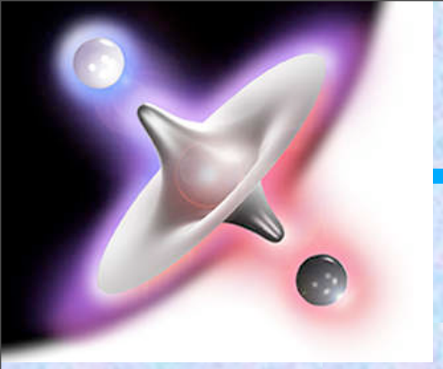
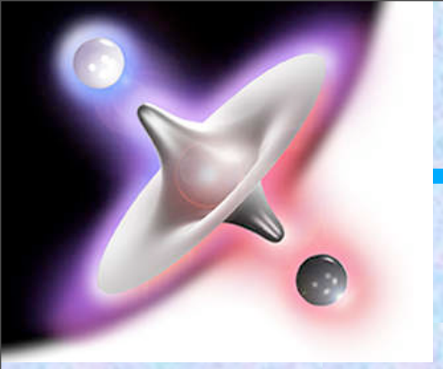
Antimatter 2 - The Sequel

Rolf Landua
CERN

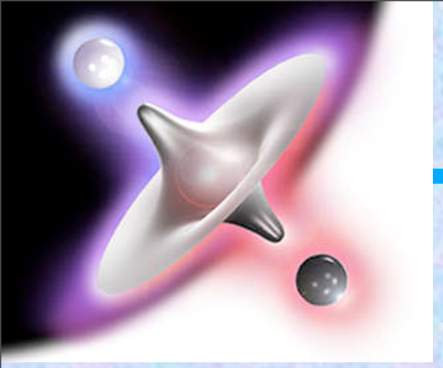


Overview Lecture 2



Overview Lecture 2

Trapping antiprotons

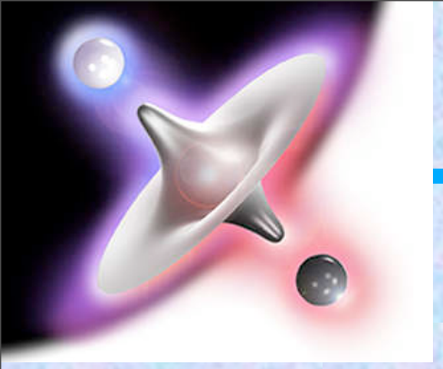


Overview Lecture 2

Trapping antiprotons

Antihydrogen

ATHENA and ATRAP
Making antihydrogen
Future developments



Overview Lecture 2

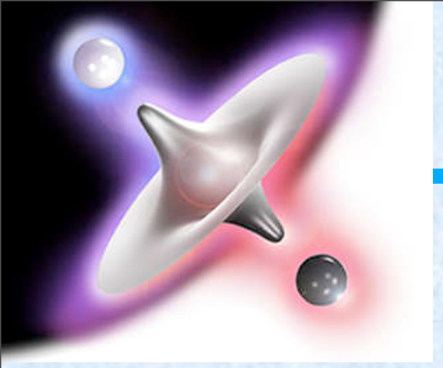
Trapping antiprotons

Antihydrogen

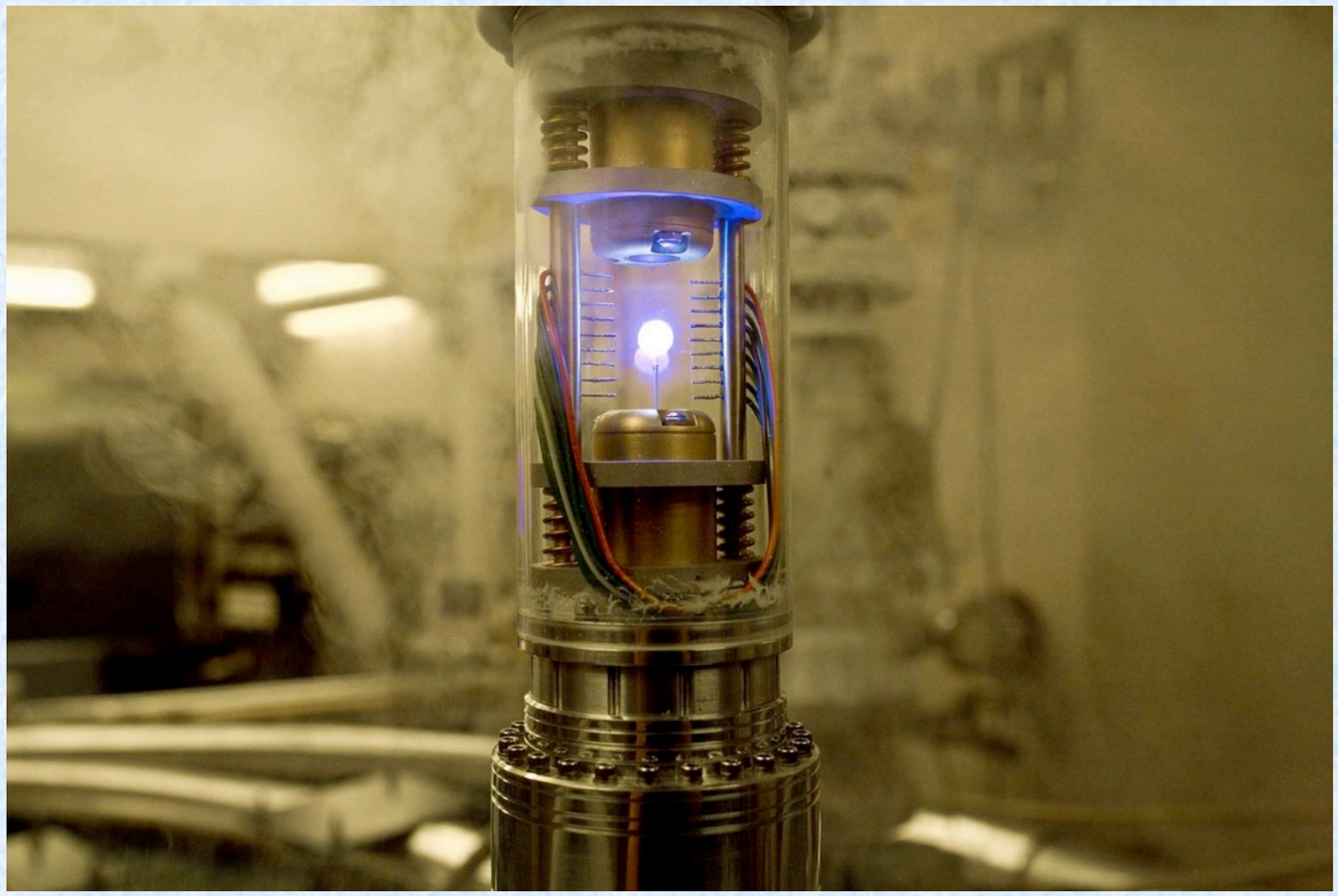
- ATHENA and ATRAP
- Making antihydrogen
- Future developments

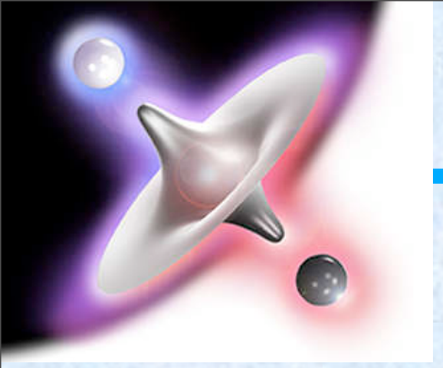
Applications

- PET
- Antiproton therapy?
- Rocket propulsion??



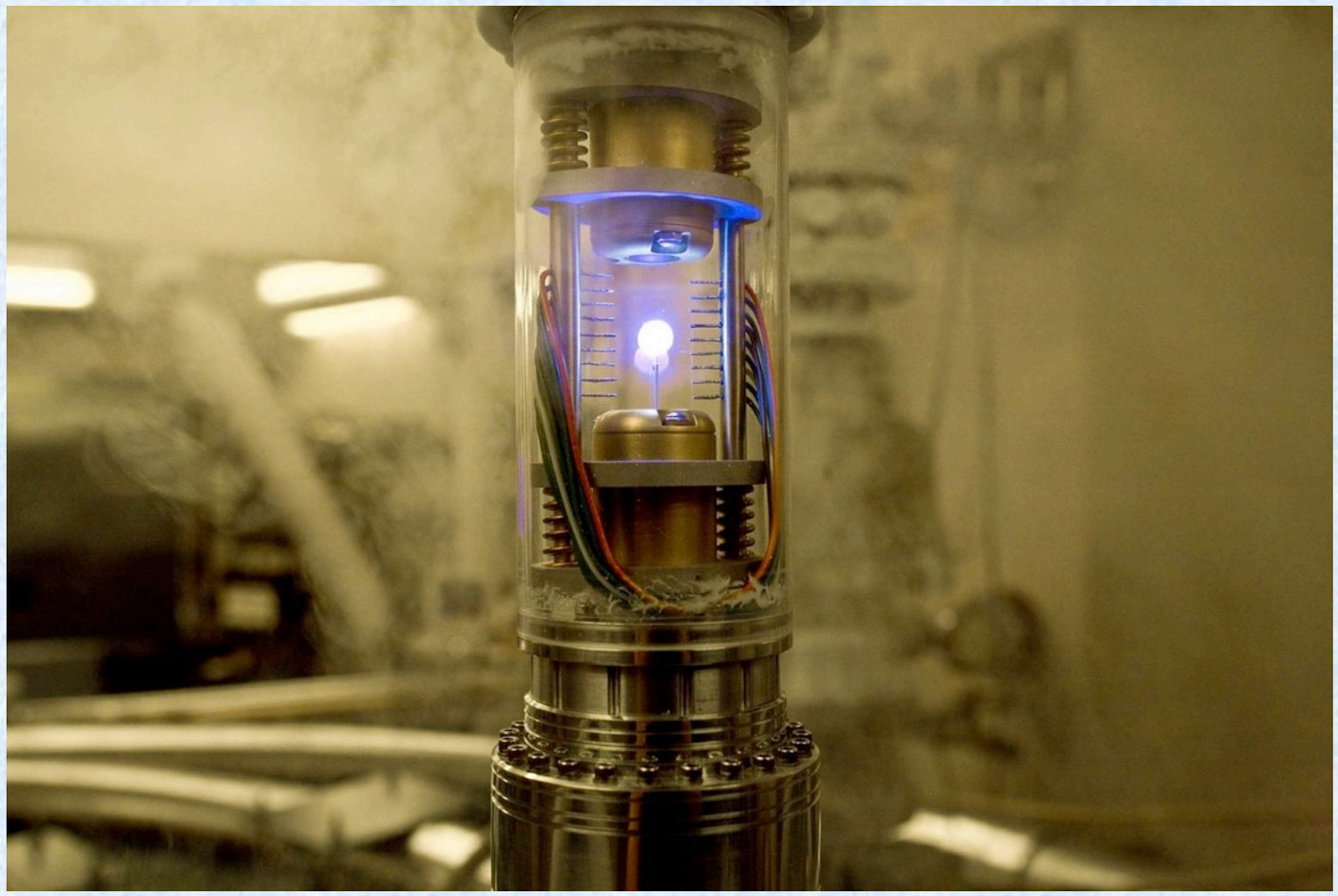
... and, of course, ...

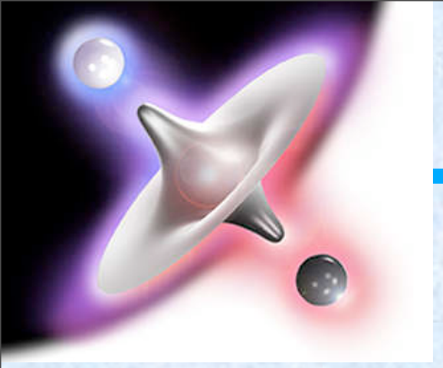




... and, of course, ...

Where is the secret antimatter lab ?

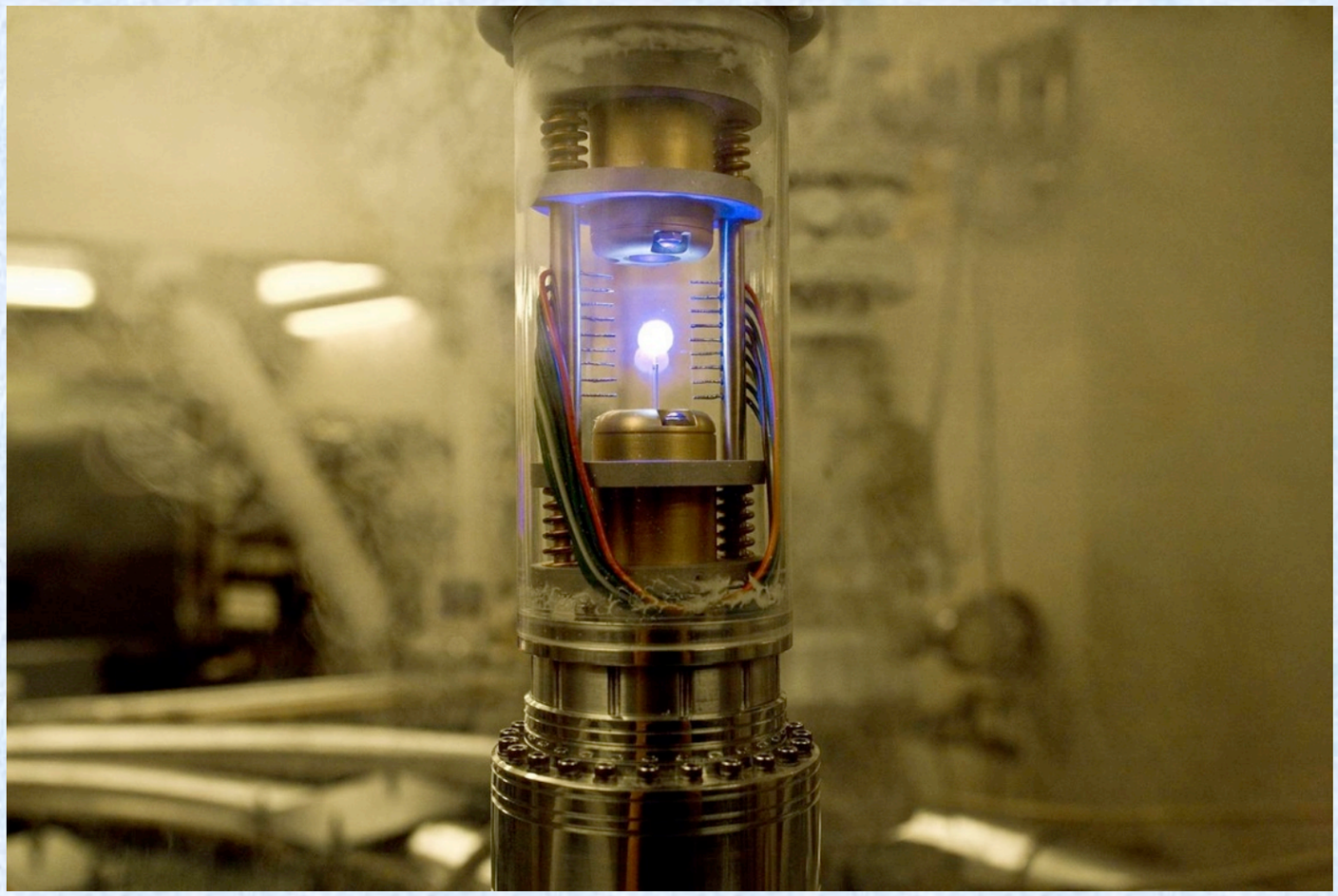


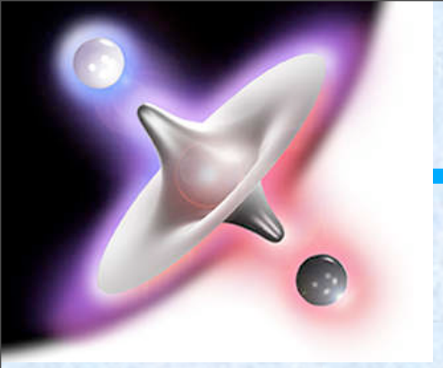


... and, of course, ...

Where is the secret antimatter lab ?

Am I a priest ?



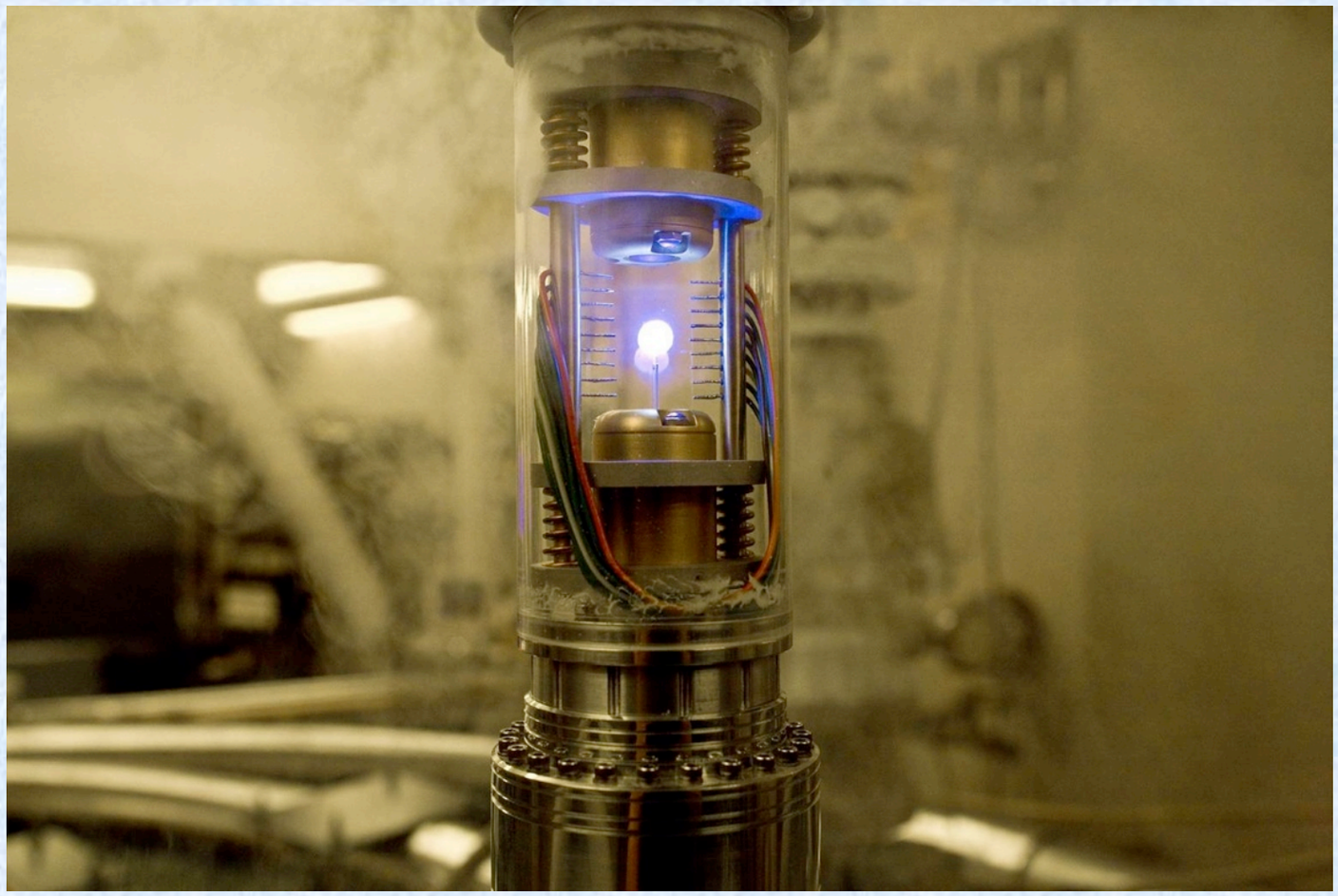


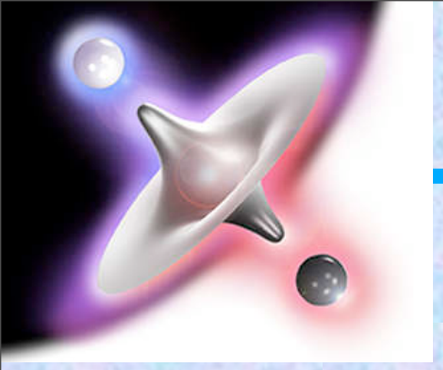
... and, of course, ...

Where is the secret antimatter lab ?

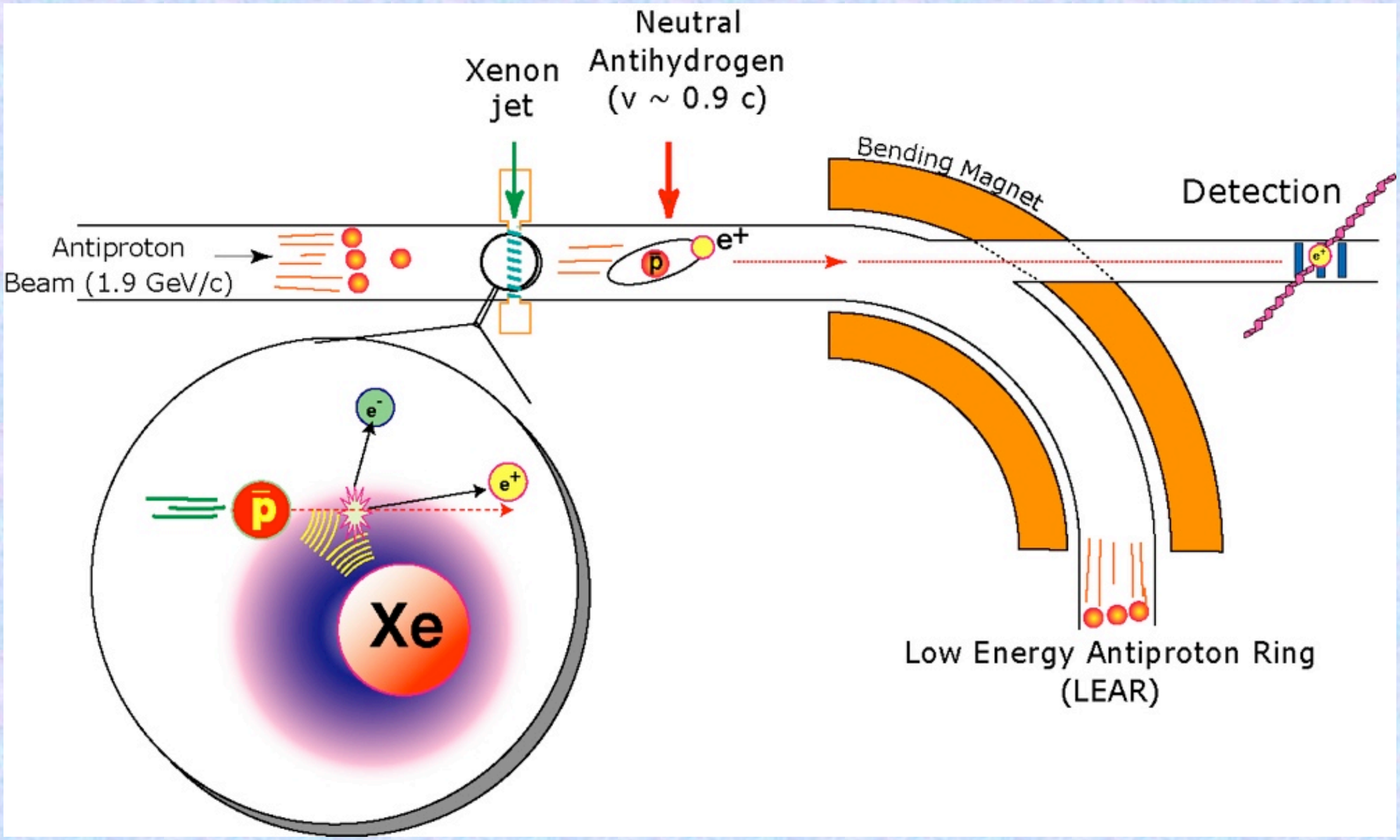
Am I a priest ?

Do we have 1 gram of antimatter ?

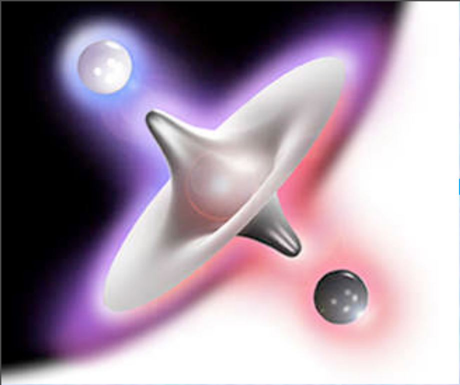




How were the 9 antihydrogen atoms made at LEAR ?



