Antihydrogen Laser PHysics Apparatus

Aarhus University, Denmark

University of British Columbia, Canada

Uni

University of Calgary,

24 faculty
13 postdocs
10 PhD students
5 - 20 undergraduates

THE UNIVERSITY of LIVERPOOL

University of Liverpool, UK

University of Manchester,

rdue University,
st Lafayette, USA

Federal University of Rio de Janeiro, Brazil

Stockholm University, Sweden

Simon Fraser University, Canada `

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

Motivations in Brief

•Tests of fundamental symmetries by applying ***precise and accurate*** atomic physics techniques to anti-atoms:

- •CPT violation?
- •Lorentz invariance violation?

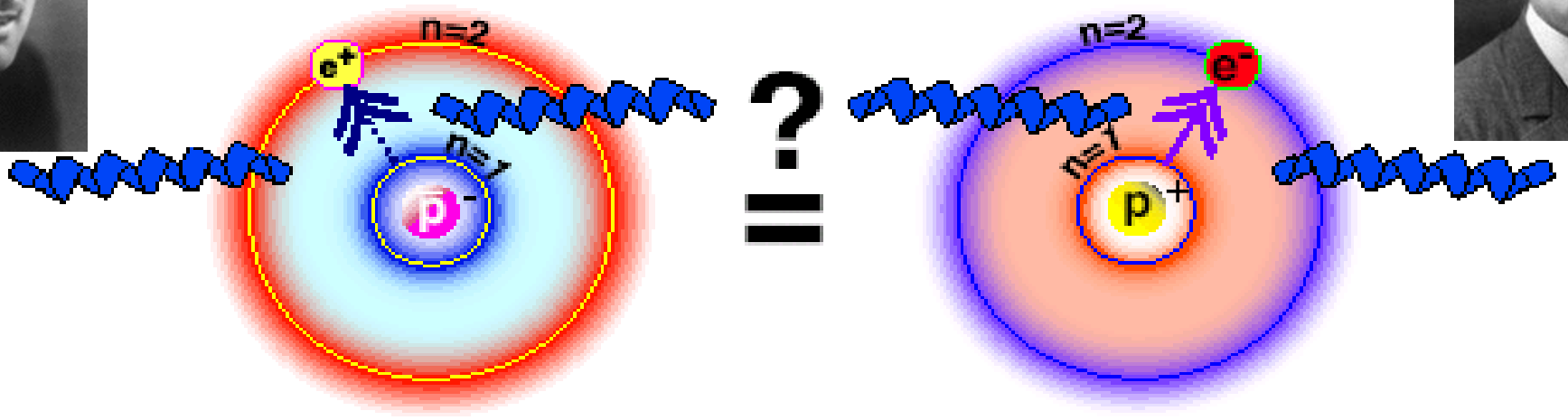
Physics beyond the Standard Model?

The initial physics goal of ALPHA was to TRAP antihydrogen atoms, so that they can be studied in detail.

•(Anti)-Gravity – two previously approved experiments at CERN; AEGIS and Gbar – proof of principle by ALPHA; now ALPHA-g is ready to go

•… of course this is all ***motivated*** by the apparent baryon asymmetry in the universe

The Question



Antihydrogen Hydrogen

How could you possibly work in Denmark and *not* want to know the answer to this?

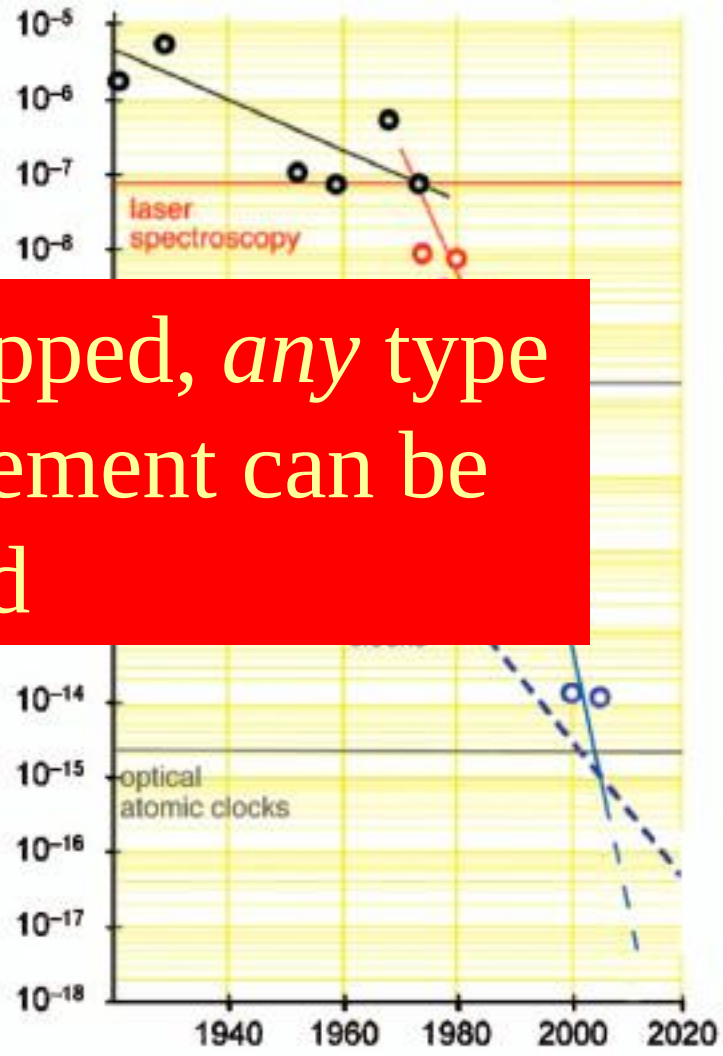
The *Holy Grail* - Antihydrogen Spectroscopy

1s-2s two-photon spectroscopy

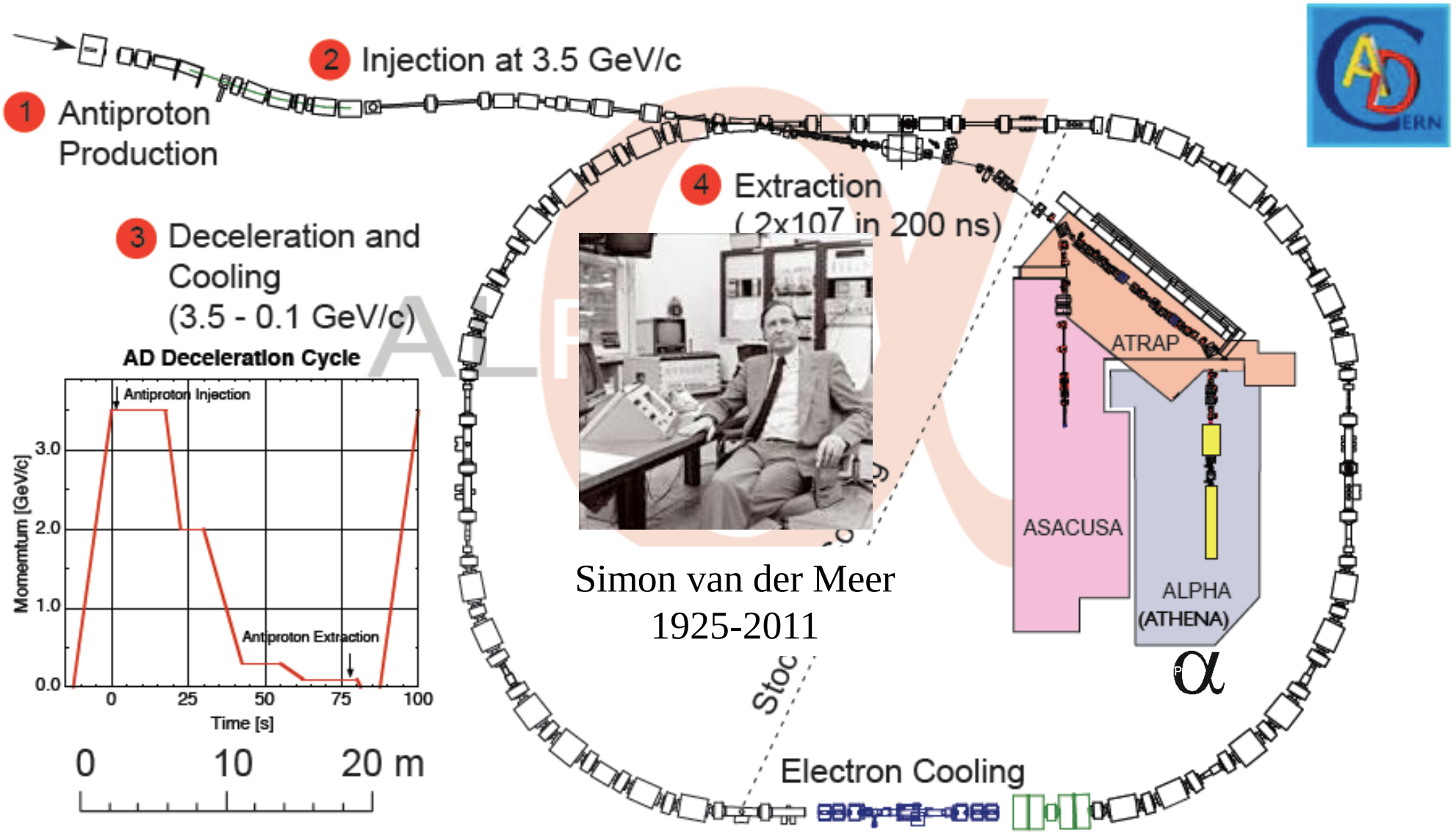
If antihydrogen can be trapped, *any* type of spectroscopic measurement can be contemplated

Antihydrogen Hydrogen

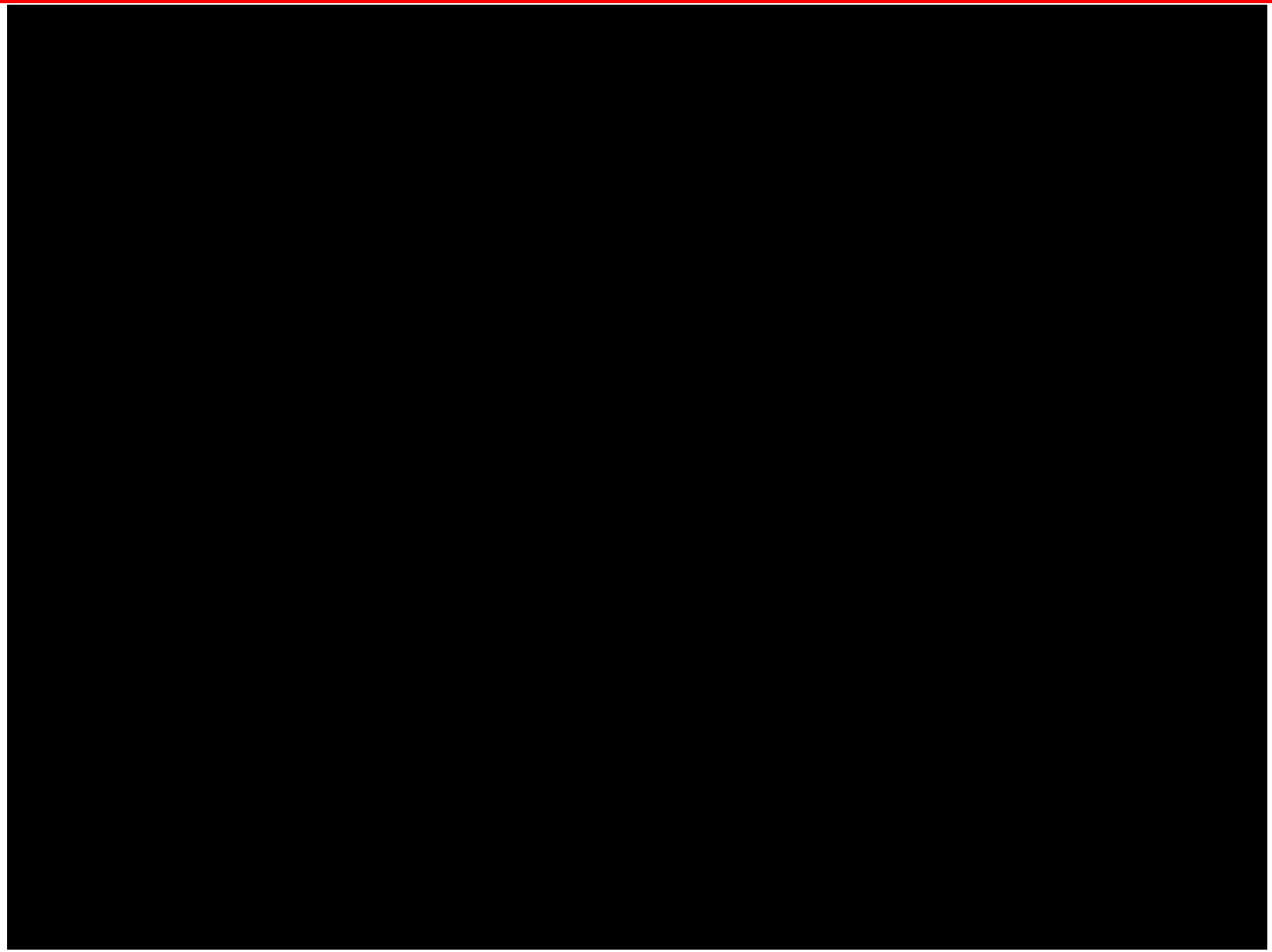
- **Doppler effect cancels**
- **High precision in matter sector**
- **test of CPT theorem**



