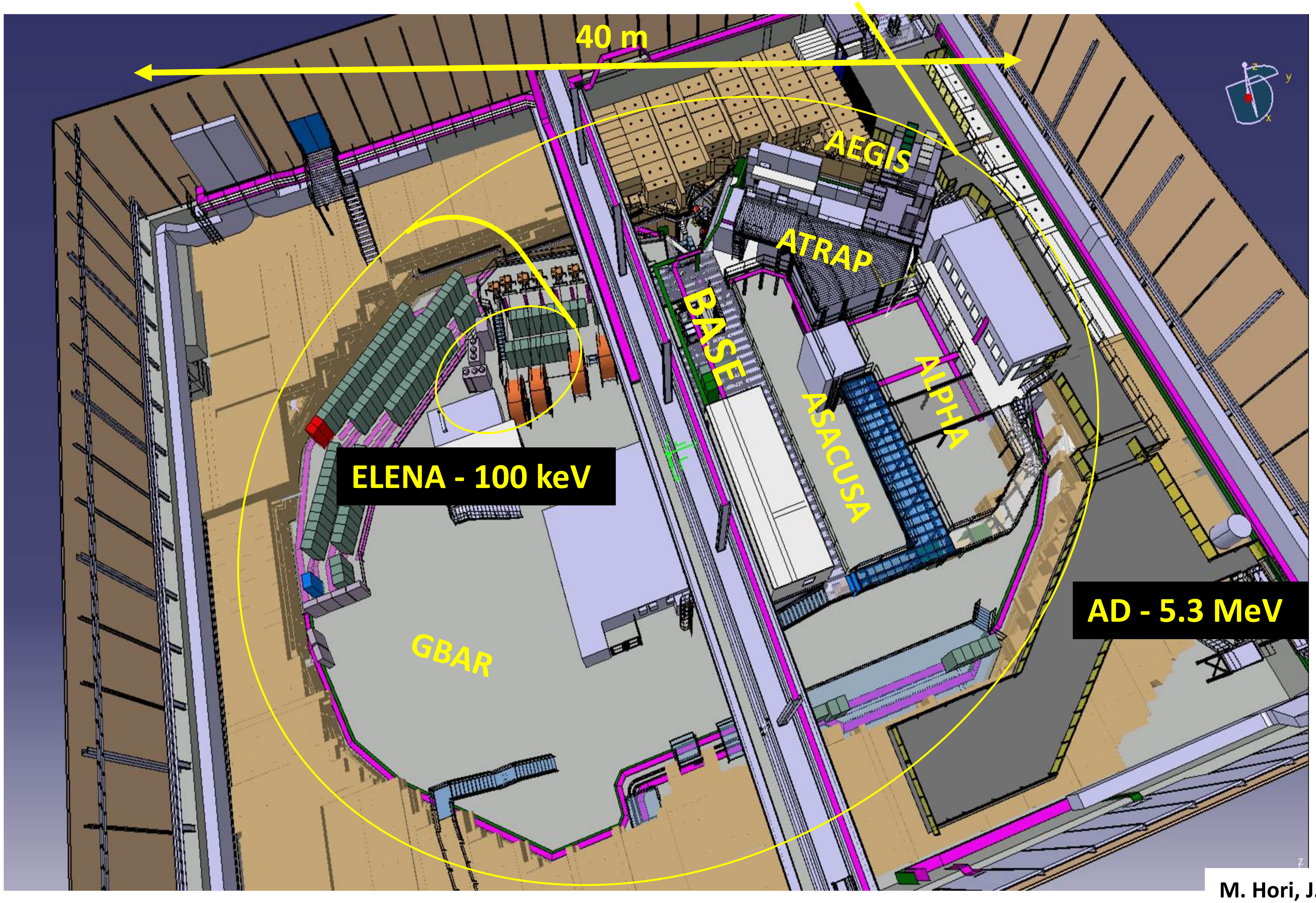
# Precision Physics and Antimatter

Summary Day 2

# Physics in the AD/ELENA-facility




**BASE, ATRAP,**
Fundamental properties of the antiproton

**ALPHA, ATRAP,**
Spectroscopy of 1S-2S in antihydrogen

**ASACUSA, ALPHA**
Spectroscopy of GS-HFS in antihydrogen

**ASACUSA**
Antiprotonic helium spectroscopy

**ALPHA, AEgIS, GBAR**
Test free fall/equivalence principle with antihydrogen

**M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).**

# Antihydrogen in the ALPHA Experiment

- Production, detection and trapping of antihydrogen

  ATHENA Collaboration, Nature 419, 456 (2002).

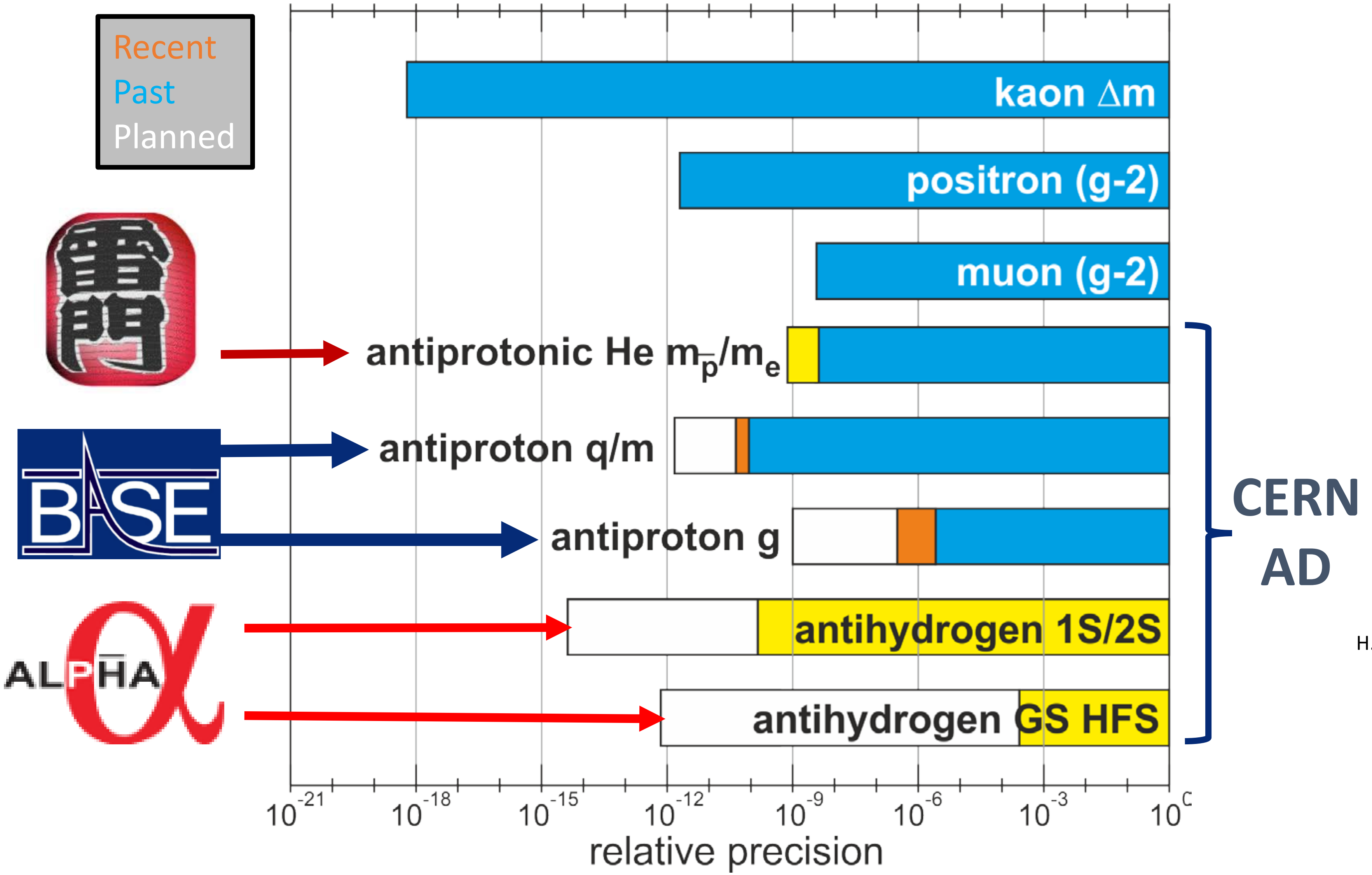
- Measurements of the GS-HFS and 1S-2S transition

  ALPHA Collaboration, Nature 541, 506 (2017).
  ALPHA Collaboration, Nature 548, 66 (2017).

# Precision Physics and Antimatter

Part 2/3 Antihydrogen – Beam and Gravity Experiments

# Some CPT tests based on particle/antiparticle comparisons




R.S. Van Dyck et al., Phys. Rev. Lett. **59**, 26 (1987).
B. Schwingenheuer, et al., Phys. Rev. Lett. **74**, 4376 (1995).
H. Dehmelt et al., Phys. Rev. Lett. **83**, 4694 (1999).
G. W. Bennett et al., Phys. Rev. D **73**, 072003 (2006).
M. Hori et al., Nature **475**, 485 (2011).
G. Gabrielse et al., PRL **82**, 3199(1999).
J. DiSciacca et al., PRL **110**, 130801 (2013).
S. Ulmer, C. Smorra, et al., Nature **524**, 196-200 (2015).
ALICE Collaboration, Nature Physics **11**, 811–814 (2015).
M. Hori et al., Science **354**, 610 (2016).
H. Nagahama, C. Smorra, et al., Nat. Comm. **8**, 14084 (2017).
M. Ahmadi et al., Nature **541**, 506 (2017).
M. Ahmadi et al., Nature **548**, 66–69 (2017).

