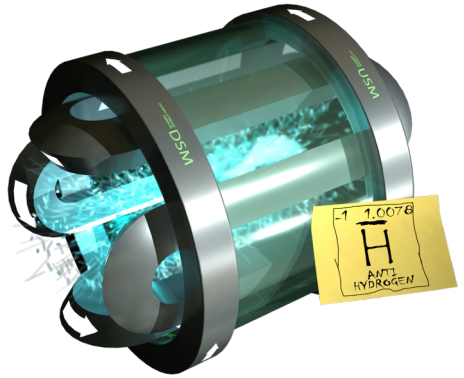
# Antihydrogen Physics

## Tangled Web of Quantum Sensors Symposium


*Jonathan Wurtele*

*UC Berkeley*


# Could CPT Be Violated?

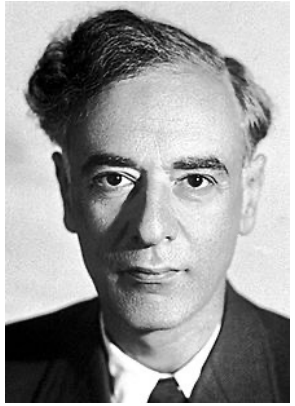
- Physicists have been wrong before…
- P violation---Wolfgang Pauli:[1]

  *"I do not believe that the Lord is a weak left-hander, and I am ready to bet a very high sum that the experiments will give symmetric results."*
- CP violation---Lev Landau:[2]

  *"If CP is violated, I will hang myself."*

Wolfgang Pauli

All results to date are consistent with CPT.



Lev Landau

Antihydrogen is an ideal system to study CPT symmetry.

$H$: electron + proton
$\bar{H}$: position + antiproton
CPT: Same spectrum and charge (if any)
1996: Antihydrogen produced at accelerator scale energies at CERN & Fermilab (1998).

[1]Pauli in a letter to Victor Weisskopf, quoted in the Ambidextrous Universe, by Martin Gardner.
[2] Oral history, as related by Dima Budker.

# The Antiproton Decelerator at CERN is the only source of low energy antiprotons

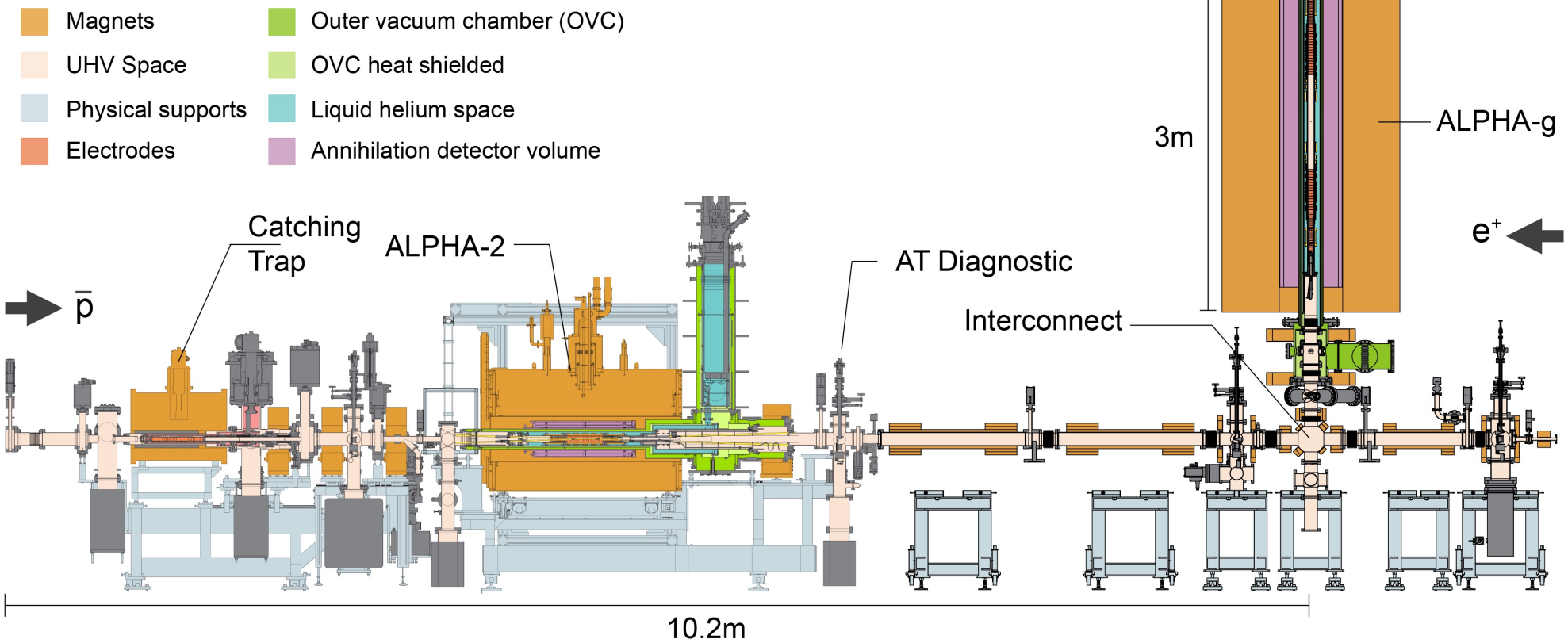

2000s: Antiprotons decelerated to 5.3MeV Antiproton Decelerator (AD) facility. Low energy untrapped $\bar{H}$