The CERN AD

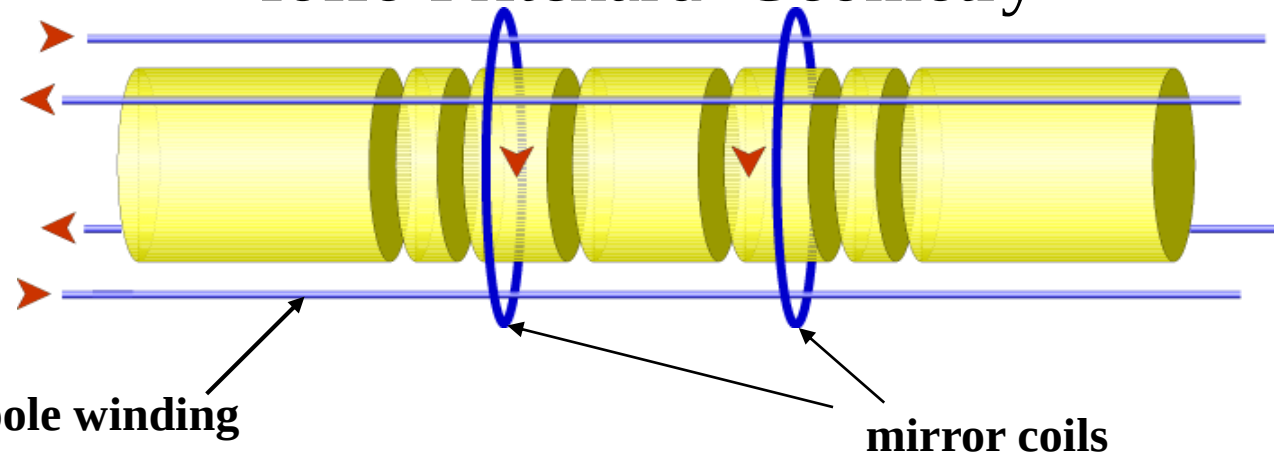

1 Antiproton Production
2 Injection at 3.5 GeV/c
3 Deceleration and Cooling (3.5 - 0.1 GeV/c)
4 Extraction (2x10^7 in 200 ns)
AD Deceleration Cycle
Antiproton Injection
Antiproton Extraction
Momentum [GeV/c]
Time [s]
0
25
50
75
100
0.0
1.0
2.0
3.0
0
10
20 m
Simon van der Meer
1925-2011
ATRAP
ASACUSA
ALPHA
(ATHENA)
Electron Cooling

Trapping Antihydrogen



Trapping Neutral Anti-atoms?

‘Ioffe-Pritchard’ Geometry



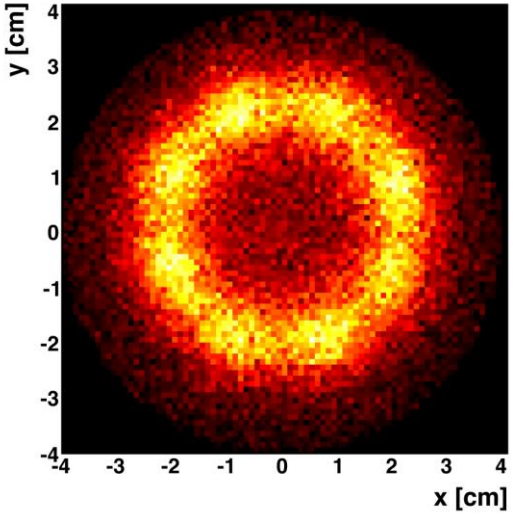
$$U = -\bar{\mu} \cdot \overline{\mathbf{B}}$$

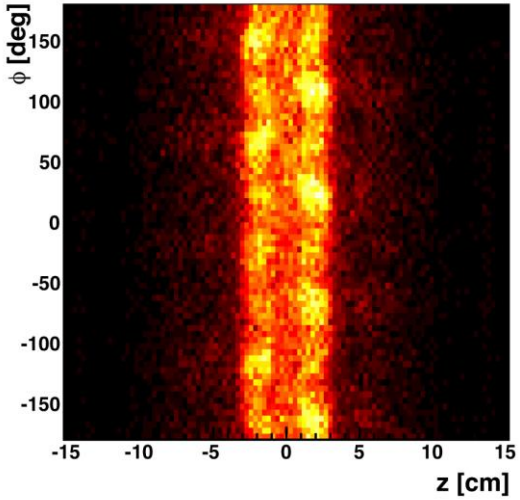
Well depth ~ 0.7 K/T

Need to produce the atoms so they are *born trapped*

Broken rotational symmetry: Can we superpose this on a Penning trap?

ALPHA Silicon Vertex Detector



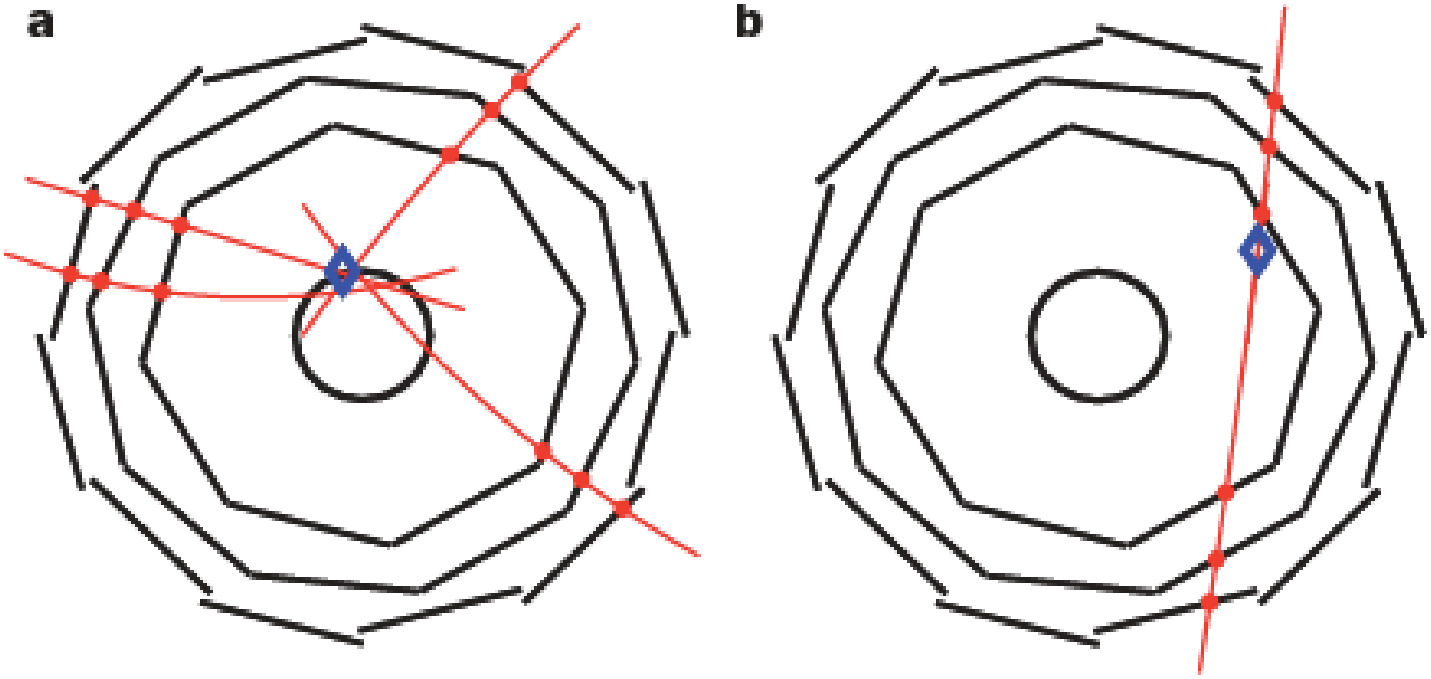


3-layer, double-sided modules
Detect antiproton anihilation (not e^+)
Fabricated by U. Liverpool

Event Topology

Typical antiproton annihilation: charged pions

Typical cosmic ray



… not much going on here

LETTER

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]

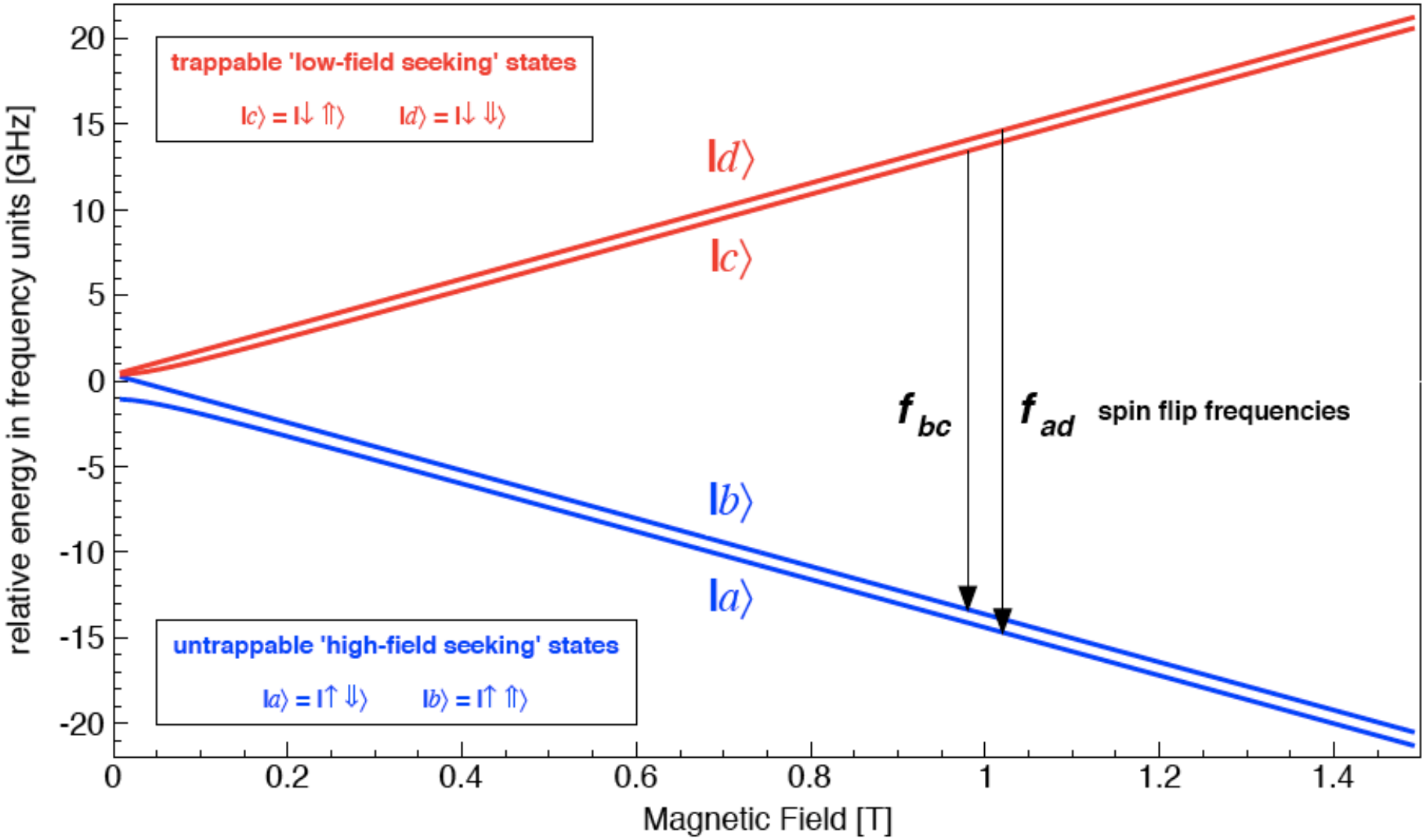
Published online in *Nature*, 17 November 2010

