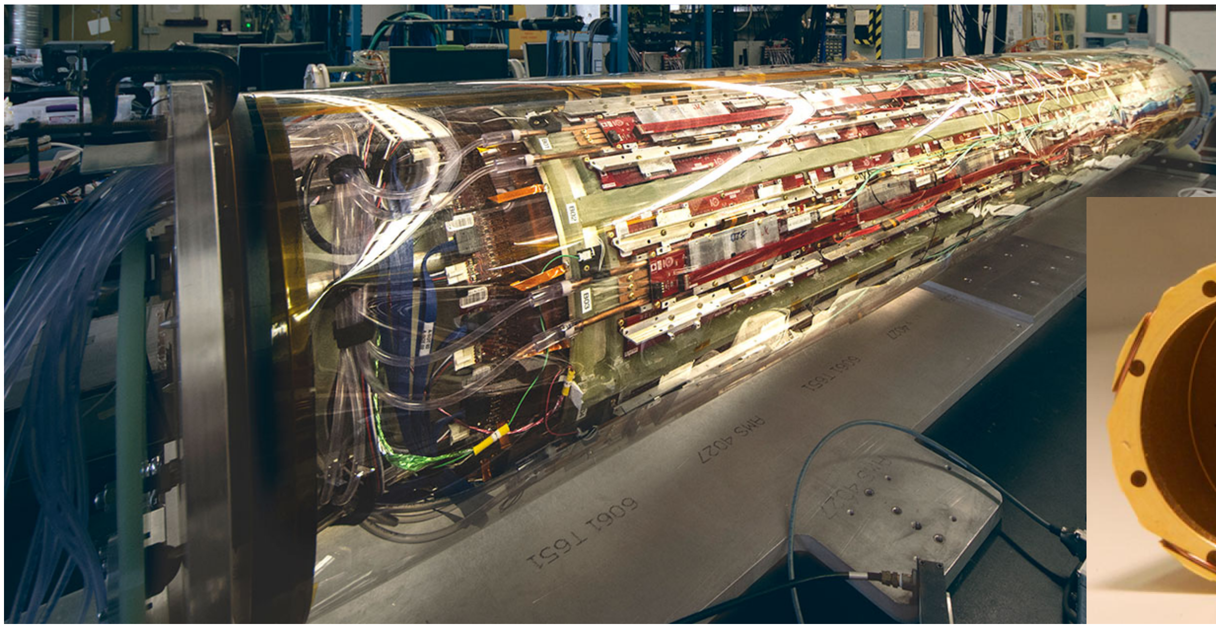
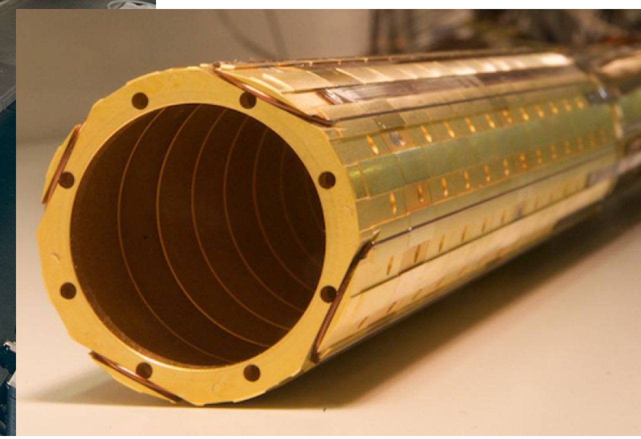
Antimatter at CERN's Antiproton Decellerator Facility (AD)

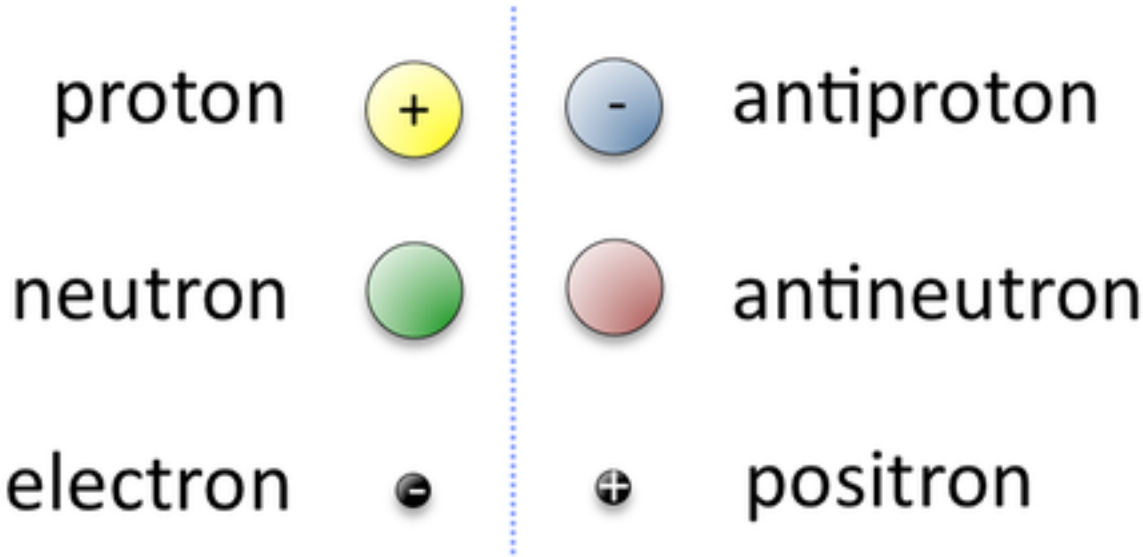




Daniel Maxwell
ALPHA Collaboration

What is antimatter ?

- For every particle there is a corresponding antiparticle with the same mass and the opposite charge.

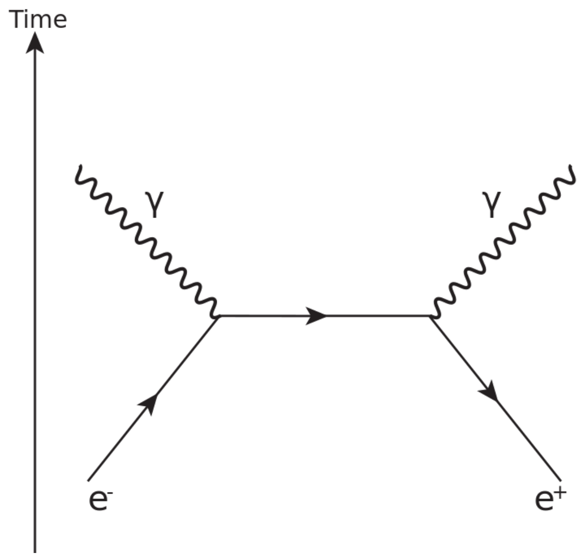


https://web2.ph.utexas.edu/~coker2/index.files/particlesanti.htm

Matter-antimatter annihilation

When a matter particle comes into contact with its corresponding antimatter particle they annihilate.

Electron-positron annihilation:

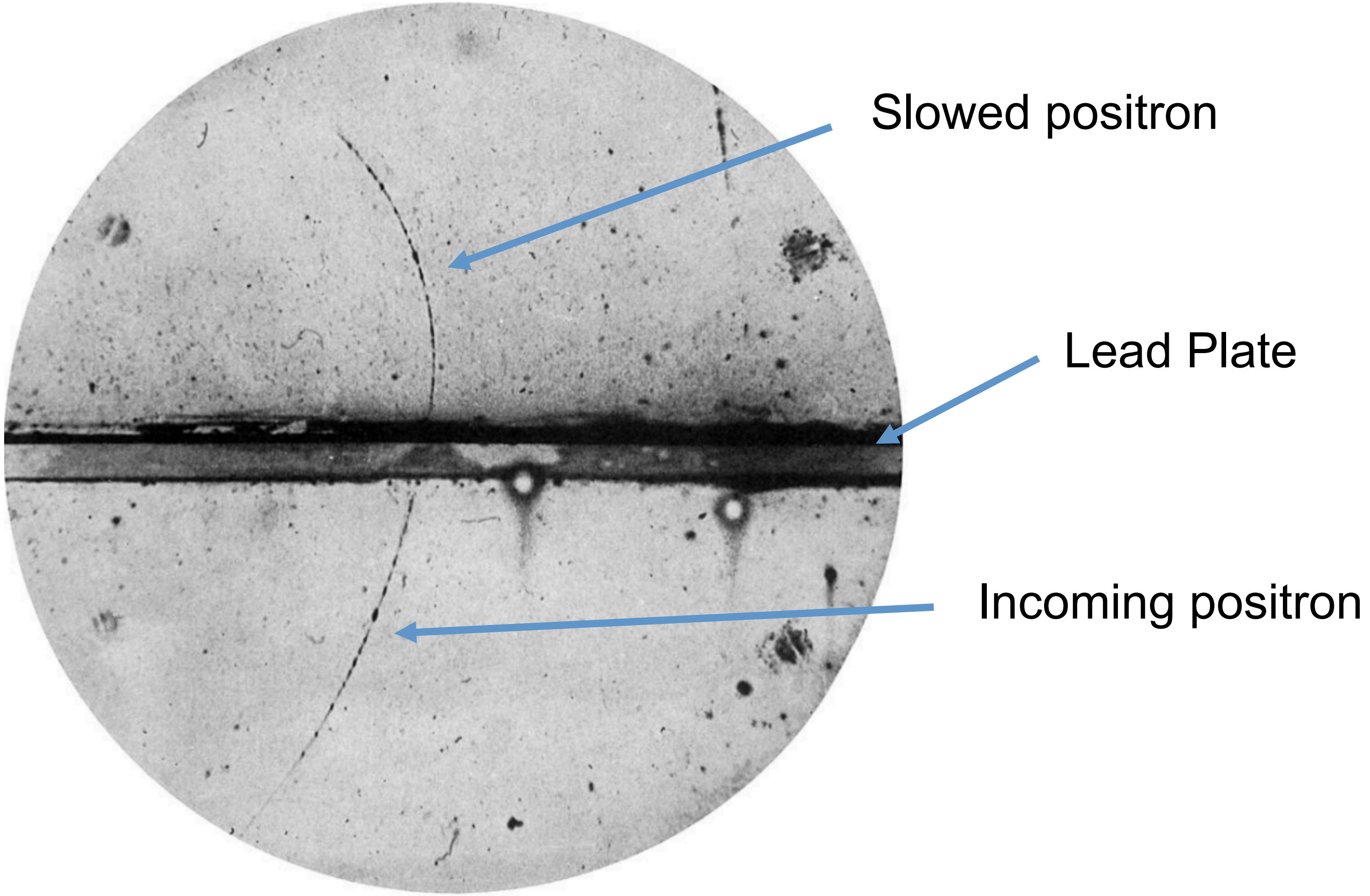


$$E = m c^2$$

Proton-antiproton annihilation is more complex and typically produces three charged pions.

The positron

- First predicted by Dirac in 1928 (although initially misunderstood).
- Observed in 1932 by Carl Andersons measurements of cosmic rays.



Sources of antimatter

- Beta decay: $p \rightarrow n + e^{+} + \nu_e$

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e.g. $^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + e^{+} + \nu_{e}$

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e.g. $^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ar} + e^{+} + \nu_e$

- Cosmic rays: high energy charged particles arrive at the earth from outer space (mostly protons). Positrons can be produced by the interaction of these particles with the earths atmosphere.

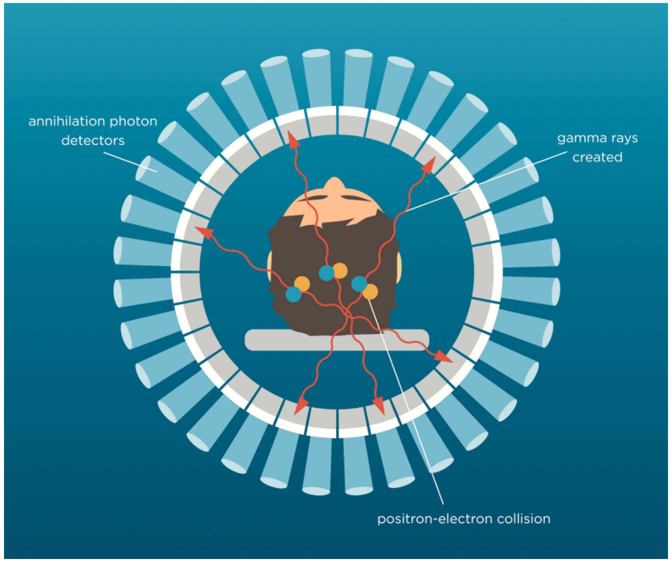
- Particle accelerators.

$$p + p \rightarrow p + p + p + \overline{p}$$

$$E = m\,c^2$$

Applications of antimatter

- PET scanners.



Applications of antimatter

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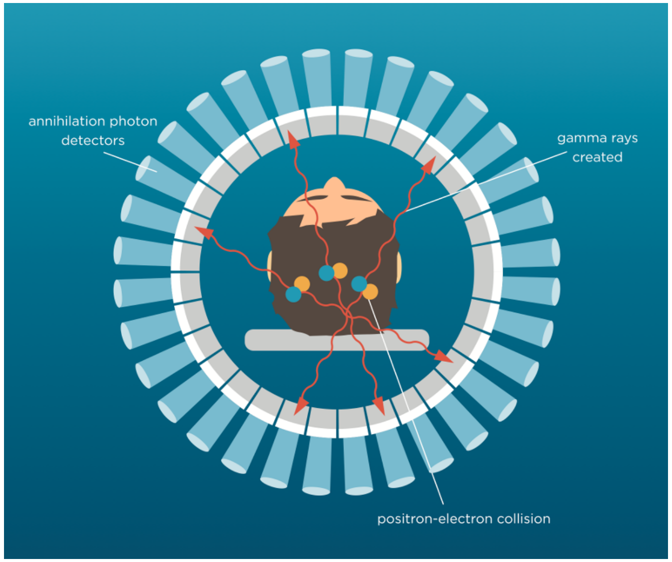
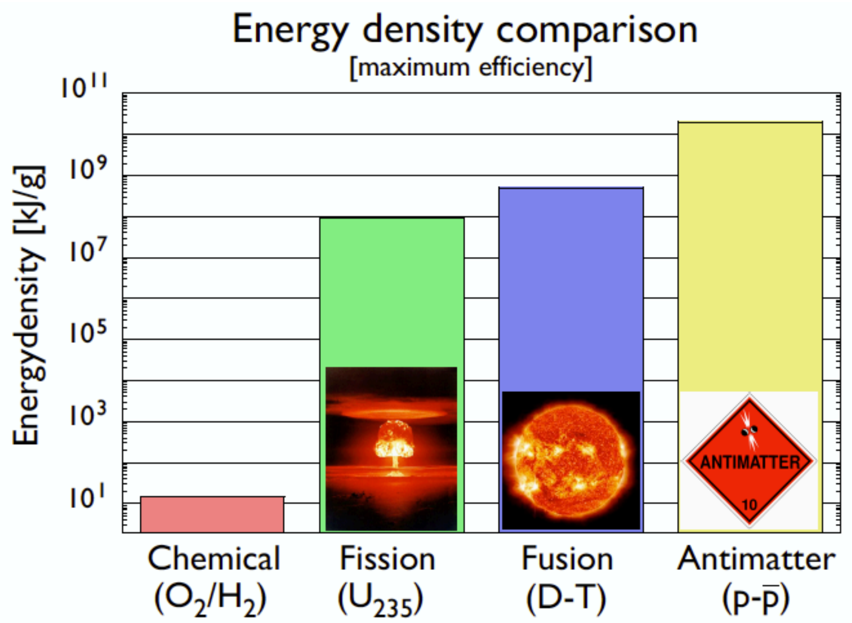


