Hyperfine structure of anti-hydrogen at ALPHA

Simone Stracka, INFN Pisa

TRIUMF Science Week - 28-31 july 2025

The ALPHA Collaboration

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Groningen, The Netherlands

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 (Pavia, Pisa) Italy

Marquette University, USA

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

University of Wales Swansea, UK

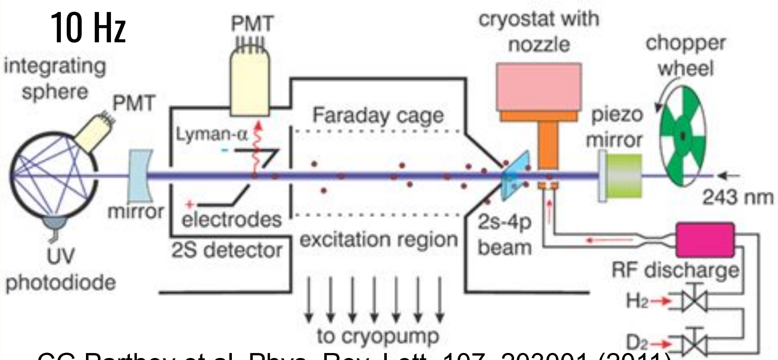
Cockcroft Institute, UK

York University, Canada

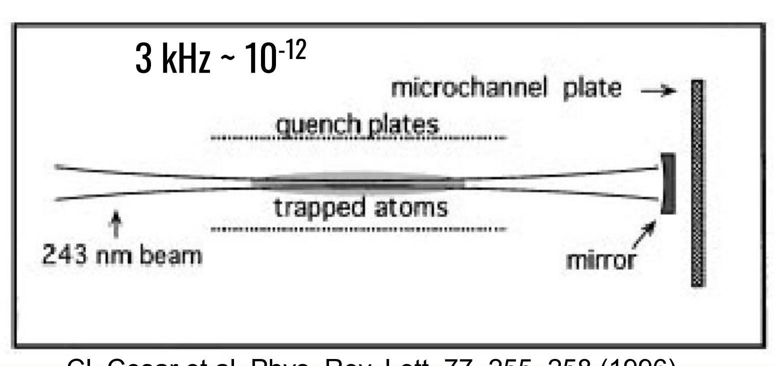
Brookhaven National Laboratory, USA

ALPHA program: antihydrogen spectroscopy and gravity

- Repeat on antihydrogen the measurements done on hydrogen over time
  - As many as it is reasonable, and maybe a few more (we don't have a wide selection of anti-elements to choose from)
- With the best achievable precision
  - A mix of old and recent techniques
  - Using today's state of the art techniques, e.g., in metrology
- Taking into account the special environment constraints imposed by dealing with antimatter
  - To study anti-atoms, we must assemble them
  - Strong inhomogeneous magnetic fields to confine anti-atoms



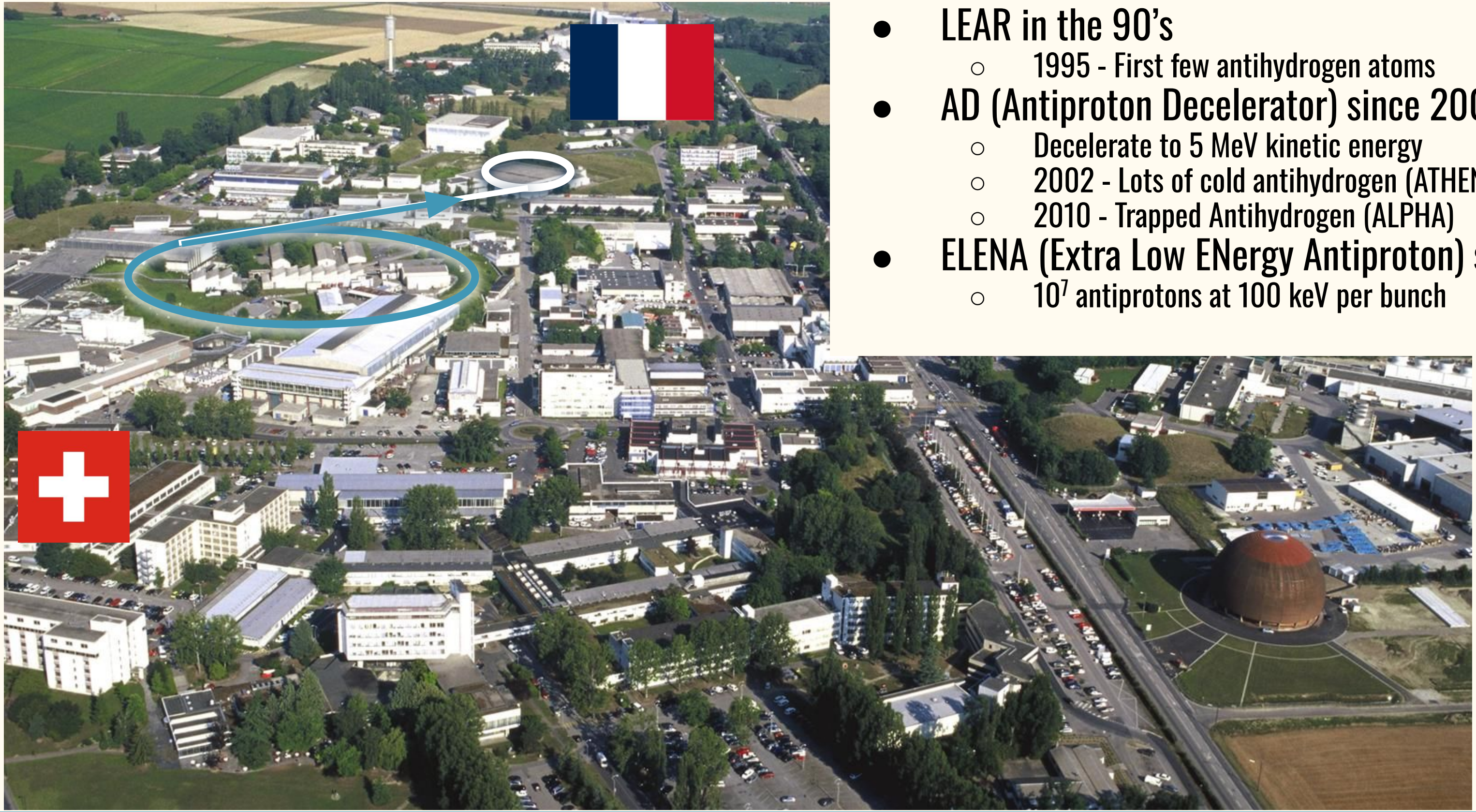
CG Parthey et al, Phys. Rev. Lett. 107, 203001 (2011)



CL Cesar et al, Phys. Rev. Lett. 77, 255–258 (1996)

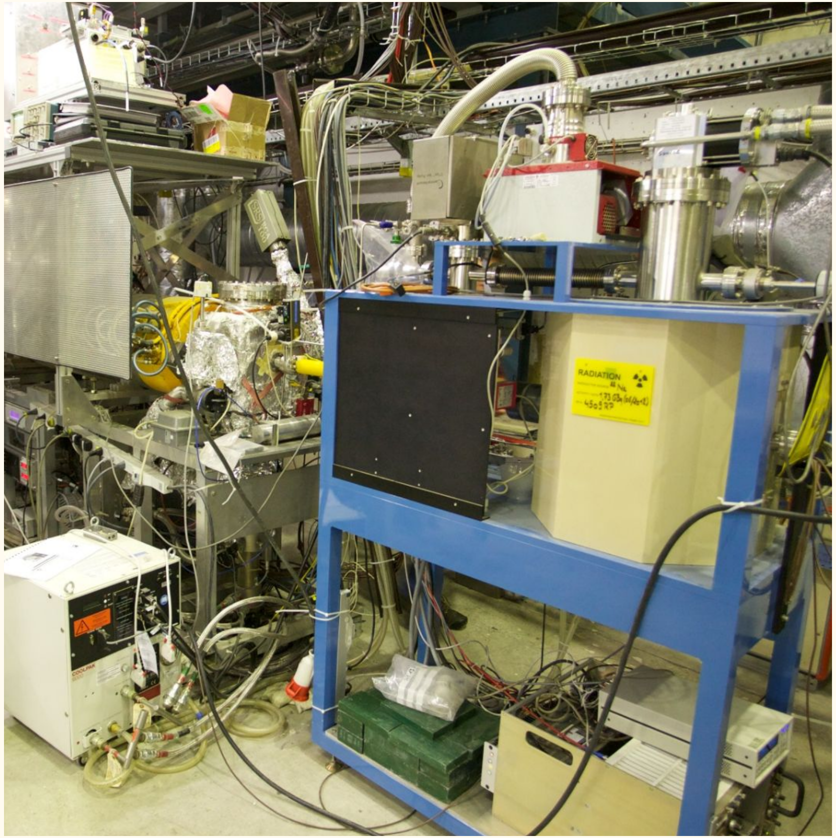
Production

The PS-AD/ELENA complex at CERN

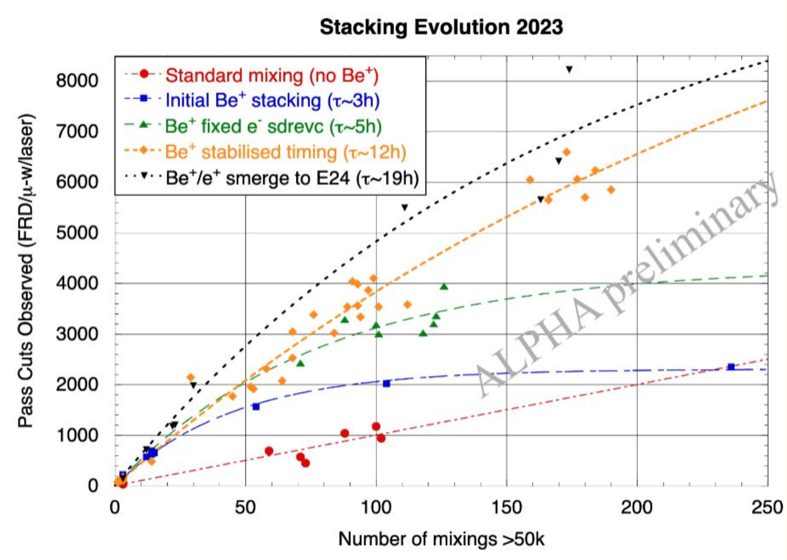


- LEAR in the 90's
  - 1995 - First few antihydrogen atoms
- AD (Antiproton Decelerator) since 2000
  - Decelerate to 5 MeV kinetic energy
  - 2002 - Lots of cold antihydrogen (ATHENA, ATRAP)
  - 2010 - Trapped Antihydrogen (ALPHA)
- ELENA (Extra Low ENergy Antiproton) since 2018
  - 10^7 antiprotons at 100 keV per bunch

