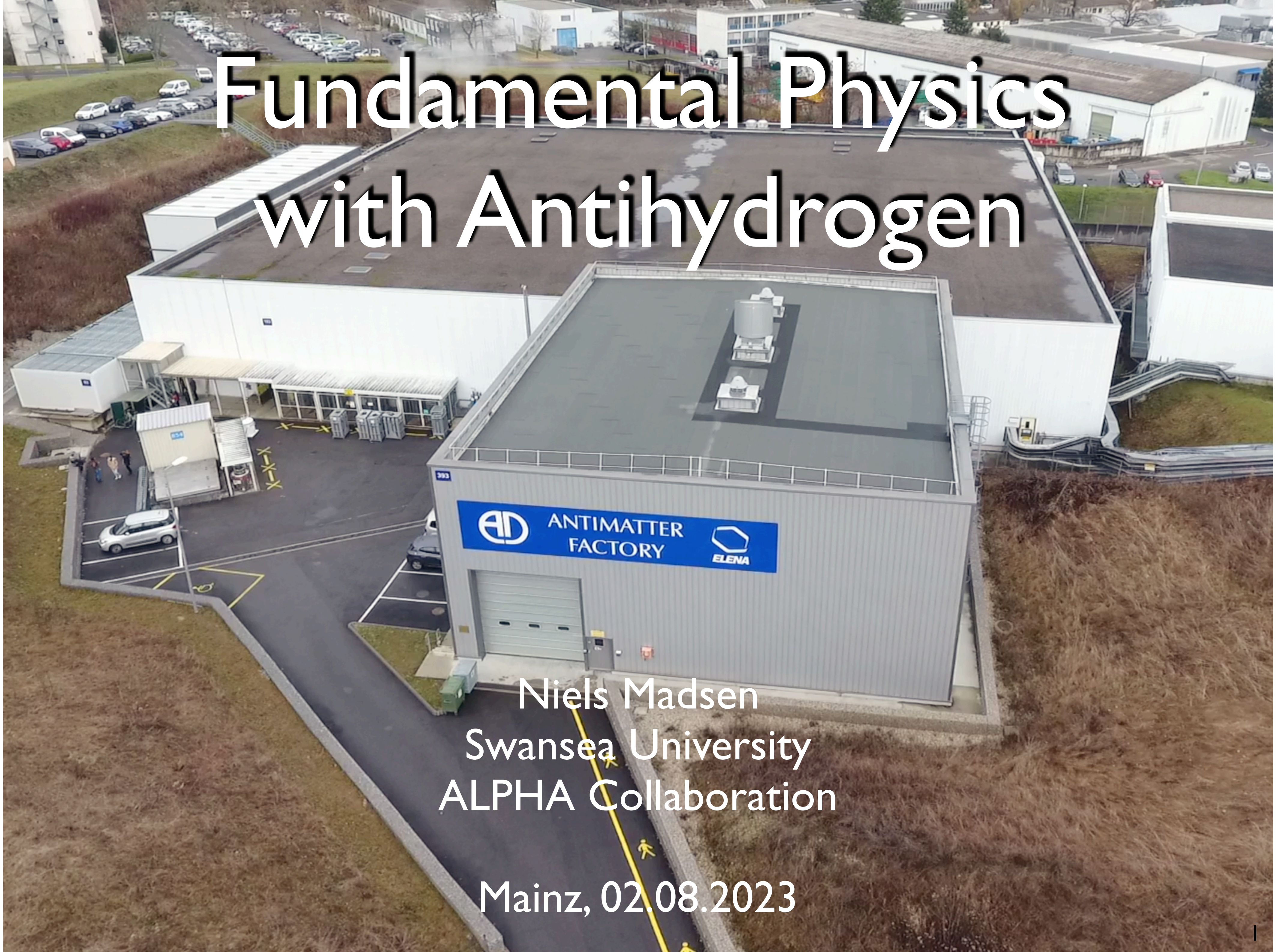
Fundamental Physics with Antihydrogen

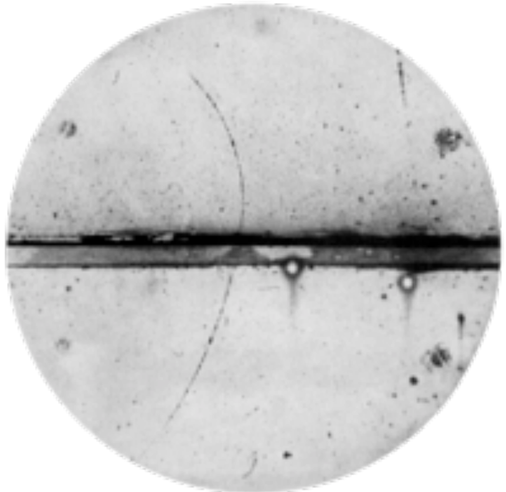


Niels Madsen
Swansea University
ALPHA Collaboration

Mainz, 02.08.2023

A bit of anti-history

1928 Dirac predicts the existence of antiparticles



1932 Discovery of positron C.A. Anderson

Quite some time….

1955 Discovery of the antiproton
at the Bevatron E. Segrè & O. Chamberlain

A long time….

1995 First antihydrogen detected (beam)

2002 First "useful" antihydrogen formed
(low energy).

2010 First trapped antihydrogen

Fundamental Physics

- In addition to spacetime translations we have some discrete transformations: charge conjugation (C), parity (P) and time reversal (T)
- In a Local, Lorentz Invariant (LLI) quantum field theory (QFT), the combined transformation (CPT) is an exact symmetry
- The Standard Model of particle physics is an example of a LLI QFT
- E.g. If CPT invariance holds the energy of bound states of antihydrogen and hydrogen are the same, so a measurement of transitions between energy levels in hydrogen and antihydrogen test CPT invariance.

In general, antimatter experiments test these principles.

So what's wrong ?

Predictions of the baryon to photon ratio are **inconsistent by about 9 orders of magnitude**

Sakharov conditions (for an asymmetric universe)

1) Baryon number violation (!?)
2) CP-violation (observed, but too small)
3) Out of thermal equilibrium (!?)

Alternatives ?

1) CPT violation
2) 5th forces
3) your favorite violation

Precise comparisons of simple antimatter/matter conjugate systems could be sensitive to CPT violations, and speculatively even 5th forces.

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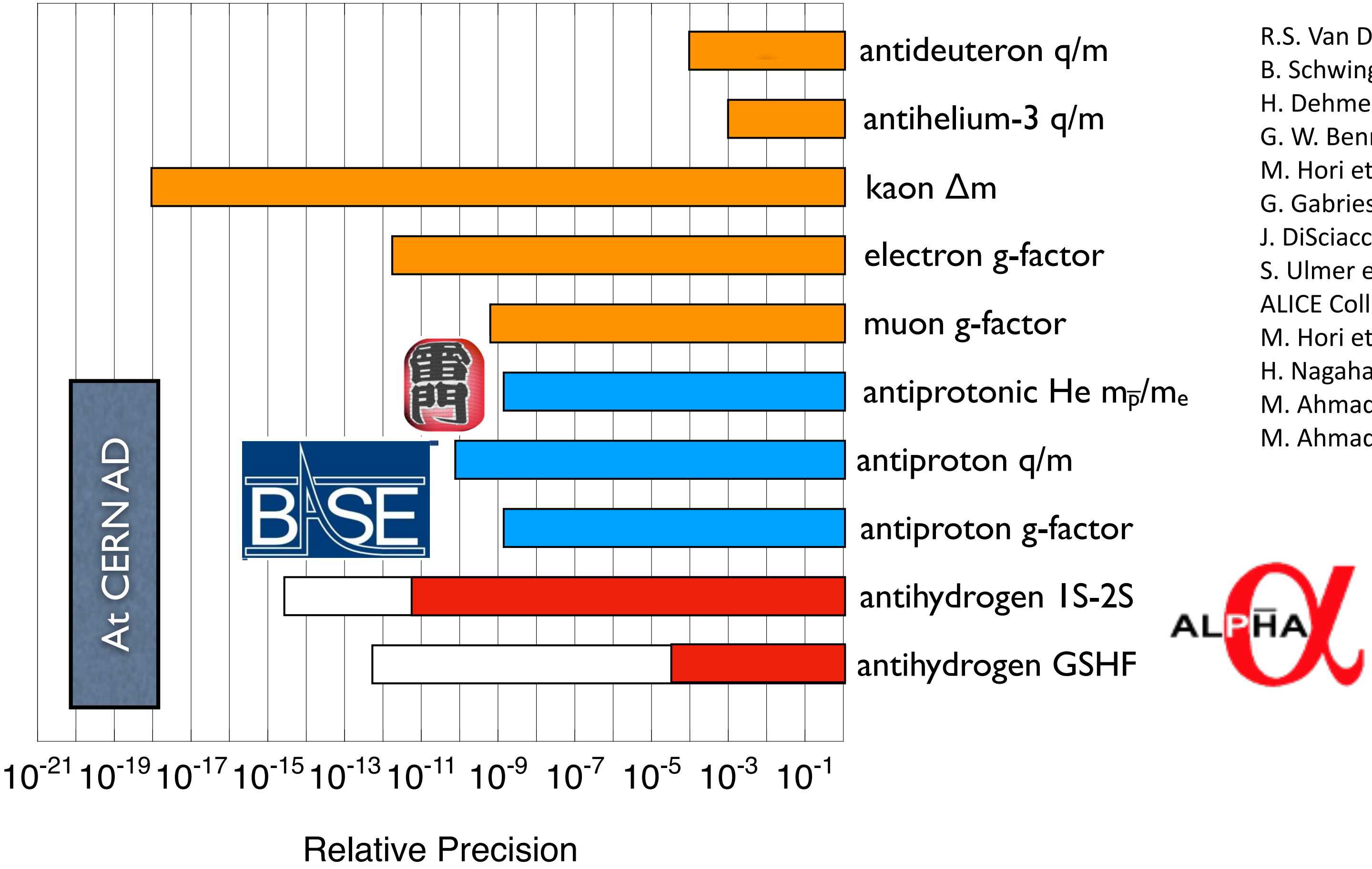
Particle/antiparticle CPT tests



