ALPHA, the Trapped Antihydrogen Experiment: Status and Prospects

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TRIUMF
on behalf of the ALPHA collaboration

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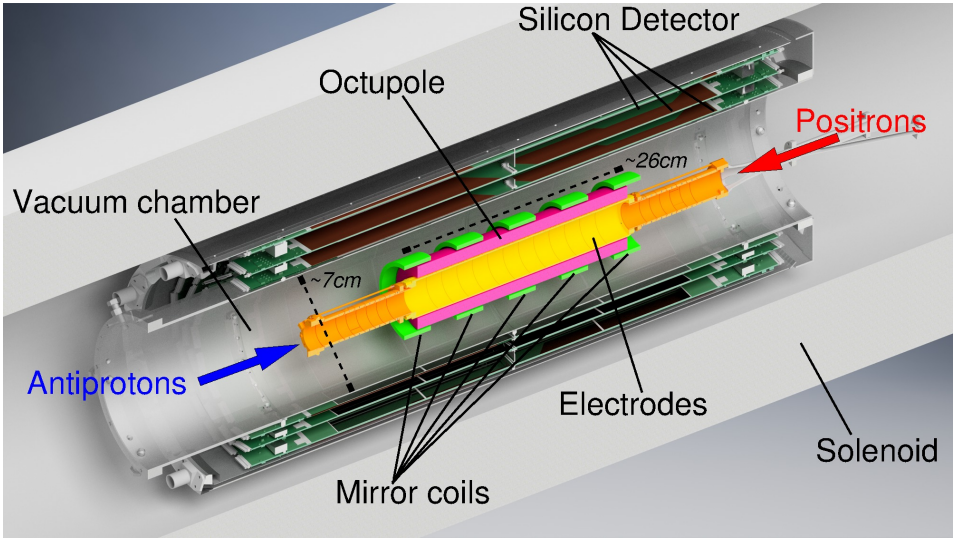
Outline

1. The ALPHA Experiment: Brief Description
2. Antihydrogen Spectroscopy
3. Prospects for Laser Spectroscopy
4. Free-Fall of Antihydrogen

ALPHA's goal

- Test CPT symmetry, by comparing $\overline{\mathrm{H}}/\mathrm{H}$ spectra
  - Probing the foundation of the SM, searching for physics beyond-SM
- Test of the Weak Equivalence Principle, by measuring $\overline{\mathrm{H}}$ gravitational mass.
  - Probing General Relativity and its structure.

The ALPHA-2 Apparatus



What's new in ALPHA

- New plasma technique: improvement on e^+ plasma manipulation, gives colder and more consistent load
  - More robust scheme to produce $\overline{H}$

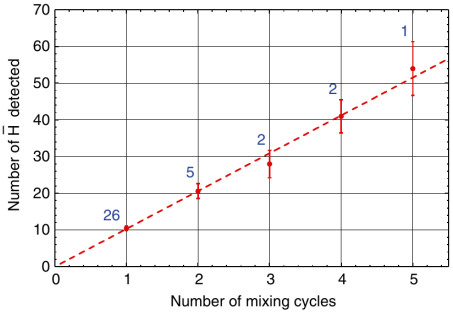
    Phys. Rev. Lett. **120**, 025001 (2018)

- Accumulation of $\overline{H}$: confining antiatoms while synthesizing new $\overline{H}$

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

- ALPHA now routinely confines ≈ 1000 $\overline{H}$ simultaneously for $\gtrsim 10$ h

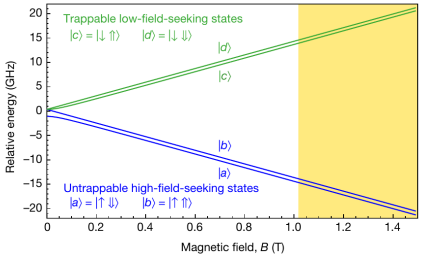
  Hyperfine Interact (2019) 240:9

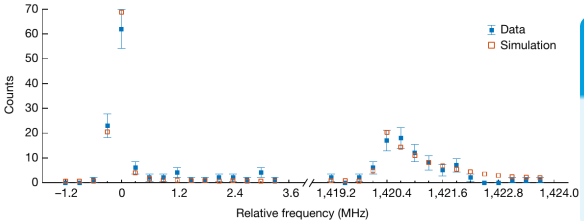


Recent results from the ALPHA-2 experiment

1. Electric Charge Neutrality Nature **529** 373 (2016)
2. 1S-2S Nature **541** 506 (2017)
3. Ground-State Hyperfine splitting Nature **548** 66 (2017)
4. 1S-2S Nature **557** 71 (2018)
5. 1S-2P Nature **561** 211 (2018)

