

# Antihydrogen and the ALPHA and GBAR experiments

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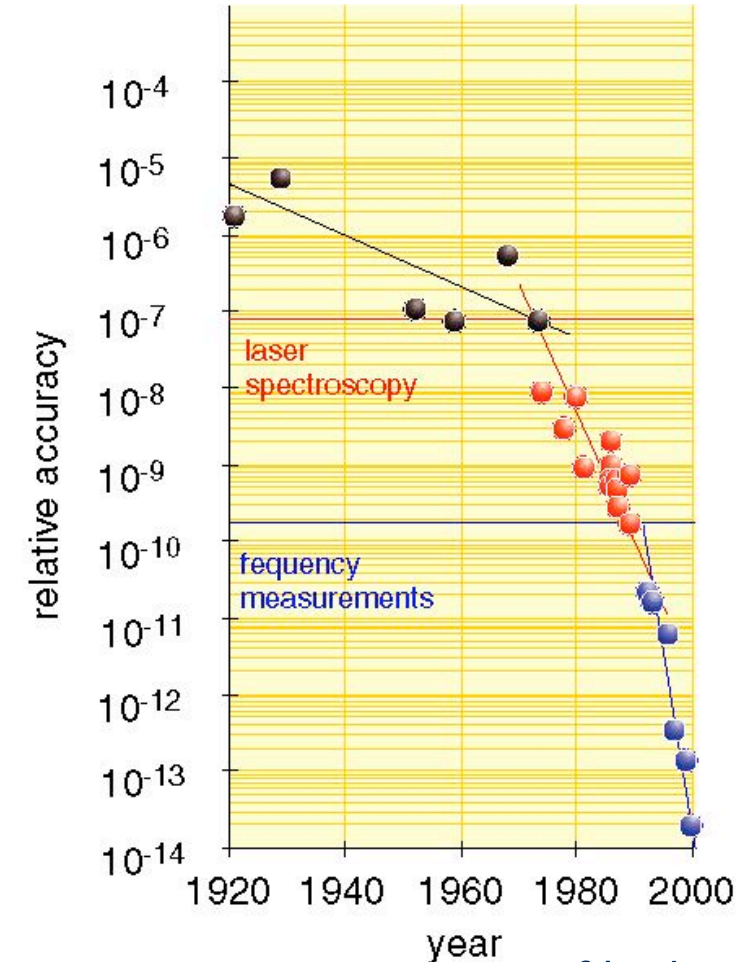
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# Complementary ways to look for new physics

- Higher energy (enter new regimes)
- Higher luminosity (rare events)
- Higher precision (undetected phenomena)

## To gain high precision:

- Go to lower energy
  - more control
  - longer time to study
  - less thermal noise
- Measure frequency
  - interferometric techniques
  - frequency combs