- A future fuel ……



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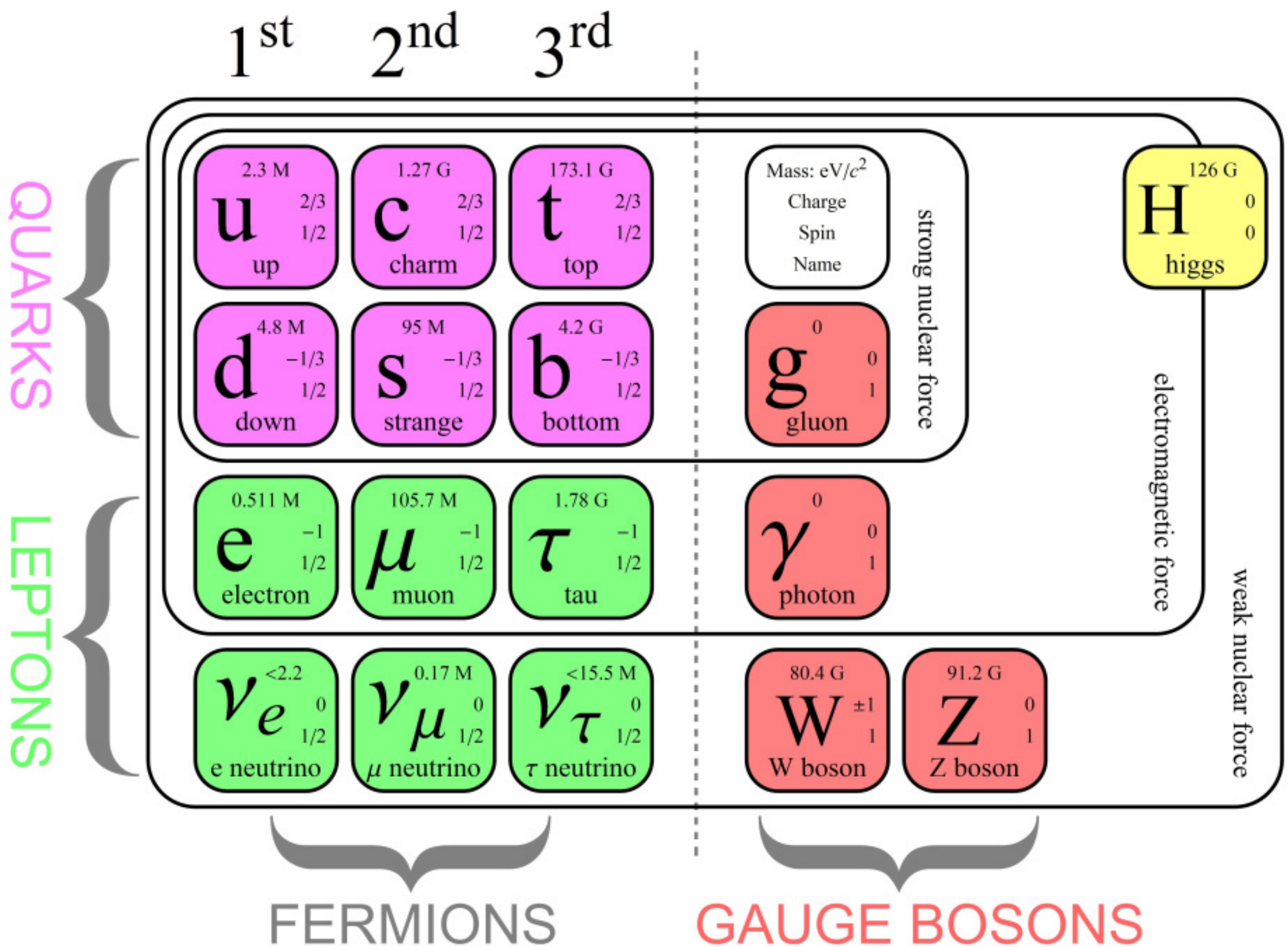
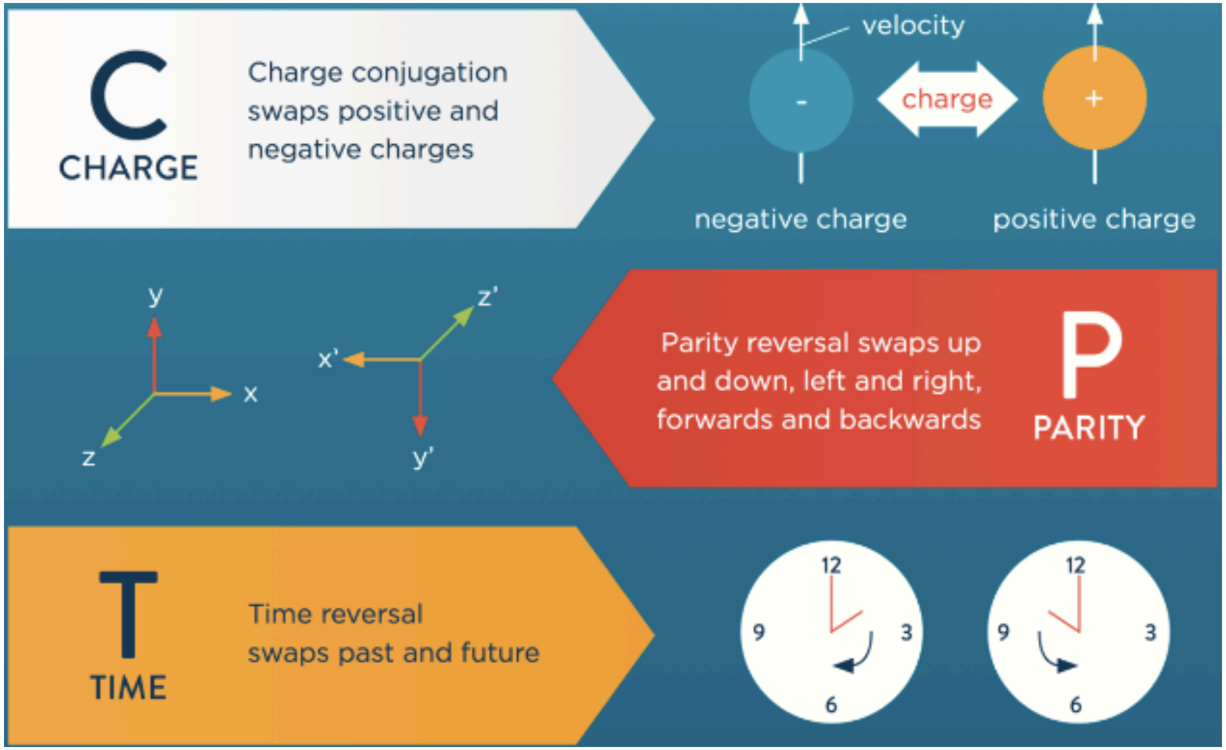
Standard Model



https://sciencesprings.wordpress.com/2016/05/13/from-physicsworld-parallel-universe-search-focuses-on-neutrons/

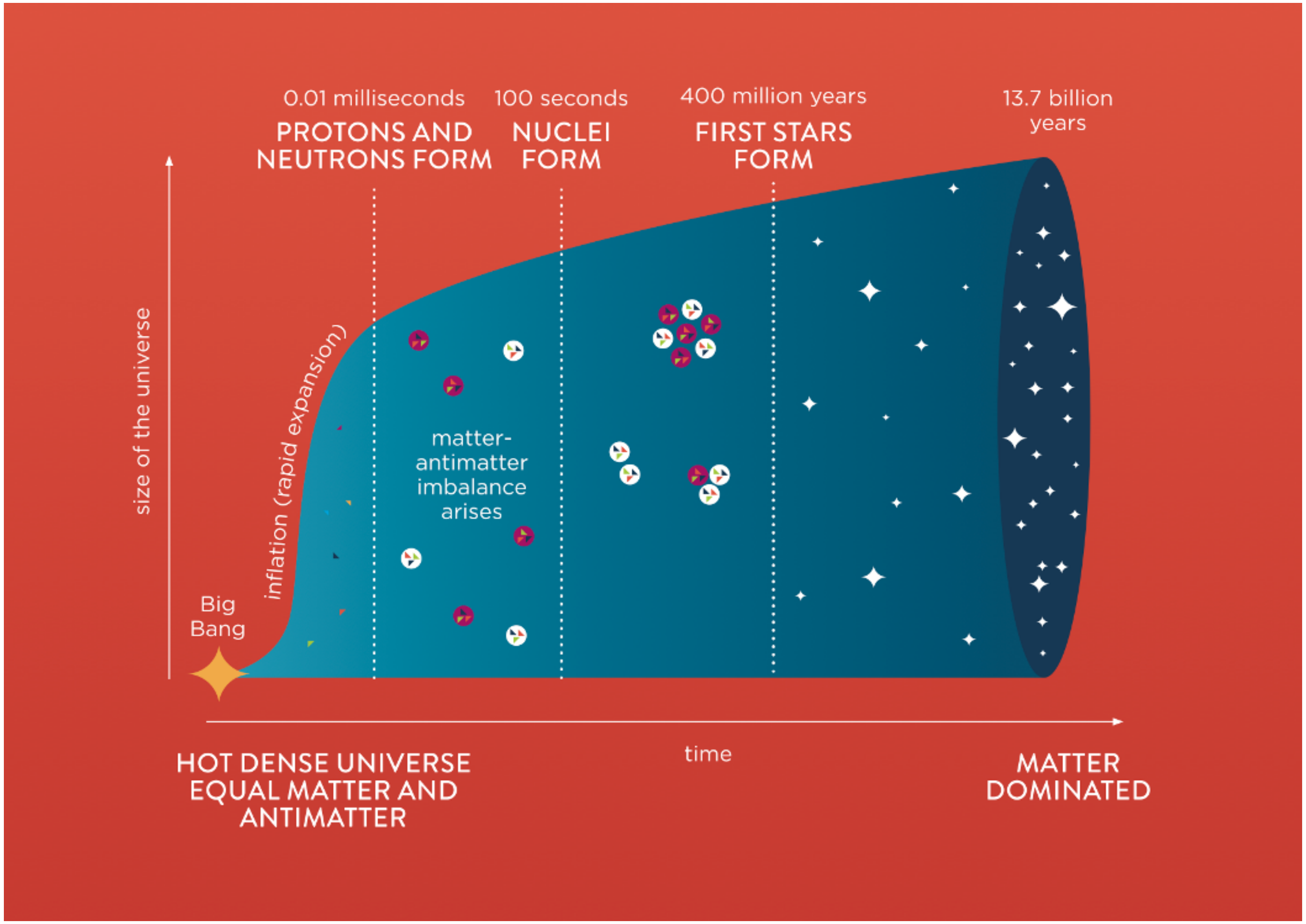
Symmetries

The physical laws described by the standard model have symmetries (only CPT (Charge-Parity-Time) is exact).



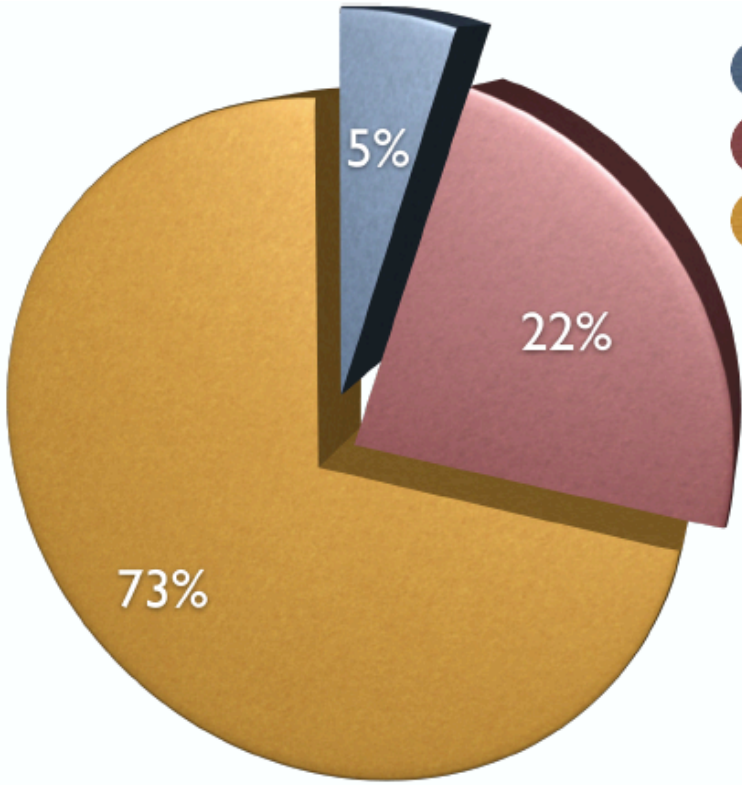
Antimatter experiments at CERN are testing these symmetries.

Why are we interested in antimatter?



Why is the universe composed almost entirely of normal matter ?

Why are we interested in antimatter?



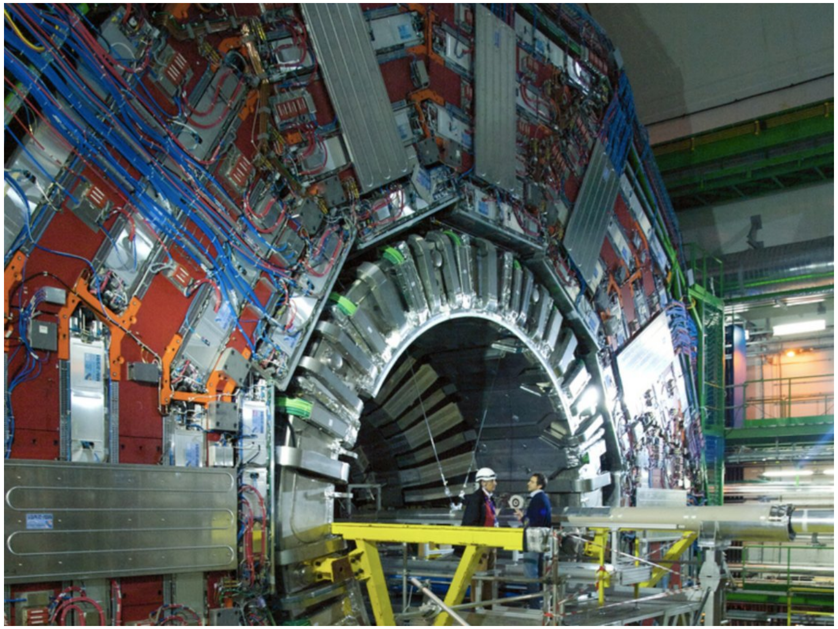
- Known [normal matter]
- Known unknowns [dark matter]
- Unknown unknowns [dark energy]

