Results and Prospects of Antihydrogen Production

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Colloquium
DIPARTIMENTO DI FISICA, UNIVERSITA’ DI TORINO
Friday, 10 October 2014, at 14:30, Aula Wataghin

Dipartimento di Fisica, Universita' di Torino

Sezione di Fisica Teorica

Venerdi 10 Ottobre, Sala Wataghin, ore 14:30

Luca Venturelli

(Universita degli Studi di Brescia)

Results and Prospects of Antihydrogen Production

The production of the first antihydrogen atoms dates back to the end of the last century. Since then several improvements have been achieved on the way to perform some of the best tests of CPT symmetry through the comparison with hydrogen. At the Antiproton Decelerator of CERN some experiments are working to precisely measure both the 1S-2S transition and the hyperfine levels of the ground state of antihydrogen. The recent results of the ASACUSA Collaboration on the production of the first beam of antihydrogen are presented together with the plan to perform high precision spectroscopy.

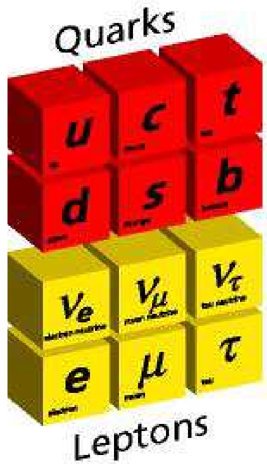
Antihydrogen

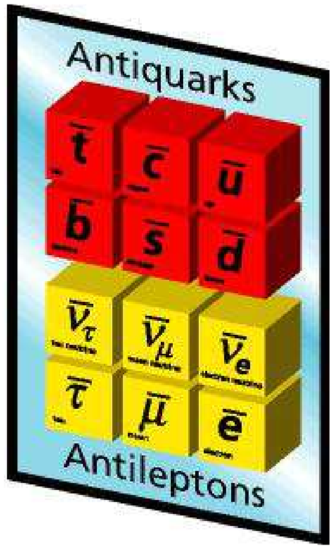
Antihydrogen is the bound state of an antiproton and a positron

Matter

Anti-matter

particles

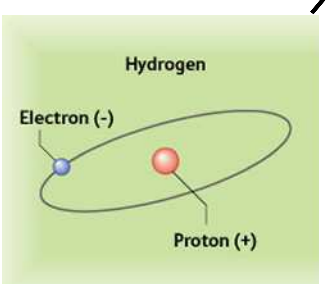


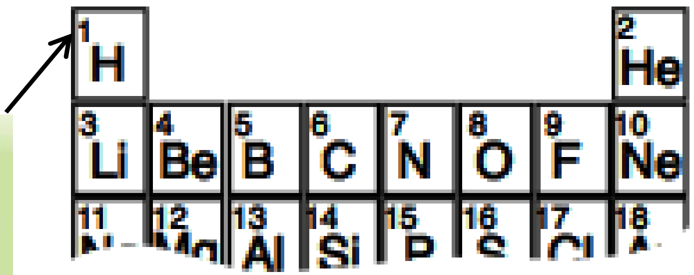


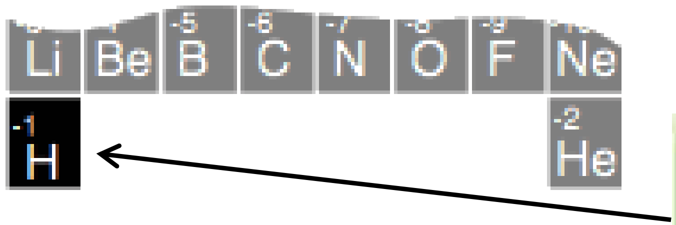
antiparticles

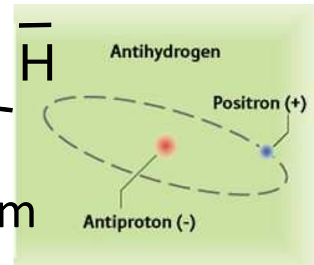
elements

anti-elements



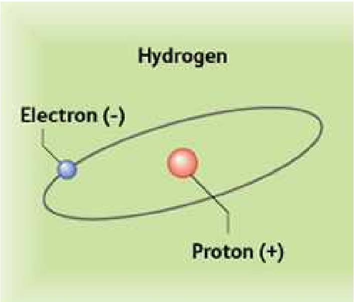






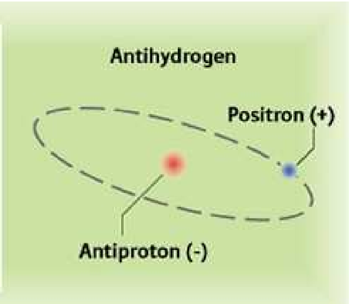
Antihydrogen is the simplest atom consisting entirely of antimatter

Antihydrogen: what is it known?



Hydrogen

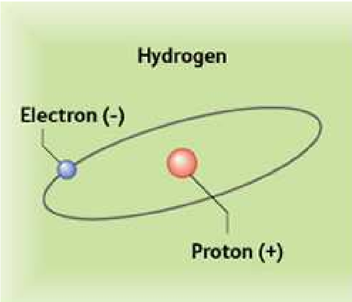
Antihydrogen

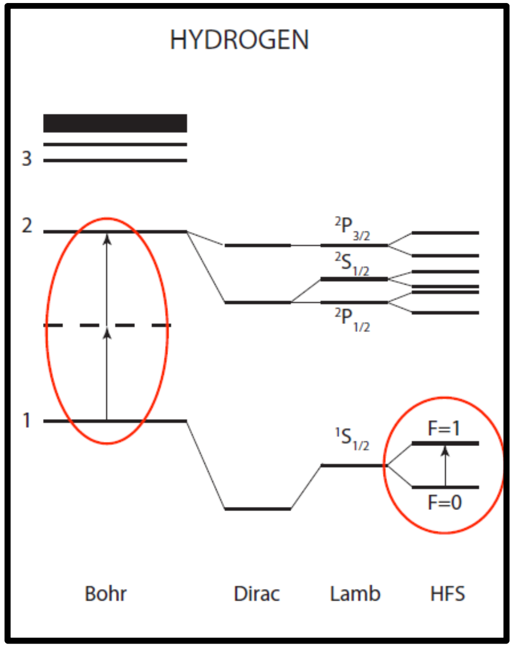


$\bar{H}$

Antihydrogen: what is it known?

Hydrogen

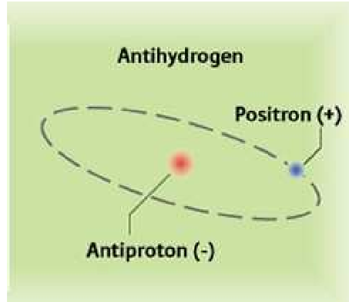




one of the best understood and most precisely measured system

quantity	exp. value [Hz]	δ_{exp}/ν	δ_{th}/ν
$\nu_{1s\text{-}2s}$	$2\,466\,061\,413\,187\,035(10)$	4.2×10^{-15}	1×10^{-11}
$\nu_{2s\text{-}2p}$	$1\,057\,8450(29)\times10^{3}$	2.7×10^{-6}	3.8×10^{-11}
ν_{HFS}	$1\,420\,405\,751.7667(9)$	6.3×10^{-13}	$(3.5\pm0.9)\times10^{-6}$

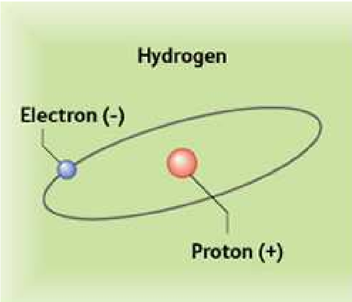
Antihydrogen

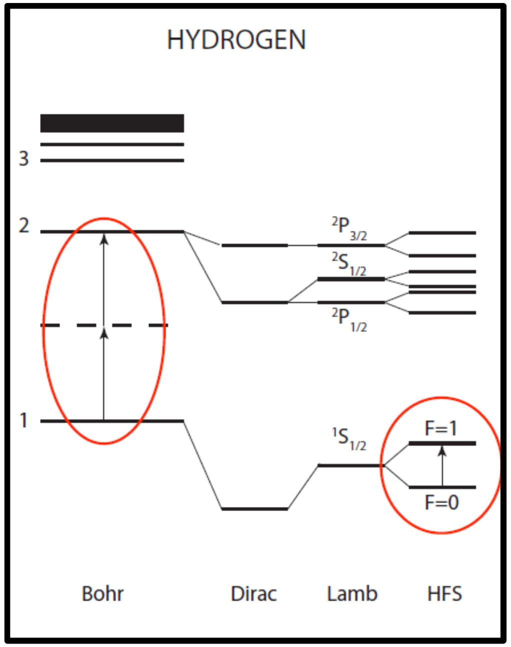


$\bar{H}$

Antihydrogen: what is it known?

Hydrogen





one of the best understood and most precisely measured system

quantity	exp. value [Hz]	δ_{exp}/ν	δ_{th}/ν
$\nu_{1s\text{-}2s}$	2 466 061 413 187 035(10)	4.2×10^{-15}	1×10^{-11}
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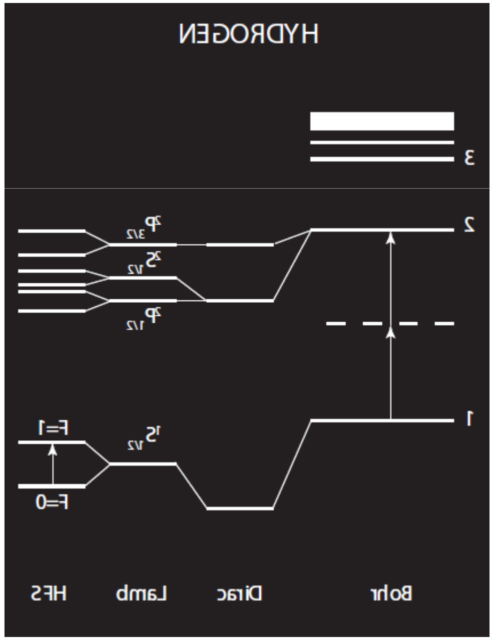
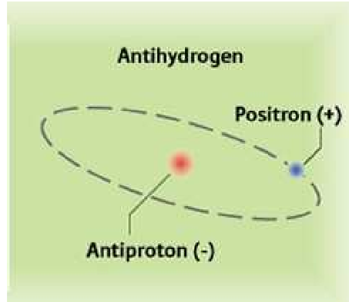
ν_{HFS}	1420 405 751.7667(9)	6.3×10^{-13}	$(3.5\pm0.9)\times10^{-6}$

Antihydrogen





$\bar{H}$

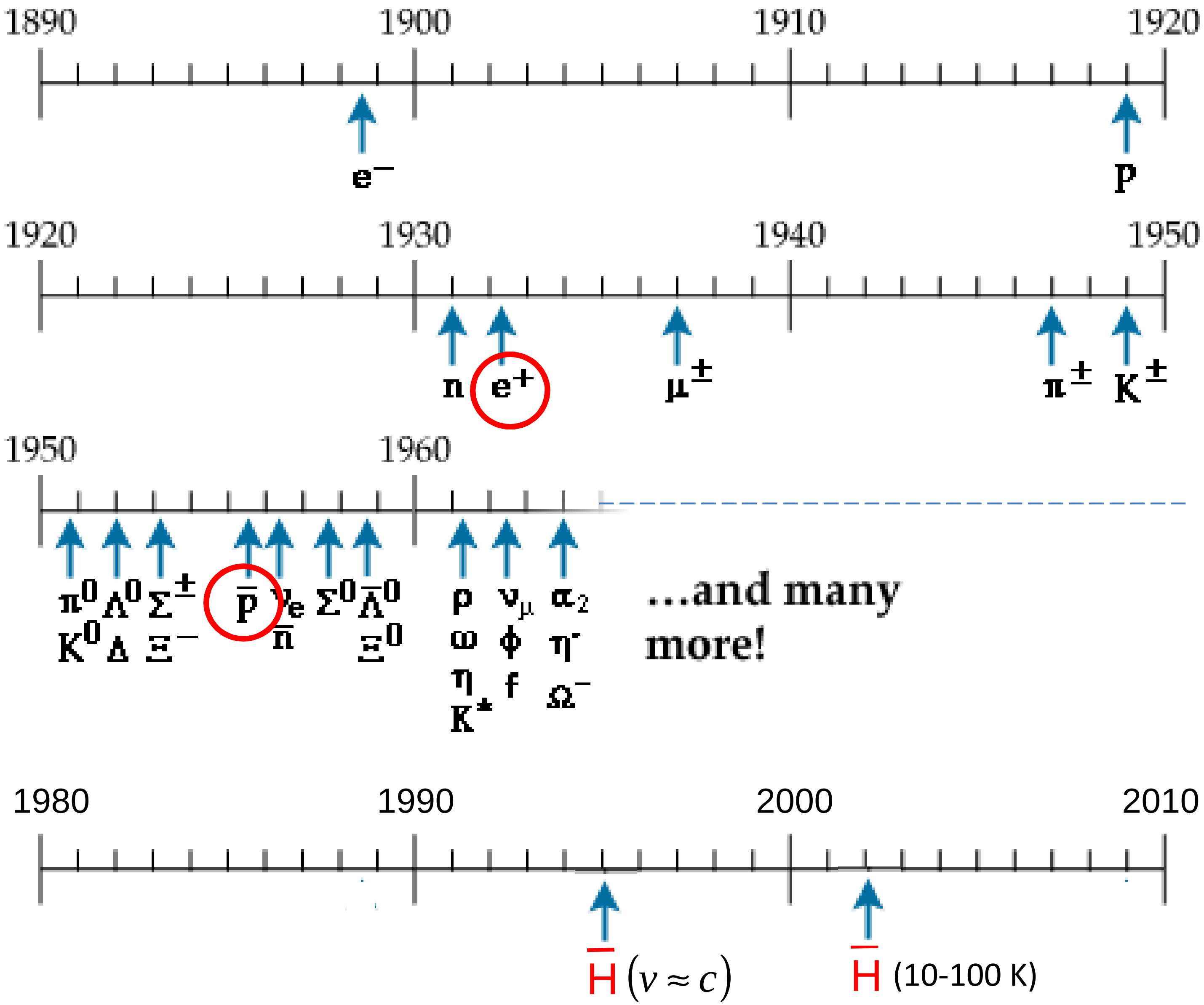
← Expected from CPT

significant milestones achieved
but
no precise measurement so far

Why?

- Annihilations
- Antihydrogen study is young

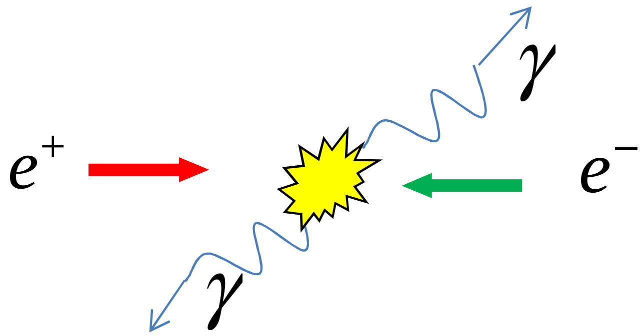
Antihydrogen history is young



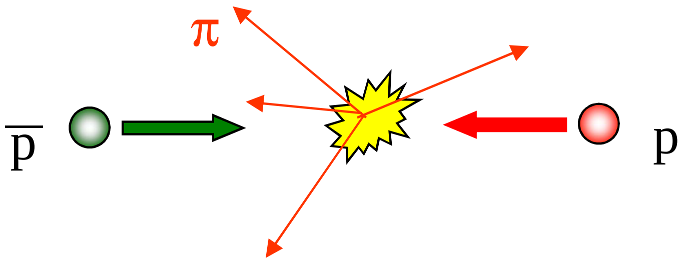
Annihilation

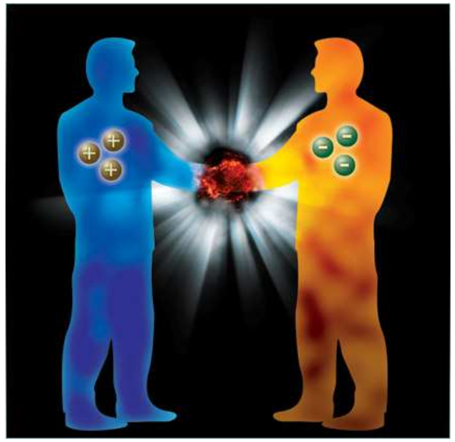
Matter-antimatter encounter → annihilation

Ex.1 electron-positron collision



Ex.2 proton-antiproton collision





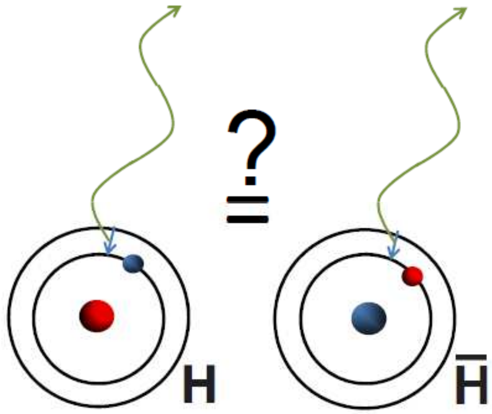
Mass converted into energy

$$E = mc^2$$

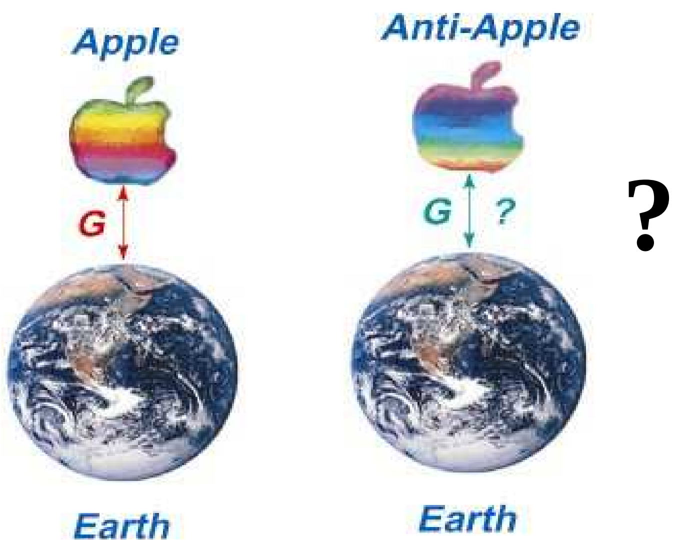
N.B. Pair production (inverse process of annihilation) permits antimatter production

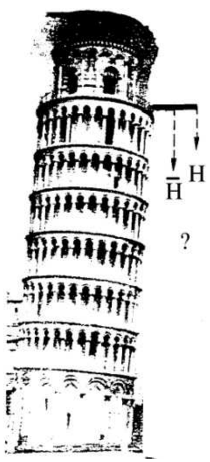
Why study antihydrogen

1) Precise matter/antimatter comparison→ test of CPT symmetry



2) Measurement of the gravitational behaviour of antimatter→ test of WEP



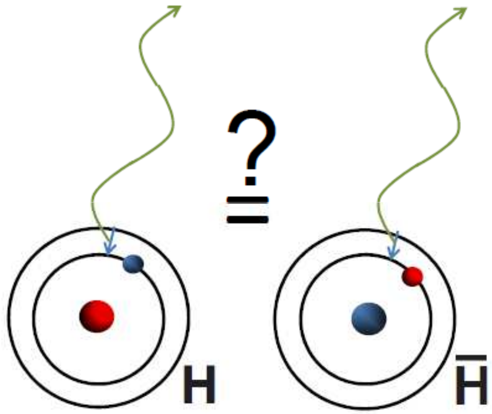


Impossible with charged antiparticle

only with neutral system → $\bar{H}$

Why study antihydrogen

1) Precise matter/antimatter comparison→ test of CPT symmetry



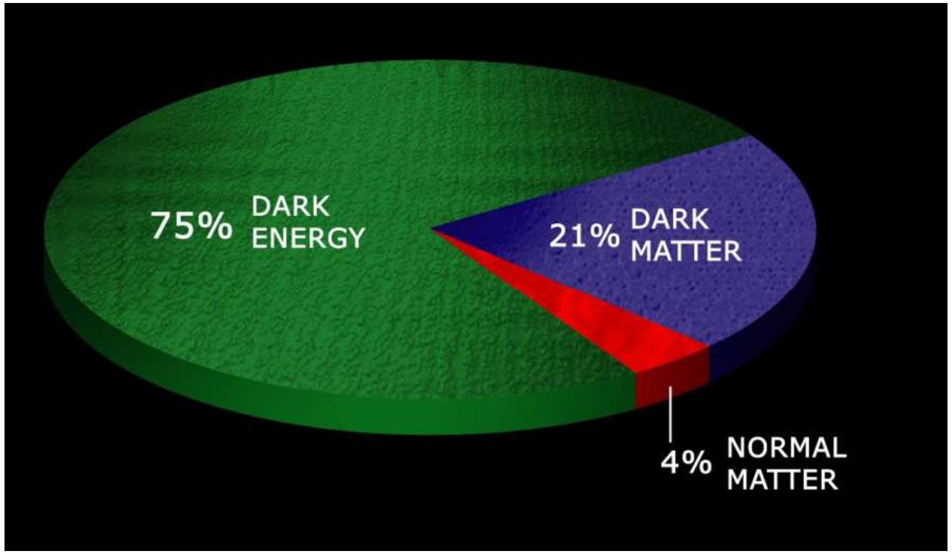
2) Measurement of the gravitational behaviour of antimatter→ test of WEP

… antiparticle

…utral system → $\bar{H}$

Not discussed here

Matter/antimatter asymmetry in the Universe

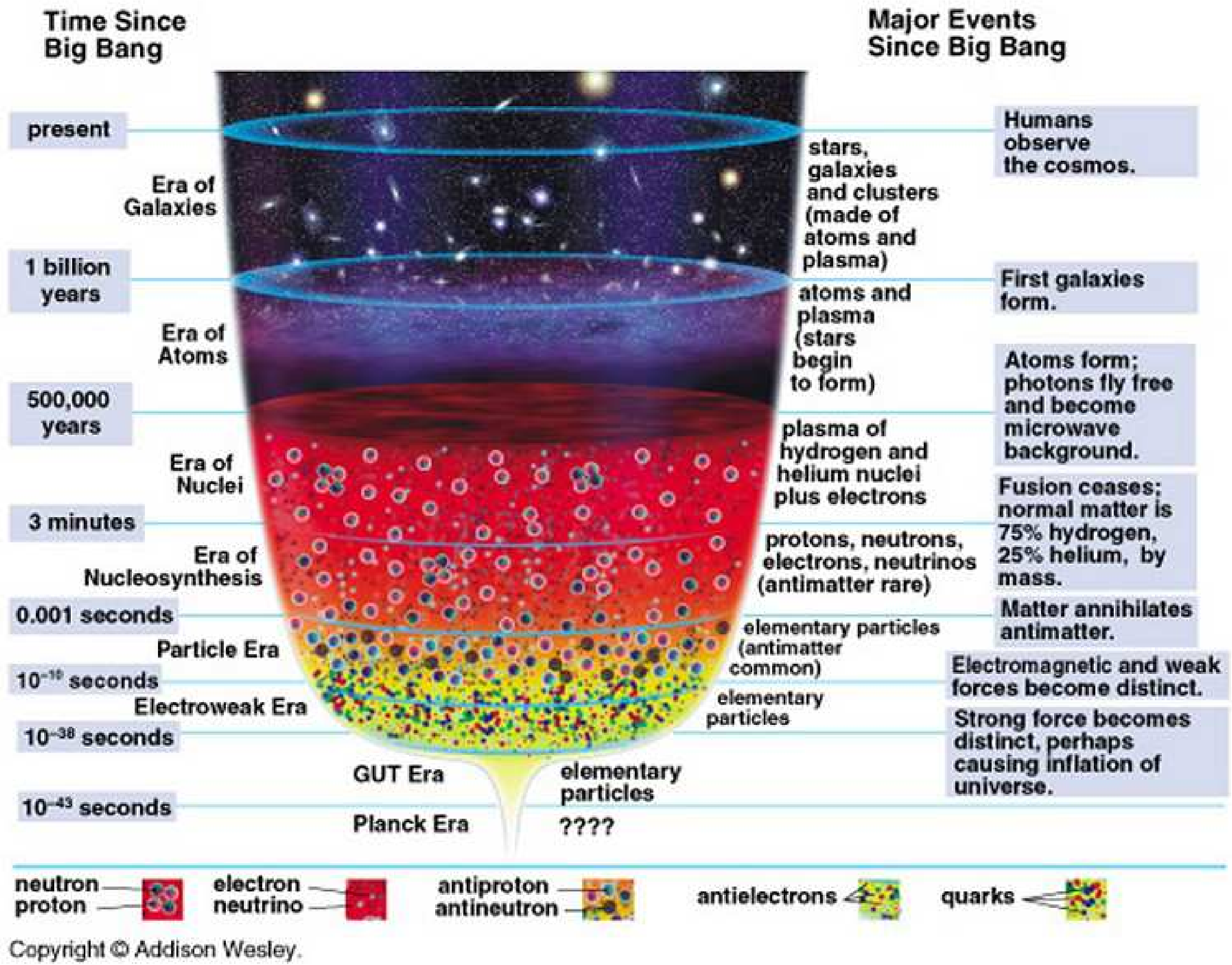


Positrons and antiprotons in the cosmics rays are compatible with secondary production (made in the matter collision with the interstellar medium)

Earth, Moon and planets made of matter

The visible Universe is made of matter

No primordial antimatter detected



$t \approx 0$ equal quantity of matter and antimatter ← expected from symmetry!?

$t < 0.001$ s All antimatter disappeared and only (part of) matter (and we) survive

Possible explanations rely on the fundamental symmetries violations

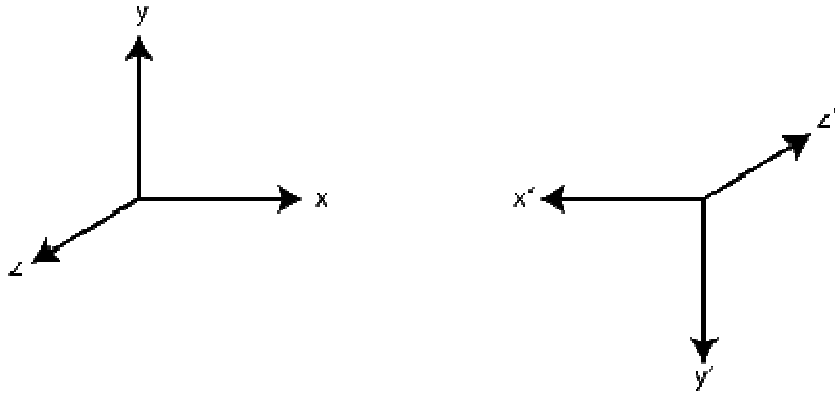
Discrete symmetries: C, P, T

Parity transformation P:

Inversion of the spatial coordinates

$$(x, y, z) \rightarrow (-x, -y, -z)$$

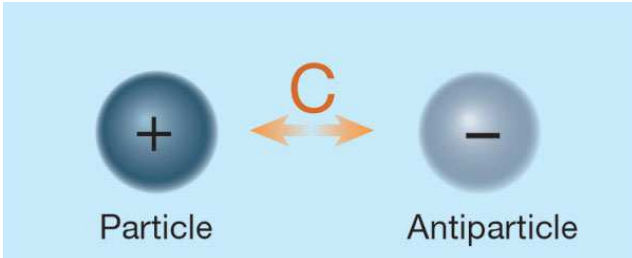
⇔ Mirror reflection



Charge coniugation transformation C:

Change of each additive quantum numbers (for example the electrical charge) in its opposite

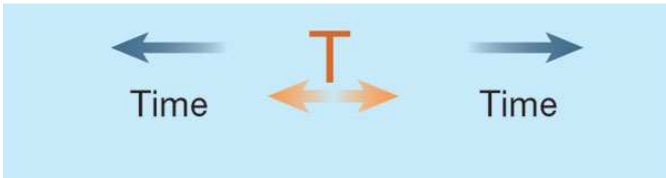
$$q \rightarrow -q$$



Time reversal transformation T:

Change the time arrow

$$t \rightarrow -t$$



Violations of the discrete symmetries

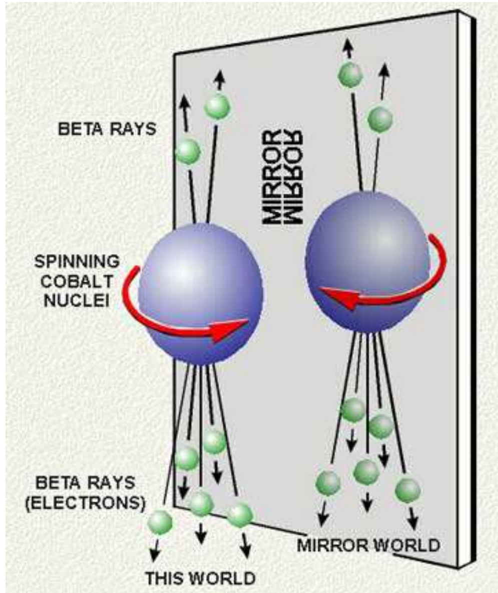
In the past C, P and T transformations were believed to be exact symmetries

But for Weak interaction :

Parity violation

Suggested by Lee & Yang (1956)

β-decay experiment by Wu et al (1957)



CP violation (1964)

K_0 decays by Cronin & Fitch (1964)

The CPT theorem

50's – Pauli, Schwinger , Lüders, Jost

The **CPT** theorem (1954): **"Any Lorentz-invariant local quantum field theory is invariant under the successive application of C, P and T"**

Assumptions:

- flat space-time, Lorentz-invariance, local interactions, unitarity, point-like particles

Consequences:

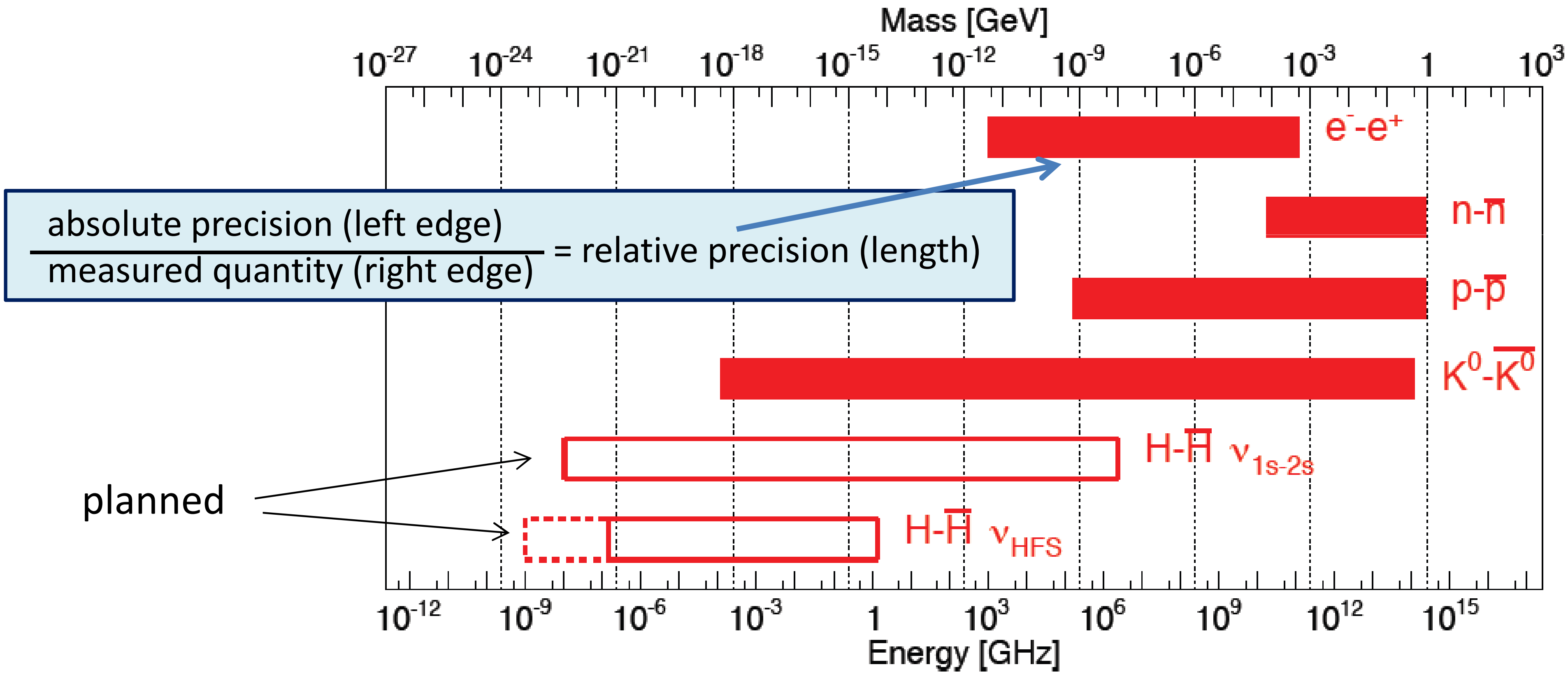
- particle/antiparticle: equal mass, lifetime; equal and opposite charge and magnetic moment
- **atom/antiatom: identical energy levels**

CPT invariance is inside the Standard Model

In string theory (and quantum gravity): assumptions non valid
→ CPT violations as a signature of string theory?