Spectroscopy GS HFS





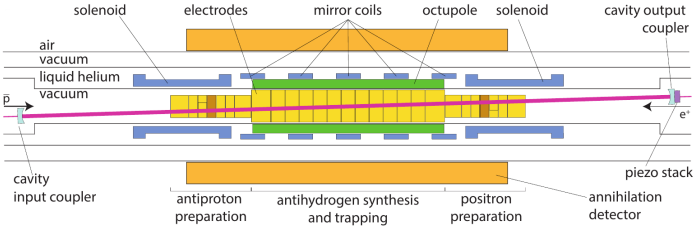
Nature **548** 66 (2017)

- e^+ spin flip: transition from trapped to un-trapped states Nature **483** 439 (2012)
  $|c\rangle \rightarrow |b\rangle$ and $|d\rangle \rightarrow |a\rangle$
- At 1 T $\Rightarrow\sim$ 29 GHz
- Continuously recording $\overline{\mathrm{H}}$ annihilation following a resonant spin flip.

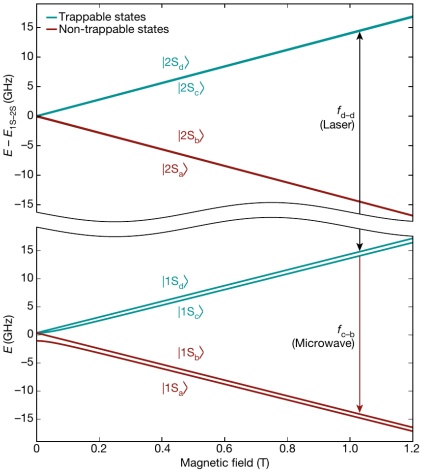
The frequency difference represents the ground-state hyperfine splitting

- independent of the field strength
- this measurement: 1420.4 ± 0.5 MHz
- CPT test at 10^{-4} level

Spectroscopy 1S-2S I

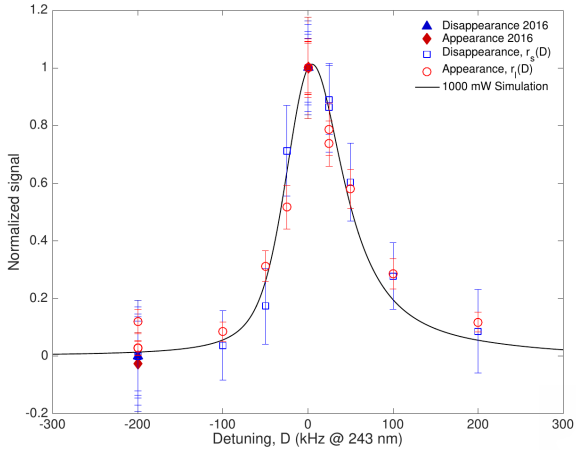


1. Trap antihydrogen (3 mixing cycles, ∼40 atoms)
2. Clear out any remaining charged particles
3. 300s laser exposure at fixed frequency near $|1S,d\rangle \rightarrow |2S,d\rangle$ transition
4. 32s microwave sweep to eject $|1S,c\rangle$
5. Ramp down magnets to detect remaining atoms



Nature **557** 71 (2018)

Spectroscopy 1S-2S II



Credit: C. Ø. Rasmussen

Observational channels:

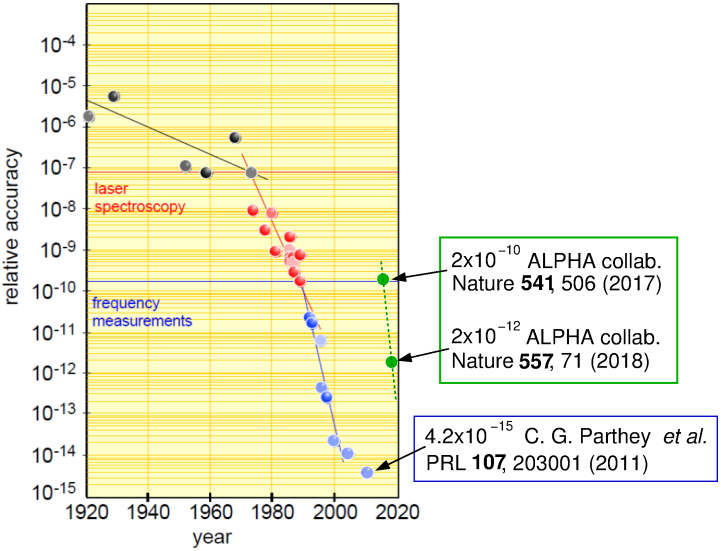
- Appearance - during laser illumination: **1991** $\overline{\text{H}}$ detected
- Disappearance - during trap shutdown: **6137** $\overline{\text{H}}$ detected

$\gtrsim$ **15000** $\overline{\text{H}}$ trapped

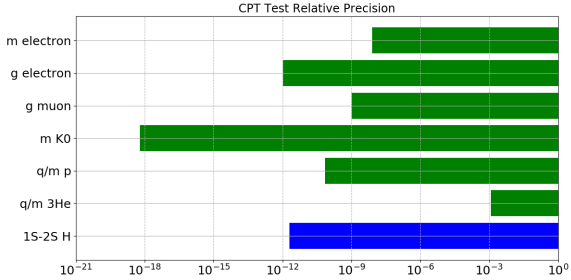
Lineshape predicted by simulation, assuming CPT conservation

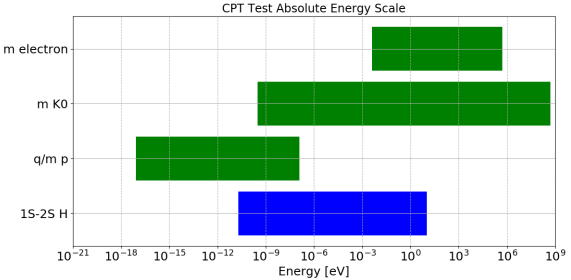
Fit of the experimental data

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

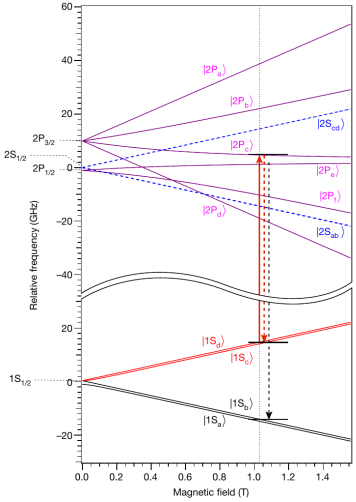

relative accuracy
year
laser spectroscopy
frequency measurements
10-4
10-5
10-6
10-7
10-8
10-9
10-10
10-11
10-12
10-13
10-14
10-15
1920
1940
1960
1980
2000
2020
2x10−10 ALPHA collab. Nature 541, 506 (2017)
2x10−12 ALPHA collab. Nature 557, 71 (2018)
4.2x10−15 C. G. Parthey et al. PRL 107, 203001 (2011)

CPT Tests - Updated

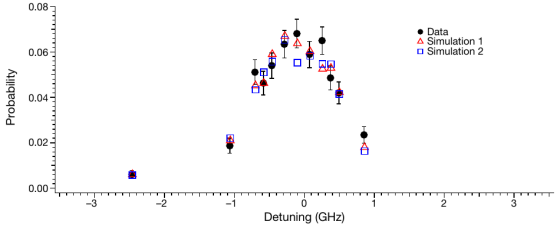




Spectroscopy 1S-2P



Using a narrow-line-width, nanosecond-pulsed, vacuum-ultraviolet laser developed by UBC+TRIUMF



- 966 detected events during irradiation over several hours (estimated background 14 events).
- Relative precision: 5×10^{-8}

Nature **561** 211 (2018)

