Fundamental studies by laser spectroscopy of antiprotonic helium atoms

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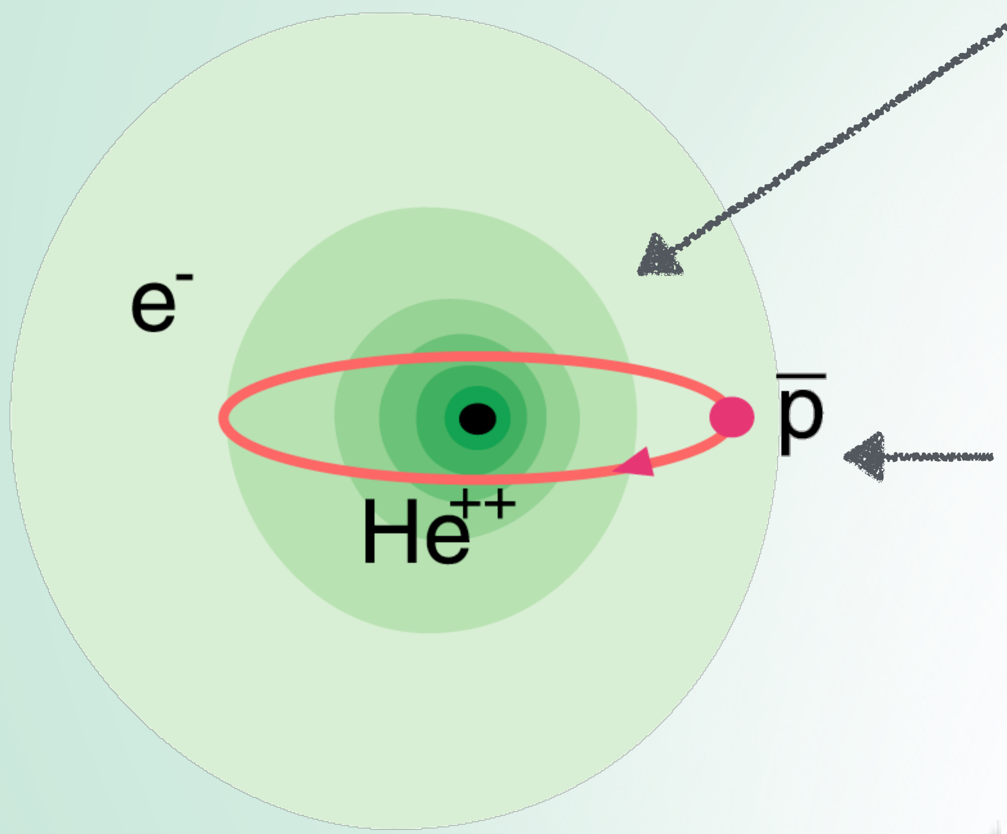
Metastable antiprotonic helium ($\bar{p}He^{+}$)

Retains a 4 μs lifetime



$\tau \sim 4\ \mu s$

Electron in 1s orbital. Attached with 25-eV ionization potential. Auger emission suppressed.

Antiproton in a 'circular' Rydberg orbital n=38, l=n-1 with diameter of 100 pm.

- Localized away from the nucleus.
- The electron protects the antiproton during collisions with helium atoms.

- Laser excitation of antiproton orbital.
- Higher laser powers needed compared to normal atoms + antihydrogen where electron/positron orbitals are excited.

$\bar{p}He^+$ most long-lived, precisely-studied hadron-antihadron system. Laser spectroscopy has yielded:

Tests of bound-state QED calculations to order $m\alpha^8$

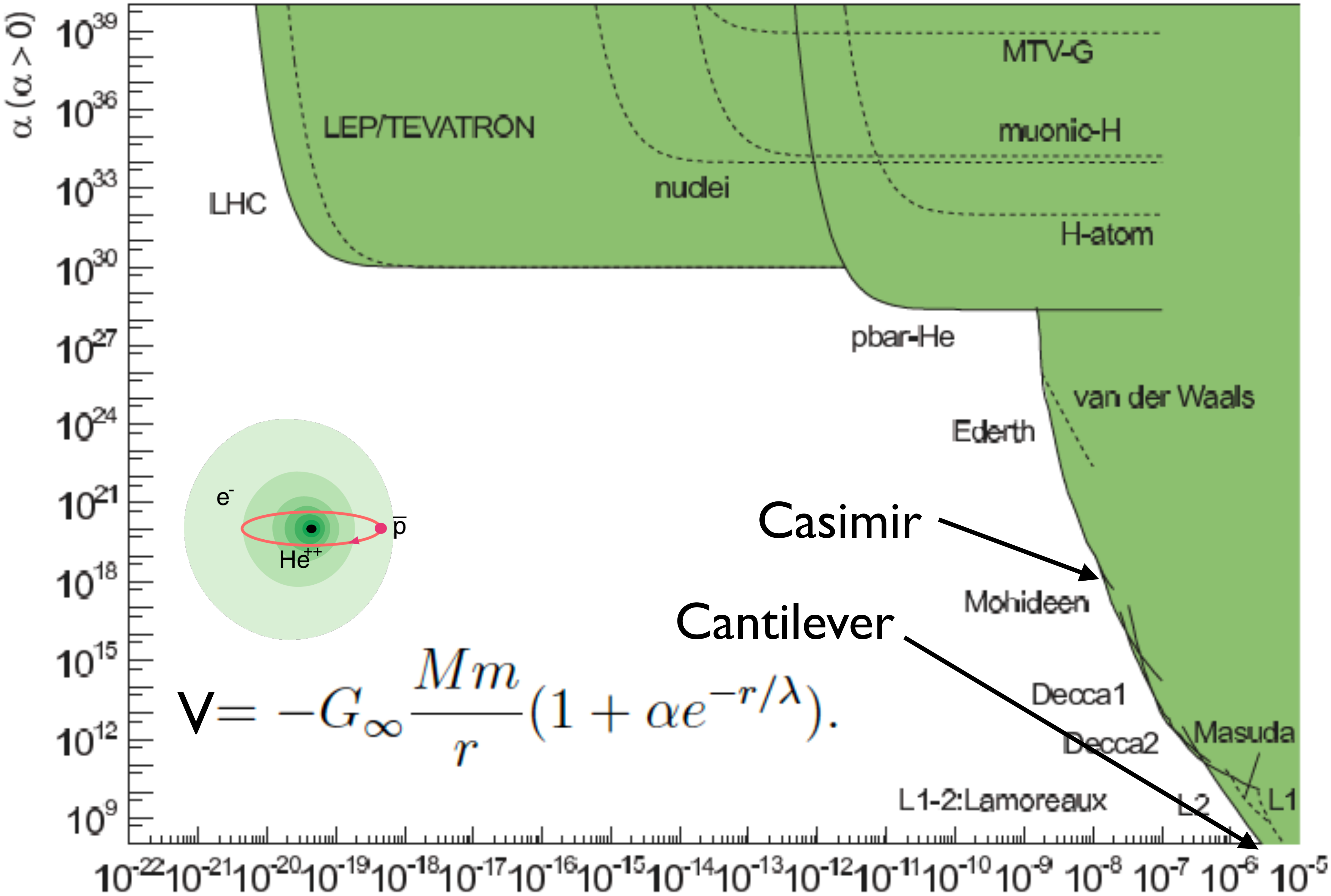
Antiproton-to-electron mass ratio to precision 8×10^{-10}

Assuming CPT invariance, **electron mass** to 8×10^{-10}

Combined with cyclotron frequency measurements of TRAP and BASE, antiproton and proton masses and charges compared to 5×10^{-10}

Recently: searches for exotic/dark fifth forces at 10-100 pm length scales.

