Antihydrogen and Hydrogen Fountain

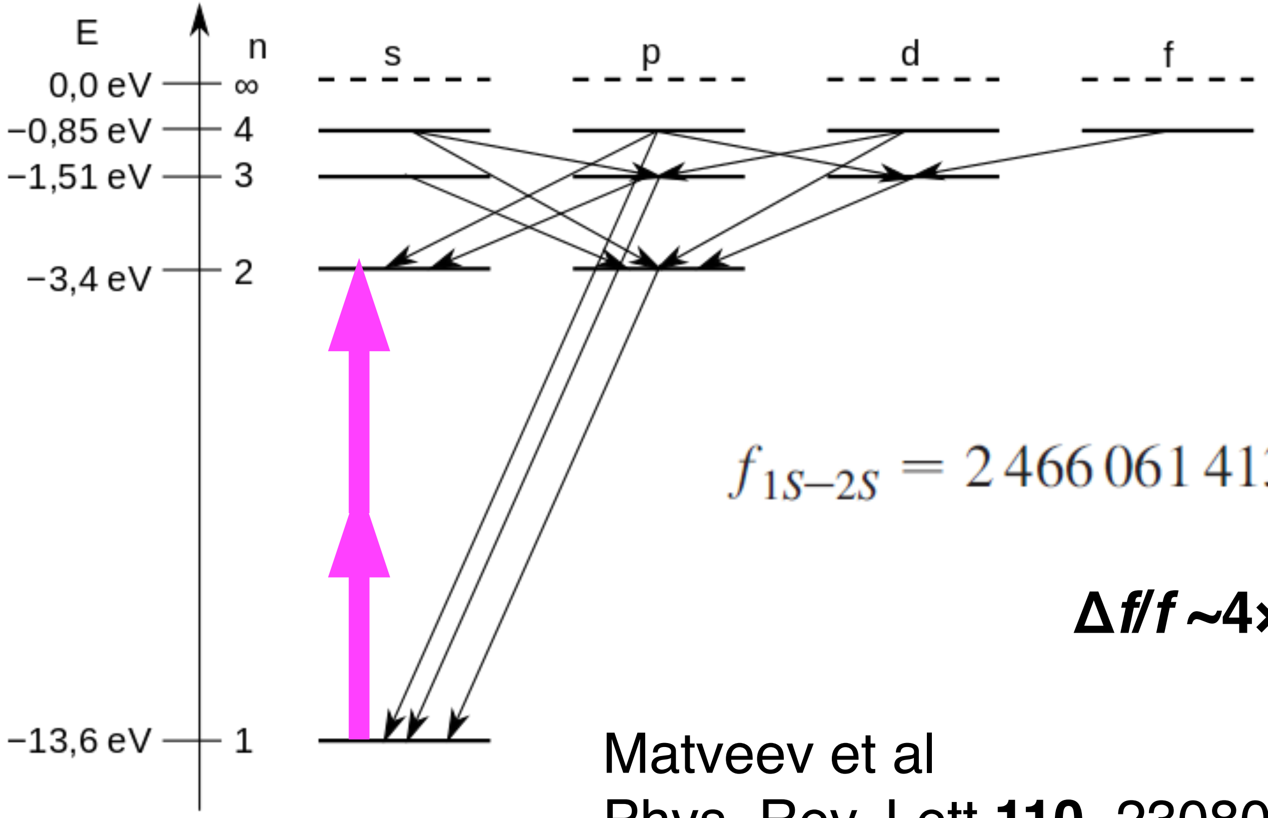
Takamasa Momose
for ALPHA collaboration

The University of British Columbia
TRIUMF
CANADA

Hydrogen Atoms

Spectroscopy of hydrogen atoms has been the chief experimental basis for theories of the structure of matter.

1S-2S : The most precisely determined transition



$$f_{1S-2S} = 2\,466\,061\,413\,187\,035\,(10)\ \mathrm{Hz}$$

$\Delta f/f \sim 4\times10^{-15}$ ($\Delta f \sim 10$ Hz)

Matveev et al
Phys. Rev. Lett **110**, 230801 (2013)

ALPHA

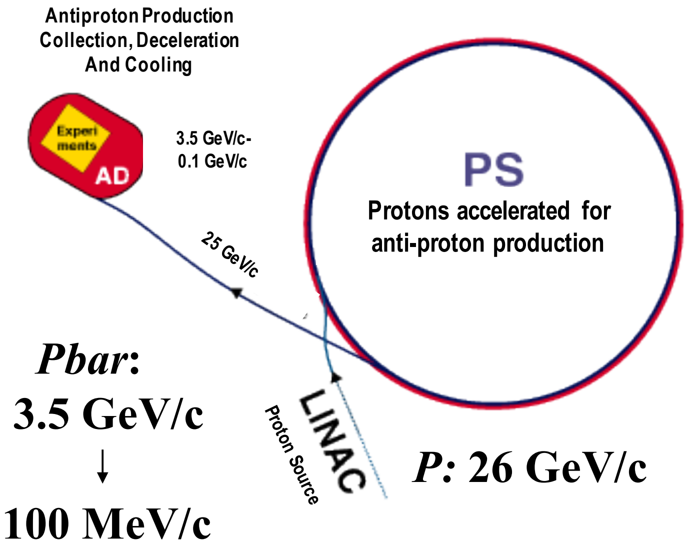
Antihydrogen **L**aser **PH**ysics **A**pparatus

International collaboration at CERN on antihydrogen precision spectroscopy

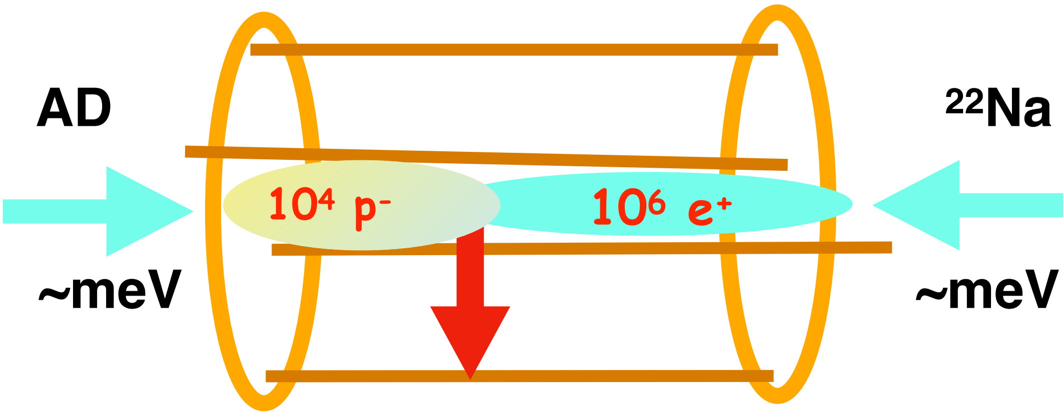
ALPHA-Canada

TRIUMF · The University of British Columbia · Simon Fraser University — Thinking of the World · University of Calgary · York Université University