No measurement of CPT violation exists

CPT tests: relative & absolute precisions

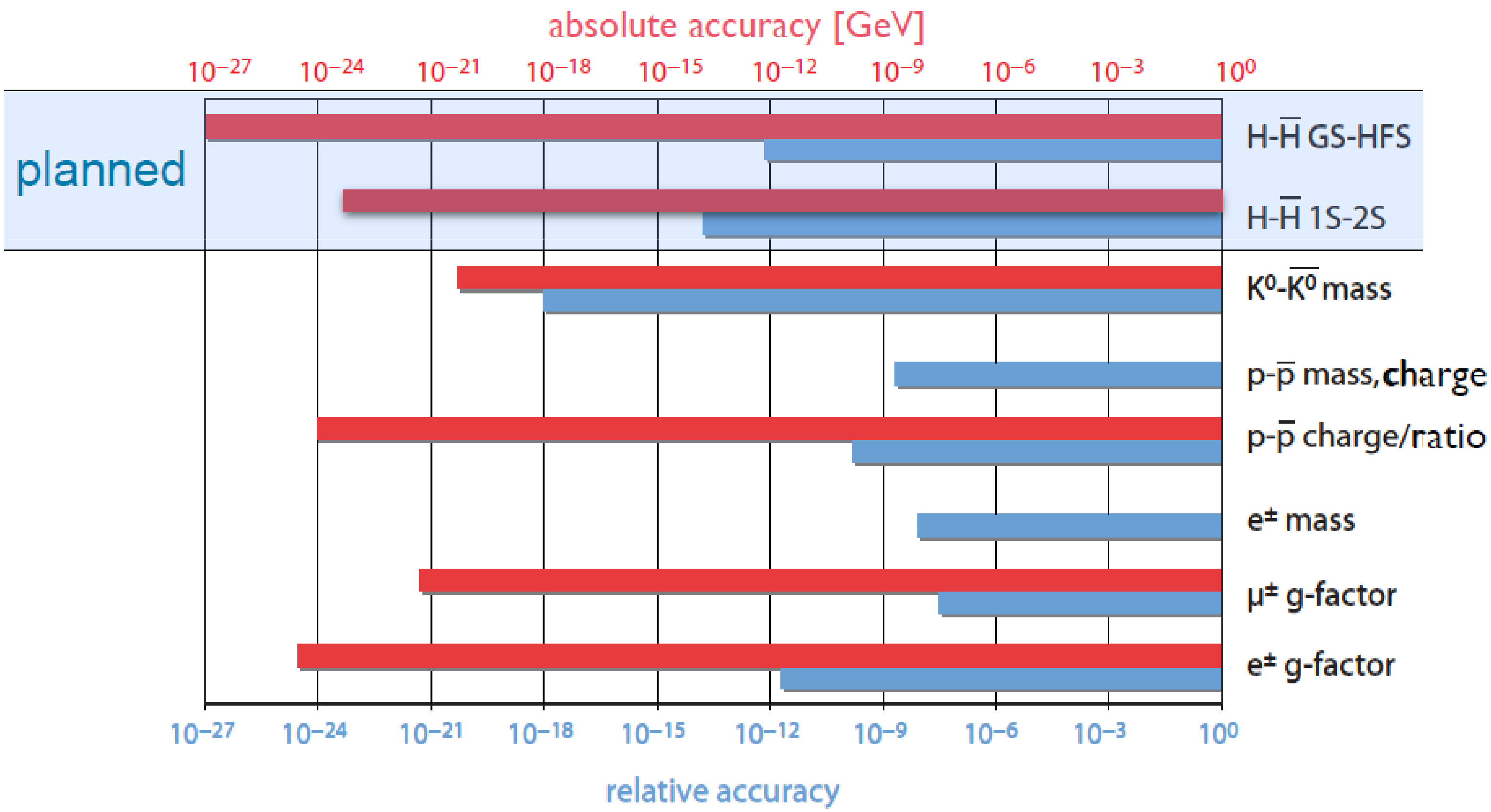


Considered "best CPT test": $K^0 - \overline{K}^0$ $\Delta m/m \sim 10^{-18} \Leftrightarrow 10^5$ Hz

but absolute precision could be relevant …→ $H - \overline{H}$ highly competitive

Where CPT violation might appear is unknown

Test of CPT symmetry



CPT violation in Standard Model Extension

Indiana group, Kostelecky et al. (since 1997)

Standard Model can be extended with CPT violation

Standard Model Extension (SME) is an effective field theory which contains:
- General Relativity
- Standard Model
- Possibility of Lorentz Invariance Violation
- CPT violation comes with Lorentz violation

Modified Dirac equation

CPT Violating terms

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu} \sigma^{\mu\nu} + i c^e_{\mu\nu} \gamma^\mu D^\nu + i d^e_{\mu\nu} \gamma_5 \gamma^\mu D^\nu)\psi = 0$$

R.Bluhm, A.Kostelecky, N.Russell, **Phys. Rev. Lett. 82, 2254 (1999)**

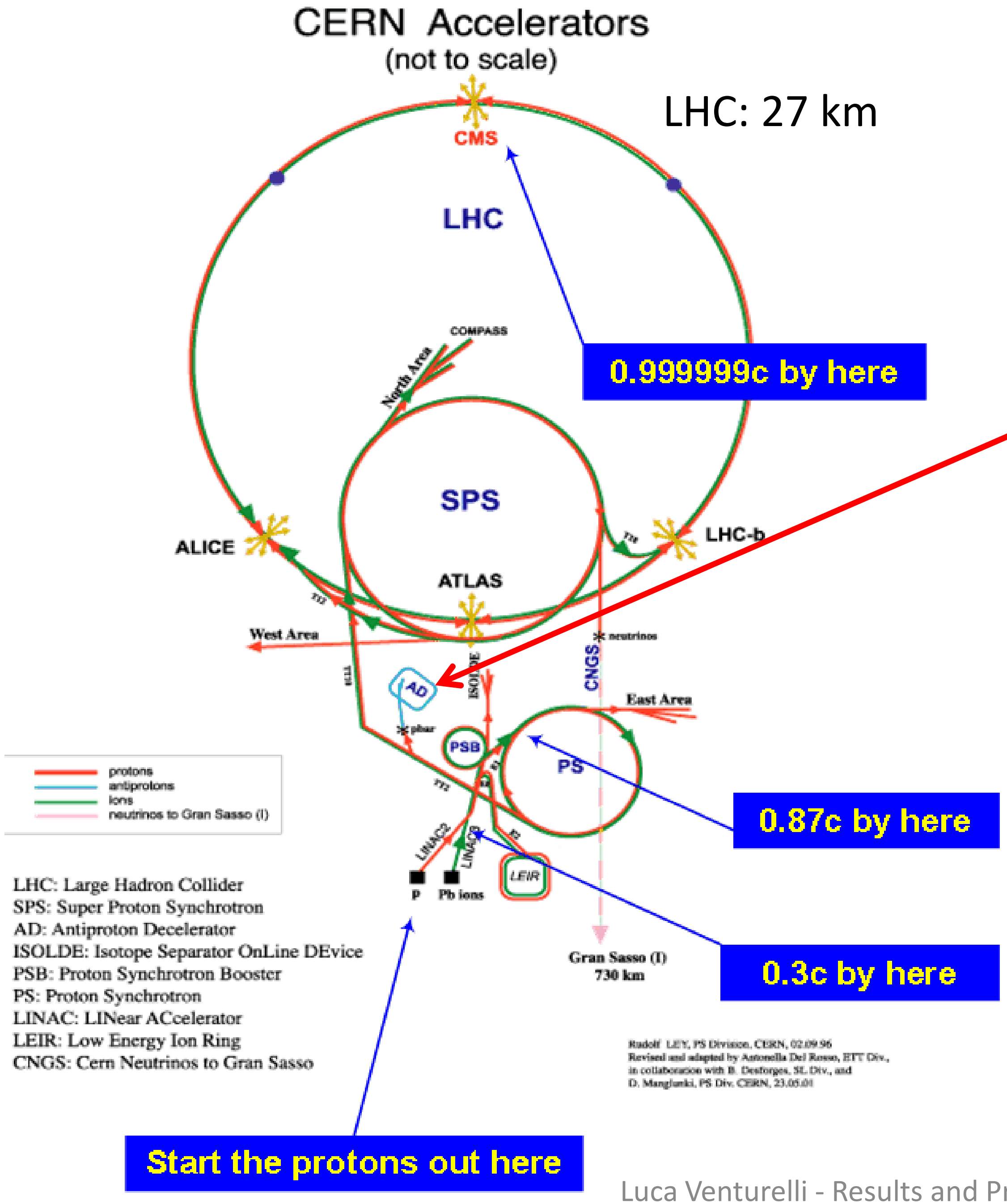
Lorentz Invariance Violating terms

- a & b have energy dimensions (→ absolute comparisons are important)

- No quantitative prediction

Antihydrogen formation

CERN Accelerators



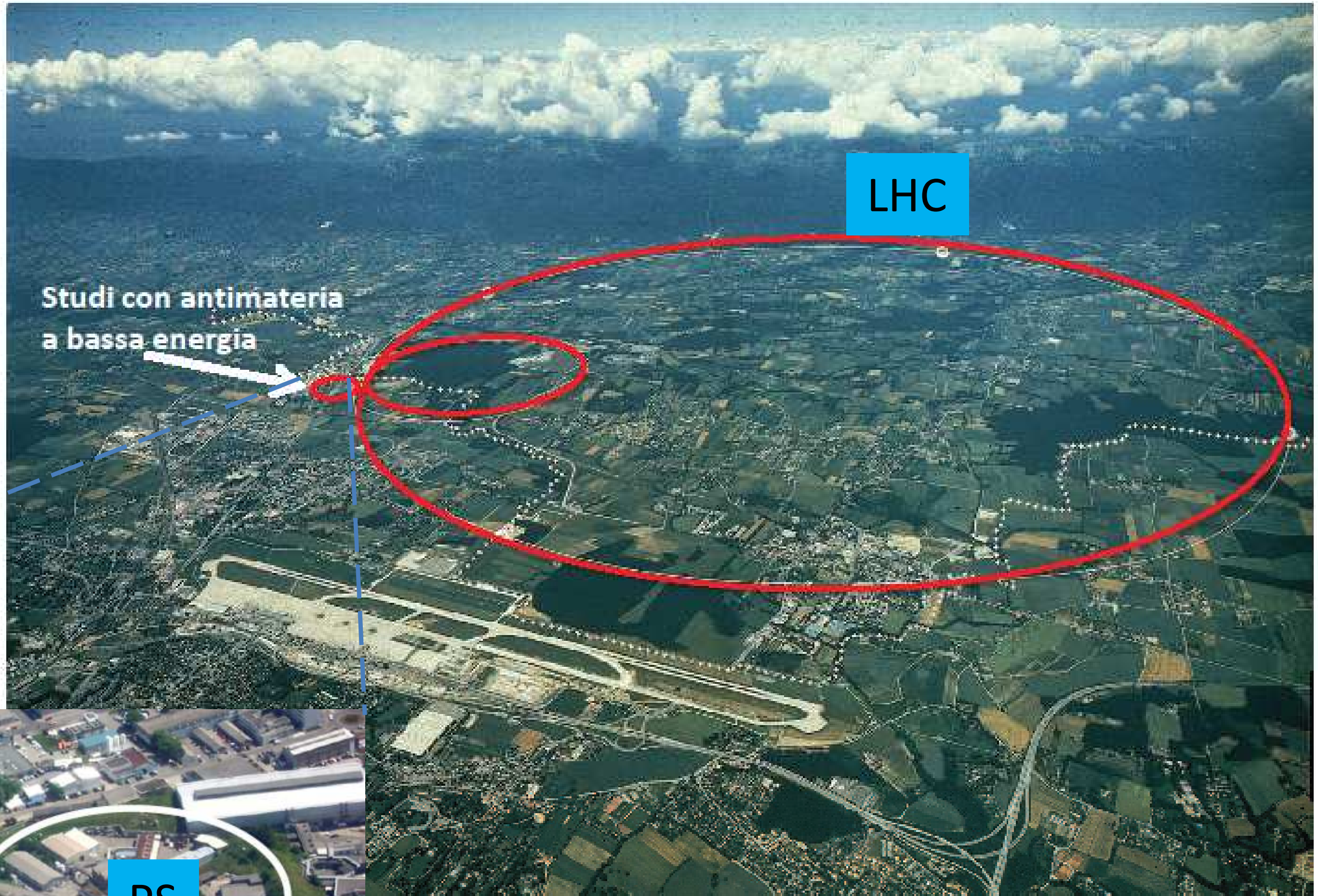
Antihydrogen experiments at AD (Antiproton Decelerator)

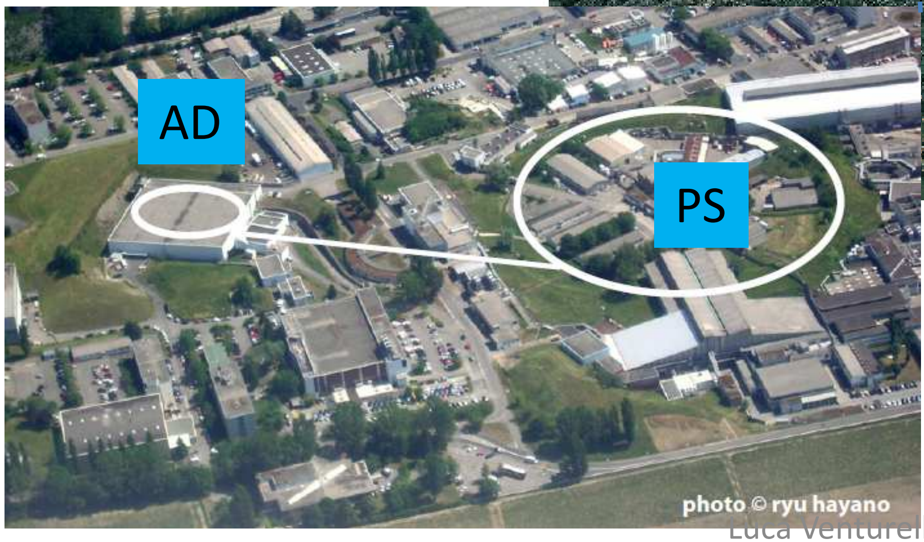
AD: 188 m

Protons:

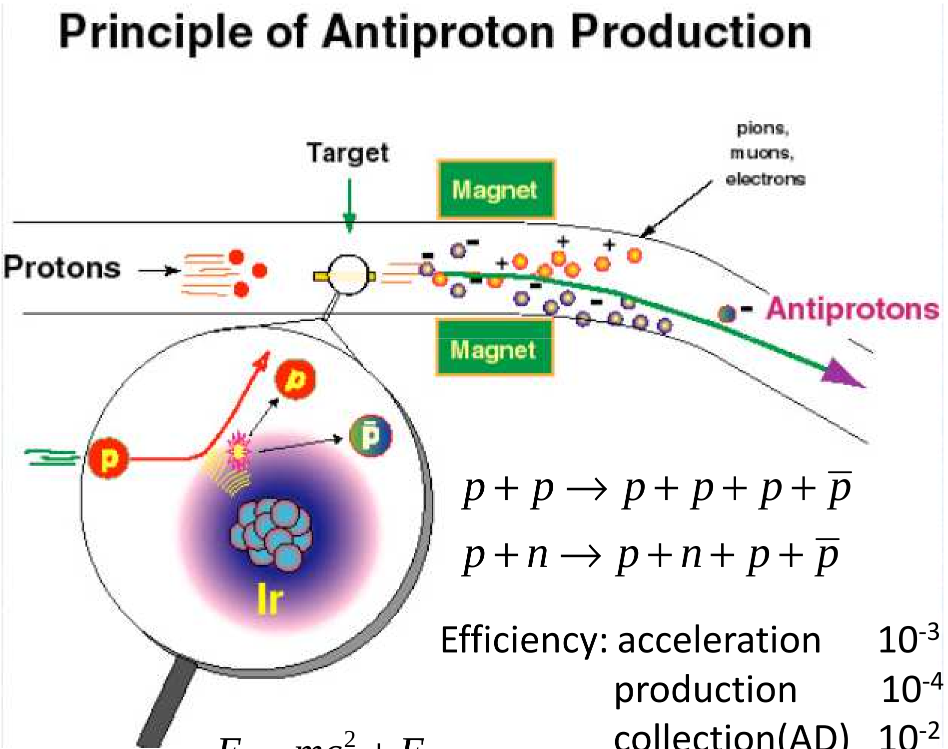
Linac2 (50 MeV)
->ProtonSyncrotonBooster(1.4 GeV)
->ProtonSyncroton(25GeV)
->AD(:antiprotons)

Antihydrogen factory





Antiproton Decelerator-AD

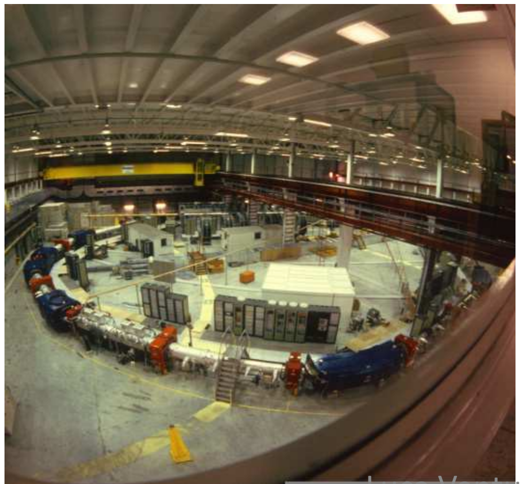


$$p + p \rightarrow p + p + p + \overline{p}$$

$$p + n \rightarrow p + n + p + \overline{p}$$

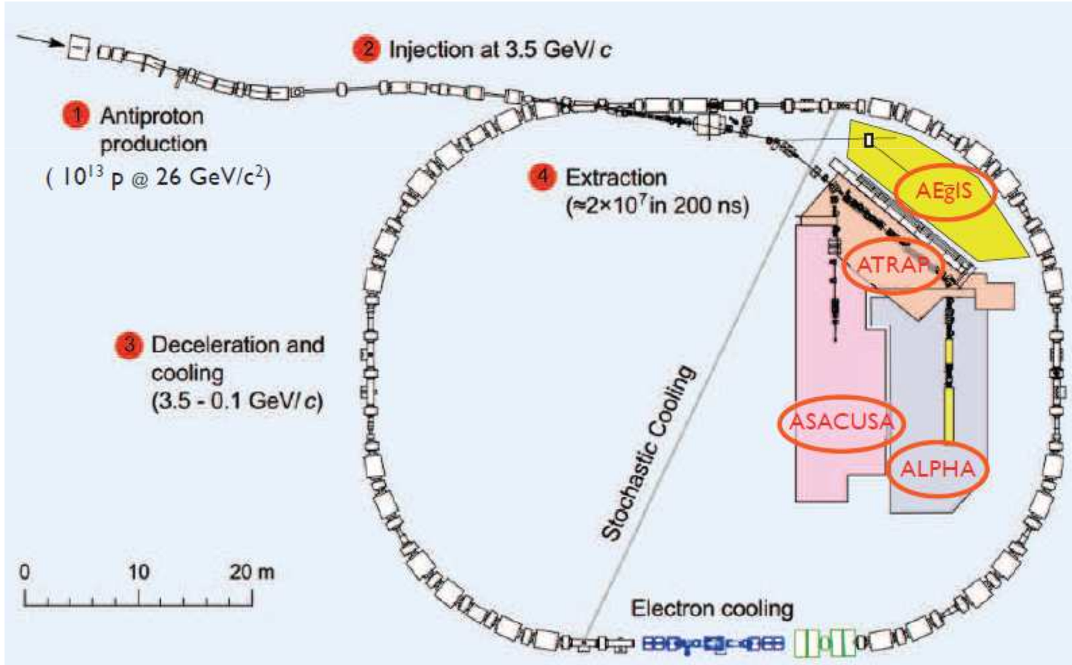
$$E = mc^2 + E_K$$

Efficiency:	
acceleration	10^{-3}
production	10^{-4}
collection(AD)	10^{-2}
total	10^{-9}



AD is the only source of low-energy antiprotons

All-in-one machine: antiproton capture , deceleration & cooling



AD delivers to the experiments :

- 2-4 10^7 antiprotons per bunch (150-300 ns length)
- 1 bunch/ 100 s
- Energy = 5.3 MeV (100 MeV/c)

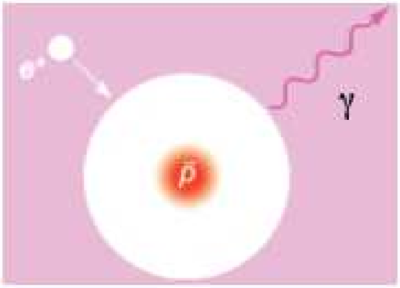
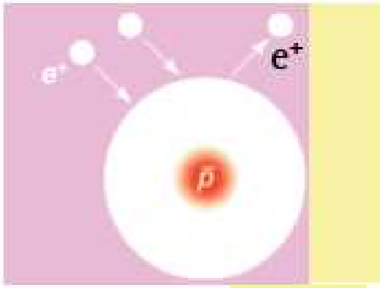
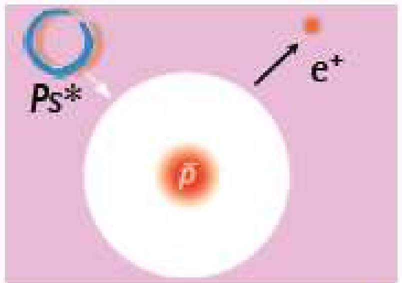
The experiments at AD

Experiments: - (2014) ALPHA, ATRAP, ASACUSA, ACE, AEgIS, BASE

- ATHENA (terminated), GBAR (future)

How to form antihydrogen

Recombination processes

	Radiative recombination $\bar{p}+e^{+}\rightarrow\bar{\mathrm{H}}+h\nu$	Three-body recombination $\bar{p}+e^{+}+e^{+}\rightarrow\bar{\mathrm{H}}+e^{+}$	Two-stage charge exchange $Ps^{*}+\bar{p}\rightarrow\bar{H}^{*}+e^{-}$
Principle			
Temperature dependence	$\propto T^{-2/3}$	$\propto T^{-9/2}$	$\propto T^{-x}$
e+ density dependence	$\propto n_e$	$\propto n_e^2$	
Cross section at 1K	10^{-16} cm^2	10^{-7} cm^2	10^{-9} cm^2
Final internal states	$\nu<10$	$\nu>>10$	$\phi(n_{Ps})$
Expected rates	few Hz	high	1Hz (?)