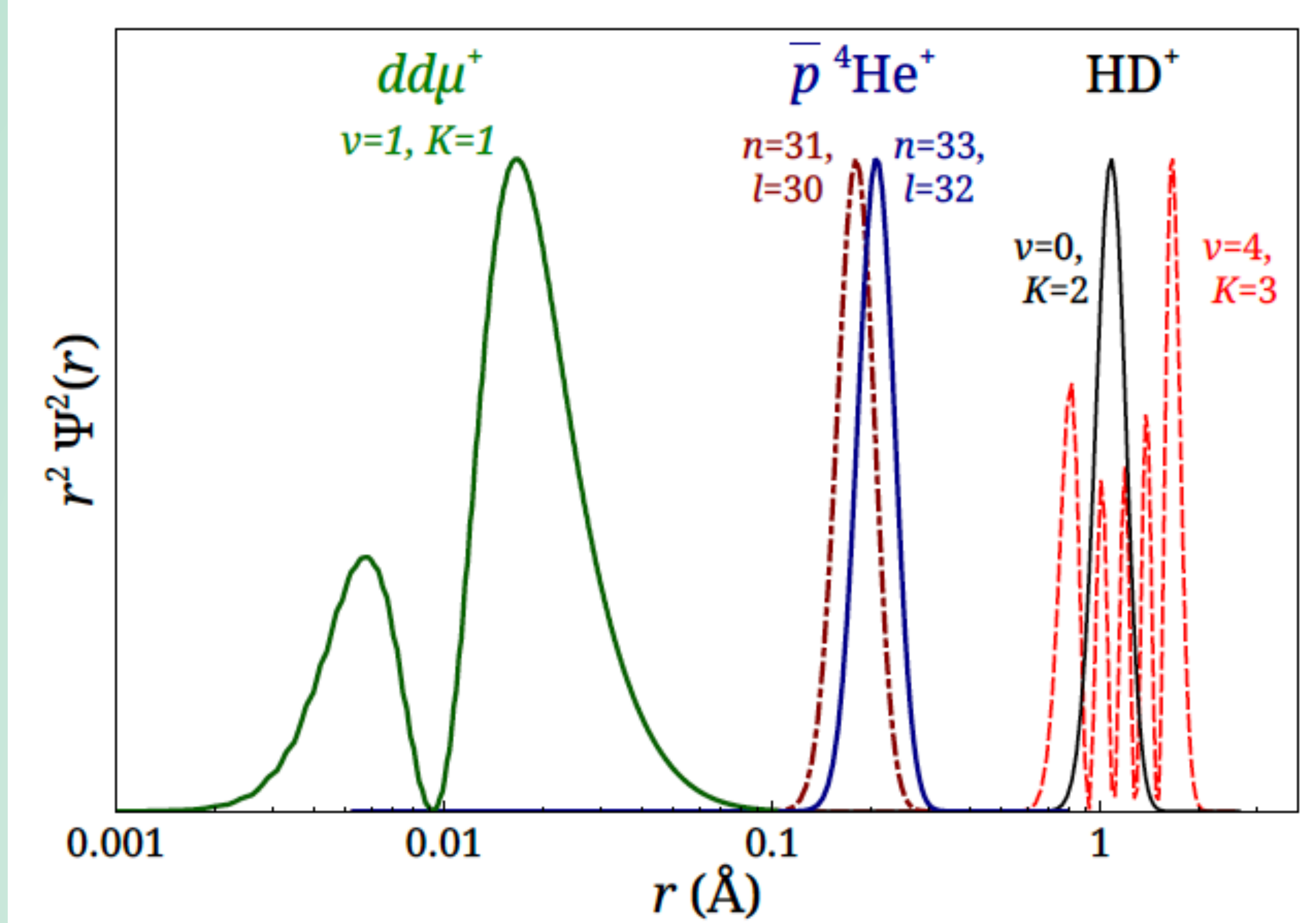
Bounds on fifth force

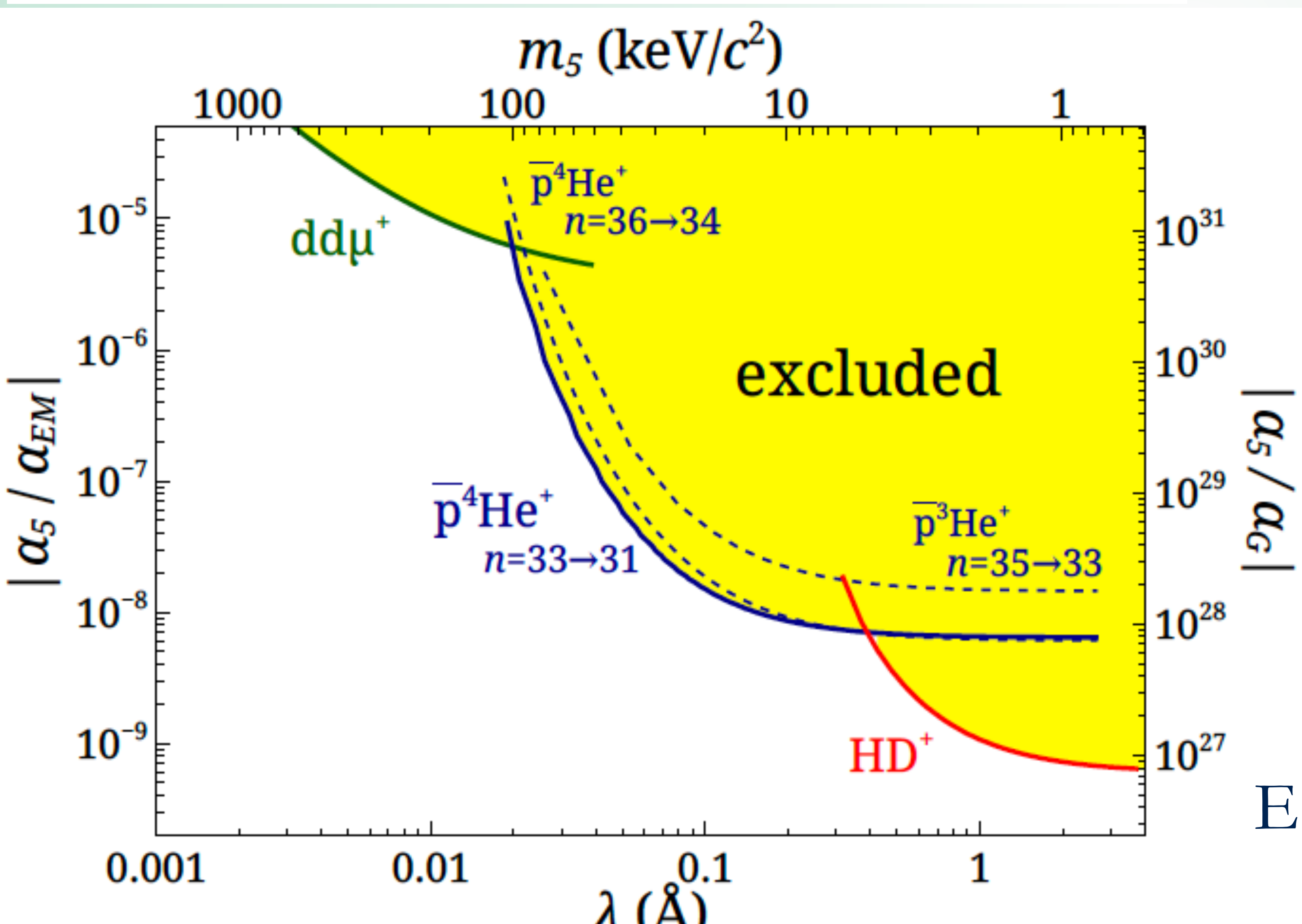


$$V = -G_\infty \frac{Mm}{r}\left(1 + \alpha e^{-r/\lambda}\right).$$

J. Murata et al., Classical Quantum Gravity (2015)

Bounds on fifth force from various atoms and molecules

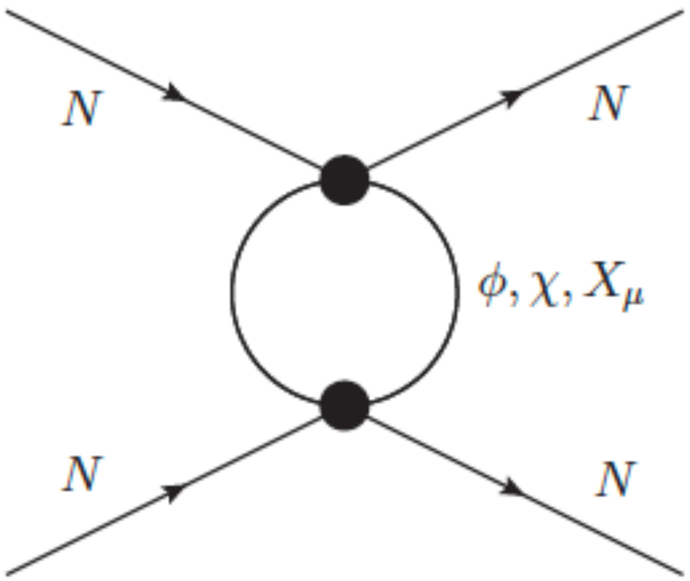




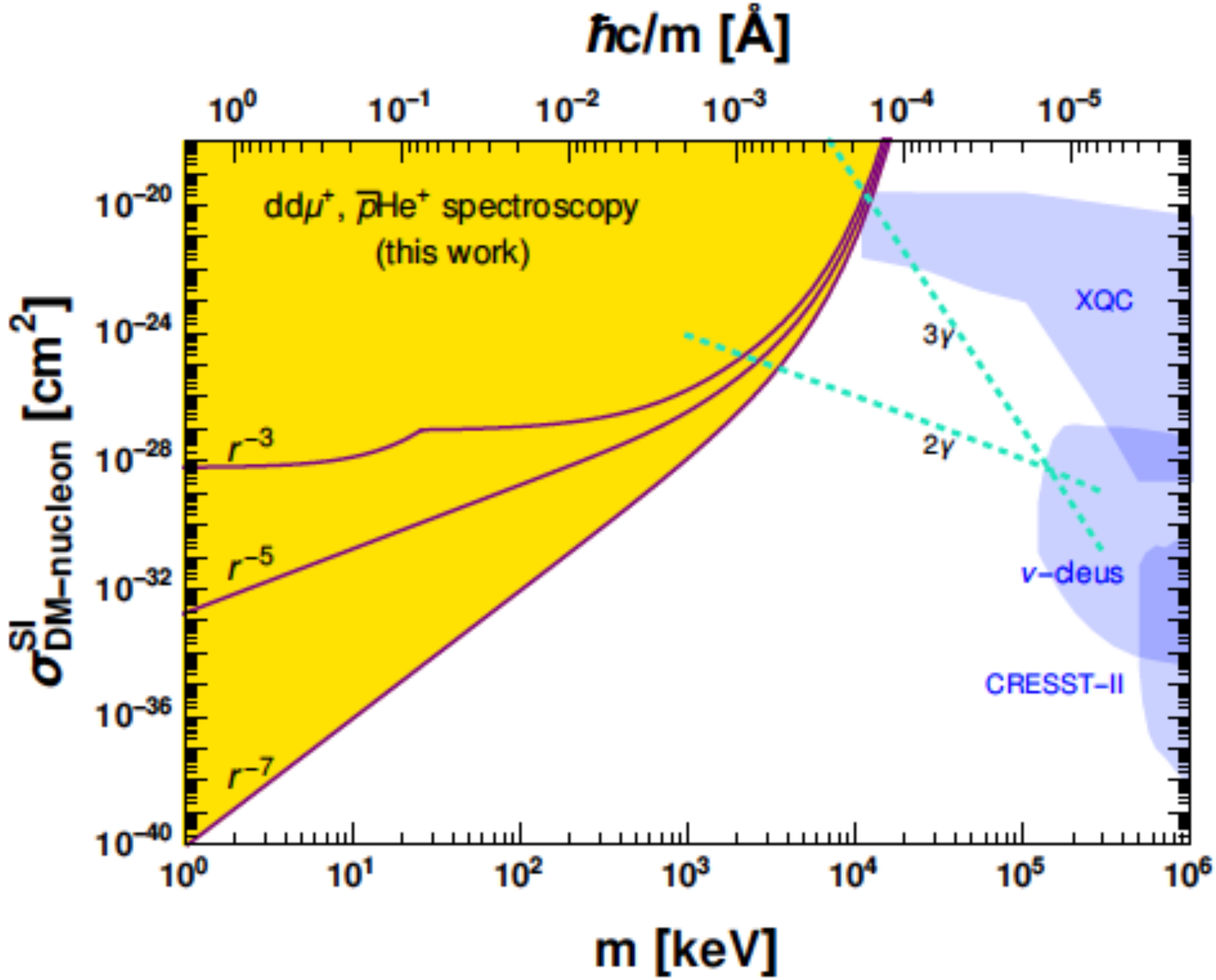
Possibility to improve these limits by 2-3 orders of magnitude?

E.J. Salumbides et al., *J. Mol. Spect.* (2013)

Bounds on dark scalar particles



"Bilinear" coupling of dark scalar particles to SM nucleons



P. Brax et al., *arXiv:1710.00850* (2017)

Calculated two-photon transition frequency $(n,l)=(36,34)\rightarrow(34,32)$

Non-relativistic energy	1 522 150 208.13 MHz
$m\alpha^4$ order corrections	-50320.64
$m\alpha^5$ order corrections	7070.28
$m\alpha^6$ order corrections	113.11
$m\alpha^7$ order corrections	-10.46(20)
$m\alpha^8$ order corrections	-0.12(12)
Transition frequency	1 522 107 060.3(2)
Uncertainty from alpha charge radius	+/-0.007
Uncertainty from antiproton charge radius	< 0.0007

Korobov, Hilico, Karr, *PRL* 112, 103003 (2014).
Korobov, Hilico, Karr, PRA 89, 032511 (2014).
Korobov, Hilico, Karr, *PRA* 87, 062506 (2013).

One-loop self-energy correction in atomic units for two-center system

$$\Delta E^{(7)}_{\rm se} = \frac{\alpha^5}{\pi}\Bigg\{\mathcal{L}(Z,n,l) + \left(\frac{5}{9}+\frac{2}{3}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle 4\pi\rho\, Q(E-H)^{-1}Q\, H_B\right\rangle_{\rm fin_{au}}$$

$$+2\left\langle H_{so}\, Q(E-H)^{-1}Q\, H_B\right\rangle + \left(\frac{779}{14400}+\frac{11}{120}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle \boldsymbol{\nabla}^4 V\right\rangle_{\rm fin_{au}}$$

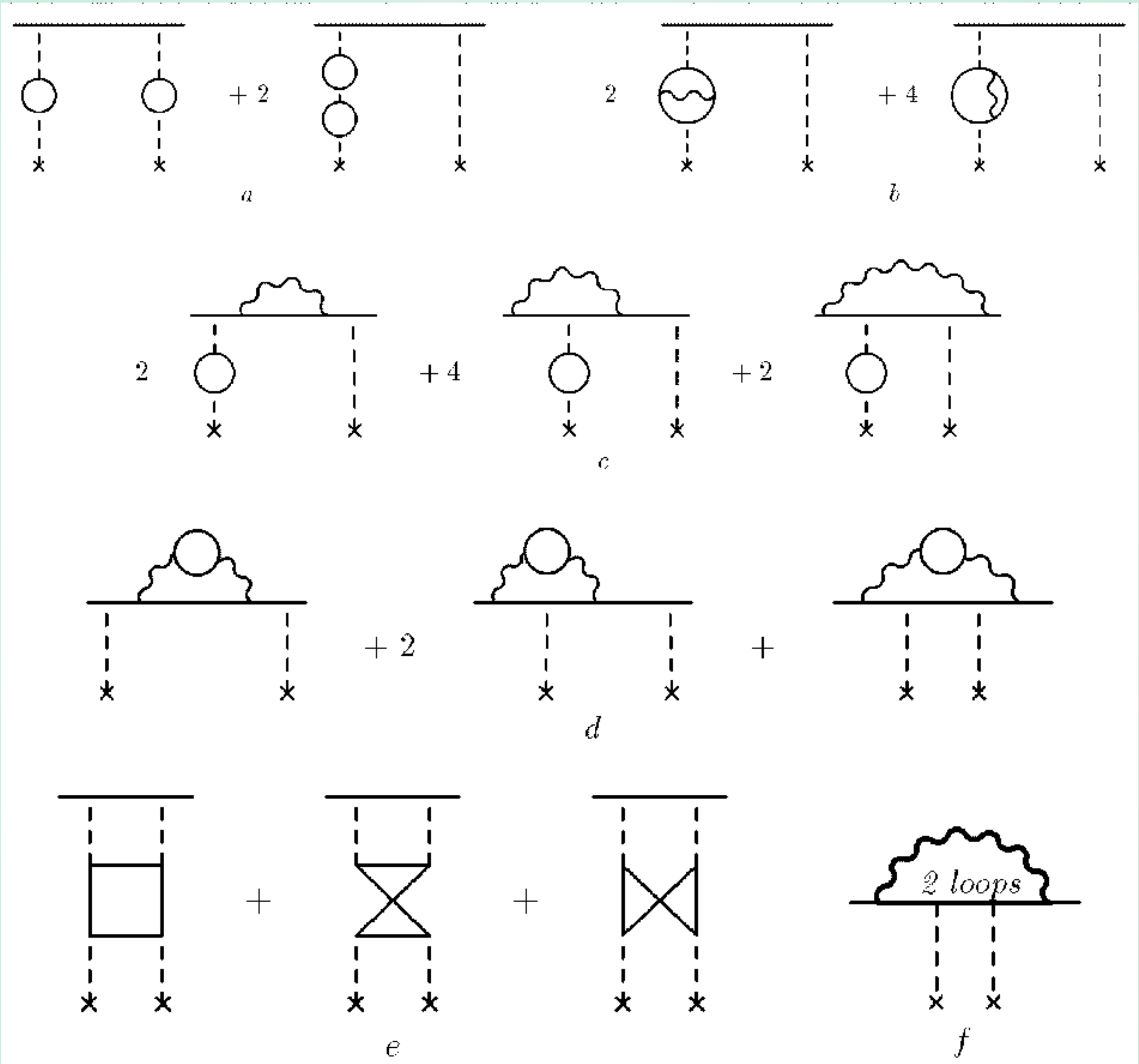
$$+\left(\frac{23}{576}+\frac{1}{24}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle 2i\sigma^{ij}p^i\boldsymbol{\nabla}^2 V p^j\right\rangle$$

$$+\left(\frac{589}{720}+\frac{2}{3}\ln\left[\frac{1}{2}\alpha^{-2}\right]\right)\left\langle(\boldsymbol{\nabla}V)^2\right\rangle_{\rm fin_{au}} + \frac{3}{80}\left\langle 4\pi\rho\,\mathbf{p}^2\right\rangle_{\rm fin_{au}} - \frac{1}{4}\left\langle \mathbf{p}^2 H_{so}\right\rangle$$

$$+Z^2\left[-\ln^2[\alpha^{-2}] + \left[\frac{16}{3}\ln 2 - \frac{1}{4}\right]\ln[\alpha^{-2}] - 0.81971202(1)\right]\langle\pi\rho\rangle\Bigg\}$$

V.I. Korobov, J.-P. Karr, L. Hilico

Two-loop QED contributions



Theoretical precision compared to other atoms

Antiprotonic He (n,l)=(33,32)→(31,30)

2 145 054 858.100(200) MHz

(Korobov 2014)

Experimental precision

Uncertainty due to $m\alpha^7$ QED on this digit

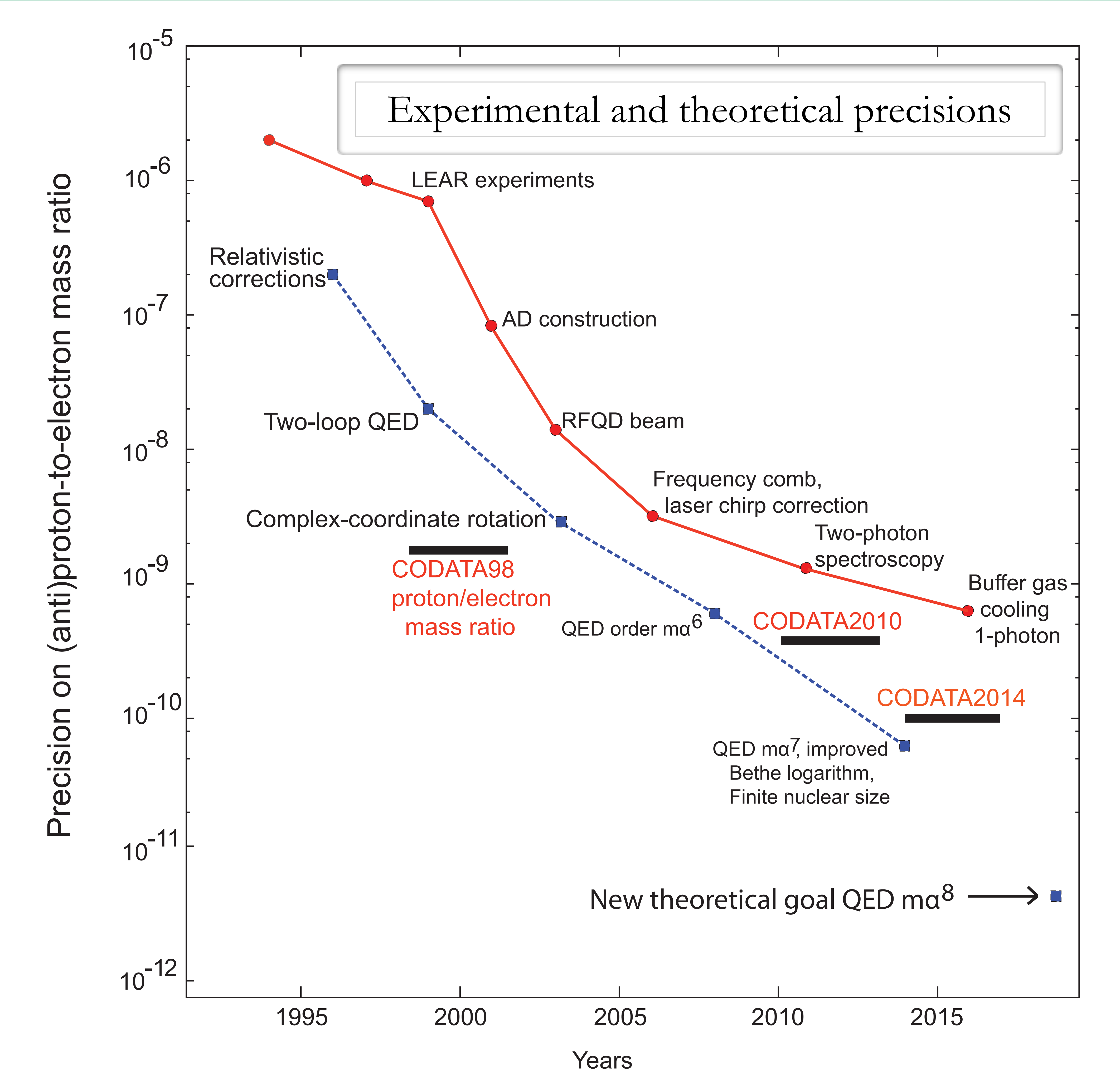
Uncertainty due to helium charge radius (to be improved by muHe experiment)

