# Antimatter 2 - The Sequel

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CERN

Summer Student Lectures 2005 - Part 2

# Overview Lecture 2

**Trapping antiparticles**

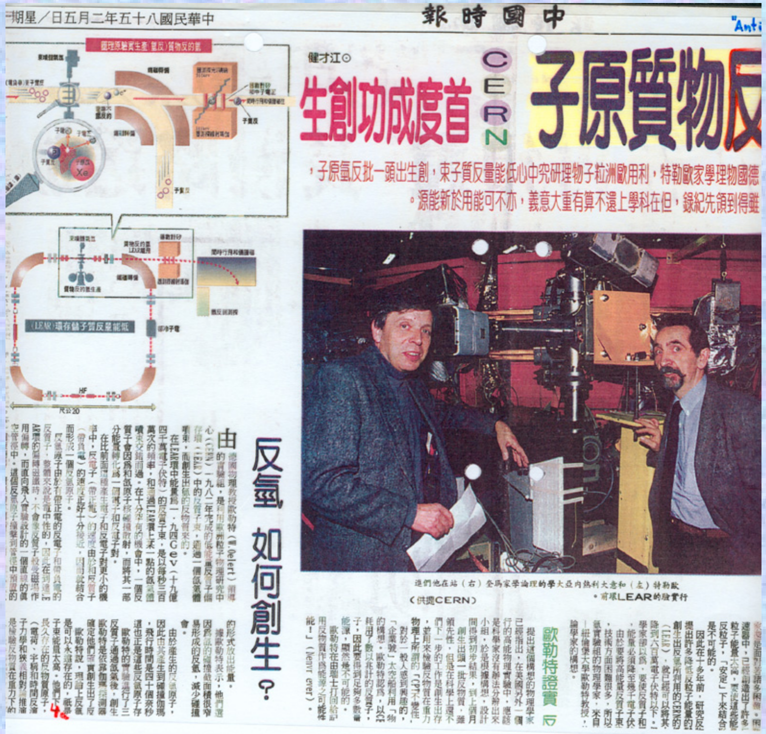
**Antihydrogen**

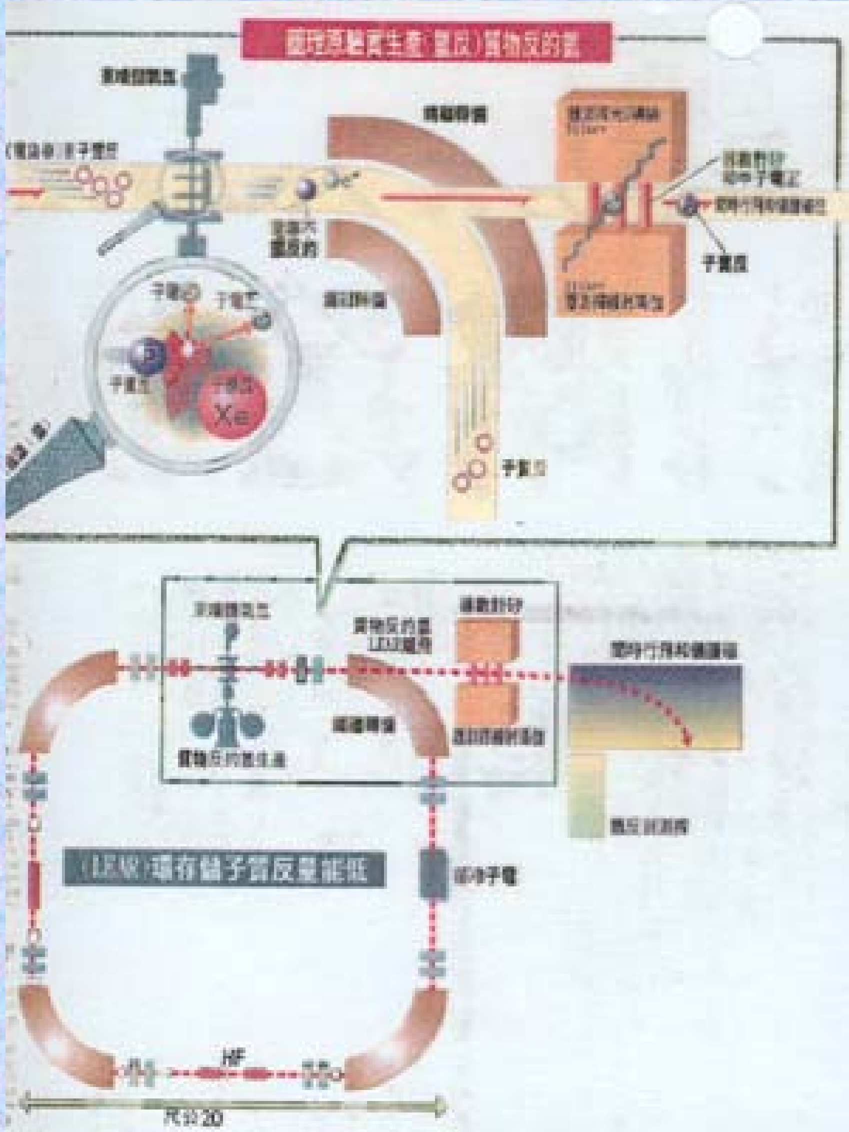
ATHENA and ATRAP
Making antihydrogen
Future developments

**Antimatter technology**

PET
Antiproton therapy?
Rocket propulsion??

# The first nine antihydrogen atoms at CERN (1996)



# Press reactions (of course)

"Liberation" (France)

Libération

**Premiers pas dans l'antimonde**

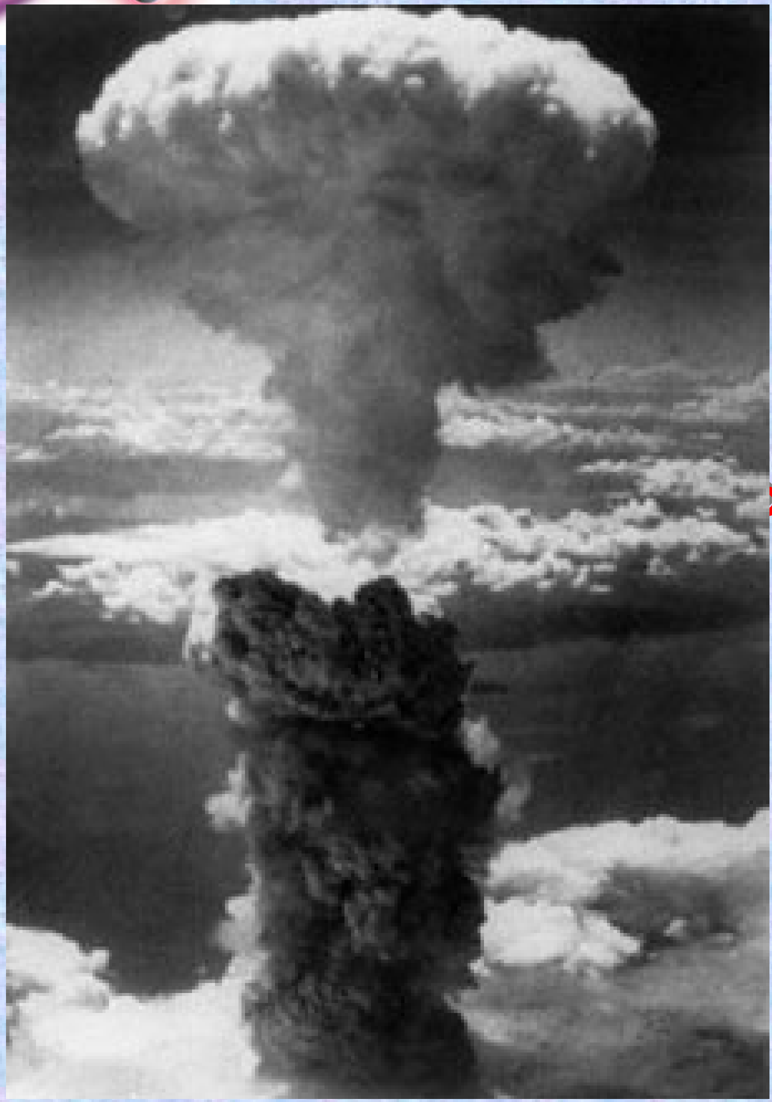
«C'est mille fois plus puissant qu'une réaction nucléaire normale»

**Le Pr Oelert ne nie pas un possible usage militaire des antiatomes.**

Walter Oelert, professeur à l'Institut de recherches nucléaires de Jülich en Allemagne, dirige la petite équipe germano-italienne réunie en 1993 qui a obtenu neuf antiatomes d'hydrogène. puis se sont déchirés en tombant sur le détecteur de silicium, l'antiproton d'un côté, l'antiélectron de l'autre.

**Pourrait-on faire une bombe avec cette antimatière?**

# Will antimatter destroy Geneva ? The Vatican ?



20 kt TNT = $8.4 \cdot 10^{13}$ J

0.5 g antimatter + 0.5 g matter

**Cost: 50,000,000 billion $**
**Production time: ~ 3 billion years**

# III.

# Trapped Antiprotons

# A short break to think about precision measurements

Precision of a measurement increases with observation time

↓

Presence of other particles may decrease precision

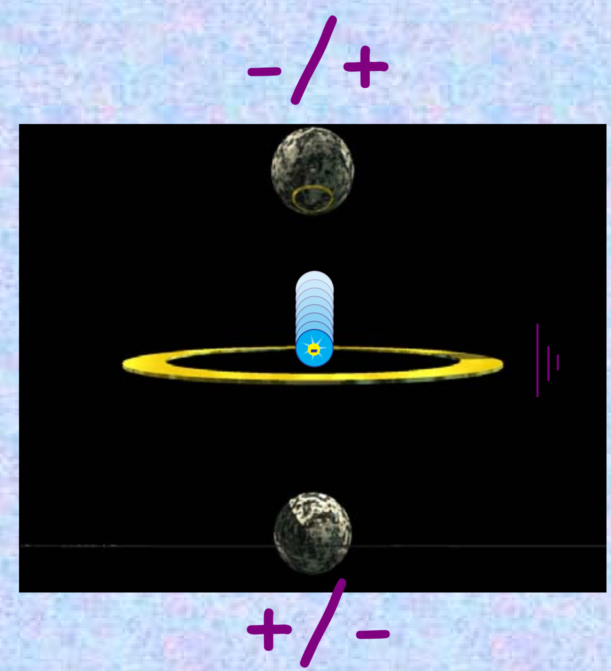
↓

Isolate (few) particles and
observe for long times:

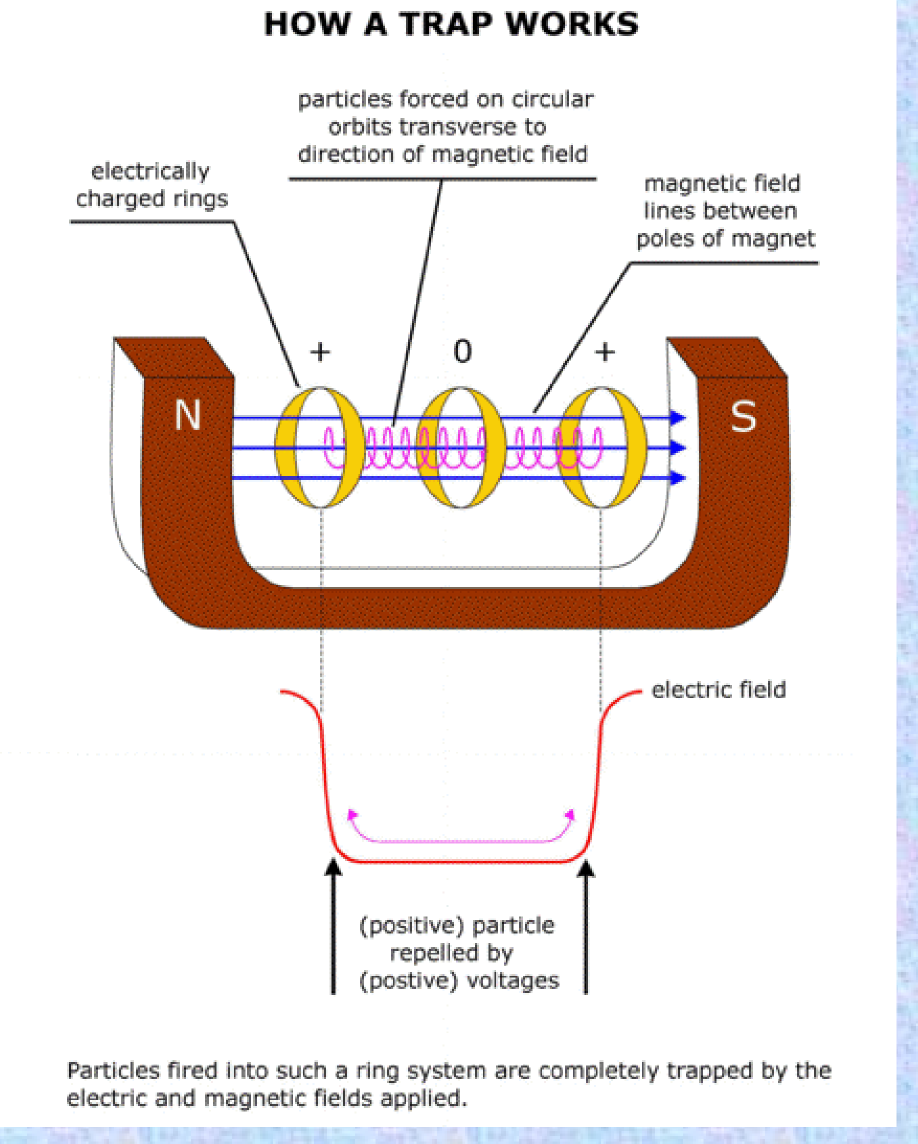
PARTICLE TRAPS

# RF-trap ("Paul trap")

A radio-frequency current on the electrodes maintains an alternating electric field that confines charged particles in a small space.

