Hyperfine spectroscopy of hydrogen and antihydrogen

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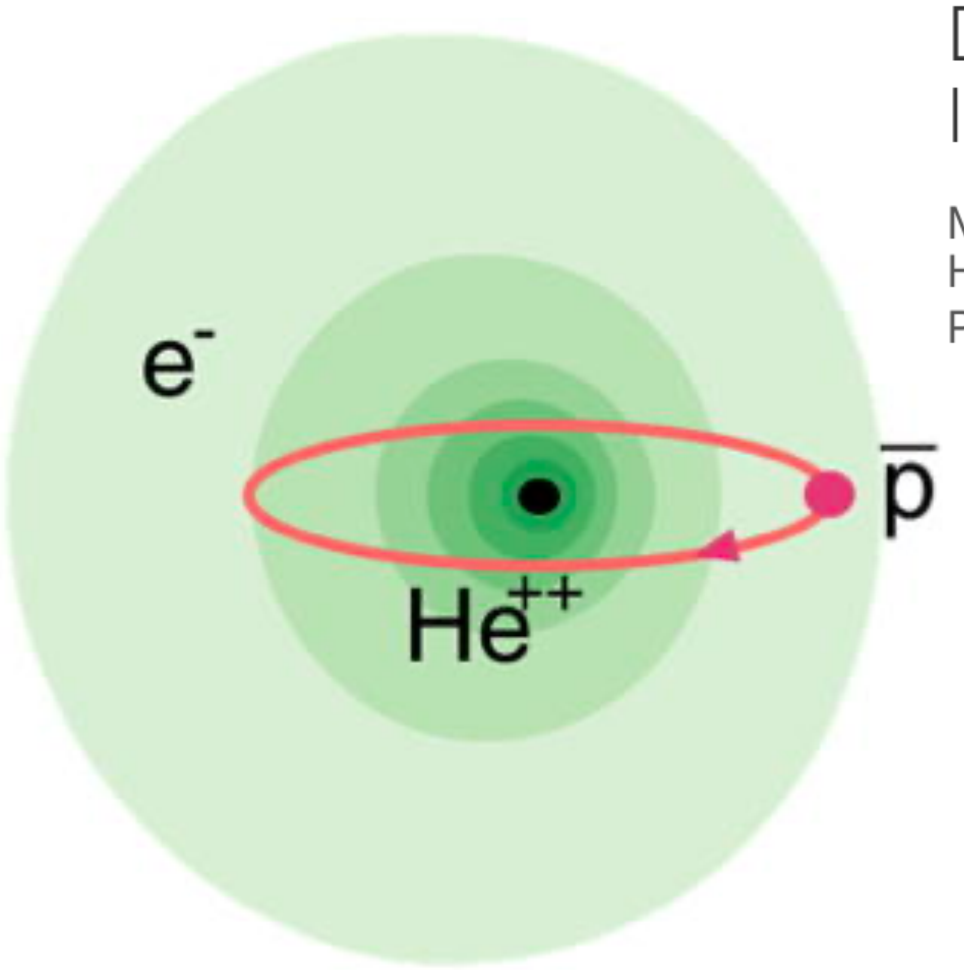
10 years retrospective and a blink at the future of the field

Spectroscopy of antiprotonic helium



Discovery of antiproton trapping by long-lived metastable states in liquid helium

M. Iwasaki, S. N. Nakamura, K. Shigaki, Y. Shimizu, H. Tamura, T. Ishikawa, R. S. Hayano, E. Takada, E. Widmann, H. Outa, M. Aoki, P. Kitching, and T. Yamazaki

Phys. Rev. Lett. **67**, 1246 – Published 2 September 1991 @KEK

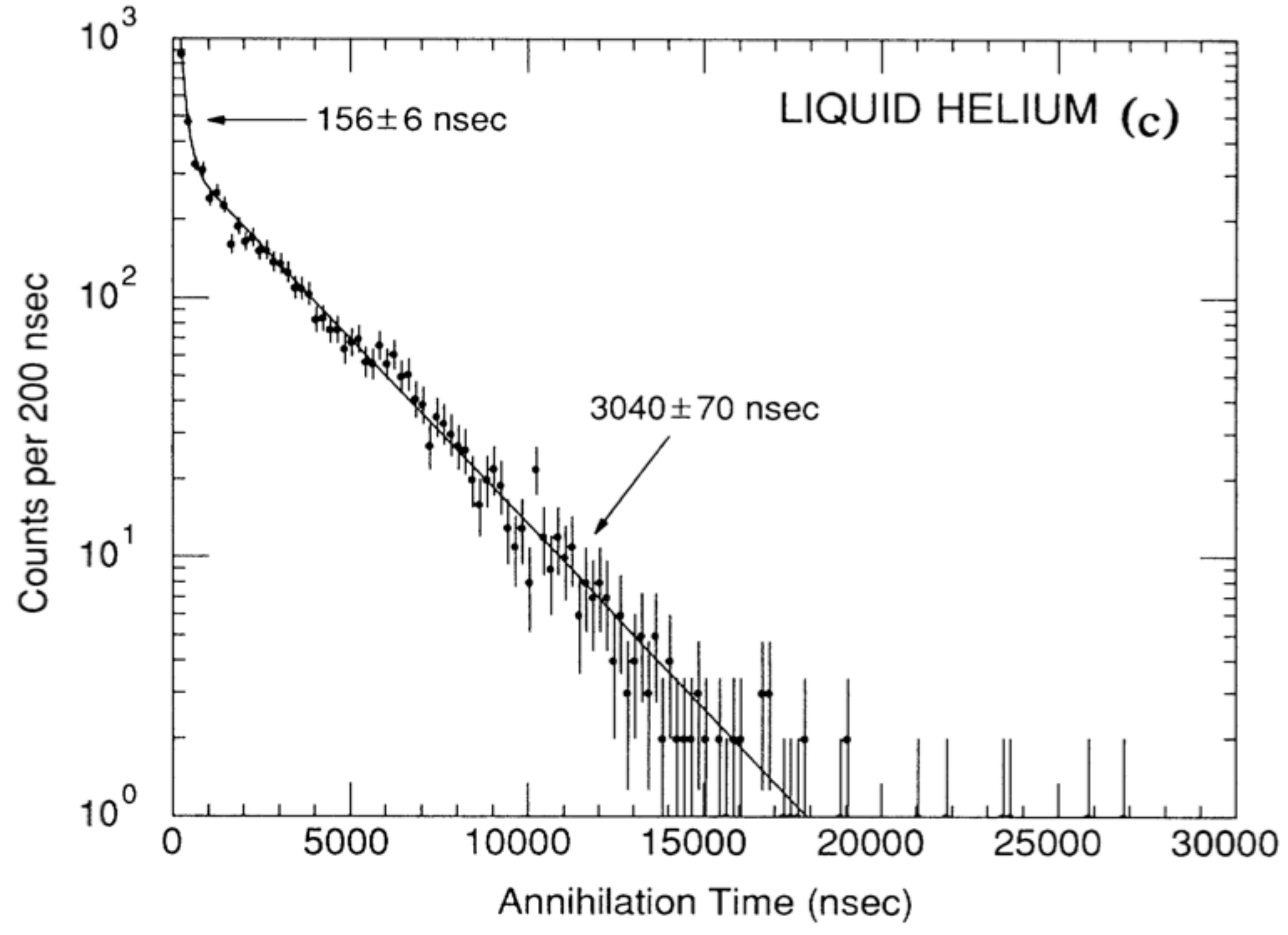
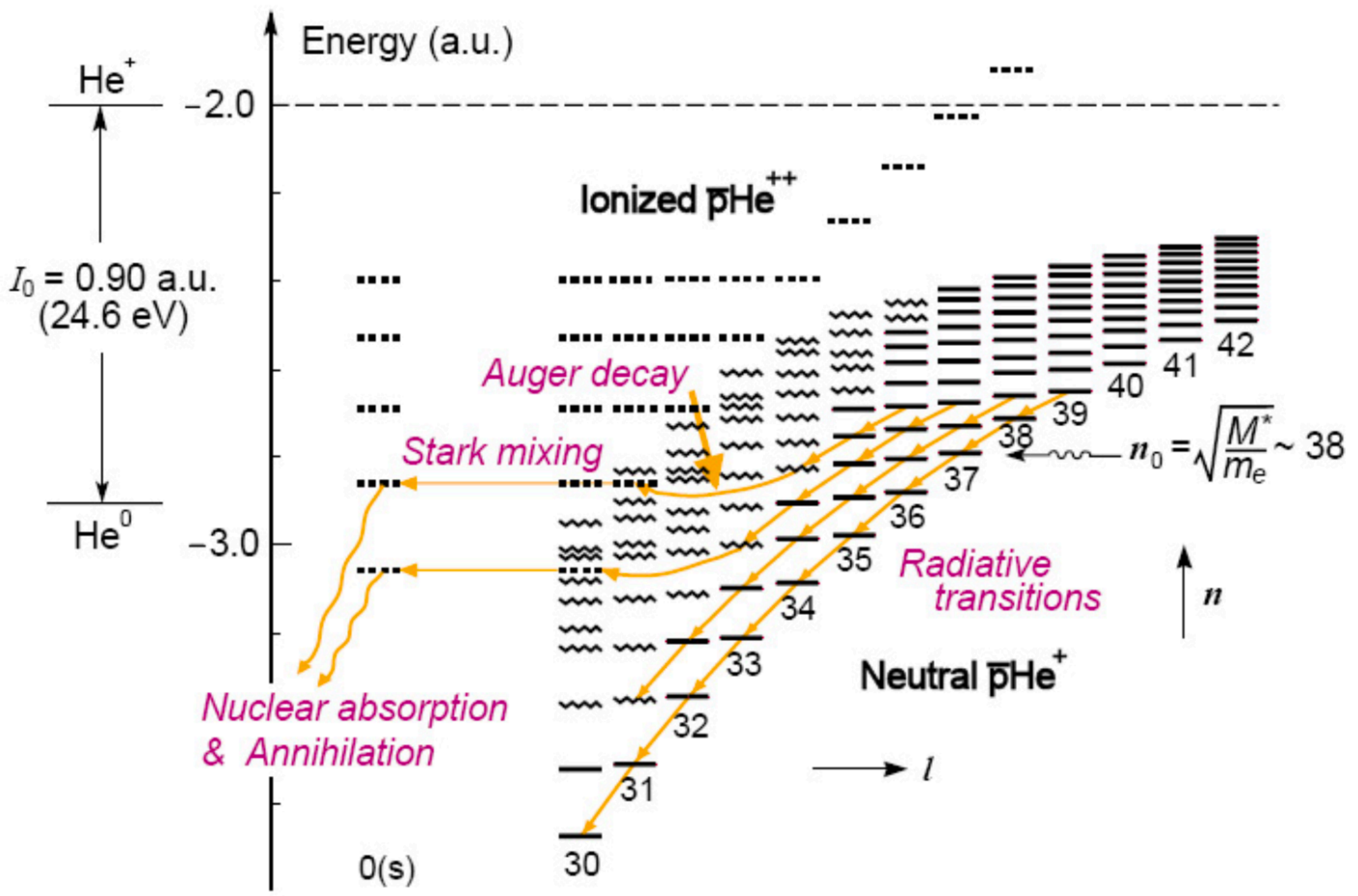


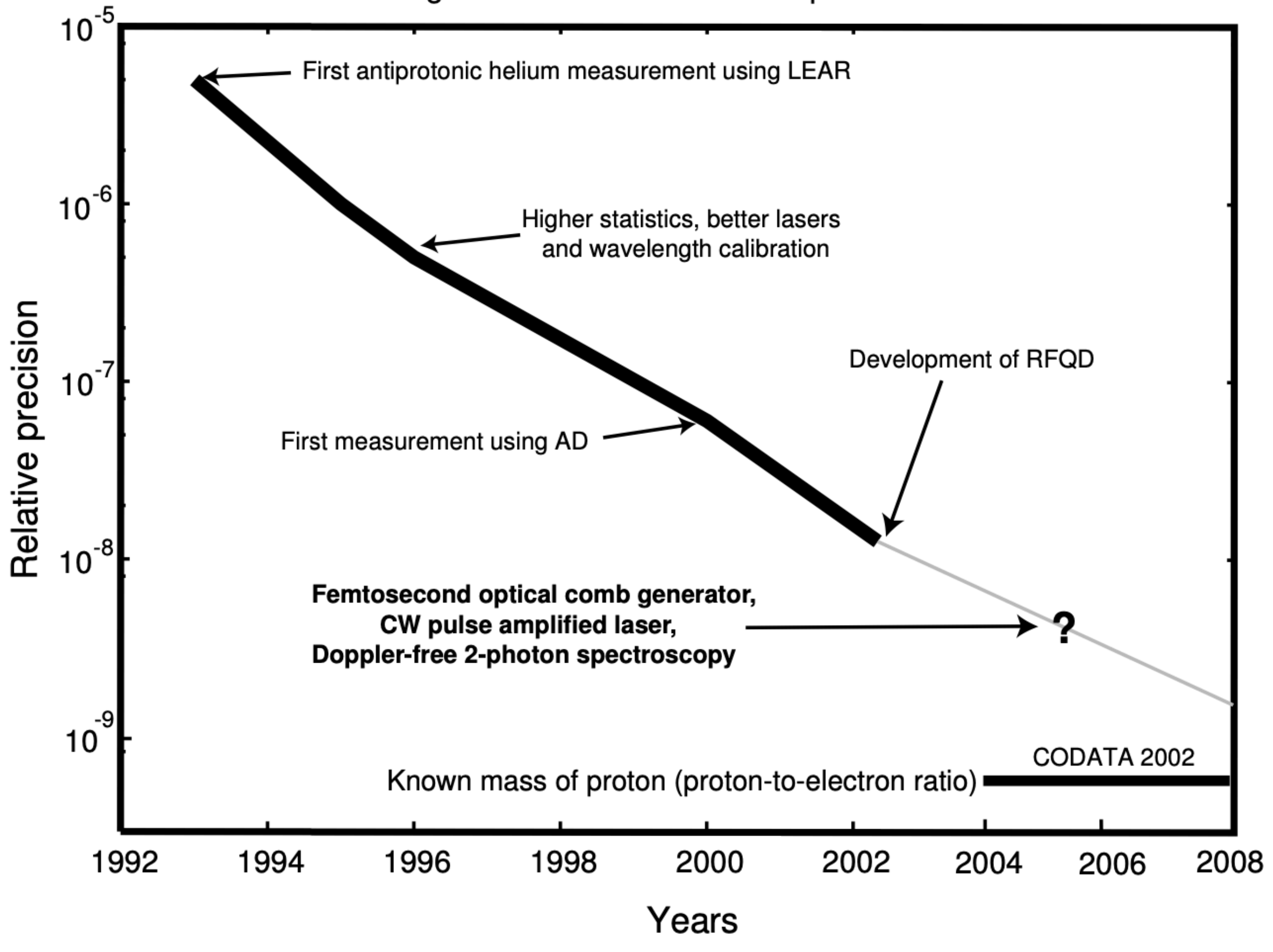
FIG. 2. Time spectra of $\bar{p}$ annihilation in liquid helium in different time ranges. (a) −80 to 170 nsec, (b) 0–1000 nsec, and (c) 0–30 μsec (only 43% of all the data are in this time range).

Spectroscopy performed at LEAR and then AD @ CERN



ASACUSA@CERN: RFQD (collaboration with CERN) - first experiment to have 100 keV p̄ (before ELENA)

Limits on the antiproton charge and mass derived by combining ASACUSA and ATRAP experimental results

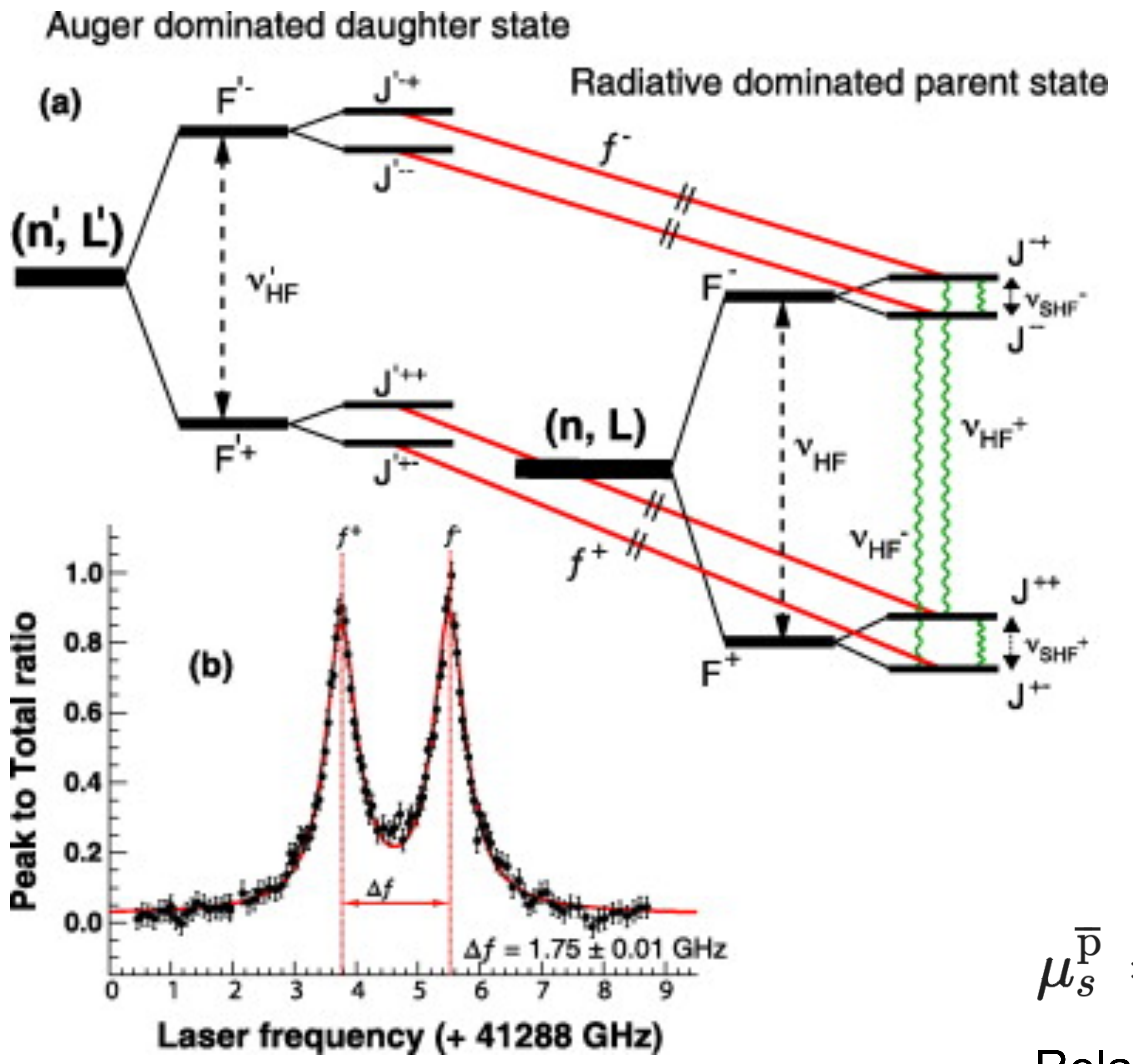


CPT test in the baryon sector

$$\delta = \frac{Q_p + Q_{\bar{p}}}{Q_p} = \frac{M_p - M_{\bar{p}}}{M_p} = \frac{1}{f}\frac{\nu_{th} - \nu_{exp}}{\nu_{exp}}, \qquad \frac{M_{\bar{p}}}{M_{e^-}}$$

Widmann, E.,. "Testing CPT with antiprotonic helium and antihydrogen – the ASACUSA experiment at CERN-AD
Nuclear Physics A 752 (2005) 87c–96c

Hyperfine spectroscopy of antiprotonic helium



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

Relative precision of ~0.3%

ELSEVIER
Physics Letters B
Volume 678, Issue 1, 6 July 2009, Pages 55-59

Antiproton magnetic moment determined from the HFS of $\overline{p}\,He^+$

T. Pask [a], D. Barna [b c], A. Dax [b], R.S. Hayano [b], M. Hori [b d], D. Horváth [c e], S. Friedreich [a], B. Juhász [a], O. Massiczek [a], N. Ono [b], A. Sótér [c d], E. Widmann [a]

Improved study of the antiprotonic helium hyperfine structure

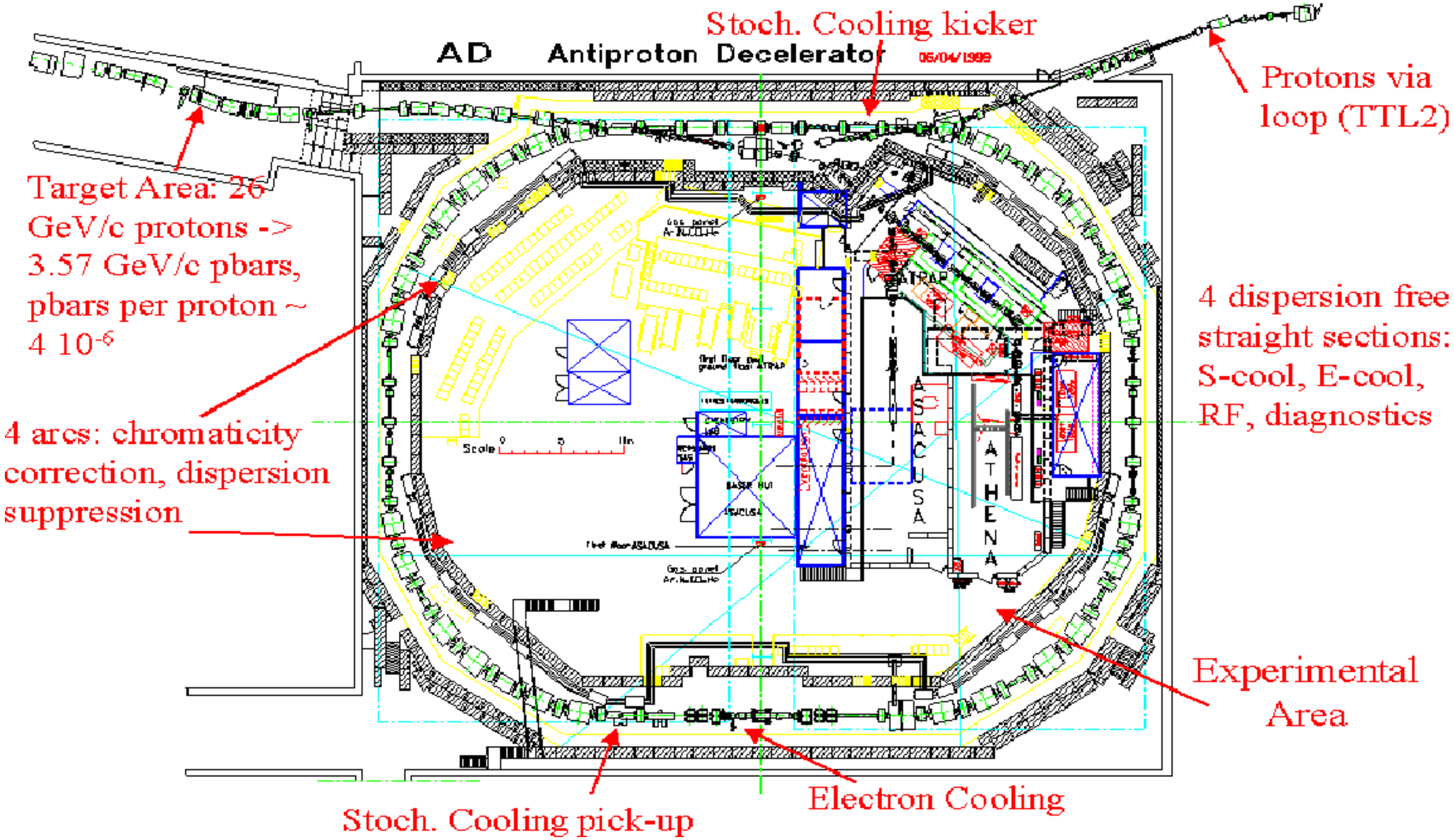
T Pask[1], D Barna[2,3], A Dax[2], R S Hayano[2], M Hori[2], D Horváth[3,4], B Juhász[1], C Malbrunot[1], J Marton[1], N Ono[2], K Suzuki[1], J Zmeskal[1] and E Widmann[1]

J. Phys. B: At. Mol. Opt. Phys. **41** 081008 2008

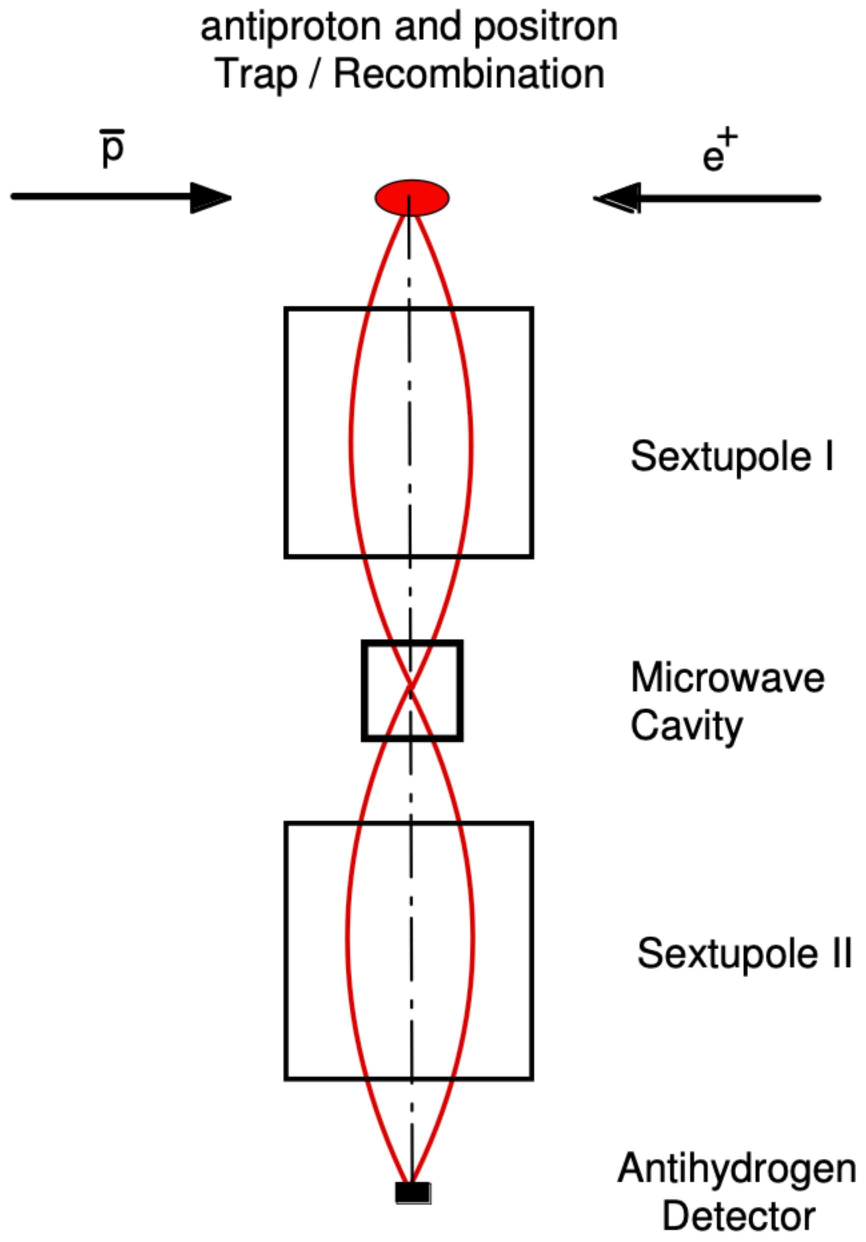
DIPLOMARBEIT

Collisional effects in the measurement of the hyperfine structure of antiprotonic helium

Producing a beam of antihydrogen atoms

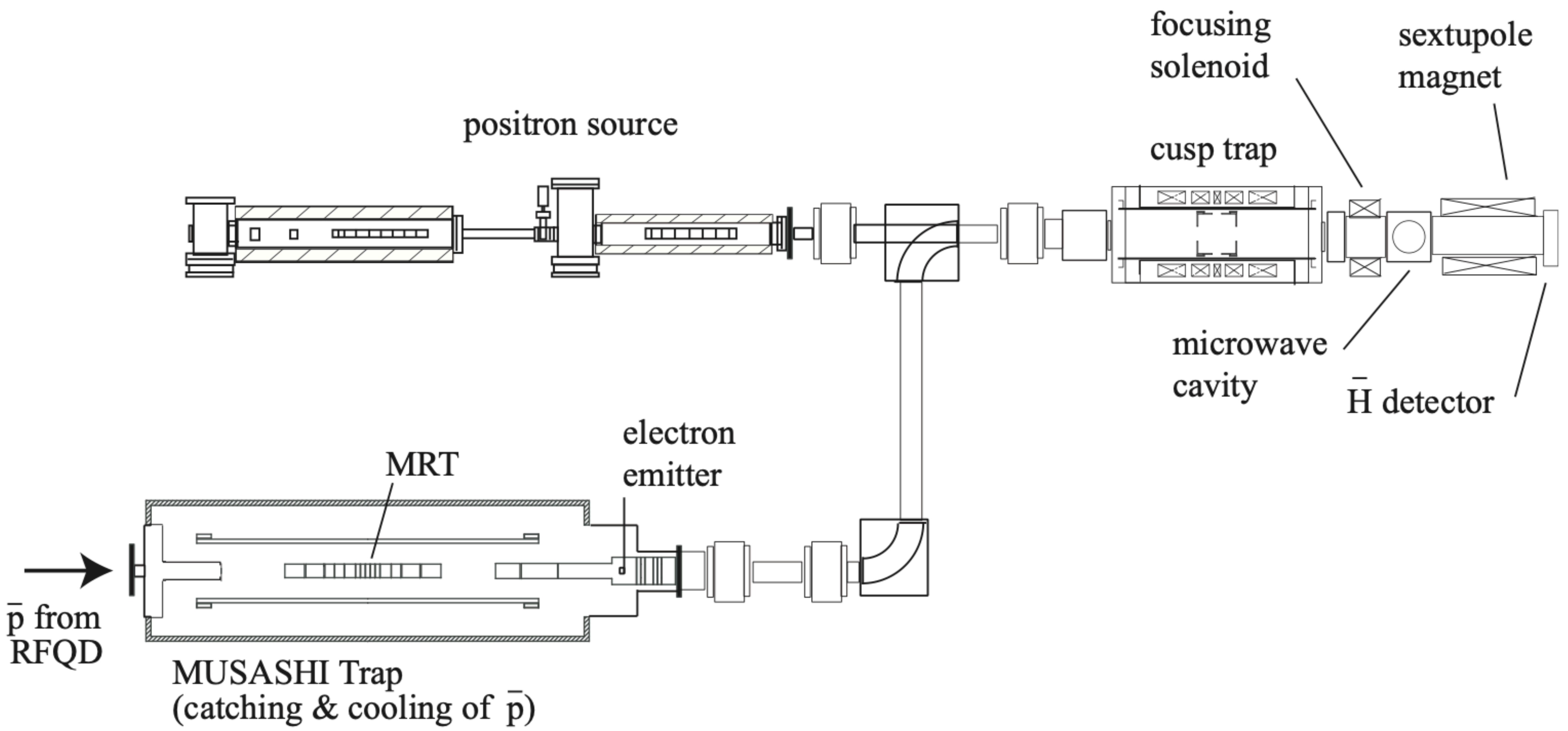


Widmann, E., et al. "Measurement of the antihydrogen hyperfine structure." ***Letter of Intent CERN-SPSC-2003-009,*** *CERN, Geneva, Switzerland* (2003).