Physics Breakthrough of the Year - 2010 *Physics World* (UK)

One of the top ten physics stories of 2010 - American Institute of Physics

Most clicked-on story on *Nature* website for all of 2010

Breit-Rabi Diagram (assumed)



ALPHA

LETTER

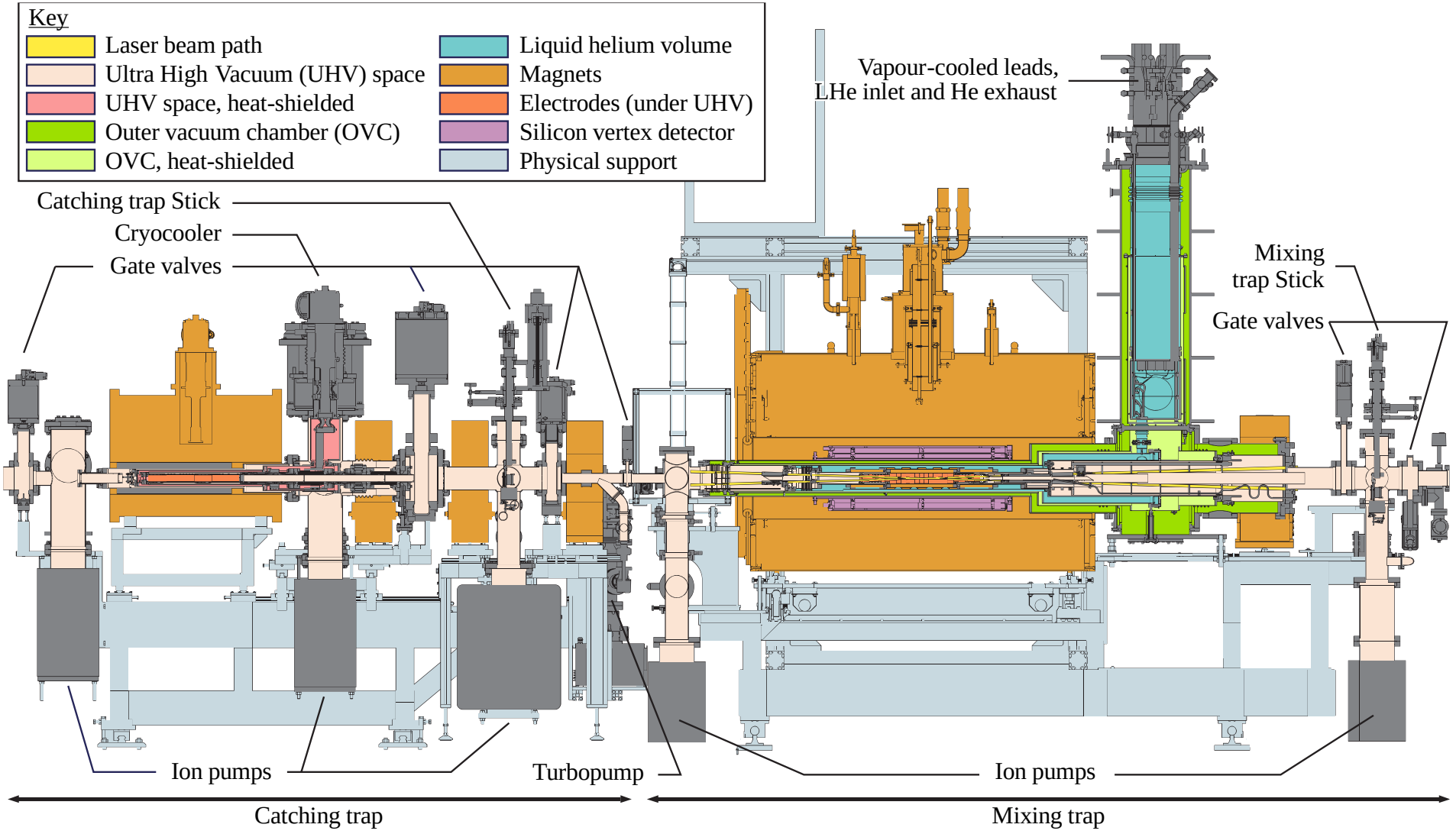
doi:10.1038/nature10942

Resonant quantum transitions in trapped antihydrogen atoms

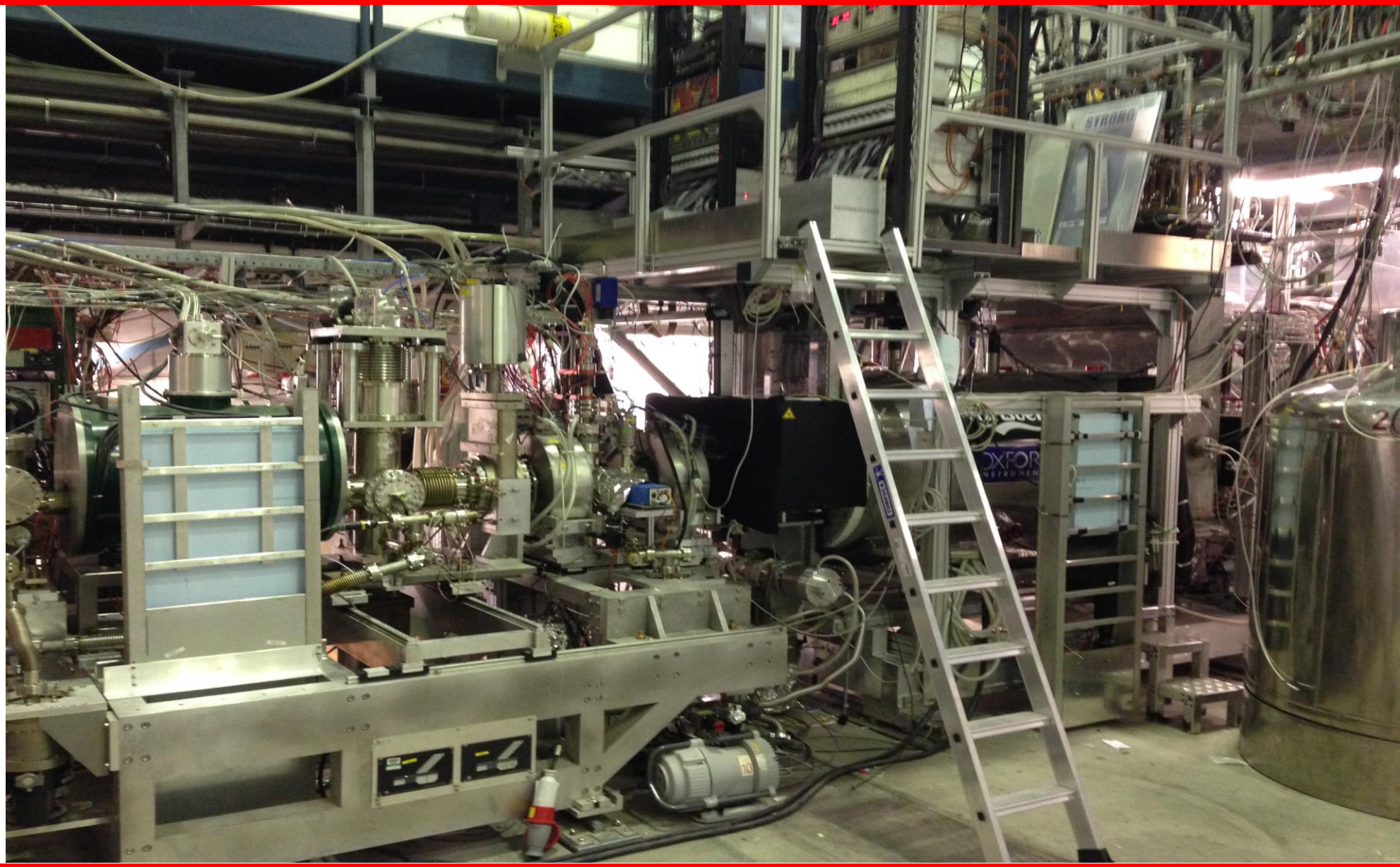
C. Amole[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4,5,6], P. D. Bowe[7], E. Butler[8], A. Capra[1], C. L. Cesar[9], M. Charlton[4], A. Deller[4], P. H. Donnan[10], S. Eriksson[4], J. Fajans[3,11], T. Friesen[12], M. C. Fujiwara[12,13], D. R. Gill[13], A. Gutierrez[14], J. S. Hangst[7], W. N. Hardy[14,15], M. E. Hayden[2], A. J. Humphries[4], C. A. Isaac[4], S. Jonsell[16], L. Kurchaninov[13], A. Little[3], N. Madsen[4], J. T. K. McKenna[17], S. Menary[1], S. C. Napoli[4], P. Nolan[17], K. Olchanski[13], A. Olin[13,18], P. Pusa[17], C. Ø. Rasmussen[7], F. Robicheaux[10], E. Sarid[19], C. R. Shields[4], D. M. Silveira[20]†, S. Stracka[13], C. So[3], R. I. Thompson[12], D. P. van der Werf[4] & J. S. Wurtele[3,11]

- Published in *nature* online 7 March, 2012
- First measurement on an antimatter atom – precision: few parts in 10^3
- Shows that it is possible to do physics with few atoms
- …but we have a lot more now

ALPHA-2 (2012)


Key
Laser beam path
Ultra High Vacuum (UHV) space
UHV space, heat-shielded
Outer vacuum chamber (OVC)
OVC, heat-shielded
Liquid helium volume
Magnets
Electrodes (under UHV)
Silicon vertex detector
Physical support
Vapour-cooled leads,
LHe inlet and He exhaust
Catching trap Stick
Cryocooler
Gate valves
Mixing
trap Stick
Gate valves
Ion pumps
Turbopump
Ion pumps
Catching trap
Mixing trap

ALPHA-2: 2012



First ALPHA-2 result published in *nature 2016*

LETTER

OPEN

doi:10.1038/nature16491

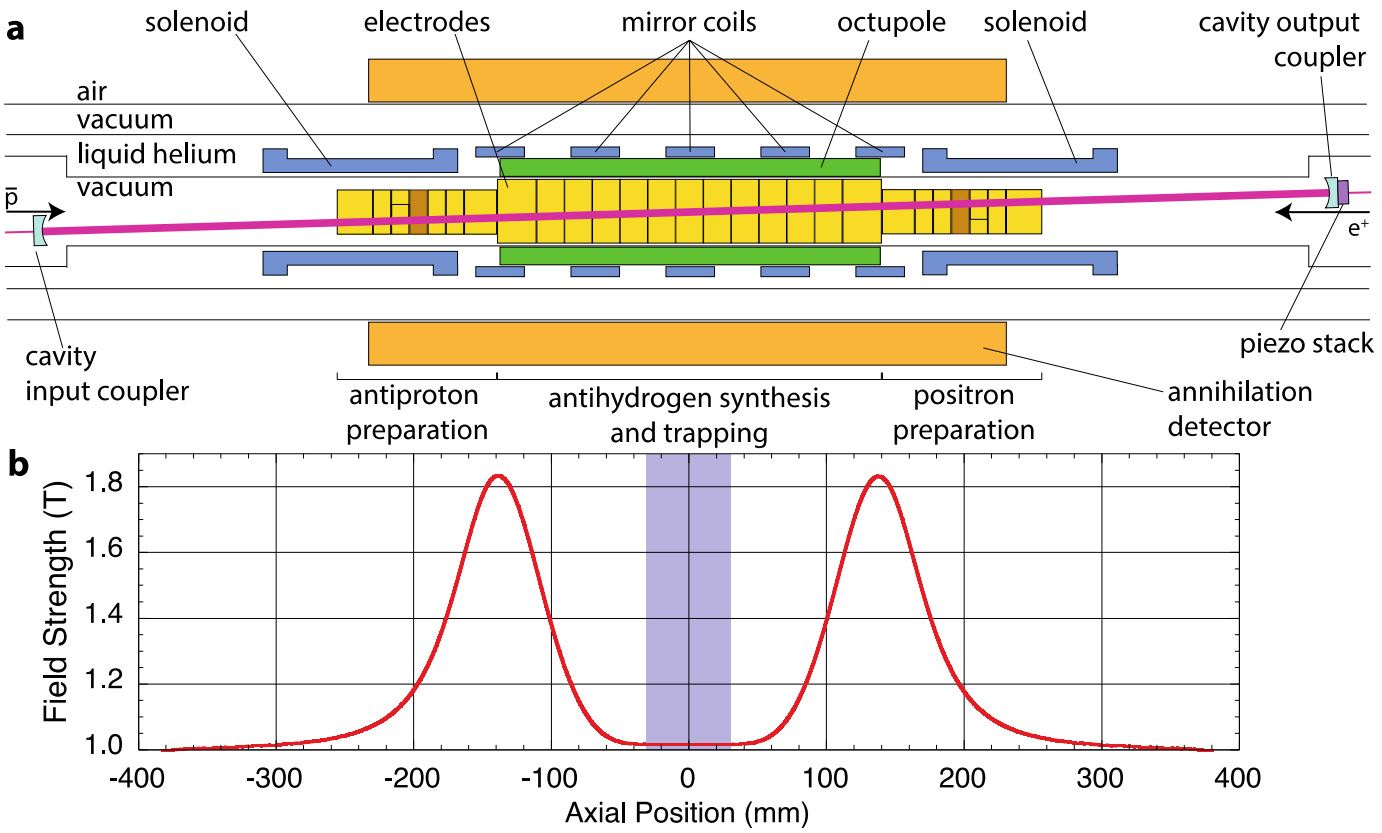
An improved limit on the charge of antihydrogen from stochastic acceleration