Forthcoming Publications

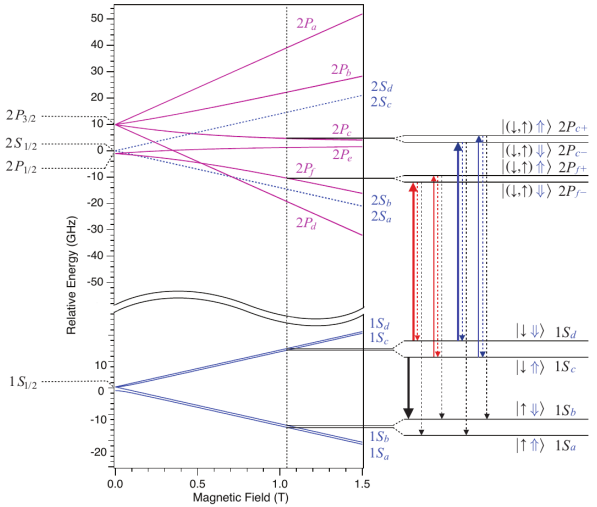
- Update on Ground-State Hyperfine splitting
- Lamb shift in $\overline{\mathrm{H}}$
- Laser cooling of $\overline{\mathrm{H}}$ and its application to spectroscopy

Spectroscopy GS HFS: Updated

- Major update: better characterization of the magnetic environment
  - precision improved by orders of magnitude.

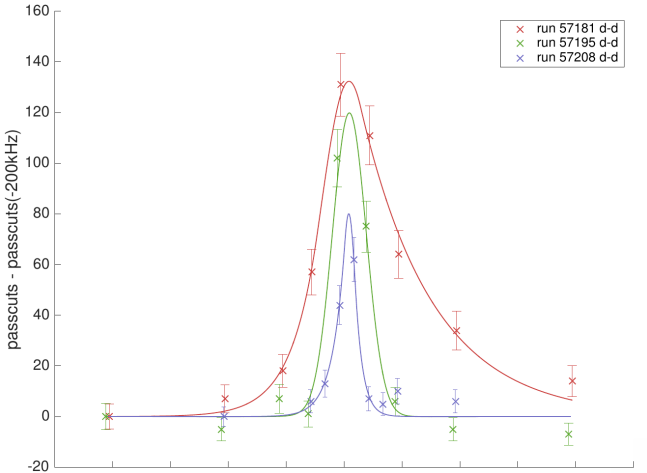
Lamb Shift: Preliminary

- Not a direct measurement (ALPHA confines GS $\overline{H}$)
- The measured frequency of the 1S-2S transition (in $\overline{H}$) is sufficient to calculate the Lamb shift
  - by measuring 1S-2P$_f$ and 1S-2P$_c$ transitions (red and blue lines)
  - and by assuming Zeeman and hyperfine interactions in H



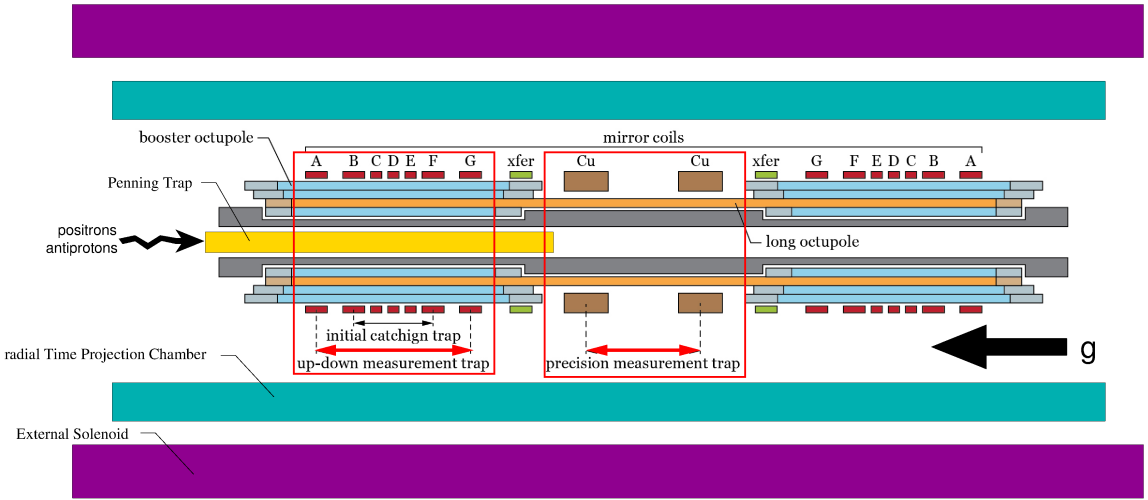
Laser Cooling: Preliminary

$1S_d - 2S_d$ line after laser cooling: analysis is ongoing...



