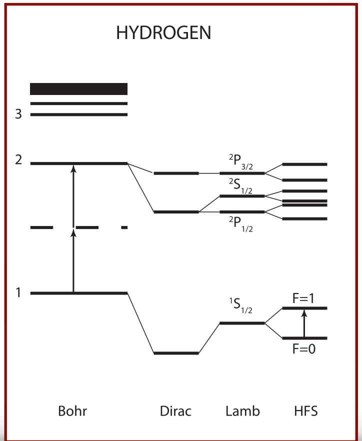
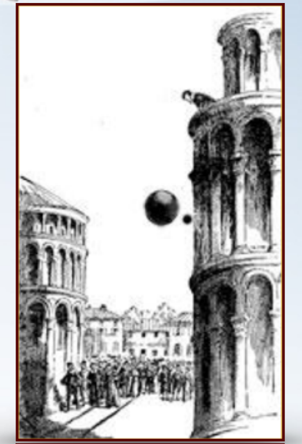




CPT SYMMETRY AND GRAVITY TESTS WITH ANTIHYDROGEN

Chloé Malbrunot [1,2]

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

ÖAW Austrian Academy of Sciences

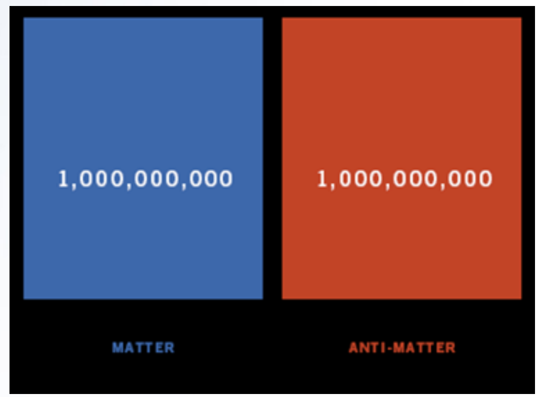
ANTIMATTER - MATTER ASYMMETRY

- No evidence of primary antimatter anywhere in the universe

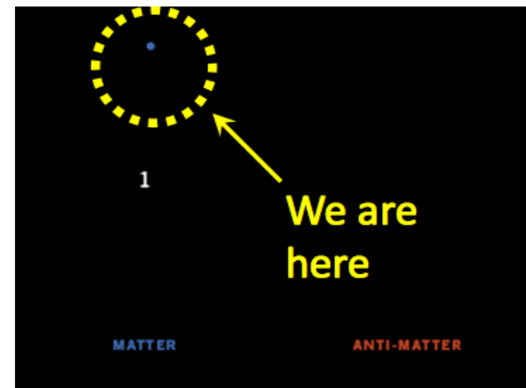
- Baryon asymmetry produced by a very small deviation

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

13.8 billions years ago :



Today :



courtesy of A. Kellerbauer

Possible explanations:

- CP or CPT violations

- Anomalous antimatter gravity: segregation of matter and antimatter in different parts of the universe

CPT SYMMETRY TEST

Charge conjugation

Parity transformation

Time reversal

CPT Theorem assumptions:

- Lorentz invariance
- Locality
- Unitarity

If **CPT symmetry holds**: properties of matter & antimatter particles have to be exactly equal (mass) or opposite (charge, magnetic moment). Atomic structures identical

Tests in different systems

$[m(K^0) - m(\bar{K}^0)]/m(\text{average}) < 10^{-18}$

proton / antiproton (compare m, q, $\vec{\mu}$)

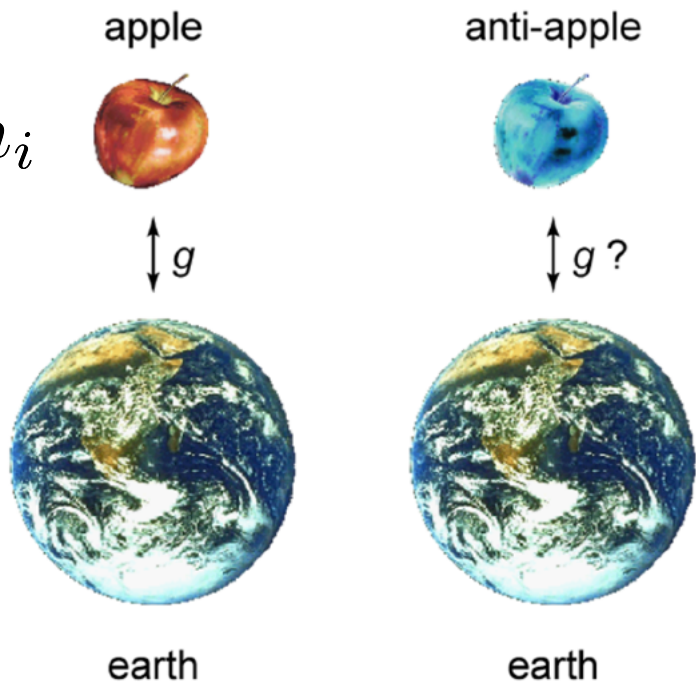
hydrogen / antihydrogen (1S – 2S, HFS)

H·HFS

ANTIMATTER GRAVITY

Weak Equivalence principle never tested for antimatter

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



No direct "precise" measurement of the fall of $\bar{H}$ in the Earth gravitational field so far

Gravity is the only force not described by quantum field theory : QFT formulation could include non-newtonian gravity (S=1,S=0 components), WEP violation etc

"Anti-gravity" could be a possible explanation for baryon asymmetry ant other cosmological puzzles

TESTS WITH ANTIHYDROGEN

Most simple anti-atom.

Only neutral antimatter made in large & controlled quantities so far

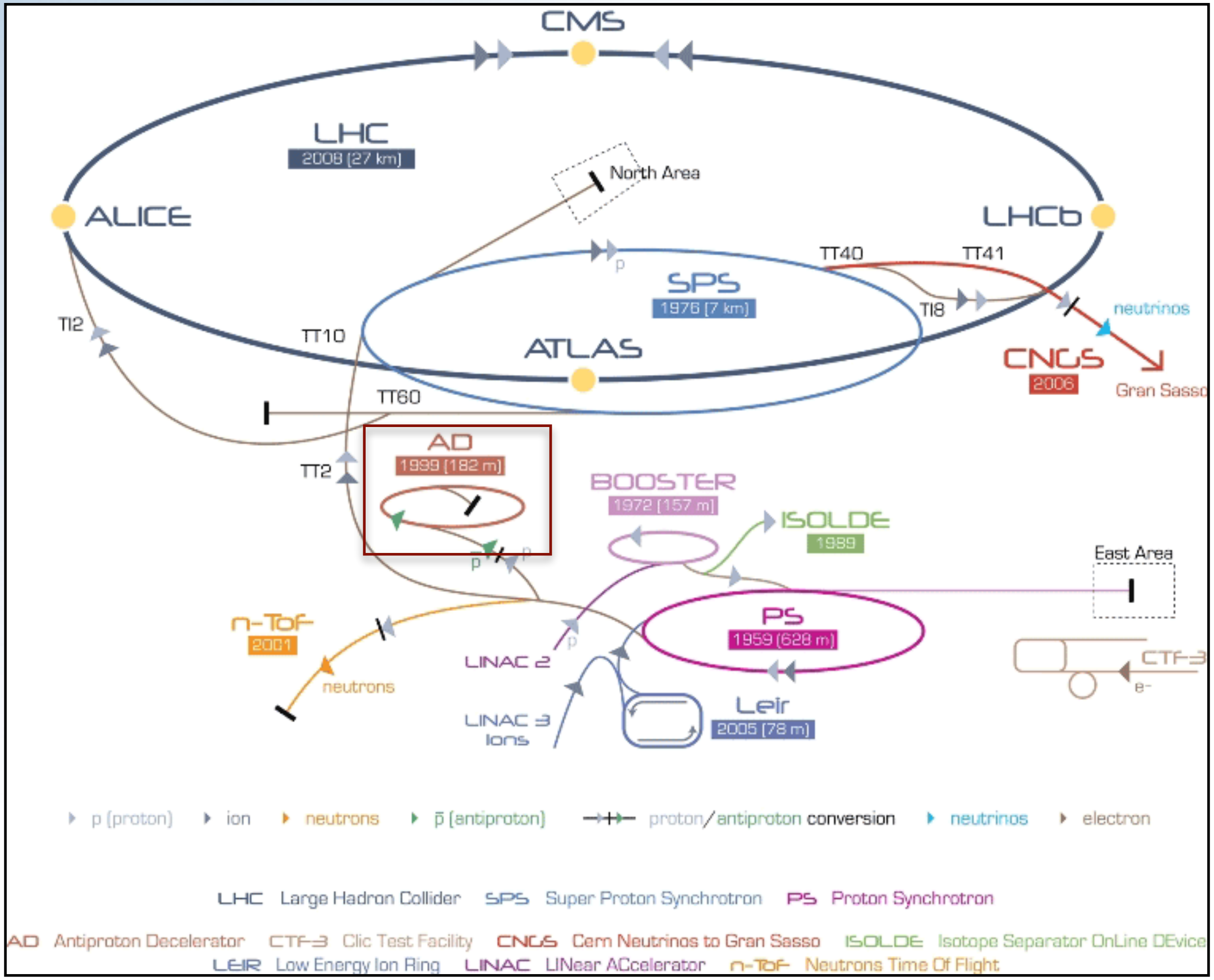
ATOM

PRECISION	NEUTRALITY
Measurement of atomic transitions	Measurement of gravitational interaction
$\frac{\Delta\nu_{\mathrm{HFS}}}{\nu_{\mathrm{HFS}}} = 7 \times 10^{-13}$	$g \stackrel{?}{=} \bar{g}$
CPT tests	WEP test
ASACUSA, ATRAP, ALPHA	AEGIS, GBAR

Antihydrogen: ideal test body for fundamental physics

H·HFS

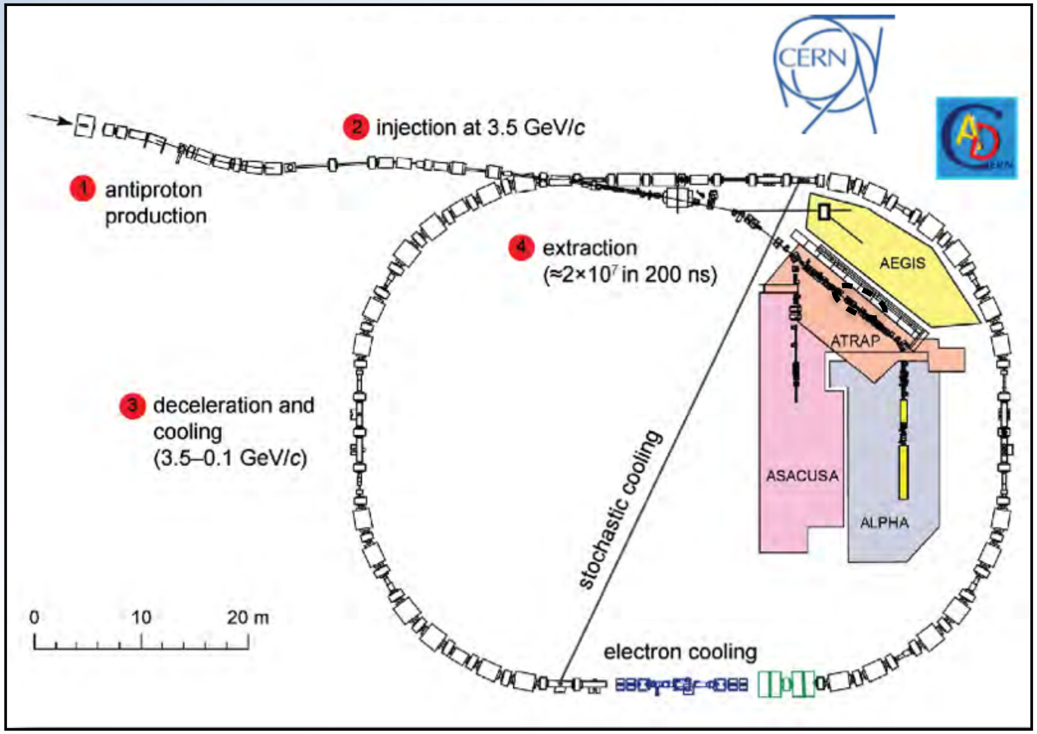
ANTIHYDROGEN EXPERIMENTS @ CERN



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

ANTIHYDROGEN EXPERIMENTS @ CERN

The Antiproton Decelerator : cools antiprotons from ~3GeV to 5.3MeV
few eV needed for trapping



