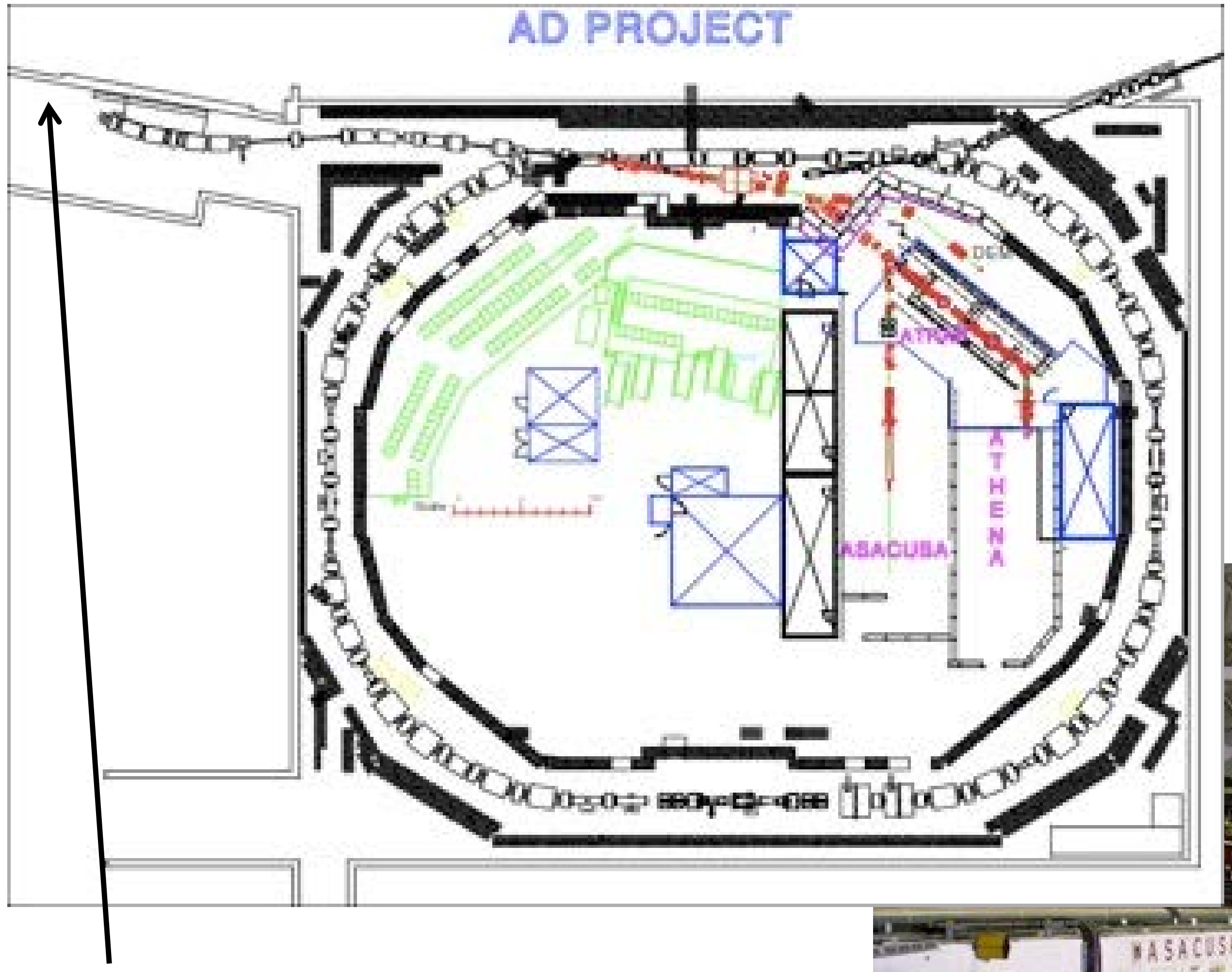
Precision measurement of antihydrogen properties at CERN-AD/ELENA

E. Widmann
Stefan Meyer Institute, Vienna

FFK-2019 Tihany, Hungary 10 Jun 2019

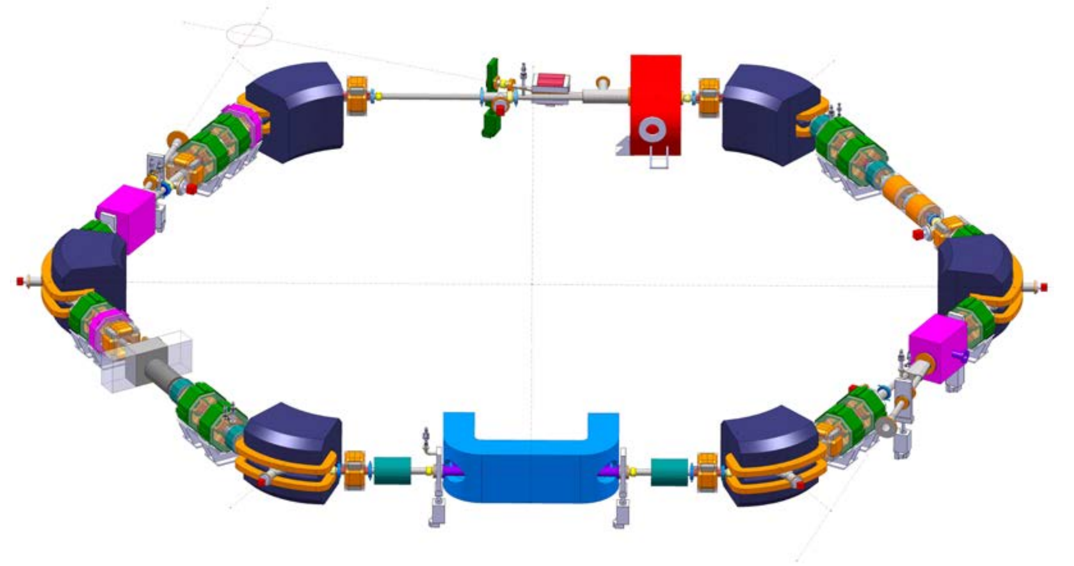
Antiproton Decelerator @ CERN

- All-in-one machine:
  - 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 / 85–120 seconds



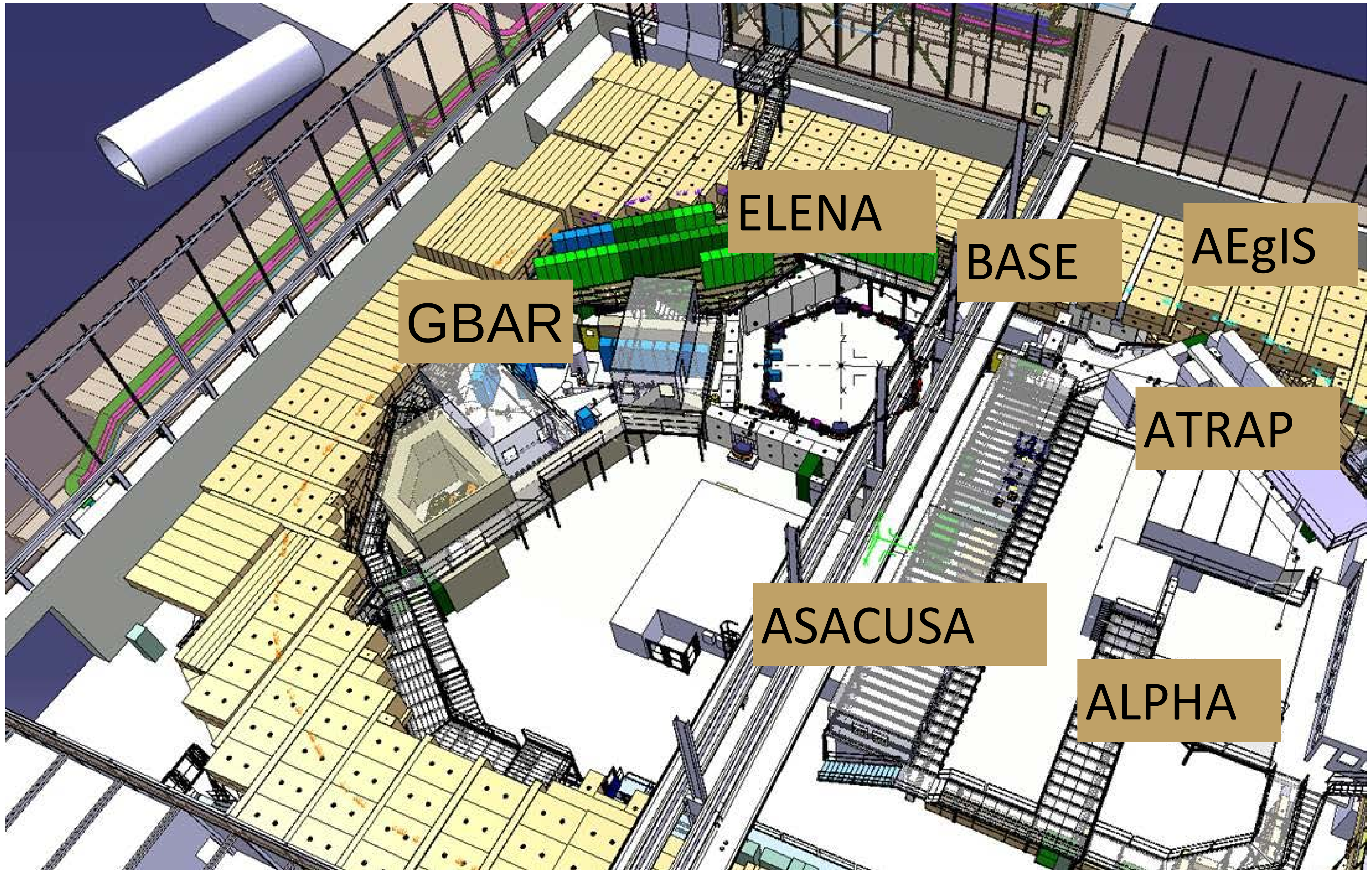
Antiproton production

ELENA @ CERN



Energy range, MeV	5.3 - 0.1
Intensity of ejected beam	1.8×10^7
$\varepsilon_{x,y}$ of extracted beam, π·mm·mrad, [95%], standard	4 / 4
Δp/p of extracted beam, [95%], standard	$8 \cdot 10^{-3}$

ELENA commissioning 2018
2021 (after LS2) full operation



AD experiments

- ATRAP - G. Gabrielse, Harvard
- ALPHA - J. S. Hangst, Aarhus
  - Antihydrogen trapping and 1S-2S spectroscopy
- ASACUSA – M. Hori (MPQ), EW
  - Antiprotonic atoms, collisions, antihydrogen hyperfine structure
- AEgIS - M. Doser, CERN
  - Antimatter gravity
- GBAR - P. Perez, Saclay
  - Antimatter gravity
- BASE - S. Ulmer, RIKEN
  - $\bar{p}$ magnetic moment
- ACE (*finished*) - M. Holzscheiter, Heidelberg
  - biological effects of $\bar{p}$ annihilations

ASACUSA collaboration

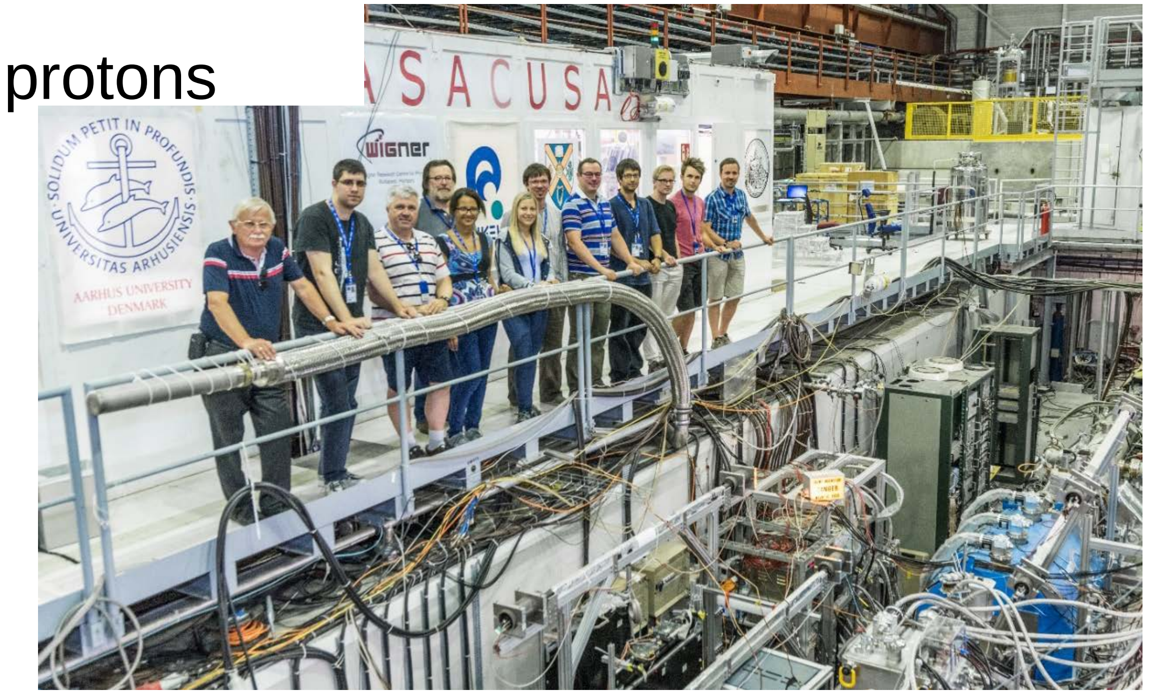
- **A** tomic
- **S** pectroscopy
- **A** nd
- **C** ollisions
- **U** sing
- **S** low
- **A** ntiprotons

ASACUSA Scientific projects

(1) Spectroscopy of $\bar{p}$He

(2) $\bar{p}$ annihilation cross-section

(3) $\bar{H}$ production and spectroscopy



The Antihydrogen team

University of Tokyo, Komaba: M. Fleck, N. Kuroda, Y. Matsuda

RIKEN: Y. Kanai, V. Mäckel , S. Ulmer, Y. Yamazaki

Hiroshima University: H. Higaki

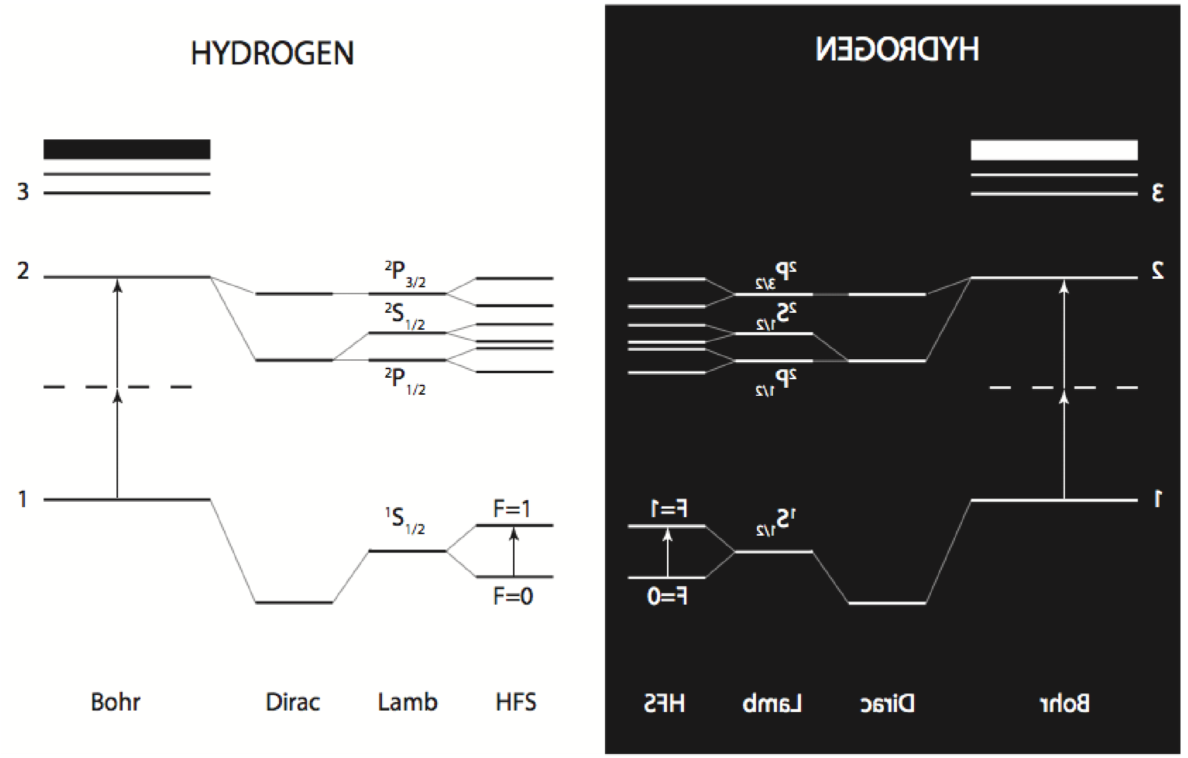
Univerita di Brescia & INFN Brescia: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli

Stefan Meyer Institut für Subatomare Physik: C. Amsler, A. Gligorova, B. Kolbinger, A. Lanz, D. Murtagh, A. Nanda, M.C. Simon, H. Spitzer, M. Strube, E. Widmann, J. Zmeskal

CERN: H. Breuker, C. Malbrunot

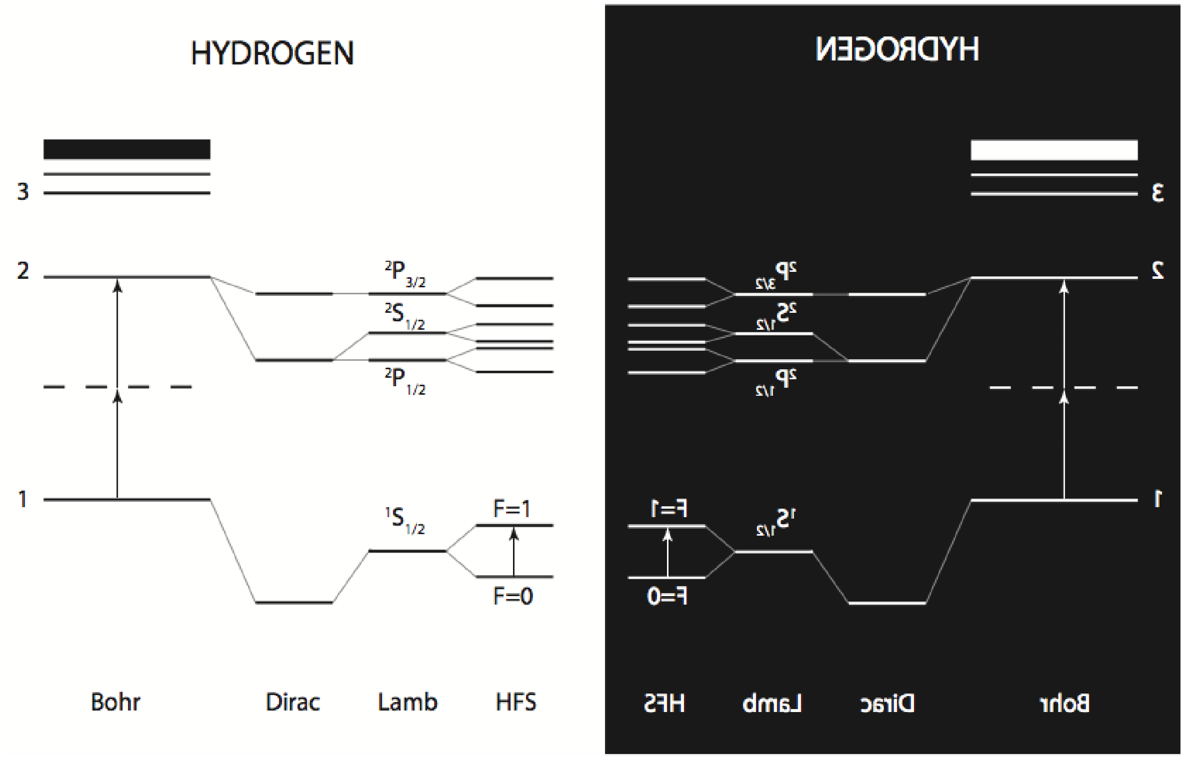
Antihydrogen experiments

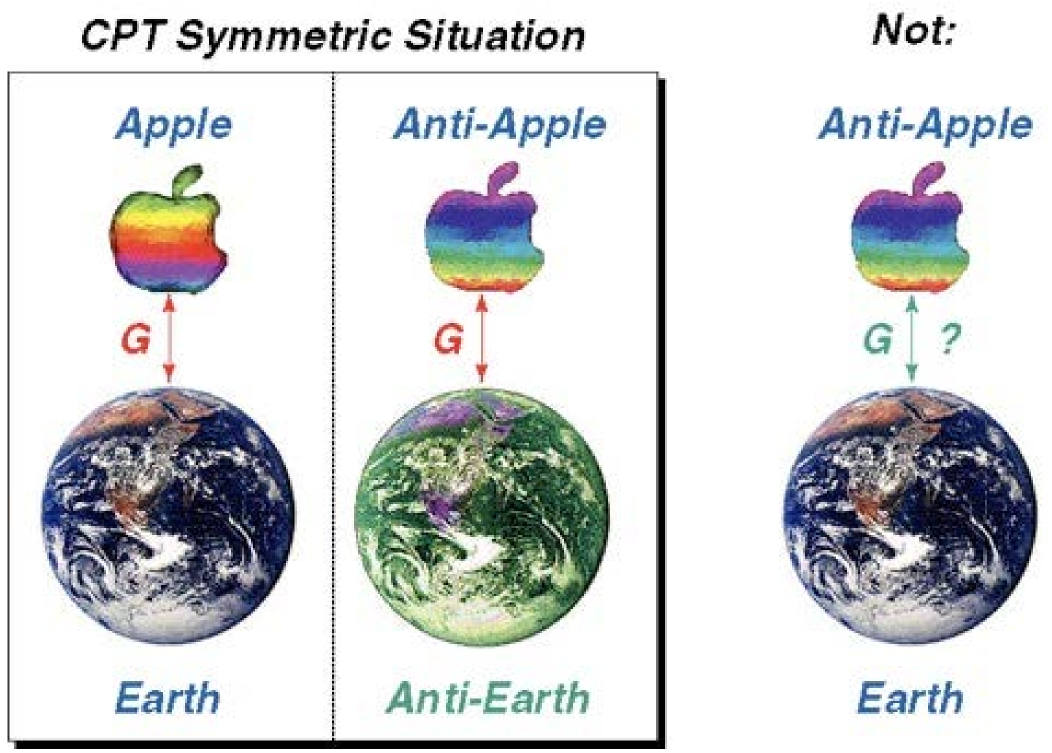
- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT



Antihydrogen experiments

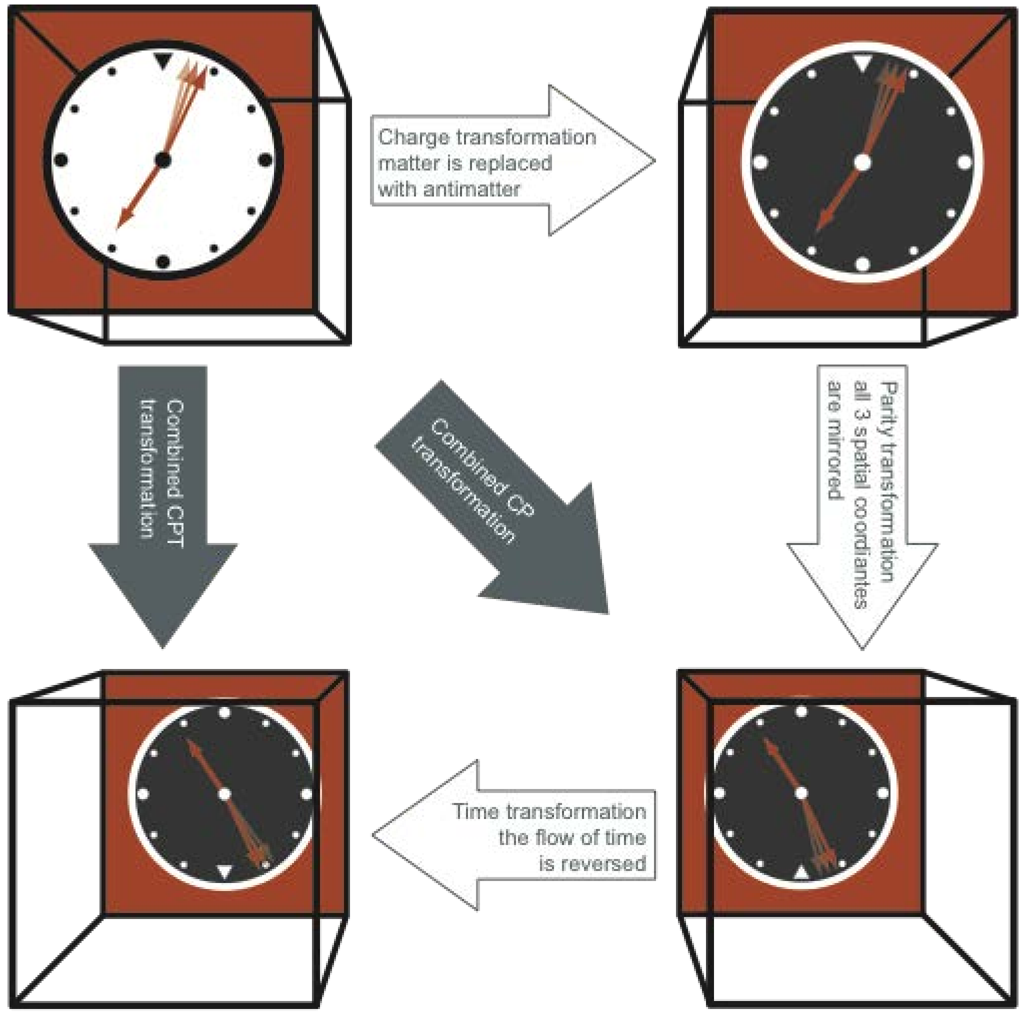
- Matter-Antimatter Symmetry
  - Charge conjugation-Parity-Time reversal: CPT
- Antimatter gravity
  - Weak Equivalence principle: WEP





Fundamental symmetries C, P, T

- C: charge conjugation particle - antiparticle
- P: parity: spatial mirror
- T: time reversal
- CPT theorem: consequence of
  - Lorentz-invariance
  - local interactions
  - unitarity
    - *Lüders, Pauli, Bell, Jost 1955*
- all QFT of SM obey CPT
- not necessarily true for string theory



