H·HFS
Hyperfine Structure of Antihydrogen

ERC Advanced Grant
PI: Prof. Dr. Eberhard Widmann

Prospects of in-flight hyperfine spectroscopy of (anti)hydrogen for tests of CPT symmetry

E. Widmann
Stefan Meyer Institute for Subatomic Physics, Vienna
Austrian Academy of Sciences

SMI erc ÖAW

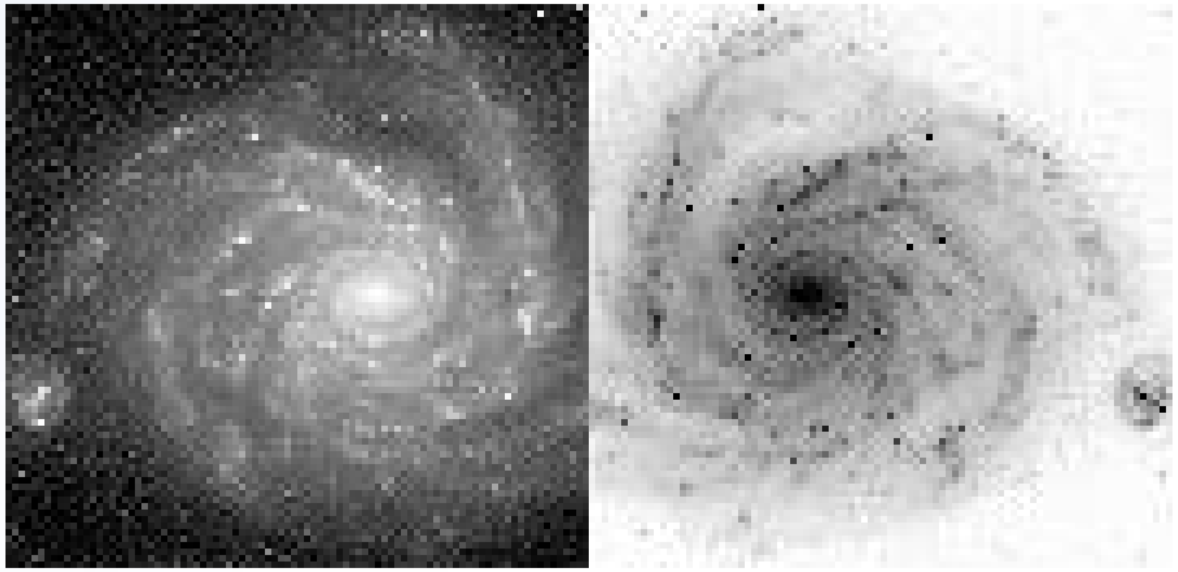
HISEBSM – Rencontres de Vietnam
1 Aug 2016

Layout

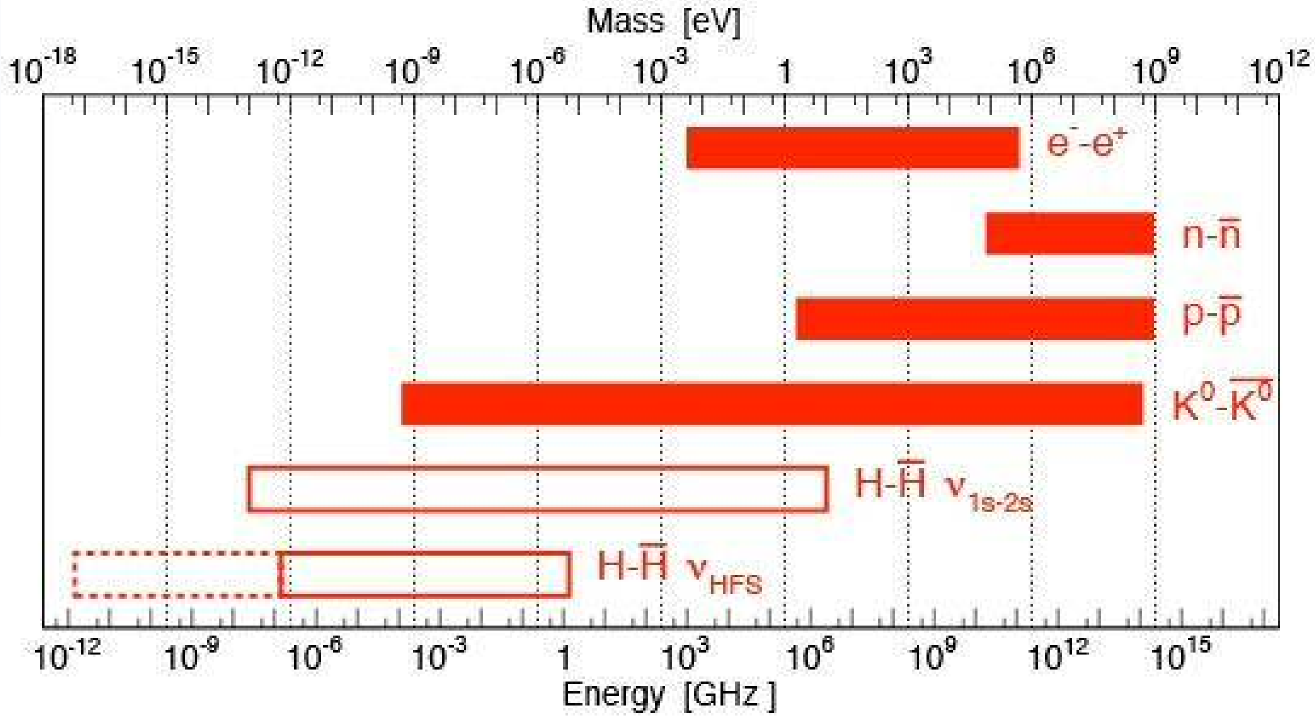
- CPT and Lorentz symmetry tests
- Antiproton Decelerator
- Antihydrogen production and spectroscopy experiments
- Hyperfine structure in and H

Matter-antimatter symmetry

- Cosmological scale:
  - Asymmetry

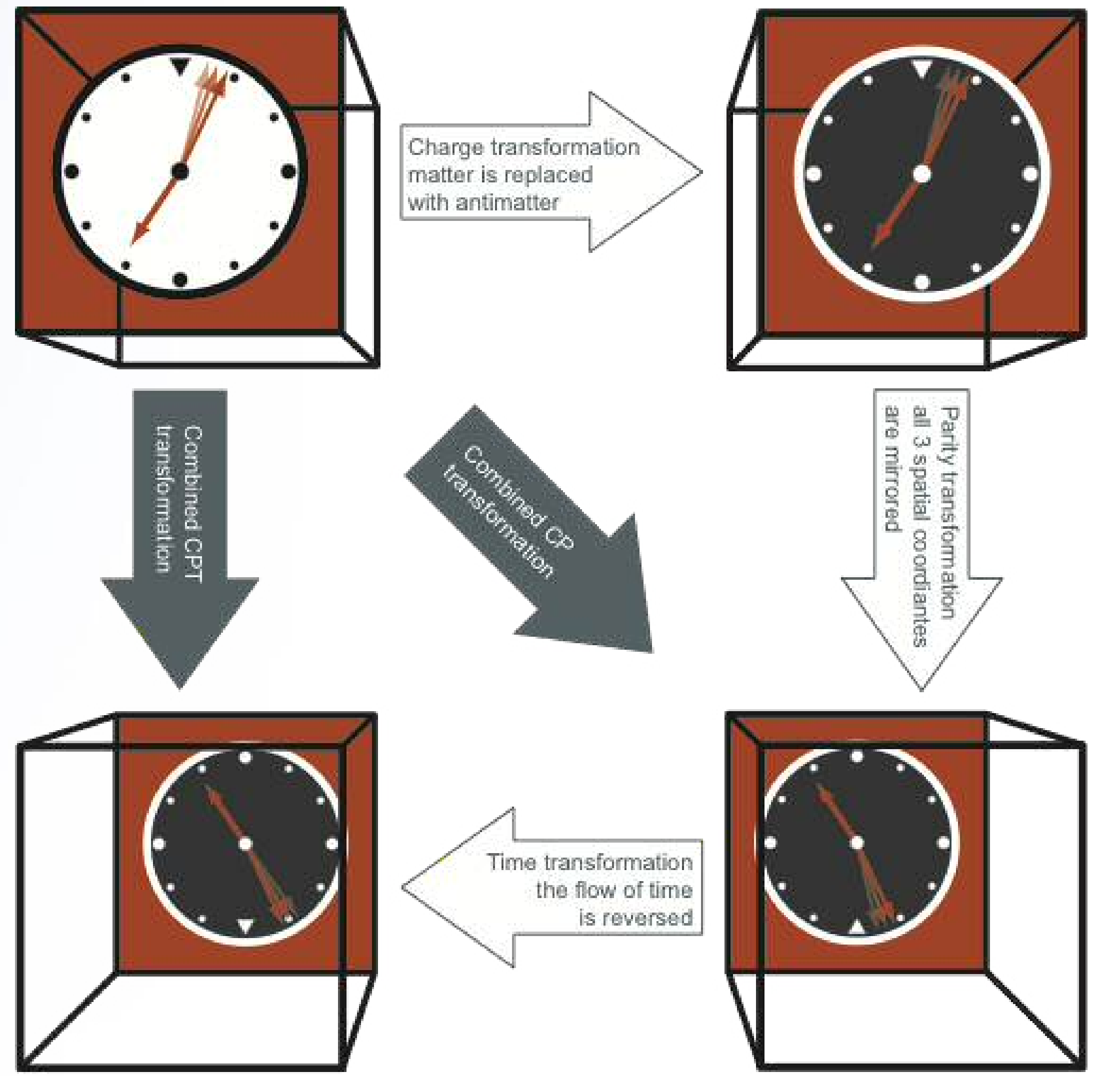


- CPT
  - Microscopic: symmetry?



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

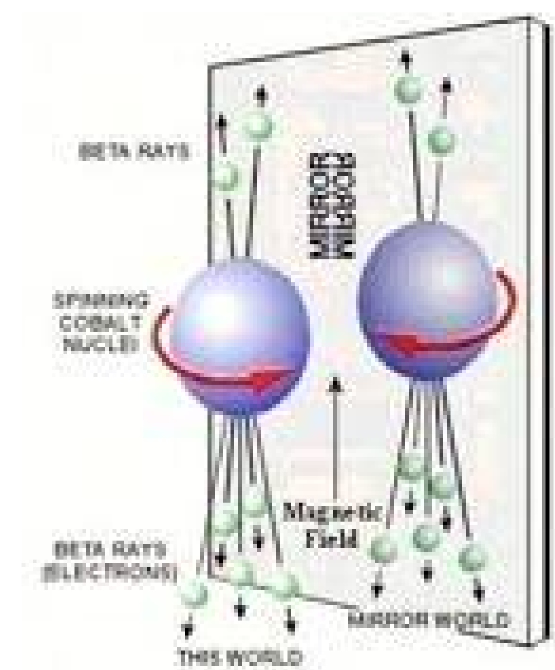


CPT → particle/anitparticle: same masses, lifetimes, g-factors, |charge|,...

Violations of fundamental symmetries

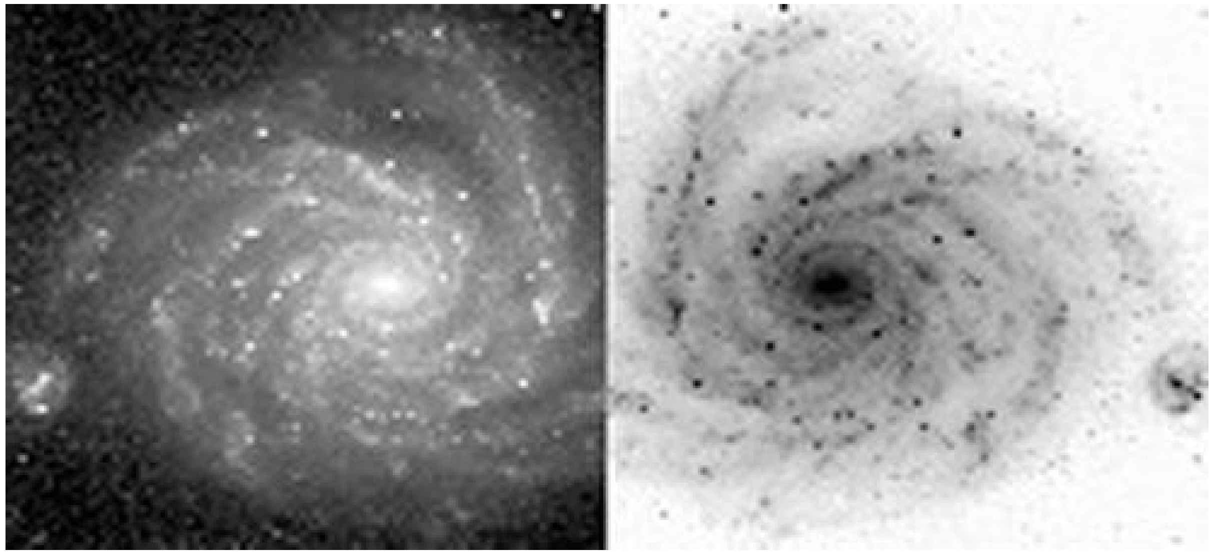
- Historically it was believed that nature would conserve symmetries of space
- Observed symmetry violations in weak interaction:

		Size of effect
Parity violation	1956 Theory: Lee & Yang 1957 ß-decay Wu et al. $\pi \to \mu \to e$ decay	100%
CP violation	1964 K_0 decays: Cronin & Fitch 2001 B decays: BELLE, BaBar	$\varepsilon \sim 2.3 \times 10^{-3}$



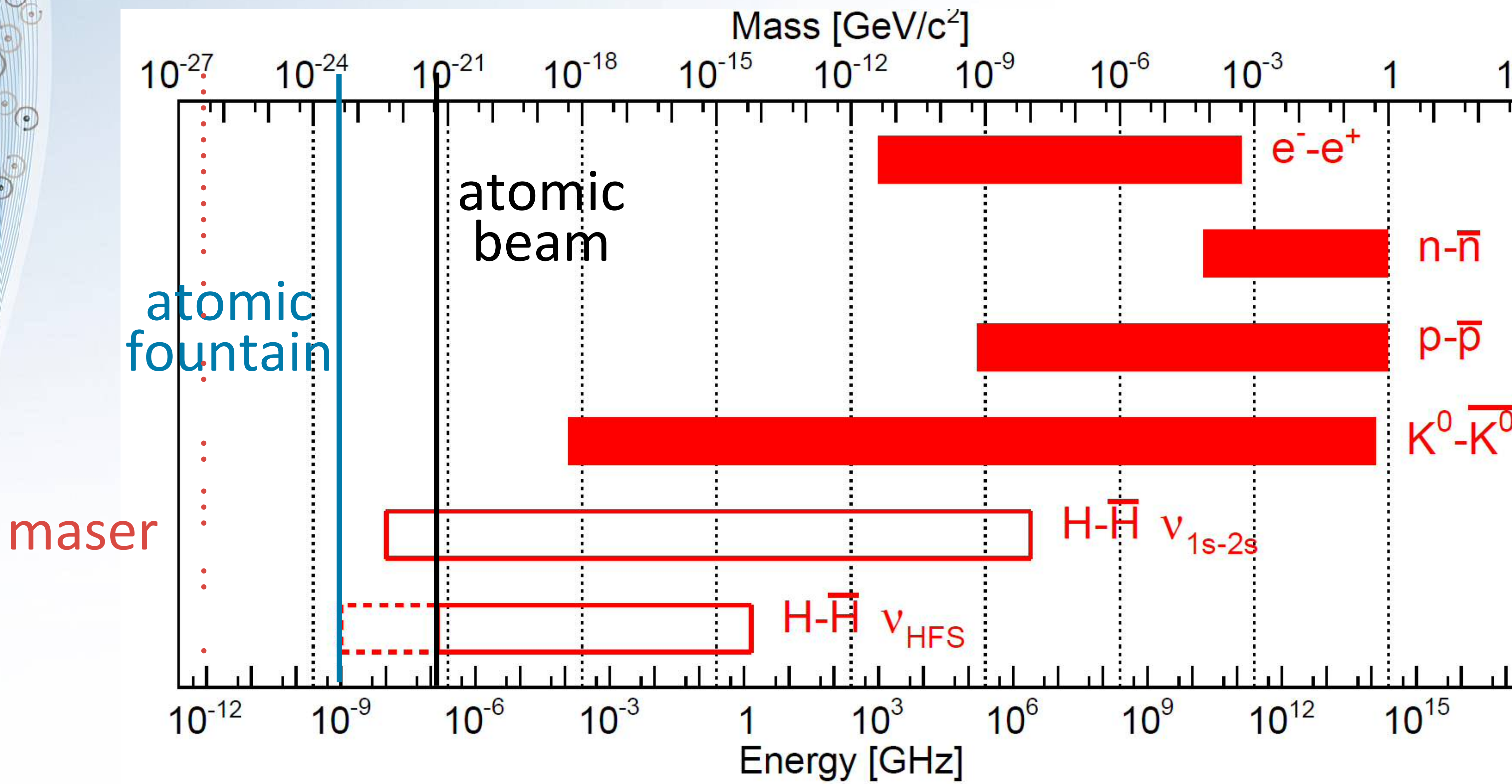
CPT symmetry & cosmology

- 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?



