Antihydrogen and the ALPHA and GBAR experiments

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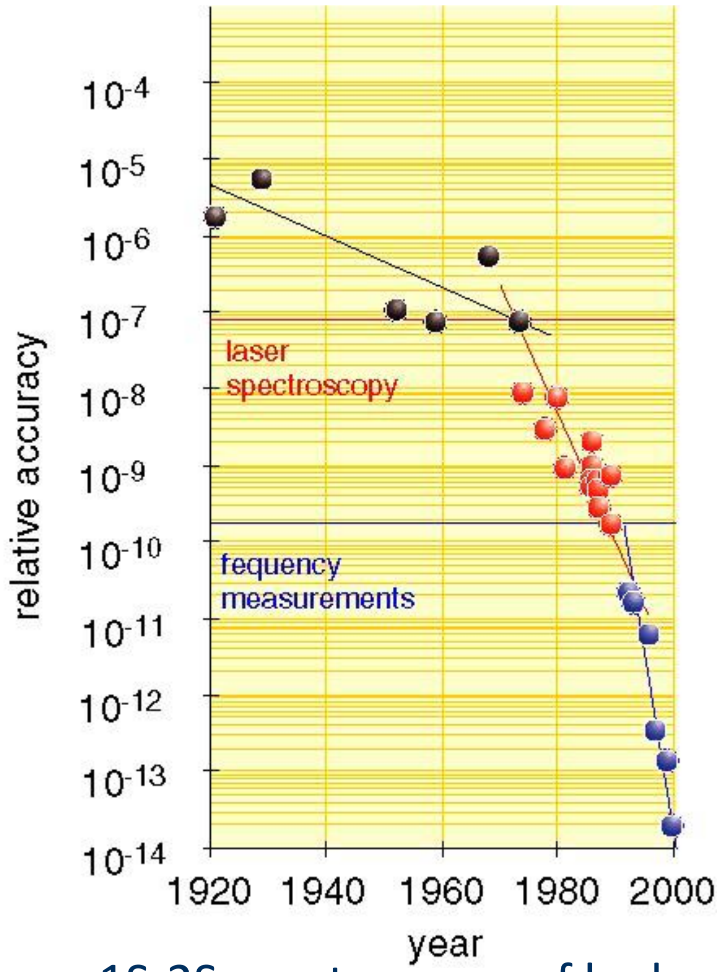
Complementary ways to look for new physics

