Antimatter in the Laboratory 2/2

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CERN, 01-08-2024

Precision measurements with antimatter

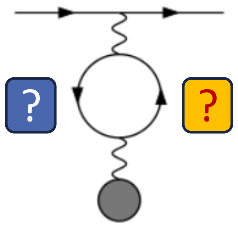
Precision Physics Approach

- What we observe and investigate is always a well understood simple system

$$i\hbar\partial_t|\psi\rangle = H_0|\psi\rangle$$

(correspondence principle: $E \rightarrow i\hbar\partial_t$)

…and we are looking for interactions which add small perturbations



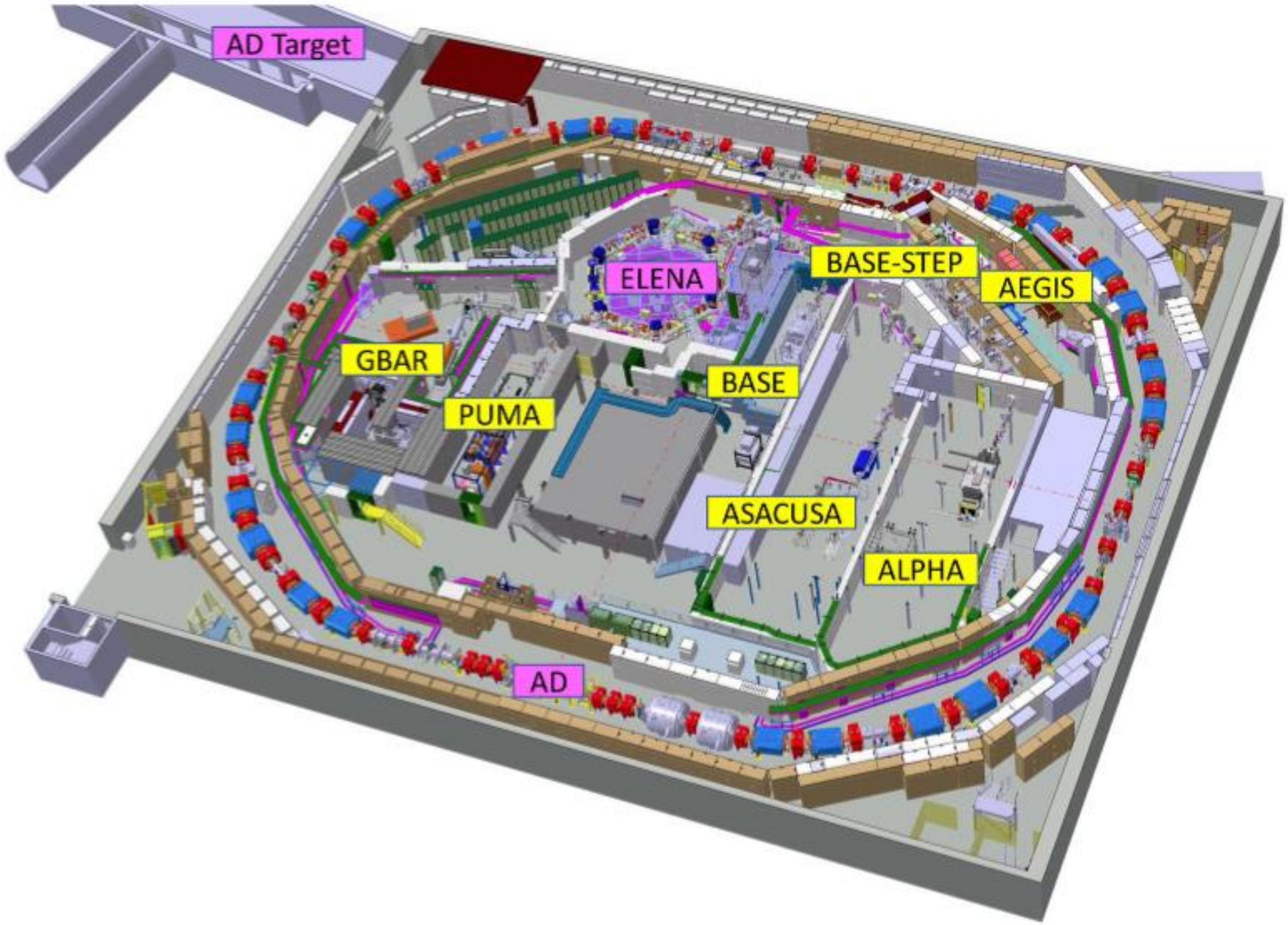
$$i\hbar\partial_t|\psi\rangle = (H_0 + V_{pert})|\psi\rangle$$

As you know from QM lectures, these interactions cause energy shifts in spectra (LS / HFS / QED / other?)

- For example: exotic or yet not observed interactions mediated by very heavy exchange bosons add extremely short ranged (weak?) interactions to the known standard model physics

Measure extremely precisely and compare to known theory.

The AD/ELENA-Facility



60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations

Antihydrogen

Spectroscopy

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

Gravity

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

Antiprotons

Antiprotons

BASE, BASE-STEP
Fundamental properties of the proton/antiproton, tests of clock WEP / tests of exotic physics / antimatter-dark matter interaction, etc...

Egzotic Atoms

ASACUSA
Antiprotonic helium spectroscopy

Nuclear Physics

PUMA
Antiproton/nuclei scattering to study neutron skins

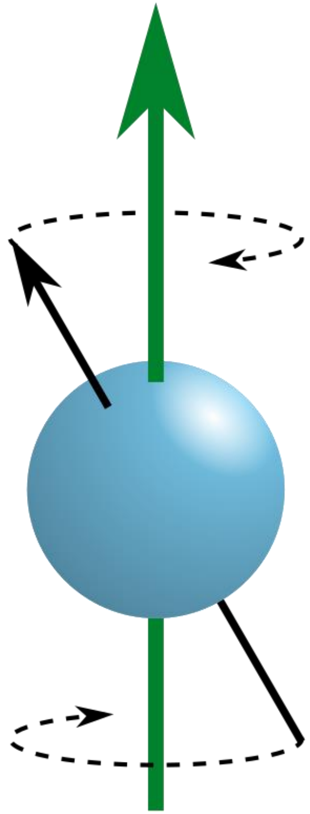
Question to all of you:

Do you know what is the most precise test of the Standard Model?

Magnetic moment of a particle

- Magnetic moment and a spin of a particle are related through a dimentionless parameter called g-factor:

$$\mu = g\frac{q}{2m}S$$



- Electron /positron / proton / antiproton spin S = ½
- We know that in classical systems g = 1.
- From Dirac equation we expect that g=2 for an electron or positron.

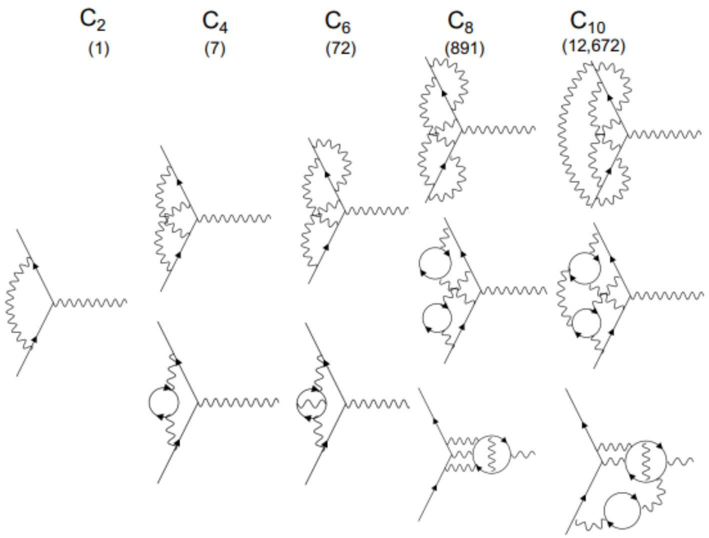
- Larmor frequency – spin precession in a given magnetic field:

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

The Most Precise Test of The Standard Model

- For the electron and positron, g/2 differs from the Dirac equation's prediction of 1 by about one part per thousand due to interactions with the fluctuating quantum vacuum (T. Aoyama, T. Kinoshita, and M. Nio, Atoms 7, 28 (2019)).

$$\frac{g}{2} = 1 + C_2\left(\frac{\alpha}{\pi}\right) + C_4\left(\frac{\alpha}{\pi}\right)^2 + C_6\left(\frac{\alpha}{\pi}\right)^3 + C_8\left(\frac{\alpha}{\pi}\right)^4 + C_{10}\left(\frac{\alpha}{\pi}\right)^5 + \ldots + a_{\mu,\tau} + a_{\text{hadron}} + a_{\text{weak}}.$$

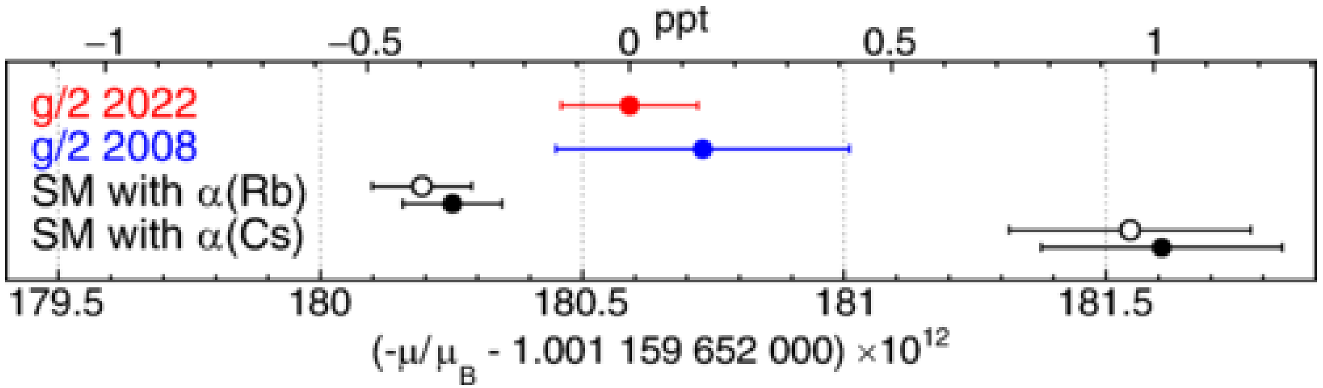


- Electron g/2 is **the most precisely measured property of an elementary particle**, with a value measured at Northwestern / Harvard in 2023 (Phys. Rev. Lett. **130**, 071801):

$$\frac{g_{e^-}}{2} = 1.001\ 159\ 652\ 180\ 59\ (13)\ [0.13\ \text{ppt}],$$

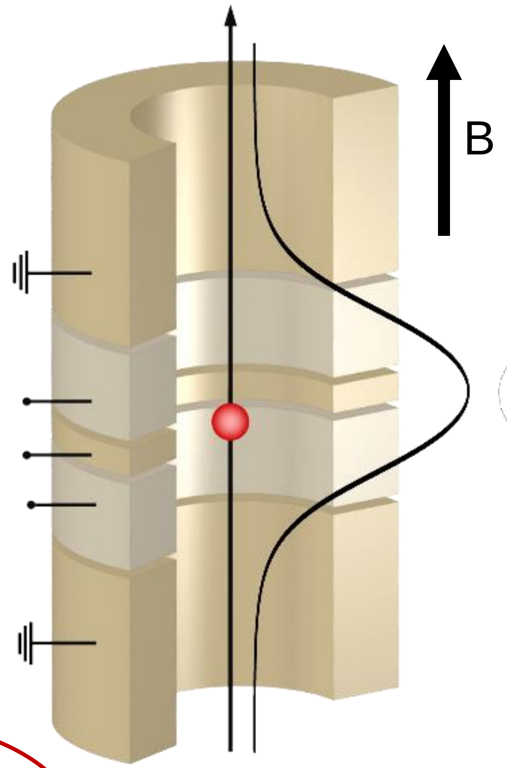
- The positron g/2 was measured 33 times less precisely at the University of Washington in 1987:

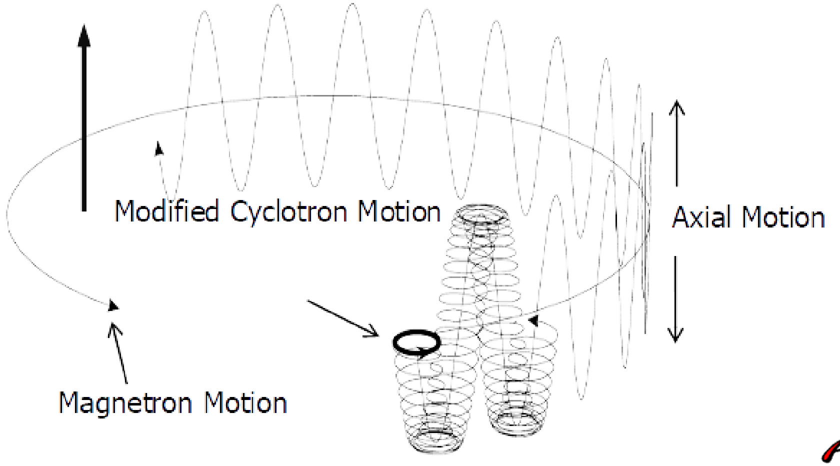
$$\frac{g_{e^+}}{2} = 1.001\ 159\ 652\ 187\ 9\ (4\ 3)$$



Fundamental properties of antiprotons

Penning trap - reminder





- **Penning trap with:**
  -> radial confinement: $\vec{B} = B_0 \hat{z}$
  -> axial confinement: $\Phi(\rho, z) = V_0 c_2 \left(z^2 - \frac{\rho^2}{2} \right)$

- **Invariance theorem:**
  Cyclotron frequency of a particle

$$\nu_c = \sqrt{\nu_+^2 + \nu_z^2 + \nu_-^2} \longleftrightarrow \nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

which is correct also for any small angle misalignment of the trap or quadratic imperfections of the field (G. Gabrielse)!