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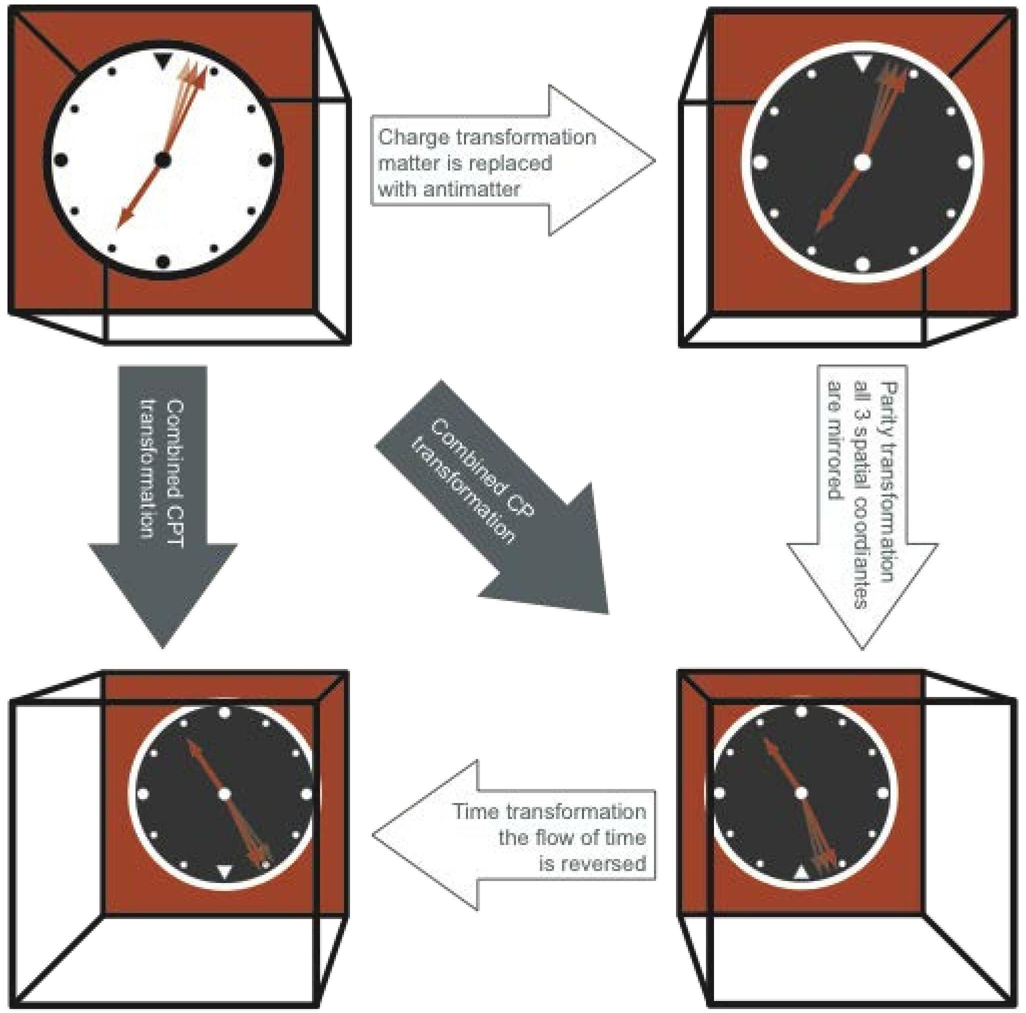
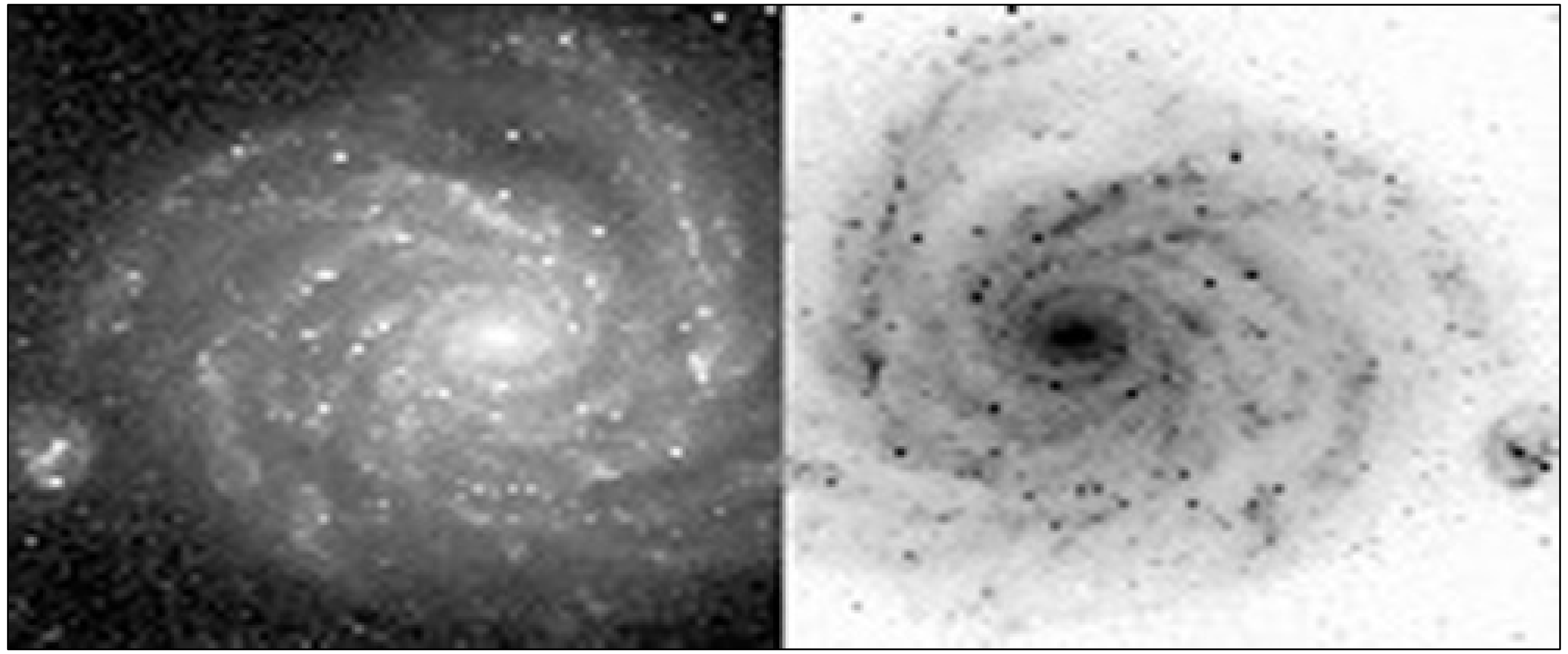


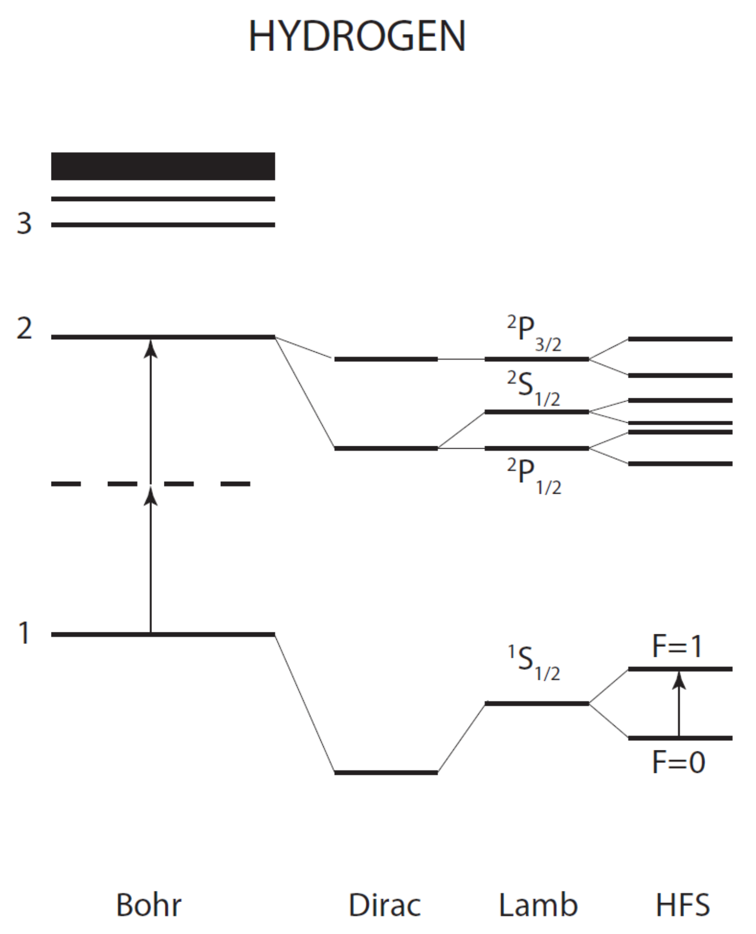
CPT → particle/anitparticle: same masses, lifetimes, g-factors, |charge|,...

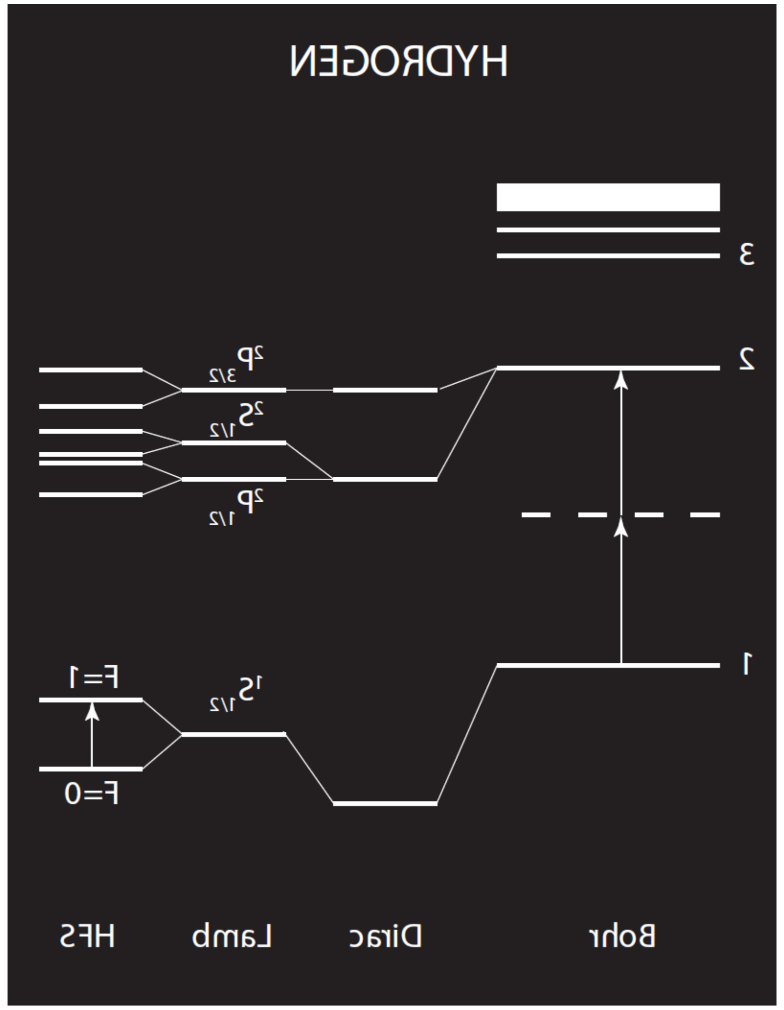
CPT symmetry & cosmology

- 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 of 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?



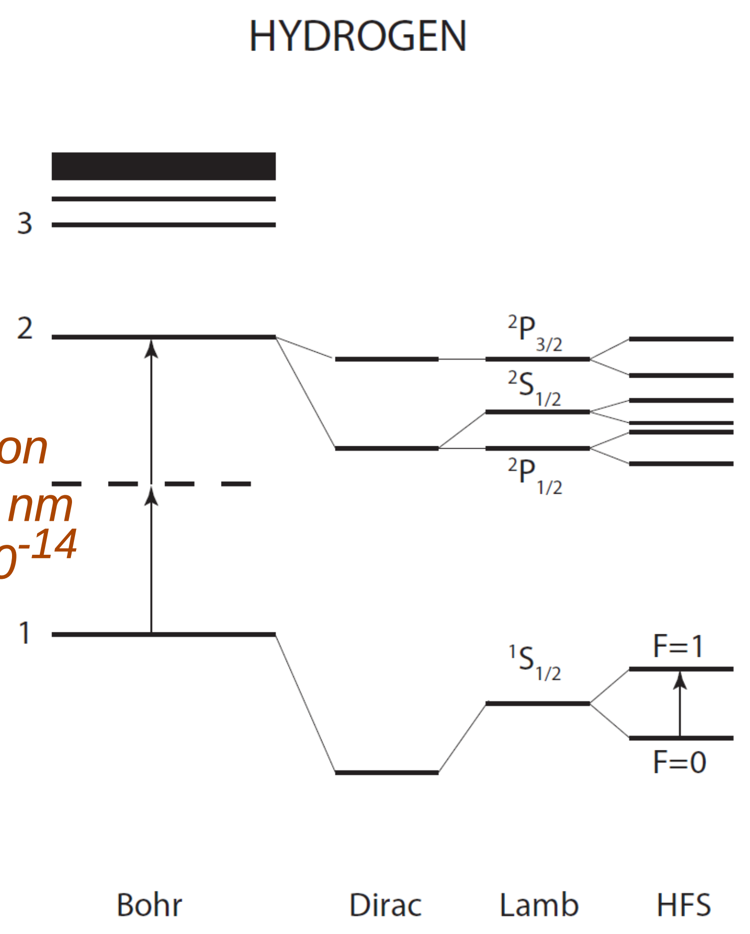
Antihydrogen spectroscopy & sensitivity

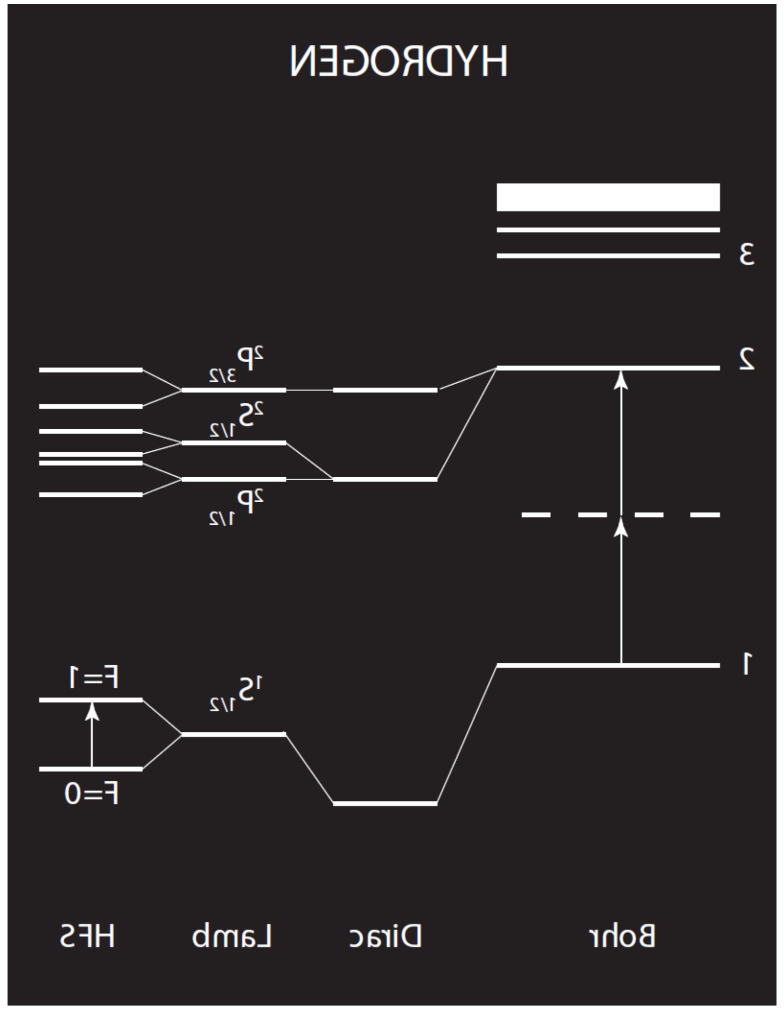




Antihydrogen spectroscopy & sensitivity

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

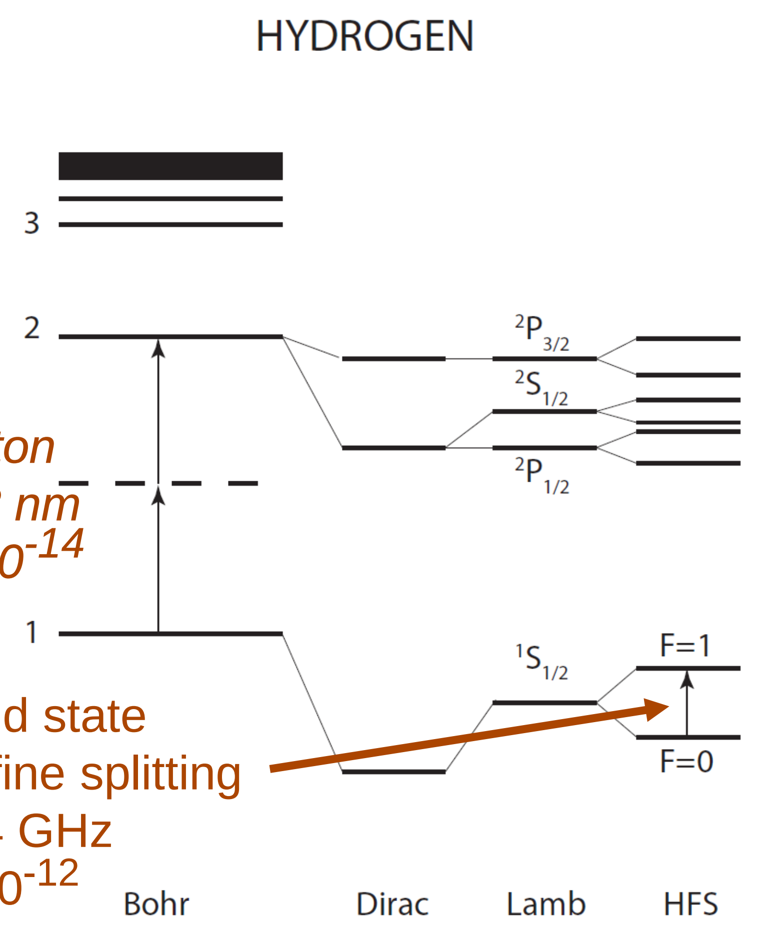


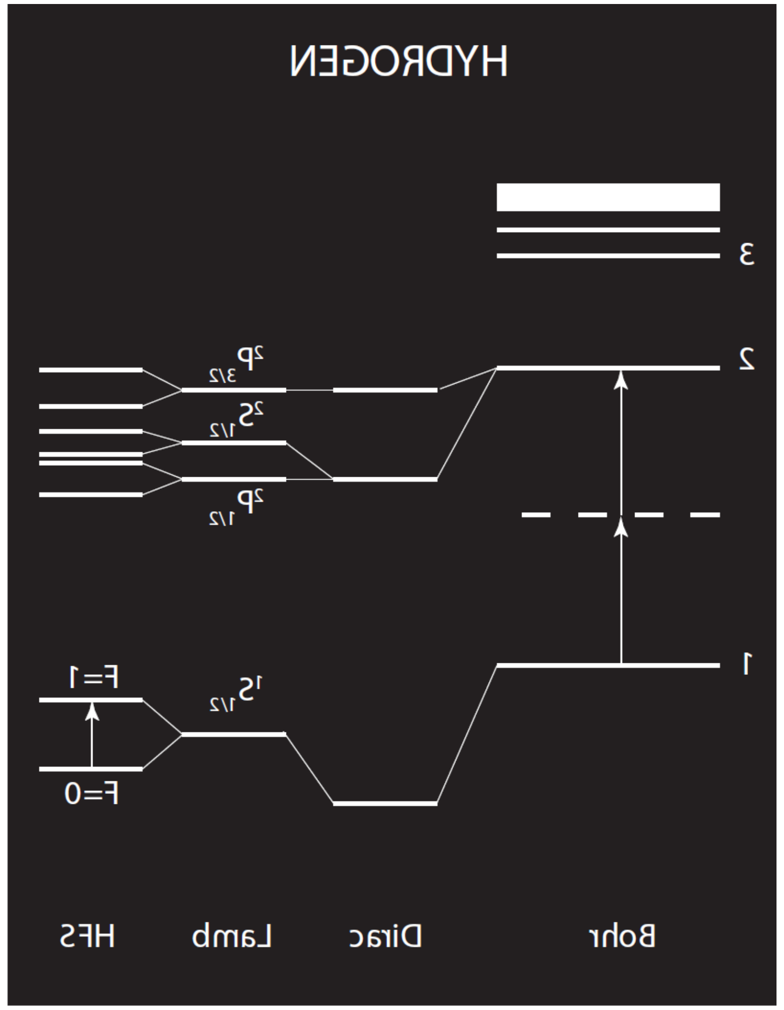


Antihydrogen spectroscopy & sensitivity

1s-2s
2 photon
λ=243 nm
Δf/f=10^-14

Ground state
hyperfine splitting
f = 1.4 GHz
Δf/f=10^-12





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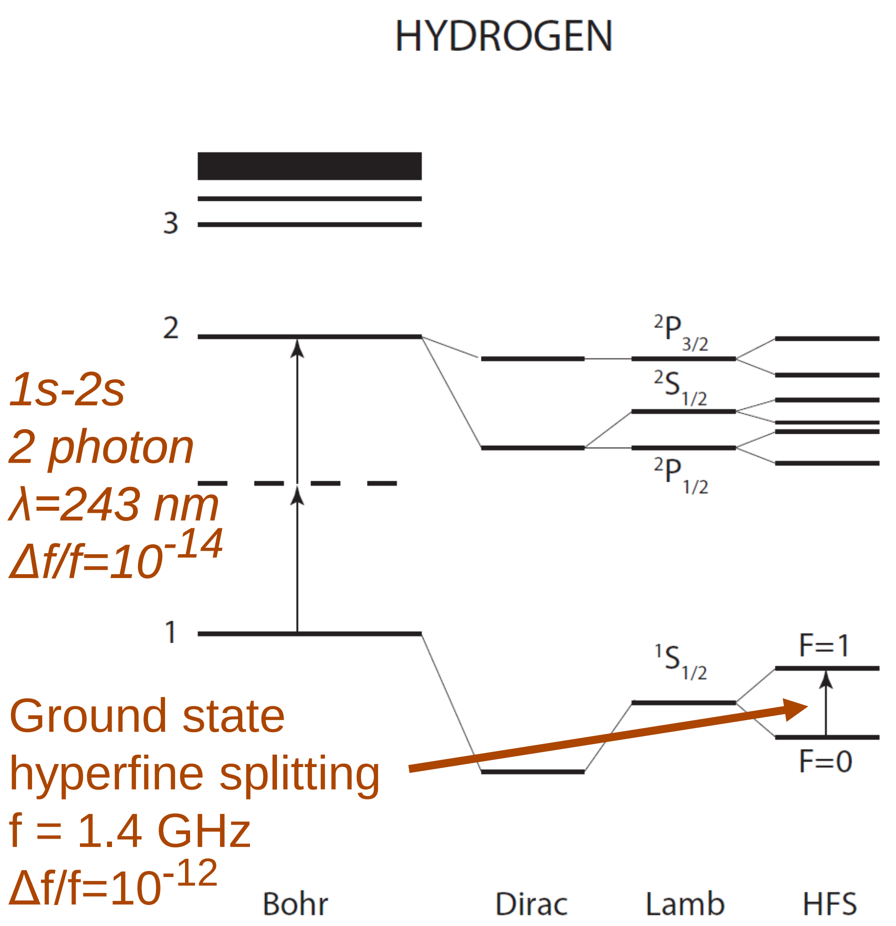
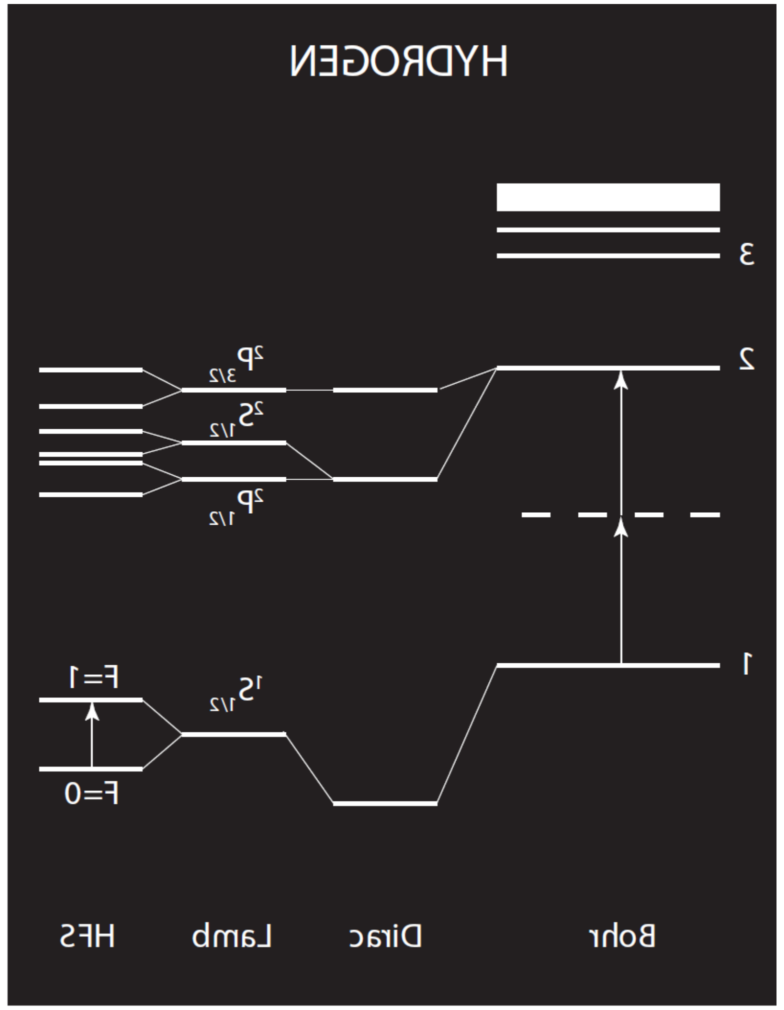
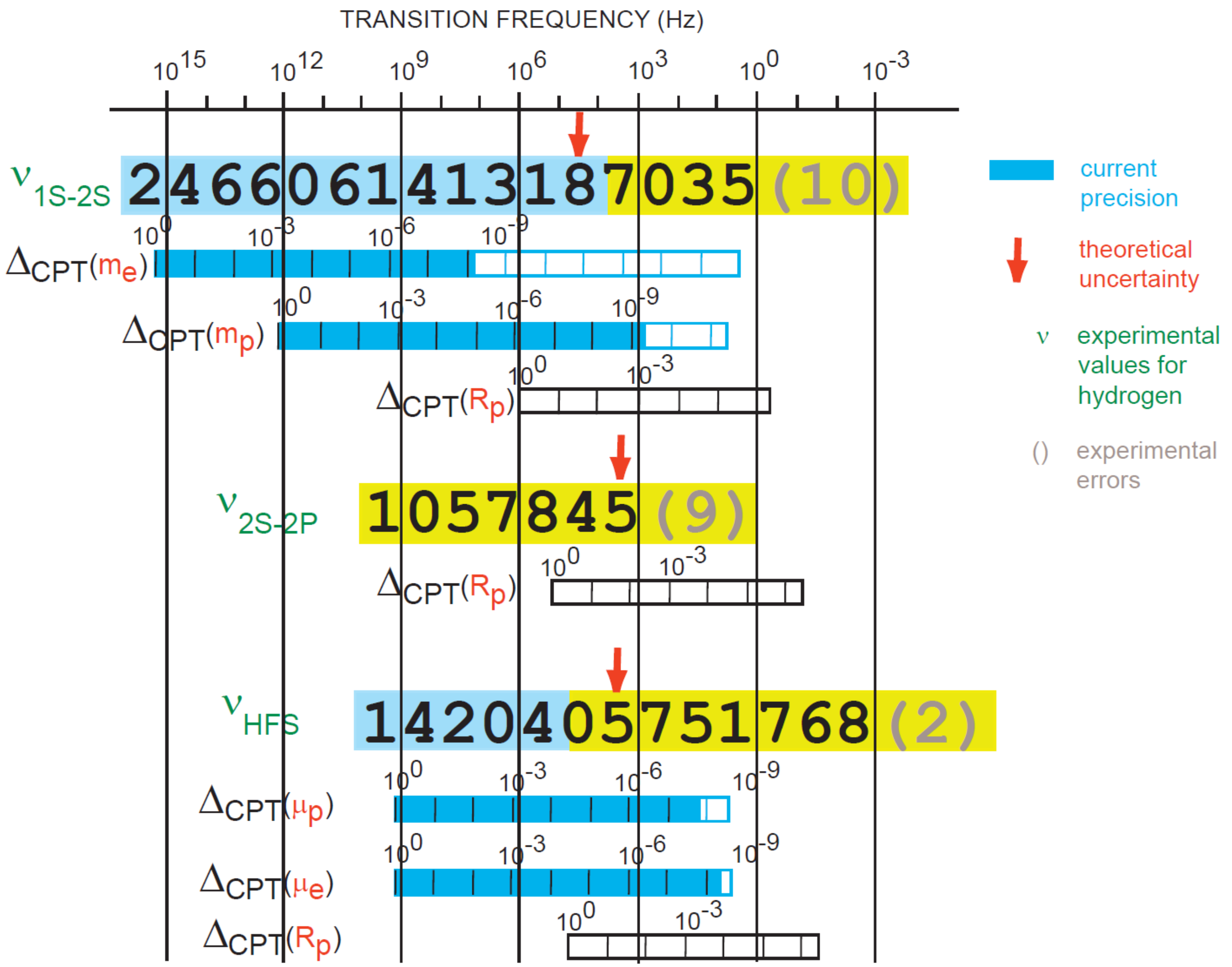
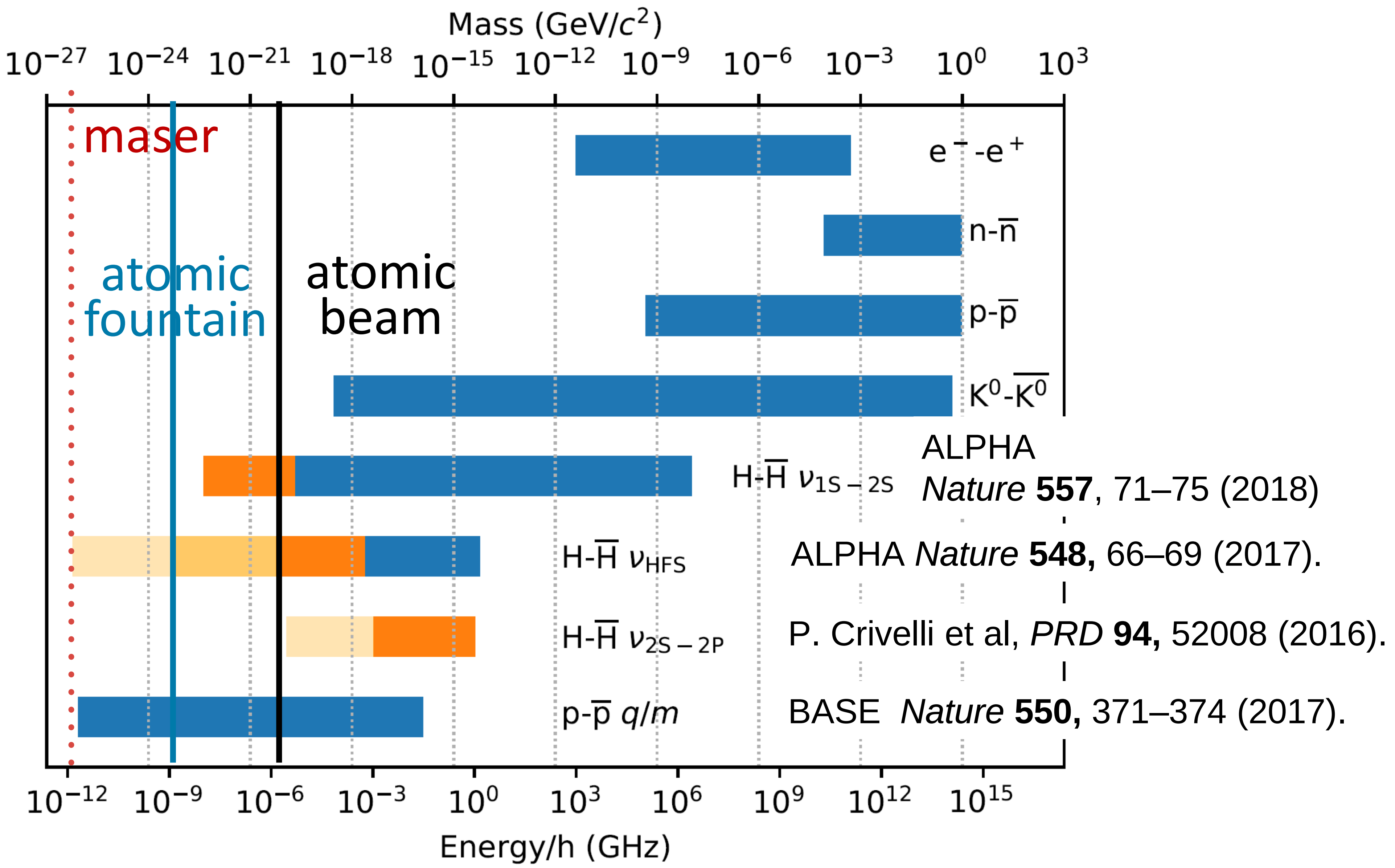






Comparison of CPT tests I

- Mass & frequency



- Right edge: value
- Bar length: relative precision
- Left edge: absolute sensitivity
  - Source: PDG
  - Blue: measured
  - Orange: planned
  - Yellow: potentially reachable

Widmann, E. et al. *Hyperfine Interact. 240:5 (2019)*
https://doi.org/10.1007/s10751-018-1536-9.

