H̄-HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

HADRONIC ATOMS: Precision spectroscopy of ANTIPROTONIC HELIUM and ANTIHYDROGEN

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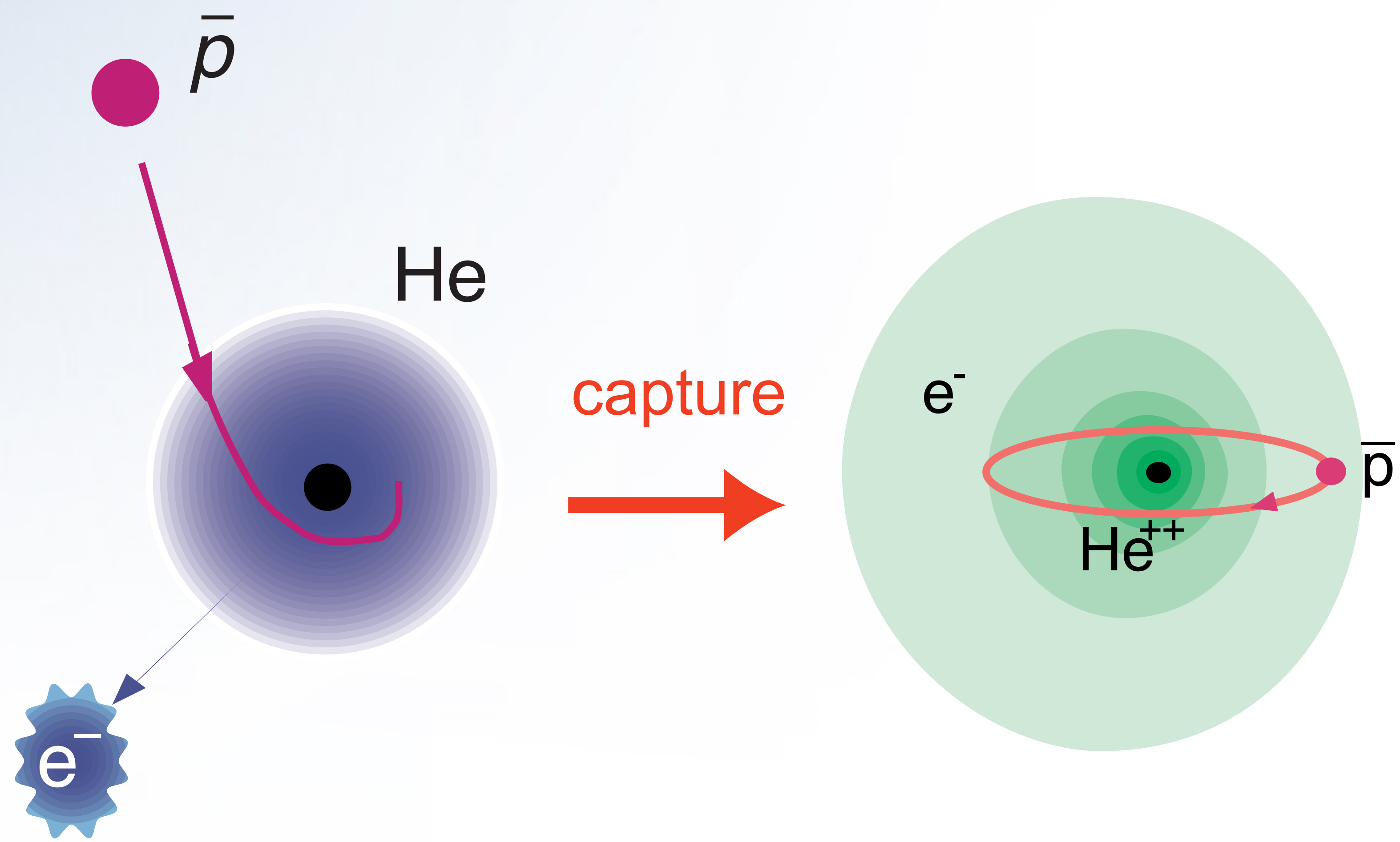
STEFAN MEYER INSTITUTE FOR SUBATOMIC PHYSICS, VIENNA

HADRON PHYSICS IN CHINA AND THE US
LANZHOU
JULY 21-24, 2014

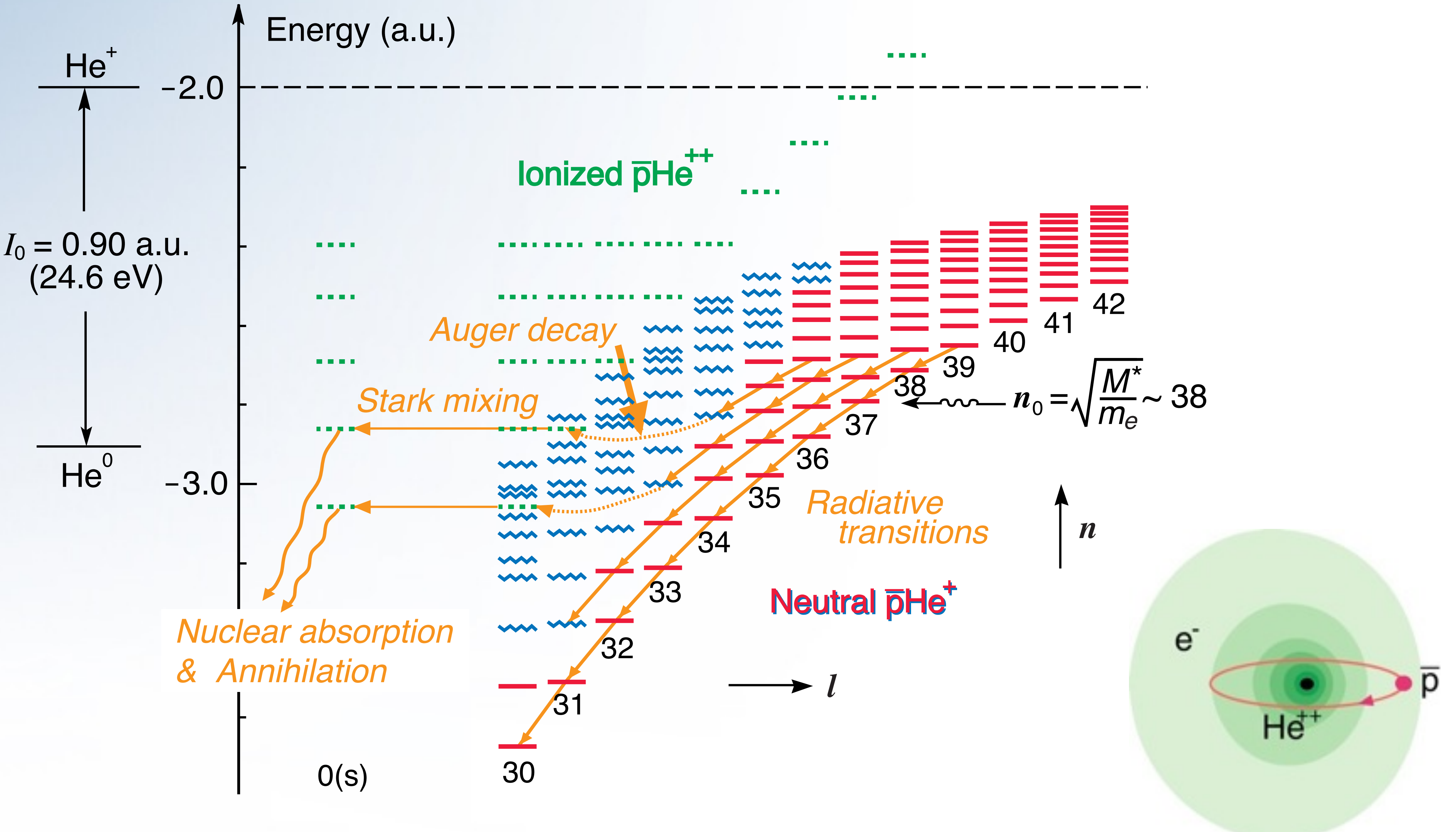
Exotic atom formation

- energy loss until E_{kin} < ionization energy
- capture



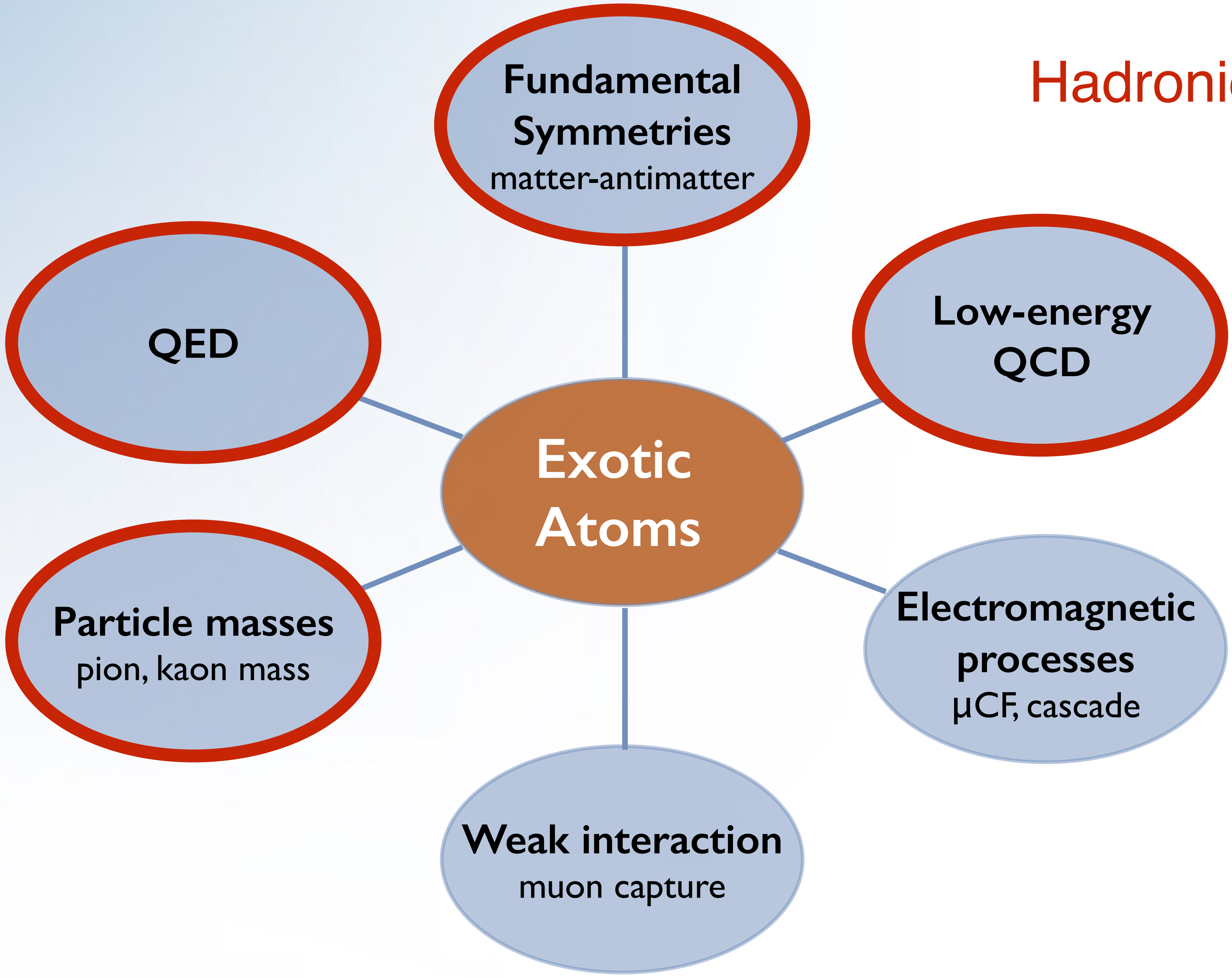
Fermi and Teller *Phys. Rev. 72, 399–408 (1947)*

ANTIPROTONIC HELIUM

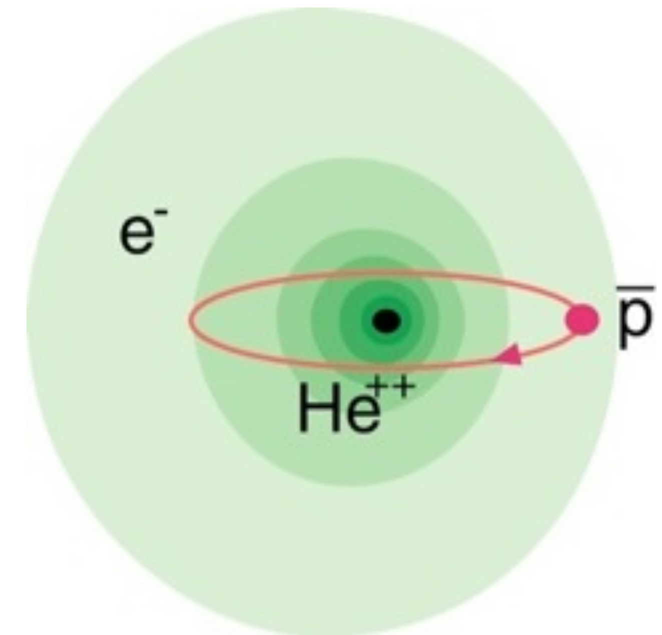


Exotic atoms

Hadronic atoms

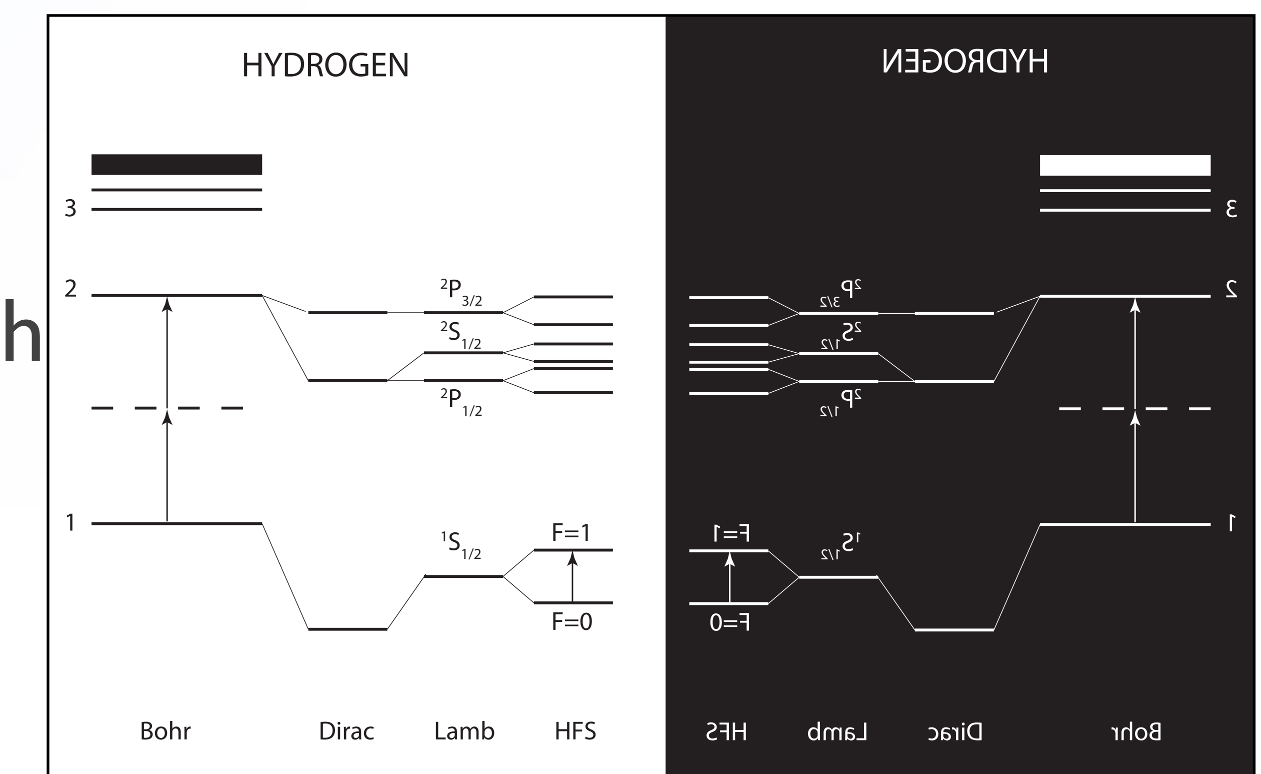


Atoms containing antiprotons



- **Antiprotonic helium**
  - laser and microwave spectroscopy CPT test antiproton properties
    - mass,charge: 7×10^{-10} 2011
    - magnetic moment: 2.9×10^{-3} 2009
  - most precisely calculated 3-body system