Axial	680 kHz	$\nu_z = \frac{1}{2\pi}\sqrt{\frac{2C_2 q V_0}{m}}$
Magnetron	8 kHz	$\nu_- = \frac{1}{2}\left(\nu_c - \sqrt{\nu_c^2 - 2\nu_z^2}\right)$
Modified Cyclotron	28.9 MHz	$\nu_+ = \frac{1}{2}\left(\nu_c + \sqrt{\nu_c^2 - 2\nu_z^2}\right)$

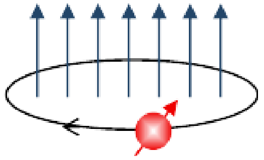
Main Measurements at BASE

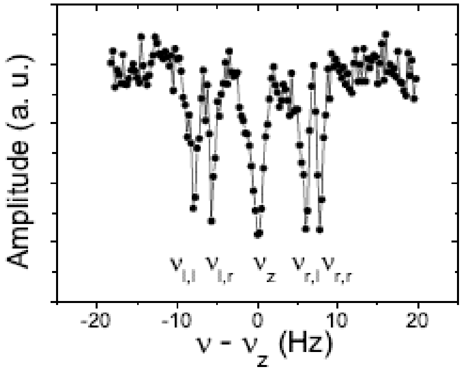
High precision mass spectroscopy

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Cyclotron Motion

$$\omega_c = \frac{e}{m_p} B$$





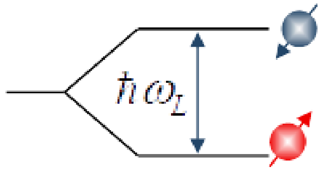
- **A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio,** Nature 601.7891 (2022): 53-57.

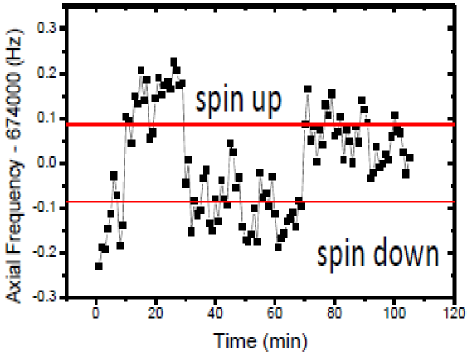
High precision magnetic moment measurements

$$\frac{\nu_L}{\nu_c} = \frac{\mu_p}{\mu_N} = \frac{g_p}{2}$$

Larmor Precession

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





- **1.5 p.p.b. Measurement of antiproton magnetic moment,** Nature 550, 371-374 (2017)

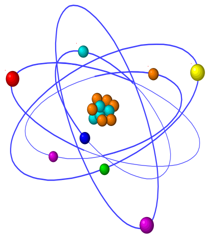
Precision

m_{A380} = 500 T = 500.000.000.000 mg = $5 \cdot 10^{11}$ mg

$m_{ant} \approx$ 3-7 mg

$$\frac{m_{ant}}{m_{A380}} \approx 2 \cdot 10^{-11}$$

BUT: Precision achieved on the atomic scale!



in the near future ~10^{-12}

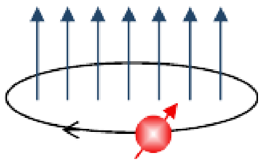
Main Measurements at BASE

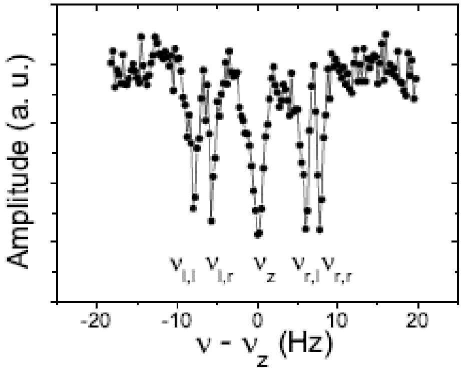
High precision mass spectroscopy

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{e_{\bar{p}}/m_{\bar{p}}}{e_p/m_p}$$

Cyclotron Motion

$$\omega_c = \frac{e}{m_p} B$$





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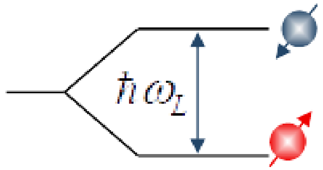
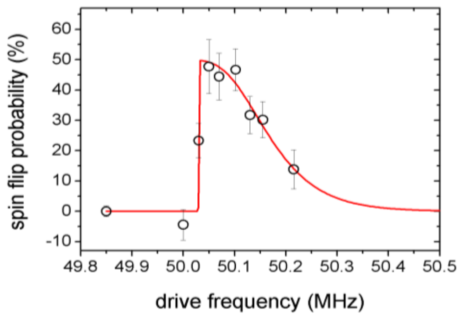
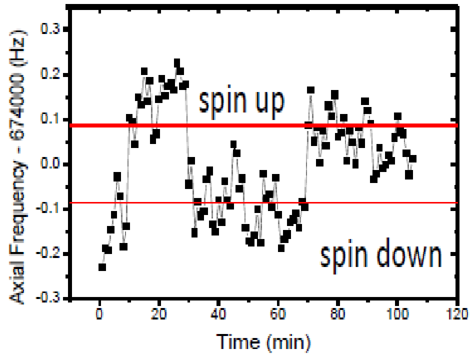
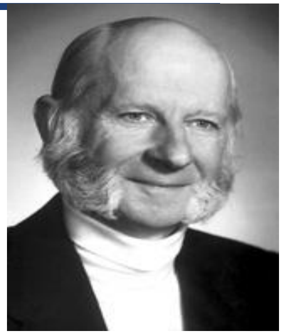




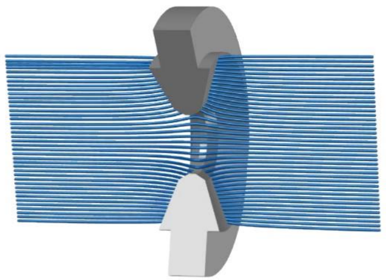


- **1.5 p.p.b. Measurement of antiproton magnetic moment,** Nature 550, 371-374 (2017)

Larmor Frequency – extremely hard



- Measurement based on continuous Stern Gerlach effect.

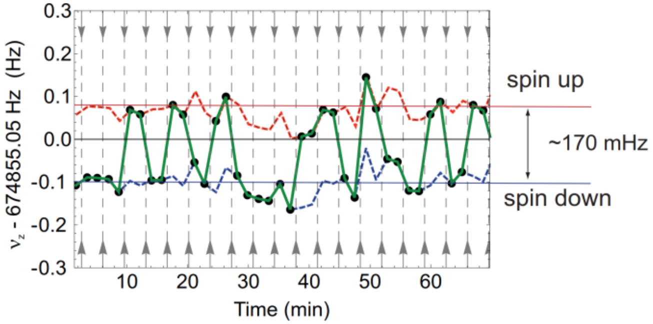


- Energy of magnetic dipole in magnetic field: $\Phi_M = -(\vec{\mu_p} \cdot \vec{B})$
- Leading order magnetic field $B_z = B_0 + B_2\,(z^2 - \frac{\rho^2}{2})$

Correction:

This term adds a spin dependent quadratic axial potential
-> Axial frequency becomes a function of the spin state

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

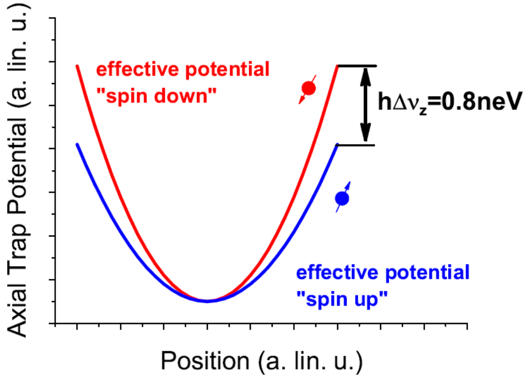


-> Very difficult for the proton/antiproton system.

$$B_2 \sim 300000\ T/m^2$$

-> Most extreme magnetic conditions ever applied to single particle.

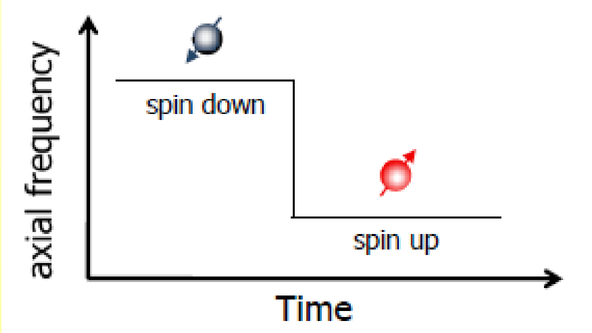
$$\Delta\nu_z \sim 170\ mHz$$

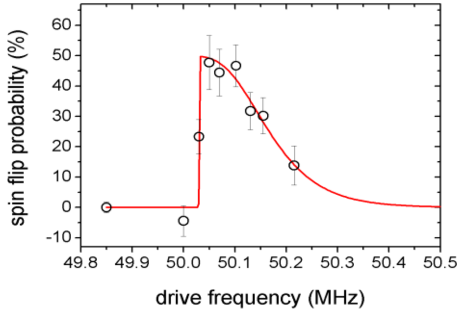


	B2	$\Delta\nu_z$
Electron	300 T/m2	~1.3 Hz
Antiproton	300 000 T/m2	170 mHz

Frequency Measurement

Spin is detected and analyzed via an axial frequency measurement

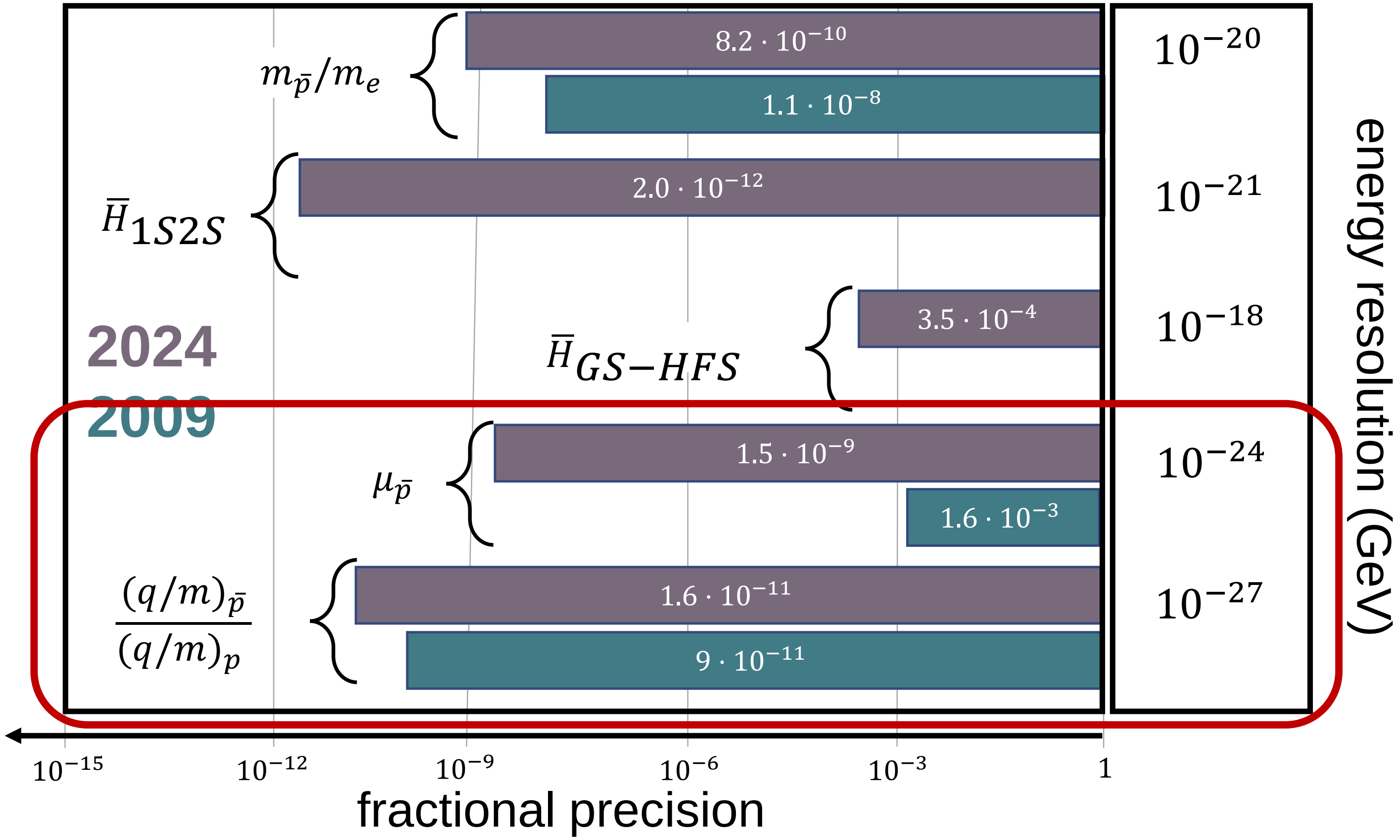




S. Ulmer, A. Mooser *et al.* PRL 106, 253001 (2011)

Subject of this lecture -> how to get these numbers?