Comparison of CPT tests II

- Standard Model Extension SME

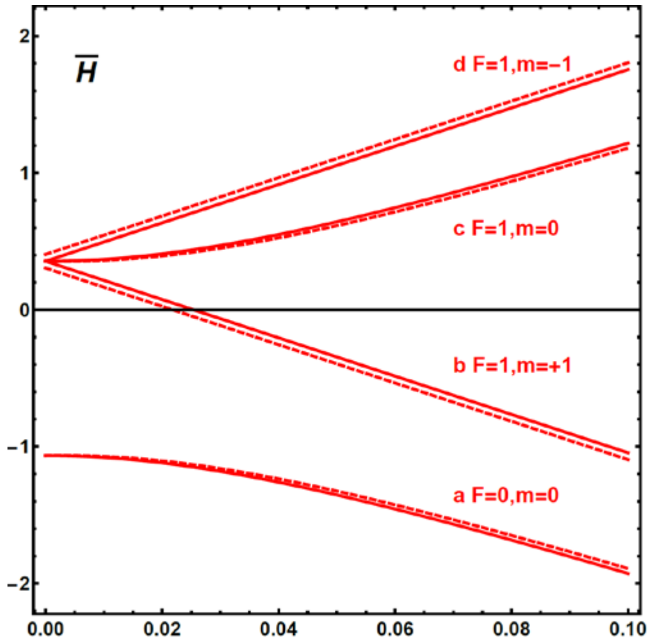
CPT & LORENTZ VIOLATION

$$(i\gamma^\mu D_\mu - m_e - a^e_\mu\gamma^\mu - b^e_\mu\gamma_5\gamma^\mu - \frac{1}{2}H^e_{\mu\nu}\sigma^{\mu\nu} + ic^e_{\mu\nu}\gamma^\mu D^\nu + id^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0\,.$$

LORENTZ VIOLATION

D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

- Minimal SME: only HFS
- Non-minimal SME: also 1S-2S shows CPTV



Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

Comparison of CPT tests II

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$$(i\gamma^\mu D_\mu - m_e - a^e_\mu \gamma^\mu - b^e_\mu \gamma_5 \gamma^\mu - \tfrac{1}{2} H^e_{\mu\nu}\sigma^{\mu\nu} + i c^e_{\mu\nu}\gamma^\mu D^\nu + i d^e_{\mu\nu}\gamma_5\gamma^\mu D^\nu)\psi = 0\,.$$

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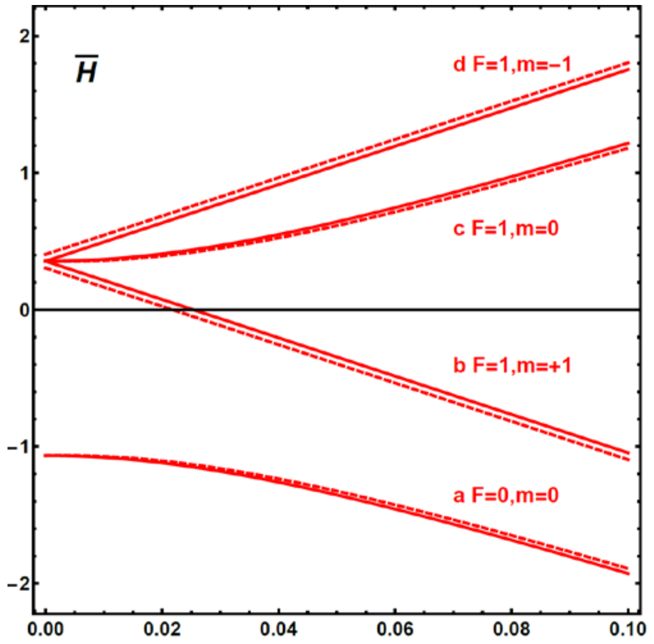
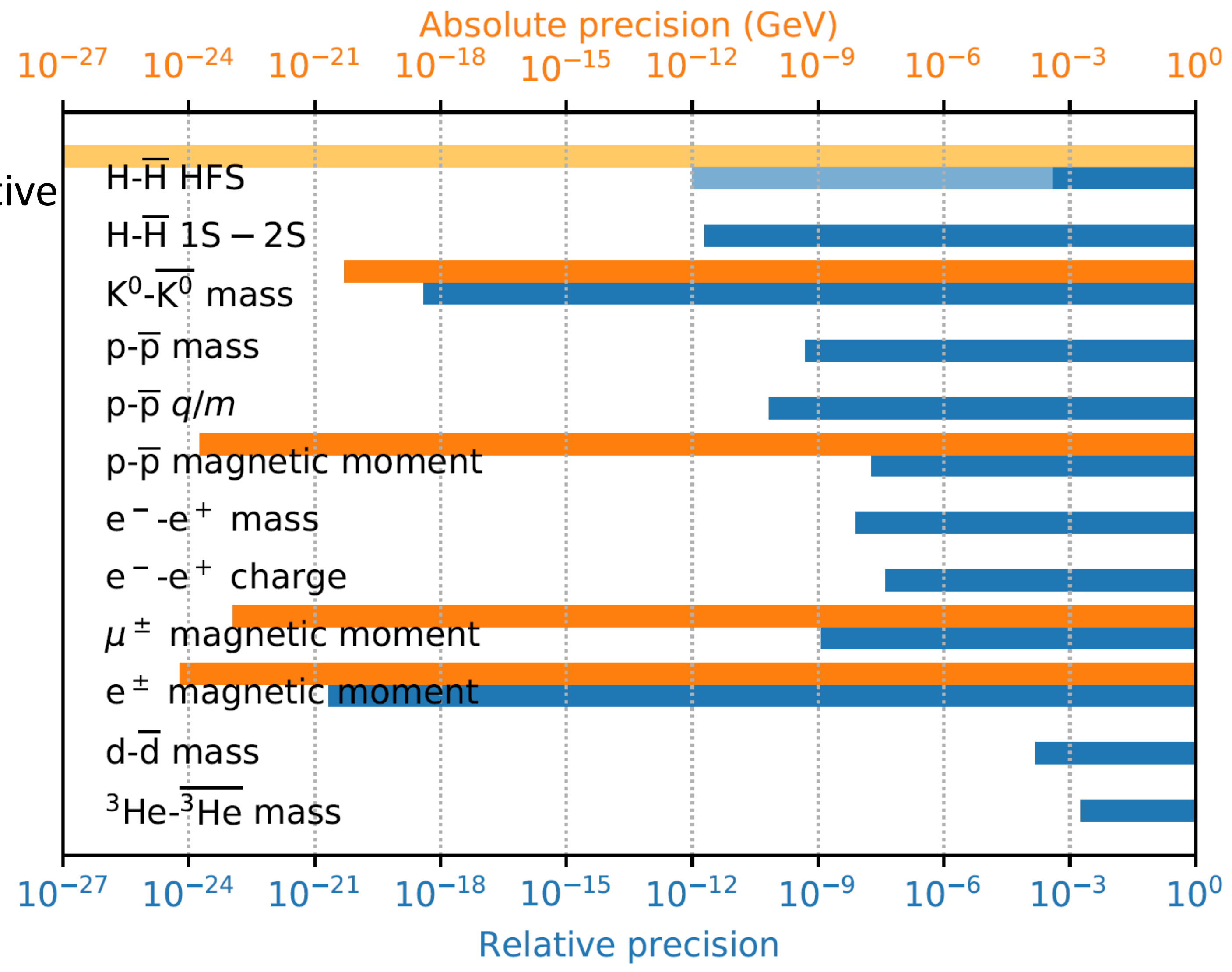


Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

ALPHA:
Not sensitive to SME



PDG, Kostelecky & Bluhm arXiv:0801.0287

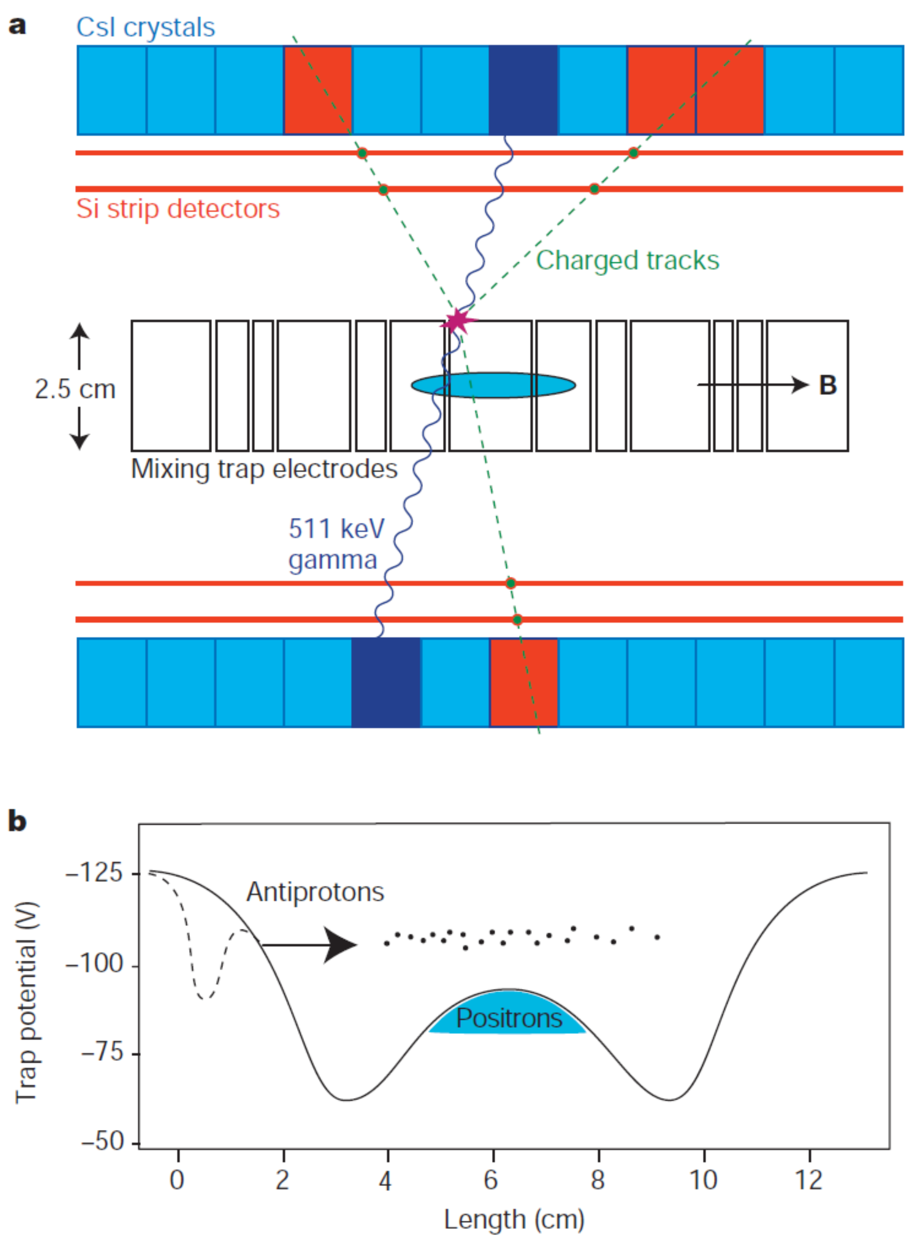
First Cold Antihydrogen 2002@AD

- Nested Penning traps
- Capture energy: few keV

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



VOLUME 89, NUMBER 21 PHYSICAL REVIEW LETTERS 18 NOVEMBER 2002

Background-Free Observation of Cold Antihydrogen with Field-Ionization Analysis of Its States

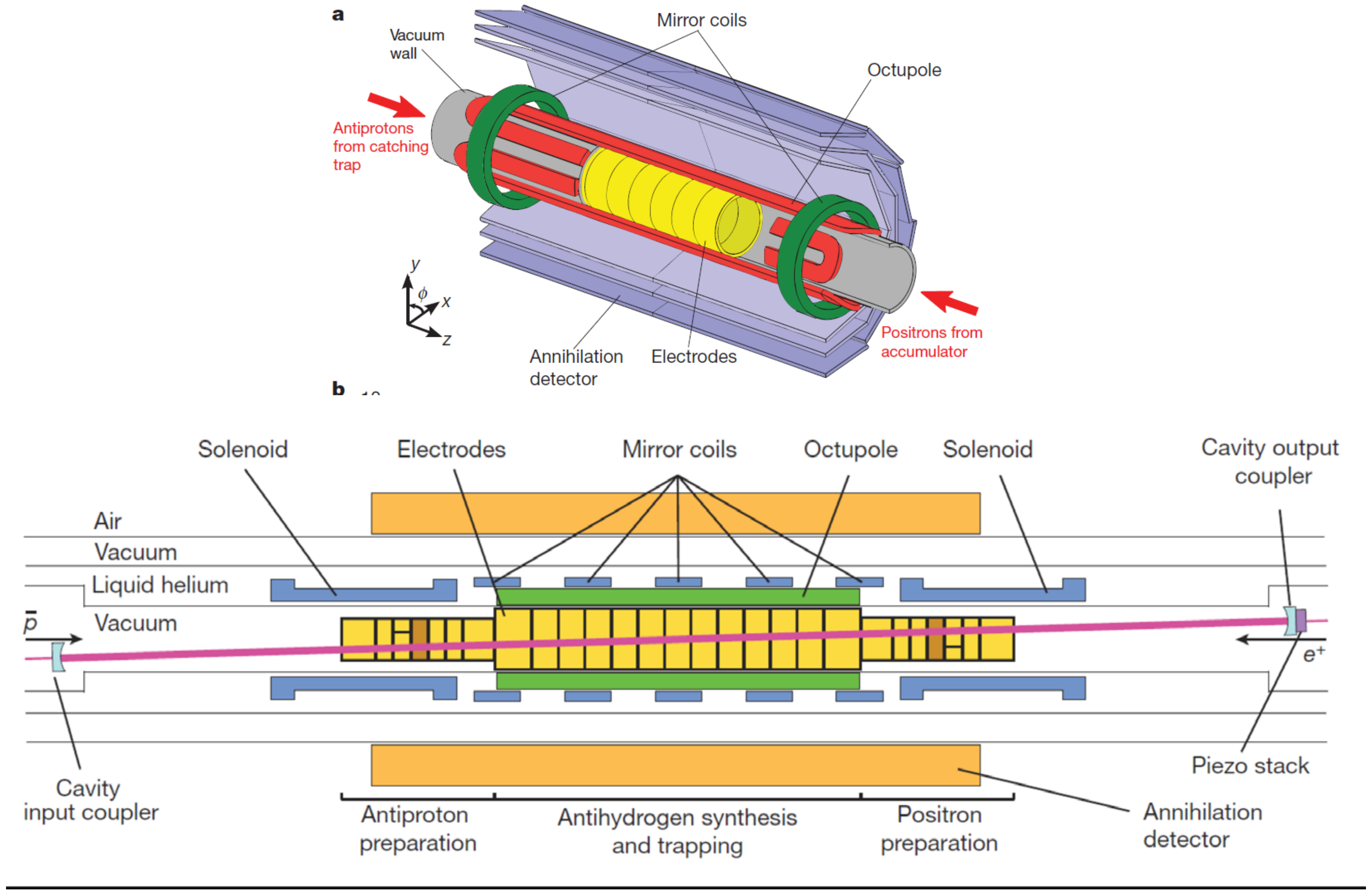
G. Gabrielse,[1,*] N. S. Bowden,[1] P. Oxley,[1] A. Speck,[1] C. H. Storry,[1] J. N. Tan,[1] M. Wessels,[1] D. Grzonka,[2] W. Oelert,[2] G. Schepers,[2] T. Sefzick,[2] J. Walz,[3] H. Pittner,[4] T. W. Hänsch,[4,5] and E. A. Hessels[6]

(ATRAP Collaboration)

ATRAP PRL 89 (2002) 213401

Laser spectroscopy of trapped $\bar{\mathrm{H}}$: 1s-2s

- Ioffe-Pritchard trap



Ahmadi, M., et al. *Nature 557, 71-75 (2018)*

Laser spectroscopy of trapped $\bar{\mathrm{H}}$: 1s-2s

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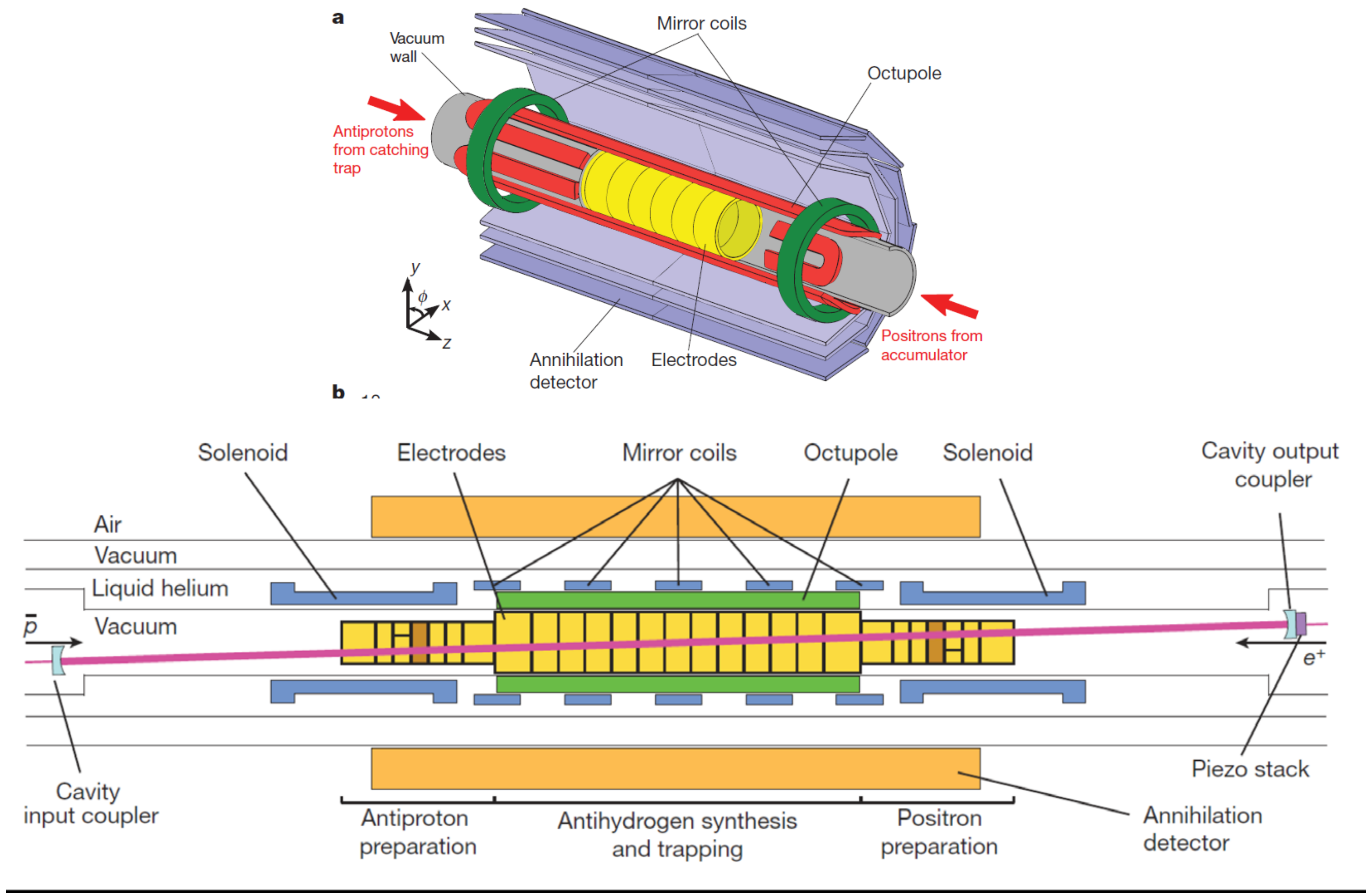

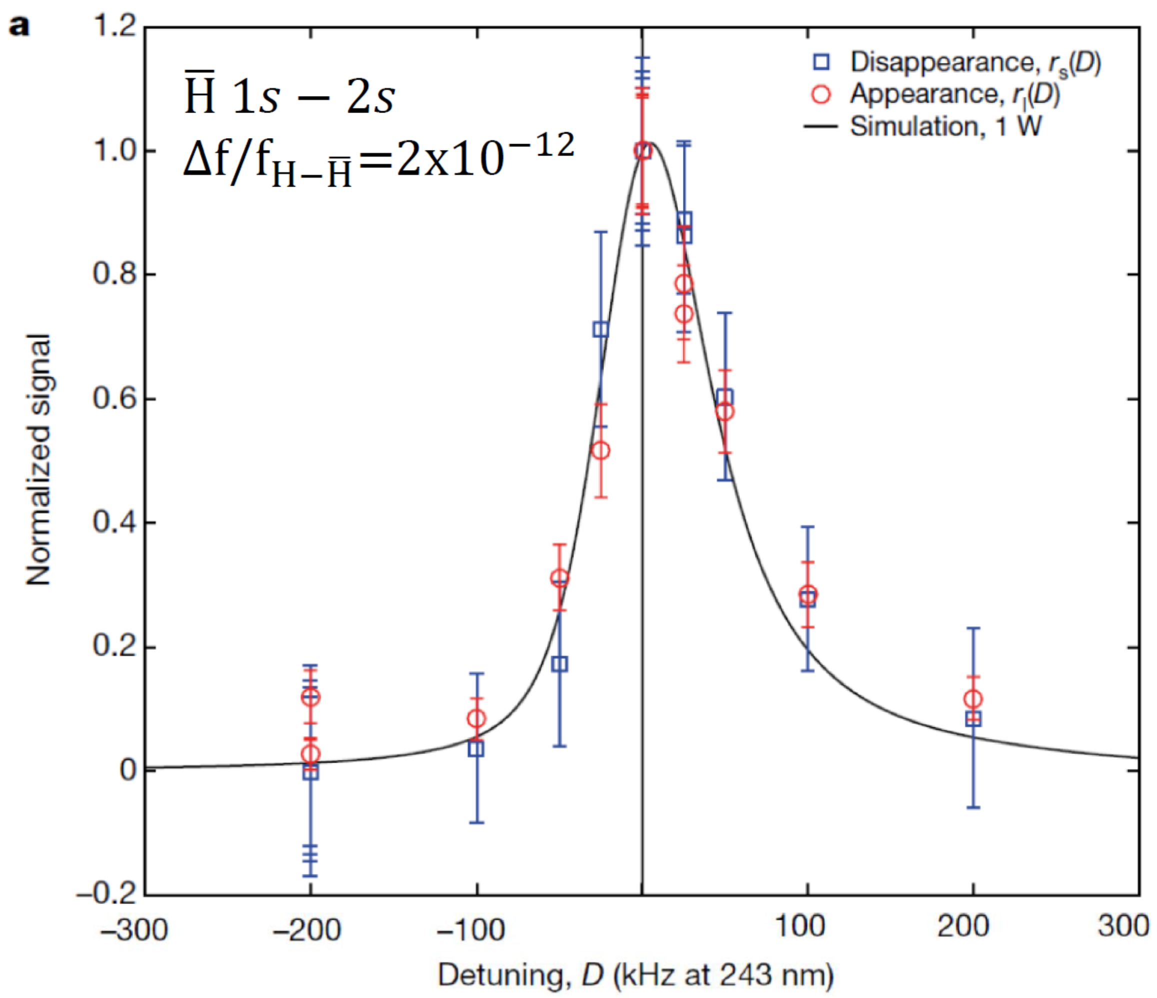

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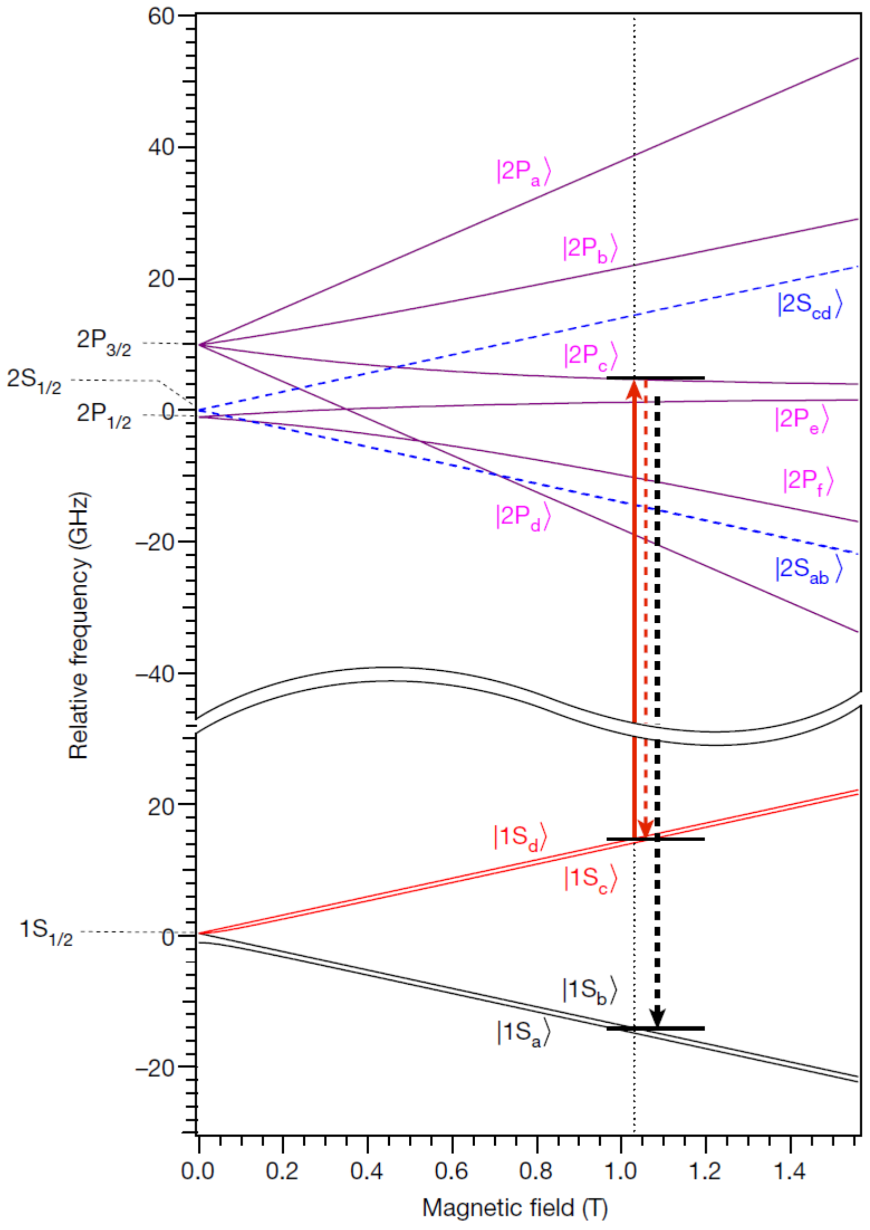