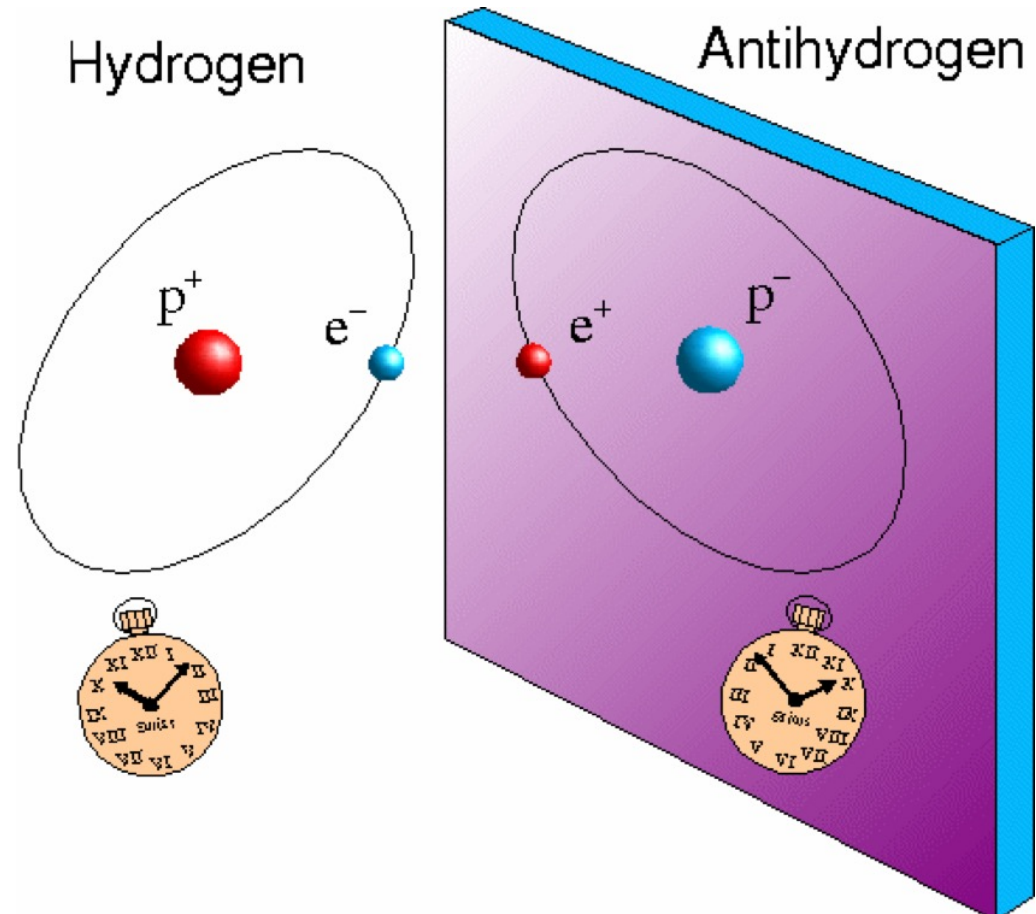
1S-2S spectroscopy of hydrogen

(Latest:  $4.2 \times 10^{-15}$  in 2011, *PRL* **107** 203001)

# Hydrogen spectroscopy

- Bohr's model of the hydrogen atom (1913),  $\sim$ PHz
- Quantum mechanics (1920s)
- Relativistic quantum mechanics (fine structure)  $\sim$ 10 GHz
- Quantum Electro Dynamics (Lamb shift, 1947)  $\sim$  GHz
- Radio astronomy (1420 MHz)
- Charge radius of proton (muonic hydrogen)

# An ideal probe: antihydrogen



- Hydrogen very well understood
- Neutral
- Can be trapped with magnetic fields
- Single atom detection possible
- Laser spectroscopy with extreme accuracy possible
- Many different sectors can be probed (leptons/baryons/B-fields/etc.)

# Missing antimatter problem

- Antimatter is believed to be a perfect mirror image of ordinary matter
- Created in equal amounts at big bang?
- Annihilated and created in pairs
- Why do we (almost) only see one kind?
- Balanced universe?
- Matter-antimatter asymmetry?

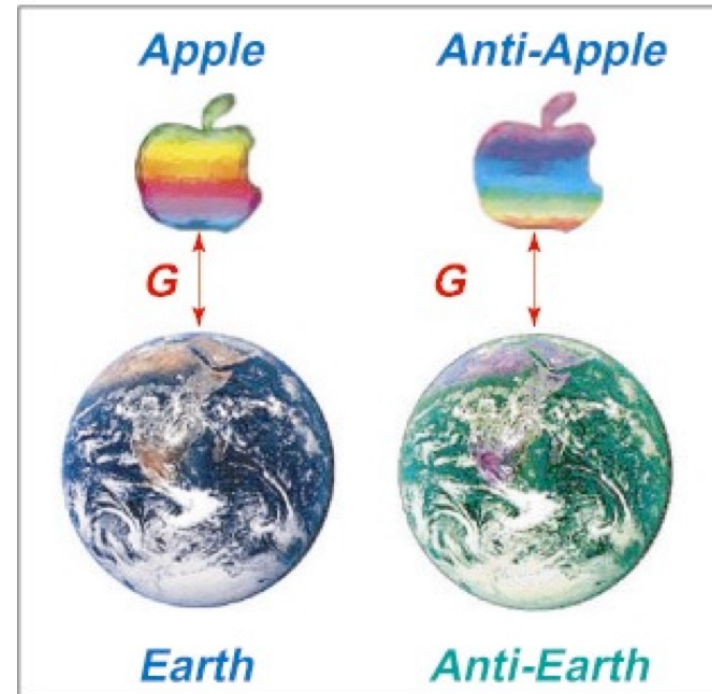
# Looking for cracks in the mirror image: a look at symmetry