Accumulating positrons



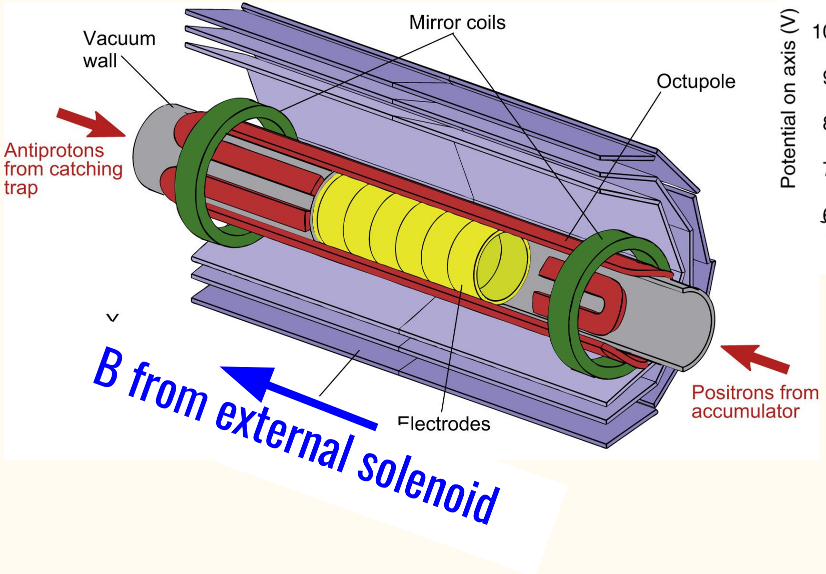
- e+ from ^{22}Na radioactive source
- sympathetically cooled with Berillium ions

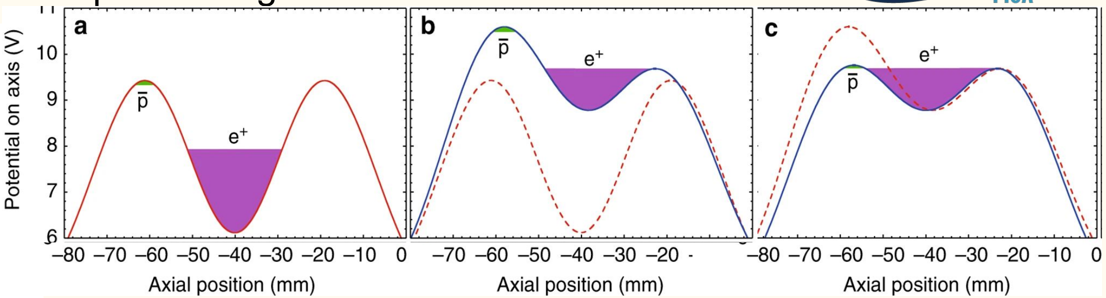


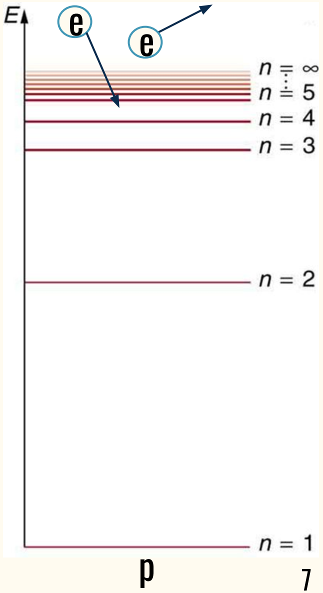
average 15 mixings per hour

Mixing positrons and antiprotons

https://doi.org/10.1038/s41467-017-00760-9





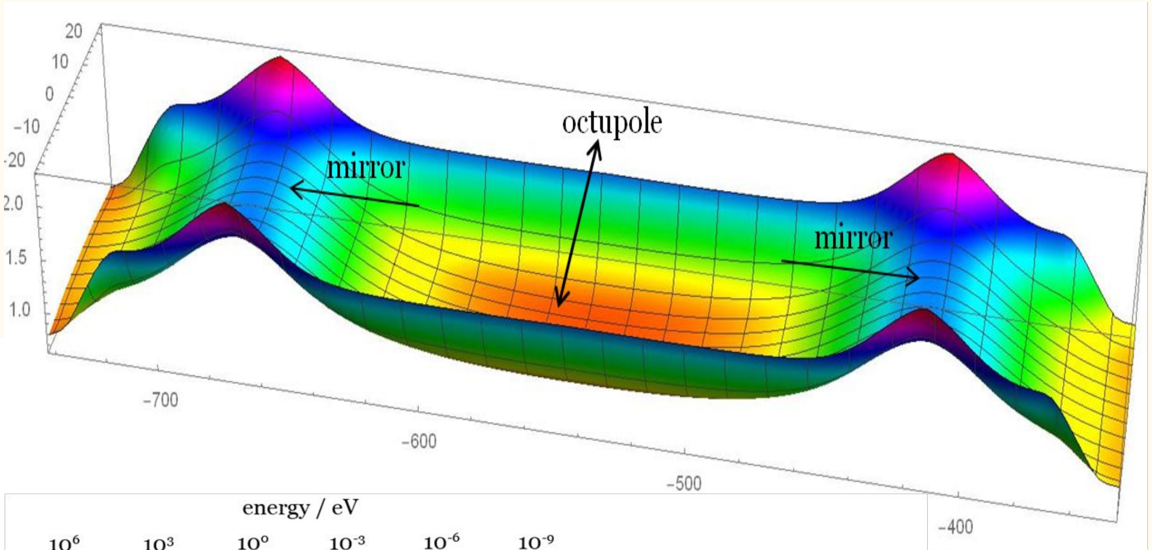


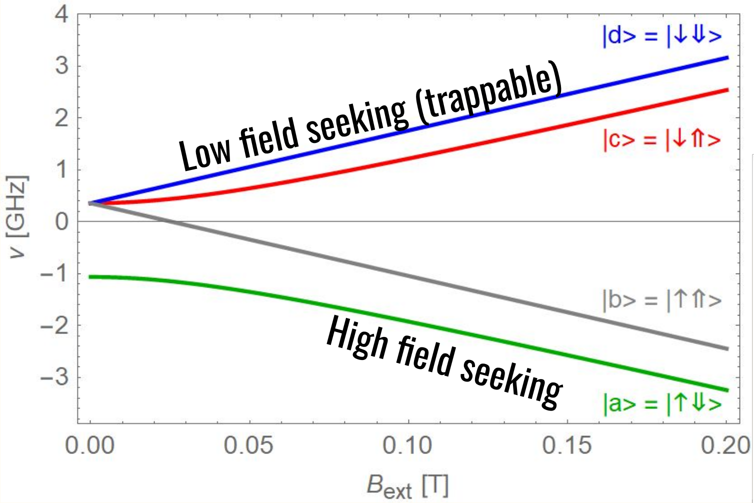
- Nested wells in the same Penning trap, with positrons separated from antiprotons
- Antiprotons are gradually moved closer to, and then into, the positron cloud
- Anti-hydrogen is formed in a three-body recombination process (1 s mixing)
  - Then quickly cascade to the ground state (τ < 0.5 s)

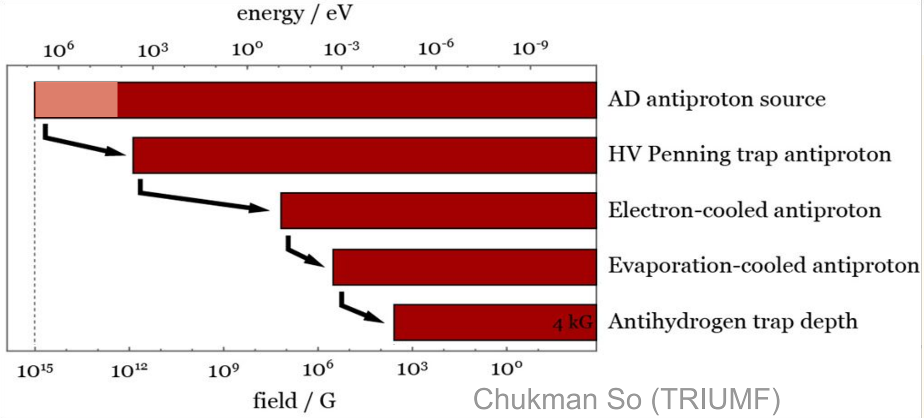
- Extra magnets to confine the produced anti-atoms

Trapping antihydrogen

- Magnetic potential well $U = -\boldsymbol{\mu}\cdot\mathbf{B}$
  - 1T background field B_{ext}
- Well depth: 0.54 K / 50 μeV
- Good vacuum
  - can keep trapped Hbar for several hours





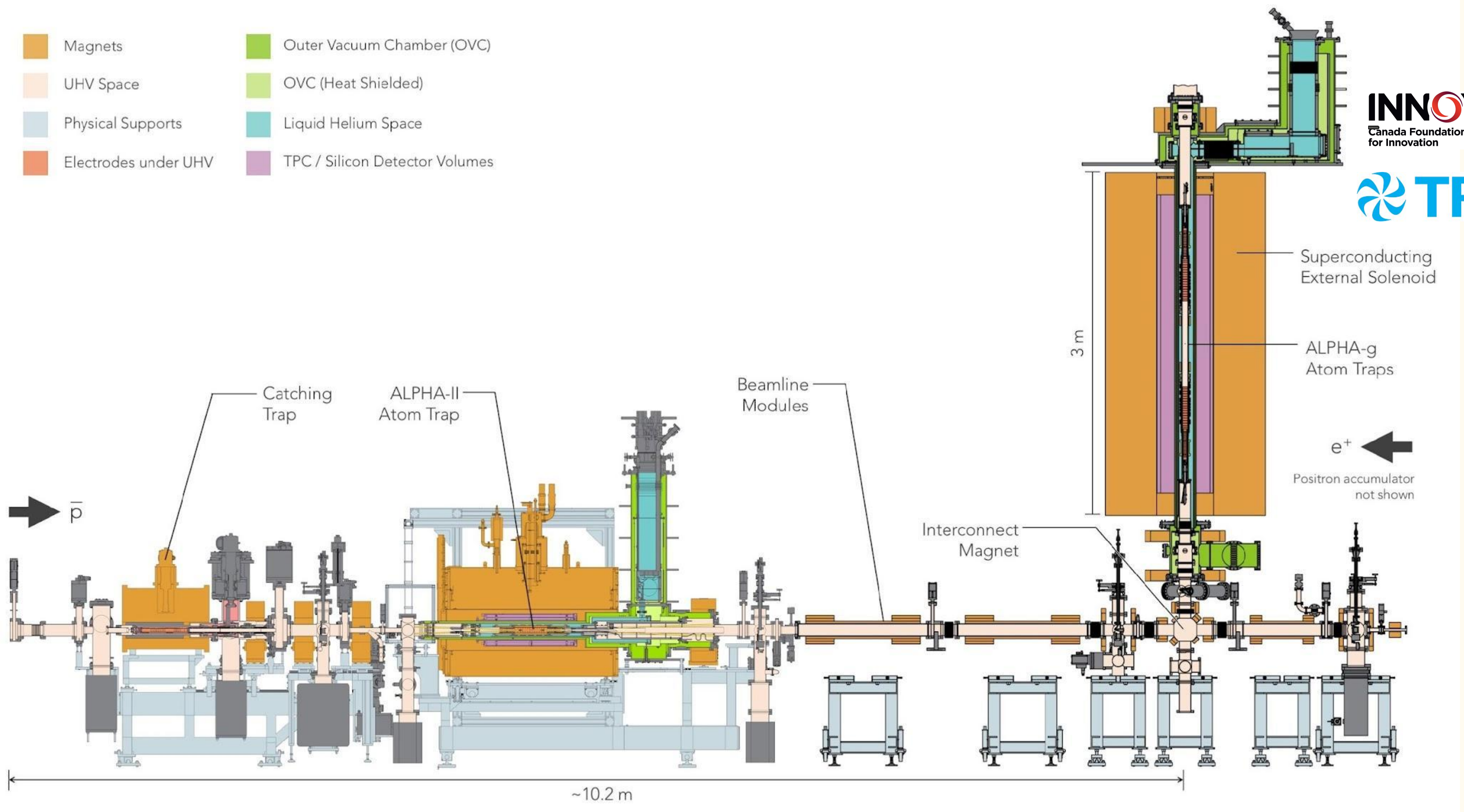


Chukman So (TRIUMF)