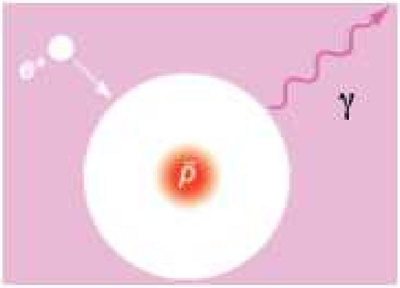
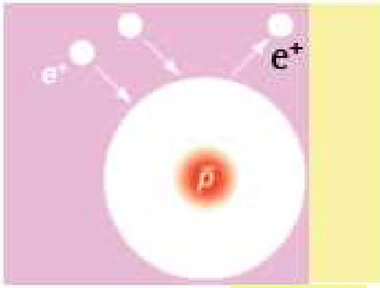
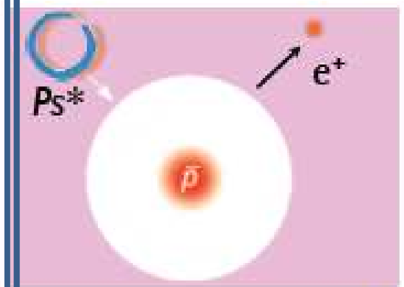
How to form antihydrogen

Recombination processes

ATHENA, ALPHA, ATRAP, ASACUSA

ATRAP, AEGIS

Superposition of e+ plasma and pbar cloud

	Radiative recombination	Three-body recombination	Two-stage charge exchange
	$\bar{p} + e^{+} \rightarrow \bar{\mathrm{H}} + h\nu$	$\bar{p} + e^{+} + e^{+} \rightarrow \bar{\mathrm{H}} + e^{+}$	$\mathrm{Ps}^{*} + \bar{p} \rightarrow \bar{\mathrm{H}}^{*} + e^{-}$
Principle			
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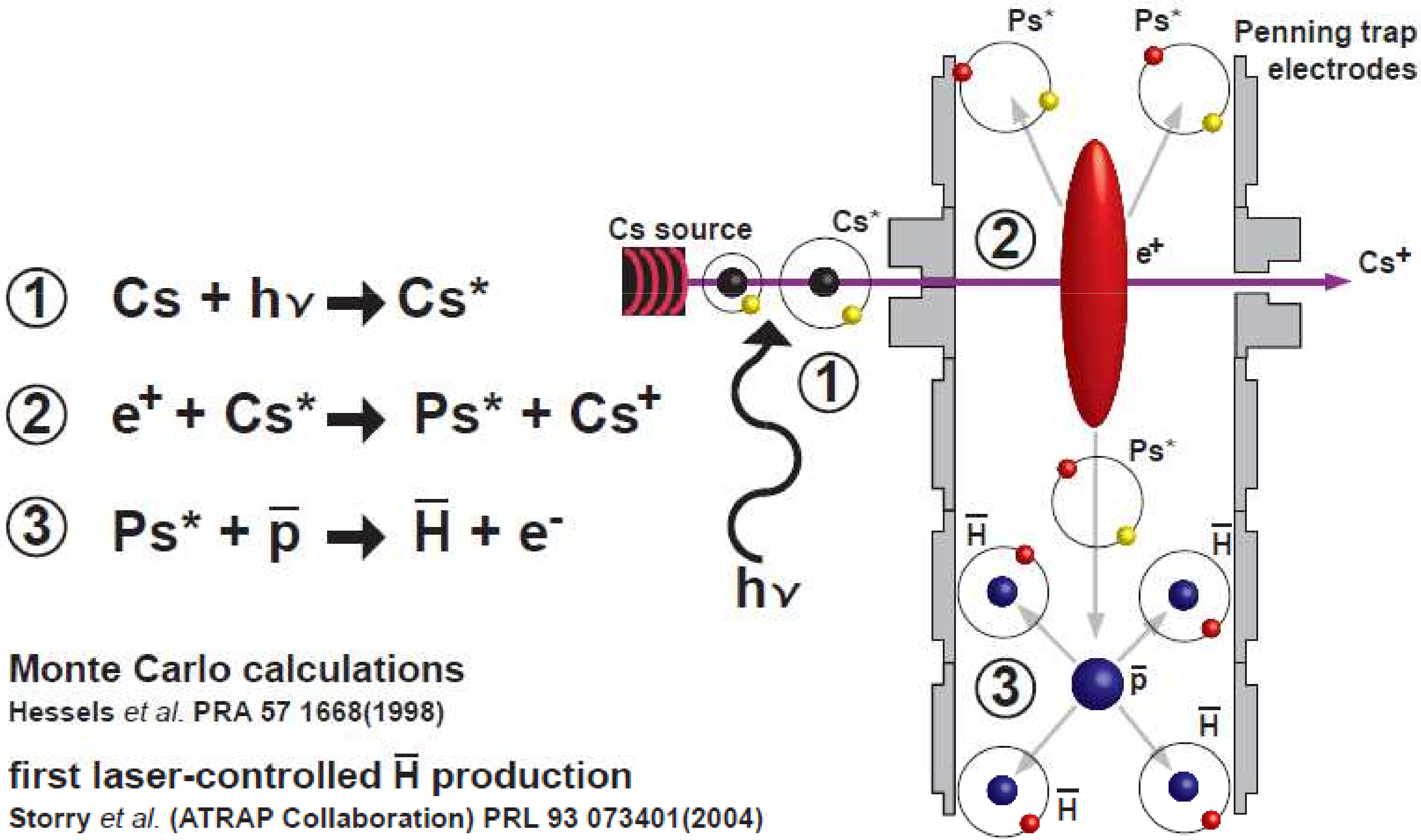
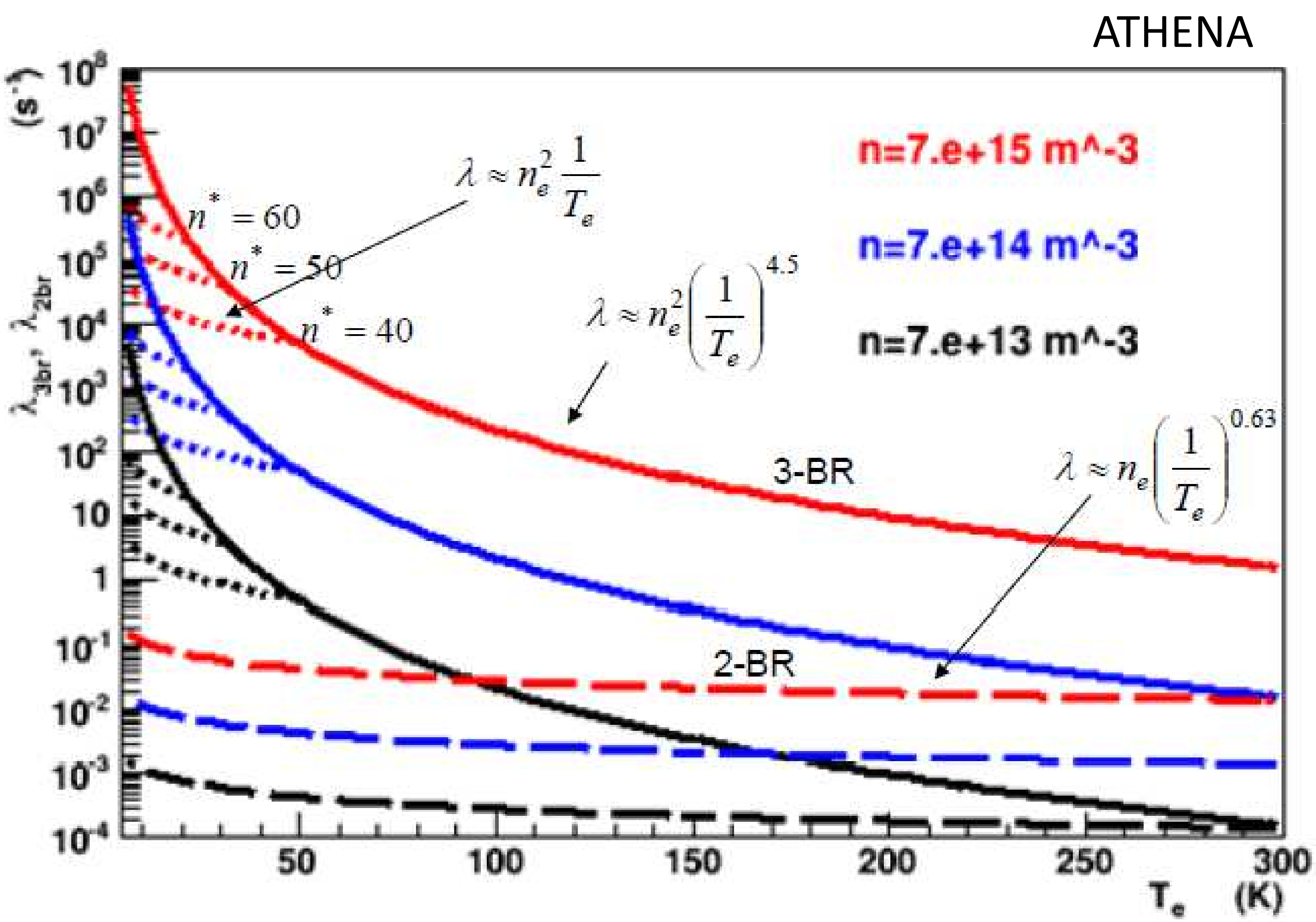
Two-stage charge exchange

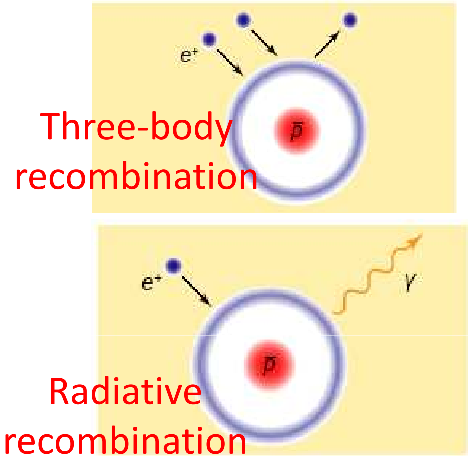


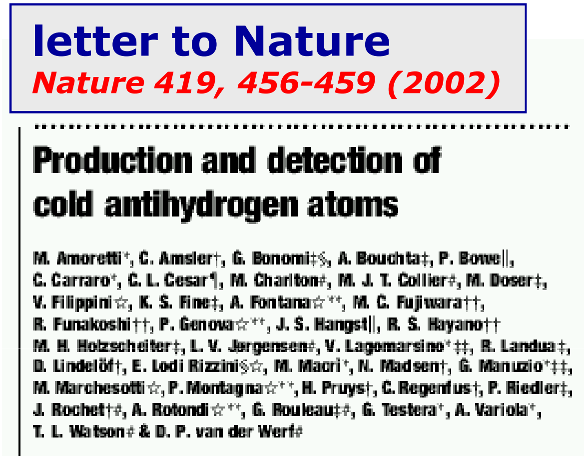
-Cold antihydrogen (← antiproton at rest)
- antihydrogen n-state can be controlled by laser (n-antihydrogen=n- Cs*)

Radiative and 3-body recombination rates



Typical antihydrogen experiment: ATHENA





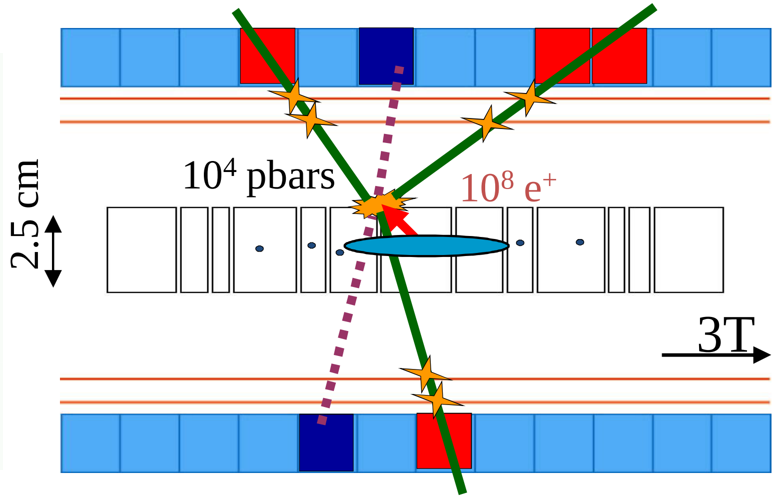
letter to Nature

Nature 419, 456-459 (2002)

Production and detection of cold antihydrogen atoms

M. Amoretti*, C. Amsler†, G. Bonomi‡§, A. Bouchta‡, P. Bowe||, C. Carraro*, C. L. Cesar¶, M. Charlton#, M. J. T. Collier#, M. Doser‡, V. Filippini☆, K. S. Fine‡, A. Fontana☆**, M. C. Fujiwara††, R. Funakoshi††, P. Genova☆**, J. S. Hangst||, R. S. Hayano†† M. H. Holzscheiter‡, L. V. Jørgensen#, V. Lagomarsino*‡‡, R. Landua‡, D. Lindelöf†, E. Lodi Rizzini§☆, M. Macri*, N. Madsen†, G. Manuzio*‡‡, M. Marchesotti☆, P. Montagna☆**, H. Pruys†, C. Regenfus†, P. Riedler‡, J. Rochet†#, A. Rotondi☆**, G. Rouleau‡#, G. Testera*, A. Variola*, T. L. Watson# & D. P. van der Werf#

First cold antihydrogens



antiprotons ← from AD

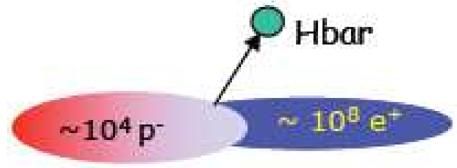
positrons ← from the experiment with radioactive sources (^{22}Na: 400 M e+ /s)

Procedure:

1) Trapping and cooling of antiprotons — 10^7 (AD) → 10^4-10^5 (trapped)

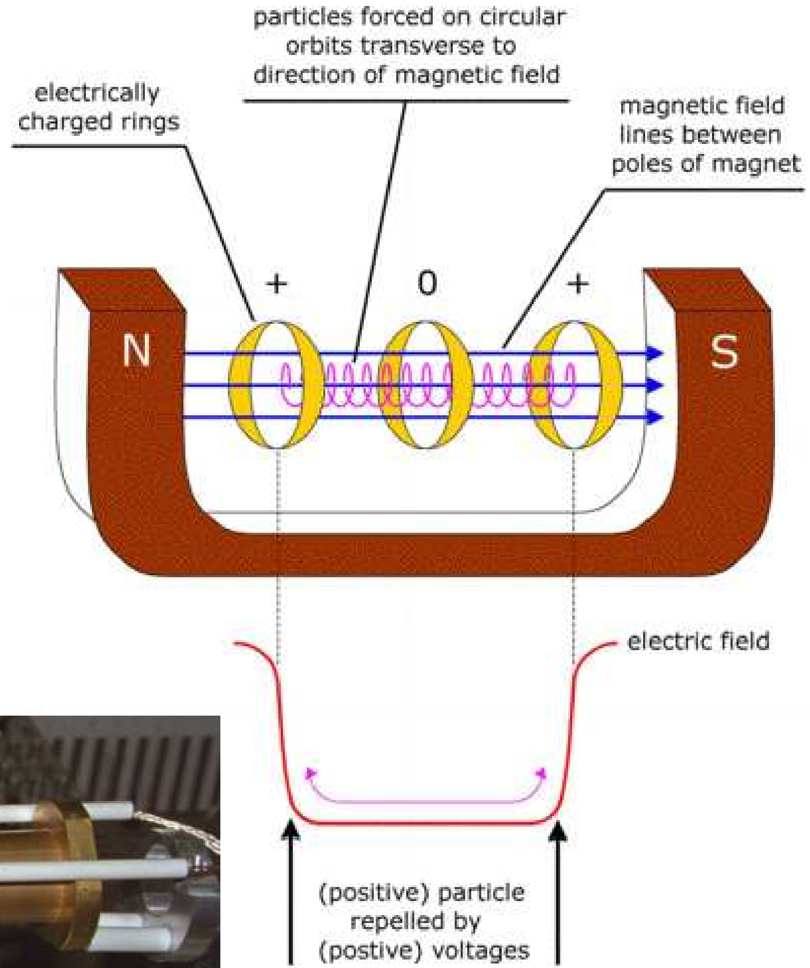
2) Trapping and cooling of positrons — 1.5 GBq ^{22}Na → 10^8 (trapped)

3) antiprotons & positrons mixing to form antihydrogens — 1-1000 Hz



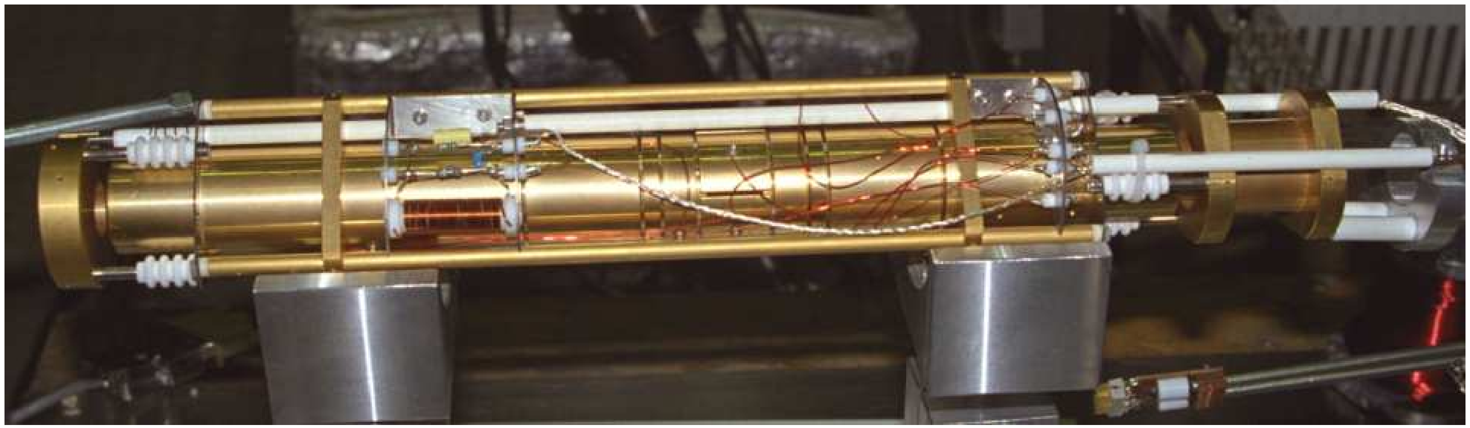
(charged) antimatter trap

Charged particles are confined by:
radially by **B** and longitudinally by **E**

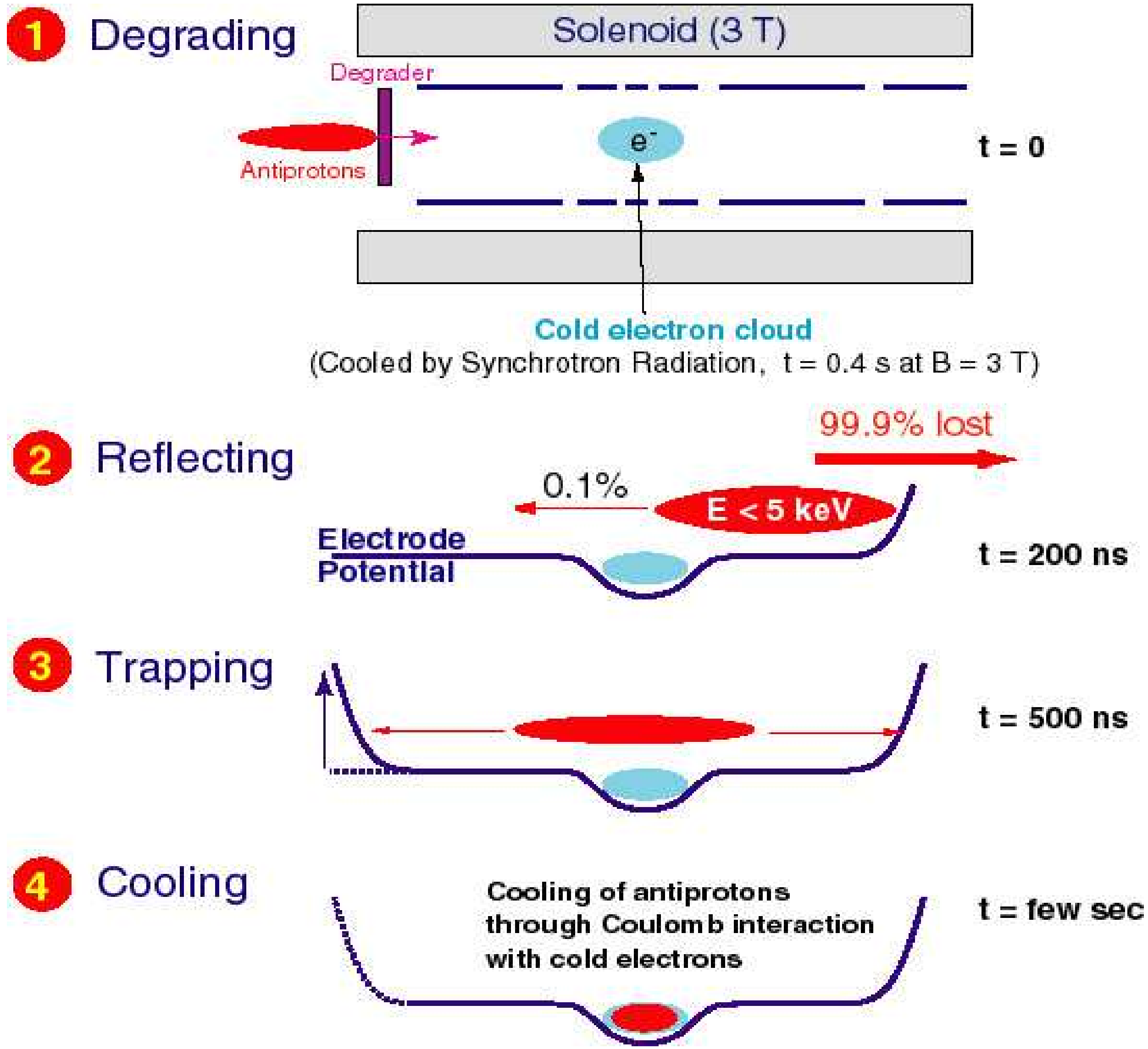


Penning trap

ATHENA trap(2002):



Trapping and cooling of antiprotons

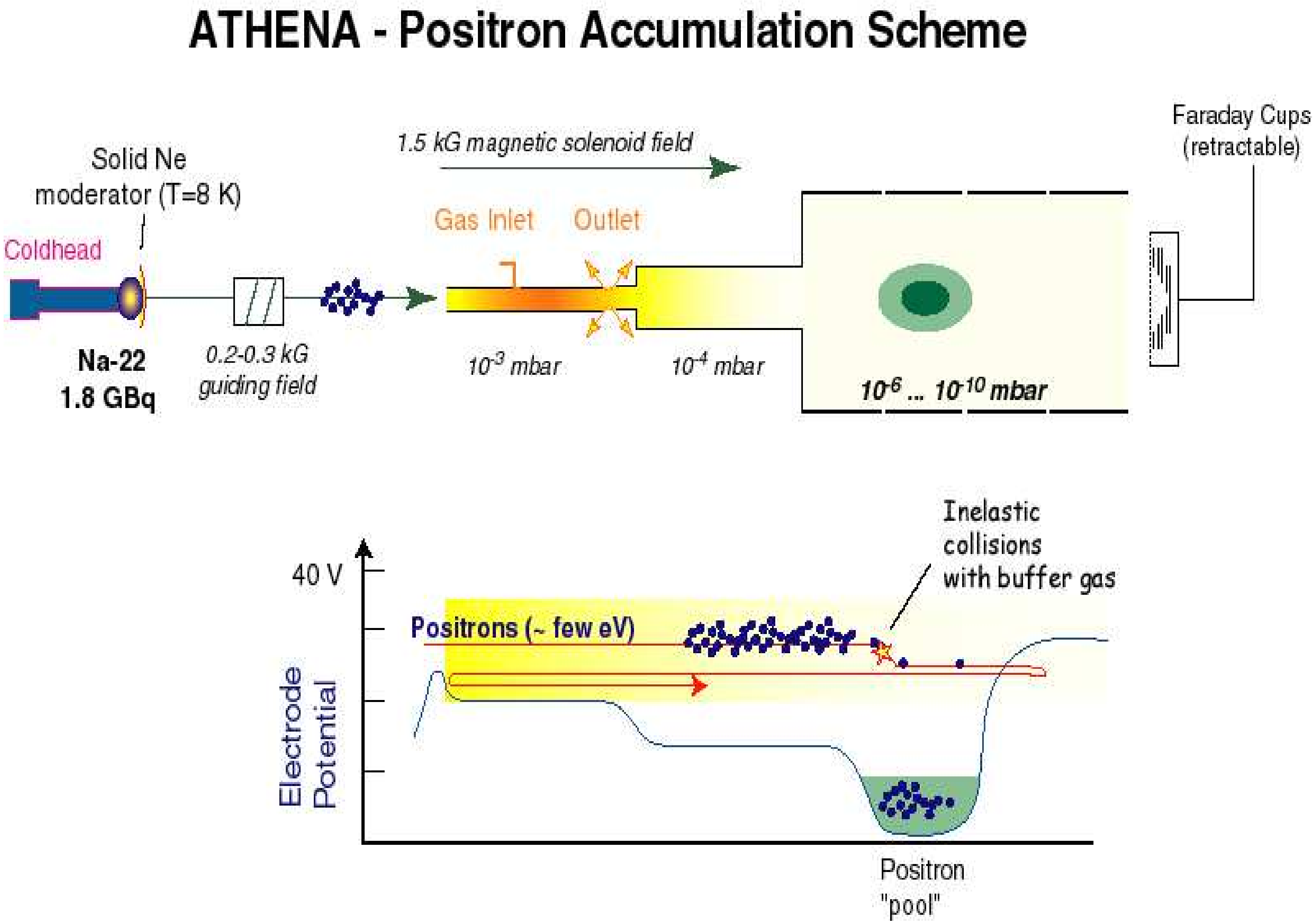


T=15 K

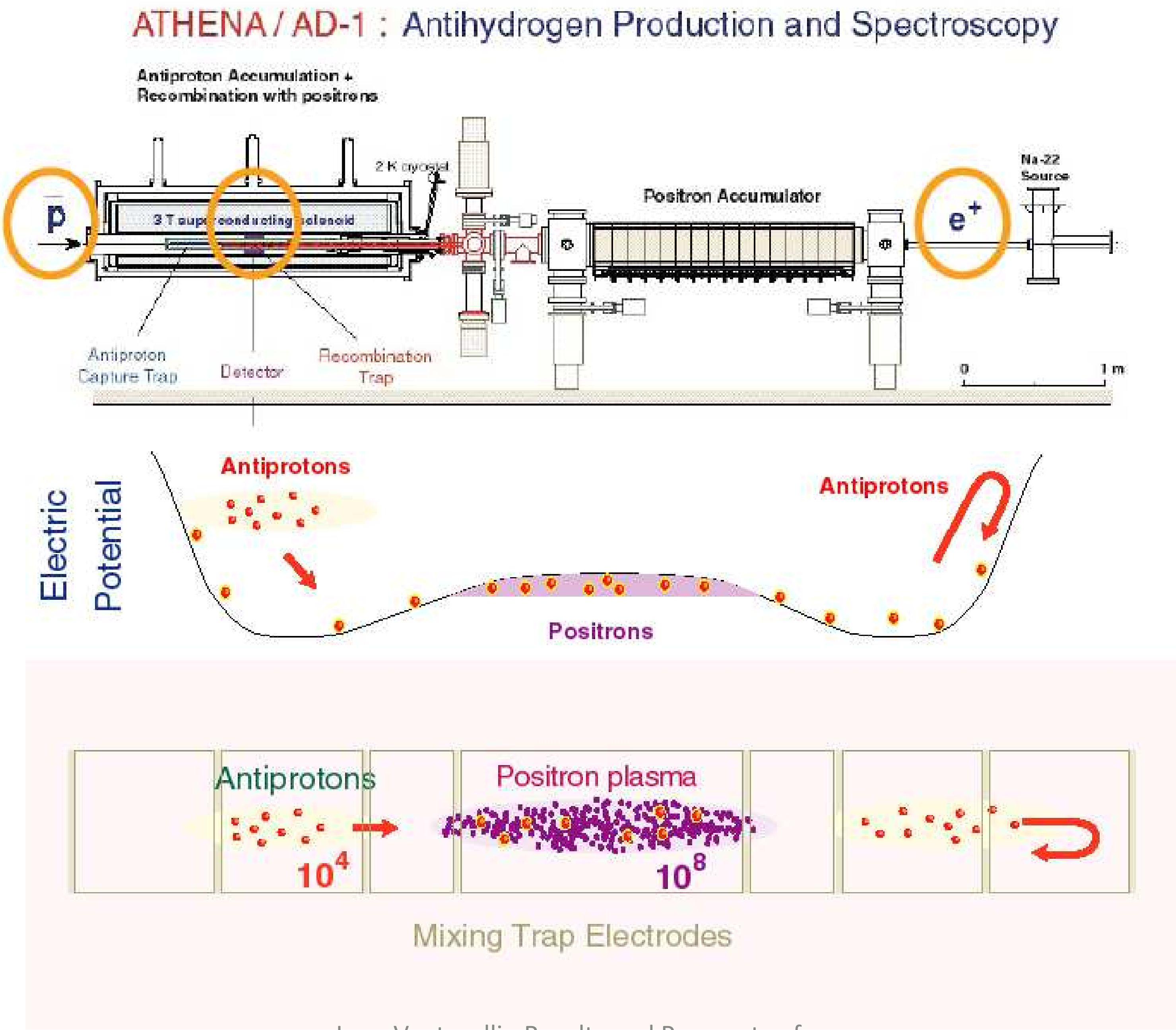
p<10^{-12} mb

Technique developed by TRAP Collaboration

Trapping and cooling of positrons



Antiprotons and positrons mixing



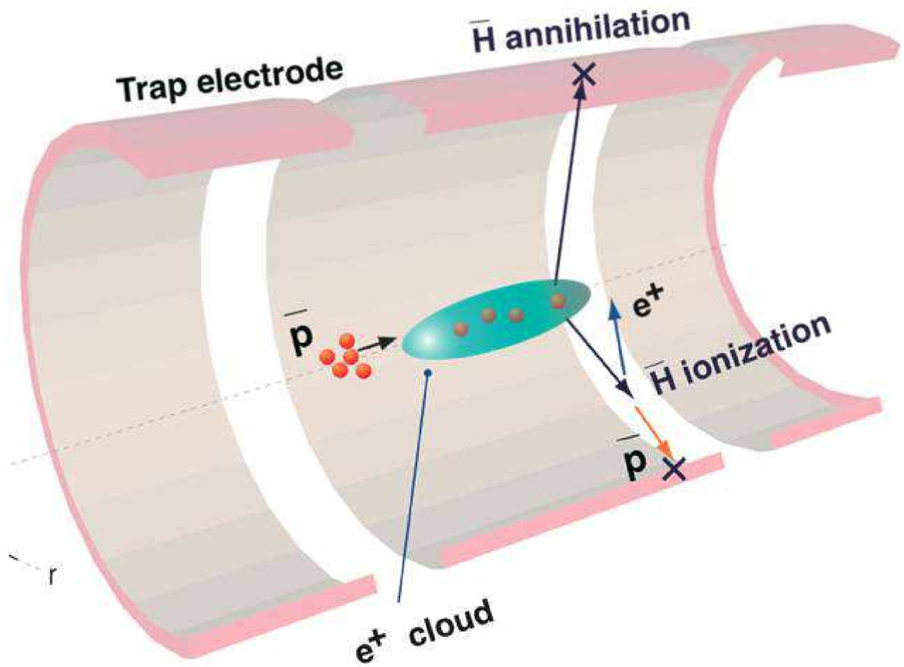
Antihydrogen formation

When antiprotons and positrons have similar velocities

$$\overline{p} + e^{+} + e^{+} \rightarrow \overline{\mathrm{H}} + e^{+}$$

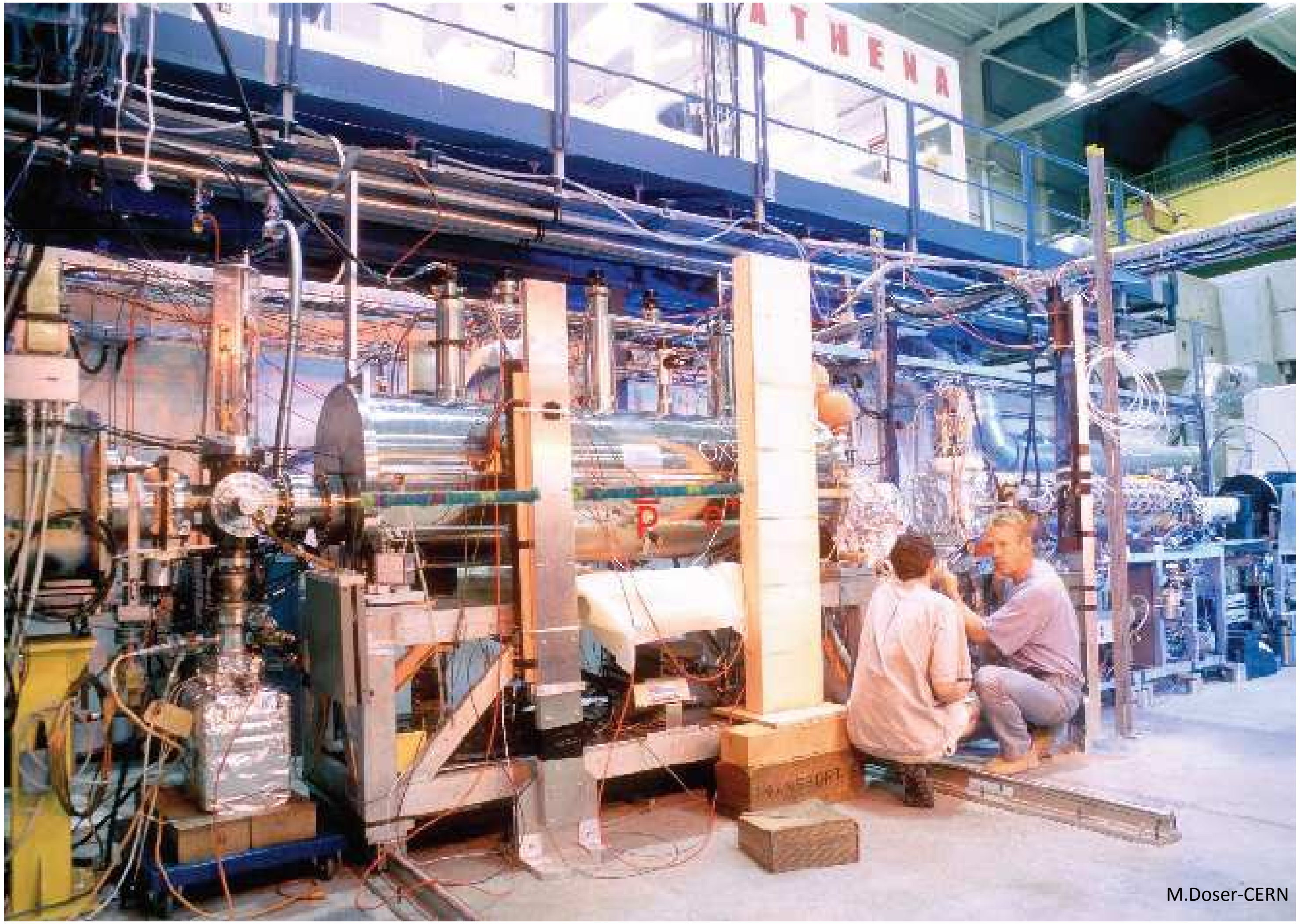
$$\overline{p} + e^{+} \rightarrow \overline{\mathrm{H}} + h\nu$$

