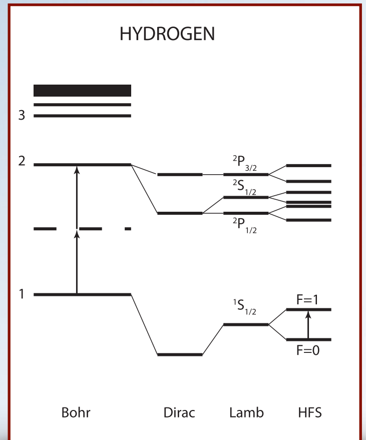


CPT SYMMETRY AND GRAVITY TESTS WITH ANTIHYDROGEN

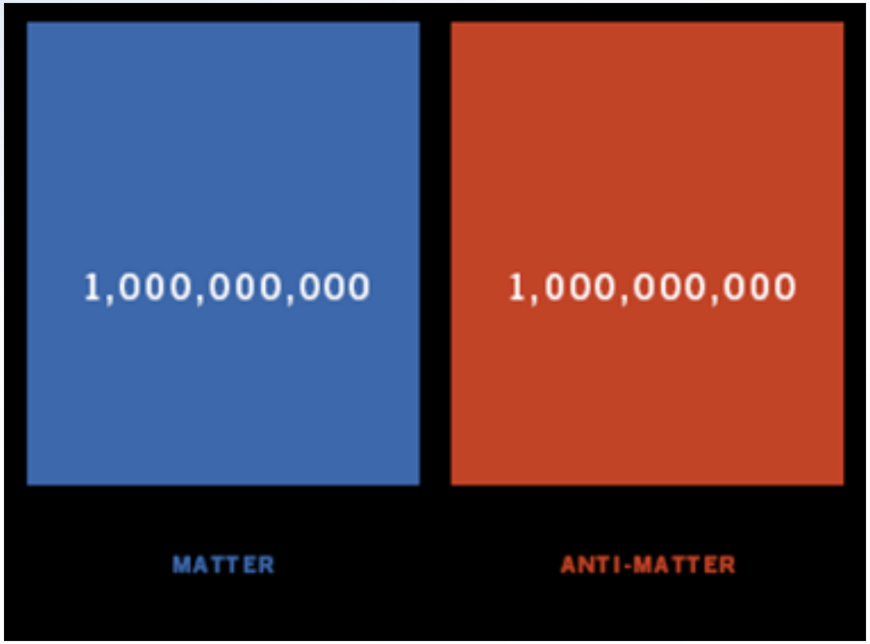
Chloé Malbrunot [1,2]

[1] CERN, Geneva, SWITZERLAND
[2] Stefan Meyer Institute for Subatomic Physics, Vienna, AUSTRIA

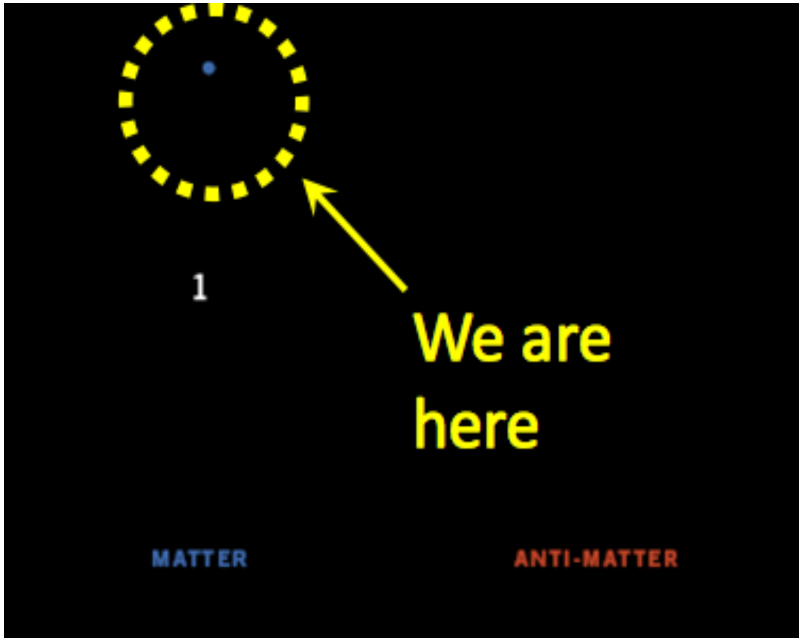
MOTIVATIONS

$$\boxed{\frac{n(B) - n(\bar{b})}{n(\gamma)} < 10^{-9}}$$

13.8 billions years ago :

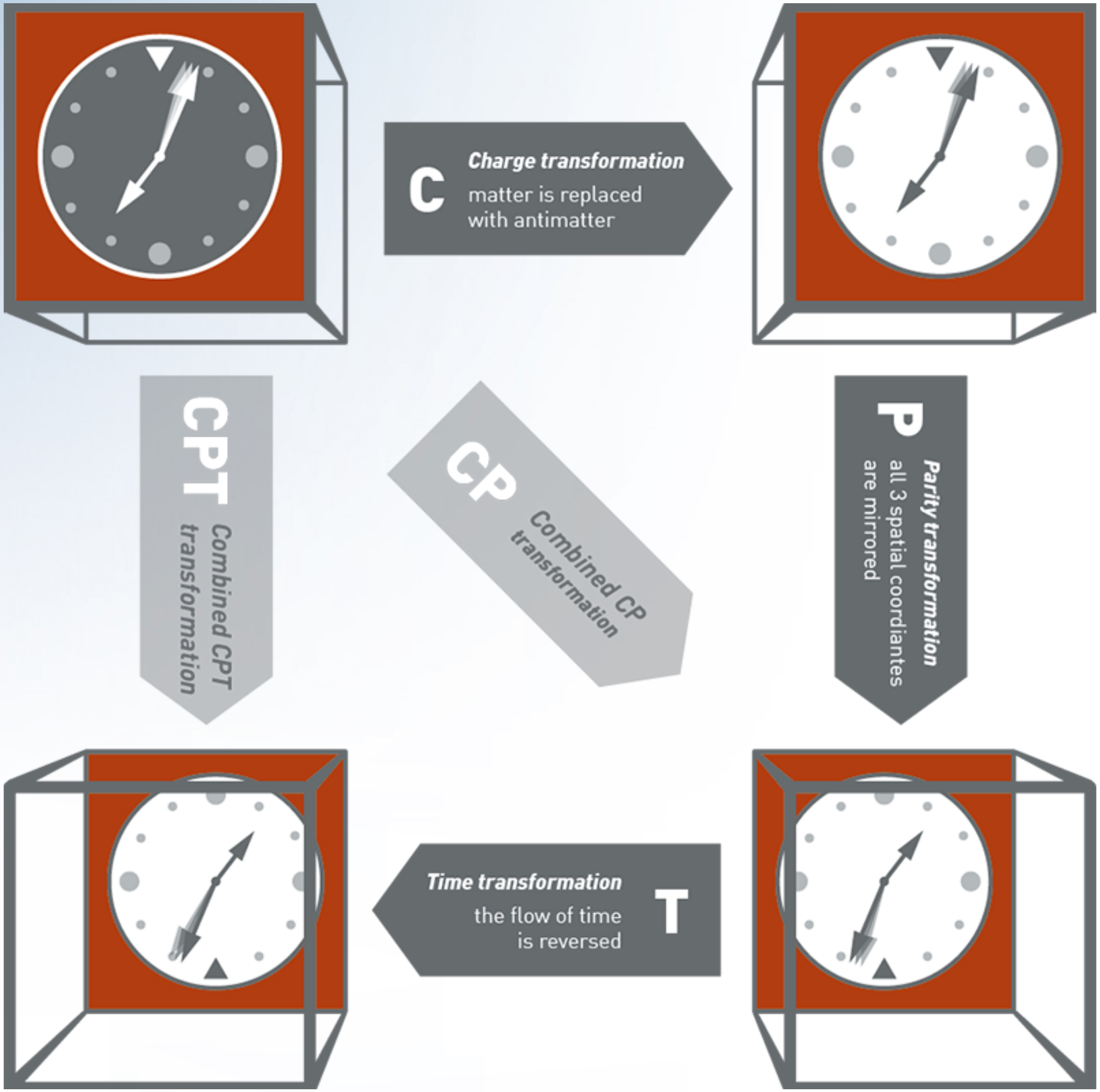


Today :



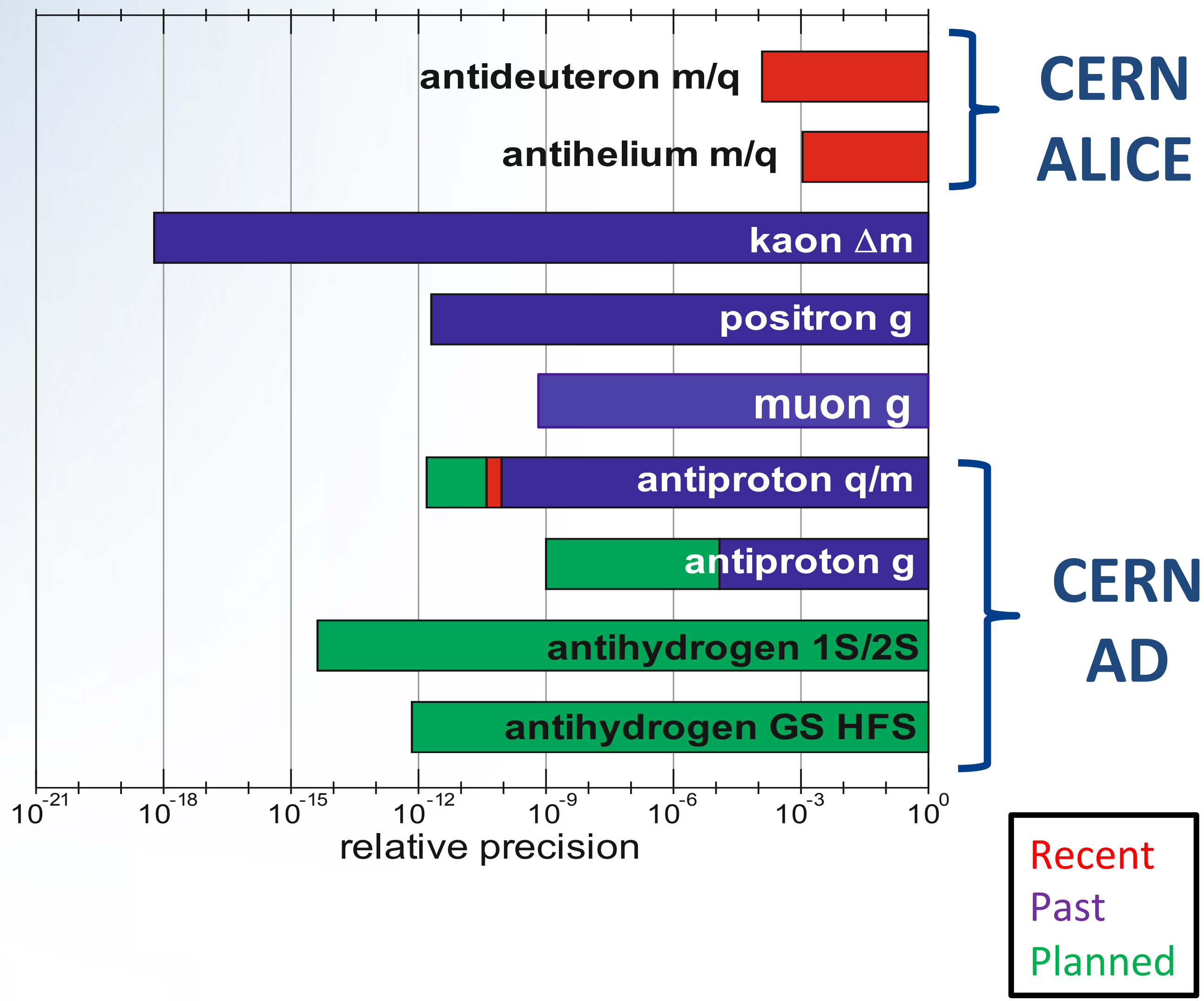
Courtesy: A. Kellerbauer

MOTIVATIONS



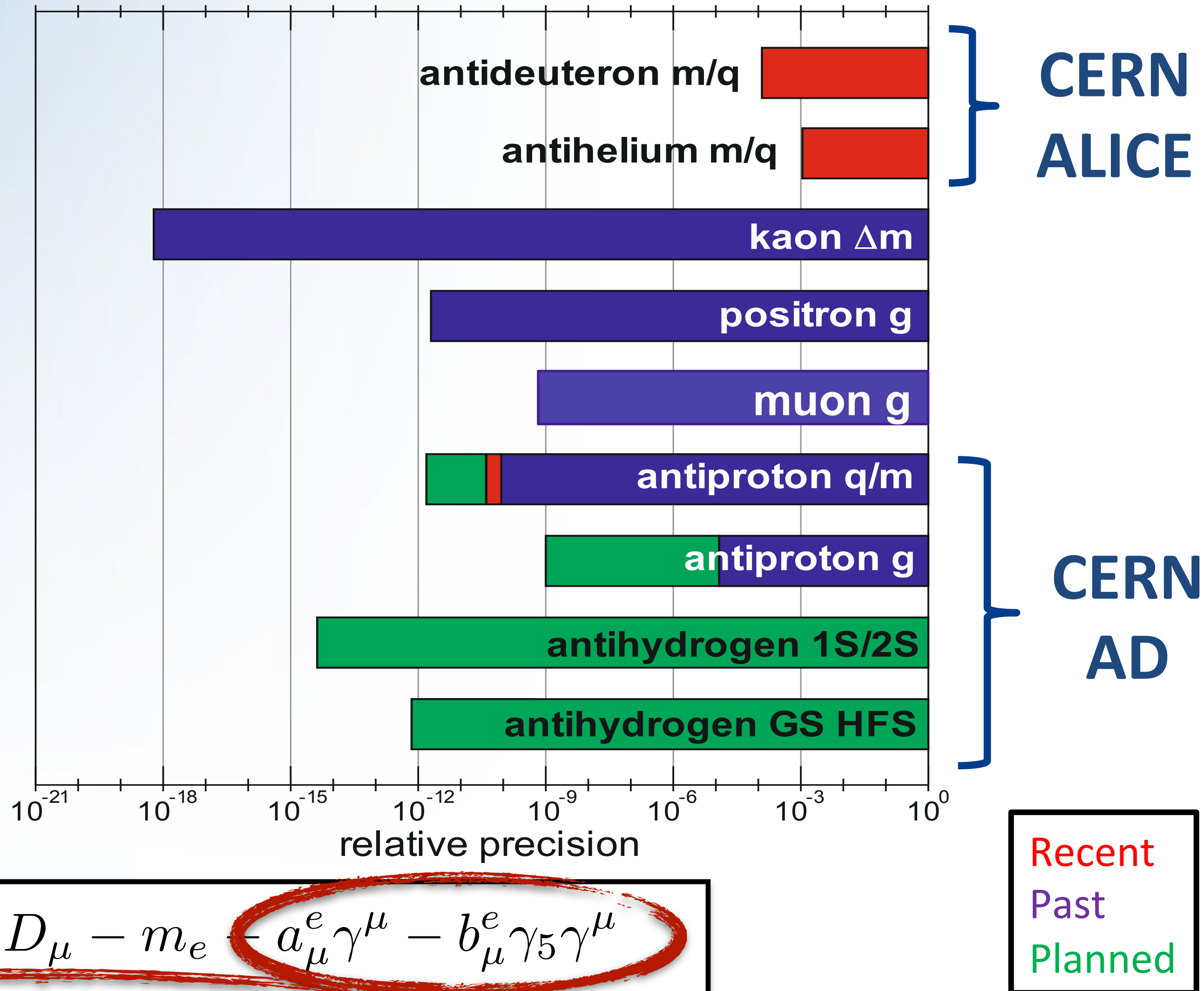
Courtesy: B. Juhasz

MOTIVATIONS



Courtesy: C. Smorra

MOTIVATIONS

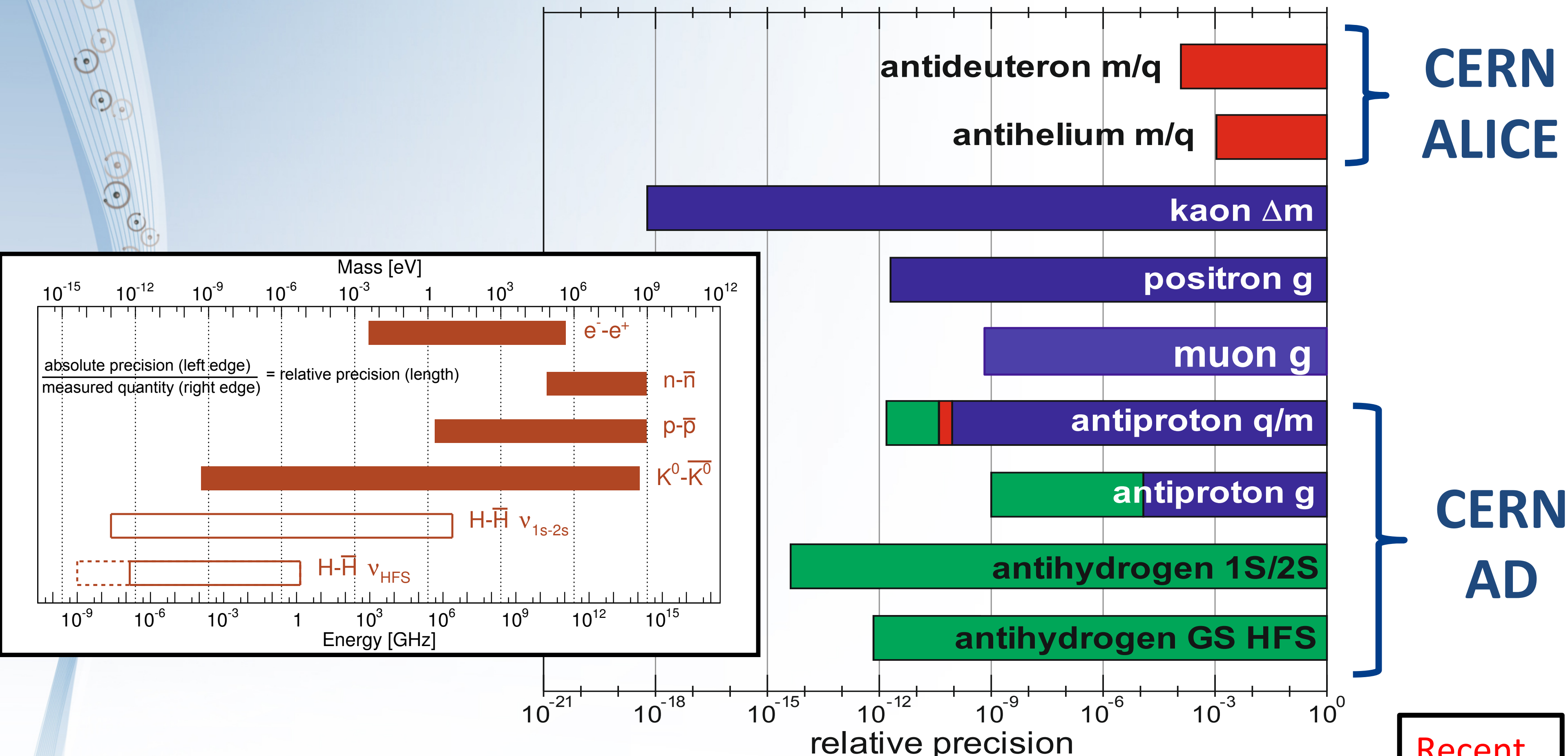


Standard Model Extension

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

Courtesy: C. Smorra

MOTIVATIONS



Recent
Past
Planned

Standard Model Extension

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

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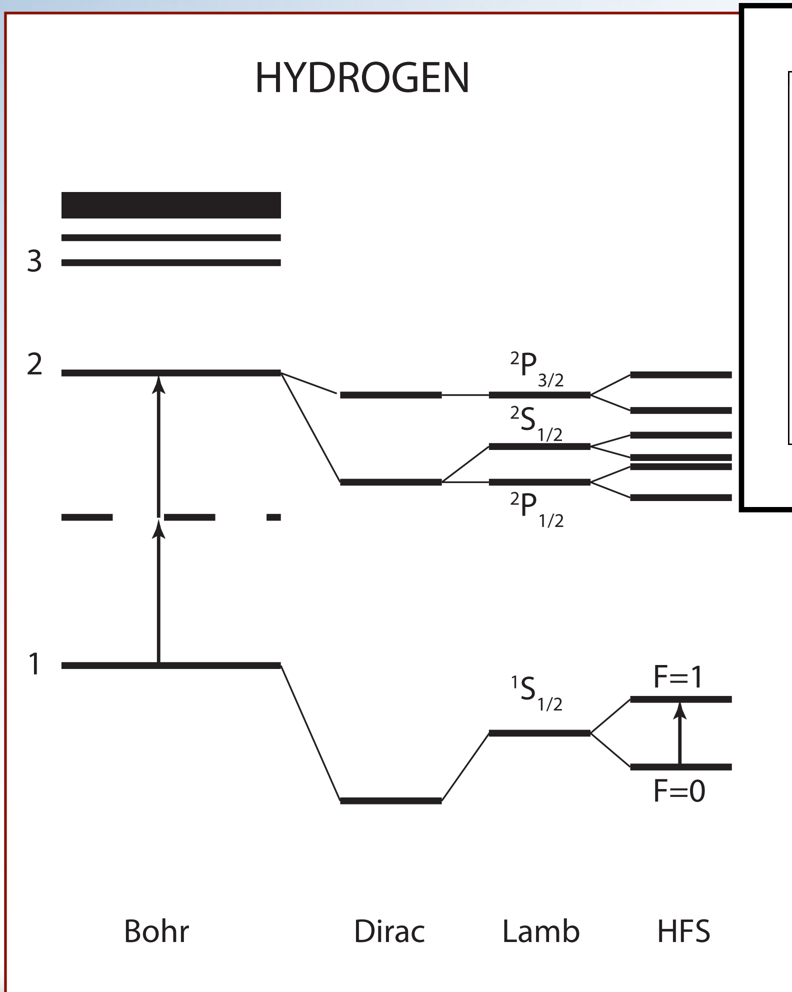
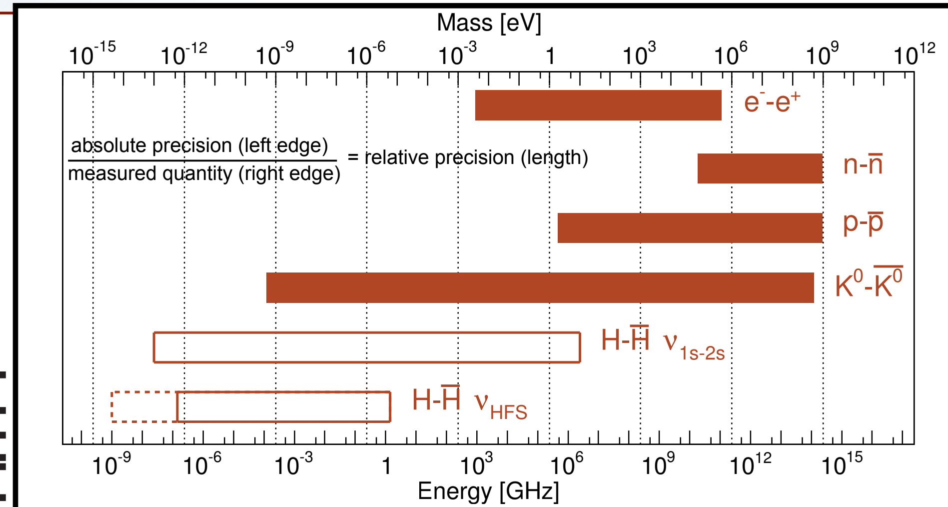
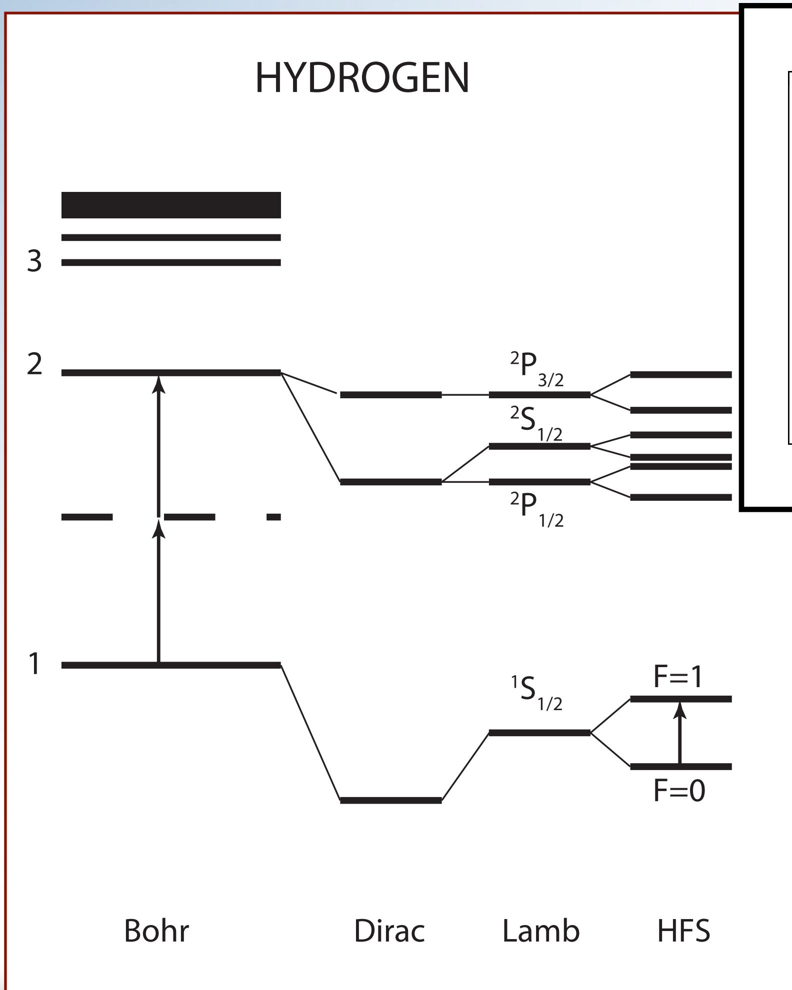
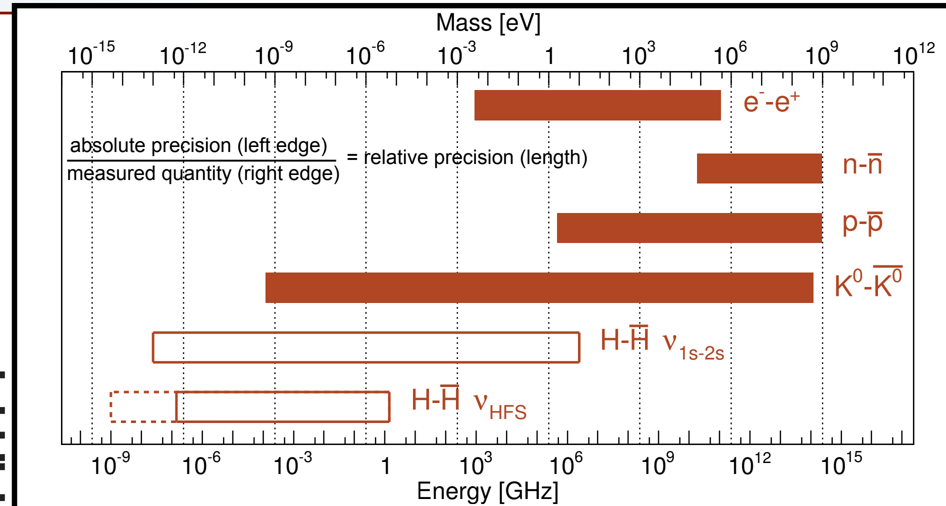
MOTIVATIONS