Ahmadi, M.,, et al., *Nature 561, 211-215 (2018)*

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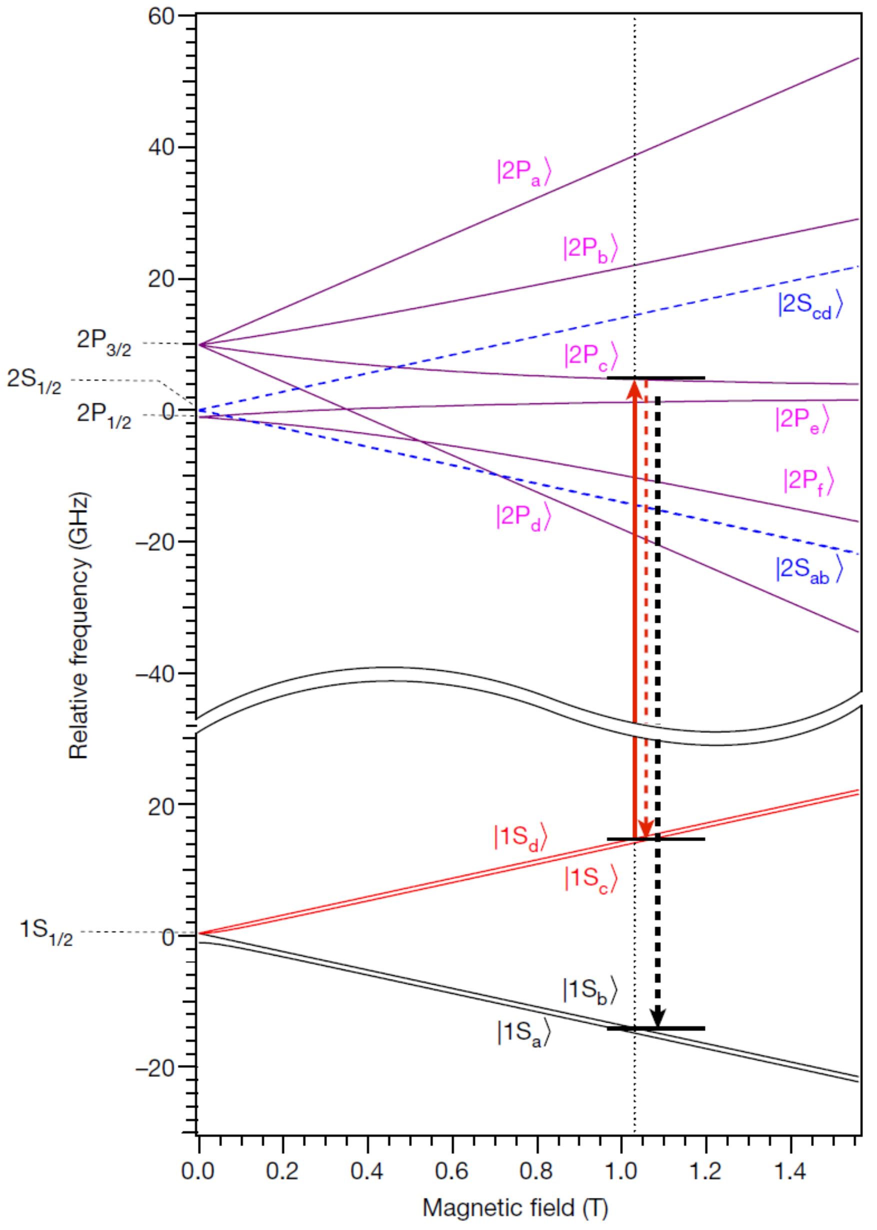
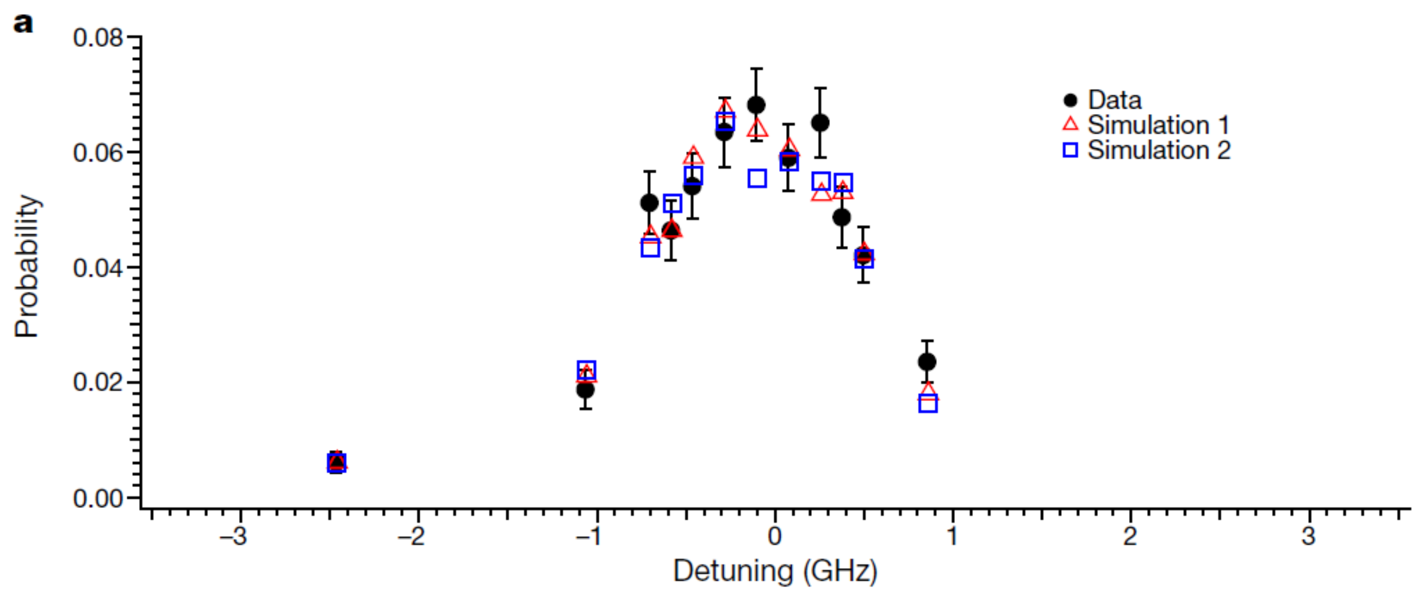




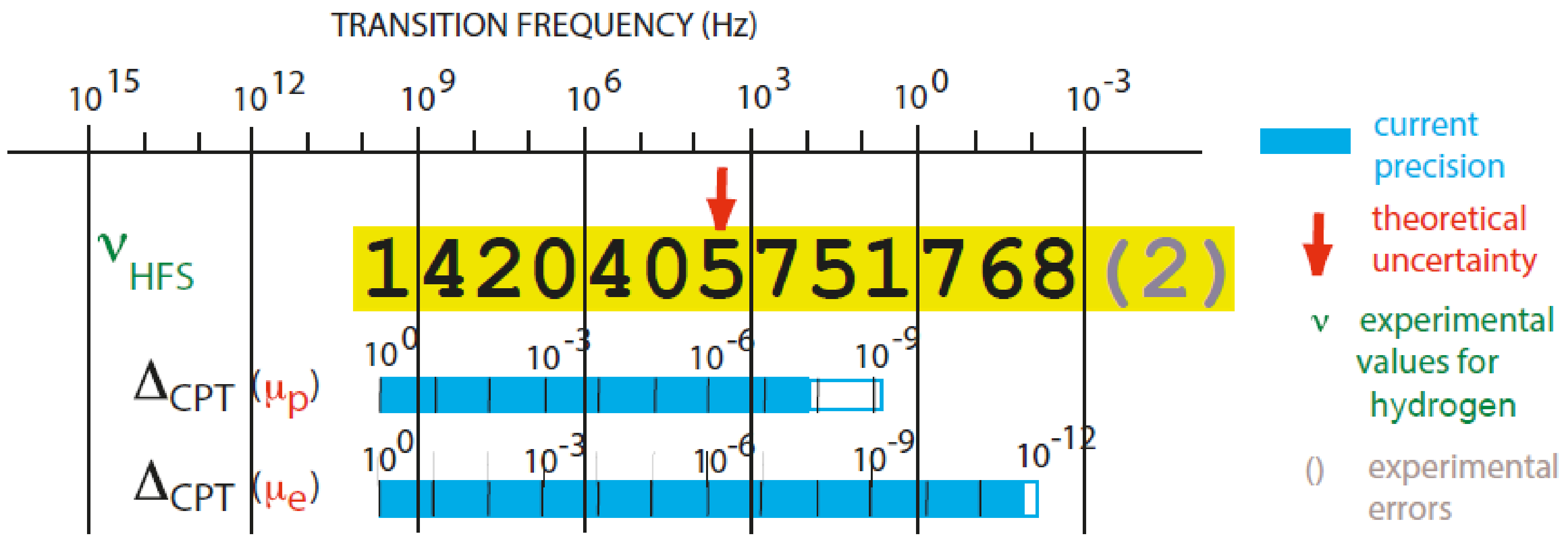
- Precision limited: 5x10^{-8}
- Proof of principle of pulsed Ly-α laser
  - Laser cooling

Ahmadi, M.,, et al., *Nature 561, 211-215 (2018)*

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

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

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



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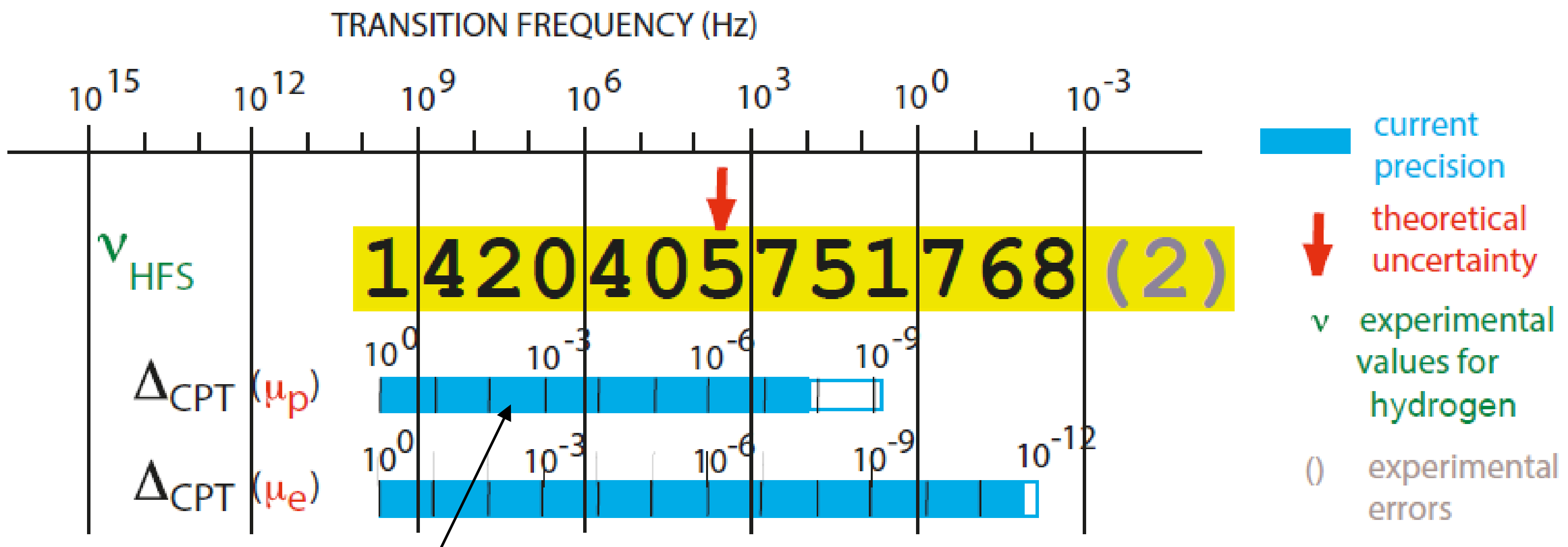
Hydrogen HFS and QED: finite size effects

H: deviation from Fermi contact term:	–32.77(1) ppm
finite electric & magnetic radius (Zemach corrections):	–41.43(44) ppm
polarizability of p/p̄	+1.88(64) ppm
remaining deviation theory-experiment:	+0.86(78) ppm

C. E. Carlson et al., *PRA 78, 022517 (2008)*

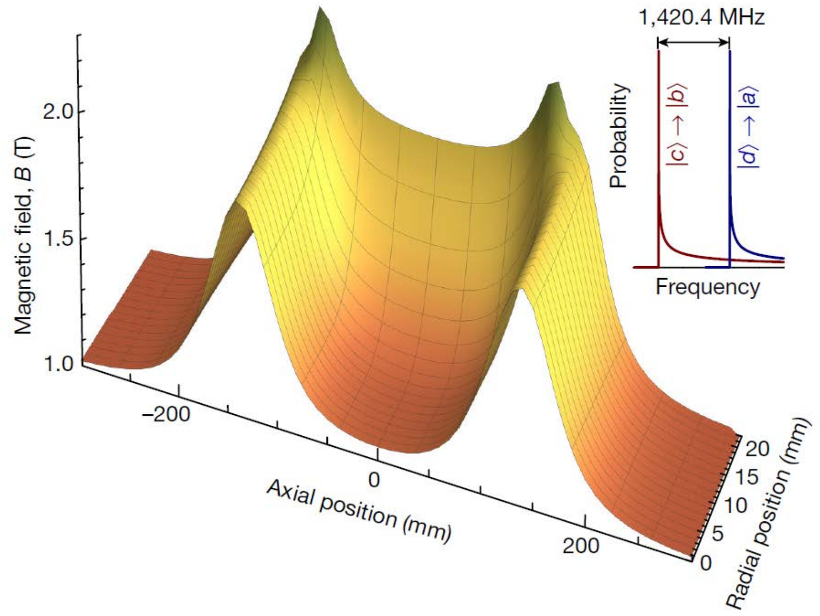


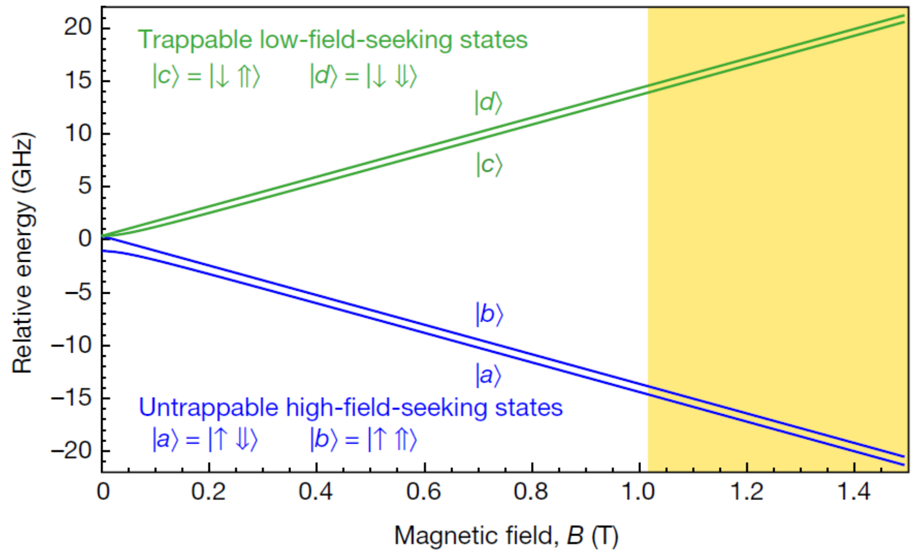
BASE C. Smorra et al., *Nature 550*, 371–374 (2017).

Finite size effect of proton/antiproton important below ~ 10 ppm

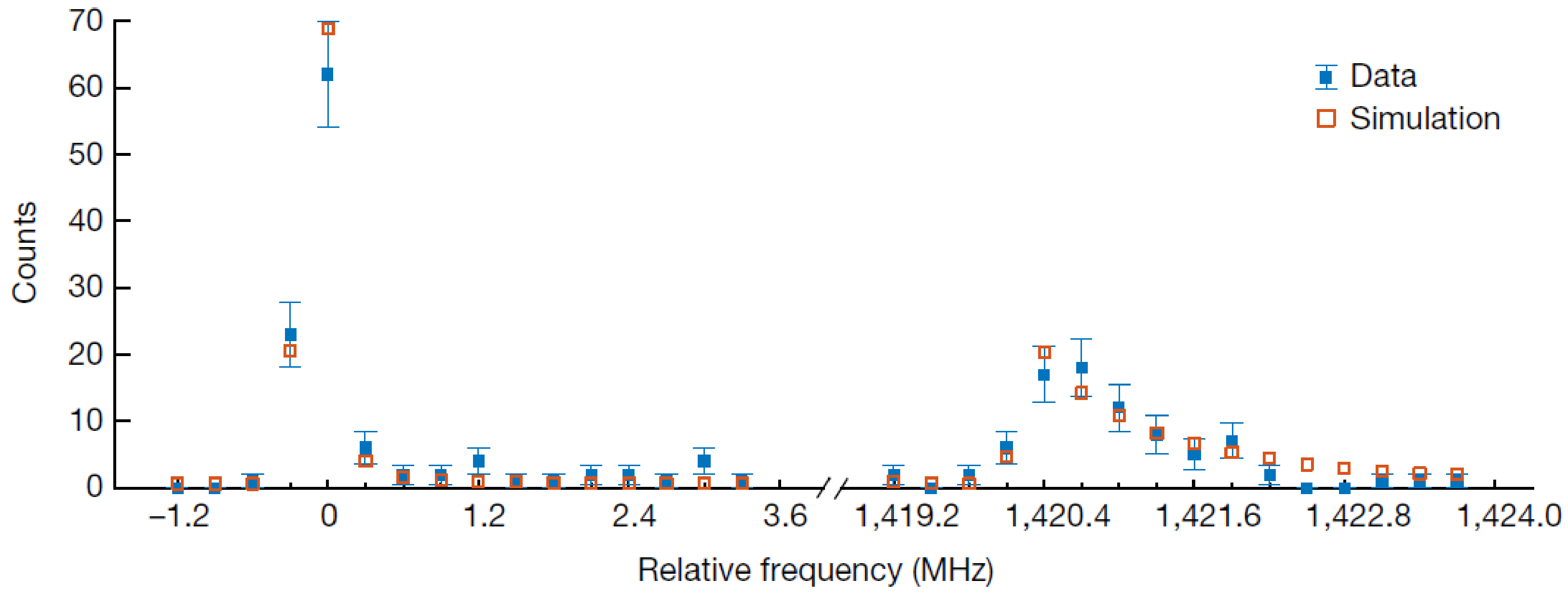
ALPHA HFS: in trap

- Inhomogeneous magnetic fields



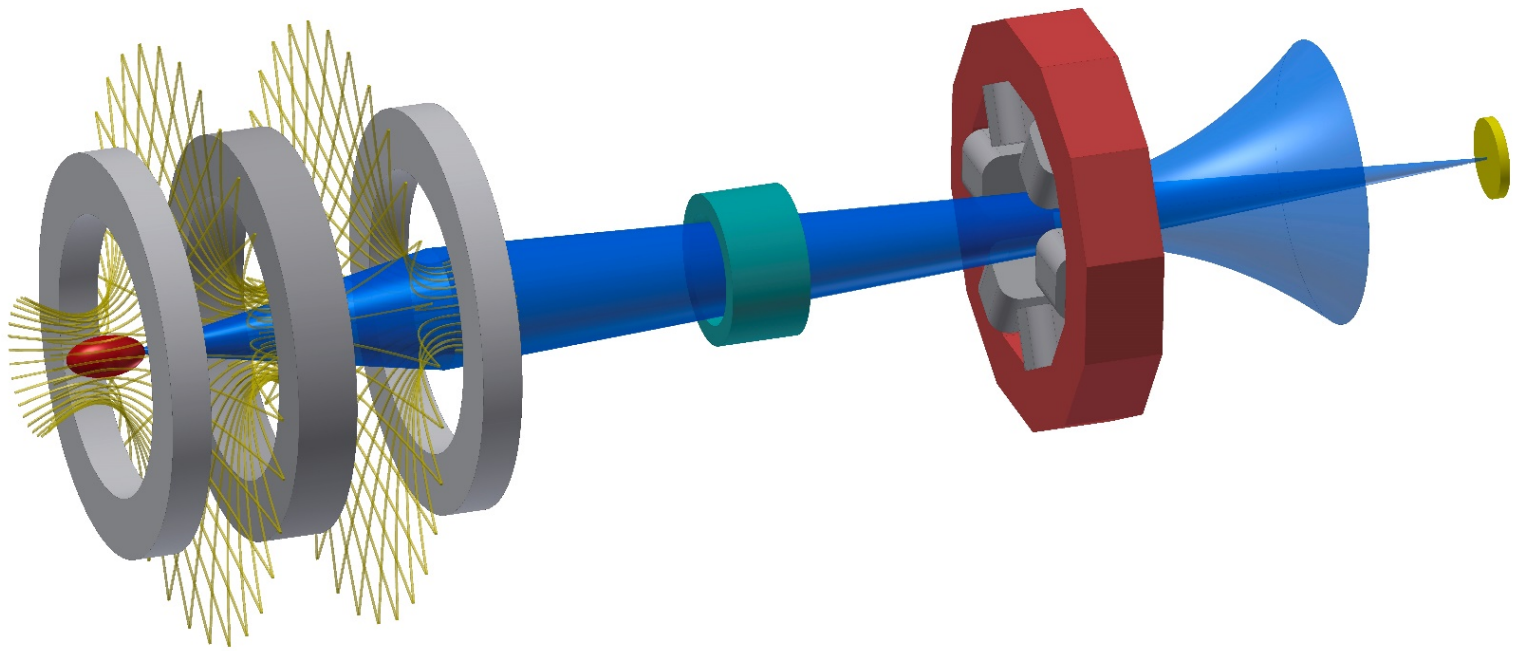


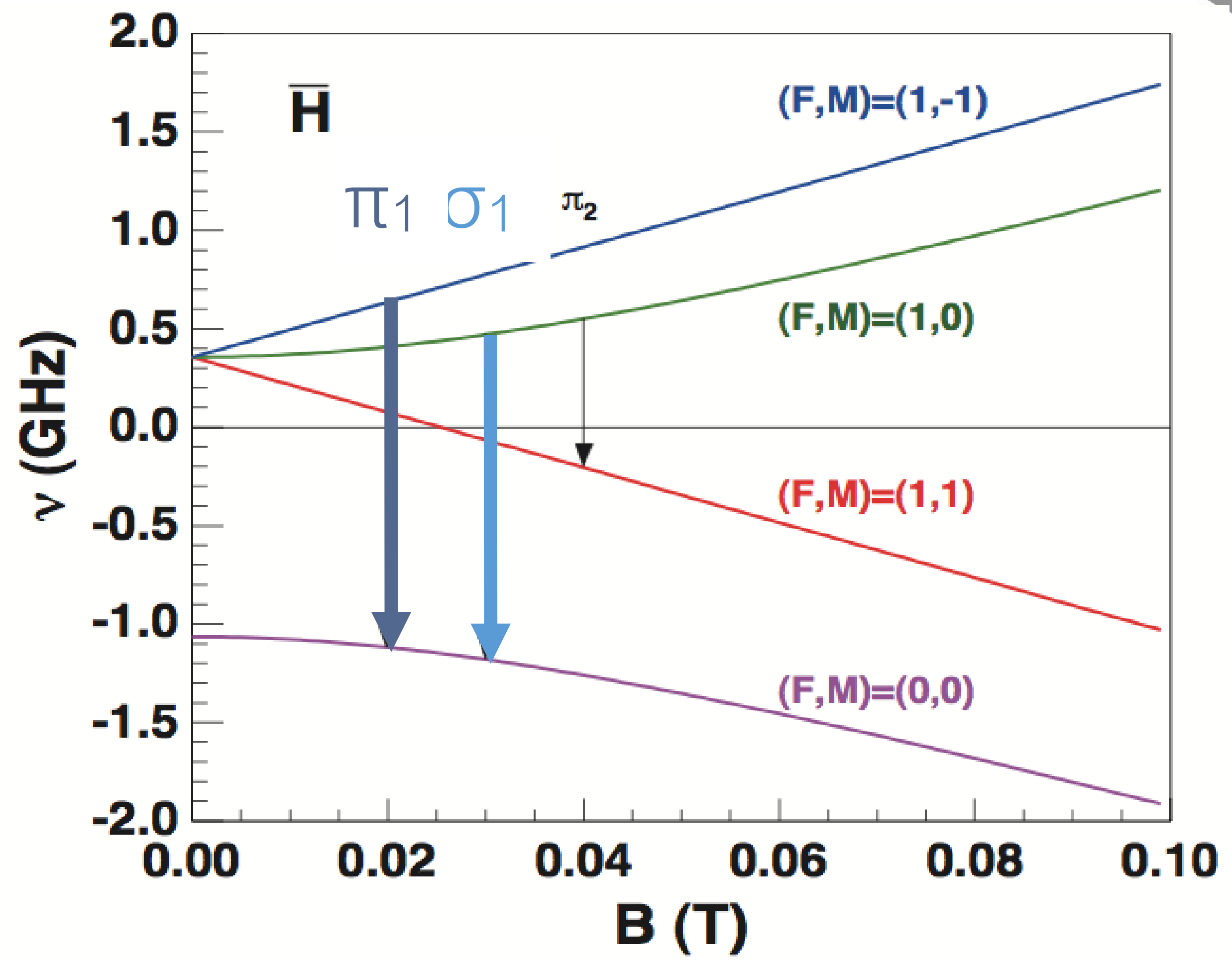
- $\nu_{HF} = \nu_{d->a} - \nu_{c->b}$
  - No CPT effect in SME!!
  - Accuracy $4x10^{-4}$



Ahmadi, M. *et al.*. *Nature* **548**, 66–69 (2017).