Antihydrogen escapes from the trap centre and annihilates on the trap wall



Antihydrogen detection

ATHENA

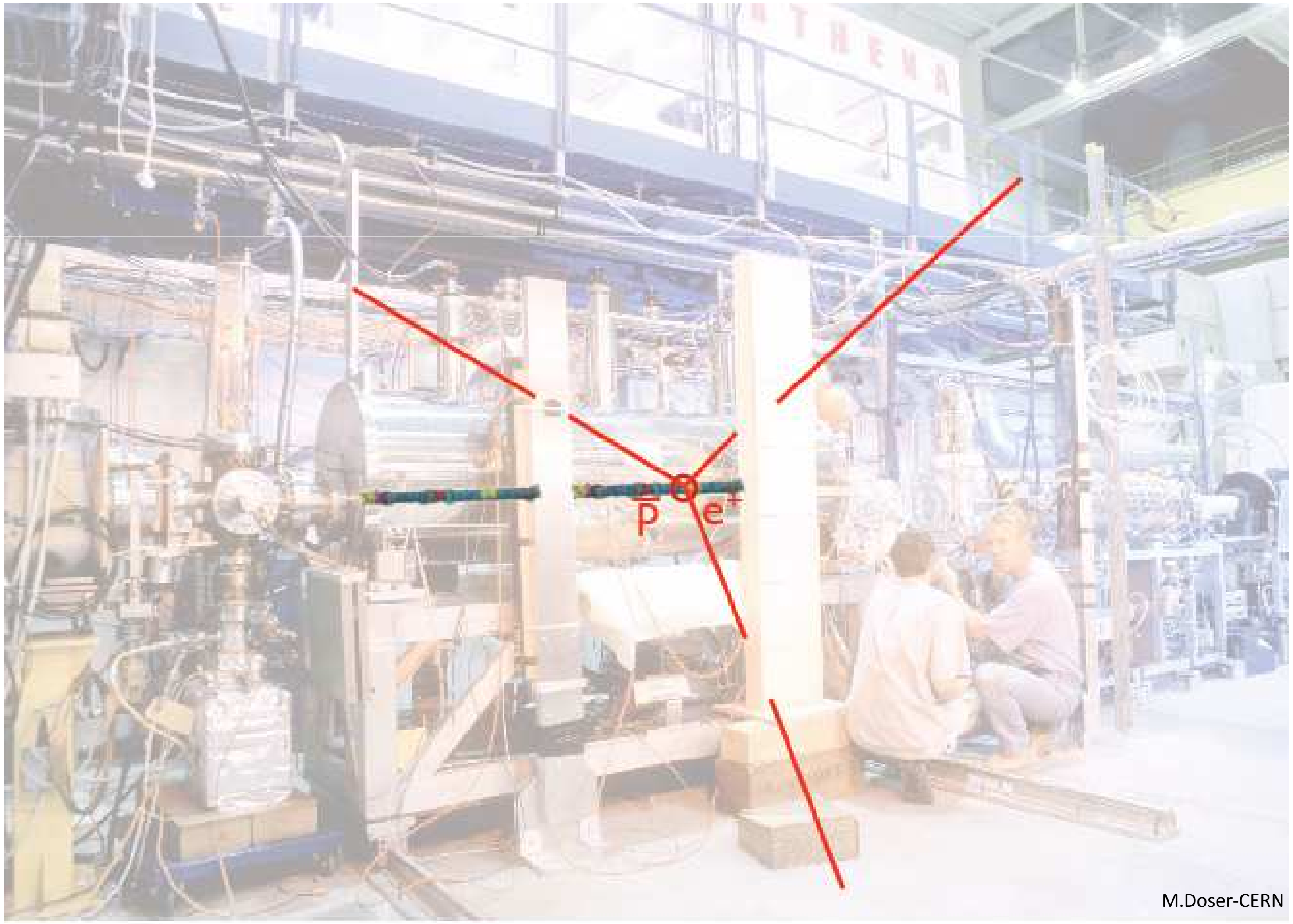


Antihydrogen detection

ATHENA

Antihydrogen detection

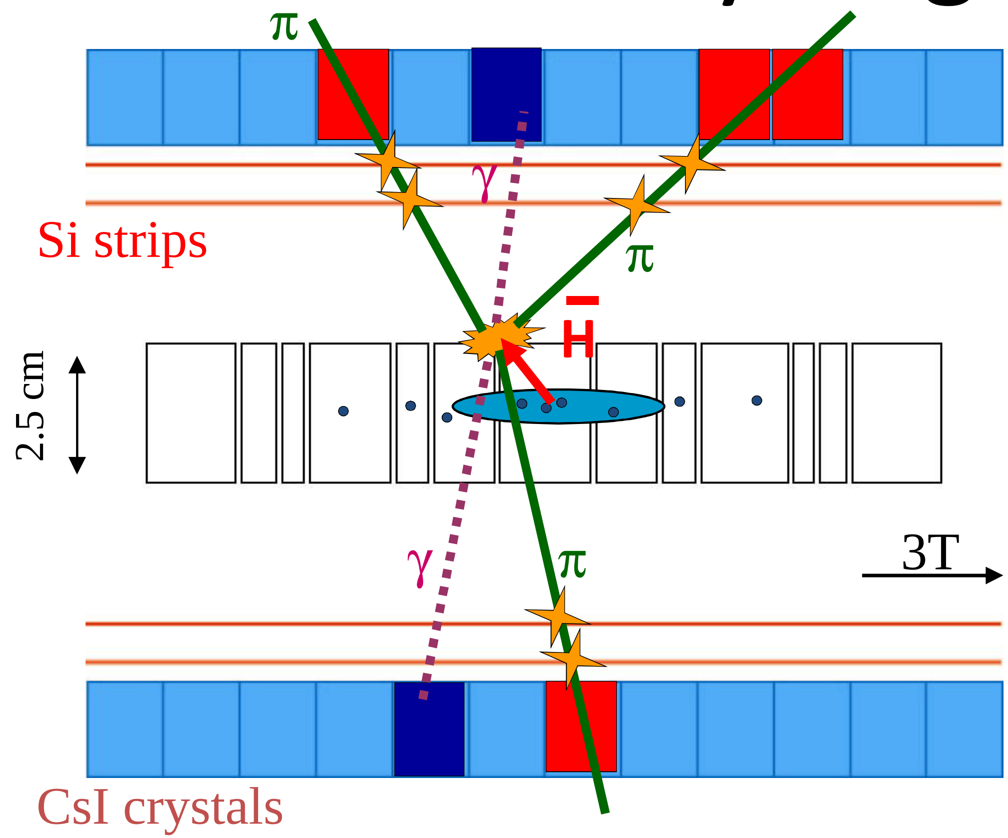
ATHENA



First antihydrogen detection (2002)

Millions of antihydrogens produced

Antihydrogen detection



- $10^4\ \bar{p}$ & $10^8\ e^+$ are mixed in Penning trap
- $\bar{H}$ form and fly away
- $\bar{H}$ annihilate on trap wall

Offline selection of $\bar{H}$ annihilation:

Coincidence in space & time (<5μs) of:

- $\bar{p}$ annihilation (charged pion vertex)
- e^+ annihilation (2 back-to-back 511 keV γ)

Antihydrogen detection: field ionization technique

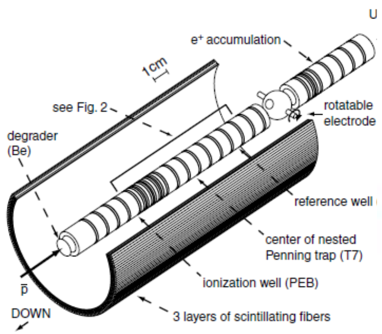
VOLUME 89, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 2002

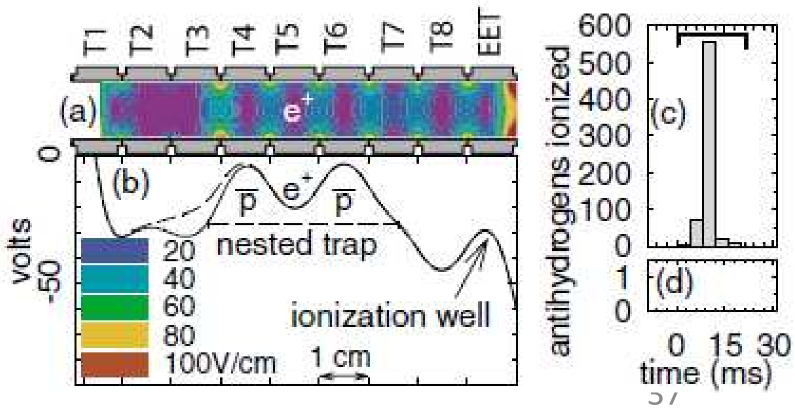
Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

(ATRAP Collaboration)

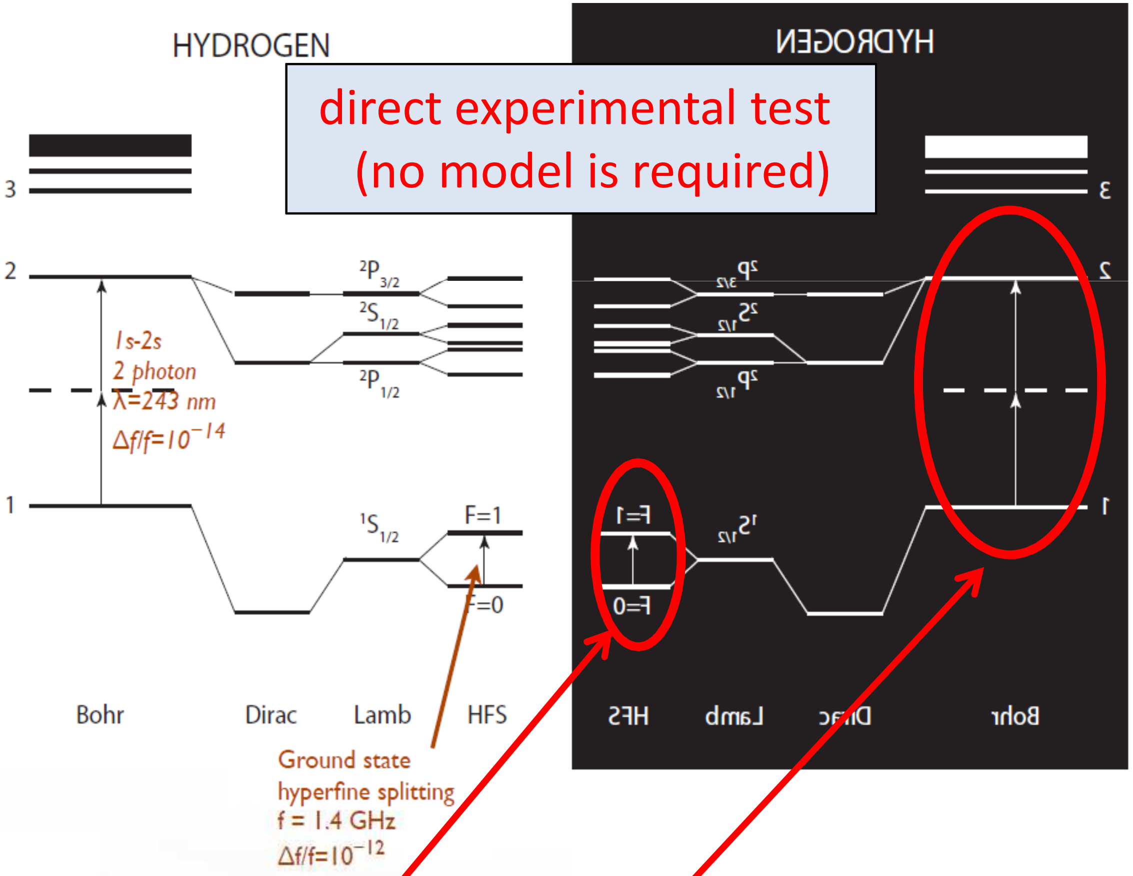
ATRAP Coll.





Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



Plans for antihydrogen:

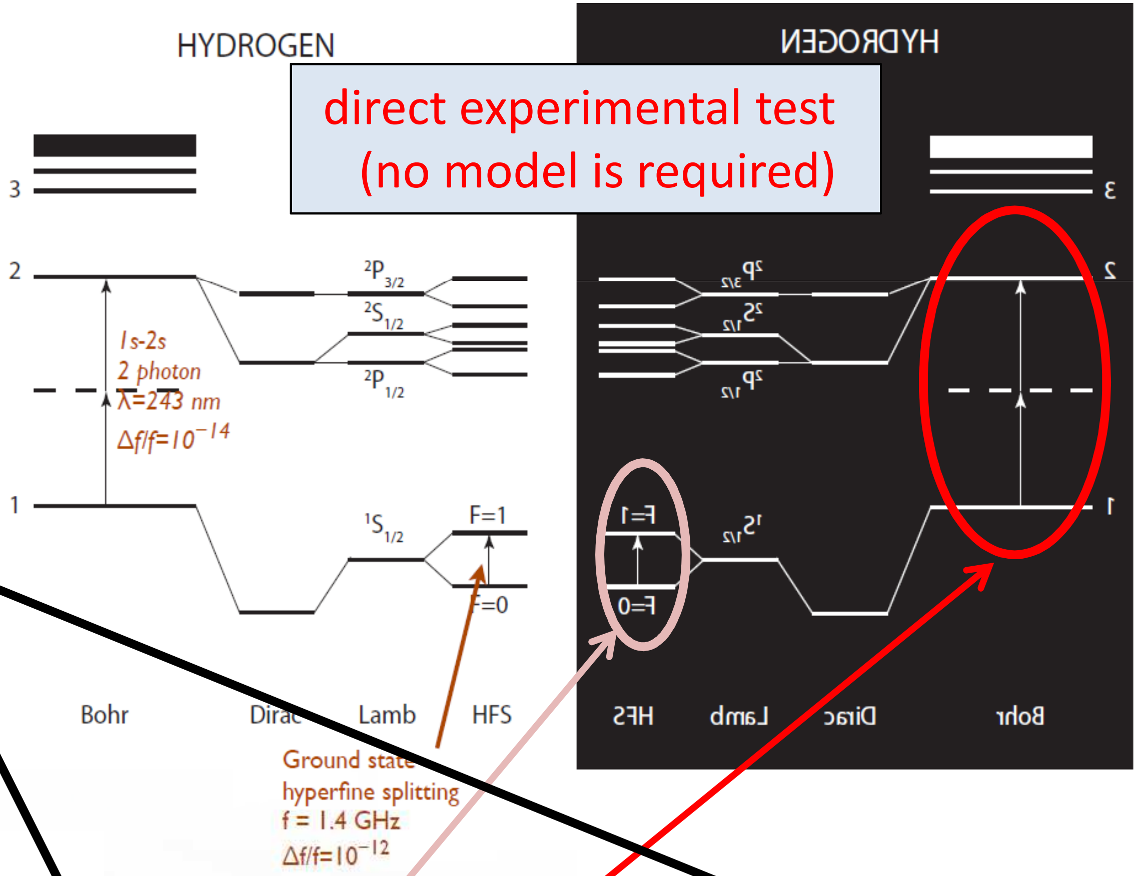
- measurements: - Hyperfine splitting of ground state
  - 1S-2S transition

- methods: - Antihydrogen trapping
  - Antihydrogen beam

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy

ALPHA
ATRAP



Plans for antihydrogen:

- measurements: **-** Hyperfine splitting of ground state
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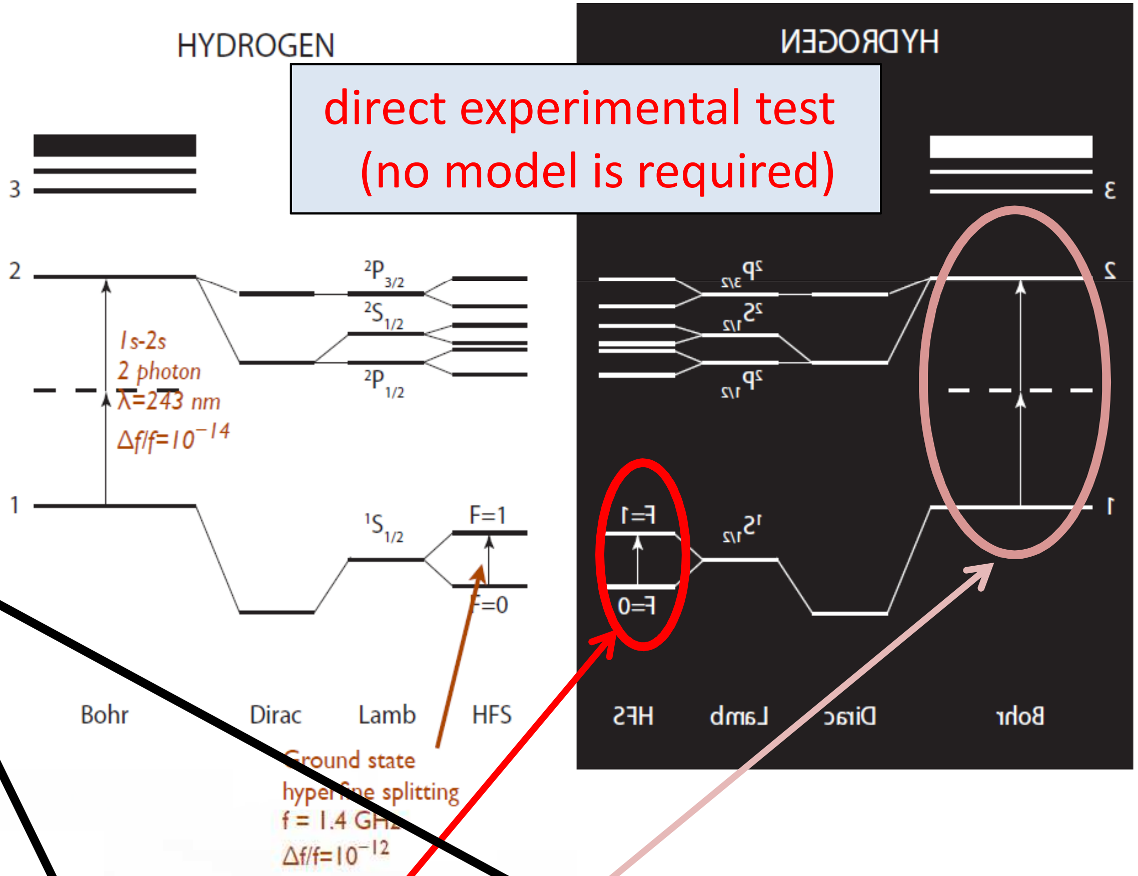
- methods: - **Antihydrogen trapping**
  - Antihydrogen beam

Antihydrogen for CPT test

matter-antimatter precise comparison by means of spectroscopy



direct experimental test
(no model is required)

ASACUSA

AEGIS

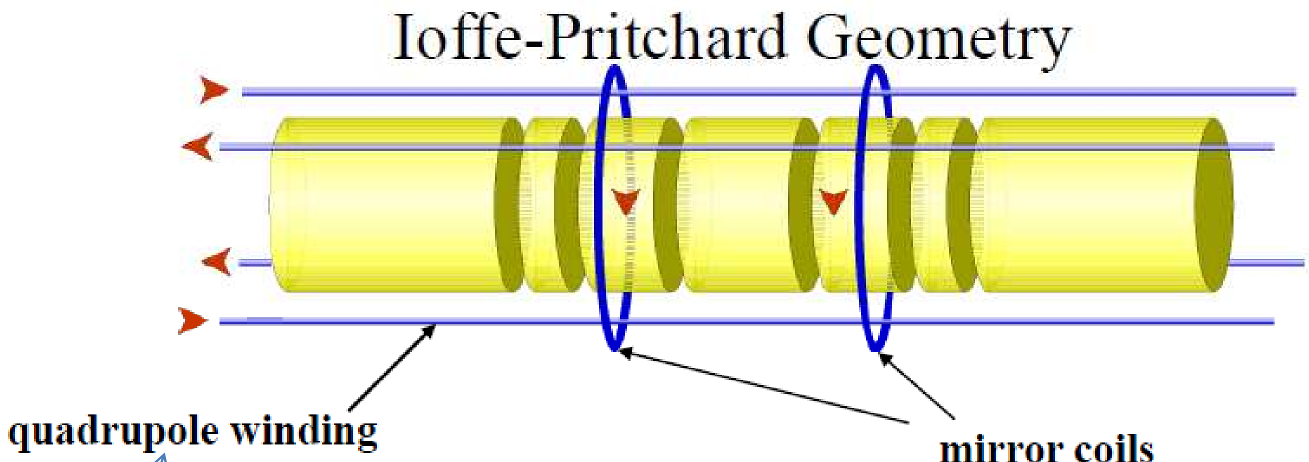
Plans for antihydrogen:

- measurements: **- Hyperfine splitting of ground state**
  - 1S-2S transition

- methods: - Antihydrogen trapping
  - **Antihydrogen beam**

Trapped antihydrogen for 1S-2S spectroscopy

Antihydrogen trap



$$U = -\overline{\mu} \cdot \overline{\mathbf{B}}$$

Well depth ~ 0.7 K/T

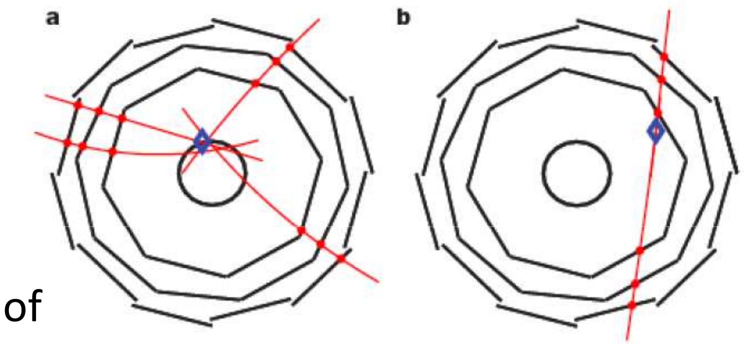
Broken rotational symmetry: can a Penning trap be superposed?

large B-fields needed for pbars trapping, cooling, etc.
but large ΔB needed for Hbar trapping

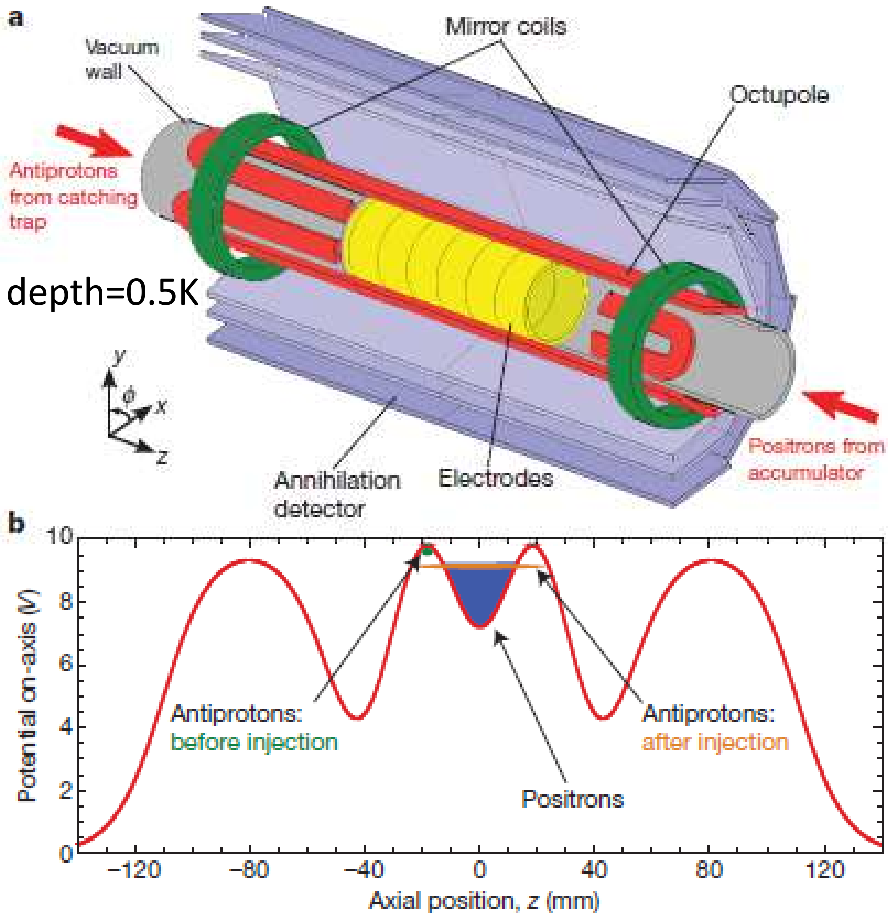
ALPHA: first trap of antihydrogen

Trapped antihydrogen **Nature 468, 673 (2010)**

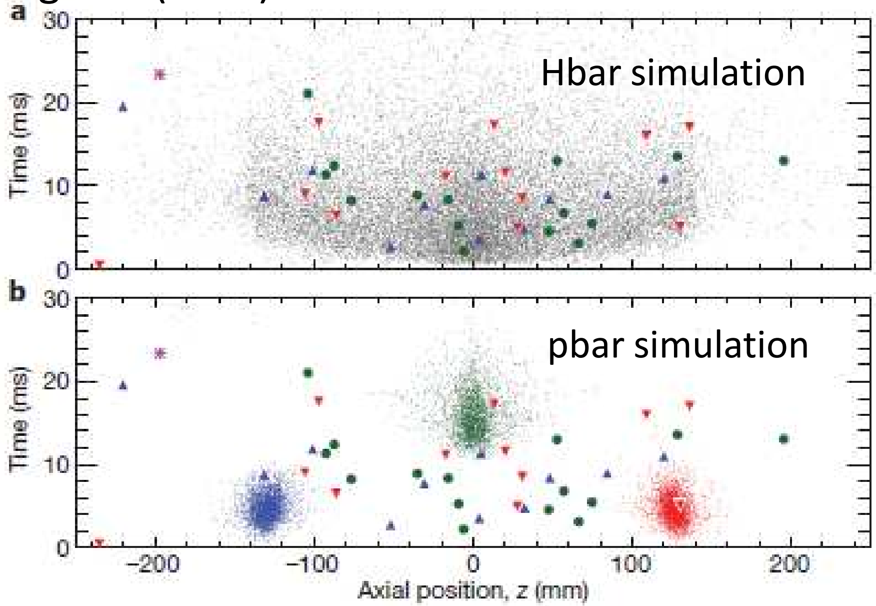
G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]