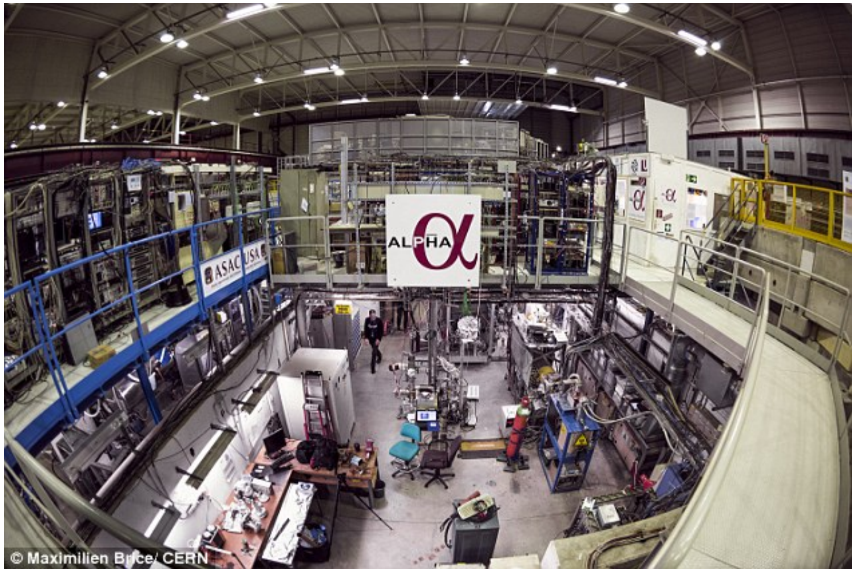
Antimatter ? : 0%

Antimatter at CERN

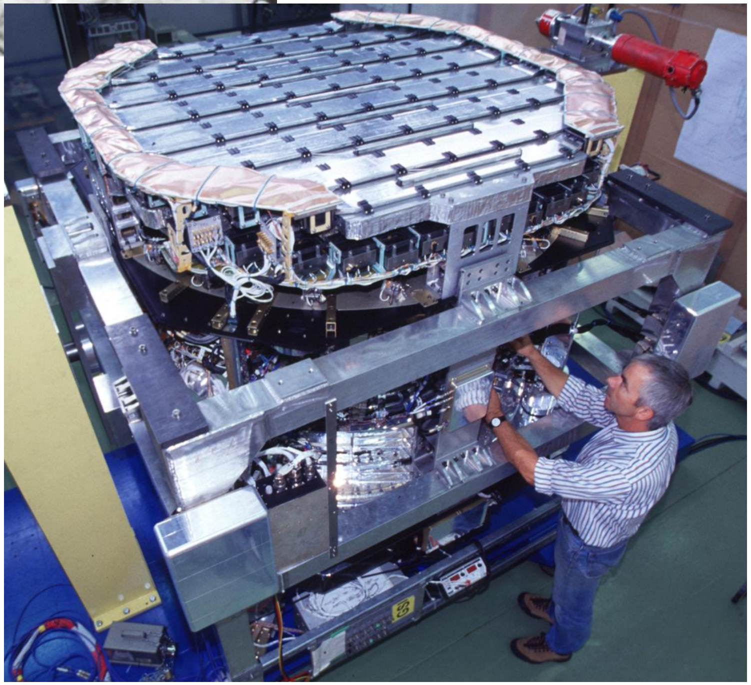
- High energy proton-proton collisions in LHCb. Looking at the relative amounts of matter and antimatter produced to test the symmetries of the standard model.

- Low energy experiments at the antiproton decelerator (AD) facility.



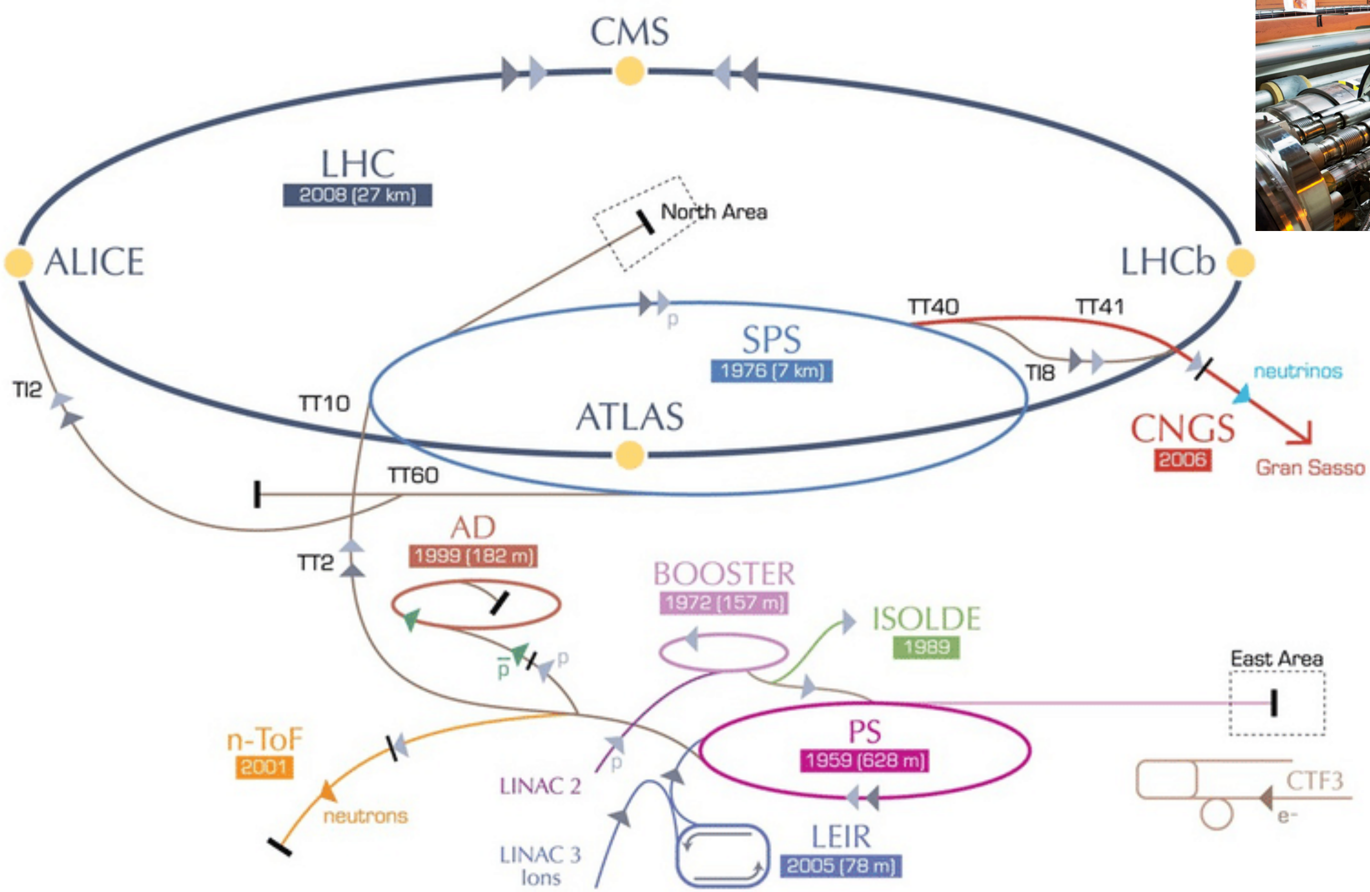


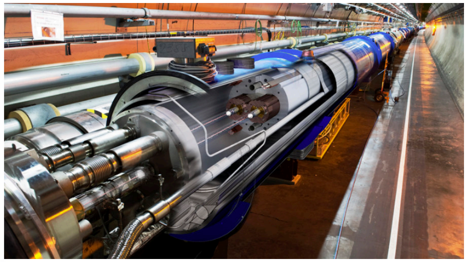
Antimatter in space



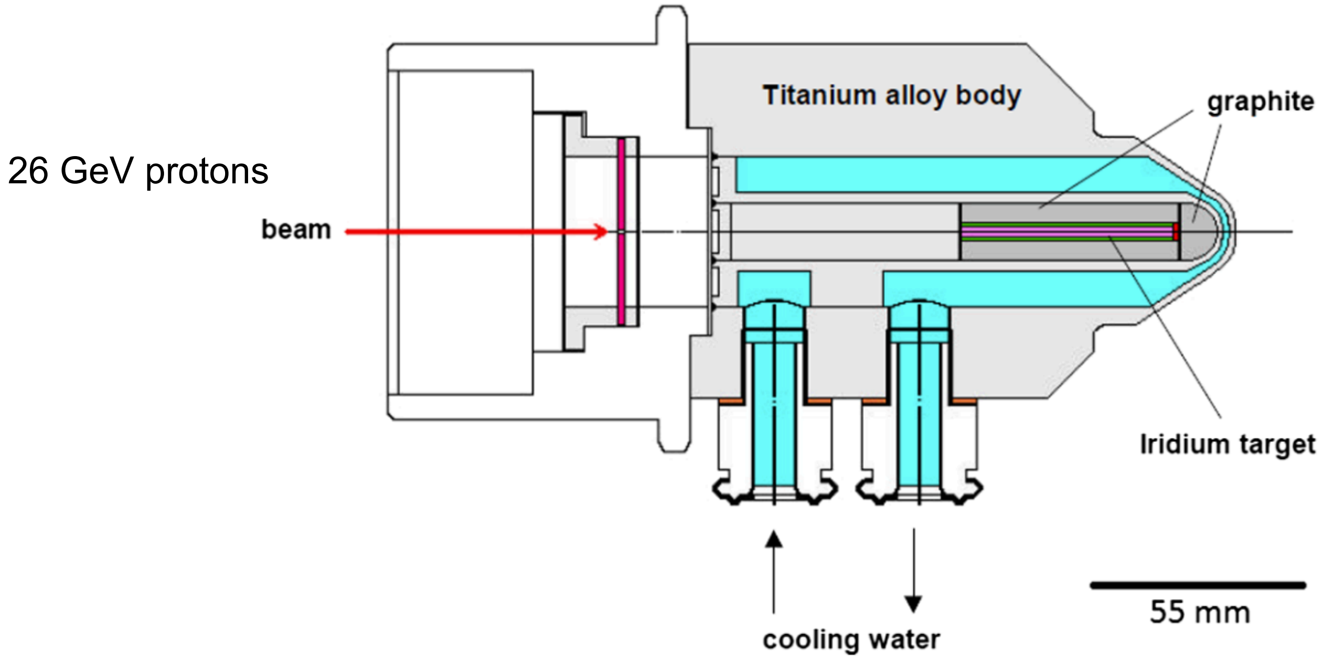
- The AMS detector has measured the flux of antiprotons to be 10,000 times smaller than the proton flux.
- Heavy nuclei could originate from regions of space with an abundance of antimatter e.g. anti-stars!

Antiprotons at CERN





Making antiprotons

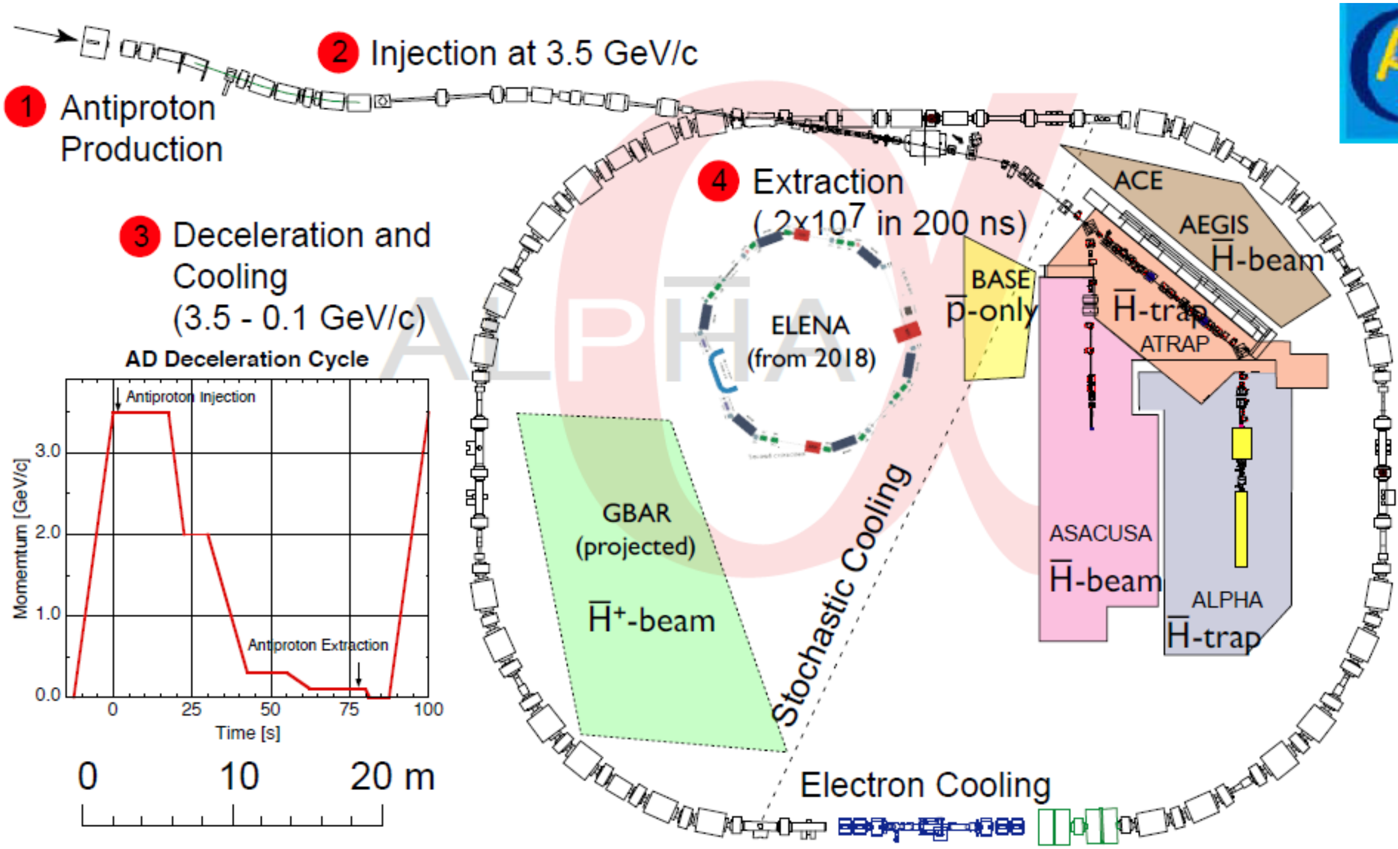


$$p + p \rightarrow p + p + p + \bar{p}$$

Around 5×10^7 antiprotons are produced every 120s at an energy of 3.5 GeV

The antiproton decelerator

The antiproton decelerator (AD) provides ~2x10^7 antiprotons every 120 s at ~5 MeV.



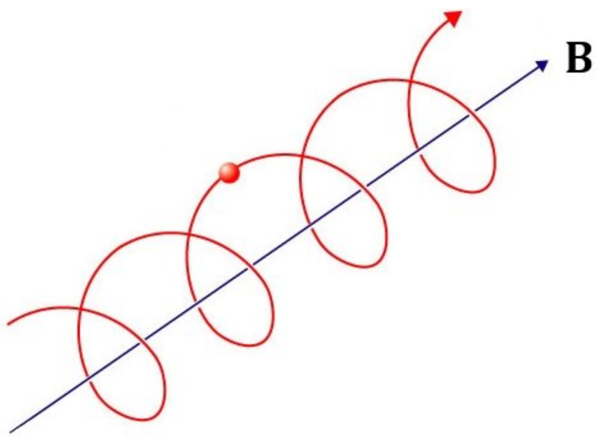
S. Maury *et al.*, Hyp. Int. **109**, 43 (1997).