The work on CPT invariance tests
in general has been summarized in:

V. A. Kostelecky, N. Russell, 0801.0287v10 (2017).

# ASACUSA

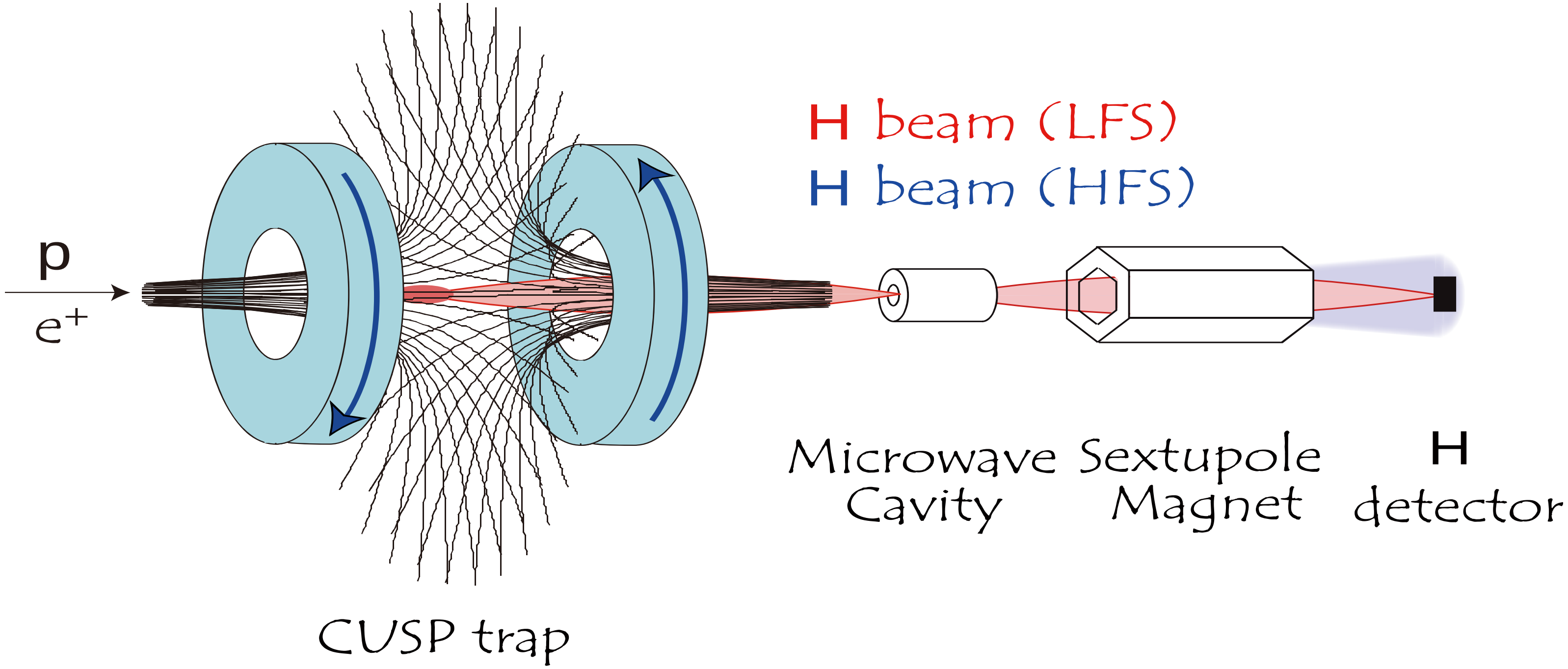
## Atomic Spectroscopy and Collisions using Slow Antiprotons

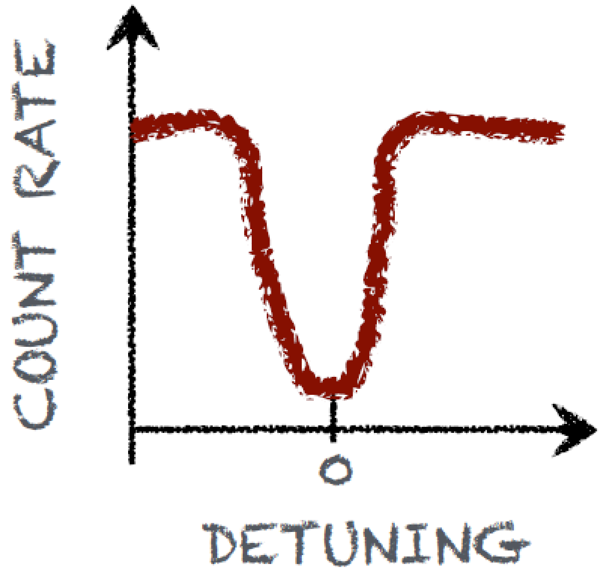
~ 36 people, 10 institutes

# A Rabi-Experiment with Antihydrogen

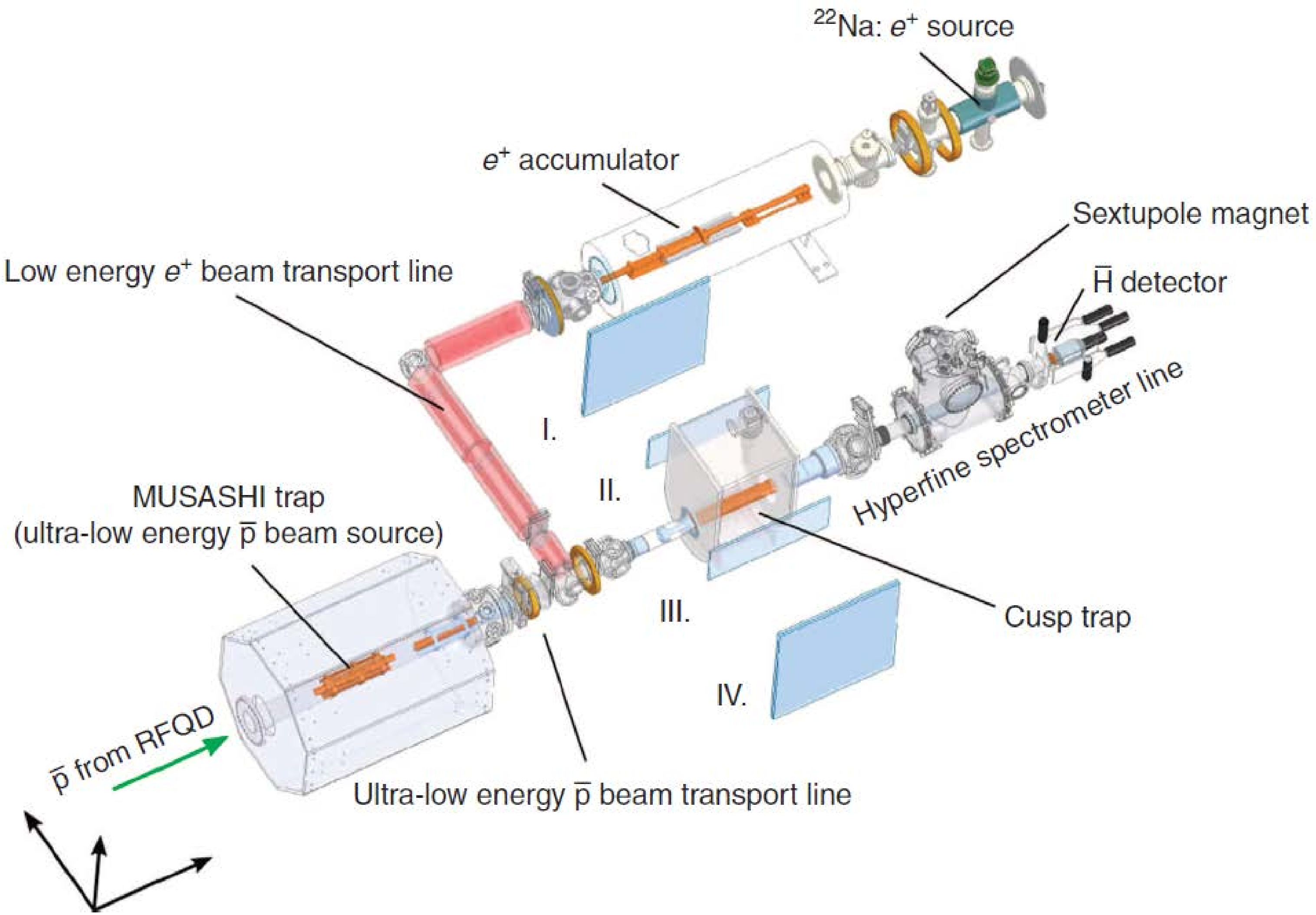
Aim of the collaboration is precise spectroscopy of antihydrogen hyperfine structure