ALPHA-2 and ALPHA-g

- ALPHA-2 (2012-): optimized for laser spectroscopy
- ALPHA-g (2018-): optimized for control of magnetic fields
- All share the same working principles

ALPHA-2 and ALPHA-g



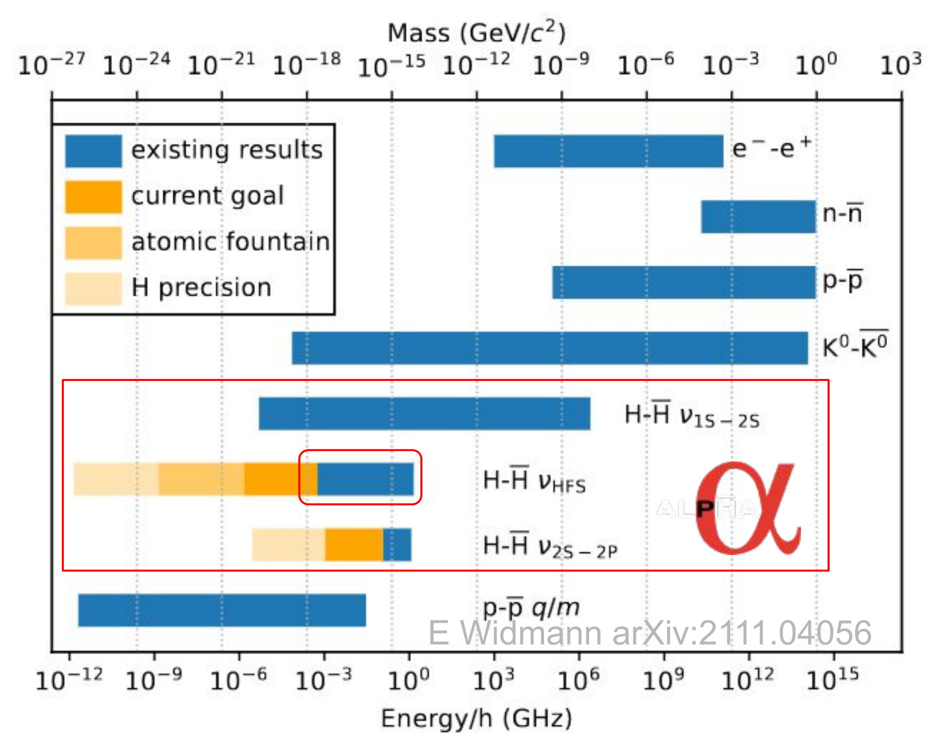
Spectroscopy timeline

- 2012: Observation of microwave driven spin-flips [Nature 483, 439]
- 2017: Observation of the 1S-2S transition [Nature 541, 506]
- 2017: Measurement of the ground-state hyperfine splitting [Nature 548, 66]
- 2018: Characterisation of the 1S-2S transition lineshape [Nature 557, 71]
- 2020: Investigation of the 1S-2P transition [Nature 578, 375]
- 2025: Hyperfine components of the 1S–2S transition [Nature Physics 21, 201]

microwave laser

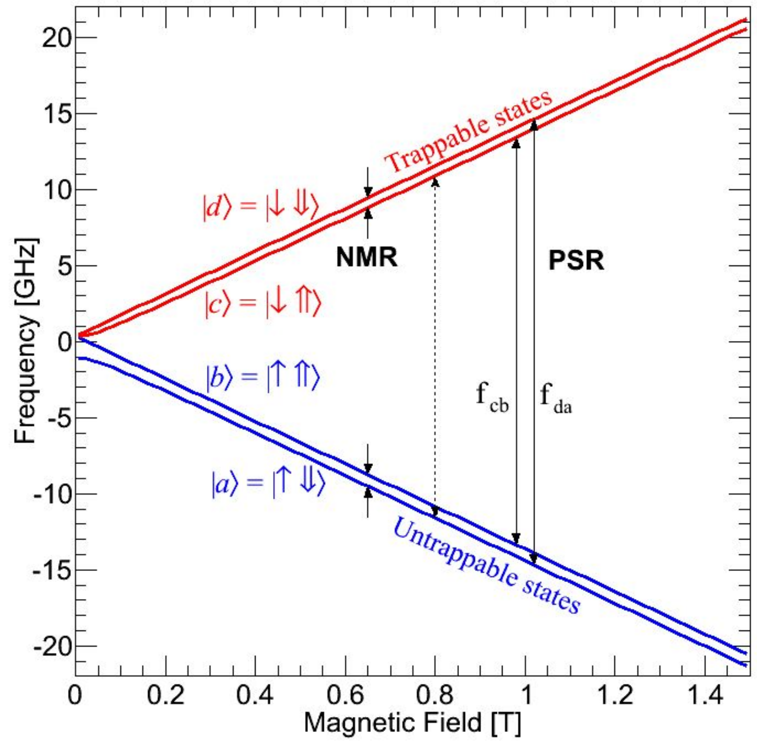
What use for antihydrogen spectroscopy?

- Compare hydrogen and antihydrogen spectra: under CPT they should be the same
    - symmetry holds in the usual (local, Lorentz invariant) QFT, but may be broken, e.g., when introducing gravity
    - different systems probe different combinations of specie-dependent operators in effective theories (SME [Kostelecky et al.])



1S-HFS Spectroscopy

Hyperfine structure of ground state antihydrogen



- c-b and d-a transitions are easily accessible
  - Microwave can travel down the Penning trap electrodes
  - Difference of frequencies ~ constant with B ("21 cm line")
  - These transitions flip the positron spin and push the atom from the trap

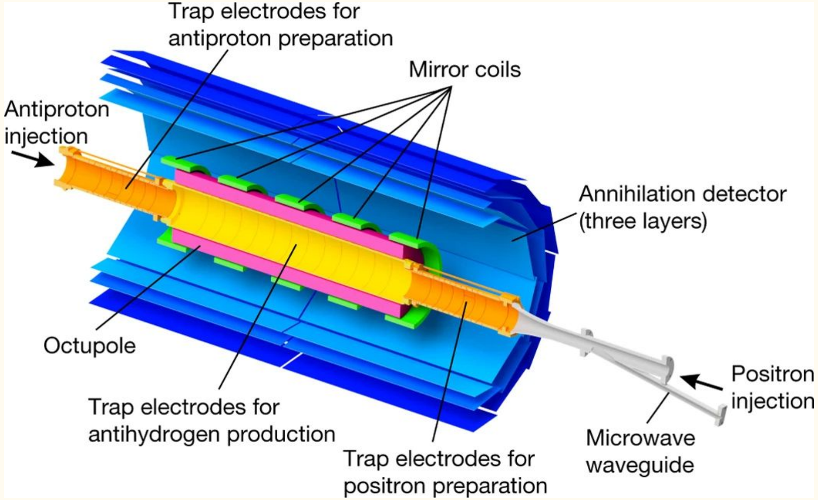
- NMR transitions below microwave frequency cutoff for Penning trap electrodes
  - 30 GHz ~ 1 cm
  - 1420 MHz ~ 21 cm
  - 650 MHz ~ 45 cm

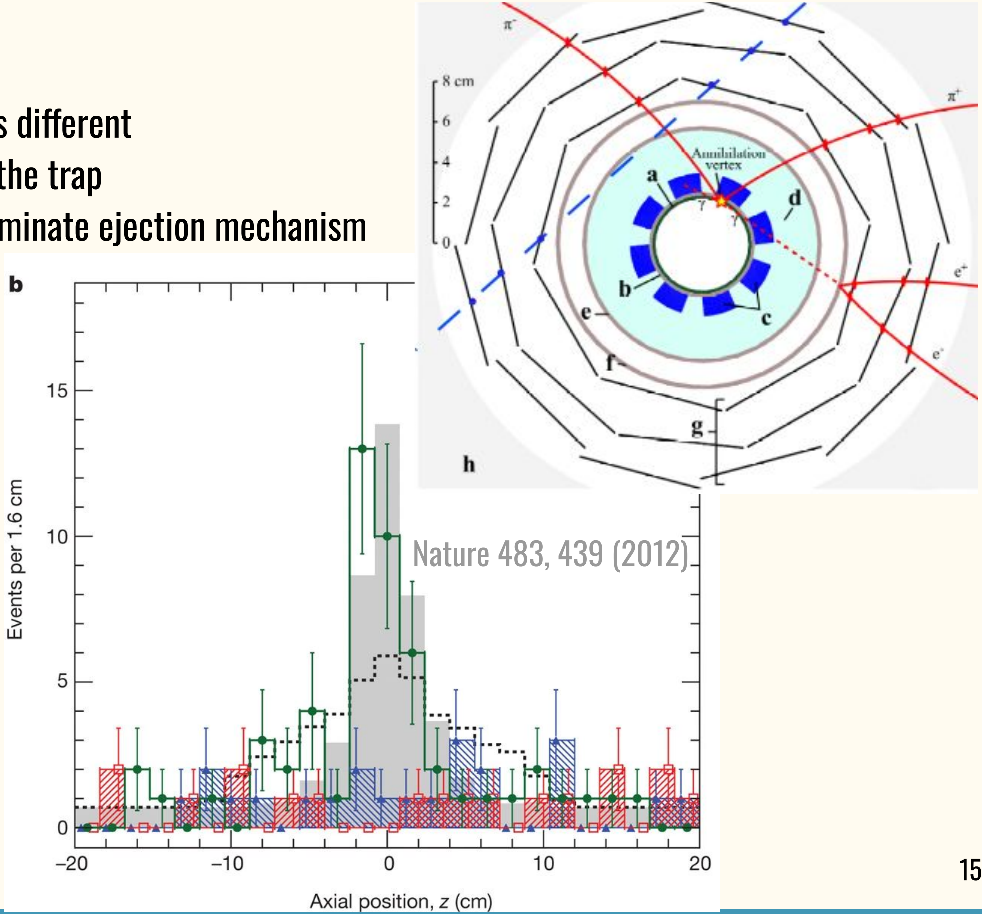
$$E = E_{n00} + \frac{\mathcal{A}}{4} \pm \mu_B B$$

$$E = E_{n00} - \frac{\mathcal{A}}{4} \pm \sqrt{\left(\frac{\mathcal{A}}{2}\right)^2 + (\mu_B B)^2}.$$

Detecting antihydrogen

- Hbar forced out of the trap annihilate
- Imaged by silicon strip detector
  - Main reducible background is cosmics: topology is different
  - Confined Hbar also annihilates on residual gas in the trap
  - Time and z profile of annihilations useful to discriminate ejection mechanism