3 experimental groups focus on antihydrogen spectroscopy

- ATRAP -> *trap*
- ALPHA -> *trap*
- ASACUSA -> *beam*

1 group focusses on WEP test (and spectroscopy)

-AEGIS -> *beam*

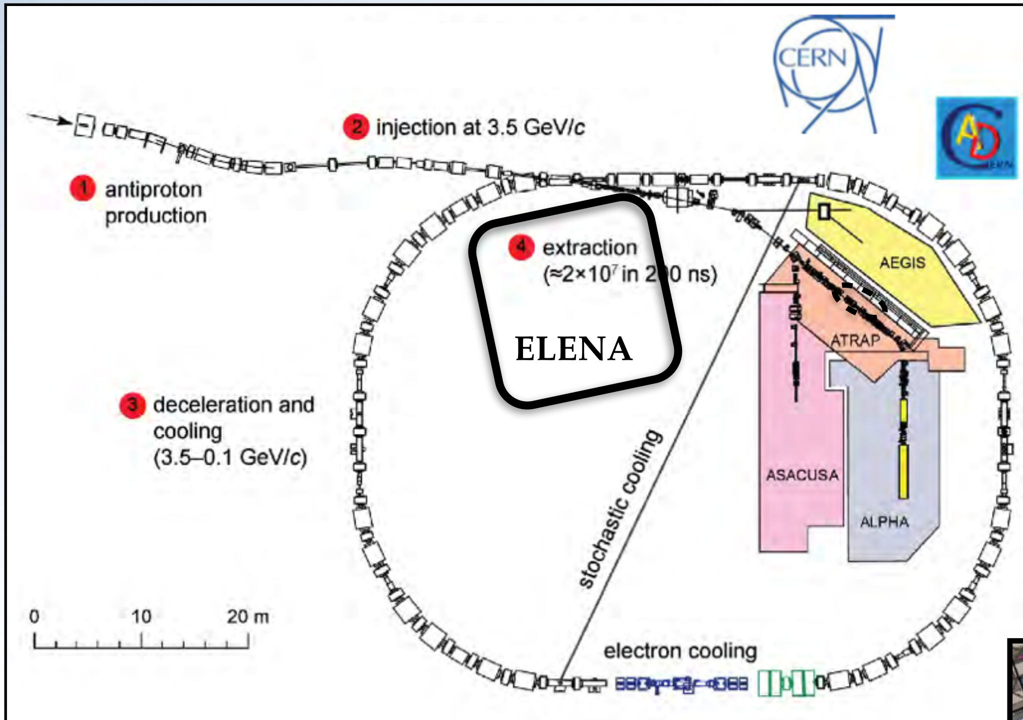
-(GBAR to come in 2017)

Other research foci with p̄: ASACUSA, BASE, ACE

H·HFS

ANTIHYDROGEN EXPERIMENTS @ CERN

The Antiproton Decelerator : cools antiprotons from ~3GeV to 5.3MeV
few eV needed for trapping



3 experimental groups focus on antihydrogen spectroscopy
- ATRAP -> *trap*
- ALPHA -> *trap*
- ASACUSA -> *beam*

1 group focusses on WEP test (and spectroscopy)
-AEGIS -> *beam*
-(GBAR to come in 2017)

Other research foci with p̄: ASACUSA, BASE, ACE

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

- **1995** — First production of antihydrogen at LEAR (CERN)
  - Phys. Lett. B 368 (1996) 251-258
- **2000** — **Start up of the AD**
- **2002** — ATHENA and ATRAP make "cold" $\bar{H}$ at the AD
  - *Nature* **419**, 456-459
  - Phys. Rev. Lett. 89, 213401
- **2004** — First Laser-Controlled $\bar{H}$ Production by ATRAP
  - *Phys. Rev. Lett. 93, 263401*
- *ALPHA & ASACUSA #1 Physics World Breakthrough 2010*
- **2010** — Synthesis of $\bar{H}$ by ASACUSA
  - *Phys. Rev. Lett. 105, 243401 (2010)*
- **2010** — First trapping of $\bar{H}$ by ALPHA
  - *Nature* **468**, 673 (2010)
- **2011** — ALPHA traps $\bar{H}$ for 1000 seconds
  - *Nature Physics*, 7, 558 (2011)
- **2012** — First resonant Quantum Transition on trapped $\bar{H}$ by ALPHA
  - 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**

STATUS OF ANTIHYDROGEN EXPERIMENTS @ CERN

- "Cold" antihydrogen produced daily
  Need enhanced production rate for precision measurements

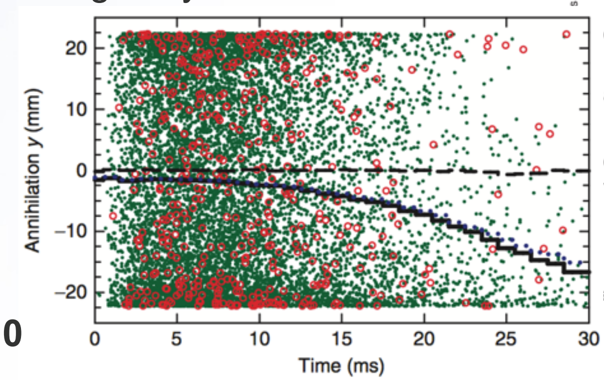
Nature Communications 4, 1785 (2013)

- Long trapping times achieved

- "First" beam of $\bar{H}$ observed

- "Crude" limits : proof of principle

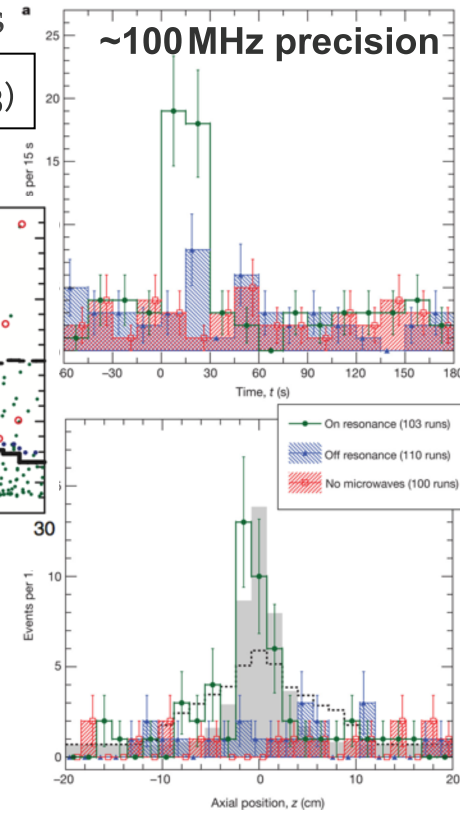
gravity "test"



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

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

GS-HFS



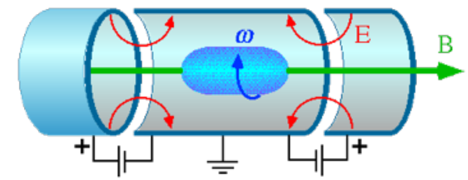
Nature 483, 439 (2012)

<u>COMING NEXT:</u>

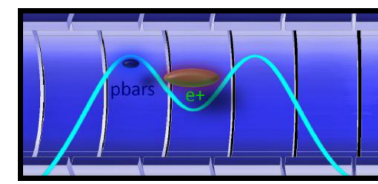
Production of colder $\bar{H}$ for trap exp. and gravity

Enhanced production of Ground state $\bar{H}$ for beam exp.

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 plamas
- Form $\bar{H}$
  - → Trap very cold (<0.5K) $\bar{H}$, wait for deexcitation to ground state
  - → Produce a cold (<100K) and low QS beam of $\bar{H}$

==> Perform SPECTROSCOPY

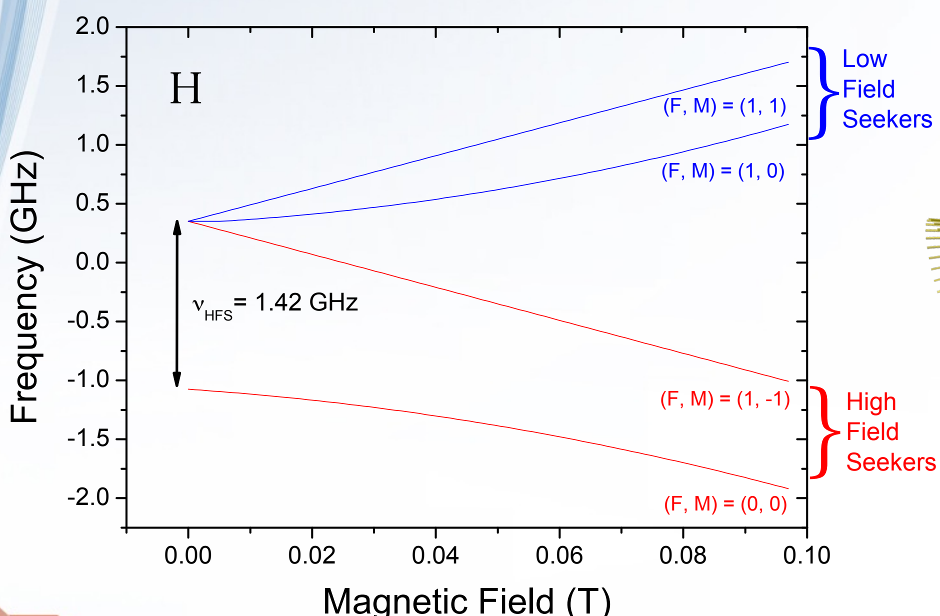
MEASUREMENT PRINCIPLE

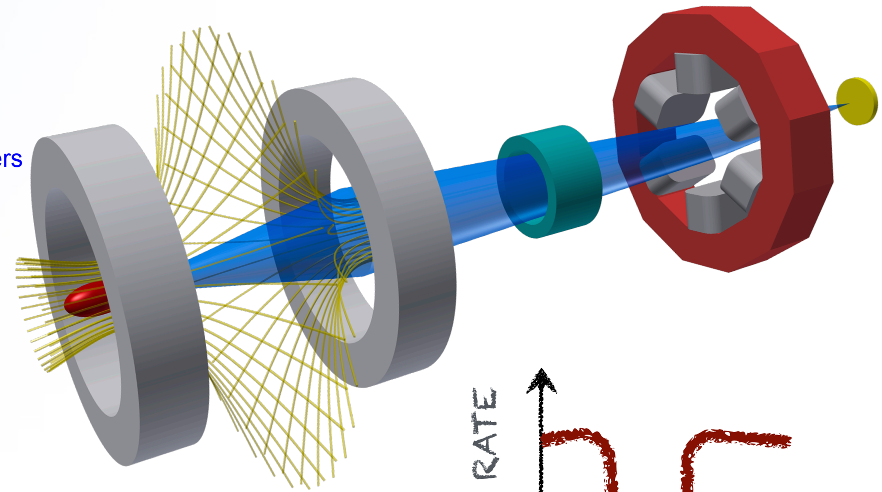
Atomic beam with RF resonance

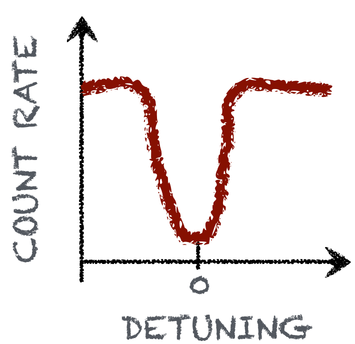
1) no $\overline{\mathrm{H}}$ trapping needed → no need for ultra-cold (< 1 K) $\overline{\mathrm{H}}$