- **Antihydrogen**
  - hydrogen measured to high precision
    - 1S-2S: $<10^{-14}$
    - ground-state HFS 10^{-12}



ASACUSA COLLABORATION @ CERN-AD

ASAKUSA KANNON TEMPLE
BY UTAGAWA HIROSHIGE (1797–1858)

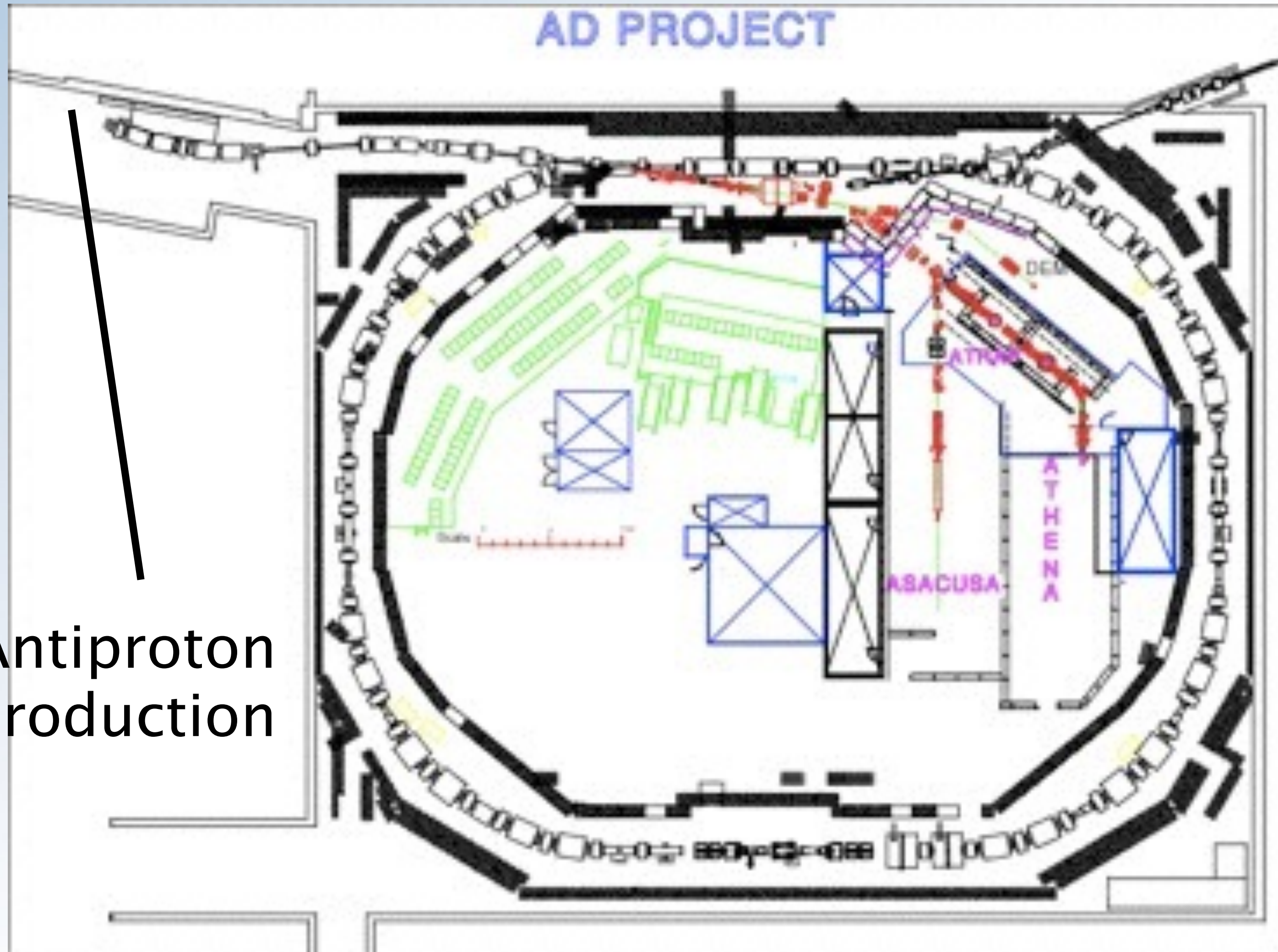
Atomic Spectroscopy And Collisions Using Slow Antiprotons

SPOKESPERSON: R.S. HAYANO, UNIVERSITY OF TOKYO

- University of Tokyo, Japan
  - INSTITUTE OF PHYSICS
  - FACULTY OF SCIENCE, DEPARTMENT OF PHYSICS
- RIKEN, Saitama, Japan
- SMI, Austria
- Aarhus University, Denmark
- Max-Planck-Institut für Quantenoptik, Munich, Germany
- KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- ATOMKI Debrecen, Hungary
- Brescia University & INFN, Italy
- University of Wales, Swansea, UK
- The Queen's University of Belfast, Ireland

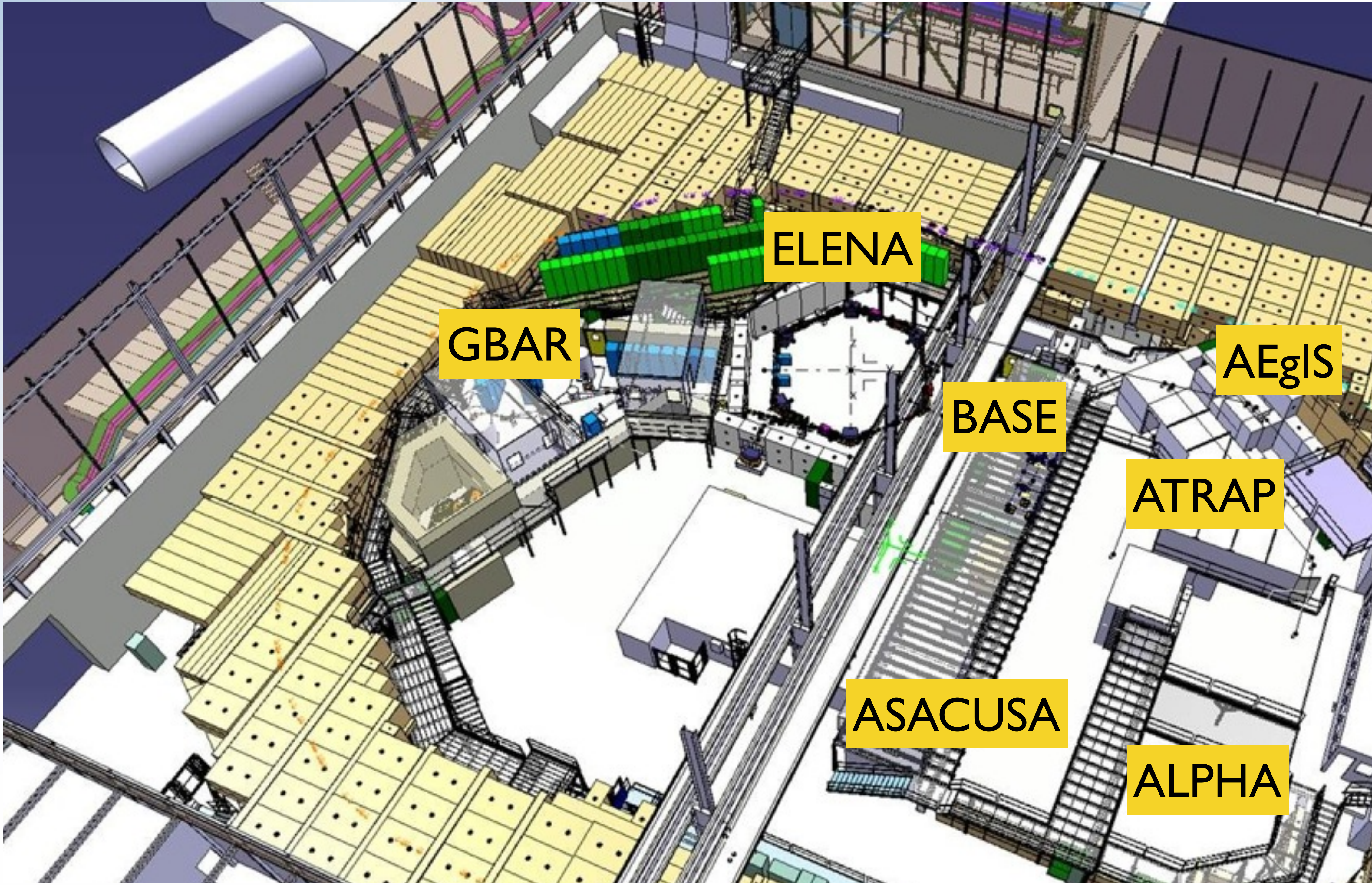
~ 44 MEMBERS

Antiproton Decelerator @ CERN



- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 107 antiprotons per pulse of 100 ns length
  - 1 pulse / 85−120 seconds