Hydrogen 1s-2s

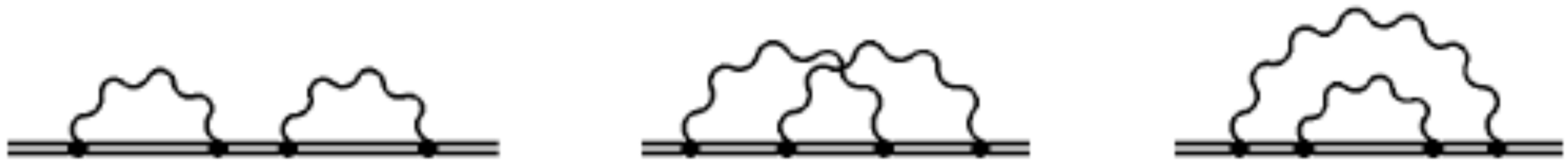
2 466 061 413.18 MHz

(Parthey *et al.* 2014)

Uncertainty due to proton charge radius on these digits


Experimental and theoretical precisions
Precision on (anti)proton-to-electron mass ratio
Years
LEAR experiments
AD construction
RFQD beam
Frequency comb, laser chirp correction
Two-photon spectroscopy
Buffer gas cooling 1-photon
Relativistic corrections
Two-loop QED
Complex-coordinate rotation
QED order mα6
QED mα7, improved Bethe logarithm, Finite nuclear size
CODATA98 proton/electron mass ratio
CODATA2010
CODATA2014
New theoretical goal QED mα8

Two-loop self-energy corrections:



Extremely difficult theoretical problem to solve in **all** orders of Zα.

Will in several years limit the theoretical precision on:

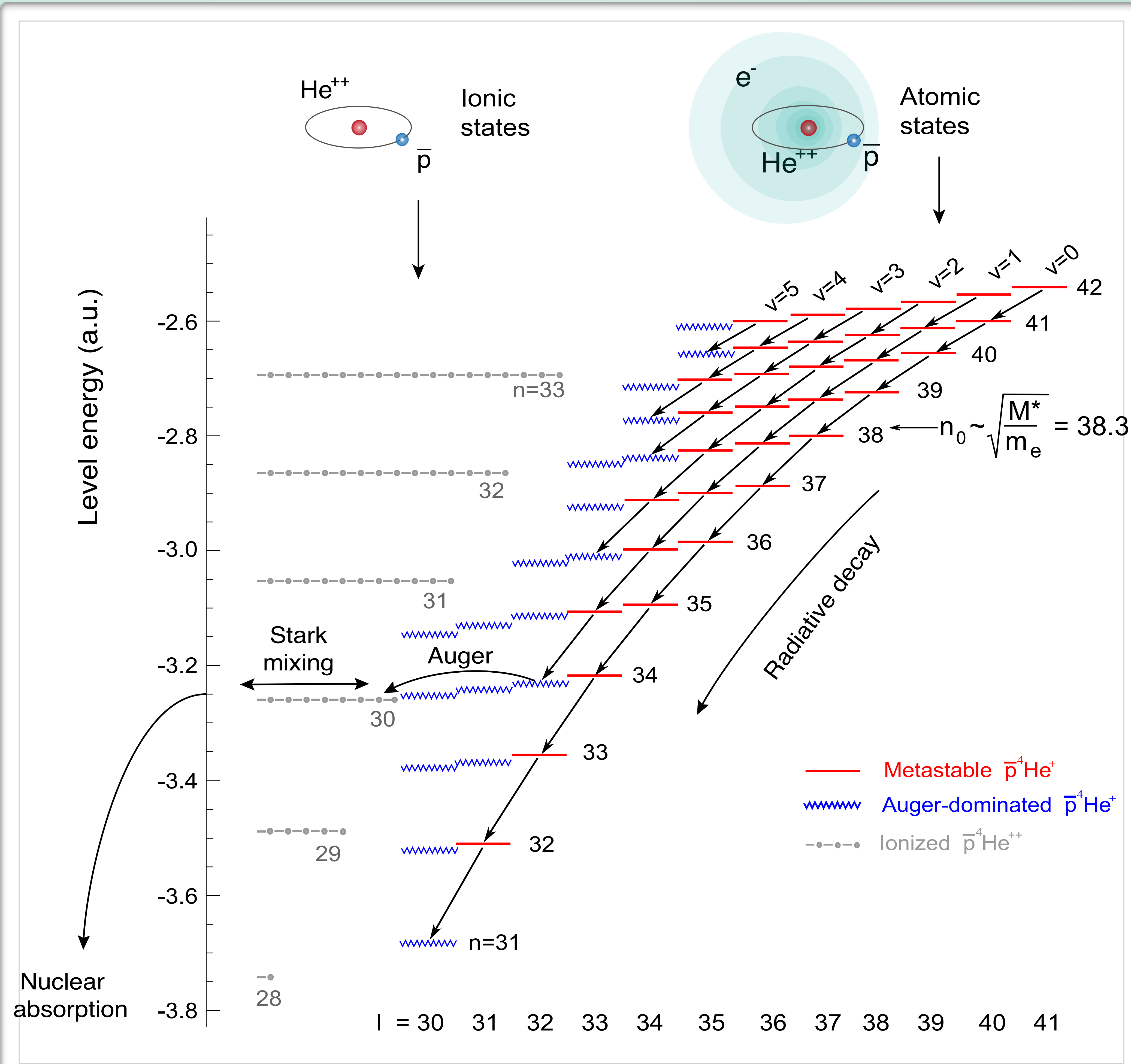
$\bar{p}He^+$: 5×10^{-12} (goal, not yet achieved)

HD^+, H_2^+ : Used to determine proton-to-electron mass ratio, proton charge radius (complementary)

$^{12}C^{5+}$ ion : Used to determine electron mass in a.u. (CODATA)

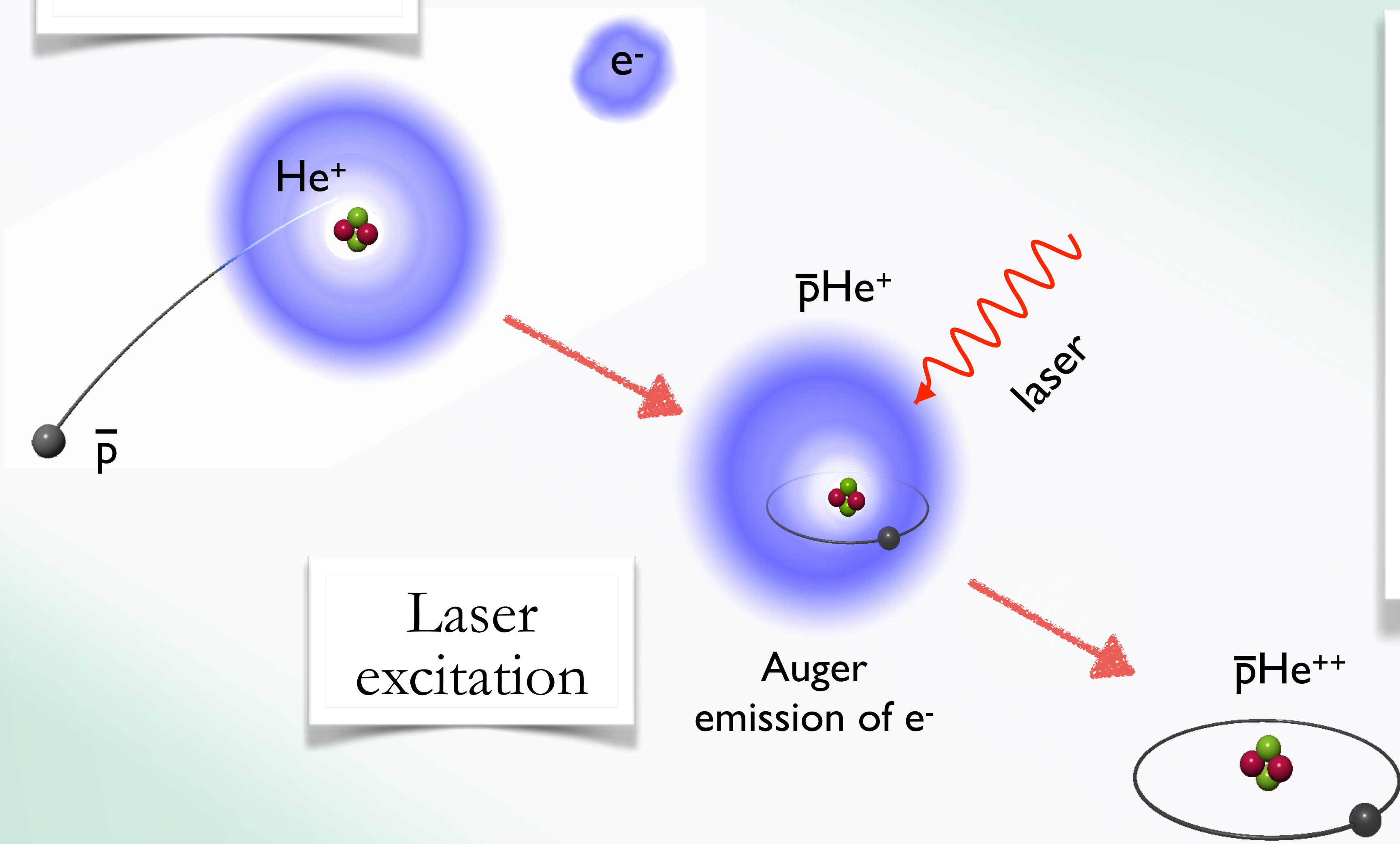
- Theory 1.5×10^{-11}
- Experiment 3×10^{-11}