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



The first nine antihydrogen atoms at CERN (1996)

Excellent explanation

中國時報

中華民國八十五年二月五日星期一

反物質原子 CERN 首度成功創生

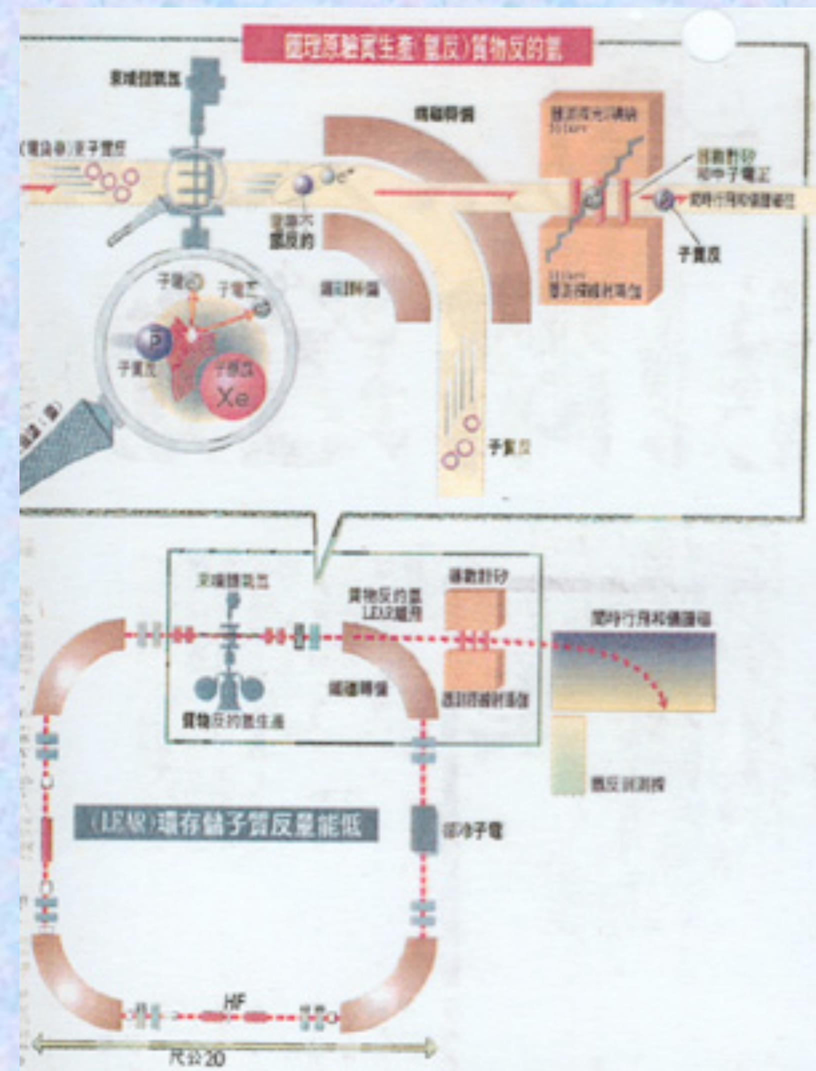
◎江才健

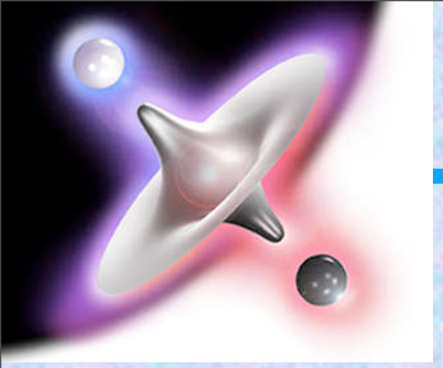
德國物理學家歐勒特，利用歐洲粒子物理研究中心低能量反質子束，創生出頭一批反氫原子，雖得到領先紀錄，但在科學上還不算有重大意義，亦不可能用於新能源。

反氫 如何創生？

歐勒特證實反

（CERN提供）





Press reactions (of course)

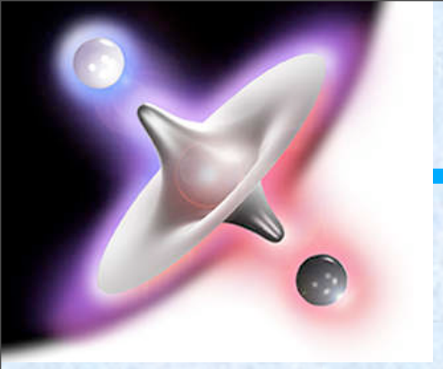
"Liberation" (France)

«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?**



A welcome interruption of the antimatter panic

The LHC will destroy the Earth by making a black hole:

September 10, 2009

Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

HERAUSGEGEBEN VON WERNER D'INKA, BERTHOLD KOHLER, GÜNTHER NONNENMACHER, FRANK SCHIRRMACHER, HOLGER STELTZNER

Papier:
für
rkschafter

Verschwinden wir im
zen Loch?

Urknall in Genf – Heute wird ein gigantischen Experiment gestartet: Wasserstoffkerne werden in der Schweiz hundert Meter unter der Erde in einer 27 Kilometer langen Kreisbahn be-
Oder bekommt ein Tübinger Forscher recht, der vor Gericht zog, weil er glaubt, es entstünden „schwarze Löcher", die so lange Materie anziehen, bis **Natur und Wissenschaft**, ja die

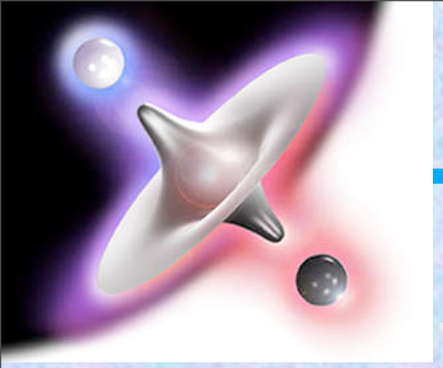
Nicht Dritter

Von Berthold Kohler

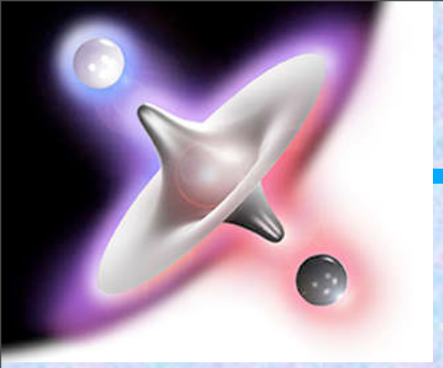
Er wisse, was auf ihn zukomme, sagte Frank-Walter Steinmeier, als er selbst verkünden musste, dass er der Erwählte sei. Das haben schon viele Kandidaten und vor allem Vorsitzende der SPD gedacht. Meistens, das erfuhr jetzt auch Kurt Beck, kam es aber doch ganz anders, nämlich so wie immer in der SPD. Wollte Steinmeier uns also sagen, er habe sein politisches Ende schon vor Augen? Am vergangenen Wochenende konnte er aus nächster Nähe verfolgen, wie wieder ein Vorsitzender die SPD durch die Hintertür verließ. Die lässt ihre ganze Frustration darüber, dass der Lauf der Welt sich nicht nach ihren Utopien richtet, gewohnheitsmäßig an ihren Vorsitzenden aus. Leichten Mutes können daher nur Männer auf die Brücke dieser Partei treten, die, wie Müntefering, ihre politische Zukunft schon hinter sich haben.

Dessen von Steinmeier beförderte Rückkehr in den Führungskreis der Partei aber war für Beck nach all dem Spott und der Häme der vergangenen Wochen zu viel des Guten. Der alte Vorsitzende hätte wohl gerade noch damit leben können, im ersten Amt

Ring f



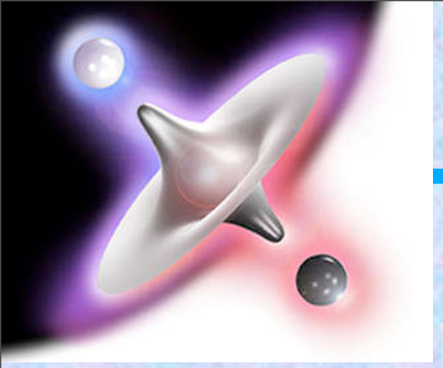
Two questions to keep you awake



Two questions to keep you awake

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

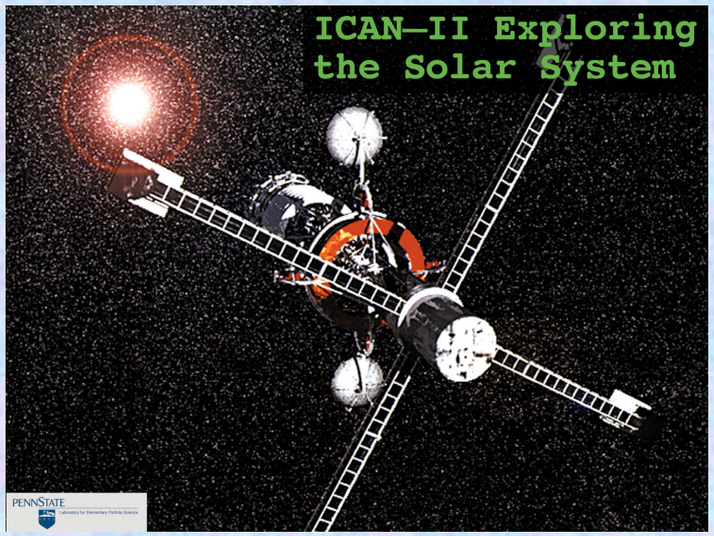
The Vatican ?



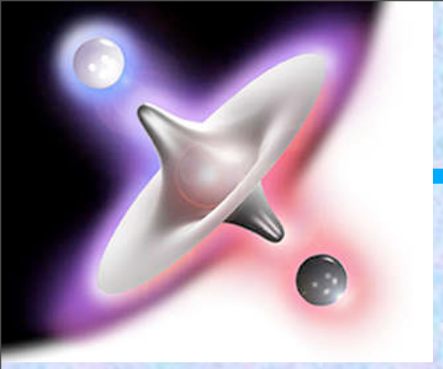
Two questions to keep you awake

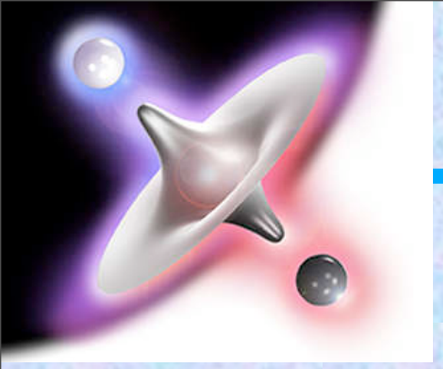
1. With present techniques, what would be the price and delivery time for an 0.5 g anti-hydrogen bomb?

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

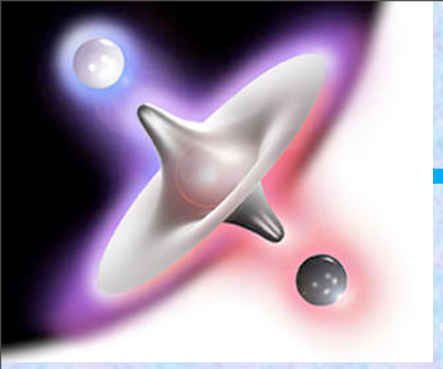


The Vatican ?





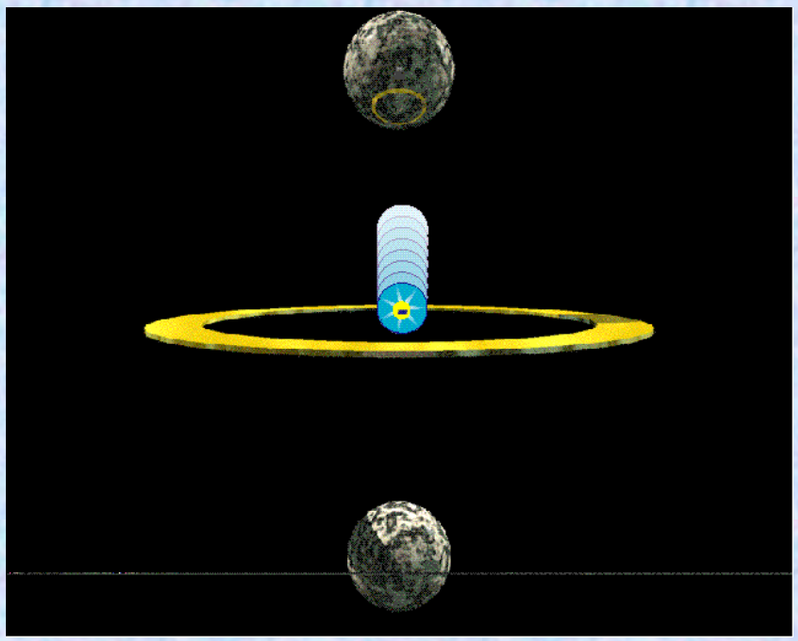
III. TRAPPING ANTIPARTICLES



RF trap (“Paul trap”)

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

- / +



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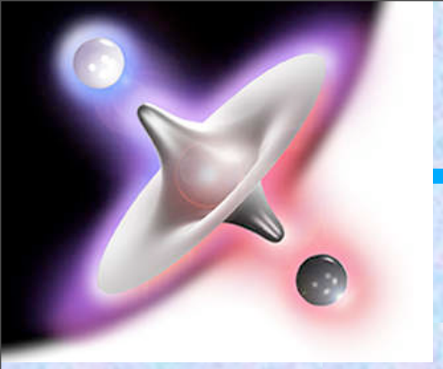

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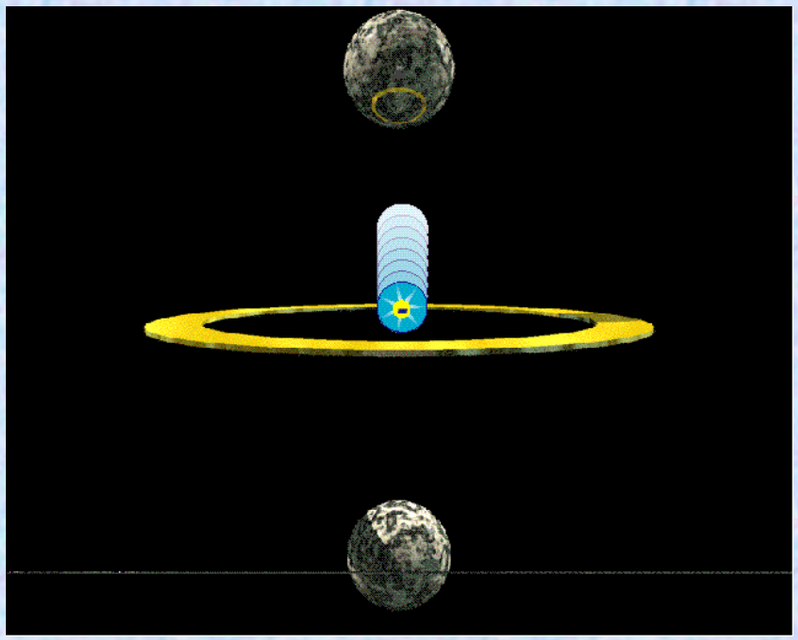

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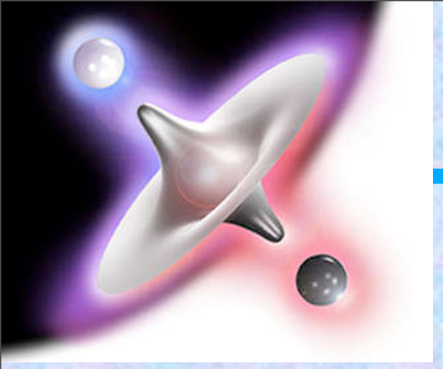
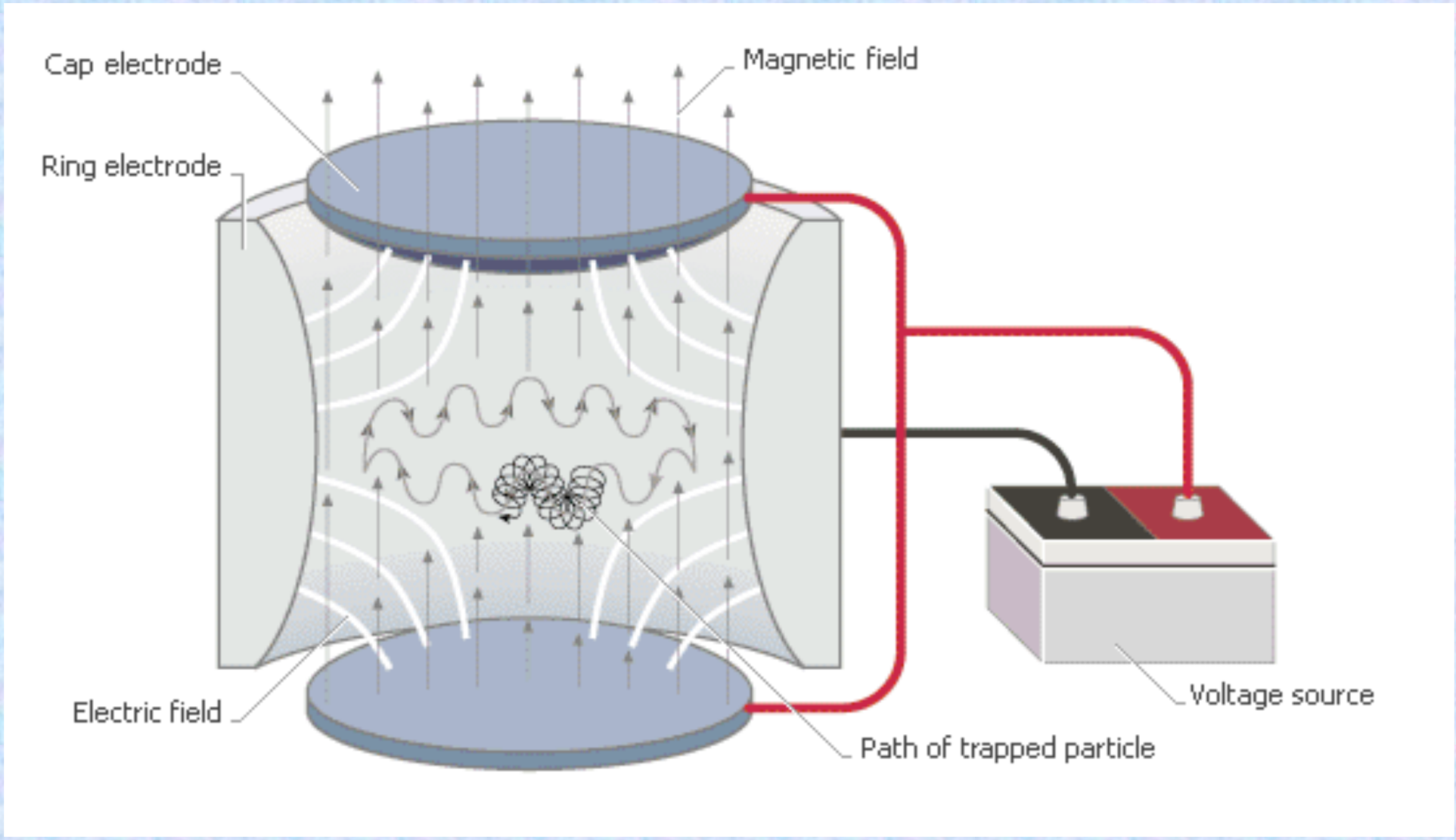


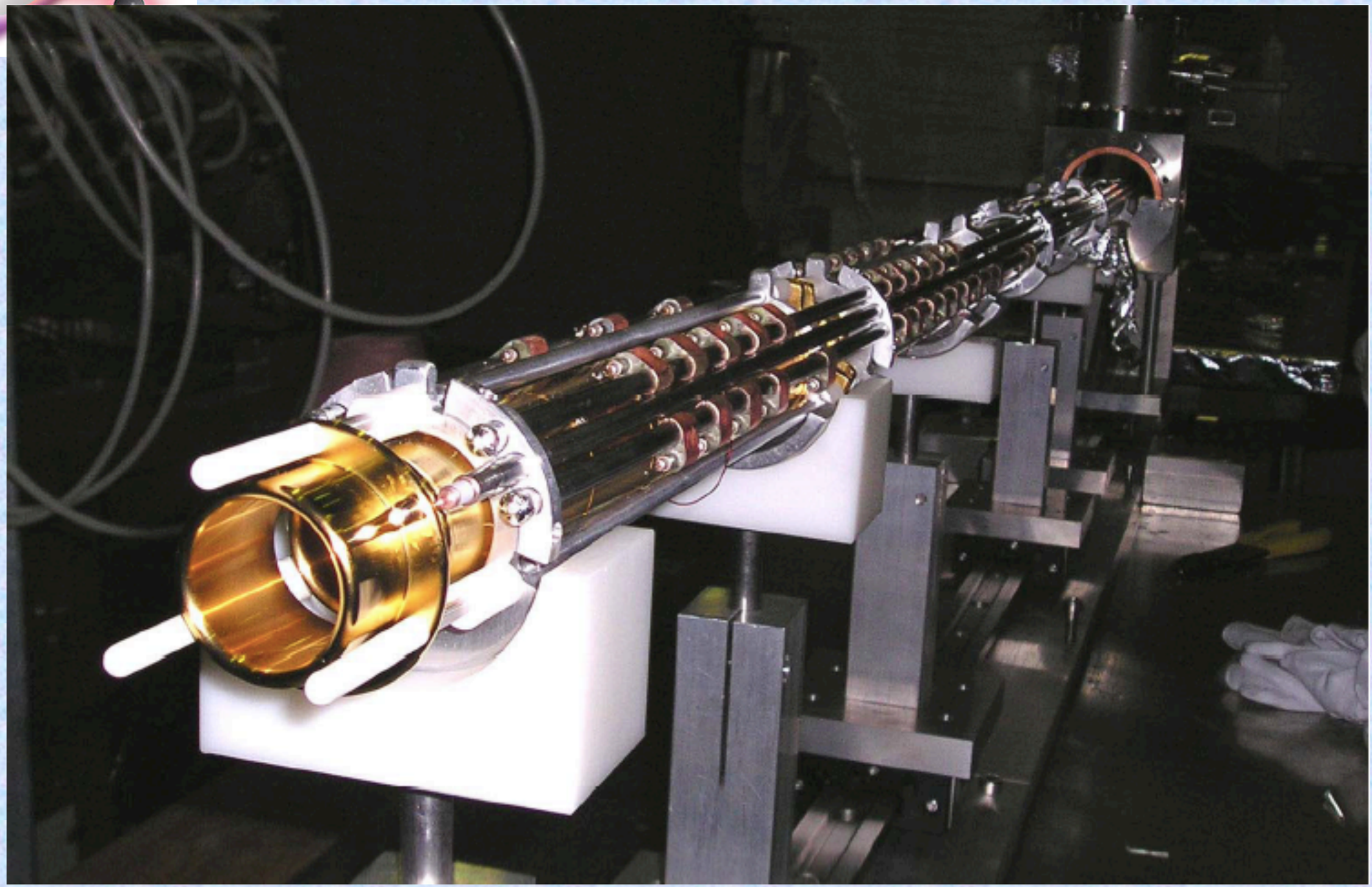
Magnetic trap ("Penning trap")

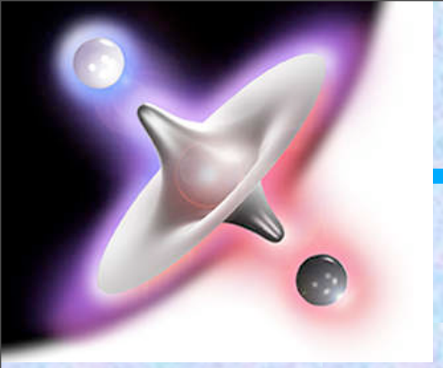
Charged particles are spiraling along magnetic field lines (~ Tesla)

and oscillate (harmonically) between electrodes on electric potentials (~ Volts)



Trap for antiproton capture and storage





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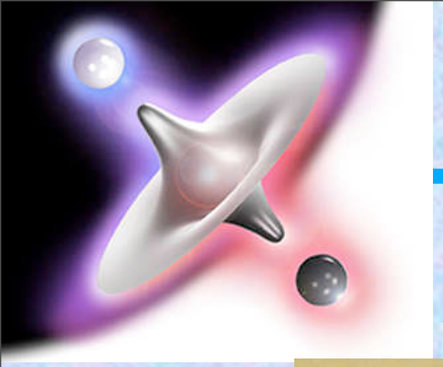