2) atomic beam method can work up to 50-100 K

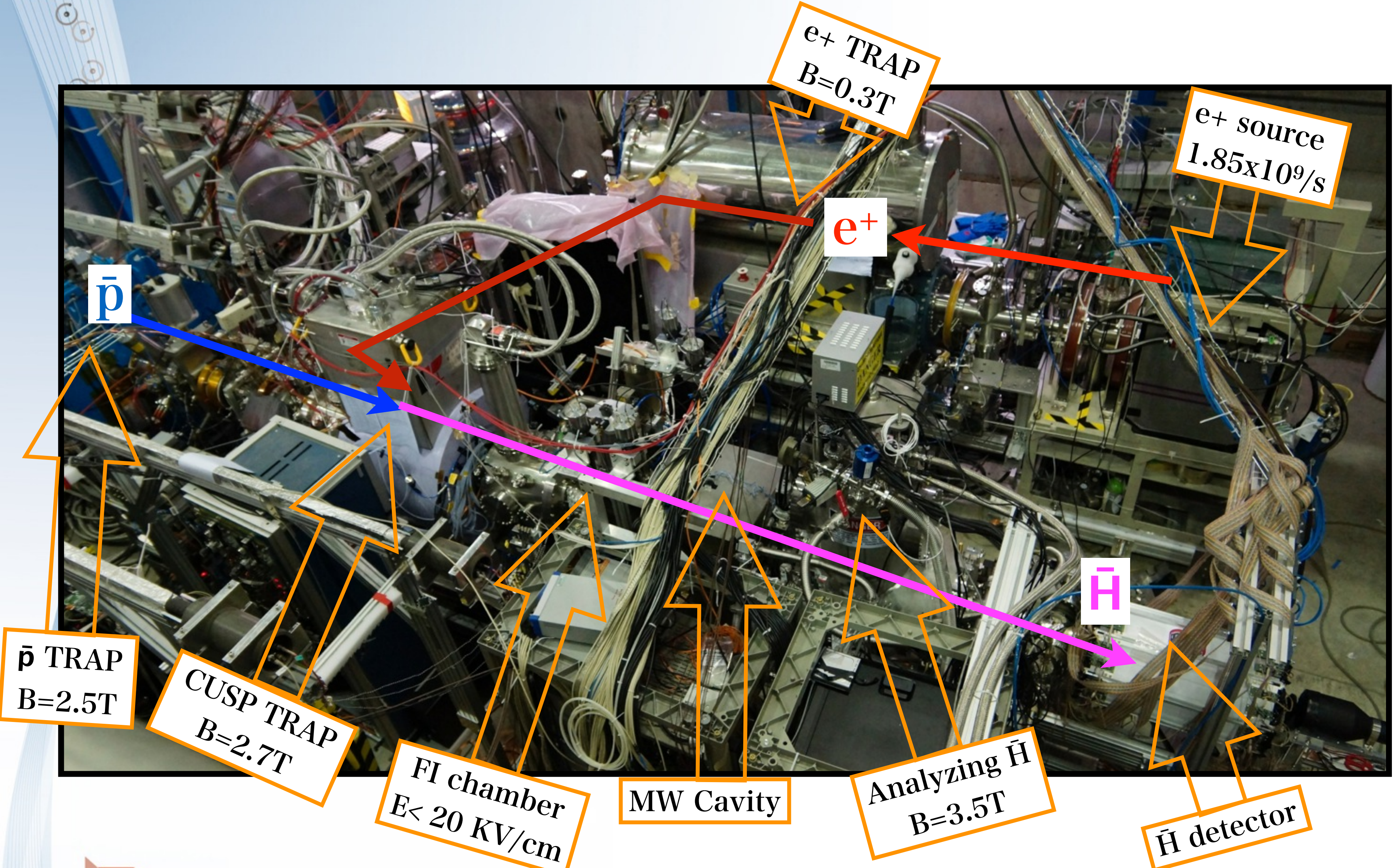
3) $\overline{\mathrm{H}}$ atoms can be guided with inhomogeneous magnetic field