ALPHA trapped $\bar{H}$ in 2010

# The ALPHA Apparatuses

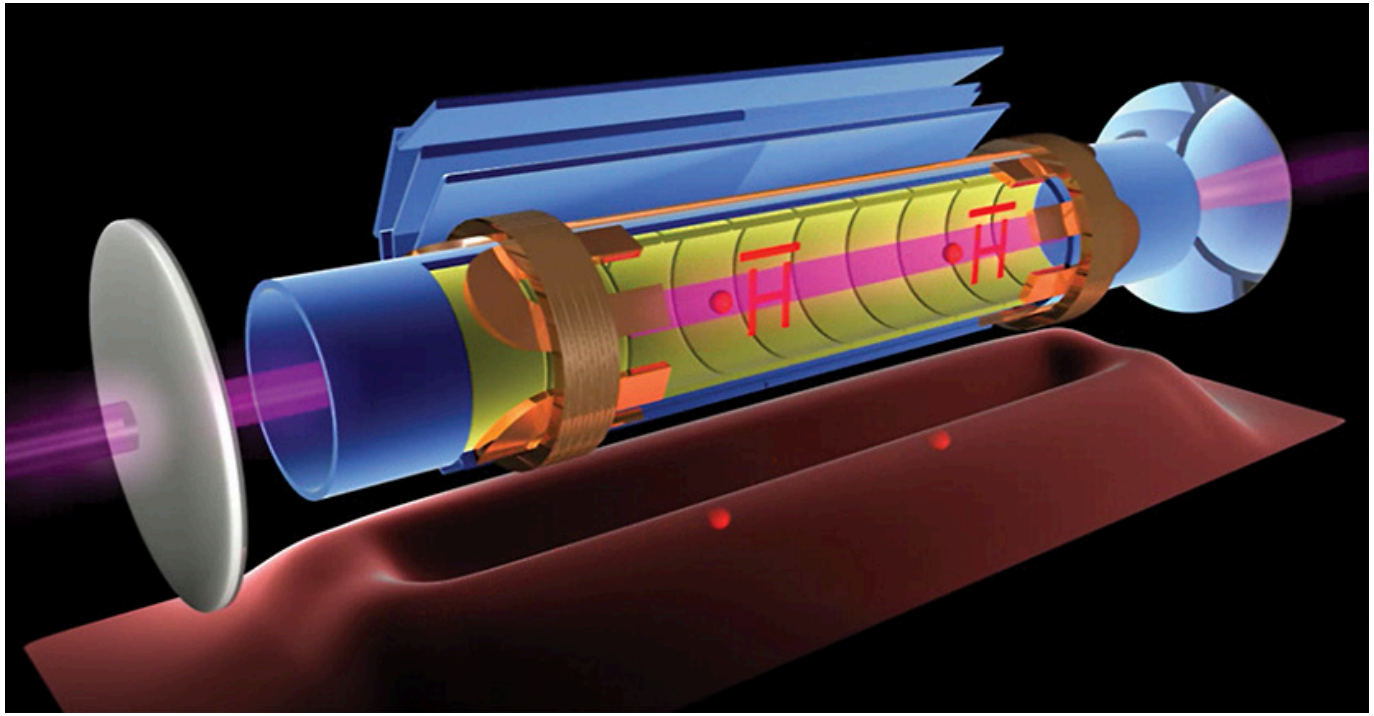
As head of the Cockroft Institute, Swapan offered early and enthusiastic support of Prof. Will Bertsche's design and construction of the antiproton catching trap. The catching trap gets its antiprotons from the Antiproton Decelerator (AD). The AD uses stochastic cooling, Swapan's research field in and after graduate school.

