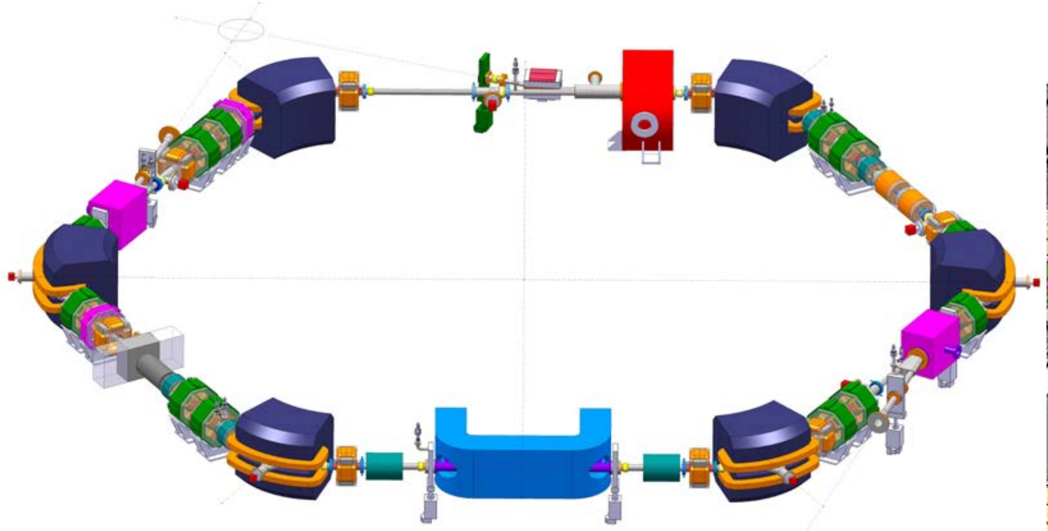
SMI - STEFAN MEYER INSTITUTE

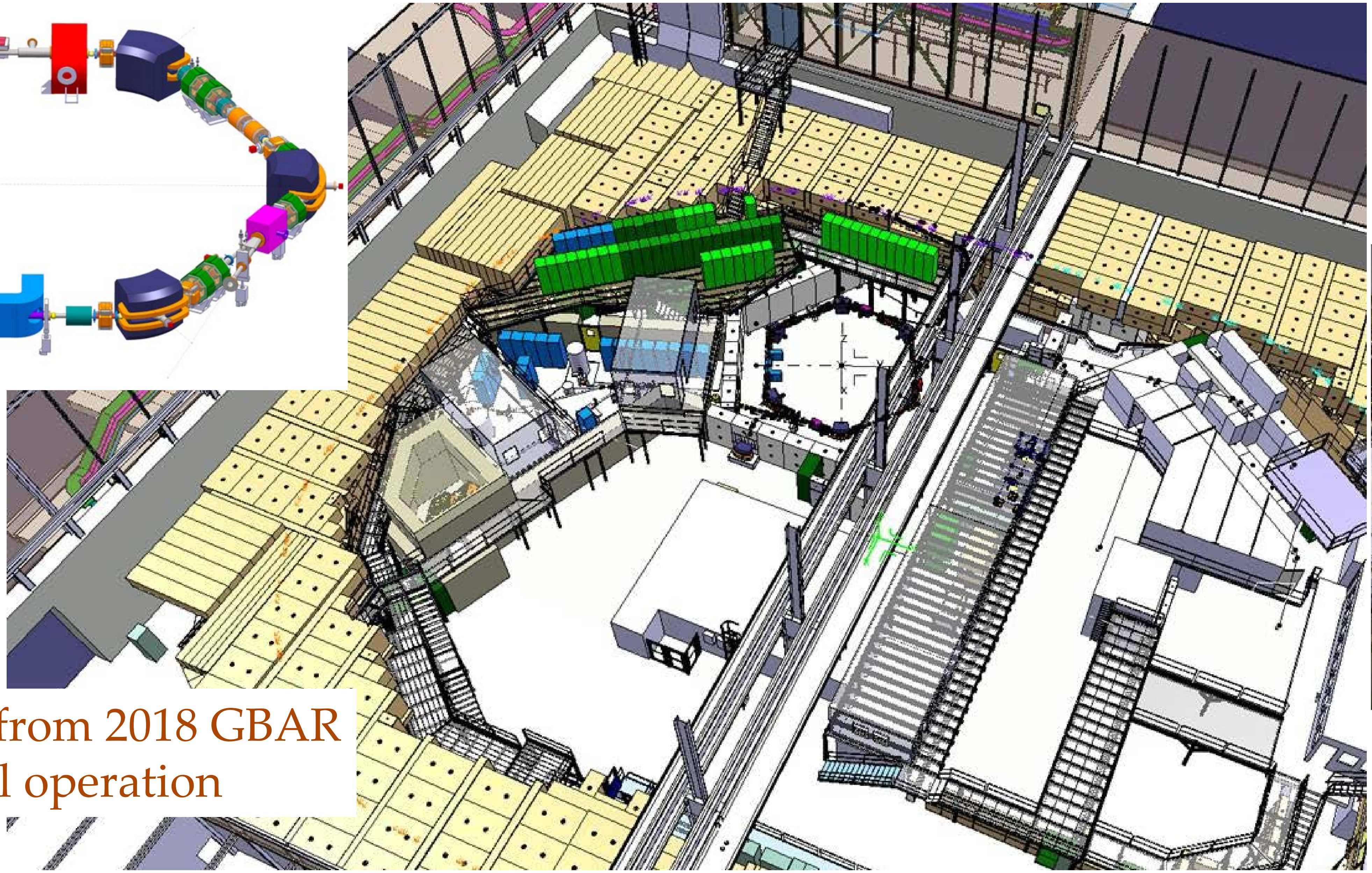
# In-beam hyperfine spectroscopy of (anti)hydrogen

E. Widmann
Stefan Meyer Institute, Vienna

*Quantum Workshop Frascati 5 Jul 2018*

# Antiproton Decelerator & ELENA @ CERN





AD: 5 MeV
ELENA: 5 MeV → 100 keV
Pulsed beam, $3\times10^7$ $\bar{p}$ every ~ 100 s

ELENA operation from 2018 GBAR
2021 (after LS2) full operation

# ASACUSA collaboration

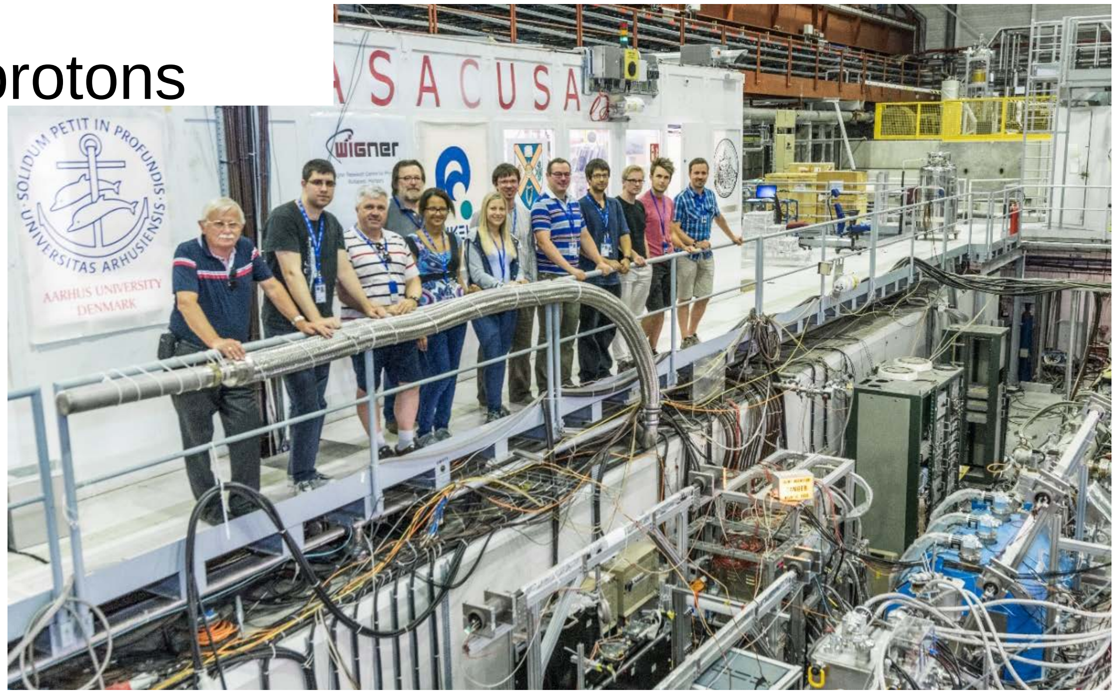
A tomic
S pectroscopy
A nd
C ollisions
U sing
S low
A ntiprotons

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**: 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

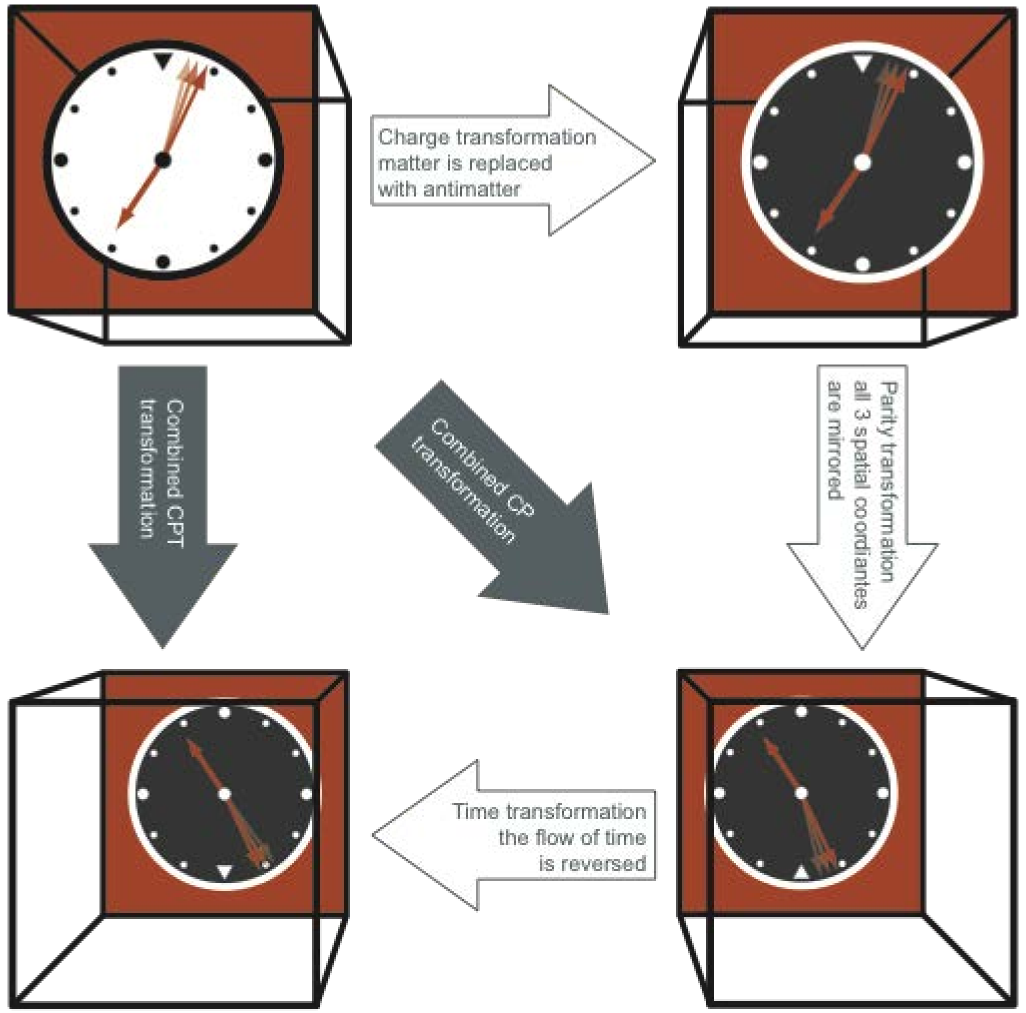
**Univerita di Brescia & INFN Brescia**: M. Leali, E. Lodi-Rizzini, V. Mascagna, L. Venturelli

**Stefan Meyer Institut für Subatomare Physik**: C. Amsler, S. Cuendis, M. Fleck, A. Gligorova, B. Kolbinger, V. Mäckel, A. Nanda, M.C. Simon, H. Spitzer, M. Strube, D. Than, E. Widmann, M. Wiesinger, J. Zmeskal

**CERN**: H. Breuker, C. Malbrunot

# Fundamental symmetries C, P, T

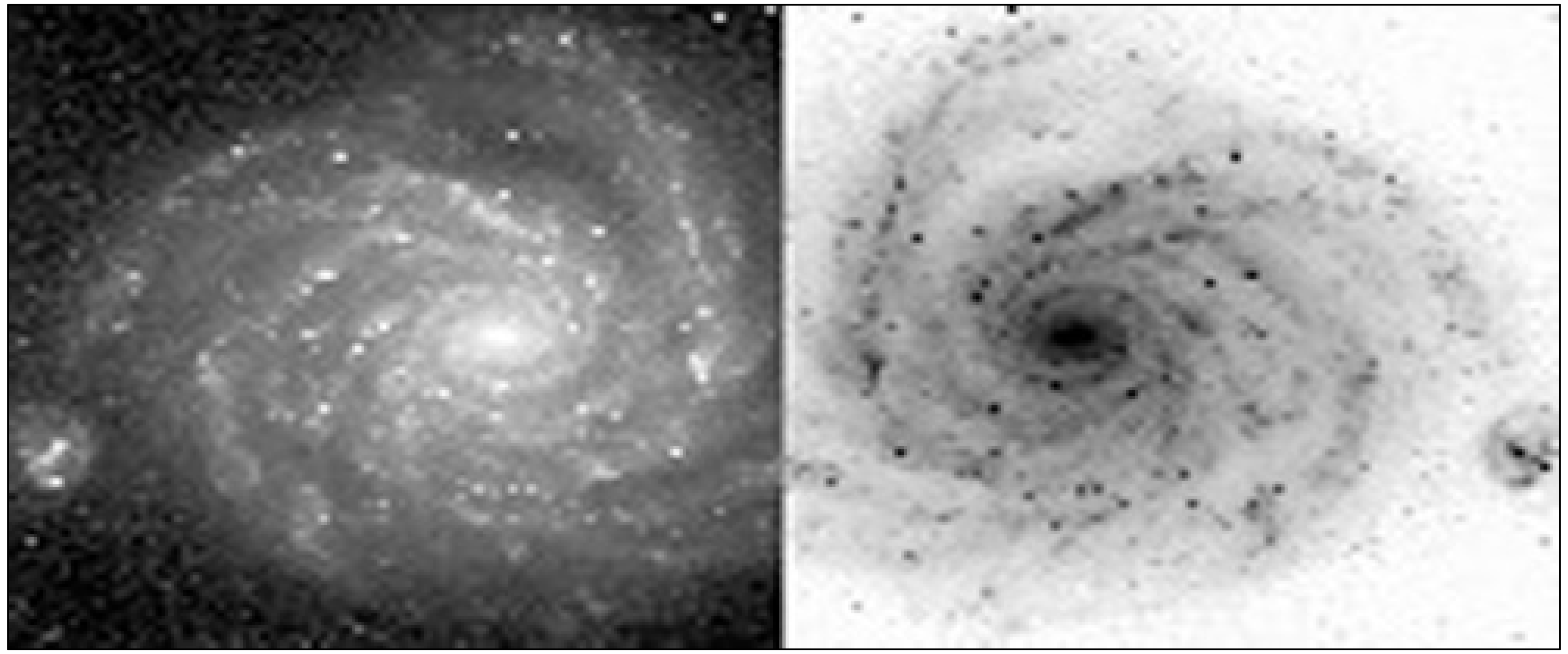
- C: charge conjugation particle - antiparticle
- P: parity: spatial mirror
- T: time reversal
- CPT theorem: consequence of
  - Lorentz-invariance
  - local interactions
  - unitarity
    - *Lüders, Pauli, Bell, Jost 1955*
- all QFT of SM obey CPT
- not necessarily true for string theory