- AD -> measure fundamental properties of antimatter systems and compare them with theory // matter.



BASE-STEP Experiment

$$\nu_c = \frac{1}{2\pi} \frac{q_{ion}}{m_{ion}} B$$

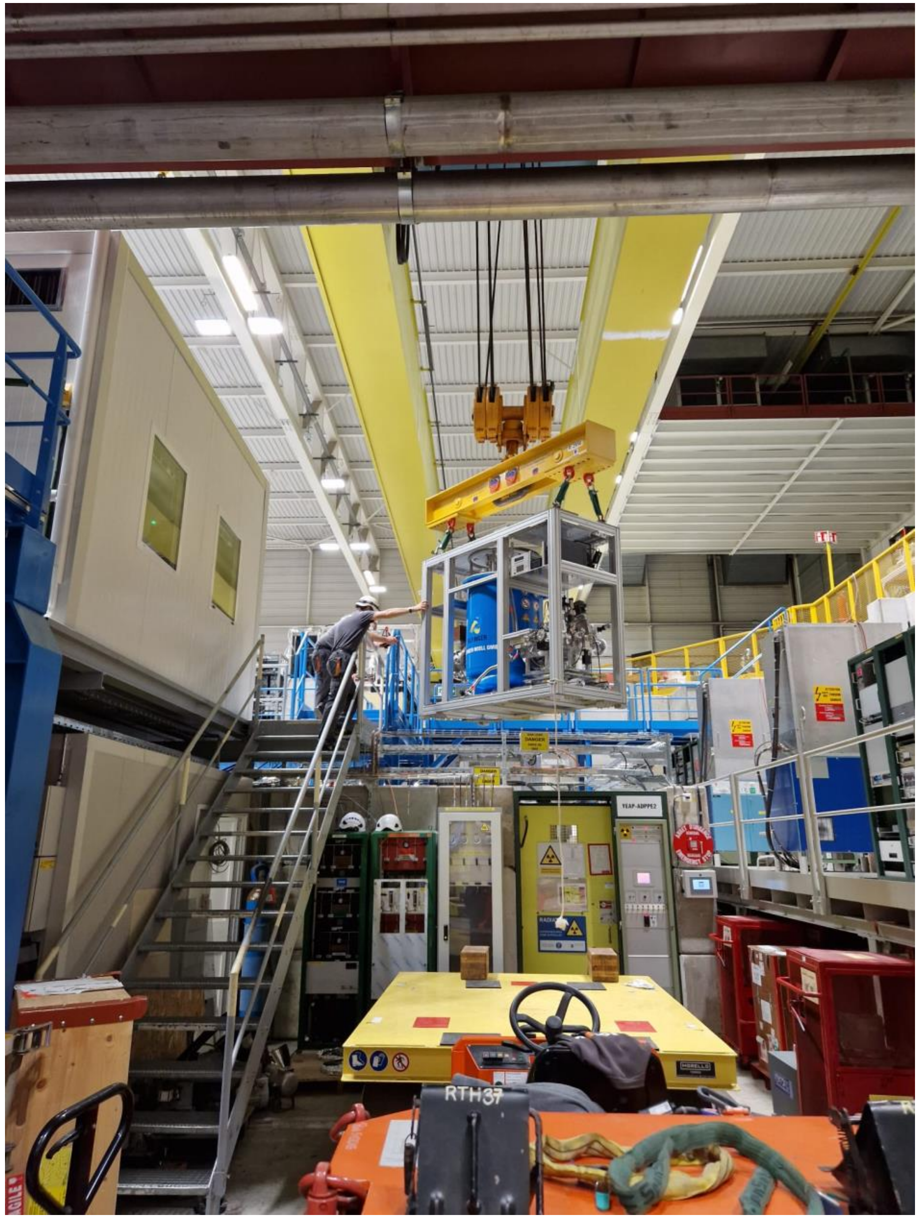
- Main concept:

Penning Trap measurements are very sensitive to magnetic field fluctuations. However, Antimatter Factory is an accelerator hall which means high magnetic field noise, which can not be switched off.

If you can not switch off the accelerator...

Transport yourself out of the accelerator hall.

- **Goal is to transport antiprotons to the Univeristy of Dusseldorf (Germany) to perform ultra precise measurements on single antiprotons.**



Antihydrogen spectroscopy

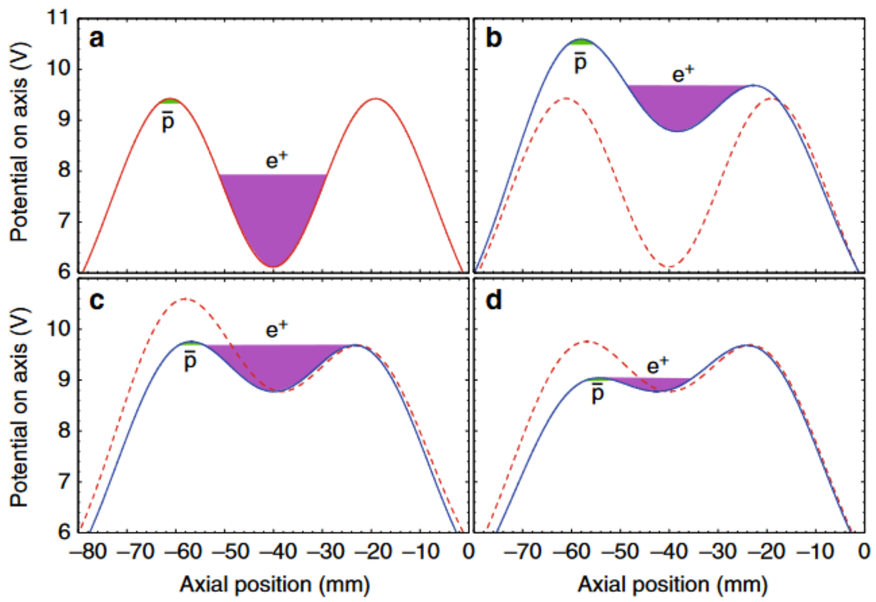
Antihydrogen production

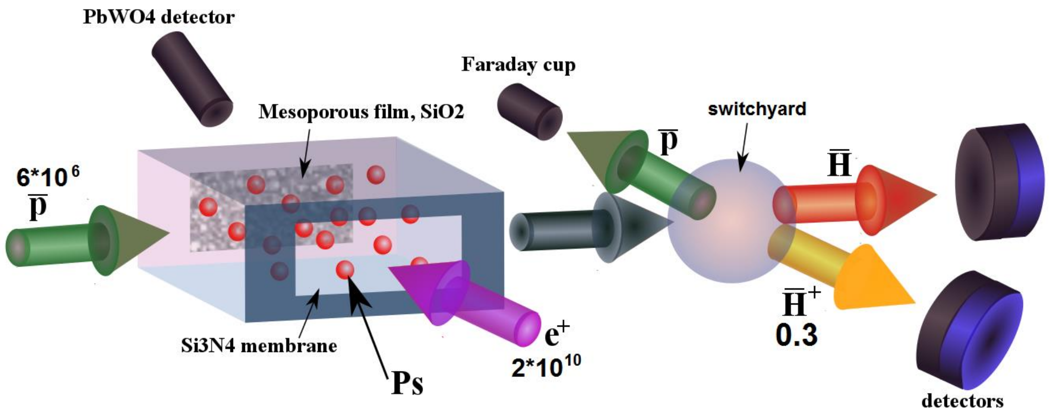
- Three main methods:
  1. Recombination: $\bar{p} + e^+ \rightarrow \bar{H} + \text{UV photon}$
  2. Three body recombination (ALPHA, ASACUSA):

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

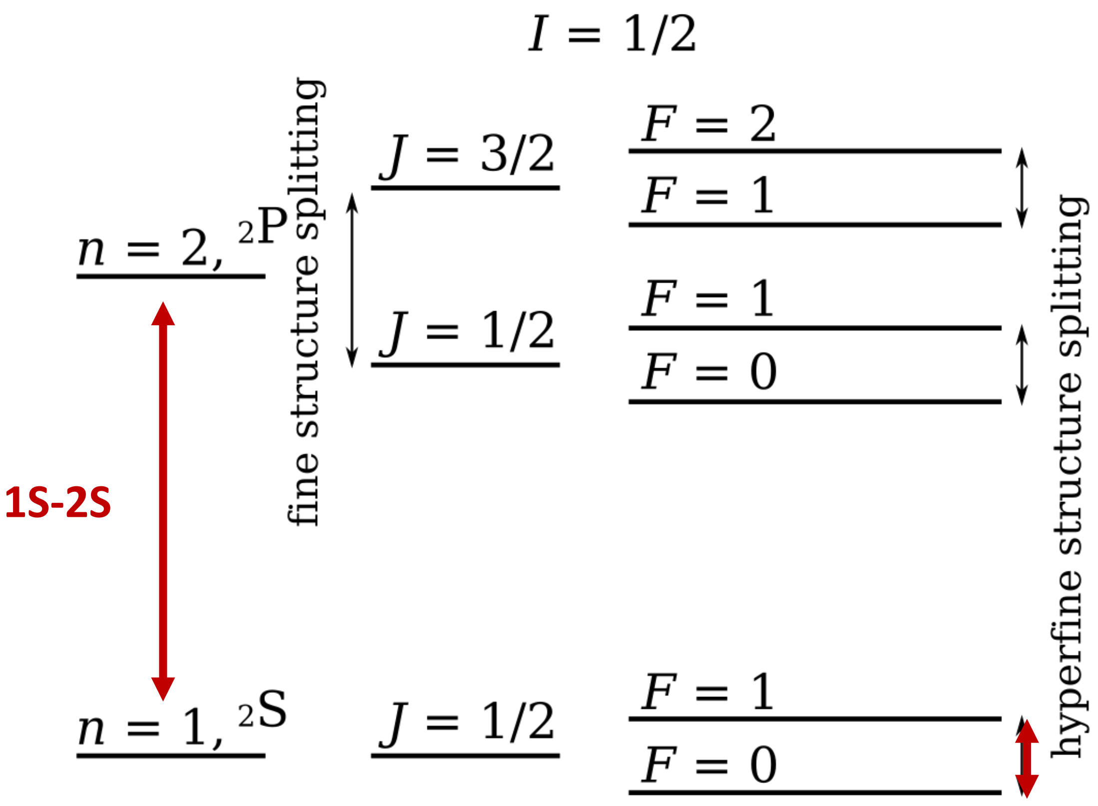
    - ALPHA: 50 000 in 4 minutes
    - ASACUSA: 2 atoms per 15 minutes

  3. Charge transfer (GBAR, AEgIS): $\bar{p} + \text{Ps} \rightarrow \bar{H} + e^-$
    - AEgIS: 0.021(5) $\bar{H}$ per 15 minutes
    - GBAR: 0.015 $\bar{H}$ per 20 minutes



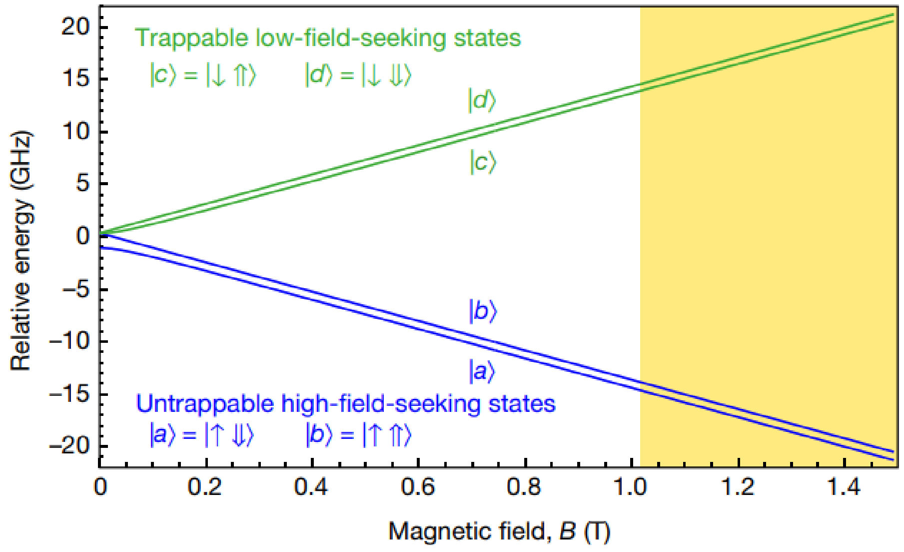


Spectroscopy of (anti)hydrogen atom



GS-HFS -> Ground State Hyperfine Splitting

- Fine structure - results from the interaction between the magnetic moments associated with electron spin and the electrons' orbital angular momentum.
- Hyperfine structure - electron spin aligns in the magnetic field of the spin of the proton