$$\Delta\nu = \frac{v_H}{L_{cav}}$$

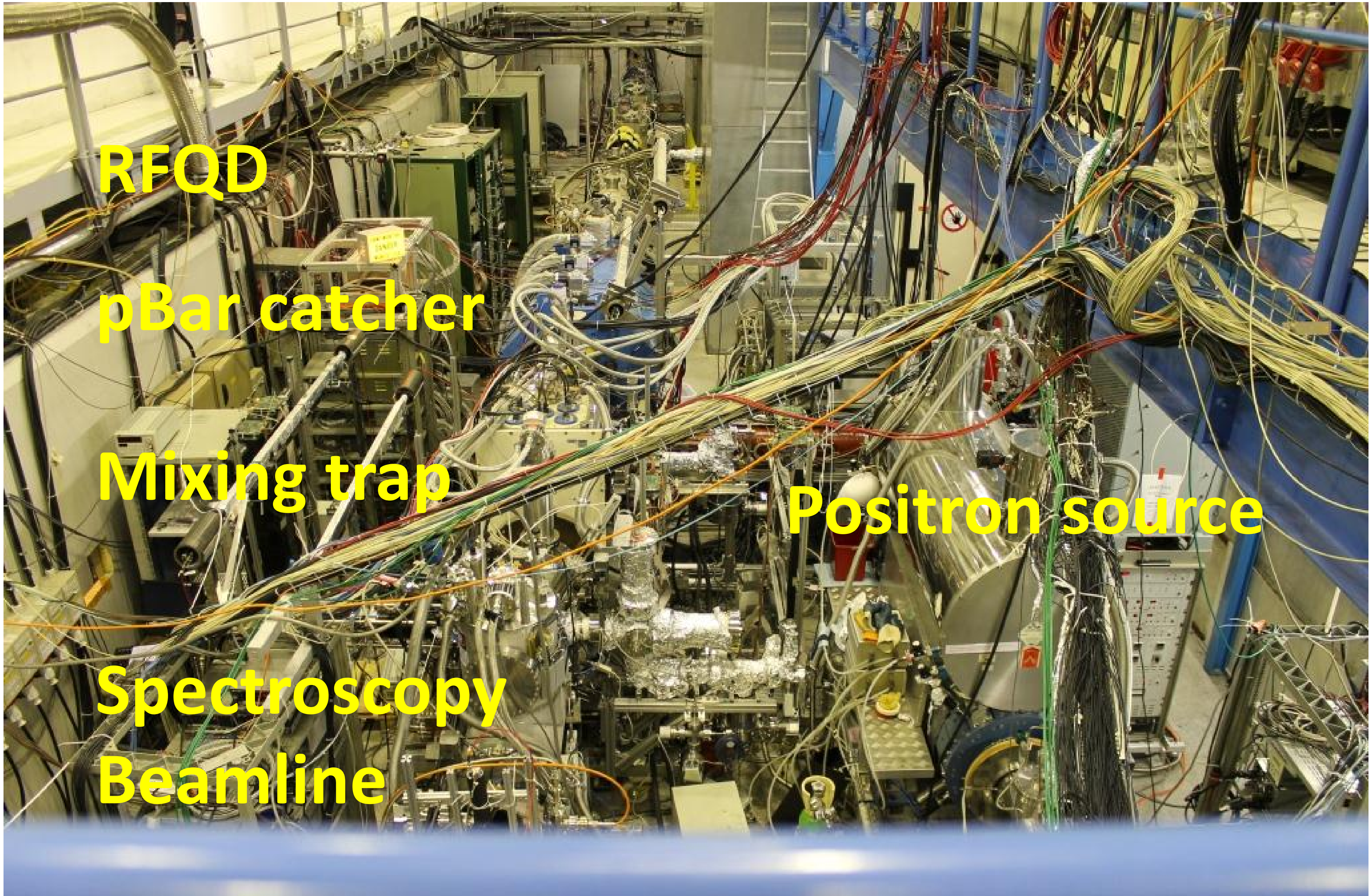


# ASACUSA – CUSP
# An Antihydrogen Experiment

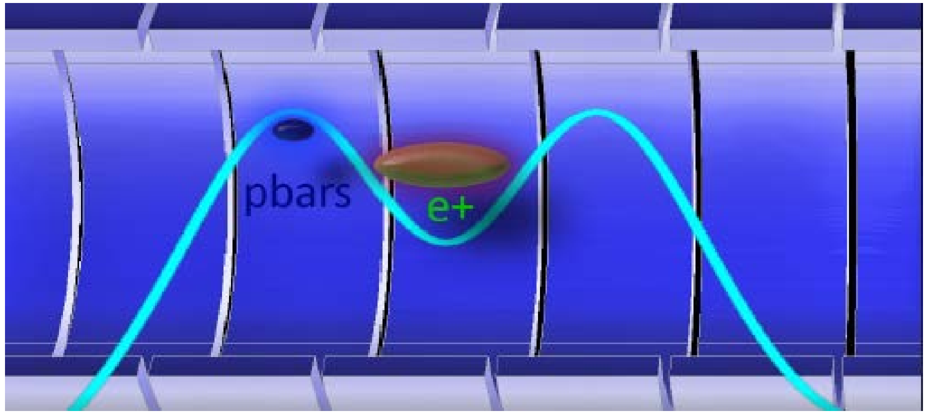


# How it actually looks like:

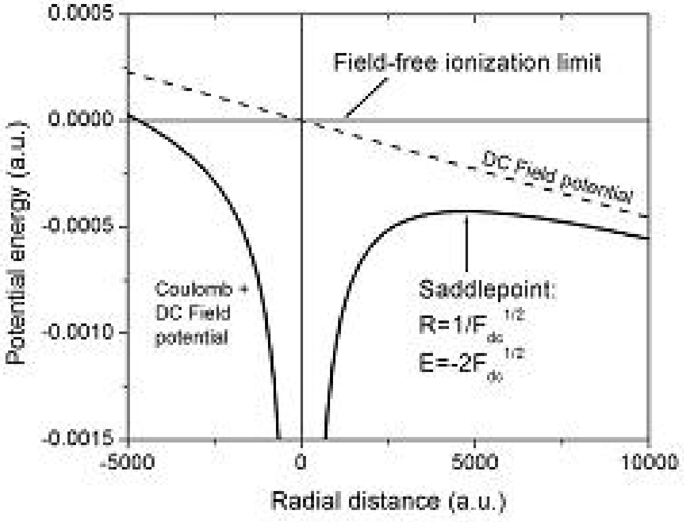


# Experimental Procedure

- Catch positrons
- Ramp to nested well
- Inject antiprotons from MUSASHI trap (typical energy is at some eV)
- Mixing



# Field Ionization




## Effective Hamiltonian:

$$H = H_H - \mathrm{q}\,\mathrm{E}\,\mathrm{x}$$

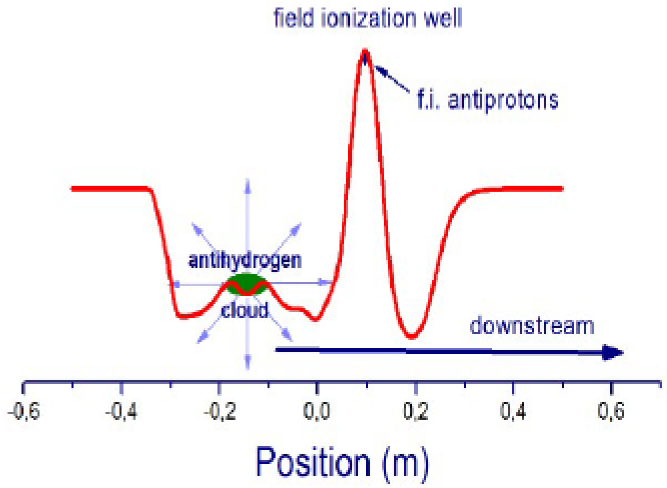
Modifies the coulomb potential and high n-state positrons are stripped

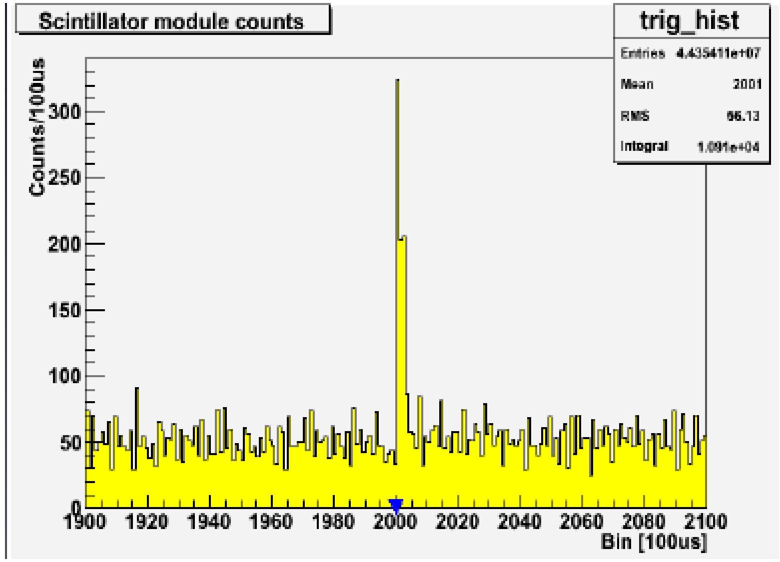
Equating effective potential and particle energy

Ionizable n-state: $$F = \frac{3.2 \cdot 10^8}{n^4} V/_{cm}$$

# Antihydrogen Detection by F.I.

- Accumulate positrons
- Direct injection of antiprotons
- Apply field ionization trap
- Release field ionization trap




- No F.I. signal without positrons
- Clear indication on antihydrogen production

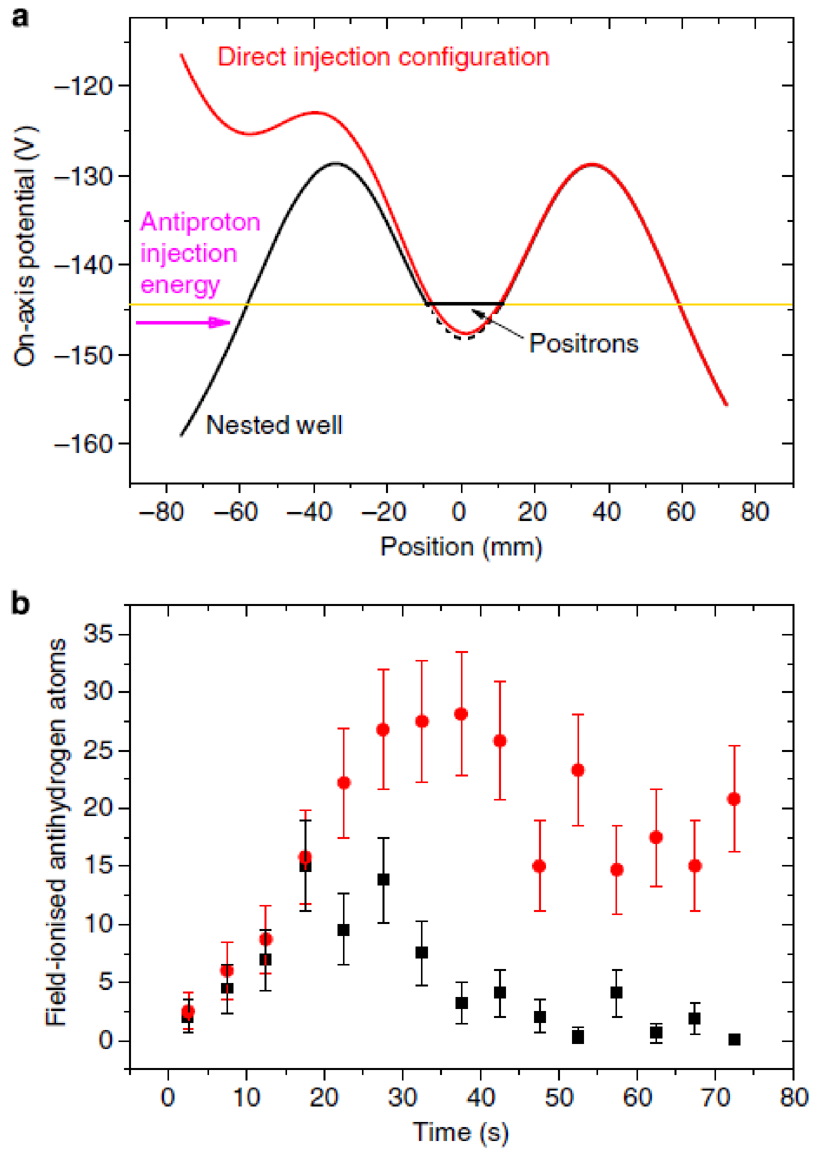
# Antihydrogen production

Antihydrogen production drops after a few seconds

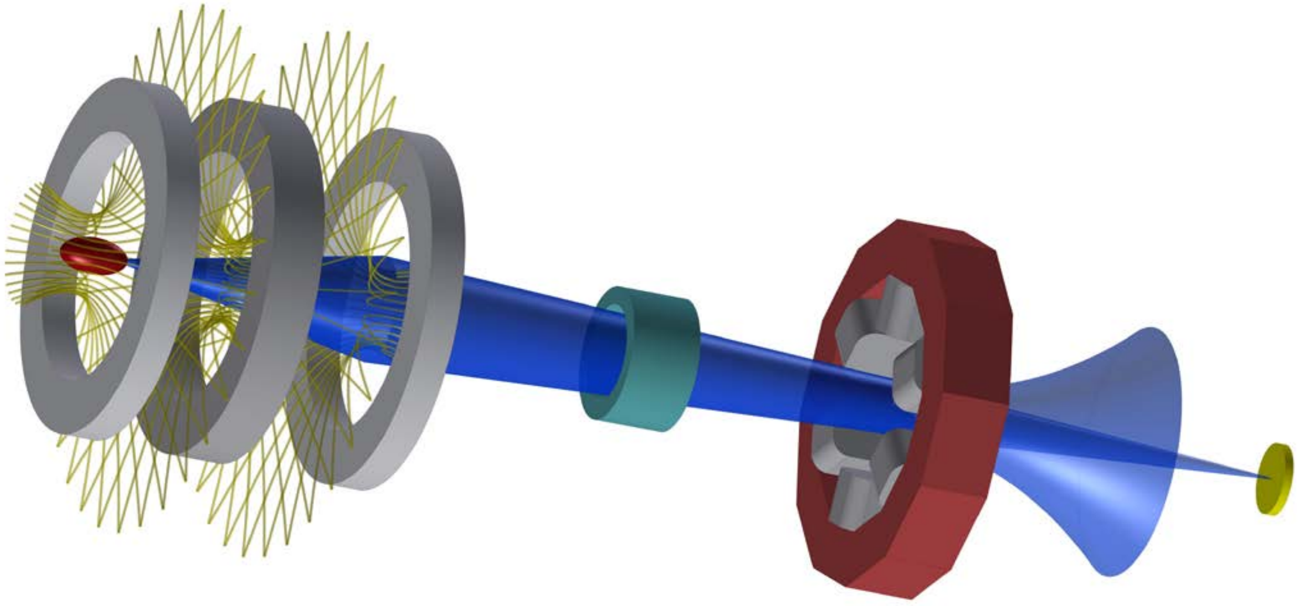
Antiproton cool / Plasma overlap decreases