- 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



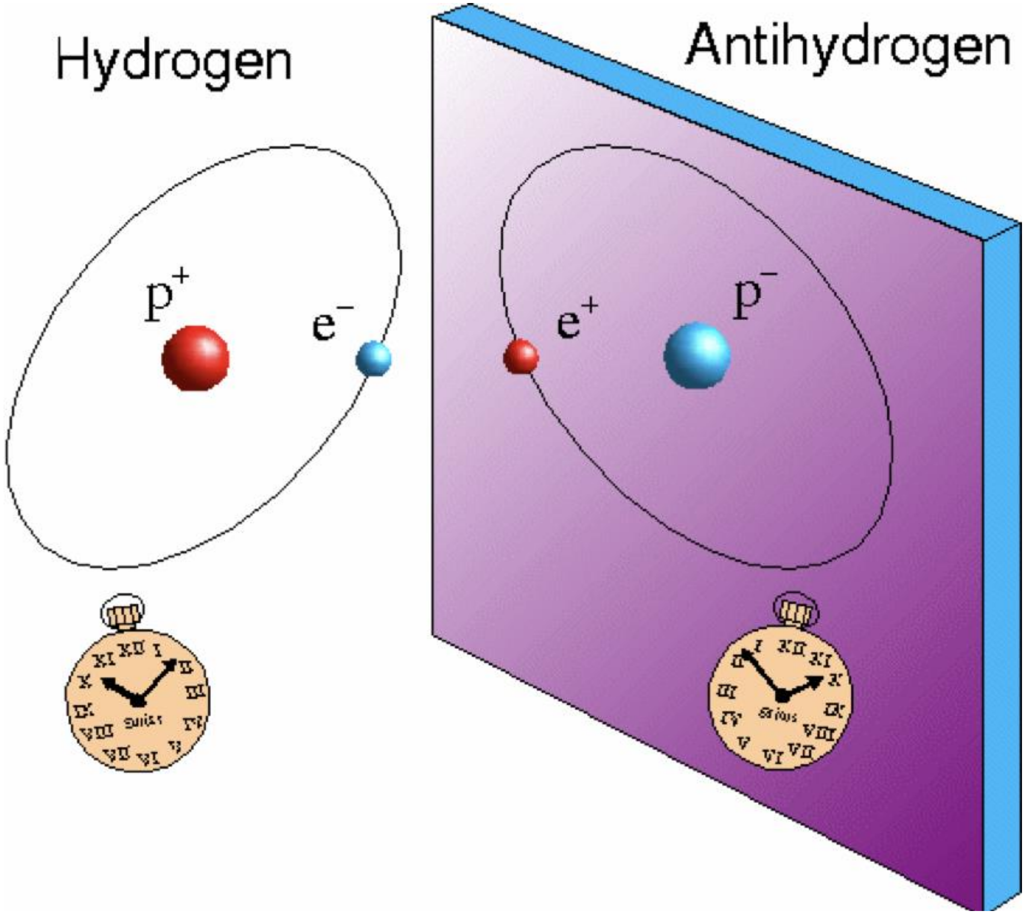
1S-2S spectroscopy of hydrogen

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

Hydrogen spectroscopy

- Bohr's model of the hydrogen atom (1913), ~PHz
- Quantum mechanics (1920s)
- Relativistic quantum mechanics (fine structure) ~10 GHz
- Quantum Electro Dynamics (Lamb shift, 1947) ~ 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

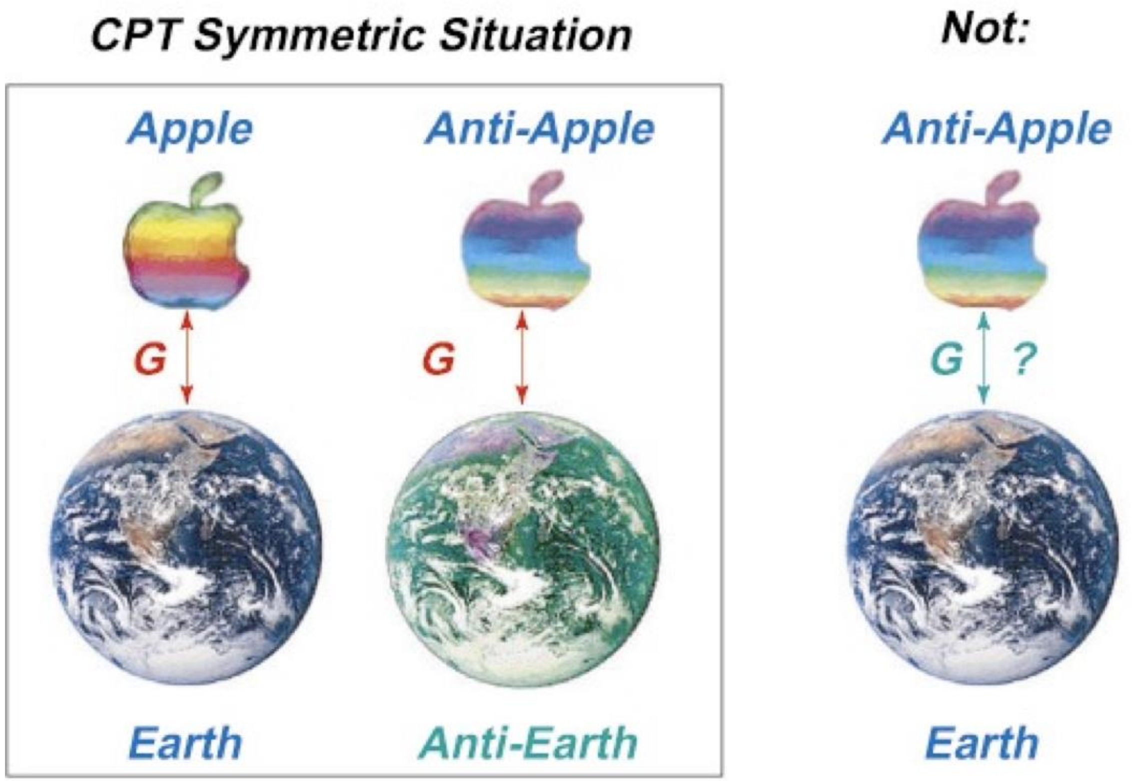
- Antimatter is believed to be a perfect mirror image of ordinary matter
- Created in equal amounts at big bang?
- Annihilated and created in pairs
- Why do we (almost) only see one kind?
- Balanced universe?
- Matter-antimatter asymmetry?