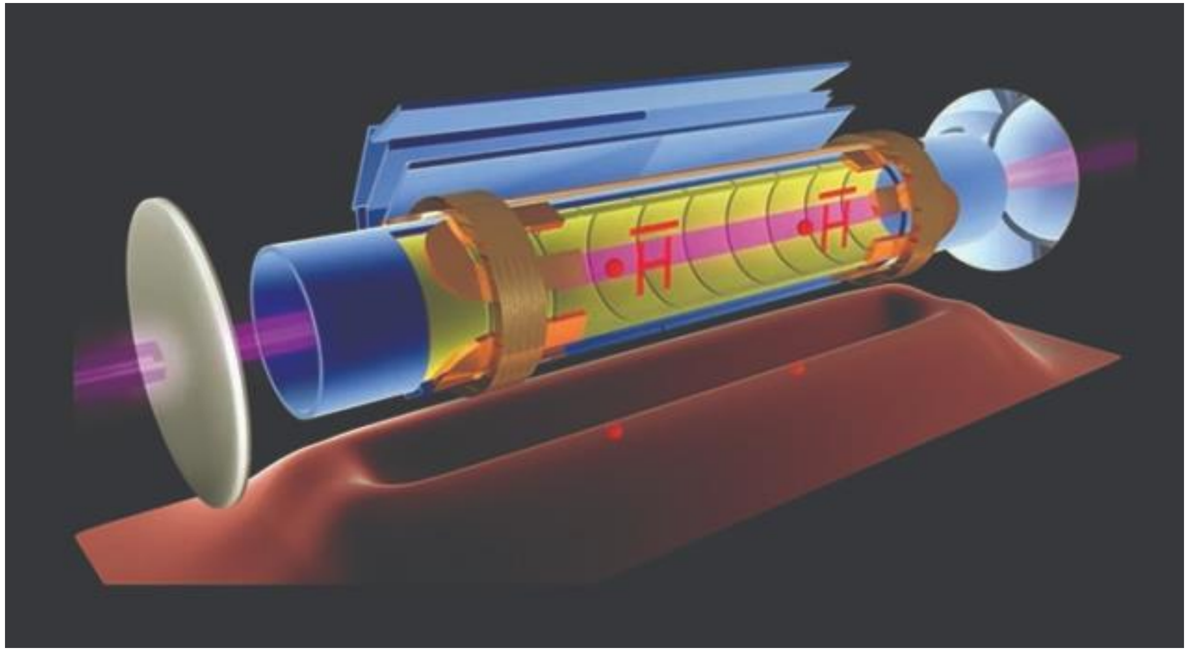


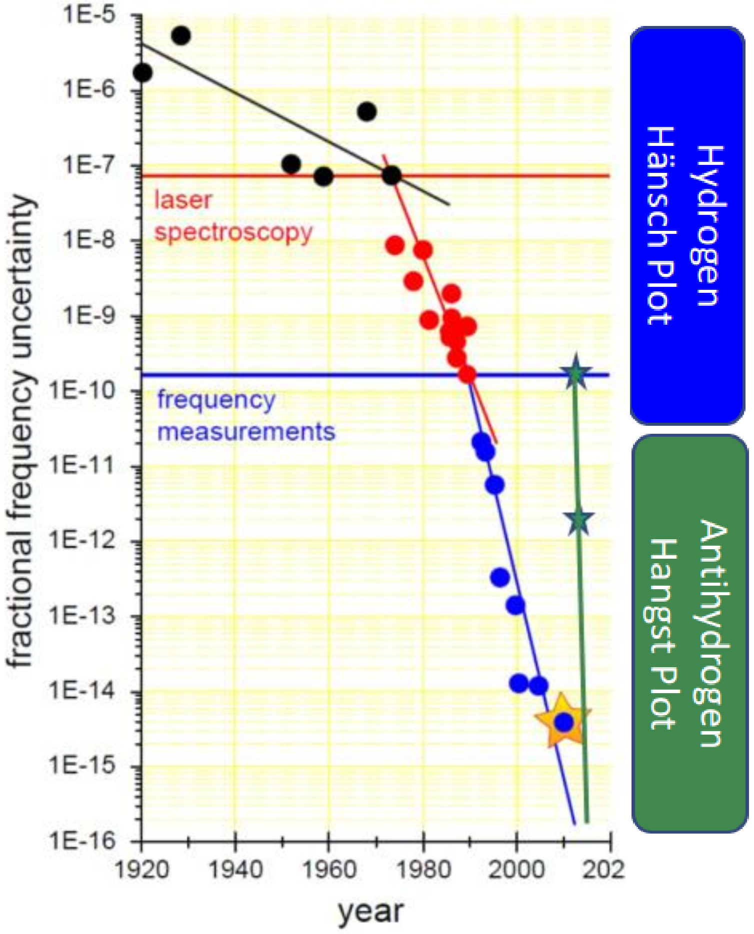
- The energy levels in hydrogen atoms are analytically calculable which allows to compare the predicted values with measurements for both hydrogen and antihydrogen.

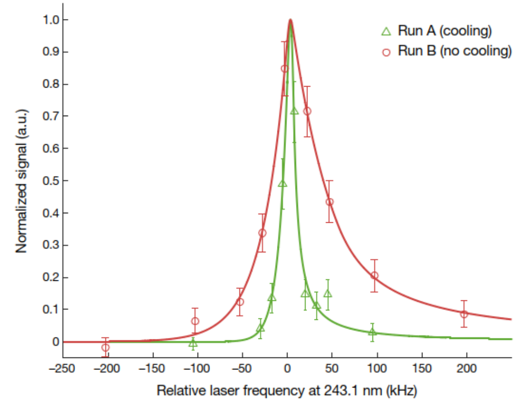
1S-2S transition in antihydrogen

- **Characterization of the 1S–2S transition in antihydrogen**. *Nature* **557**, 71–75 (2018) at 2×10^{-12} precision.
- Counterpropagating two pulses from 243-nm laser to cancel Doppler broadening.

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



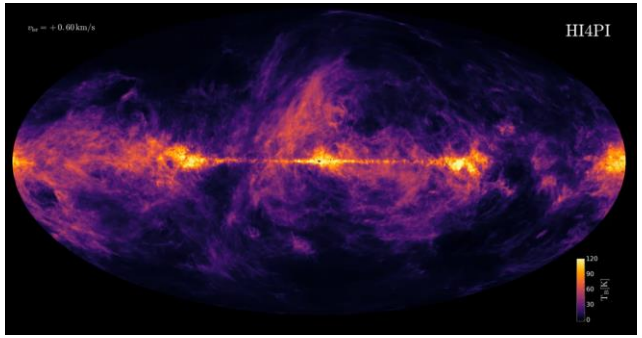




- Laser cooling of antihydrogen atoms *Nature* **volume 592**, pages35–42 (2021)

Ground state hyperfine splitting

- The electron spin aligns in the magnetic field of the spin of the proton, which gives the hyperfine structure.
- Most important in radio astronomy – 21cm line => RF spectroscopy



Trapped antihydrogen - ALPHA

Beam of antihydrogen - ASACUSA

Hydrogen	f_H = 1420405 751.773 ± 0.001 **Hz**	7×10^{-13}	P Petit *et al* 1980 *Metrologia* **16** 7
Hydrogen beam	f_H = 1,420,405,748.4(3.4) (1.6) Hz	2.7×10^{-9}	ASACUSA, *Nat. Commun.* **8**, 15749 (2017)
Antihydrogen	f_H = 1,420 (0.5) MHz	1×10^{-4}	ALPHA, Nature **548**, 66-69 (2017)

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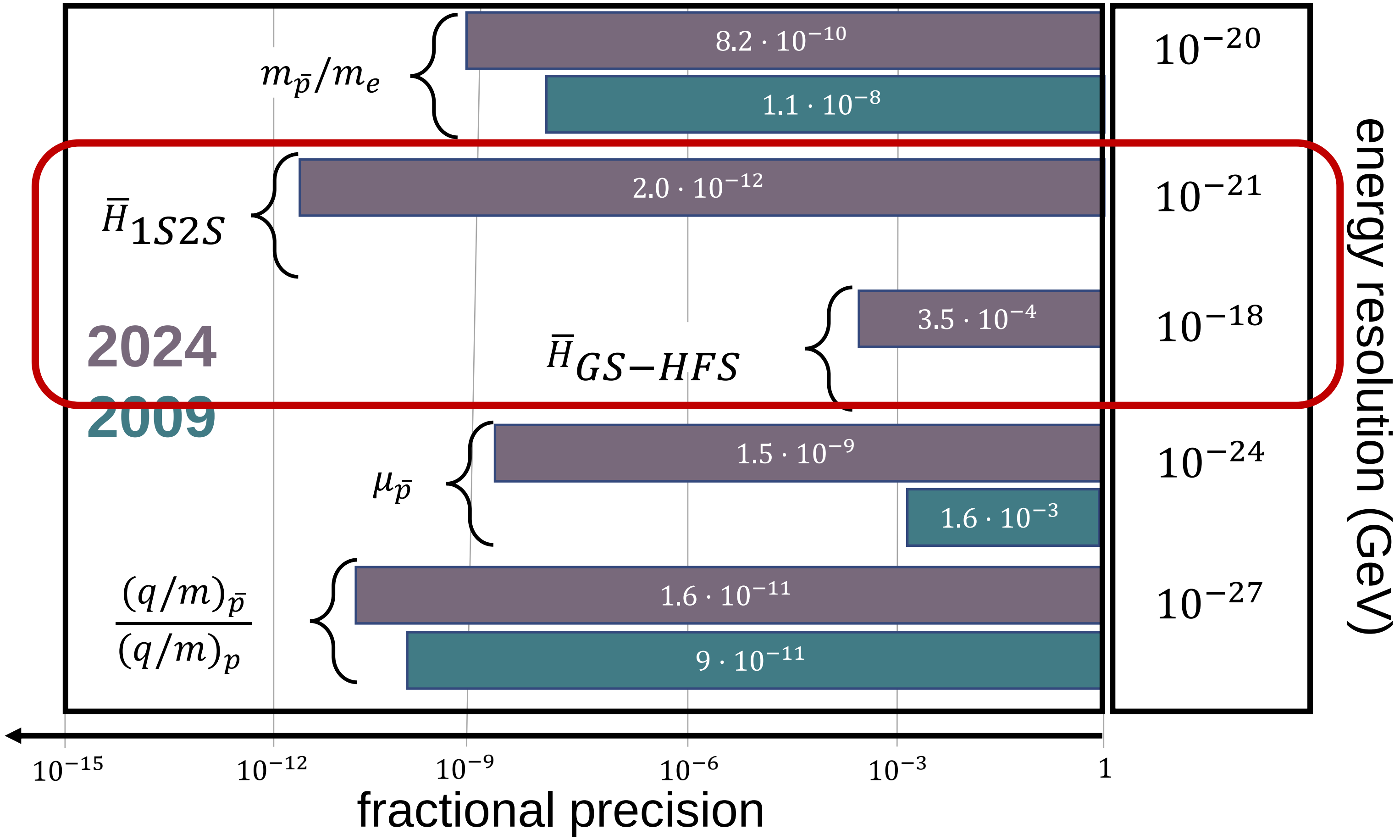
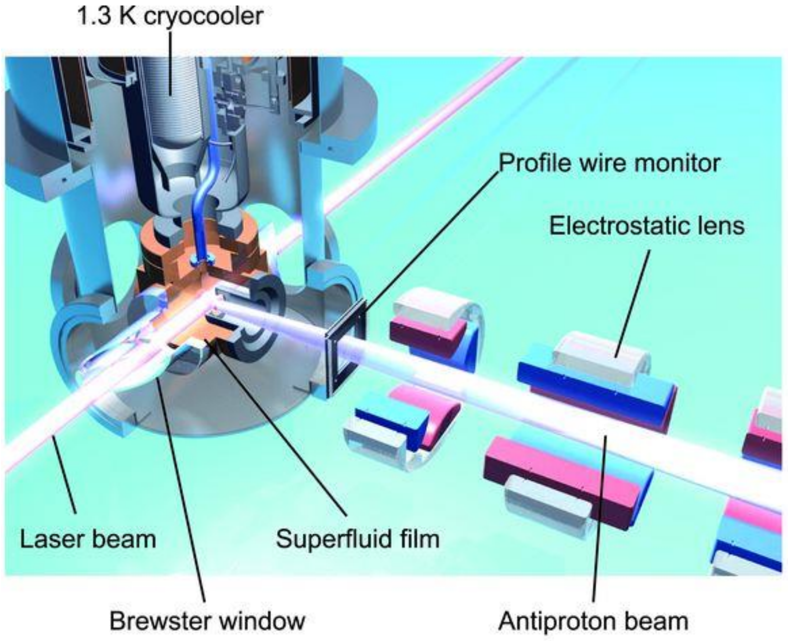