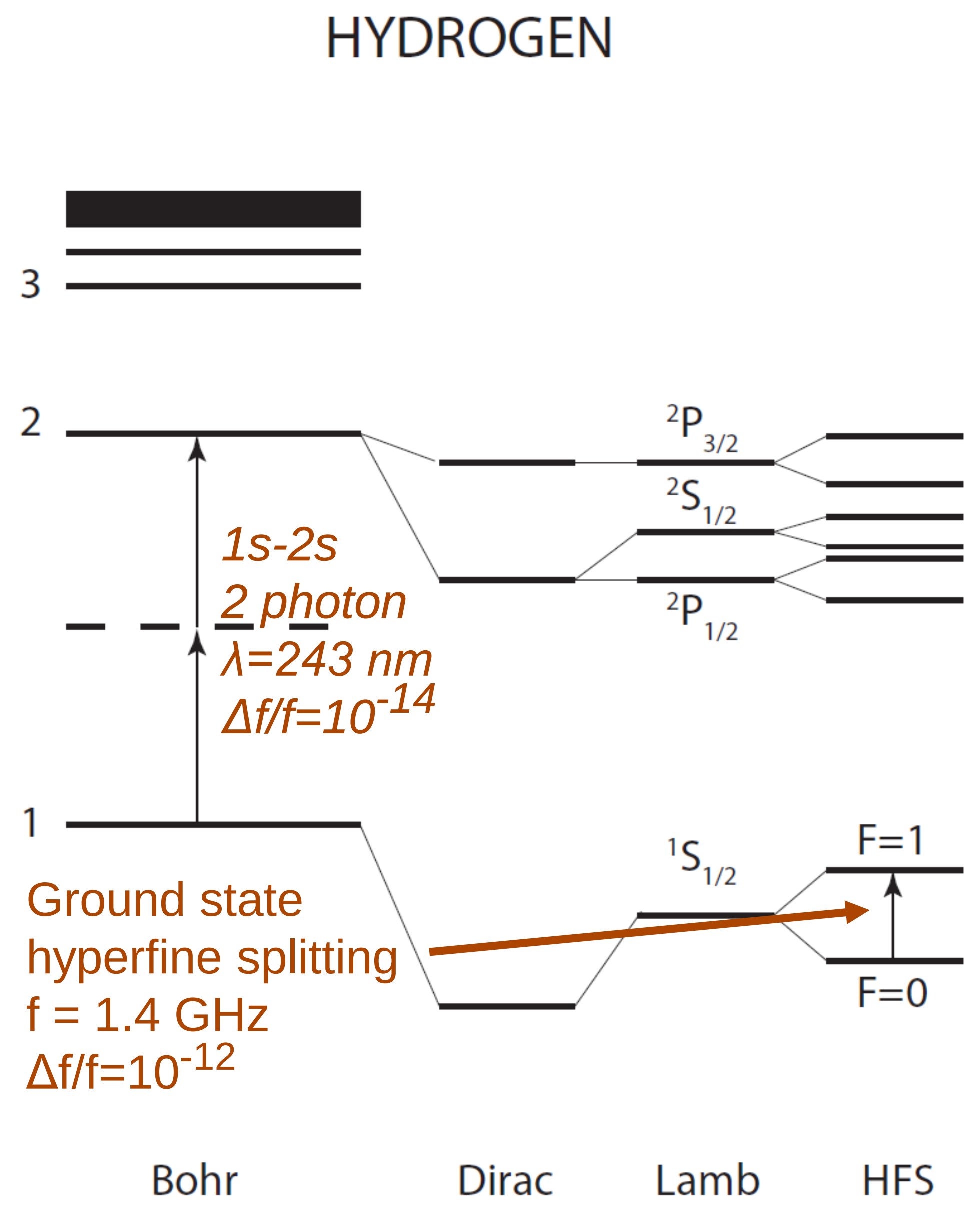

CPT → particle/anitparticle: same masses, lifetimes, g-factors, |charge|,...

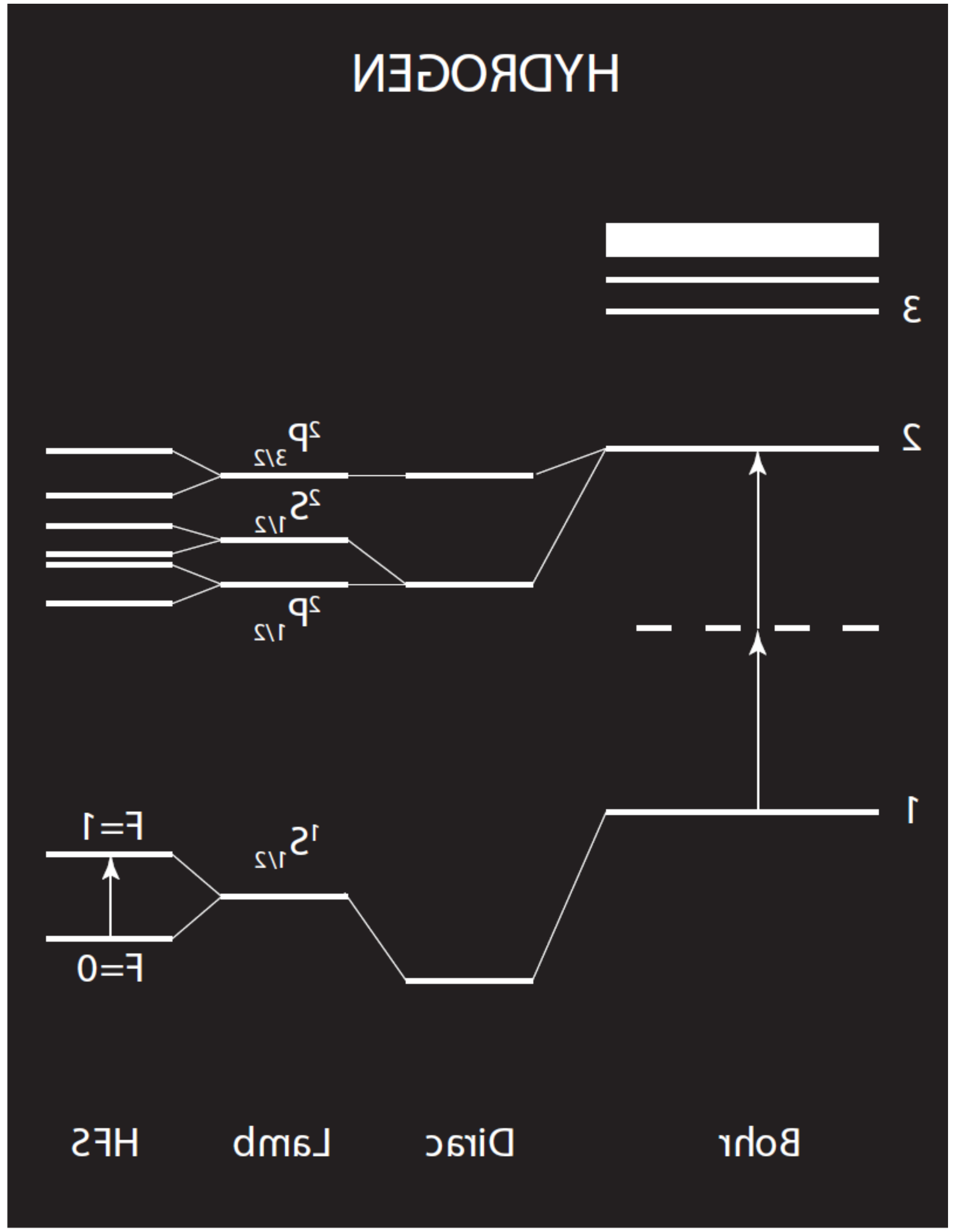
# CPT symmetry & cosmology

- 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?

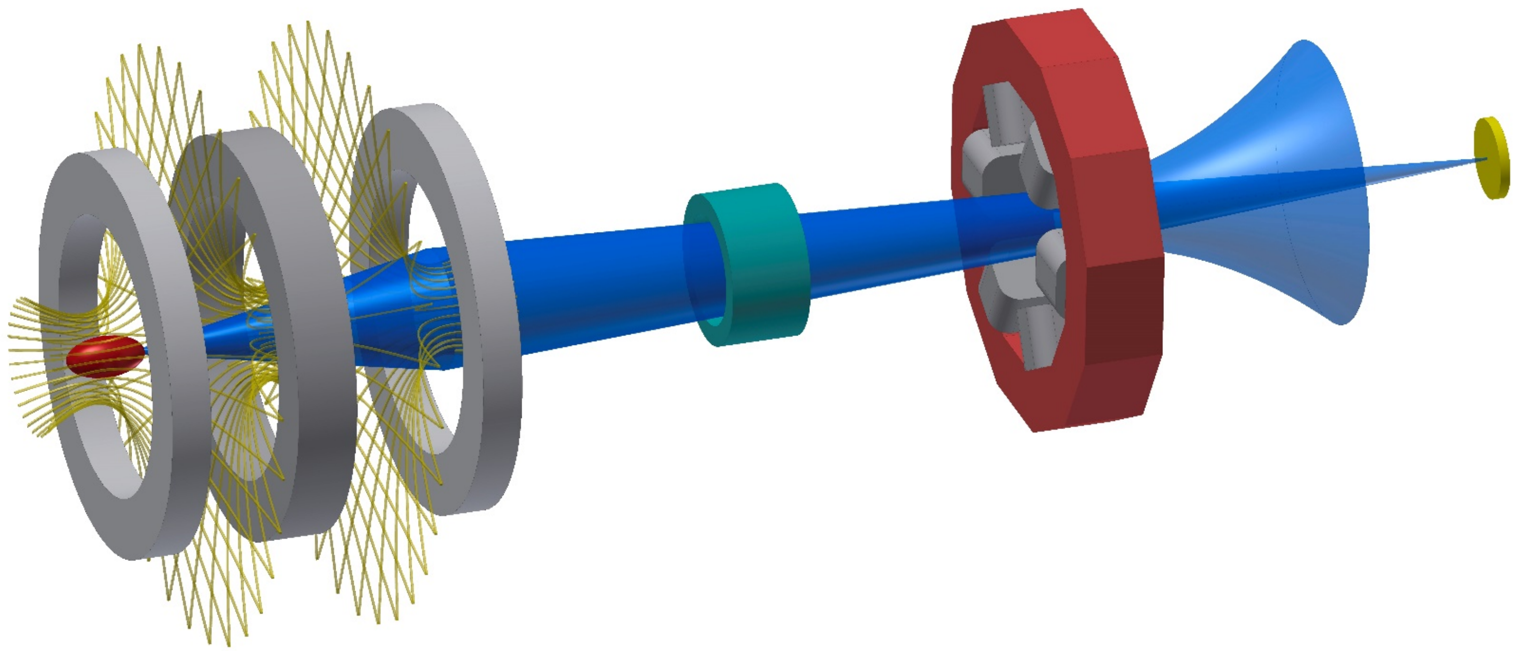


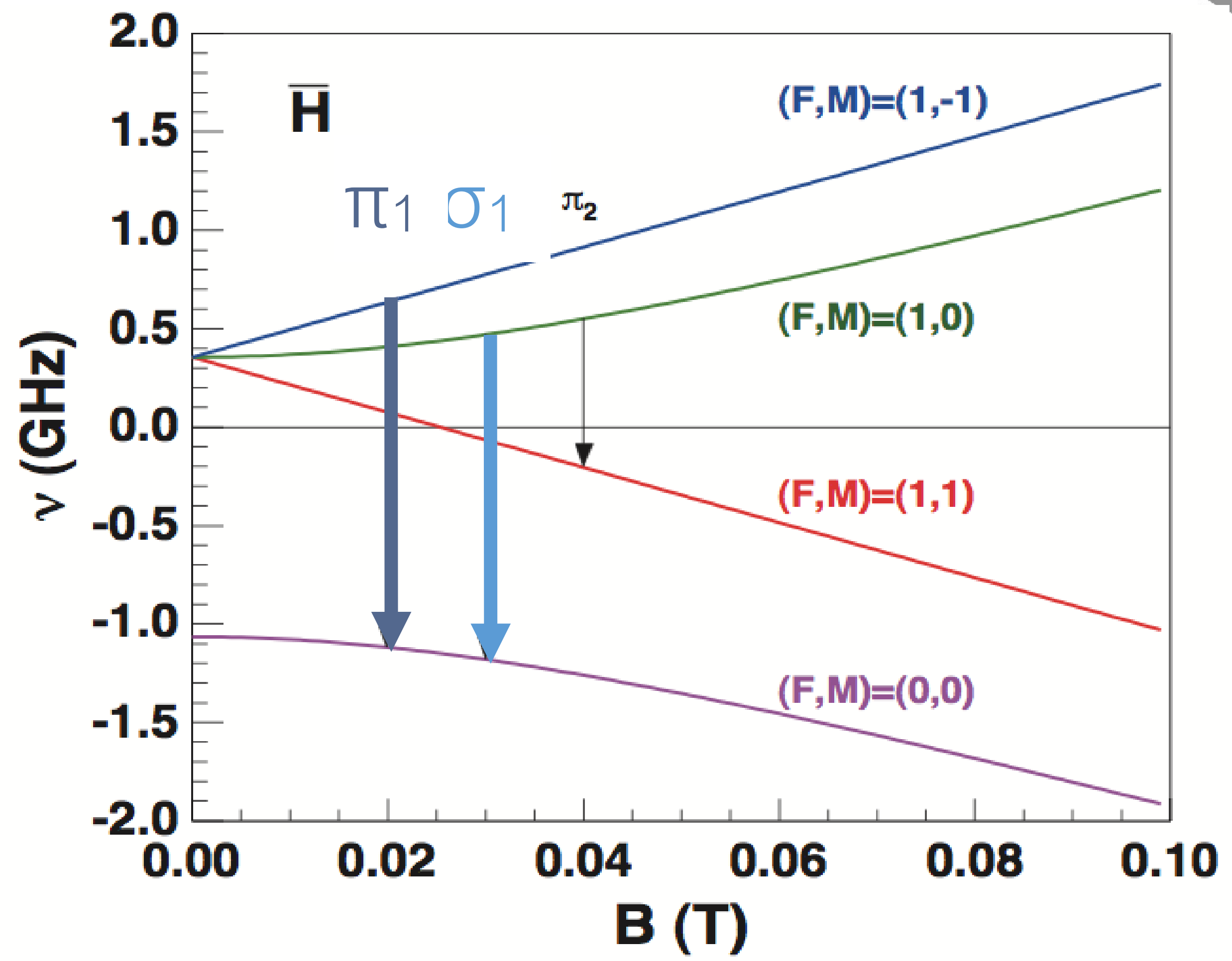
# Antihydrogen spectroscopy



# In-beam HFS spectroscopy





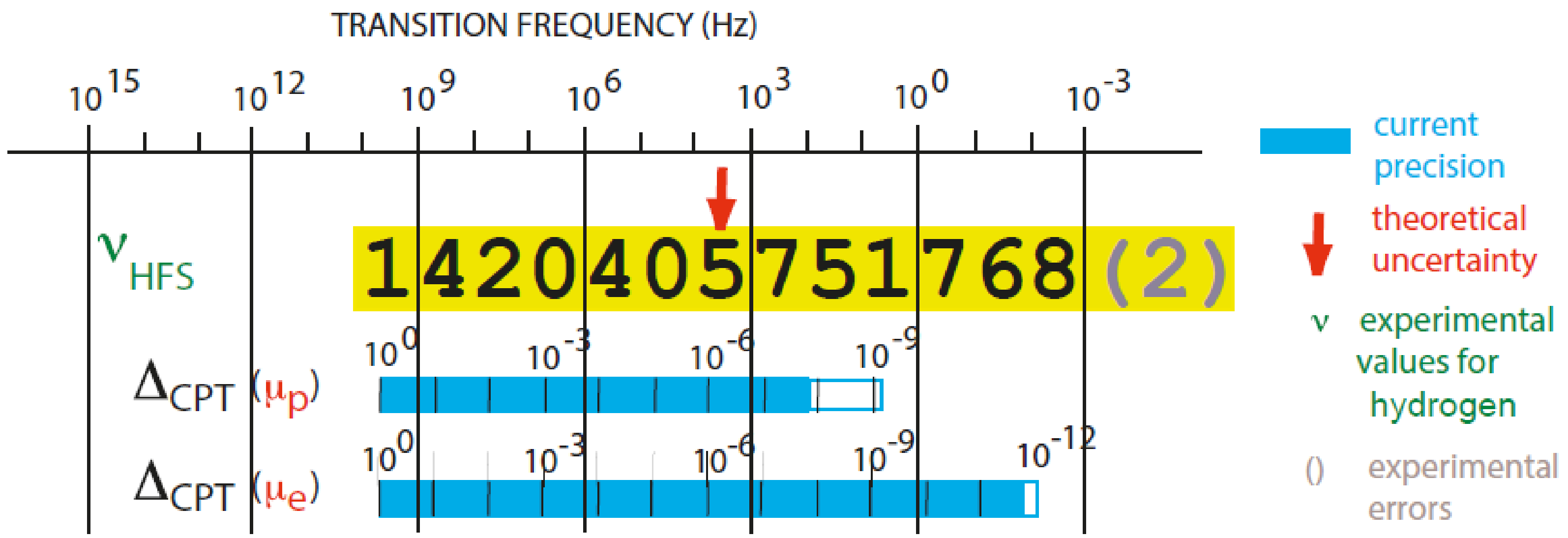

- Goals
  - In-beam measurement of ground-state hyperfine structure of antihydrogen to ppm-level and below
  - Produce polarized slow (<100 K) Hbar beam