ALPHAg: Gravity

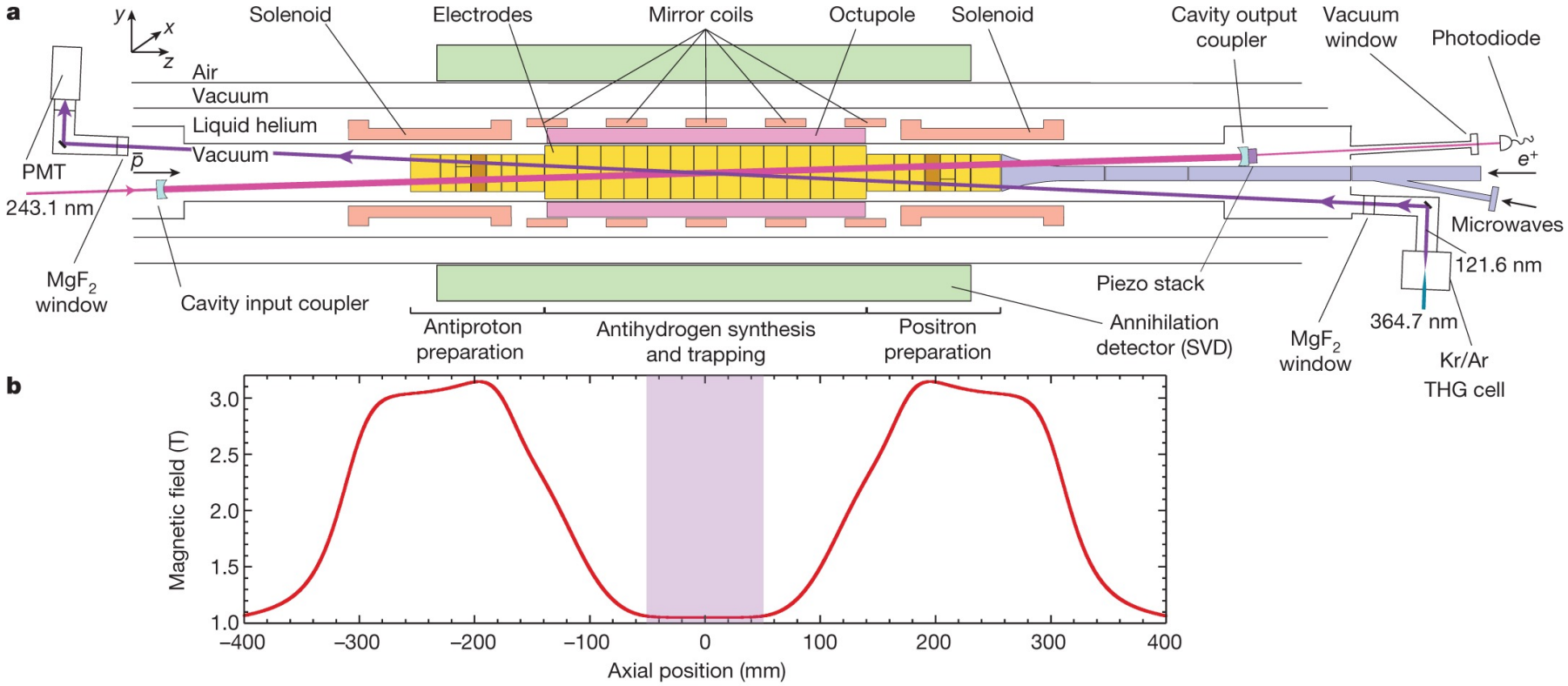



- Antimatter can only be confined in a “can” with no material walls.
- Walls are electric and magnetic fields---charged particle are dense enough for collective effects to be important: plasmas.
- Neutral antihydrogen is confined by its magnetic moment in a magnetic well (depth~.5K).
- When antimatter hits the walls we detect it. We can see single antiatom annihilation
- Trapping properties depend on the internal state of antiatoms, which we manipulate with lasers and microwaves.

2009: 6 total anti-atoms; ~1 in trap at a time; 2017:>70,000 total, >1000 at a time. Cooled and probed for hours.

