Experimental Low Energy Antiproton Physics

Eberhard Widmann

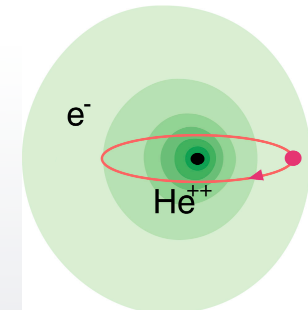
Workshop on Critical Stability
Ettore Majorana Centre, Erice 15.10.2008

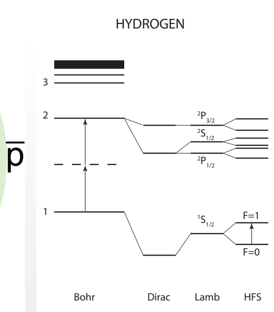
ÖAW
Austrian Academy of Sciences

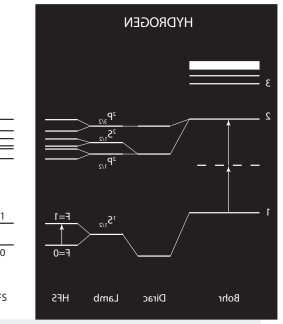
Stefan Meyer Institute for subatomic Physics, Wien

Low Energy Antiproton Physics

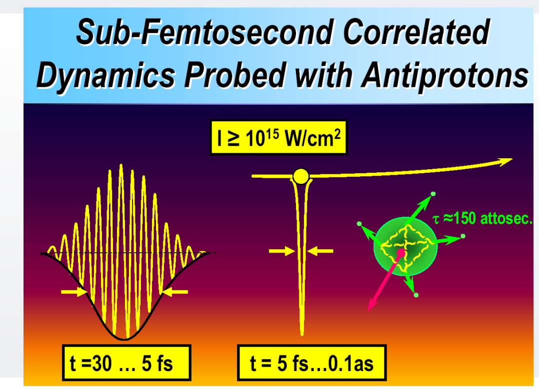
- Spectroscopy for tests of CPT and QED
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen



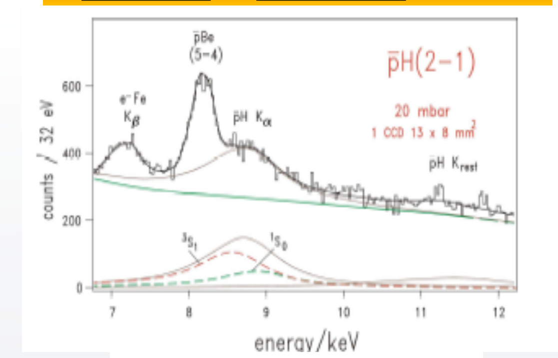


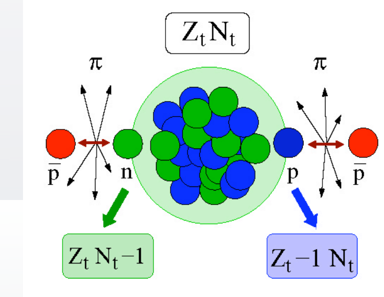


- Atomic collisions
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions

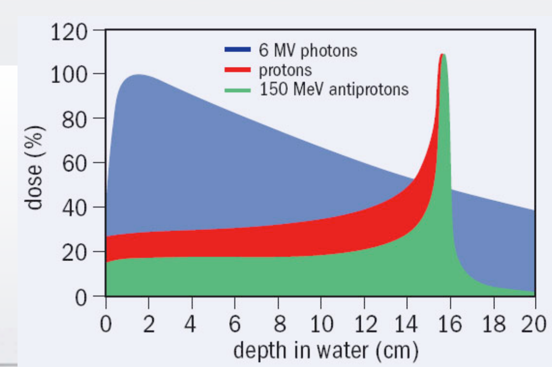


- Antiprotons as hadronic probes
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction
  - Strangeness –2 production



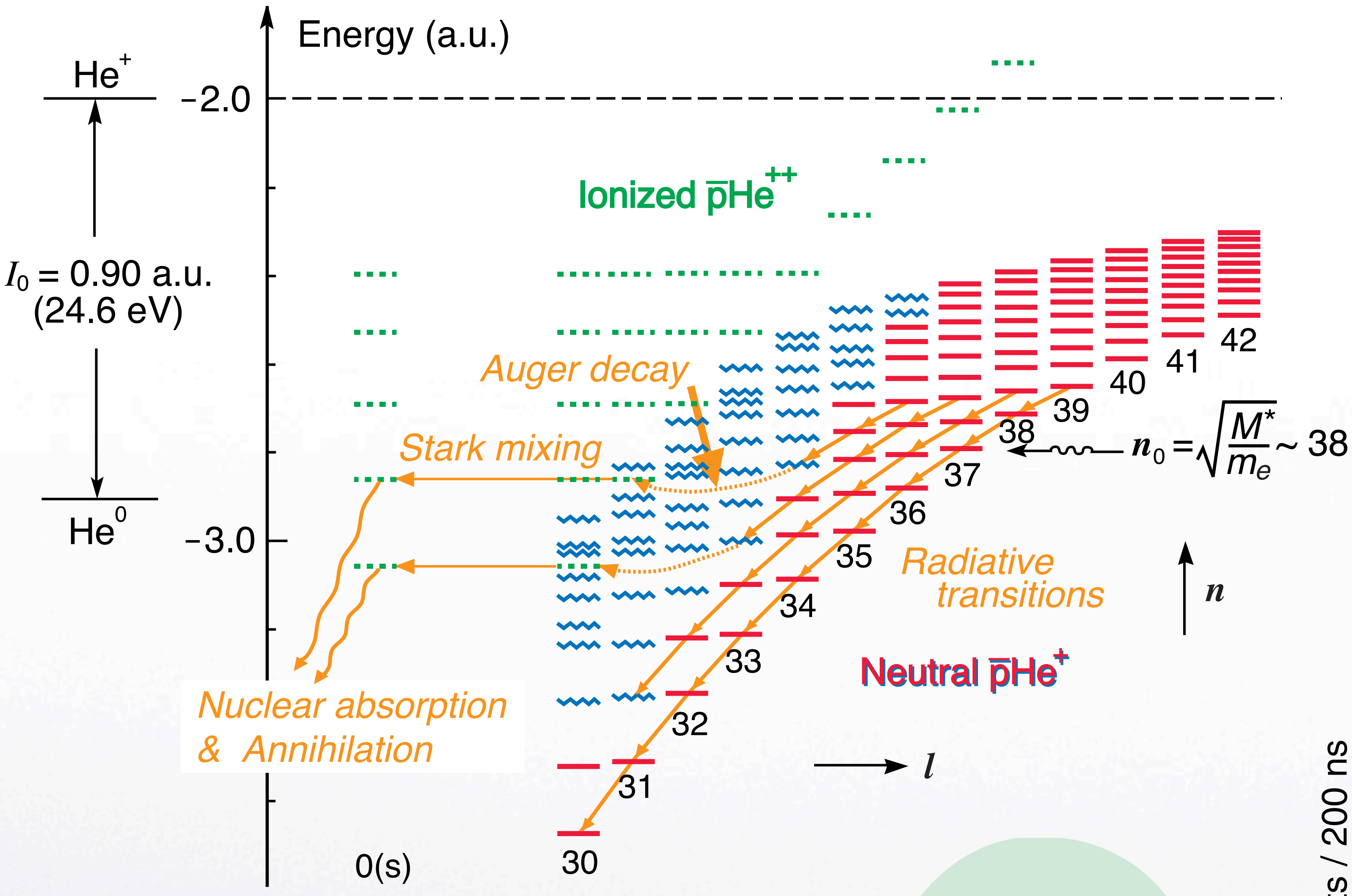


- Medical applications: tumor therapy



FLAIR LoI http://www.oeaw.ac.at/smi/flair

Antiprotonic helium



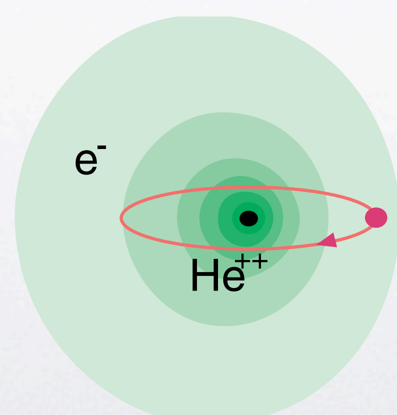
Metastable states

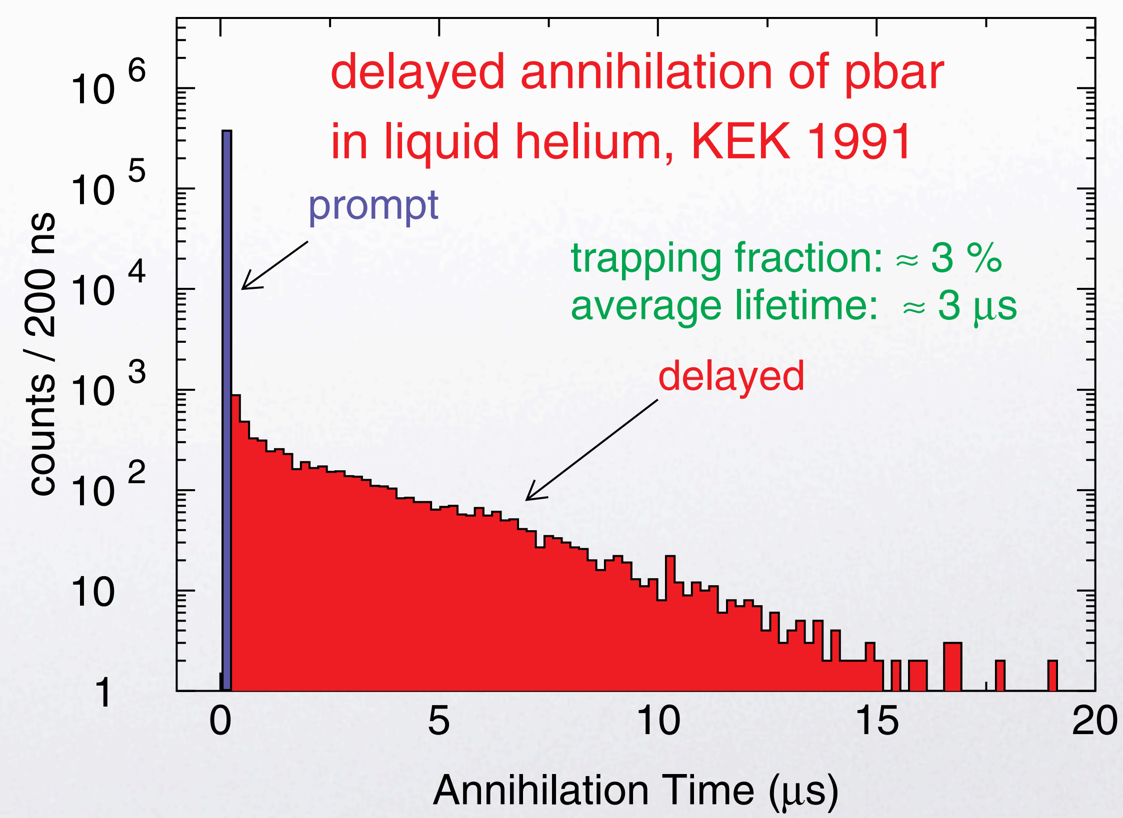
τ~ μs

short-lived states

(Auger decay)

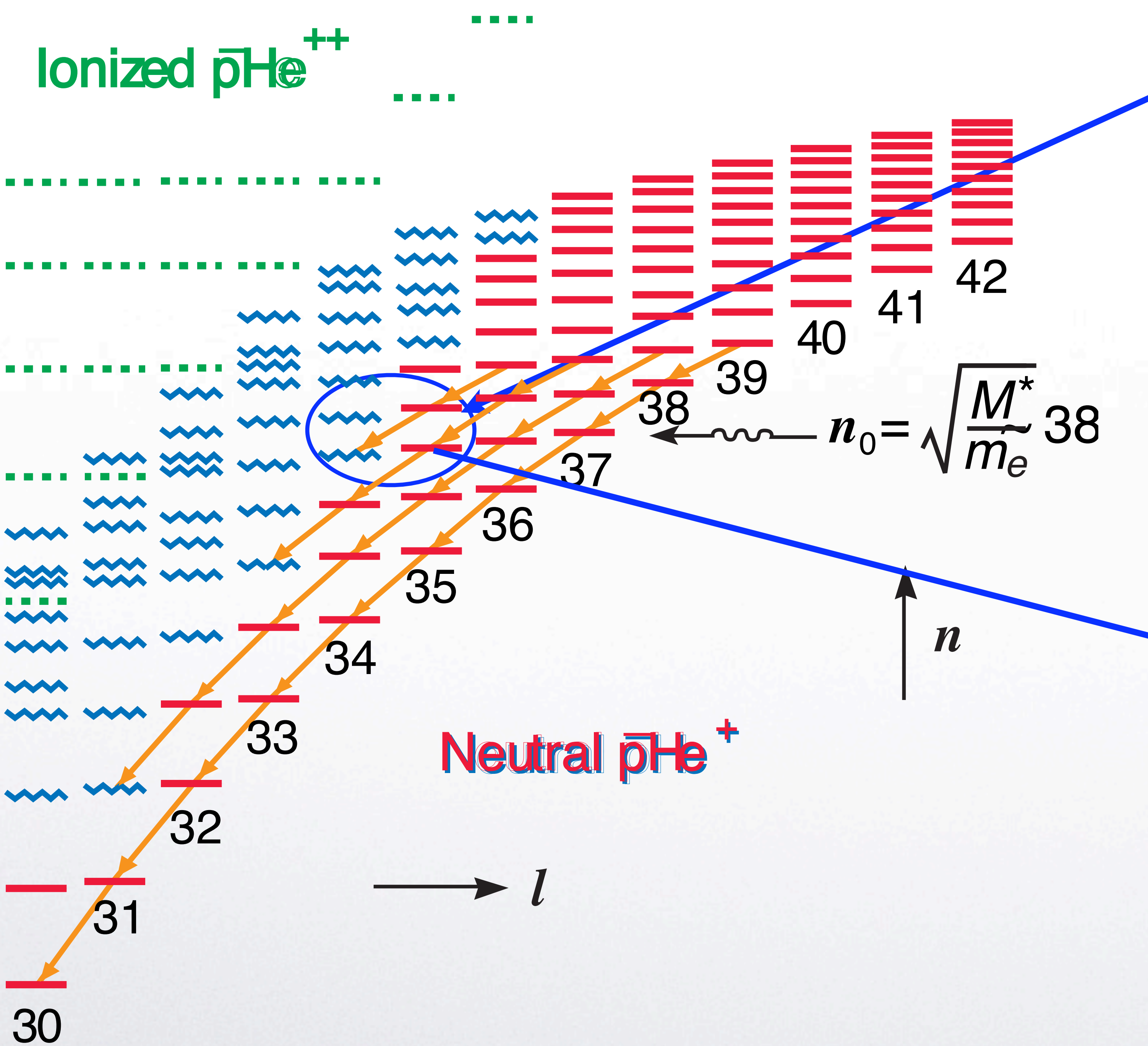
τ ≤ 10 ns



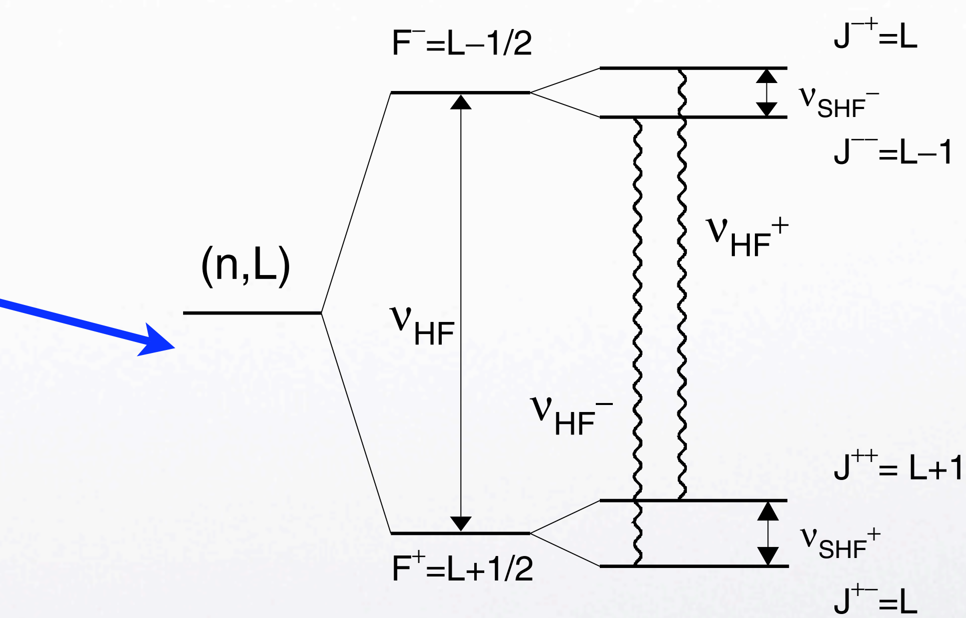


possibility of precision spectroscopy

Precision spectroscopy



- pairs of metastable - short-lived state
- laser spectroscopy



- hyperfine structure
- magnetic moment of antiproton

ASACUSA collaboration @ CERN-AD

Asakusa Kannon Temple
by Utagawa Hiroshige (1797-1858)

