In situ magnetic-field diagnostics for a 4 ppm measurement of the antihydrogen hyperfine splitting

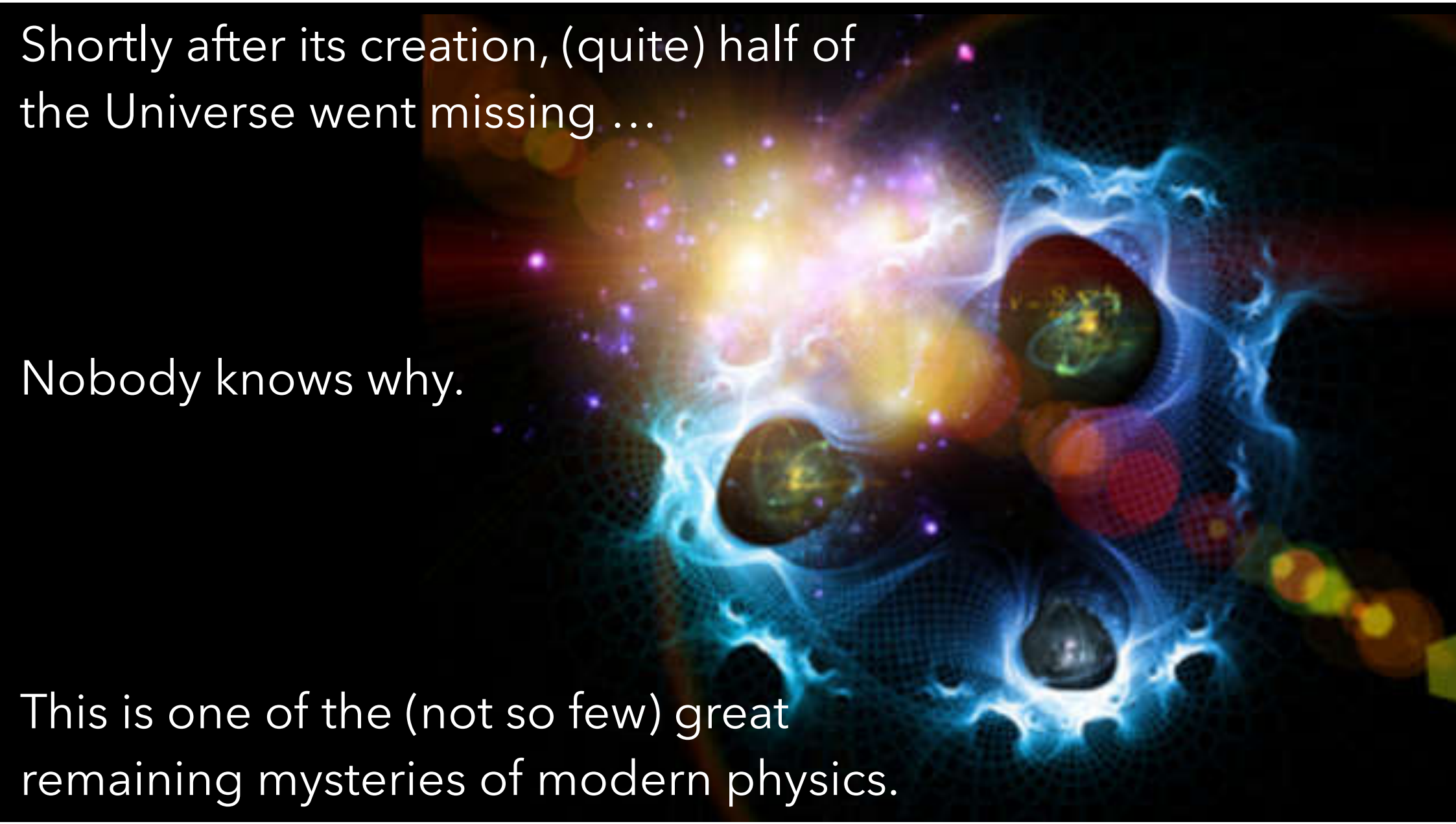
R. Akbari et al. (ALPHA), Nature 653, 1022 (2026)

Germano Bonomi

University of Brescia & INFN Pavia — on behalf of the ALPHA Collaboration

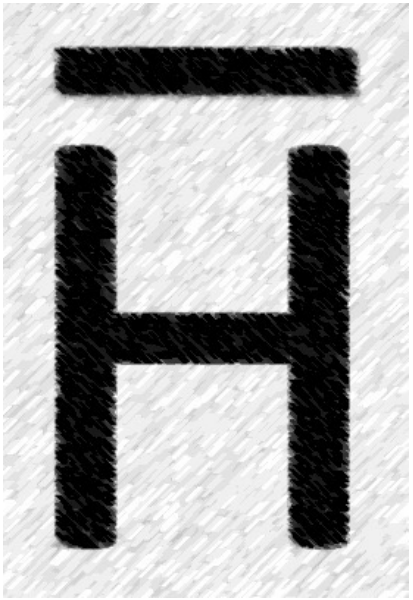
ICFDT8 · 8th International Conference on Frontier in Diagnostic Technologies · Frascati, 19–21 October 2026

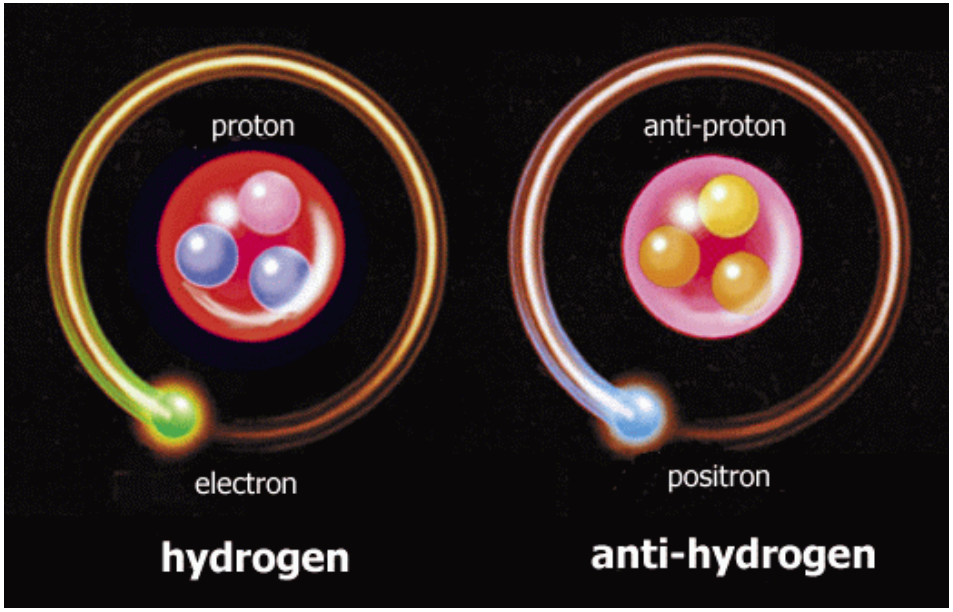



Shortly after its creation, (quite) half of
the Universe went missing …
Nobody knows why.
This is one of the (not so few) great
remaining mysteries of modern physics.

