FLAIR @ FAIR

Part 2

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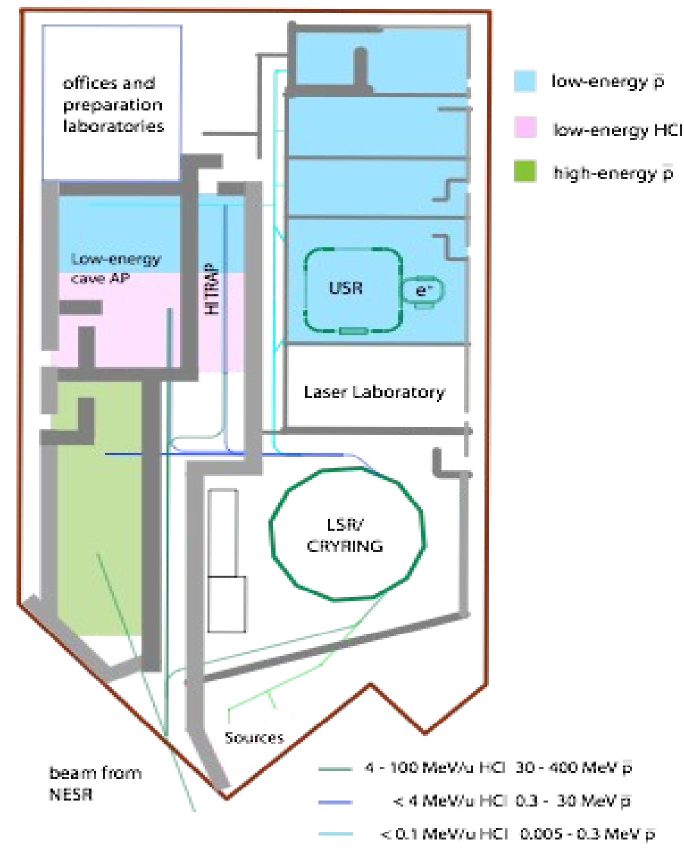


23rd Indian-Summer School of Physics
&
6th HADES Summer School

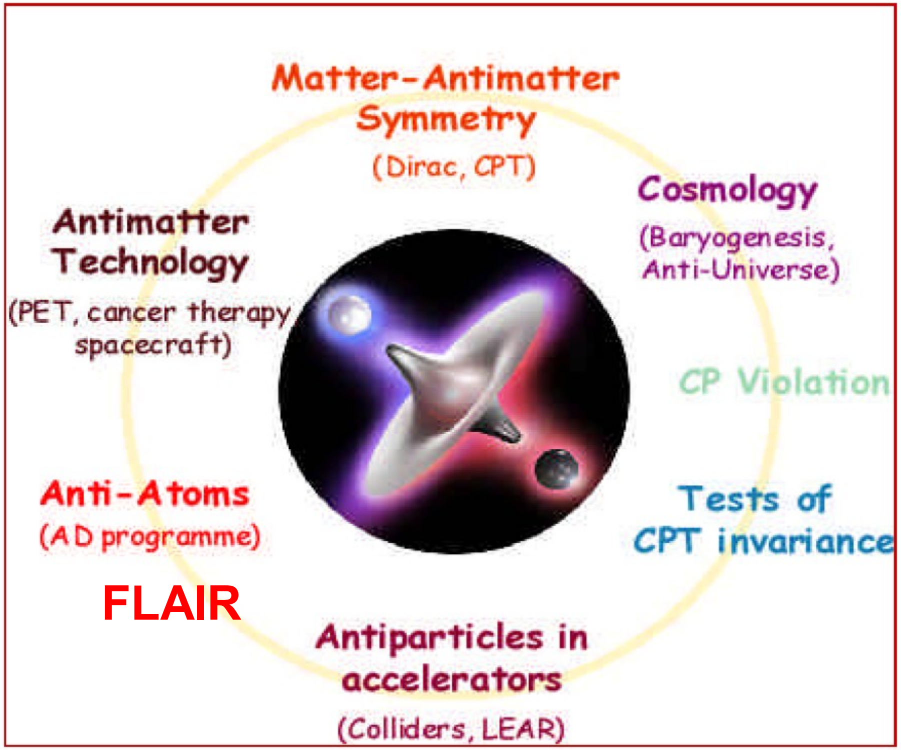
Physics @ FAIR

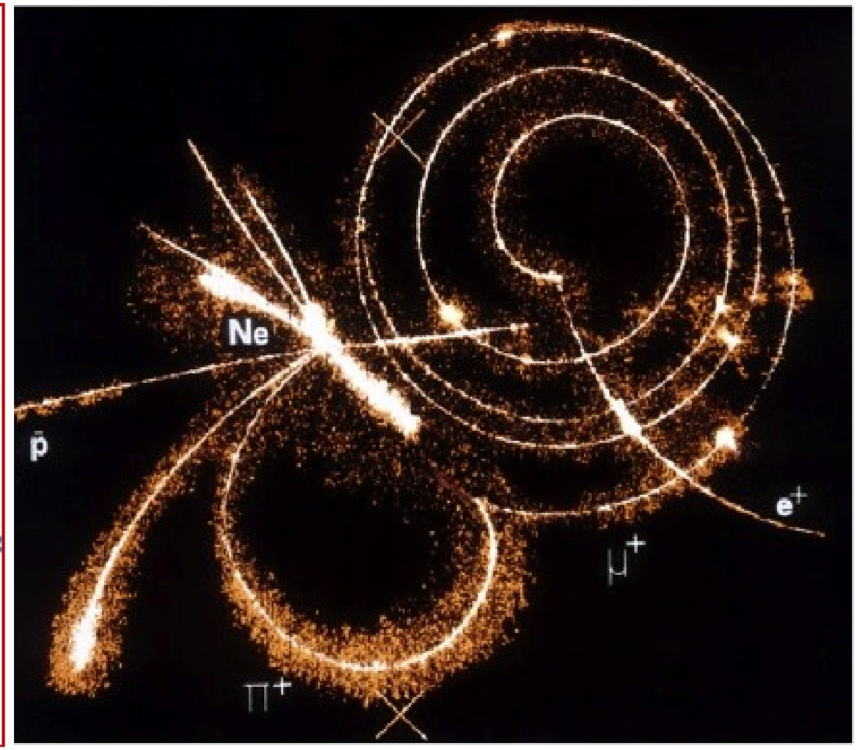
October 3-7, 2011
Rez/Prague, Czech Republic

Content

- Tests of CPT symmetry
  - General considerations: CPT
  - Experiments with antiprotons
    - Cyclotron frequency measurement of the antiproton
    - Precision spectroscopy of antiprotonic helium
    - Antihydrogen

Antimatter and Antiproton





- Matter – antimatter symmetry
- CPT

- Matter – antimatter interaction
- Antiproton annihilation in emulsion

- **in the framework of the STANDARD MODEL the general field theory requires the *Lagrangian* to be invariant under the operation of C, P and T**

- **an observation of CPT—violation would mean the existence of yet unknown properties of fields and interactions — that is why searches for effects of CPT—violation in different processes are necessary**

Fundamental symmetries C,P,T

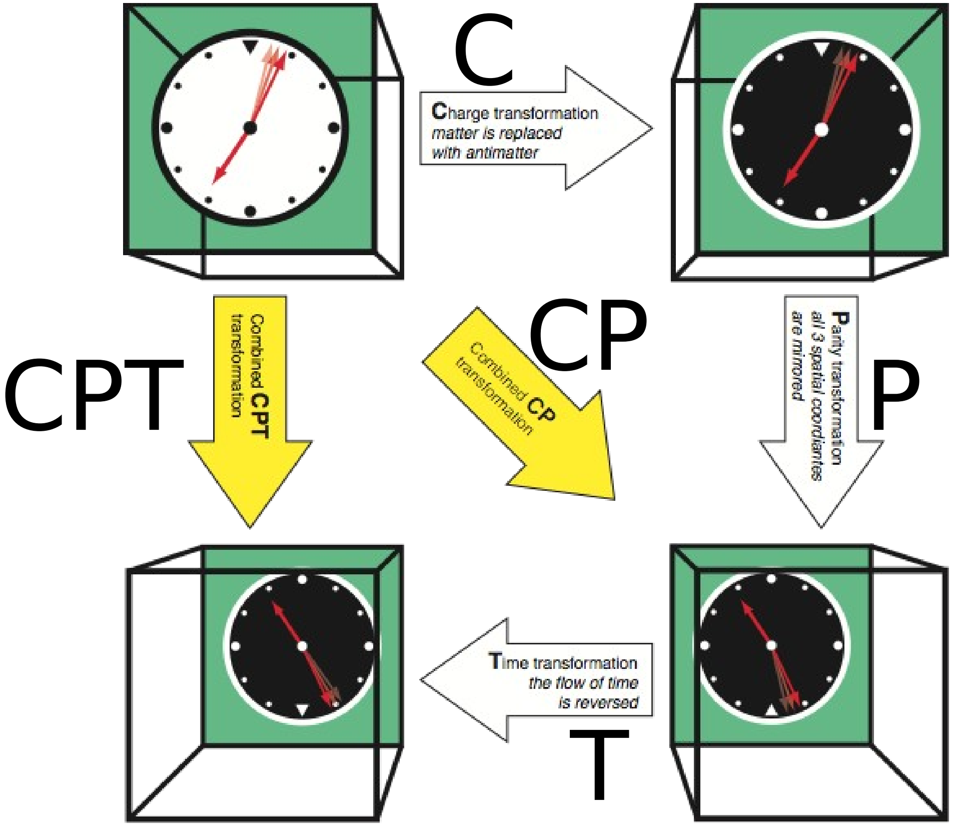
C: charge conjugation
particle ↔ antiparticle

P: parity: spatial mirror

T: time reversal

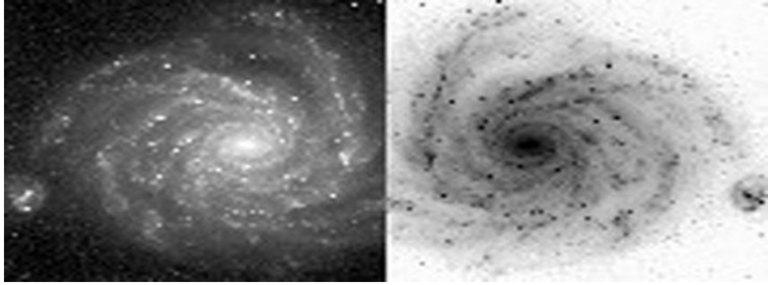
CPT theorem:
consequence of
Lorentz-invariance
local interactions
unitarity
Lüders, Pauli, Bell, Jost 1955

- all QFT of SM obey CPT
- not necessarily true for string theory

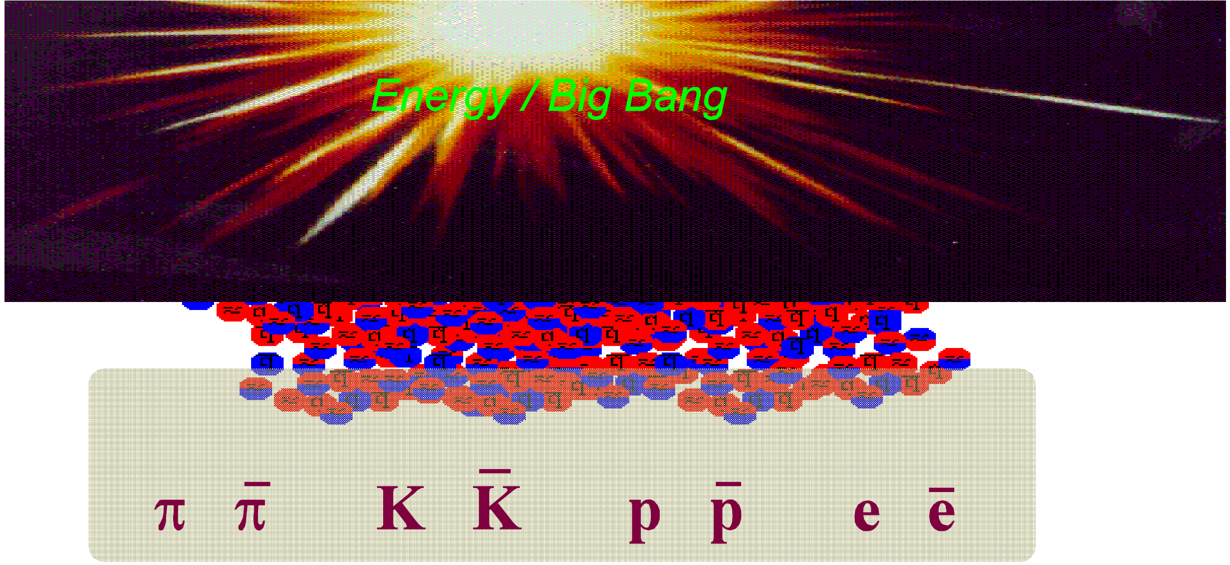


CTP → particle/anitparticle: same masses, lifetimes, g-factors, |charge|,...

CPT symmetry & cosmology



- **possible hint for CPTV → antimatter absence in the**
  universe
  - Big Bang -> if CPT holds: equal amounts matter/antimatter
  - Standard scenario for Baryogenesis (Sakharov 1967)
    - Baryon-number non-conservation
    - C and CP violation
    - Deviation from thermal equilibrium
- Currently known CP violation is not large enough
- Other source of baryon asymmetry?
  CPT non-conservation?

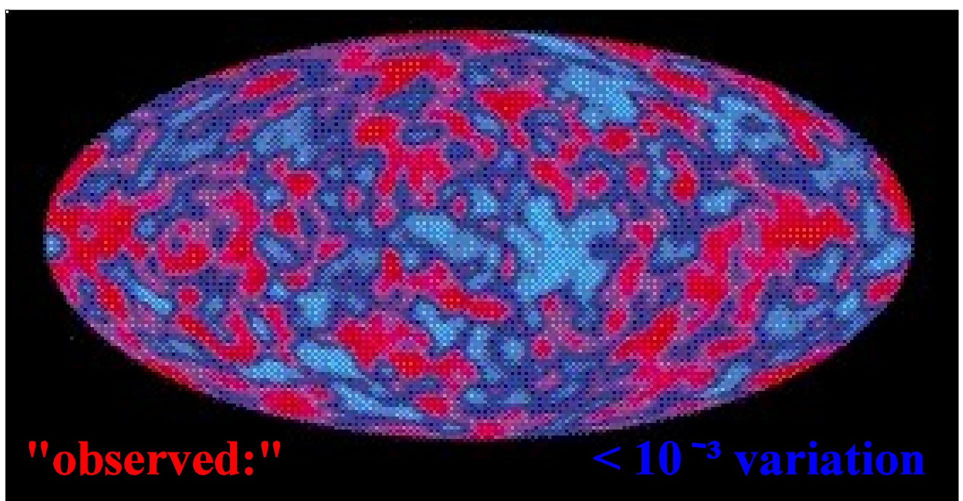


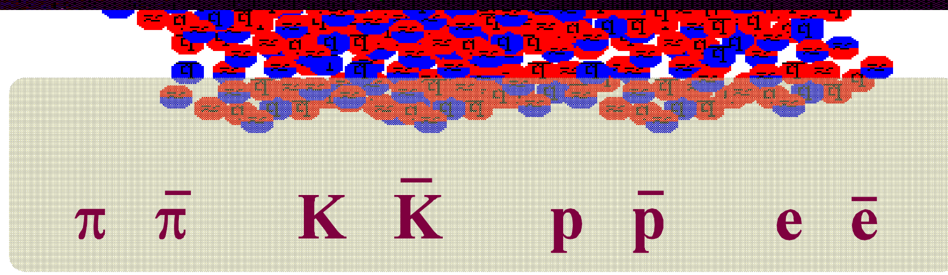
world with

no CP or CPT violation:

100 % annihilation of particle plus antiparticle to light:

only uniform distribution of 3 K γ -- quanta





world with

some CP or (even) CPT violation:

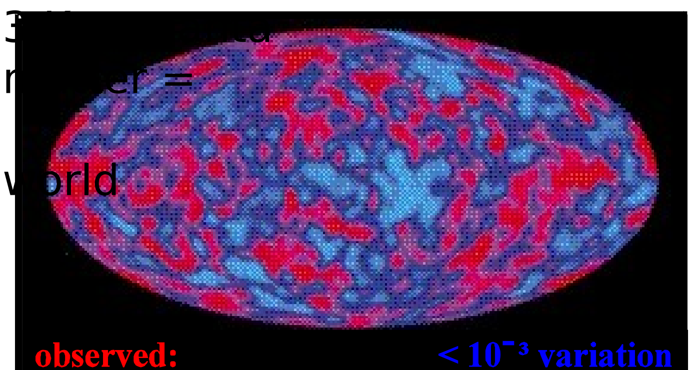
99.9999999 %

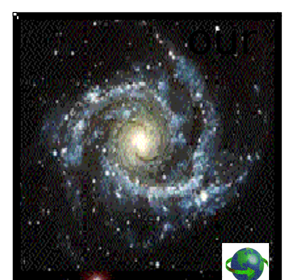
annihilation of particle

plus antiparticle to light:

uniform distribution of

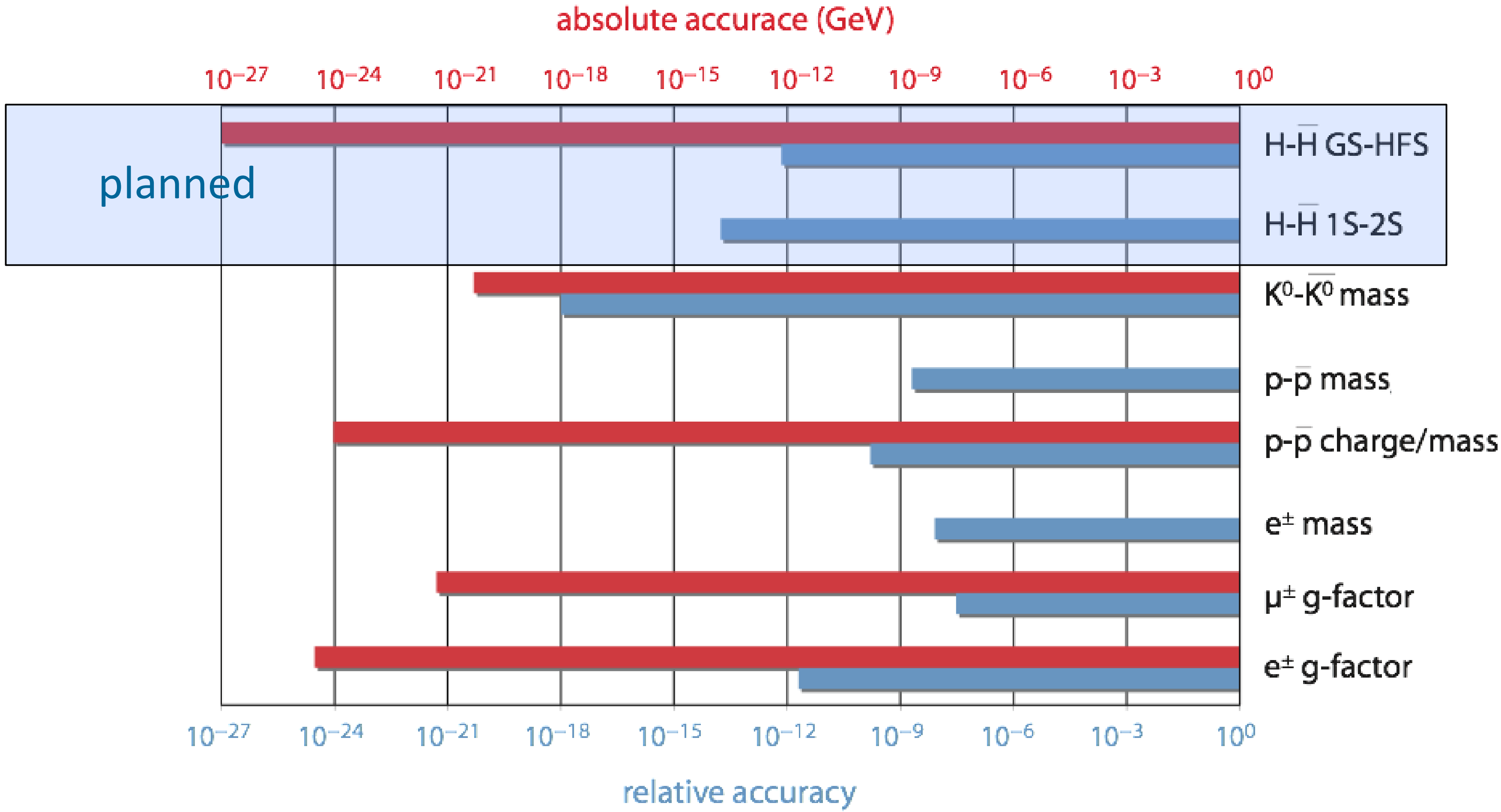
0.0000001 %





Verifications of CPT symmetry

Tests of particle/antiparticle symmetry (PDG)

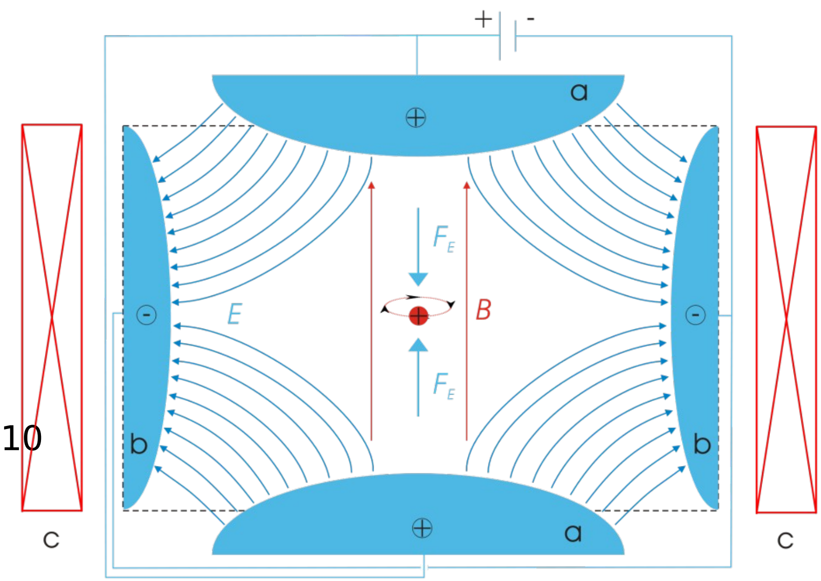


Absolute energy scale: standard model extension (Kostelecky)

Inconsistent definition of figure of merit: comparison difficult

Pattern of CPT violation unknown (P: weak interaction, CP: mesons)

Precision measurements of p^{bar}



- **Cyclotron frequency**
  - TRAP (LEAR)
  - Penning trap
  - Precision reached:

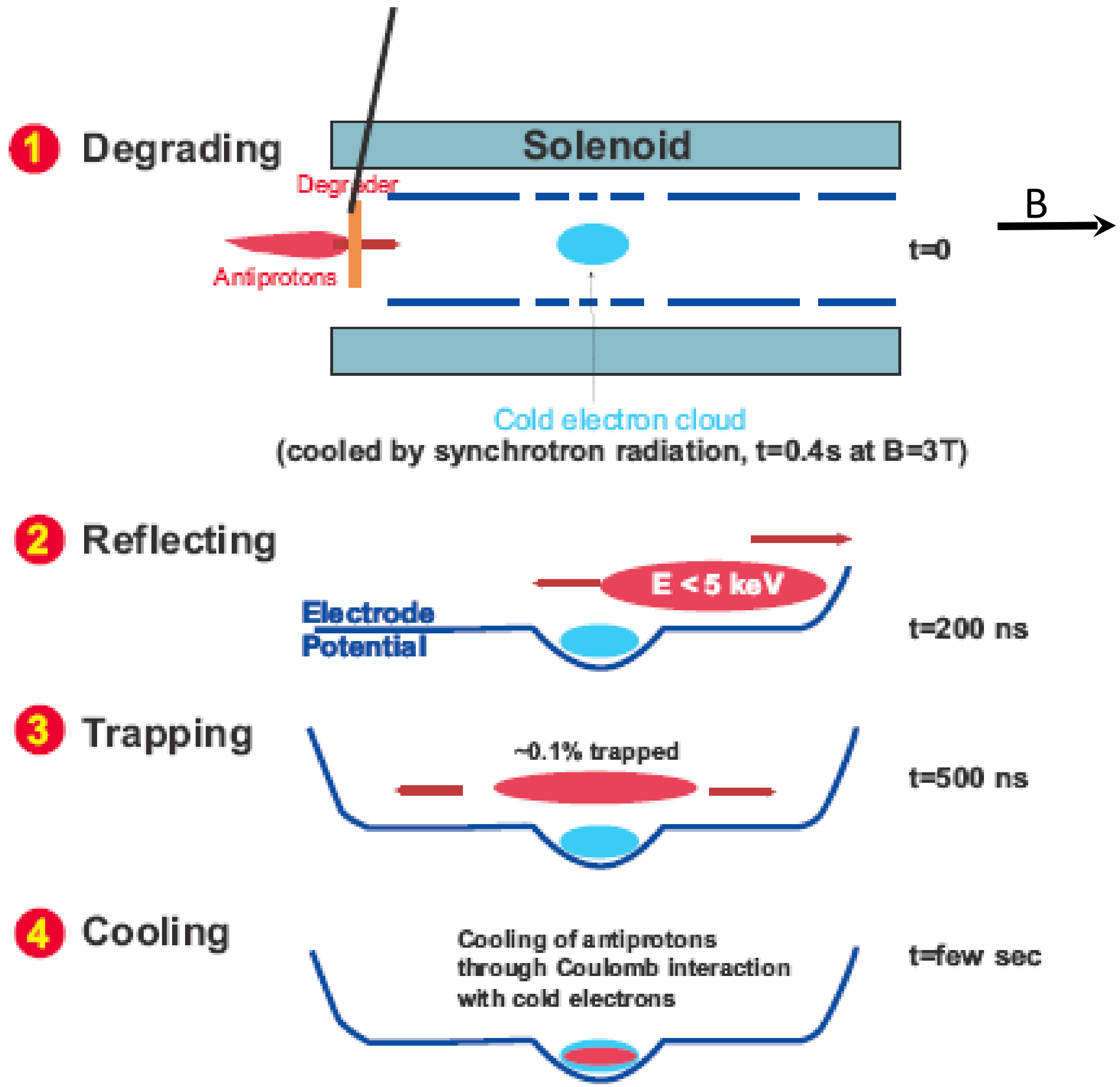
    mass-to-charge ratio 10^{-10}

- **Spectroscopy of antiprotonic helium**
  - PS205 (LEAR), ASACUSA (AD)
  - “naturally occurring” trap
  - Precision reached:

    mass ratio 10^{-9}

    magnetic moment 10^{-3}

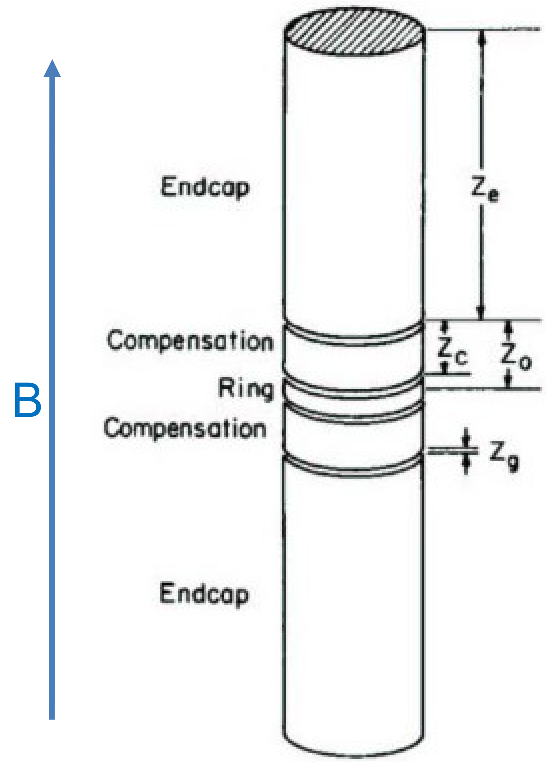
Trapping of Antiprotons
in Penning Traps

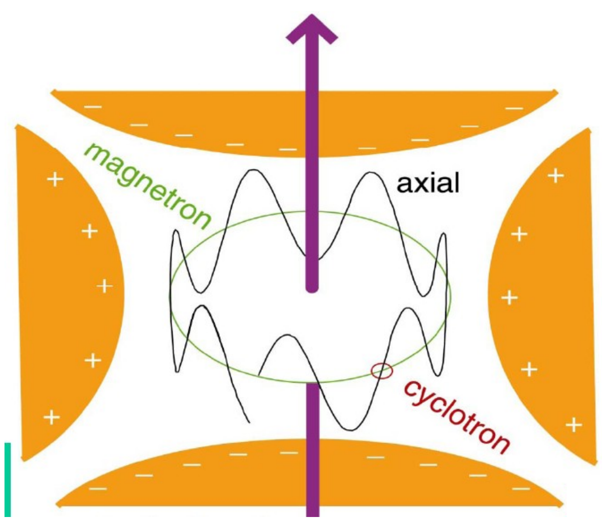


Single antiproton in Penning trap

- Open access penning trap
- Inject antiprotons
  along magnetic field axis
  – energy ~ few keV
- Precision measurement:
  only 1 antiproton
- Detection by cryogenic
  resonance circuit

$$\nu_c = \frac{q}{m} \cdot B$$





G. Gabrielse, W. Quint (LEAR)

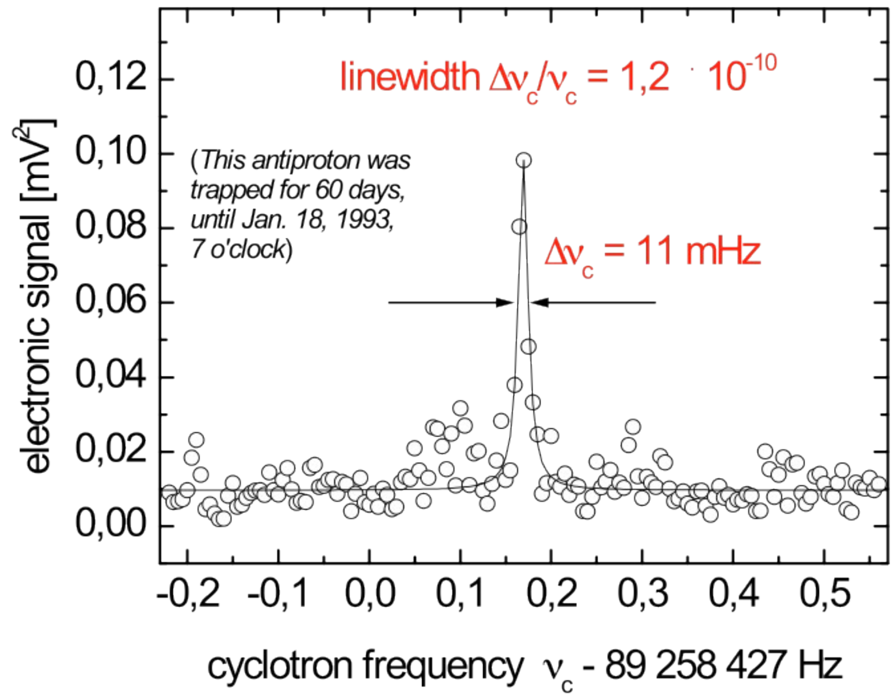
Cyclotron frequency of the antiproton

- ν_c gives Q/M
- Problem: accuracy of B?
- Compare particles in same magnetic field
  - Antiproton, proton
  - Antiproton, H^-
- Final accuracy: 10^{-10}

$$\nu_c = \frac{1}{2\pi}\frac{Q_{\bar{p}}}{M_{\bar{p}}} B$$

$$\frac{Q_{\bar{p}}}{M_{\bar{p}}} \Big/ \frac{Q_p}{M_p} = -0.999'999'999'91(9)$$

G. Gabrielse et al.,
PRL 82 (1999) 3198



G. Gabrielse, D. Phillips, W. Quint, 1993

AD experiments

ASACUSA collaboration @ CERN-AD

Atomic Spectroscopy And Collisions Using Slow Antiprotons

Spokesperson: R.S. Hayano, University of Tokyo

Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

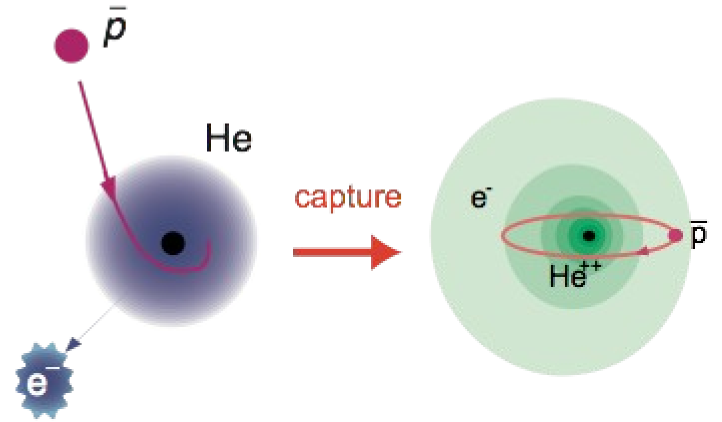
- University of Tokyo, Japan
  - College of Arts and Sciences, Institute of Physics
  - Faculty of Science, Department of Physics
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University & ISA, Denmark
- Niels Bohr Institute, Copenhagen, Denmark
- Max-Planck-Institut für Kernphysik, Heidelberg, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- University of Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen's University of Belfast, Ireland