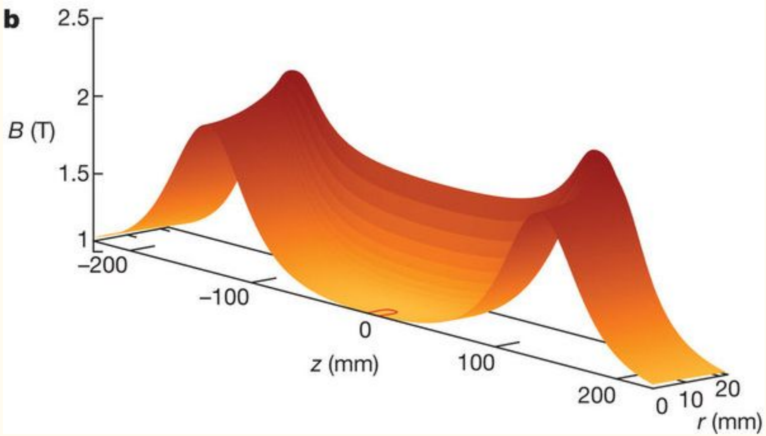


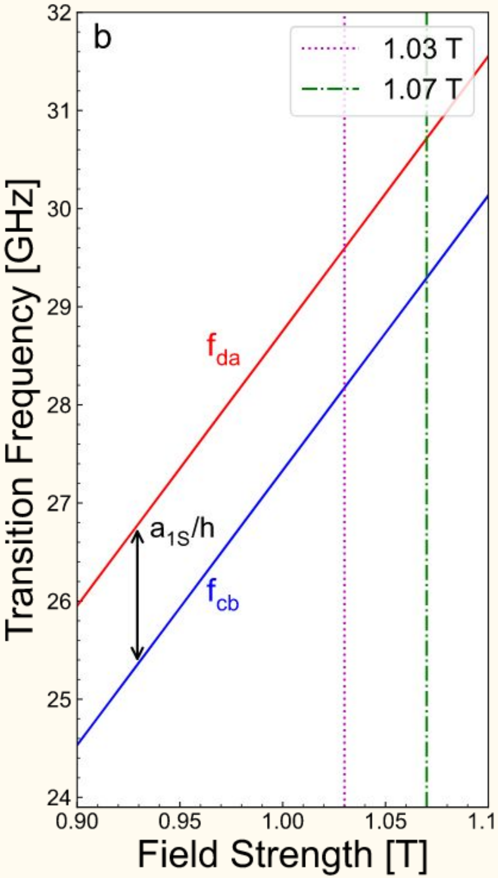


Nature 483, 439 (2012)

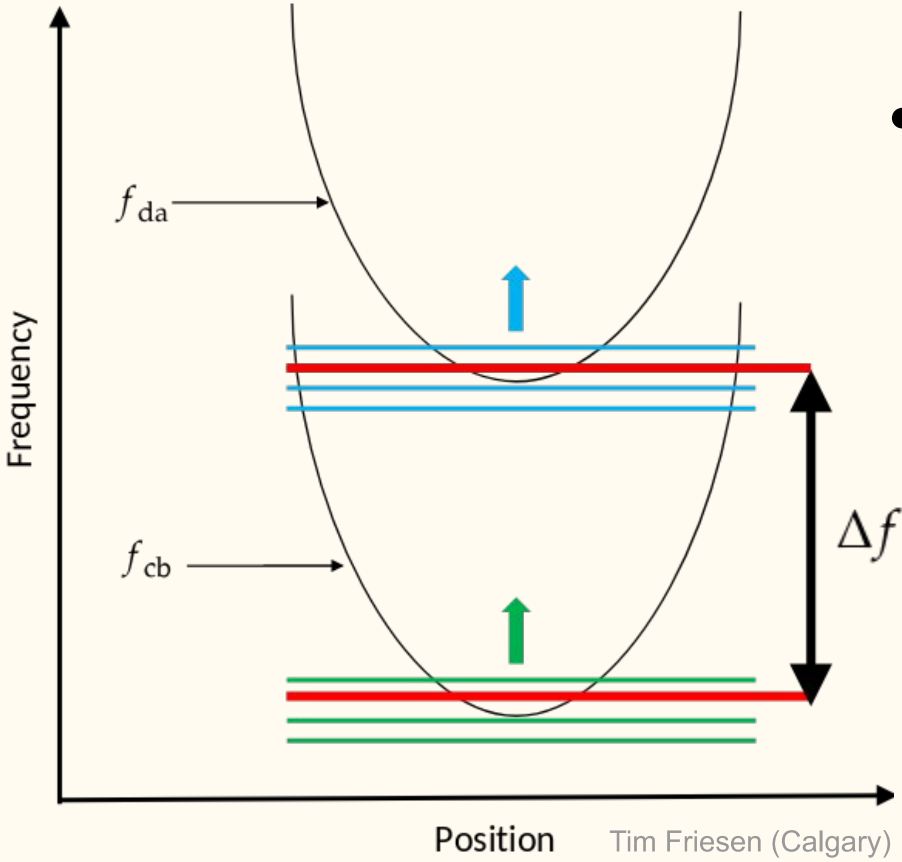
Frequency scan

- PSR transition frequencies strongly depend on magnetic field
- Particles wander through highly inhomogeneous confining B-field
  - Warmer particles spend more time at higher B-fields





Frequency scan

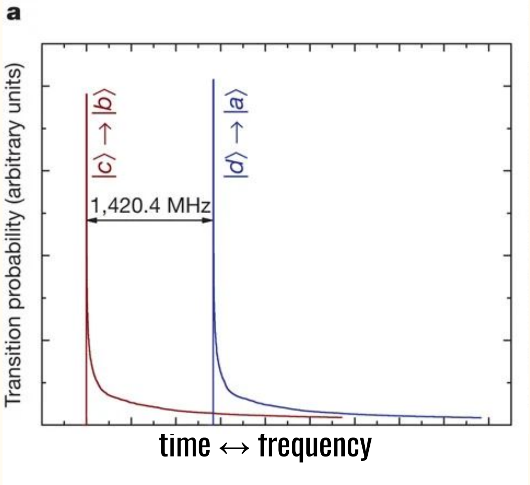


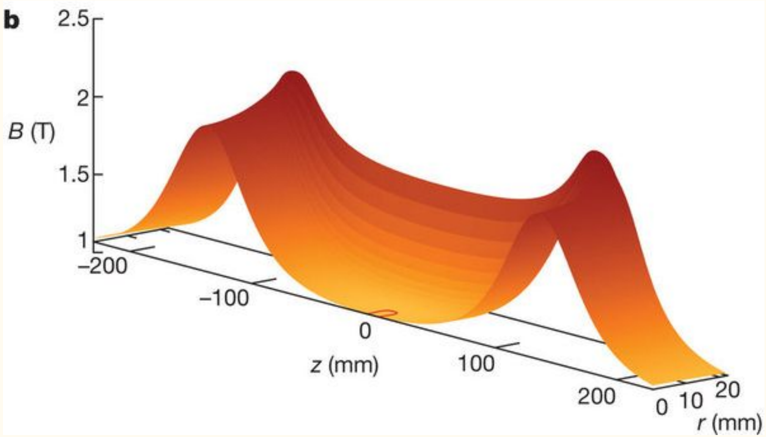
Tim Friesen (Calgary)

$$\Delta f_{hfs} = f_{\mathrm{da,min}} - f_{\mathrm{cb,min}}$$

- Frequency scan by monotonically increasing frequency over time
  - Preferentially drive the transitions close to the region of minimum B-field
    - ~ same for the two transitions
  - Associate time of observed annihilations to injected microwave frequency

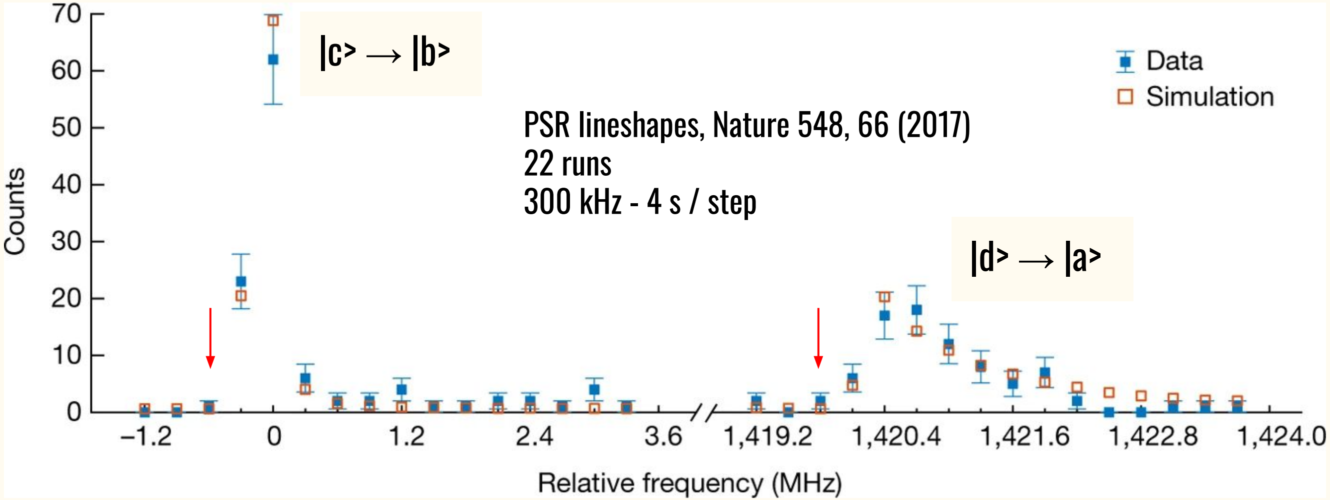
Features of anticipated annihilation time distribution





- Abrupt onset of annihilations, associated with minimum in magnetic field
  - The difference between onsets is the HFS frequency
  - The position of the onset can be used to monitor the B-field. Initially limited by statistics
- Long tail related to more energetic atoms
- The power at the two transitions may be different
  - Unknown frequency-dependent microwave field structure
  - Lineshape need not be the same for the two transitions

Hbar HFS1S: current experimental status



- $f_{HFS}(1S) = 1420.4 \pm 0.5$ MHz
  - from the frequency difference between the first signals from the two transitions

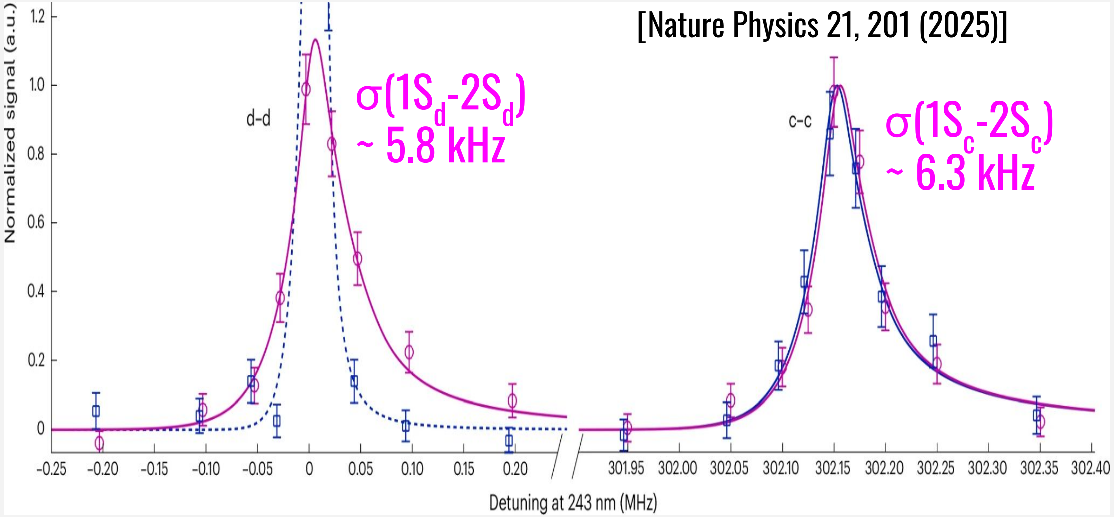
- Sources of uncertainty:
  - Determination of onset frequencies (0.3 MHz)
  - Combination of data from different runs (0.3 MHz)
  - Drifts in the magnetic field during the scan (0.3 MHz)