- What if the mirror image is not perfect?
- Parity symmetry (3D mirror) broken
- Combination Charge conjugation (particle- $\rightarrow$  antiparticle) and Parity broken
- CP breaking too small to solve the problem
- Combination CPT (T=time reversal) valid in any local, Lorentz-invariant Quantum Field Theory
- CPT implies that atoms of matter and antimatter have identical spectra
- Test this!

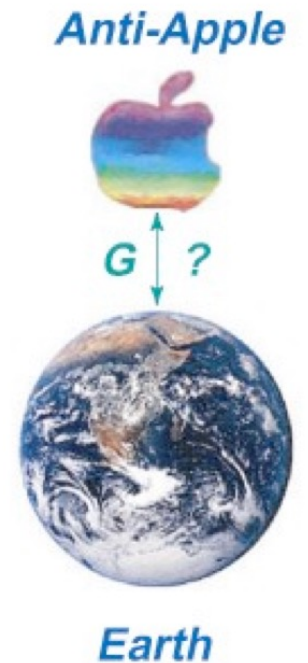
# Matter-antimatter gravity

- CPT -> antimatter attracts antimatter same as matter attracts matter
- Einstein's Weak Equivalence principle (~ everything falls the same way) says that matter attracts antimatter the same way.
- Test using neutral bodies

*CPT Symmetric Situation*



*Not:*



# Antiprotons at CERN

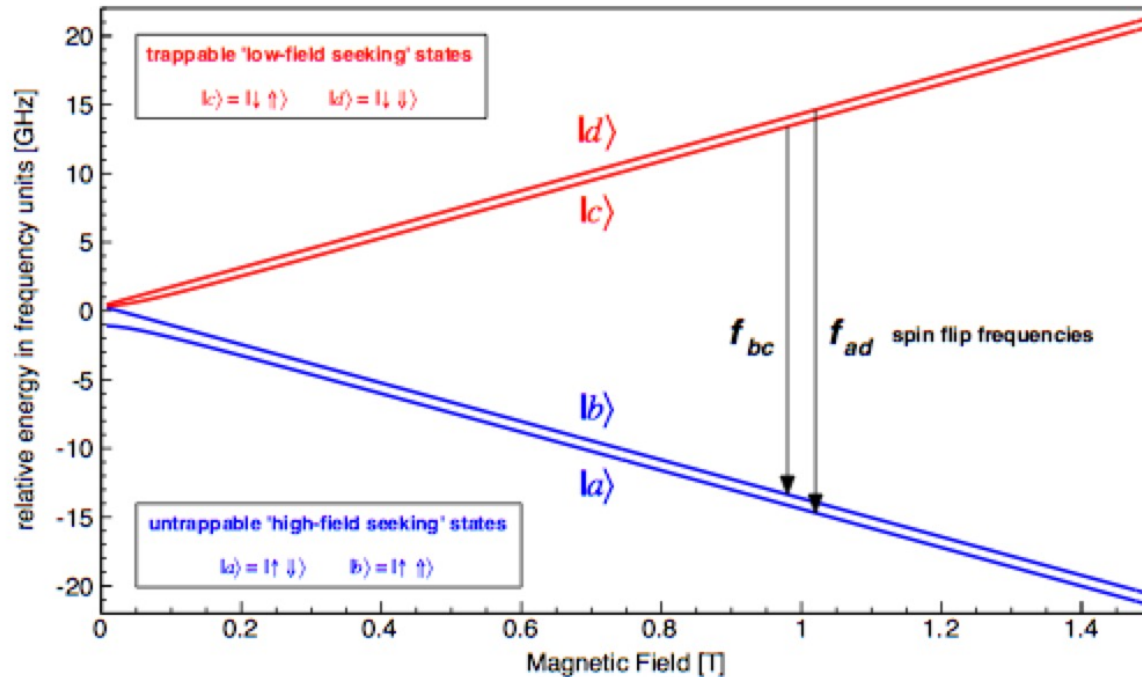
- At CERNs Proton Synchrotron  $10^{13}$  protons with energy 26 GeV are collided with a target
- Antiprotons are formed in the collision, some enter the Antiproton Decelerator (AD)
- The AD slows  $\sim 3 \cdot 10^7$  antiprotons from 3-4 GeV to 5.3 MeV
- ELENA further slows to 0.1 MeV and delivers to experiments (ALPHA, GBAR, BASE, ASACUSA, AEGIS, formerly also ATHENA and ATRAP)
- ALPHA traps antihydrogen with energies less than 0.5 Kelvin (0.04 meV)
- Overall cooling by a factor  $6 \cdot 10^{14}$



