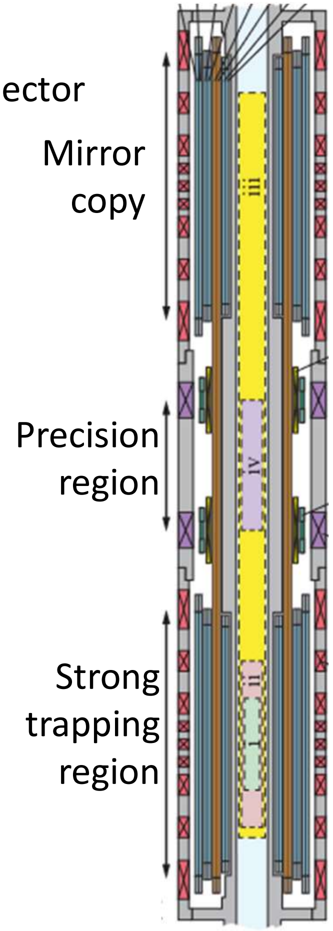
Freefall

Clock comparison

High precision needed- If proton is any guide, antiquark masses only ~1% of the antiproton

# ALPHA-g



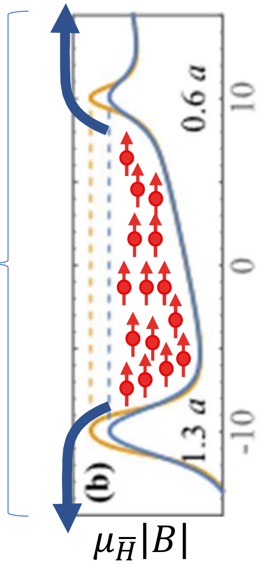


Mirror copy of lower region to keep fields symmetric

Region optimized for gravity measurement

Region optimized for $\bar{H}$

$$V = \mu_{\bar{H}}|B| - m_{\bar{H}}gh$$



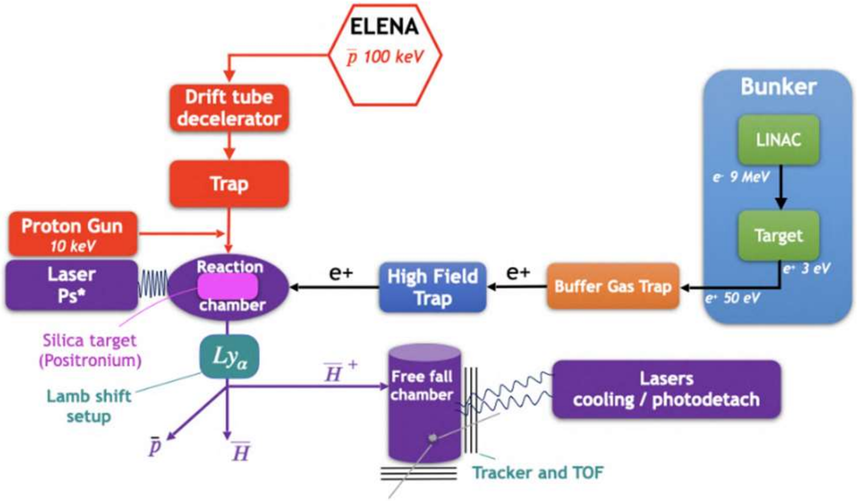
Slowly ramp magnetic fields until equal numbers escape up and down, Infer $m_{\bar{H}}$

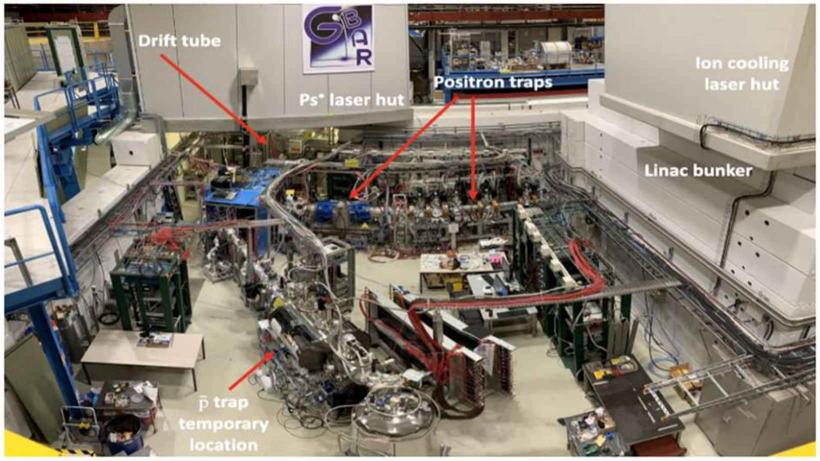
Colder the better!
Initially <0.54 mK
With laser cooling
Initially <0.05 mK