Rf-drive reexcites the antiproton plasma

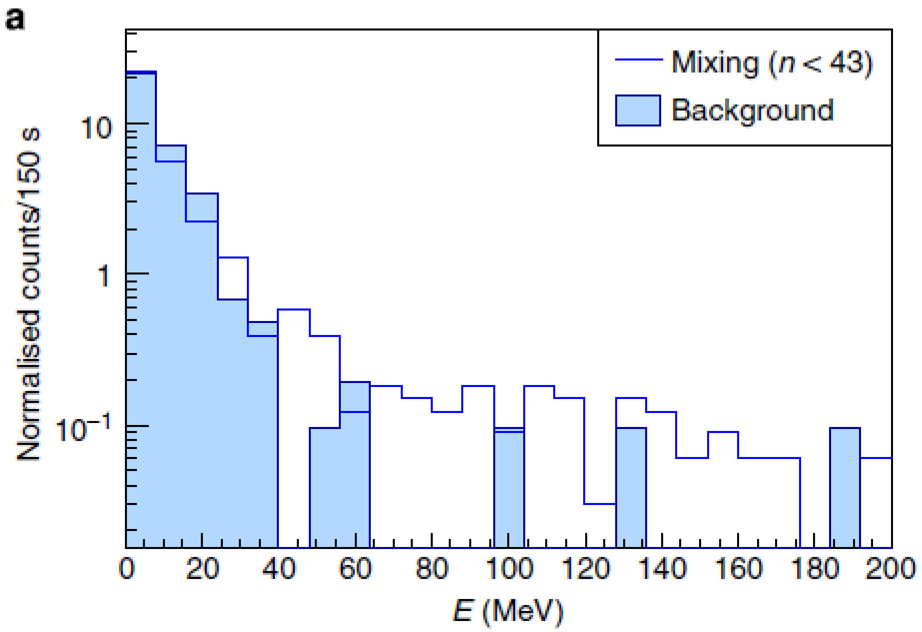
-> Boost antihydrogen production by a factor ~5



# Formation of an antihydrogen beam



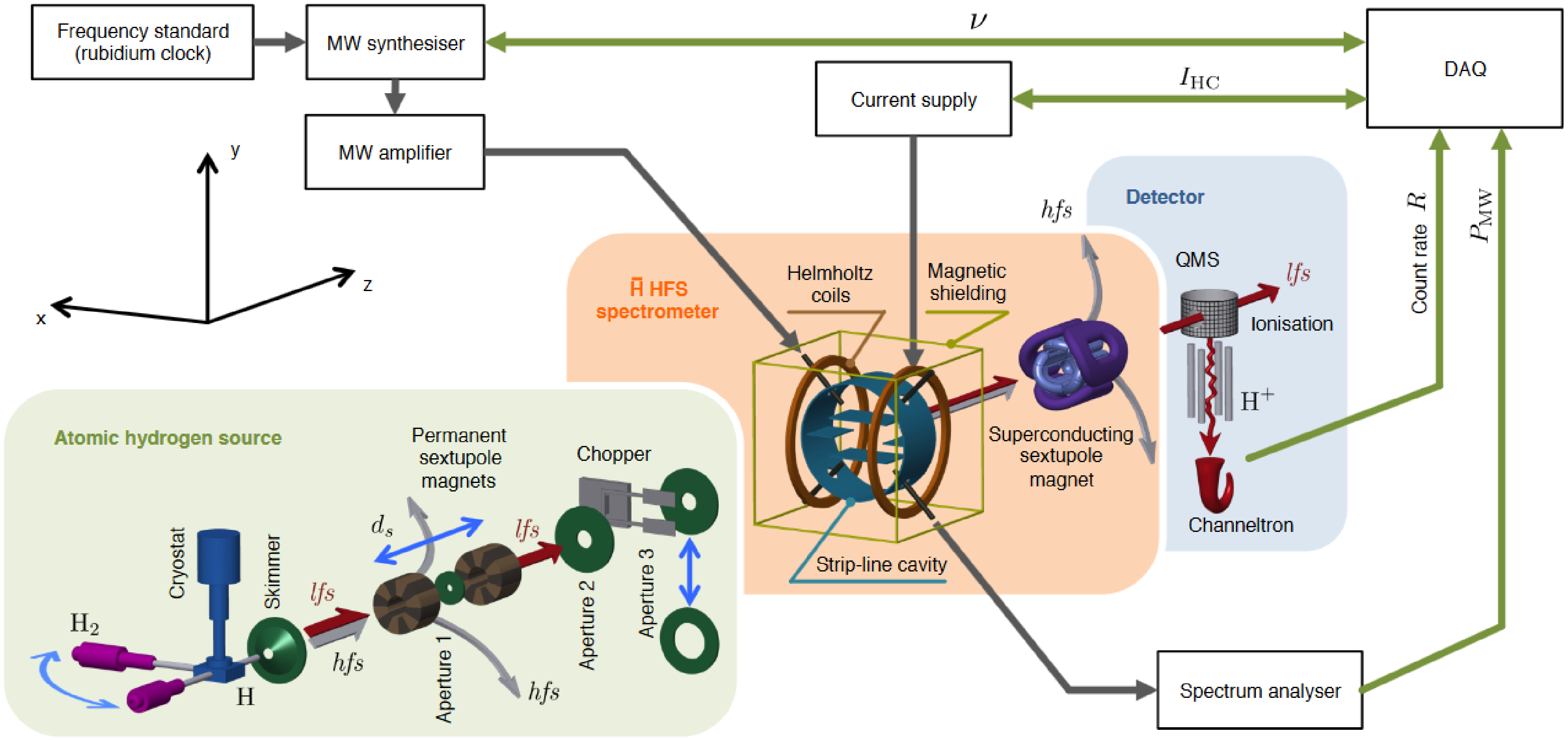
Antihydrogen on the detector,
~3 m distance from the mixing region




First spectroscopy can be done with a ~10-fold improved production rate

N. Kuroda, S. Ulmer et al., Nat. Comm. 5, 3089 (2014).

# ASACUSA Hydrogen apparatus




M. Diermaier et al., Nat. Comm. 8, 15749 (2017).

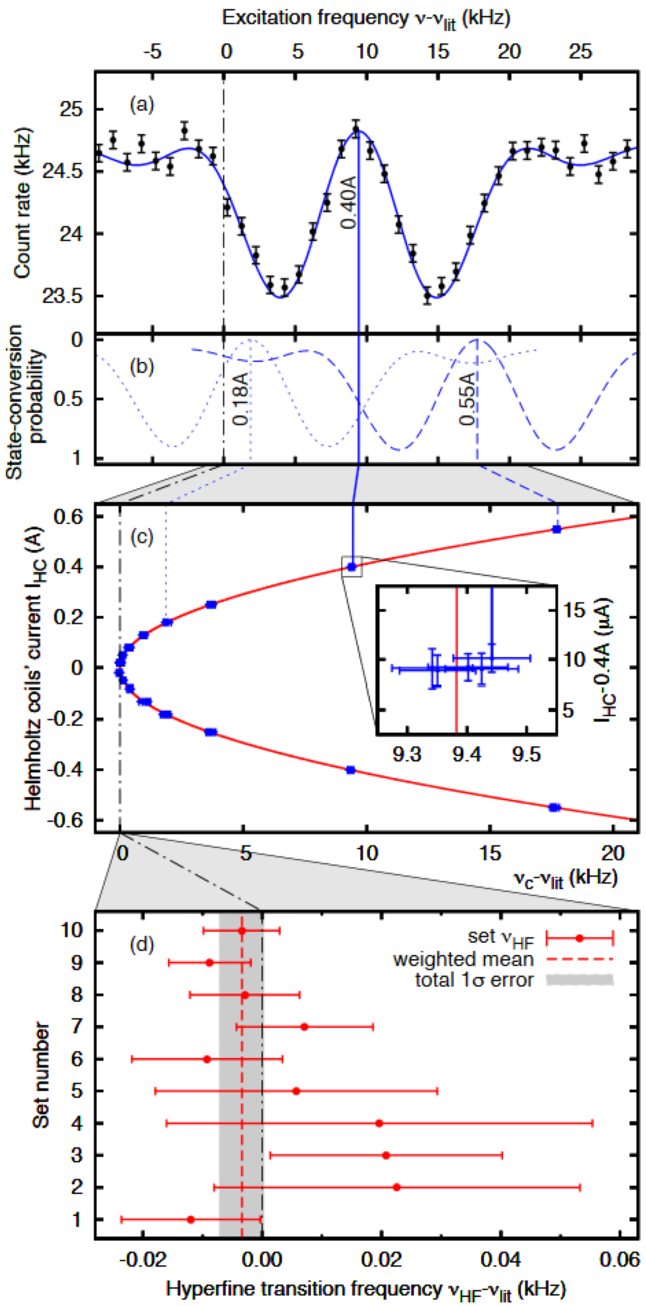
# Hydrogen spectroscopy

**Table I.** *Error budget*

| contribution | $1\sigma$ st.dev. (Hz) |
|---|---|
| systematic error | |
| frequency standard | 1.62 |
| common fit parameters | |
| $\bar{v}_H$ | 0.05 |
| $\sigma_v$ | 0.03 |
| $B_{osc}$ | 0.02 |
| systematic error total | 1.62 |
| statistical error | 3.43 |
| total error | 3.79 |

- Non-homogenous amplitude in the MW-cavity
- State conversion probability depends on velocity

