ASACUSA collaboration

Recent achievements

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Atomic Spectroscopy And Collisions Using Slow Antiprotons

Austria - SMI Vienna

Denmark - University of Aarhus

Germany - Max-Planck Institute for Quantum Optics

Hungary - KFKI Budapest, ATOMKI Debrecen

Italy - INFN Brescia

Japan - University of Tokyo, RIKEN Saitama

United Kingdom - University of Swansea, Queens University of Belfast

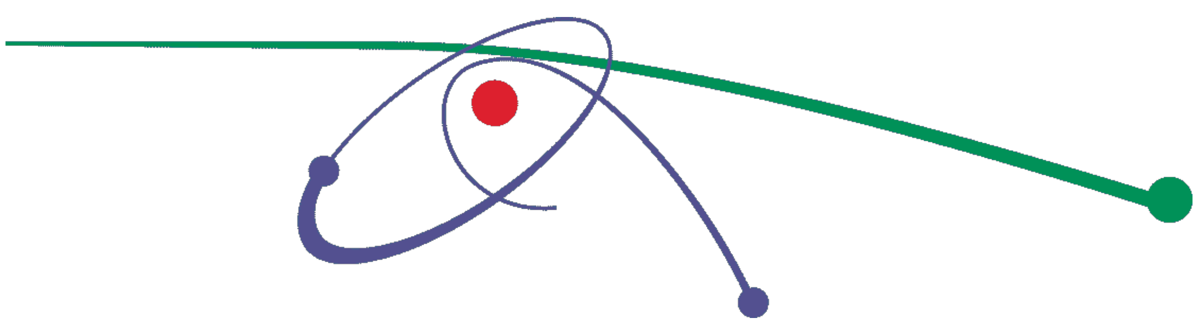
Asakusa, Tokyo

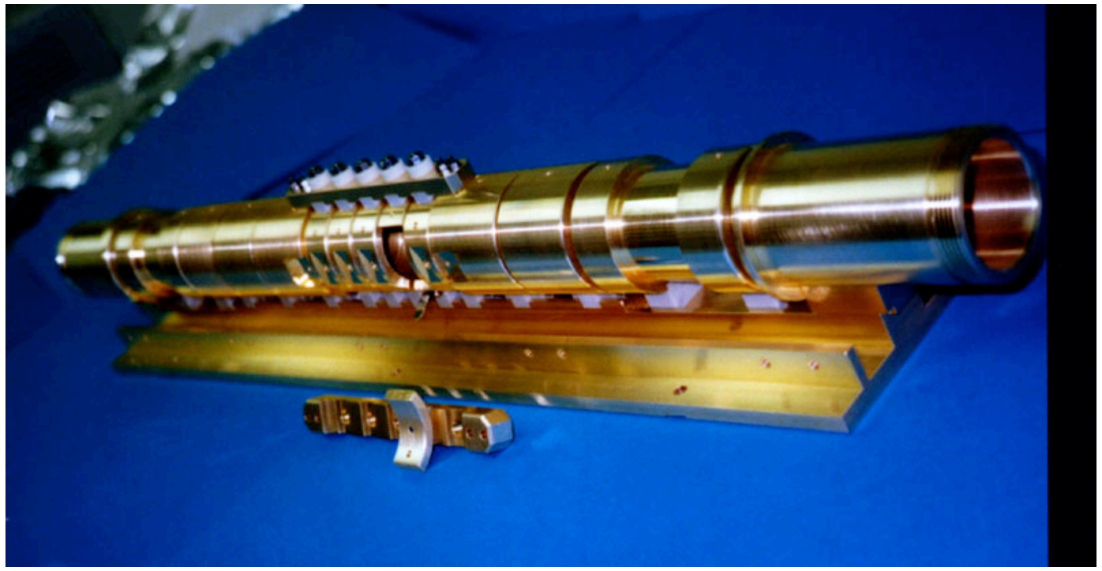
7 countries, 10 institutions, 40 researchers
Started in 1997 by merger of PS194, PS205, etc. collaborations.
Members active in CERN's antiproton programme since >20 years.

ASACUSA - physics goals

We use antiproton beams of various energies to explore fundamental properties and reactions of antimatter.

- **5 MeV** -- Antiproton magnetic moment, Nuclear collisions
- **60 keV** -- Antiproton mass and charge.
- **0.5-10 kV** -- Atomic collisions
- **< 1 eV** -- Antihydrogen