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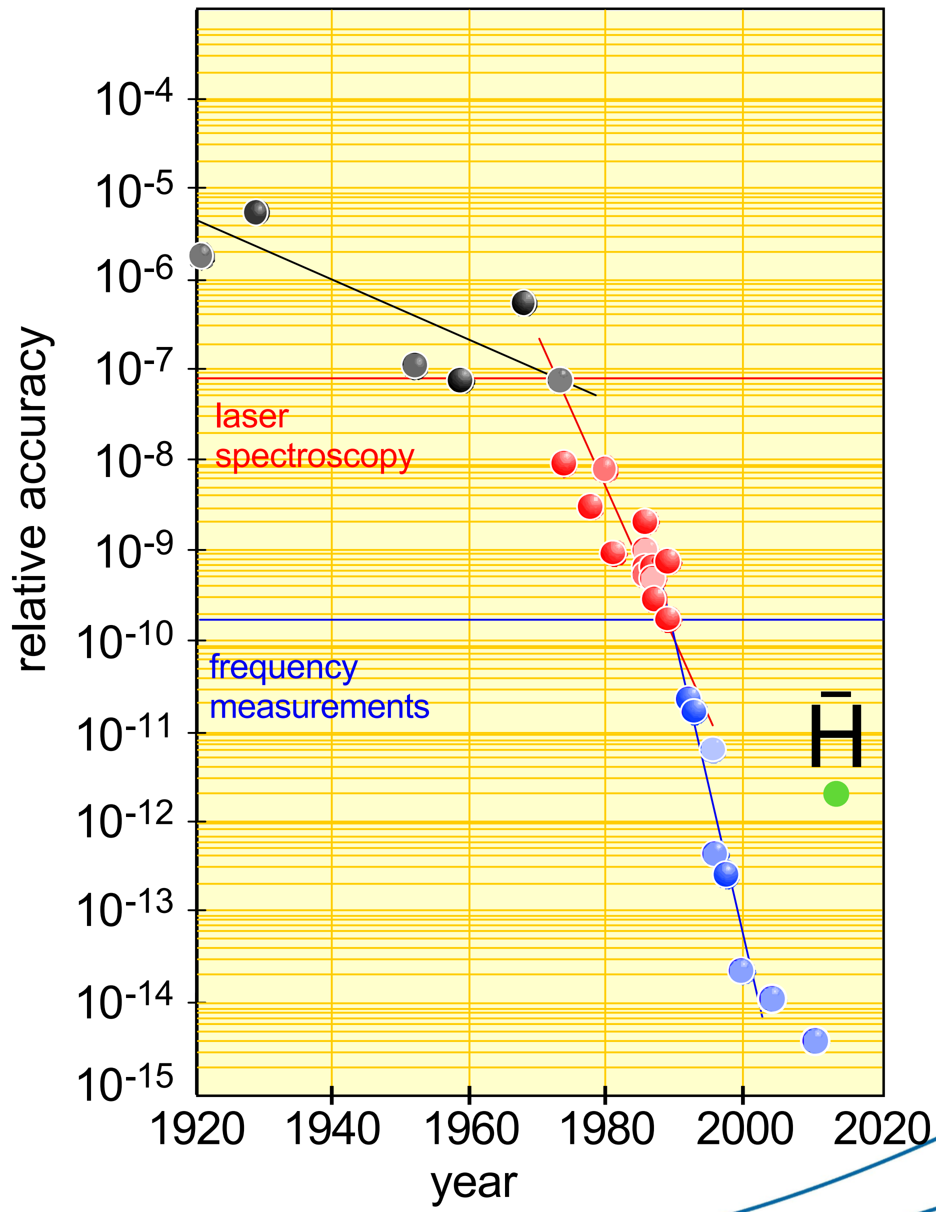
How does antihydrogen help ?

- Only pure antimatter system so far!
- Antihydrogen is neutral! [makes gravity possible]
- Spectroscopic techniques can be brought to bear.
- Ex: H-$\bar{H}$ comparison by 1s-2s two photon spectroscopy.



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Einsteins Equivalence principles

General Relativity (GR)

- Strong equivalence principle : In a local inertial frame, the laws of physics take their special relativistic form.
- Weak equivalence principle (WEP) :
  - WEPff : Universality of free-fall - all (anti)particles fall with the same acceleration in a gravitational field.
    → Free fall measurements of antihydrogen (AEGIS, GBAR, ALPHA)
  - WEPc: Universality of clocks - all dynamical systems that can be viewed as clocks measure the same time dilation independently of their composition (e.g. atomic clocks).
    → Antiproton g-factor (ATRAP, BASE)
    → Transitions in antihydrogen (ALPHA, ASACUSA, GBAR)

Reference frames

- It's not enough just to measure a number!

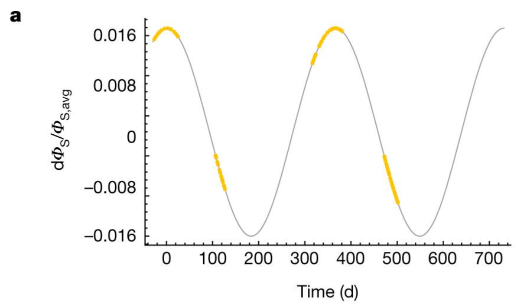
Article | Published: 05 January 2022

A 16-parts-per-trillion measurement of the antiproton-to-proton charge–mass ratio

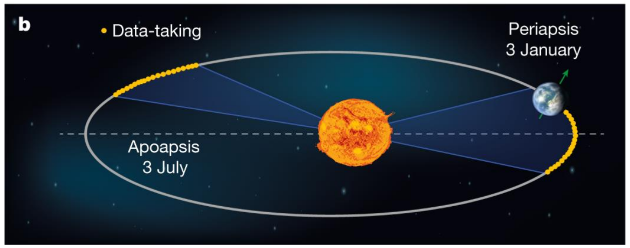
(BASE)

M. J. Borchert, J. A. Devlin, S. R. Erlewein, M. Fleck, J. A. Harrington, T. Higuchi, B. M. Latacz, F. Voelksen, E. J. Wursten, F. Abbass, M. A. Bohman, A. H. Mooser, D. Popper, M. Wiesinger, C. Will, K. Blaum, Y. Matsuda, C. Ospelkaus, W. Quint, J. Walz, Y. Yamazaki, C. Smorra & S. Ulmer

Nature **601**, 53–57 (2022) | Cite this article



$|\alpha_{g,D} - 1| < 0.030$ (CL 0.68)

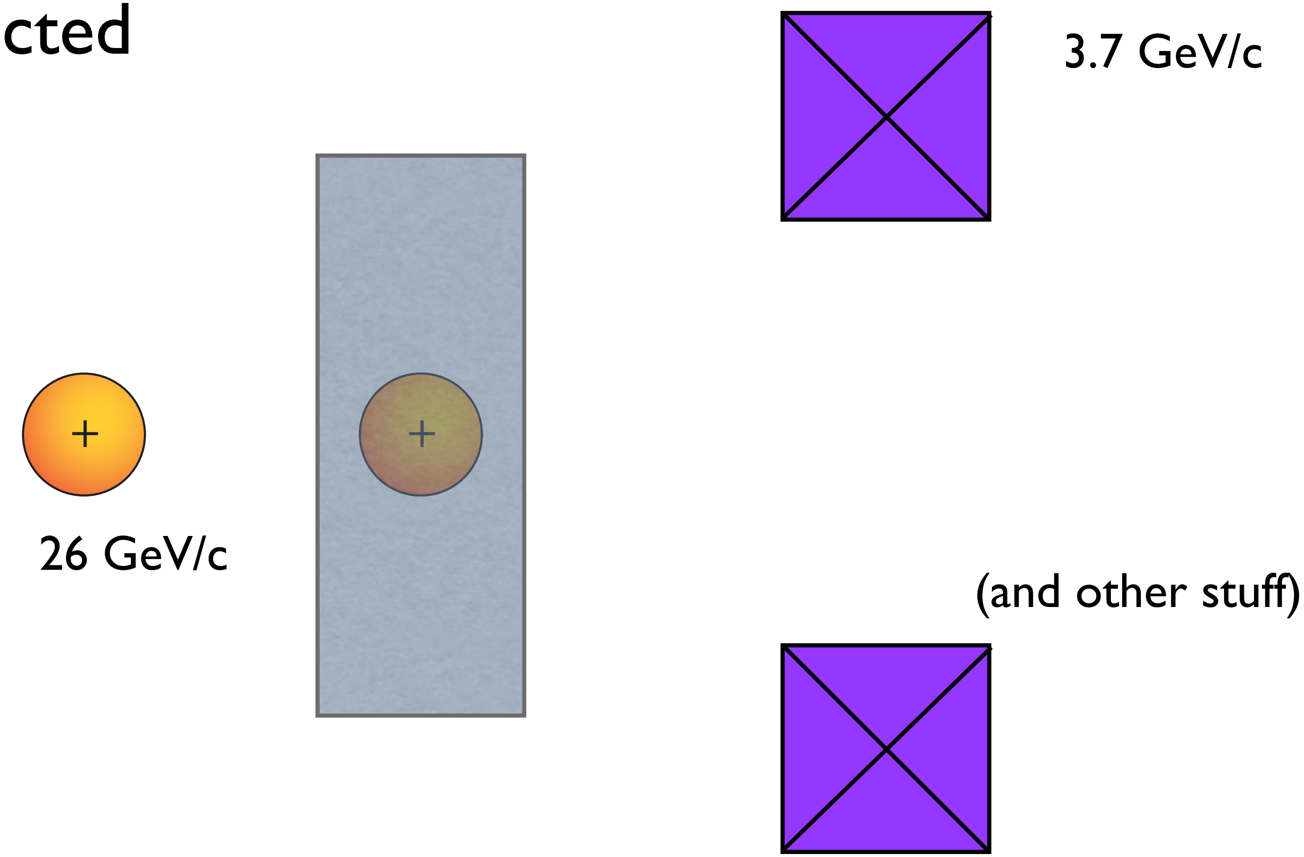


- Reference, time & place are key!
- Experimentalist: No model - so do best possible job - and try to make your measurement model independent.