AD Antiproton Complex at CERN



Magnetic trap



20 ~ 30 antihydrogen below 500 mK per cycle

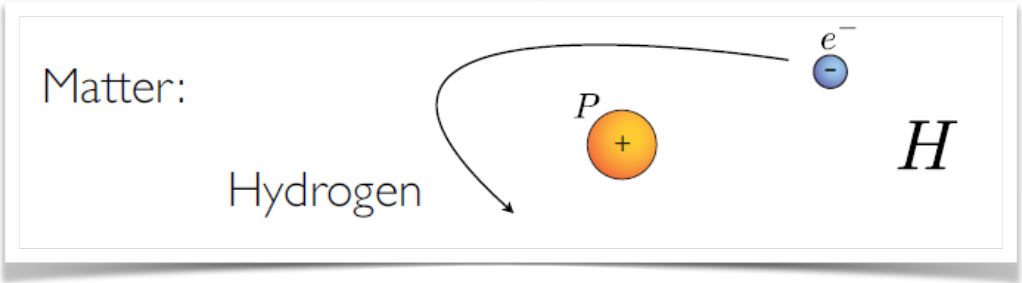
Exotic Hydrogen Atoms

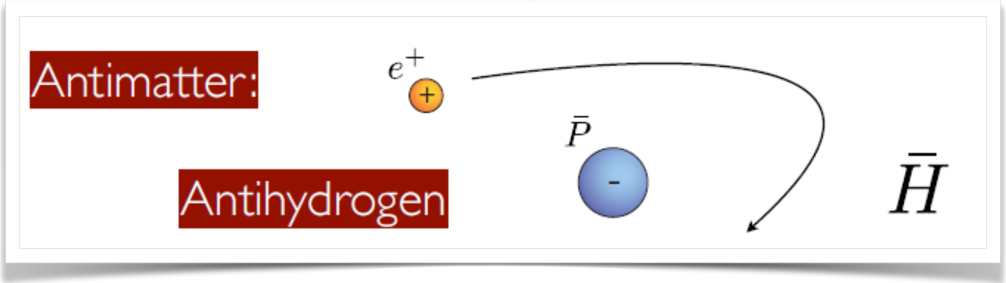
Precision Spectroscopy using Bound states atoms

Muonium
Positronium
Muonic atom

Pionic Helium
Antihydrogen

Hydrogen **Antihydrogen**





Tests of QED, Quantum Field Theory, General Relativity
Fundamental Symmetries (CPT, Equiv. Principle etc)

Matter-Antimatter Asymmetry

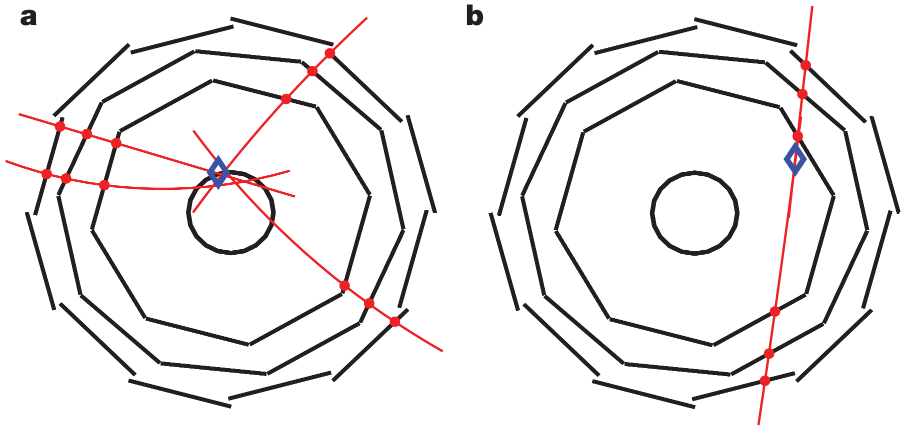
Antihydrogen at ALPHA-1 (- 2012)

2010 First trapping

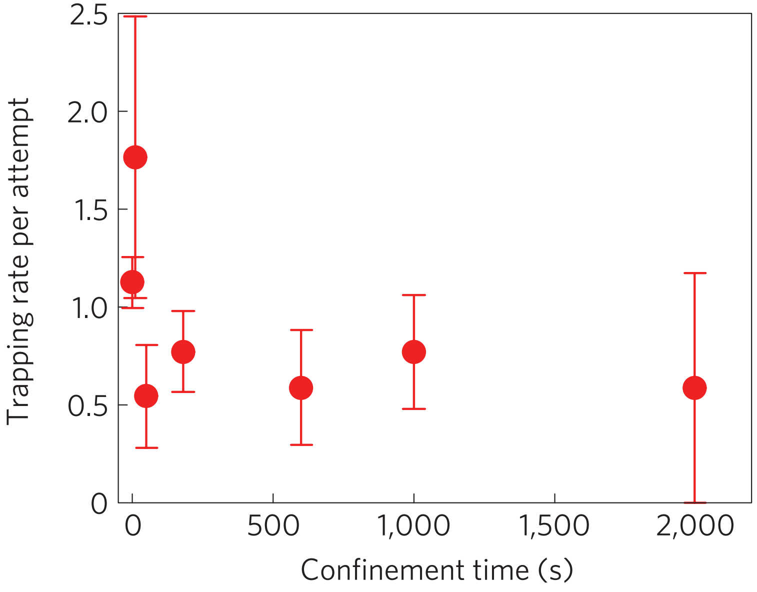
LETTER *Nature* **468**, 673–676 (02 December 2010)
doi:10.1038/nature09610

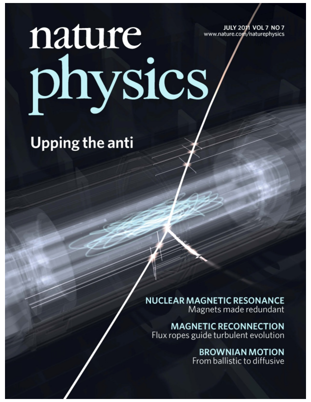
Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]



2011 Confinement for >2000 s





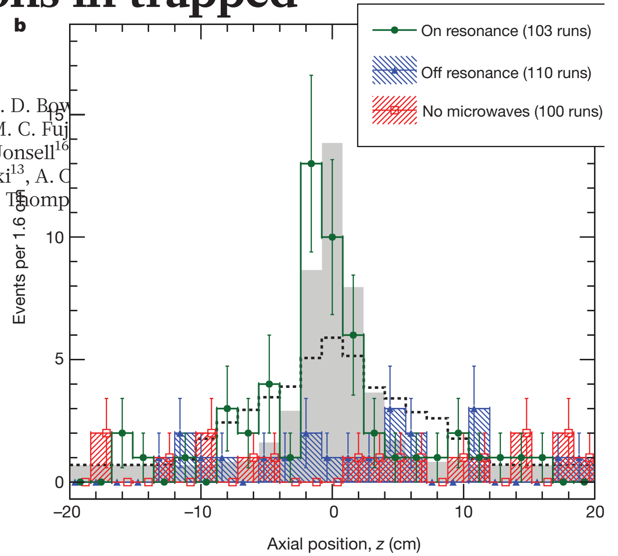
Nat. Phys. **7**, 558–564 (05 June 2011)