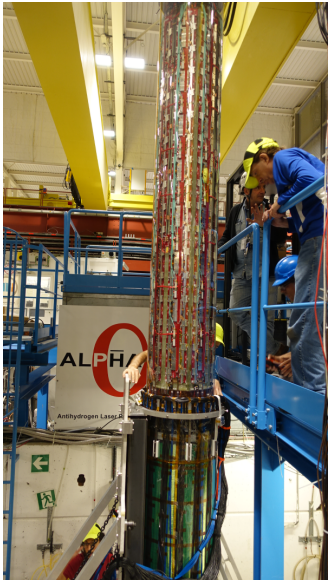
Credit: C. Ø. Rasmussen

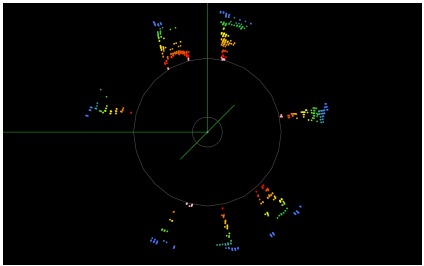
The ALPHA-g Apparatus

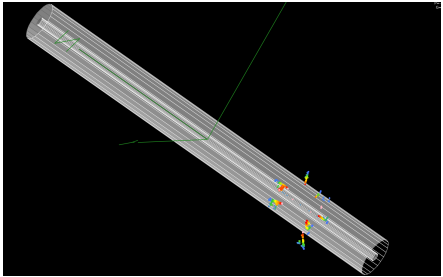


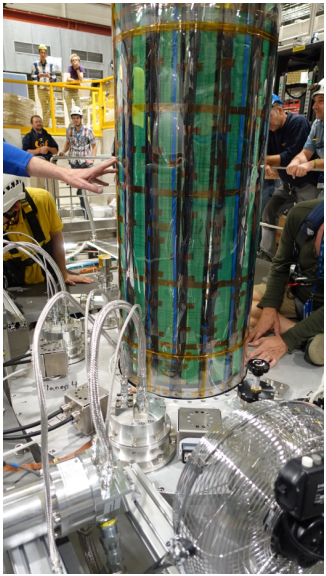
NOT TO SCALE

rTPC and Barrel Veto Built @ TRIUMF





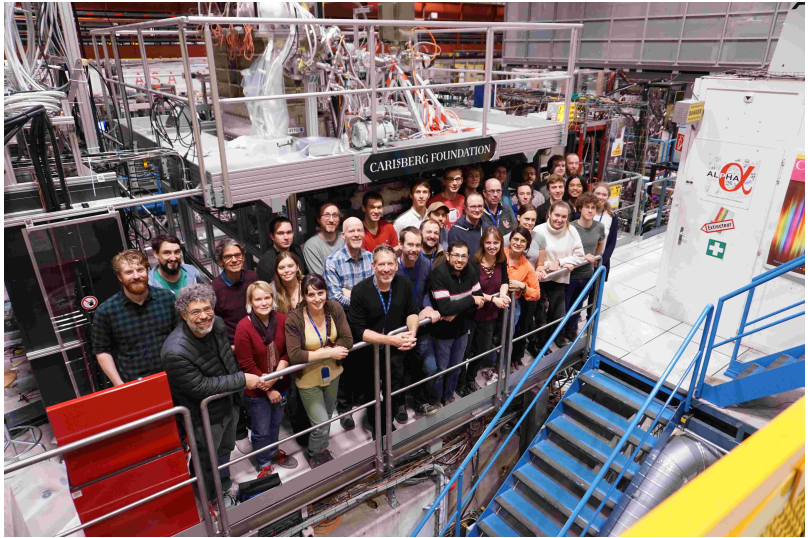




Conclusions

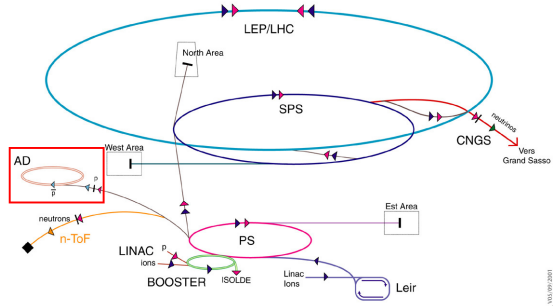
- $\overline{\text{H}}$ is a portal to study CPT invariance violation
- The ALPHA antimatter apparatus is designed to perform precision spectroscopy of $\overline{\text{H}}$
  - 1S-2S transition measured at ppt level
  - ground state hyperfine splitting
  - 1S-2P to open the door for laser cooling of $\overline{\text{H}}$