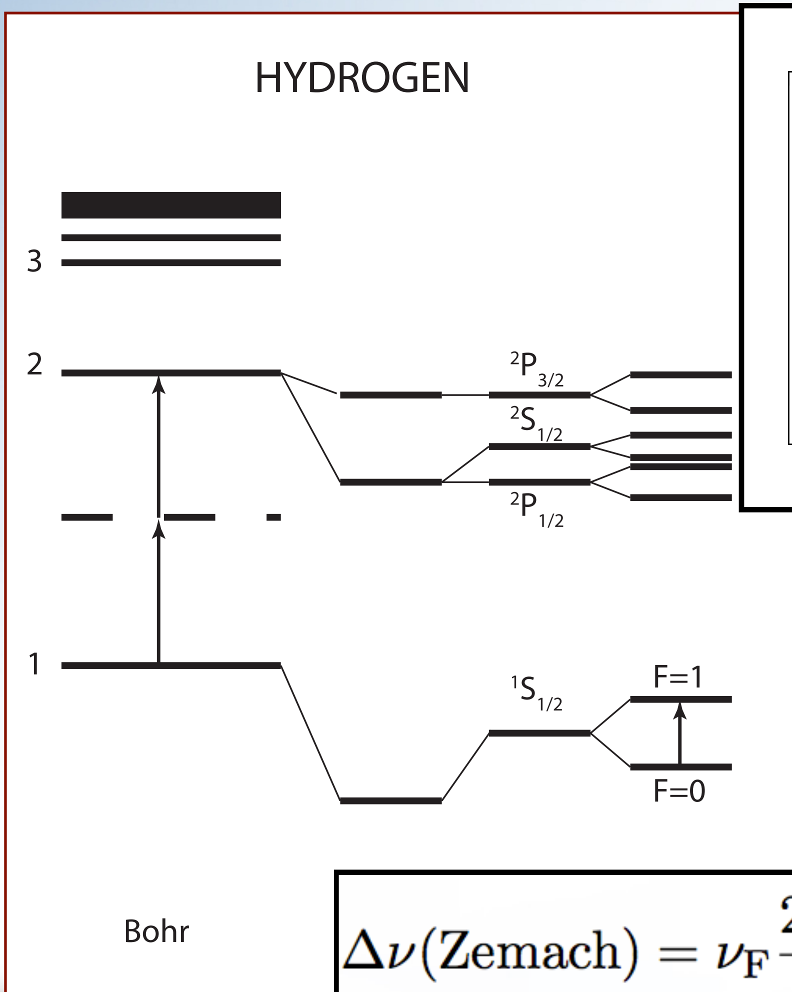
MOTIVATIONS

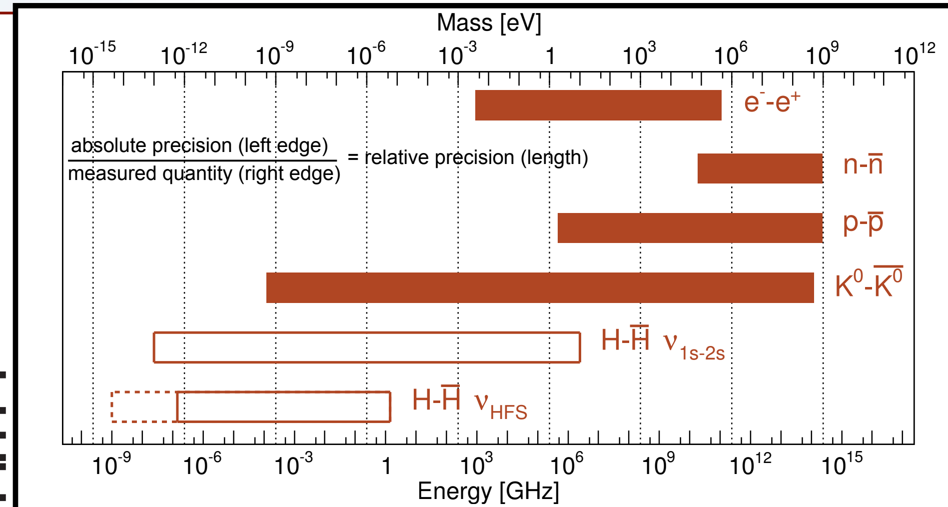




$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 c R_y$$

MOTIVATIONS



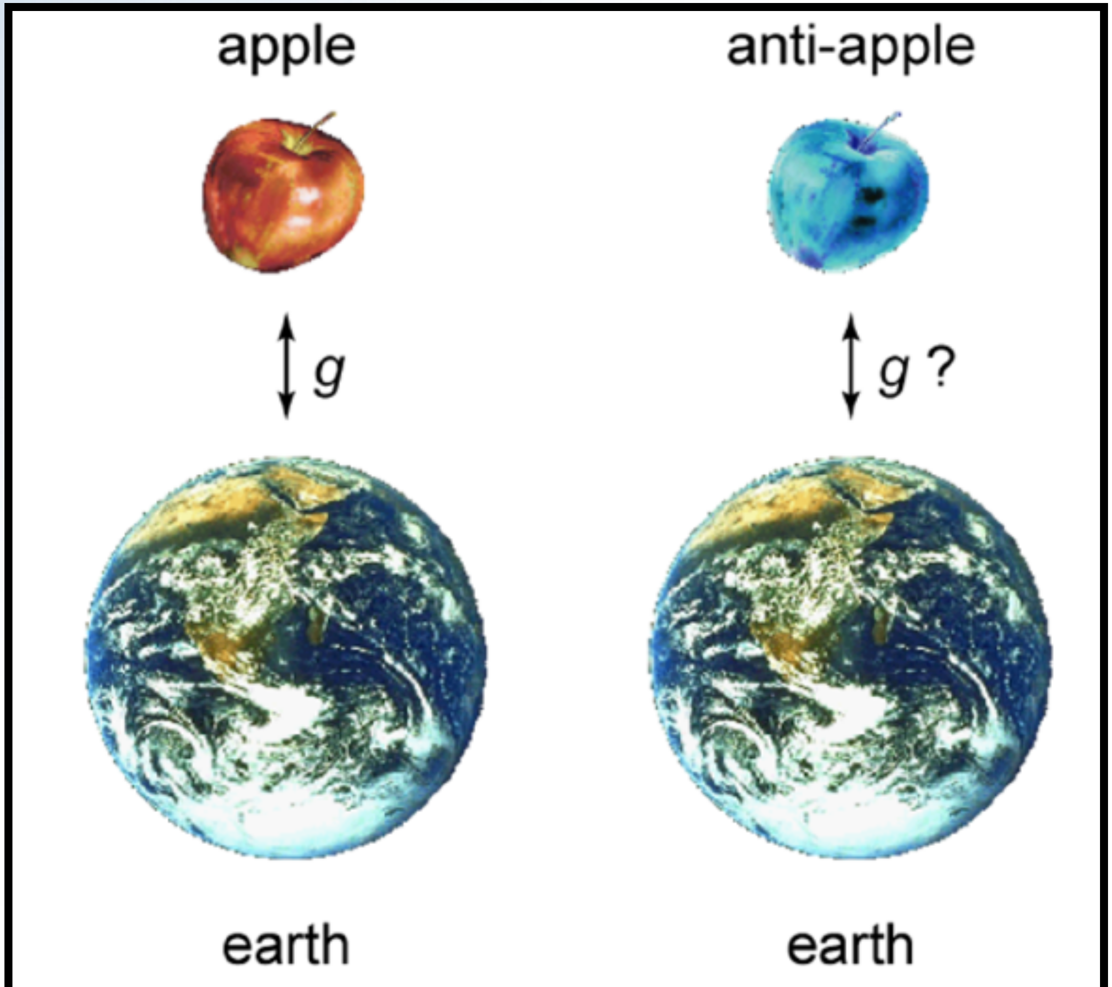


$$\nu_F = \frac{16}{3}\left(\frac{M_p}{M_p + m_e}\right)^3 \frac{m_e}{M_p}\frac{\mu_p}{\mu_N}\alpha^2 c R_y$$

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

MOTIVATIONS

$$\bar{m}_g \stackrel{?}{=} \bar{m}_i$$



ANTIHYDROGEN

ATOM

PRECISION

NEUTRALITY

Measurement of atomic transitions

$$\frac{\Delta\nu_{\mathrm{HFS}}}{\nu_{\mathrm{HFS}}} = 7 \times 10^{-13}$$

CPT tests

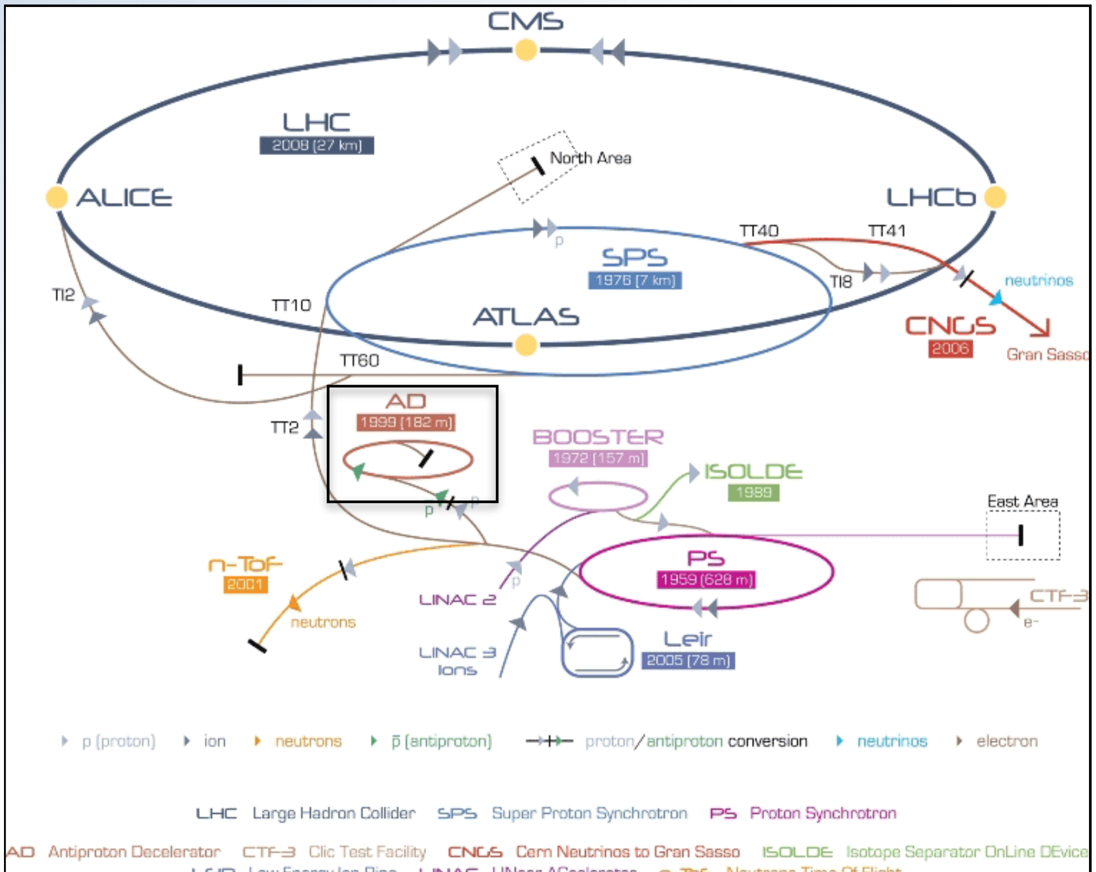
Measurement of gravitational interaction

$$\mathrm{g} \stackrel{?}{=} \bar{\mathrm{g}}$$

WEP test

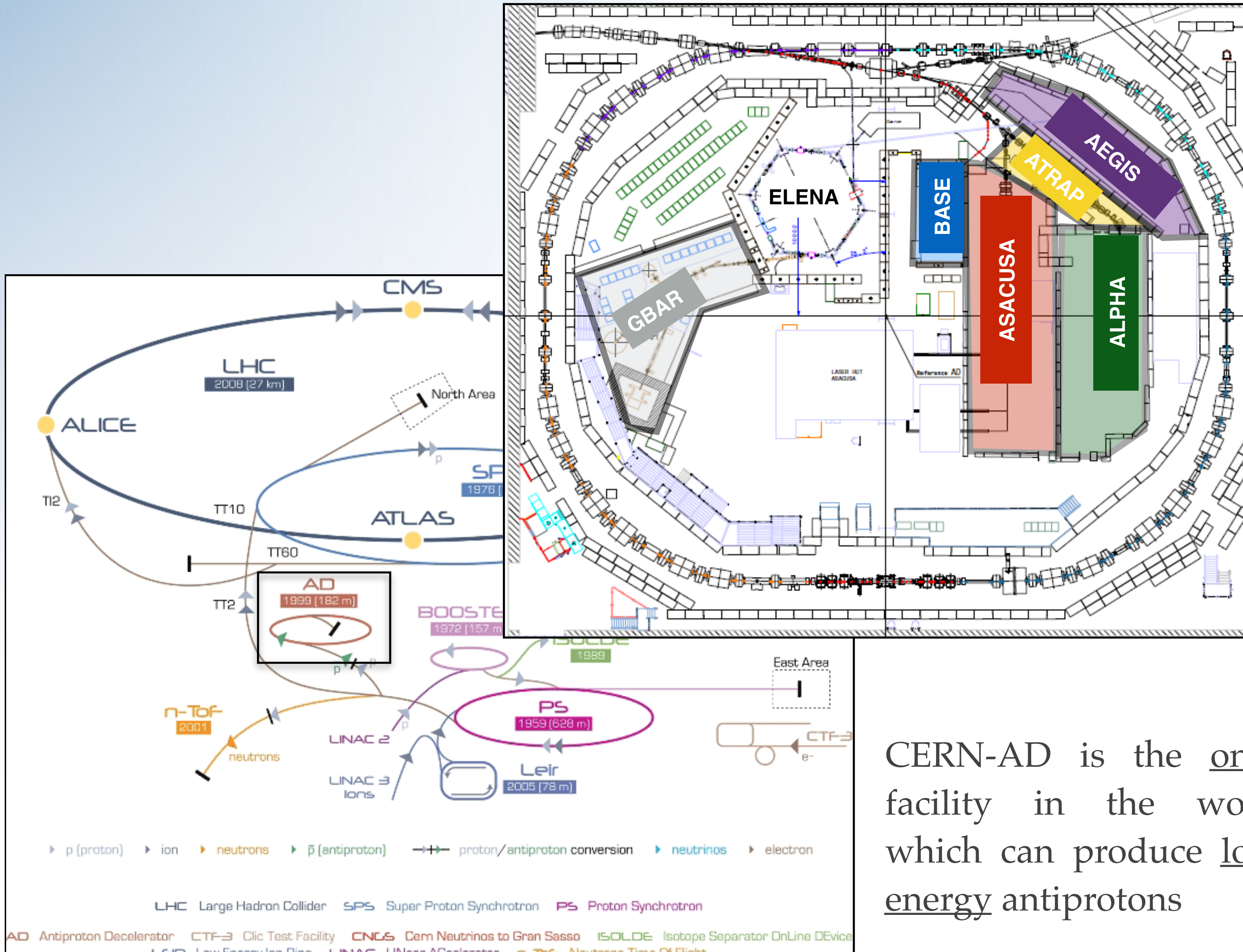
Antihydrogen: ideal test body for fundamental physics

ANTIHYDROGEN EXPERIMENTS @ CERN



CERN-AD is the <u>only</u> facility in the word which can produce <u>low energy</u> antiprotons

ANTIHYDROGEN EXPERIMENTS @ CERN



CERN-AD is the only facility in the word which can produce low energy antiprotons

>20 YEARS OF $\bar{H}$ EXPERIMENTS @ CERN

1995 First production of antihydrogen at LEAR

2000 **Start up of the AD**

2002 ATHENA and ATRAP make “cold” $\bar{H}$

2004 First Laser-Controlled $\bar{H}$ Production by ATRAP

ALPHA & ASACUSA #1 Physics World Breakthrough 2010

2010 Synthesis of $\bar{H}$ by ASACUSA

2010 First trapping of $\bar{H}$ by ALPHA

2011 ALPHA traps $\bar{H}$ for 1000 s

2012 First resonant Quantum Transition on trapped $\bar{H}$ by ALPHA

2013 ALPHA “probes” antimatter gravity

2014 ALPHA puts limits on the charge of $\bar{H}$

2014 ASACUSA creates the first “beam” of “cold” $\bar{H}$

2017 **Start up of ELENA**

20 YEARS OF $\bar{H}$ EXPERIMENTS @ CERN

1995 First production of antihydrogen at LEAR (CERN)
Phys. Lett. B 368 (1996) 251-258

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Nature **419**, 456-459
Phys. Rev. Lett. 89, 213401

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Phys. Rev. Lett. 93, 263401

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Nature **468**, 673 (2010)

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Nature Physics, 7, 558 (2011)

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Nature **483**, 439 (2012)