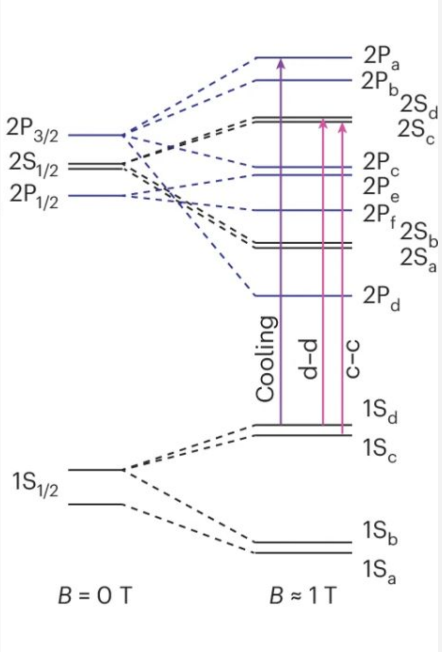
2S state hyperfine splitting

- $D_{21} = 8f_{HFS}(2S) - f_{HFS}(1S)$ → Nuclear size effects cancel out
- Combine optical measurement of 1S-2S (for each component) with HFS1S
  - HFS2S = (177.6 +/- 0.5) MHz

$$f^{\bar{\mathrm{H}}}_{\text{c-c}} - f^{\bar{\mathrm{H}}}_{\text{d-d}} = \frac{1}{2}(\mathrm{HFS1S} - \mathrm{HFS2S}) + \frac{2B}{h}\left(\mu_{\mathrm{p}}(2\mathrm{S}) - \mu_{\mathrm{p}}(1\mathrm{S})\right)$$

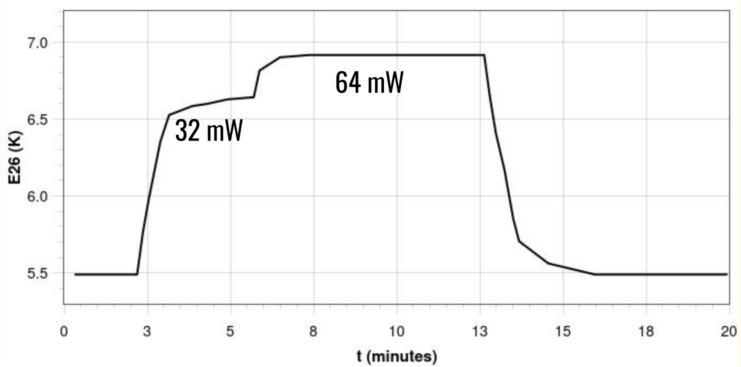
- Precision limited by HFS1S for antihydrogen → want to push to 10 kHz

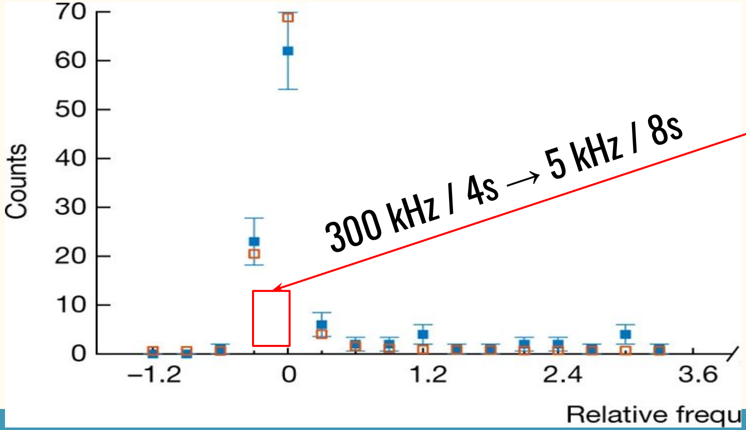


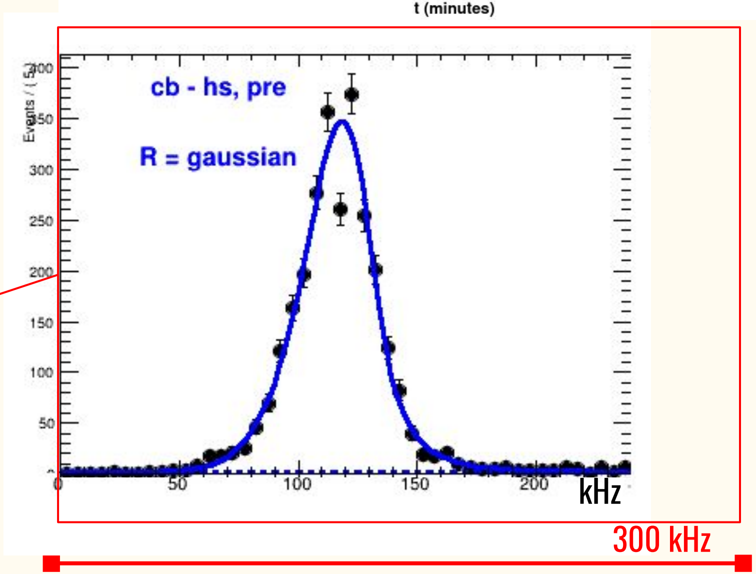


Sharper distribution, more fine-grained frequency scan

- Heating of the trap: limits on injected microwave power and irradiation time
- To increase spin-flip probability near B_{min} , flatten B-field = increase time spent by Hbar at lower B
- Steeper rising edge of annihilation time distribution → reduce the frequency step





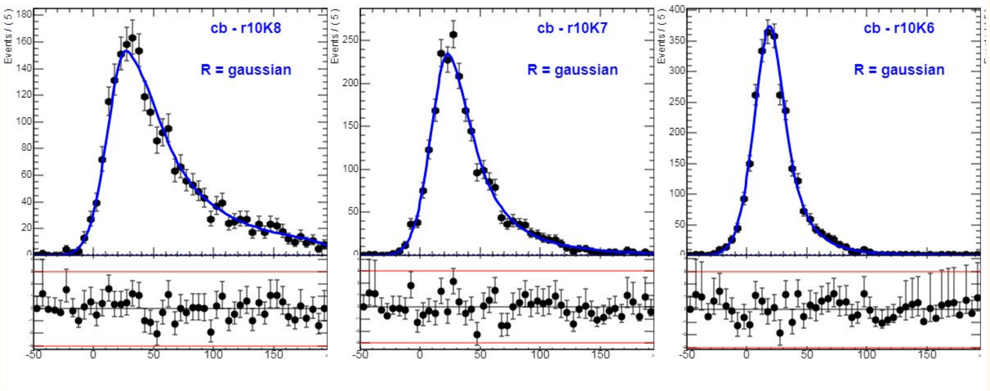


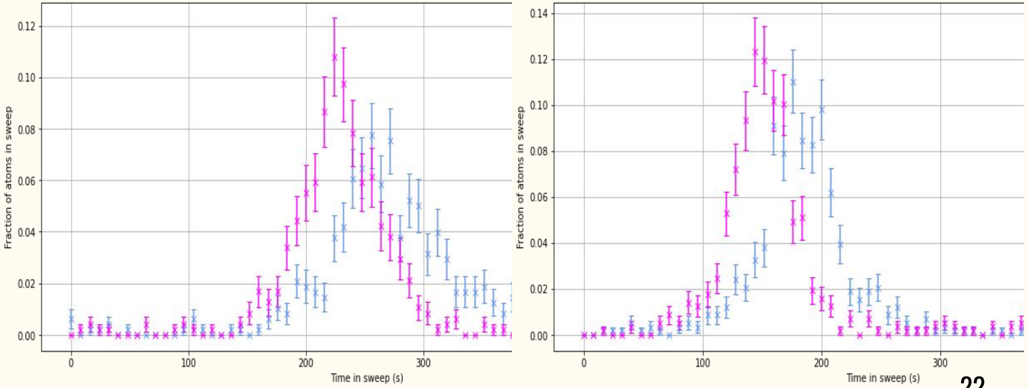
Modelling the signal

- Extract frequency shift between annihilation signals for the two transitions

- Depletion distributions resulting from
  - structure of the non-uniform trapping field
  - local microwave power seen by the atoms
  - motional broadening effects → O(10 kHZ), not relevant in 2017 analysis

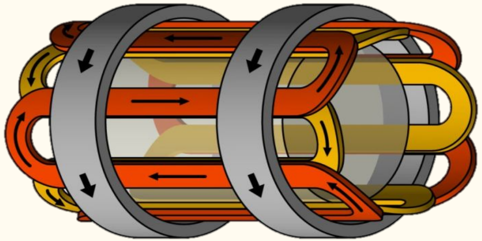
- Empiric model informed by simulation → largest source of systematic uncertainty
  - Orbits of the atoms through the magnetic field
    - ~ the same for |c> → |b> and |d> → |a>
  - Balance microwave powers at the two transitions
    - equalize the distributions

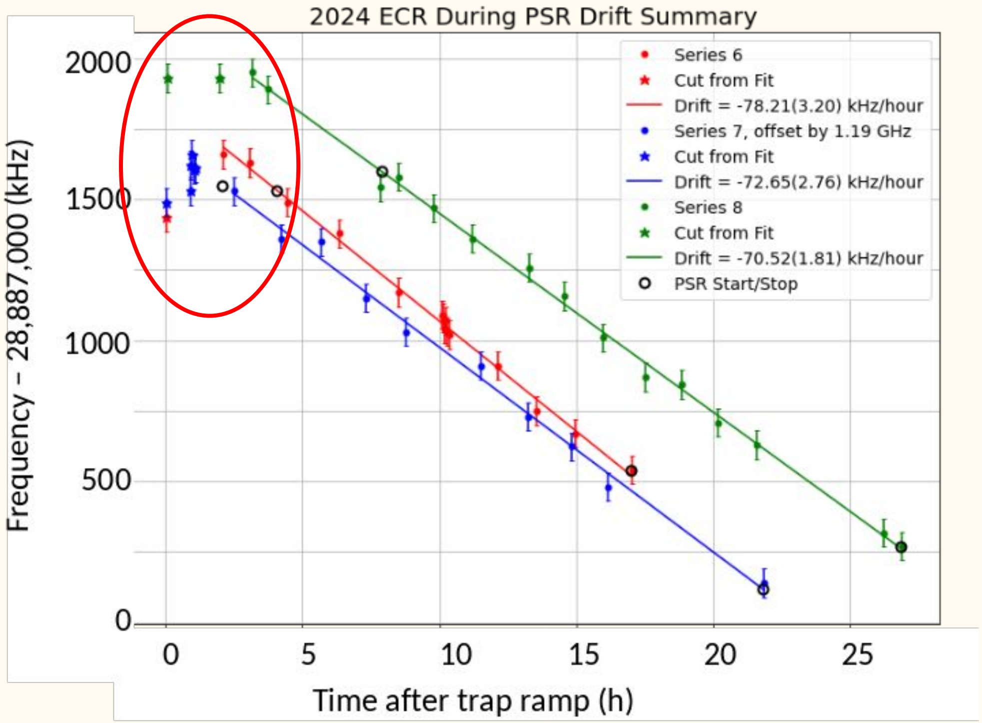




Better control of magnet operations and characterization

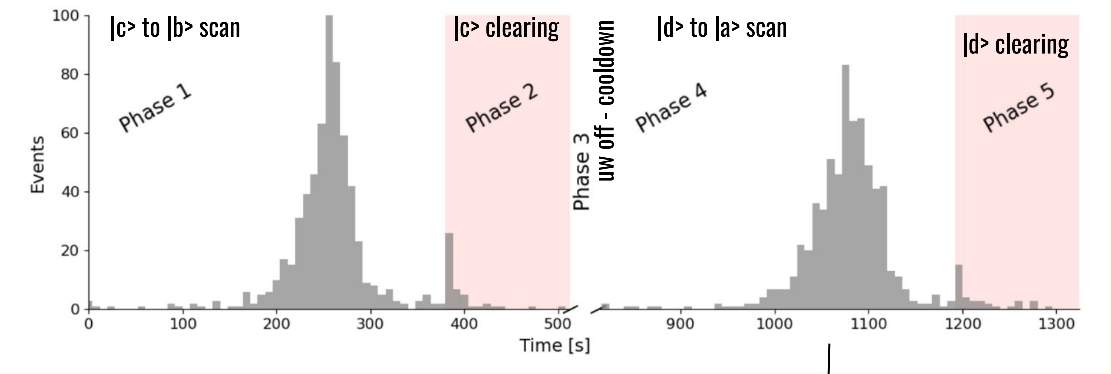
- External solenoid set to target field & into persistent mode
- Energize trap magnets
  - Short-term upward B drift, depends on history of magnet operations
  - After 1-2 hr, enter linear decay (@ ~74 kHz/hr)