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-> 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



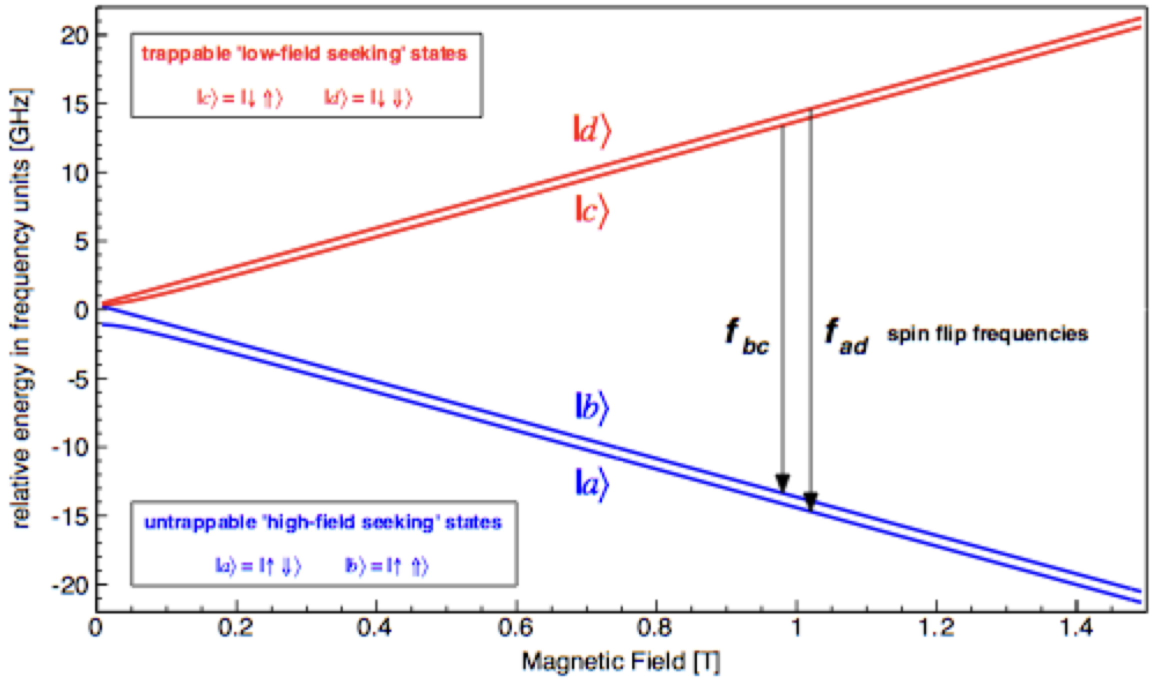
Antiprotons at CERN

- 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 ~3 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 $6*10^{14}$