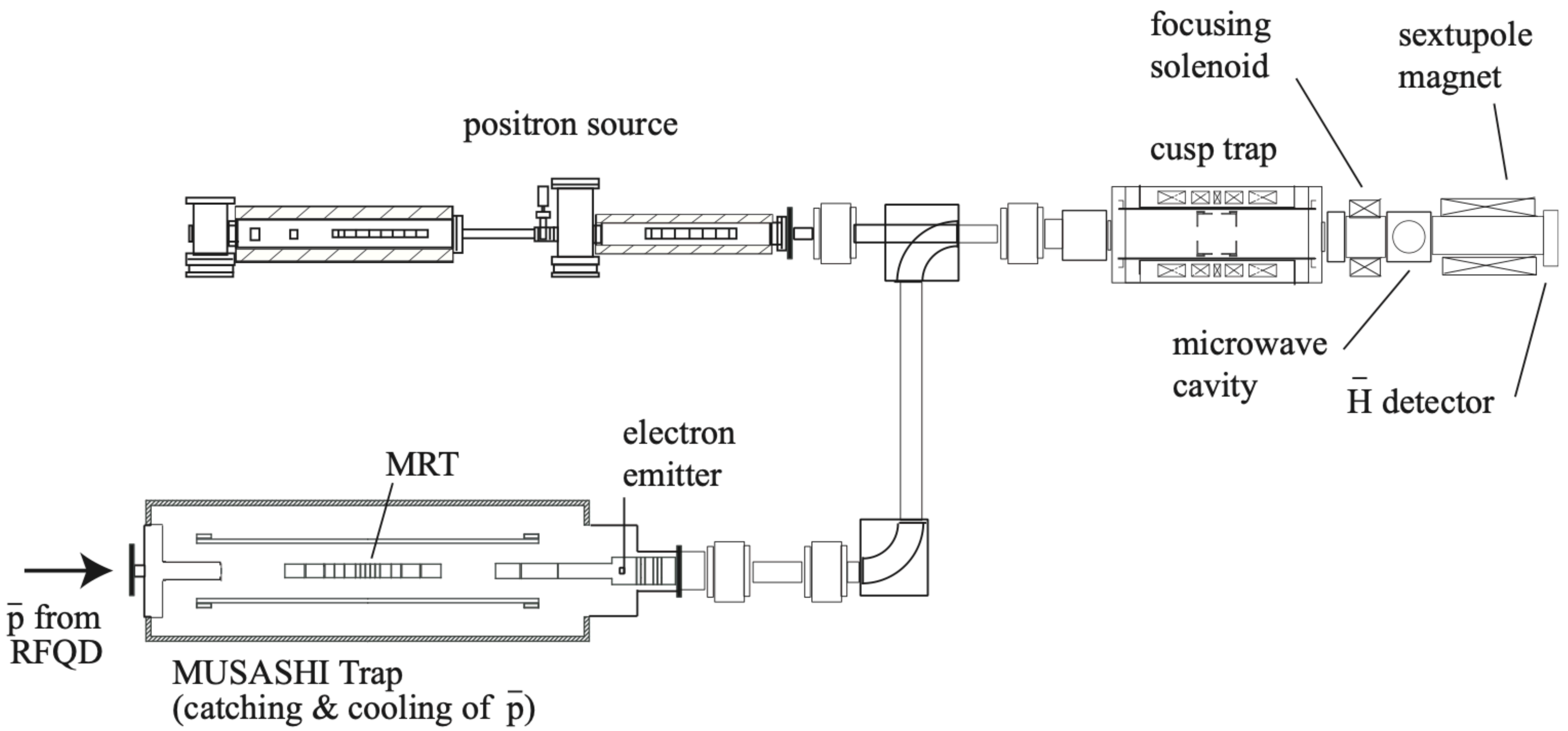
2003 : ATHENA and TRAP experiments were producing some H̄ atoms.
Goal: 1S-2S spectroscopy in a magnetic trap

Producing a beam of antihydrogen atoms



ASACUSA Collaboration
Proposal for Extending ASACUSA programme
CERN - 2005
https://cds.cern.ch/record/813195/files/spsc-2005-002.pdf

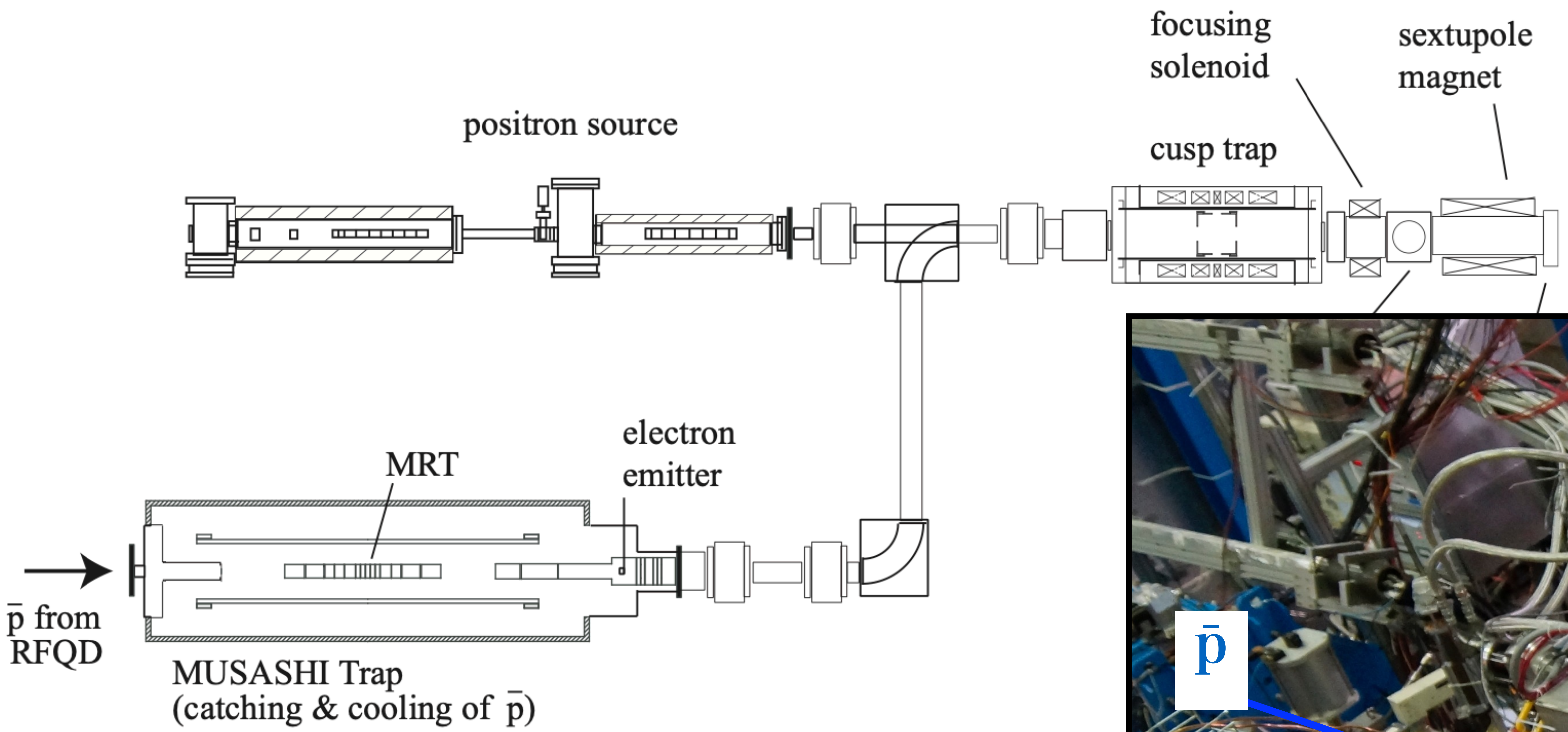
Producing a beam of antihydrogen atoms



… 8 YEARS LATER

ASACUSA Collaboration
Proposal for Extending ASACUSA programme
CERN - 2005
https://cds.cern.ch/record/813195/files/spsc-2005-002.pdf

Producing a beam of antihydrogen atoms



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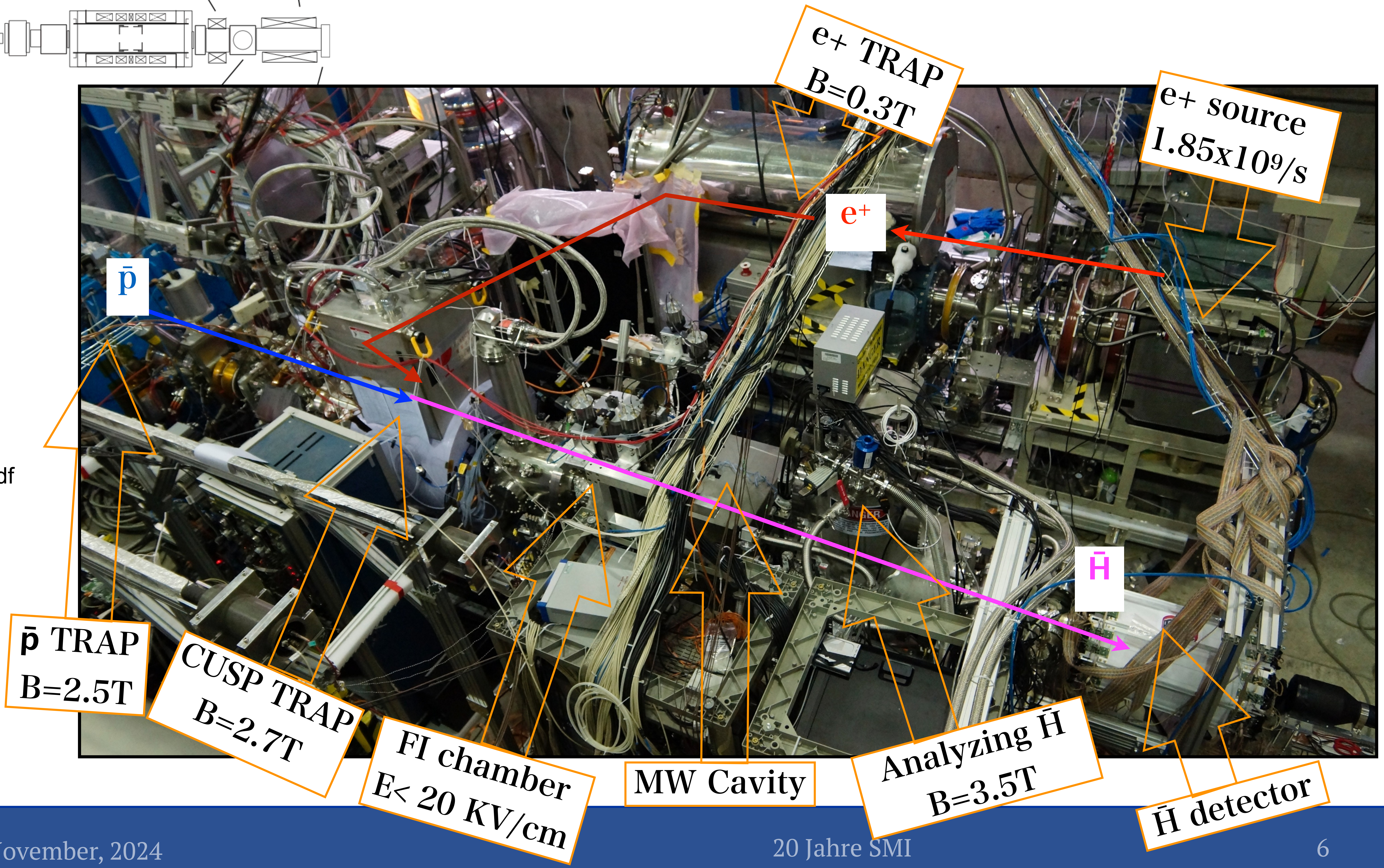
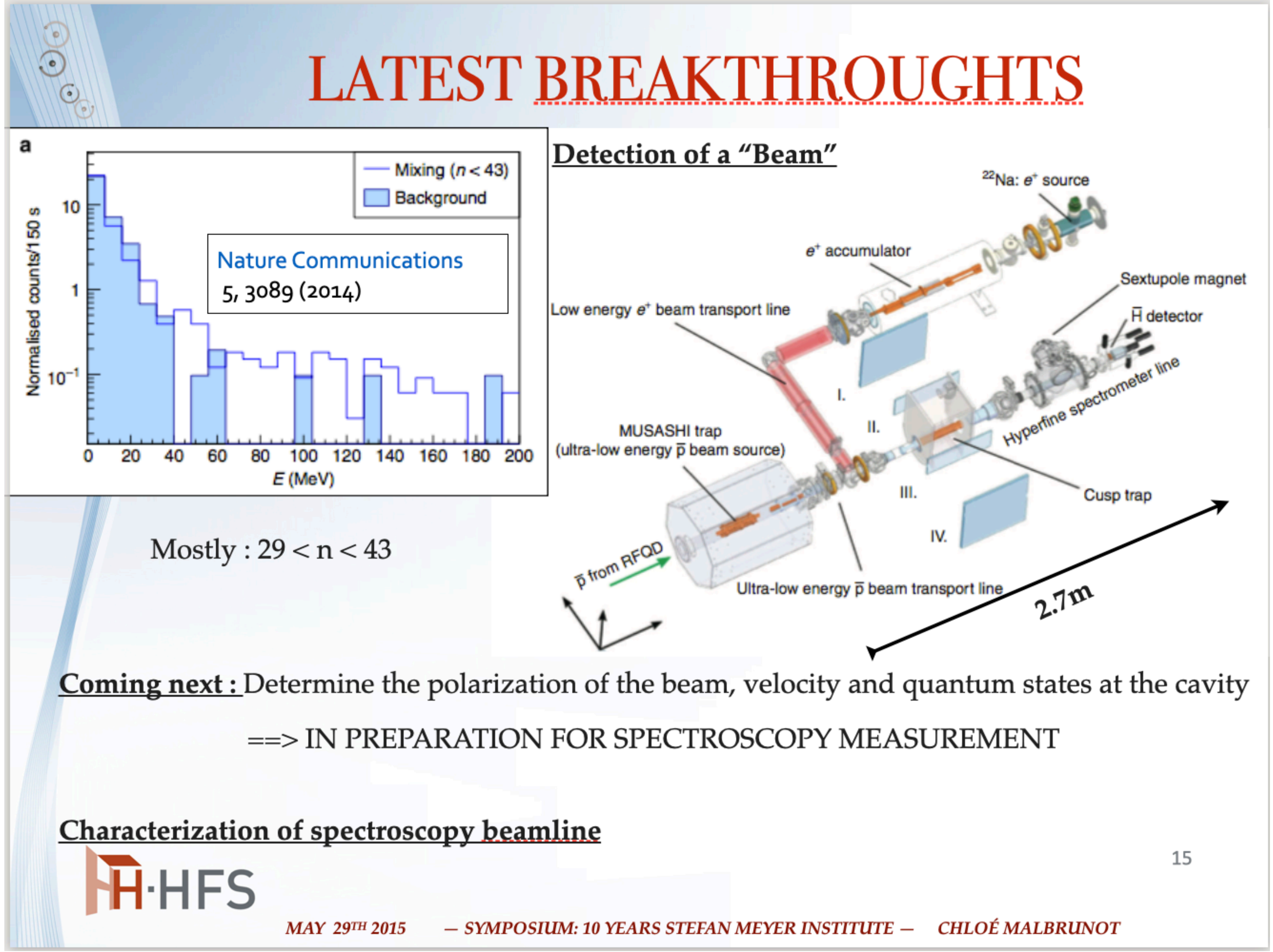


Producing a beam of antihydrogen atoms

Slide presented at the "10 years of SMI" Symposium

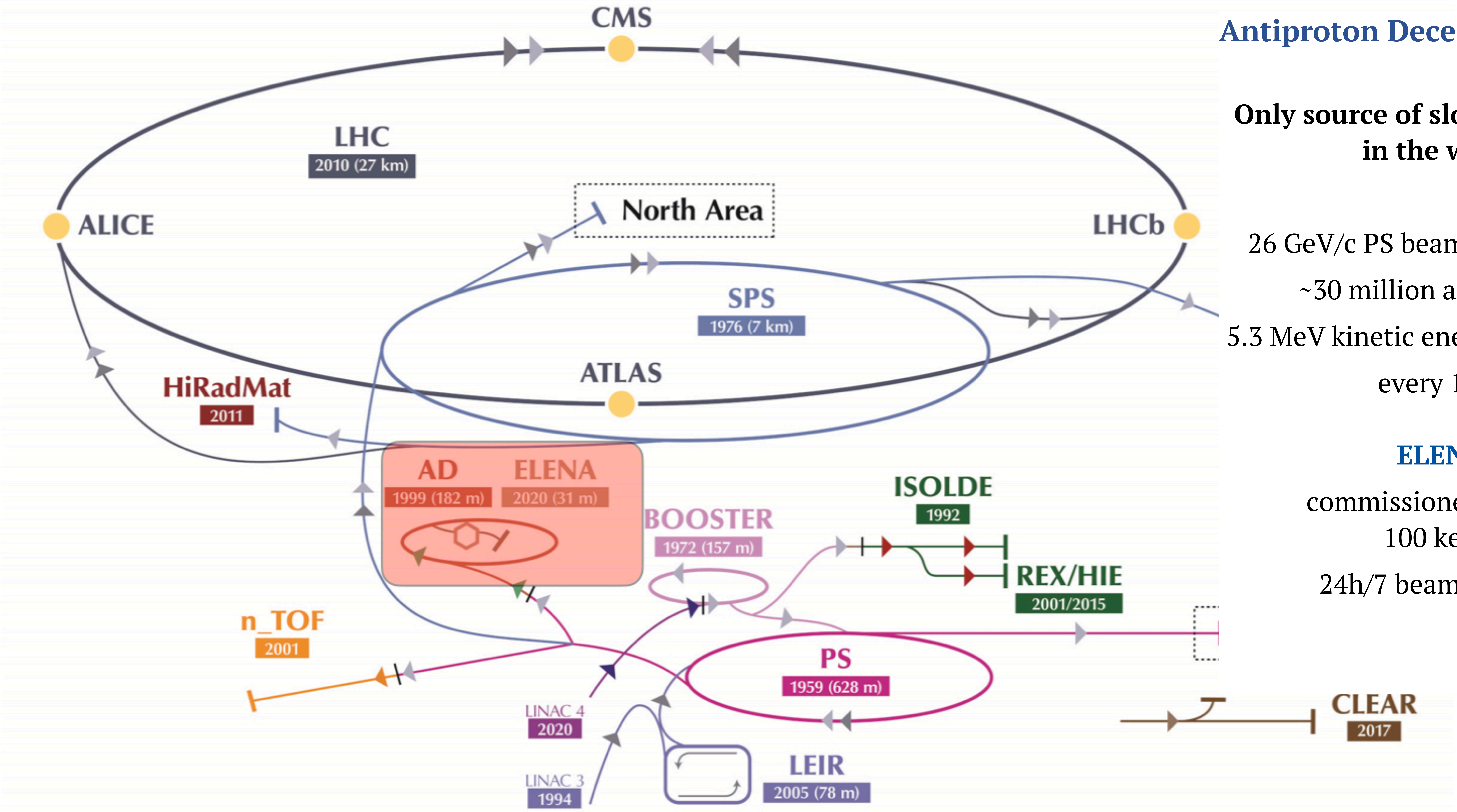


Article | Open access | Published: 21 January 2014

A source of antihydrogen for in-flight hyperfine spectroscopy

N. Kuroda, S. Ulmer, D. J. Murtagh, S. Van Gorp, Y. Nagata, M. Diermaier, S. Federmann, M. Leali, C. Malbrunot, V. Mascagna, O. Massiczek, K. Michishio, T. Mizutani, A. Mohri, H. Nagahama, M. Ohtsuka, B. Radics, S. Sakurai, C. Sauerzopf, K. Suzuki, M. Tajima, H. A. Torii, L. Venturelli, B. Wu¨nschek, J. Zmeskal, N. Zurlo, H. Higaki, Y. Kanai, E. Lodi Rizzini, Y. Nagashima, Y. Matsuda, E. Widmann & Y. Yamazaki — Show fewer authors

Nature Communications **5**, Article number: 3089 (2014) | Cite this article



Antiproton Decelerator (AD)

Only source of slow antiprotons in the world

26 GeV/c PS beam onto Ir target

~30 million antiprotons

5.3 MeV kinetic energy (100 MeV/c)

every 120s

ELENA

commissioned in 2019

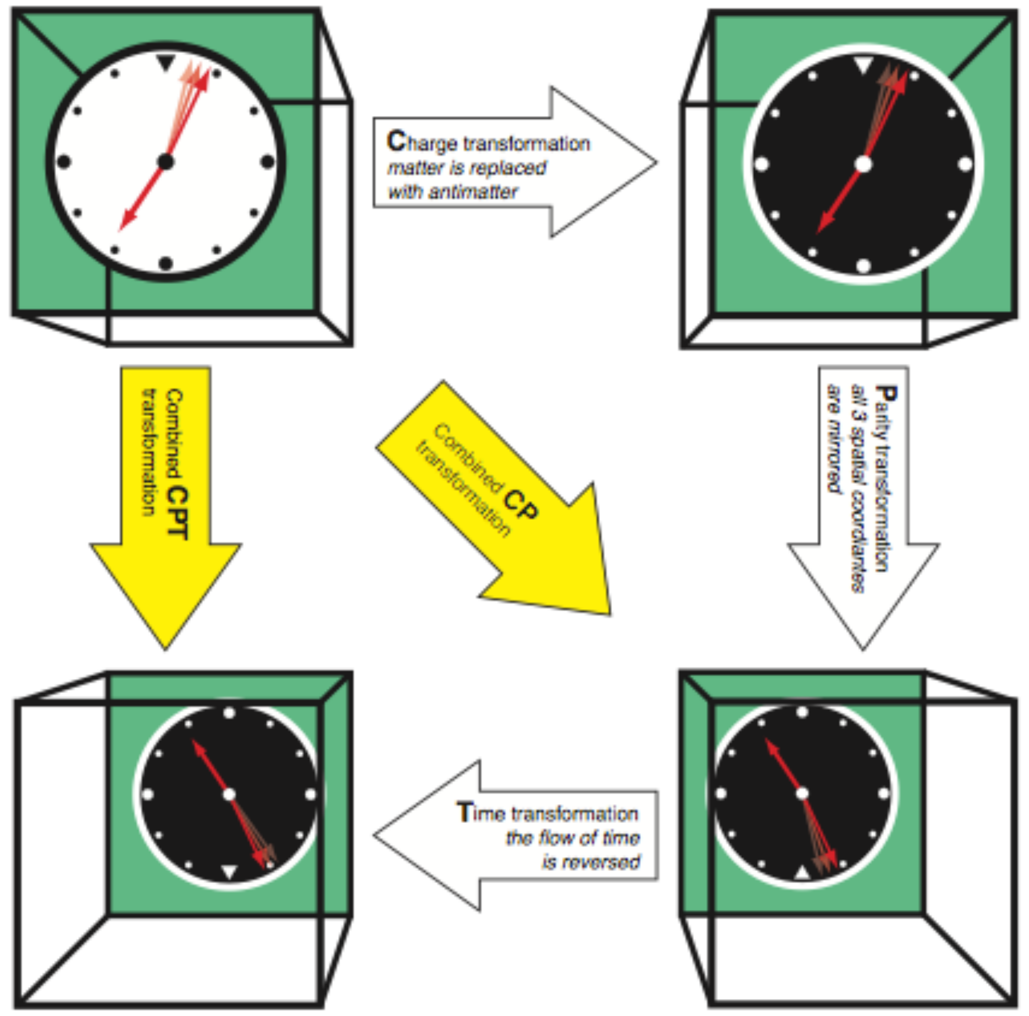
100 keV $\bar{p}$

24h/7 beam delivery


CMS
LHC
2010 (27 km)
ALICE
ATLAS
HiRadMat
2011
AD
1999 (182 m)
ELENA
2020 (31 m)
n_TOF
2001
LINAC 4
2020
LINAC 3
1994
ELENA
GBAR
PUMA
BASE
AEGIS
BASE-STEP
ASACUSA
ALPHA

Motivation: Matter/antimatter asymmetry and CPT tests

CPT symmetry **"cornerstone" of QFT**



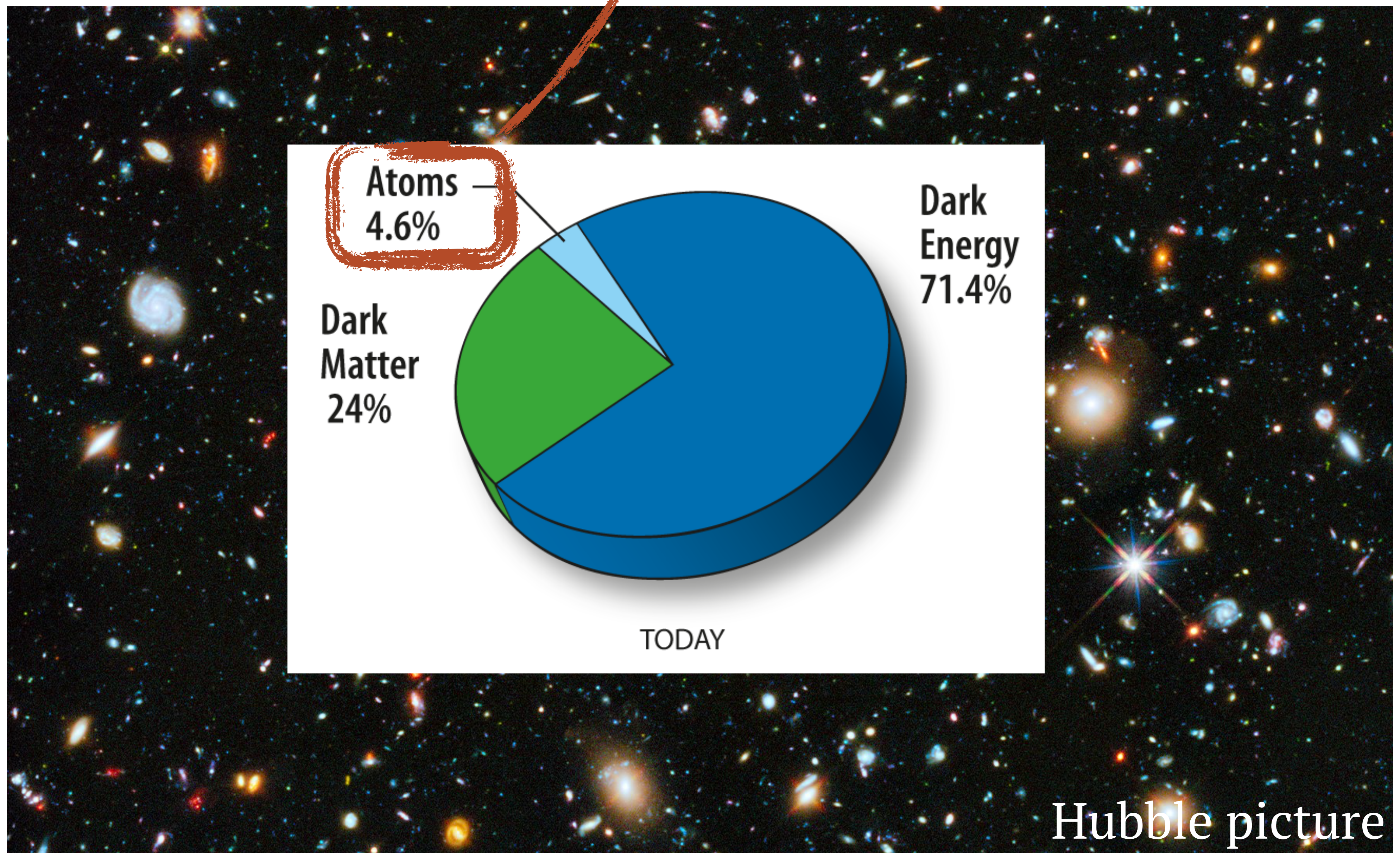
CPT theorem: any **local**, **unitary**, **Lorentz invariant** QFT include conservation of CPT

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

Dirac equation in the minimal Standard Model Extension

e.g. Lorentz and CPT Tests in Hydrogen, Antihydrogen, and Related Systems, A. Kostelecky and A. Vargas, Phys. Rev. D 92, 056002 (2015)

Where are the anti-atoms??