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

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

- 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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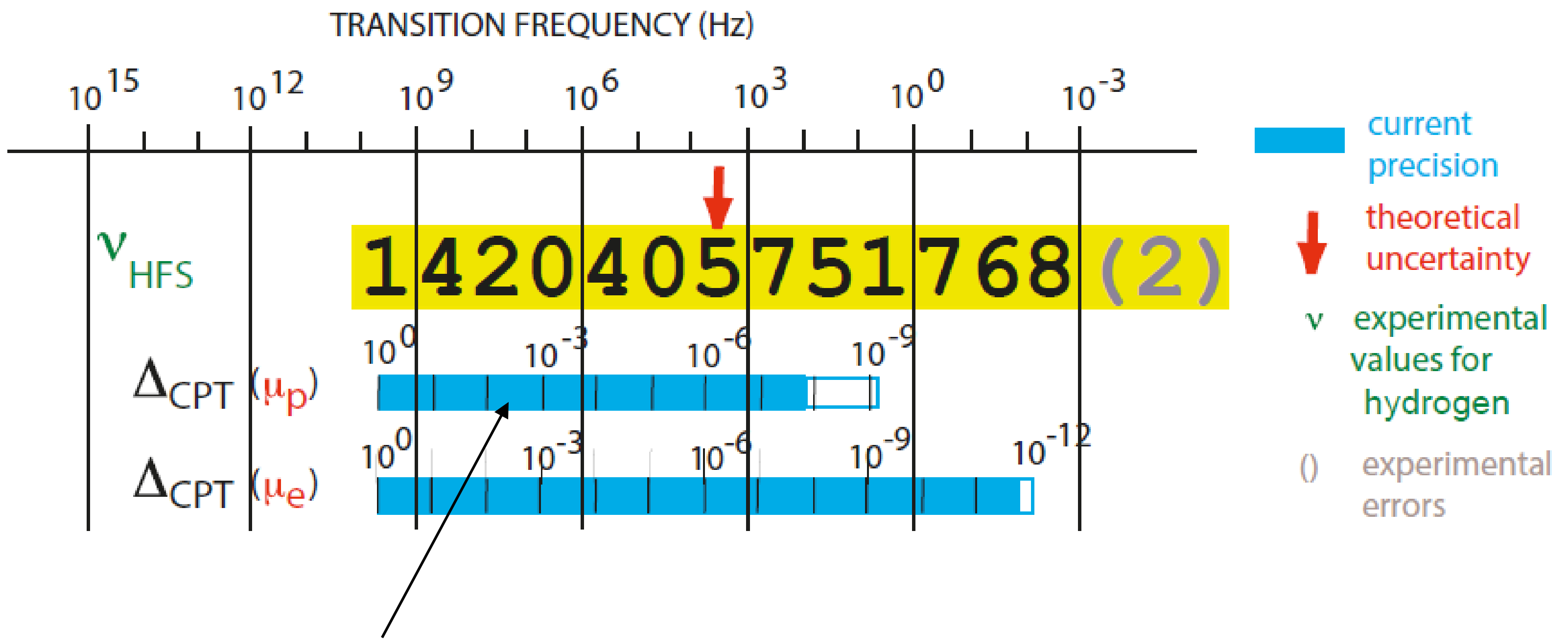
Hydrogen HFS and QED: finite size effects

| | |
|---|---|
| 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)*

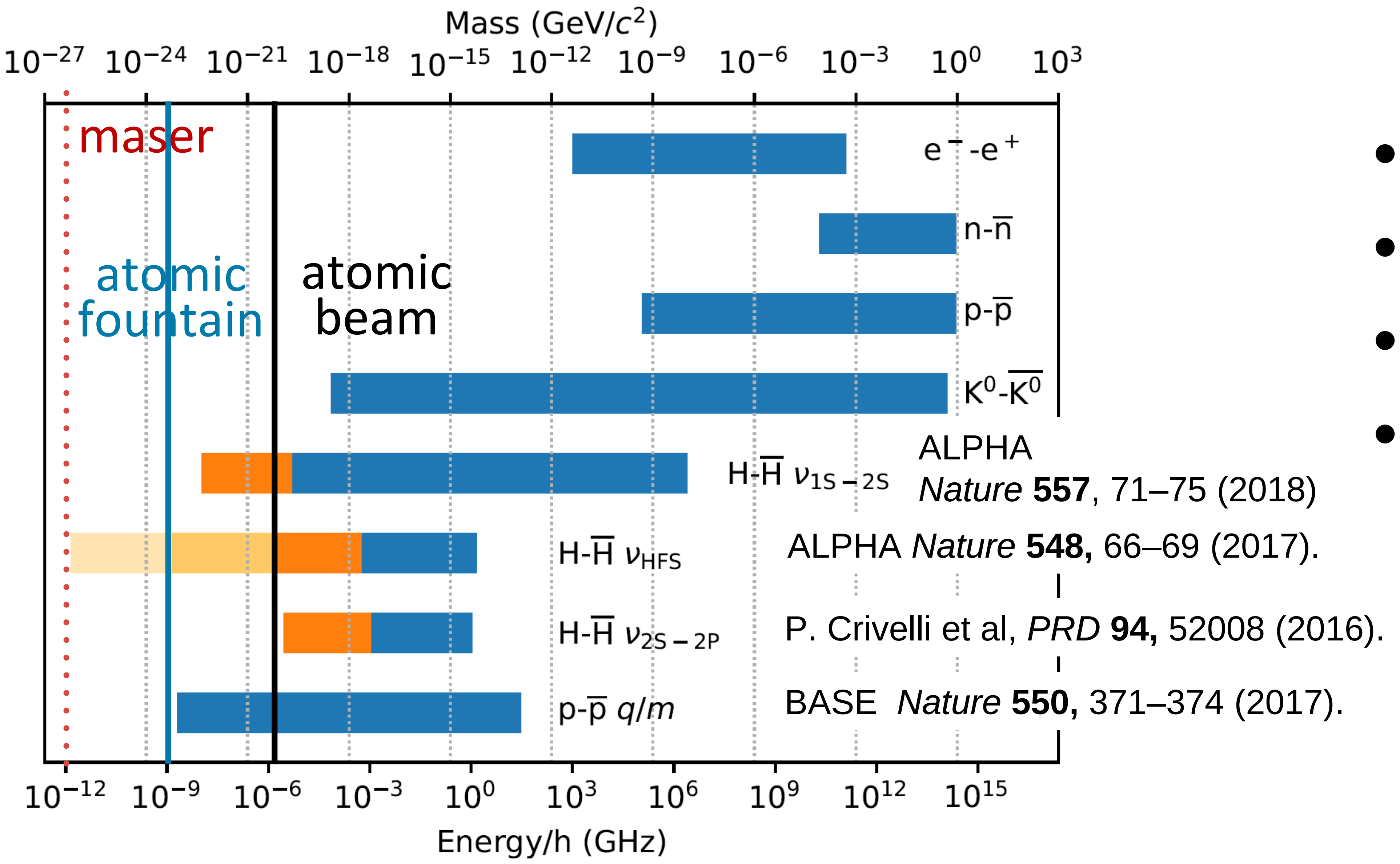



BASE C. Smorra et al.,. *Nature*, *550*(7676), 371–374.

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

# Comparison of CPT tests I

- Mass & frequency




- Right edge: value
- Bar length: relative precision
- Left edge: absolute sensitivity
- Source: PDG

# Comparison of CPT tests II

- Standard Model Extension SME

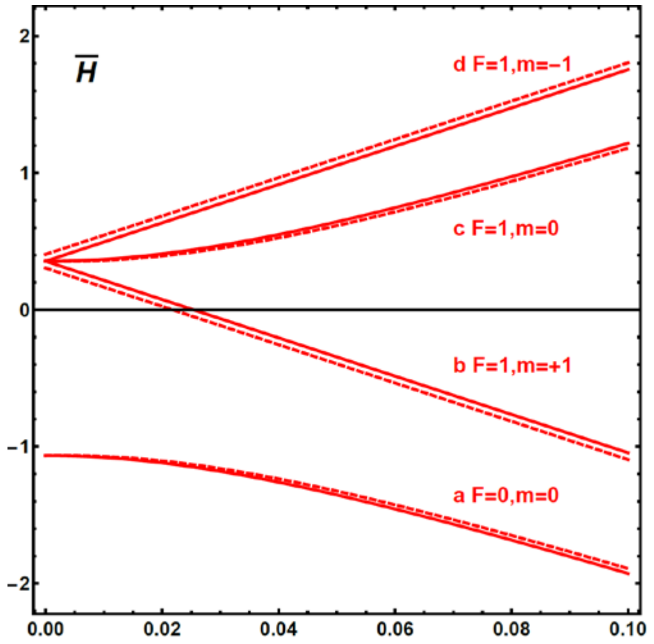
CPT & LORENTZ VIOLATION

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

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).

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

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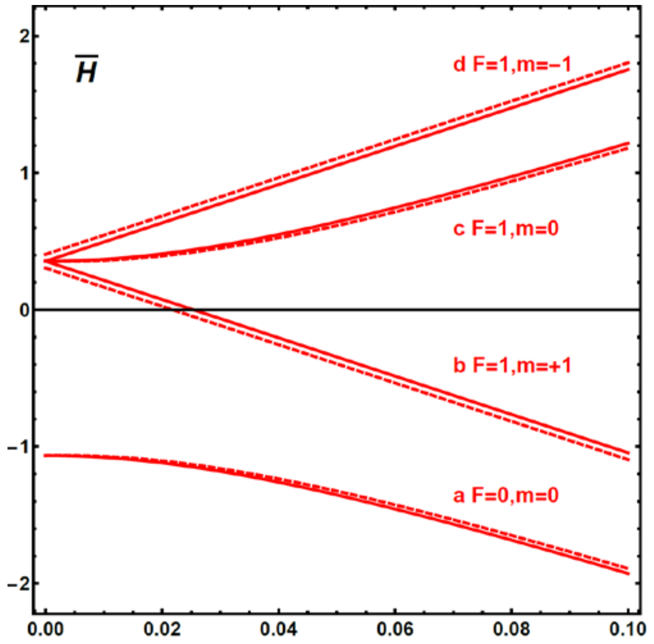
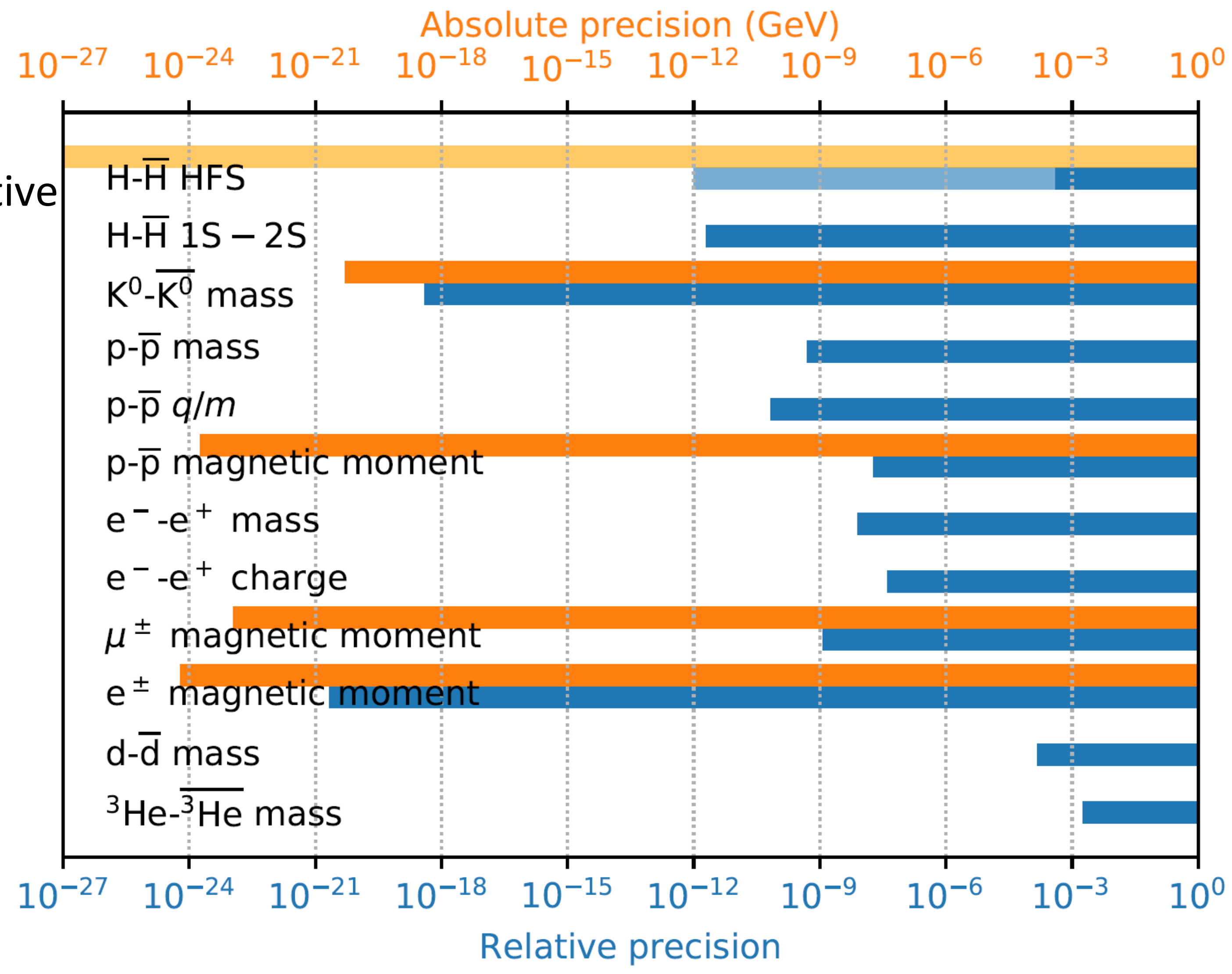