Fast shutdown of trap magnets (9 ms)



Trap depth=0.5K



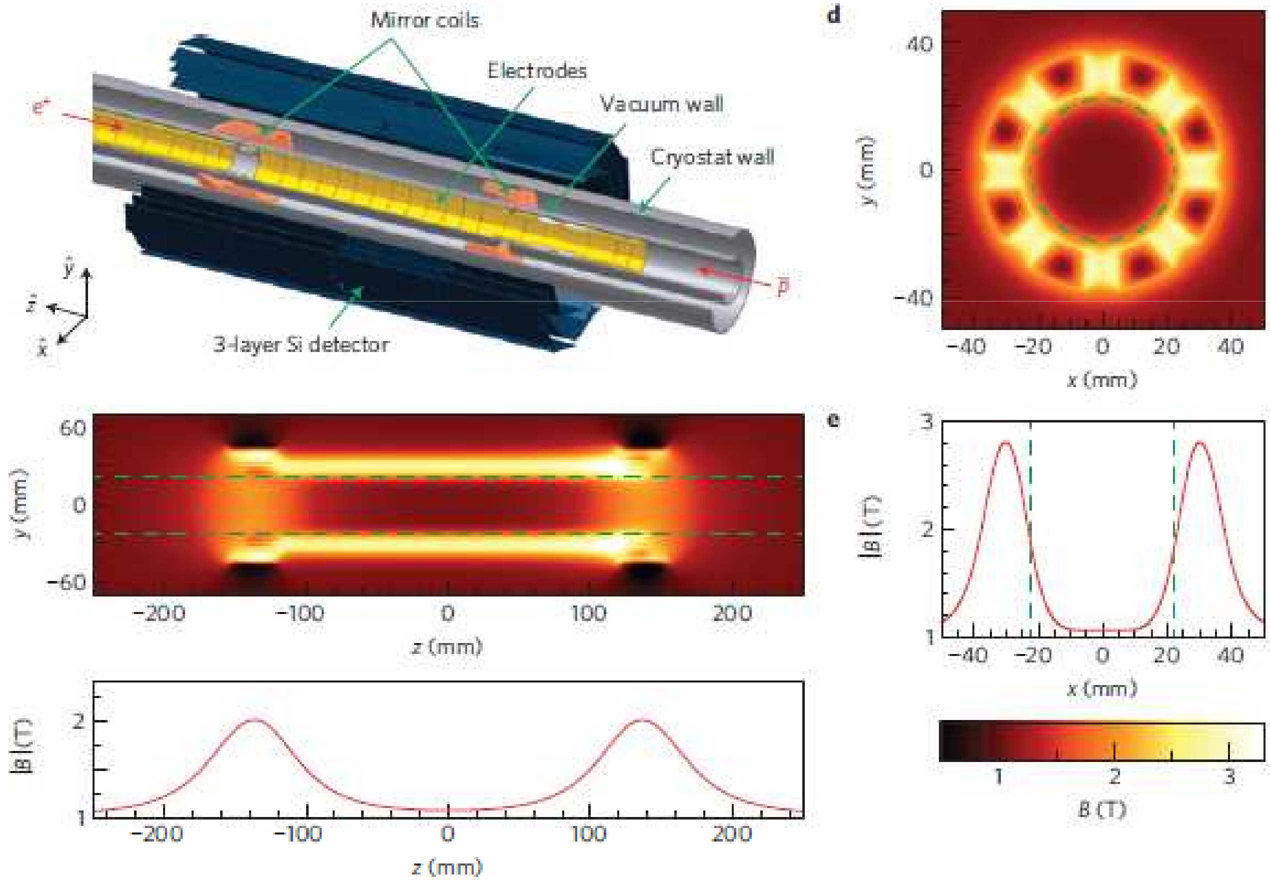
38 annihilations in 335 attempts

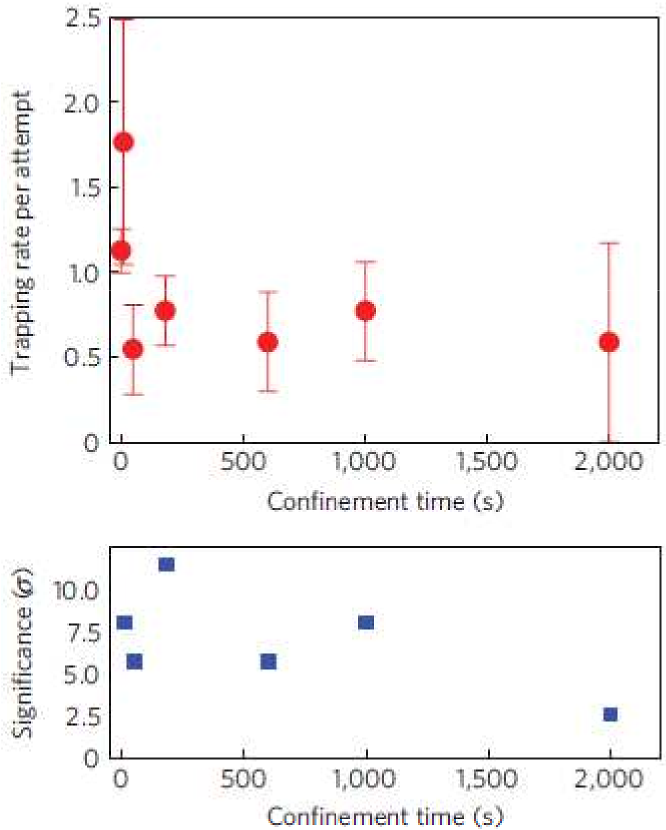
Final number: 1 trapped Hbar per trial

Trapped antihydrogen for at least 172 ms

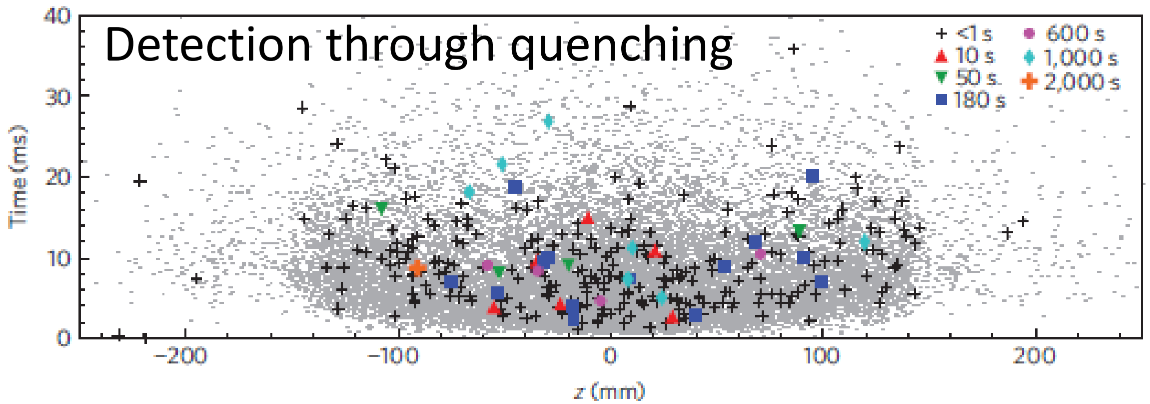
ALPHA: trap of antihydrogen for 1000 s

ALPHA Coll. Nature Physics 2011





Trapping rate



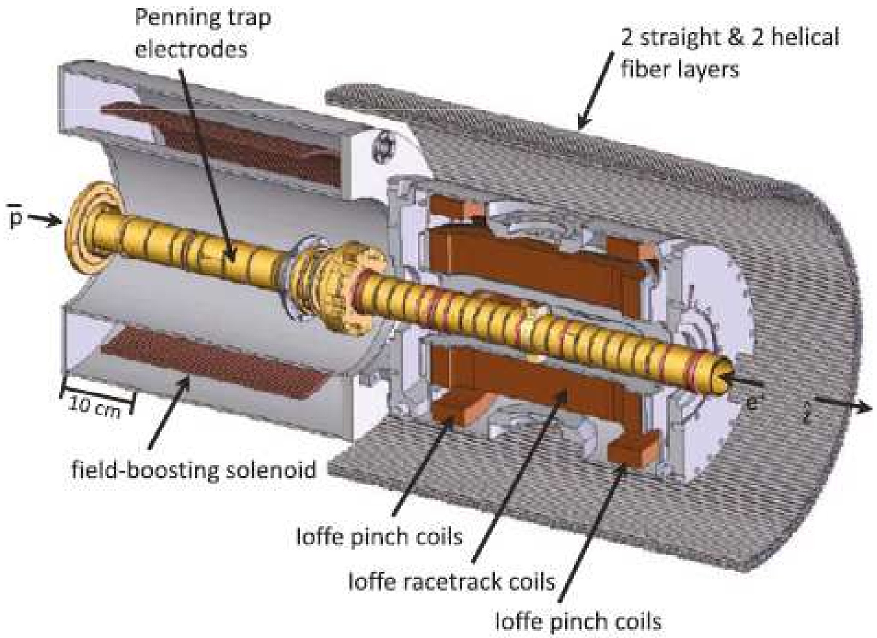
antihydrogens at 1S state

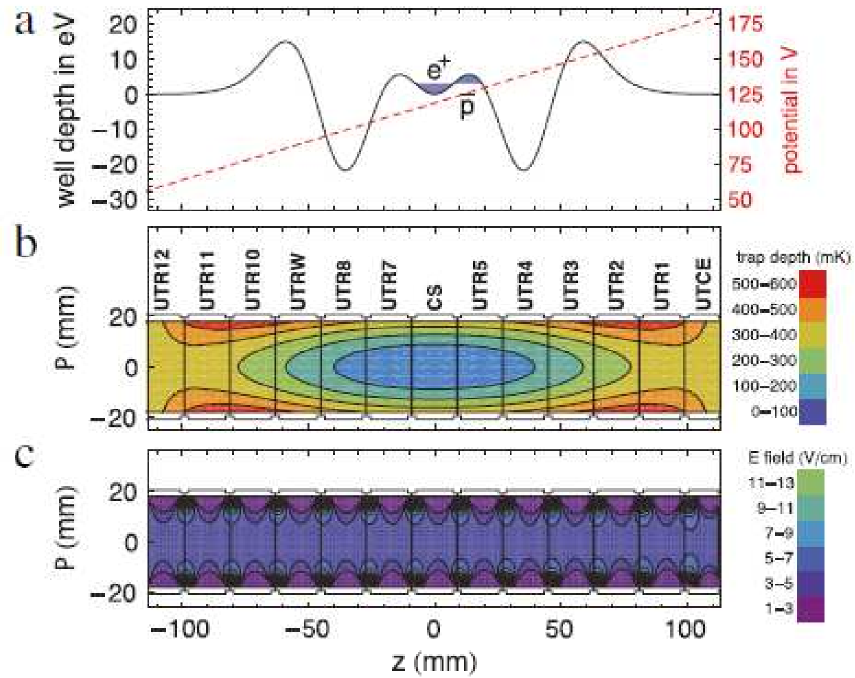
cts of

Antihydrogen Production

ATRAP: trap of antihydrogen

Gabrielse et al. PRL 2012





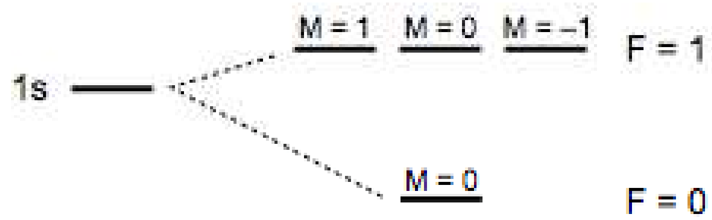
Confinement for 15-1000 s

High trapping rate: 5+-1 annihilations per trial

Ground-state hyperfine splitting of antihydrogen

(Anti)hydrogen ground-state hyperfine splitting

- Interaction between (anti)proton and (anti)electron spin magnetic moments
- Between the triplet (F = 1) and singlet (F = 0) sublevels :



$$\nu_{\mathrm{HF}} = \frac{16}{3}\left(\frac{m_p}{m_p+m_e}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\alpha^2 c R_\infty (1+\delta) \simeq 1.42\ \mathrm{GHz}$$

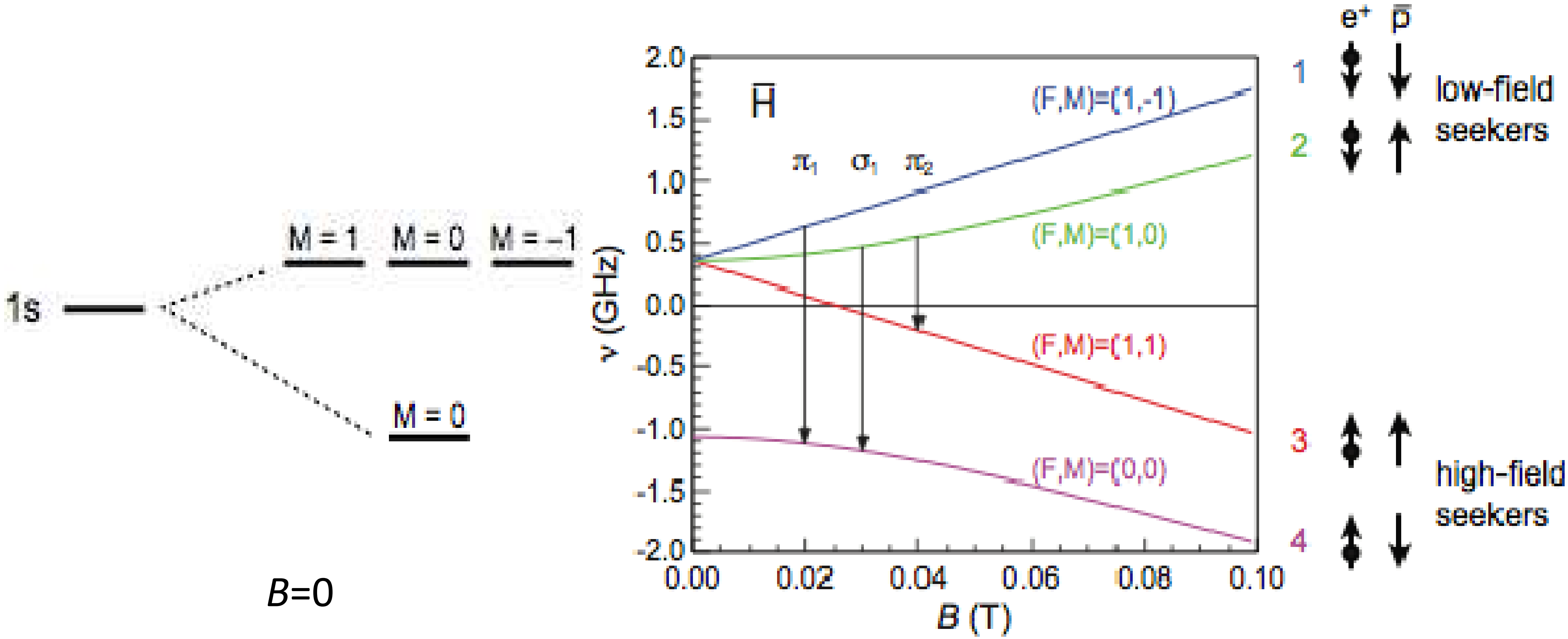
- ν_{HF} is proportional to the (anti)proton magnetic moment $\mu_{\bar{p}}$ (5 ppm 2012 Gabrielse, previously 0.3%)
- δ: higher-order QED & strong interaction corrections: ~10^{-3}
- Theoretical uncertainty on δ: ~10^{-6}

Antihydrogen GS-HFS in magnetic field

Hyperfine levels depend on magnetic field:

Energy increases for (*F*, *M*) = (1, −1) and (1, 0): low-field seekers (μ < 0)

Energy decreases for (*F*, *M*) = (1, 1) and (0, 0): high-field seekers (μ > 0)

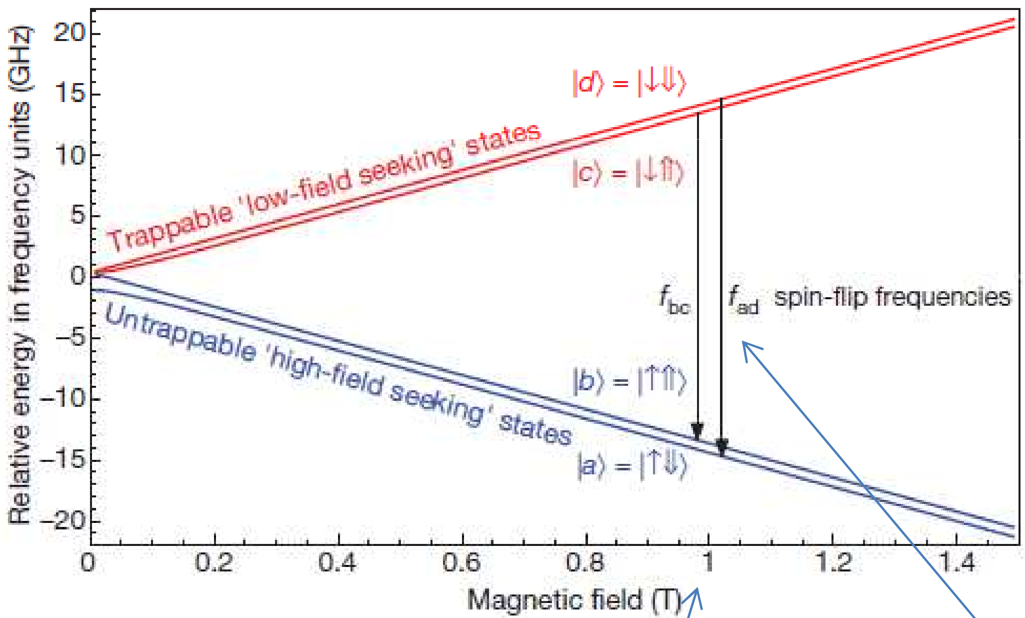


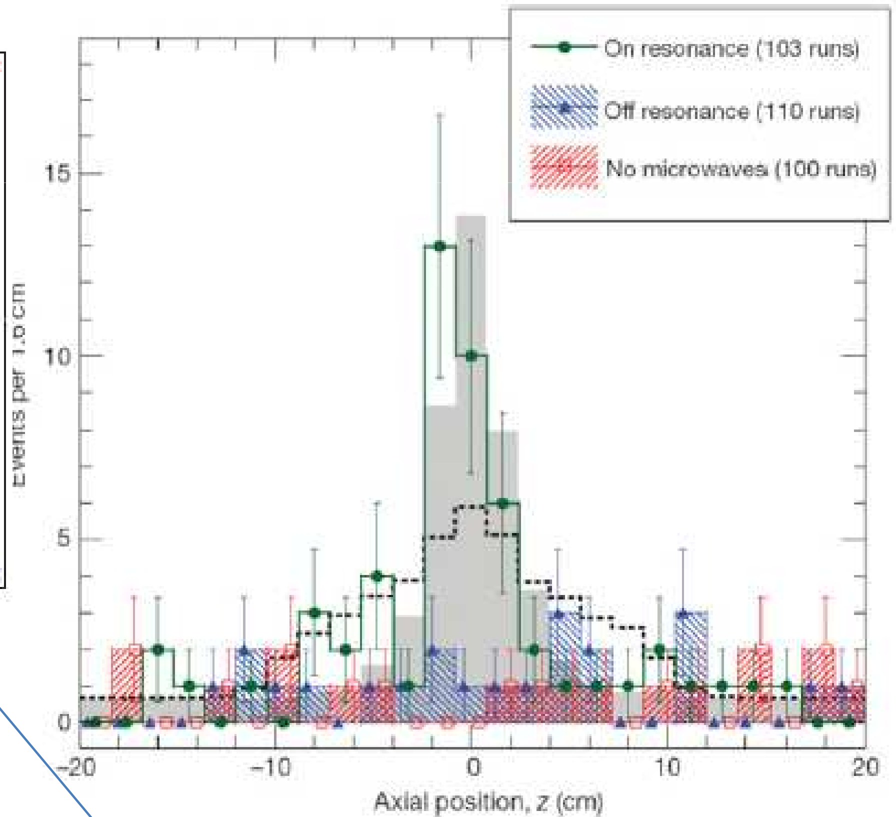
Antihydrogen GS-HFS measurement

- For hydrogen: 10^{-12} precision (hydrogen maser)
- But maser not possible for antihydrogen
- Spectroscopy of trapped antihydrogen → low precision due to strong confining field
- Spectroscopy of $\bar{H}$ beam
  - far from large **B**
  - atomic beam method can work up to 50-100 K (for trapped $\bar{H}$: << 1 K)
  - $\bar{H}$ can be guided with inhomogeneous magnetic field

ALPHA: Antihydrogen GS-HFS in a trap

C Amole et al., Nature 483, 439 (2012)





High magnetic field

Only proof of principle ($\Delta f/f$=100 MHz/29 GHz = 4 10^{-3})

Start of Hbar spectroscopy

GS-HFS with antihydrogen beam

ASACUSA

ASAKUSA KANNON TEMPLE
BY UTAGAWA HIROSHIGE (1797-1858)

Atomic **S**pectroscopy **A**nd **C**ollisions
Using **S**low **A**ntiprotons

Spokesperson: R. Hayano

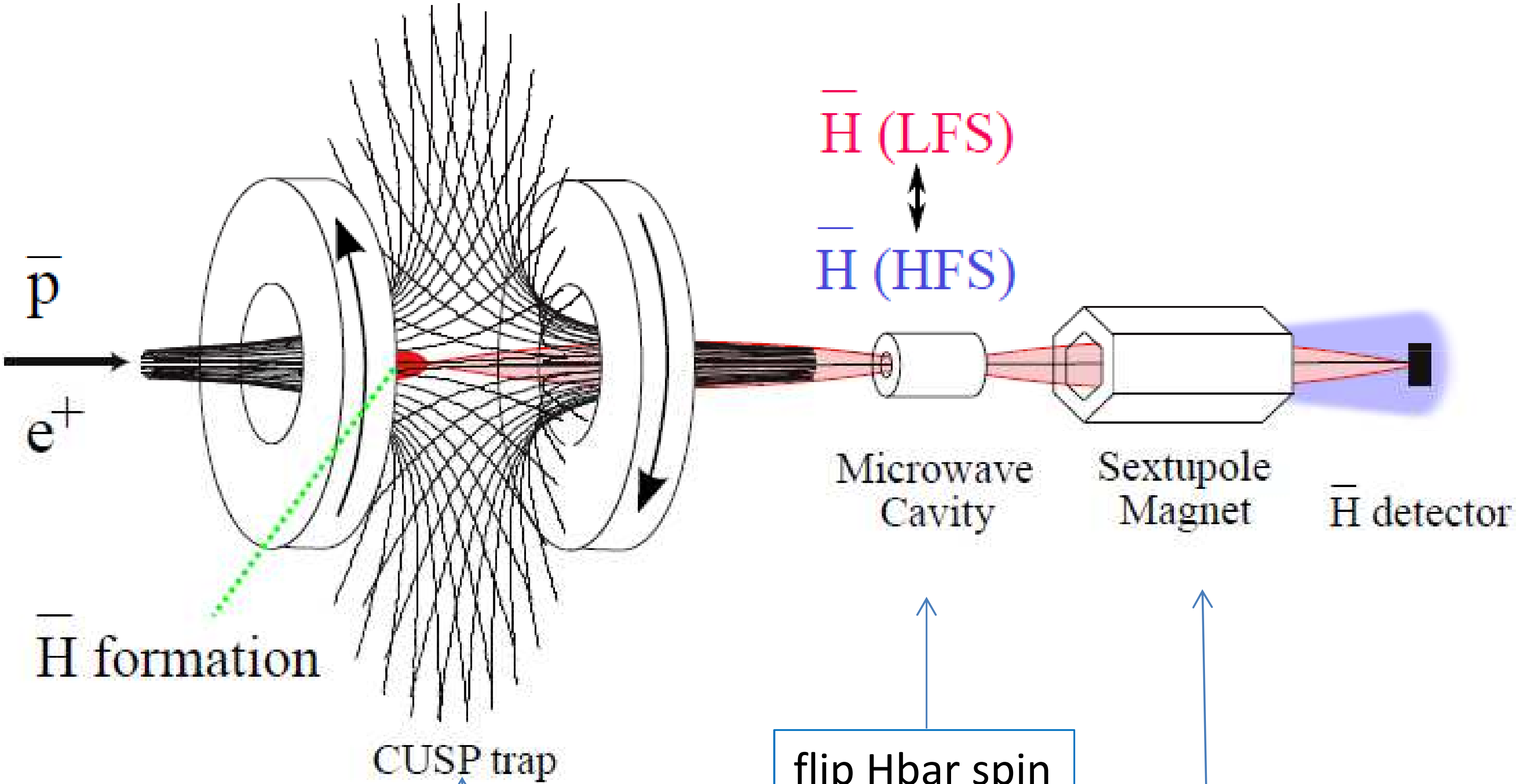
Not only antihydrogen

- $\bar{p}$He laser spectroscopy : $m_{\bar{p}}$ vs. m_p
- $\bar{p}$He microwave spectroscopy : $\mu_{\bar{p}}$
- $\bar{p}$A collision : formation and ionization cross section
- $\bar{p}$N collision : in flight annihilation cross section
- $\bar{p}e^+ = \bar{H}$ beam microwave spectroscopy :

N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[4,5], M. Leali[6], C. Malbrunot[4], V. Mascagna[6], O. Massiczek[4], K. Michishio[7], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[8], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[1], H.A. Torii[1], L. Venturelli[6], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[8], Y. Kanai[3], E. Lodi Rizzini[6], Y. Nagashima[7], Y. Matsuda[1], E. Widmann[4], & Y. Yamazaki[1,3]

1 Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Tokyo 153-8902, Japan
2 Ulmer Initiative Research Unit, RIKEN, Saitama 351-0198, Japan
3 Atomic Physics Laboratory, RIKEN, Saitama 351-0198, Japan
4 Stefan-Meyer-Institut für Subatomare Physik, Österreichische Akademie der Wissenschaften, 1090 Wien, Austria
5 CERN, 1211 Genève, Switzerland
6 Dipartimento di Ingegneria dell'Informazione, Università di Brescia & Istituto Nazionale di Fisica Nucleare, Gruppo Collegato di Brescia, 25133 Brescia, Italy
7 Department of Physics, Tokyo University of Science, Tokyo 162-8601, Japan
8 Graduate School of Advanced Sciences of Matter, Hiroshima University, Hiroshima 739-8530, Japan