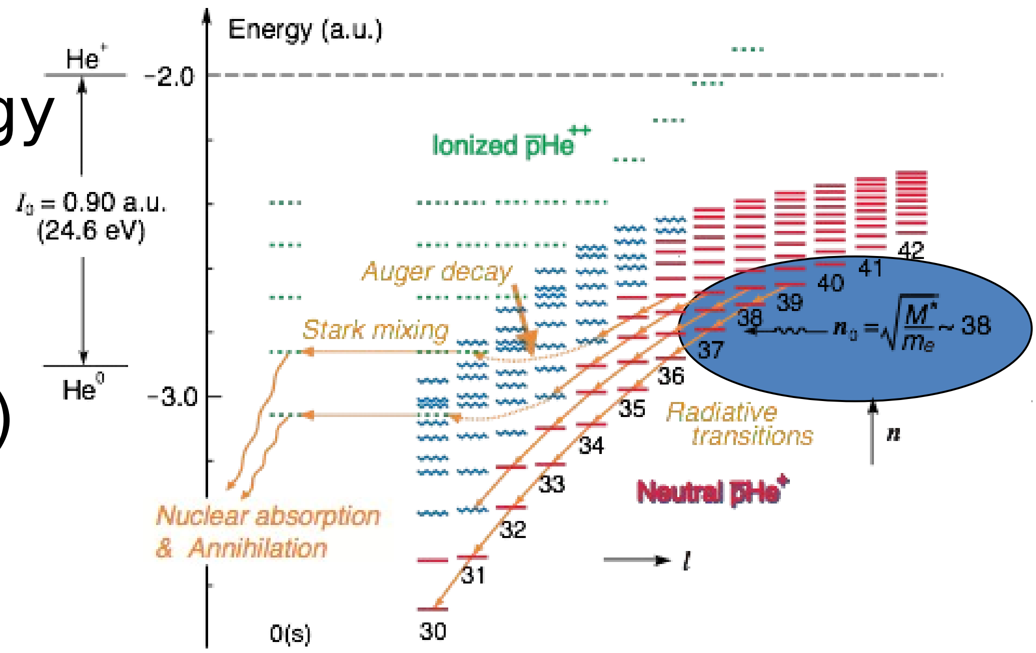
~ 44 members

Exotic atom formation

stopping of negatively charged particles in matter

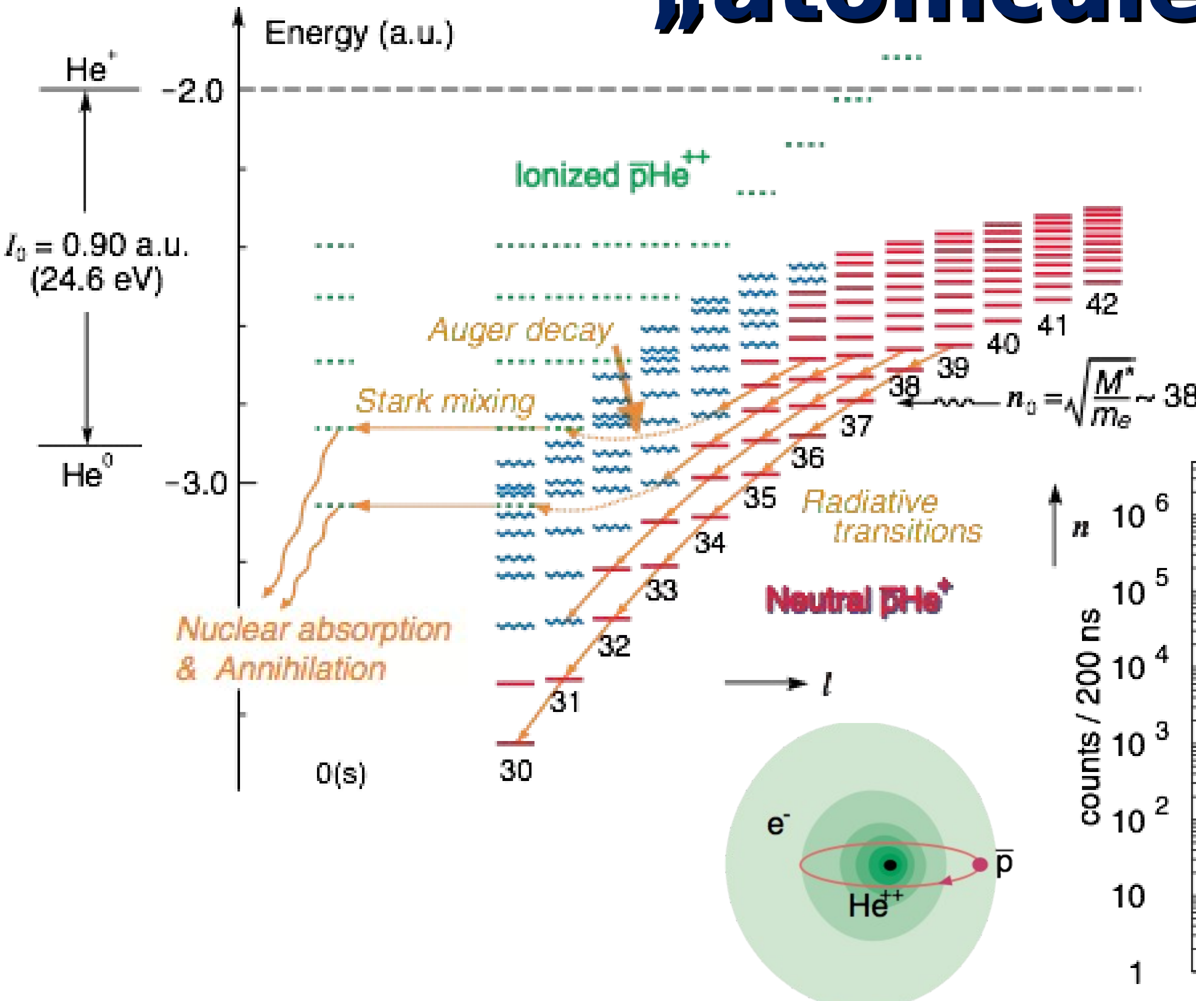
- slowing down by ionization (normal energy loss)
- end when kinetic energy < ionization energy
- capture in high-lying orbits with $n \sim \sqrt{M^*/m_e}$





example: antiprotonic helium

Antiprotonic helium „atomcule“

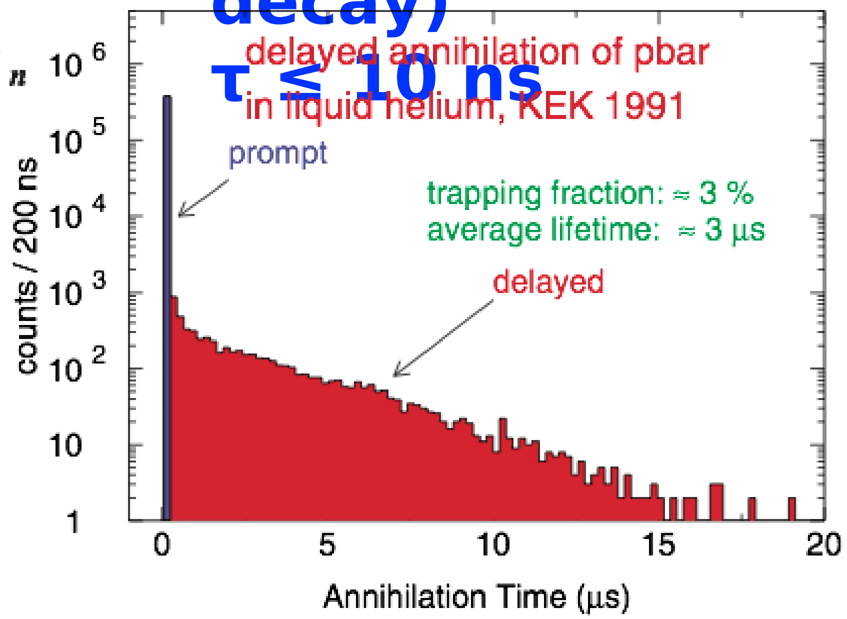


Metastable states

τ~ µs

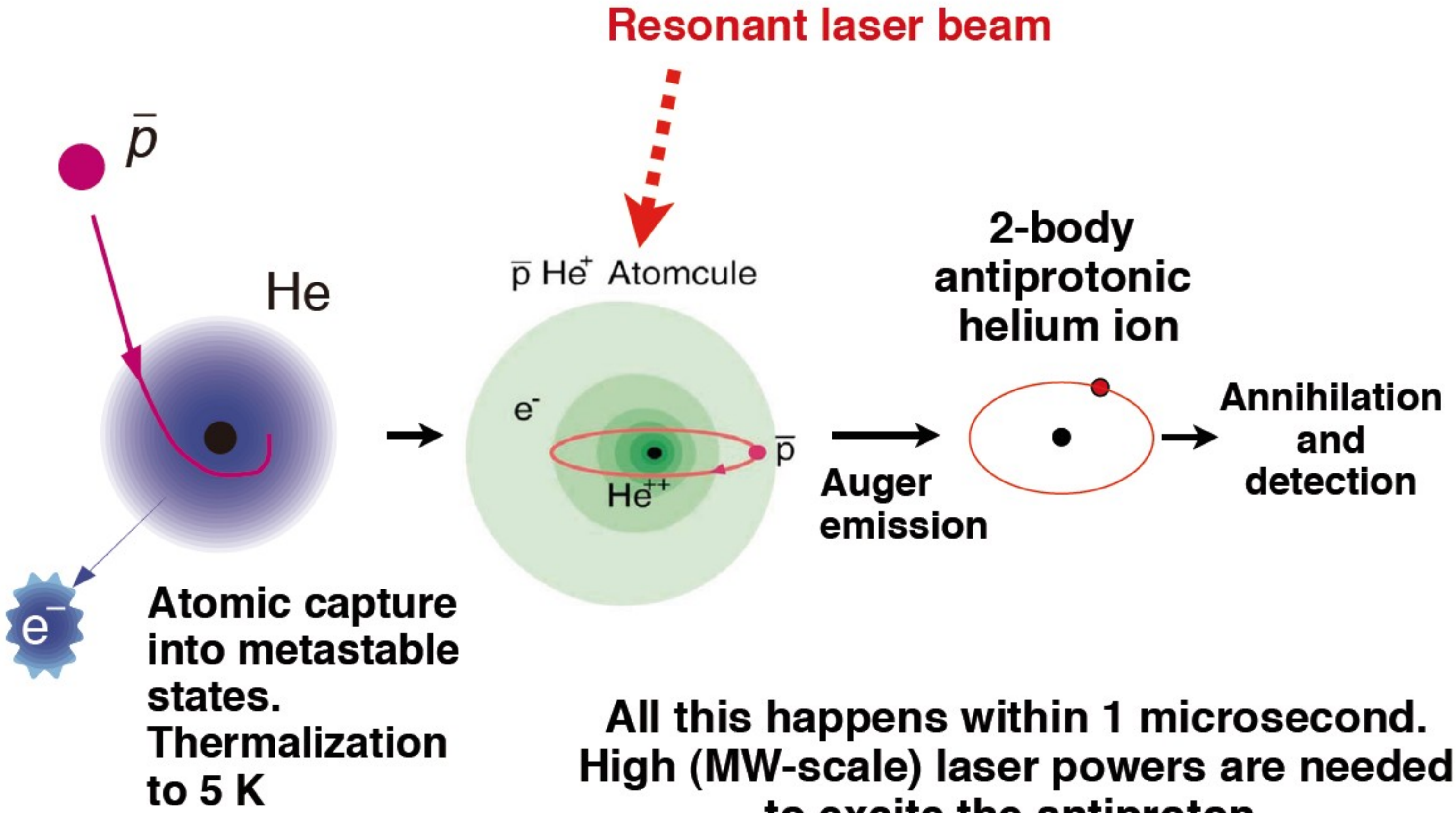
short-lived states (Auger decay)

τ ≤ 10 ns



- ➢ possibility of precision spectroscopy
  due to metastable states

Laser spectroscopy of $\bar{p}^4He$

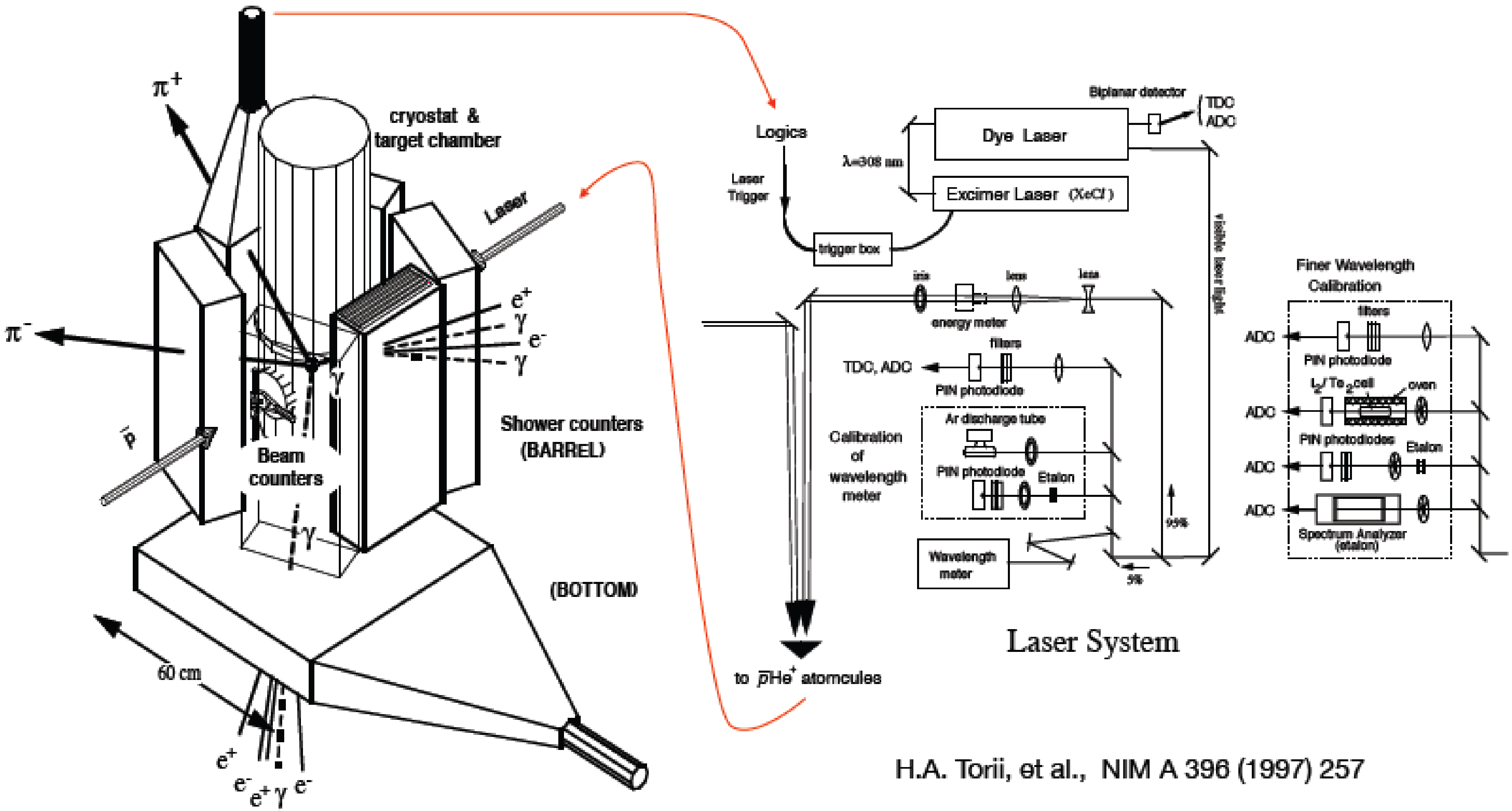


All this happens within 1 microsecond. High (MW-scale) laser powers are needed to excite the antiproton.

PS205 setup

LEAR ultra-slow extracted $\bar{p}$.

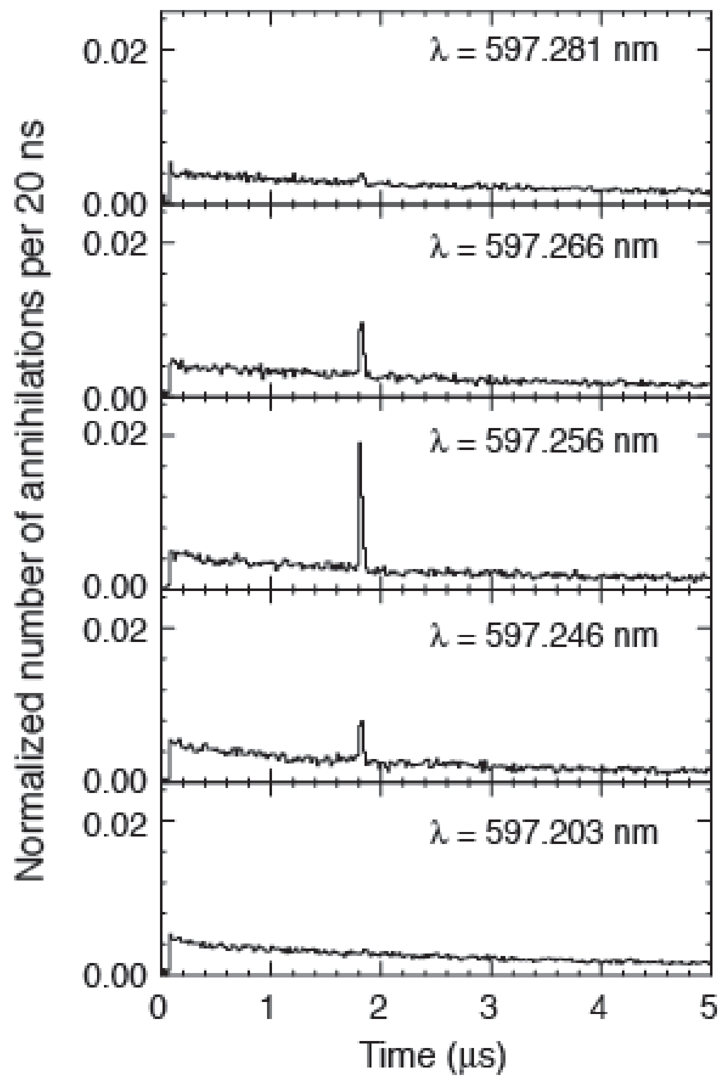
Laser randomly triggered for each $\bar{p}$He candidate



H.A. Torii, et al., NIM A 396 (1997) 257

An example, (n,l)=(39,35)→(38,34)

N. Morita, et al., Phys. Rev. Lett. 72 (1994) 1180.



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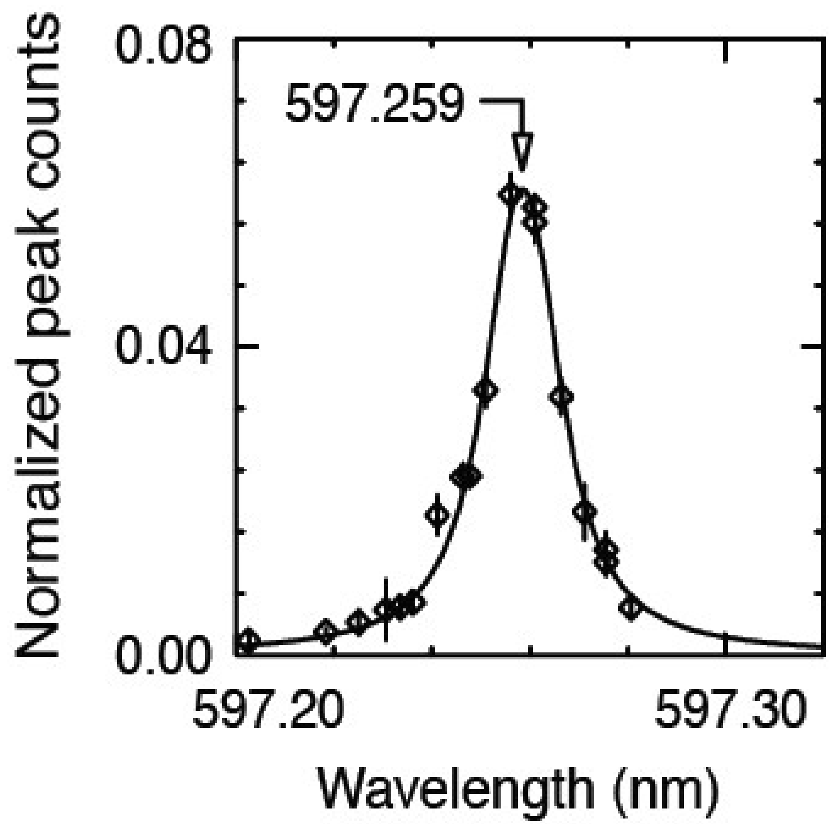