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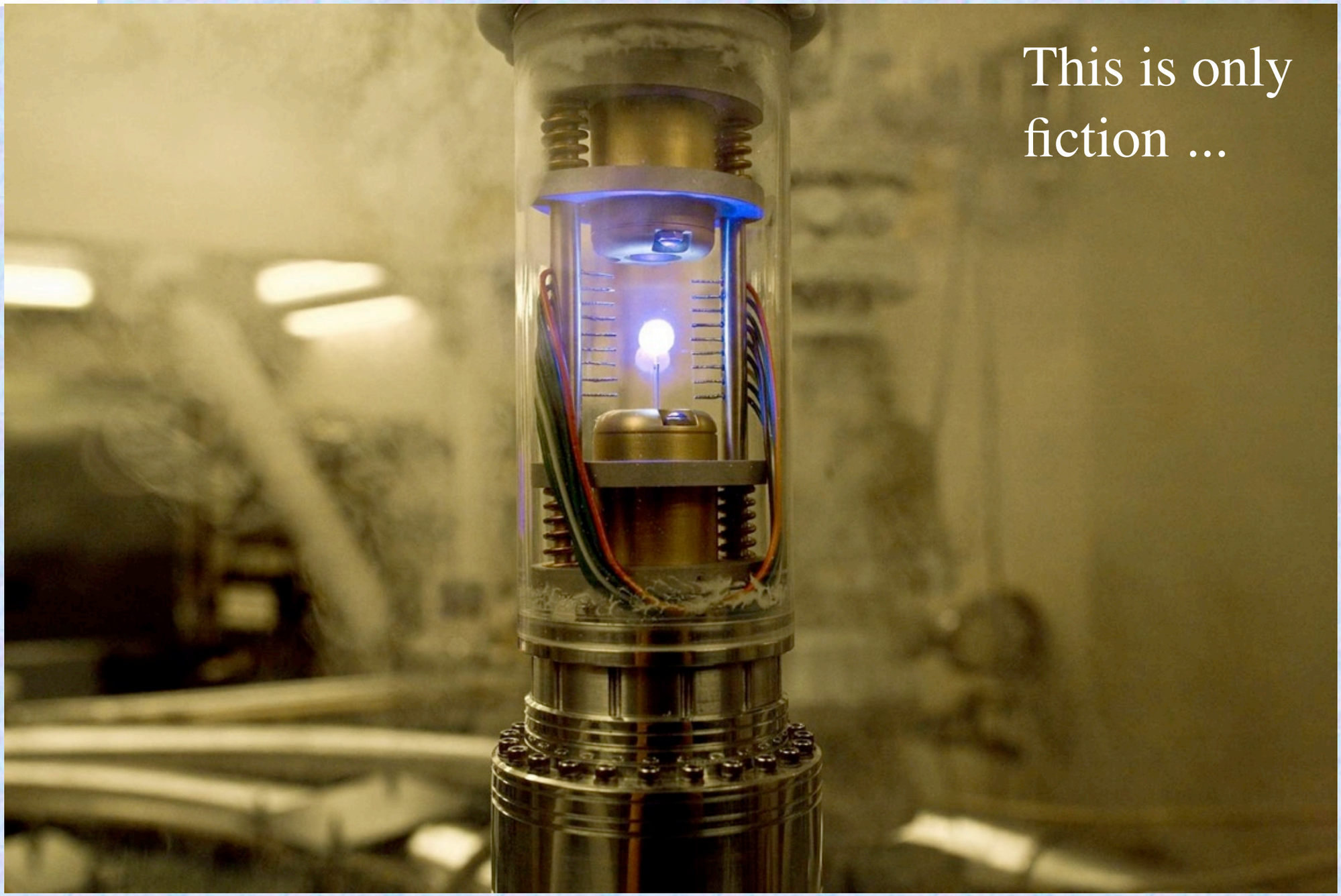
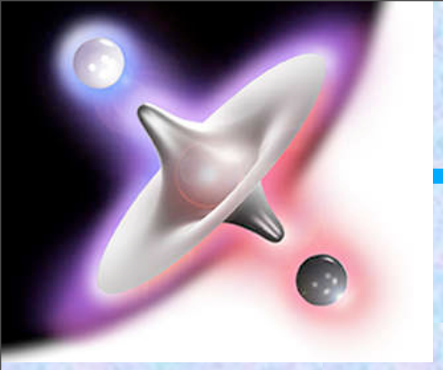
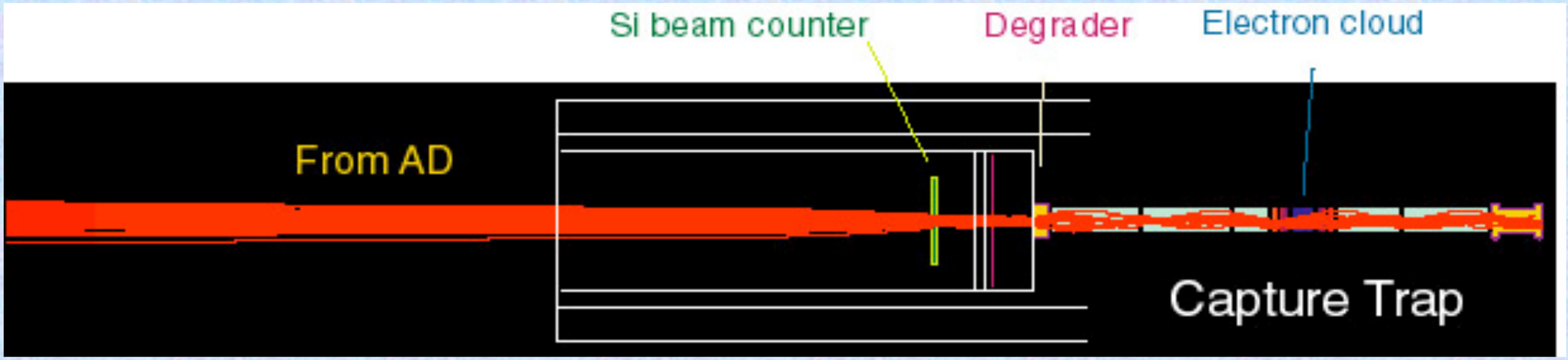
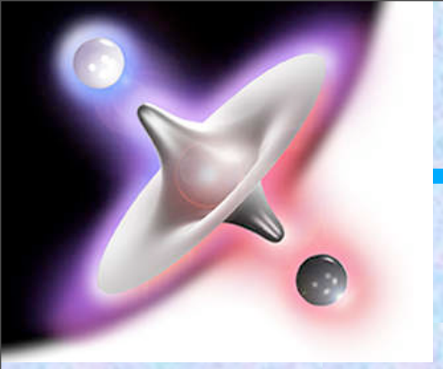




Trapping antiprotons





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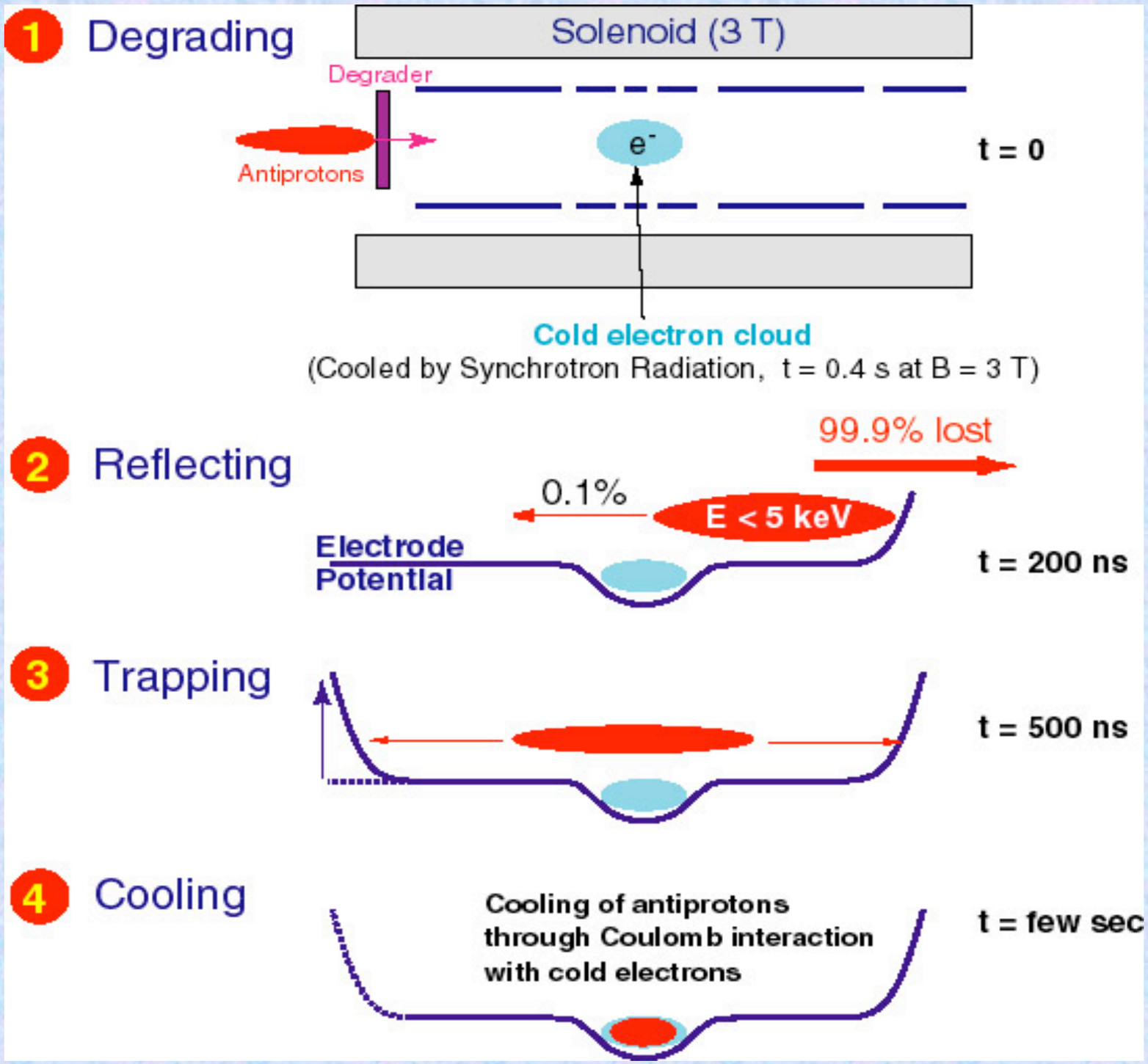
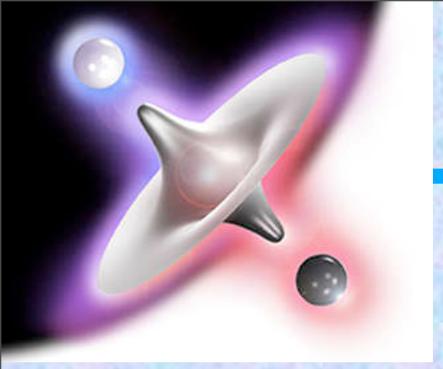
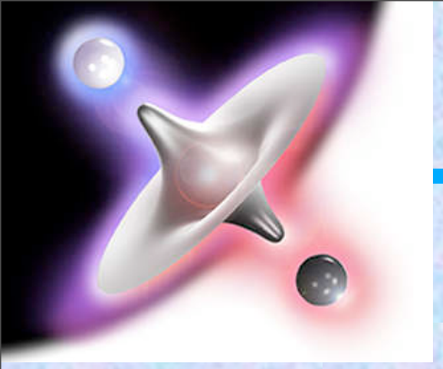




IV. ANTIHYDROGEN

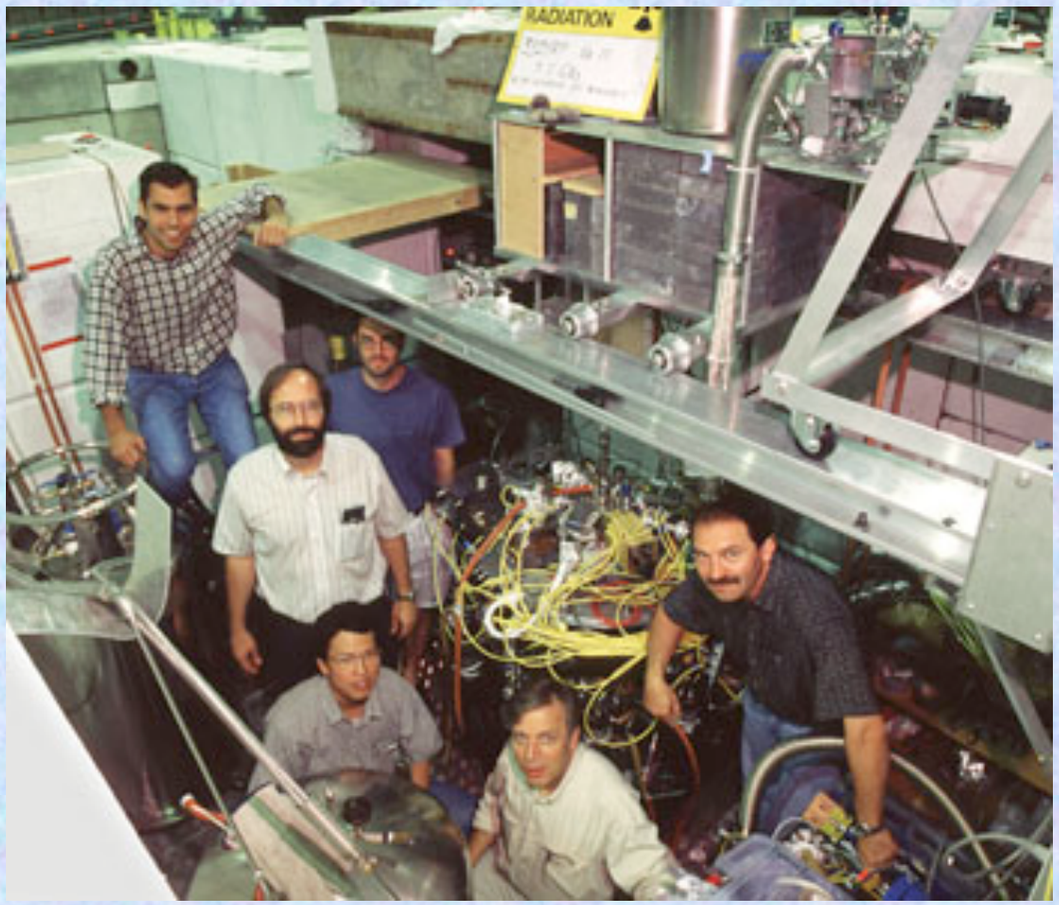


The race for cold antihydrogen

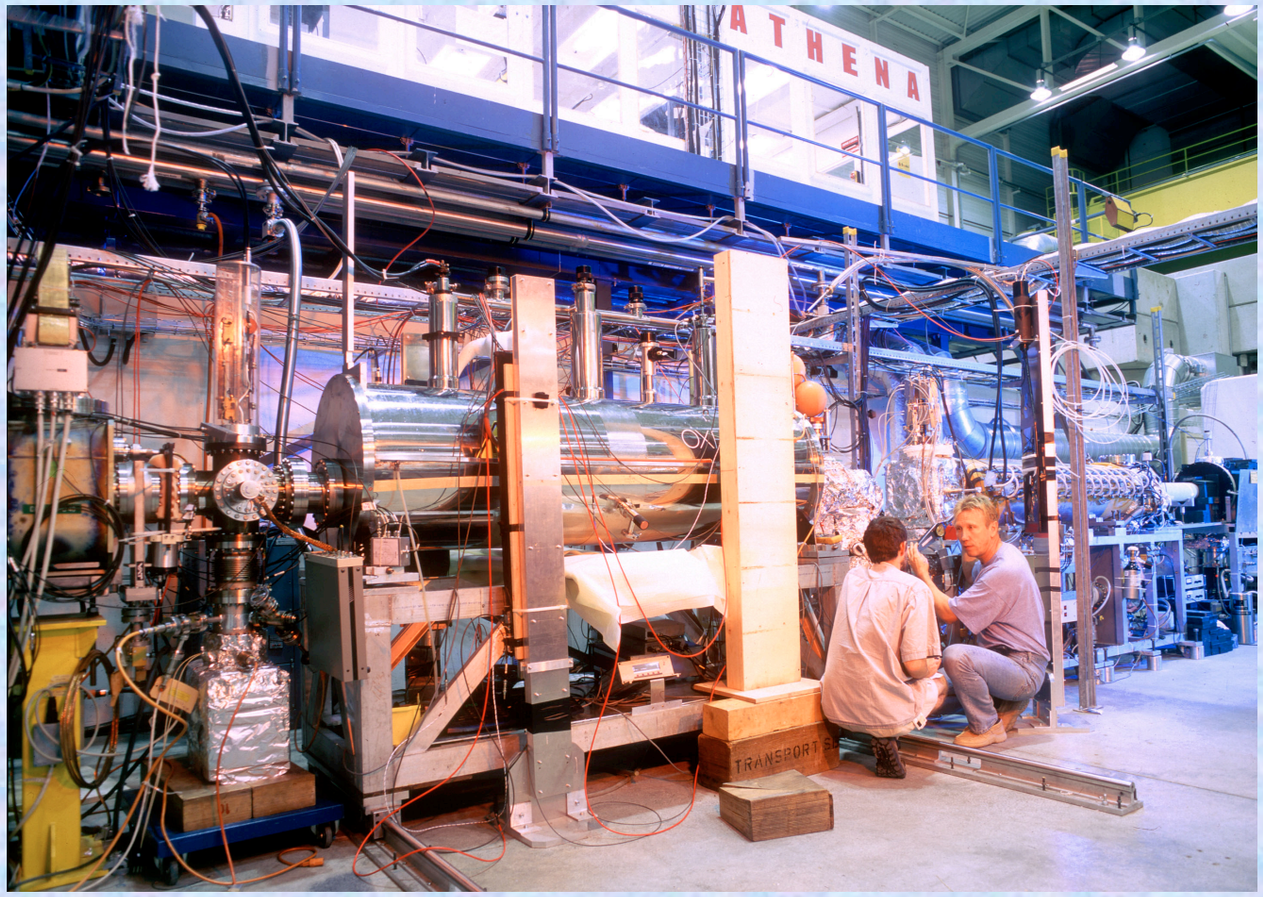
ATHENA and ATRAP - Experiments (Start 2000)

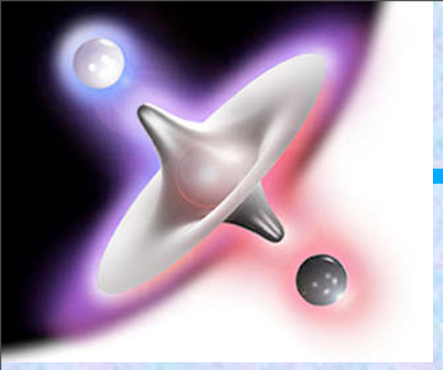
Find a way to make cold antihydrogen (done)
Trap and cool antihydrogen (challenge!)
Precision measurements ('easier')

ATRAP

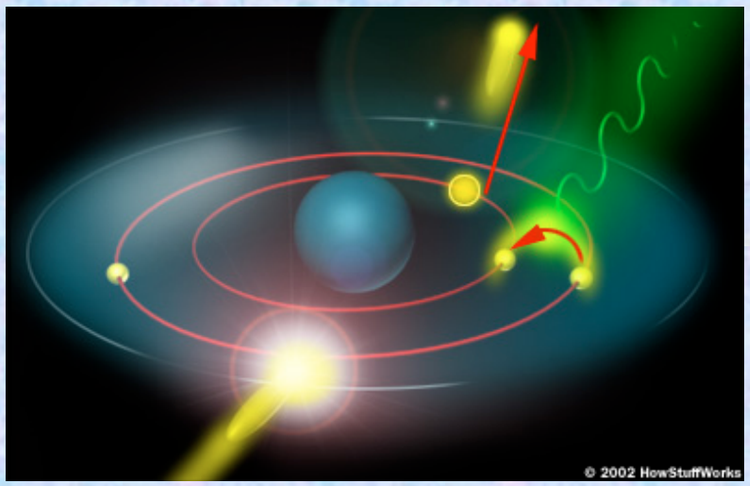


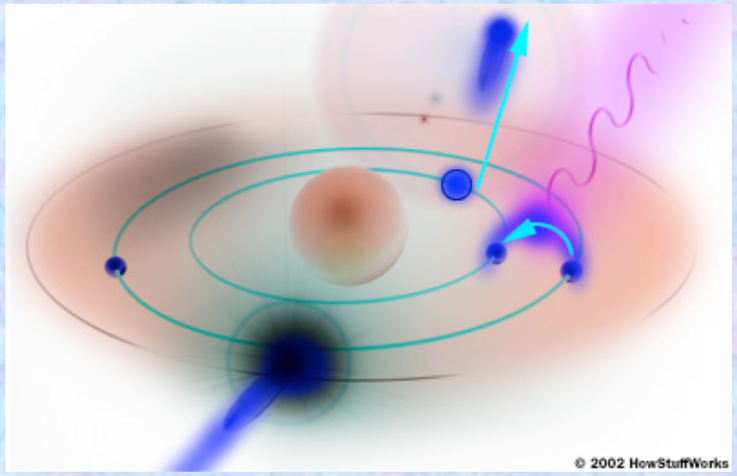
ATHENA

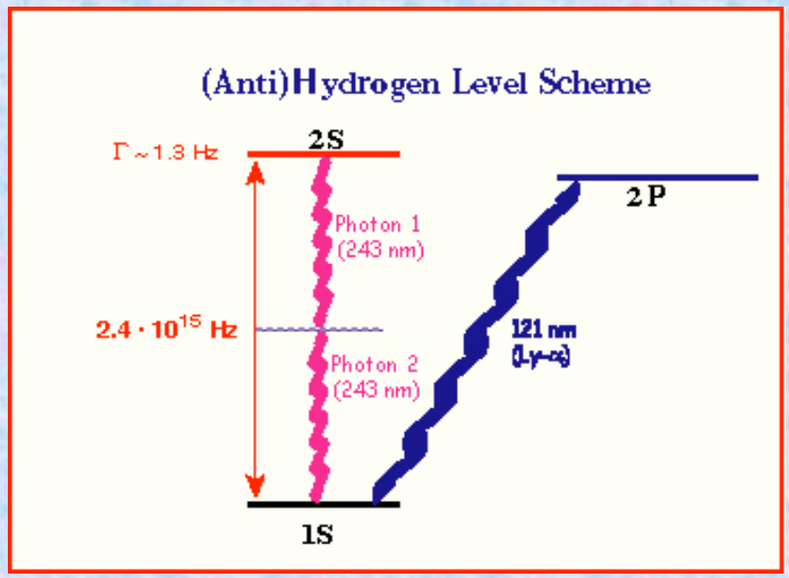


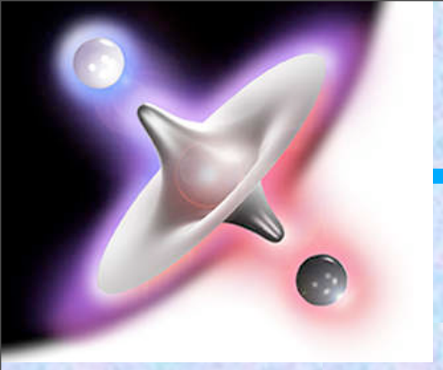


Antihydrogen = Hydrogen ??









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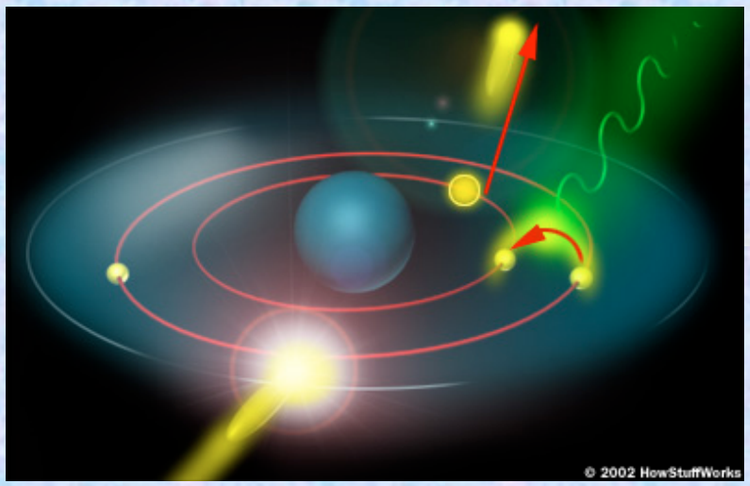
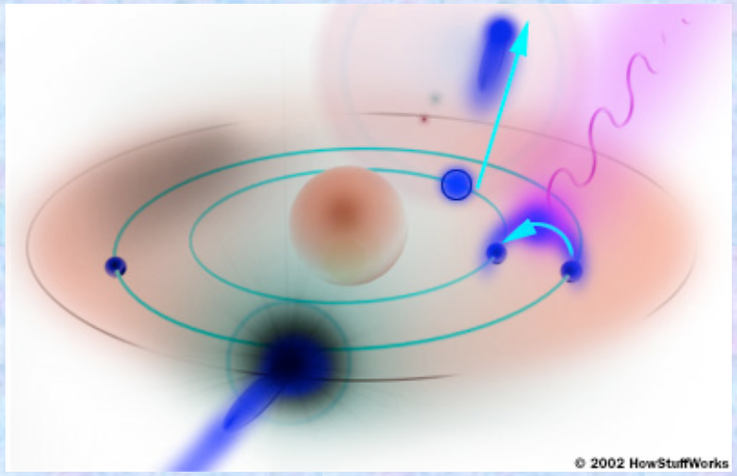
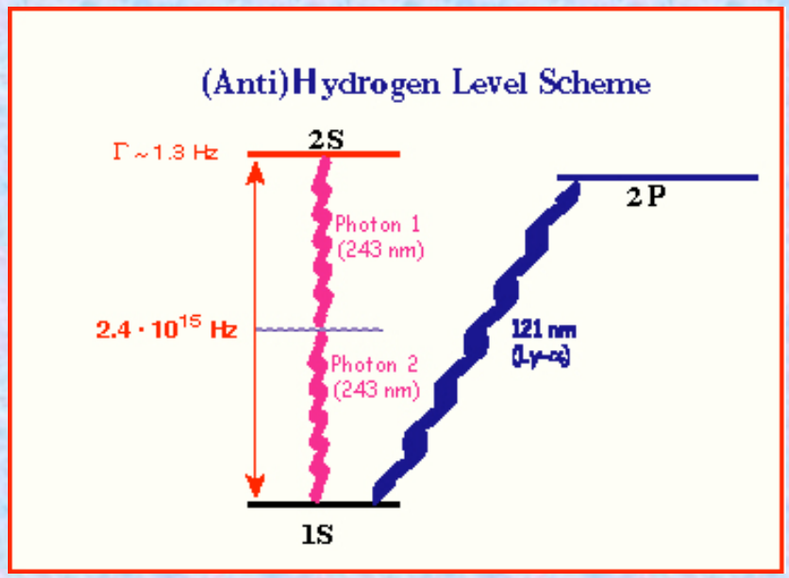
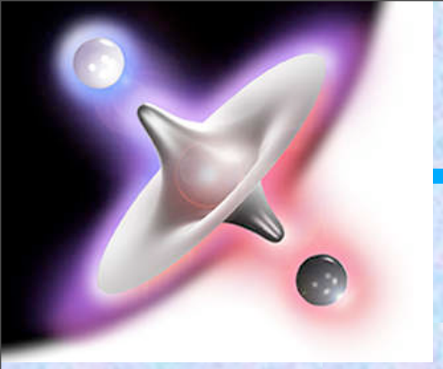




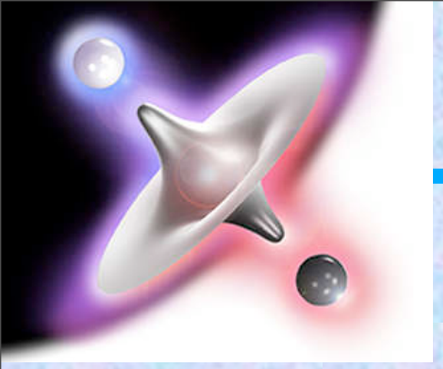


2S level is metastable (T ~ 120 ms)