M. Ahmadi[1], M. Baquero-Ruiz[2,3], W. Bertsche[4,5], E. Butler[6,7], A. Capra[8], C. Carruth[2], C. L. Cesar[9], M. Charlton[10], A. E. Charman[2], S. Eriksson, L. T. Evans[2], N. Evetts[11], J. Fajans[2], T. Friesen[12], M. C. Fujiwara[13], D. R. Gill[13], A. Gutierrez[11], J. S. Hangst[12], W. N. Hardy[11], M. E. Hayden[14], C. A. Isaac[10], A. Ishida[7], S. A. Jones[10], S. Jonsell[15], L. Kurchaninov[13], N. Madsen[10], D. Maxwell[10], J. T. K. McKenna[13], S. Menary[8], J. M. Michan[13], T. Momose[16], J. J. Munich[14], P. Nolan[1], K. Olchanski[13], A. Olin[13,17], A. Povilus[2], P. Pusa[1], C. Ø. Rasmussen[12], F. Robicheaux[18], R. L. Sacramento[9], M. Sameed[10], E. Sarid[19], D. M. Silveira[9], C. So[2], T. D. Tharp[12], R. I. Thompson[20], D. P. van der Werf[10], J. S. Wurtele[2,21] & A. I. Zhmoginov[2]

charge is consistent with zero to 0.71 ppb

atoms of normal matter are neutral to 1 in 10^{21}

Configuration for Laser Physics – 1S-2S transition



ALPHA

LETTER

OPEN

doi:10.1038/nature21040

Observation of the 1S–2S transition in trapped antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], E. Butler[6], A. Capra[7], C. Carruth[8], C. L. Cesar[9], M. Charlton[3], S. Cohen[10], R. Collister[7], S. Eriksson[3], A. Evans[11], N. Evetts[12], J. Fajans[8], T. Friesen[2], M. C. Fujiwara[7], D. R. Gill[7], A. Gutierrez[13], J. S. Hangst[2], W. N. Hardy[12], M. E. Hayden[14], C. A. Isaac[3], A. Ishida[15], M. A. Johnson[4,5], S. A. Jones[3], S. Jonsell[16], L. Kurchaninov[7], N. Madsen[3], M. Mathers[17], D. Maxwell[3], J. T. K. McKenna[7], S. Menary[17], J. M. Michan[7,18], T. Momose[12], J. J. Munich[14], P. Nolan[1], K. Olchanski[7], A. Olin[7,19], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[20], R. L. Sacramento[9], M. Sameed[3], E. Sarid[21], D. M. Silveira[9], S. Stracka[22], G. Stutter[2], C. So[11], T. D. Tharp[23], J. E. Thompson[17], R. I. Thompson[11], D. P. van der Werf[3,24] & J. S. Wurtele[8]

Published online 19 December 2016; print version 26 January 2017

CPT tested to 2×10^{-10}

~15 atoms trapped at a time

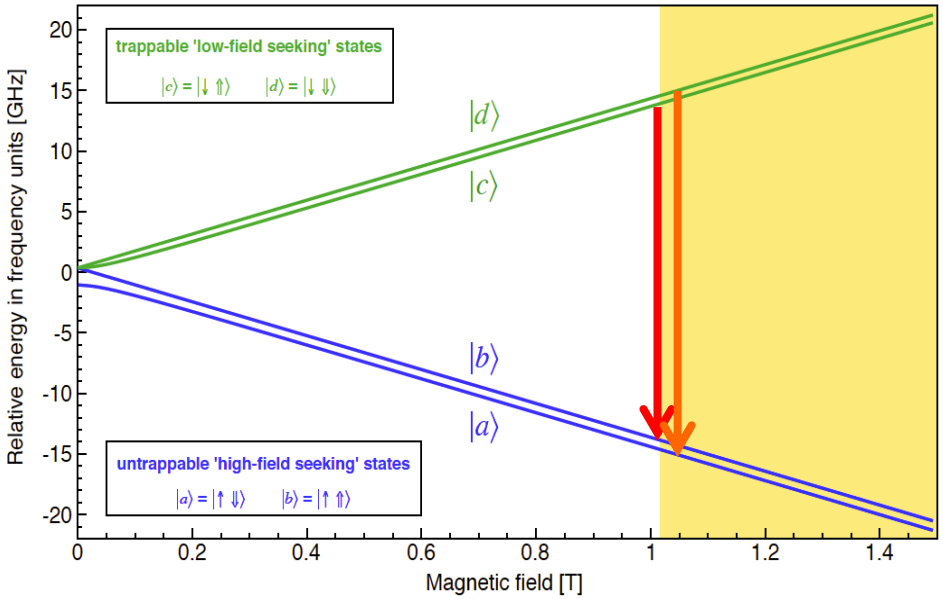
2010 – first trapping

"The very fact of a proof-of-principle demonstration of wall-free confinement of even a small number of antimatter atoms has an intrinsic philosophical value."

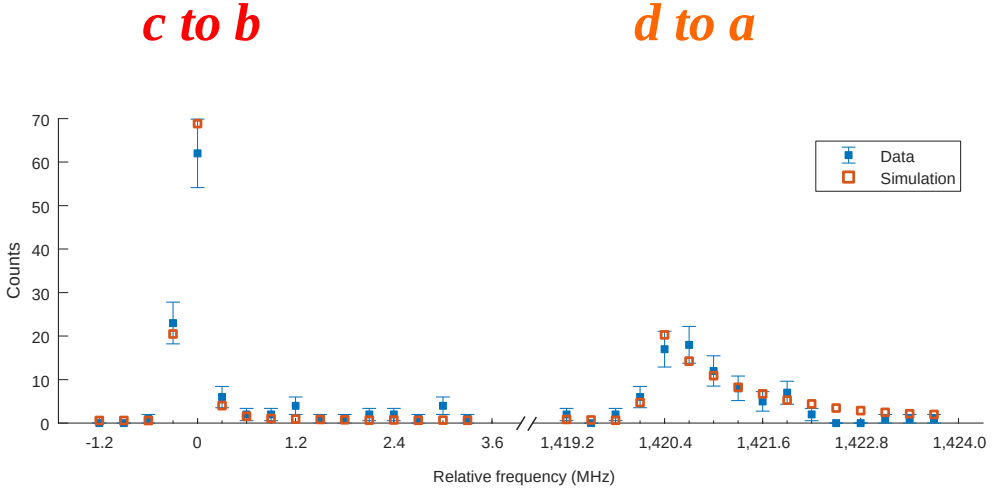
2016 - spectroscopy

There is no doubt that this result is of high originality and of highest relevance to a broad scientific community, and thus, merits publication in any journal the authors have selected. I congratulate the editors that the ALPHA collaboration has selected Nature to publish this ground-breaking work.

Hyperfine Studies – 2016



1S ground state



$\delta f_{hf} = (1420.4 \pm 0.5)$ MHz

LETTER

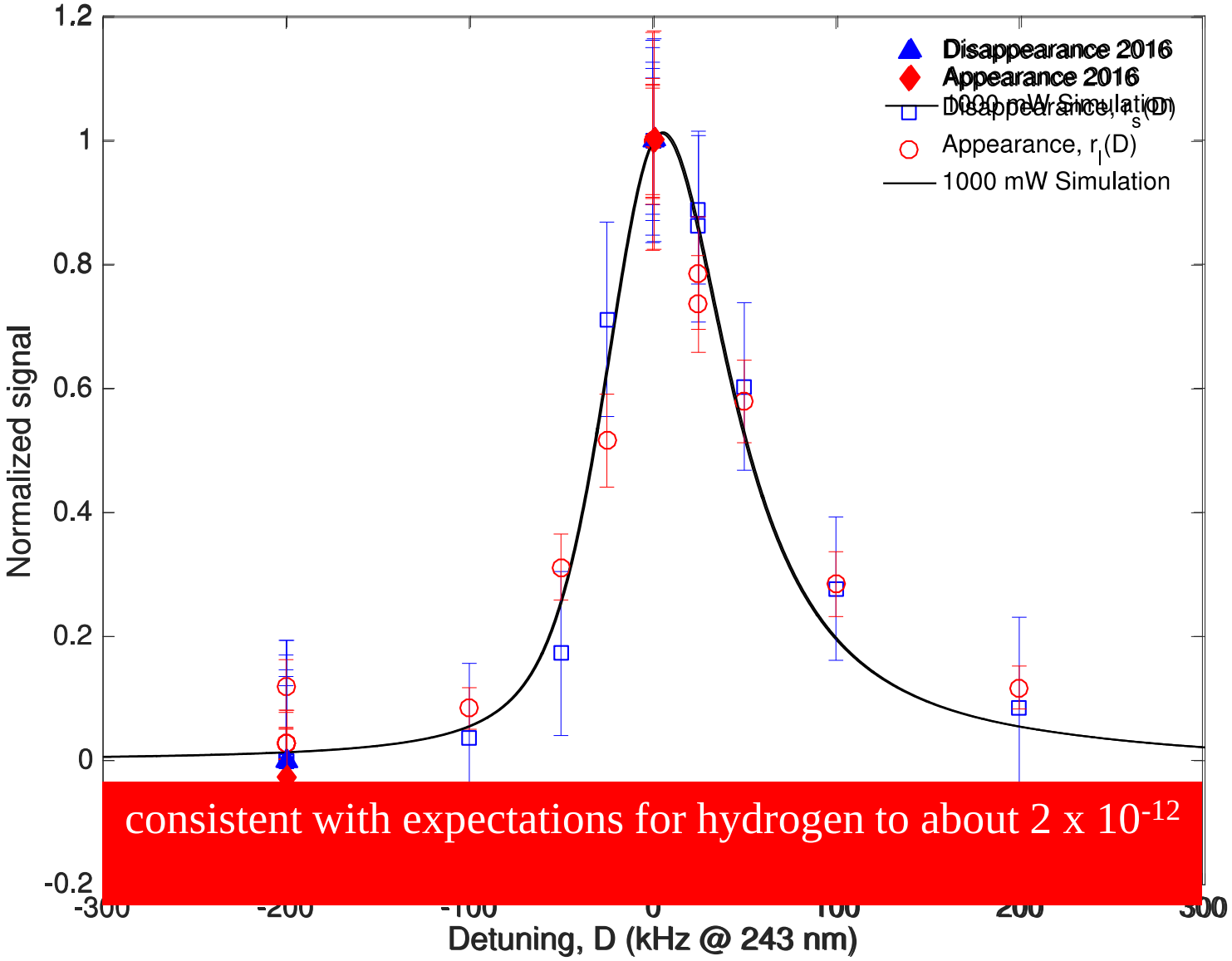
OPEN

doi:10.1038/nature23446

Observation of the hyperfine spectrum of antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], E. Butler[6], A. Capra[7], C. Carruth[8], C. L. Cesar[9], M. Charlton[3], S. Cohen[10], R. Collister[7], S. Eriksson[3], A. Evans[11], N. Evetts[12], J. Fajans[8], T. Friesen[2], M. C. Fujiwara[7], D. R. Gill[7], A. Gutierrez[12,13], J. S. Hangst[2], W. N. Hardy[12], M. E. Hayden[14], C. A. Isaac[3], A. Ishida[15], M. A. Johnson[4,5], S. A. Jones[3], S. Jonsell[16], L. Kurchaninov[7], N. Madsen[3], M. Mathers[17], D. Maxwell[3], J. T. K. McKenna[7], S. Menary[17], J. M. Michan[7,18], T. Momose[12], J. J. Munich[14], P. Nolan[1], K. Olchanski[7], A. Olin[7,19], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[20], R. L. Sacramento[9], M. Sameed[3], E. Sarid[21], D. M. Silveira[9], S. Stracka[7,22], G. Stutter[2], C. So[11], T. D. Tharp[23], J. E. Thompson[17], R. I. Thompson[11], D. P. van der Werf[3,24] & J. S. Wurtele[8]