CPT tests - relative & absolute precision

- Atomic physics experiments, especially antihydrogen offer the most sensitive experimental verifications of CPT



Minimal Standard Model Extension

Modified Dirac equation

CPT & LORENTZ VIOLATION

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

LORENTZ VIOLATION

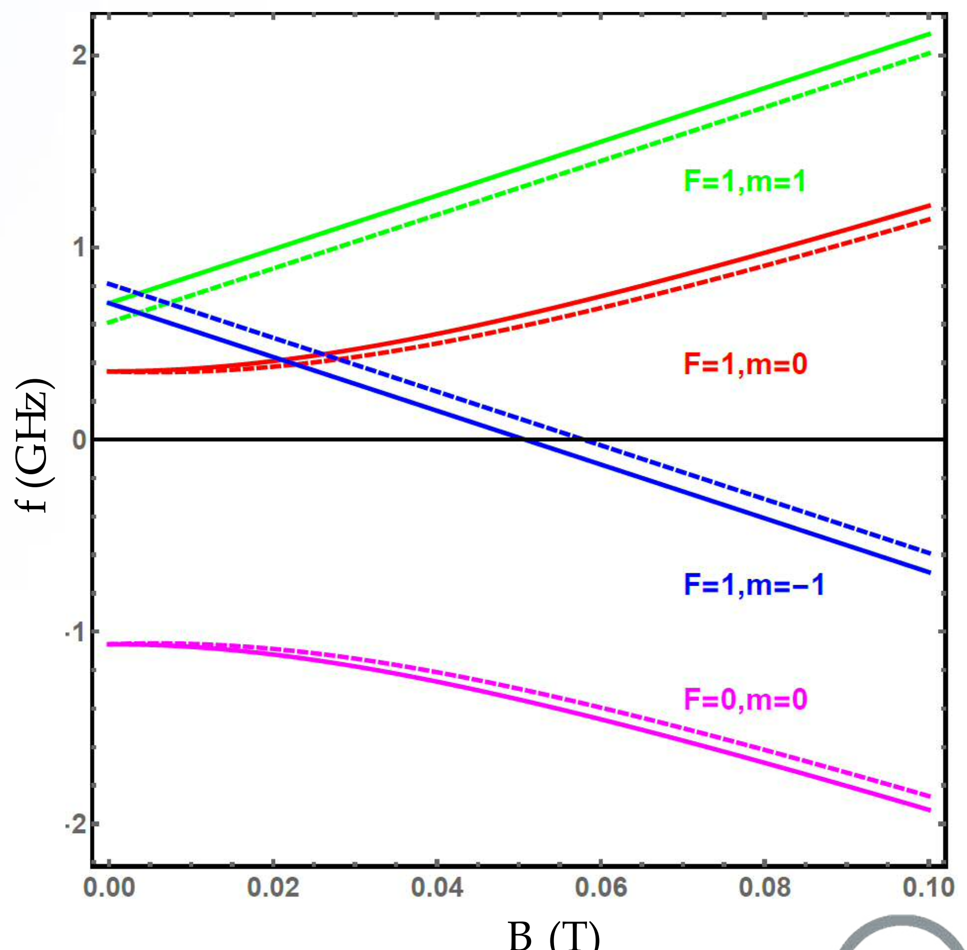
D. Colladay and V.A. Kostelecky, PRD 55, 6760 (1997)

H HFS energy shift:

$$\Delta E^{\rm H}(m_J, m_I) = a^e_0 + a^p_0 - c^e_{00}m_e - c^p_{00}m_p + (-b^e_3 + d^e_{30}m_e + H^e_{12})m_J/|m_J| + (-b^p_3 + d^p_{30}m_p + H^p_{12})m_I/|m_I|.$$

→ reverse sign

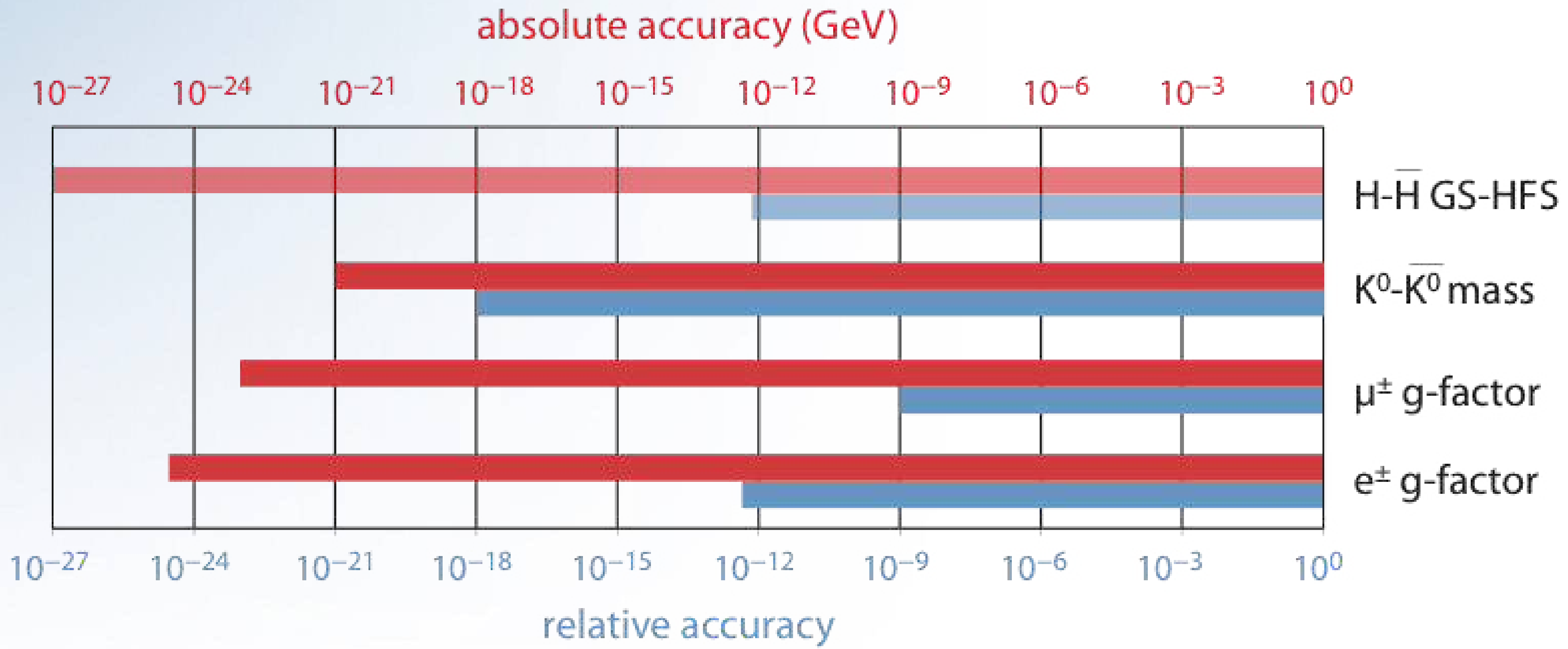
Only transitions with Δm≠0 show CPTV



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

HFS and Standard Model Extension

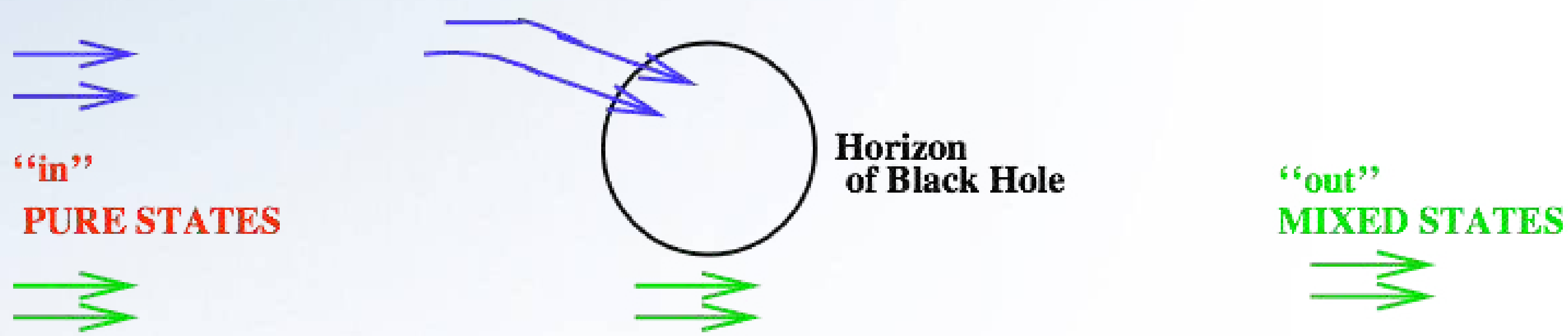
- Minimal SME



no CPT effect on 1S-2S transition *(changes in non-minimal SME)*
allows to compare different quantities in different sectors

Other possibility: foam and unitarity violation

SPACE–TIME FOAMY SITUATIONS
NON UNITARY (CPT VIOLATING) EVOLUTION
OF PURE STATES TO MIXED ONES



10^{-35} m

After Weinberg 99

$$\frac{d}{dt}\rho = i[\rho, H] + \Delta H(\rho)\,\rho$$

quantum mecha–nical terms

quantum mechanics violating term

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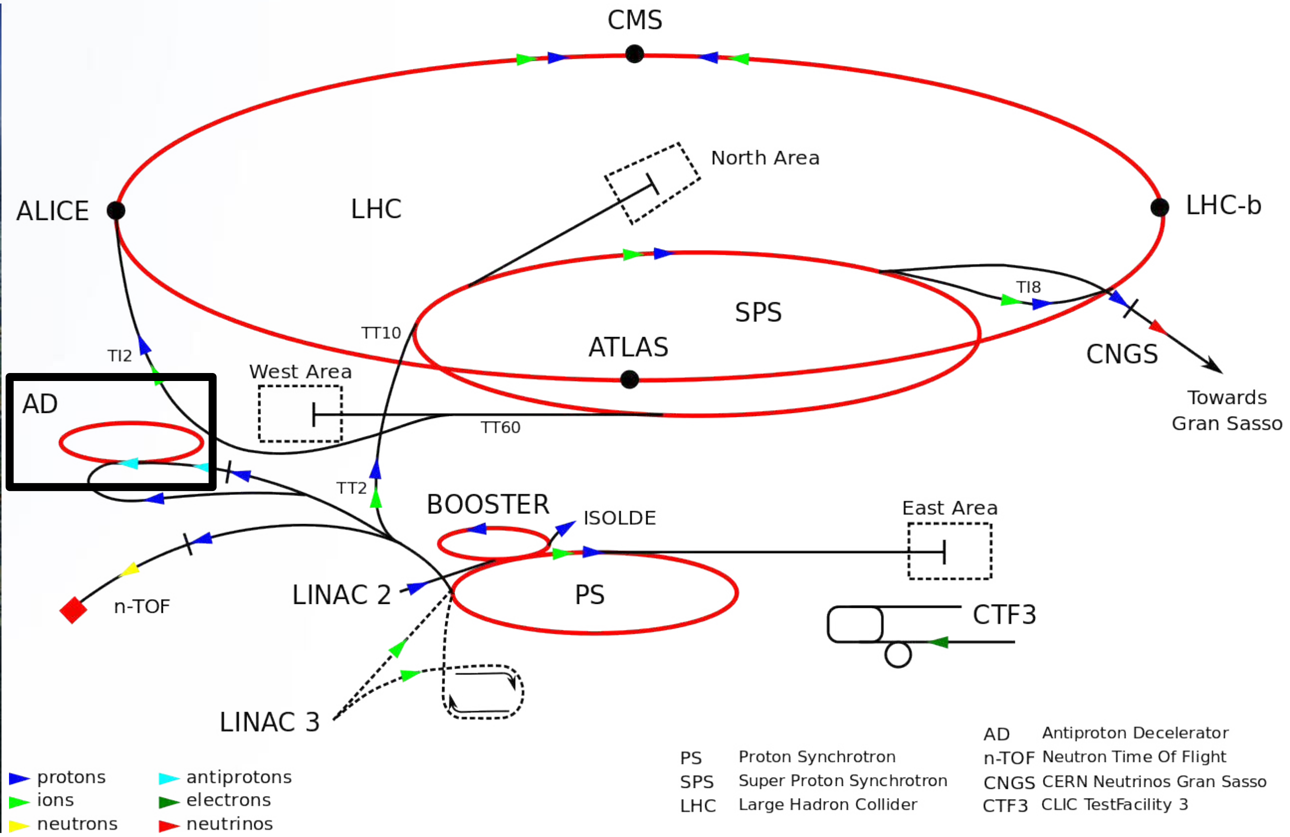
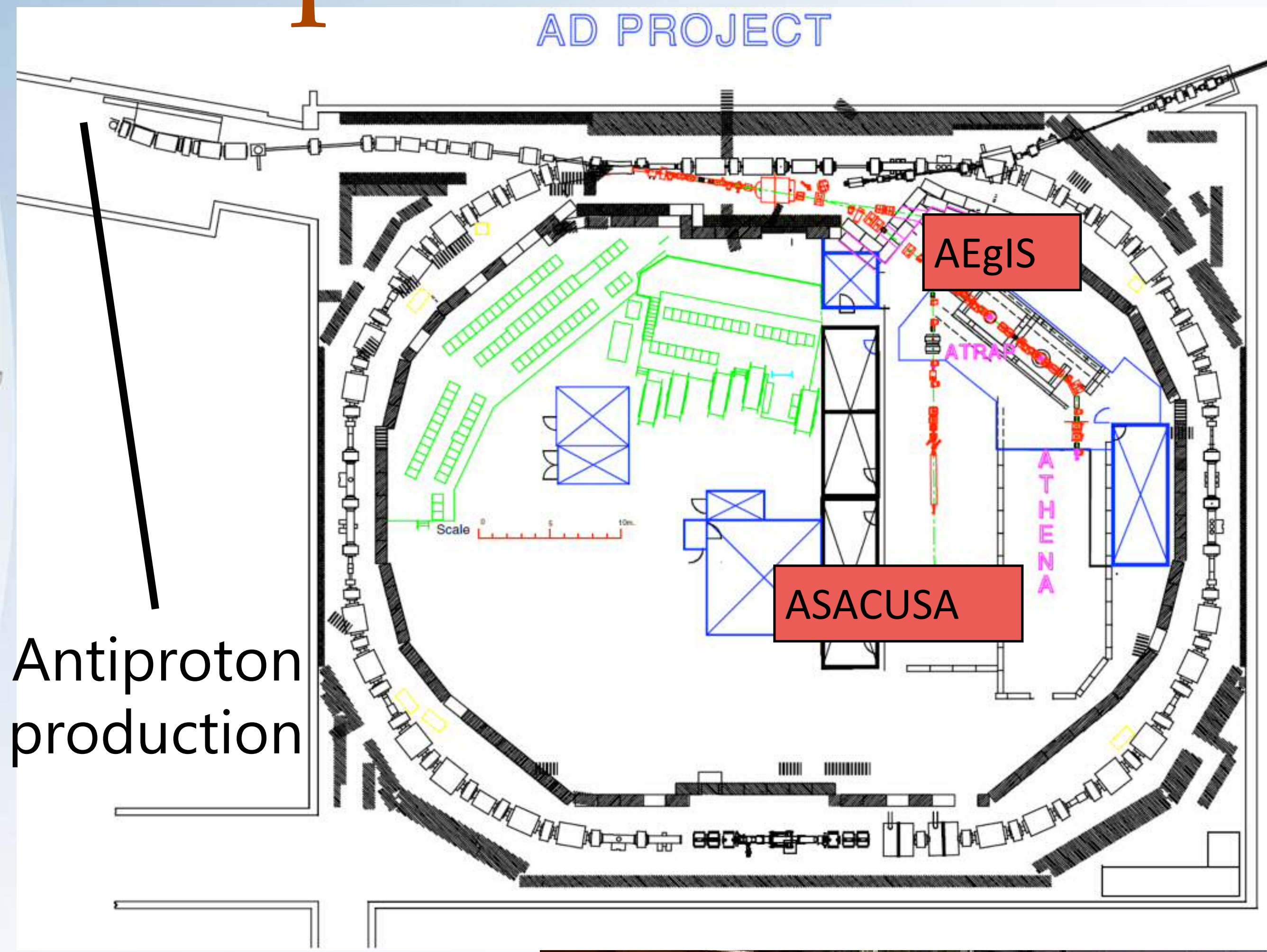
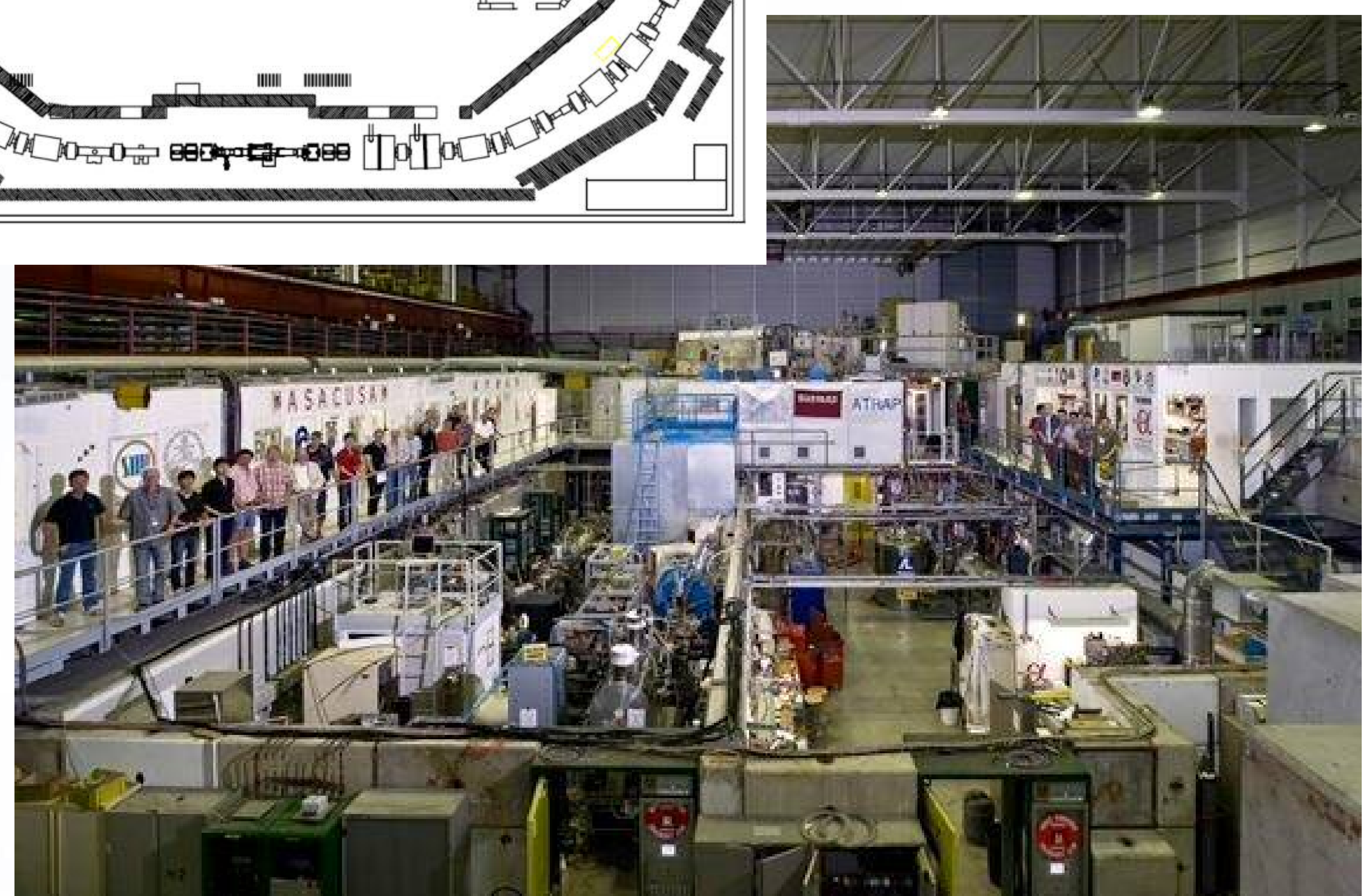
CERN accelerators