→ 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



5 Steps to Antihydrogen

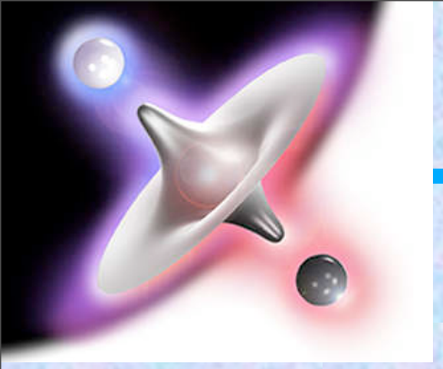


5 Steps to Antihydrogen

AD

p- Production (GeV)

Deceleration (MeV)



5 Steps to Antihydrogen

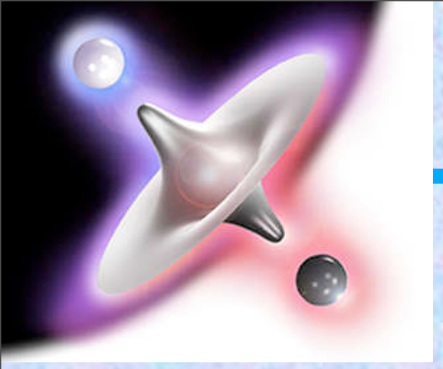
AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)



5 Steps to Antihydrogen

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

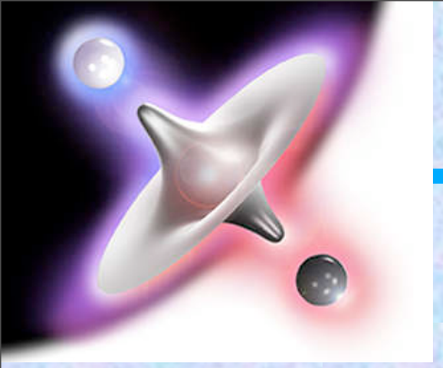
Cooling (meV)

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



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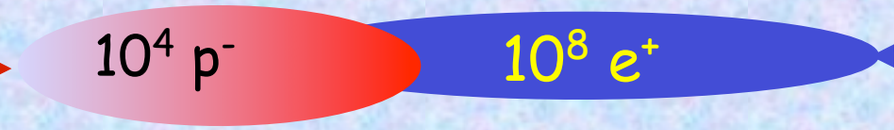
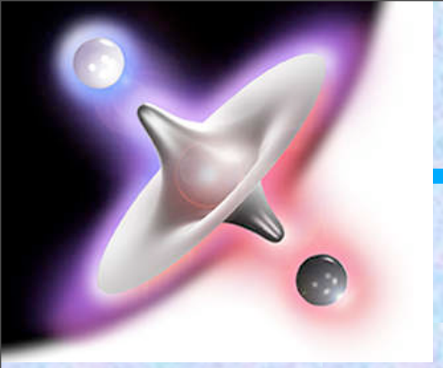


Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



5 Steps to Antihydrogen

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

Antihydrogen formation

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

Cooling (meV)

10^4 p^-

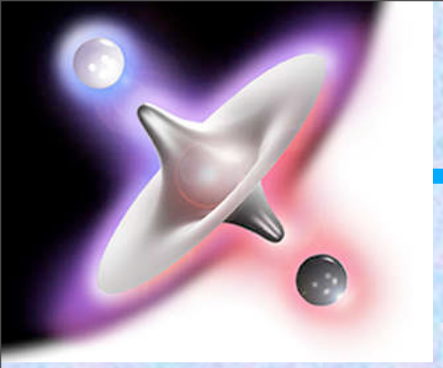
10^8 e^+

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



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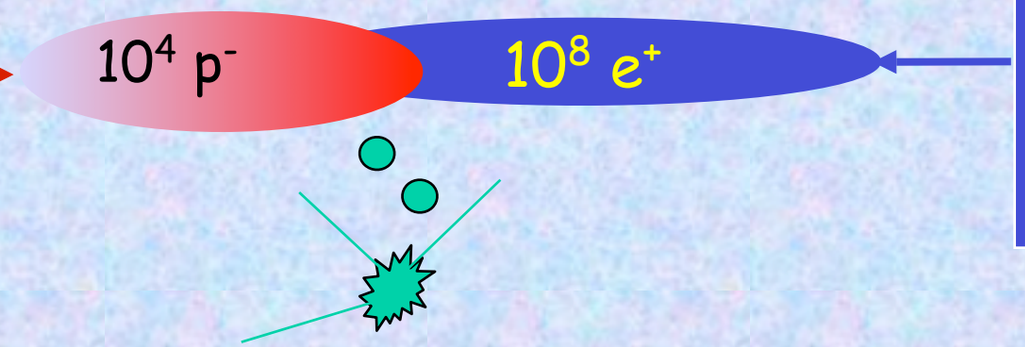


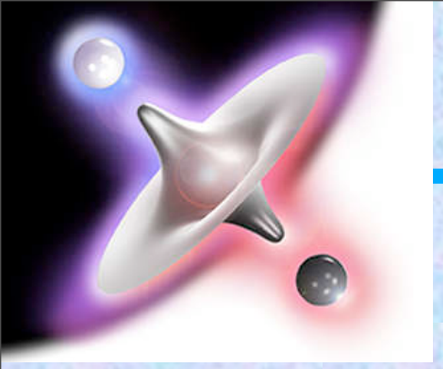
Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)

Detection of annihilation



Overview - ATHENA

Antiproton capture trap

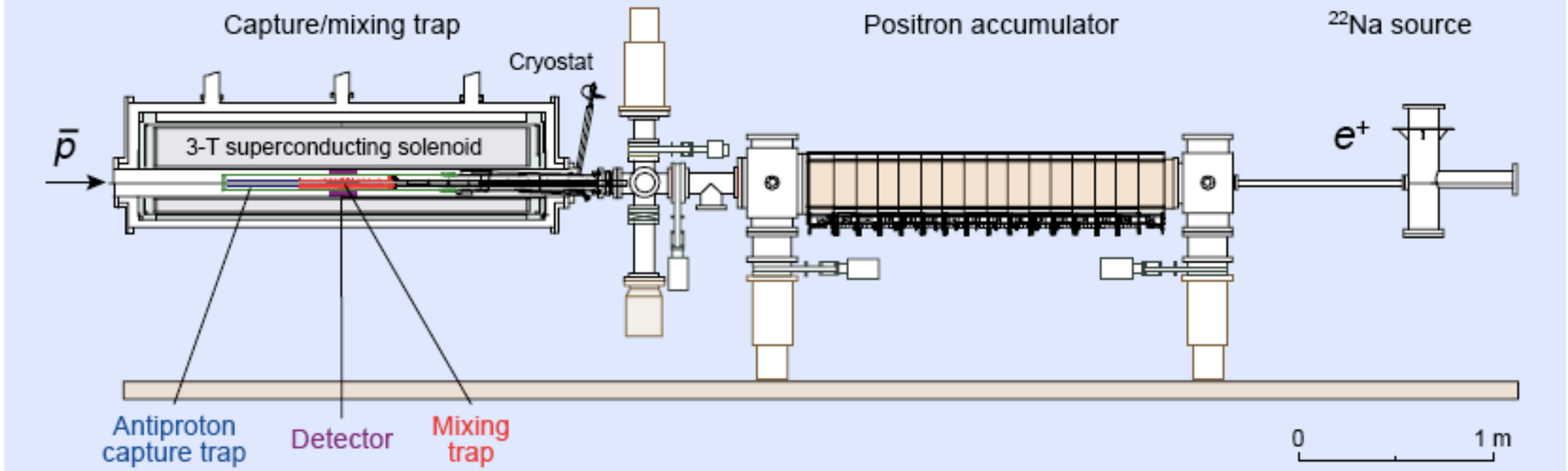
- Deceleration and capture of antiprotons
- Penning trap in 3-T field at 15 K
- Cooling and accumulation in e^- plasma

^{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



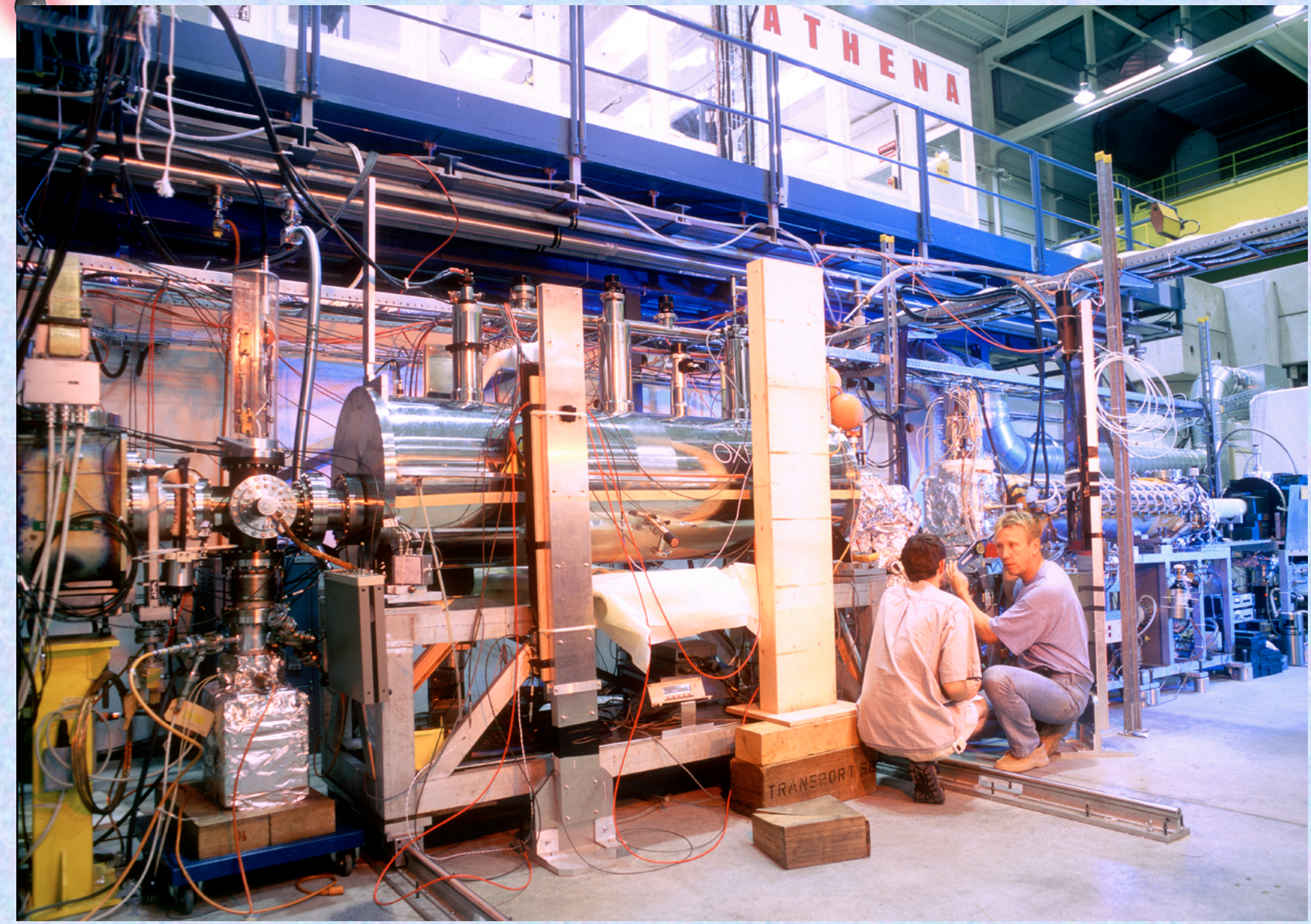
Mixing trap

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

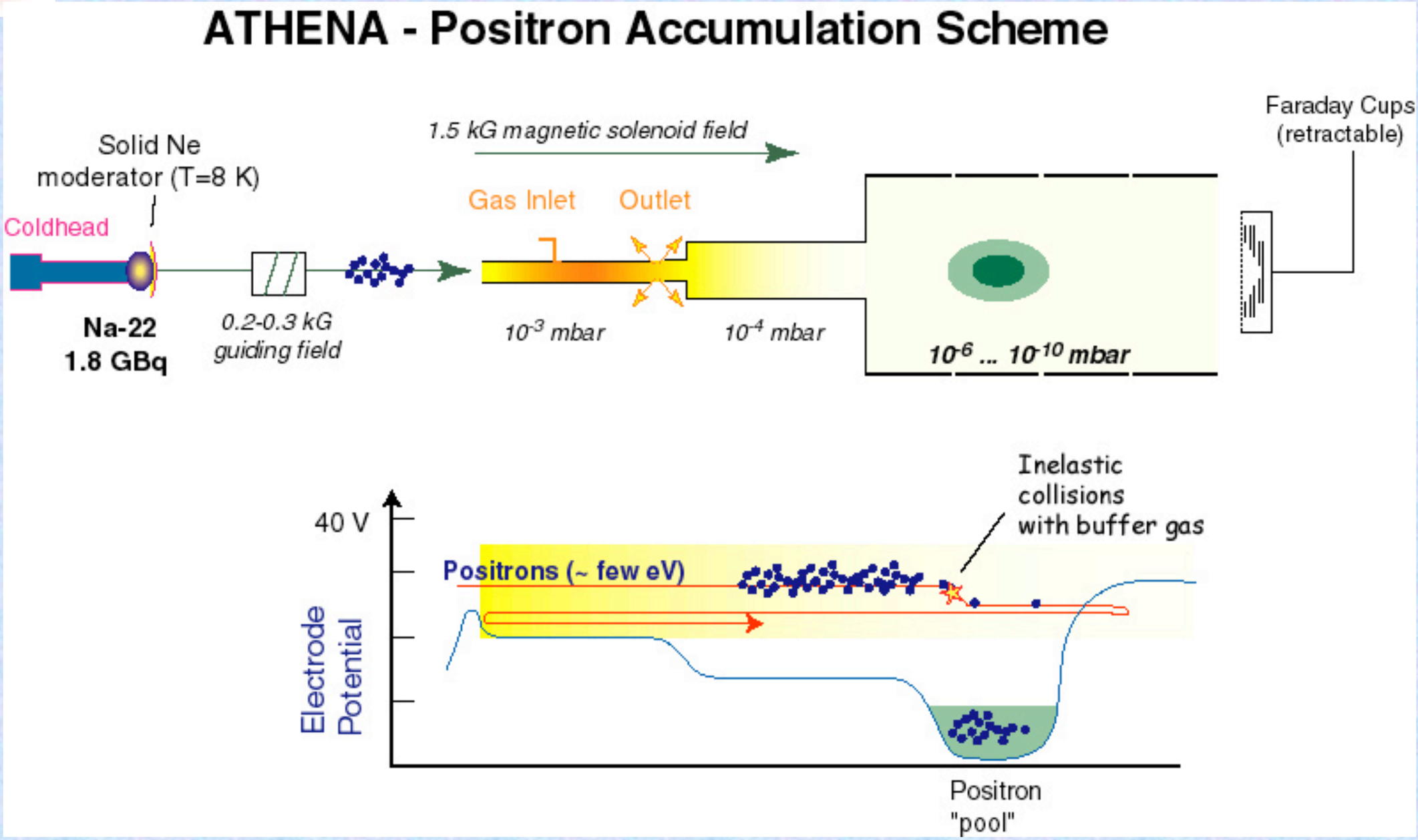
Detector

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

ATHENA Experiment



Positron Accumulation using Buffer Gas



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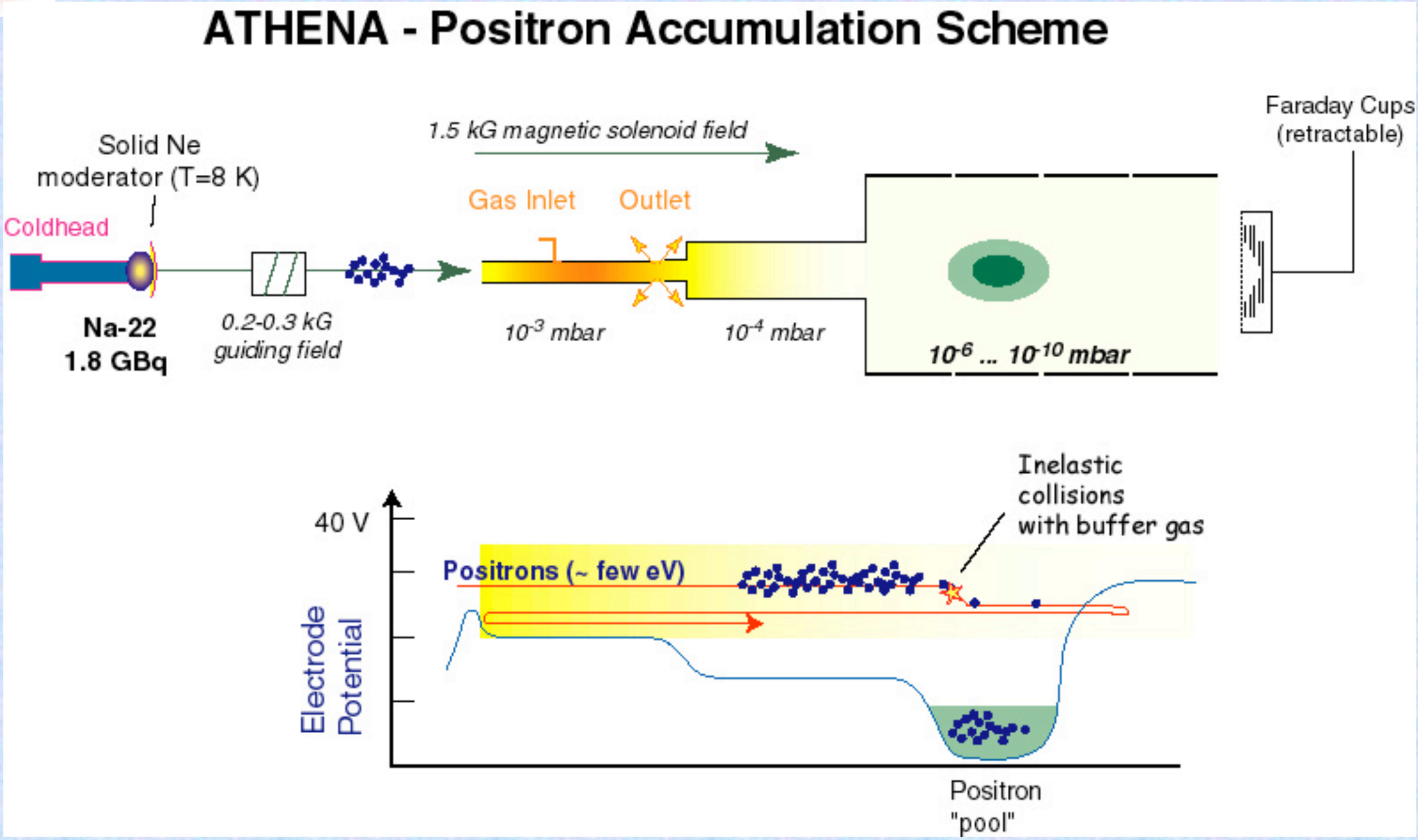
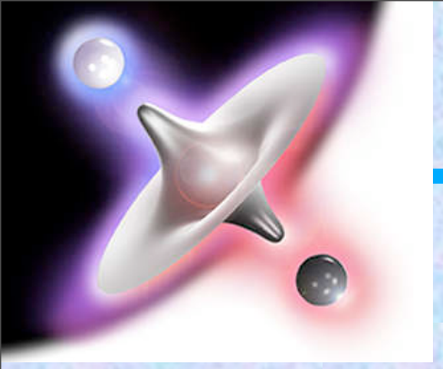
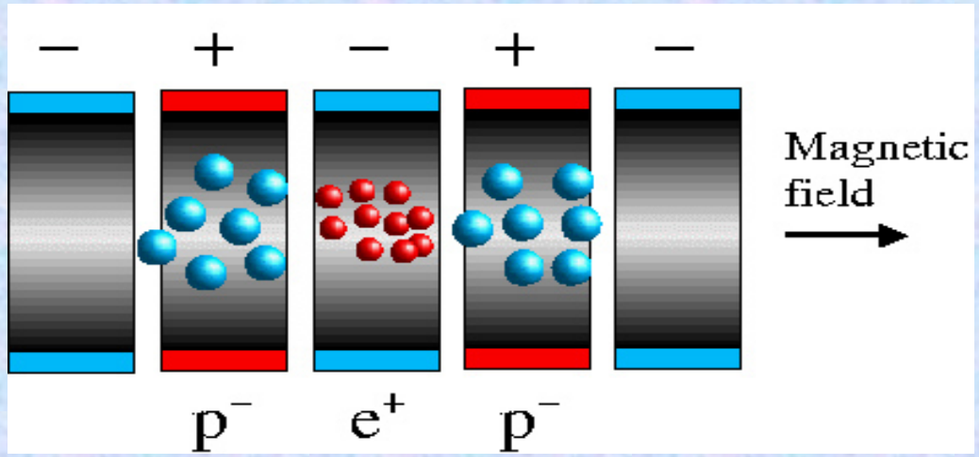
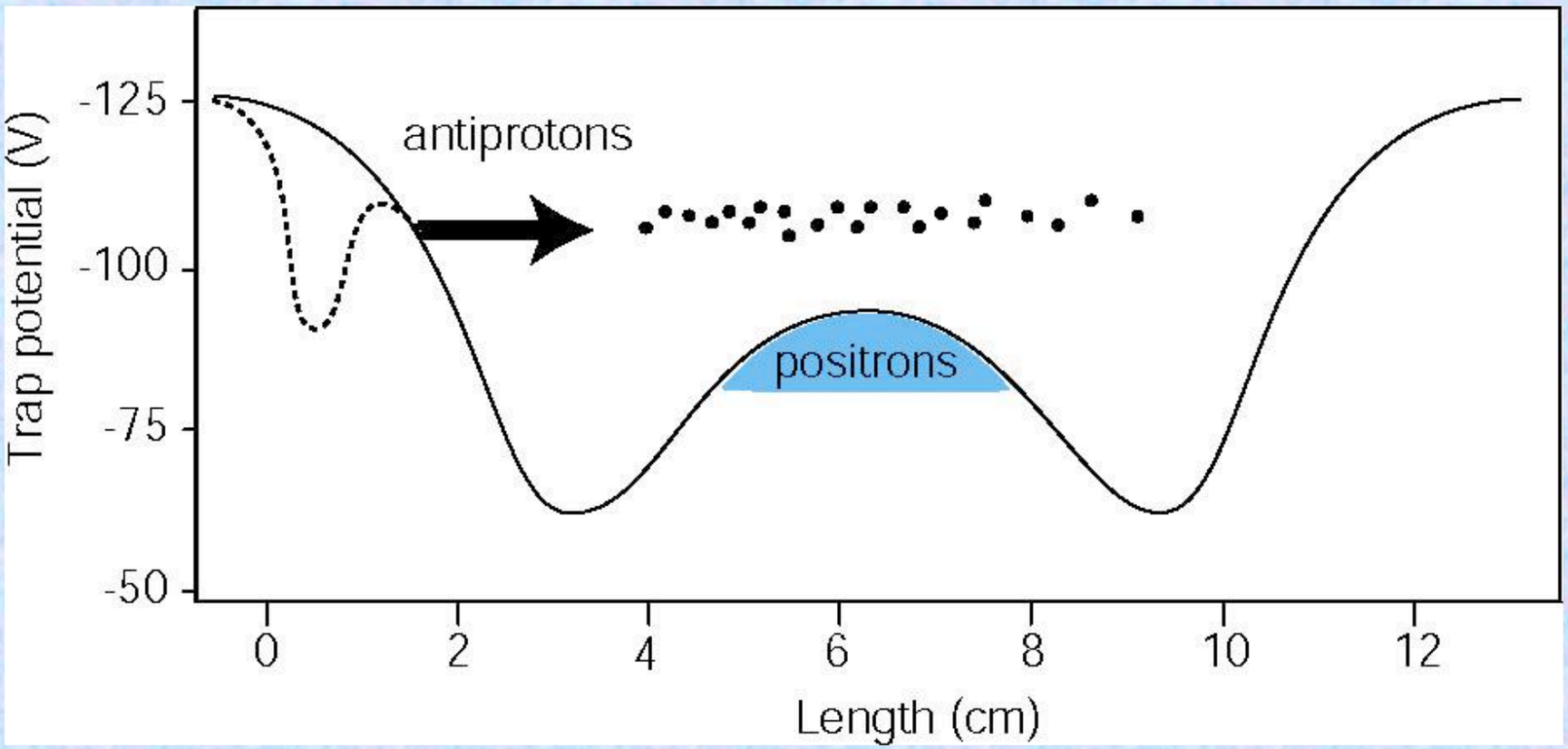