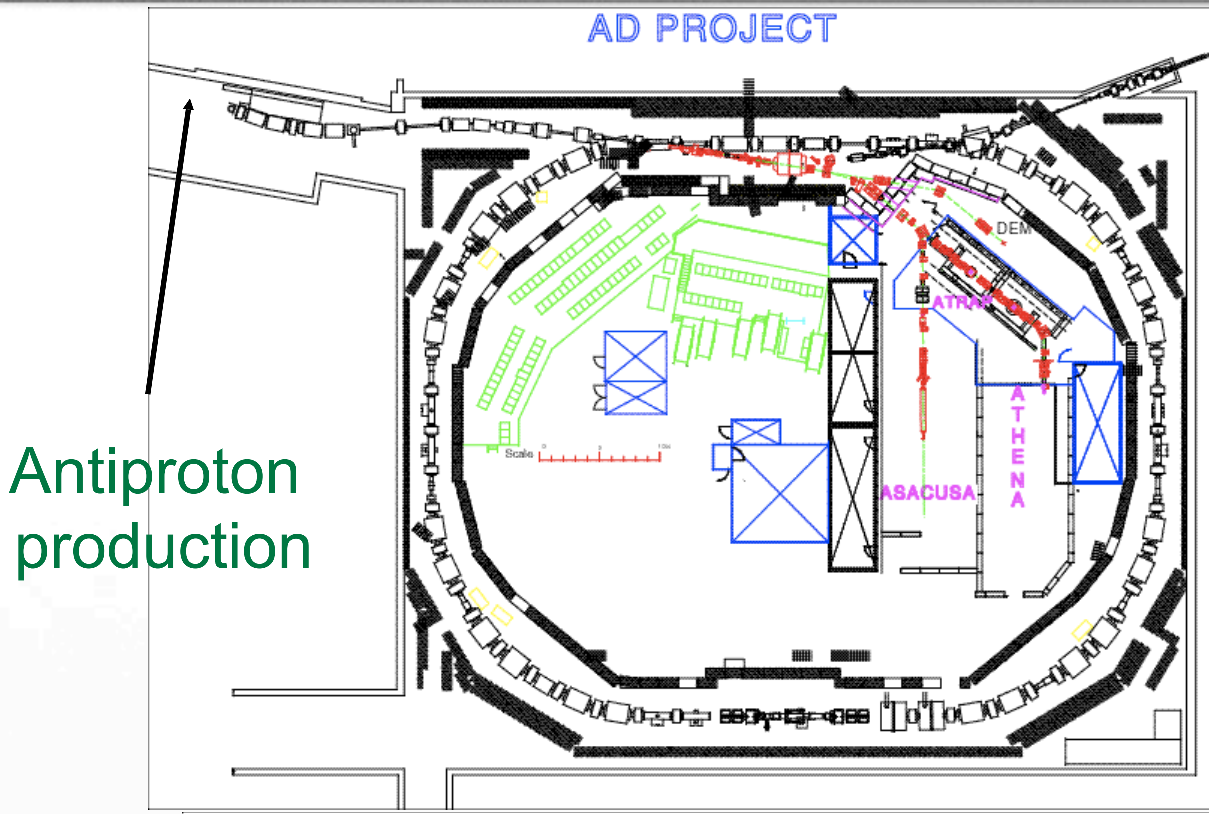
Atomic Spectroscopy And Collisions Using Slow Antiprotons

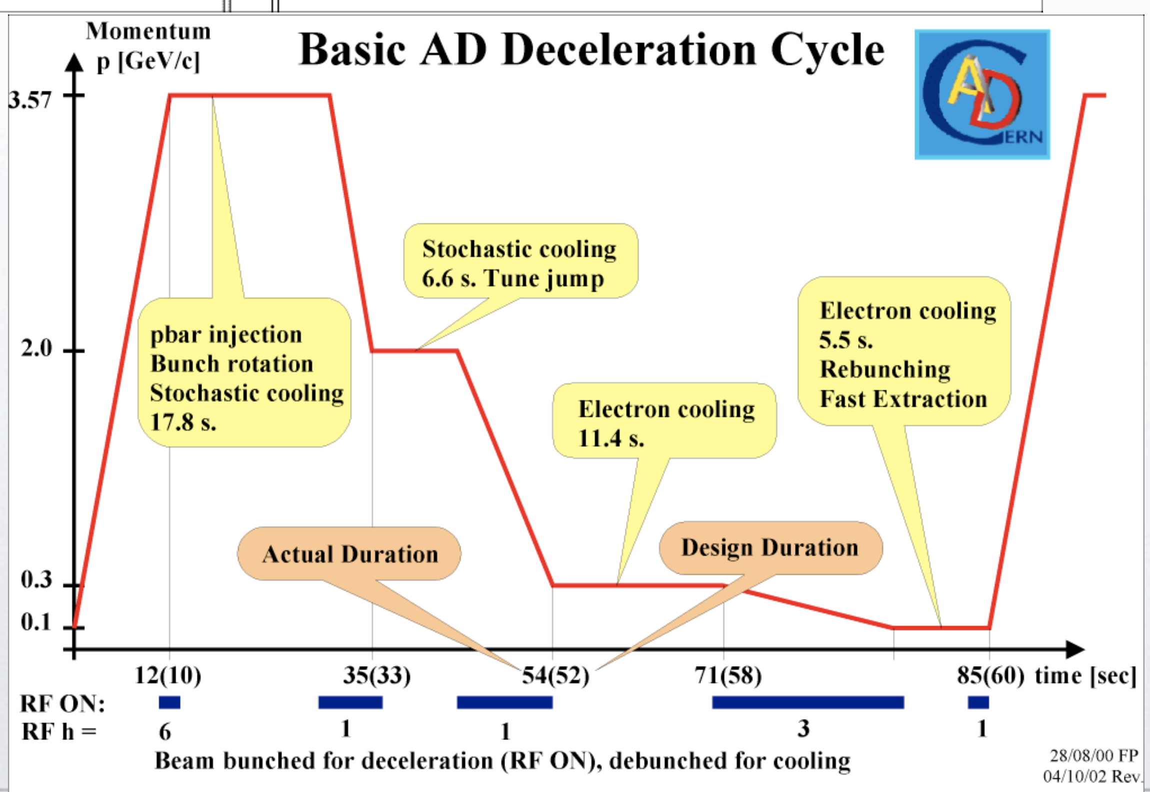
Spokesperson: R.S. Hayano, University of Tokyo

- 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

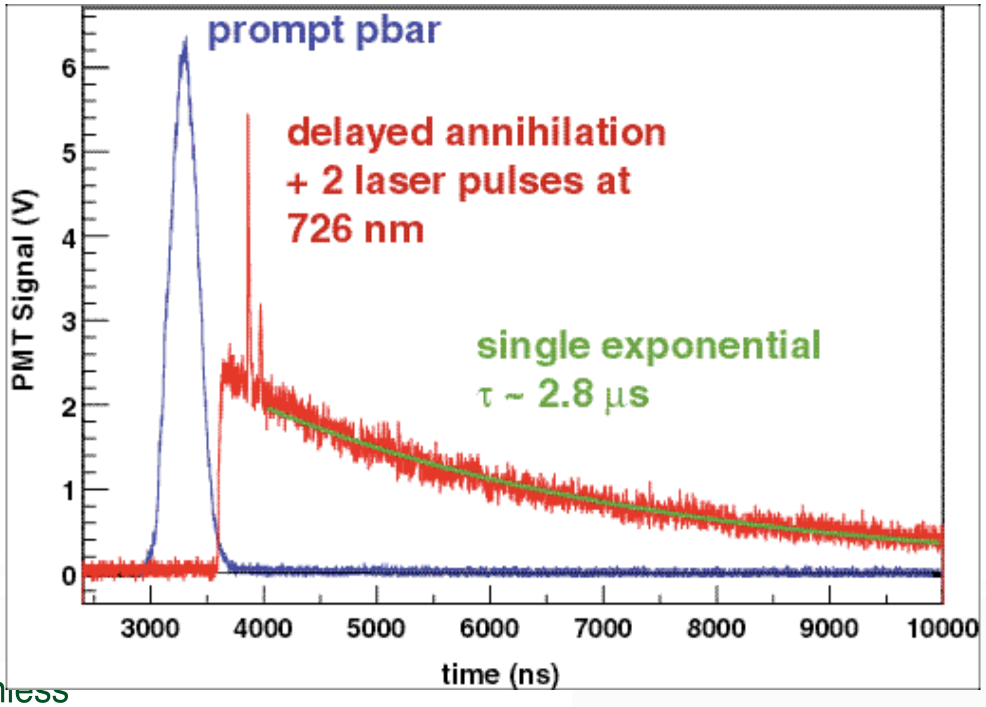
Antiproton Decelerator (AD) at CERN





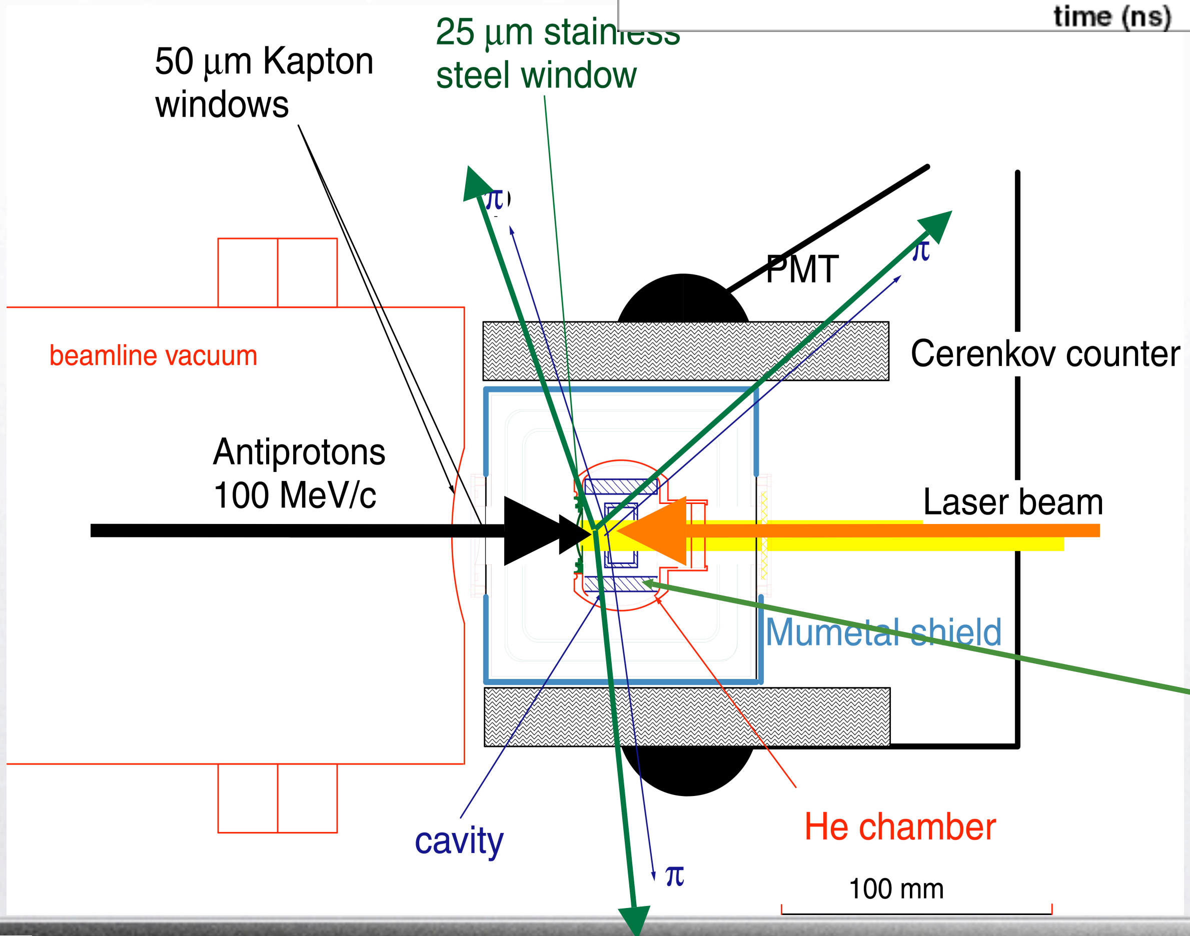
- Antiproton capture, deceleration, cooling
  - 100 MeV/c (5.3 MeV)
- ***Pulsed*** extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85 seconds
- Antiprotonic atom, Antihydrogen formation and spectroscopy, atomic collisions

Experimental Setup at AD



Analog Measurement of Delayed Annihilation using Cerenkov counters and digital oscilloscope