Antiprotons

- Energetic proton creates Proton/Antiproton pair
- Charge/Mass selected

Cern Proton Synchrotron

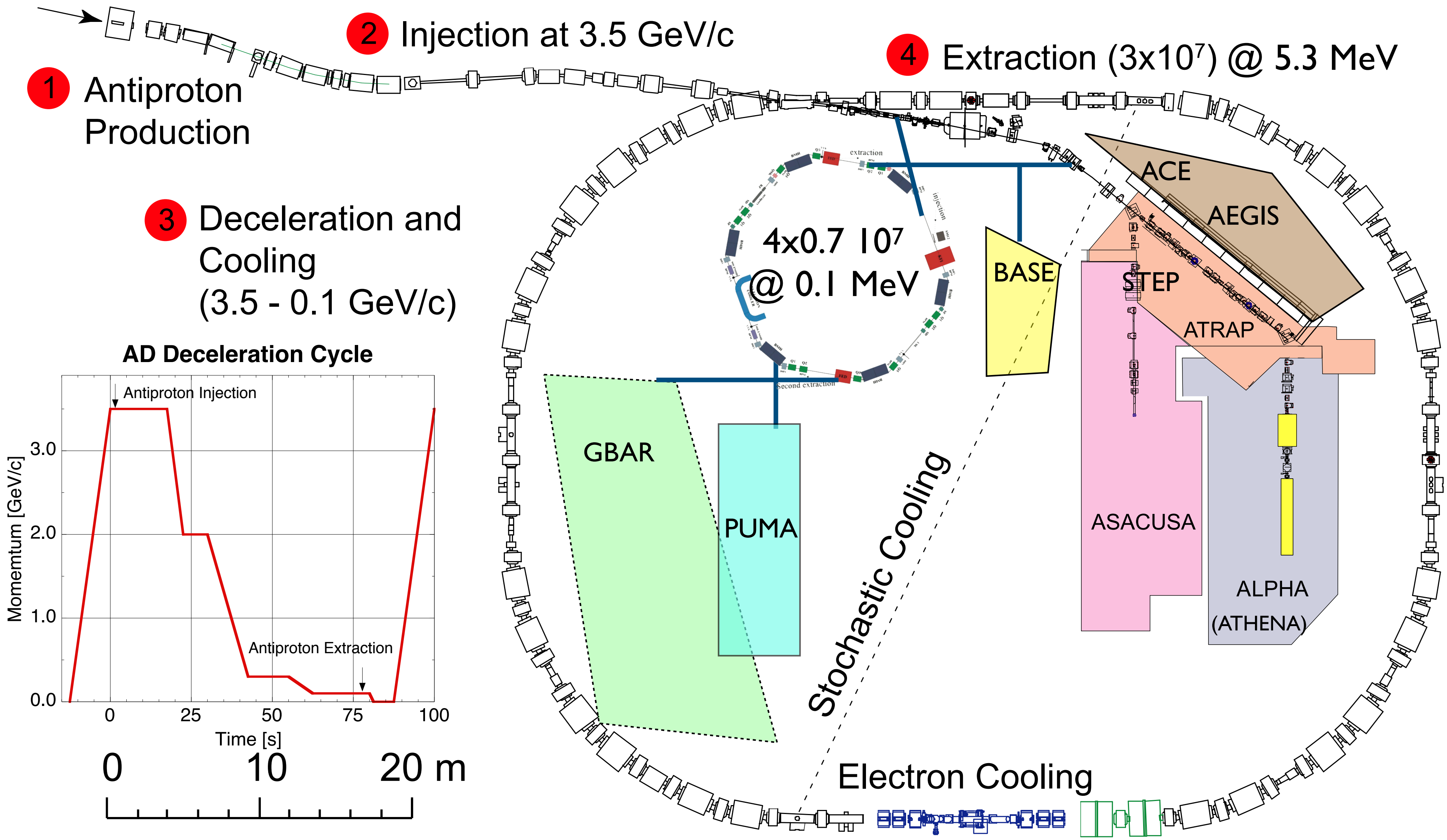


1.5×10^{13} protons result in 3×10^{7} antiprotons in the AD

ELENA : ~8M antiprotons per shot per experiment

Maury. S. *et al.* Hyp. Int. **109** 43 (1997)
Maury. S. *et al.* Hyp. Int. **229** **105** (2014)

Antiproton Decelerator



ELENA: Since 2021

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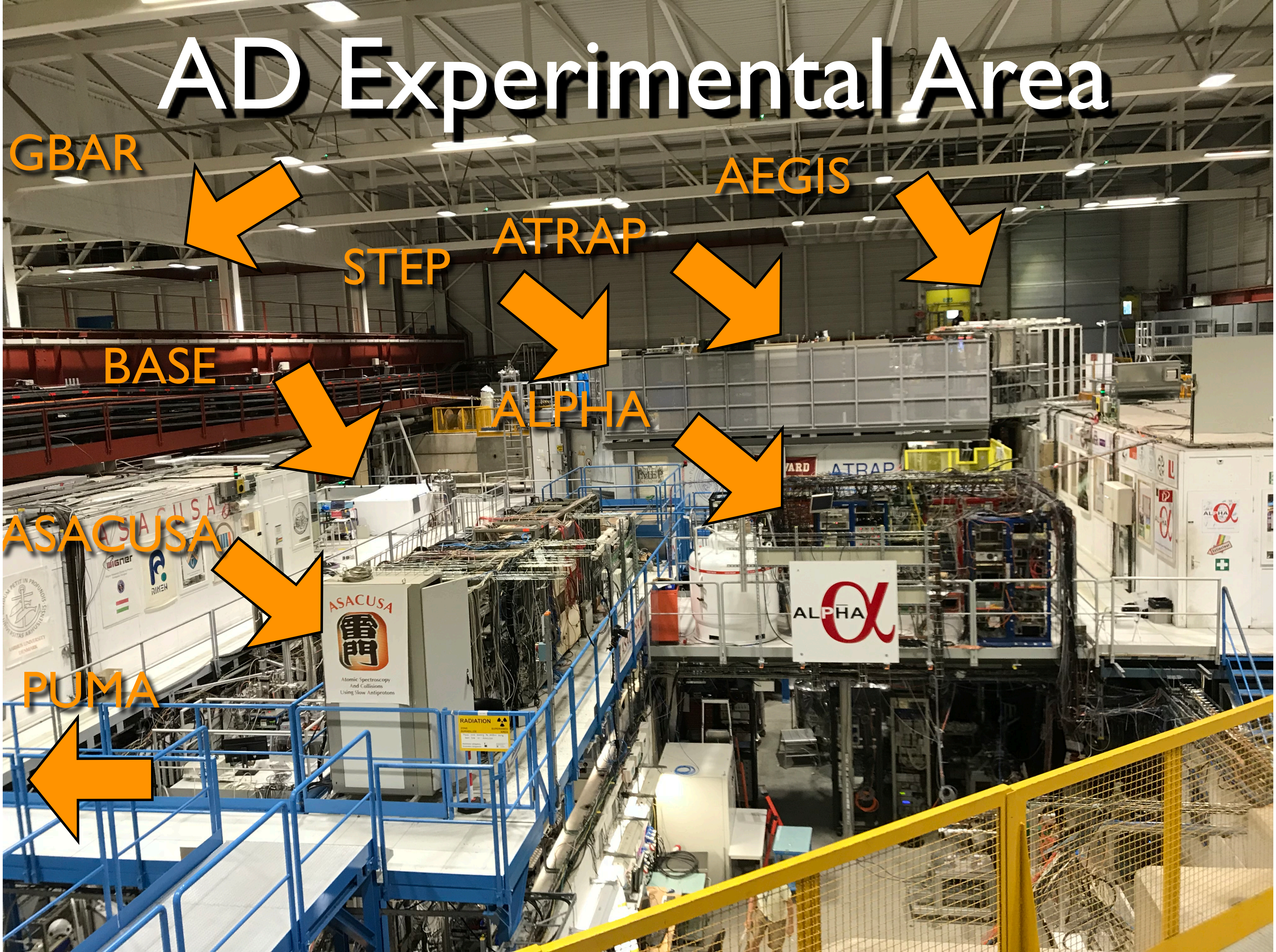
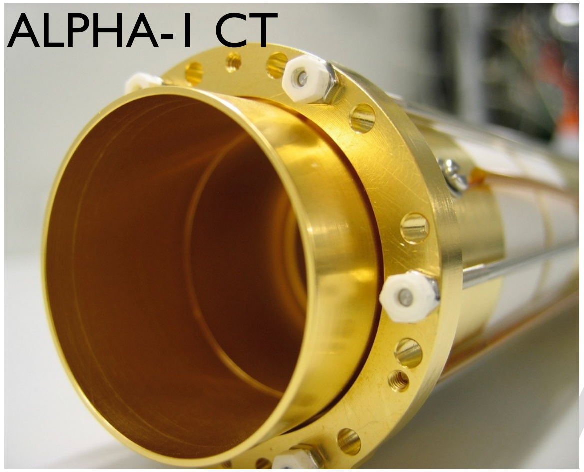
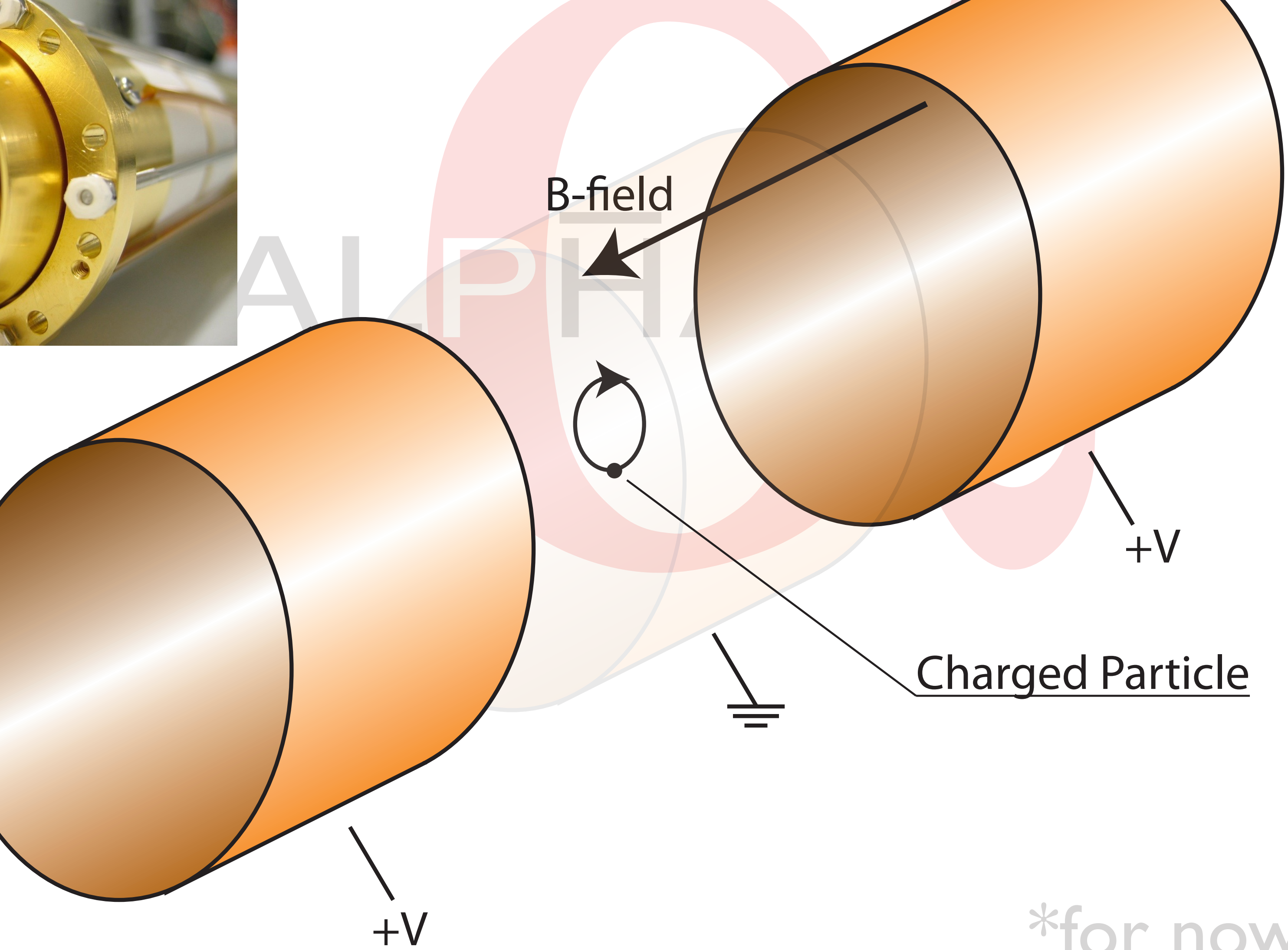
AD Experimental Area



