Determination of the antiproton-to-electron mass ratio
by
two-photon laser spectroscopy of antiprotonic helium atoms

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Collaborators and Funding

ASACUSA @ CERN AD

Atomic **S**pectroscopy **A**nd **C**ollisions **U**sing **S**low **A**ntiprotons

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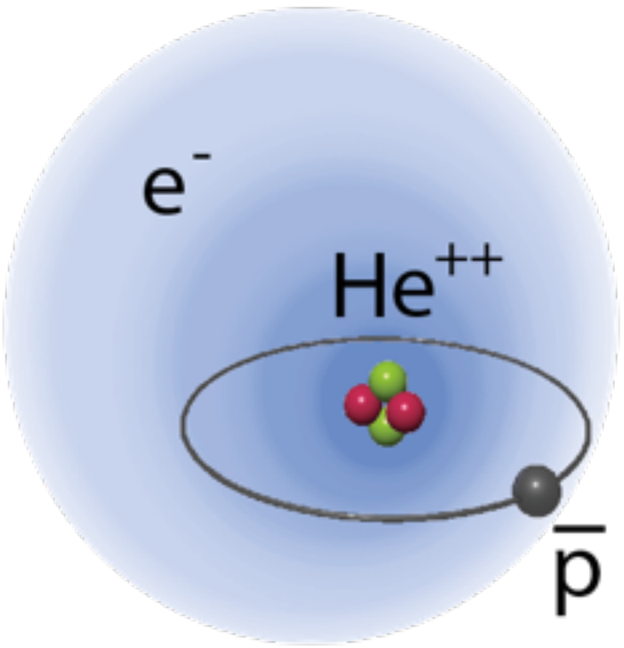
Antiprotonic helium atoms



Antiprotonic helium atom: 3-body bound system consisting of:

- helium nucleus
- electron in 1s-ground state,
- antiproton in Rydberg state *n=30-40, l=n-1.*

Long-lived (~3-4us) even in dense helium targets because:

- antiproton has negligible overlap with nucleus.
- electron cloud protects antiproton against collisions with other He.
- electron ionization is suppressed (large ionization potential 26 eV).

These characteristics make the atom amenable to laser spectroscopy!

Motivation

By precision spectroscopy measurements of the transition frequencies and comparisons with 3-body QED calculations we obtained:

- antiproton-to-electron mass ratio to 1.3 x 10^{-9}.
  → Dimensionless fundamental constant of nature.

- assuming CPT invariance the electron mass in a.u. to 1.3 x 10^{-9}
  → One of the data points used in CODATA2010 average.

When combined with cyclotron frequency of antiprotons in a Penning trap measured by TRAP collaboration, comparison of antiproton and proton mass and charge to 7 x 10^{-10}
→ CPT consistency test in PDG2012.

