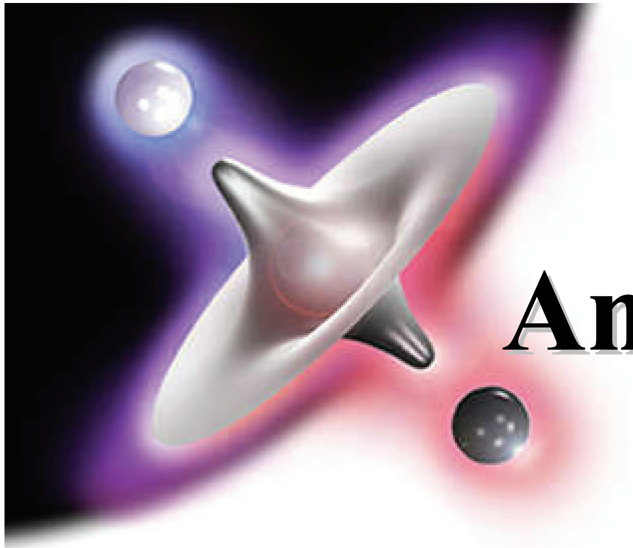


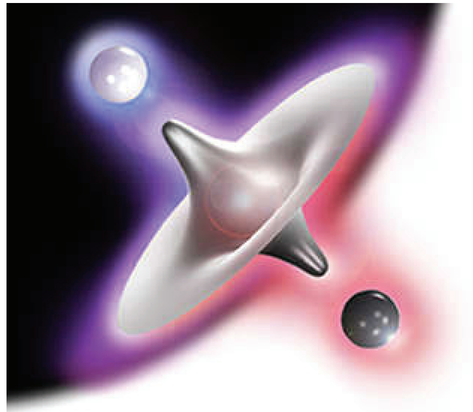
Antimatter

Jan Meier

Seminar: Experimental Methods in Atomic Physics

May, 8th 2007

Overview



- Antimatter and CPT theorie
  - what is antimatter?
  - what physics does it follow to?
- First observations of antimatter
- Natural sources of antimatter
- Artificial sources of antimatter and experiments with antihydrogen
  - PS210, E862 (first detections of $\overline{\mathrm{H}}$)
  - ATHENA, ATRAP (spatial and velocity distribution and temperature measurements)
  - ALPHA (trapping of $\overline{\mathrm{H}}$)
  - AEGIS (gravity measurement)

Antimatter and CPT theorie

Prediction of antimatter

1928 - Paul Dirac

(Nobel prize 1933)

Dirac equation of a free electron

$$\left(i\hbar \frac{\partial}{\partial t} + i\hbar c \vec{\hat{\alpha}} \cdot \vec{\nabla} - \hat{\beta} m_e c^2 \right) \vec{\Psi}\left(\vec{r}, t\right) = \vec{0}$$

solution delivers two energy eigenvalues:

$$\boxed{E_{\pm} = \pm\sqrt{c^2 \left|\vec{p}\right|^2 + m_e^2 c^4}}$$

Does negative enery eigenvalue have physical meaning?

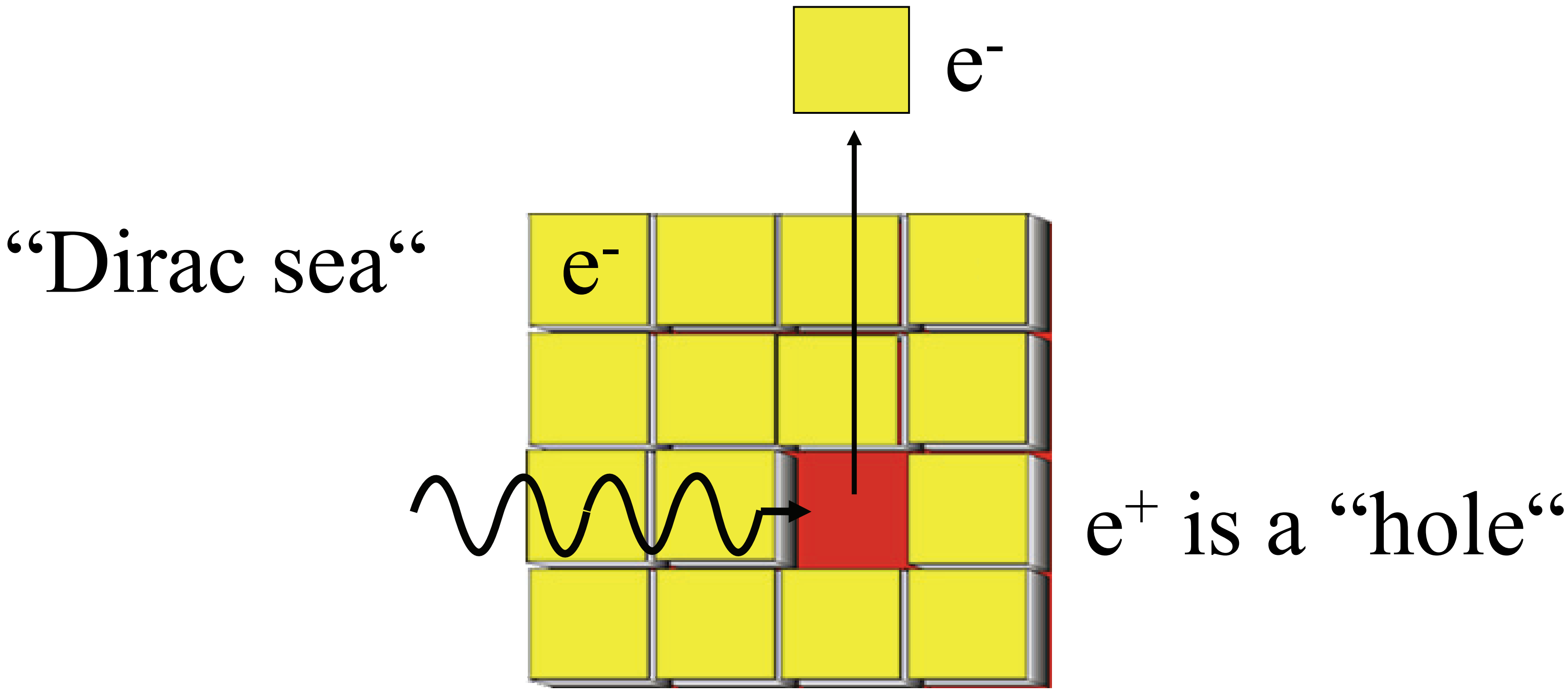
(P.A.M. Dirac, Proc. R. Soc. A 117 (1928) 610)

$$\hat{\beta} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

$$\vec{\hat{\alpha}} = \begin{pmatrix} \hat{\alpha}_x \\ \hat{\alpha}_y \\ \hat{\alpha}_z \end{pmatrix}$$

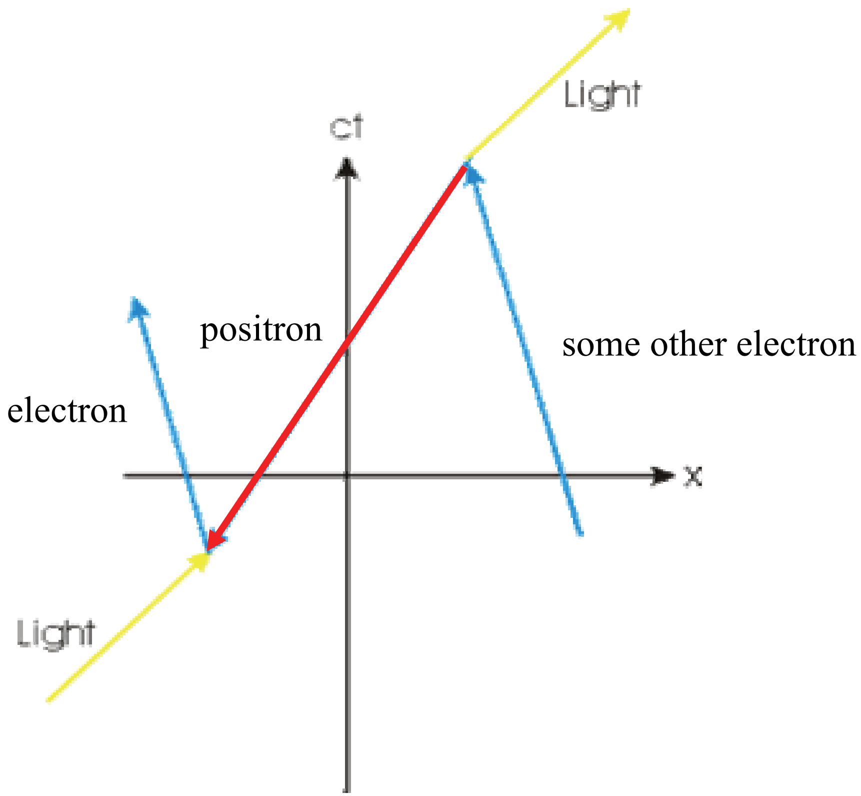
$$\hat{\alpha}_x = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \qquad \hat{\alpha}_y = \begin{pmatrix} 0 & 0 & 0 & -i \\ 0 & 0 & i & 0 \\ 0 & -i & 0 & 0 \\ i & 0 & 0 & 0 \end{pmatrix} \qquad \hat{\alpha}_z = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$$

Dirac interpretation



1949 Feynman-Stückelberg interpretation

- Positron is a particle (not a “hole“)
- Positron is a (positively charged) electron, travelling backwards in time



CPT-Theory

Transformations C, P and T:

C (charge conjugation) $q \to -q$; $B \to -B$ …

P (parity inversion) $\vec{x} \to -\vec{x}$

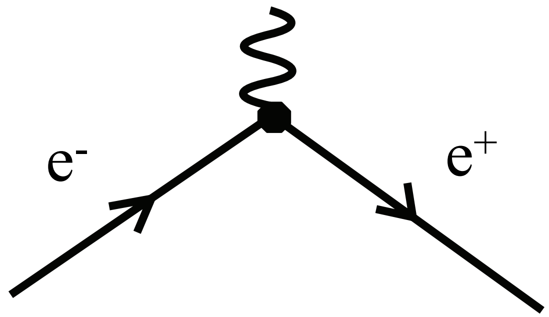
T (time inversion) $t \to -t$

CPT transformation:

$$f(q,\vec{x},t) \to f(-q,-\vec{x},-t)$$

CPT Symmetry

A CPT transformation transforms a particle into its corresponding anti-particle



particle

Anti-particle

$$q,\vec{x},t \xleftrightarrow{\text{CPT}} -q,-\vec{x},-t$$

$\Rightarrow$ Standard Model:

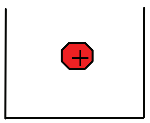
For every particle type there is a corresponding antiparticle type