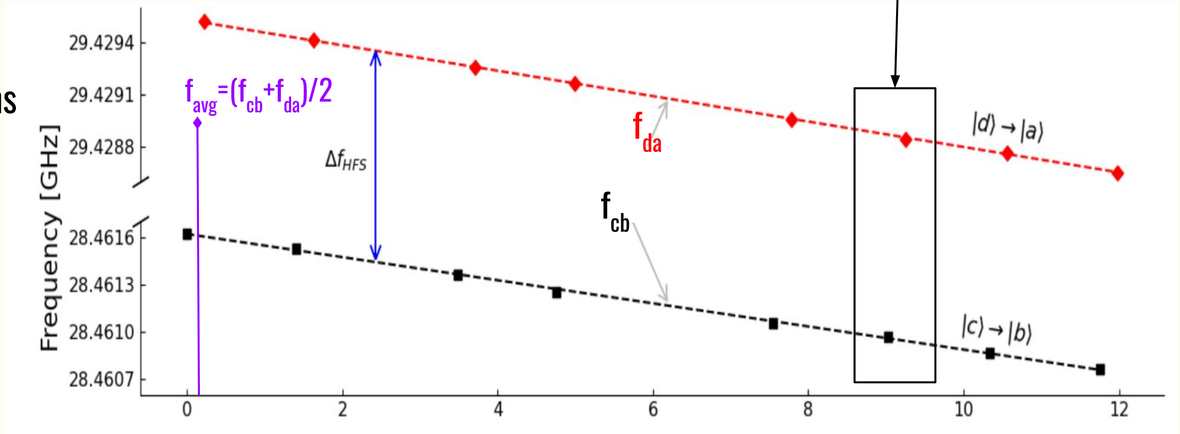




Better control of magnet operations and characterization

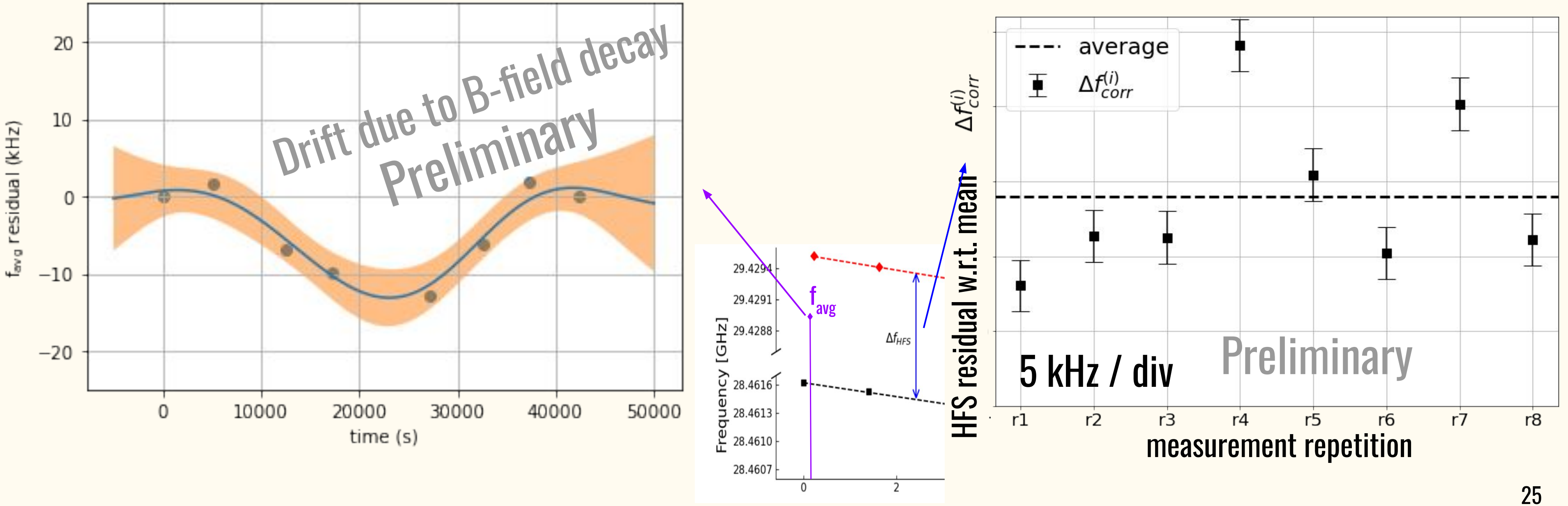
- Consecutive measurements without resetting the trap
  - Measure and correct for the ~ 20 kHz drift between ‘cb’ and ‘da’ scans
- Use average f_{cb} and f_{da} to monitor magnetic field drift
  - Allow to correct for drift occurring between the |c>⟶|b> and |d>⟶|a> scans



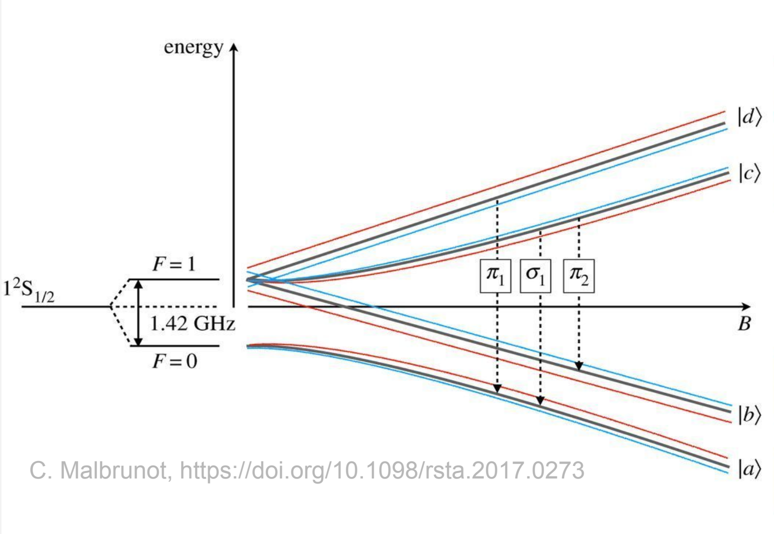


Approaching a 10 kHz HFS-1S measurement at 1T

- A 50x improvement w.r.t. previous measurement
  - Match precision of optical spectroscopy of $1S_c$-$2S_c$ and $1S_d$-$2S_d$ → HFS-2S
- Precise in-situ monitoring of the variations due to magnetic field drift



Implications for CPT tests?



- Competing experiment: ASACUSA
  - slightly different experimental goals
    → different choice of trade-offs

- f_{ad}-f_{bc} is not sensitive to SME, but f_{ca} or - equivalently - f_{dc} (NMR) are
  - f_{ca} very challenging
  - f_{dc} requires new hardware

- Experiment in intense inhomogeneous magnetic fields
  - Extrapolations
  - Systematic effects

- Solution 1: measure hydrogen under the same conditions

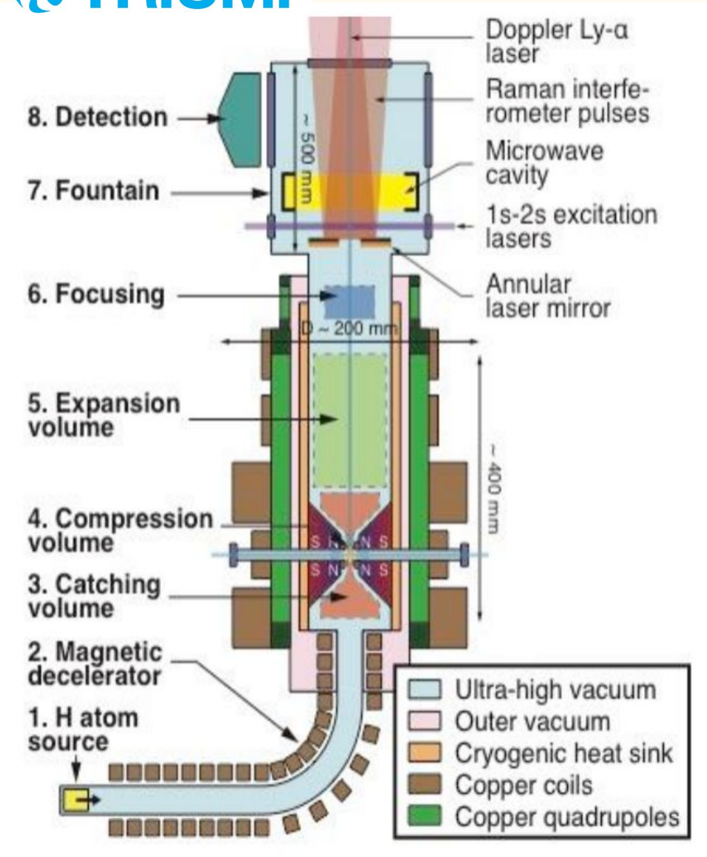
- Solution 2: measure several transitions with similar precision
  - Monitor magnetic field (f_{avg})
  - Validate control of systematic effects (f_{HFS})
  - Measure CPTV-sensitive process (e.g., f_{NMR})

Outlook 1: Working with hydrogen

- Detection of H cannot rely on annihilations
  - For 1S-2S spectroscopy, a viable approach exists
    - E.g., C. L. Cesar, J. Phys. B 49 (2016) 074001
  - For GSHFS, a new protocol would need to be devised

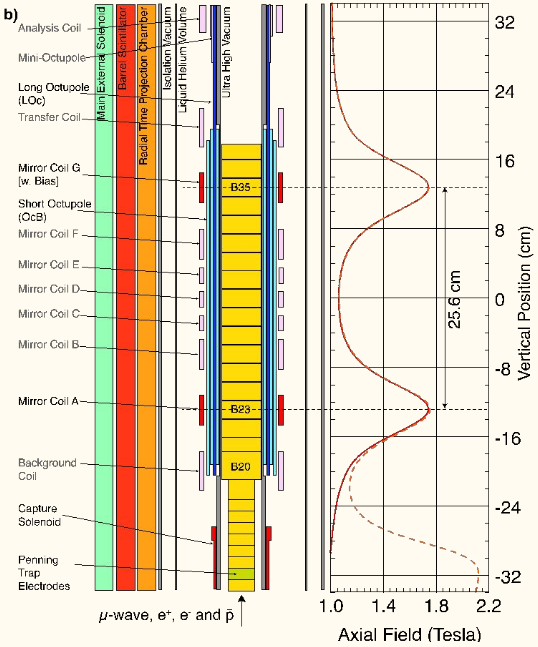
- ALPHA set to benefit from HAICU program at TRIUMF
  - A. Capra @ Science Week 2024
  - Poster by Giles Wankling yesterday