Trapping antiparticles

- Like charges repel.

$$F = q\vec{E}$$

- Moving charged particles experience a force in a magnetic field:

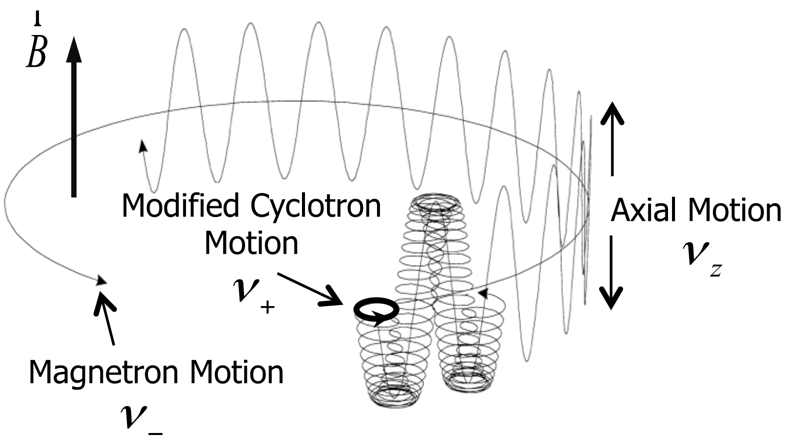


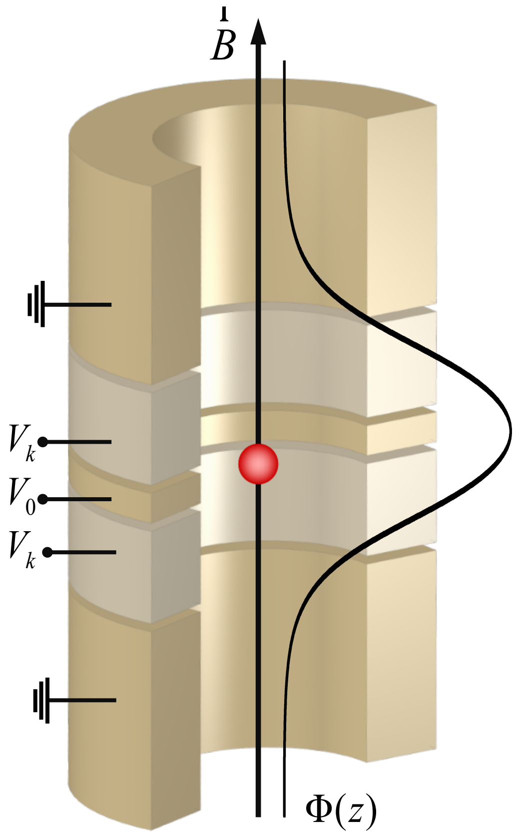
$$F = q\vec{V} \times \vec{B}$$

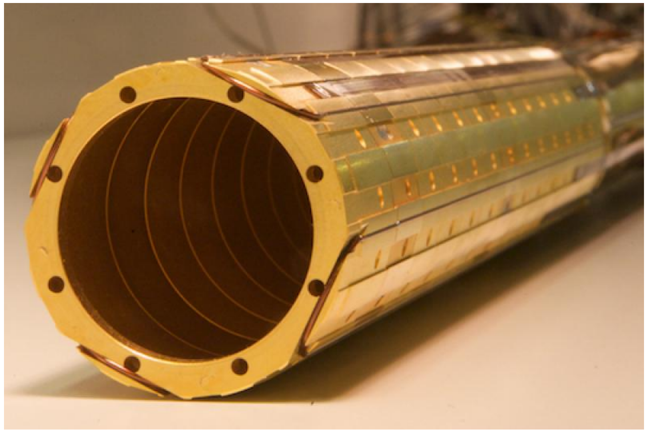
- Combine these two effects in a Penning trap.

Penning Trap

Traps are typically cooled down to ~4K (-270 degrees C).



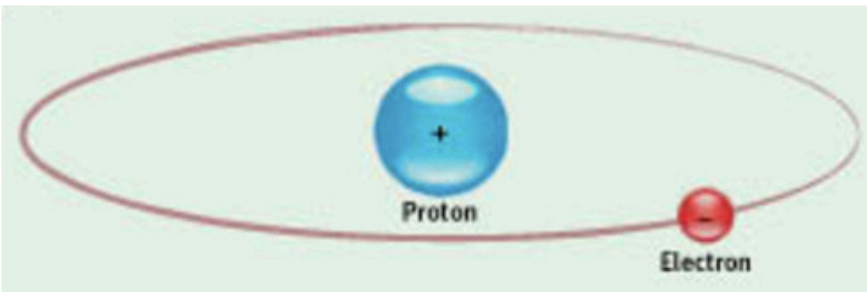




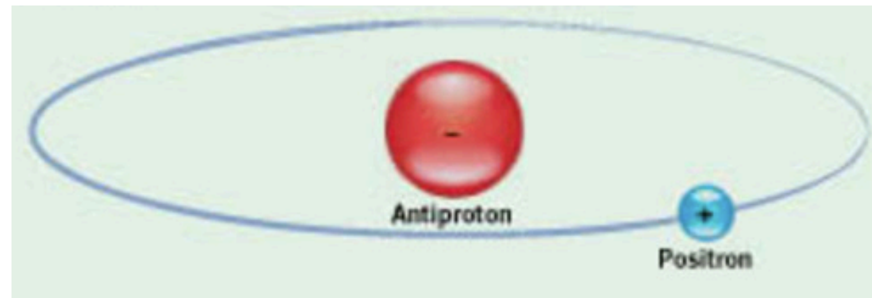
The ALPHA experiment

- ALPHA: **A**ntihydrogen **L**aser **PH**ysics **A**pparatus.

hydrogen

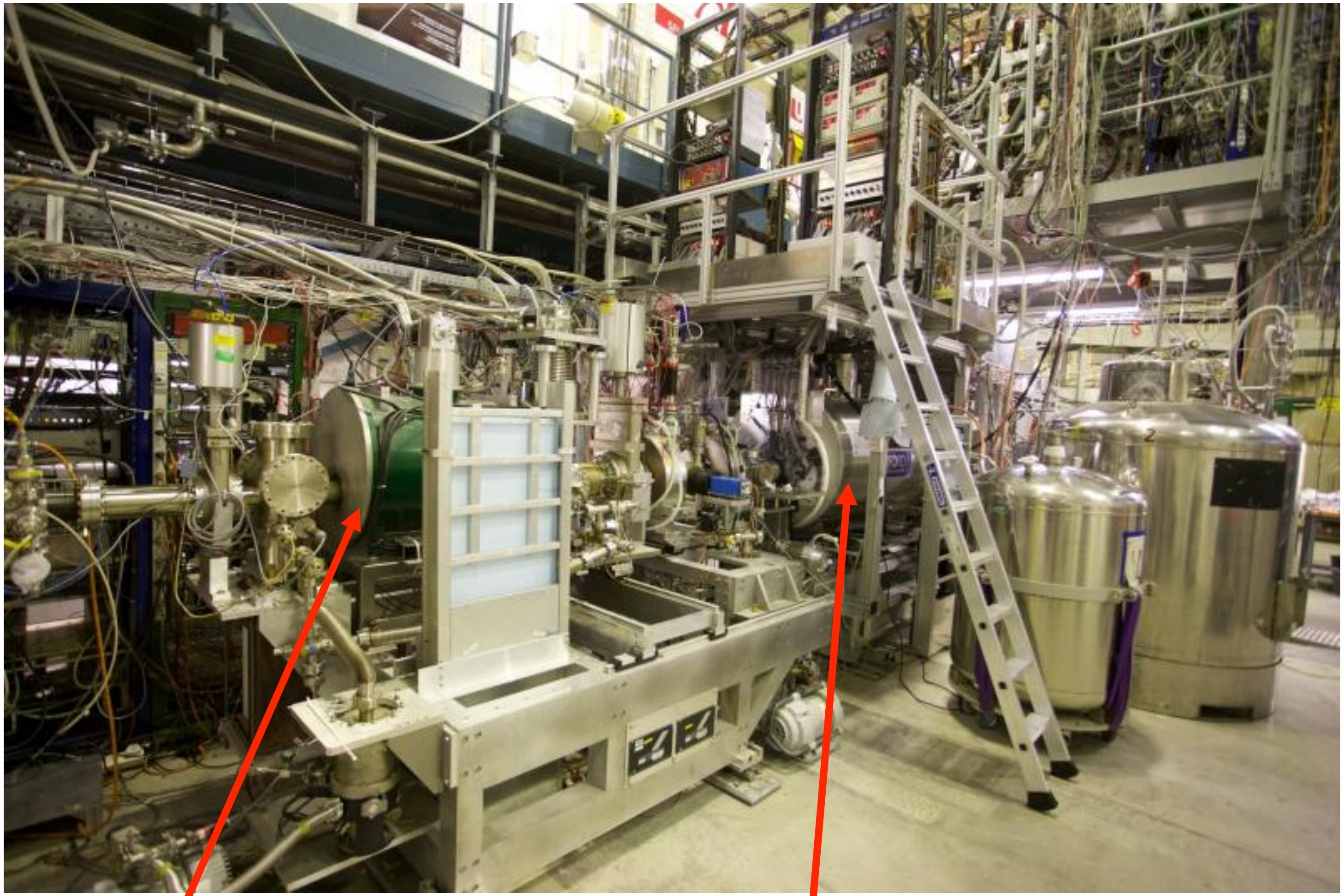


antihydrogen



- Why antihydrogen?
    - It's the simplest pure antimatter system.
    - It is electrically neutral.
    - Hydrogen is very well understood theoretically, and measurements of its properties have been performed to extraordinary levels of precision.

ALPHA-2 Apparatus

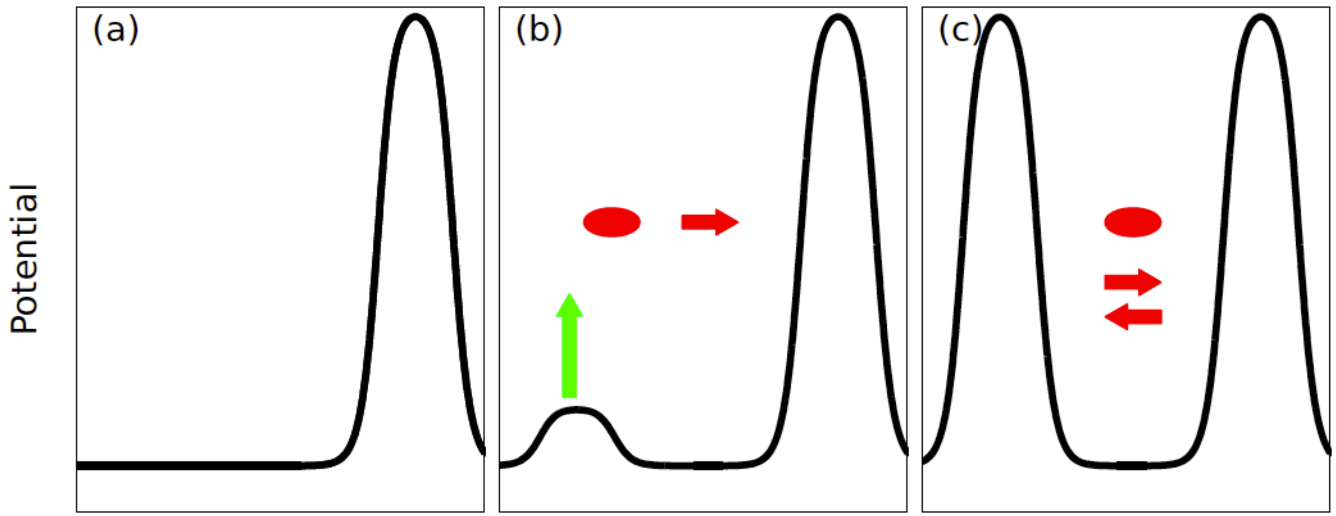


Antiproton “catching trap”

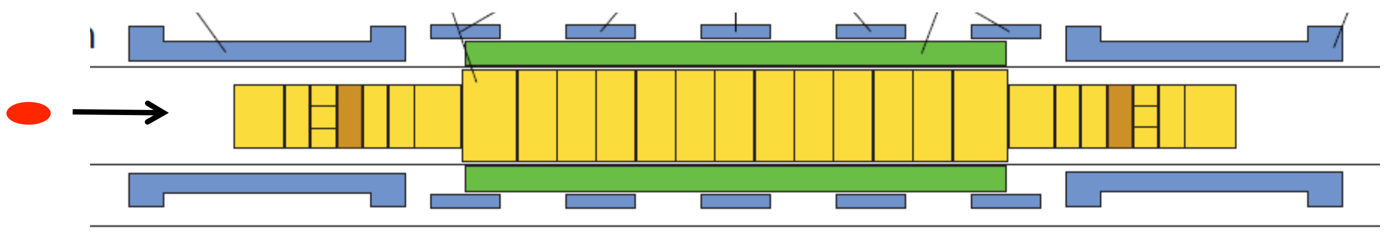
Antihydrogen “atom trap”

Catching antiparticles in the Penning traps

- Antiprotons from the AD are degraded from 5 MeV to 5 keV by a thin foil.



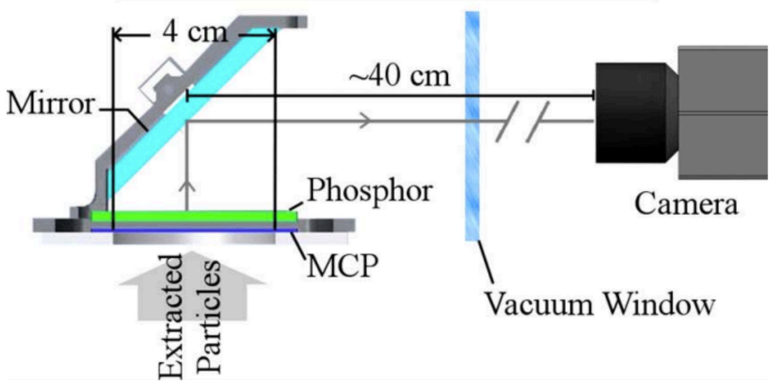
E. Butler PhD thesis.

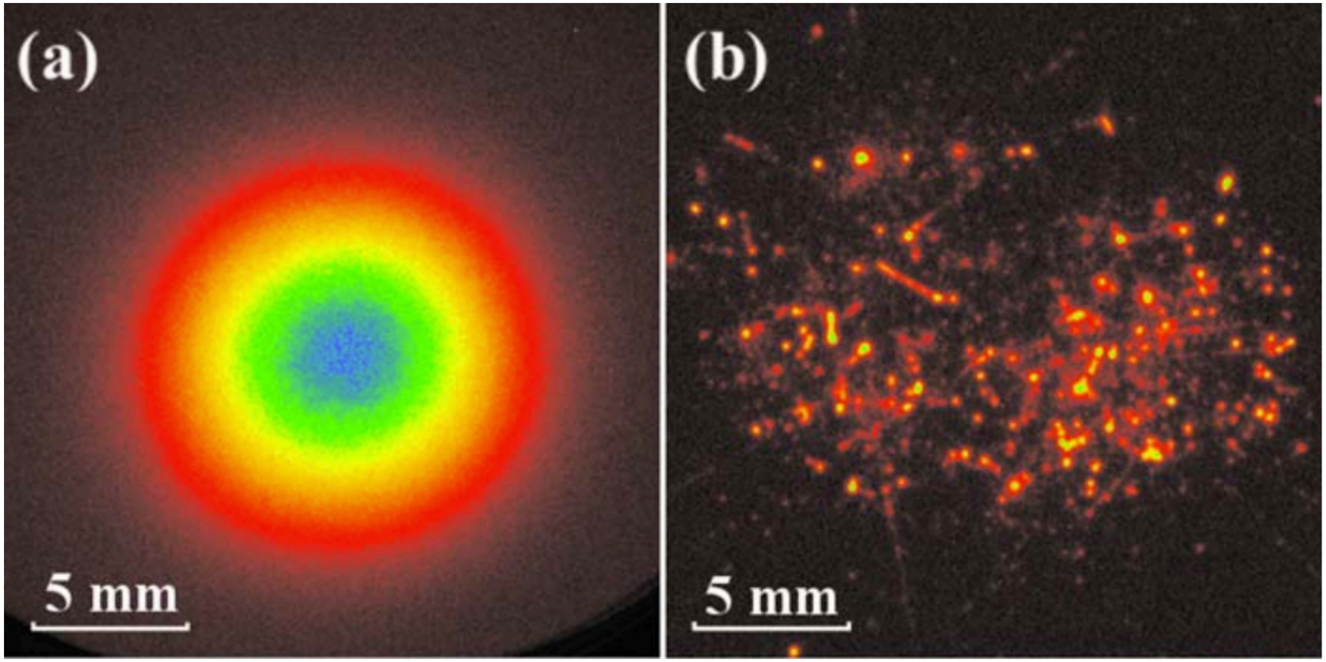


- Positrons from a radioactive sodium source are accumulated in a separate trap.