Charged Particle Traps

All C.P. traps at the AD are Penning-Malmberg traps*

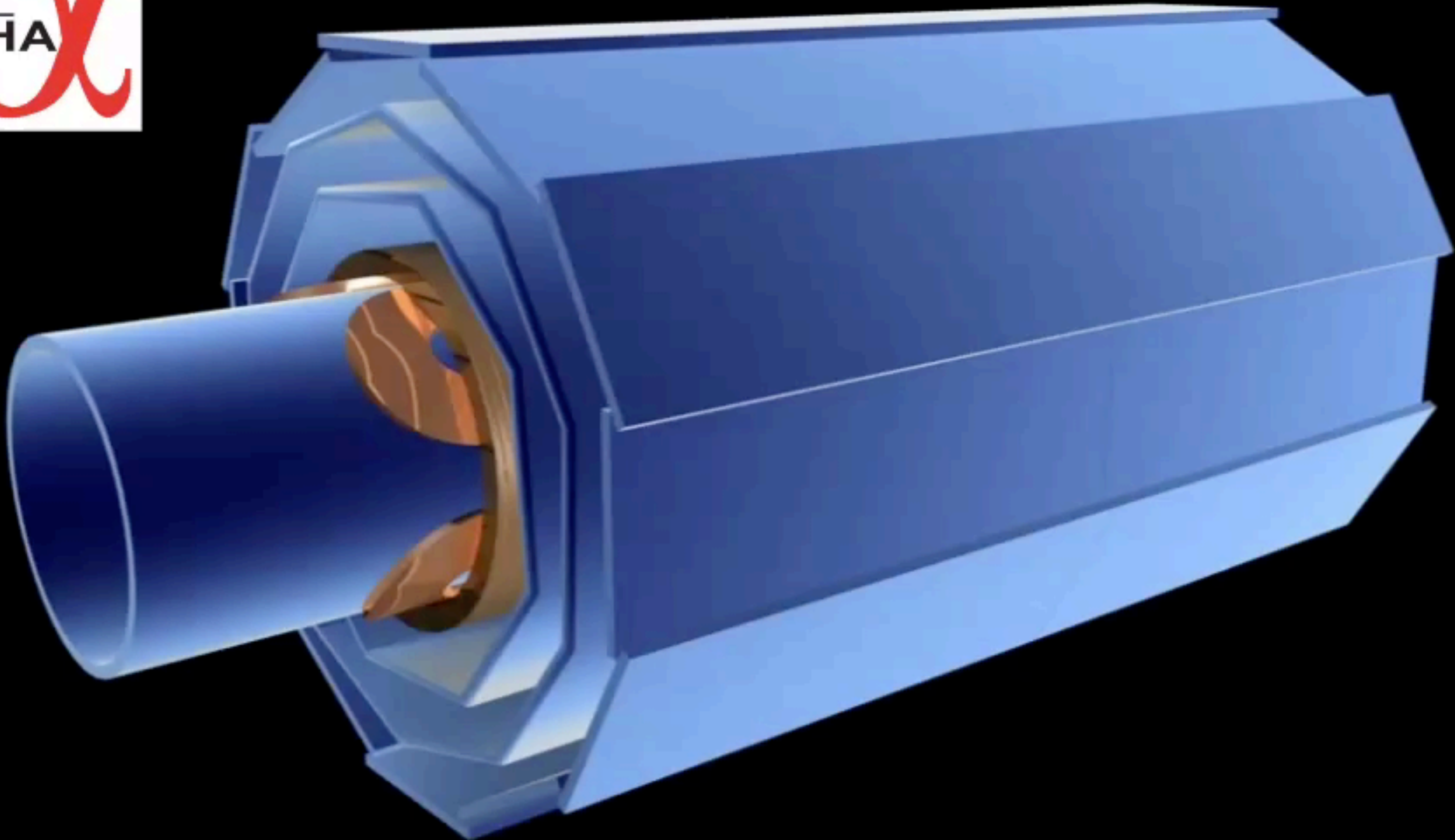




*for now - I think

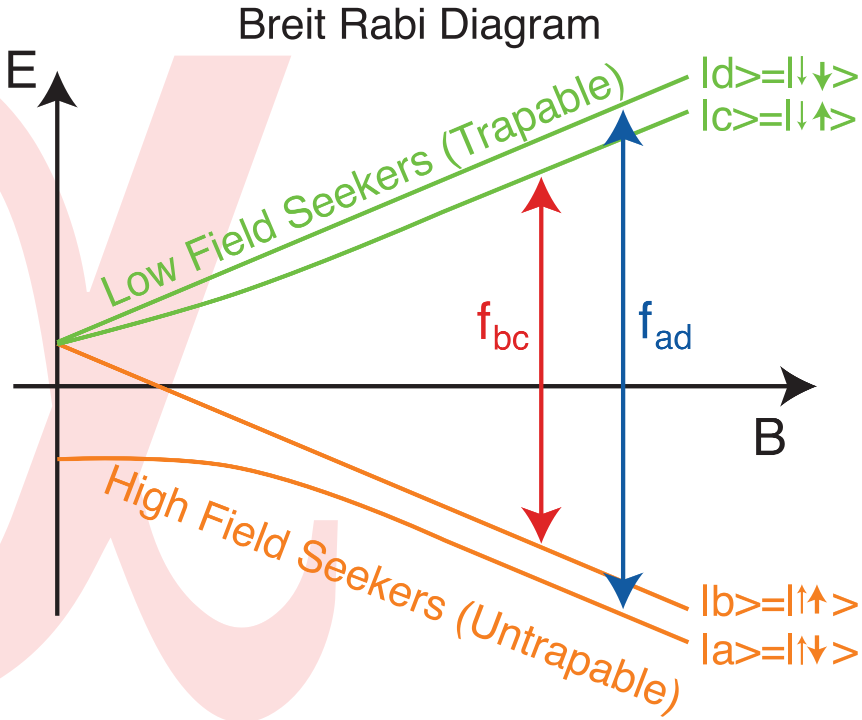
Antihydrogen work

- AEGIS (2012-) : Antihydrogen gravity with a cold beam of $\bar{H}$.
- ALPHA (2005-) : Antihydrogen spectroscopy and gravity using trapped antihydrogen.
- ASACUSA (1999-) : Antihydrogen micro-wave spectroscopy using an cold beam of $\bar{H}$.
- ATRAP (1999-2018) : Antihydrogen production and trapping.
- GBAR (2018-) : Antihydrogen gravity and spectroscopy using a low-energy beam of $\bar{H}$ and $\bar{H}^+$.