Strong baryon asymmetry in the universe

originating from a ~10^{-10} imbalance

CP violation in the SM is by far not enough to explain this imbalance

Different measurements (even of the same quantity) are sensitive (or not) to different SME coefficients

Sensitivity of an experiment to SME coefficients is governed by absolute precision

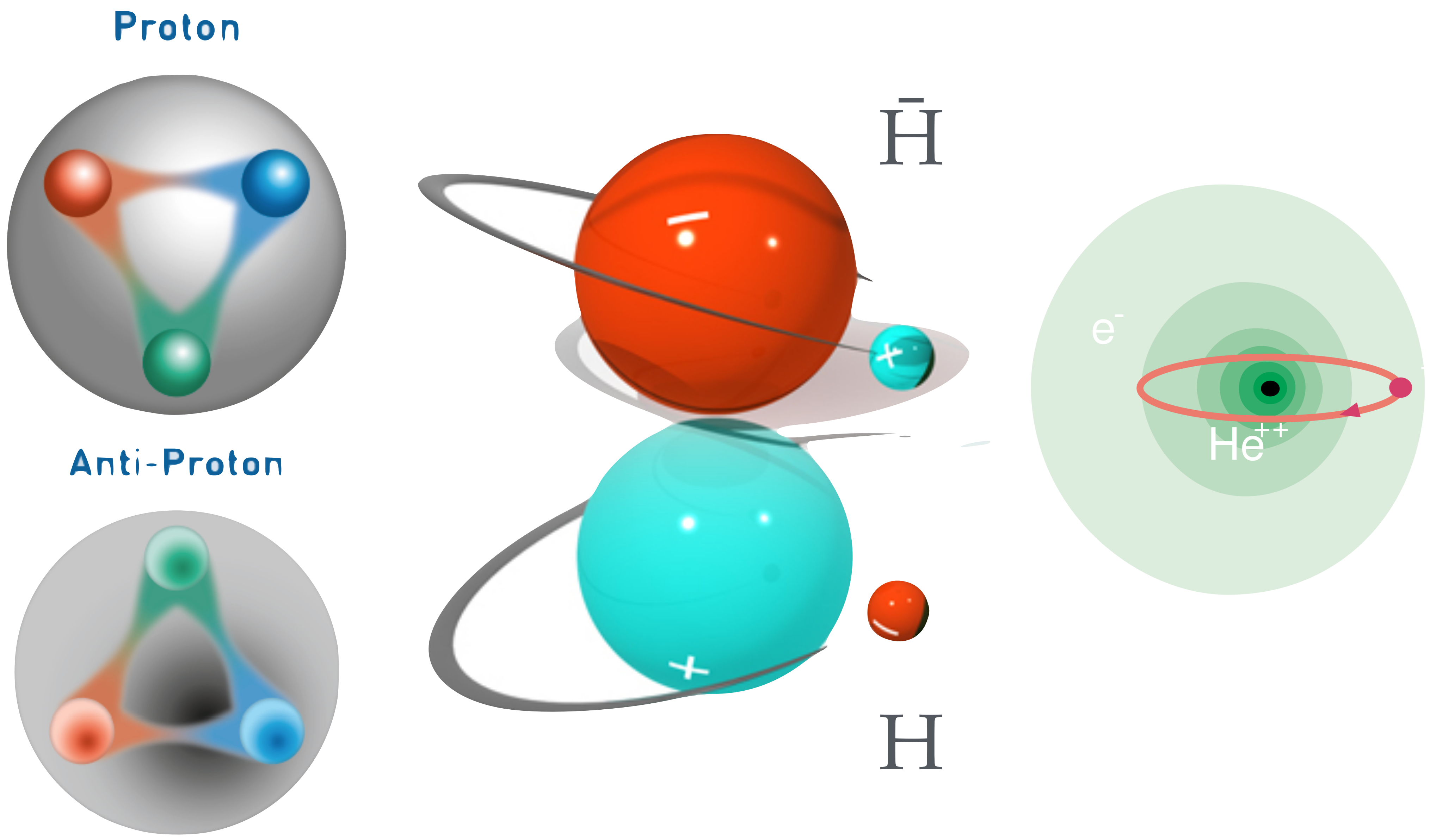
New physics searches with low energy antiprotons at AD-ELENA

BASE/STEP ($\bar{p}$ in Penning trap), ASACUSA ($\bar{p}He$)
Fundamental properties of the antiproton

ALPHA
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ALPHA, AEgIS, GBAR
Test free fall/equivalence principle with antihydrogen



antiproton antihydrogen antiprotonic helium

AD community: ~60 research institues/universities - 400 researchers - 5 collaborations
+1 : connection to nuclear physics with the PUMA experiment

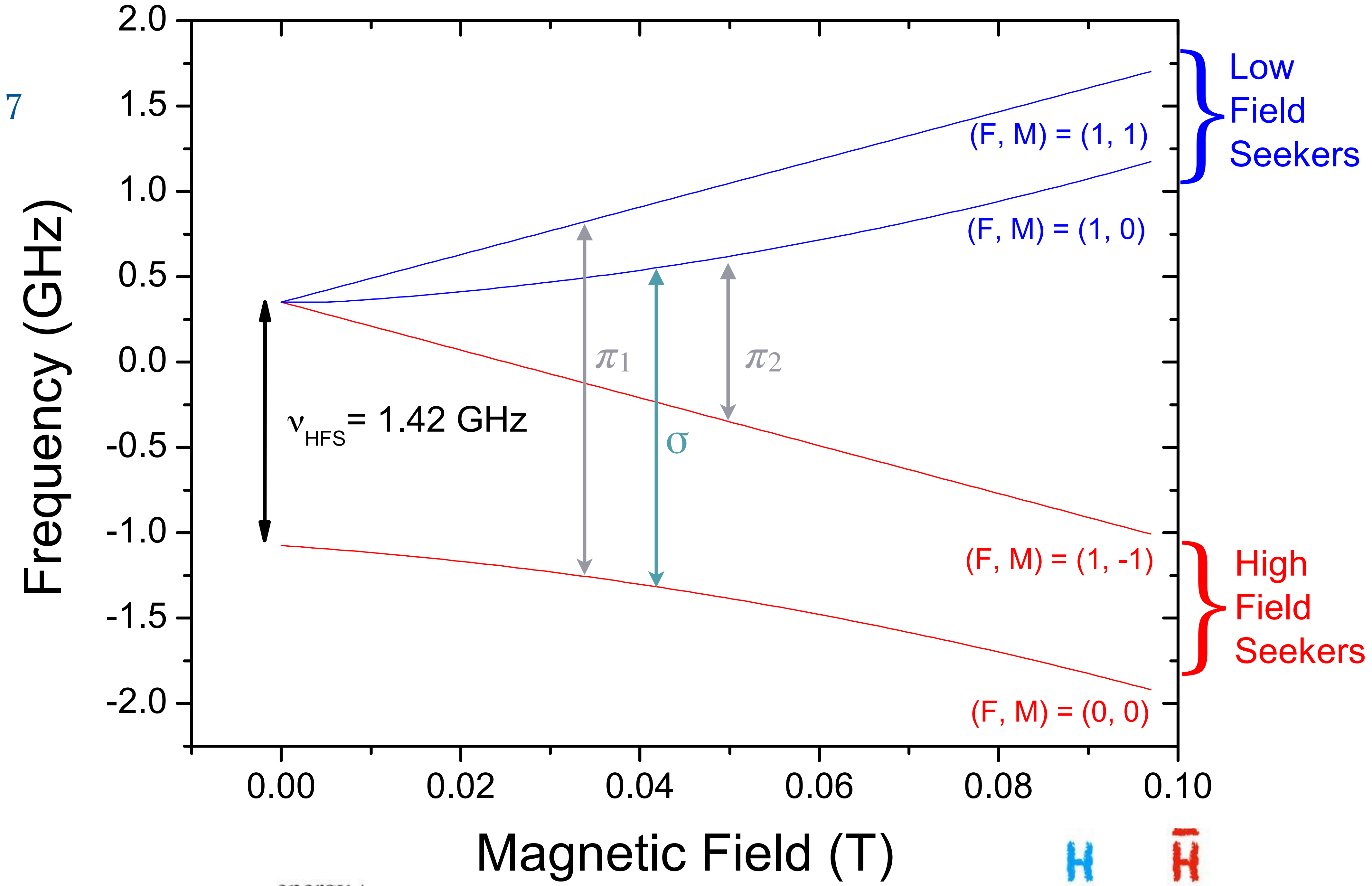
H/H̄ hyperfine splitting

The antihydrogen hyperfine splitting

known at ~1ppb level
C Smorra et al. *Nature*, 550(7676), 10 2017

$$\nu_{HF} = \frac{16}{3}\mathcal{R}_y\alpha^2 c\left(\frac{m_{\bar{p}}}{m_{\bar{p}}+m_{e^+}}\right)^3 \frac{m_{e^+}}{m_{\bar{p}}}\frac{\mu_{e^+}}{\mu_B}\frac{\mu_{\bar{p}}}{\mu_N}(1+\delta_{str}+\delta_{QED})$$

$$\Delta\nu(\text{Zemach}) = \nu_{HF}\frac{2Z\alpha m_e^+}{\pi^2}\int\frac{d^3p}{p^4}\left[\frac{G_{E(\bar{p})}(p^2)G_{M(\bar{p})}(p^2)}{1+\kappa}-1\right]$$

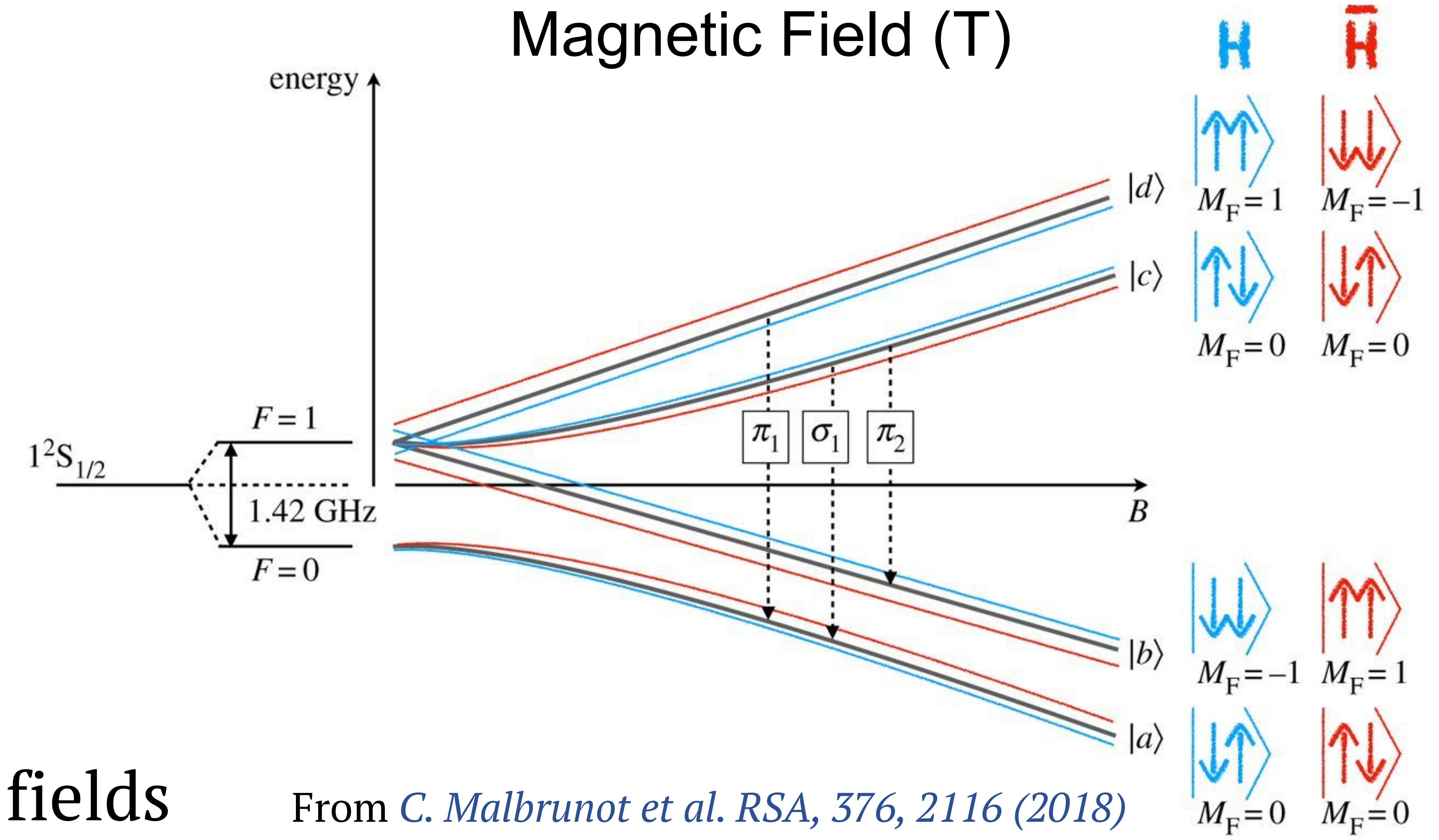


- Access to antiproton magnetic moment
- Probe antiproton substructure
- Probe SME coefficients

All are **CPT tests** but not all constrain **SME parameters**

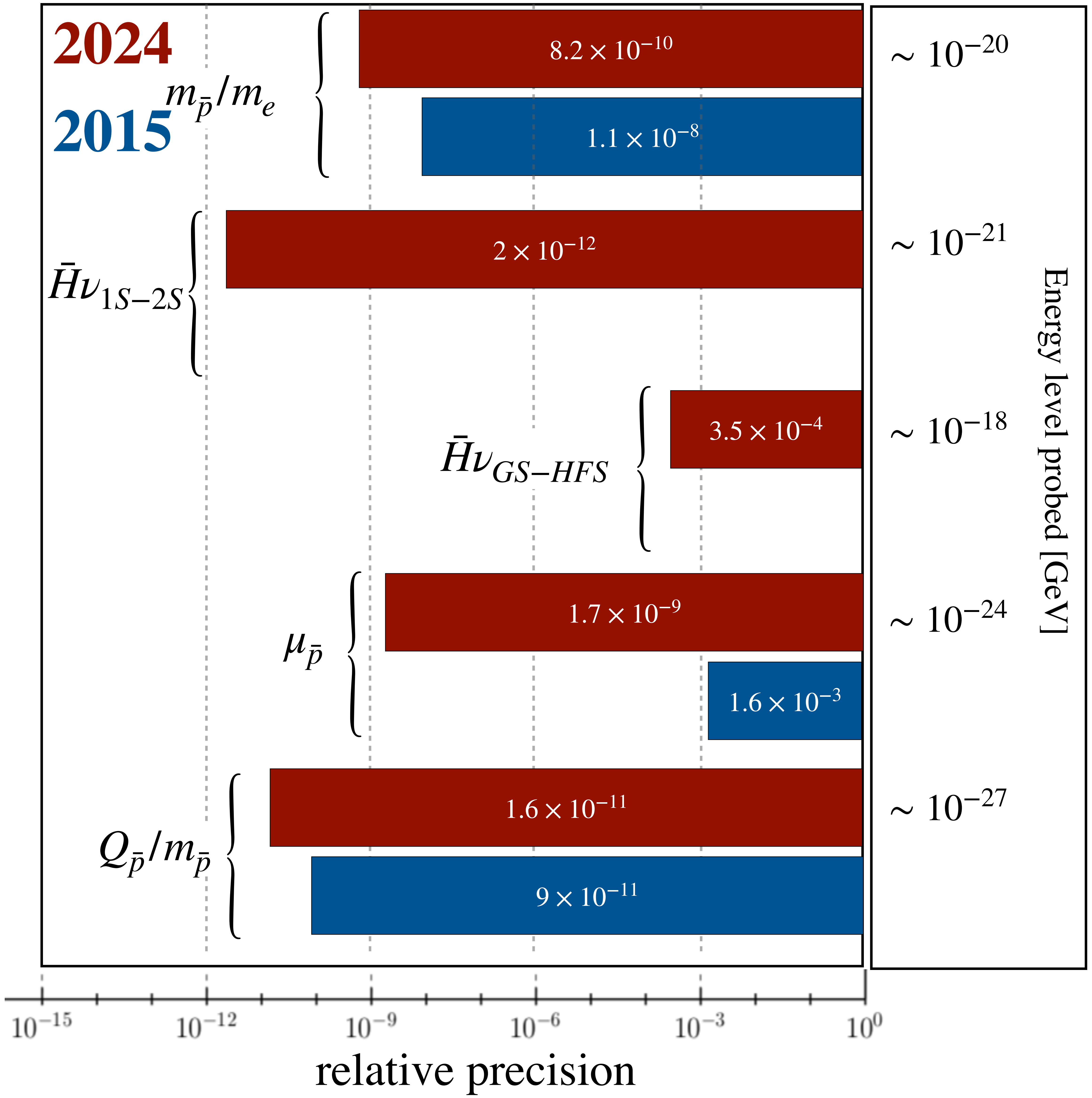
Several options to measure ν_{HF}

- $\pi_1 - \pi_2$ at a given B field
- π_1 and σ_1 at a given B field
- Extrapolate either transitions from several measurements at different B fields



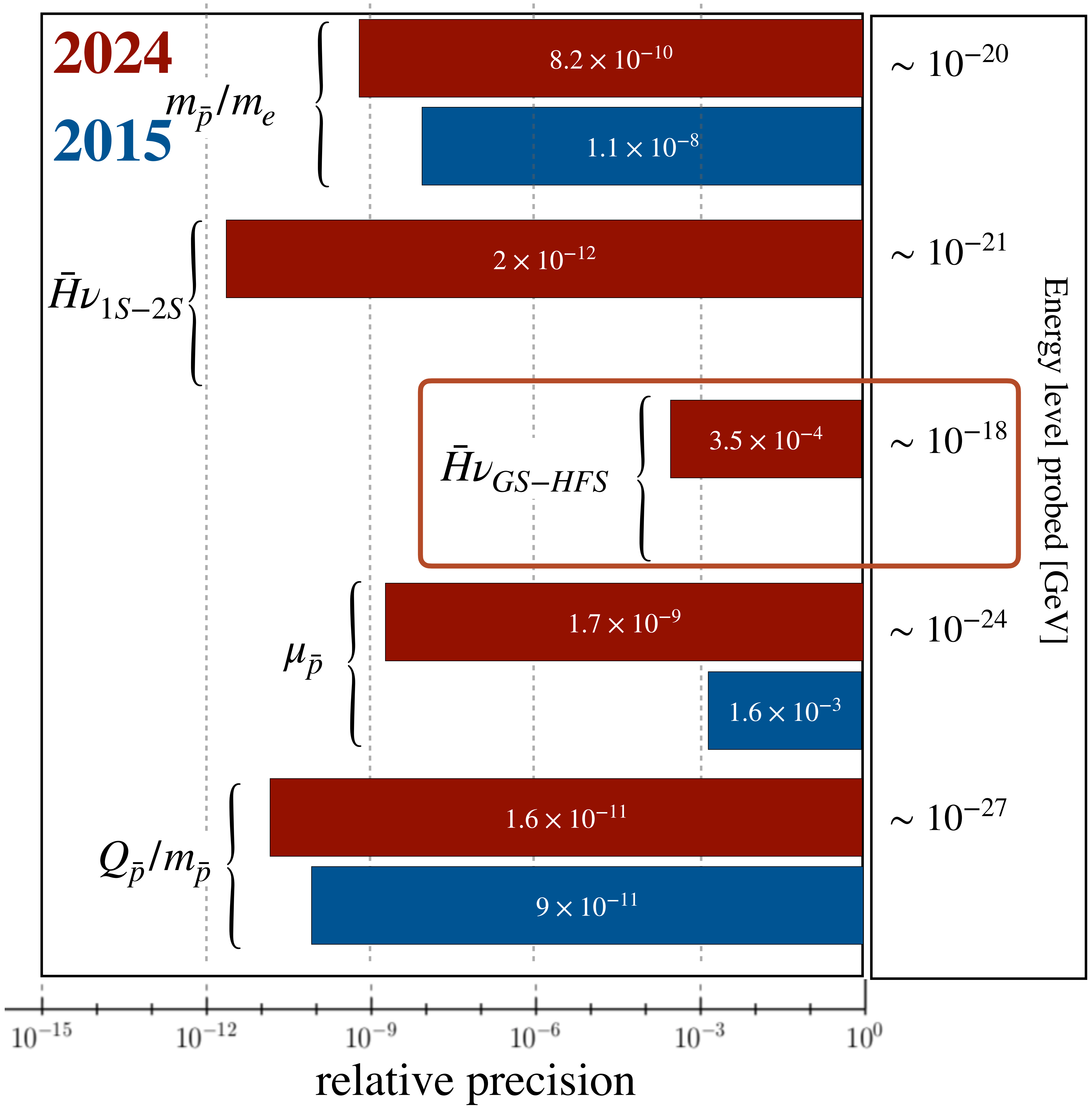
From *C. Malbrunot et al. RSA, 376, 2116 (2018)*

Progress in the last 10 years



Carli, C., Gamba, D., Malbrunot, C., Ponce, L., & Ulmer, S. (2022). ELENA: Bright Perspectives for Low Energy Antiproton Physics. Nuclear Physics News, 32(3), 21–27. https://doi.org/10.1080/10619127.2022.2100646

Progress in the last 10 years



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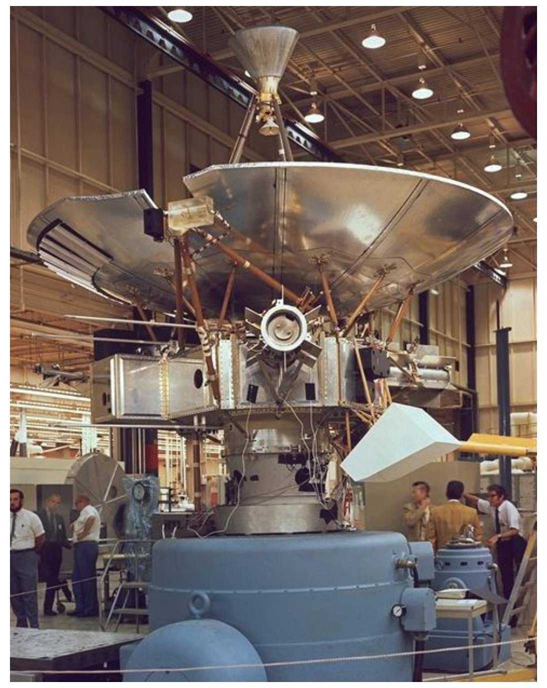
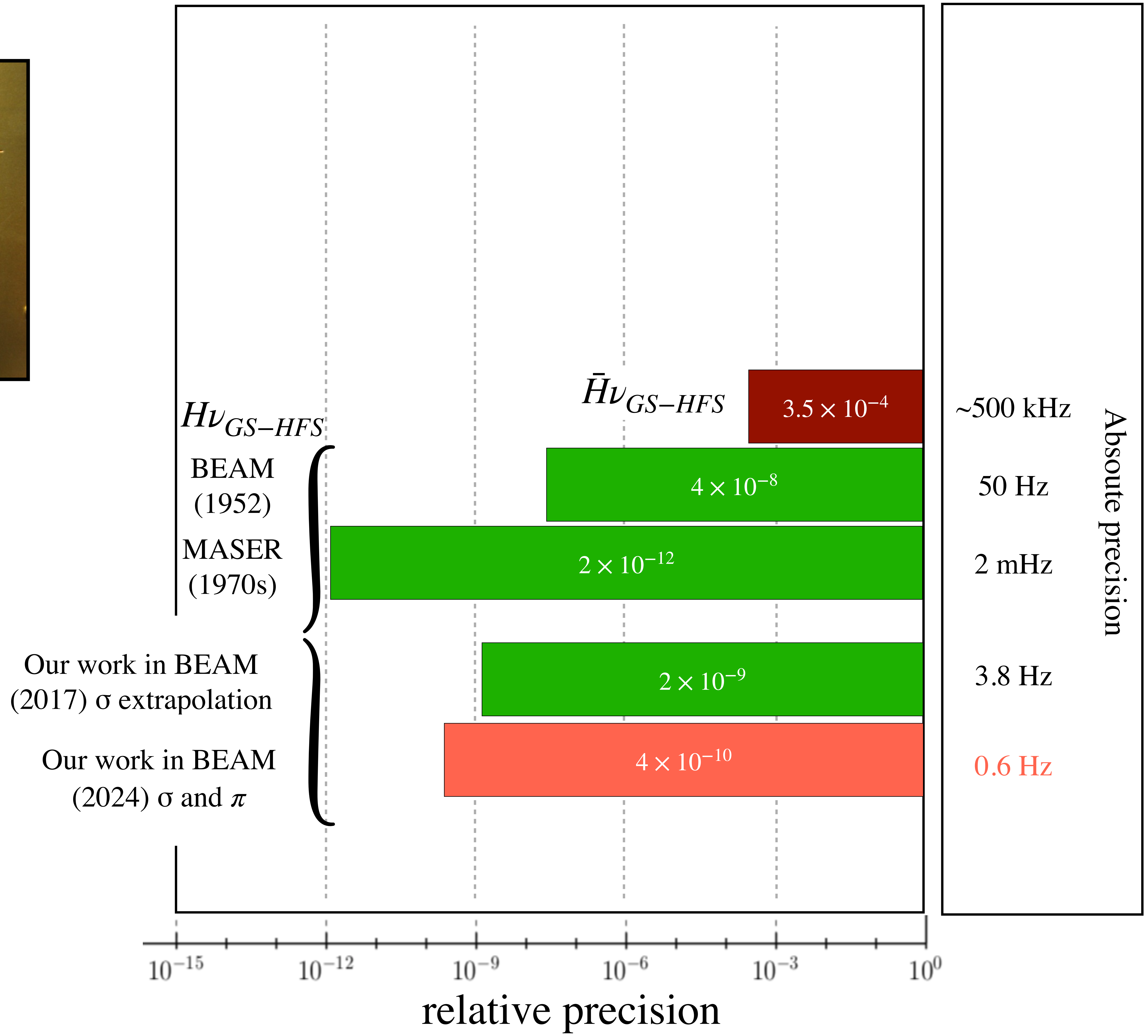
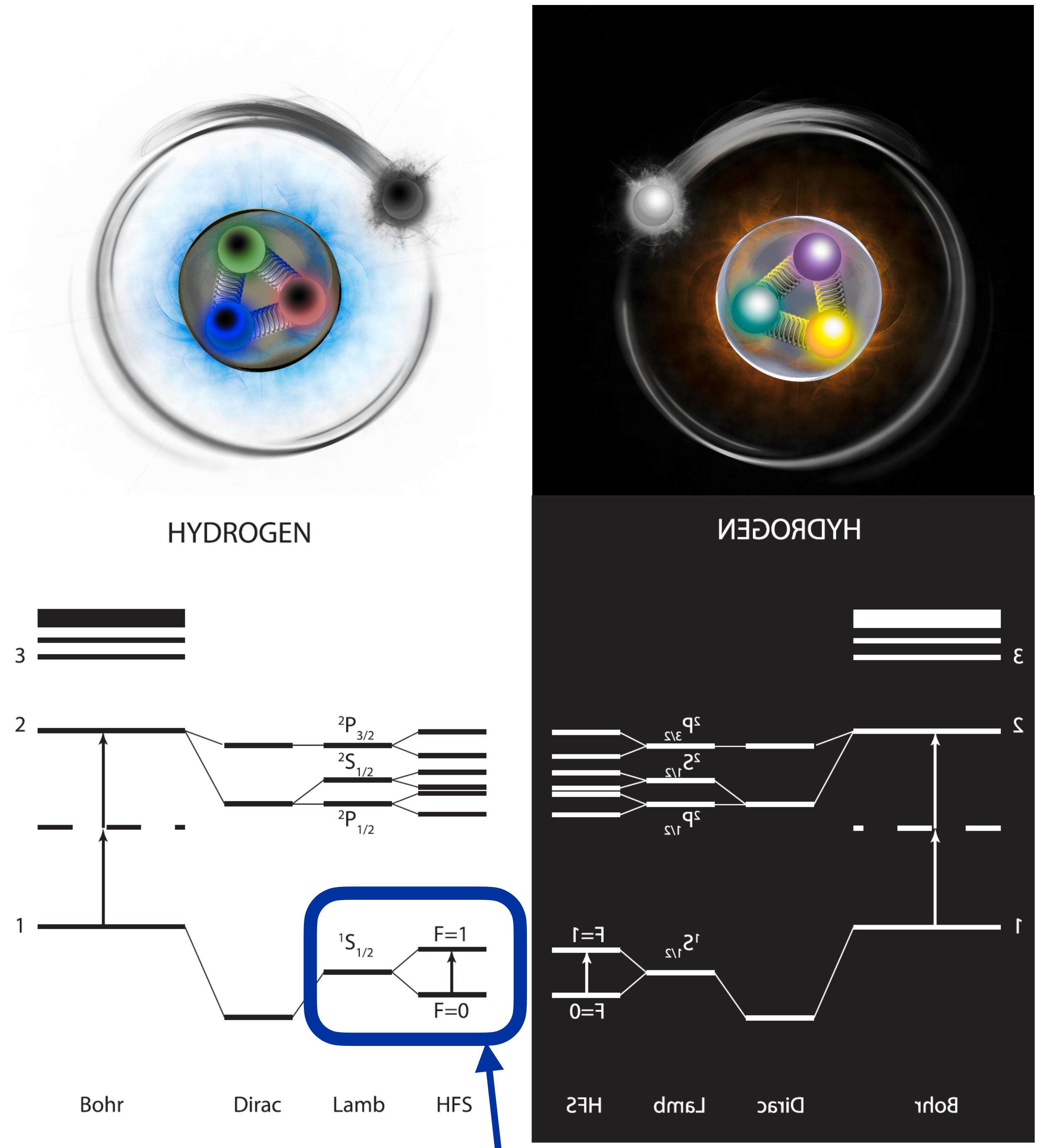
Hydrogen vs antihydrogen