Imaging positrons and antiprotons

Light produced when particles hit a phosphor screen allows us to image the particles.





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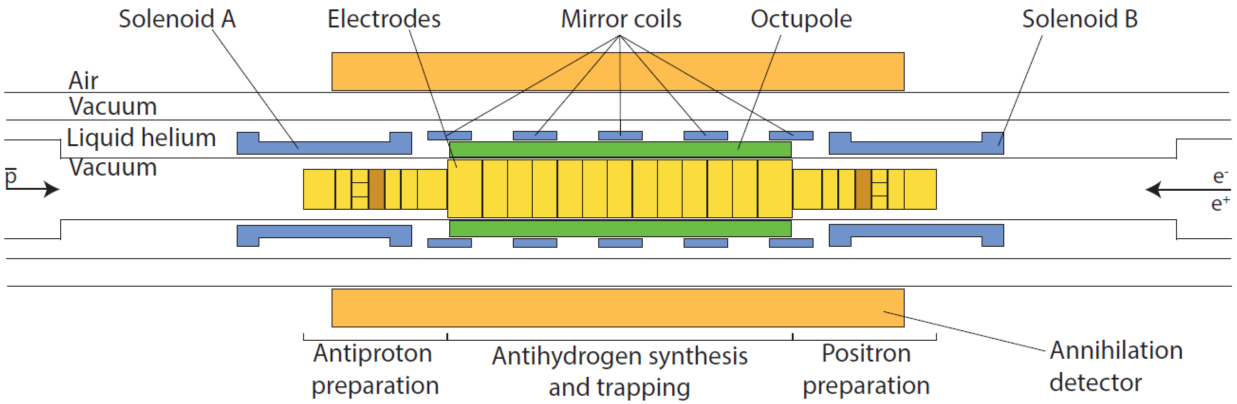
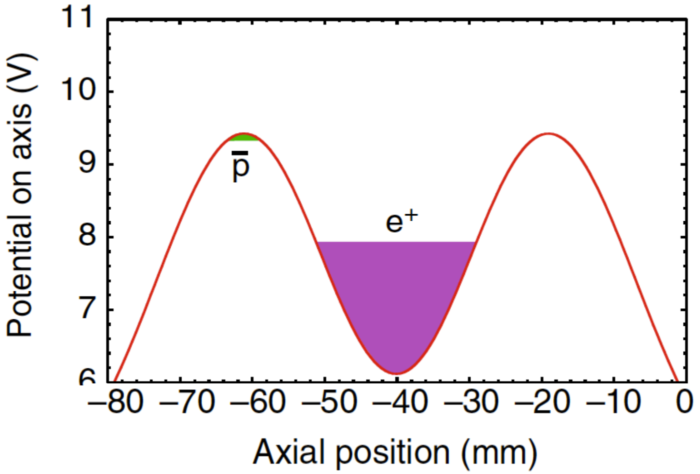
Antihydrogen synthesis

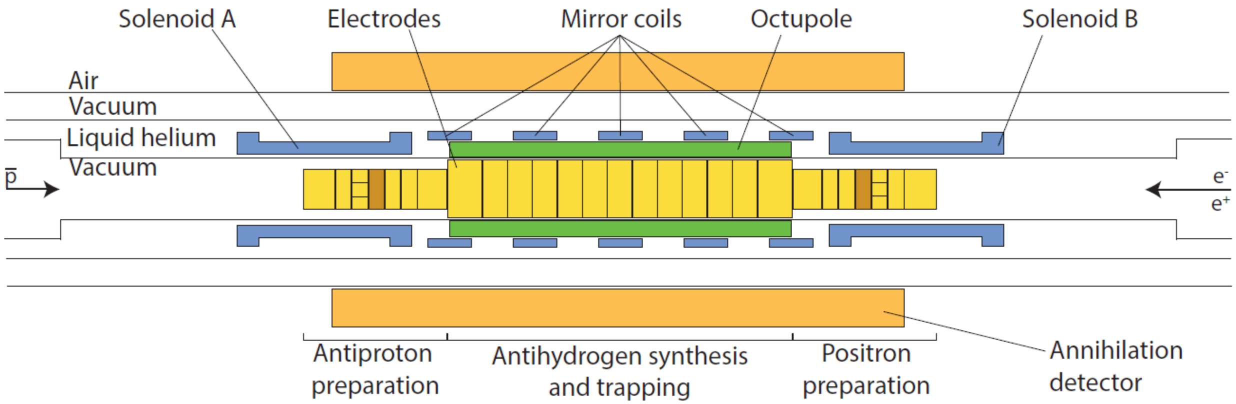


Trap positrons and antiprotons in adjacent potential wells of a Penning trap.

- Slowly merge the particles (in 1s) by lowering the barrier between them.
- We typically mix 3 million positrons (at ~20K) with 90,000 antiprotons (at ~50K) forming around **50,000 antihydrogen atoms**.



Antihydrogen synthesis



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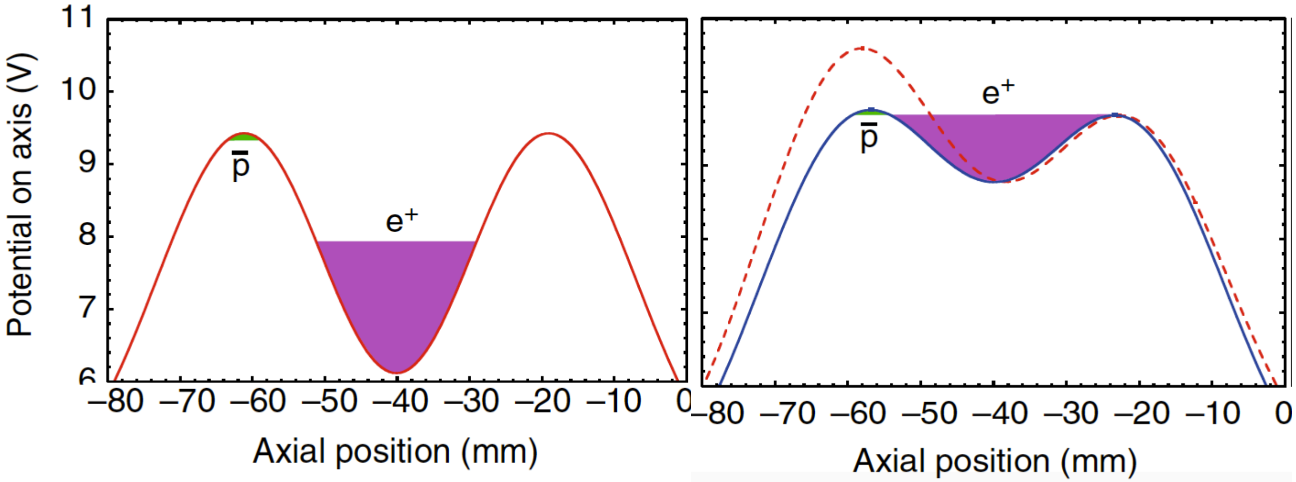

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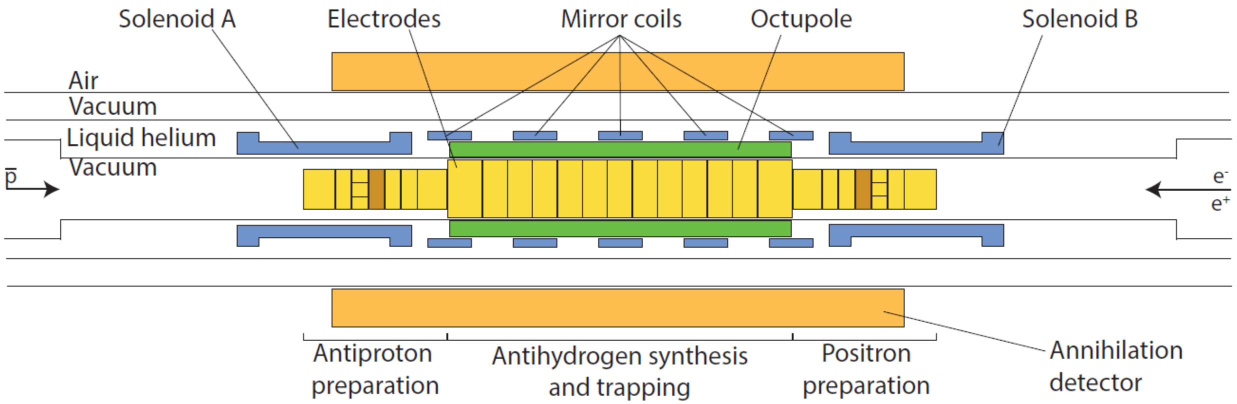

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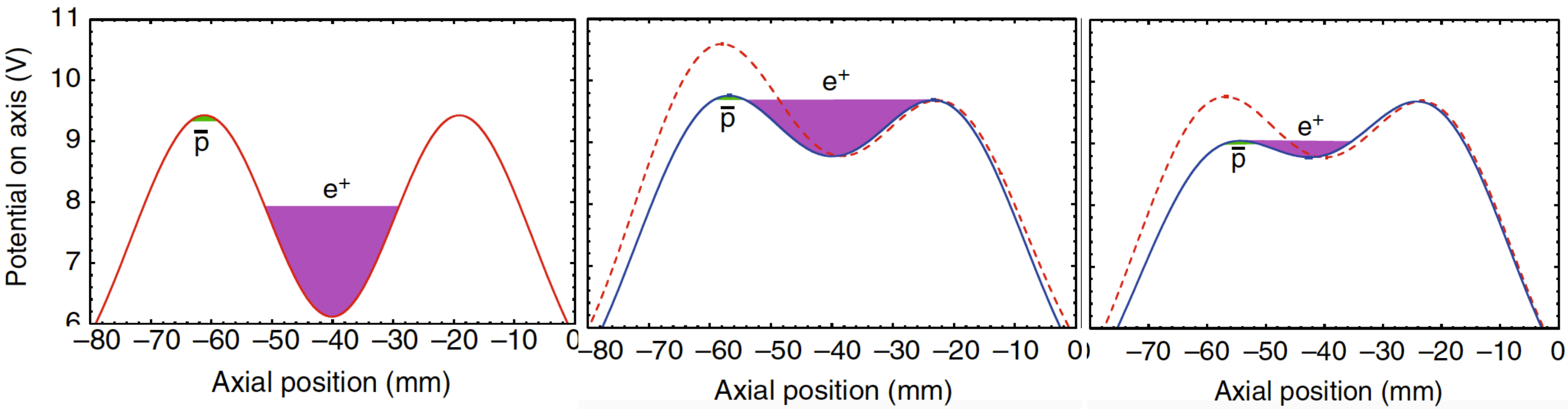
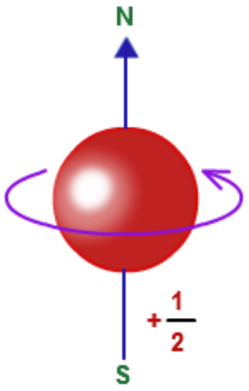
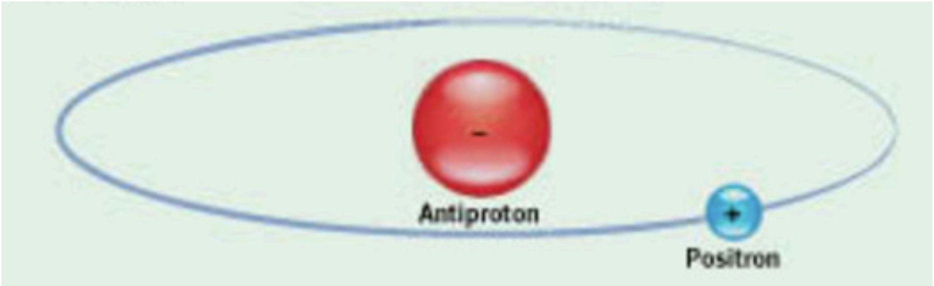
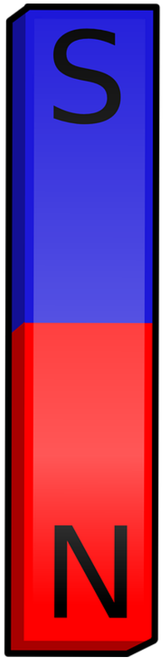


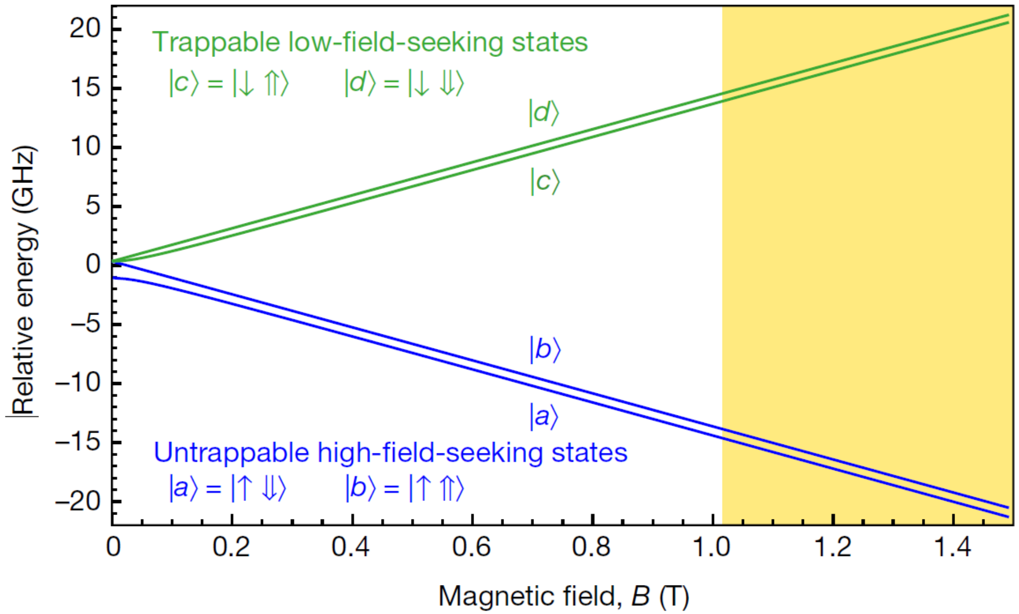
Antihydrogen trapping

Antihydrogen is neutral – can't trap with a Penning trap. We make use of the fact that it is slightly magnetic (has a magnetic moment).









