Antimatter 2 - The Sequel

Rolf Landua
CERN

Overview Lecture 2

The first lecture was about the
- history of antimatter
- the cosmic 'antimatter mystery'

In the following two lectures,
we will focus on two of the remaining,
big questions:

Why was my role in the movie so short ?

Why does this person earn so much money ?

Overview Lecture 2

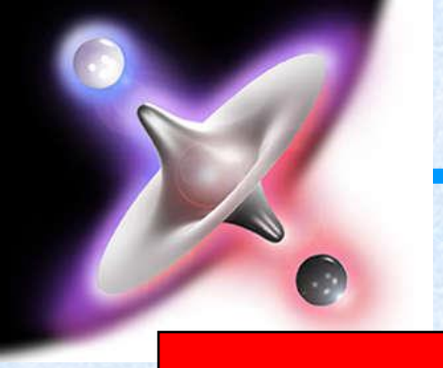
... and also:

Antimatter 'Factory' How are antiprotons made?

Antihydrogen Short history
How to make antihydrogen
Future developments

Antimatter technology PET
Antiproton therapy?
Rocket propulsion??

First attempt: 1955 Berkeley



The Antiproton

1905
Special relativity

1925
Quantum Mechanics

1927
Dirac Equation

1932
Positron

1948
Positronium

1955
Antiproton

1956
Antineutron

1965
Antideuteron

1970
Anti-Helium-3

1978
Anti-Tritium

Primordial Antimatter?
Anti-Stars?

1956-1980s:
Scattering, annihilation, Meson spectroscopy

1980s-now:
W,Z, b,t physics

Technical developments

1970s
Accumulation + Cooling

1980s-now
Colliders (SppS, Tevatron)

1983-1996
LEAR

1996: Hot (v~c) Antihydrogen

2000-now
Antiproton Decelerator

Trapping

Cold Antihydrogen

Antiproton Discovery (1955)

First antiproton annihilation

PHYSICAL REVIEW

A journal of experimental and theoretical physics established by E. L. Nichols in 1893

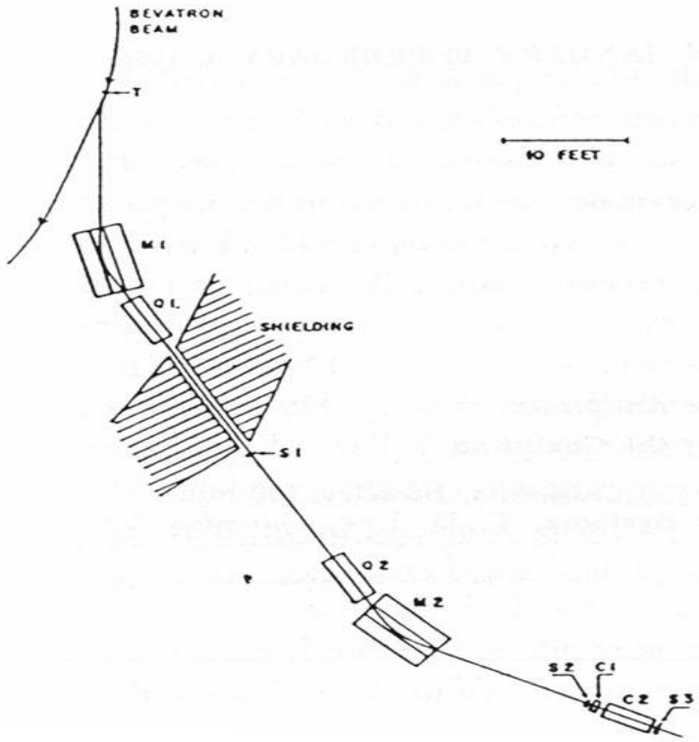
SECOND SERIES, VOL. 100, NO. 3 NOVEMBER 1, 1955

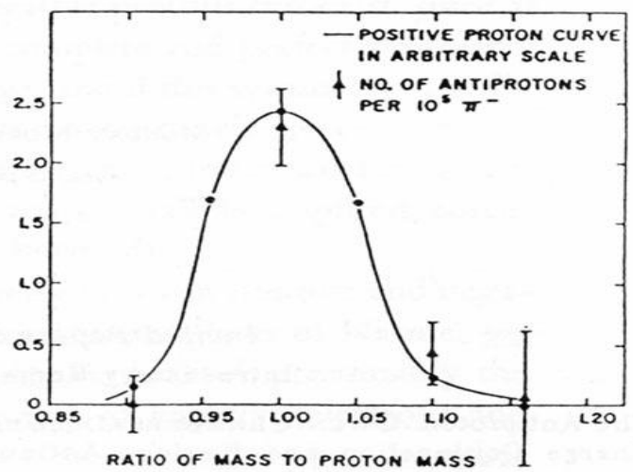
Observation of Antiprotons*

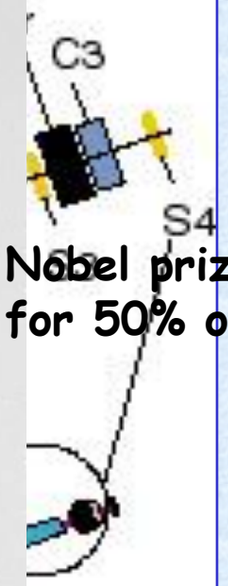
OWEN CHAMBERLAIN, EMILIO SEGRÈ, CLYDE WIEGAND, AND THOMAS YPSILANTIS

Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received October 24, 1955)







Nobel prize (1959) for 50% of the collaboration

Tedious analysis ….

How to make an antiproton ?

Brute force: collide a proton with another proton

$$p_{beam} + p_{target} \rightarrow p_{beam} + p_{target} + (p + \bar{p})$$

But unfortunately:

$$p_{beam} + p_{target} \rightarrow p_{beam} + p_{target} + (\text{pions, kaons, } \ldots)$$

First rule of quantum physics:

Everything that is not forbidden MUST HAPPEN

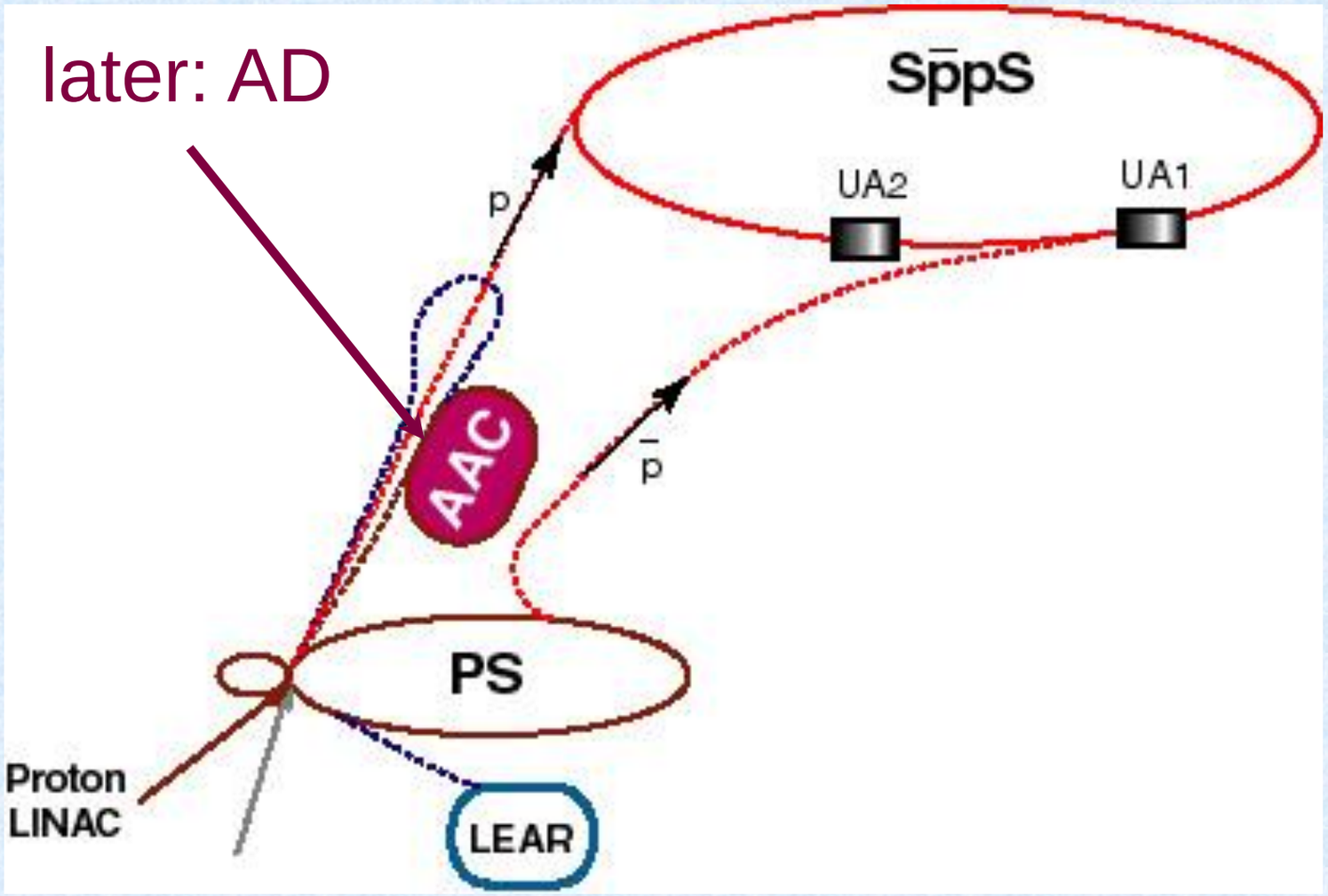
Production of antiprotons competes with all other processes

Antiproton beams at CERN (1980): the high energy frontier

Antiprotons were needed for the SppS collider (270+270 GeV)

Use of antiproton beams led to discovery of W, Z bosons

Search for Higgs, SUSY, top, …



Efficiency of antiproton production

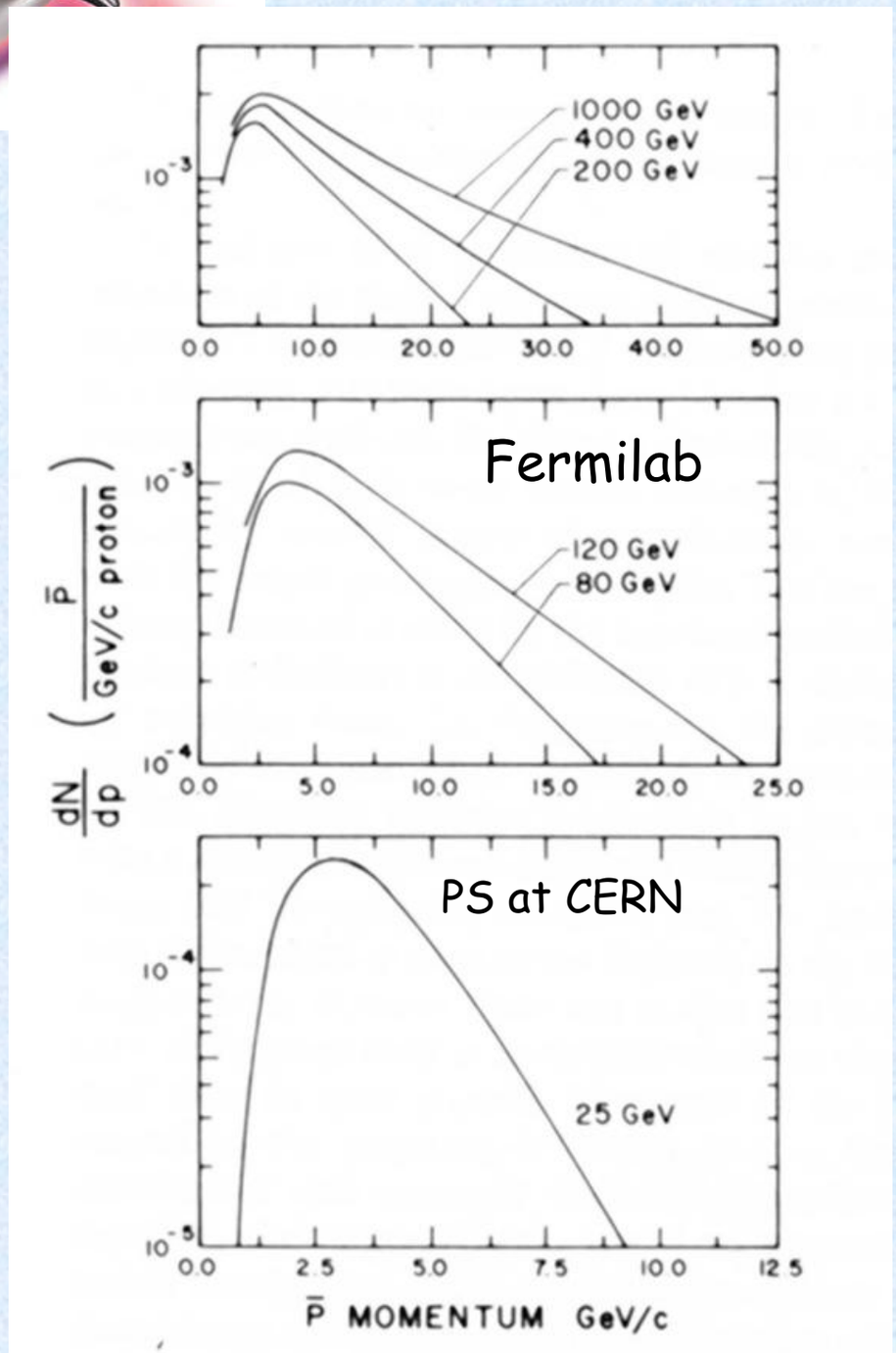


Fig. 7. Total laboratory $\bar{p}$ production on tungsten below 0.30 GeV/c from eq. (1) (per interacting proton).

Energy dependent

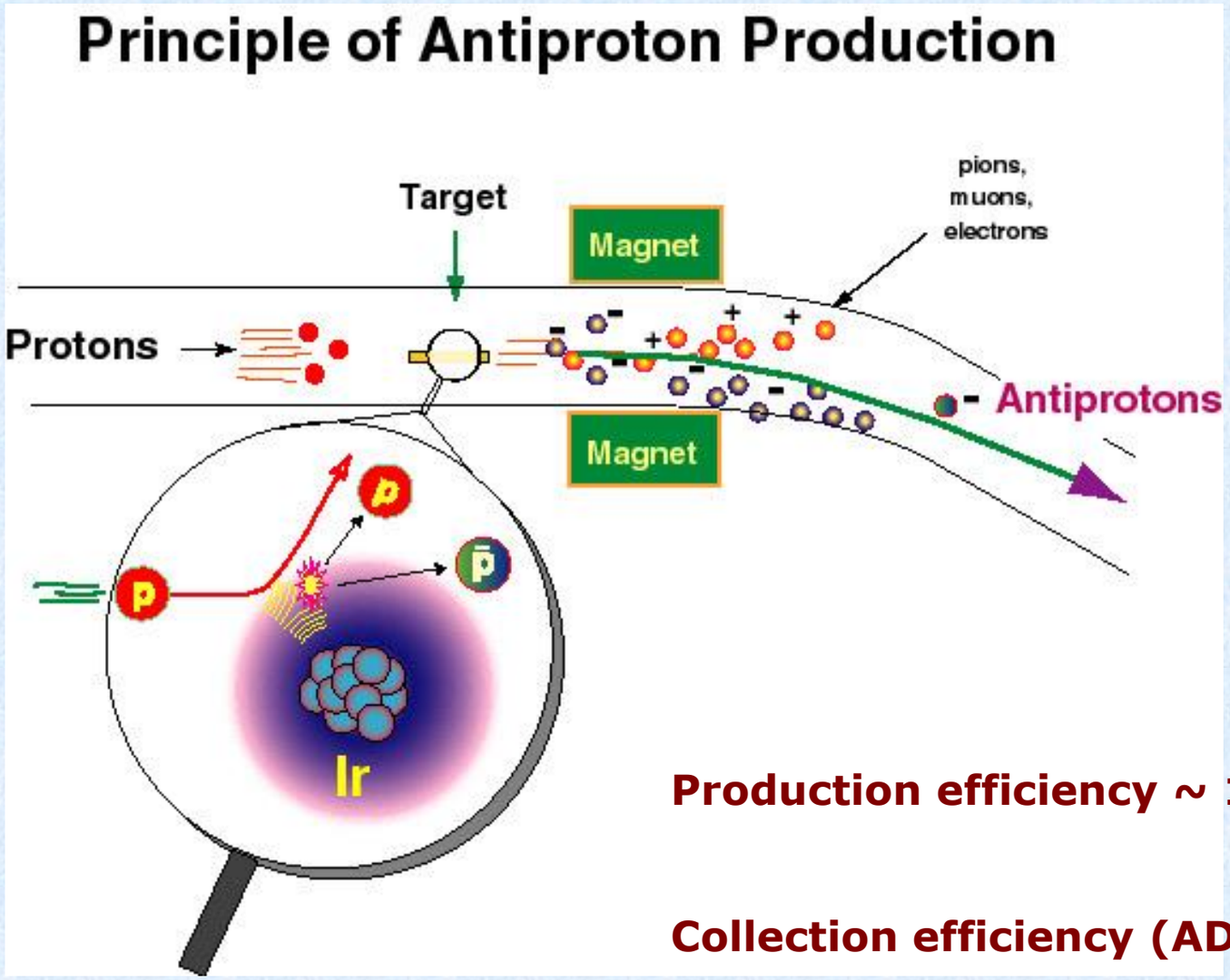
Few 10^{-4} (CERN, 26 GeV/c)

Few 10^{-3} (Fermilab, 120 GeV)

➢99 % of interacting protons
do NOT produce antiprotons

Antiproton Production

Acceleration efficiency ~ 10^{-3}



Production efficiency ~ 10^{-4}

Collection efficiency (AD) ~ 10^{-2}

Peak production at CERN

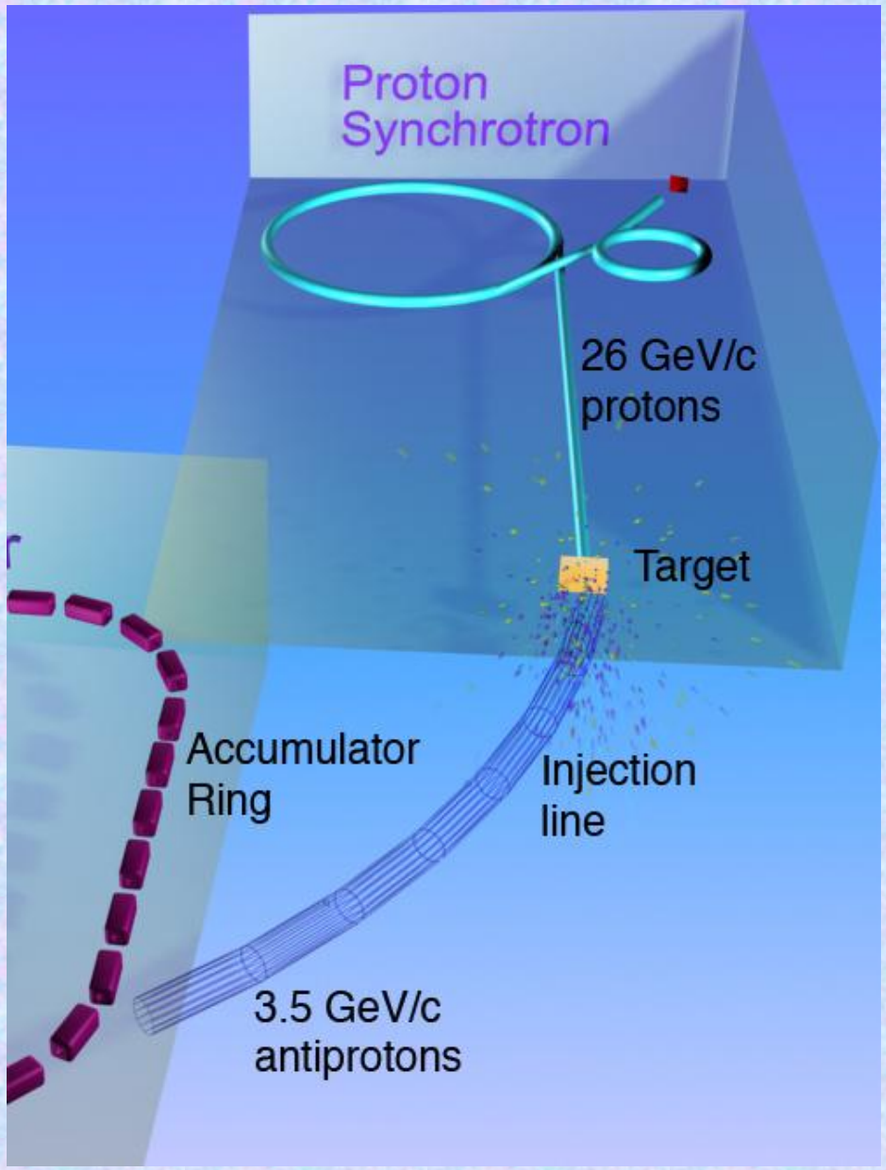
~ 200,000,000,000,000 antiprotons/year

(only 0.3 nano-gram, overall efficiency ~ 10^{-9})

Optimizing antiproton production + collection

Maximum no. of protons before target breaks
($1.5 \cdot 10^{13}$ p, every 2.4 s; ~ 20 ns bunch, 1x1 mm^2)

Primary interaction --> long target
Antiproton absorption --> short target
Compromise: Ir, 6 cm length (1 IL)



Focussing with magnetic horn (high pulsed current)

$1.5 \cdot 10^{13}$ protons at 26 GeV/c produce $5 \cdot 10^{7}$ antiprotons

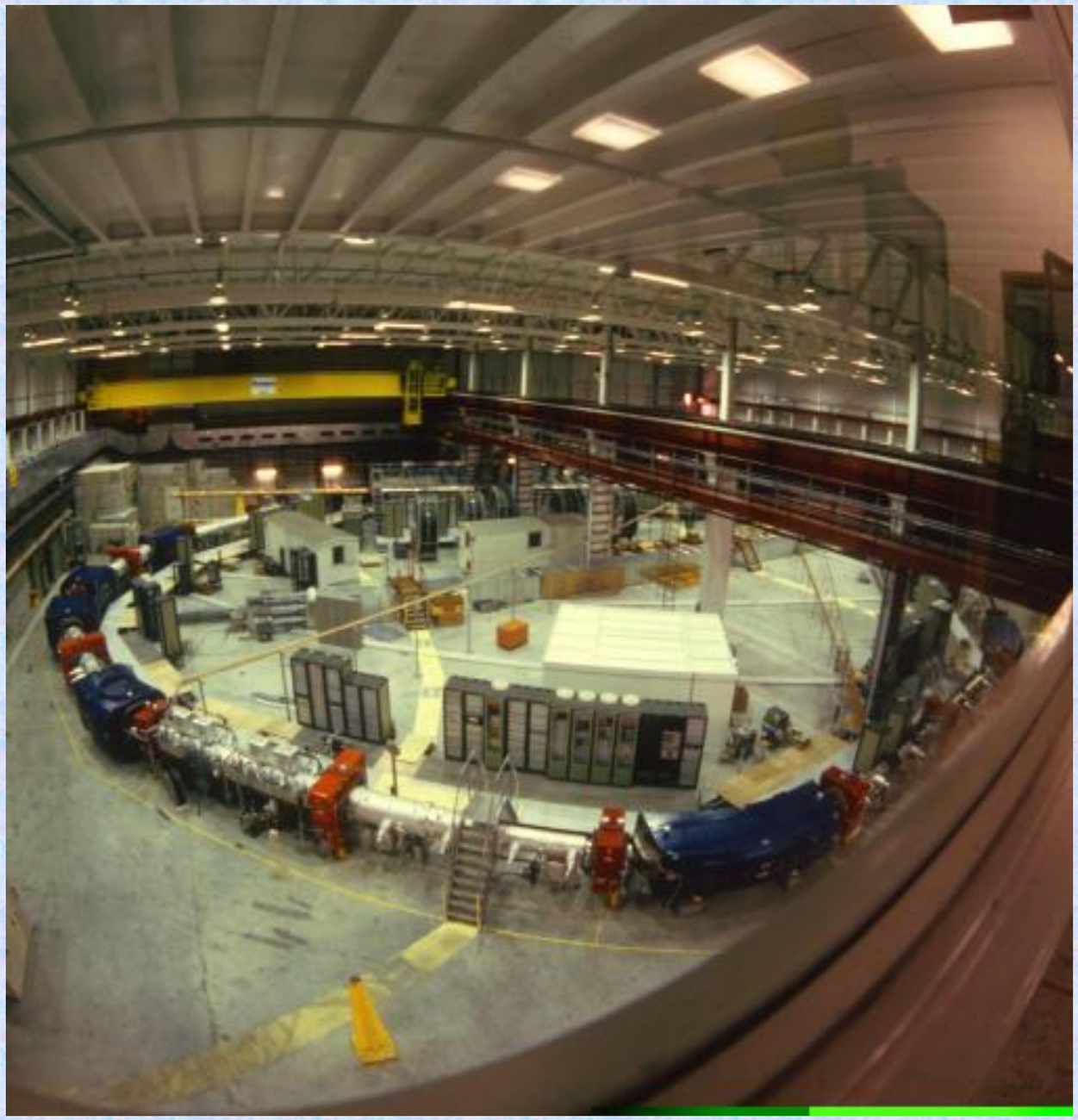
Antiproton Accumulator + Collector (AAC)