In-beam HFS spectroscopy



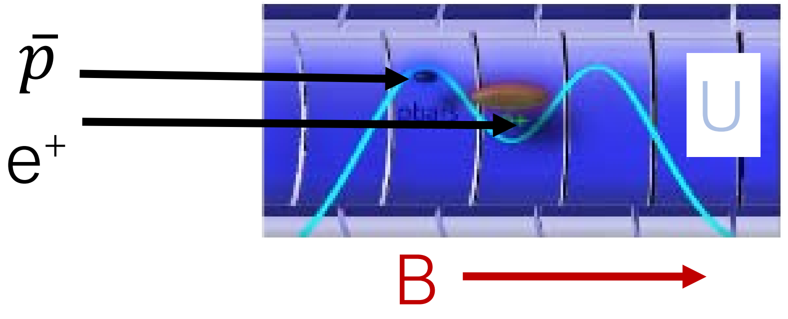


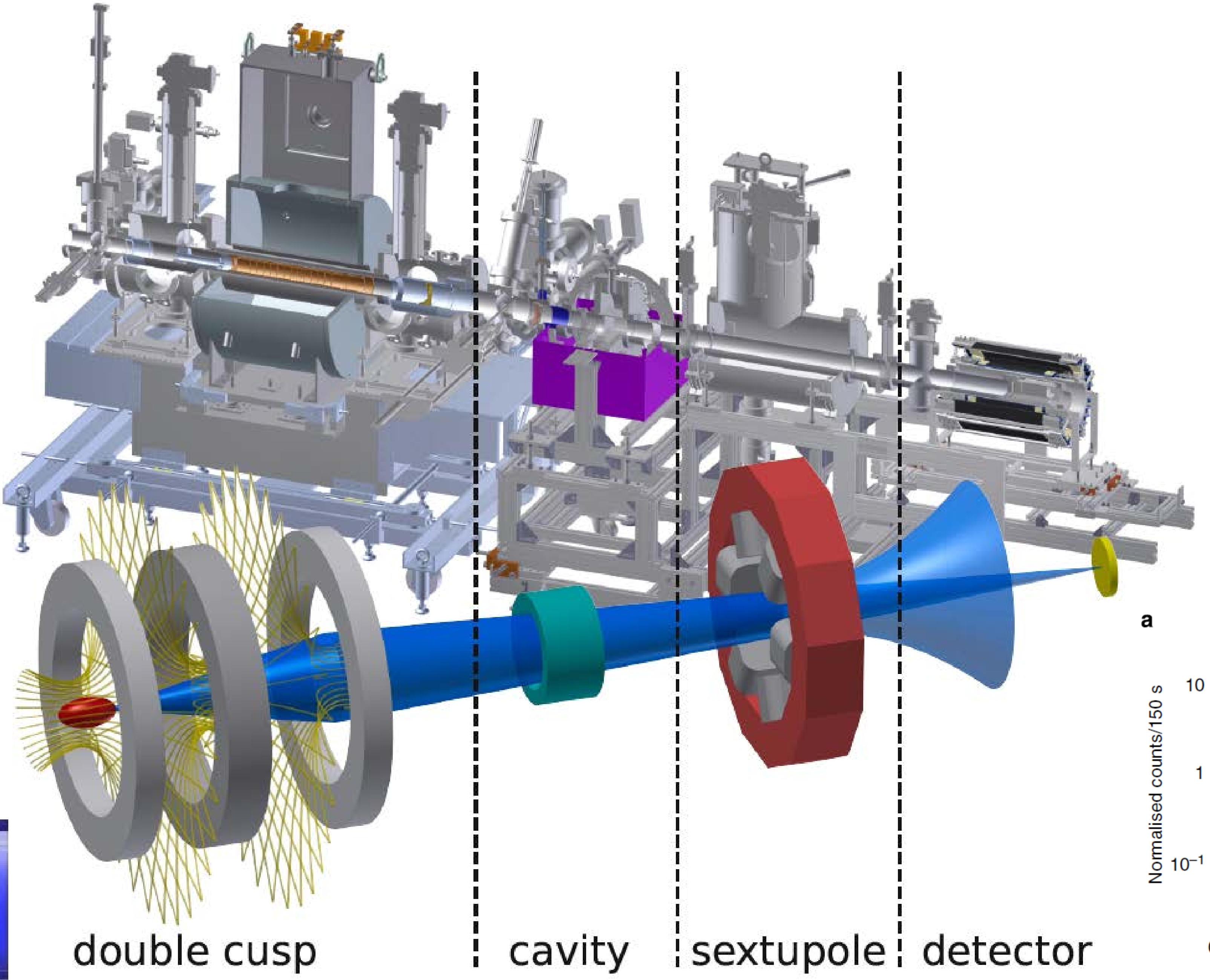
- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Produce polarized slow (<100 K) Hbar beam

- Resolution: line width $\Delta\nu \sim 1/T$
  - 1000 m/s, 10 cm:
  - $7\text{x}10^{-6}$ for T = 50 K *cf part IV*
  - > 100 $\bar{\text{H}}$/s in 1S state into 4π needed
  - event rate 1 / minute: background from cosmics, annihilations upstreams

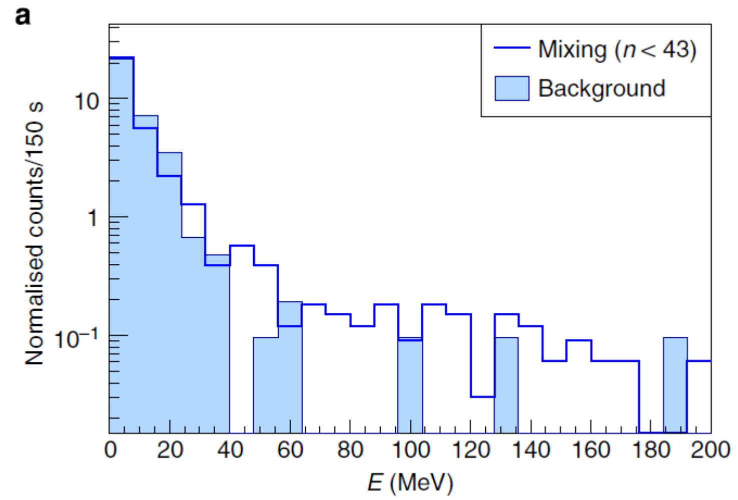
Antihydrogen beam status

- $\overline{\mathrm{H}}$ production 1st time in 2010 in nested Penning trap
- Three body recombination expected to produce Rydberg states
- 1st observation of beam in field free region 2014
  - *n*≤43: 6 $\overline{H}$/15 min
  - *n*≤29: 4 $\overline{H}$/15 min



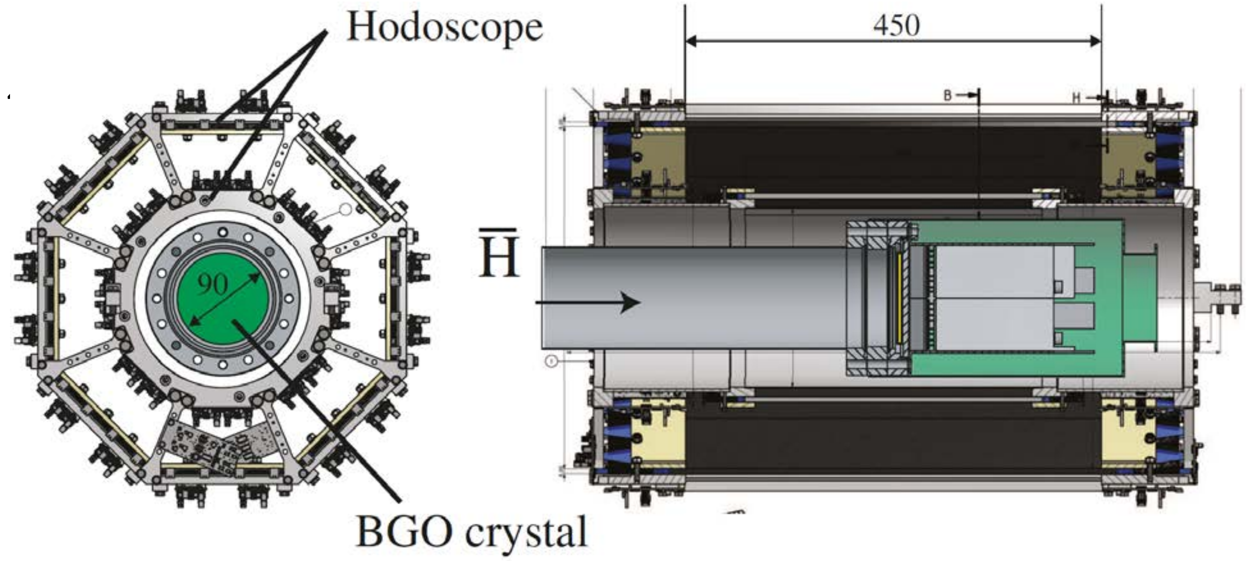


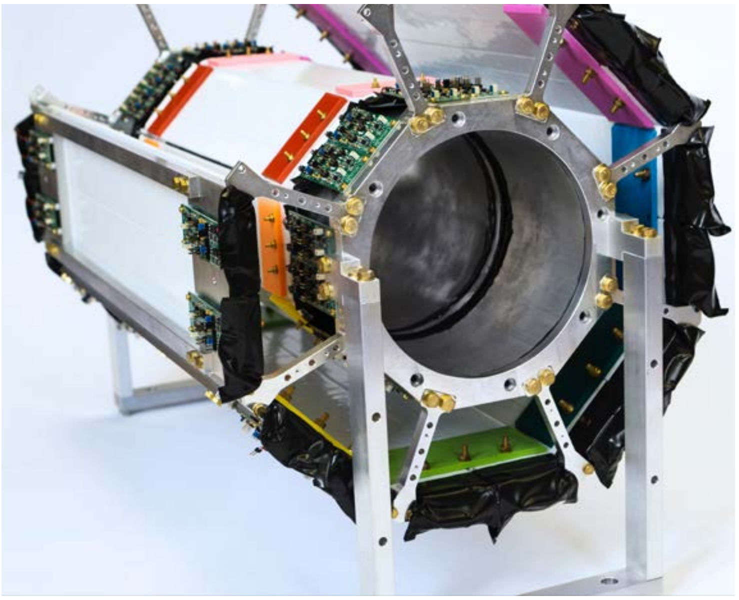
N. Kuroda et al, *Nat. Commun.* **5,** 3089 (2014).



$\bar{\mathrm{H}}$ detector analysis of 2016 data

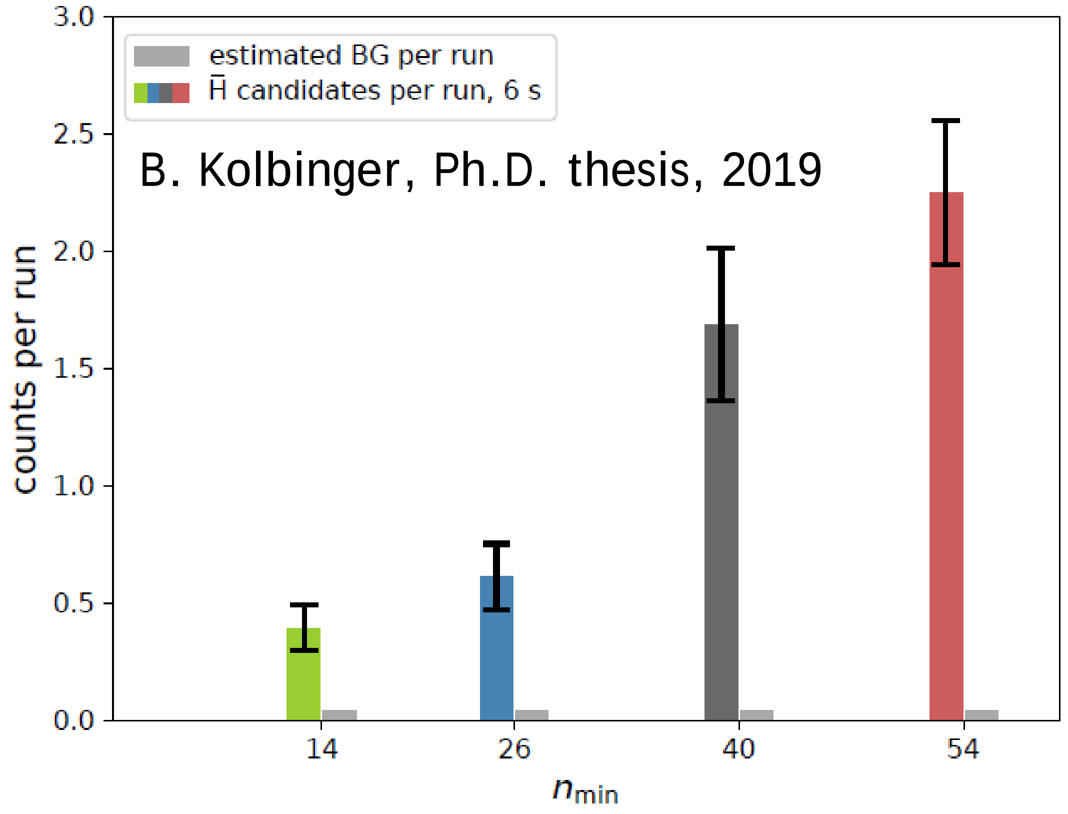
- Direct injection scheme
-



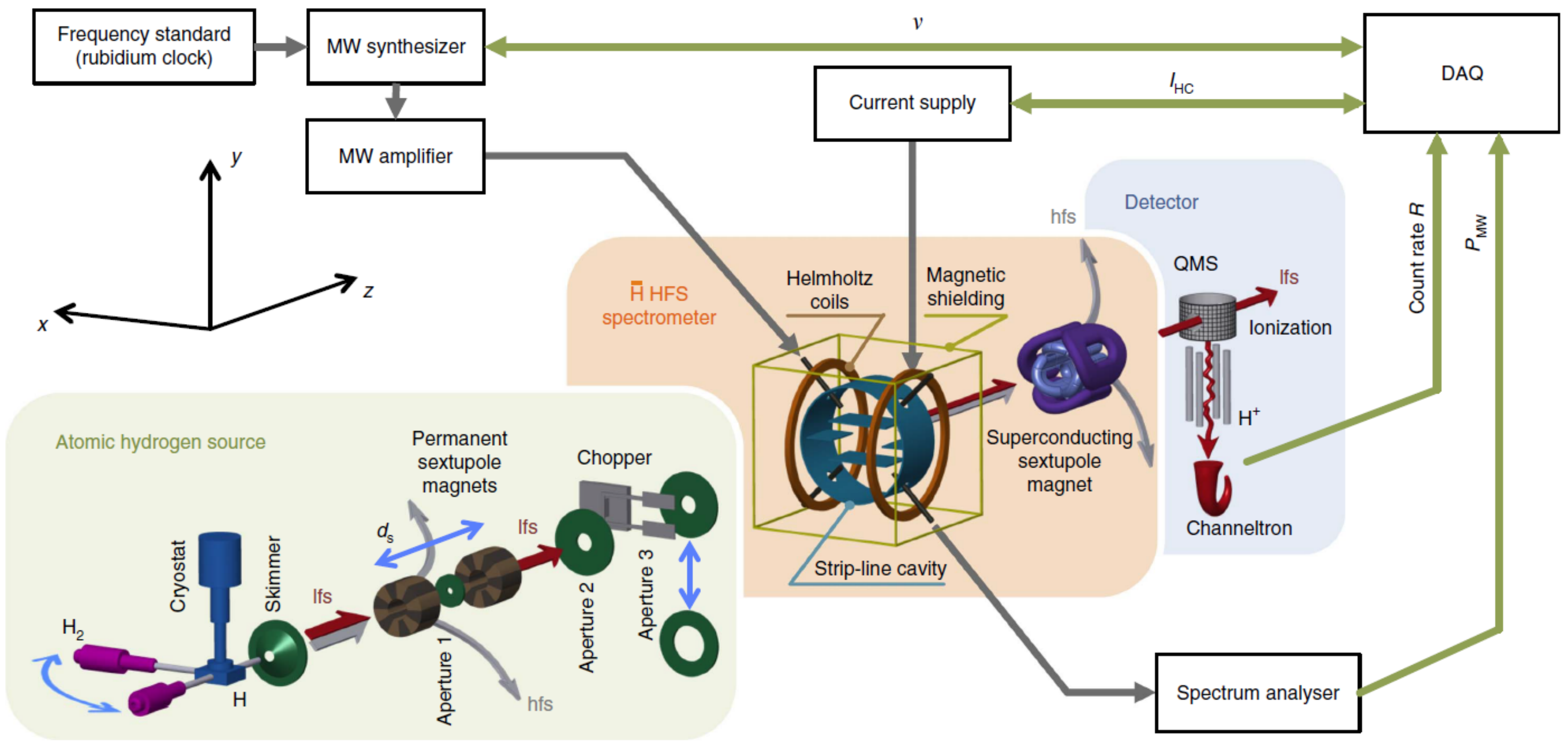


- Machine learning optimization
  - Cosmics rejection 98,4%
  - False positive rate: 0.0077(15) s^{-1}
  - $\bar{p}$ efficiency 80(1)%

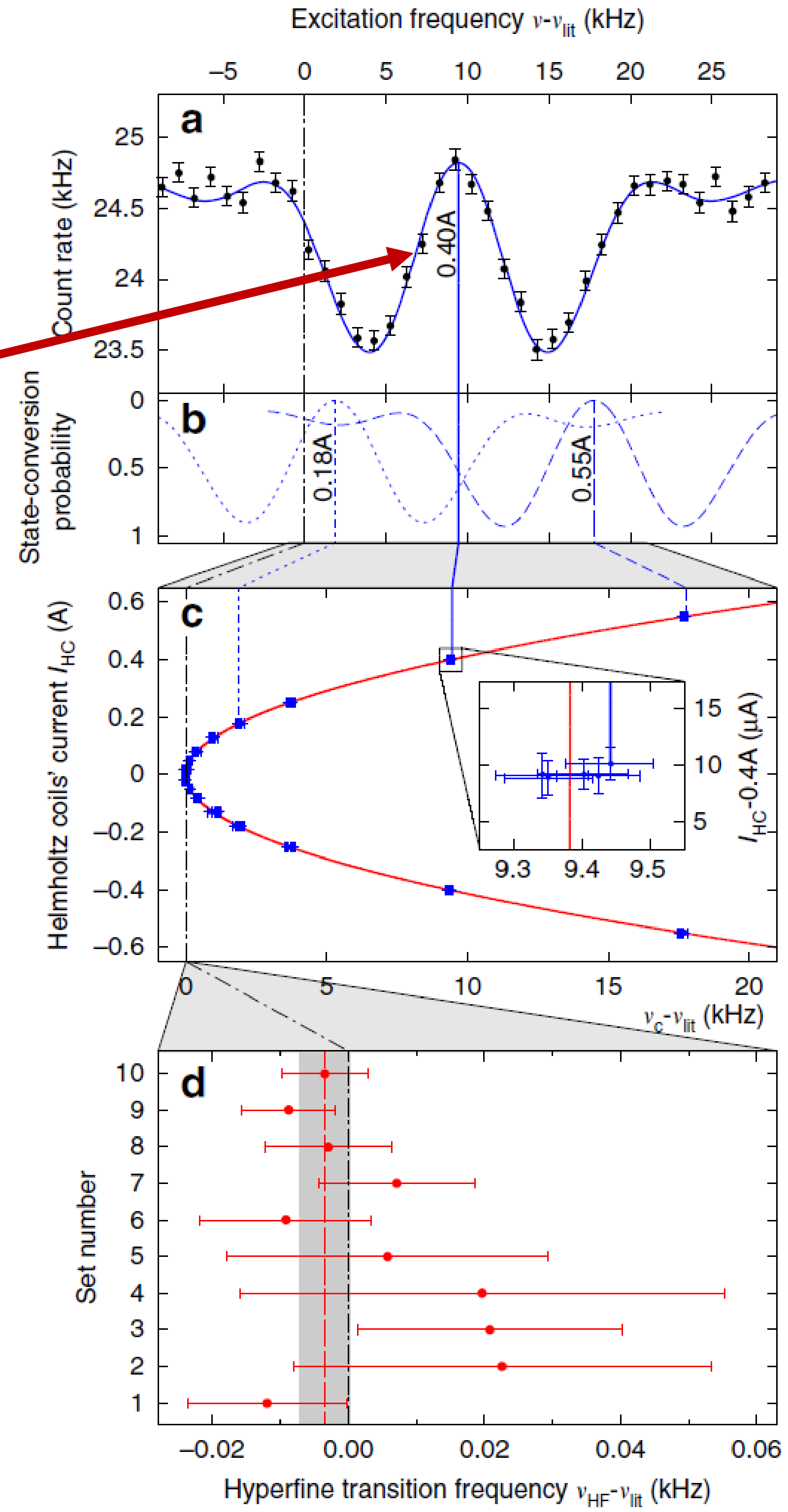
n<14 rate 0.16 → **0.395(96)/cycle**
P-value significance 4.5σ → **6.8 σ**
17 evts/5 shifts: 4σ poisson
τ(n=14 →n=1) ~ 50 µs
Needed: 2000 $\bar{\mathrm{H}}$(1S)/B_{ext} for 1 ppm



σ-transition in H using $\bar{\mathrm{H}}$ setup



Line width ~ 6 kHz:
4 ppm
(v~900 m/s)



$$\nu_{\mathrm{HF}}=1\ 420\ 405\ 748.4(3.4)(1.6)\ \mathrm{Hz}$$

Received 4 Oct 2016 | Accepted 24 Apr 2017 | Published 12 Jun 2017 DOI: 10.1038/ncomms15749 OPEN

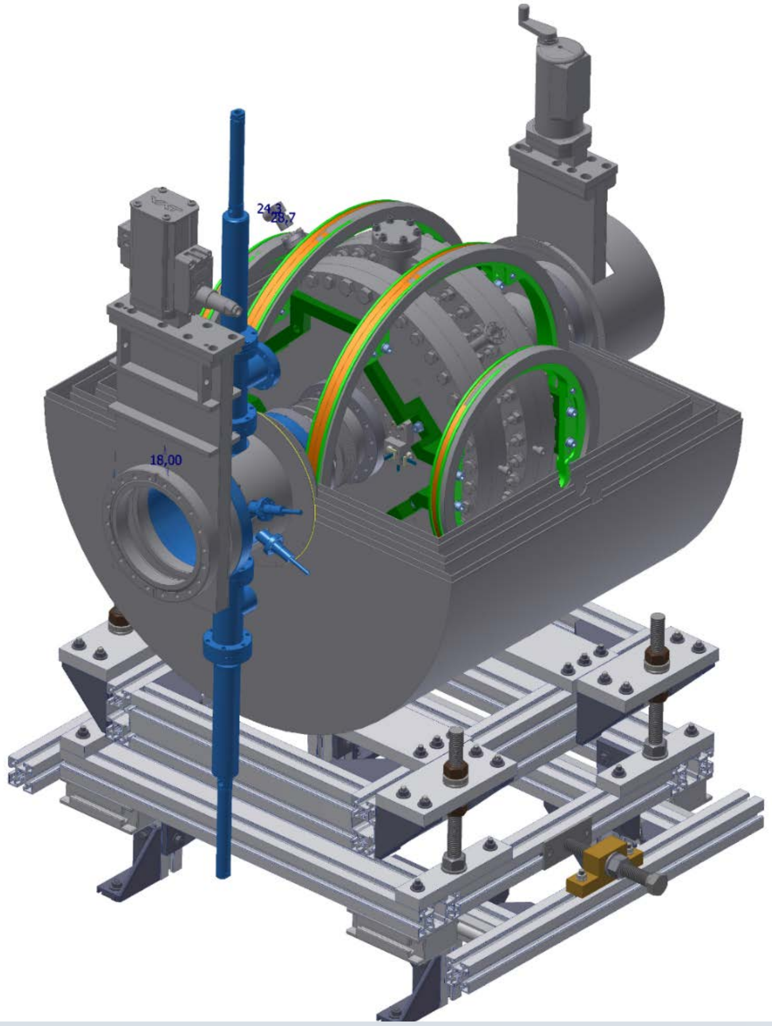
In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

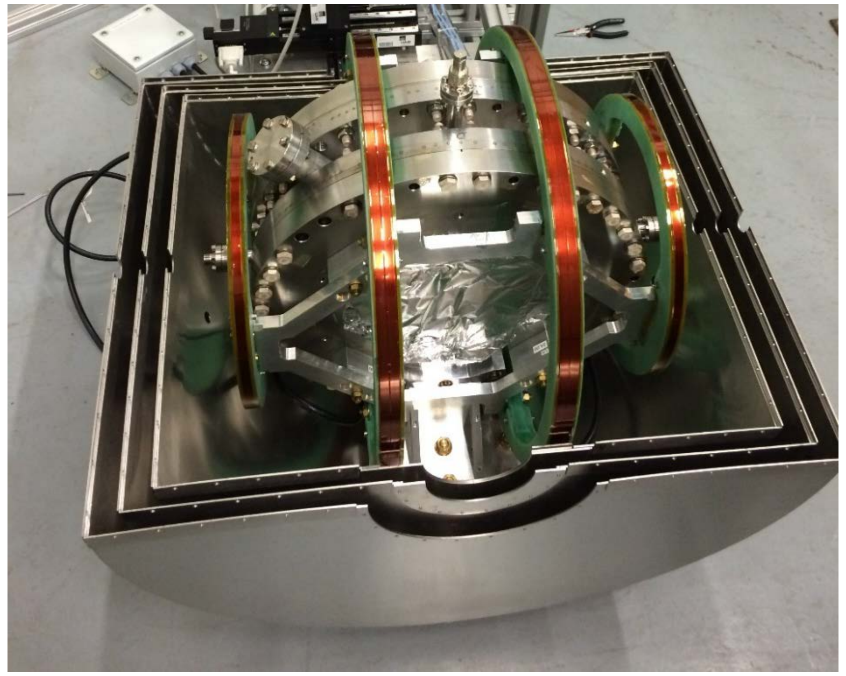
M. Diermaier[1], C.B. Jepsen[2,†], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]

Error **2.7 ppb**: 18x improvement over
Kush, Phys. Rev. 100, 1188 (1955)
Deviation from maser ($\Delta f/f \sim 10^{-12}$) :
3.4 Hz < 1σ error
Extrapolation to $\bar{\mathrm{H}}$: **8000** atoms needed to achieve **1 ppm**

H-beam next steps and non-minimal SME

- π_1 transition
  - Better field homogeneity
    - Inproved coils, shielding
  - SME: effect only in π_1
  - Non-minimal SME: direction dependent coefficients accessible by beam
- Conditions
  - Invert direction of B-field
  - Rotate B-field
  - Measure also σ_1 (no CPTV) as reference



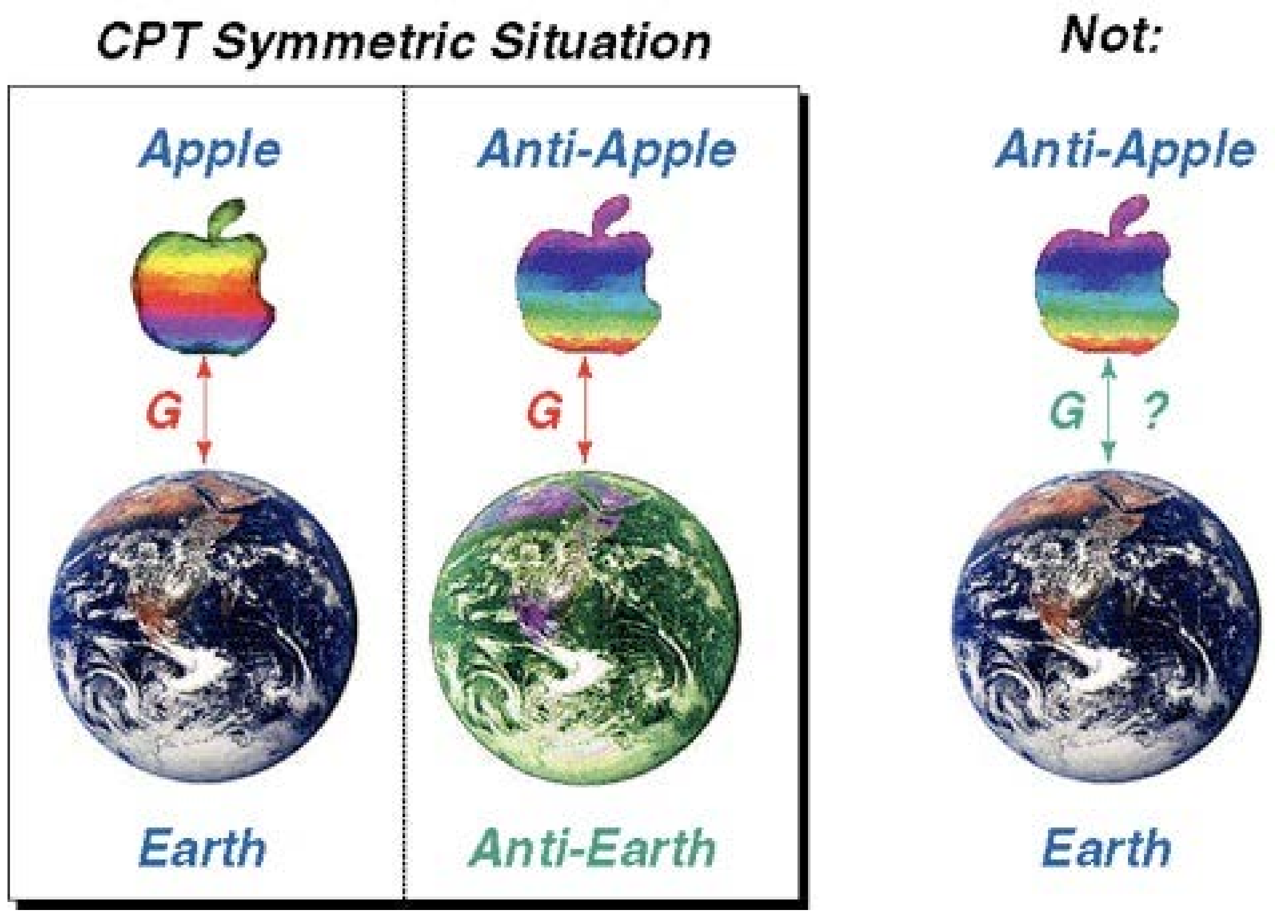


$$\Delta(2\pi\nu_\pi) \equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B})$$
$$= -\frac{\cos\vartheta}{\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_r)^{2q}(1+4\delta_{q2}) \sum_w \left[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)} - 2H_{w(2q)10}^{\mathrm{NR,Sun}(1B)}\right]$$

Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

Gravitational Acceleration of Antimatter

- No direct test of CPT
  - Weak equivalence principle
- no precise experimental test available
  - $|m_{grav}/m_{inertial}| < 110$ *
- indirect arguments against antigravity exist
- Highest precision reachable with neutral antimatter
  - AEḡIS
  - Antimatter Experiment - ḡravity, Interferometry, Spectroscopy



*ALPHA collaboration, Nature Communications 4, 1785 (2013)

Antimatter and gravity

- Antigravity: gmatter = −gantimatter
  - separation of matter and antimatter in Universe
- Quantum gravity
  - Graviton (S=2) → adds Gravivector (S=1), Graviscalar (S=0)
  - simplest case: static potential

$$V = -\frac{G m_1 m_2}{r}\left(1 \mp a\, e^{-r/v} + b\, e^{-r/s}\right)$$

  - a: Gravivector, b: Graviscalar
  - − attractive (matter-matter), +: repulsive: matter-antimatter
  - matter experiments: |a−b|
  - antimatter: a+b