Energy levels of $\bar{p}He^+$

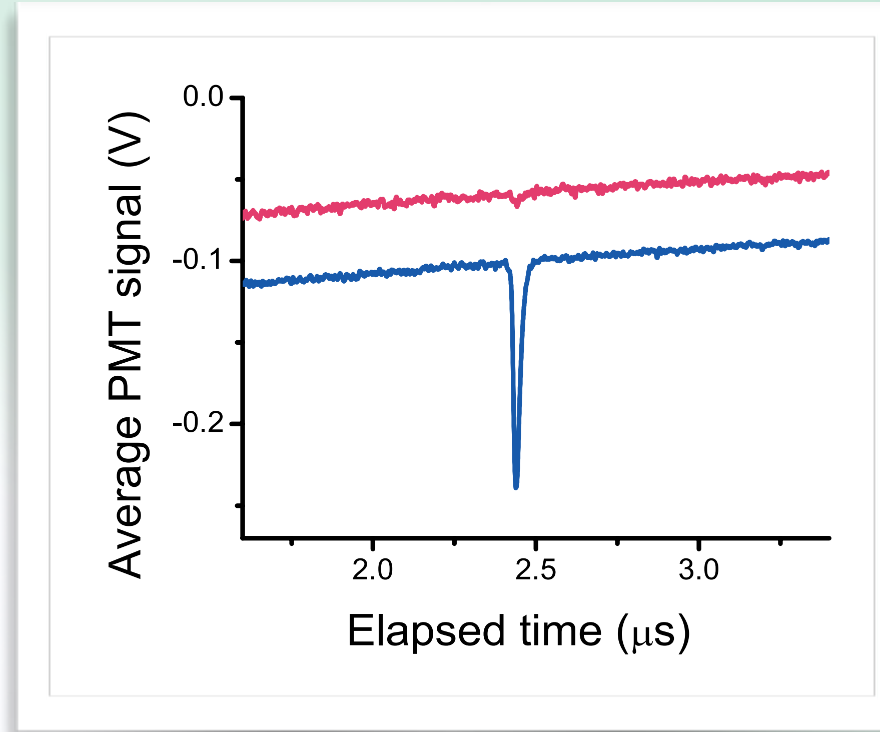


Laser spectroscopy method

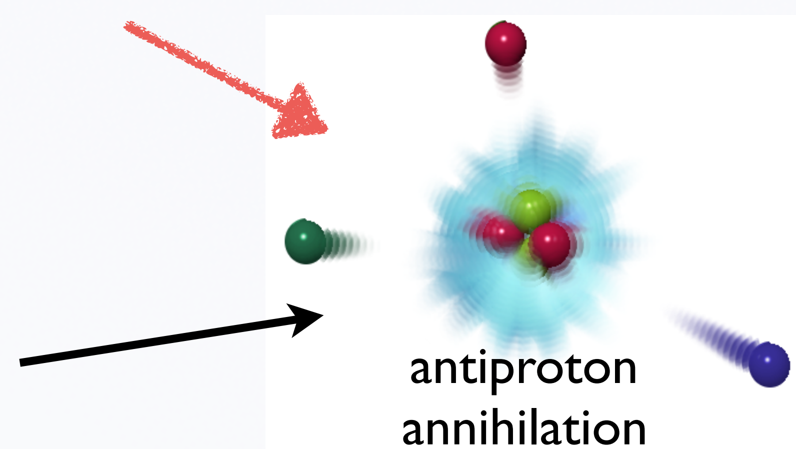
Formation



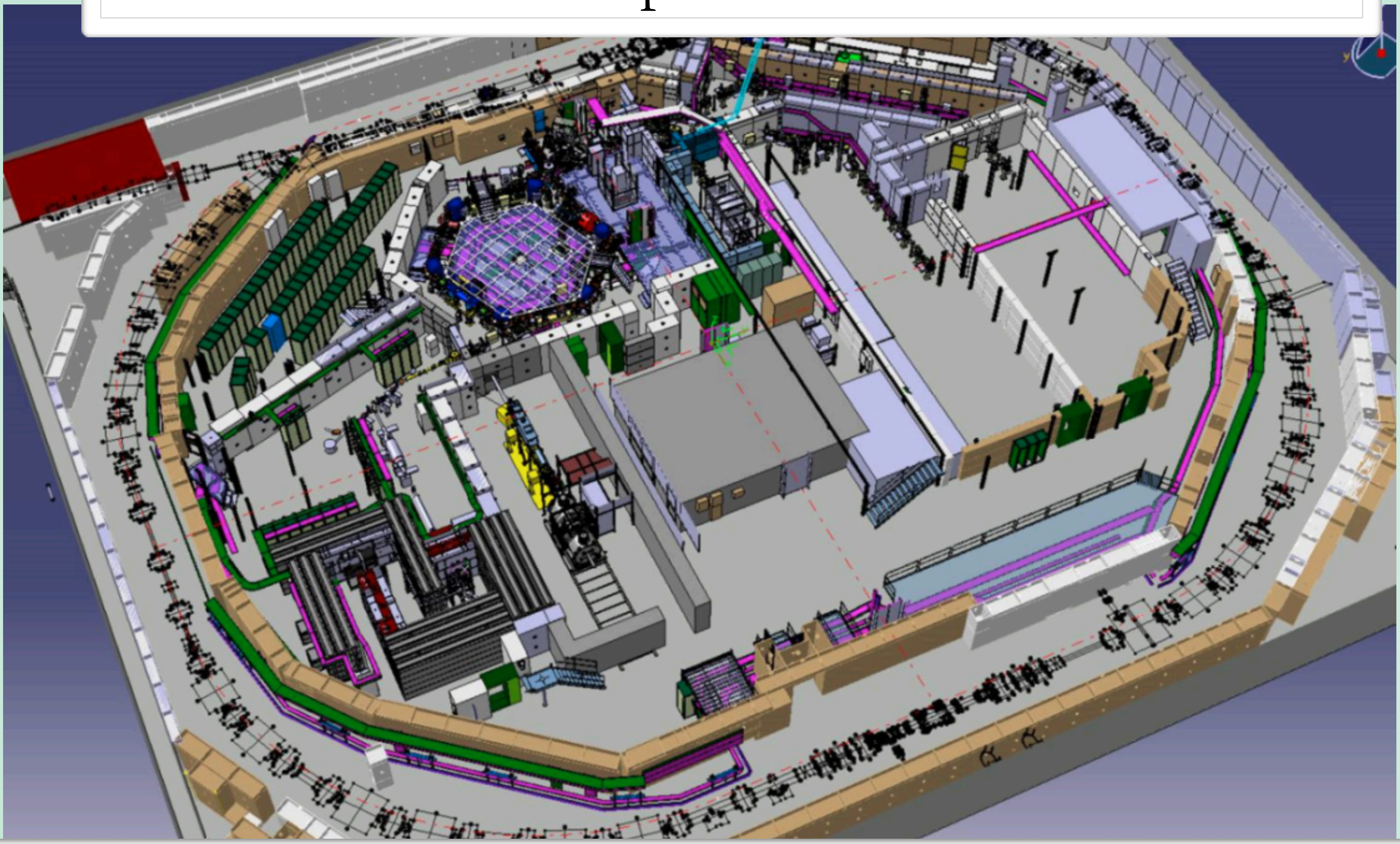
Laser excitation



Charged pions signal the resonance condition between laser and atom.

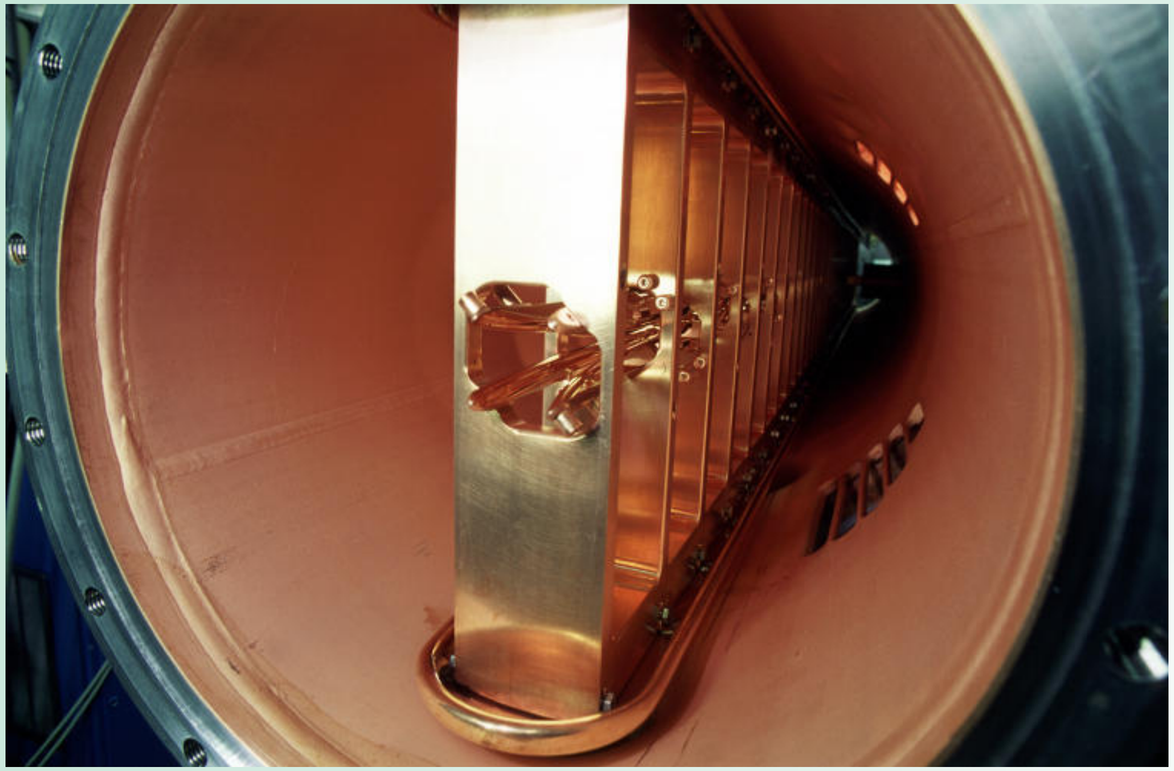


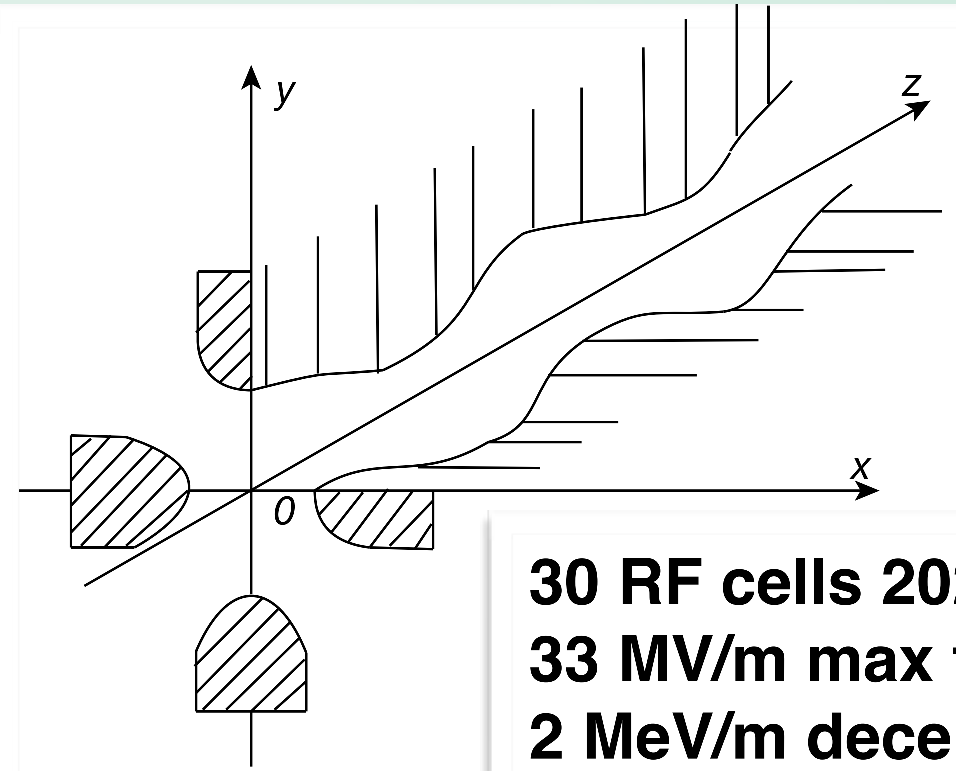
CERN Antiproton Decelerator



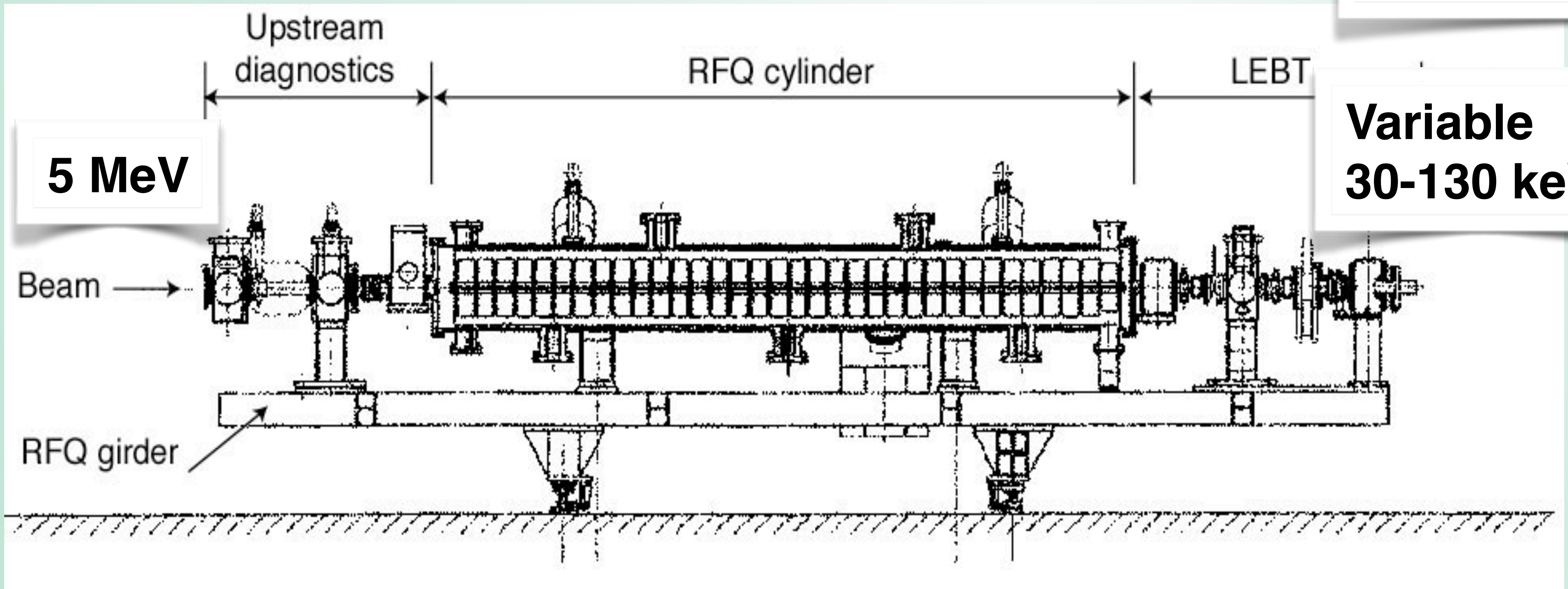
- Deceleration + cooling of 30 million@5.3 MeV / 110 sec.
- ATRAP, AEGIS, ALPHA, BASE, GBAR, ASACUSA.
- Atomic physics experiments using ion traps.