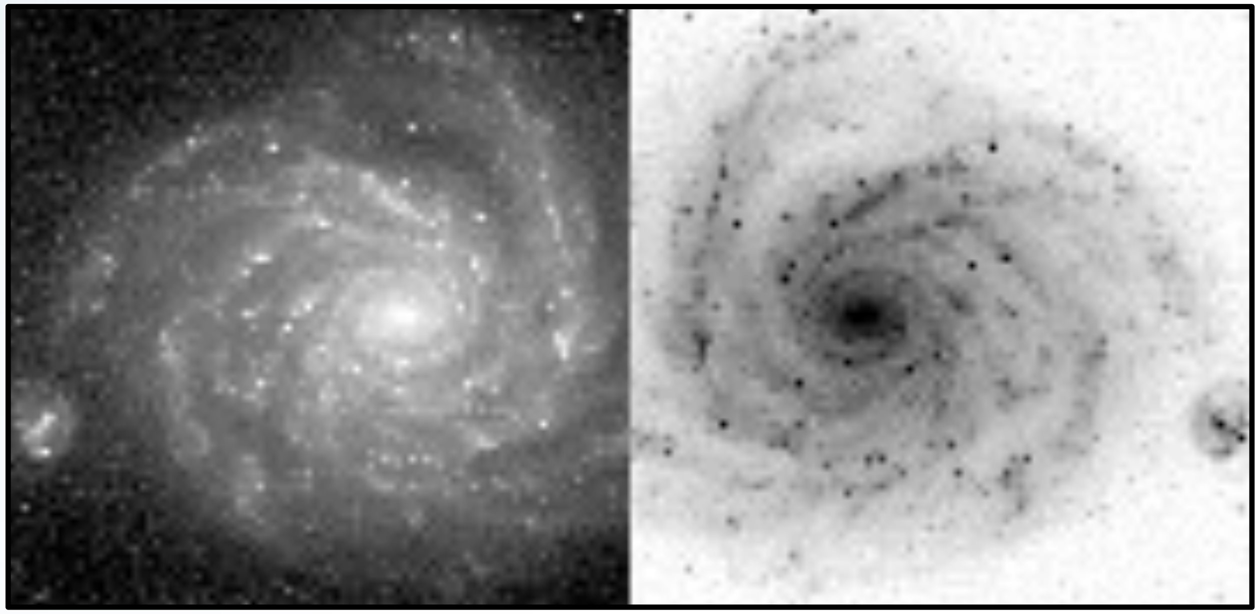
AD & ELENA AREA AND EXPERIMENTS



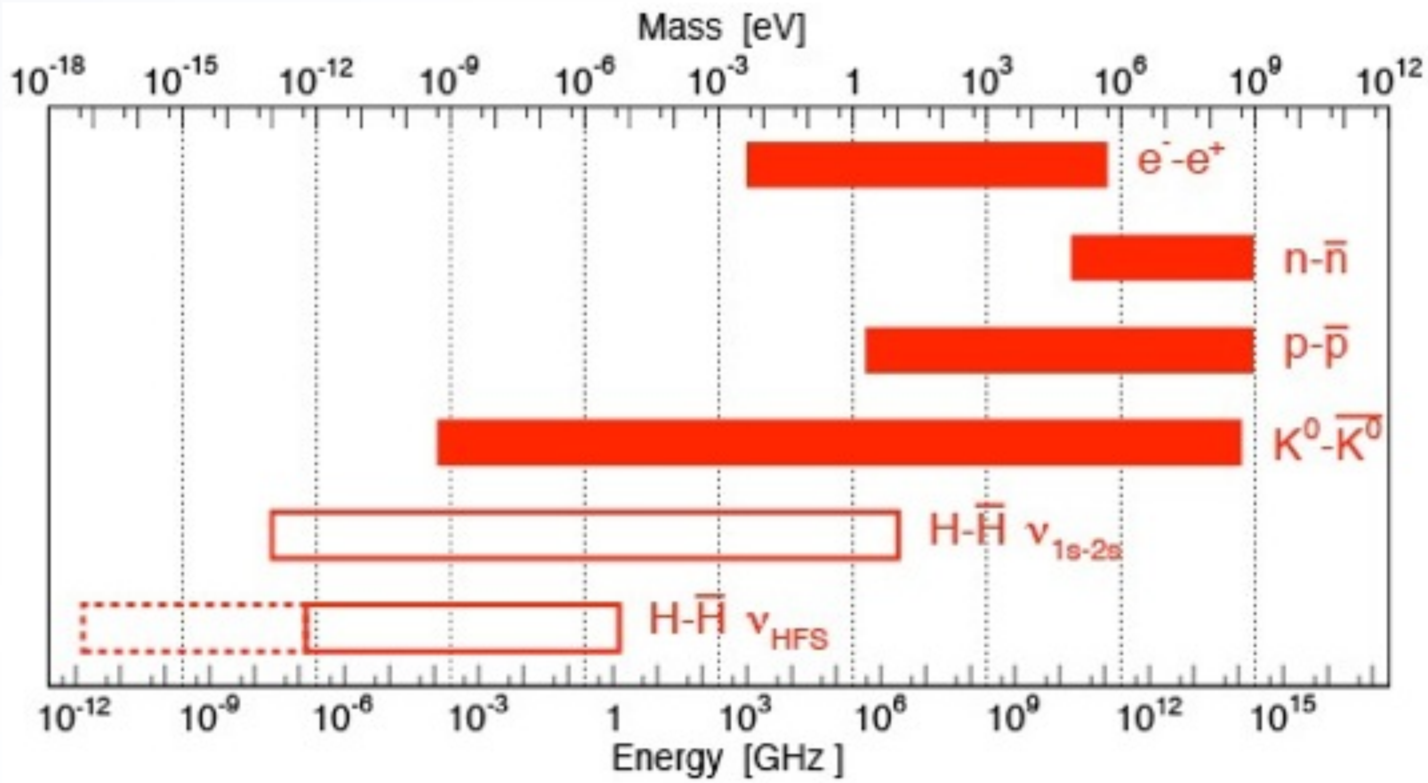
ELENA operation from 2017

Matter-antimatter symmetry

- Cosmological scale:
  - Asymmetry

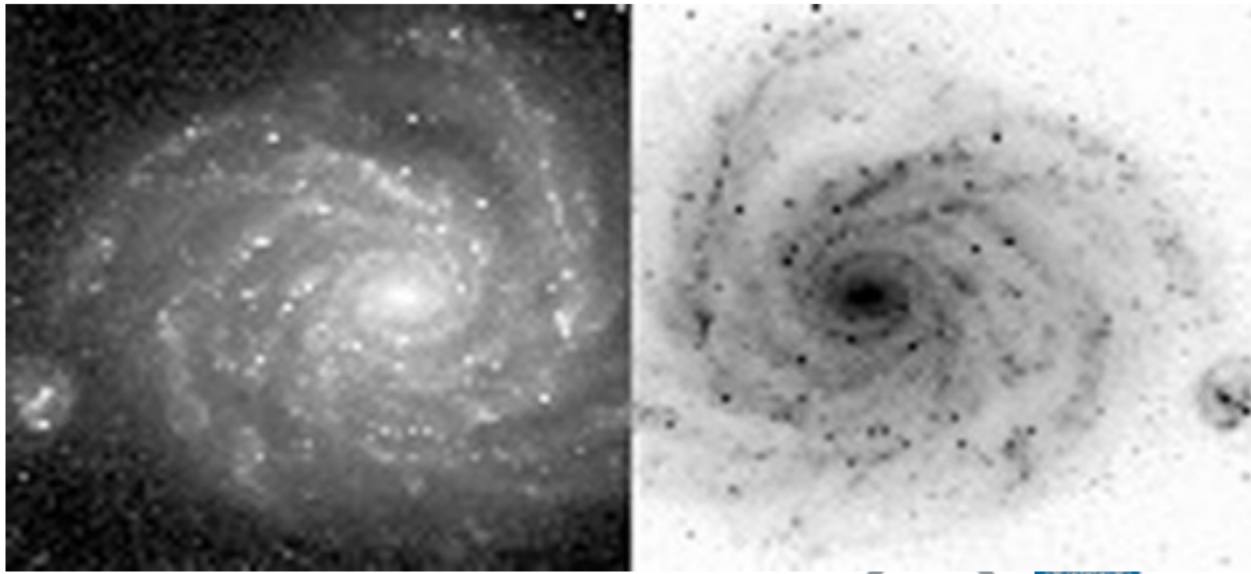


- CPT
  - Microscopic: symmetry?

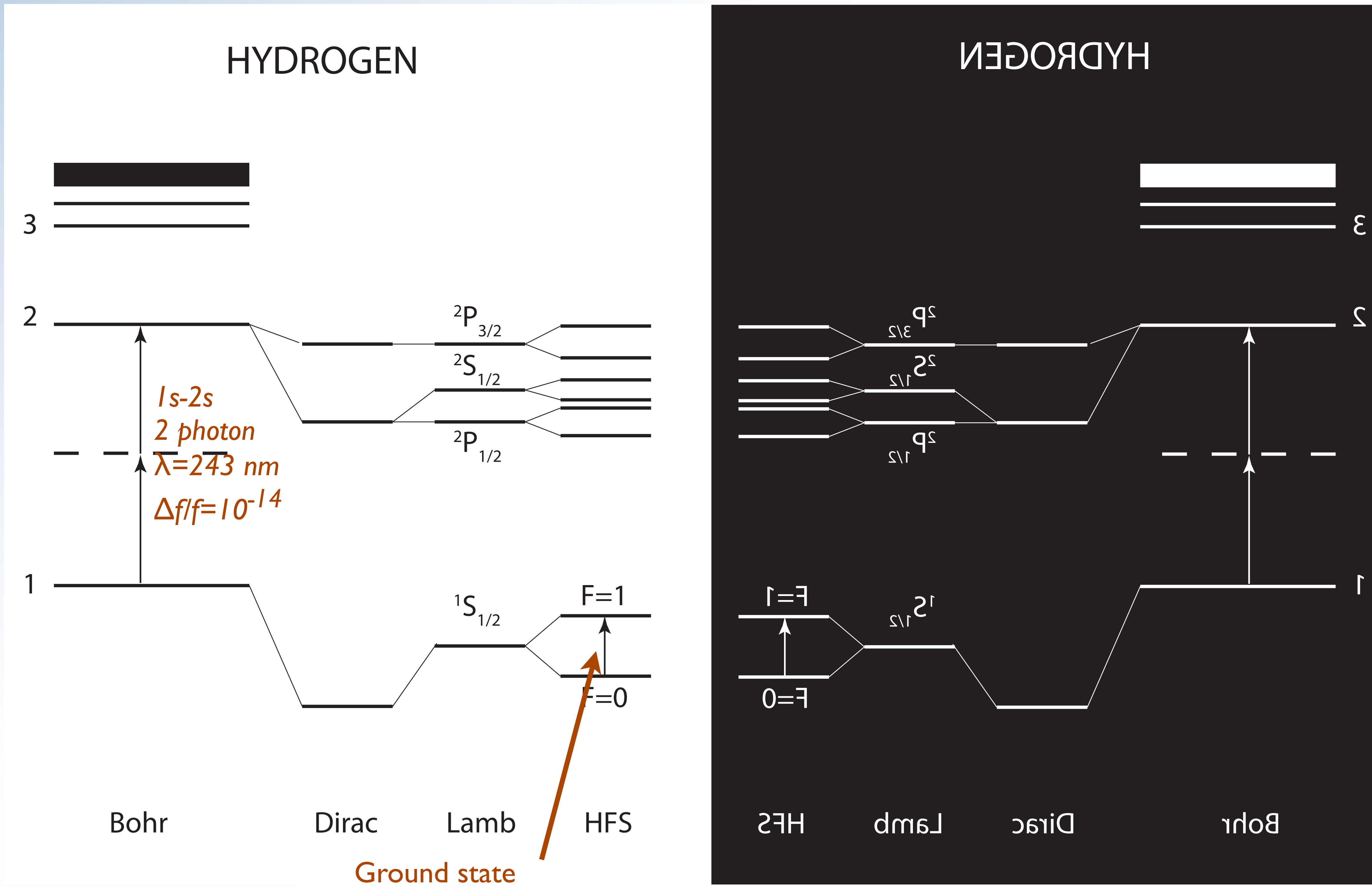


CPT SYMMETRY & COSMOLOGY

- mathematical theorem, not valid e.g. in string theory, quantum gravity
- possible hint: 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 CPV not large enough
  - Other source of baryon asymmetry?
    CPT non-conservation?