2012 First 1S hyperfine spectroscopy

LETTER *Nature* **483**, 439–443 (22 March 2012)
doi:10.1038/nature10942

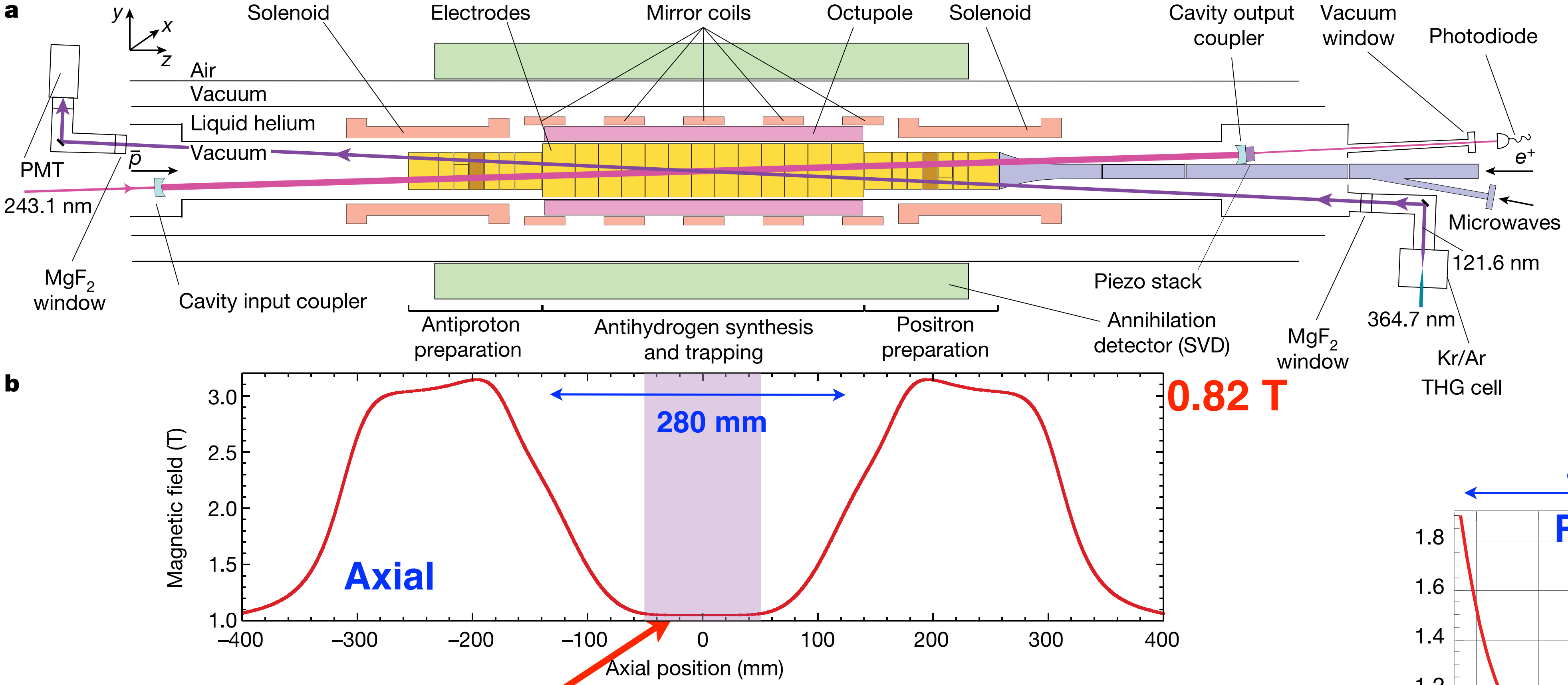
Resonant quantum transitions in trapped antihydrogen atoms

C. Amole[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4,5,6], P. D. Bow
A. Deller[4], P. H. Donnan[10], S. Eriksson[4], J. Fajans[3,11], T. Friesen[12], M. C. Fuj
W. N. Hardy[14,15], M. E. Hayden[2], A. J. Humphries[4], C. A. Isaac[4], S. Jonsell[16]
J. T. K. McKenna[17], S. Menary[1], S. C. Napoli[4], P. Nolan[17], K. Olchanski[13], A. C
E. Sarid[19], C. R. Shields[4], D. M. Silveira[20]†, S. Stracka[13], C. So[3], R. I. Thomp



ALPHA-2 (2016 -)