It would be nice to have an anti-world in a test tube

Antihydrogen





- **Antiproton + positron**: the mirror image of hydrogen
- CPT symmetry ⇒ **identical spectra** for H and $\bar{H}$
- Hydrogen is one of the best-known systems in physics: the 1S hyperfine line (21 cm) is known to **7 parts in 10^{13}**

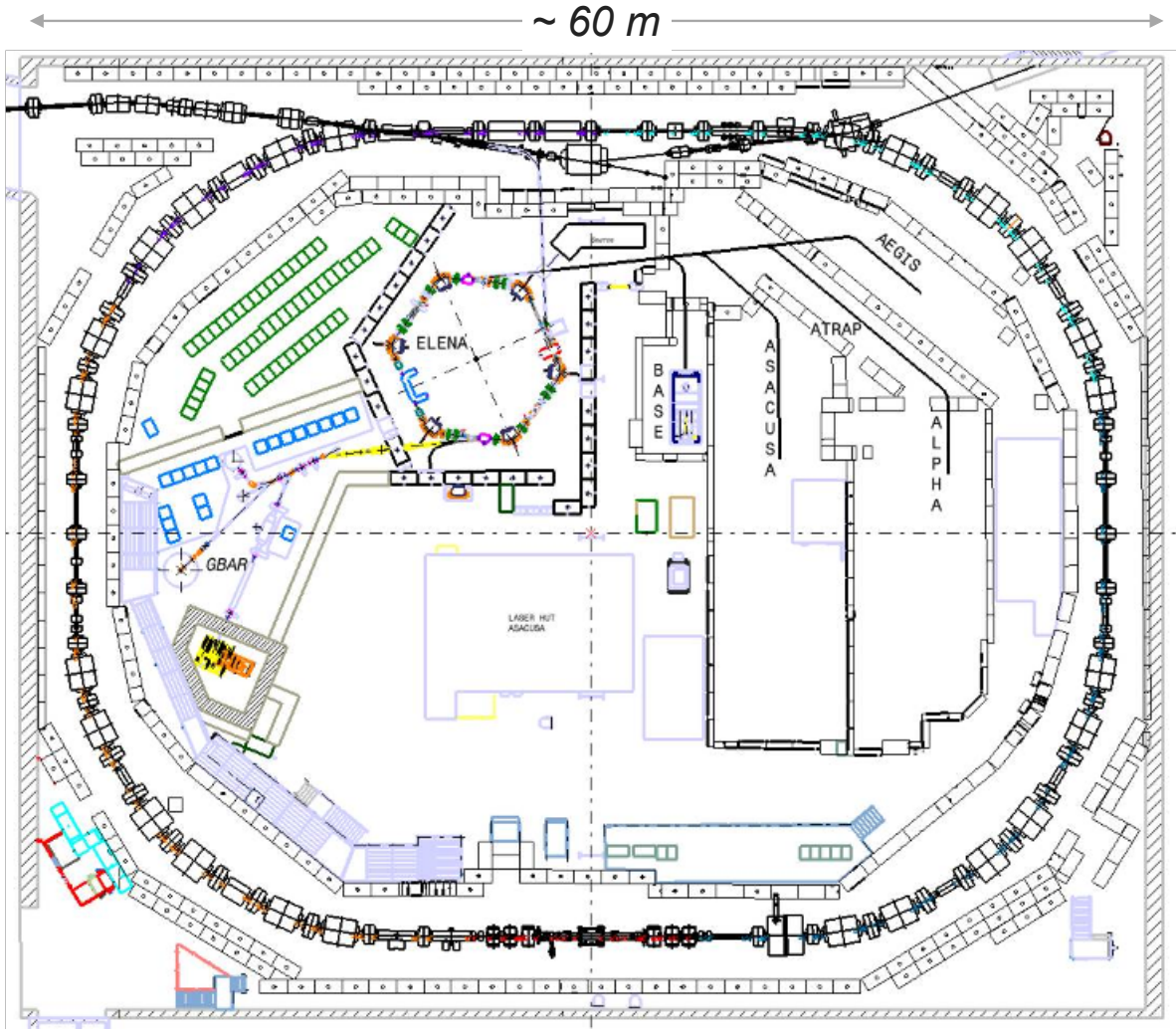
Precision spectroscopy of trapped antihydrogen is a direct test of CPT invariance

- *Any difference would point to physics beyond the Standard Model*


393
ANTIMATTER
FACTORY
ELENA

CERN Antimatter Factory

Antihydrogen



Two accelerators in tandem

- **AD** (Antiproton Decelerator) since 2000
  - Decelerates antiprotons to 5 MeV kinetic energy
- **ELENA** (Extra Low ENergy Antiproton ring) since 2018
  - ~10^7 antiprotons at **100 keV** per bunch, every ~120 s

Positrons for anti-hydrogen are produced "in-house" with a ^{22}Na source

Experiments on the floor:
*BASE, AEgIS, **ALPHA**, ASACUSA, GBAR, PUMA*

The ALPHA experiment

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

INFN (Firenze, Pavia, Pisa)
G. Bonomi, A. Del Vincio, S. Stracka, G. Tino, C. Mancini

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

Cockcroft Institute, UK

York University, Canada

4

The ALPHA experiment

ALPHA-2 antihydrogen spectroscopy

Trapped antihydrogen *Nature 468 (2010)*

Confinement of antihydrogen for 1,000 s *Nature Phys. 7 (2011)*

Resonant quantum transitions in trapped $\bar{H}$ *Nature 483 (2012)*

Observation of the hyperfine spectrum of $\bar{H}$ *Nature 548 (2017)*

Observation of the 1S–2S transition in trapped $\bar{H}$ *Nature 541 (2017)*

Observation of the 1S–2P Lyman-α transition *Nature 561 (2018)*

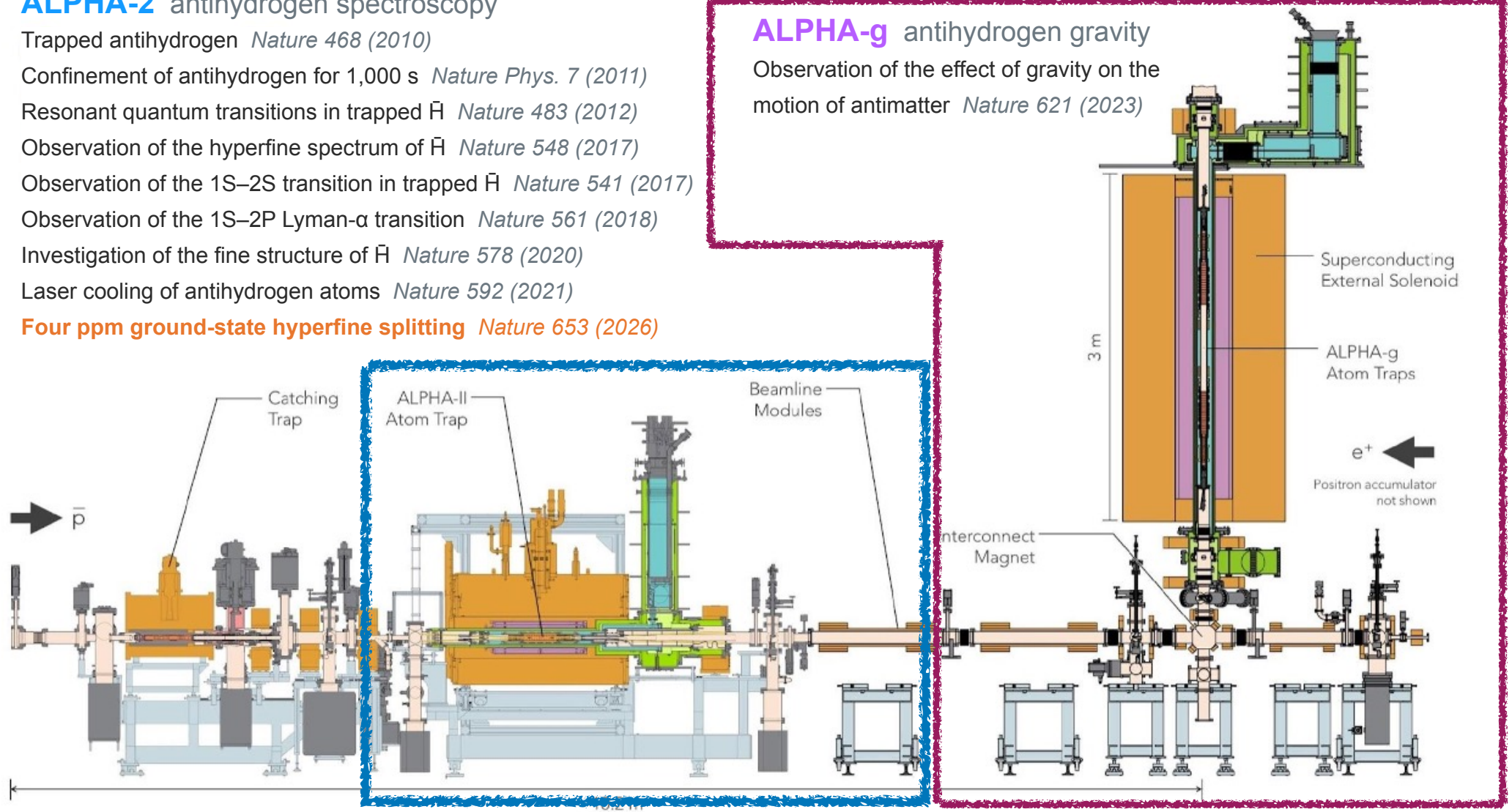
Investigation of the fine structure of $\bar{H}$ *Nature 578 (2020)*