Target 5-1% measurement on $m_{\bar{H}}$

W. A. Bertsche, Phil. Trans. R. Soc. A **376** (2018)
C. So et al., IEEE Trans. Appl. Super. **30** 4 (2020)

# GBAR





1. Make $\overline{H}^+$ by reacting $\overline{H}$ with positronium
2. Sympathetically laser cool $\overline{H}^+$ with $\mathrm{Be}^+$ to 20 $\mu$K
3. Photoionise $\overline{H}^+$ to $\overline{H}$
4. Drop and measure effect of gravity

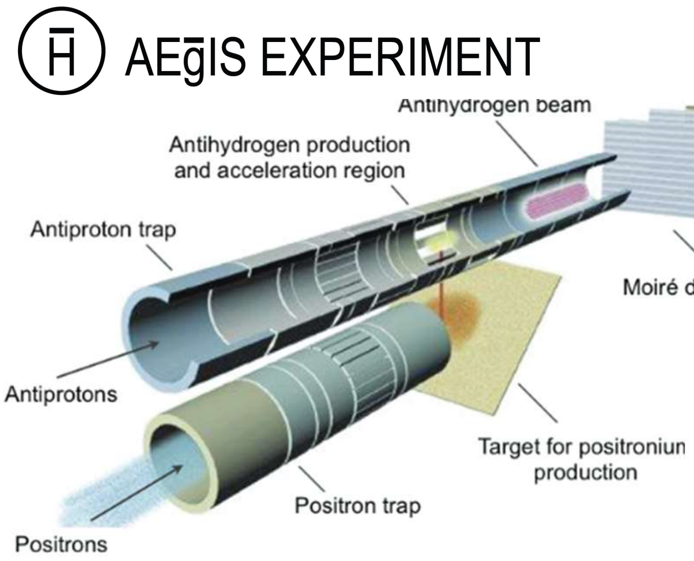
Initial goal 1%, final goal 0.1% with quantum measurement

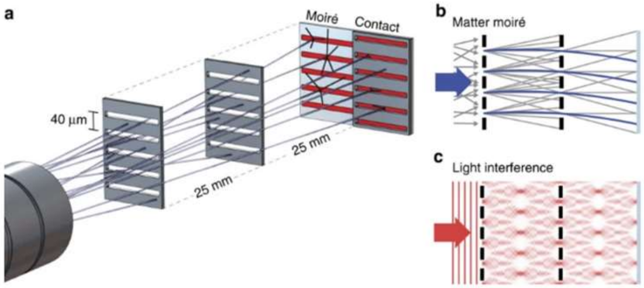
Also, long term possibility to produce $\overline{H}_2^+$ molecules and do antimolecular spectroscopy!

D. P. van der Werf, Antimatter and Gravity (WAG 2013) **30** (2014)
GBAR status report CERN-SPSC-2022-003 / SPSC-SR-302 (2022)