1980: *AA construction*

- capture antiprotons at 3.5 GeV/c
- stochastic cooling
- transfer to PS/SPS
- injection into SppS collider

~ 10^{11} (1987, *AC*: 10^{12}) antiprotons/day

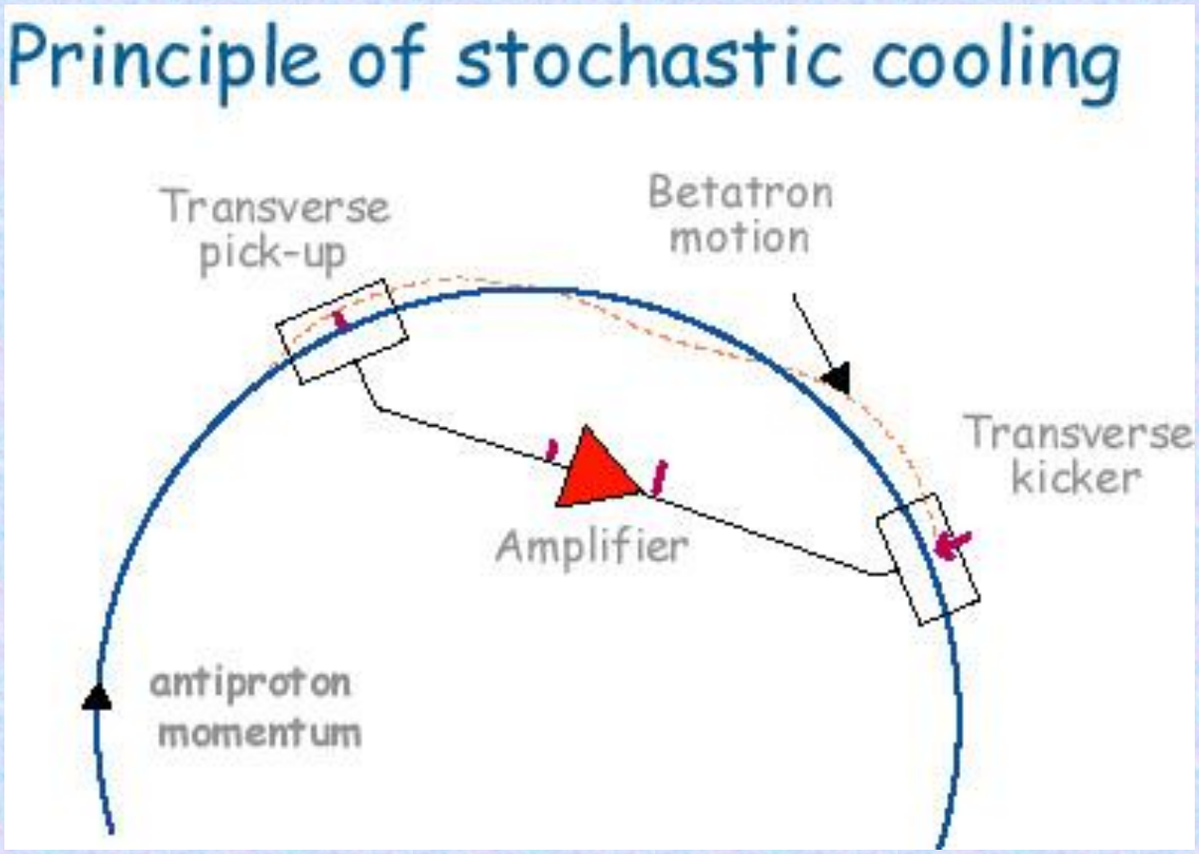
- Investment ~ 100 MCHF



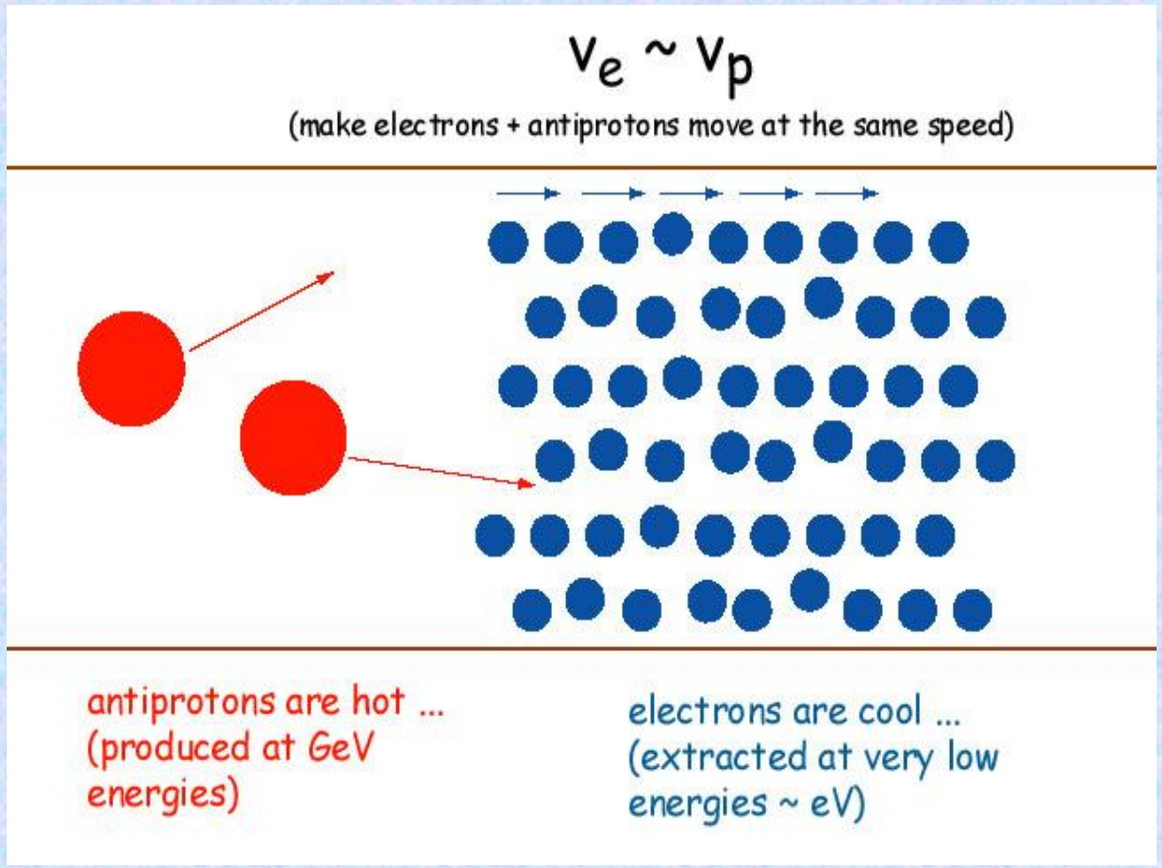
“Cool” antiproton beams needed for colliders

Electron cooling

(Novosibirsk, Budkers 1966)



S. van der Meer

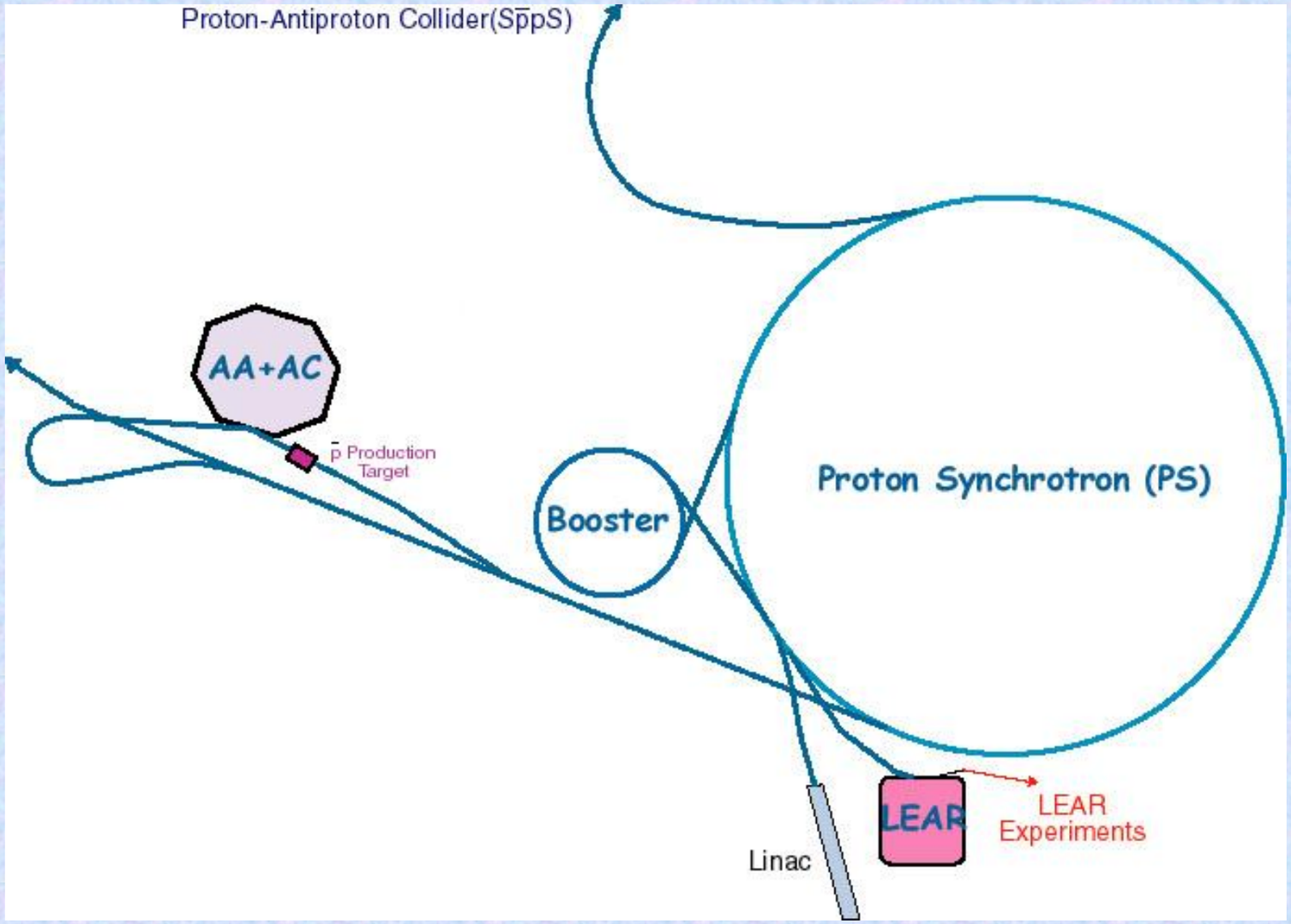


Electron cooling at CERN was developed at LEAR and is now used at the AD. It works best at low momenta (< 1 GeV/c)

Low Energy Antiproton Ring (LEAR)

AC: Antiproton collection and pre-cooling (3.57 GeV/c)
AA: Accumulation and further cooling (same momentum)
PS: Decelerates 10^9 antiprotons from AA (to 0.6 GeV/c); injection into LEAR
LEAR: Momentum range: 0.1 - 2.0 GeV/c;
Stochastic and (later) electron cooling: $\otimes p/p \sim 5 \cdot 10^{-4}$

LEAR was built in 1982 as an 'appendix' to the CERN antiproton collider programme



Low energy antiproton yield improvements

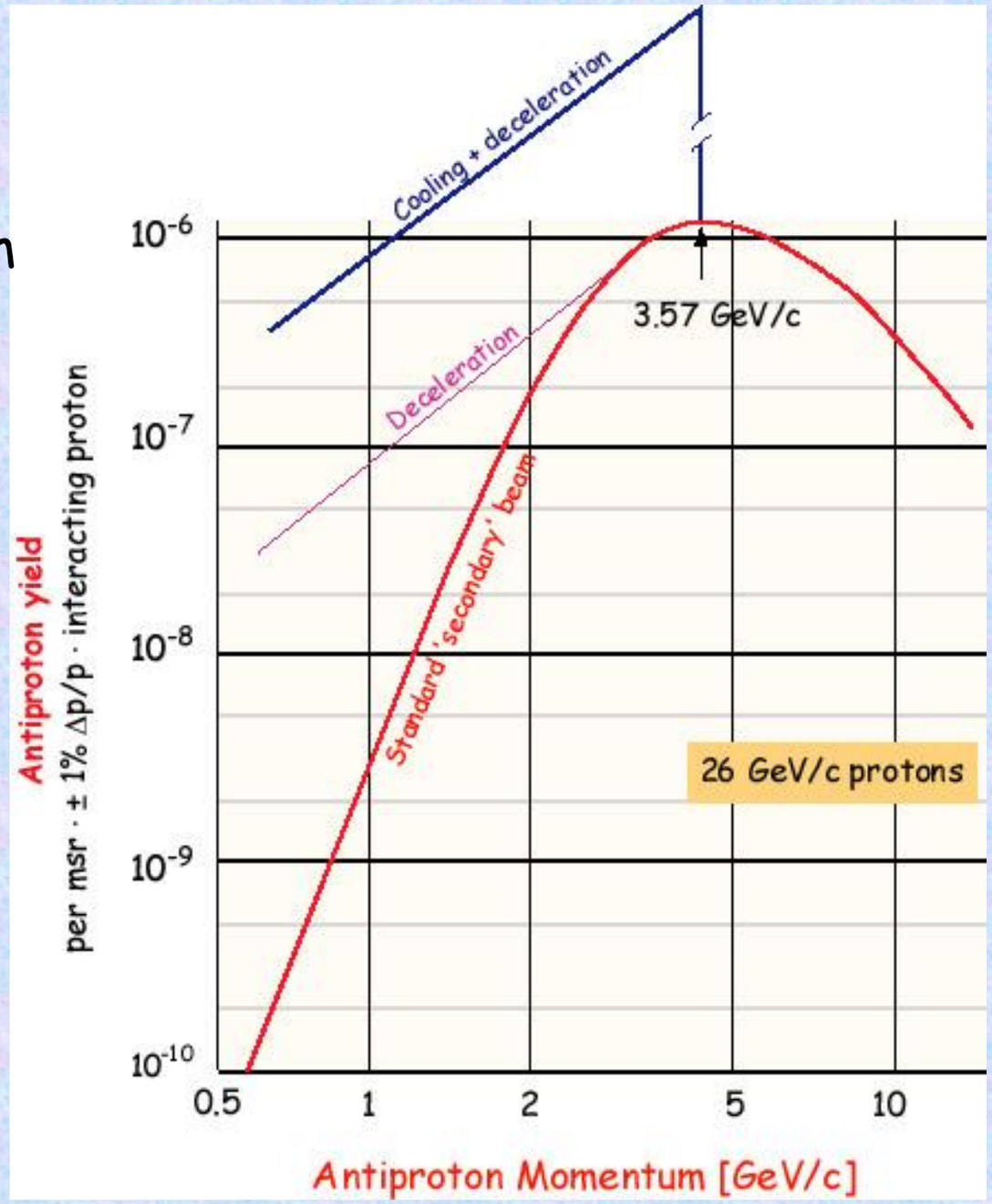
Capture antiprotons at optimum momentum

3.57 GeV/c (±6 %) at CERN

Decelerate to lower energies

Problem: Beam 'blows up'

Solution: Beam 'cooling'



The Story of Antihydrogen

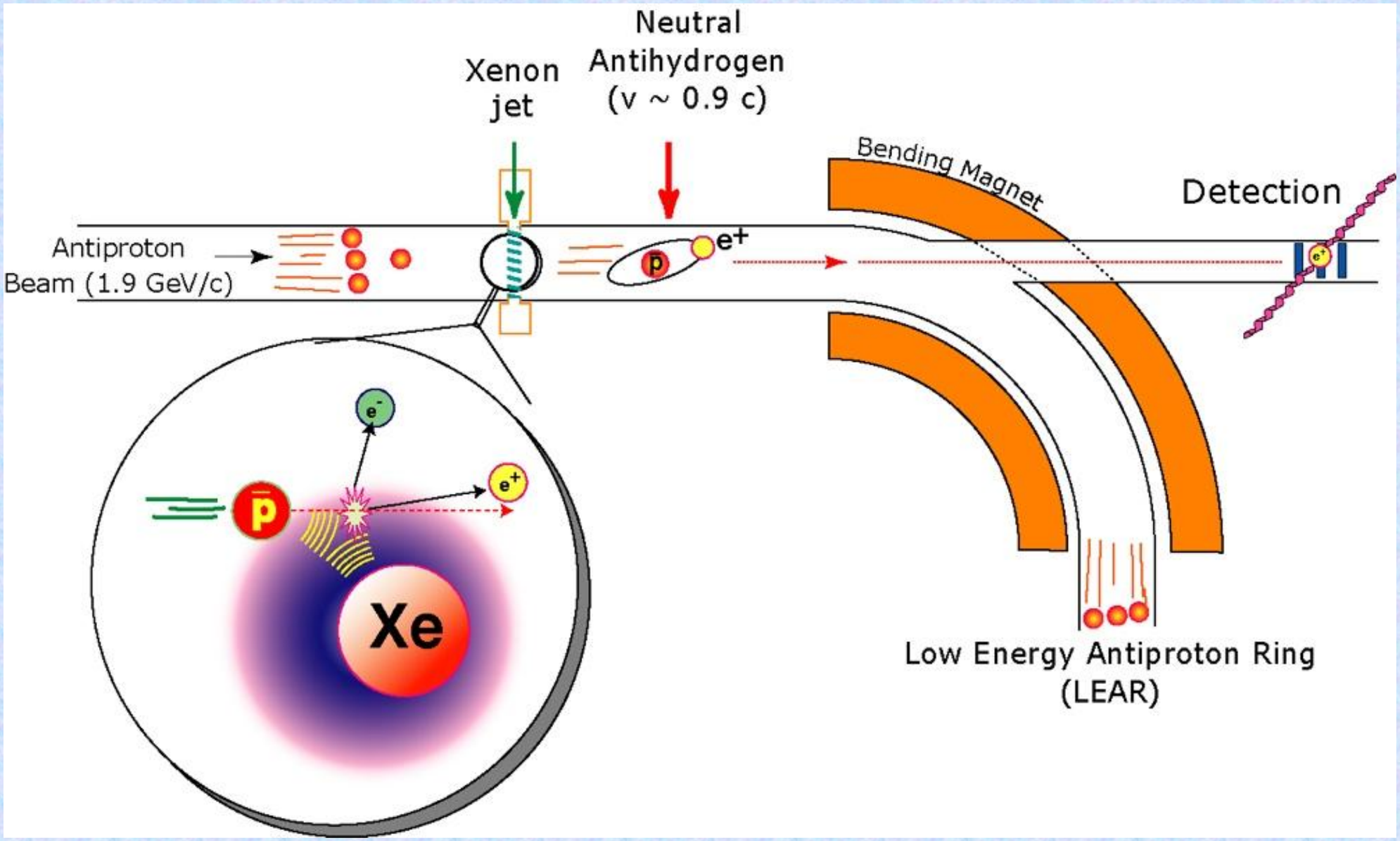
ANTIHYDROGEN - Early days

From 1983-1995, the LEAR programme was only known to insiders.

This would change in 1995:

the first nine antihydrogen atoms were made

How were the 9 antihydrogen atoms made at LEAR ?



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

The World Press took note …

The World started to fear CERN's antimatter bombs

Fortunately, fear of CERN antimatter bombs only lasted 12 years

Sep 10, 2008: The LHC will destroy the Earth


Frankfurter Allgemeine

ZEITUNG FÜR DEUTSCHLAND

Papier:
für
rkschafter

Verschwinden wir im … zen Loch?