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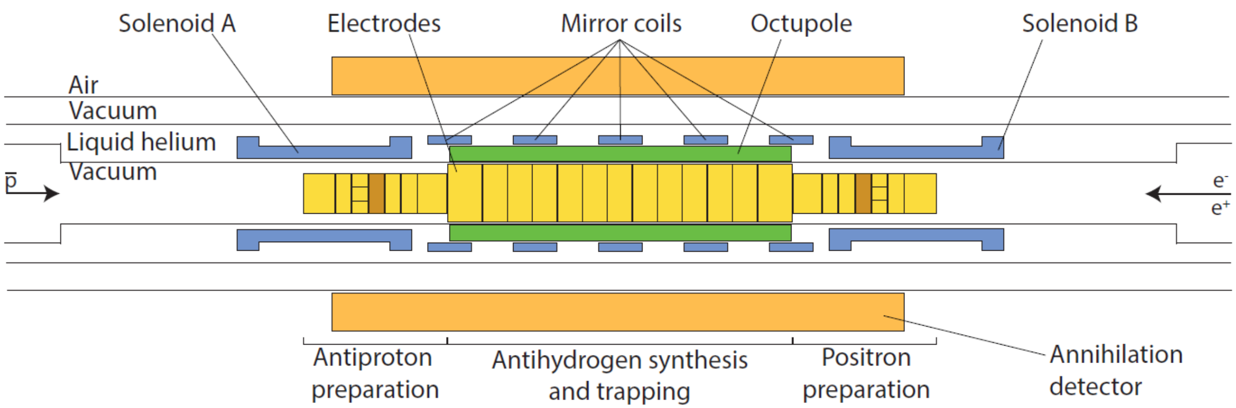
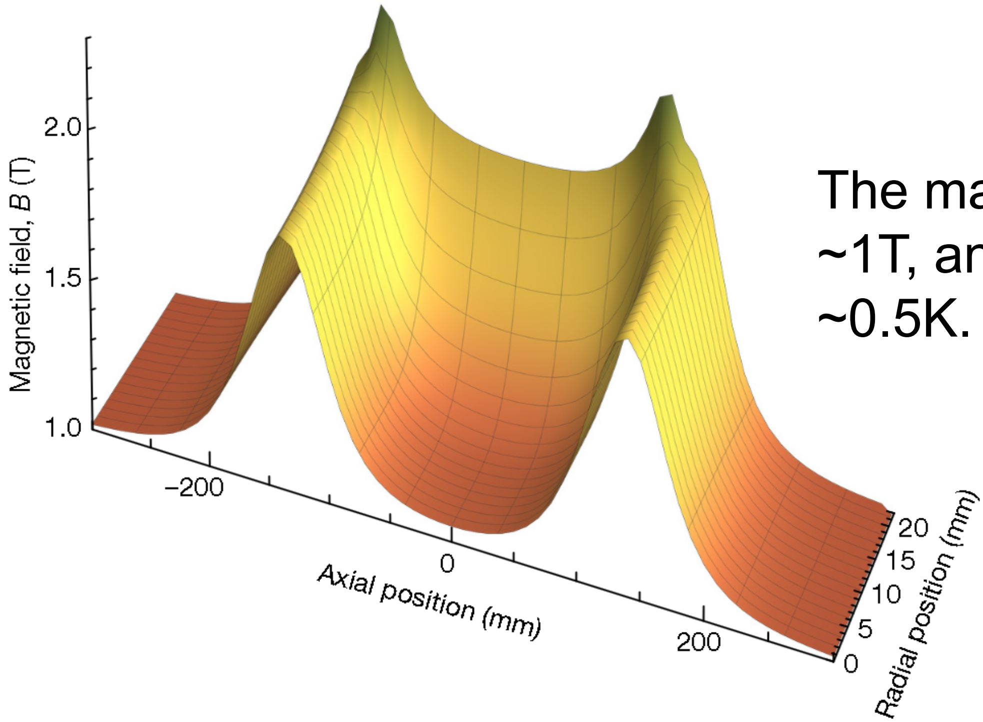
Antihydrogen trapping



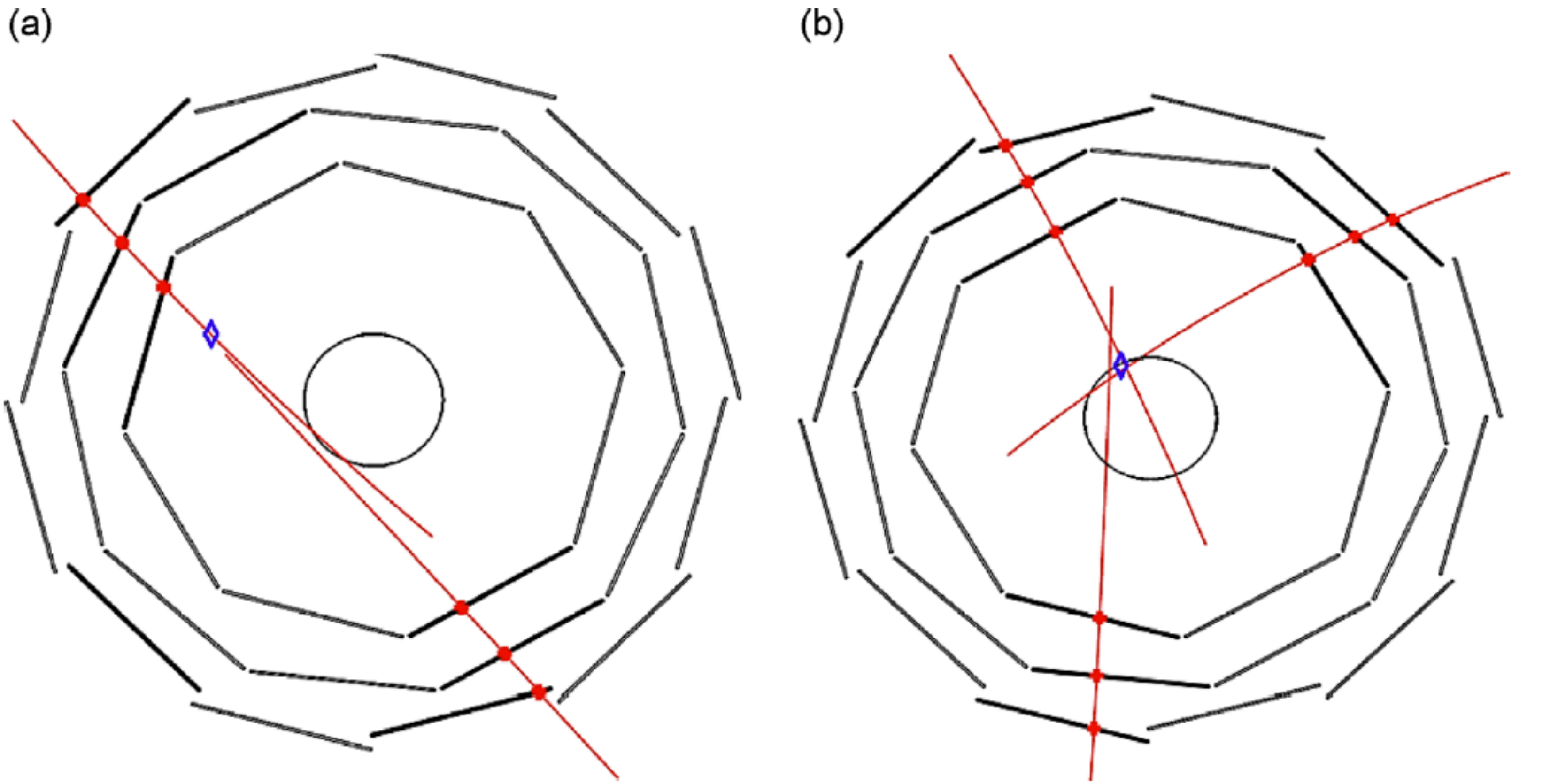
Before mixing the particles, a magnetic minimum trap is energised consisting of an octupole and five mirror coils.



The magnetic field at the trap center is ~1T, and the trap depth corresponds to ~0.5K.

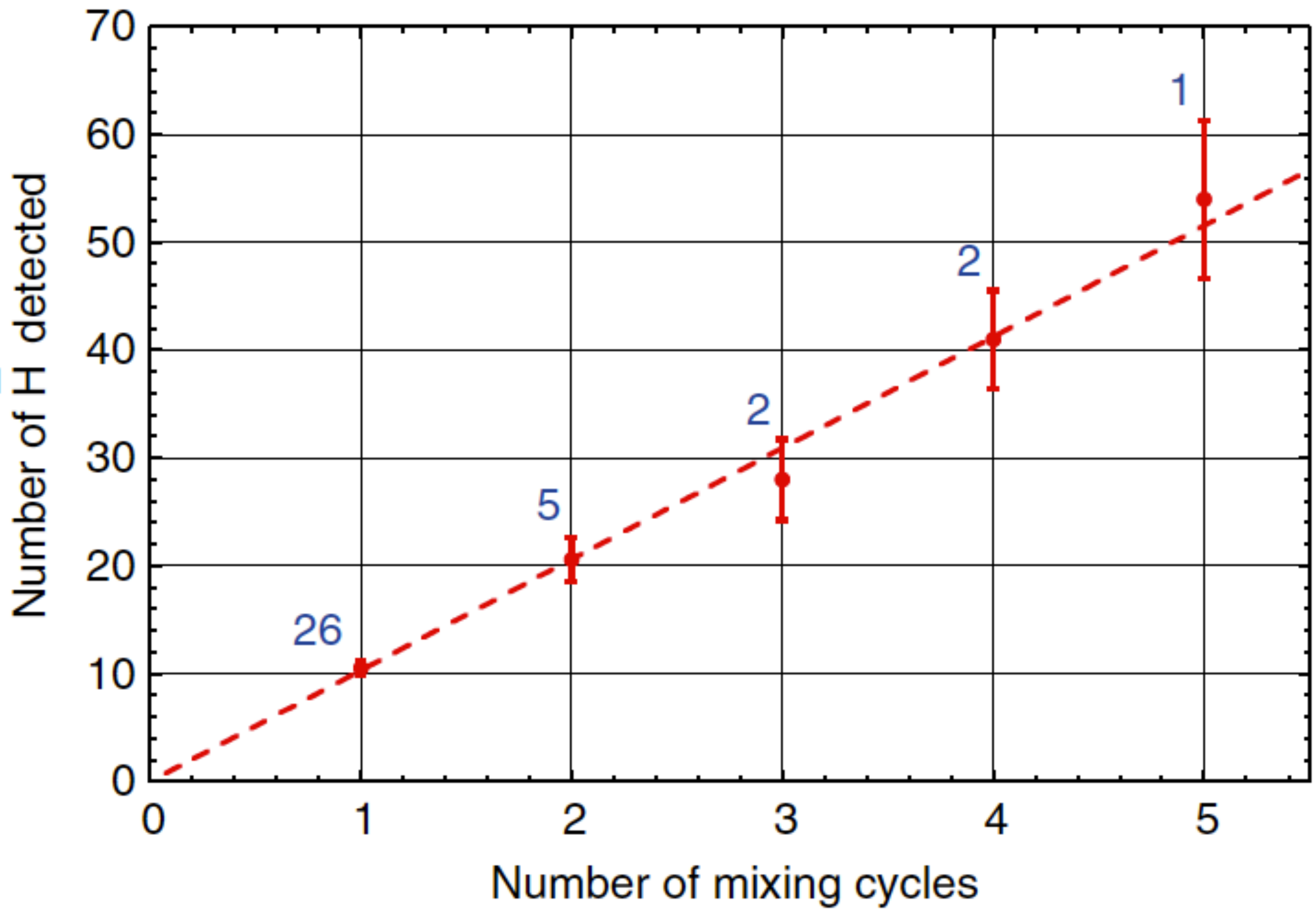
Antihydrogen detection

- We detect antihydrogen by ramping down the trap magnets to release the atoms – **we have to destroy the antihydrogen!**
- Image the annihilation products with a silicon vertex detector.
- Event topology allows us to distinguish antiproton annihilations from cosmic rays.



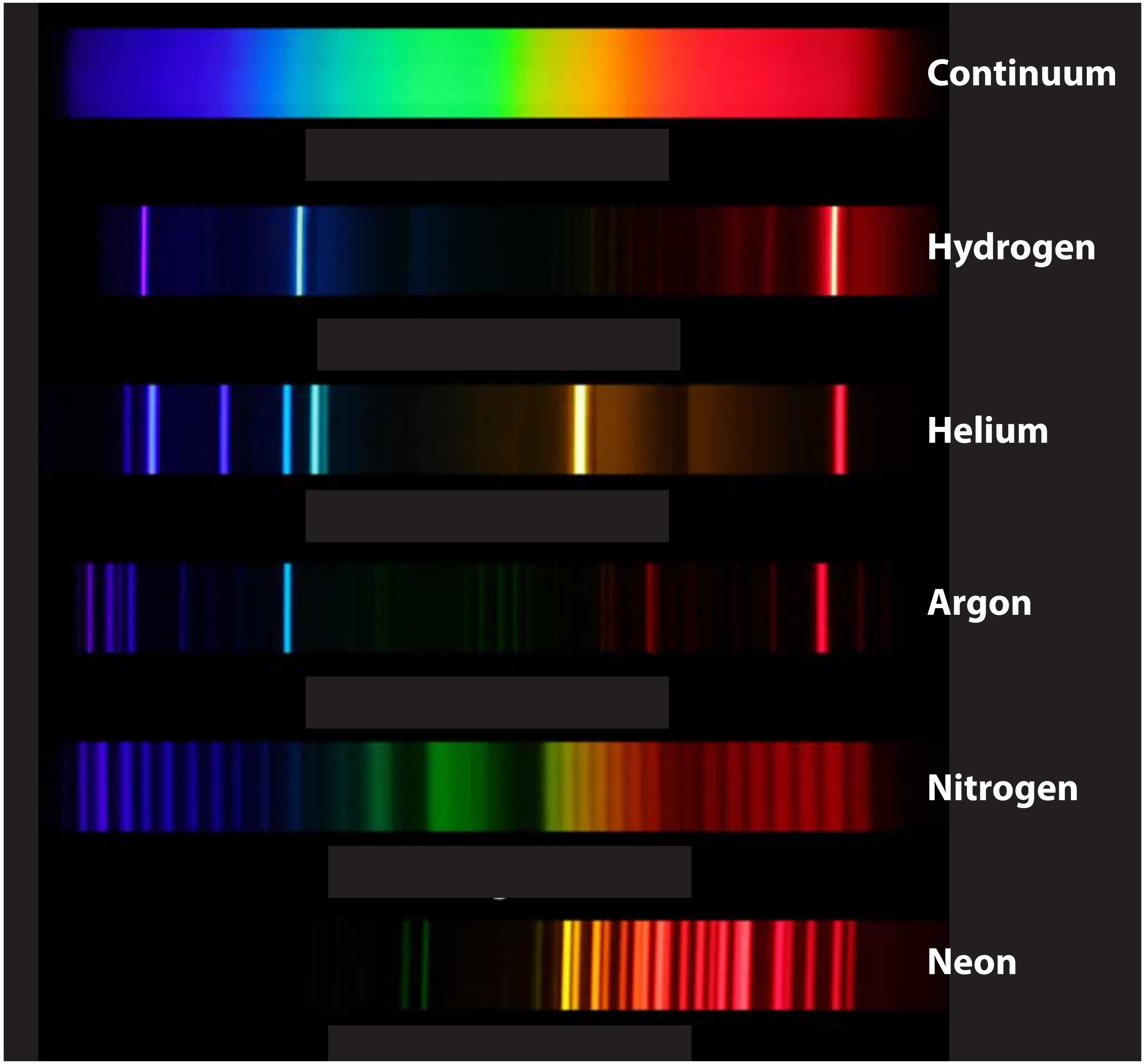
Antihydrogen accumulation

- Only trap **~20 atoms** per experimental cycle!
- However, we can accumulate trapped antihydrogen and have trapped >1000 atoms this way.