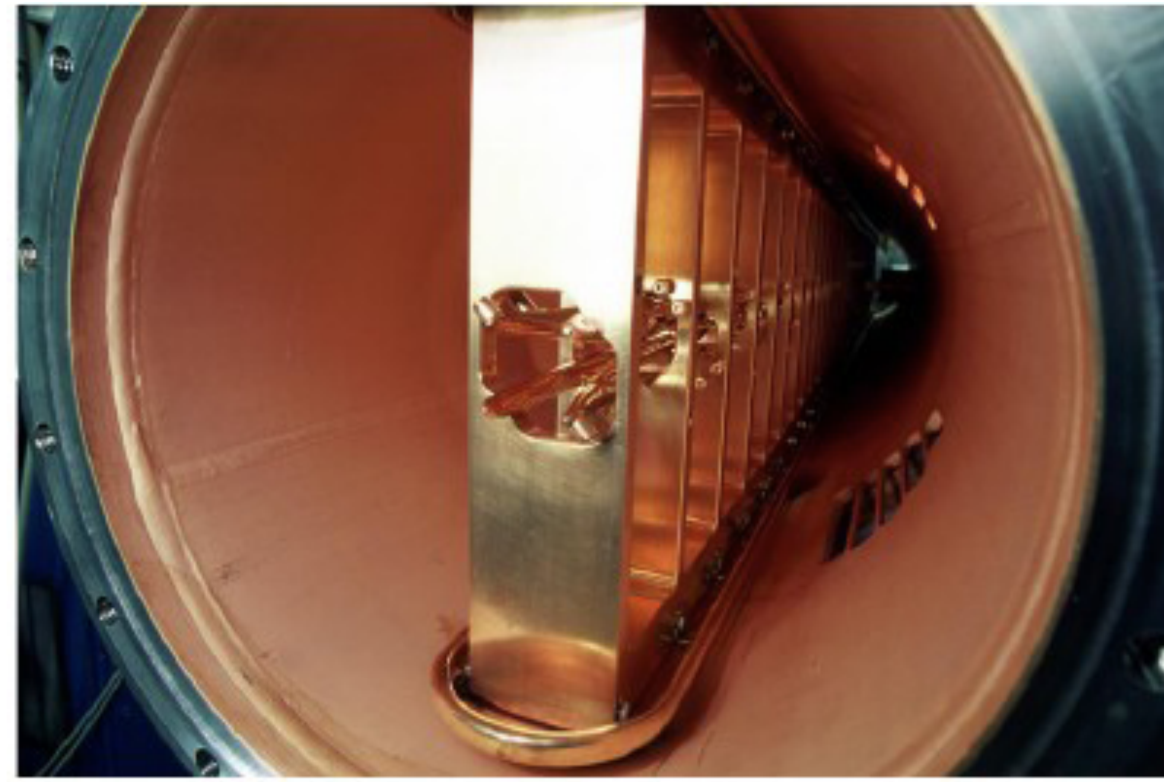




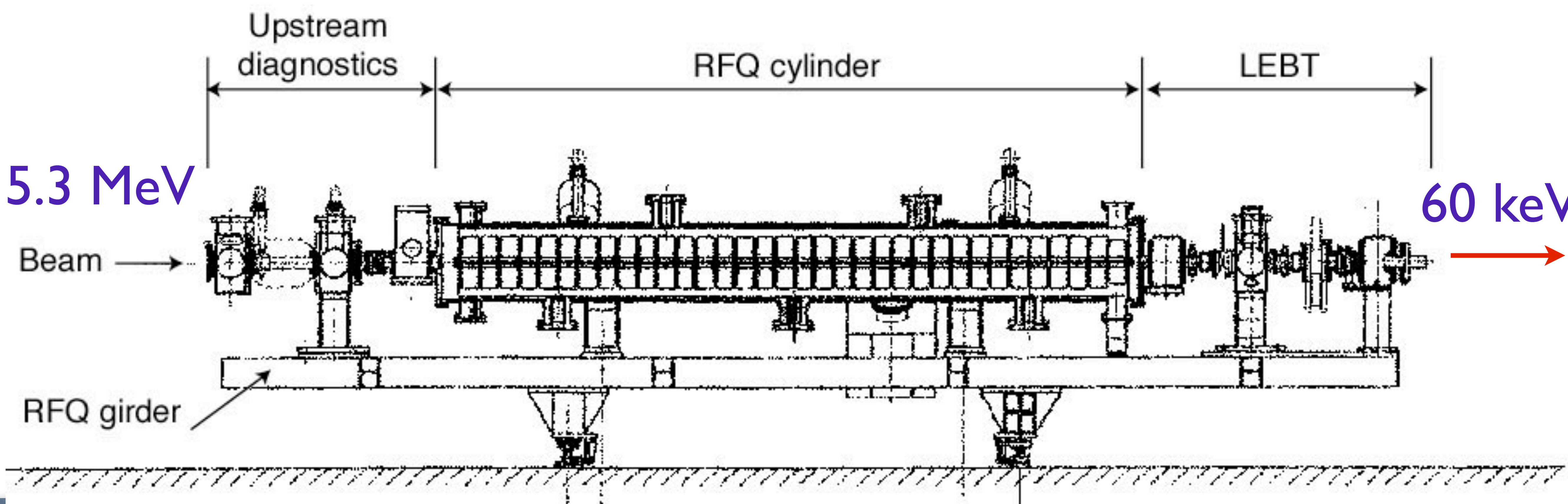
"Musashi" trap

Radiofrequency Quadrupole Decelerator

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



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

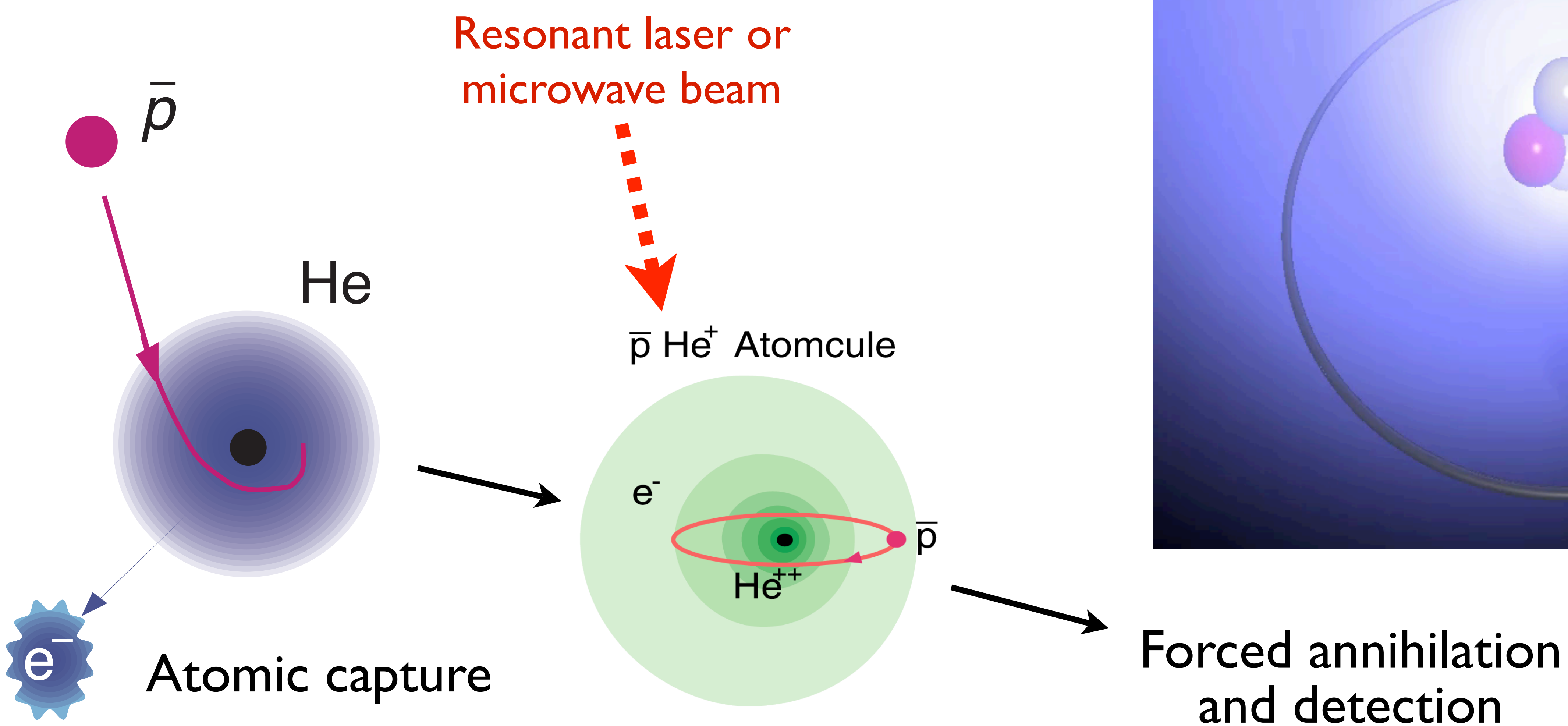


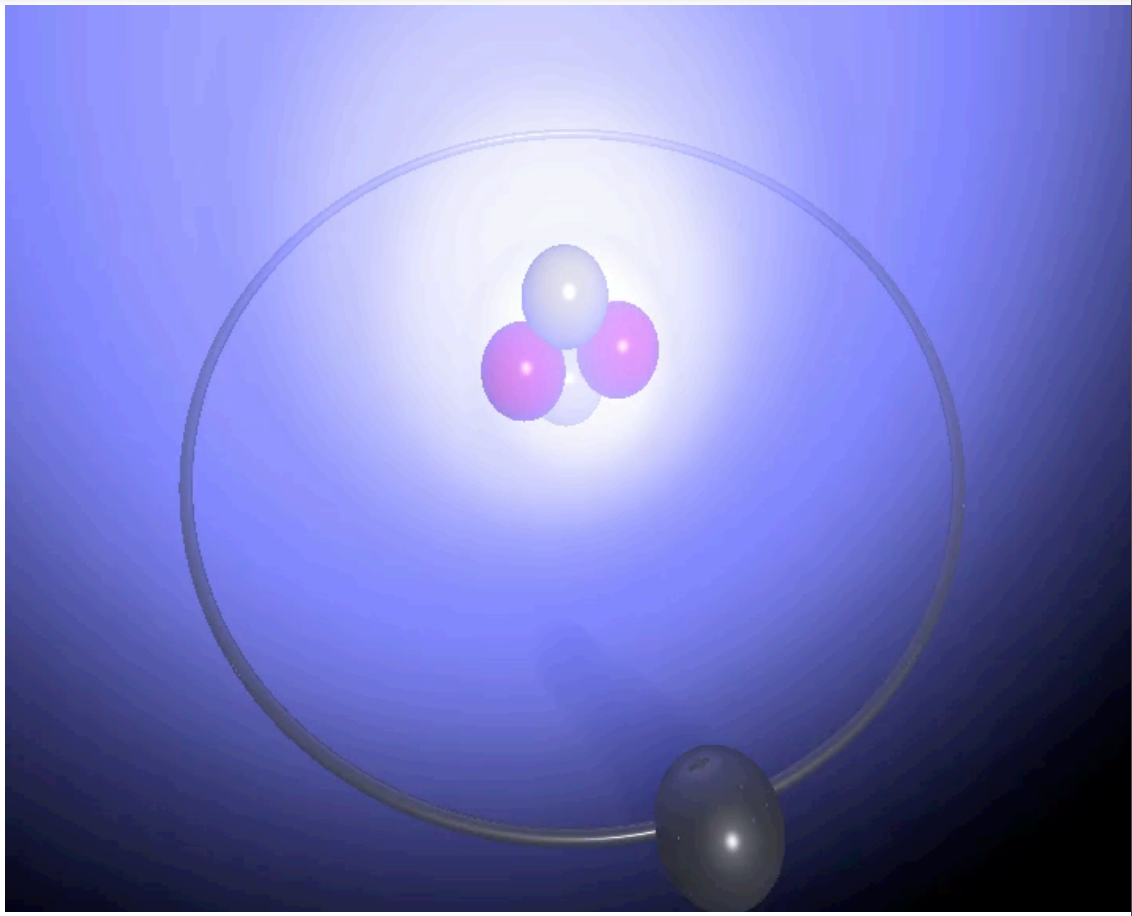
Studies of *CPT symmetry* by atomic spectroscopy

Goals:

- Two-photon laser spectroscopy of antiprotonic helium :
  → Antiproton mass with <10^{-10} precision.