TOP VIEW

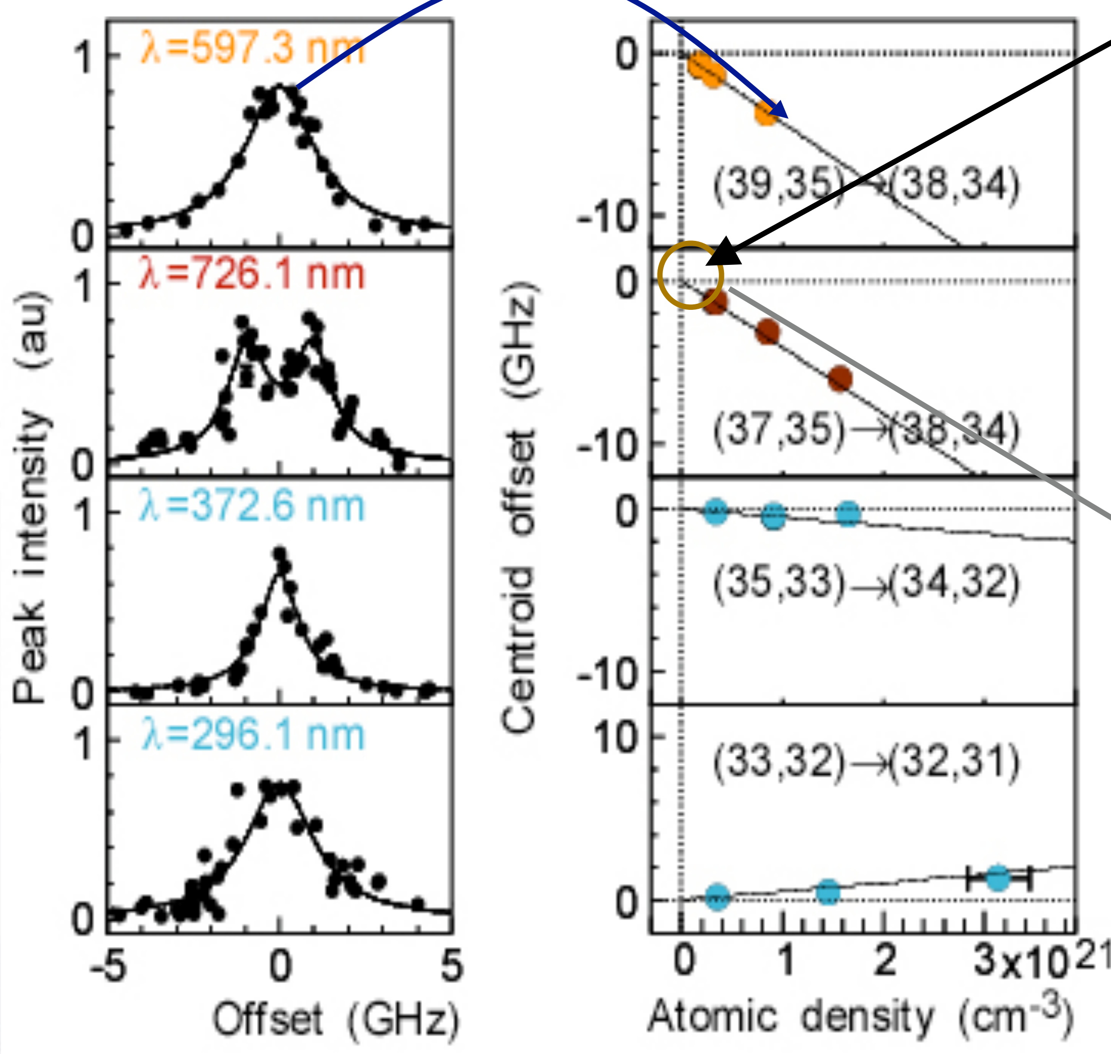


5.3 MeV antiprotons are stopped in ~ 6 K 0.5 – 3 bar He gas

Microwave cavity 12.91 GHz:
28.8 mm diameter, 24.5 mm length

Precise Measurement of Transition Wavelength

5.3 MeV AD beam



Resonance scans

Shift of center with density

Exp. Accuracy 1.3 x 10^{-7}

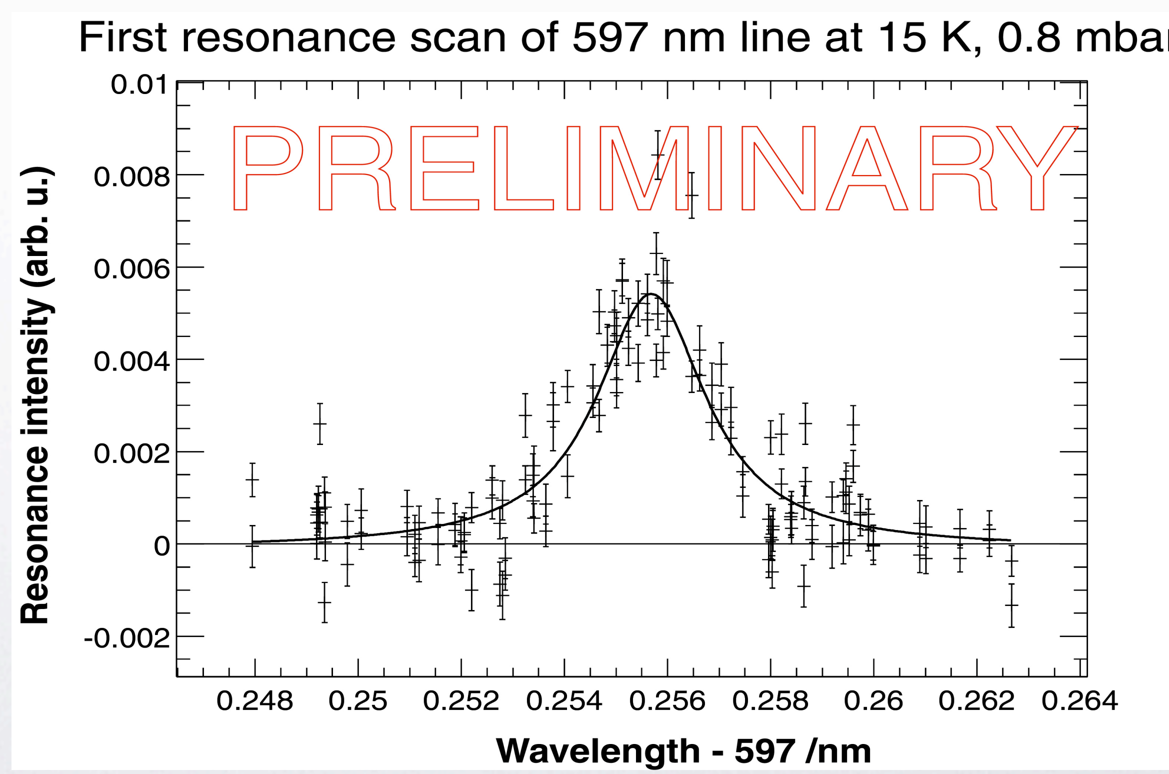
M. Hori et al., PRL 87, 093401 (2001)

- Zero-density values compared to state-of-the-art three-body QED calculations
- $\bar{p}$ mass and charge CPT limit: 60 ppb

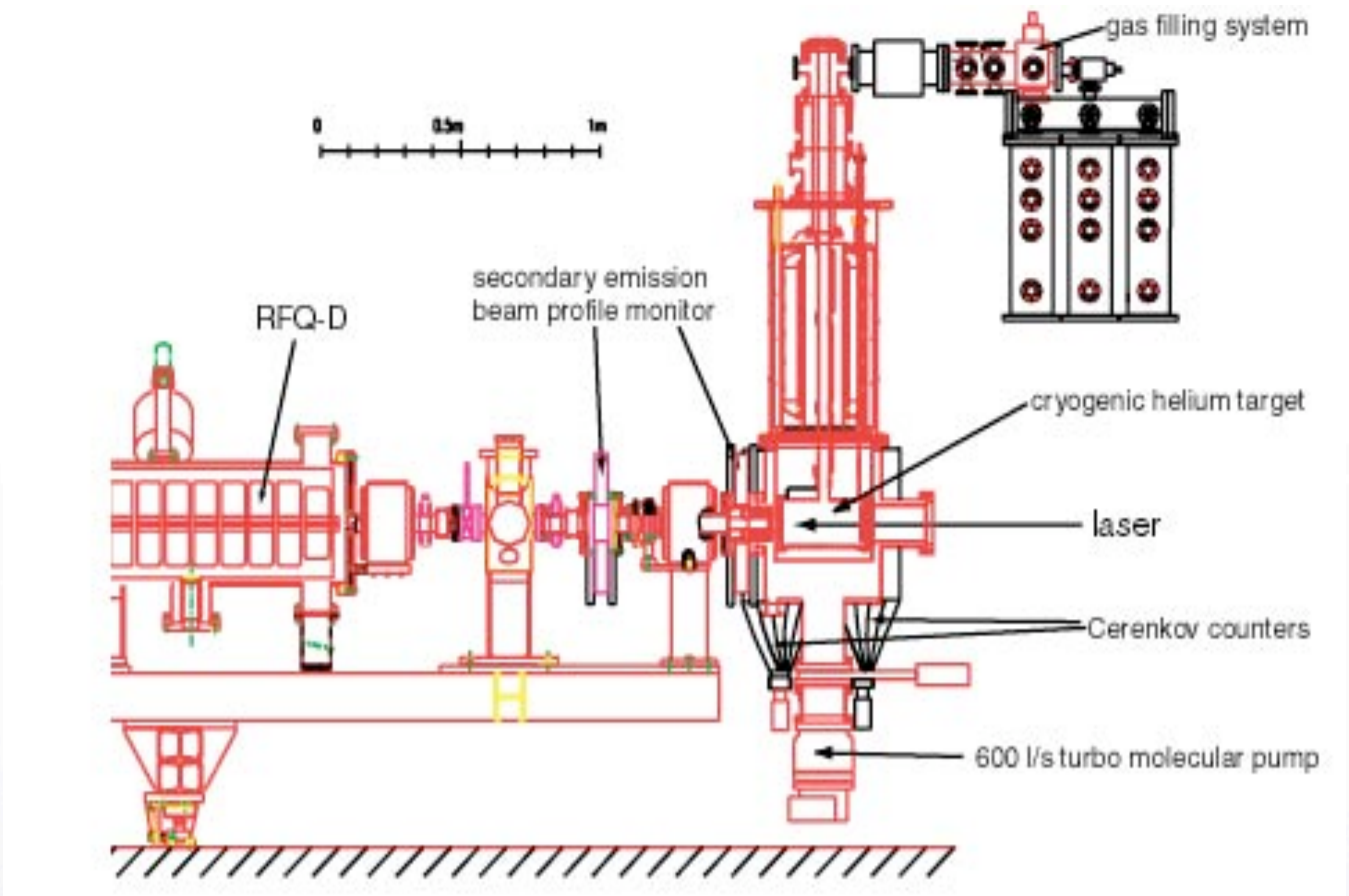
M. Hori et al., PRL 87, 093401 (2001)

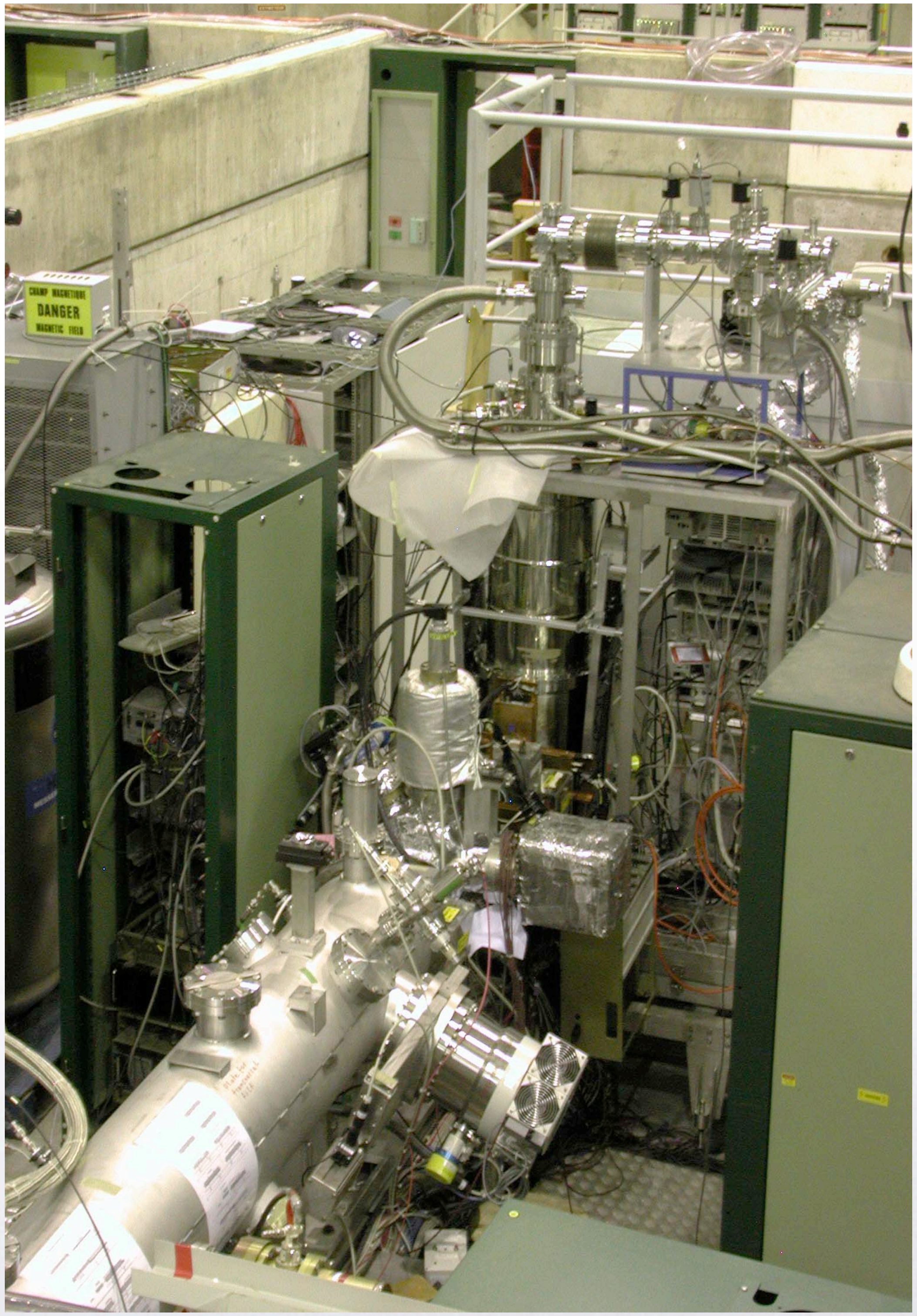
With RFQD: direct measurement at zero density (in "vacuum")

100 keV RFQD beam



Laser Spectroscopy at Ultra-low Density: Radio Frequency Quadrupole Decelerator: 20-120 keV

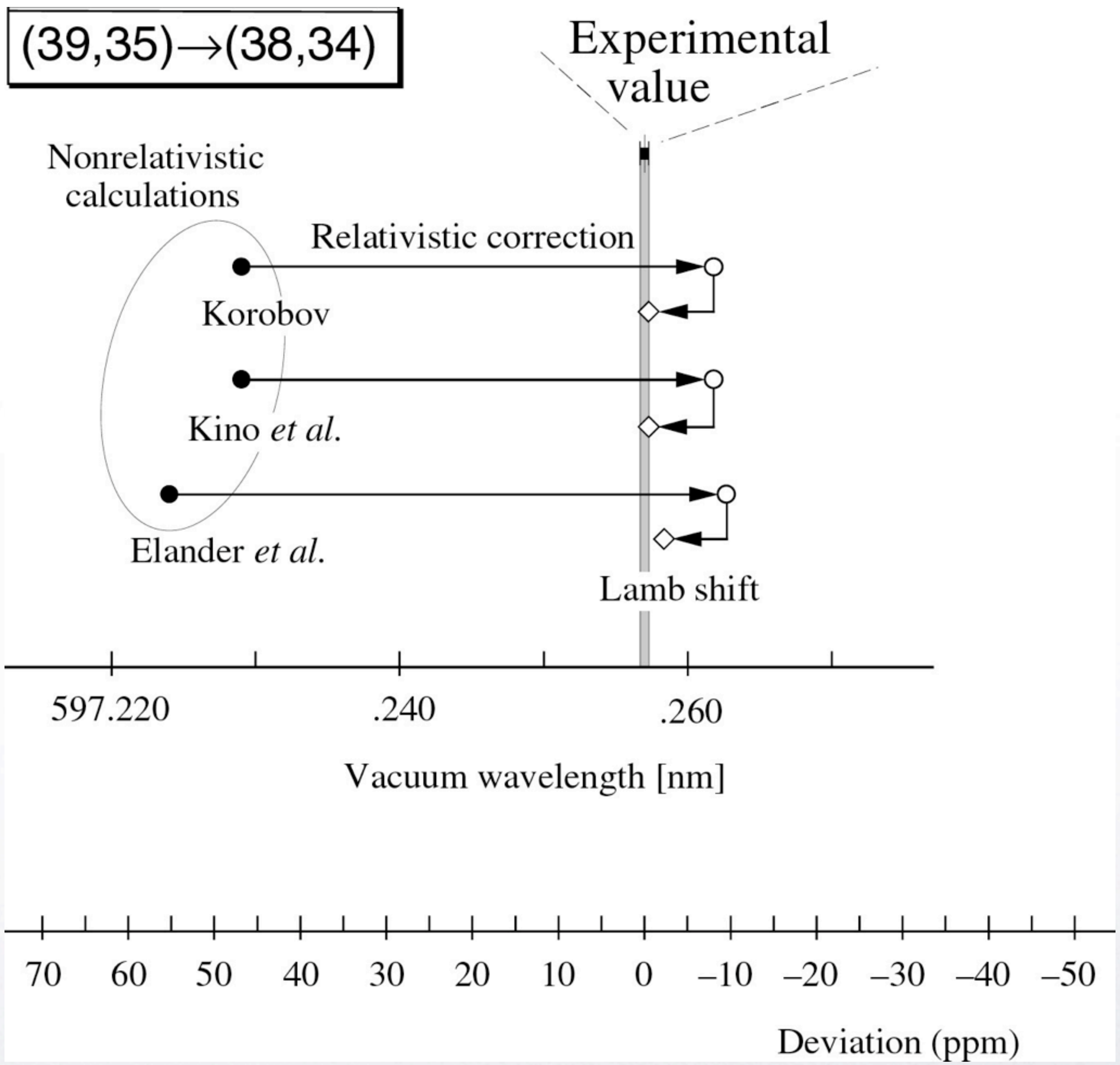




- RFQD: 5.3 MeV -> 20 – 120 keV (eff. > 25%)
- Differential pumping + ultra-thin beam window (~ 1 μm Mylar)
- high efficiency of stopping antiprotons at ultra-low densities (p < 1 mbar, T~20 K)