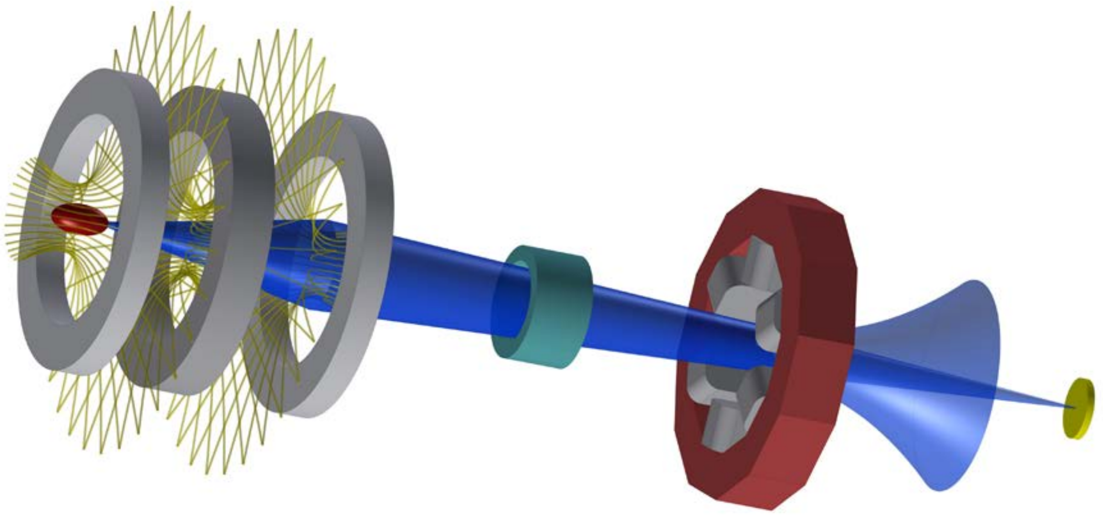
$$\Delta\nu = 1420405748.4(3.4)(1.6)\ \text{Hz} \quad - \quad 2.7\ \text{ppb}$$

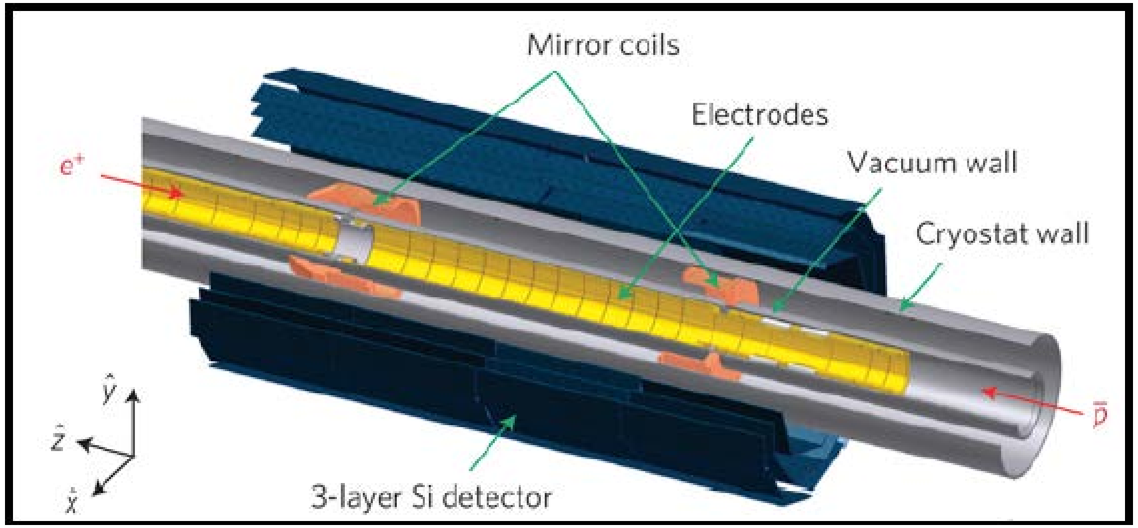



M. Diermaier et al., Nat. Comm. 8, 15749 (2017).

# Comparison: Beam vs. Trap Methods

- Requires a lot of antihydrogen atoms
- Dedicated GS-HFS spectrometer
- Antihydrogen is not necessarily in the ground state
- No systematic limits up to ~ $10^{-11}$?
- Limits:
  Statistics (~1000 atoms for $10^{-6}$)






- Works with a few antihydrogen atoms
- It is not primarily a GS-HFS experiment
- Limits:
  Magnetic field stability,
  Magnetic field gradients

# Conclusion

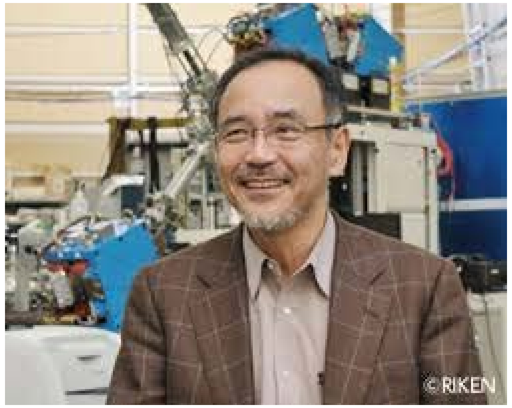
- ASACUSA has a very powerful spectrometer to measure the antihydrogen GS-HFS (~2.7 ppb, no showstoppers for another factor of ~100?)

- Open challenges:
  - More antihydrogen is needed
  - Antihydrogen is required in the ground state -> no trapping / decay in flight
  - Low temperature/velocity boosts the precision

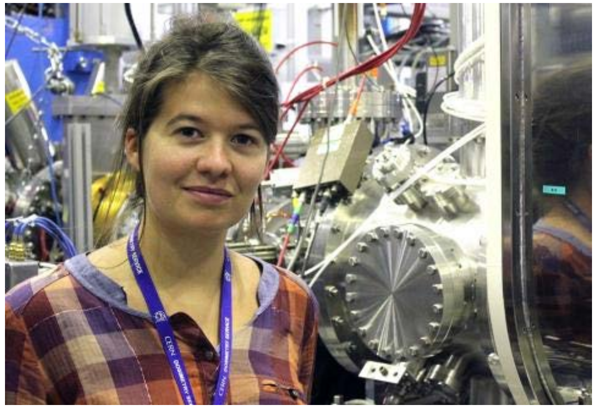
# Some ASACUSA People

Supporters of this presentation:

Yasunori Yamazaki




Chloe Malbrunot



Stefan Ulmer

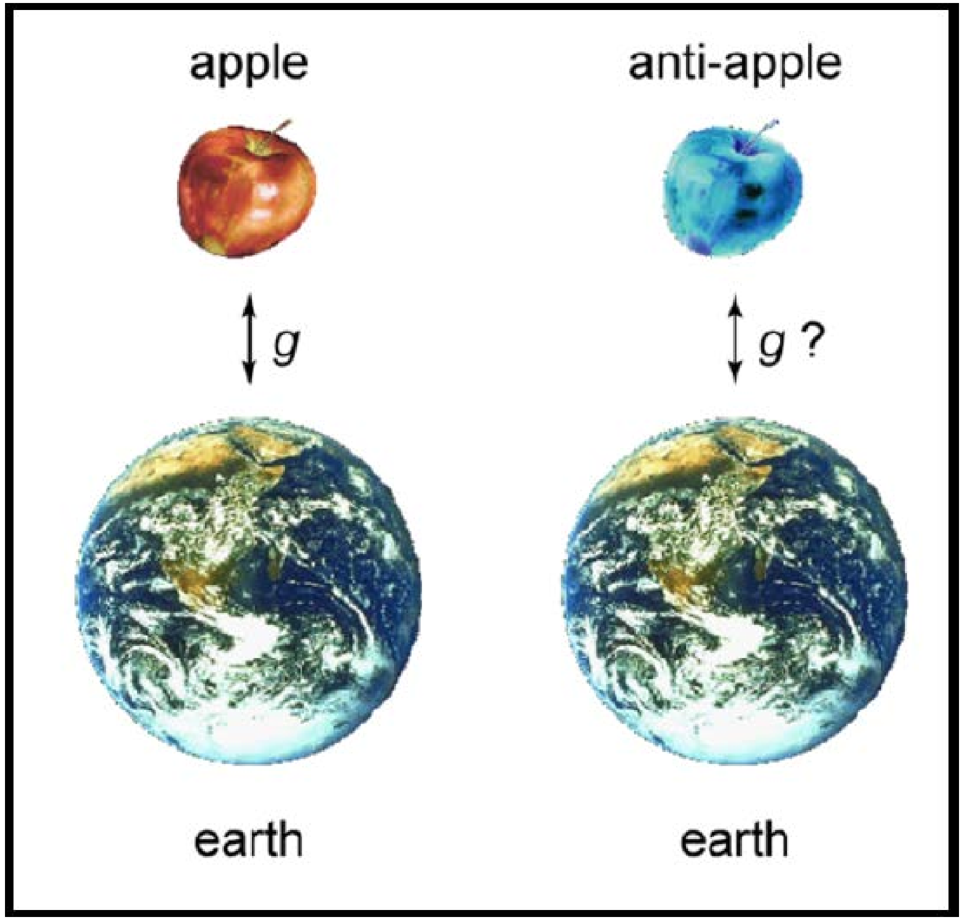

**List of Collaboration Members**

C. Amsler[3], D. Barna[1], H. Breuker[2], A. Capon[3], M. Corradini[4],M. Diermaier[3], P. Dupre[5], R.S. Hayano[6], H. Higaki[7], Y. Higashi[8], M. Hori[9], D. Horváth[1], Y. Kanai[5], C. Kaga[7], H. Knudsen[10], B. Kolbinger[3], N. Kuroda[8], M. Leali[4], E. Lodi-Rizzini[4], C. Malbrunot[2], V. Mascagna[4], Y. Matsuda[8], Y. Murakami[6], Y. Nagata[5], C. Sauerzopf[3], M. Simon[3], A. Sótér[9], M. Tajima[8], H.A. Torii[8], U. Uggerhøj[10], S. Ulmer[5], L. Venturelli[4], E. Widmann[3], H. Yamada[6], Y. Yamazaki[5], J. Zmeskal[3]