# ALPHA (and ATHENA) achievements

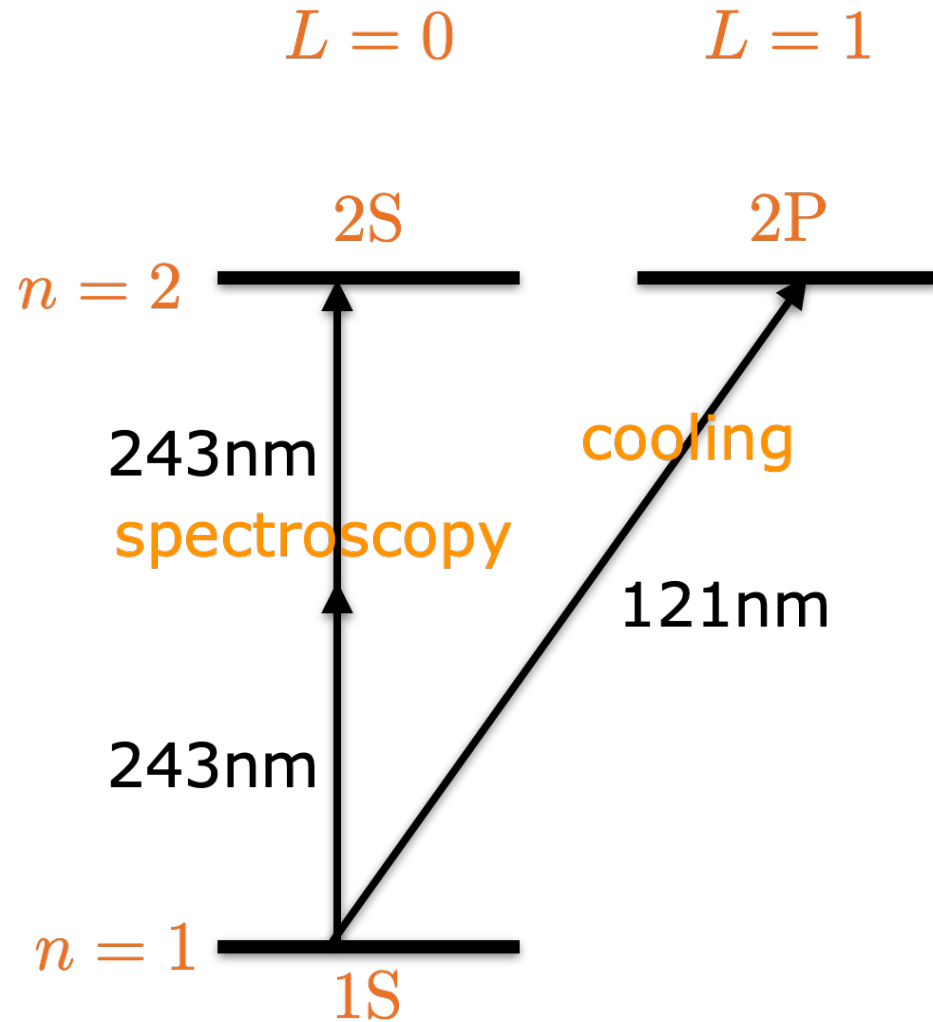
- 2002 first “cold” antihydrogen formed
- 2010 first antihydrogen trapped in magnetic trap (on average 1 per 2 tries)
- 2011 antihydrogen trapped for 15 minutes (ground state!)
- 2012 first study of internal structure (spin flip of positrons using microwave)
- 2012 original ALPHA upgraded to ALPHA2 (e.g. laser access)
- 2016 antihydrogen 1S-2S transition observed
- 2017 now trapping for hours, about 10 per shot, but up to 1000 by accumulating
- 2018 antihydrogen 1S-2S measured with relative accuracy  $2 \cdot 10^{12}$  (hydrogen still  $\cdot 1000$  better)
- 2018 1S-2P (Ly- $\alpha$ ) observed (needed for laser cooling, very difficult wavelength: 121 nm)
- **2021 Laser cooling of antihydrogen**