Nicht Dritter

Von Berthold Kohler

Ring fi

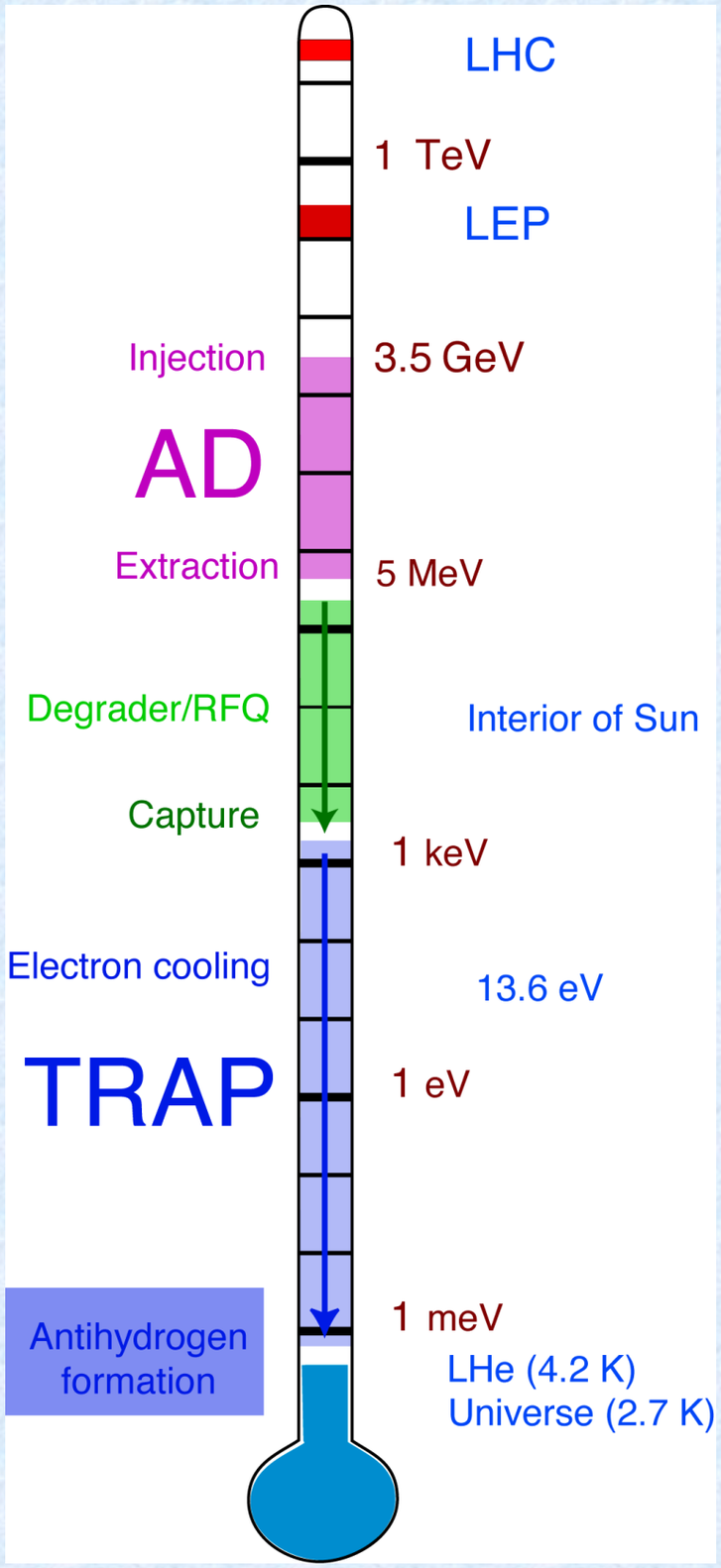
Challenge of antihydrogen production

Antiprotons and positrons (when young) are hot

Hydrogen atom is a weakly bound system:

E (1s) = - 0.000 000 013 6 GeV

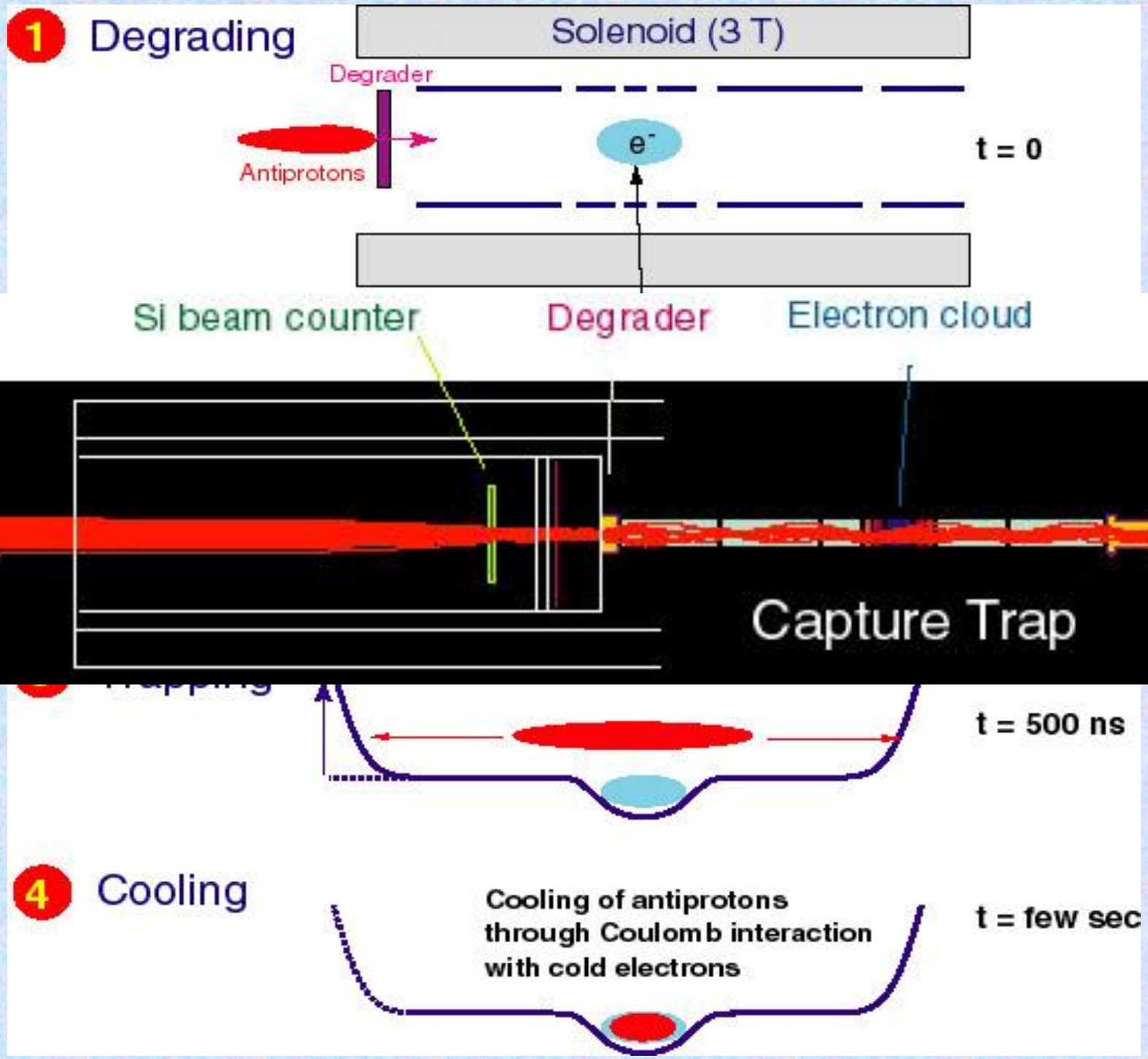
Constituents need to chill before mating



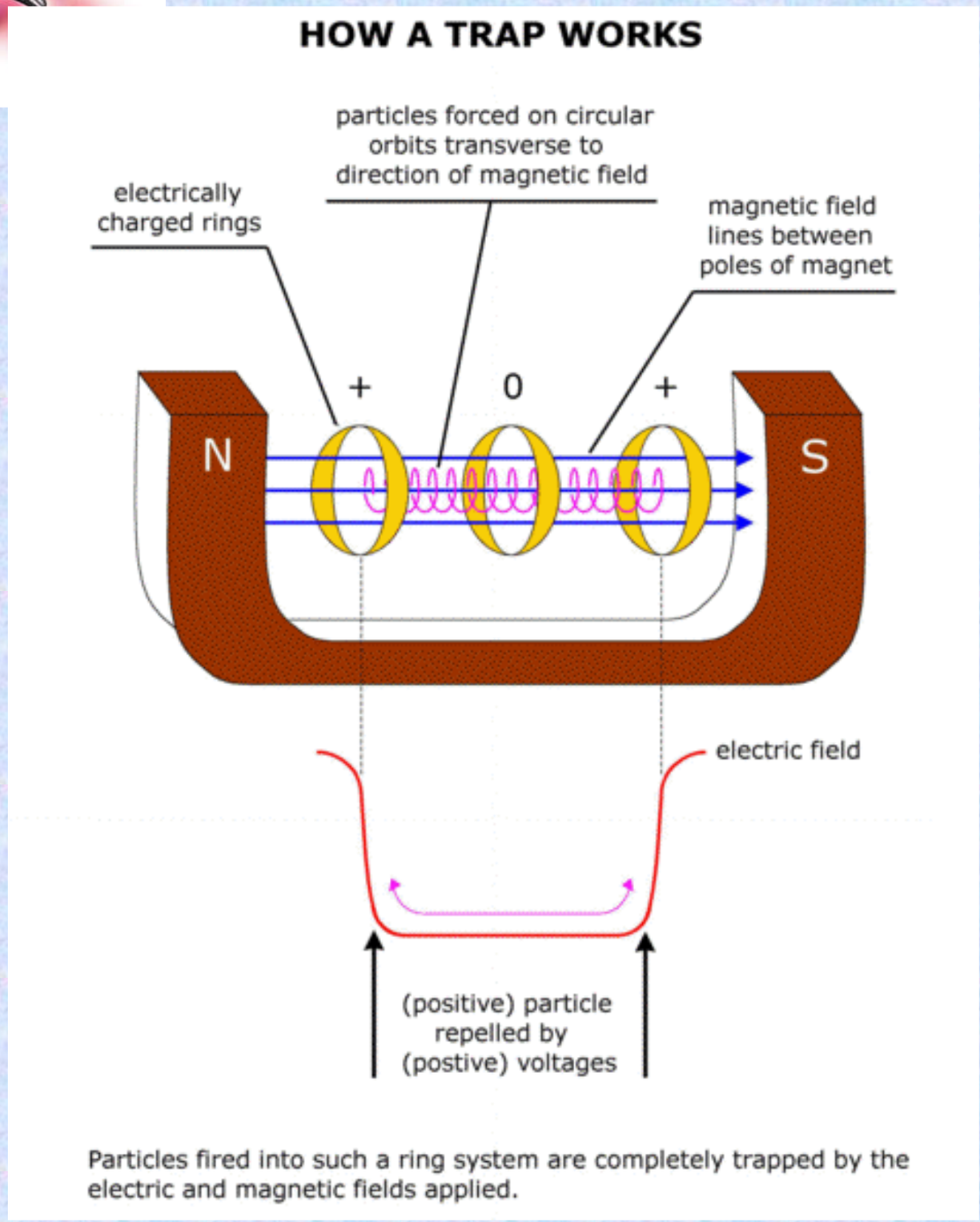
Trapping antiprotons (?)

The “trapping technology” for antiprotons had already been developed in 1986 at LEAR.

Trapping antiprotons



Charged particle traps (principle)



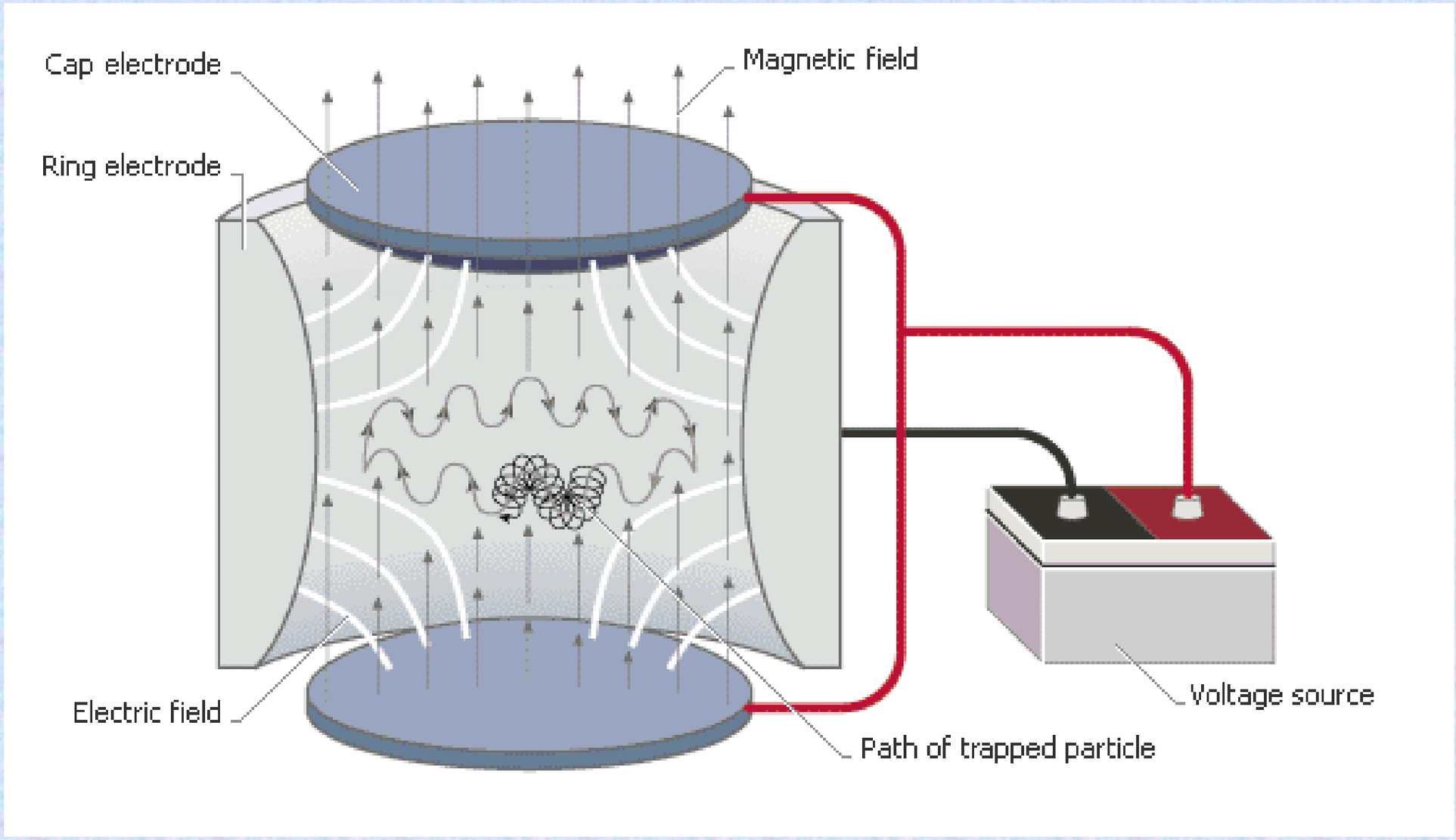
Typical voltages:
1 - 100 V

For trapping:
~ several kV

Magnetic trap (“Penning trap”)

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

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



Antiproton-Proton mass comparison

G. Gabrielse

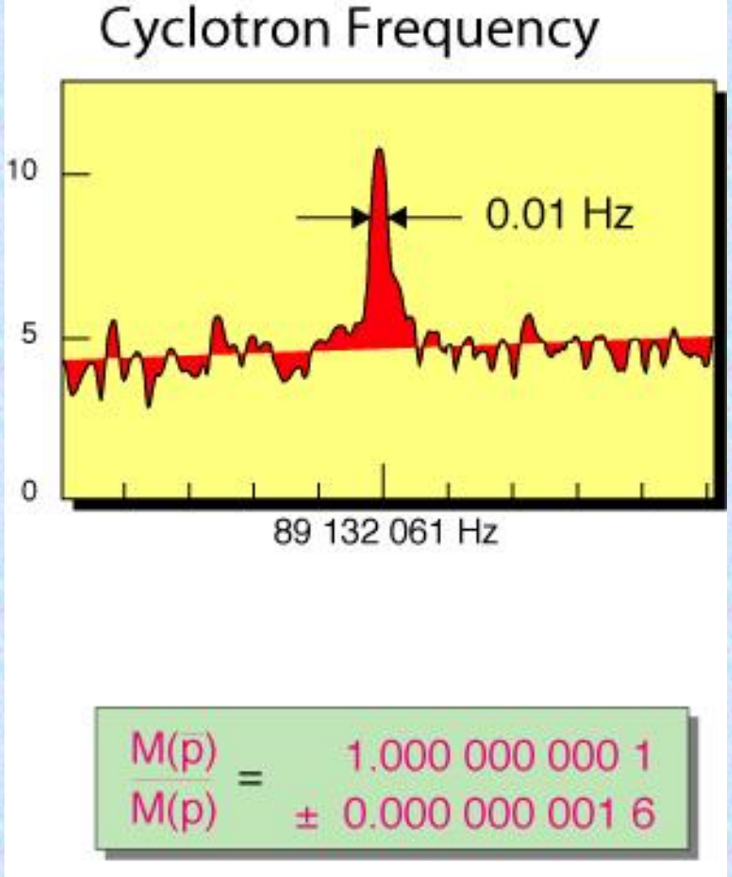
Moving antiprotons induce currents in trap wall

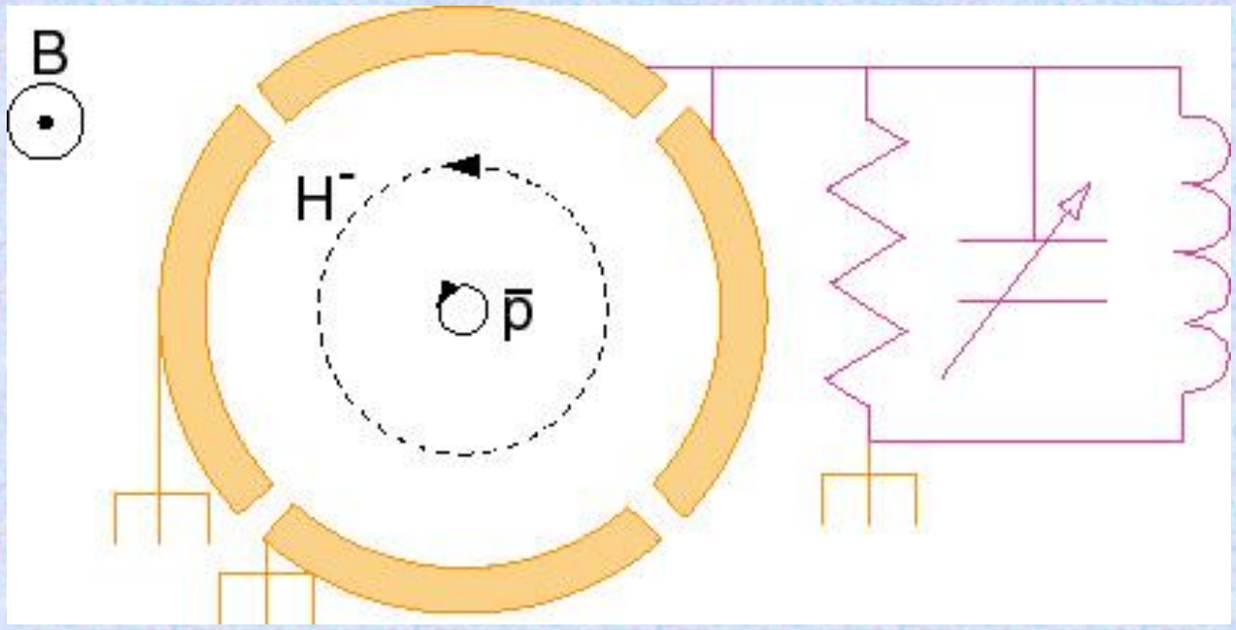
The 'sound of antiprotons' - at 89.3 MHz (cyclotron frequency)

Compare frequency with negative hydrogen ions

KEPT SINGLE ANTIPROTON FOR 58 DAYS IN TRAP

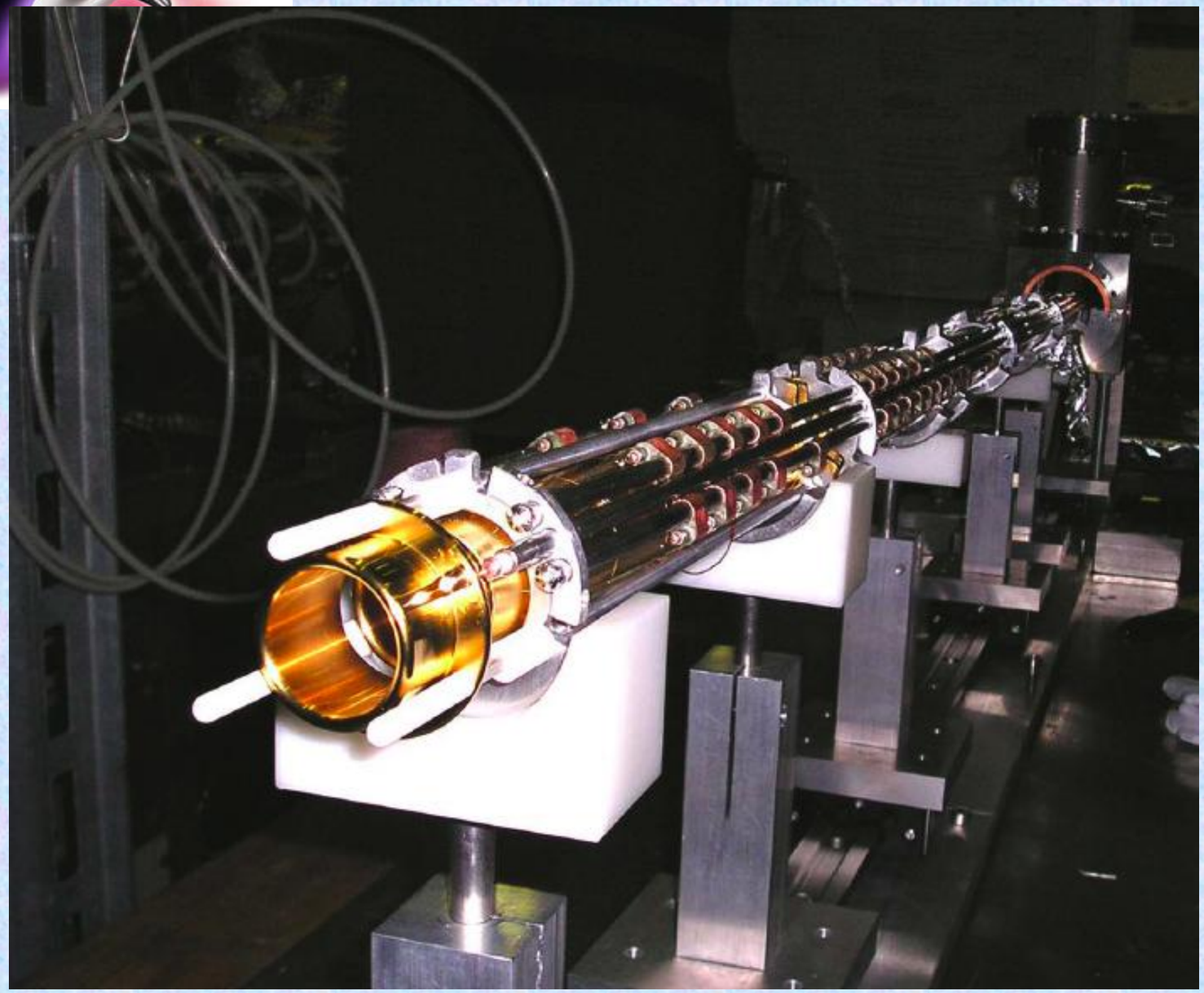
'PORTABLE' TRAP (for electrons) DEMONSTRATED

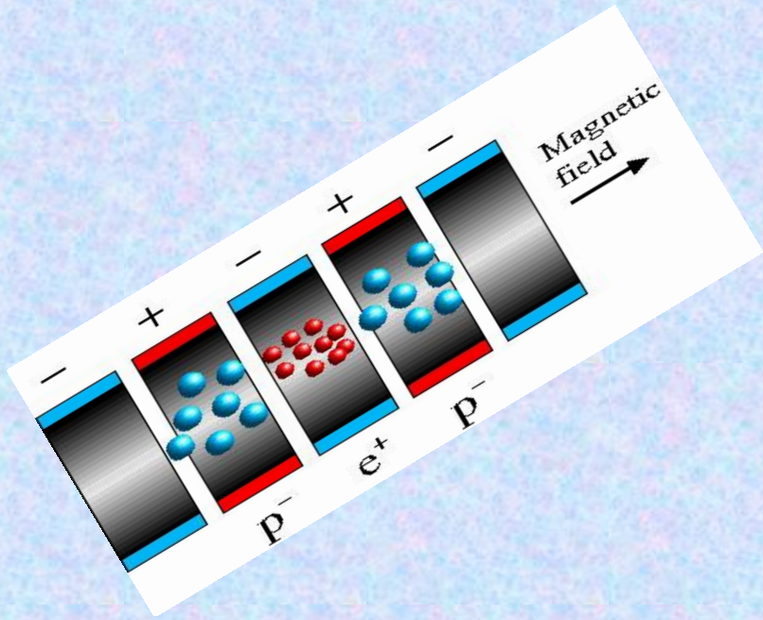




Penning Trap
B = 5.3 T

Electrical Landscapes



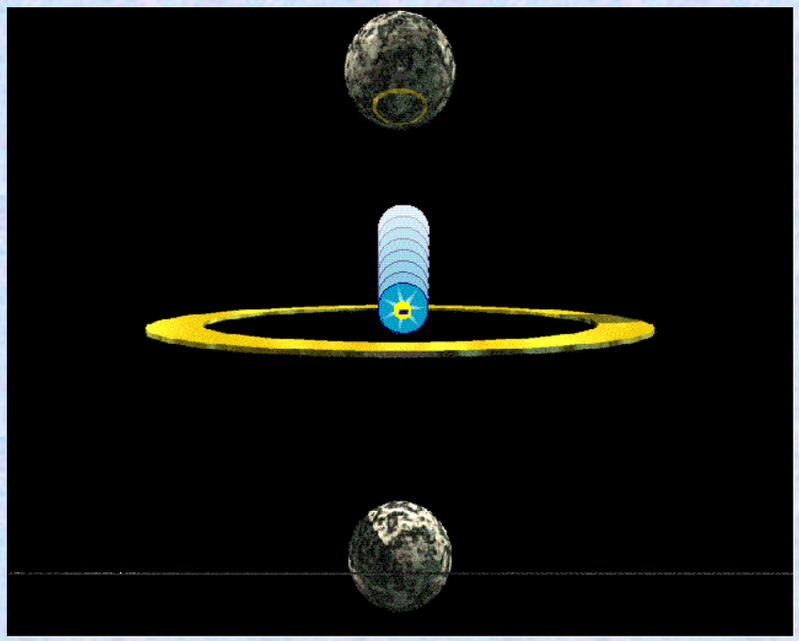


ATHENA multi-electrode trap

RF trap (“Paul trap”)