3-body QED description

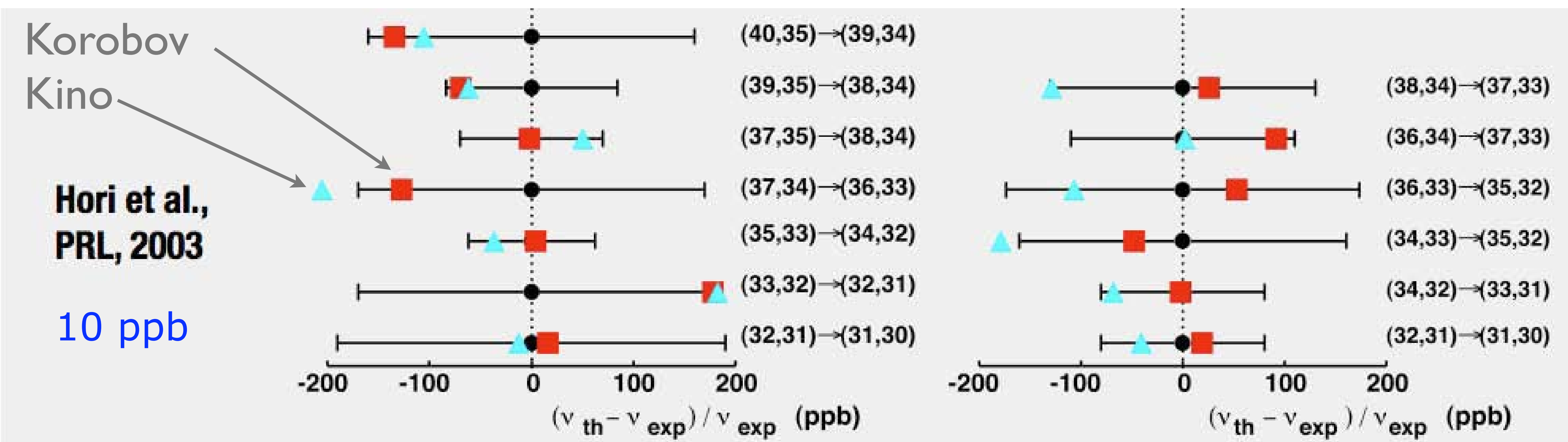
- non-relativistic 3-body calculations differ about 50 ppm
- relativisitc corrections: 10 ppm difference left
- Lamb shift and higher QED corrections needed



H.A. Torii et al. PRA 59 (1999) 223

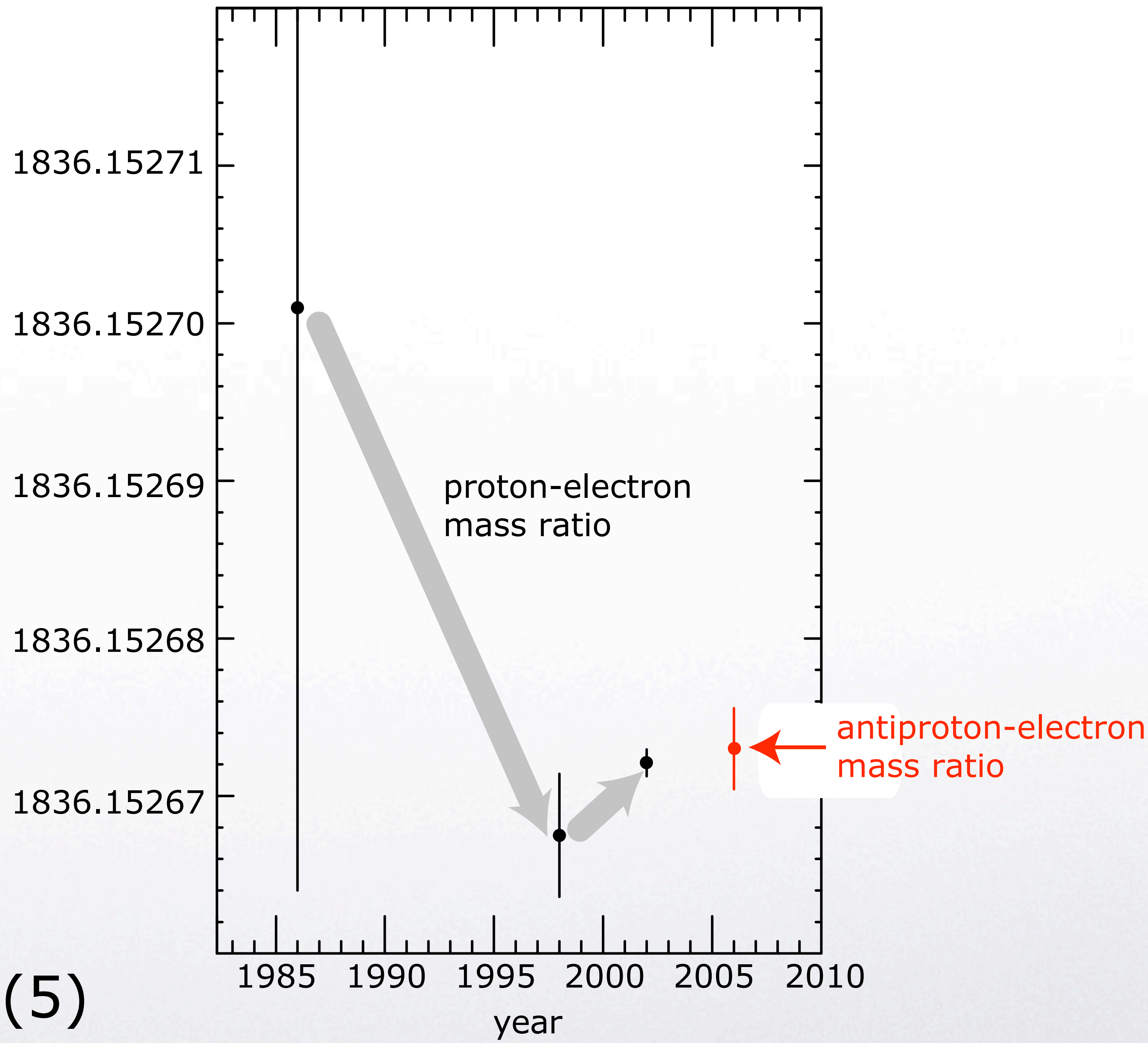
Experimental results and theory

$\bar{p}\,{}^4He^+$ $\bar{p}\,{}^3He^+$



p(bar)-e mass ratio

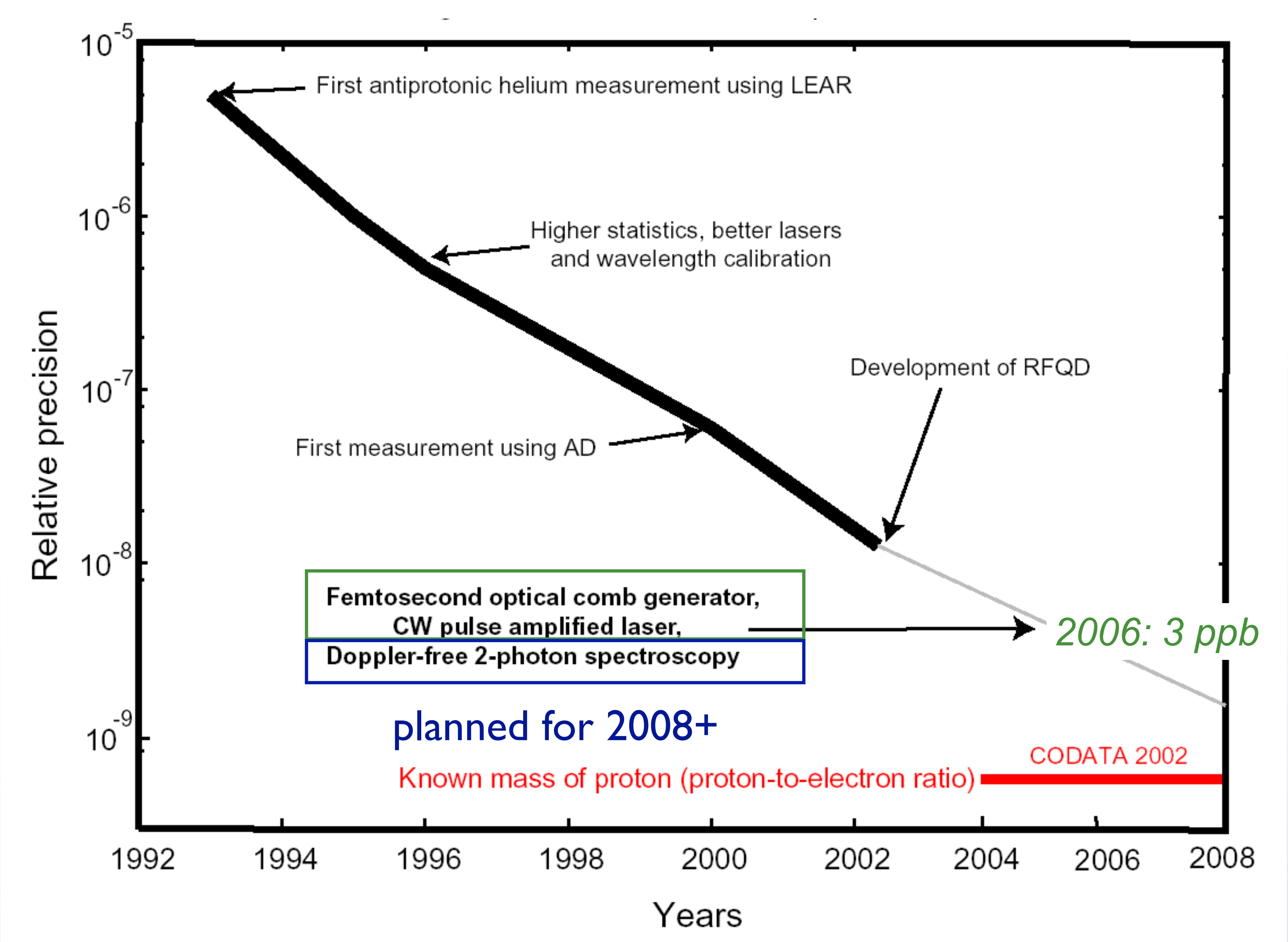
- CODATA value m_p/m_e changes over time
- antiproton mass measurement agrees with latest value for proton



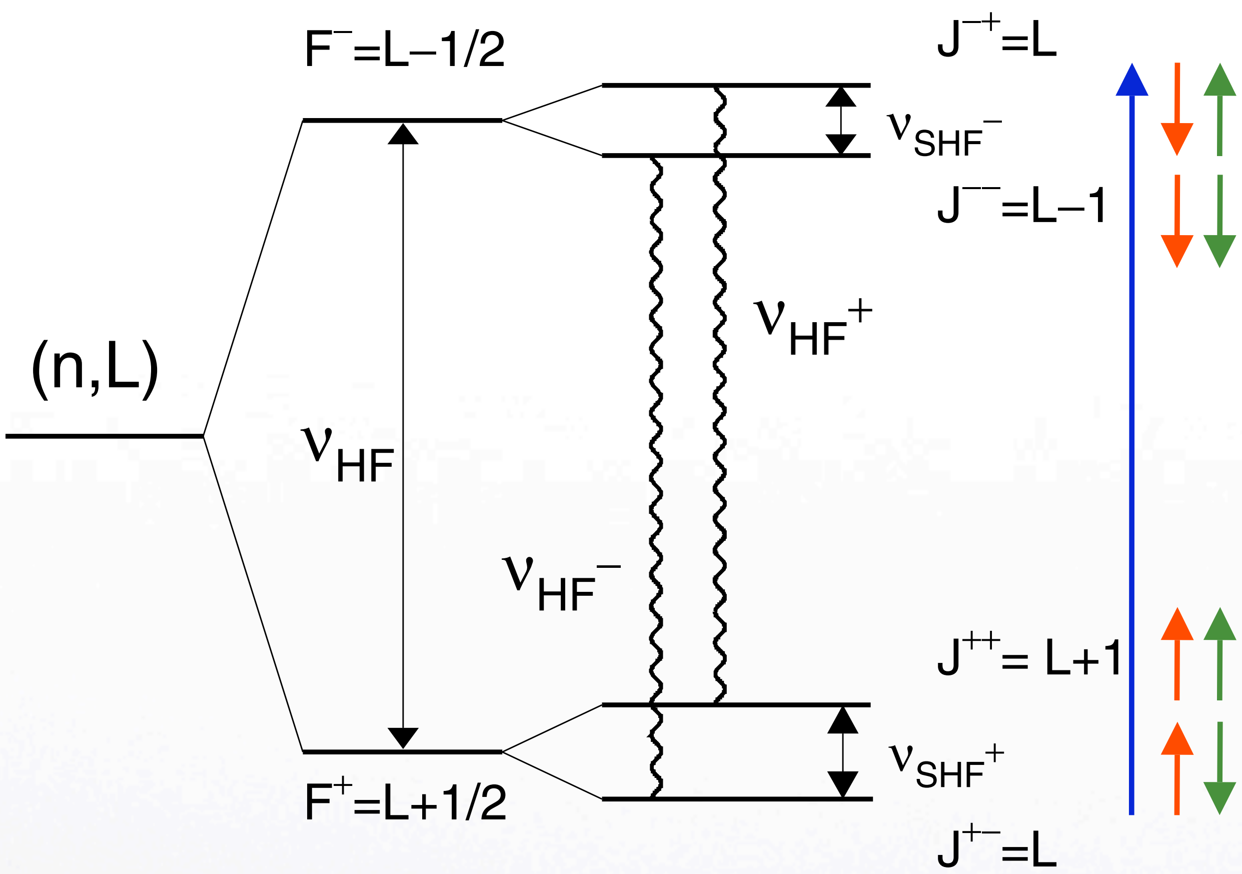
$m_{\bar{p}}/m_e = 1836.152674(5)$

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

Progress in atomcule spectroscopy



Hyperfine Structure of $\bar{p}\,^4He^+$



- *interactions of magnetic moments:*
  - electron: $\vec{\mu}_e = g\mu_B \vec{S}_e$
  - pbar: $\vec{\mu}_{\bar{p}} = [g_s(\bar{p})\vec{S}_{\bar{p}} + g_l(\bar{p})\vec{L}_{\bar{p}}]\mu_N$
- *"Hyperfine" splitting HFS:*

  $\vec{L}_{\bar{p}} \cdot \vec{S}_e$
  - dominant because of large L
- *"Superhyperfine" splitting*