Radiofrequency quadrupole decelerator



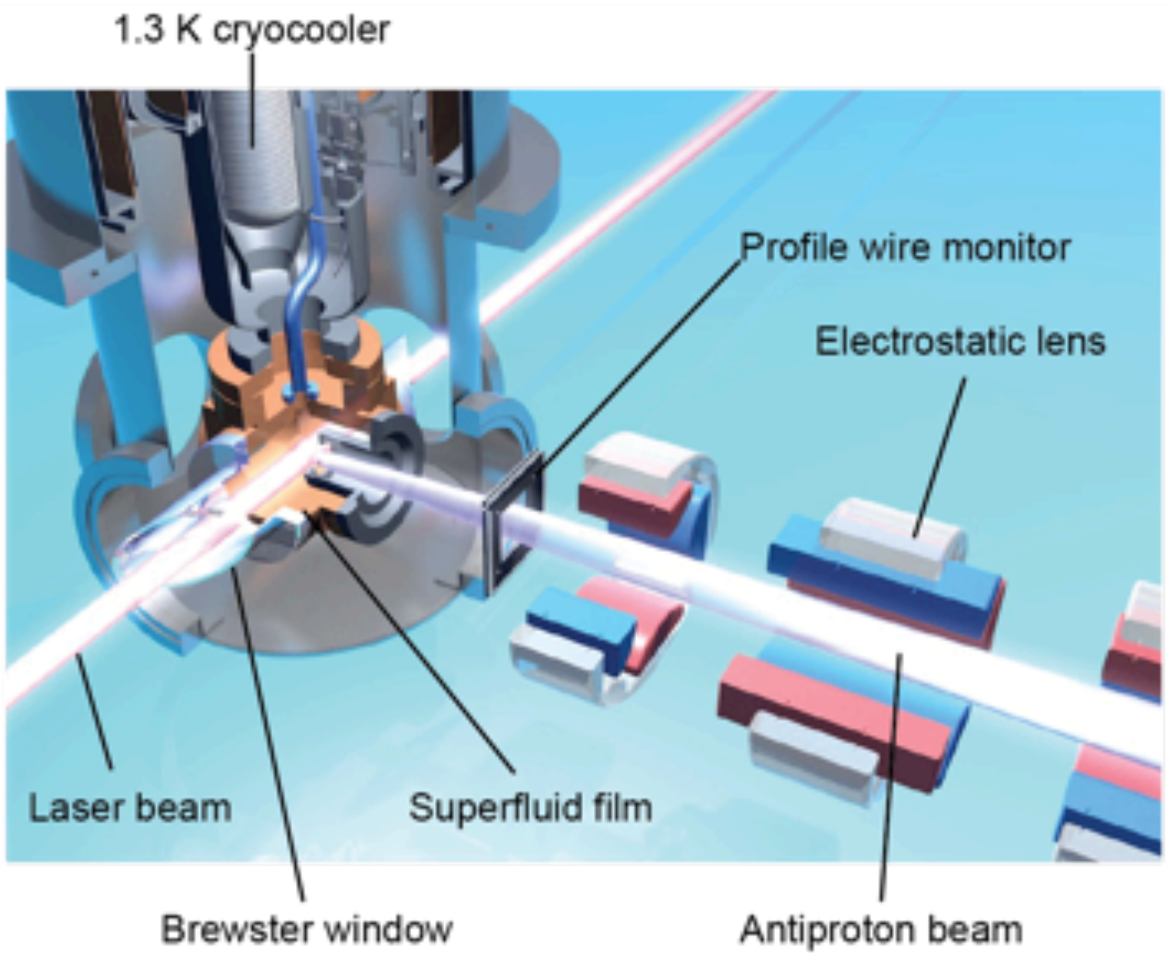


30 RF cells 202.5 MHz
33 MV/m max field
2 MeV/m deceleration field
Deceleration efficiency 20%



5 MeV

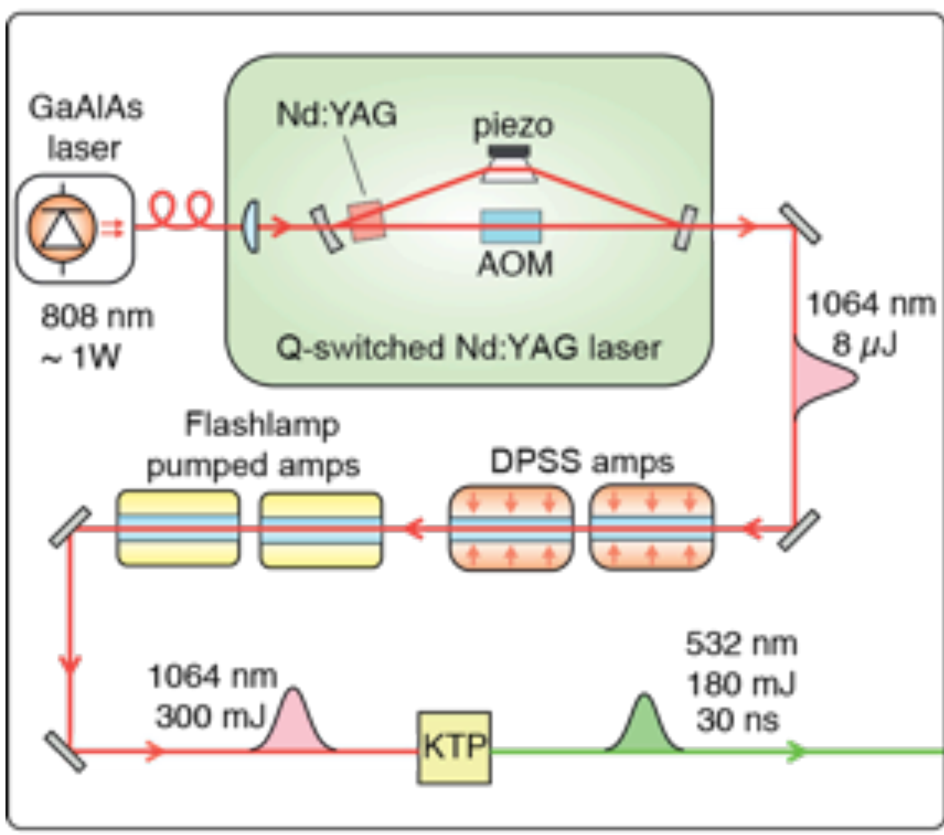
Variable
30-130 keV

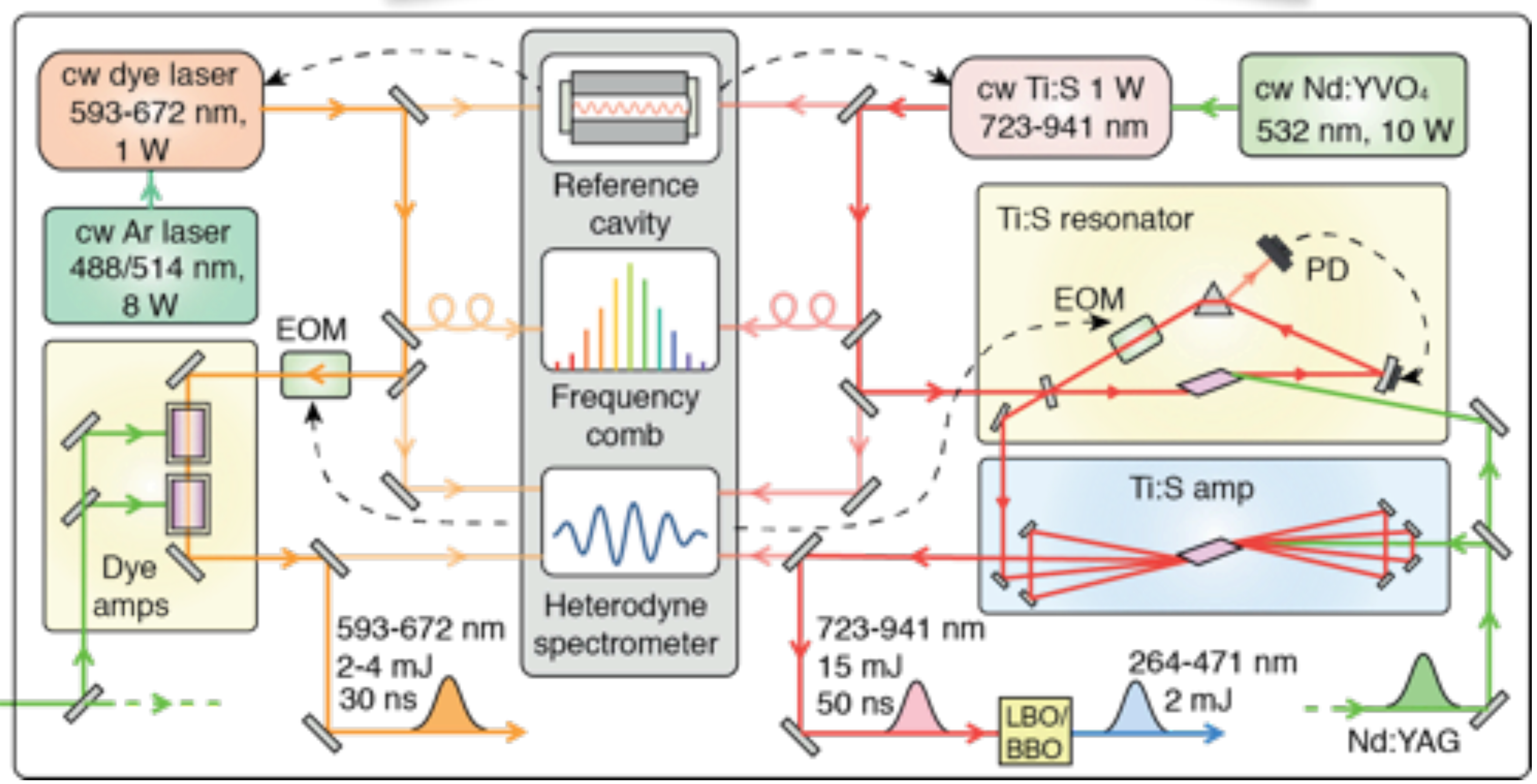


Layout

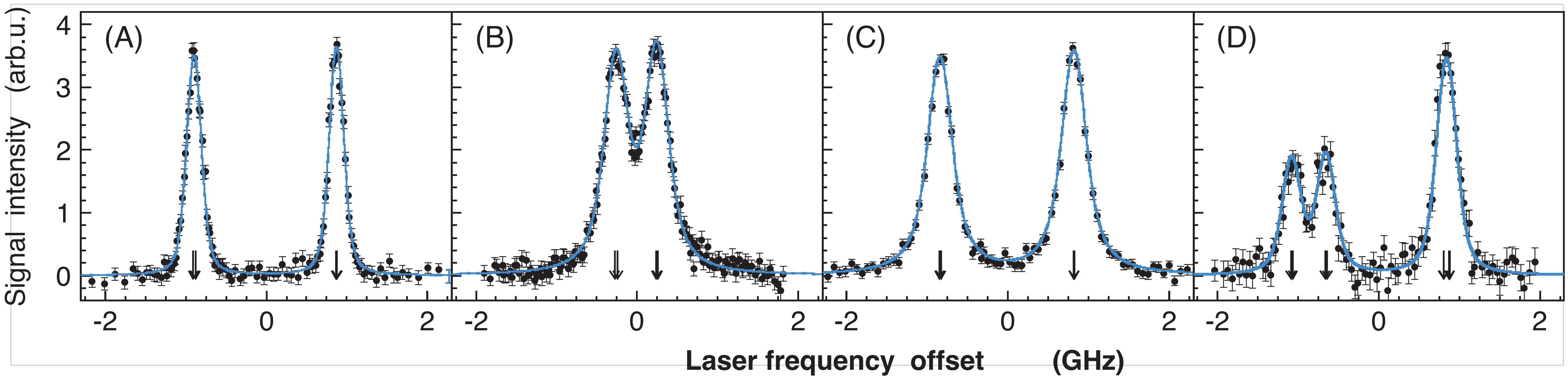
Target helium gas
T = 1.3 K P=0.4 - 1.2 mb

Better lasers, geometry, antiproton beam, higher statistics, systematic studies compared to 2006 experiment.





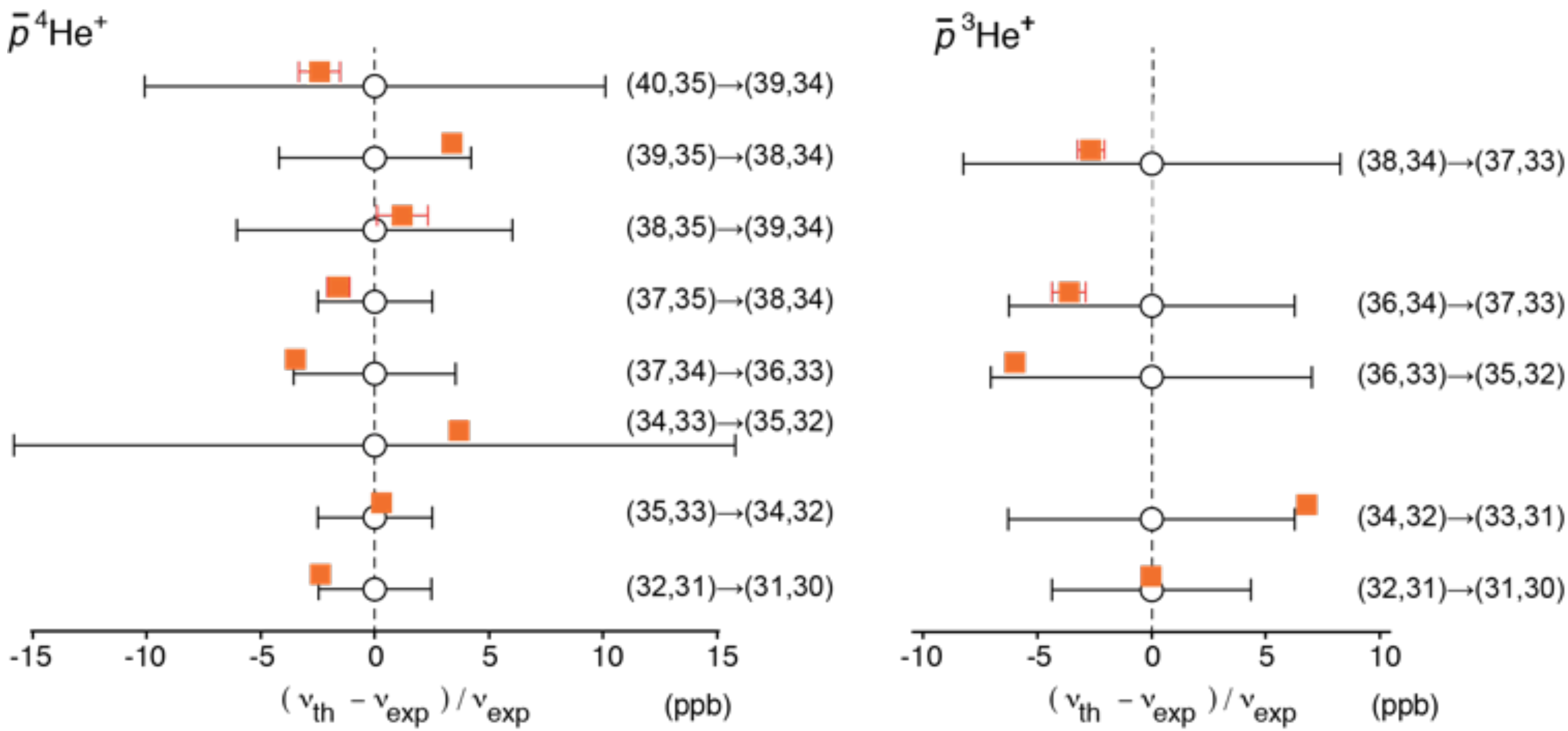
Reduction of Doppler width by buffer gas cooling



- Cooled 2×10^9 $\bar{p}He^+$ atoms to ~1.5 K
- Resolved hyperfine structure in single-photon resonance
- Experimental precision improved by factor 1.4 to 10 depending on the resonance, compared to previous result