# Spectroscopy with a handful of antiatoms



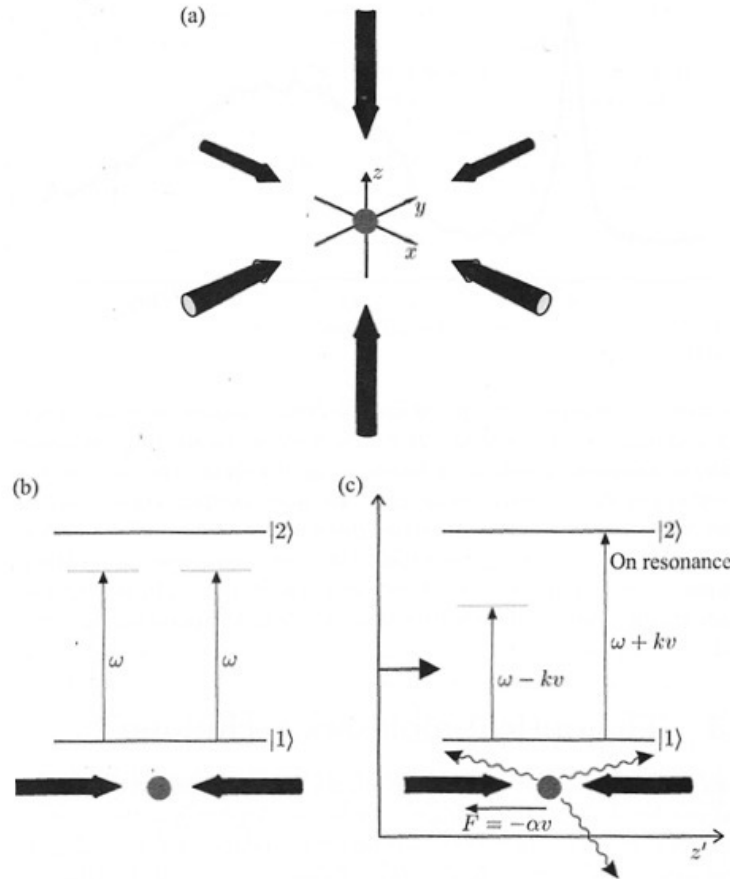
- Design experiment so that signal = loss of antiatoms
- Individual antiatoms can be detected through annihilation
- **Either:** hold antiatoms while you do something to them – turn off trap and see if they are still there
- **Or:** detect antiatoms when they are kicked out (more difficult)

# Level structure of (anti-)hydrogen



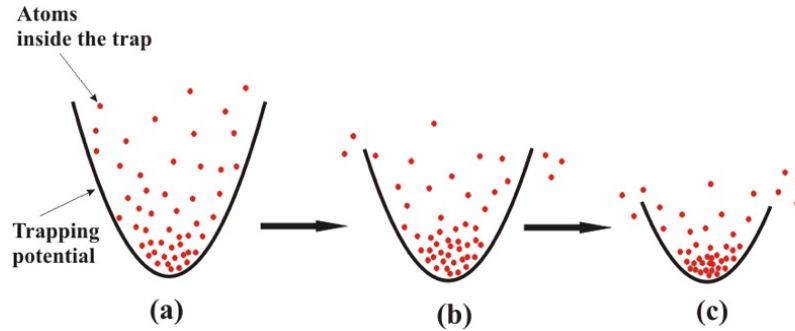
- Photon angular momentum  $L=1$
- Conservation of angular momentum  
 $1S-2P$ : 1 photon  
 $1S-2S$ : 2 photons
- $2S$  has no 1-photon decay  
lifetime  $0.125\text{ s}$   
width  $5.2 * 10^{-15}\text{ eV}$
- 2-photon spectroscopy is Doppler free (to first order)