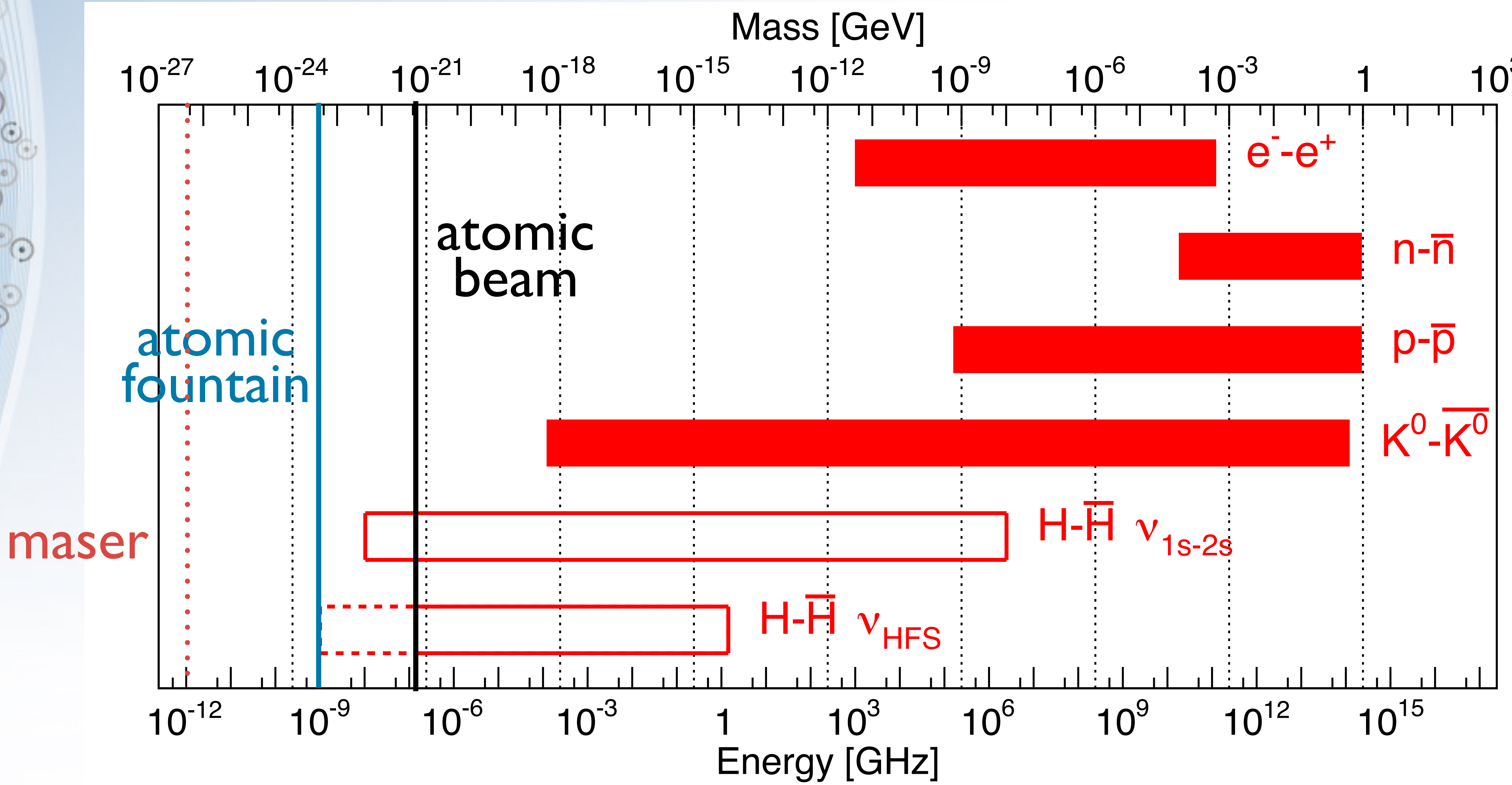
ANTIHYDROGEN SPECTROSCOPY



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

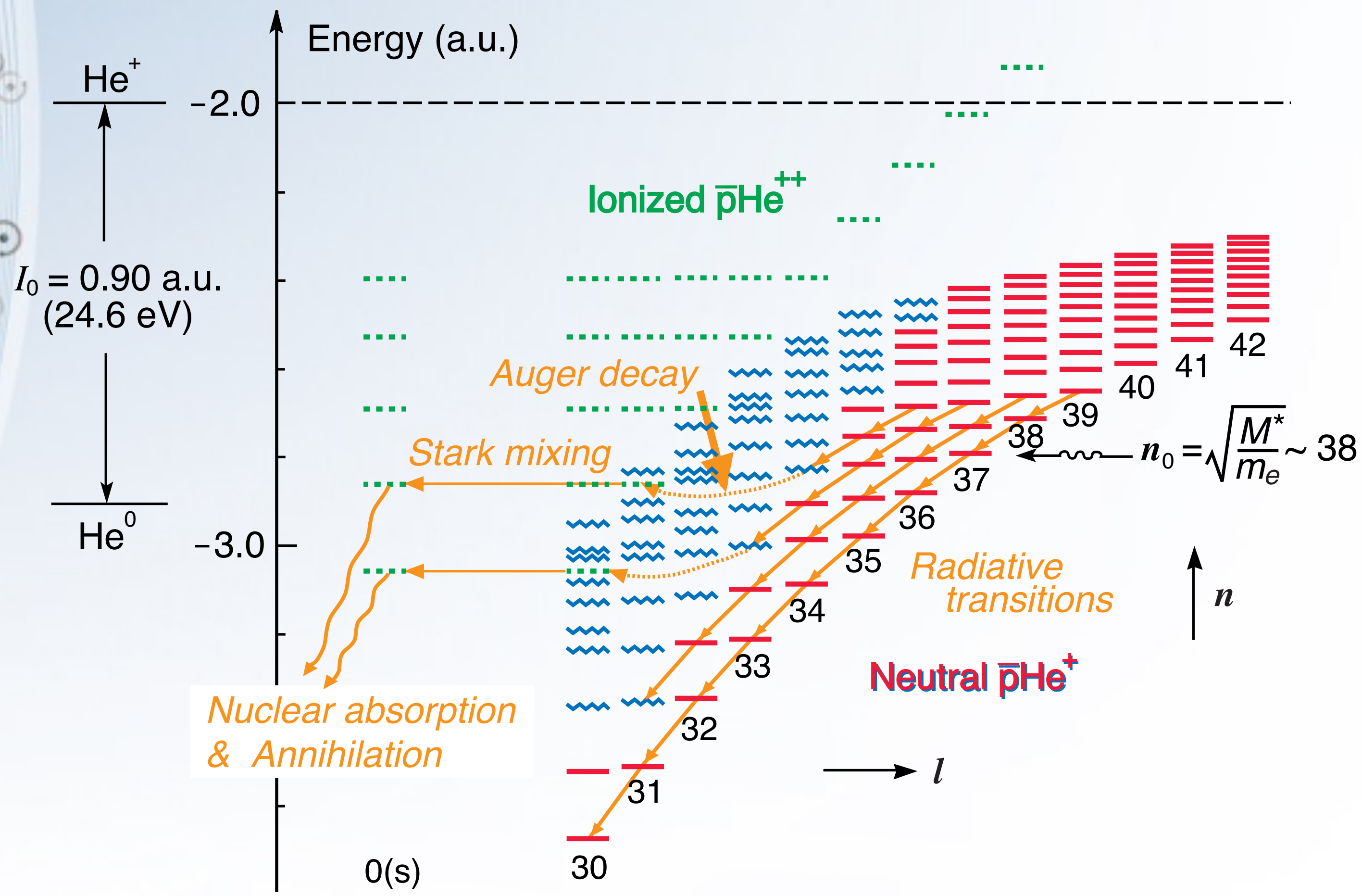
H·HFS

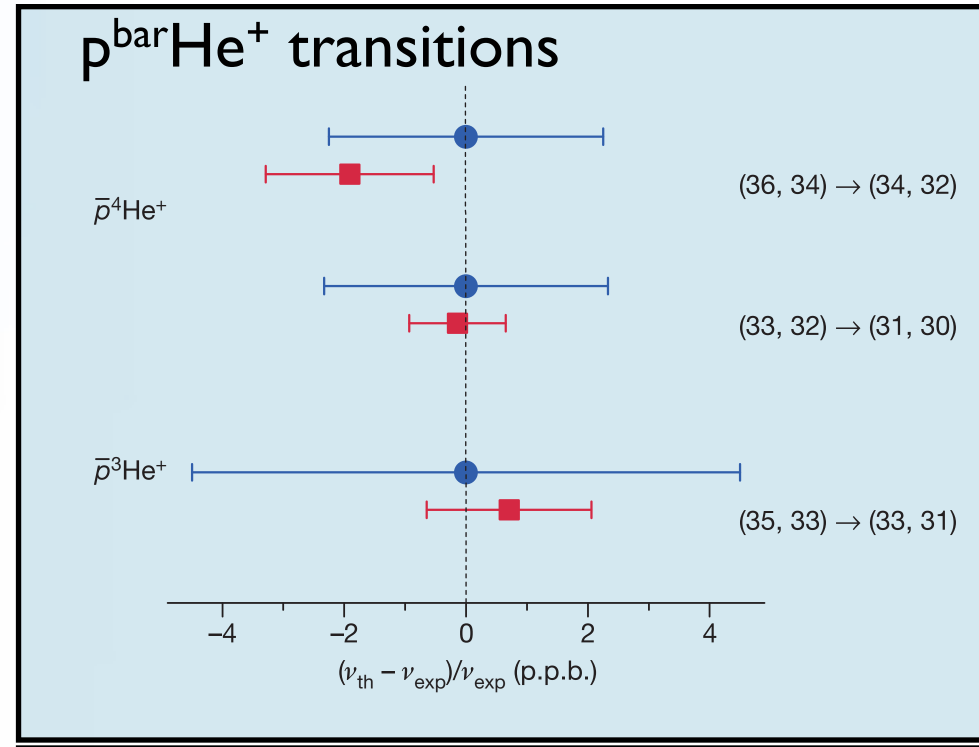
CPT TESTS - RELATIVE & ABSOLUTE PRECISION

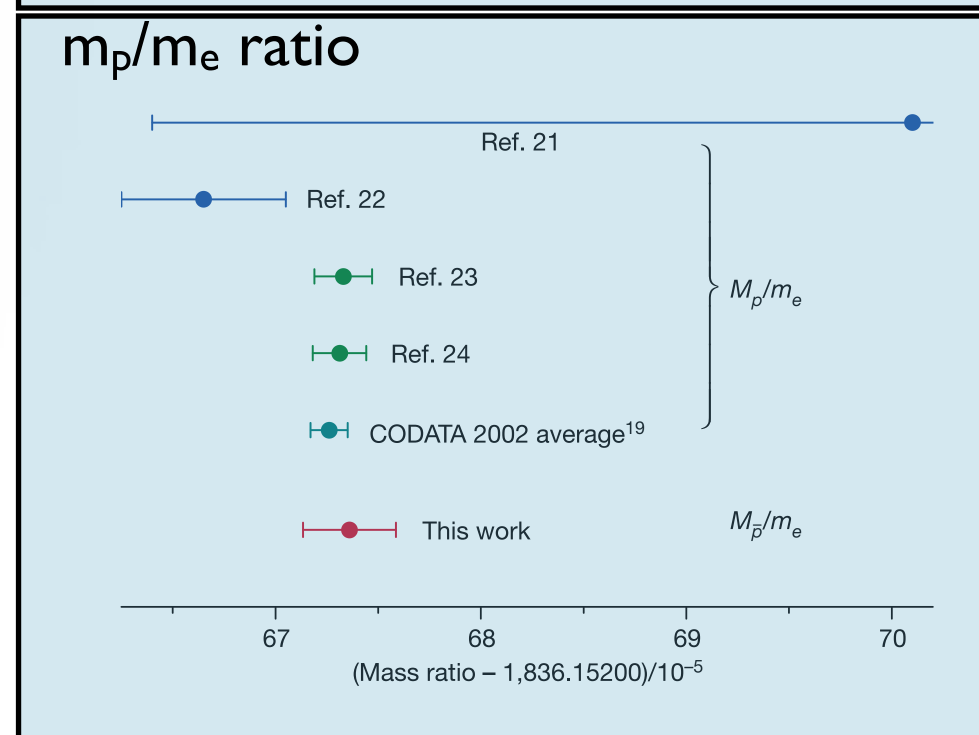


- ATOMIC PHYSICS EXPERIMENTS, ESPECIALLY ANTIHYDROGEN OFFER THE MOST SENSITIVE EXPERIMENTAL VERIFICATIONS OF CPT

ANTIPROTONIC HELIUM LASER SPECTROSCOPY



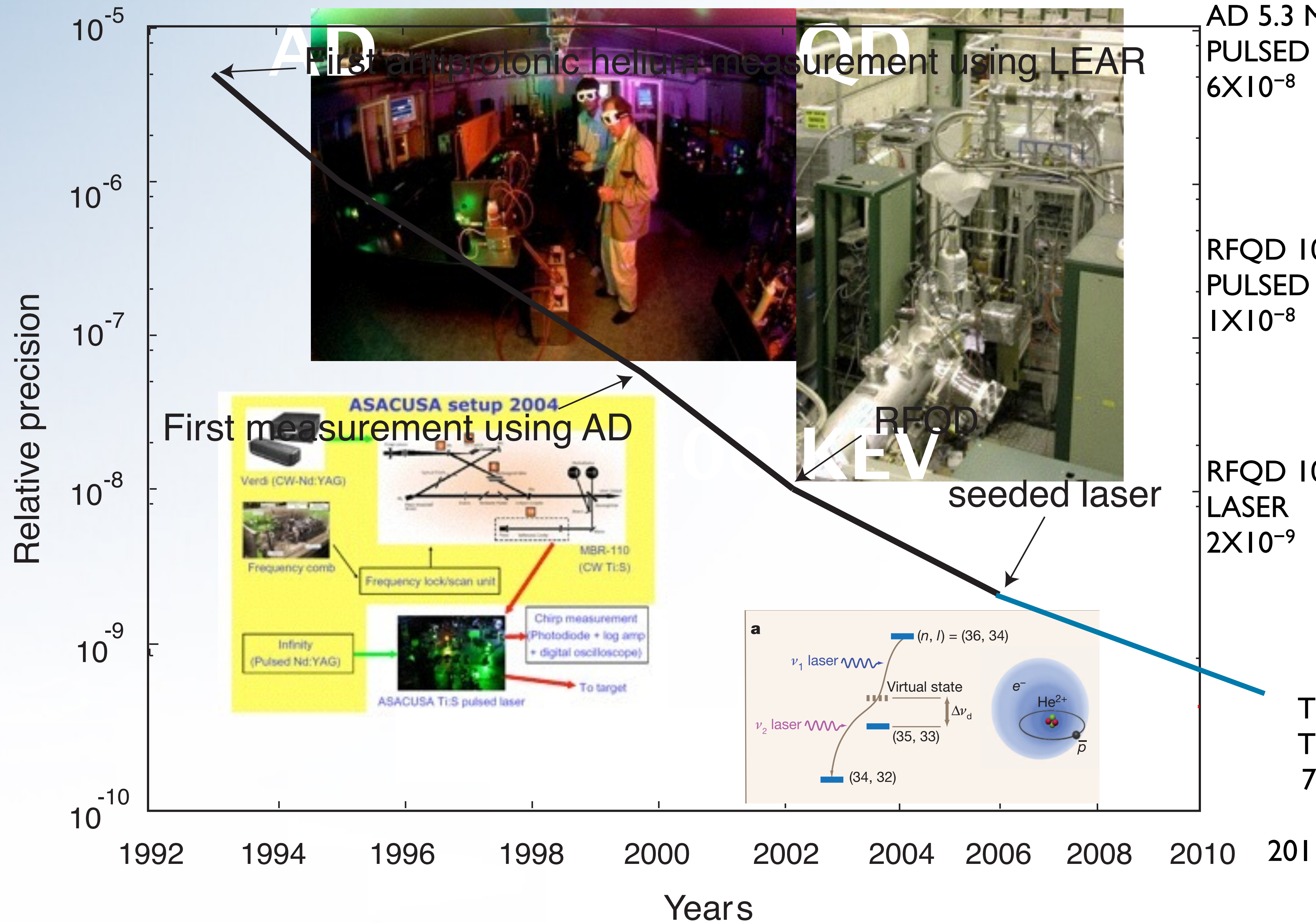




M. Hori et al. Nature 475, 484 (2011)
listed in PDG
included in CODATA as proton value

$m_{\bar{p}}/m_e$=1,836.1526736(23)
$(m_{\bar{p}} - m_p)/\text{av.} < 7\times10^{-10}$

PROGRESS IN ATOMCULE SPECTROSCOPY



AD 5.3 MEV,
PULSED DYE LASER
6×10^{-8}

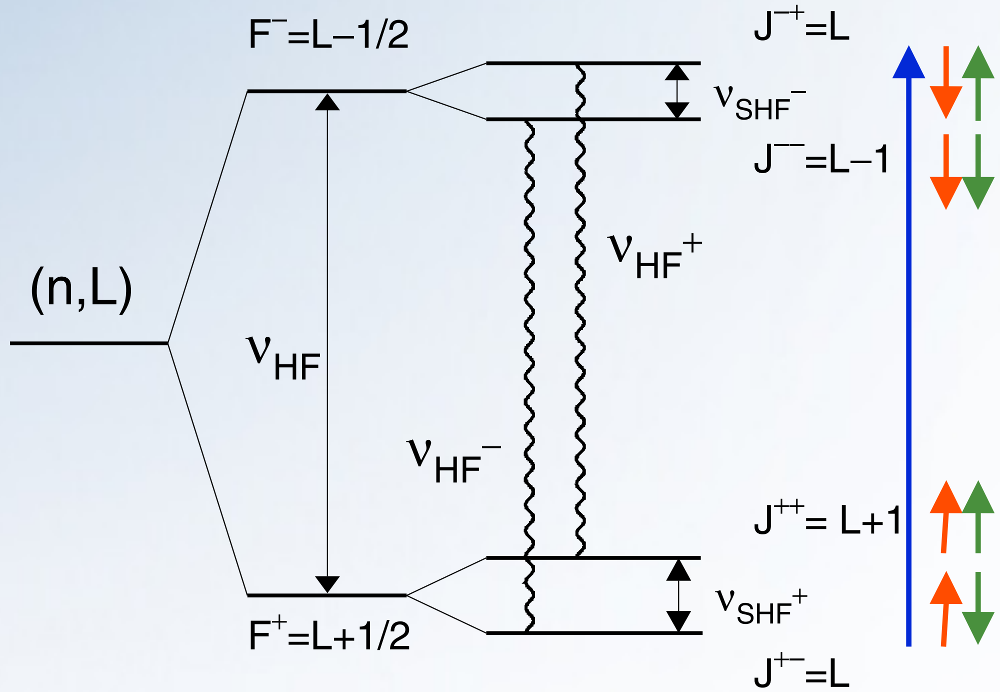
RFQD 100 KEV,
PULSED DYE LASER
1×10^{-8}

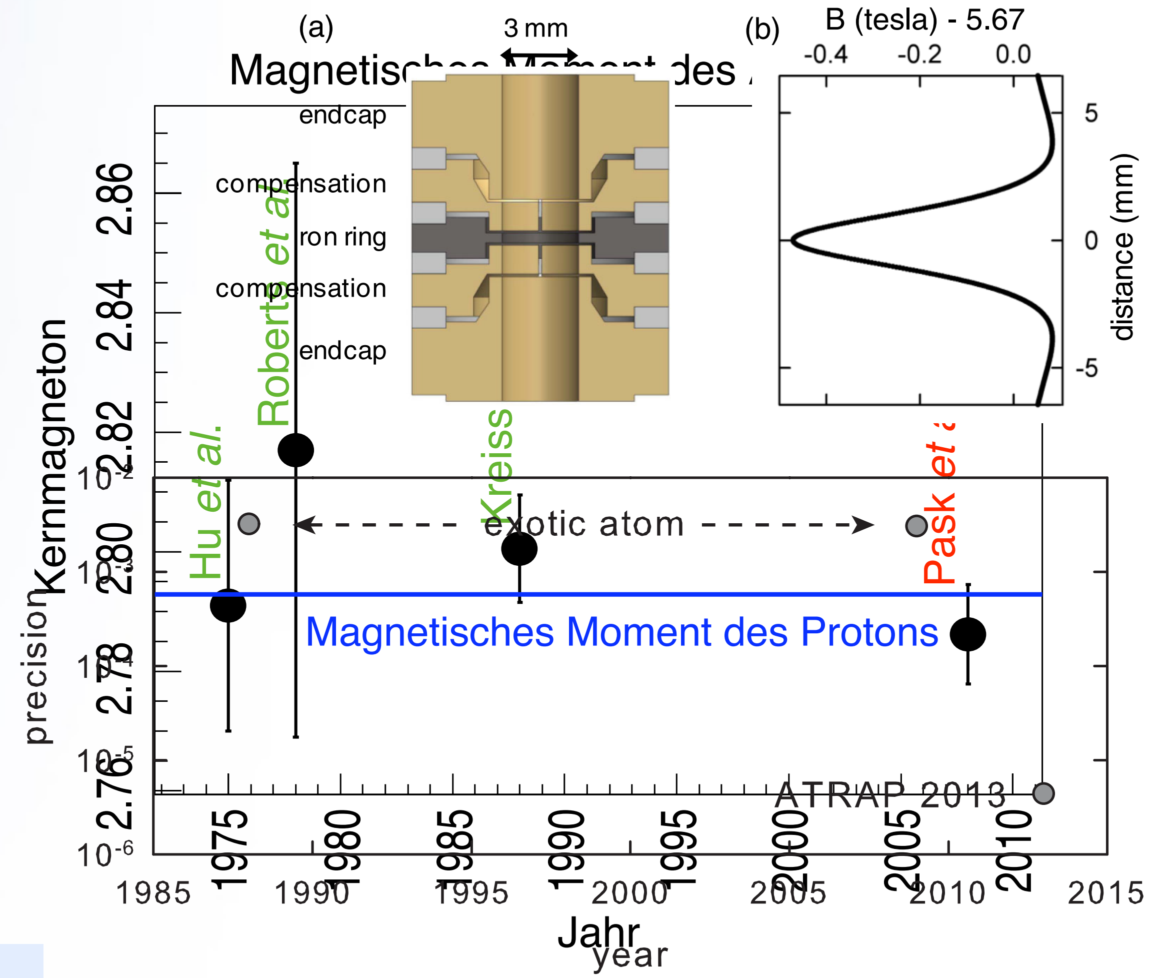
RFQD 100 KEV, SEEDED LASER
2×10^{-9}

TWO-PHOTON TRANSITIONS
7×10^{-10}

MAGNETIC MOMENT OF $\bar{p}$

Hyperfine structure of $\bar{p}He^+$





ASACUSA: Comparison Theory-Experiment

$$\mu_s^{\bar{p}} = -2.7862(83)\mu_N$$

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

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

Atrap Collaboration

Penning Trap

Physical Review Letters 110,130801 (2013)