2013 ALPHA "probes" antimatter gravity
Nature Communications 4, 1785 (2013)

2014 ASACUSA creates the first "beam" of "cold" $\bar{H}$
Nature Communications. 5, 3089 (2014)

2014 ALPHA puts limits on the charge of $\bar{H}$
Nature Communications 5, 3955 (2014)

2017 **Start up of ELENA**

HOW TO MAKE ANTIHYDROGEN

$\bar{p}$

e^+

HOW TO MAKE ANTIHYDROGEN

AD

$\bar{p}$

$$\boxed{\bar{p} + e^{+} \rightarrow \bar{H} + \gamma}$$

$$\boxed{\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}}$$

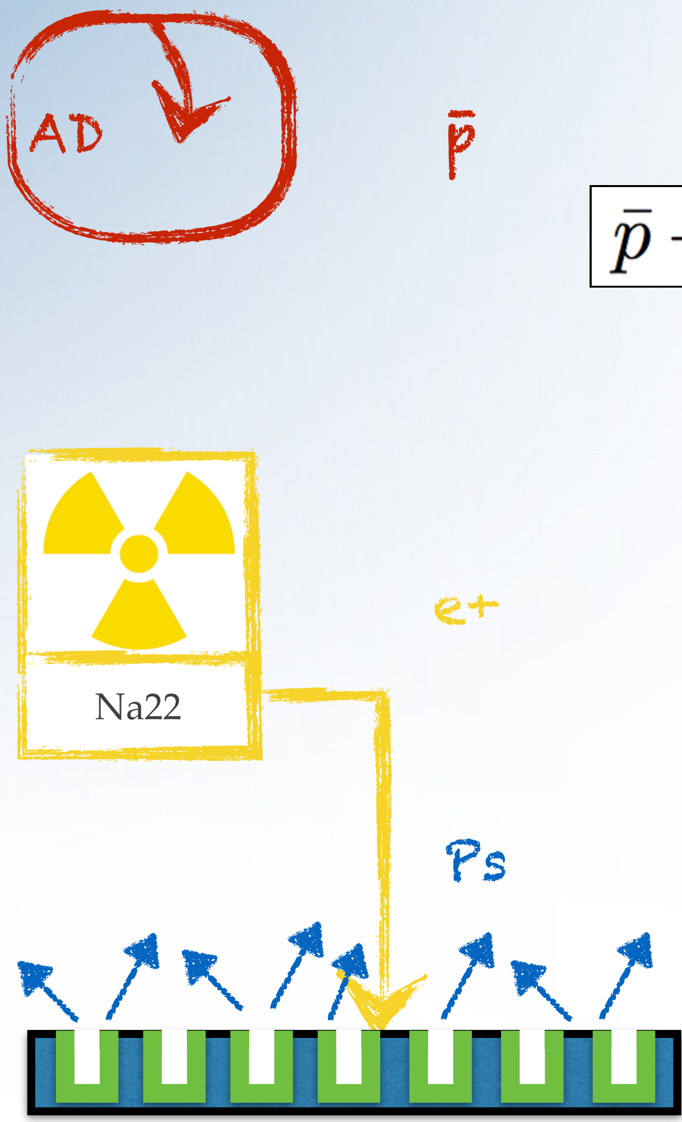
ASACUSA

ALPHA

ATRAP

e^{+}

HOW TO MAKE ANTIHYDROGEN



$$\boxed{\bar{p} + e^+ \rightarrow \bar{H} + \gamma}$$

$$\boxed{\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+}$$

ASACUSA

ALPHA

ATRAP

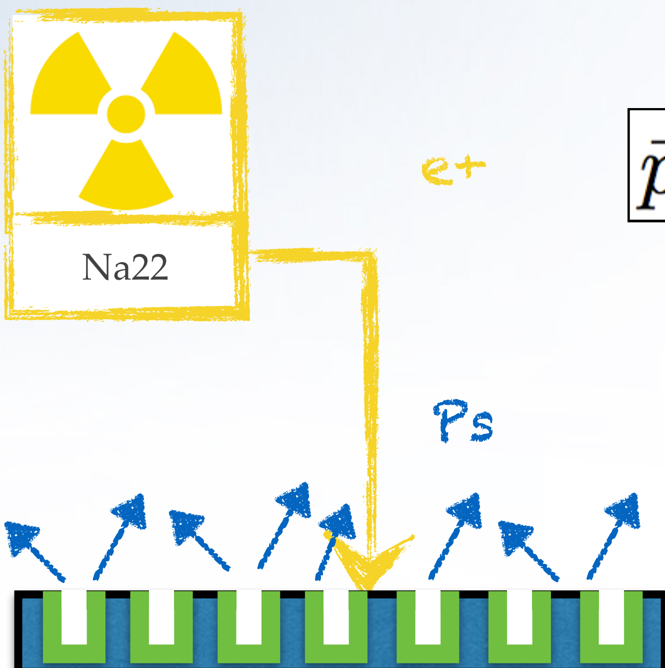
HOW TO MAKE ANTIHYDROGEN

$\bar{p}$

$$\boxed{\bar{p} + e^+ \rightarrow \bar{H} + \gamma}$$

$$\boxed{\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+}$$

ASACUSA
ALPHA
ATRAP



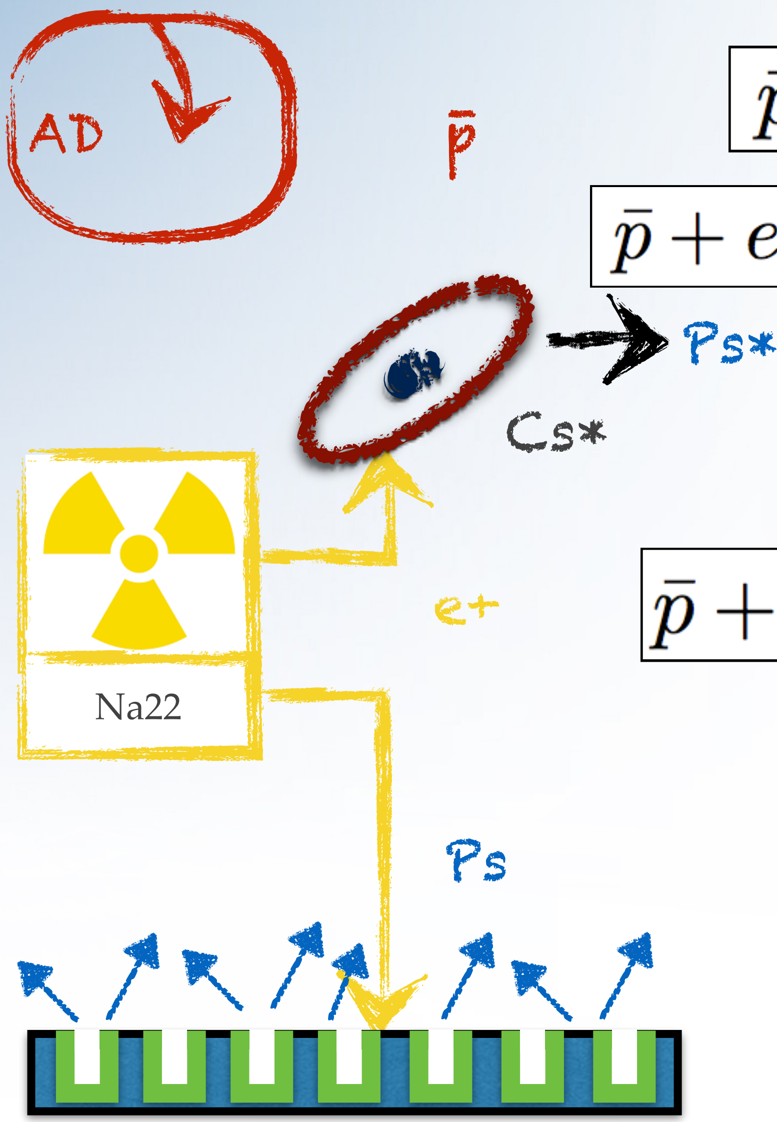
e^+

Ps

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

AEGIS
ATRAP

HOW TO MAKE ANTIHYDROGEN



$$\boxed{\bar{p} + e^{+} \rightarrow \bar{H} + \gamma}$$

ASACUSA

ALPHA

$$\boxed{\bar{p} + e^{+} + e^{+} \rightarrow \bar{H} + e^{+}}$$

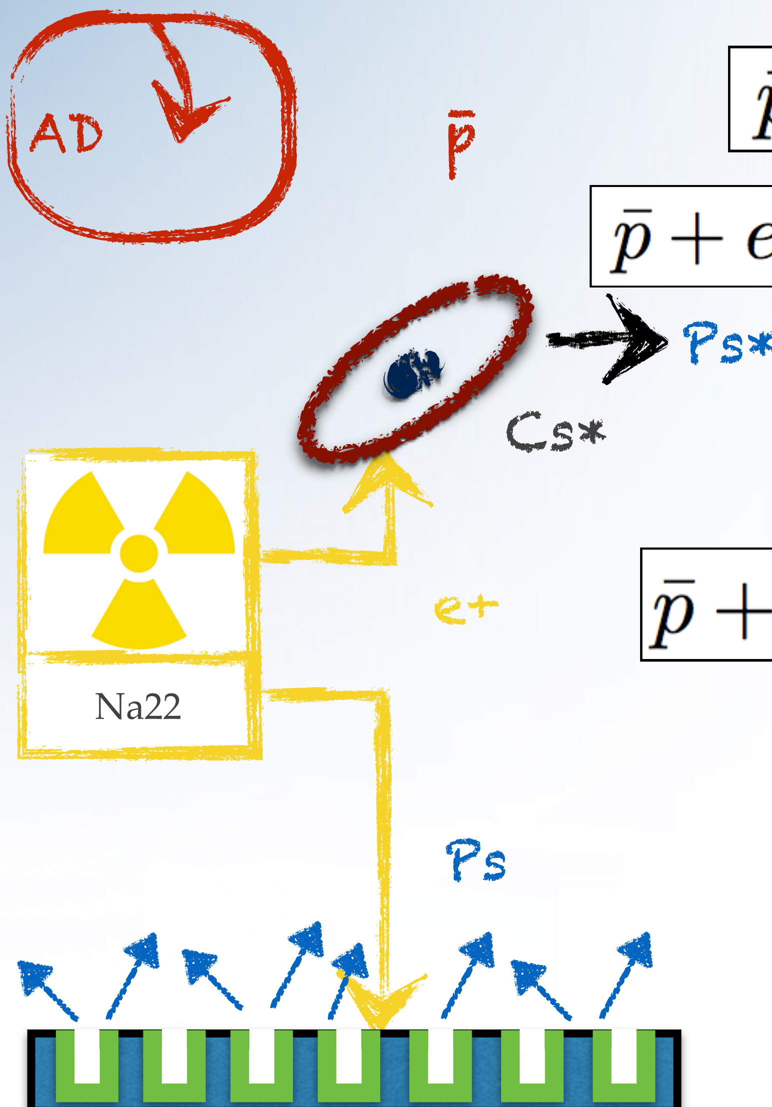
ATRAP

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

AEGIS

ATRAP

HOW TO MAKE ANTIHYDROGEN



$$\bar{p} + e^+ \rightarrow \bar{H} + \gamma$$

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

ASACUSA
ALPHA
ATRAP

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

AEGIS
ATRAP

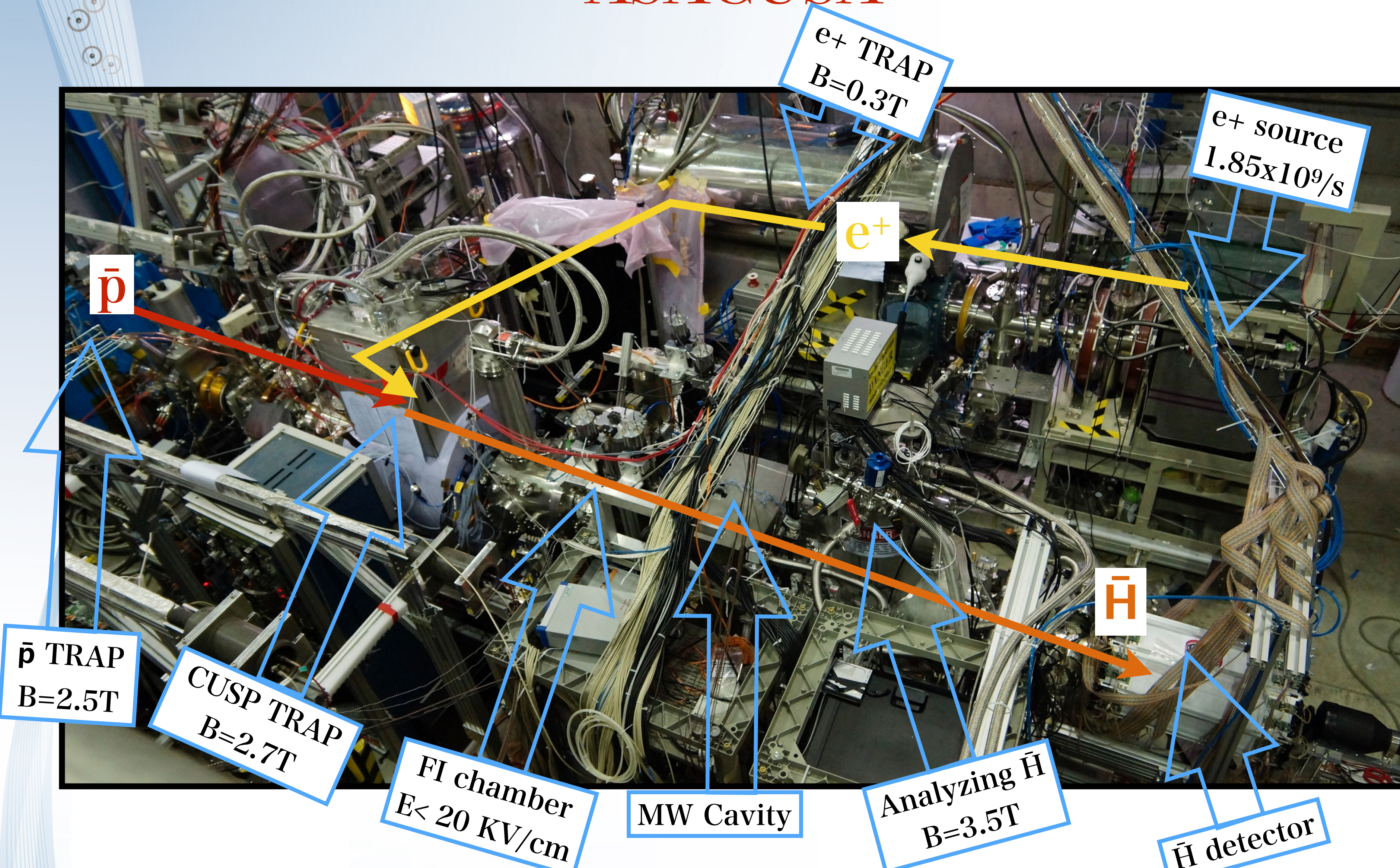
Antihydrogen ION !

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

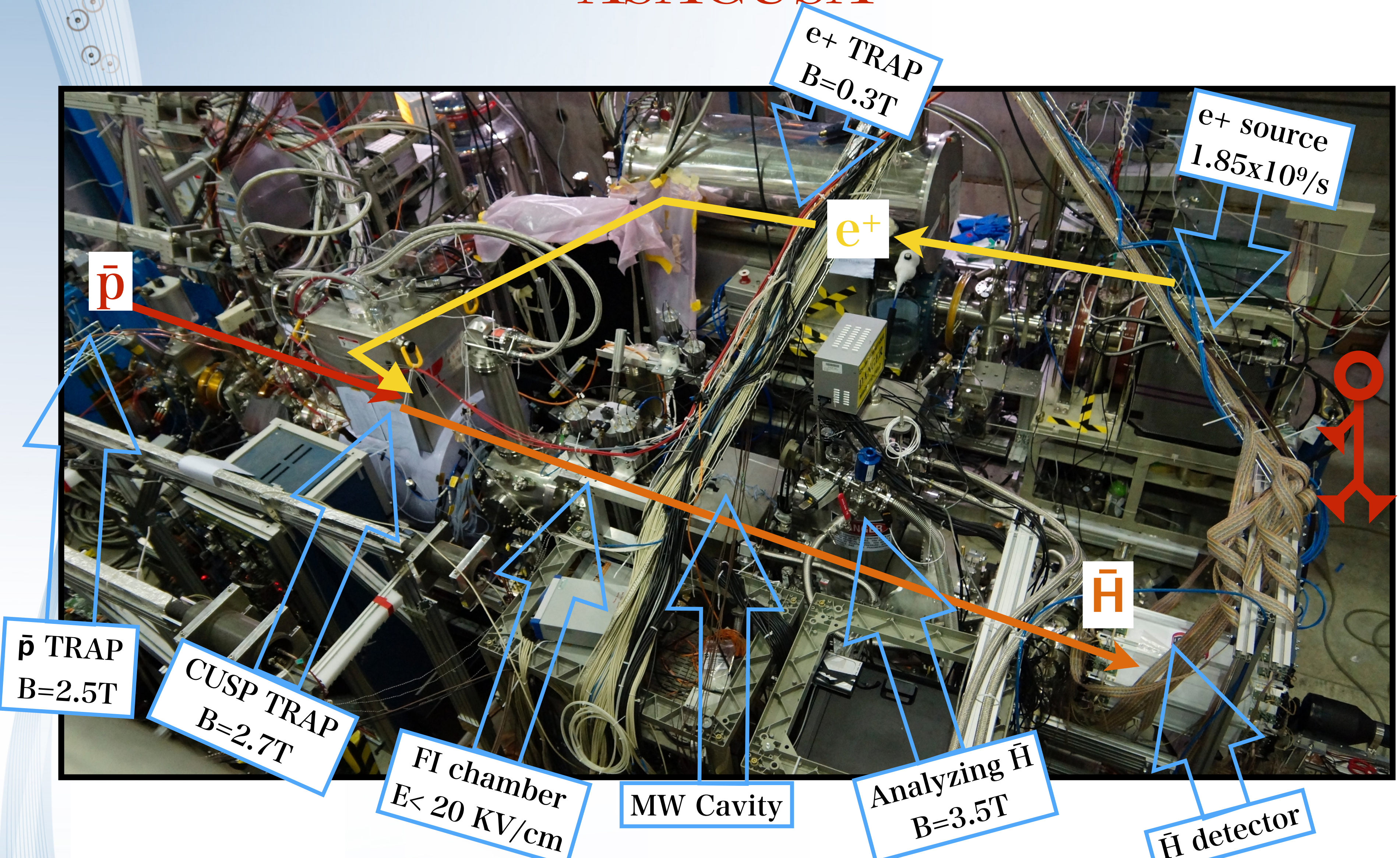
GBAR

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

ANTIHYDROGEN PRODUCTION IN ASACUSA

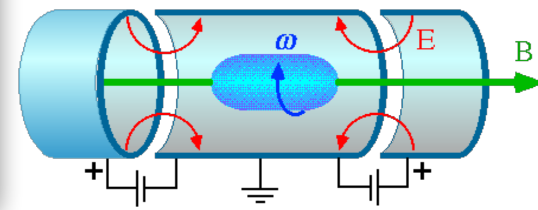


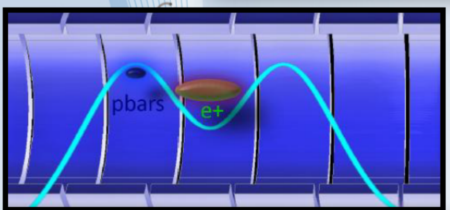
ANTIHYDROGEN PRODUCTION IN ASACUSA



HOW TO MAKE "COLD" ANTIHYDROGEN

- Trap $\bar{p}$ in an electromagnetic trap (Penning traps)
- Cool $\bar{p}$
- Accumulate and cool e+ from Na^{22} source





- "Store" $\bar{p}$ and e+ in a nested well (3-body recombination technique)
- Combine the two plasmas: $\bar{H}$ form

- cool $\bar{p}$ further
- Form Ps through e.g implantation of e+ in nano-porous Si target
- laser excite Ps
- Let $\bar{p}$ and Ps* interact: $\bar{H}$ form

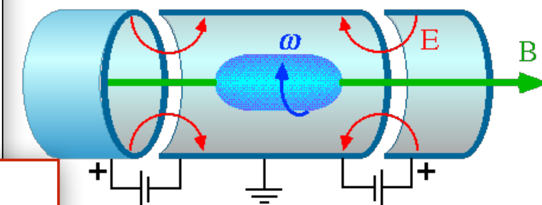
- Trap cold (<0.5K) $\bar{H}$, wait for deexcitation to ground state
- Perform SPECTROSCOPY

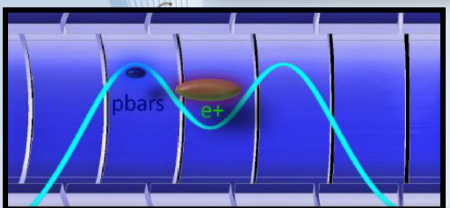
- beam of $\bar{H}$ (< 100K) and low QS beam
- Perform SPECTROSCOPY

- very slow $\bar{H}$ (~100mK)
- Measure fall of $\bar{H}$

HOW TO MAKE "COLD" ANTIHYDROGEN

- Trap $\bar{p}$ in an electromagnetic trap (Penning traps)
- Cool $\bar{p}$
- Accumul





- "Store"
  (3-body
- Combi

KEY POINTS

- Quantum state
- Temperature
- Polarisation
- Flux
- Rate at detector

her

rough e.g
on of e+ in nano-
arget

e Ps

Ps* interact: $\bar{H}$ form

- Trap cold (<0.5K) $\bar{H}$, wait for deexcitation to ground state
- Perform SPECTROSCOPY

low QS beam

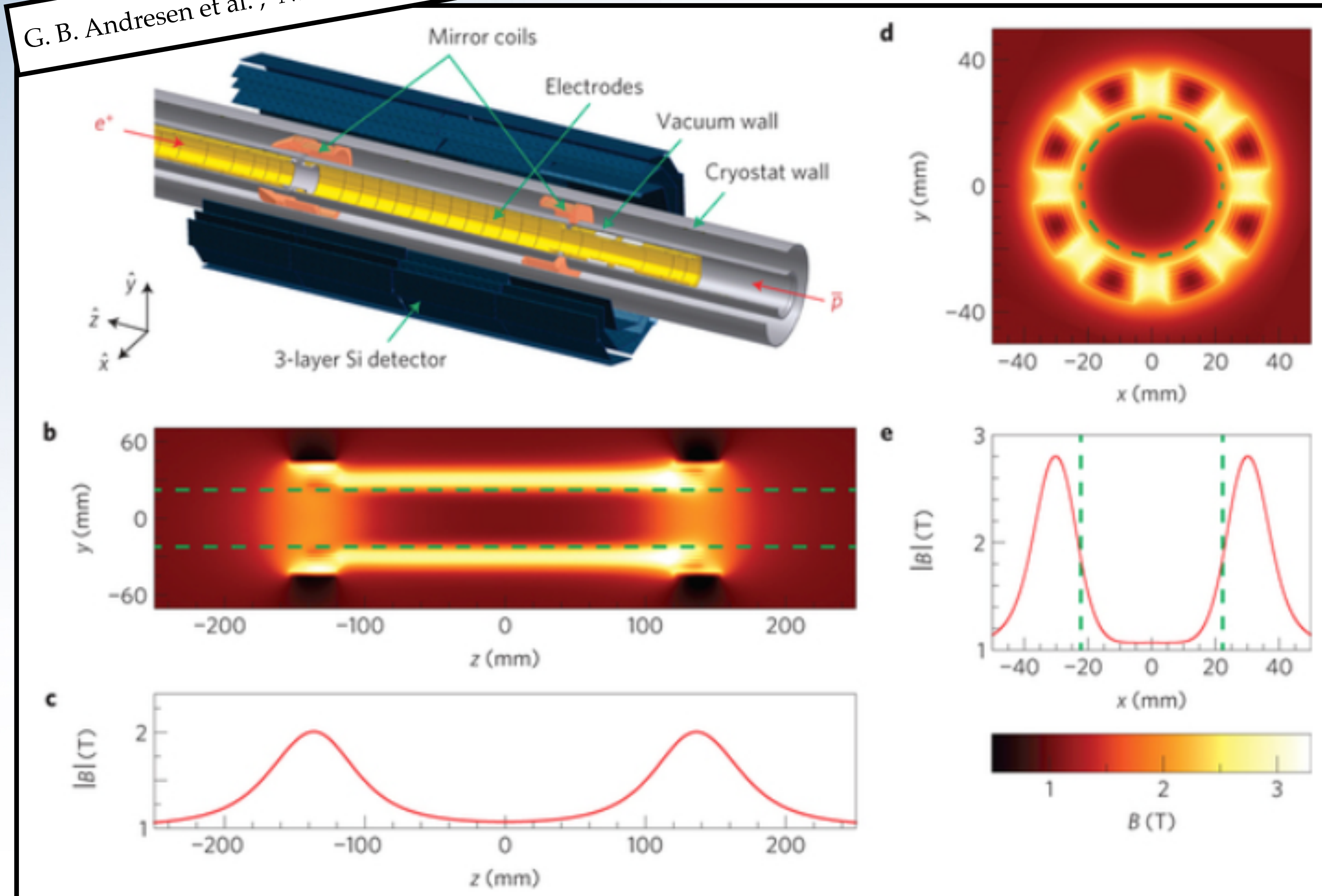
- Perform SPECTROSCOPY

very slow $\bar{H}$ (~100mK)

- Measure fall of $\bar{H}$

EITHER TRAP ANTIHYDROGEN…

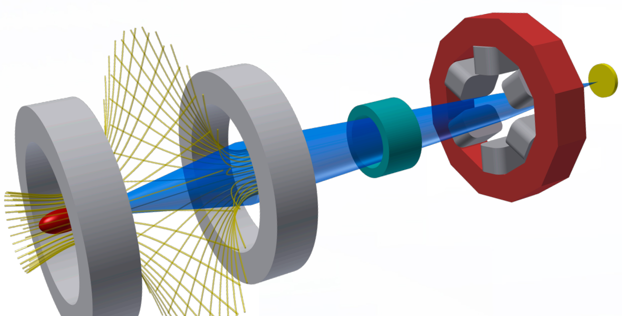
G. B. Andresen et al. , *Nature Physics* 7, 558–564 (2011)