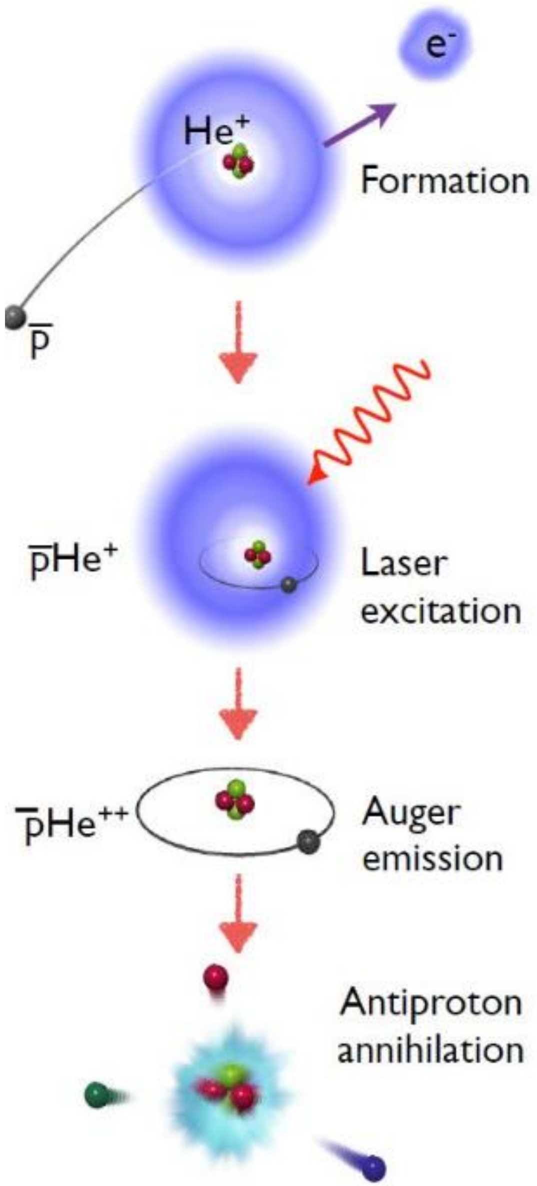
Antiprotonic helium

- **M. Hori et al., Science 354, 610 (2016)**
- Lifetime for states at n~38 -> 1-2 us
- Ground state lifetime: 100 ns
- Laser resonance leads to electron ejection and rapid $\bar{p}He^{2+}$decay emitting pions, detected via Cherenkov detectors



$$E_n = -hcR\frac{Z^2}{n^2}$$

$$R = R_\infty \frac{m_{\bar{p}}}{m_e}\frac{1}{\left(\frac{m_{\bar{p}}}{m_e}+1\right)}$$



$${M_{antip}}/{m_{electron}} = \mathbf{1836.1526734(15)}$$

which agrees with proton-to-electron experimental value within 8×10^{-10}

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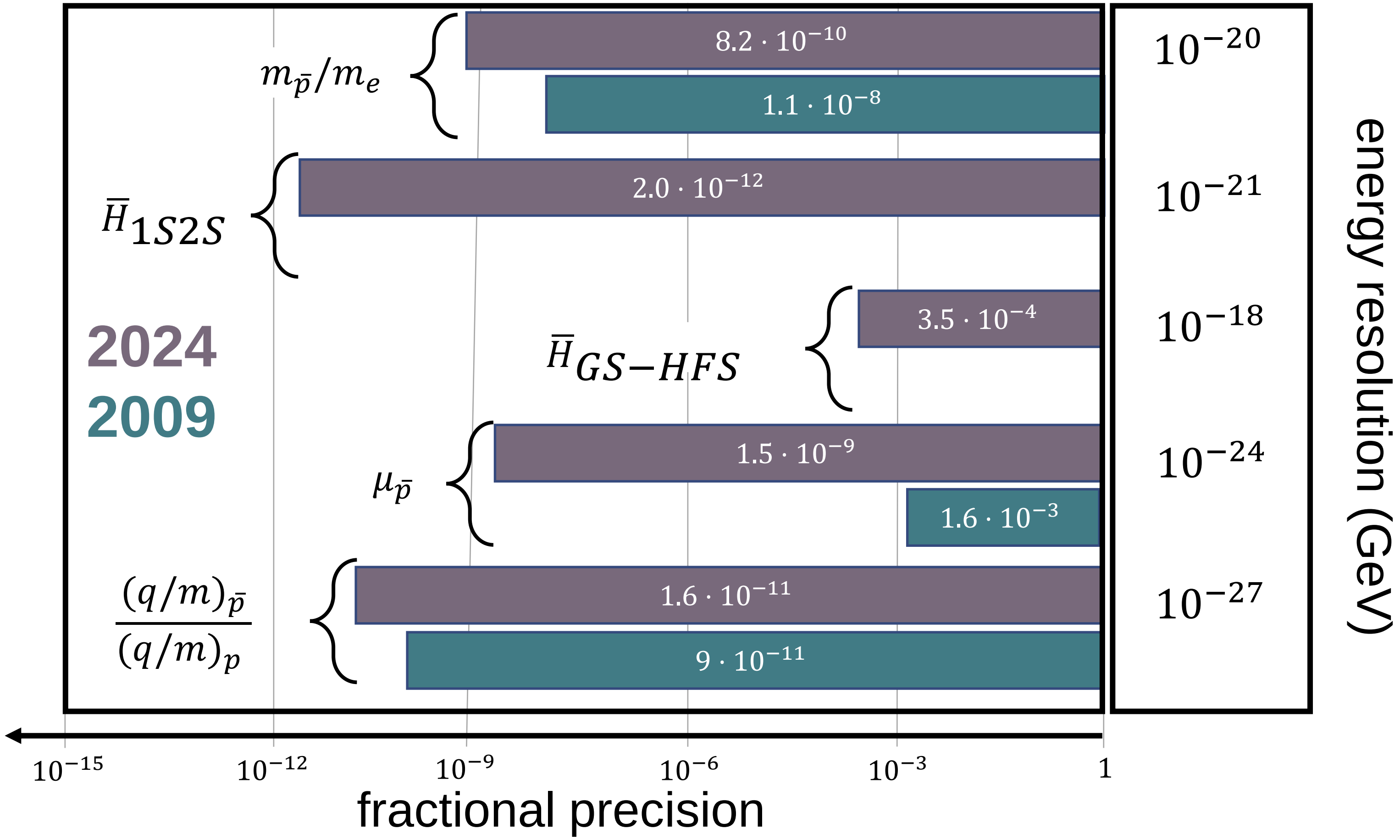
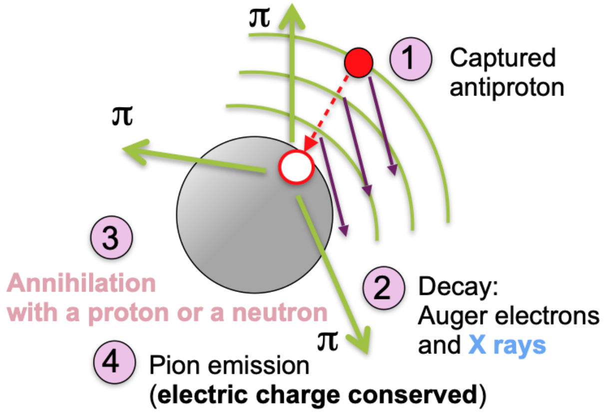
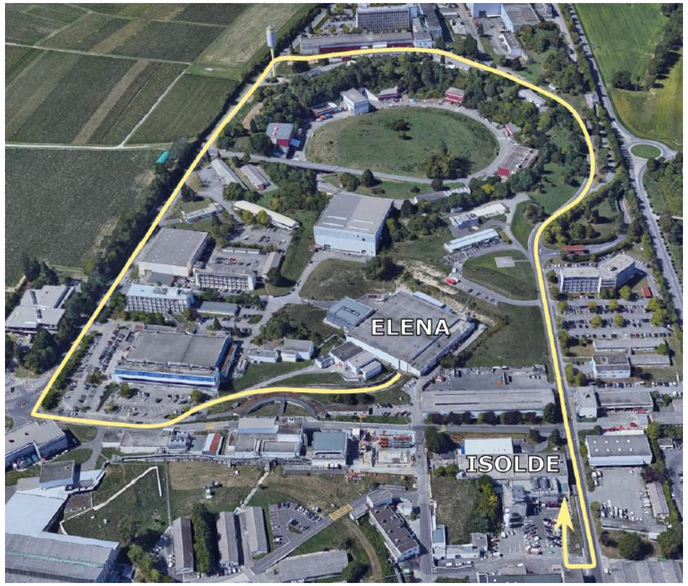


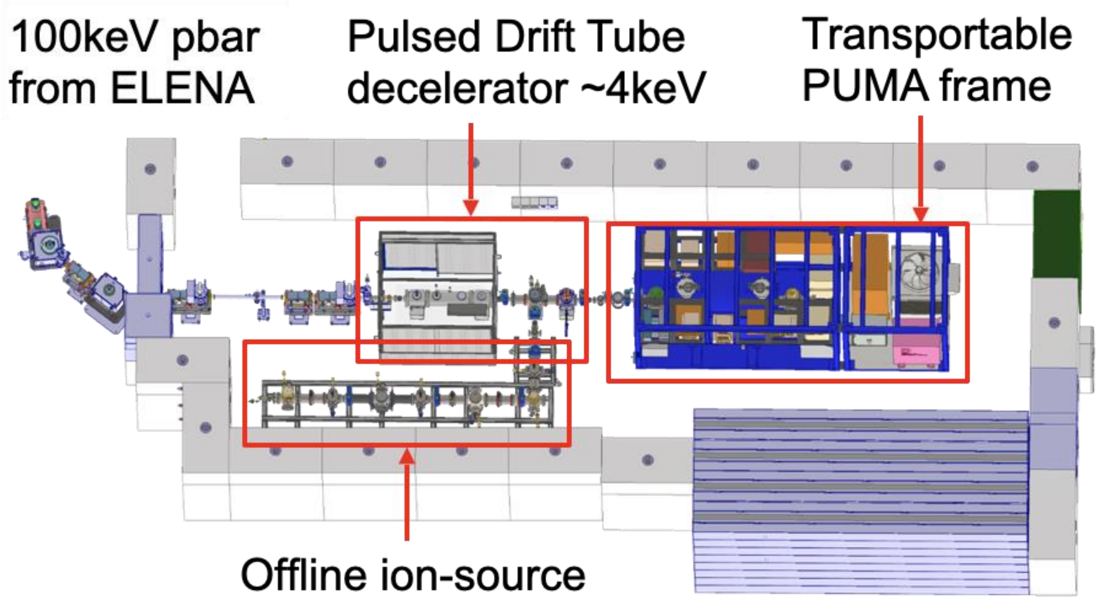
Nuclear physics in the AD

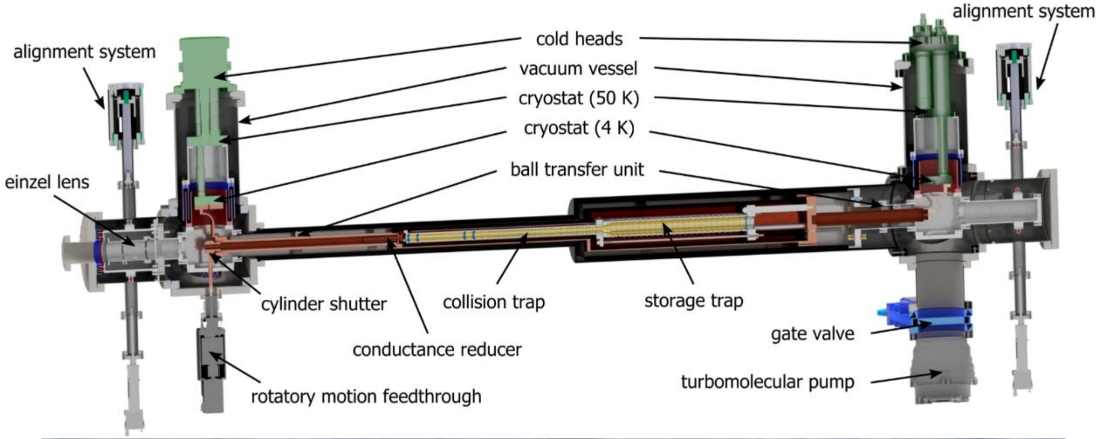
PUMA Experiment

- **General:** Low-energy antiprotons to probe the neutron-to-proton content of the radial density tail of stable (ELENA) and unstable (ISOLDE) nuclei
- **Main tools:** transportable Penning trap and time projection chamber for tracking of charged pions