New ALPHA trap designed for spectroscopy

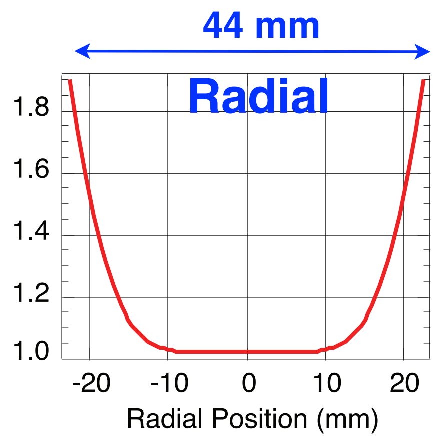


0.82 T

44 mm

1.03 T

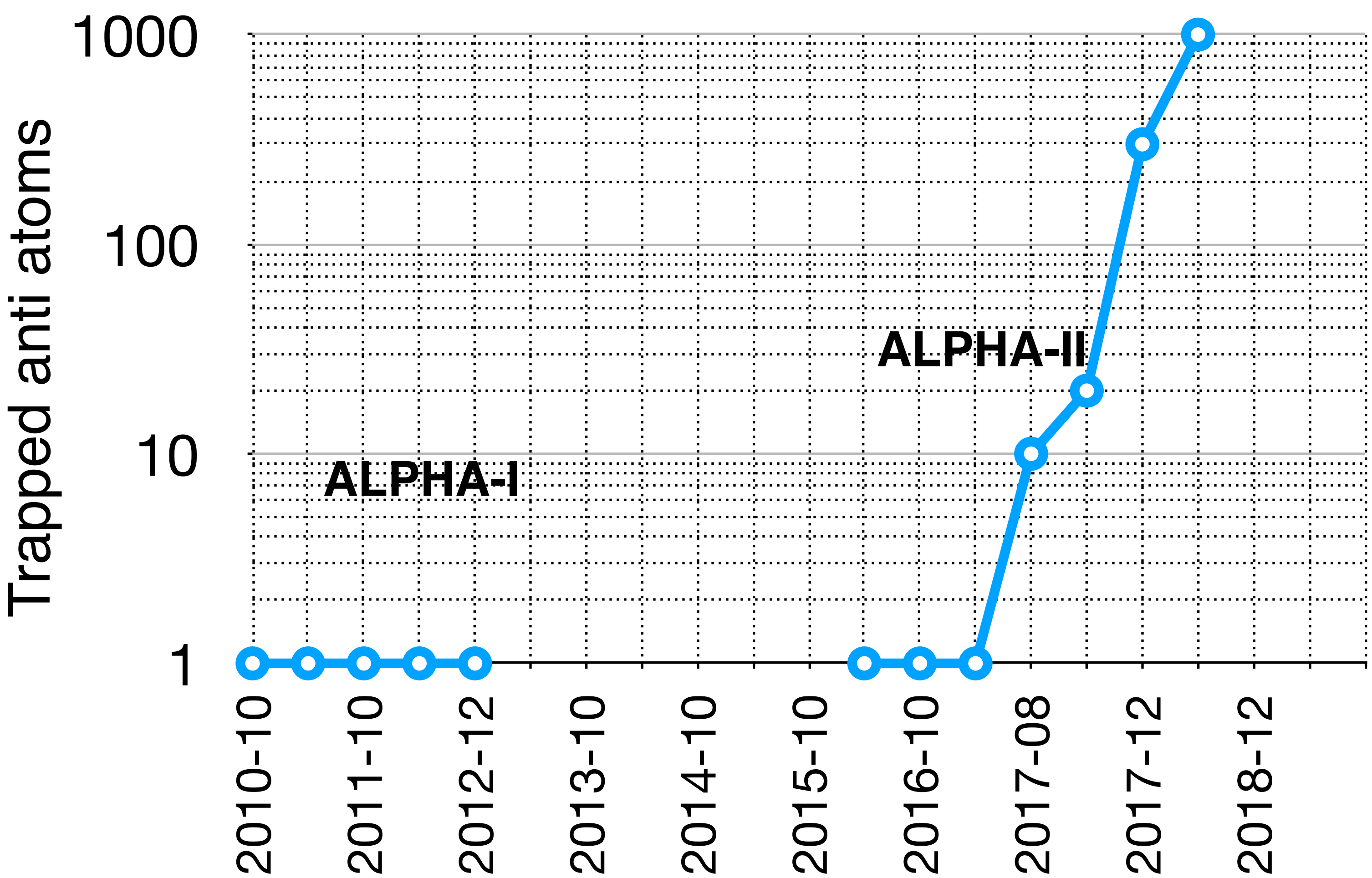
Magnetic field distribution



0.84 T

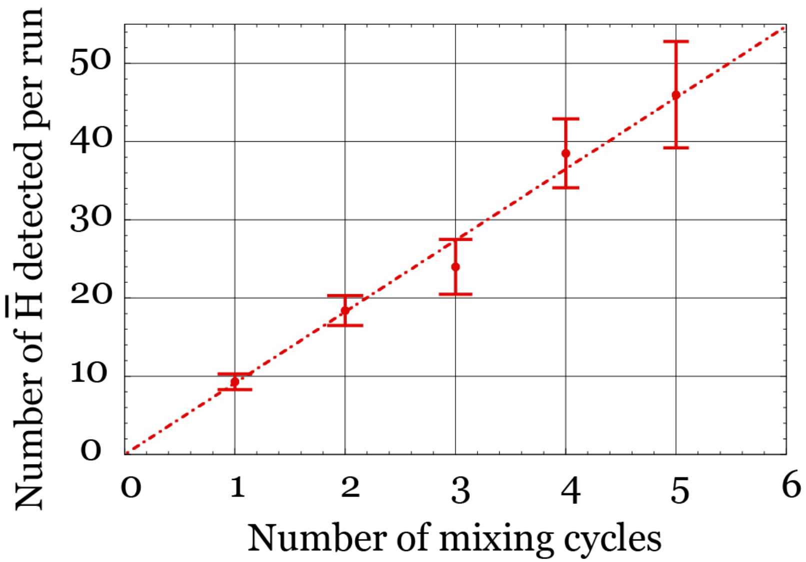
ALPHA-2 (2016 -)

The number of trapped atoms



Stacking

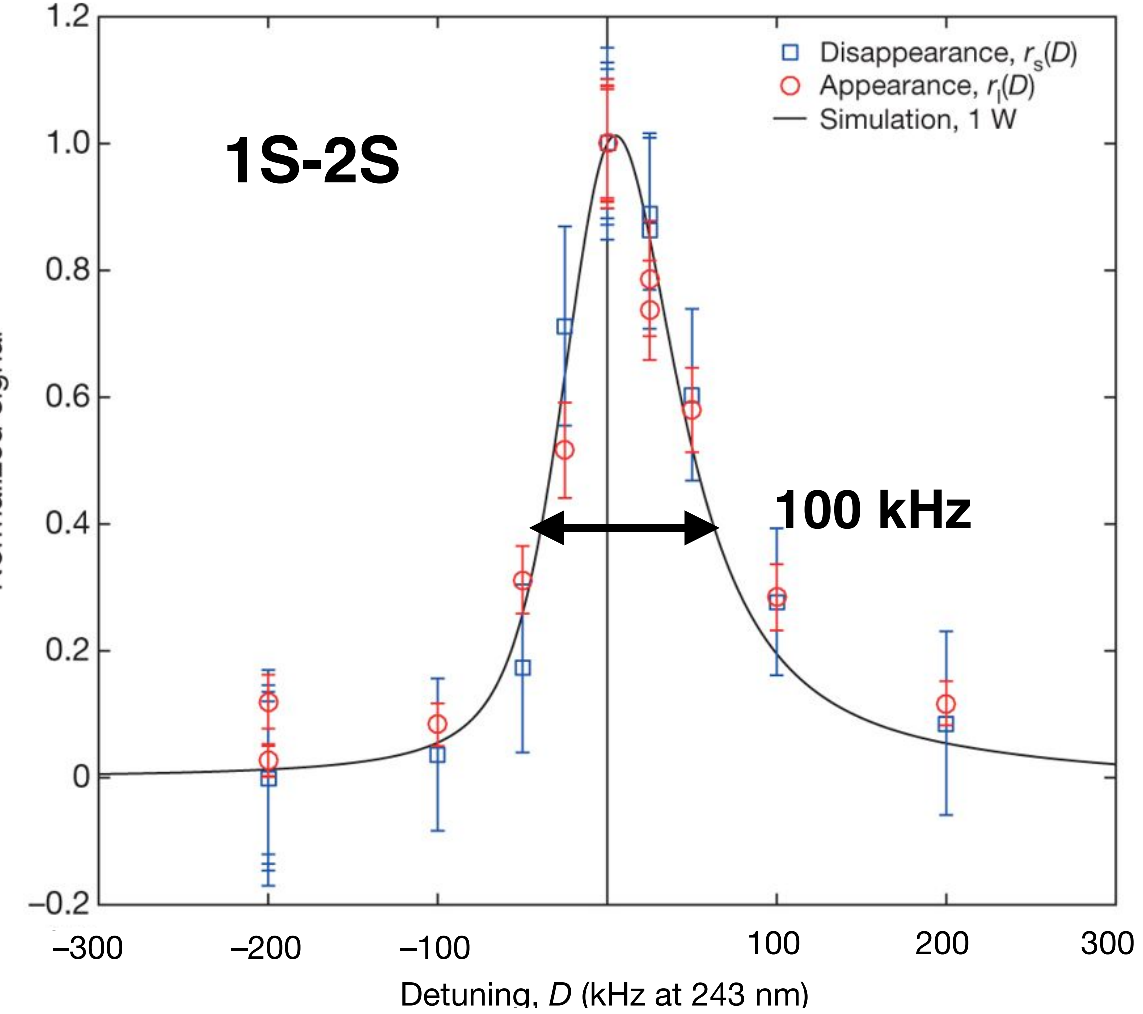
Repeated loading of anti-H in trap
Each cycle ~ 200 sec;