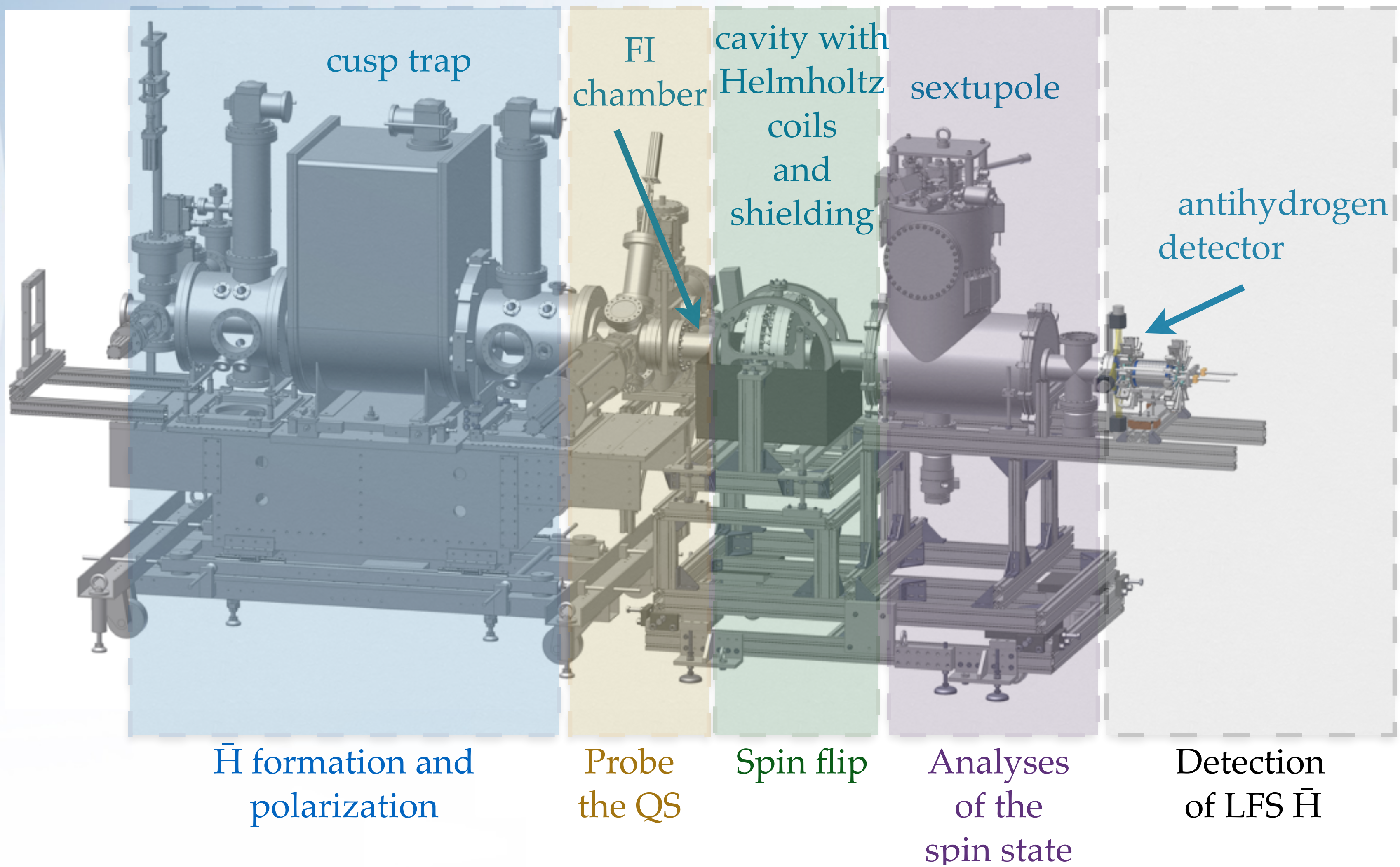




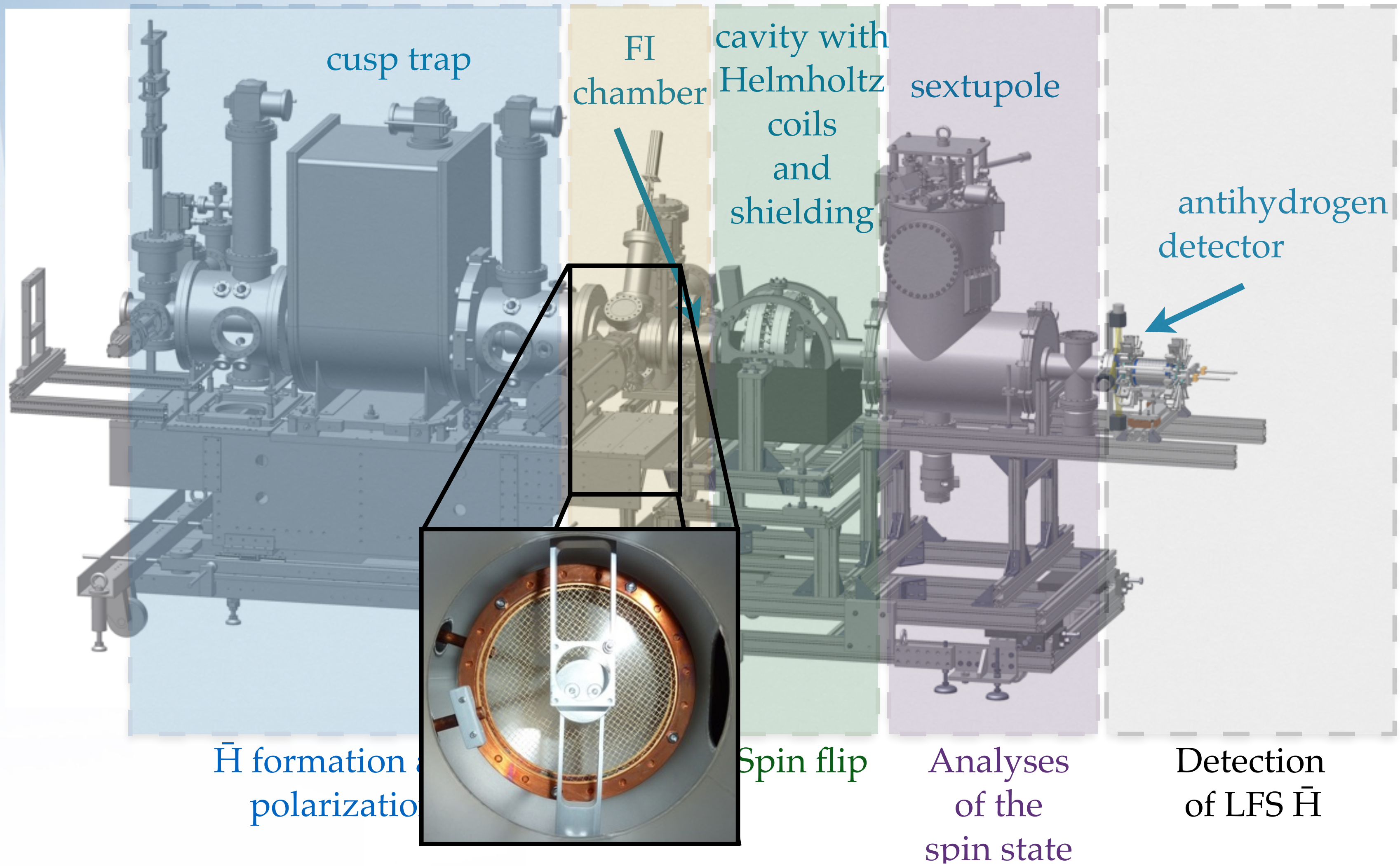
ANTIHYDROGEN PRODUCTION IN ASACUSA



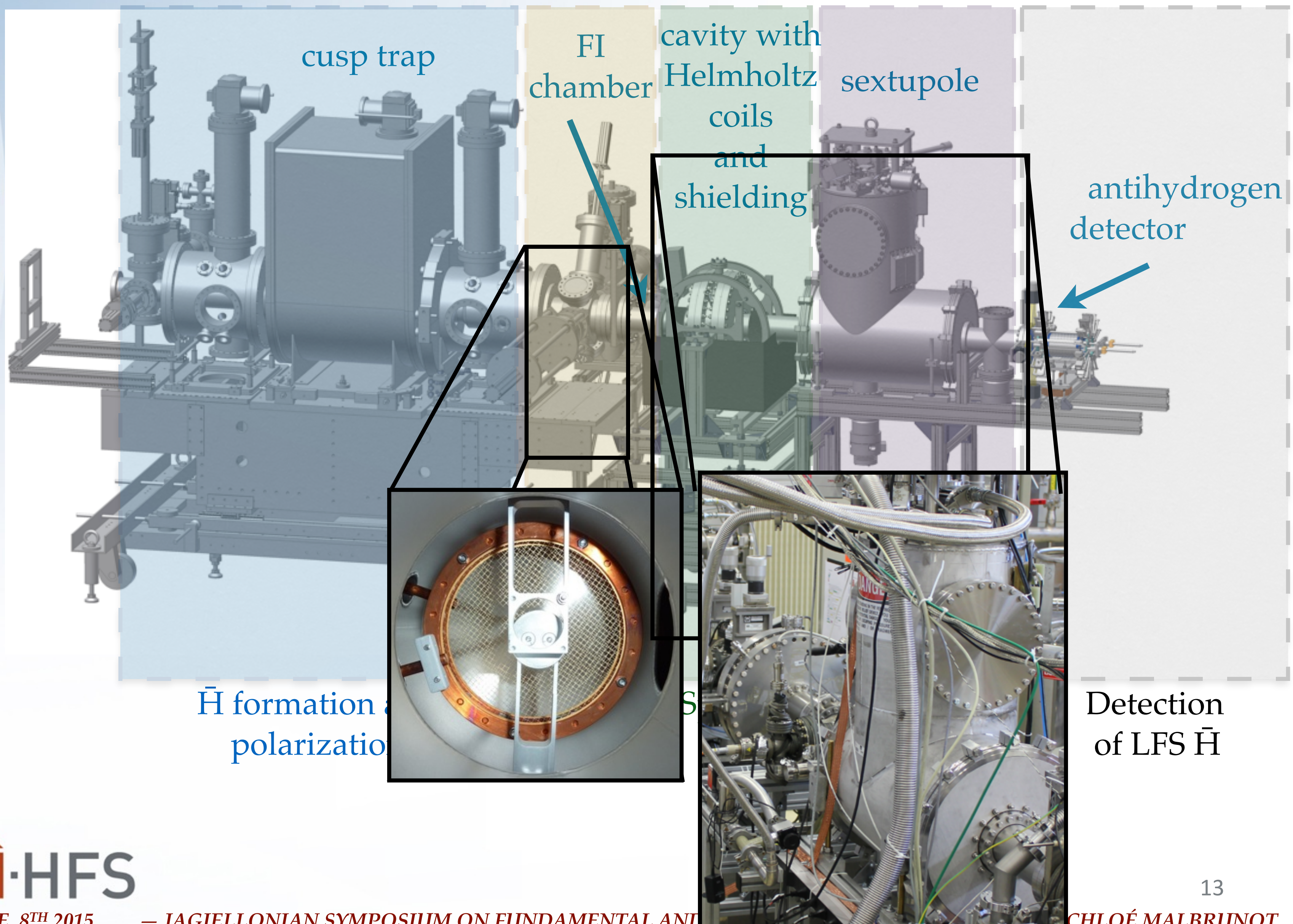
FOCUS ON SPECTROMETER LINE



FOCUS ON SPECTROMETER LINE

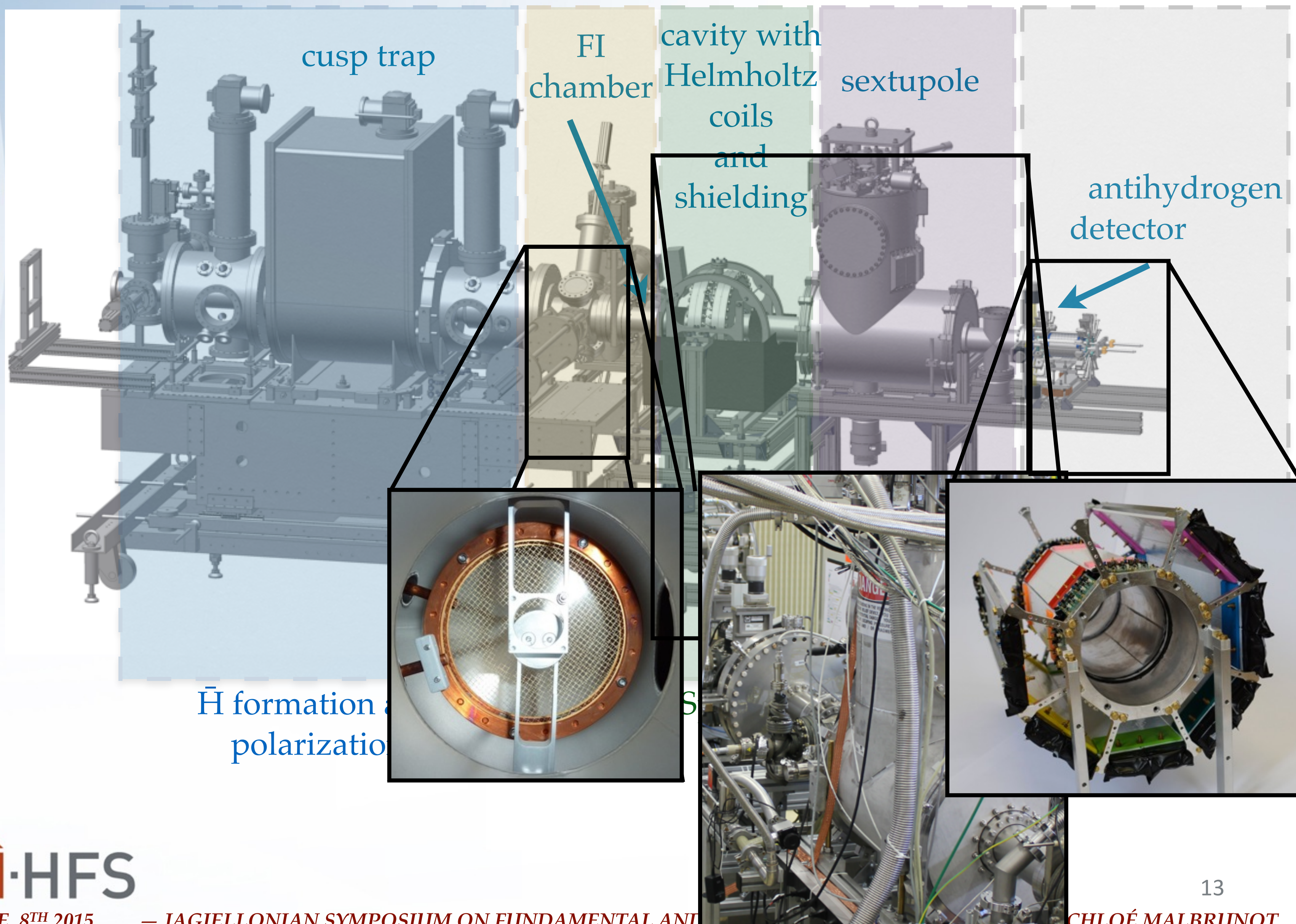


FOCUS ON SPECTROMETER LINE



H·HFS

FOCUS ON SPECTROMETER LINE

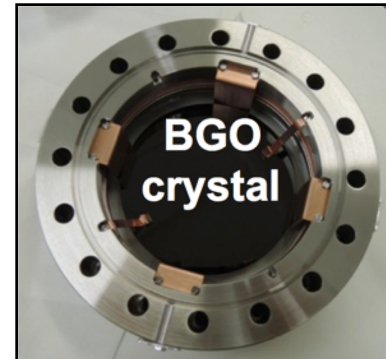


$\bar{H}$ formation a
polarizatio

$\bar{H}$ DETECTORS

Annihilation: BGO crystal (position sensitive calorimeter)

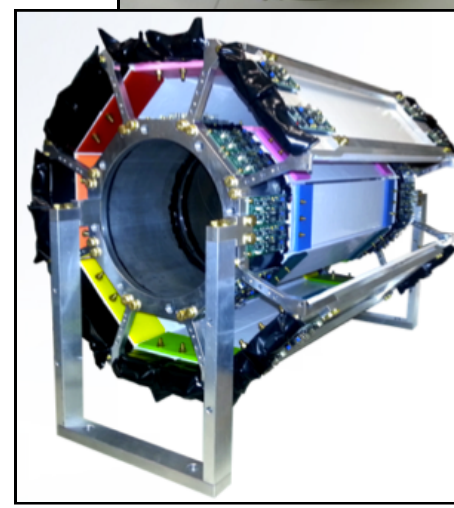
read out by MchPMT array of 16x16 for position resolution



Pion tracking:
- 2 layers hodoscope
- 32 (8x4) scintillator bars each
- SiPMs on each side

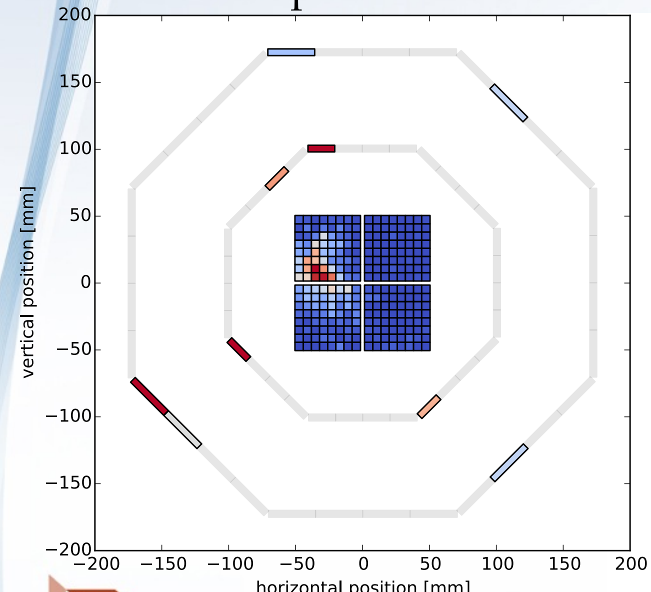
axial resol. by time difference

Cosmics suppression
- energy deposit
- trigger: triple coincidence
- fast timing
- >50% efficiency
  < 5% false IDs