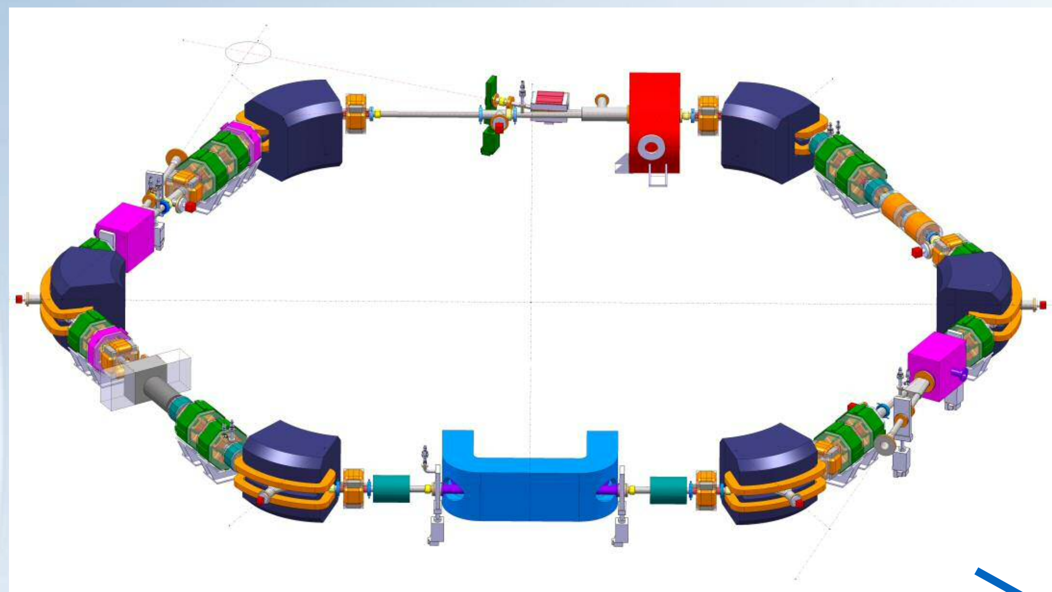
Antiproton Decelerator @ CERN



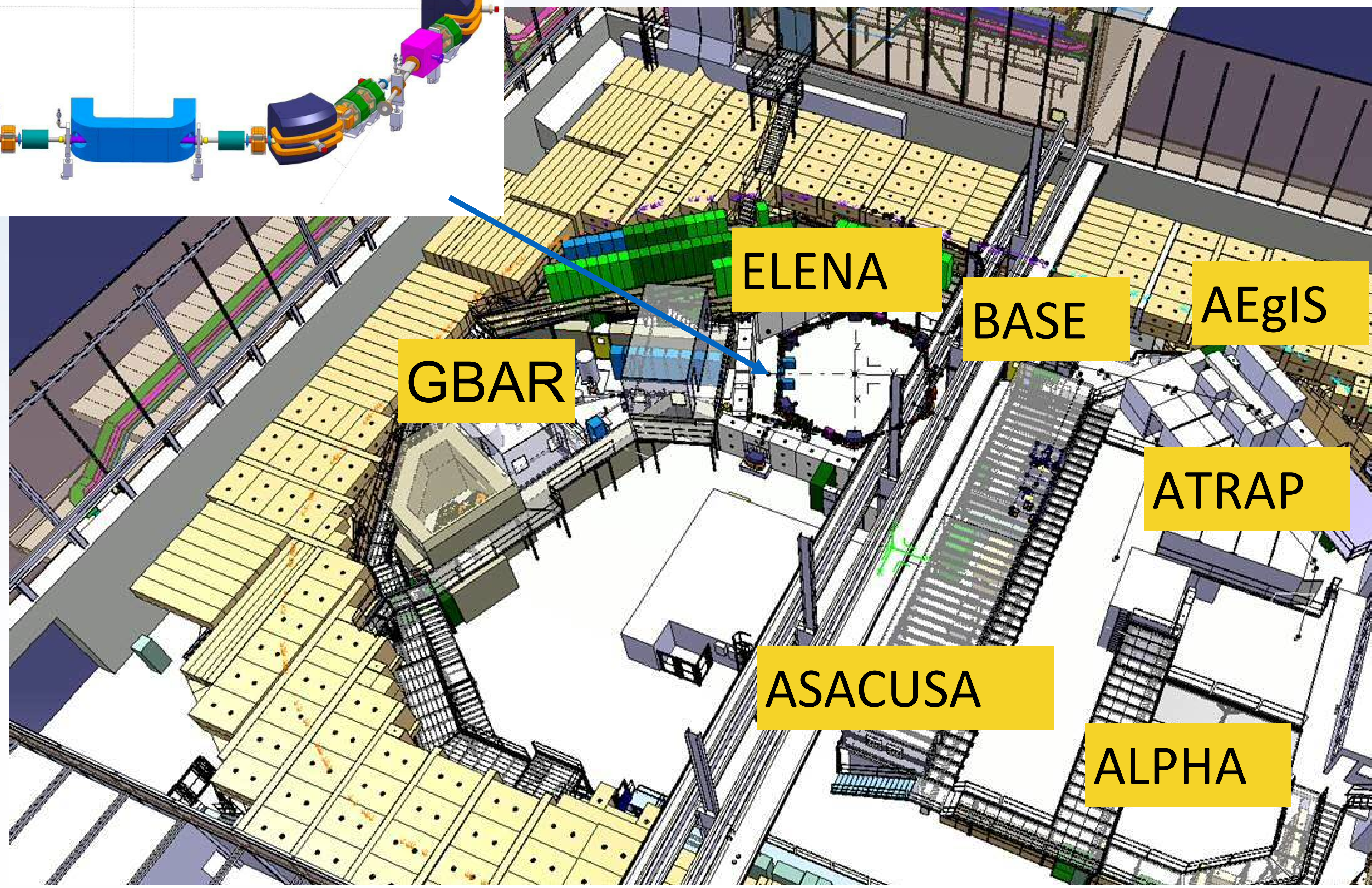
- All-in-one machine:
  - Antiproton capture
  - deceleration & cooling
  - 100 MeV/c (5.3 MeV)
- Pulsed extraction
  - 2-4 x 10^7 antiprotons per pulse of 100 ns length
  - 1 pulse / 85–120 seconds



AD & ELENA area and experiments



New decelerator: 5 MeV → 100 keV



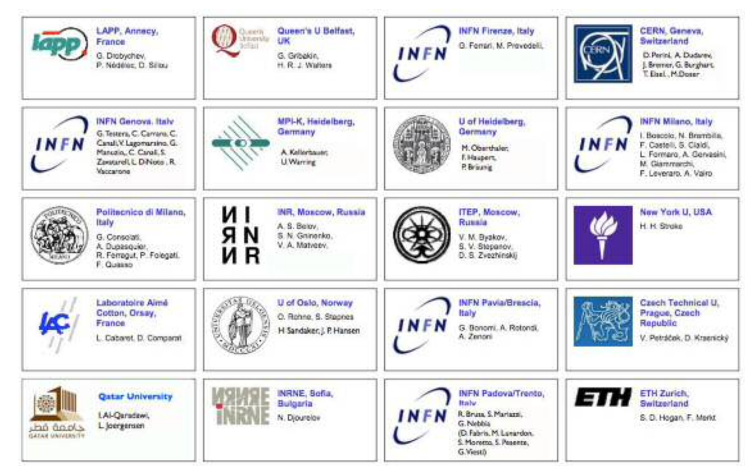
ELENA operation from 2017

AD experiments

- ATRAP - G. Gabrielse, Harvard
- ALPHA - J. S. Hangst, Aarhus
  - Antihydrogen trapping and 1S-2S spectroscopy
- ASACUSA* - R.S. Hayano, Tokyo
  - Antiprotonic atoms, collisions, antihydrogen hyperfine structure
- AEgIS* - M. Doser, CERN
  - Antimatter gravity
- GBAR - P. Perez, Saclay
  - Antimatter gravity
- BASE - S. Ulmer, RIKEN

  magnetic moment
- ACE - M. Holzscheiter, Heidelberg
  - biological effects of annihilations

AEGIS



*E.W.

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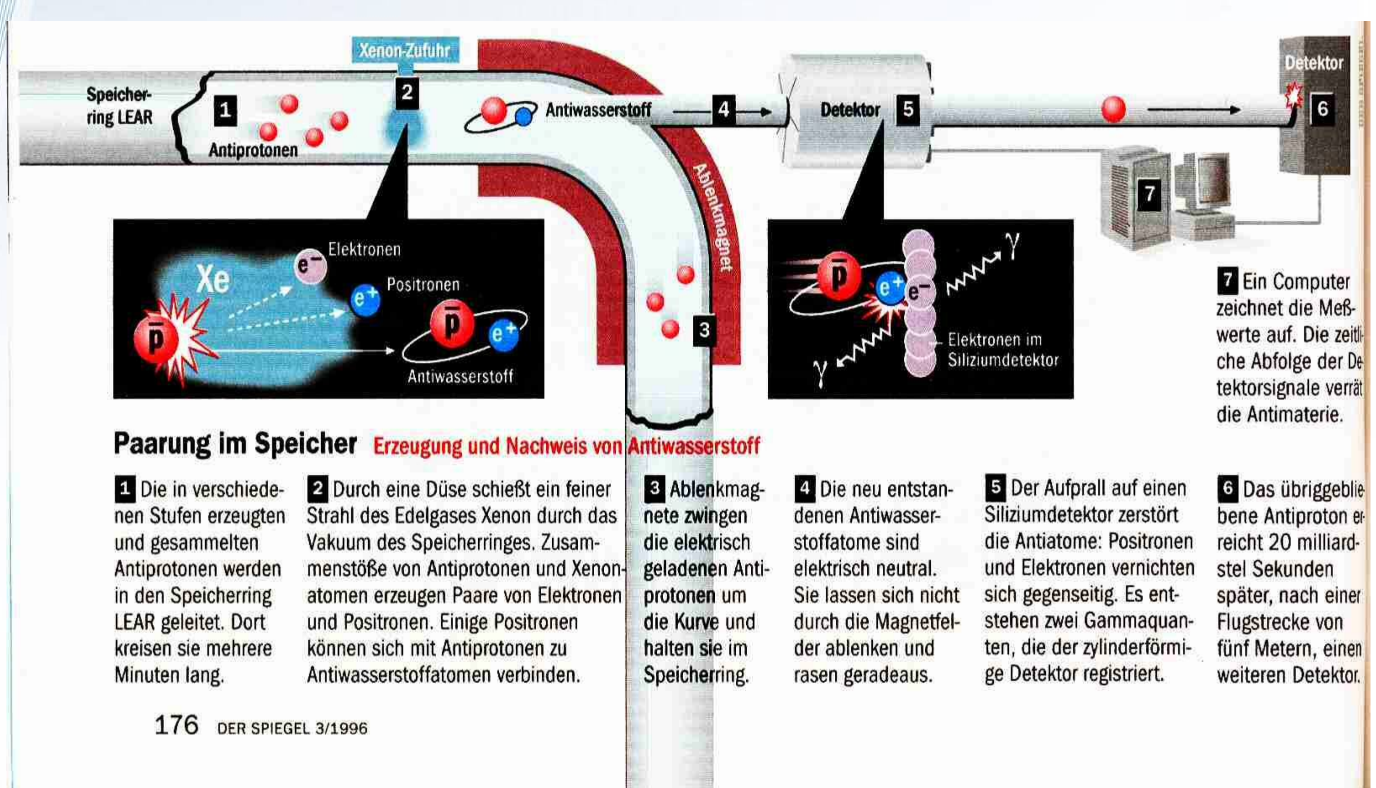
First Antihydrogen Atoms 1996 @ LEAR

9 relativistic antihydrogen atoms



Paarung im Speicher Erzeugung und Nachweis von Antiwasserstoff

1 Die in verschiedenen Stufen erzeugten und gesammelten Antiprotonen werden in den Speicherring LEAR geleitet. Dort kreisen sie mehrere Minuten lang.

2 Durch eine Düse schießt ein feiner Strahl des Edelgases Xenon durch das Vakuum des Speicherringes. Zusammenstöße von Antiprotonen und Xenonatomen erzeugen Paare von Elektronen und Positronen. Einige Positronen können sich mit Antiprotonen zu Antiwasserstoffatomen verbinden.

3 Ablenkmagnete zwingen die elektrisch geladenen Antiprotonen um die Kurve und halten sie im Speicherring.

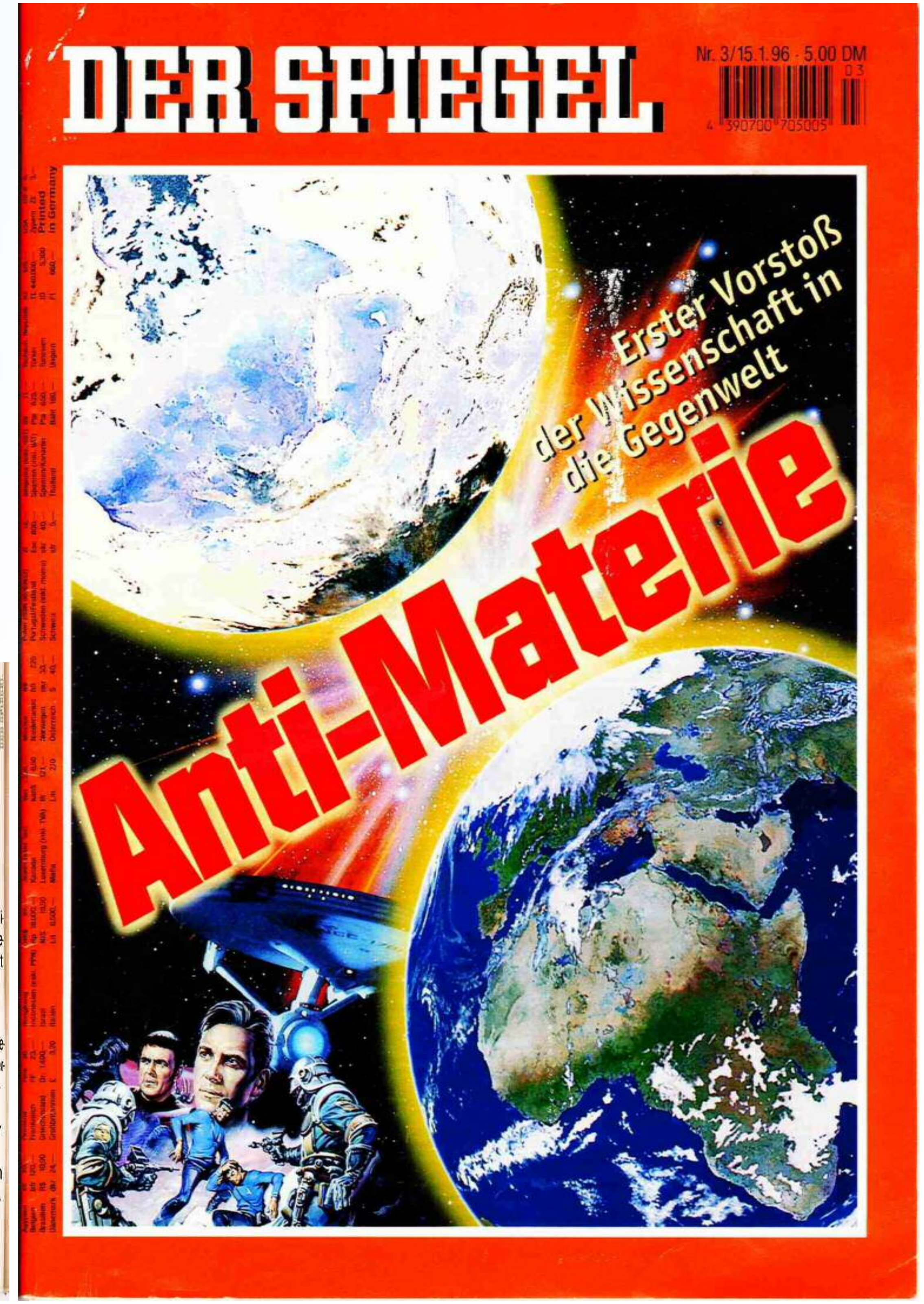
4 Die neu entstandenen Antiwasserstoffatome sind elektrisch neutral. Sie lassen sich nicht durch die Magnetfelder ablenken und rasen geradeaus.

5 Der Aufprall auf einen Siliziumdetektor zerstört die Antiatome: Positronen und Elektronen vernichten sich gegenseitig. Es entstehen zwei Gammaquanten, die der zylinderförmige Detektor registriert.

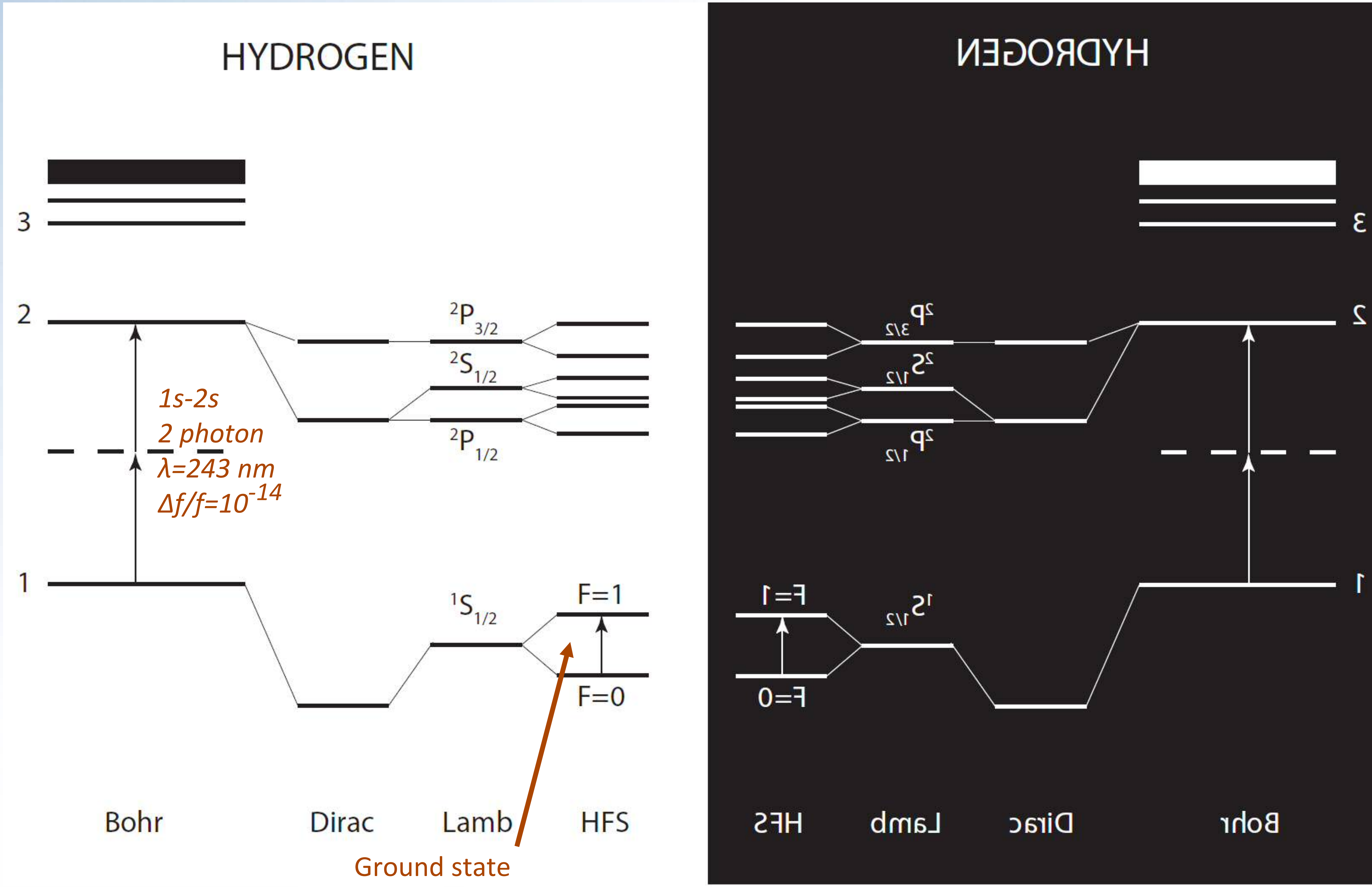
6 Das übriggebliebene Antiproton erreicht 20 milliardstel Sekunden später, nach einer Flugstrecke von fünf Metern, einen weiteren Detektor.