# Laser cooling



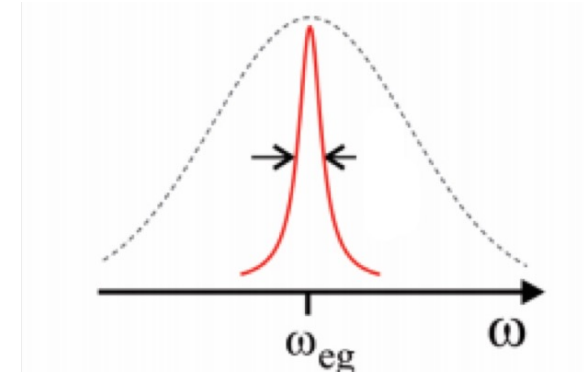
- Photon hits atom
- “hit” = absorption and re-emission in random direction
- Overall effect: slowing in one direction
- Problem: push from behind
- Photon energy must match transition
- Trick: slightly mismatch photon energy
- Doppler effect selects atoms moving towards laser

# Why is colder better??



Higher density!

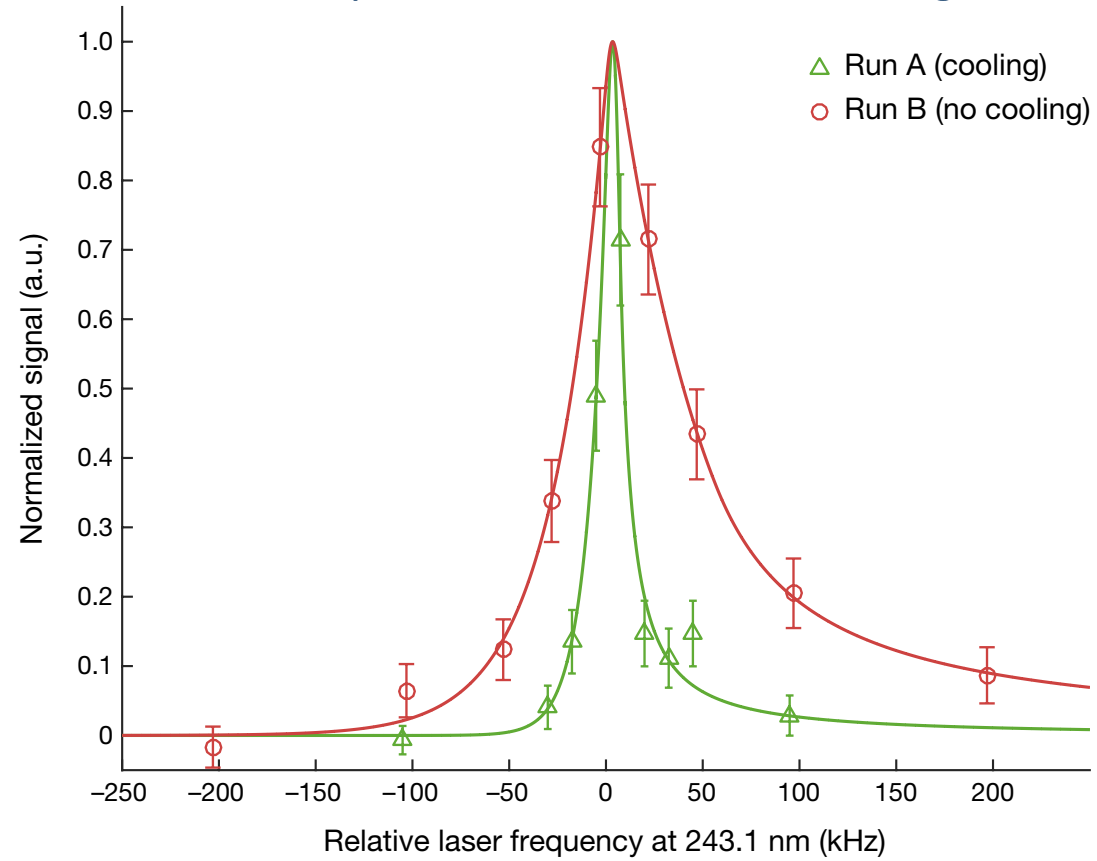
- Less line broadening!
- Transit time
  - Doppler (2nd order)