***Nature Comm.*, 8, 681 (2017)**

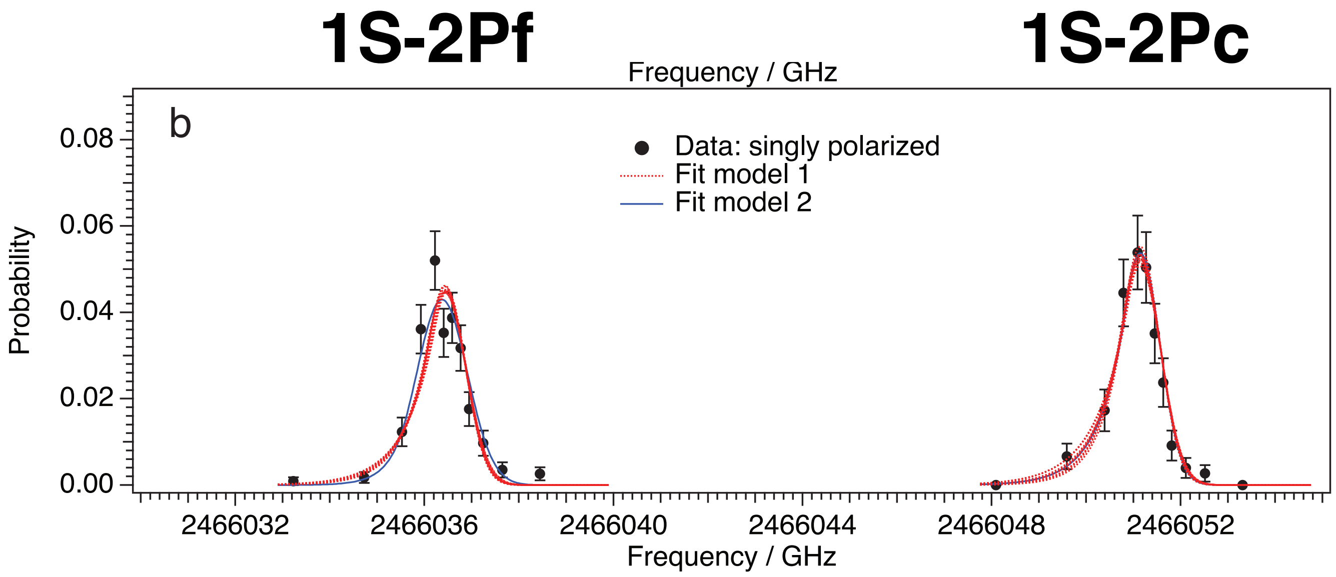
1S-2S / 1S-2P Spectroscopy of Antihydrogen

Two photon transition at 243.2 nm



***Nature*, 557, 71-75 (2018)**

One photon transition at 121.6 nm



"Doppler" width ~ 900 MHz

***Nature*, 561, 211 (2018)**

***Nature*, 578, 375 (2020)**

Precision Spectroscopy of Antihydrogen

1S-2S at 243.2 nm

Anti hydrogen

Precision $\Delta f/f \sim 2\times10^{-12}$ ($\Delta f \sim 5$ kHz)

$f_{d\text{-}d}$ = 2 466 061 103 079.4 (5.4) kHz.

at 1.03 T

No difference at the 12 digits

Hydrogen **$\Delta f/f \sim 4\times10^{-15}$ ($\Delta f \sim 10$ Hz)**

$$f_{1S-2S} = 2\,466\,061\,413\,187\,035\,(10)\ \text{Hz}$$

Matveev et al
Phys. Rev. Lett **110**, 230801 (2013)

at 0 T

1S-2P at 121.6 nm

Anti hydrogen

Fine Structure	10.88 ± 0.19 GHz
Lamb Shift	0.99 ± 0.11 GHz

No difference within a few %

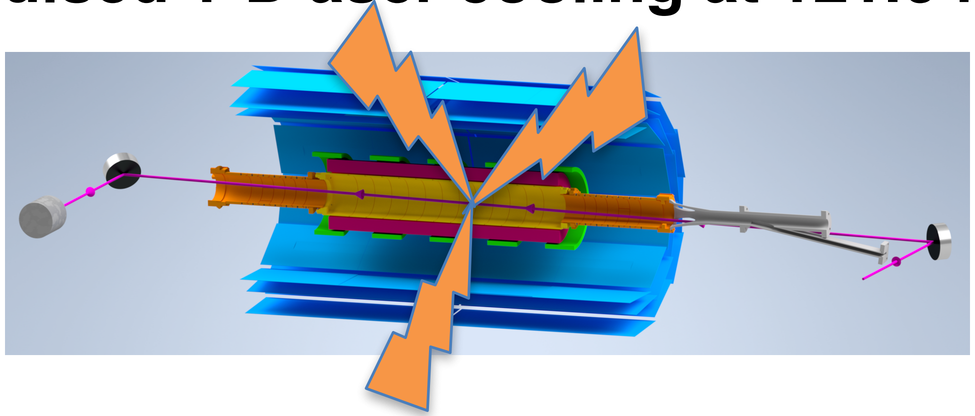
Hydrogen

Fine Structure	10.96913 (10)GHz
Lamb Shift	1.057847(9) GHz

Laser Cooling of Antihydrogen

Pulsed 1-D aser cooling at 121.6 nm

Nature, **592**, 35 (2021, April 1st)