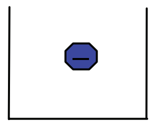
(some electrically neutral bosons, like Z^0, γ and $\eta_c = c\bar{c}$ are their own antiparticles)

CPT invariance

under certain conditions, relativistic quantum field theories say:

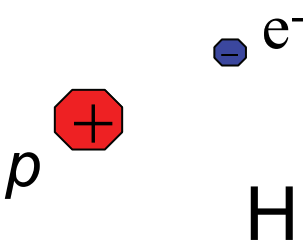
Physics (i.g. all physical laws, equations, processes) is invariant under CPT transformations

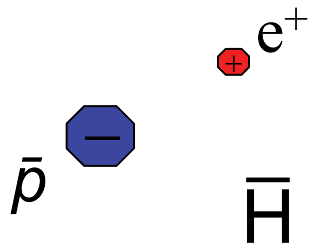




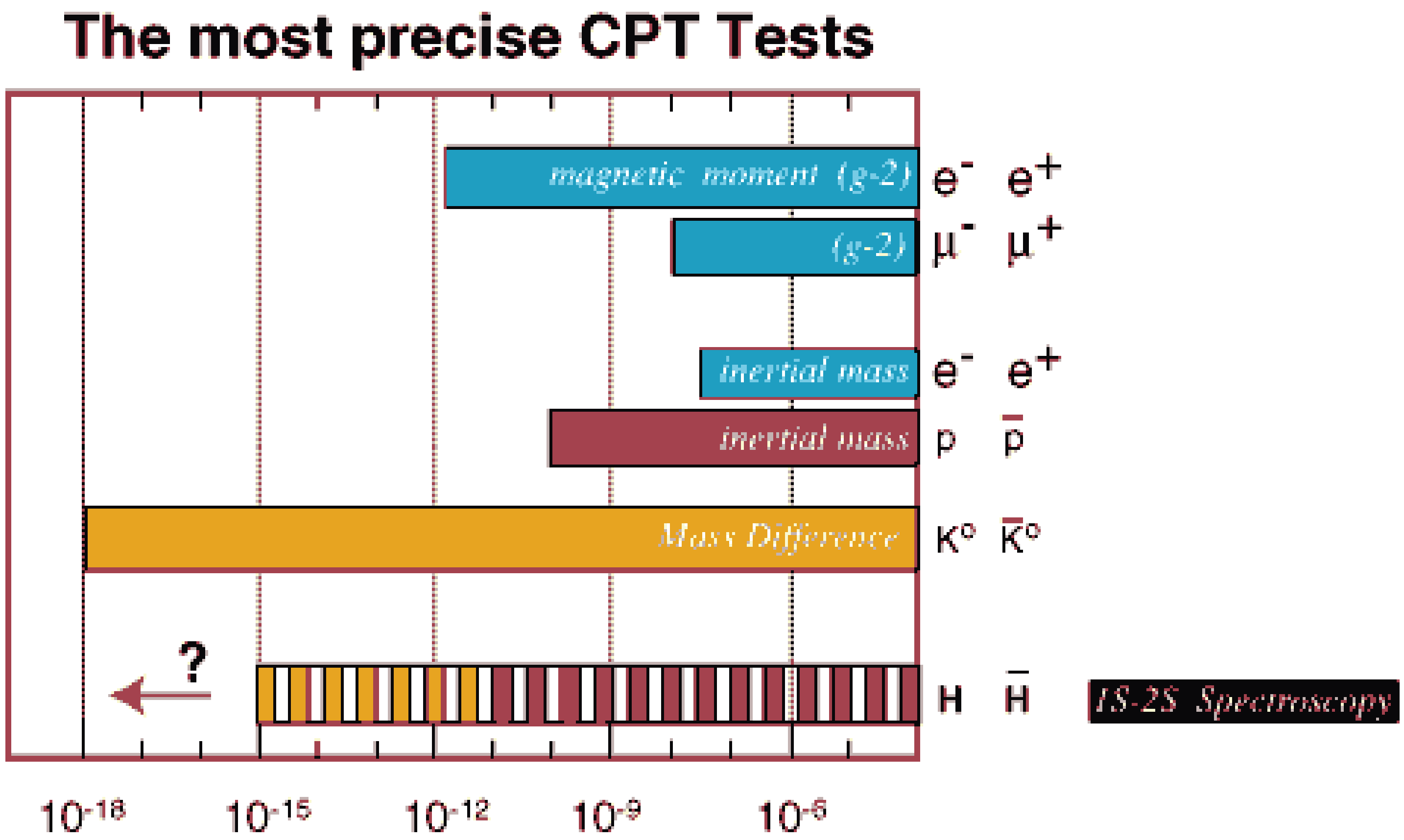
CPT transformation

$$\hat{H}\left|\Psi\right\rangle = i\hbar\frac{\partial}{\partial t}\left|\Psi\right\rangle \quad \longleftrightarrow \quad CPT(\hat{H}\left|\Psi\right\rangle) = CPT(i\hbar\frac{\partial}{\partial t}\left|\Psi\right\rangle)$$





Prospect of $\bar{\mathrm{H}}$ spectroscopy



Violation of CPT invariance

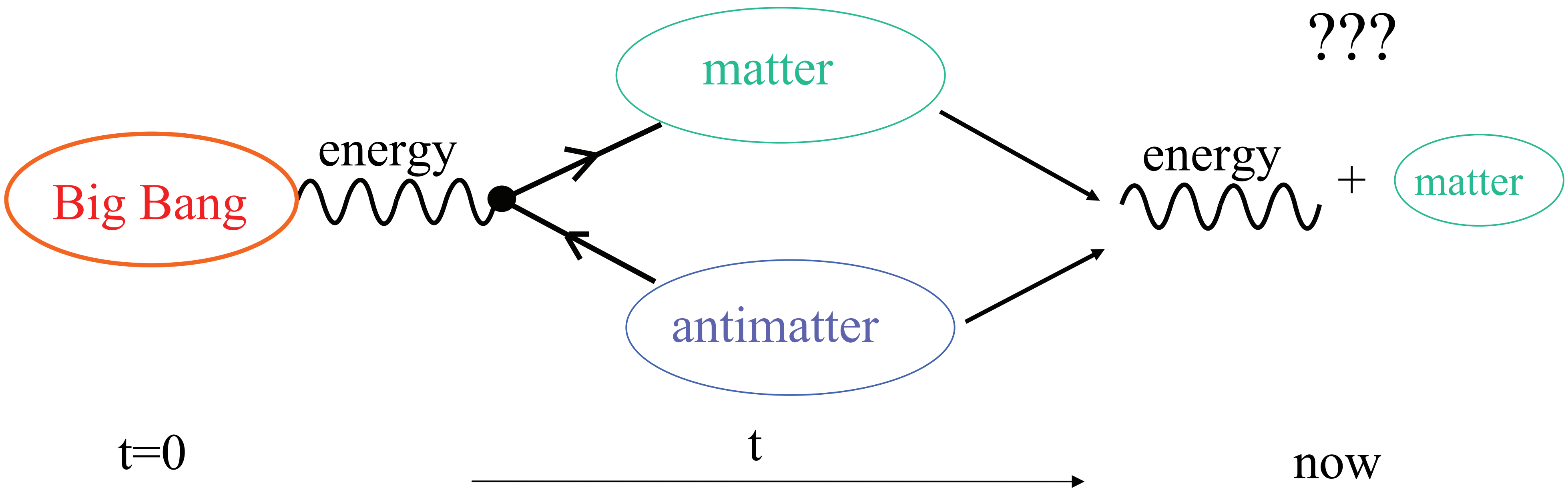
Historical: P (theory:Lee,Yang; Exp.:Wu), CP violations (J.H. Christenson)

(C.S. Wu et al., Phys. Rev. 105 (1957) 1413)
(J.H. Christenson et al., Phys. Rev. Lett. 13 (1964) 138)

- String theory
- Kostelecky (standard model extension)
- …

(R. Bluhm et al., Phys. Rev. Lett. 82 (1999) 2254)

Matter-antimatter asymmetry



possible explanations:

- CPT violation, breaking of Baryon number conservation
- CP violation, breaking of Baryon number conservation, out of equilibrium situation

(H.R. Quinn, SLAC-PUB-8784 (2001))

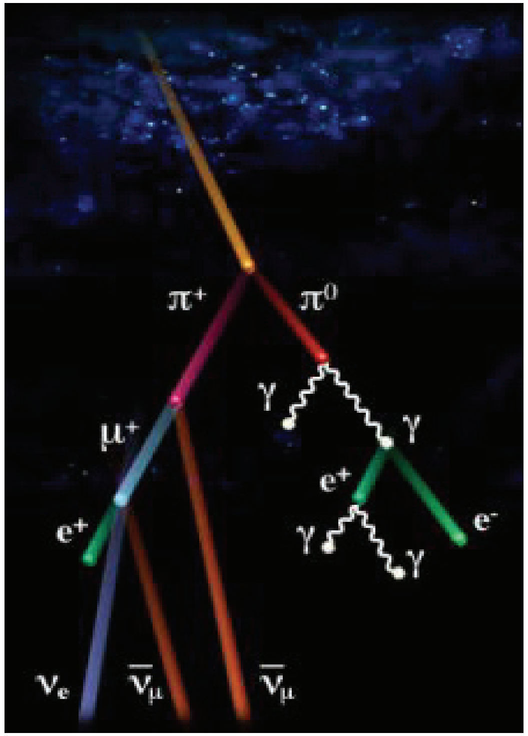
First observations of antimatter

First detection of antimatter

1932 - Carl Anderson

(Nobel prize 1936)

secondary cosmic rays



cloud chamber

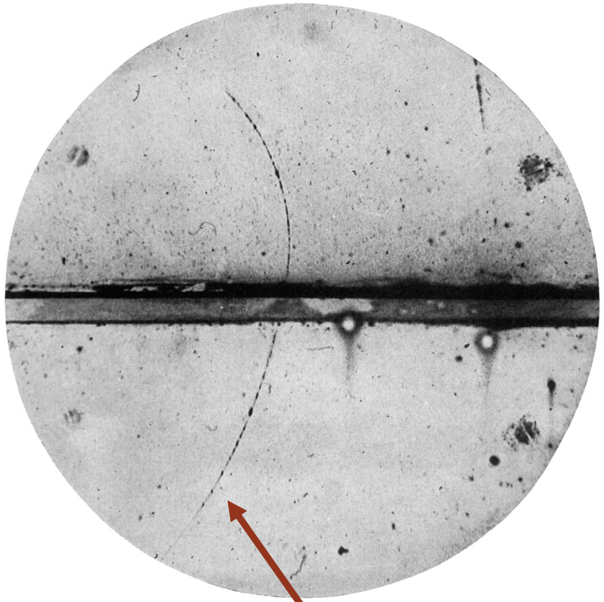


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.$[illegible]$\times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

"Positron" (e^+)