$(n,L)=(39,35)\rightarrow(38,34)$ in $\overline{p}^4He$

Non-relativistic energies	501,972,347.9 MHz
Relativistic correction for e^-	-27,526.1 MHz
e^- anomalous magnetic moment	233.3 MHz
One-loop transverse photon self-energy	3818.1 MHz
One-loop vacuum polarization	-122.5 MHz
Relativistic correction for helium/antiproton	37.3 MHz
One transverse photon exchange order α^2	-34.7 MHz
One transverse photon exchange order α^3	0.8 MHz
Two-loop QED corrections	0.9 MHz
Finite size of nucleus	2.4 MHz
α^4 corrections	-2.6 MHz
$\alpha^5 \ln\alpha$ corrections	< 1.3 MHz
Transition energy	501 948 754.9 (1.3)(0.5) MHz
Experiment (PRL 2006)	501 948 752 (4) MHz

PHYSICAL REVIEW A VOLUME 54, NUMBER 3 SEPTEMBER 1996

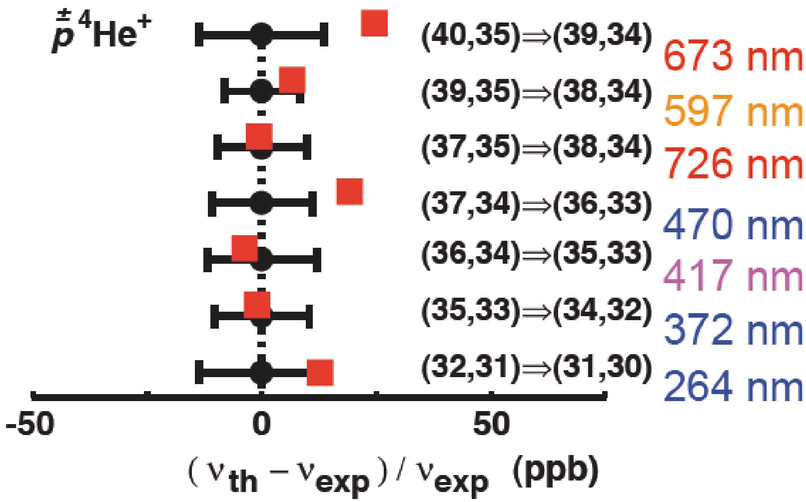
Variational calculation of energy levels in p He$^+$ molecular systems

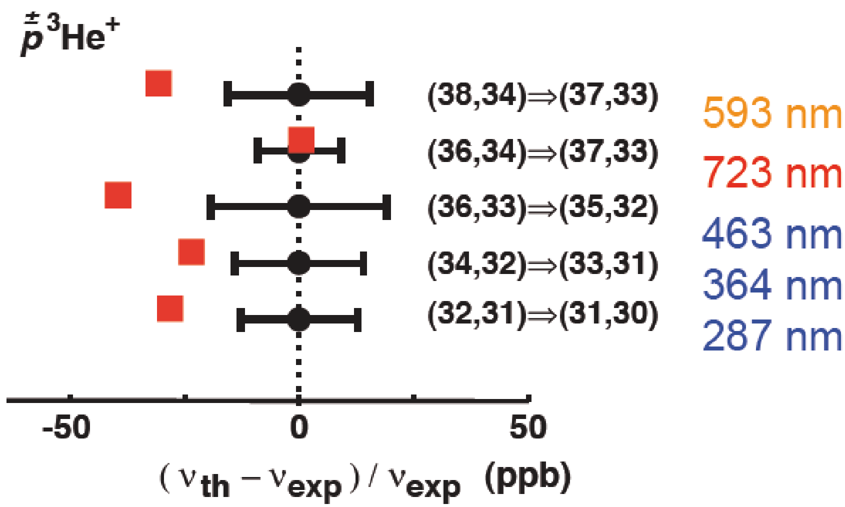
V. I. Korobov
Joint Institute for Nuclear Research, Dubna, Russia
(Received 29 April 1996)