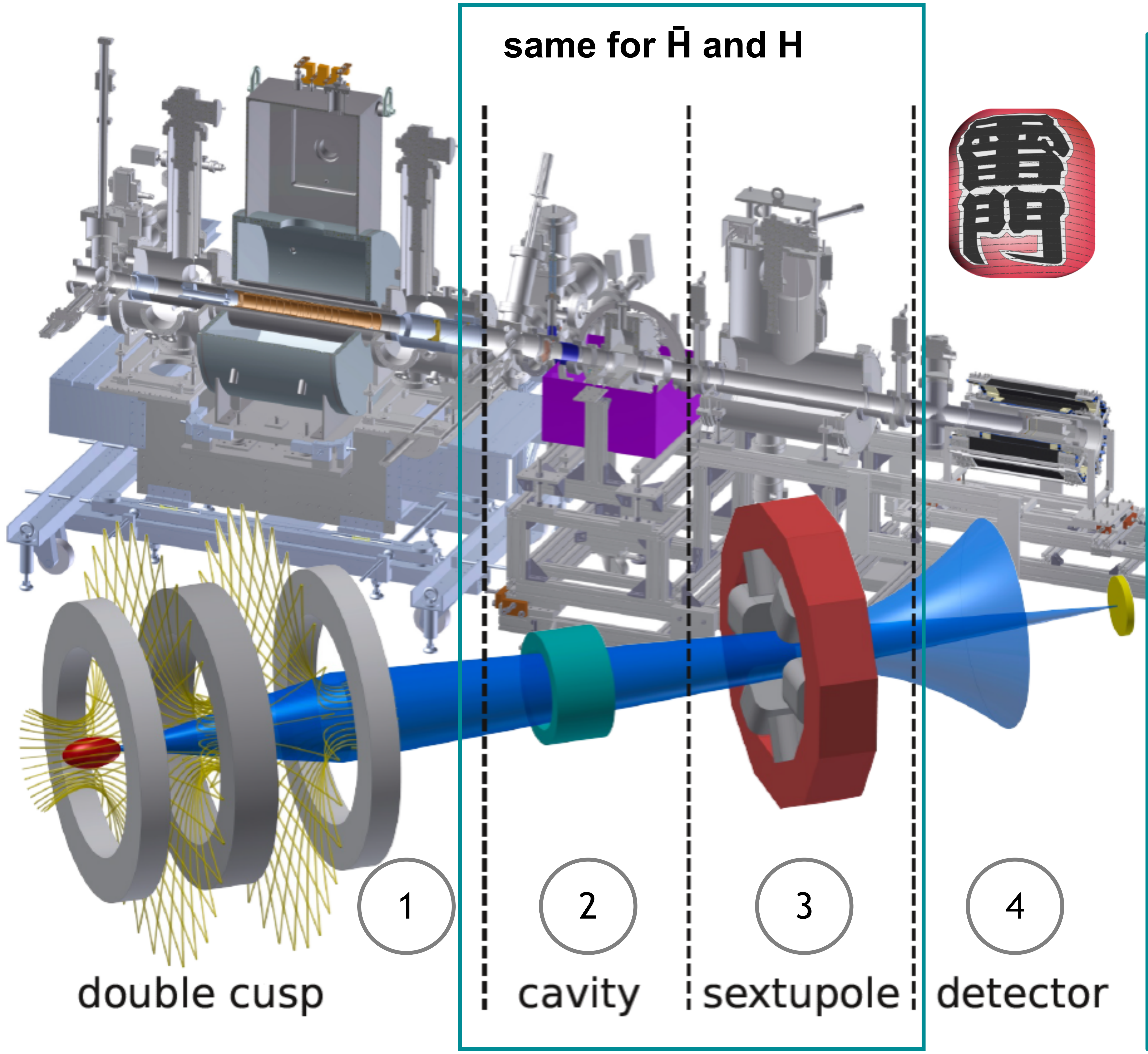
Pioneer 10 (1973)

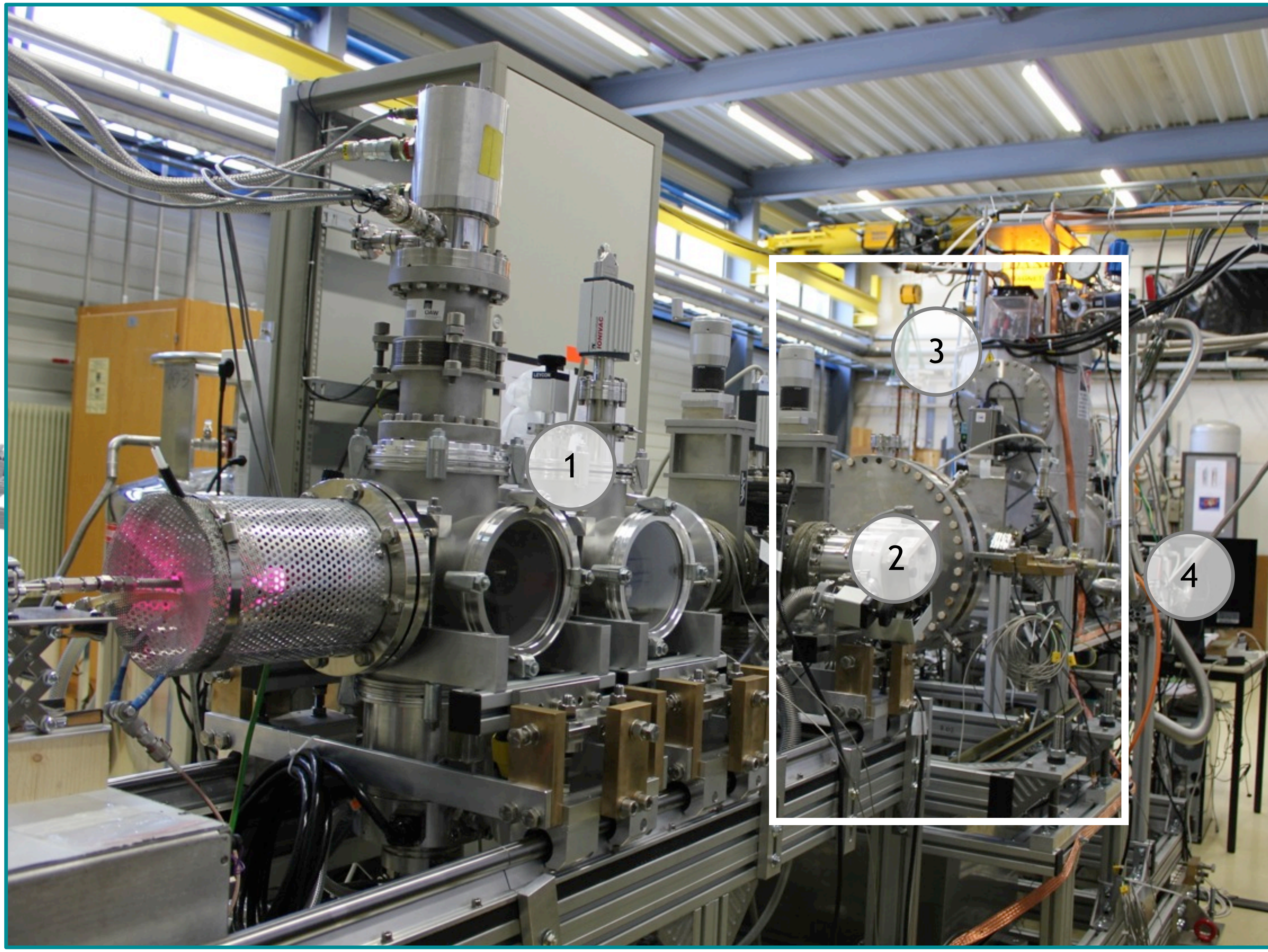


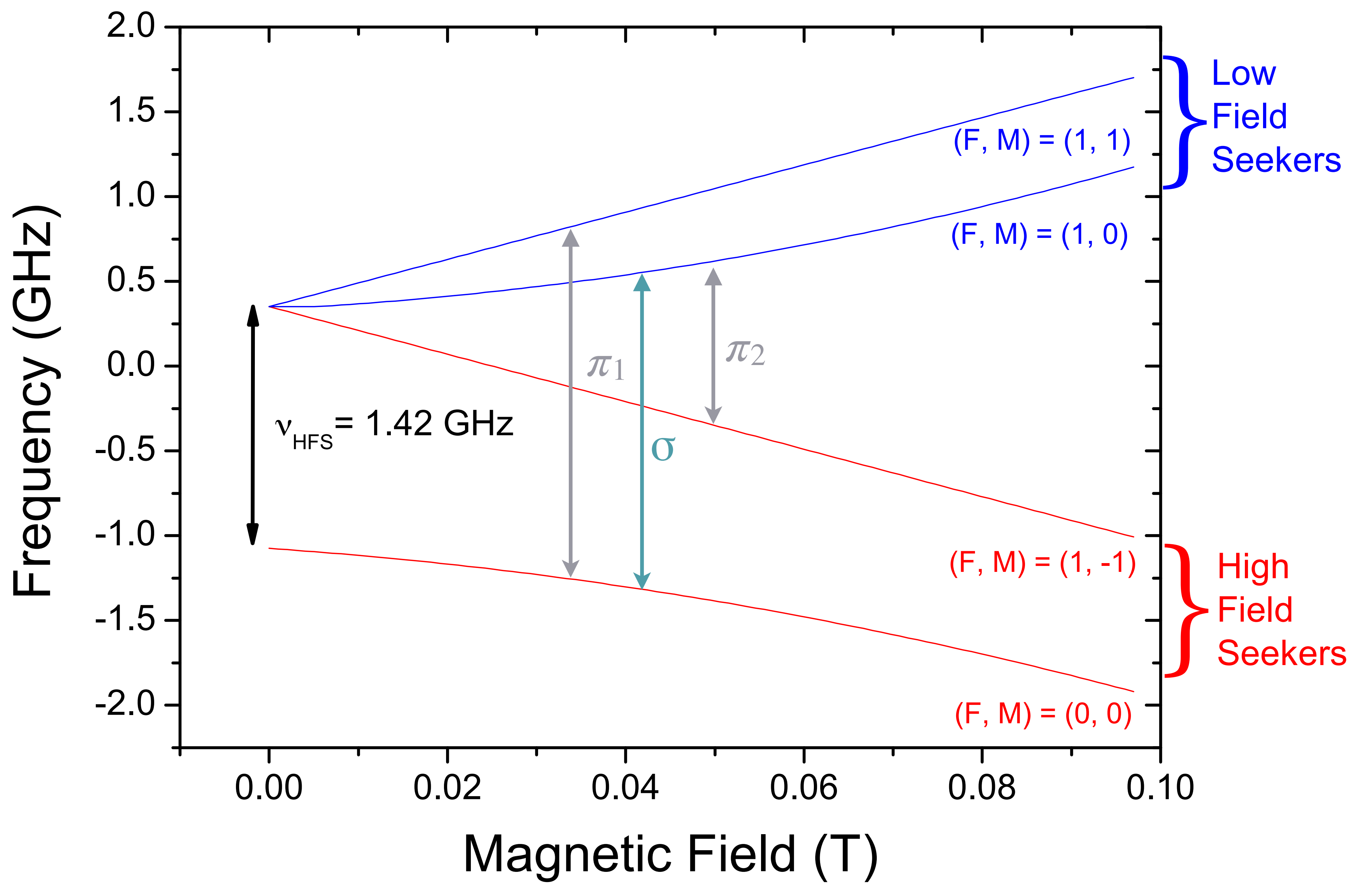


Hydrogen hyperfine splitting: highest absolute precision

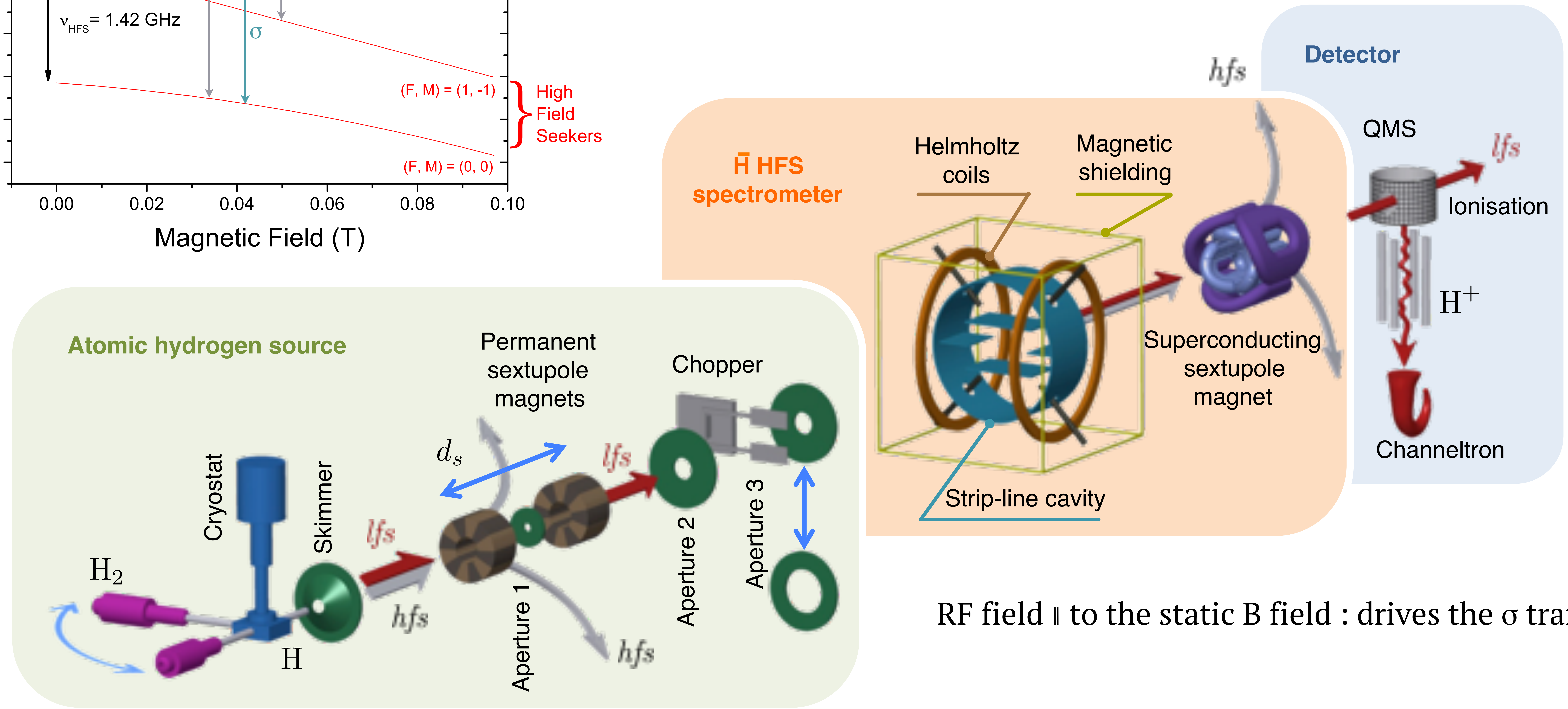
Hyperfine splitting spectrometers





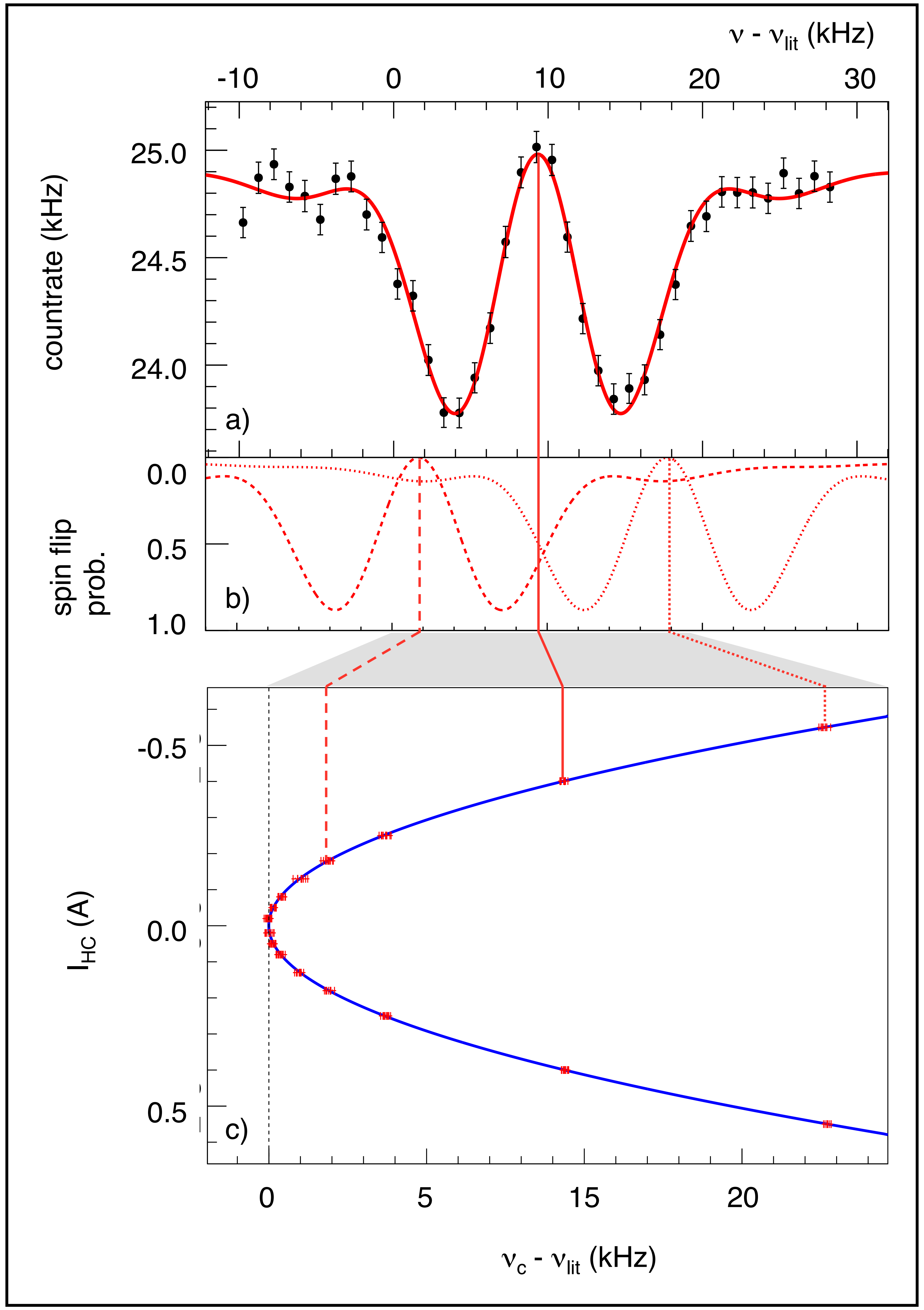


A hydrogen beam to characterize the ASACUSA antihydrogen hyperfine spectrometer
C. Malbrunot, M. Diermaier, M.C. Simon et al.
Nucl. Instrum. and Meth. in Phys. Research 935 (2019) 110



RF field ∥ to the static B field : drives the σ transition

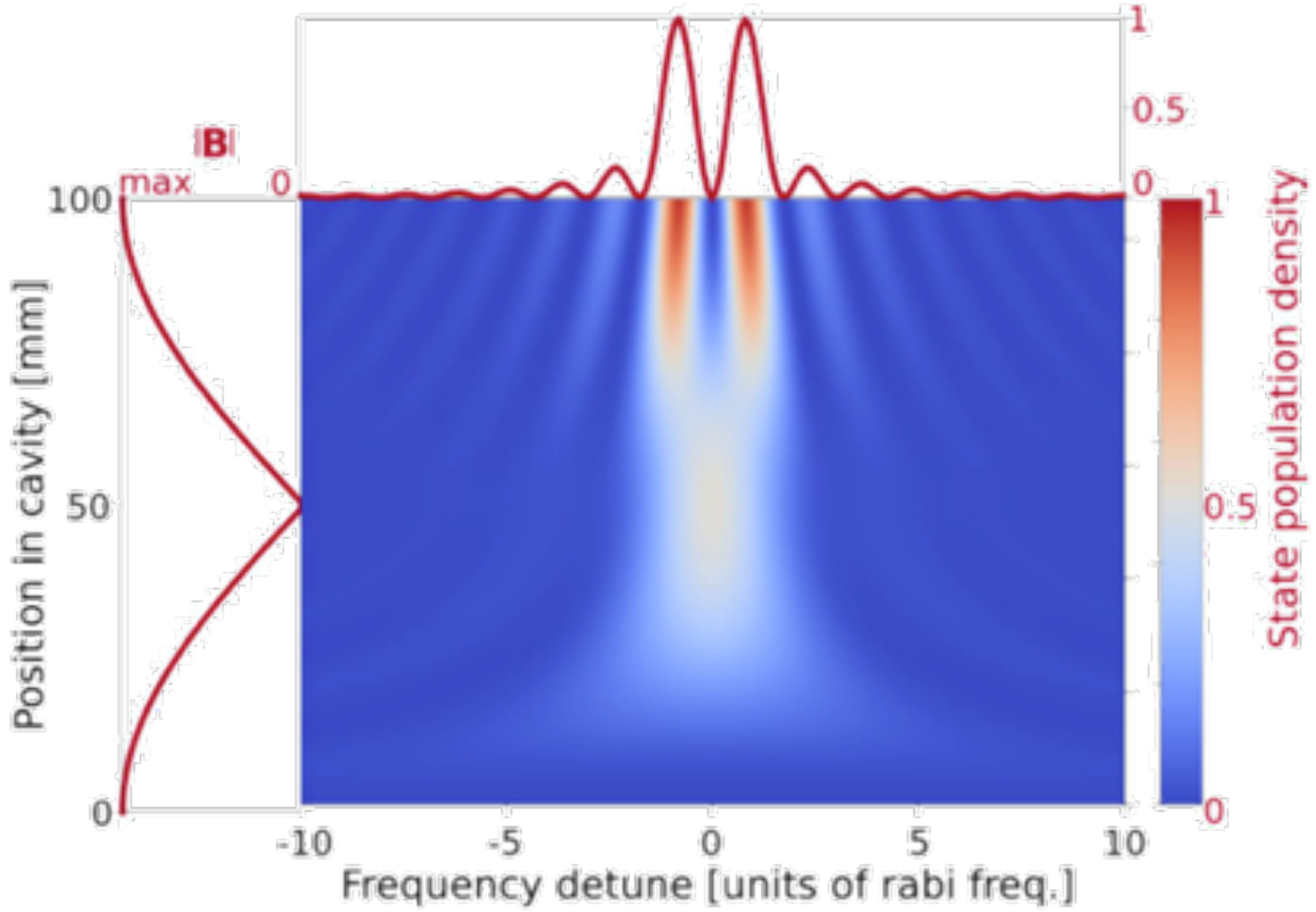
$$\nu_{\mathrm{HF}} = 1\ 420\ 405\ 748.4(3.4)(1.6)\ \mathrm{Hz}$$



$\Delta\nu/\nu = 2.7$ ppb

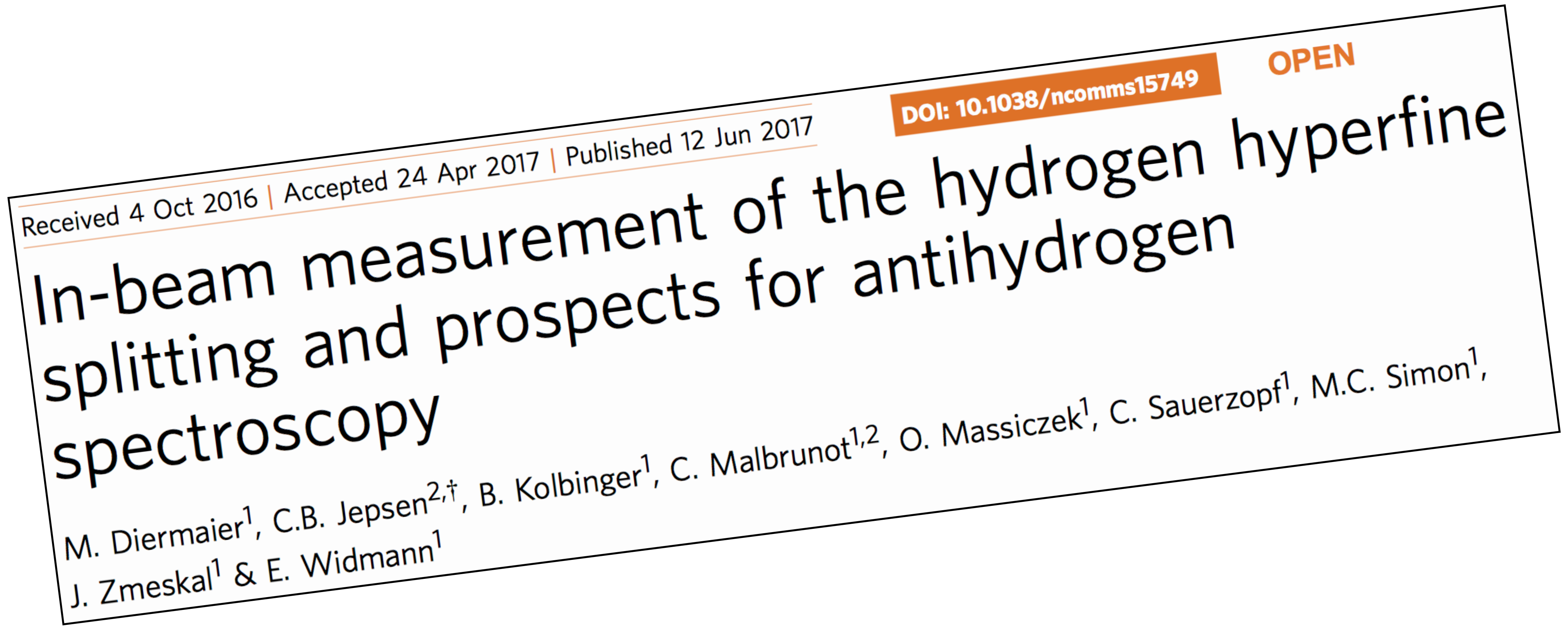
Table 2 | Error budget.