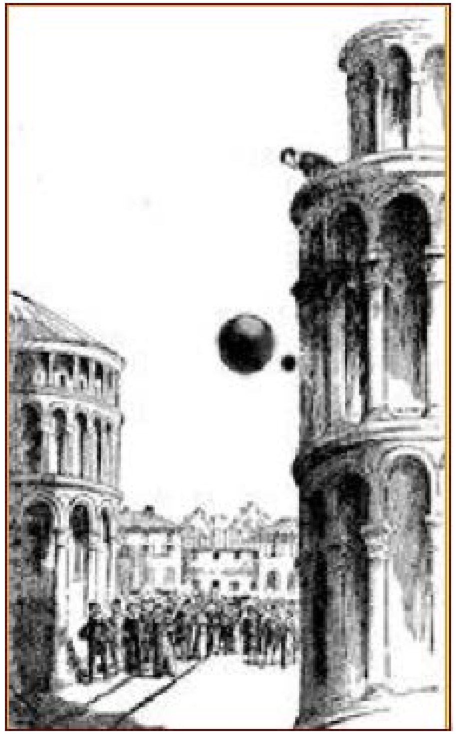
1. Wigner Research Center of Physics (HU)
2. CERN (CH)
3. Stefan Meyer Institute (AT)
4. Università di Brescia and INFN (IT)
5. RIKEN (JP)
6. The University of Tokyo (JP)
7. Hiroshima Univerity (JP)
8. The University of Tokyo, Komaba (JP)
9. Max-Planck-Institut für Quantenoptik (DE)
10. University of Aarhus (DK)

# Antimatter and Graviation

# Antimatter and Antigravitation?




The experiment idea:



# Some considerations

- Thermal velocity of antihydrogen at 4.2 K:

$$\sqrt{\langle v^2 \rangle} = 263 \text{ m/s}$$

- Change of position/velocity in 10 ms:

$$\Delta x = 2.63 \text{ m} + 0.49 \text{ mm}$$

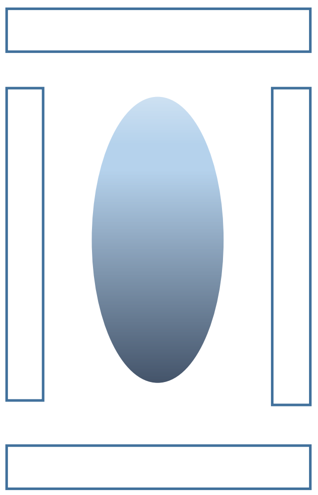
$$\Delta v = 263 \text{ m/s} + 98.1 \text{ mm/s}$$

- You want to see a tiny effect on top of a thermal distribution!
- Low temperature antihydrogen is essential for these measurements!

# Experiment ideas

**ALPHA-g**

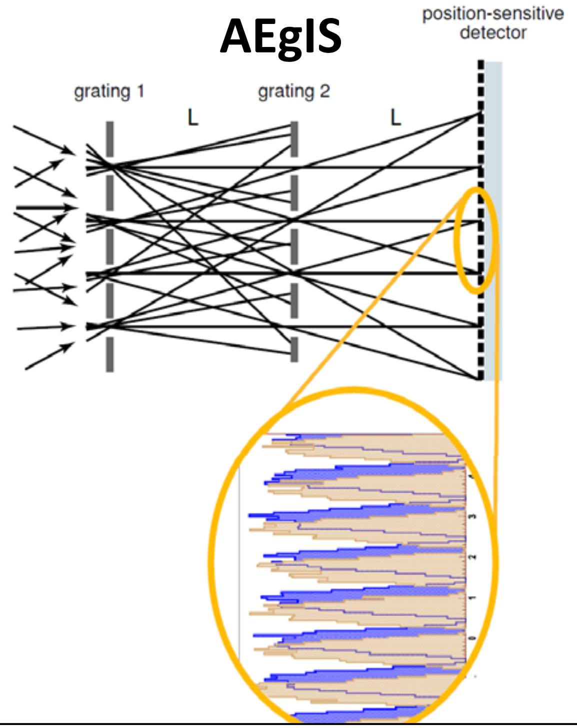
Magnetic antihydrogen trap



Bias in the number of events in the vertical direction

Requires cold antihydrogen

**AEgIS**

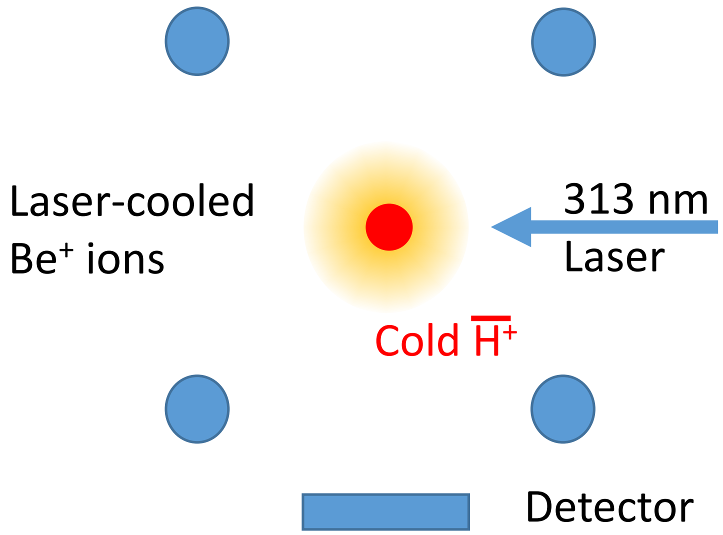



Observe interference pattern of photons and antihydrogen in a deflectometer

Requires cold antihydrogen

**GBAR**

Radiofrequency trap




Sympathetically cooled $\bar{H}$+ ion is neutralized and dropped

Requires $\bar{H}$+

# First constraints set in the horizontal apparatus

ARTICLE

Received 14 Jan 2013 | Accepted 22 Mar 2013 | Published 30 Apr 2013

DOI: 10.1038/ncomms2787

OPEN

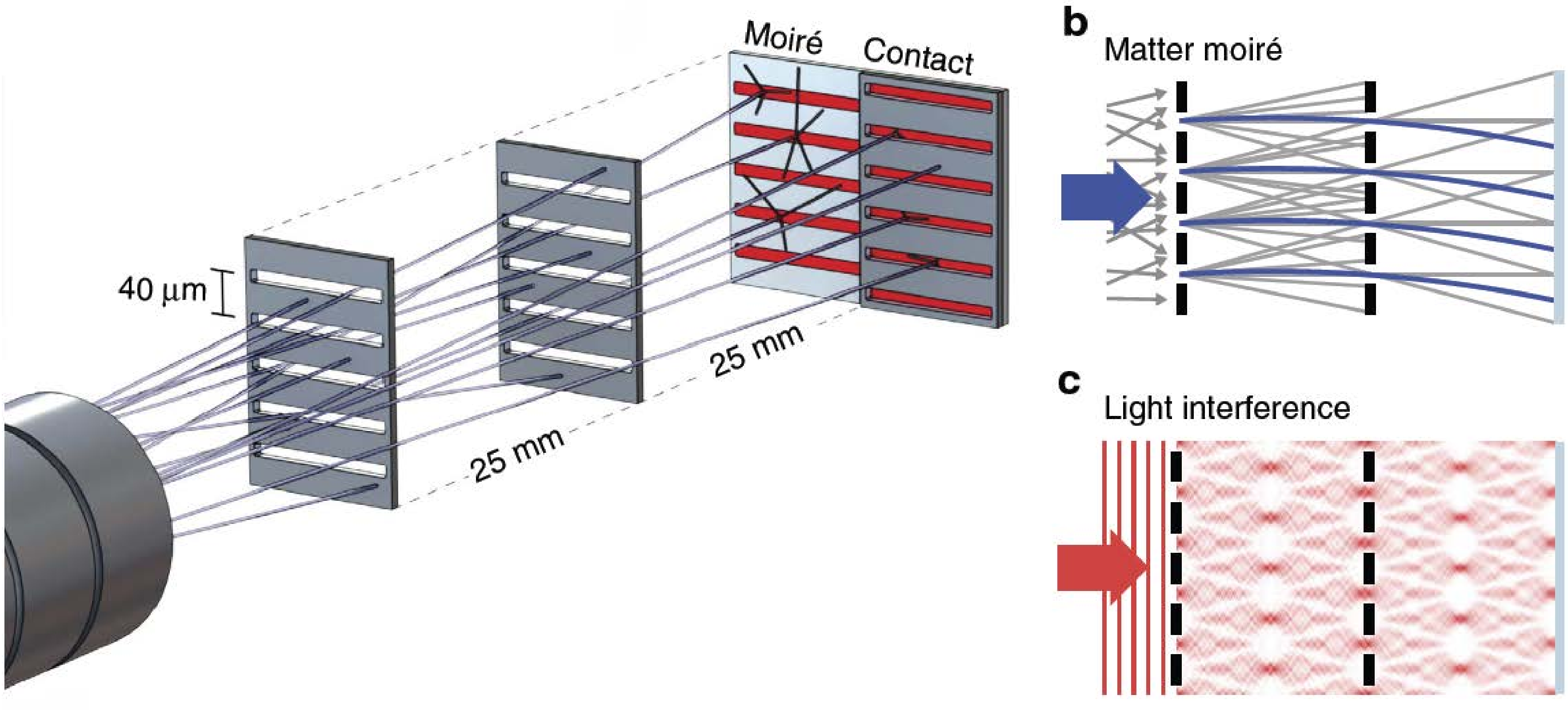
## Description and first application of a new technique to measure the gravitational mass of antihydrogen

The ALPHA Collaboration* & A.E. Charman[1]