Scheme of the measurement



confine pbars and e$^+$;
select Hbar spin state

flip Hbar spin

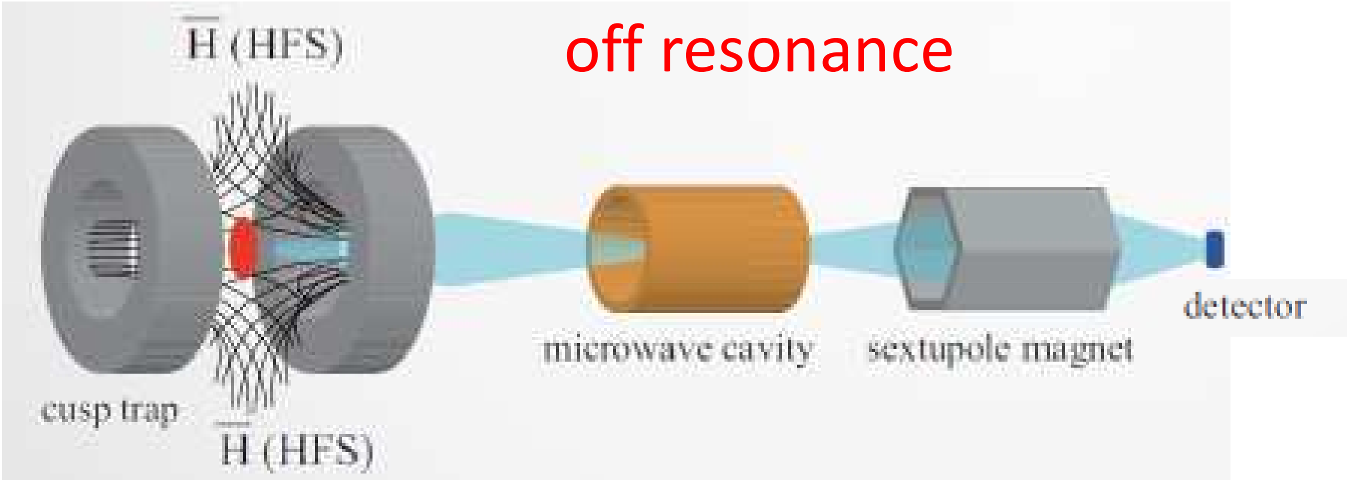
select spin state

HFS-states: de-focused
LFS-states: focused

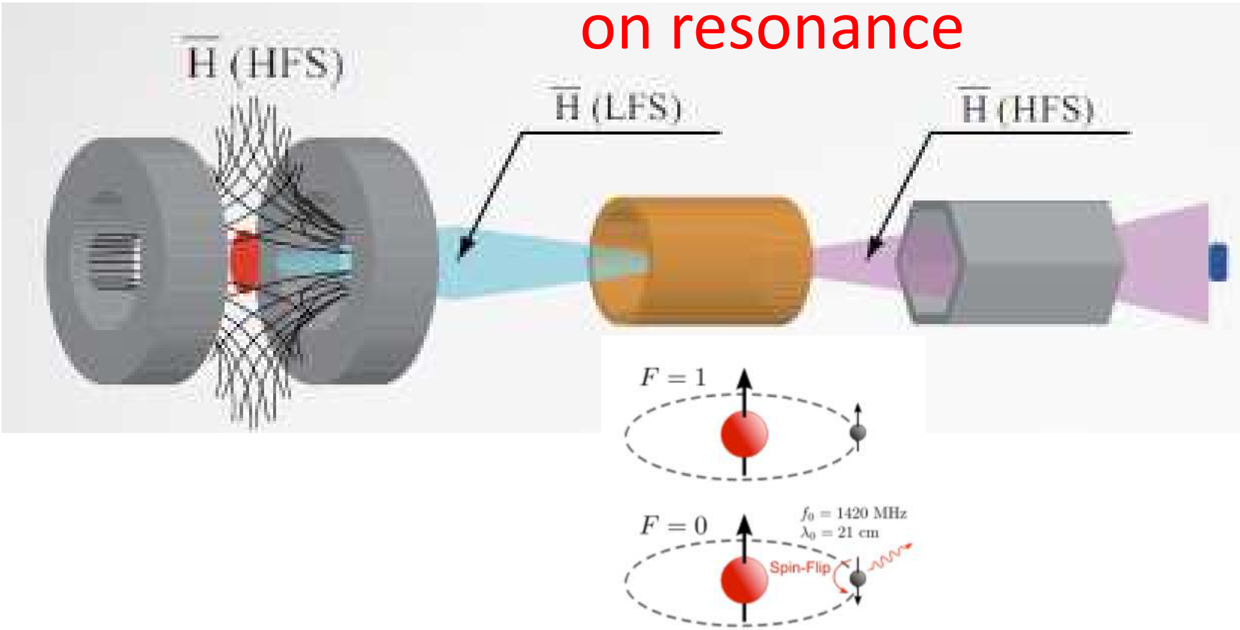
B and **E** axially symmetric

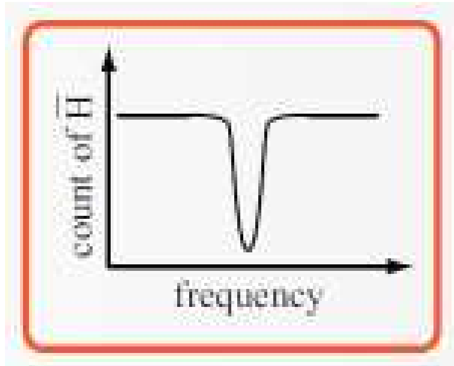
Scheme of the measurement

off resonance



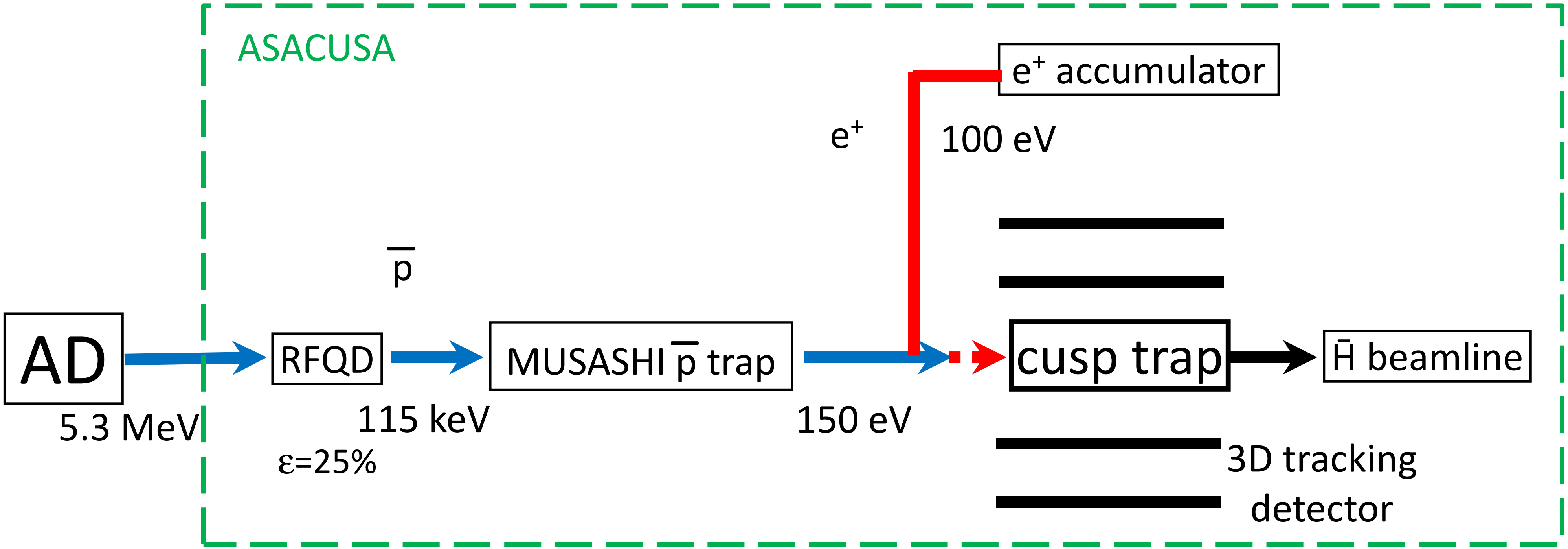
on resonance





"Disappearance Mode"

Scheme of the experimental set-up



$\bar{p}$:

deceleraed by RFQD

e- cooling, accumulation (3–5 AD shots), compression in MUSASHI

pulse extraction from MUSASHI

transfer of 3 10^5 to the cusp trap

guided by magnetic fields

e^+:

^{22}Na source (0.6 GBq), Ne moderator, N_2 gas moderator, MRE

accumulation (10–100 stacks)

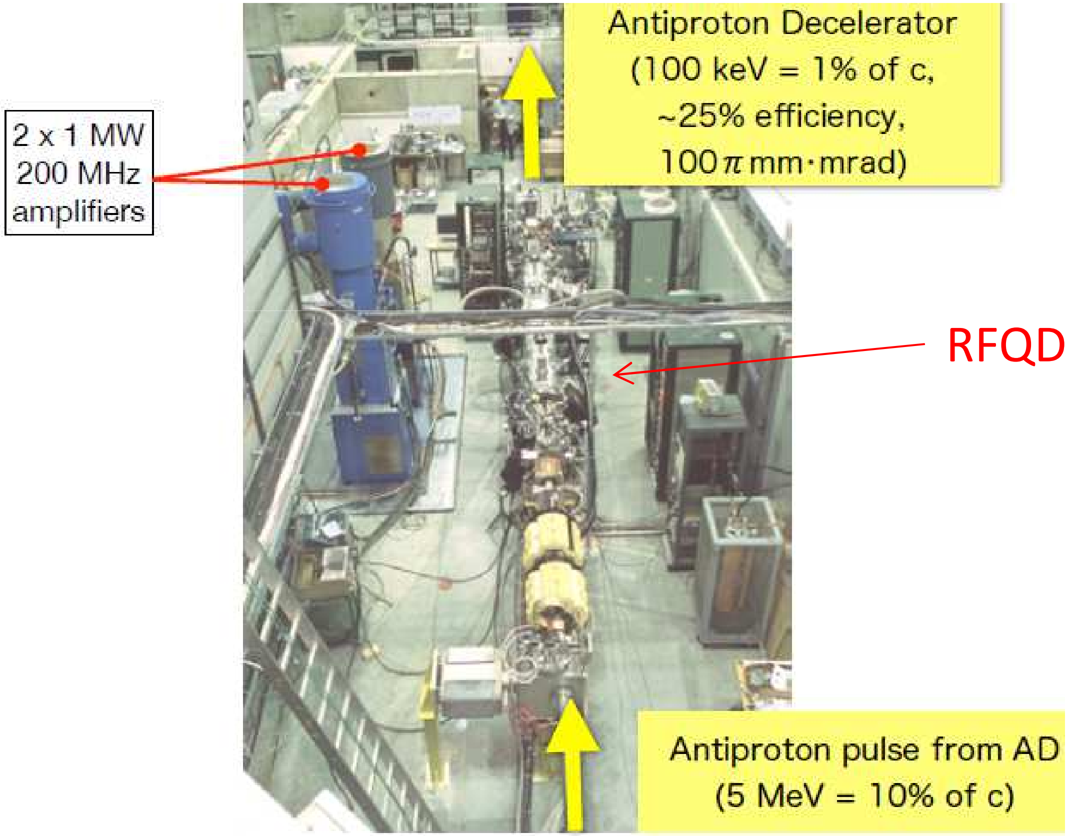
transfer of 3 10^7 every 10 min to the cusp

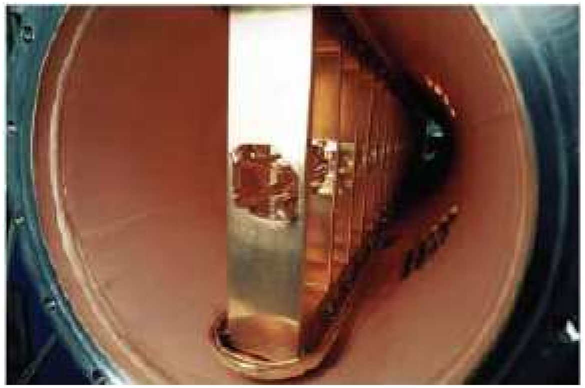
Radiofrequency Quadrupole Decelerator

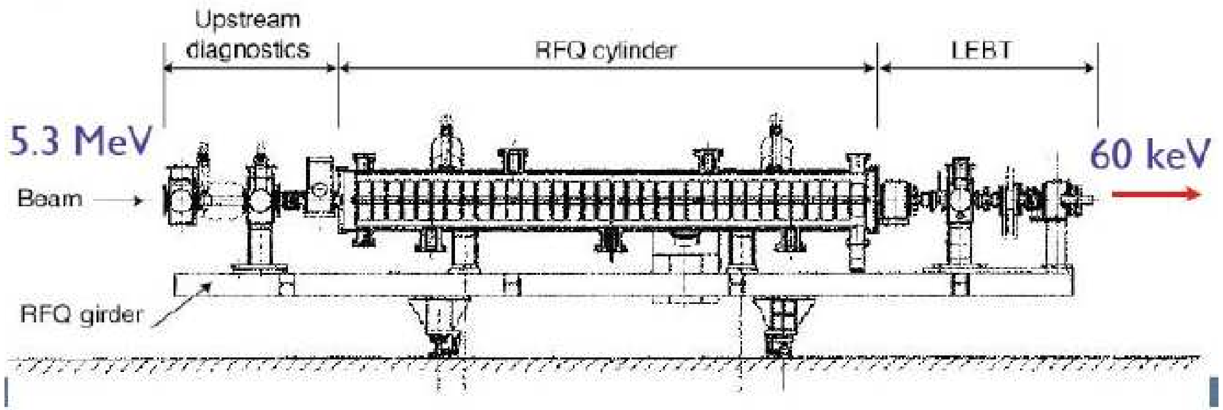
RFQD – inverse linac

Crucial part of ASACUSA.
Slows down antiprotons to E<100 keV.
Delivers >7 million antiprotons every 100
Beam emittance > 100 pi mm mrad,
Energy spread > 10 keV.

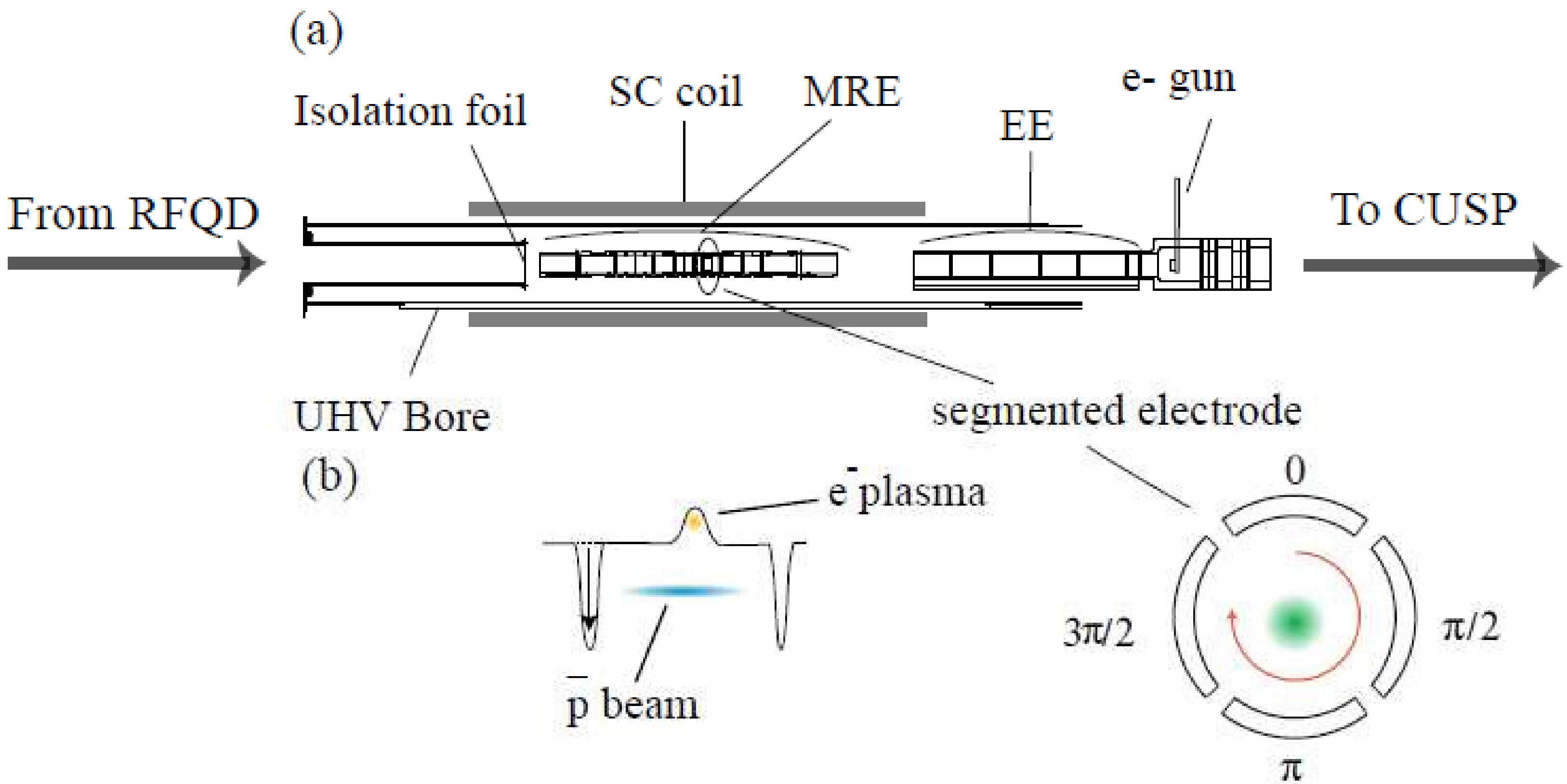
10-100-fold improvement of many parameters with new ELENA machine.







Antiproton accumulator (MUSASHI)



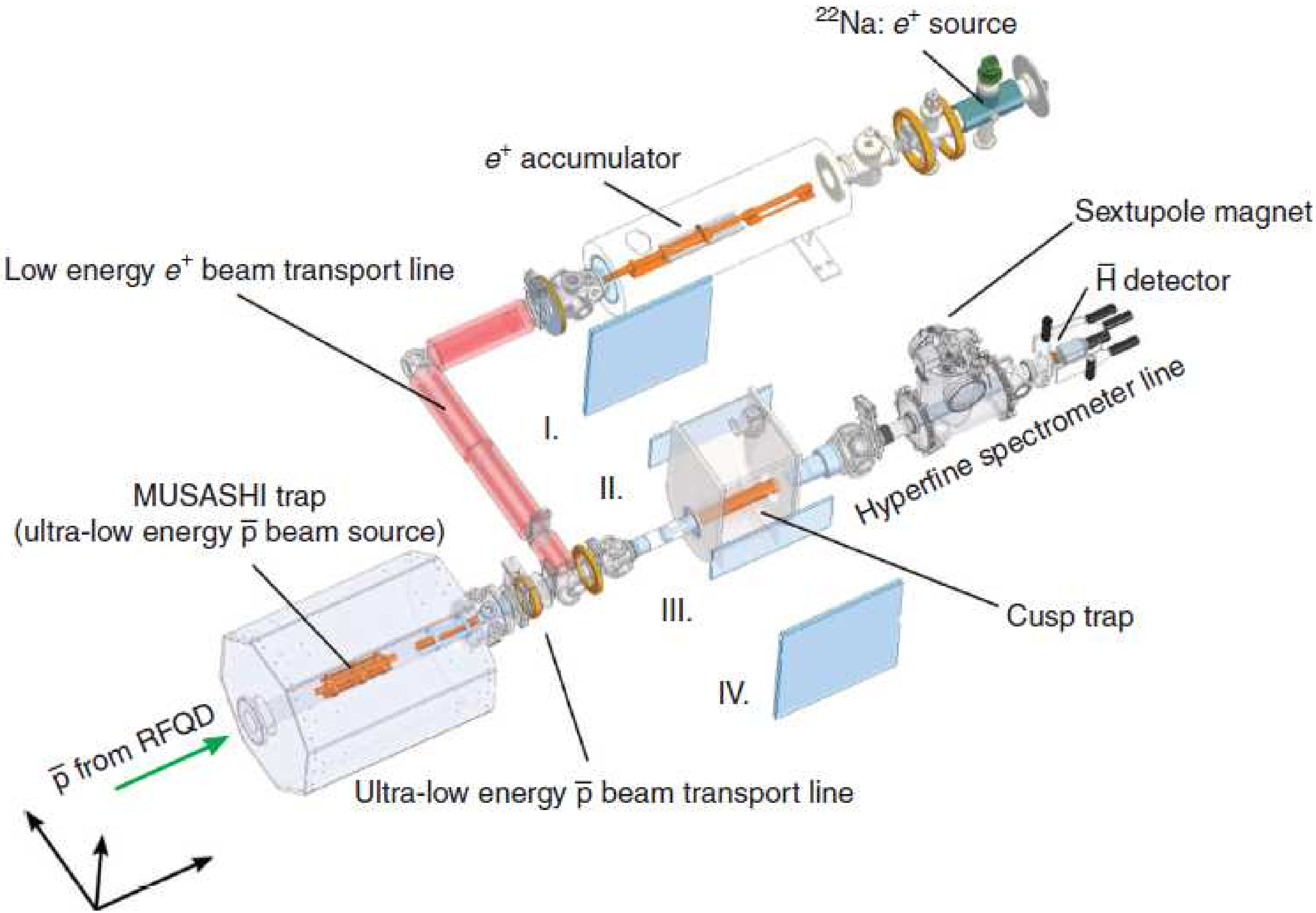
RFQD→ foil → capture → cool with e- → compress → transport to CUSP

RFQD+MUSASHI → 5-50 more pbars than other experiments

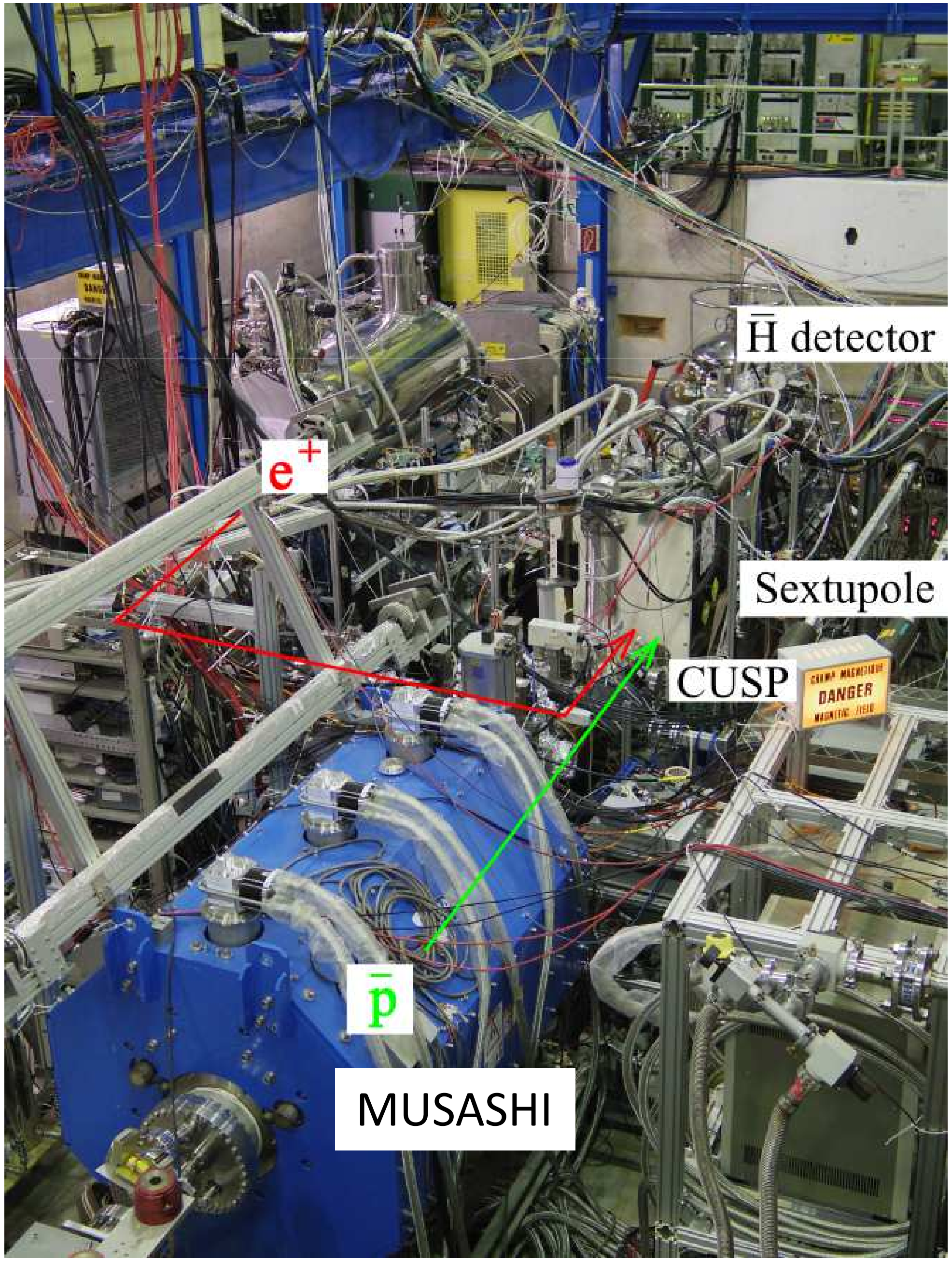
AD	5.3 MeV	2.0–2.5×10^7/AD shot
RFQD	110 keV	$\sim5\times10^6$/AD shot
trapped&cooled	$\lesssim1$ eV	0.5–0.8×10^6/AD shot
slow extraction	250 eV	$\lesssim3.0\times10^5$/extraction
pulse (new optics)	150 eV	$\lesssim1.5\times10^5$/extraction

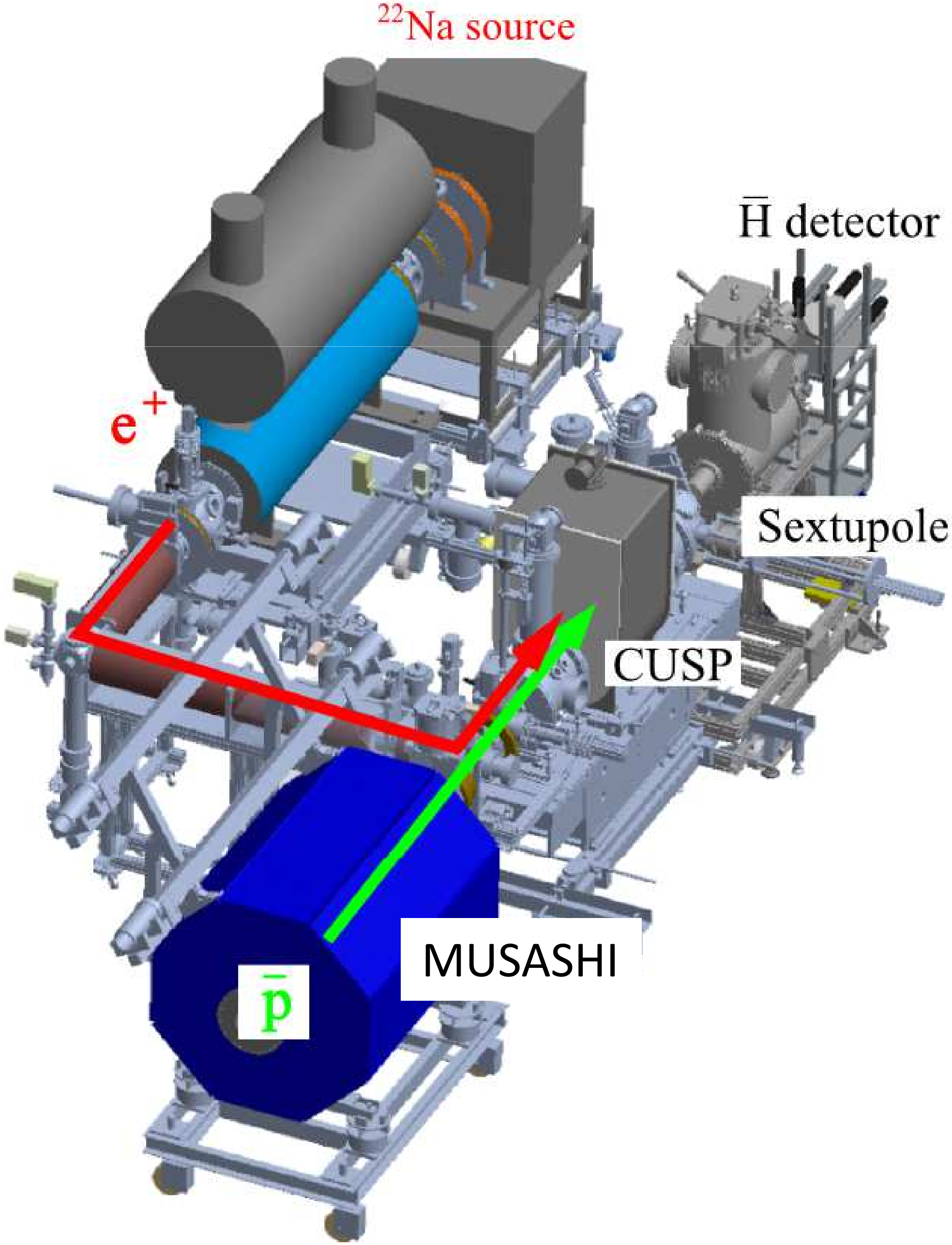
3 AD shots per 1 MUSASHI extraction.