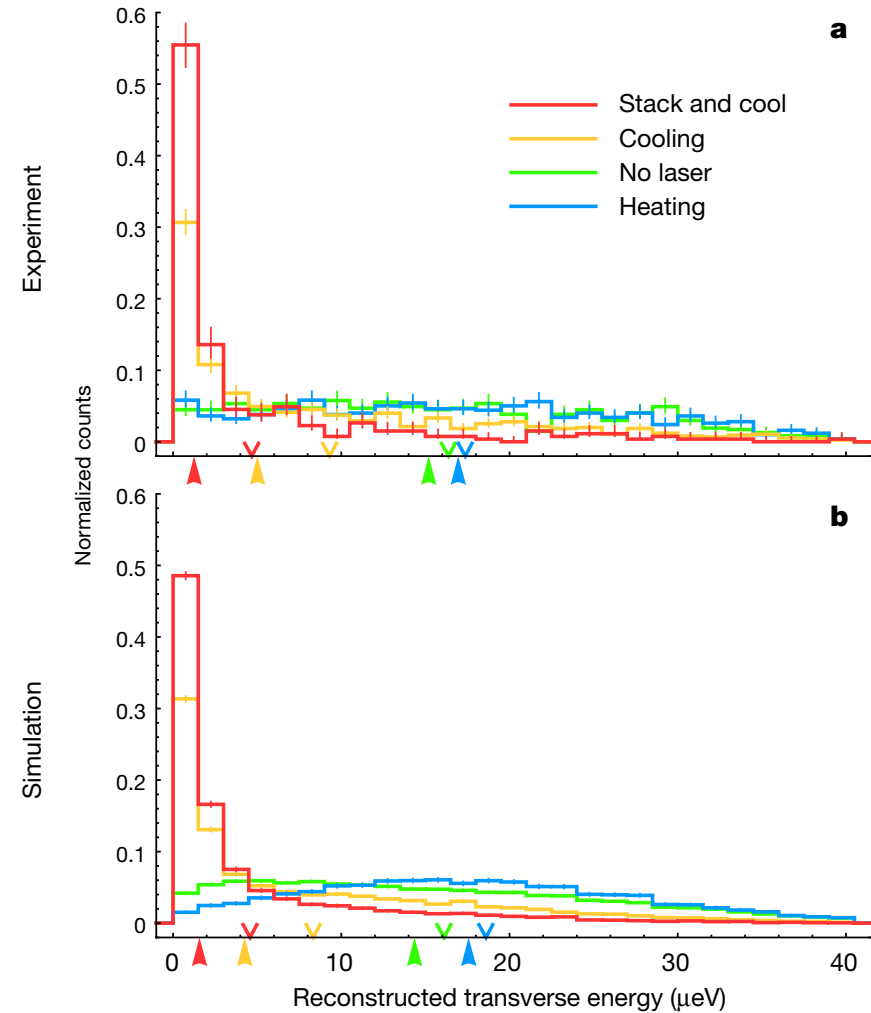
More complex anti-systems?