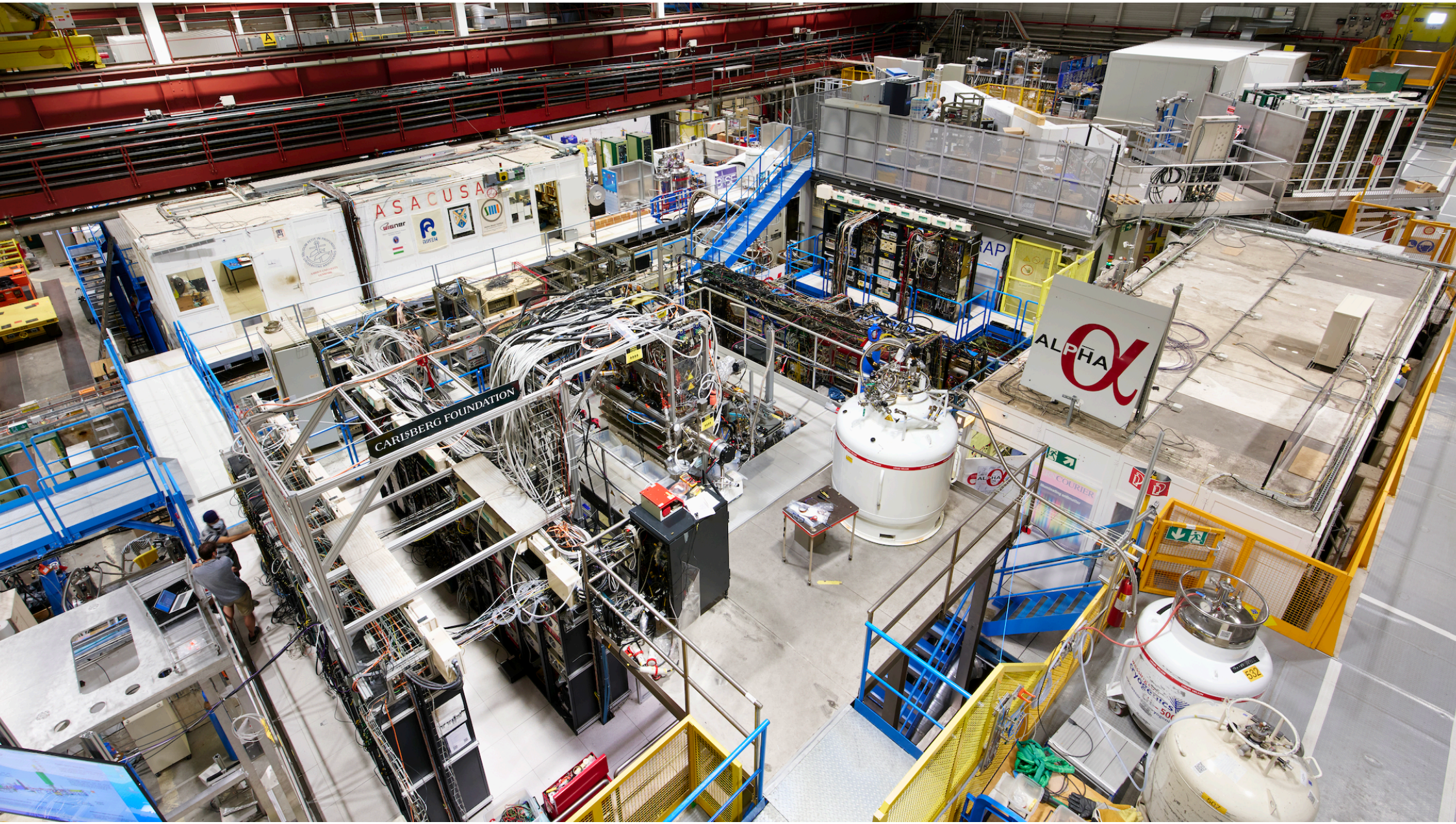
Laser cooling of antihydrogen atoms *Nature 592 (2021)*

Four ppm ground-state hyperfine splitting *Nature 653 (2026)*

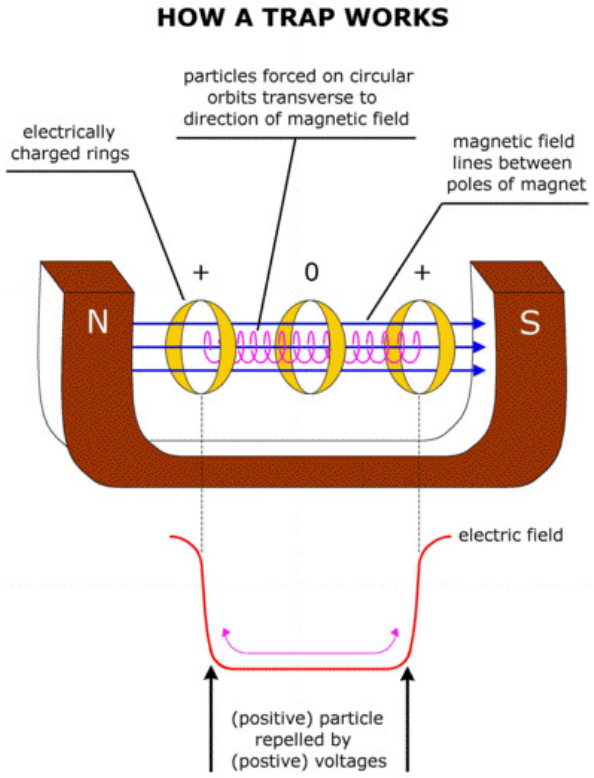
ALPHA-g antihydrogen gravity

Observation of the effect of gravity on the motion of antimatter *Nature 621 (2023)*



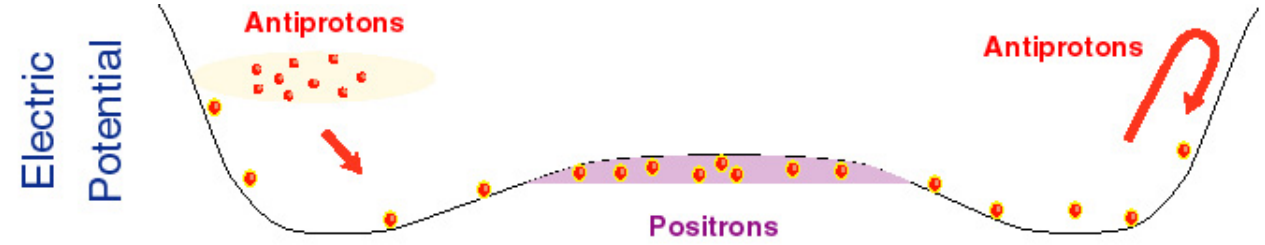

ASACUSA
CARLSBERG FOUNDATION
ALPHA

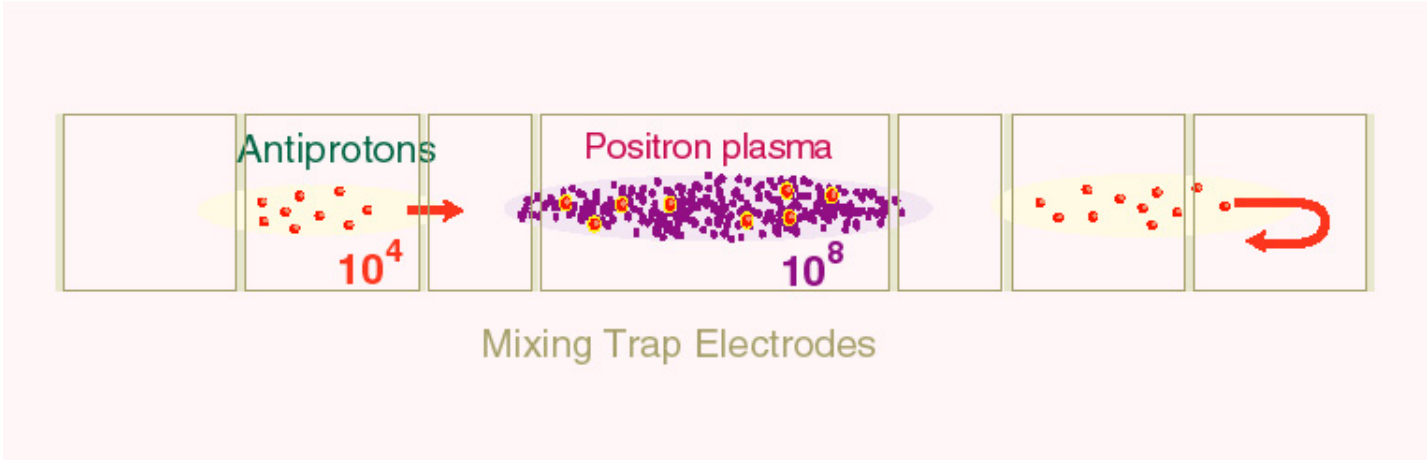
Making anti hydrogen



Scheme proposed by
G. Gabrielse et al., Phys. Lett. A 129, 38 (1988)