Contribution	1σ s.d. (Hz)
Systematic error	
Frequency standard	1.62
Common fit parameters	
$\bar{V}_H$	0.05
σ_V	0.03
B_{osc}	0.02
Systematic error total (σ_{sys})	1.62
Statistical error (σ_{stat})	3.43
Total error (σ_{tot})	3.79



Robust lineshape fit

Extraction of amplitude of oscillatory field, velocity and velocity spread



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]

σ measurements

ppm result with antihydrogen should be in reach if enough statistics can be gathered

line-shape dependent factor

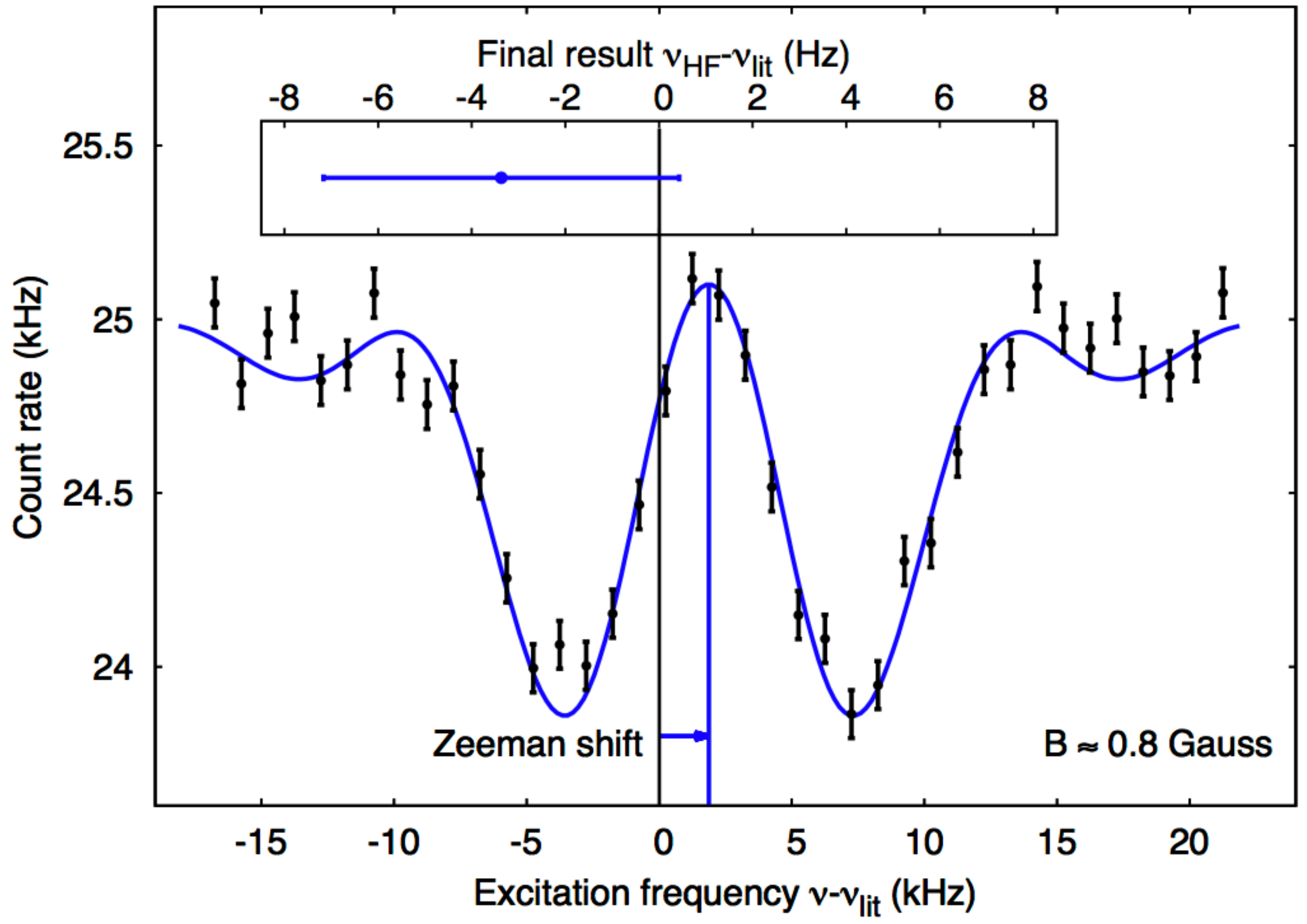
error bar of a data point

$$\delta\nu_c = \frac{C}{\varepsilon\, T_{\mathrm{int}} \sqrt{N}} \frac{\sigma_R}{\Delta R}$$

Interaction time

Number of data points

Count rate drop



Assuming background :
- 50% atoms are in excited states
- 50% of remaining are in wrong lfs state
- polarisation P=1/3

Assuming MB distribution @ 50K

$$\mathcal{P} = \frac{f_{\mathrm{LFS}} - f_{\mathrm{HFS}}}{f_{\mathrm{LFS}} + f_{\mathrm{HFS}}}$$

For ppm measurement using 4 resonances we estimate ~ 8000 atoms should be recorded at the $\bar{\mathrm{H}}$ detector

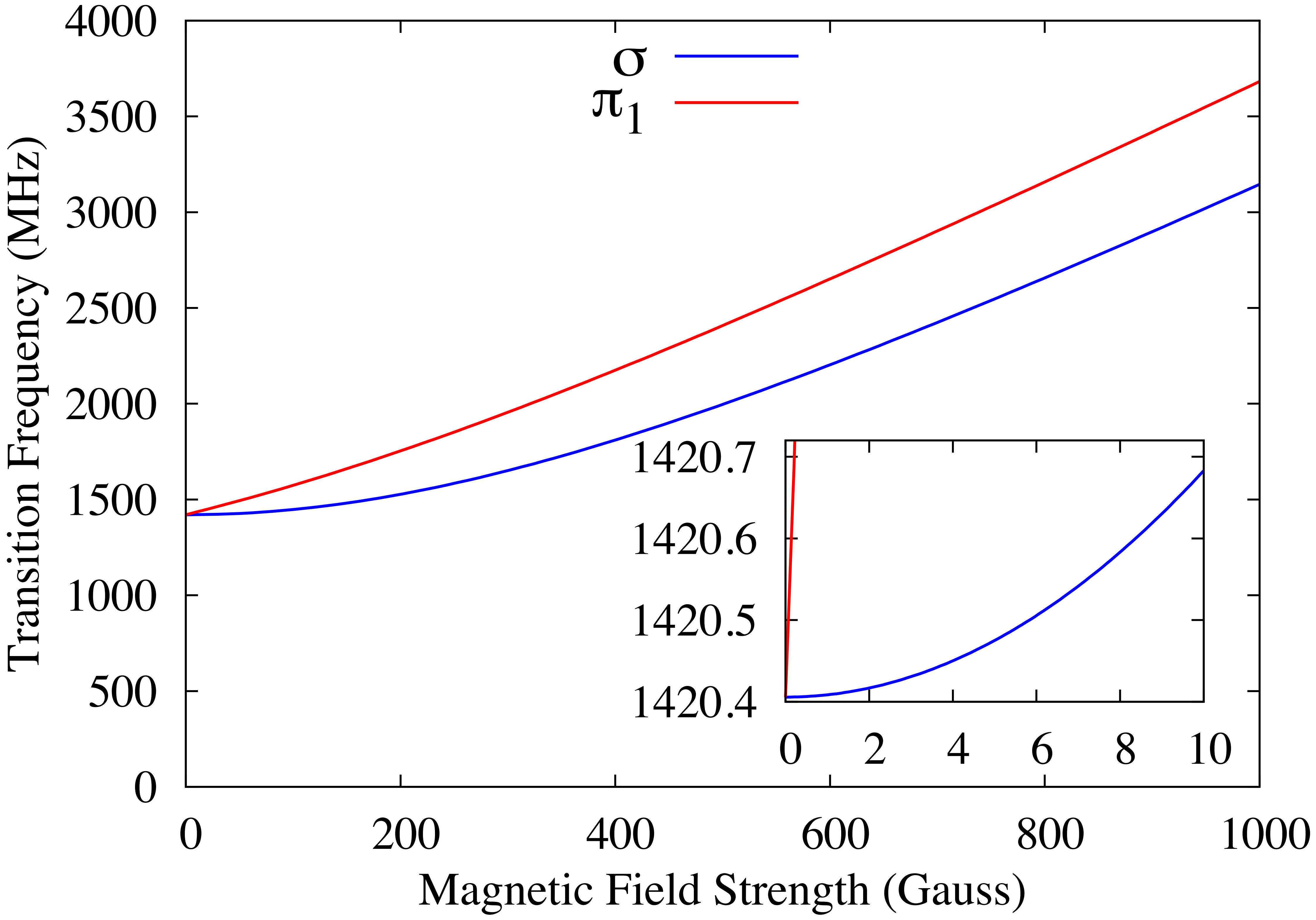
π measurements

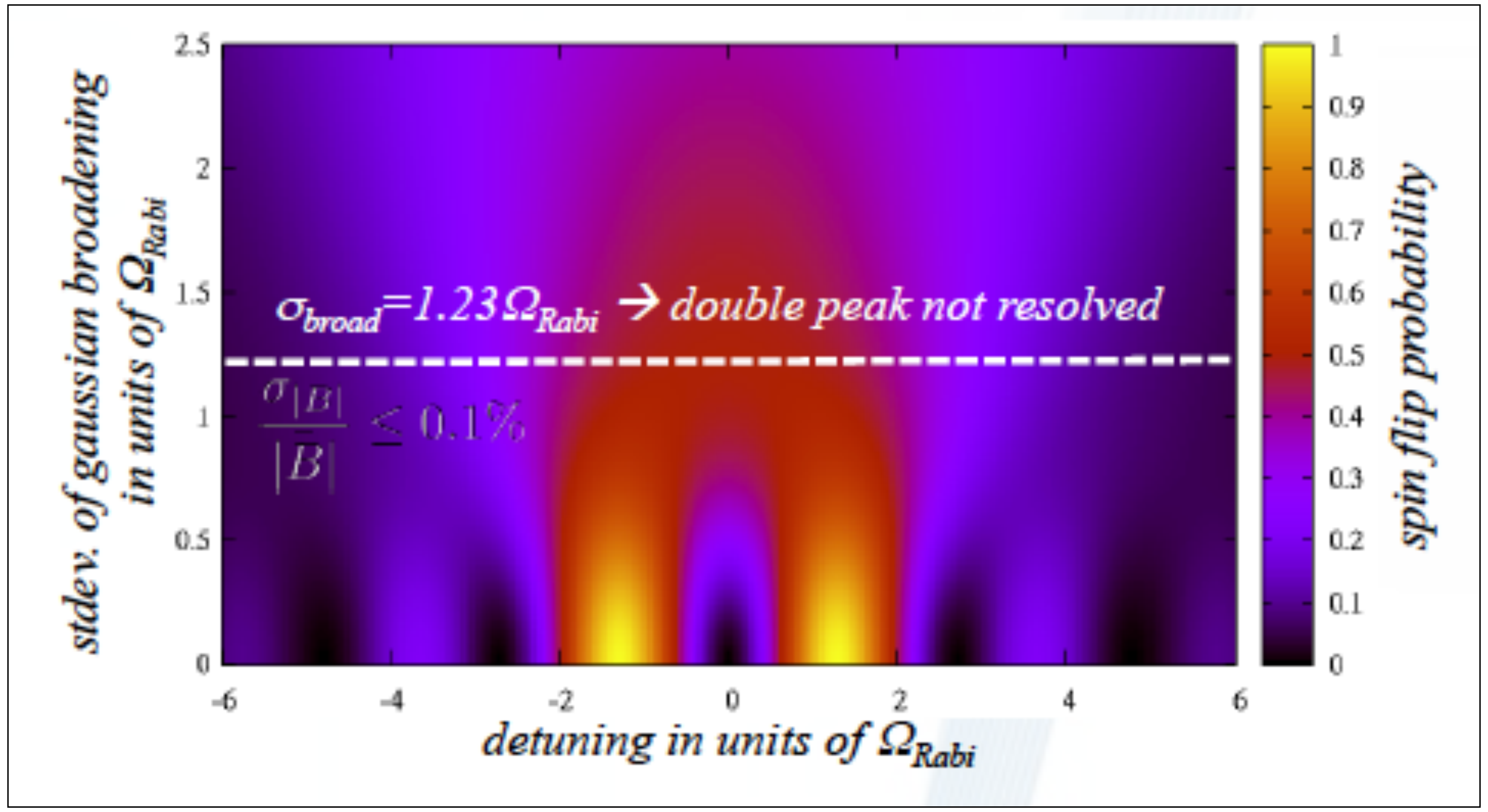
Other possibility :

Measure π_1 & σ_1 at the same field : 2 resonances needed

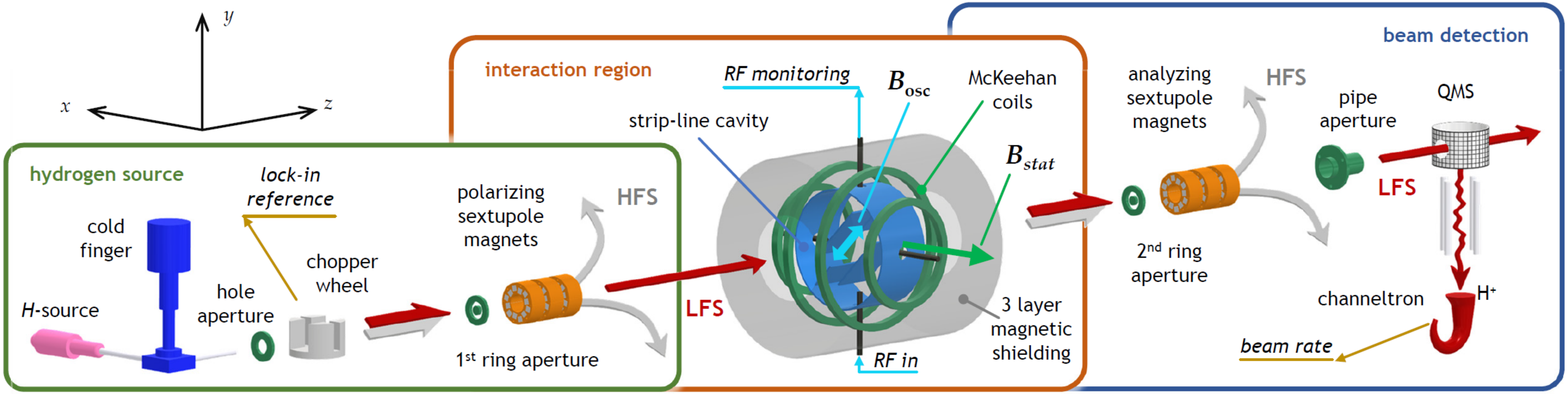
Advantage : π_1 is sensitive to SME coefficients

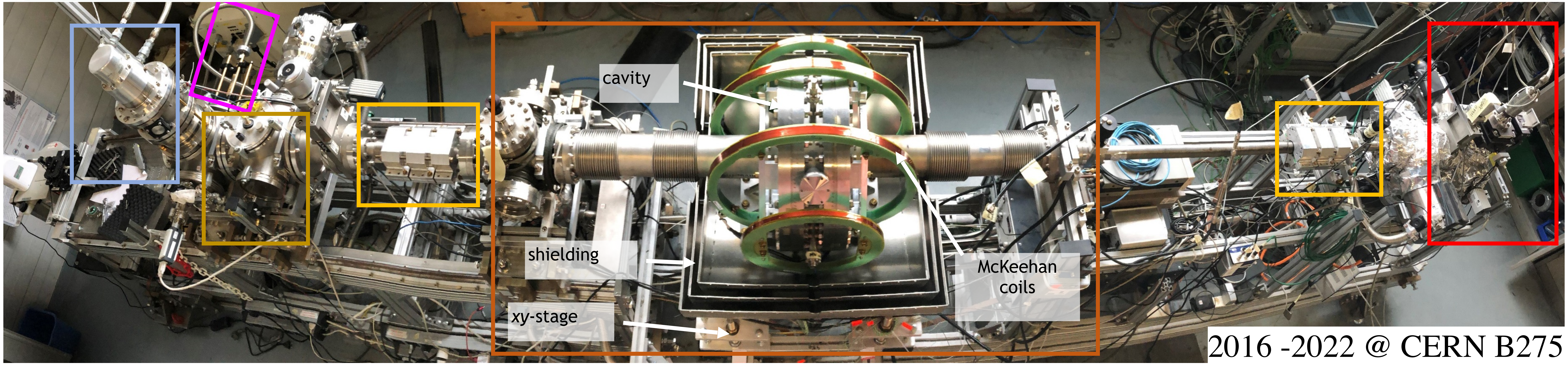
BUT π_1 more sensitive to magnetic field inhomogeneities





π measurements





2016 -2022 @ CERN B275

SME measurements

Siderial variations constrained by Harvard-Smithsonian maser at mHz level (constrain on the proton coefficients at the 2×10^{-27} GeV level)

$$\mathcal{K}^{Lab}_{\mathcal{W}k10} = \mathcal{K}^{Sun}_{\mathcal{W}k10}\cos(\theta) - \sqrt{2}\,\mathfrak{Re}\left(\mathcal{K}^{Sun}_{\mathcal{W}k11}\right)\sin(\theta)\cos(\omega_\oplus T_\oplus) + \sqrt{2}\,\mathfrak{Im}\left(\mathcal{K}^{Sun}_{\mathcal{W}k11}\right)\sin(\theta)\sin(\omega_\oplus T_\oplus)$$

V A Kostelecky and A J Vargas, *PRD* **92** 056002 (2015)

Angle between B-field and Earth's rotational axis

Earth rotation frequency

sidereal time

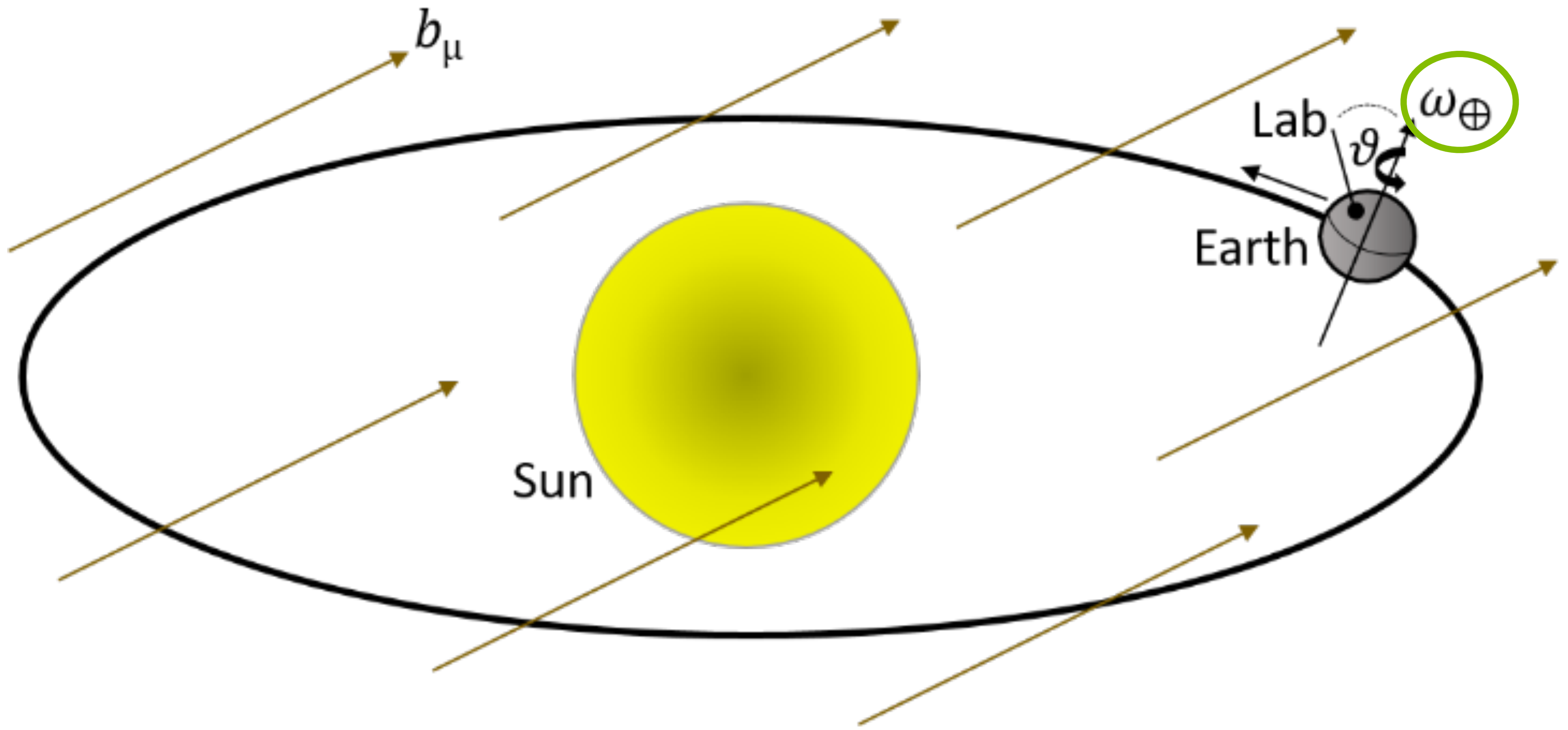
72 SME coefficients involved. 48 constrained, **24 remaining** and can be constrained by swapping the direction of the static B-field

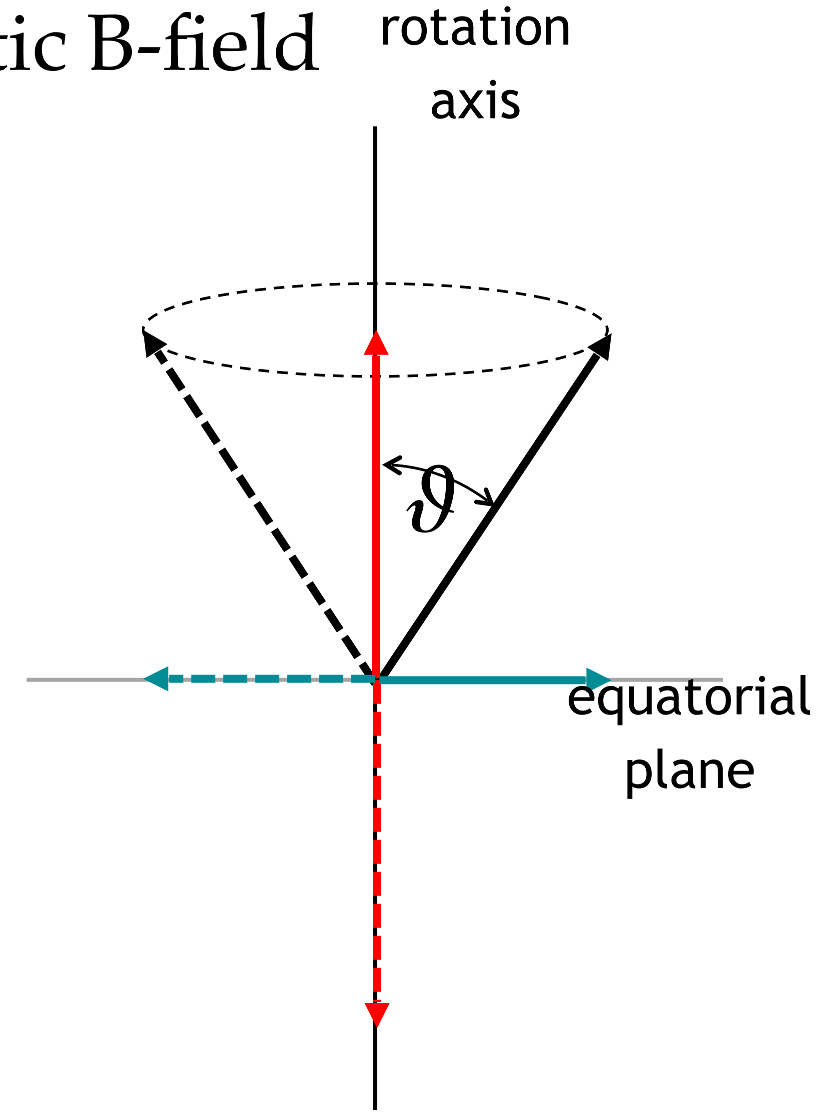
Principle: compare π transition in B-fields of same strength, but opposite polarity

Challenge: B-field determination

Approach: Use σ transition ($\Delta M_F = 0$) for independent B-field measurement

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





Limit of B ➛ 0

CPT odd

$$2\pi\delta\nu(\Delta M_F) = \frac{\Delta M_F}{2\sqrt{3\pi}} \sum_{q=0}^{2} \alpha m_r^{2q}(1 + 4\delta_{q2}) \times \sum_{\mathcal{W}} [-g^{0B}_{\mathcal{W}(2q)10} + H^{0B}_{\mathcal{W}(2q)10} - 2g^{1B}_{\mathcal{W}(2q)10} + H^{1B}_{\mathcal{W}(2q)10}]$$

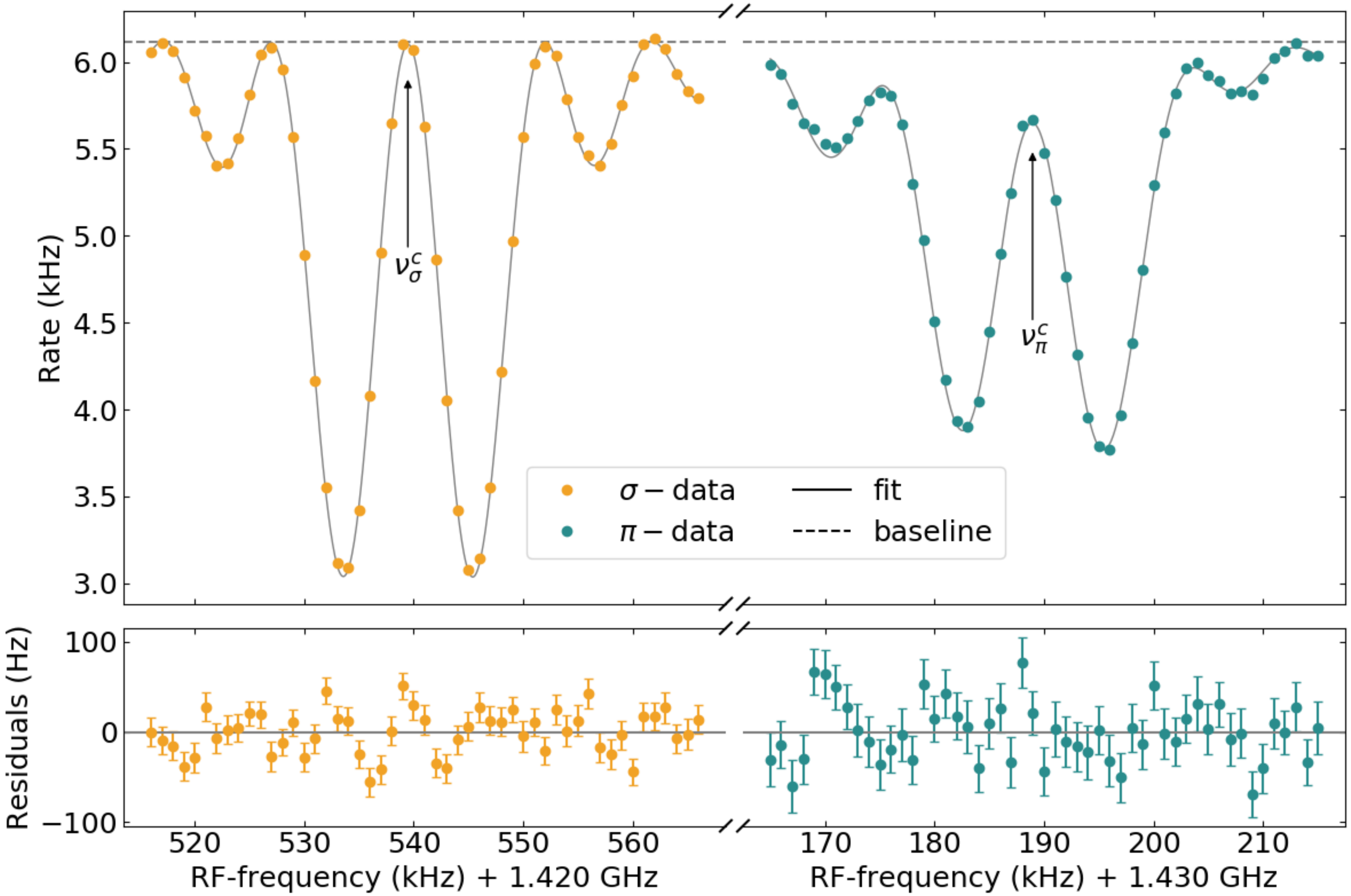
CPT even

SME measurements

Example of a σ–π pair :
-0.68 mT (-3 A)