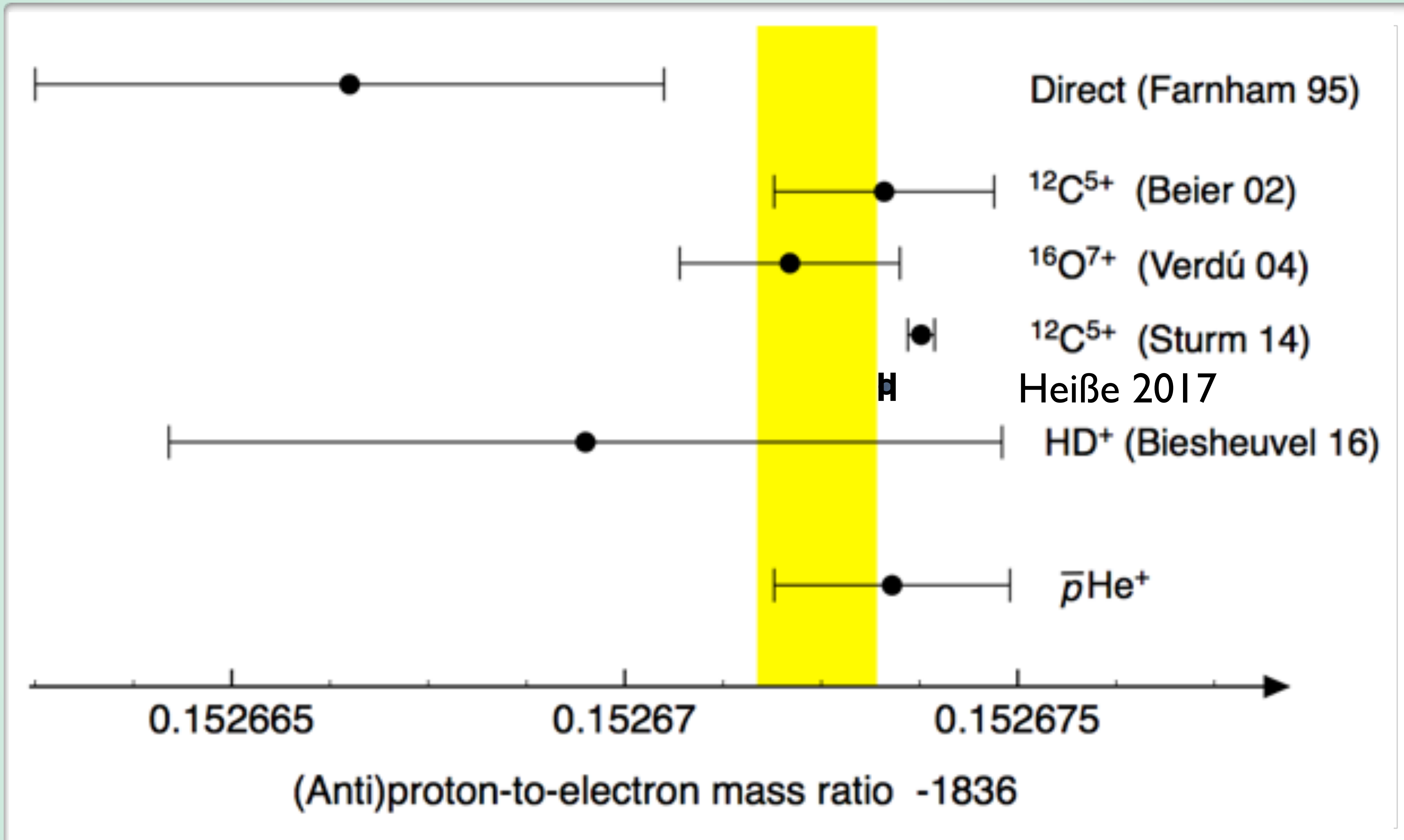
Datum	Error (MHz)
Experimental errors	
Statistical error, σ_{stat}	3
Collisional shift error	1
A.c. Stark shift error	0.5
Zeeman shift	<0.5
Frequency chirp error	0.8
Seed laser frequency calibration	<0.1
Hyperfine structure	<0.5
Line profile simulation	1
Total systematic error, σ_{sys}	1.8
Total experimental error, σ_{exp}	3.5
Theoretical uncertainties	
Uncertainties from uncalculated QED terms*	2.1
Numerical uncertainty in calculation*	0.3
Mass uncertainties*	<0.1
Charge radii uncertainties*	<0.1
Total theoretical uncertainty*, σ_{th}	2.1

Comparison between experimental and theoretical transition frequencies of 13 single-photon resonances



- Higher precision and better exp-theory agreement.

Antiproton-to-electron mass ratio 2016

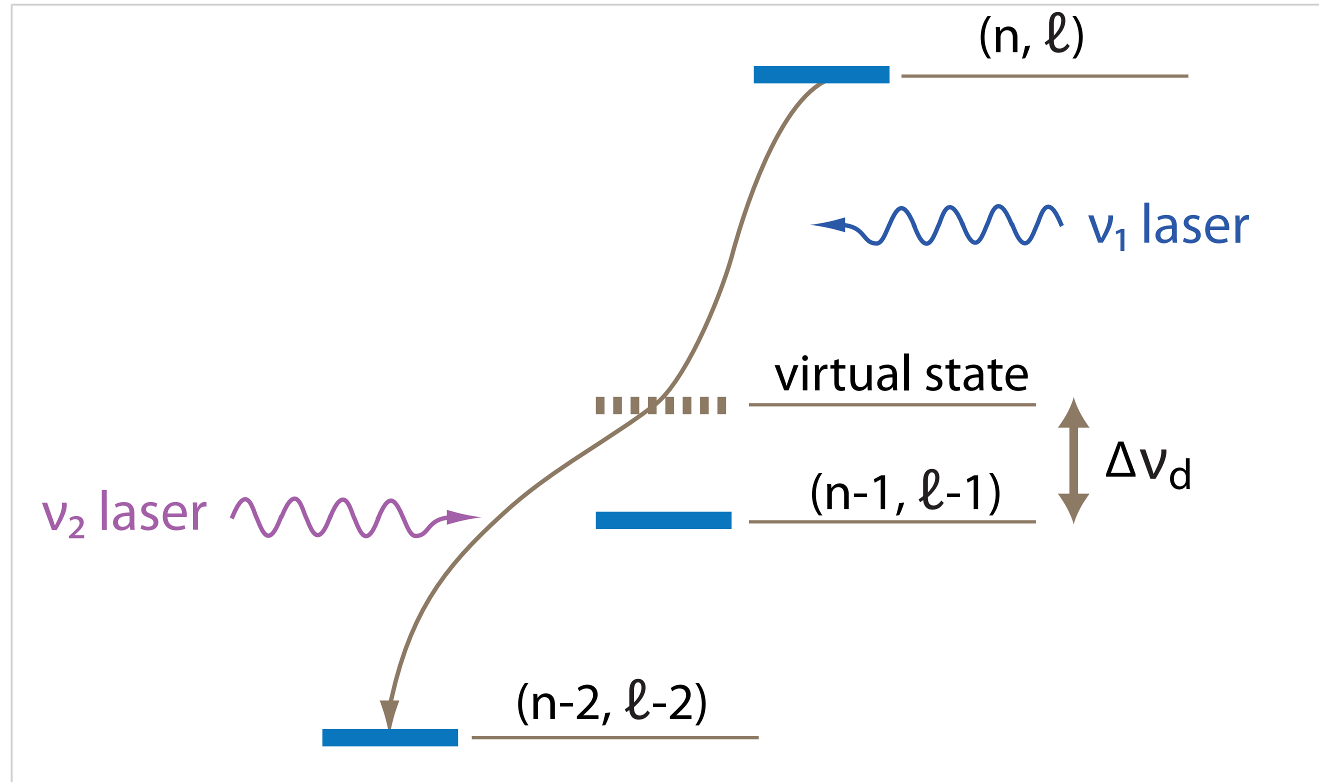


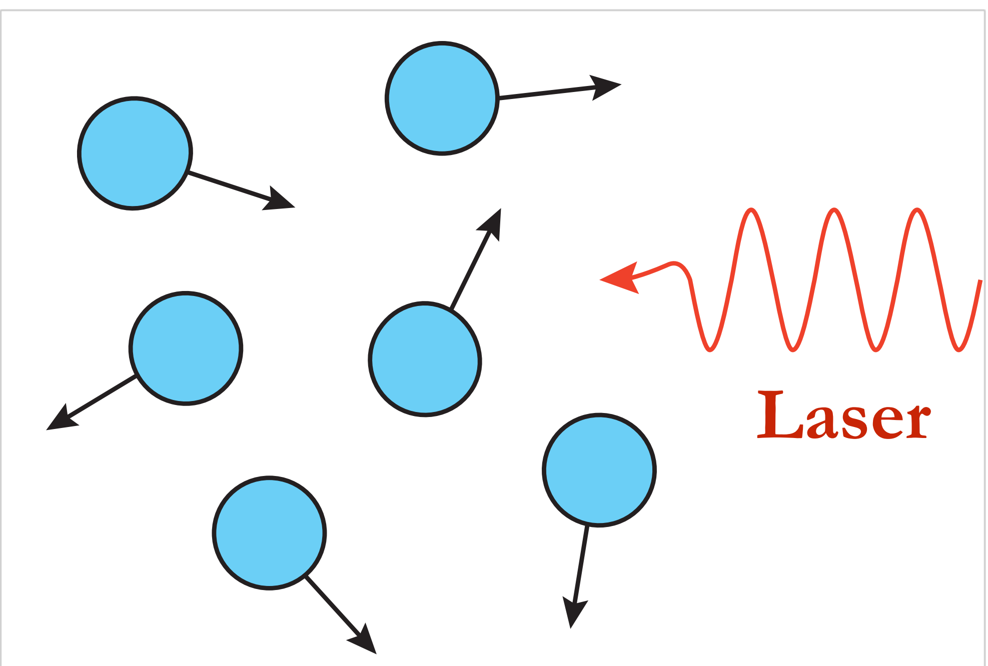
Antiproton-to-electron mass ratio 1836.1526734 (15)

Science 354, 610 (2016)

2015-2018: sub-Doppler two-photon spectroscopy

Thermal Doppler motion of atoms broadens the UV spectral lines to 2 GHz at T=1.5 K.





Exciting a nonlinear antiproton transition with the absorption of two counter-propagating laser photons reduces first-order Doppler width by factor 20-30:

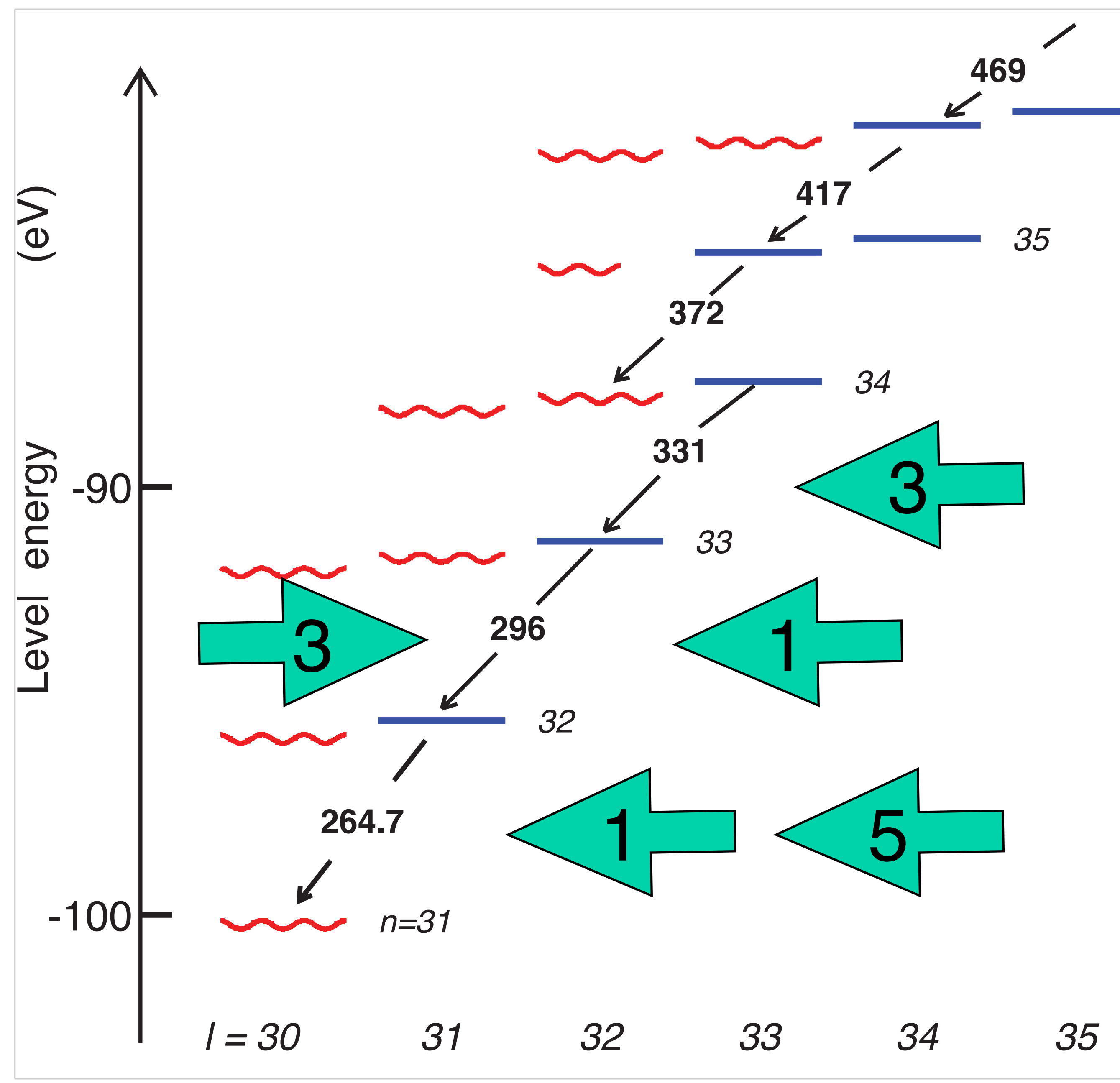
$$\Gamma = \frac{|\nu_1 - \nu_2|}{\nu_1 + \nu_2} \times 2.35(\nu_1 + \nu_2)\sqrt{\frac{kT}{M}}$$