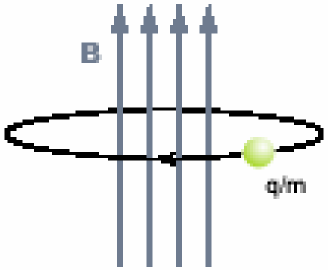


# Magnetic traps



# Special case: Penning trap

Motion of a charged particle in pure magnetic field:

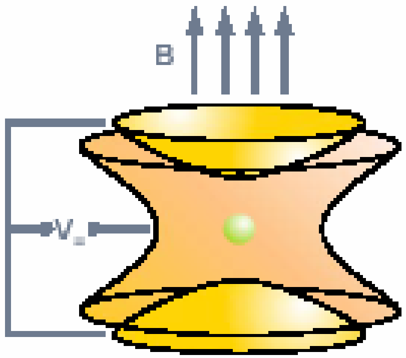



Cyclotron frequency:

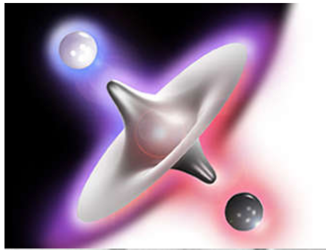
$$f_c = \frac{1}{2\pi}\frac{q}{m}B$$

Penning trap:

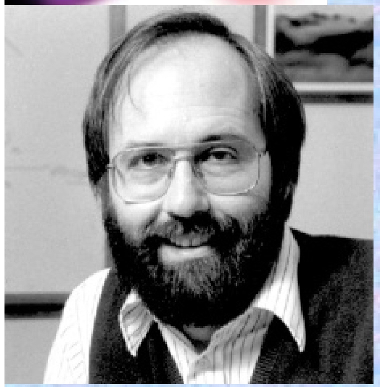
- Strong homogeneous magnetic field
- Weak electric 3D quadrupole field



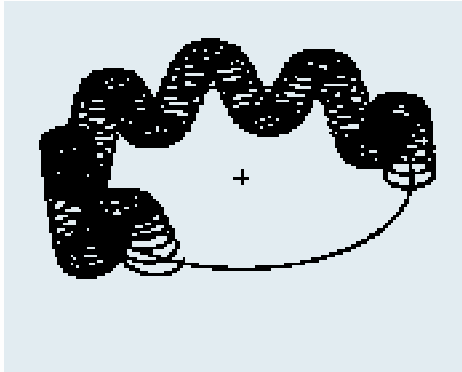

H. G. Dehmelt
1959



# Antiproton Charge-to-Mass ratio (PS 196, LEAR)

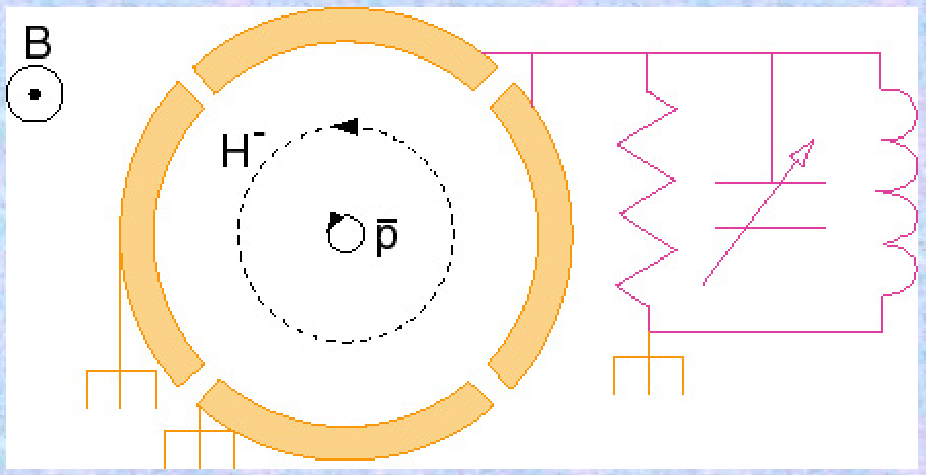


G. Gabrielse




Typical frequencies
$q = \pm e, \; B = 3$ T
$\Rightarrow$ $f_- \approx$ kHz
$f_+ \approx 45$ MHz $(p/\bar{p})$
$f_+ \approx 100$ GHz $(e^\pm)$

Antiproton
FM
(79.5 MHz)




Compare cyclotron frequency of antiprotons and H- ions (B = 5.3 T)

Q/M difference (proton/antiproton) : < $9 \times 10^{-11}$

# IV. ANTIHYDROGEN

# Scientific American, June 2005

By Graham P. Collins

## MAKING COLD ANTIMATTER

**It is the nemesis of normal matter: antimatter.**

Like evil twins of ordinary particles, antimatter versions mirror their mundane counterparts in every way, except for hav-

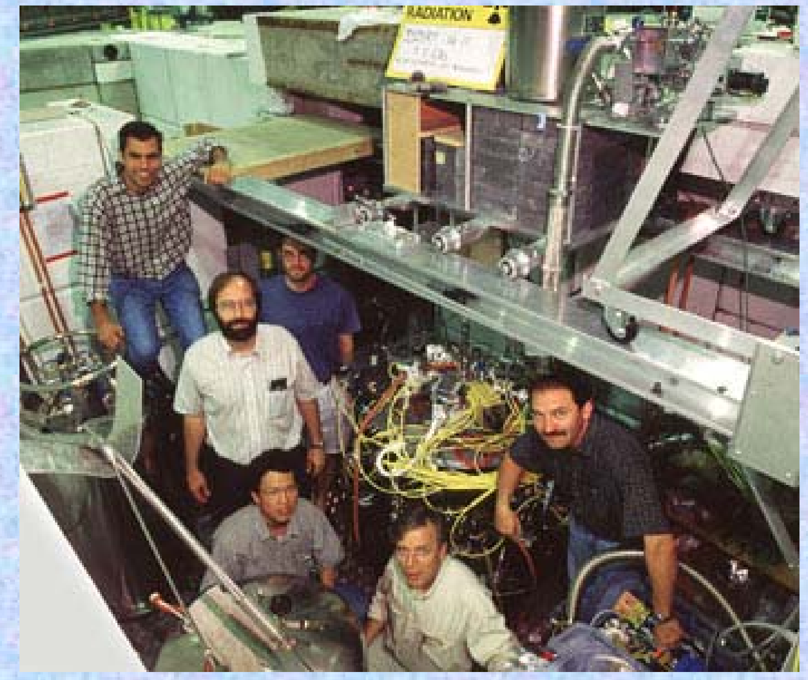
tor at Lawrence Berkeley National Laboratory, by smashing protons into a piece of copper. The process is the reverse of

# Antihydrogen

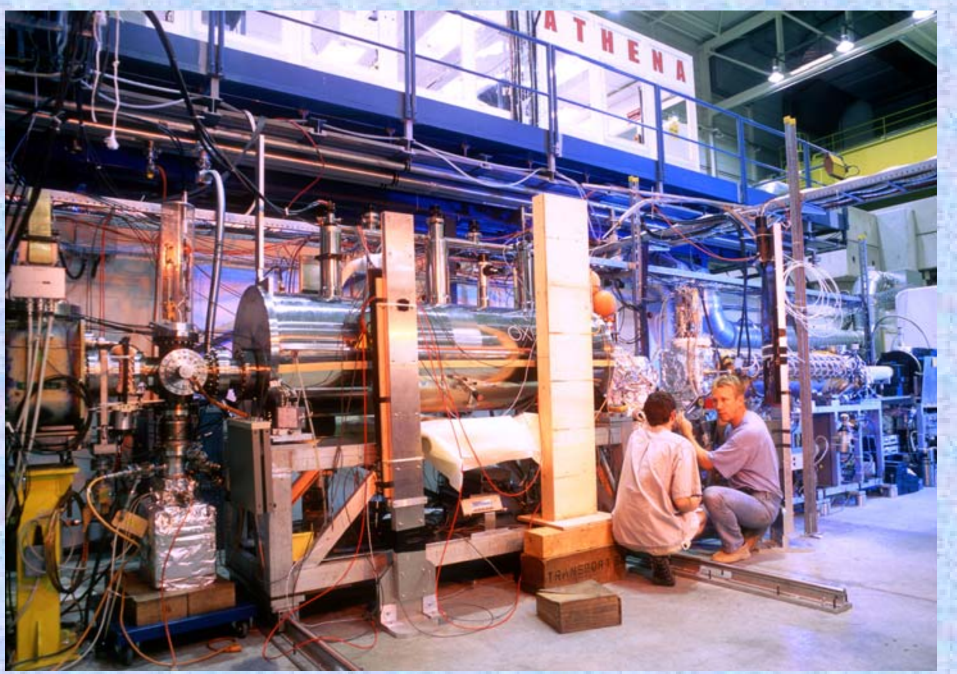
**ATHENA and ATRAP** - Experiments (Start 2000)

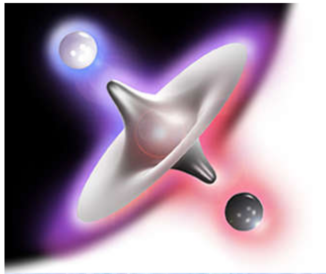
Find a way to make cold antihydrogen (done)
Trap and cool antihydrogen
Precision measurements

ATRAP

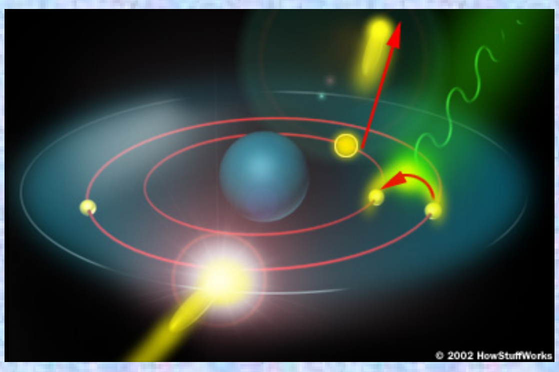


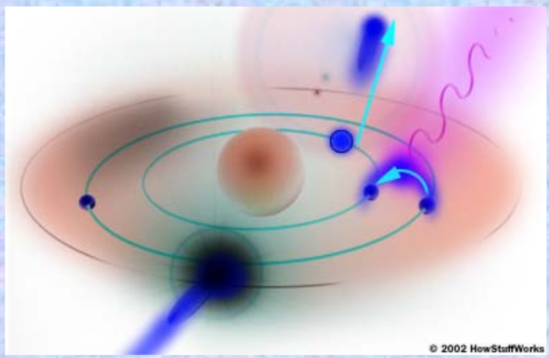
ATHENA

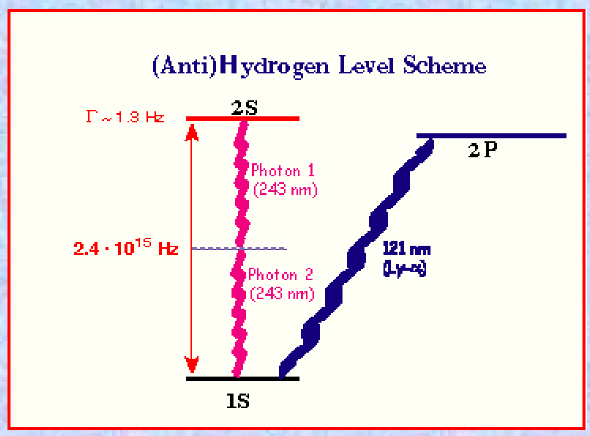




# Antihydrogen = Hydrogen ??



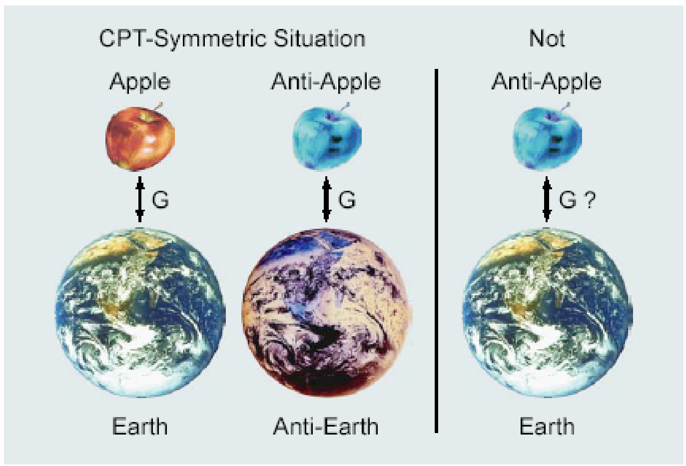



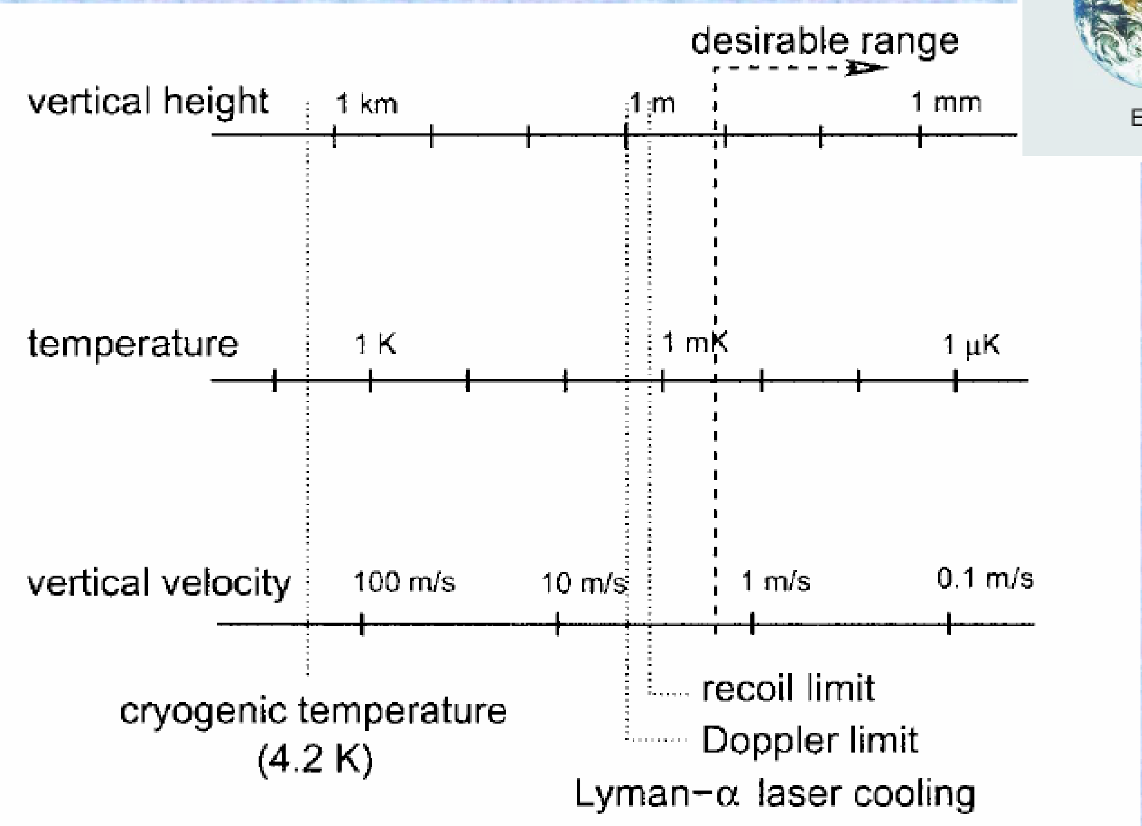




2S level is metastable (T ~ 120 ms)

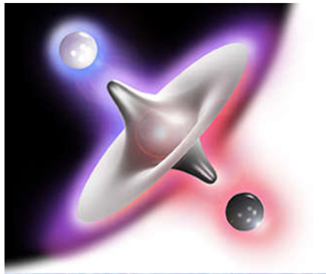
→ Two photon laser-spectroscopy (1S-2S energy difference
→ very narrow line width = high precision: $\Delta\nu/\nu \sim 10^{-15}$
→ Long observation time - need trapped (anti)atoms

# Gravitation?



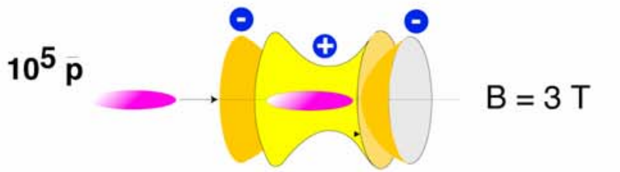




Extremely low
Kinetic energy
Anti-atoms

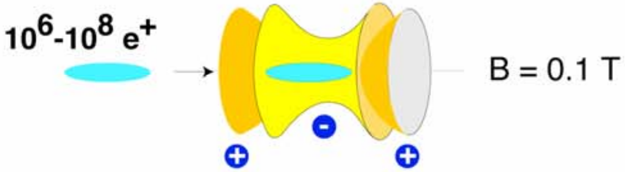


# Antihydrogen milestones

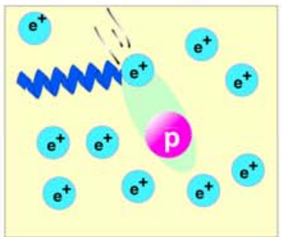
1 Antiproton Capture into Penning Trap




2 Positron Accumulation from Na-22 source




3 Positron-Antiproton Recombination in multi-ring trap

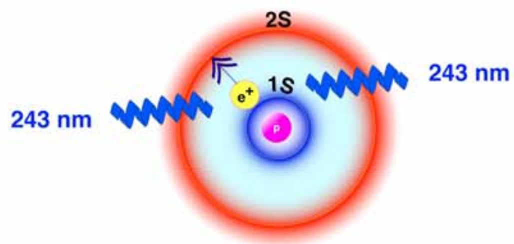



4 Antihydrogen **Detection**

- Annihilation products: 2 layers x 16 Si Strips
- 511 keV Gammas: 192 CsI Xtals + Photodiodes

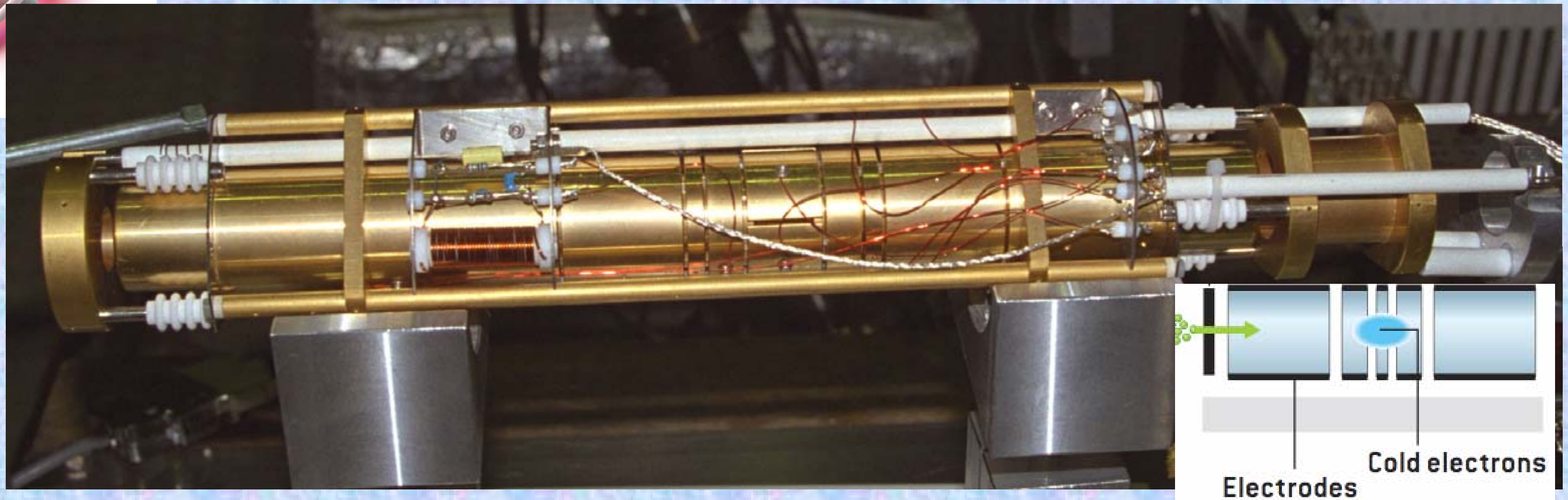
5 Antihydrogen **Storage** in Magnetic Bottle
Magnetic well depth ~ 0.35 K (35 μeV)
(PHASE 2)

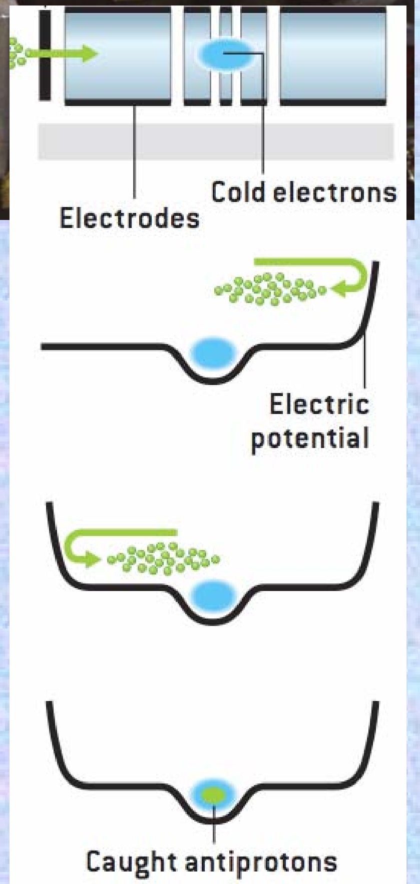
6 2-Photon Laser **Spectroscopy**: ΔE (1S-2S)
(PHASE 2)



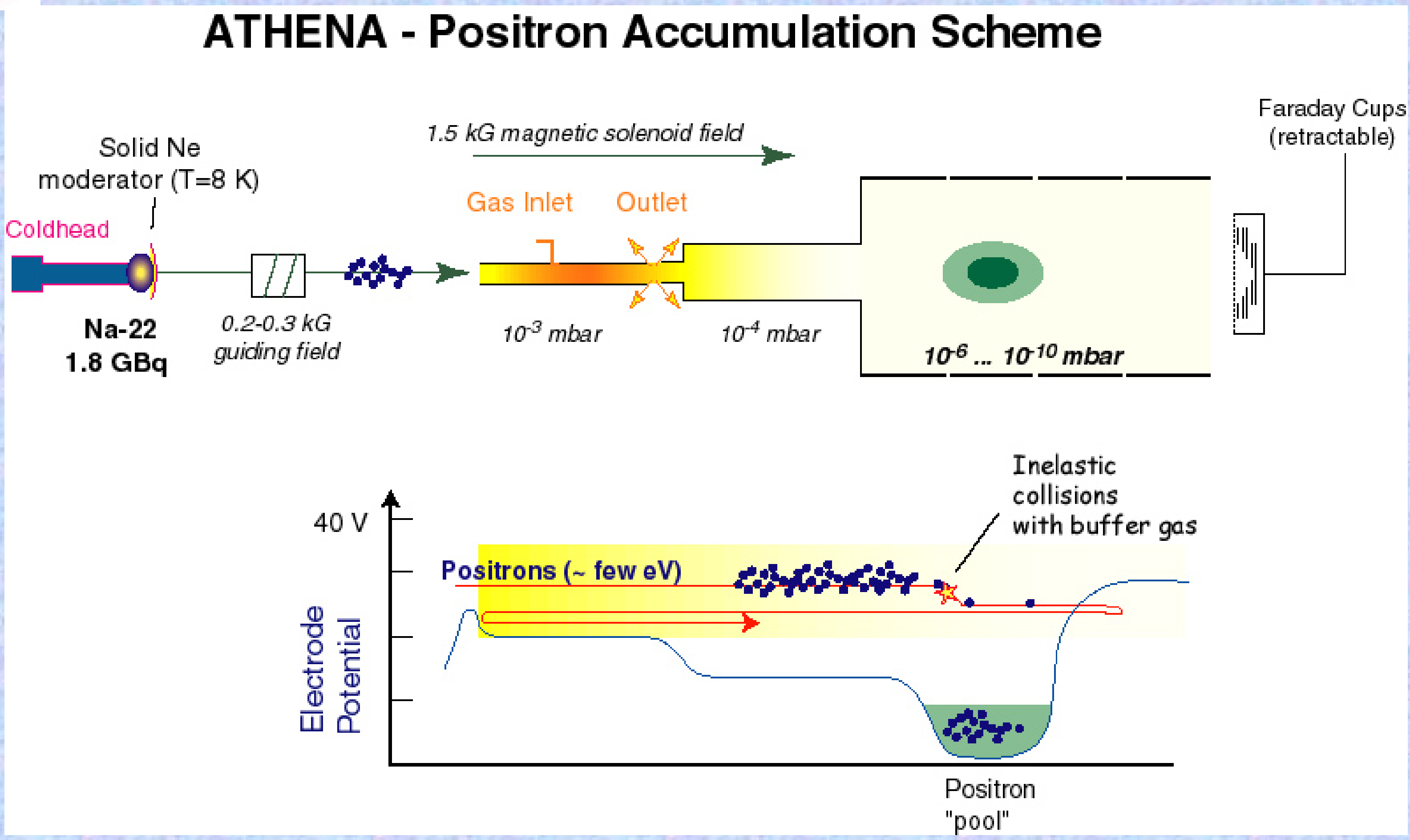

**Comparison $\bar{H}$ : H with precision $10^{-12}$ ...$10^{-15}$**

# Trapped antiprotons*



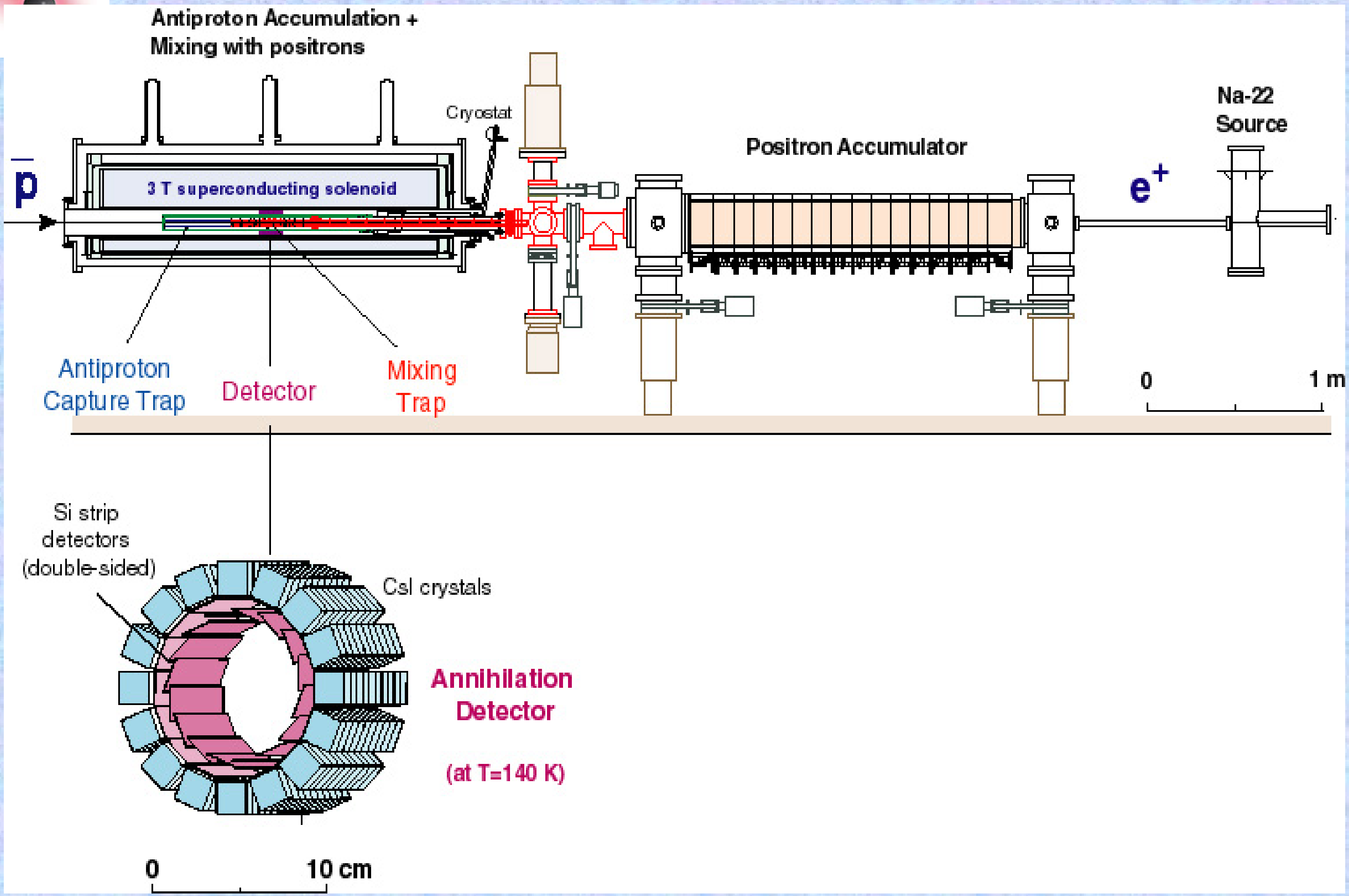


# Positron Accumulation (ATHENA)



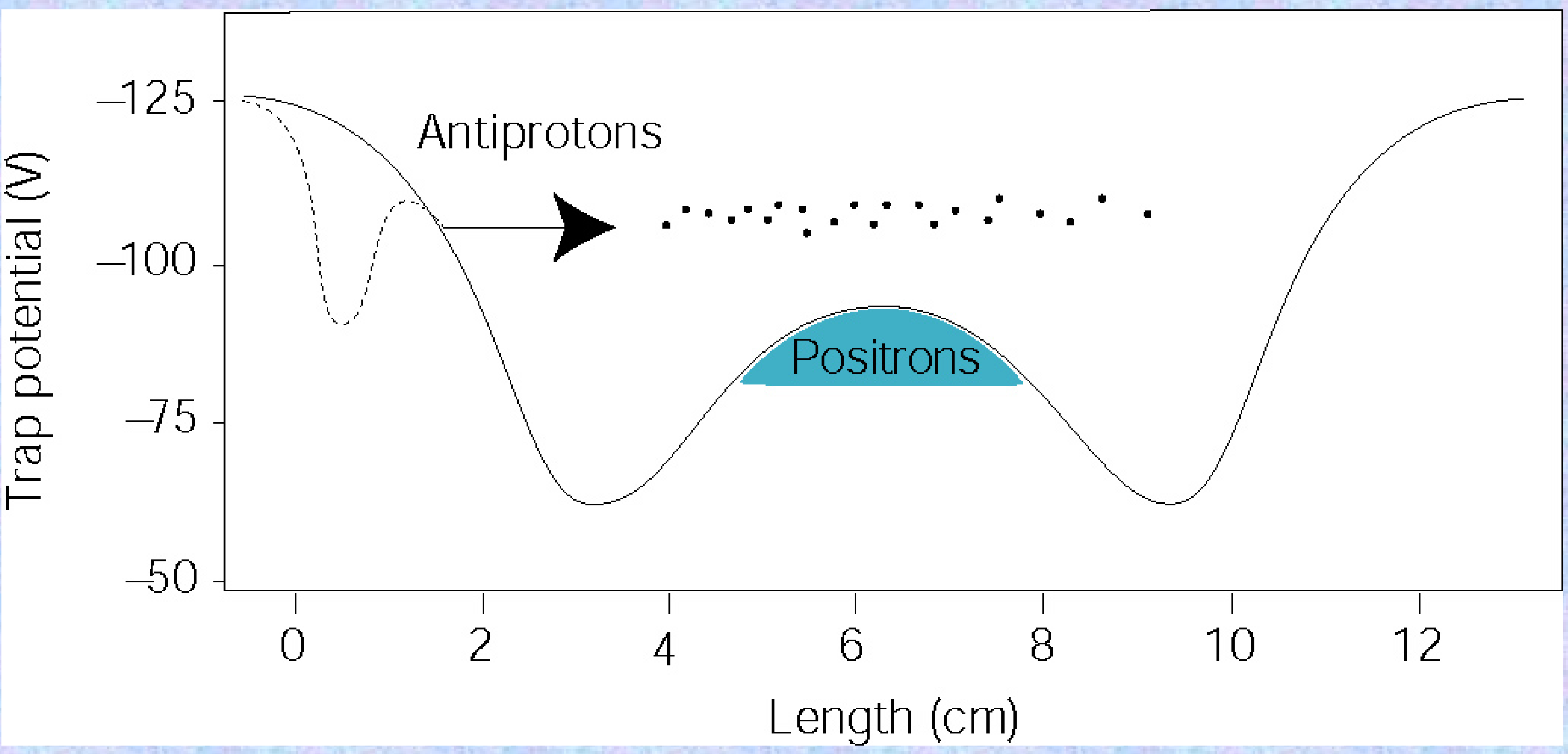

100 million positrons in 2 min

# Overview - ATHENA / AD-1

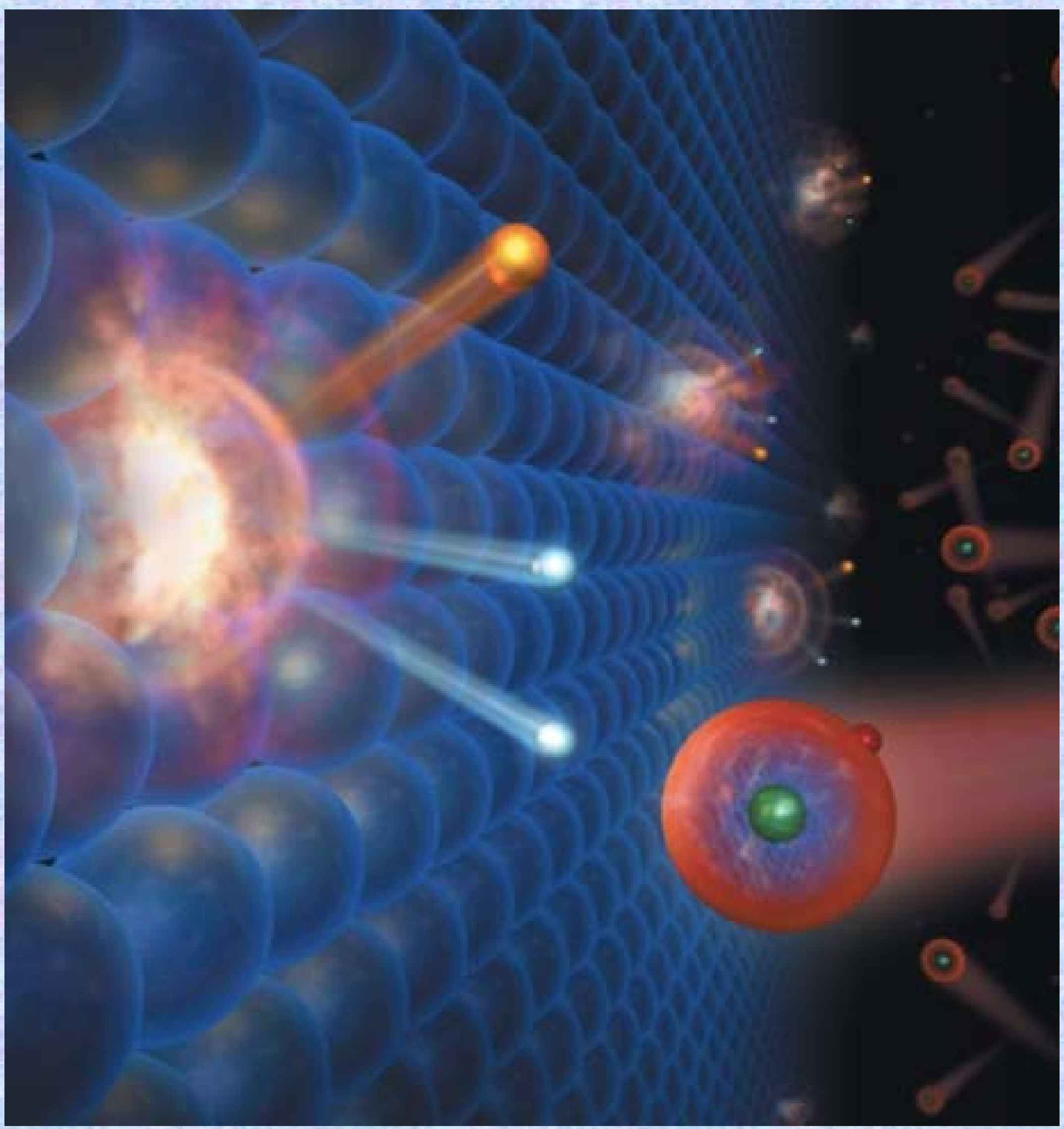


# Recombination

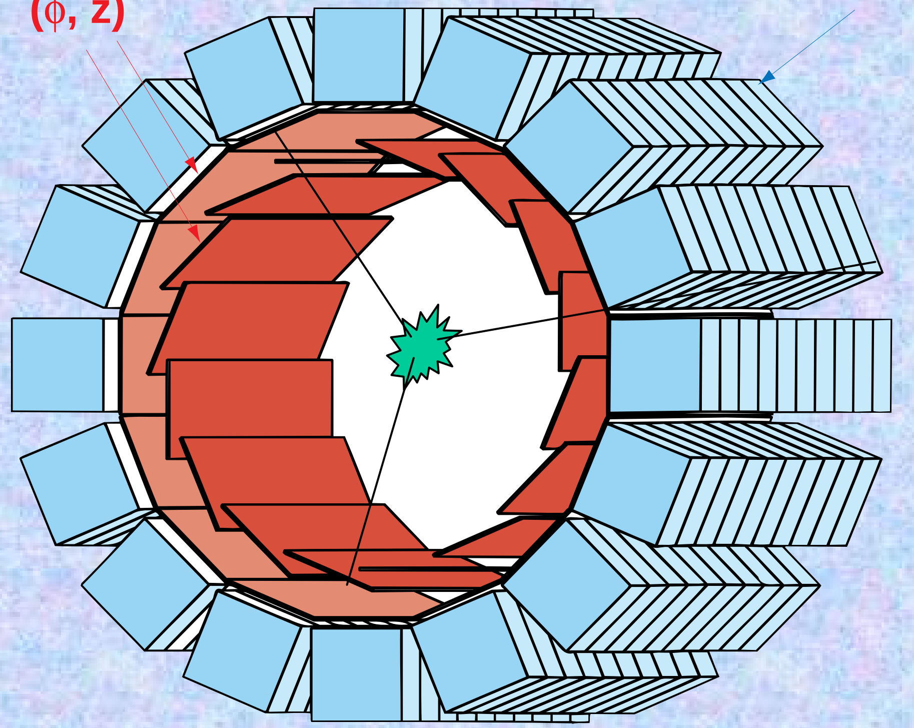
Recombine free positrons + antiprotons using “nested traps”



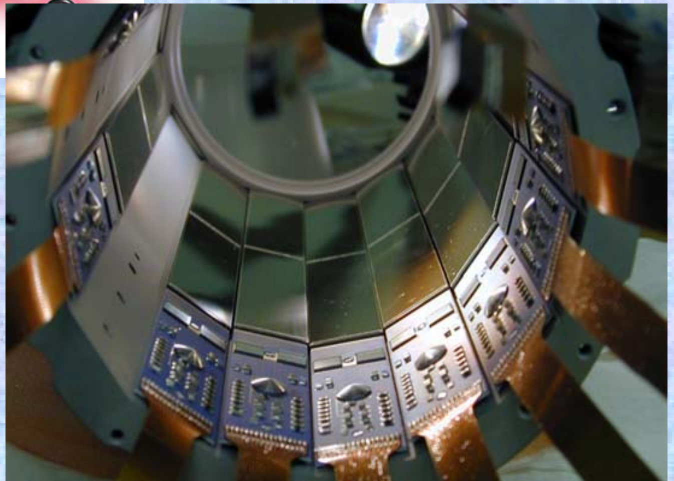
# Antihydrogen Atoms are NOT captured



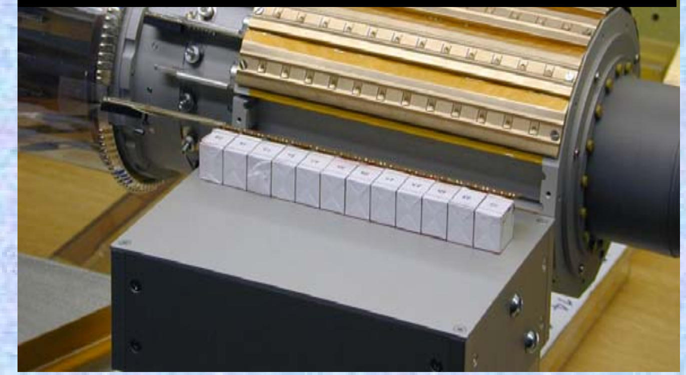
# Antihydrogen Detector

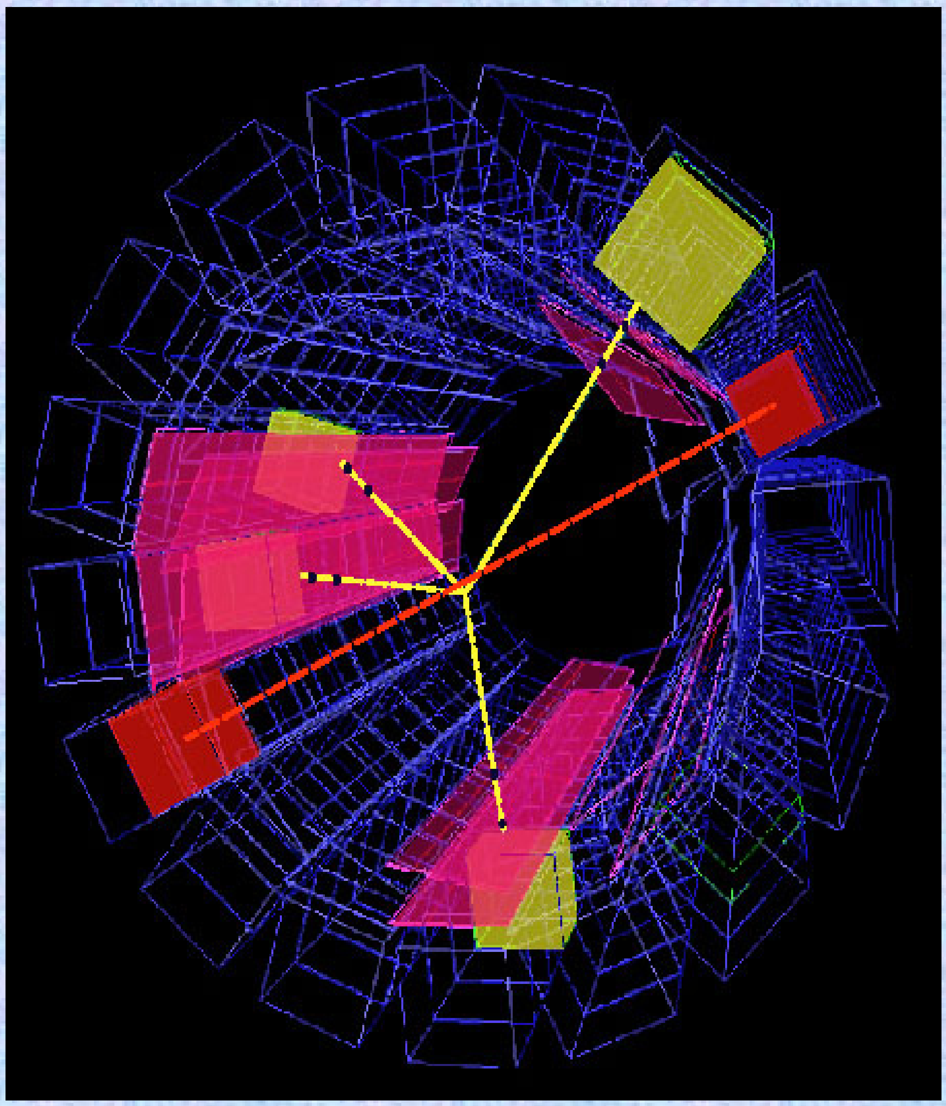


# Antihydrogen Detector

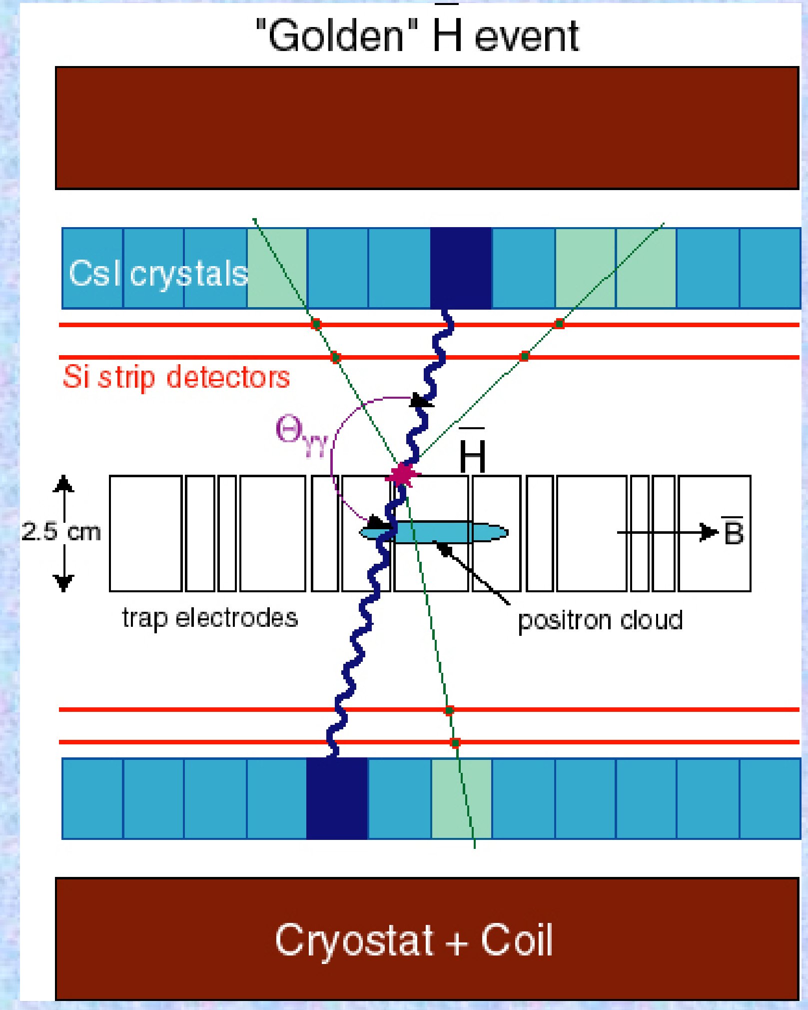


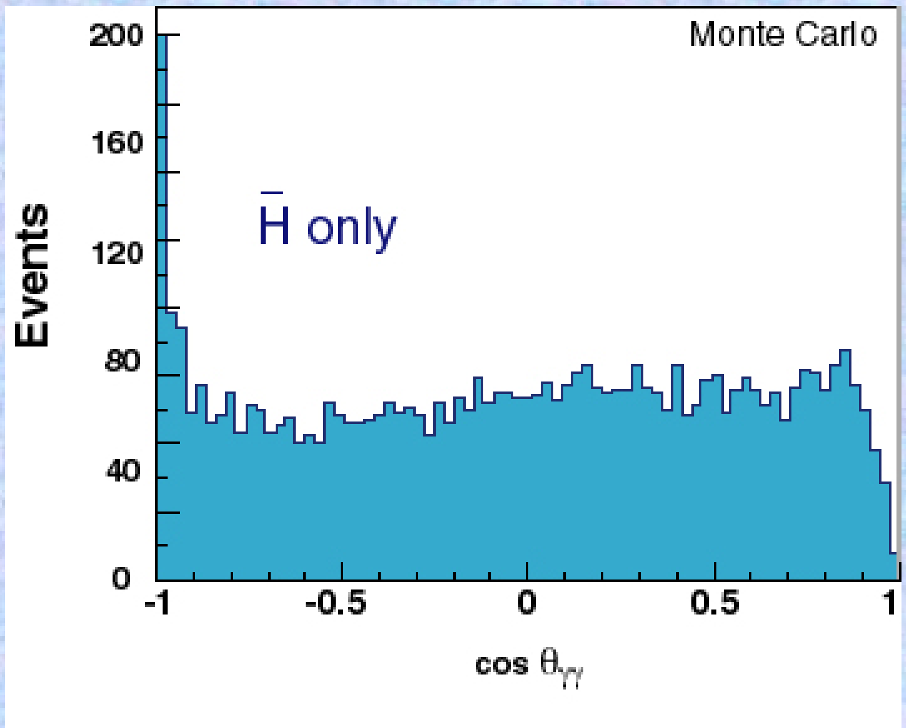
Operated at 140K, 3T, small space
- 2 x 16 Si microstrip detectors
- 192 CsI crystals, APD readout



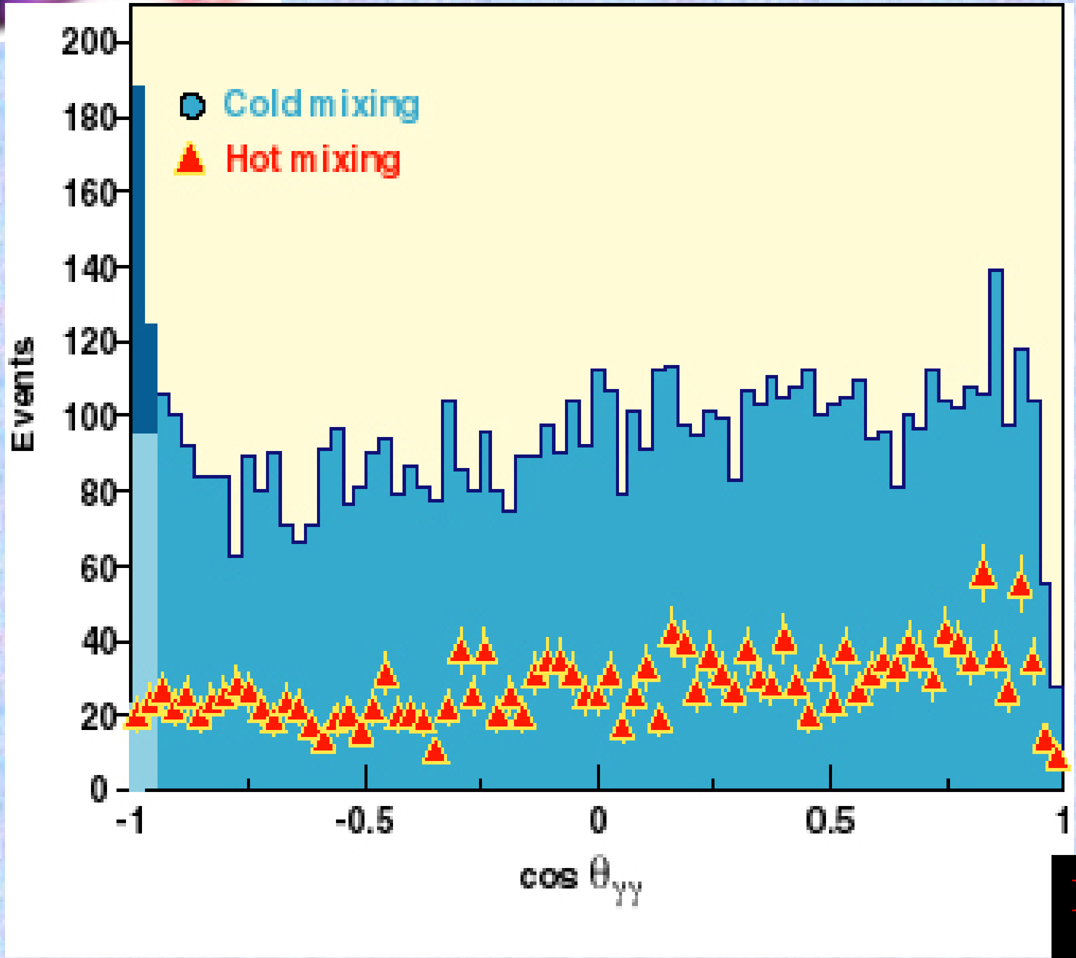


# Expected antihydrogen signal (simulation)



# First observation of cold antihydrogen




M. Amoretti et al., ***Nature*** **419**, 456 (2002)

Aug 2002:

131 ± 22 events

(above flat spectrum at cos < -0.95)

> 50,000 produced antihydrogen

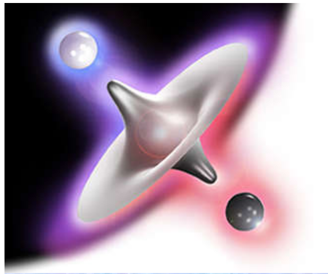
(conservative estimate)

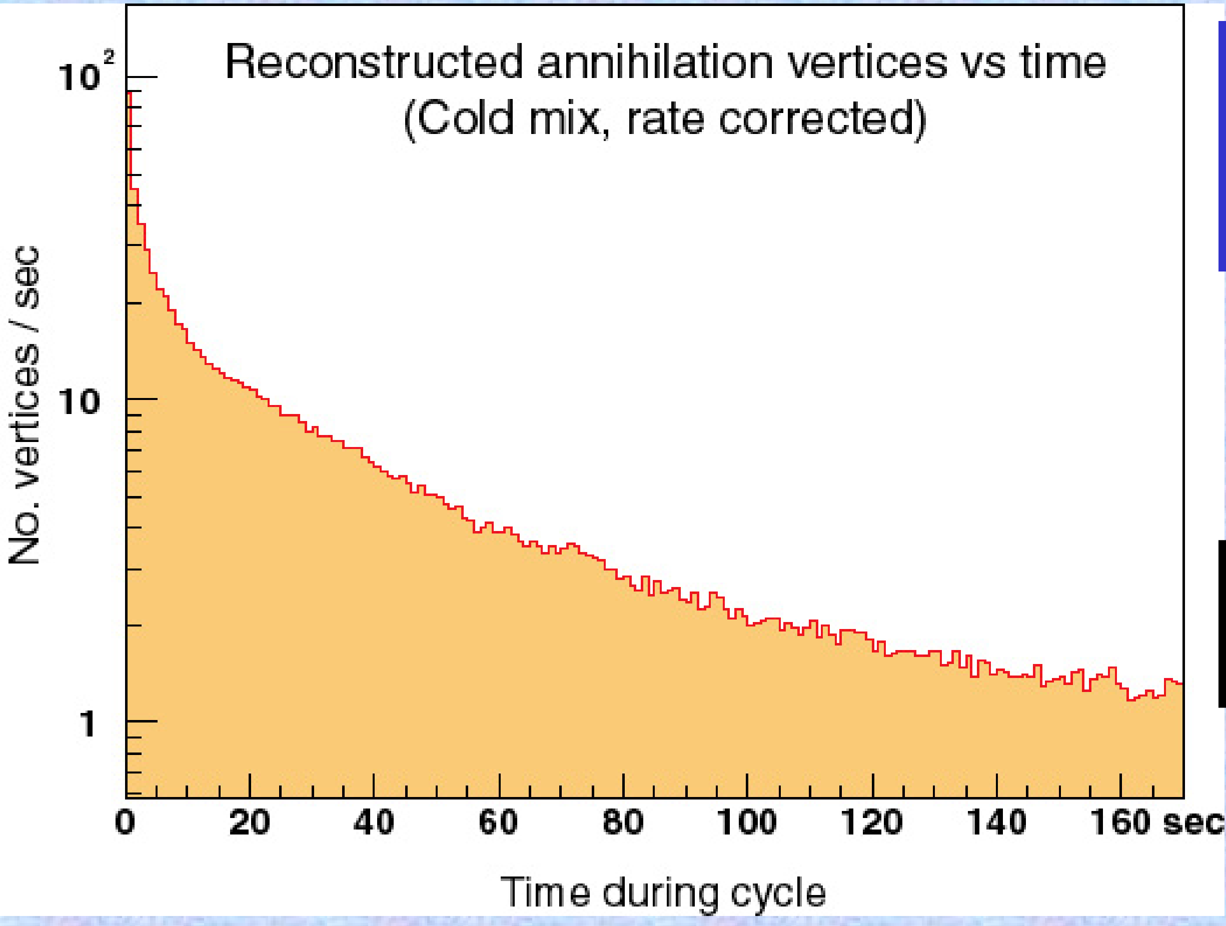
Background:

Mixing with 'hot' positrons(~ 3000 K)

[suppressed recombination]

# Rate of antihydrogen production





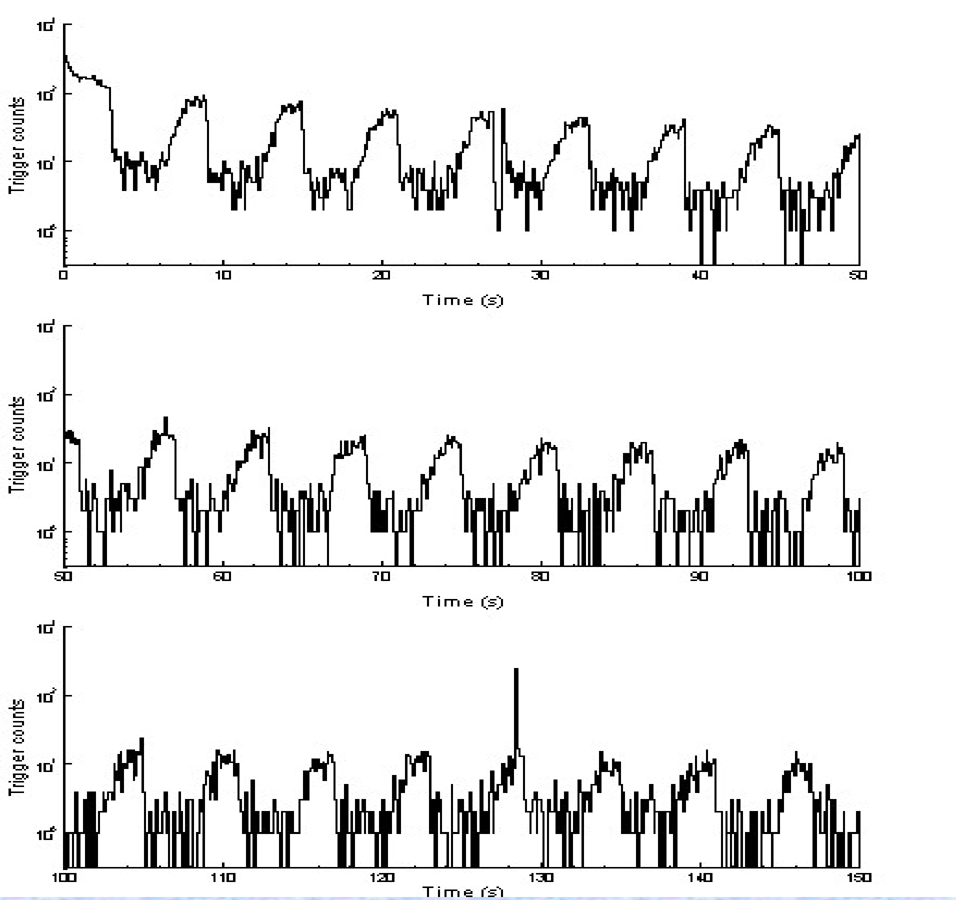

Analysis:

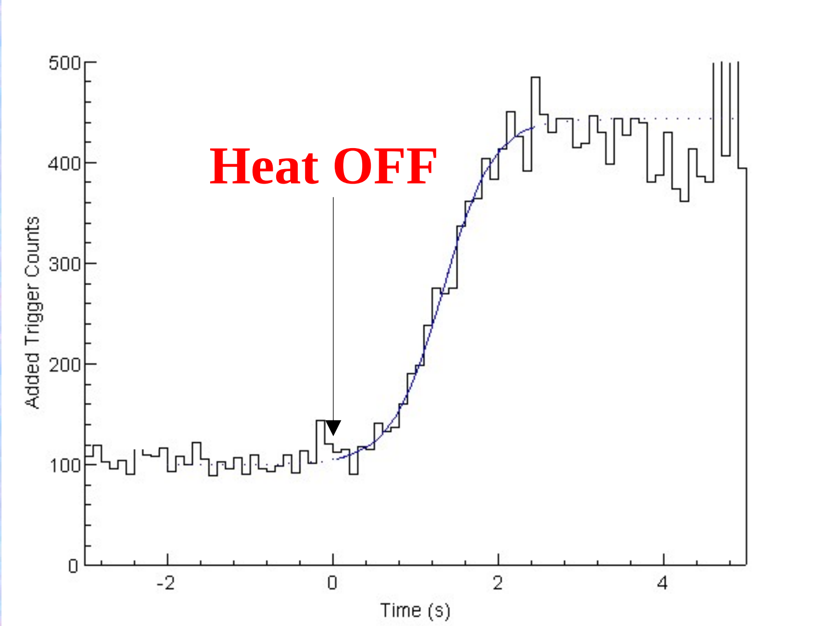
- 65 ± 10 % antihydrogen
- ~ 50 % vertex / annihilation

High Initial Rate **(> 100 Hz)**

High S/B (~ 10:1) in first seconds

# Pulsed antihydrogen production

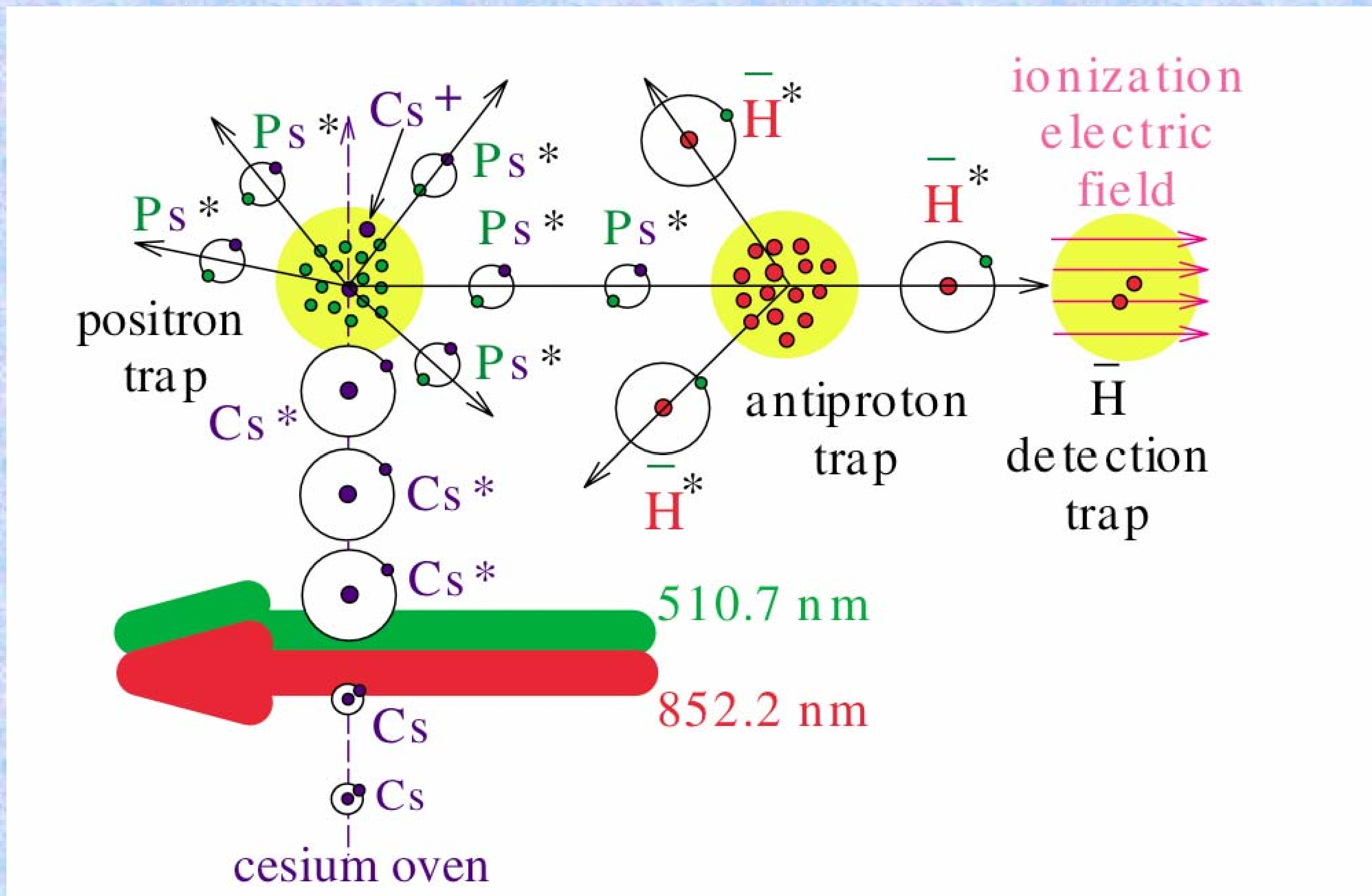



**Heat On/Off every 3 sec**

# Other ways to make antihydrogen

ATRAP method - colder antihydrogen (?)

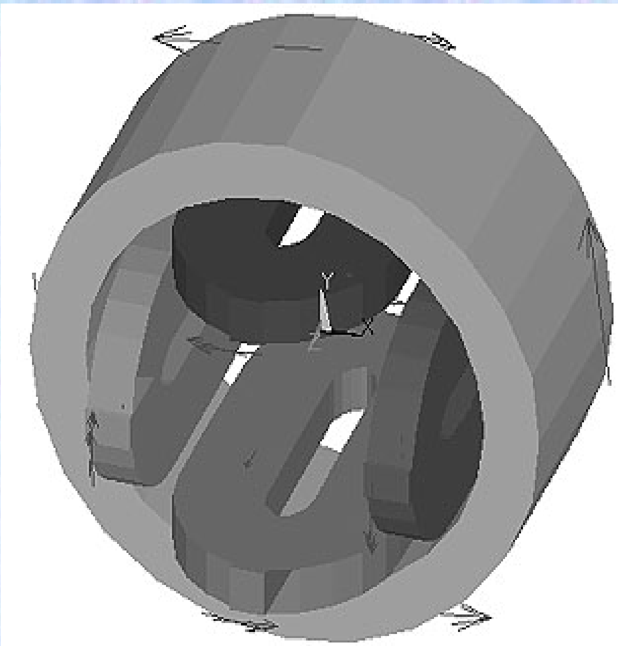


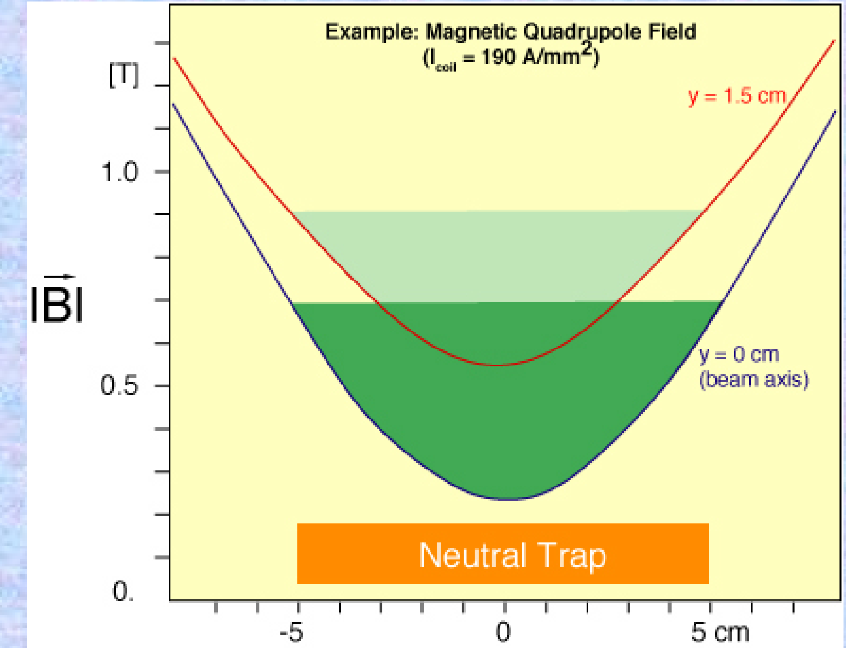
# Unsolved problems with antihydrogen trapping

Antihydrogen could be trapped in magnetic gradient field (quadrupole, sextupole), via magnetic moment, but:

a) very shallow potential (~ 0.07 meV/Tesla)

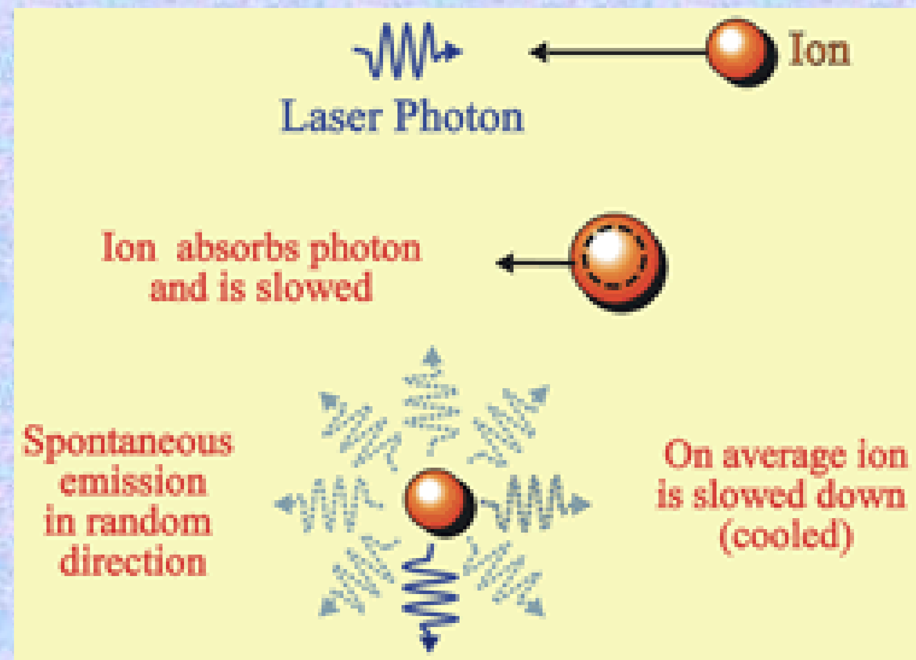
b) Anti-atoms may be too fast (>> 1 meV ?)

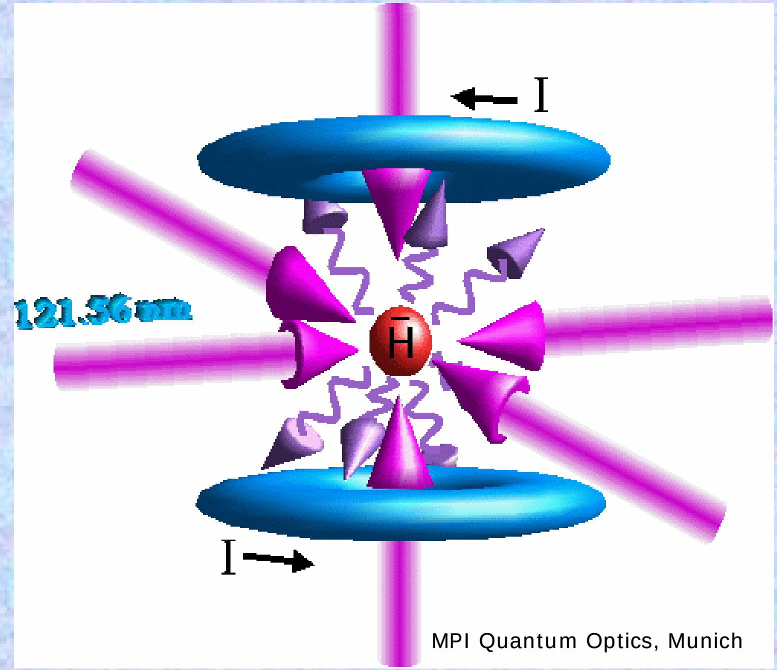




# Unsolved problems with laser cooling

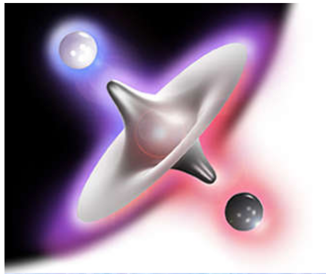
Antihydrogen laser cooling (121 nm) (2002: 50 nW)



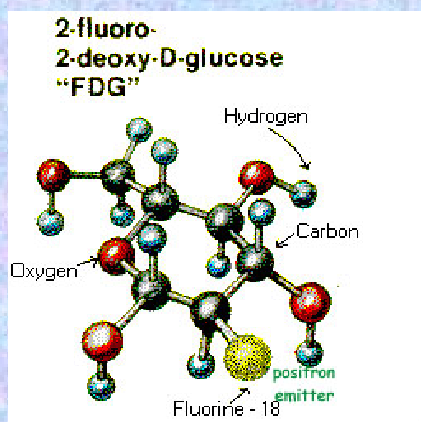

Very small laser power; anti-atoms too fast

# V. APPLICATIONS

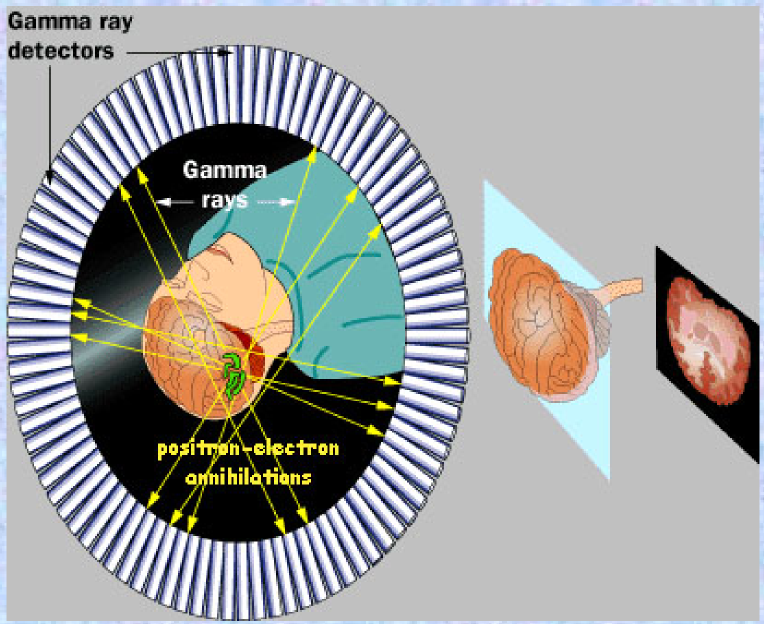


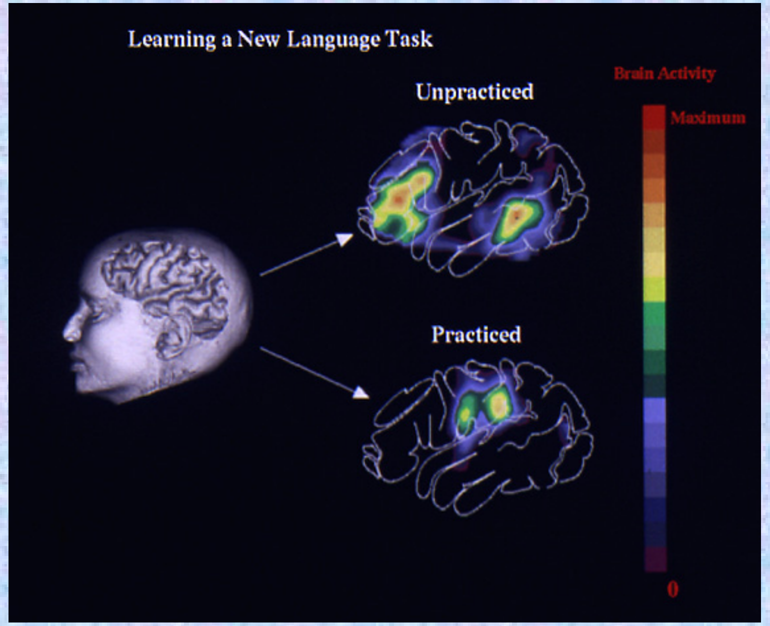
# Applications of antimatter - PET

Insert e+ emitting isotopes (C-11, N-13, O-15, F-18) into physiologically relevant molecules ($O_2$, glucose, enzymes) and inject into patient.




Study positron annihilation with crystal calorimeter ( Positron Emission Tomography, PET)