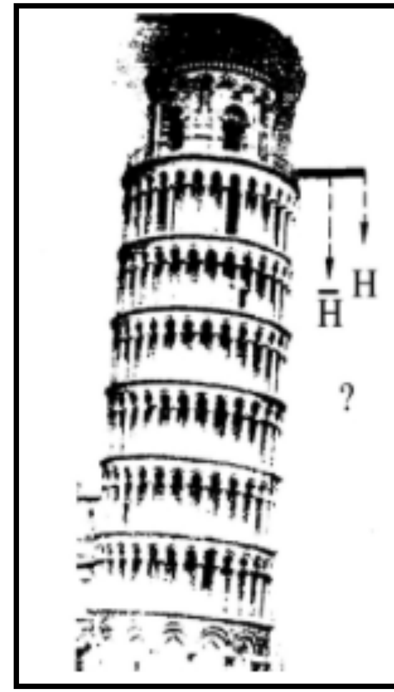


OR MAKE A BEAM OF ANTIHYDROGEN…

ASACUSA

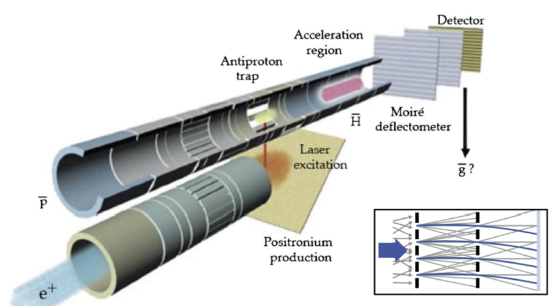
SPECTROSCOPY FOR CPT



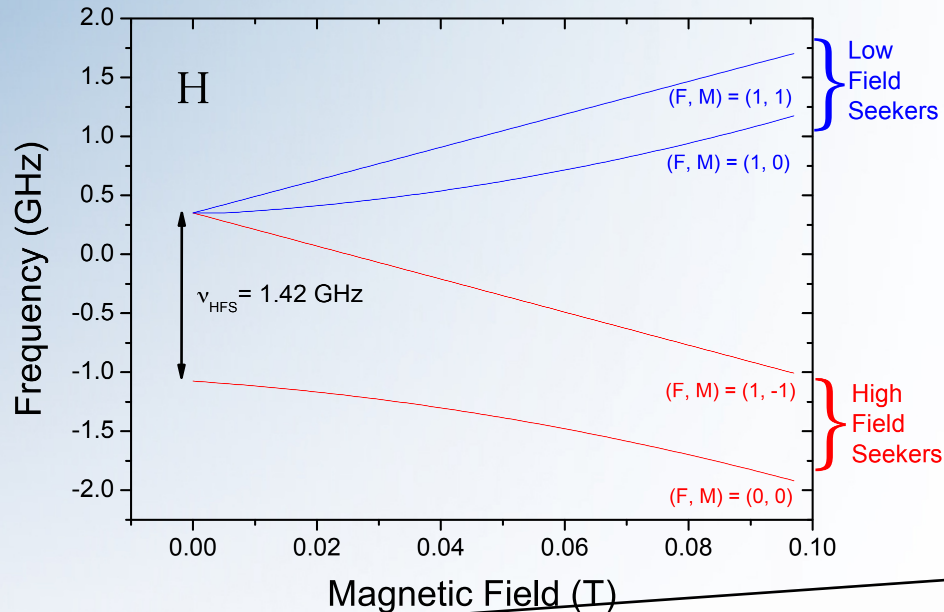


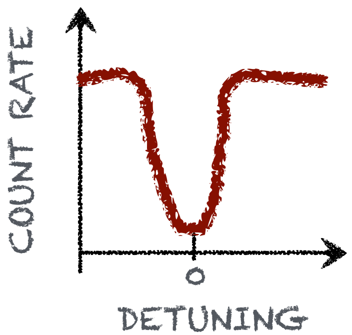
AEGIS

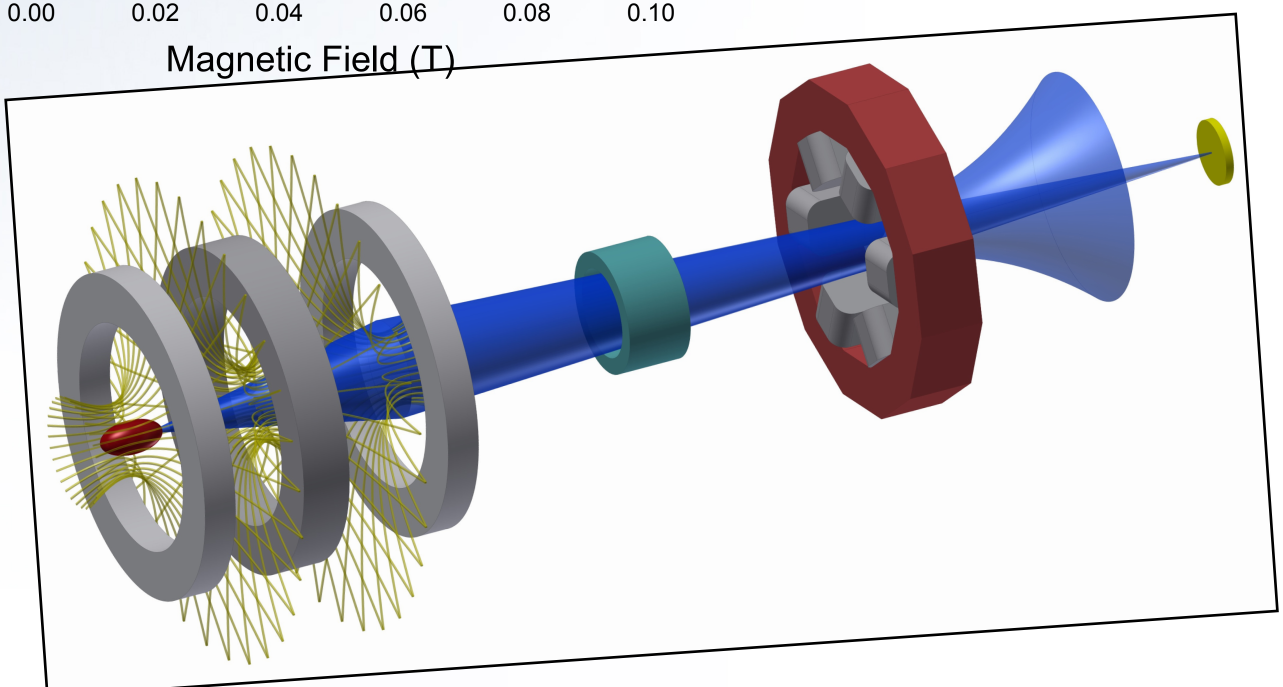
FALL OF ANTIHYDROGEN



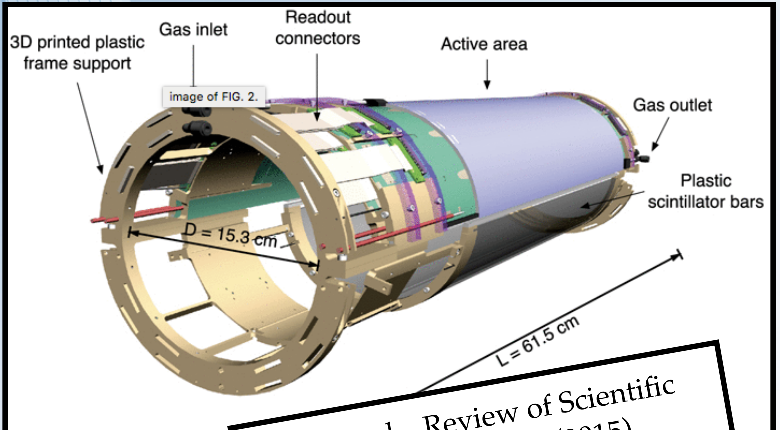
MEASUREMENT PRINCIPLE





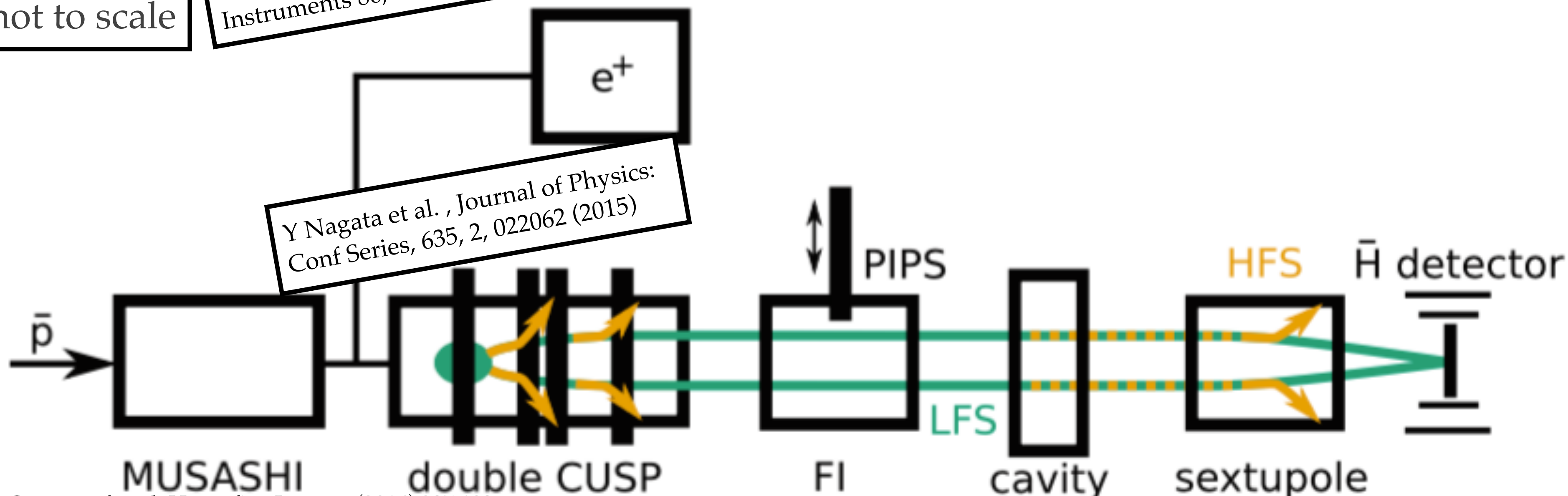


ASACUSA ANTIHYDROGEN BEAMLINE



Radics et al., Review of Scientific Instruments 86, 083304 (2015)

not to scale



Y Nagata et al. , Journal of Physics: Conf Series, 635, 2, 022062 (2015)

C. Sauerzopf et al. Hyperfine Interact (2016) 237:103

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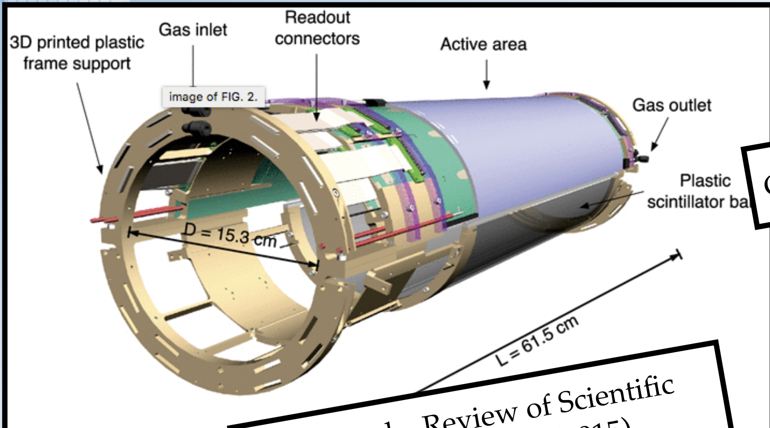

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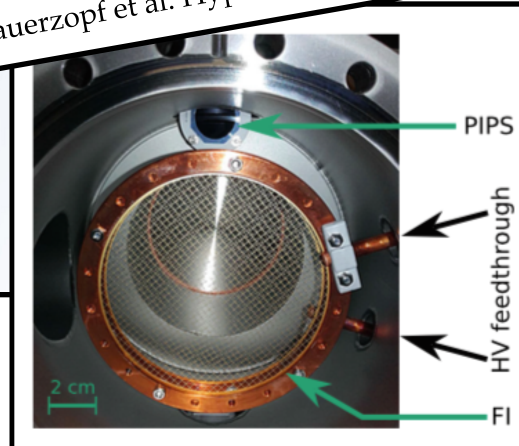

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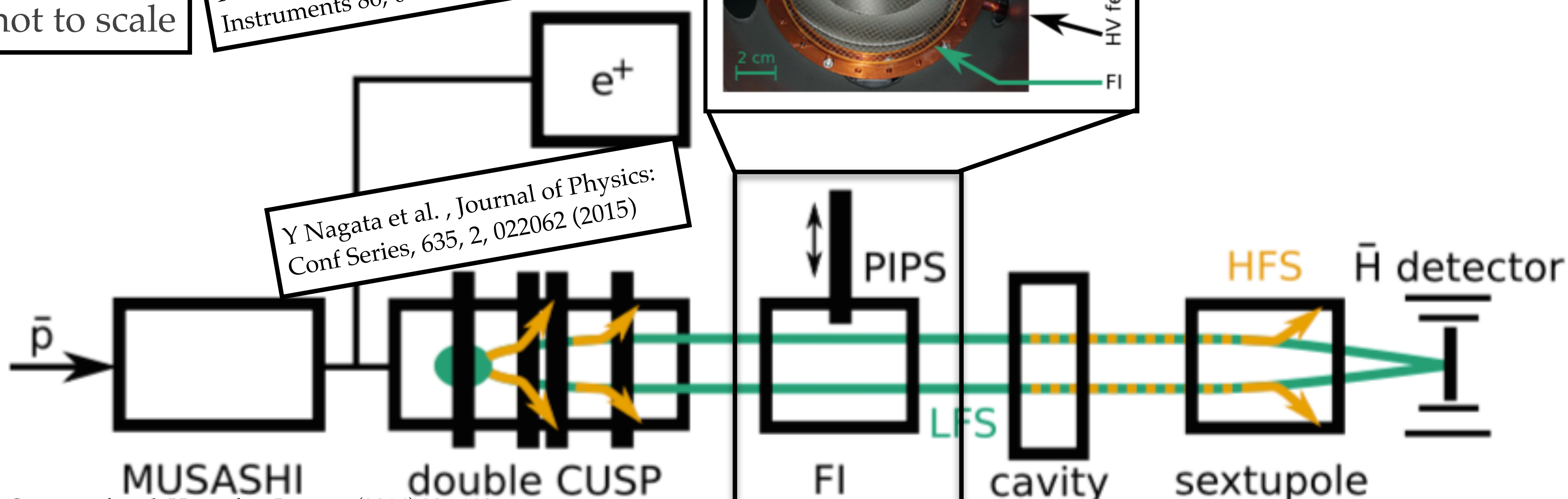

C. Sauerzopf et al. Hyperfine Interact (2016) 237:103

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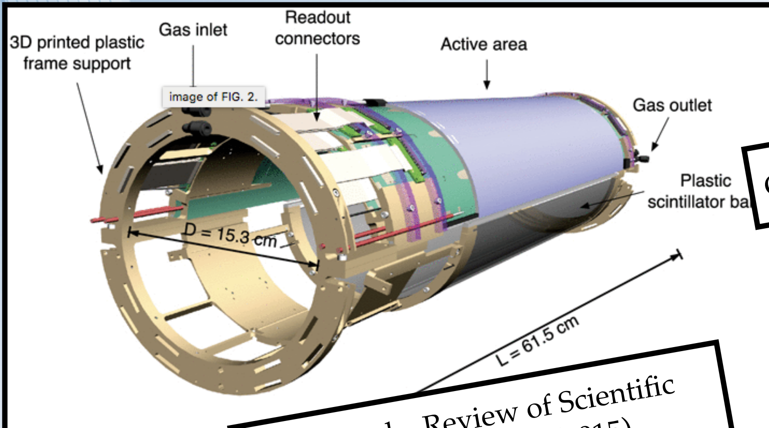

Radics et al., Review of Scientific Instruments 86, 083304 (2015)

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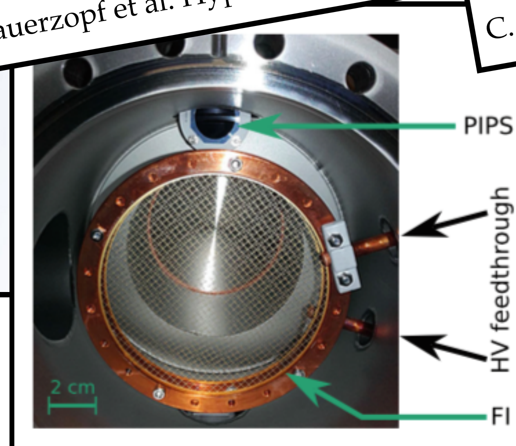
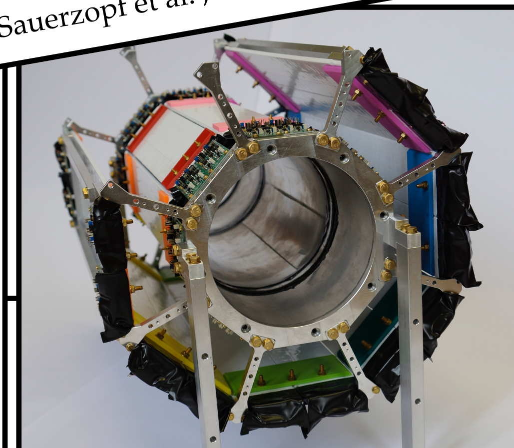


C. Sauerzopf et al. , NIM A , 0168-900 (2016)



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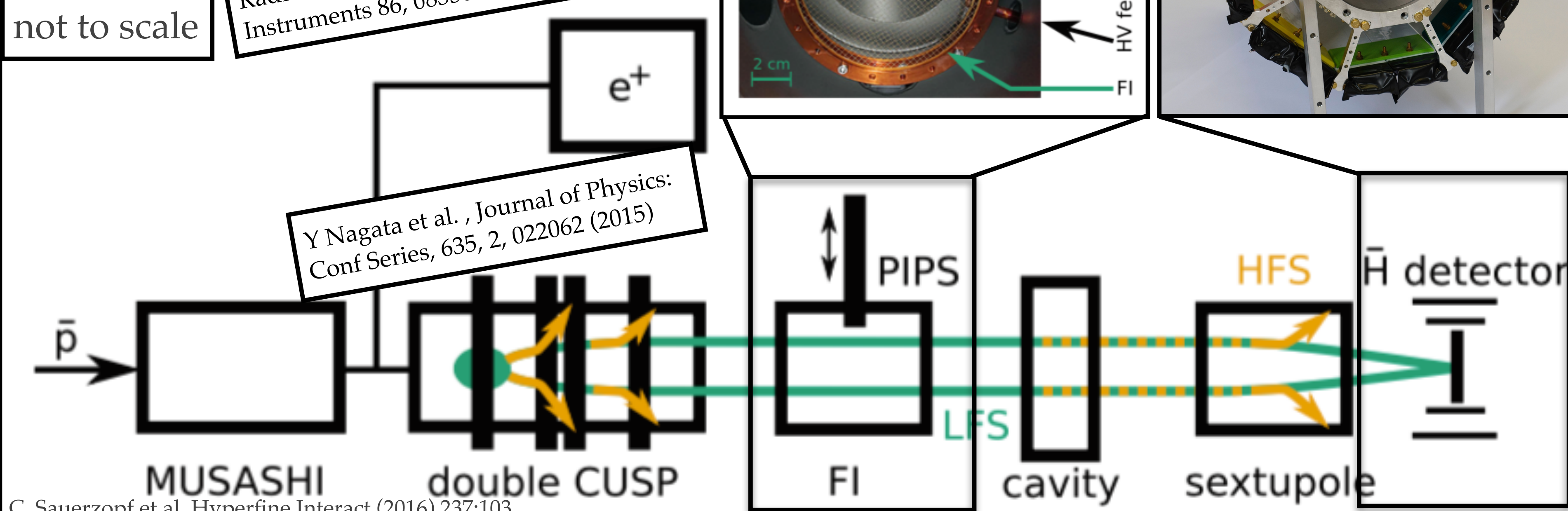
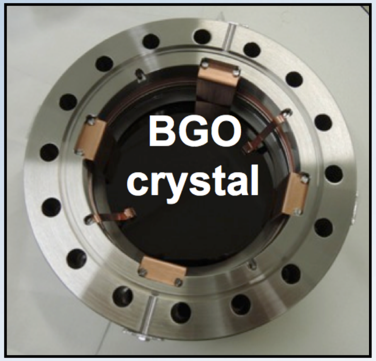


C. Sauerzopf et al. Hyperfine Interact (2016) 237:103

$\bar{H}$ CHARACTERIZATION

$\bar{H}$ Detector

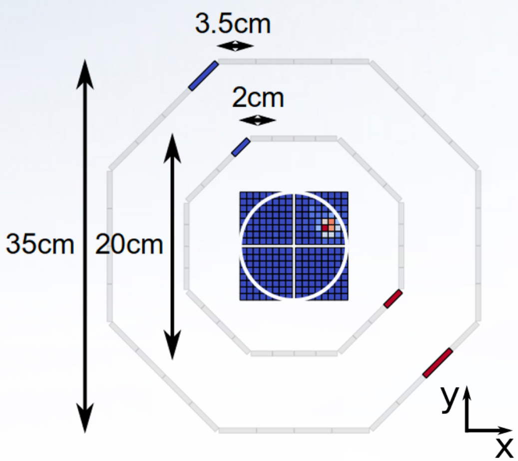
Solid angle (mixing point - detector): ~0.004%



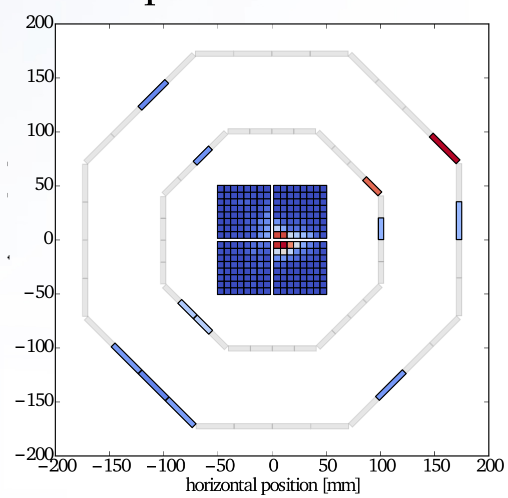
Annihilation: BGO crystal (position sensitive calorimeter)

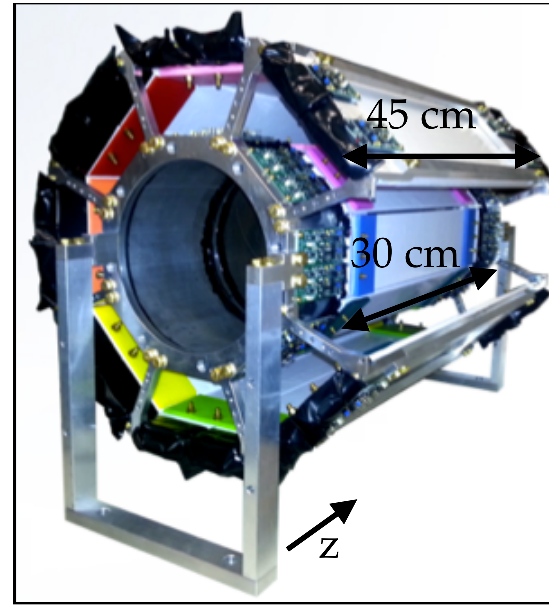
read out by MchPMT array of 16x16 for position resolution

Cosmic event



$\bar{p}/\bar{H}$ event



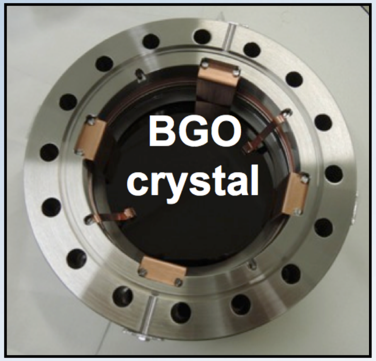


- 2 layers hodoscope
- 32 (8x4) scintillator bars each
- SiPMs on each side
- axial resol. by time difference (vertex reconstruction capability
- fast timing enables cosmic discrimination
- >50% efficiency, <1% false IDs