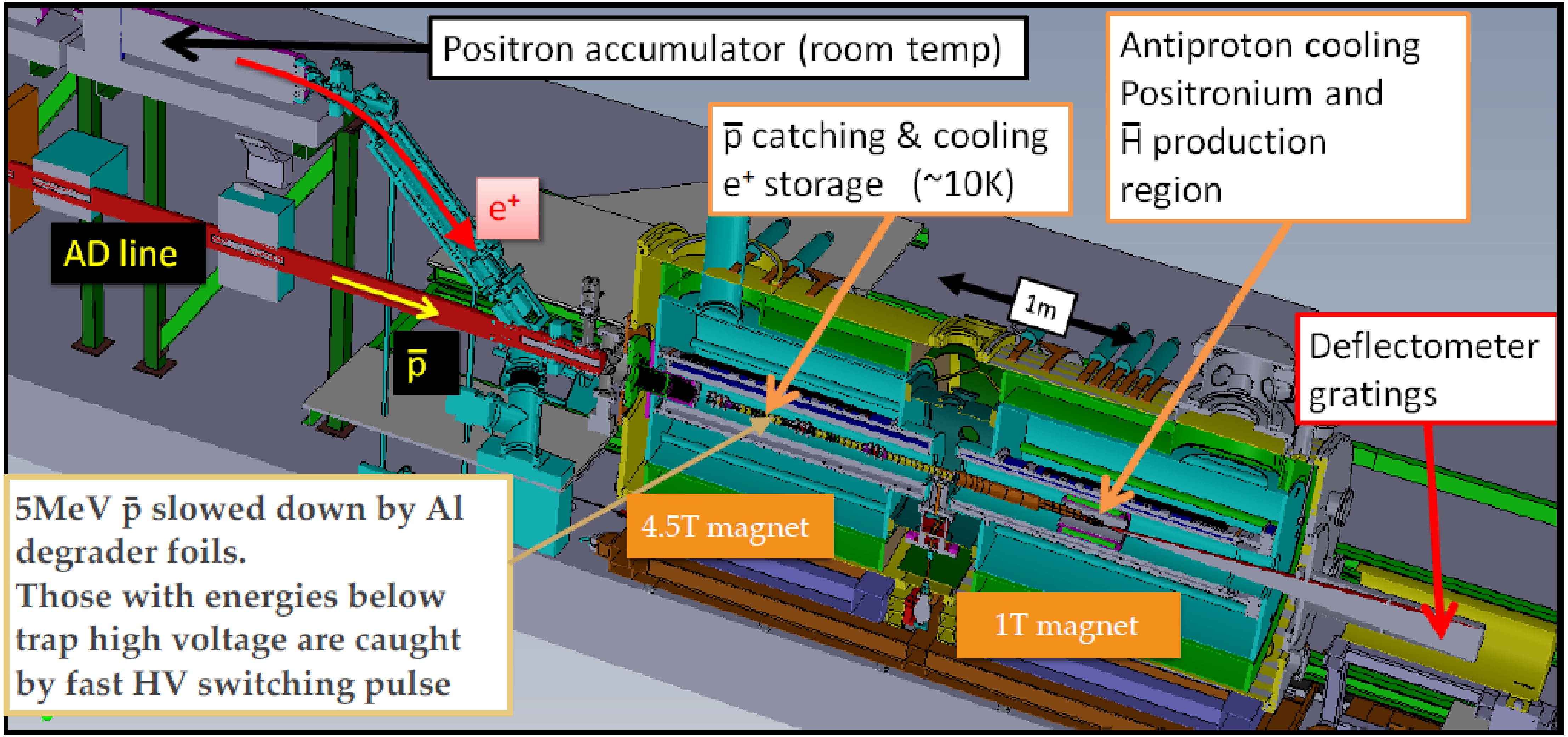
Gravitational force of antihydrogen is not more than +/- 110-fold larger than the one on hydrogen

See Publication for details.

# AEgIS: The experiment idea

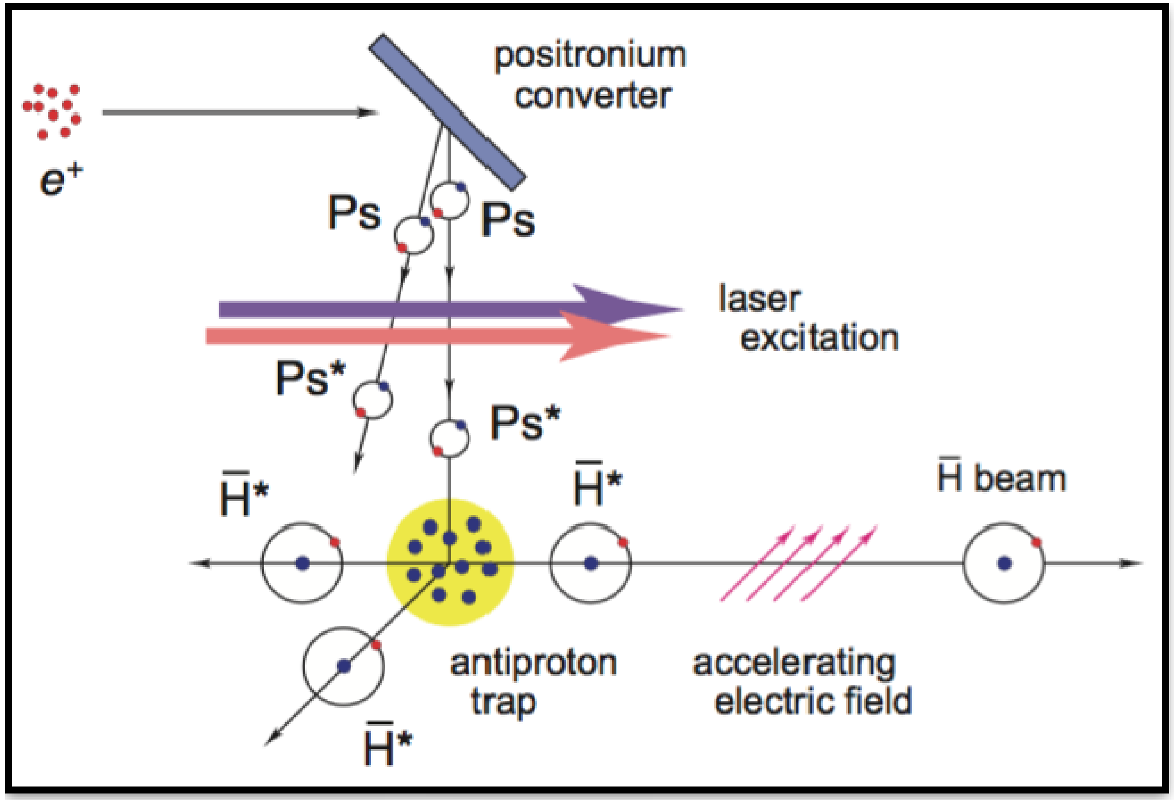


# AEgIS experimental setup

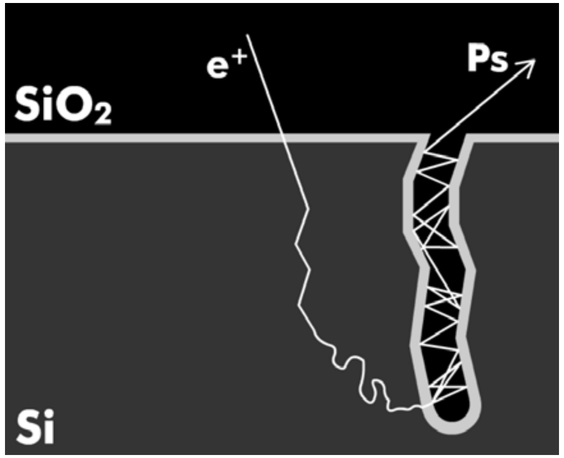



Courtesy of C. Malbrunot

# Antihydrogen production in AEgIS



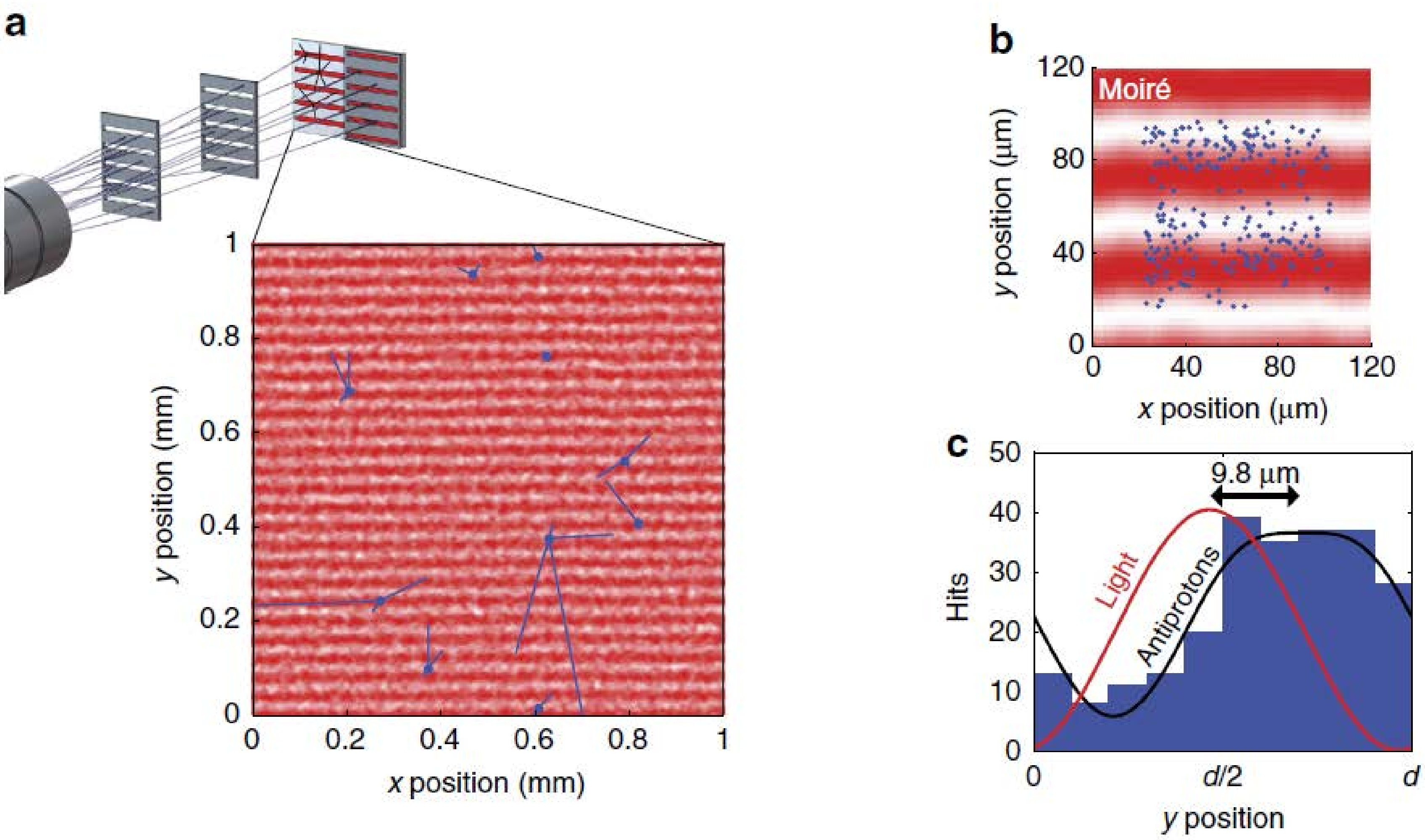

$$Ps^{*} + \bar{p} \rightarrow \bar{H}^{*} + e^{-}$$




**Porous target for positronium production**

http://aegis.web.cern.ch/aegis/

# Moire deflectometer tested with antiprotons




Gravitational force:
10^-26 N

Magnetic force on antiprotons:
5 10^-16 N

AEgIS collaboration, Nat. Comm. 5, 4538 (2014).

