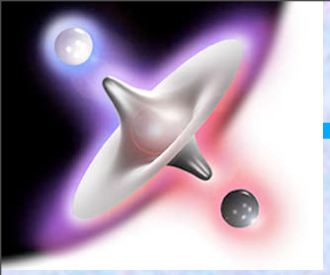
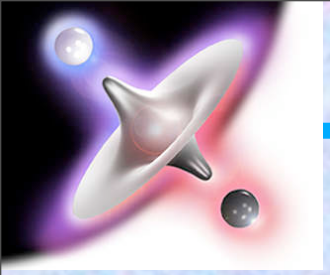
Antimatter 2 - The Sequel

Rolf Landua
CERN



LATEST NEWS +++ LATEST NEWS



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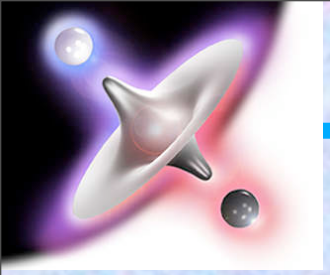

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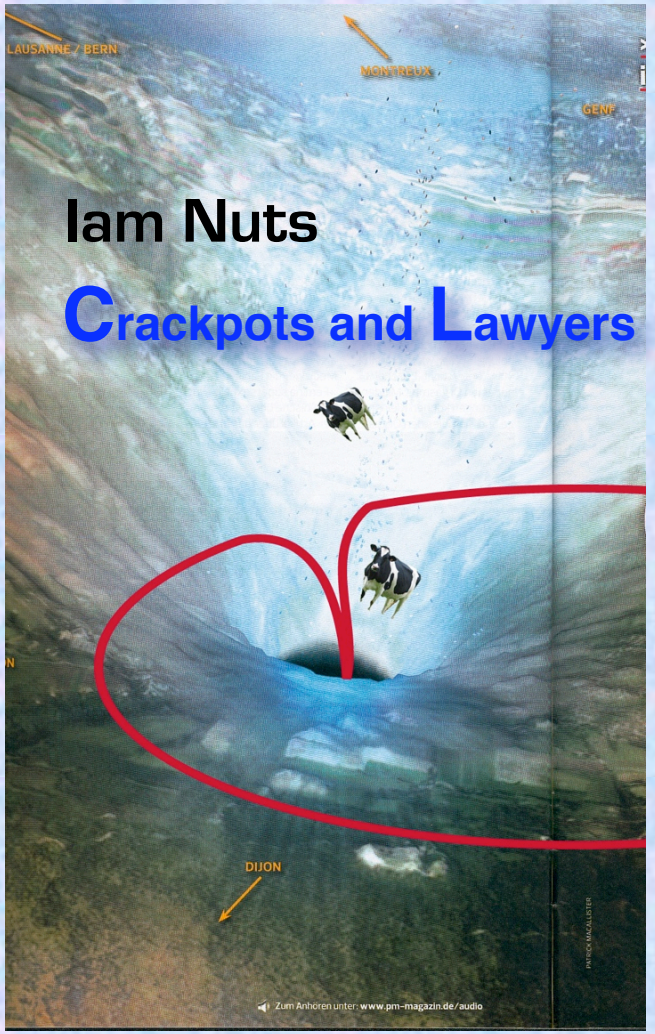

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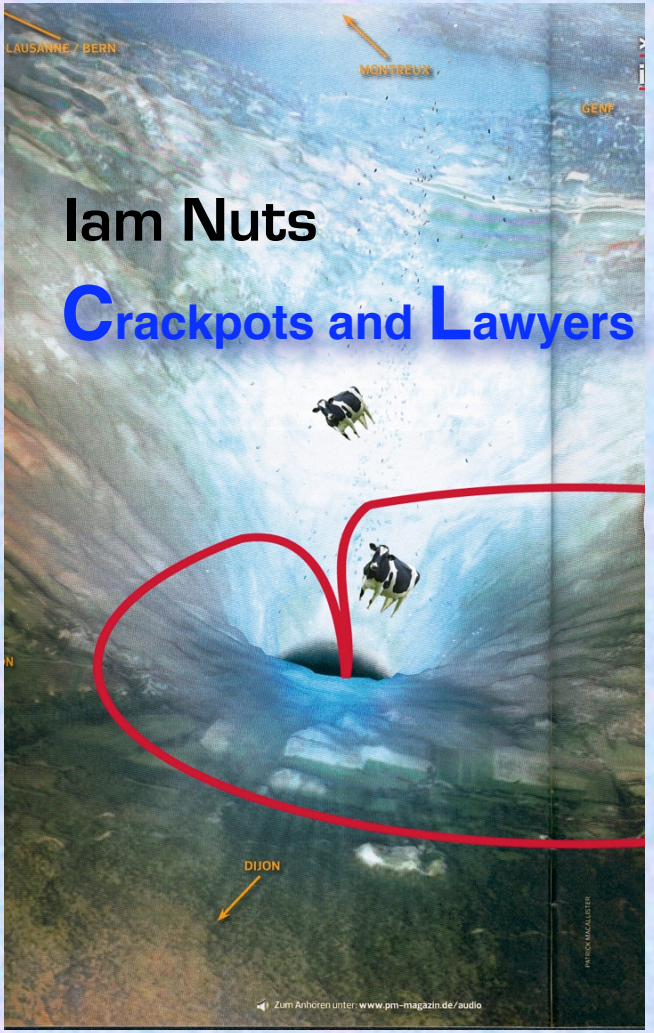

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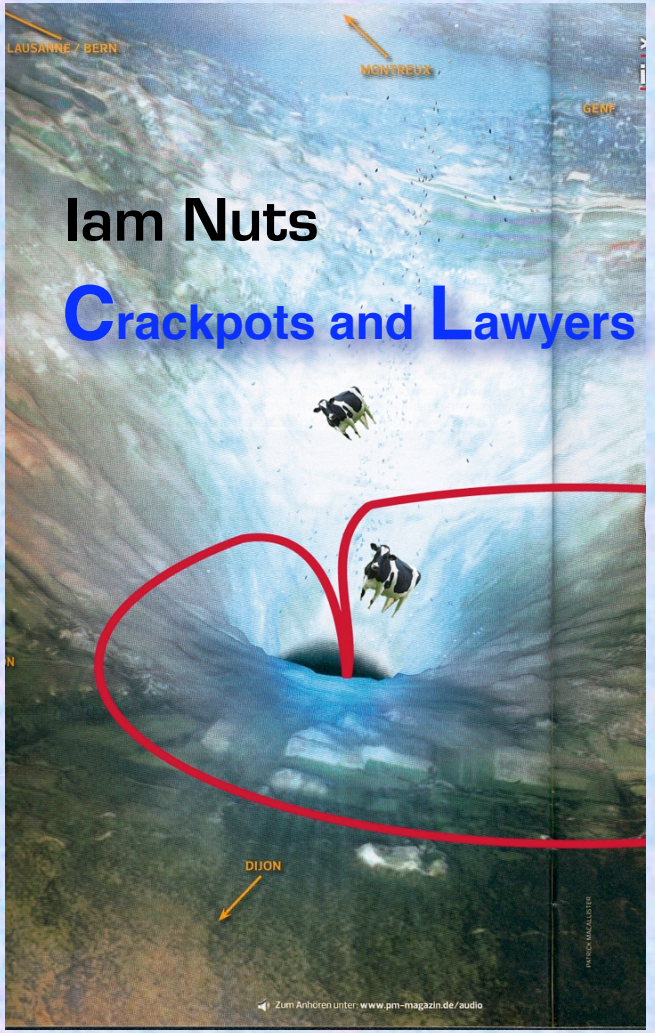

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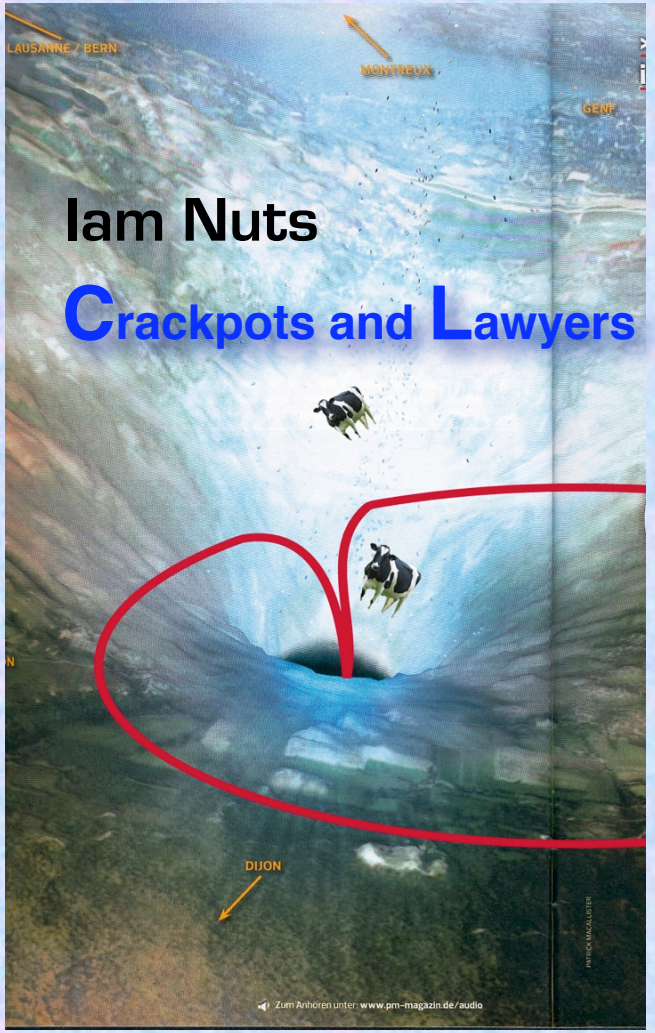

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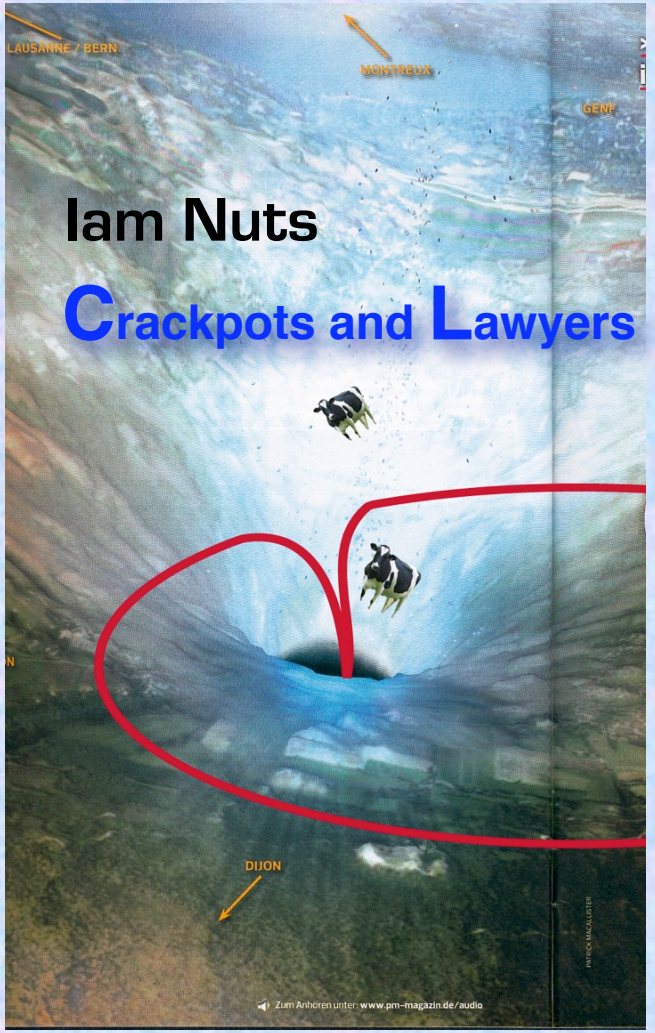

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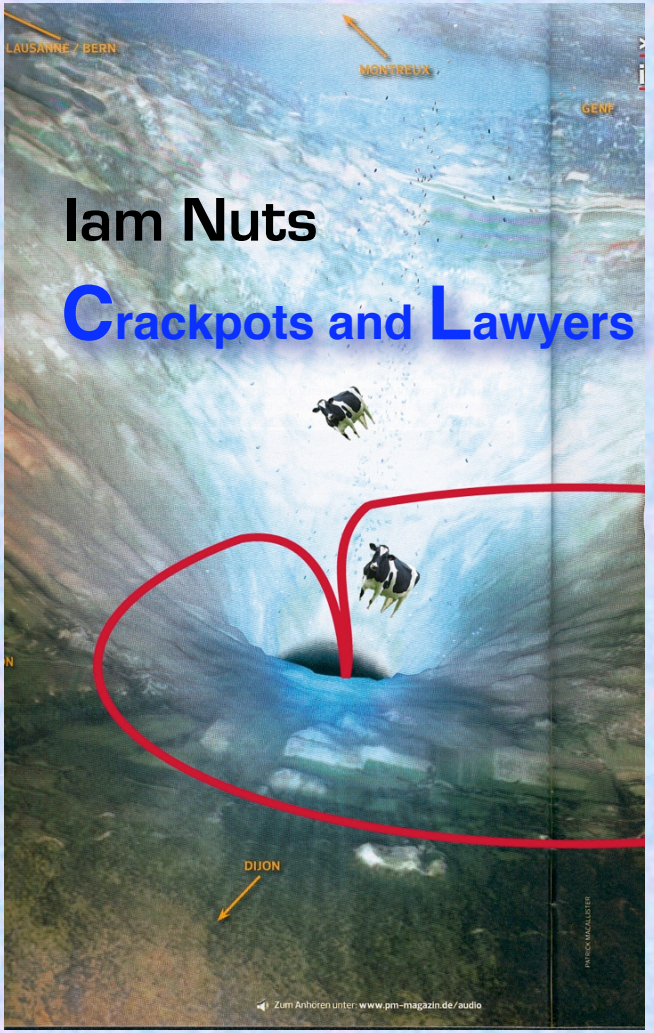

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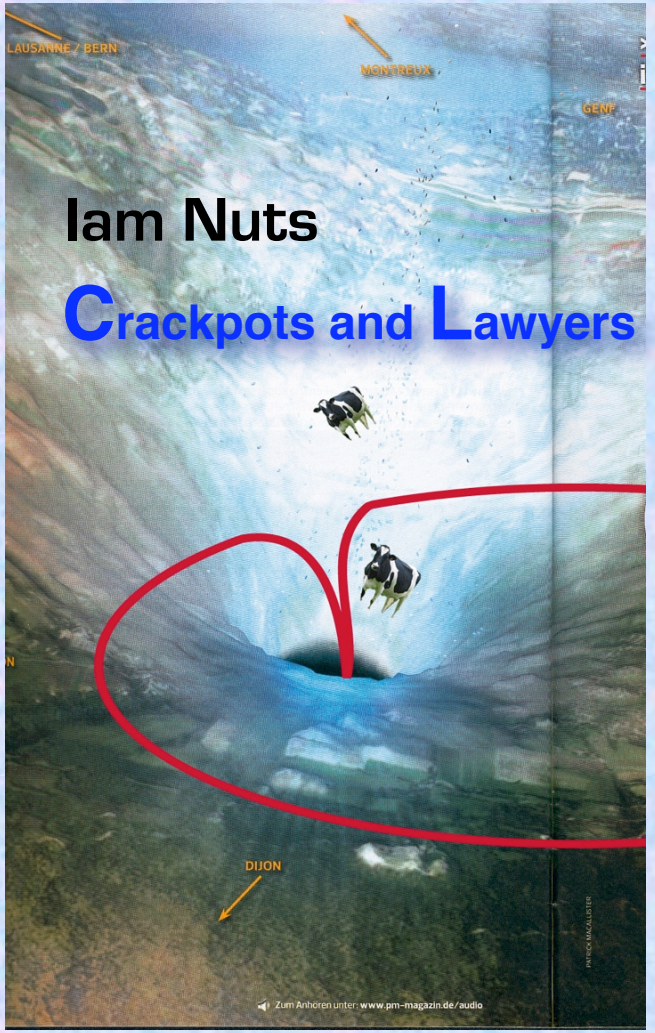

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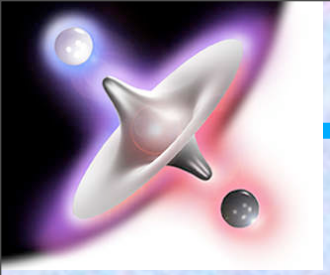
How will it end?



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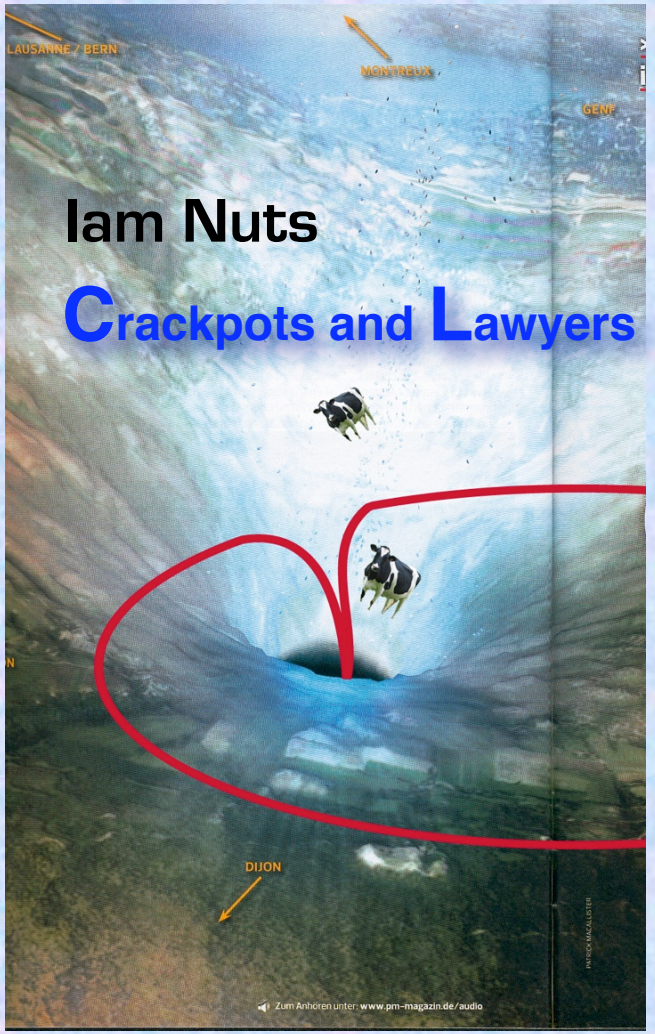

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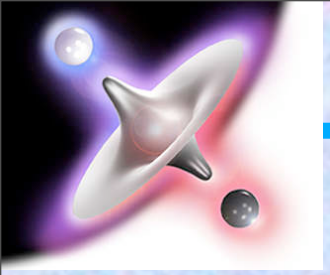
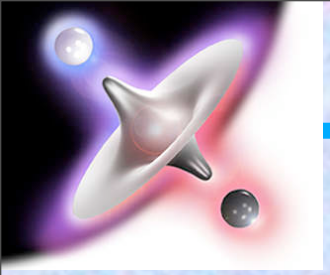
Too absurd??

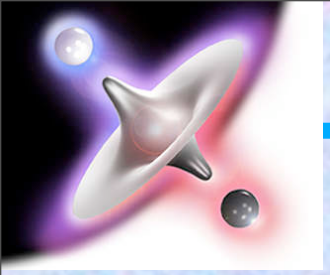
cern.ch/lsag/LSAG-Report.pdf



Overview Lecture 2



Trapping antiprotons

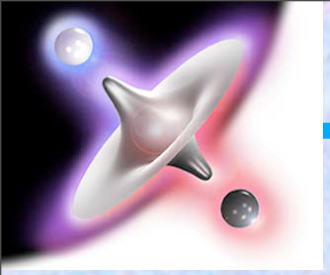


Overview Lecture 2

Trapping antiprotons

Antihydrogen

ATHENA and ATRAP
Making antihydrogen
Future developments



Overview Lecture 2

Trapping antiprotons

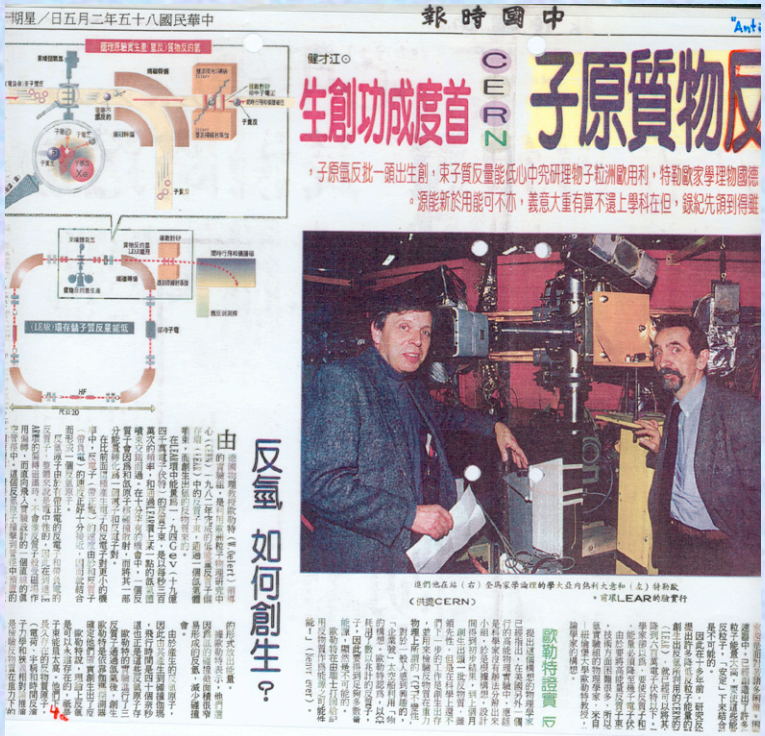
Antihydrogen

- ATHENA and ATRAP
- Making antihydrogen
- Future developments

Applications

- PET
- Antiproton therapy?
- Rocket propulsion??

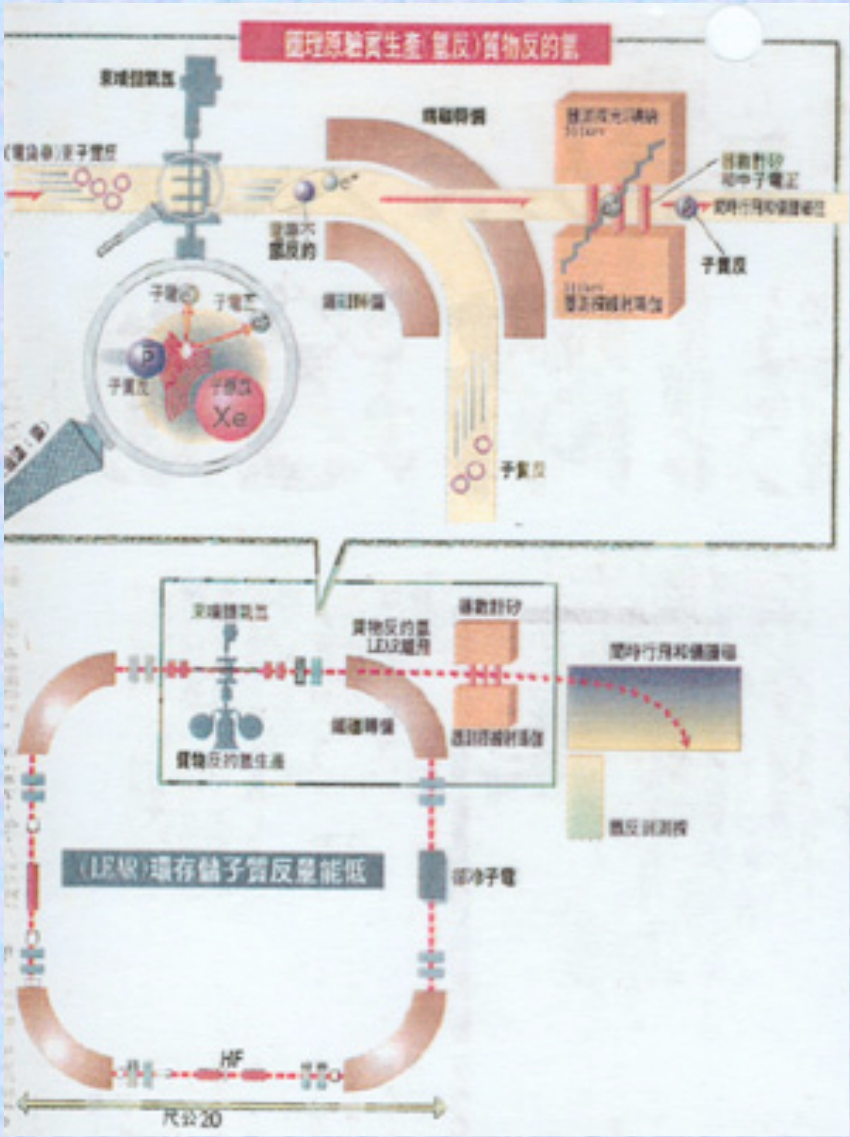
The first nine antihydrogen atoms at CERN (1996)



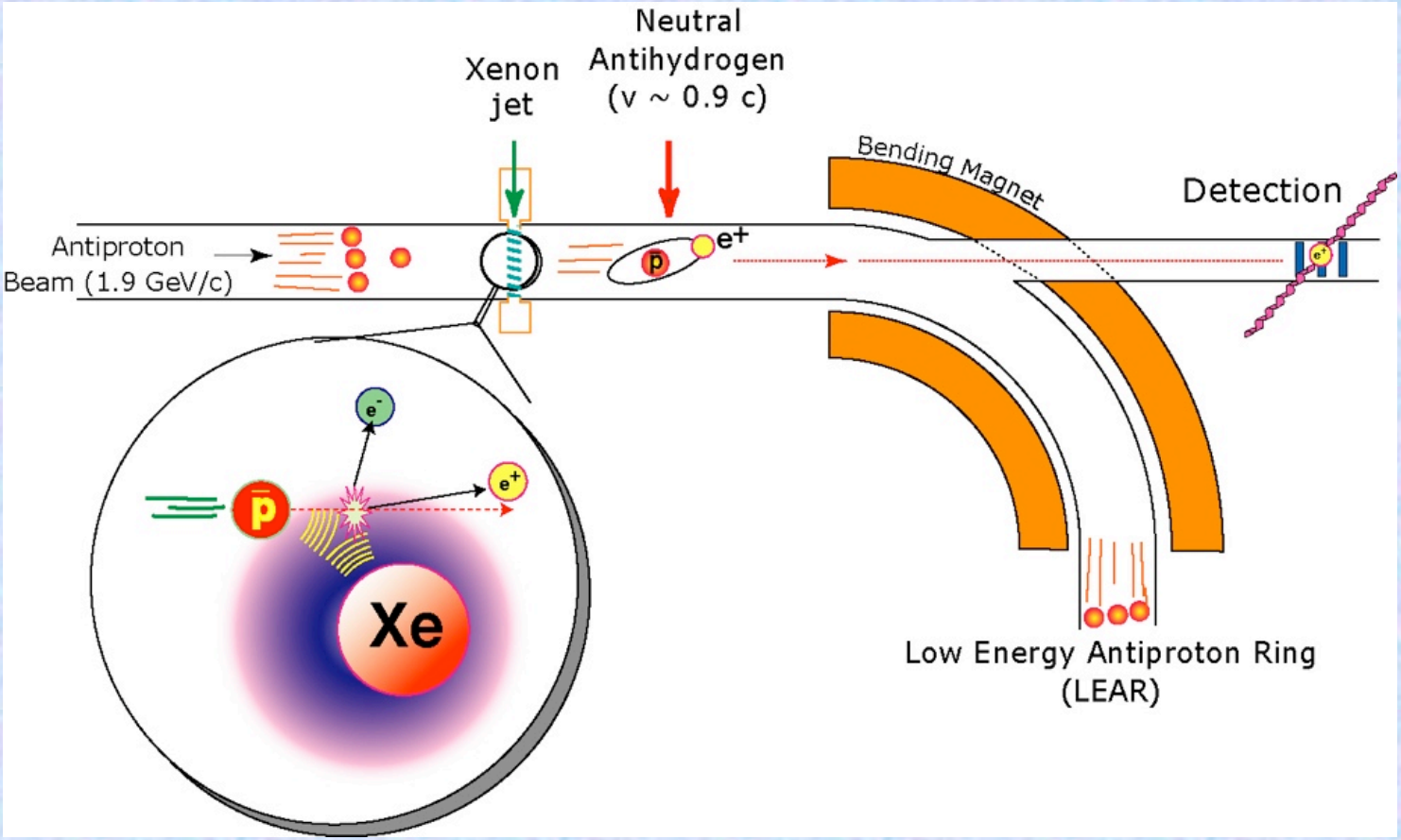
中時國中

生創功成度首 CERN 子原質物反

反氫 如何創生？



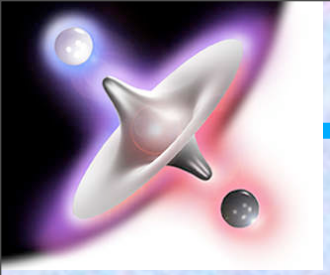
How were the 9 antihydrogen atoms made at LEAR ?



Annihilation of 9 anti-atoms ~ 2 nJ ~ Lifting a mosquito by 1 μm

Press reactions (of course)

"Liberation" (France)



Two questions to keep you awake

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1. With present techniques, what would be the price and delivery time for an 0.5 g anti-hydrogen bomb?

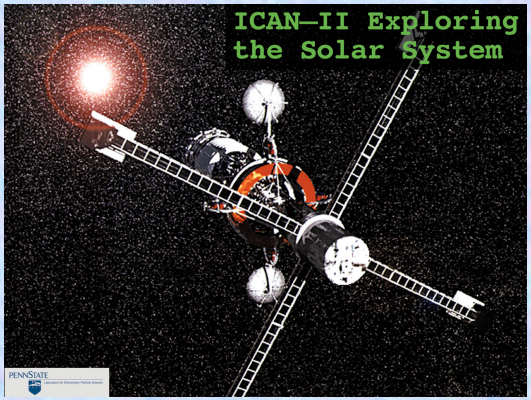
The Vatican ?

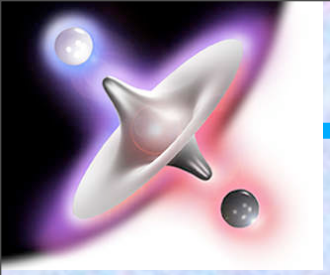
Two questions to keep you awake

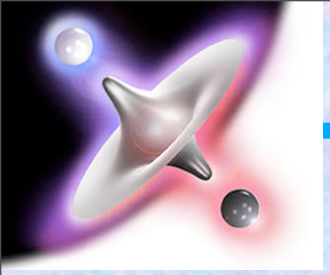
The Vatican ?

1. With present techniques, what would be the price and delivery time for an 0.5 g anti-hydrogen bomb?

2. How much antimatter propellant would you need to accelerate a 10-ton spacecraft to 95 % of the speed of light (assuming 100% efficiency)





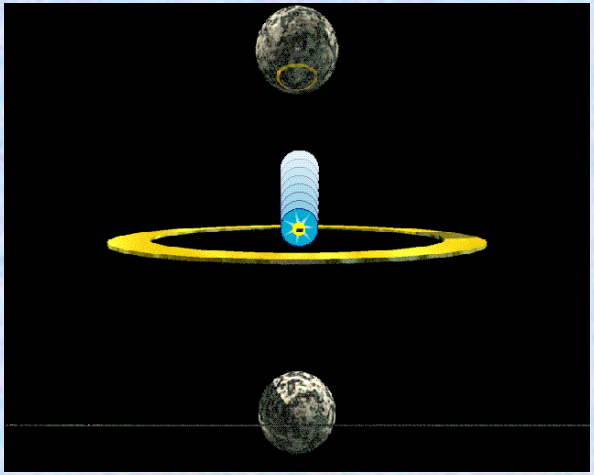


III. TRAPPING ANTIPARTICLES

RF trap ("Paul trap")

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

- / +



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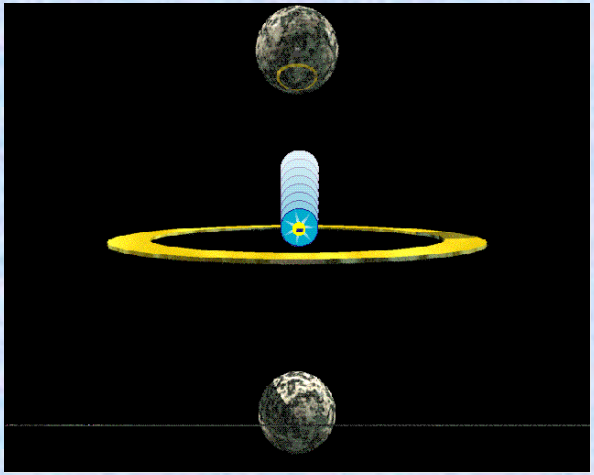
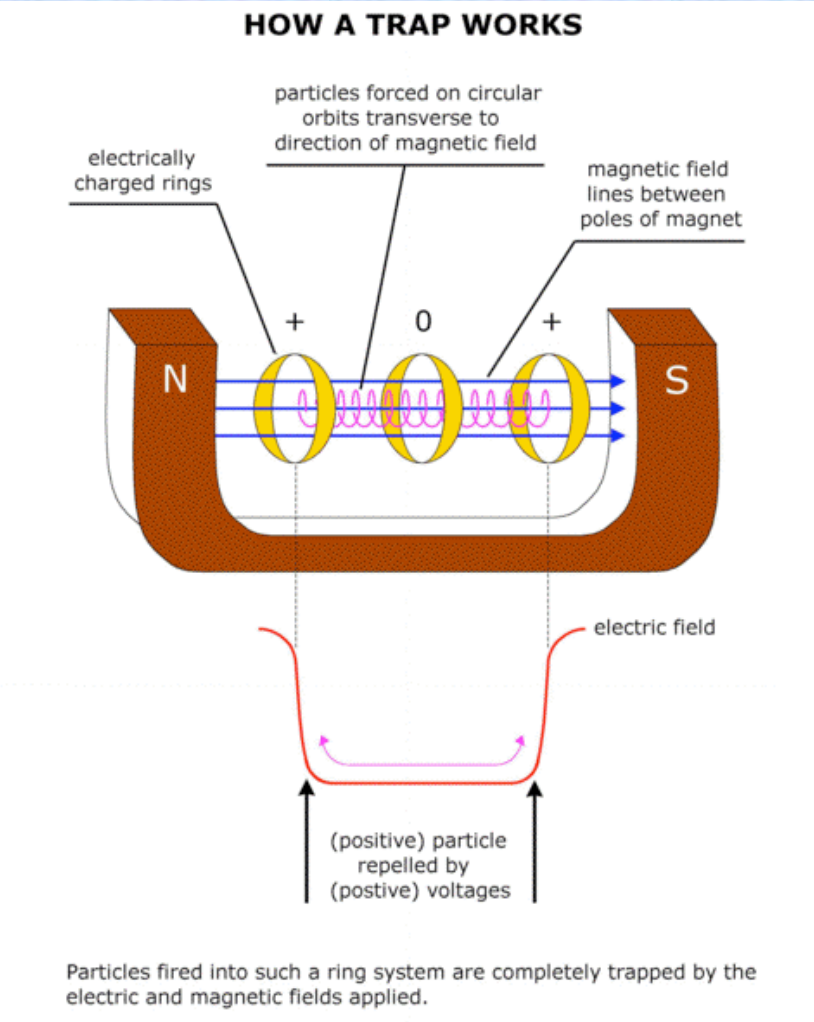


+ / -

Magnetic traps



Typical voltages:
1 - 100 V

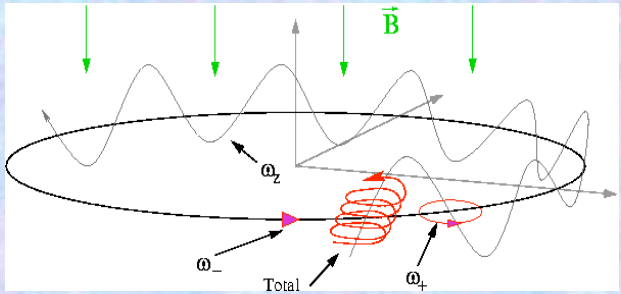
For trapping:
~ several kV

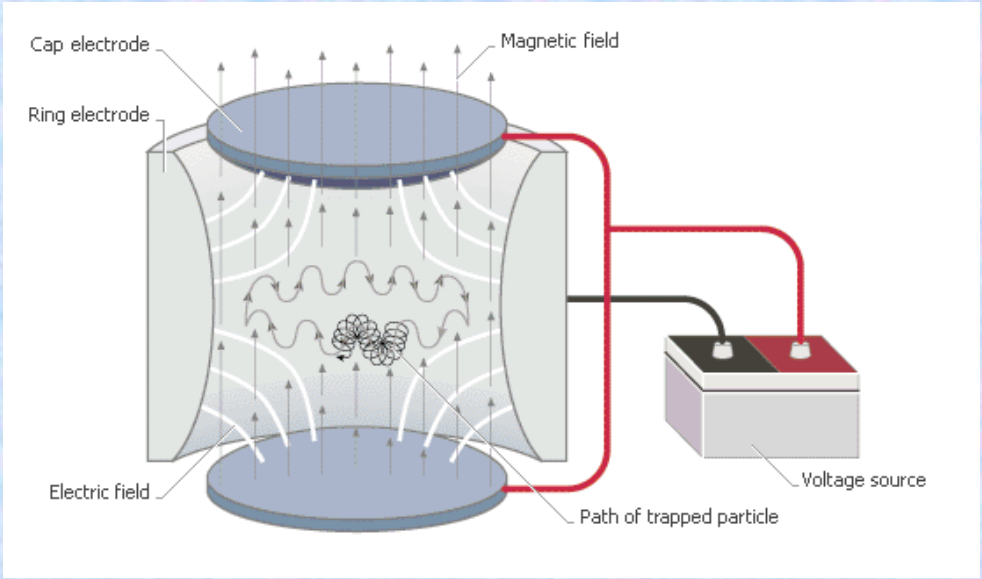
Special case: Penning trap

Electrodes with hyperbolic shape **harmonic forces: $E_r \sim r$, $E_z \sim z$**

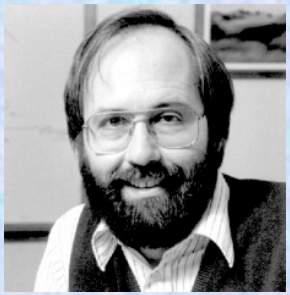
precise oscillation frequencies !

$$V(x,y,z) = U_0 \left(\frac{x^2 + y^2 - 2z^2}{2r_0^2} \right)$$





The inertial mass of antiprotons (PS 196, LEAR)

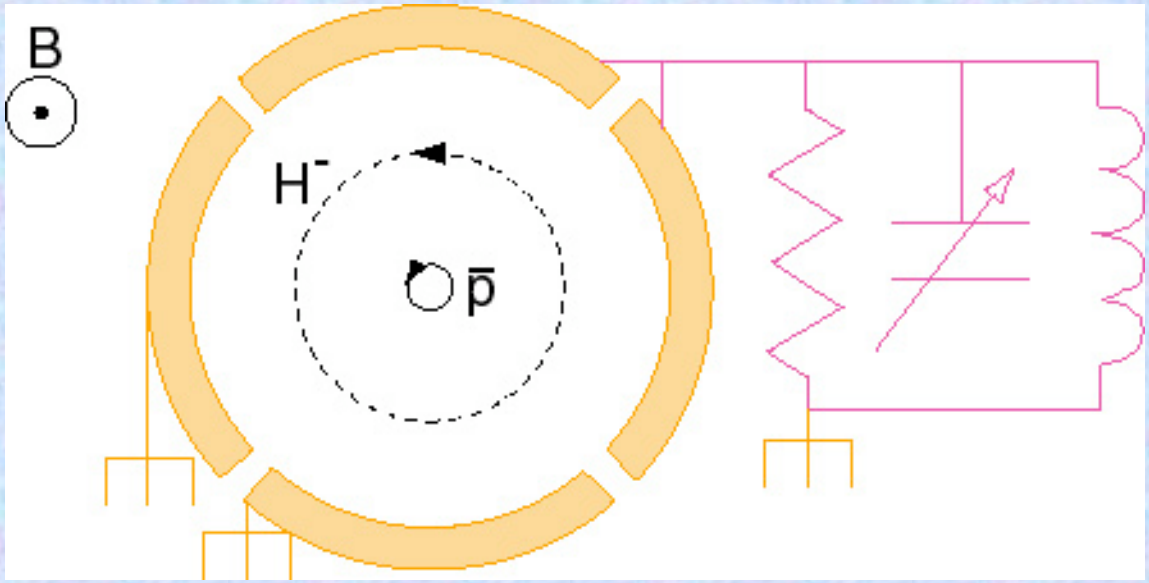


G. Gabrielse

Moving antiprotons **induce currents** in trap wall

The 'sound of antiprotons' - at 89.3 MHz (cyclotron frequency)

Compare frequency of antiproton and negative hydrogen ions



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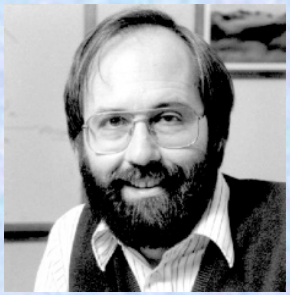

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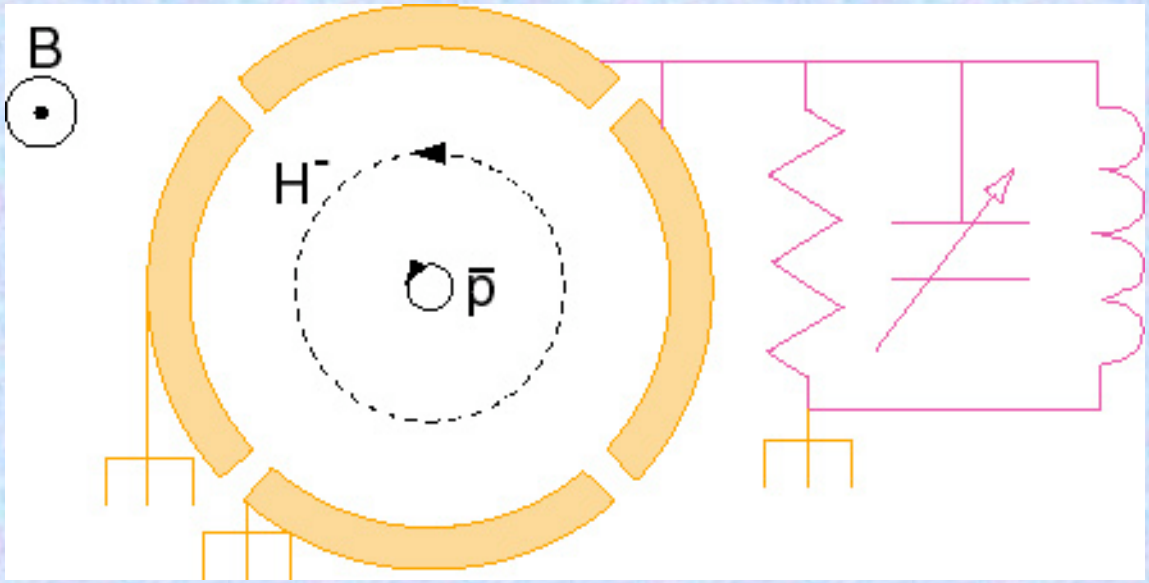


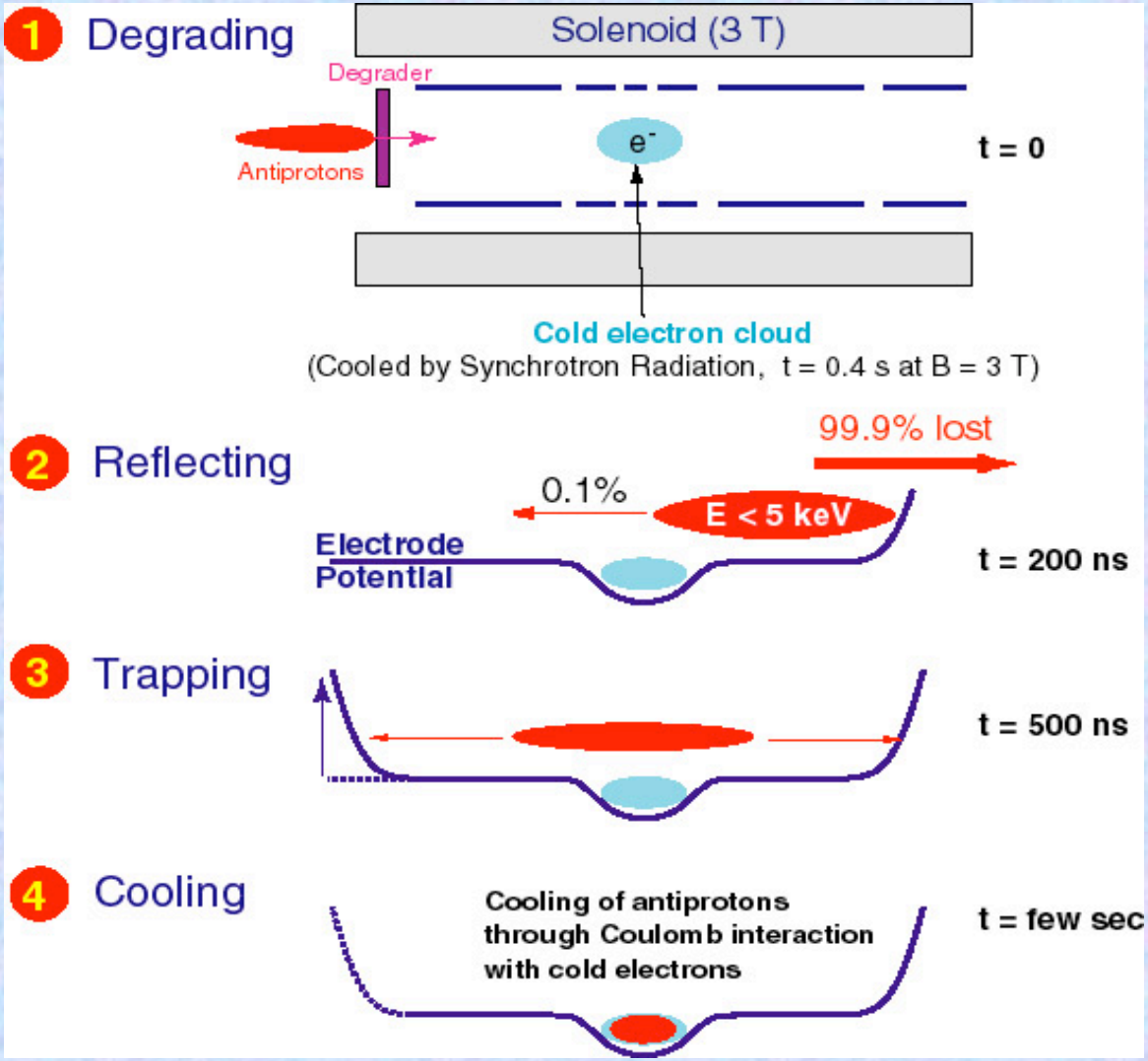
Agreement to a precision of 9×10^{-11}

Extraction from AD to experiments: 5.3 MeV (~ 0.1 c), $3 \cdot 10^7$

Reminder: Antiproton Production

Extraction from AD to experiments: 5.3 MeV (~ 0.1 c), $3 \cdot 10^7$

Trapping antiprotons



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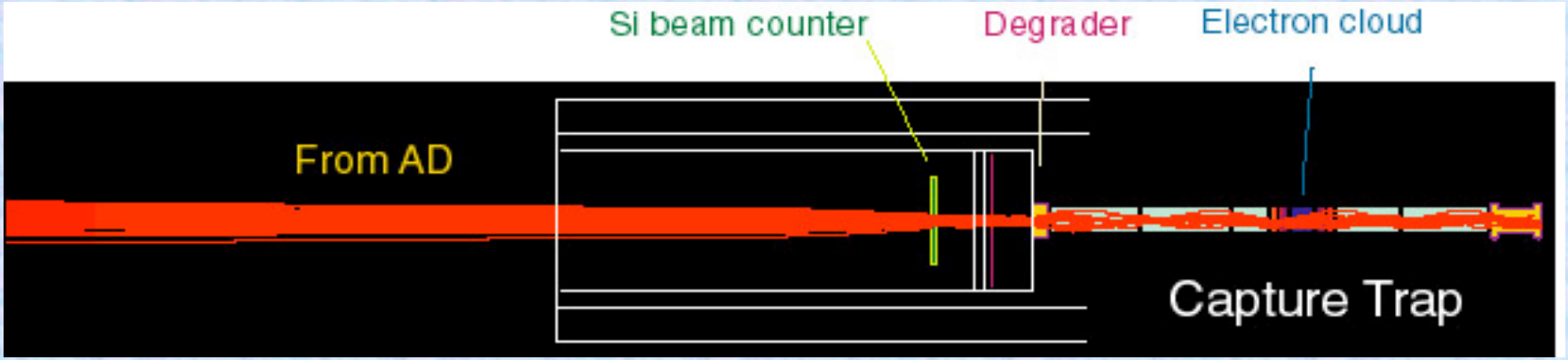
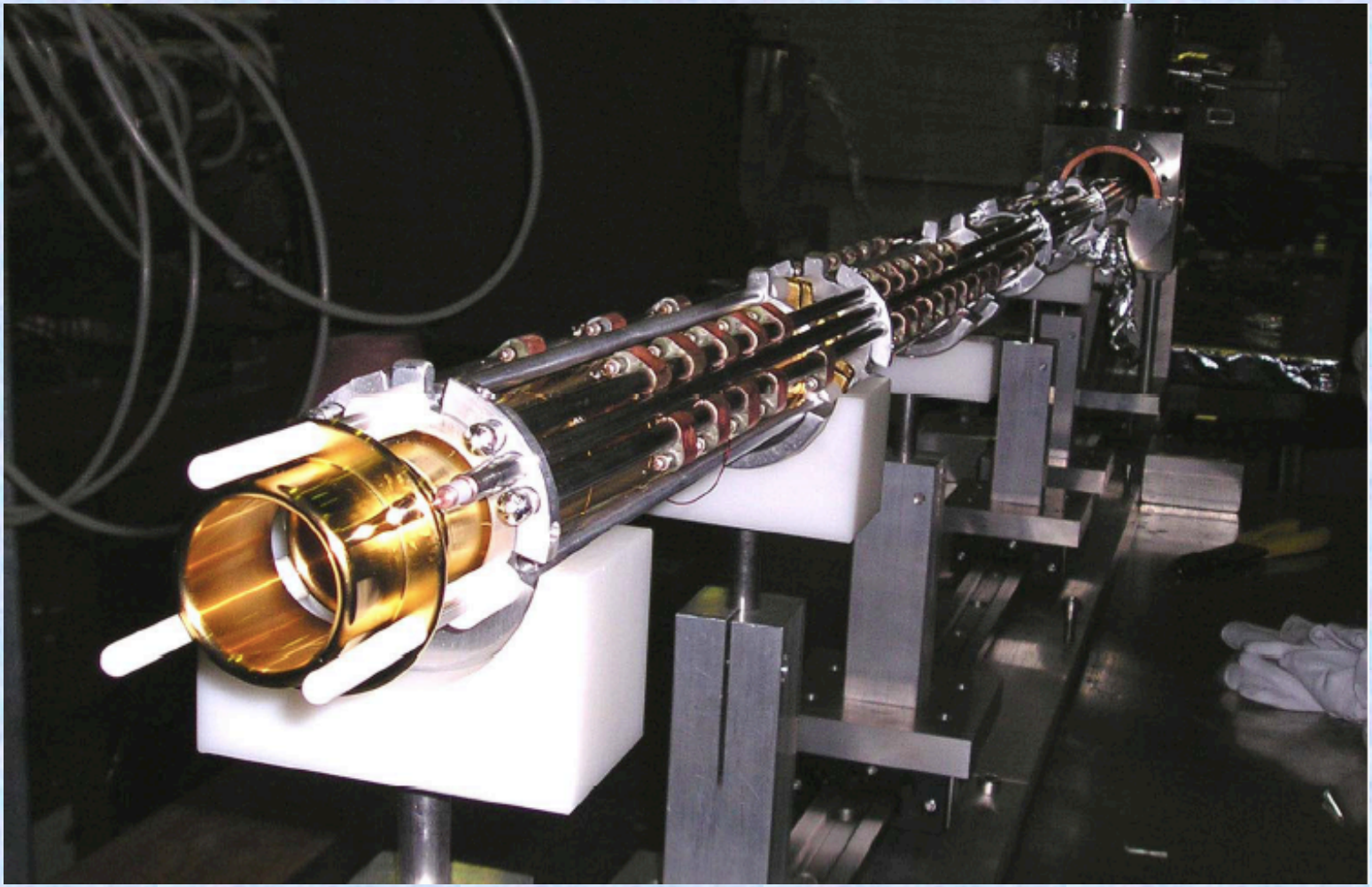
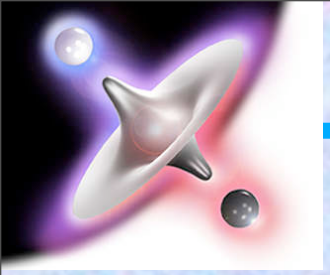


Trap for antiproton capture and storage





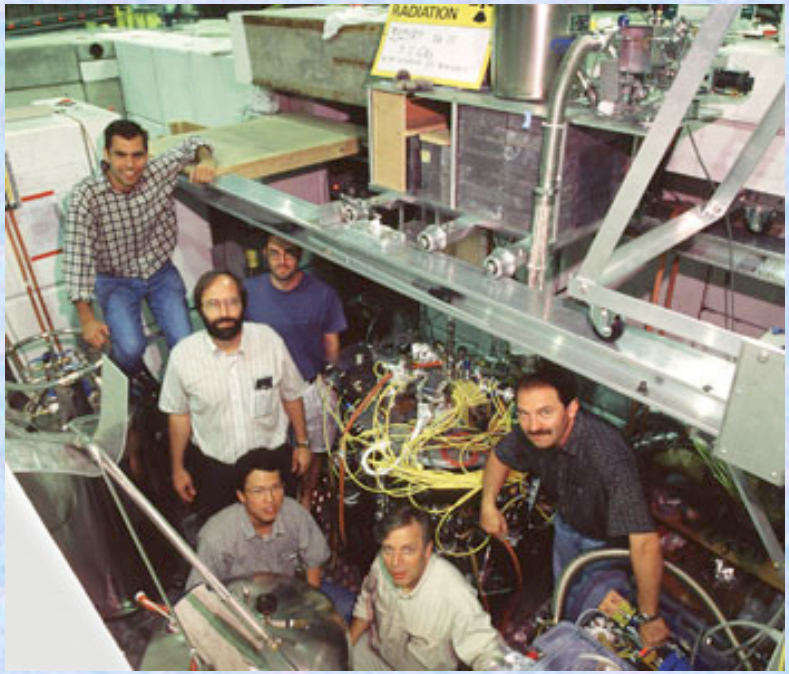
IV. ANTIHYDROGEN

The race for cold antihydrogen

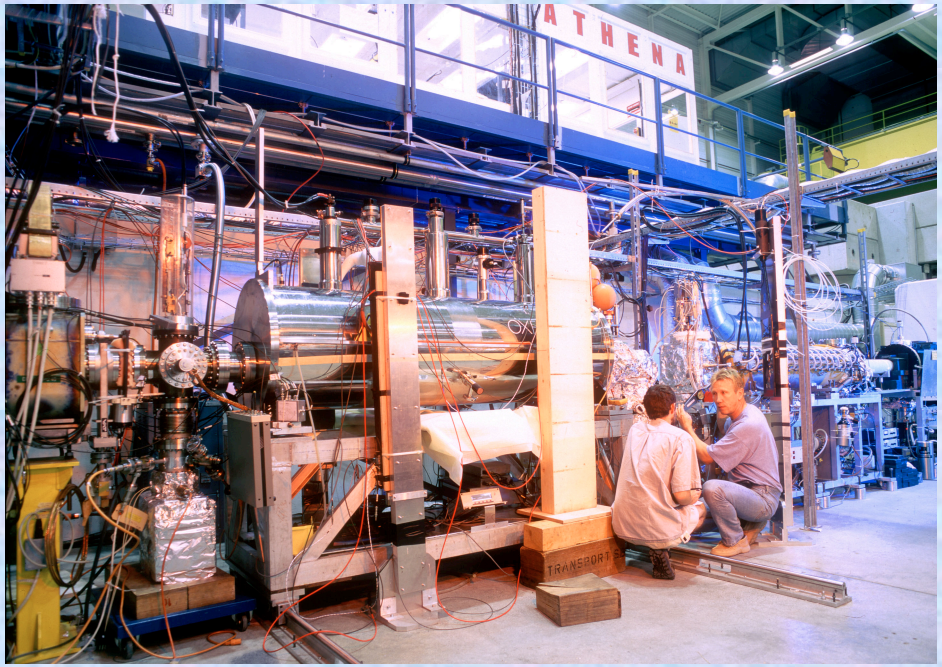
ATHENA and ATRAP - Experiments (Start 2000)

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

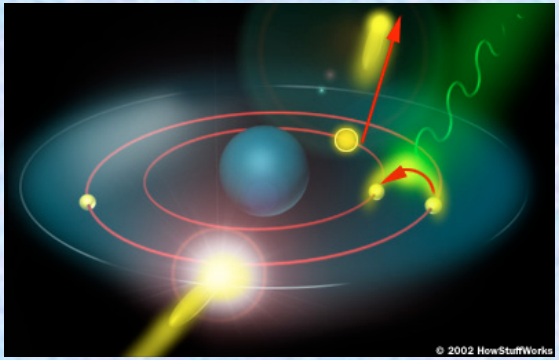
ATRAP

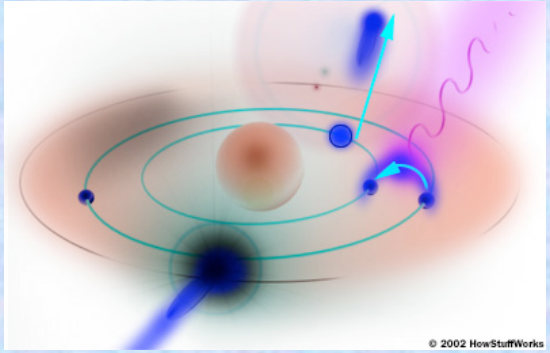


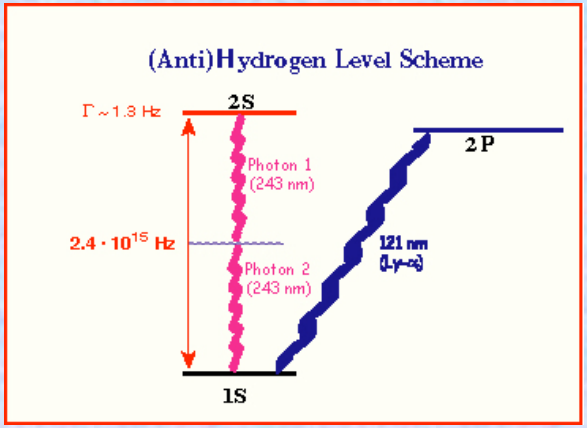
ATHENA



Antihydrogen = Hydrogen ??







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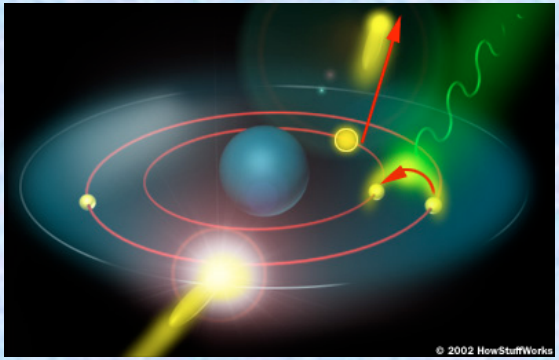
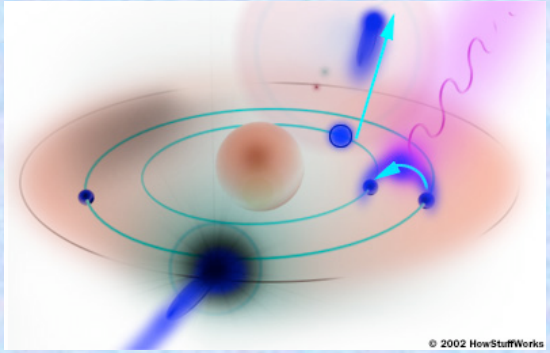
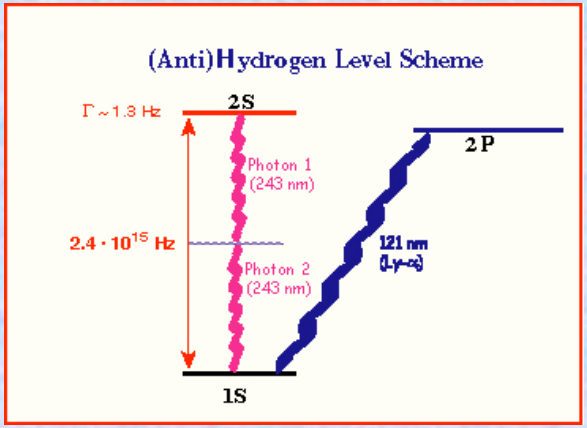
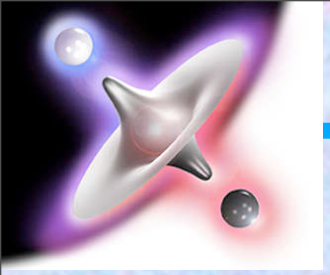




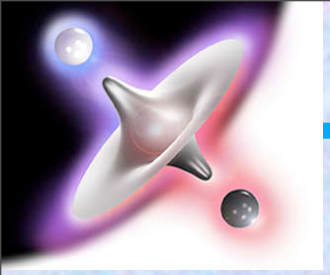


2S level is metastable (T ~ 120 ms)

→ 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



Antihydrogen milestones

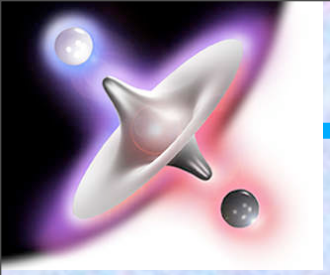


Antihydrogen milestones

AD

p- Production (GeV)

Deceleration (MeV)



Antihydrogen milestones

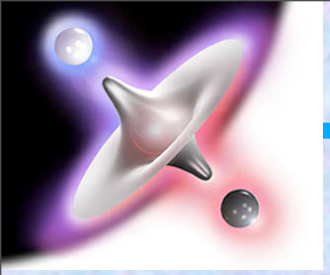
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)



Antihydrogen milestones

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

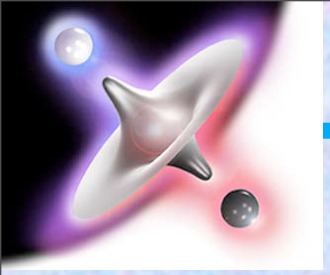
Cooling (meV)

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



Antihydrogen milestones

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)

10^4 p^-

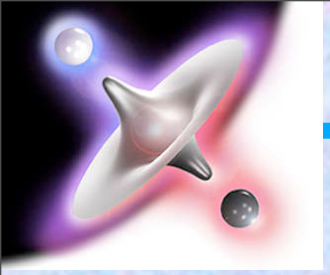
10^8 e^+

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



Antihydrogen milestones

p^- and e^+ in mixing trap (cooling)

Antihydrogen formation

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)

10^4 p^-

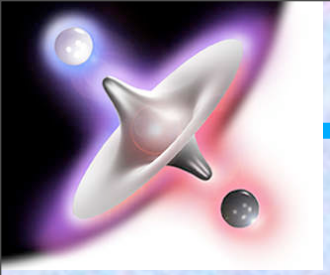
10^8 e^+

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



Antihydrogen milestones

p^- and e^+ in mixing trap (cooling)

Antihydrogen formation

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)

10^4 p^-

10^8 e^+

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

Detection of annihilation

Overview - ATHENA / AD-1

Antiproton capture trap

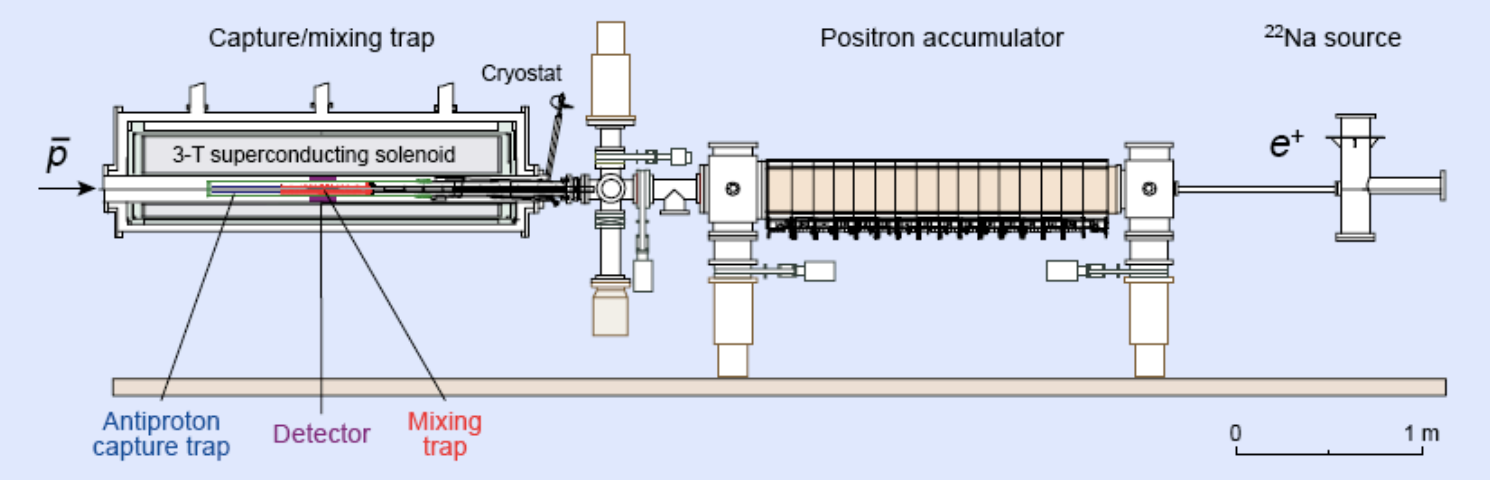
- Deceleration and capture of antiprotons
- Penning trap in 3-T field at 15 K
- Cooling and accumulation in e^- plasma

^{22}Na source

- Positron production via $^{22}Na(\beta^+)^{22}Ne$ at 5.5 K

Positron accumulator

- Penning trap in 0.14-T field at 300 K



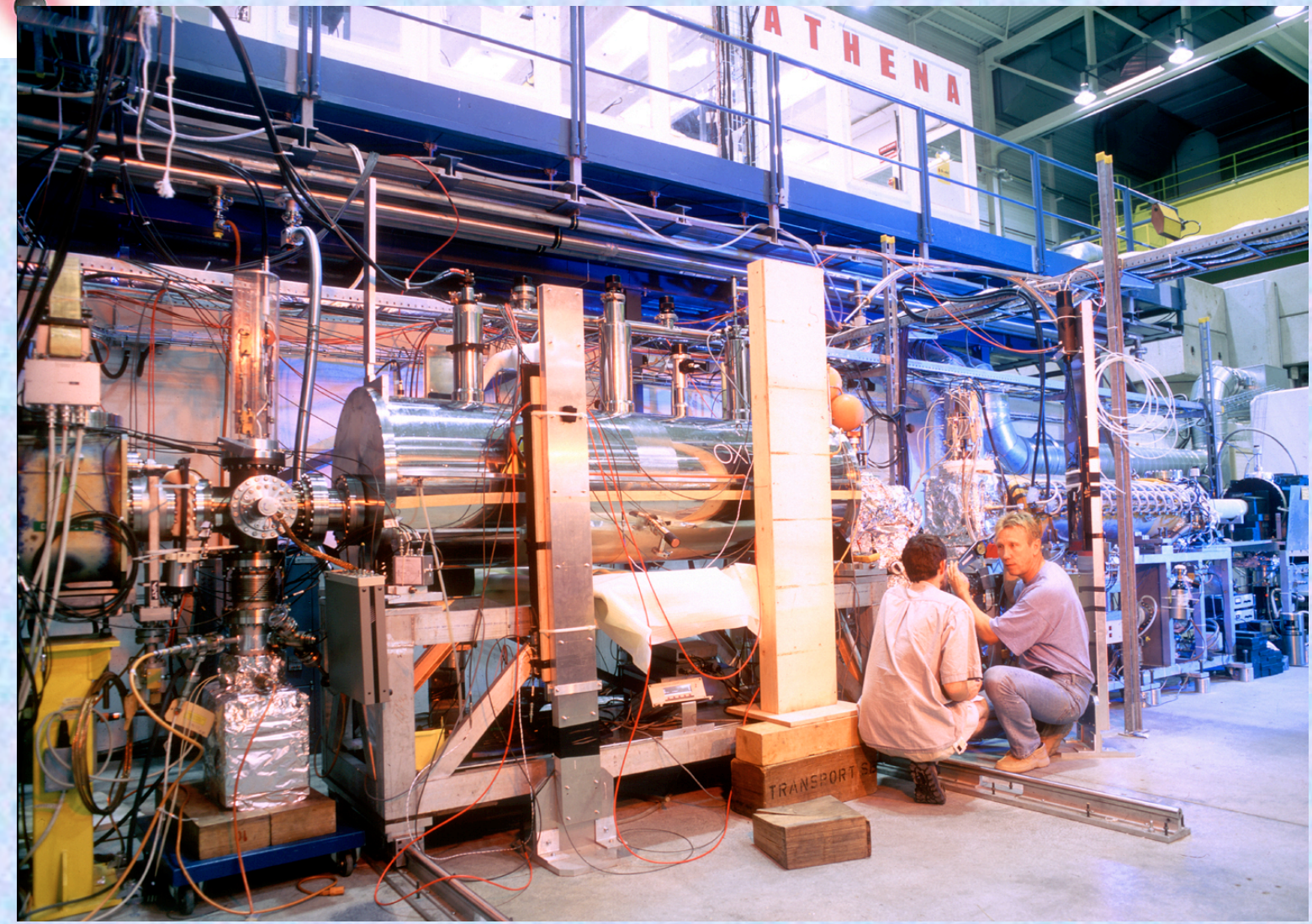
Mixing trap

- Antihydrogen production
- Nested Penning trap in 3-T field at 15 K

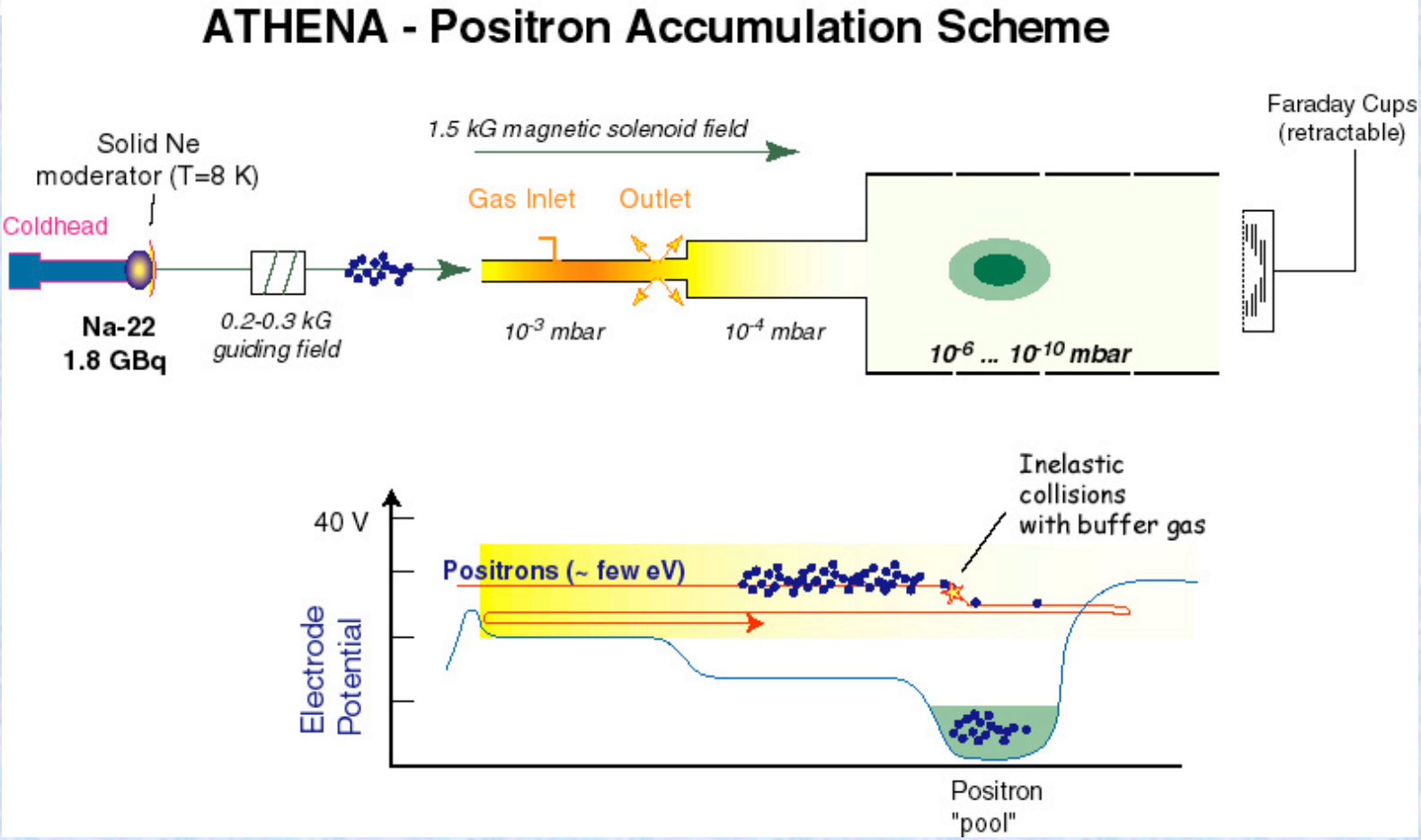
Detector

[M. Amoretti *et al.*, NIM A **518** (2004) 679]

ATHENA Experiment



Positron Accumulation using Buffer Gas



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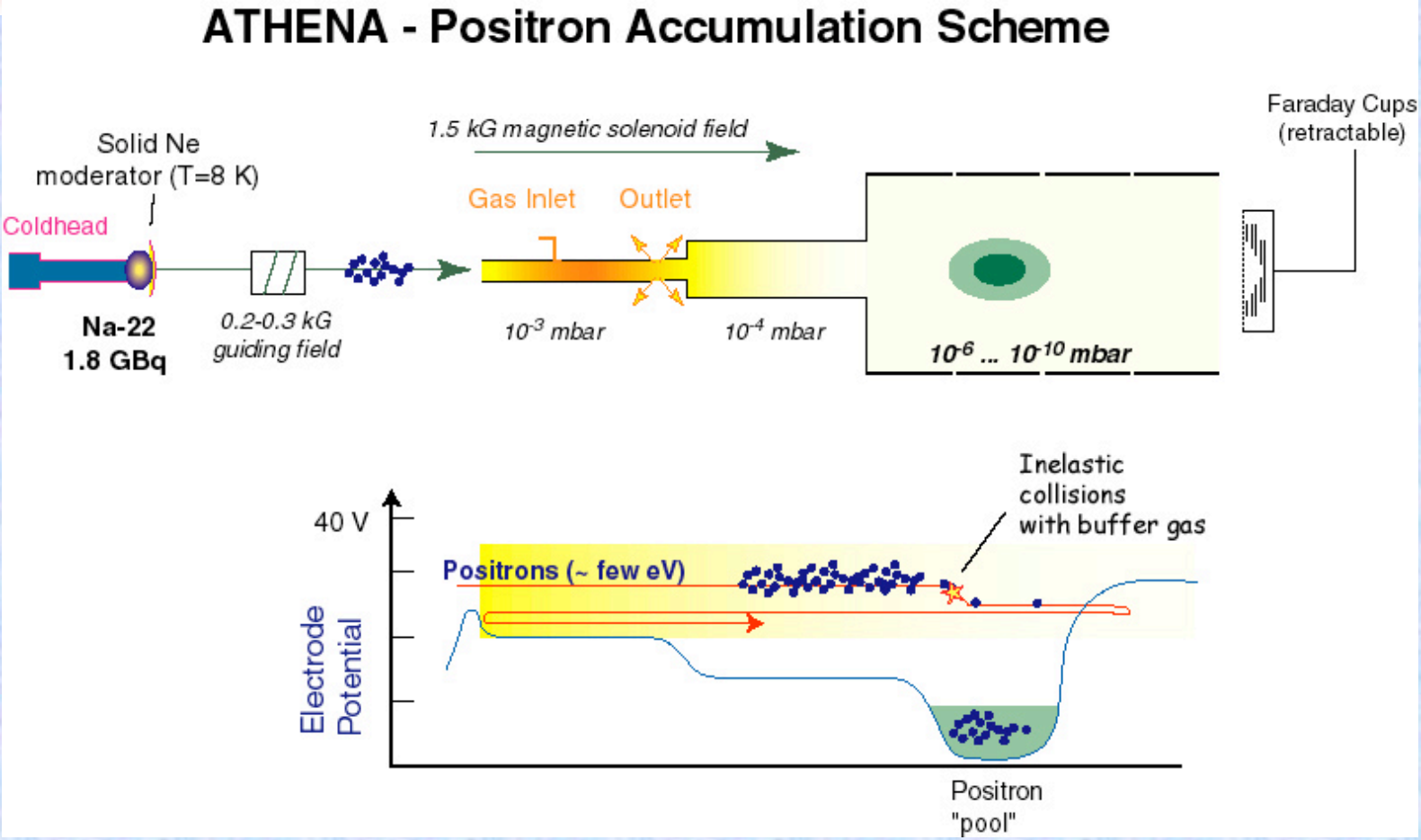
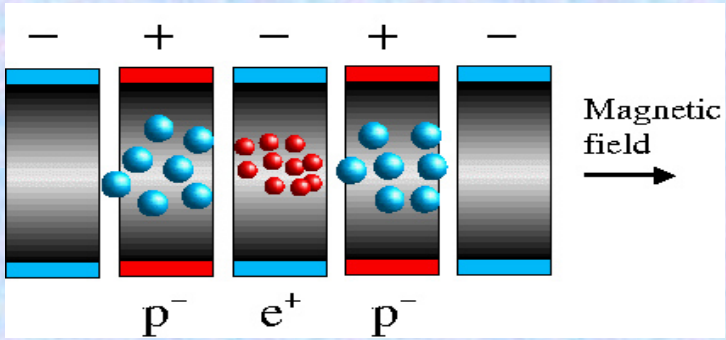
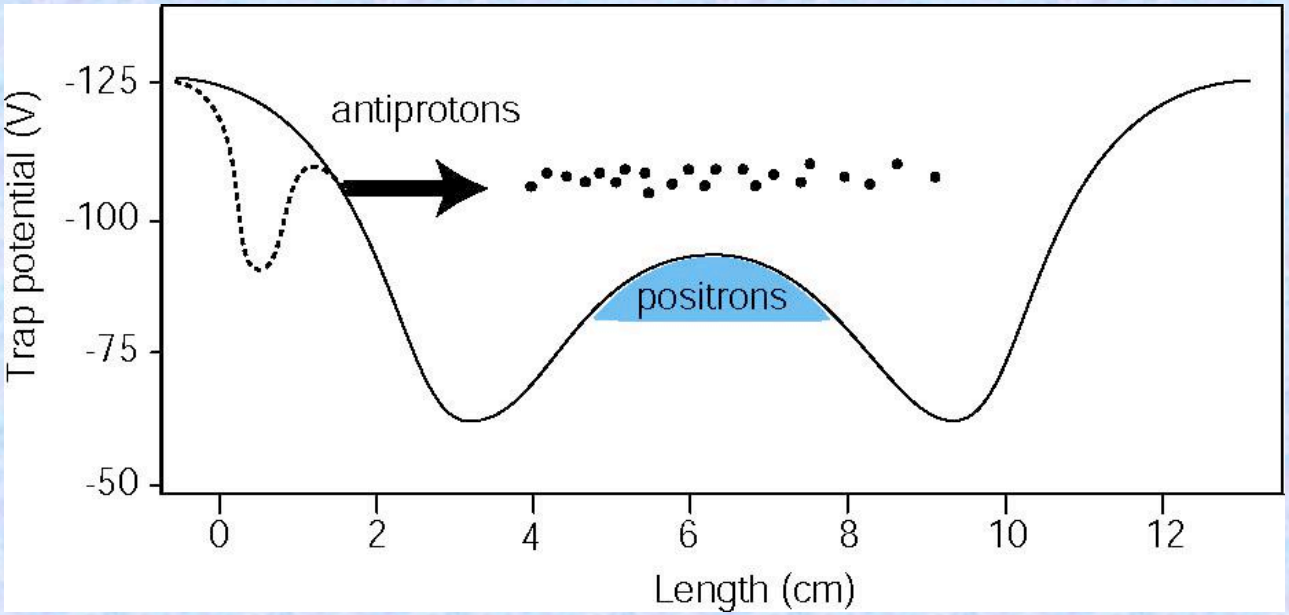


100 million positrons accumulated in 2 min

Recombination





*D.S. Hall, G. Gabrielse, Phys. Rev. Lett. **77**, 1962 (1996)

Antihydrogen Detection

Charged particles

2 layers of Si microstrip detectors

511 keV gammas

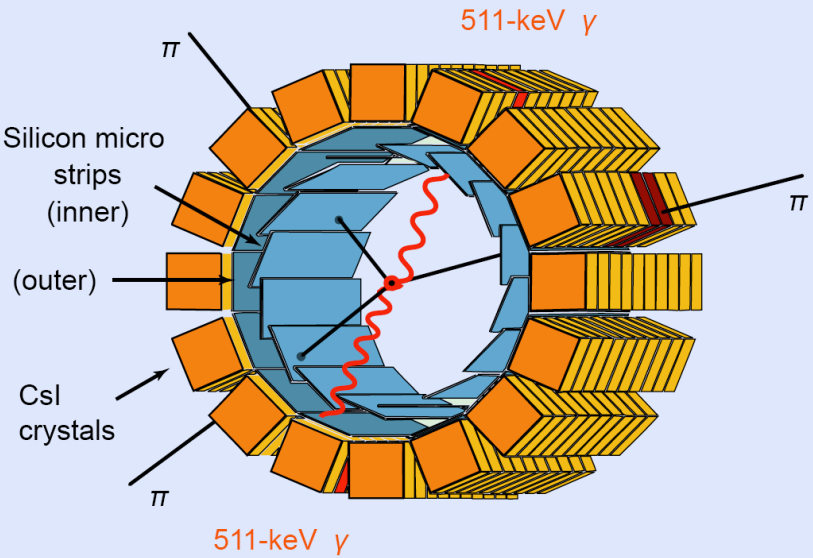
192 CsI crystals

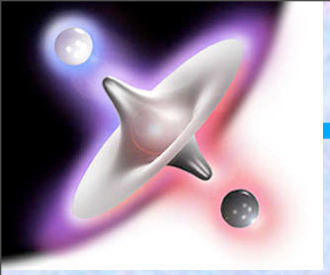
Inner radius 4 cm, thickness ~ 3 cm

70% solid angle coverage

Operates at 3 Tesla, 140 Kelvin

(C. Regenfus et al., NIM **A501**, 65 (2003))





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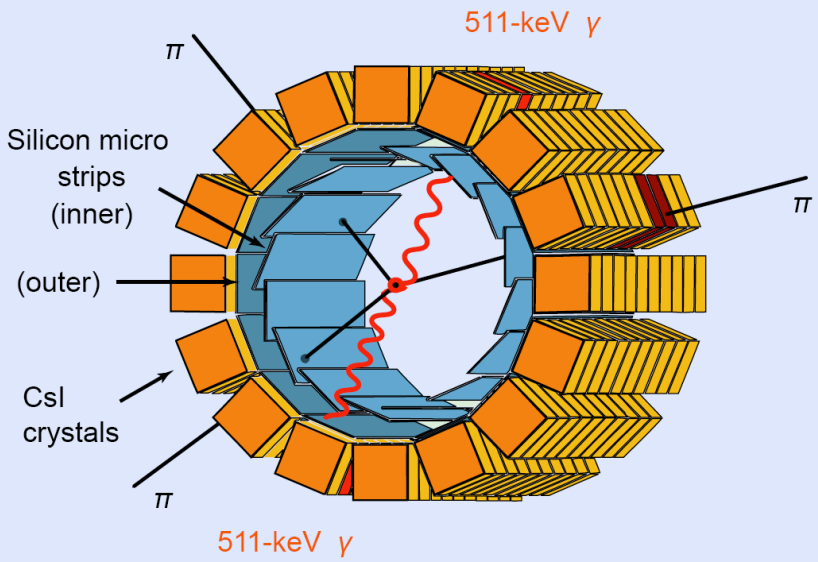
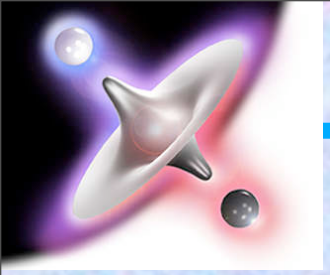


Event analysis:

1. Reconstruct vertex from tracks of charged particles
2. Identify pairs of 511 keV γ-rays in time coincidence
3. Measure opening angle between the two γ -rays



Antihydrogen - The Movie

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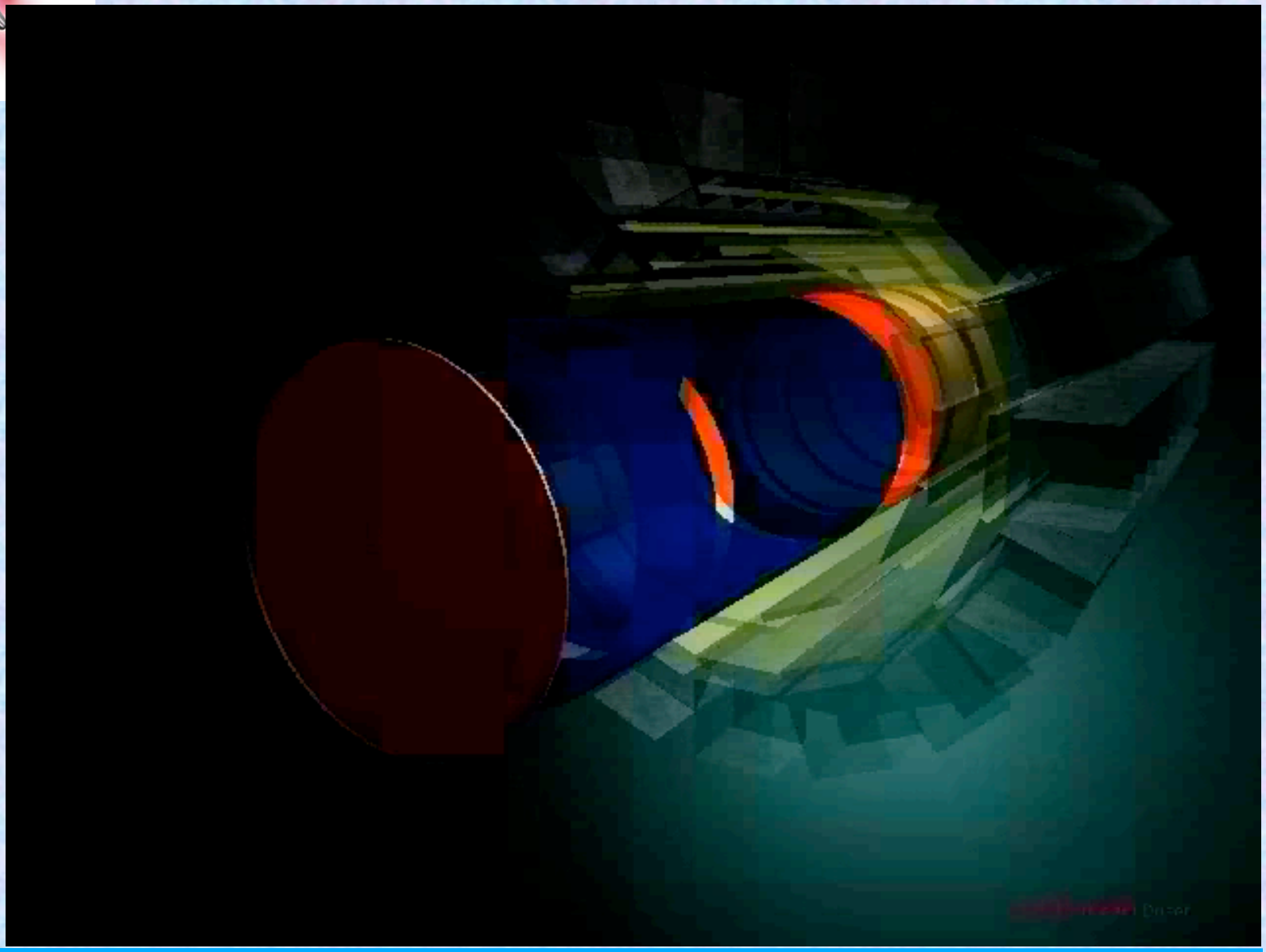

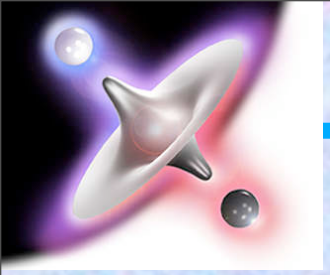

Antihydrogen Detector

Antihydrogen Detector

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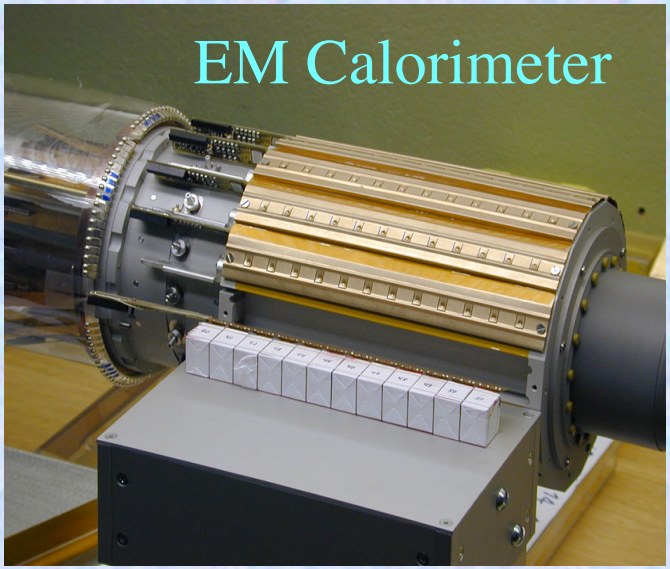

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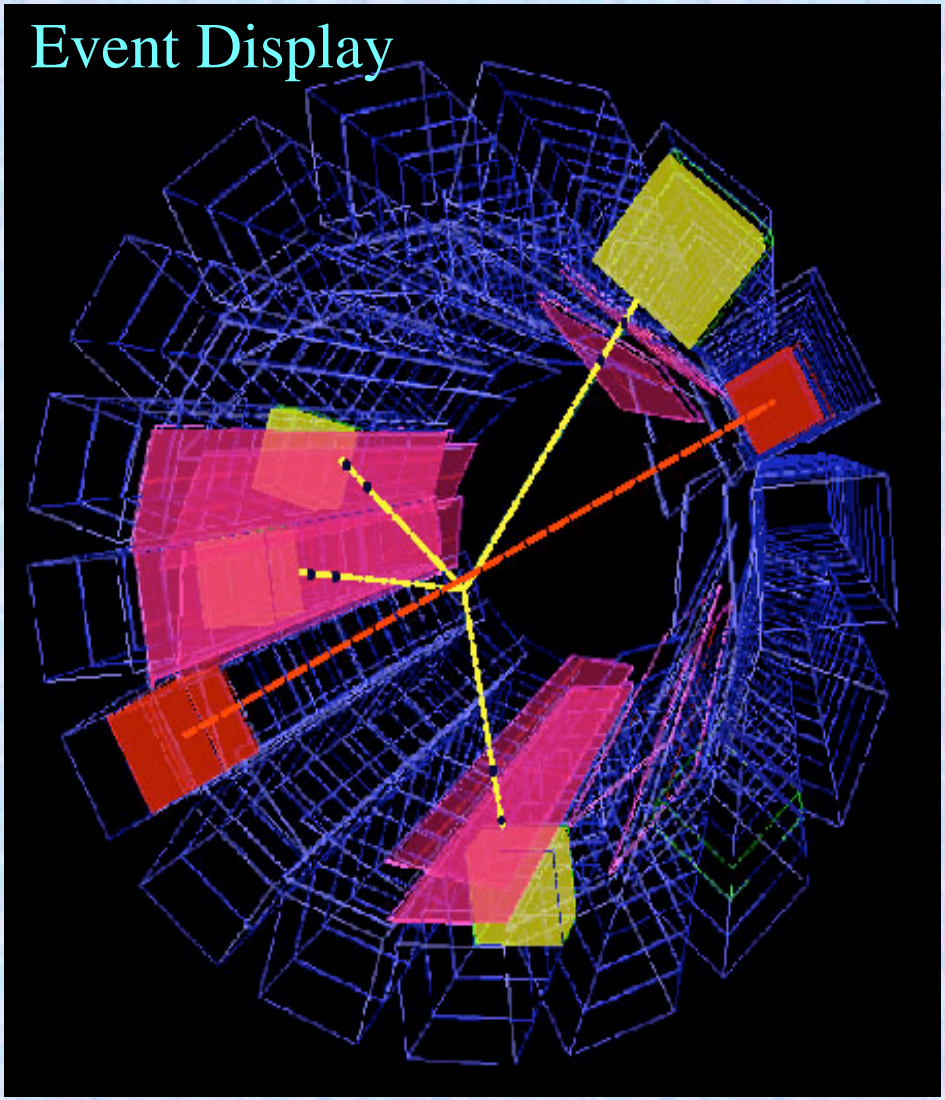
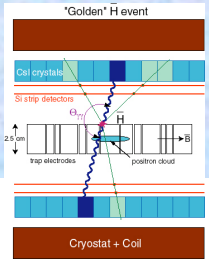
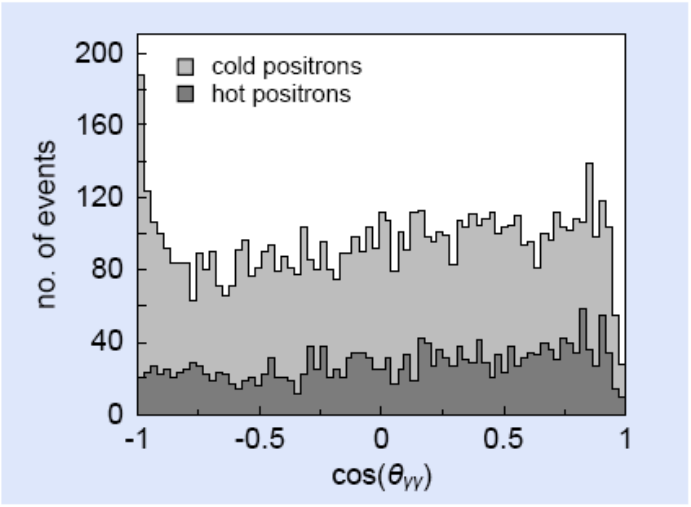


First observation of cold antihydrogen

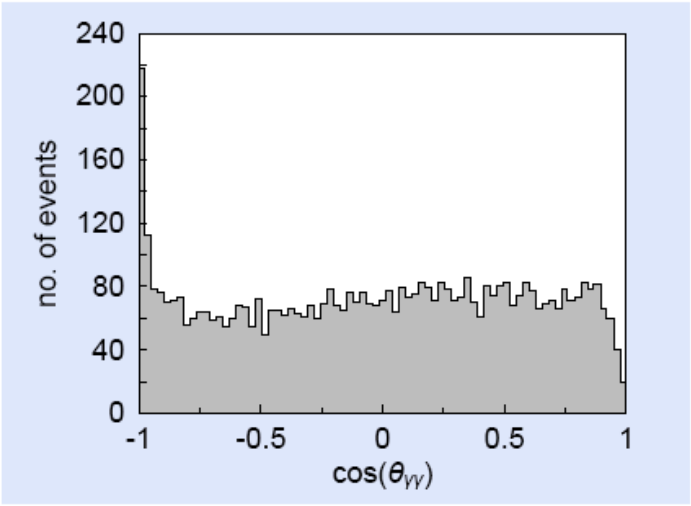
Opening Angle Distribution





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

Data



Monte Carlo

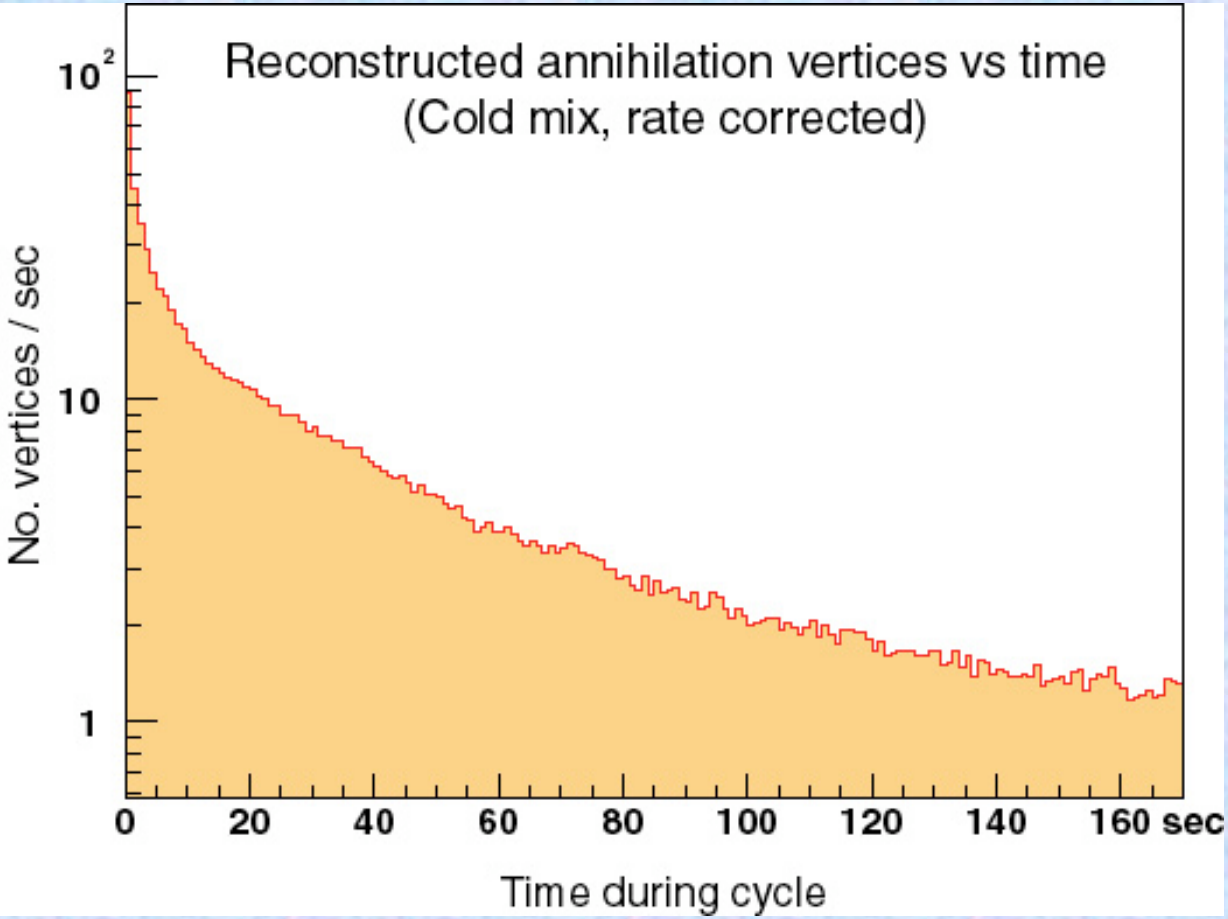
Peak from back-to-back 511 keV photon pairs

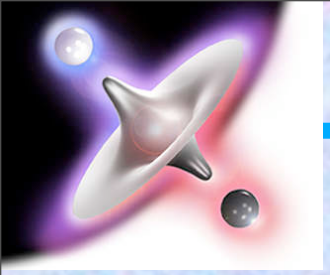
Test: peak disappears when positrons are 'heated' (RF)

Correcting for detection efficiency: > 100,000 anti-atoms

Rate of antihydrogen production quite high

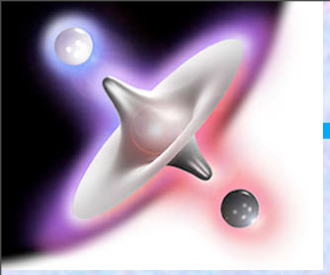
Initially > 100 Hz





Present state of the art

Number of produced antihydrogen atoms		Energy
1996:	9 (PS210, CERN)	2 GeV
1998:	60 (Fermilab)	3 GeV
2002:	> 1,000,000 (AD)	0.001 eV



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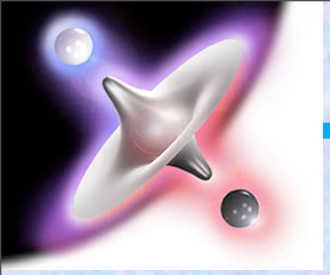
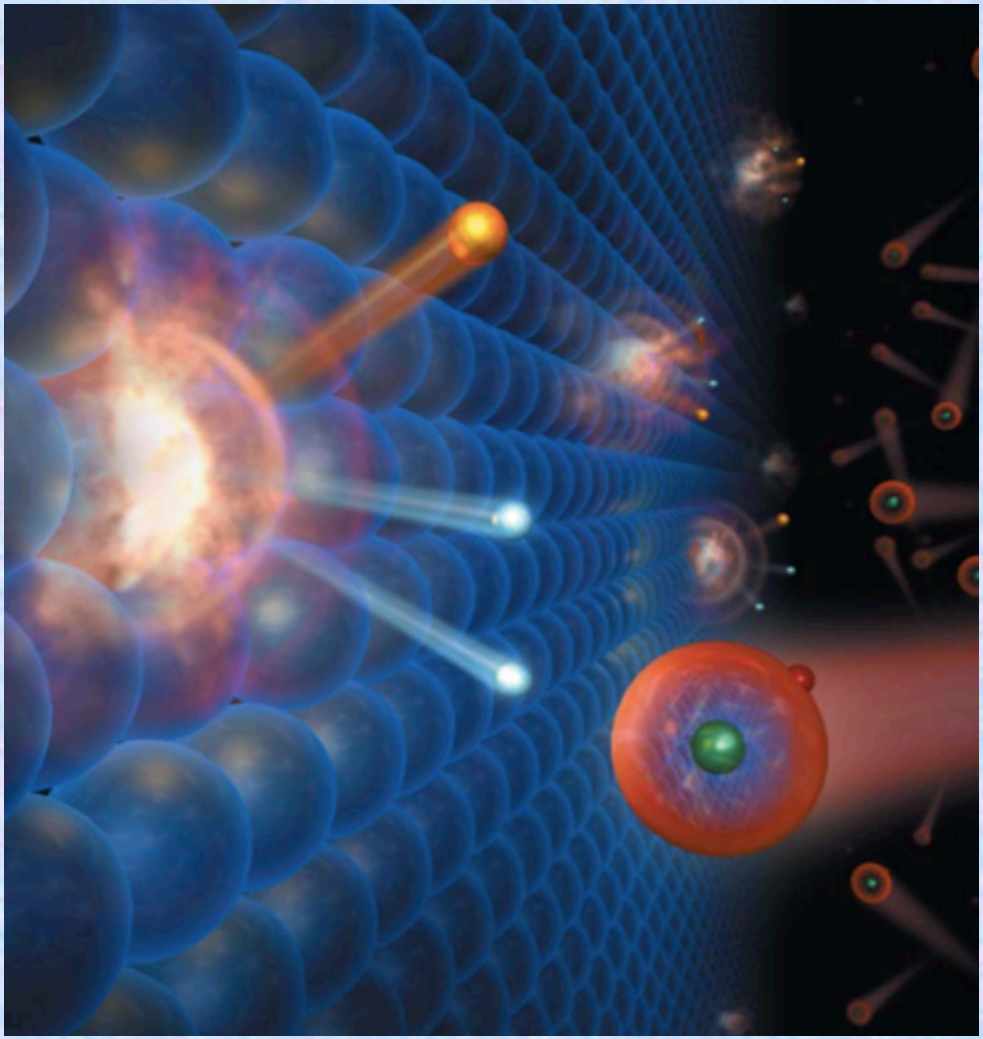
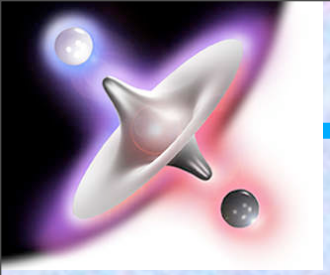
Antihydrogen production works
What about trapping?



FUTURE DEVELOPMENTS

Next step: Trapping antihydrogen





How to trap (neutral) antihydrogen?

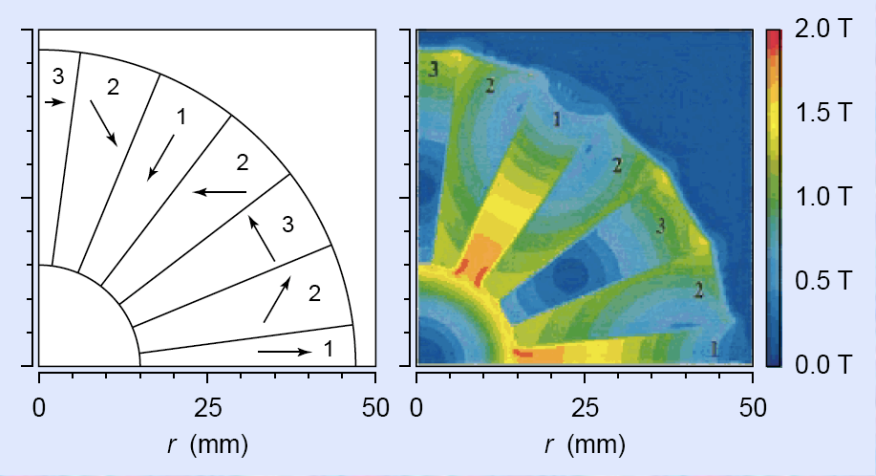
1) magnetic moment (~ μ_{e+}) ?

2) Laser cooling at 121.5 nm ?

3) Other methods ??

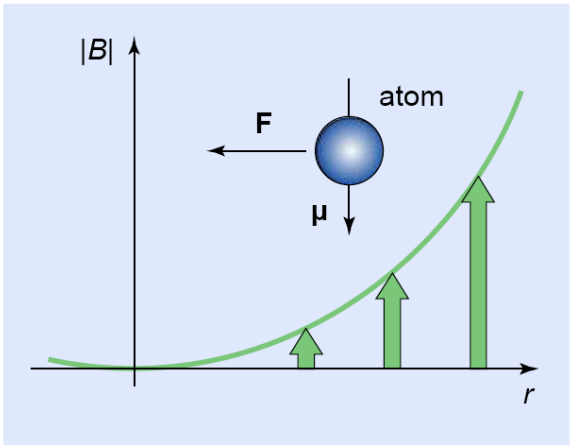
Magnetic bottles ?

Example: Sextupole magnet



$$U = -\vec{\mu}\,\vec{B}$$

$$\vec{F} = -\vec{\nabla} U$$



Low field seeking atoms (50%) at r=0

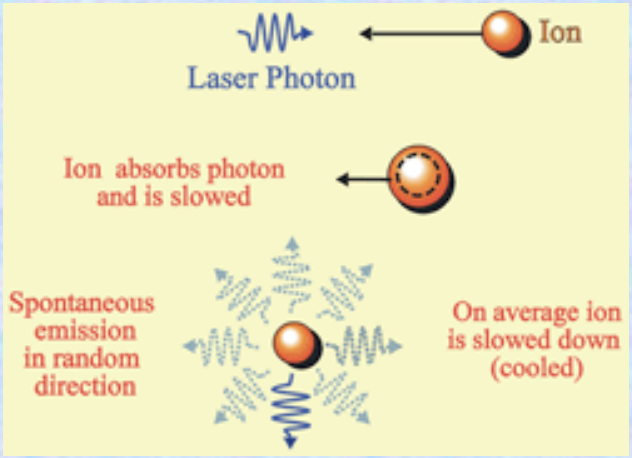
BUT: Very shallow potential (~ 0.07 meV/T)

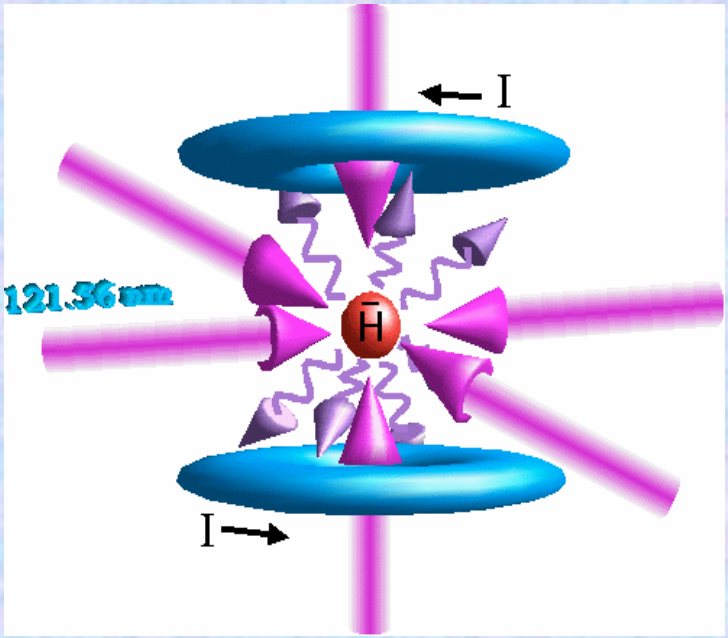
Realistic ΔB ~ 0.2-0.3 T ➪ **E < 0.02 meV**

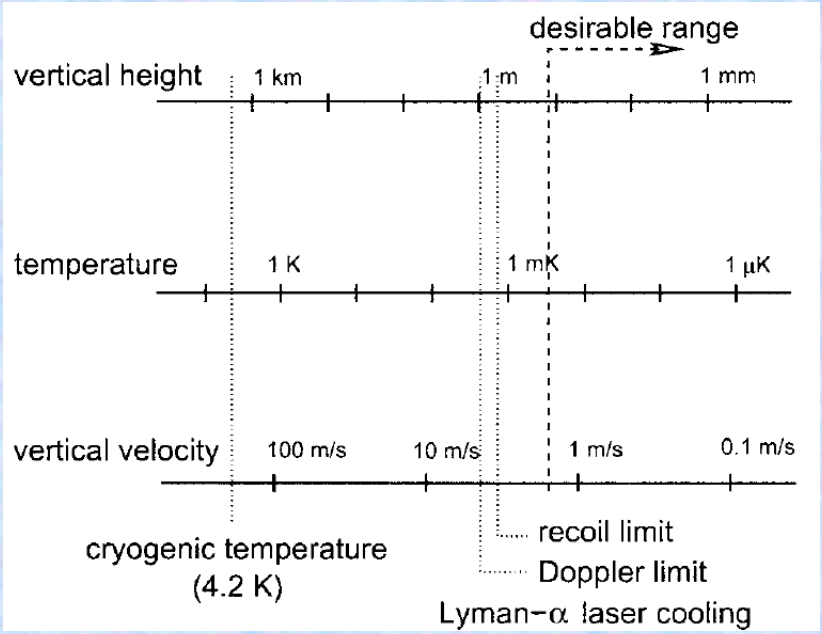
(reminder: produced antihydrogen has E_{kin} ~ 1-200 meV)

Trap antihydrogen from low energy 'Boltzmann tail' ?

Antihydrogen trapping: Laser cooling ?



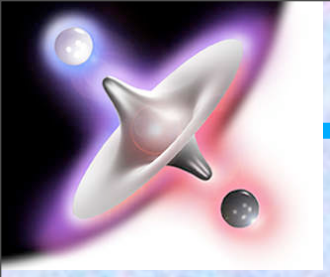




121 nm laser needed

Prototype at MPI Munich

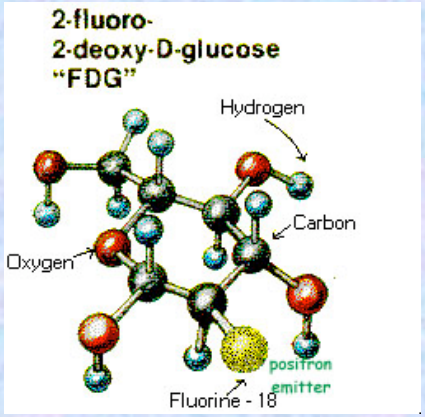
... only 50 nW



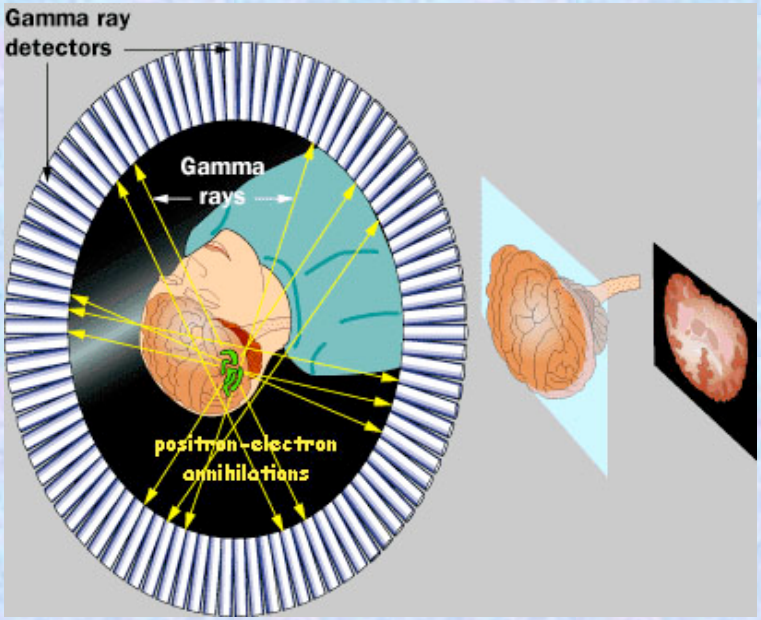
V. APPLICATIONS

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.



Reconstruct place of positron annihilation with crystal calorimeter



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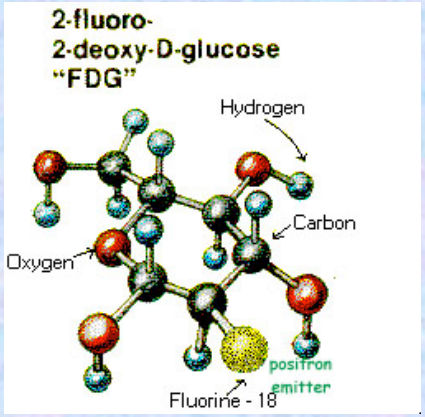

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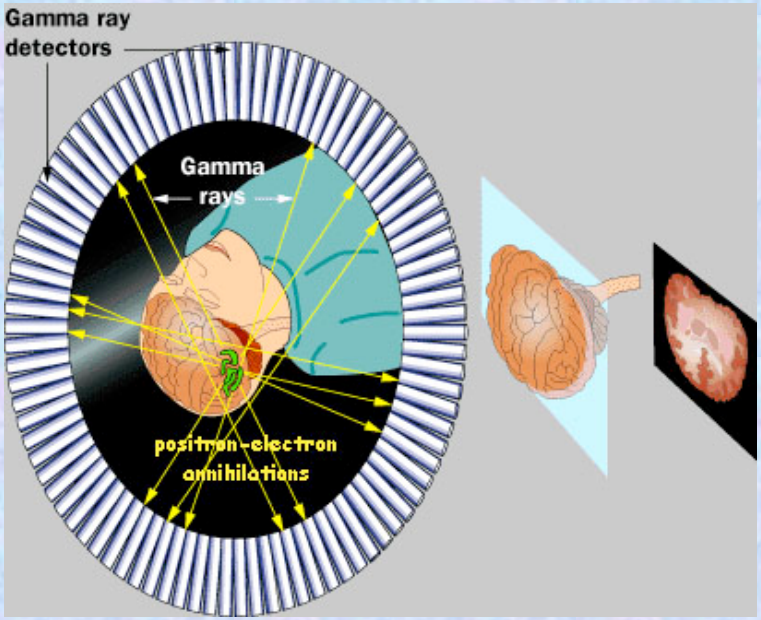
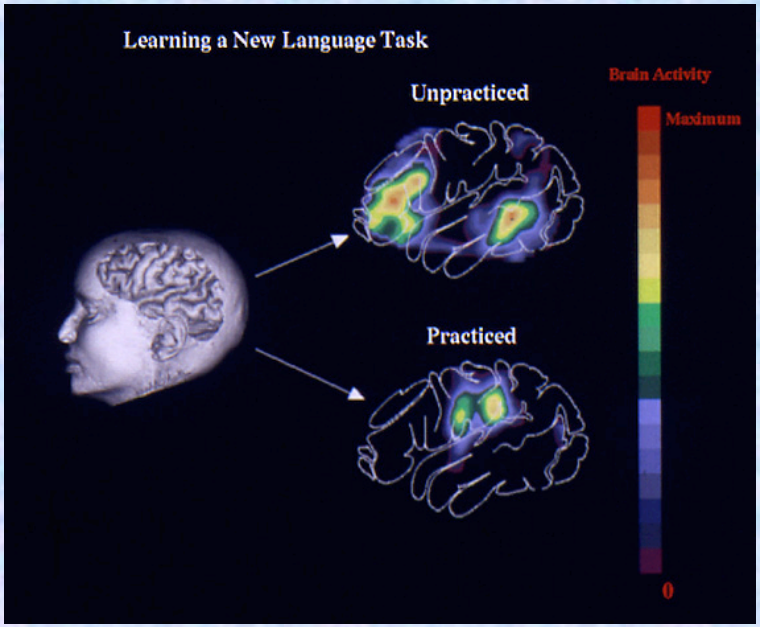
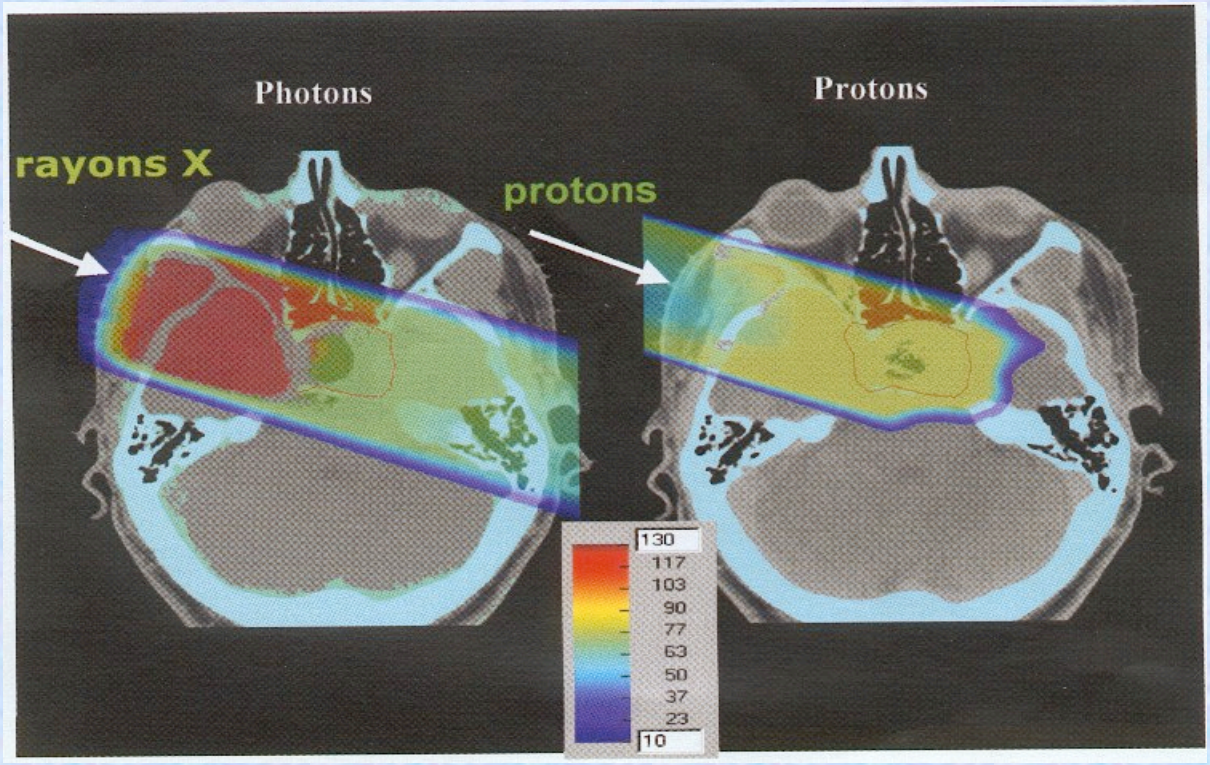