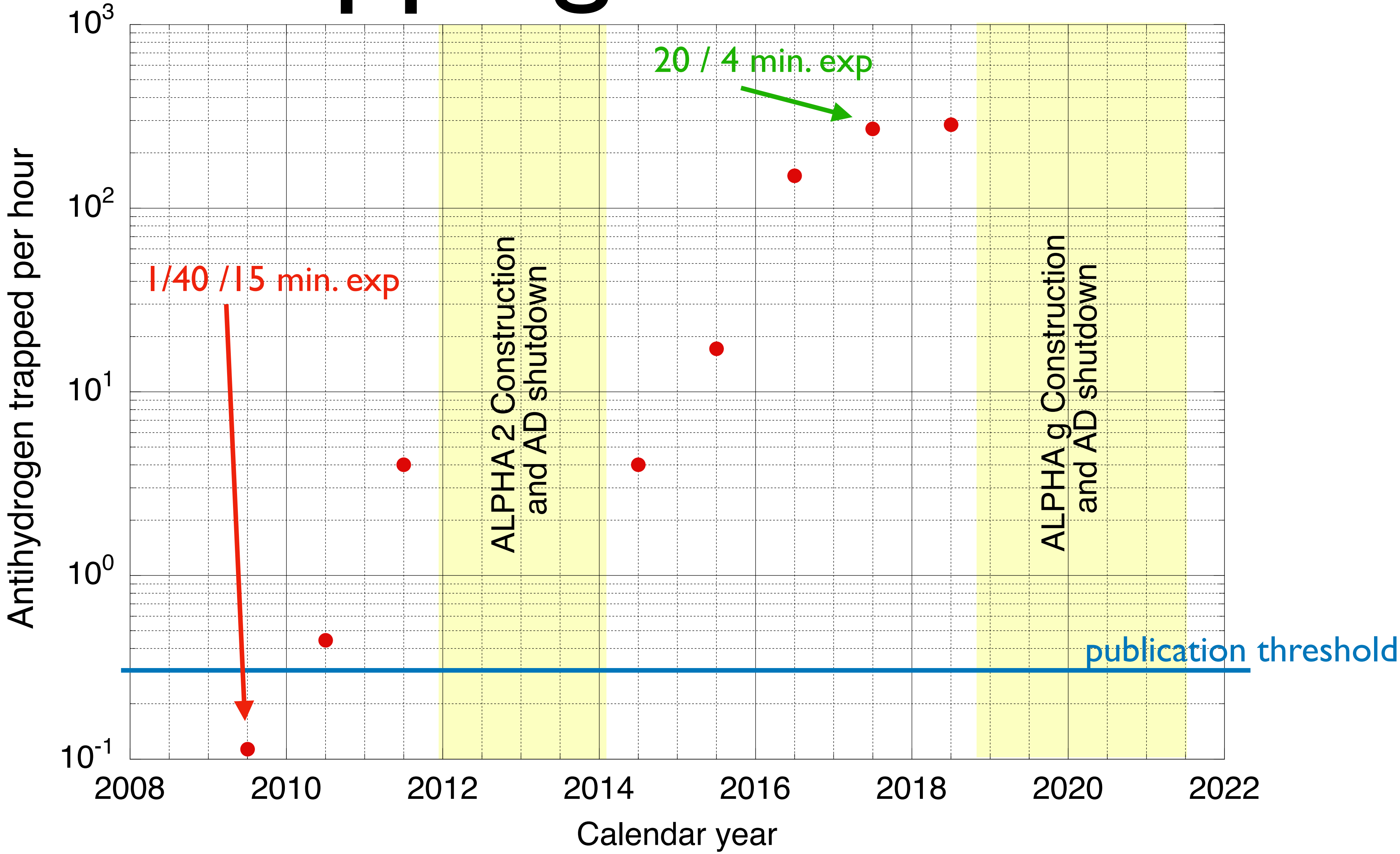
Experiments with ~1 $\bar{H}$

- Hold for 15 minutes -> ground state.
  Nature Physics **7**, 558 (2011)
- Spin-flip transition observed
  Nature **483**, 439 (2012)
- Demonstration of gravitational measurement.
  $|M_{gravity}/M_{inertial}| < 75$
  Nature Comm. **4**, 1785 (2013)



- Charge of $\bar{H}$ measured |Q|<0.71ppb at 68% conf.
  Nat. Comm. **5**, 3955 (2014), Nature **529**, 7585 (2016)

Trapping evolution



Seems predominantly linked to e^+ temperature

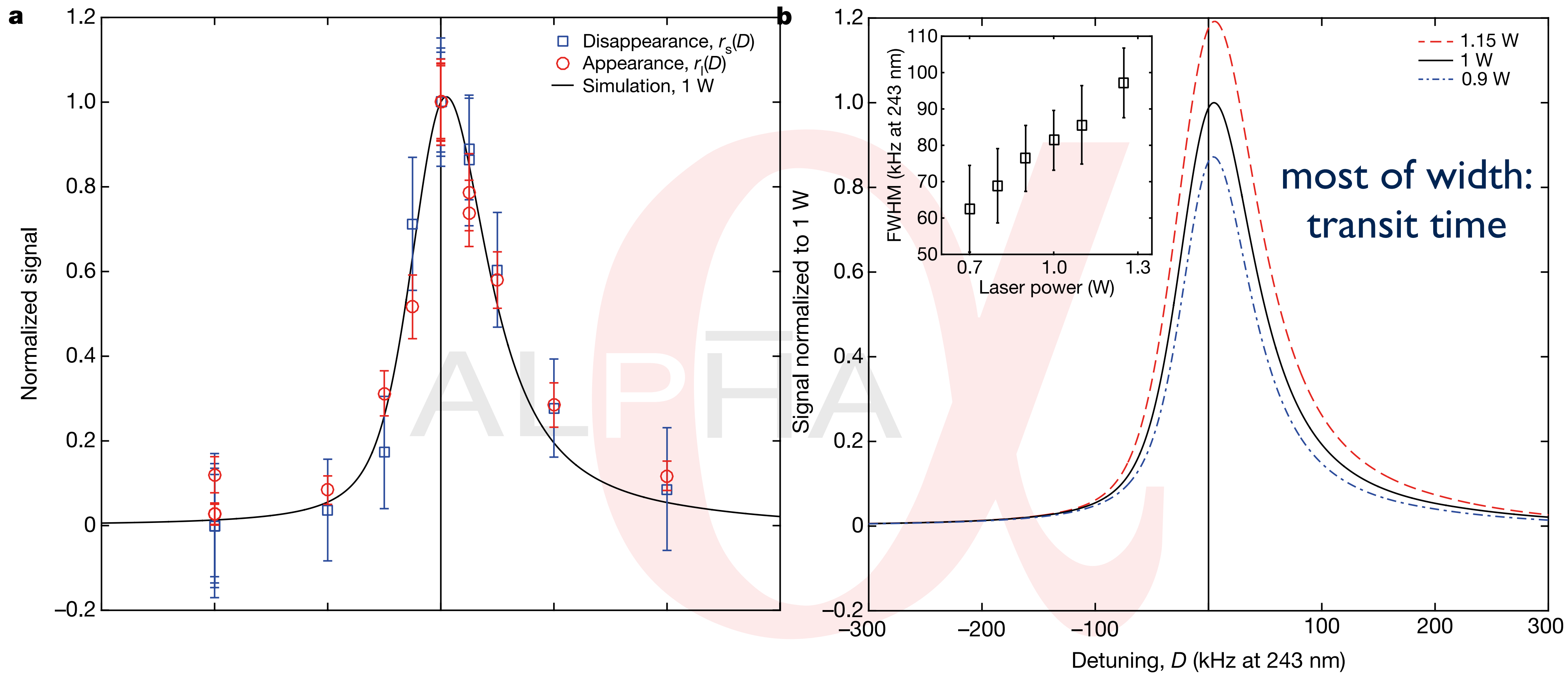
1s-2s in Antihydrogen

- Density of $\bar{H}$ low (~14/exp, trap of 28cm * ø4cm = 0.4L)
- "High" temperature (short transit time).
- Needs lots of laser intensity - so laser small - and (as it turns out) must be cavity enhanced
- Excite 2s (|c> and |d>) - photo-ionise, lyman-alpha not detectable (and spin-flip not quite frequent enough).
- Disappearance : Need to hit both hyperfine states (cc/dd)
- Appearance (observe "lost" $\bar{p}$/$\bar{H}$): large background…
- Need ~100s to interact…

1S - 2S Excitation

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

Spectral Lines of $\bar{H}$



- Appearance scaled response detuning D: L(D)/L(0) (L = lost $\bar{H}$)
  Disappear. : [S(-200kHz)-S(d)]/[S(-200kHz)-S(0)] (S = survived)
- Fit result: P1=1135(50mW), P2=904(30)mW, P3=1123(43)mW, P4=957(31)mW and df = -0.44±1.9kHz (@ 243nm)

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

Result

- At a magnetic field of 1.03285(63) T :
- $f_{d\text{-}d}^{exp}$ = 2,466,061,103,079.4(5.4) kHz
- $f_{d\text{-}d}^{calc}$ = 2.466,061,103,080.3(0.6) kHz
- Consistency to 2 x 10^{-12}
- Hydrogen precision state of the art : 4.2 x 10^{-15}
- Used ~ 15000 antihydrogen atoms.
- The most precise and accurate measurement on antimatter to date.

Uncertainties

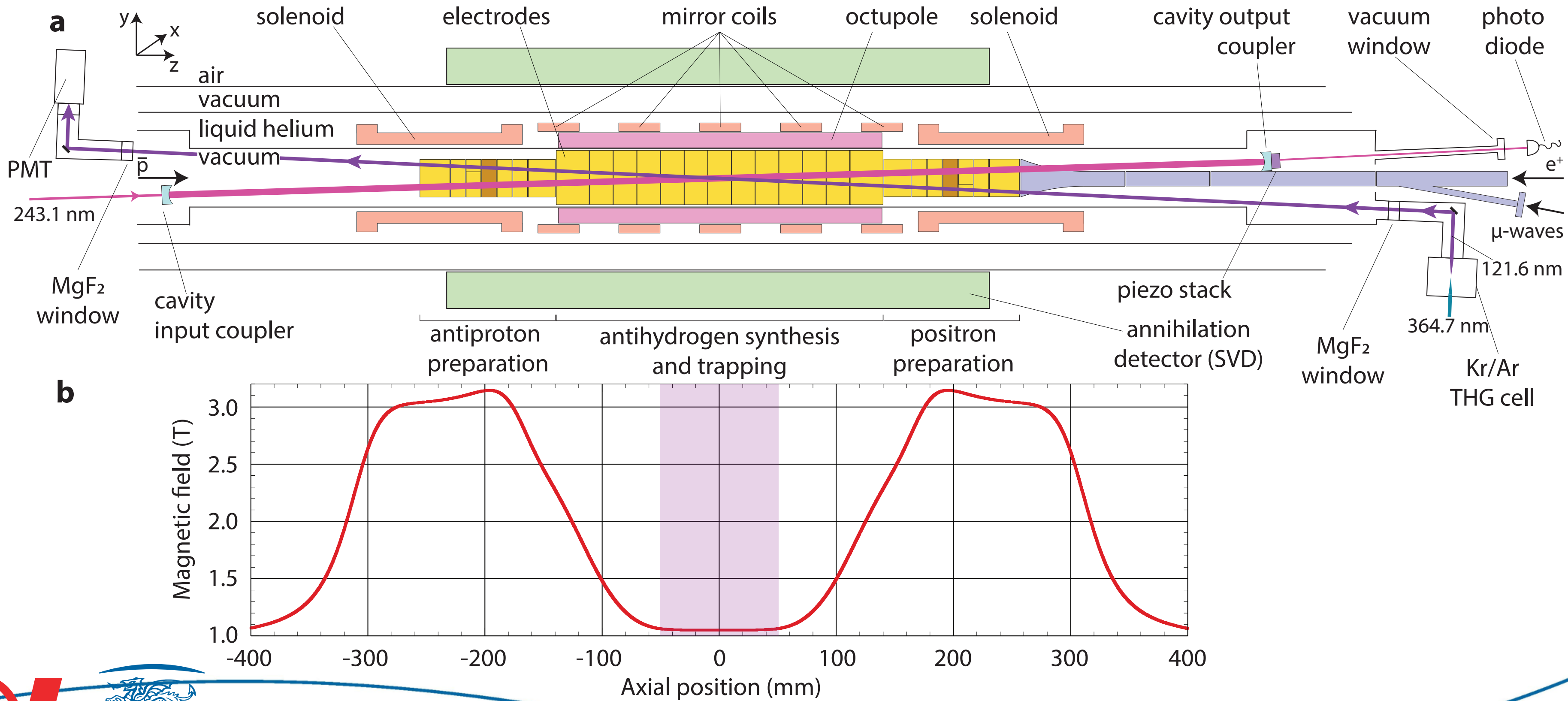
Table 3 | Summary of uncertainties

Type of uncertainty	Estimated size (kHz)	Comment
Statistical uncertainties	3.8	Poisson errors and curve fitting to measured data
Modelling uncertainties	3	Fitting of simulated data to piecewise-analytic function
Modelling uncertainties	1	Waist size of the laser, antihydrogen dynamics
Magnetic-field stability	0.03	From microwave removal of $1S_c$-state atoms (see text)
Absolute magnetic-field measurement	0.6	From electron cyclotron resonance
Laser-frequency stability	2	Limited by GPS clock
d.c. Stark shift	0.15	Not included in simulation
Second-order Doppler shift	0.08	Not included in simulation
Discrete frequency choice of measured points	0.36	Determined from fitting sets of pseudo-data
Total	5.4	

The estimated statistical and systematic errors (at 121 nm) are tabulated.