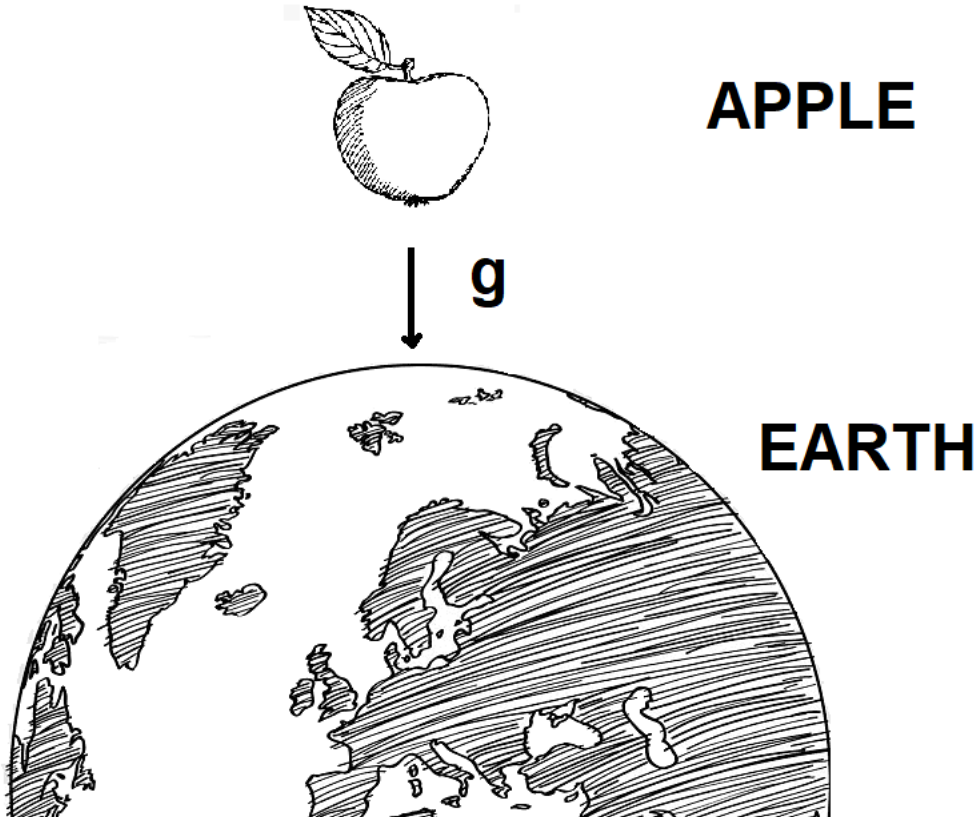








Gravity measurements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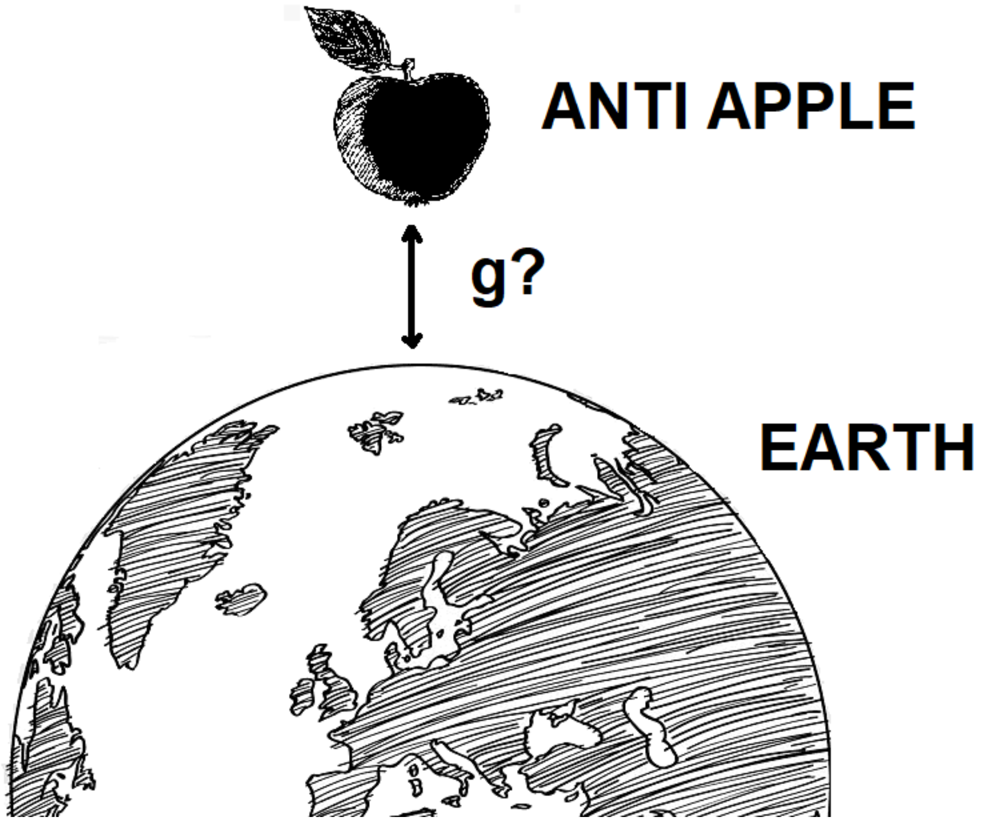
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Gravity tests with antimatter

- The Weak Equivalence Principle - the universality at the heart of the General Relativity:
  - Universality of free-fall - all particles (or antiparticles) fall with the same acceleration in a gravitational field (WEPff).
  - Universality of clocks - all dynamical systems which can be viewed as clocks (e.g. (anti)atomic transition frequencies or frequency of (anti)particle motion in the Penning trap) measure the same gravitational time dilation independently of their composition (WEPc).

Universality of clocks ?= **Universality of free-fall**

Weak Equivalence Principle Tests

- Single particle in a Penning trap -> **A cyclotron frequency clock**.
- In the gravitational field of the earth clocks experience a «red-shift» caused by the gravitational potential.
- Hughes and Holzscheiter

(PRL 66, 854 (1991)):

$$\frac{\nu_{c,\bar{p}} - \nu_{c,p}}{\nu_{c,avg}} = \frac{3\Phi}{c^2}(\alpha_g - 1)$$

where $\frac{\phi}{c^2} = \frac{GM}{rc^2} = 2.99 \times 10^{-5}$ is a potential of the local supergalactic cluster.

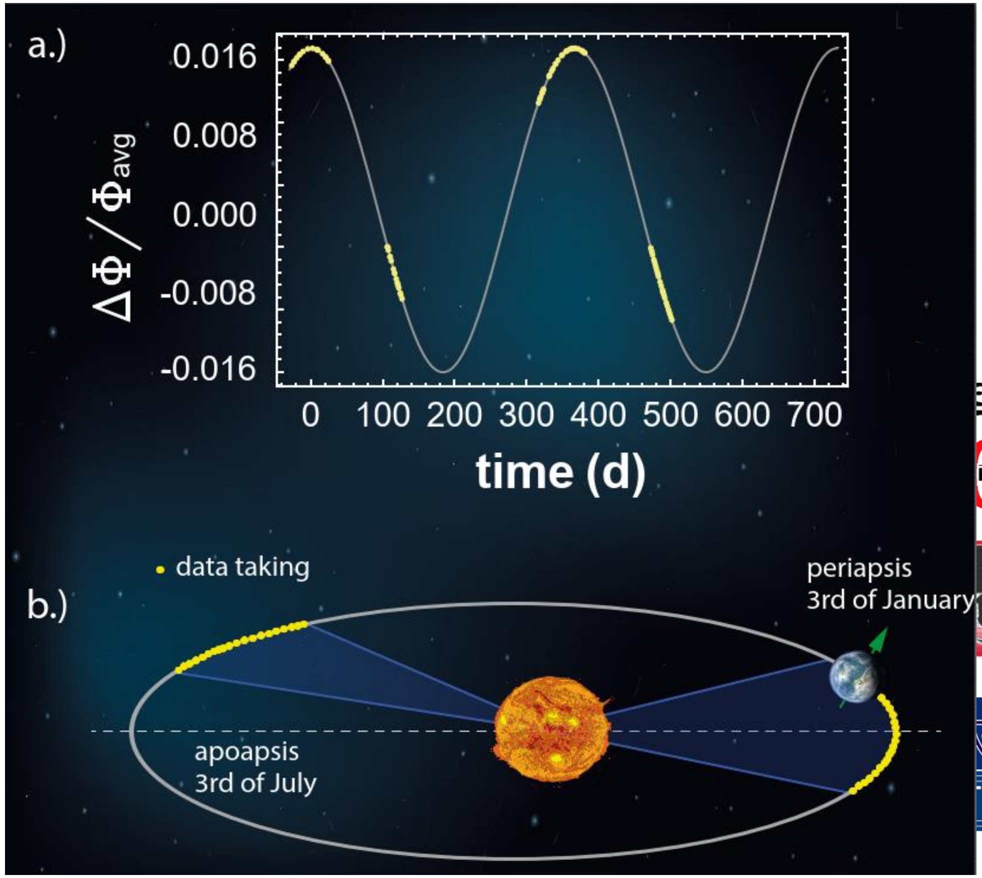
Then

$$\boldsymbol{\alpha_g < 1.8 \times 10^{-7}}.$$

- Differential analysis: $O(t) = D_p(1-\varepsilon^2)/[1+\varepsilon\cos\left(\left(\frac{2\pi}{t_{sid}}\right)t\right)$

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

$$\boldsymbol{\alpha_{g,D} < 0.0301}.$$

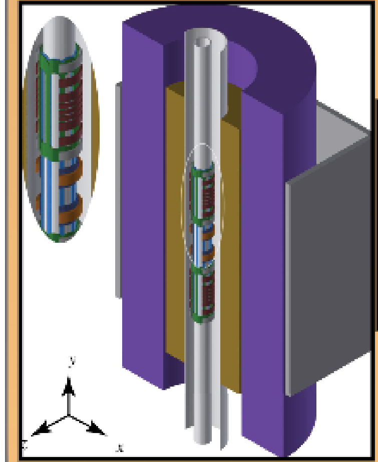


BASE, Nature 601(7891):53-57 (2022)

Free Fall experiments with antihydrogen

VERTICAL TRAP
- increase up/down sensitivity (up to 1.3m trapping range)
- much improved field control

Sign measurement planned soon
1% targeted H̄ cooling to ~20 mK and advanced magnetometry

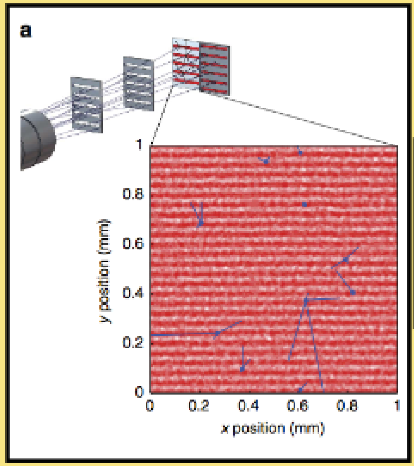


W. A. Bertsche
Phil. Trans. R. Soc. A 2018 376 20170265;
DOI: 10.1098/rsta. 2017.0265. (2018)

ALPHA-G

H̄ BEAM
- Sensitivity to ~10 μm deflection needed
- cold antiproton translates in cold H̄ thanks to CE mechanism

Sign measurement targeted

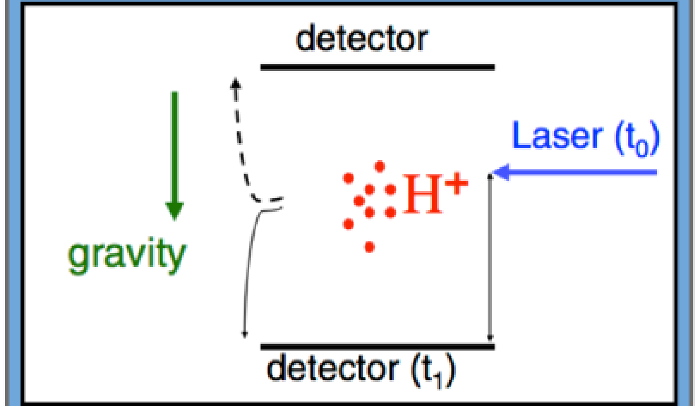


S. Aghion et al.
Nature Communications
5 (2014) 4538

AEGIS

H̄⁺ BEAM
- Cooling below 1 m/s : Sympathetic cooling of H̄⁺
- opens new horizons

1% measurement targeted



e.g.: The GBAR antimatter gravity experiment
P. Pérez et al., Hyperfine Interactions 233, 21-27 (2015)