- Microwave spectroscopy of antiprotonic helium (completed):
  → Antiproton magnetic moment with 0.3% precision
- Microwave spectroscopy of antihydrogen :
  → Ground-state hyperfine structure with 10^{-6} precision.

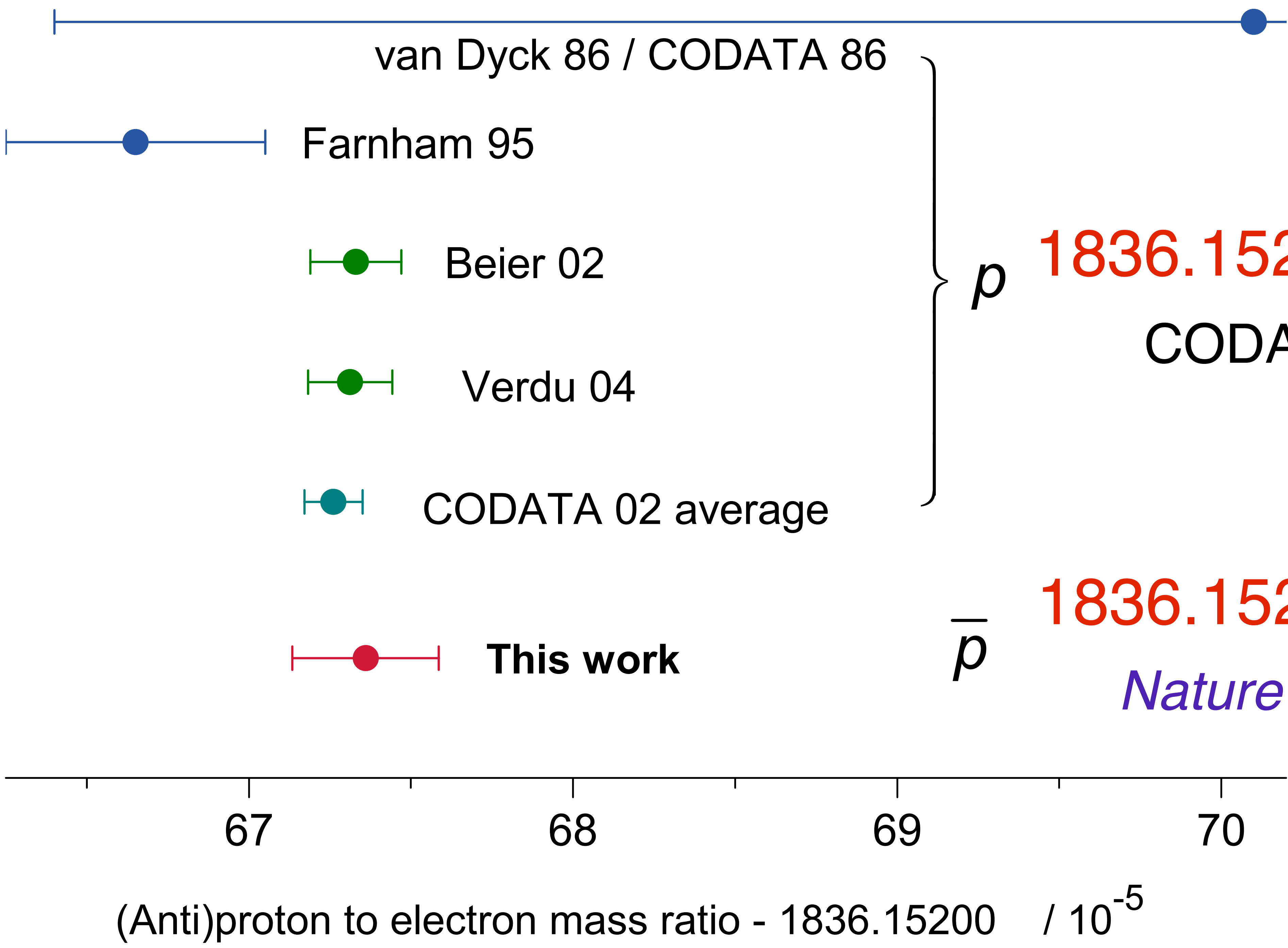
Spectroscopy of antiprotonic helium





- 3-body atom made of antiproton, He, and electron.
- Survives for >10 microseconds.
- >1 billion atoms synthesized per day.
- Amenable to high-precision laser and microwave spectroscopy.