7 Ein Computer zeichnet die Meßwerte auf. Die zeitliche Abfolge der Detektorsignale verrät die Antimaterie.

176 DER SPIEGEL 3/1996

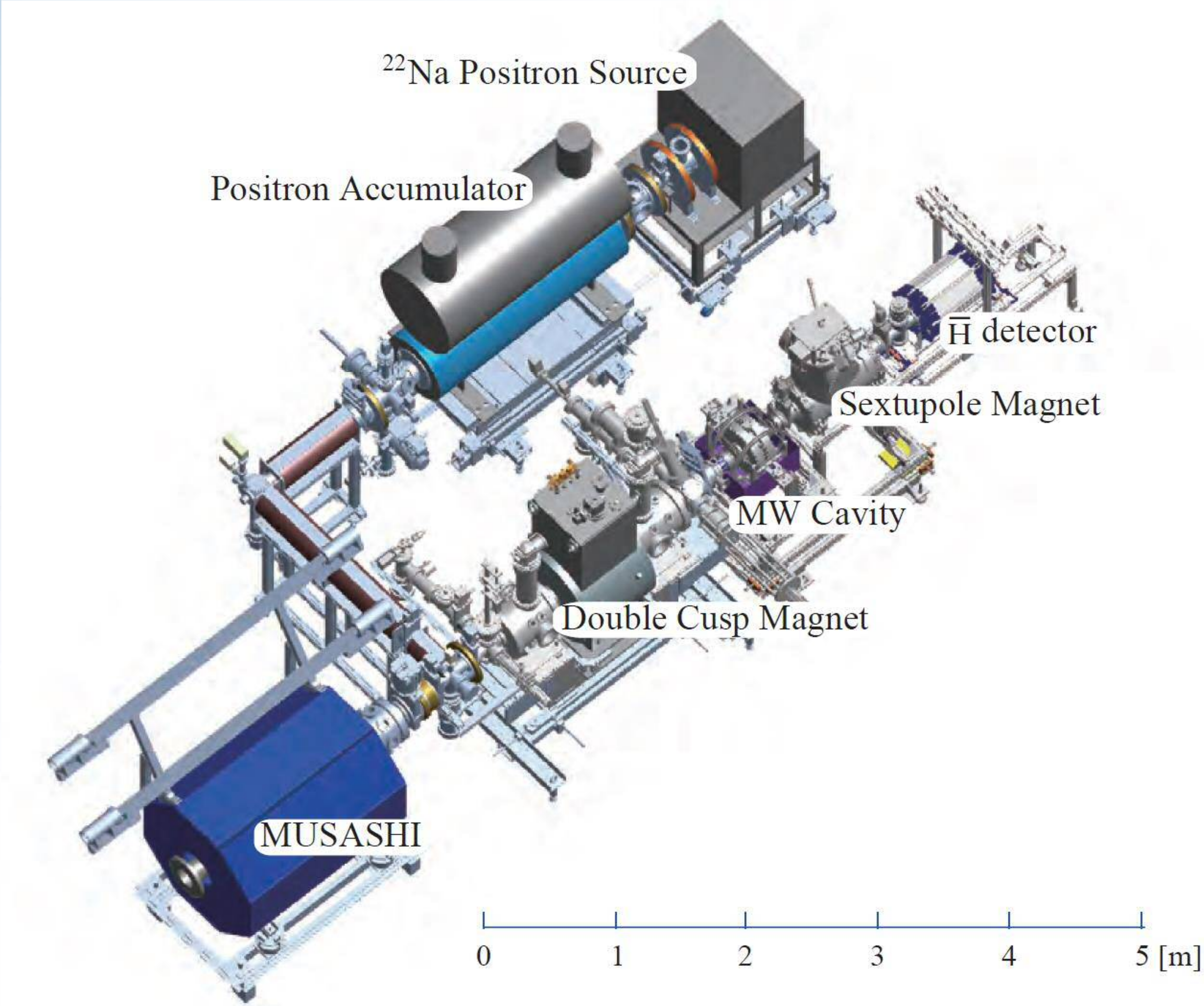


Antihydrogen spectroscopy



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

ASACUSA production 2014~



1st cold 2002@CERN-AD

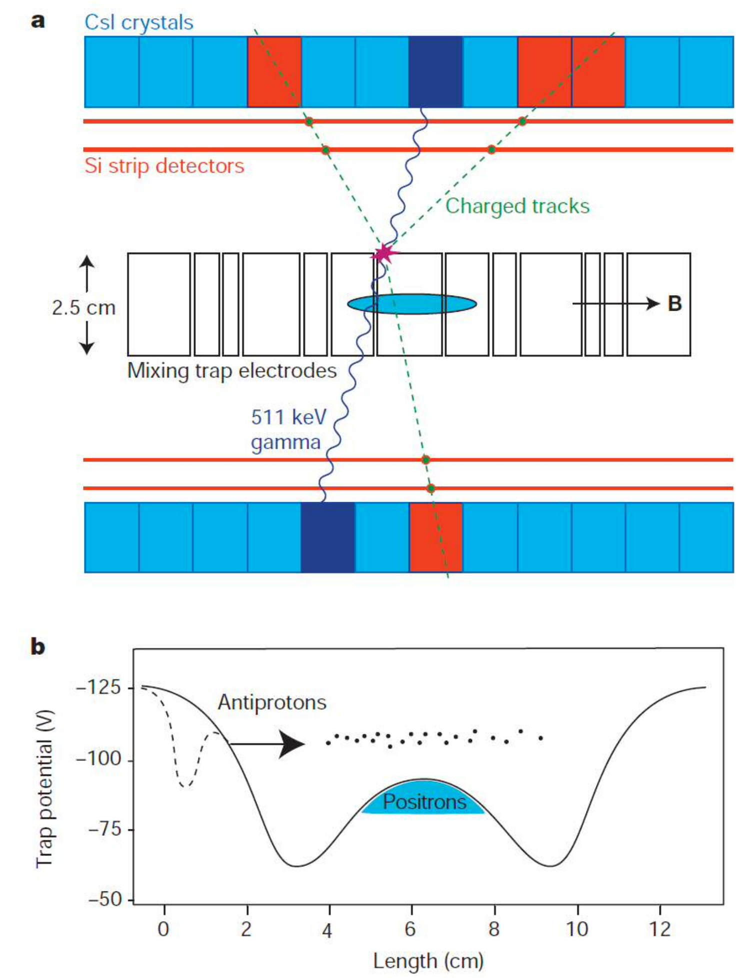
Nested Penning traps

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

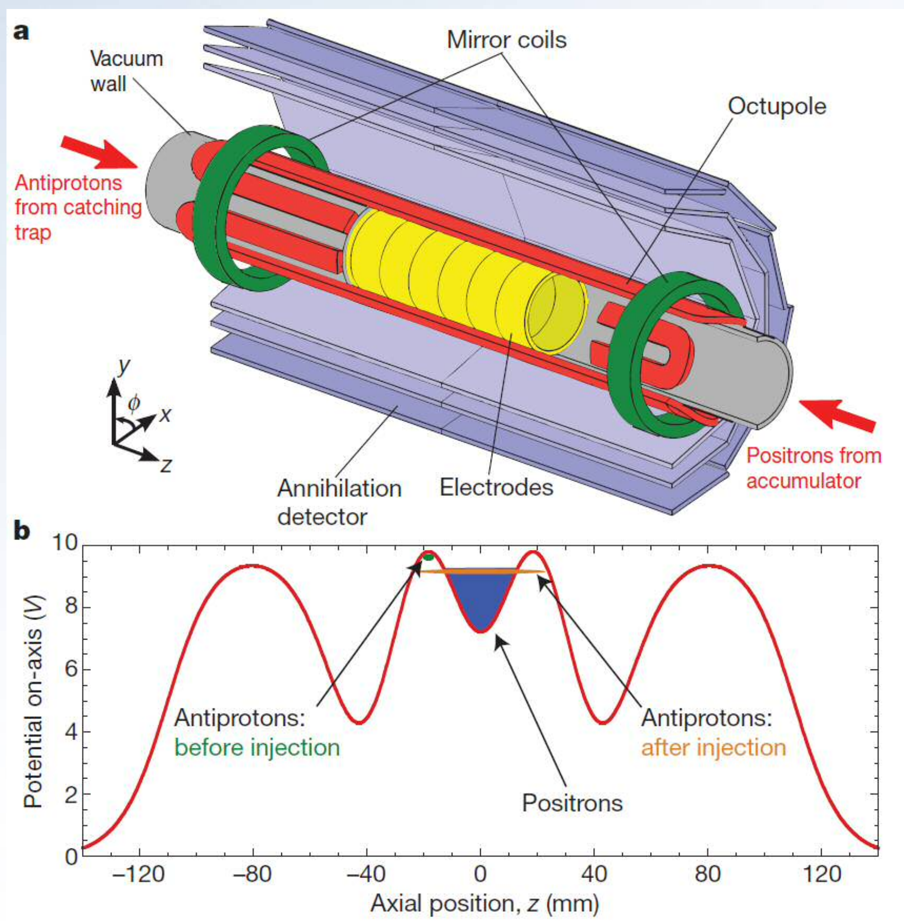
Formation by three-body recombination, preferably populates Rydberg states

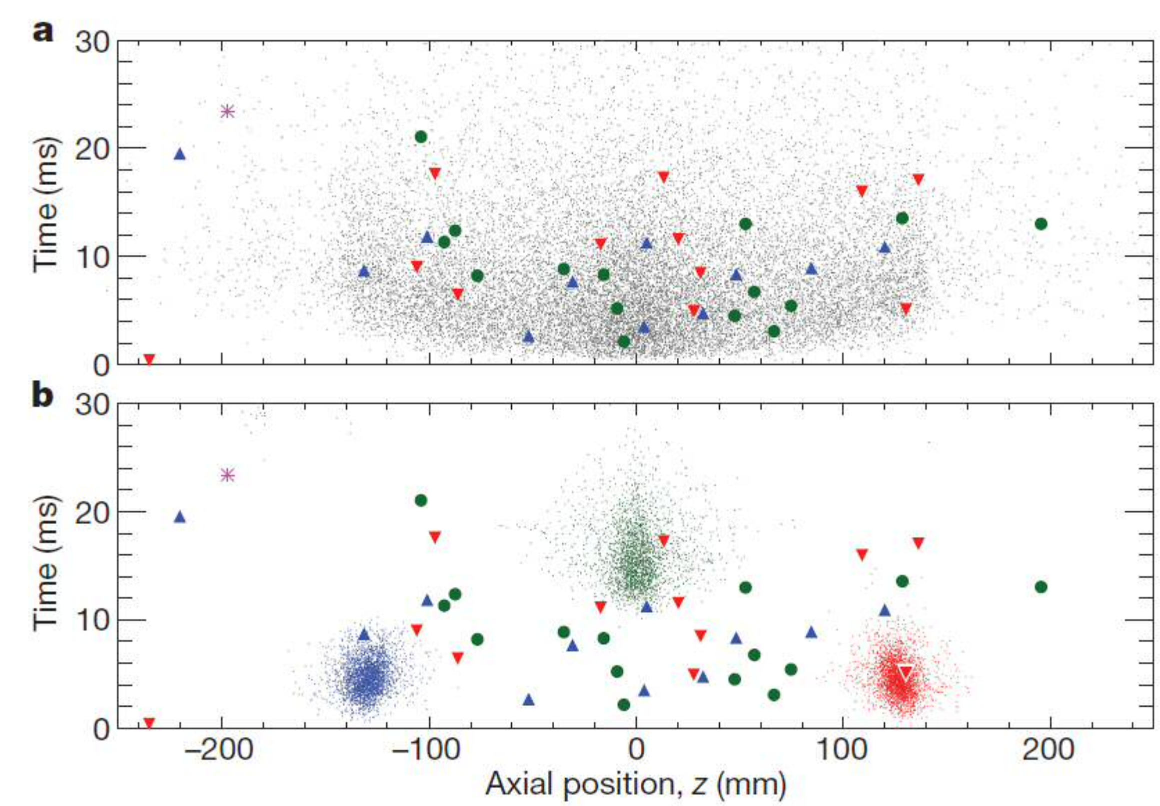
ALPHA: 1st trapping of

Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], S. Chapman[3], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], J. S. Hangst[1], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgensen[4], L. Kurchaninov[8], N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sarid[14], S. Seif el Nasr[9], D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazaki[15,16]

NATURE 468, 673 (2010)





latest numbers: 1 trapped per mixing (100 s every 15 min)

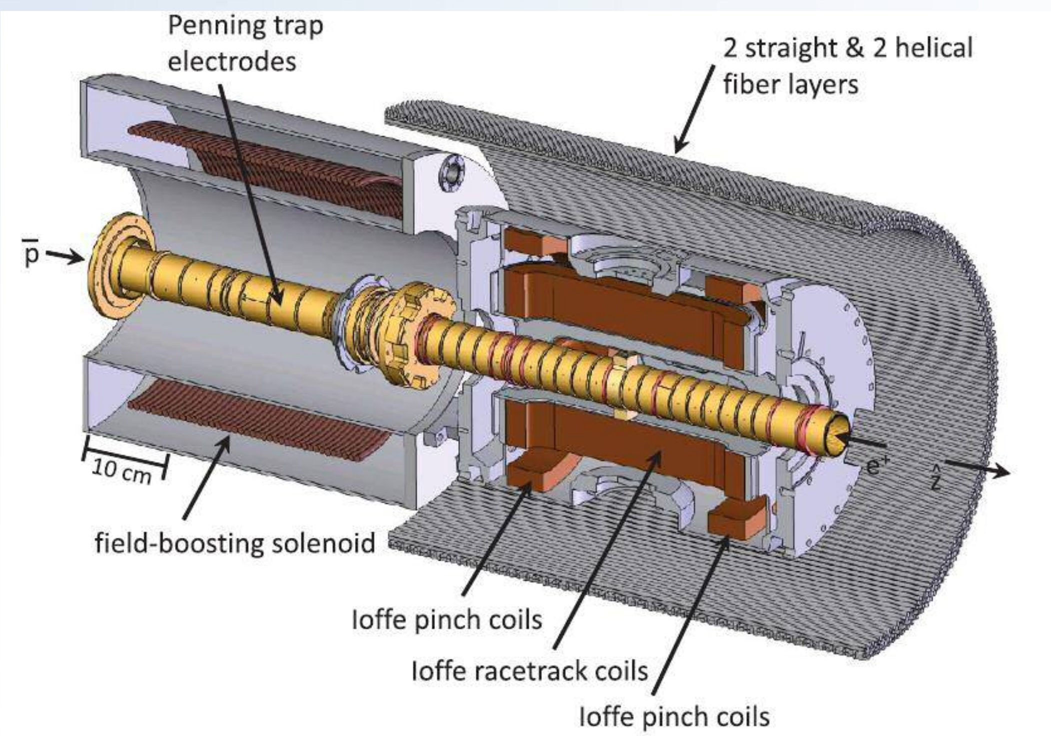
confinement for 1000 s achieved

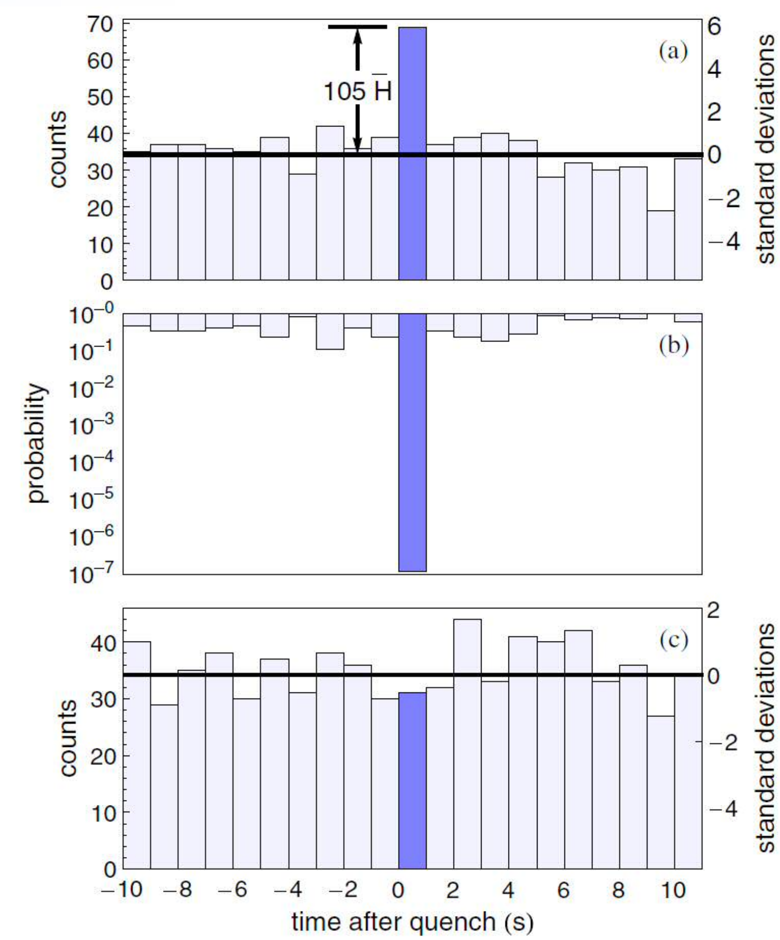
Trapped in ATRAP

PRL 108, 113002 (2012) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2012

Trapped Antihydrogen in Its Ground State

G. Gabrielse,[1,*] R. Kalra,[1] W. S. Kolthammer,[1] R. McConnell,[1] P. Richerme,[1] D. Grzonka,[2] W. Oelert,[2] T. Sefzick,[2] M. Zielinski,[2] D. W. Fitzakerley,[3] M. C. George,[3] E. A. Hessels,[3] C. H. Storry,[3] M. Weel,[3] A. Müllers,[4] and J. Walz[4]





5 trapped per mixing (100 s length every 15 min)

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- Antiproton Decelerator
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ASACUSA COLLABORATION

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

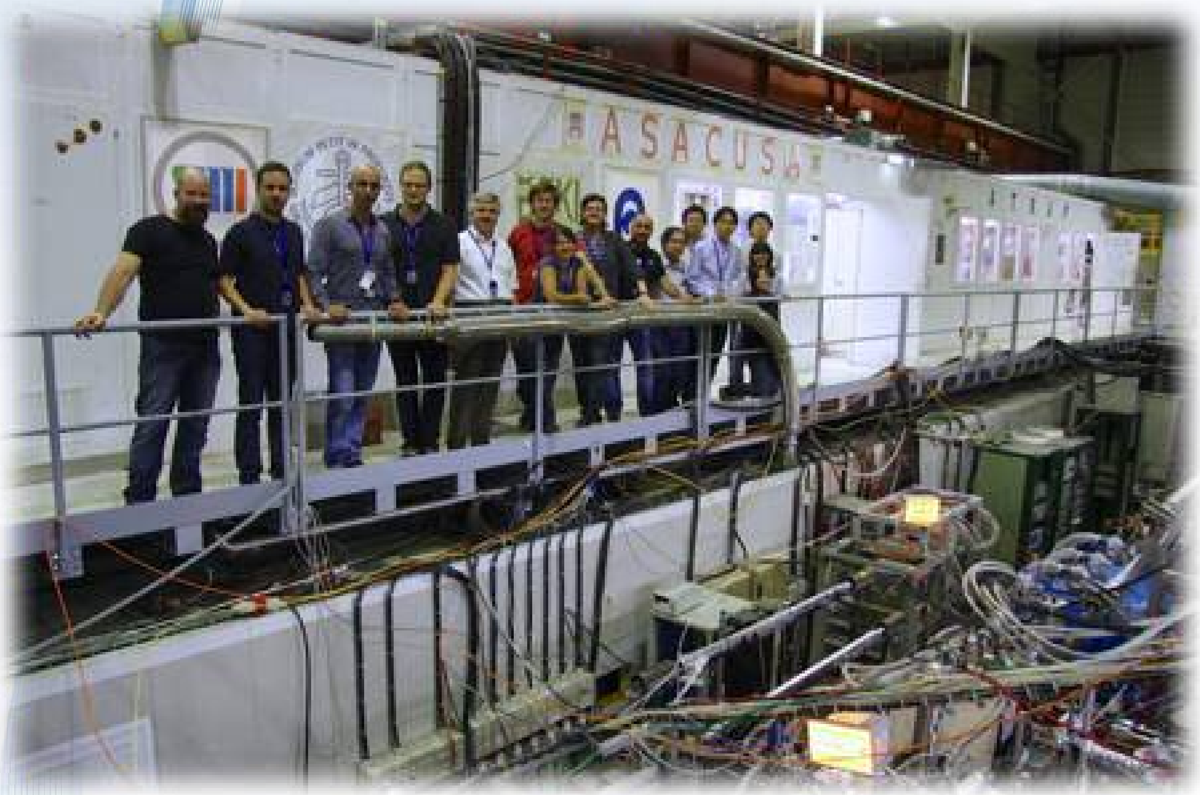
ASACUSA Scientific project

(1) Spectroscopy of He^+

(2) annihilation cross-section

(3) production and spectroscopy

The Antihydrogen team



University of Tokyo, Komaba: N. Kuroda, T. Matsudate, M. Tajima, Y. Matsuda

RIKEN: P. Dupré, Y. Kanai, Y. Nagata, B. Radics, S. Ulmer, Y. Yamazaki

Hiroshima University: C. Kaga, H. Higaki

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

Stefan Meyer Institut für Subatomare Physik: A. Capon, M. Diermaier, B. Kolbinger, O. Massiczek, C. Sauerzopf, M.C. Simon, K. Suzuki, E. Widmann, J. Zmeskal