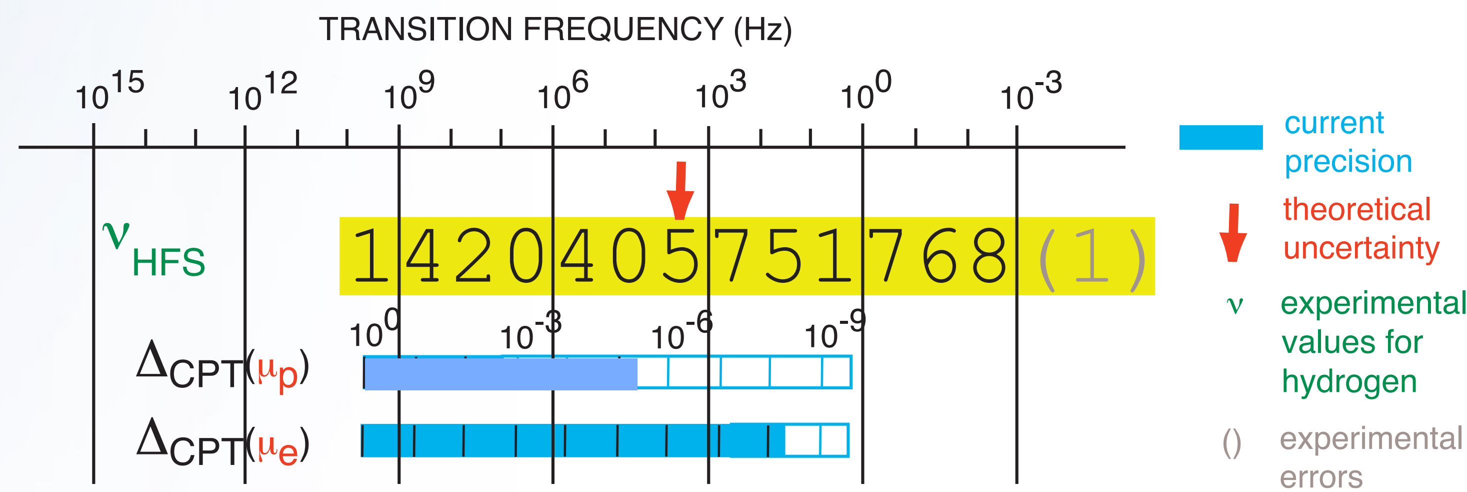
$$\mu_{\bar{p}}/\mu_N = -2.792\,845 \pm 0.000\,012 \qquad [4.4 \text{ ppm}].$$

$$\mu_{\bar{p}}/\mu_p = -0.9999992 \pm 0.0000044 \qquad [4.4\,\text{ppm}]$$

Ground-State Hyperfine Splitting of H/$\bar{\text{H}}$

- spin-spin interaction positron - antiproton
- Leading: Fermi contact term

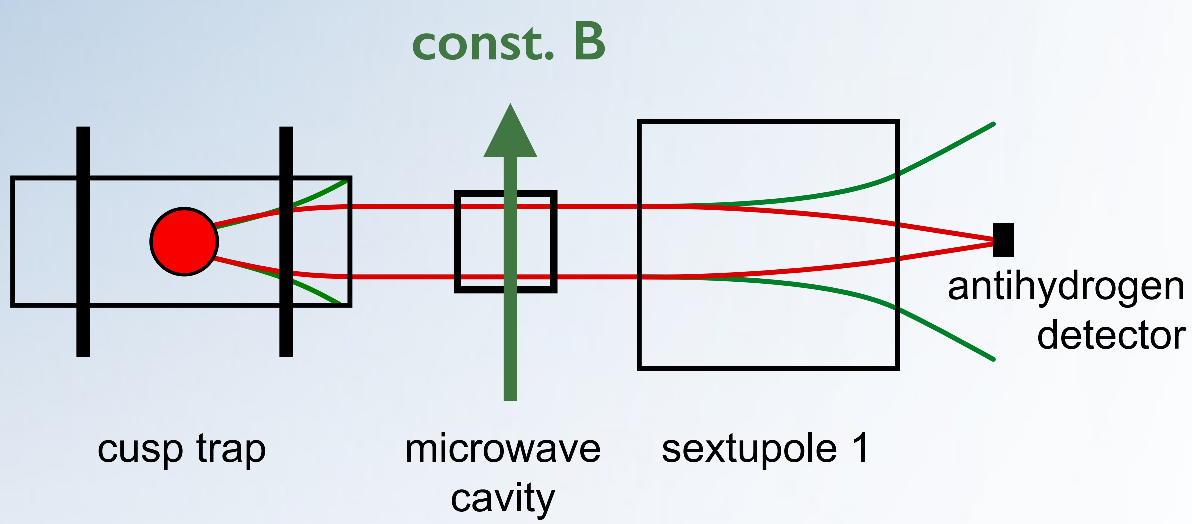
$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 c\, Ry,$$

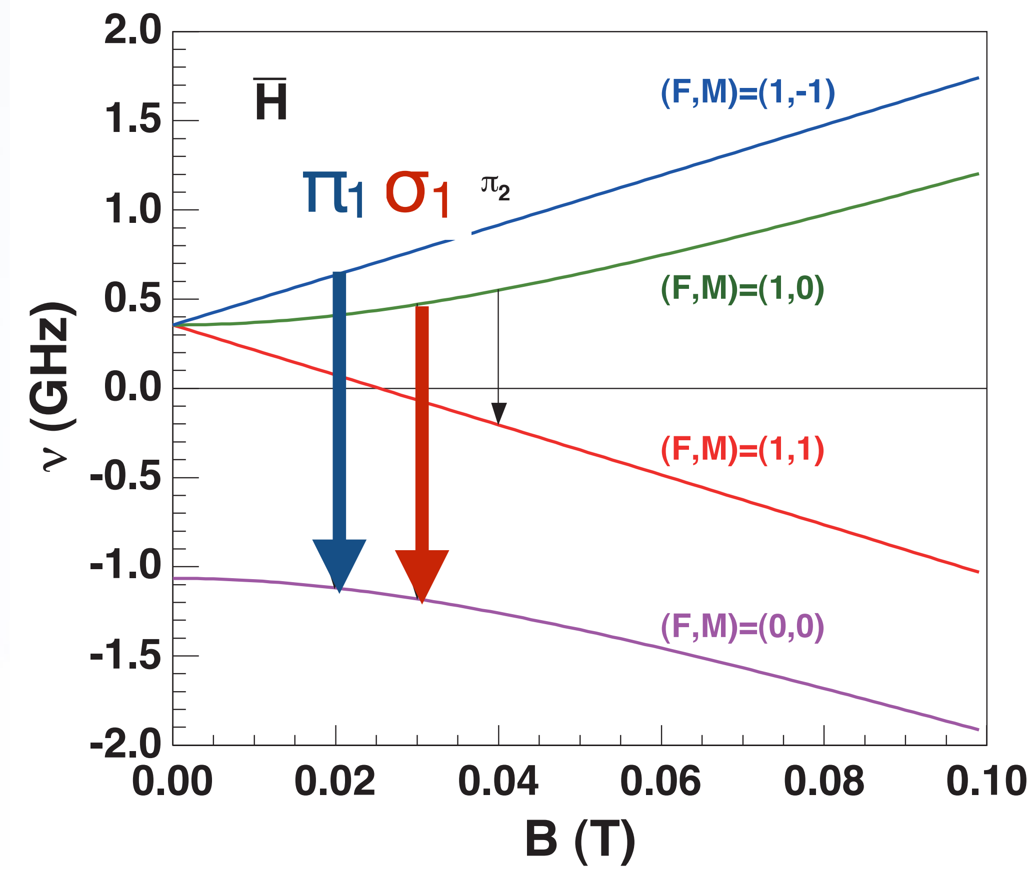


- magnetic moment of $\bar{p}$
  - previously known to 0.3%, 2012 Gabrielse Penning trap 4.4 ppm PRL 110,130801 (2013)
- H: deviation from Fermi contact term: −32.77±0.01 ppm
  - finite electric & magnetic radius (Zemach corrections): −41.43±0.44 ppm
  - polarizability of p/$\bar{p}$ (g_1,g_2, *PRA 78, 022517 (2008)*): 1.88±0.64 ppm
  - remaining deviation th-exp: 0.86±0.78 ppm

$$\Delta\nu(\text{Zemach}) = \nu_F \frac{2Z\alpha m_e}{\pi^2}\int \frac{d^3p}{p^4}\left[\frac{G_E(p^2)G_M(p^2)}{1+\kappa} - 1\right]$$

HFS MEASUREMENT IN AN ATOMIC BEAM





- atoms evaporate - no trapping needed
- cusp trap provides polarized beam
- spin-flip by microwave
- spin analysis by sextupole magnet
- low-background high-efficiency detection of antihydrogen

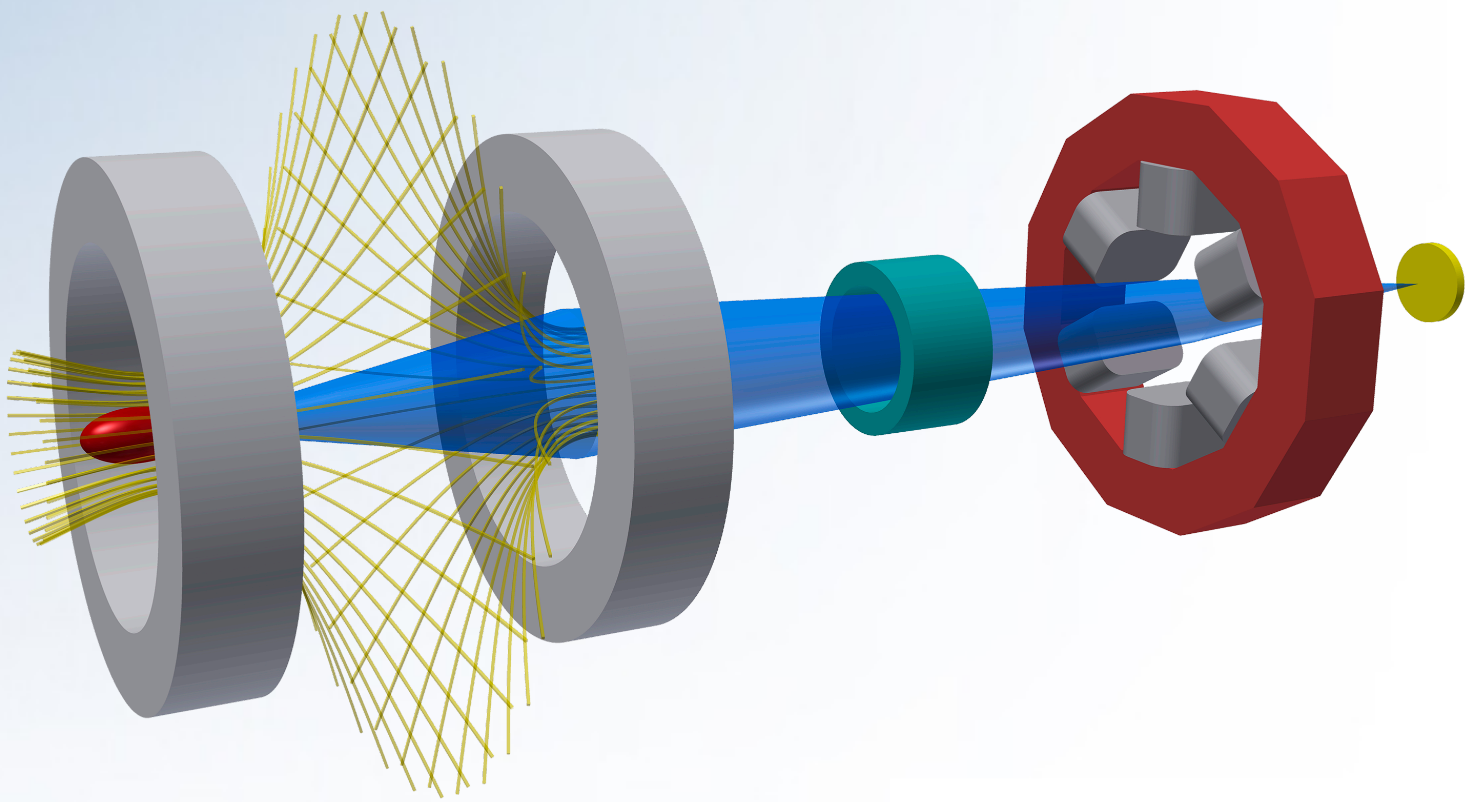
E.W. et al. ASACUSA proposal addendum CERN-SPSC 2005-002

achievable resolution

- better 10^{-6} for $T \leq 100$ K
- > 100 $\bar{H}$/s in 1S state into 4π needed
- event rate 1 / minute: background from cosmics, annihilations uptsreams

Polarized $\overline{\text{H}}$ beam from "CUSP"