Antiproton mass measurement



p 1836.15267245(75)

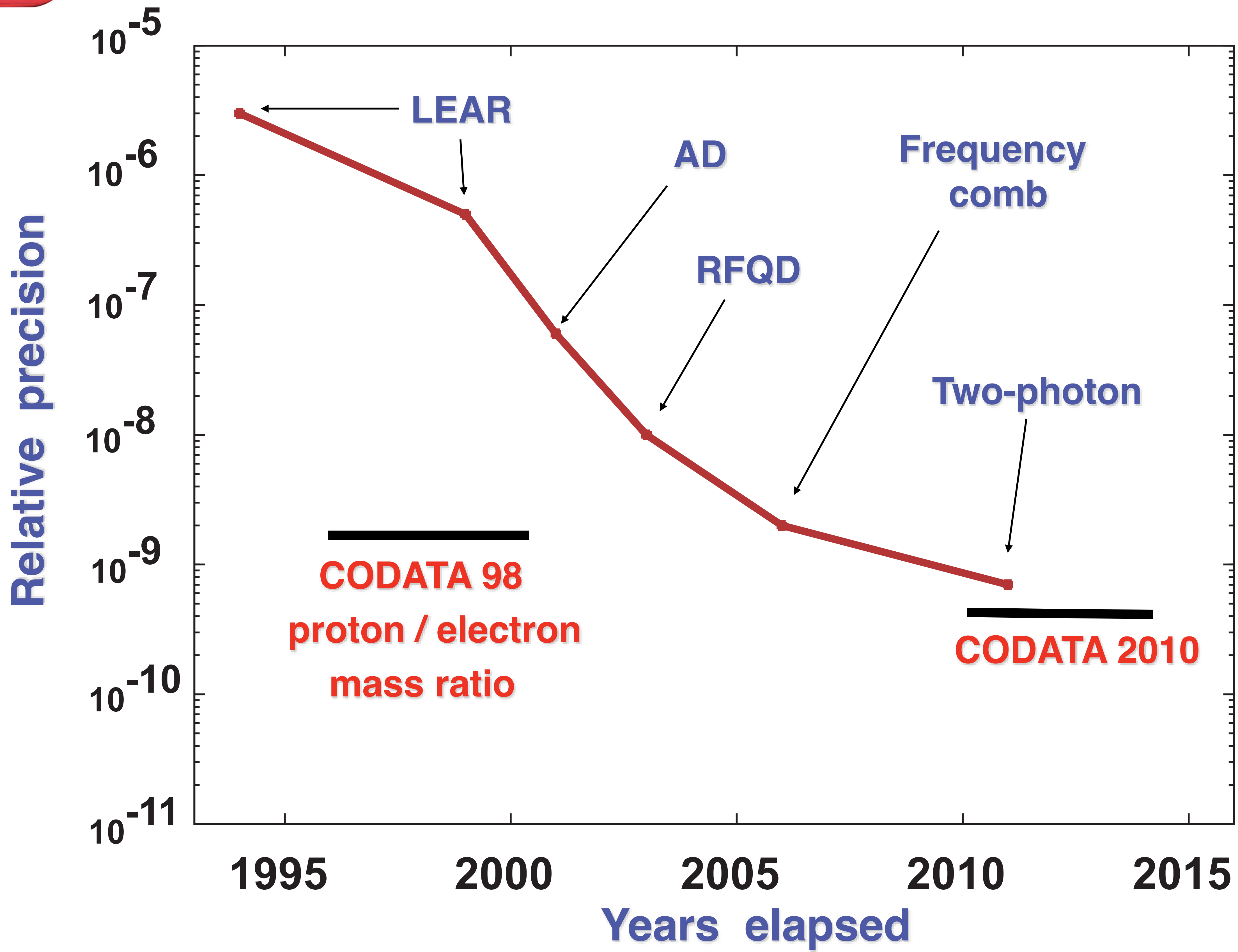
CODATA 2010

$\bar{p}$ 1836.1526736(23)

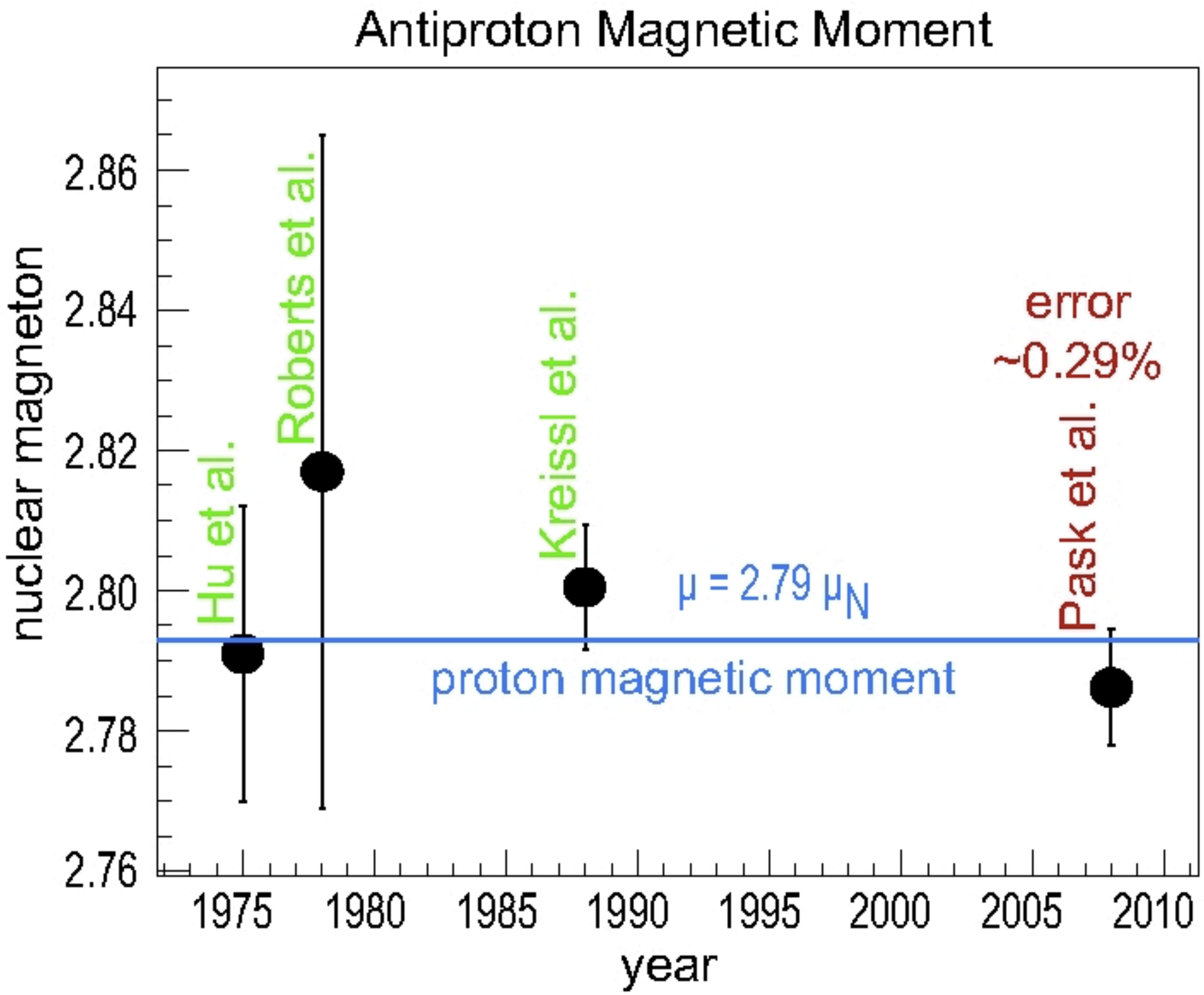
Nature 475, 484 (2011).