From particle track:

$$q_{Positron} < +2e$$

$$m_{Positron} < 20 m_e$$

(C.D. Anderson, Phys. Rev. 43 (1933) 491)

Further detections of antiparticles

- **1955** - antiproton at Lawrence Berkeley National Laboratory (Chamberlain, Sergé, Wiegand, Ypsilantis)
- **1956** - antineutron (B. Cork)

(S.L. Chamberlain, Phys. Rev. 100, 947 (1955))

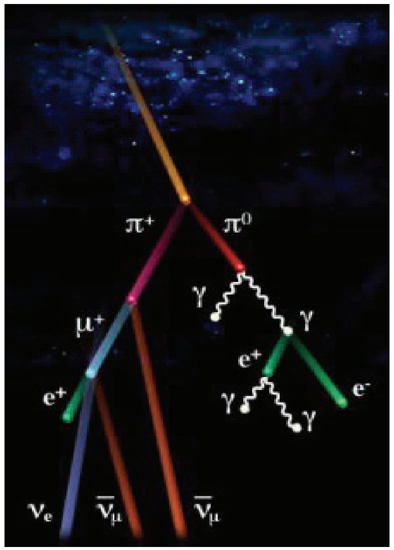
(B. Cork, Phys. Rev. 104, 1193 (1956))

Natural sources of antimatter

- Beta(plus)-decay

$$^{22}_{11}Na \rightarrow ^{22}_{10}Ne + e^{+} + \nu_{e}$$

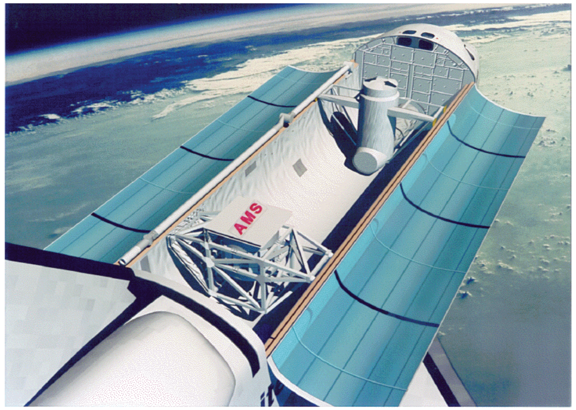
- secondary cosmic rays



$$e^{+}, \mu^{+}, \pi$$

Is there antimatter in (primary) cosmic rays?

1998 - AMS-01

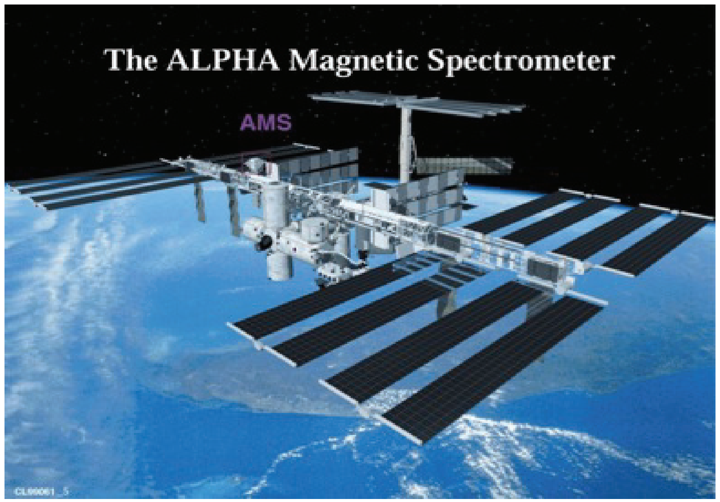


ten day flight on Discovery

"prototype" m ~ 3 tons

No evidence for primary antimatter!

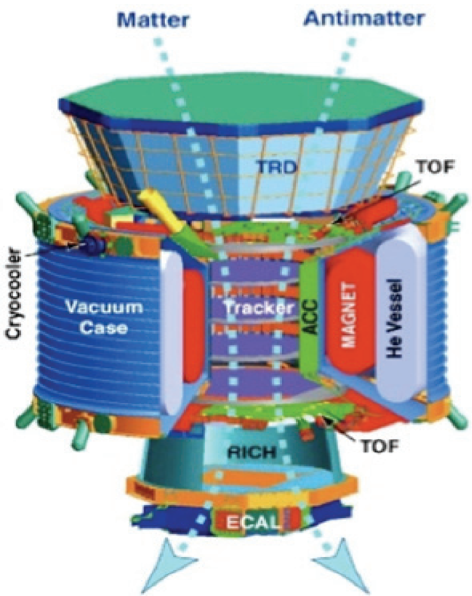
2009 – 2012
AMS-02

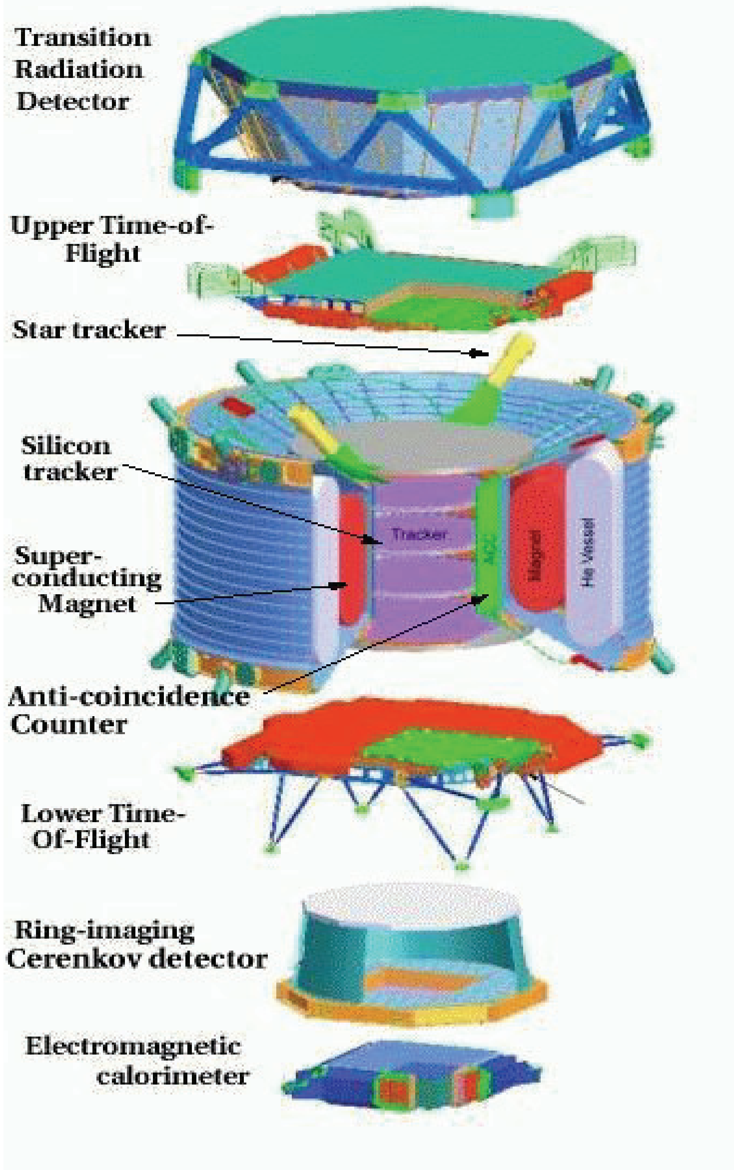


three years on ISS

m ~ 7 tons

Goal:
detection of He, $\overline{He}$
and heavier nuclea

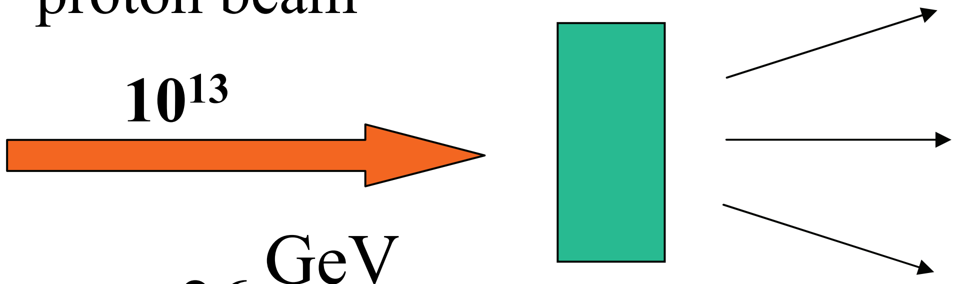

Matter
Antimatter
TRD
TOF
Cryocooler
Vacuum Case
Tracker
ACC
MAGNET
He Vessel
TOF
RICH
ECAL


Transition Radiation Detector
Upper Time-of-Flight
Star tracker
Silicon tracker
Tracker
Magnet
He Vessel
ACC
Super-conducting Magnet
Anti-coincidence Counter
Lower Time-Of-Flight
Ring-imaging Cerenkov detector
Electromagnetic calorimeter

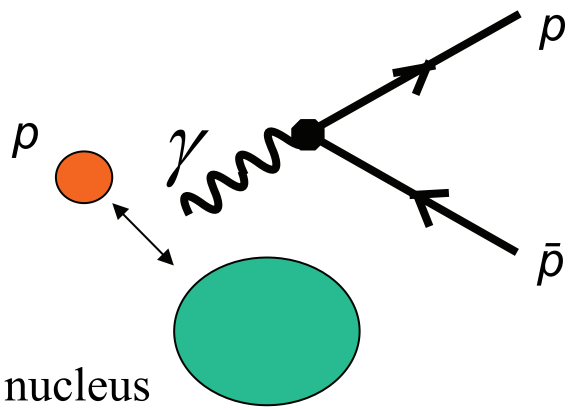
Artificial sources of antimatter and experiments with $\overline{\mathrm{H}}$

antiproton production

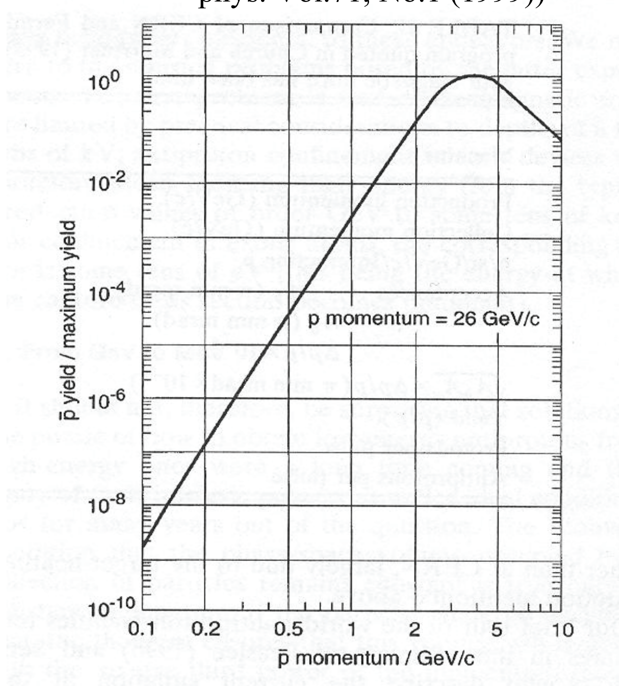
principle (since 1954):