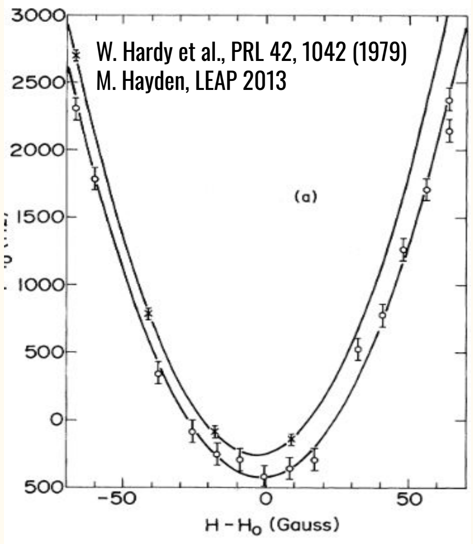
  - Develop quantum sensing techniques for H
    - trapping and detection compatible with ALPHA
  - Proxy for next generation of Hbar experiments (e.g., atomic fountain)



Outlook 2: antihydrogen hyperfine structure in ALPHA-g

- Nuclear Magnetic Resonance
  - Broad maximum at 0.65 T (f_{dc} = 654.9) , 10^{-6}-10^{-7} precision within reach
  - Remove |c> population, excite |d> → |c>, observe regenerated |c> population
- We have just started experimenting with a vertical trap in ALPHA
  - New waveguide to deliver microwaves for Positron Spin Resonance @ 0.65 T
  - Plan to include a resonator to drive NMR d-c transition





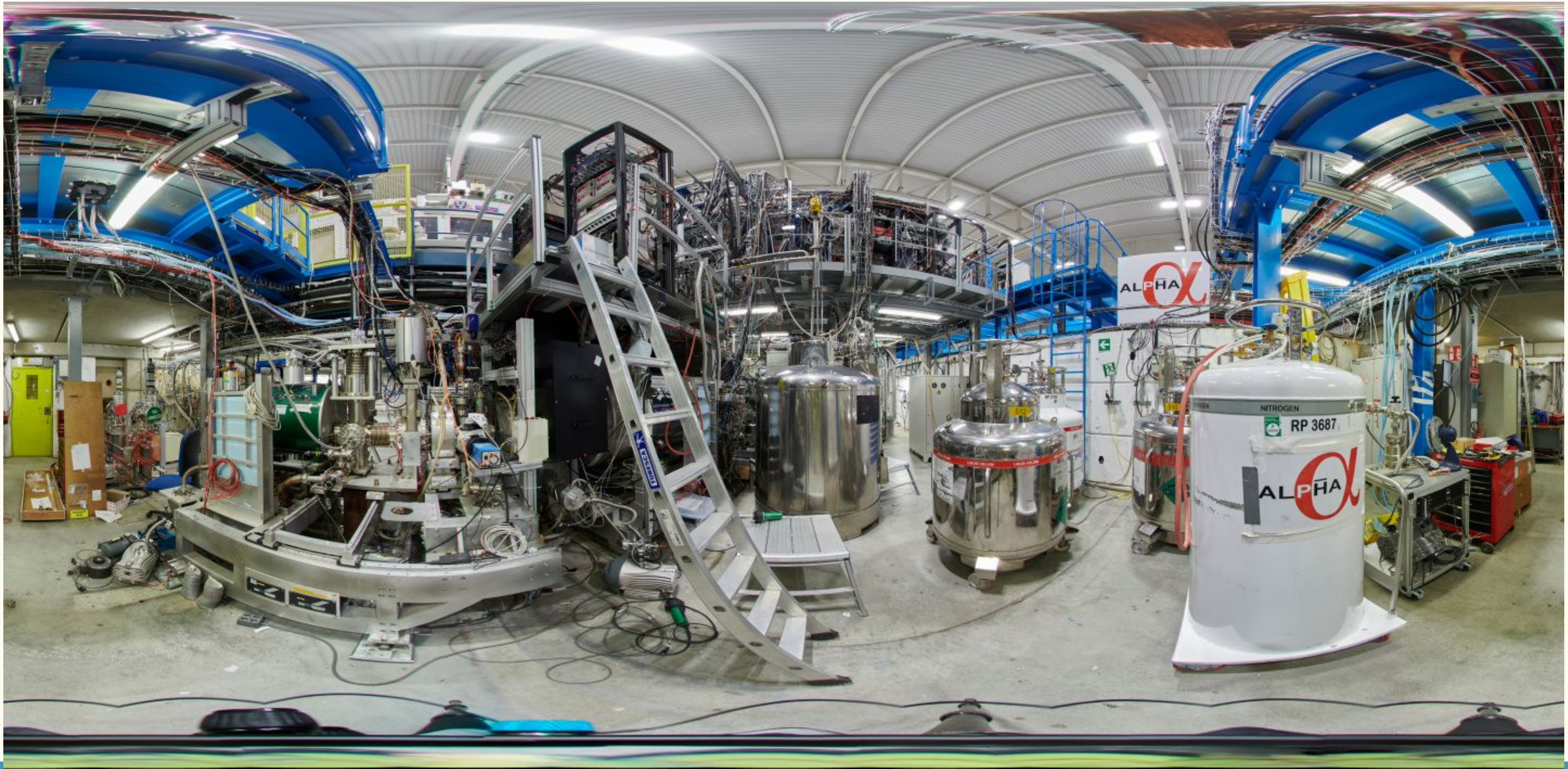
Recap

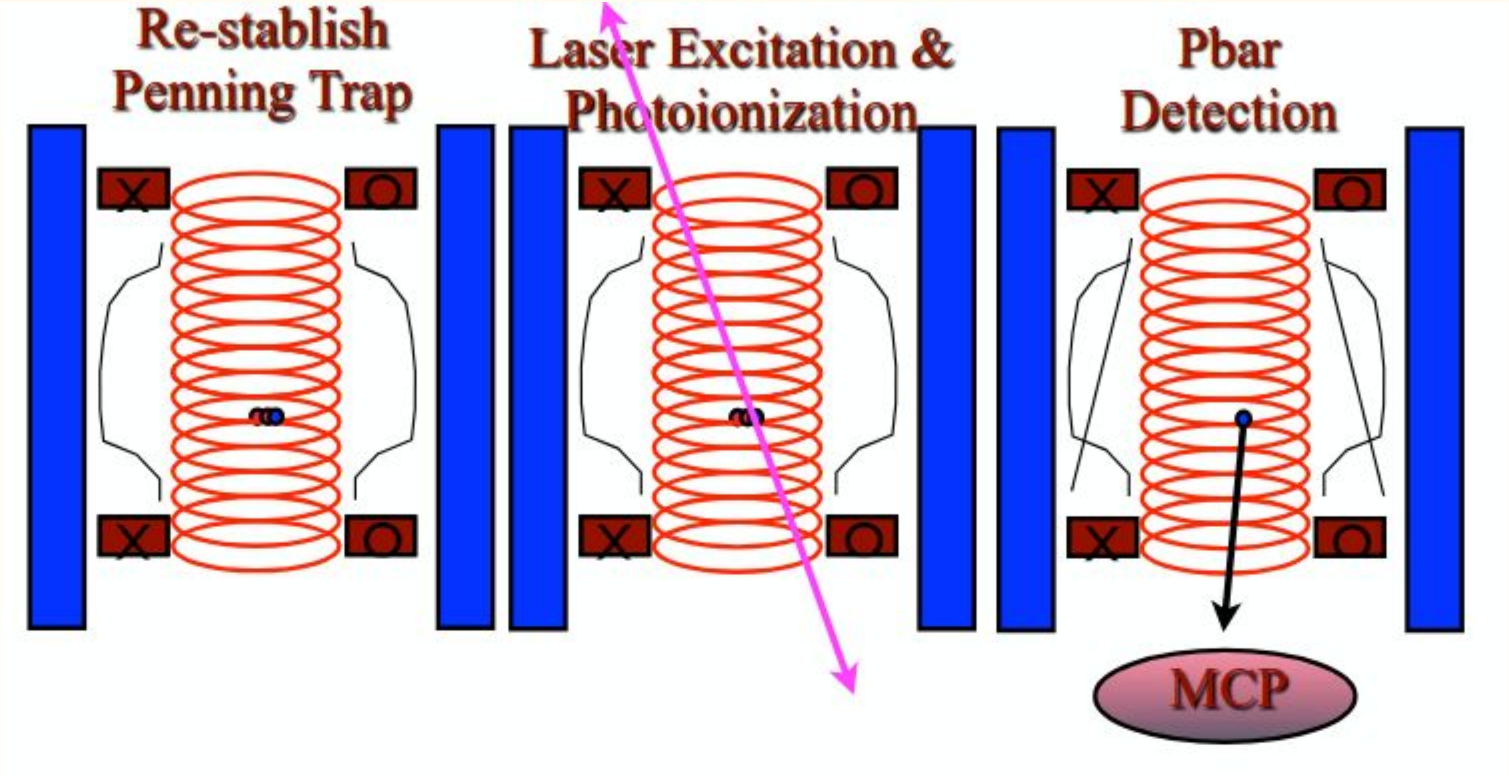
- Measurements of the hyperfine structure of antihydrogen have reached a 10 kHz precision
  - Comparable to the corrections to the 1S-HFS due to the structure of the proton
  - Can be combined with laser measurements → quantities insensitive to nuclear size effects, comparison to theory
  - Offer a tool for in-situ measurements of magnetic field variations @ O(0.01 Gauss)

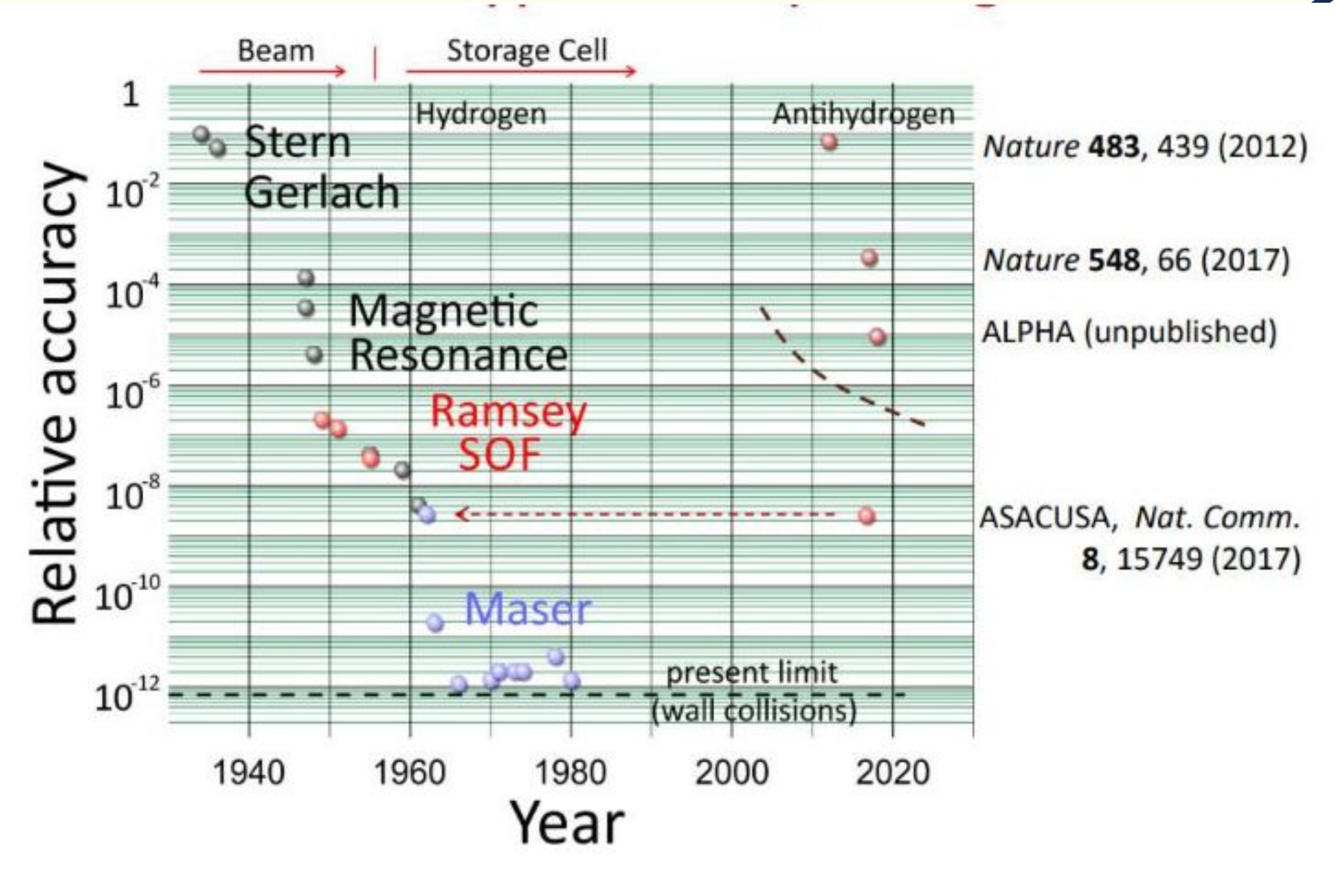
- To provide meaningful tests of CPT:
  - measure more transitions (NMR), at different magnetic fields
  - repeat the measurements with hydrogen