# Results

## Line shape with and without cooling



## Reconstructed kinetic energy perp. to laser



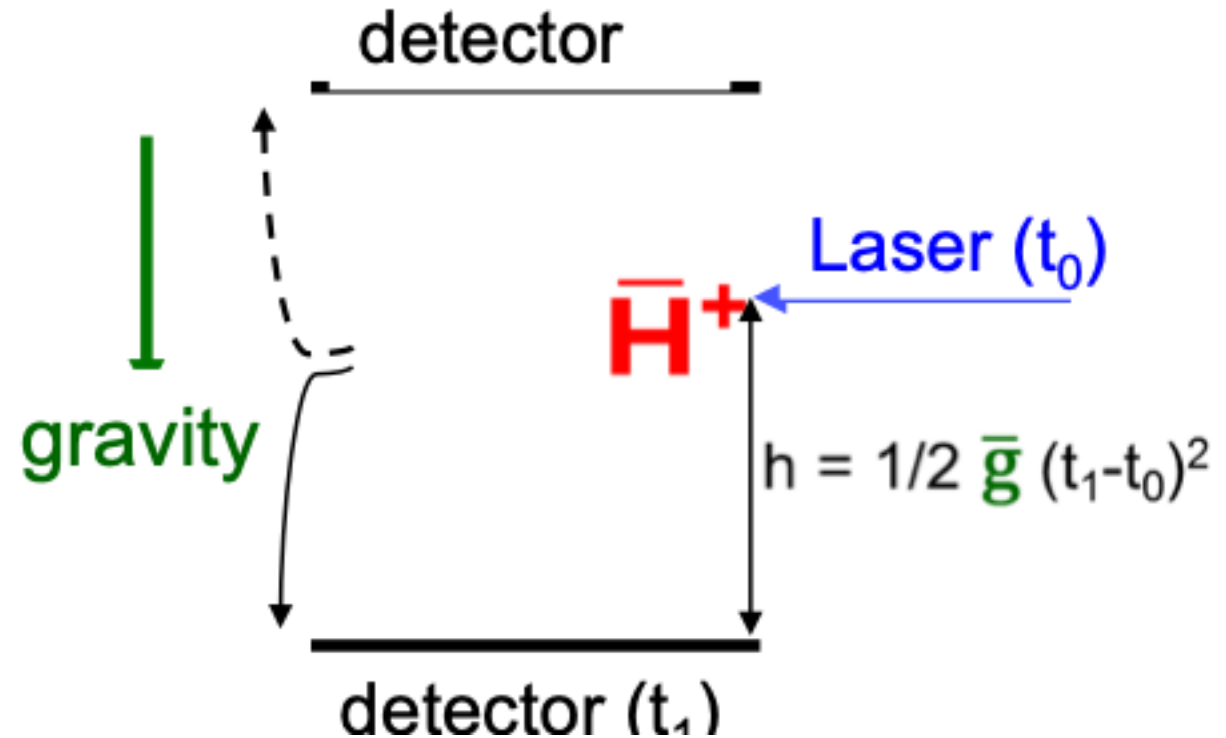
# Gravitational Behaviour of Antimatter at Rest (GBAR)



- measure  $g$  for antiatoms
- Drop and measure time-of-flight + position
- Gravity is very weak
- Attempts with antiprotons failed due to interaction with stray electric fields
- Thermal motion must be reduced
- Laser cooling helps, but GBAR chose different method

# GBAR: cooling scheme

- Form the antihydrogen ion  $\text{anti-H}^+$  ( $\bar{p} e^+ e^+$ )
- Charged  $\rightarrow$  easier to manipulate
- trap together with very cold ions (e.g.  $\text{Be}^+$ )
- Ion cools through collisions
- ++ Repulsion  $\rightarrow$  never gets close enough to annihilate
- a very carefully tuned laser removes one positron
- The neutral antiatom falls





# GBAR: creating the antihydrogen ions

- Scheme: slow beam of antiprotons enter a cloud of positrons
- First antihydrogen is formed through the reaction



- A second collision makes the ion
- $$\bar{H} + e^+ + e^+ \rightarrow \bar{H}^+ + e^+$$
- Reaction rates are very low
  - Need lots and lots of positrons
  - GBAR has its own little accelerator to create positrons



# Conclusions

- High-precision studies of antihydrogen at low energies is a probe for new physics.
- Comparing to spectra of normal hydrogen tests the Charge-Parity-Time reversal symmetry
- Spectroscopy at ALPHA is approaching accuracy of normal hydrogen
- So far no differences have been detected
- Antimatter gravity will be studied by GBAR (and others)