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

\- / +

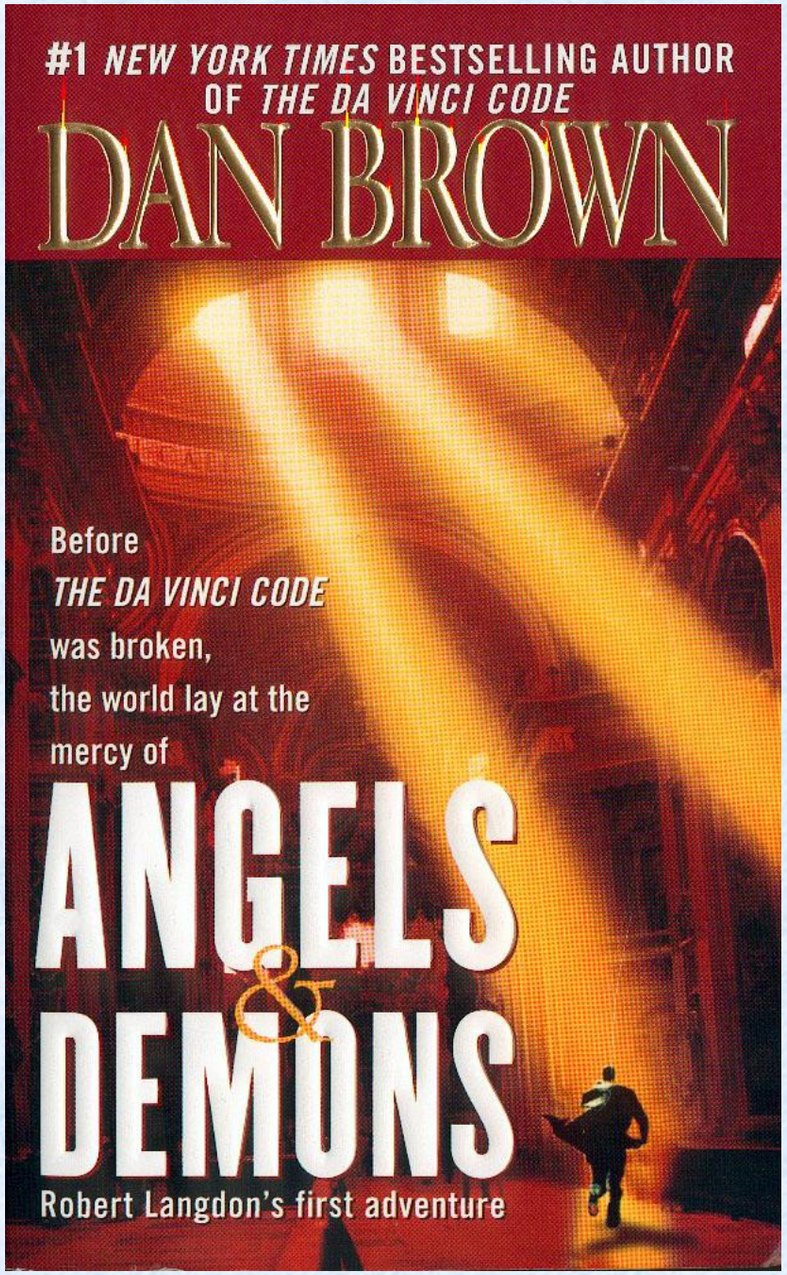


\+ / -

QuickTime™ and a
H.263 decompressor
are needed to see this picture.

How CERN **really** became famous

2000
Start of CERNs 'Antimatter Factory' (AD)
Antihydrogen experiments started (ATHENA, ATRAP)
Visit of Dan Brown (Dan Who?)

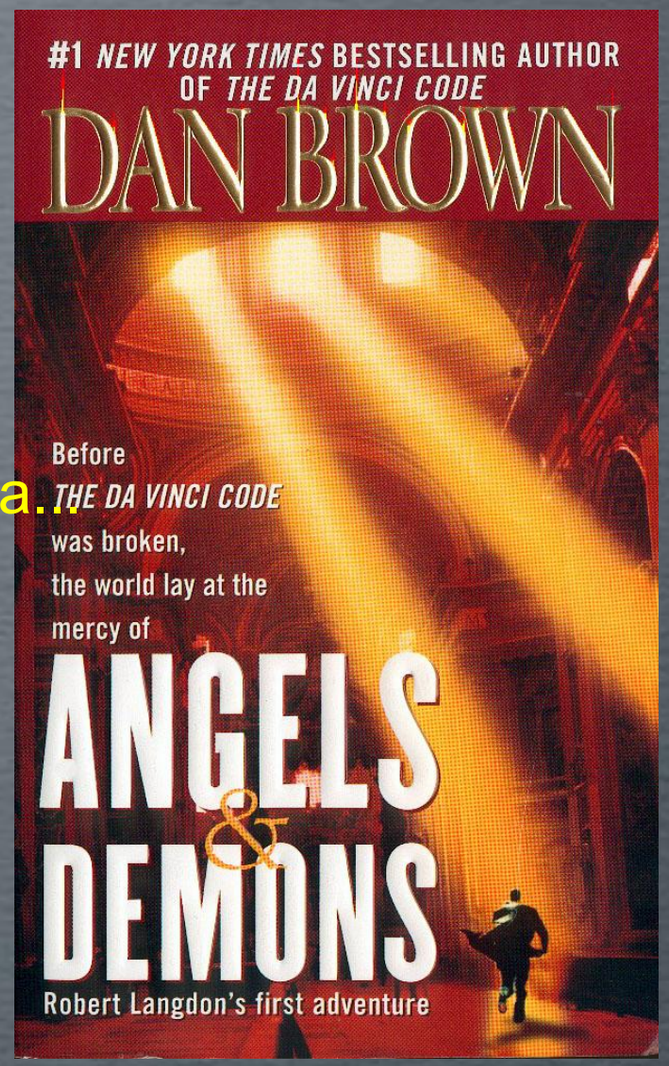


angels and demons

Illuminati

Detective story about a secret society which ...

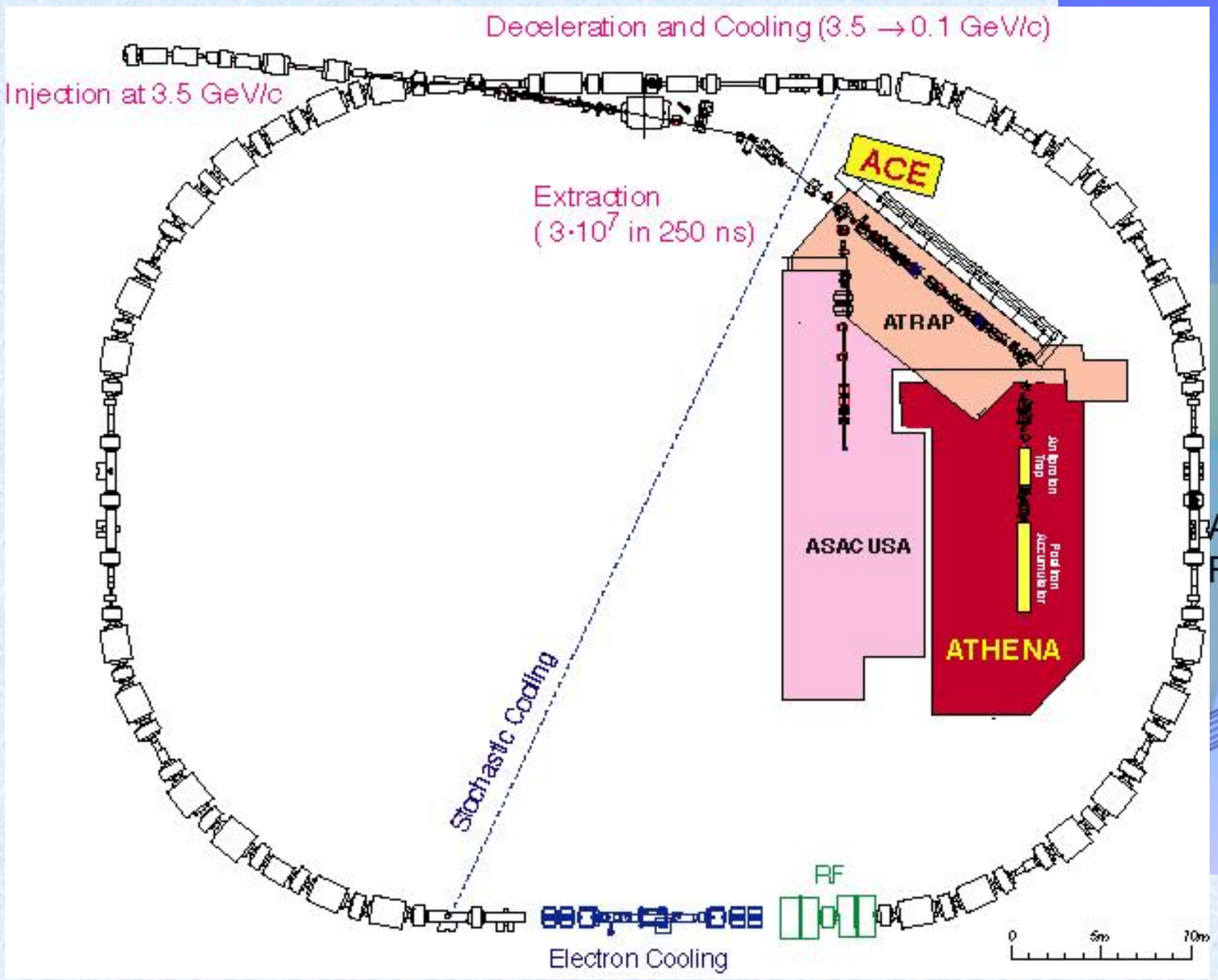
... steals 1 g of antimatter from a place called “CERN” in Geneva...

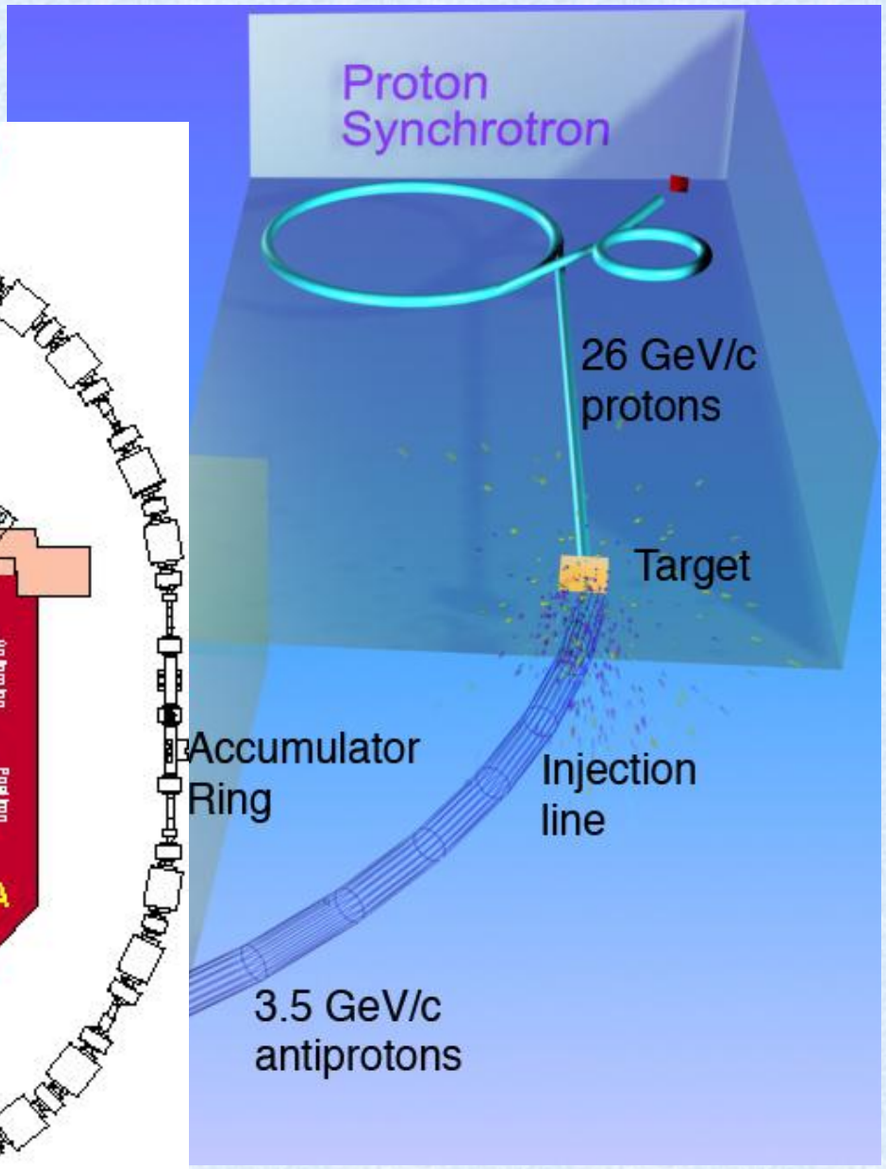


... to blow up the Vatican, an old “enemy of science and CERN”.

A mix of fact and fiction. What is true? What is false?

Antiproton Decelerator (AD)





The AD Movie

QuickTime™ and a
MPEG-4 Video decompressor
are needed to see this picture.

The AD - a machine and its team

Ron Howard, director of “Angels and Demons”

What did Ron Howard* say after he had seen CERN on his first visit in 2007?

That’s how small I feel after seeing this huge detectors ...

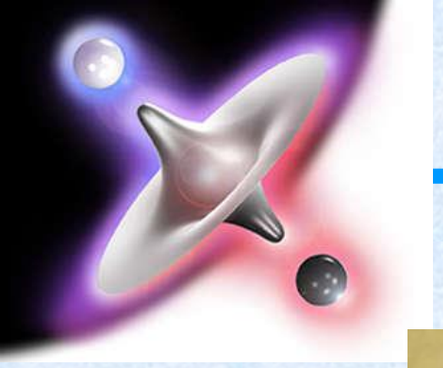
That’s the budget of my new movie “Angels and Demons”

This much science will be in the “Angels and Demons” movie ...

This is what Dan Brown understands about antimatter ....

*Da Vinci Code, Apollo 13, Beautiful mind, ...

The correct answer at the end of this lecture....



... more deep questions ....

Where is the secret antimatter lab ?

Do we have 1 gram of antimatter ?

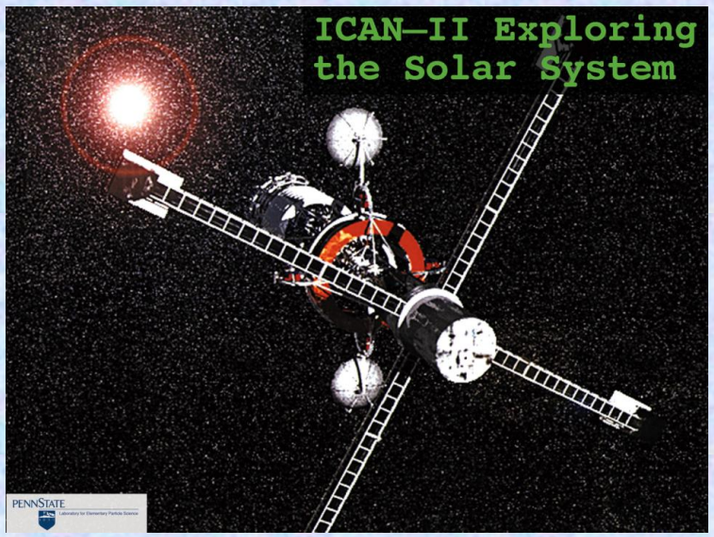
INTERLUDE (15 min)

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 99.5 % of the speed of light (assuming 100% efficiency)



Is it possible to make slow antihydrogen ?

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

Antihydrogen formation

AD

p- Production (GeV)

Deceleration (MeV)

Trapping (keV)

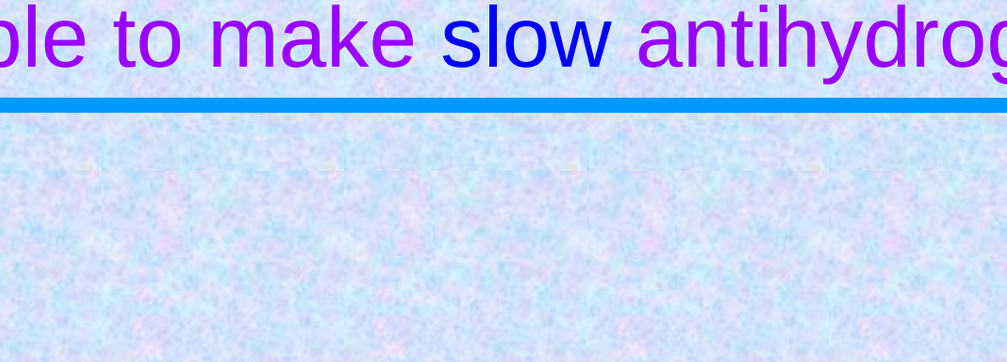
Cooling (meV)

Na-22

e^+ Production (MeV)

Moderation

Accumulation (eV)



Detection of annihilation

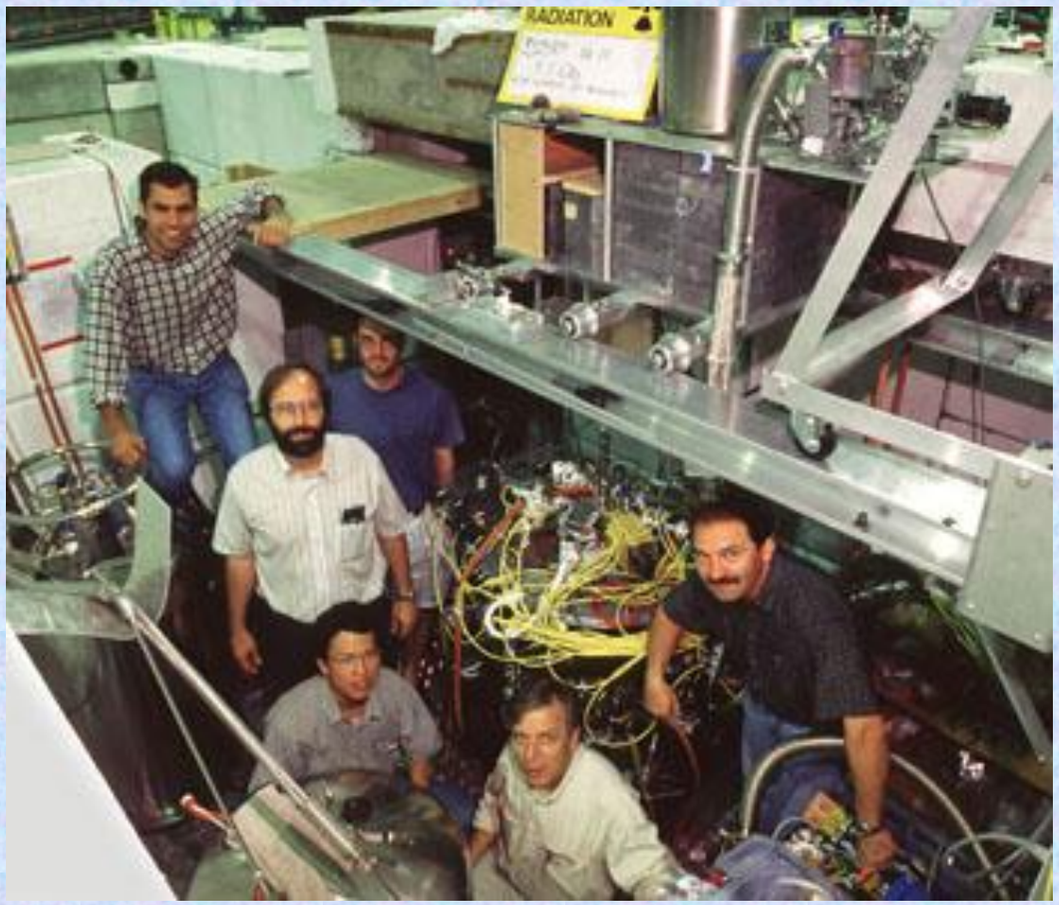
Needs trapping of antiprotons and positrons

The race for cold antihydrogen

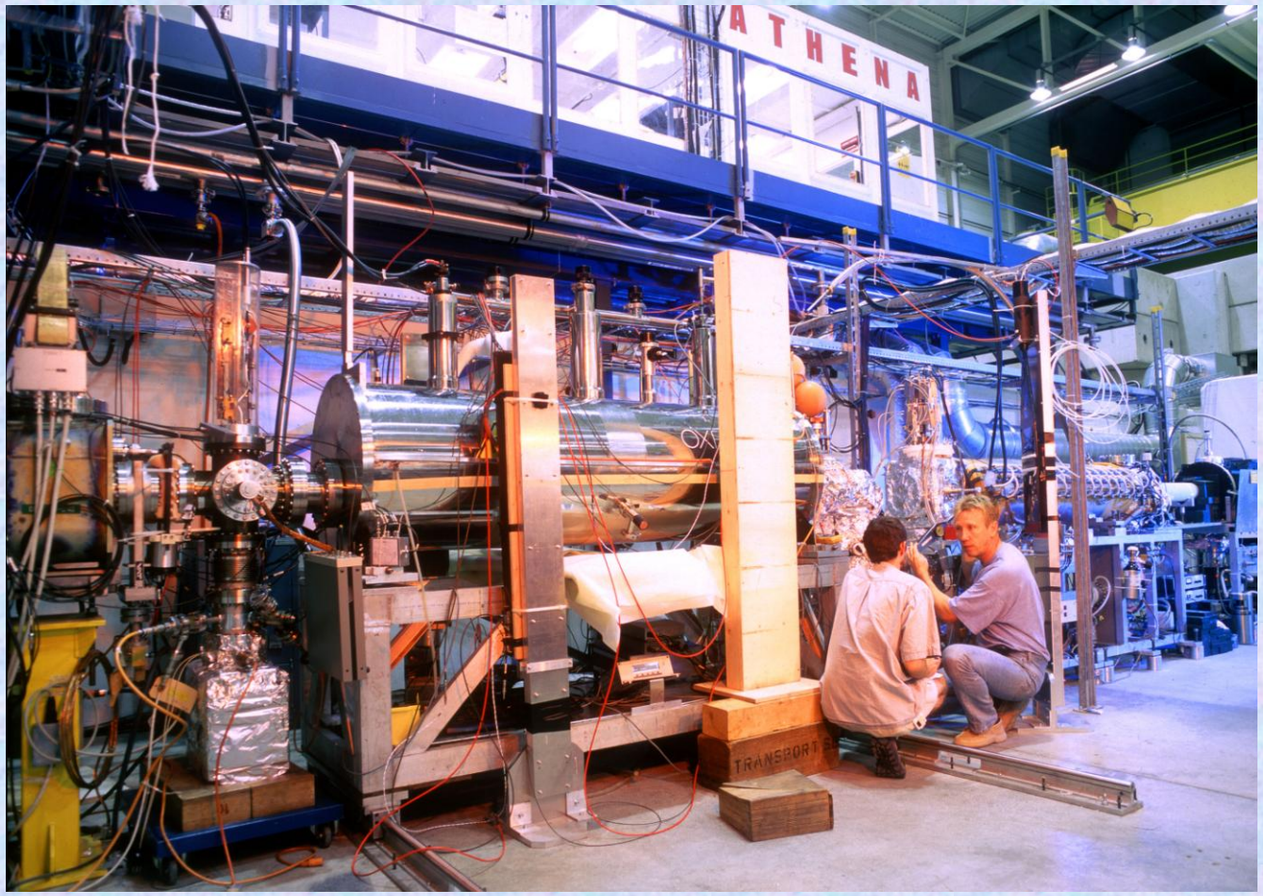
ATHENA and ATRAP - Experiments (Start 2000)