ALPHA (and ATHENA) achievements

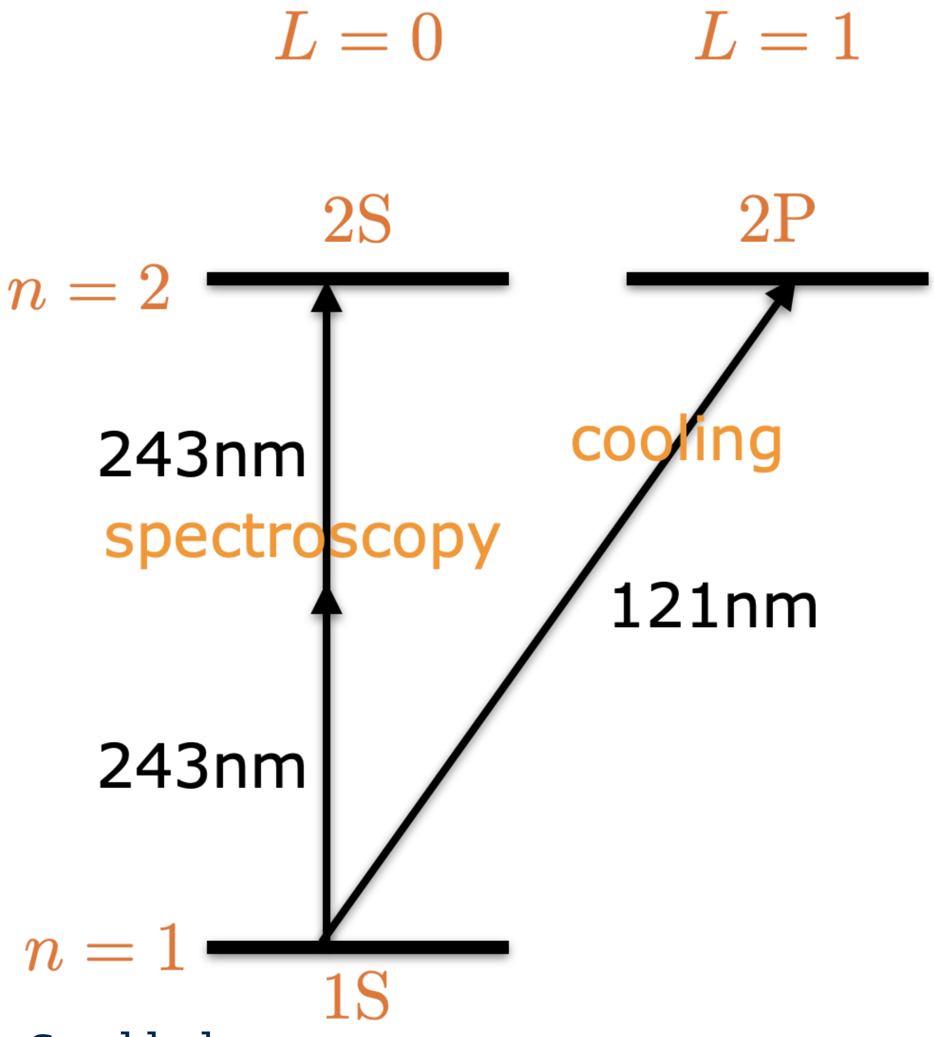
- 2002 first “cold” antihydrogen formed
- 2010 first antihydrogen trapped in magnetic trap (on average 1 per 2 tries)
- 2011 antihydrogen trapped for 15 minutes (ground state!)
- 2012 first study of internal structure (spin flip of positrons using microwave)
- 2012 original ALPHA upgraded to ALPHA2 (e.g. 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 $2*10^{12}$ (hydrogen still *1000 better)
- 2018 1S-2P (Ly-a) observed (needed for laser cooling, very difficult wavelength: 121 nm)
- 2021 Laser cooling of antihydrogen

Spectroscopy with a handfull of antiatoms



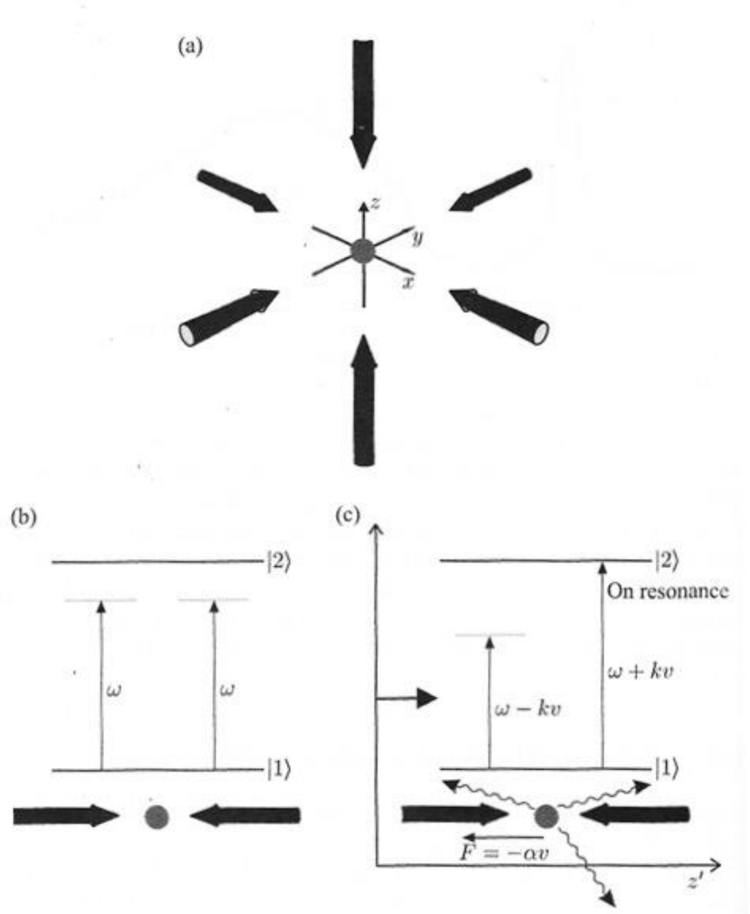
- Design experiment so that signal = loss of antiatoms
- Individual antiatoms can be detected through annihilation
- Either: hold antiatoms while you do something to them – turn off trap and see if they are still there
- Or: detect antiatoms when they are kicked out (more difficult)