2016 Result 1S-2S line



consistent with expectations for hydrogen to about 2×10^{-12}

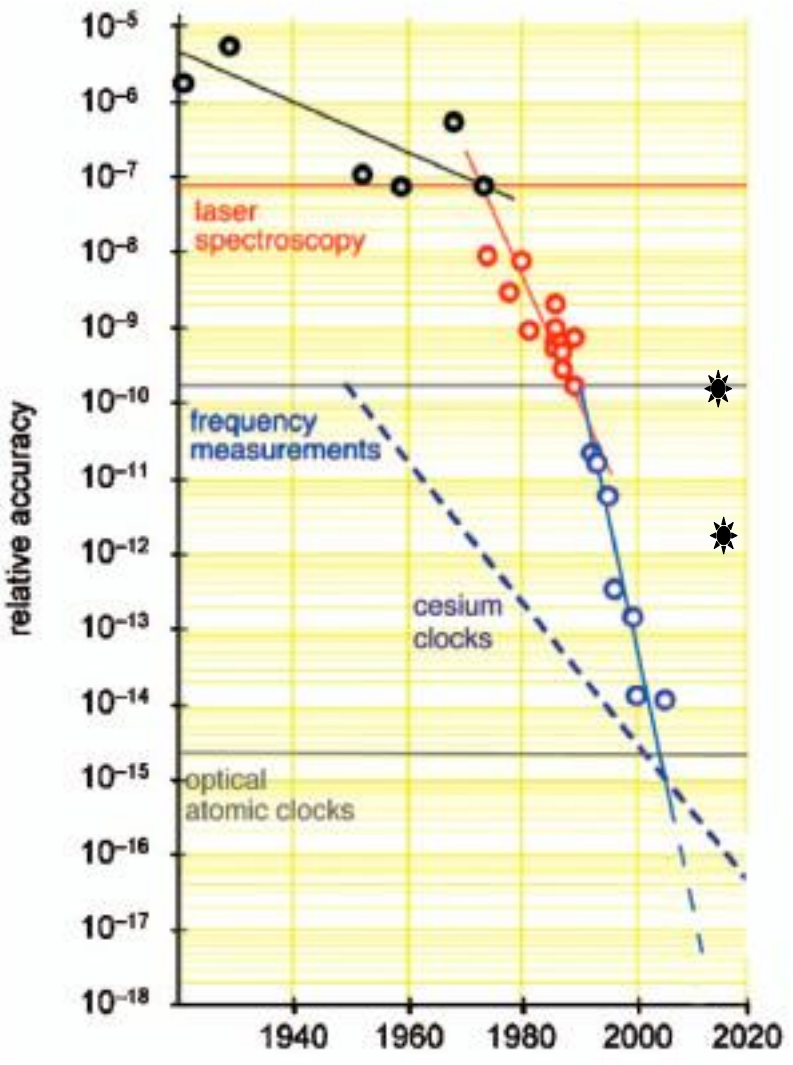
LETTER

OPEN
https://doi.org/10.1038/s41586-018-0017-2

Characterization of the 1S–2S transition in antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], A. Capra[6], C. Carruth[7], C. L. Cesar[8], M. Charlton[3], S. Cohen[9], R. Collister[6], S. Eriksson[3], A. Evans[10], N. Evetts[11], J. Fajans[7], T. Friesen[2], M. C. Fujiwara[6], D. R. Gill[6], J. S. Hangst[2]*, W. N. Hardy[11], M. E. Hayden[12], C. A. Isaac[3], M. A. Johnson[4,5], J. M. Jones[3], S. A. Jones[2,3], S. Jonsell[13], A. Khramov[6], P. Knapp[3], L. Kurchaninov[6], N. Madsen[3], D. Maxwell[3], J. T. K. McKenna[6], S. Menary[14], T. Momose[11], J. J. Munich[12], K. Olchanski[6], A. Olin[6,15], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[16], R. L. Sacramento[8], M. Sameed[3,4], E. Sarid[17], D. M. Silveira[8], G. Stutter[2], C. So[10], T. D. Tharp[18], R. I. Thompson[10], D. P. van der Werf[3,19] & J. S. Wurtele[7]

State of the Art



Theodor Hänsch

LETTER

OPEN

https://doi.org/10.1038/s41586-018-0435-1

Observation of the 1S–2P Lyman-α transition in antihydrogen

M. Ahmadi[1], B. X. R. Alves[2], C. J. Baker[3], W. Bertsche[4,5], A. Capra[6], C. Carruth[7], C. L. Cesar[8], M. Charlton[3], S. Cohen[9], R. Collister[6], S. Eriksson[3], A. Evans[10], N. Evetts[11], J. Fajans[7], T. Friesen[2,10], M. C. Fujiwara[6]*, D. R. Gill[6], J. S. Hangst[2]*, W. N. Hardy[11], M. E. Hayden[12], E. D. Hunter[7], C. A. Isaac[3], M. A. Johnson[4,5], J. M. Jones[3], S. A. Jones[2,3], S. Jonsell[13], A. Khramov[6], P. Knapp[3], L. Kurchaninov[6], N. Madsen[3], D. Maxwell[3], J. T. K. McKenna[6], S. Menary[14], J. M. Michan[6,15], T. Momose[11,16]*, J. J. Munich[12], K. Olchanski[6], A. Olin[6,17], P. Pusa[1], C. Ø. Rasmussen[2], F. Robicheaux[18], R. L. Sacramento[8], M. Sameed[4], E. Sarid[19], D. M. Silveira[8], D. M. Starko[14], G. Stutter[2], C. So[10], T. D. Tharp[20], R. I. Thompson[6,10], D. P. van der Werf[3,21] & J. S. Wurtele[7]

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Article | Open Access | Published: 19 February 2020

Investigation of the fine structure of antihydrogen

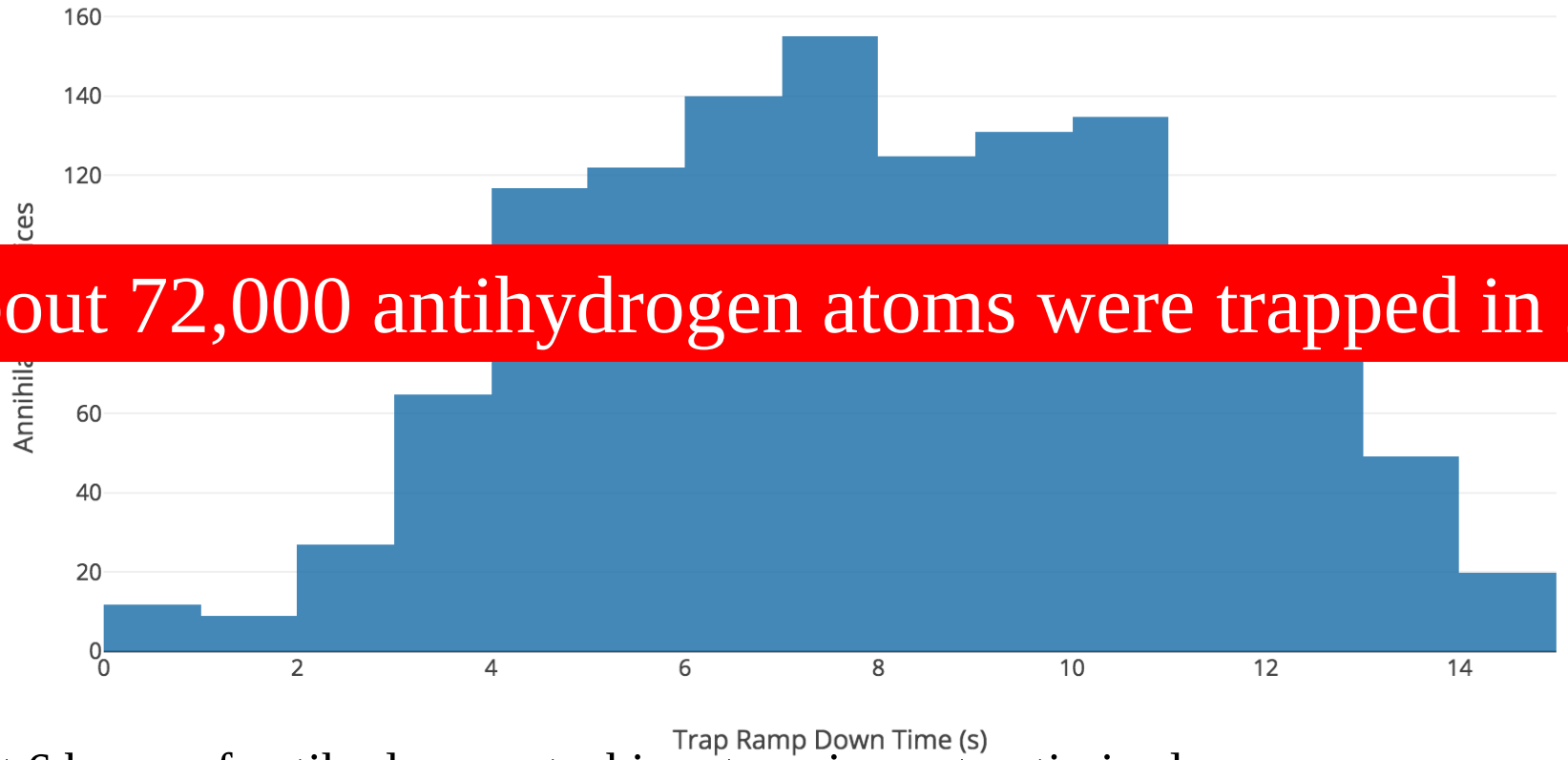
The ALPHA Collaboration

Nature **578**, 375–380(2020) | Cite this article

24k Accesses | **6** Citations | **364** Altmetric | Metrics

- **Determination of the Lamb shift ($^2S_{1/2}$ to $^2P_{1/2}$) in antimatter**

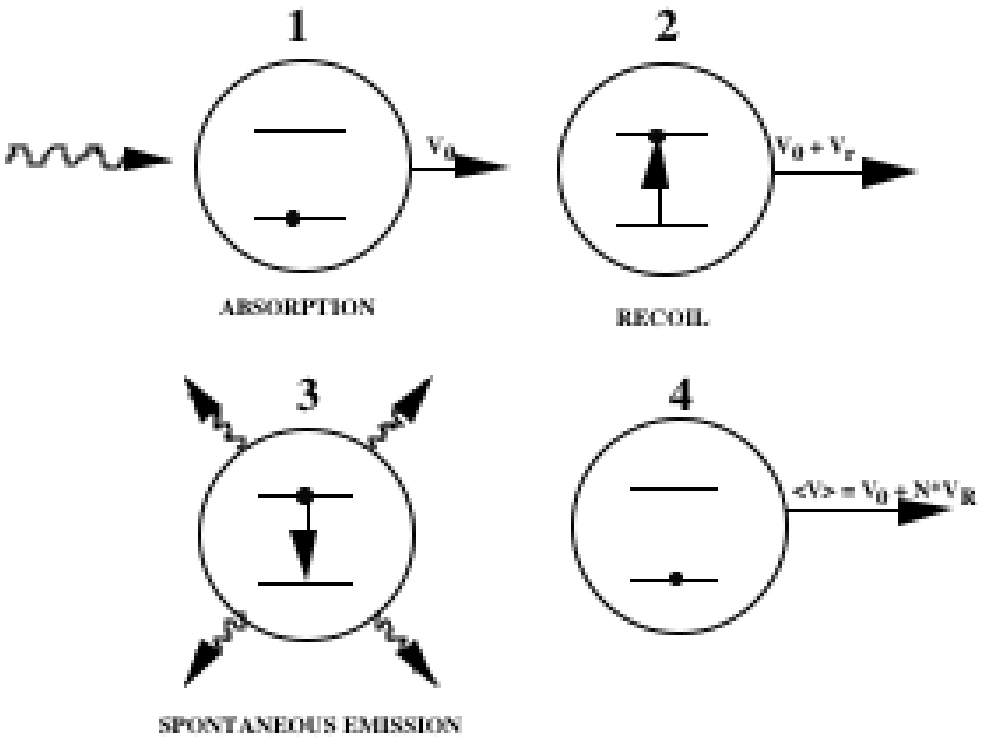
Accumulating Antihydrogen Atoms
18 December 2017