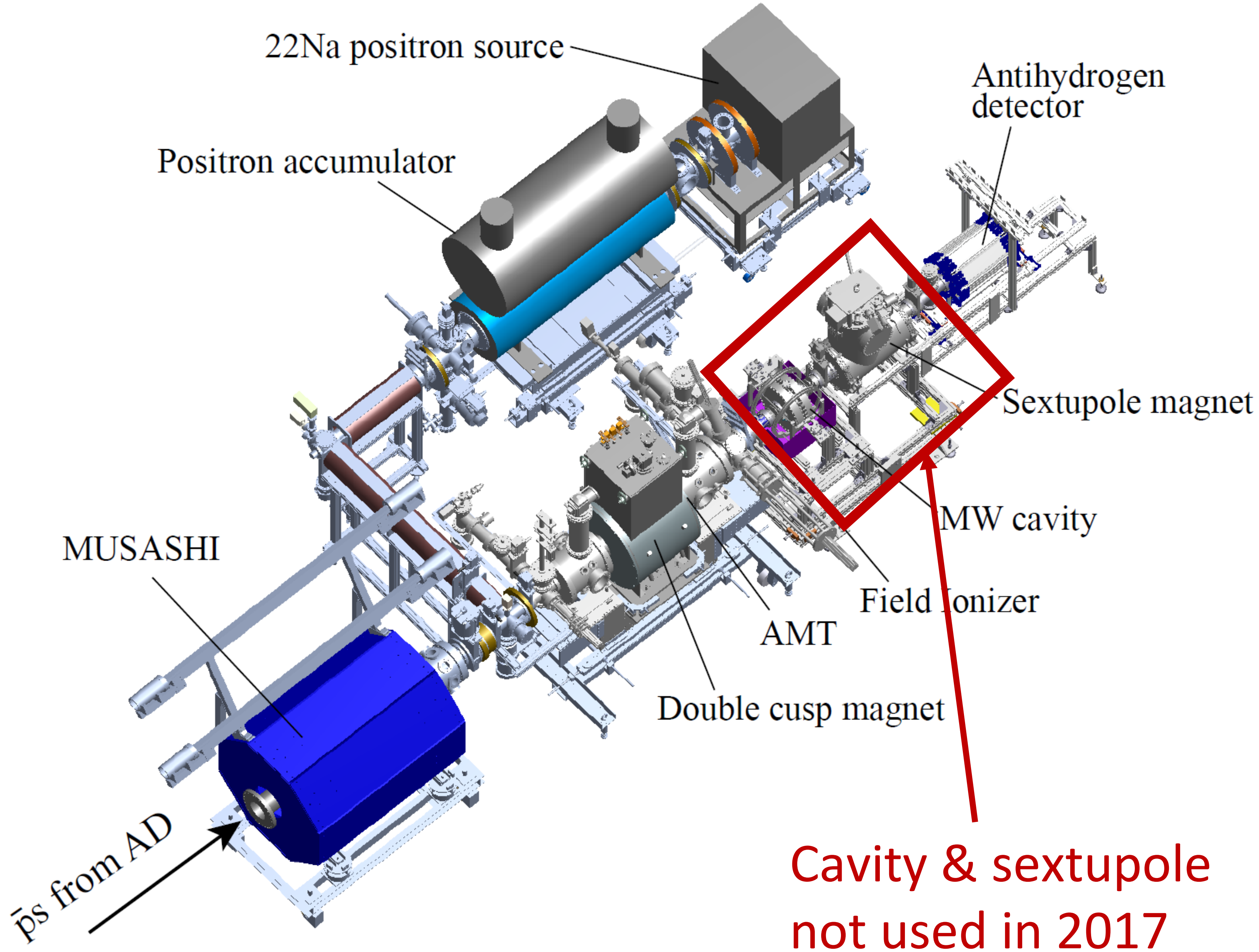

Bluhm, R., Kostelecky, V., & Russell, N., PRL *82*, 2254–2257 (1999).

ALPHA: Not sensitive to SME

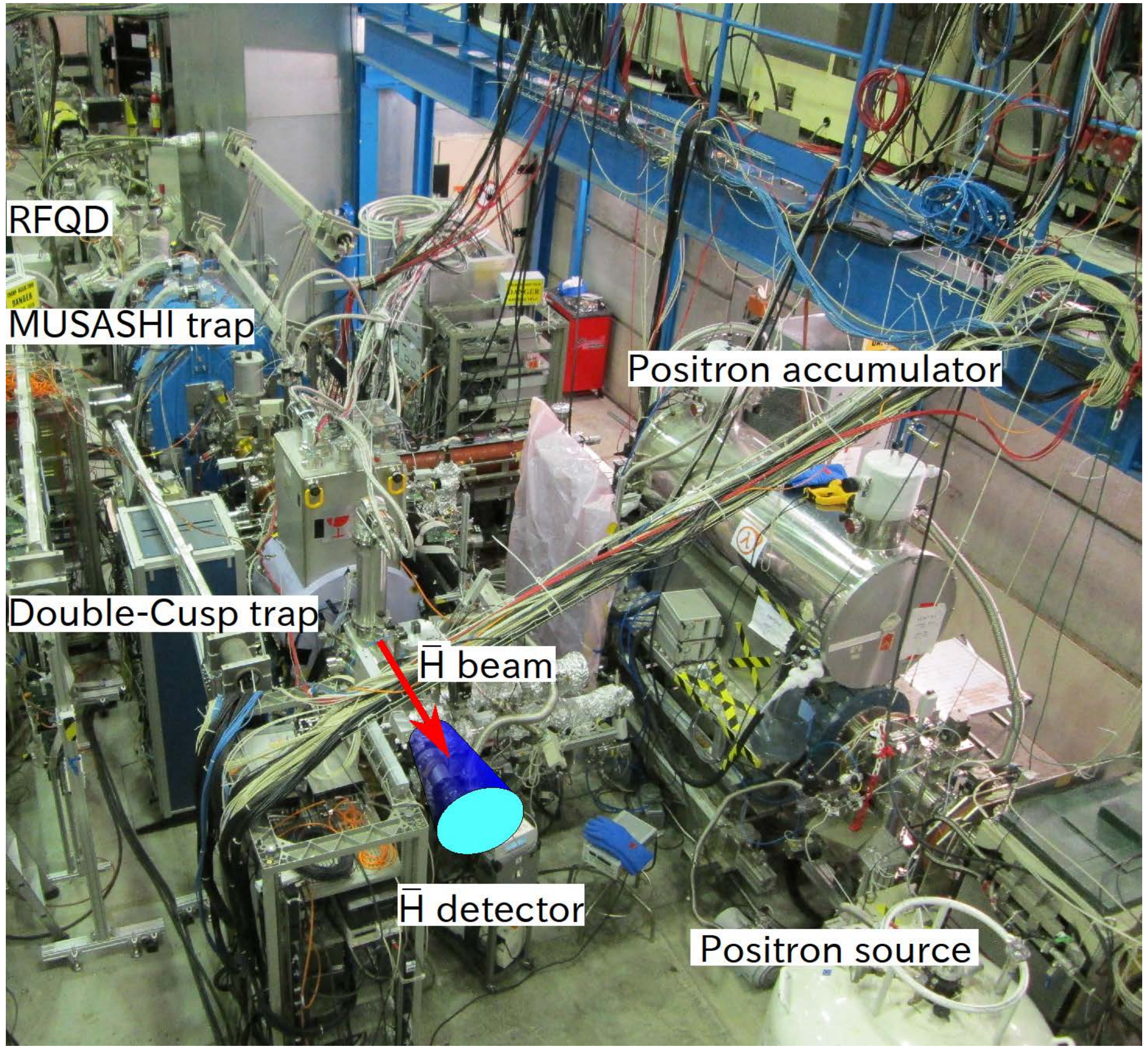



*PDG, Kostelecky & Bluhm arXiv:0801.0287*

# Setup

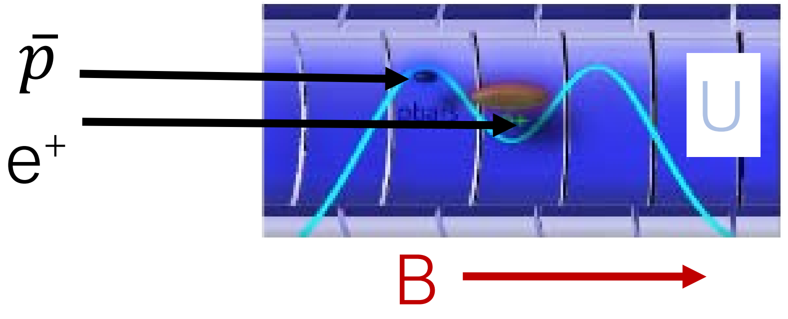


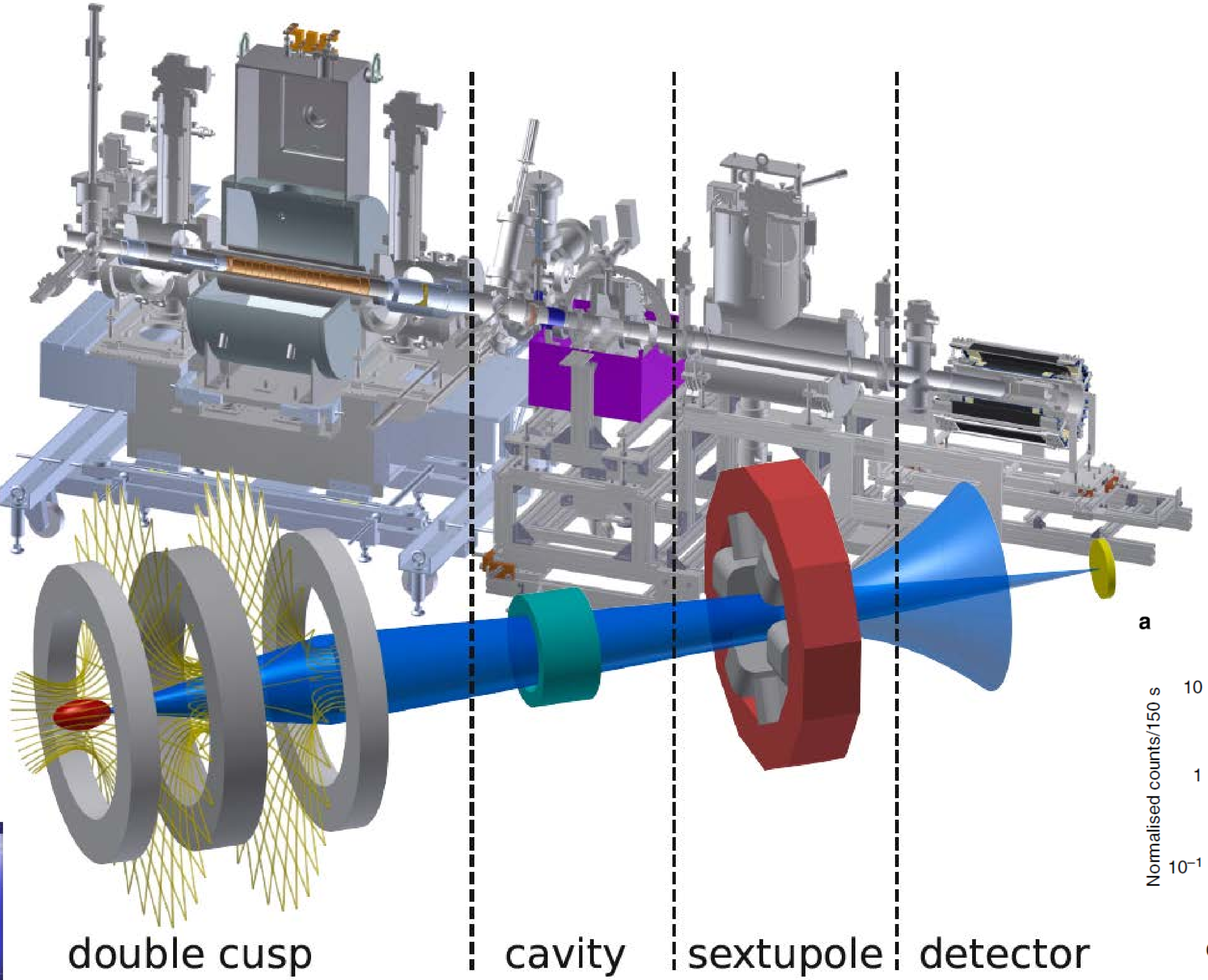

Cavity & sextupole
not used in 2017



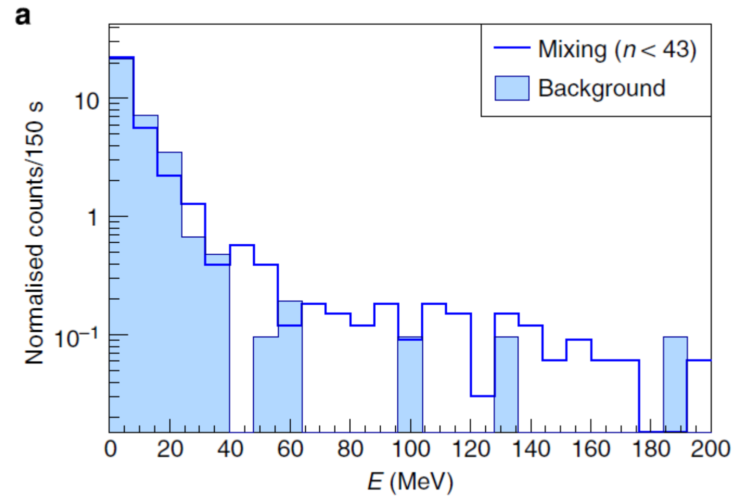
# Antihydrogen beam status

- $\bar{\mathrm{H}}$ 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
  - $n \leq 43$: 6 $\bar{H}$/15 min
  - $n \leq 29$: 4 $\bar{H}$/15 min