Experimental results and theory

Status as of 2006

M. Hori et al., PRL 96, 243401 (2006)

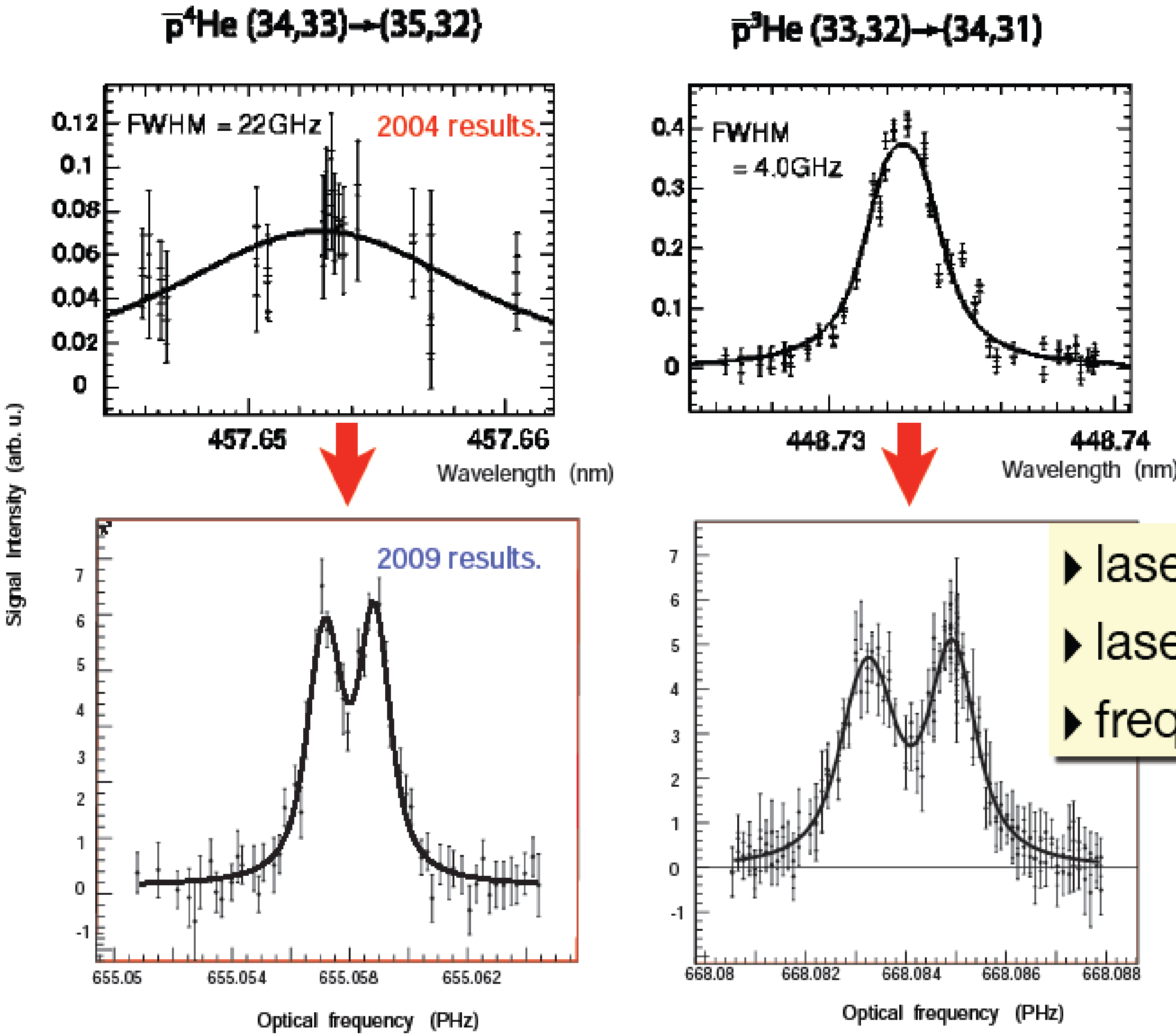




For 4 transitions in $\bar{p}\,^3He$ ν_{exp} larger than ν_{th} by 20-40 ppb

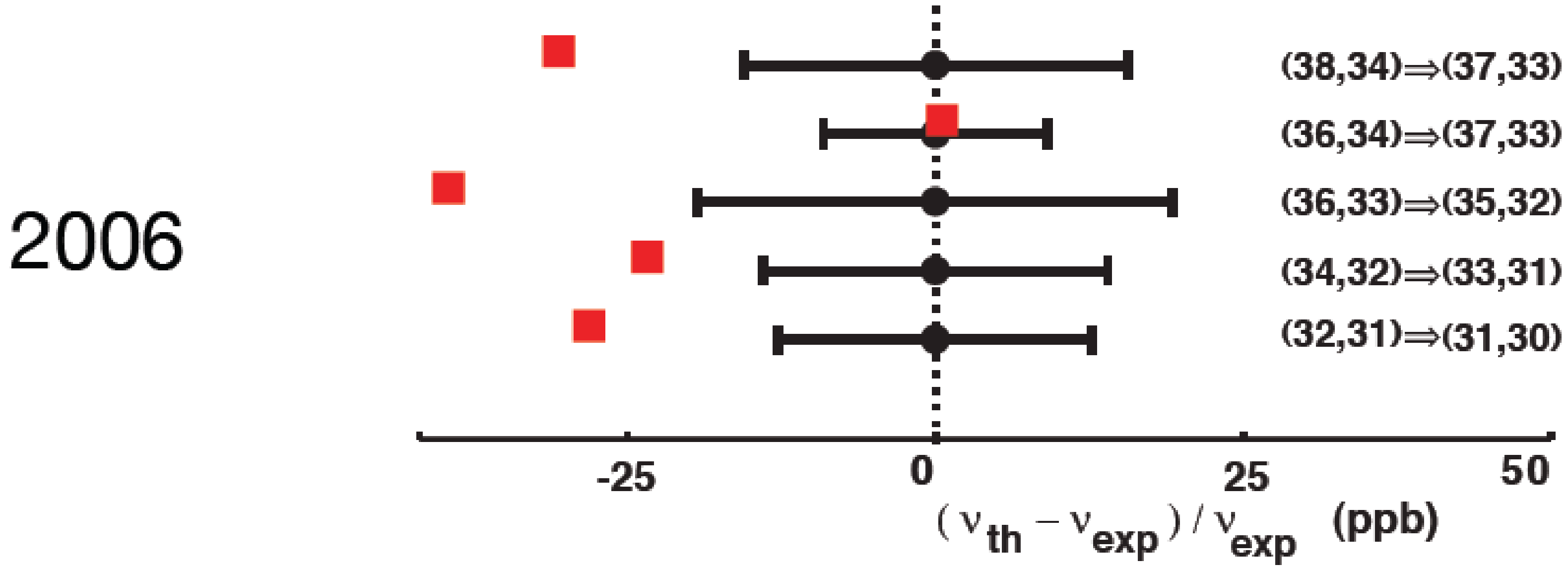
ASACUSA

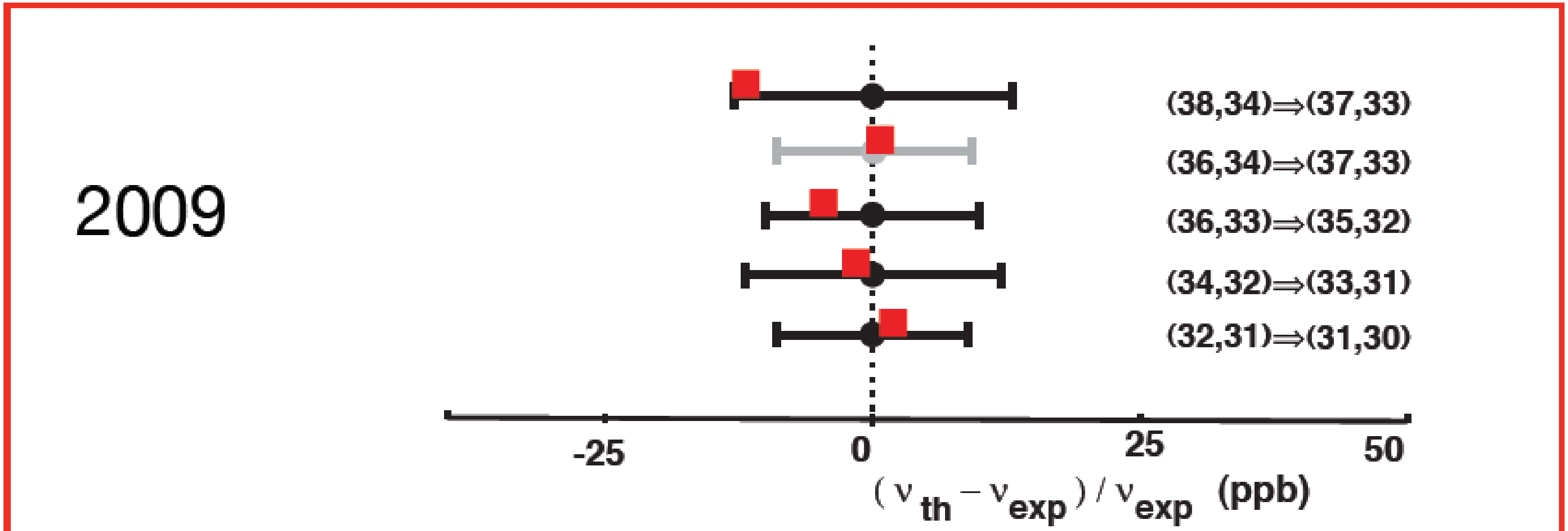
2004 vs 2009



- laser spectral resolution x100
- laser power x5
- frequency stability x200

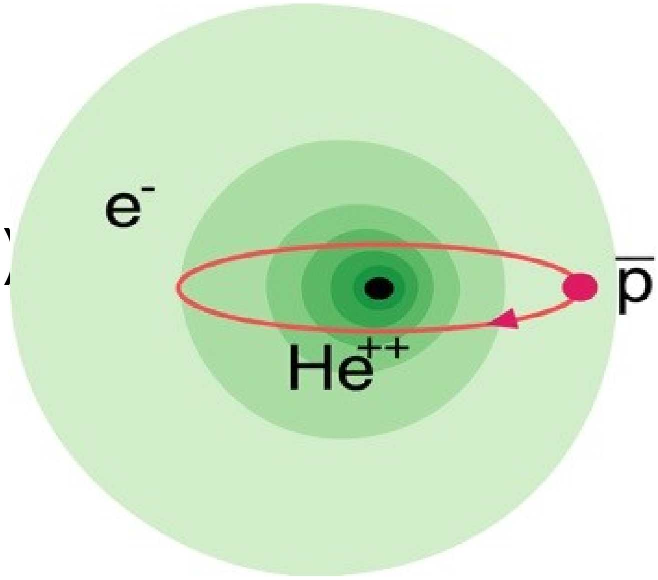
$\overline{p}{}^3He$ 2006 vs 2009

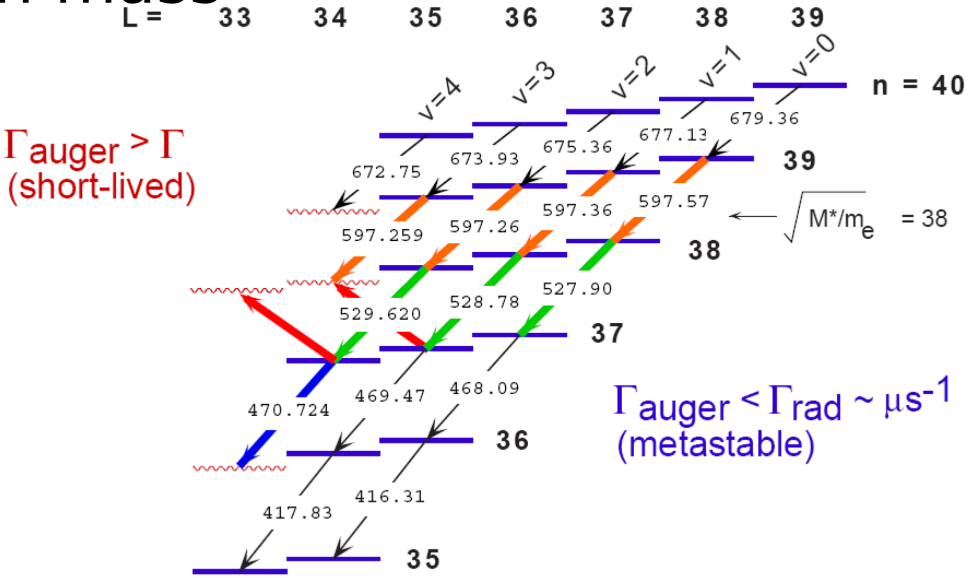




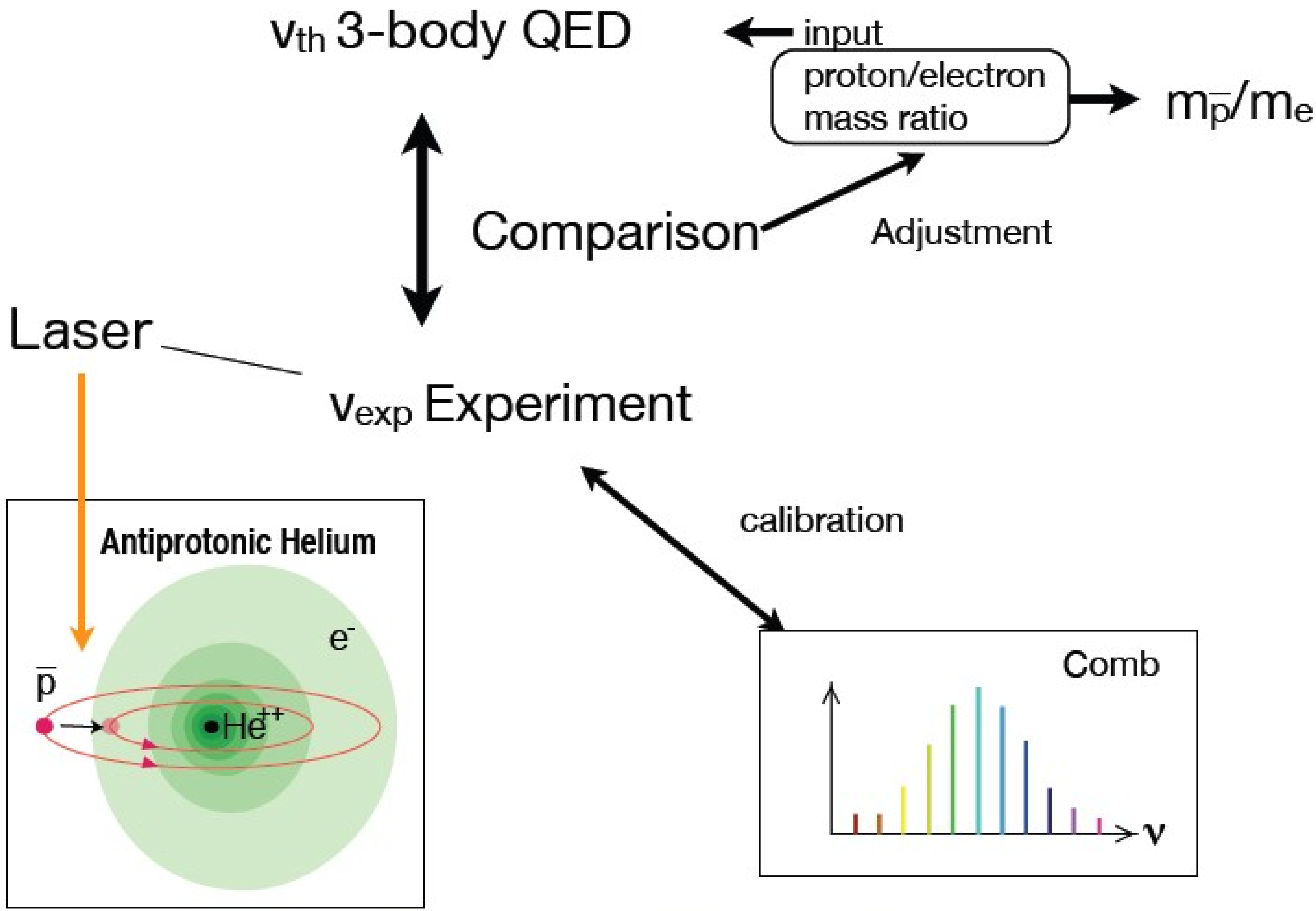
Antiprotonic Helium and CPT

- Three-body system He^{++}-e^{-}-p^{bar}
  – p^{bar} in highly excited,
  near circular states (n,l) ~ (38,37)
- Easy formation
- Comparison to 3-body QED calculations
  that use proton mass





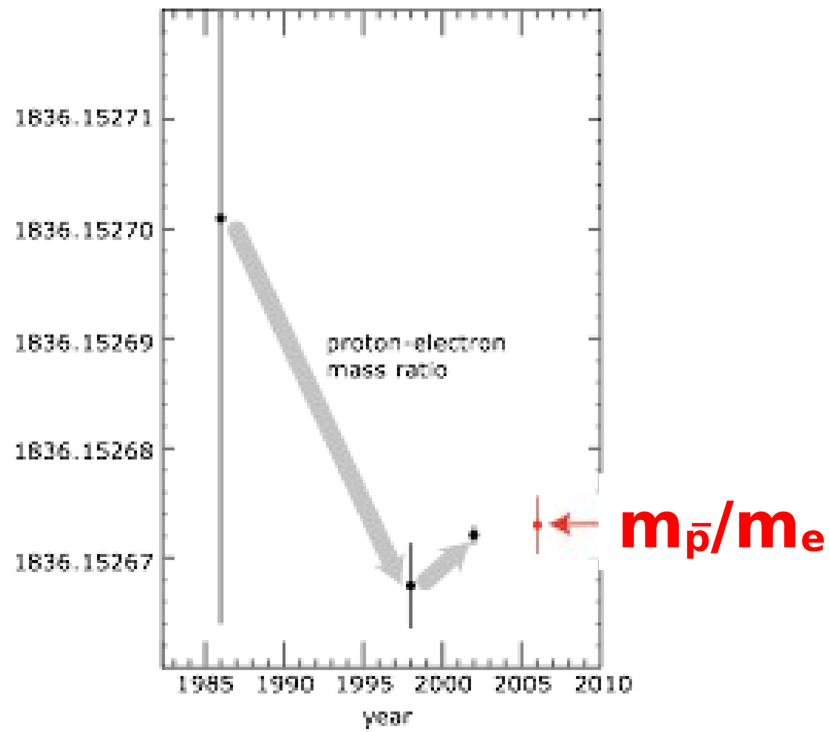
$m_{\bar{p}}/m_e$



ν_{th} 3-body QED
input
proton/electron mass ratio
$m_{\bar{p}}/m_e$
Comparison
Adjustment
Laser
ν_{exp} Experiment
calibration
Antiprotonic Helium
e^-
$\bar{p}$
He^{++}
Comb
ν

Antiproton-electron mass ratio

- Compare experiment to three-body QED theory
- CODATA value m_p/m_e changes over time
- ➢ antiproton mass measurement agrees with latest value for proton (test of CPT)



M. Hori et al. PRL 96 (2006) 243401

Two-photon laser spectroscopy of antiprotonic helium and the antiproton-to-electron mass ratio

Masaki Hori, Anna Sótér, Daniel Barna, Andreas Dax, Ryugo Hayano, Susanne Friedreich, Bertalan Juhász, Thomas Pask, Eberhard Widmann, Dezső Horváth, Luca Venturelli & Nicola Zurlo

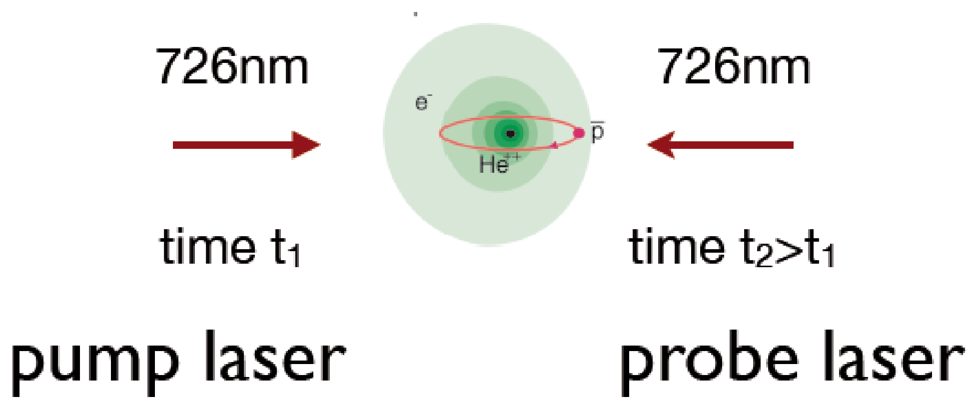
Nature 475, 484–488 (28 July 2011) doi:10.1038/nature10260
Received 12 April 2011 Accepted 26 May 2011 Published online 27 July 2011

$m_{\bar{p}}/m_e =$

$\bar{p}^3He$ 2009-2010

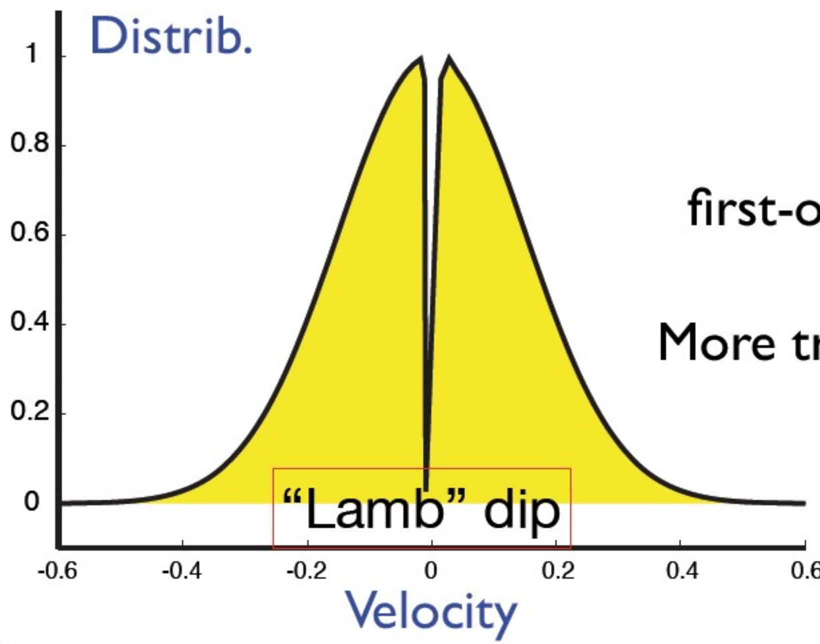
- Preliminary results appear to show convergence between theory-experiment for $\bar{p}^3He$ at 10-20 ppb level.
- But this is still ongoing work.
  - All 12 transitions must be measured under similar conditions.
  - Power shifts, more background measurements.
- Building a colder cryogenic target (1.8K) to reduce thermal Doppler broadening

1.4 Doppler-free “hole-burning” spectroscopy (being developed)



Doppler-free "hole-burning" spectroscopy

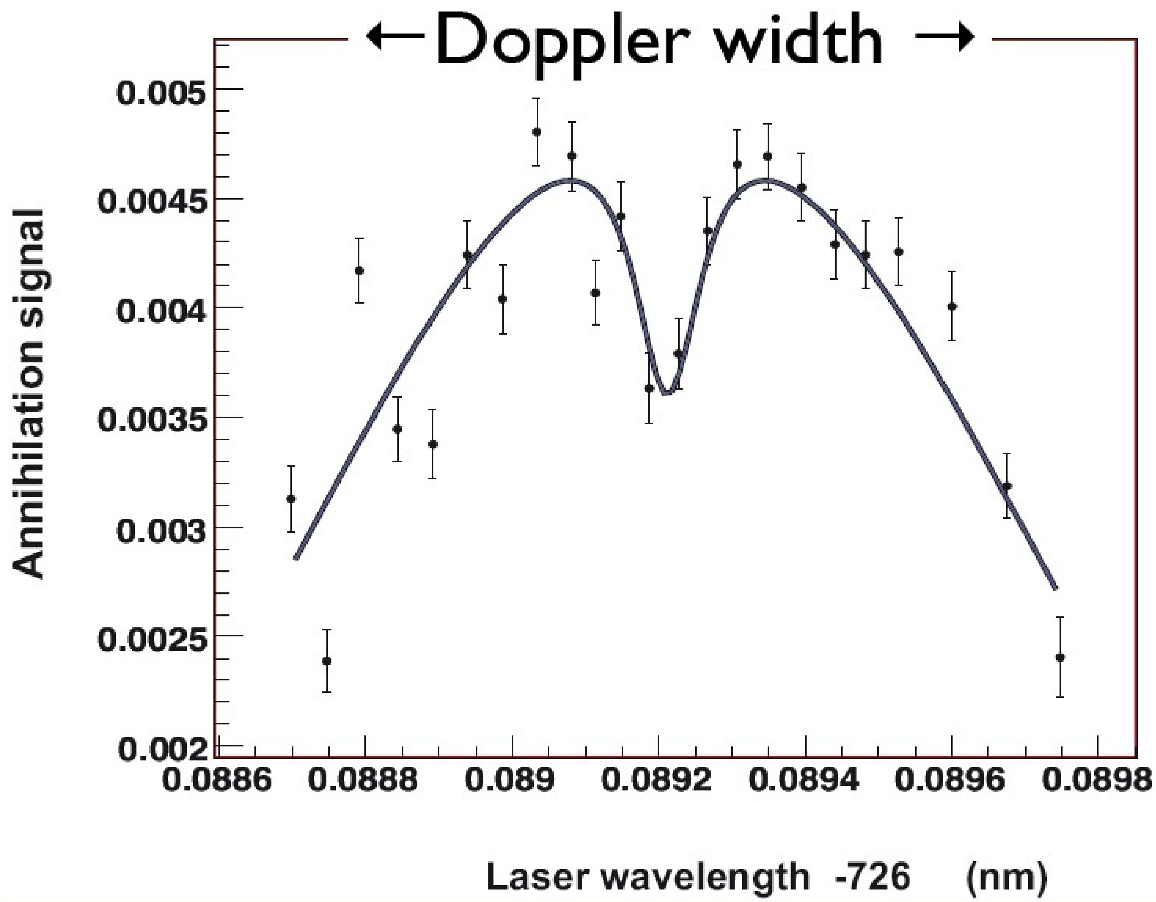
Two lasers resonantly tuned to E1 transitions.
1st strong laser burns "hole" in Doppler profile,
which is probed by second weak laser after a delay.



Full cancellation of
first-order Doppler broadening.

More transitions can be measured.

2009 result (poor $\bar{p}$ beam)



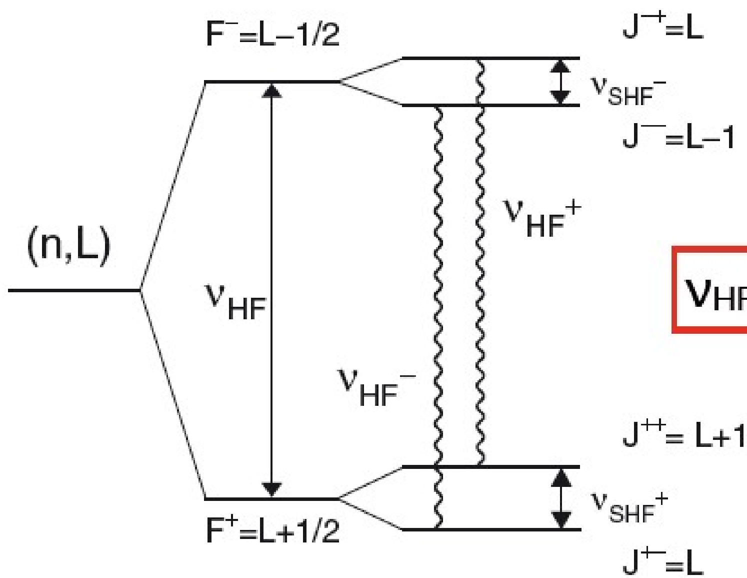
the dip was observed

position and width agree with theory

need more statistics, systematic tests, etc.

Antiprotonic helium hyperfine structure

$\bar{p}^4He$

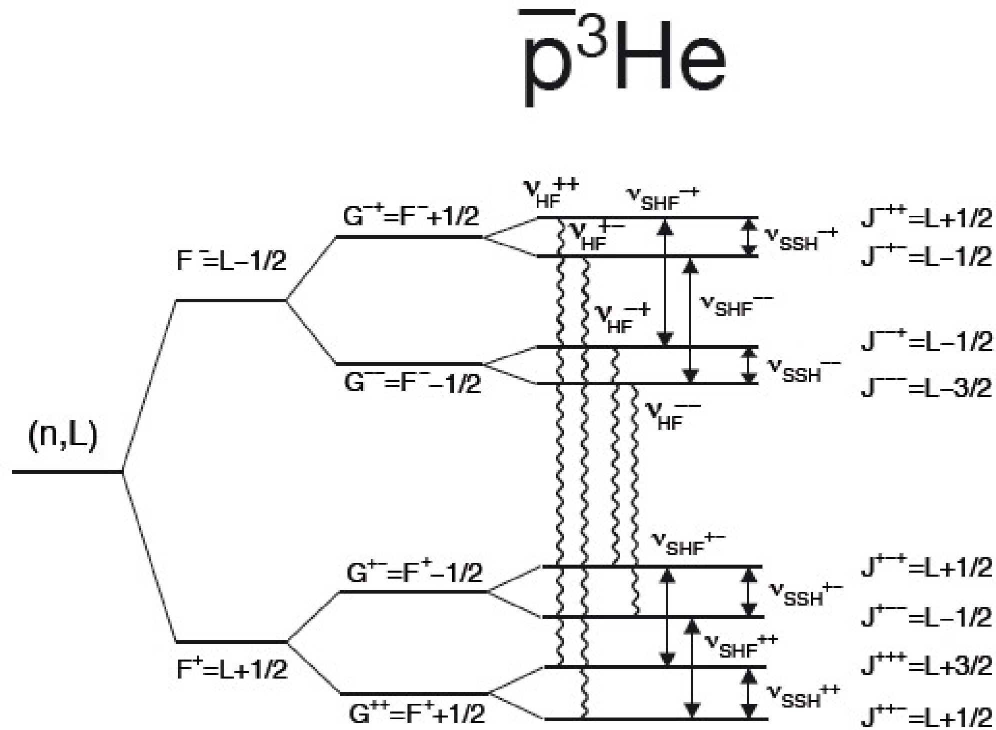


$\nu_{HF} \sim 13$ GHz

^{4}He observables ν_{HF}^+, ν_{HF}^- : $L_{\bar{p}}$ S_e

- $\Delta\nu_{HF} = \nu_{HF}^+ - \nu_{HF}^- = \nu_{SHF}^+ - \nu_{SHF}^- \sim \mu_{\bar{p}}$
- Sensitivity: 3-body bound state QED