experimental set-up

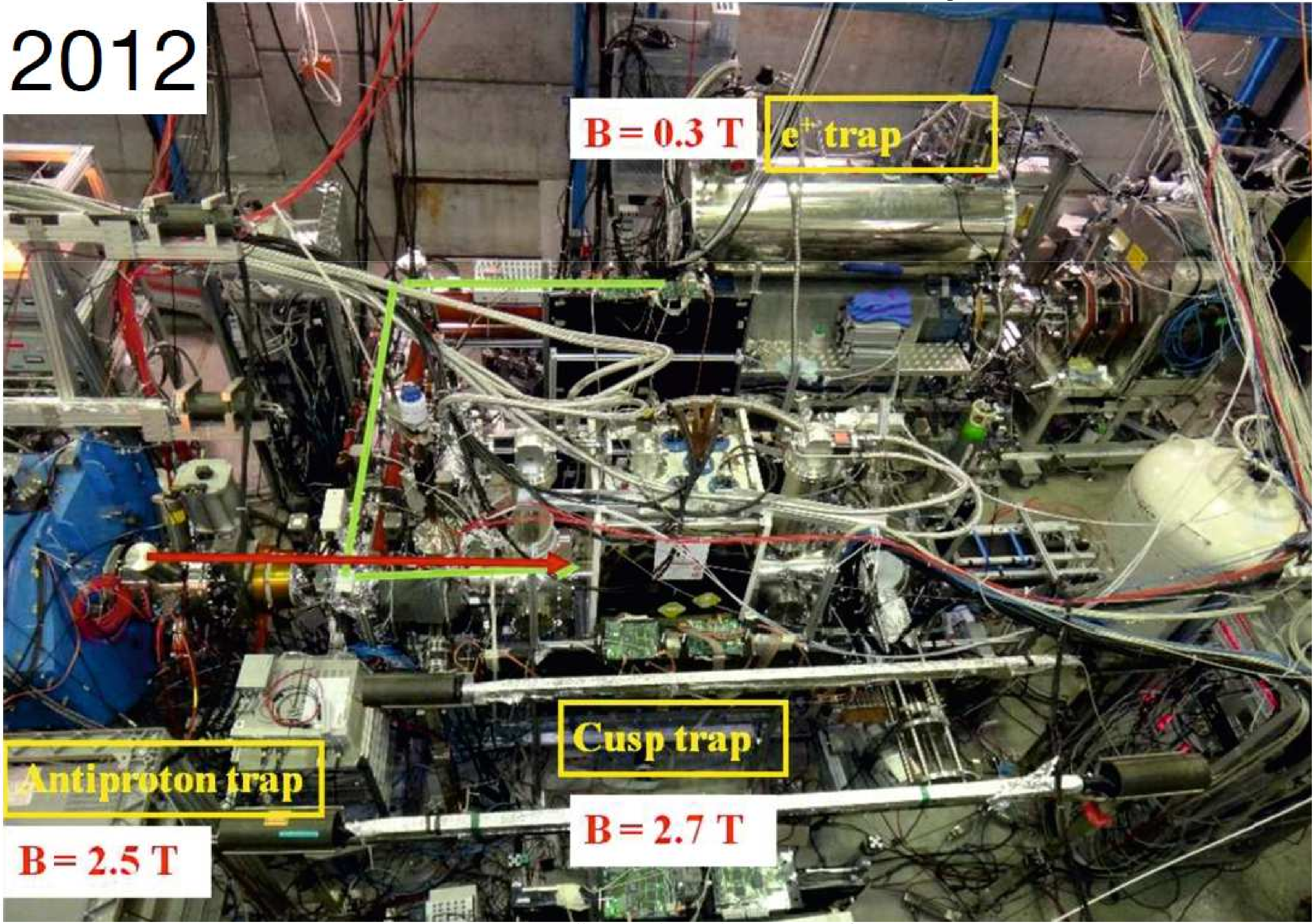


experimental set-up

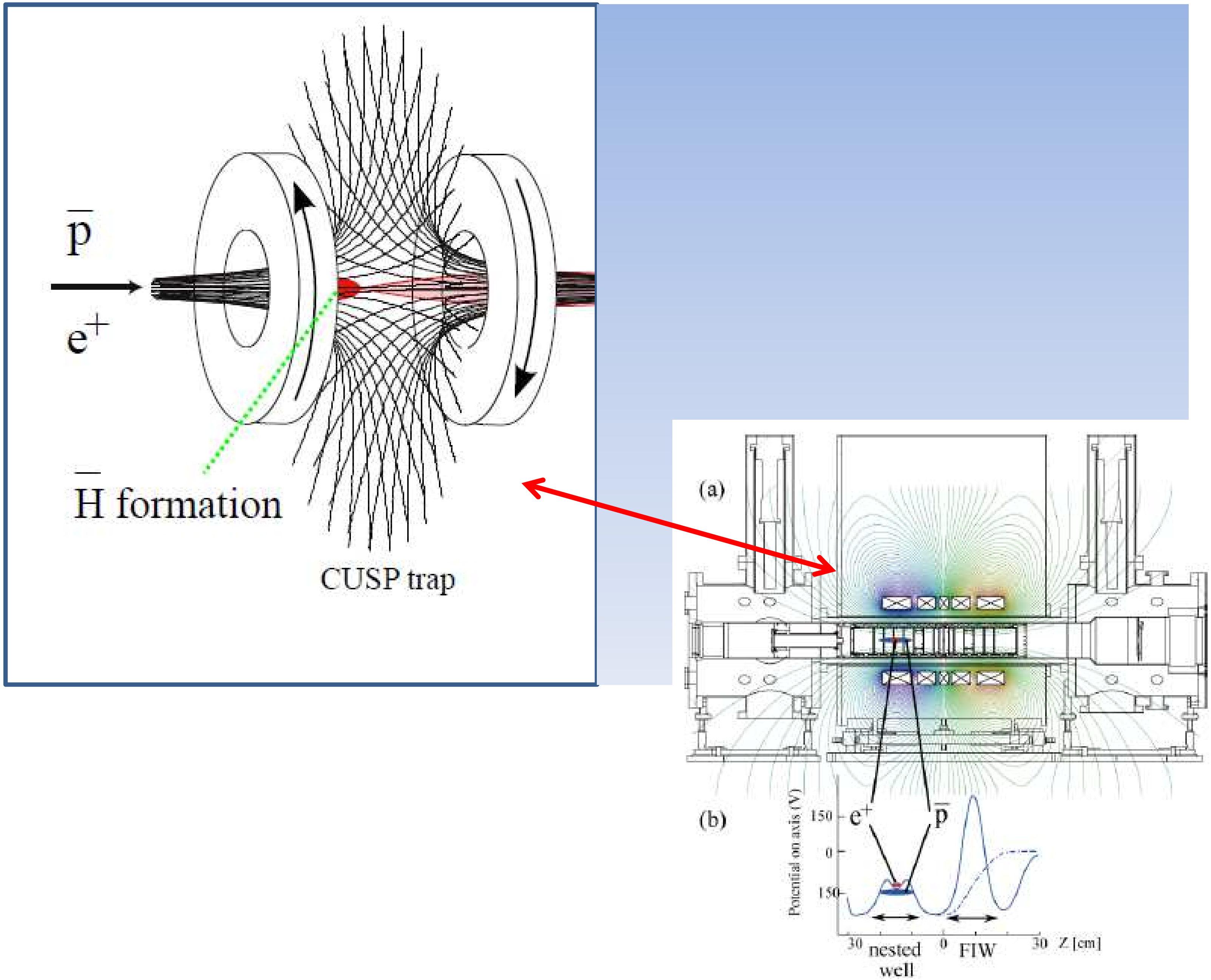




experimental set-up



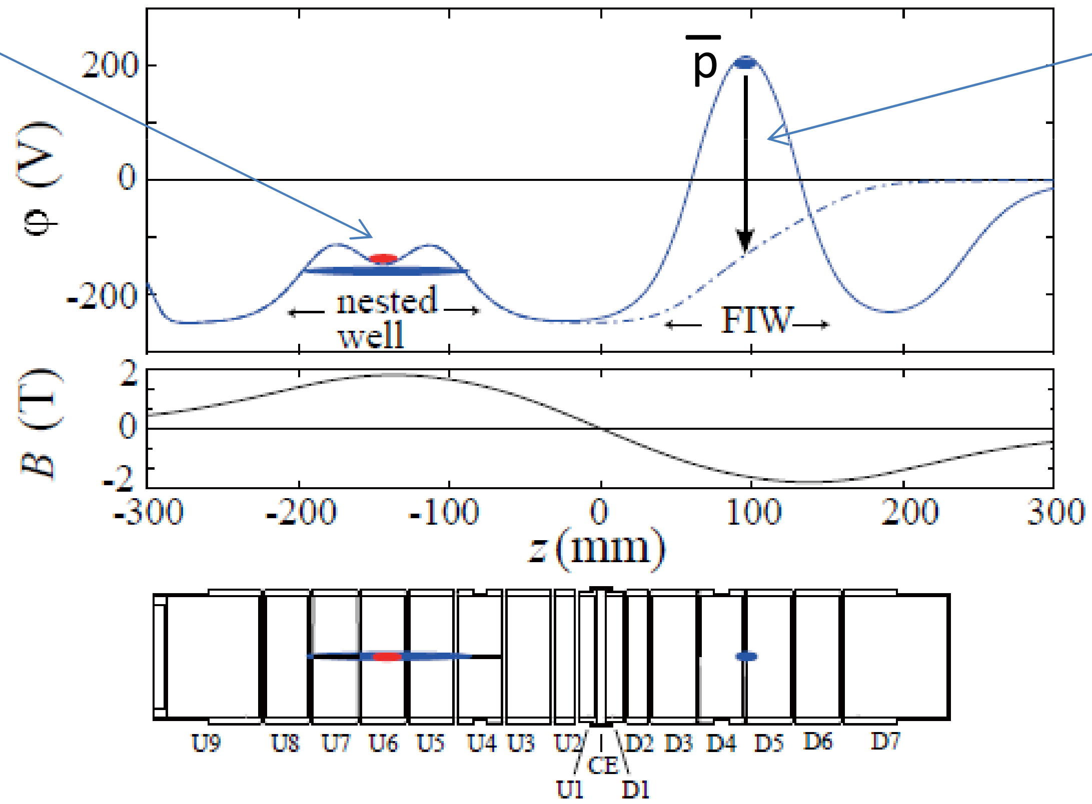
Antihydrogen formation



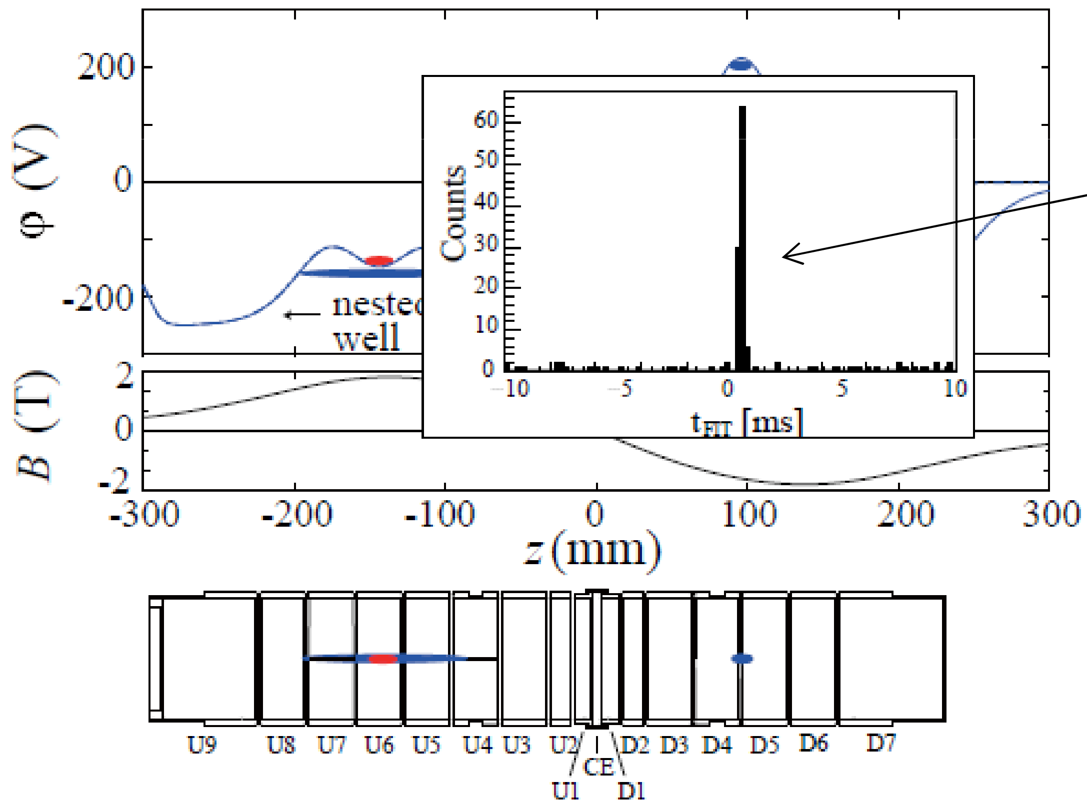
Antihydrogen formation

Hbar formation

Field Ionization of Hbar
(→ pbar capture)



Antihydrogen formation



$\overline{p}$ annihilation signal

Y. Enomoto et al.
Phys. Rev. Lett 243401, 2010

First antihydrogen production in a "cusp trap"

$\bar{H}$ production in the "cusp" trap

Physics World reveals its top 10 breakthroughs for 2010

Dec 20, 2010   25 comments

It was a tough decision, given all the fantastic physics done in 2010. But we have decided to award the *Physics World* 2010 Breakthrough of the Year to two international teams of physicists at CERN, who have created new ways of controlling antiatoms of hydrogen.

Shared glory at CERN as antihydrogen research takes the gong

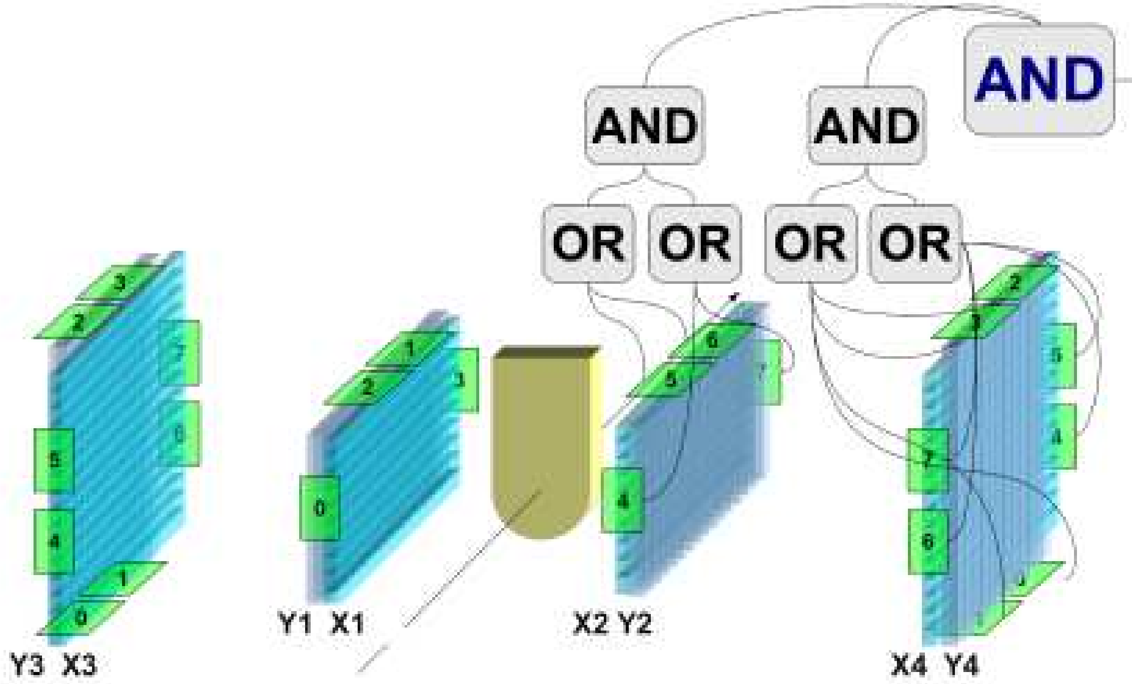
The ALPHA collaboration announced its findings in late November, which involved trapping 38 antihydrogen atoms (an antielectron orbiting an antiproton) for about 170 ms. This is long enough to measure their spectroscopic properties in detail, which the team hopes to do in 2011.

Just weeks later, the ASACUSA group at CERN announced that it had made a major

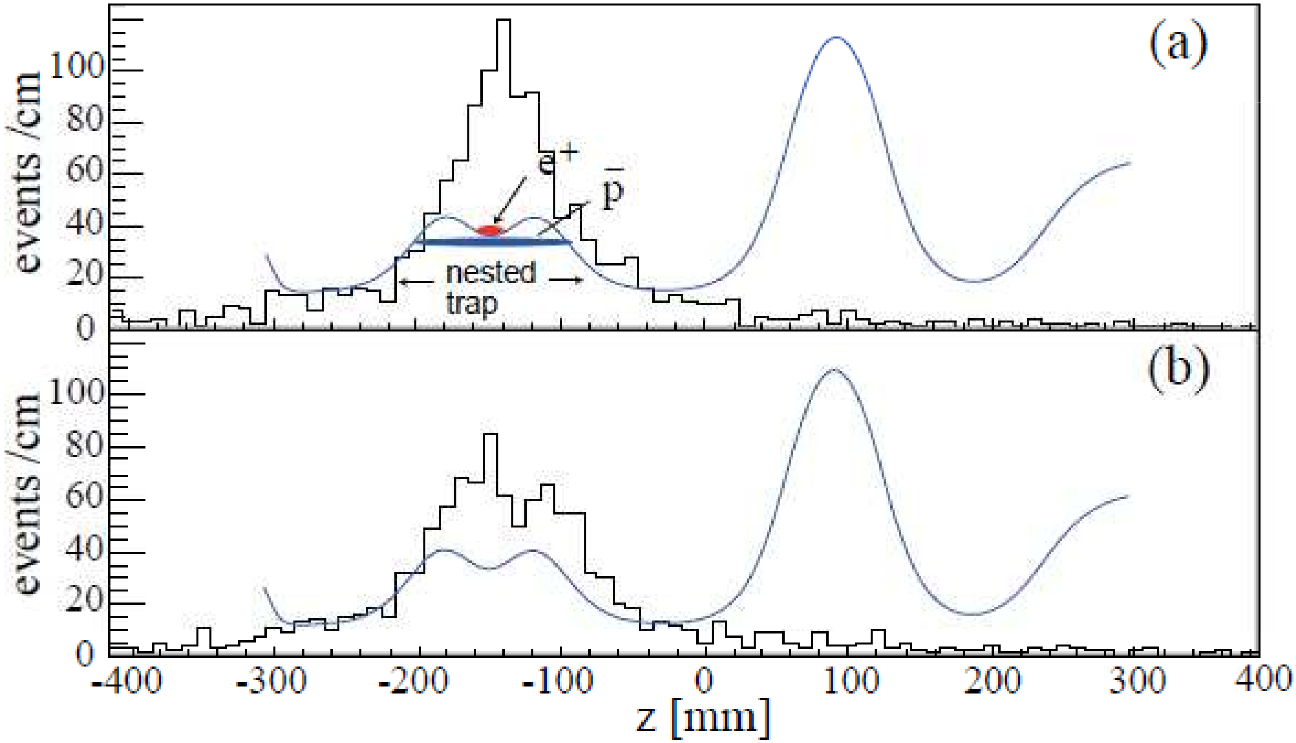
ASACUSA

Tracking detector

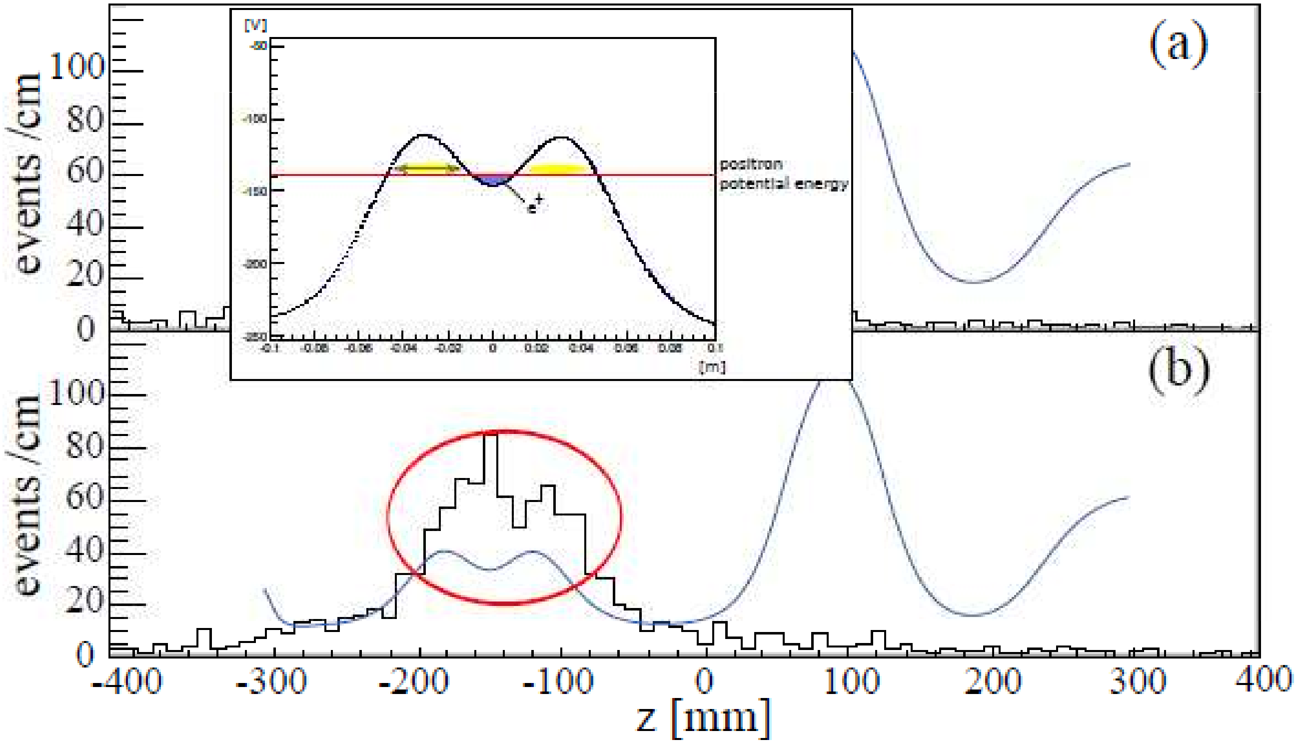
- Scintillator bars
  15 mm × 15 mm
  960 mm in length
- $\Omega/4\pi = 6.6\% + 8.6\%$
  for each side
- for $\pi^{\pm}$ multiplicity 3
  $\Rightarrow$ 39%
- double coincidence
  $\Rightarrow$ 3.3%



Annihilations vertices



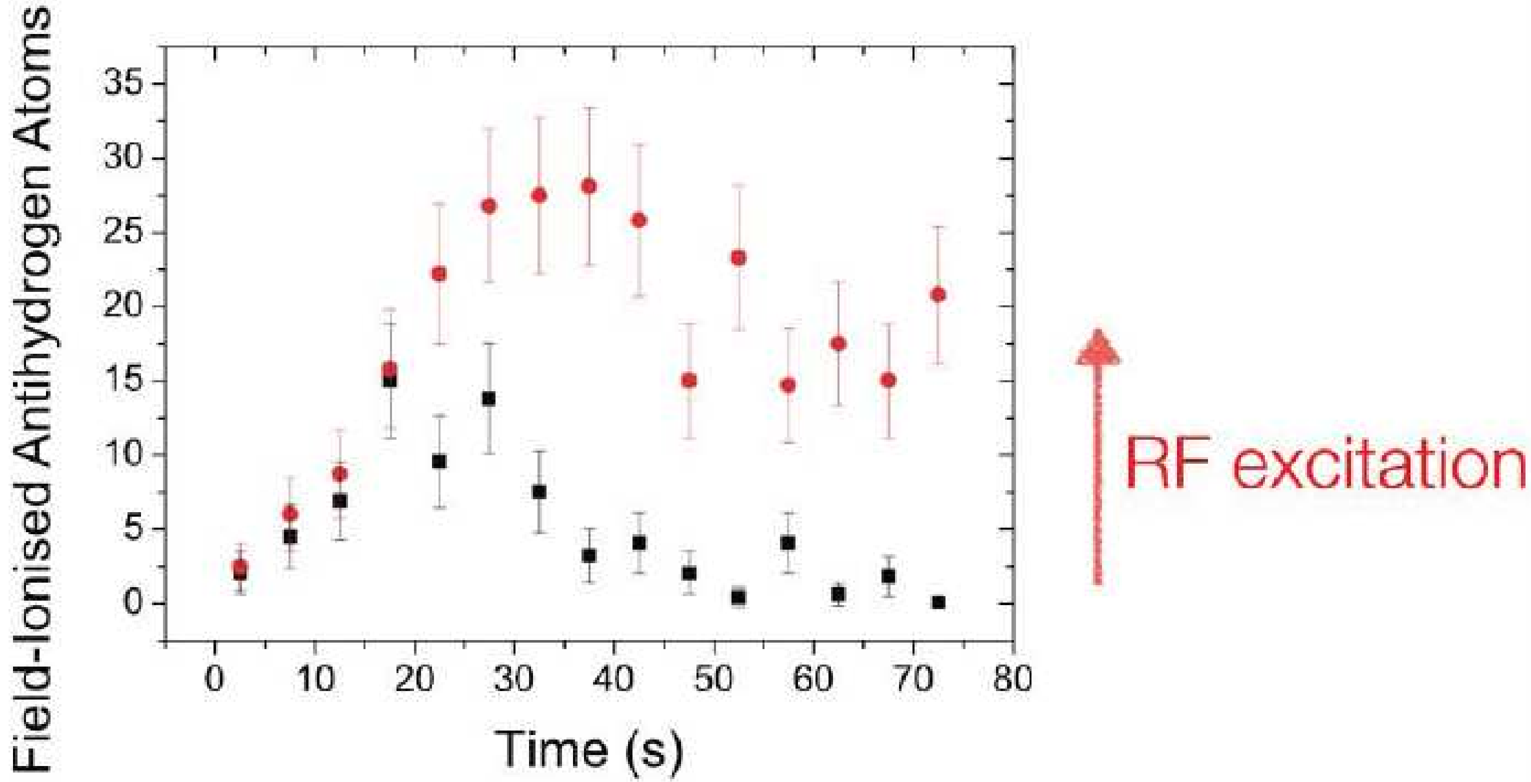
Annihilations vertices



Increase antihydrogen production

$3x10^5$ $\overline{p}$ mixed with $3x10^7$ e^+

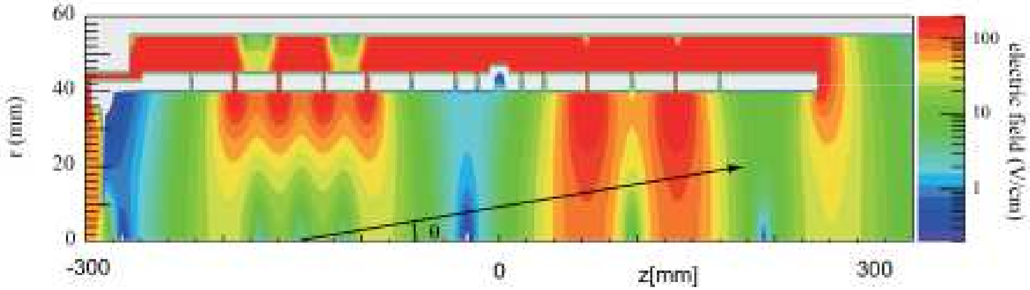
Field Ionization for n ≳ 39 : 75 $\overline{H}$ ⇒ 260 $\overline{H}$ (× 3.5)

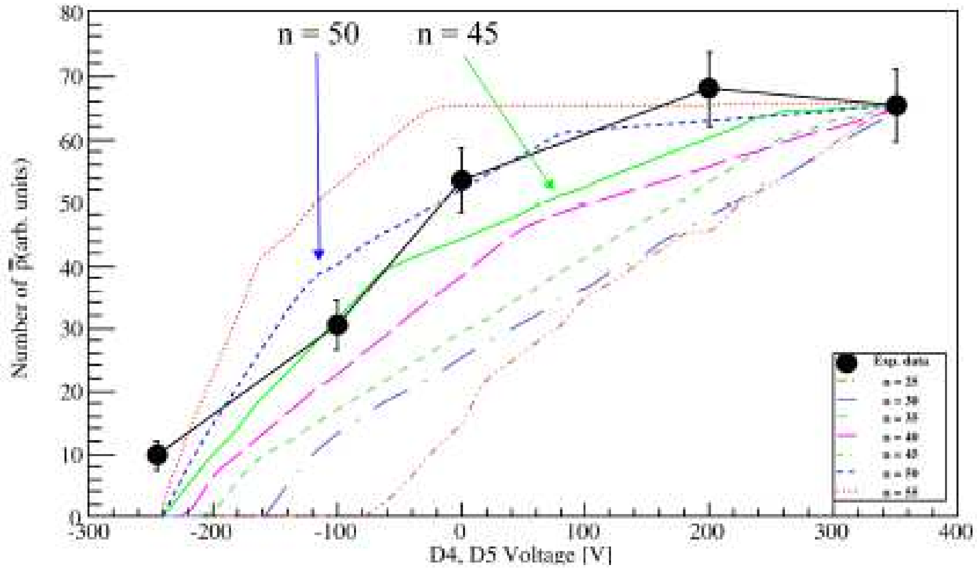


Field ionization measurement

Field Ionization measurement

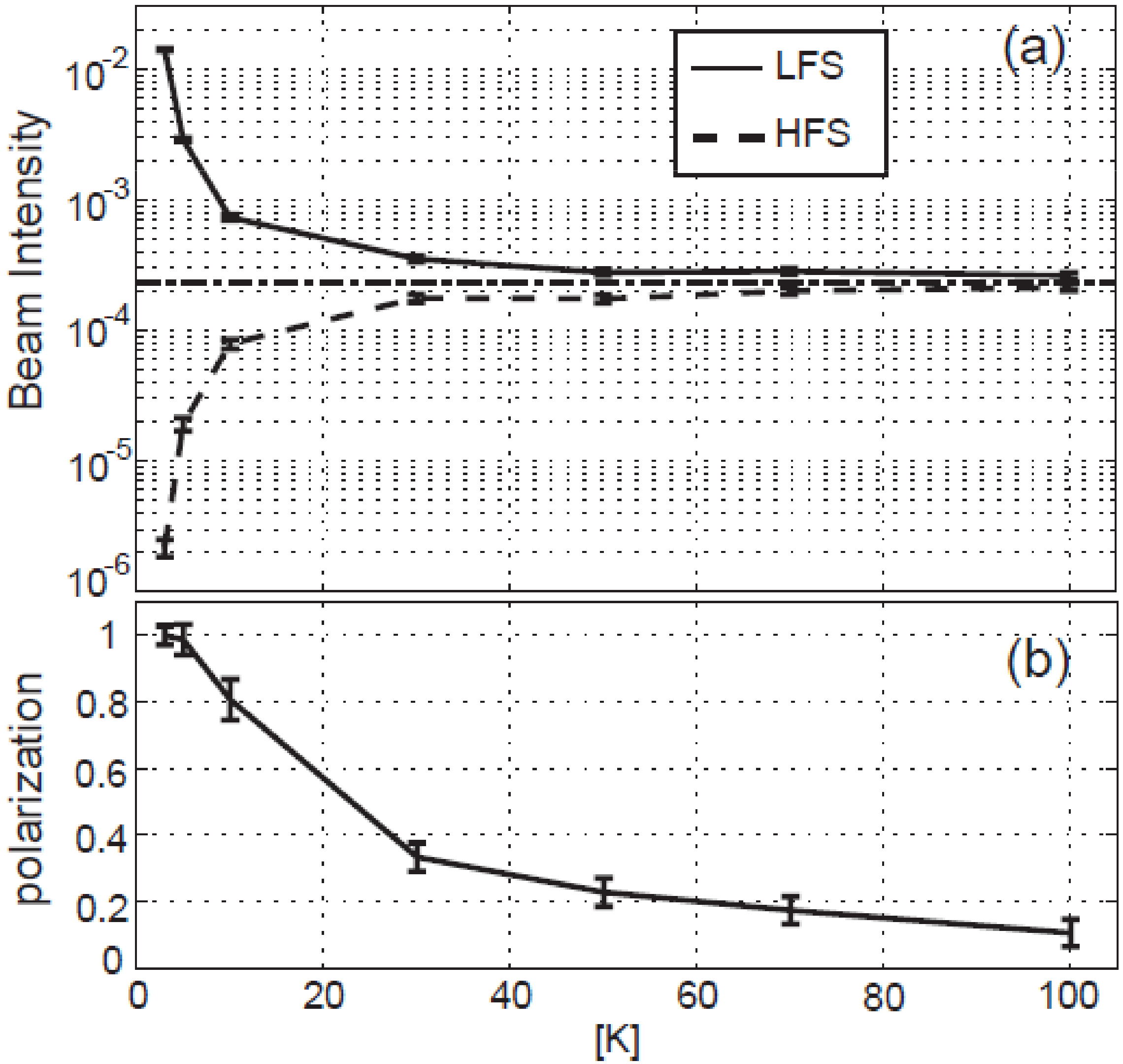
- considering electric field map
- $\mathcal{E} \sim 3.2 \times 10^8 n^{-4}$ (V/cm)
- changing F.I. well depth
- on average $n \sim 45$–50
- $n \sim 400/\sqrt{T_{e^+}}$
- observed e^+ temperature $T_{e^+} \sim 1 \times 10^2$ K