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

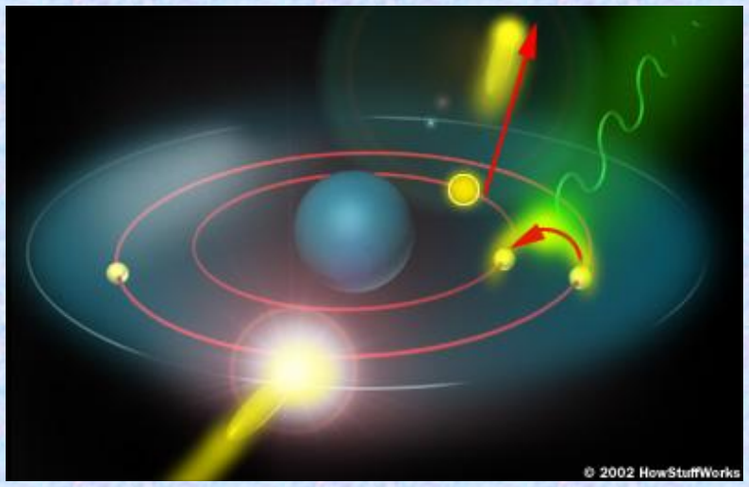
ATRAP

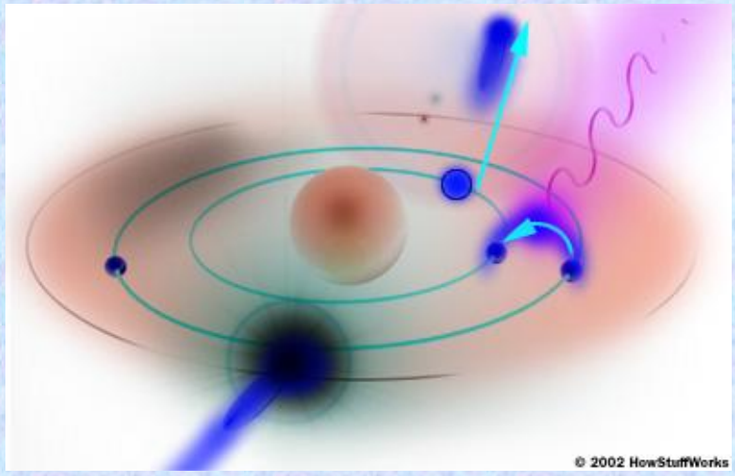


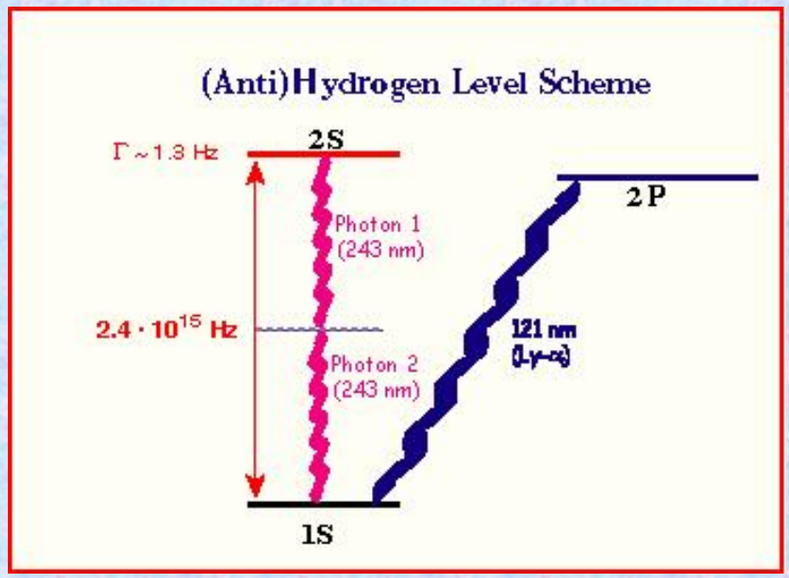
ATHENA



Antihydrogen = Hydrogen ??







2S level is metastable (T ~ 120 ms)

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

Overview - ATHENA

Antiproton capture trap

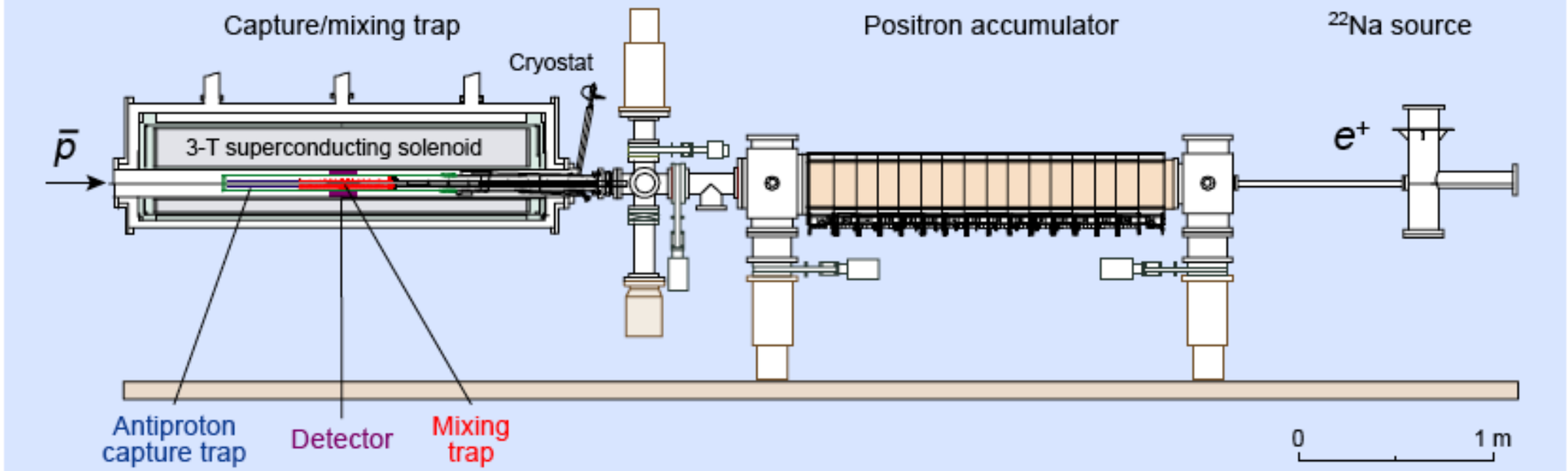
- Deceleration and capture of antiprotons
- Penning trap in 3-T field at 15 K
- Cooling and accumulation in e^- plasma

^{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



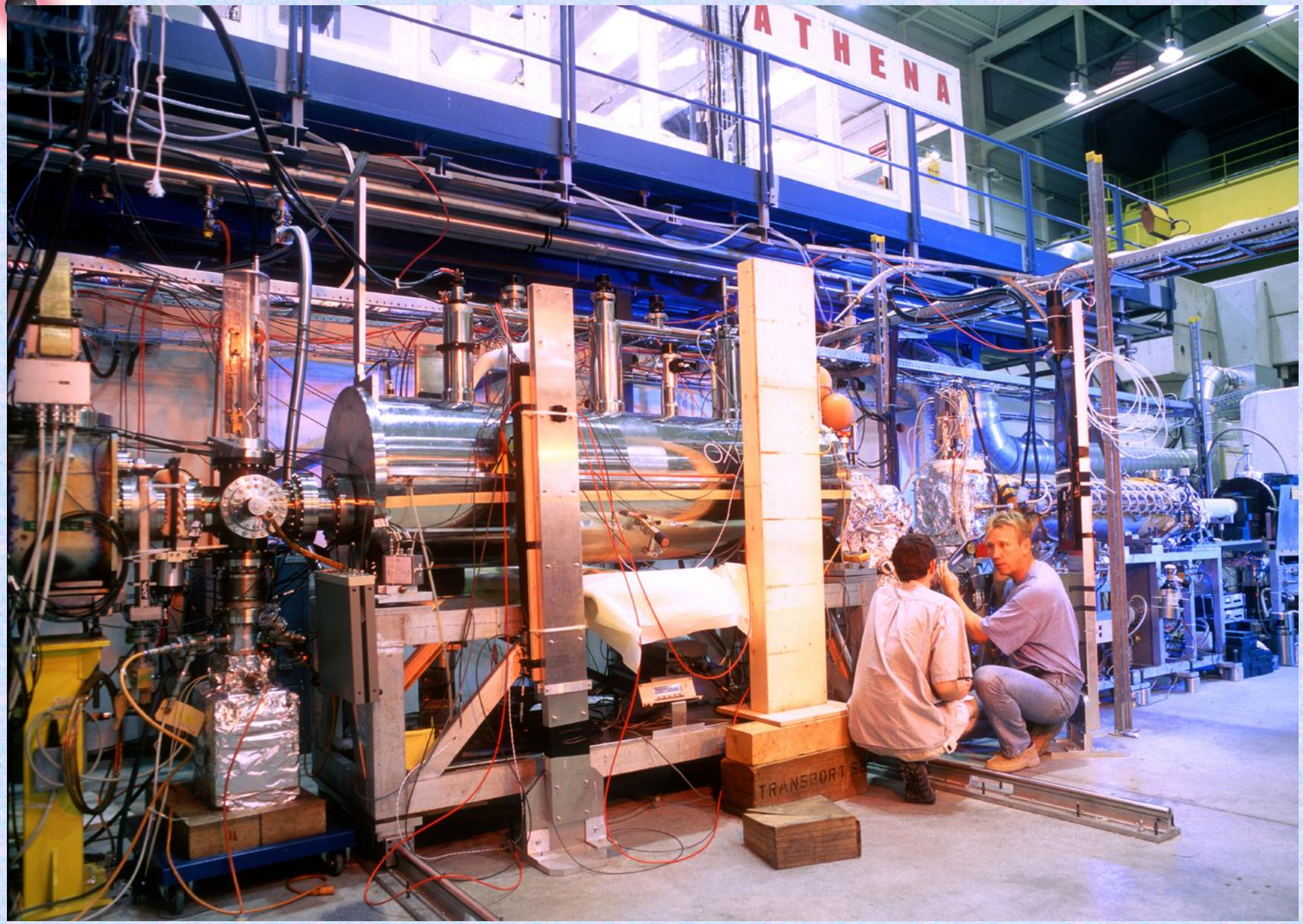
Mixing trap

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

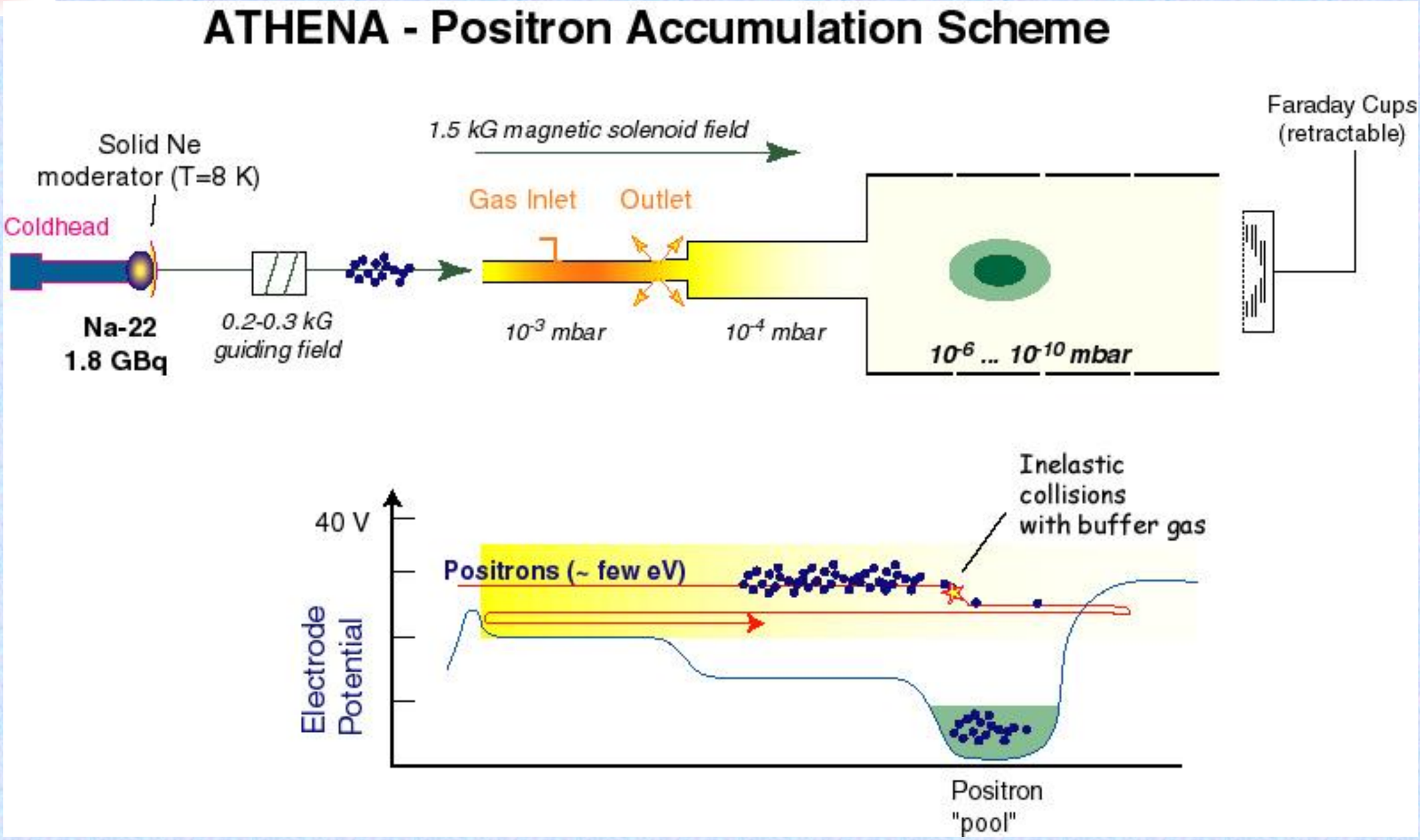
Detector

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

ATHENA Experiment

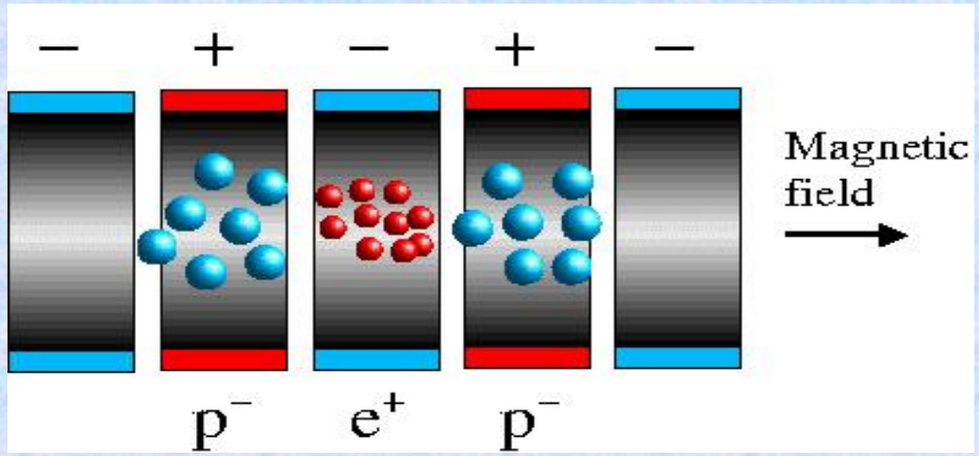


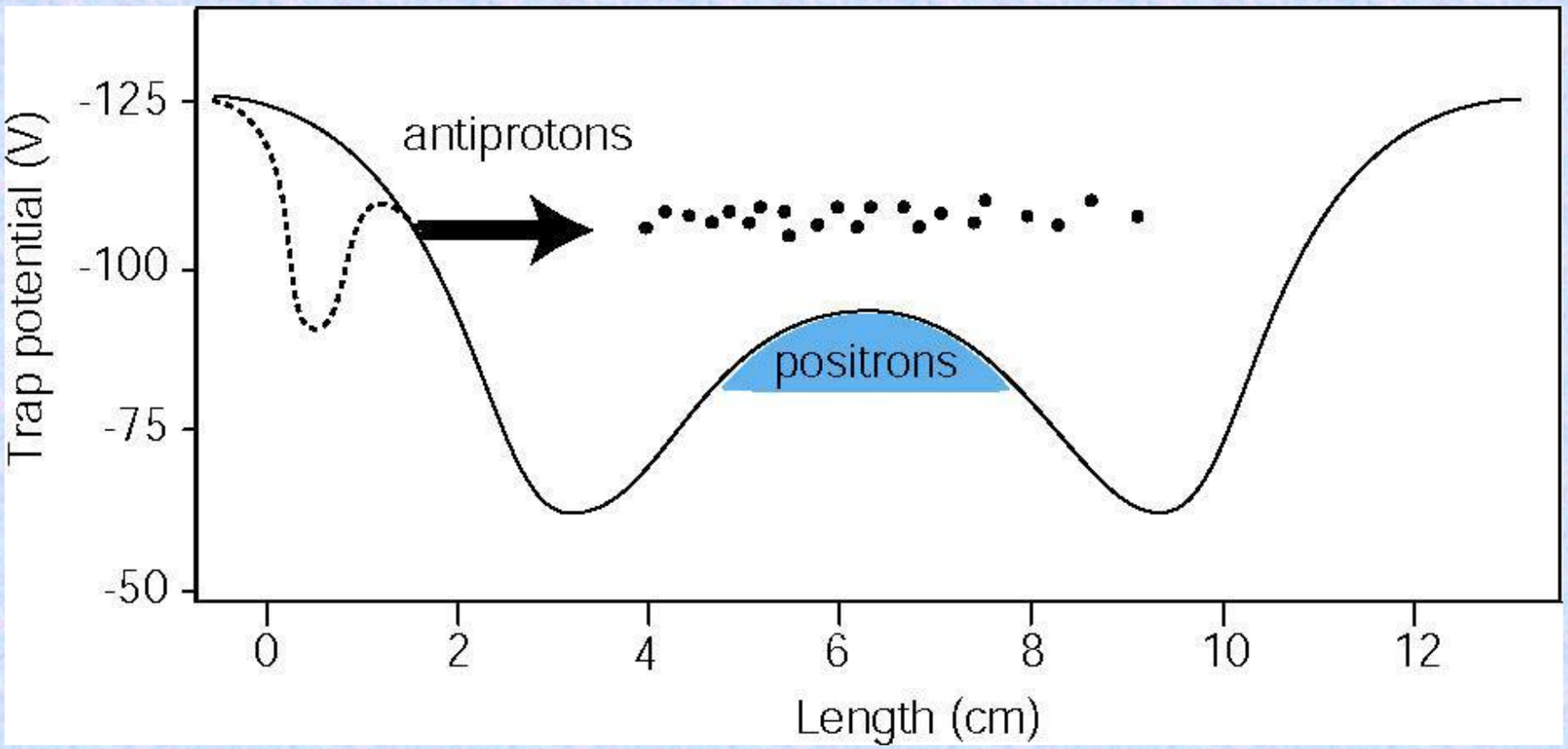
Positron Accumulation using Buffer Gas



100 million positrons accumulated in 2 min

Recombination





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

Antihydrogen Detection

Charged particles

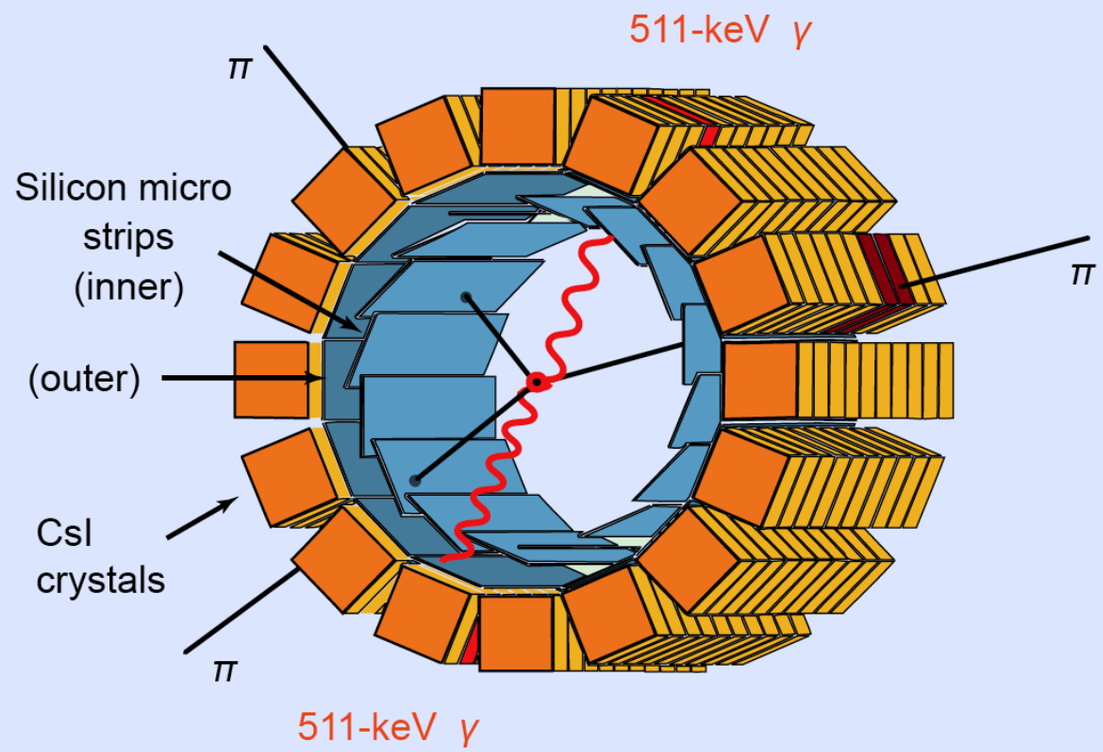
2 layers of Si microstrip detectors

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))



Event analysis:

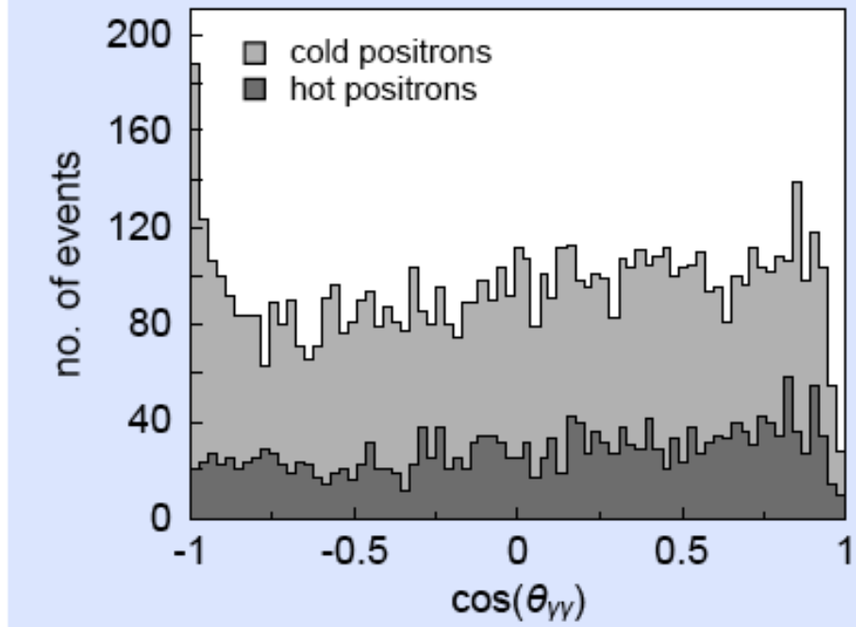
- Reconstruct vertex from tracks of charged particles
1. Identify pairs of 511 keV ©-rays in time coincidence
2. Measure opening angle between the two © -rays

Antihydrogen - The Movie

QuickTime™ and a
Sorenson Video decompressor
are needed to see this picture.