# AEgIS

Use beam of $\overline{H}$ for gravity measurement

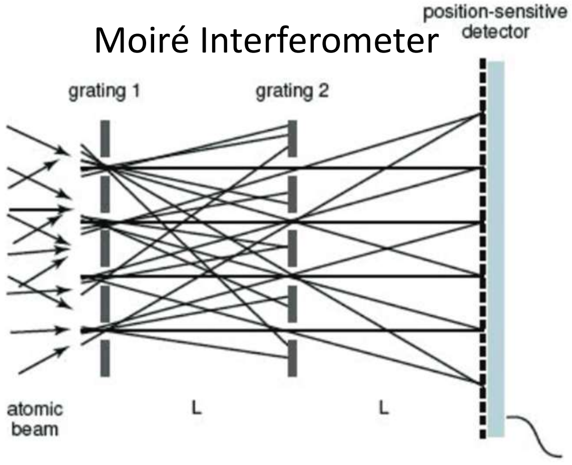


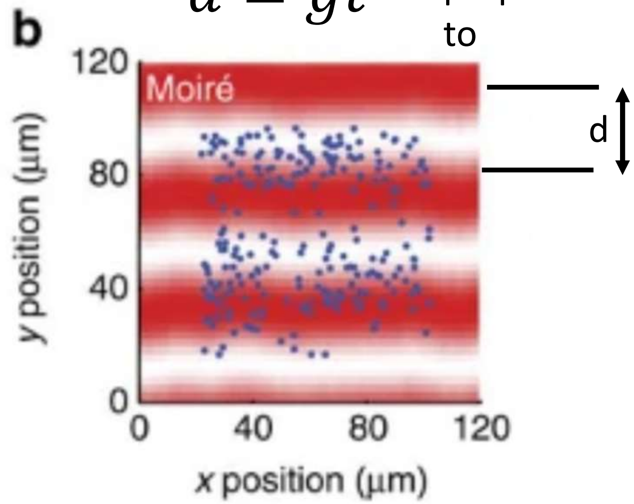


Fringe shift proportional to

$$d = gt^2$$

Moiré Interferometer





First used to measure force on antiprotons
530±50 aN (stat.)±350 aN (syst.) in 2014
Next antihydrogen -> 100 mK required, 1% accuracy sought

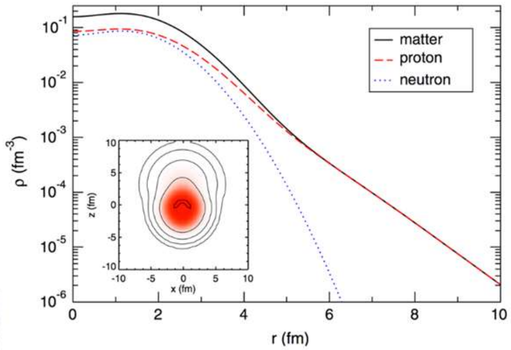
S. Aghion et al., *Nature Communications* **5** 4538 (2014)
P. Scampoli et al., Modern Physics Letters A **29** 17 (2014)
A. Kellerbauer et al., NIM B 226 **3** (2008)

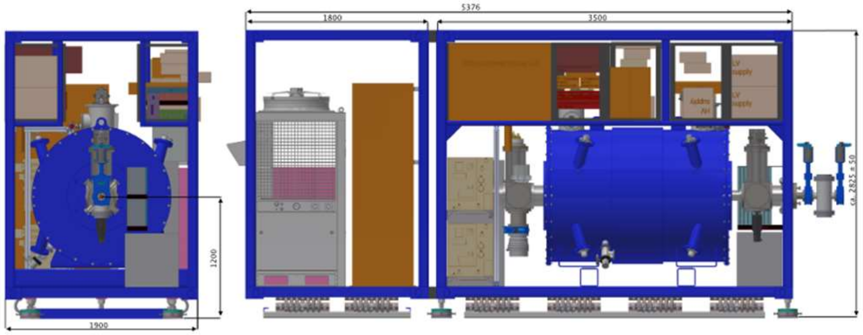
# Taking antimatter out of the lab

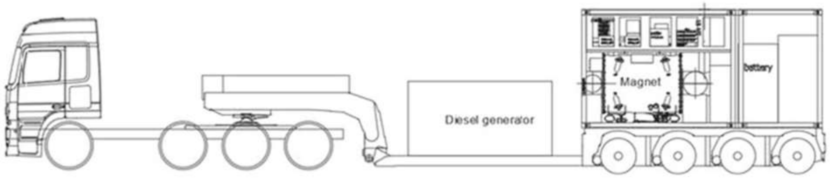
# PUMA

**Take $10^9$ antiprotons from the antimatter factory to ISOLDE**

Some nuclei at the limits of N>Z have a neutron halo a where one or more neutrons are found far outside the nucleus.
Other’s have neutron skins, where the density of neutrons is larger than protons at the nuclear surface – antiproton annihilation study these effects