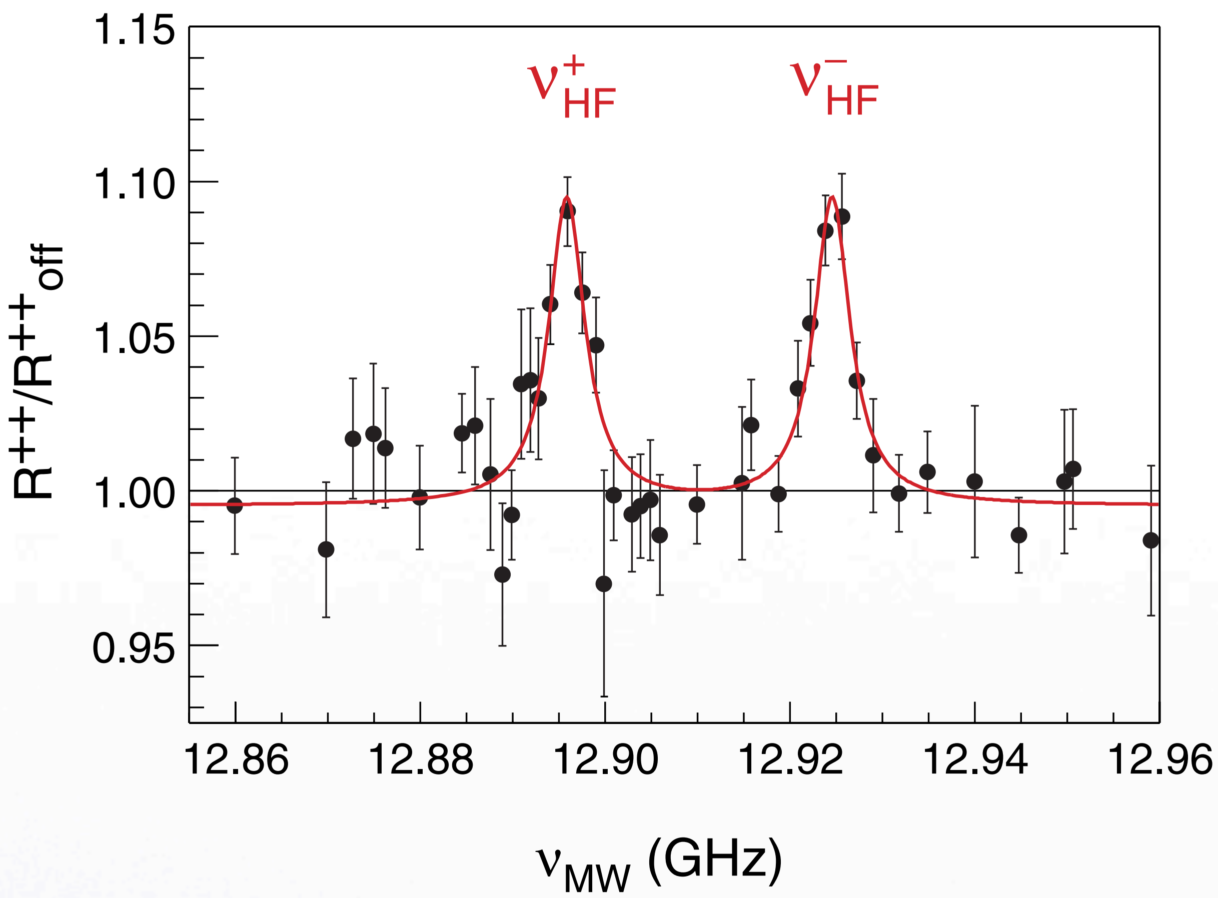
  $\vec{S}_{\bar{p}}$
- *HFS: 10 ... 15 GHz*
- *SHFS: 0.1 ... 0.3 GHz*

νSHF sensitive to magnetic moment of pbar

(known to 3×10^{-3})

νHF tests ***orbital*** angular moment: g_l

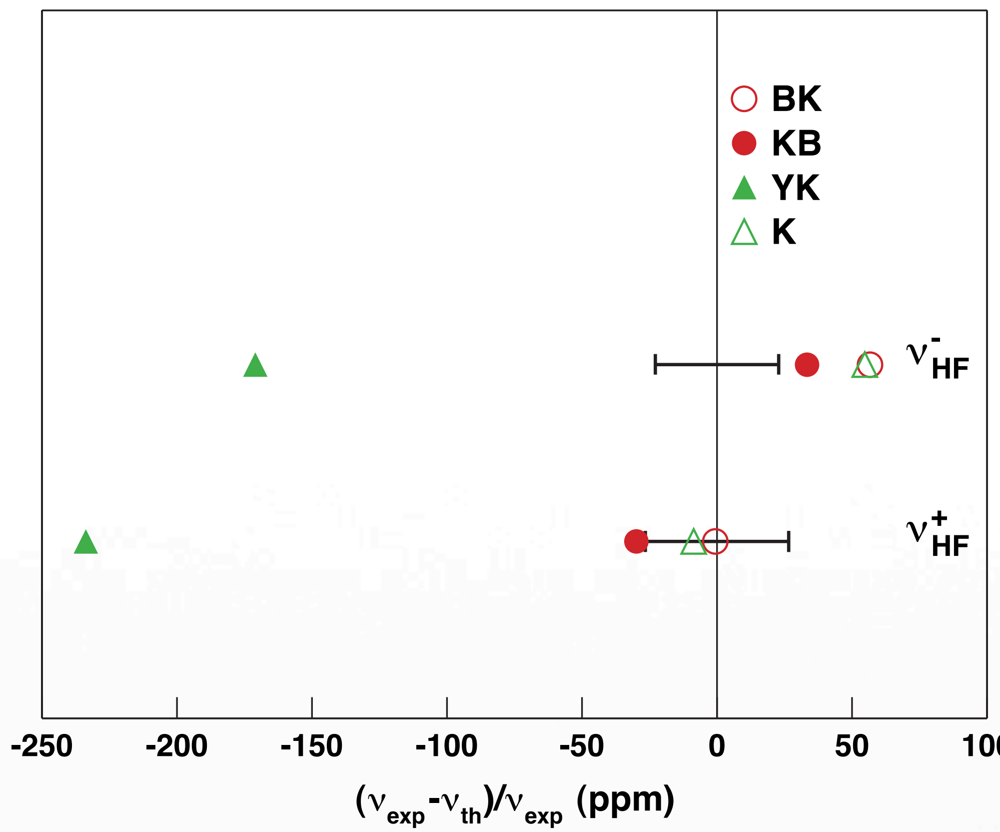
First observation of HFS transition



- Experimental accuracy: ~ 3 x 10^{-5}

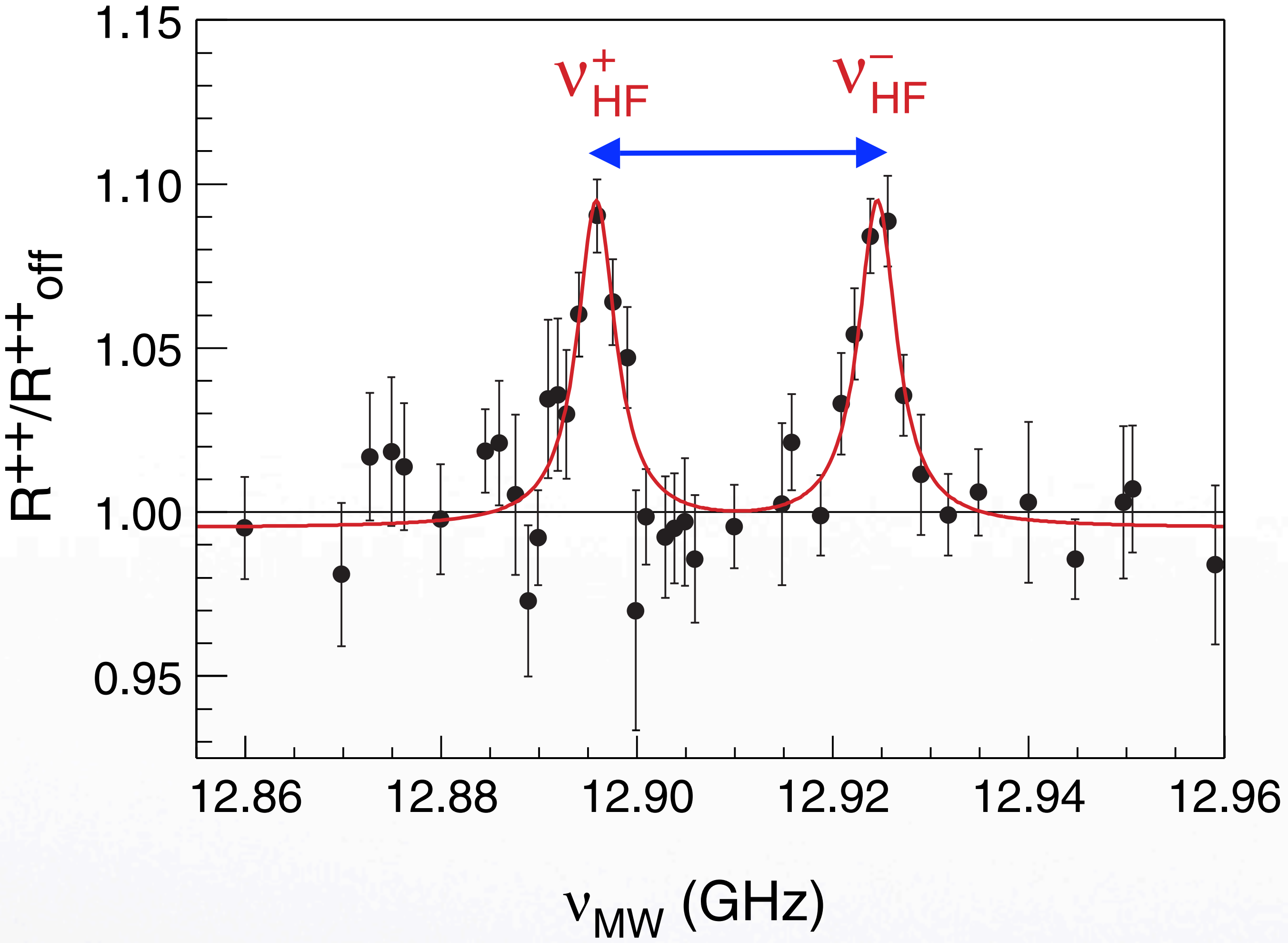
ν_{HF}^+	12.895 96(34) GHz	27 ppm
ν_{HF}^-	12.924 67(29) GHz	23 ppm

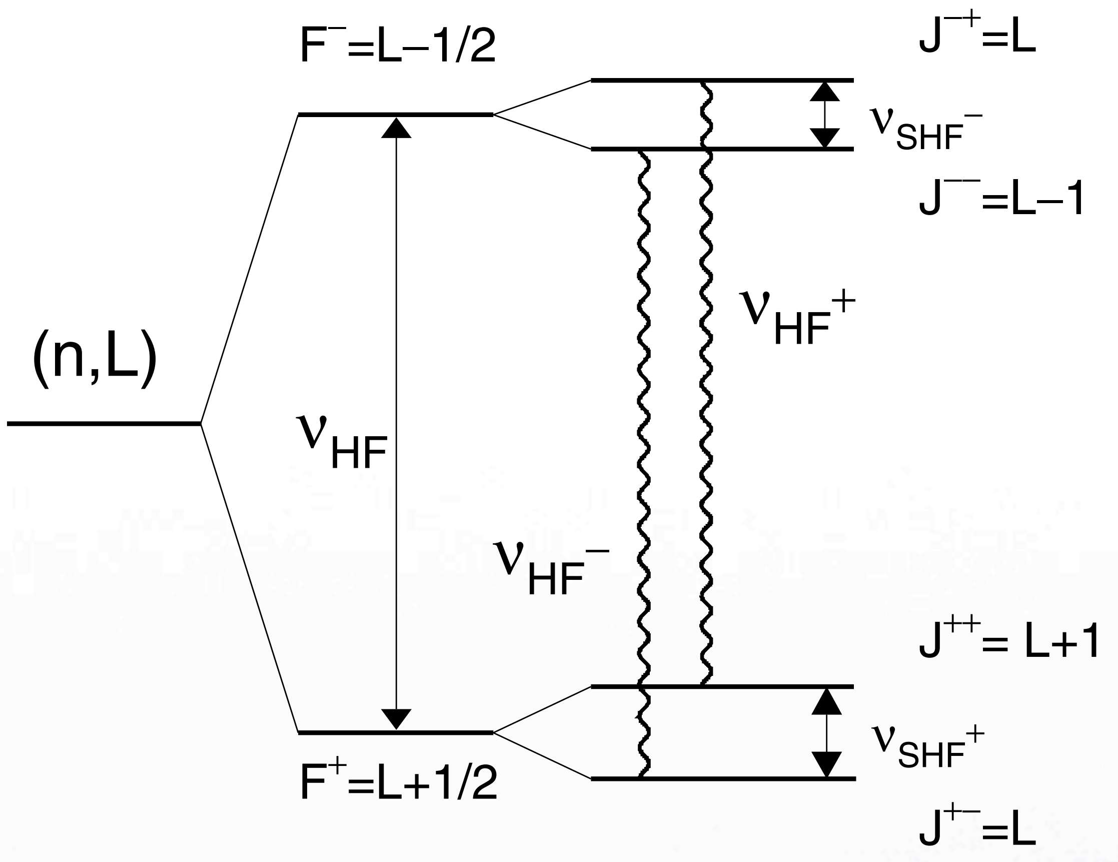
- E.W. et al. PRL 89 (2002) 243402



- *Comparison to theory favours most recent results of both groups*
  - *Korobov & Bakalov JPB 34 L519 2001*
  - *Kino et al. Proc. APAC 2001*
- *Difference < 6 x 10^{-5}*
- *Corresponds to theoretical uncertainty*
  - Omission of terms $O(\alpha^2)$~5×10^{-5}