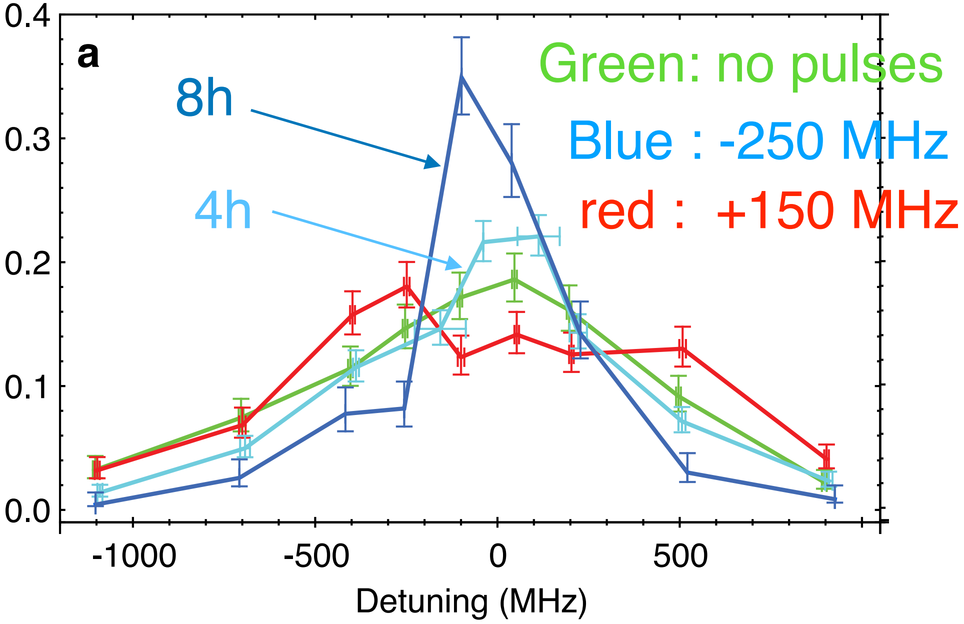


Doppler width ~ 900 MHz

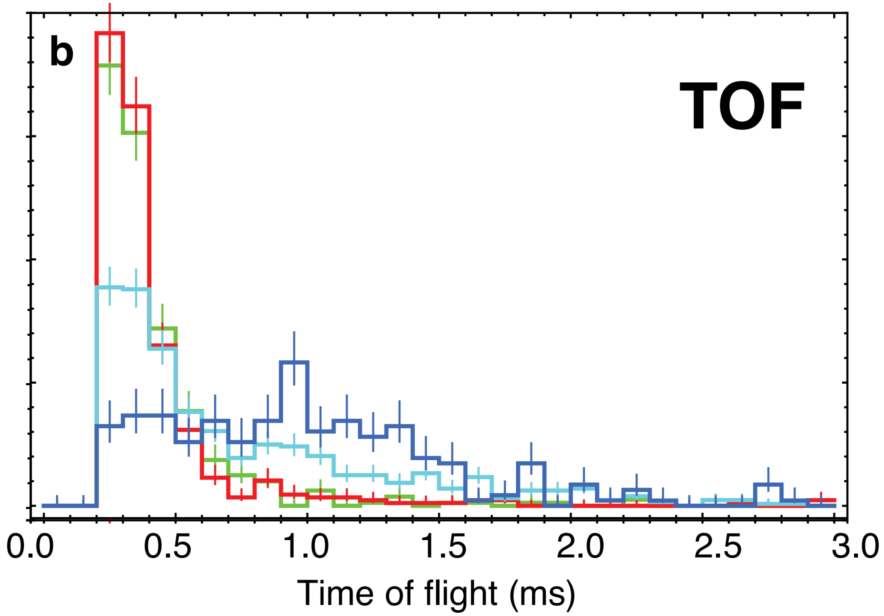
Detuning +150 MHz ⟶ heating

Detuning - 250 MHz ⟶ cooling

Longitudinal cooling



Transverse cooling

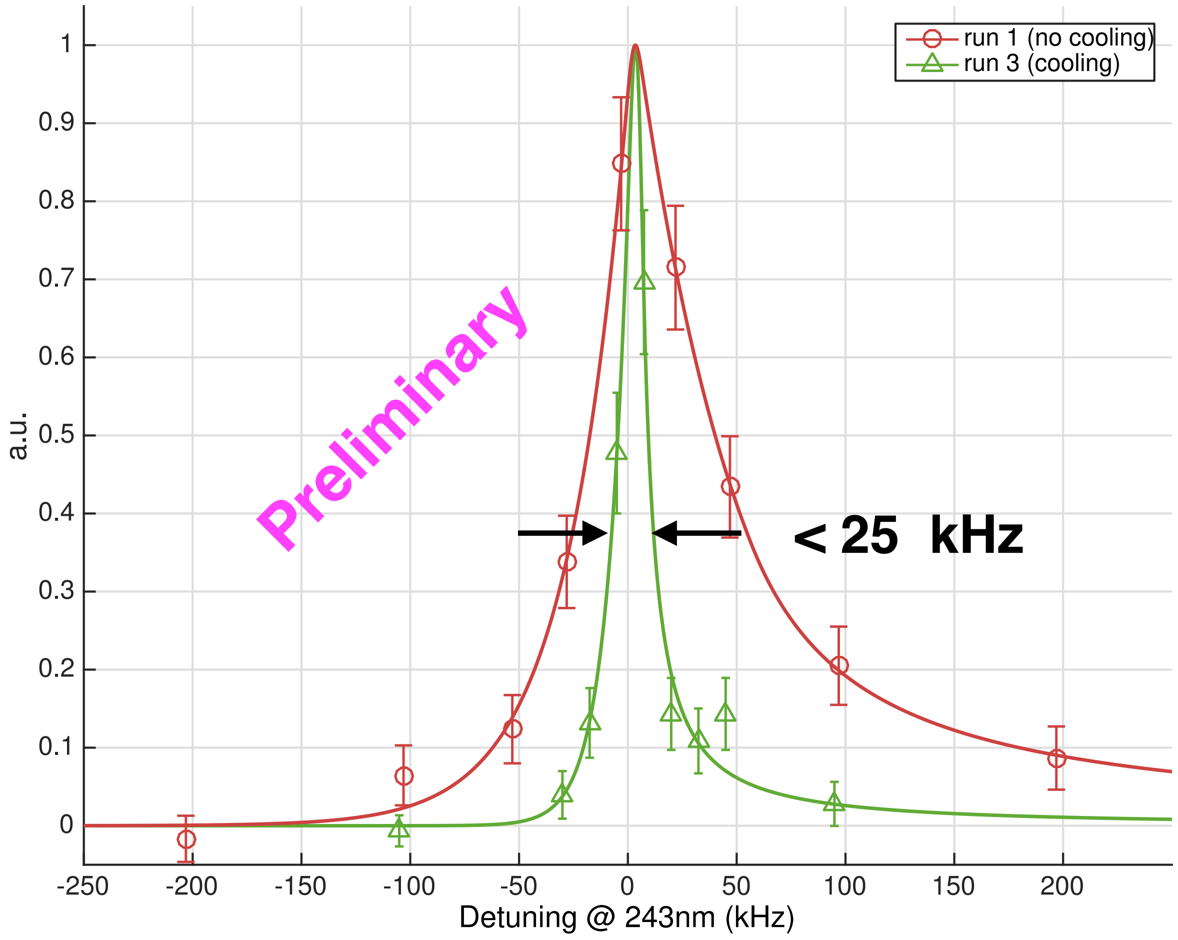


E_L : 6.6 μeV→1.7 μeV (80 mK → 20 mK)

E_T : 18 μeV→4.8 μeV(200 mK → 55 mK)