Calculated two-photon transition frequency

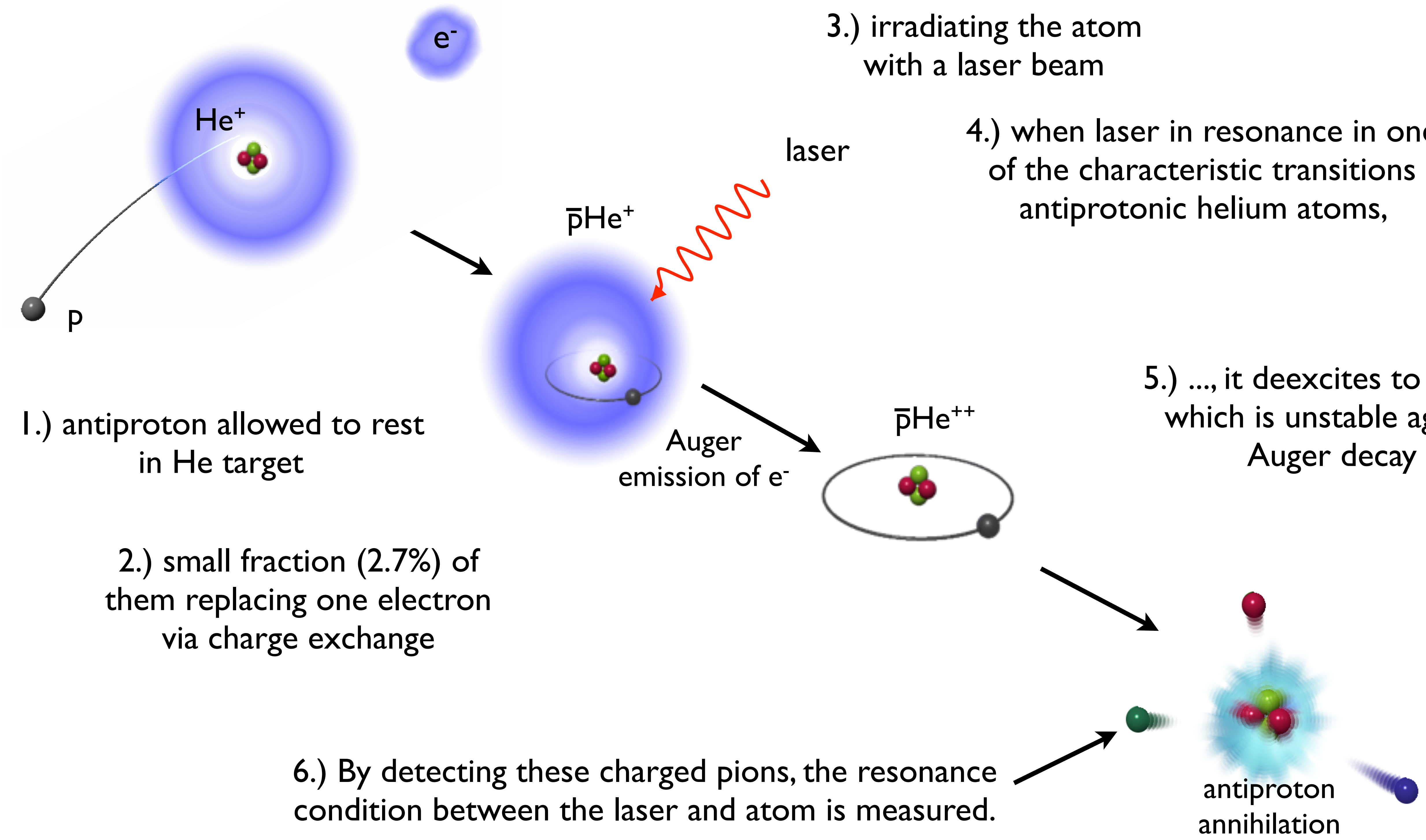
$(n,l)=(36,34) \rightarrow (34,32)$ V.I. Korobov

Non-relativistic energy	1 522 150 208.3 MHz
Relativistic correction of electron	-50 800.9
Anomalous magnetic moment of electron	454.9
One transverse photon exchange	-84.9
Relativistic correction of heavy particles	105.7
Finite charge radius of helium nucleus	4.7
One-loop self-energy correction	7 311.0
Vacuum polarization	-243.0
Recoil corrections order $R_\infty \alpha^3 (m/M)$	1.4
All $R_\infty \alpha^4$ order corrections	113.1
All $R_\infty \alpha^5$ order corrections	-11.5
Transition frequency	1 522 107 058.9(2.1)(0.3) MHz

Several parts in 10^{10} seems feasible in the near future.

V.I. Korobov (PRA 77 042506 (2008))

Laser spectroscopy method of $\bar{p}He$ atoms



1.) antiproton allowed to rest in He target

2.) small fraction (2.7%) of them replacing one electron via charge exchange

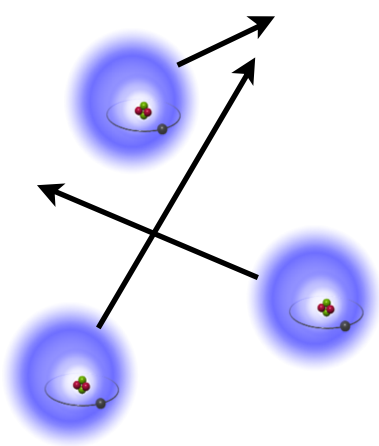
3.) irradiating the atom with a laser beam

4.) when laser in resonance in one of the characteristic transitions antiprotonic helium atoms,

5.) ..., it deexcites to a state which is unstable against Auger decay

6.) By detecting these charged pions, the resonance condition between the laser and atom is measured.