- Compare laser frequency with 3-body QED calculations.
- Antiproton-to-electron mass ratio measured to 1.3 ppb

Antiproton mass measurement



Microwave spectroscopy of antiprotonic helium



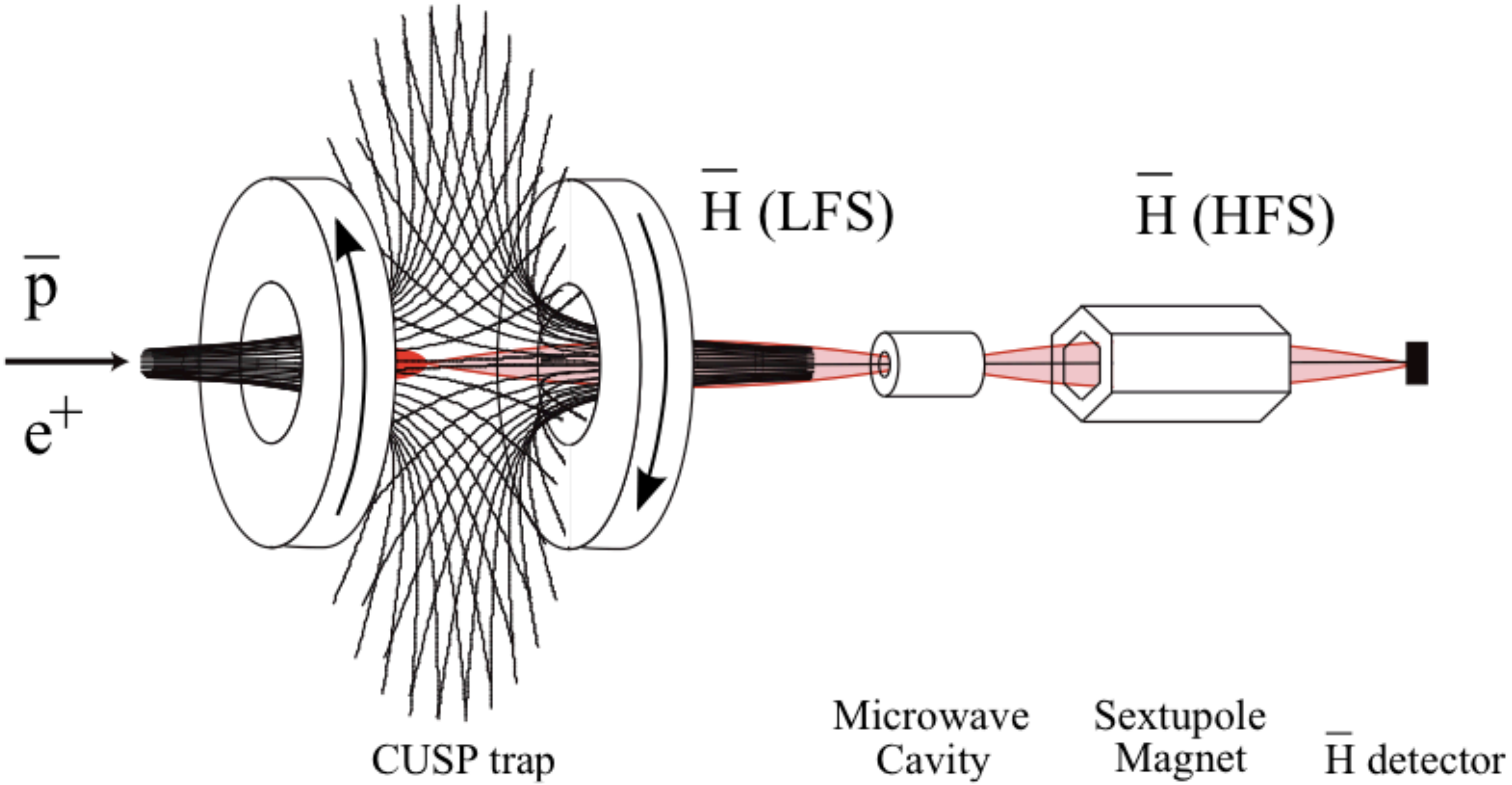
- Latest 3He results in

  S. Friedrich et. al,
  Phys. Lett. B 700, 1 (2011).

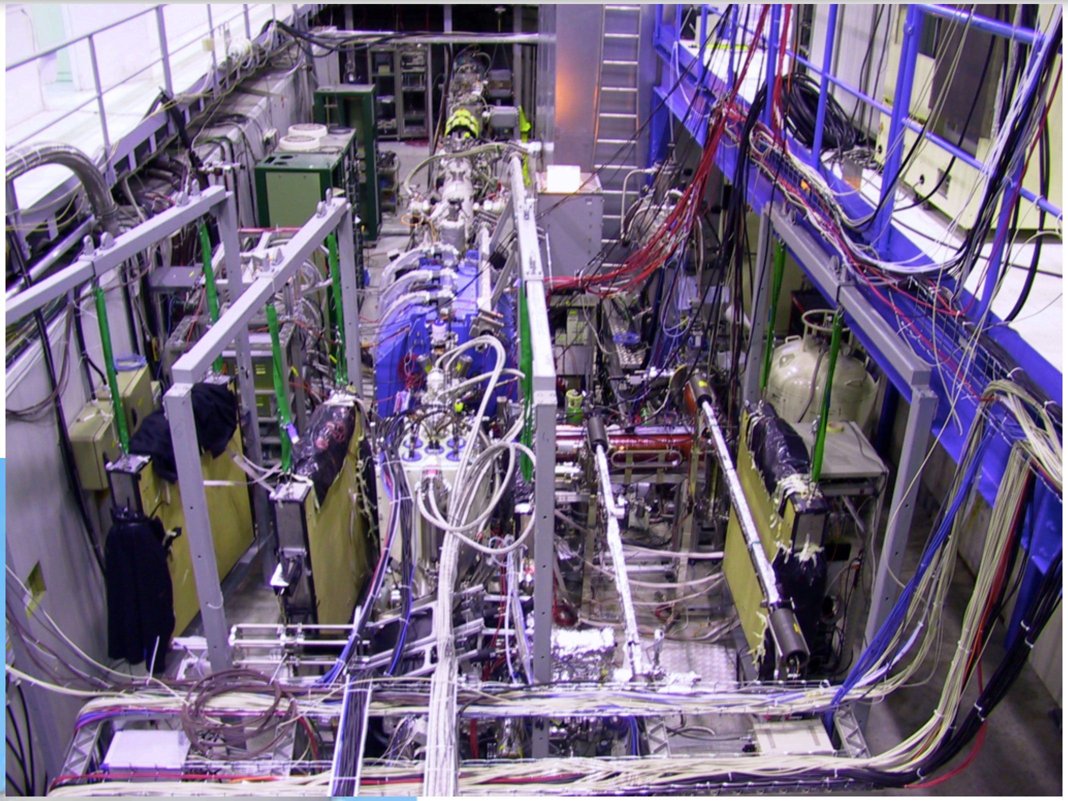
- Flip spin of electron in atom by 11-16 GHz microwaves.
- Compare frequency with 3-body QED calculations.
- Antiproton magnetic moment measured to 0.29% precision.