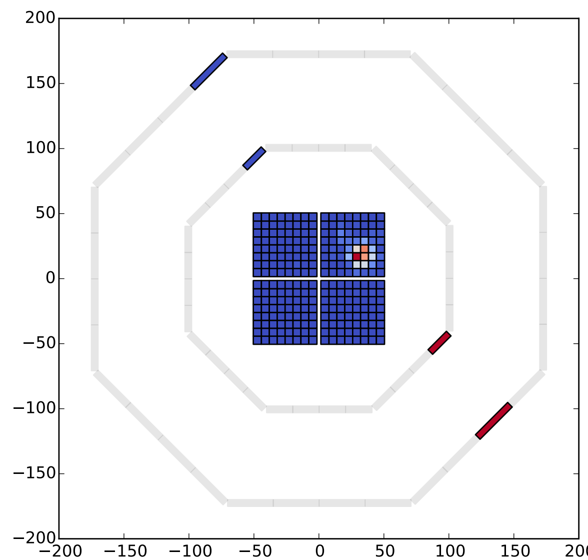


Event display

$\bar{p}$ event

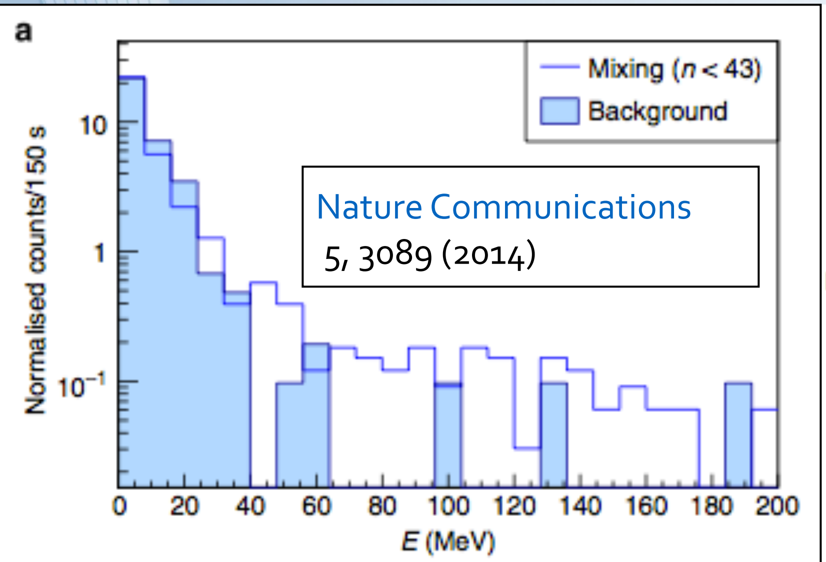


Cosmic event

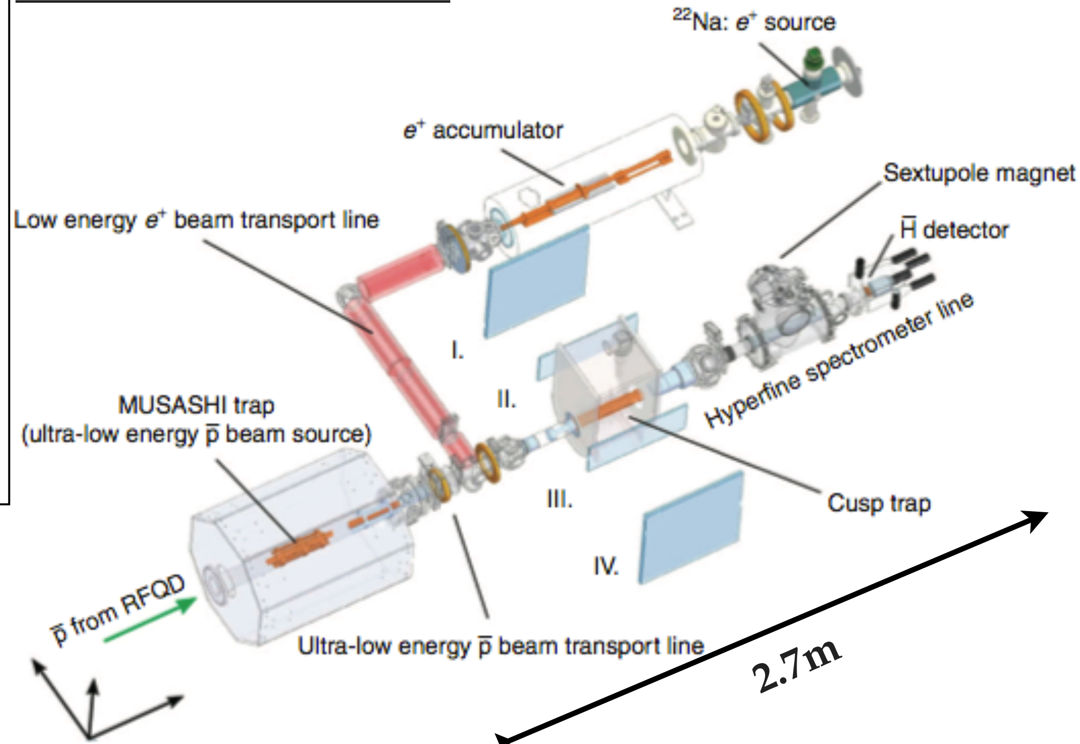


Solid angle (mixing point - detector): ~0.004%

LATEST BREAKTHROUGHTS



Detection of a "Beam"



Mostly : $29 < n < 43$

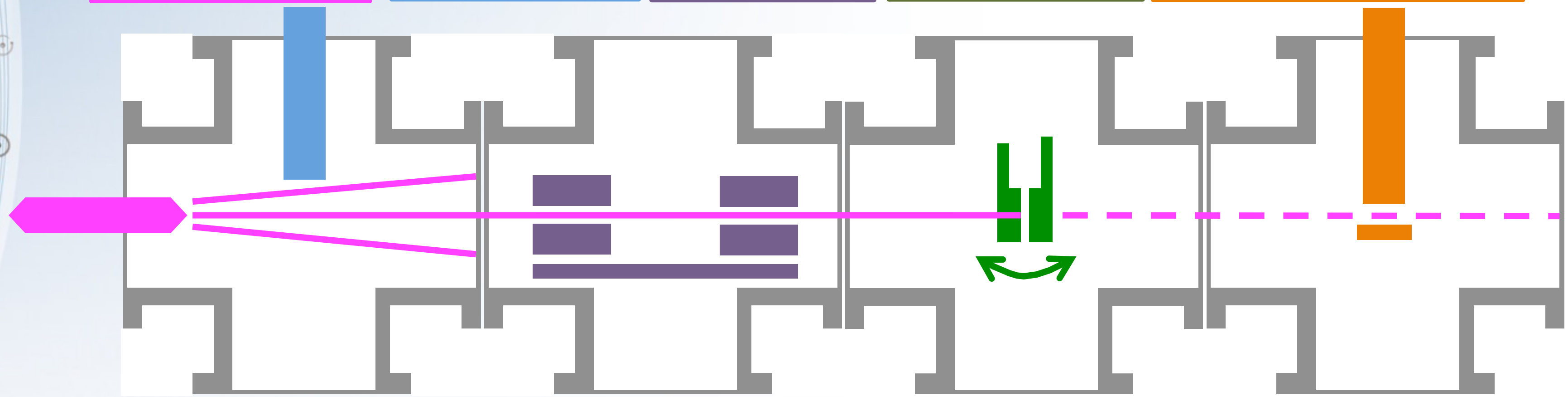
Coming next : Determine the polarization of the beam, velocity and quantum states at the cavity

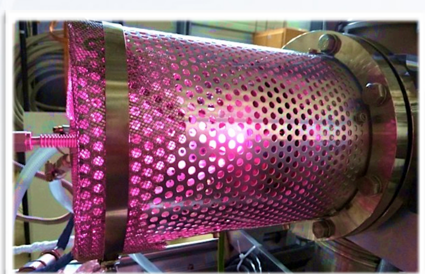
==> IN PREPARATION FOR SPECTROSCOPY MEASUREMENT

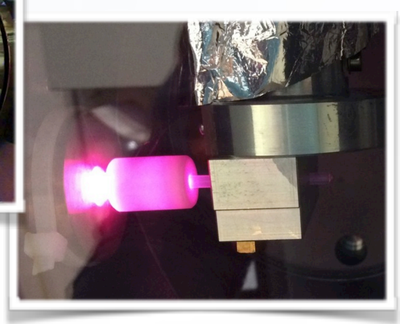
Characterization of spectroscopy beamline

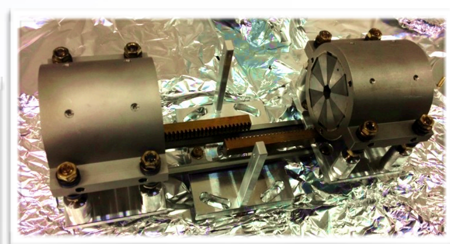
CHARACTERIZATION WITH H BEAM

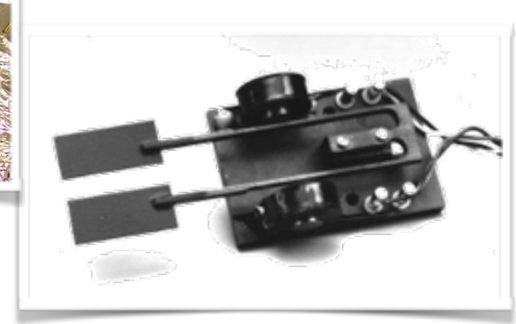
atomic H source	Cryogenic (cold head) for 50-100K beam	Sextupole for polarized beam	Fork-Chopper	Quadrup. Mass Spec.
ON → H and H_2 OFF → H_2 only			f ≈ 178 Hz 50% duty cycle	detects mass=1 H_1^+ or mass=2 H_2^+