Antihydrogen





- **Charged particles:** axial magnetic field confines radially, electrode voltages confine axially
- **Antiprotons** (from ELENA) and **positrons** (^{22}Na source) are cooled, compressed and merged

Antihydrogen

How to trap antihydrogen?

Antihydrogen has a dipole magnetic moment => gradients of the magnetic field are used

How to detect antihydrogen?

Making it annihilate and detecting annihilation byproducts with particle detectors

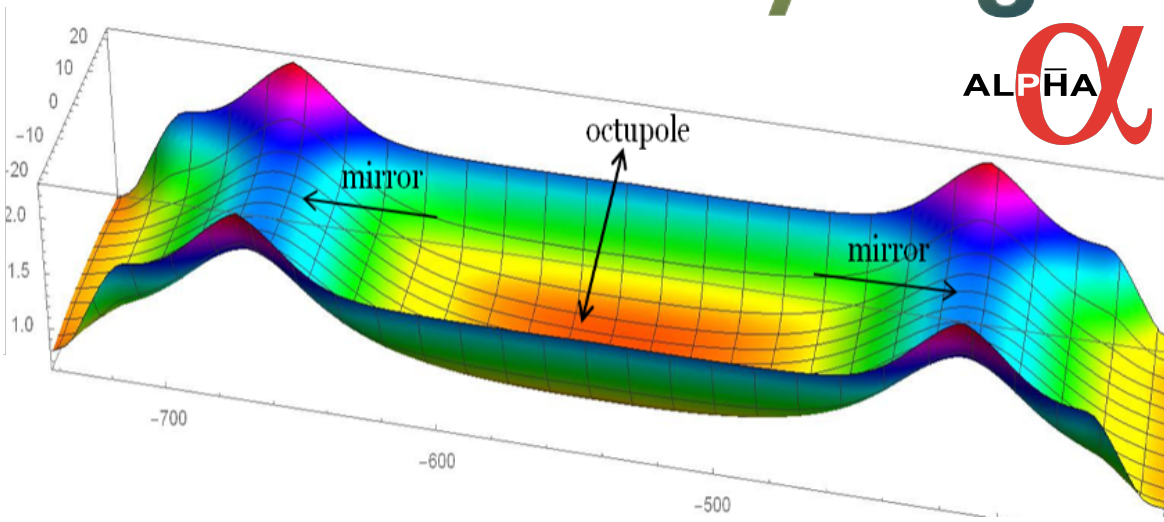
Antihydrogen in a trap

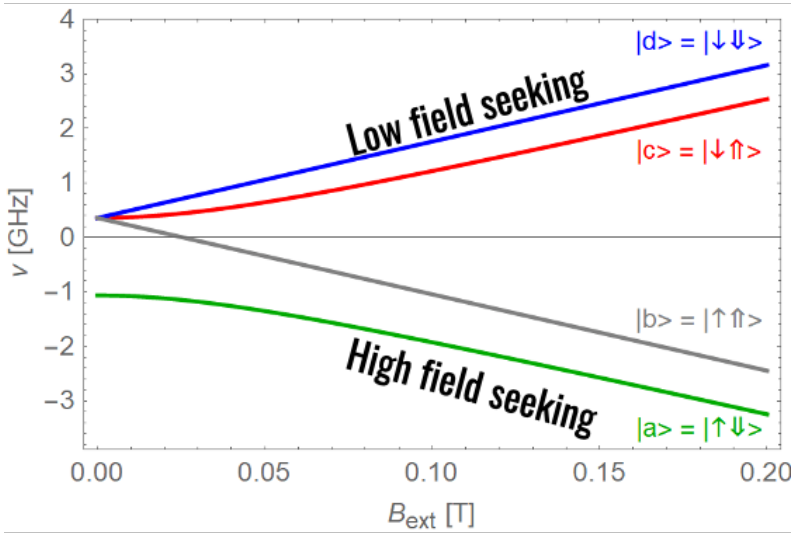
- **Neutral atom:** trapped by its magnetic moment, U = **−μ·B**
  - minimum-|B| trap: octupole (radial) + mirror coils (axial), inside a 1 T solenoid
- **Well depth:** 0.54 K (≈ 50 μeV) — only the coldest atoms stay
- **Detection:** $\bar{H}$ hits the wall and annihilates; pions tracked by a 3-layer silicon vertex detector
- **Zeeman splitting of the hyperfine levels**

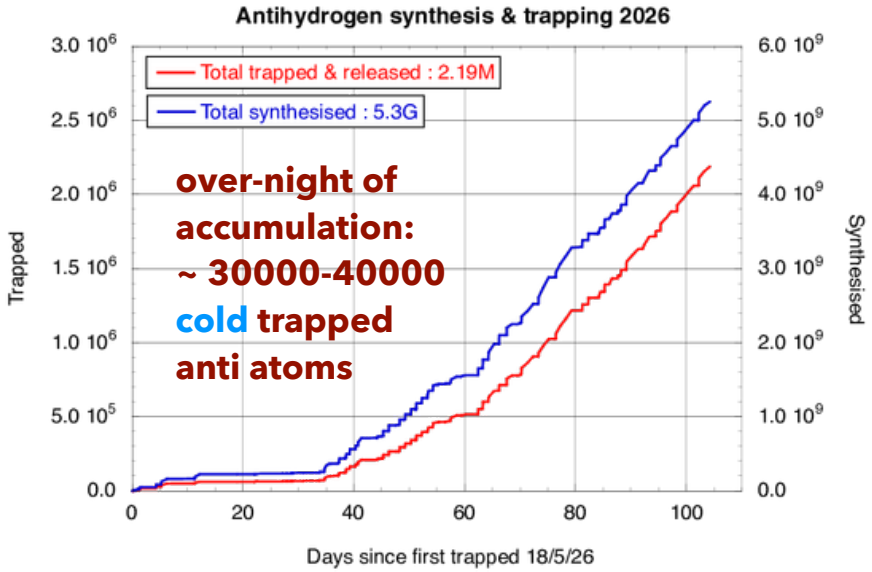
  Only low-field seekers (states |c⟩, |d⟩) are trapped