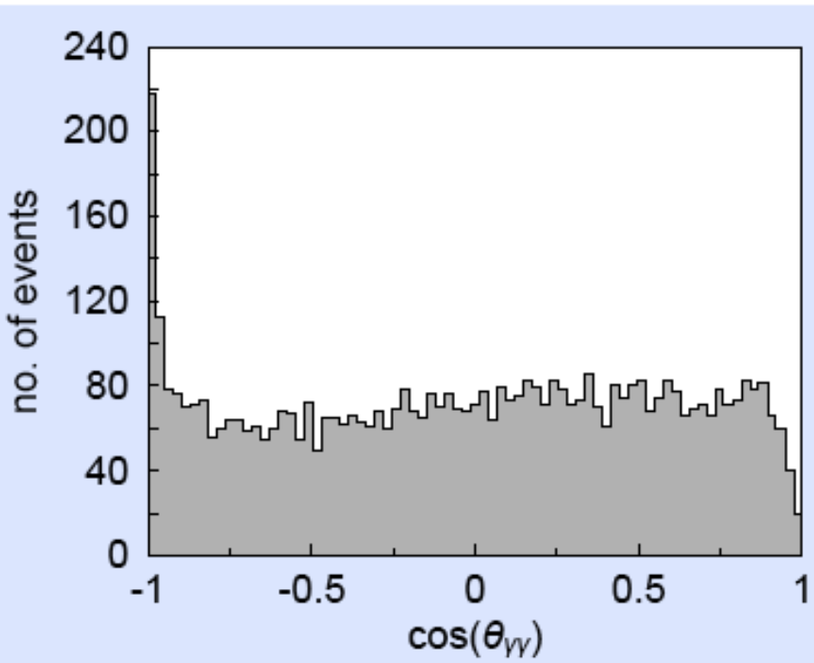
First observation of cold antihydrogen (ATHENA, 2002)

Opening Angle Distribution



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

Data

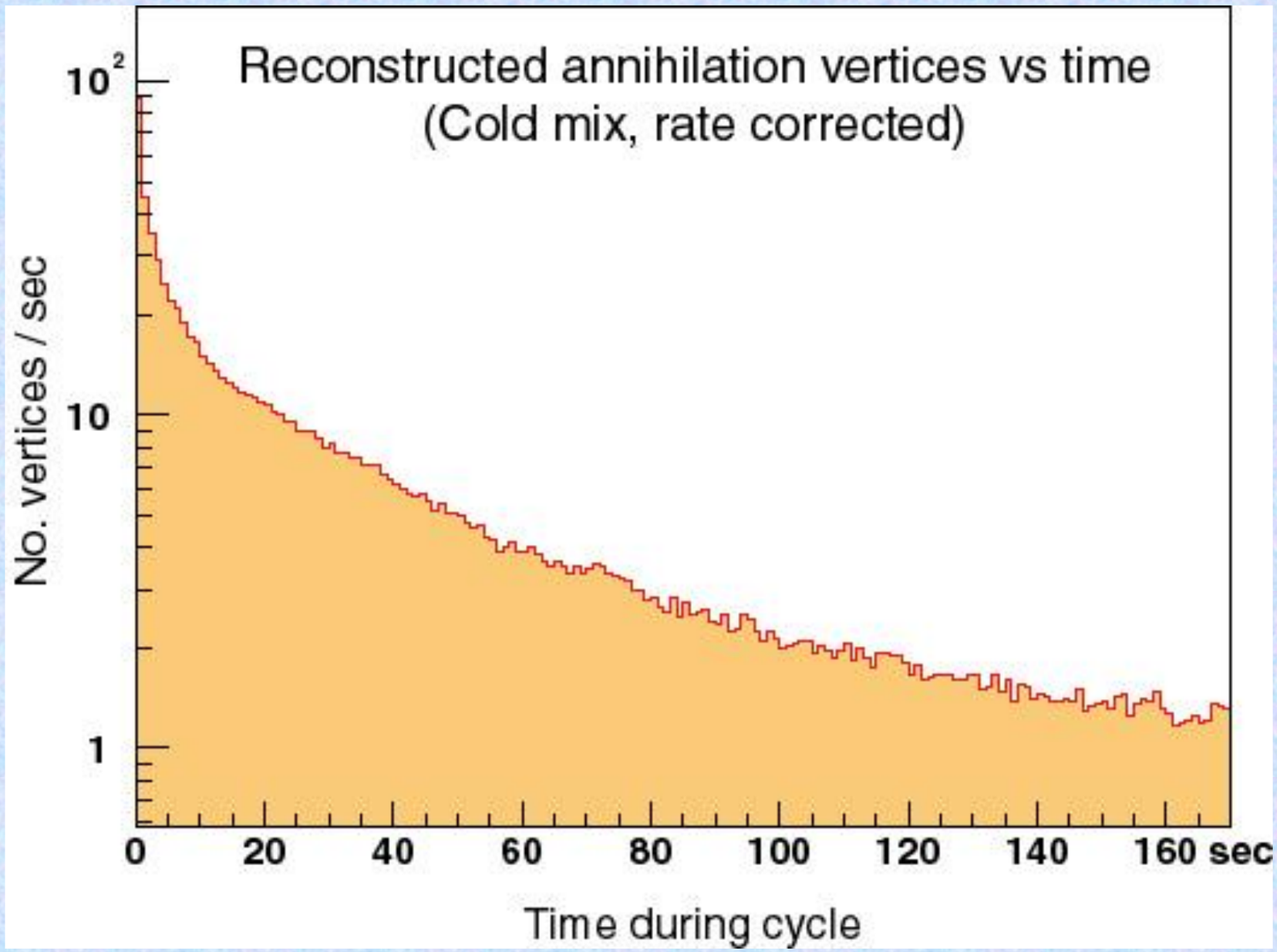


Monte Carlo

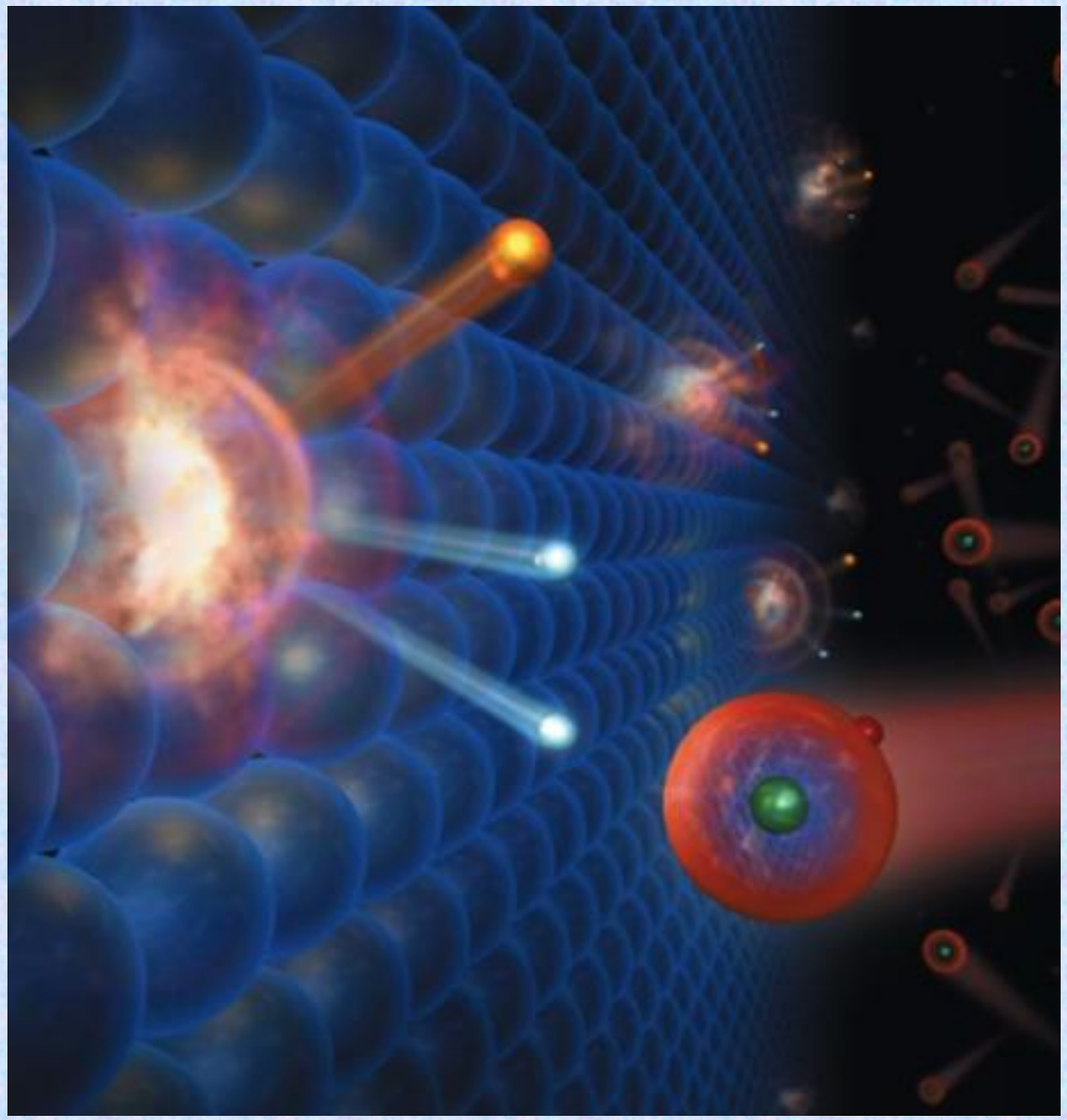
Peak from back-to-back 511 keV photon pairs
Test: peak disappears when positrons are 'heated' (RF)
Correcting for detection efficiency: **> 100,000 anti-atoms**

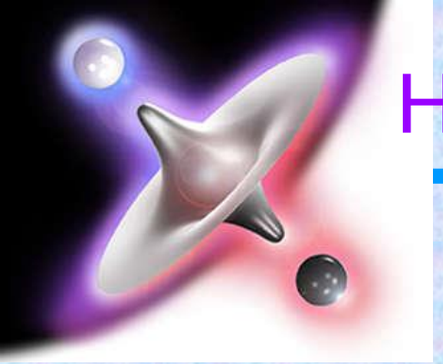
Rate of antihydrogen production quite high

Initially > 100 Hz



Problem:
antihydrogen escapes and annihilates (~ 1 μs).





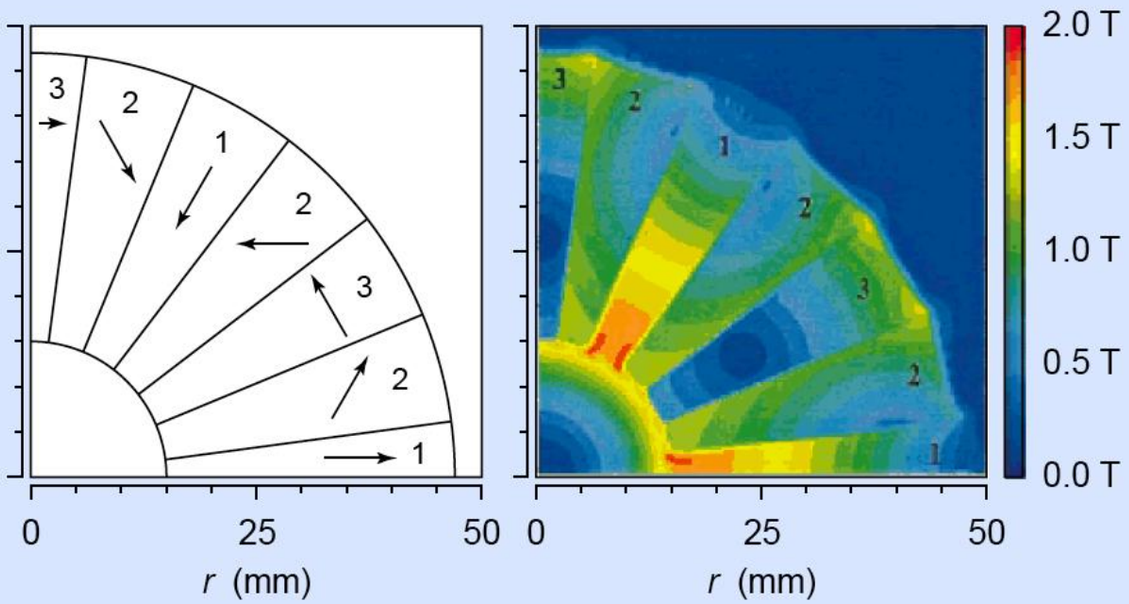
How to make measurements with trapped antihydrogen

1) magnetic moment (~ μ_{e+}) ?

2) Laser cooling at 121.5 nm ?

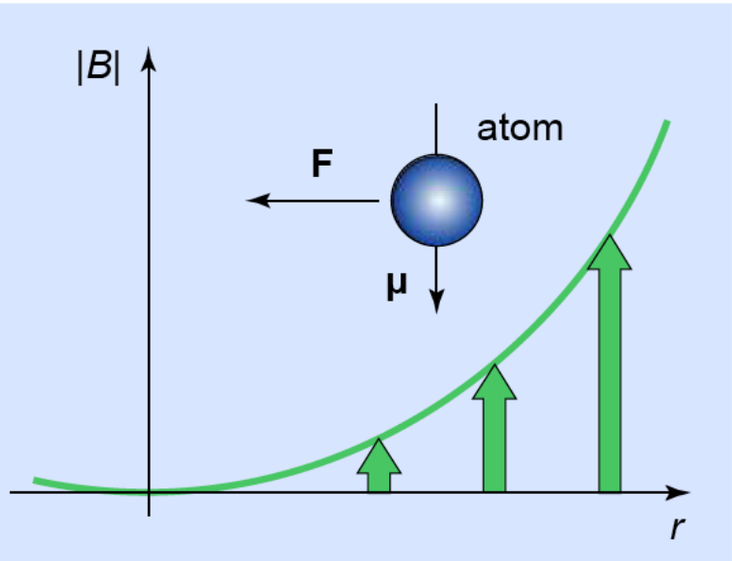
Magnetic bottles ?

Example: Sextupole magnet



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

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



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

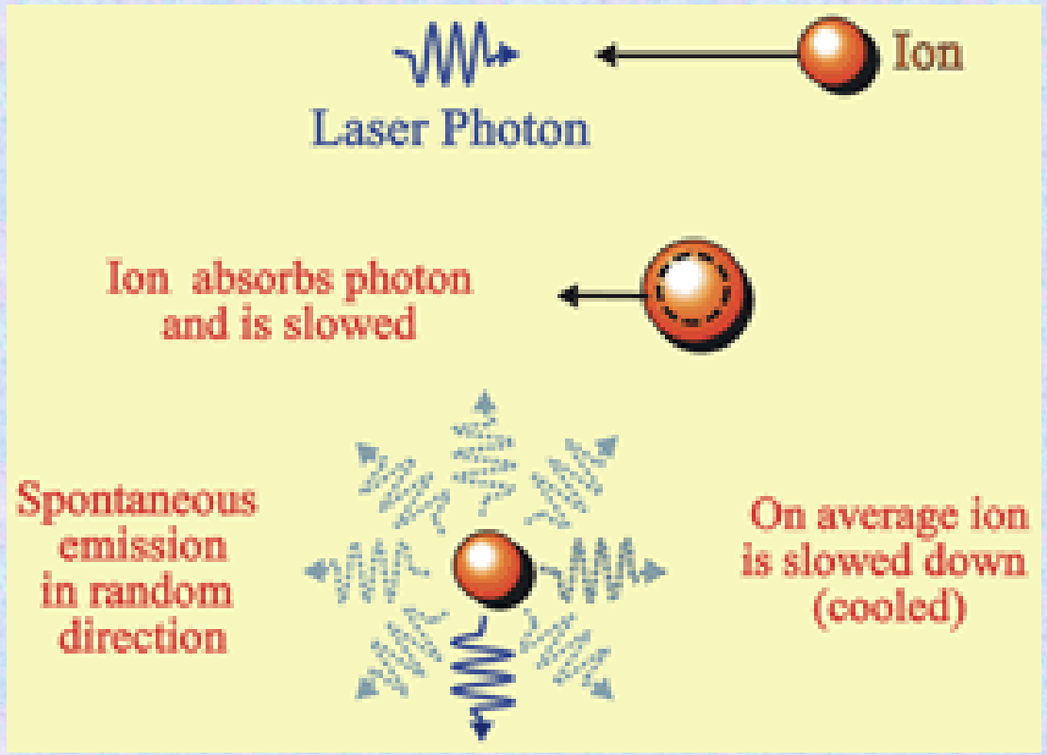
BUT: Very shallow potential (~ 0.07 meV/T)

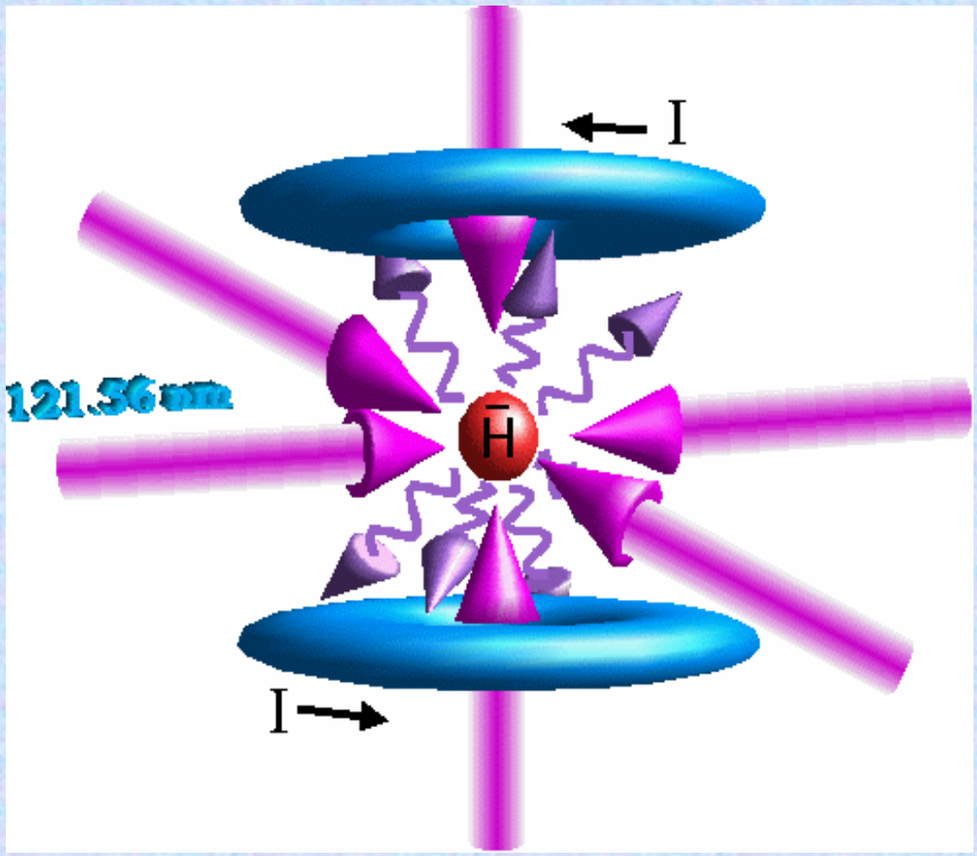
Realistic ⊗B ~ 0.2-0.3 T ➪ **E < 0.02 meV**

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

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

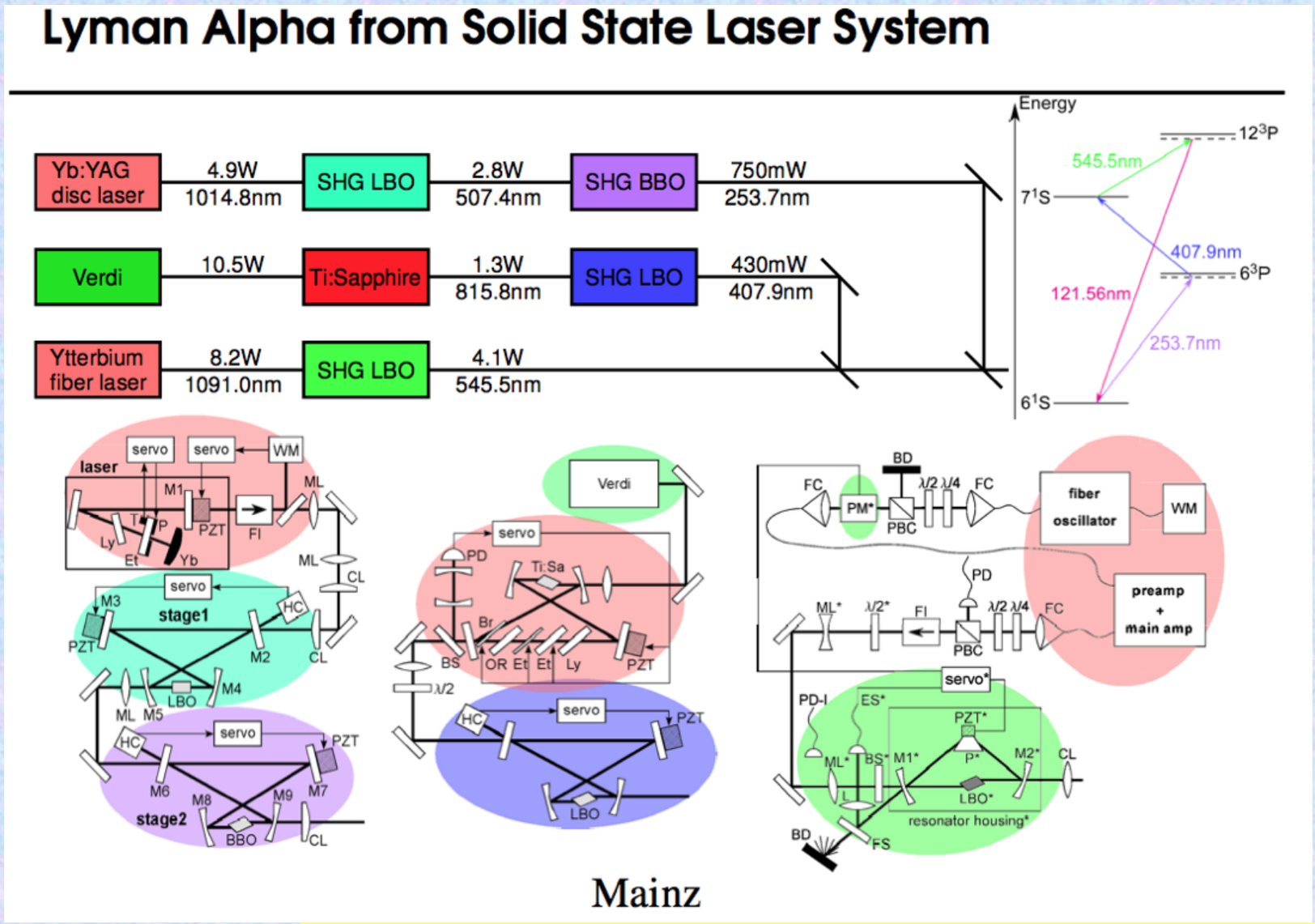
Antihydrogen trapping: Laser cooling ?