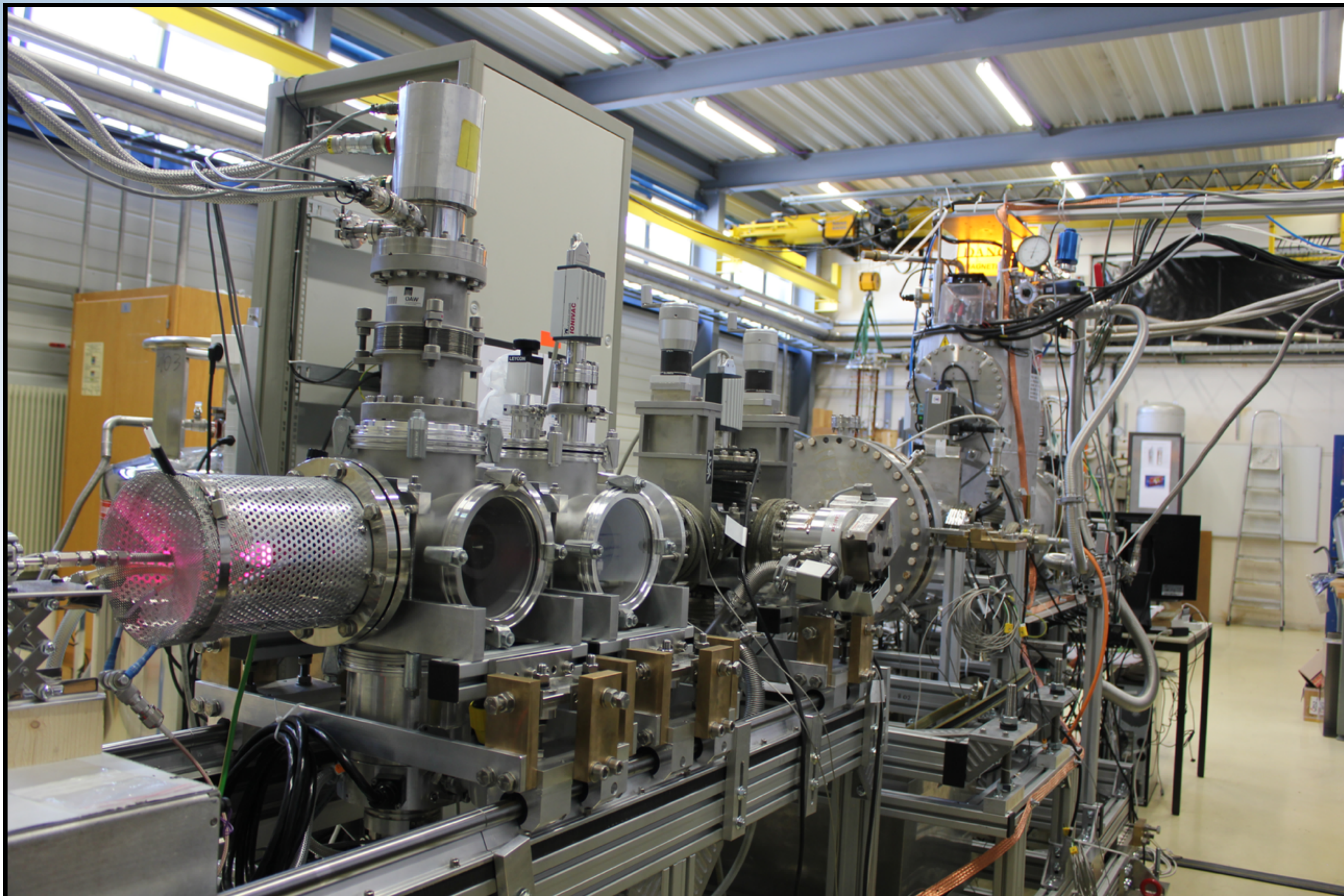








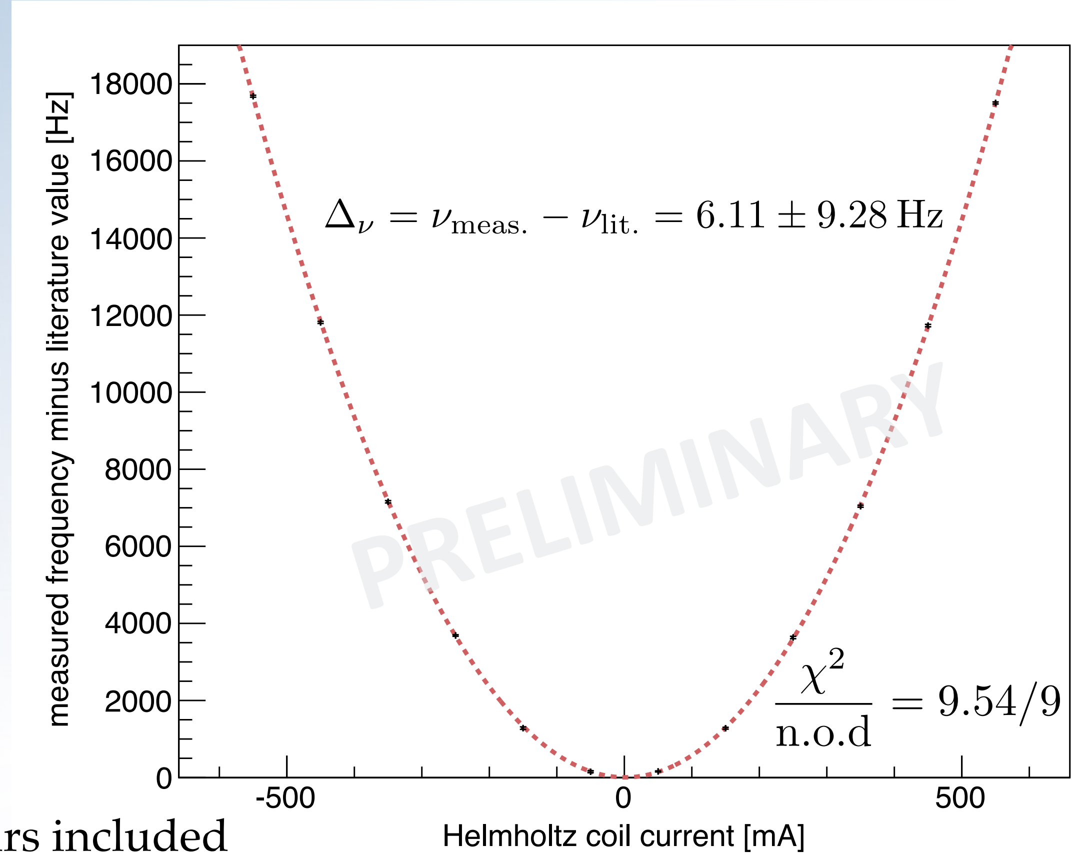
H BEAM APPARATUS

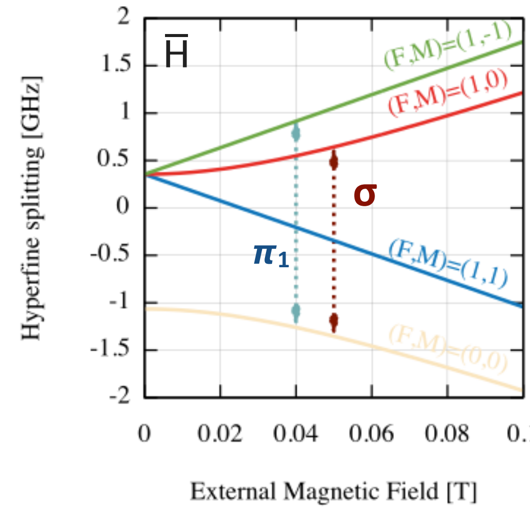


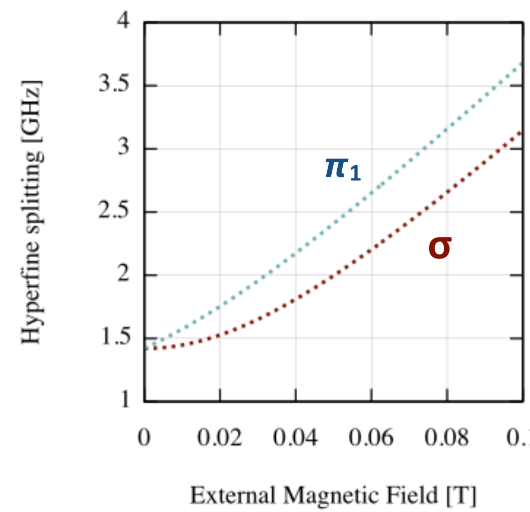
HYDROGEN MEASUREMENT

Fitting the theoretical curve to the data

Helmholtz coil currents: external B field is a fit paramete







Error bars included

B field are consistent (within 1 sigma) with flux gate readings

Maser measurement	Last Best beam measurement	This measurement
$\frac{\Delta\nu}{\nu} = 7 \times 10^{-13}$	$\frac{\Delta\nu}{\nu} = 3.5 \times 10^{-8}$	$\frac{\Delta\nu}{\nu} = 6.5 \times 10^{-9}$

PRELIMINARY

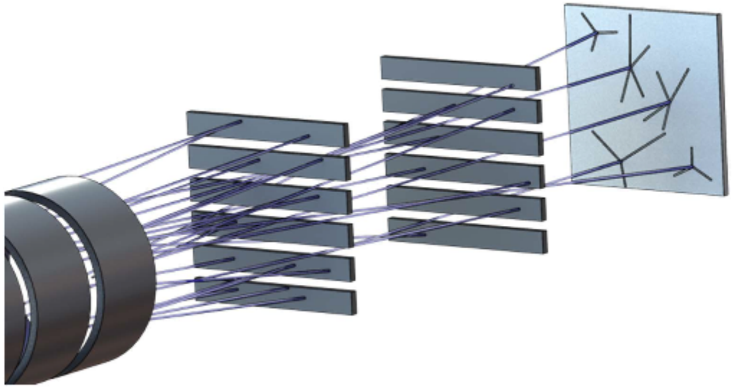
H·HFS

AEḡIS Goal

- First goal is to measure ḡ (i.e g(H̄)) to 1% accuracy
- Test of WEP on antimatter in Earth's gravitational field
    - First direct measurement for an anti-atom - free of any assumptions
    - Need "large" amount (~1000) of cold neutral anti-atoms.

AEḡIS method:

- Produce cold H̄*
- Accelerate H̄* into a neutral beam
- Measure the gravitational deflection of such cold H̄ beam



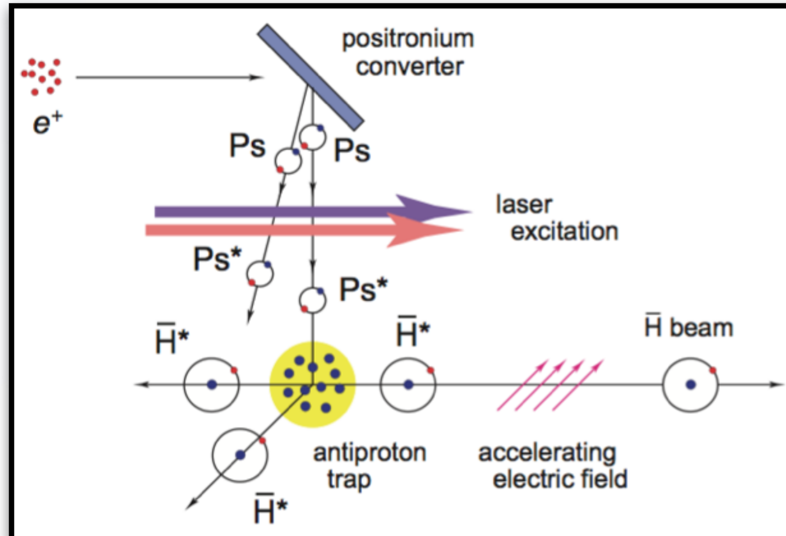
H·HFS

ANTIHYDROGEN PRODUCTION IN AEGIS

NEW TECHNIQUE: MORE AND COLDER ANTIHYDROGEN VIA CHARGE EXCHANGE

1. Production, moderation & **trapping** of **e^+**
2. Capture and accumulation of $\bar{p}$ from the AD
3. **Cooling** of $\bar{p}$
4. **o-Ps** production by impact of e+ on SiO_2 target (nano-porous insulator material)
5. Ps **laser excitation** into Rydberg levels
6. Interaction of **Rydberg Ps** with the cloud of cold antiprotons
7. **Recombination** of $\bar{H}$ by resonant charge exchange

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



- Formation rate enhanced

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

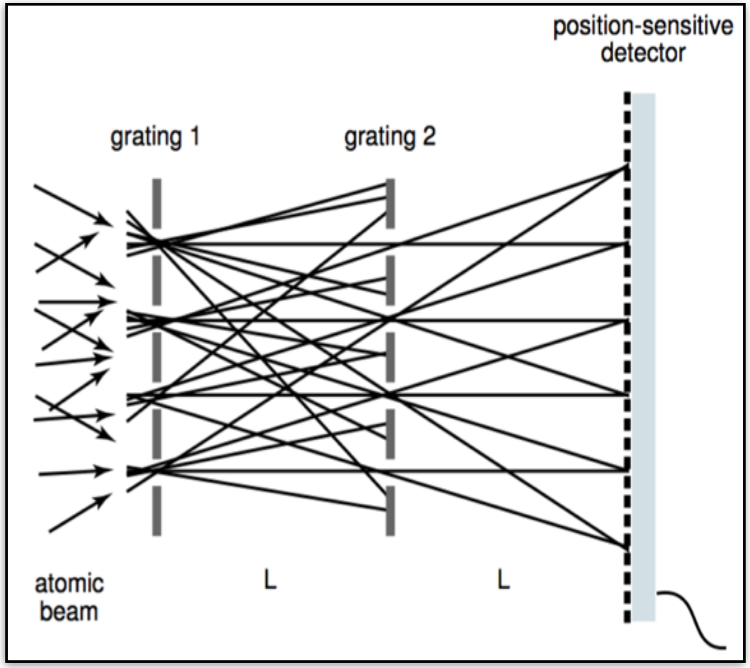
- $\bar{H}$ state defined by Ps state
- $\bar{H}$ velocity dominated by $\bar{p}$