Antihydrogen

ALPHA





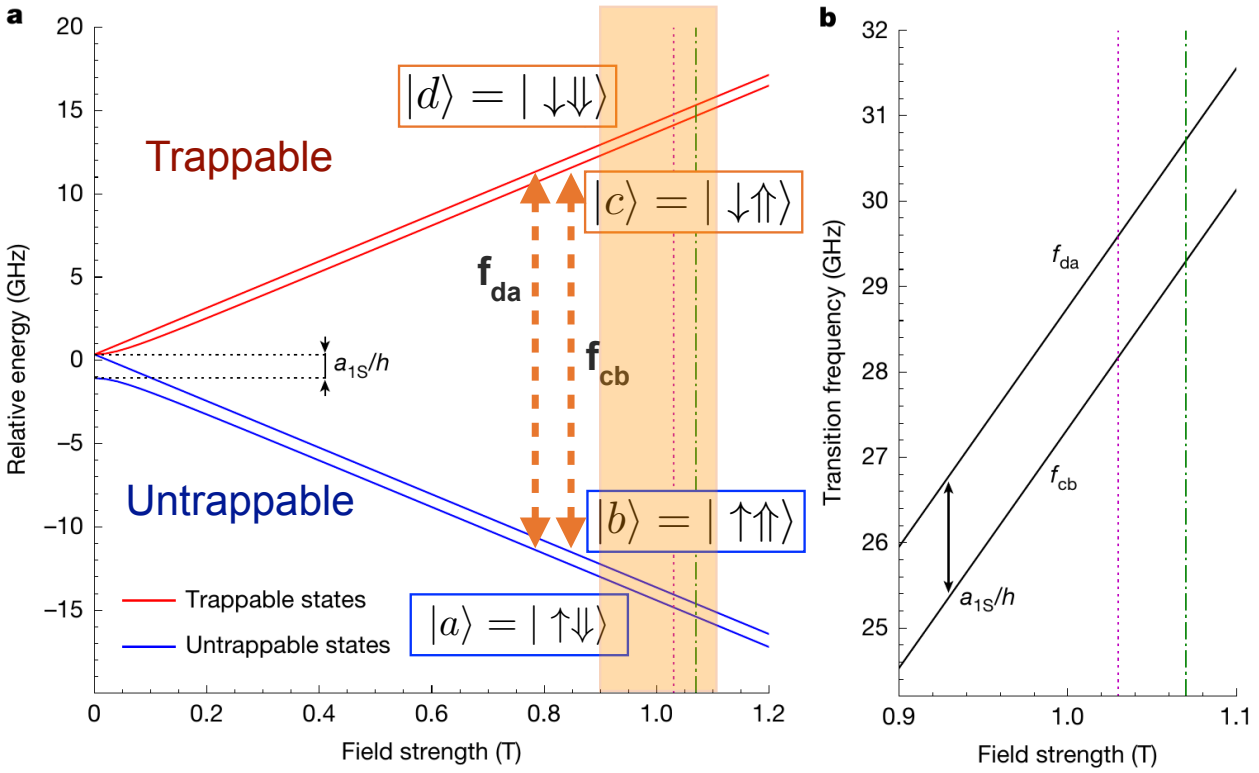


First anti-atoms produced by Athena Exp. 2002
50000 in ~ year

Alpha Exp. In 2026
Few hundred thousands in ~ 2 min

Ground state hyperfine splitting

How we do measurement : induce positron spin flips



R. Akbari et al. (ALPHA), Nature 653, 1022 (2026), Fig. 2

- Ground state split into **four hyperfine sublevels**
- Drive **|c⟩→|b⟩** then **|d⟩→|a⟩** with 28–31 GHz microwaves; flipped atoms are expelled and annihilate
- Breit–Rabi: at the same field B

  $a_{1S}/h = f_{da}(B) - f_{cb}(B)$

$df_{da}/dB \approx df_{cb}/dB \approx 28$ GHz/T

1 μT (0.01 G) field change ⇒ 28 kHz shift ≈ 20 ppm of a_{1S}

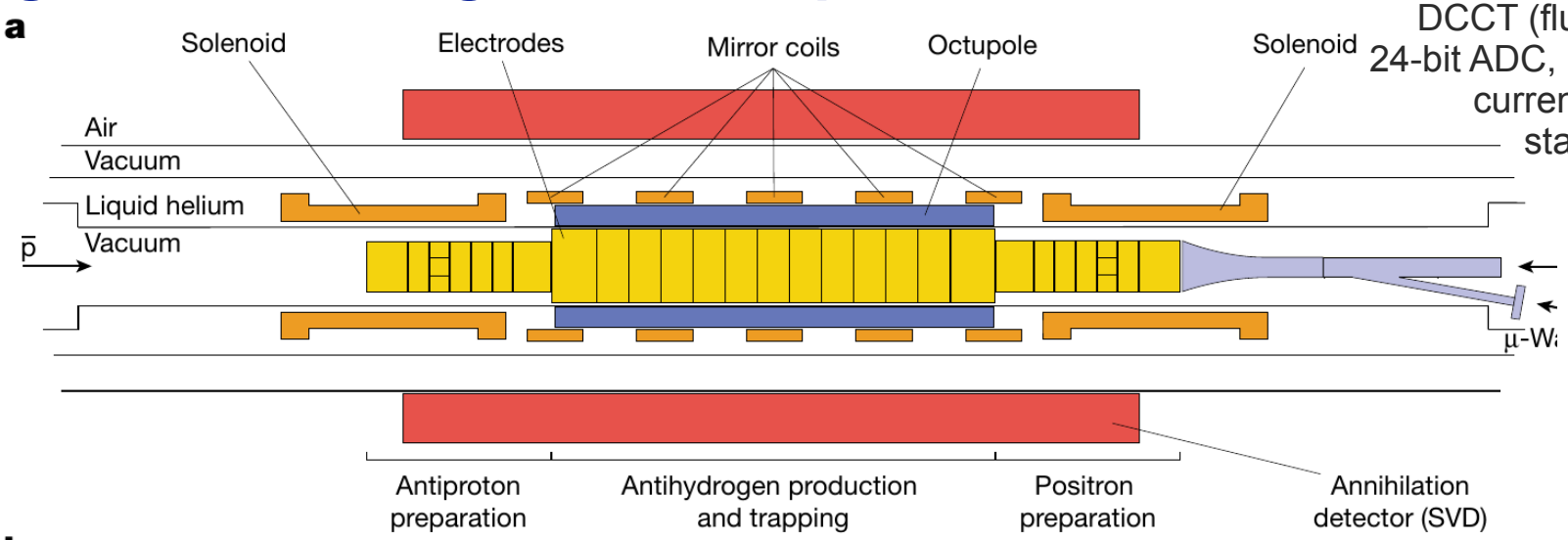
the field must be controlled and known far below 1 ppm

Take away: for precise HFS measurement => high control on B

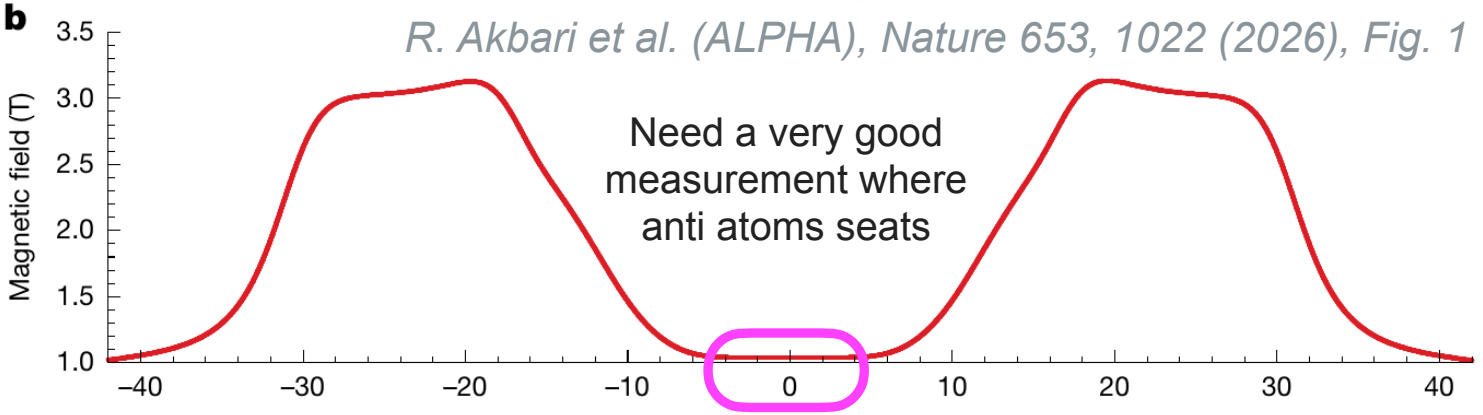
Ground state hyperfine splitting

The challenge: an inhomogeneous trap

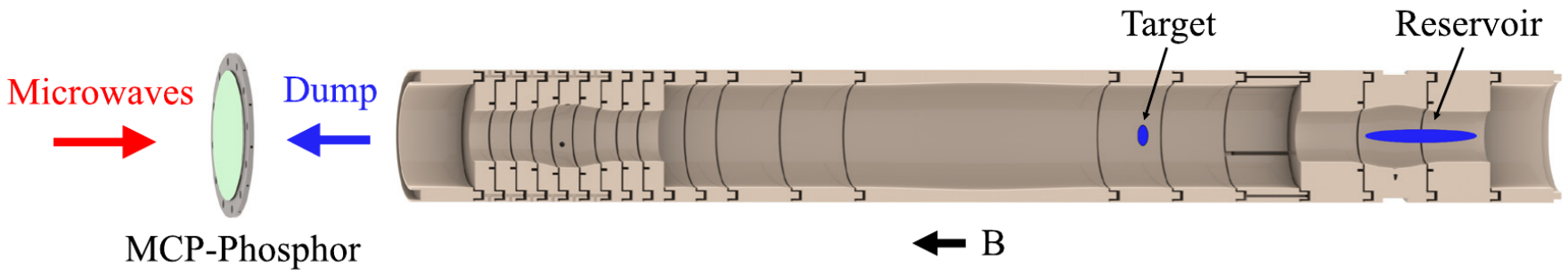
Magnet currents
DCCT (fluxgate) readout, 24-bit ADC, FPGA PID loop: currents (up to 900 A) stable to a few mA