- Technical challenges will keep ALPHA busy for several years to come
  - ALPHA-g expected to play an increasingly important role
  - Profit from R&D at HAICU with hydrogen

Thank you

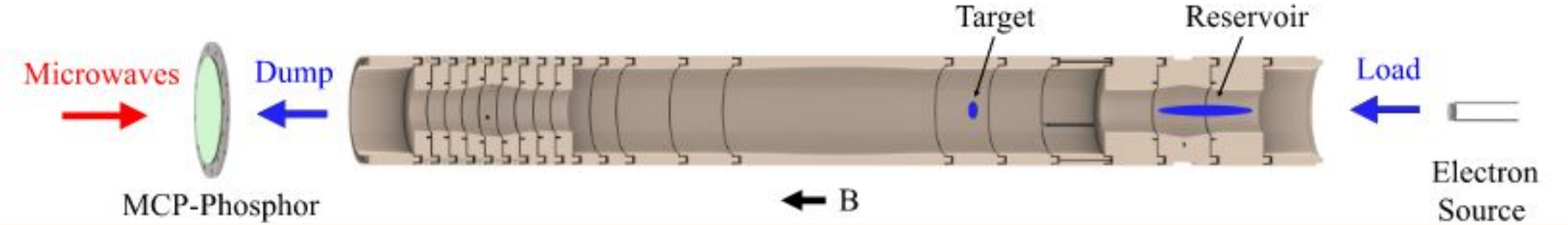

ALPHA
NITROGEN
RP 3687
ALPHA


Re-stablish
Penning Trap
Laser Excitation &
Photoionization
Pbar
Detection
MCP

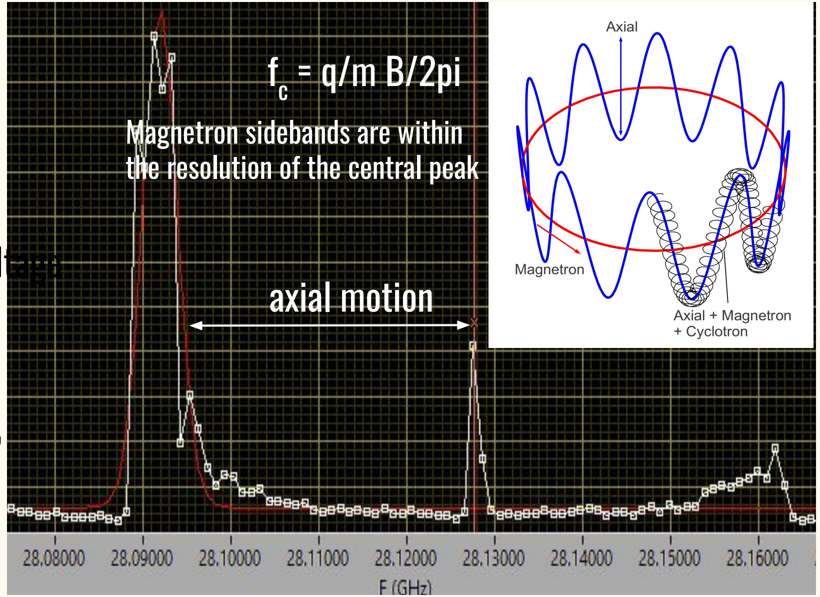


Beam
Storage Cell
Hydrogen
Antihydrogen
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
Relative accuracy
Stern
Gerlach
Magnetic
Resonance
Ramsey
SOF
Maser
present limit
(wall collisions)
1940
1960
1980
2000
2020
Year
Nature **483**, 439 (2012)
Nature **548**, 66 (2017)
ALPHA (unpublished)
ASACUSA, *Nat. Comm.* **8**, 15749 (2017)

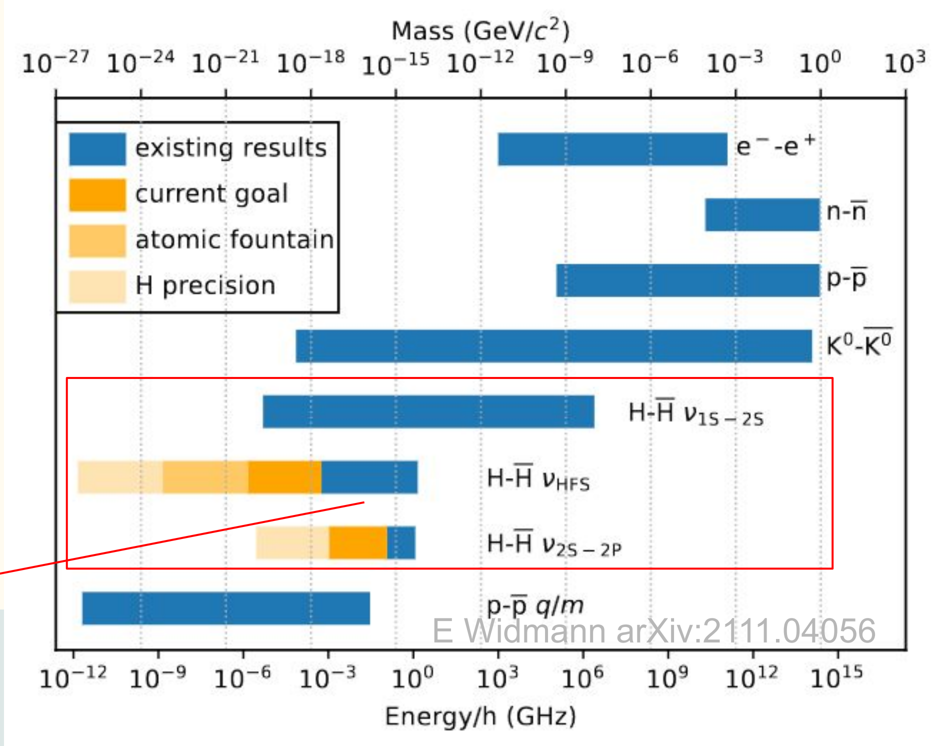
Electron Cyclotron Resonance to measure magnetic field



- Load an electron plasma in measurement location
- Heat plasma with microwaves at given frequency
- Measure temperature
  - Look at time-development of MCP signal as the blocking voltage is gradually lowered to release the plasma, or
  - Use non-destructive methods calibrated on the former
- Wait for plasma to cool down (or load a new plasma, from a reservoir) and repeat at different frequency



T Friesen et al, New Journal of Physics 16 (2014) 013037 doi:10.1088/1367-2630/16/1/013037
ED Hunter et al, Phys. Plasmas 27, 032106 (2020) doi:10.1063/1.5141999



$$E_{1S\text{-HFS}}(\mathrm{H}) = \Big[\underbrace{1418840.082(9)}_{E_F} \underbrace{+1612.673(3)}_{\text{QED+weak}} \underbrace{+0.274}_{\mu\text{VP}} \underbrace{+0.077}_{\text{hVP}}$$

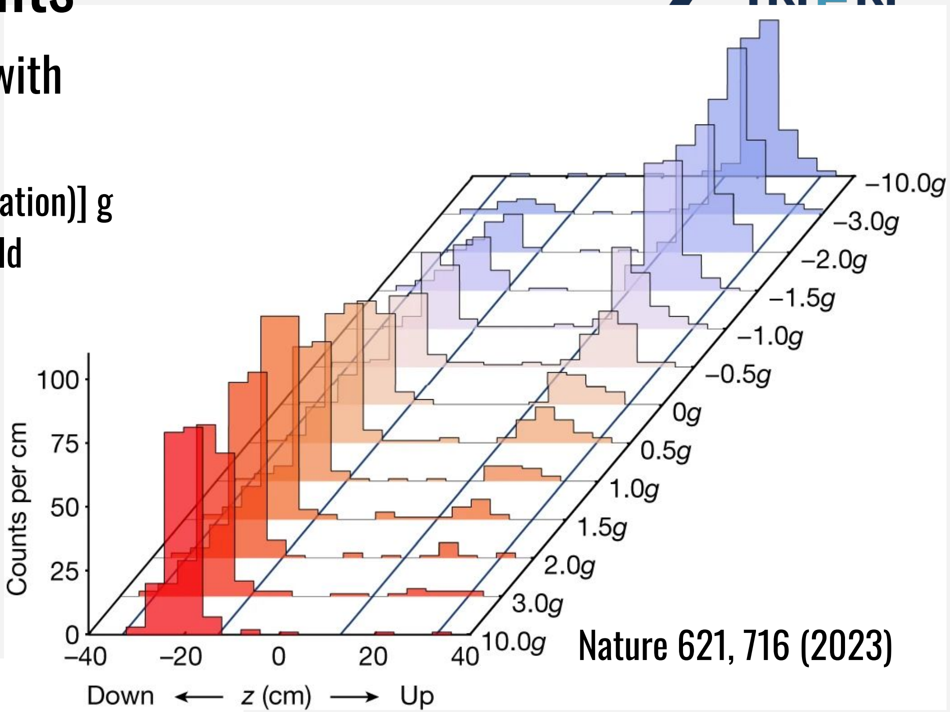
$$\underbrace{-54.430(7)\left(\frac{r_{Zp}}{\text{fm}}\right) + E_F\left(0.99807(13)\,\Delta_{\text{recoil}} + 1.00002\,\Delta_{\text{pol}}\right)}_{2\gamma\text{ incl. radiative corr.}} \Big]\,\text{kHz}$$

A. Antognini, Annu. Rev. Nucl. Part. Sci. 72:389 2022

Implications for other measurements

- First measurement in ALPHA-g: balance gravity with magnetic field
  - a_g = [0.75 ± 0.13 (statistical + systematic) ± 0.16 (simulation)] g
  - Limited by control and characterization of magnetic field

- PSR transitions can be part of the toolbox
  - state selection
  - in-situ magnetometry



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