100 million positrons accumulated in 2 min

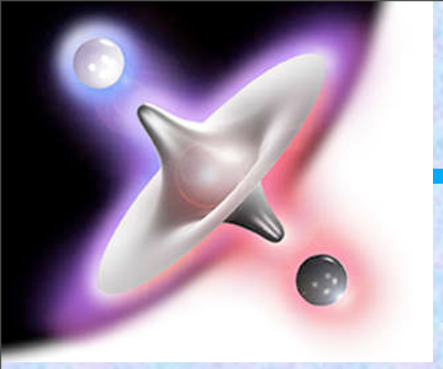


Recombination





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



Antihydrogen Detection

Charged particles

2 layers of Si microstrip detectors

511 keV gammas

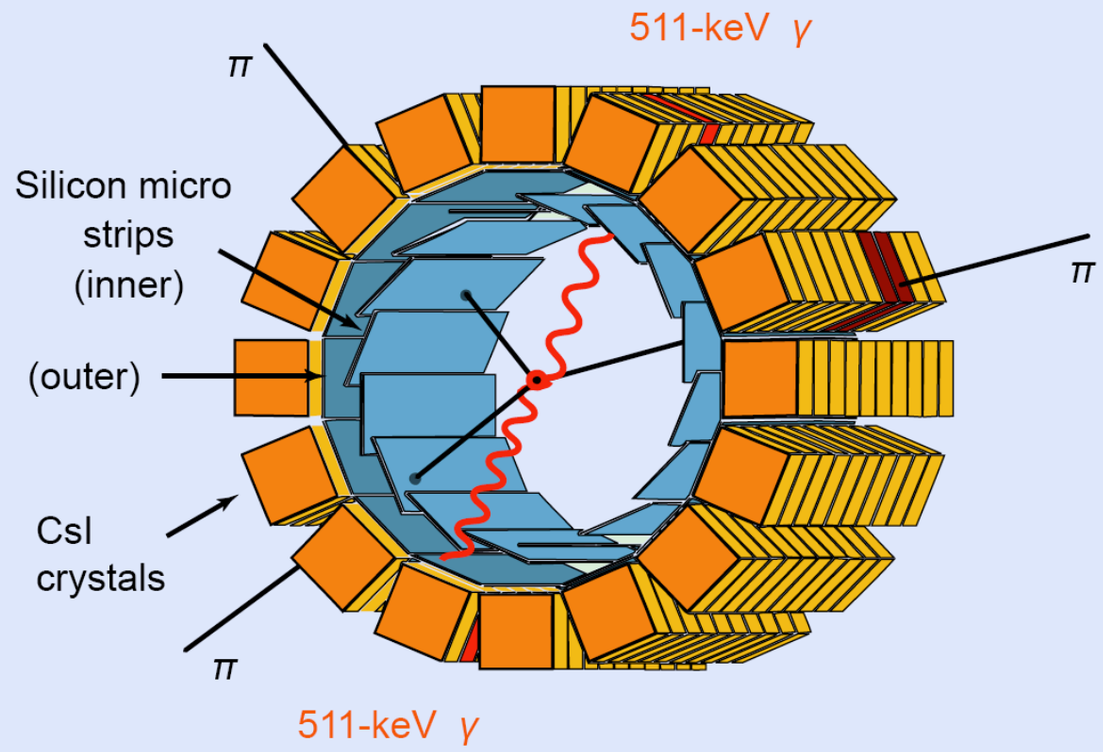
192 CsI crystals

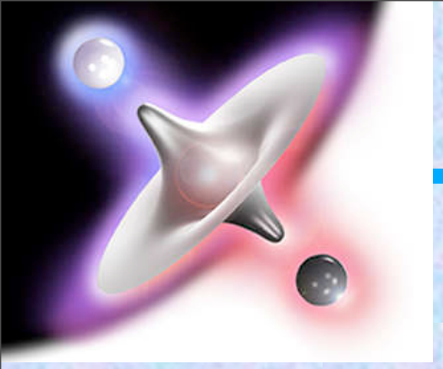
Inner radius 4 cm, thickness ~ 3 cm

70% solid angle coverage

Operates at 3 Tesla, 140 Kelvin

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





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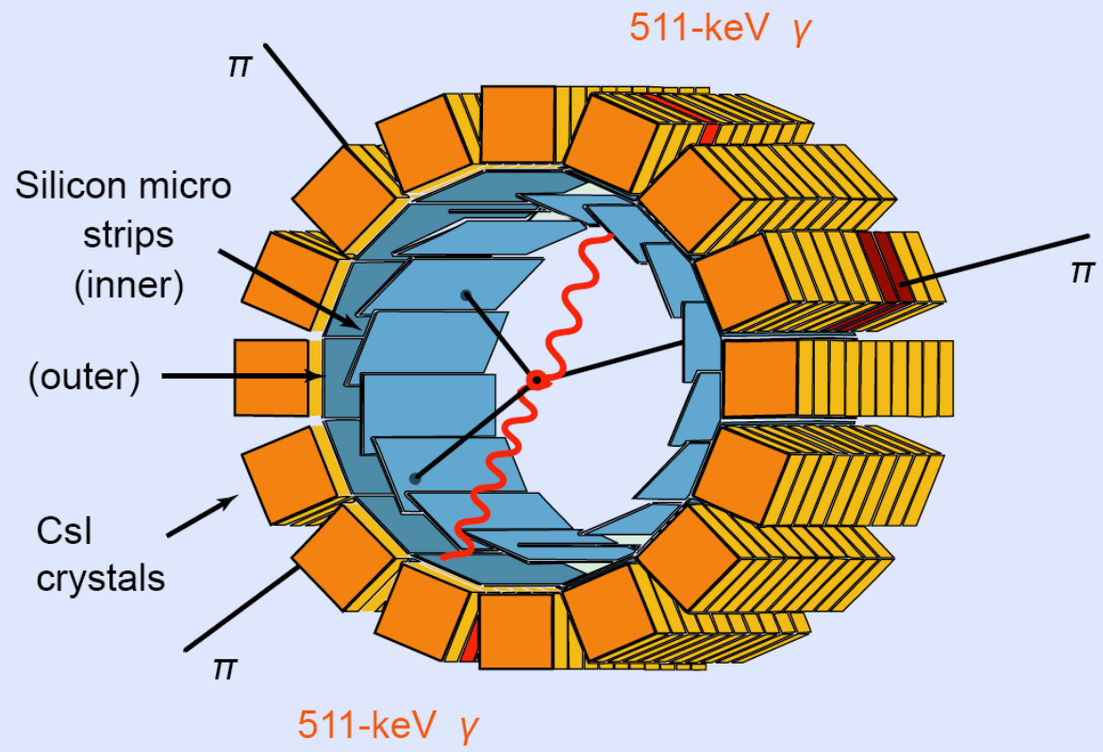
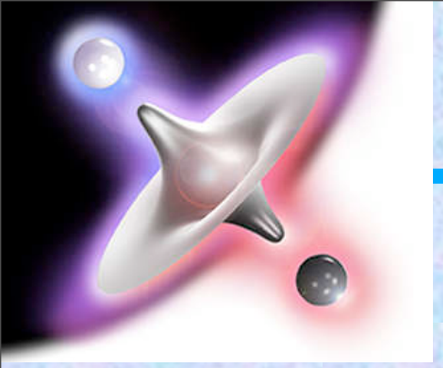


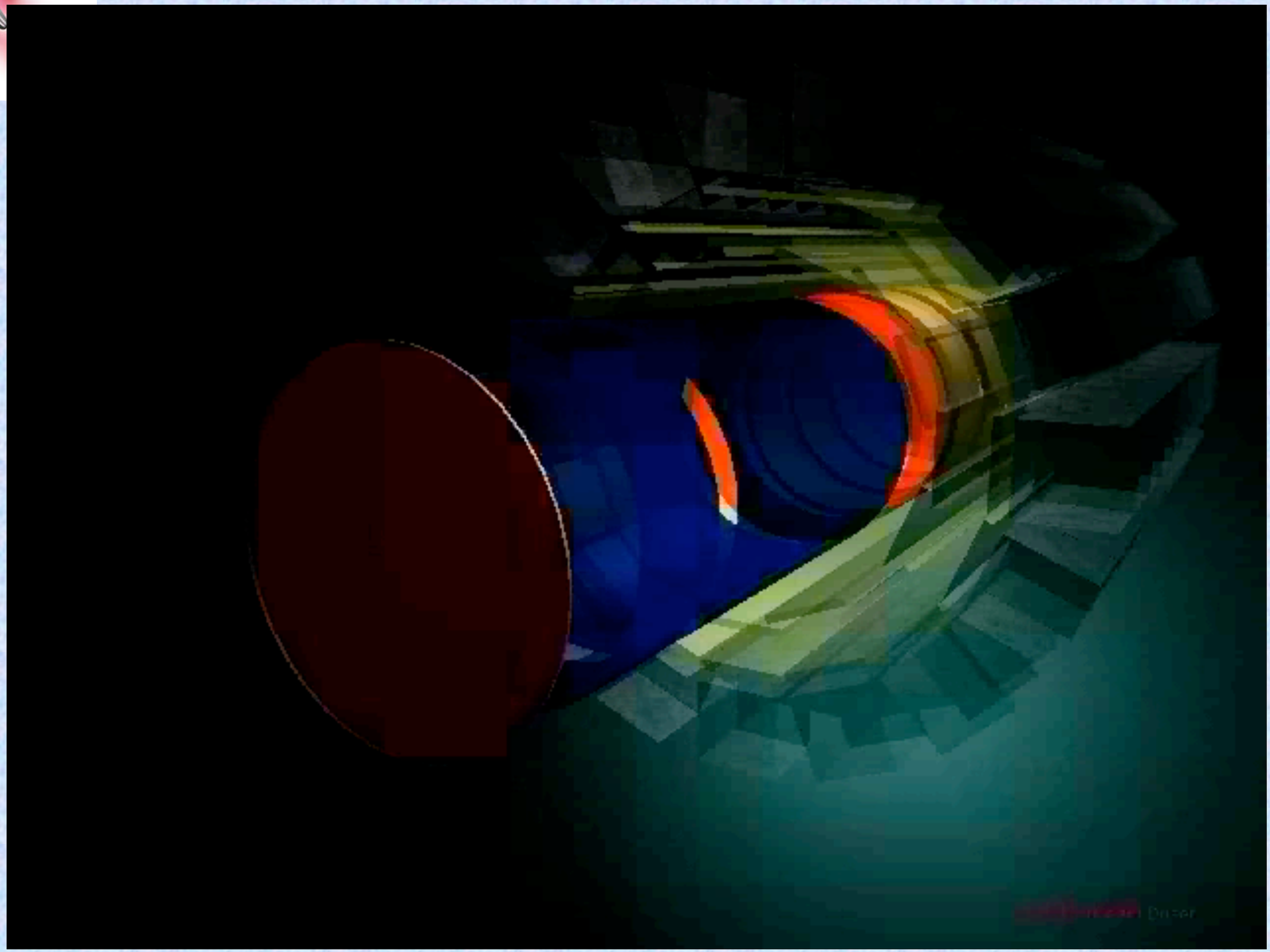
Event analysis:

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



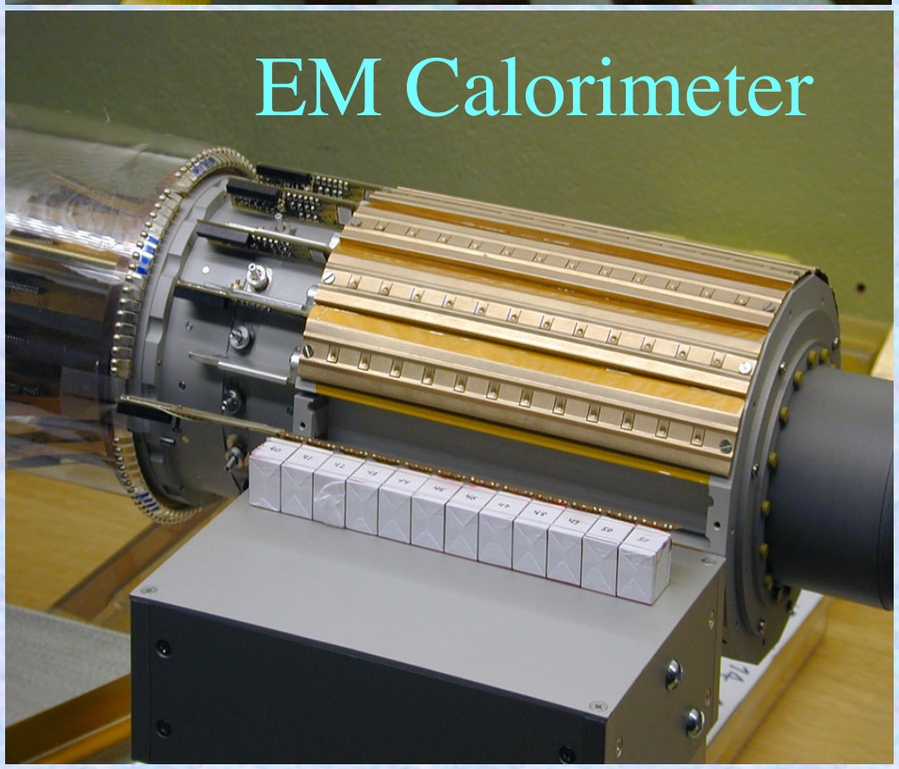
Antihydrogen - The Movie

Antihydrogen - The Movie

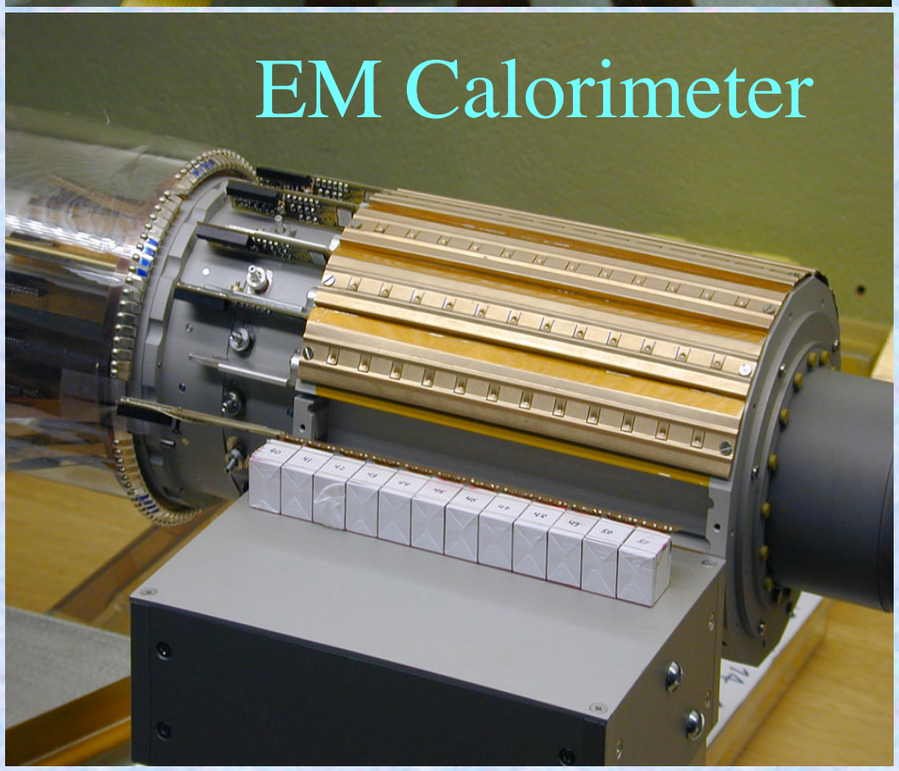


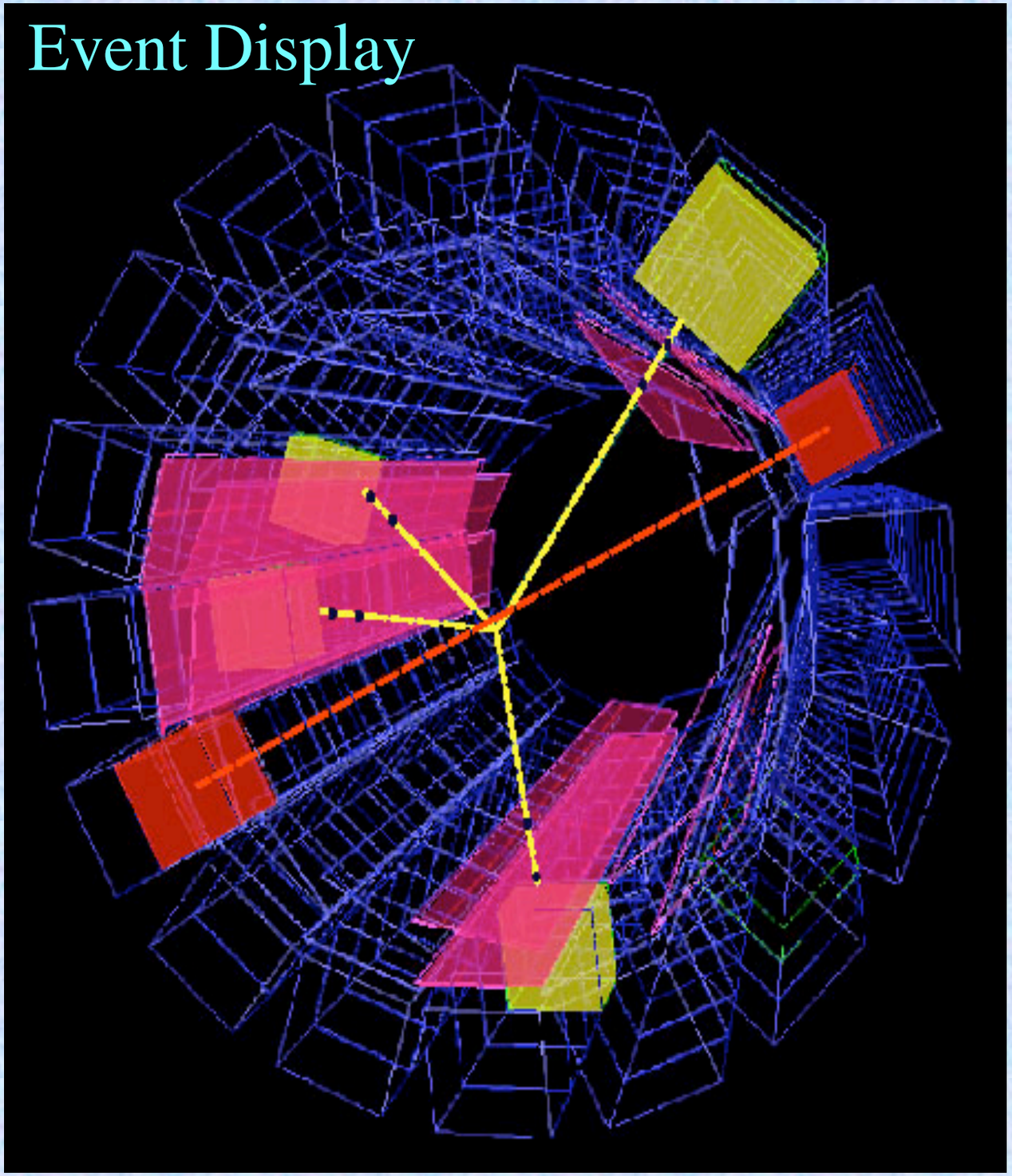
Antihydrogen Detector

Antihydrogen Detector



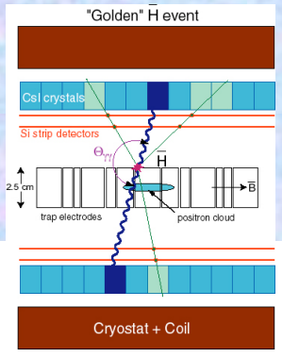
Antihydrogen Detector

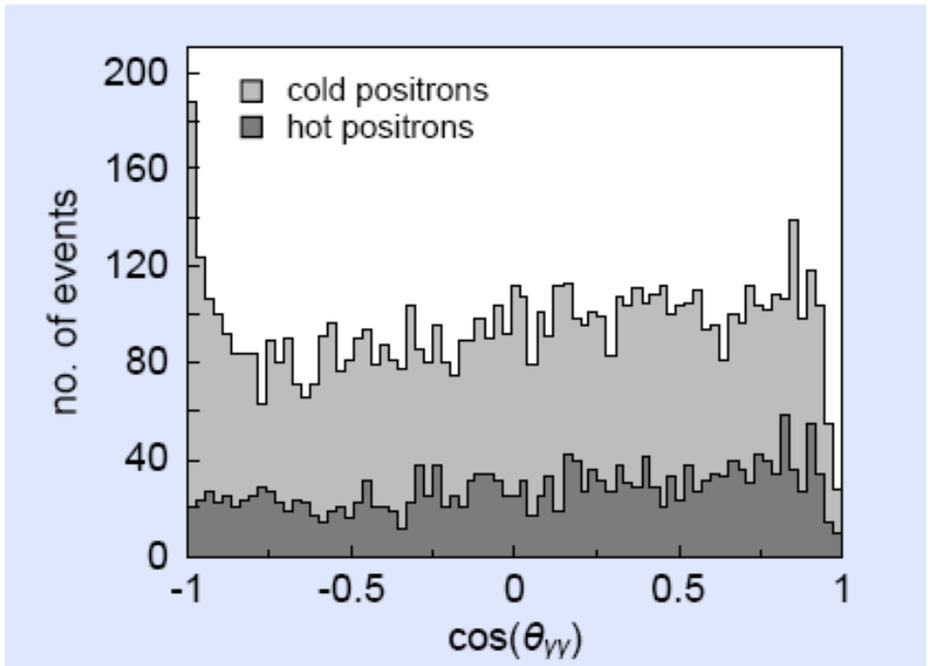




First observation of cold antihydrogen

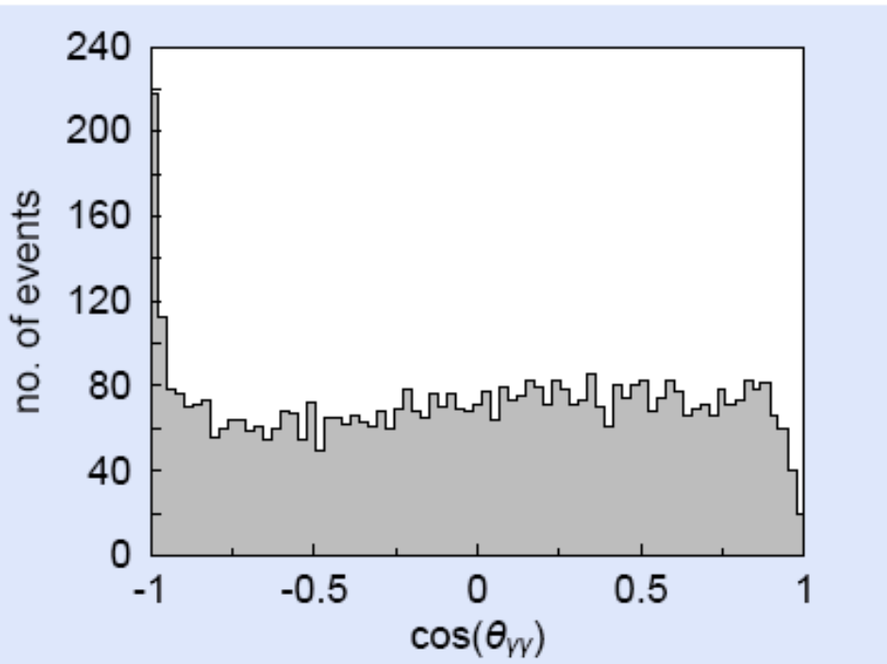
Opening Angle Distribution





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

Data

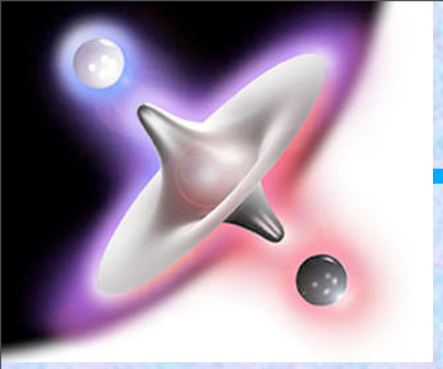


Monte Carlo

Peak from back-to-back 511 keV photon pairs

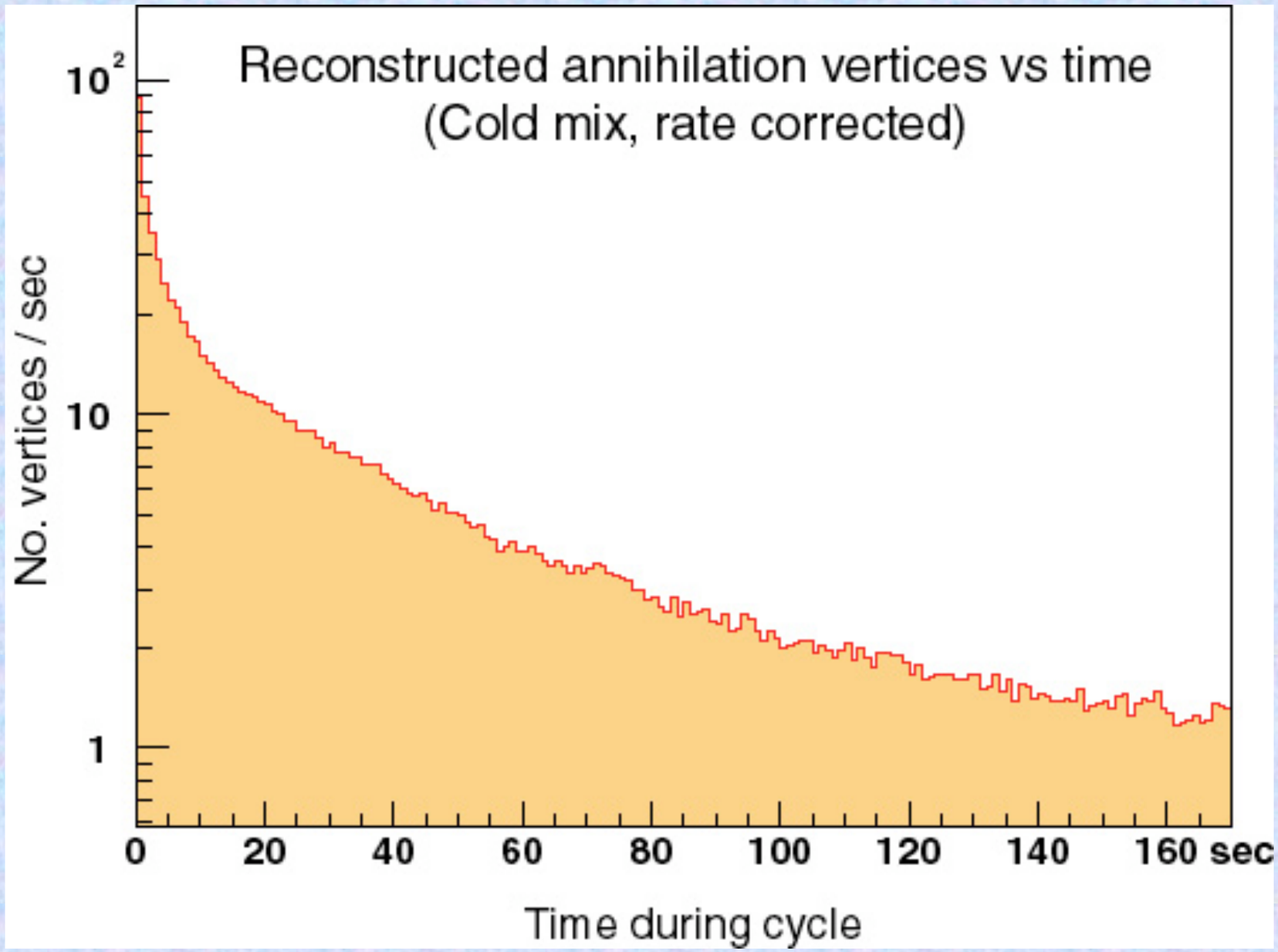
Test: peak disappears when positrons are 'heated' (RF)