Sub-Doppler two-photon spectroscopy



Systematic error from Doppler broadening of the atoms undergoing thermal motion limited experimental precision to 10^{-7}-10^{-8}

Atoms moving towards laser are blue-shifted, those moving away are red-shifted. This broadens the spectral line.

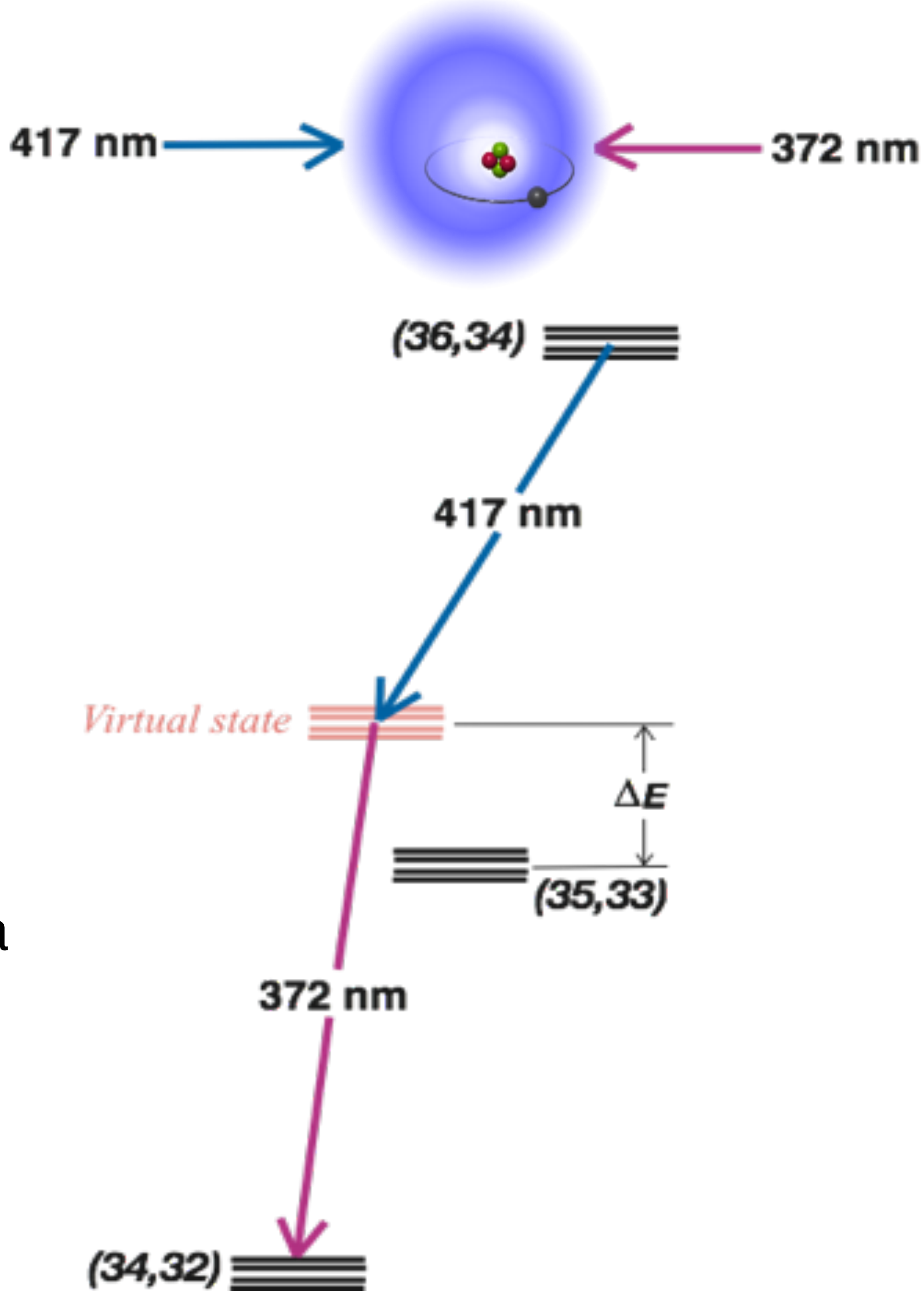
New experiment:

Reduced broadening by 20x using two-photon spectroscopy:

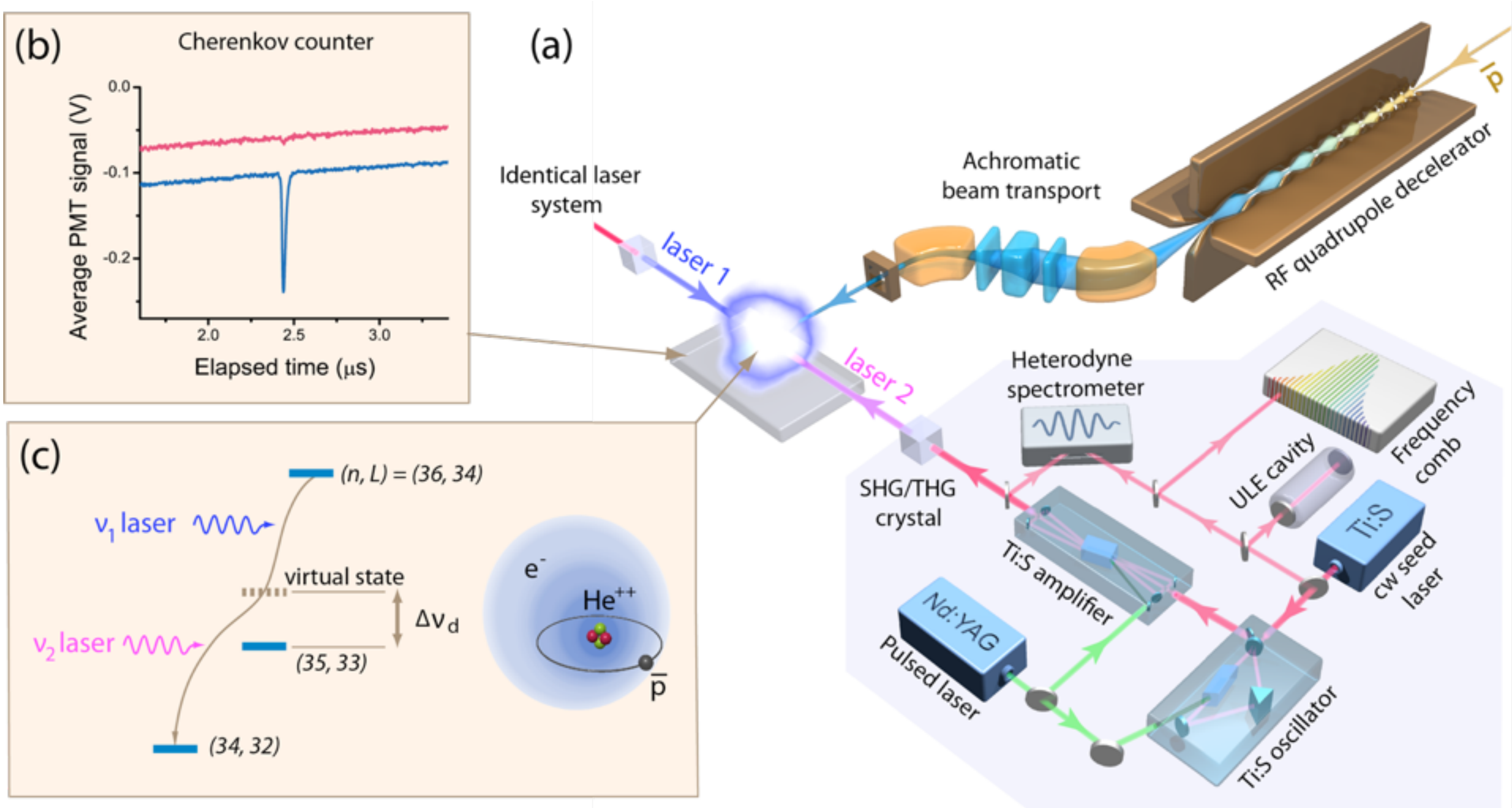
- Two counter-propagating laser beam irradiated the atoms
- Atom absorb two photons simultaneously from each beam.
- By tuning "virtual" intermediate state near (within 10 GHz) a real state, transition probability enhanced by factor >10000.