ALPHA gravity measurement

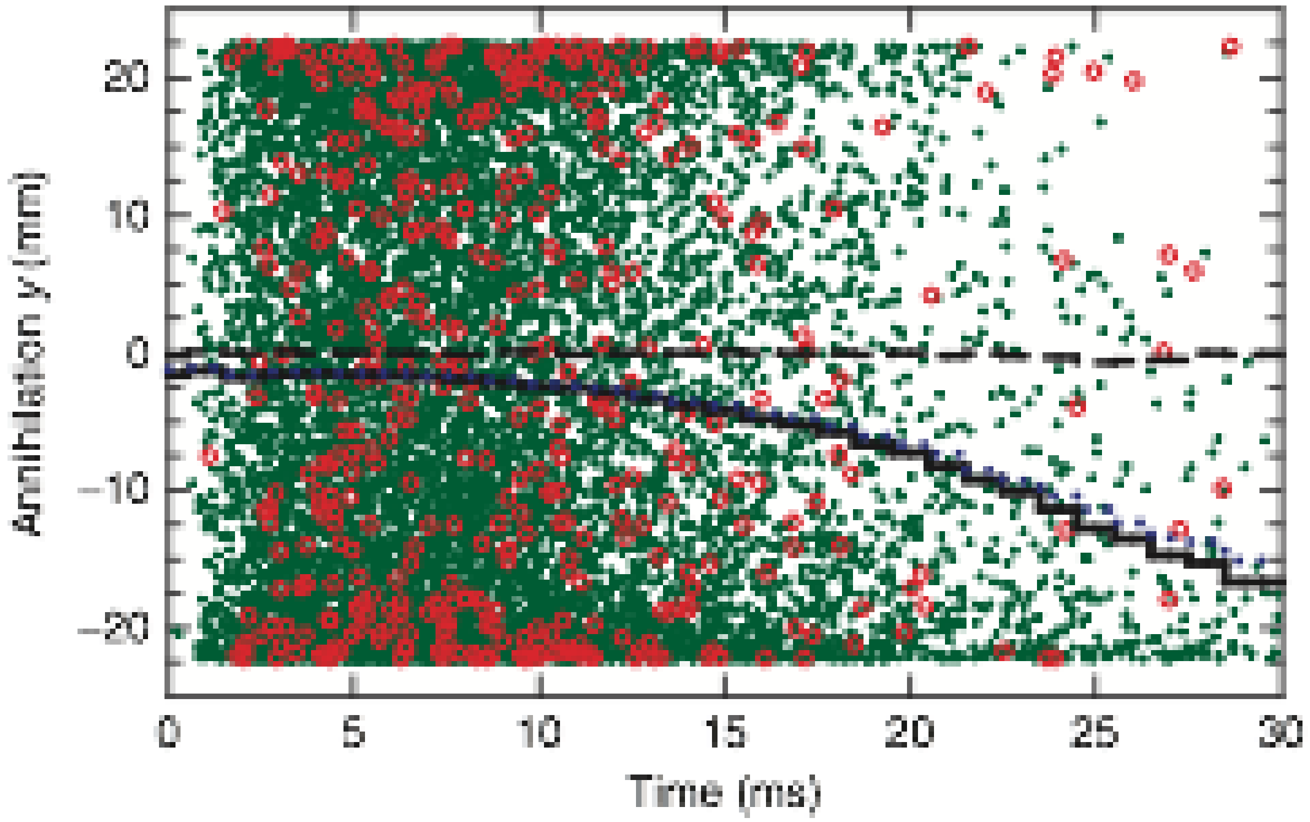
- Release trapped $\bar{\mathrm{H}}$
- too hot for gravitational force
  - limits on ratio inertial and gravitational mass
- Gravity
  - no systematics
    - $m_{grav}/m_{inertial} < 75$
  - with systematics
    - $m_{grav}/m_{inertial} < 110$
- Antigravity
  - $m_{grav}/m_{inertial} > -65$

ARTICLE

Received 14 Jan 2013 | Accepted 22 Mar 2013 | Published 30 Apr 2013 DOI: 10.1038/ncomms2787 OPEN

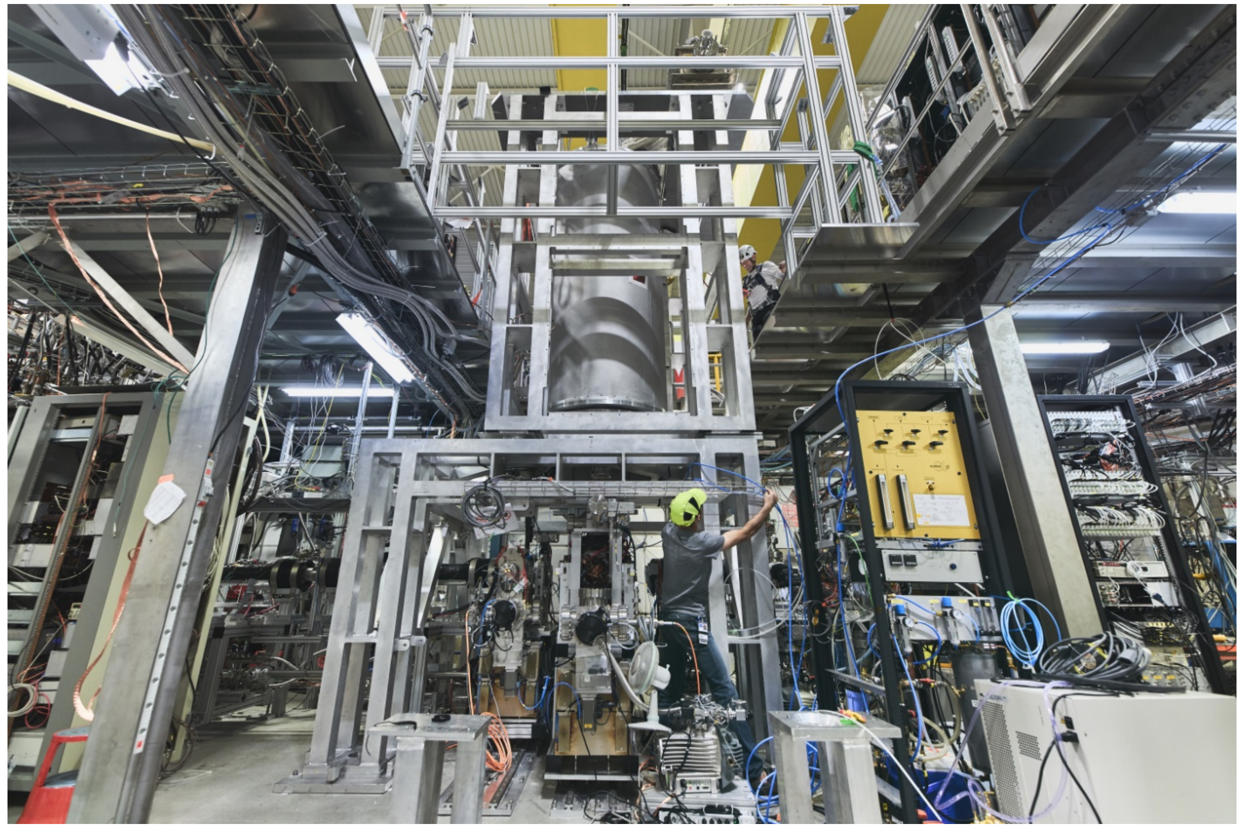
Description and first application of a new technique to measure the gravitational mass of antihydrogen

The ALPHA Collaboration* & A.E. Charman[1]

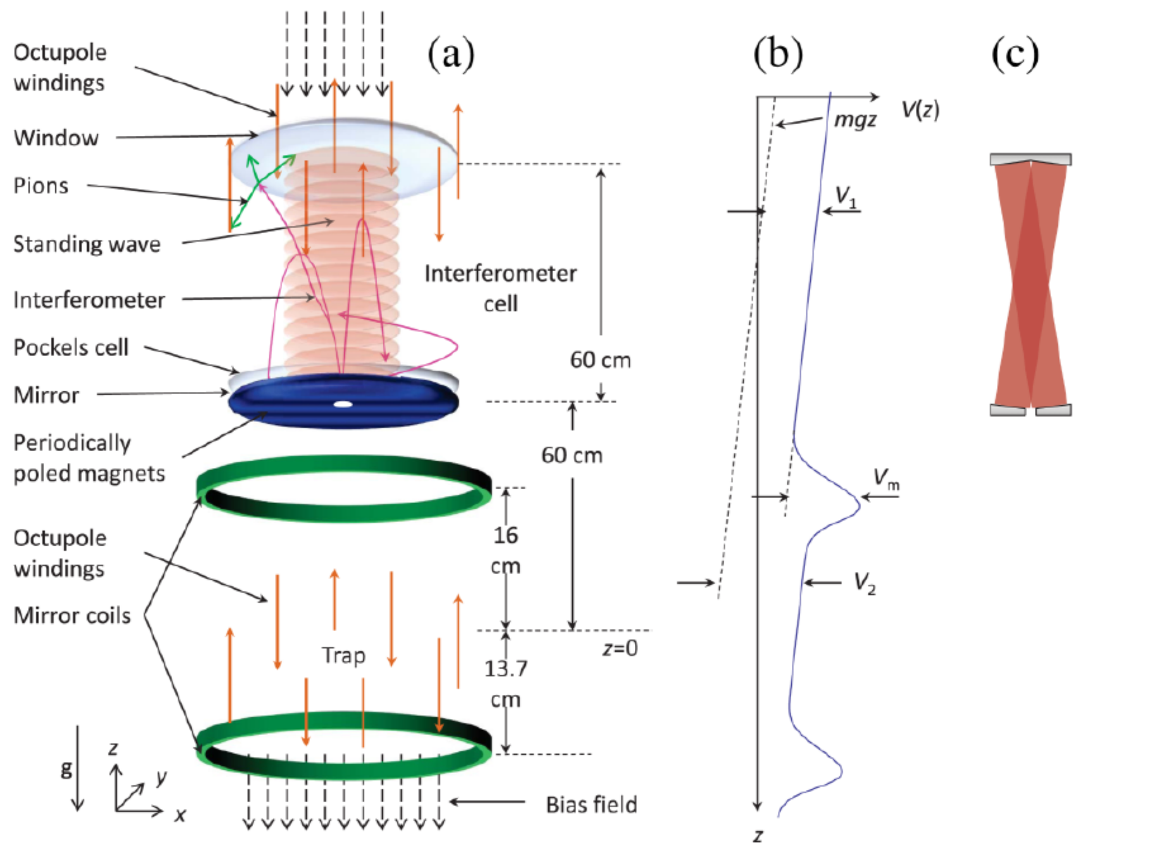


ALPHA-g

- Vertical trap
- Laser cooling
- Installed for ELENA



PRL **112,** 121102 (2014) PHYSICAL REV

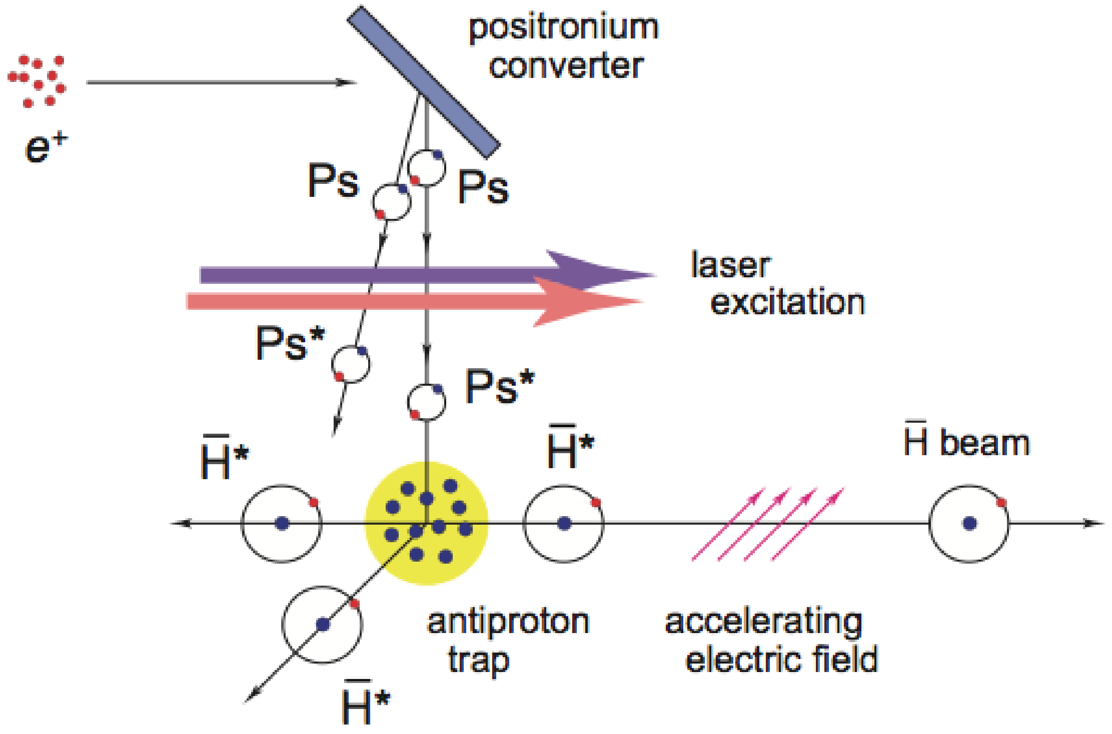


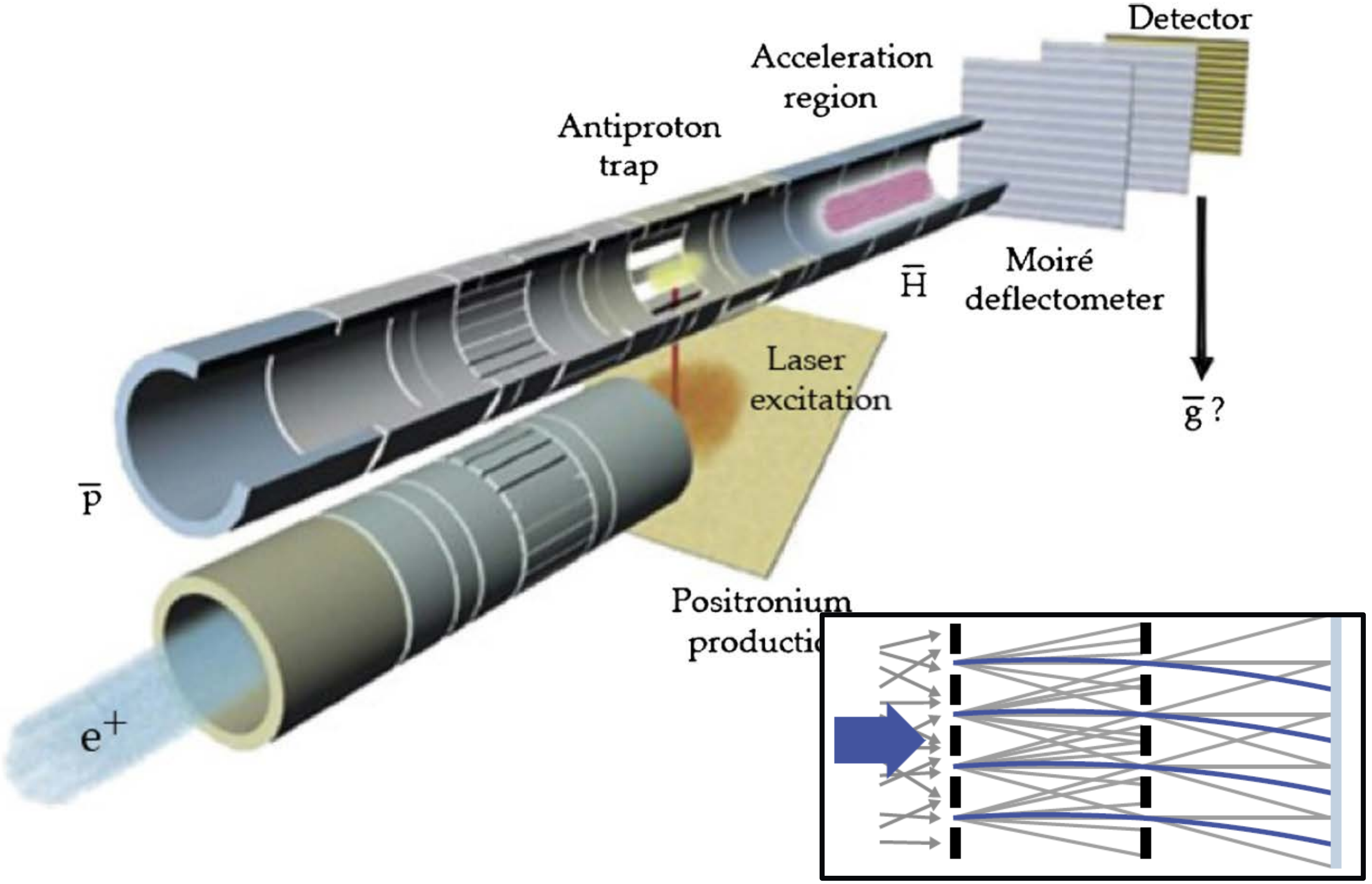
PRL **112,** 121102 (2014) PHYSICAL REVIEW LETTERS week ending 28 MARCH 2014

Antimatter Interferometry for Gravity Measurements

Paul Hamilton,[1] Andrey Zhmoginov,[1] Francis Robicheaux,[2,‡] Joel Fajans,[1,†] Jonathan S. Wurtele,[1,†] and Holger Müller[1,*,†]
[1]*Physics Department, University of California, Berkeley, California 94720, USA*
[2]*Department of Physics, Auburn University, Auburn, Alabama 36849, USA*
(Received 12 August 2013; published 25 March 2014)

AEḡIS: cold beam





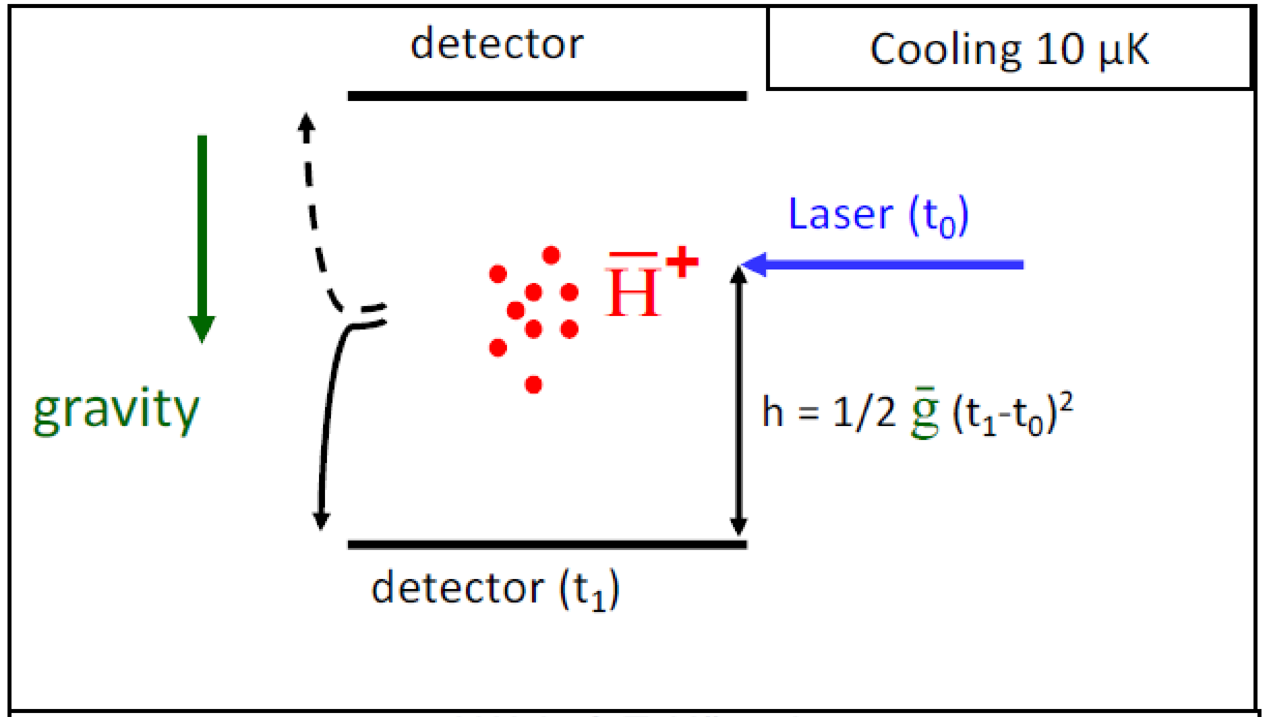
$$Ps^* + \bar{p} \rightarrow e^+ + \bar{H}$$

$$h = \frac{1}{2}\bar{g}t^2$$

GBAR

Principle

- $\overline{H}^{+} = \bar{p}\, e^{+}e^{+}$
- Sympathetic cooling with $Be^{+} \rightarrow 10\ \mu K$
- Photodetachment of e^{+}
- Time of flight (h = 10 cm → Δt = 0.14 s)



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561

Beam production

- instead of 3-body process with 2 e^{+}
- use $Ps = e^{+}e^{-}$, twice
- excite Ps (n=3)

$$\bar{p} + Ps \rightarrow \overline{H} + e^{-}$$

$$\overline{H} + Ps \rightarrow \overline{H}^{+} + e^{-}$$

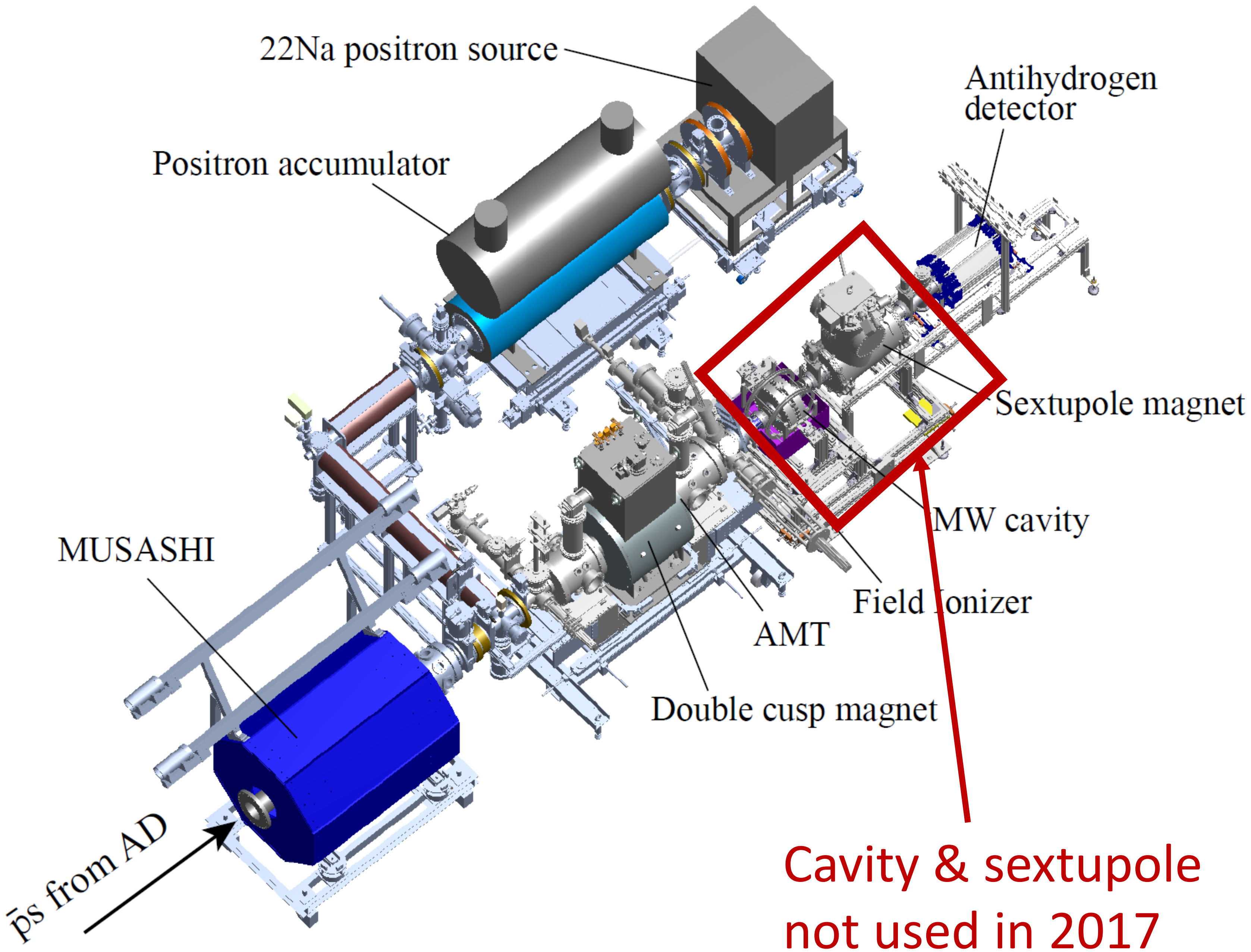
P.Pérez & A. Rosowsky, NIM **A 532** (2004) 523

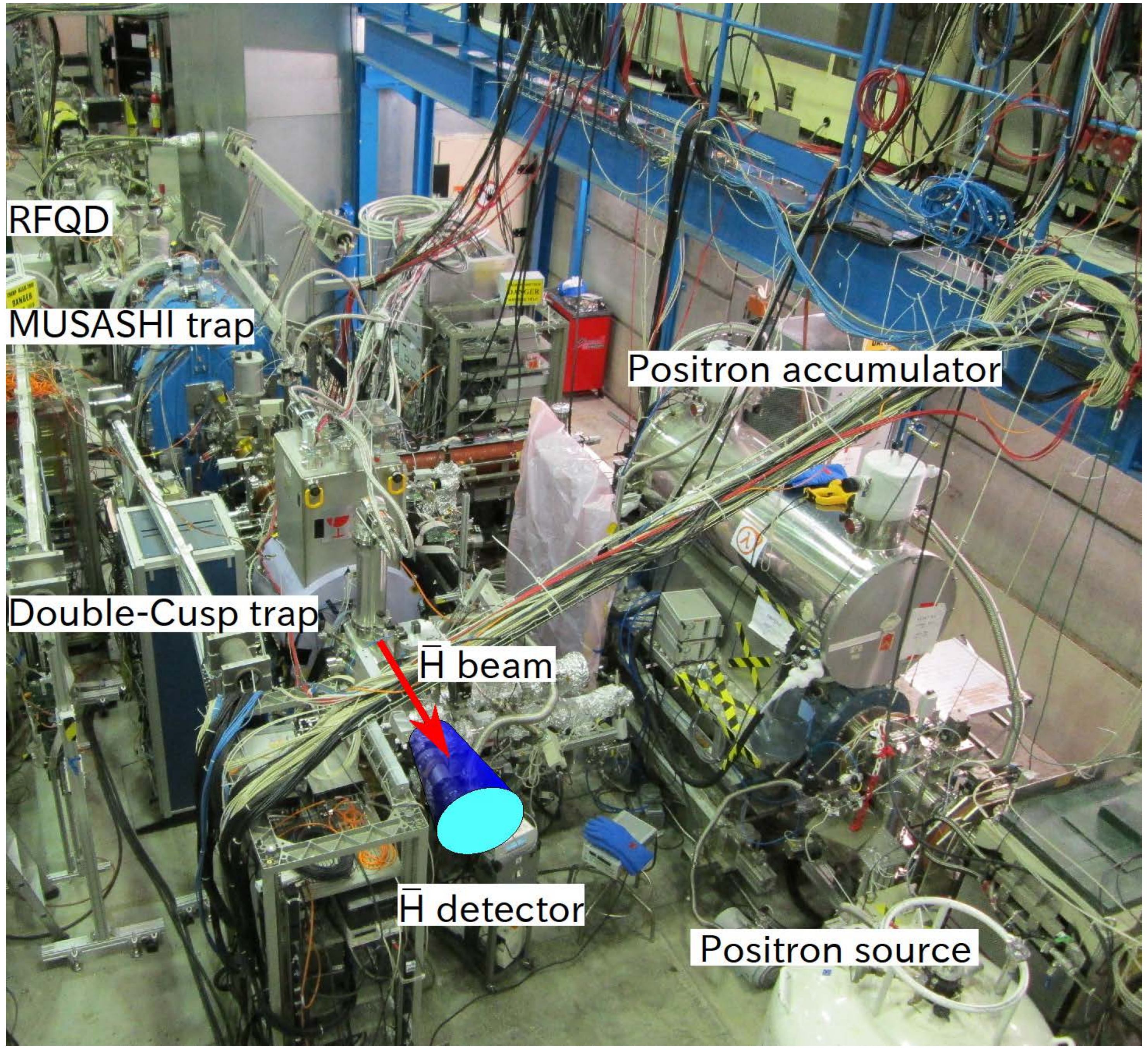
Summary

- First spectroscopy results with antihydrogen
  - 1s-2s (~10^{-12}), 1s-2p (~10^{-8}), HFS (~10^{-4})
  - No SME coefficients yet determined
  - More to come with ELENA 2021 onwards
- Antimatter gravity experiments under preparation