R. Akbari et al. (ALPHA), Nature 653, 1022 (2026), Fig. 1

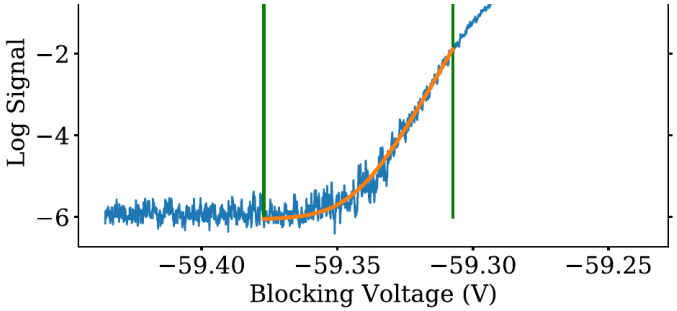


Electron Cyclotron Resonance (ECR)



E. D. Hunter et al., Phys. Plasmas 27, 032106 (2020)

1. **Prepare** a tiny electron plasma at the point to be measured
2. **Heat** with a 100 ms microwave pulse at frequency f
3. **Measure T** slowly lower the barrier, count escaping e^- (MCP + SiPM)
4. **Scan f (4 kHz steps)** the heating peak sits at the cyclotron frequency



Escaping-charge signal vs barrier voltage: the exponential tail gives T (here 99 K)

$f_c = eB/2\pi m_e$

≈ 28 GHz

same band and same microwave line as the spin-flip spectroscopy

1,500 e^-
target plasma size

0.1–0.2 mm
plasma length (radius ~1 mm)

60–120
targets per reservoir

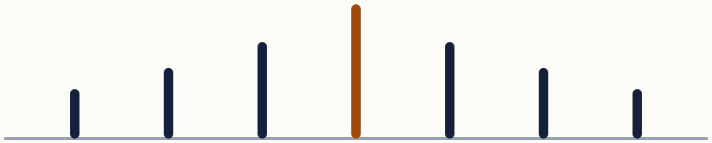
~1 min
for a complete frequency scan

The scan shows many peaks, not one

Bounce sidebands

Electrons also bounce along the axis in the well. That motion modulates the field they feel, adding a comb of peaks.

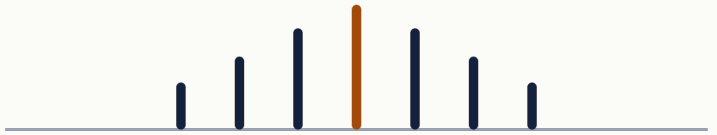
$$\omega = \omega'_c + m\,\omega_z,\ \mathrm{m} = 0, \pm1, \pm2\ldots$$



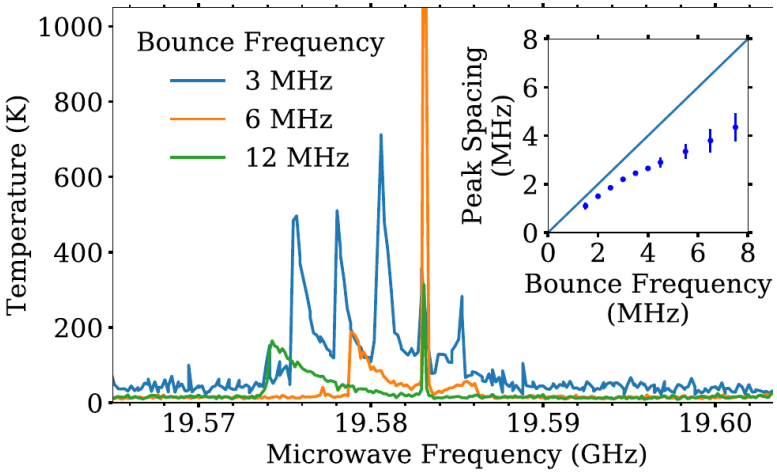
Rotation subpeaks

The plasma also rotates slowly, so each peak splits into a cluster of subpeaks.

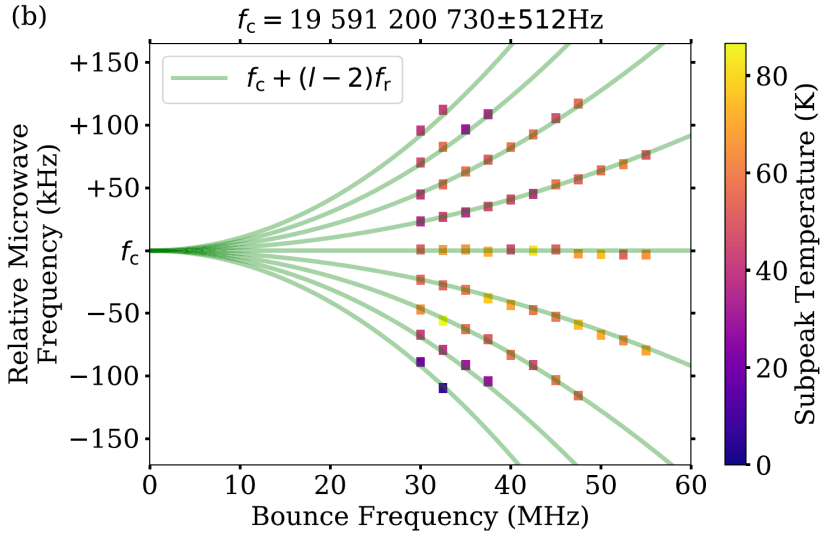
$$\delta\omega = (l-2)\,\omega_r,\ \omega_r \approx \omega_z^2 / 2\omega_c$$



Changing the depth of the trapping well, change the bounce frequency **ω_z**, so every sideband shifts, except the **m = 0 peak(s)** which does not move.