$$\Delta\nu_{2\gamma} = \left| \frac{\nu_1 - \nu_2}{\nu_1 + \nu_2} \right| \Delta\nu_{\mathrm{D}}$$

PRA 81, 062508, (2010)

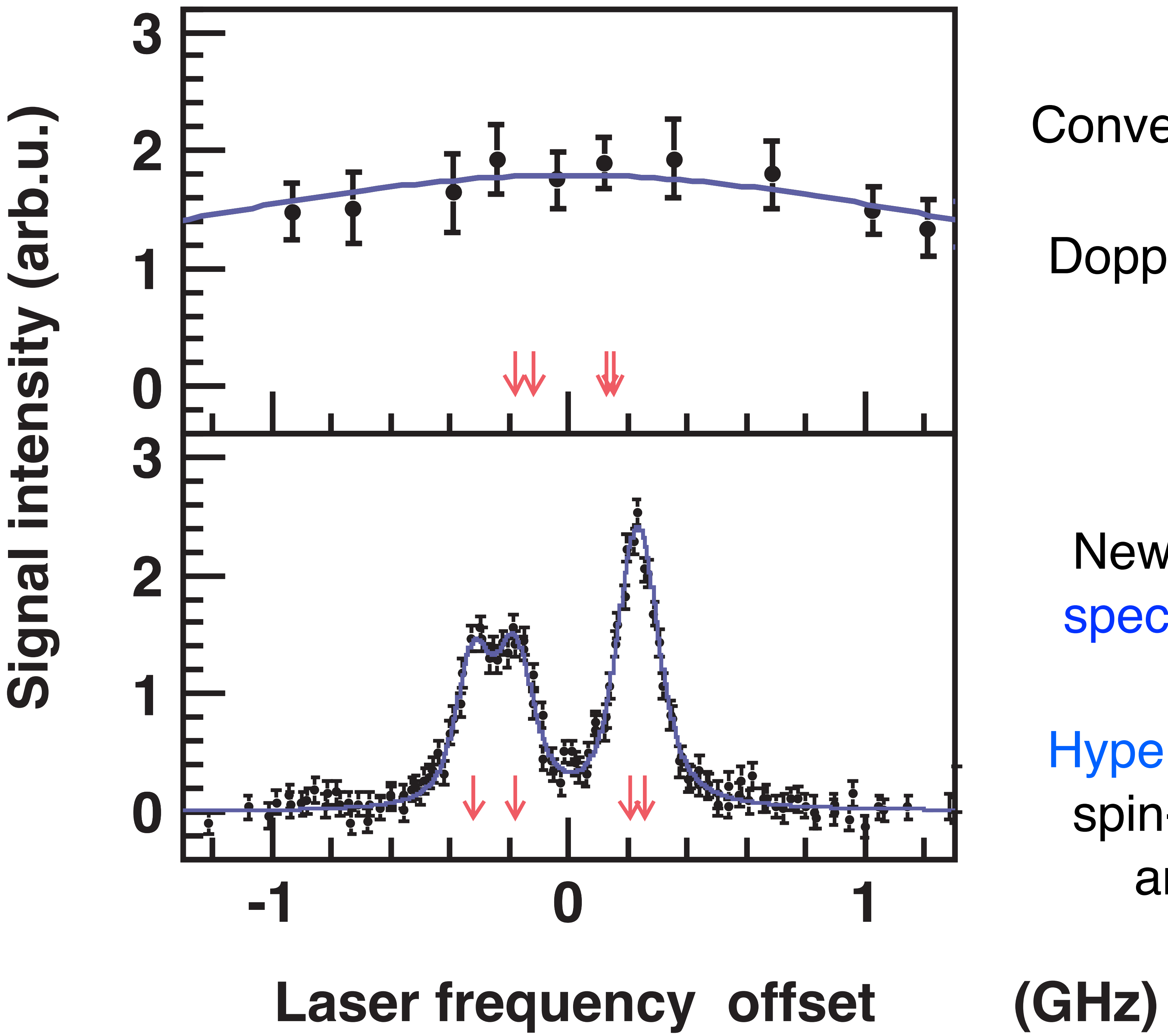


Experimental setup



Nature 475, 484 (2011)