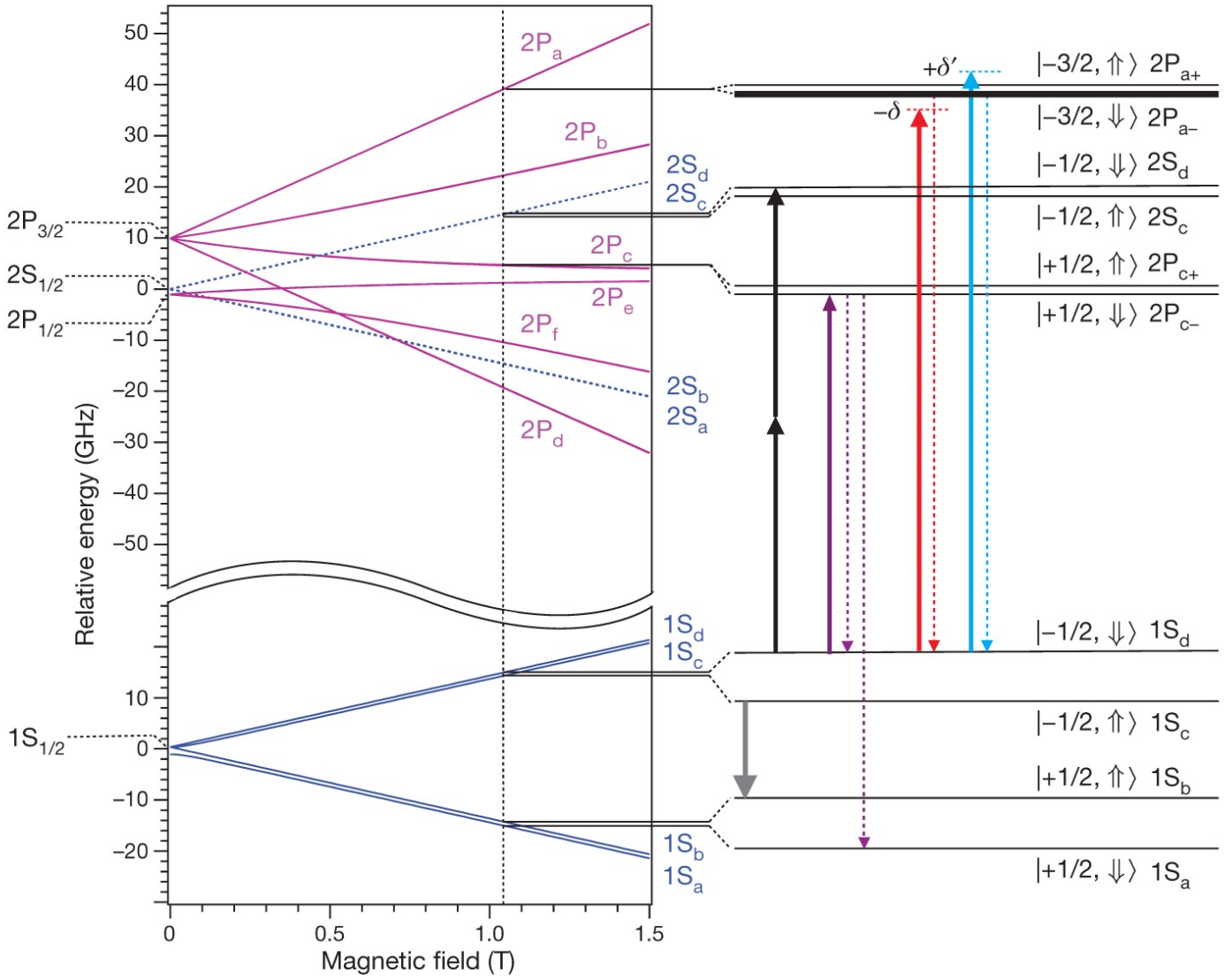


# ALPHA-2 apparatus

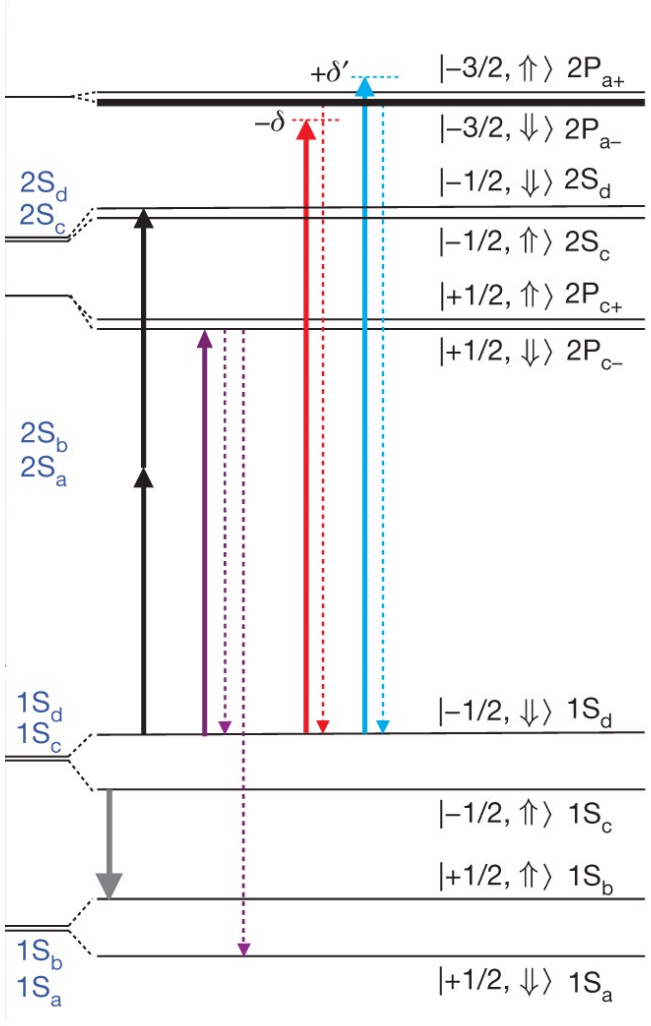

ALPHA Nature 2021

# Energy Transitions for the ALPHA Cooling Experiment




ALPHA Nature 2021

Cool (red arrow)
Heat (blue arrow)
Probe (purple arrow)
Spectrum 1S-2S (black arrows)




Protocol example:

(i) Stack: Produce 500-1000 anti-atoms over 2-4 hrs

(ii) Hyperfine polarization: Prepare doubly spin polarized $\bar{H}$ by illuminating with resonant microwaves (gray arrow) for 32s to induce the transition from $1S_c \rightarrow 1S_{b\ (untrapped)}$

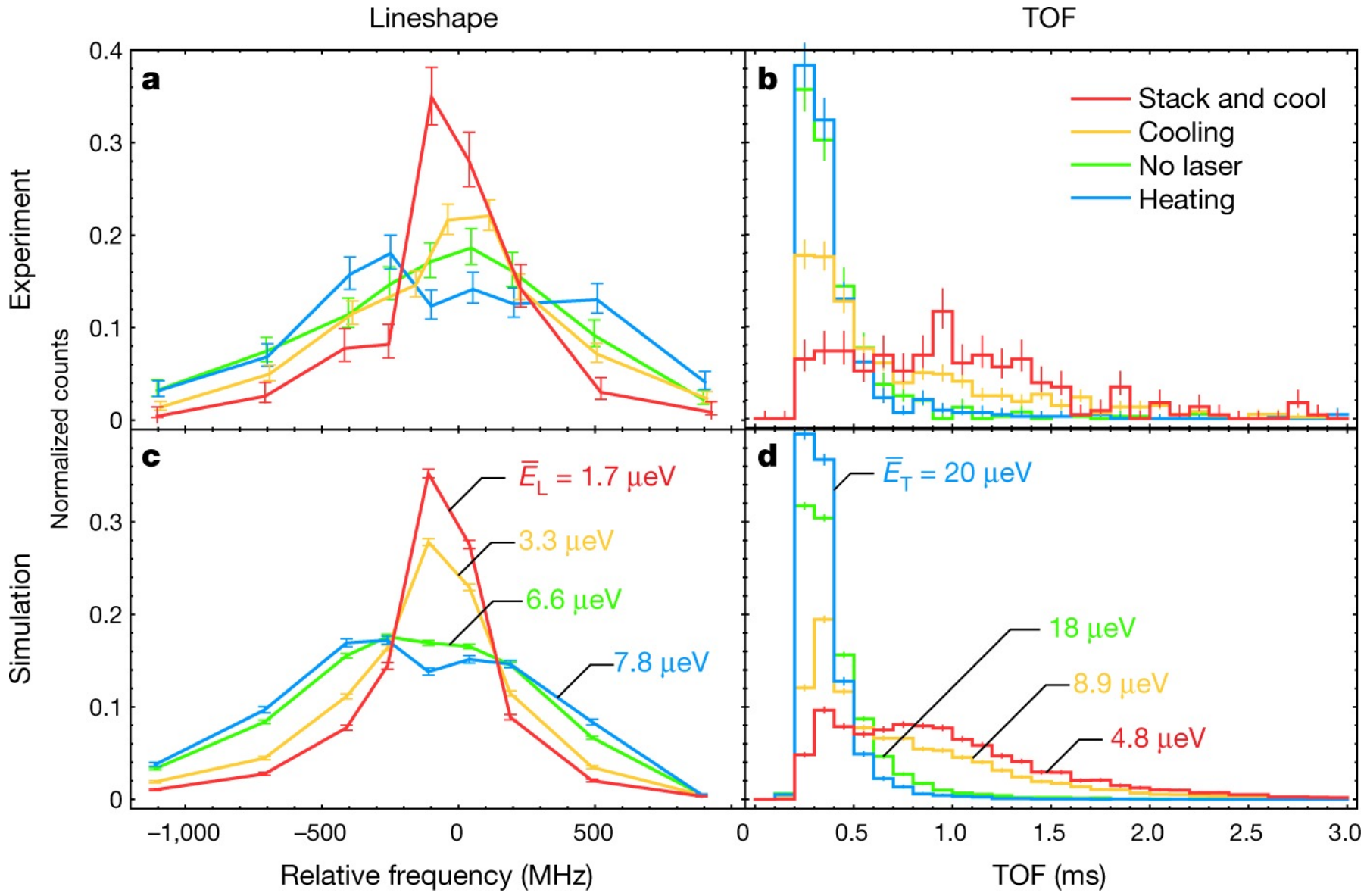
(iii) Cool (red arrow): Excite $1S_d \rightarrow 2P_{a-}$ with 121.6nm laser detuned by -240MHz relative to separation with Zeeman shift from B in trap. 2-4 hrs