- First antihydrogen production in 2010



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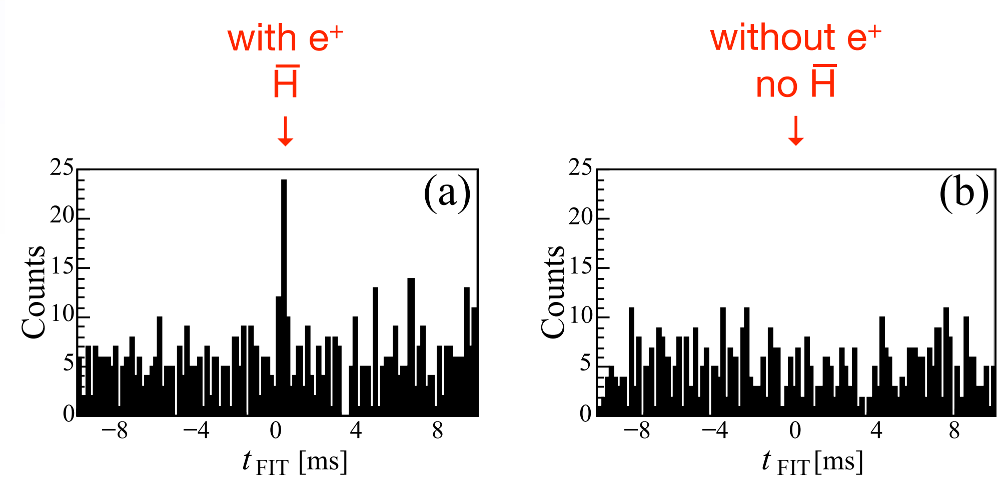
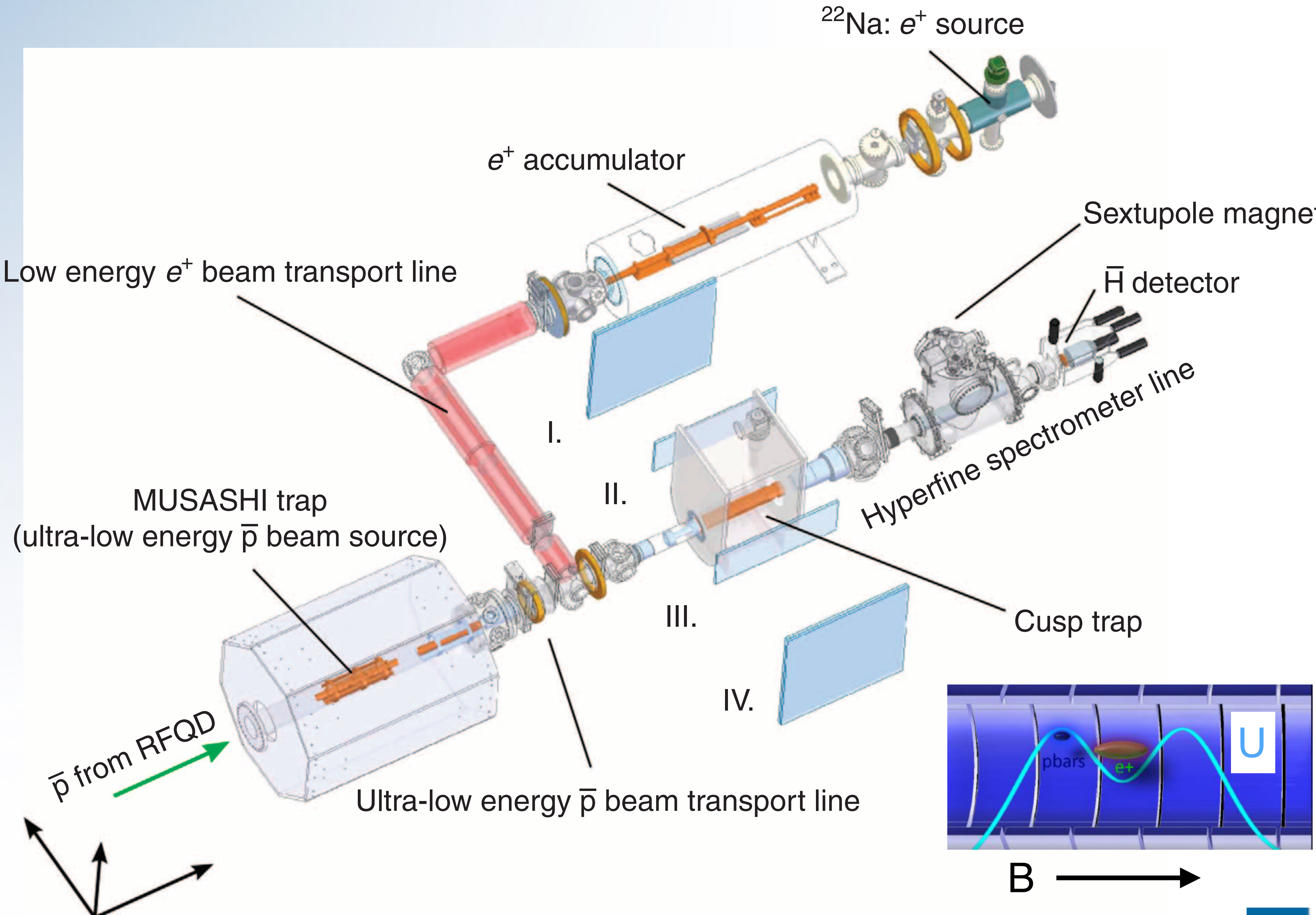
A. Mohri & Y. Yamazaki,
Europhysics Letters 63, 207 (2003).

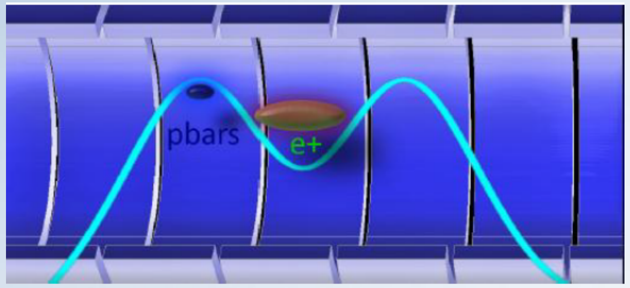
Y. Enomoto et al.
Phys. Rev. Lett 243401, 2010



ASACUSA $\overline{\text{H}}$ PRODUCTION



Recent results



- Background
  - e^- cooling of $\bar{p}$
  - mix e^- and $\bar{p}$
- Scheme I
  - e^- cooling of $\bar{p}$
  - mix e^+ and $\bar{p}$

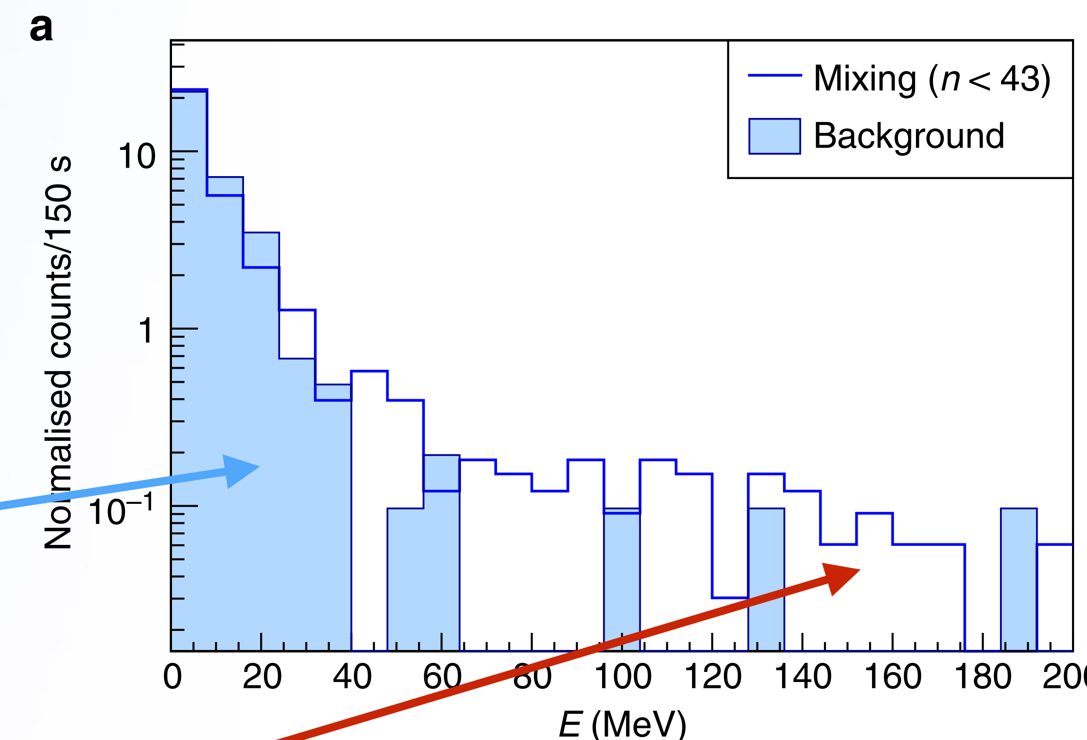


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—

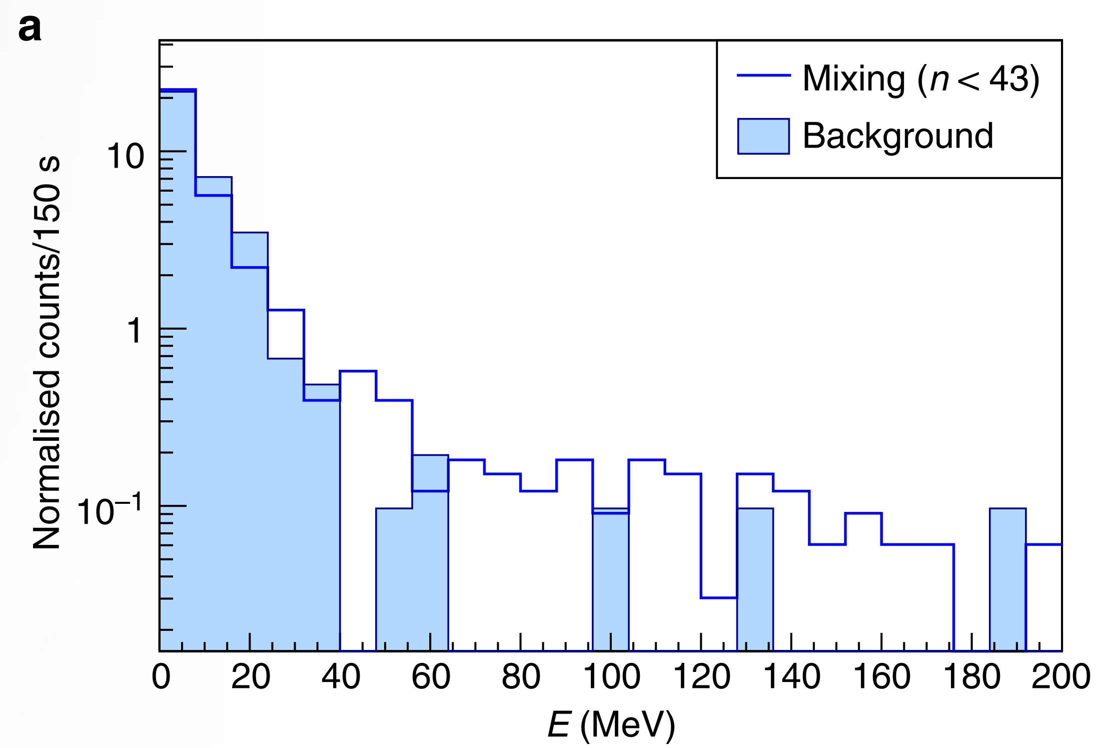
N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[5], M. Leali[6,7], C. Malbrunot[4,†], V. Mascagna[6,7], O. Massiczek[4], K. Michishio[8], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[9], C. Sauerzopf[4], K. Suzuki[4], M. Tajima[1], H.A. Torii[1], L. Venturelli[6,7], B. Wünschek[4], J. Zmeskal[4], N. Zurlo[6], H. Higaki[9], Y. Kanai[3], E. Lodi Rizzini[6,7], Y. Nagashima[8], Y. Matsuda[1], E. Widmann[4] & Y. Yamazaki[1,3]

NATURE COMMUNICATIONS | 5:3089 | DOI: 10.1038/ncomms4089 | www.nature.com/naturecommunications

$n \lesssim 43$ $n \lesssim 29$

Recent results

- $\overline{H}$ beam observed with 5σ significance
  - n≲43 (field ionization)
  - 6 events / 15 min
- significant fraction in lower n
  - n≲29: 3σ
  - 4 events / 15 min
  - τ ~ few ms



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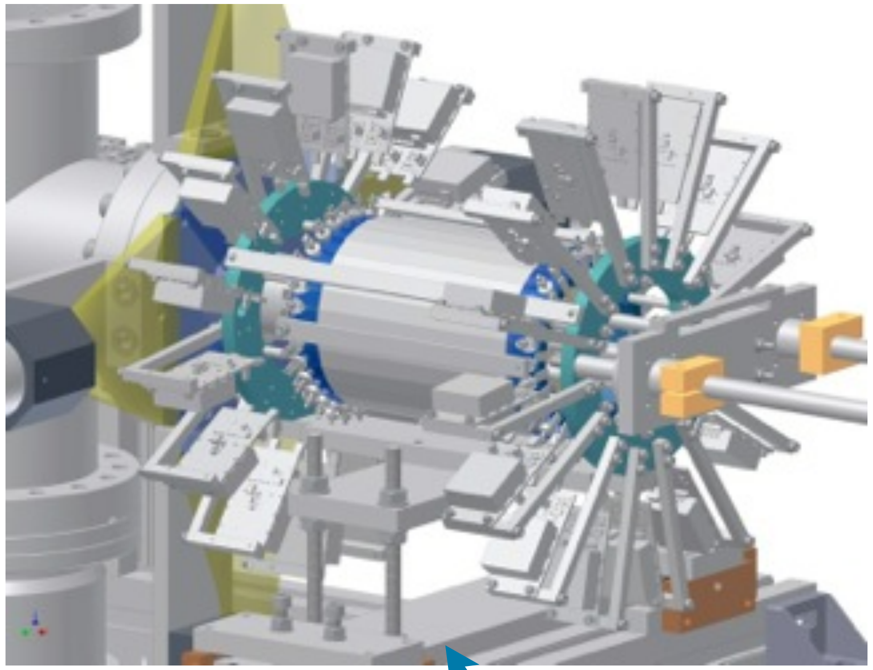
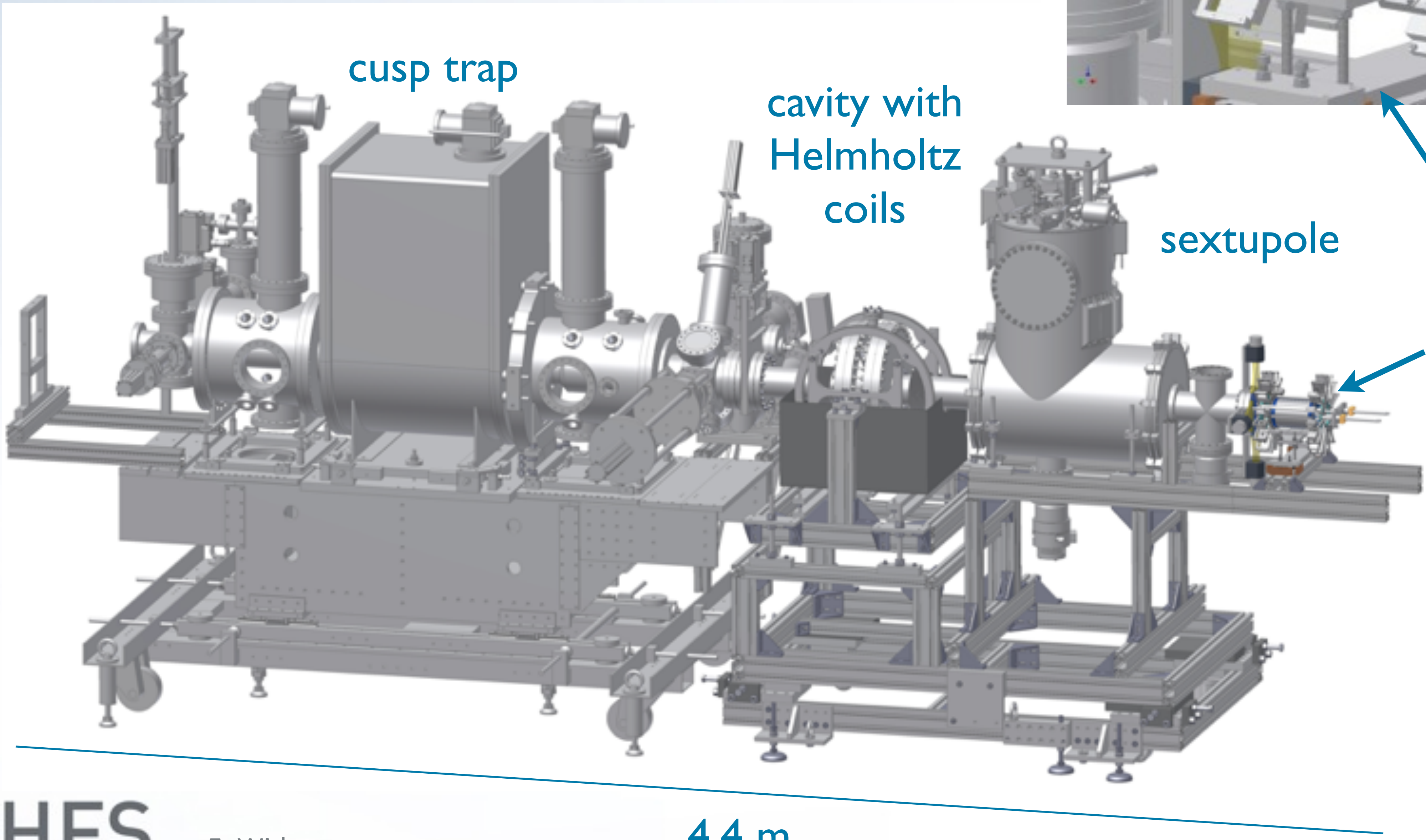
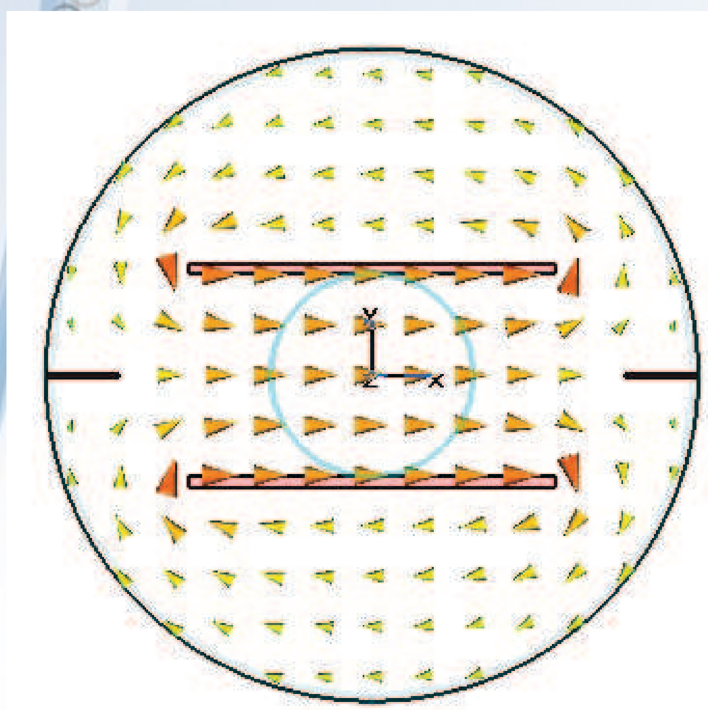
$\bar{H}$ HFS BEAM LINE 2012