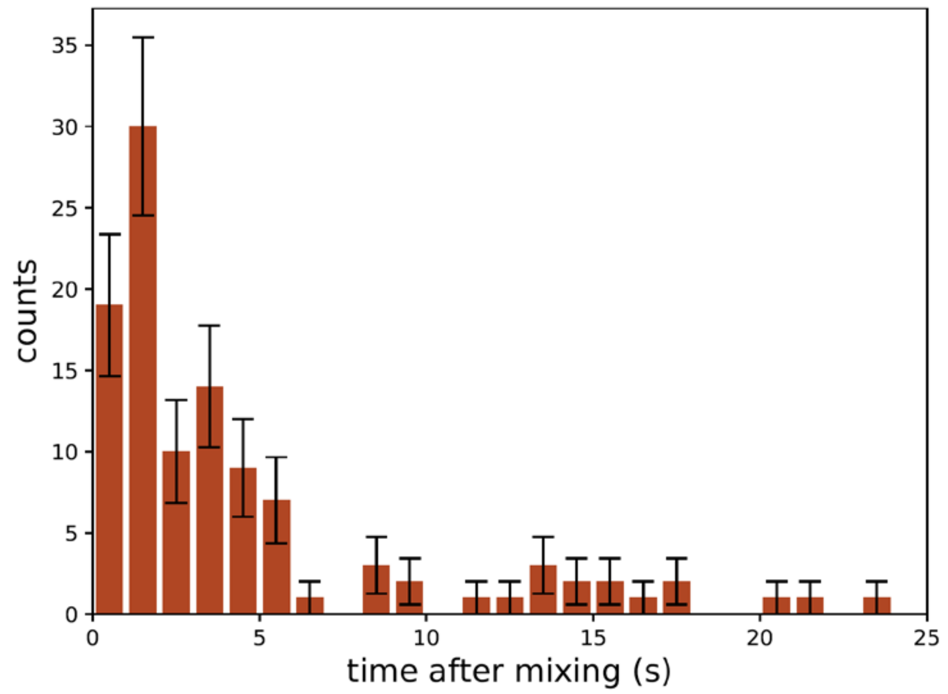



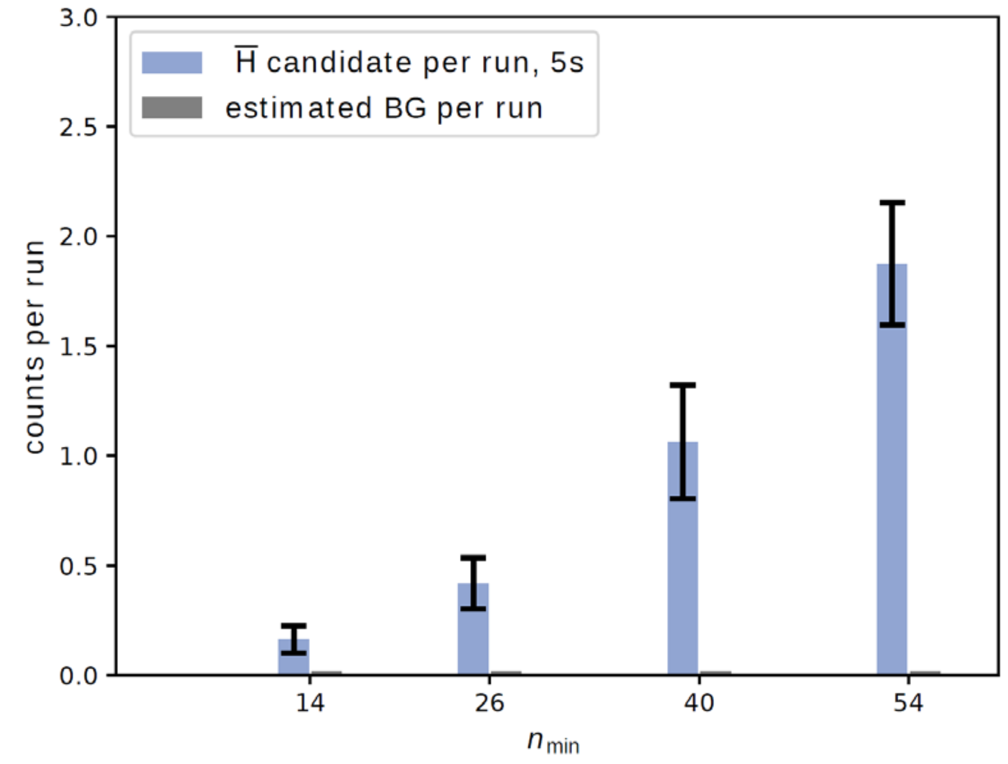

N. Kuroda et al, *Nat. Commun.* **5,** 3089 (2014).



# Results 2016

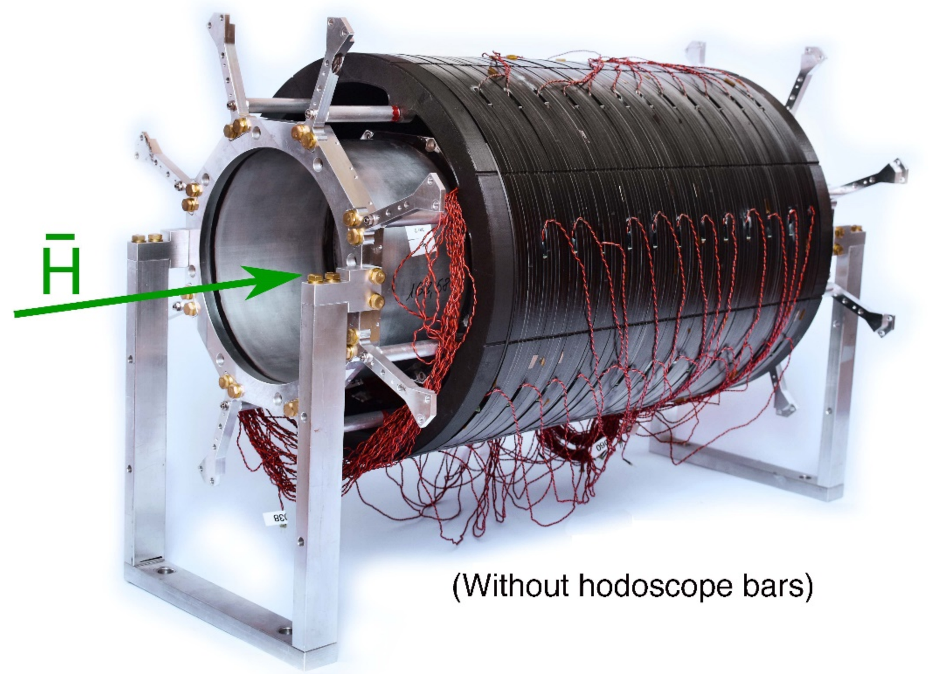
- Time distribution of $\bar{H}$ within mixing cycle
  - At cavity position
- Principal quantum number by field ionization
  - 0.5 m upstream of cavity
  - n<14 significance 4.5σ
    - Using machine learning techniques
  - $\tau(n=14) \sim 50\ \mu s$



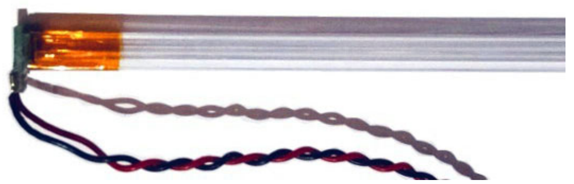



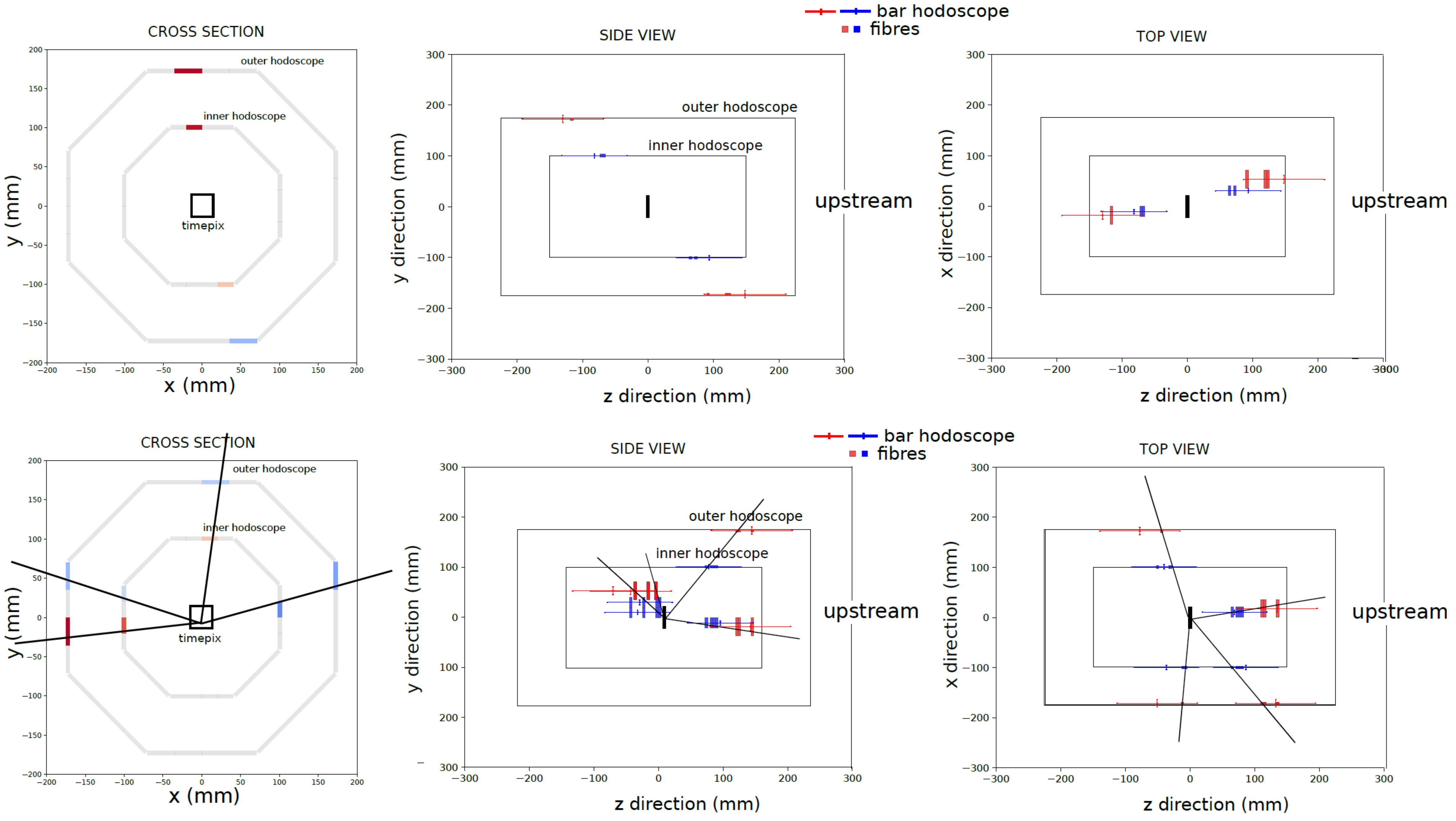

C. Malbrunot et al., Phil. Trans. R. Soc. A 376: 20170273 (2018)

# Antihydrogen detector fibre upgrade



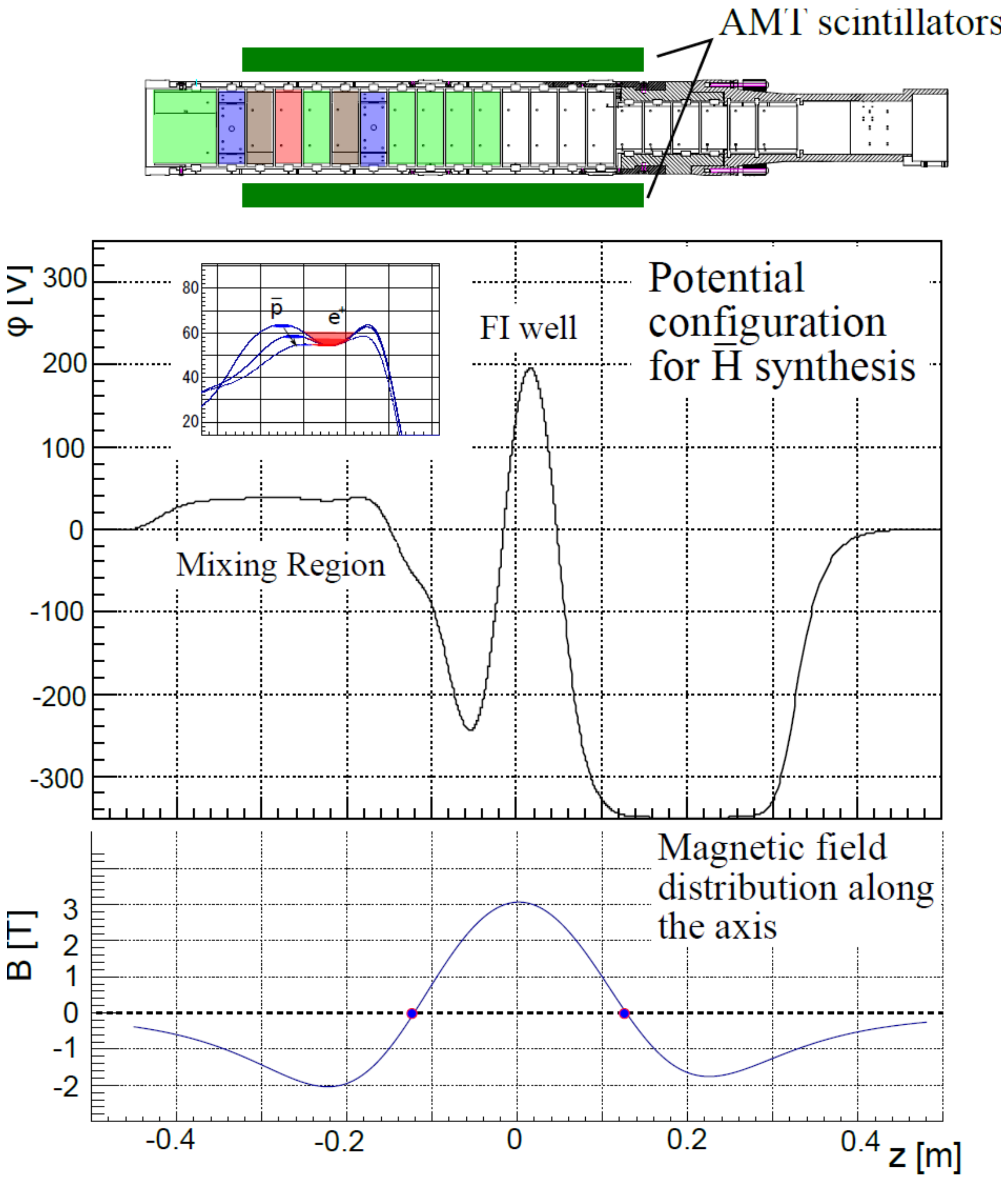
(Without hodoscope bars)



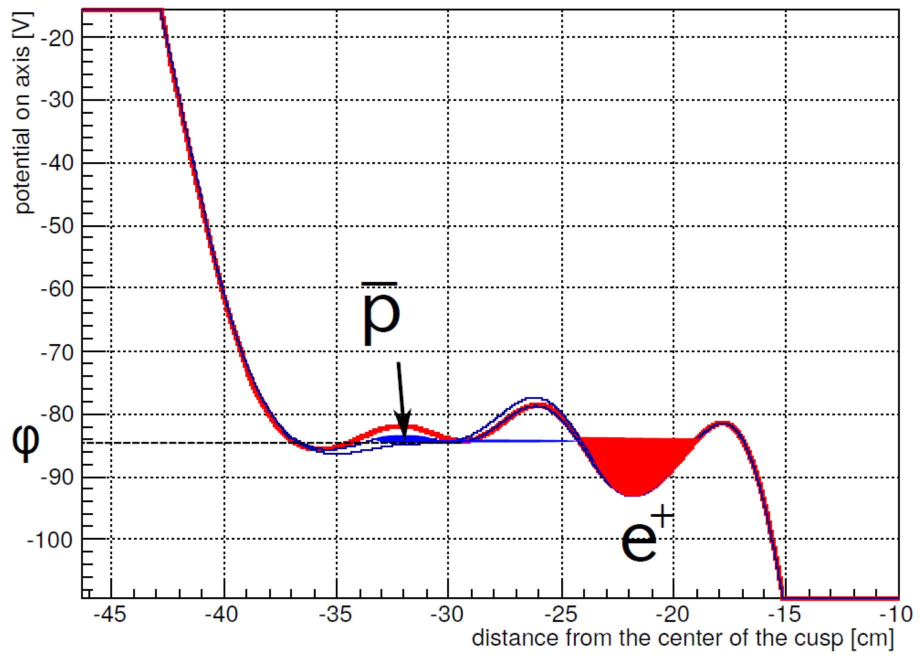



Fibre bundle 2x2 of 1x1 mm2 fibres
2 layers
7.7 mm geometrical resolution in *z* at *r*=0