Spares

Setup





Cavity & sextupole not used in 2017

First observation of $\bar{H}$ beam

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

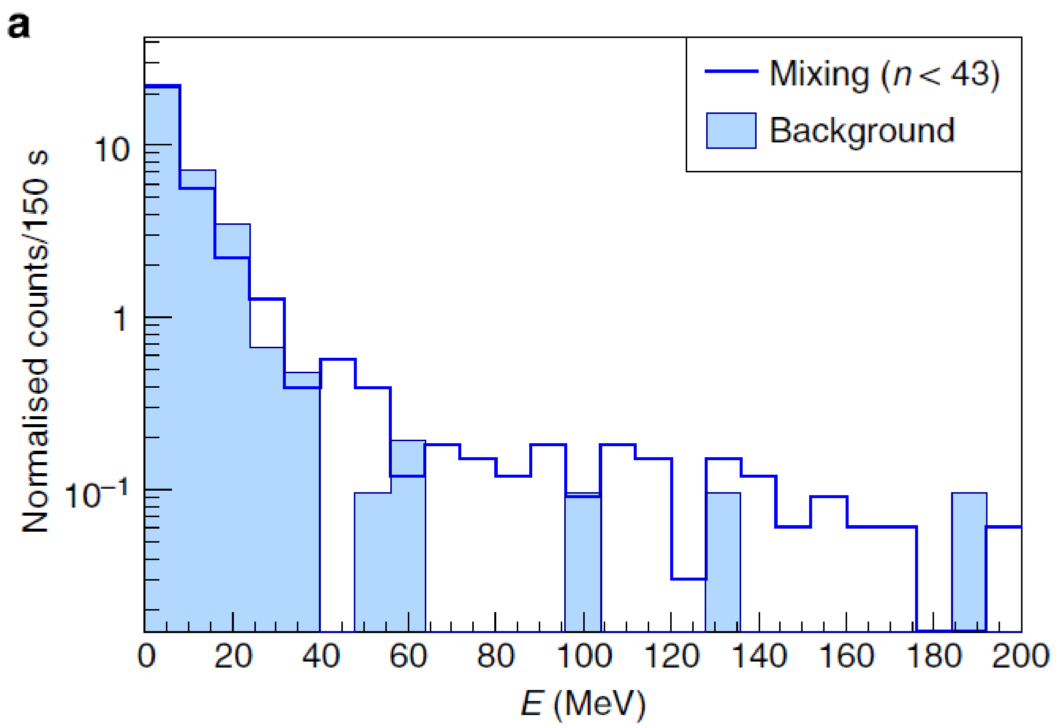


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

	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	—

$n \leq 43$ $n \leq 29$

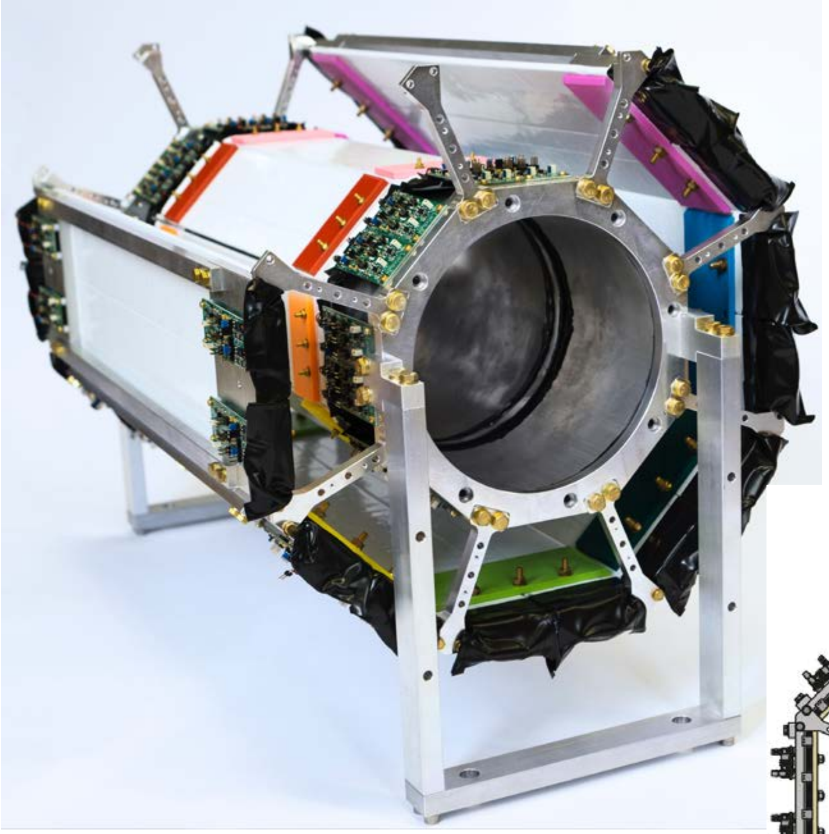
N. Kuroda[1], S. Ulmer[2], D.J. Murtagh[3], S. Van Gorp[3], Y. Nagata[3], M. Diermaier[4], S. Federmann[5], M. Leali[6,7], C. Malbrunot[4,†], V. Mascagna[6,7], O. Massiczek[4], K. Michishio[8], T. Mizutani[1], A. Mohri[3], H. Nagahama[1], M. Ohtsuka[1], B. Radics[3], S. Sakurai[9], C. Sauerzopf[4], K. 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

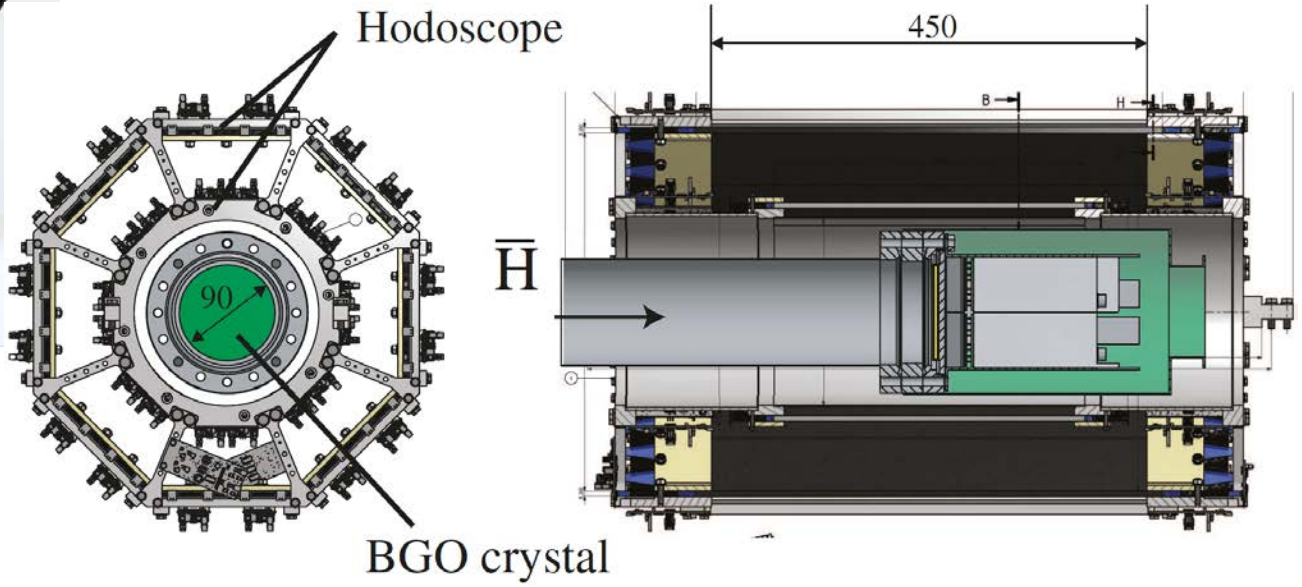
$\bar{H}$ detector analysis

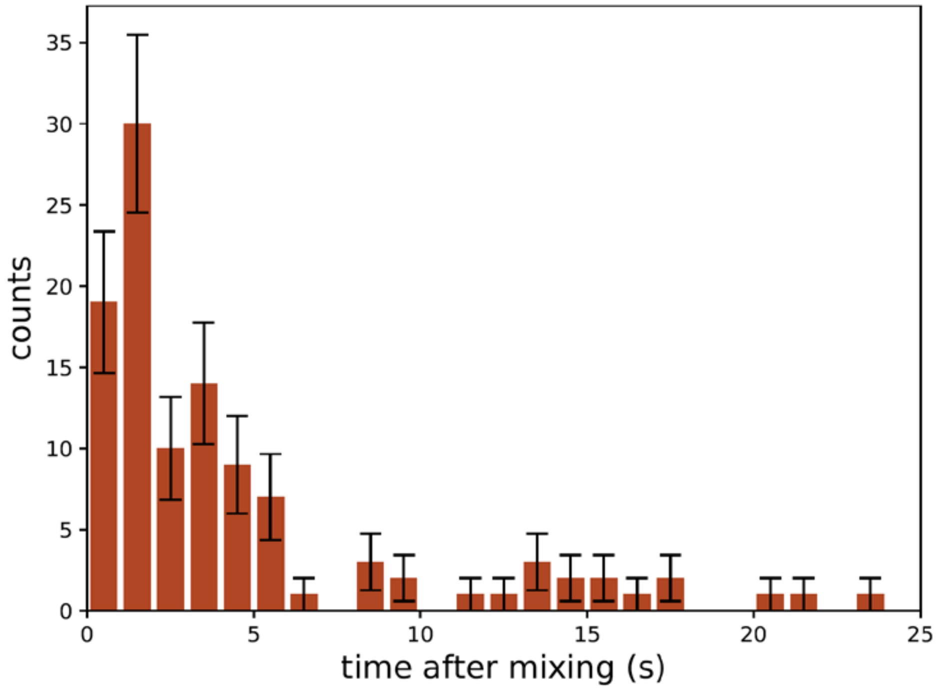
- 2D BGO & track fitting

- Machine learning
  - Cosmics rejection 99,7%
  - False positive rate: 0.0039 s–1
  - $\bar{p}$ efficiency ~ 80%



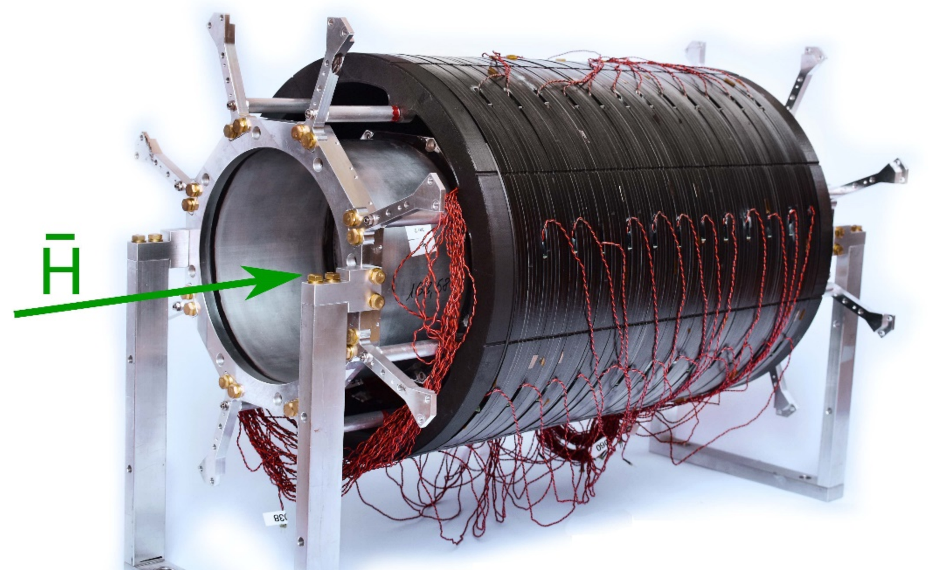
PhD Clemens Sauerzopf



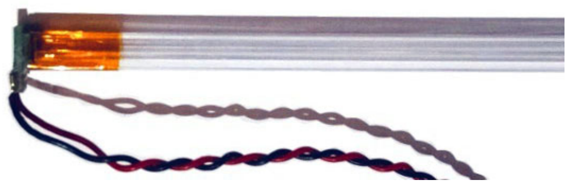


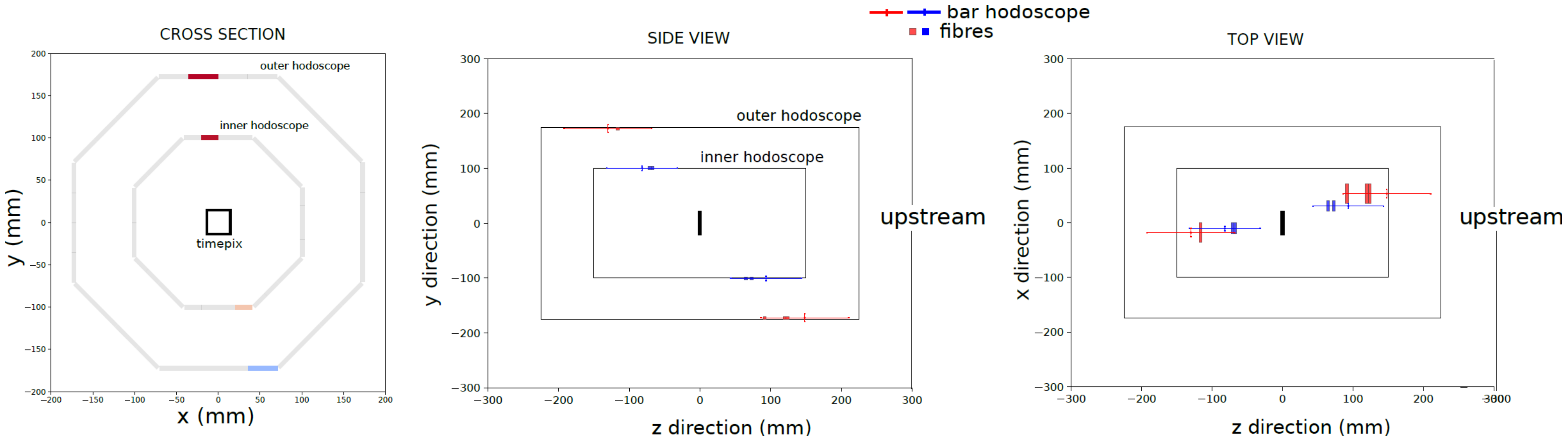
$\bar{H}$ counts (110) at the detector during 104 mixing cycles with FID in 2017

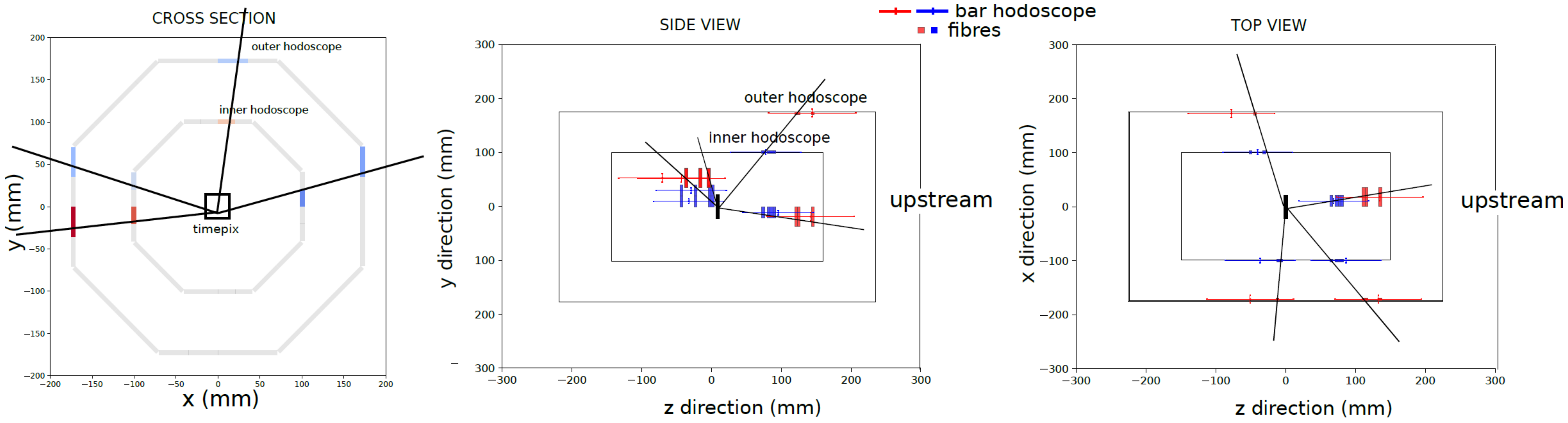
Antihydrogen detector fibre upgrade



(Without hodoscope bars)



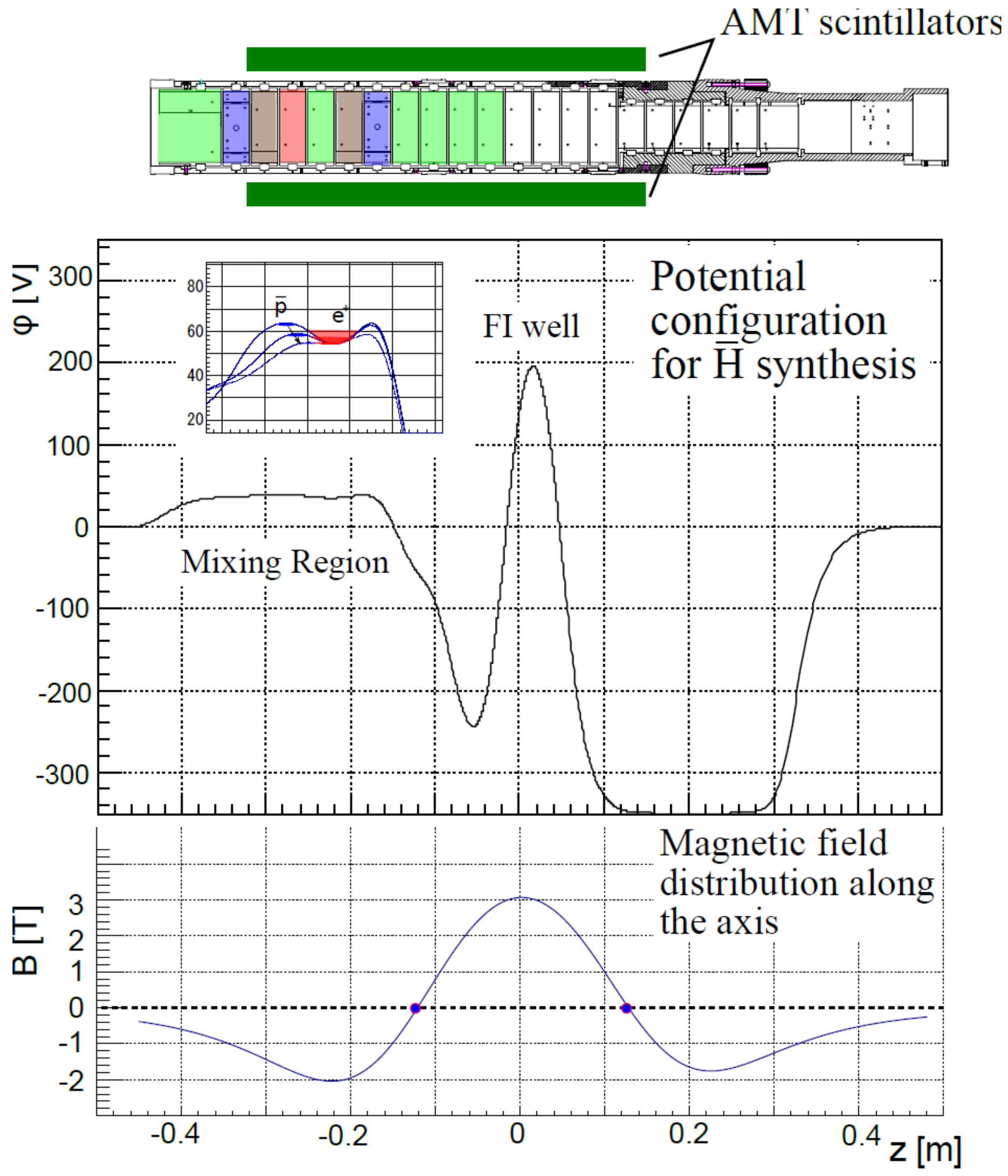




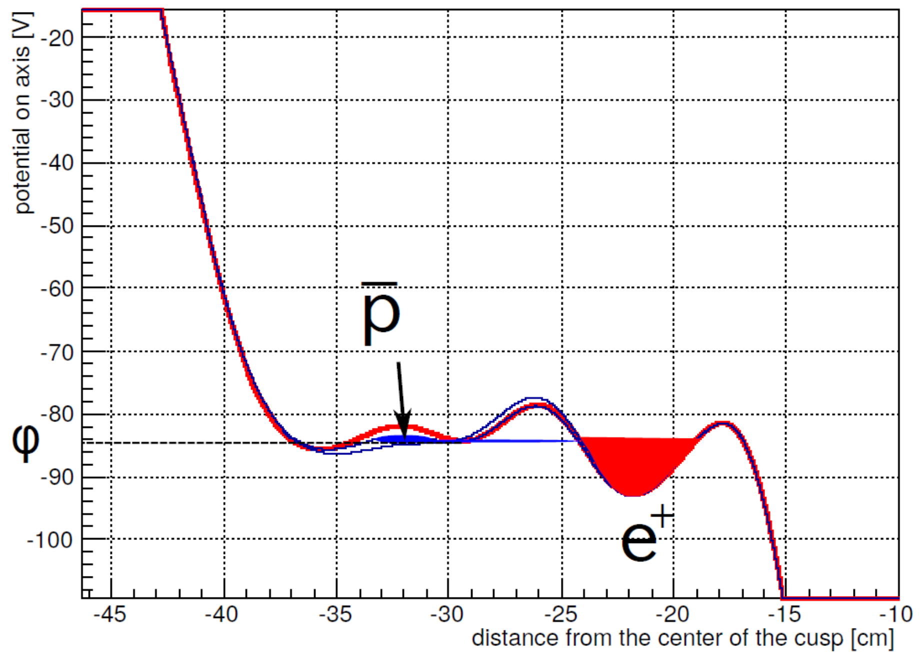
Fibre bundle 2x2 of 1x1 mm2 fibres
2 layers
7.7 mm geometrical resolution in *z* at *r*=0

PhD Bernadette Kolbinger

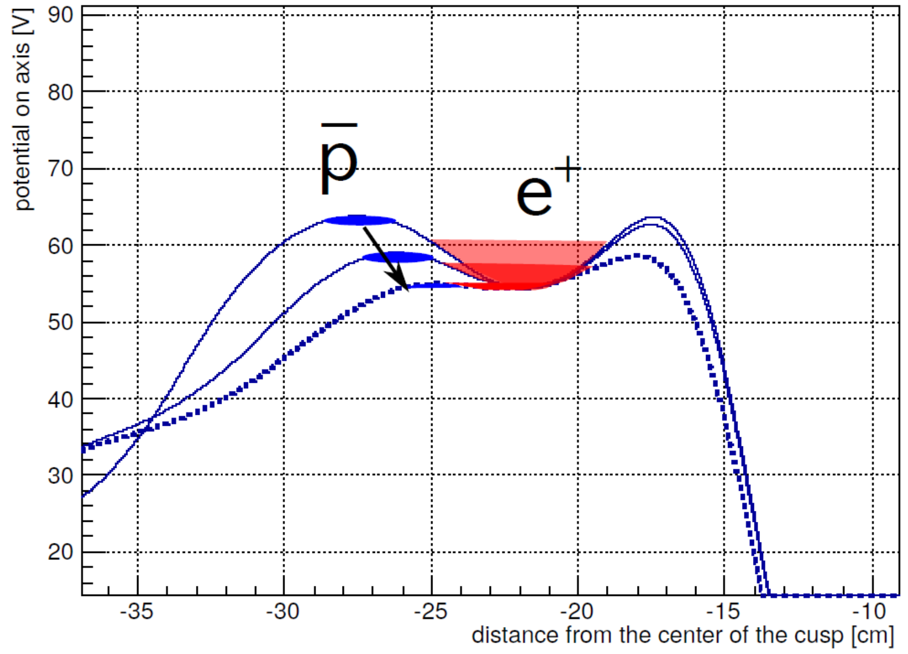
New mixing schemes 2017~



- Slow extraction scheme



- Cross merging scheme



Future directions

- Increase production rate
  - Positron temperature, density

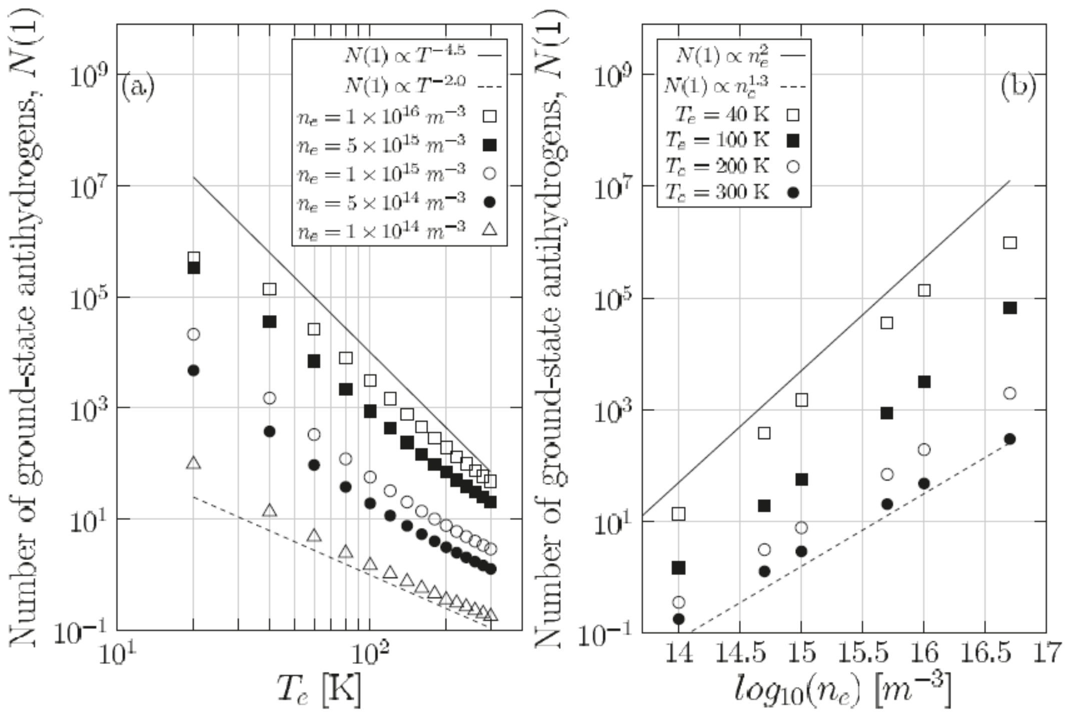


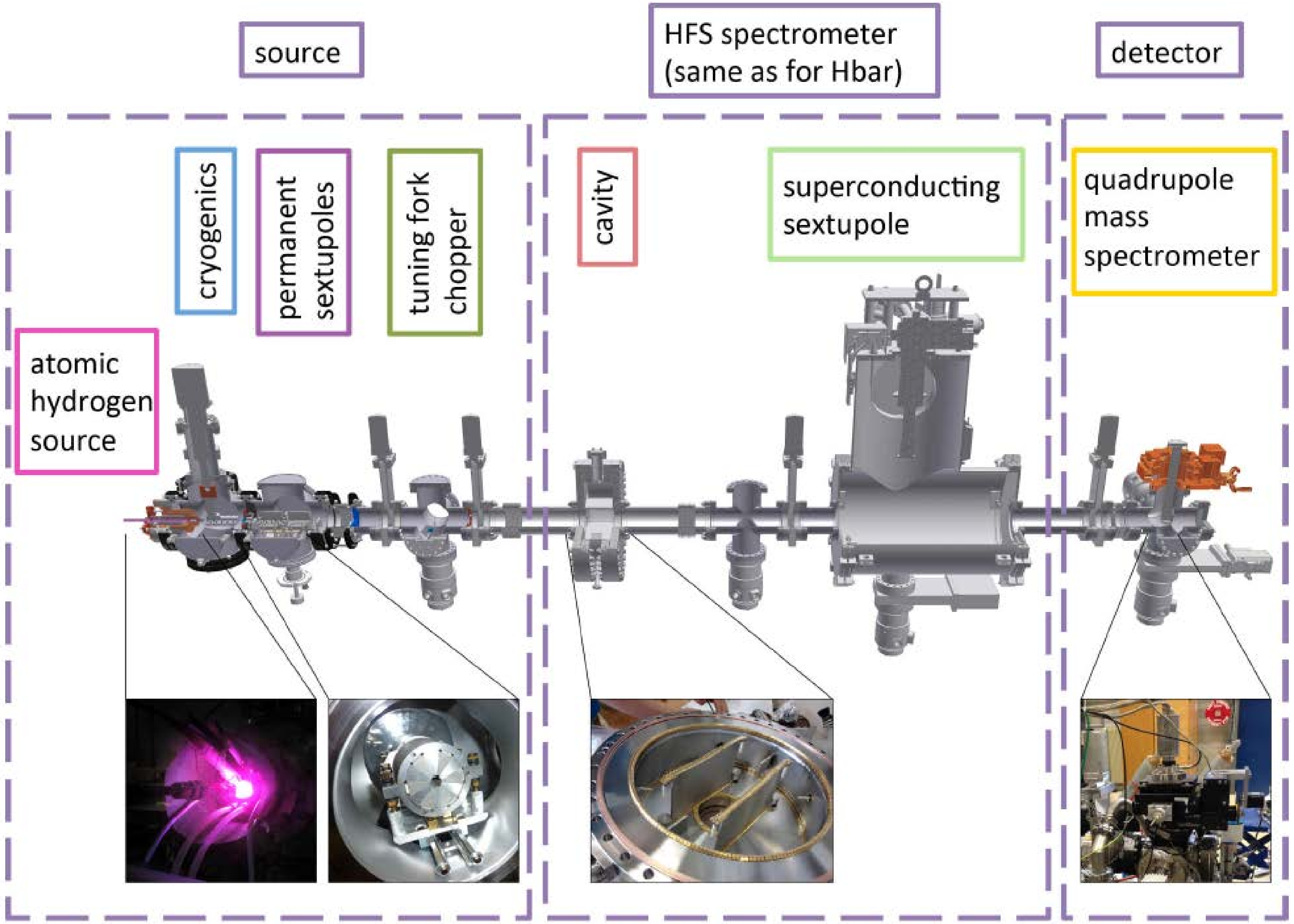
FIG. 6. Dependence of ground-state antihydrogen atoms on positron temperature (a) and density (b) for various positron density and temperature values (respectively) after 1 ms of flight. The $\propto n_e^2 T_e^{-4.5}$ (solid line) and $\propto n_e^{1.3} T^{-2.0}$ (dashed line) scaling behaviors are indicated for reference.