Results of Sub-Doppler laser spectroscopy

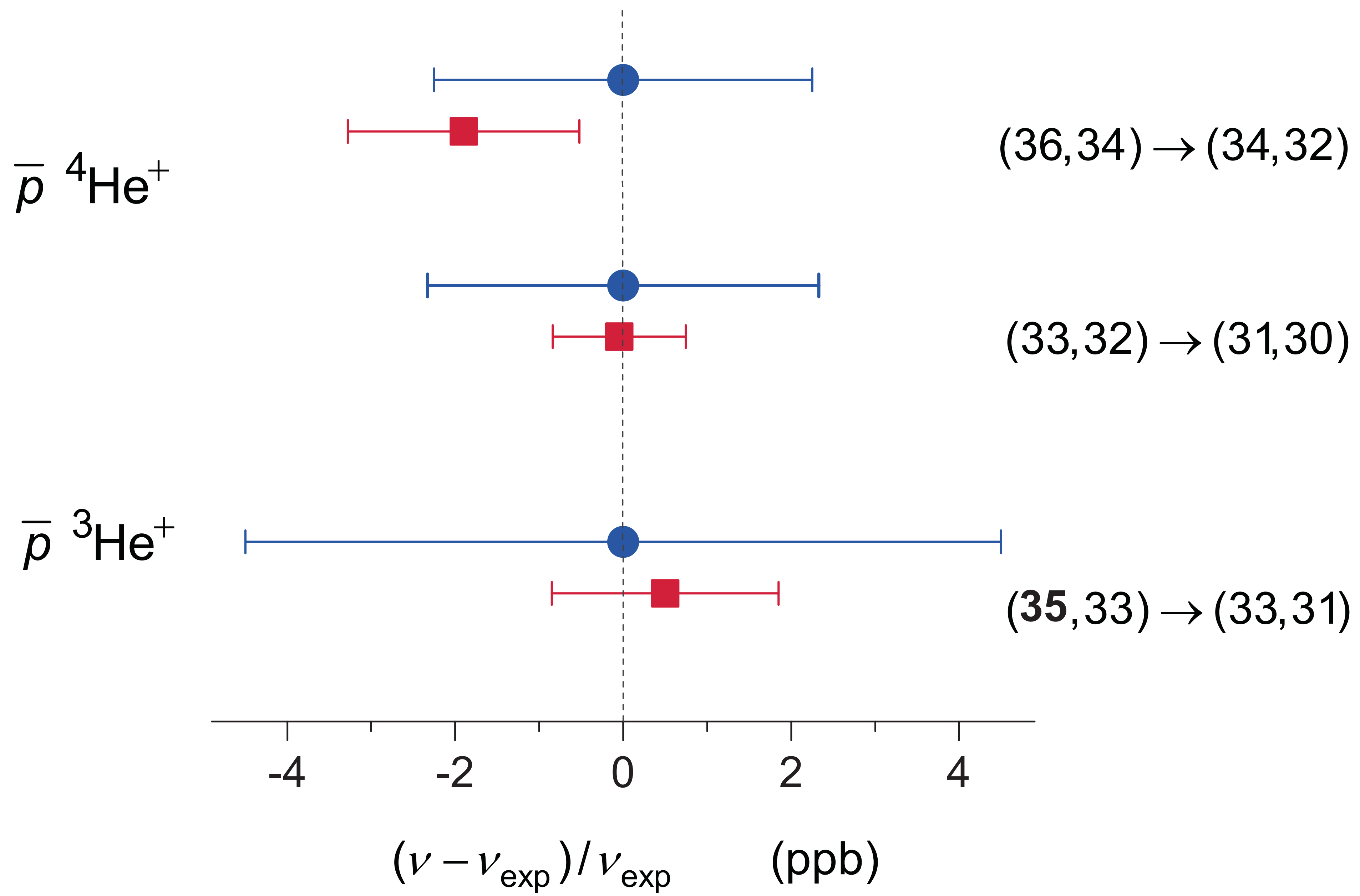


Conventional single-photon laser spectroscopy.
Doppler- and power-broadened lines.