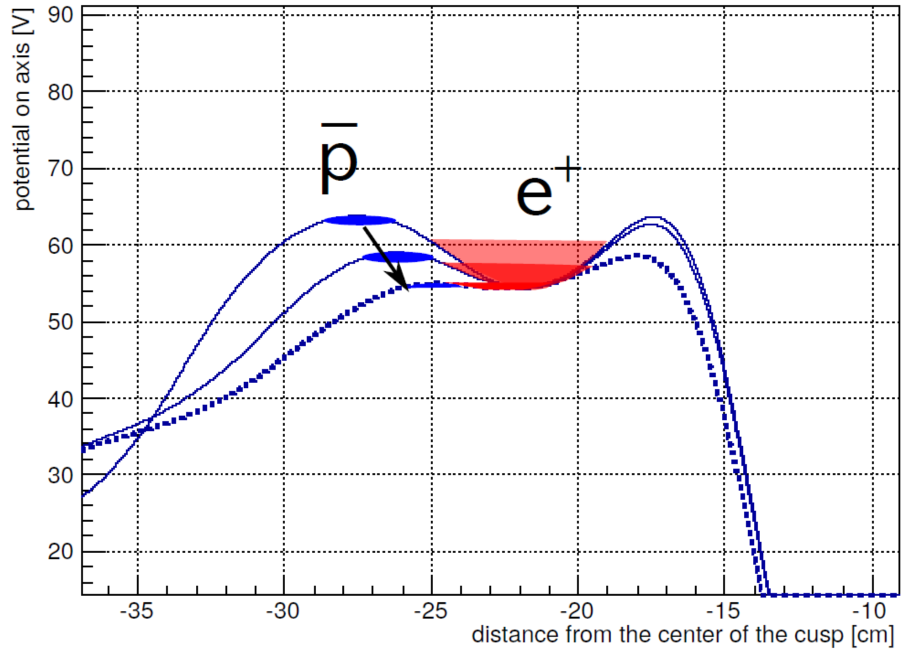
# New mixing schemes 2017~




- Slow extraction scheme




- Cross merging scheme



# Future directions

- Increase production rate
  - Positron temperature, density

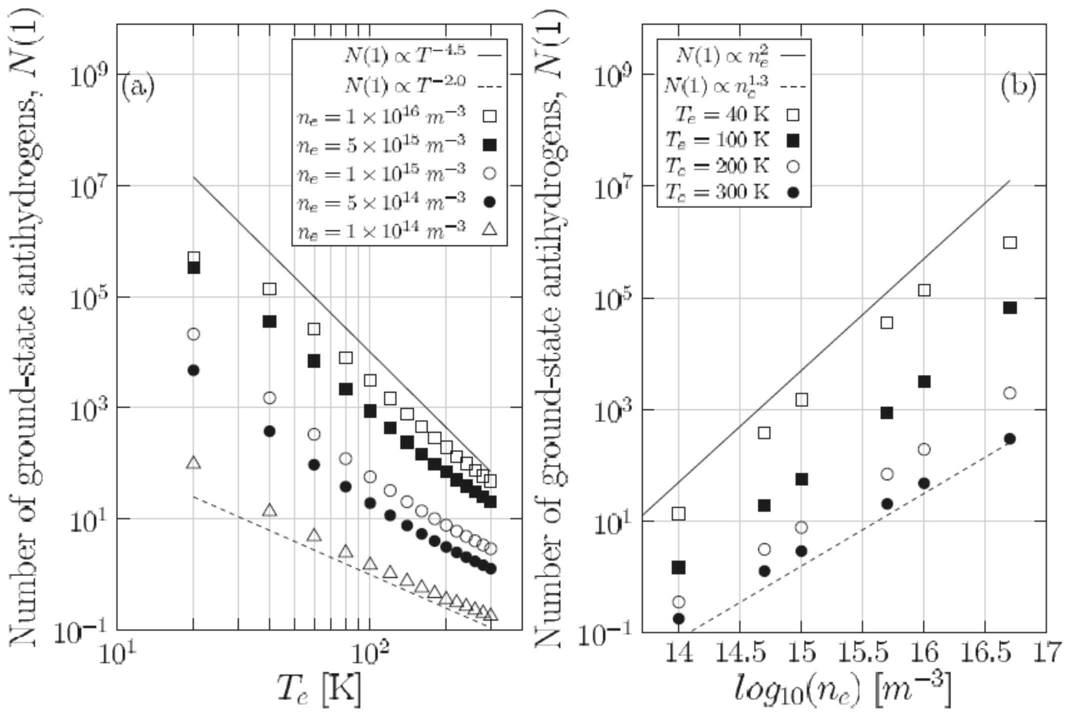


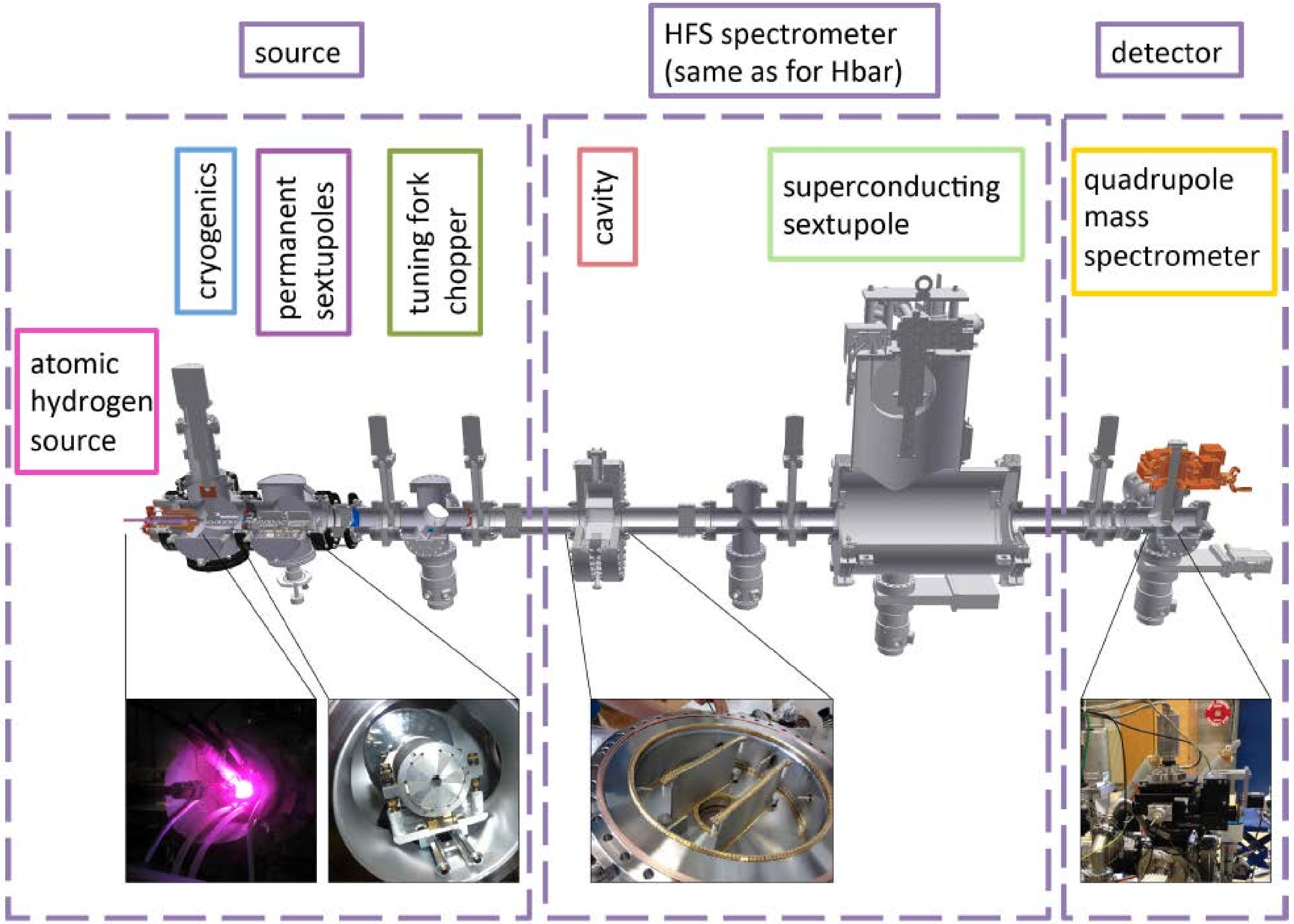

FIG. 6. Dependence of ground-state antihydrogen atoms on positron temperature (a) and density (b) for various positron density and temperature values (respectively) after 1 ms of flight. The $\propto n_e^2 T_e^{-4.5}$ (solid line) and $\propto n_e^{1.3} T^{-2.0}$ (dashed line) scaling behaviors are indicated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

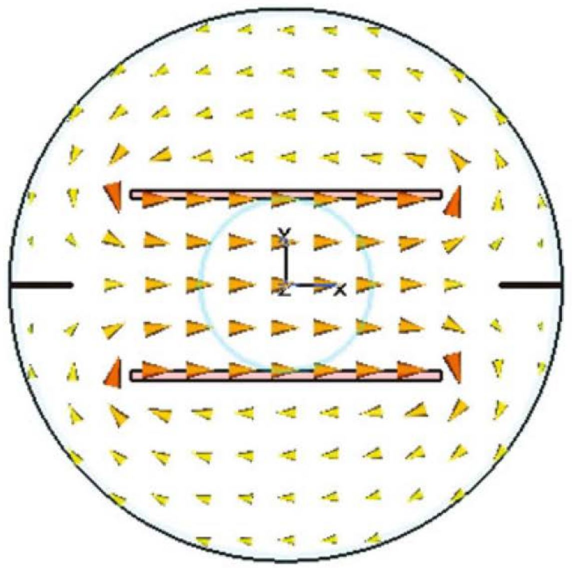
# Hydrogen beam measurments

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

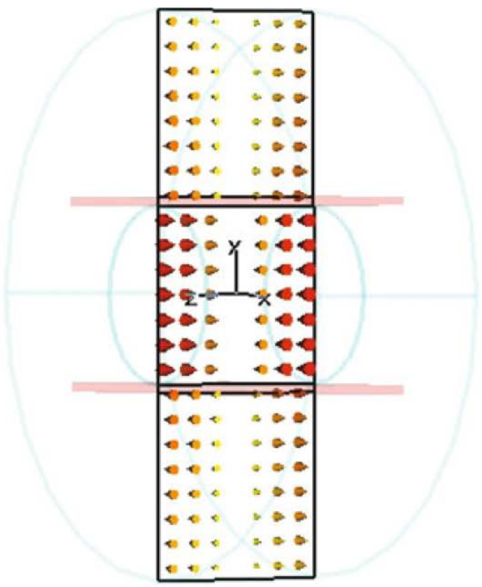


# Spin-flip resonator

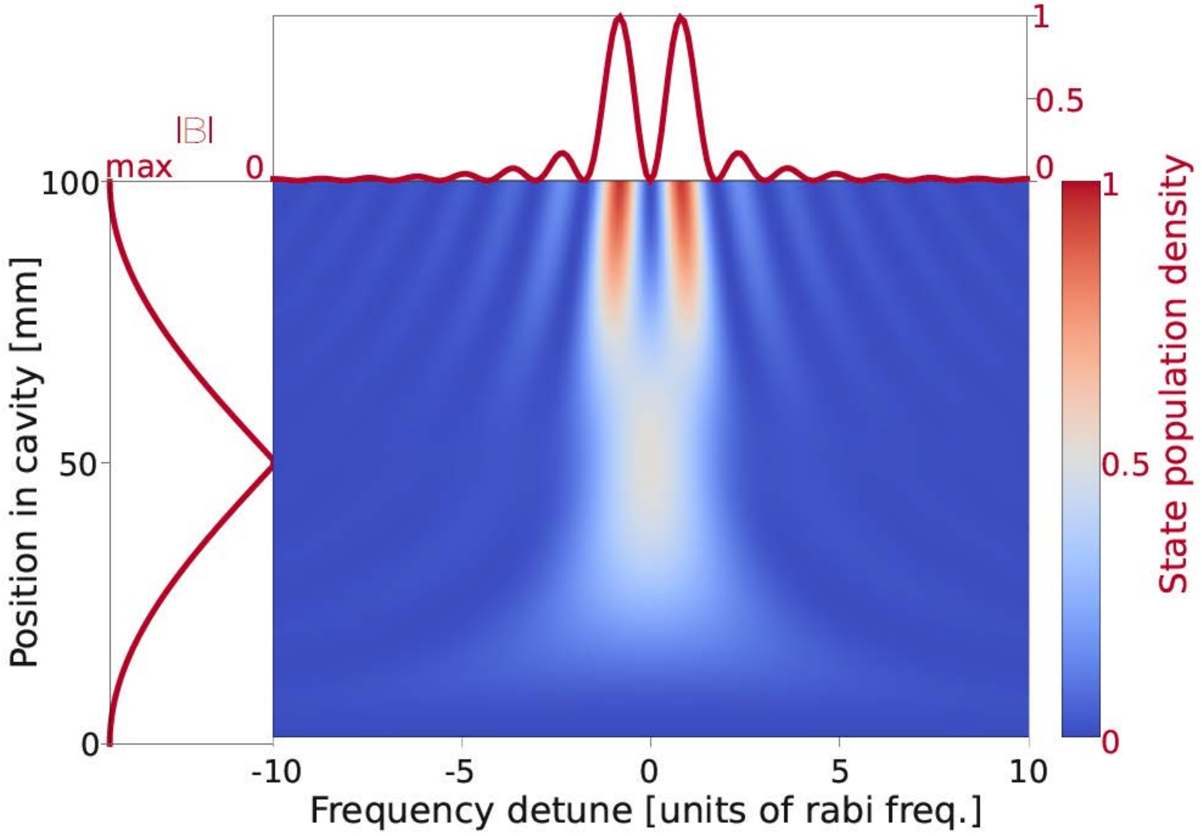
- $f$ = challenge: homogeneity over 10x10x10cm$^3$@ $\lambda$=21cm
- solution: strip line
- 1.420 GHz, $\Delta f$ = few MHz,



transverse field: homogeneous



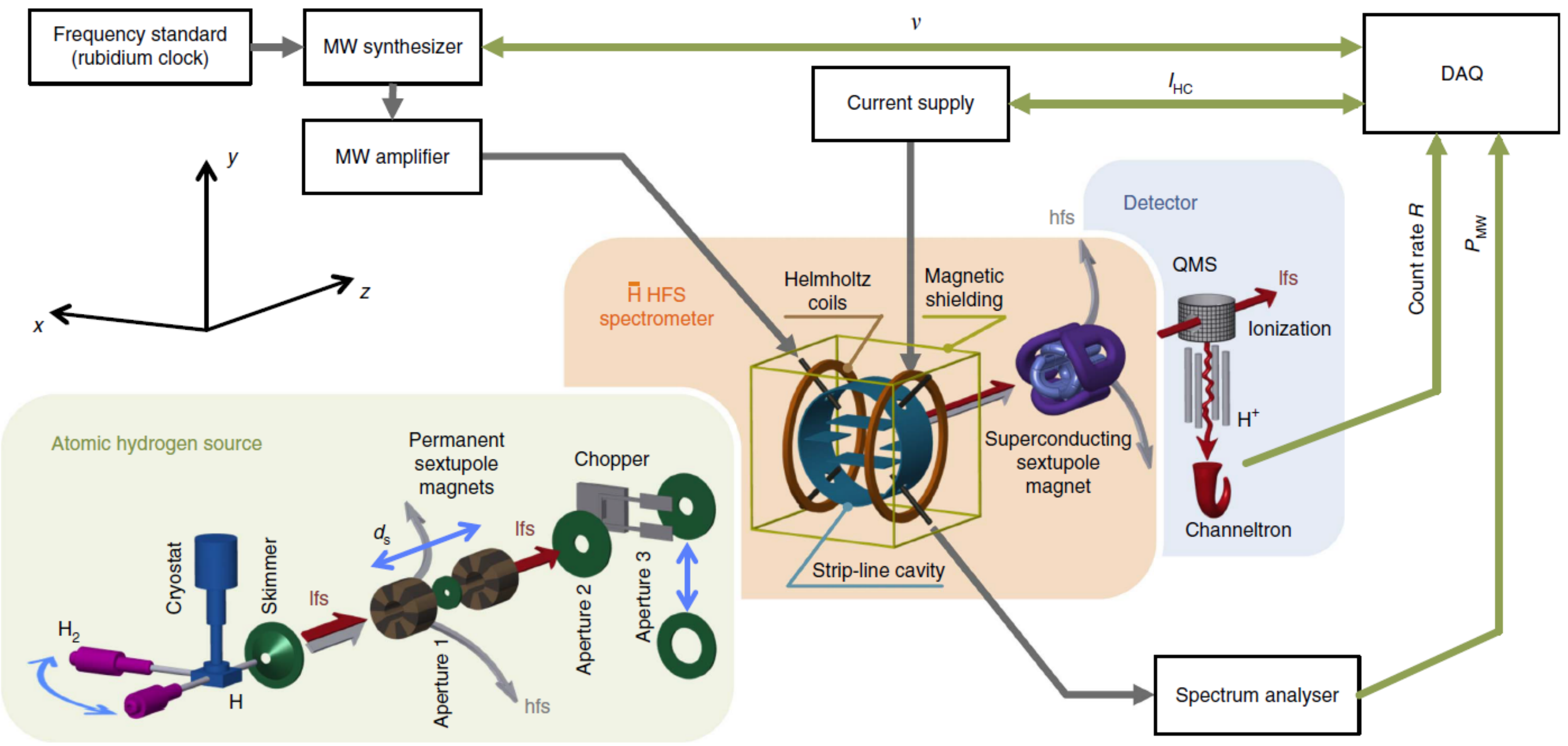
longitudinal field: cos(z)