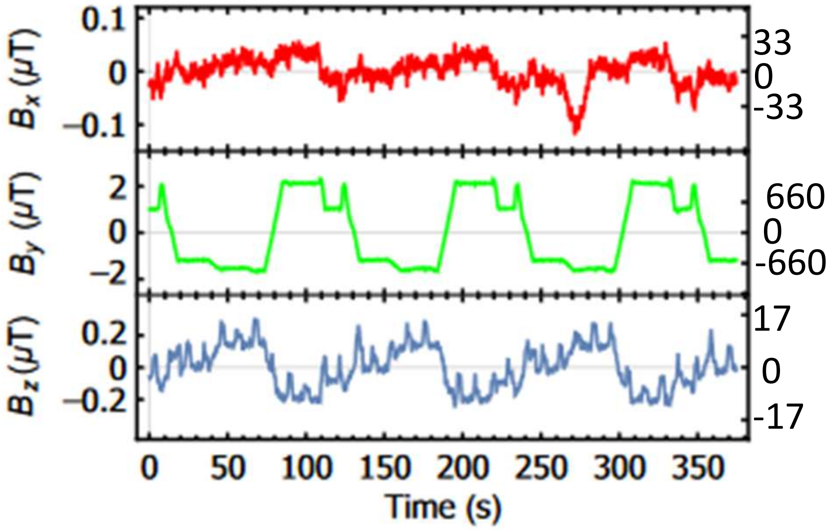




T. Aumann et al., Eur. Phys. J. A 58:88 (2022)

# BASE-STEP

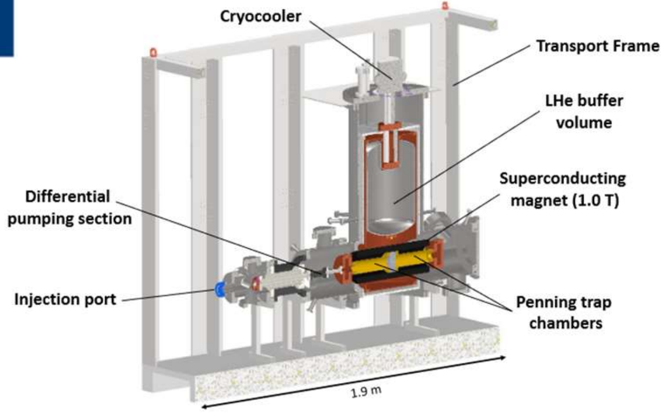
BASE trying to measure frequencies to parts-per-trillion level



Fractional magnetic field fluctuations (ppb)

STE p̄

Take the antimatter somewhere quiet

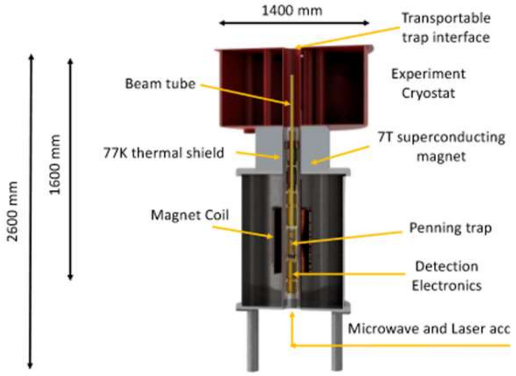


Magnetic field fluctuating in the background up to one million times more strongly

Hard to push the limits in this environment

BASE

Inject into a separate magnet in a quiet lab



# Should we be worried?

EXPRESS

Antimatter bombs: Could antimatter weaponry wipe out all life on Earth? Expert weighs in

Wed 21 Jul 2021

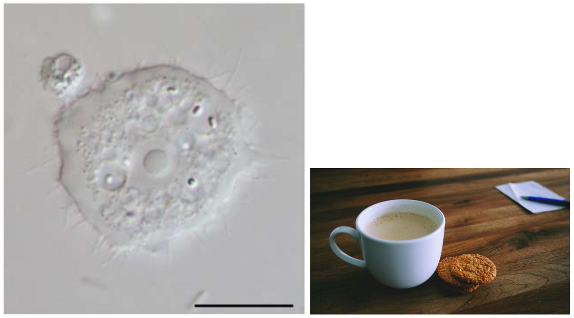
NO!

Professor Robson said: “The idea you can produce masses of antimatter and make a bomb from it or something is not realistic. It’s not something anyone needs to worry about.”