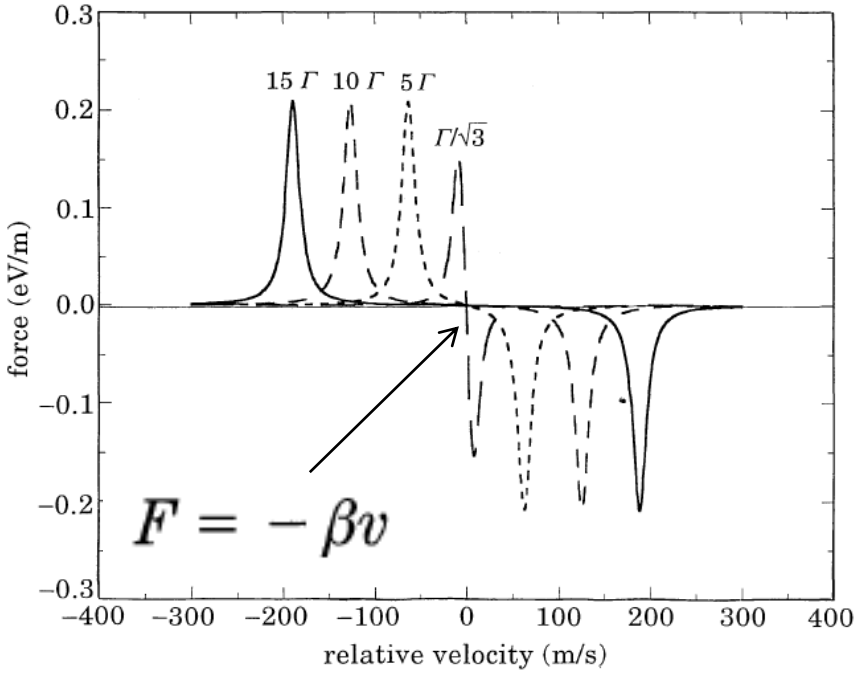


About 72,000 antihydrogen atoms were trapped in 2017

- about 6 hours of antihydrogen stacking; trapping not optimised
- 90/93 good shots from AD (we catch every second one)
- interesting future perspectives – better control of systematics for spectroscopy, gravitation, continuous laser cooling, release to zero field (hbar beam)
- this is larger than any per-YEAR sample we ever considered in the initial design of ALPHA-g

Laser cooling





counter-propagating lasers

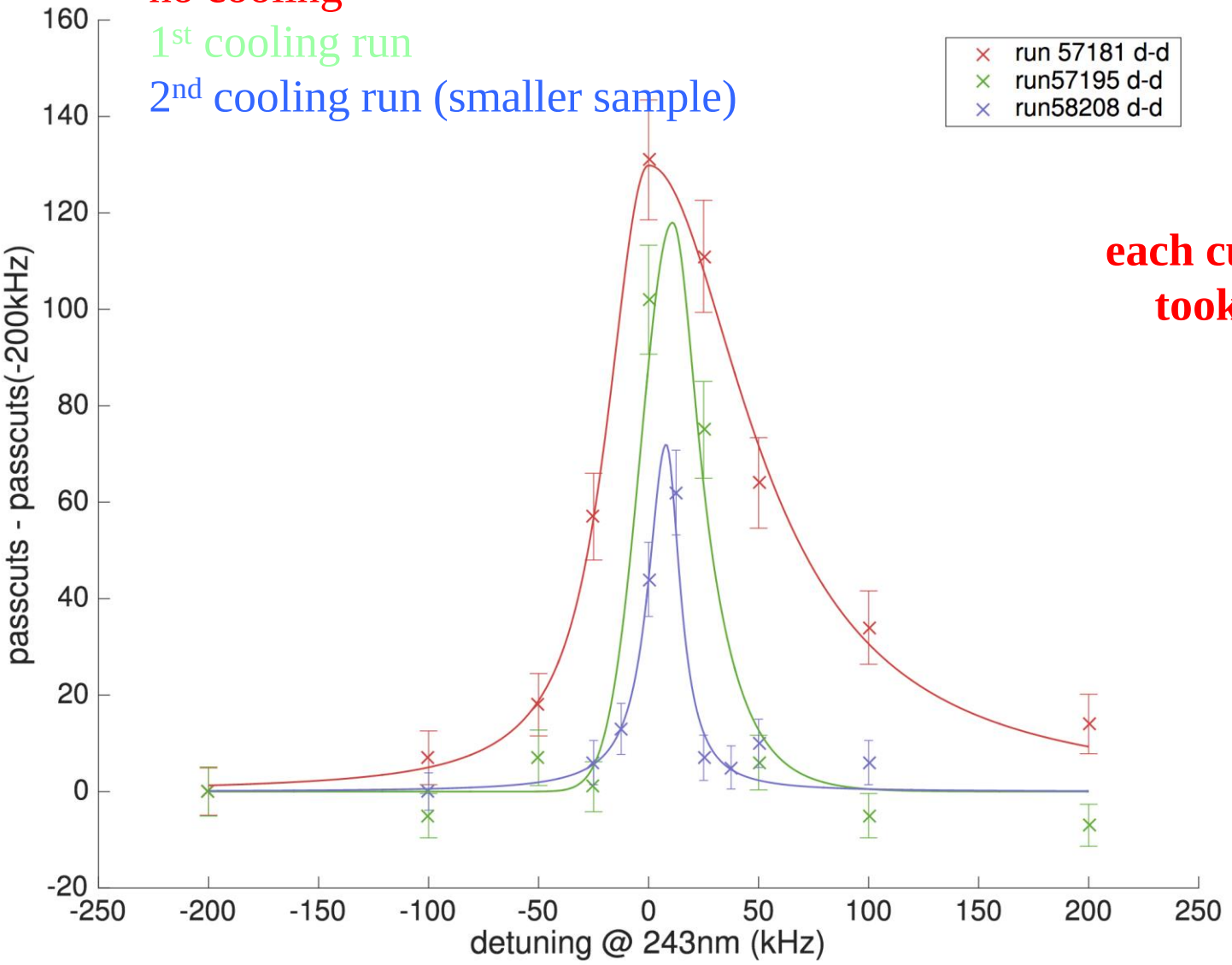
- Need a closed, two level system
- Typical photon energies of a few eV, recoil momentum of a few eV/c
- High scattering rates on resonance for CW lasers – transitions can be *ns*
- The Doppler shift introduces velocity dependence
- Level width determines ultimate temperature obtainable – Doppler cooling (~mK)

1S-2S Lineshape with Laser Cooling

no cooling

1st cooling run

2nd cooling run (smaller sample)



each curve obtained in 1 day took 10 weeks in 2017...

Finally on the cover – April 2021!

nature

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Article | Open Access | Published: 31 March 2021

Laser cooling of antihydrogen atoms

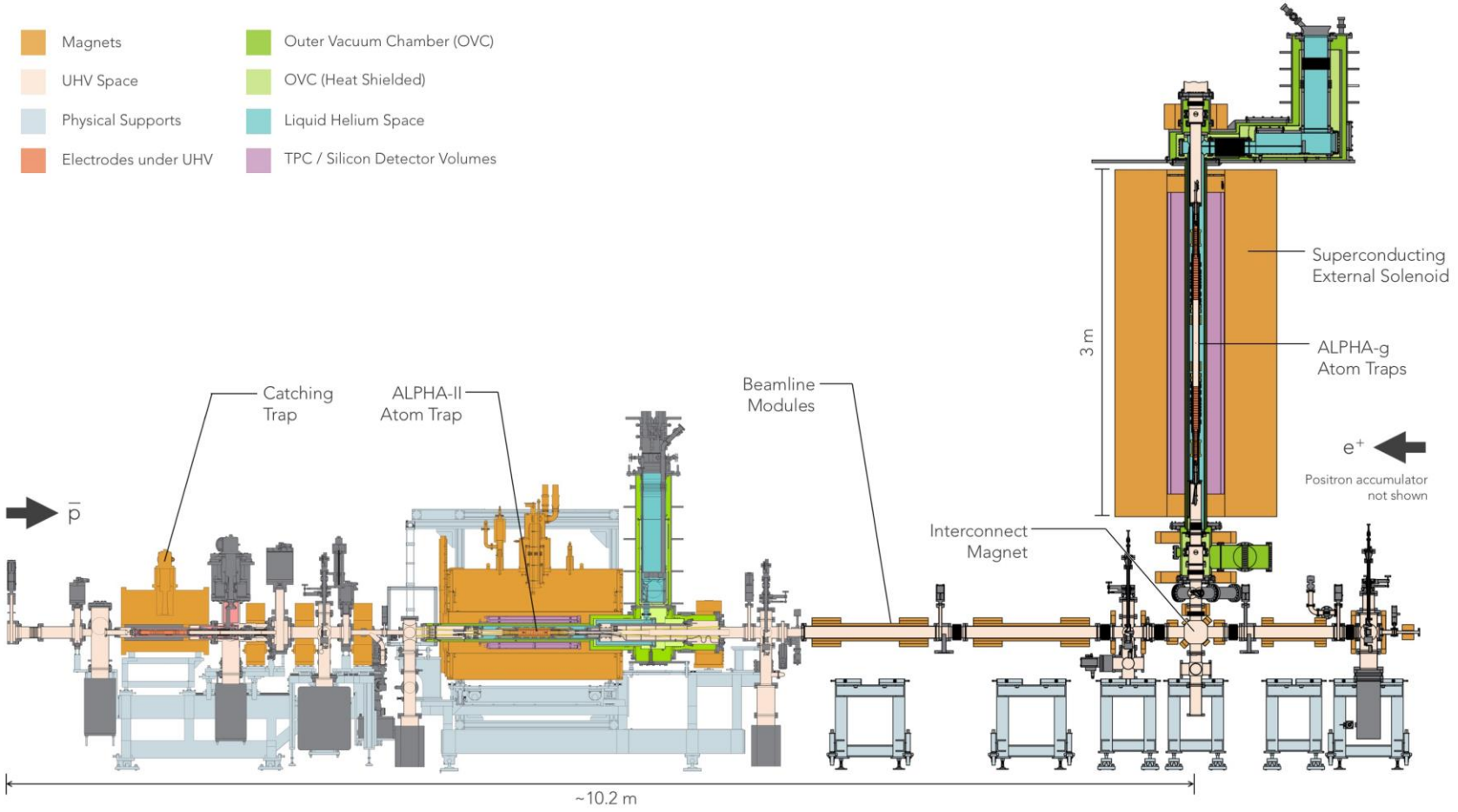
C. J. Baker, W. Bertsche, ... J. S. Wurtele + Show authors

Nature **592**, 35–42 (2021) | Cite this article

35k Accesses | **8** Citations | **655** Altmetric | Metrics

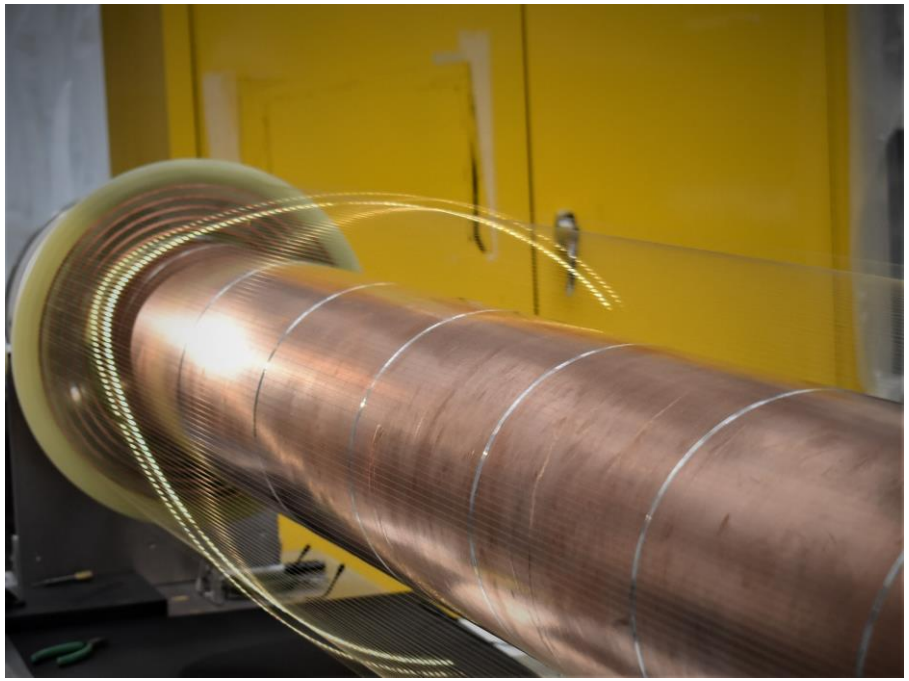
Again nominated for Physics Breakthrough of the Year (Physics World)– but didn't win…