Beyond 2021: Experiments at ELENA

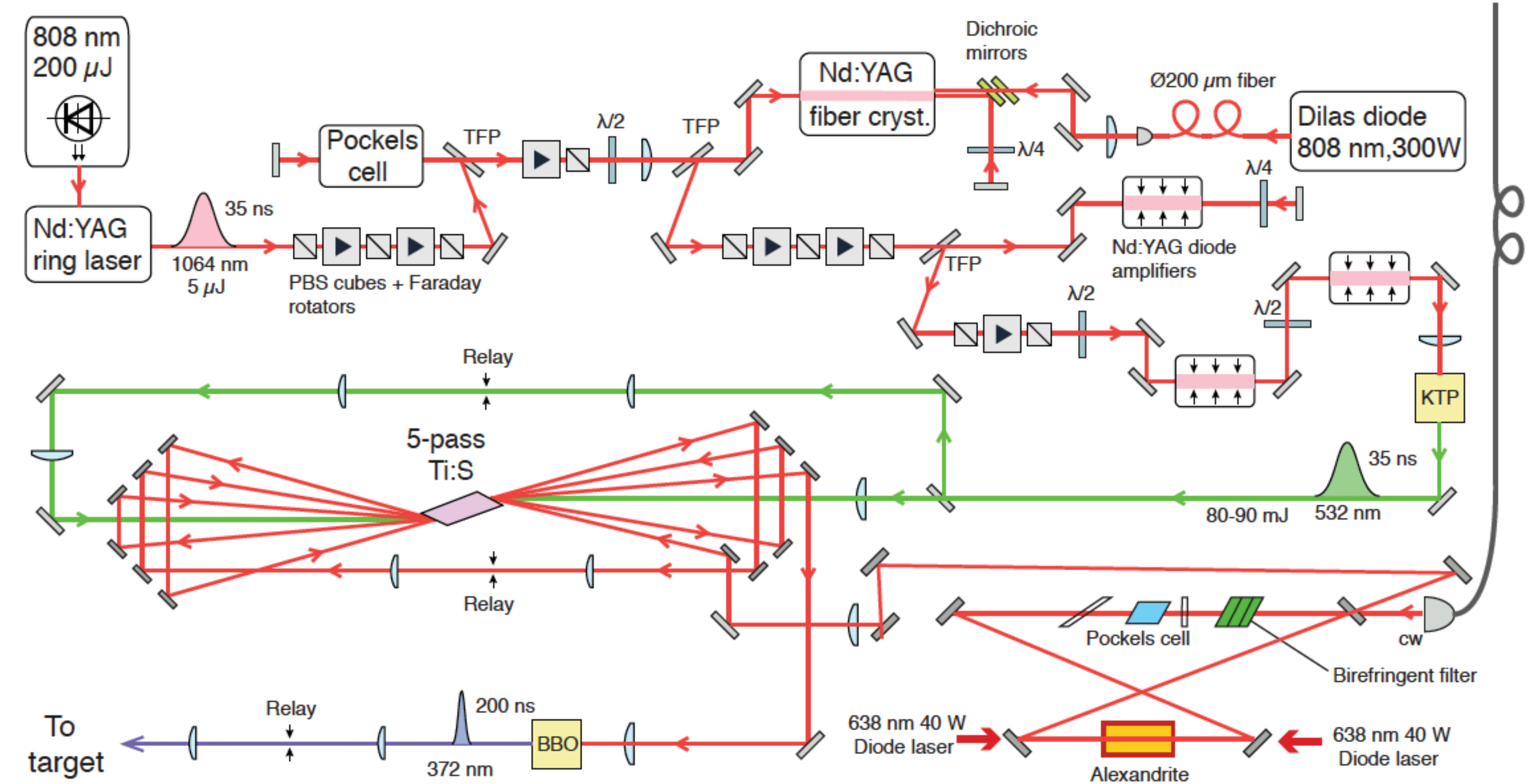
So far we measured $\bar{p}He^+$ transition frequencies between metastable (τ=1 μs) and short-lived (1.4 – 4.5 ns) states.

Hard-to-see metastable-metastable transitions have natural widths of <1/300 (200 kHz).
Possibility to improve the precision by **factor >100**.

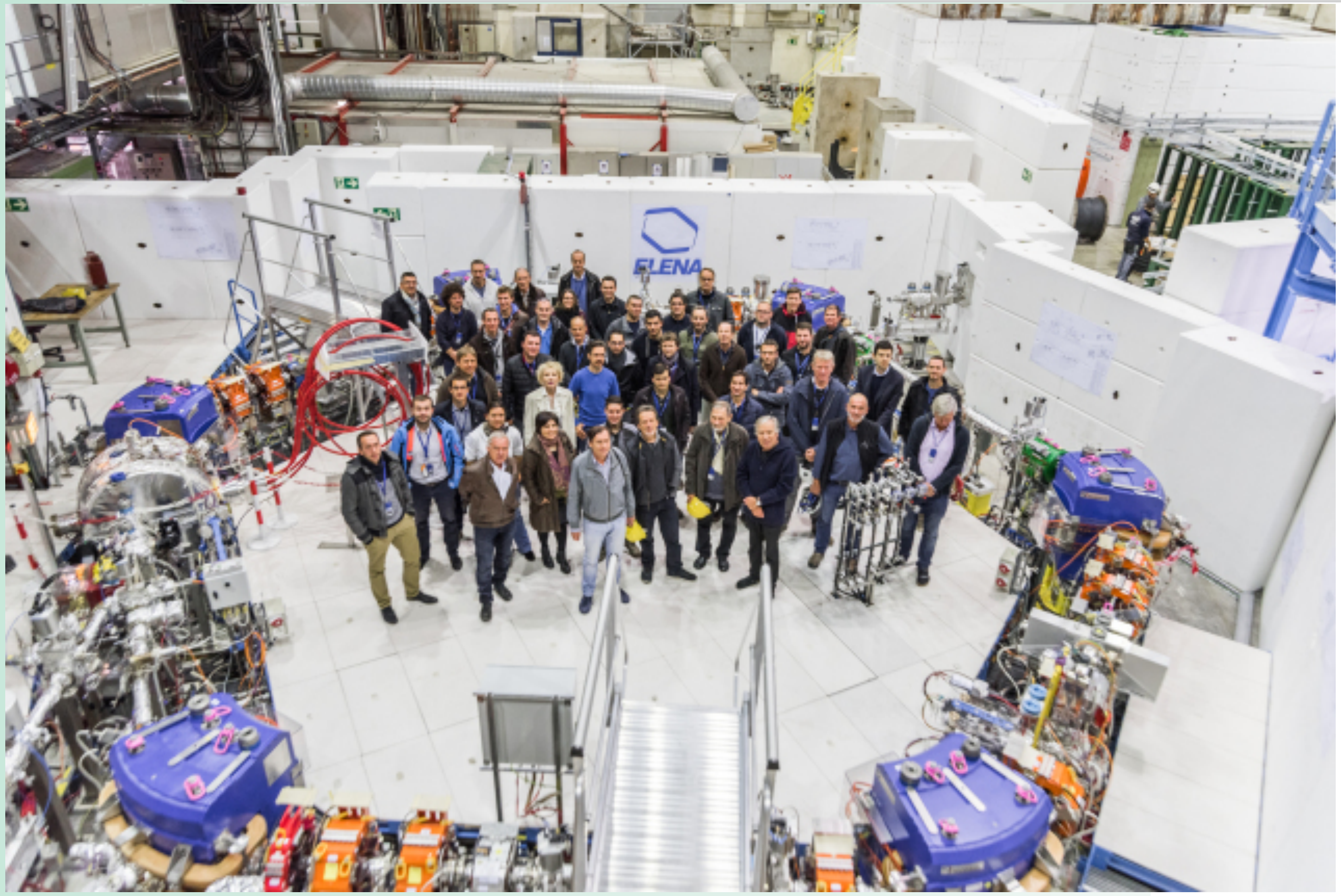
Buffer gas cooling to lower (T<1 K) temperature

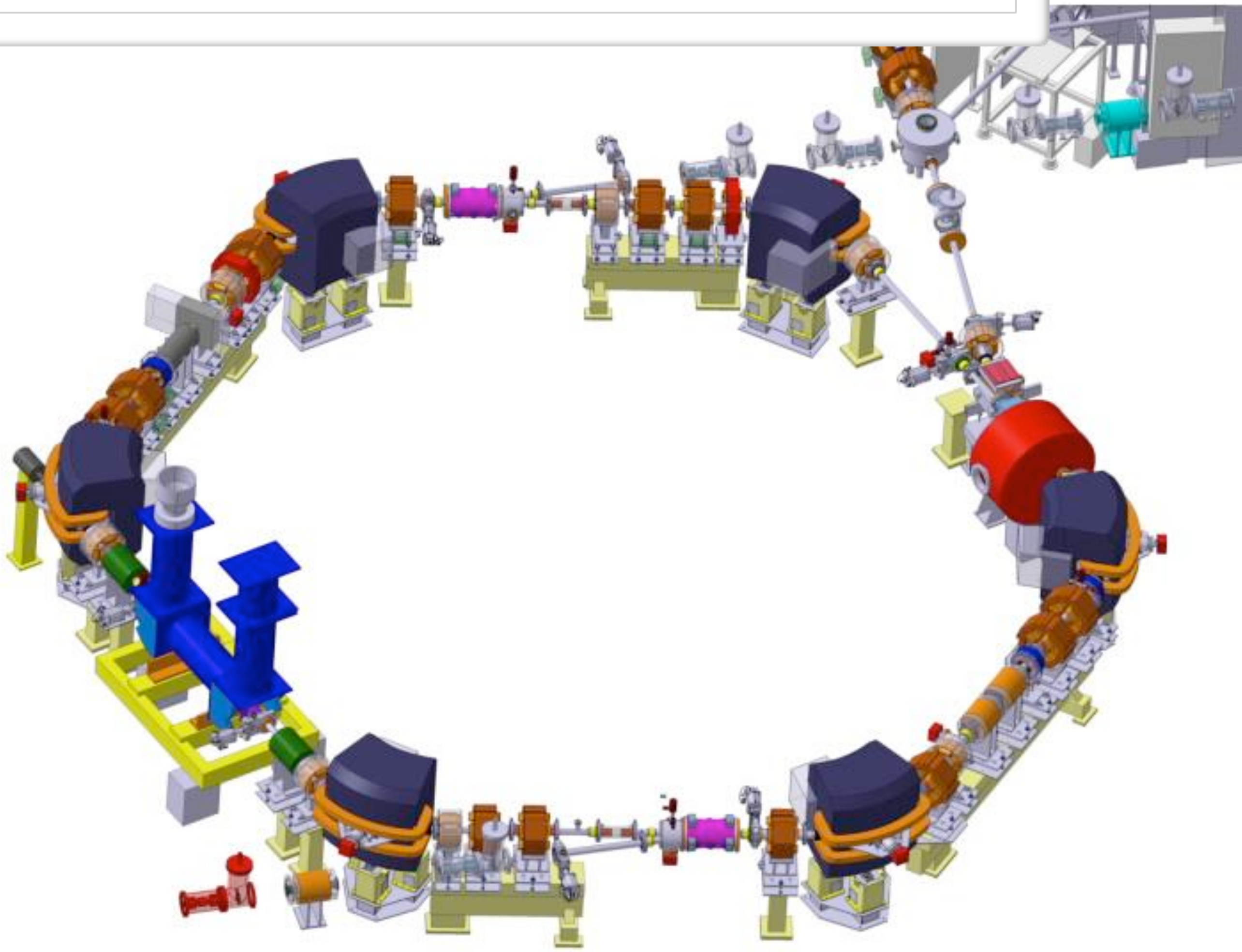


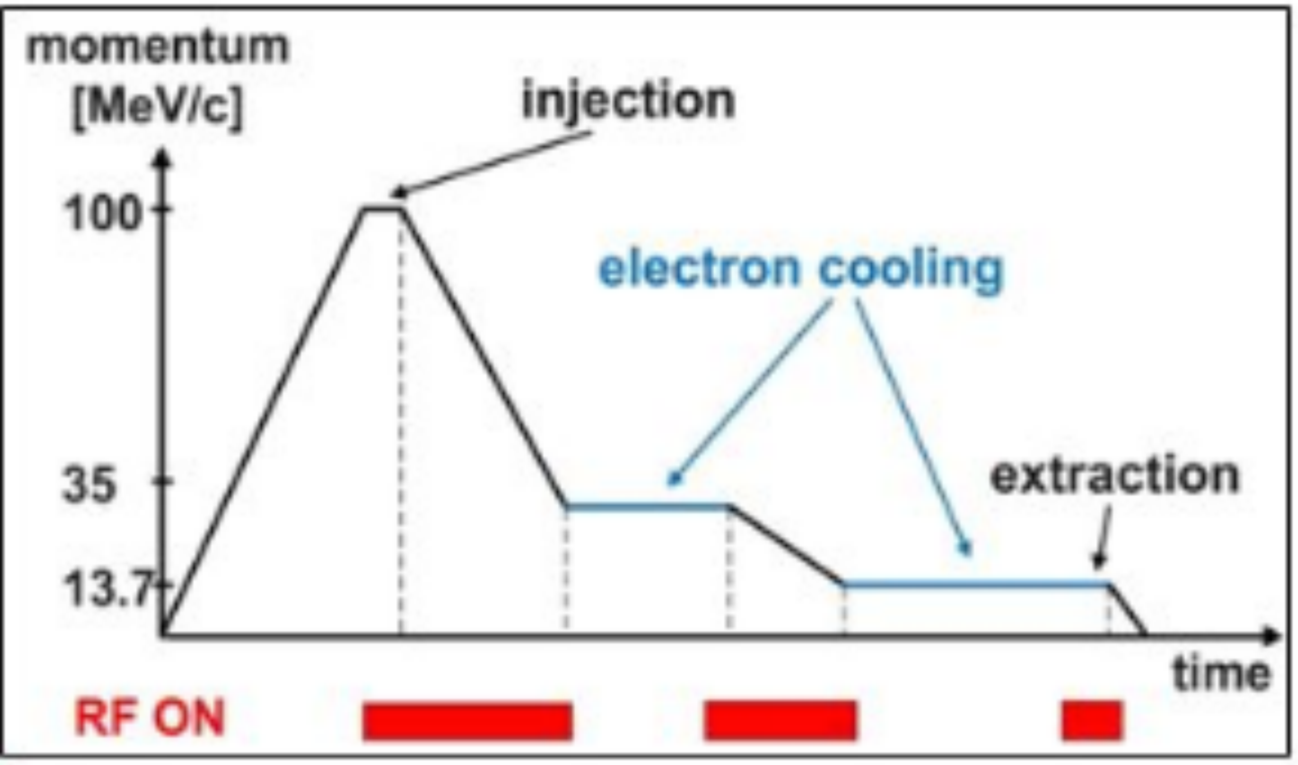
Fully DPSS Nd:YAG laser pumped Ti:Sapphire laser with long-pulse alexandrite oscillator