Precision Spectroscopy

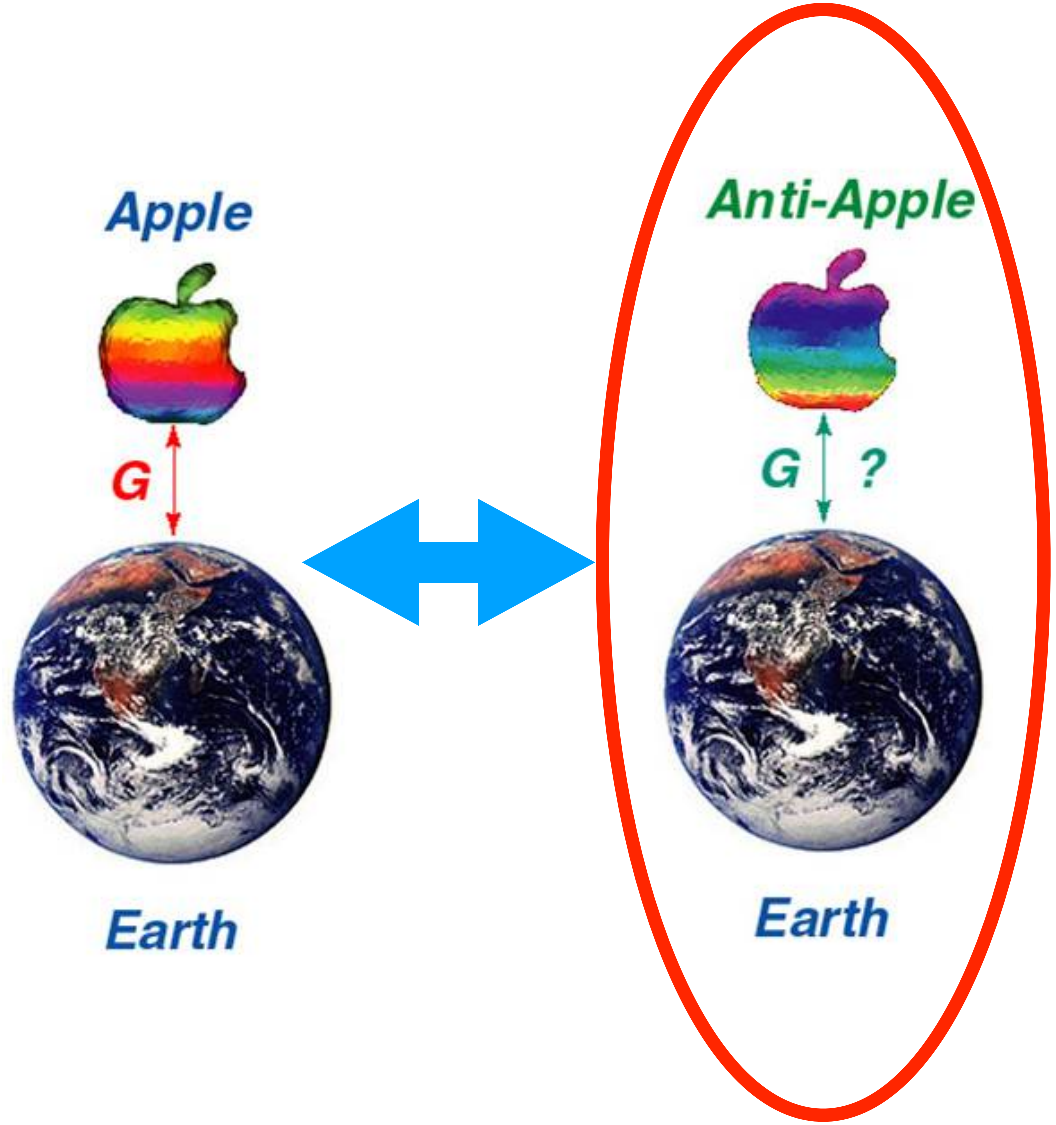
1S-2S of Laser Cooled Anti-H



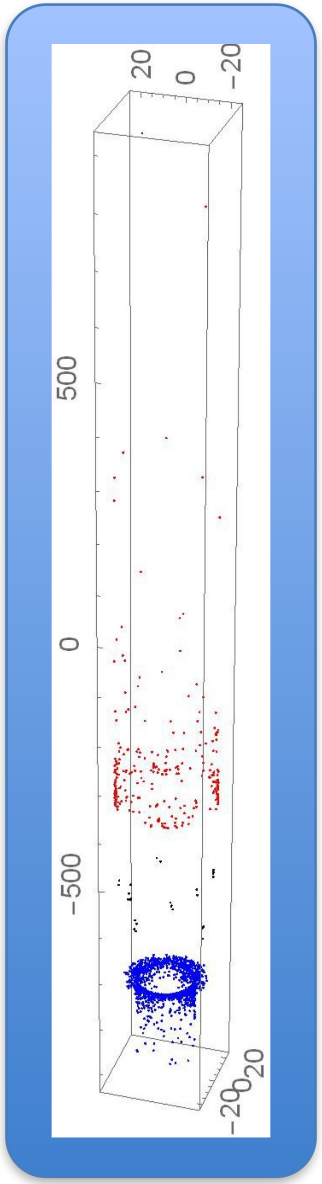
Doppler cooling limit

500 mK → a few mK

ALPHA-g: Measurement of anti-H gravity



Free "fall" of ant-H



HAICU(俳句) : 2022-

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

R&D platform for development for "quantum sensing" techniques for anti-H

Use H (and other cold atoms) as proxy
- (Anti)atomic fountain
- (Anti)Matter-wave interferometer
- Ramsey hyperfine spectroscopy
- Optical trapping
- Anti-molecular clock

Hydrogen difficult to handle
- 1s-2p transition at 121 nm
- Difficult to trap
- No fountain made with H

Ultimate Goal:

Make precision H--antiH comparison in the same apparatus

HAICU(俳句) : 2022-

Key Concept

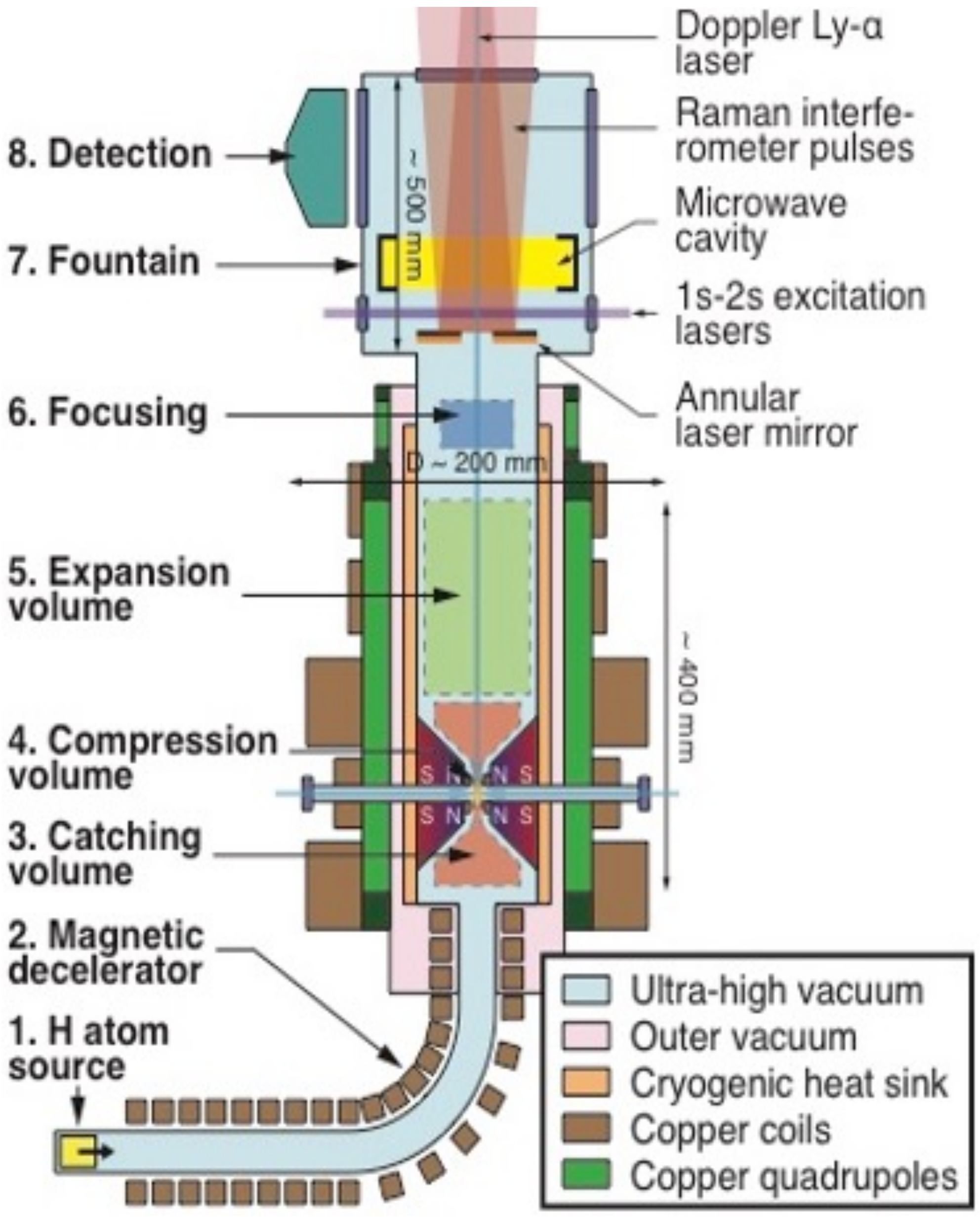
A: Magnetic compression of atomic clouds in
a small, high density quadrupole trap (~mm radius)