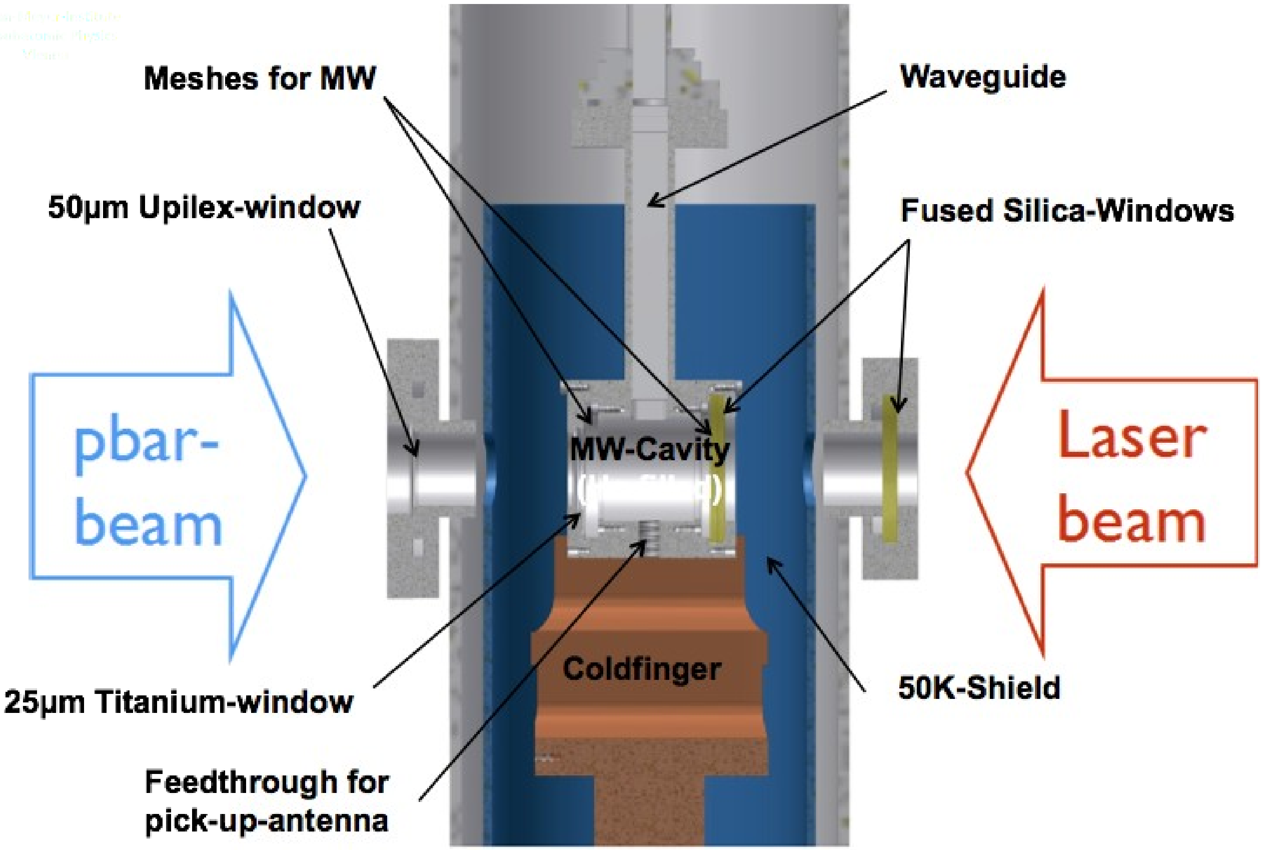
Antiprotonic helium hyperfine structure



^3He

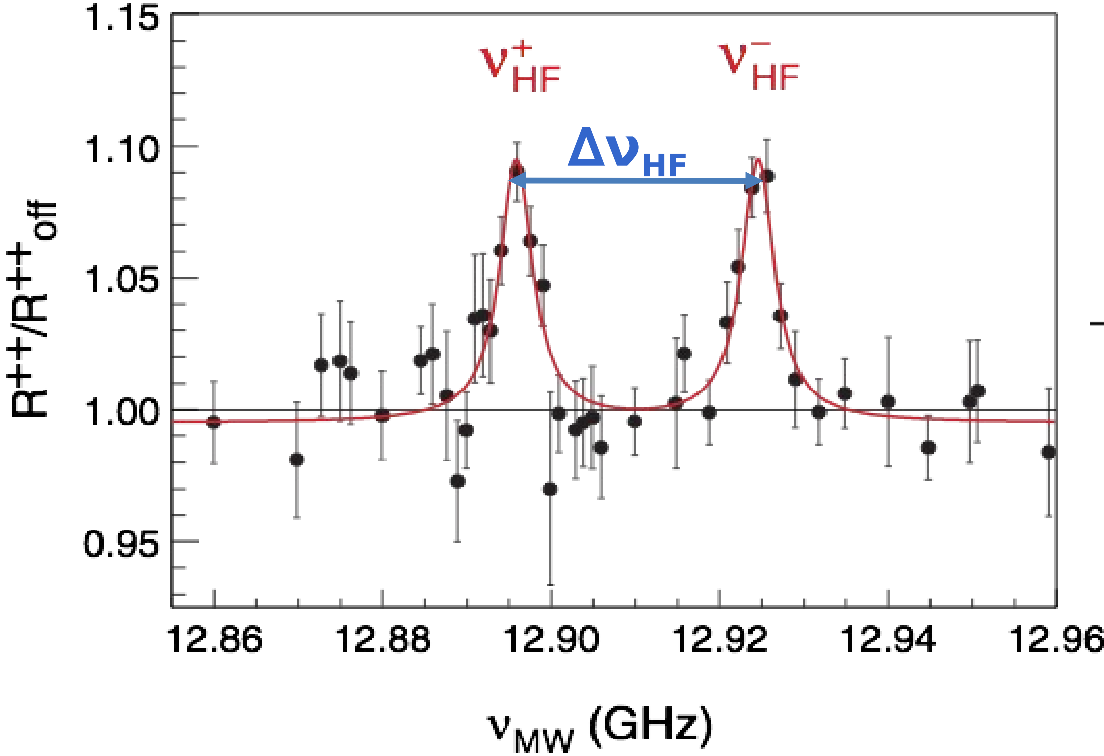
- more complex structure: rigorous test of theory

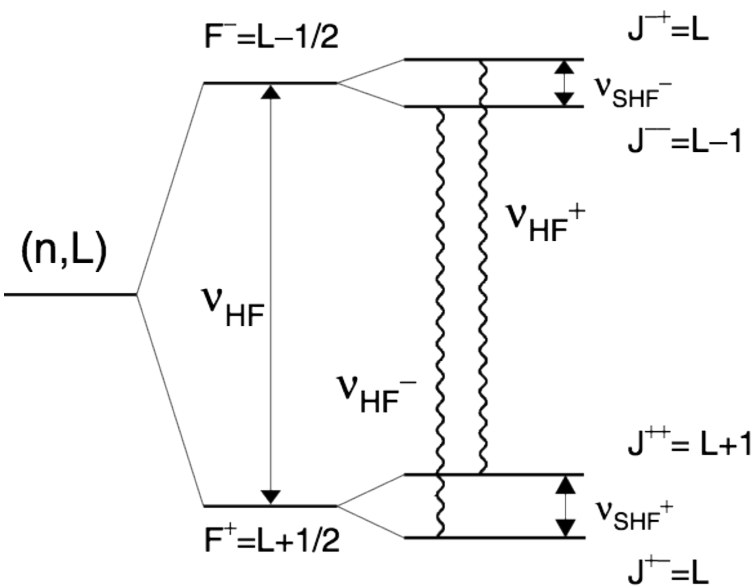
Microwave cavity and setup



- cavity for 13 GHz at < 10 K to reduce Doppler broadening
- Meshes to allow p^{bar} and laser light to enter

determination of $\mu_{\bar{p}}$

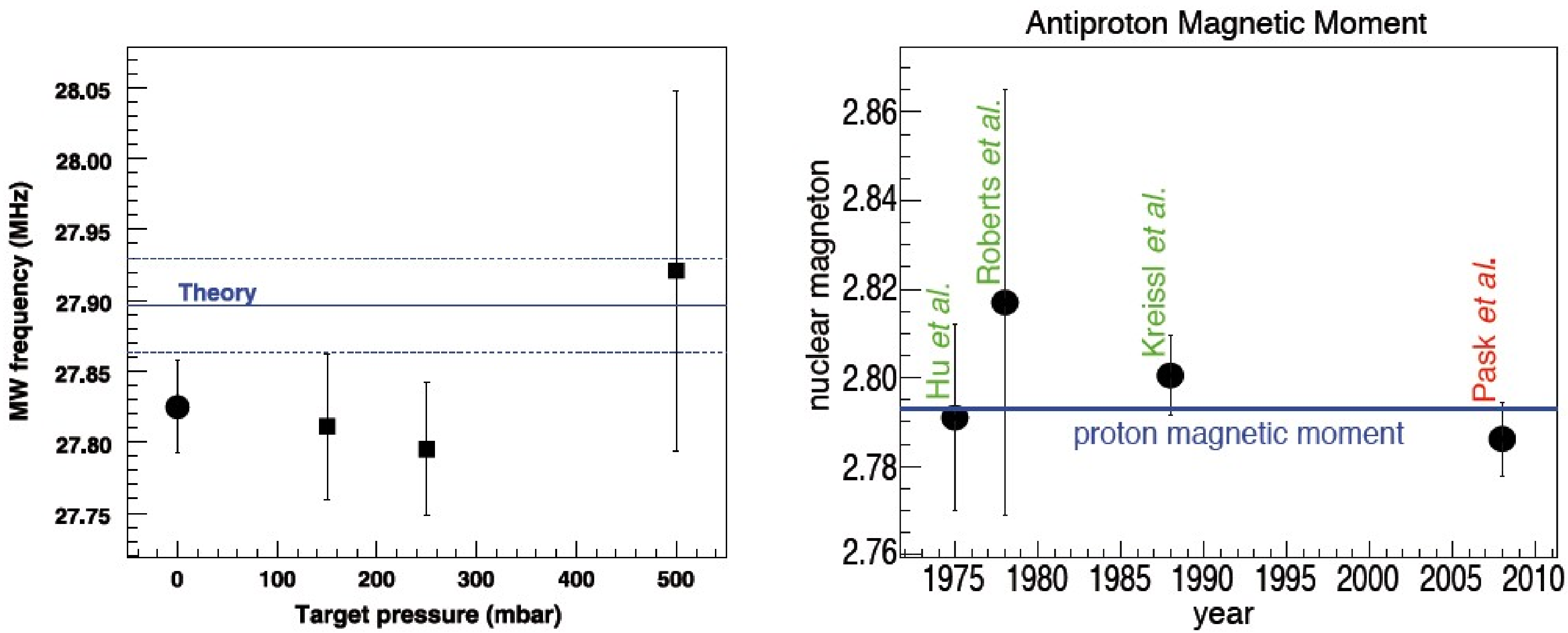




- **ν_{SHF}^{+} , ν_{SHF}^{-} most sensitive to $\mu_{\bar{p}}$,** but impossible to measure (power requirement)
- $\Delta\nu_{HF}$ **$= \nu_{HF}^{-} - \nu_{HF}^{+} = \nu_{SHF}^{+} - \nu_{SHF}^{-}$: sensitive to $\mu_{\bar{p}}$**
- **sensitivity factors from theory (D. Bakalov and E.W., PRA 76 (2007) 012512)**

Magnetic moment of the antiproton

T. Pask et al. / Physics Letters B 678 (2009) 55–59



Precision determination of HFS of (37,35) state in $\bar{p}^4$He

- $\Delta\nu_{HF}$ determined to accuracy of theory
- comparison leads to new value of magnetic moment

$$\mu_s^{\bar{p}} = -2.7862(83)\mu_N \qquad \frac{\mu_s^p - |\mu_s^{\bar{p}}|}{\mu_s^p} = (2.4 \pm 2.9) \times 10^{-3}$$

Antihydrogen

ATRAP, ALPHA (ATHENA)

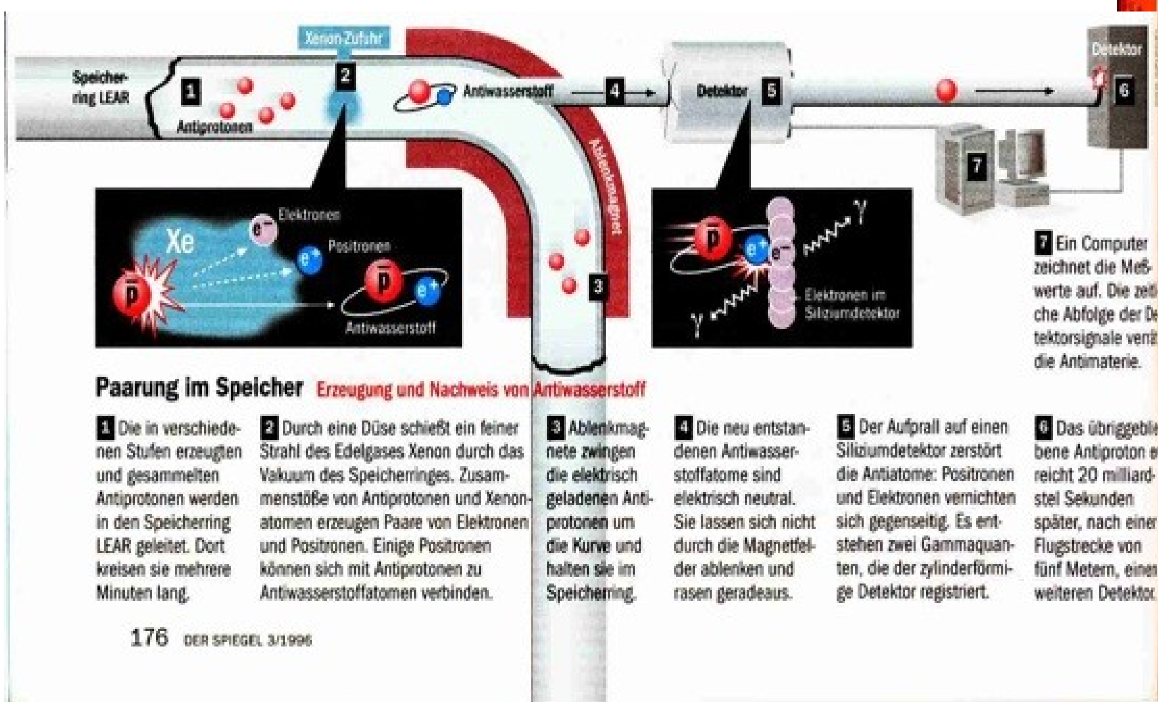
ASACUSA (just starting)

AEgIS: antimatter gravity

- Nested Penning traps
- “cusp” trap

First Antihydrogen Atoms 1996 @ LEAR

9 relativistic antihydrogen atoms detected



Paarung im Speicher Erzeugung und Nachweis von Antiwasserstoff

1 Die in verschiedenen Stufen erzeugten und gesammelten Antiprotonen werden in den Speicherring LEAR geleitet. Dort kreisen sie mehrere Minuten lang.

2 Durch eine Düse schießt ein feiner Strahl des Edelgases Xenon durch das Vakuum des Speicherringes. Zusammenstöße von Antiprotonen und Xenonatomen erzeugen Paare von Elektronen und Positronen. Einige Positronen können sich mit Antiprotonen zu Antiwasserstoffatomen verbinden.

3 Ablenkmagnete zwingen die elektrisch geladenen Antiprotonen um die Kurve und halten sie im Speicherring.

4 Die neu entstandenen Antiwasserstoffatome sind elektrisch neutral. Sie lassen sich nicht durch die Magnetfelder ablenken und rasen geradeaus.

5 Der Aufprall auf einen Siliziumdetektor zerstört die Antiatome: Positronen und Elektronen vernichten sich gegenseitig. Es entstehen zwei Gammaquanten, die der zylinderförmige Detektor registriert.

6 Das übriggeblie bene Antiproton e reicht 20 milliard stel Sekunden später, nach einer Flugstrecke von fünf Metern, einen weiteren Detektor

7 Ein Computer zeichnet die Meß werte auf. Die zeit che Abfolge der De tektorsignale verr die Antimaterie.

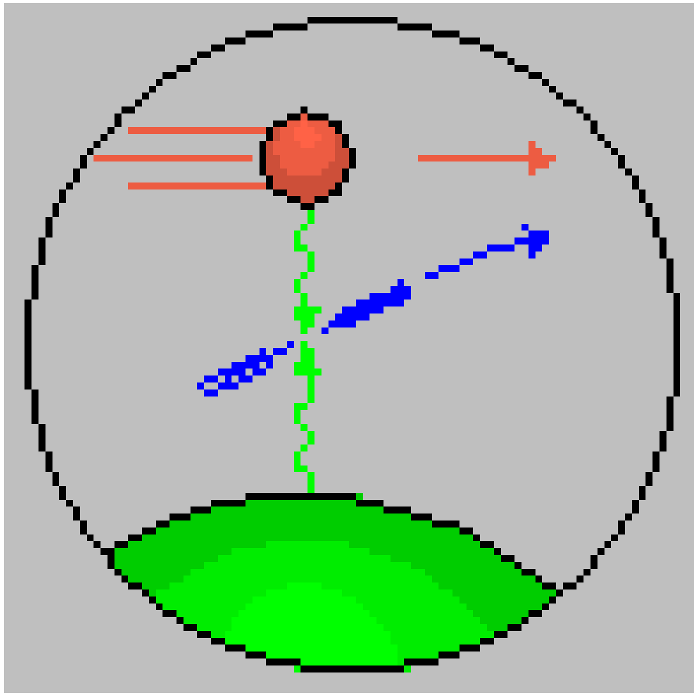
176 DER SPIEGEL 3/1996

First Antihydrogen Atoms

Antihydrogen production

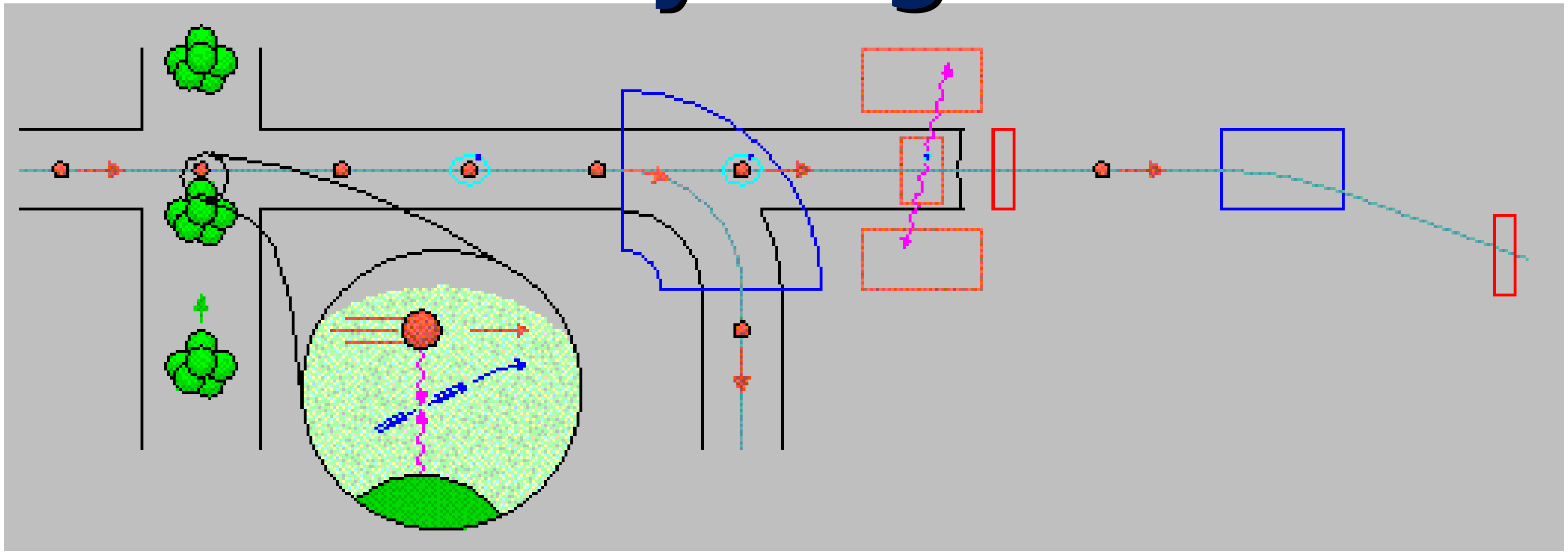
In the PS210 experiment antihydrogen atoms were produced in the following way. When a antiproton (red), circulating in an accelerator, passes a heavy target-nucleus (green), e.g. Xenon, close enough, electron-positron pairs (blue) are produced accidently.