H̄ CHARACTERIZATION

H̄ Detector

<u>Solid angle </u>(mixing point - detector): ~0.004%



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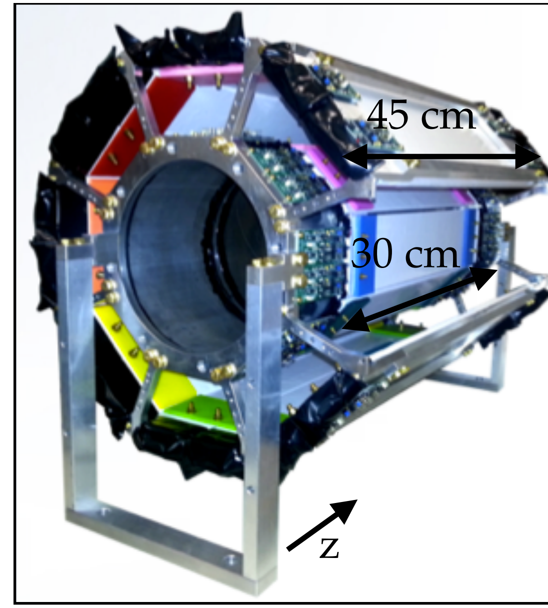
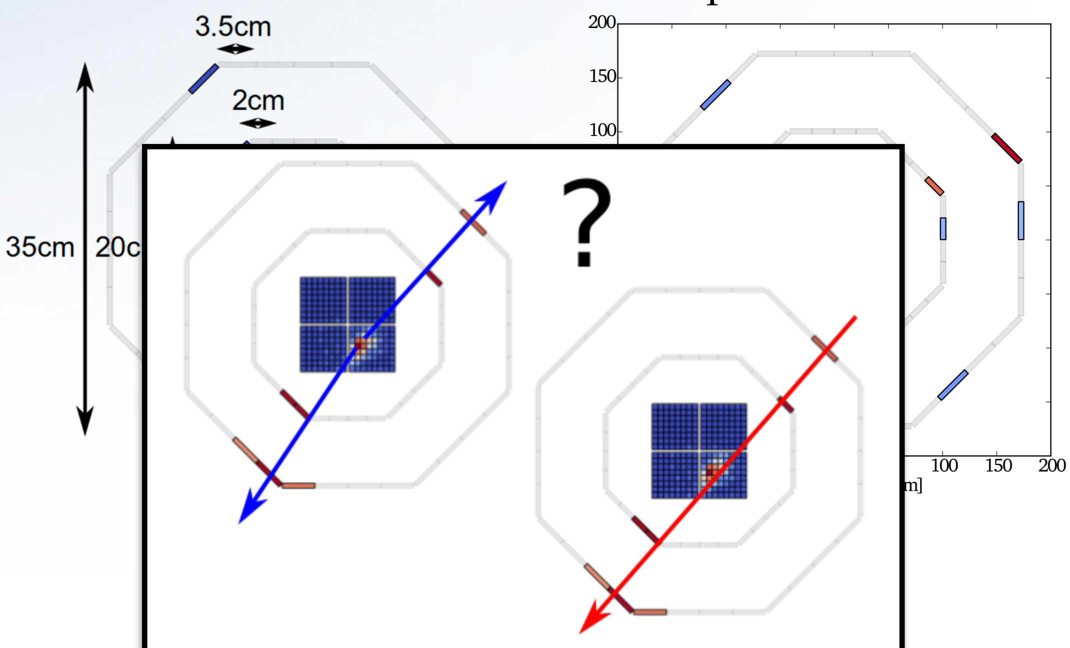


Cosmic event

p̄ / H̄ event

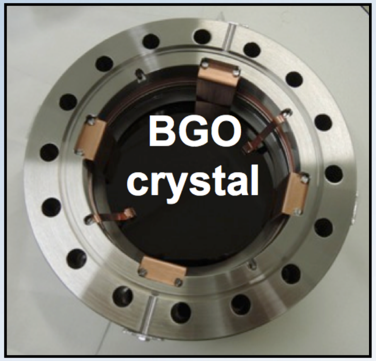


- 2 layers hodoscope
- 32 (8x4) scintillator bars each
- SiPMs on each side
- axial resol. by time difference (vertex reconstruction capability
- fast timing enables cosmic discrimination
- >50% efficiency, <1% false IDs

$\bar{H}$ CHARACTERIZATION

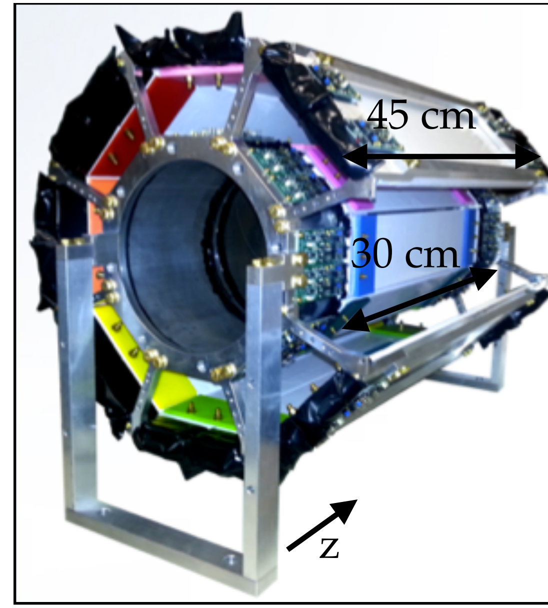
$\bar{H}$ Detector

Solid angle (mixing point - detector): ~0.004%



Annihilation: BGO crystal (position sensitive calorimeter)

read out by MchPMT array of 16x16 for position resolution



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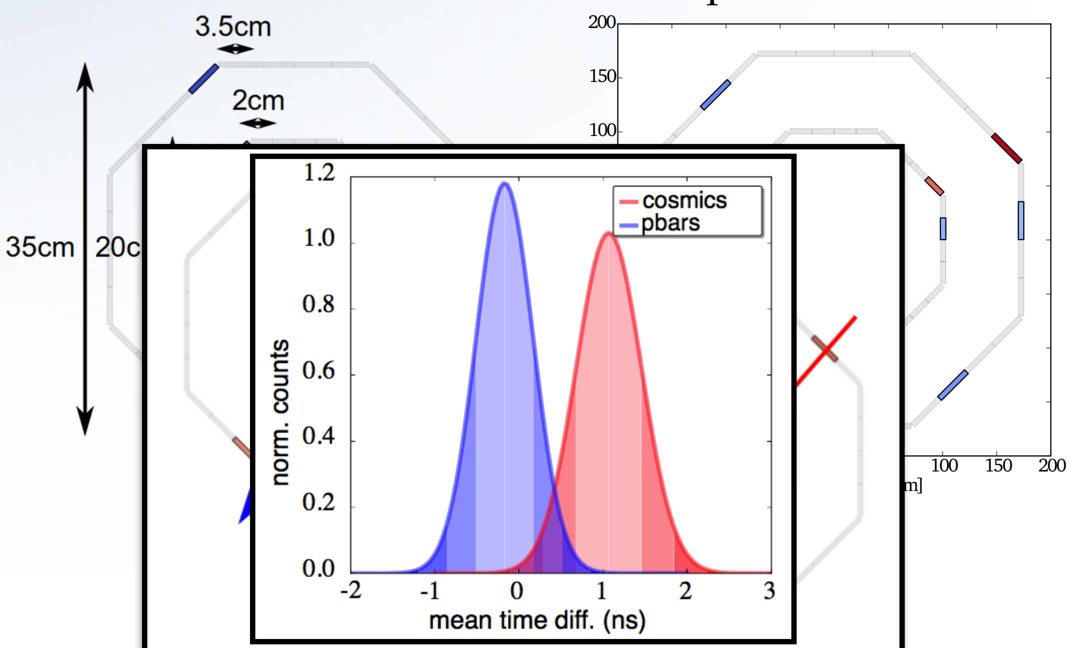
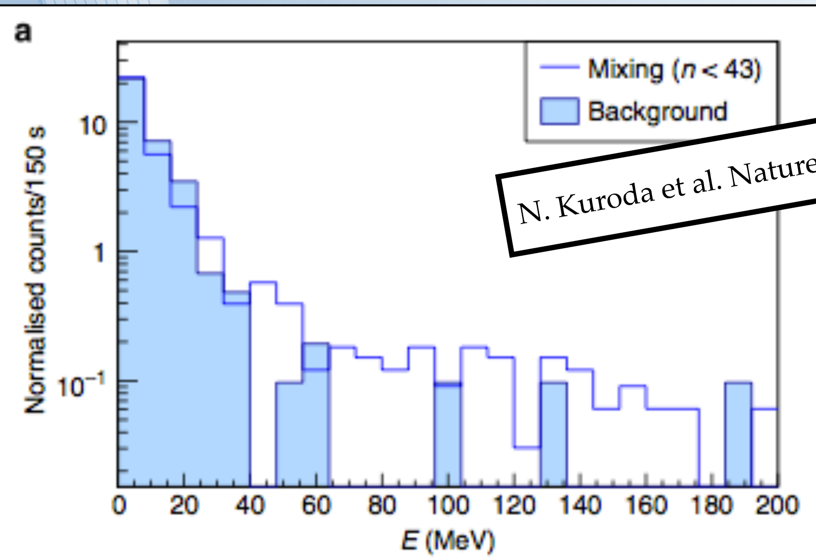
Cosmic event

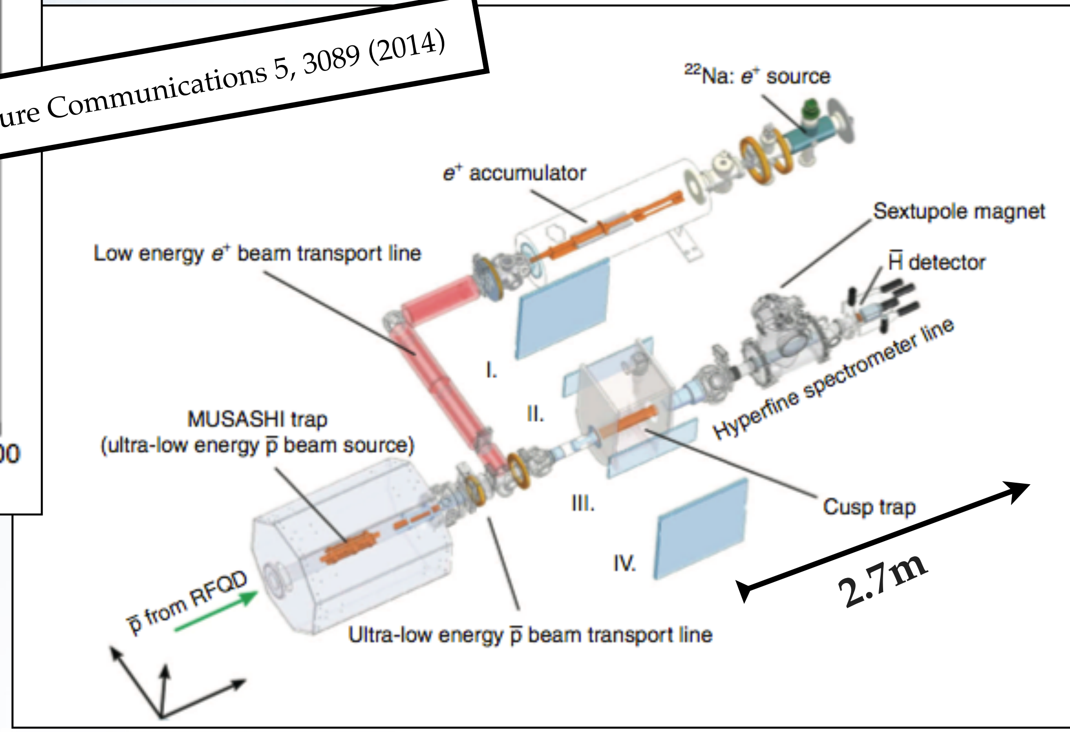
$\bar{p}/\bar{H}$ event



"BEAM" OBSERVATION



N. Kuroda et al. Nature Communications 5, 3089 (2014)



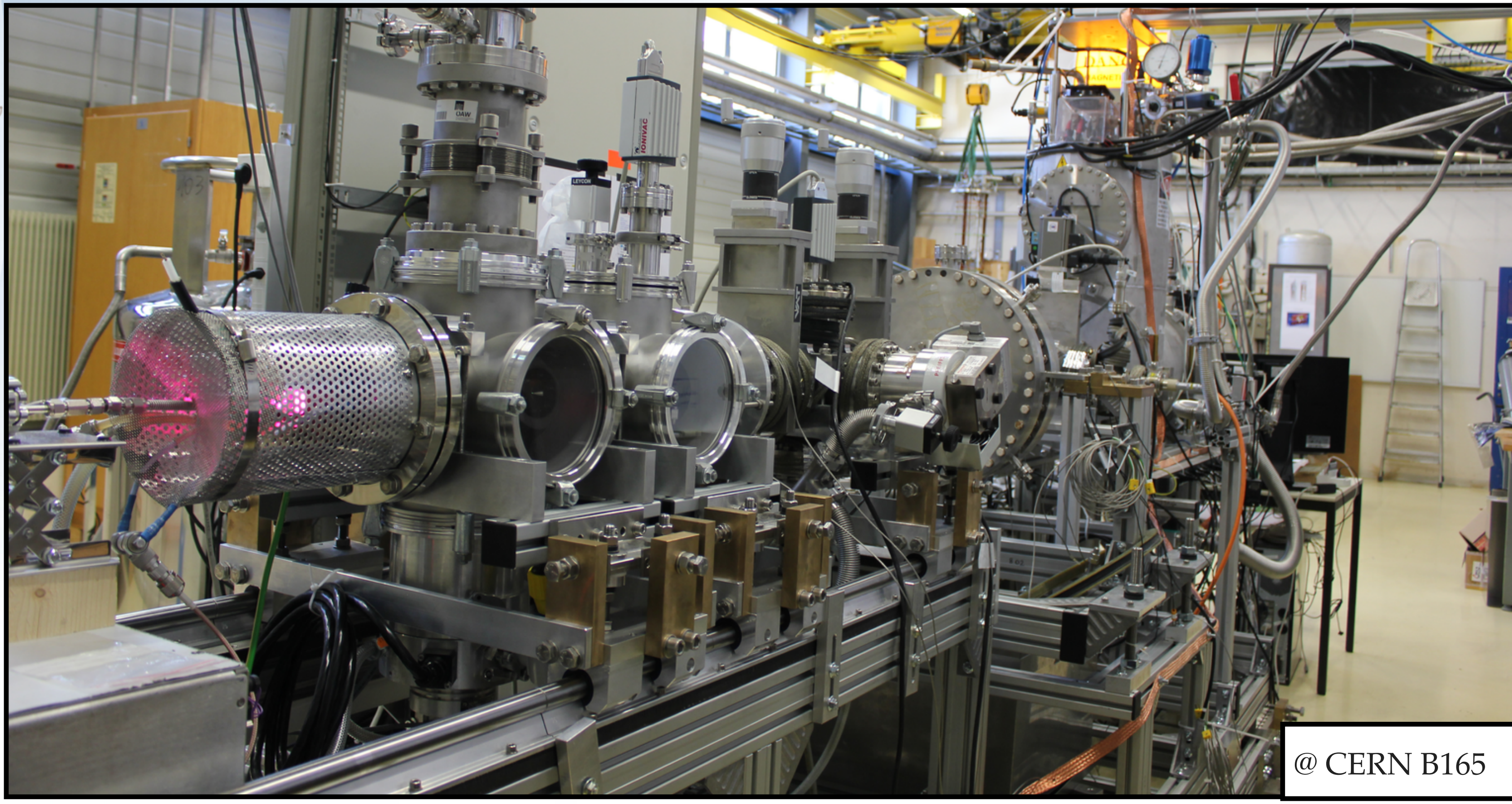
80 atoms detected in a <u>field-free</u> region

Internal CUSP field ionizer to investigate the time structure of antihydrogen formation
Field ionizer before the detector : detection of n<43 (some n<29)

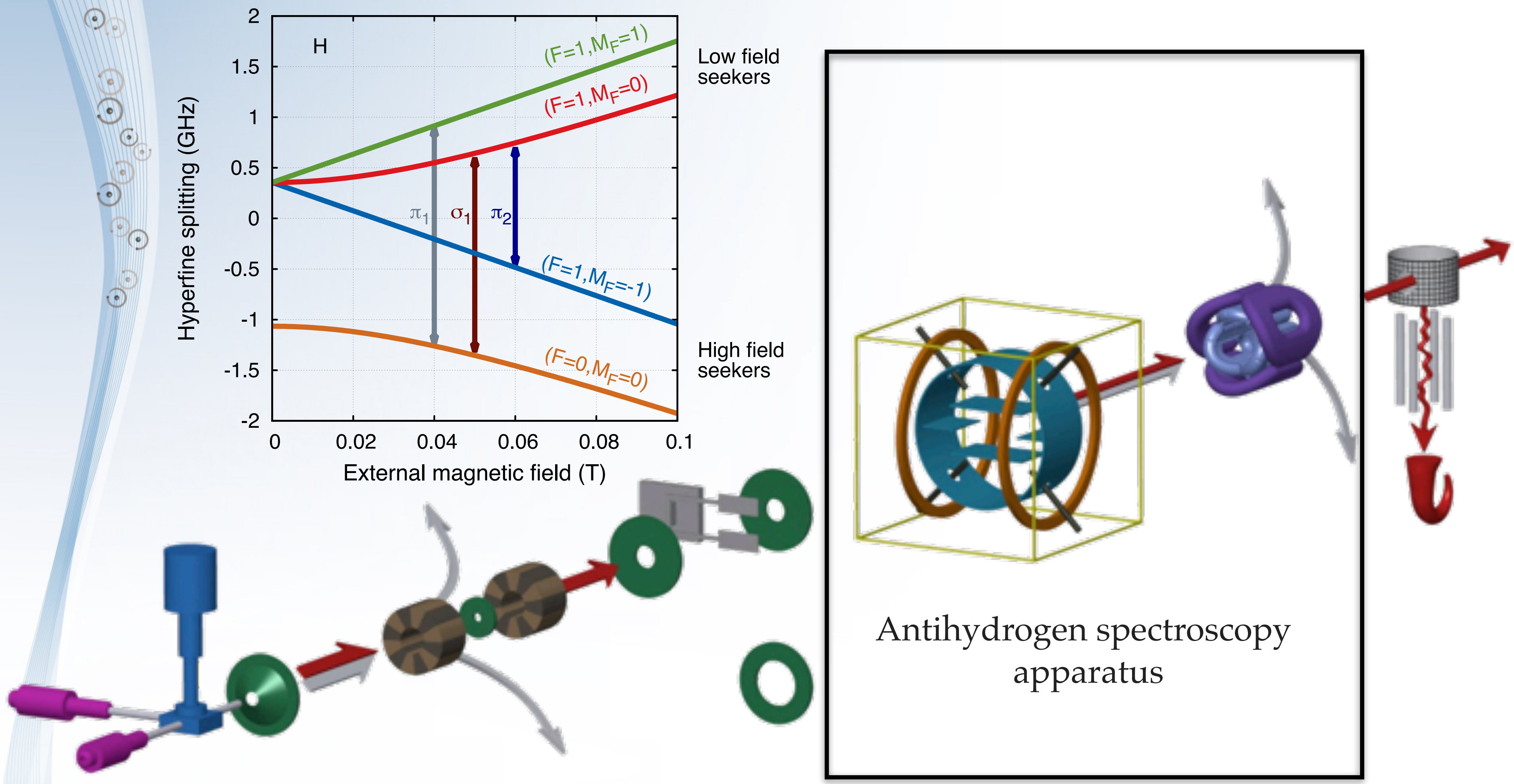
<u>NEXT</u>:

1) Further characterization of the antihydrogen beam : Quantum state distribution, velocity, polarisation
2) Characterization of spectroscopy beamline