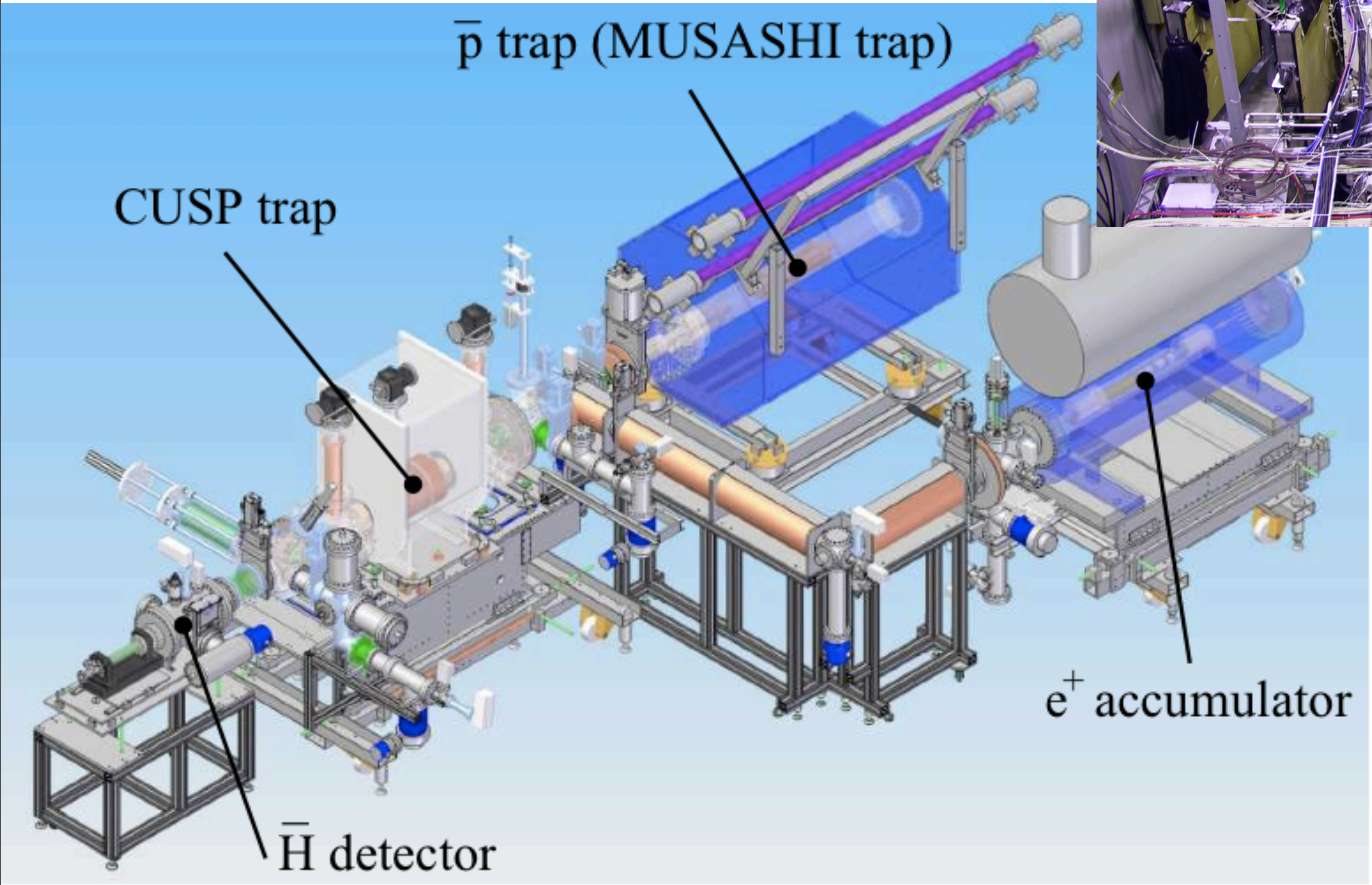
Ground-state hyperfine structure of antihydrogen

- Measured to 0.6 ppt in hydrogen case: 1.420405751 7667(9) GHz.
- Sensitive to magnetic radius and polarizability of antiprotons.
- Classic atomic-beam spectroscopy with polarized antihydrogen beam, microwave cavity, and sextupole magnet.
- Precision 1 part per million (typical for this type of experiment).