(iv) Probe: $1S_d \rightarrow 2P_{c-}$ (frequency changed every 50s to account for depletion of $\bar{H}$ ). Measure decays to untrapped $1S_b$-state. 2-4 hrs

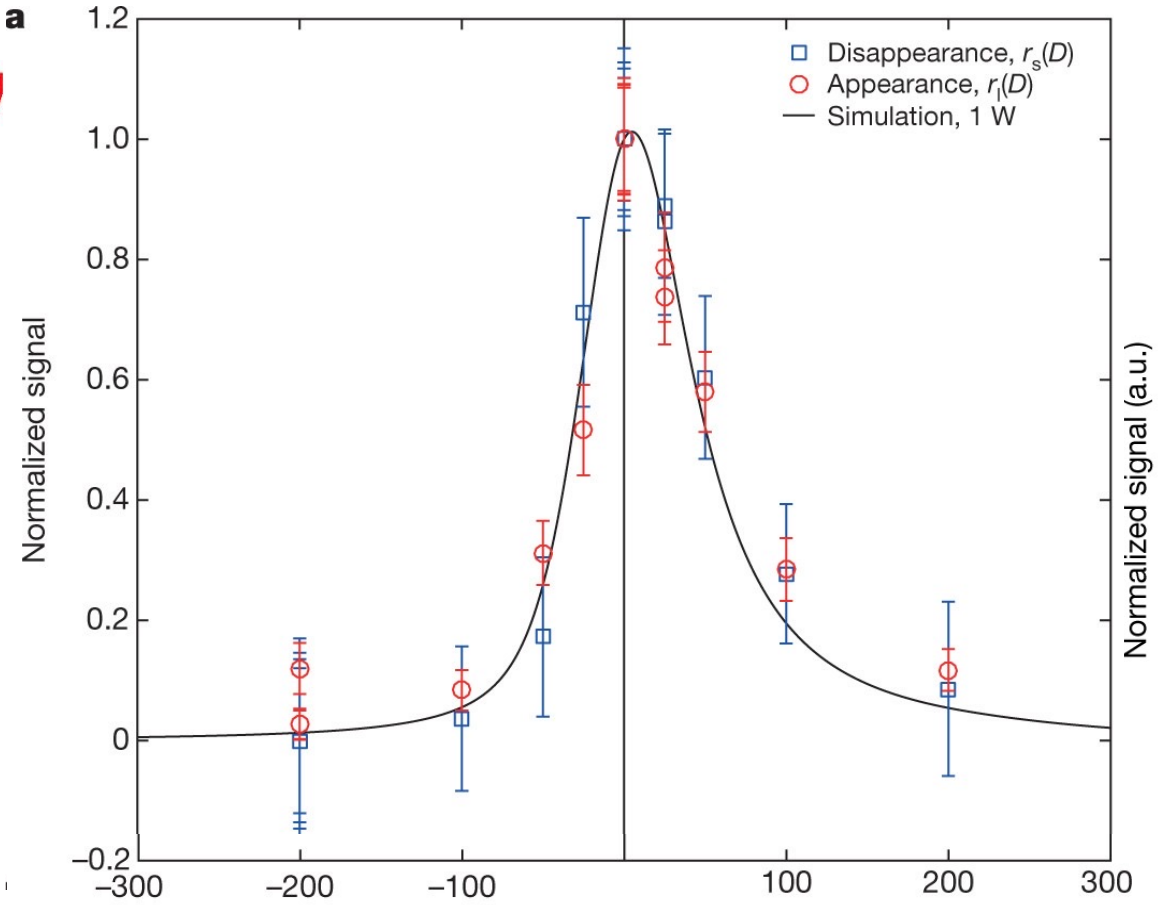
(v) Dump: turn off trap and measure remaining $\bar{H}$