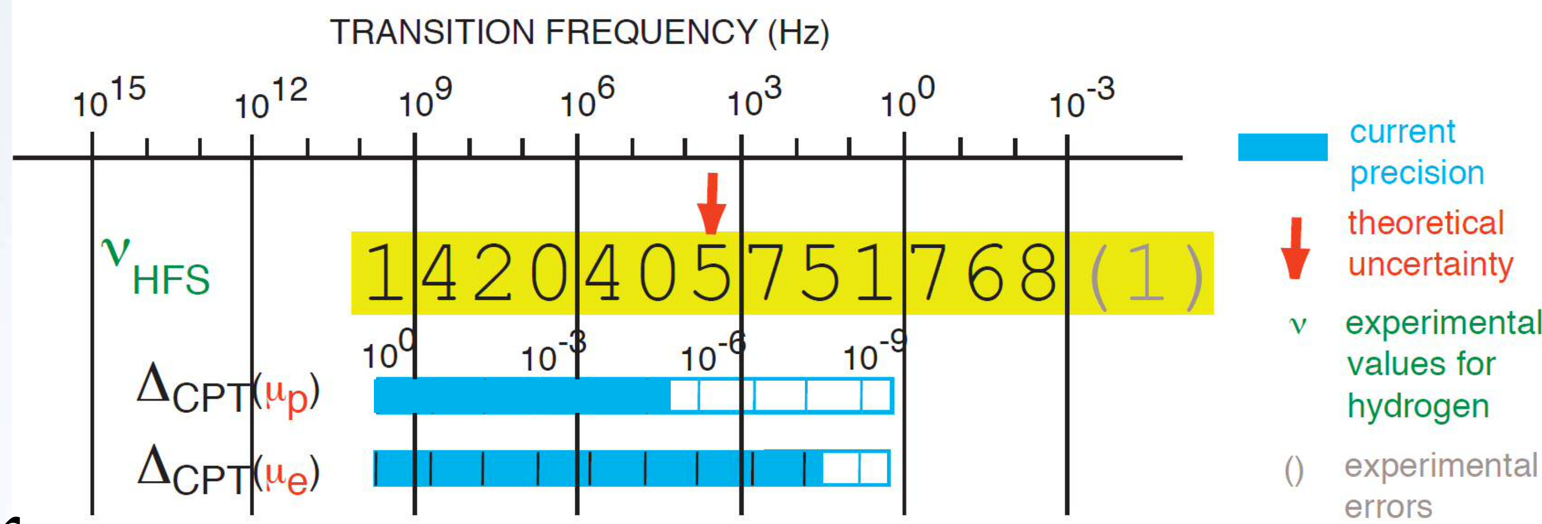
CERN: H. Breuker, C. Malbrunot

H·HFS

Ground-State Hyperfine Splitting of H/

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

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



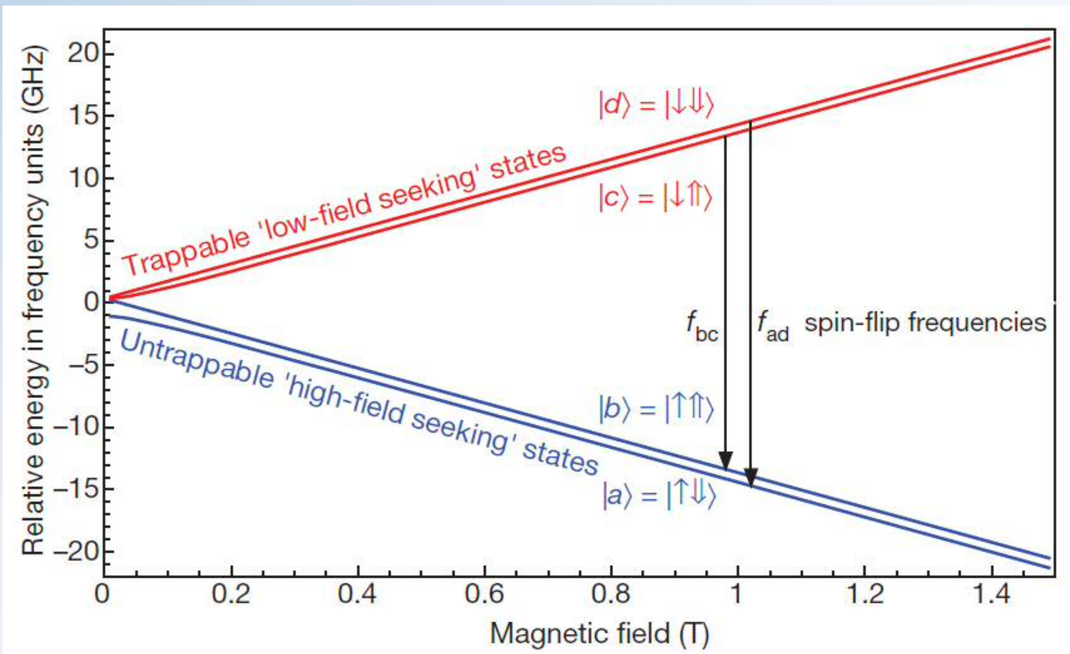
- magnetic moment of
  - 2012 Gabrielse Penning trap 4.4 ppm PRL 110,130801 (2013)

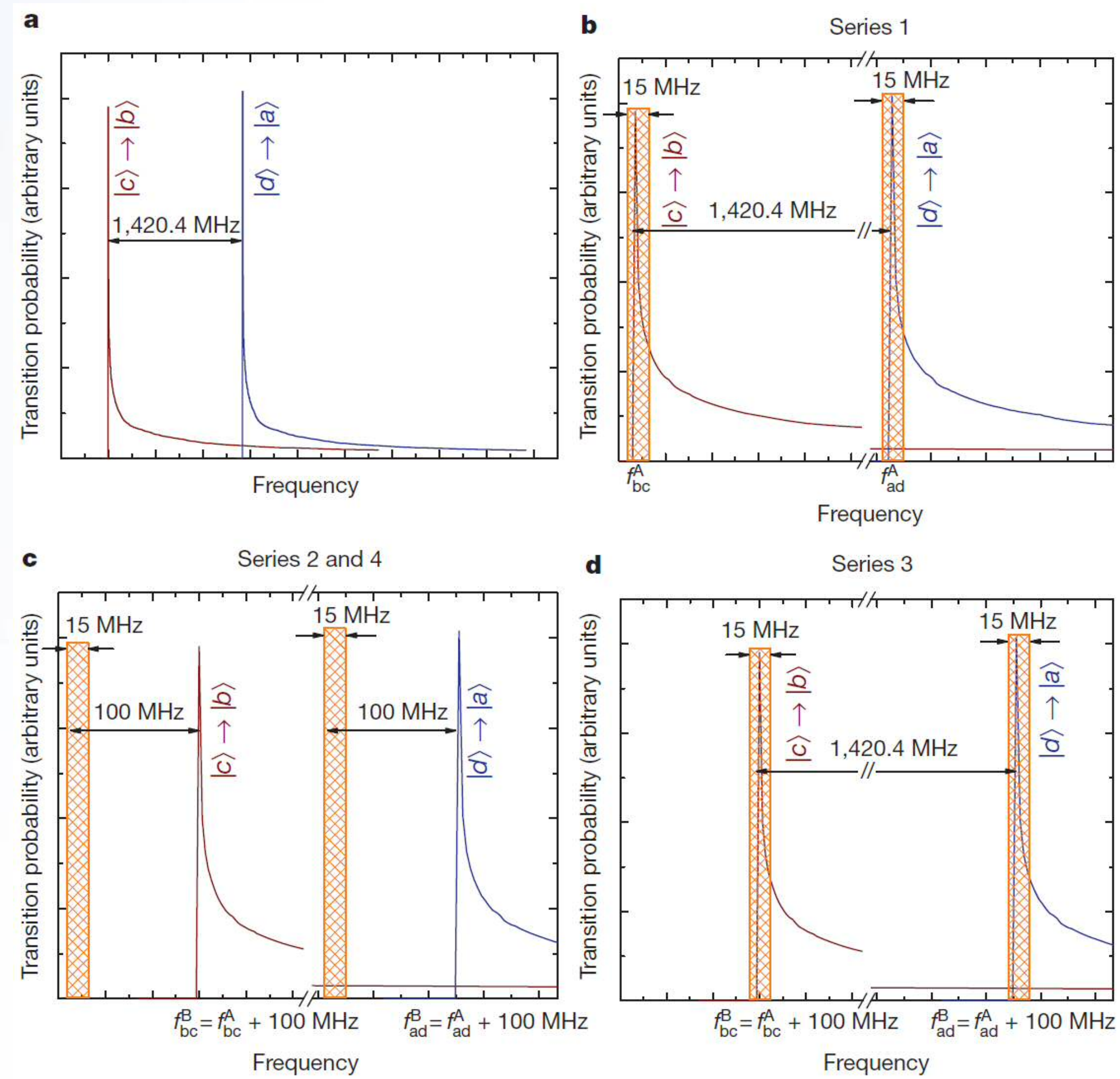
H: deviation from Fermi contact term:	–32.77(1) ppm
finite electric & magnetic radius (Zemach corrections):	–41.43(44) ppm
polarizability of p/p̄	+1.88(64) ppm
remaining deviation theory-experiment:	+0.86(78) ppm

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

Finite size effect of proton/antiproton becomes visible < 1 ppm

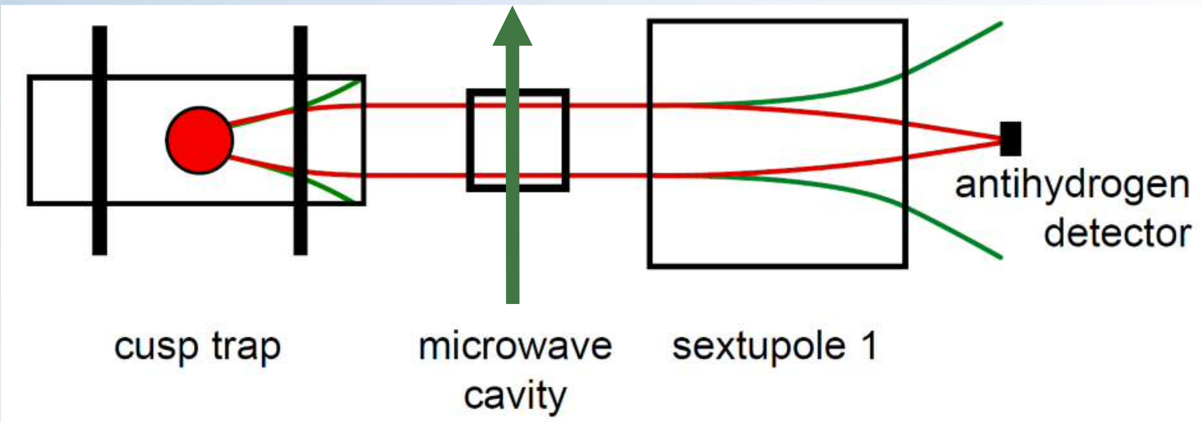
ALPHA: quantum transitions in a trap





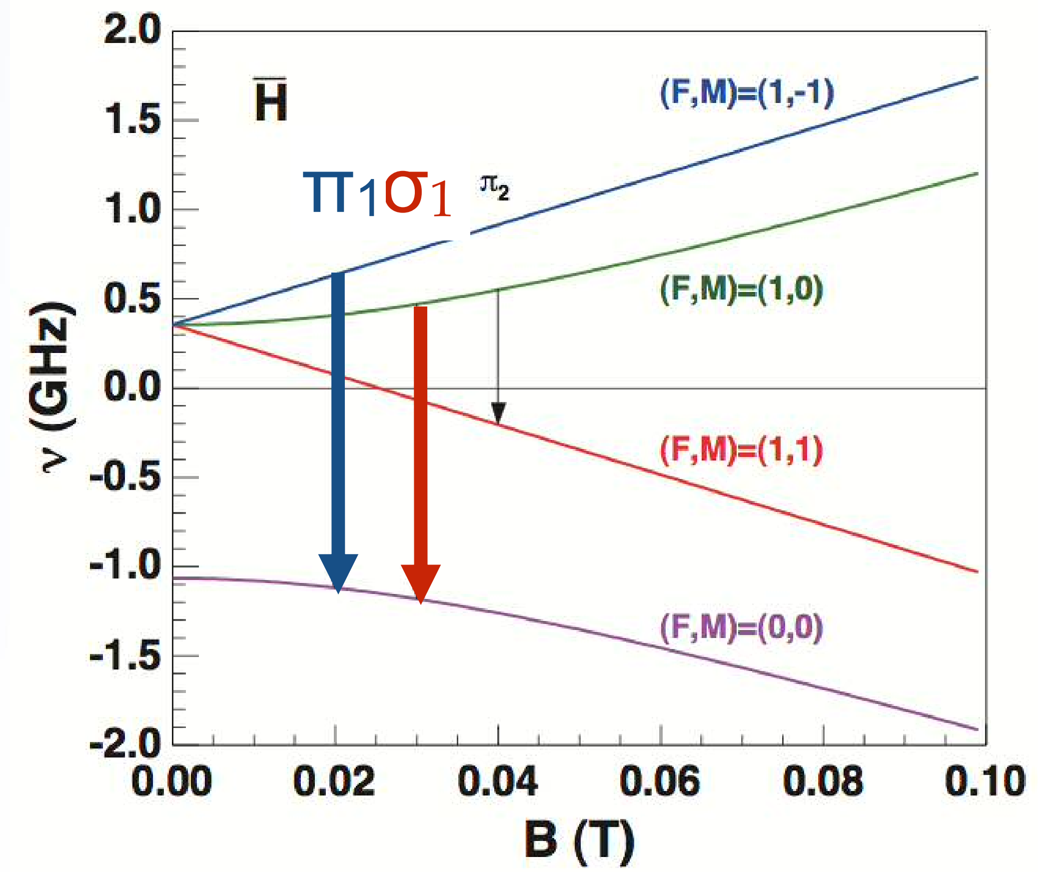
- high magnetic field
- $f_{bc} - f_{ad} = f_{HFS}$ independent of B
- only proof of principle

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



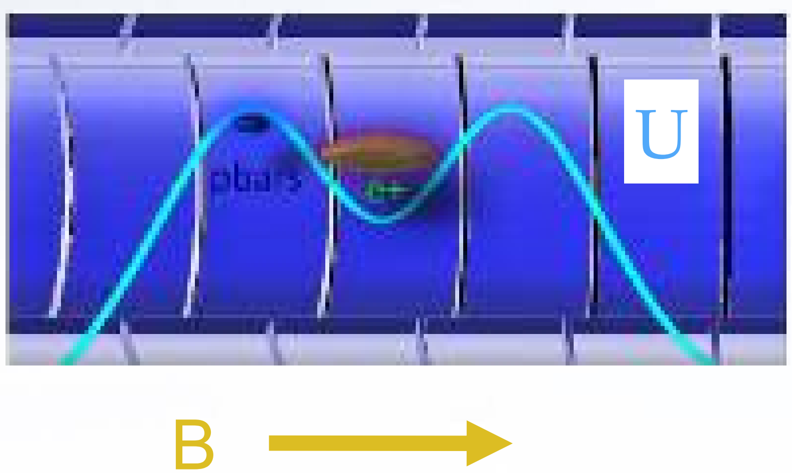
achievable resolution

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

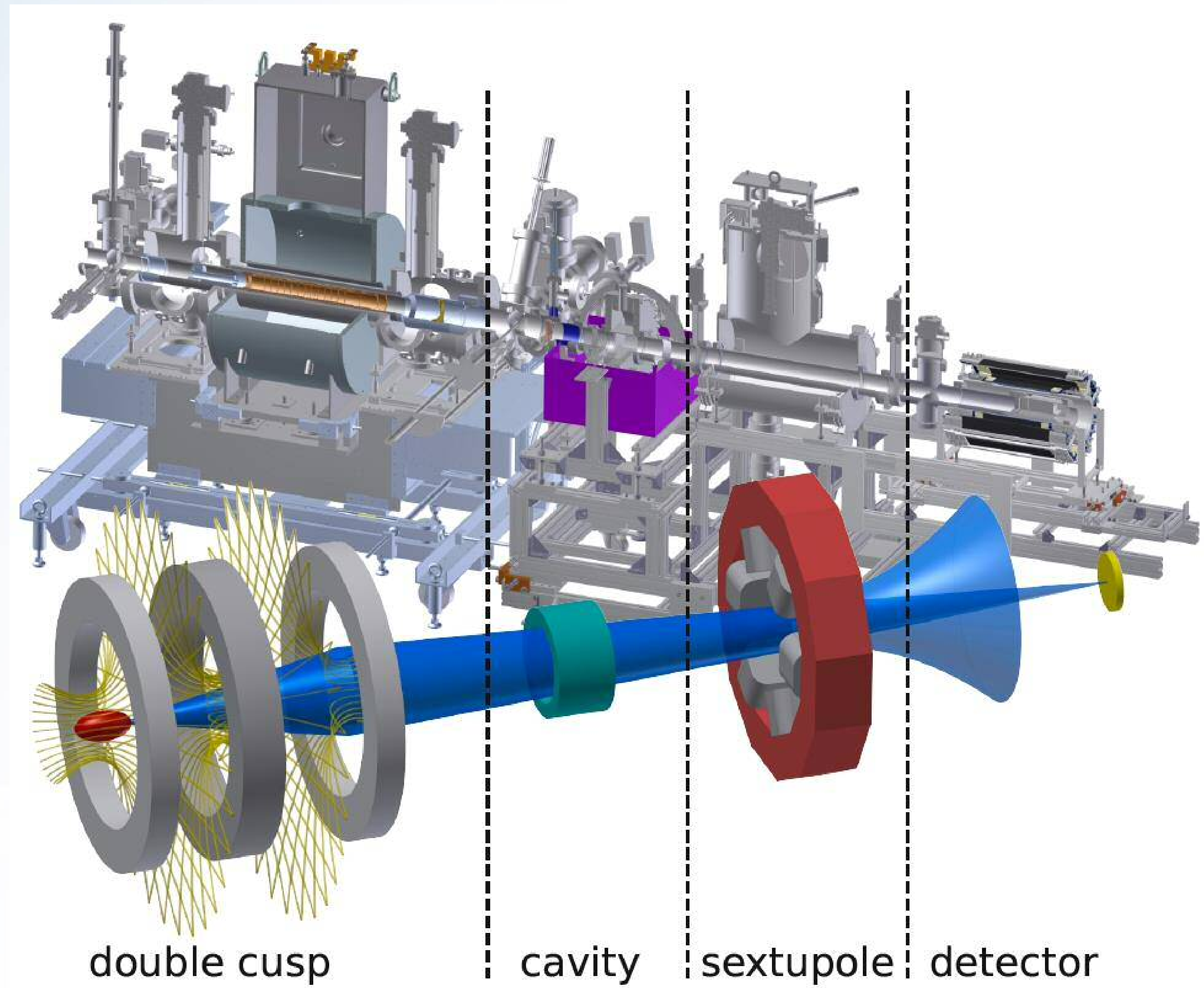
Double CUSP and HFS line

production
1st time achieved
in 2010 in
nested Penning trap
in splindle cusp region
of CUSP field

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



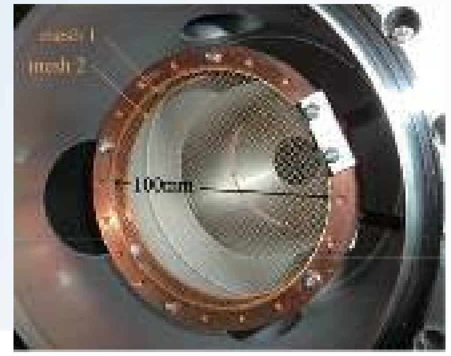
Y. Enomoto et al.
Phys. Rev. Lett 243401, 2010