ASACUSA (ANTI)HYDROGEN BEAMLINE

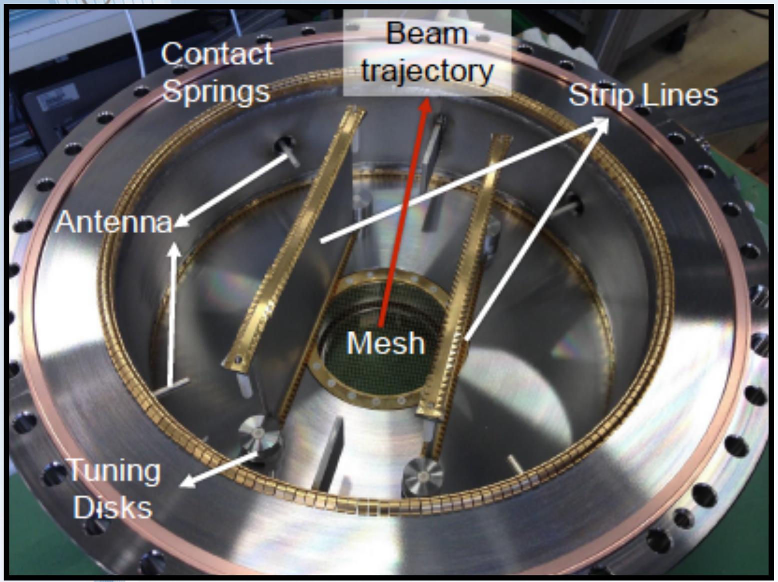


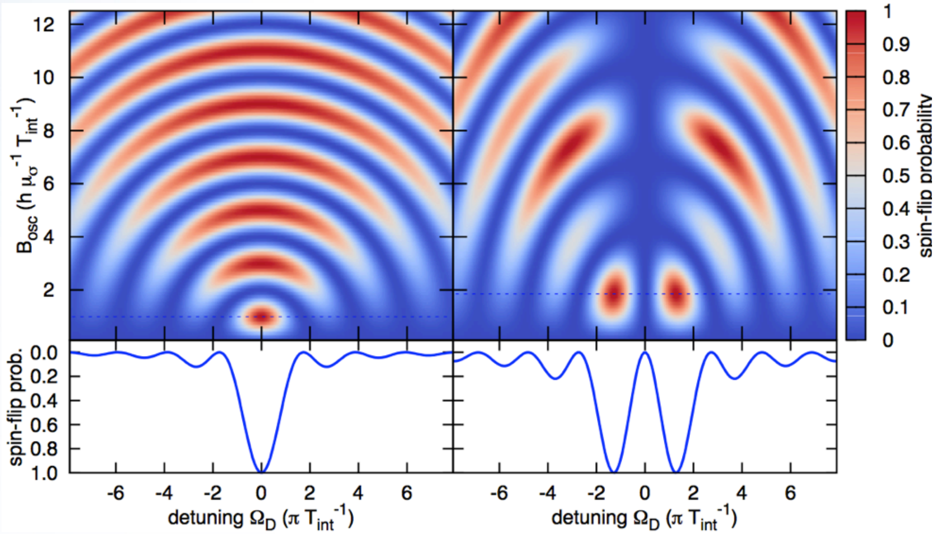
ASACUSA (ANTI)HYDROGEN BEAMLINE

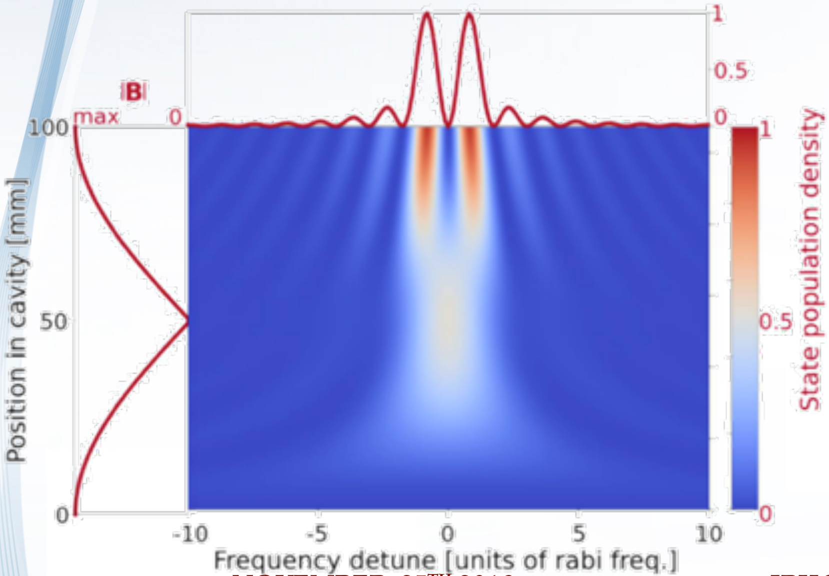


MEASUREMENT OF SIGMA RESONANCE

"strip-line" cavity design

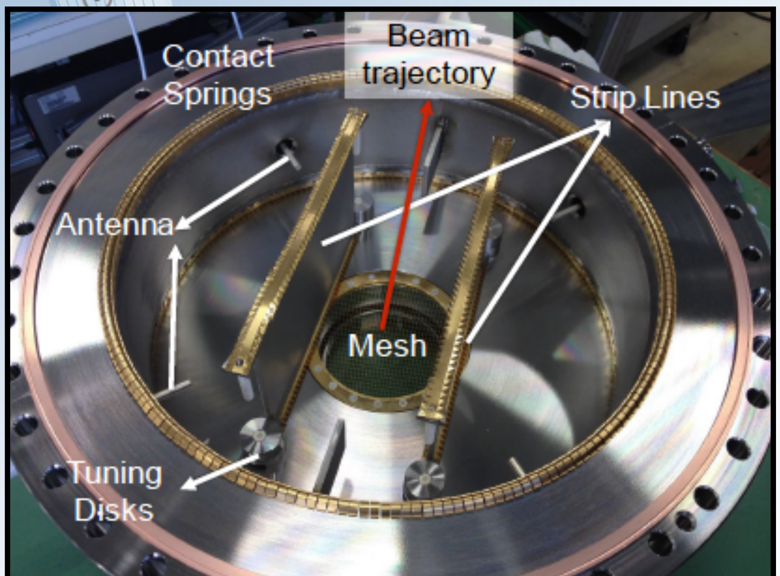


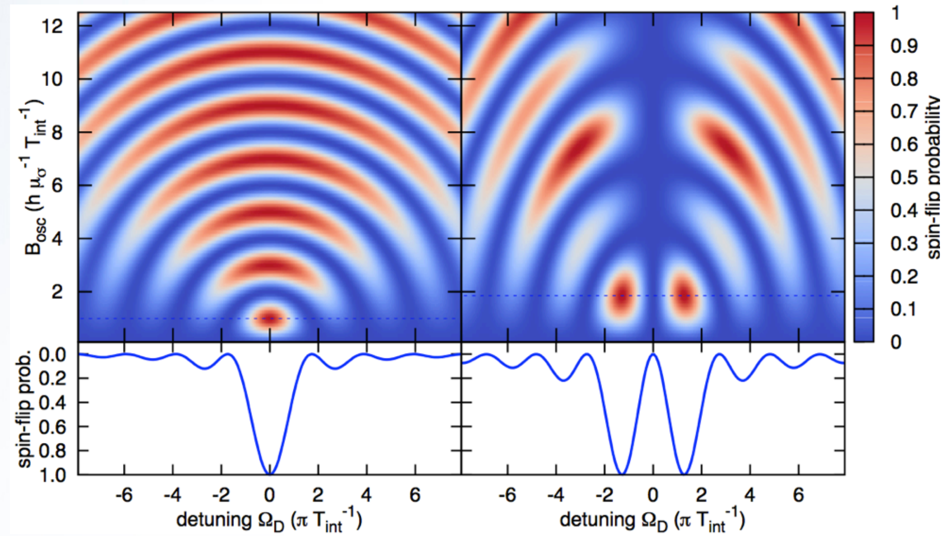


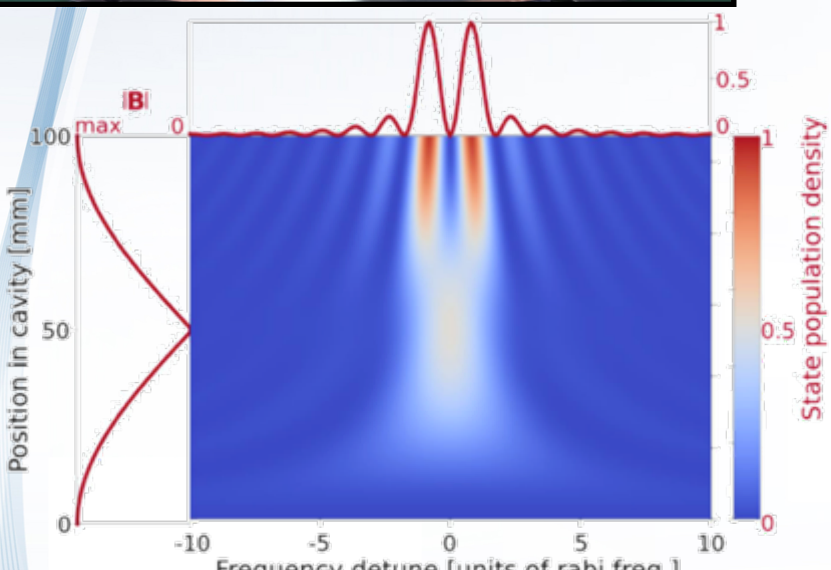


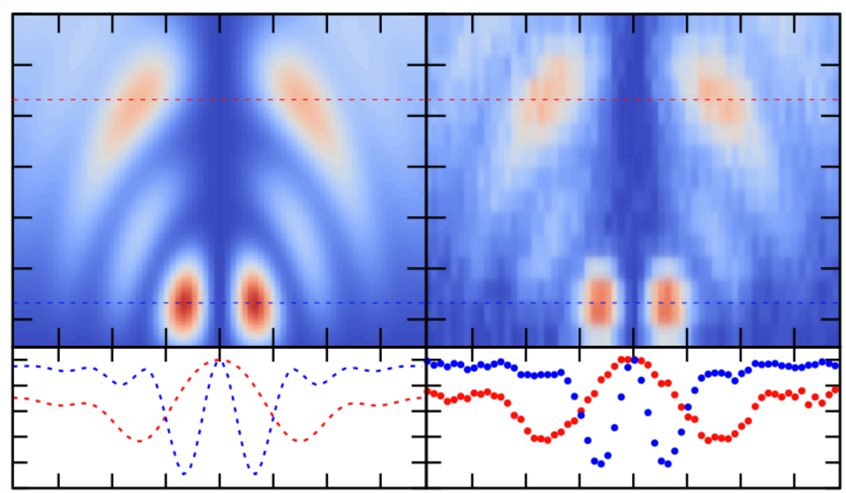
MEASUREMENT OF SIGMA RESONANCE

"strip-line" cavity design



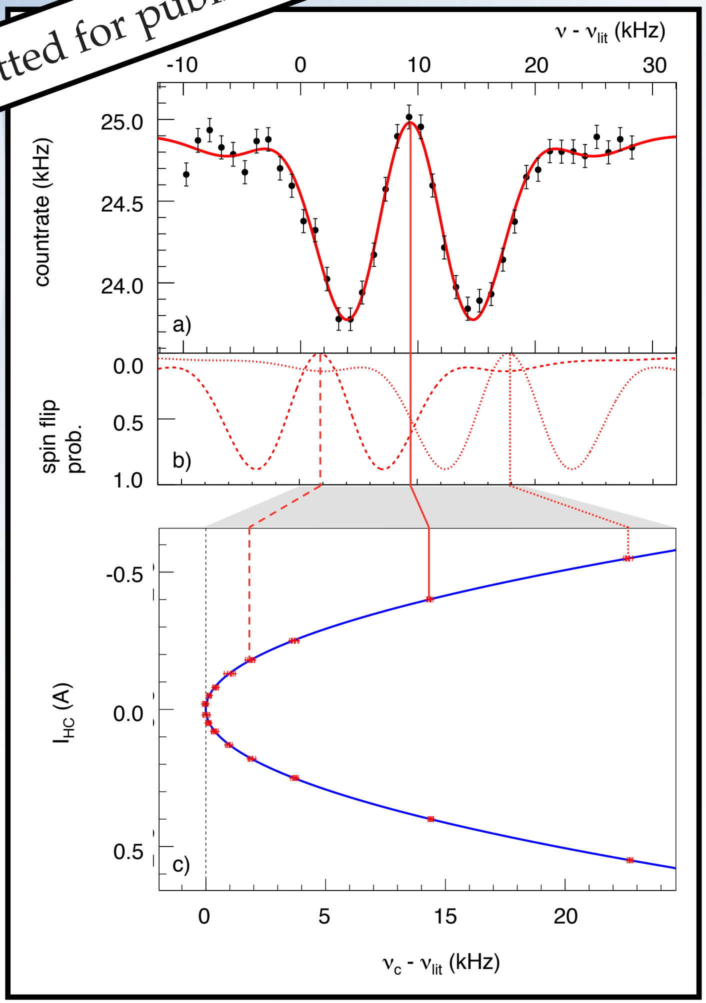






RESULTS

Submitted for publication



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

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

Robust lineshape fit

Extraction of amplitude of oscillatory field, velocity and velocity spread

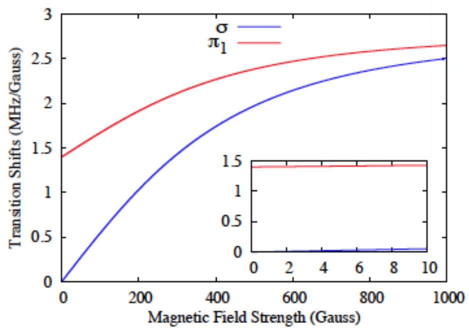
The spectroscopy apparatus if fully commissioned

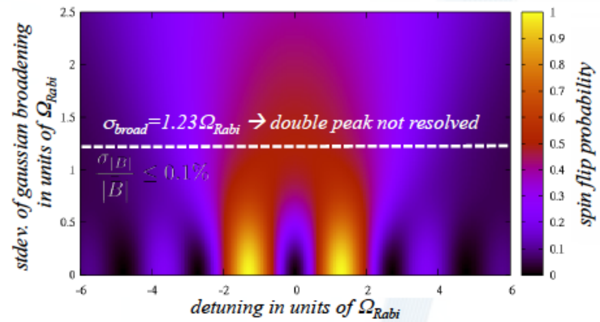
ppm result with antihydrogen should be in reach if enough statistics can be gathered

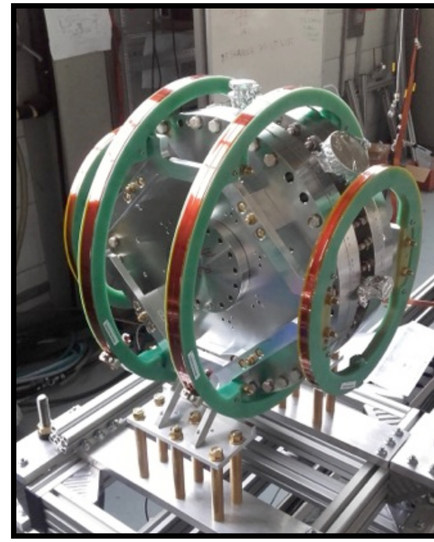
MEASURING Π RESONANCE

$$\Delta f = \frac{\partial f}{\partial B}\Delta B \approx \frac{\mu_B}{h}\sigma_B \approx 1.4\frac{\text{MHz}}{\text{Gauss}}\sigma_B$$

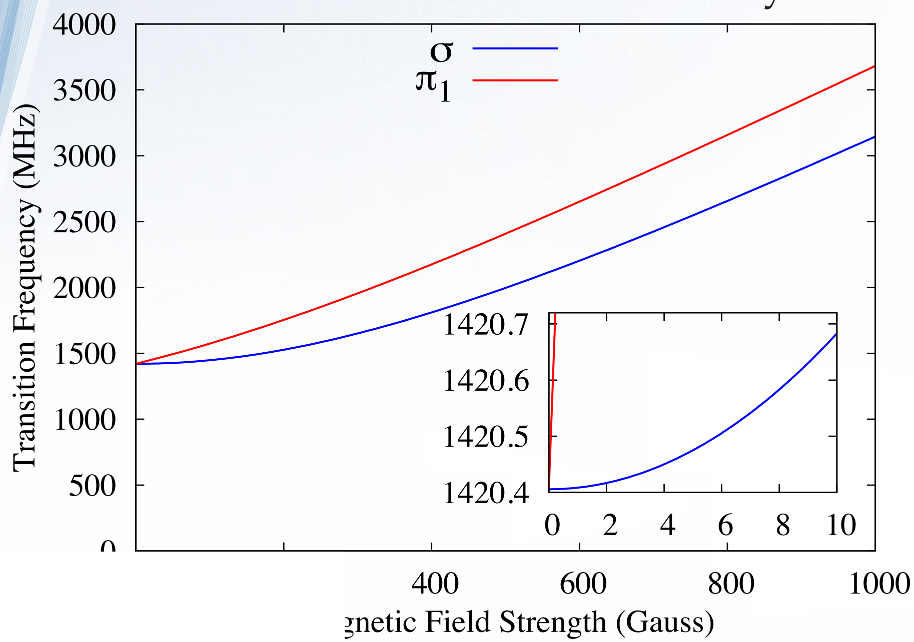
$$\delta f \propto \frac{v_{\bar{H}}}{L_{\text{cav}}} \approx \frac{1\text{km/s}}{0.1\text{m}} \approx 10\text{kHz}$$

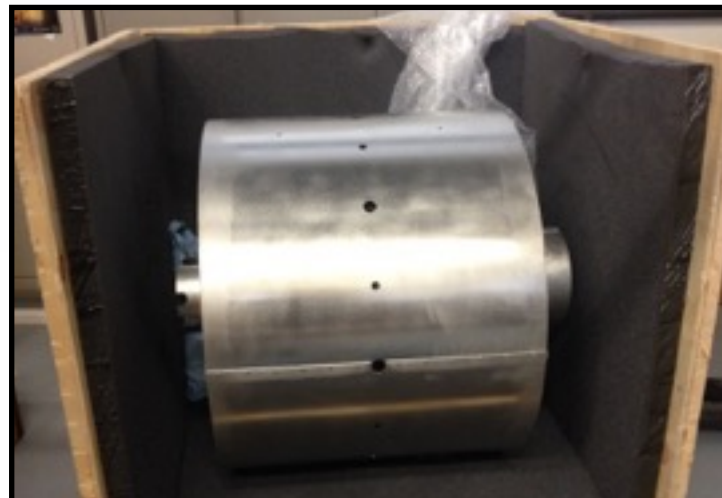






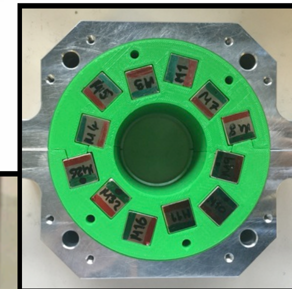
New coil and new 3-layers Mu metal shielding

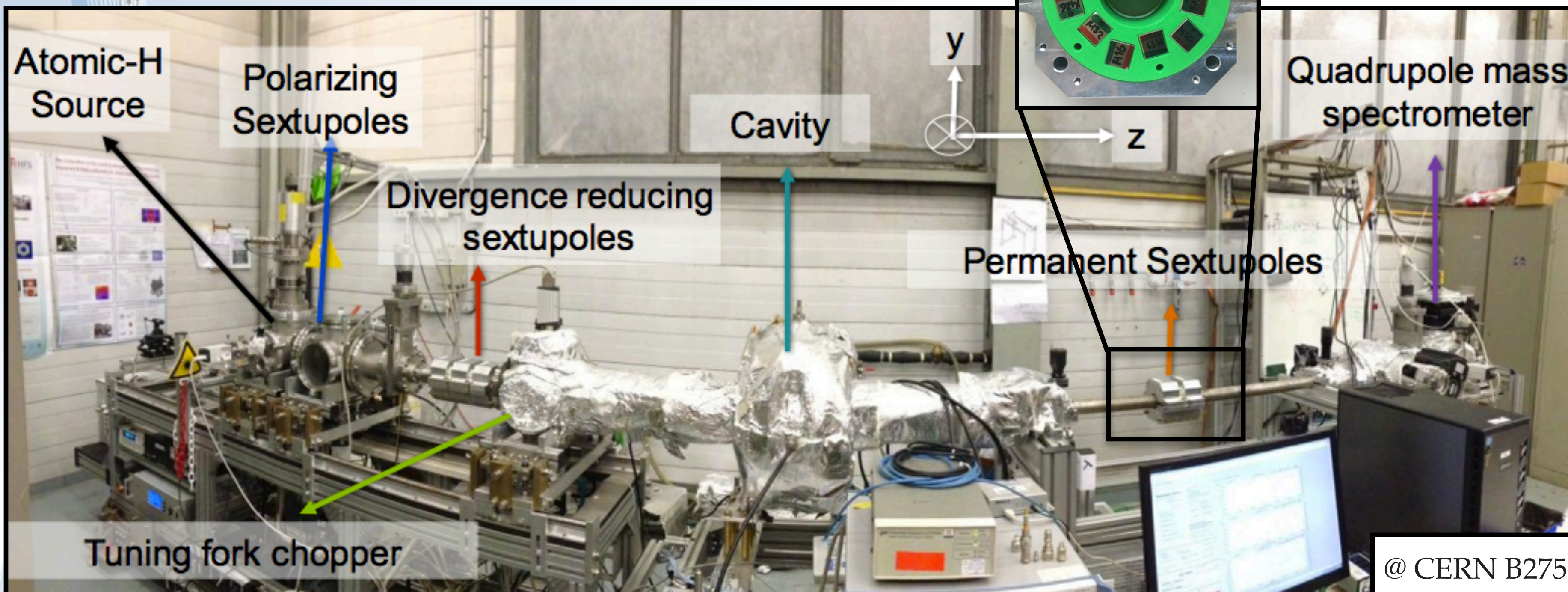


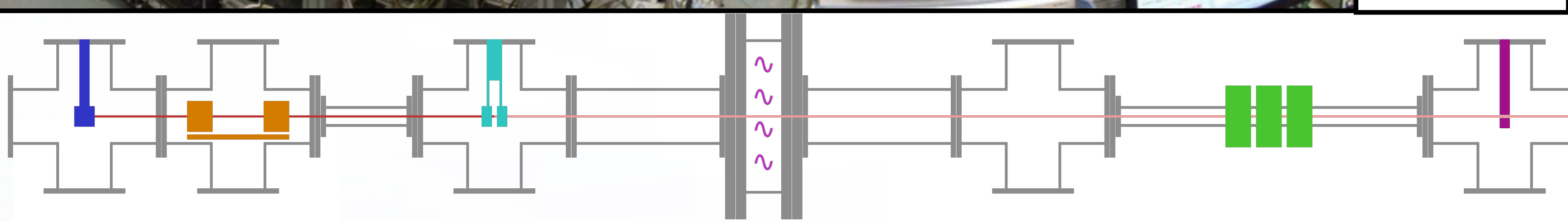


MEASURING Π RESONANCE

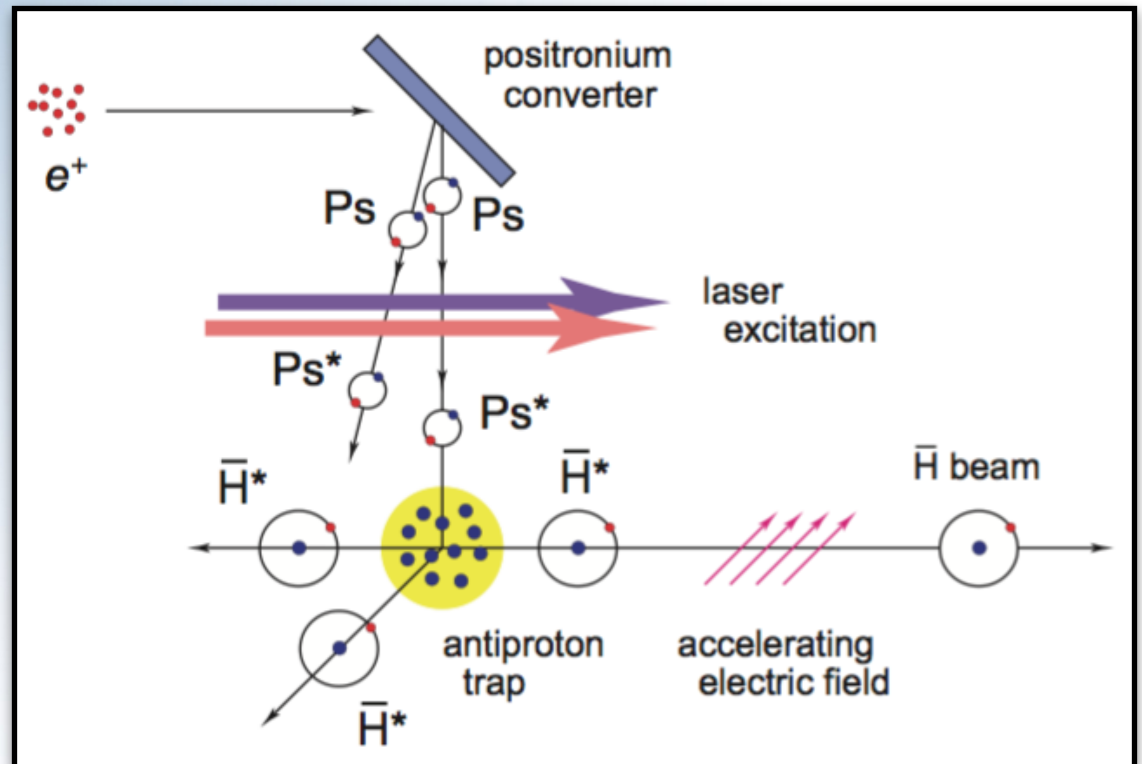
- π and σ sigma can be measured “simultaneously”
- π is better motivated for SME test
- Measure sidereal variations and different angles
- Improved precision using Ramsey
- Measurement with Deuterium







ANTIHYDROGEN PRODUCTION IN AEGIS



1. **o-Ps** production by impact of e+ on SiO_2 target (nano-porous insulator material)

2. Ps **laser excitation** into Rydberg levels

Formation rate enhanced

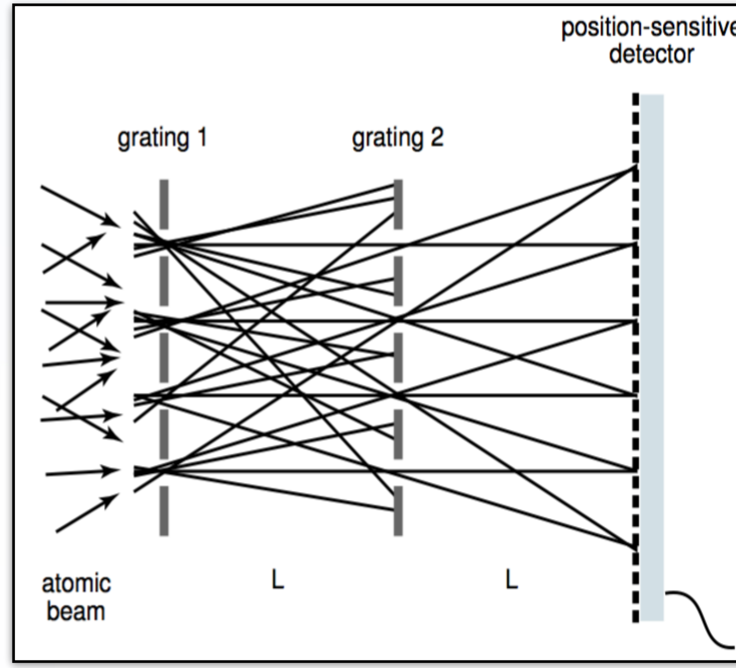
$$\sigma \propto n^4$$
$$\sigma(n_{\mathrm{Ps}} = 20) \sim 10^{-9}\mathrm{cm}^2$$