- $\overline{\text{H}}$ is a tool to test the Equivalence Principle
- ALPHA is gearing towards a measurement of the $\overline{\text{H}}$ gravitational mass with the ALPHA-g apparatus

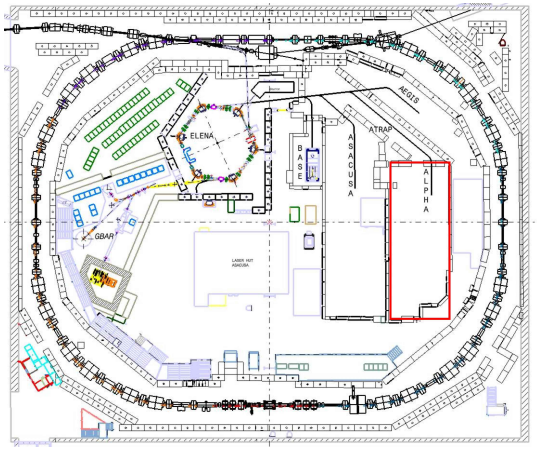
ALPHA Collaboration



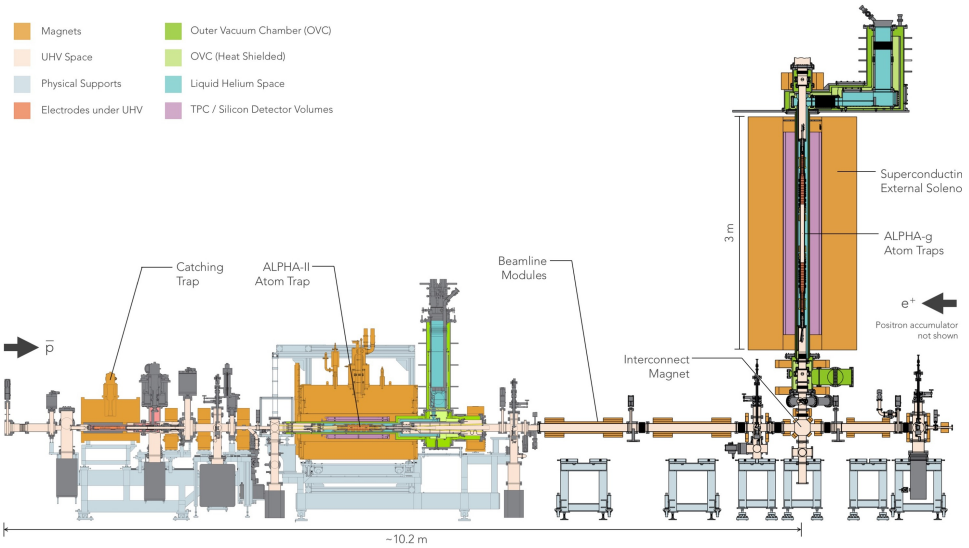
AARHUS UNIVERSITET
THE UNIVERSITY OF BRITISH COLUMBIA
UNIVERSITY OF CALGARY
UNIVERSITY OF LIVERPOOL
MANCHESTER
The Cockcroft Institute
PURDUE UNIVERSITY
SFU SIMON FRASER UNIVERSITY THINKING OF THE WORLD
Stockholm University
Swansea University Prifysgol Abertawe
TRIUMF
YORK UNIVERSITY

Accelerator chain of CERN (operating or approved projects)