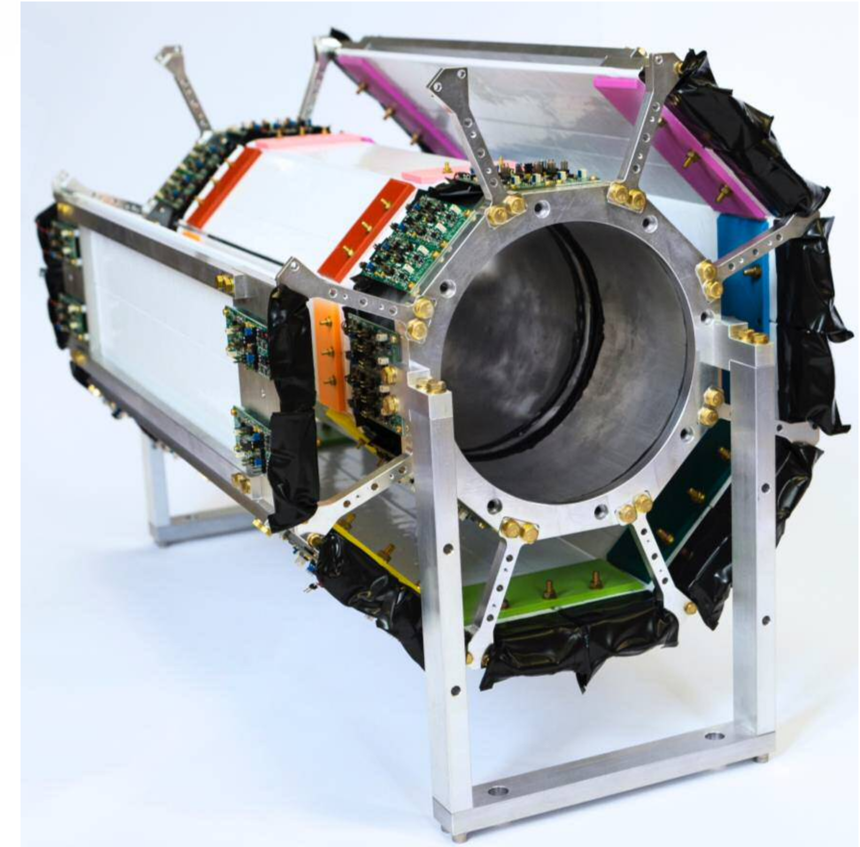


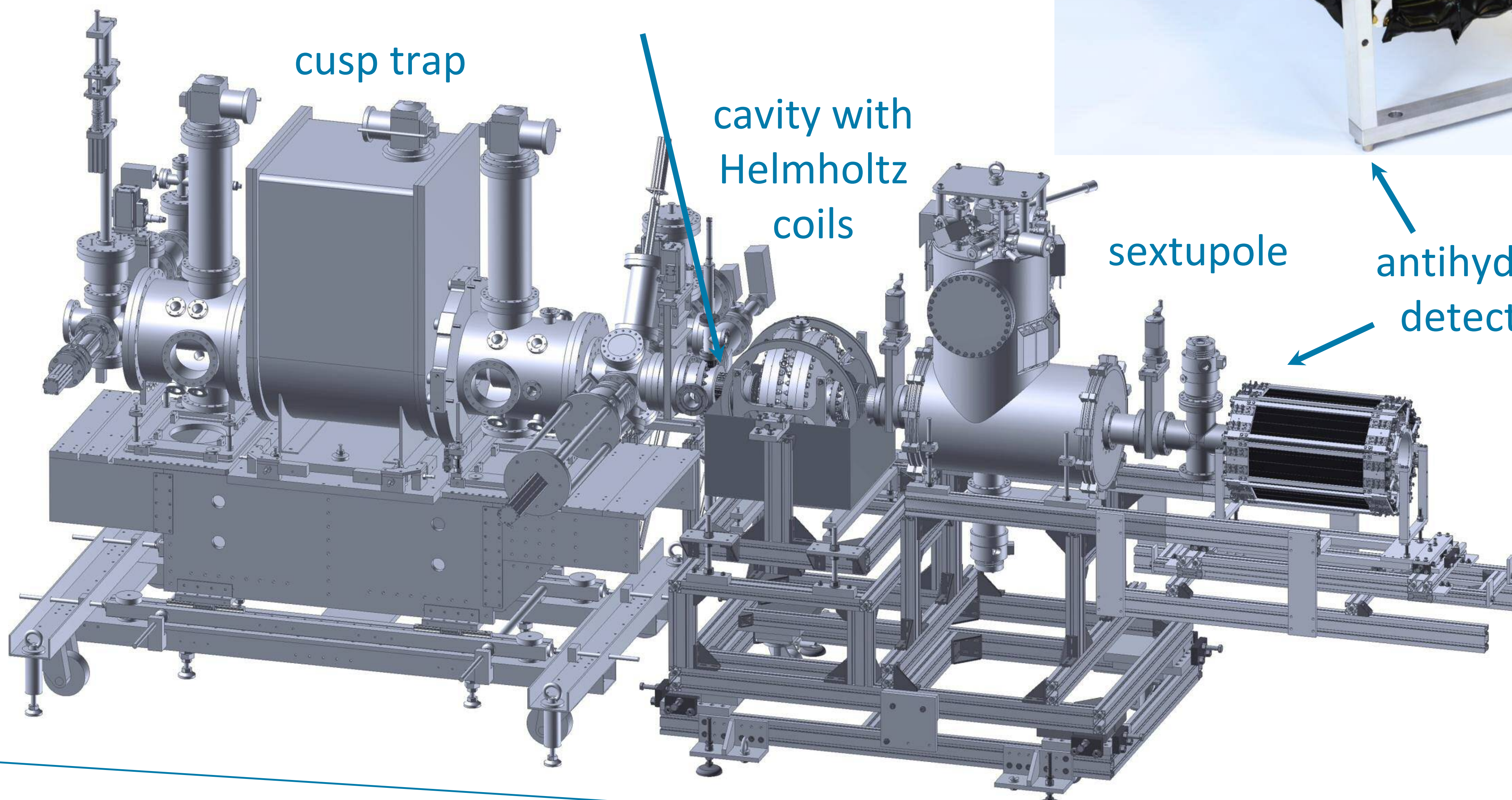
HFS beam line 2014

field ionizer

±8.7 kV
→ 17.4 kV/cm
→n   12 ionized







First observation of „beam“ 2014

- H^{bar} 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

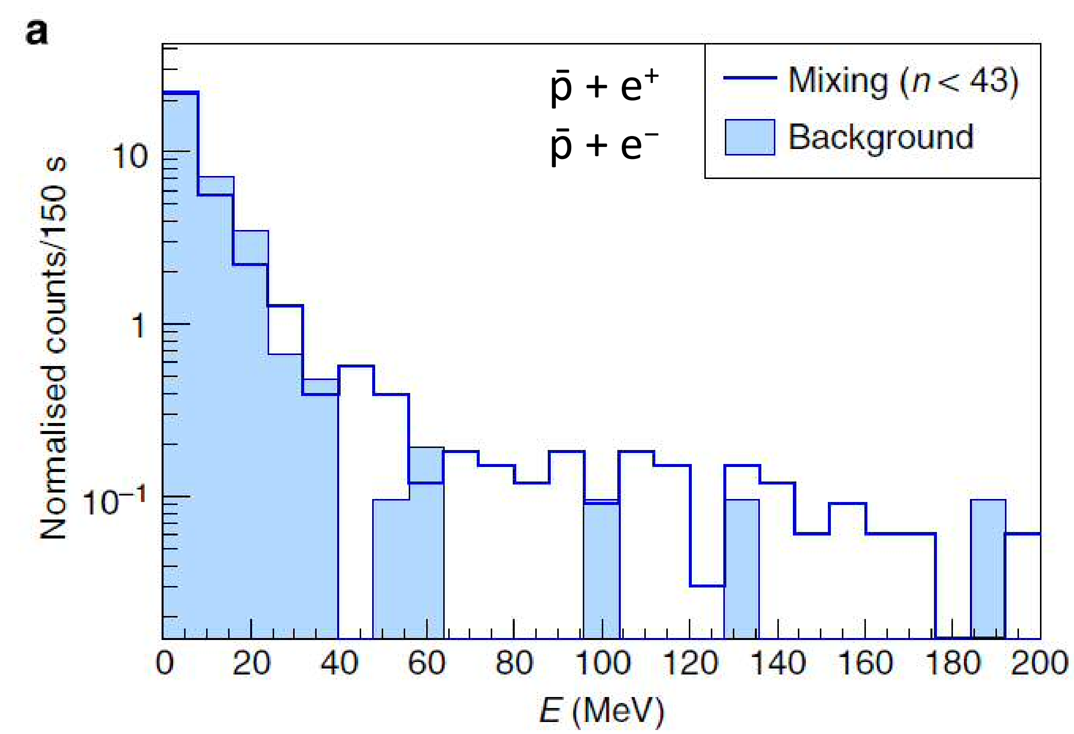


Table 1 | Summary of antihydrogen events detected by the antihydrogen detector.

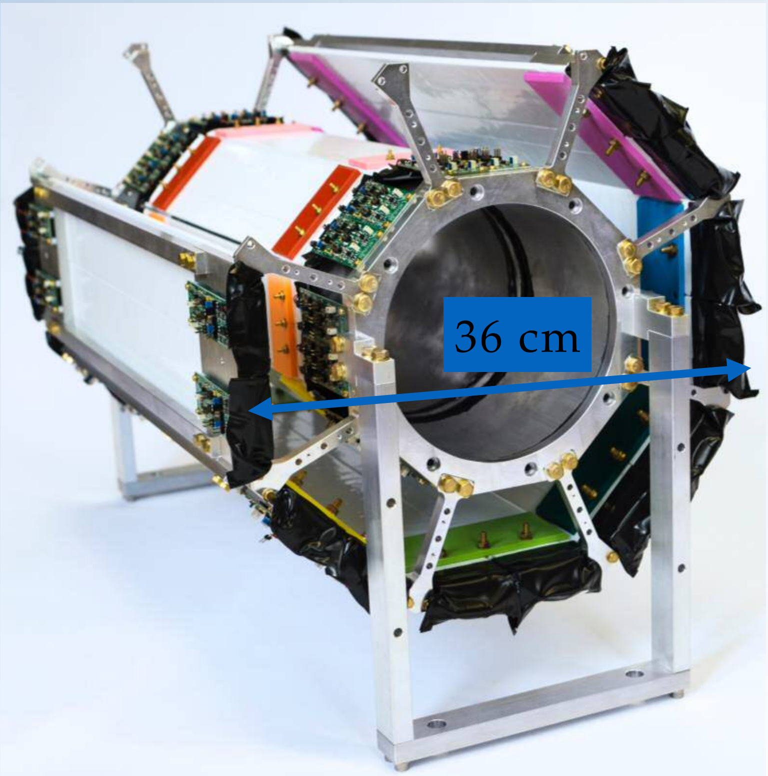
	Scheme 1	Scheme 2	Background
Measurement time (s)	4,950	2,100	1,550
Double coincidence events, N_t	1,149	487	352
Events above the threshold (40 MeV), $N_{>40}$	99	29	6
Z-value (profile likelihood ratio) (σ)	5.0	3.2	—
Z-value (ratio of Poisson means) (σ)	4.8	3.0	—

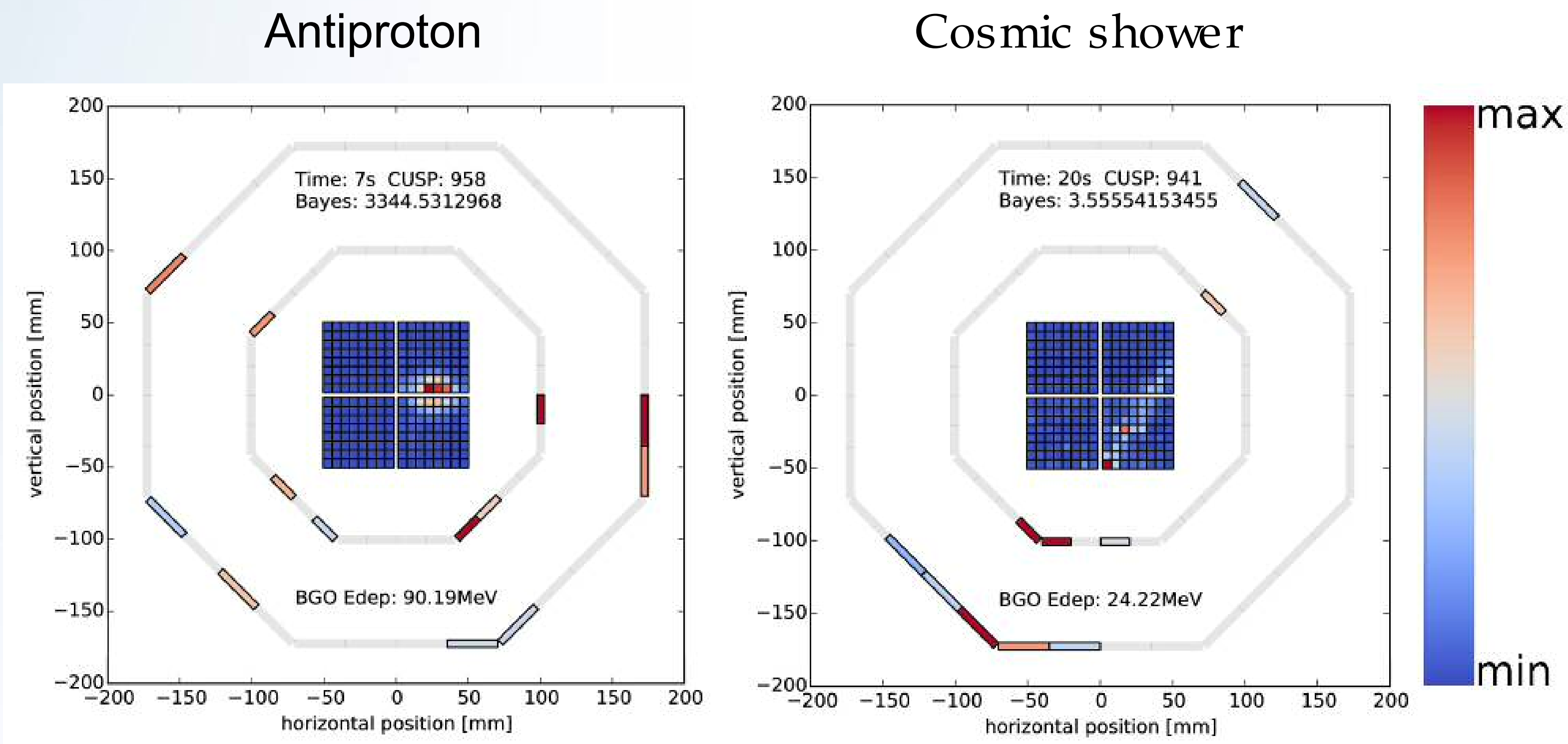
n≤43 n≤29

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

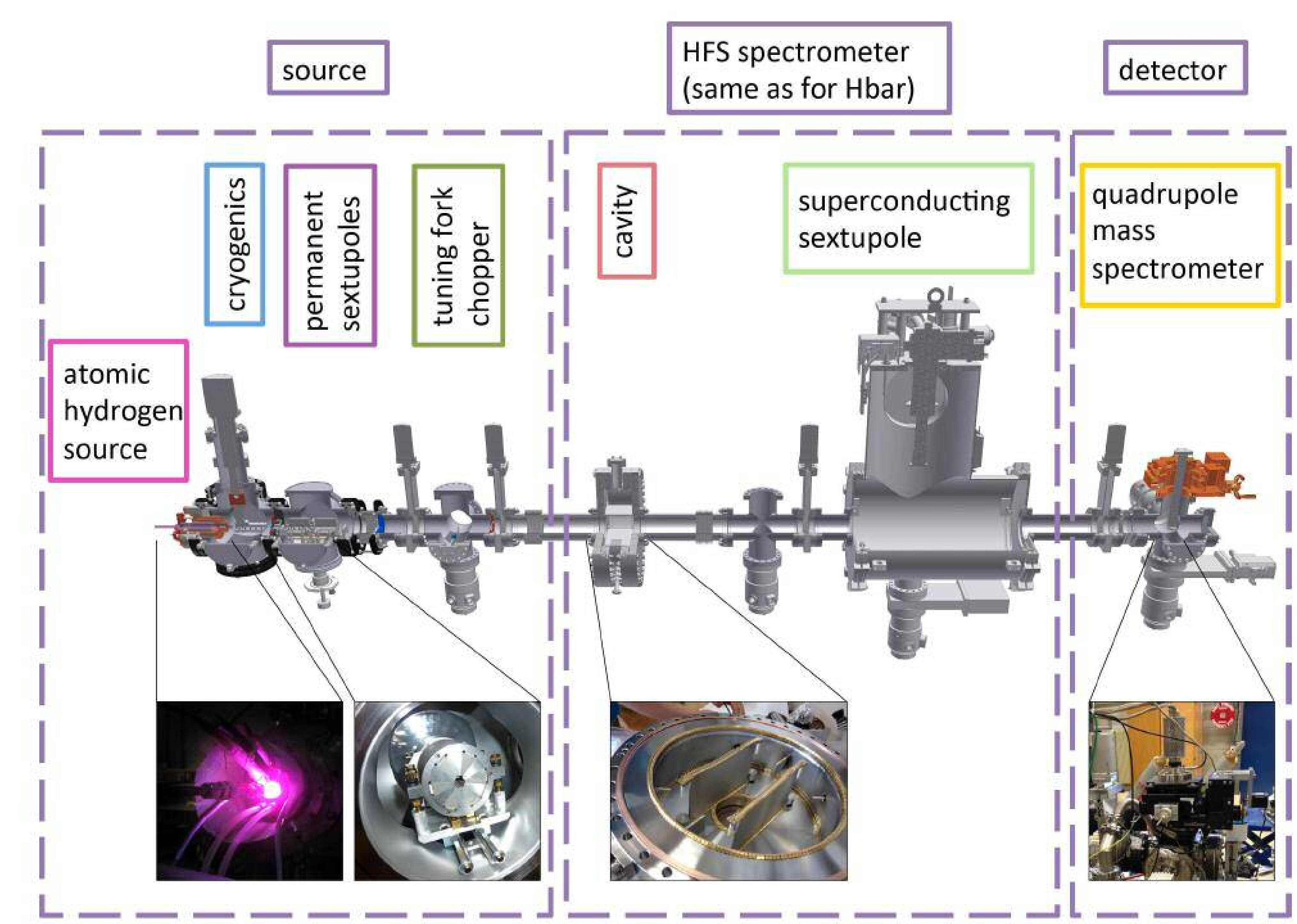
Compact pion tracking detector (2015)