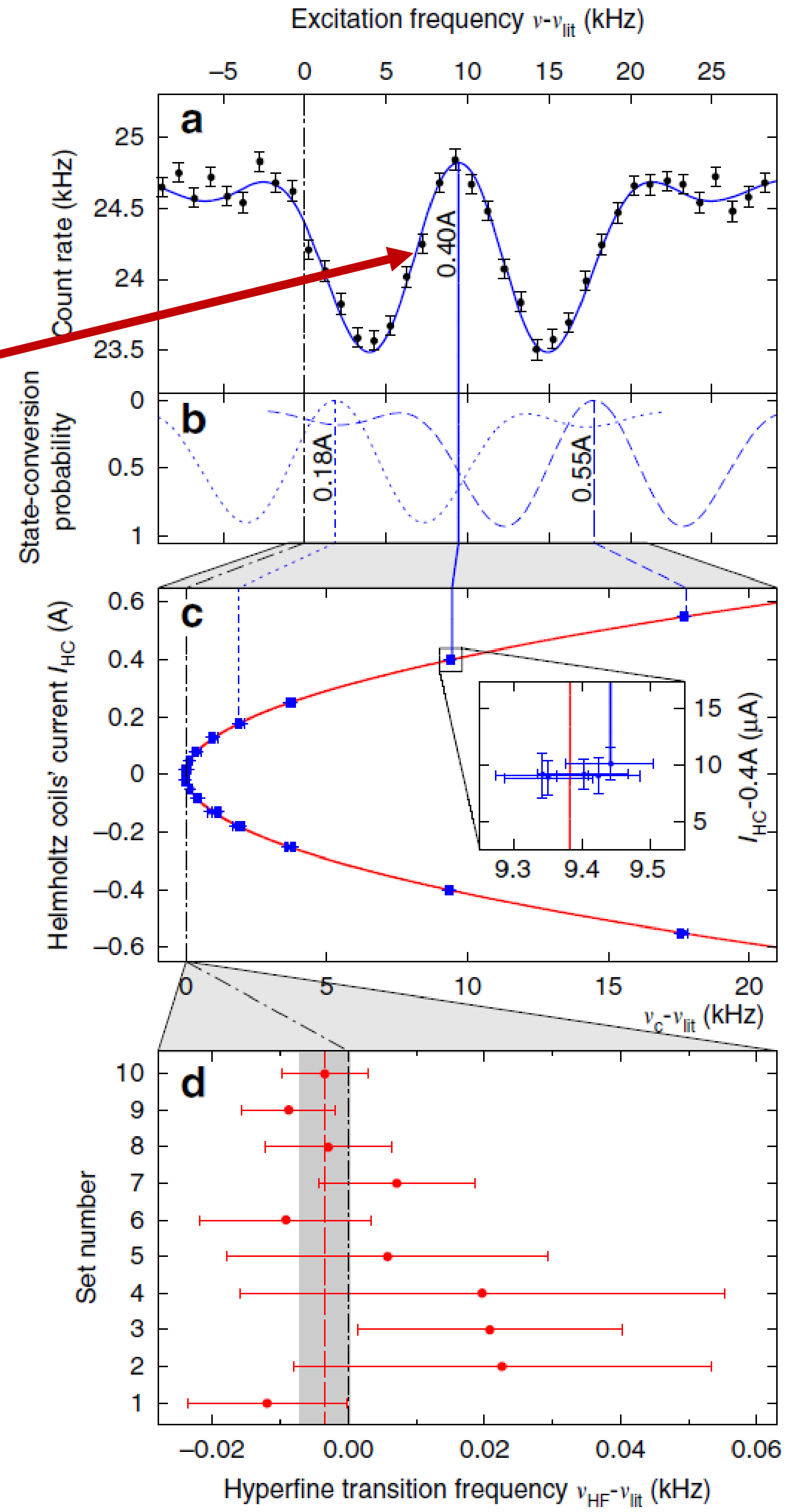

Line shape by optical Bloch equations for single velocity

- Full line shape: sum of simulated line shape for velocity distribution

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




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




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

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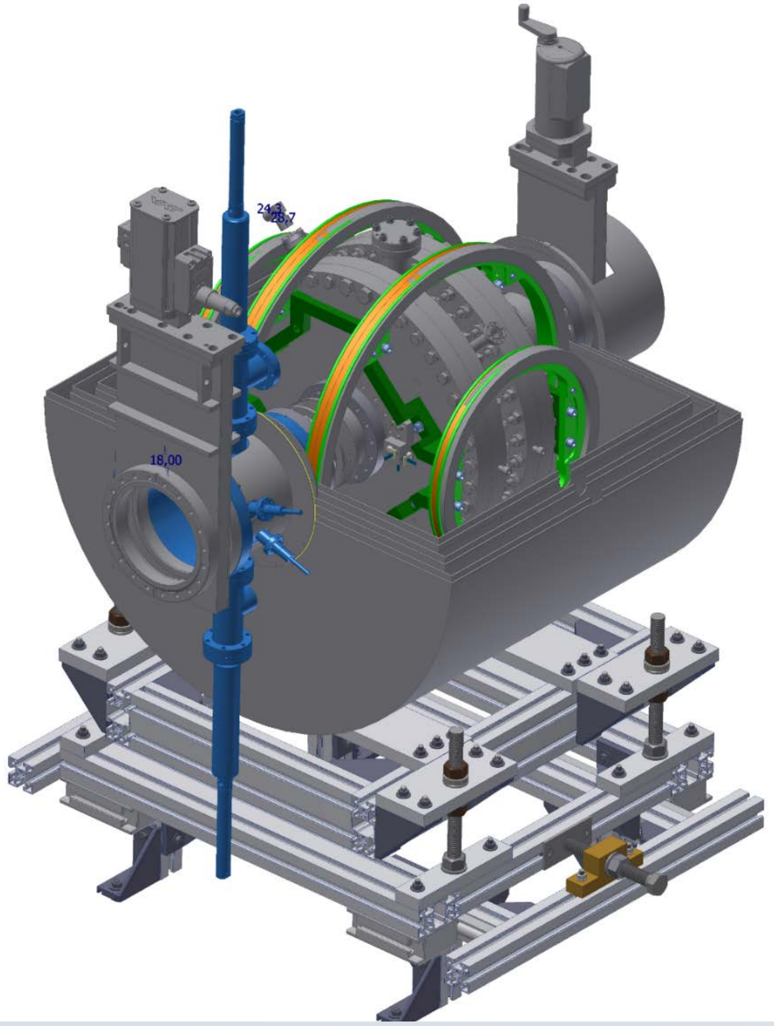
In-beam measurement of the hydrogen hyperfine splitting and prospects for antihydrogen spectroscopy

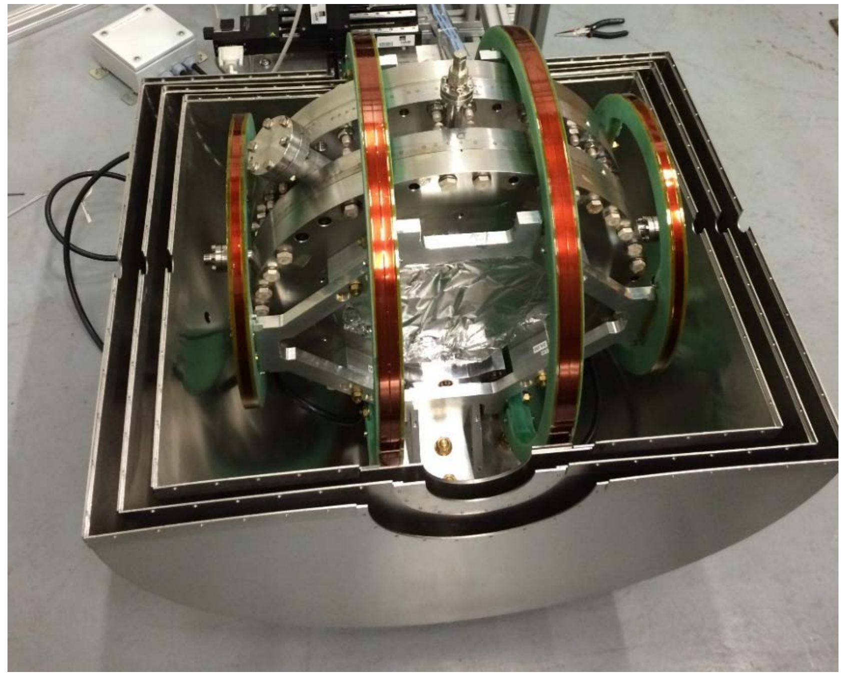
M. Diermaier[1], C.B. Jepsen[2,†], B. Kolbinger[1], C. Malbrunot[1,2], O. Massiczek[1], C. Sauerzopf[1], M.C. Simon[1], J. Zmeskal[1] & E. Widmann[1]

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

# H-beam next steps and non-minimal SME

- $\pi_1$ transition
  - Better field homogeneity
    - Inproved coils, shielding
  - SME: effect only in $\pi_1$
  - Non-minimal SME: direction dependent coefficients accessible by beam
- Conditions
  - Invert direction of B-field
  - Rotate B-field
  - Measure also $\sigma_1$ (no CPTV) as reference



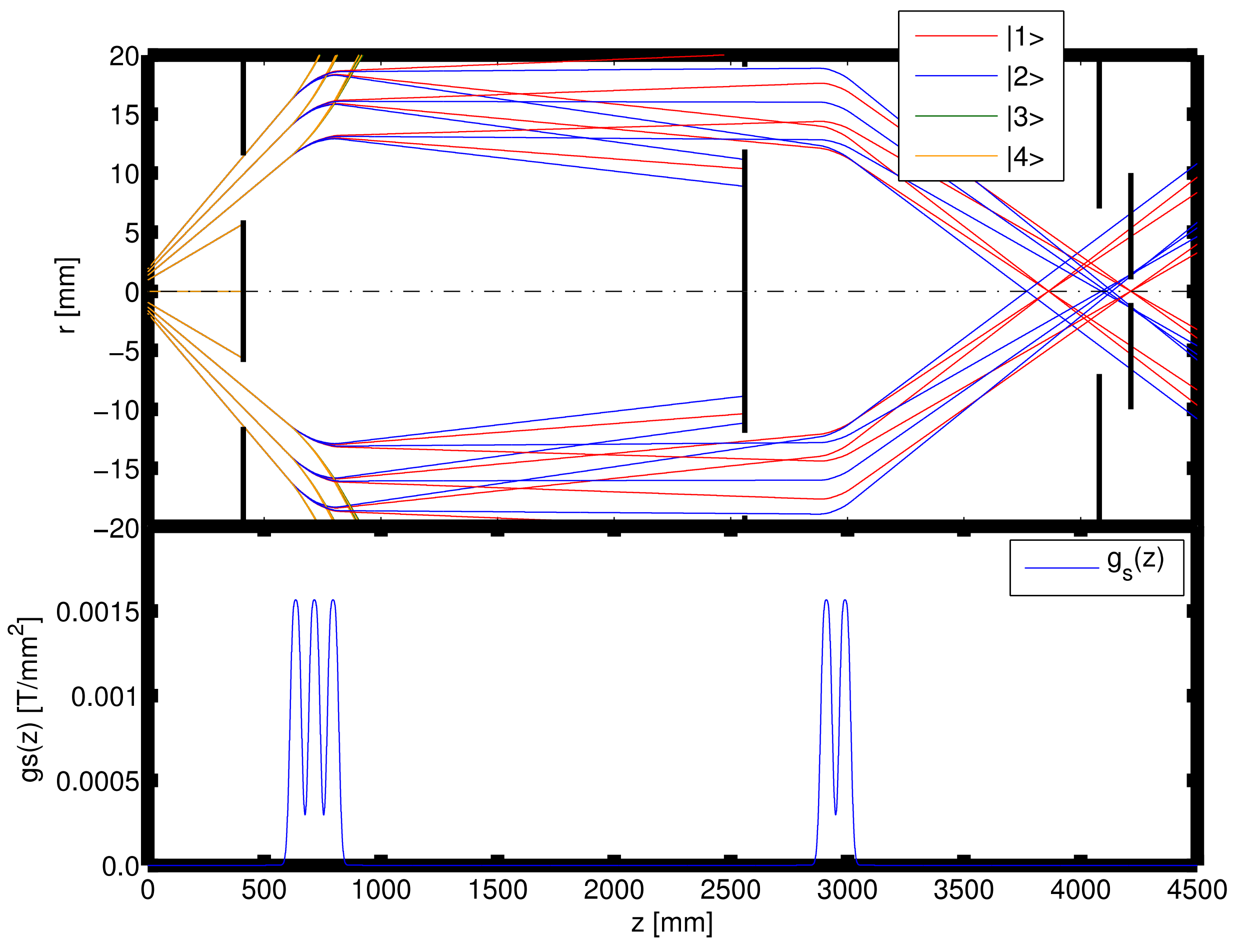


$$\begin{aligned}\Delta(2\pi\nu_\pi) &\equiv 2\pi\nu_\pi(\boldsymbol{B}) - 2\pi\nu_\pi(-\boldsymbol{B}) \\ &= -\frac{\cos\vartheta}{\sqrt{3\pi}}\sum_{q=0}^{2}(\alpha m_{\mathrm{r}})^{2q}(1+4\delta_{q2})\sum_{w}\left[g_{w(2q)10}^{\mathrm{NR,Sun}(0B)} - H_{w(2q)10}^{\mathrm{NR,Sun}(0B)} + 2g_{w(2q)10}^{\mathrm{NR,Sun}(1B)}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

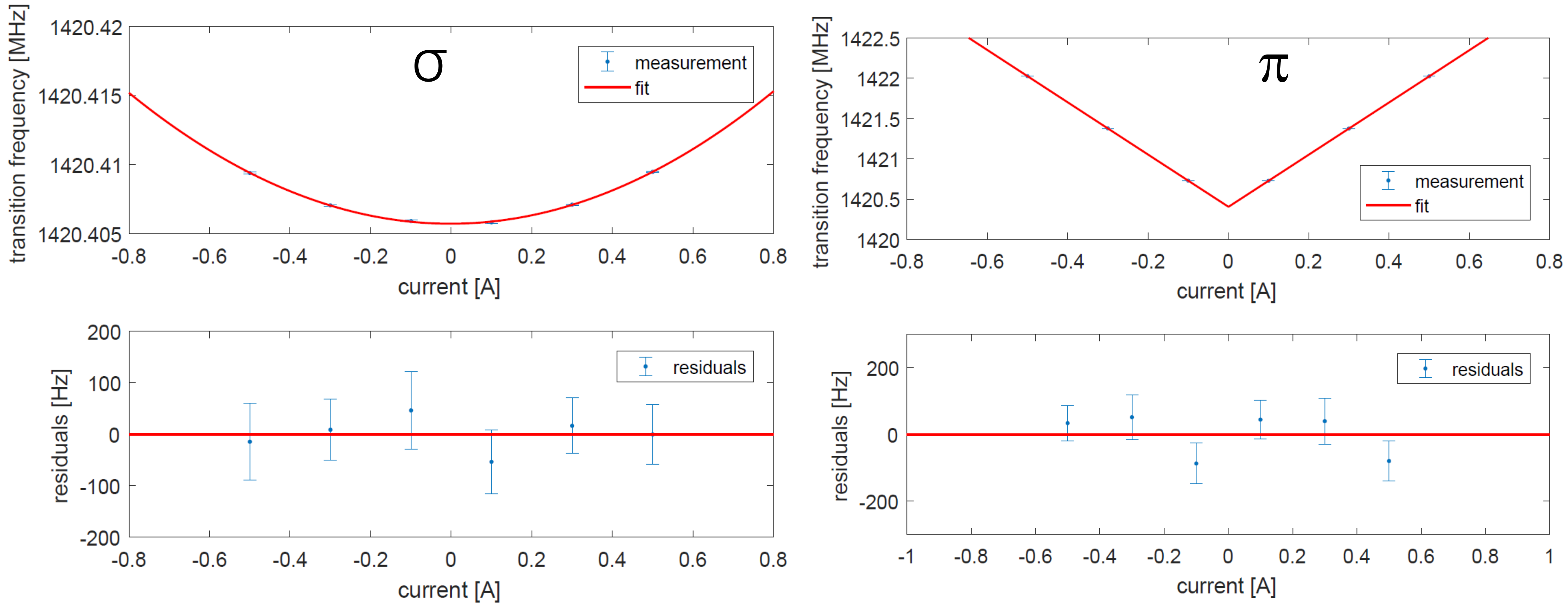
Kostelecký, V. A., & Vargas, A. J. *PRD*, *92*, 056002 (2015).