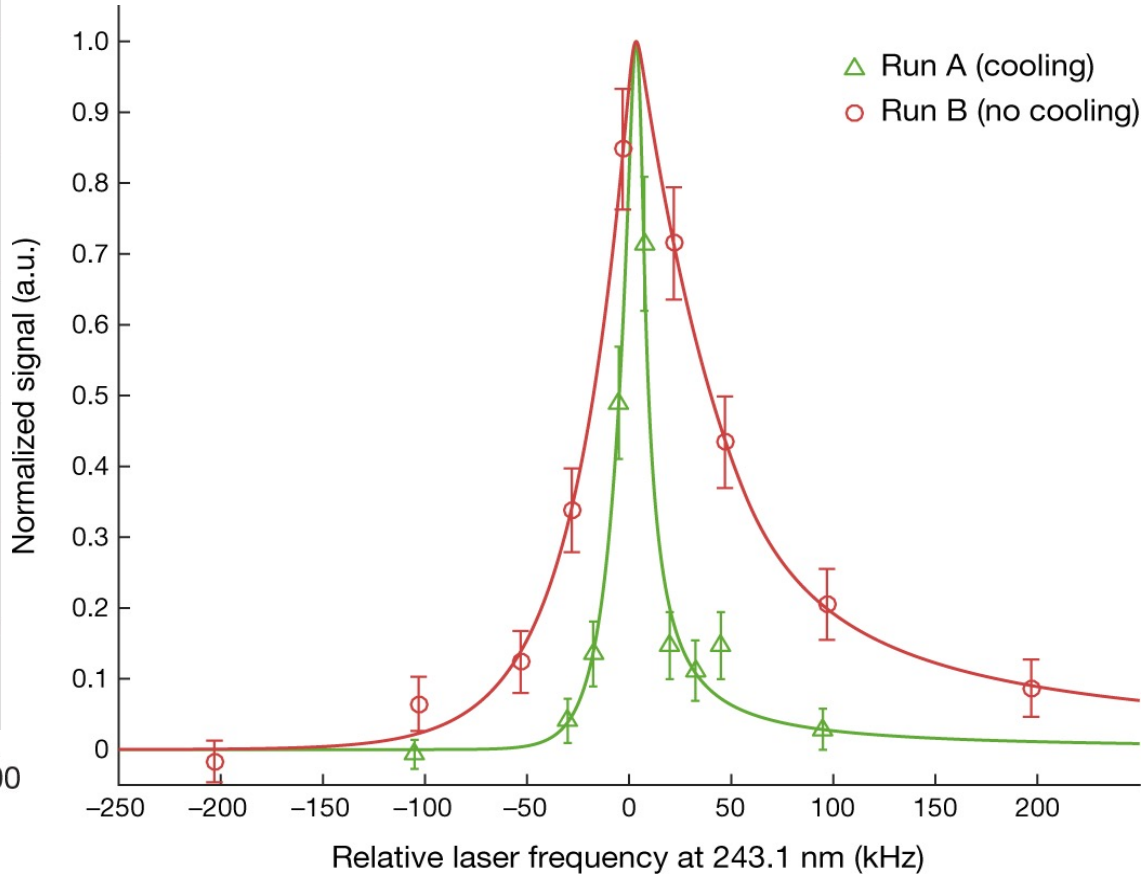
ALPHA Nature 2021

Application of different probe laser frequencies + detector time-of-flight measurements allows us to reconstruct the energy distribution of antiatoms




ALPHA Nature 2021



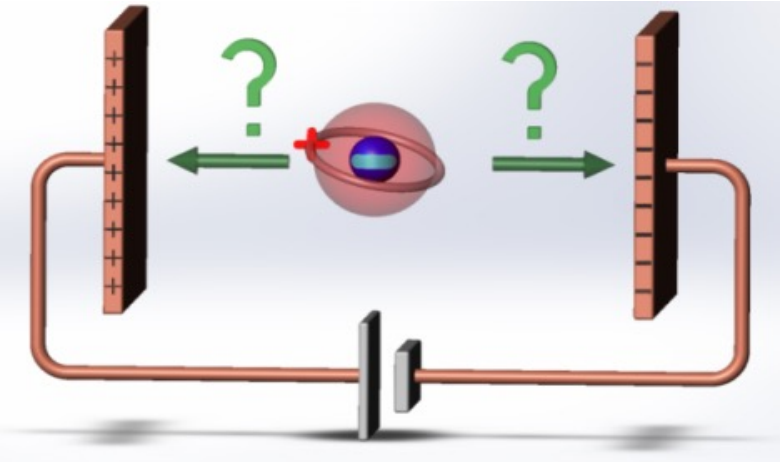




ALPHA Nature 2018

1S-2S CPT test: $2 \times 10^{-12}$

Cooling narrows linewidth
ALPHA Nature 2021

# Antihydrogen Charge



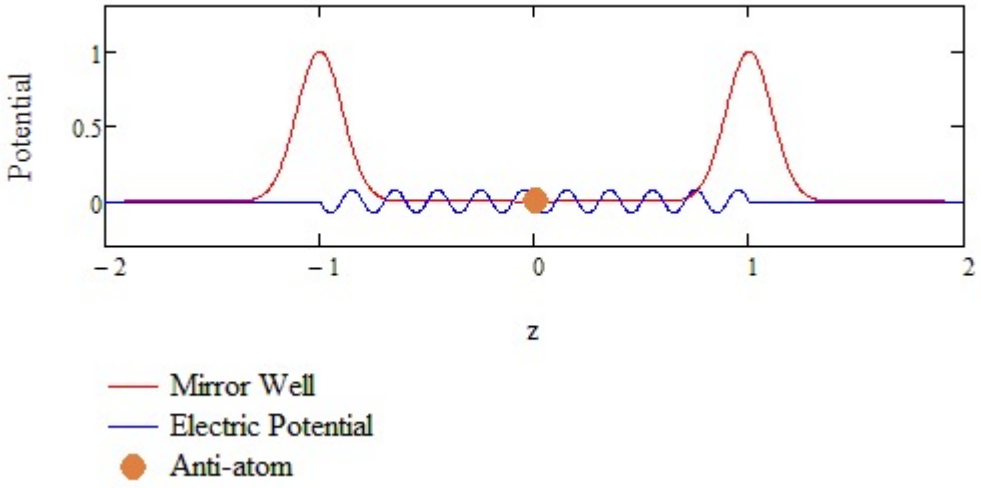

- Normal matter atoms are known to be charge neutral to remarkable precision: on the order of $10^{-21}e$.
- CPT and quantum anomaly cancellation demand that antihydrogen be charge neutral to a similar level.
- How well is the charge of antihydrogen known?
  - Techniques used for normal matter atoms are inapplicable.
  - Only prior limits on antihydrogen at the $10^{-2}e$ level.
  - Using superposition:
    - Charge of the antiproton is known to $710^{-10}e$.
    - Charge of the positron is known to $2.510^{-8}e$.
    - *Can we be sure that superposition is valid? Almost surely…*

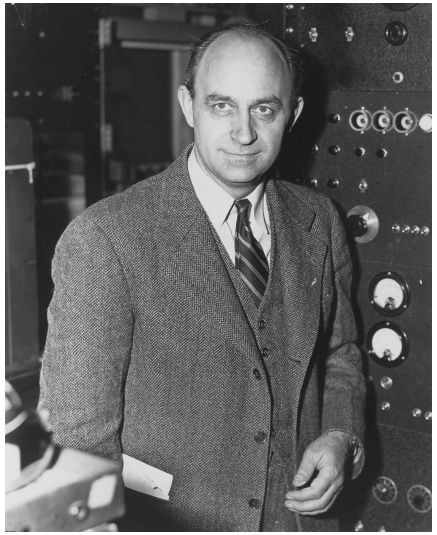
- A search for the charge of antihydrogen is a novel and potentially interesting test of fundamental physics.