If an electron-positron pair has been created, (very rare process), then it is possible that the antiproton catches the positron (an even more rare case).



- **Antihydrogen** is produced
  The probability for this process is $\sim 10^{-19}$

First Antihydrogen Atoms

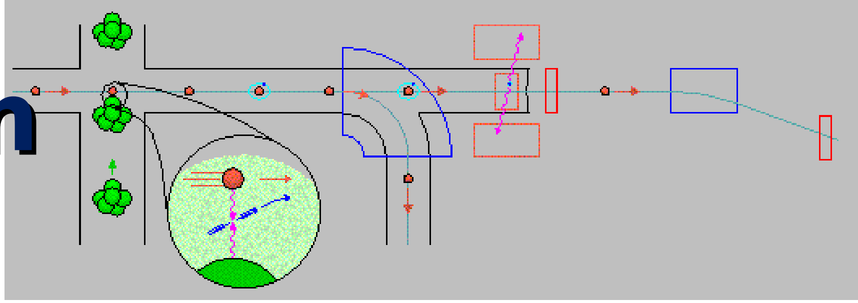


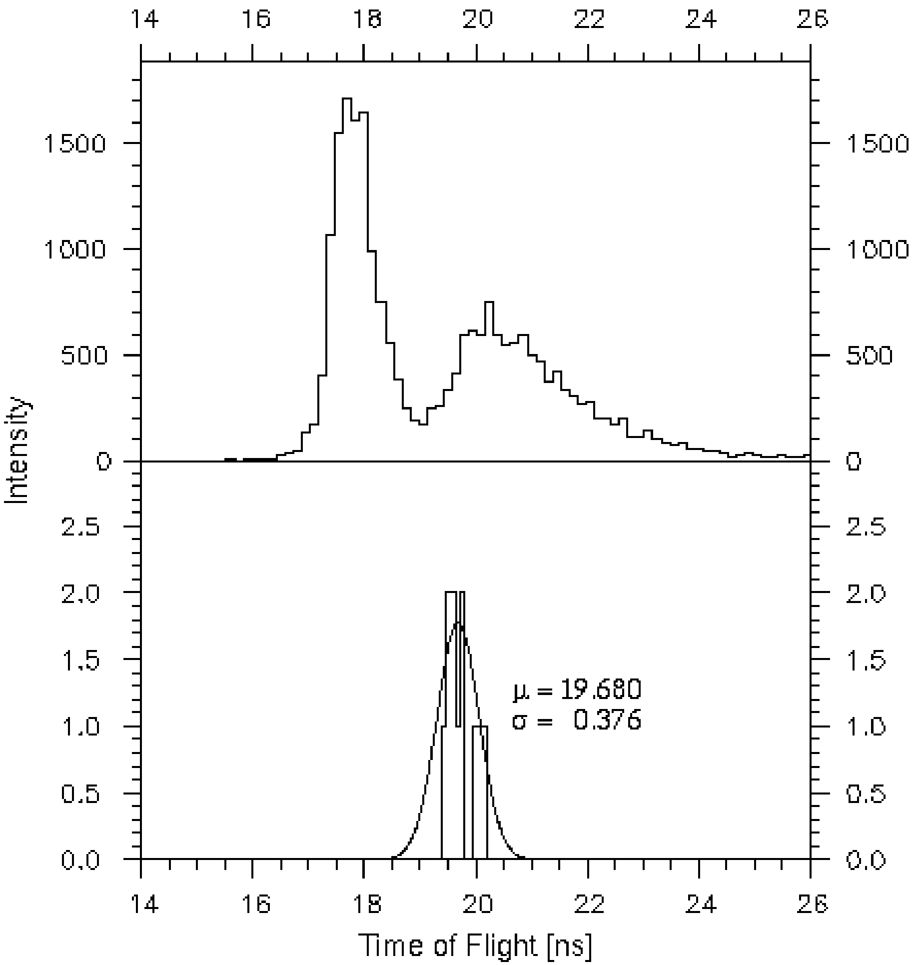
- Antiprotons (red) circulating in the LEAR ring
- Xenon clusters cross the path of the antiprotons
- antihydrogen atom (red with blue positron) is formed

- in the first detector (red box) the antihydrogen is 'ionized', the positron annihilates with an electron 2 photons of are measured

➢ the antiproton passes several detectors, measuring:
  - velocity
  - sign of charge

First Antihydrogen Atoms



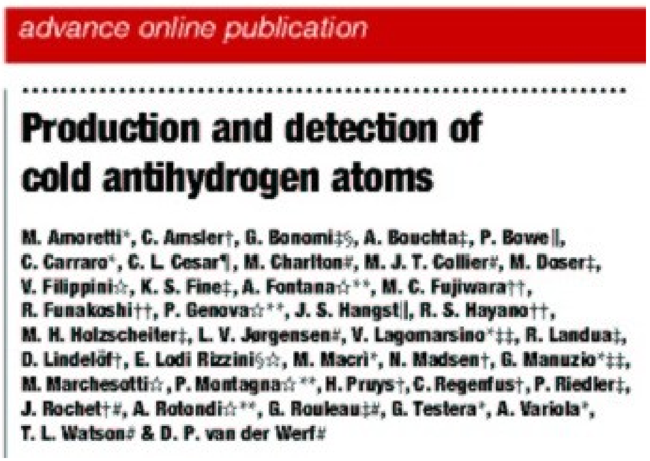


11 events with correct antiproton time-of-flight (19.7 nsec) and positron annihilation signal.
2±1 events may be due to background reactions.

Final result
a clear signature of
9 antihydrogen atoms

First Cold Antihydrogen 2002 @ AD

Nested Penning traps
Capture energy: few keV


advance online publication

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. Macrì*, 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#

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

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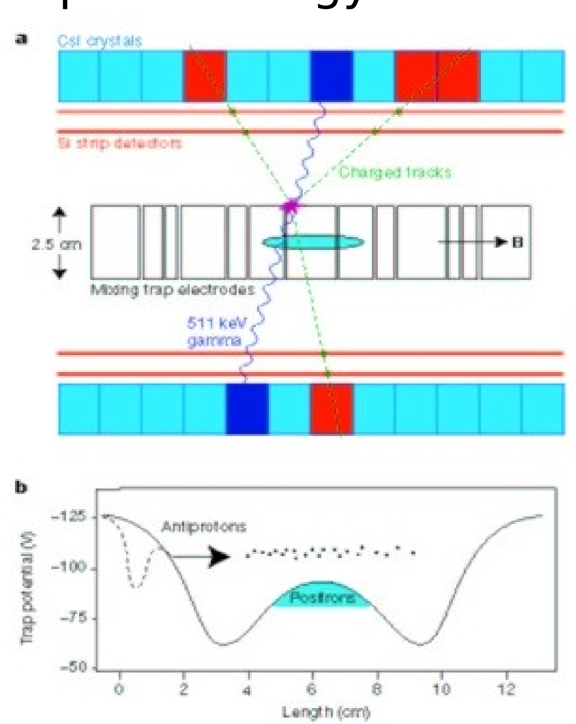


No "useful" Hbar produced (ground-state, < 1 K temperature for trapping)
Ultimate precision: neutral atom trap and laser cooling to milli-Kelvin temperature

Precision Spectroscopy of Hydrogen

1S-2S sensitive to:

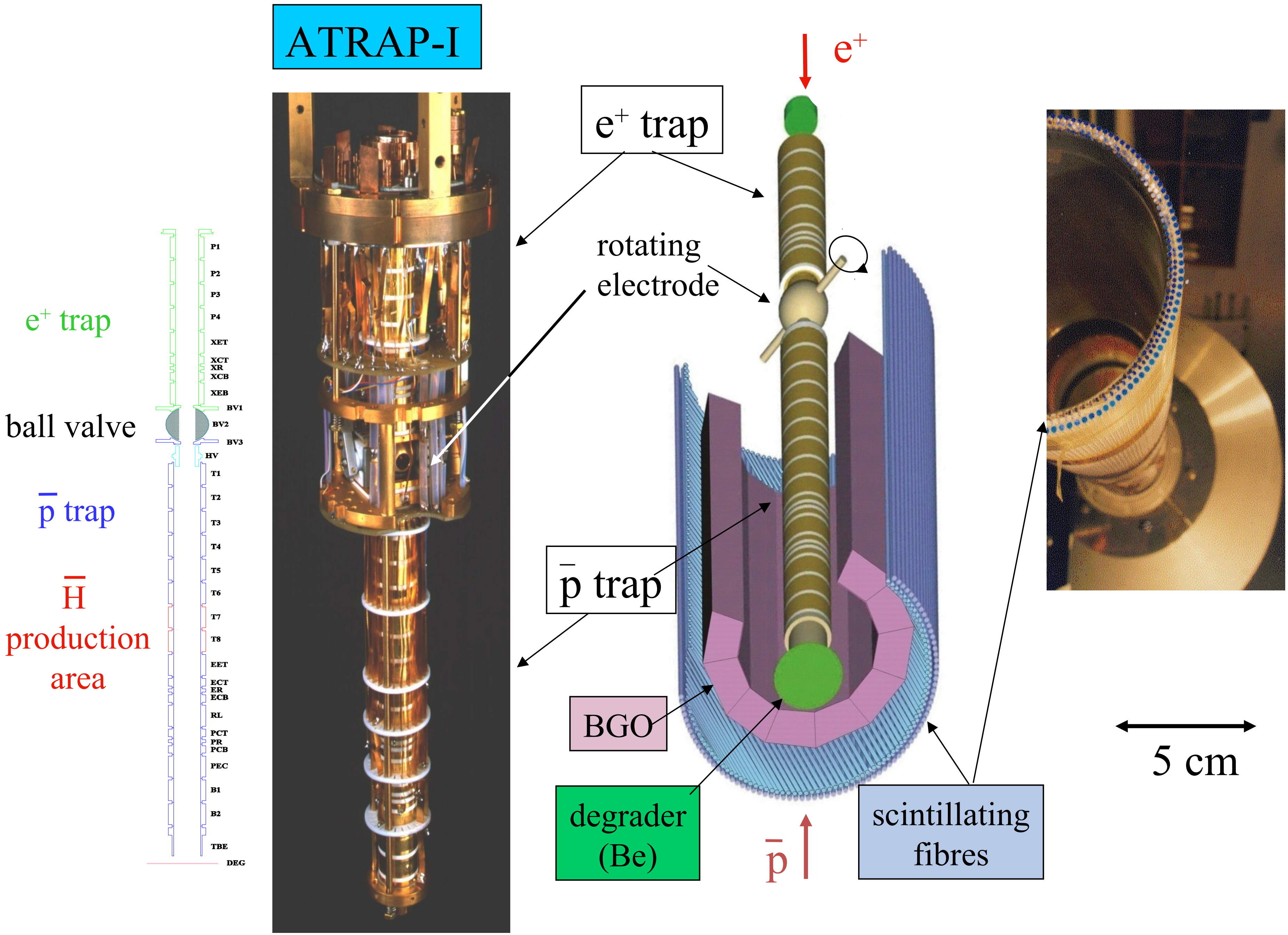
- Electron mass
- Proton mass
- proton charge radius R_p

2S-2P (Lamb shift) sensitive to:

- proton charge radius R_p

GS-HFS

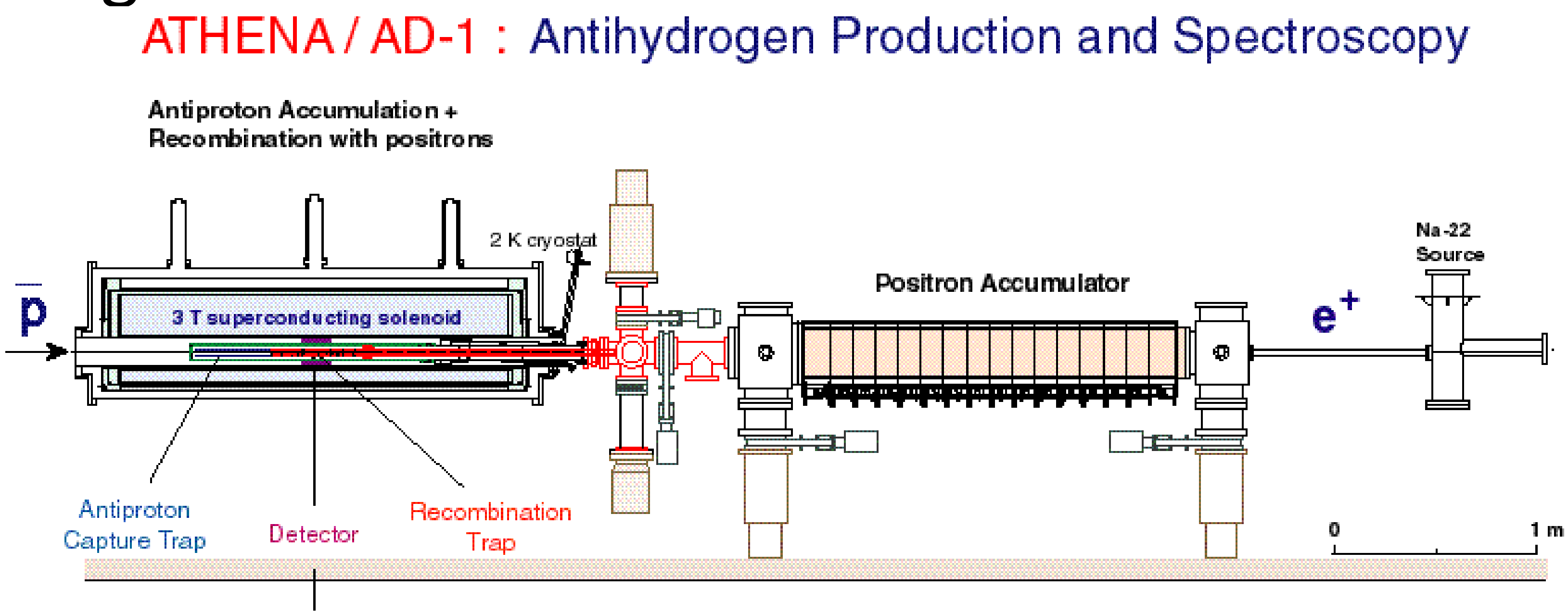
- Proton magnetic moment μ_p
- Proton magnetic radius R_M