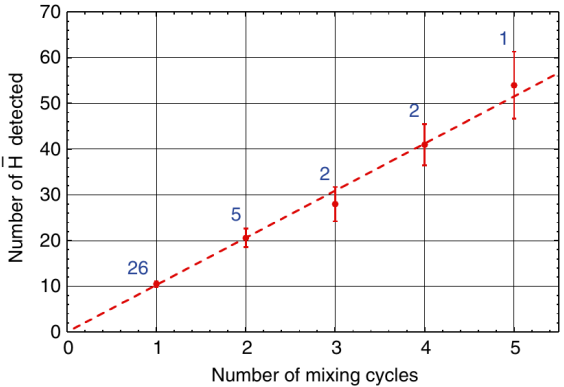




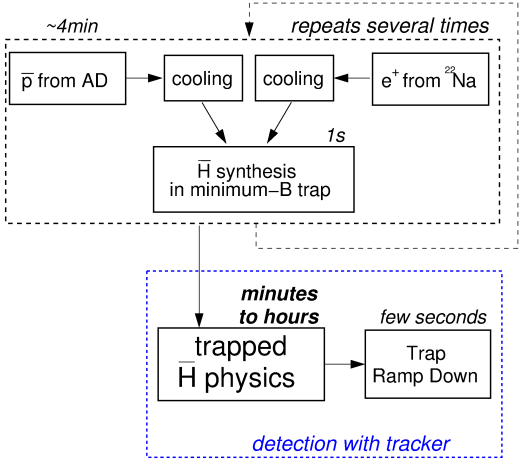
A view of ALPHA-2 and ALPHA-g



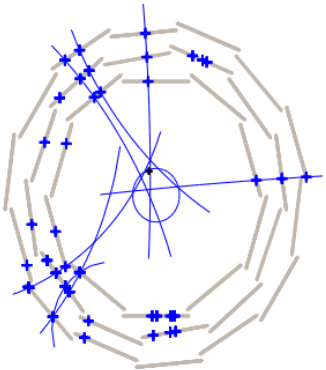
Antihydrogen Stacking

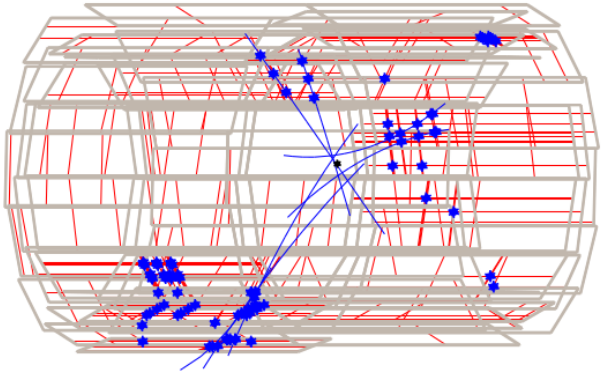


Nat. Comm. **8** 681 (2017)

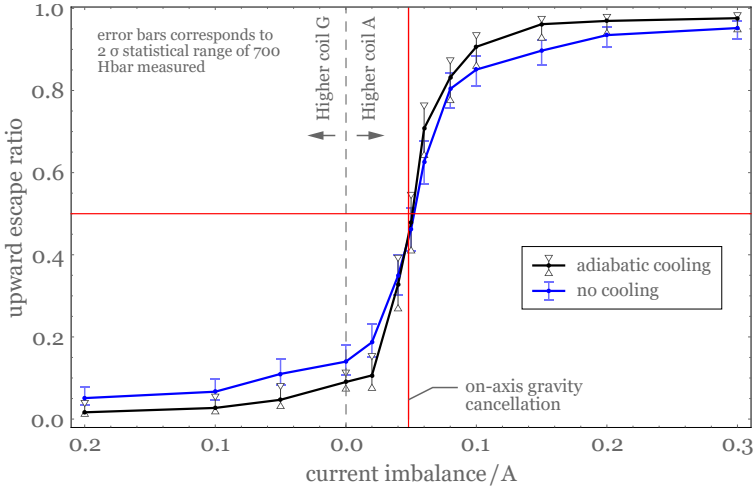


High-Multiplicity Annihilation





Prospective for Free-Fall Observation



- Steeper curve ⇒ More sensitivity

⇒ Colder $\overline{H}$ is better (no surprise)

- For equal currents, "upward fraction" is 10-20%

⇒ Efficient measurement with hypothesis testing with $O(10^2)$ $\overline{H}$ annihilation