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

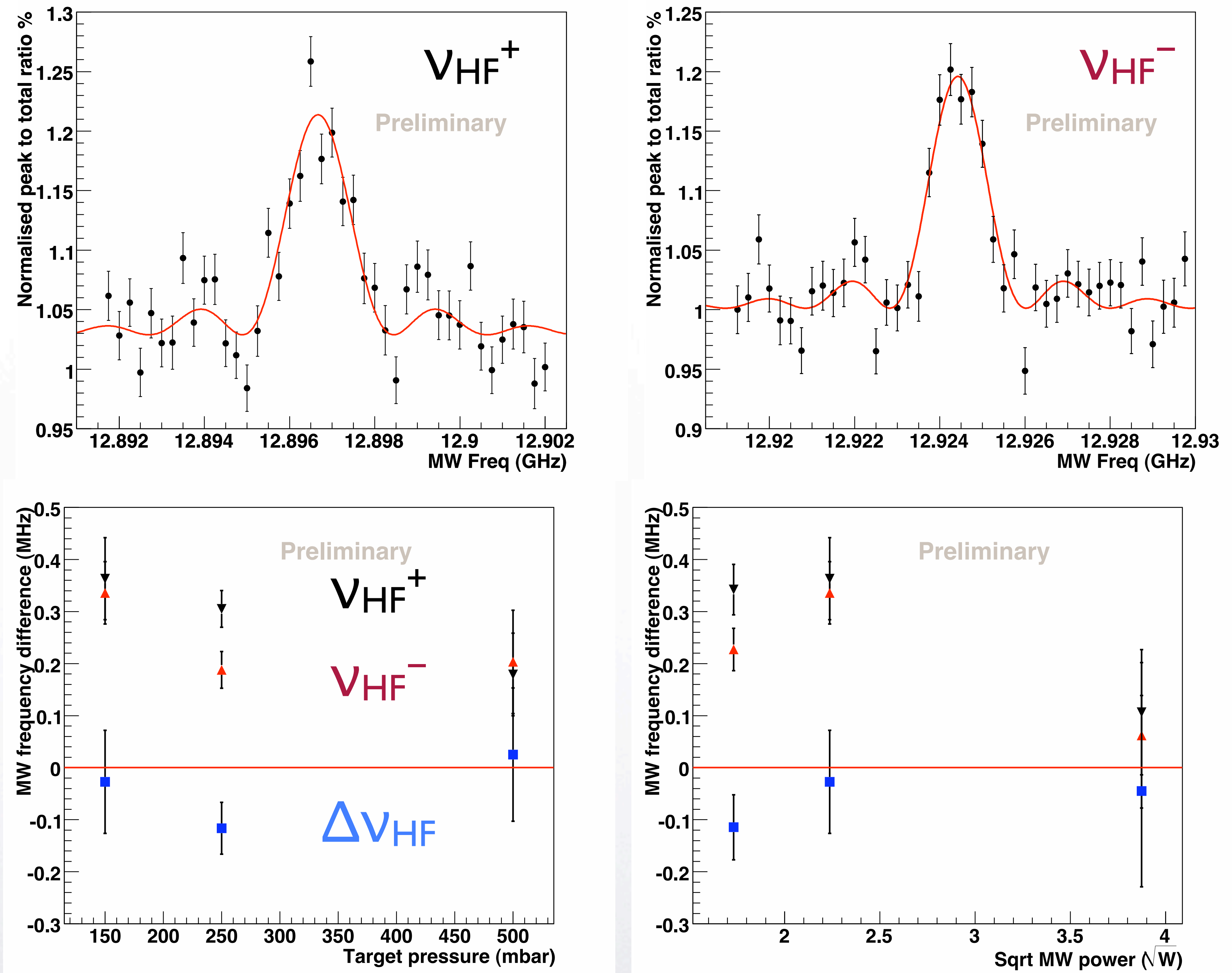




- ν_{SHF}^{+} , ν_{SHF}^{-} most sensitive, but impossible to measure (power requirement)
- $\Delta\nu_{HF} = \nu_{HF}^{-} - \nu_{HF}^{+} = \nu_{SHF}^{+} - \nu_{SHF}^{-}$: sensitive to $\mu_{\bar{p}}$
- sensitivity factors from theory (D. Bakalov and E.W., PRA 76 (2007) 012512)
  - $S(F,J) = \partial E_{nFLJ} / \partial \mu_{\bar{p}} \,|_{\mu_{\bar{p}} = -\mu_p}$
  - $S(\nu_{HF}^{+}) = S(F^{-}J^{--}) - S(F^{+}J^{+-})$

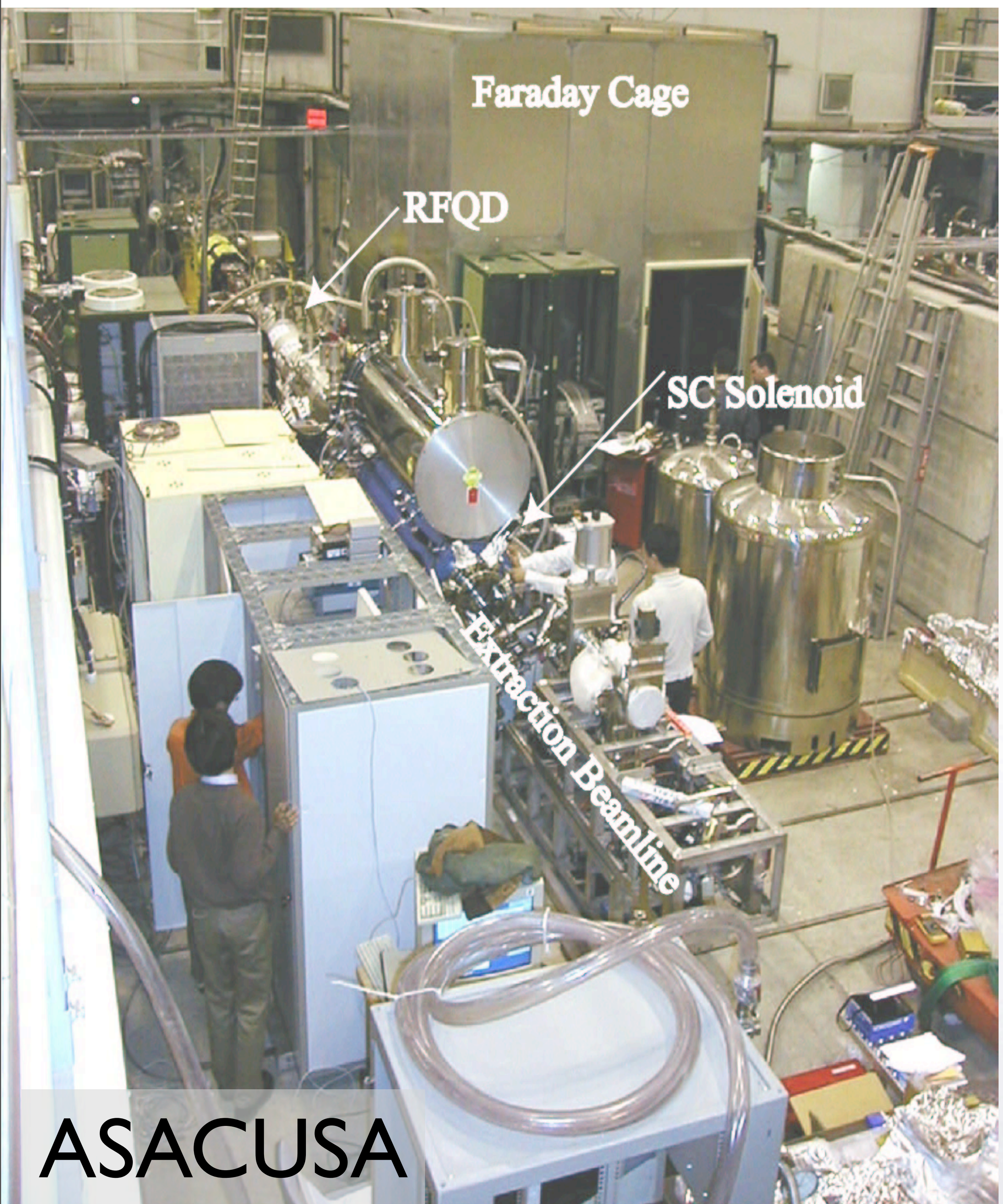
Recent results

- statistical error: 20 kHz on $\nu_{HF}^{\pm}$: $\Delta\nu/\nu = 1.5 \times 10^{-6}$
- 30 kHz on $\Delta\nu_{HF}$: $\Delta\nu/\nu = 10^{-3}$
- no density nor power shift observed
- agreement to theory not yet perfect

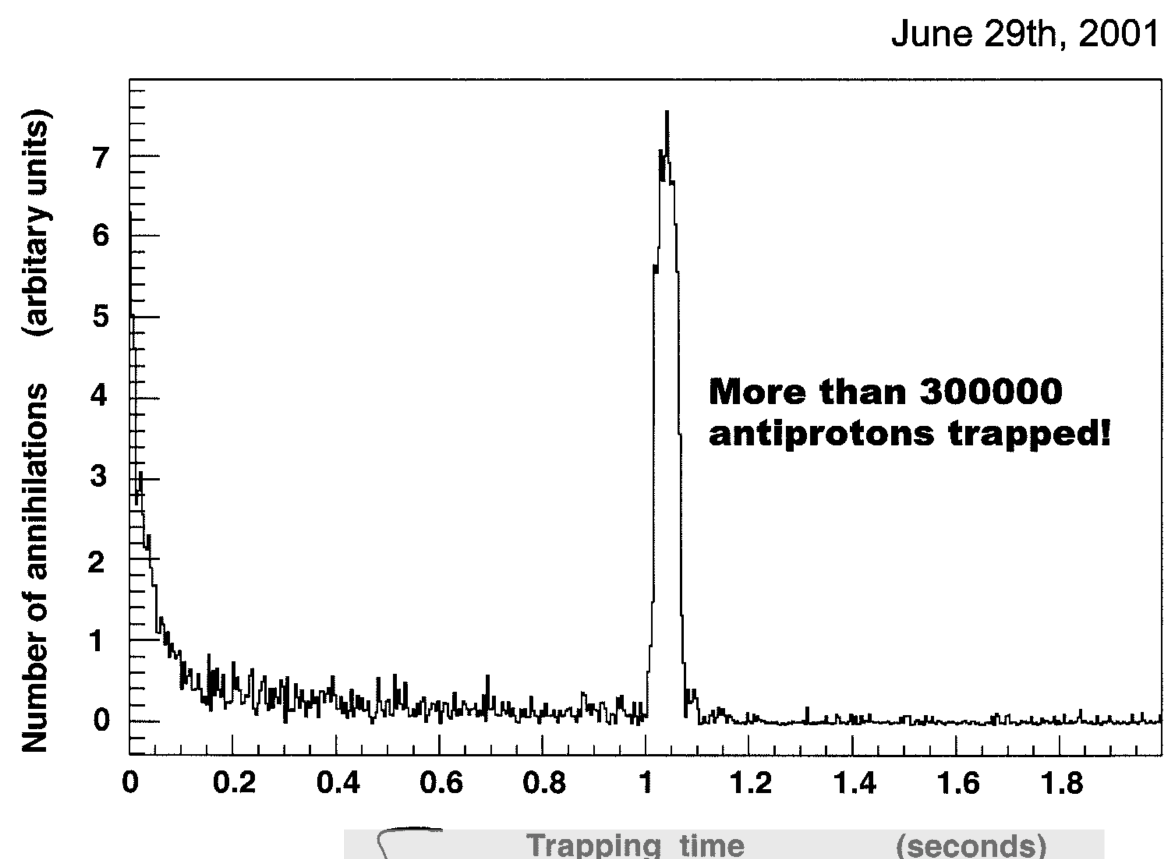


(a) (b)

MUSASHI – Mono-energetic Ultra Slow Antiproton Source for High-precision Investigations



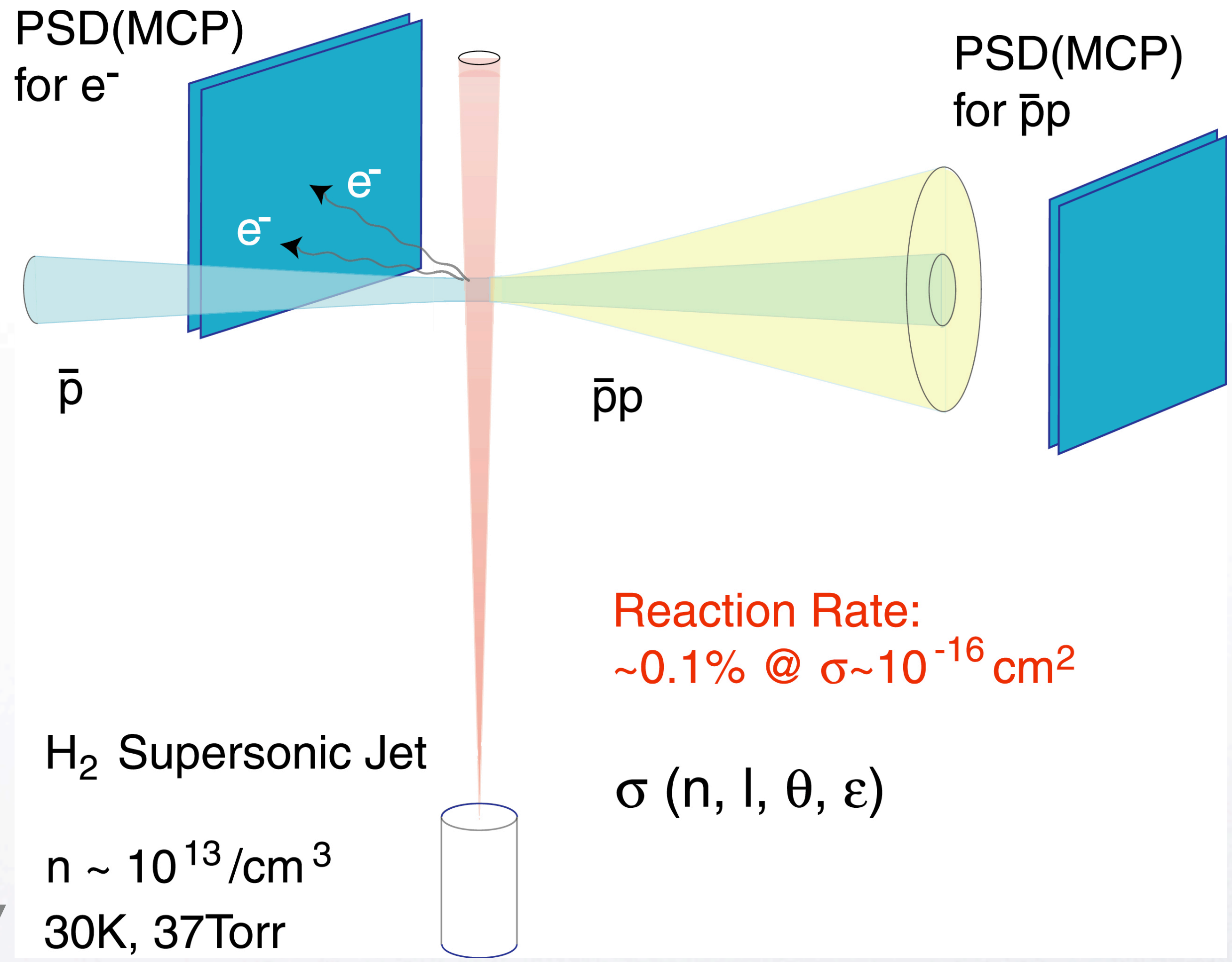
First antiprotons trapped by ASACUSA collaboration!