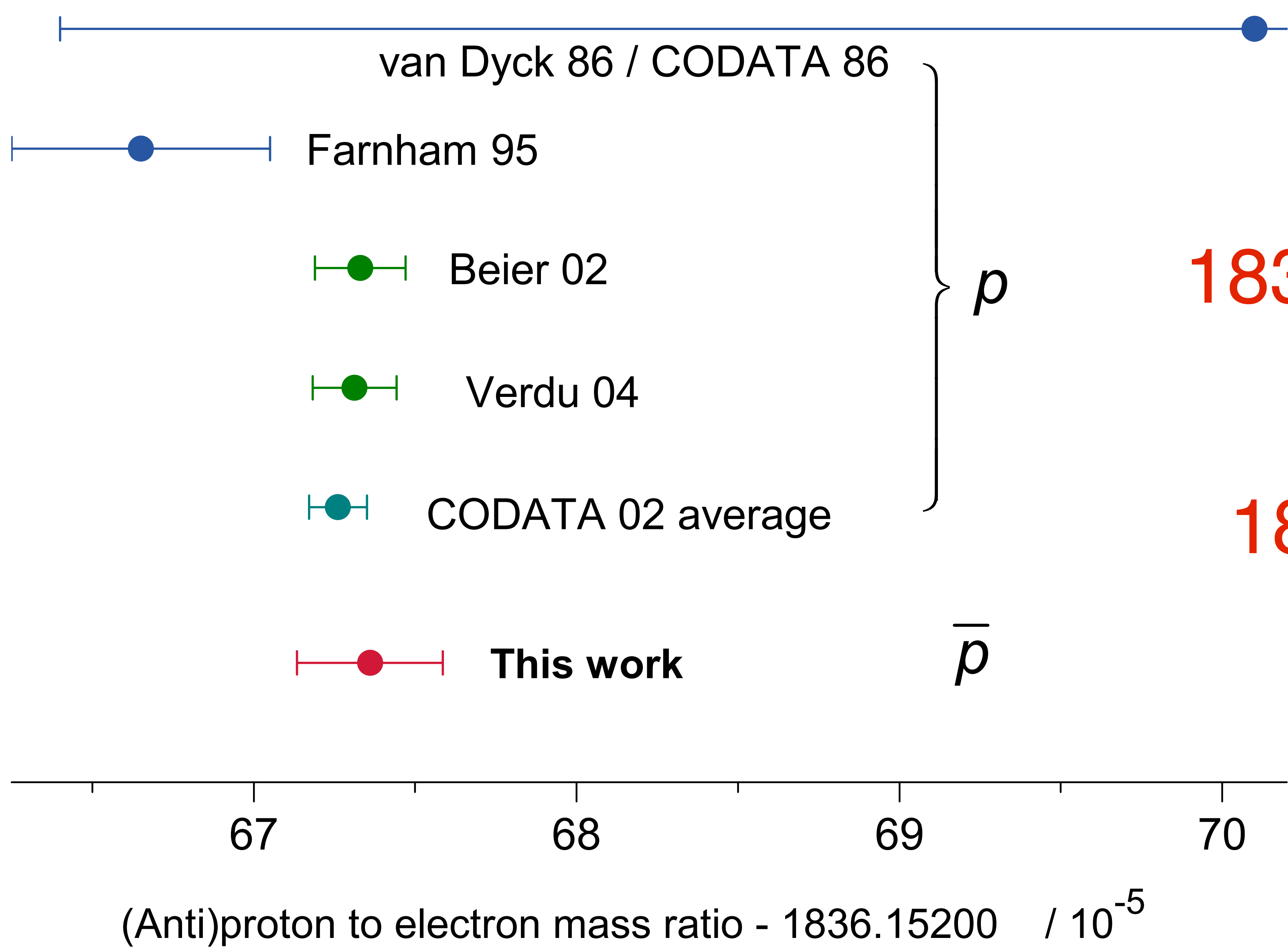
New sub-Doppler two-photon spectroscopy. High resolution.

Hyperfine structure arising from spin-spin interaction between antiproton and electron.