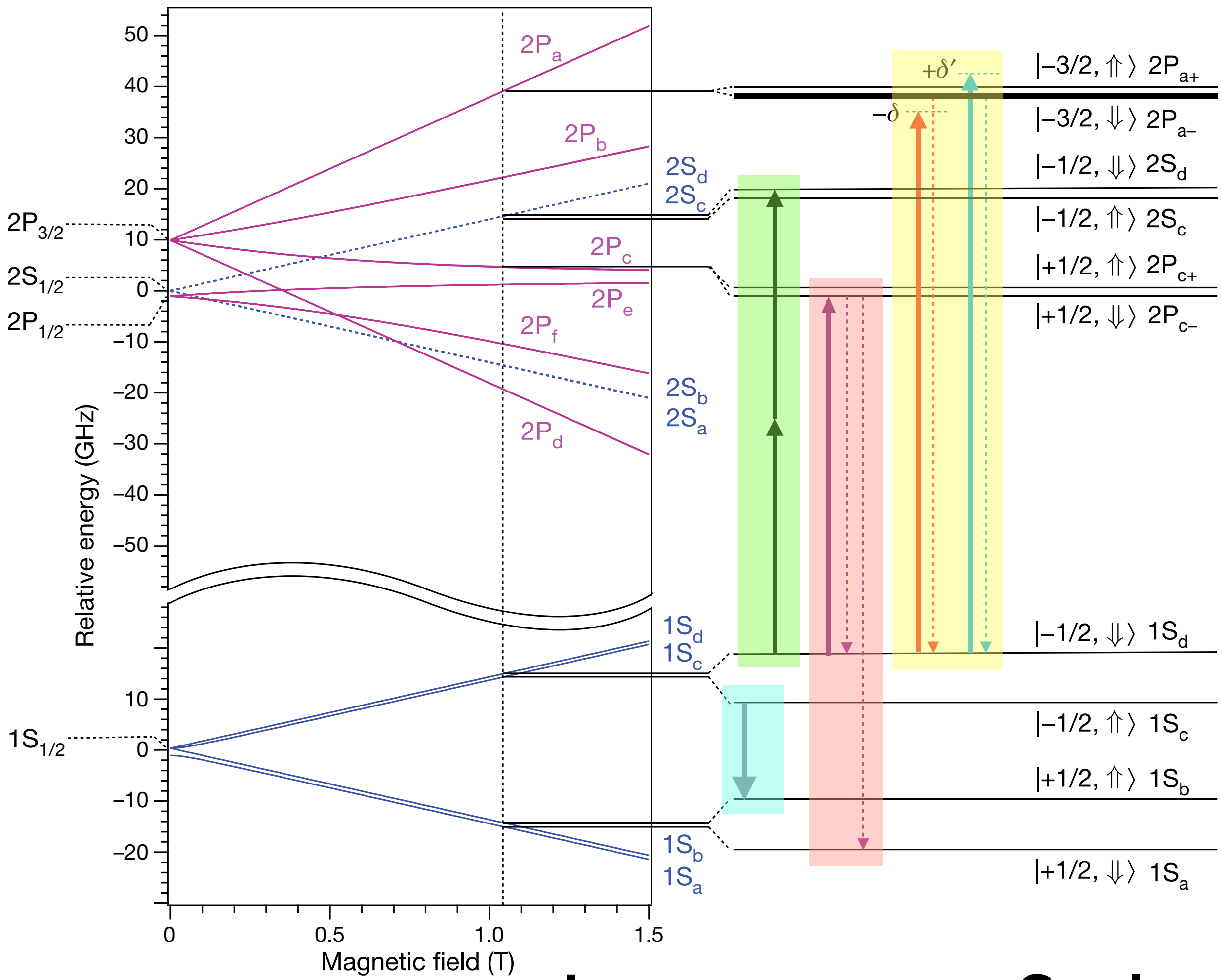
Laser-cooling

- We can exchange photons of 121nm with antihydrogen - they carry momentum.
- So at least 1D-laser-cooling should be possible if we can avoid spin-flips.



Nature **592**, 35 (2021)

Laser-cooling - transitions



Cooling/heating

Ly-α probe

1S-2S Probe

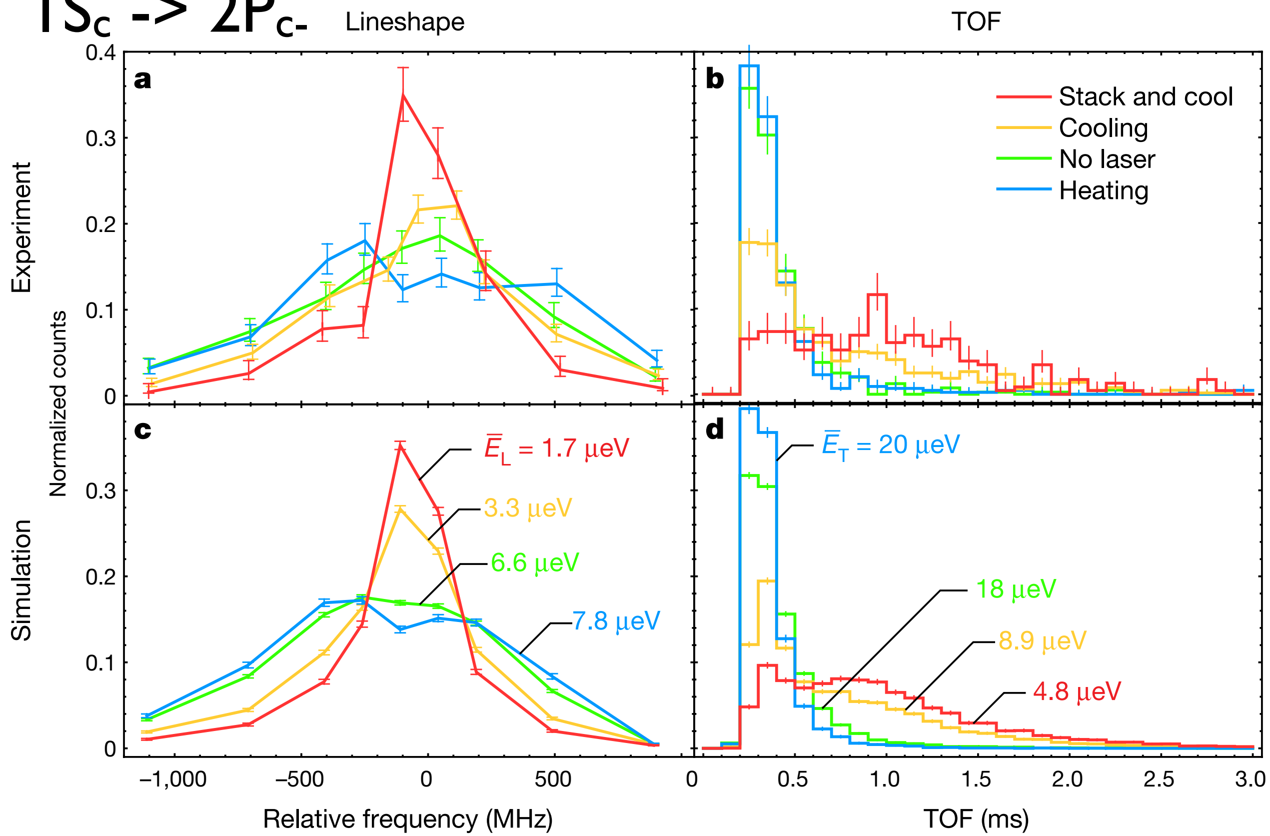
µ-wave probe

Low power : So laser-cooling is 6h long!

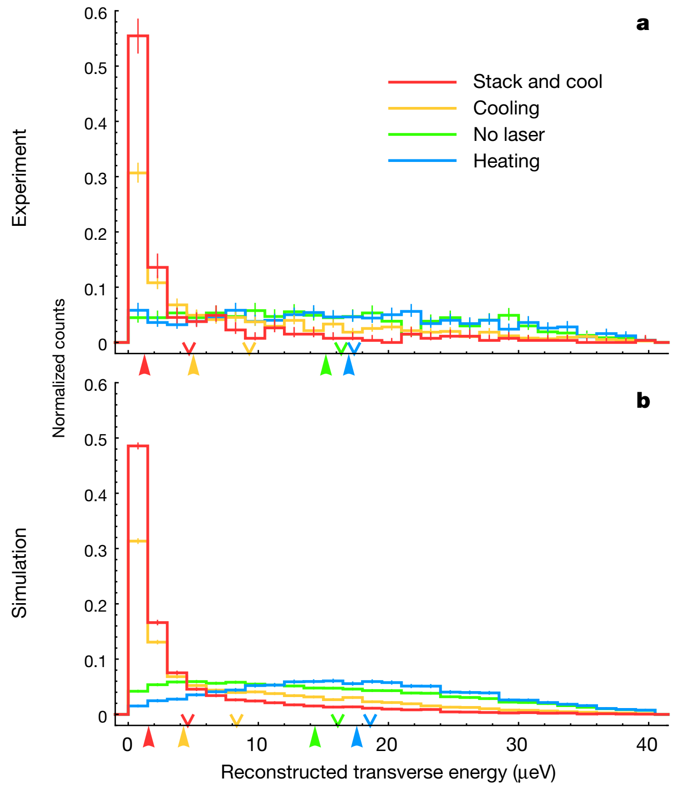
Nature **592**, 35 (2021)