Level structure of (anti-)hydrogen



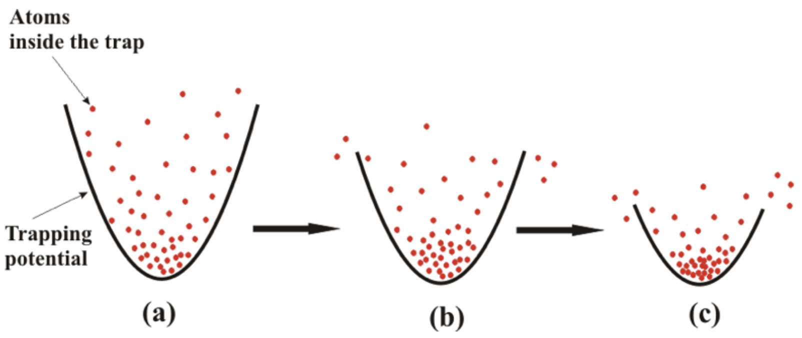
- Photon angular momentum L=1
- Conservation of angular momentum
  1S-2P: 1 photon
  1S-2S: 2 photons
- 2S has no 1-photon decay
  lifetime 0.125 s
  width 5.2 $*10^{-15}$ eV
- 2-photon spectroscopy is Doppler free (to first order)

Laser cooling



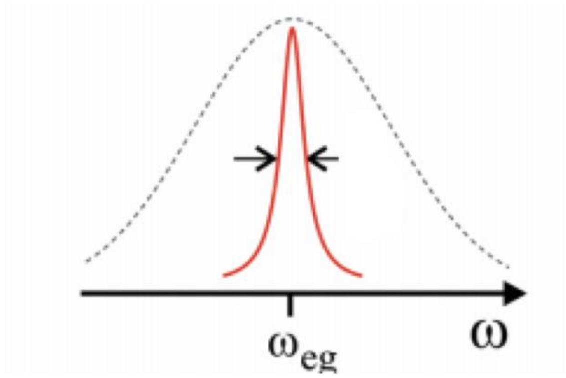
- Photon hits atom
- "hit" = absoption and re-emission in random direction
- Overall effect: slowing in one direction
- Problem: push from behind
- Photon energy must match transition
- Trick: slightly mismatch photon energy
- Doppler effect selects atoms moving towards laser

Why is colder better??



Higher density!