One billion antiprotons annihilating

$$E = mc^2 = (2 \times 1 \times 10^9 \times 1.6 \times 10^{-27})c^2 = 1\ \mathrm{nJ}$$

1nJ can heat 3 picogram of water from 20->100 $^{o}$C



About enough to make an espresso for an amoeba

(2015). "An update on *Acanthamoeba* keratitis: diagnosis, pathogenesis and treatment". *Parasite* **22**: 10.

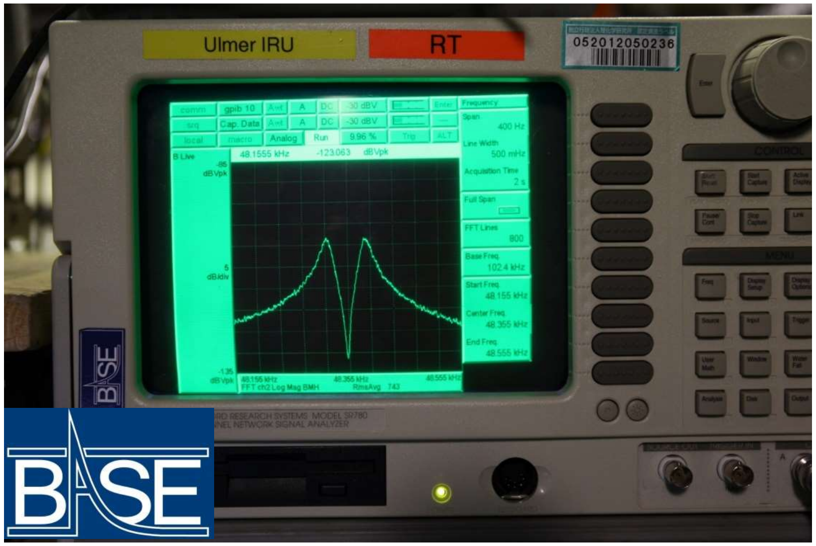
# Thank you

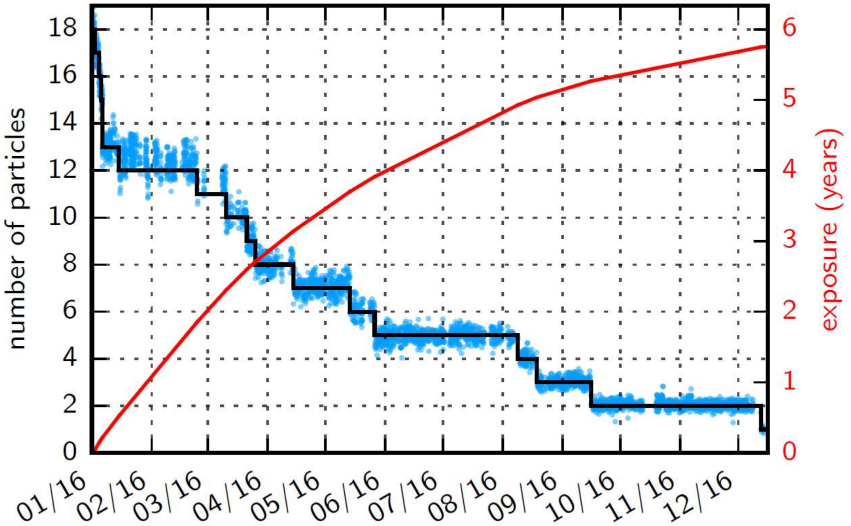
Thanks to Stefan Ulmer, Christian Smorra & Andi Mooser for providing slides and materials for these lectures

And thank you for listening

# Storing antiprotons

BASE holds record for antiprotons stored from 03.11.2015 – 22.12.2016





- Storage of antiprotons for more than one year: **405.5 days**
- Extraction of single particles by a potential tweezer scheme

Inversion of the baryon asymmetry:

Antibaryon density: ~ $10^8/\text{cm}^3$ $V < (50\ \mu\text{m})^3$
Baryon density: ~ $1\ /\ \text{cm}^3$ $p < 10^{-16}$ Pa

C. Smorra et al., Int. J. Mass Spectr. **389**, 10 (2015).
S. Sellner et al., New J. Phys. 19, 083023 (2017).