Laser cooling - Ly-a probe

$1S_c \rightarrow 2P_{c-}$



Transverse energy



Line shape narrowing & lower <E_{kin}> observed (and understood)

Demonstrated continuous cooling while stacking & much longer stacking (1 day)

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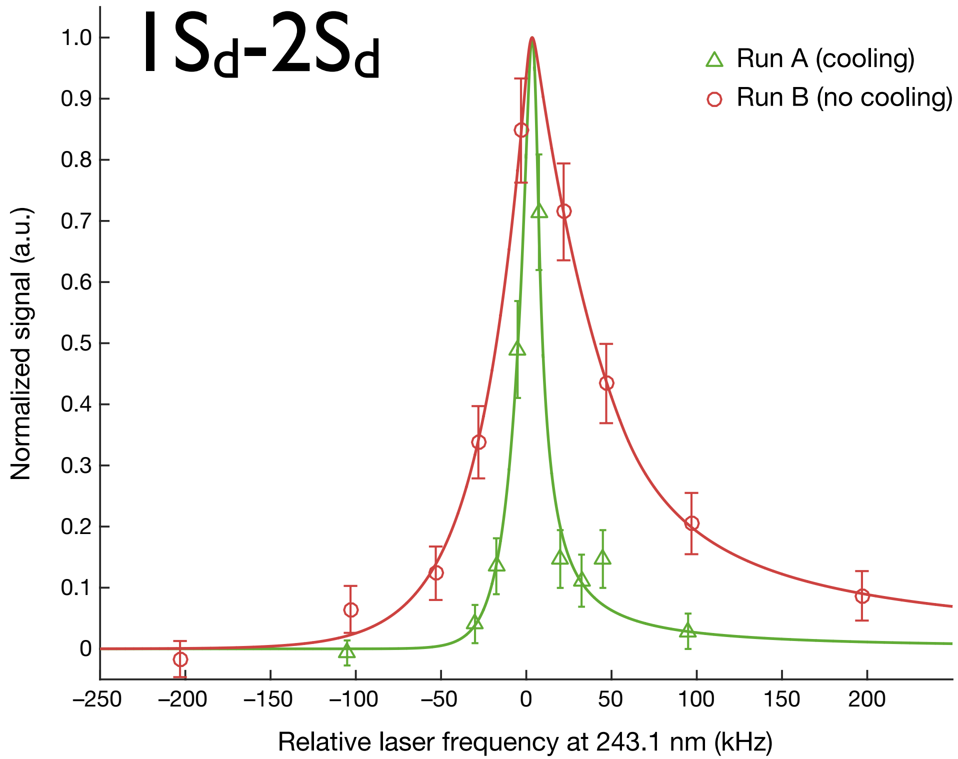
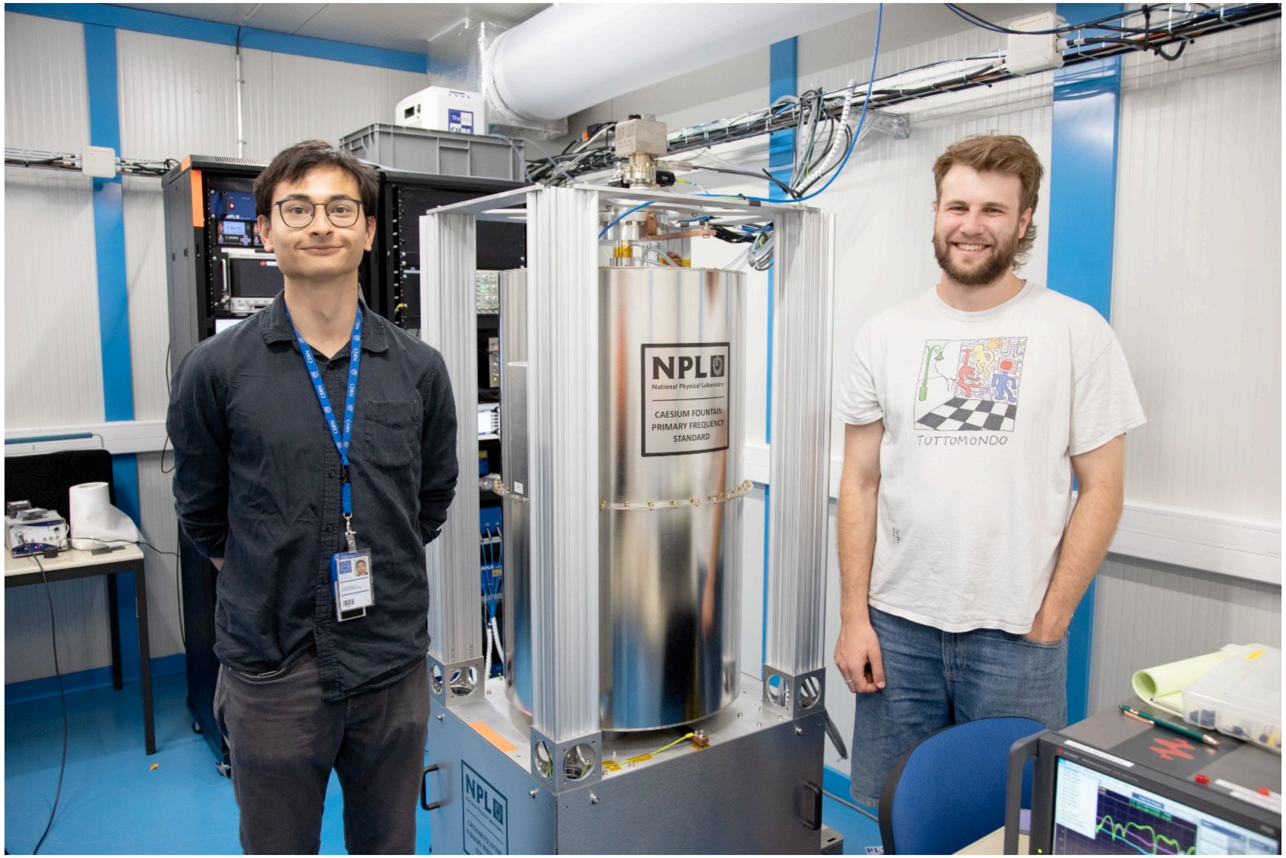
Nature **592**, 35 (2021)

Spectroscopy 2.0: w. laser-cooling

- With the full-day stacking we have 1000-2000 $\bar{H}$ - and we can do the line shape in "one" go - by quickly doing multiple stepped sweeps across the transition.



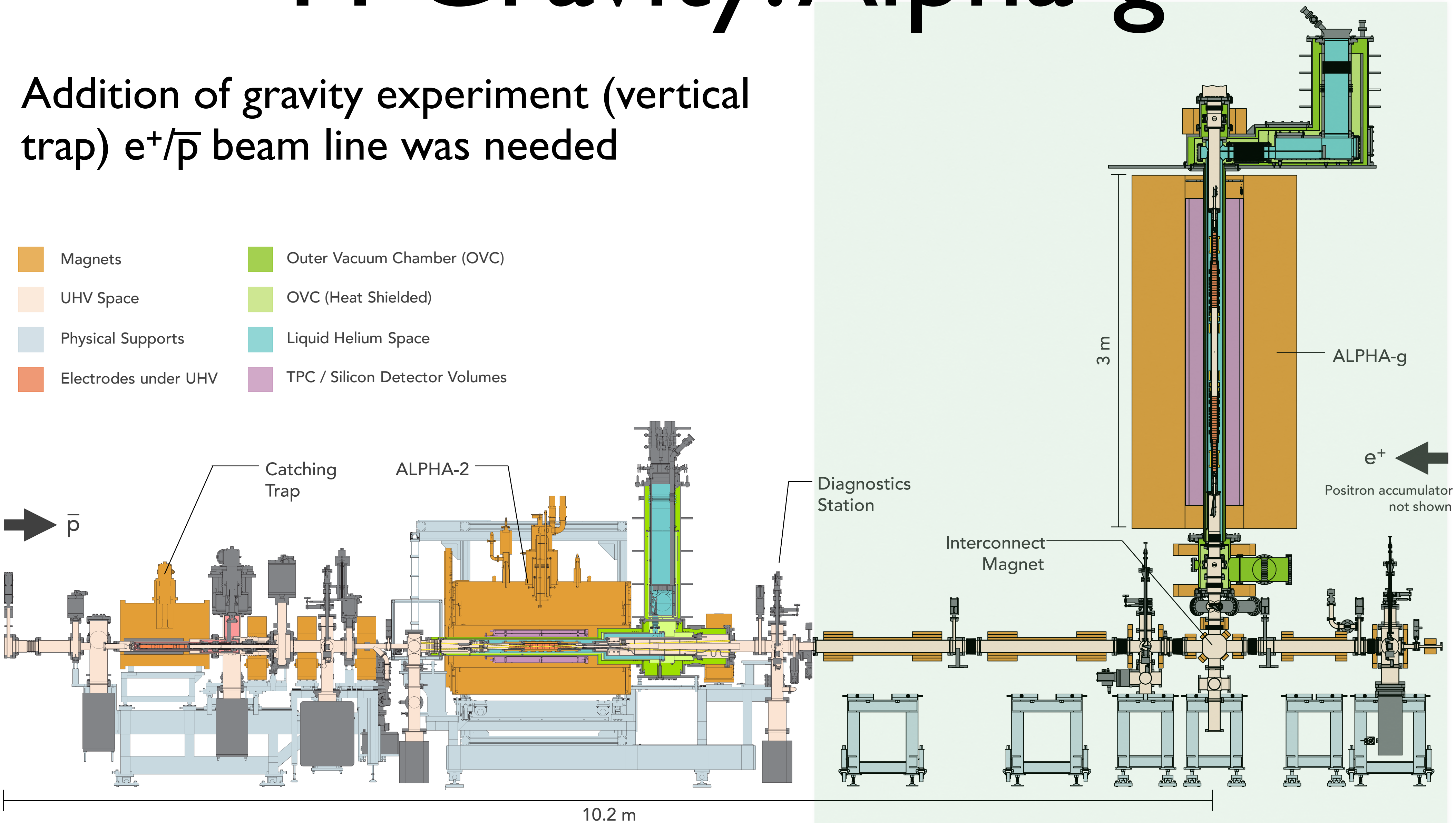
Spectroscopy 2.0: Reference



- Cs-fountain installed and “ticking” at CERN, guiding an active hydrogen maser : 10^{-16} freq. reference