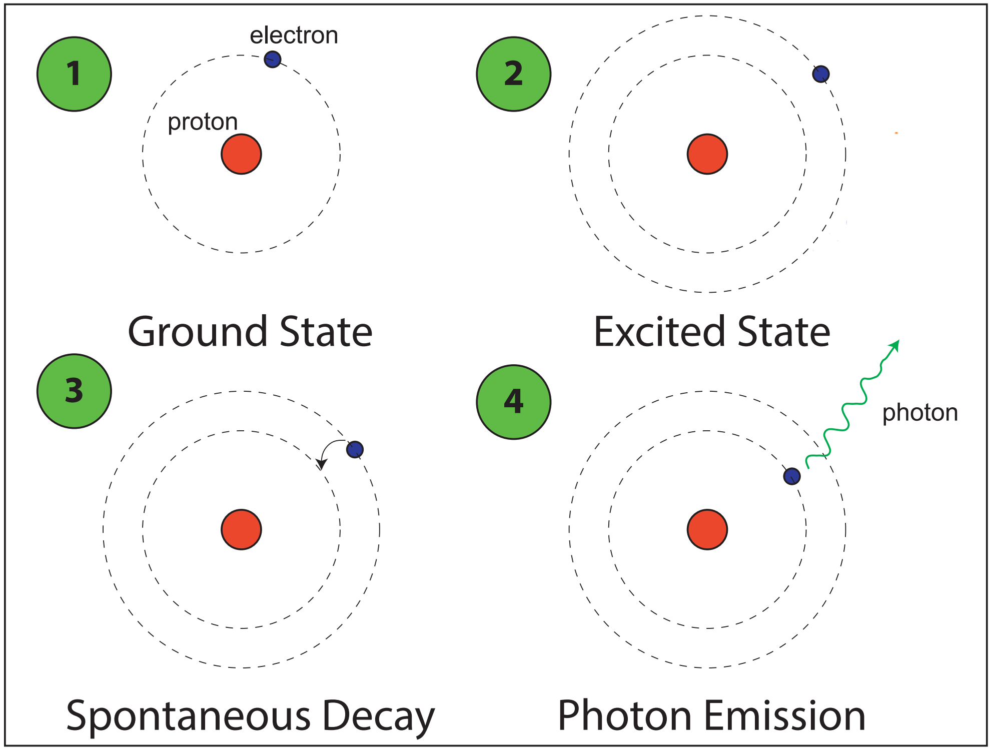
ALPHA Collaboration, Nat. Comms. **8**, 681 (2017).

Spectroscopy

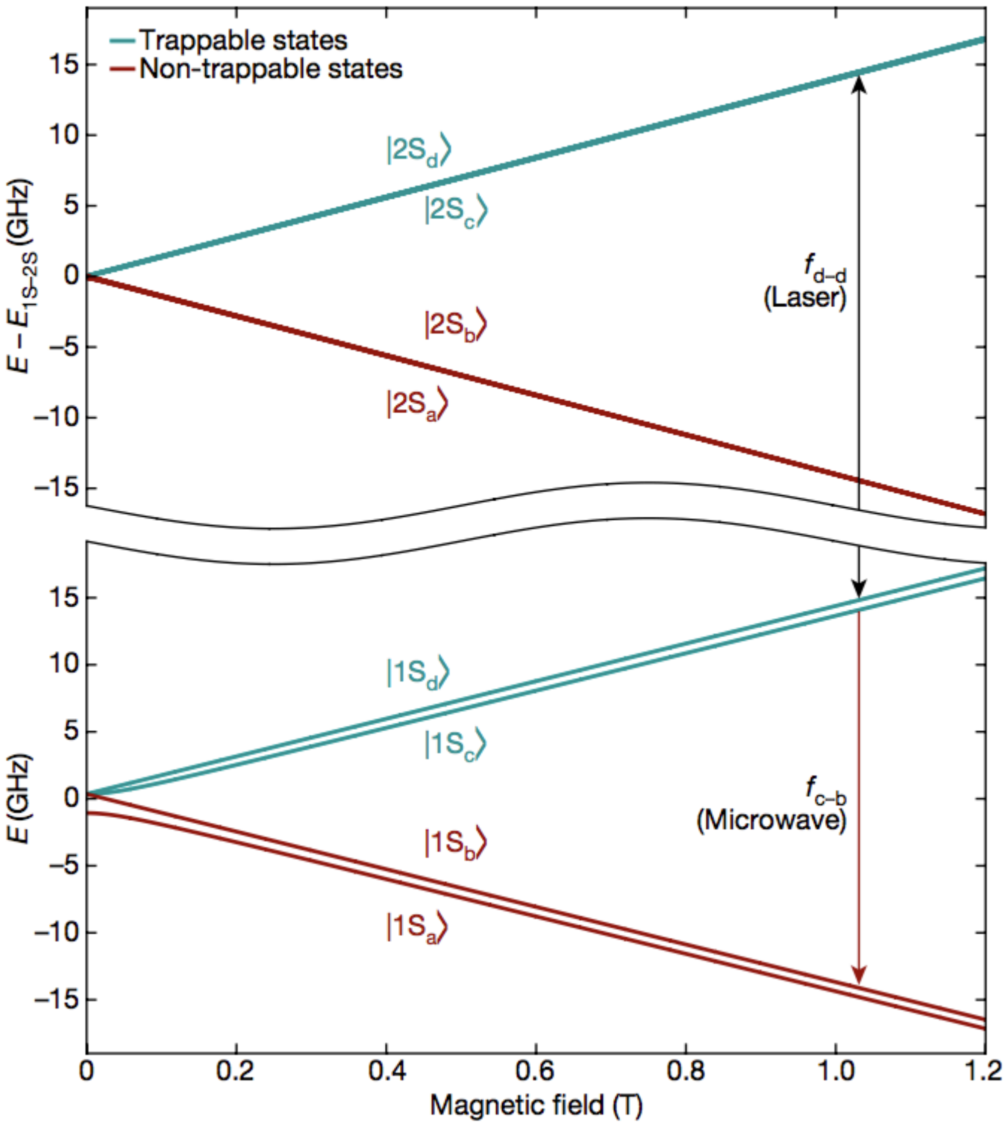


Spectroscopy

- The discrete wavelengths correspond to transitions of an atoms internal state.

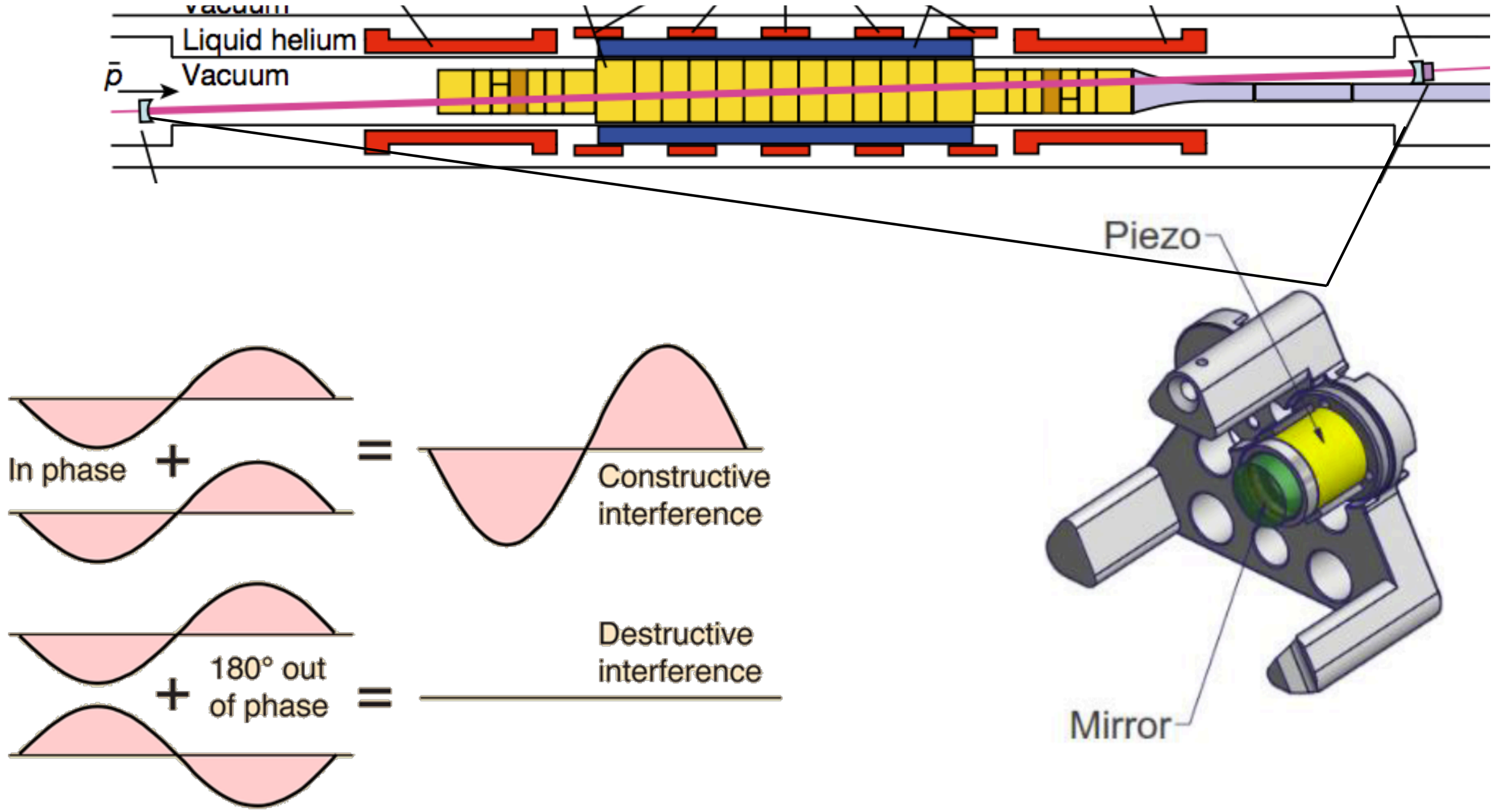


1S-2S transition



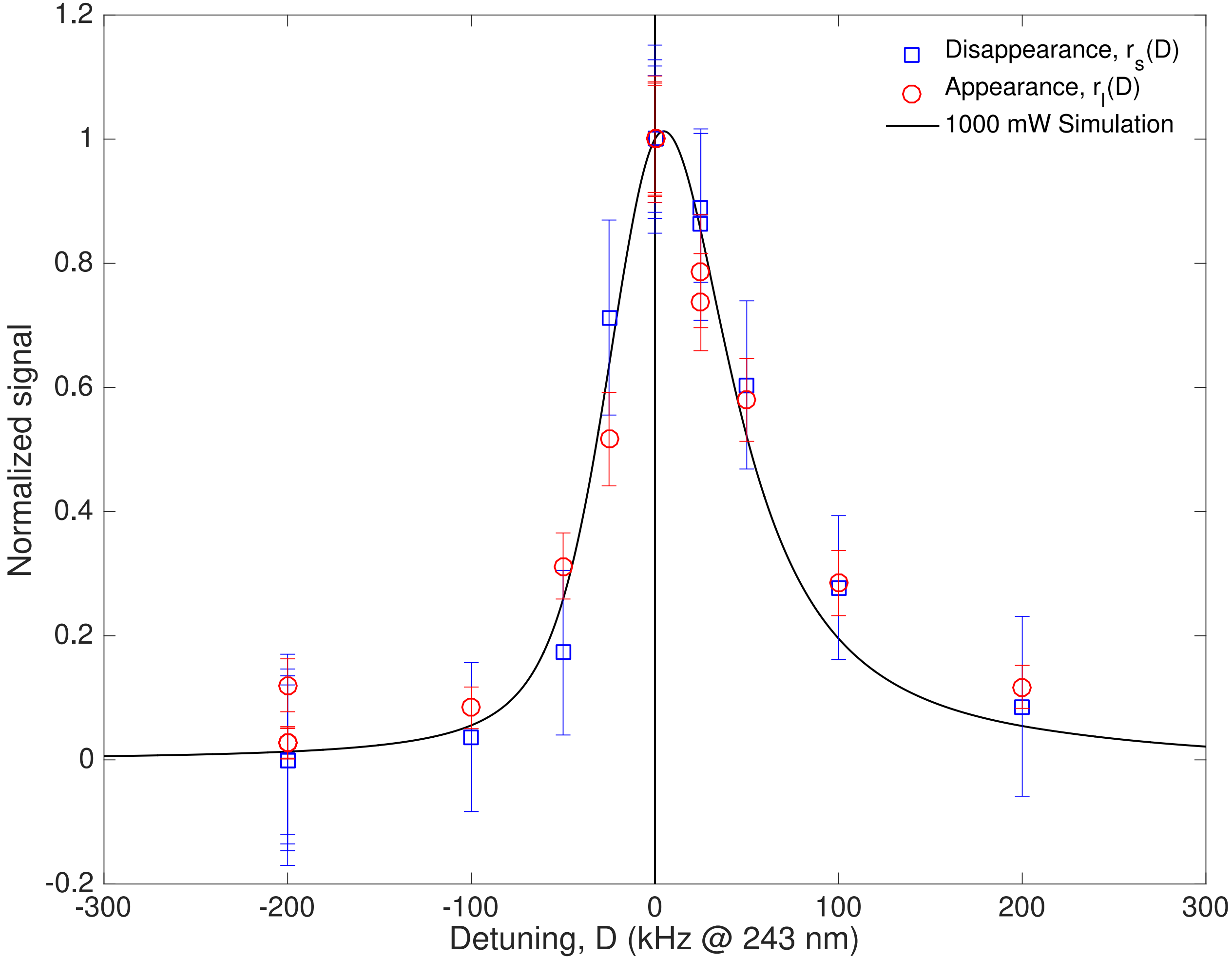
Measure the resonant frequency of the $1S_d$-$2S_d$ transition, and compare with the expected value in hydrogen (in the same trap environment).