2003: >1 M/shot
Extracted @ 250 eV:
60'000 / 2 shots

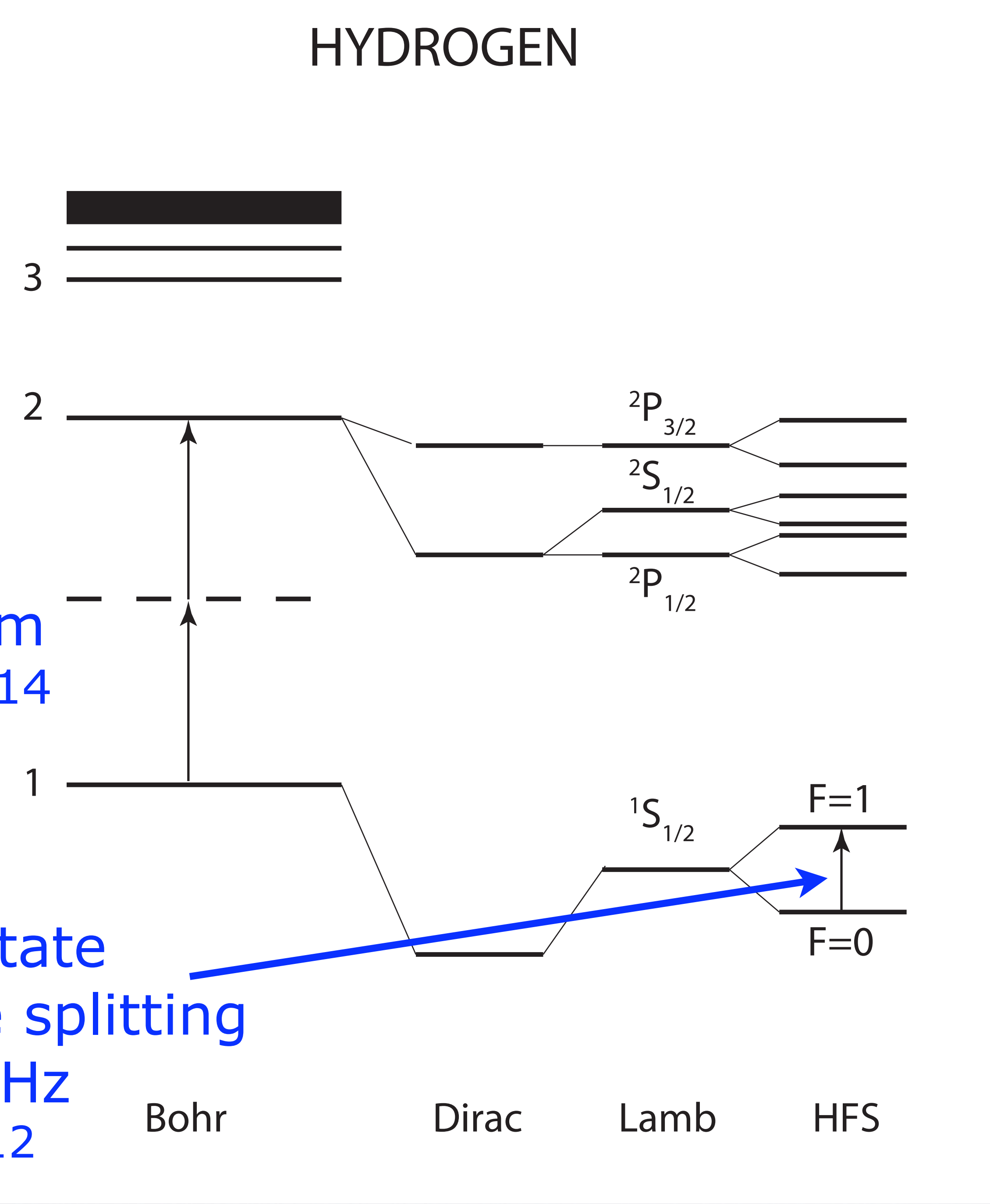
Physics with MUSASHI

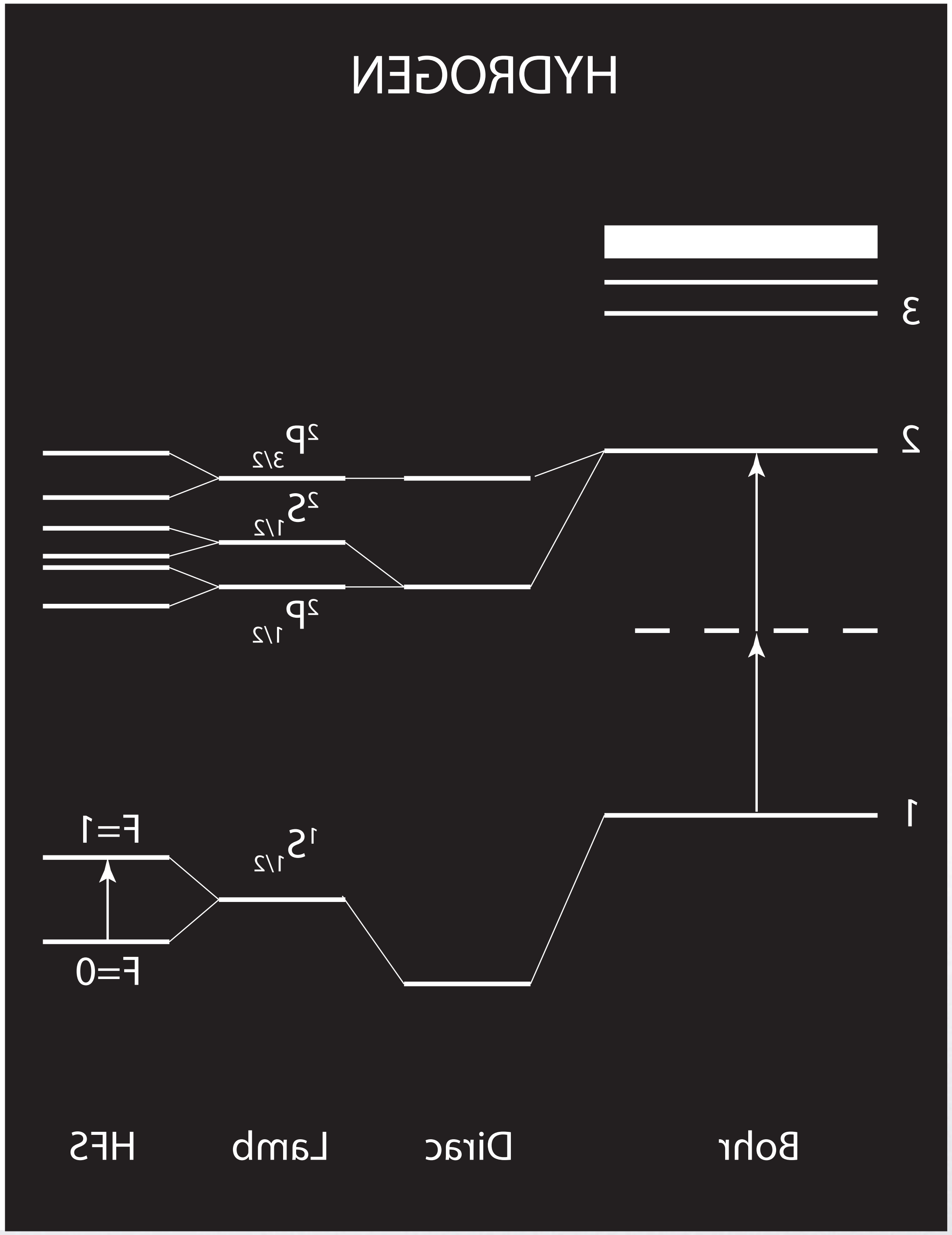
- 10 – 1000 eV antiproton beam useful for
  - Formation of antiprotonic atoms (protonium, …)
  - Ionization in single collision by slow antiprotons
    - Ionization chamber to be installed at AD in October
  - Many other applications
    - Protonium X-ray spectroscopy
    - Probing neutron and proton distribution in nuclei



Y. Yamazaki & H.A. Torii U Tokyo

Hydrogen and Antihydrogen





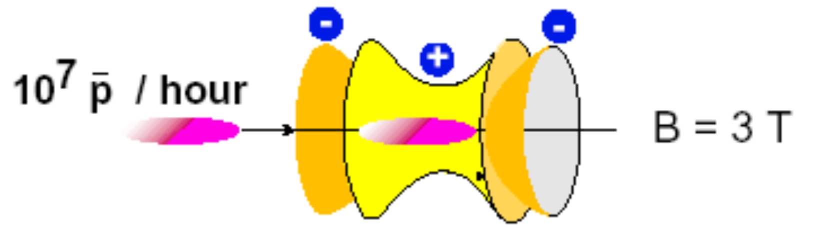
1s-2s
2 photon
λ=243 nm
$\Delta f/f=10^{-14}$

Ground state
hyperfine splitting
f = 1.4 GHz
$\Delta f/f=10^{-12}$

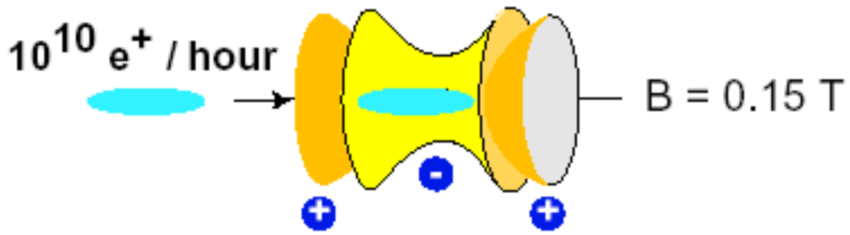
Antihydrogen 1S-2S Spectroscopy

ATHENA Collaboration *

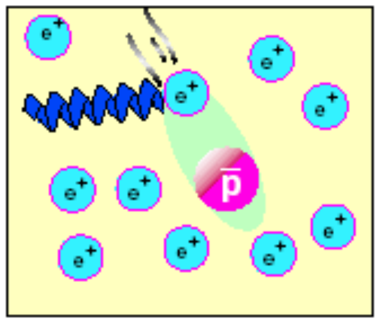
1. Antiproton **Capture** into Penning Trap



2. Positron Accumulation from Na-22 source



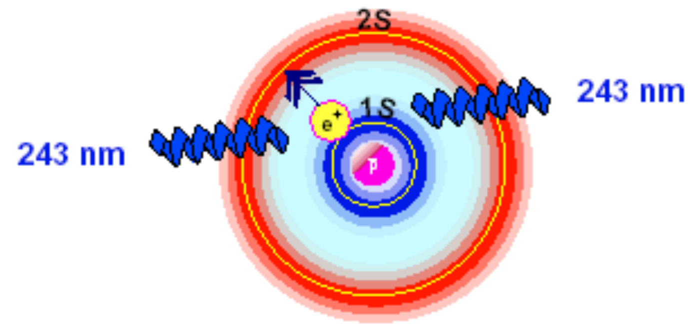
3. Positron-Antiproton Recombination in multi-ring trap at 4.2 K



4. Antihydrogen **Storage** in Magnetic Bottle
Magnetic well depth ~ 0.35 K (35 meV)
(PHASE 2)

5. Antihydrogen **Detection**
   - Annihilation products: Si Pad Detectors
   - 511 keV Gammas: CsI or BGO + Photodiodes

6. 2-Photon Laser **Spectroscopy**: DE (1S-2S)
(PHASE 2)



Comparison H̄ : H with precision 10^{-12} ...10^{-15}

Data taking: 1999 -

Achieved, but
- temperature?
- quantum state?

Most critical !!

* Aarhus, Brescia, CERN, Genoa, UC London, MIT, Pavia, Penn State, Pisa, Rio de Janeiro, Rome, Stockholm, Tokyo, Zurich (14 institutes, ~ 50 physicists)

First Cold Antihydrogen 2002 @ AD

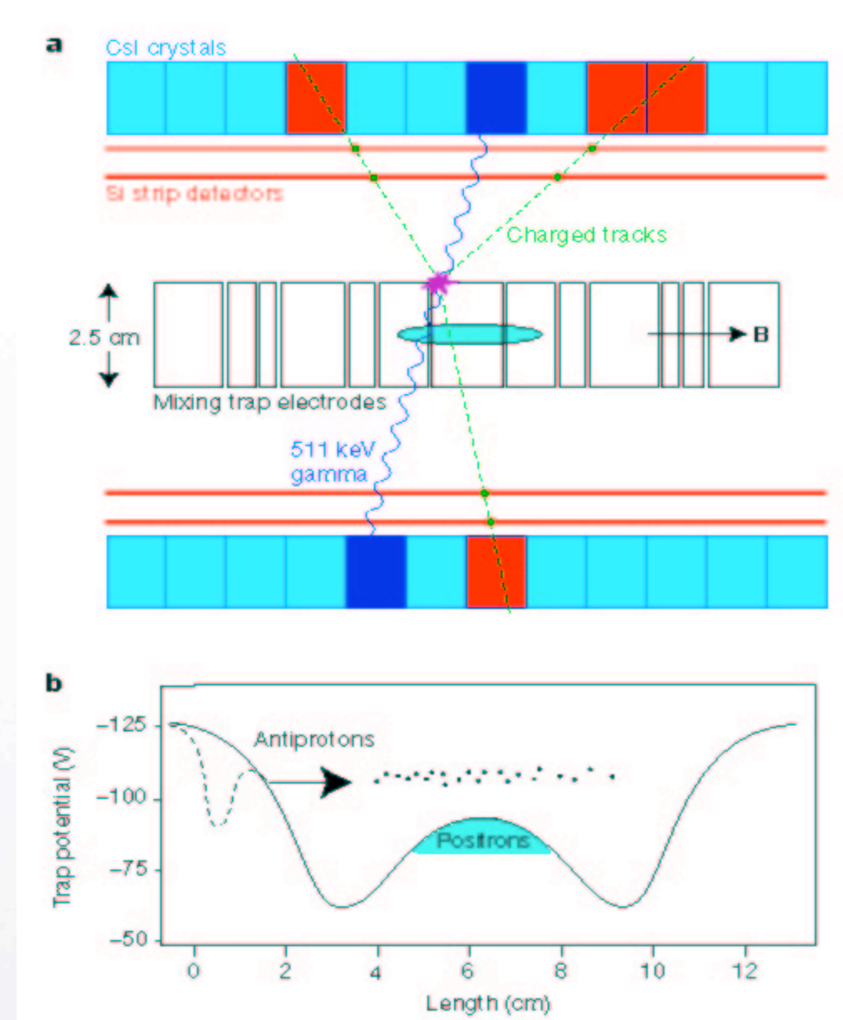
advance online publication

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#

ATHENA
Nature 419 (2002) 456

Nested Penning traps
Capture energy: few keV



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)

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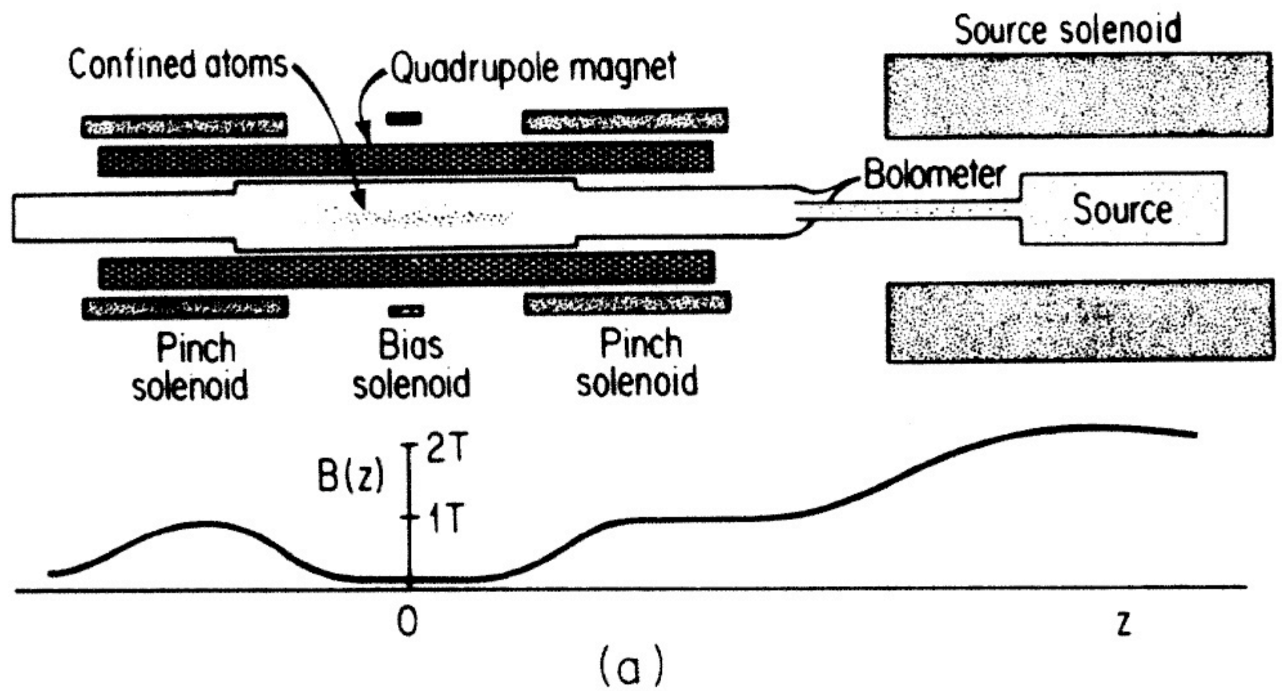
ATRAP PRL 89 (2002) 213401