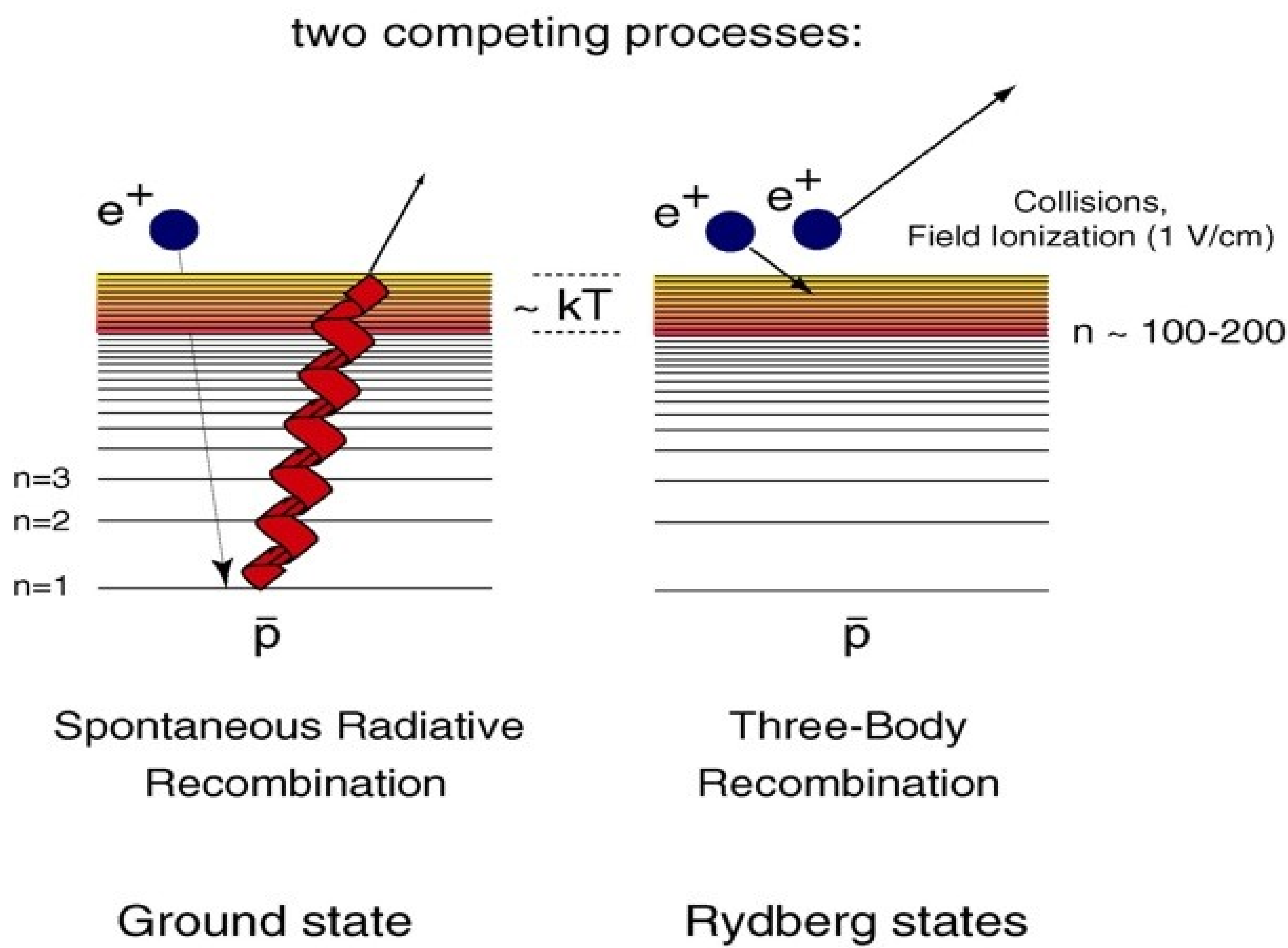
ATRAP-I
e+ trap
ball valve
p̄ trap
H̄ production area
P1
P2
P3
P4
XET
XCT
XR
XCB
XEB
BV1
BV2
BV3
HV
T1
T2
T3
T4
T5
T6
T7
T8
EET
ECT
ER
ECB
RL
PCT
PR
PCB
PEC
B1
B2
TBE
DEG
e+ trap
rotating electrode
e+
p̄ trap
BGO
degrader (Be)
p̄
scintillating fibres
5 cm

ATHENA (ALPHA)

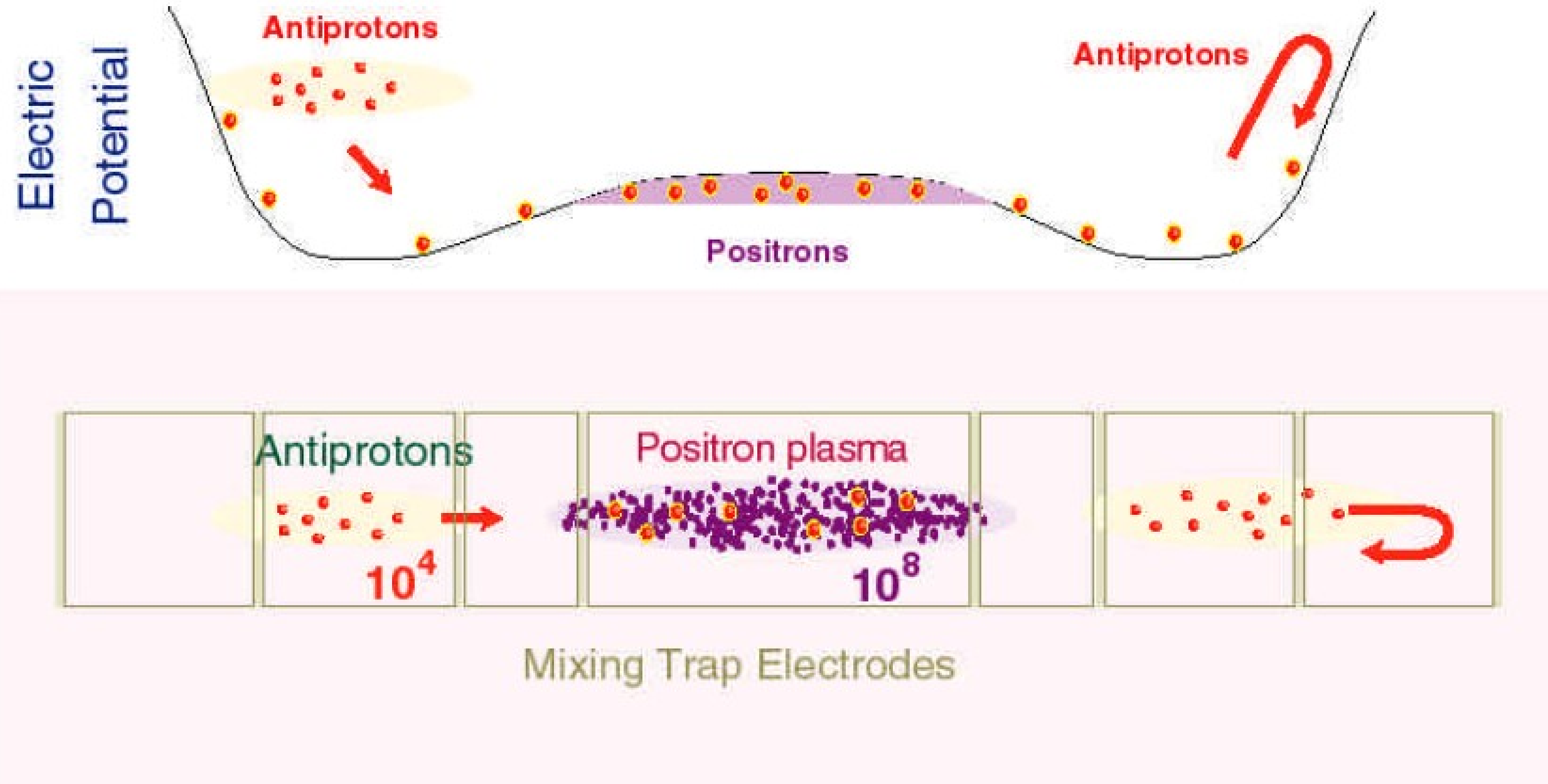
- Capture, trap, cool antiprotons
- Capture, trap, cool positrons
- Merge and recombine



Recombination Mechanisms

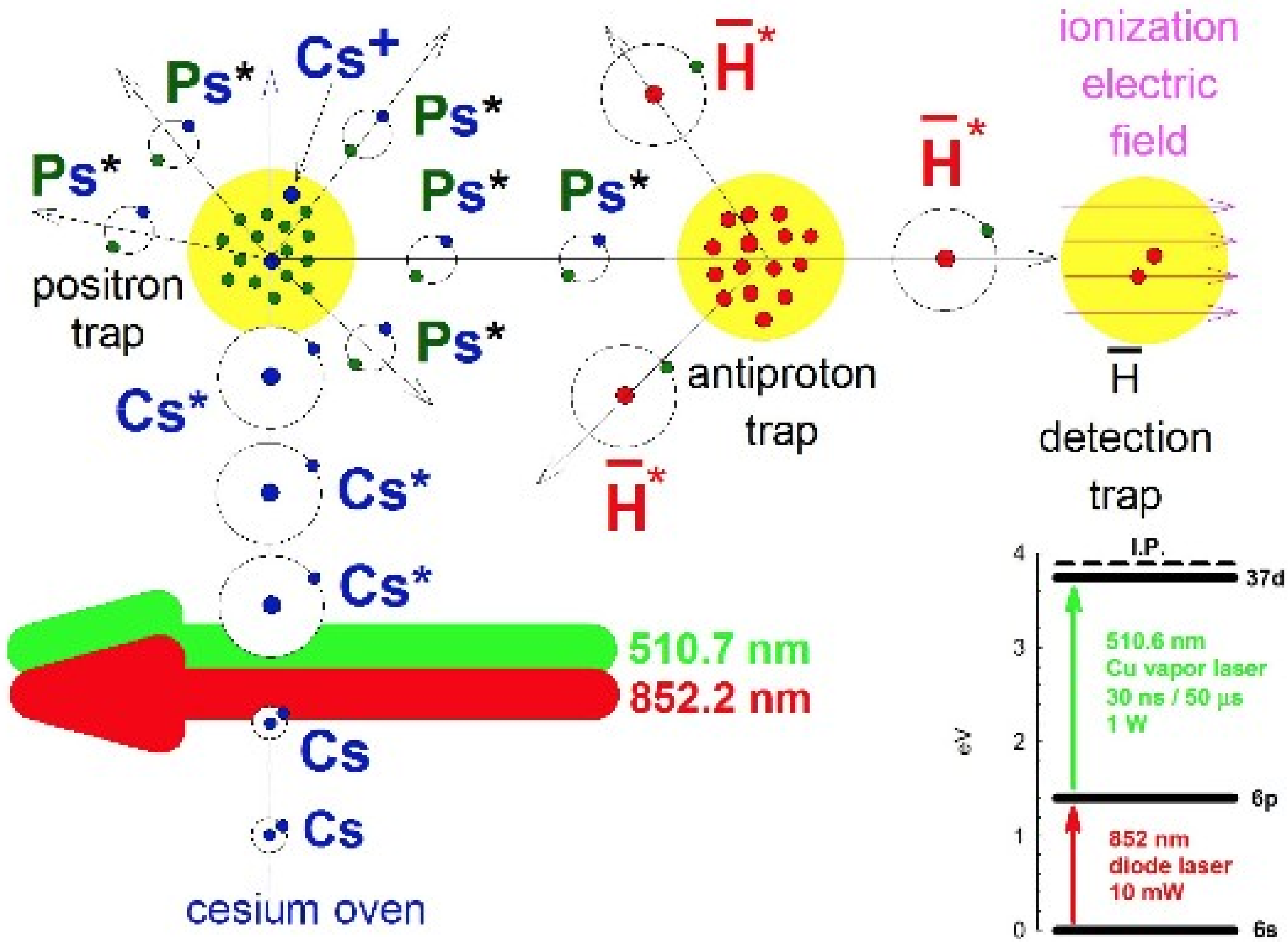


Mixing procedure



Scheme proposed by G. Gabrielse et al. - Phys.Lett. A129, 38 (1988)

Double charge exchange reaction



ATRAP, Phys. Rev. Lett. **93**, 263401 (2004)

Neutral atom trap for antihydrogen

First Antihydrogen Production within a Penning-Ioffe Trap

G. Gabrielse,[1,*] P. Larochelle,[1] D. Le Sage,[1] B. Levitt,[1] W.S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] J. Wrubel,[1] A. Speck,[2] M.C. George,[3,4] D. Grzonka,[3] W. Oelert,[3] T. Sefzick,[3] Z. Zhang,[3] A. Carew,[4] D. Comeau,[4] E.A. Hessels,[4] C.H. Storry,[4] M. Weel,[4] and J. Walz[5]
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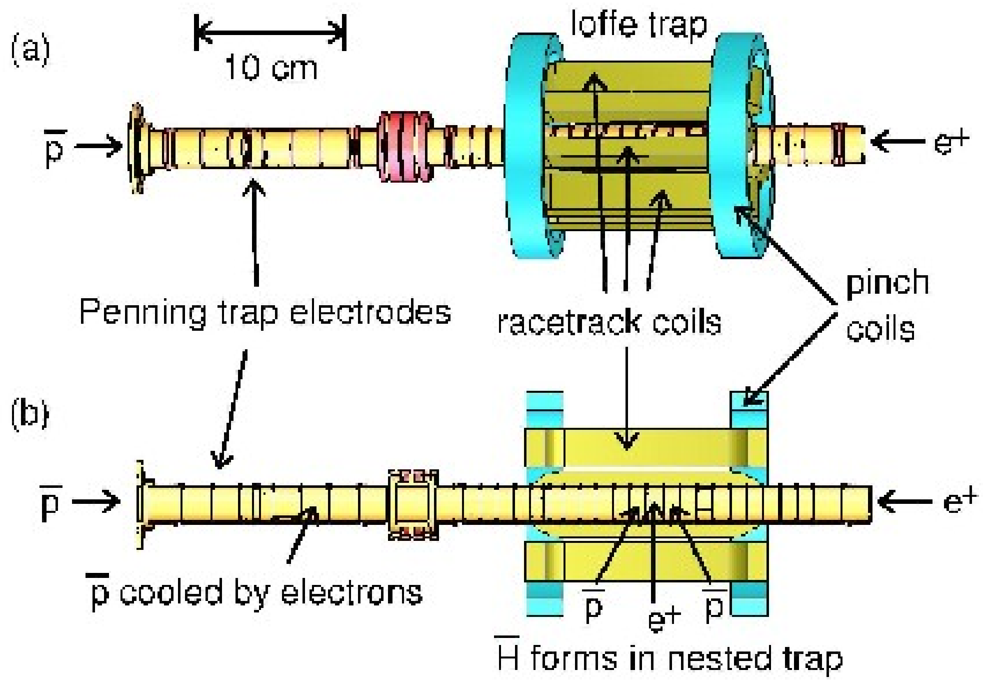
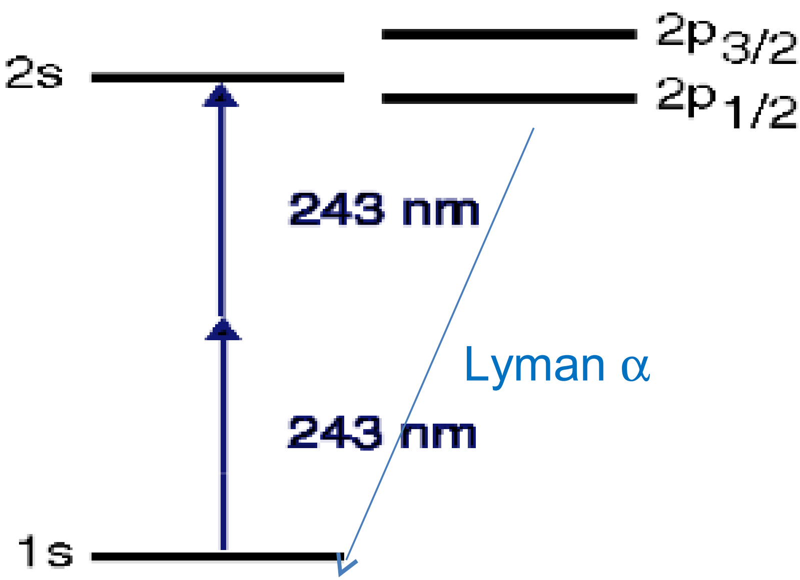
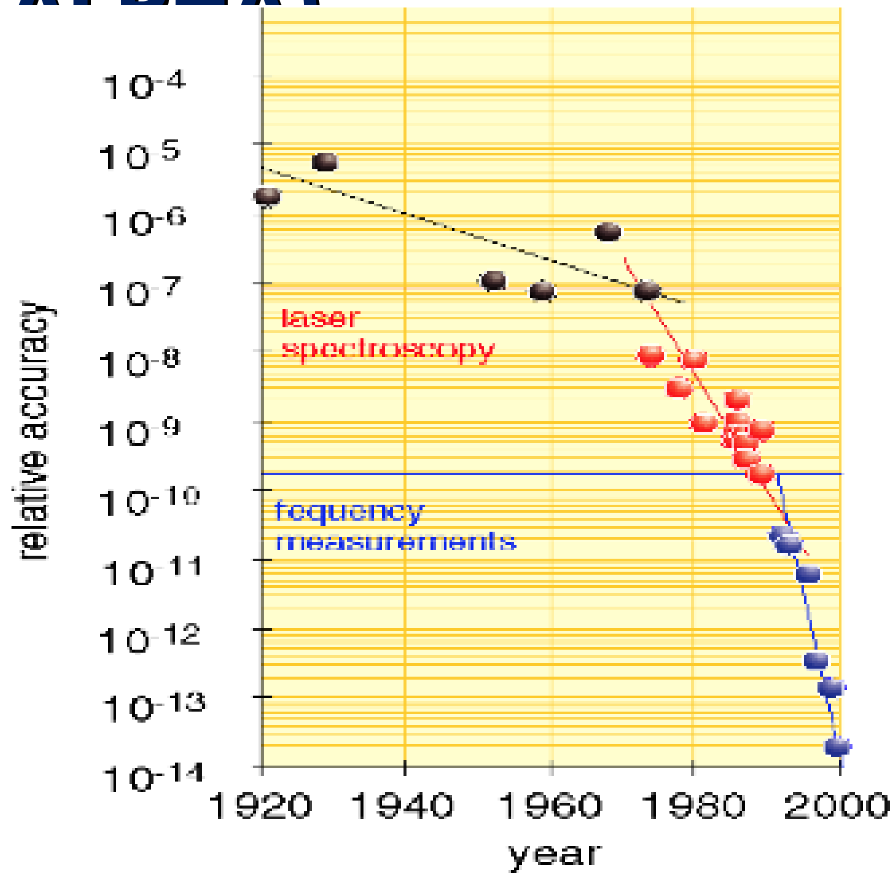


PRL 2008

(Anti)-Hydrogen 1s-2s spectroscopy
(ATRAP, ALPHA)





Phys. Rev. Lett. 84, 5496–5499 (2000)

Measurement of the Hydrogen 1*S*- 2*S* Transition Frequency by Phase Coherent Comparison with a Microwave Cesium Fountain Clock

1s-2s: 2 466 061 413 187 103(46) Hz

Why measure HFS instead of 1S-2S