Radics, B., Murtagh, D. J., Yamazaki, Y. & Robicheaux, *Phys. Rev. A* 90, 1–6 (2014).

- Other improvements
  - Deexcite high-n Hbar
    - Starck mixing: simulations
    - THz radiation, MW: Chloé
- Other geometries
  - Inhomogeneous CUSP field -> mixing in MUSASHI?
    - CUSP magnet makes inhomoeneous field at cavtiy
  - New ideas?

Hydrogen beam measurements

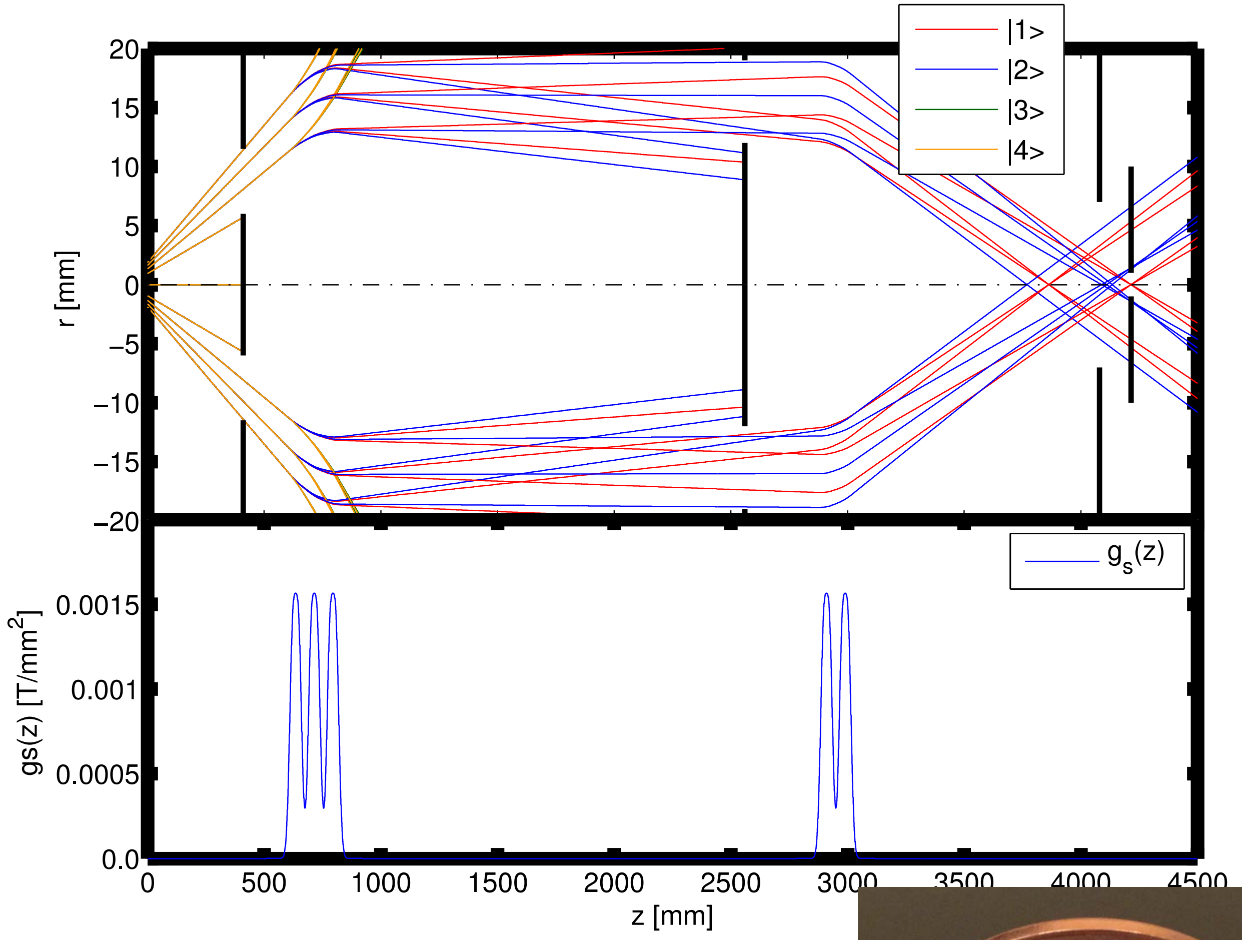
- Polarized source of cold hydrogen
- Primary goal: verify spectroscopy method:
  - reproduce expected antihydrogen beam parameters
  - Use same spectroscopy apparatus



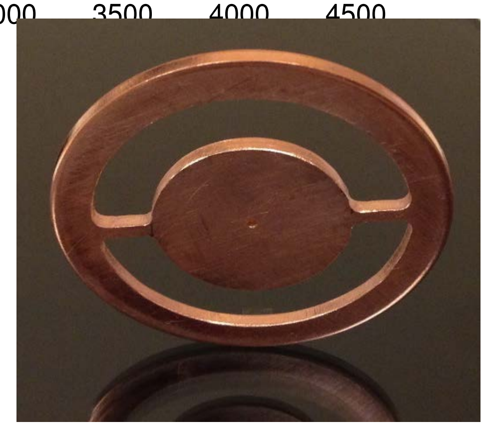
Malbrunot, C., et al., NIMA *935*, 110–120 (2019)

First π_1 measurements

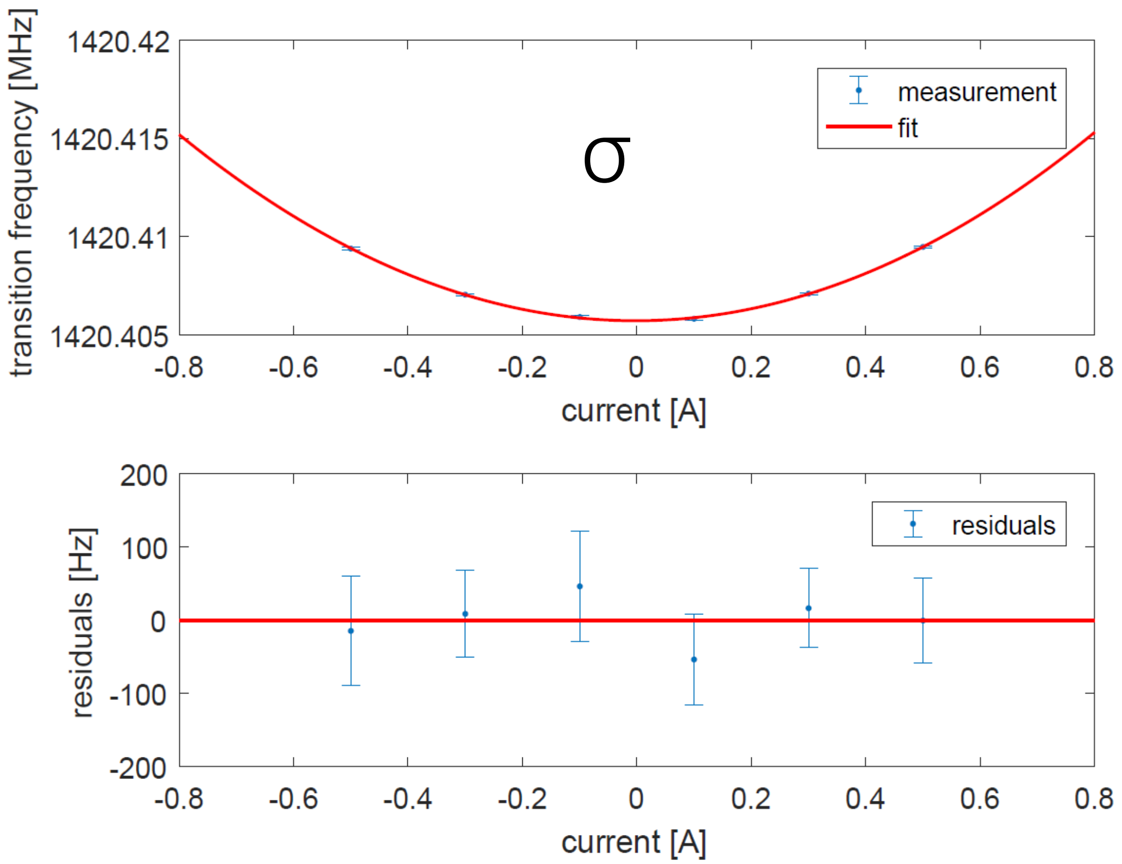
- New optics

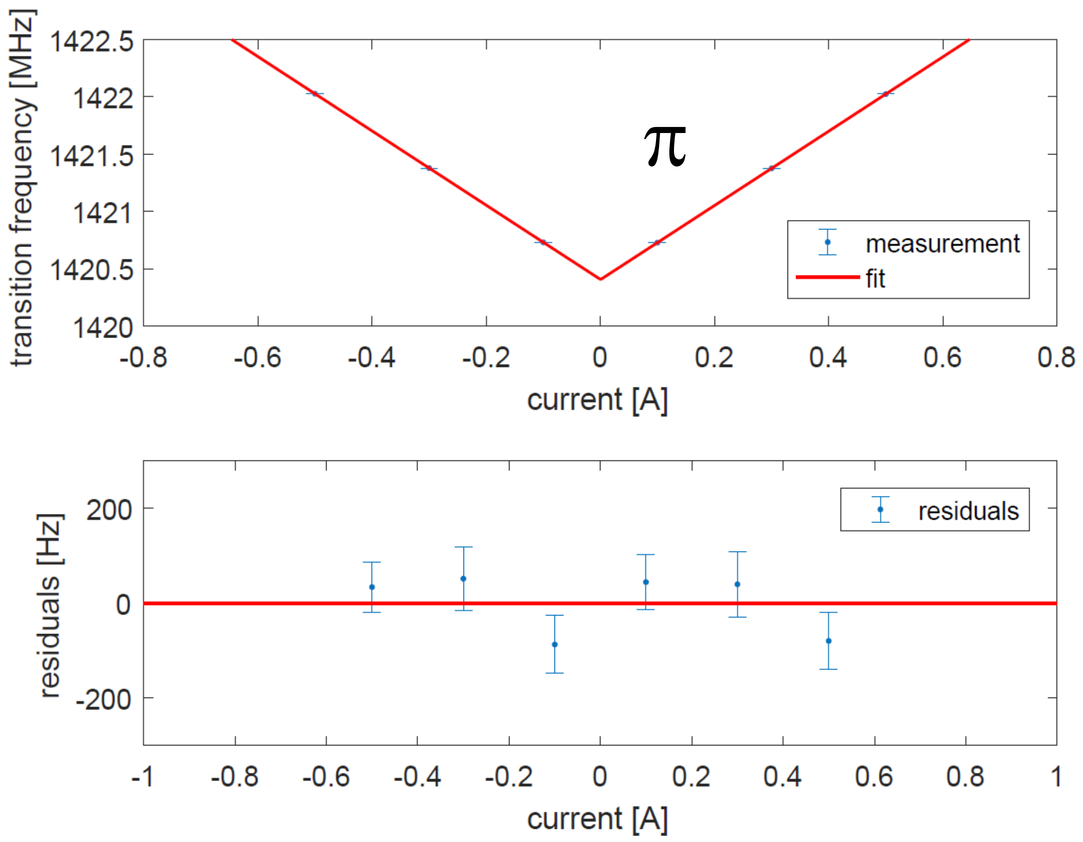


Ring aperture



- 1st extrapolations





- Accuracy $\nu_{HF}(B=0)$~ 10 Hz
  - ~ 100 hours of data taking
  - Measurement campaign to start soon

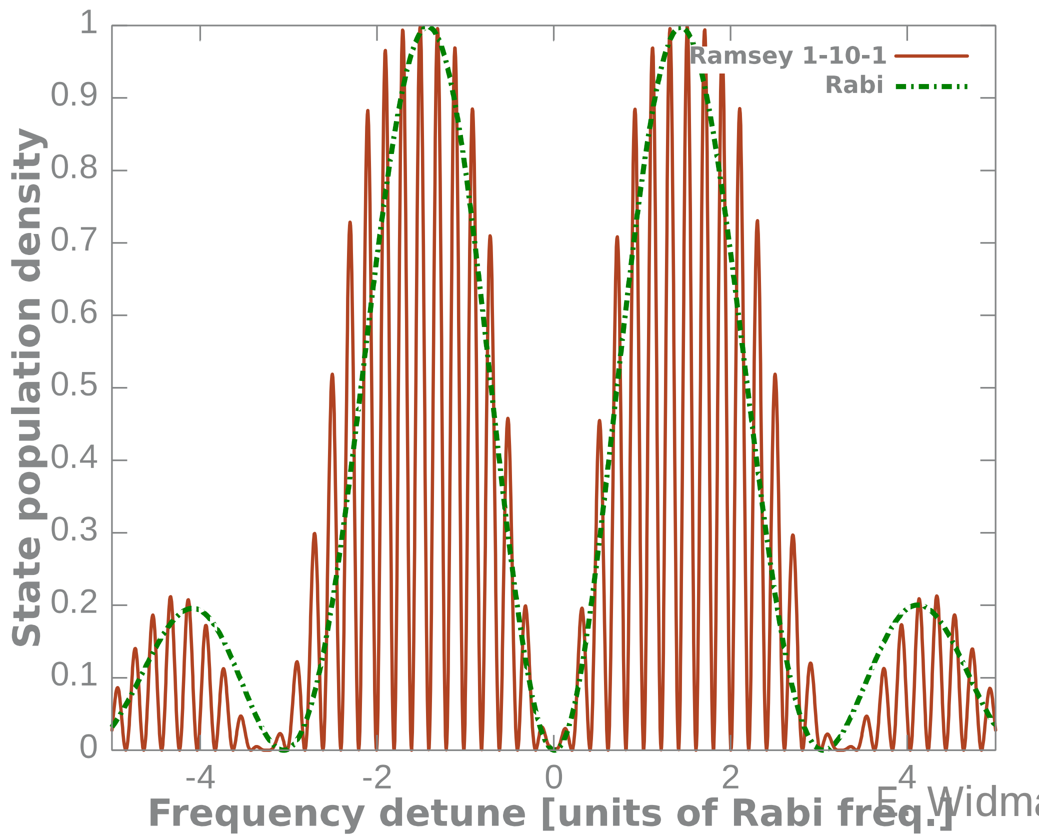
EW at al. arXiv:1809.00875

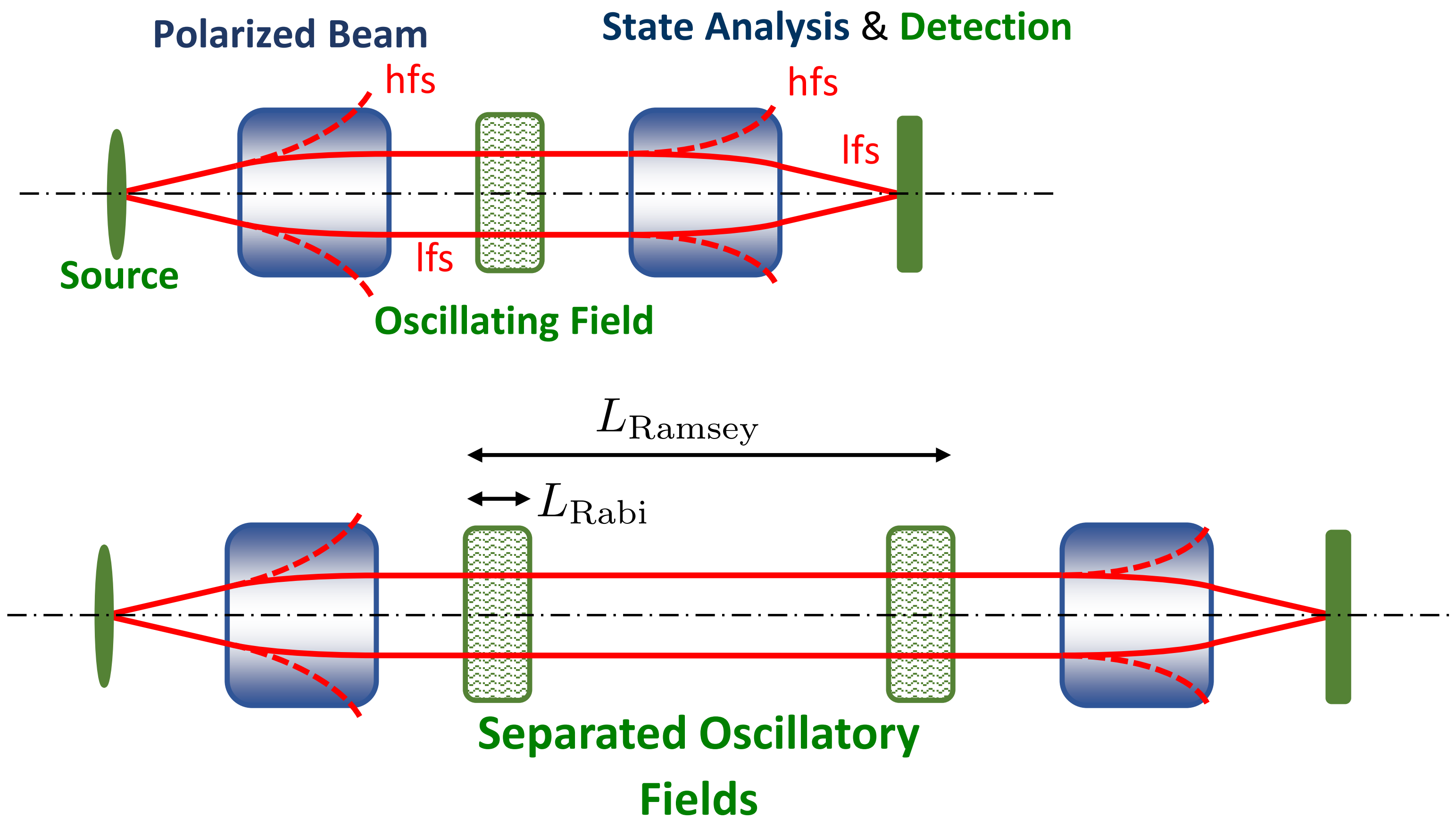
From Rabi to Ramsey

- Amit Nanda (AVA Fellow)
- Boost precision of HFS in-beam measurement by introducing Ramsey's method

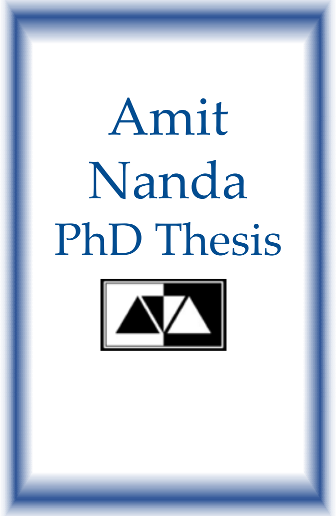
Resolution:

$$\delta\nu \propto \tau_{\mathrm{int}}^{-1} = \frac{v_{\mathrm{beam}}}{L_{\mathrm{Osc.F.}}}$$

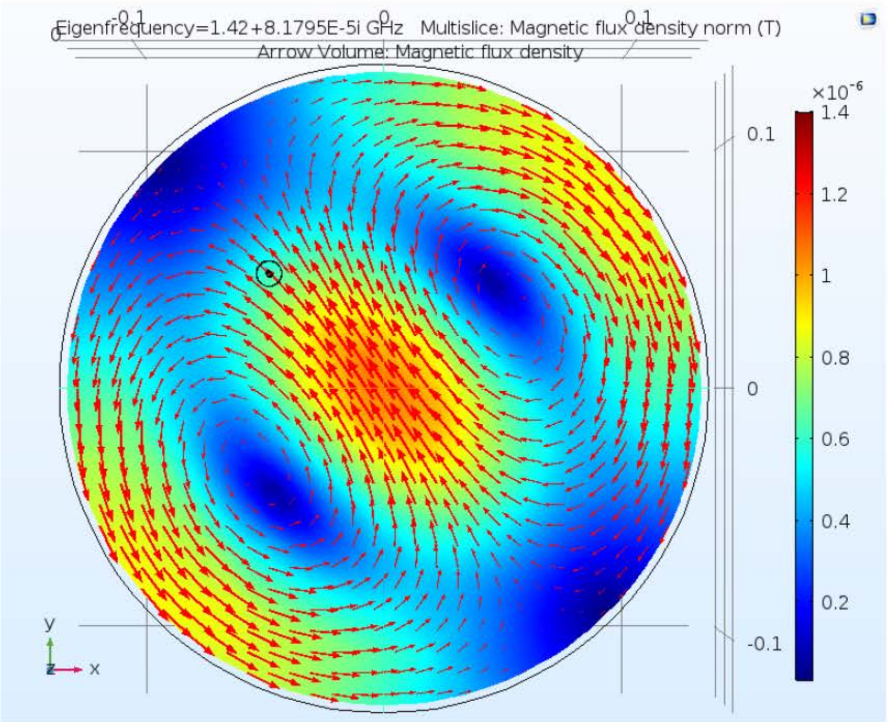


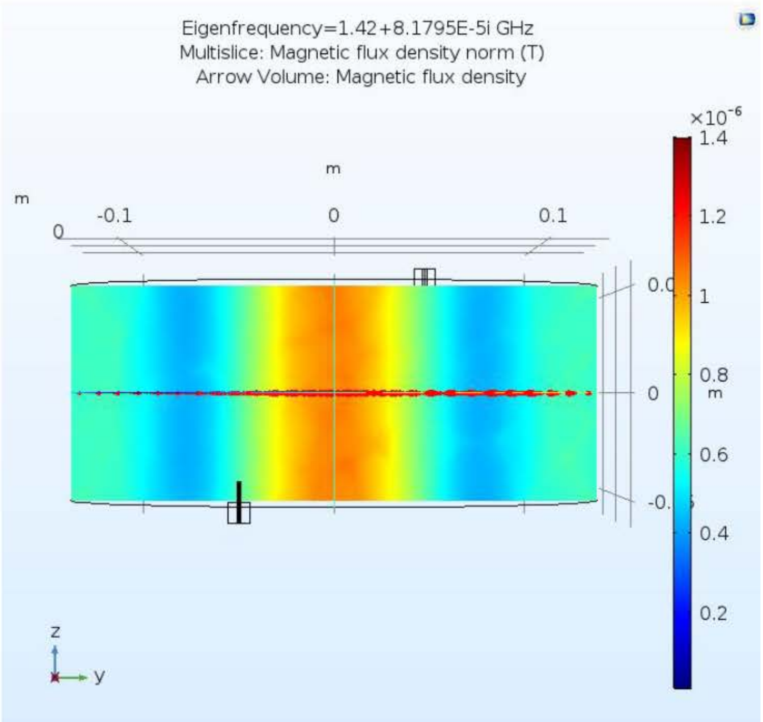


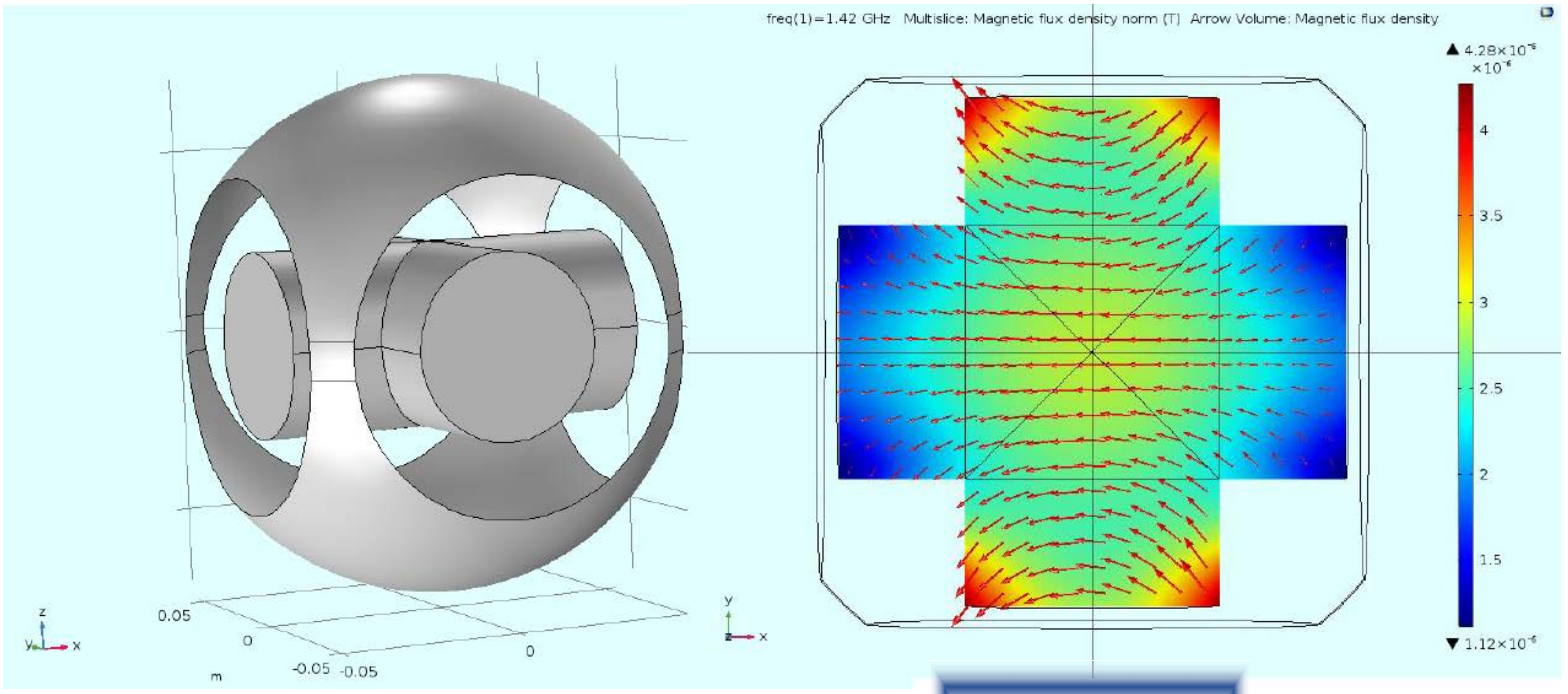
→ strip-line cavity:
line-shape not ideal for Ramsey



New RF structure: cavity vs. Surface coils



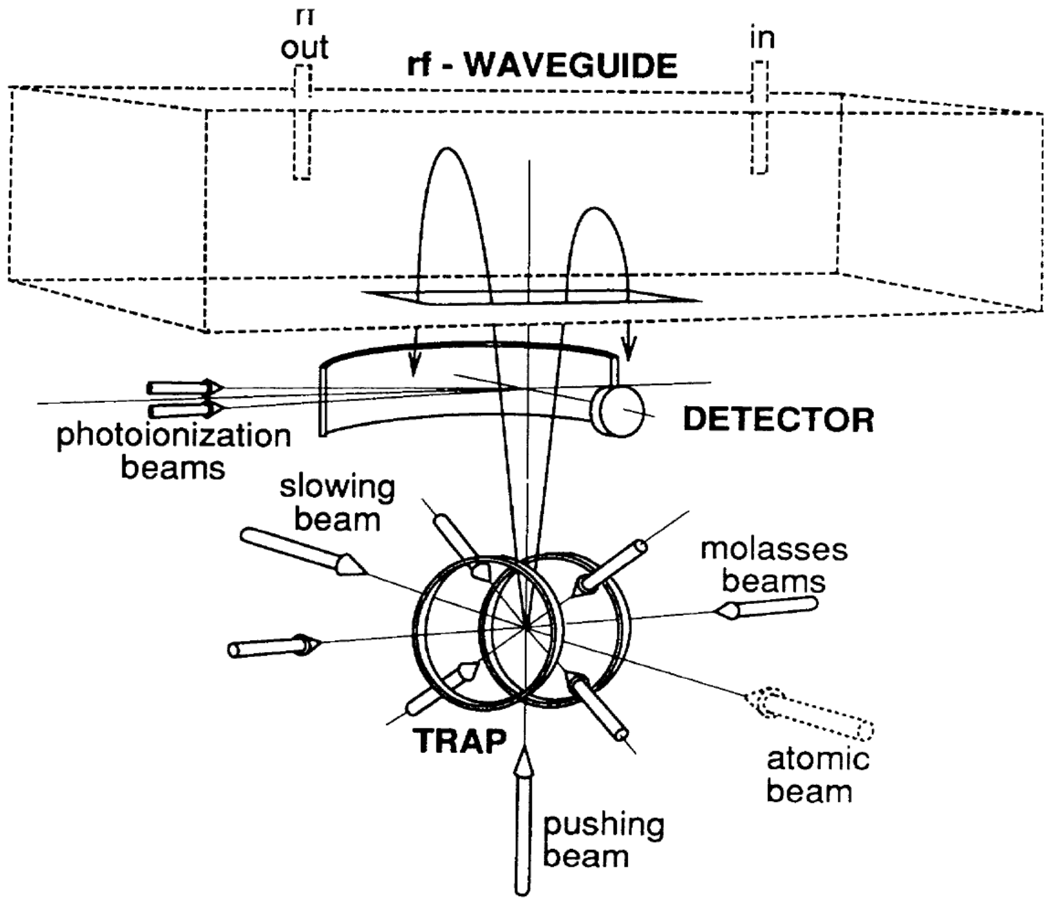




Amit
Nanda
PhD Thesis

(Far) future experiments

- Phase 3: trapped $\overline{\mathrm{H}}$
  - 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
    - Δf ~3 Hz, $\Delta f/f \sim 2\text{x}10^{-9}$



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