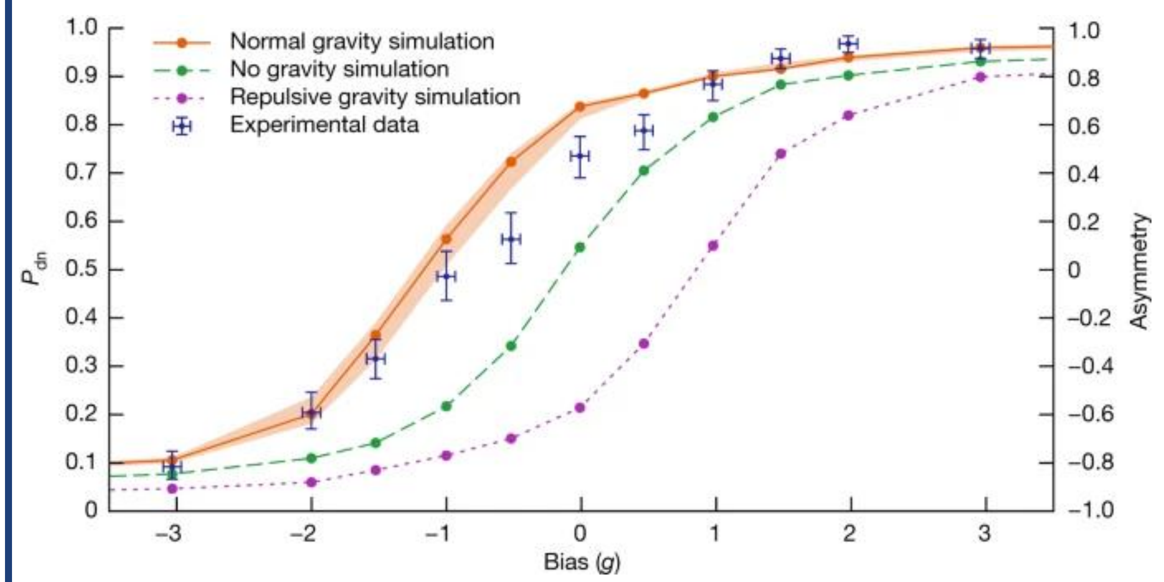
GBAR

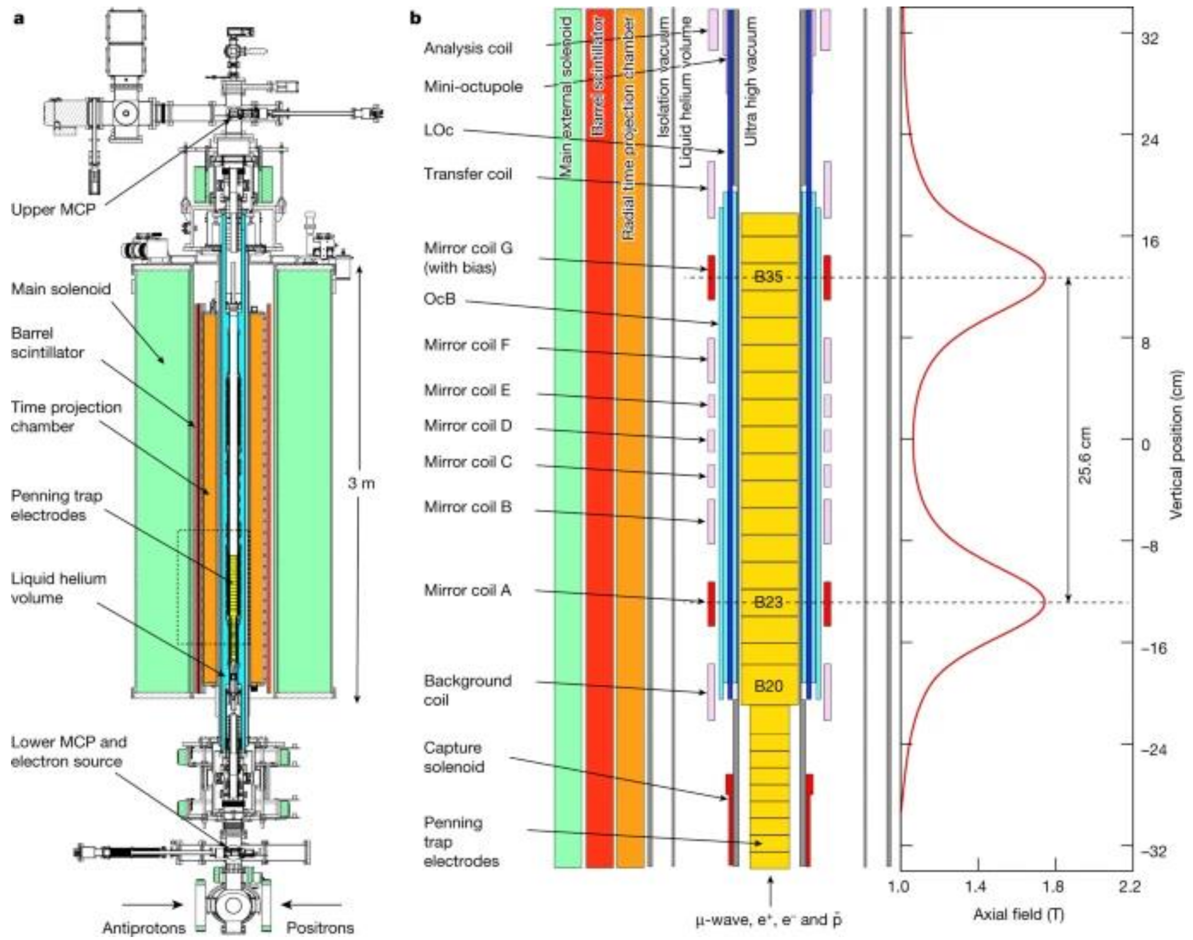
Ch. Malbrunot

Free Fall experiments with antihydrogen – first results, ALPHA

- **Observation of the effect of gravity on the motion of antimatter, *Nature* volume 621, pages716–722 (2023)**

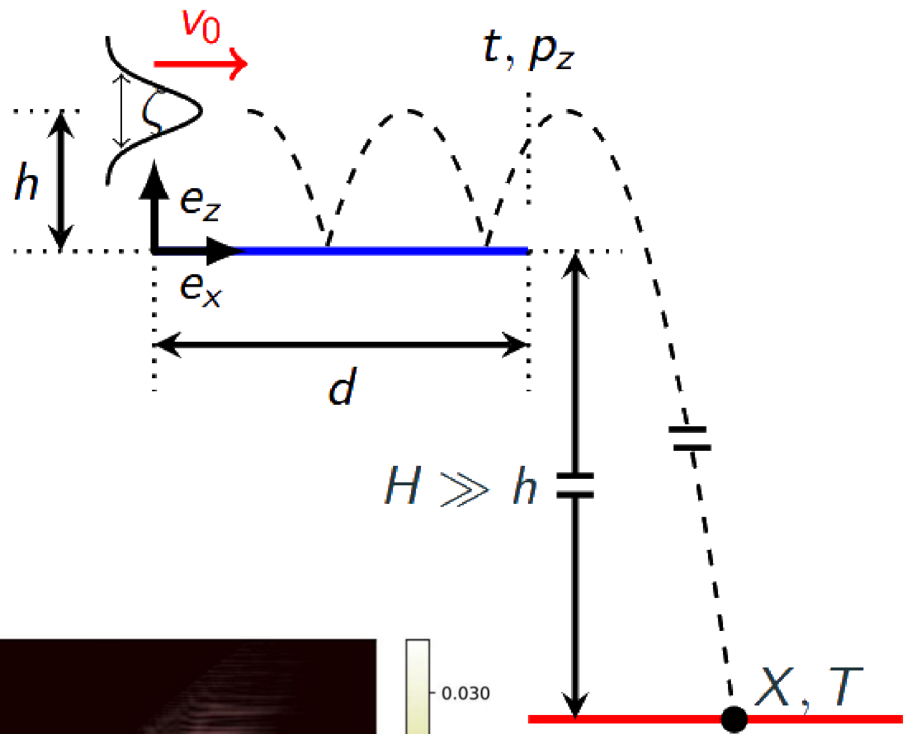
$a_g =$ **(0.75 ± 0.13 (statistical + systematic) ± 0.16 (simulation))g, , where g = 9.81 m s−2**

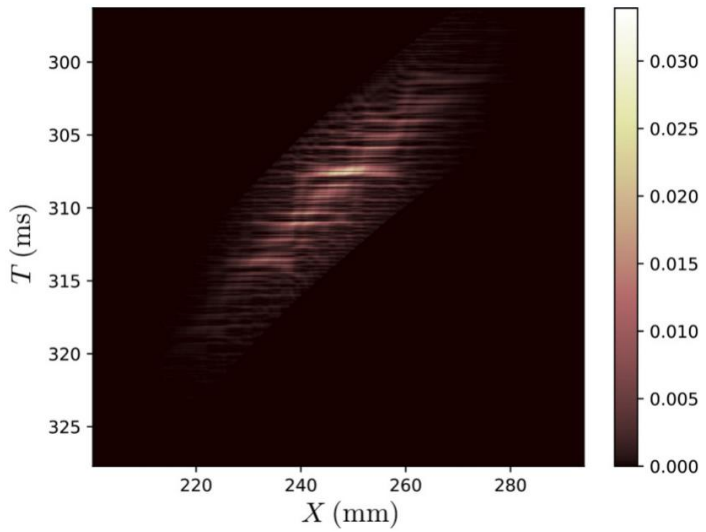




GBAR -> Quantum states of antihydrogen in the Earth's gravitational field

- If you can make ultra-cold antihydrogen $< 10\ neV$ you can make antihydrogen „bounce”
- **Quantum states of neutrons in the Earth's gravitational field,** Valery V. Nesvizhevsky et.al., Nature, 415, 297–299 (2002), GRANIT collaboration.
- ”Gravitational quantum states (GQS) are formed when ultracold light particles are trapped by gravity on top and a specularly reflecting horizontal mirror with a sharply changing surface potential on bottom.”
- Casimir-Polder force - a manifestation of the electromagnetic quantum fluctuations which are coupled to the atomic dipole.
- Antihydrogen Lowest qunatum state ≈ 10 µm.
- **Expected precision $< 10^{-5}$ level.**





Thank you for your attention!

- Many thanks to Prof. Stefan Ulmer and Dr. Jack Devlin for providing slides and materials for these lectures.

- **If you want to join experiments in the AD contact:**

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  - AEgIS -> Ruggero Caravita ruggero.caravita@cern.ch, Michael Doser michael.doser@cern.ch
  - ASACUSA (antihydrogen) -> Eberhard Widmann e.widmann@cern.ch, Eric Hunter eric.david.hunter@cern.ch
  - ASACUSA (antiprotonic helium) -> Masaki Hori m.hori@imperial.ac.uk
  - GBAR -> Patrice Perez patrice.perez@cern.ch, Pauline Comini pauline.comini@cea.fr
  - PUMA -> Alexandre Obertelli alexandre.obertelli@cern.ch

  - AD/ELENA accelerators -> Laurette Ponce laurette.ponce@cern.ch

AEgIS

ALPHA

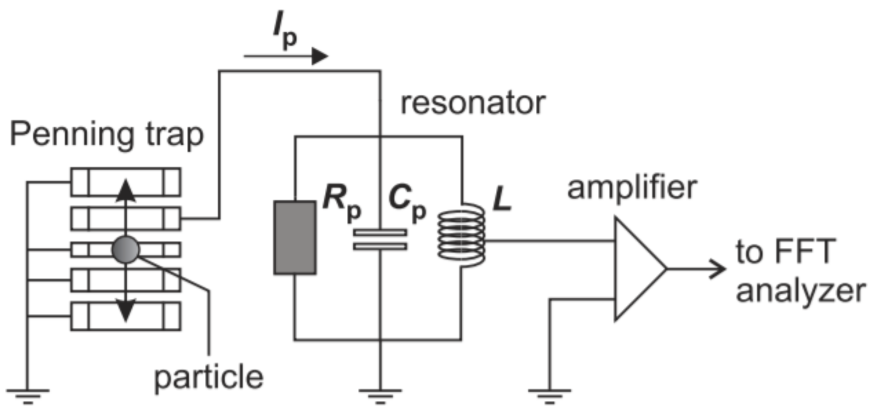
BASE

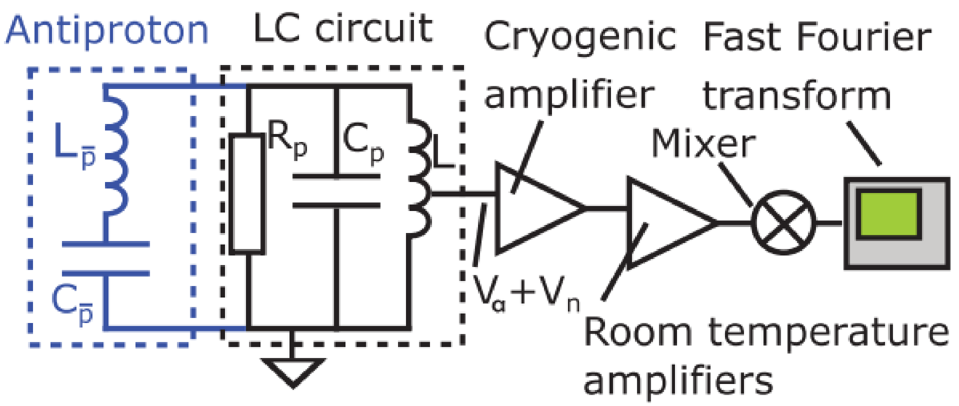
STEP

GBAR

Frequency Measurements

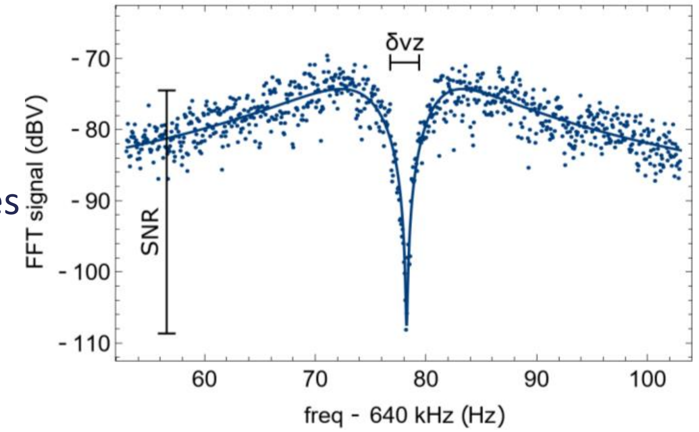
- Measurement of fA image currents induced in trap electrodes