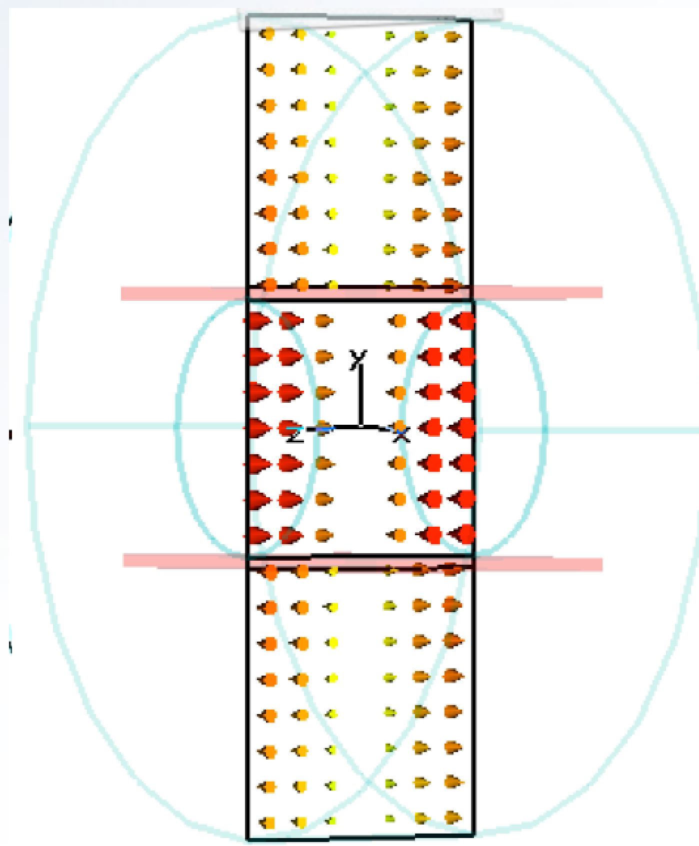


SPIN-FLIP RESONATOR

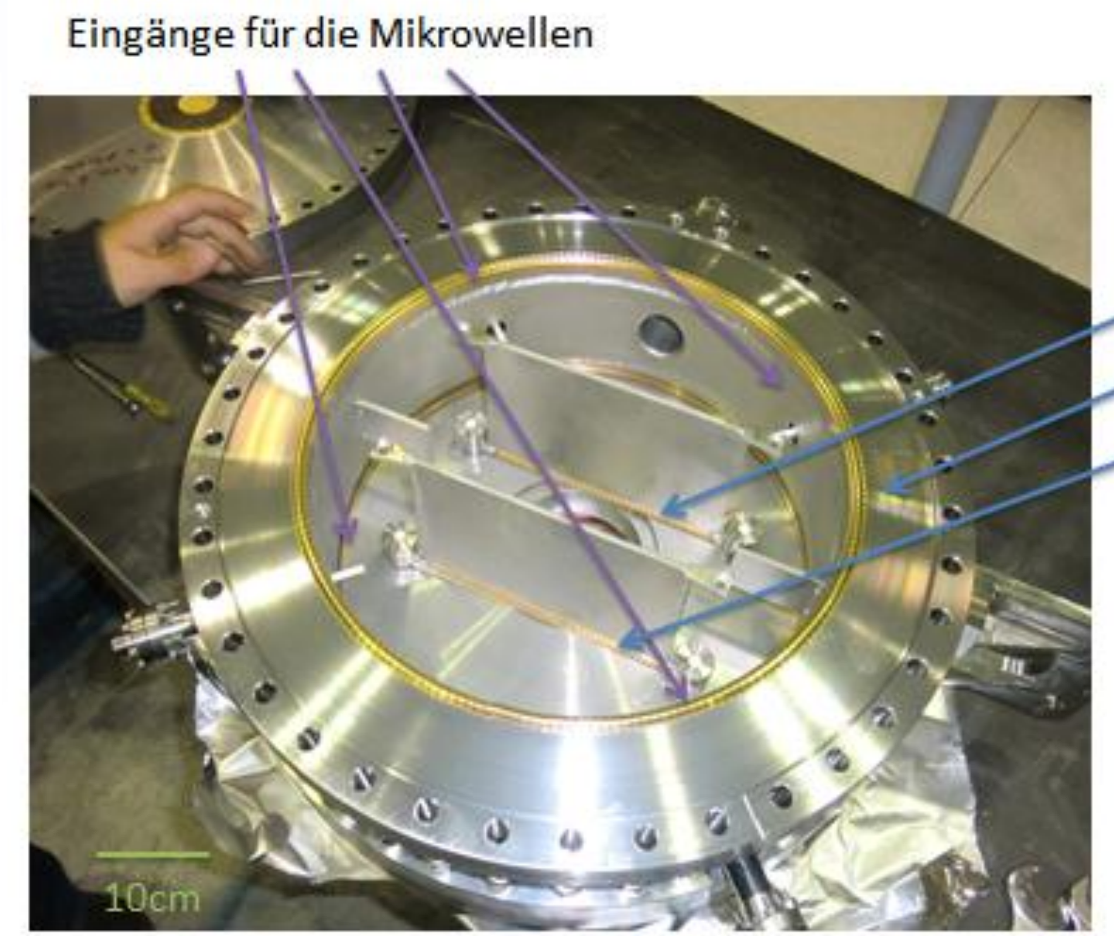
- f = 1.420 GHz, Δf = few MHz, ~ W power
- challenge: homogeneity over 10x10x10cm^3@ λ=21cm
- solution: strip line



transverse field: homogeneous



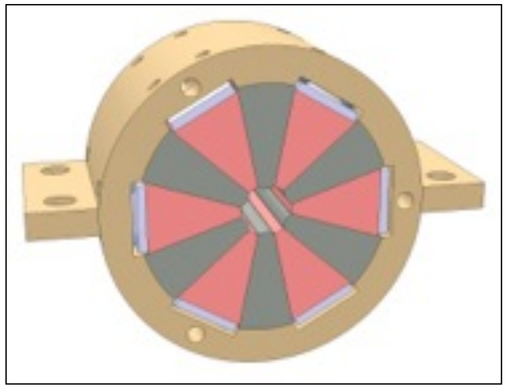
longitudinal field: cos(z)

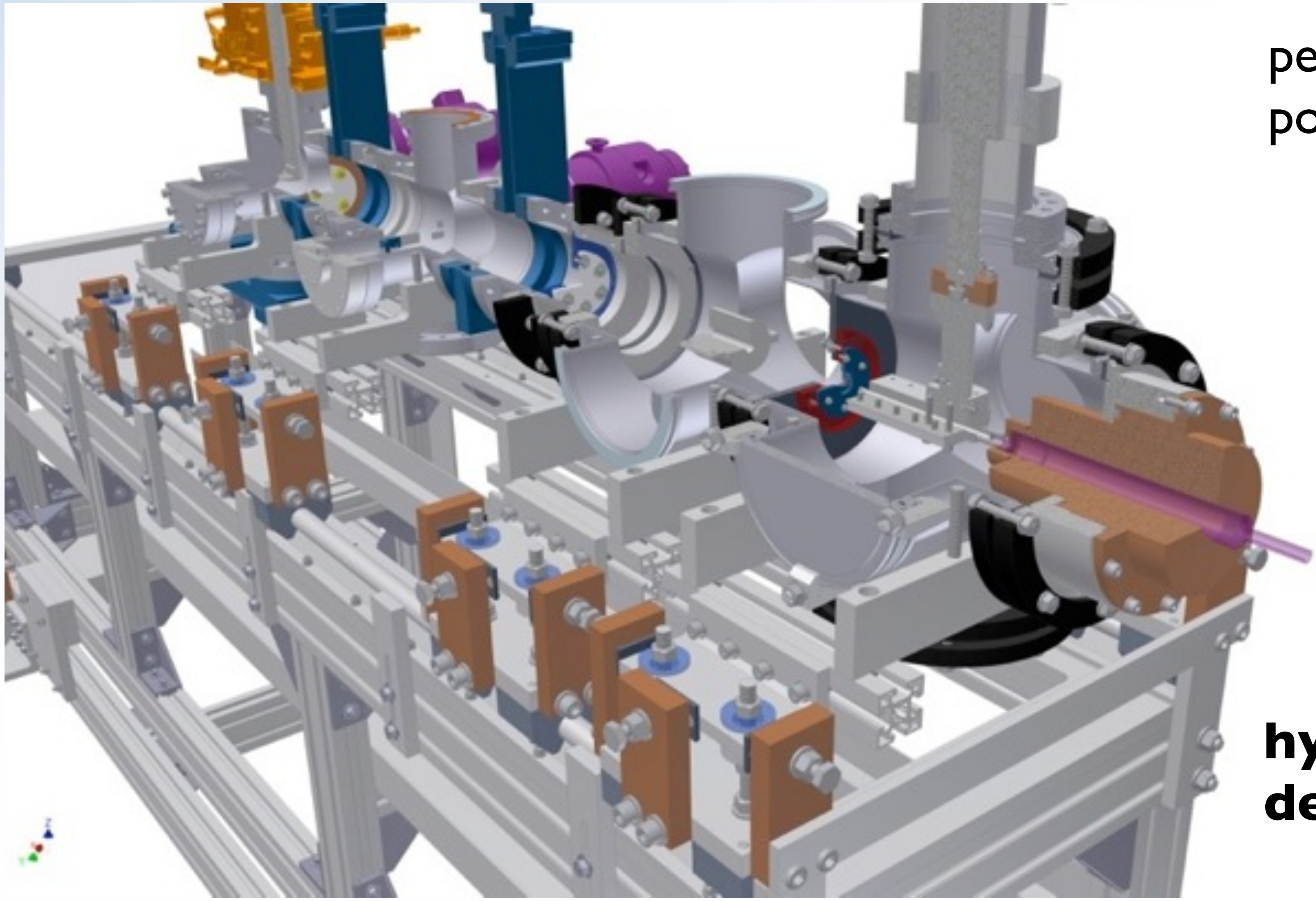


RF cavity

SETUP TESTING DURING LS1

Polarized cold hydrogen beam:
•Source of atomic hydrogen (microwave discharge)
•Permanent sextupoles create polarized hydrogen beam
•QMS detect GS hydrogen
•Choppers connected to a lock-in amplifier for noise reduction