$$p_p = 26 \frac{\text{GeV}}{\text{c}}$$

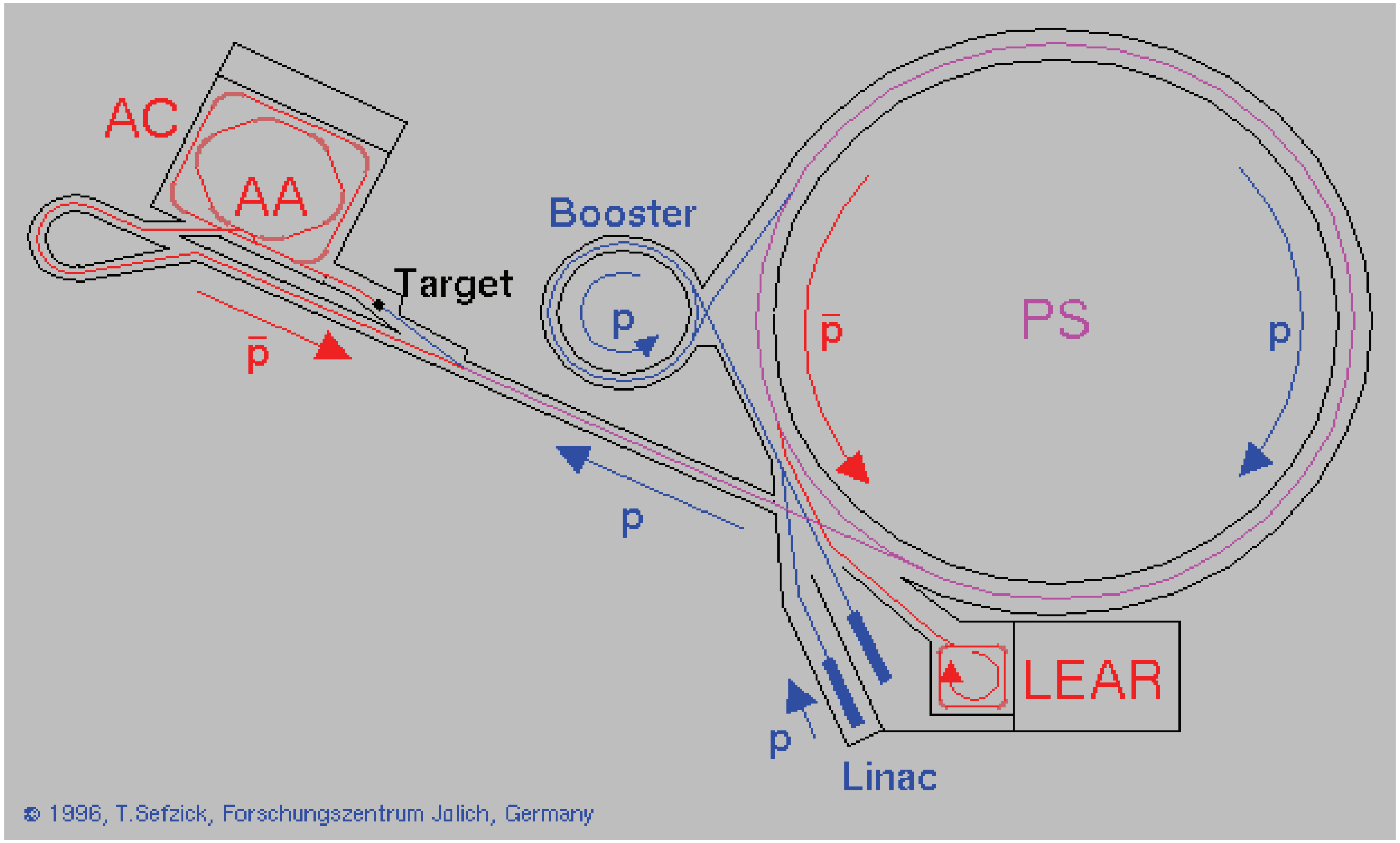


(J. Eades, Rev. of modern phys. Vol.71, No.1 (1999))



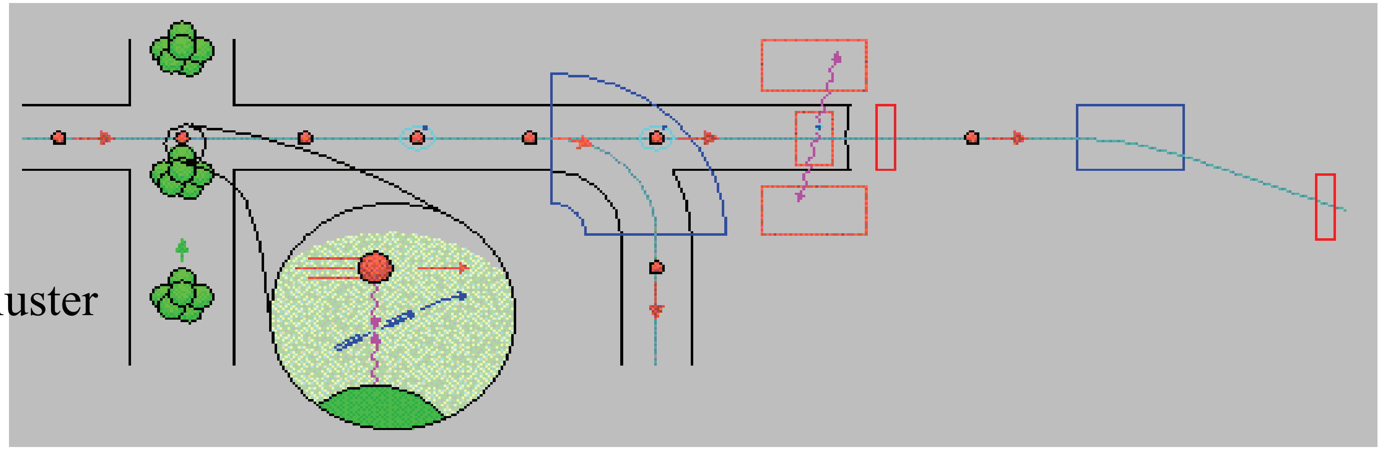
PS210 Experiment (1995 first $\bar{H}$ detection)

PS (Proton Synchrotron) at CERN

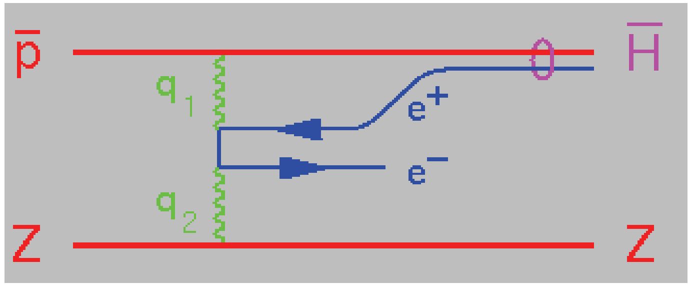


PS210 at LEAR (Low Energy Antiproton Ring) p = 1.94GeV/c

Xe cluster



11 $\bar{H}$ detected!



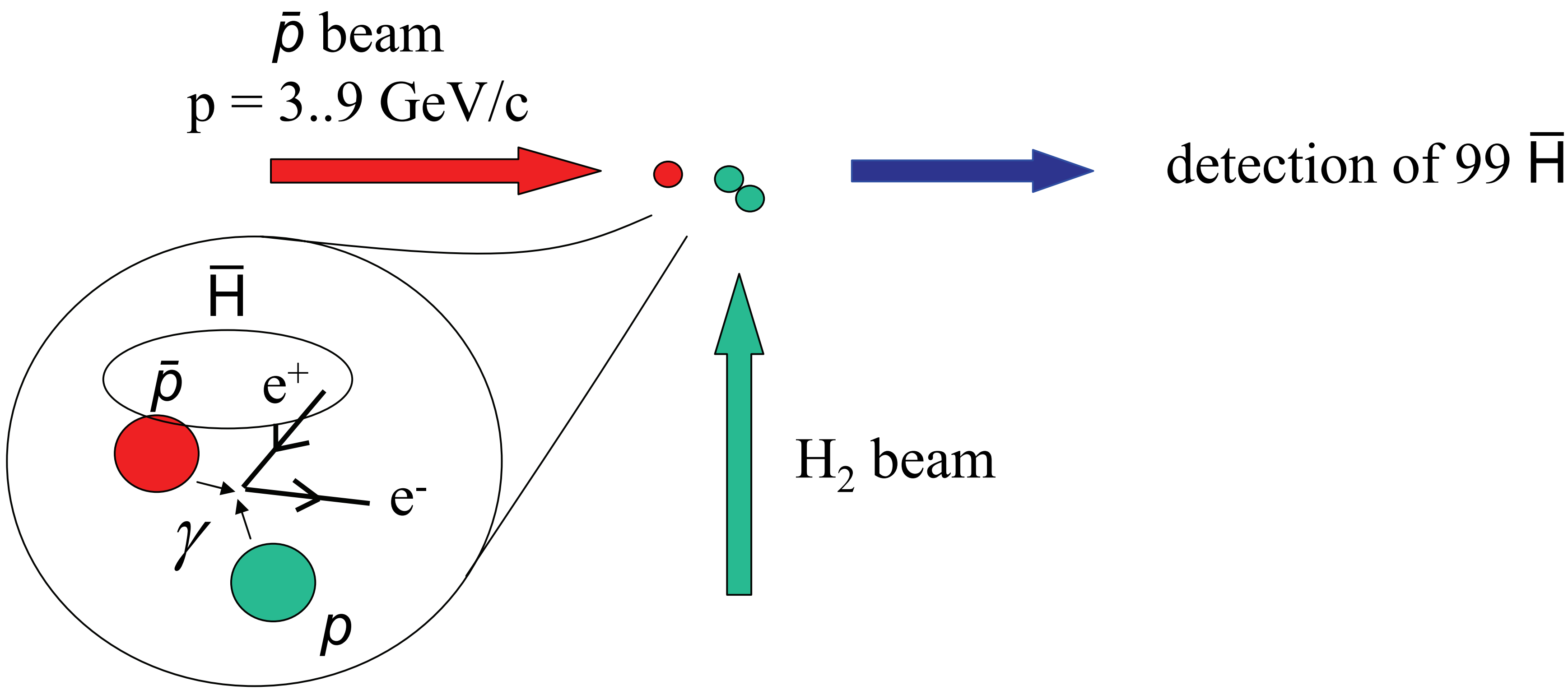
e$^-$,e+ pair creation is a <u>rare</u> process