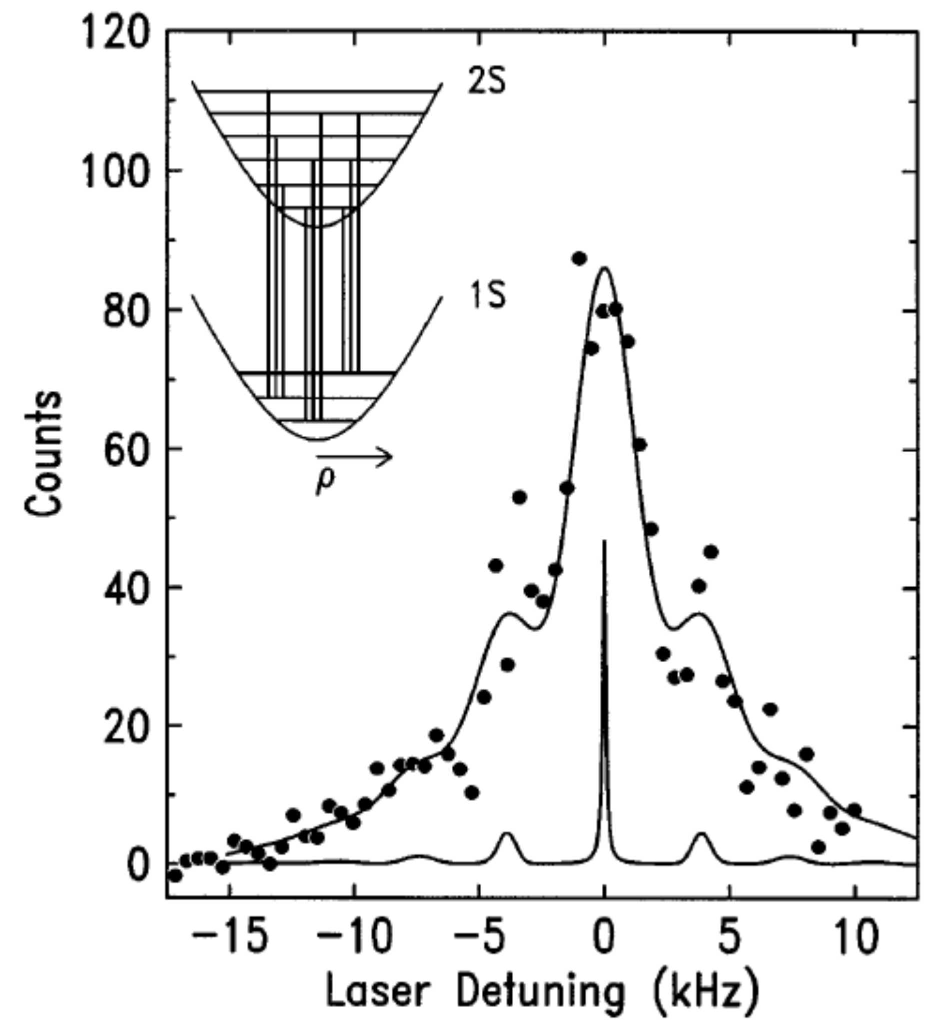
No "useful" Hbar produced (ground-state, < 1 K temperature for trapping)
Ultimate precision: neutral atom trap and laser cooling to milli-Kelvin temperature

Hydrogen spectroscopy in a neutral atom trap

- Force of magnetic field gradient on magnetic moment of atom
- "depth" typically < 1 K (50 μeV)
- Constant holding-field $B_{z,0}$ to avoid spin flips
- Typical configuration:

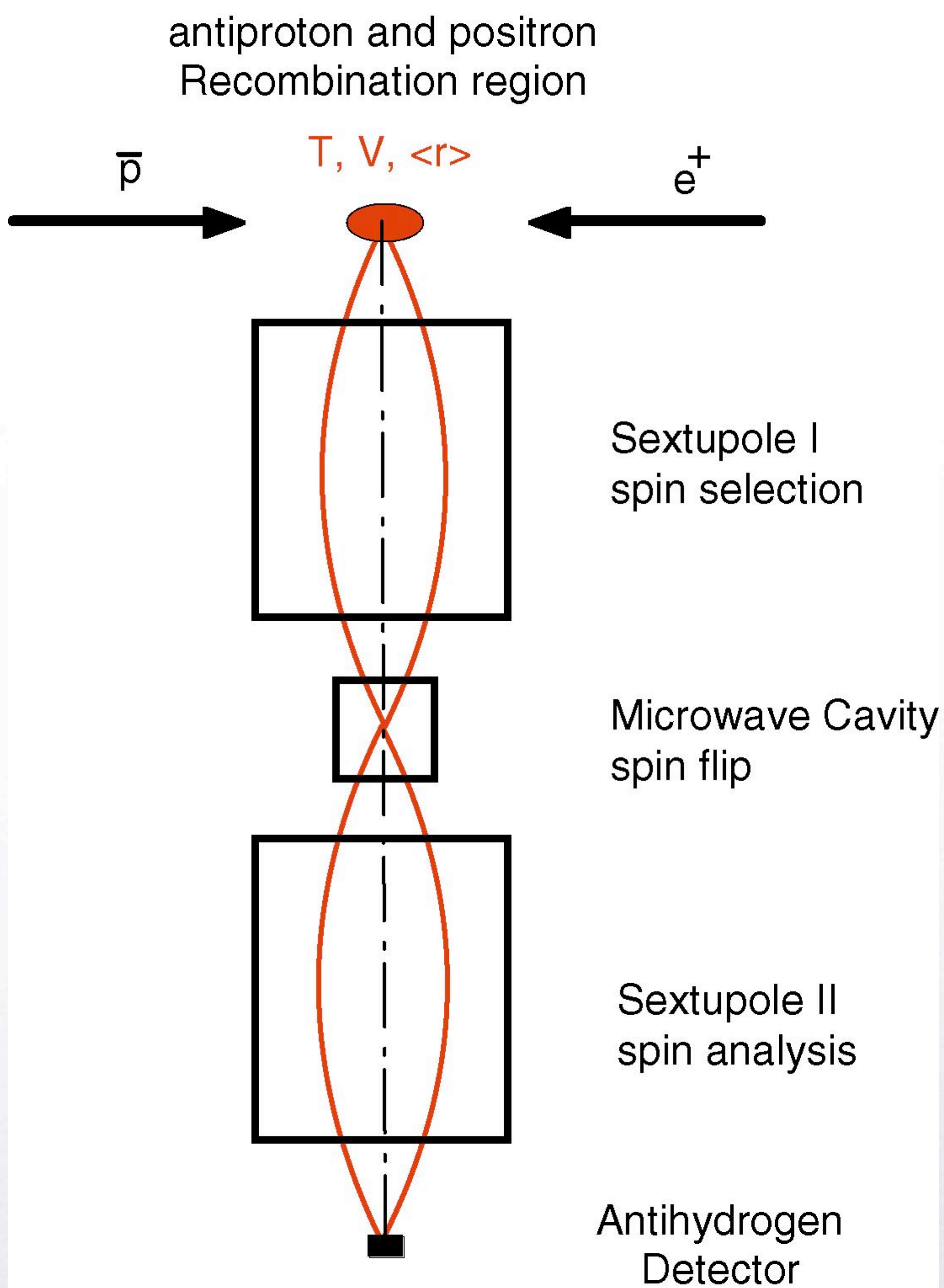


- Trapped hydrogen
  - Cesar et al., PRL 77, 255 (1996)
  - Precision less than MPQ



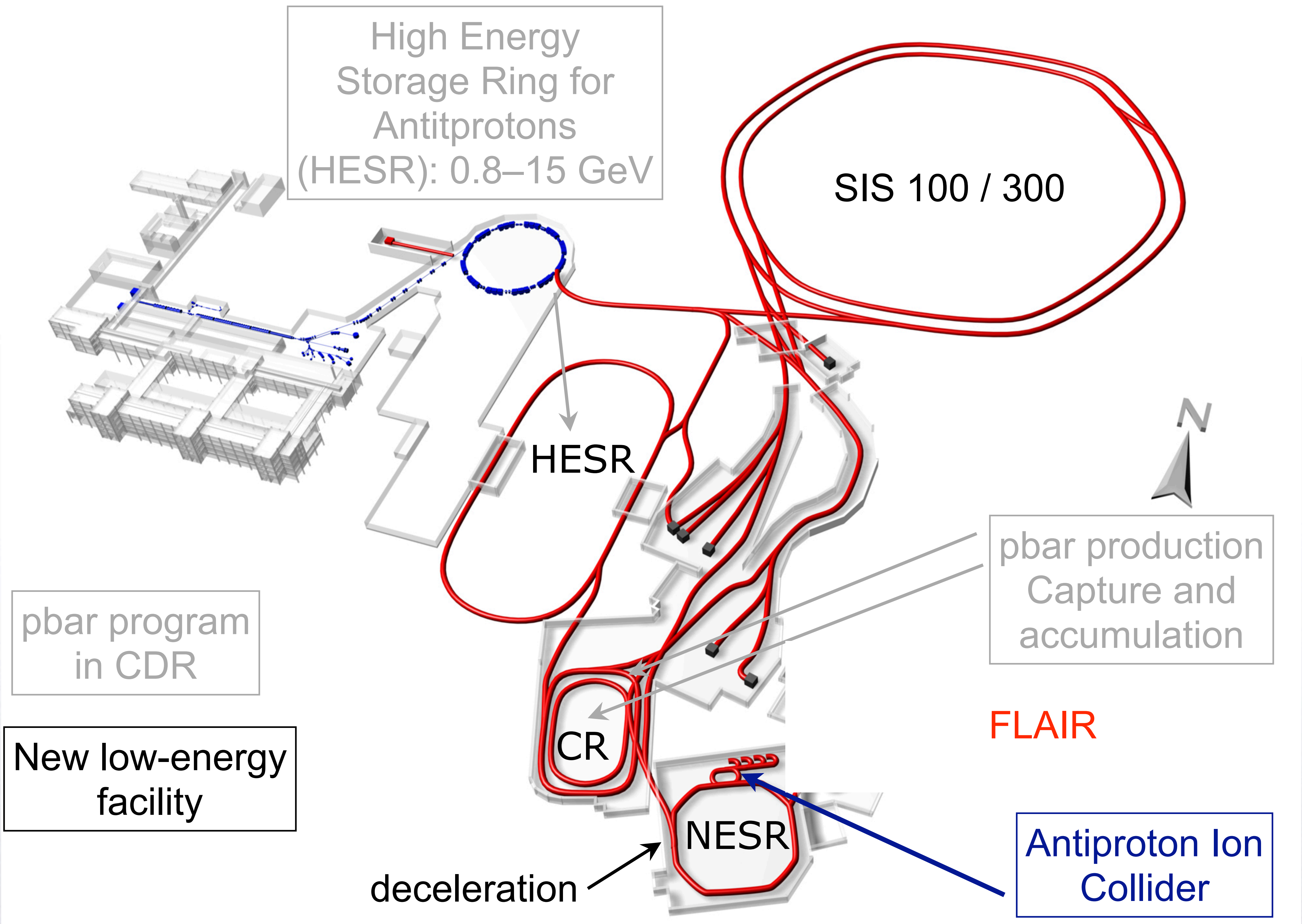
$\bar{H}$ Ground-state Hyperfine Structure

- atoms “evaporate”
  - No trapping needed !!
- atomic beam for focussing and spin selection
- spin-flip by microwave radiation
- low-background high-efficiency detection of antihydrogen through annihilation
- achievable resolution
  - better 10–6 for T ≤ 100 K
  - > 100 $\bar{H}$/s in 1S state needed
- ultimate precision:
  - atomic fountain of $\bar{H}$ -> FLAIR



ASACUSA proposal for AD
E.W. et al. CERN-
SPSC-2003-009

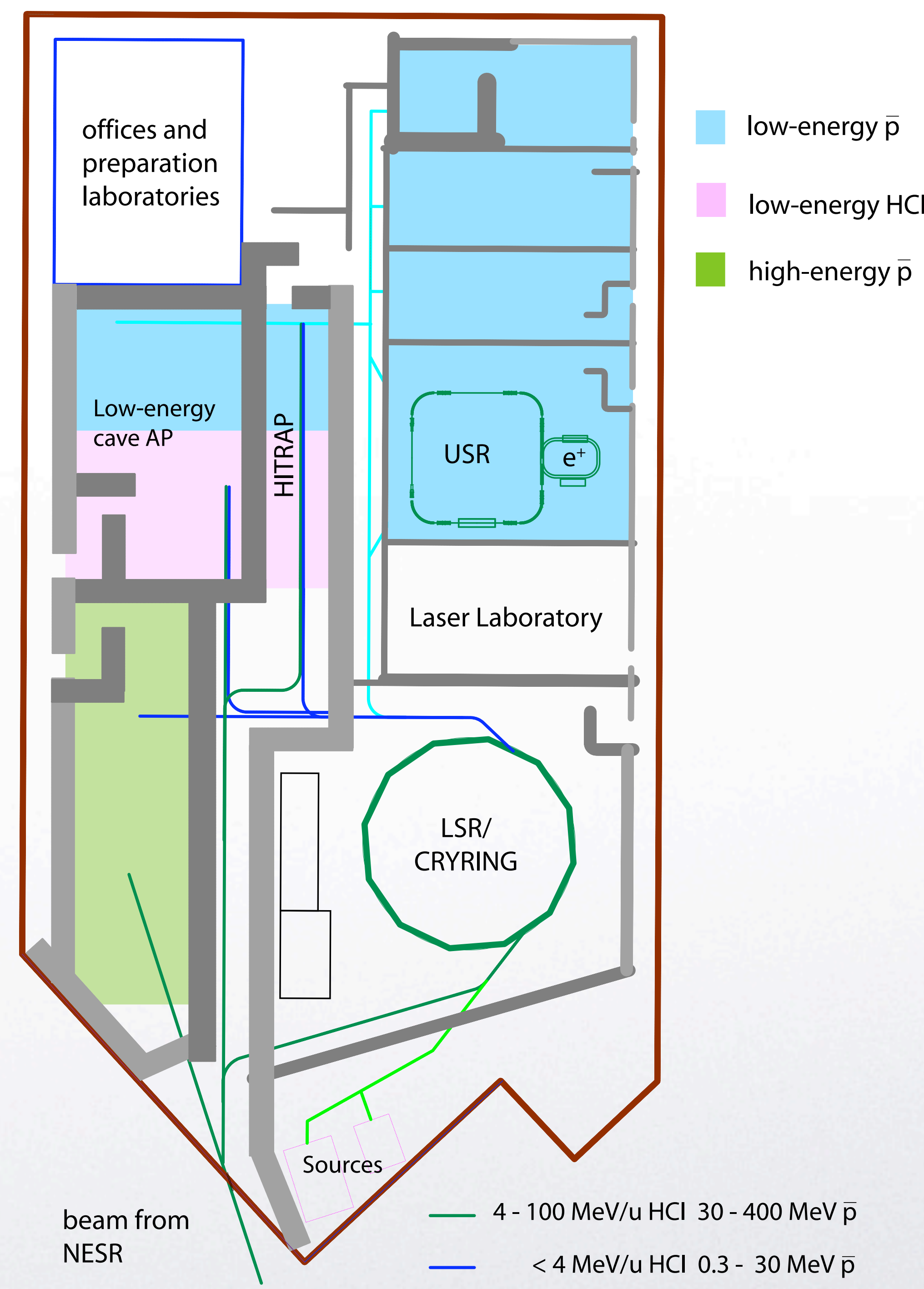
Antiprotons at FAIR



FLAIR@ FAIR

- High brightness low energy beams
  - two storage rings with 300 keV (LSR) and 20 keV (USR)
  - electron cooling
    - ε ~ 1 π mm mrad
    - Δp/p ~ 10–4
- Storage rings with internal targets for collision studies
- Slow and fast extraction
- Ion traps
  - HITRAP facility for HCI & pbar
- Many new experiments possible
- same facilities can be used for HCI

Factor 100 more pbar trapped or stopped in gas targets than now



Summary and Outlook

- Low energy antiprotons offer many opportunities to study fundamental interactions and symmetries
- FLAIR facilities offers new possibilities
- Cooled antiprotons at 20 keV will revolutionize low- energy antiproton physics
- DC beams enable nuclear and particle physics type experiments (not possible at AD)
- Availability of radioactive ion beams (RIB) offers new synergies

- ~2015: first low-energy antiproton beam at FLAIR