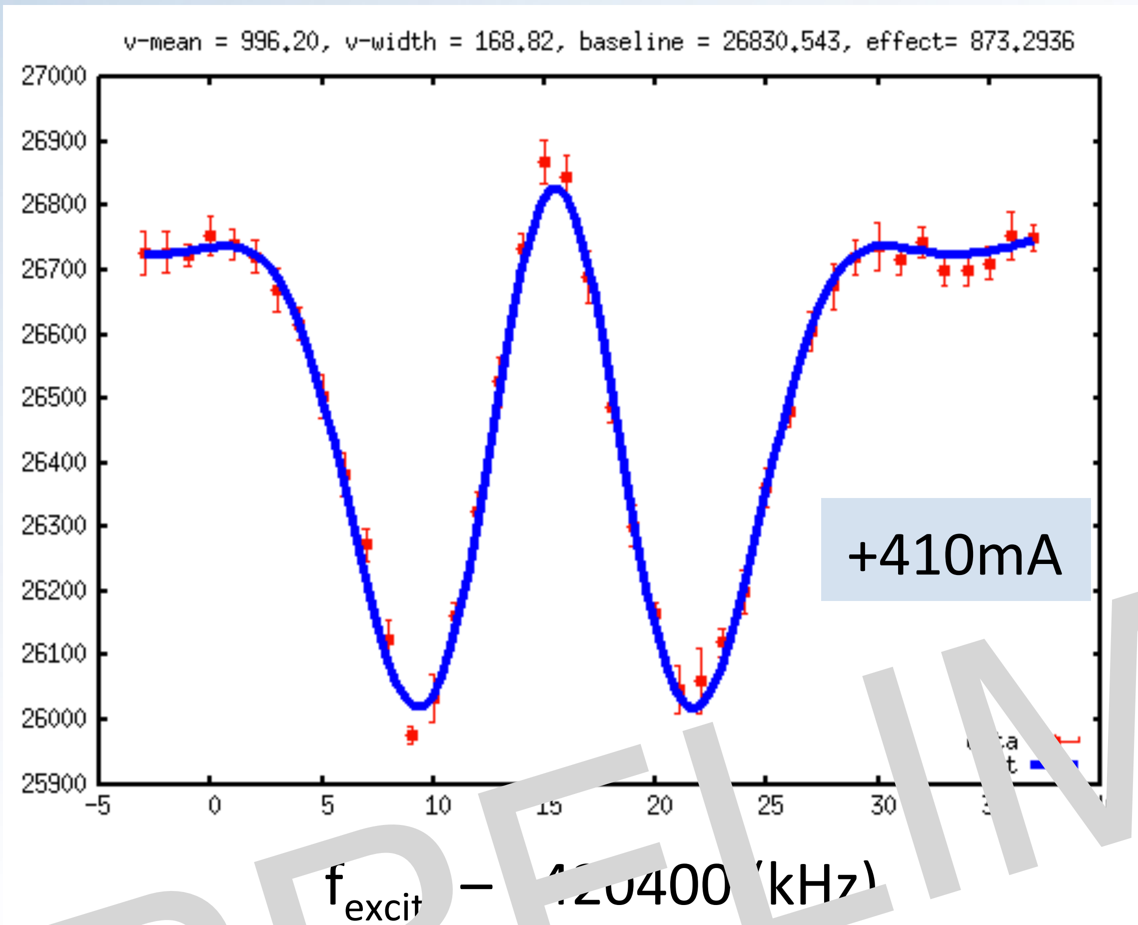


permanent sextupole for initial polarization developed at CERN
1.4 T integrated field
10mm inner diameter
Permendur/permanent magnet

hydrogen beamline developed at SMI

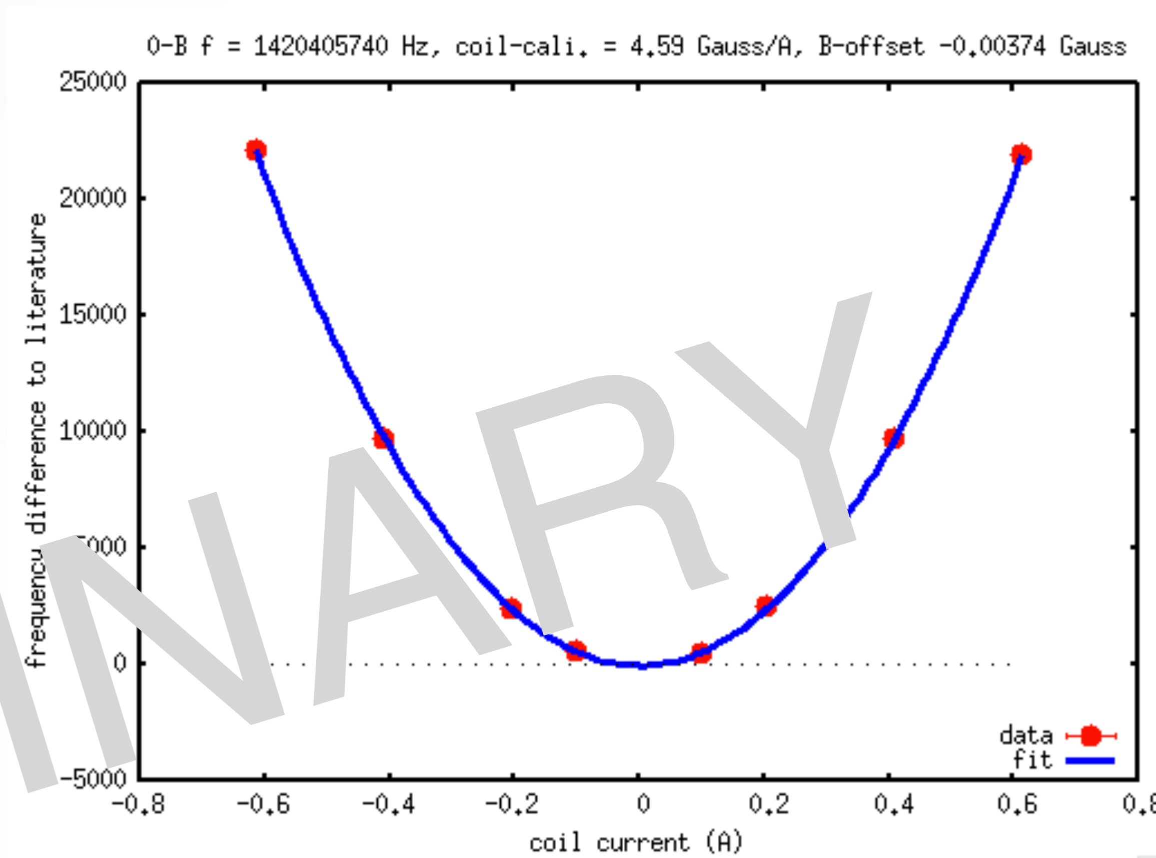
CURRENT PRECISION

Individual scans



error ~30 ppb

B field scan



f_{meas} = 1420405740 +- 24 Hz → 1.7e-8

f_{lit} = 1420405751.7667 Hz → Δf = 12 Hz

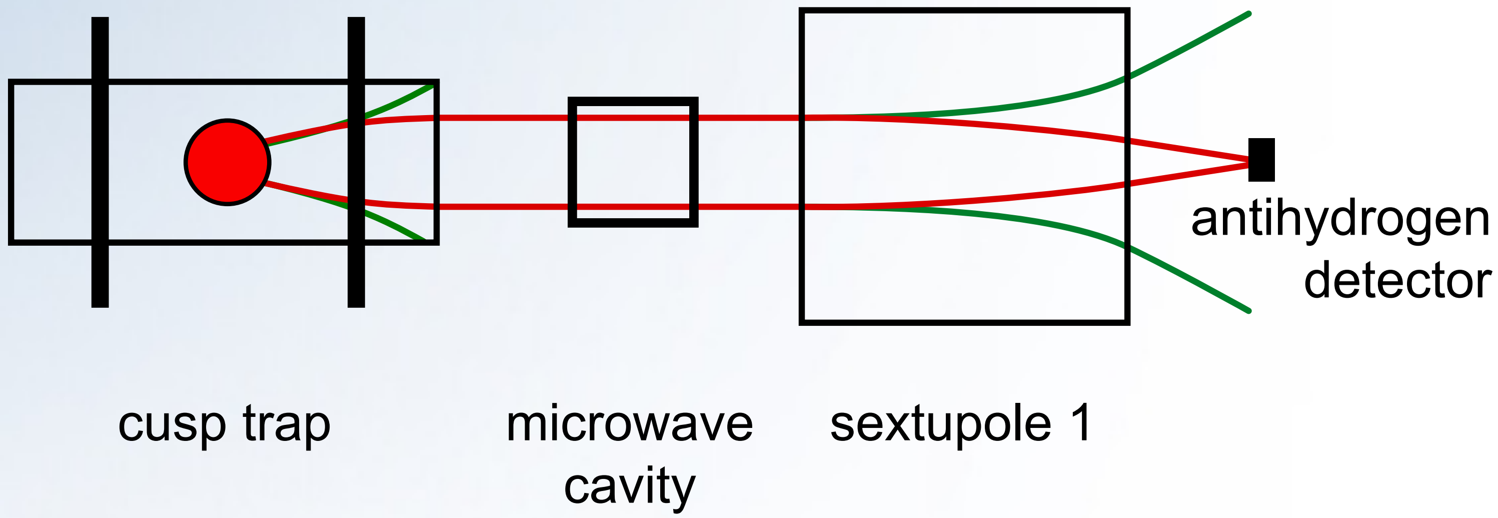
error ~20 ppb

Δ_{lit} ~ 8 ppb

PRELIMINARY

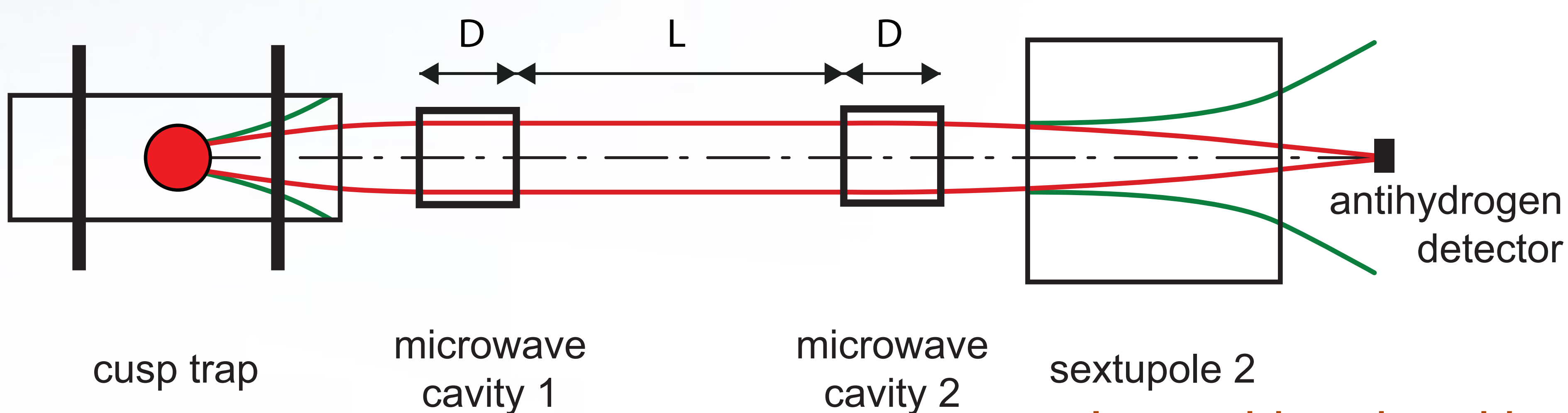
EXPERIMENTS IN AN ATOMIC BEAM

- Phase 1 (ongoing): Rabi method



$\Delta\nu/\nu \sim 10^{-7}$

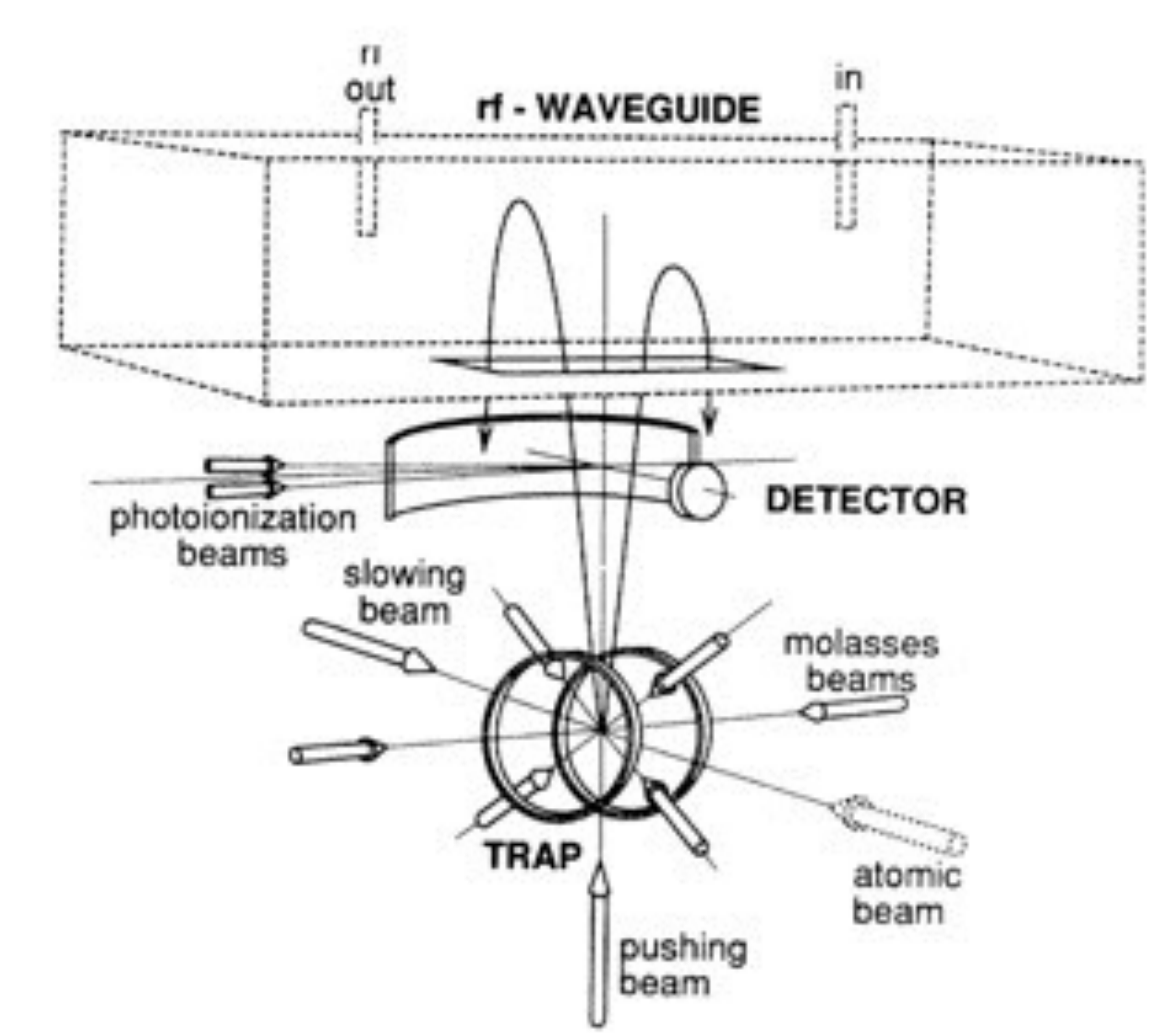
- Phase 2: Ramsey separated oscillatory fields



Linewidth reduced by D/L

(FAR) FUTURE EXPERIMENTS

- PHASE 3: TRAPPED $\bar{H}$
  - Hyperfine spectroscopy in an atomic fountain of antihydrogen
  - needs trapping and laser cooling outside of formation magnet
  - slow beam & capture in measurement trap
  - Ramsey method with d=1m
    - $\Delta f \sim 3$ Hz, $\Delta f/f \sim 2 \times 10^{-9}$



M. Kasevich, E. Riis, S. Chu, R. Devoe, Prl 63, 612–615 (1989)

Summary

- Antiprotonic helium allows best $\bar{p}$ mass determination
- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry
- First "beam" of $\bar{H}$ observed in field-free region
- Next steps: optimize rate, check polarization, velocity
- HFS measurement of H beam ~10^{-8} achieved
- Time scale of precision experiments is 5-10 years

ERC Advanced Grant 291242
HbarHFS
www.antimatter.at
PI EW