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

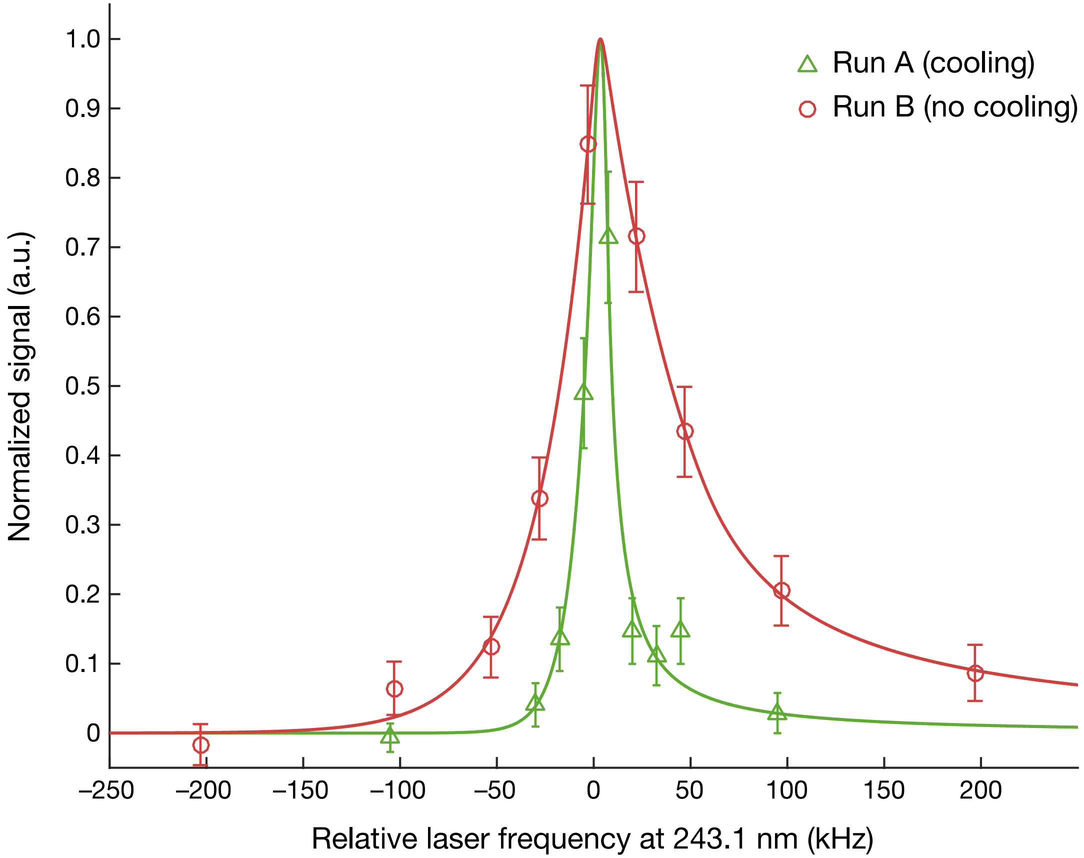


$$\overline{\mathrm{H}} + \overline{\mathrm{H}} \rightarrow \overline{\mathrm{H}}_2^- + e^+$$

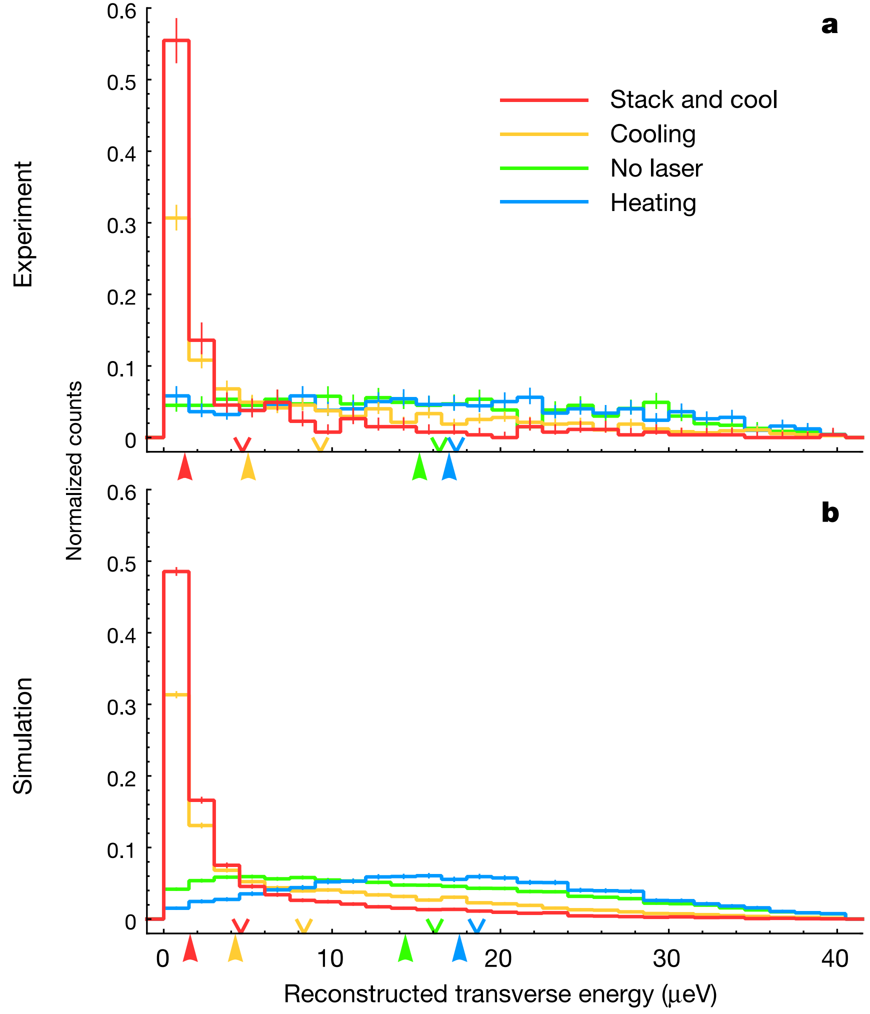
More complex anti-systems?