- only if $\bar{p}$, Z get close
- two photon collision

$\bar{H}$ production only if
rel. energy $\bar{p}$, e+ < 13.7 eV

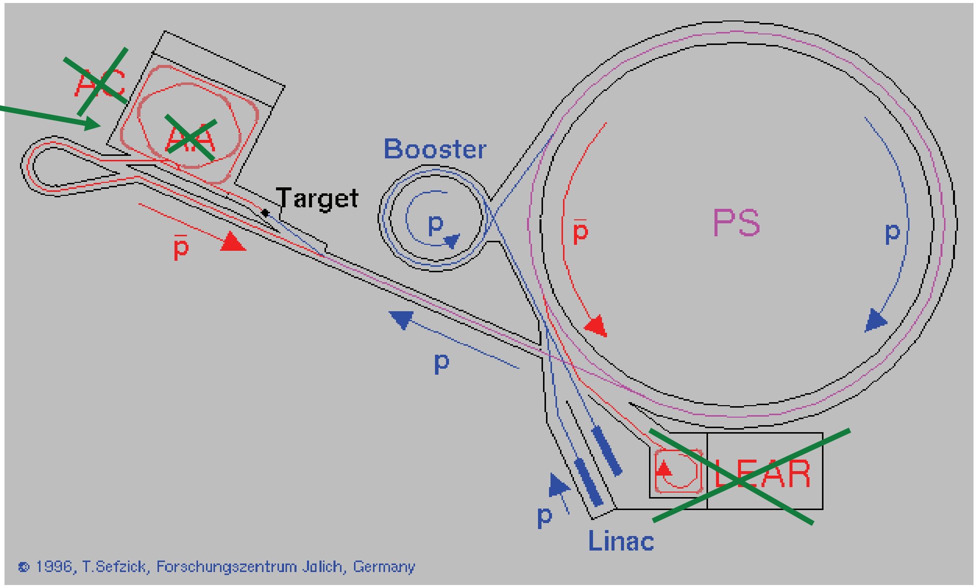
probability = 0.000 000 000 000 000 01 %

E862 at Fermilab (1996)

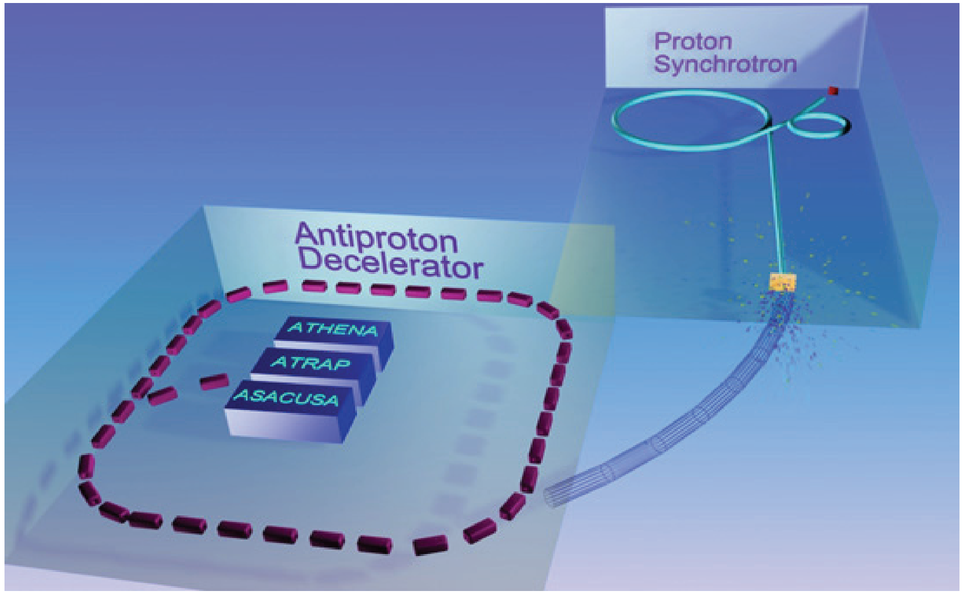


AD (Antiproton Decelerator) (since July 2000)

AD

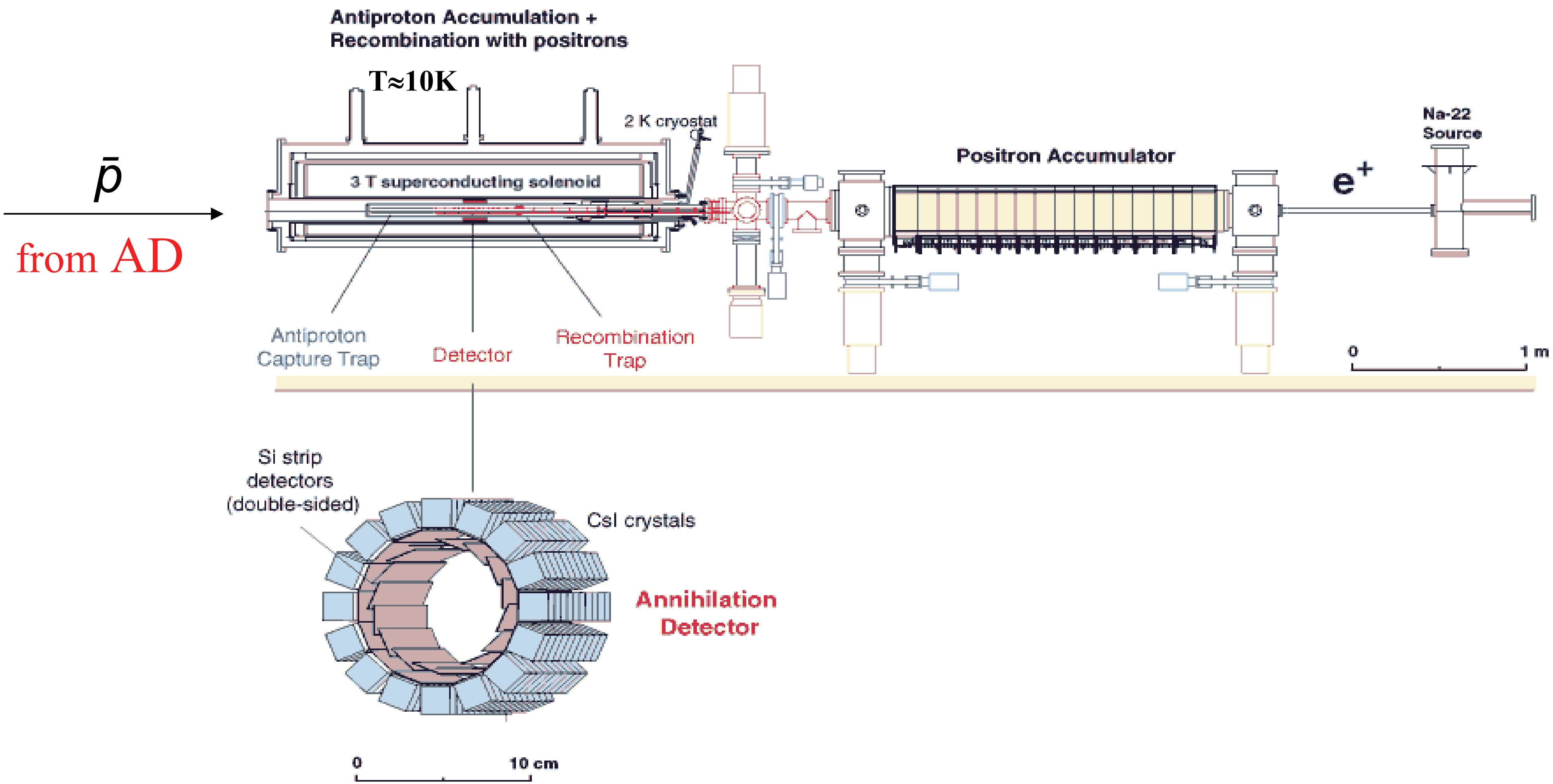


deceleration and cooling
$p_{\bar{p}}$: 3.5 -> 0.1 GeV/c

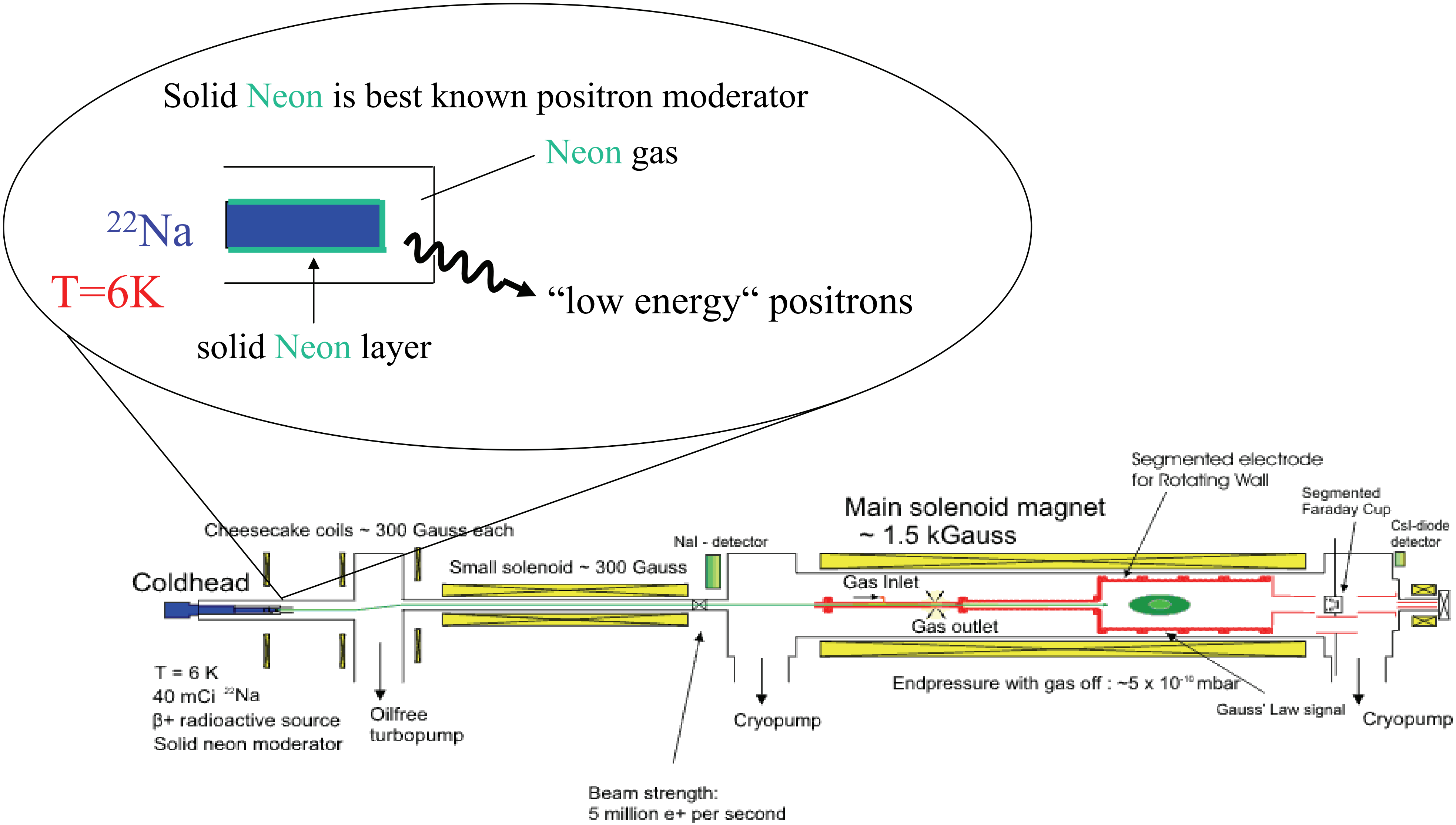


- ATHENA (2002) ($\bar{\mathrm{H}}$ detection by detector)
- ATRAP (2002) ($\bar{\mathrm{H}}$ detection by reionization)

The ATHENA experiment



positron production

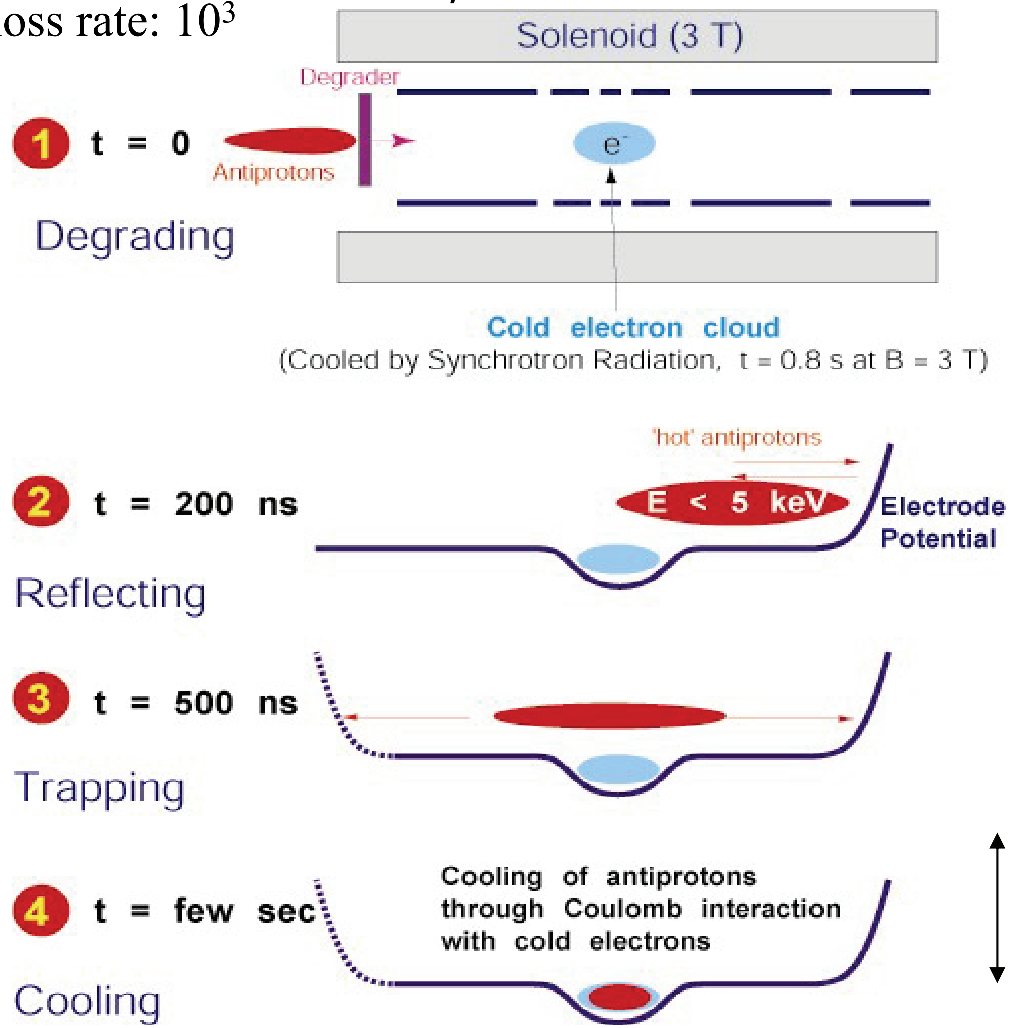


Antiproton capturing

$E_{\bar{p}} = 5$ MeV
$t_p = 200$ ns
$n_{\bar{p}} \approx 10^7$

$n_{\bar{p}} \approx 10^4$

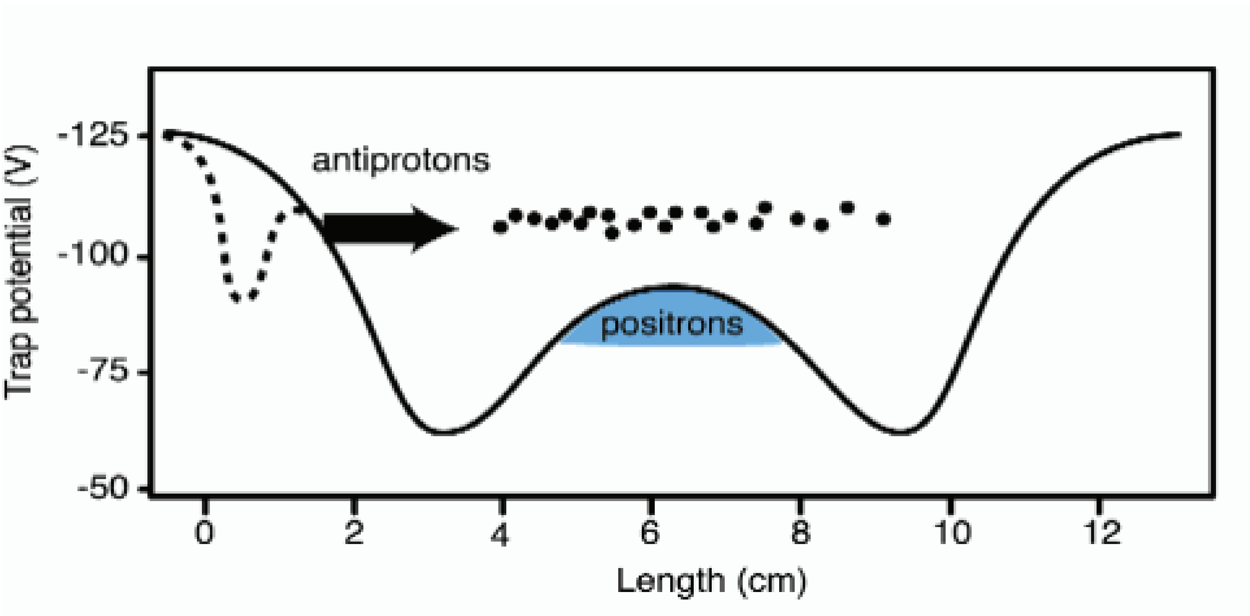
loss rate: 10^3



5kV

Antiproton positron mixing

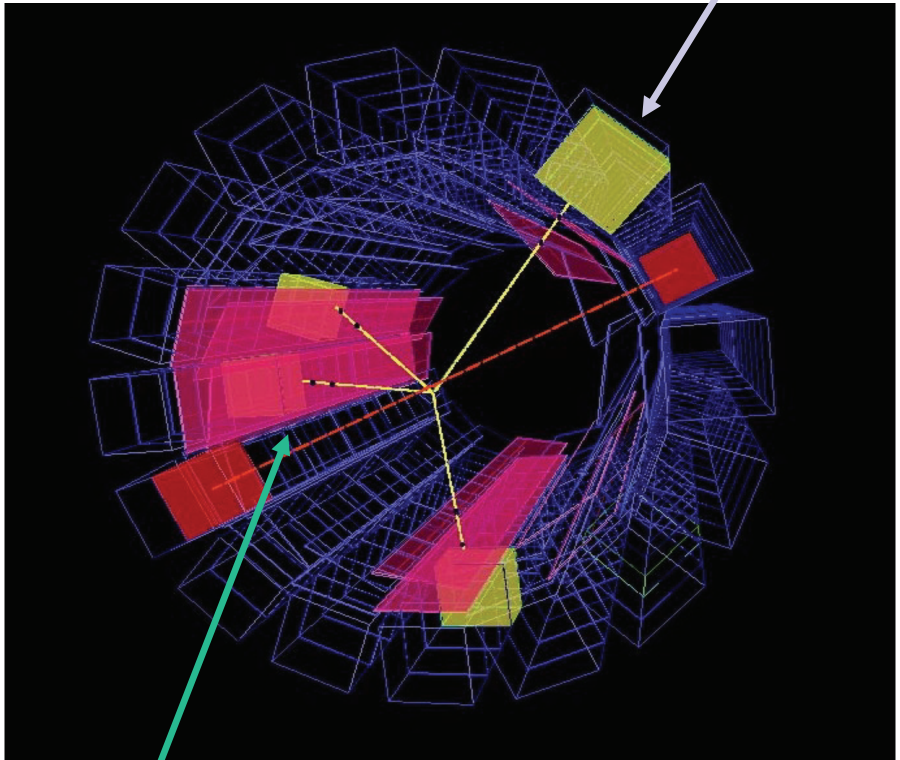
"Mixing trap": nested potential with **both** positive and negative ions



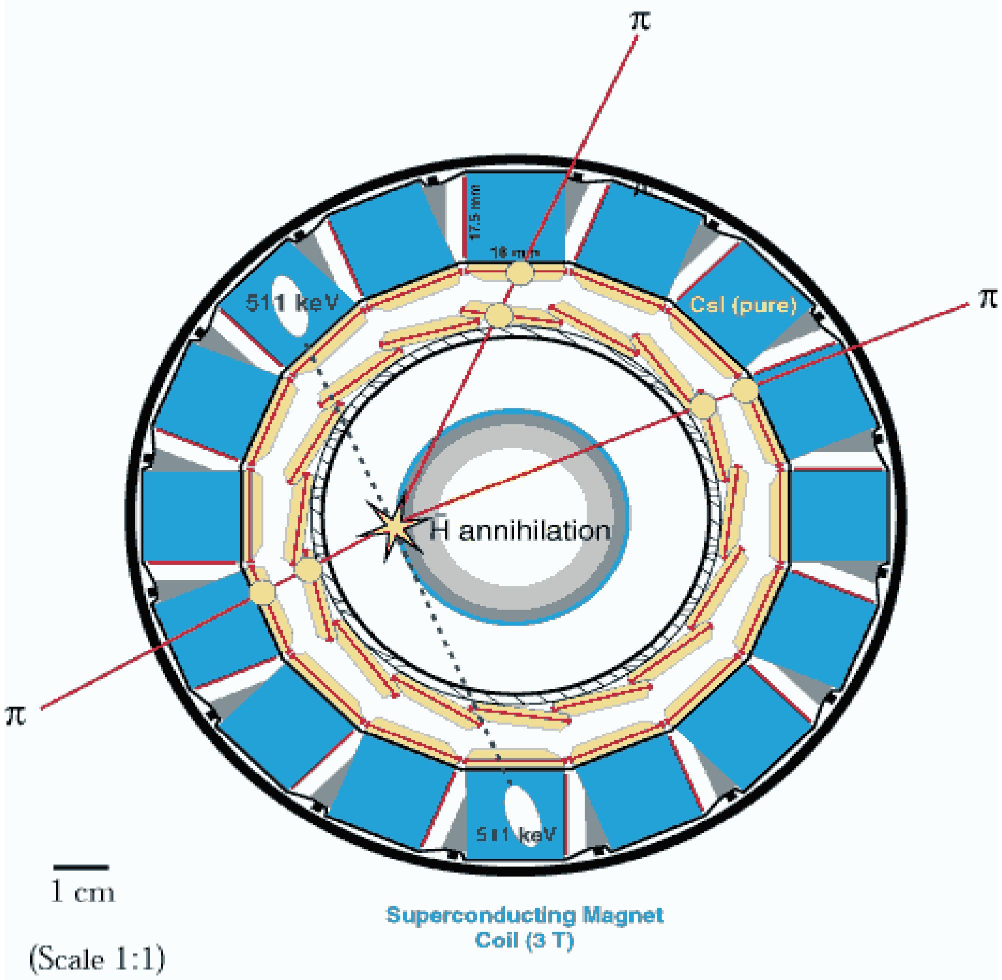
- production of several million $\bar{\mathrm{H}}$ between 2002 and 2004

$\overline{\text{H}}$ detection

CsI crystal calorimeter



Si strips to “follow the path“



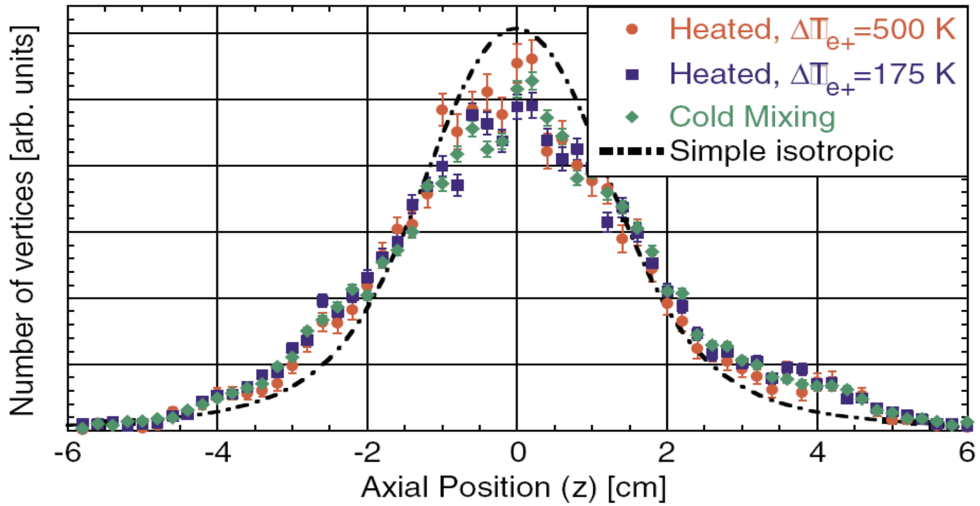
Discriminate Antihydrogen Annihilation from background of Antiproton annihilation and Positron annihilation

Good spatial resolution (< 1 cm) of vertex for
- Antiproton Annihilation (≥ 2 prongs)
- Positron Annihlation (2 x 511 keV γ)

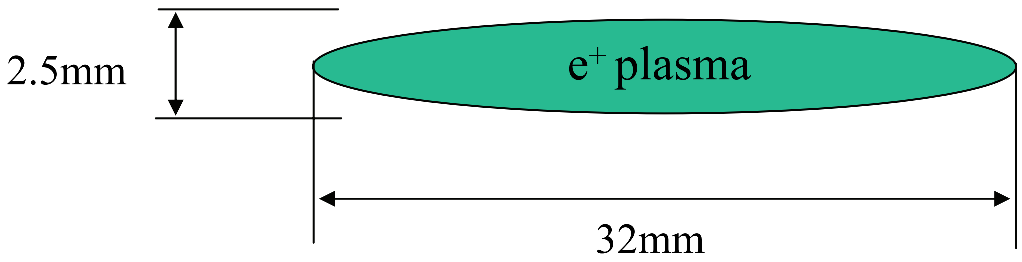
Time coincidence (~ 1 μsec)
High rate capability

ATHENA measurements

Measurement of the spatial distribution of $\bar{\mathrm{H}}$
in dependence of e^+ plasma temperature



model:



and

isotropical emission of $\bar{\mathrm{H}}$

- spatial distribution is independent of e^+ plasma temperature
- $\bar{\mathrm{H}}$ is not emitted isotropically

temperature measurement

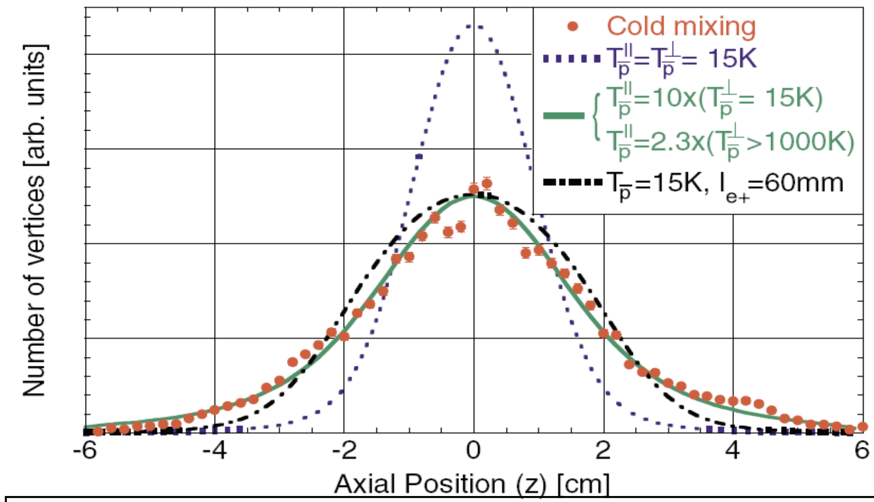
Model:

-Recombining $\bar{p}$ rotate with e$^+$ plasma; isotropically produced $\overline{\mathrm{H}}$ propagates with momentum of $\bar{p}$

-using two temperatures to describe nonequilibrium conditions

-spatial distribution measurement provides temperature ratio

from measurement: $$T_{\bar{p}}^{para} = (10 \pm 2) T_{\bar{p}}^{perp}$$



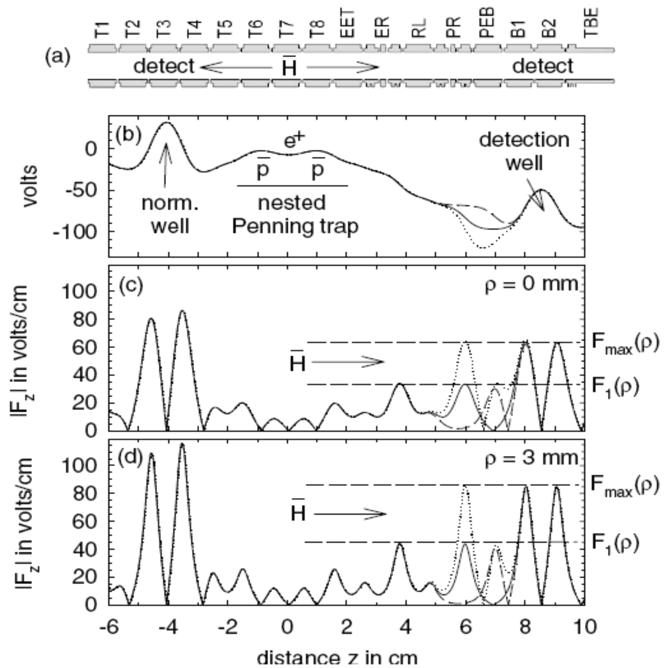
With $T_{\bar{p}}^{perp} \geq 15\mathrm{K}$ surrounding temperature

$$\boxed{\Rightarrow T_{\bar{p}}^{para} \geq 150\mathrm{K}}$$

$\bar{p}$ and e$^+$ are not in thermal equilibrium i.g. cooling rate is much lower than recombination rate!

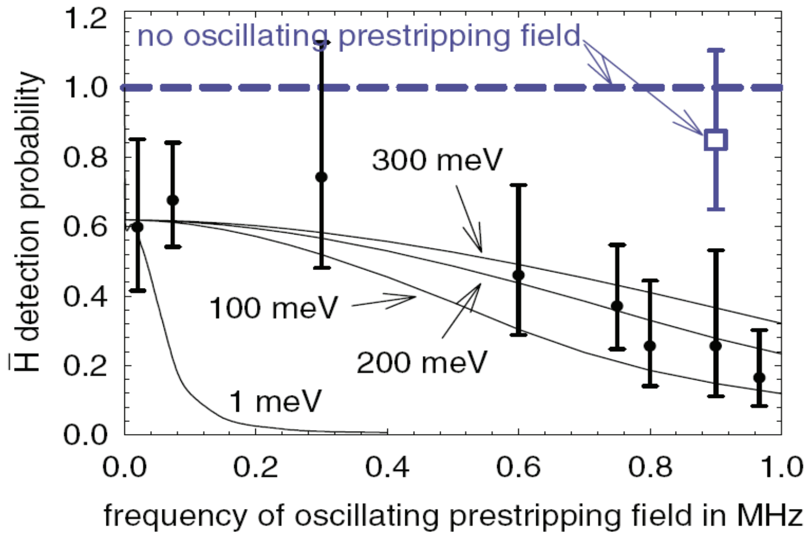
(N. Madsen, Phys. Rev. Lett. 94 (2005) 033403)

Temperature measurement at ATRAP



Measurement of velocity distribution:

- Oscillating field (at radiofrequencies)
- Ionization probability in oscillating field is higher for slower H̄
- detection of ionized H̄ (antiprotons)



Best fit for : $\overline{E}_{kin} = 200\text{meV}$

corresponds to $T_{\overline{H}} = 2400\text{K}$

(G. Gabrielse, Phys. Rev. Lett. 93 (2004) 073401)