$\bar{H}$ Gravity: Alpha-g

Addition of gravity experiment (vertical trap) $e^+/\bar{p}$ beam line was needed



H̄ Gravity in ALPHA-g

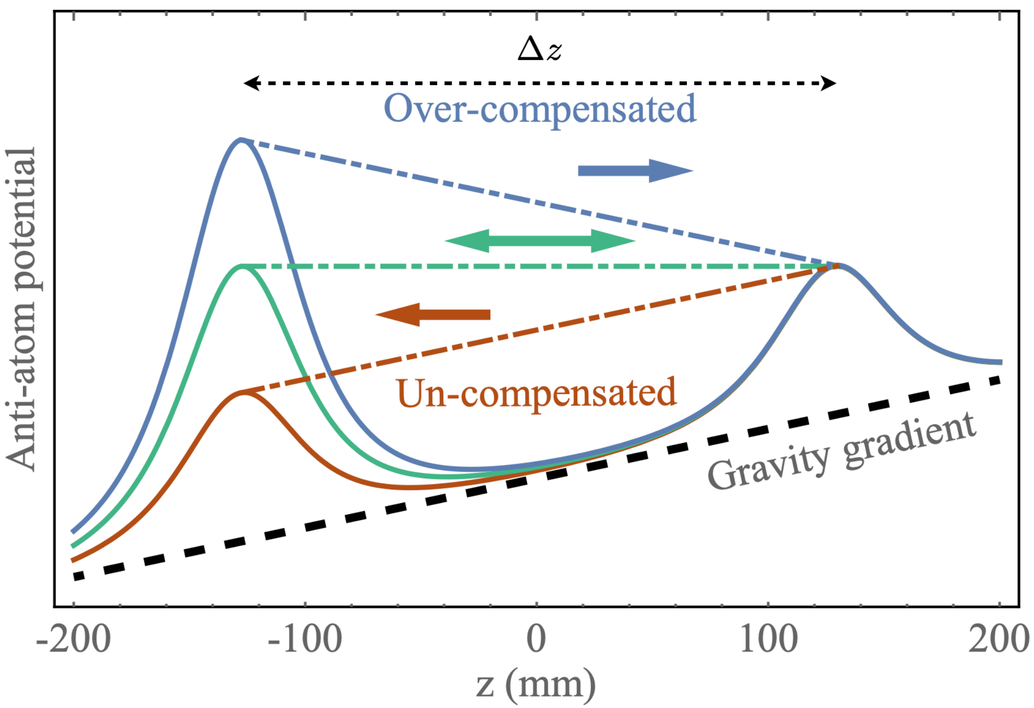
- A trapped (GS) H̄ experiences a potential equal to :

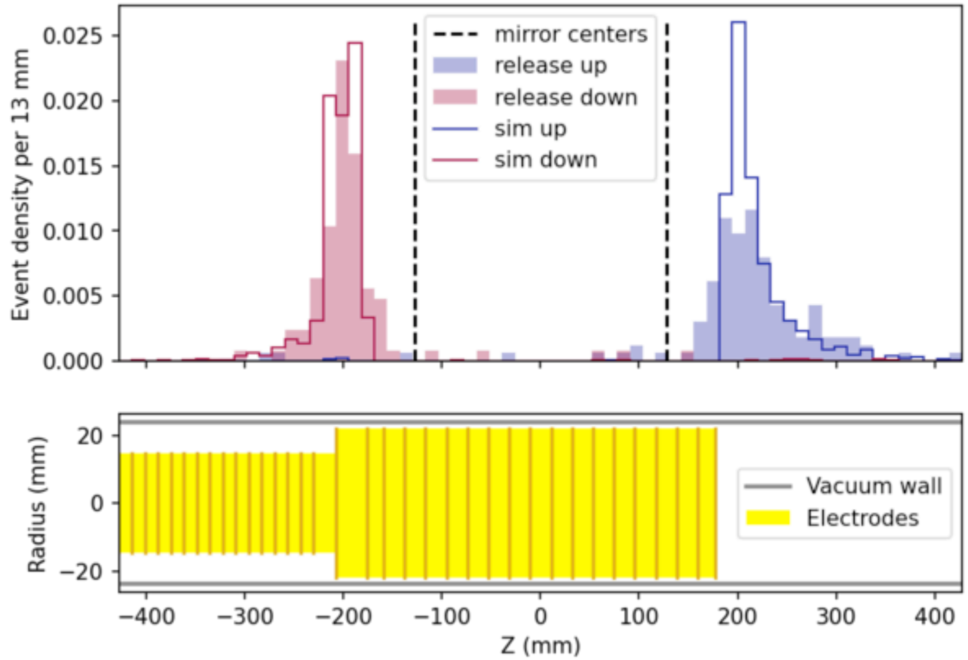
$$\Phi(\mathbf{r}) = \mu_B |\mathbf{B}(r)| - m_{\bar{H}} \bar{\mathbf{g}} \cdot \mathbf{r}$$

- The gravitational potential difference over 1 meter corresponds with a potential difference arising from a 17 Gauss change in the magnetic field.
- So, a priori, avoid B-fields (e.g. AEGIS & GBAR)… but we can trap them, so we will start from that.
- With identical B in a vertical apparatus, they would tend to fall our the bottom of the trap (assuming "normal" gravity). Quantitatively were expect 70% to fall out the bottom and 30% top.

$\bar{\mathrm{H}}$ Gravity in ALPHA-g

- We can add a bias field : $B_g = m_{\bar{H}} \bar{g} \Delta z / \mu_B$ to the bottom





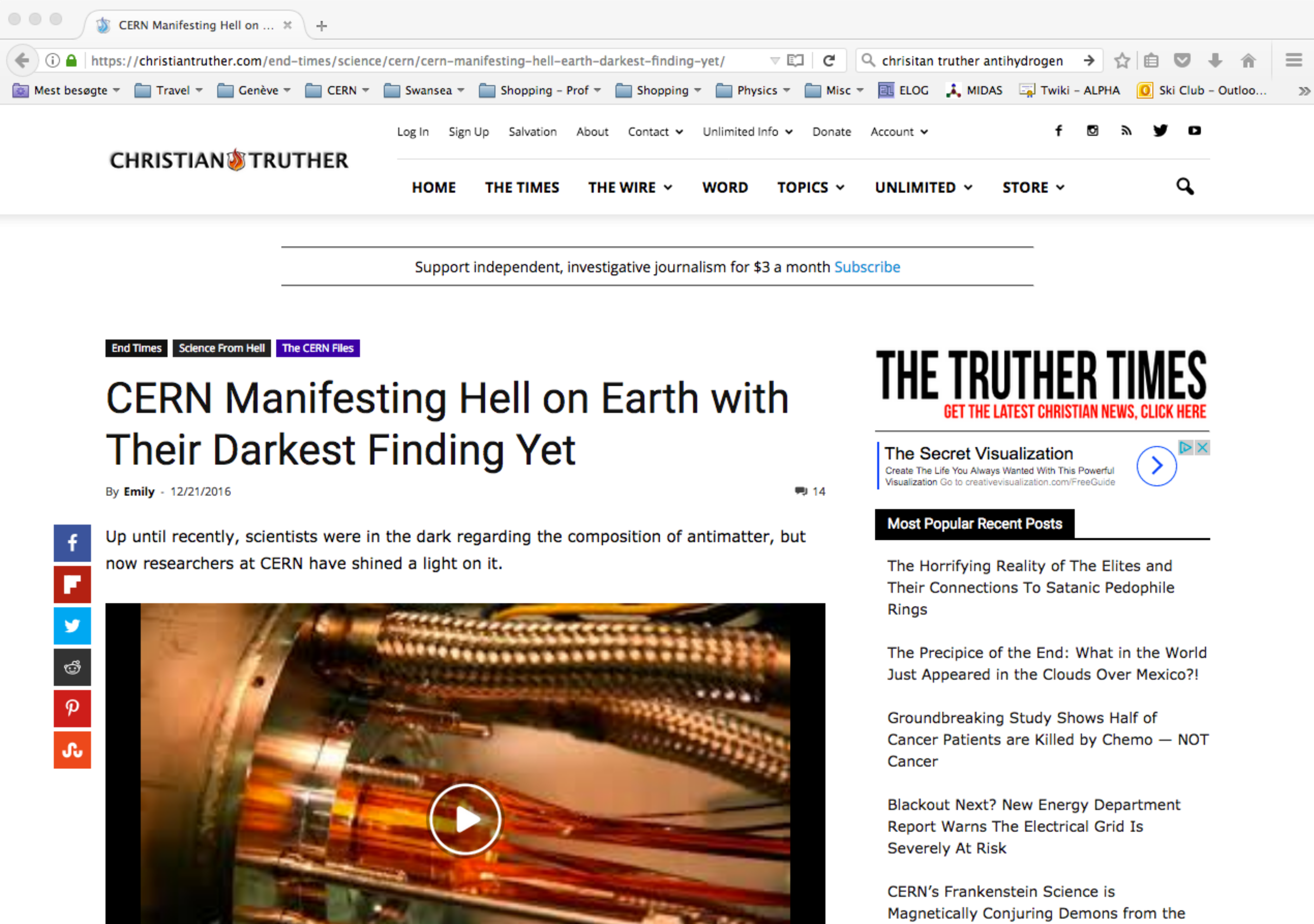
- 2022: ALPHA-g operational and trapping antihydrogen. Analysis of gravity measurement attempts ongoing.

Outlook

- Antihydrogen gravity
- Improved resolution of 1S-2S and cc component* (with laser-cooling!).
- Observing first photons from antihydrogen.
- Rydberg constant, Lamb shift, antiproton charge radius… (1S→3S?, 2S→3S?, 2S→4S?)
- Further improvements of GS HF splitting
- More $\bar{H}$ with sympathetically cooled positrons

*cc component tentatively observed in 2018

Thank you for listening…



CERN Manifesting Hell on ...

https://christiantruther.com/end-times/science/cern/cern-manifesting-hell-earth-darkest-finding-yet/

chrisitan truther antihydrogen

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CERN Manifesting Hell on Earth with Their Darkest Finding Yet

By **Emily** - 12/21/2016 14

Up until recently, scientists were in the dark regarding the composition of antimatter, but now researchers at CERN have shined a light on it.

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