# First $\pi_1$ measurements

- New optics




- 1st extrapolations



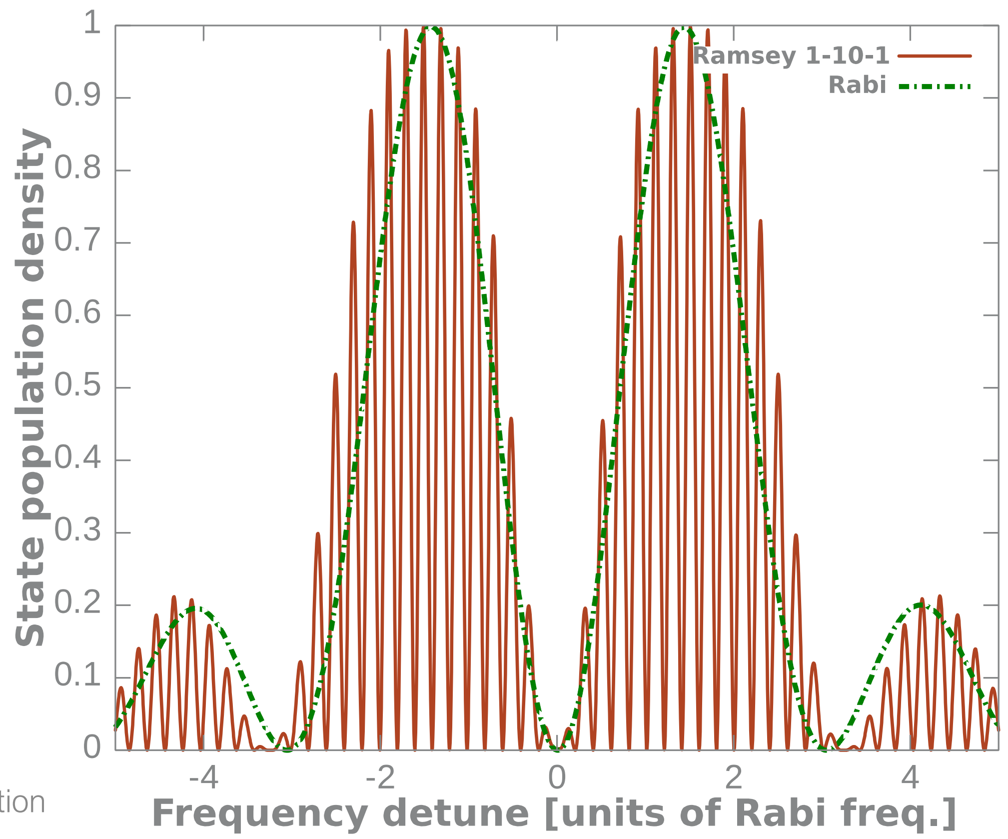

- Accuracy $\nu_{\mathrm{HF}}(B = 0) \sim 10$ Hz
  - ~ 100 hours of data taking
  - Measurement campaign to start

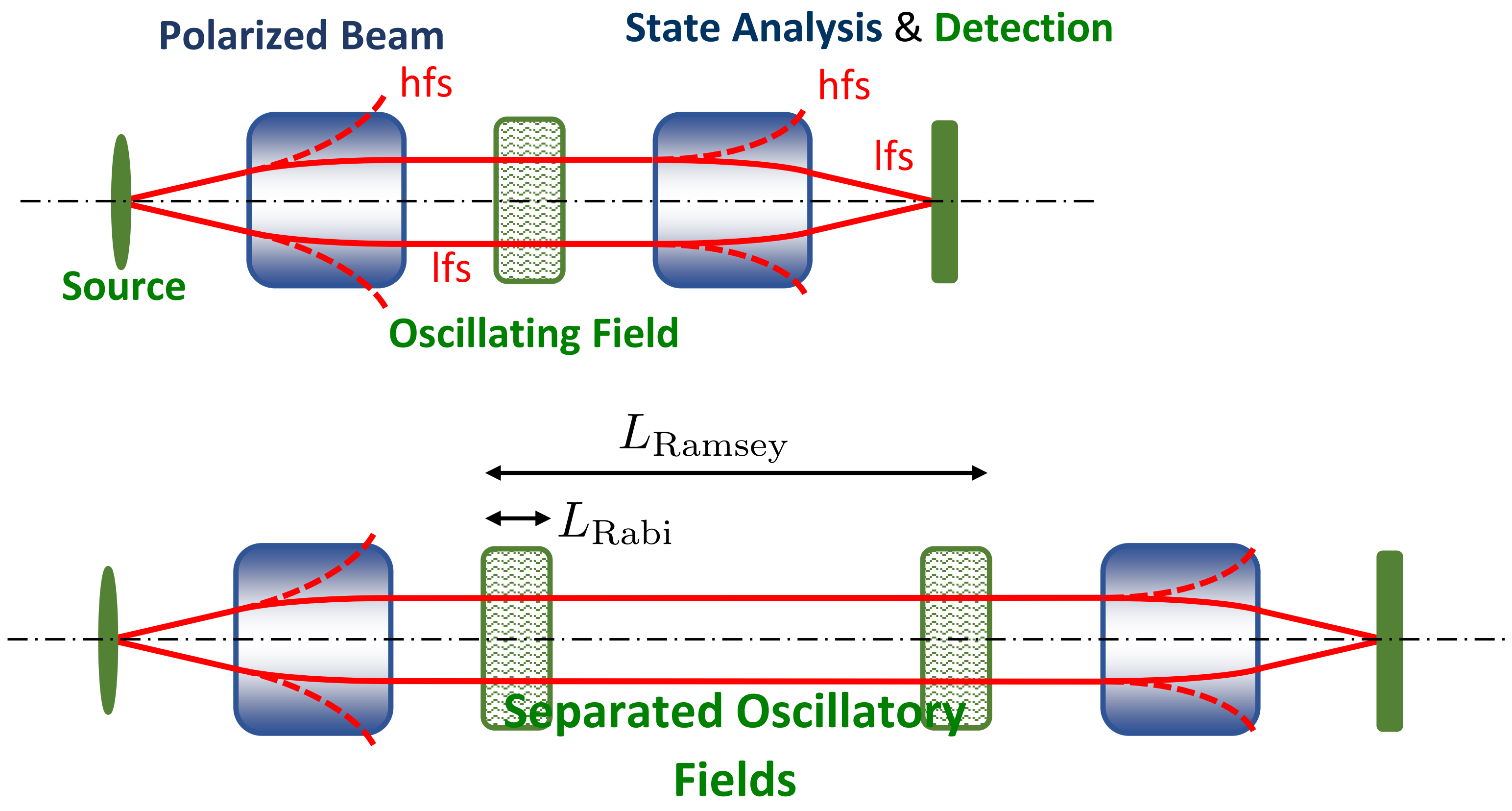
# From Rabi to Ramsey

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

Resolution:

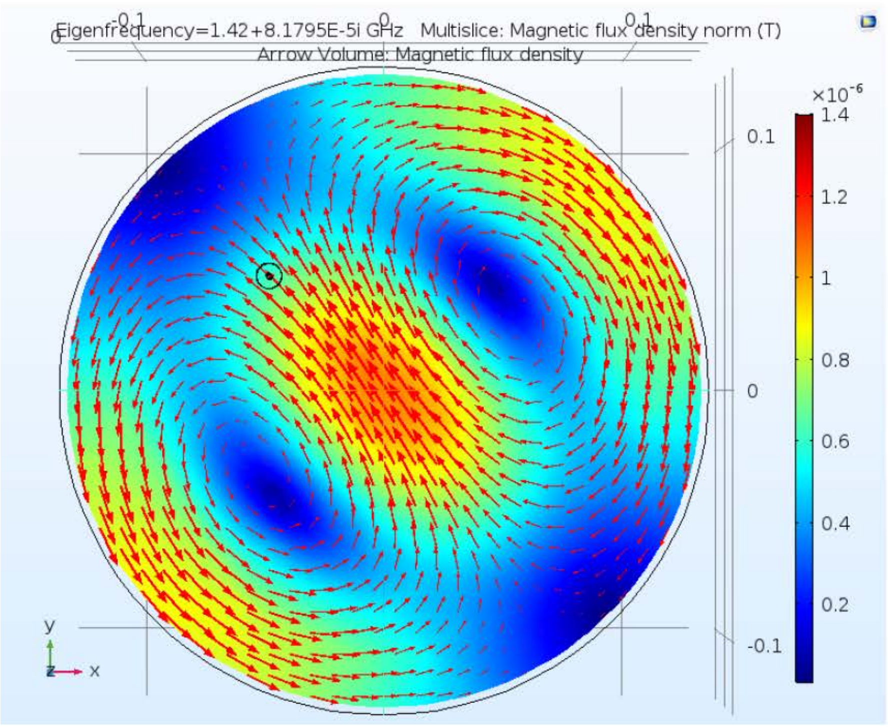
$$\delta\nu \propto \tau_{\text{int}}^{-1} = \frac{v_{\text{beam}}}{L_{\text{Osc.F.}}}$$

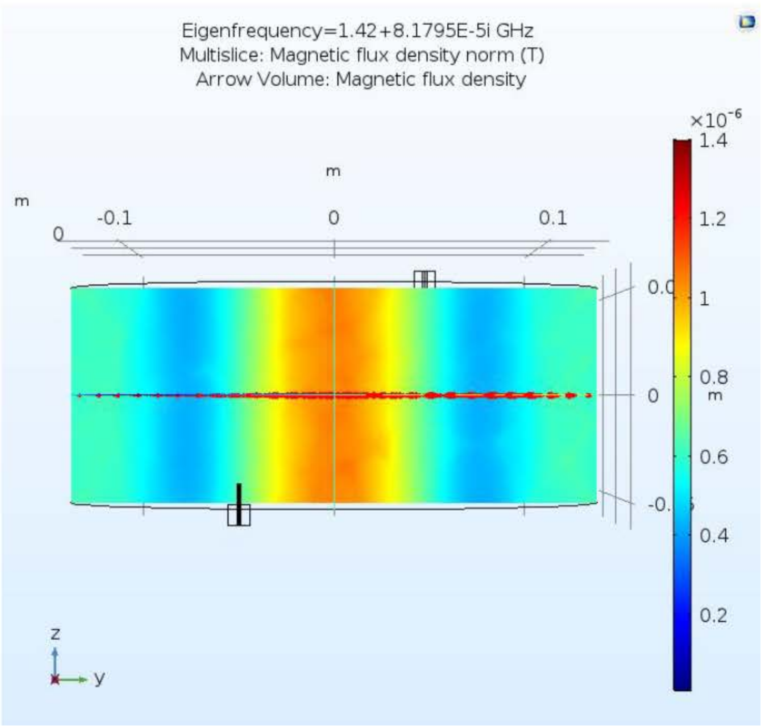


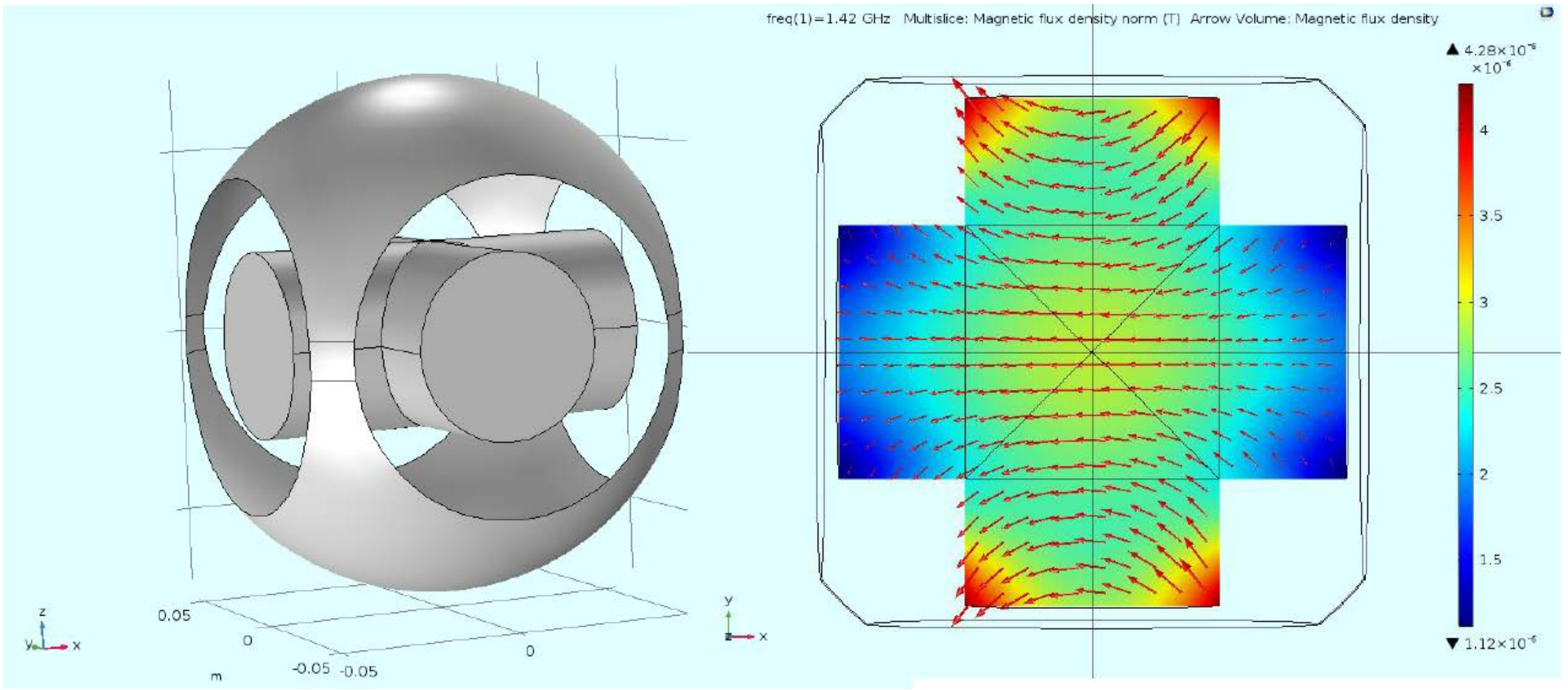




→ strip-line cavity:
line-shape not ideal for Ramsey

# New RF structure: cavity vs. surface coils



# Summary

- Precise measurement of the hyperfine structure of antihydrogen promises one of the most sensitive tests of CPT symmetry
  - First "beam" of $\bar{\mathrm{H}}$ observed in field-free region
  - 1st quantum state distribution at zero B-field
  - Next steps: optimize rate, check polarization, velocity
- HFS measurement in H beam of 2.7 ppb achieved
  - Proof-of-principle for $\bar{\mathrm{H}}$ measurement
  - Potential to measure non-minimal SME coefficients
  - Modifications to increase precision being studied
  - Other atoms: D looks feasible

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

bmwfw Bundesministerium für Wissenschaft, Forschung und Wirtschaft
FWF Der Wissenschaftsfonds.
DOKTORATSKOLLEG PI ∫dk Π Particles and Interactions
CERN RIKEN INFN