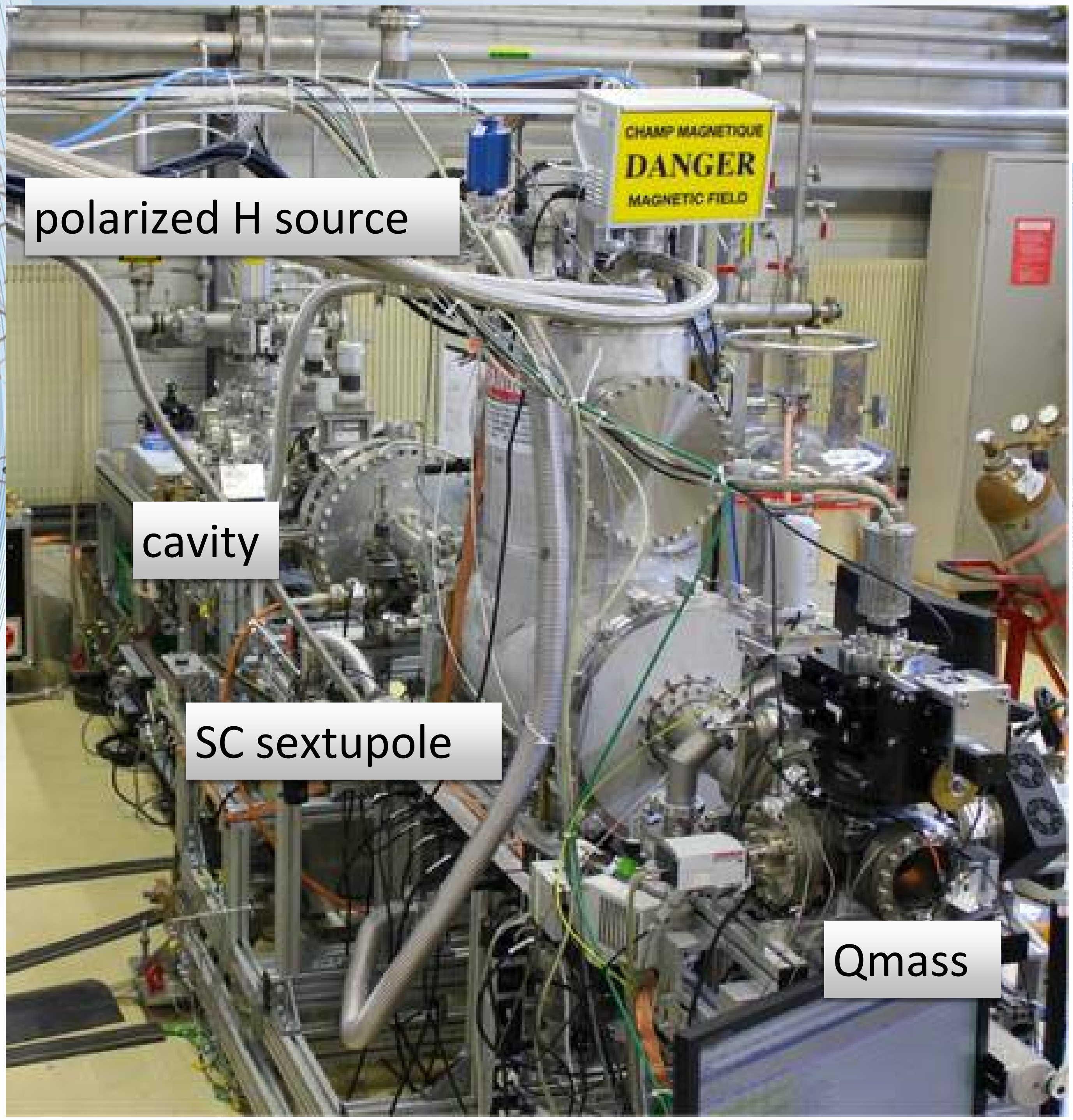


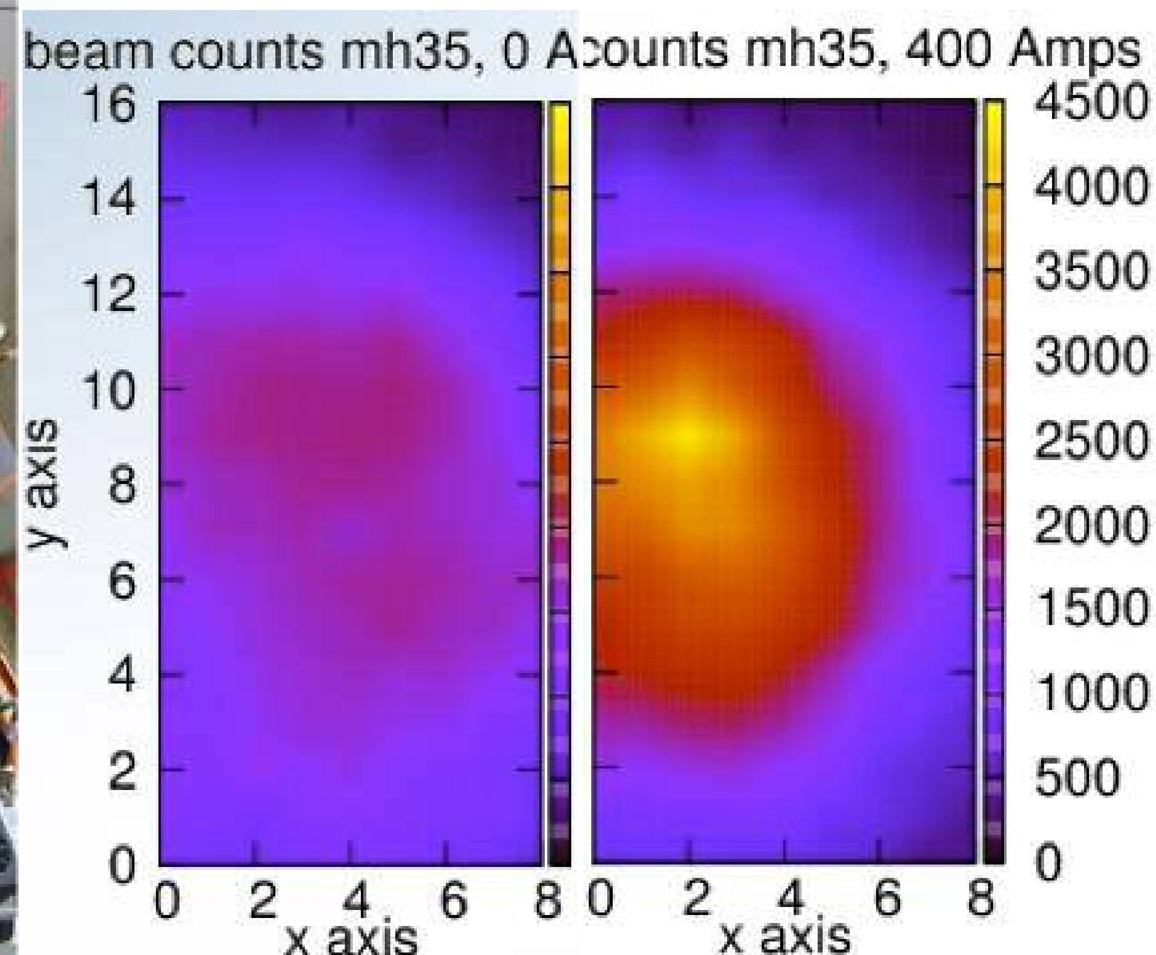
- Central calorimeter: BGO plate
  - Position sensitive read out
- 2 layer hodoscope with SiPM readout
  - Time resolution 840ps FWHM
  - Bayes analysis due to low rate

Hydrogen beam setup



Hydrogen beam line test setup @ CERN

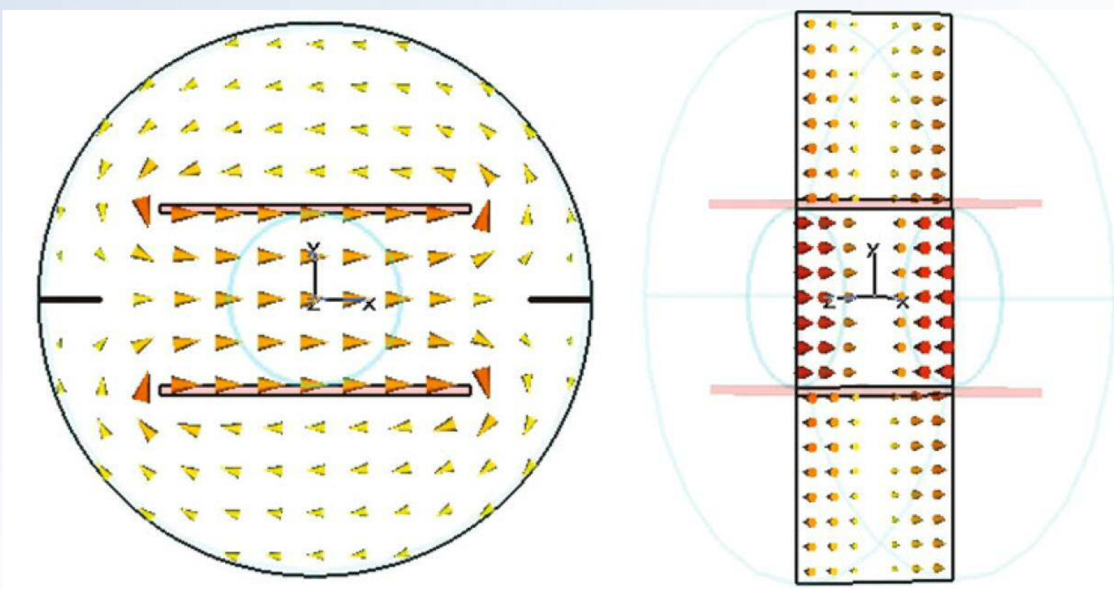




beam focusing by superconducting sextuple observed

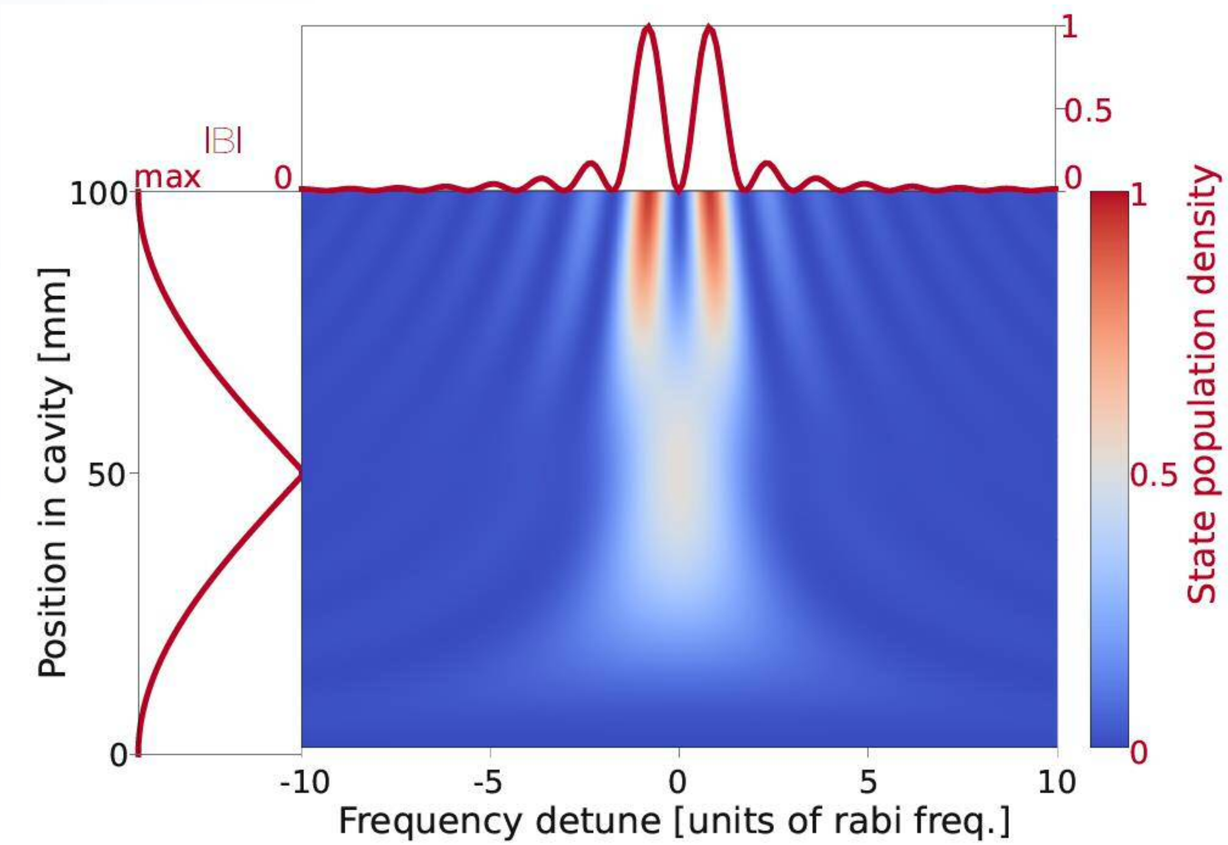
Spin-flip resonator

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



transverse field: homogeneous

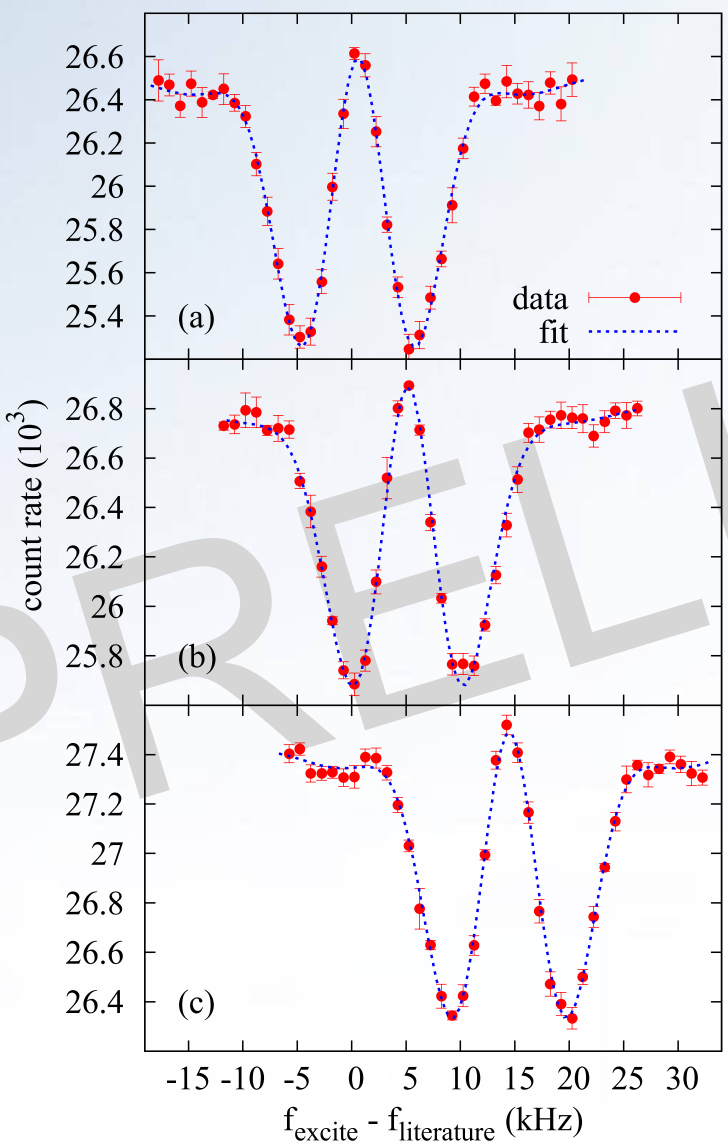
longitudinal field: cos(z)



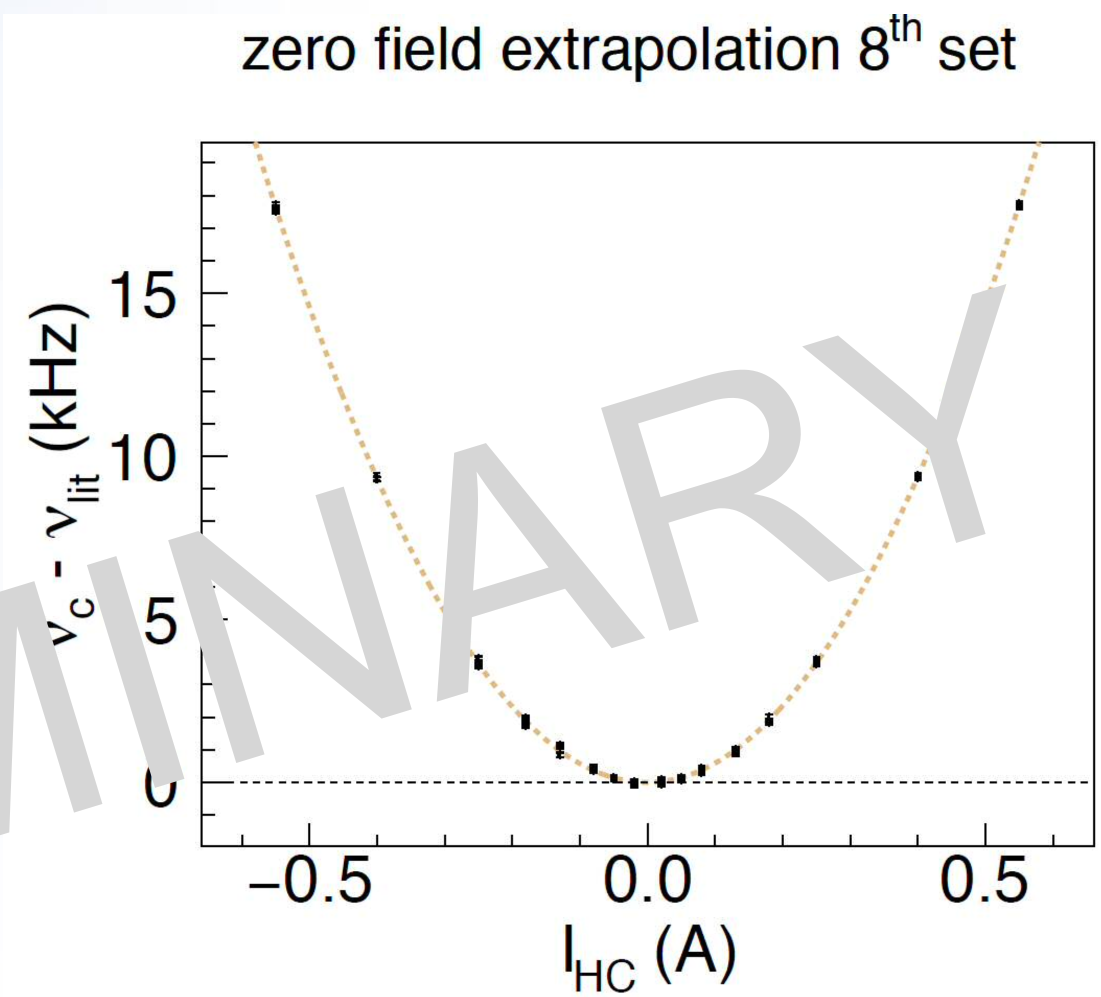
Line shape by optical Bloch equations

H beam HFS: σ_1 transition

- $\sigma_1(B)$, extrapolate $B \rightarrow 0$
- Fit the data with numerically simulated line shape



shift of resonances in magn. field
(a) 100 mA (b) 300 mA (c) 500 mA



One extrapolation result:

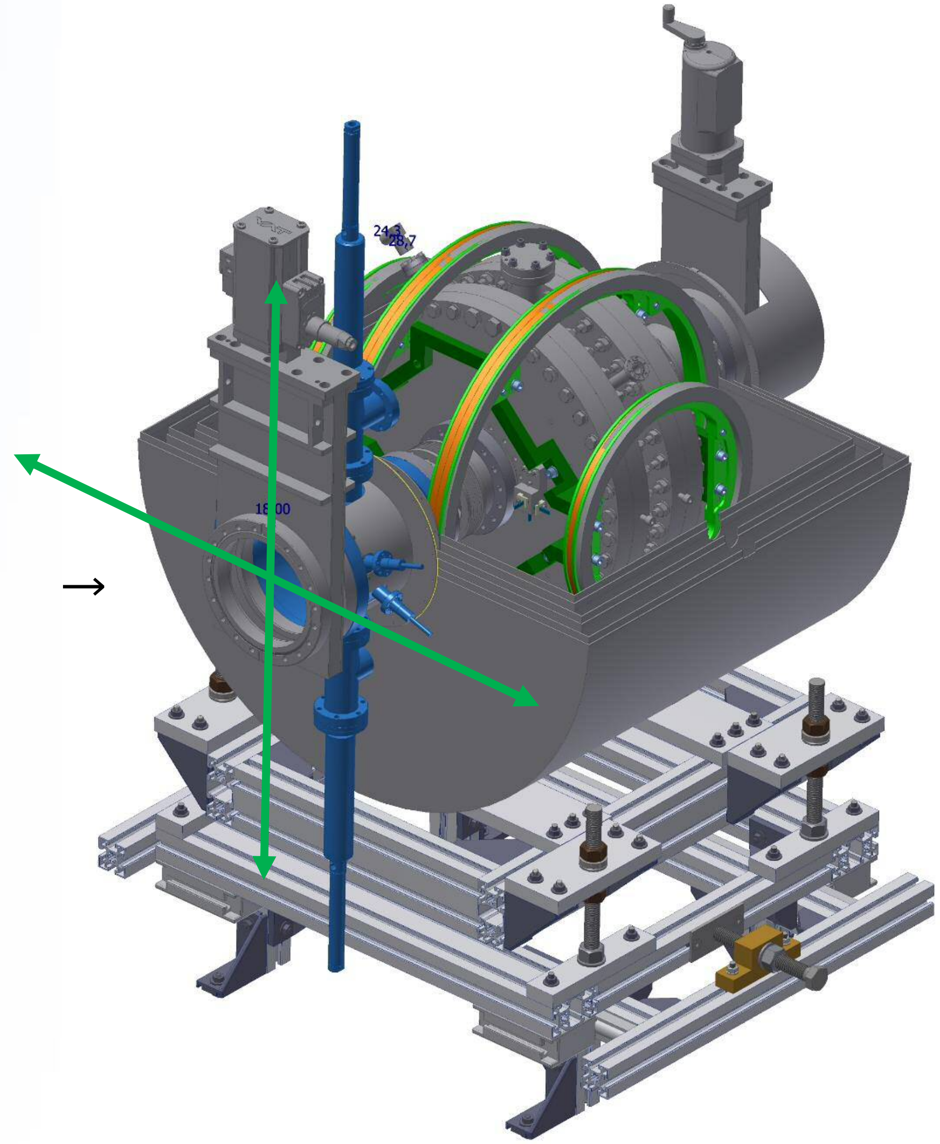
$$\nu = 1420.405748(9)\ \text{MHz}$$

$$\frac{\Delta\nu}{\nu} = 6.5 \times 10^{-9}$$

H maser: $\Delta\nu/\nu \sim 10^{-12}$

Outlook for H-beam

- 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



Non-minimal SME

- Operators of arbitrary dimensions
  - Non-relativisitc spherical coefficients
  - Shift only for π-transition ($\Delta m_F \neq 0$)
  - B direction dependence

$$\mathcal{L} \supset \frac{1}{2}\overline{\psi_w}(\gamma^\mu i\partial_\mu - m_w + \hat{\mathcal{Q}}_w)\psi_w + \mathrm{H.}$$

$$\delta h_{\mathrm{H}}^{\mathrm{NR}} = \delta h_e^{\mathrm{NR}} + \delta h_p^{\mathrm{NR}}$$