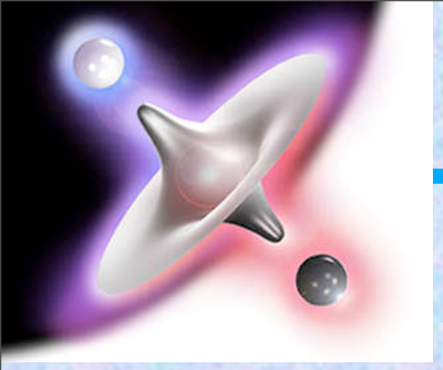
Correcting for detection efficiency: **> 100,000 anti-atoms**



Rate of antihydrogen production quite high

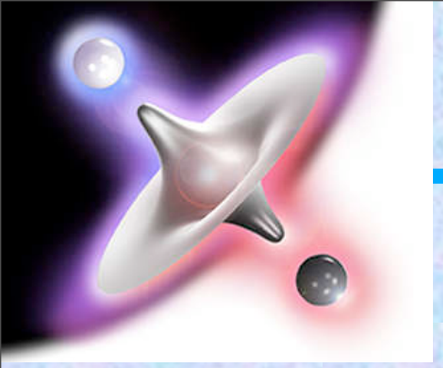
Initially > 100 Hz





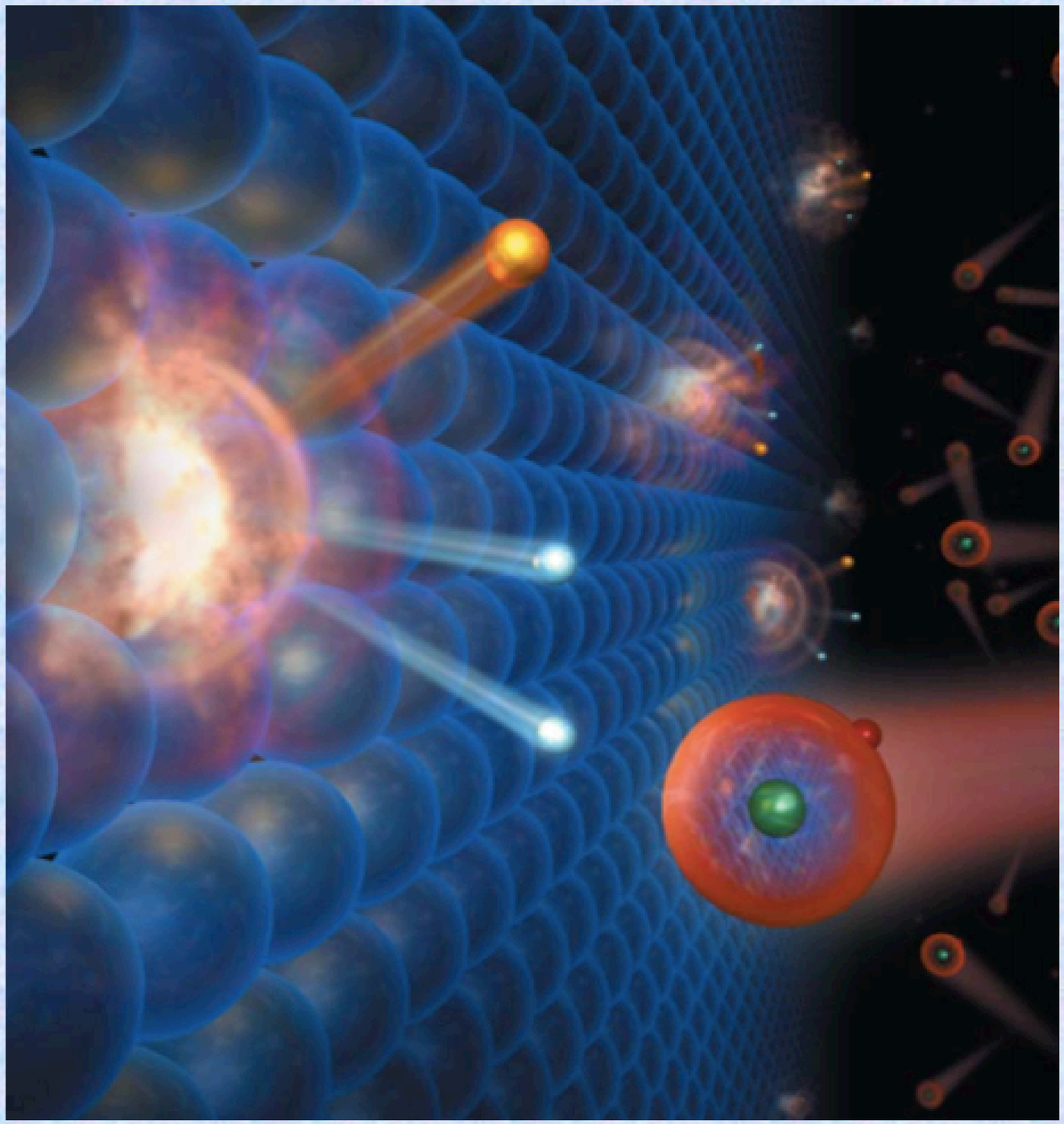
Present state of the art

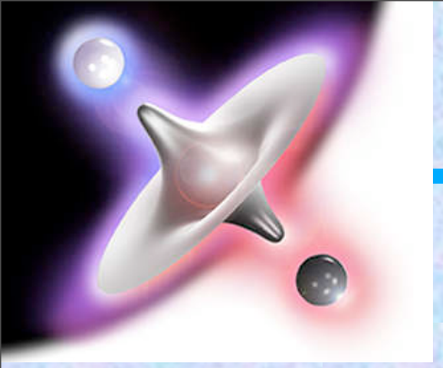
Number of produced antihydrogen atoms		Kinetic energy
1996:	9 (PS210, CERN)	2 GeV
1998:	60 (Fermilab)	3 GeV
2002:	> 1,000,000 (AD)	~ 0.001 eV



FUTURE DEVELOPMENTS

Next step: Trapping antihydrogen



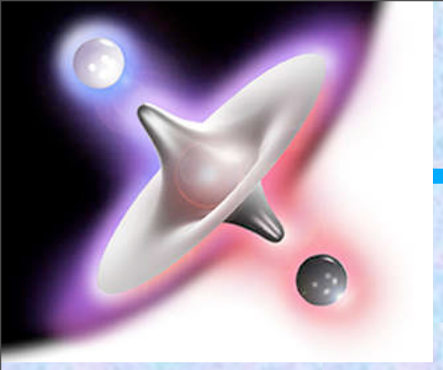


How to trap antihydrogen

1) magnetic moment (~ μ_{e+}) ?

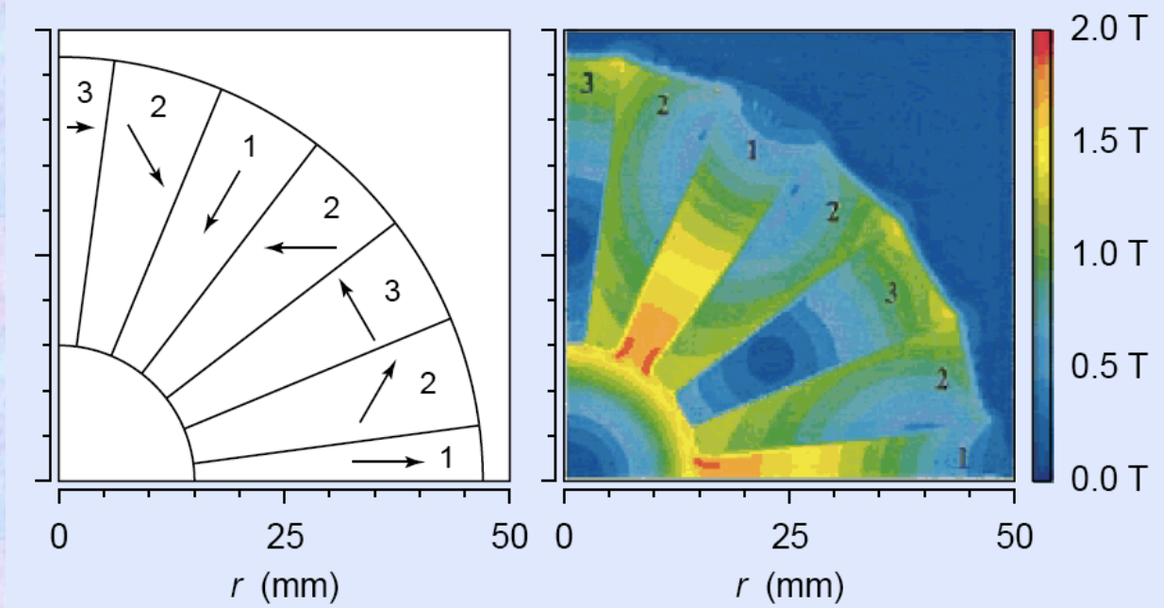
2) Laser cooling at 121.5 nm ?

3) Other methods ??



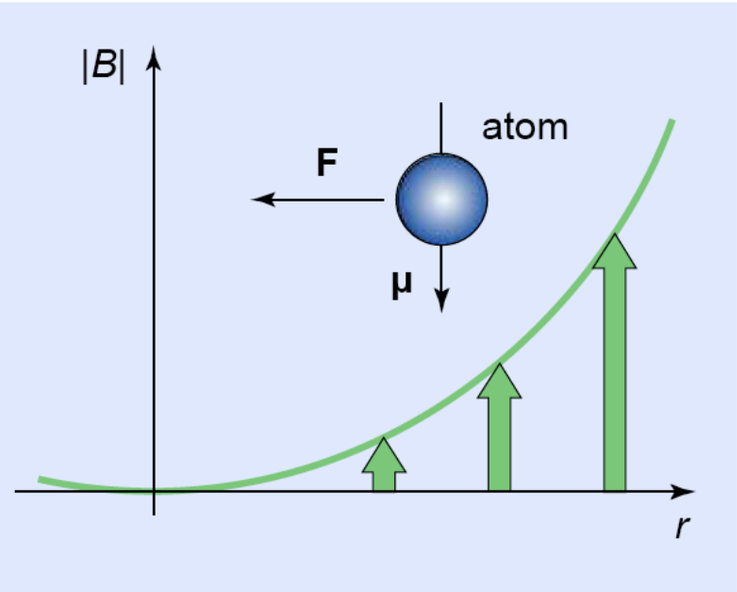
Magnetic bottles ?

Example: Sextupole magnet



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

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



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

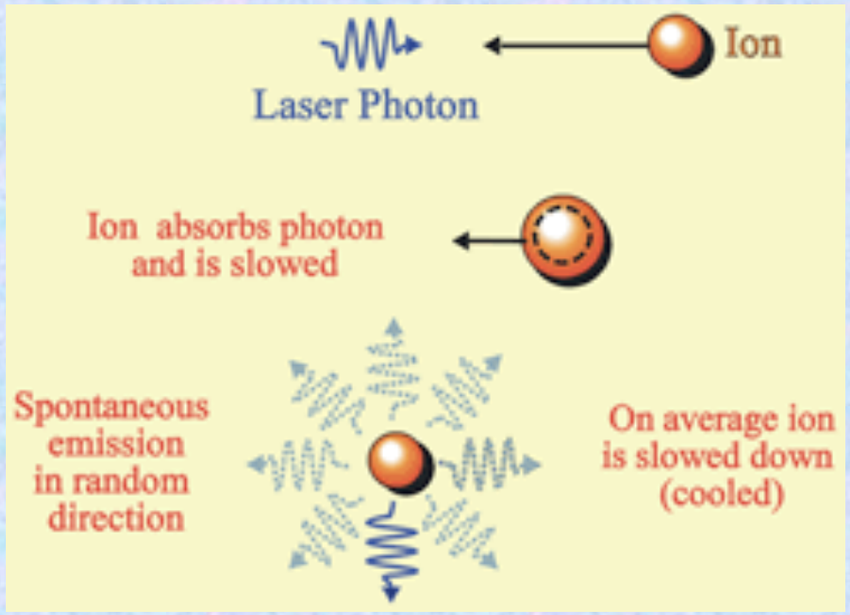
BUT: Very shallow potential (~ 0.07 meV/T)

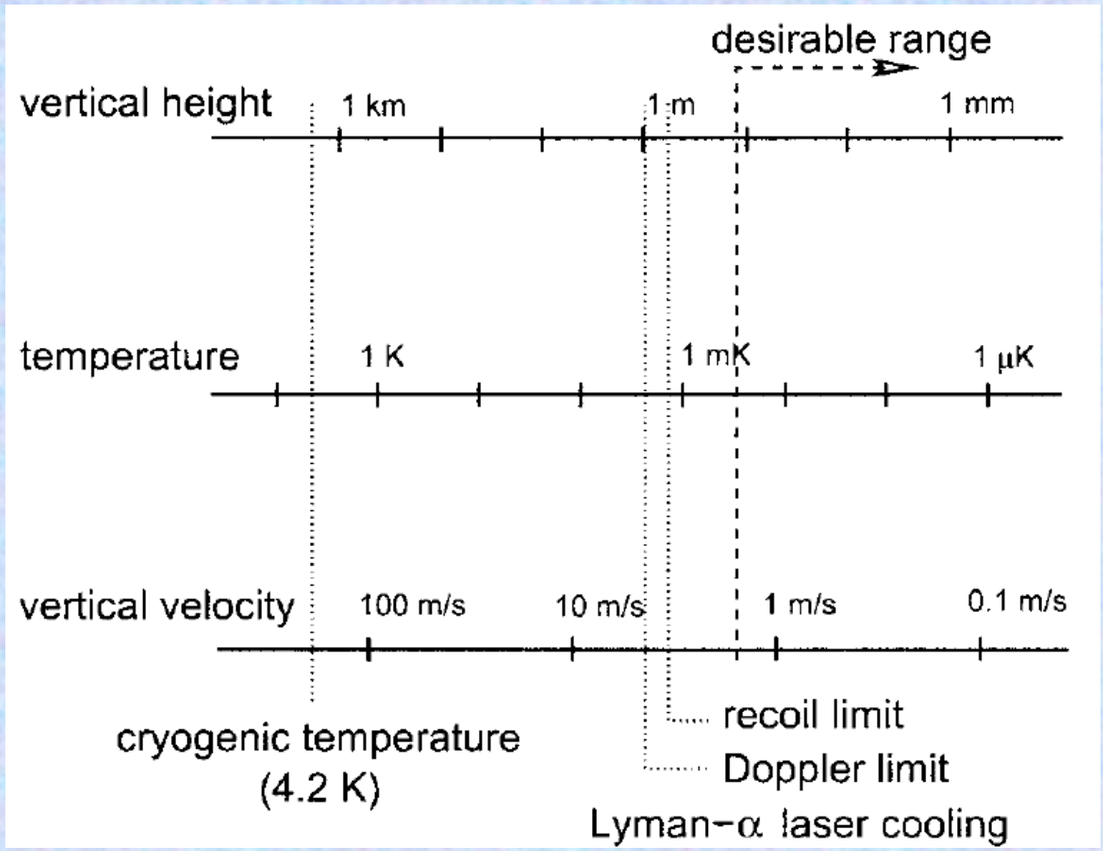
Realistic ΔB ~ 0.2-0.3 T ➪ **E < 0.02 meV**

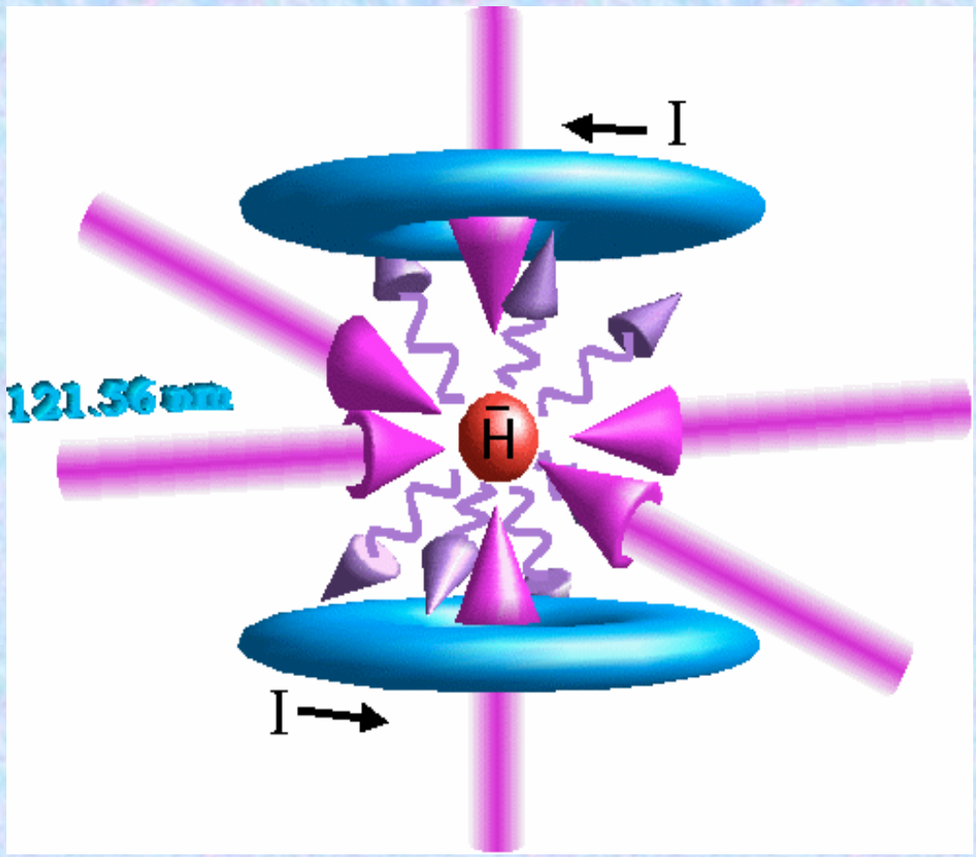
(reminder: produced antihydrogen has E_{kin} ~ 1-200 meV)

Hope for low energy 'Boltzmann tail' (ALPHA, ATRAP)

Antihydrogen trapping: Laser cooling ?



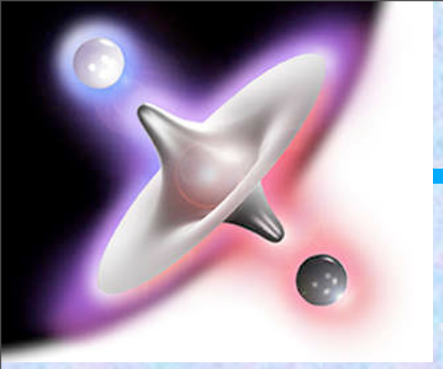




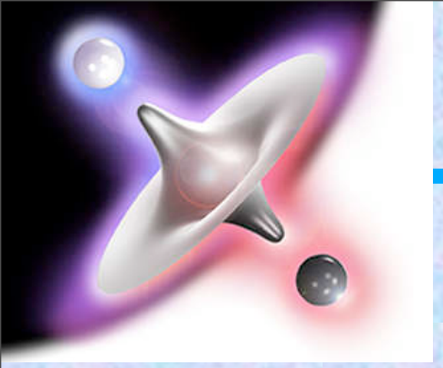
121 nm laser needed

Prototype at MPI Munich

… only 50 nW

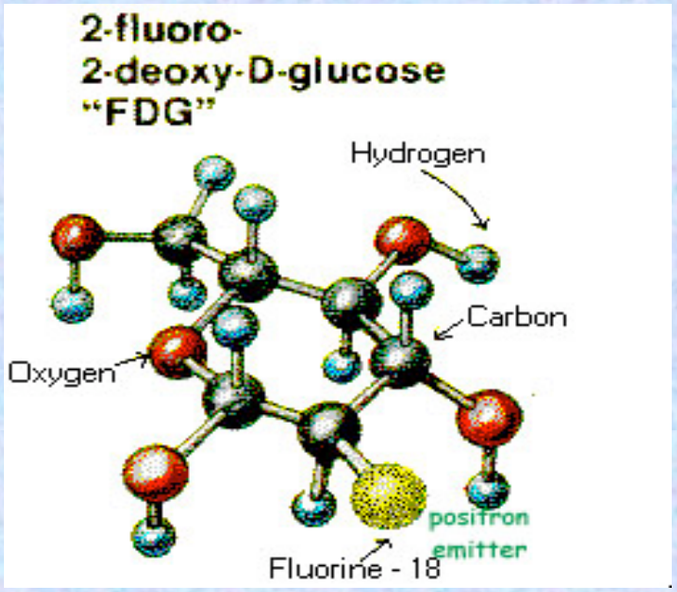


V. APPLICATIONS

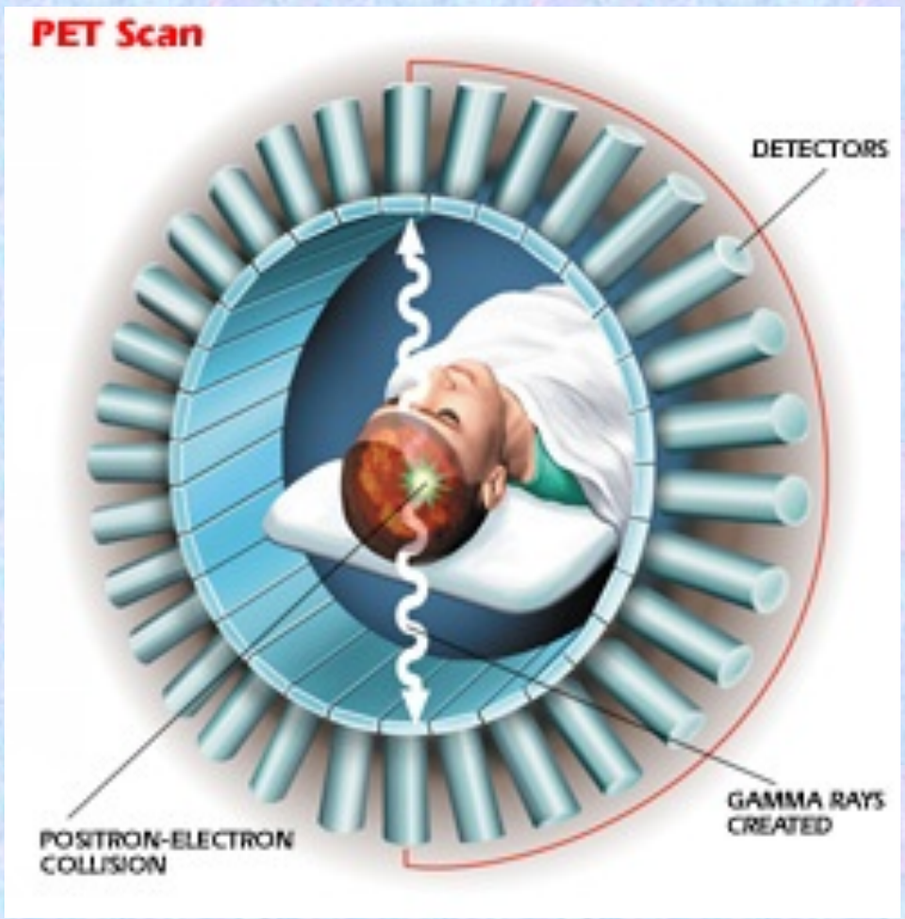


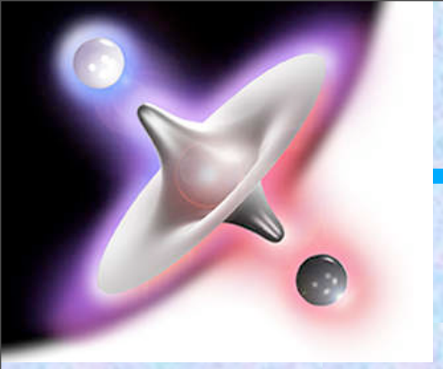
Applications of antimatter - PET

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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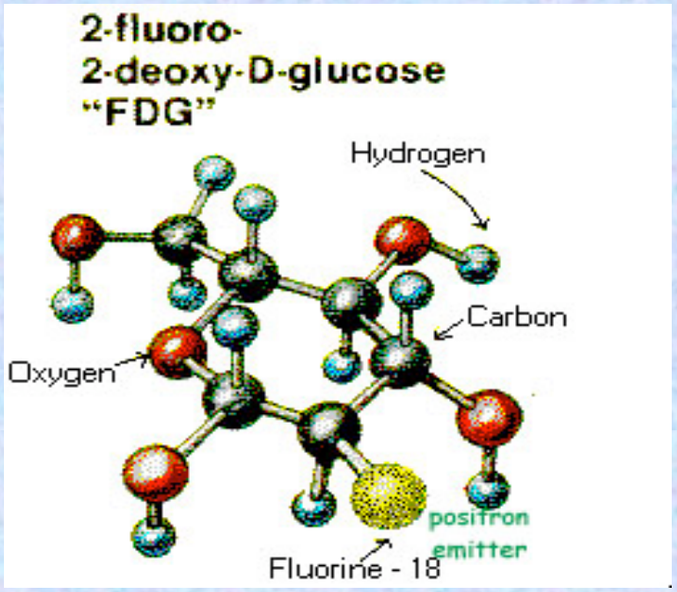