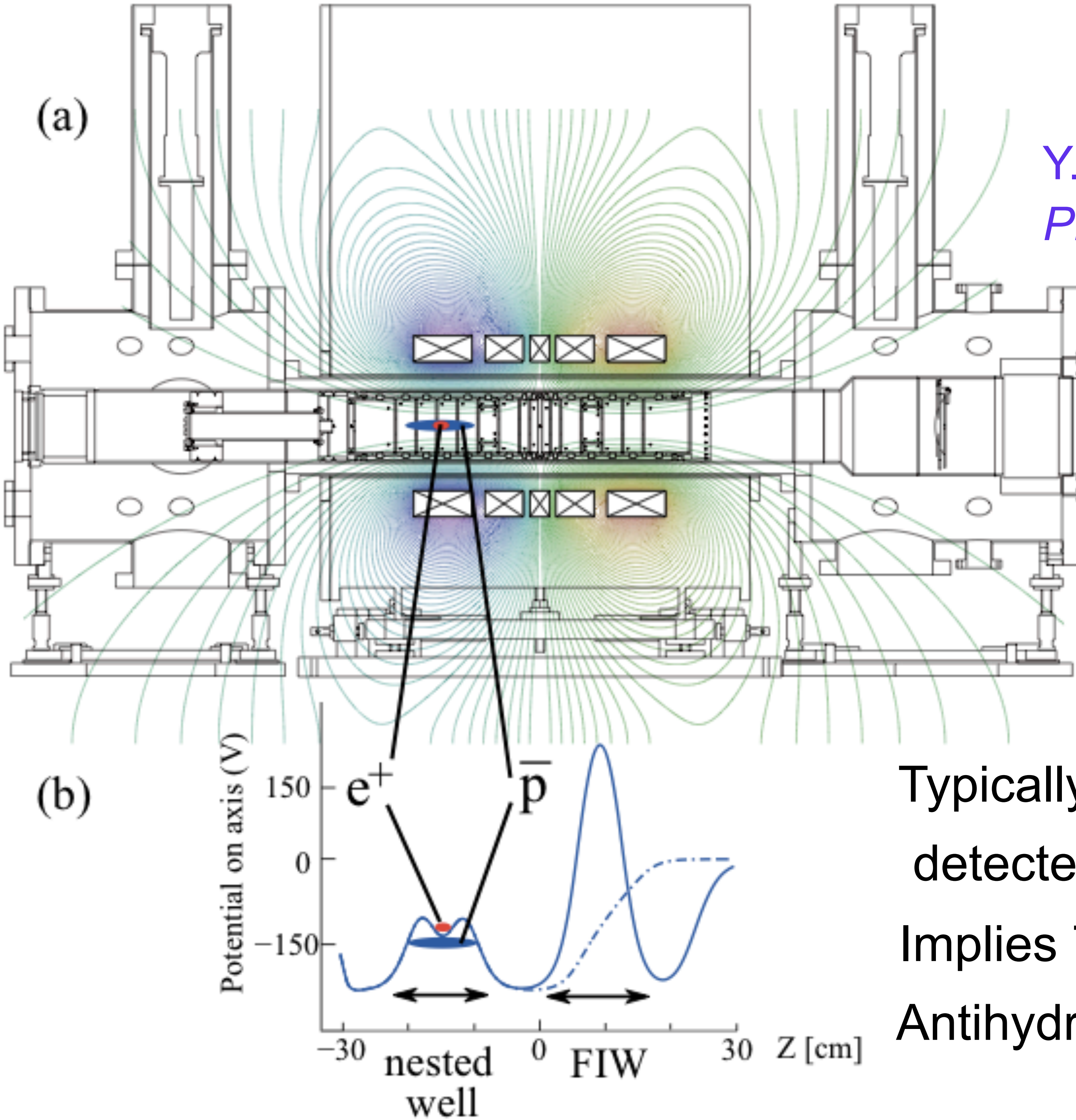


Toward production of antihydrogen beams





Toward production of antihydrogen beams



Y. Enomoto et. al,
Phys. Rev. Lett. 105, 243401 (2010)

Mixed 3 million positrons

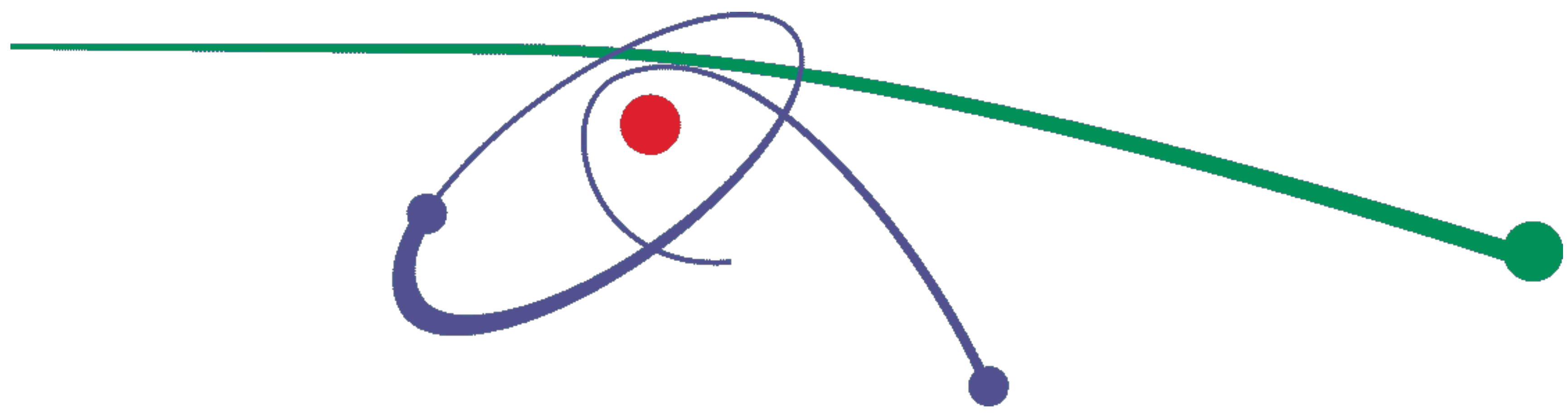
0.3 million antiprotons

Typically 70 antihydrogen counts detected per mixing cycle.

Implies 7000 antihydrogens formed.

Antihydrogen in *n=45-50* Rydberg state.

Atomic collisions with antiprotons



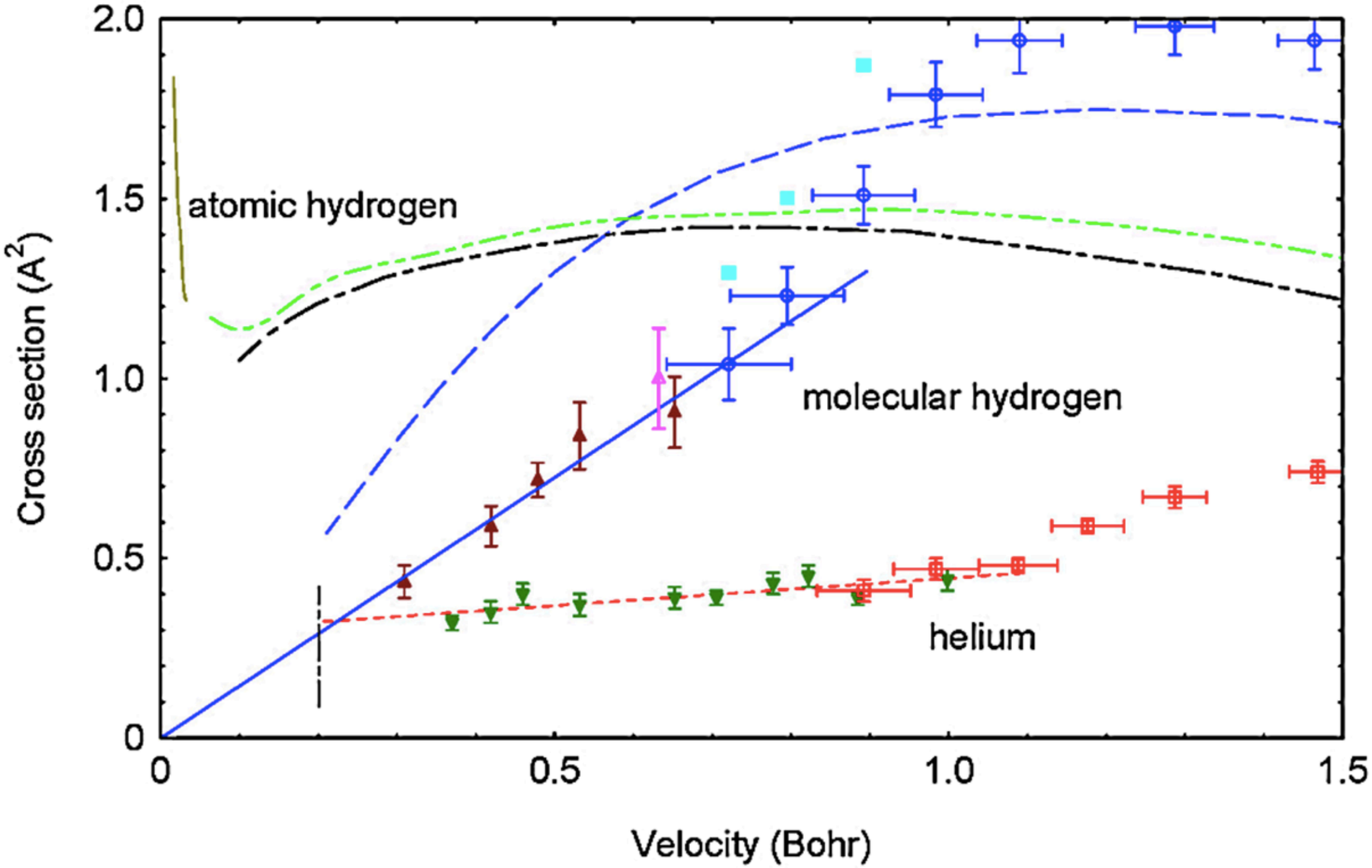
Aarhus, RIKEN

•Collide antiprotons with atoms and molecules at ultra-low energies E<10 keV and measure single and double ionization.

•Even simple observables like total cross section are difficult to predict with advanced theoretical techniques due to quantum-mechanical nature of dynamics.

•Fundamentally new problem compared to proton collisions, since atomic electrons are repelled instead of being attracted and picked up by projectile.