$\bar{\mathrm{H}}$ state defined by Ps state
$\bar{\mathrm{H}}$ velocity dominated by $\bar{\mathrm{p}}$

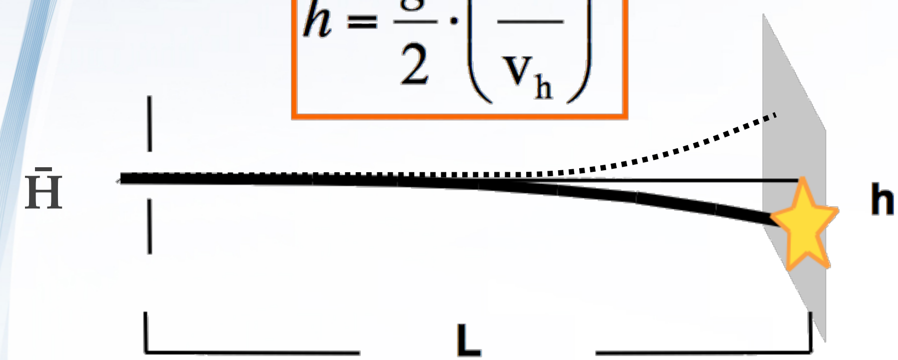
ANTIHYDROGEN DETECTION IN AEGIS

3. Formation of an $\bar{H}$ beam by **Stark acceleration** with inhomogeneous electric fields

4. Measurement of $\bar{g}$ in a two-grating **moiré deflectometer** coupled to a position-sensitive detector.



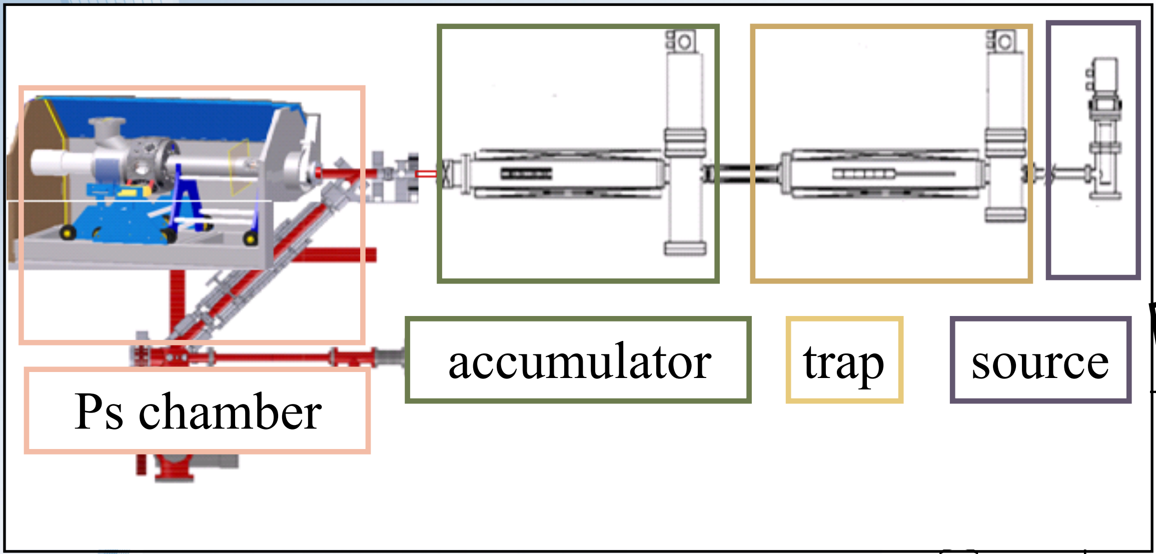
$$h = \frac{g}{2} \cdot \left(\frac{L}{v_h} \right)^2$$



- Rydberg atoms are sensitive to el. field gradients.
- Accelerate the $\bar{H}$ along z-axis to few 100m/s

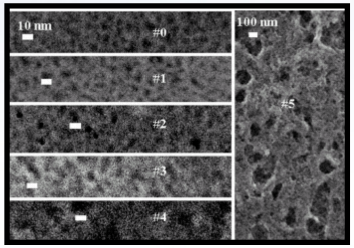
POSITRONIUM FORMATION&EXCITATION

Single Shot Positron Annihilation Lifetime Spectroscopy (SSPALS) measurement
Positrons impinging:
(a) passive surface (MCP)
(b) nanochanneled Si

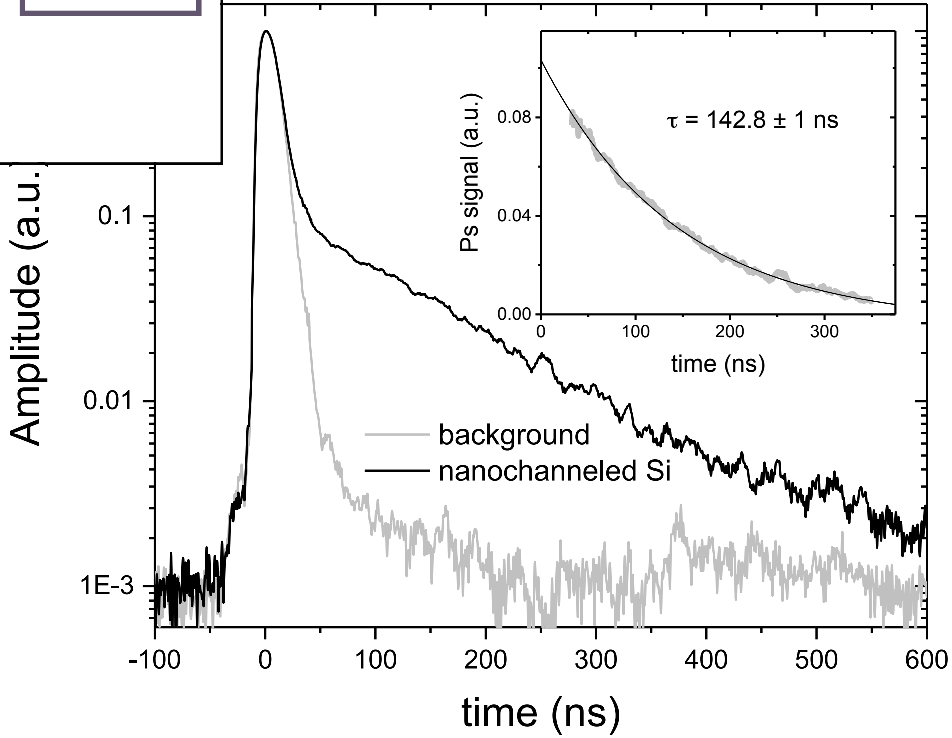


S. Aghion et al., NIMB 362 (2015) 86

~4 10^6 Ps atoms in vacuum

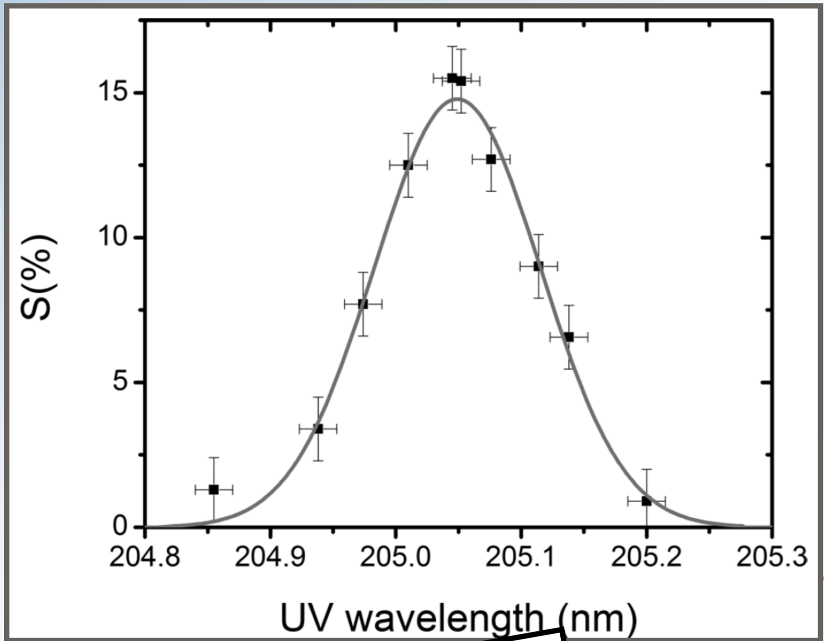


nanochanneled Si
(5-100 nm range, depth 2 um)



POSITRONIUM FORMATION &EXCITATION

$$S(\%) = (\text{Area laser OFF - Area laser ON})/\text{Area laser OFF}$$

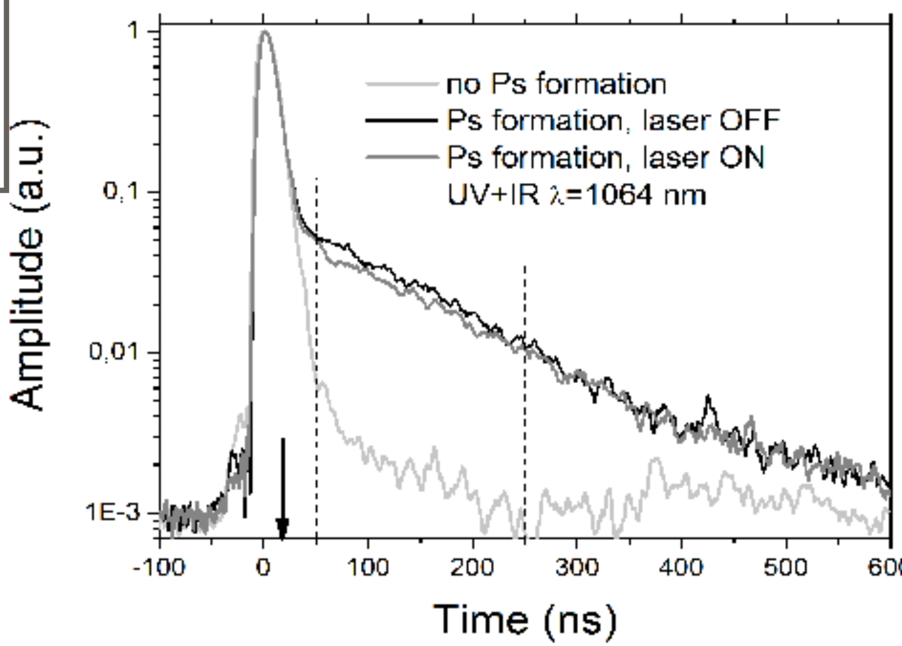


S. Aghion et al., PRA 94 (2016) 012507]

3P Excitation line centered at

$\sim 205.05 \pm 0.02\text{nm}$

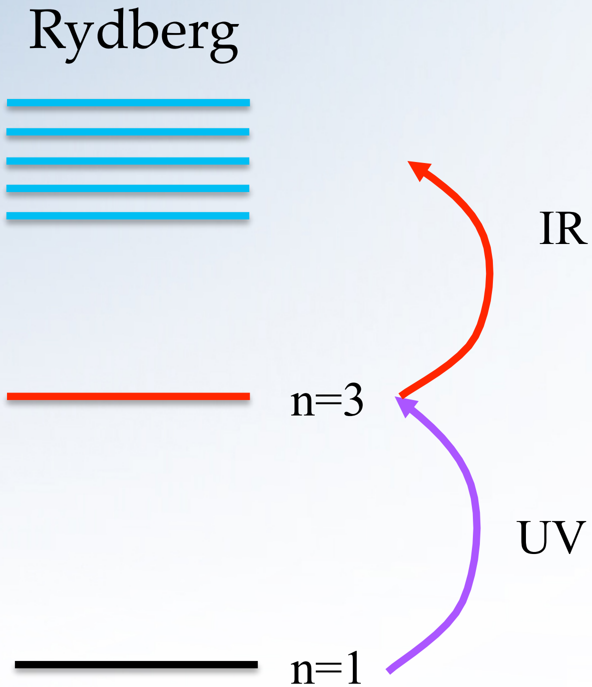
METHOD:
- quenching in a magnetic field
- photo-ionization