σ–π pair data:

- Successively recorded
- σ: 45min
- π: 15min
- Polarisation close to 50:50



SME measurements

Example of a σ–π pair :
-0.68 mT (-3 A)

σ–π pair data:

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- σ: 45min
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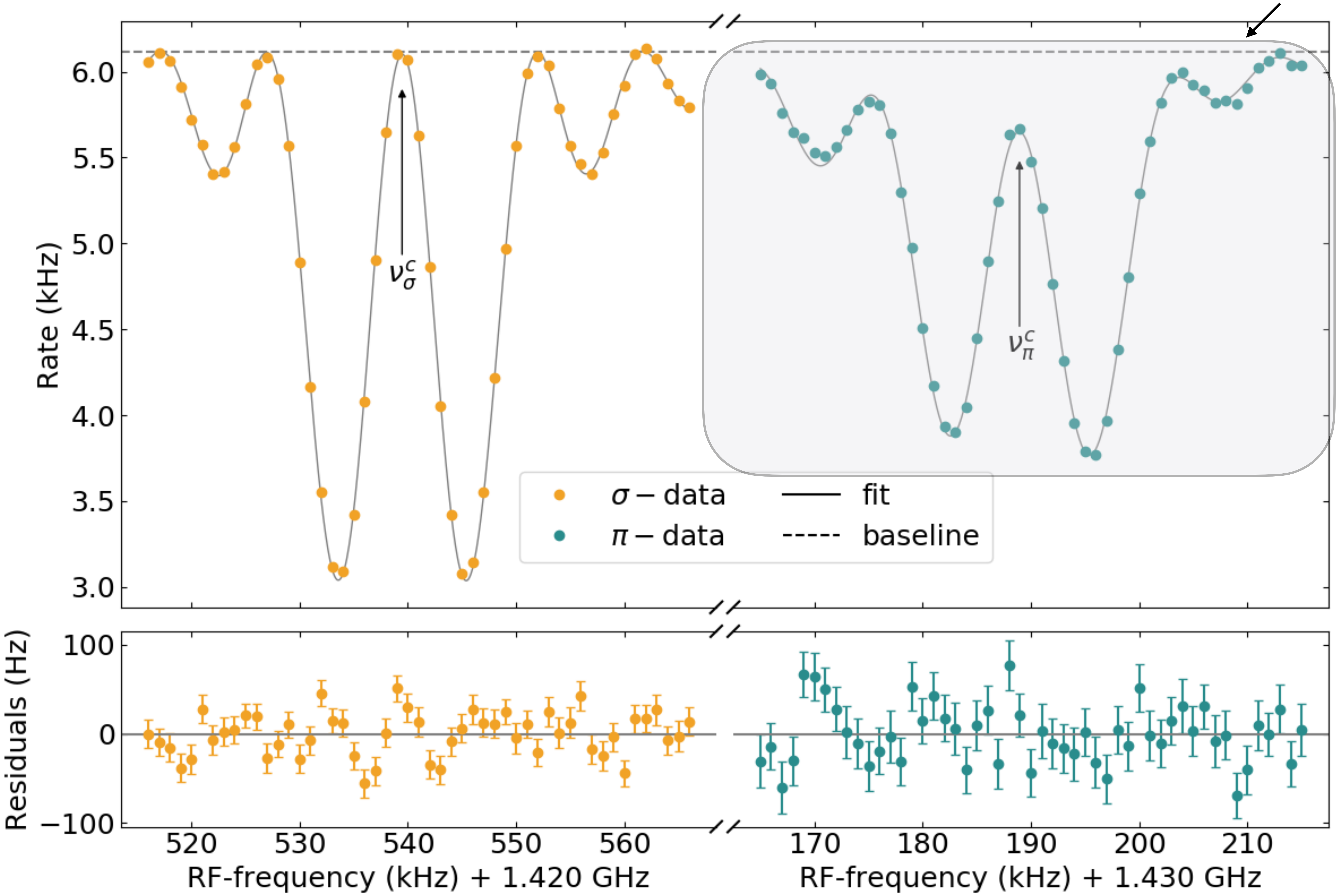
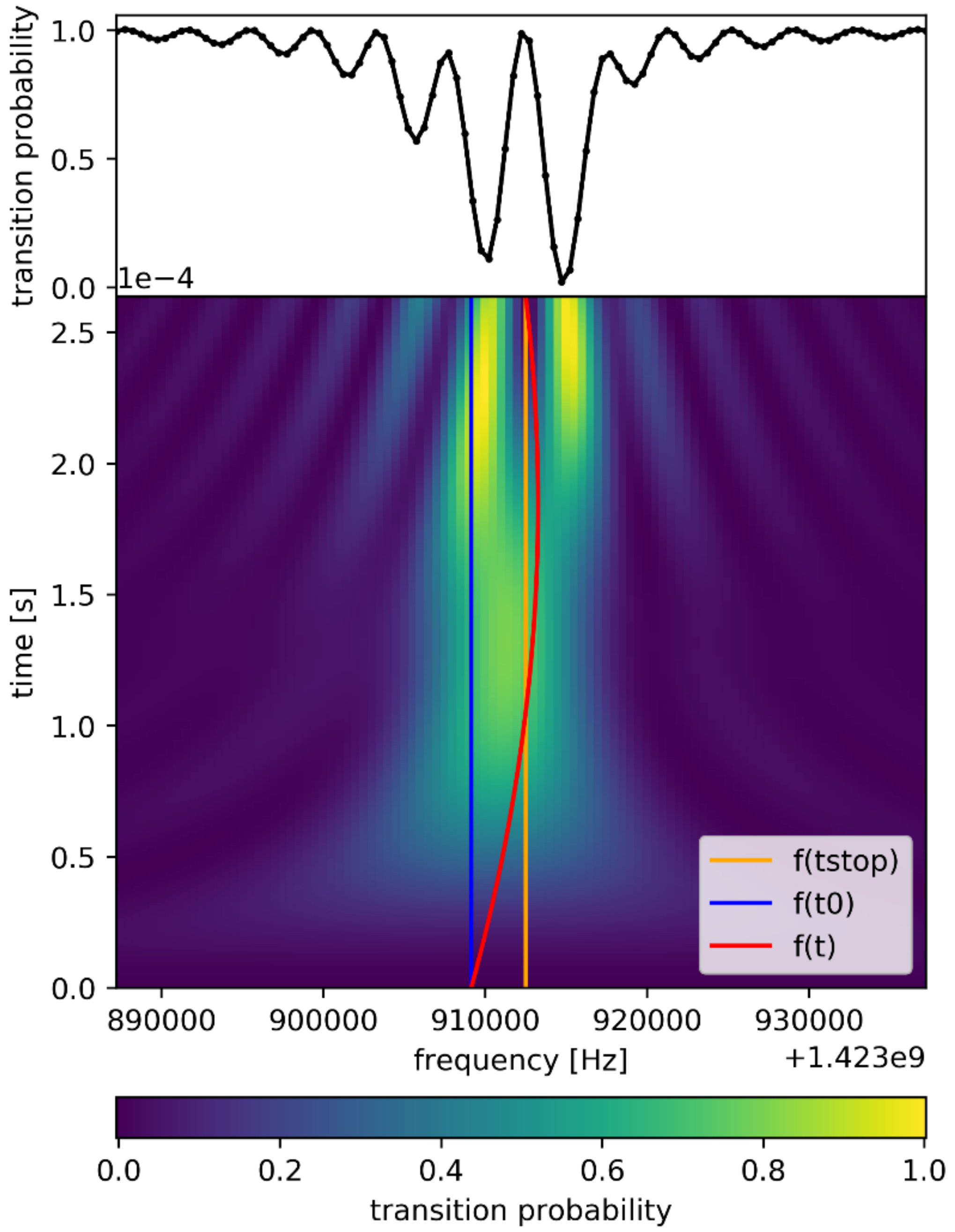
Effect of static B field inhomogeneities

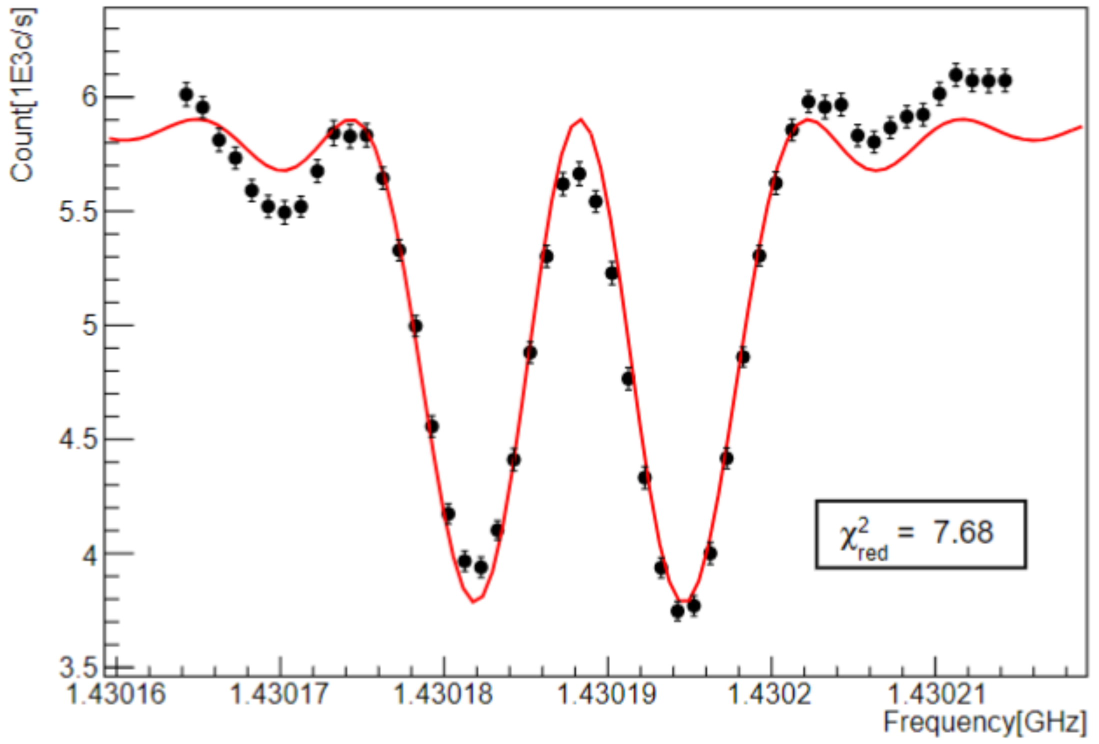


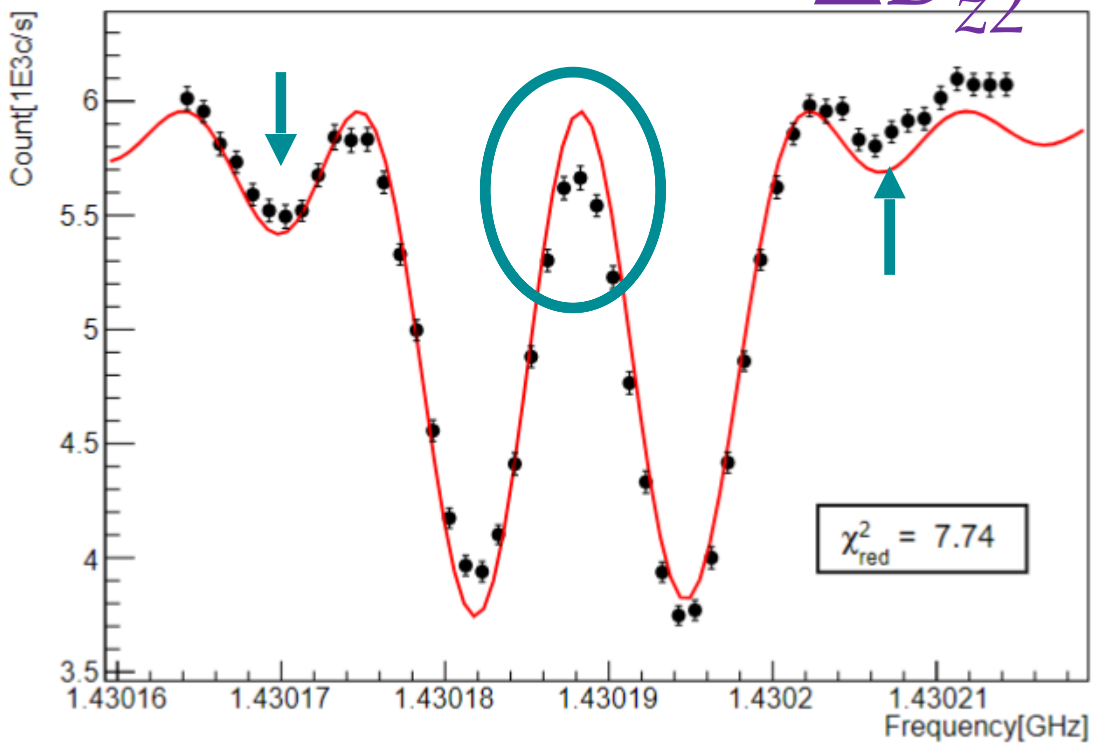
Effect of B field inhomogeneities



Inclusion of a B field inhomogeneity in the direction of propagation of the atoms

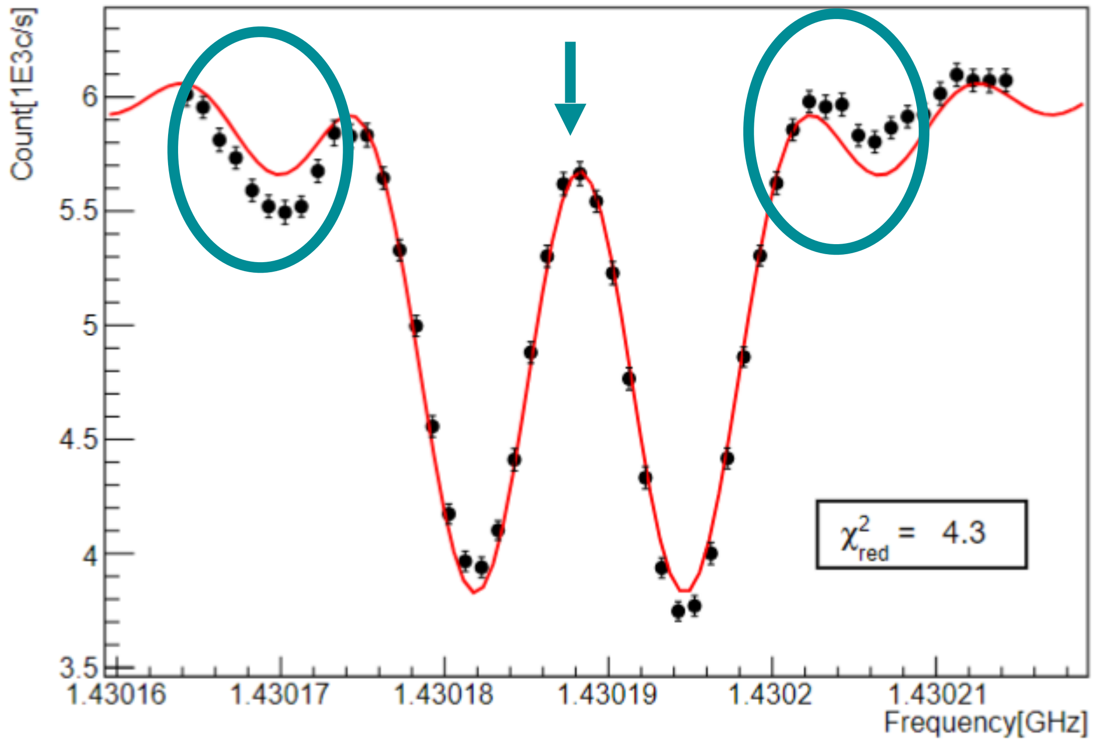
ΔB_{z2}

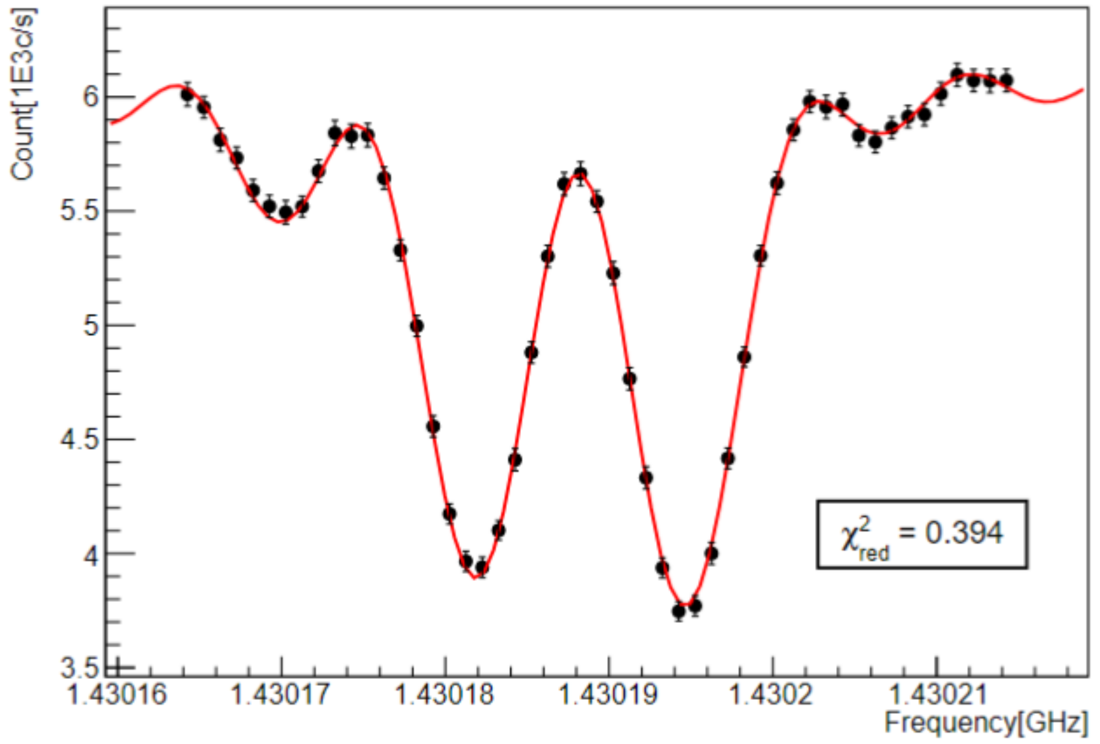




$\Delta\nu_{xy}$

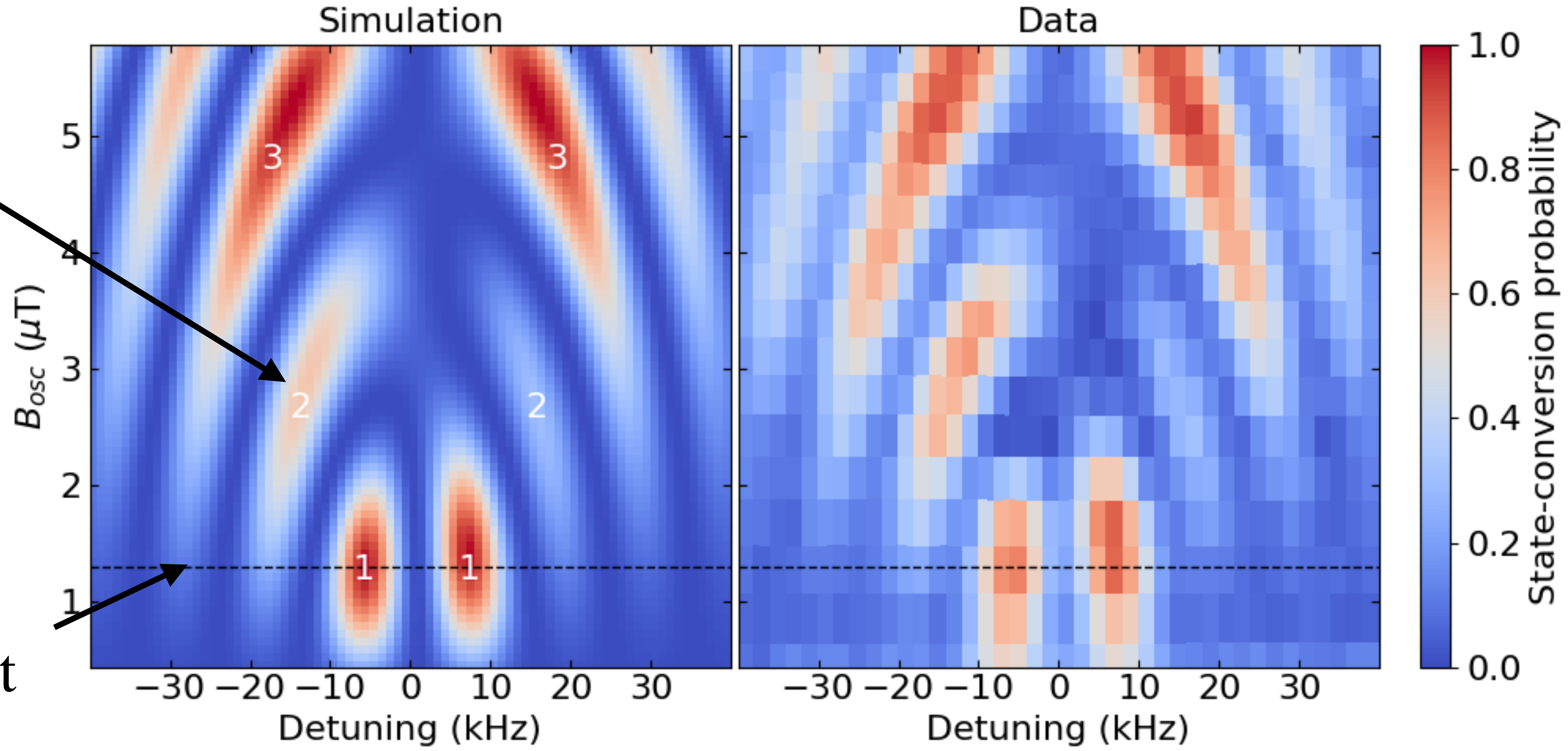
$\Delta\nu_{xy}$ & ΔB_{z2}



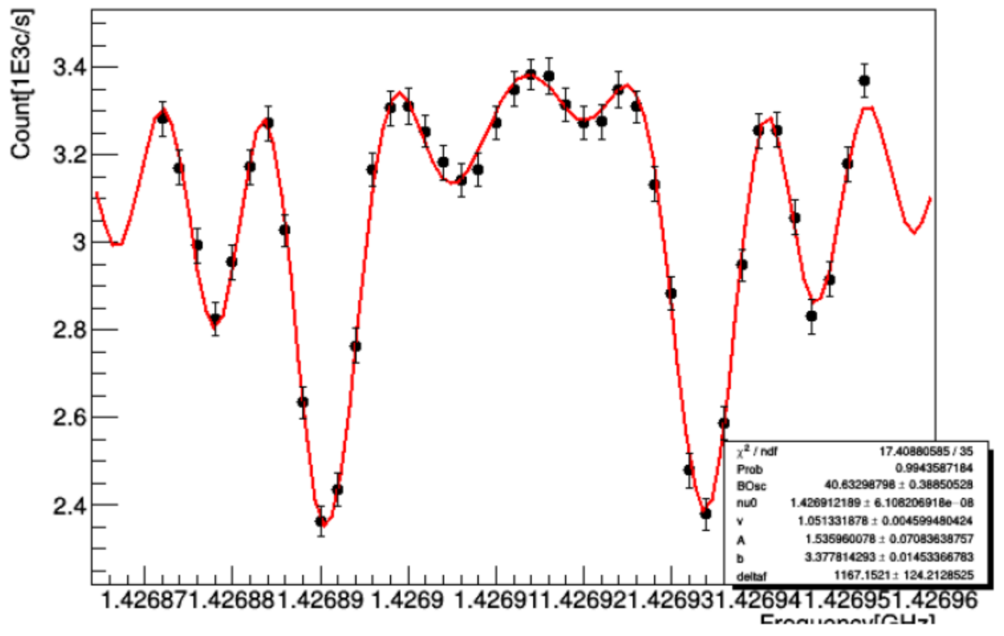


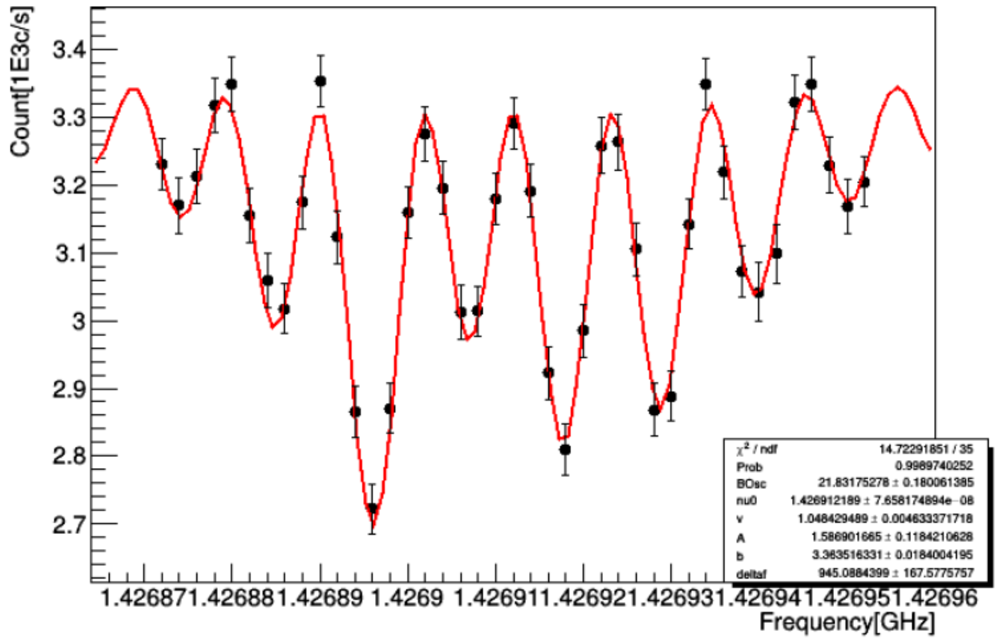
example at -3A

High B field sensitivity at second conversion

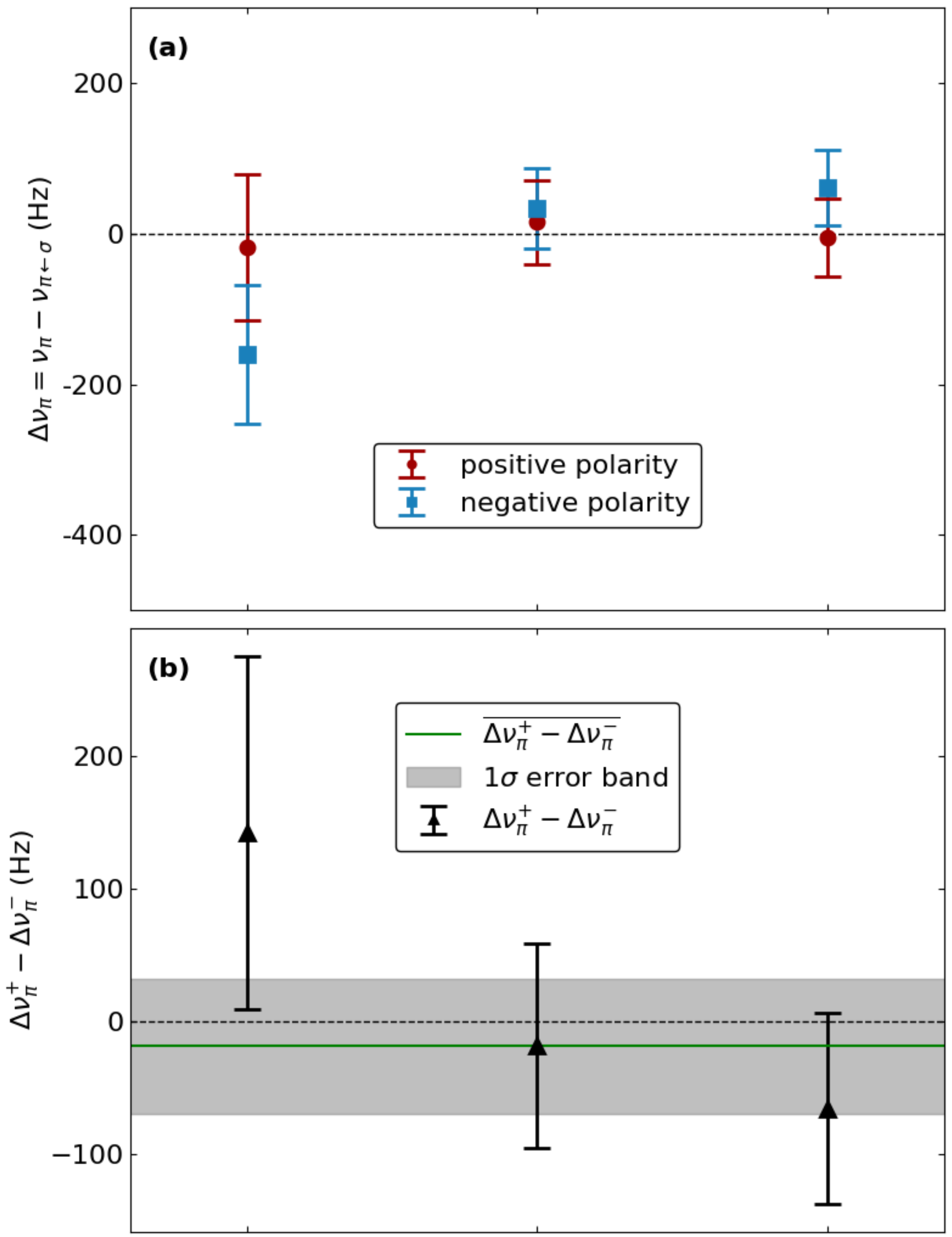


σ−π pairs taken at first conversion





SME Results



CPT and Lorentz symmetry tests with hydrogen using a novel in-beam hyperfine spectroscopy method applicable to antihydrogen experiments
L. Nowak, C. Malbrunot, M.C. Simon et al
Phys. Lett. B 858 (2024) 139012