K_{kjm}	Mass-dimensions	CPT sign	Spin-dependence
c_{kjm}^{NR}	Even numbers	+1	Independent
a_{kjm}^{NR}	Odd numbers	−1	Independent
$g_{kjm}^{\mathrm{NR}(qP)}$	Even numbers	−1	Dependent
$H_{kjm}^{\mathrm{NR}(qP)}$	Odd numbers	+1	Dependent

$$a_{200}^{\mathrm{NR}} \supset a_{200}^{(5)} + a_{200}^{(7)} m_0^2 + a_{200}^{(9)} m_0^4 \ldots$$

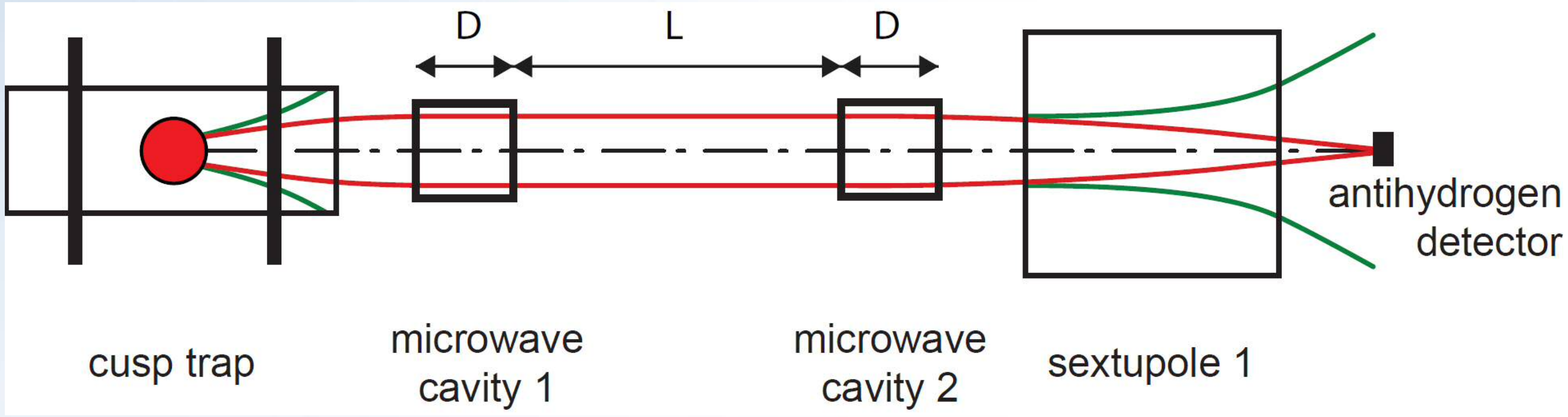
$$2\pi\delta\nu = -\frac{\Delta m_F}{2\sqrt{3\pi}} \sum_{q=0}^{2} (\alpha m_{\mathrm{r}})^{2q}(1 + 4\delta_{q2}) \times \sum_w [g_{w(2q)10}^{\mathrm{NR}(0B)} - H_{w(2q)10}^{\mathrm{NR}(0B)} + 2g_{w(2q)10}^{\mathrm{NR}(1B)} - 2H_{w(2q)10}^{\mathrm{NR}(1B)}].$$

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

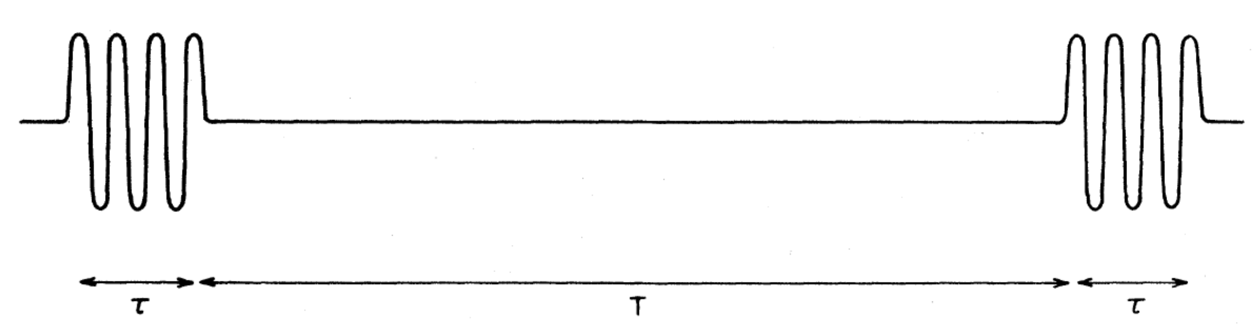
Kostelecký, V. A., & Mewes, M.. *PRD 88*, 096006 (2013).
Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

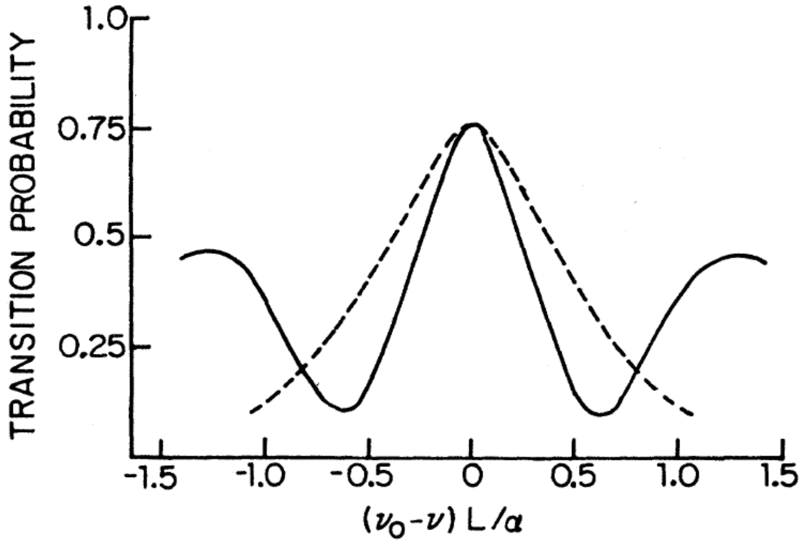
Experiments in an atomic beam

- Phase 2: Ramsey separated oscillatory fields

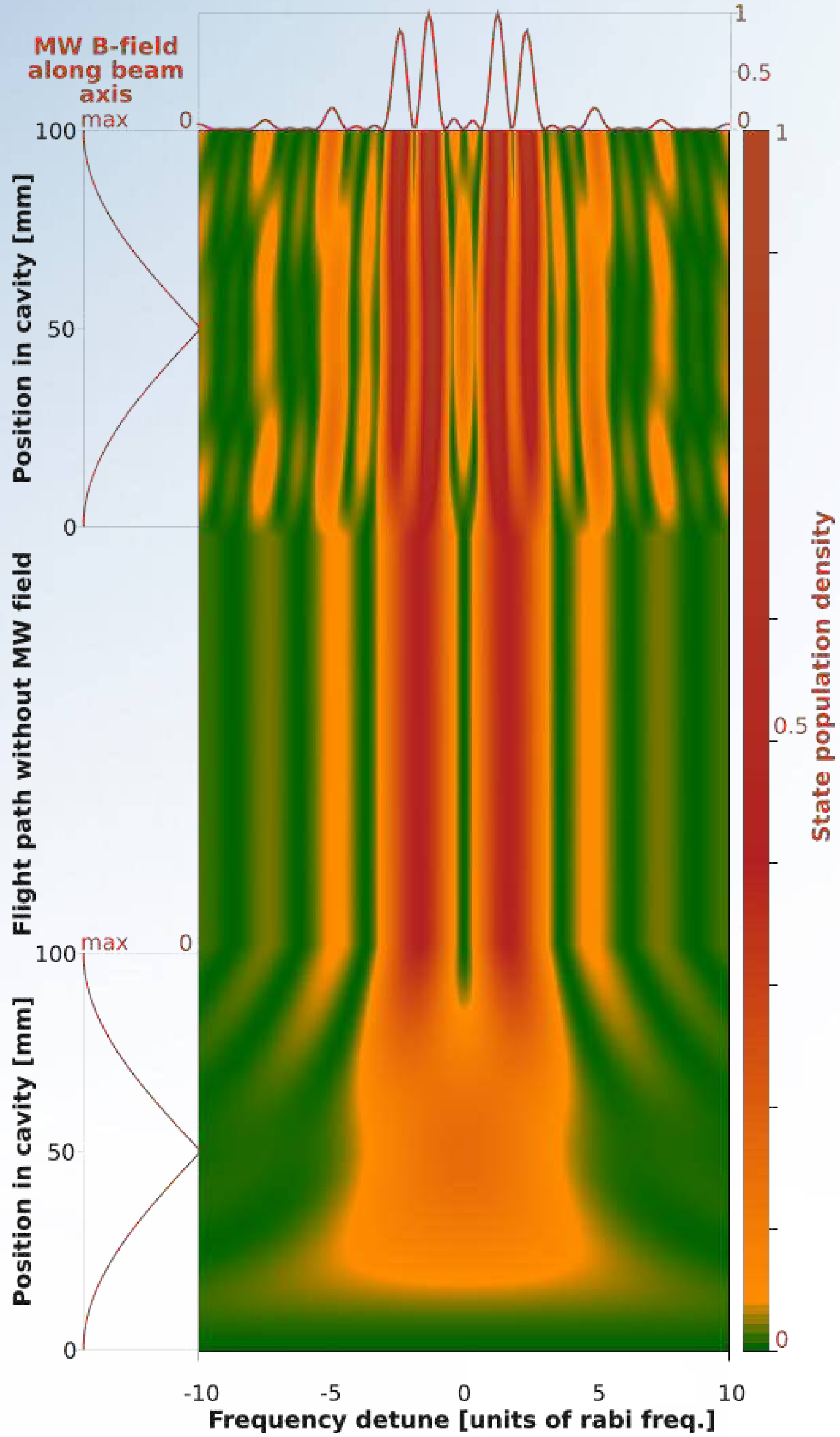


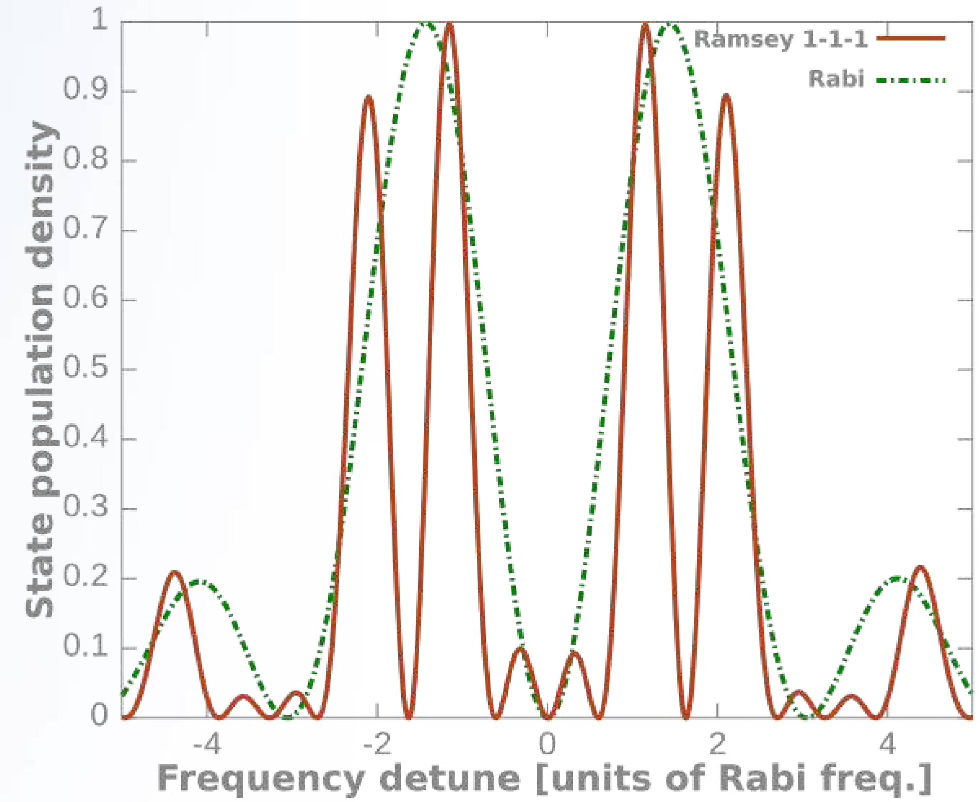
Linewidth reduced by D/L



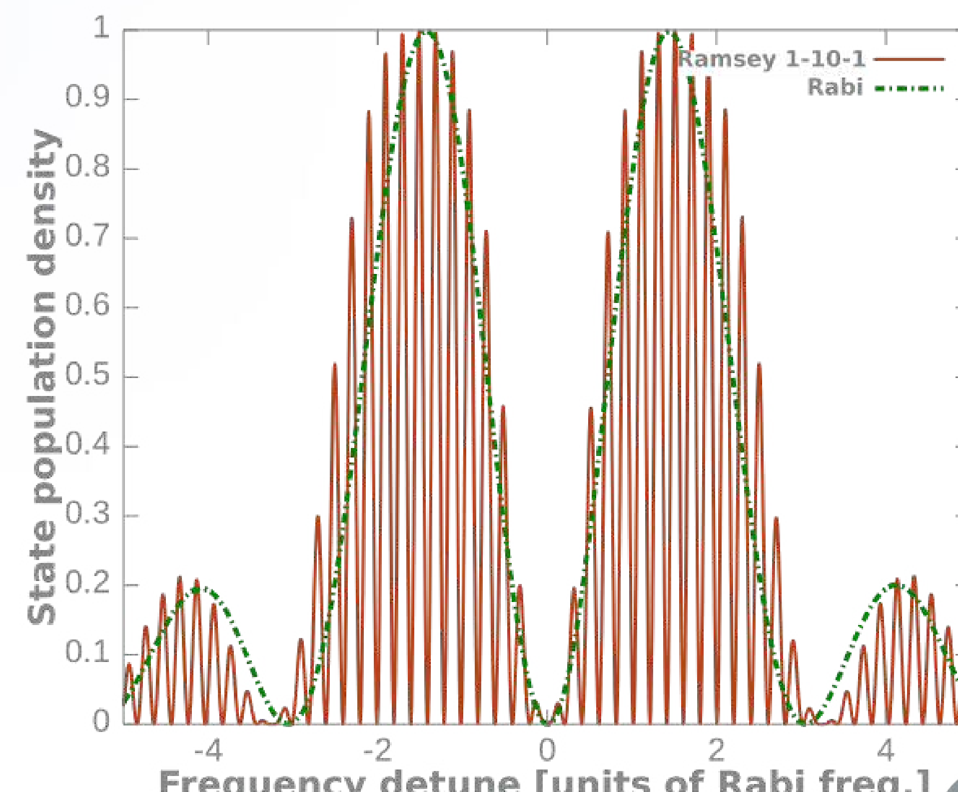


Optical Bloch Equation solution





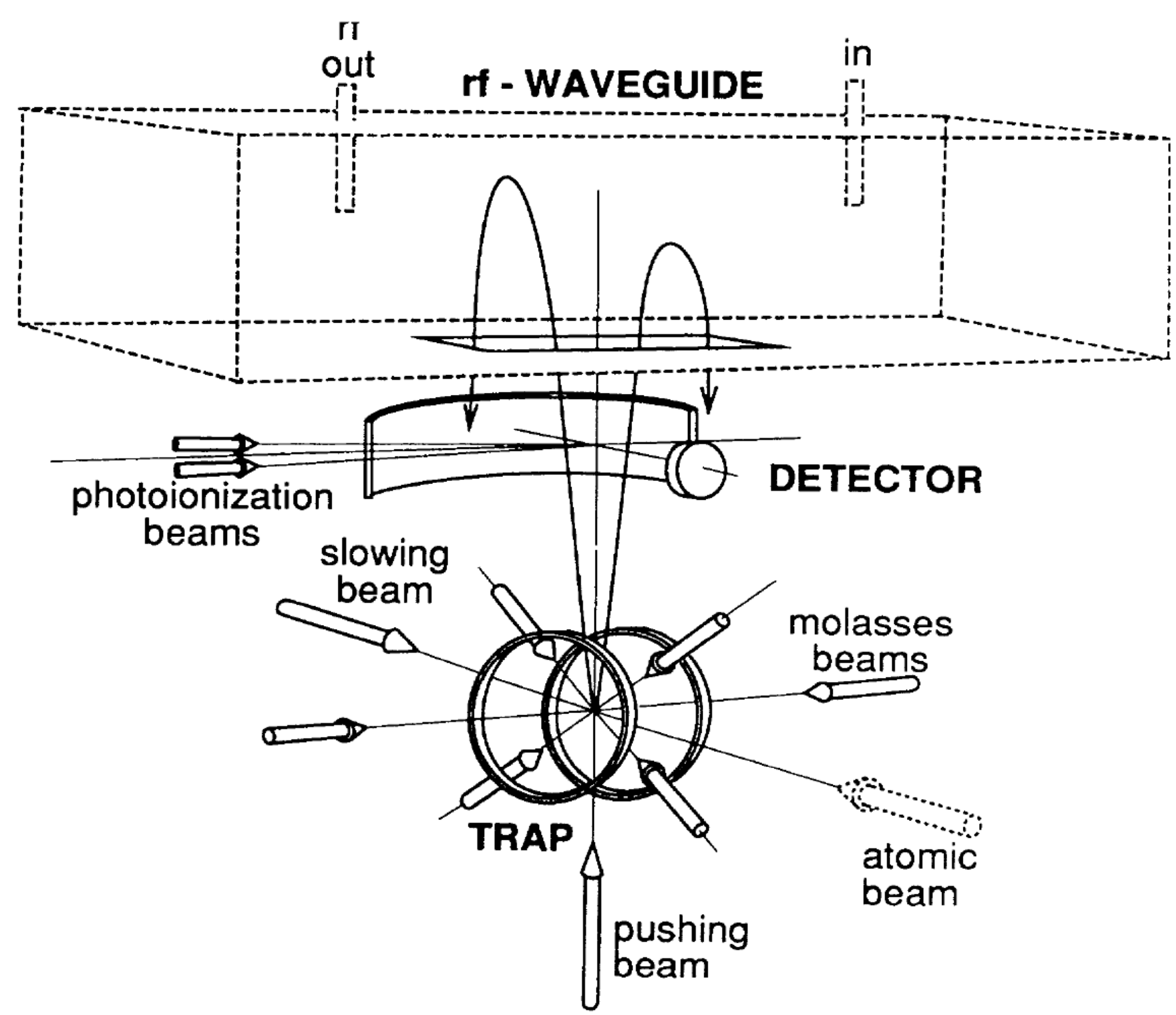
10cm RF
10cm free
10cm RF



10cm RF
1 m free
10cm RF

(Far) future experiments

- Phase 3: trapped
  - 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: line width
    - Δf ~3 Hz, Δf/f ~ 2×10^{-9}



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

Summary

- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry
  - First “beam” of observed in field-free region
  - Next steps: optimize rate, check polarization, velocity
- HFS measurement in H beam of ~3 ppb achieved
  - Potential to measure non-minimal SME coefficients

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