Results

Line shape with and without cooling



Reconstructed kinetic energy perp. to laser

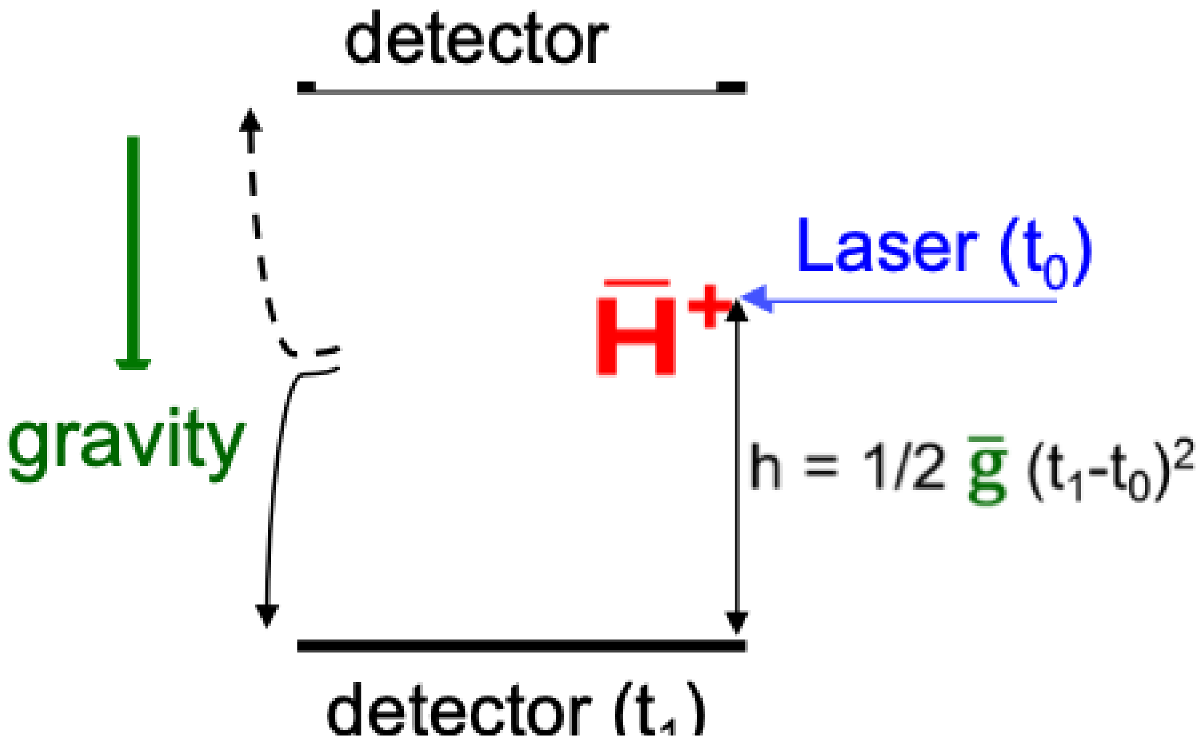


Gravitational Behaviour of Antimatter at Rest (GBAR)

- 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 anti-H⁺ ($\bar{p}\, e^+ e^+$)
- Charged -> easier to manipulate
- trap together with very cold ions (e.g. Be^+)
- Ion cools through collisions
- ++ Repulsion -> 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 could of positrons
- First antihydrogen is formed though the reaction

$$\bar{p} + e^{+} + e^{+} \rightarrow \bar{\mathrm{H}} + e^{+}$$

- A second collision makes the ion

$$\bar{\mathrm{H}} + e^{+} + e^{+} \rightarrow \bar{\mathrm{H}}^{+} + e^{+}$$

- Reaction rates are very low
- Need lots and lots of positrons
- GBAR has its own little accelerator to create prositrons

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)