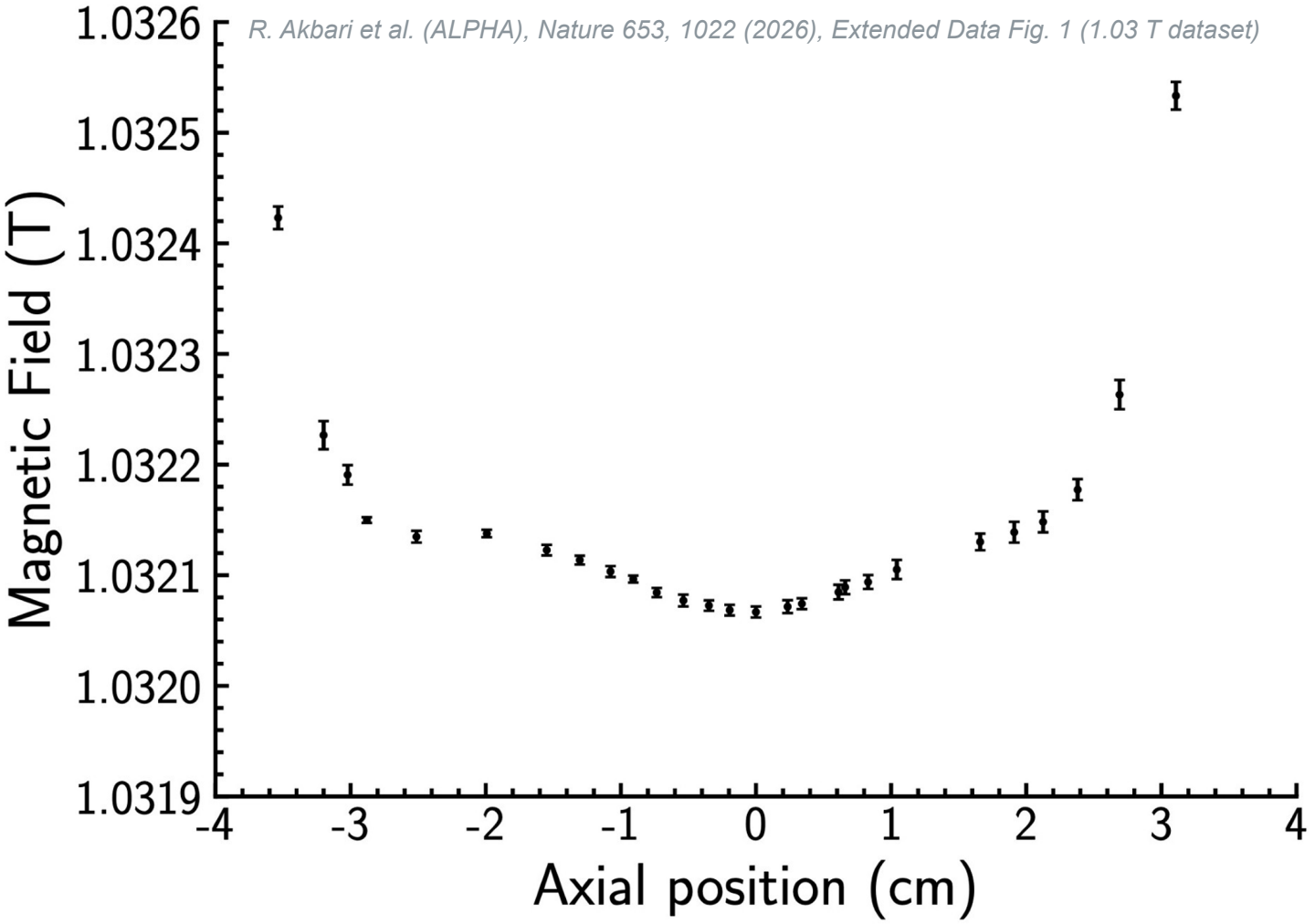


In situ	no probe to insert in the 4 K vacuum
< 1ppm	Single scan ~ 3 kHz
26 ppb	Multiple scans/fits < 0.5 kHz



E. D. Hunter et al., Phys. Plasmas 27, 032106 (2020), Figs. 6 and 8

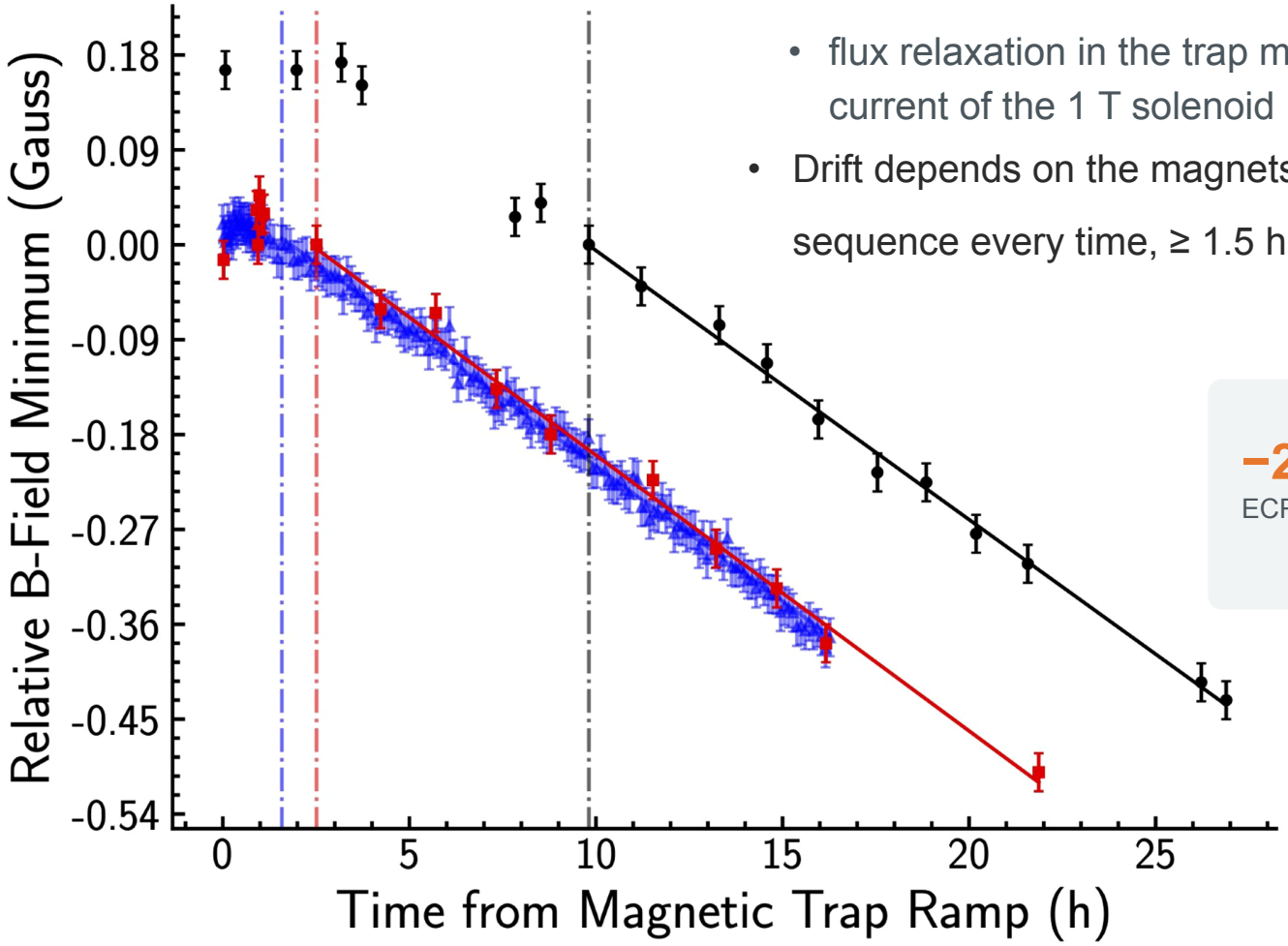
ECR in ALPHA-2: mapping the minimum as a function of Z



ECR along the axis
No measurement at higher radii

ECR in ALPHA-2: tracking the field drift as a function of time

R. Akbari et al. (ALPHA), Nature 653, 1022 (2026), Extended Data Fig. 2



- After the ramp: B_{min} rises, levels off, then **decays linearly**
  - flux relaxation in the trap magnets + decay of the persistent current of the 1 T solenoid
- Drift depends on the magnets' **history** ⇒ identical ramp sequence every time, ≥ 1.5 h wait

−2.5 μT/h
ECR slope

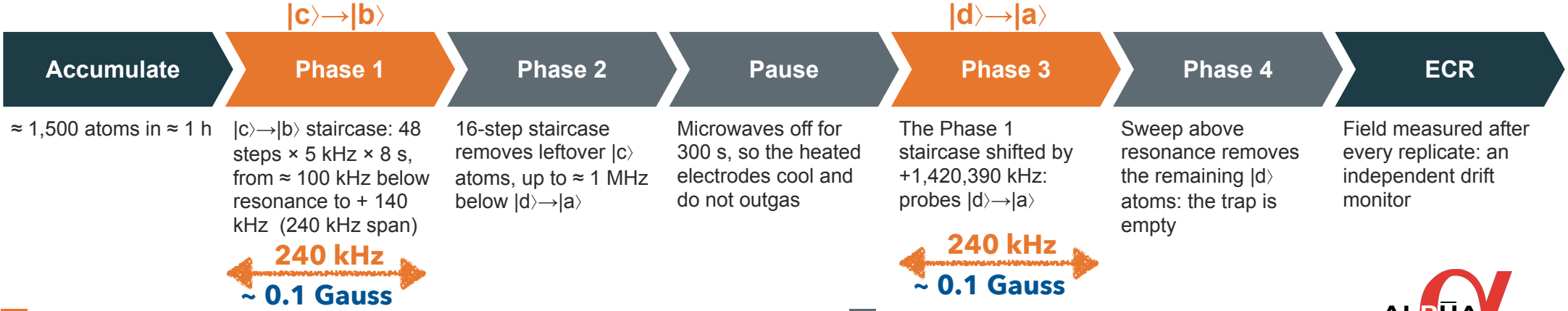
1 μT (0.01 G) field change
⇒ 28 kHz shift ≈ 20 ppm of a_{1S}