Bressi, G. et al. Testing the neutrality of matter by acoustic means in a spherical resonator. Phys. Rev. A **83**, 052101 (2011).
Greenland, P. T. Antimatter, Contemporary Physics **38**, 181 (1997).
Olive, K. A. *et al*. Review of particle physics. *Chinese Phys. C* **38**, 090001 (2014).
Fee, M. S. *et al*. Measurement of the positronium $1\,^3S_1$–$2\,^3S_1$ interval by continuous-wave two-photon excitation. *Phys. Rev. A* **48**, 192 (1993).
Hori, M. *et al*. Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio. *Nature* **475**, 484 (2011).
Hughes, R. J. & Deutch, B. I. Electric charges of positrons and antiprotons. *Phys. Rev. Lett.***69**, 578 (1992).

# Improved Antihydrogen Charge Bound Using Stochastic Fields

- Stochastic acceleration (Fermi acceleration) can eject charged anti-atoms from the trap.



- Using stochastic acceleration, we expect that we can determine the charge to the $10^{-12}e$ level.

$$\Delta E_{\bar{H}} \sim Qe\Delta\Phi_{kick}N_{kick}^{1/2}$$

$$\Delta E_{\bar{H}} \leq U_{trap}$$

$$Q \leq \frac{U_{trap}}{e\Delta\Phi}\sqrt{\frac{1}{N}}$$

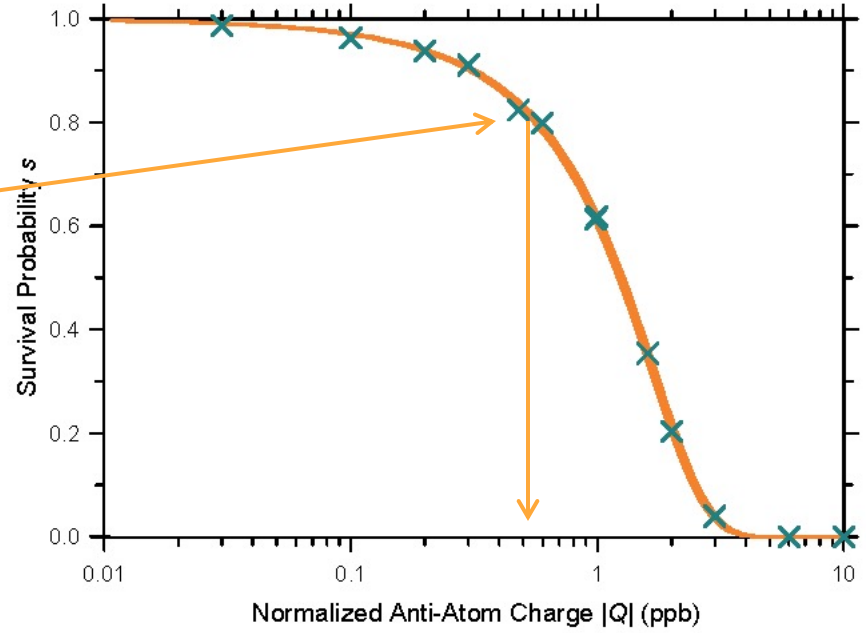

M. Baquero-Ruiz, Studies on the neutrality of antihydrogen. Ph.D. thesis, University of California, Berkeley, 2013.
M. Baquero-Ruiz and A. E. Charman and J. Fajans and A. Little and A. Povilus and F. Robicheaux and J.S. Wurtele and A. I. Zhmoginov, Measuring the electric charge of antihydrogen by stochastic acceleration, New J. Phys. **16** 083013, (2014).

# Stochastic Acceleration Experimental Results

| | Number of Trials | Observed Antiatoms |
|---|---|---|
| Stochastic Trials | 10 | 12 |
| Null Trials | 10 | 12 |

Cosmic background is negligible.

- Clearly, most antiatoms survive.
  - Appropriate survival cutoff is significantly greater than 50%.
- After much Bayesian statistical analysis…
  $Q < 0.59$ ppb (one sigma).
- After much systematic analysis…
  $\boldsymbol{Q < 0.71}$**ppb** (one sigma).
- Using superposition, this sets a limit on the positron charge anomaly of $|q_{\mathrm{pos}} - e|/e < 1\mathrm{ppb}$, an improvement by a factor of 25.





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L. Evans, Phenomenology of creation of antihydrogen and measurement of antihydrogen properties, Ph.D. thesis, Berkeley (2016).

# Weak Equivalence Principle: $M_I = M_G$

- Average energy of uncooled antiatoms T ~300mK.
- Typical velocity: ~90m/s.
- Equivalent height: ~400m.
  - Fountain is impossible at this energy.
    - Gbar collaboration intends to trap antihydrogen$^+$ ions, cool and strip the ions, and make a fountain.

- Downward deflection in 1m: 0.6mm ("falling" beam)
  - A deflection measurement is possible, but difficult.
    - AEGIS collaboration intends to make a much lower energy antihydrogen beam.

- Magnetic confinement force is strong (G is small)

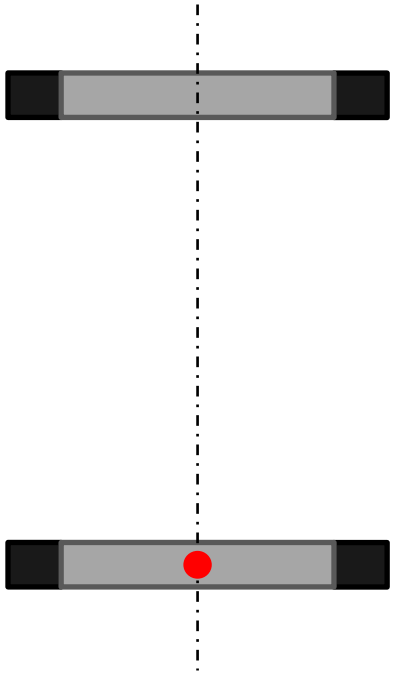
→in situ knowledge of B is vital

We expect to reach a precision of ~1% with this apparatus

# Gravity

- In 2013, we made a crude measurement using this technique, and determined that the antimatter *g* was constrained by $\pm 100g$.
  - While there are many indirect tests of antimatter gravity, this was the first “Leaning Tower of Pisa” measurement.