Tumour therapy

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

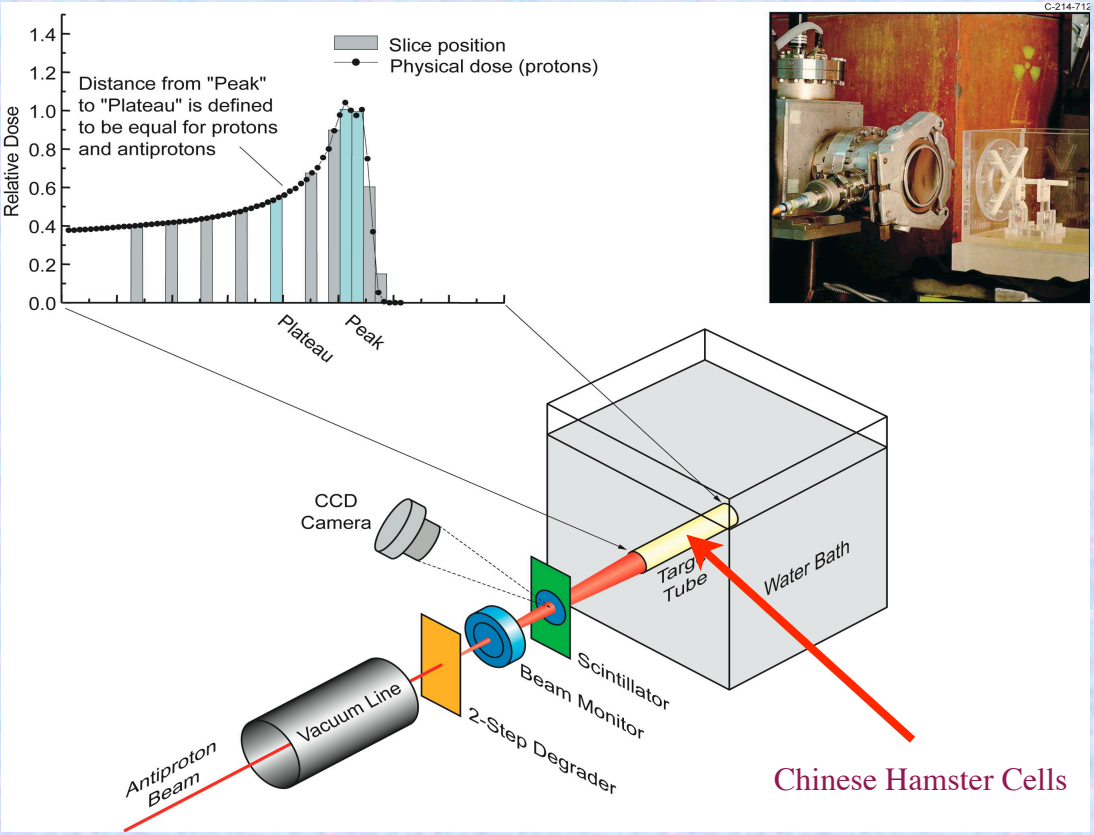
Gammas: exponential decay (peaks at beginning)
Charged particles: Bragg peak (Plateau/Peak better for high Z)
Antiprotons: like protons, but enhanced Bragg peak from annihilation



Antiproton Cell Experiment

Biological effectiveness of antiproton annihilation in cells

Additional damage by nuclear fragments of short range



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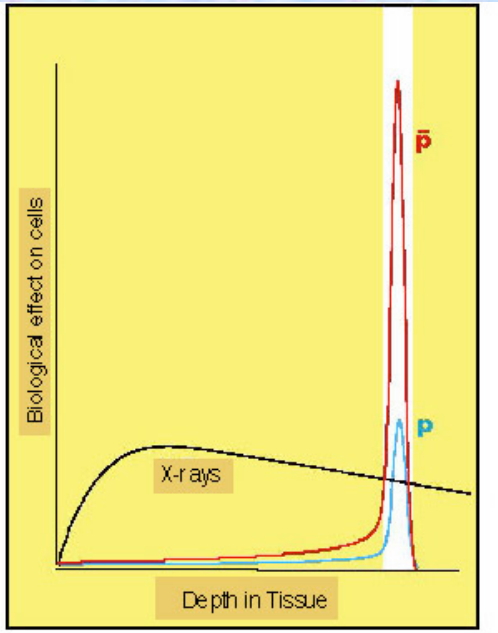
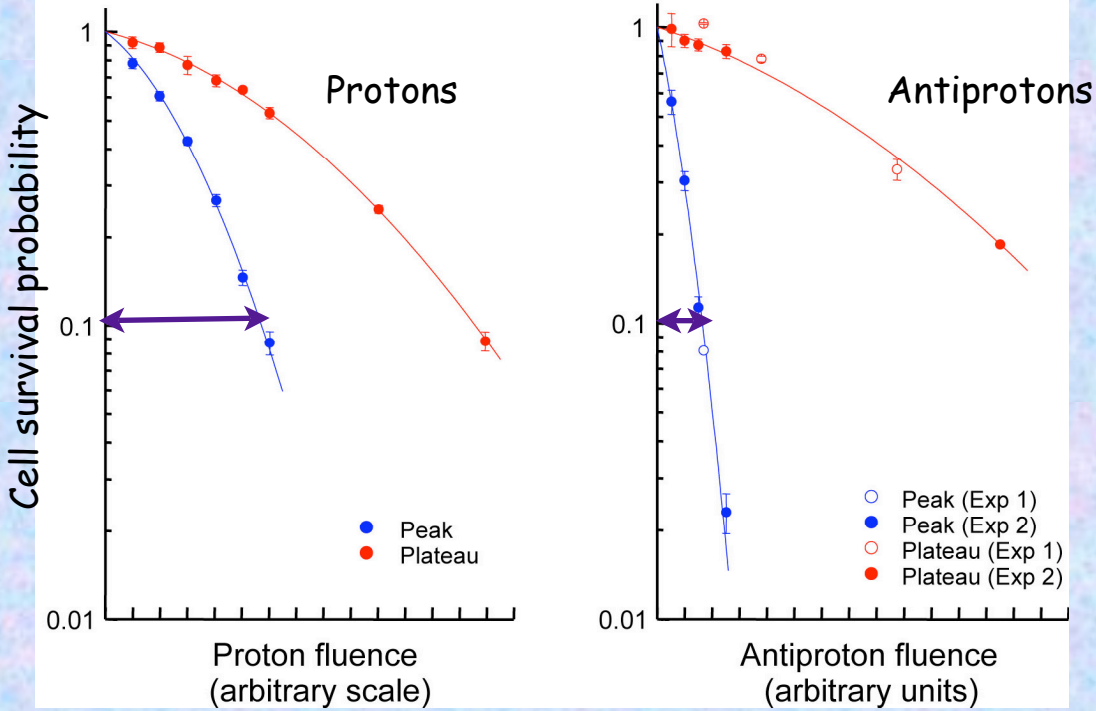
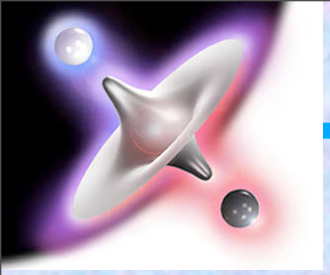




Equal cell mortality for tumour cells with 1/3 radiation dose (= damage to healthy cells)

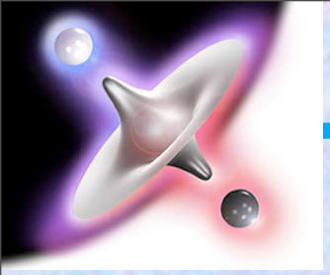
Interesting result - now compare with Carbon ion therapy - dedicated facility ???



Antiproton bombs ?

$E = mc^2$

20 kt TNT ~ $8 \cdot 10^{13}$ J
0.5 g antimatter + 0.5 g matter



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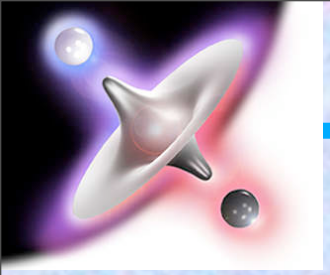

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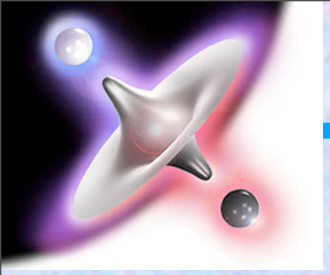

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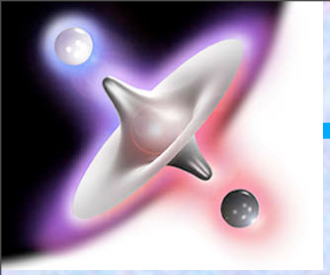
EDF discount price CERN (1 kWh = $3.6 \cdot 10^{6}$ J = 0.1 €):

Price ~ 10^{15} €



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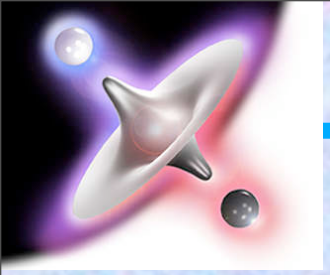

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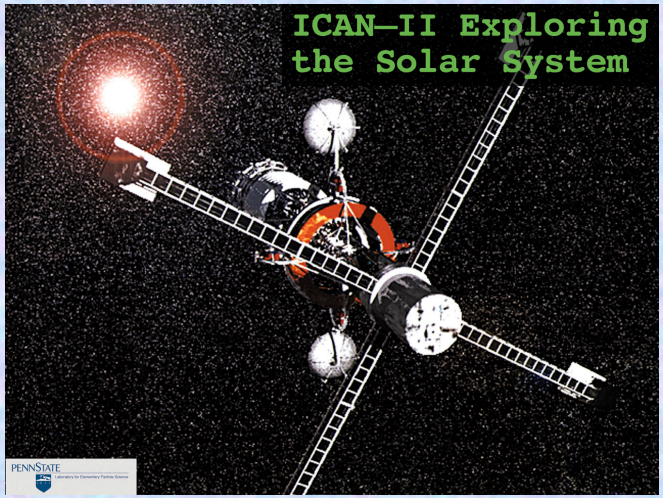
Delivery time ~ 3 billion years

Antimatter driven space engines?

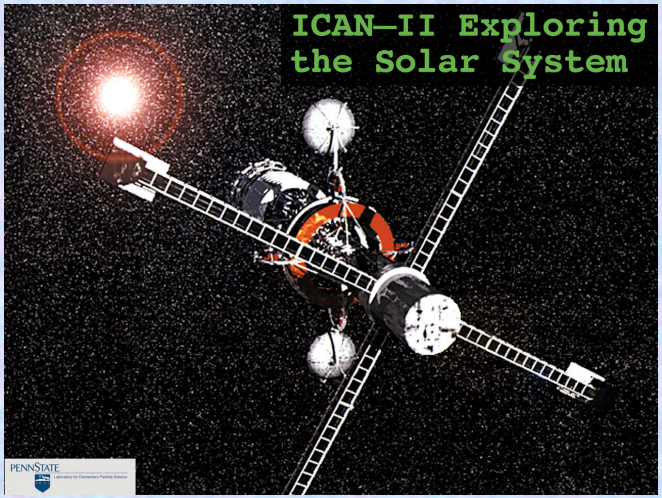


Antimatter driven space engines?

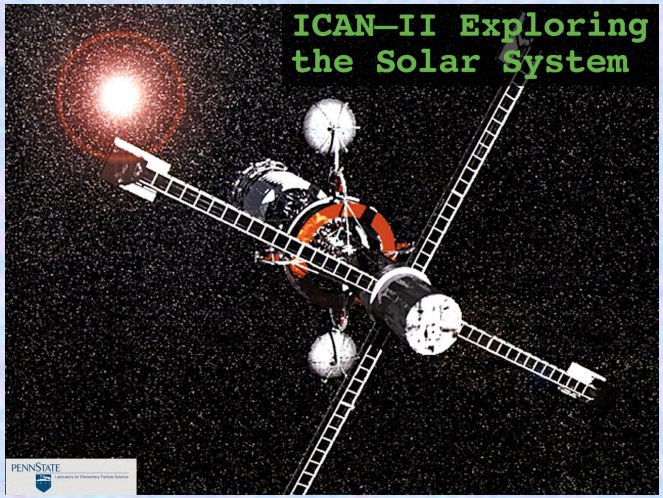
10-ton spacecraft at 0.95 c:

$E = \gamma mc^2 \sim 10 \cdot 10^4$ kg =

50 tons of antimatter + 50 t of matter



Antimatter driven space engines?



10-ton spacecraft at 0.95 c:

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

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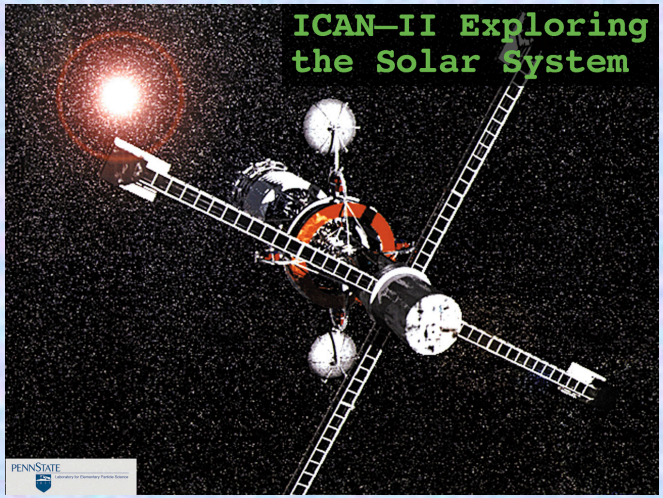

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In Genf wurde Wunder-Energie entdeckt

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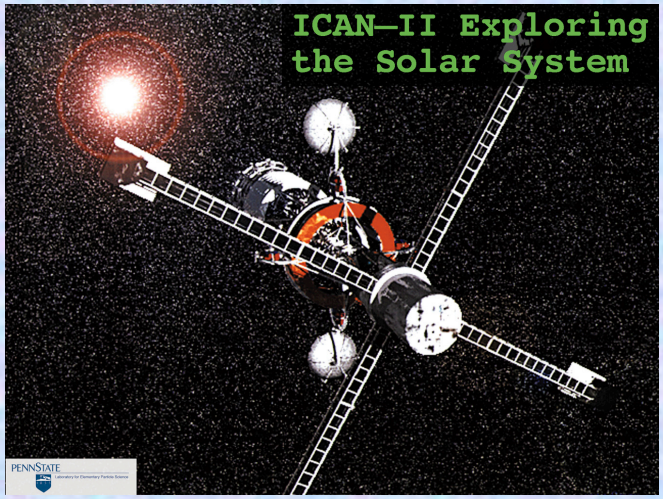

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The End.