121.5 nm laser prototype

... not so easy ...



121.5 nm laser needed (Lyman-Alpha line of hydrogen)

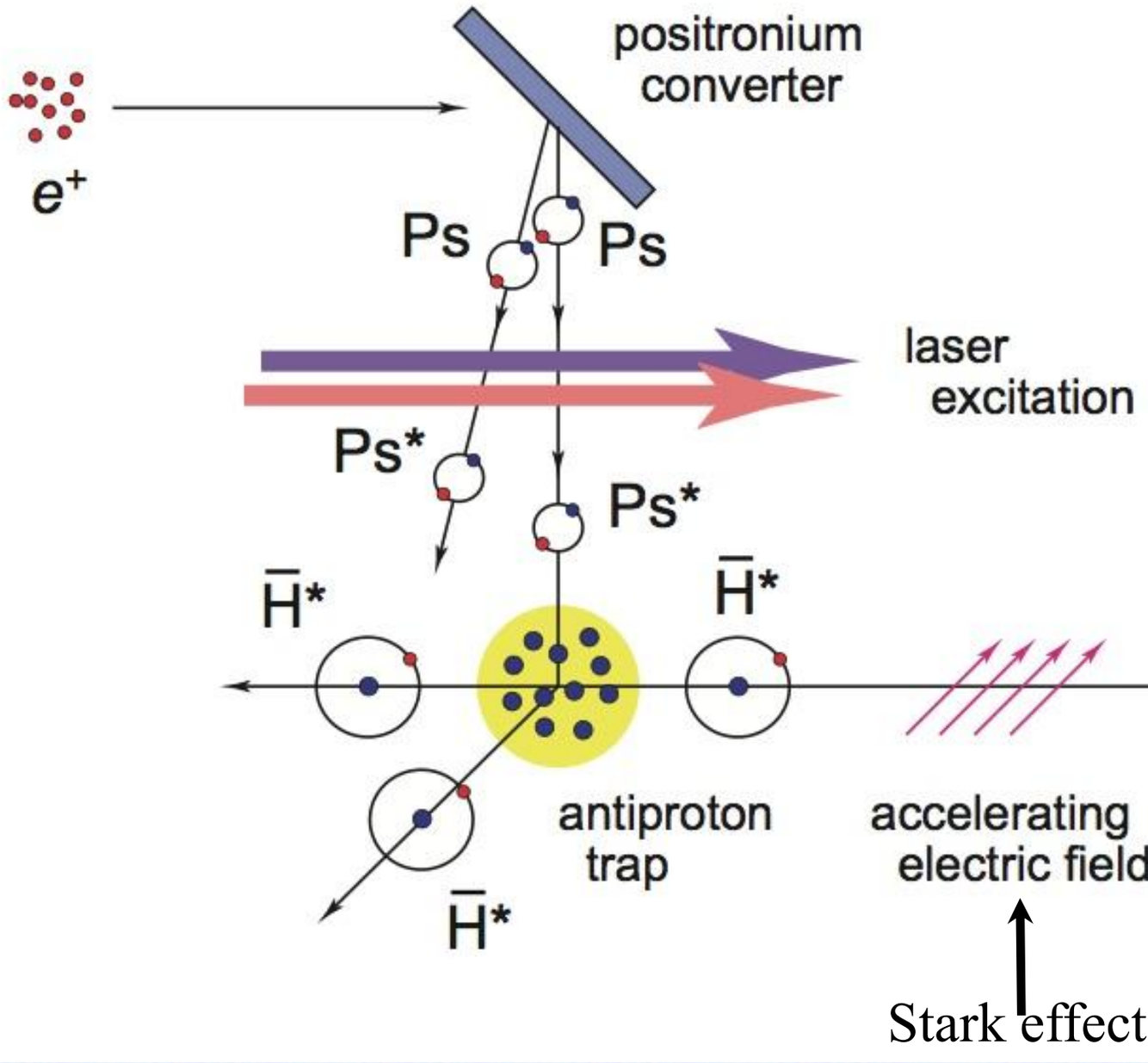
Prototypes exist … only 50 nW

A promising new experiment at CERN:

Antihydrogen in flight (AEGIS)

[**A**ntimatter **E**xperiment: **G**ravity, **I**nterferometry, **S**pectroscopy]

Antihydrogen in flight: AEGIS



Ps excitation in two steps:
1 - 3, then 3 - n

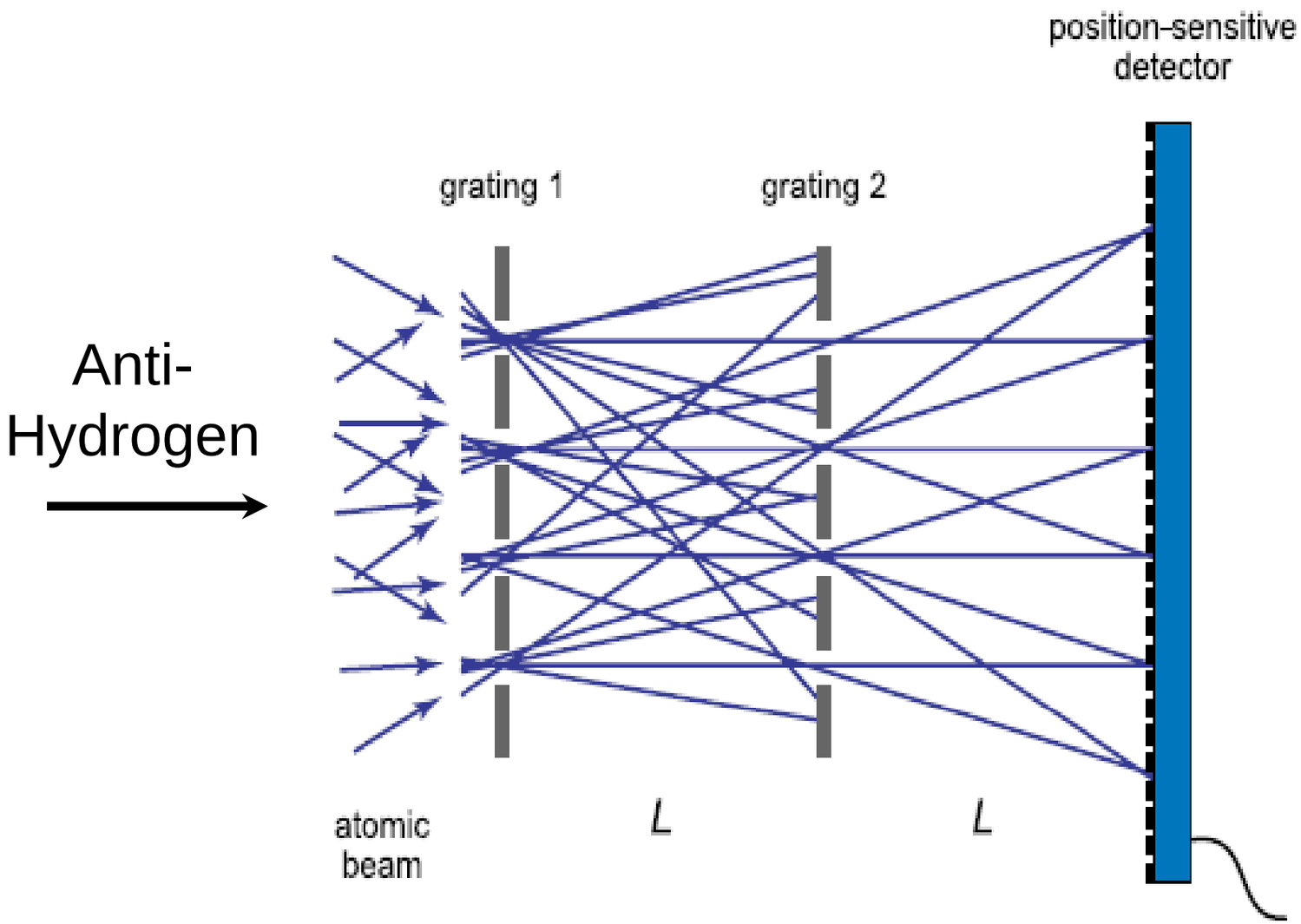
Laser excitation defines ‘start’ of antihydrogen production

AEGIS: Gravitational deflection & Moiré deflectometer (I)

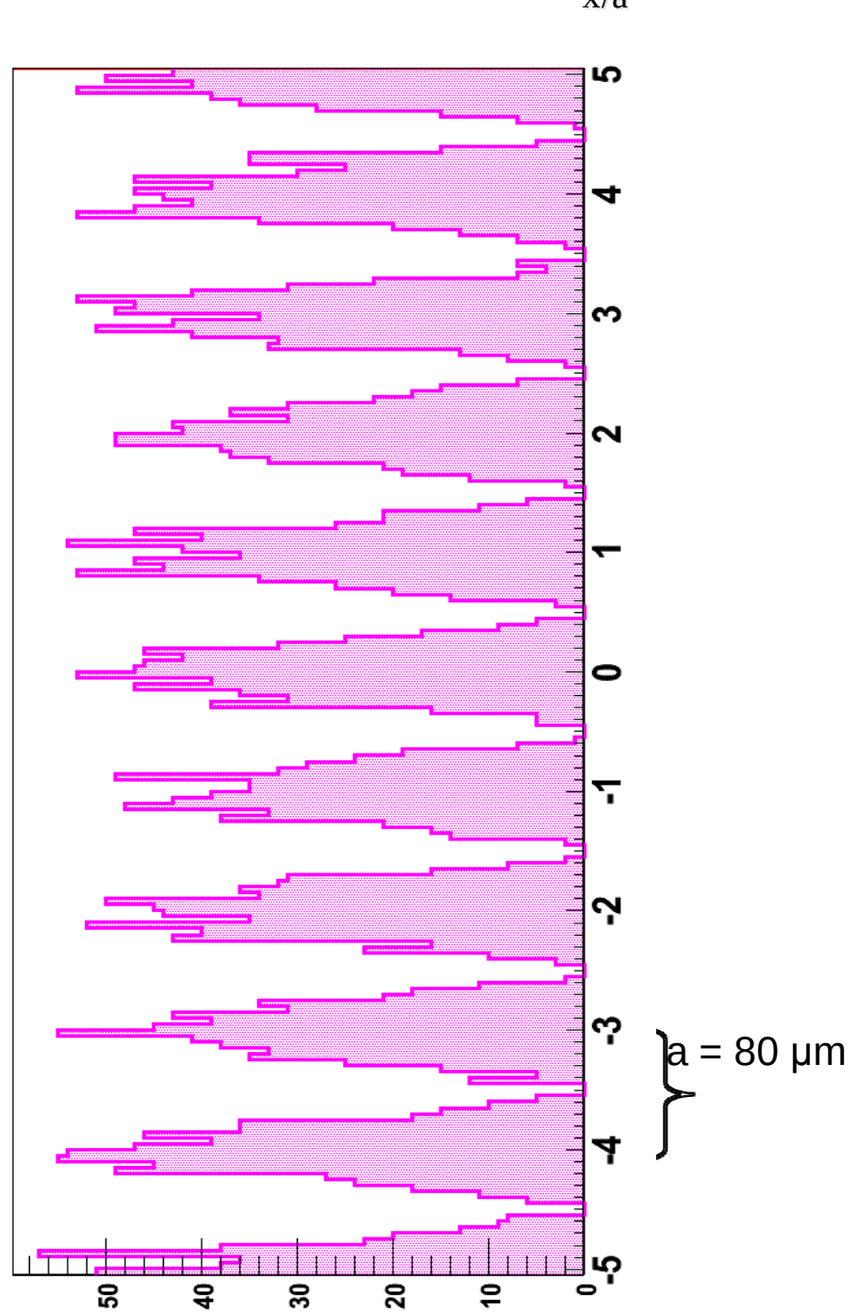
(based on measurement carried out on Argon atoms (3 gratings) M. Oberthaler et al., Phys. Rev. A 54 (1996) 4)

simulations of the experiment

a) no gravity. very high statistics



Counts vs. vertical coordinate



Grating period a = 80 μm

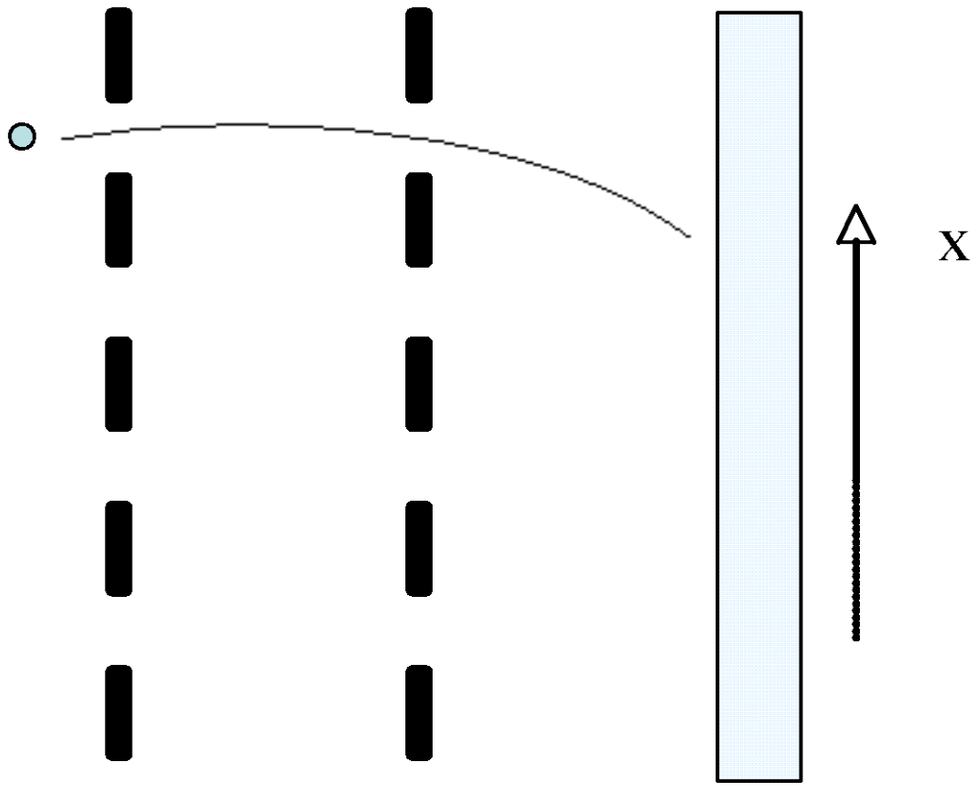
Grating size = 20 cm (2500 slits)

Gravitational deflection & Moiré deflectometer (III)

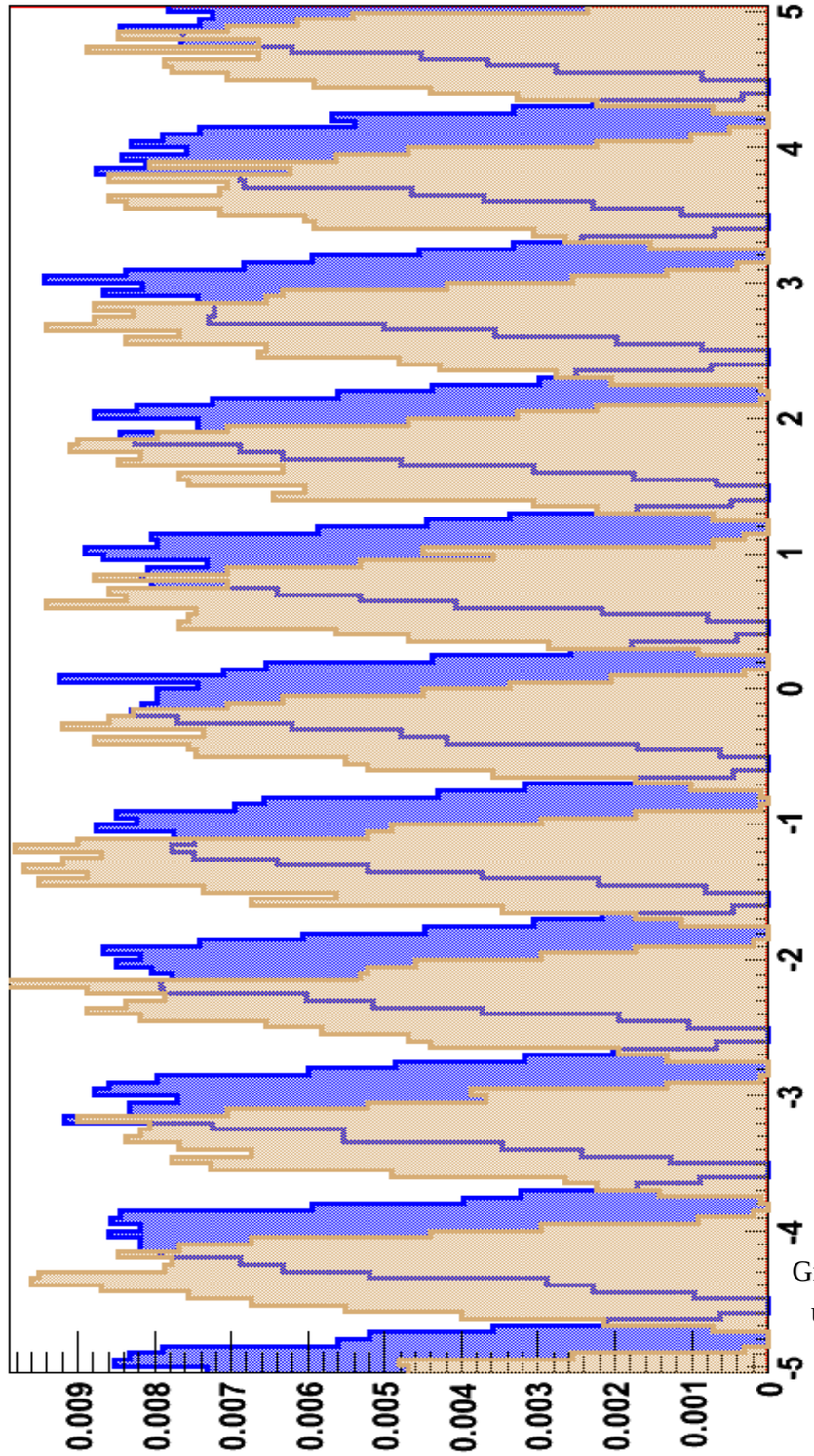
with gravity

v =250 m/s

v =600 m/s



$$\delta = \frac{gt^2}{a}$$



start: laser excitation of positronium

stop: annihilation signal

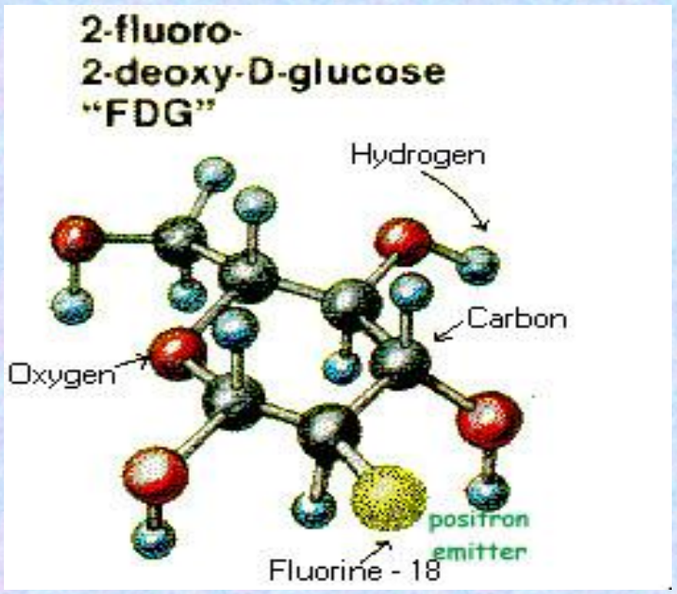
TOF: velocity

FINALLY:

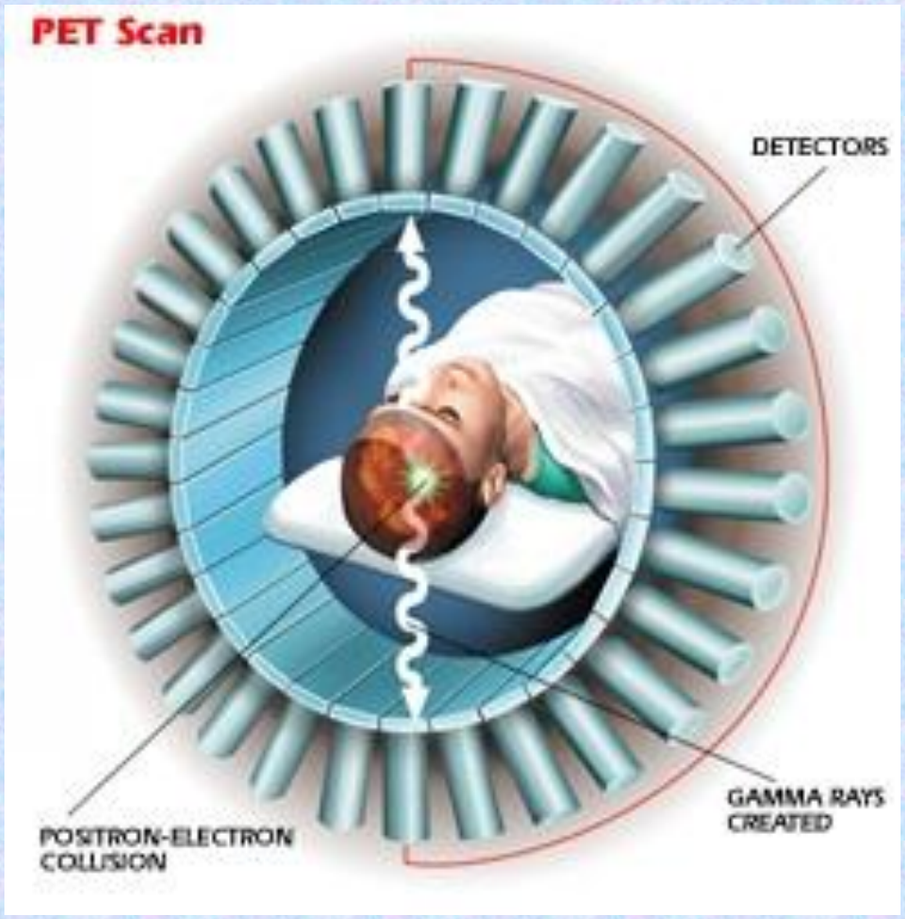
Antimatter technology PET
Antiproton therapy?
Rocket propulsion??