B: Laser cooling →high phase space density
(~100 um radius, 2 mm length)
Target densities $10^7 – 10^8$ cm^{-3}
(currently ~ 1 cm^{-3} in ALPHA)

C: Expansion cooling
Create (anti)H gas in micro-Kelvin regime!

D: Launch into free space as fountain for
informetric and other interrogations
(~100 nK regime)

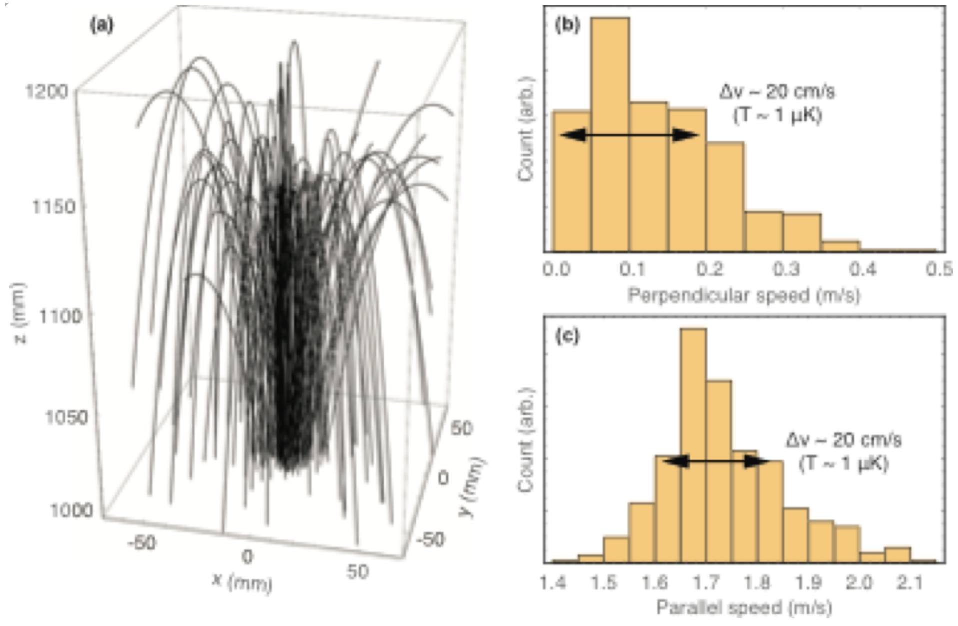
Up to $10^7 – 10^8$ colder and denser anti-H cloud!



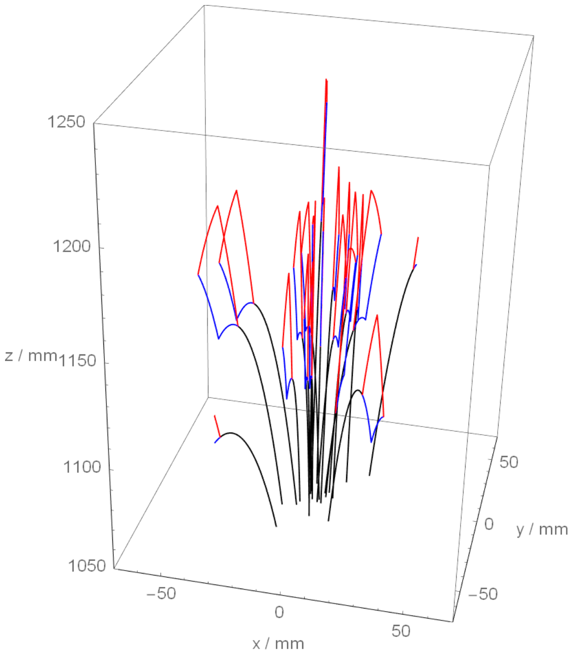
HAICU(俳句) : 2022-

HAICU: Hydrogen-**A**ntihydrogen **I**nfrastructure at **C**anadian **U**niversities

(Anti)hydrogen fountain



(Anti)hydrogen Interferometer



(Anti)hydrogen molecule

$$\overline{H}(2S) + \overline{H}(2S) \rightarrow \overline{H}_2^- + e^+.$$

TRIUMF
THE UNIVERSITY OF BRITISH COLUMBIA
SFU SIMON FRASER UNIVERSITY THINKING OF THE WORLD
UNIVERSITY OF CALGARY
YORK UNIVERSITÉ UNIVERSITY

Antihydrogen Physics

22 years since the start of Antiproton Decelerator at CERN, we are entering a new era

Tremendous progress in past few years

- Laser spectroscopy at 10-12 level
- Microwave, charge neutrality, etc.
- Laser cooling opens up new opportunities

Since 2021-

- ELENA, upgraded AD, became operational
- Gravity measurement, ALPHA-g started
- The HAICU project just initiated

Exciting future with antihydrogen physics!

ALPAH Collaboration

AARHUS UNIVERSITET

THE UNIVERSITY OF CALIFORNIA 1868

BERKELEY LAB

UBC THE UNIVERSITY OF BRITISH COLUMBIA

UNIVERSITY OF CALGARY

CERN

UNIVERSITY OF LIVERPOOL

MANCHESTER 1824

The Cockcroft Institute of Accelerator Science and Technology

NRCN

clear Research Center Negev

UNIVERSIDADE DO BRASIL

Purdue University

SFU SIMON FRASER UNIVERSITY THINKING OF THE WORLD

Stockholm University

Swansea University Prifysgol Abertawe

TRIUMF

YORK UNIVERSITÉ UNIVERSITY