1S-2S experiment setup



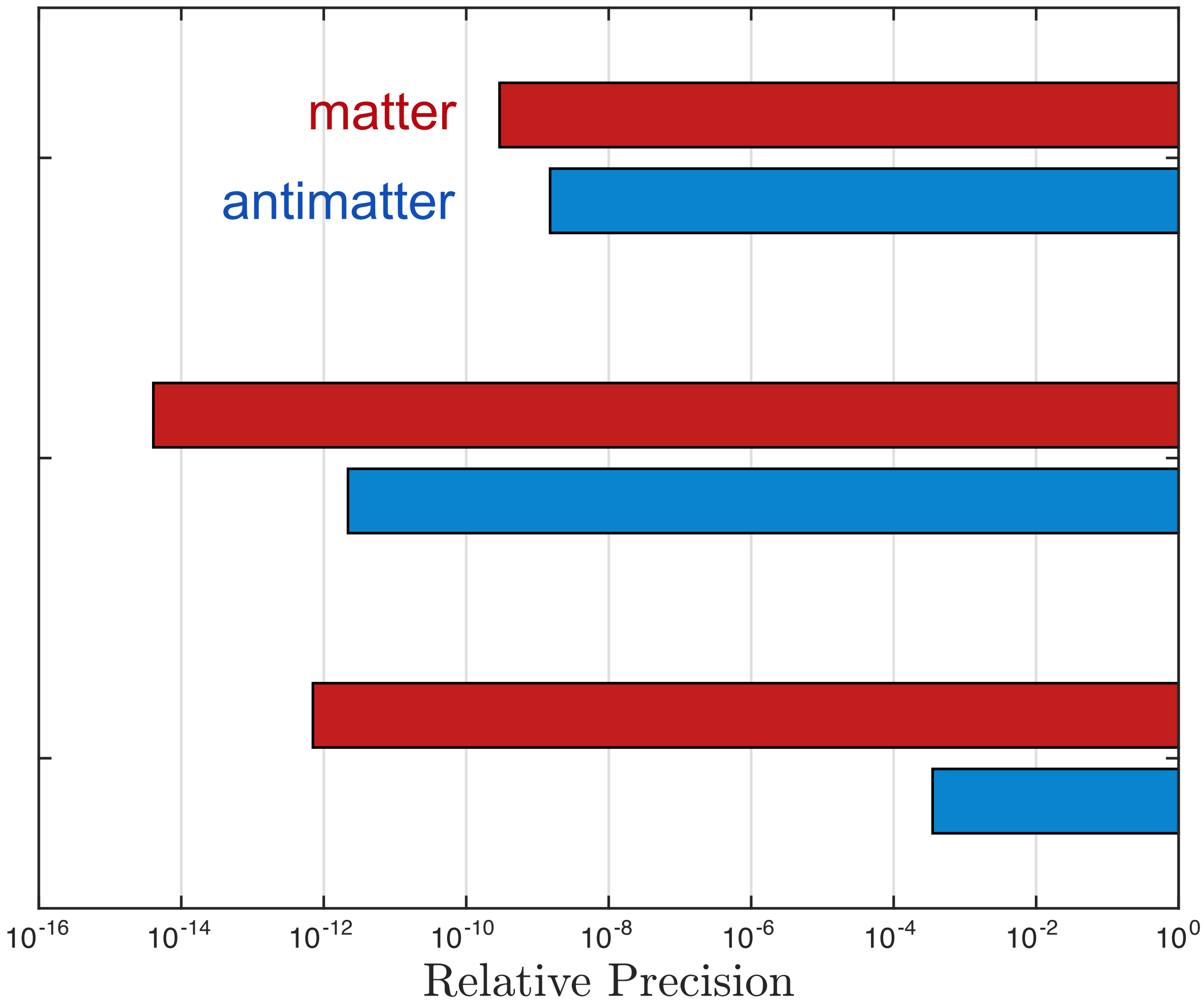
The distance between the mirrors which are 1 m apart is controlled to within 50 nm to achieve constructive interference of the laser beam.

1S-2S lineshape



Measured resonance frequency is consistent with the expected resonance frequency in hydrogen, and therefore consistent with CPT invariance, to a precision of 2×10^{-12}.

Matter-antimatter comparisons



G. Schneider *et al.*, Science **358**, 1081 (2017)

(anti)proton g-factor

C. Smorra *et al.*, Nature **550**, 371 (2017)

A. Matveev et al., Phys. Rev. Lett. **110**, 230801 (2013)

(anti)hydrogen 1S-2S

M. Ahmadi *et al.*, Nature **557**, 71 (2018)

N. F. Ramsey, Rev. Mod. Phys. **62**, 541 (1990)

(anti)hydrogen GS HFS

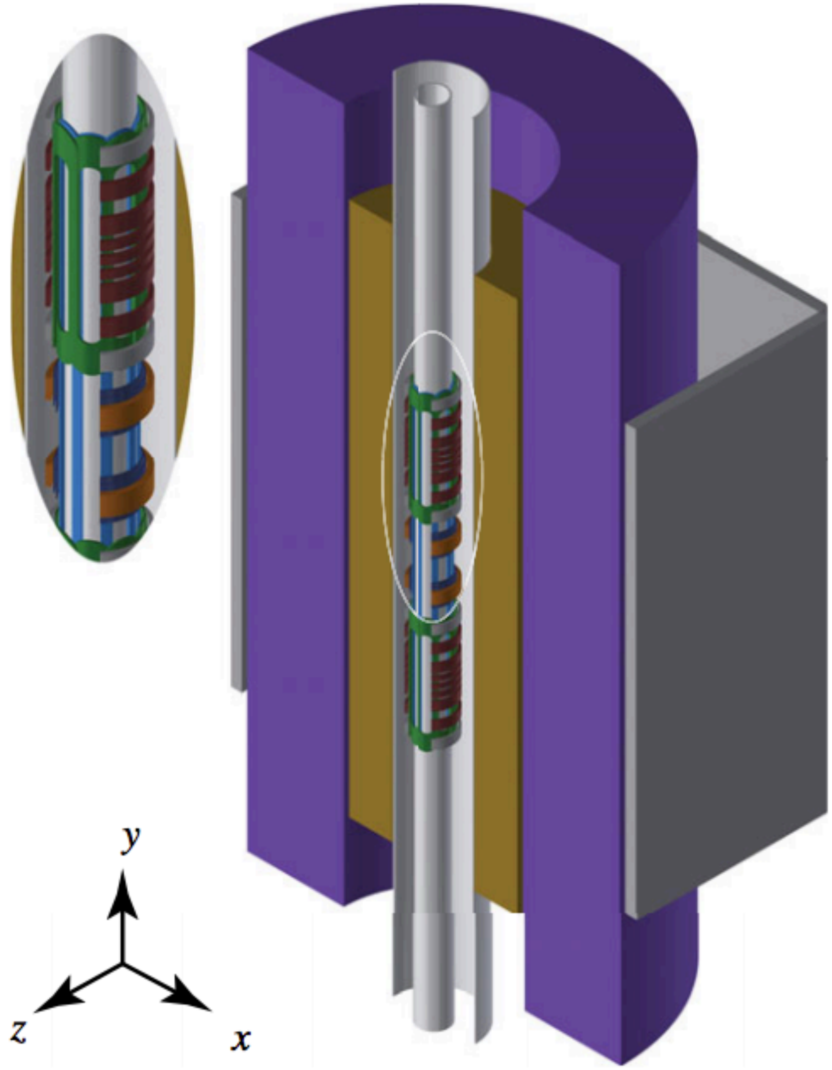
M. Ahmadi *et al.*, Nature **548**, 66 (2017)

Measuring gravity with antimatter: ALPHA-g

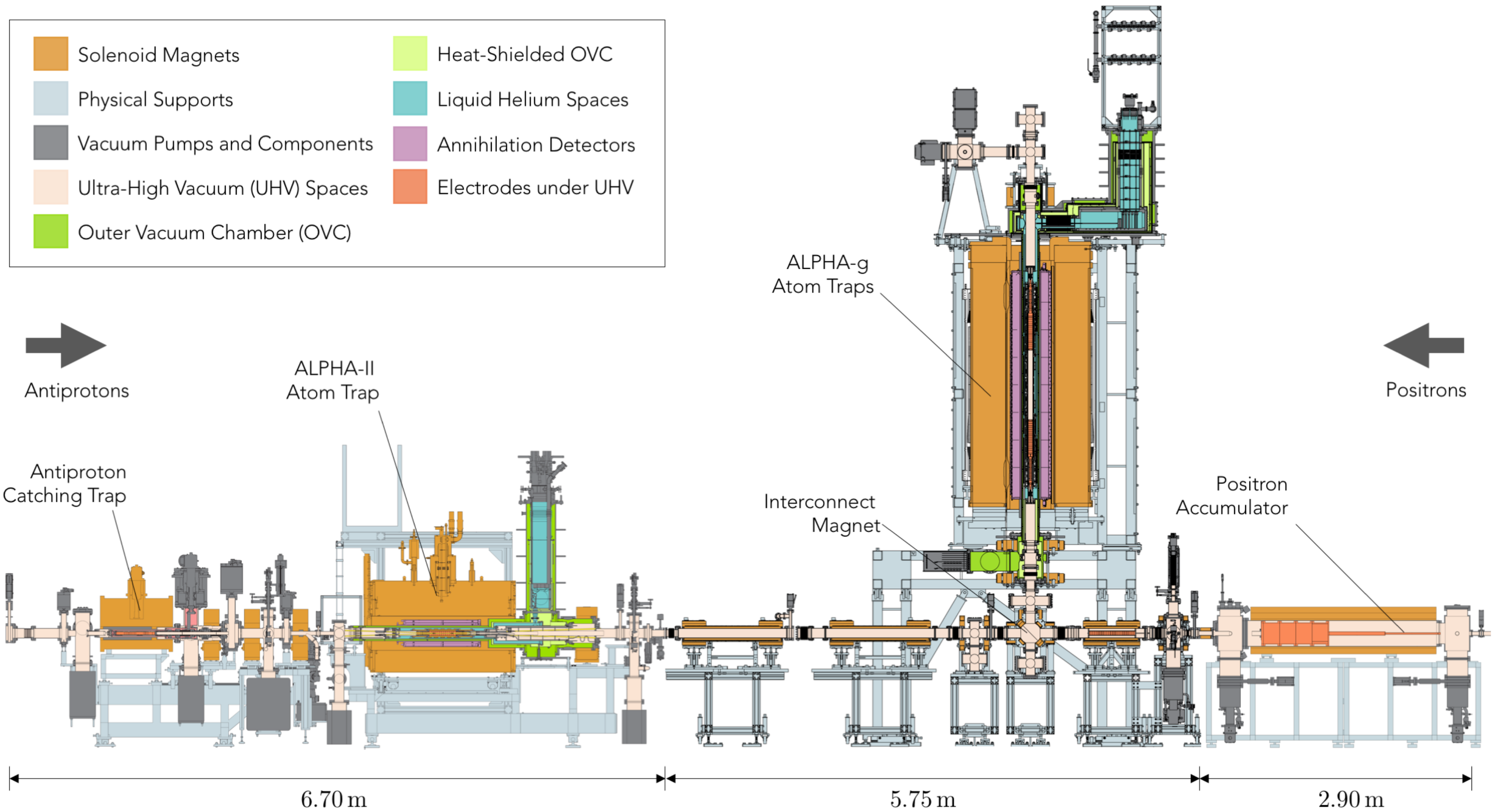
Which way does antimatter fall under the influence of gravity?

Never been measured directly!

Create antihydrogen in a vertical trap and release.



ALPHA-g



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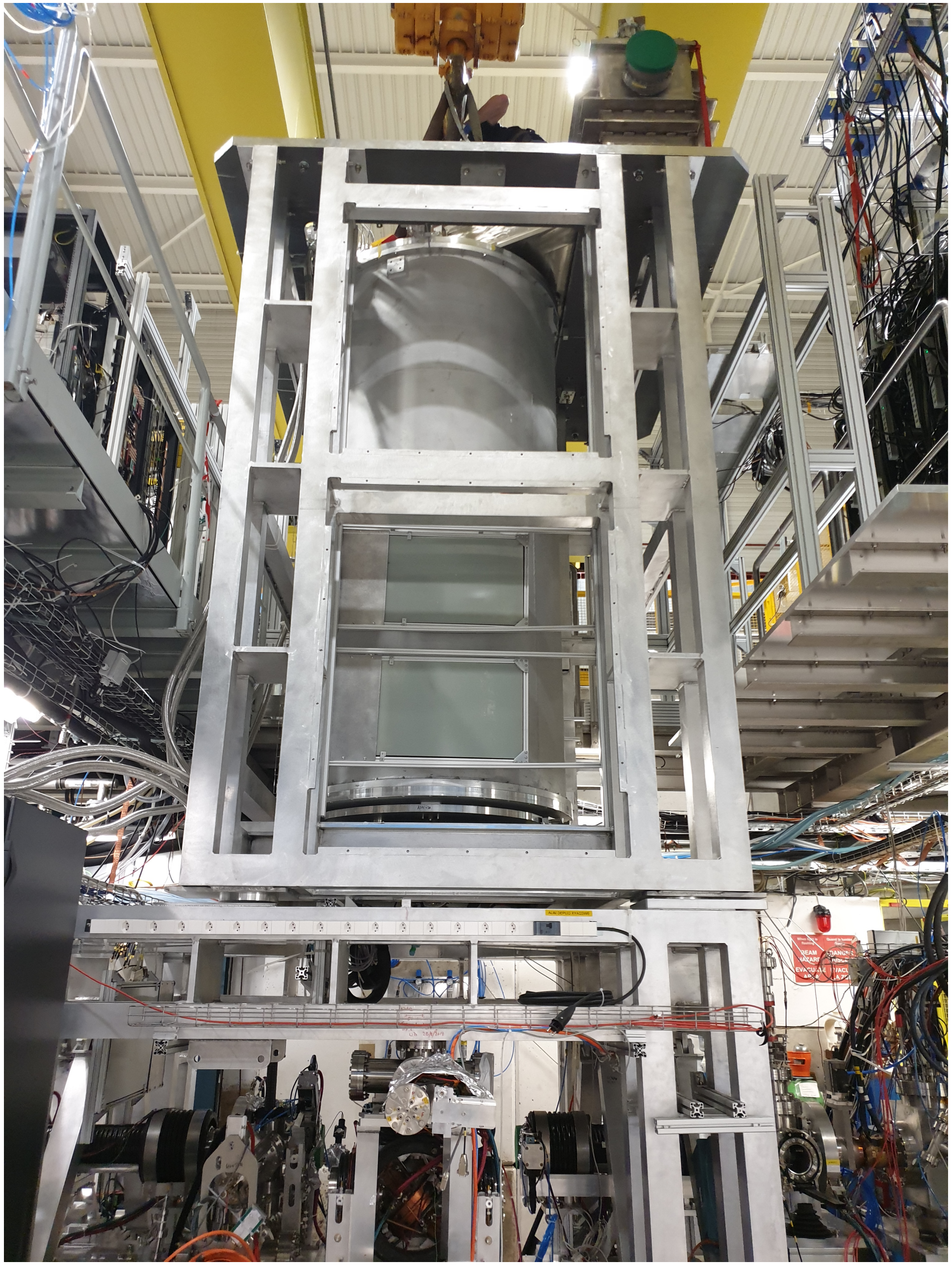
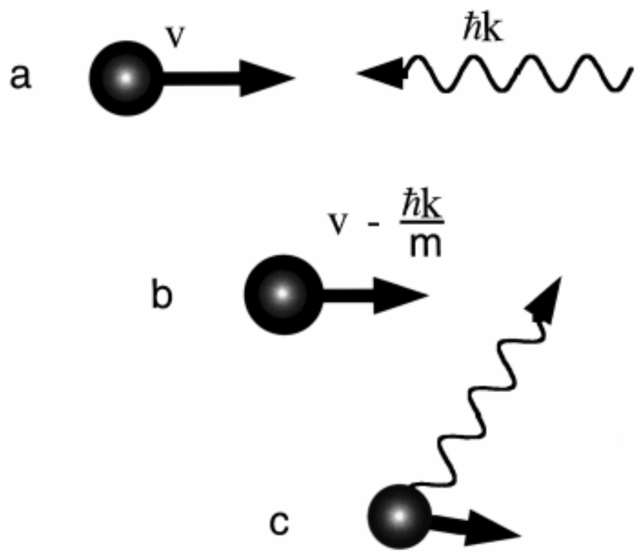
ALPHA-g



Laser cooling to make very cold antimatter



Photons carry momentum

This momentum is transferred to the atom which absorbs the photon

Make use of the Doppler effect to have a net friction force on the atoms

In 2018 we demonstrated this for the first time with antihydrogen – will ultimately lead to more precise measurements of gravity and with spectroscopy.

Current state of antimatter research

- Violations of CP symmetry have been measured, but these are not large enough to explain the matter-antimatter asymmetry of the universe.
- Electromagnetic properties of antimatter are now starting to be measured at levels of precision comparable to those measured in hydrogen.
- Whether antimatter falls up or down is not yet known!
- We still do not know why there is no significant amount of antimatter observable in the universe!

Thank you for listening!