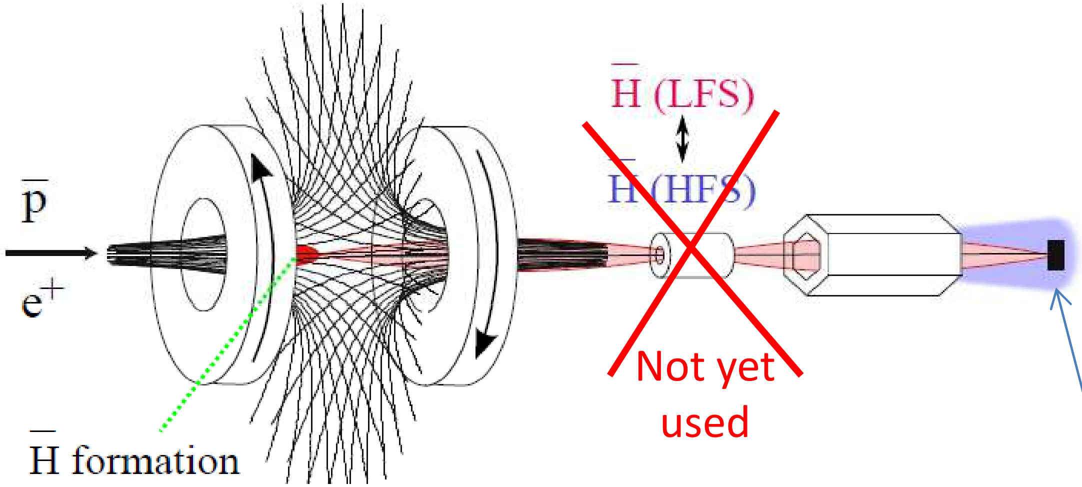


Antihydrogen beam

expected polarization of antihydrogen beam



Antihydrogen beam



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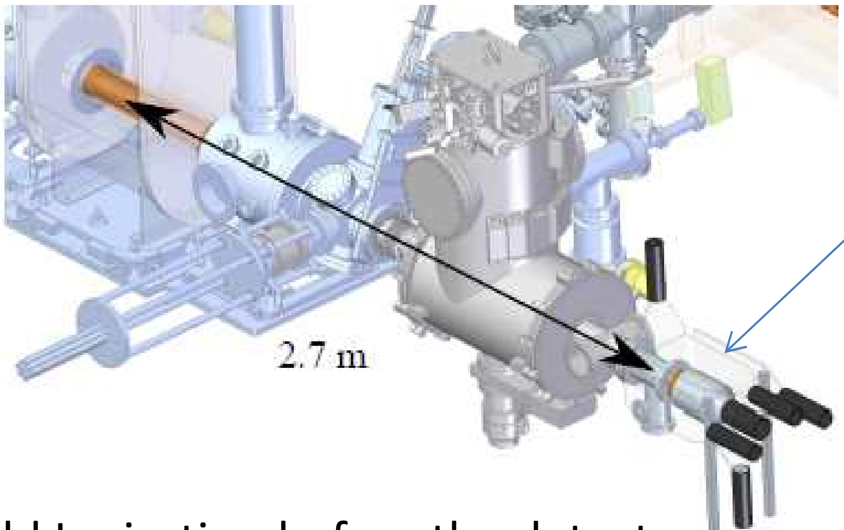
A source of antihydrogen for in-flight hyperfine spectroscopy

N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[5], M. Leali[6,7], C. Malbrunot[4,†], V. Mascagna[6,7], O. Massiczek[4], K. Michishio[8], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[9], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[1], H.A. Torii[1], L. Venturelli[6,7], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[9], Y. Kanai[3], E. Lodi Rizzini[6,7], Y. Nagashima[8], Y. Matsuda[1], E. Widmann[4] & Y. Yamazaki[1,3]

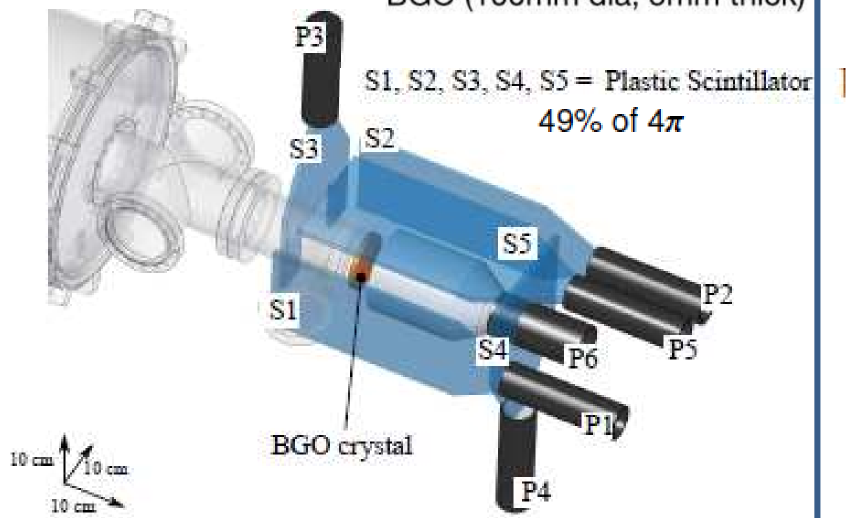


Field Ionization before the detector

→ Only Hbars with n<43 (or n<29) reach the detector

Hbar detector

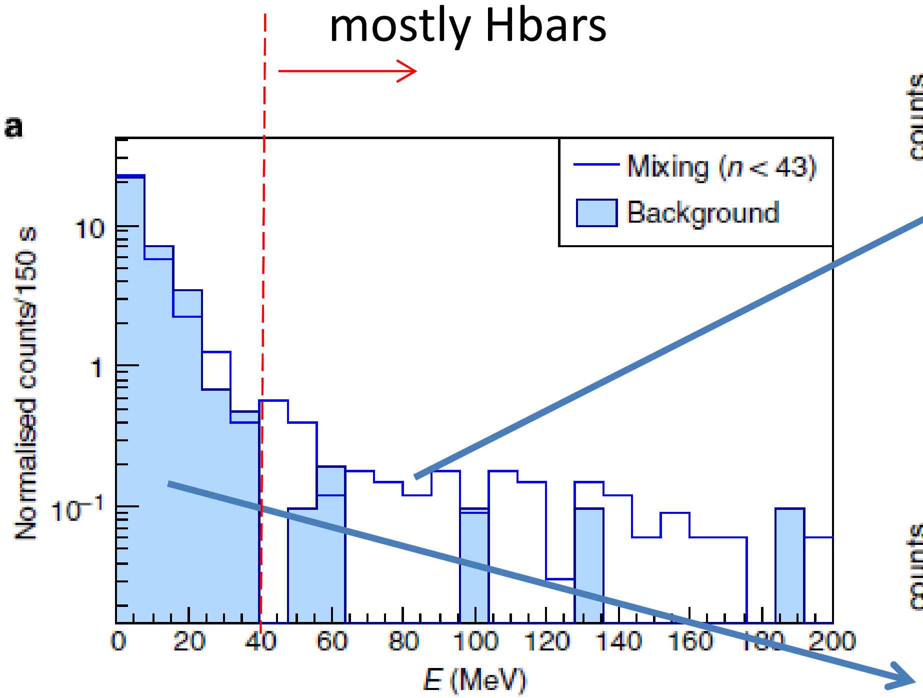
plastic +
BGO (100mm dia, 5mm thick)

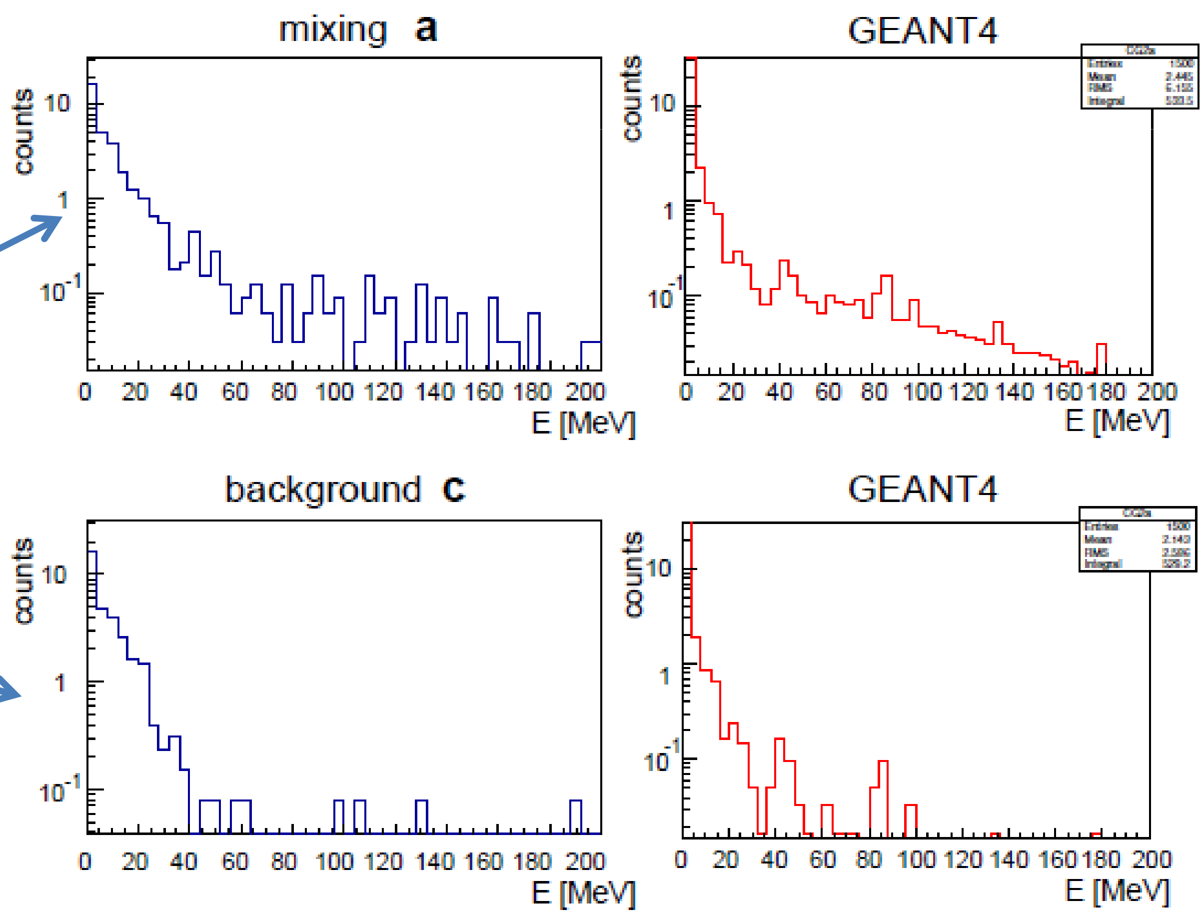


BGO measures energy deposition by Hbar annih.

coincidence: BGO AND (>1 S)

Energy deposition in the BGO





Unshaded histo → pbar-e+ mix

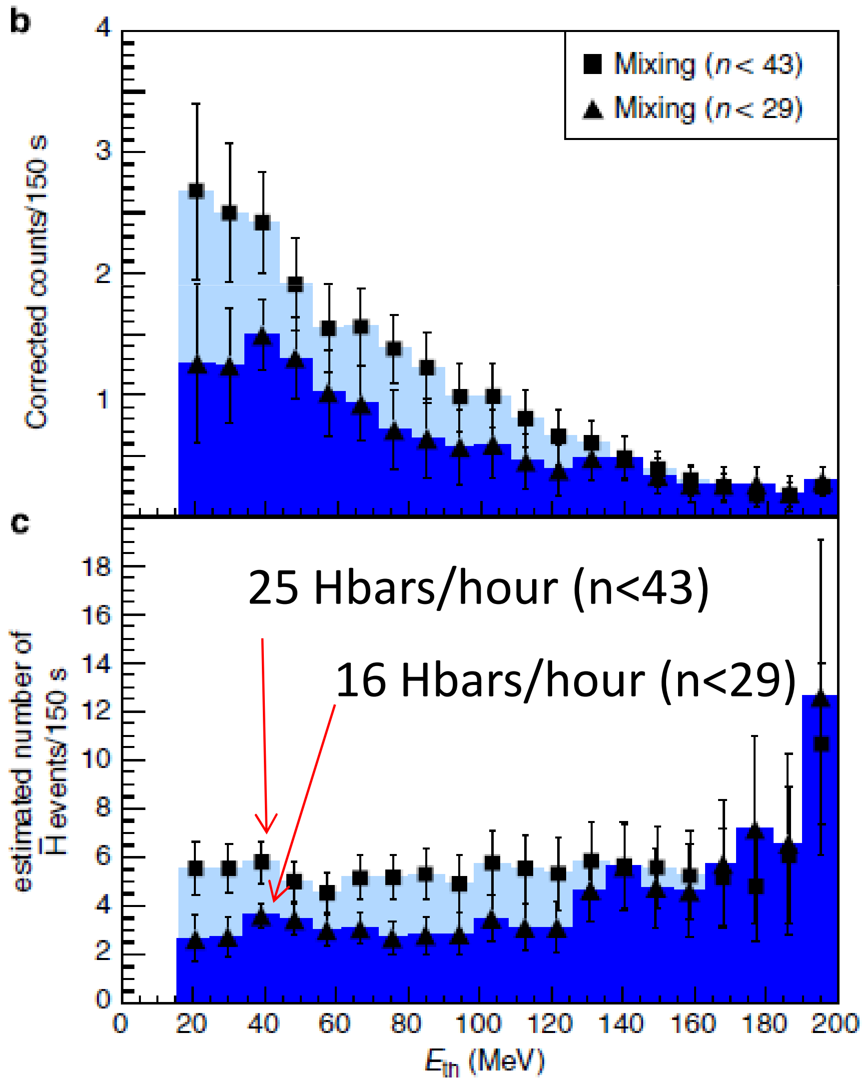
Shaded histo → pbar-e- mix (background run)

Antihydrogens reaching the BGO

a-c (see previous slide)

Integration from E_{th} to 200 MeV

After detection efficiency correction (from GEANT)



Detected antihydrogen atoms

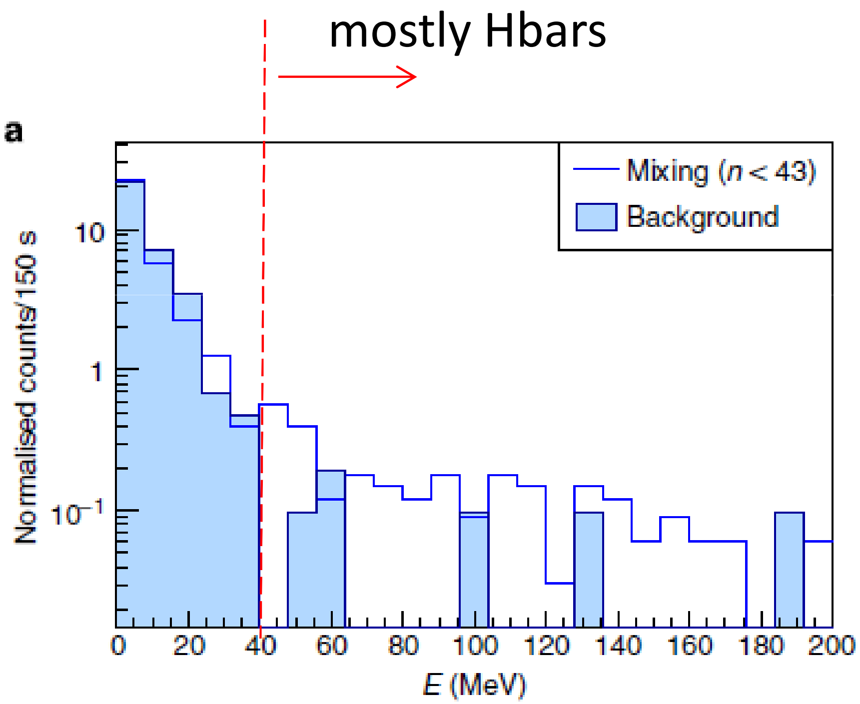


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—

Antihydrogens (n<43) detected with 5 σ significance 2.7 m far from their production region

➔ Antihydrogen beam has been produced

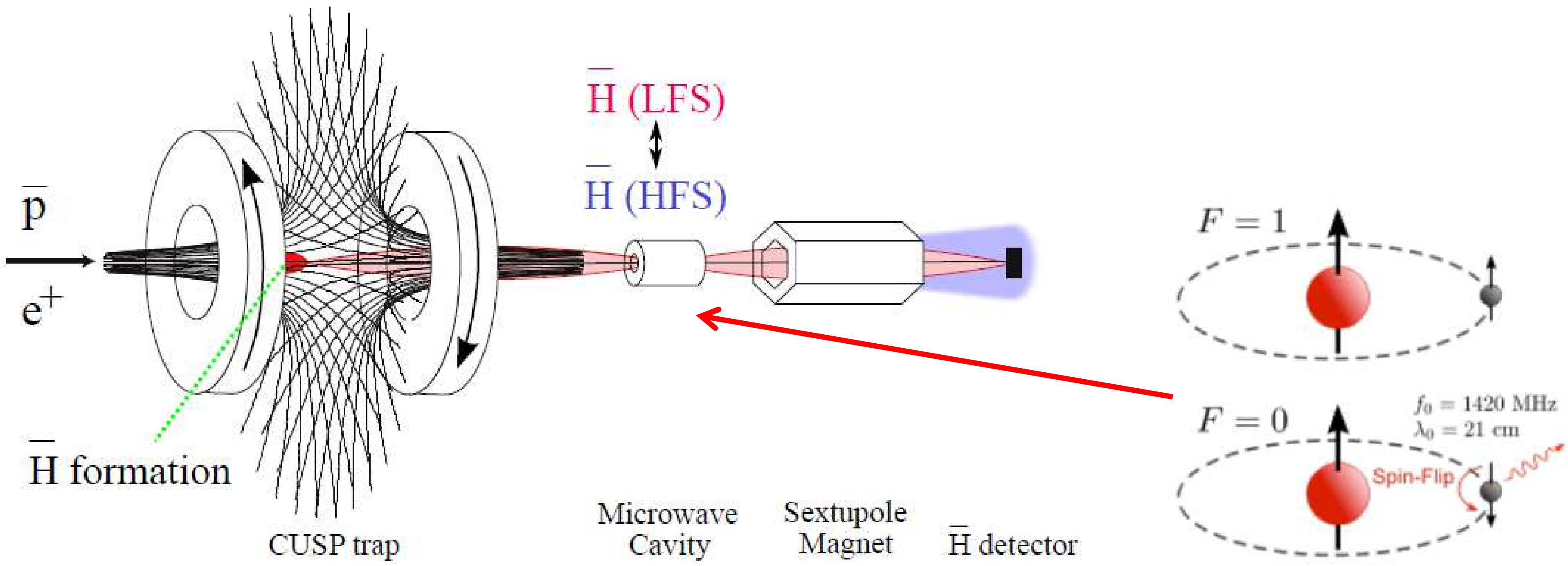
25 Hbars/hour (n<43)

16 Hbars/hour (n<29) ← significant fraction in lower n

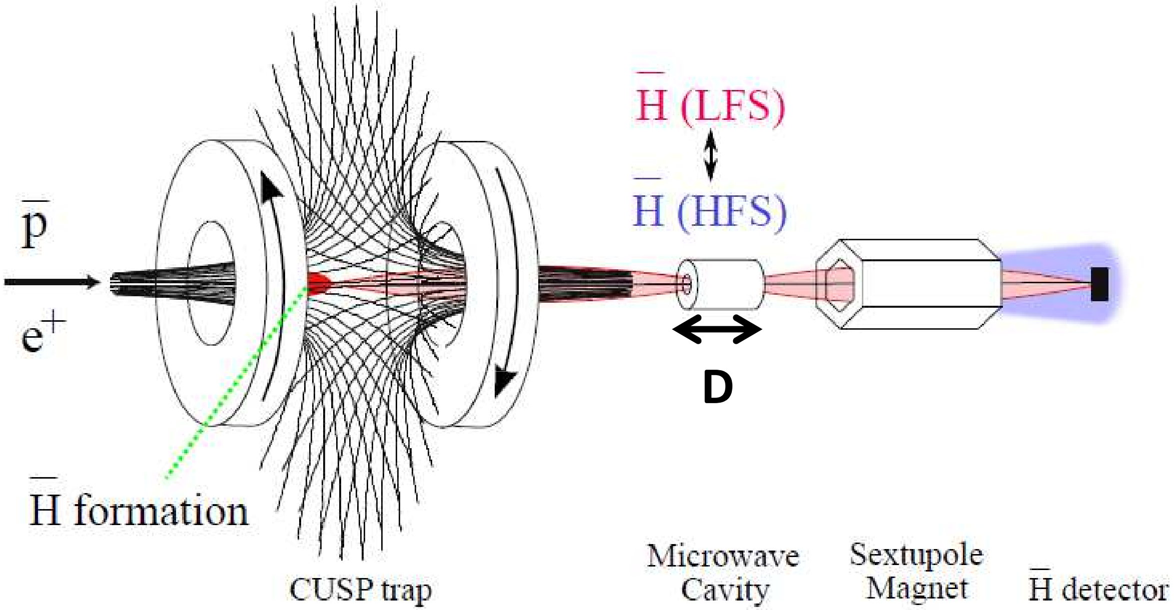
Next steps

Study and improve the beam features (Hbar numbers, temperature, n-states,…)

Introduce MW cavity



Expectations

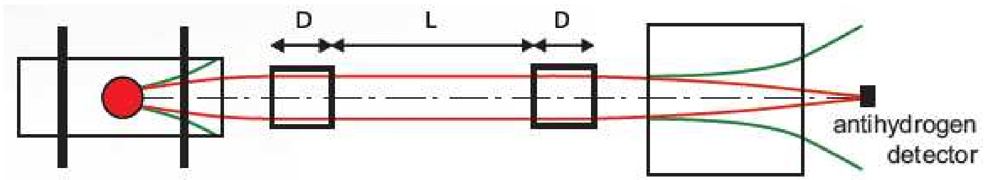


D=10 cm, v=1 km/s
1/T=10 kHz → $\Delta f/f=7\times10^{-6}$
→ $\sigma=7\times10^{-7}$

Achievable resolution:

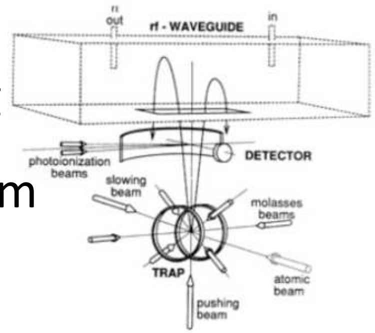
- better than 10^{-6} for T < 100 K
- 100 Hbar/s in 1S state needed (in 4 π)→ event rate=1/min.

1° improvement (Ramsey):



Linewidth reduced by D/L

Antihydrogen fountain: <-- AEGIS



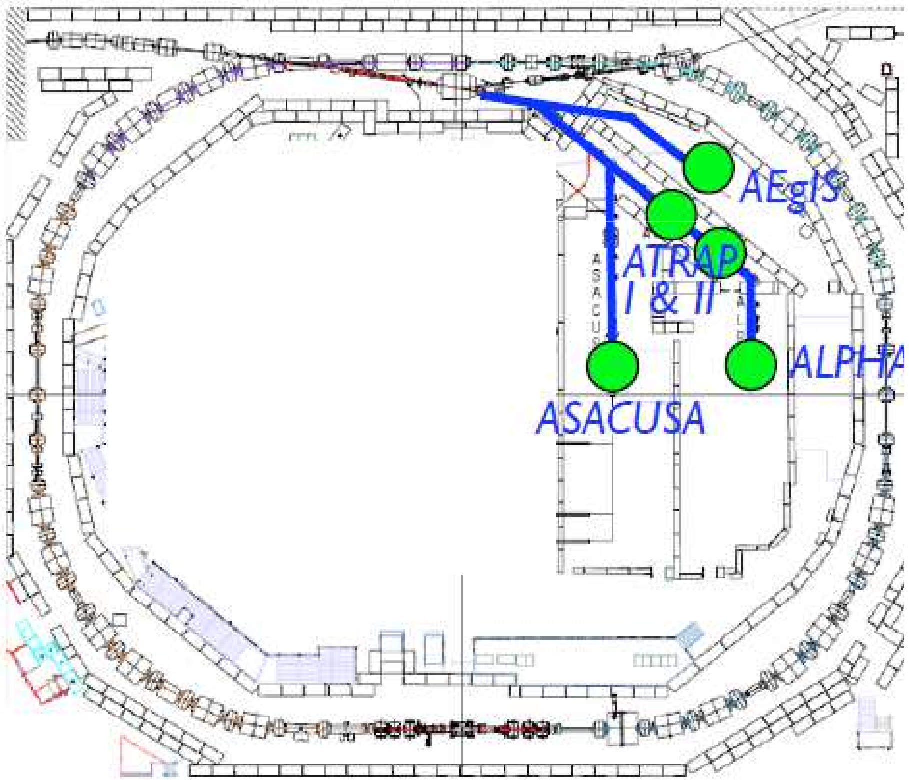
-trapping and laser cooling

- Ramsey method with L=1m

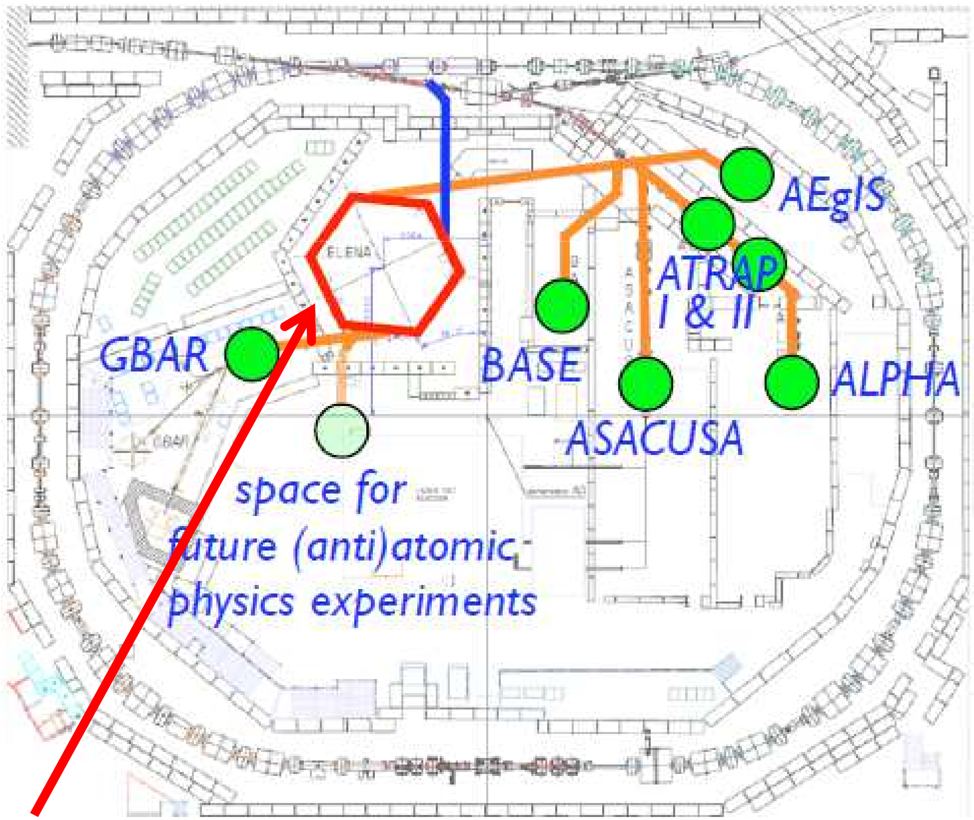
Δf ~3 Hz, $\Delta f/f \sim 2\times10^{-9}$

Future

2014



2017 →



ELENA decelerator:

5.3 MeV → 100 keV

x 100 pbars trapping efficiencies

4 experiments can run in parallel

Summary

Antihydrogen research:

- covers many fields of physics (particle, atomic, plasma, accelerators,…)
- requires modest resources (but needs time)
- promises high sensitive tests of CPT symmetry
- several improvements performed
- recent results on production, trapping and beam formation → spectroscopy era