⇓

−71 kHz/h
expected spin-flip drift (±3 kHz/h)

Ground state hyperfine splitting

One measurement (replicate)



Order and direction matter

Each lines is scanned

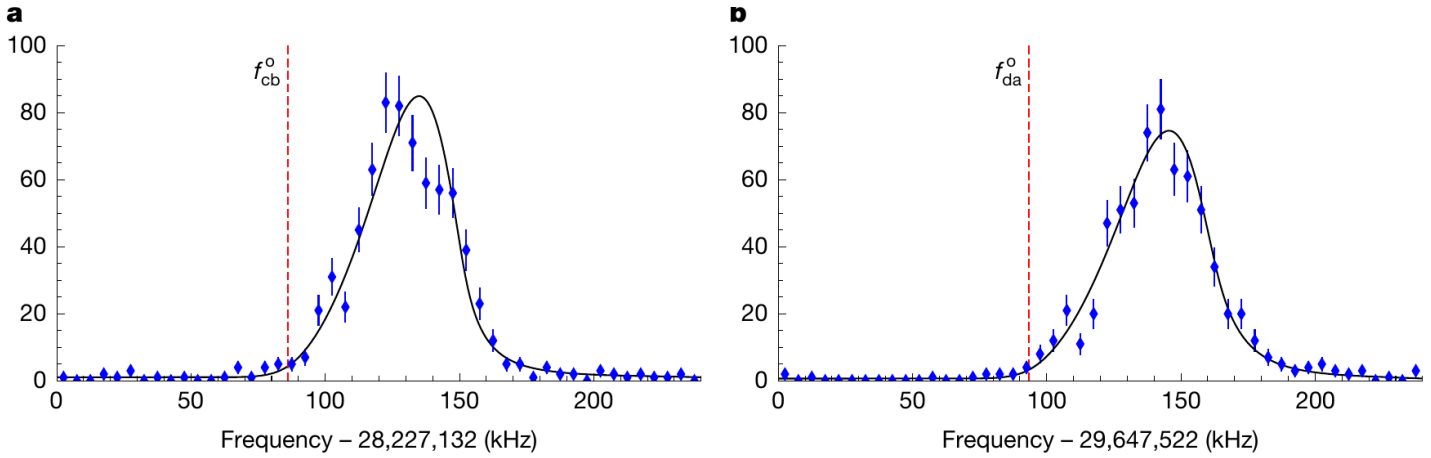
- o) from low to high frequency, to find the “onset” (first frequency at the B-minimum);
- o) c⟩→|b⟩ first, otherwise |c⟩ atoms at high field (higher radii, higher Z) may resonate during the |d⟩→|a⟩ scan.

8
replicates per base field, at minimum fields of 1.03 T and 1.07 T

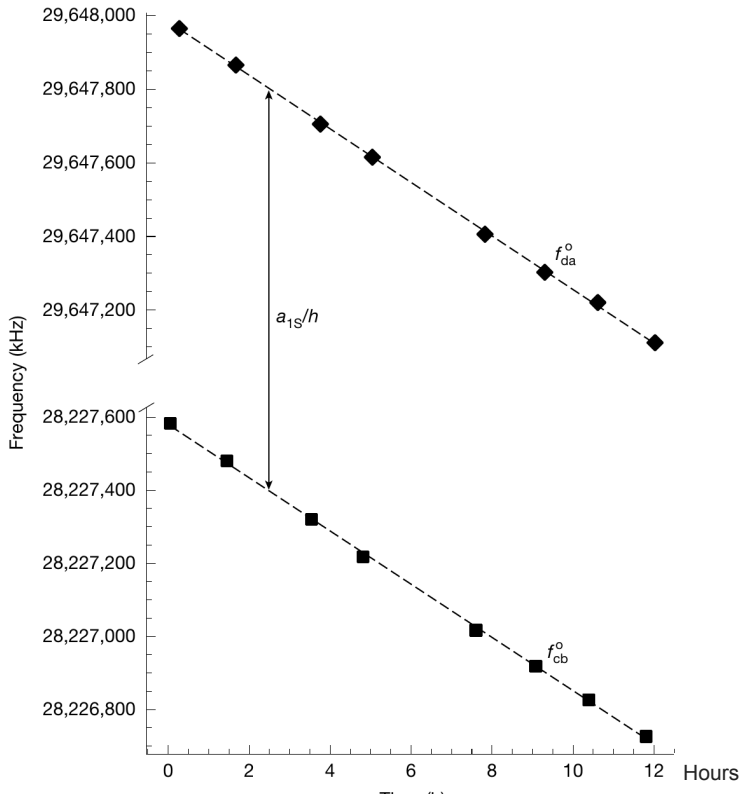
812 s
between the |c⟩→|b⟩ and |d⟩→|a⟩ scans: ≈ 16 kHz of field drift, 3× the final uncertainty

≈ 900 kHz
downward shift of the lines over 8 replicates: each staircase starts lower to stay centered

Ground state hyperfine splitting



From fit: drift slope & a_{1S}/h



- **Fit:** empirical lineshape (power-law rise ⊗ asymmetric resolution)
- **Onset frequency:** (f_{cb} & f_{da} proxies)

R. Akbari et al. (ALPHA), Nature 653, 1022 (2026), Figs. 3 and 4

From fit: −72.82 kHz/h ± 0.04 kHz/h vs ECR: −71 ± 3 kHz/h: two independent magnetometers agree

Results

$a_{1S}/h = 1\ 420\ 404.8 \pm 1.1\ (stat.) \pm 5.6\ (sys.)$ kHz

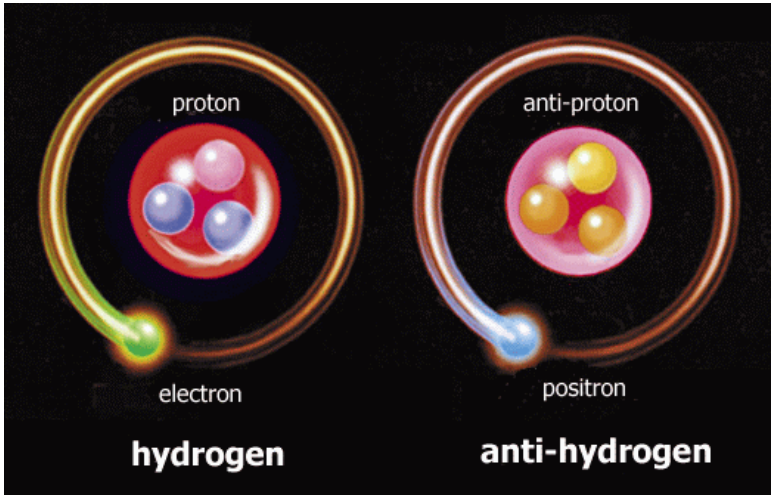
4 ppm

100× better than 2017

~24,000 anti-atoms · two base fields (1.03 T and 1.07 T) · consistent with hydrogen (1 420 405.75 kHz) and CPT

B (T)	Value (kHz)	Stat.	Reprod.	Signal model	Binning	B-drift	Total sys.
1.03	1 420 403.9	1.7	7.0	4.8	2.0	1.2	8.8
1.07	1 420 405.8	1.5	2.8	5.5	2.0	2.6	7.0

Uncertainties in kHz. Field drift contributes only 1–3 kHz once tracked.



The best measurement for hydrogen is

1 420 405 751.768 Hz ± 2 mHz

A long way to go … (*at the moment Δ = 1 kHz*)

ALPHA

Thanks



For your attention