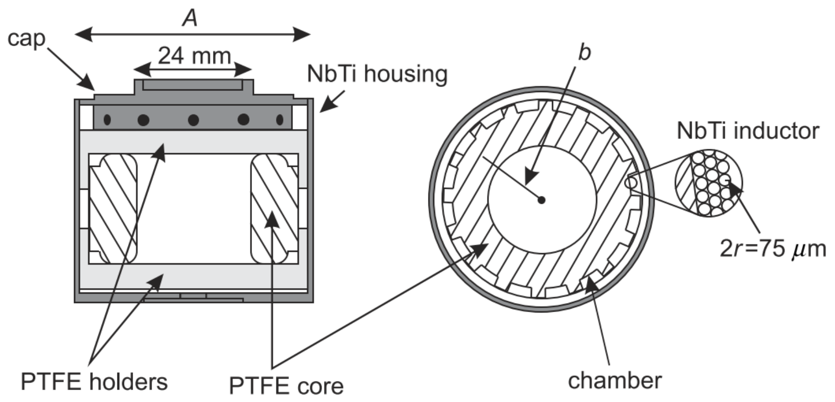




- In thermal equilibrium:
  - Particles short noise in parallel
  - Appear as a dip in detector spectrum
  - Width of the dip -> number of particles

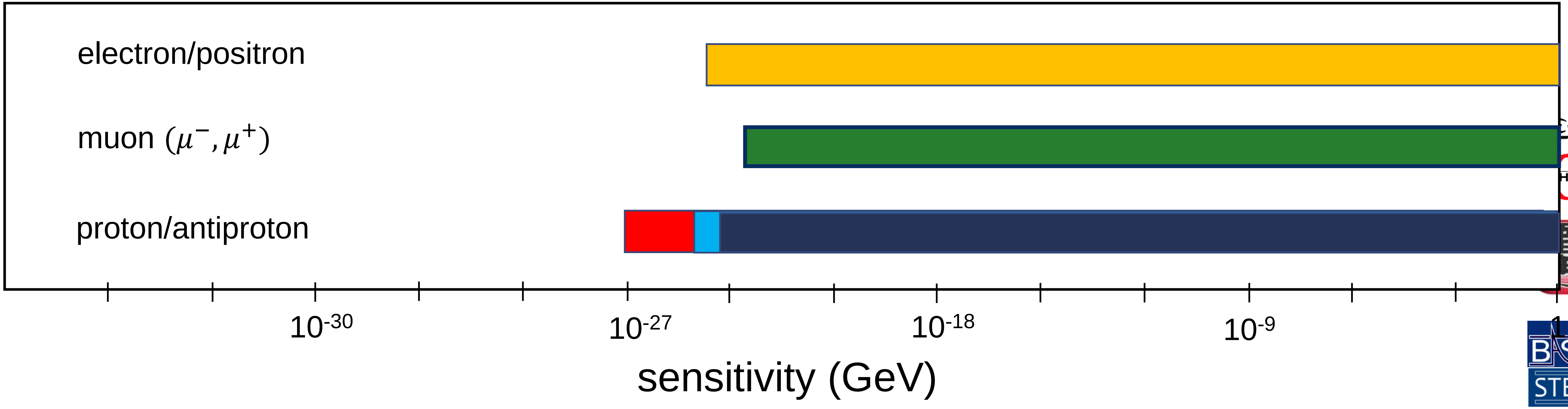
$$\Delta\nu = \frac{1}{2\pi}\frac{R}{m}\left(\frac{q}{D}\right)^2 \cdot N$$





The Most Precise Tests of CPT Invariance

Year	Matter $g/2$	Antimatter $\bar{g}/2$	CPT $\lvert g/\bar{g}\rvert - 1$	System	SME $\lvert b_L\rvert$ (GeV)	$\lvert f_X^0\rvert$ (μ_B)
1987	1.001 159 652 188 9 (43)	1.001 159 652 187 9 (43)	0.000 000 000 000 5 (21)	electron/positron	$6 * 10^{-25}$	$2 * 10^{-12}$
2022	1.001 165 921 5 (11)	1.001 165 920 4 (12)	0.000 000 001 1 (12)	muon (μ^-, μ^+)	$1 * 10^{-23}$	$3 * 10^{-11}$
2017	**2.792 847 344 62 (82)**	**2.792 847 344 1 (42)**	**0.000 000 000 2 (15)**	**proton/antiproton**	$8 * 10^{-25}$	$2 * 10^{-12}$



- In a Penning Trap at CERN, comparing the magnetic moments of protons and antiprotons.
- This measurement constitutes the most precise test of CPT invariance and related exotic physics in the baryon sector.

Antiproton-to-proton charge to mass ratio

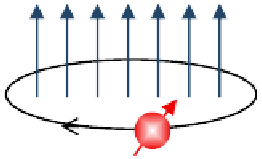
High precision mass spectroscopy

- Charge to mass ratio:

$$R = \frac{(q/m)_{\bar{p}}}{(q/m)_p} = \frac{\upsilon_{c,\bar{p}}}{\upsilon_{c,p}} = a_{corr}\frac{\upsilon_{c,\bar{p}}}{\upsilon_{c,H^-}}$$

Cyclotron Motion

$$\omega_c = \frac{e}{m_p}B$$



with H^- as a perfect proxy of a proton

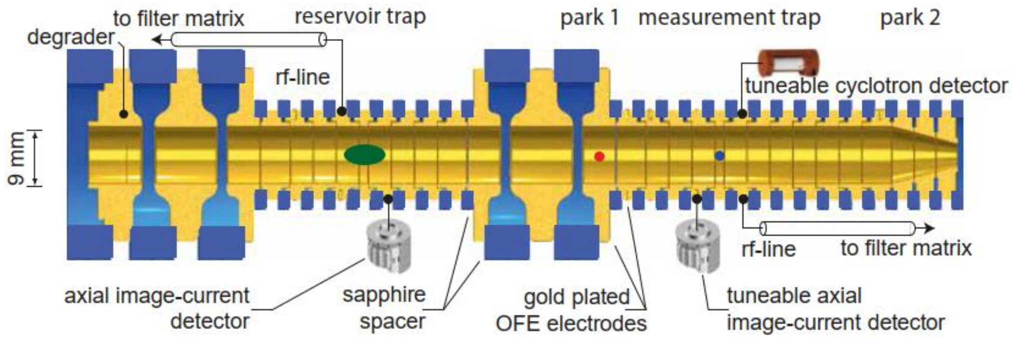
$$m_{H^-} = m_p\left(1 + 2\frac{m_e}{m_p} - \frac{B_e}{m_p} - \frac{A_e}{m_p} + \alpha_{H^-}\frac{B^2}{m_p}\right)$$

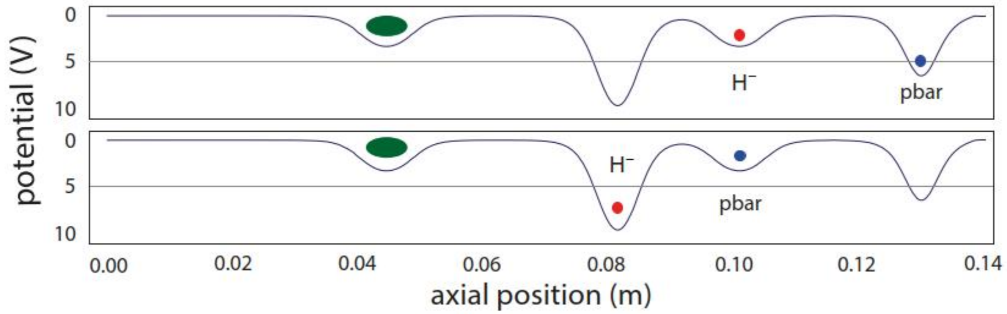
B_e - binding energy of an electron in hydrogen

A_e - afinity energy of a second electron

Effect	Magnitude	
m_e/m_p	0.001 089 234 042 95 (5)	MPIK/HHU-D
$-B_e/m_p$	0.000 000 014 493 061 …	MPQ
$-A_e/m_p$	0.000 000 000 803 81 (2)	Lykke

- Pioneered by BASE shuttling measurement method:

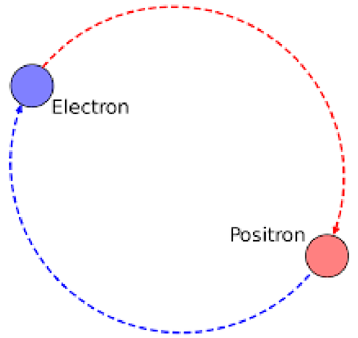


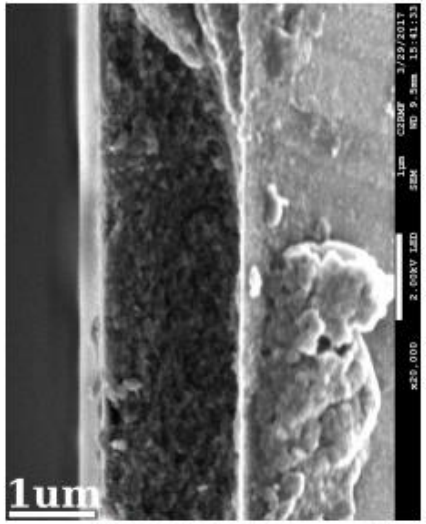


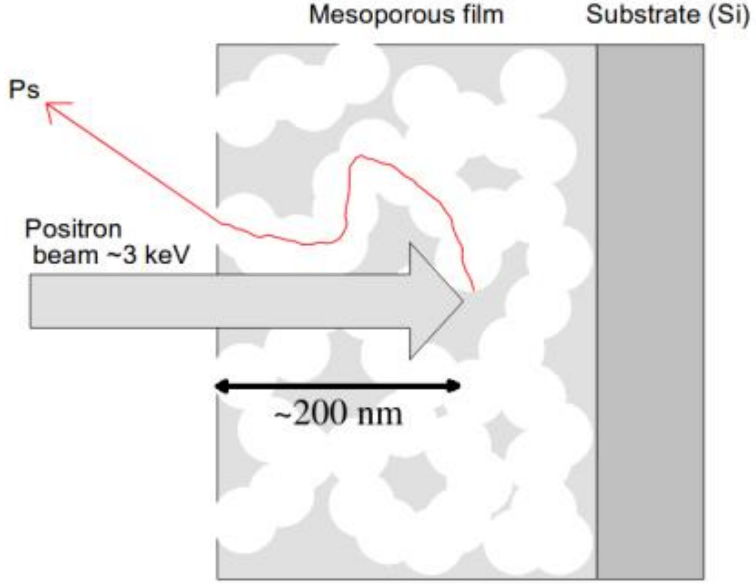
- In BASE one frequency ratio measurement takes 240 s, 50 times faster than in 1999.
- **A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio,** Nature 601.7891 (2022): 53-57.

Positronium production

- Positronium lifetime:
  - Para-positronium lifetime - 125 ps,
  - ortho-positronium lifetime - 142 ns.







- Positronium production using a few µm thick mesoporous SiO_2converter deposited.
- Initial positron beam has typically about 3 keV - has to be reaccelerated after the traps.
- Ortho-positronium emission yield from mesoporous silica target is 30 % with an energy of 48 ± 5 meV (P. Crivelli et al. PRA, vol. 81, no. 5, p. 052703, 2010).
- Positronium laser cooling, AEgIS collaboration, Phys. Rev. Lett. **132**, 083402.

g factor

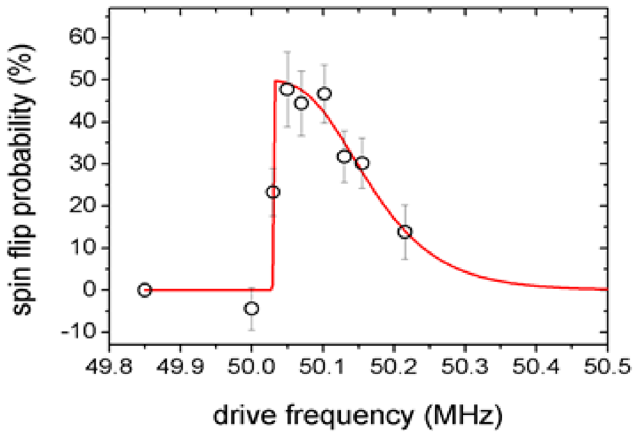
High precision magnetic moment measurements

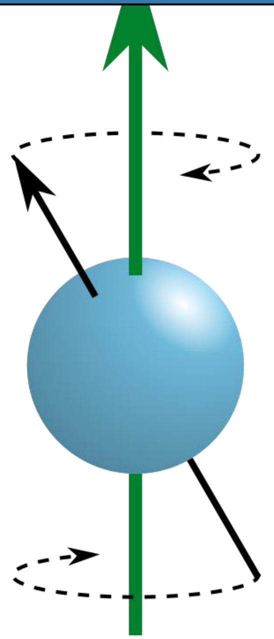
- **Magnetic moment and a spin of a particle are related through a dimentionless parameter called g-factor:**

$$\mu = g\frac{q}{2m}S \quad \Rightarrow \quad \mu = \frac{g}{2}\mu_N$$

- **(Anti)Proton / electron spin S = ½**
- **Larmor frequency – spin precession in a given magnetic field:**

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





- **g factors:**

Particle	g-factor	Relative standard uncertaintity
Electron	−2.00231930436256(35)	1.7×10^{-13}
Muon – (experiment-world-average-2021)	−2.002 331 84121(82)	4.1×10^{-10}
Proton	5.5856946893(16)	$\mathbf{2.9 \times 10^{-10}}$
Antiproton	5.5856946906(60)	$\mathbf{1.5 \times 10^{-9}}$