H·HFS

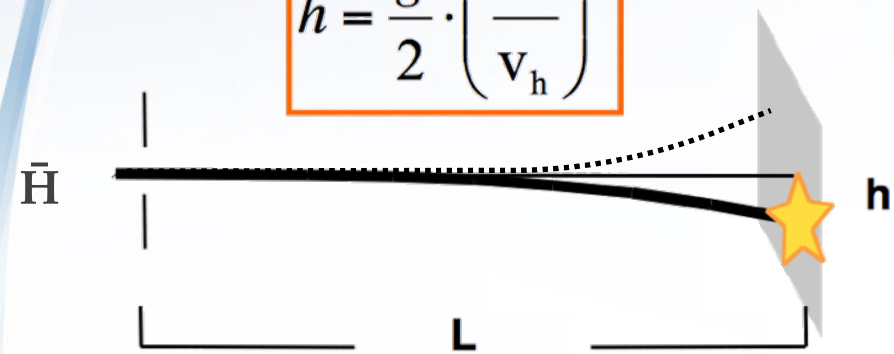
ANTIHYDROGEN PRODUCTION IN AEGIS

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

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

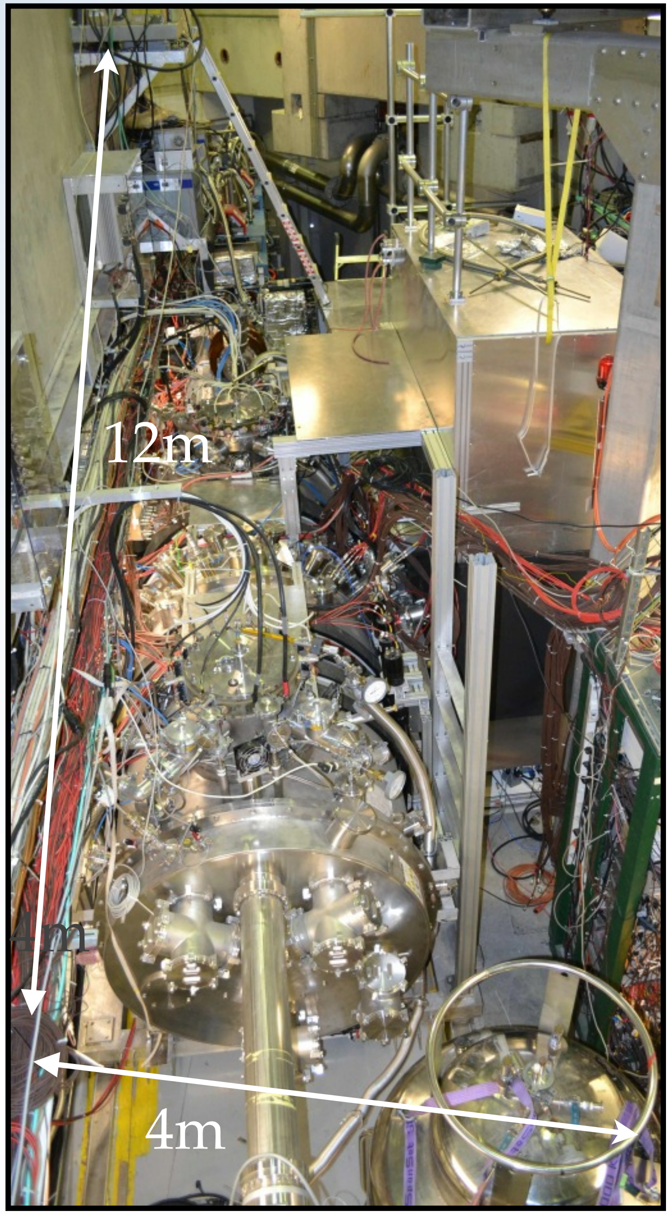


$$h = \frac{g}{2} \cdot \left(\frac{L}{v_h} \right)^2$$

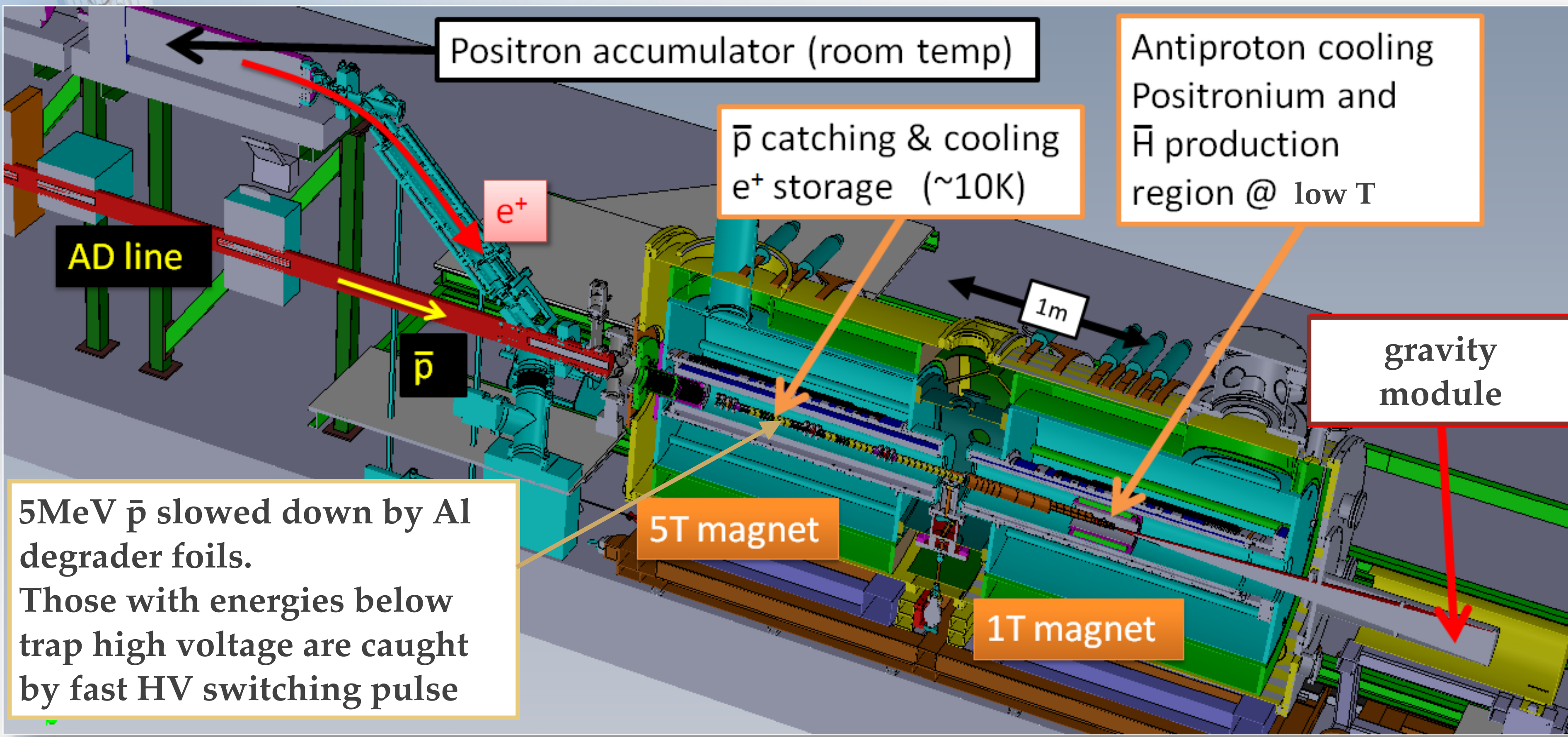


- Rydberg atoms are sensitive to el. field gradients.
- Accelerate the $\bar{H}$ along z-axis to few 100m/s