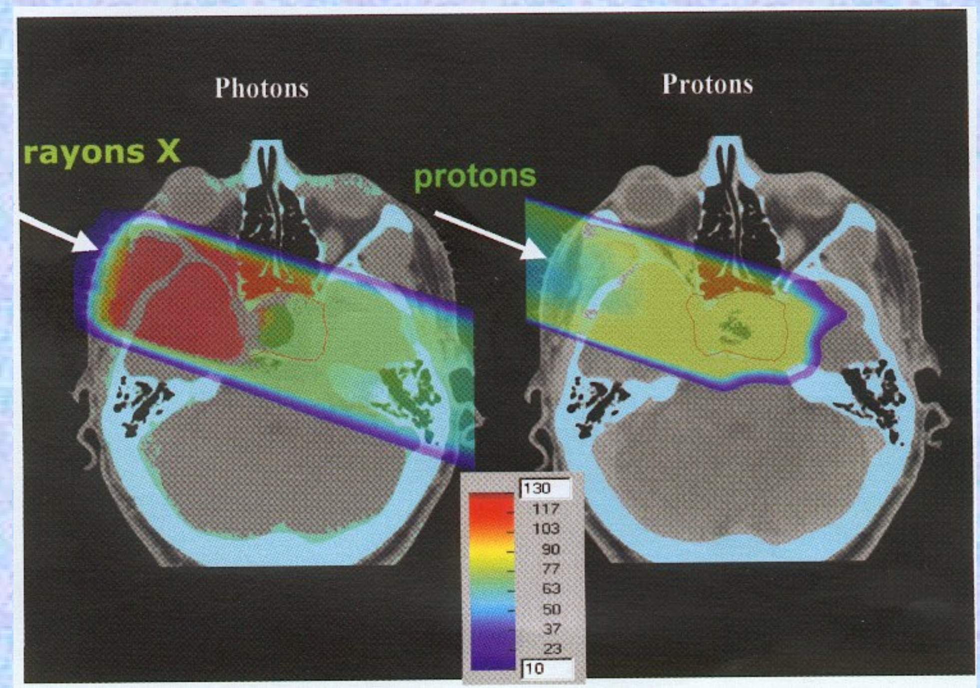


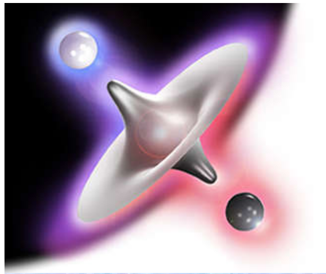



# Applications of antimatter - Tumour therapy?

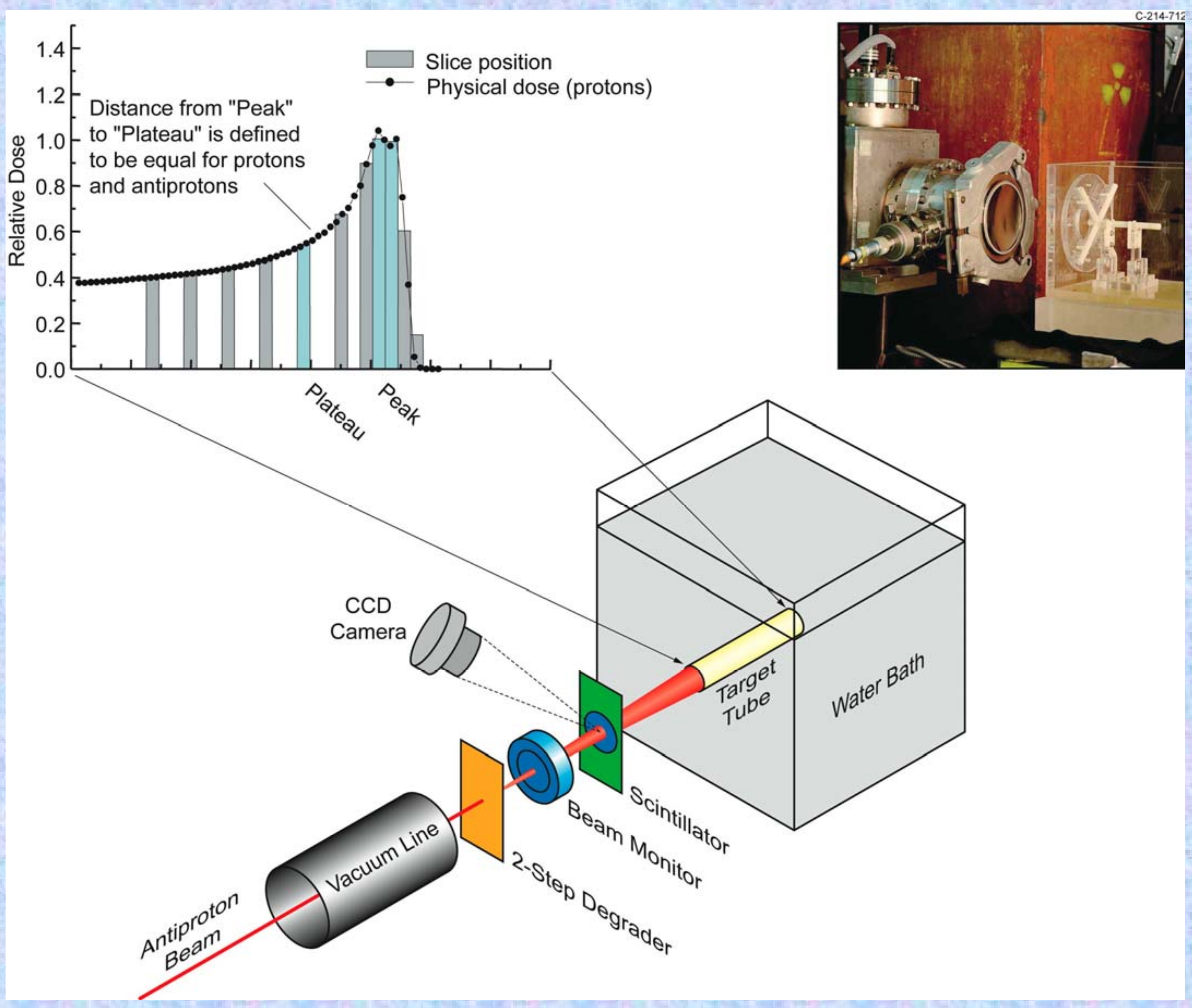
Goal: destroy tumour without (too much) harm to healthy tissue

Gammas: exponential decay (peaks at beginning)
Charged particles: Bragg peak (Plateau/Peak better for high Z)
Antiprotons: like protons, but enhanced Bragg peak from annihilation



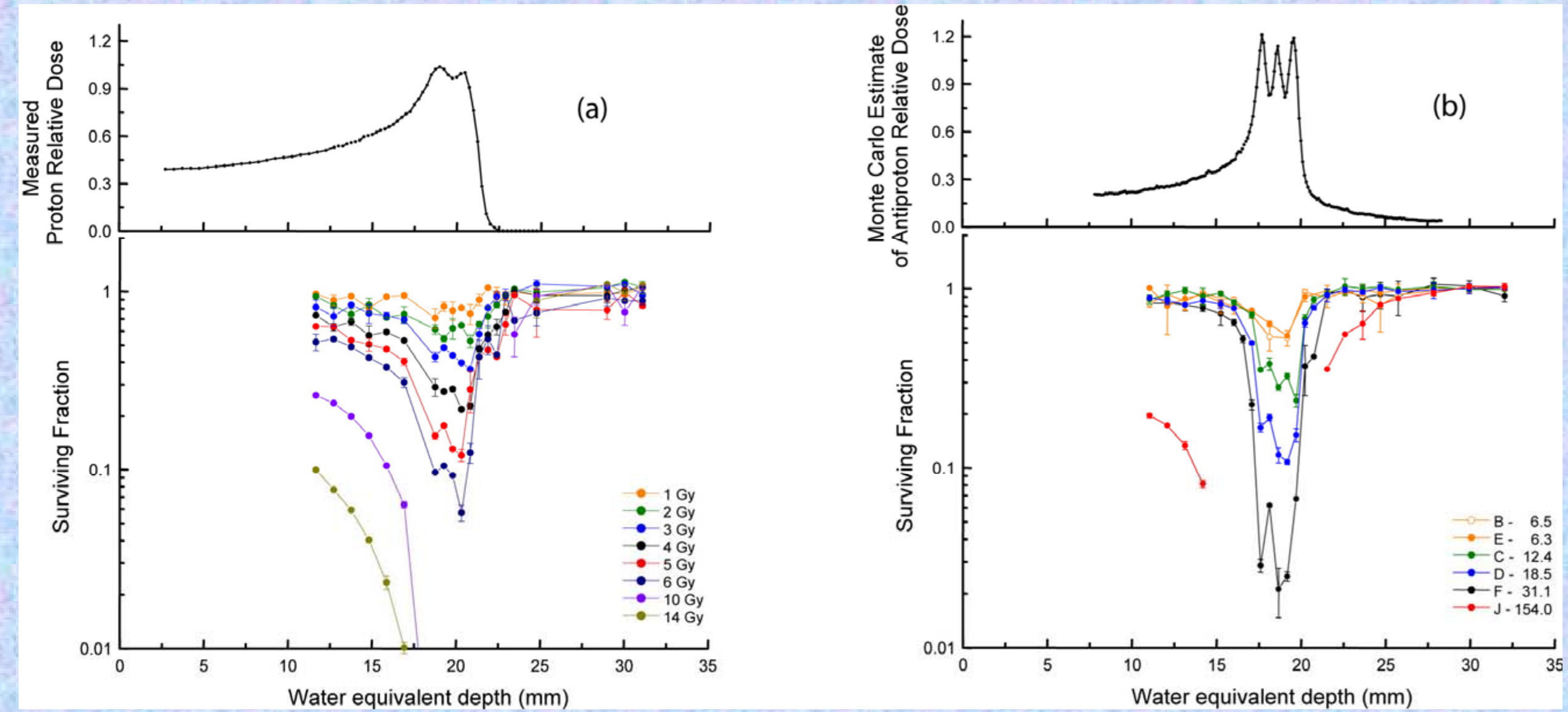


# Antiproton-Cell Experiment ACE (AD-4)



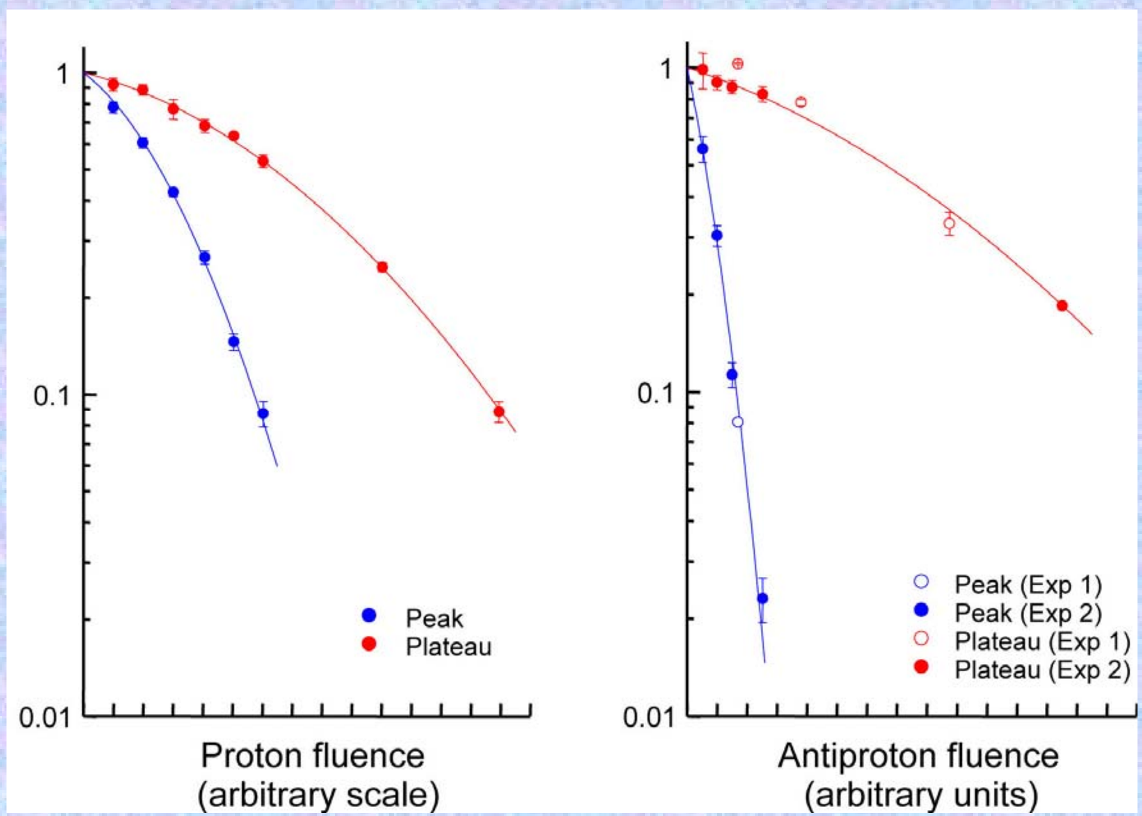
# Antiproton-Cell Experiment - First results

Relative biological effectiveness of antiprotons
significantly higher than protons

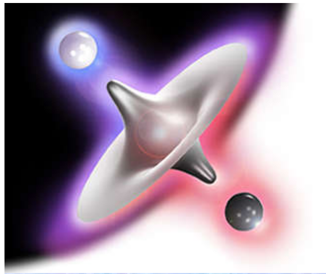


# Antiproton-Cell Experiment - First results

Same therapy effect with less radiation dose (= damage to healthy cells)




Much more work to be done, comparison with carbon ions (2005)

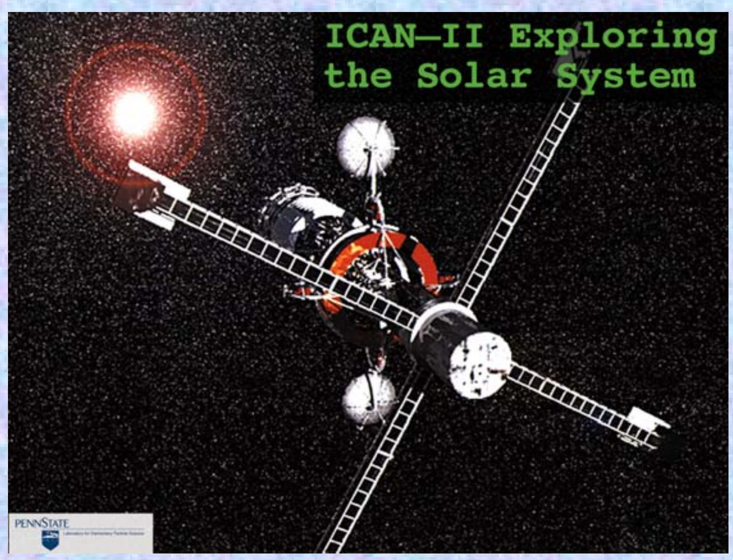


# Antimatter driven space engines?

AKTUELL

**E.T., wir kommen!**

**In Genf wurde Wunder-Energie entdeckt**




PROBLEMS:

1) Extremely low production rates (ng/yr)
2) Extremely low efficiency (~$10^{-8}$)
3) Difficult storage (space charge) of antiprotons
4) More difficulties for antihydrogen

Until somebody finds a clever way around these problems, all this will stay fiction:

**The End.**