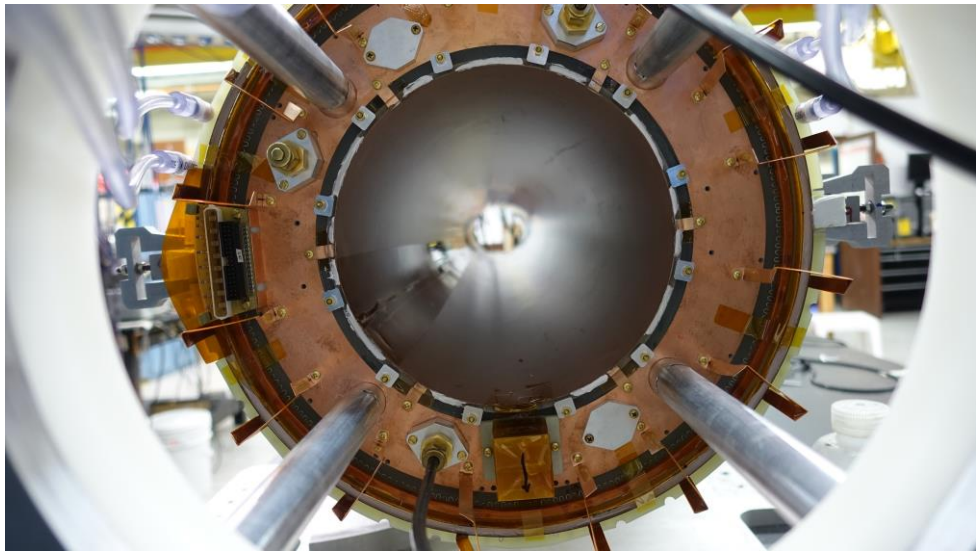
ALPHA-g



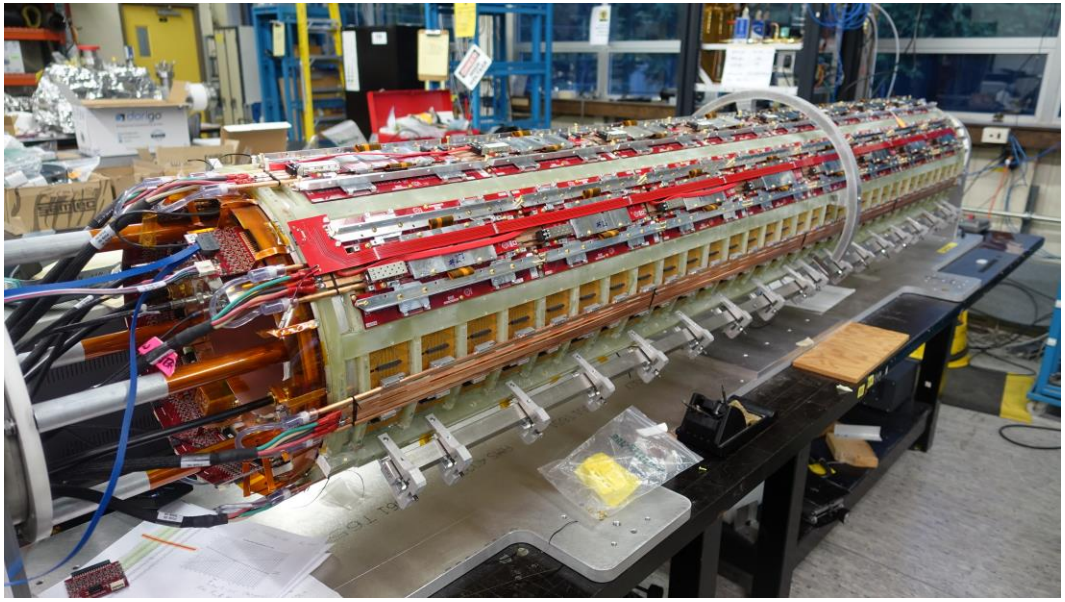
- trap some antihydrogen in a vertical trap
- release it
- see where it goes – radial time projection chamber annihilation detector

ALPHA-g Radial TPC (TRIUMF)





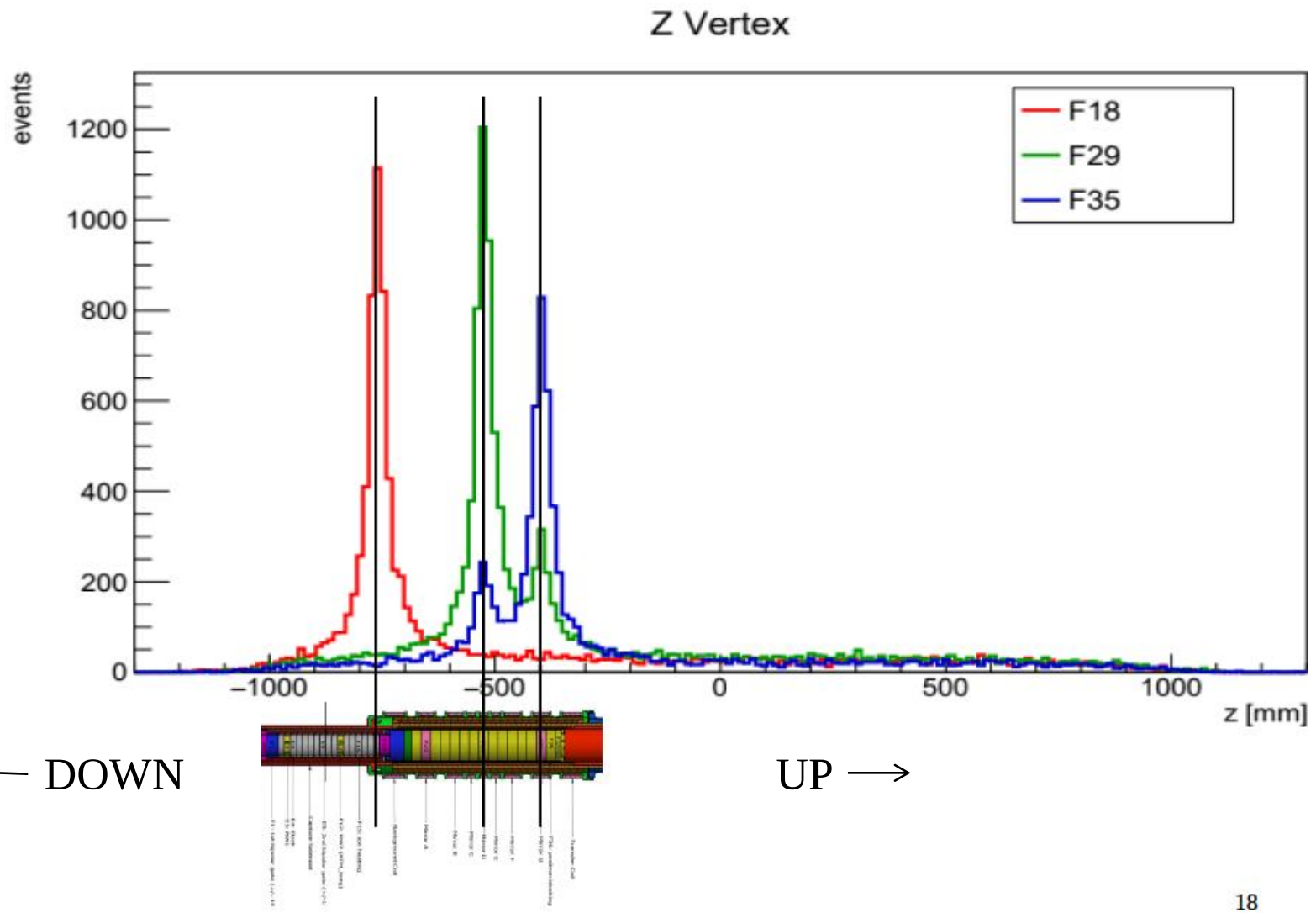
ready when needed



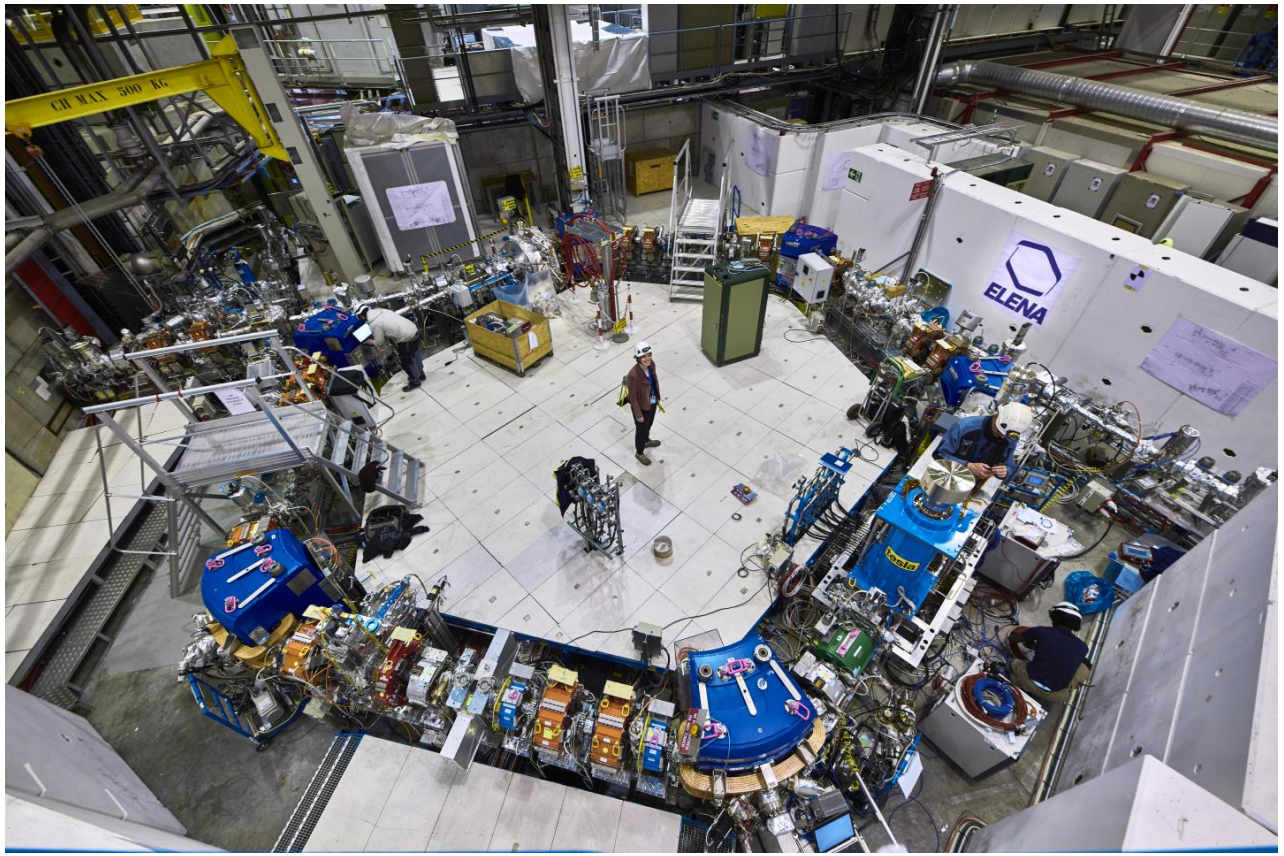

ALPHA


CARLSBERG FOUNDATION
ALPHA
Extincteur
CERN

Antiproton Annihilations observed in ALPHA-g



ELENA Ring



Approval of ELENA directly linked to ALPHA success with trapping of antihydrogen in 2010