Ionization cross section in He and H2



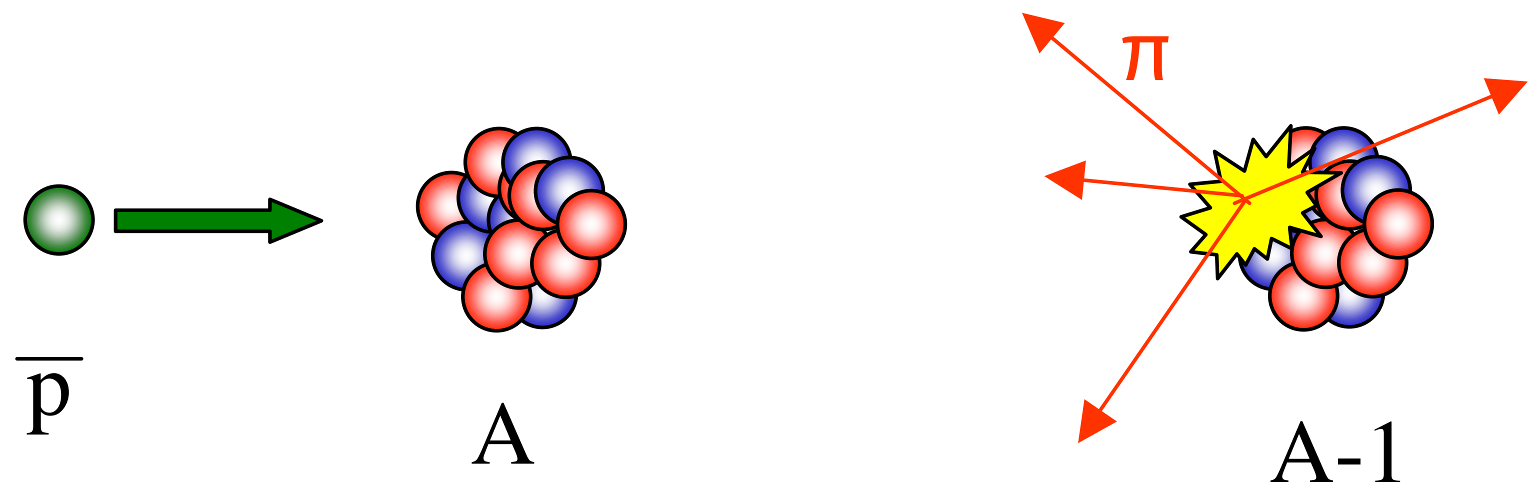
H. Knudsen et. al, *Phys. Rev. Lett.* 105, 213201 (2010).

Atomic H and He: Cross-section relatively constant at velocities 0.2 - 1 a.u.

Molecular hydrogen: Cross-section proportional to antiproton velocity.

→ New mechanism for suppression of single ionization in molecule case?

Nuclear collisions with antiprotons



INFN

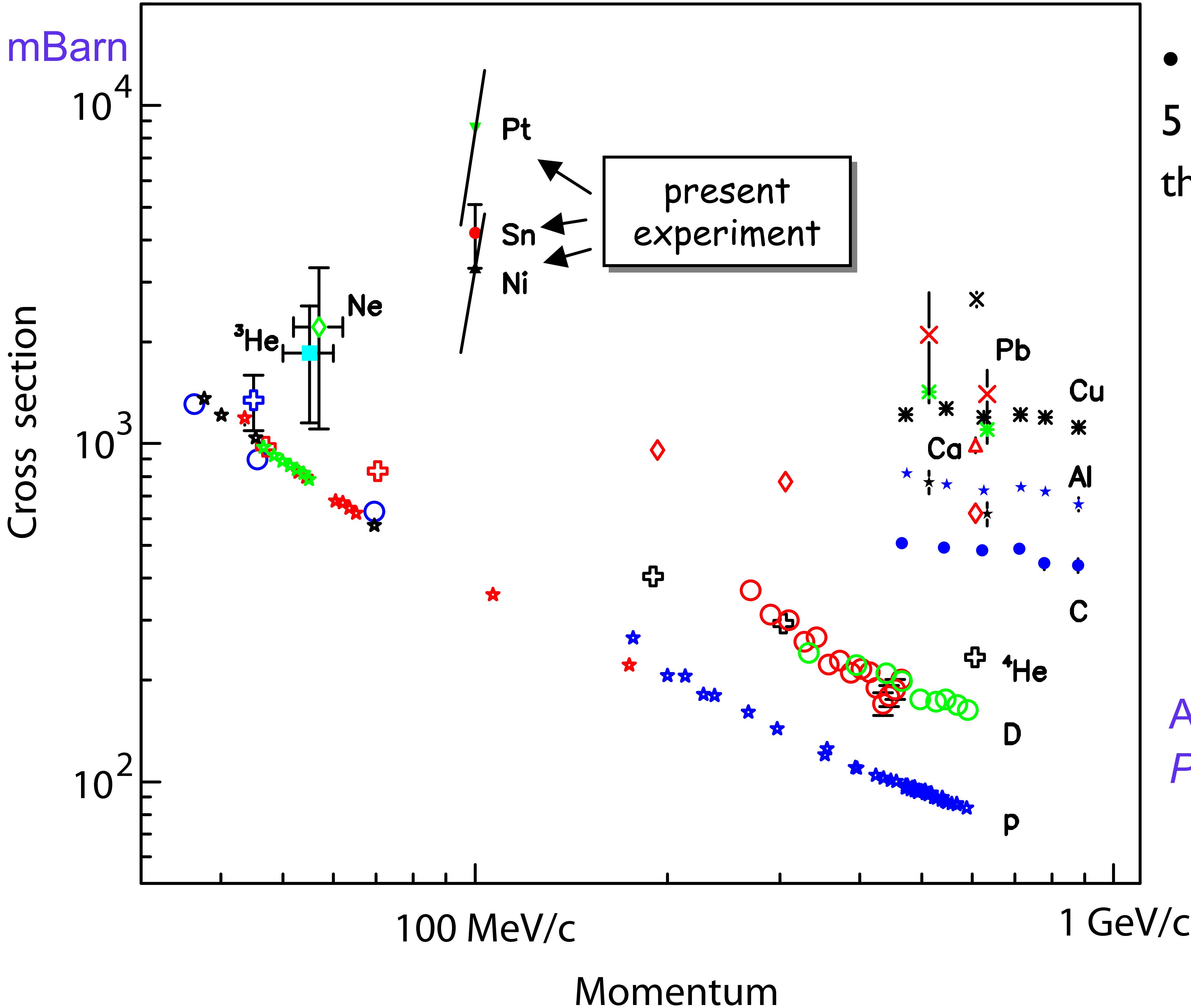
- Collide antiprotons with nuclei at energies E= 100 keV to 5 MeV and measure total annihilation cross-section σ.

- C, Ni, Sn, Pt foil targets → Simple model suggests $\sigma \propto A^{2/3}$ dependence.

- But at low energies < 1 MeV, σ should deviate from this due to Coulomb interaction which focuses the antiprotons toward the nucleus.

- Measurements at 5 MeV completed. 0.1 MeV ongoing.

Annihilation cross-sections



- Cross-sections @ 5 MeV consistent with theoretical expectations.

A. Bianconi et. al,
Phys. Lett. B, accepted

Conclusion: ASACUSA recent achievements

•First sub-Doppler two-photon laser spectroscopy of antiprotonic helium

→ Determined antiproton-to-electron mass ratio to 1.3 ppb.

•Microwave spectroscopy of antiprotonic helium

→ Determined antiproton magnetic moment to 0.3%.

•Produced Rydberg antihydrogen in cusp trap as a first step towards ground-state hyperfine structure spectroscopy with ppm-scale precision.

•First measurement of ionization cross-sections of <10 keV antiprotons in H2, He, Ar.

•First measurement of annihilation cross-sections of 5-MeV antiprotons in C, Pt, Sn, Ni.