- ALPHAg with 2018 trapping numbers would have +-g precision
  - By employing a gradient magnetic field, we plan a balance experiment and hope to measure *g* to $\pm 0.01g$.
  - Laser cooling + adiabatic cooling.
  - This will require control to the 0.1G level in a 1T background.
  - Detailed understanding of 3D nonlinear orbit dynamics. Octupole and radial mirror field coupling.



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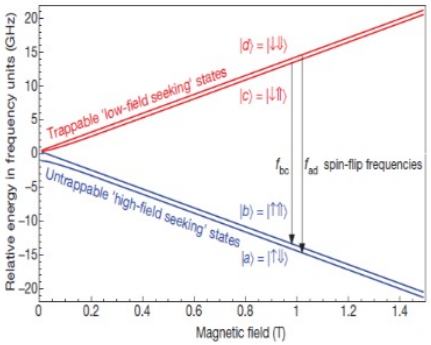
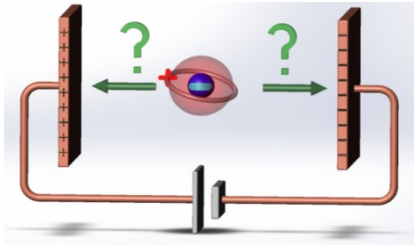
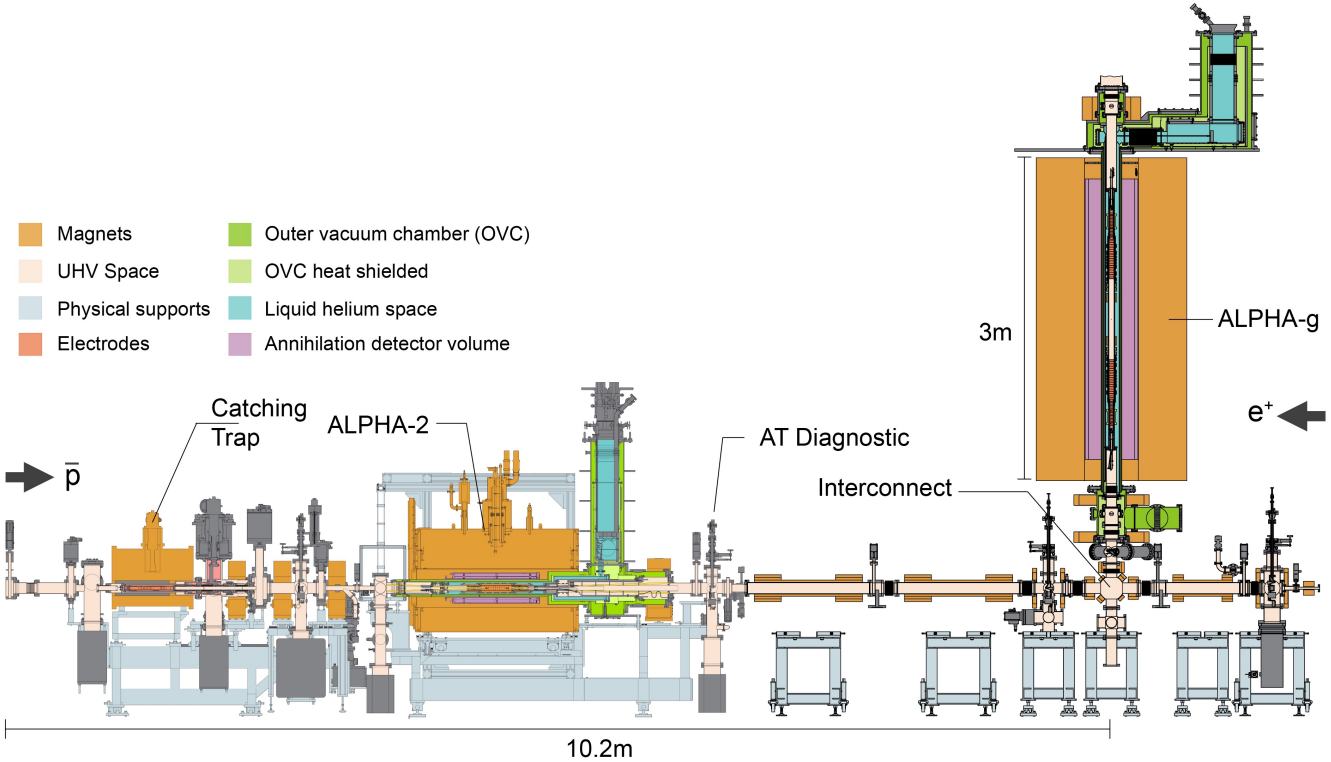
A I Zhmoginov, A E Charman, R Shalloo, J Fajans, J S Wurtele, Nonlinear dynamics of anti-hydrogen in magnetostatic traps: implications for gravitational measurements, Class. and Quantum Grav., **30** 205014 (2013). Zhong, Fajans, Zukor, NJP 2018.

# Summary

- The field of neutral antimatter science is in its infancy, enabled by advances in plasma physics,
- ALPHA can routinely trap ~1000 antiatoms/day.
  - Very crudely, antimatter *g* bound of $\pm 100g$. Next 5 years hope for 10%-1% measurement
  - The charge neutrality of antihydrogen. Improve x10 or more.
  - The 1S-2S spectrum, Lyman-α transition, laser cooling. Improve x10 or more.
  - The hyperfine spectrum
  - None of the precision antimatter CPT tests ($2\times10^{-12}$ level) have detected any CPT symmetry violations





Swapan is visionary in his physics, very adept at bringing in funding for new ideas, a champion of good physics and physicists, and a great friend.

# Welcome home, Swapan!

The real reasons for Berkeley: