Lecture Plan

today

I. History of Antimatter

II. Antimatter and the Universe

III. Production and trapping of antiparticles

IV. Precision tests of particle-antiparticle symmetry

V. AD Physics and Antihydrogen

VI. Antimatter technologies

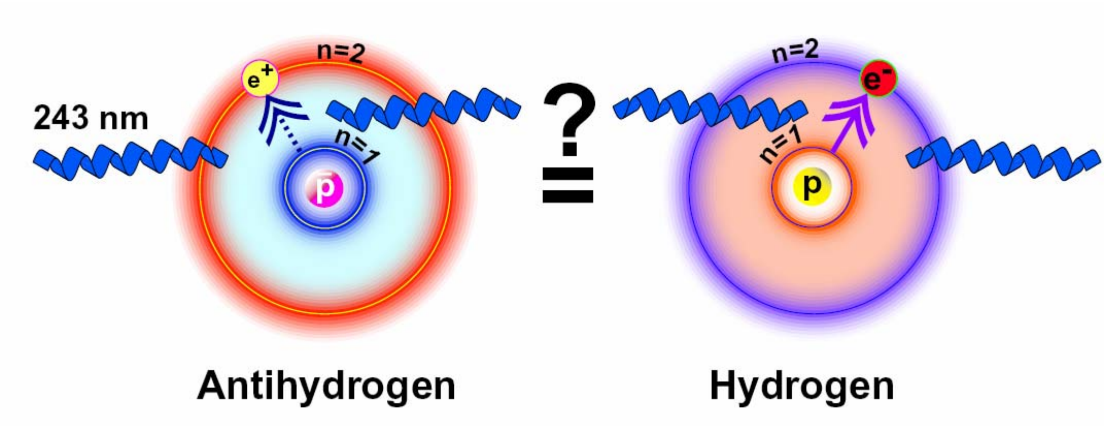
ANTIHYDROGEN

ATHENA (AD-1)

ATRAP (AD-2)

Phase 1	(2000-2004)	Production of slow antihydrogen (completed)
Phase 2	(2006-)	Trapping and cooling of antihydrogen
Phase 3	(?)	Precision experiments

Phase 3 - High precision comparison of hydrogen and antihydrogen



"Shelving" Scheme with single (trapped) atom:

Strong Lyman-a is excited and fluoresces

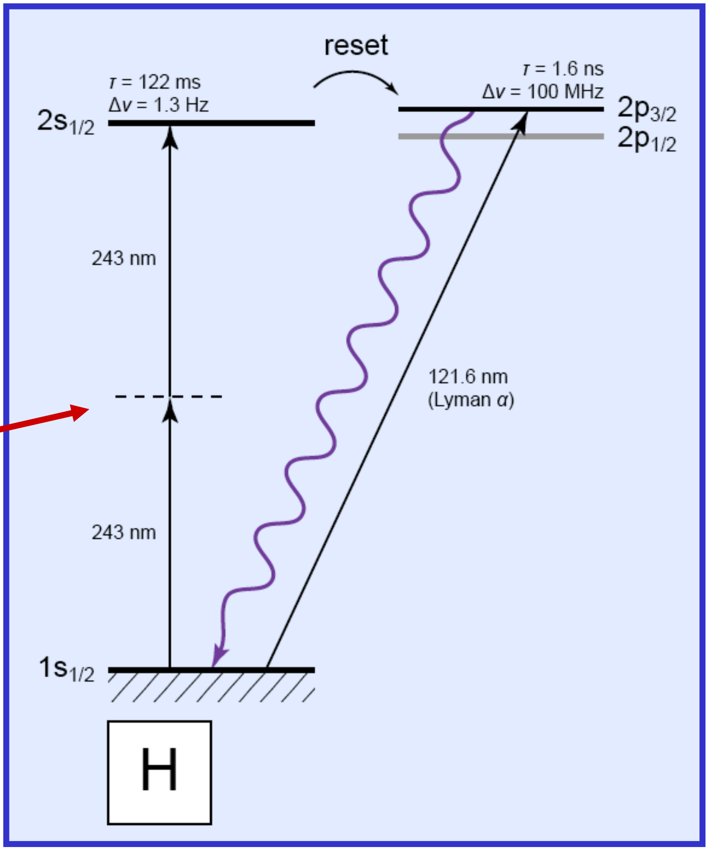
2s state is populated by 2-photon excitation

'Shelving' in (metastable) 2s suppresses fluorescence

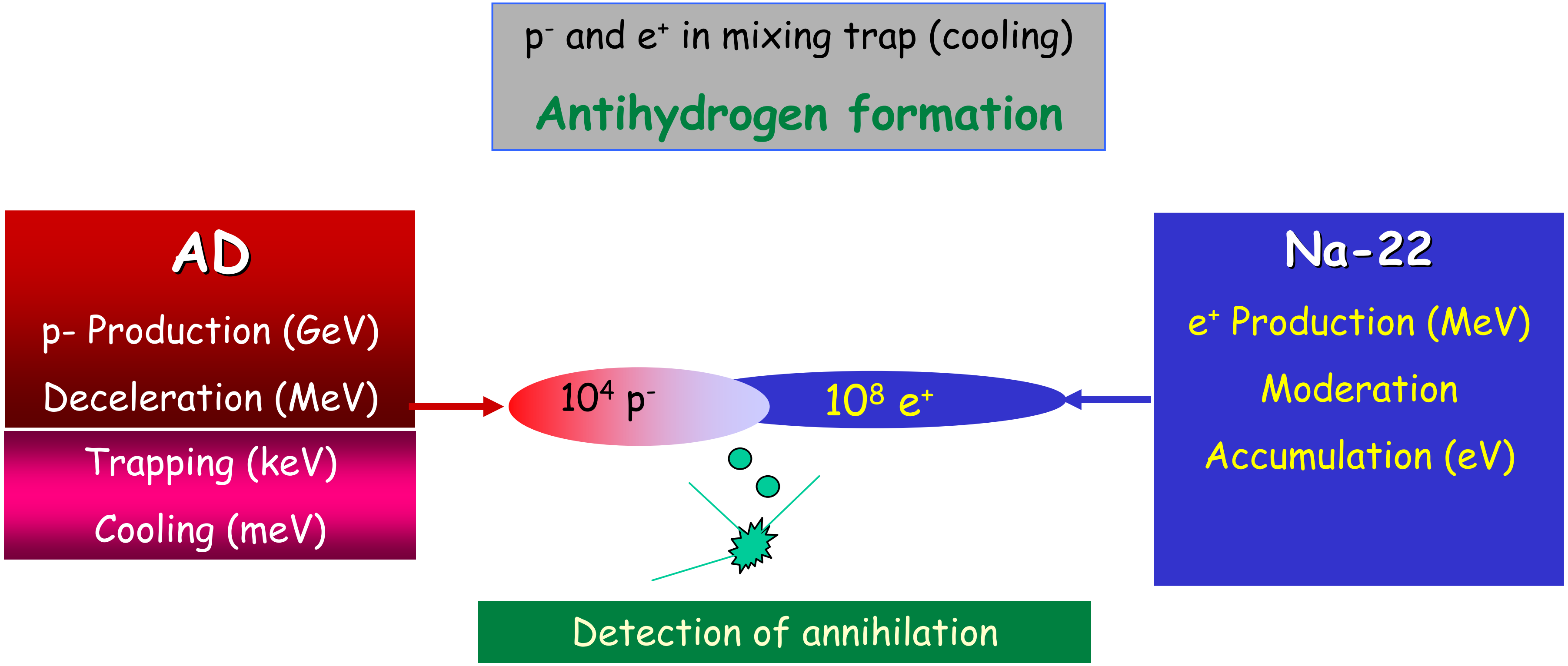
2s state is 'reset' with microwave transition into 2p

Natural line width $\mathbf{4\cdot10^{-16}}$

[J. Walz et al., Hyp. Int. **127** (2000) 167]



How to make antihydrogen (Phase 1)



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

ATHENA - Schematic view

Antiproton capture trap

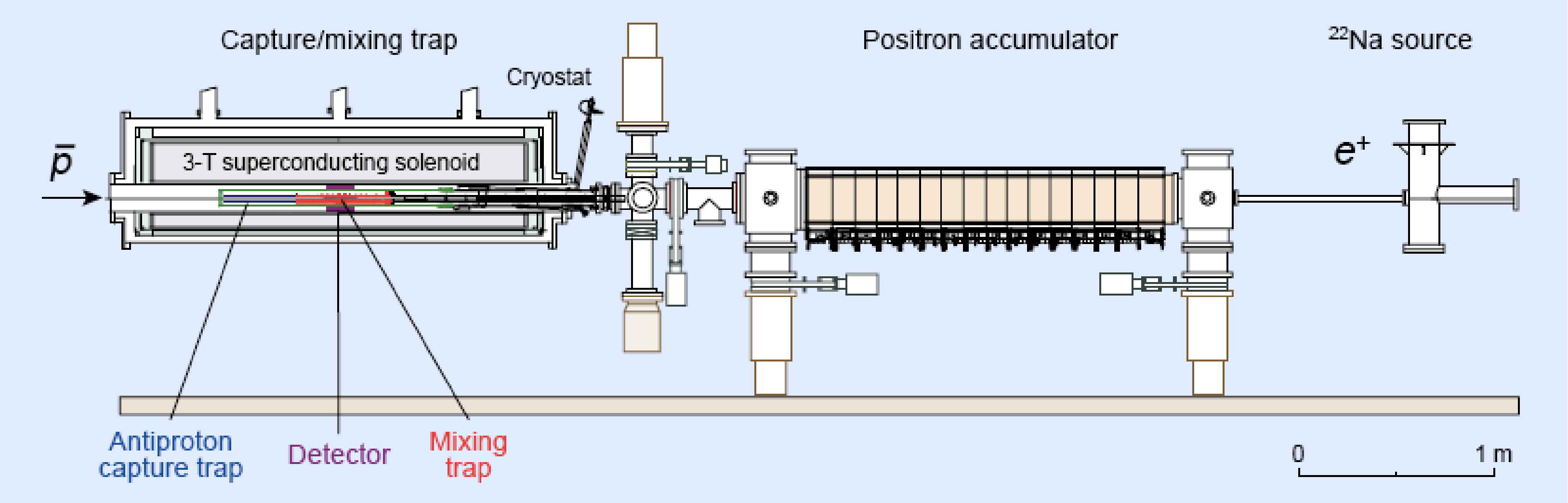
- Deceleration and capture of antiprotons
- Penning trap in 3-T field at 15 K
- Cooling and accumulation in e^- plasma

^{22}Na source

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

Positron accumulator

- Penning trap in 0.14-T field at 300 K



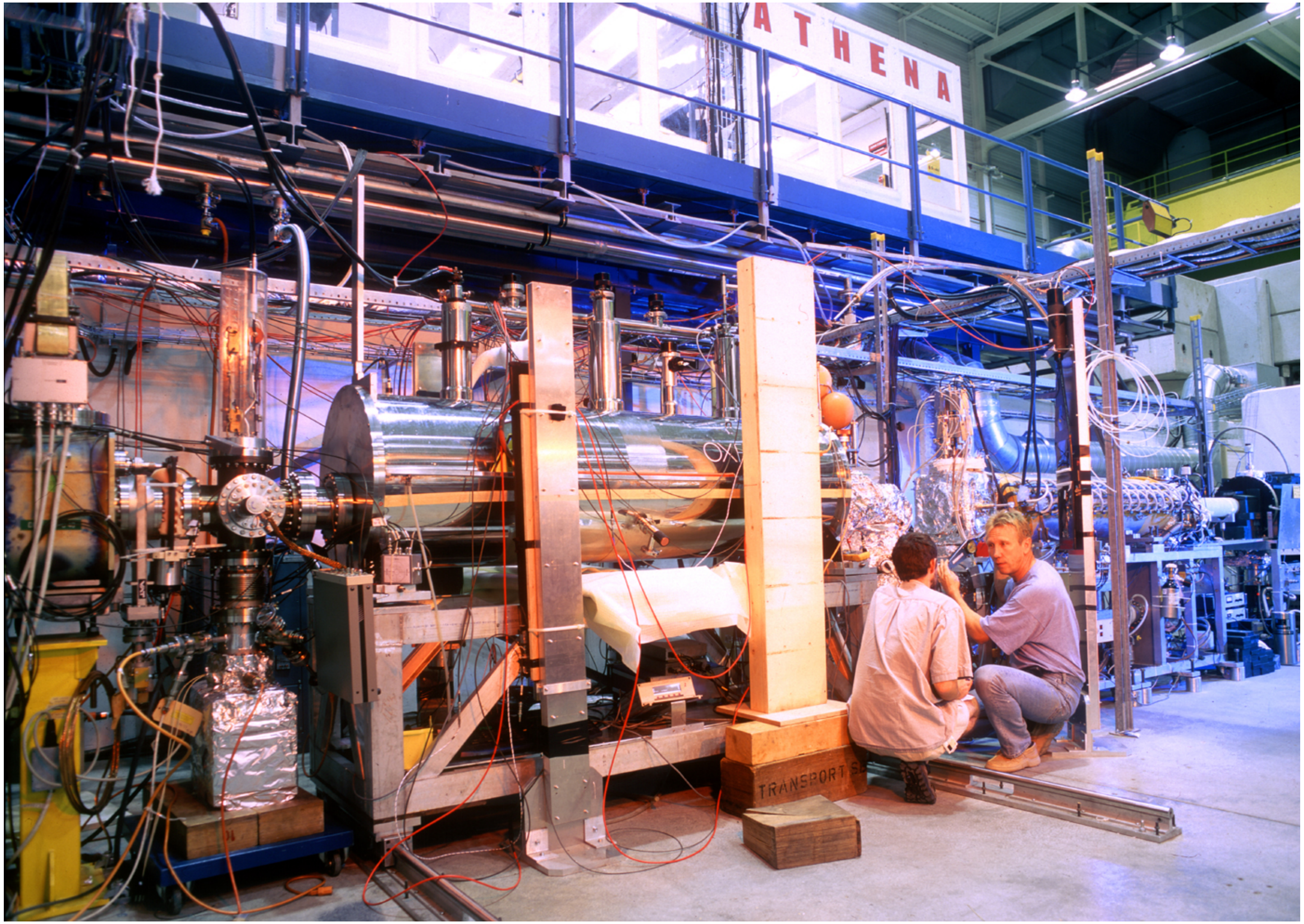
Mixing trap

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

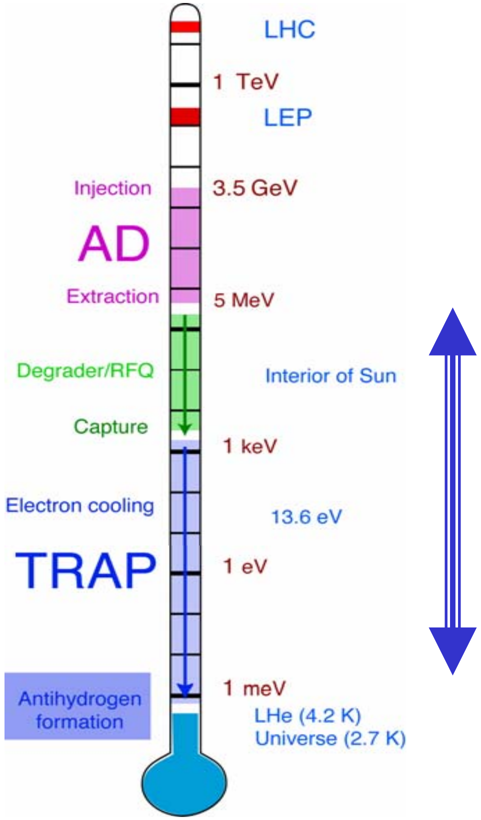
Detector

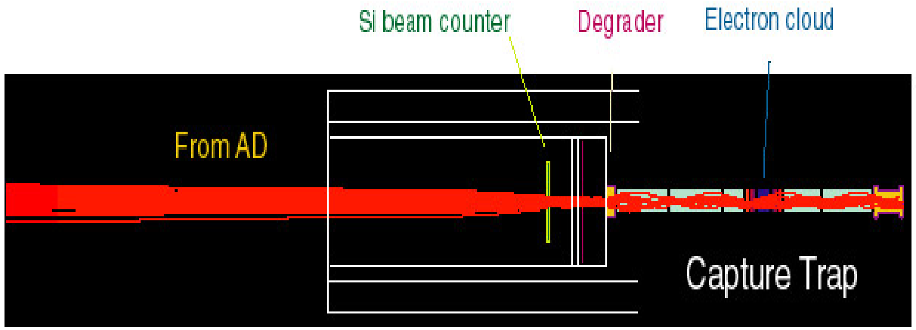
[M. Amoretti *et al.*, NIM A **518** (2004) 679]

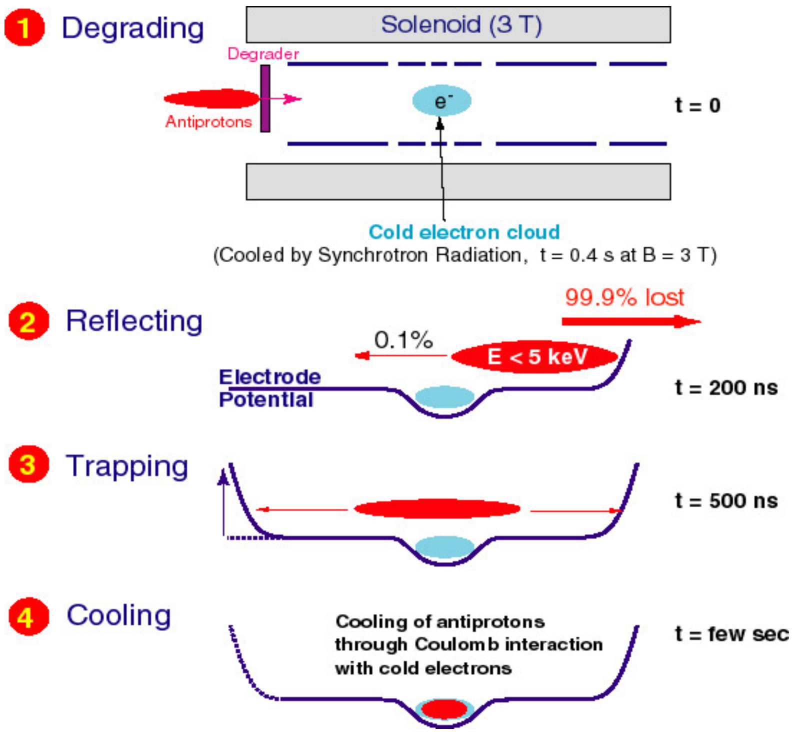
ATHENA (AD-1)



Antiprotons (capture and cooling)

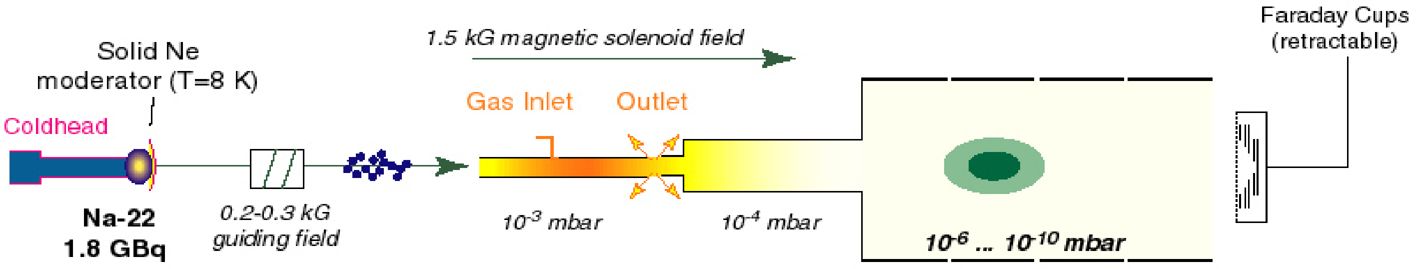


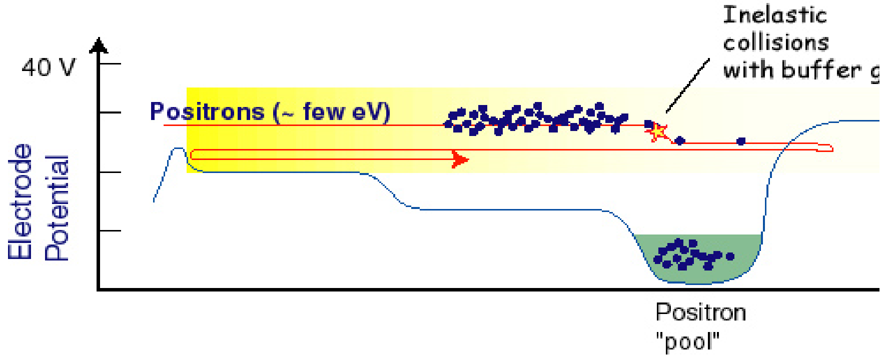




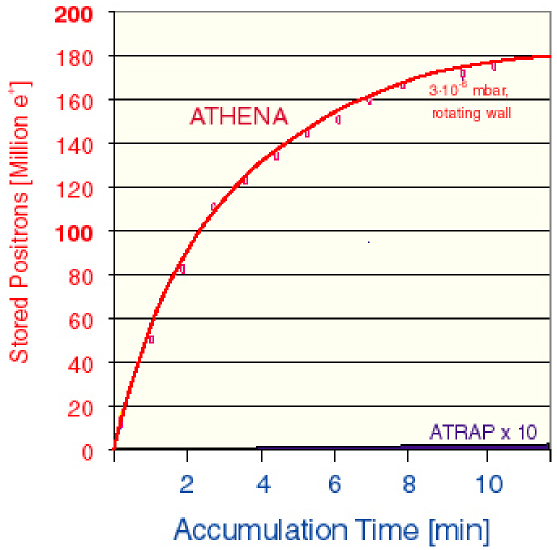
Positron Accumulation

ATHENA - Positron Accumulation Scheme

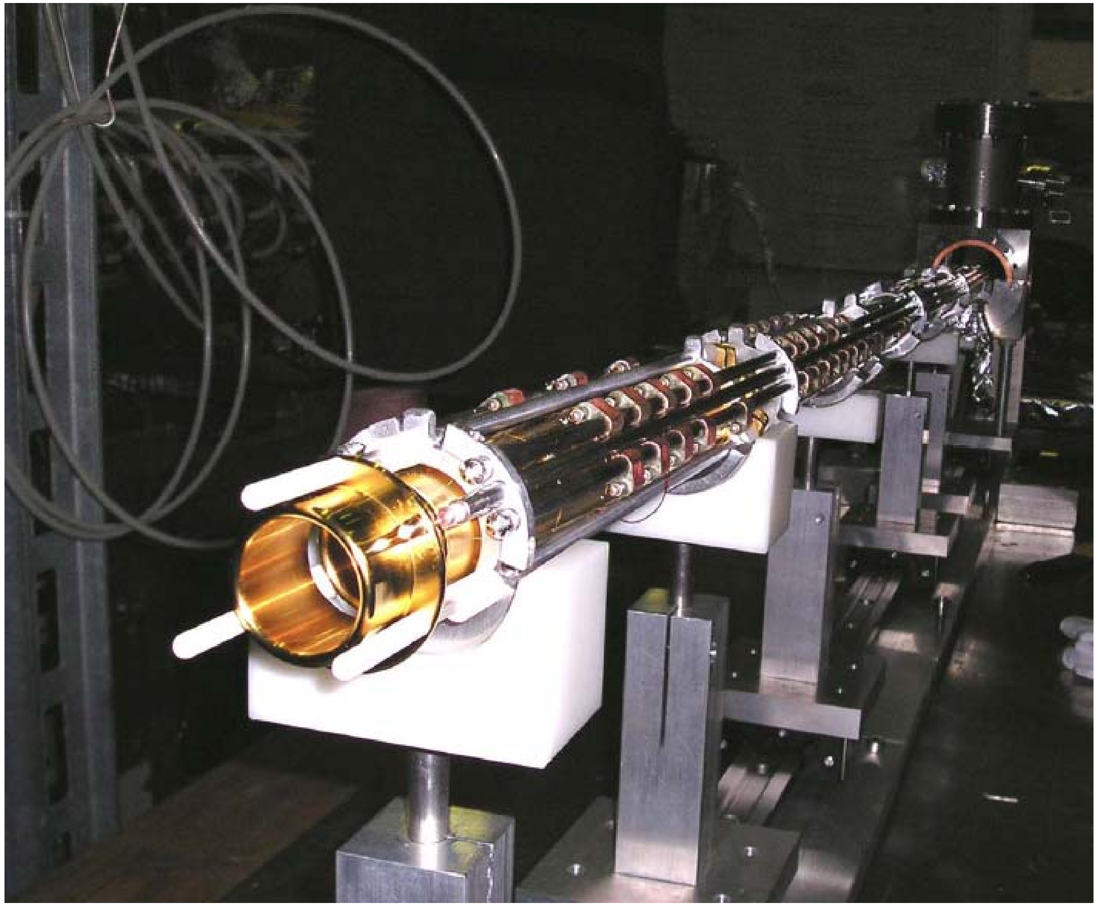


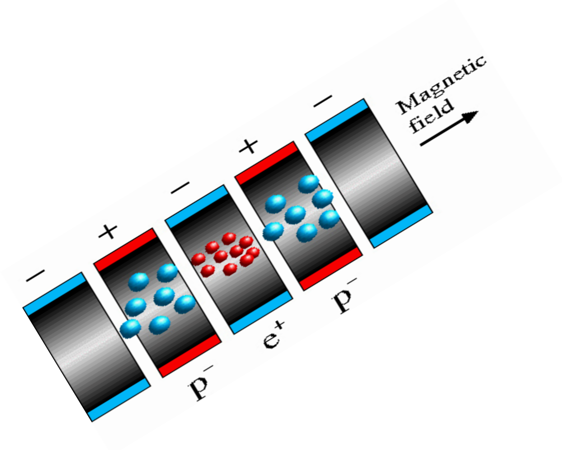


Accumulated positrons vs time



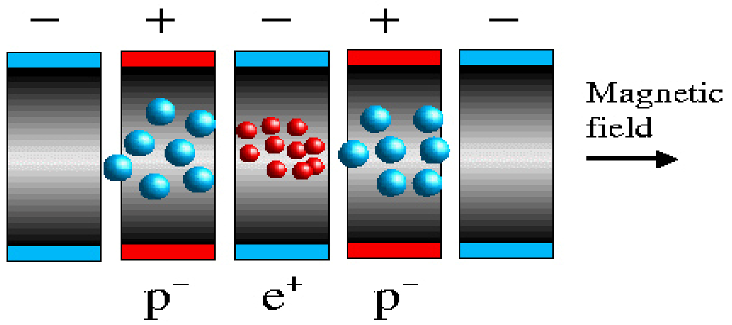
Electrical Landscapes

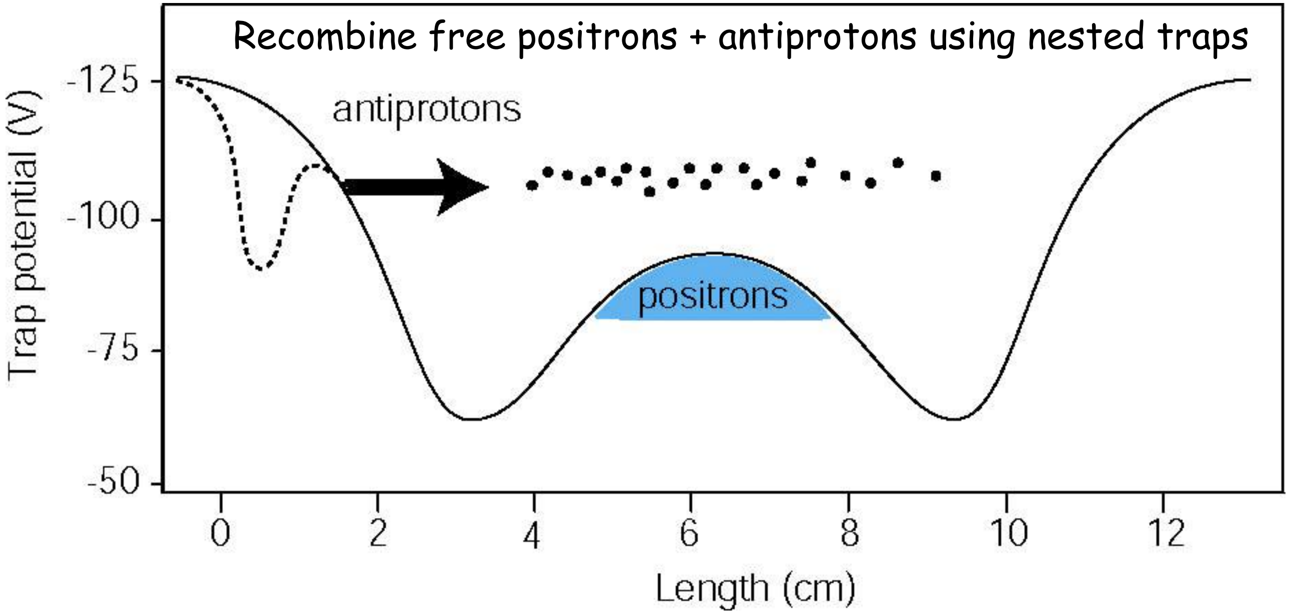




ATHENA multi-electrode trap

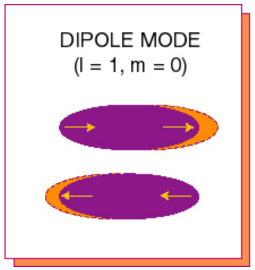
Antiproton-Positron Recombination Scheme

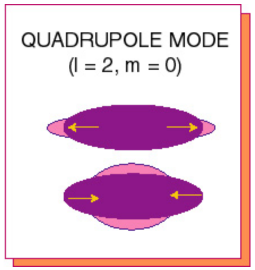



Recombine free positrons + antiprotons using nested traps

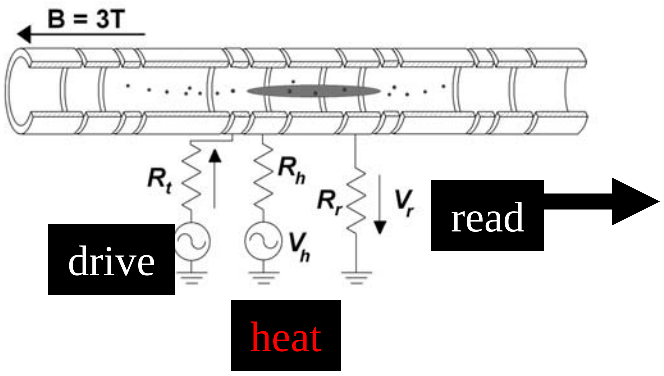
*D.S. Hall, G. Gabrielse, Phys. Rev. Lett. **77**, 1962 (1996)

Cold vs hot - Positron plasma 'heating'





'Shake' positron plasma with RF fields
Heating leads to measurable shift of 'quadrupole frequency'



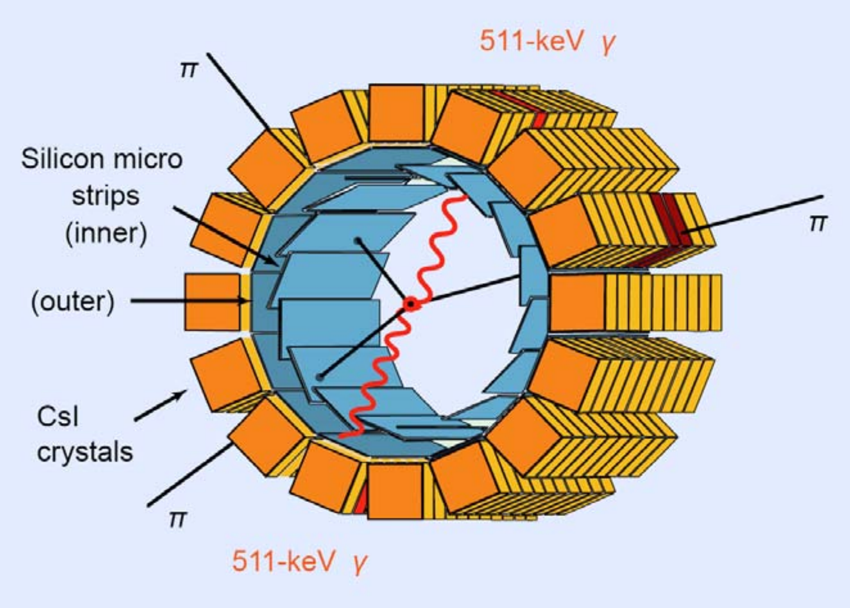
Recombination of antiprotons and positrons
is suppressed for hot positron plasma

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

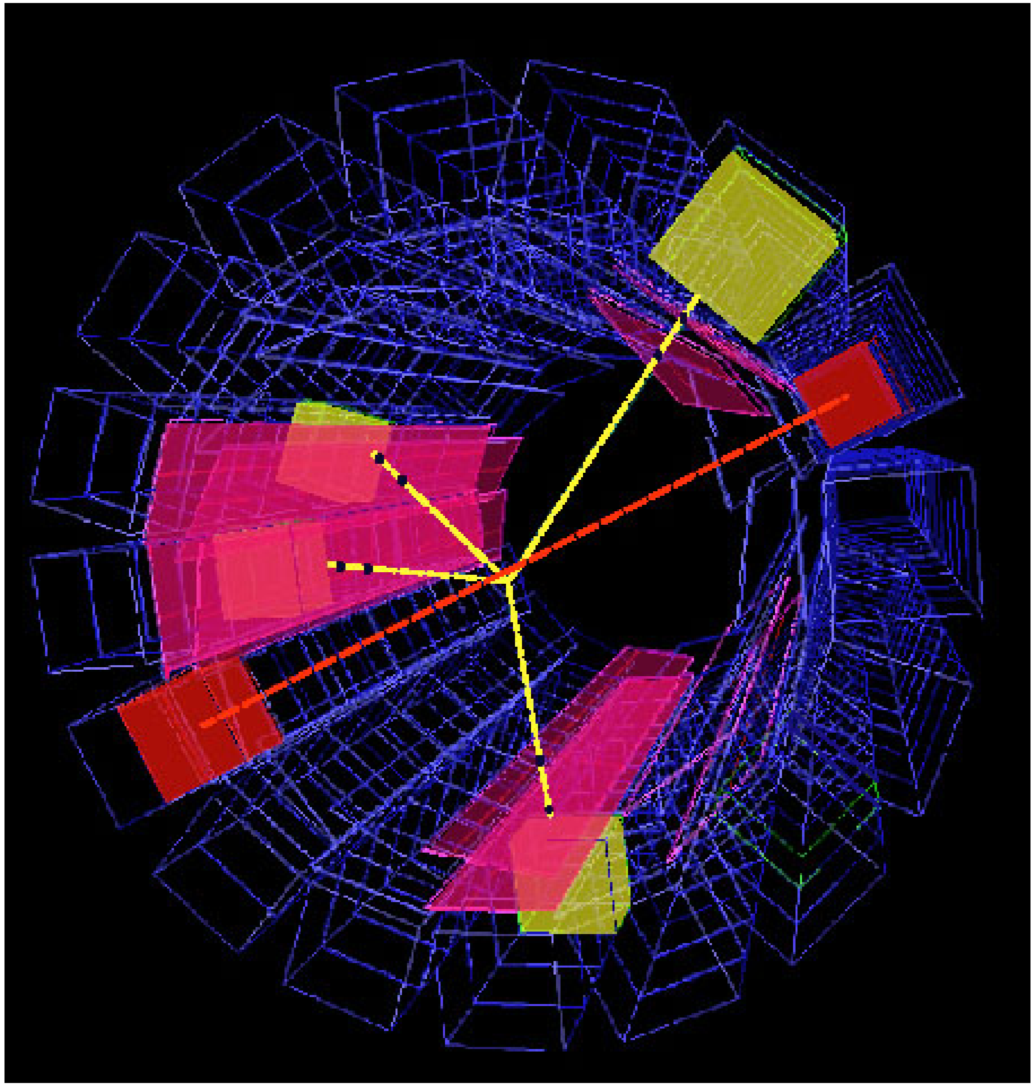
(C. Regenfus et al., NIM **A501**, 65 (2003))



Event analysis:

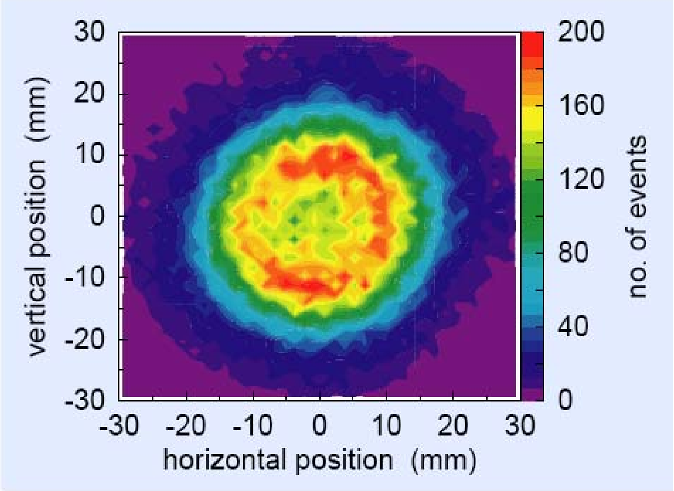
1. Reconstruct vertex from tracks of charged particles
2. Identify pairs of 511 keV γ-rays in time coincidence
3. Measure opening angle between the two γ -rays

ATHENA: Event Display



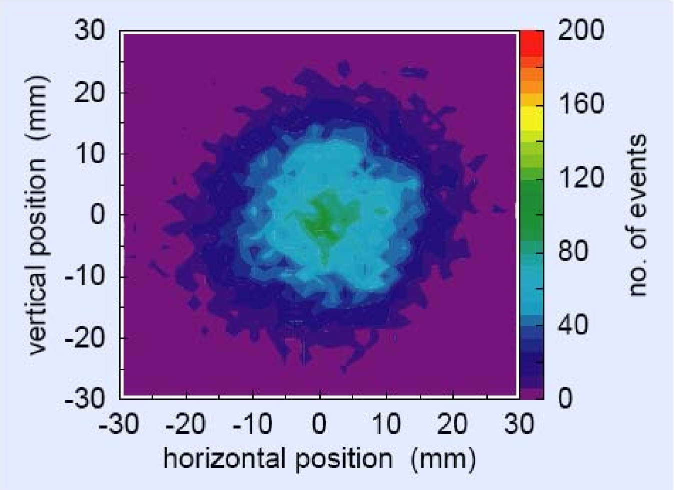
ATHENA: First observation of cold antihydrogen

1) Distribution of annihilation points



Cold positrons

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

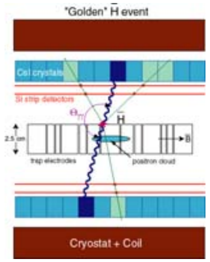


Hot positrons
(RF excitation
of axial e^+
plasma modes)

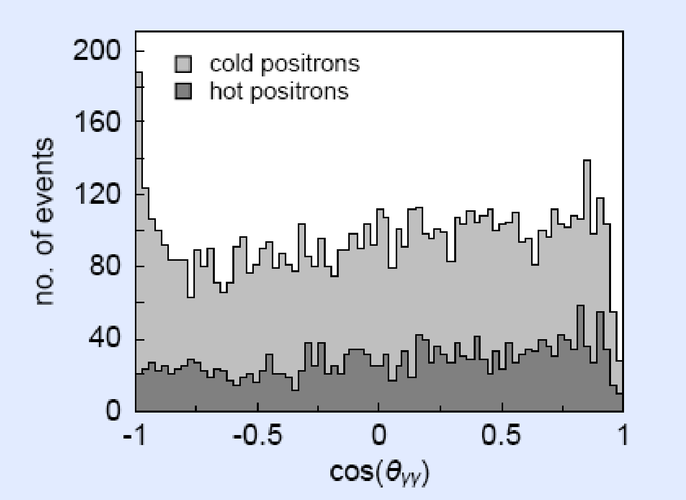
Neutral antihydrogen annihilates on trap walls (not trapped)

Heating of positrons suppresses antihydrogen formation

ATHENA - Antihydrogen (2)

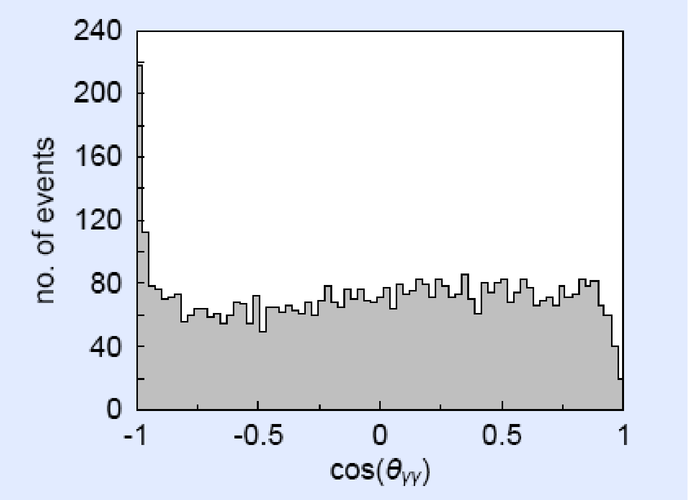


2) Opening Angle Distribution



Data

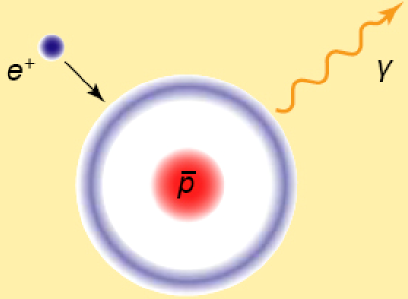
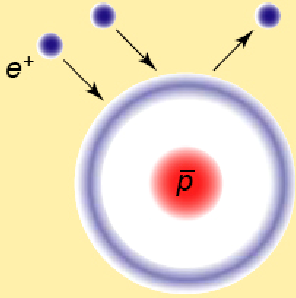
[M. Amoretti *et al.*, Nature **419** (2002) 456]



Monte Carlo

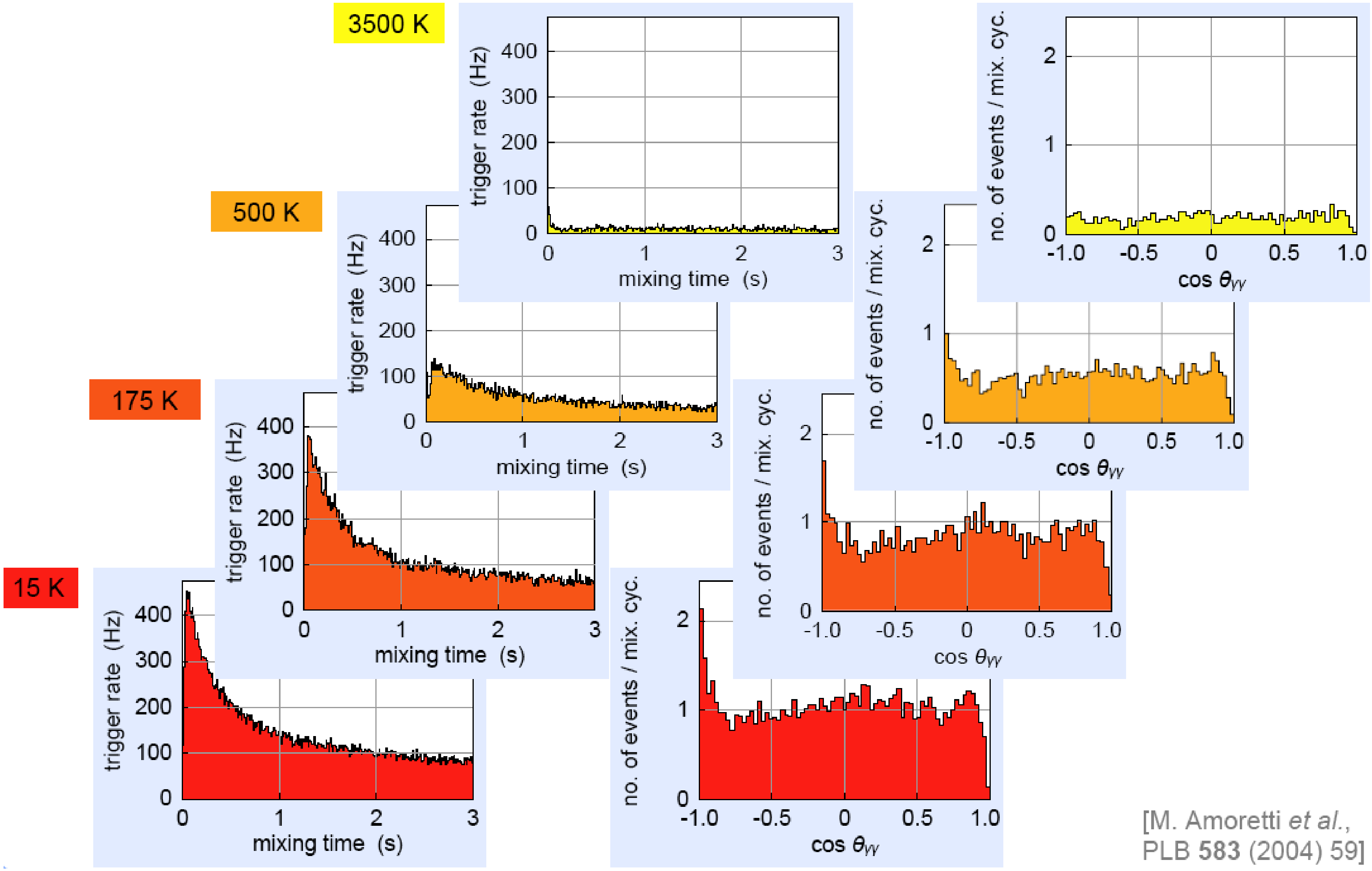
Peak from back-to-back 511 keV photon pairs
Disappears when positrons are 'hot'
Correcting for detection efficiency: > 100,000 anti-atoms

Theoretical models of recombination

	Radiative Recombination	Three-Body Recombination
Principle		
Temperature depend.	$\propto T^{-2/3}$	$\propto T^{-9/2}$
e^+ density dependence	$\propto n_e$	$\propto n_e^2$
Cross-section at 1 K	10^{-16} cm^2	10^{-7} cm^2
Final internal states	$n < 10$	$n >> 10$

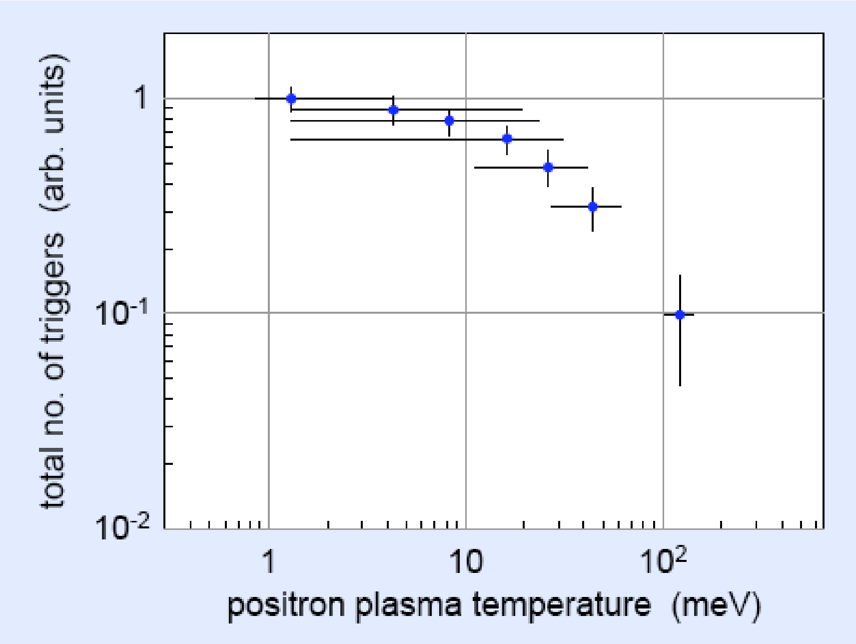
[J. Stevefelt *et al.*, PRA **12** (1975) 1246] [M. E. Glinsky *et al.*, Phys. Fluids B **3** (1991) 1279]

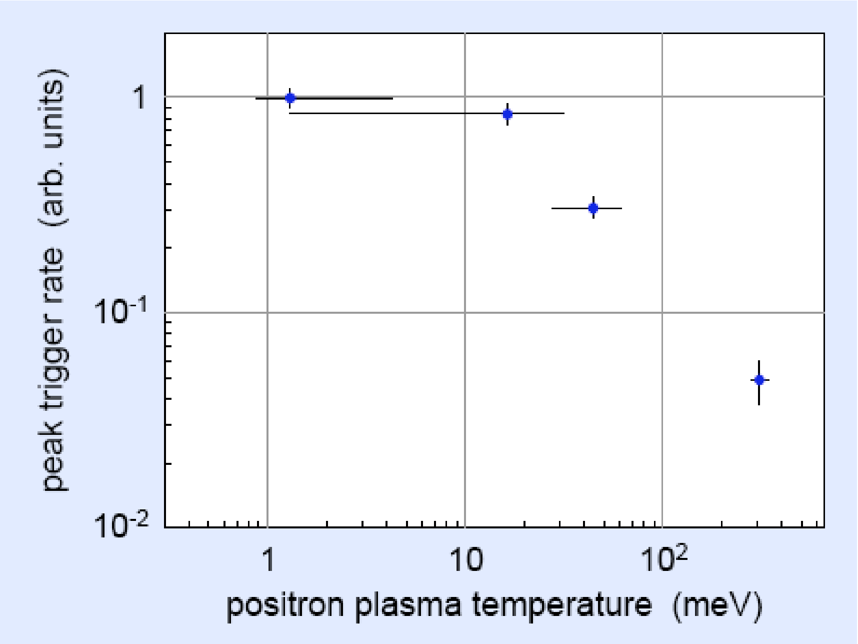
Dependence of production rate on positron temperature



[M. Amoretti *et al.*, PLB **583** (2004) 59]

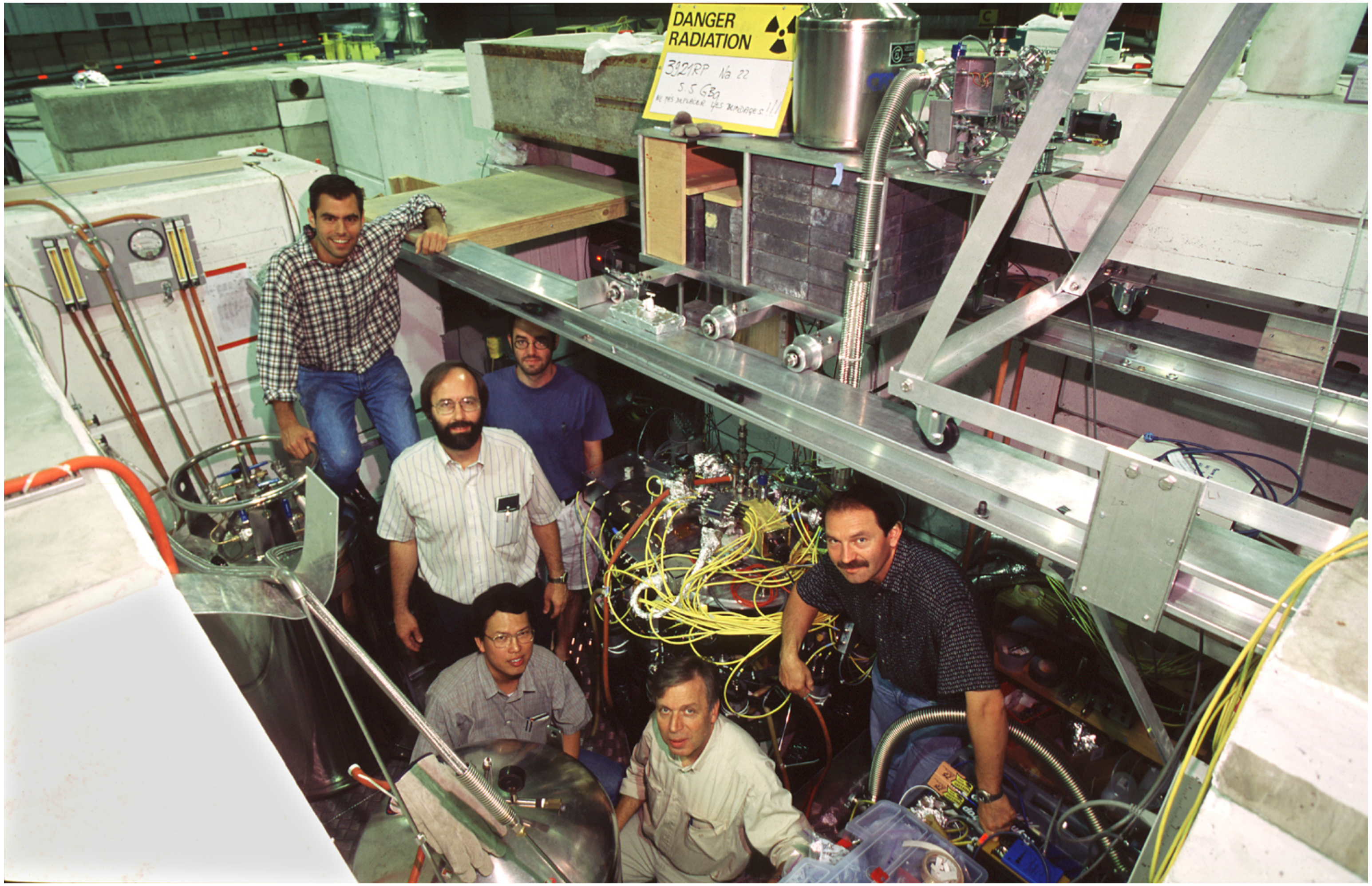
Recombination rate vs Positron Temperature



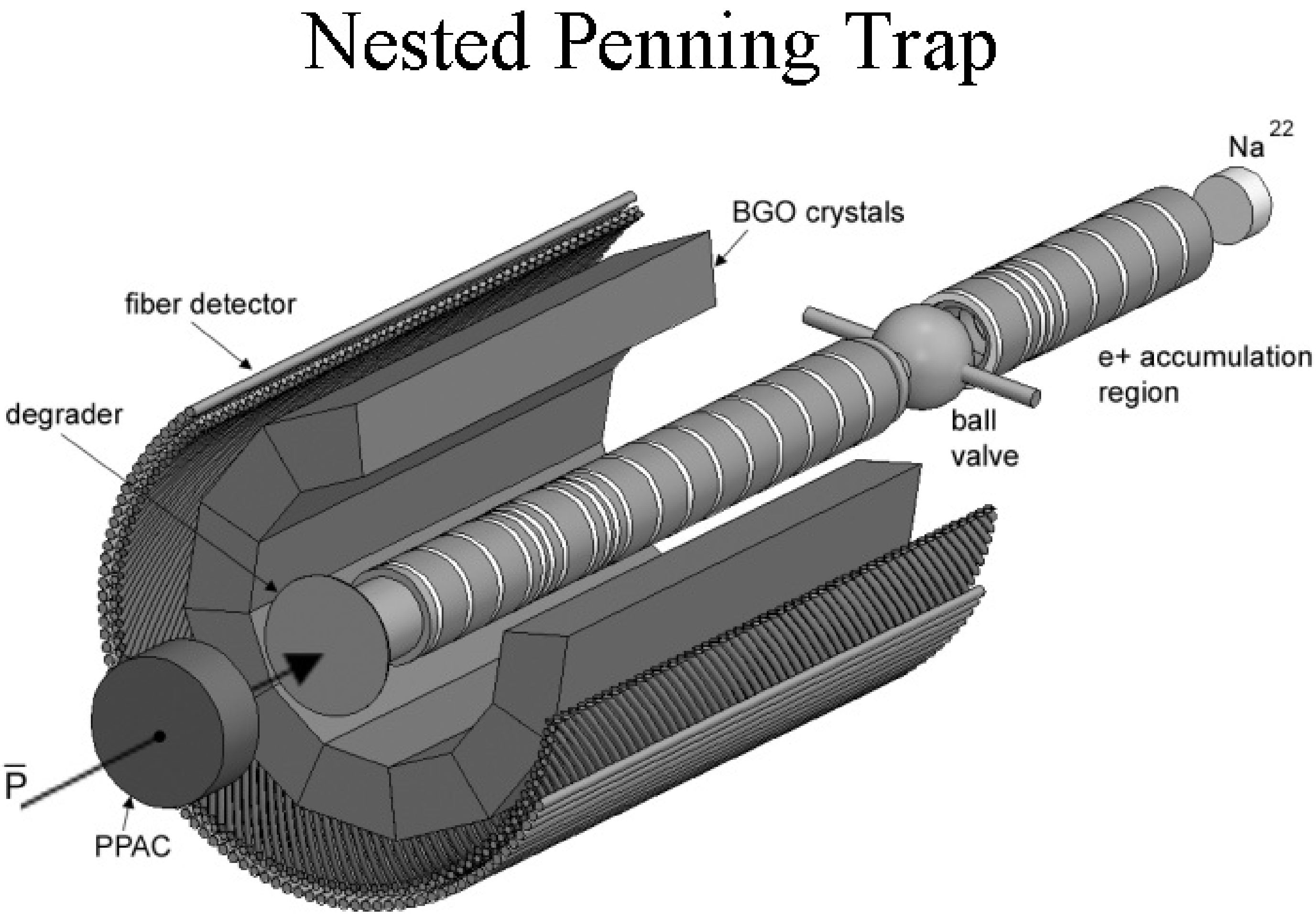


Production decreases with increasing temperature
No strong increase at very low temperature
Simplistic power law fit to data yields ~ $T^{-0.7\pm0.2}$
Note: corrections for plasma dynamics, magnetic field

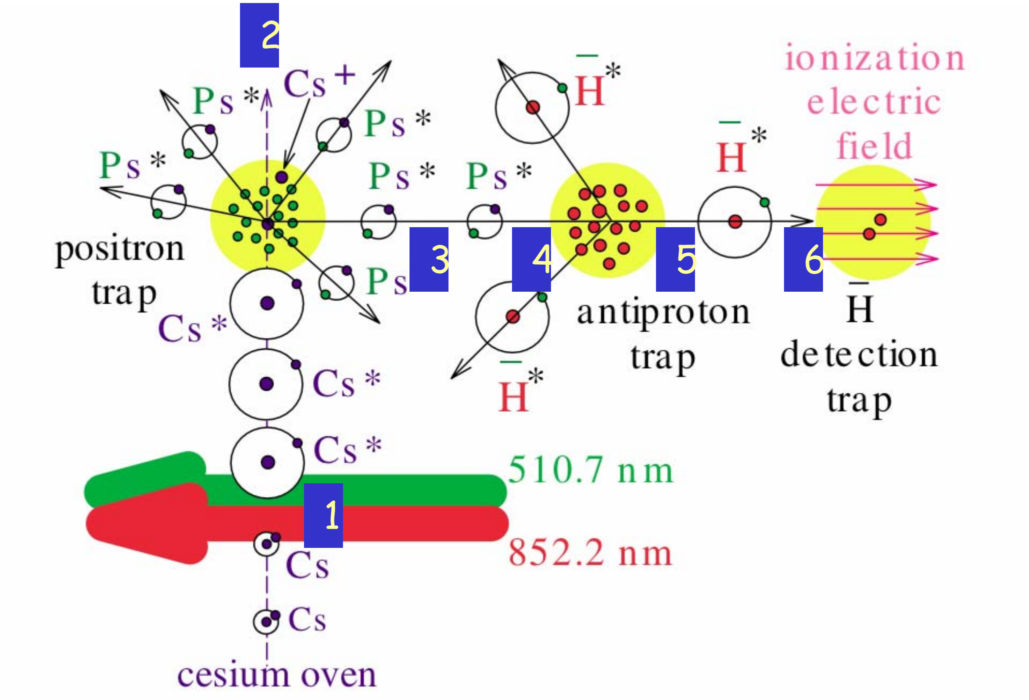
ATRAP (AD-2)



ATRAP (AD-2) - Overview



ATRAP uses positronium to make antihydrogen



1 Cs atoms are excited to n~50

2 Cs* atoms collide with positron cloud

3 Formation of excited positronium

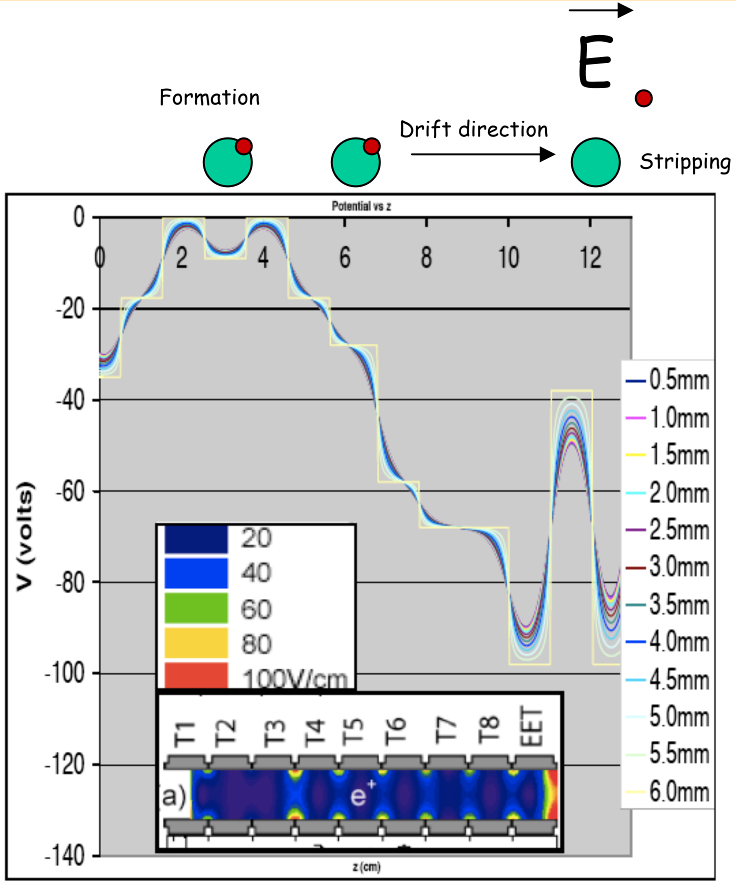
4 Ps* collides with cold antiprotons

5 Antihydrogen formation (n ~ 45)

6 Antihydrogen detection by ionisation

Advantage:	Positron attached to 'resting' antiproton
Disadvantage:	Low rate (14 antihydrogen atoms detected)

ATRAP - Detection by ionisation

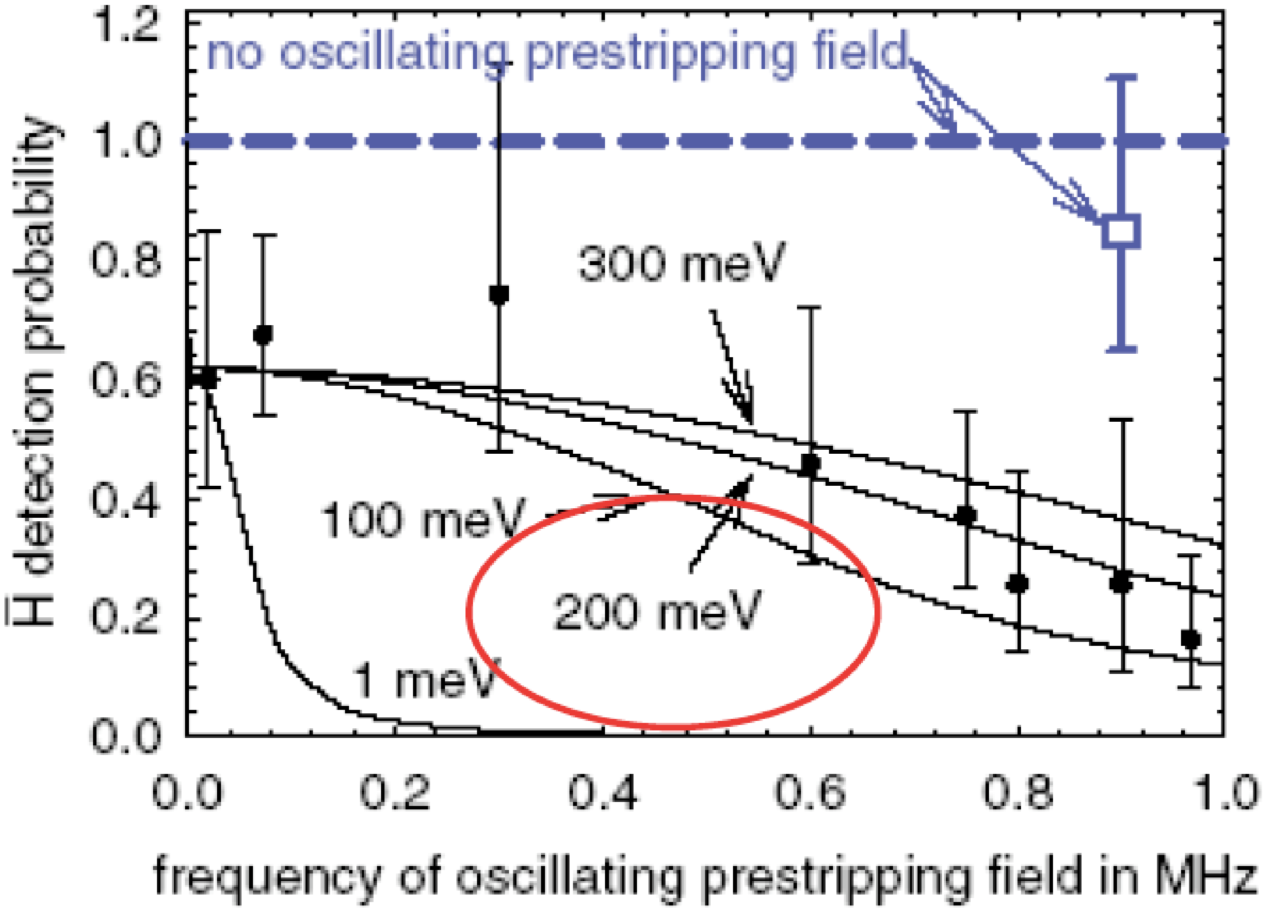


Only works for antihydrogen in high-n states (n>35) moving along magnetic axis

Field ionization - ‘rip’ positron off, antiproton left and detected by annihilation

ATRAP - Kinetic energy

By using **two** time-variable ionisation+analysis fields, ATRAP measured E_{kin} ~ 200 meV (?)



Summary - Cold antihydrogen production

Two different techniques have been demonstrated:

nested traps (large production rate)

Ps* collisions (small production rate)

Recombination process: a mixture of radiative and 3-body transitions

n-state distribution? ATRAP can only observe high-n states (field ionisation)

Velocity of antihydrogen: unknown (1 - 200 meV ?)

MANY IMPORTANT FEATURES NOT YET UNDERSTOOD

Phase 2 - Trap antihydrogen

How to trap (neutral) antihydrogen?

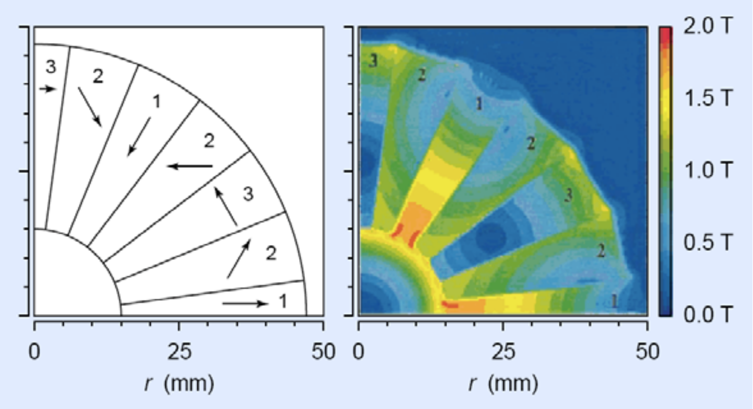
1) magnetic moment (~ μ_{e+}) - ATRAP/ALPHA approach

2) induced electric dipole moment (Stark deceleration) ?

3) Formation of positive antihydrogen ions (additional e^+) ??

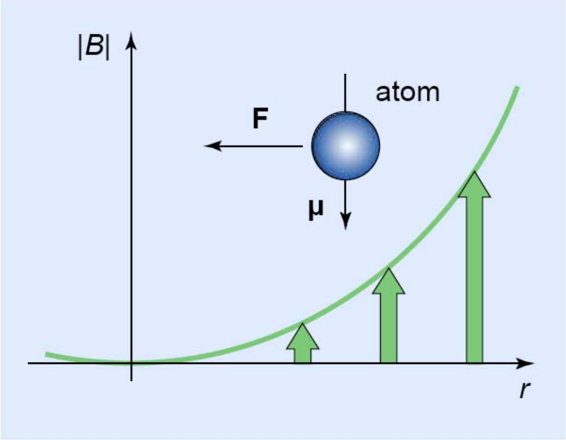
Magnetic bottle ?

Recombination e.g. inside sextupole magnet



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

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



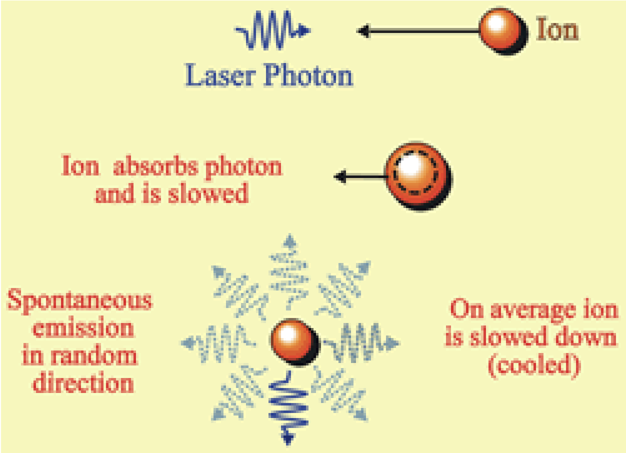
Trap 'low field seeking' atoms (50%) in middle

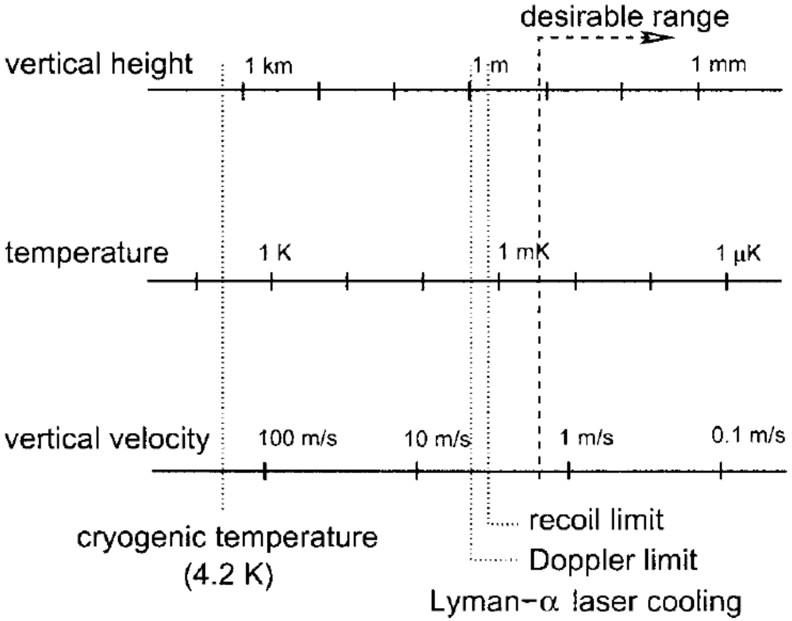
Very shallow potential (~ 0.07 meV/T)

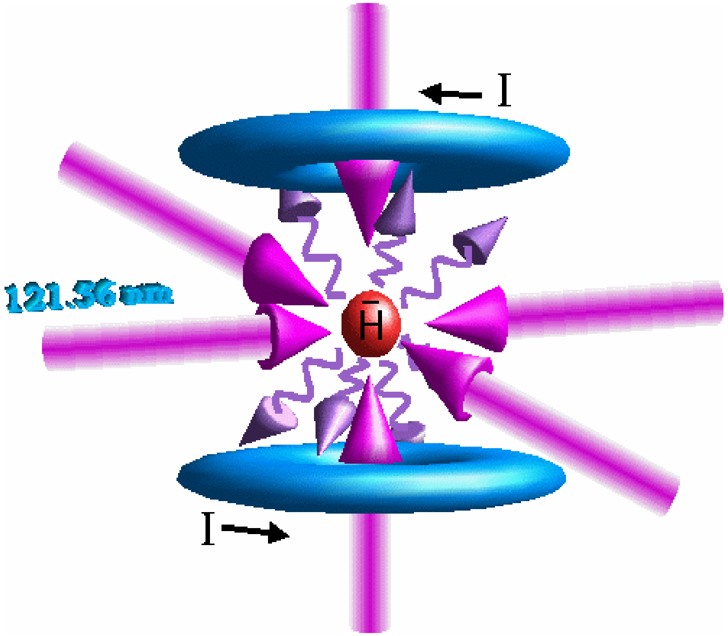
Realistic ΔB ~ 0.2-0.3 T ➪ **E < 0.02 meV**

(reminder: E ~ 1-200 meV)

Antihydrogen cooling







121 nm laser needed

Prototype at MPI Munich

… only 50 nW

Phase 3 - Ideas for precision experiments

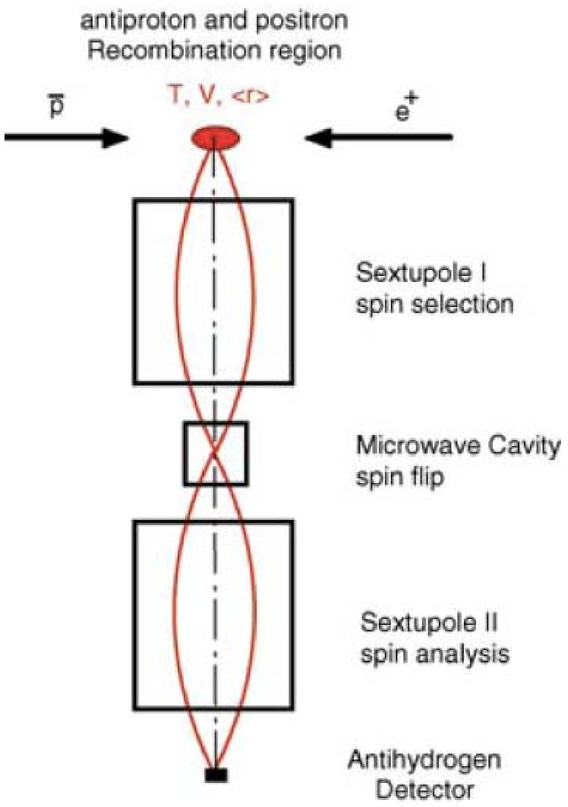
1S-2S Two-photon laser spectroscopy

Hyperfine Structure

Ballistic gravity measurement

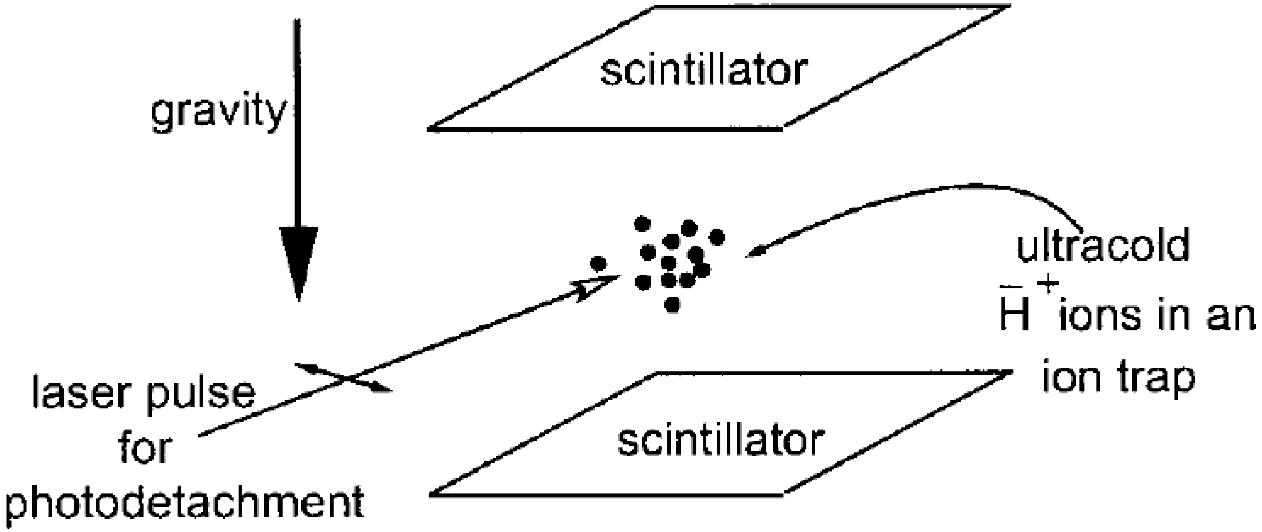
Atomic interferometry

Hyperfine Structure



Conceptual design (E. Widmann et al., CERN-SPSC-2003-009)

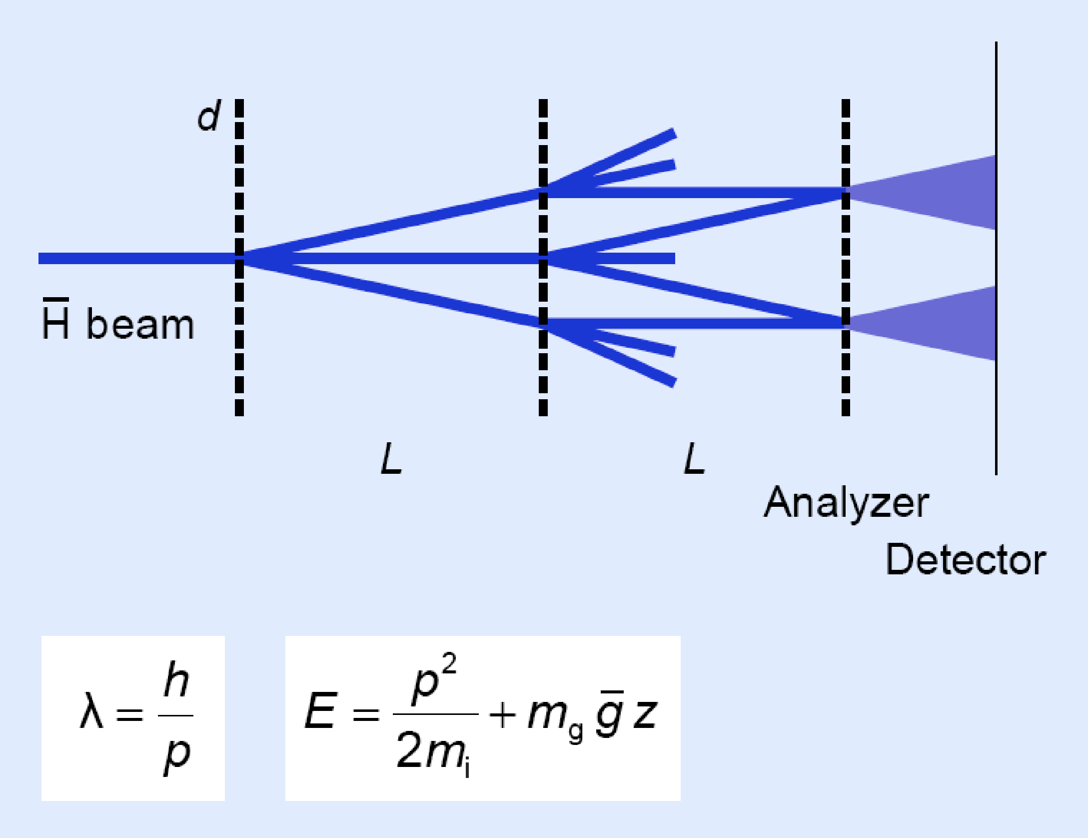
Gravity experiment - ballistic experiment



J. Walz, T. Hänsch, Gen. Rel. Gravit. 36 (2004) 561

Gravity experiment - atom interferometer

Mach - Zehnder interferometer



$$\lambda = \frac{h}{p}$$

$$E = \frac{p^2}{2m_i} + m_g \bar{g} z$$

1 mio Hbar:

$\delta g/g \sim 10^{-4}$

T.J. Philips, Hyp. Int. 109 (1997) 357

VI. ANTIMATTER - APPLICATIONS AND SPECULATIONS

The wonderful and the weird …

PET scan

Positron microscope

Tumour therapy

PET isotope production

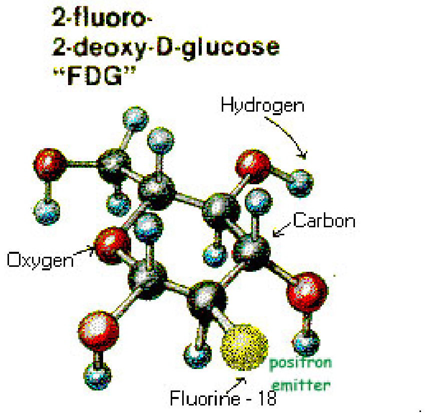
Antiproton Induced Fission/Fusion

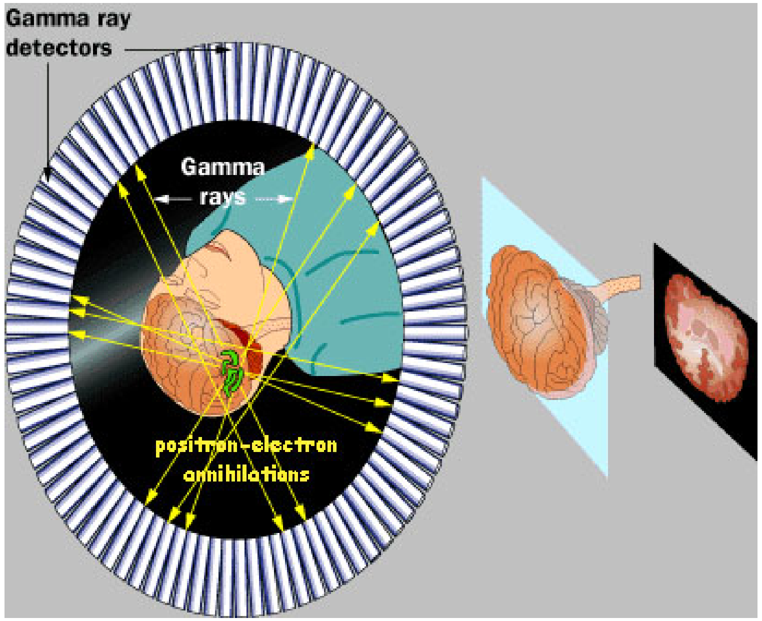
Antimatter Propulsion

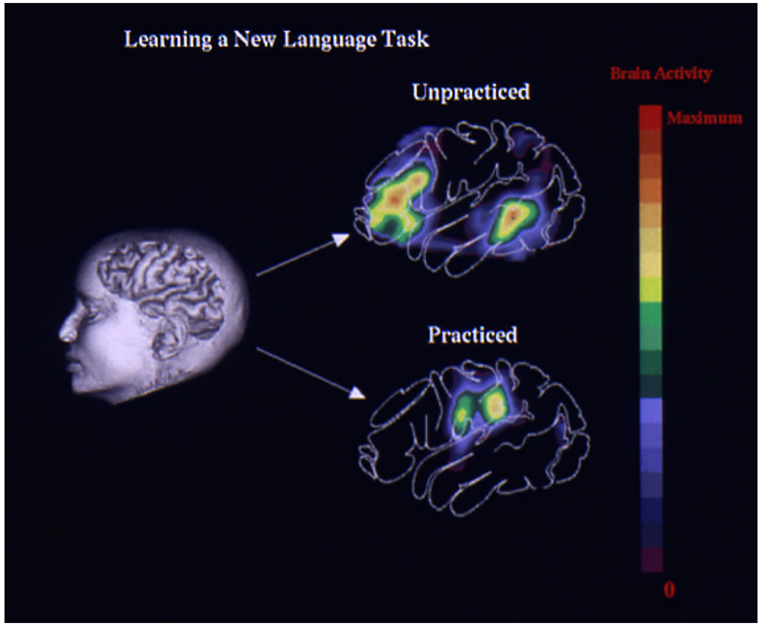
Positron Emission Tomography (PET)

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

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



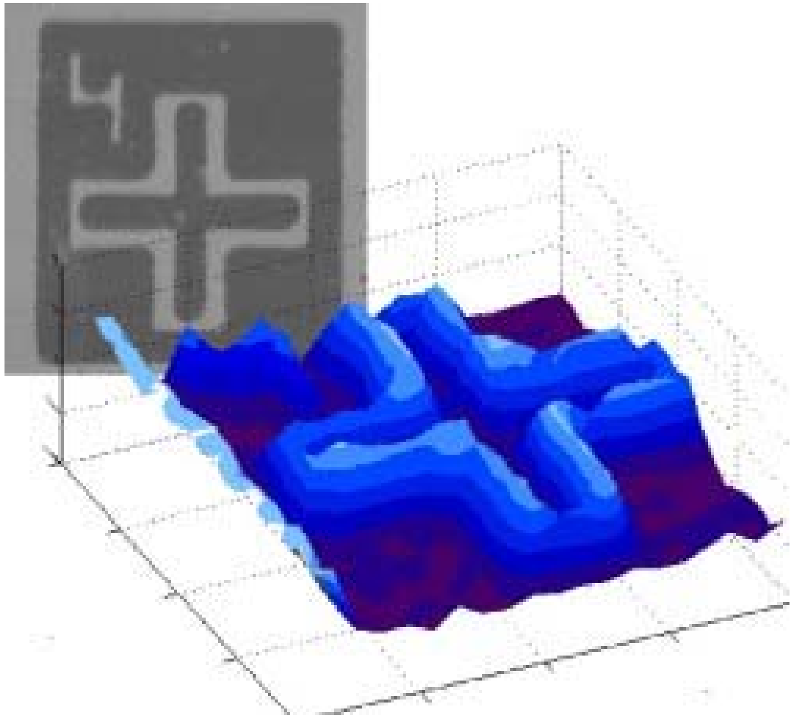




Positron Microscope

Detection of defects in semiconductor surfaces

Positrons at vacancy sites live longer (smaller electron density): **long positron lifetimes indicates vacancies.** Scan surface with pulsed (0.2 ns) positron beamfrom Na-22 source, ~ 1 μm wide. Time difference from emission to annihilation measures lifetime.



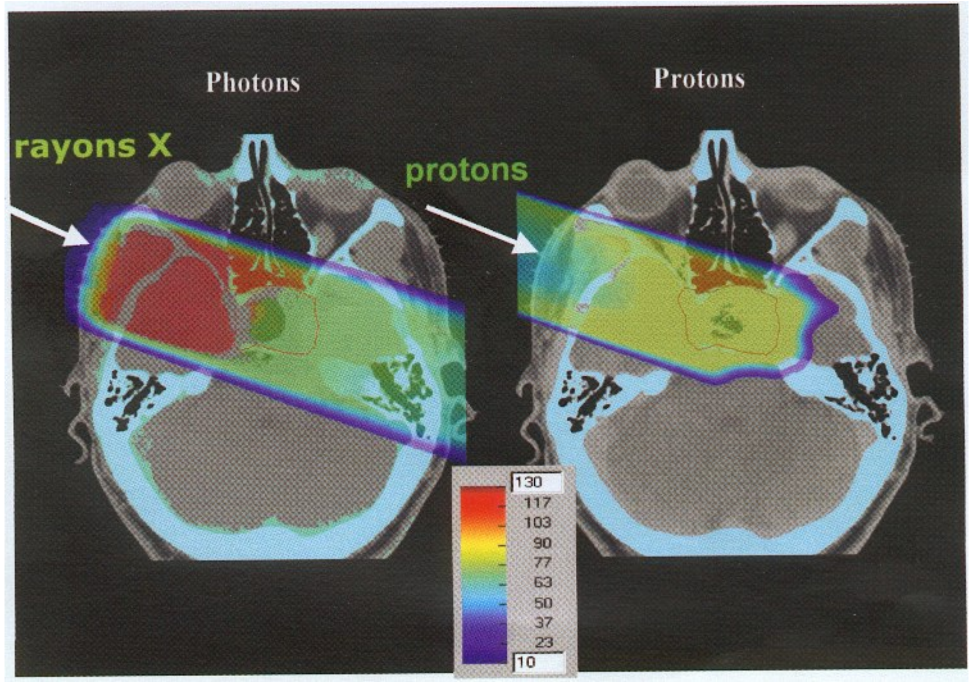
Cross-shaped pattern ~ 120 μ across
(Pt on SiO surface; positron lifetime in Si0 ~ 2x longer than in Pt)

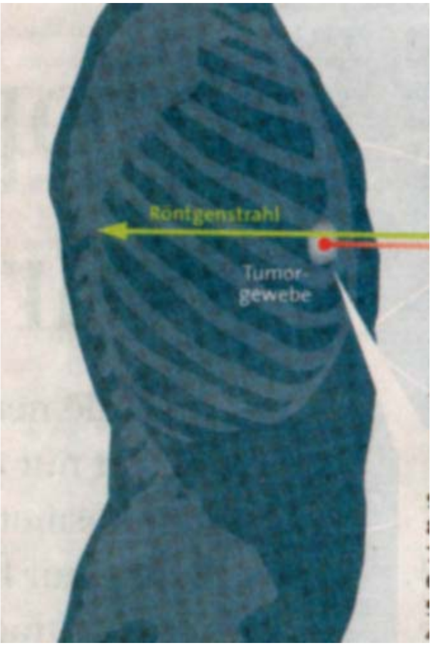
Scanning Positron Microscope: A. David et al., Phys. Rev. Lett. 87 (2001) 067402

Antiproton Beam Therapy

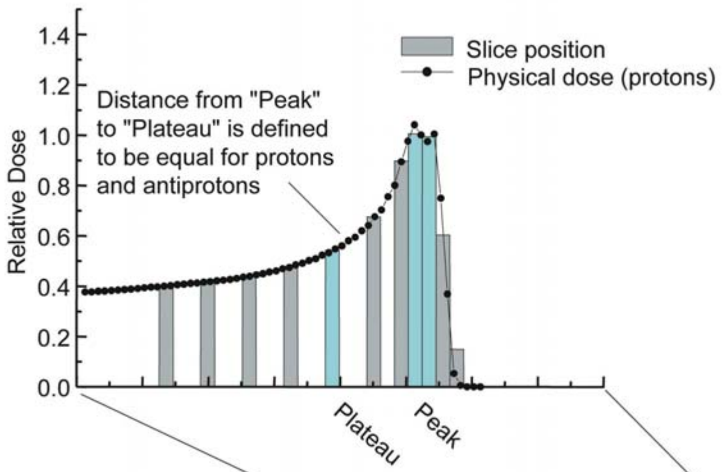
Goal: destroy tumour without (too much) harm to healthy tissue

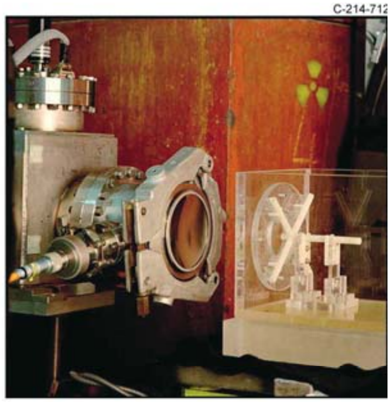
Gammas: exponential decay (peaks at beginning)
Charged particles: Bragg peak (Plateau/Peak better for high Z)
Antiprotons: like protons, but enhanced Bragg peak from annihil

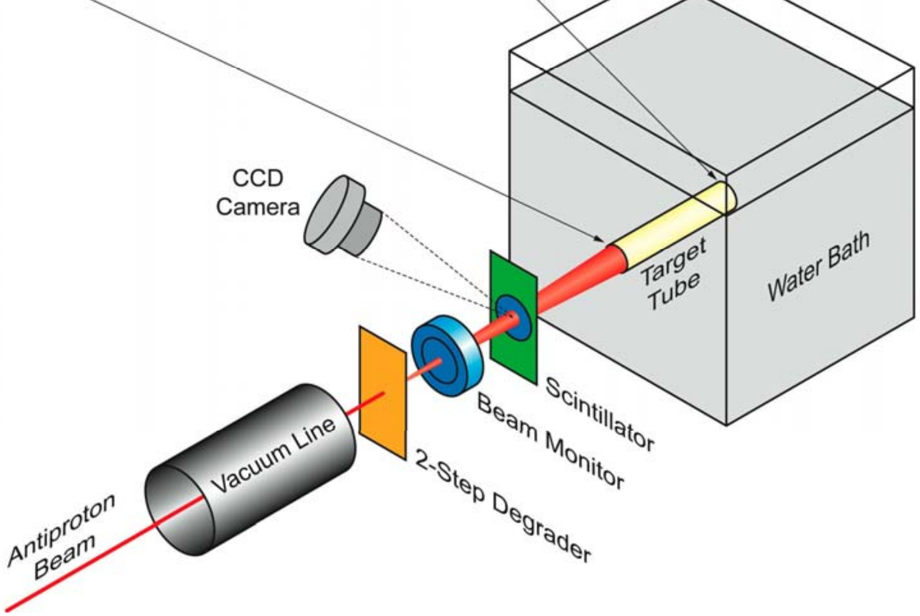




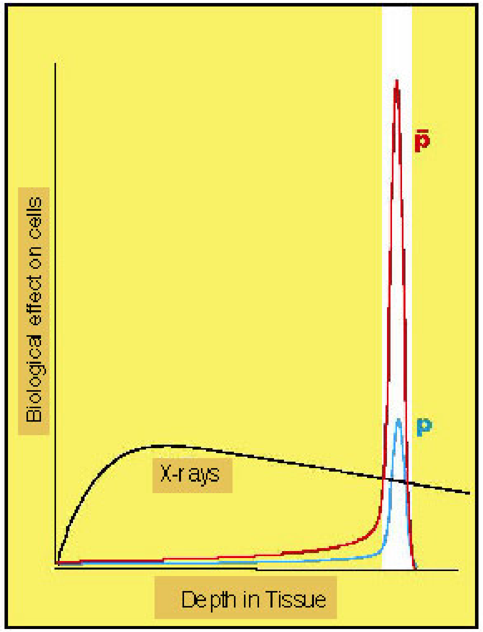
Antiproton Cell Experiment ACE (AD-4)

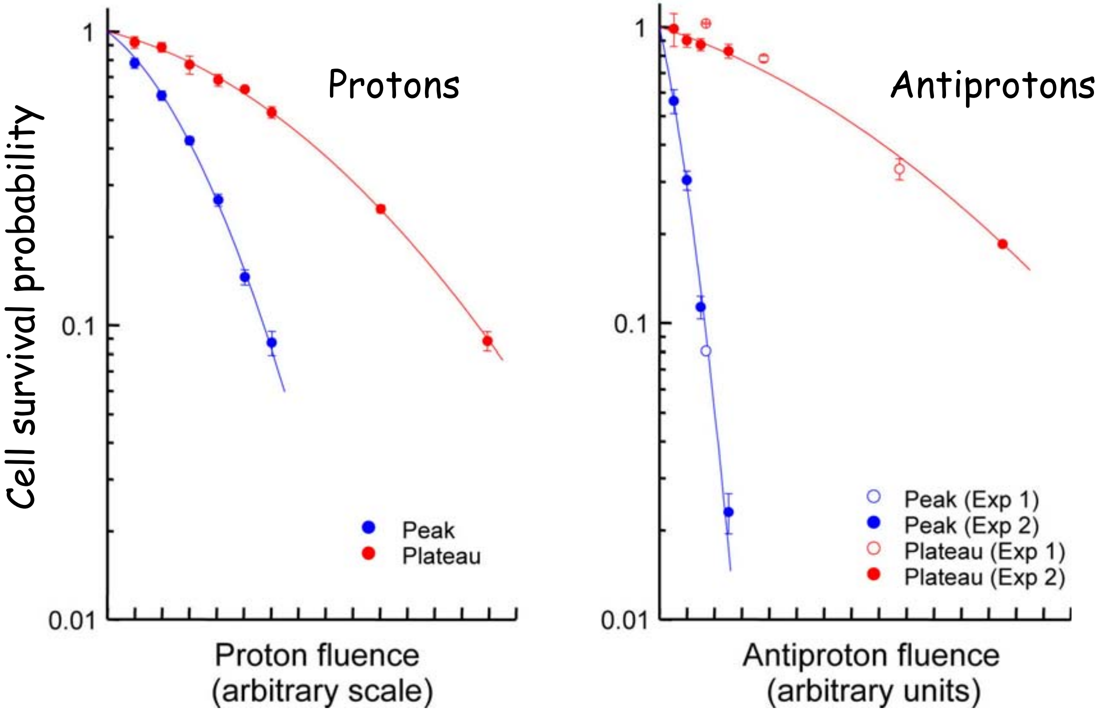






Antiprotons beams for tumour treatment ?





Equal cell mortality for tumour cells with less radiation dose (= damage to healthy cells)

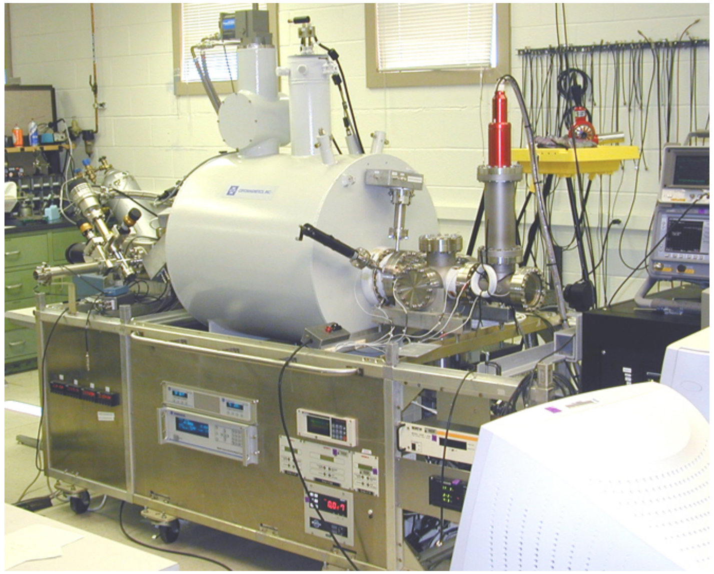
Comparison with Carbon ion therapy

In-situ production of PET isotopes using antiprotons ?

Only 40 isotope production centres (2 M$/cyclotron) for 1700 PETs in US

Problem: short half-life
(C-11: 20', N-13: 10', O-15: 2', F-18: 110')

Monte Carlo: 10^{10} - 10^{11} antiprotons for 15 mCi source (F-18)



NASA/Penn State trap designed for 10^{12} antiprotons

Plan: ~ 10^{11} antiprotons trapped transport to hospital and isotope production *in situ*

Problem: Security! Risk of antiproton loss requires severe shielding (several tons!)

N.b. Trapped electrons have been transported 5000 km; Gabrielse+Tseng, Hyperfine Interactions 76, 381 (1993)

The price of 1 g antiprotons*

The only 'official' financial estimate:

A company (Pbar-Tech, now out-of-business) offered to buy 1% of 2002 Fermilab antiprotons ($5\cdot10^{14}$ antiprotons/year): 274 K$ for $5\cdot10^{12}$ antiprotons

1g at Fermilab: 32,000,000 billion $

Production is dominated by power consumption:

CERN (PS Complex) ~ 30 MW. For a bunch of $5\cdot10^{7}$ antiprotons, need 2.4 s of operation. At a price of 0.1 € per kWh, this costs 2€ per bunch.

Energy consumption for 1 g antiprotons: $9\cdot10^{23}$ J

1g at CERN*: 24,000,000 billion €

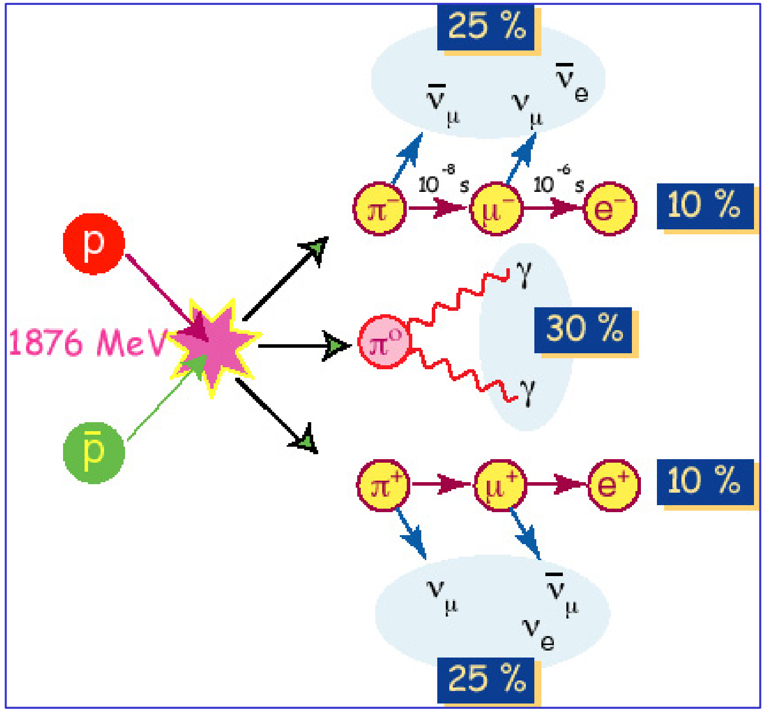
For comparison:

US debt (total, 2006);	8,400 billion $	(~ 1/4000 g antimatter)
US defense budget:	540 billion $	(~ 17 μg)
World energy consumption (2003):	$4\cdot10^{20}$ J	(2250 years for 1 g)
1 μg antiprotons	24 billion $	

*allegedly stolen from CERN; see D. Brown "Angels+Demons"

Antimatter for space propulsion ??

Ambitious long-term plans: “Mars express”, Oort cloud, Proxima Centauri, ...



Energy balance for pbar-p annihilation

Annihilation: energy release/mass =

10^{10} x H_2/O_2 combustion;

100 x fusion!

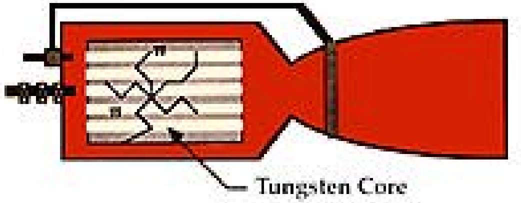
PROBLEM

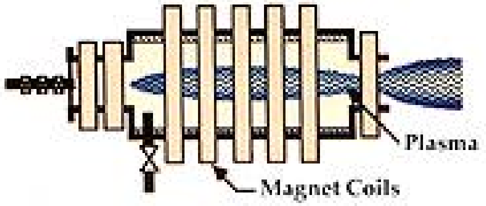
Conversion of reaction energy into propulsive thrust
-> quick decay into gamma rays and neutrinos

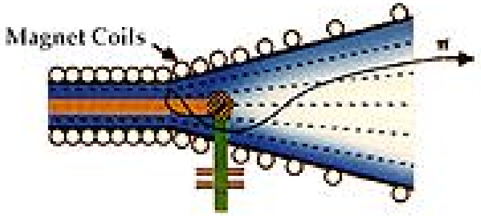
http://www.msfc.nasa.gov/STD/propulsion/research/anti/

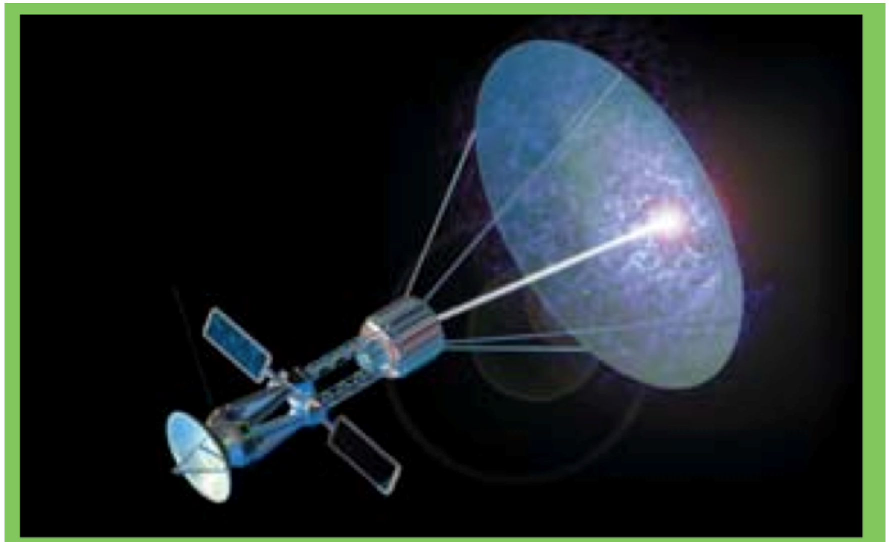
Antimatter driven space engines?

1) solid and gas-core thermal rockets (pion heating)
2) antiproton-initiated fission driving fusion rockets
(needs 1- 100 μg)









PROPOSED ANTIMATTER PROPULSION system uses antimatter pellets to trigger fission explosions on a uranium-coated sail.

PROBLEMS
- antihydrogen storage
- production cost
- Concept of antiproton-induced fission

Concluding remarks

- Antiparticles discovered 74 years ago
- Very important for the development of particle physics and cosmology
- Antiproton production, deceleration and cooling techniques well understood
- Cold antihydrogen atoms have been produced (> 1 mio)
- Next big challenge: trapping and cooling
- Antihydrogen atoms ideal for studying CPT invariance and antimatter gravity with very high precision
- Applications in daily life exist, but high production costs of antiprotons are (almost) prohibitive

Thank you for your attentio