Reduce pbar energy from 5 MeV to 100 keV

Up to10 times more pbars captured

Electrostatic switching allows delivery to multiple experiments; 24 hour operation

Sent first pbars to Gbar in 2018

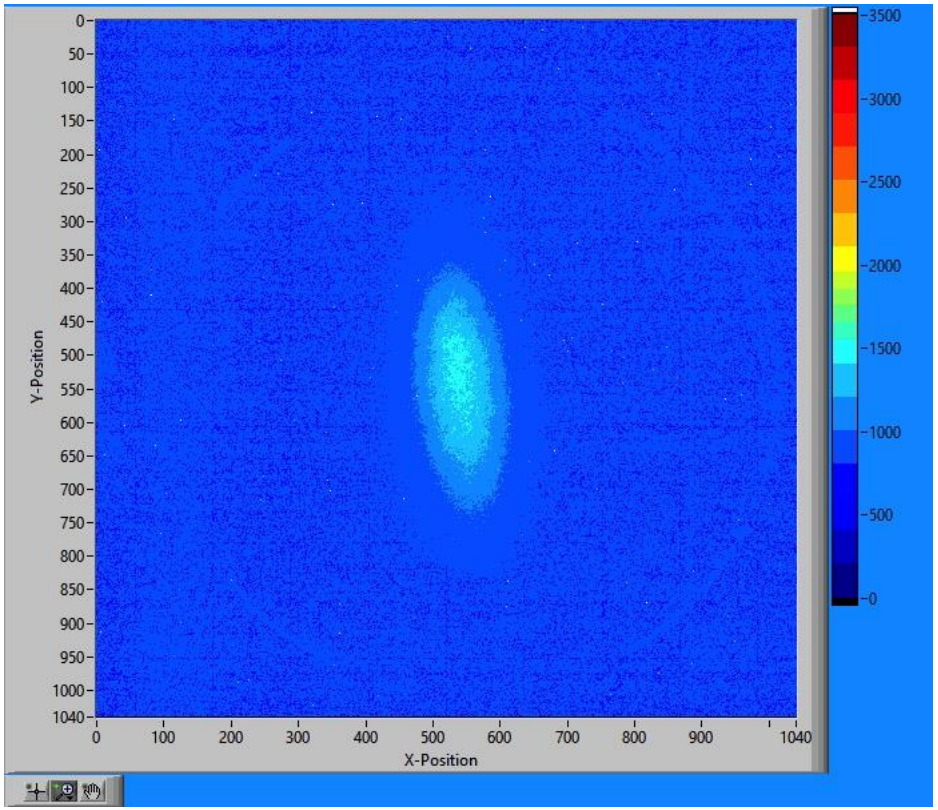
Operation for other experiments in August 2021

Worked on the very first shot to ALPHA in 2021!

Total paradigm shift: 24 hour pbars!

First shot of pbars to ALPHA from ELENA:2021

- Very first shot went down the centre of the beamline on the first day of the run!
- Awe and respect for the AD/ELENA team…



phosphor screen upstream of ALPHA catching trap

ALPHA from 2022 onward

- gravity with antimatter – up/down question and precision measurements
- antimatter spectroscopy to hydrogen-like precision:

antihydrogen can now be colder than the hydrogen used for the most precise measurements on normal matter…

ALPHA is installing a primary time/frequency standard (Cs fountain clock) at CERN in 2022

- other spectral lines – antiproton charge radius…
- measurements on hydrogen with ALPHA-developed techniques?
- long-term possibility: anti-deuterium?

ALPHA Funding

NICE (and other centres in DK) 2005-present

FNU: magnets for ELENA 2010 ~ 1 MCHF

Carlsberg Foundation: ALPHA-2 solenoid financing 2011 ! MEur

ERC Advanced Grant for ALPHA-2 spectroscopy 2013 – 2018 2.2MEur

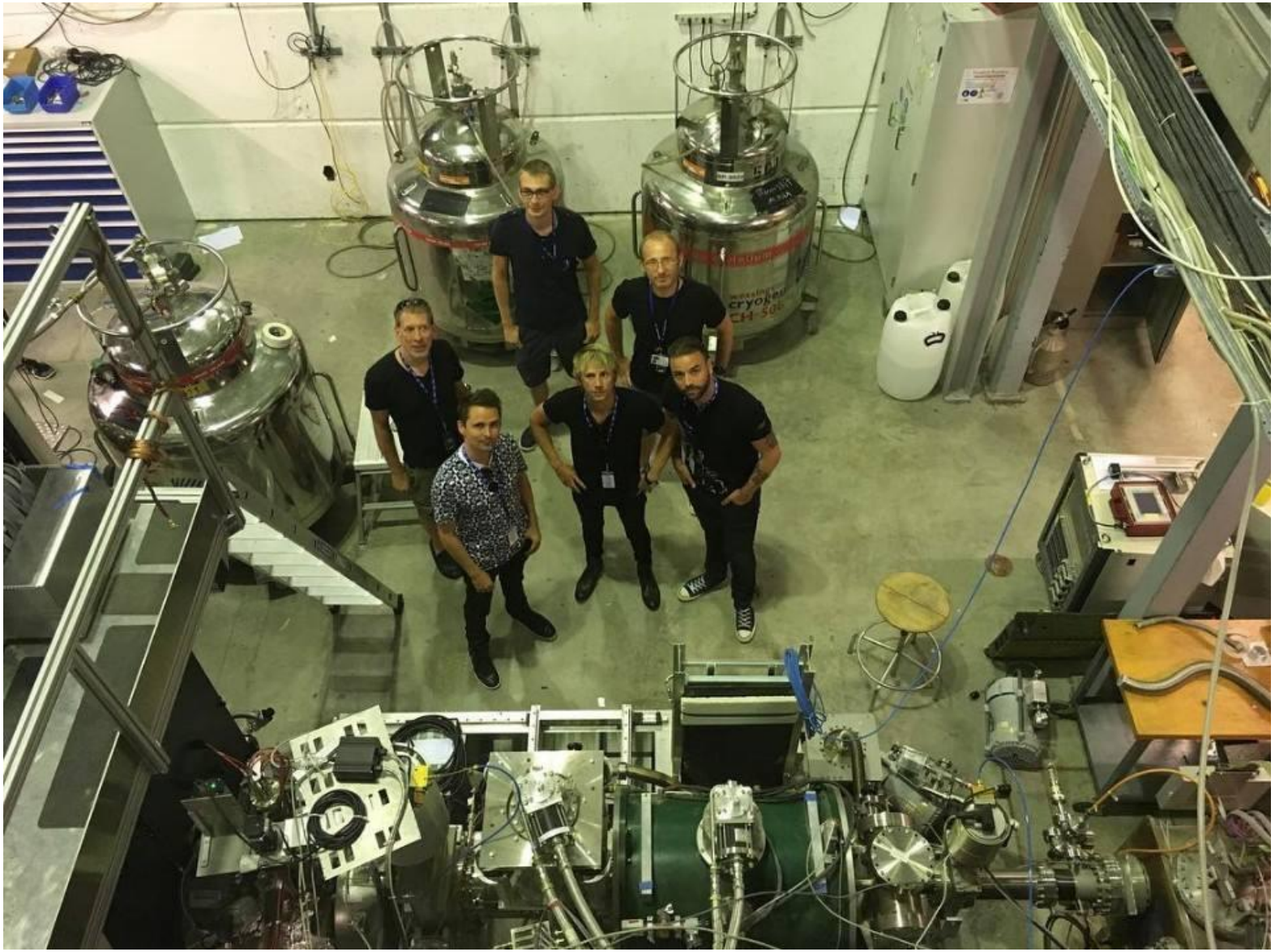
Carlsberg *Semper Ardens* Grant for ALPHA-G 2016 - 2021 2 MEur

Carlsberg *Semper Ardens* Grant for ALPHA-3 2018 – 2023 2 MEur

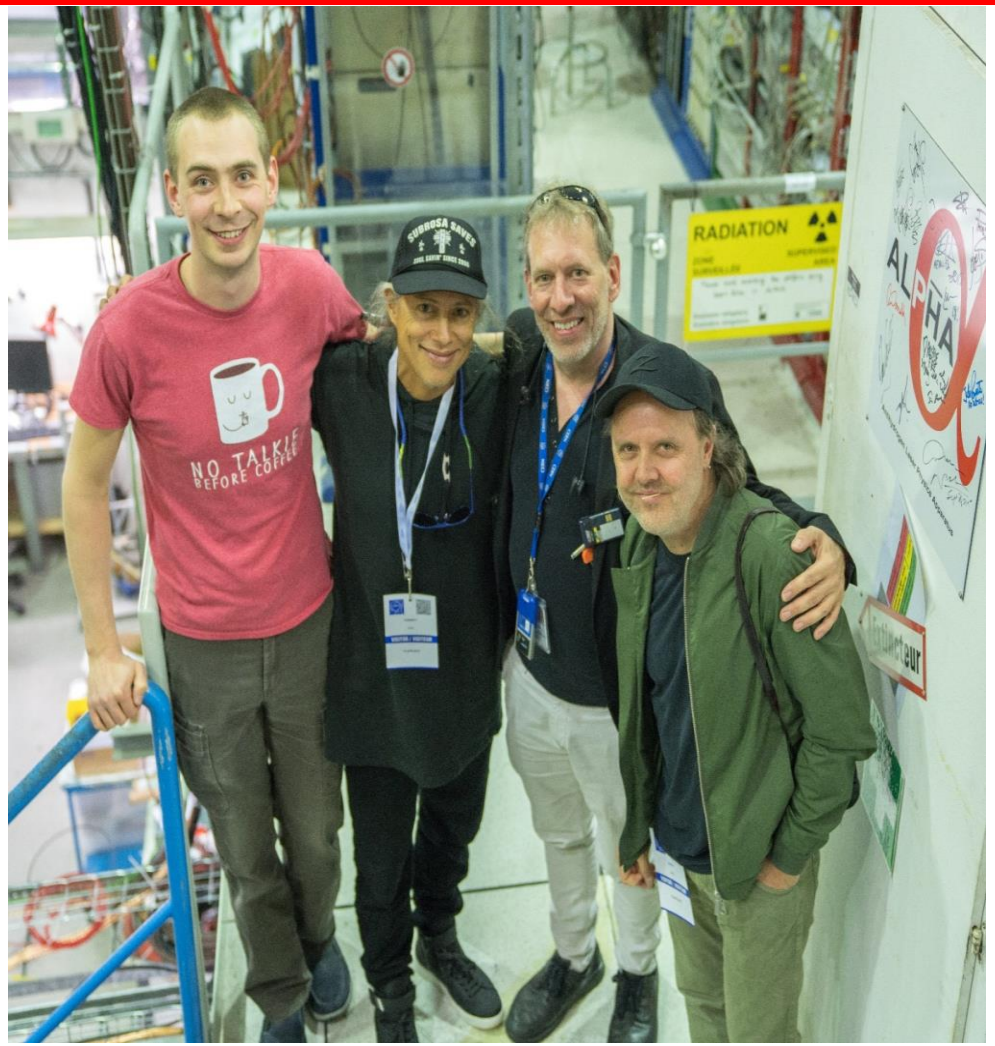
Probably the best antihydrogen experiment in the world…

All of our friends are rock stars…Crosby and Nash

All of our friends are rock stars 2…Muse



Metallica



755 official groups with 13869 international visitors in 2018

Jack White

Roger Waters

CERN 13 March 2019

Slayer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garyholt_official See this guy? One thing is certain. In any room, anywhere, when he walks into a room, he is the most intelligent guy there. His specialty? PARTICLE MATTER. Jeffrey S. Hangst from CERN. Straight up genius. Some of the guys went for a tour of the Hadron Super Collider yesterday, I sat it out to rest my back. But the show was invaded by scientists today! Slayer and science, match made in hell!! That's SCIENCE BIYATCH!
1d
lisaholt777 I'm hella smarter
7,246 likes
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CERN
slayerbandofficial Kerry King and Professor Jeffrey Hangst from @cern One man changed music and the other changed science. #Slayer #Cern #AntiMatter #JeffreyHangst #KerryKing #innovators @jeffreyhangst Thanks to @conniepotter1 for setting everything up. @clairewakesa for the tour and @xavier_espinal for taking care of our crew
5d
gtrplayer1 CERN opens the portal to Hell...Slayer same thing kinda. Lol
5d 30 likes Reply
23,513 likes
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