Blind analysis

Figure of merit- double differential:

$$(\nu_\pi - \nu_{\pi(\sigma)})_{pos} - (\nu_\pi - \nu_{\pi(\sigma)})_{neg}$$

The determination of π using σ ($\nu_{\pi(\sigma)}$) blows up the error bars

and lead to different sensitivity to proton versus electron coefficients

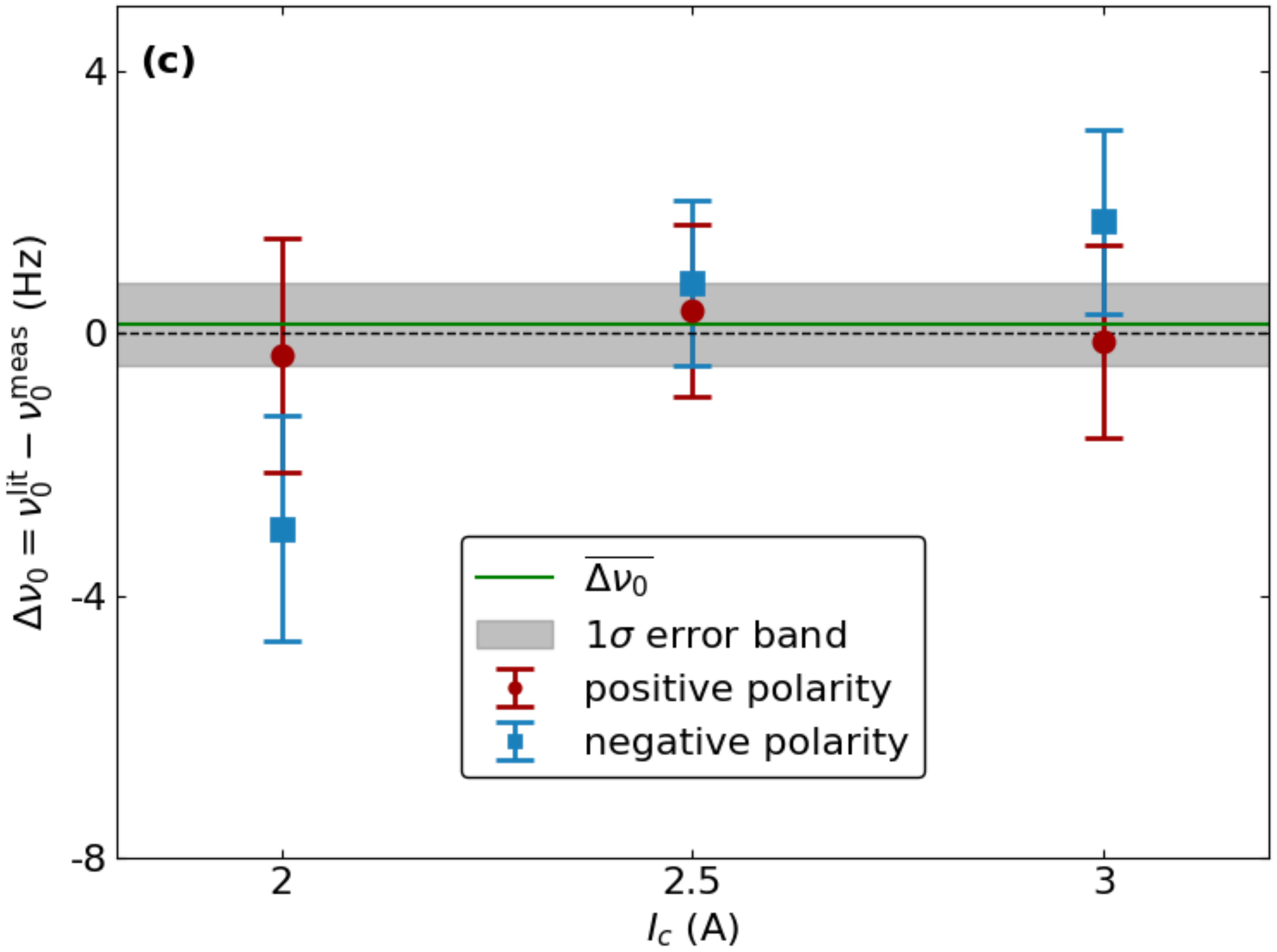
$$\Delta\nu_\pi^+ - \Delta\nu_\pi^- = (-19 \pm 51)\ \text{Hz}$$

Constraints on individual combination of coefficients can be obtained by assuming all others are null

I_c	2.0 A		2.5 A		3.0 A	
B_{stat}	0.46 mT		0.57 mT		0.68 mT	
$\partial\nu_\pi/\partial\nu_\sigma$	55.0		44.1		36.8	
# pairs +/−	56 / 55		121 / 120		93 / 92	
errors (Hz)	stat.	sys.	stat.	sys.	stat.	sys.
ν_σ^+	1.75	0.14	1.26	0.20	1.40	0.22
ν_π^+	2.37	$^{+3.19}_{-4.25}$	1.69	$^{+3.25}_{-4.30}$	2.11	$^{+3.26}_{-4.31}$
$\nu_{\pi\leftarrow\sigma}^+$	96.3	7.70	55.7	8.82	51.7	8.10
$\Delta\nu_\pi^+$	96.4	$^{+8.33}_{-8.79}$	55.8	$^{+9.40}_{-9.81}$	51.8	$^{+8.73}_{-9.18}$
ν_σ^-	1.67	0.19	1.21	0.23	1.35	0.21
ν_π^-	2.93	$^{+3.18}_{-3.66}$	2.19	$^{+3.34}_{-3.80}$	2.69	$^{+3.38}_{-3.84}$
$\nu_{\pi\leftarrow\sigma}^-$	91.9	10.5	53.1	10.1	49.7	7.73
$\Delta\nu_\pi^-$	92.0	$^{+10.9}_{-11.1}$	53.2	$^{+10.7}_{-10.8}$	49.8	$^{+8.44}_{-8.64}$
$\Delta\nu_\pi^+ - \Delta\nu_\pi^-$	133	$^{+13.7}_{-14.1}$	77.1	$^{+14.2}_{-14.6}$	71.8	$^{+12.2}_{-12.6}$

Coefficient $\mathcal{K}$	Constraint on $\lvert\mathcal{K}\rvert$
proton	
$H_{p010}^{NR(0B),Sun}$, $g_{p010}^{NR(0B),Sun}$	$< 1.2 \times 10^{-21}$ GeV
$H_{p010}^{NR(1B),Sun}$, $g_{p010}^{NR(1B),Sun}$	$< 5.8 \times 10^{-22}$ GeV
$H_{p210}^{NR(0B),Sun}$, $g_{p210}^{NR(0B),Sun}$	$< 8.4 \times 10^{-11}$ GeV^{-1}
$H_{p210}^{NR(1B),Sun}$, $g_{p210}^{NR(1B),Sun}$	$< 4.2 \times 10^{-11}$ GeV^{-1}
$H_{p410}^{NR(0B),Sun}$, $g_{p410}^{NR(0B),Sun}$	< 1.2 GeV^{-3}
$H_{p410}^{NR(1B),Sun}$, $g_{p410}^{NR(1B),Sun}$	< 0.6 GeV^{-3}
electron	
$H_{e010}^{NR(0B),Sun}$, $g_{e010}^{NR(0B),Sun}$	$< 7.7 \times 10^{-19}$ GeV
$H_{e010}^{NR(1B),Sun}$, $g_{e010}^{NR(1B),Sun}$	$< 3.8 \times 10^{-19}$ GeV
$H_{e210}^{NR(0B),Sun}$, $g_{e210}^{NR(0B),Sun}$	$< 5.5 \times 10^{-8}$ GeV^{-1}
$H_{e210}^{NR(1B),Sun}$, $g_{e210}^{NR(1B),Sun}$	$< 2.8 \times 10^{-8}$ GeV^{-1}
$H_{e410}^{NR(0B),Sun}$, $g_{e410}^{NR(0B),Sun}$	$< 8.0 \times 10^{2}$ GeV^{-3}
$H_{e410}^{NR(1B),Sun}$, $g_{e410}^{NR(1B),Sun}$	$< 4.0 \times 10^{2}$ GeV^{-3}

New hyperfine splitting determination



$$\nu_\sigma(B_{stat}) = \sqrt{\nu_0^2 + \left(\frac{\mu_B g_+ B_{stat}}{h}\right)^2},$$

$$\nu_\pi(B_{stat}) = \frac{1}{2}\left(\nu_0 + \frac{\mu_B g_- B_{stat}}{h} + \sqrt{\nu_0^2 + \left(\frac{\mu_B g_+ B_{stat}}{h}\right)^2}\right),$$

$$\nu_0^{meas} = \frac{g_+^2(2\nu_\pi^c - \nu_\sigma^c) + g_- \sqrt{g_-^2(\nu_\sigma^c)^2 - 4g_+^2(\nu_\pi^c)^2 + 4g_+^2\nu_\pi^c\nu_\sigma^c}}{g_+^2 + g_-^2}.$$

with $g_\pm = |g_e| \pm g_p m_e/m_p$

$$\nu_0^{meas} = 1.420\ 405\ 751\ 63(63)\ \text{GHz}$$

$$\nu_0^{lit} - \nu_0^{meas} = 0.14 \pm 0.59(stat) \pm 0.23(sys)$$

New best ν_0 determination for hydrogen HFS in a beam

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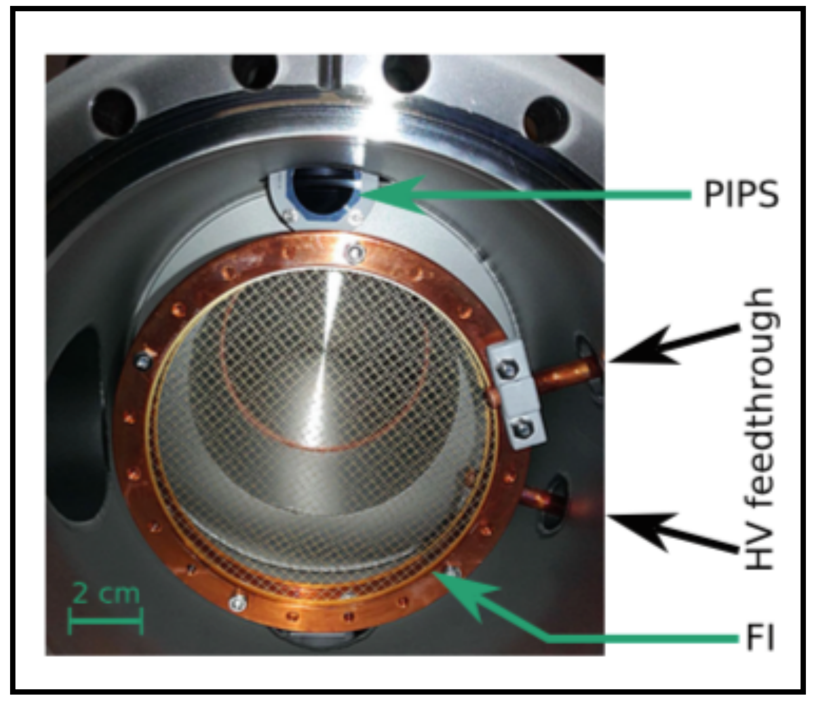
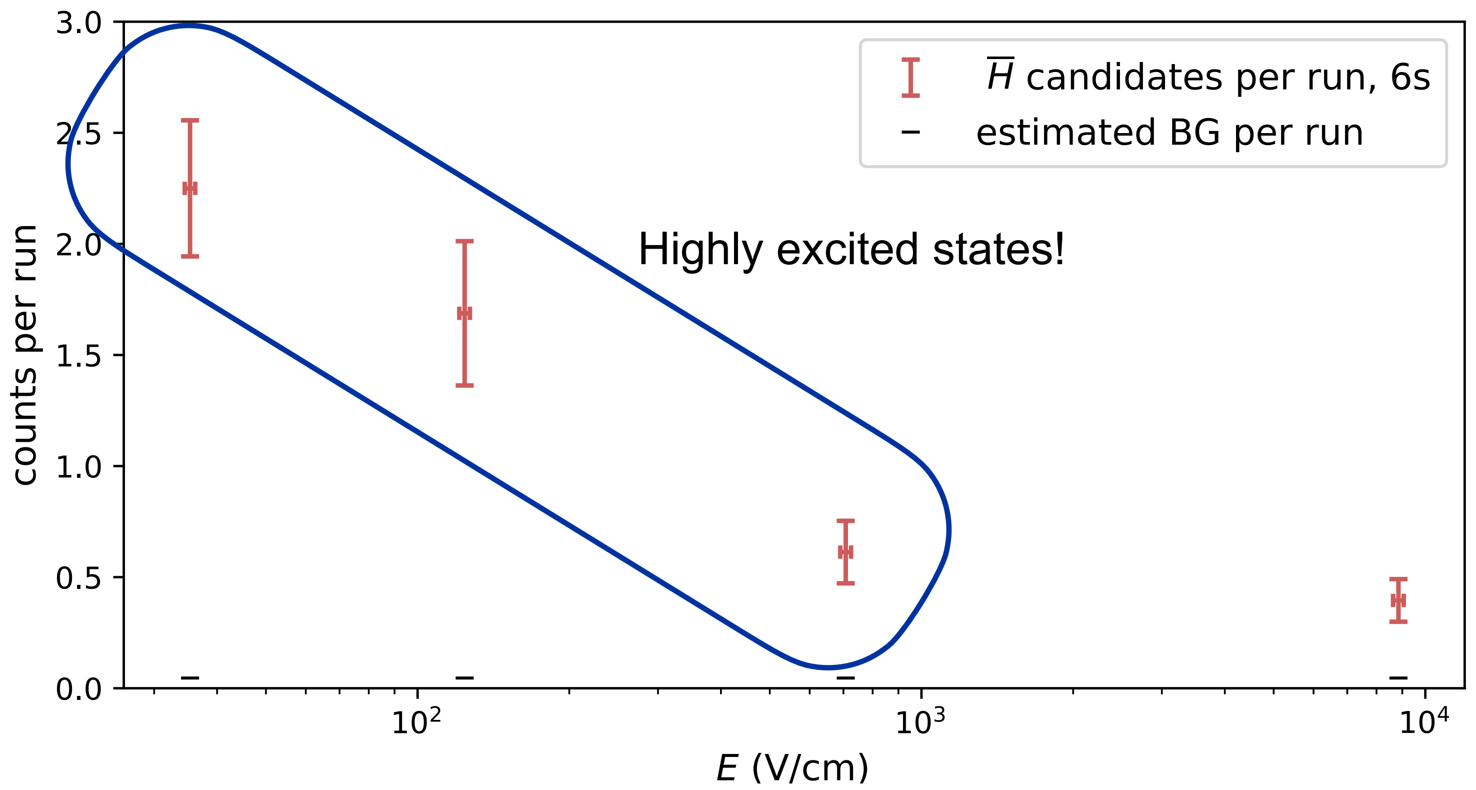
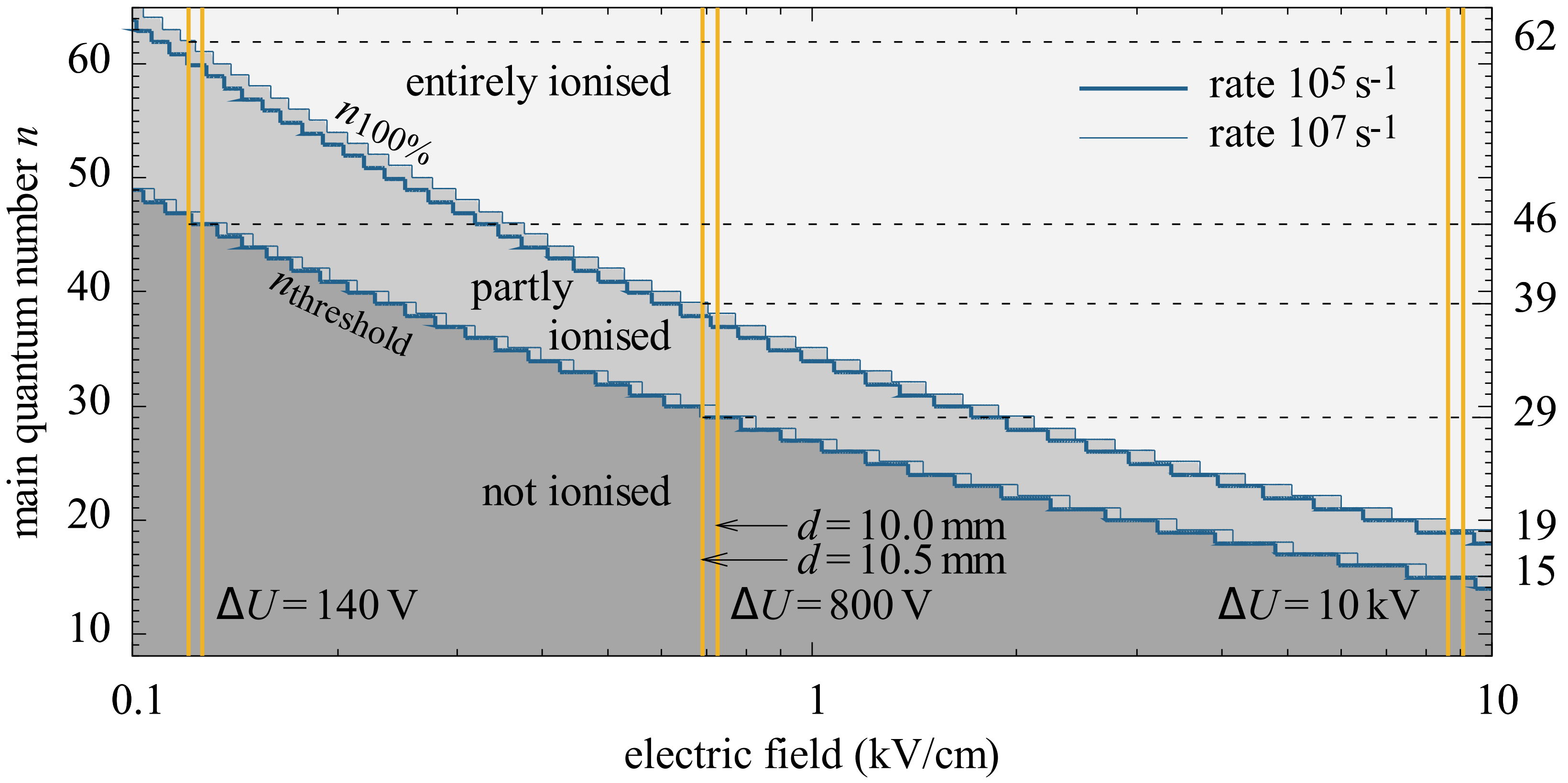
What about H̄ beam spectroscopy ?

1) H̄ beam quantum state determination







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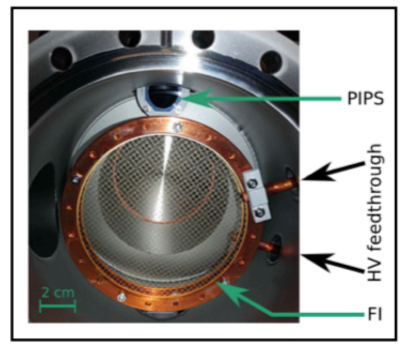

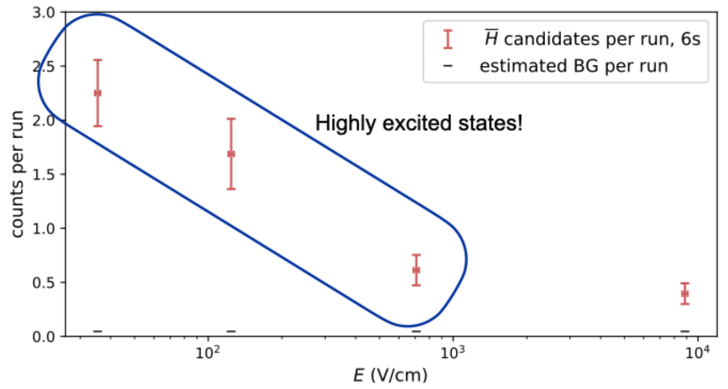

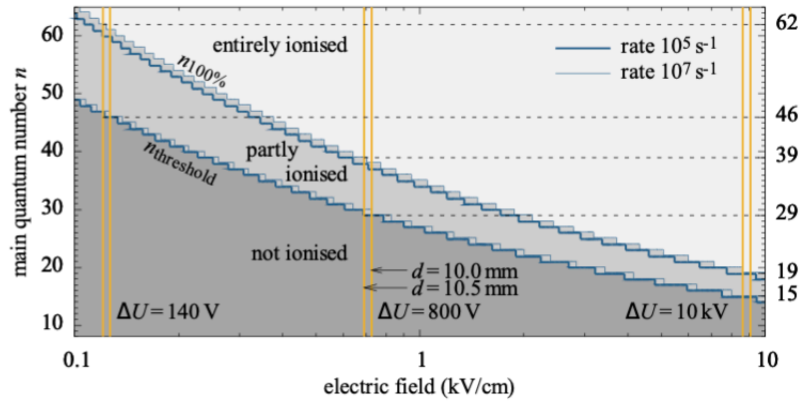

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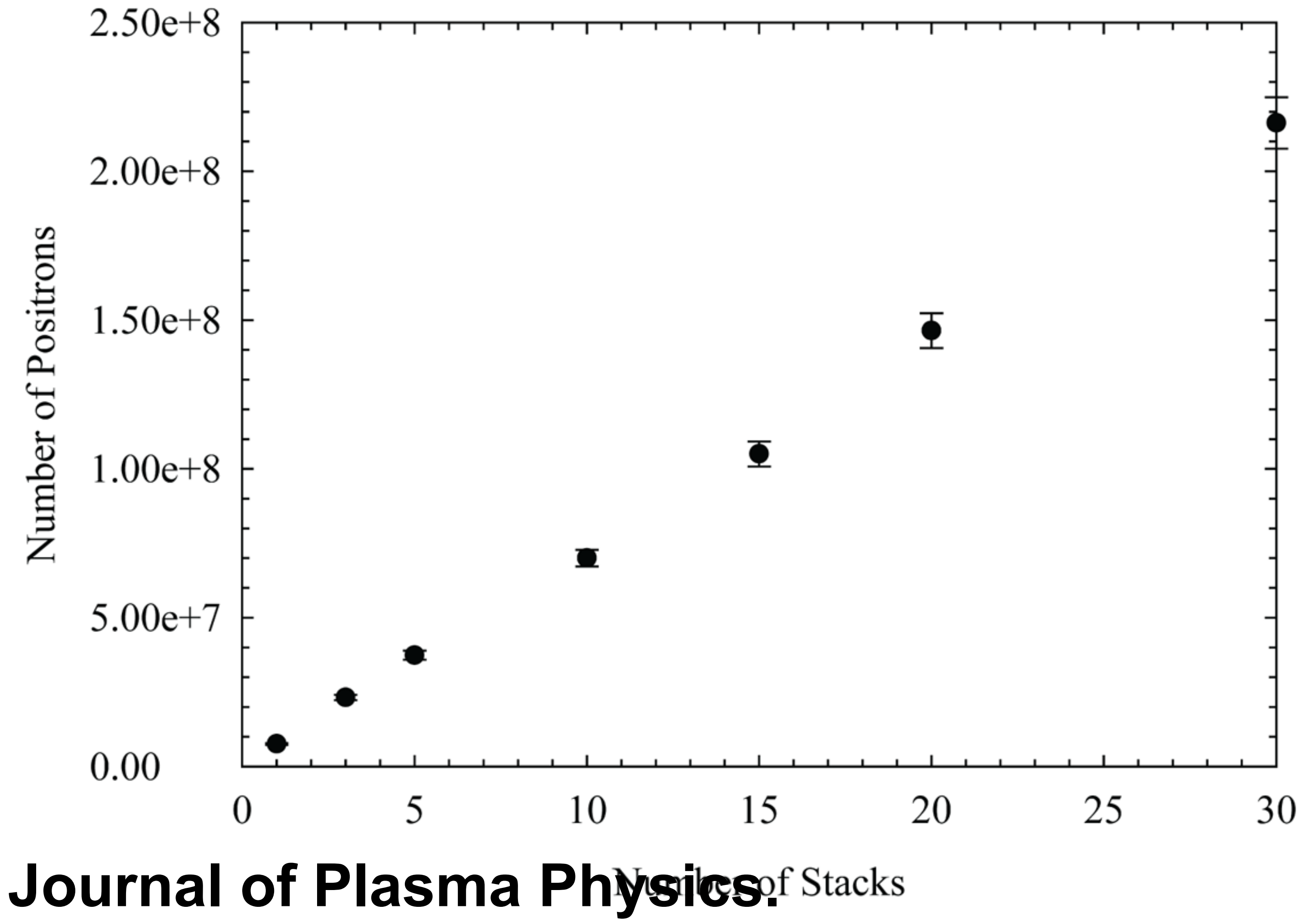
2) Positron density and temperature optimization

Improvements to the positron system - leading to a x52 rate

Slow positron production and storage for the ASACUSA-Cusp experiment
Murtagh DJ, Amsler C, Breuker H, et al.
Journal of Plasma Physics. 2023;89(6):905890608. doi:10.1017/S0022377823001034