ELENA Extra Low Energy Antiproton Ring

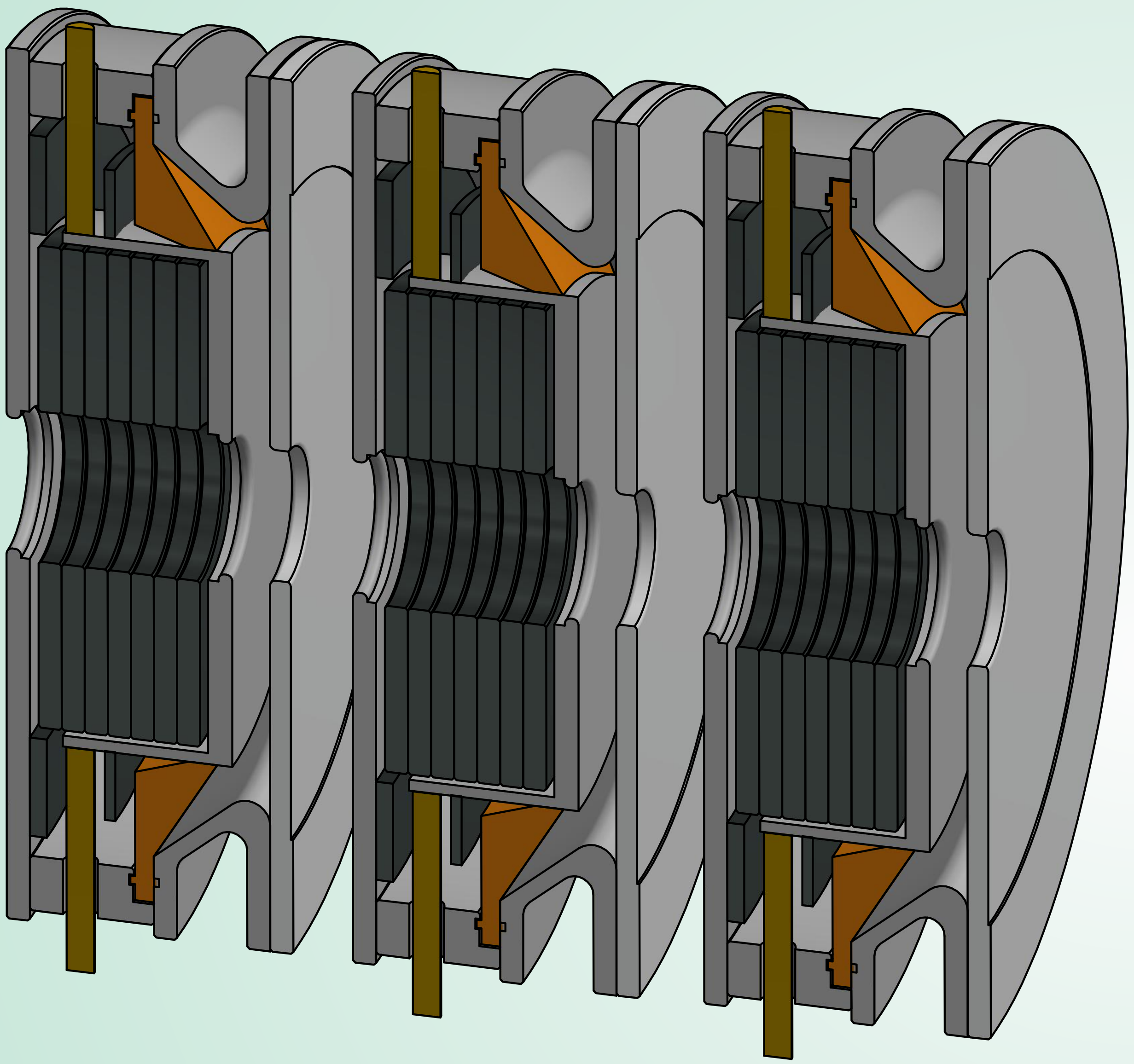


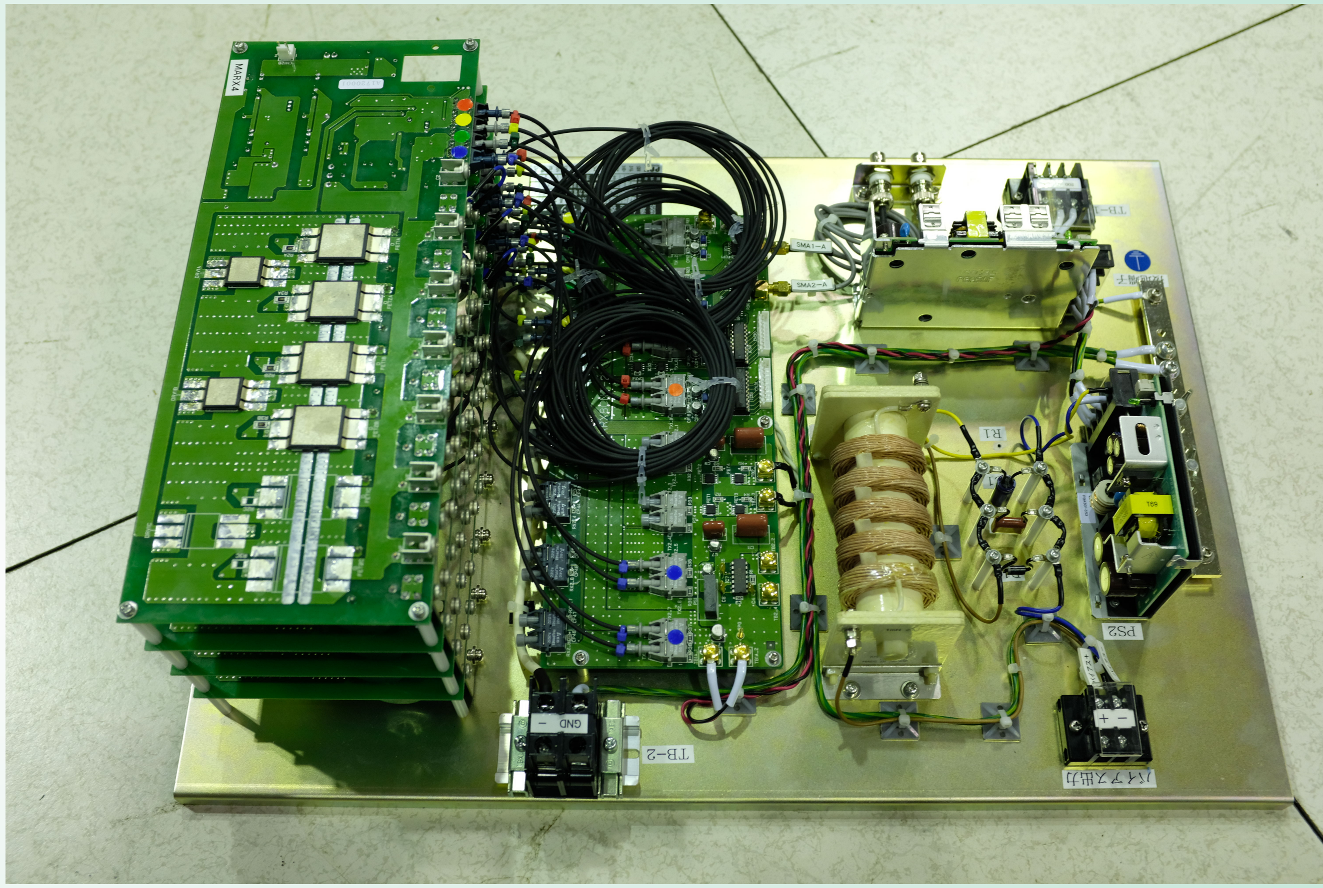




- 20 million antiprotons per 2 min
- Injection 5.3 MeV, ejection 100 keV
- Circumference 30.4 m
- Electron cooling at 13.7 and 35 MeV/c

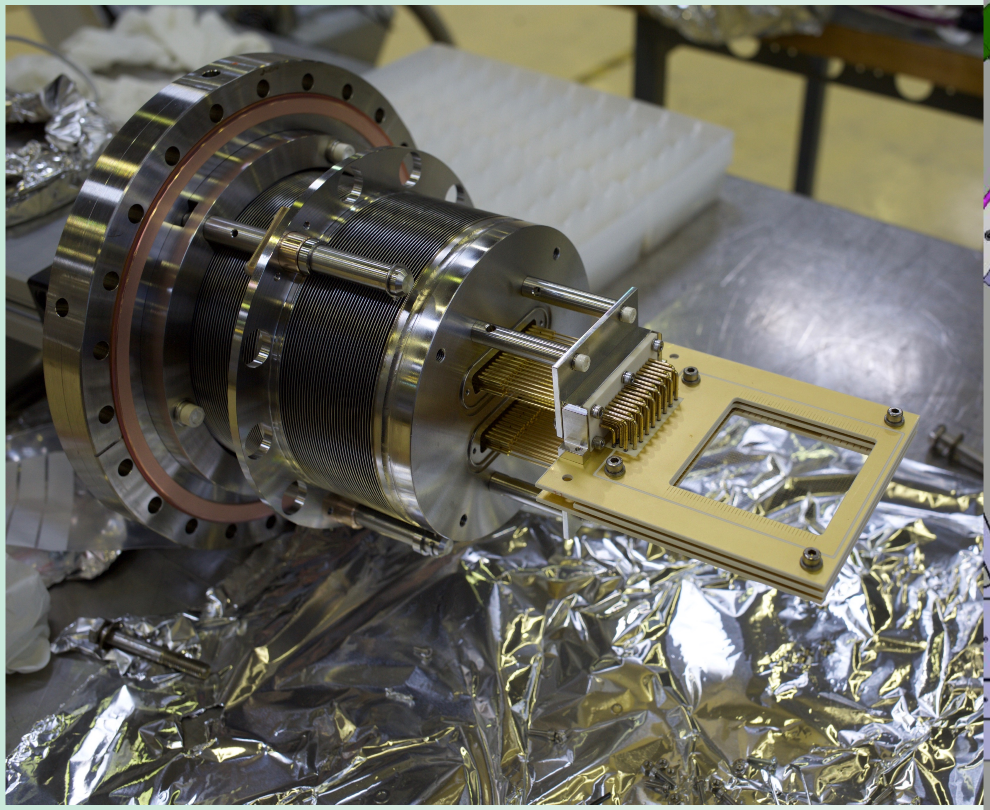
Induction decelerator for slowing down to <50 keV

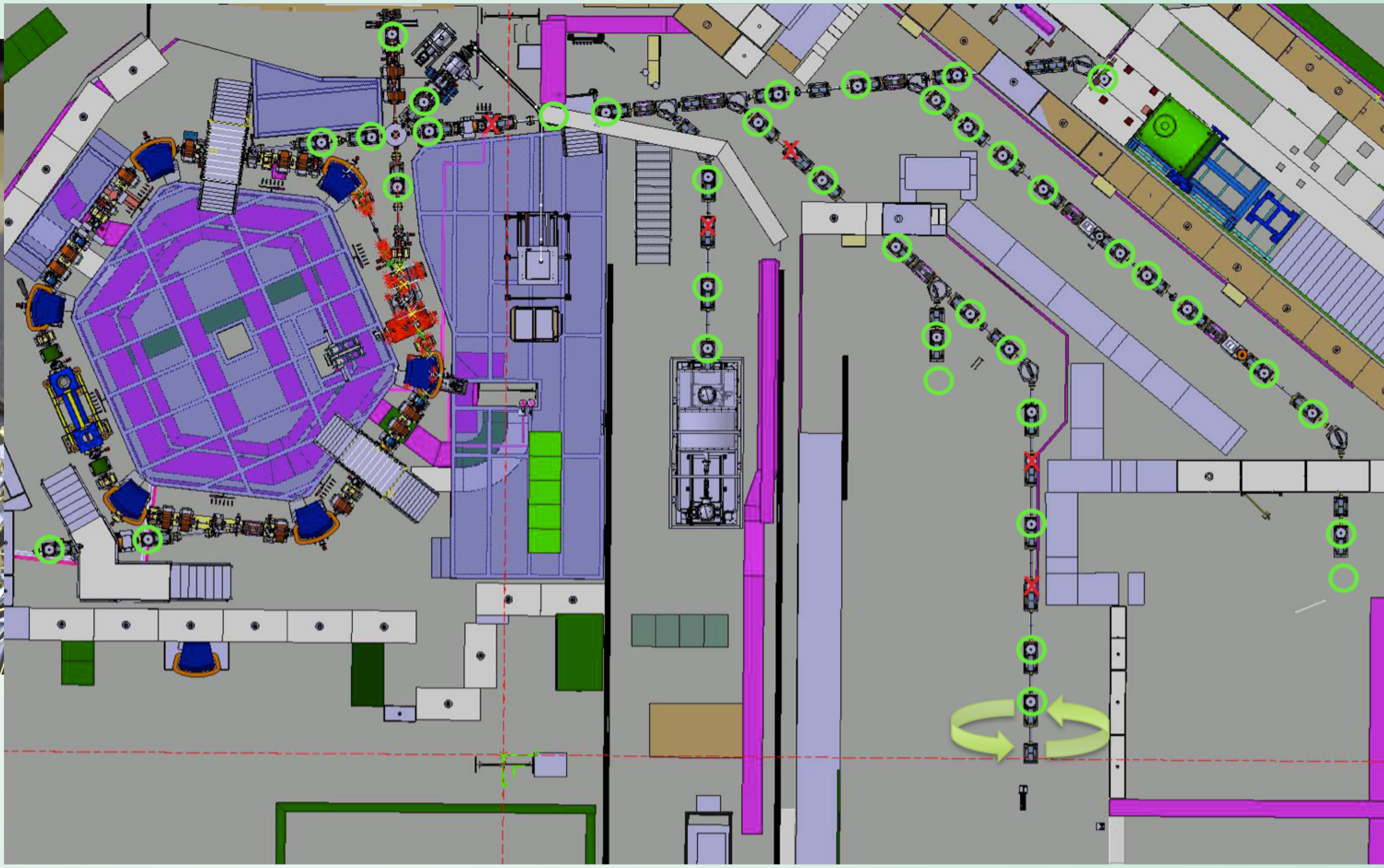




- Compact size, no need for high voltage, retain high quality beam emittances
- d>500 mm, l=25 mm, ΔB=2T Hitachi Finemet FT-3L cores
- 2-4 kV / 500 ns / 200 A pulses by cascaded SiC MOSFET drivers

Beam profile monitors for ELENA





- Semi-non-destructive detector for tuning of ELENA electrostatic beamlines
- Resolution 0.25-1 mm.
- 10 um gold-coated tungsten wires (signal level 10^4 e-)
- 43 devices as in-kind contribution to ELENA project

Summary

- Collisional buffer gas cooling of antiprotonic helium atoms to T=1.5 K. Measured 13 single-photon transitions. Experimental precision improved by factor 1.4-10x compared to previous single-photon experiments.
- Agreed with 3-body QED calculations. Determined the antiproton-to-electron mass ratio as 1836.1526734 (15).
- Two-photon laser spectroscopy experiments of cold atoms ongoing.
- 100 times higher precision aimed for ELENA era.
- Sister experiment of laser spectroscopy of pionic helium atoms at PSI ready to announce first results soon.

Pressure shift in $(n,l)=(37,35)\rightarrow(38,34)$