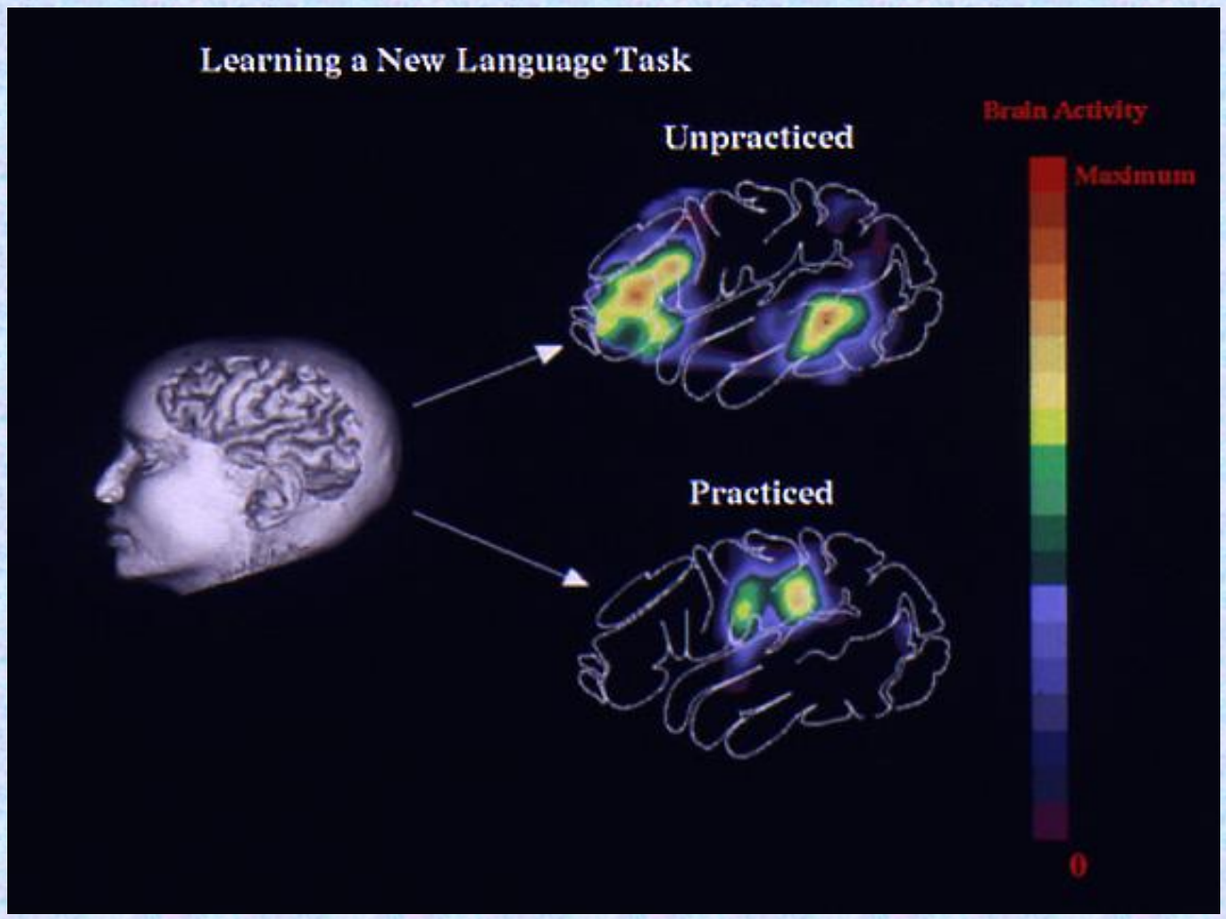
Applications of antimatter - PET

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

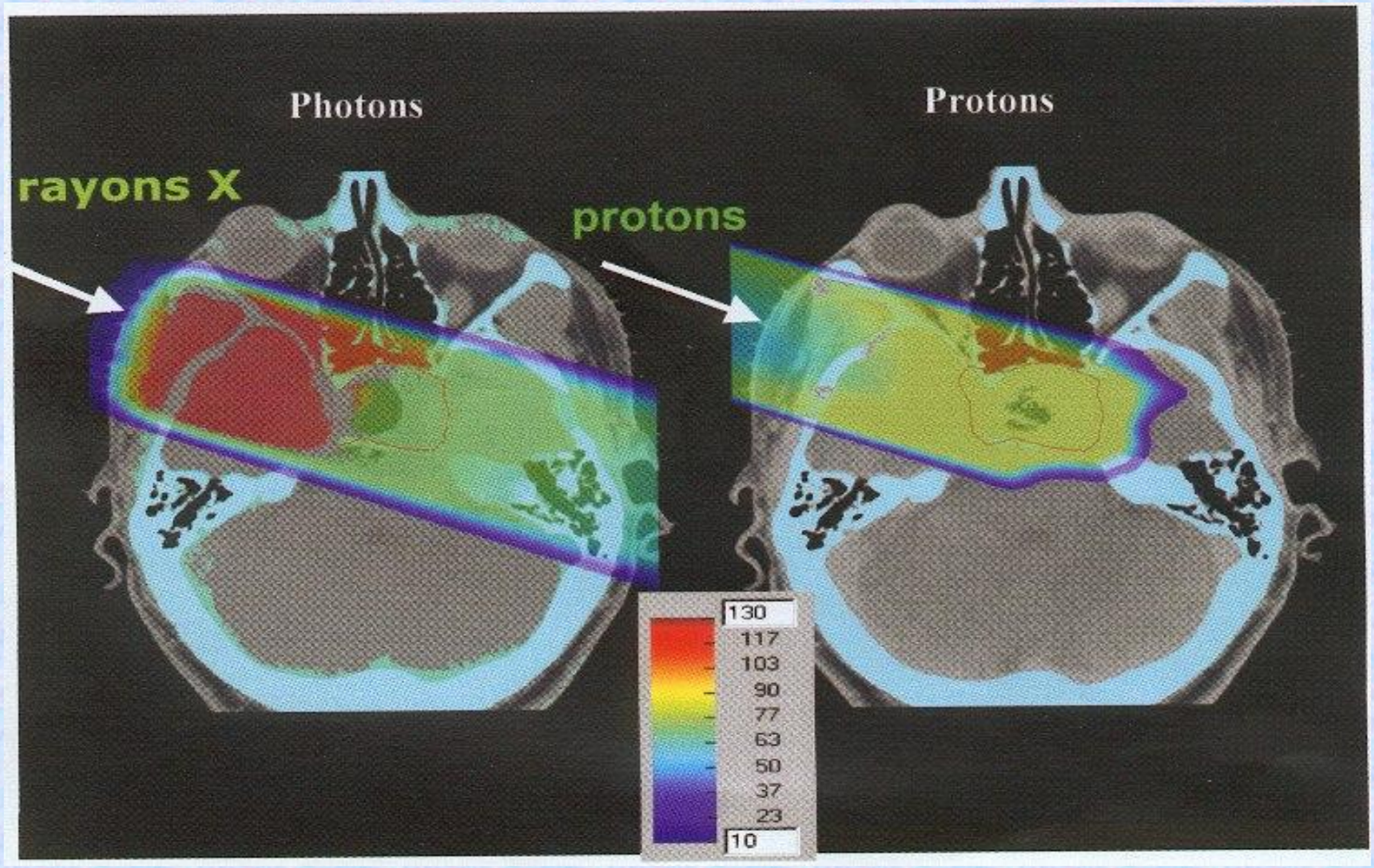




Tumour therapy

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

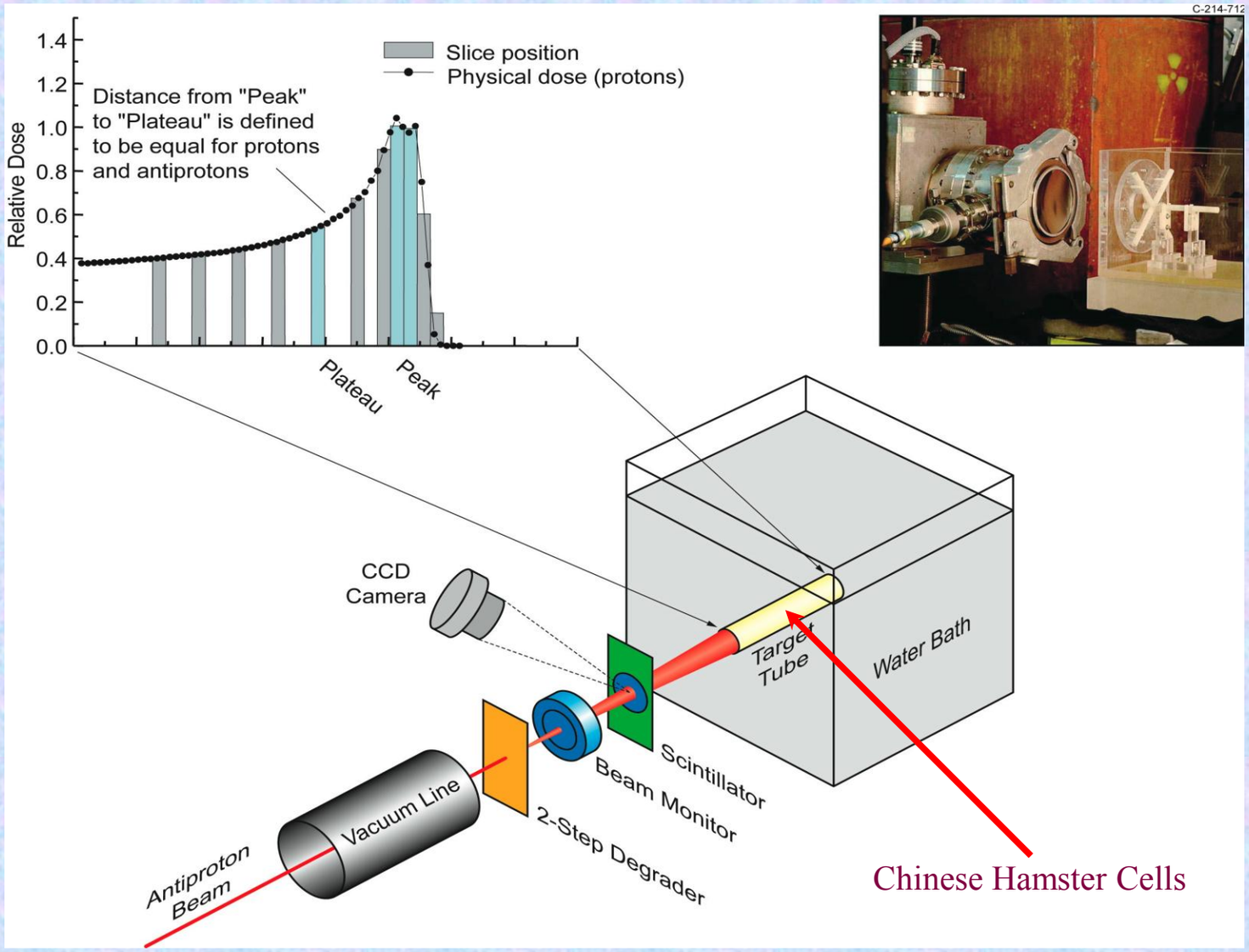
Gammas: exponential decay (peaks at beginning)
Charged particles: Bragg peak (Plateau/Peak better for high Z)
Antiprotons: like protons, but enhanced Bragg peak from annihilation



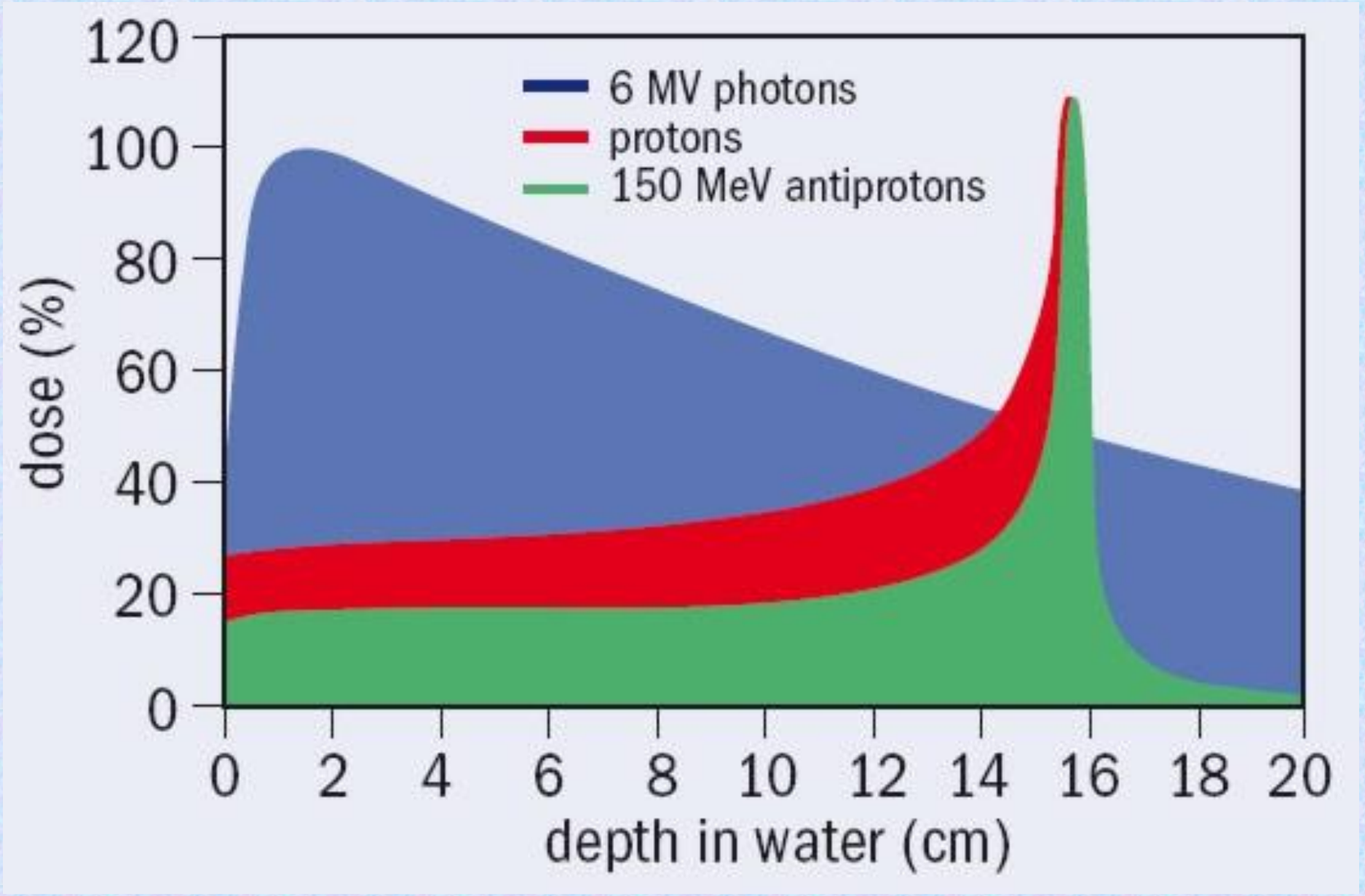
Antiproton Cell Experiment

Biological effectiveness of antiproton annihilation in cells

Additional damage by nuclear fragments of short range



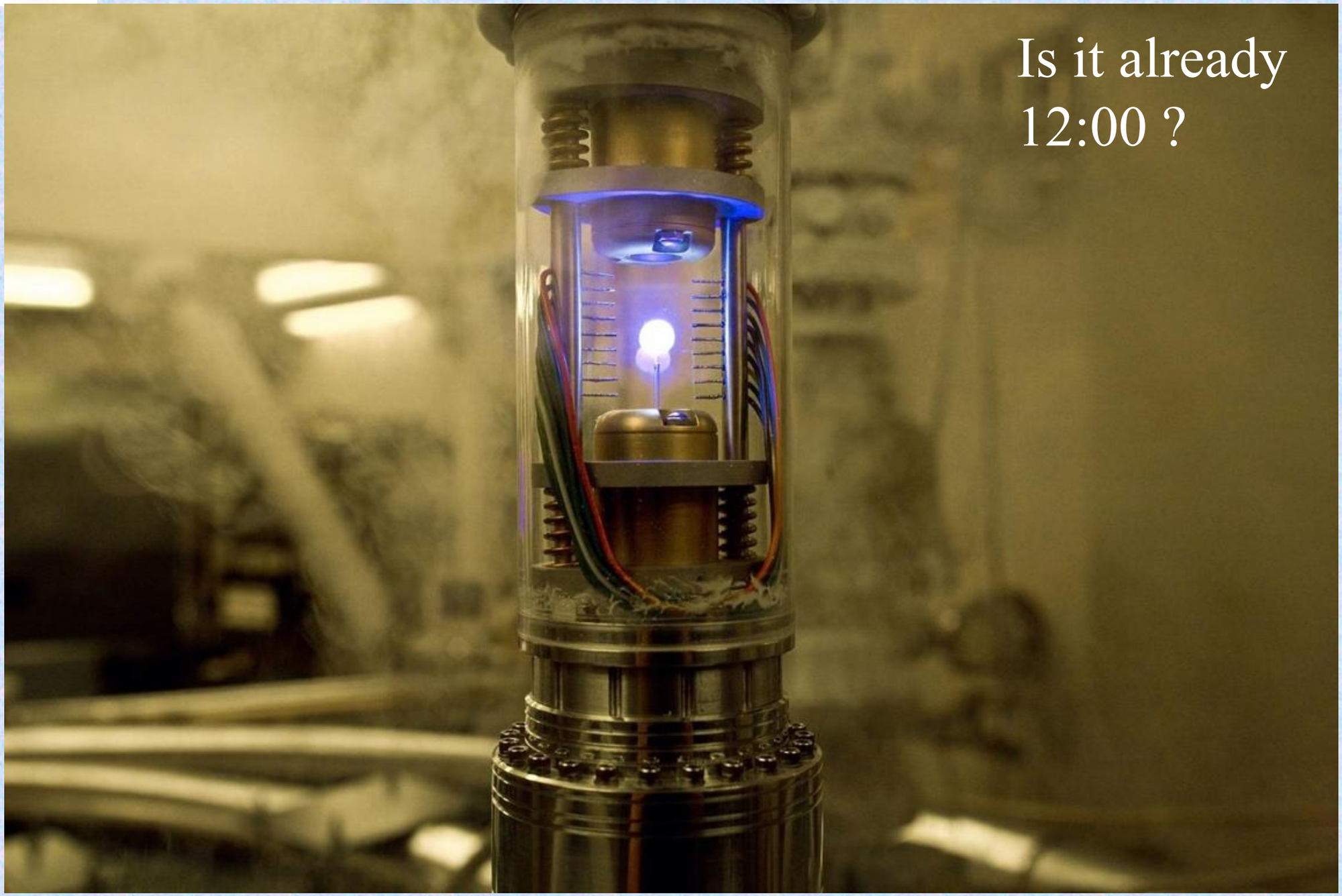
Antiproton Cell Experiment (ACE)



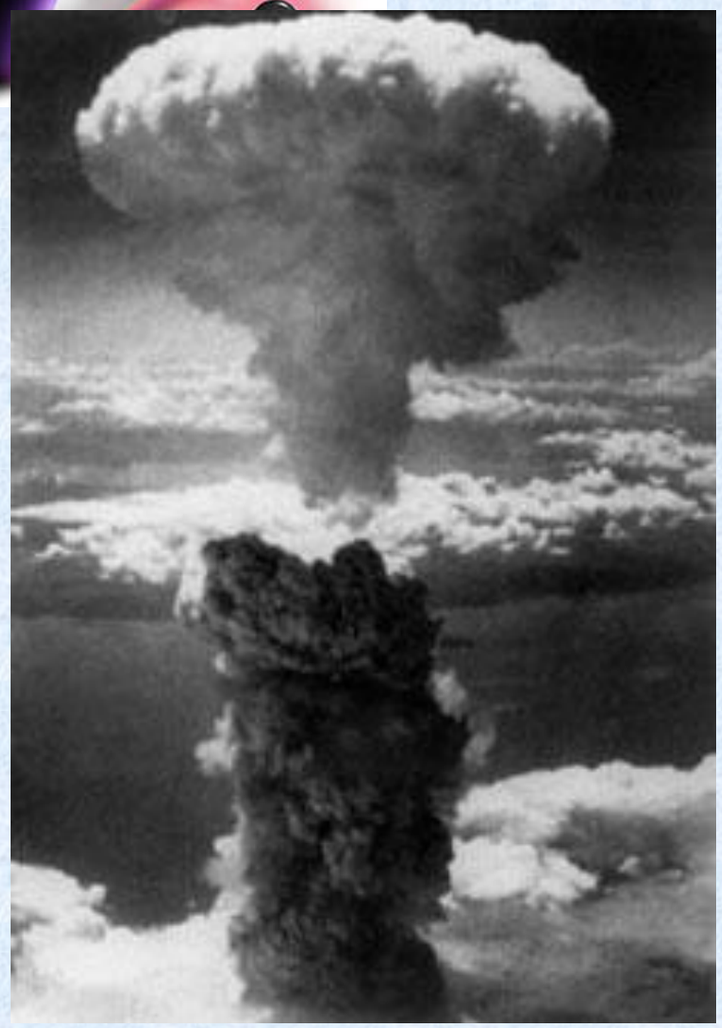
Equal cell mortality for tumour cells with less than 1/2 radiation dose

Compare with Carbon ion therapy

Lots of antimatter ?



But what about antimatter bombs ?



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

BUT:

0.5 g antimatter = $4.5 \cdot 10^{13}$ J

Total energy needed (efficiency =10^{-9}) : $4.5 \cdot 10^{22}$ J

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

Electricity discount price CERN
[1 kWh = $3.6 \cdot 10^{6}$ J = 0.1 €]

Price ~ 1,000,000,000,000,000 €

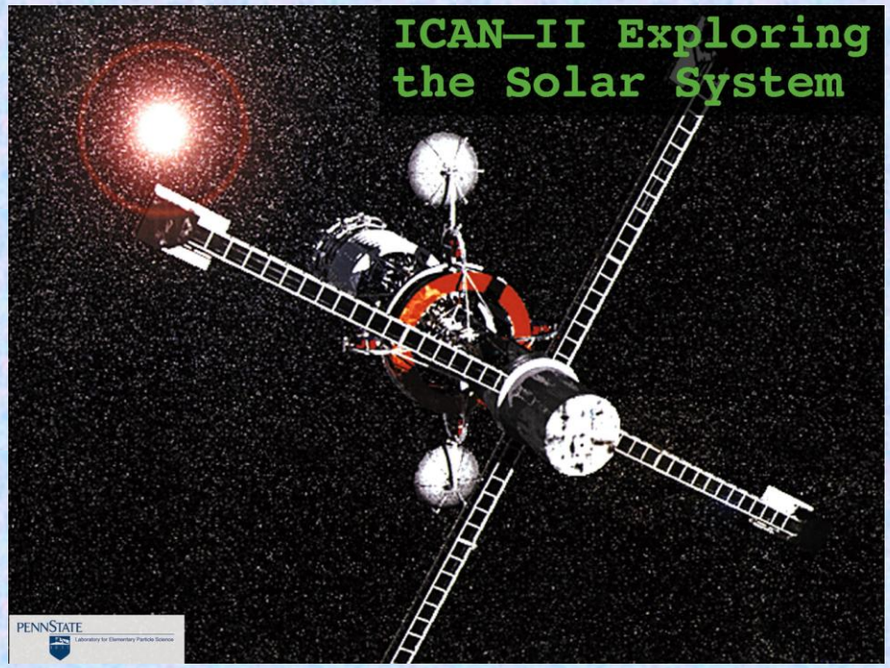
Delivery time ~ 1 000 000 000 years

Antimatter driven space engines?

10-ton spacecraft at 0.995 c:

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

50 tons of antimatter + 50 t of matter



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


2 BLICK • Samstag, 6. Januar 1996 AKTUELL

E.T., wir kommen

In Genf wurde Wunder-Energie entdeckt

VON WERNER BUCHER

noch nicht !

(E.T. we don't come yet)

The real ‘AD’ (**A**ngels + **D**emons) Movie

What did Ron Howard say after a visit to CERN?

THANK YOU FOR YOUR ATTENTION