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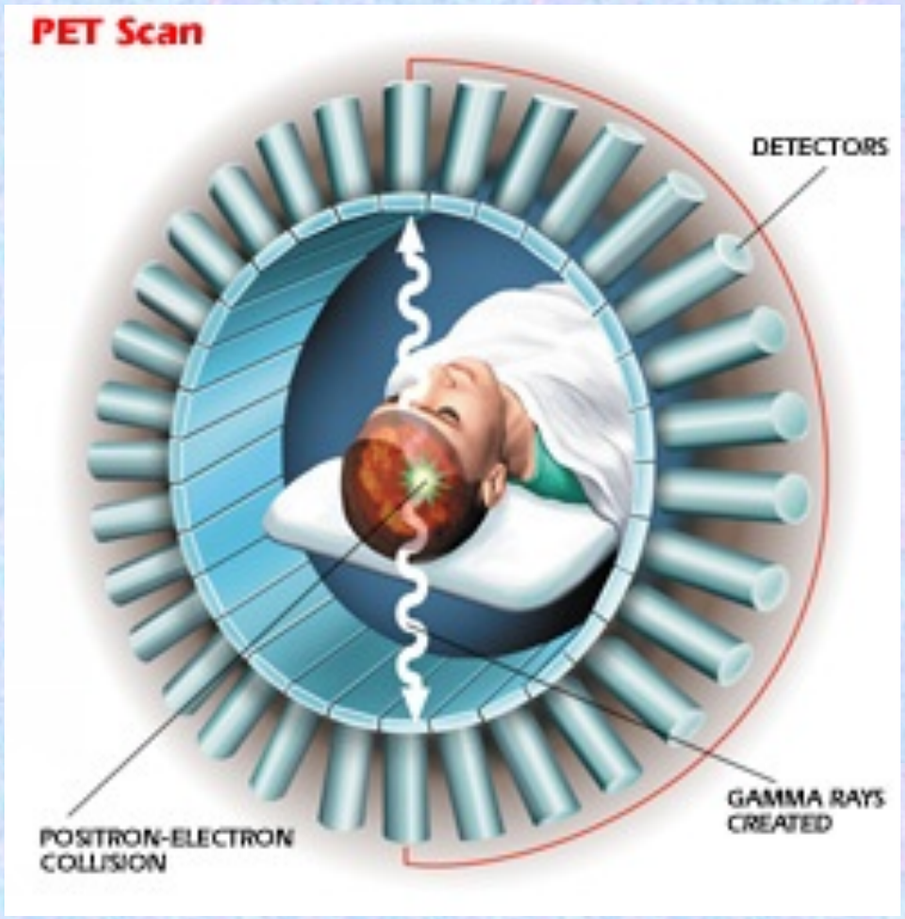
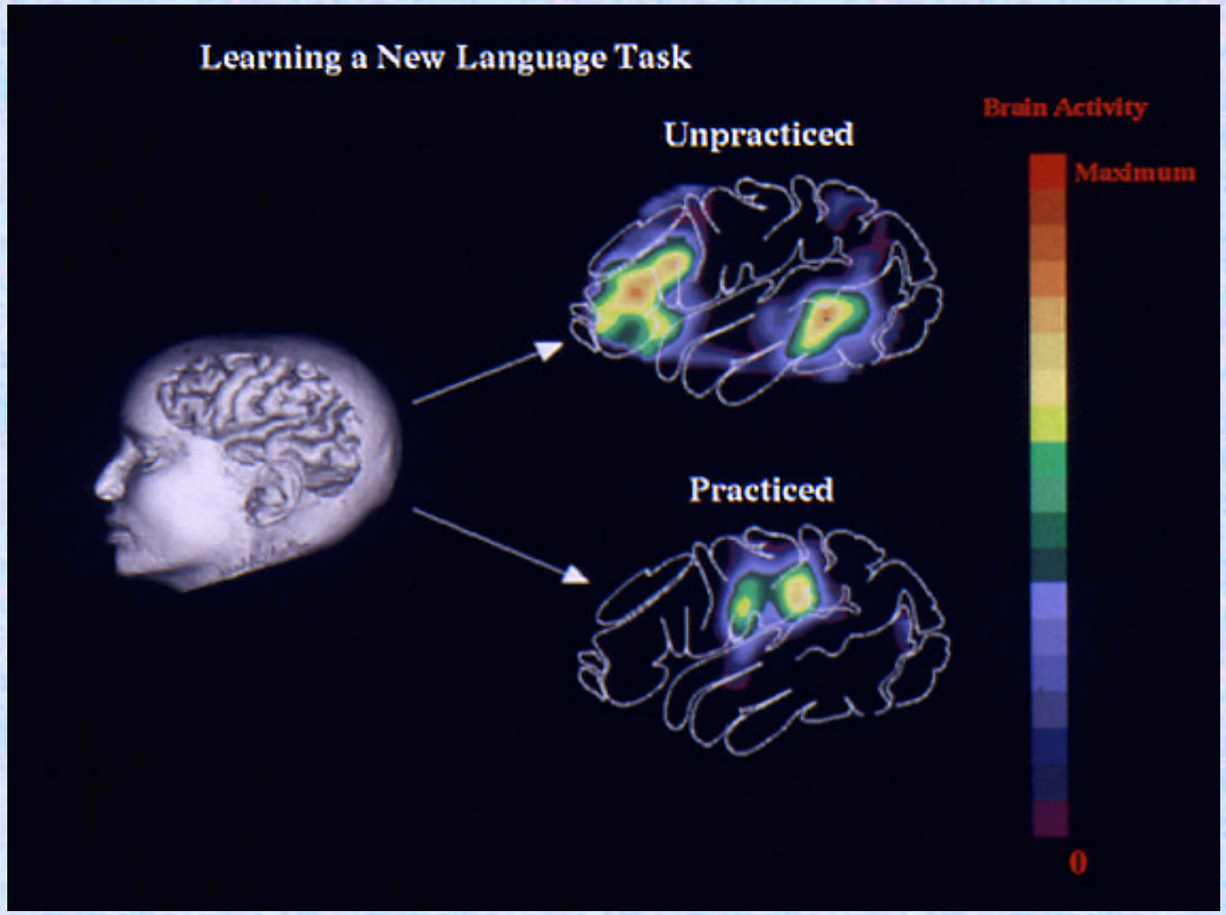
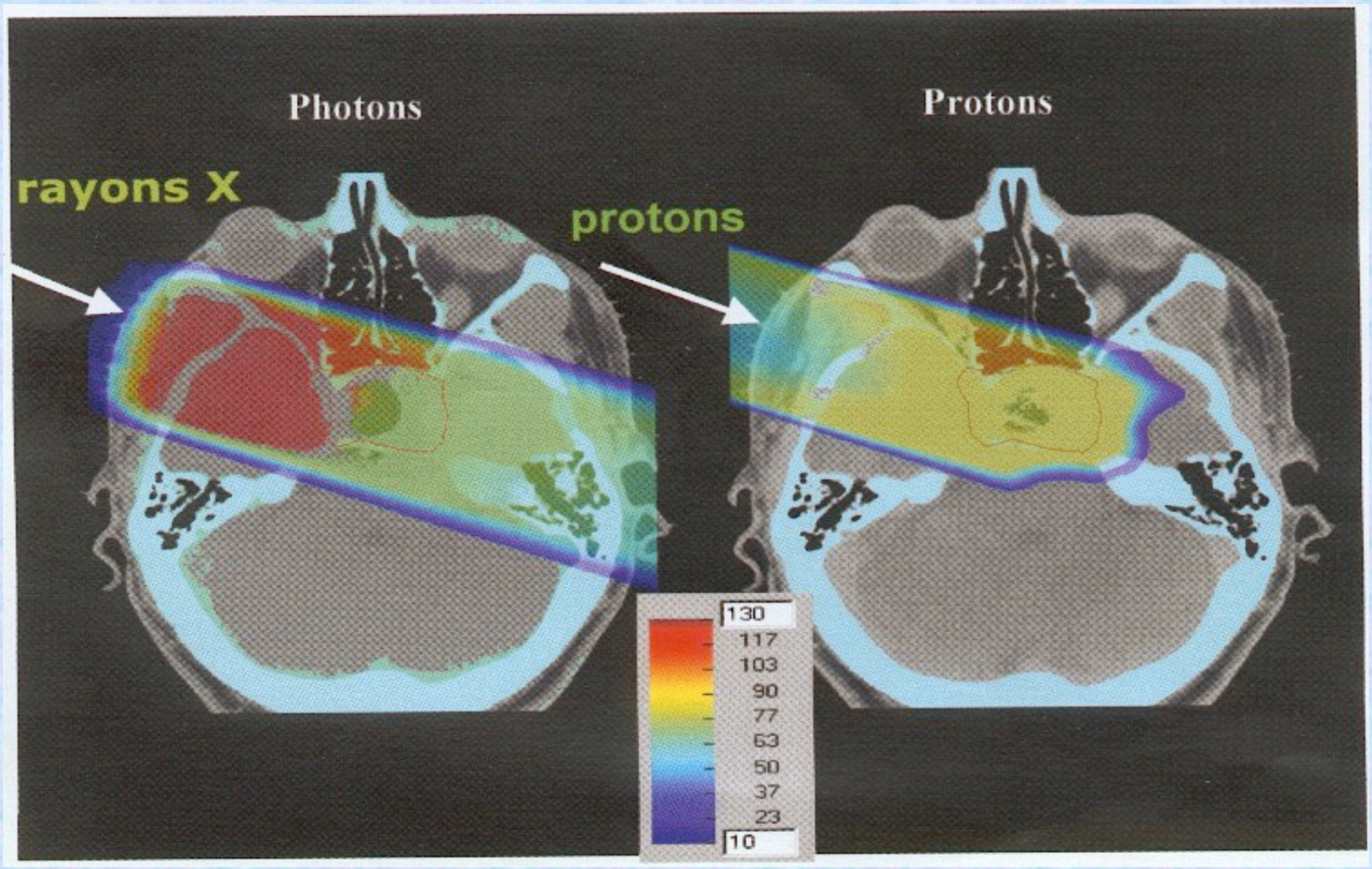


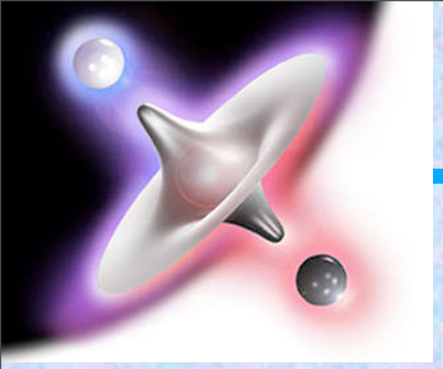


Tumour therapy

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

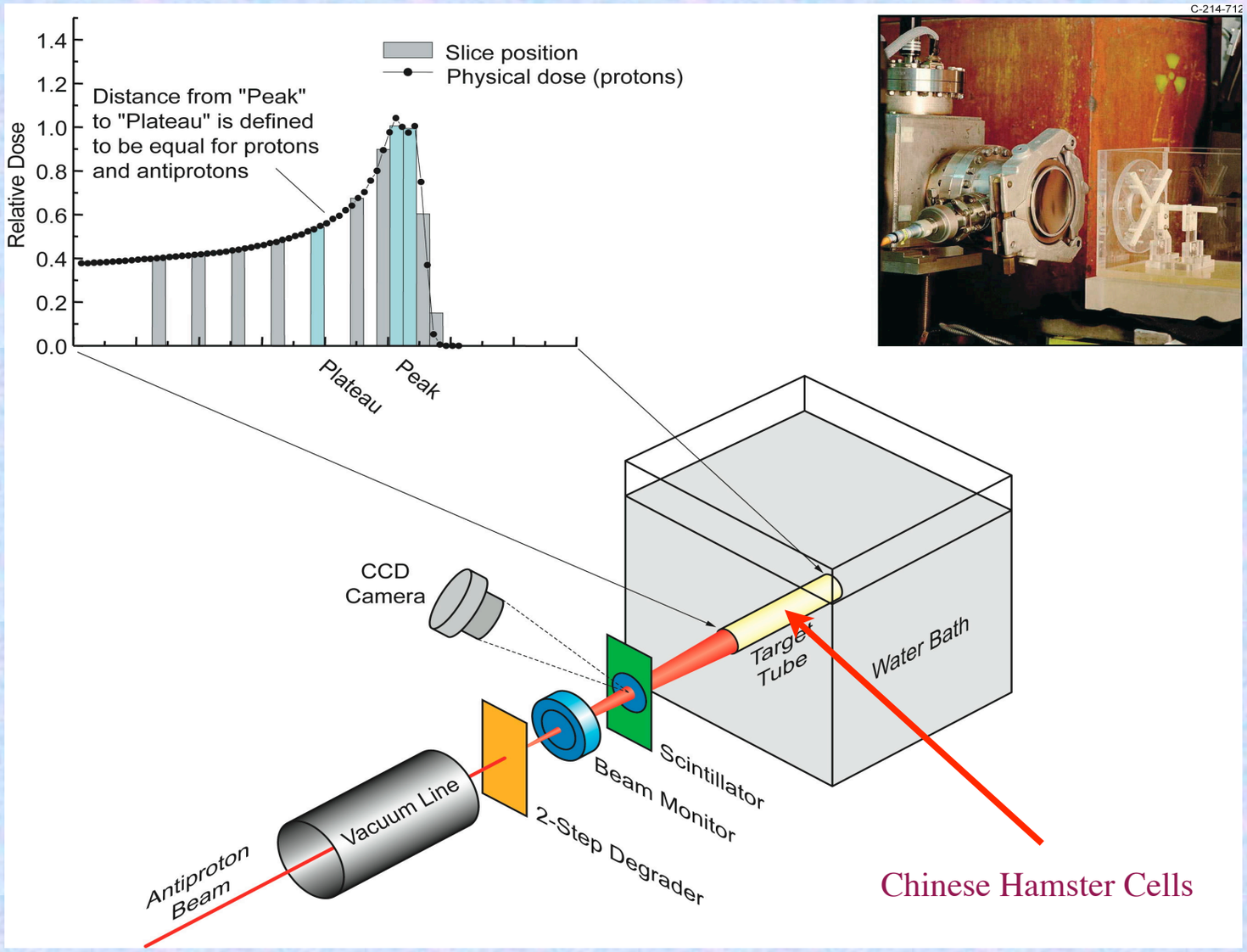


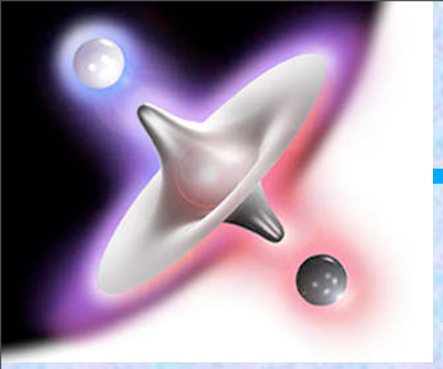


Antiproton Cell Experiment

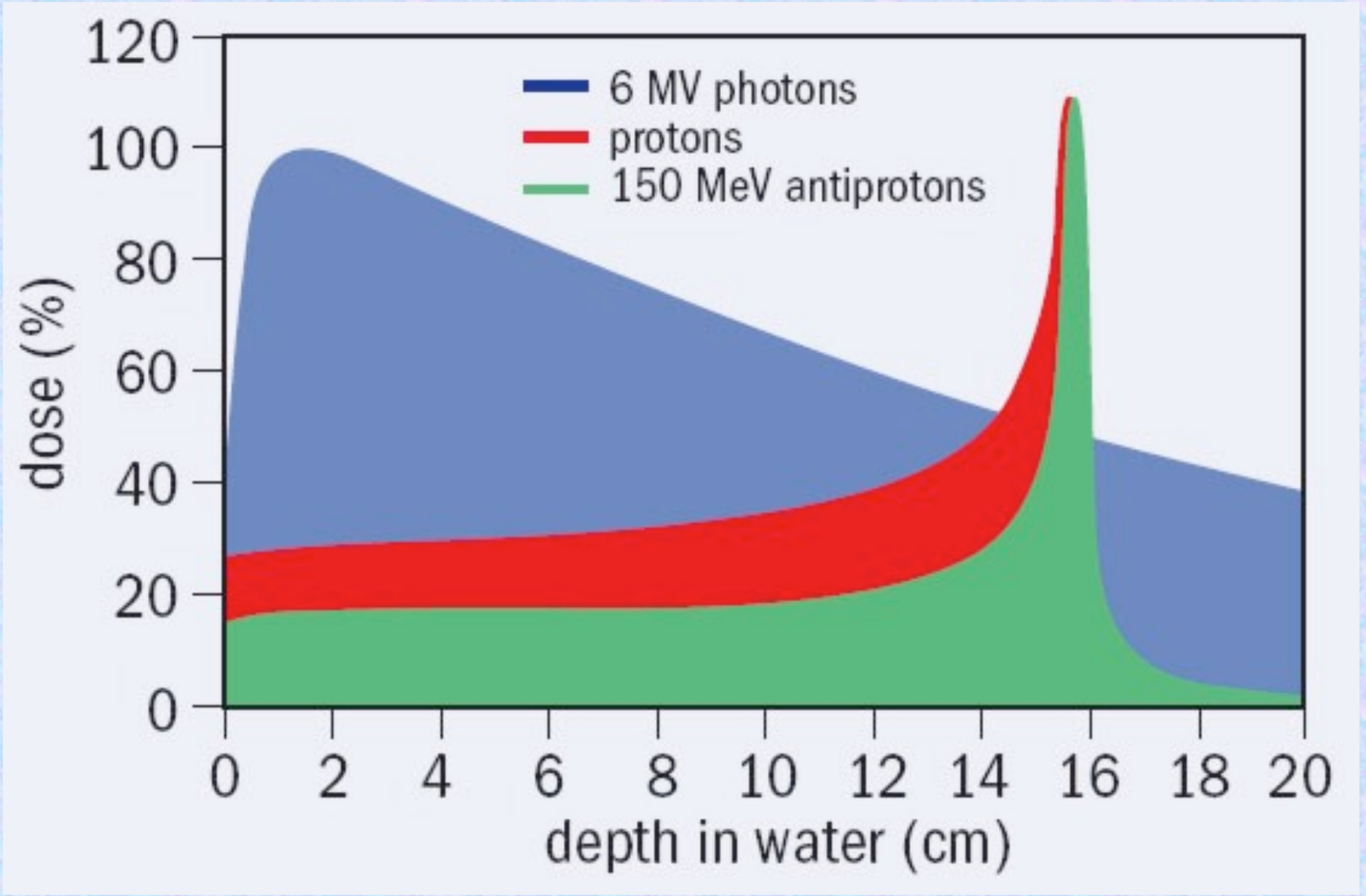
Biological effectiveness of antiproton annihilation in cells

Additional damage by nuclear fragments of short range



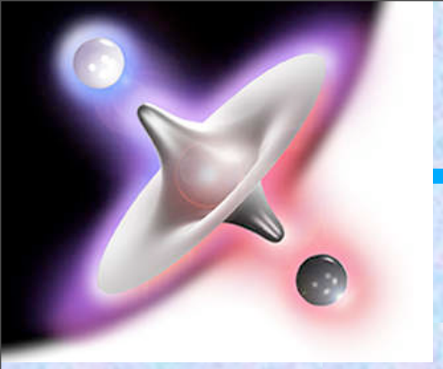


Antiproton Cell Experiment



Equal cell mortality for tumour cells with less than 1/2 radiation dose

Compare with Carbon ion therapy



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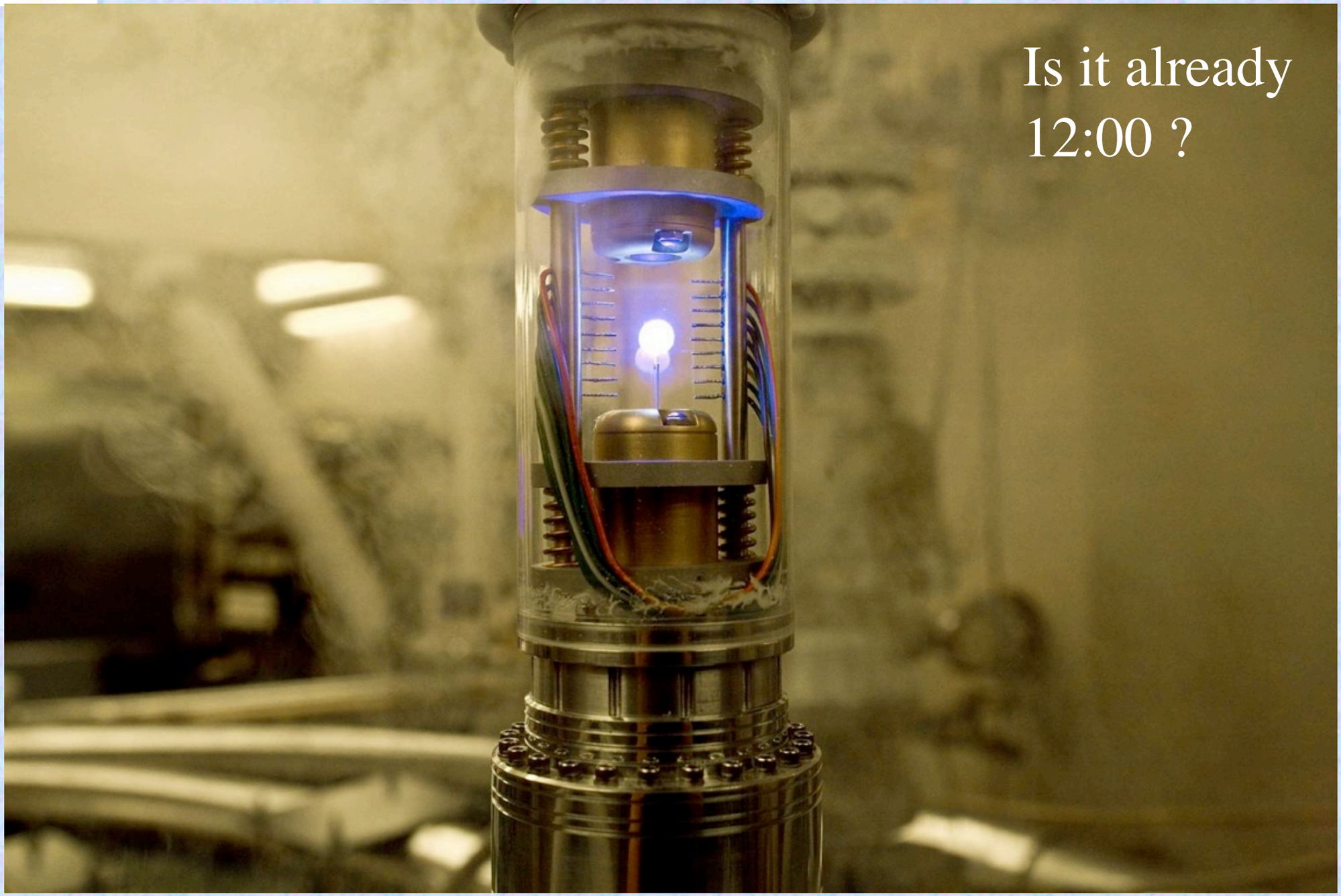

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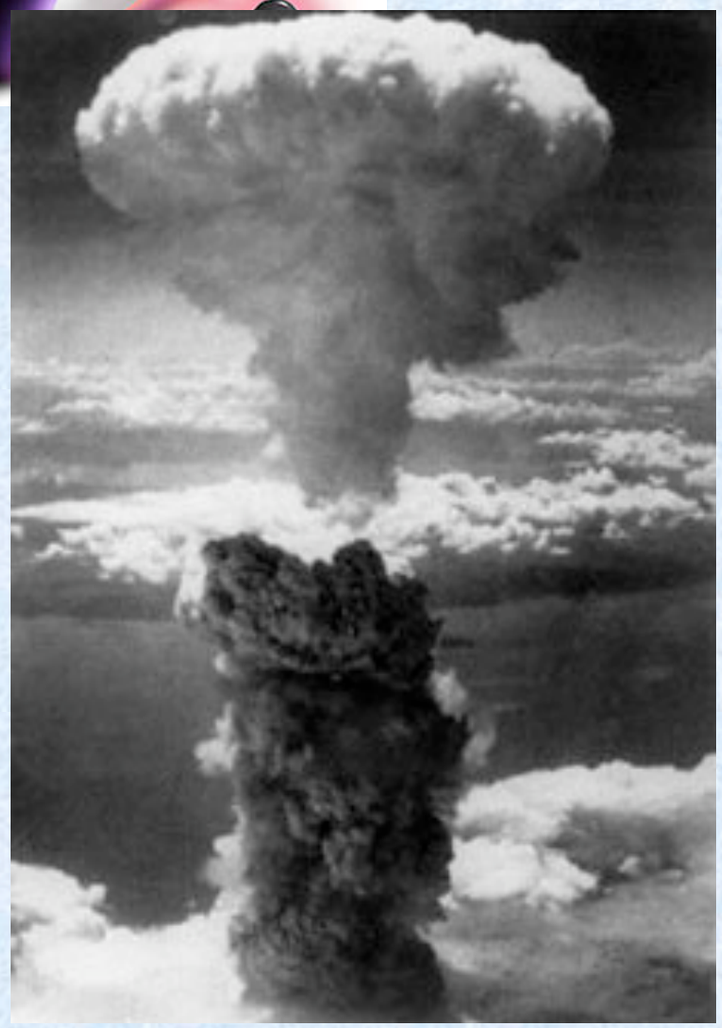

Dan Brown is right:
only 0.5 g antimatter makes an 'anti-atomic bomb'

BUT:

20 kt TNT = $8.4 \cdot 10^{13}$ J
0.5 g antimatter
+ 0.5 g matter

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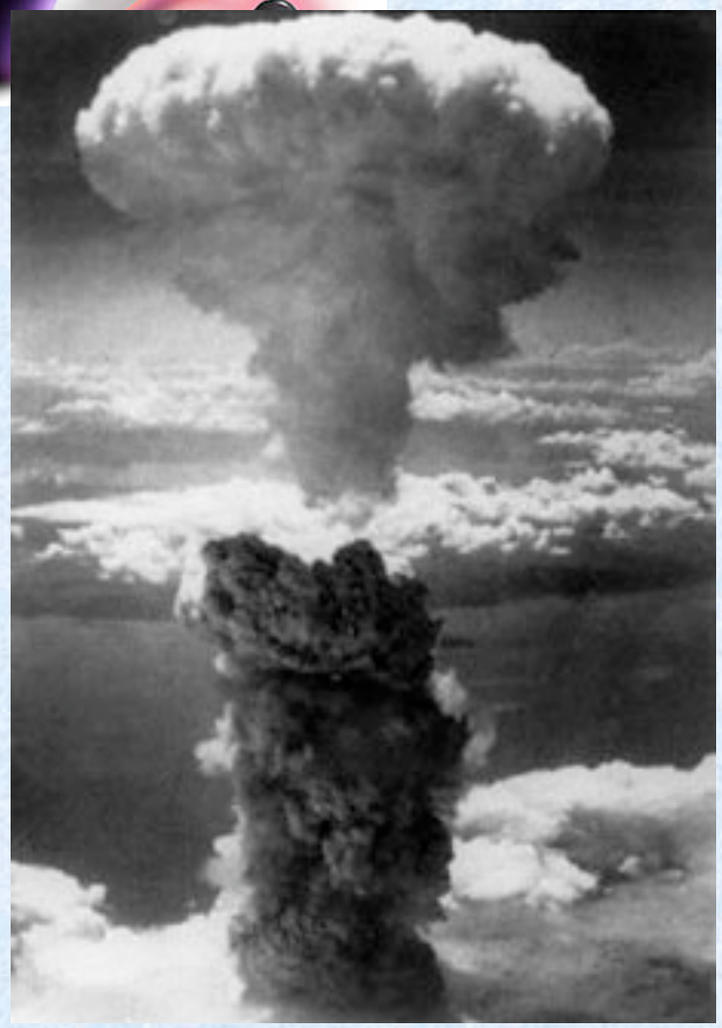

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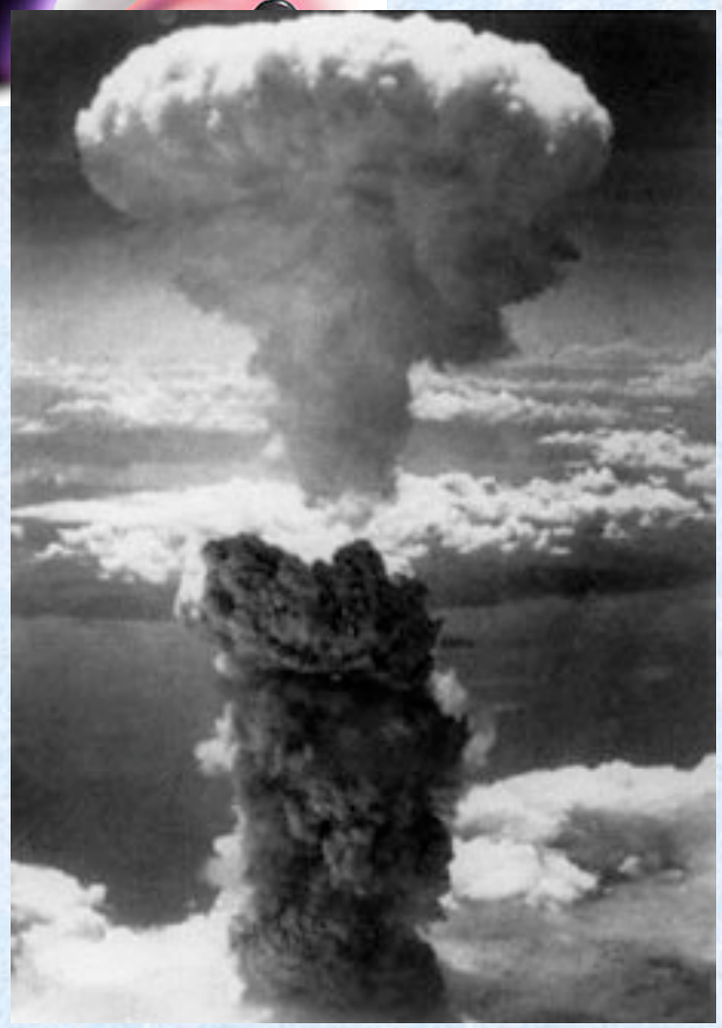

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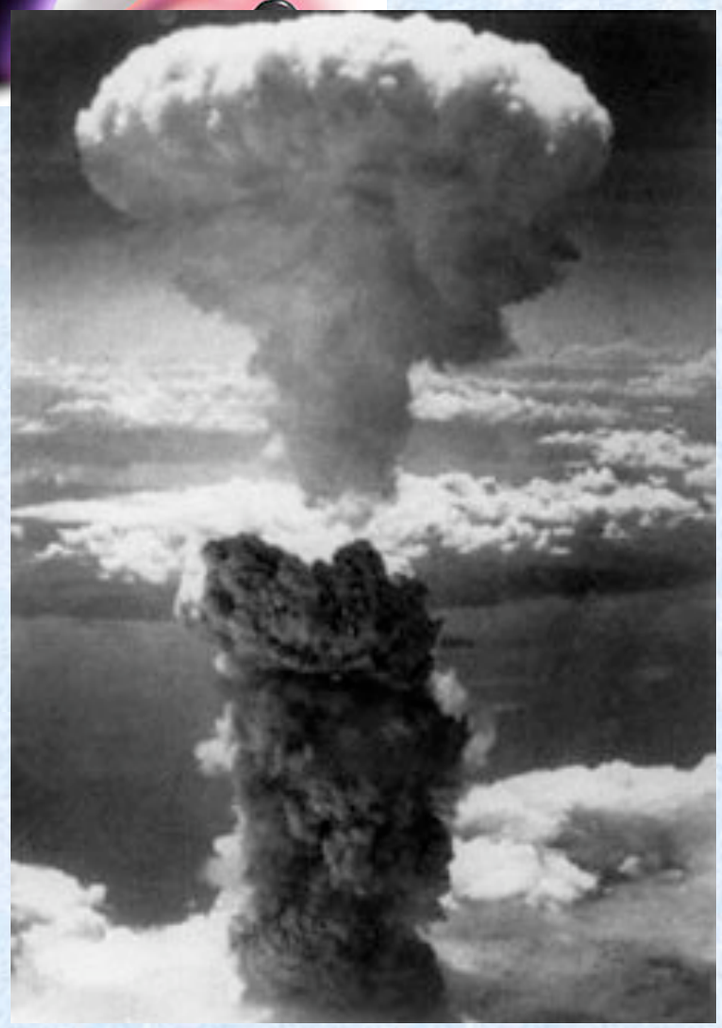

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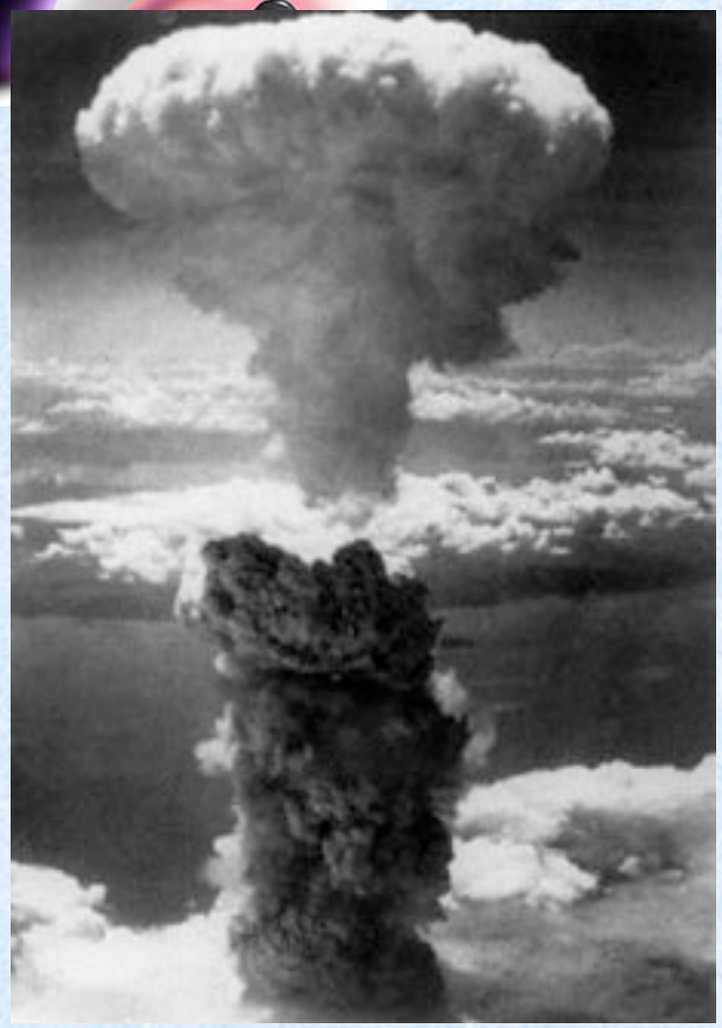

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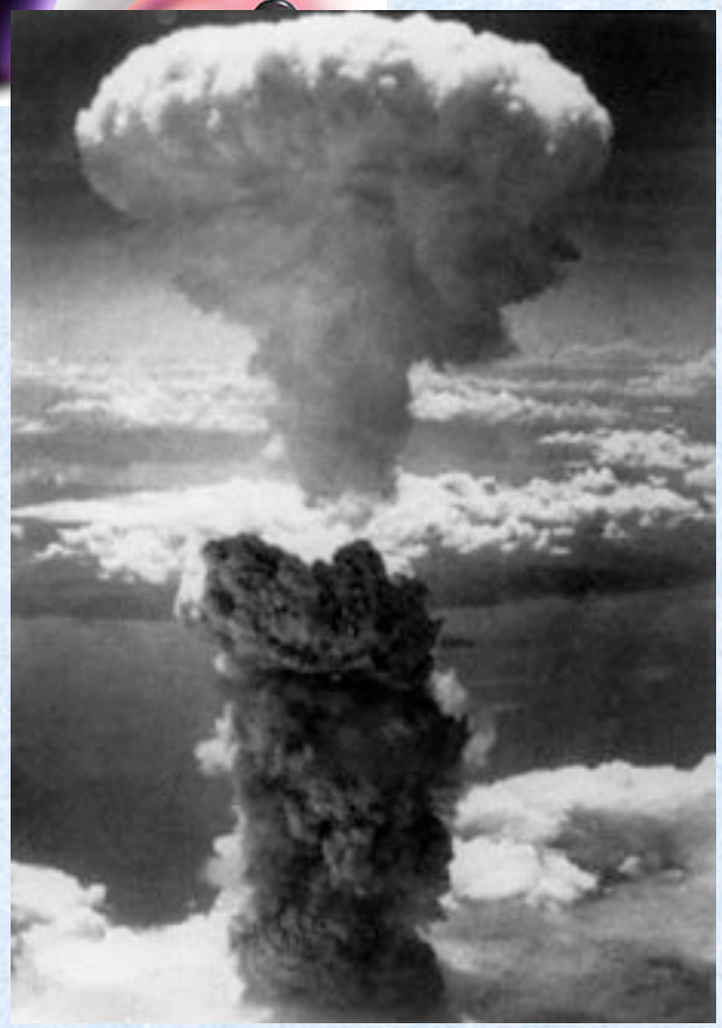

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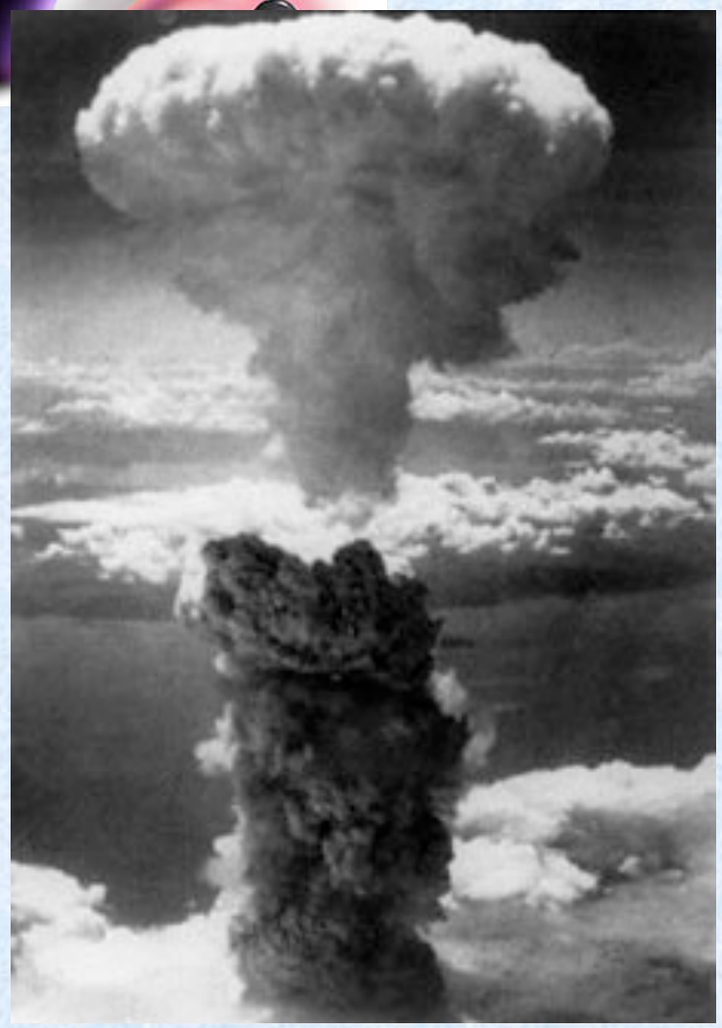

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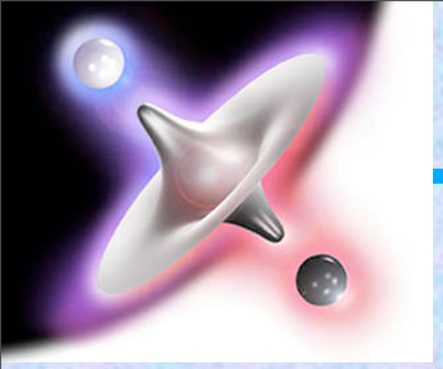
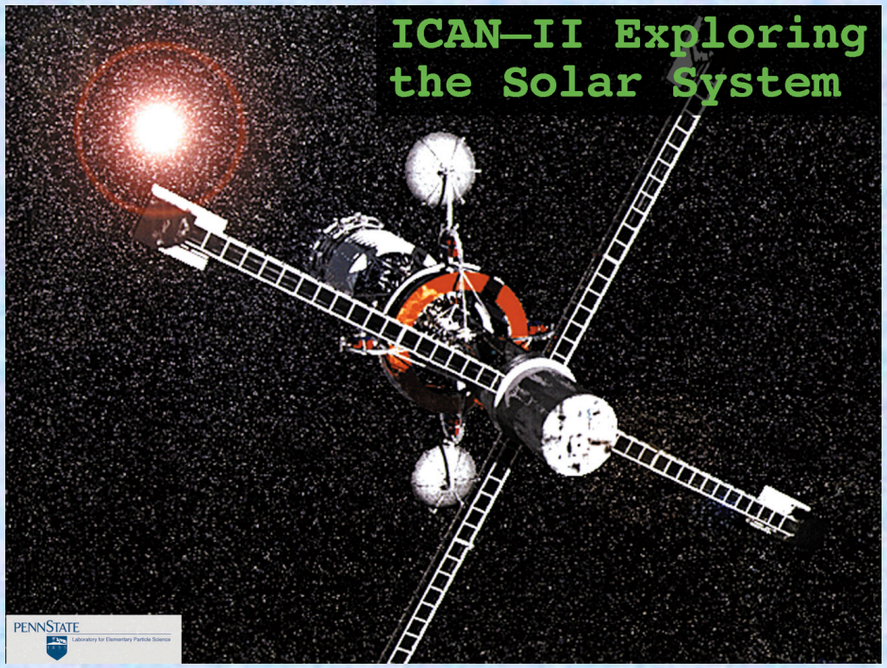
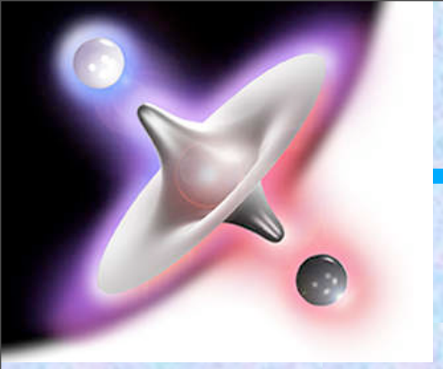


Antimatter driven space engines?





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

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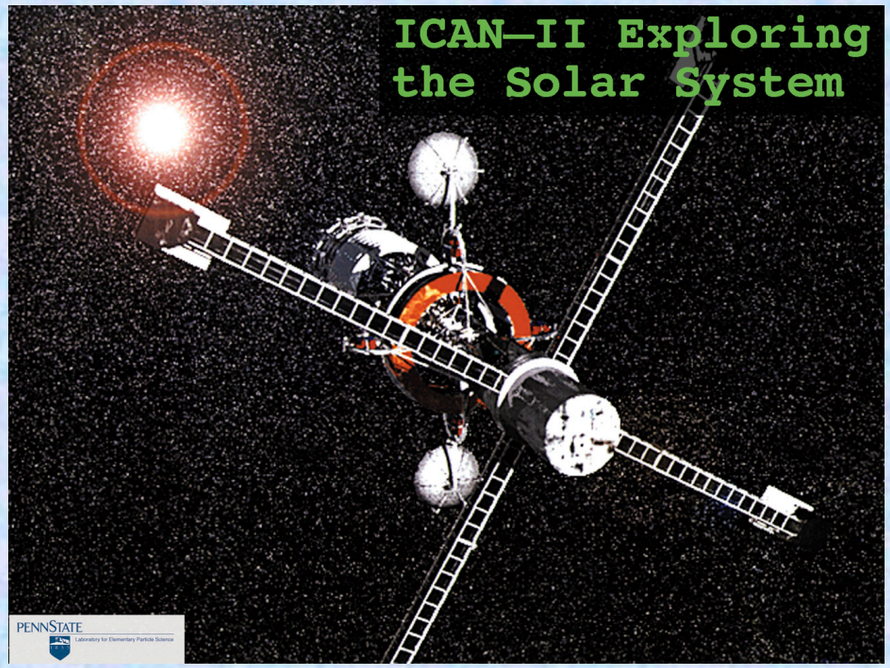

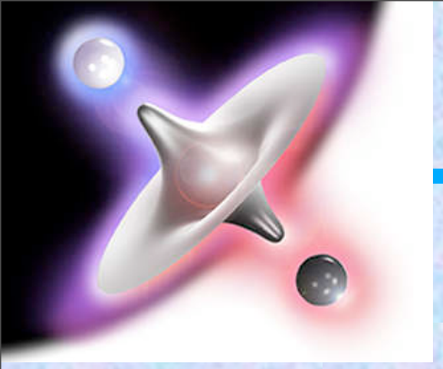

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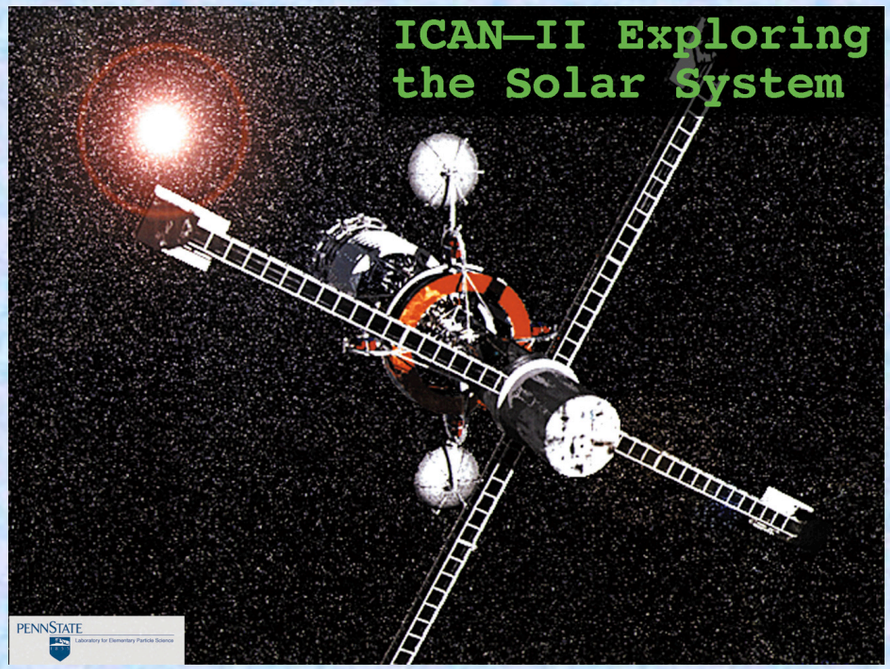

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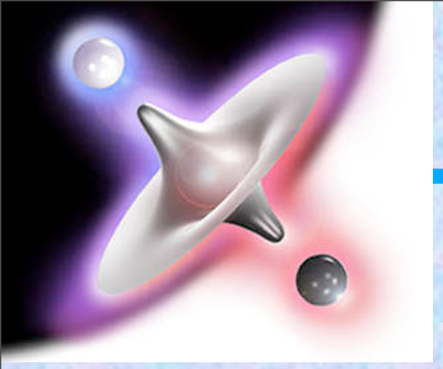

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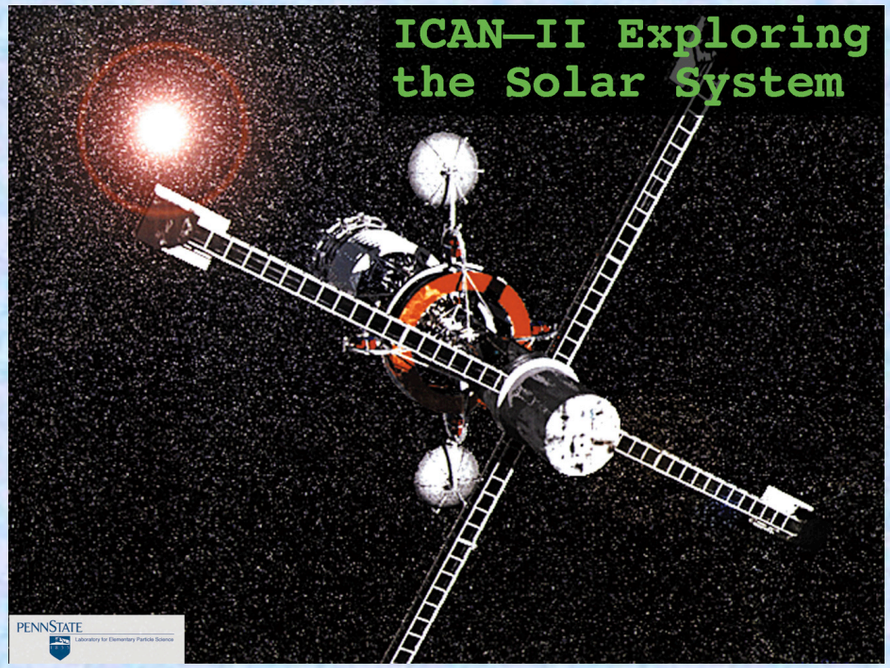

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In Genf wurde Wunder-Energie entdeckt

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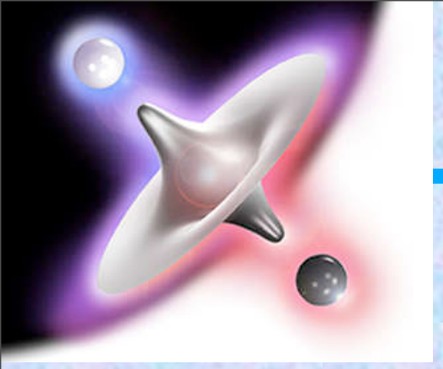

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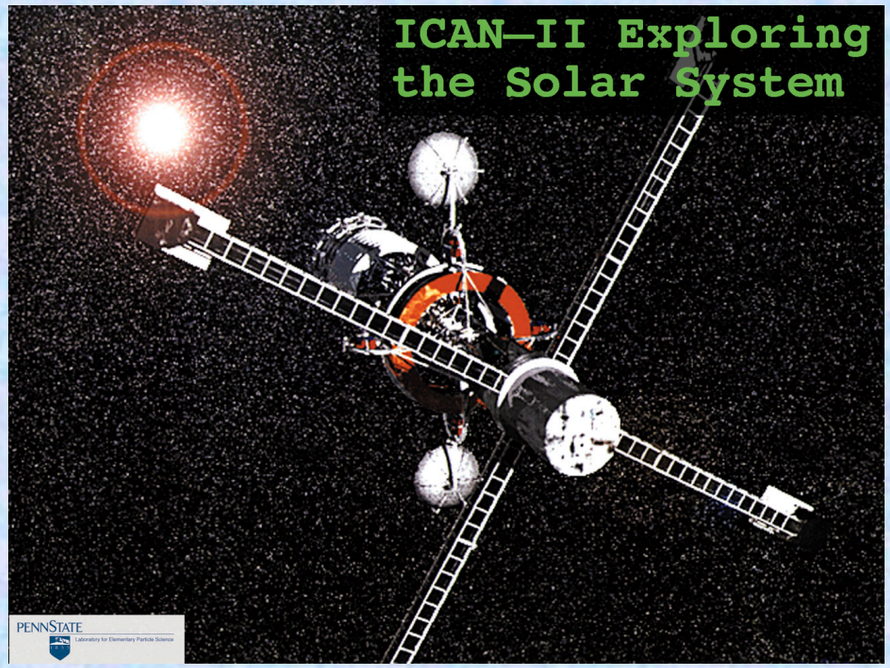

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The End.