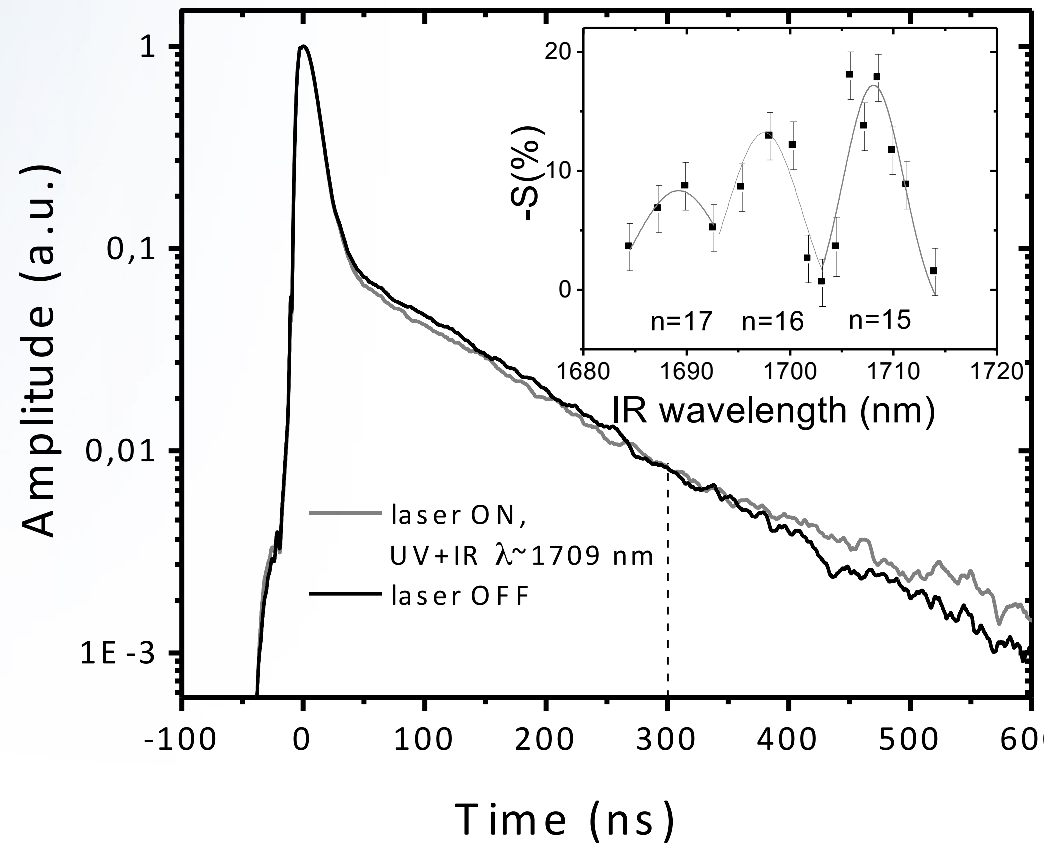


excitation- ionization efficiency ~15%

POSITRONIUM FORMATION &EXCITATION

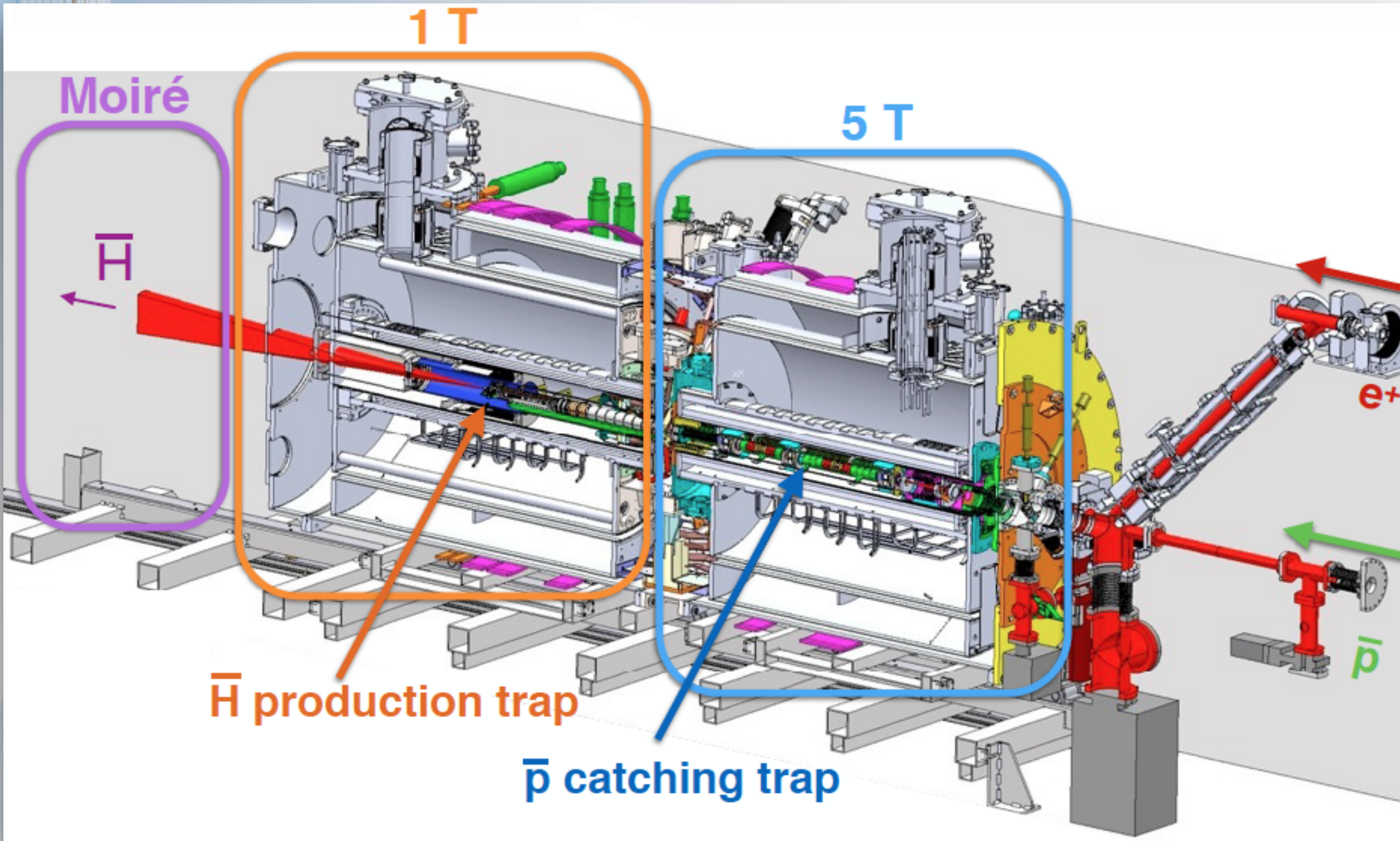
Rydberg excitation



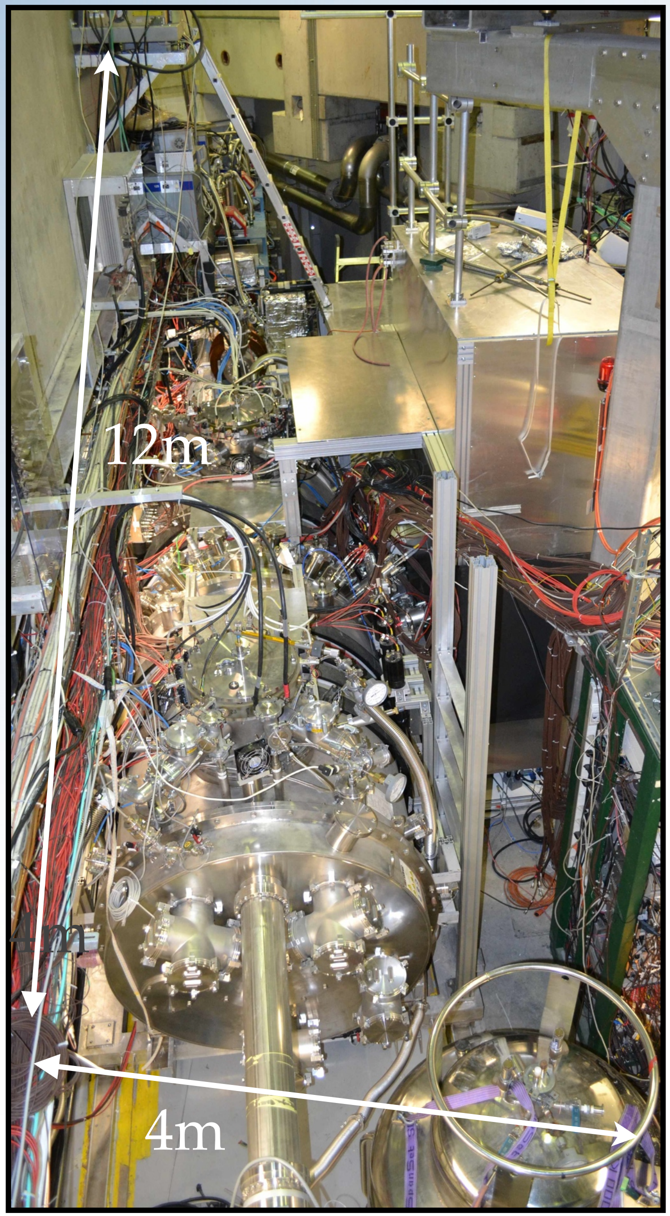


S(%)=(Area laser OFF-Area laser ON)/Area laser OFF

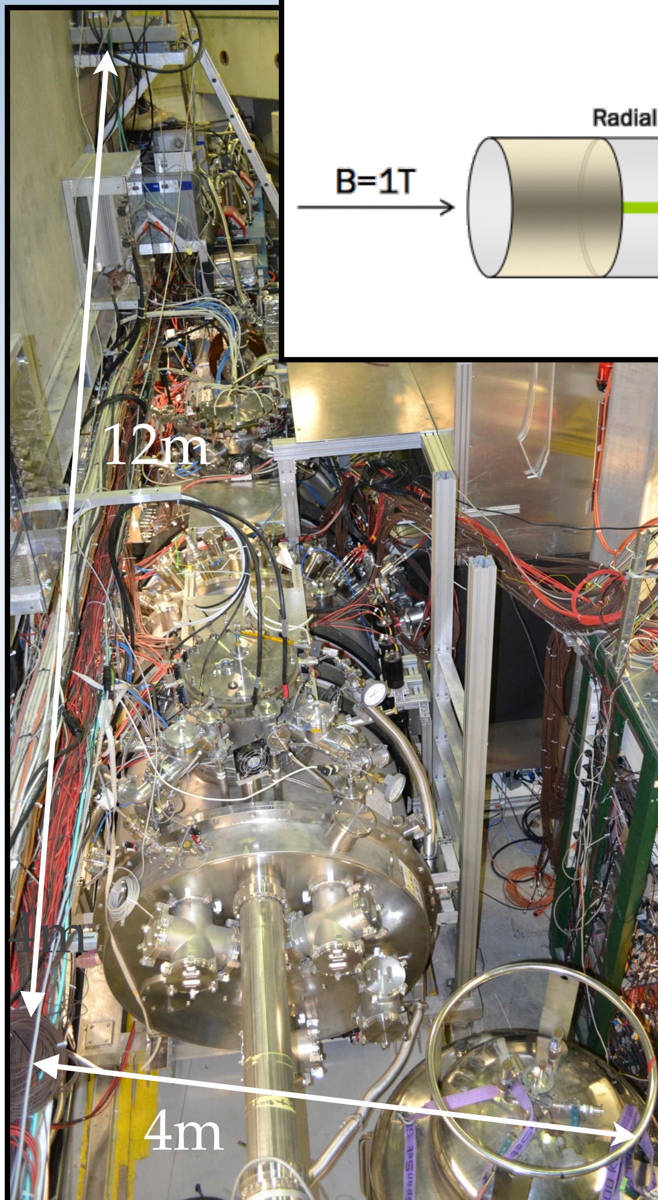
EXPERIMENTAL SETUP

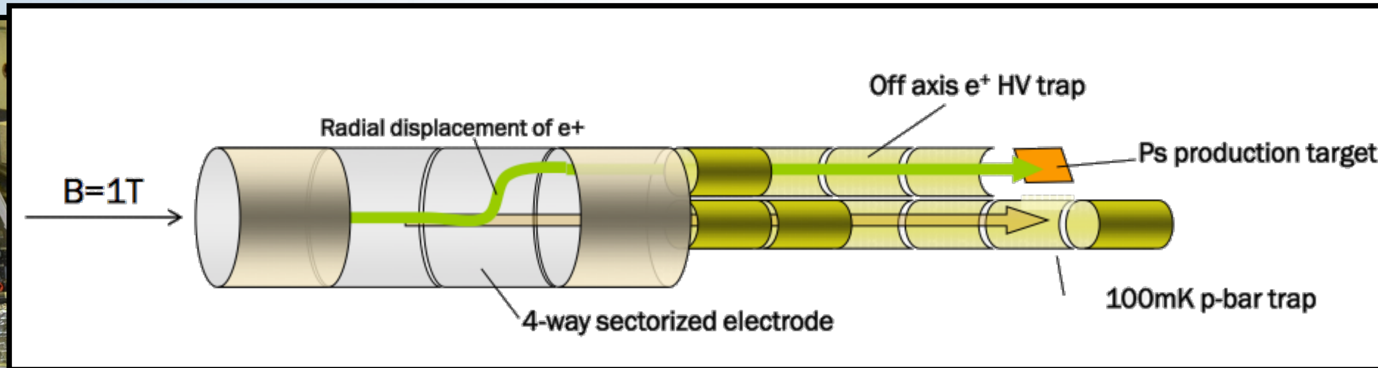


EXPERIMENTAL SETUP

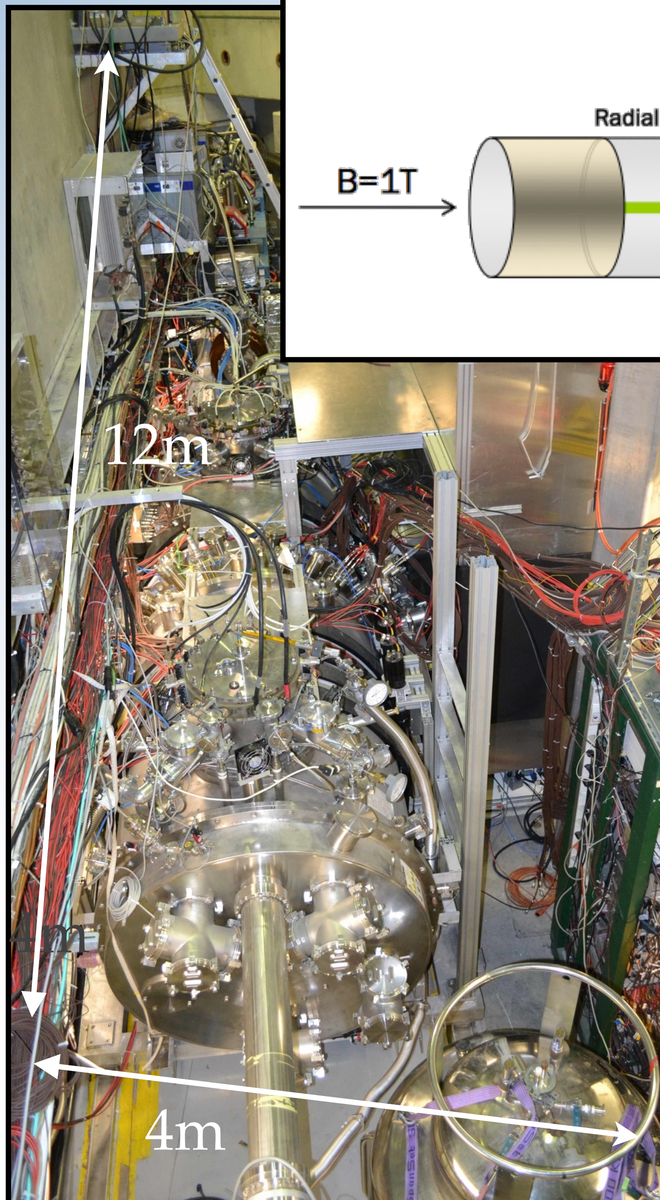


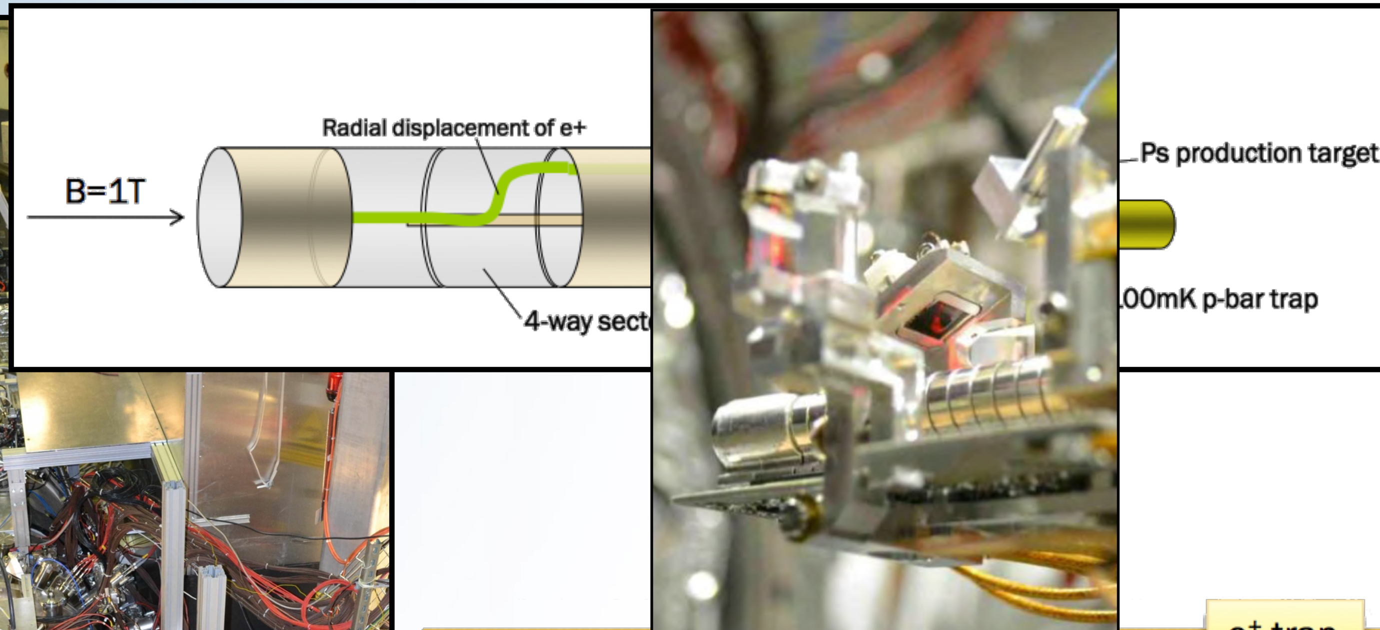
EXPERIMENTAL SETUP

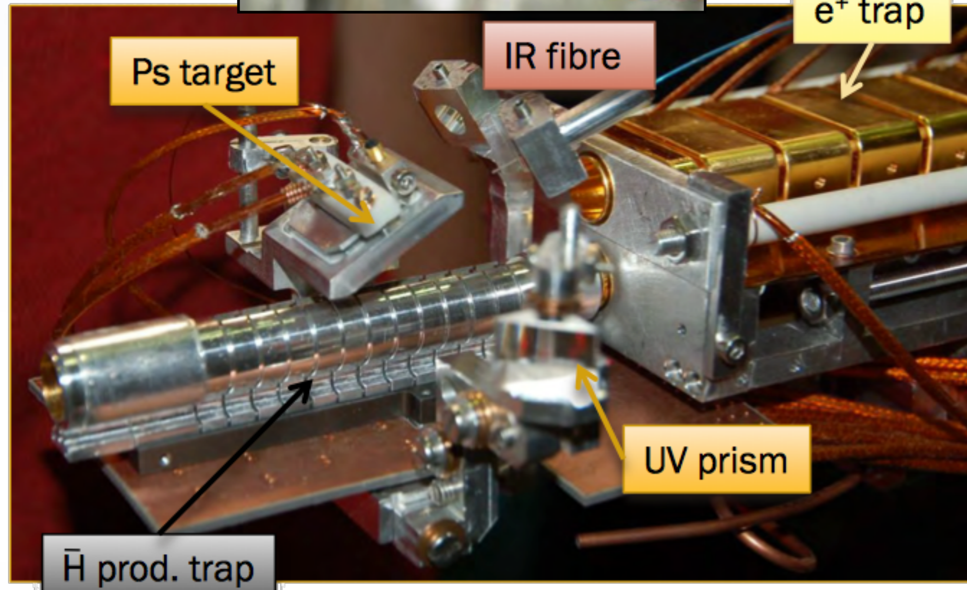




EXPERIMENTAL SETUP





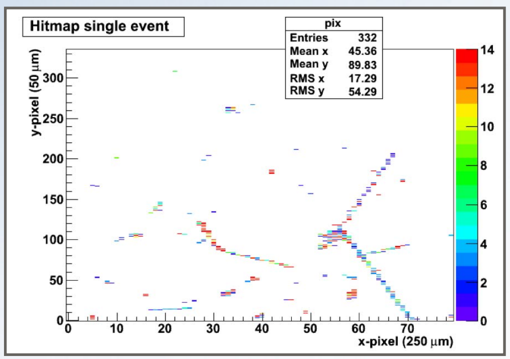


DETECTOR TECHNOLOGIES

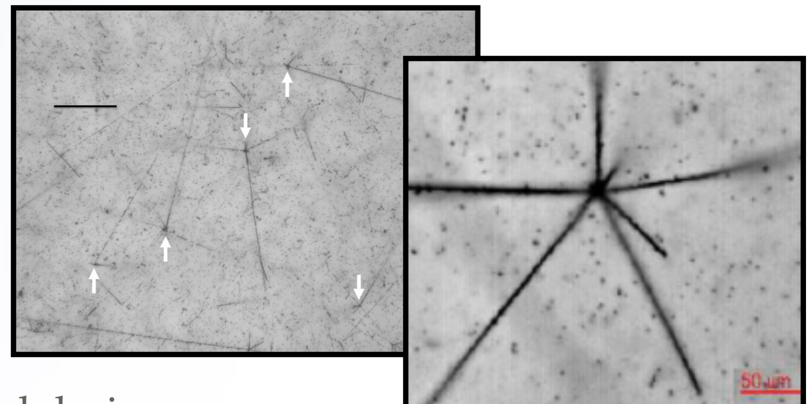
Need high vertex resolution

High signal efficiency and background reduction

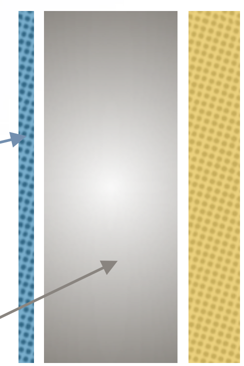
Silicon detectors (strip, pixel)



Emulsions



Hybrid detector needed: example conceptual design

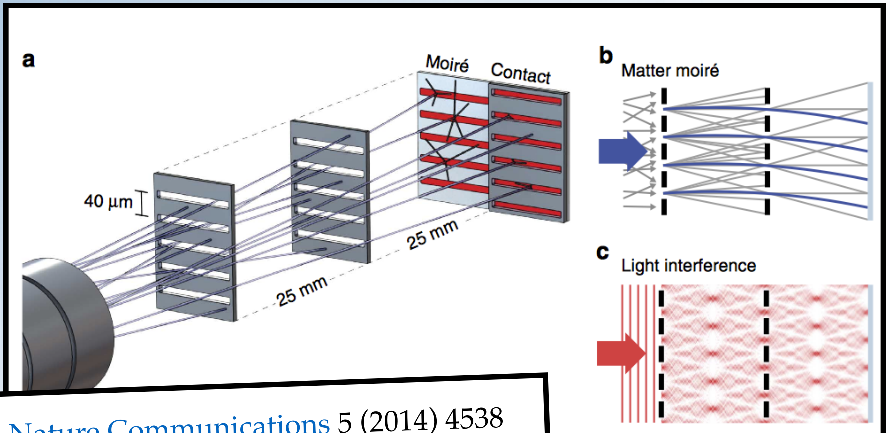


Silicon detector:
~position & TOF

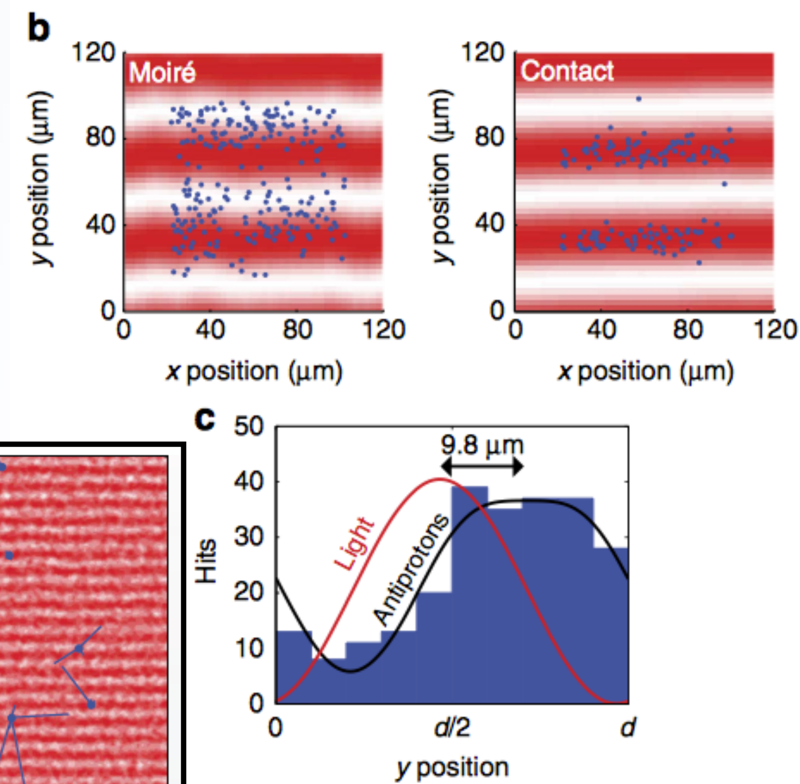
Scintillating fibers / Silicon
TOF & Pion tracks

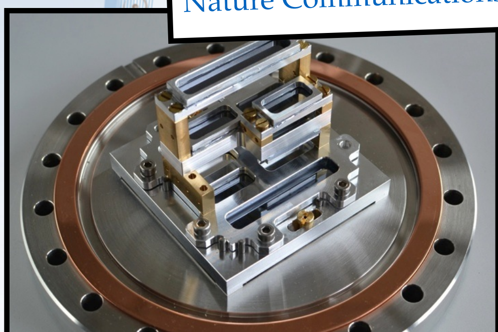
Emulsion:
precise vertex position

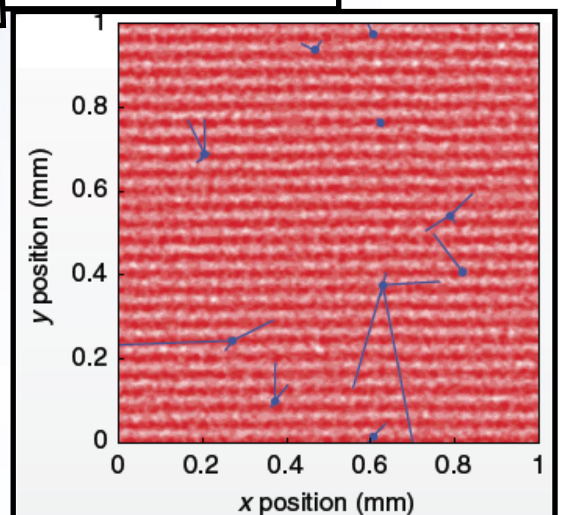
PROOF OF PRINCIPLE



Nature Communications 5 (2014) 4538







~100 keV antiprotons

7 hour exposure

Bare emulsion behind deflectometer

Alignment of gratings using light

Distance 25mm

Slit 12um, pitch 40um, 100um thick

$$\Delta y = 9.8 \pm 0.9(\mathrm{stat}) \pm 6.4(\mathrm{stat}) \mu m$$

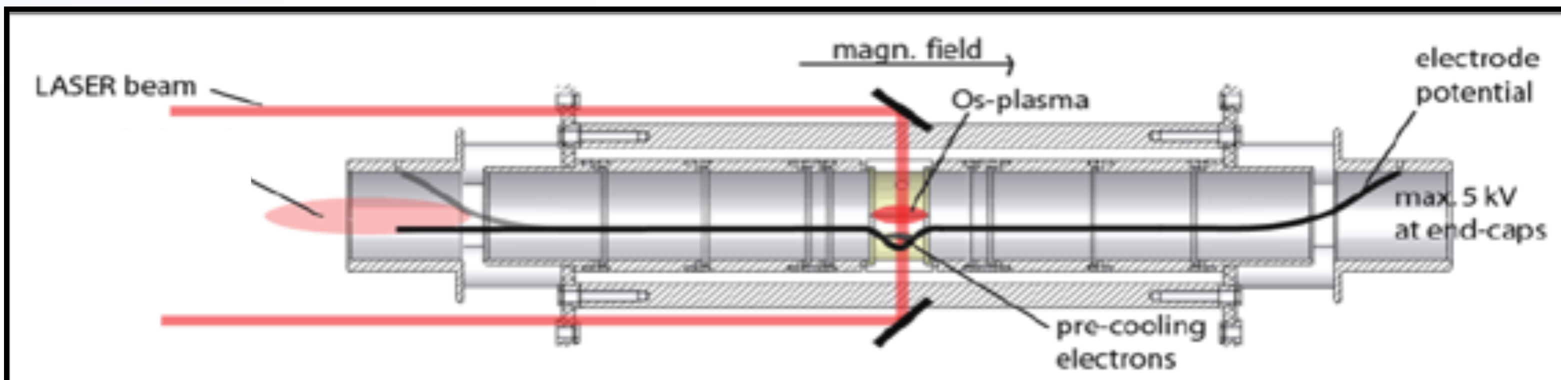
For $\bar{\mathrm{H}}$ beam: F = x 10^{-10}, resolution similar if v= x10^{-4} & L= x 40

TOWARDS PRODUCTION OF COLD $\bar{P}$

- Cool the environment to sub-Kelvin level
- Sympathetic radiation electron cooling.
- Evaporative / adiabatic cooling
- Resistive cooling
- Sympathetic laser cooling with anions :
  La- program in Heidelberg
  C_2- program at CERN

E. Jordan et al., Phys. Rev. Lett. **115** 113001 (2015)

P. Yzombard et al., Phys. Rev. Lett. **114** 213001 (2015)



SOME OTHER NEW RESULTS FROM THE AD

- "Cold" antihydrogen produced daily
  Reaching high production rate for precision measurements

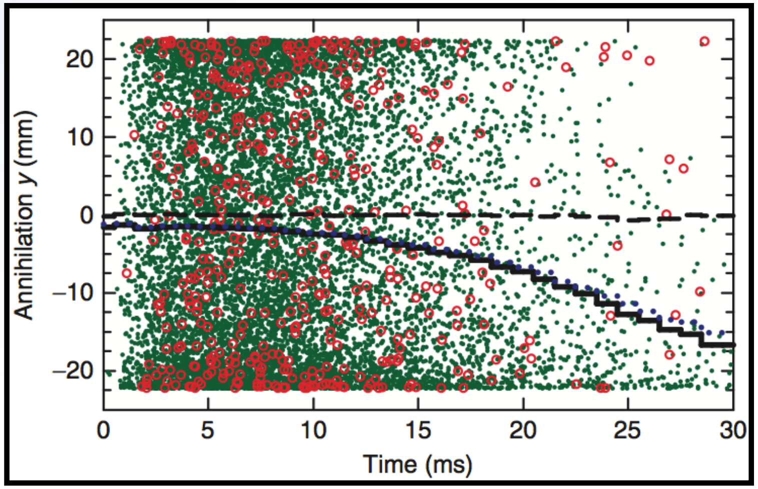
- Long trapping times achieved

Nature Communications 4, 1785 (2013)

- "Crude" limits : proof of principle

- Towards precision measurements

Nature 529, 373–376 (2016)

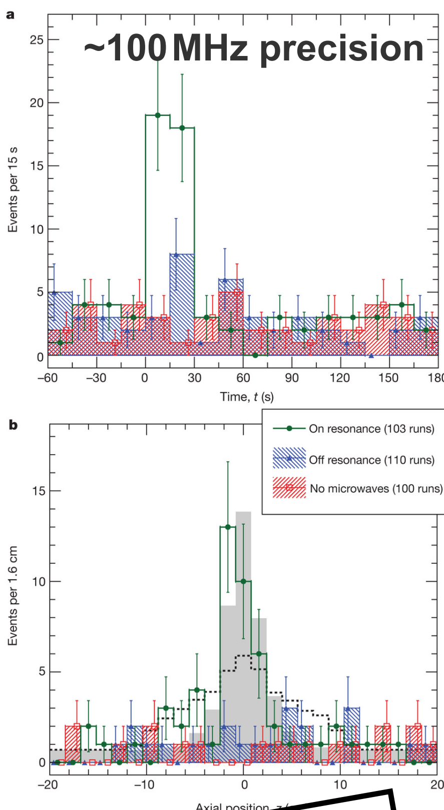


- red circles=data
- green dots: simulation for $\bar{g}/g$=100

$-65 < g/\bar{g} < 110$

Nature Communications 4, 1785 (2013)

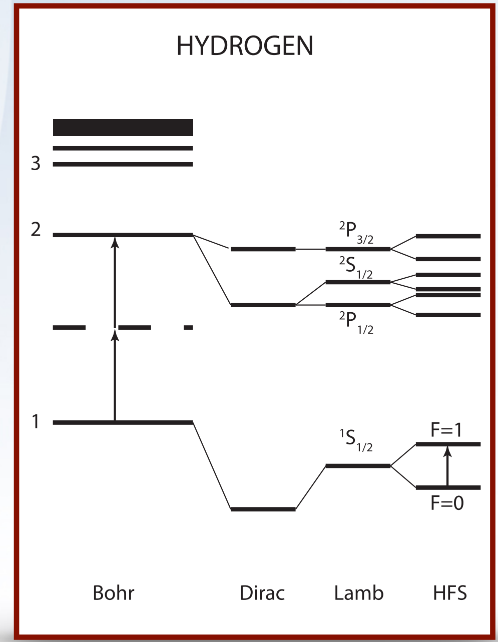
GS-HFS



Nature 483, 439 (2012)

SUMMARY

- ☑ First proof-of-principle measurements in traps
- ☑ First "beam" of $\bar{H}$ observed in field-free region
- ☑ HFS measurement of H beam ~5 ppb achieved



- ☐ Colder $\bar{H}$ needed for "precise" trap and gravity experiments
  - development of $\bar{H}$ laser cooling
  - sympathetic cooling of $\bar{p}$ and e+
- ☐ Higher yield of G-S $\bar{H}$ for beam experiments
  - polarization, velocity measurement

Time scale for precision exp. : 5-10 years

? <== **STAY TUNED** ==> ?