# GBAR installation in the AD

Antiproton Injection/Pulsed drift tube

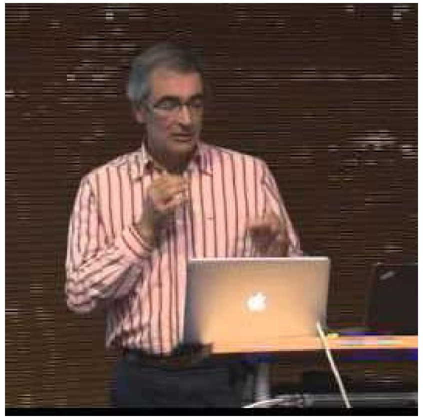
The GBAR housing of the small electron accelerator

Production of positive antihydrogen ions (Two positrons, one antiproton)
Sympathetic cooling with a single beryllium ion
Ionization and free fall experiment of an ultra-cold antihydrogen atom

http://gbar.web.cern.ch

# Some AD people

Patrice Perez

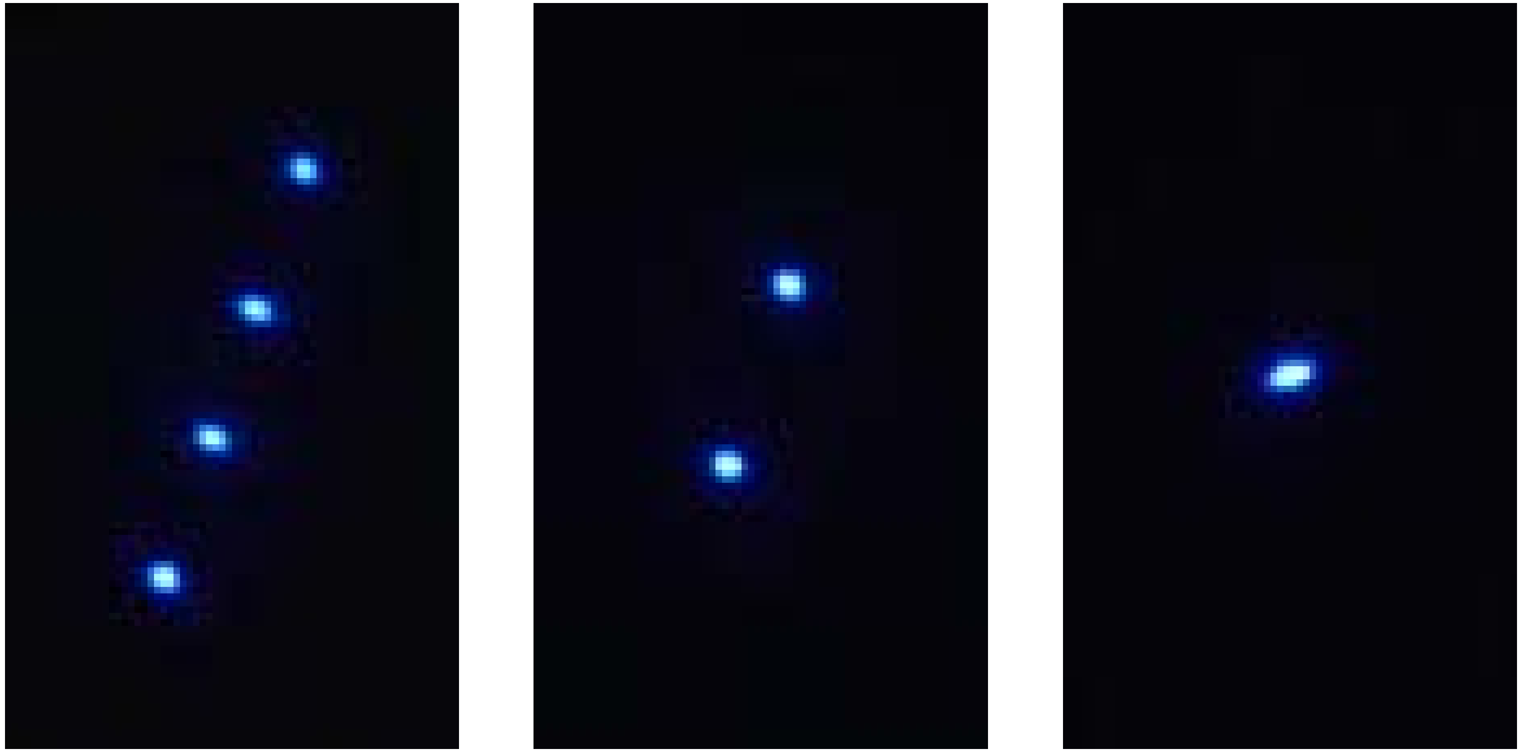


Michael Doser

Jeff Hangst

AEgIS

# A final comment on antihydrogen experiments



Images of ions in a Penning trap after Doppler laser cooling.

Each image is approximately 90µm X 150µm

99 of 100 problems can be solved with lower temperatures!

Laser-cooling in a strong magnetic field is now an established technique

Some developments:

- Positron cooling with Beryllium ions
- Hbar+ with Beryllium ions
- Sympathetic antiproton cooling with negative ions (Os-, La-, C2-)

Single particle techniques:

- “Common endcap”-technique
- Coulomb force coupling in separate wells

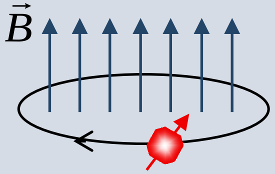
Courtesy of R. Thompson (ICL)

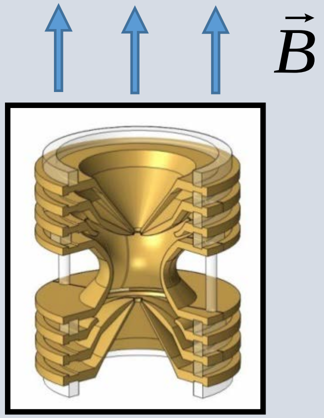
# Precision Physics and Antimatter

Part 3/1 Single Particles in Penning Traps – The Ideal Trap

# High-precision measurements in Penning traps

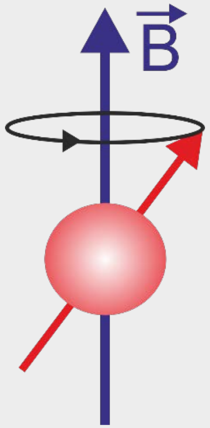
### Cyclotron Frequency

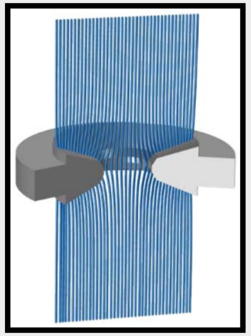



$$\omega_c = \frac{q}{m} B$$

### Larmor Frequency



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

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

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

H. G. Dehmelt and P. Ekström, Bull. Am. Phys. Soc. 18, 72 (1973).
D. J. Wineland and H. G. Dehmelt, J. Appl. Phys. 46, 919 (1975).

# Equations of motions

$$\vec{B} = B_0 \vec{e}_z \qquad V(z,\rho) = V_0 C_2 (z^2 - \rho^2/_2)$$

Newton's equation of motion:

$$m\ddot{\vec{x}} = -q\vec{\nabla}V(r,\rho) + q\dot{\vec{x}} \times \vec{B}$$

z-Direction: Harmonic Oscillator

r-Direction: Coupled DEQ due to Lorentz-force

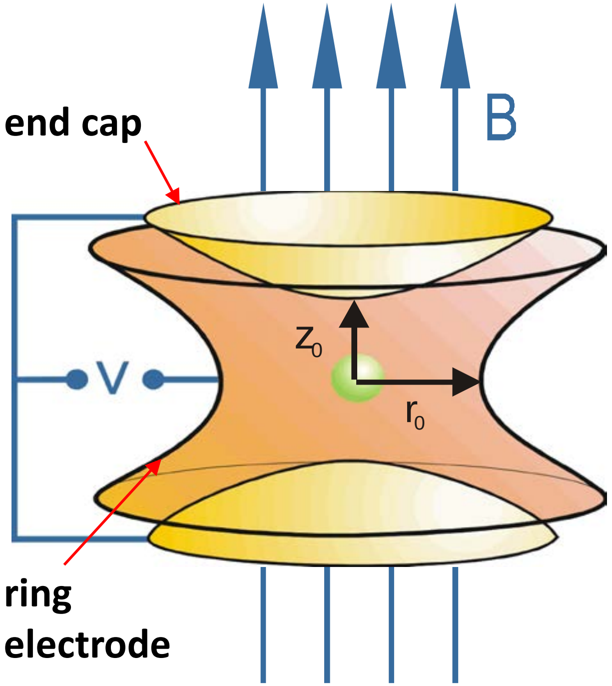
$$u = x + iy \;\Rightarrow\; \ddot{u} = \frac{1}{2}\omega_z^2 u - i\omega_c \dot{u} \;\Rightarrow$$

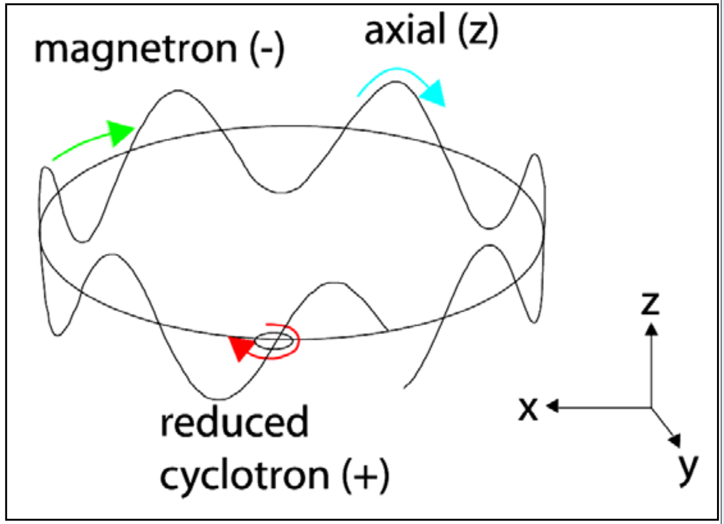
Ans.: $u = u_0 e^{-i\omega t}$

$$\Rightarrow\; 0 = \omega^2 - \omega\omega_c + \frac{1}{2}\omega_z^2$$

Two frequencies solve this equation: $\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}}$

# The Penning trap




$$\nu_c^2 = \nu_+^2 + \nu_-^2 + \nu_z^2$$

$$\nu_z = \frac{1}{2\pi}\sqrt{\frac{qV}{md^2}}$$

$$\nu_+ = \frac{\nu_c}{2} + \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$

$$\nu_- = \frac{\nu_c}{2} - \sqrt{\frac{\nu_c^2}{4} - \frac{\nu_z^2}{2}}$$

# Level scheme of the quantized Penning trap

- Some further calculations lead to the quantized Hamiltonian:

$$
\begin{aligned}
H \;=\; & \hbar\omega_+ \left( A_+^\dagger(t) A_+(t) + \frac{1}{2}\cdot \mathbb{1} \right) - \hbar\omega_- \left( A_-^\dagger(t) A_-(t) + \frac{1}{2}\cdot \mathbb{1} \right) \\
& + \hbar\omega_z \left( A_3^\dagger(t) A_3(t) + \frac{1}{2}\cdot \mathbb{1} \right) .
\end{aligned}
$$

- “Geonium atom”:

$\Rightarrow \quad \psi_{s,n_+,n_-,n_z}$