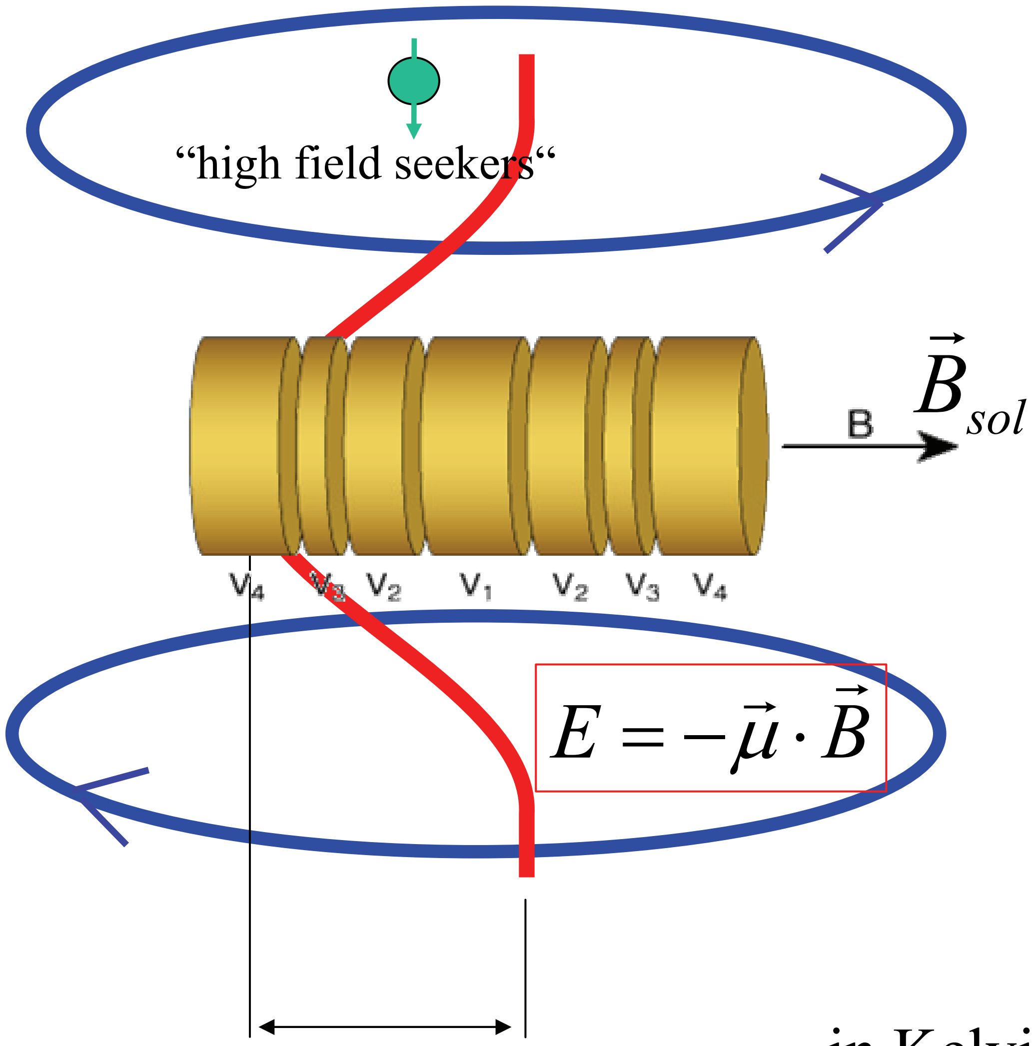
The ALPHA Project (since 2006, successor to ATHENA)

- Goal: **<u>Trapping $\bar{H}$</u>** for spectroscopy!
- Since $\bar{H}$ is neutral it can not be trapped in a Penning trap!
- Other method: using magn. momentum of $\bar{H}$
- But: How deep is such a trap? How hot is $\bar{H}$ allowed to be?

Summary:

- ATRAP:
  - $T_{\bar{H}} \approx 2400$ K
- ATHENA:
  - $T_{\bar{H}} \geq 150$ K

$\bar{\mathrm{H}}$ trapping with magn. quadrupole



For B_r = 1T, B_{sol}=6T

$$\Rightarrow \Delta B \approx 0.1\mathrm{T}$$

$$\boxed{T = 0.07\,\mathrm{K}}$$

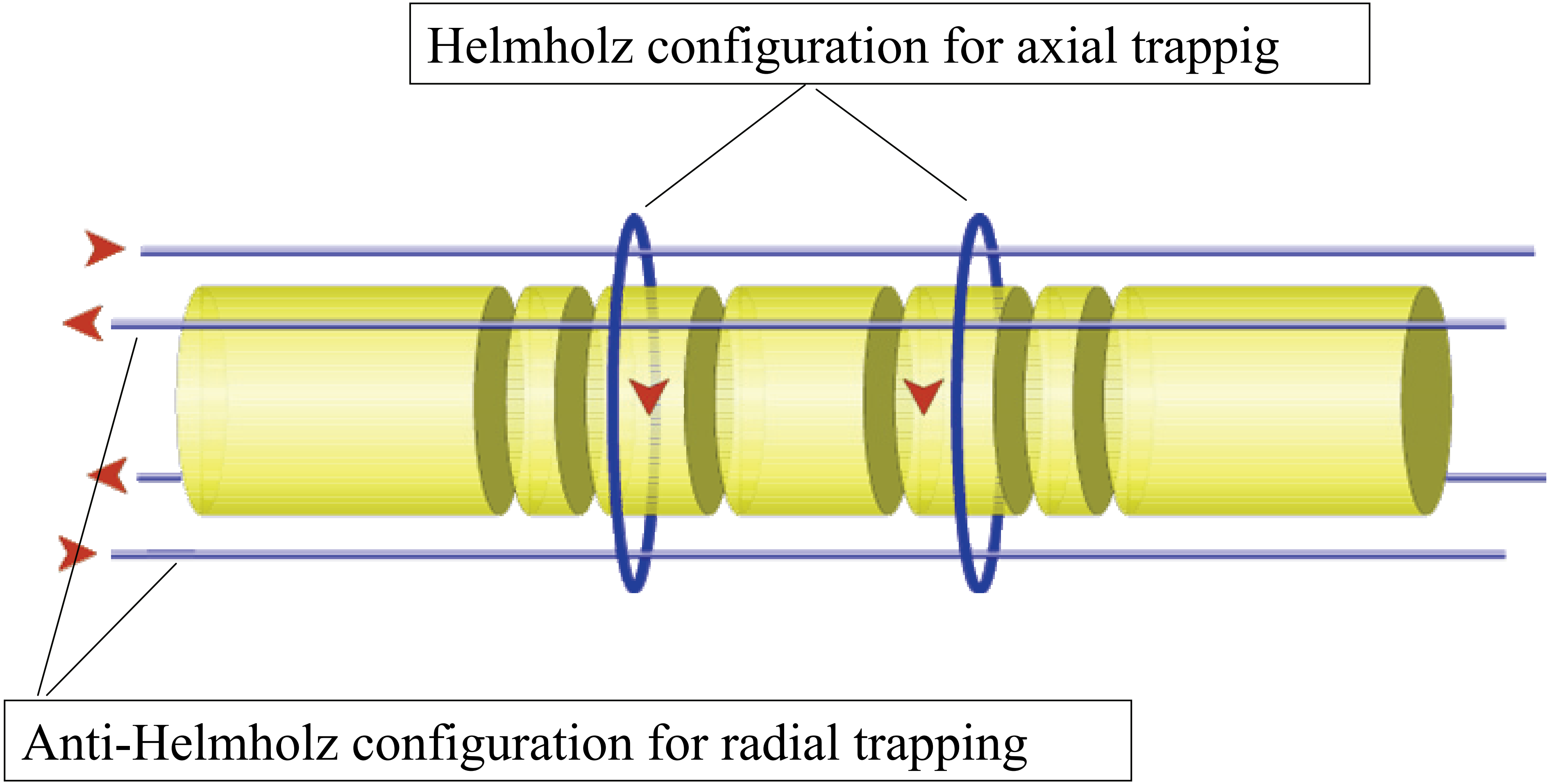
$$T \propto \frac{\Delta E}{k_B}$$

trap depth $\Delta E = \mu \cdot \Delta B$

in Kelvin $T = 0.7\frac{\mathrm{K}}{\mathrm{T}} \cdot \Delta B$

$$|B| = \sqrt{B_{sol}^2 + B_r^2}$$

$$\Rightarrow \Delta B = \sqrt{B_{sol}^2 + B_r^2} - B_{sol}$$


Helmholz configuration for axial trappig
Anti-Helmholz configuration for radial trapping

AEGIS project (planned to be in AD)

Goal: direct measurement of **g** for $\bar{H}$

Rydberg positronium Beam (laser exited)

e^+e^-

$\bar{p}$

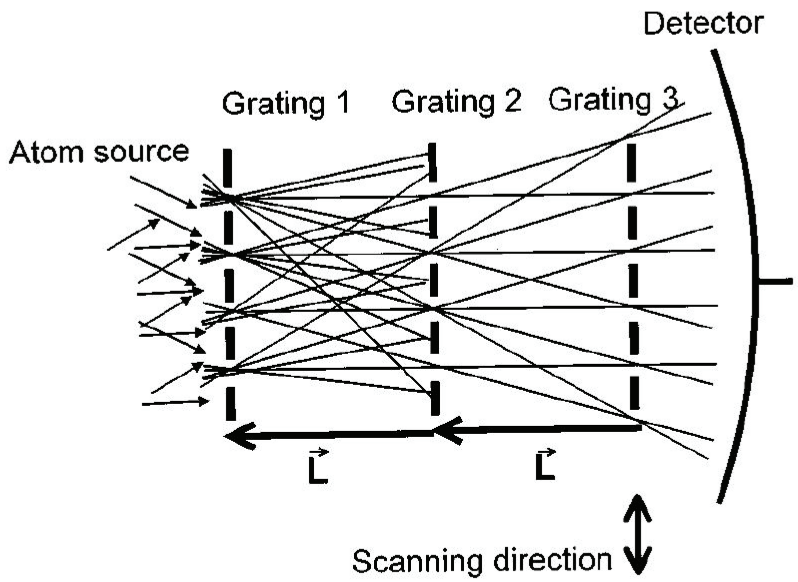
Cooled in Penning trap
$T \approx 100$mK

Stark accelerator

$\bar{H}^*$

v~100m/s

Moiré-deflectometer



In AEGIS: With two gratings and position dependent detector

<u>Precision: ~1%</u>

conclusion

- Low temperatures needed for trapping $\overline{\mathrm{H}}$ and to
  - do spectroscopy experiments (CPT test; precision 10^{13}!!!)
  - test gravity for antimatter
- Temperatures still to high for trapping!
- Challange: Cooling of negative ions ($\bar{p}$) to build $\overline{\mathrm{H}}$ at very low temperatures (~mK)
- Futher cooling of $\overline{\mathrm{H}}$ with lasercooling (if convenient lasersystems are developed)

Thank You for Your attention!