Optimization and reproducibly of plasma parameters



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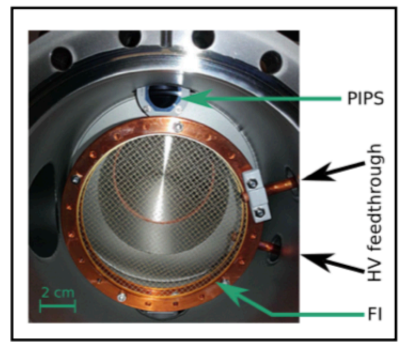

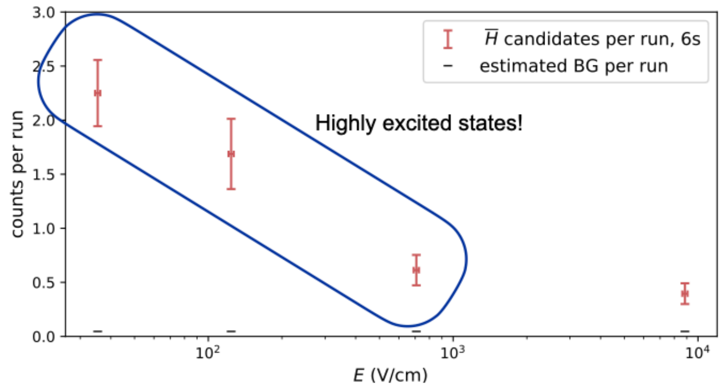

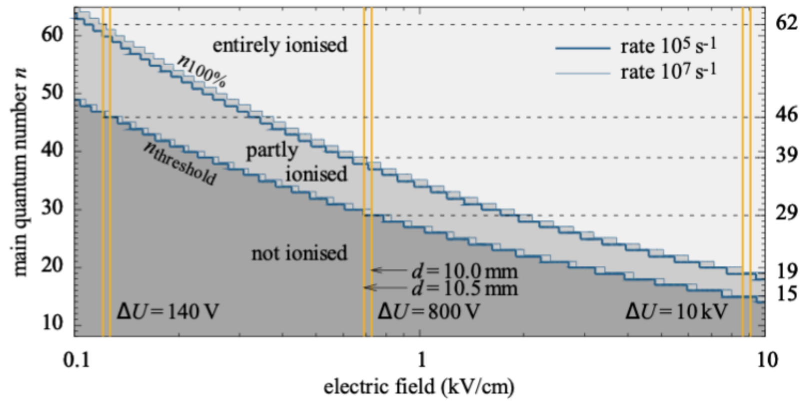

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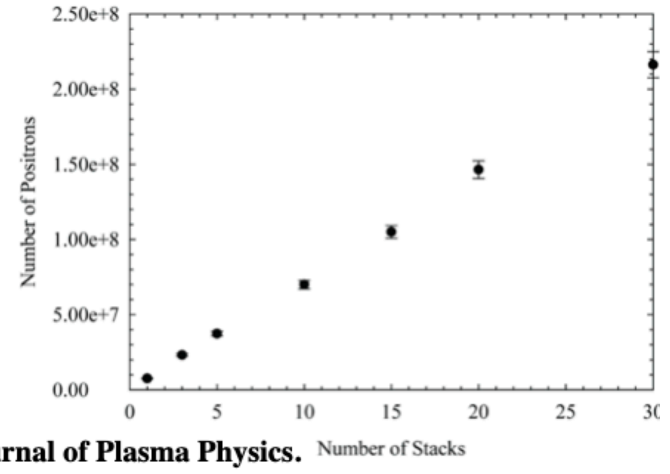

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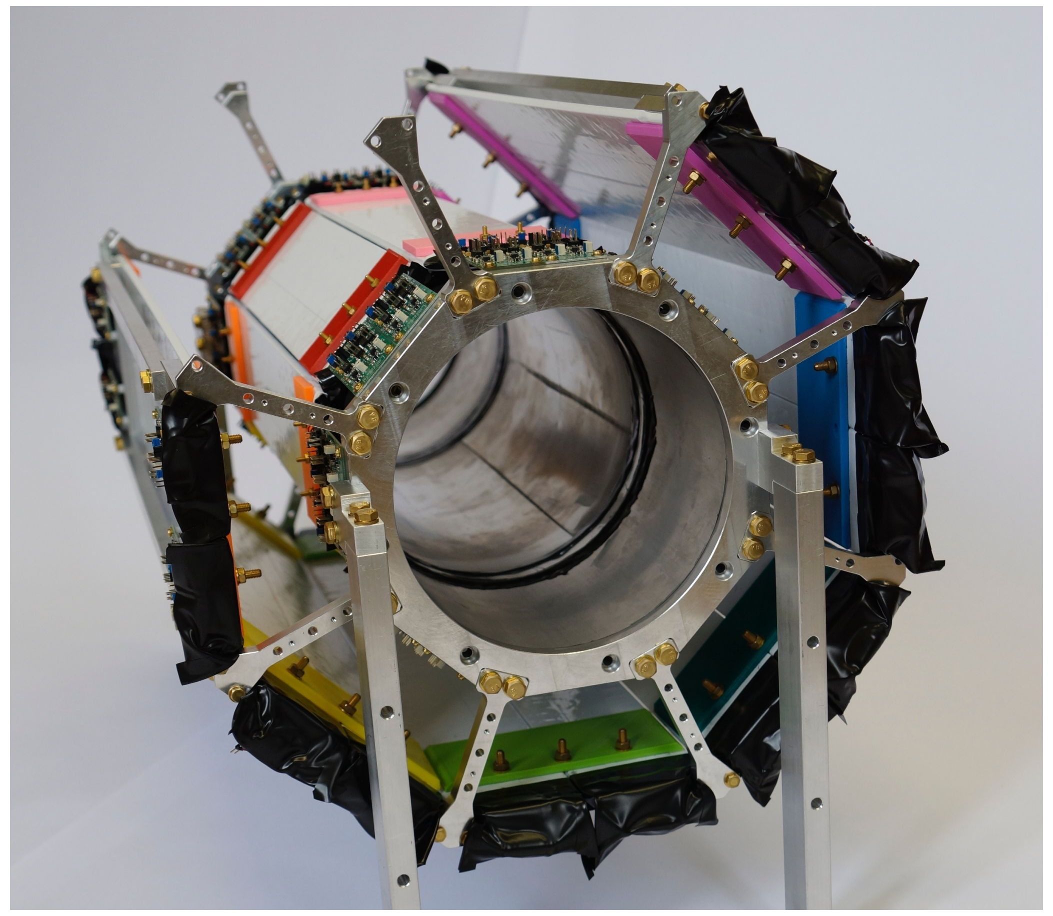
3) Detector Developments



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V. Kraxberger et al. (ASACUSA Collaboration)
Nucl. Instr. and Meth. in Phys. Res. A 1045 (2023) 167568

Upgrades to the DAQ and $\bar{\mathrm{H}}$ detector system

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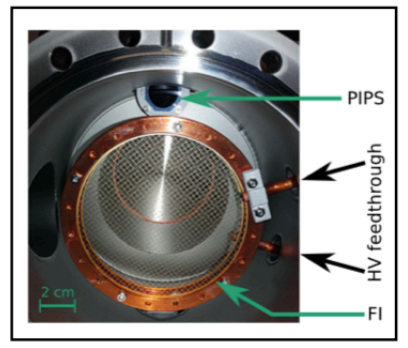

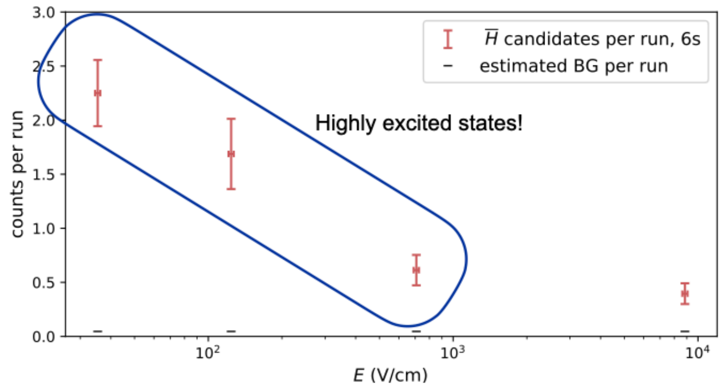

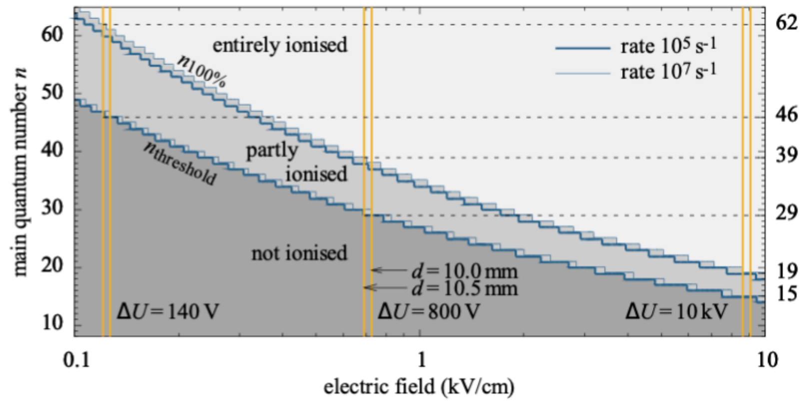

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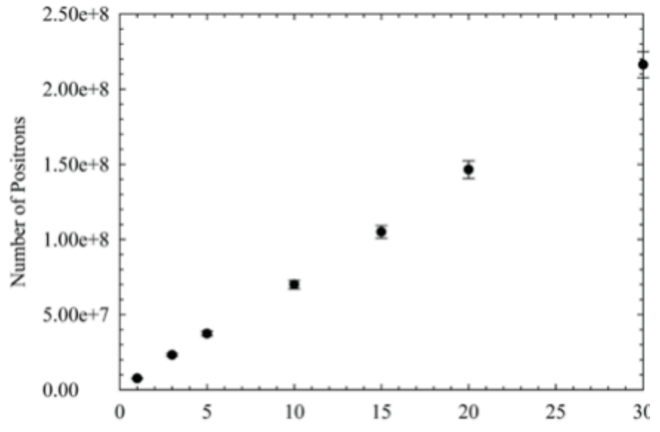

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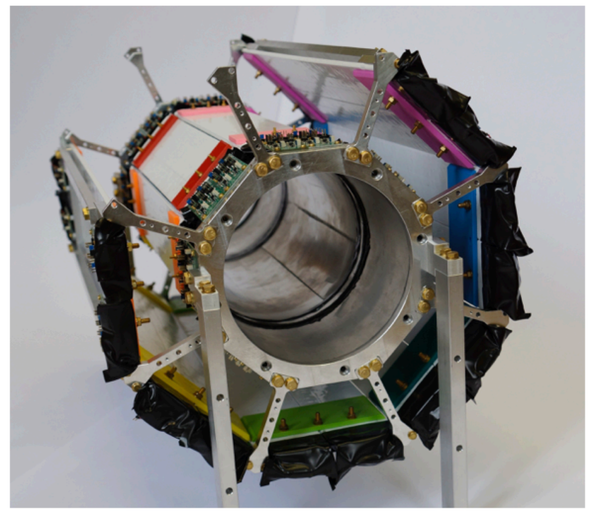

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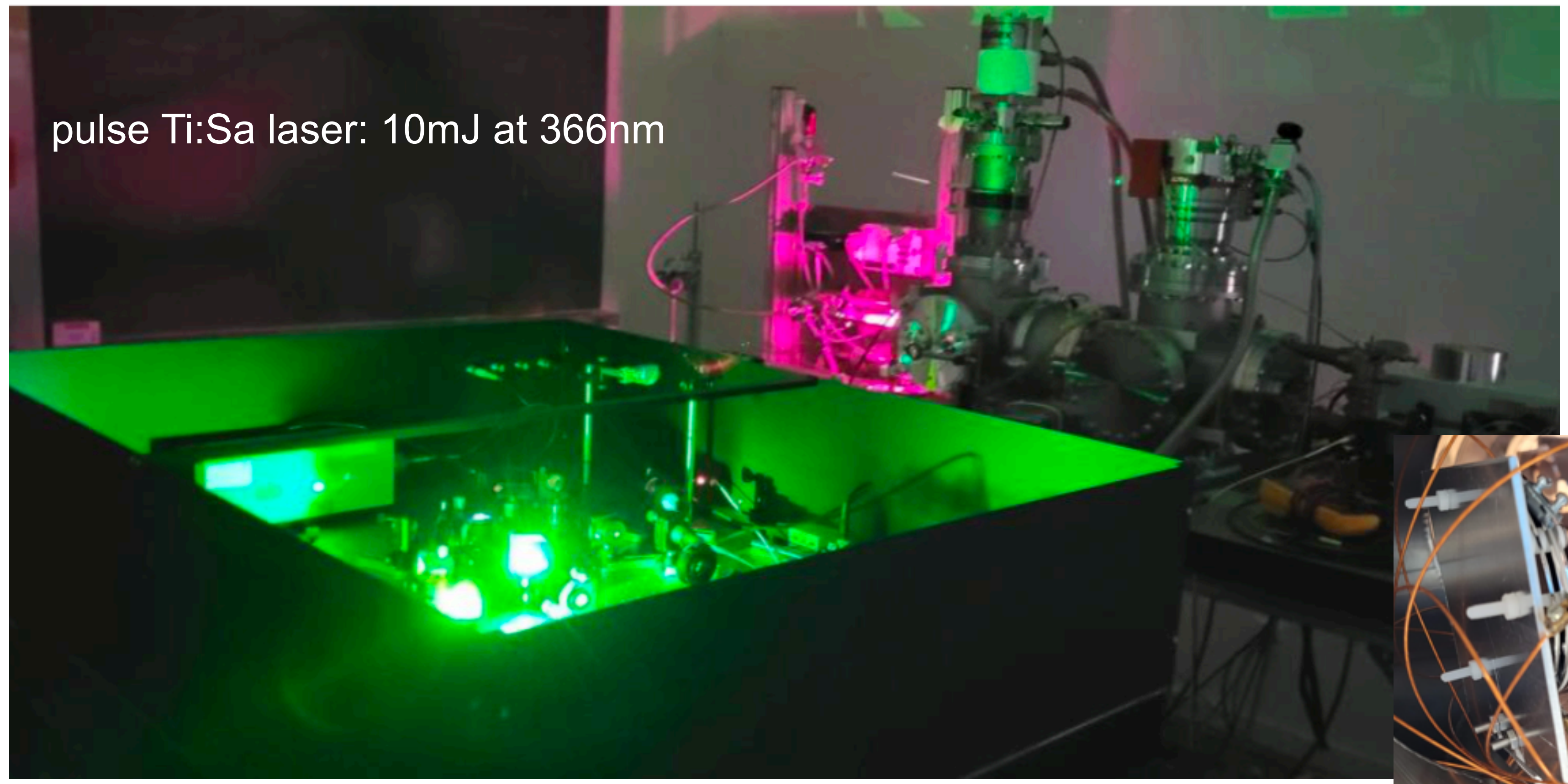
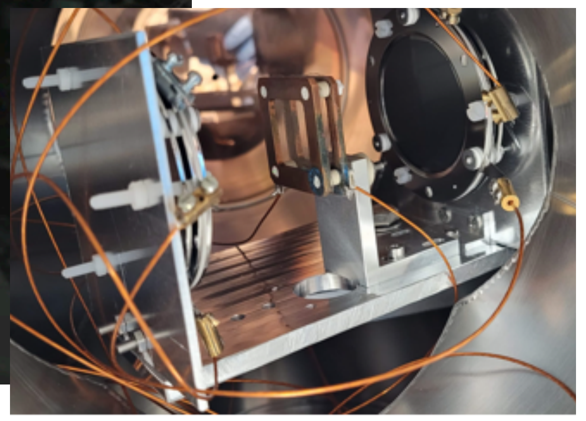
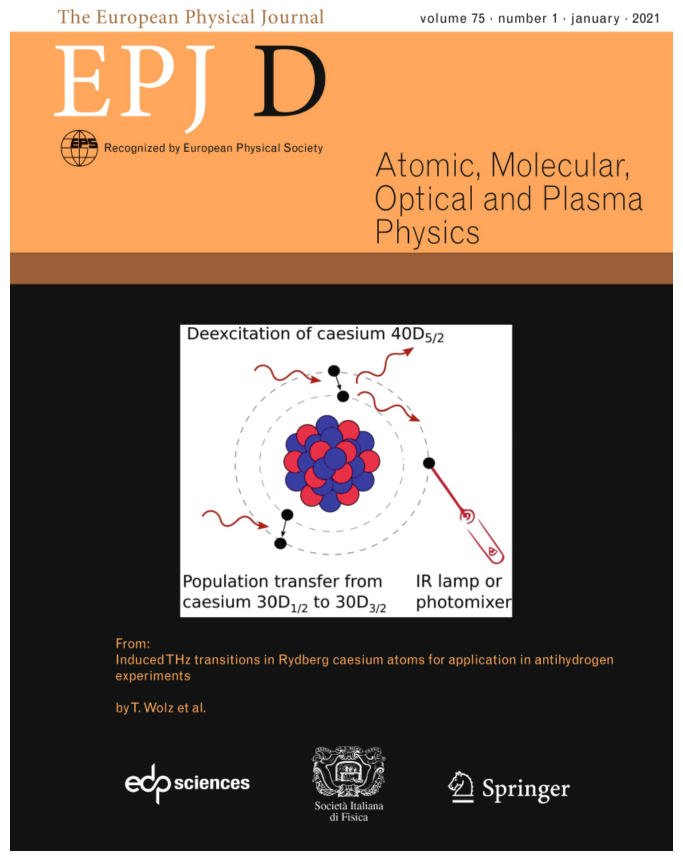
4) Stimulated deexcitation setup





Detection region

first proof of principle on a Cs beam

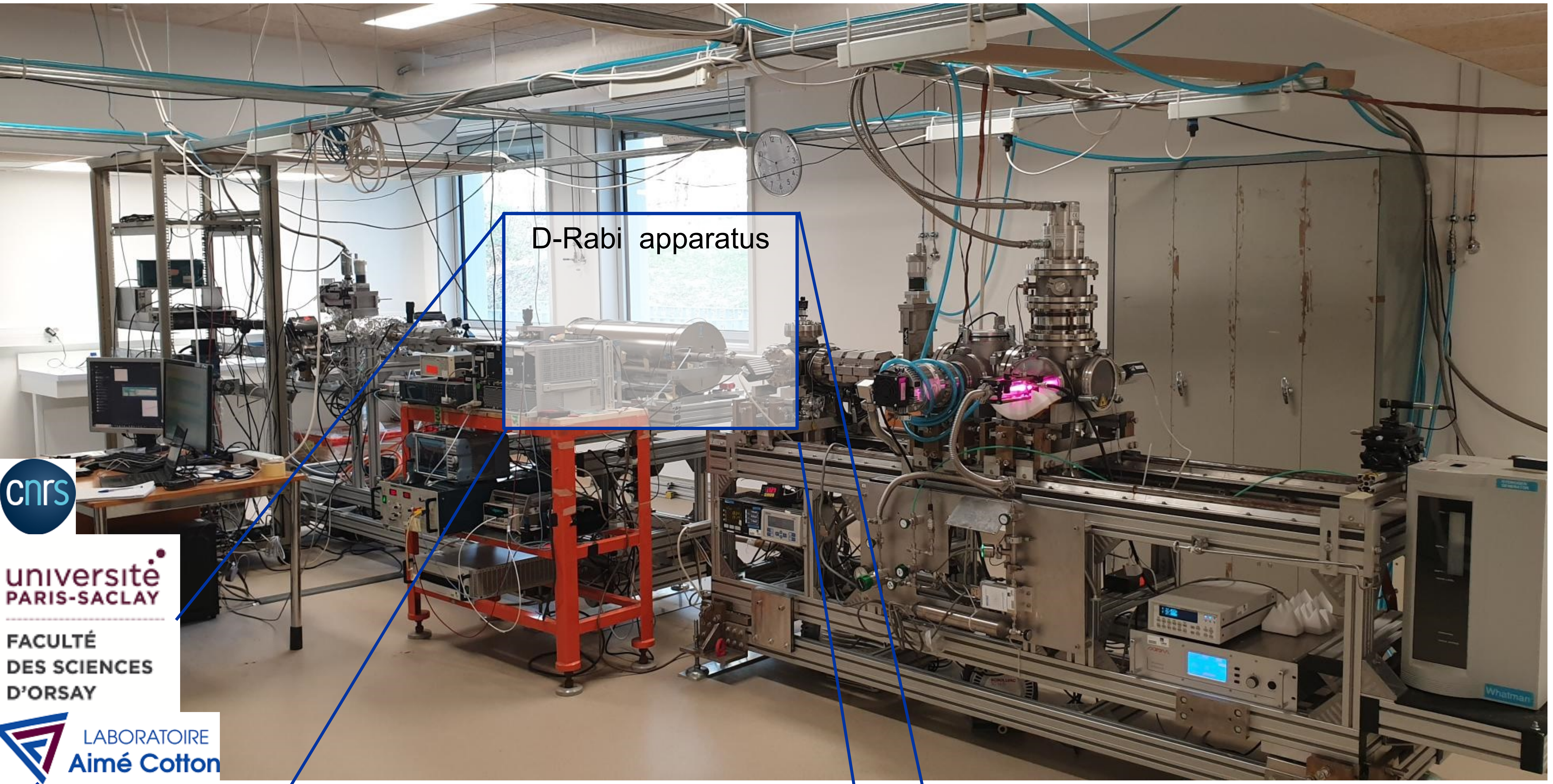


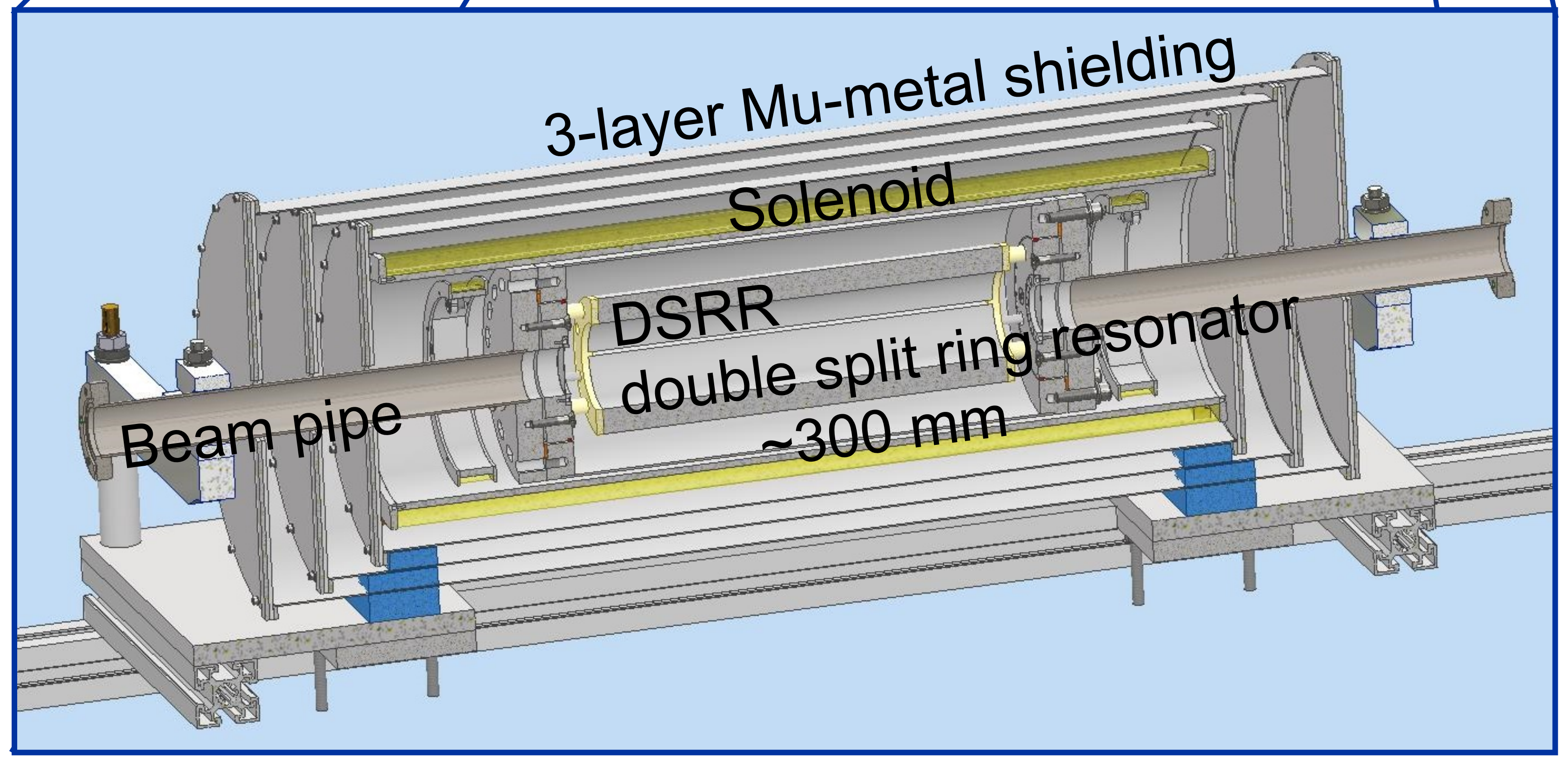
Laser-stimulated deexcitation of Rydberg antihydrogen atoms
D. Comparat and C. Malbrunot
Phys. Rev. A 99 (2019) 013418

Stimulated decay and formation of antihydrogen atoms
T. Wolz, C. Malbrunot, M. Vieille-Grosjean & D. Comparat
Phys. Rev. A 101 (2020) 043412

Induced THz transitions in Rydberg caesium atoms for application in $\bar{H}$ experiments
M. Vieille-Grosjean, E. Dimova, Z. Mazzotta, D. Comparat, T. Wolz & C. Malbrunot
Eur. Phys. J. D 75, 27 (2021)

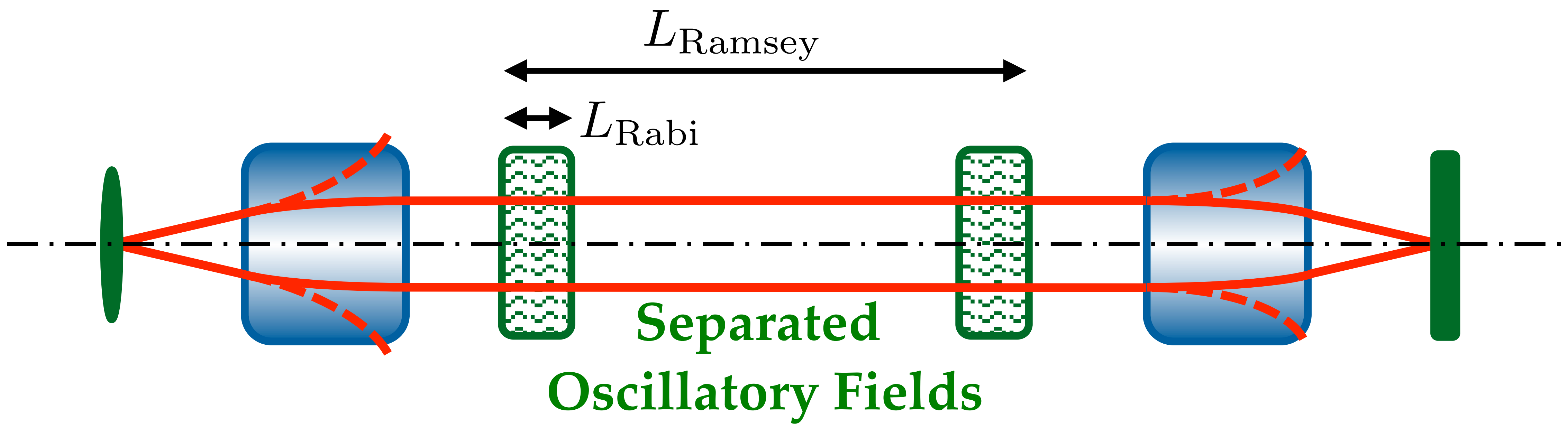
Collaboration with Laboratoire Aimé Cotton





Hydrogen setup moved to LAC in 2022

New cavity and shielding for Deuterium spectroscopy
Measurement campaigns in 2023 and 2024.
Sidereal variations and boost analysis
=> publication in preparation : improved constraints on 16 SME coefficients



<u>Next steps:</u>

- $\bar{\mathrm{H}}$ spectroscopy!
- hydrogen deceleration
- Ramsey spectroscopy

- $\bar{\mathrm{H}}/\mathrm{H}$ are **a unique tools** for high precision tests of **fundamental symmetries -** with potential **paradigm-changing** implications

- The field has a **bright and exciting future** - healthy competition leads to many innovations

- SMI is playing a leading role in the development of the field - measurements with $\bar{\mathbf{H}}$ are **around the corner!**