Fractional difference between experimental/theoretical transition frequencies



New antiproton-to-electron mass ratio



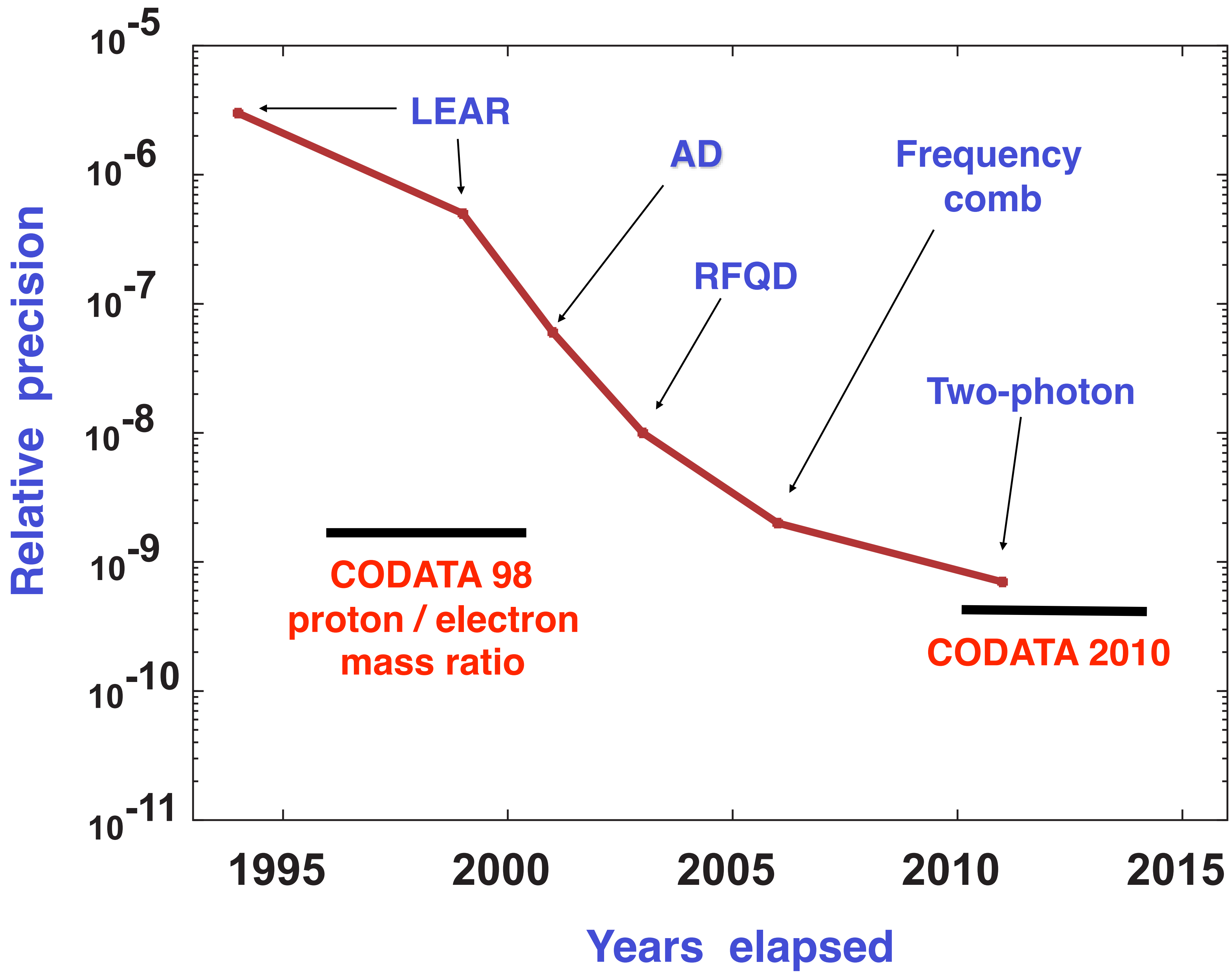
1836.15267245(75)

CODATA 2010

1836.1526736(23)

Nature 475, 484 (2011)

Antiproton charge and mass over the years



Combining antiprotonic helium (Q^2M)
with TRAP-collaboration results (Q/M)

Conclusions

• Achieved two-photon laser spectroscopy of antiprotonic helium.

• Partially cancelled Doppler broadening to measure sharp spectral lines and reach higher precision on the transition frequencies.

• By comparing to 3-body QED calculations, we determined the antiproton-to-electron mass ratio:

1836.1526736(23)

• Assuming CPT invariance, we determined the electron mass:

0.0005485799091 (7) u

Level structure of antiprotonic helium atoms