EXPERIMENTAL SETUP



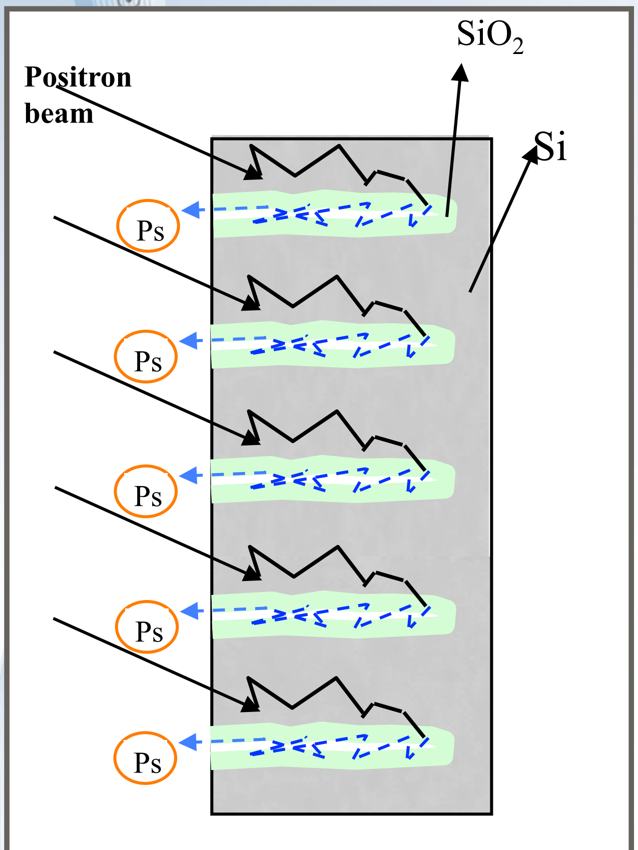
EXPERIMENTAL SETUP



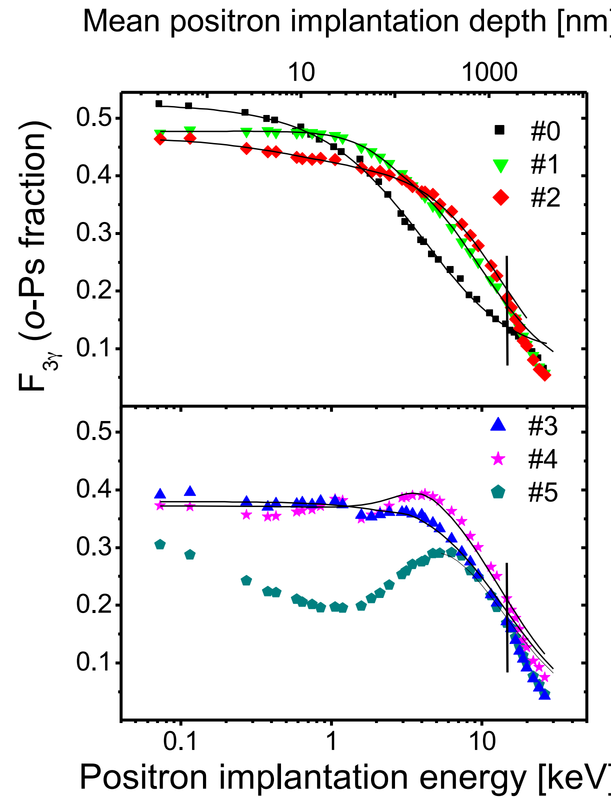
FROM e^+ to Ps

Ps production: implantation of e+ into nano-porous (Ø 8-14 nm) silica target

- ❖ ~75K o-Ps needed
- ❖ Requires deep implantation depth, i.e. high V



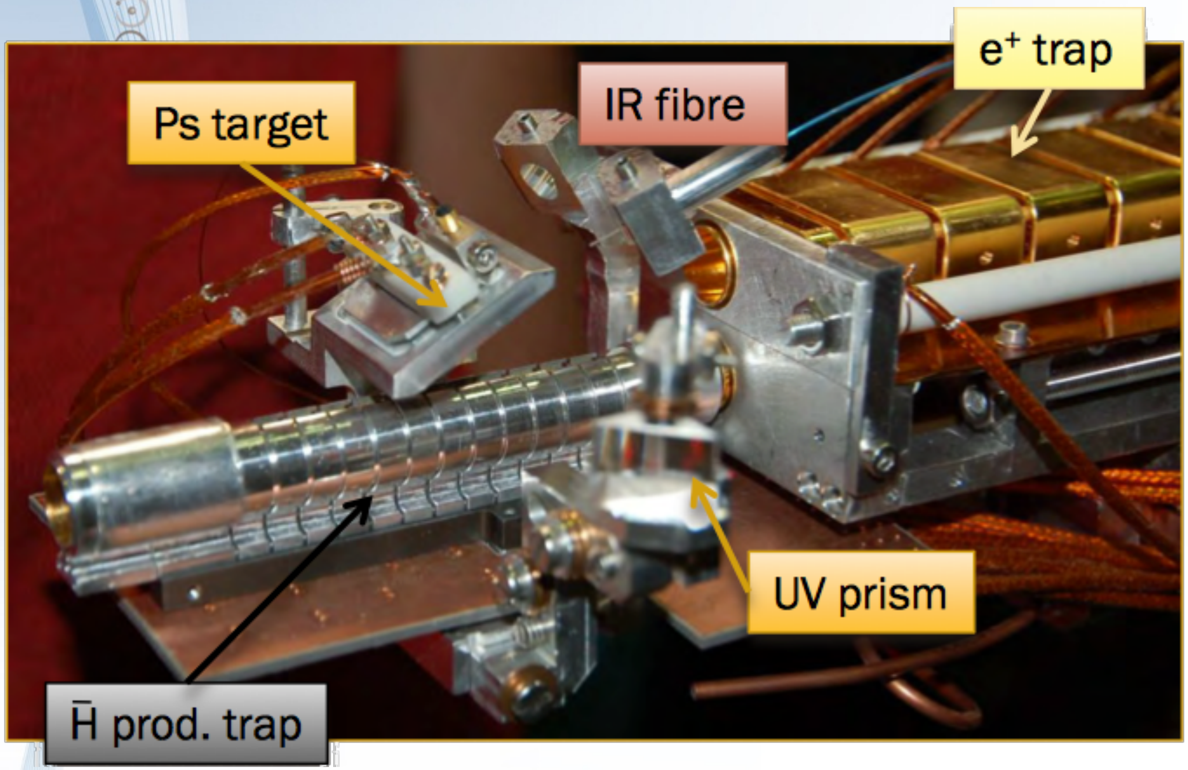
- ❖ High Ps formation rate
- ❖ Possibility to tune nano channel dimension (influences the temperature of Ps)

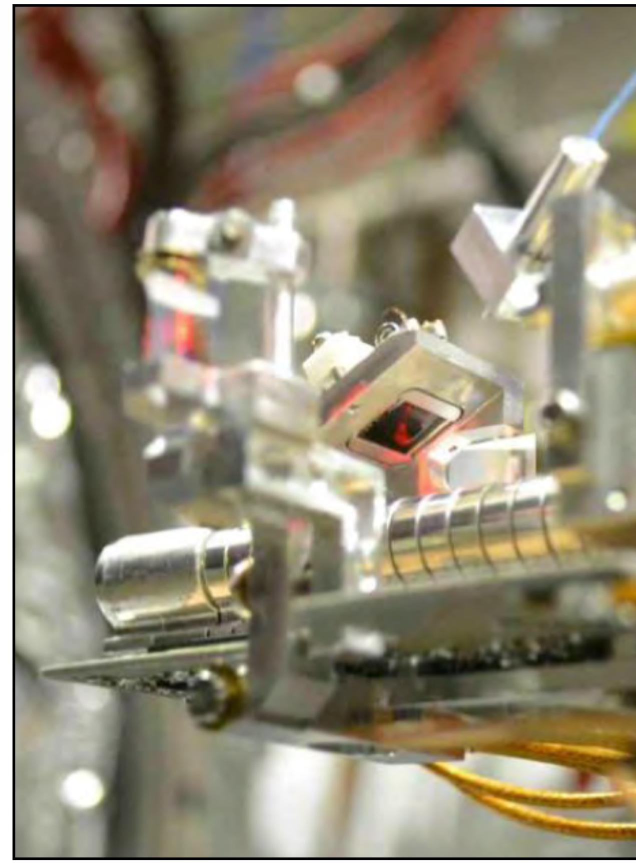


S. Mariazzi et al., Phys. Rev. B 78 085428 (2008).

S. Mariazzi et al., Phys. Rev. B 81 235418 (2010).

FROM e^+ to Ps



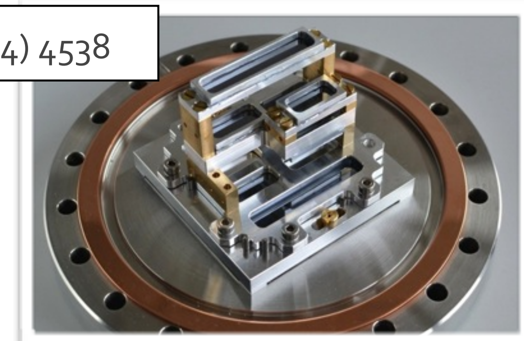


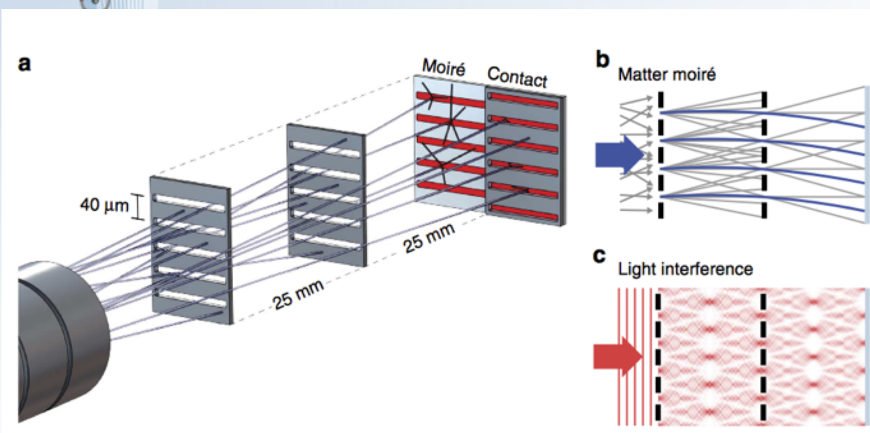
PROOF OF PRINCIPLE

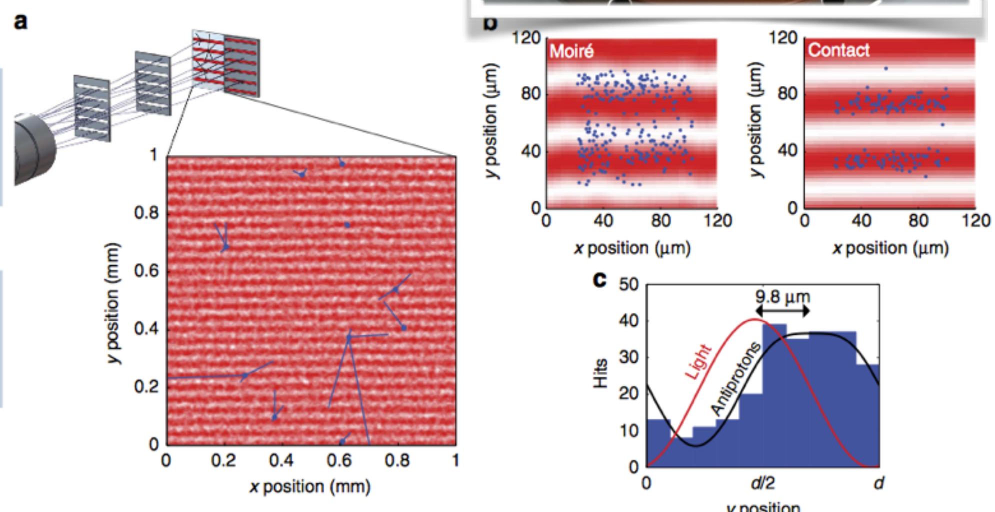
Mini-Moiré setup

- ~100 keV antiprotons
- 7 hour exposure
- Bare emulsion behind deflectometer
- Alignment of gratings using light and single grating

Nature Communications 5 (2014) 4538







Parasitic measurements primordial to converge to the optimal detector / deflectometer configuration

- Shift between $\bar{p}$ and light observed
- Consistent with B, E residual fields
- μm sensitivity reached

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

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

TOWARDS PRODUCTION OF COLD $\bar{P}$

Possible ways :

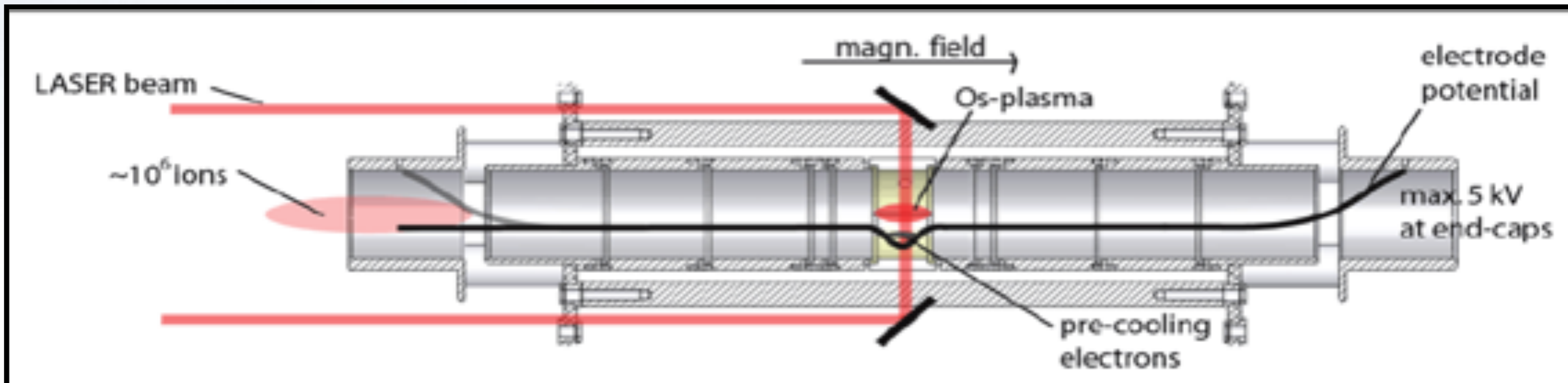
- Cool the environment to sub-Kelvin level

- indirect laser cooling of antiprotons to mK level and below

La- program in Heidelberg eg: *New Journal of Physics* 8 (2006) 45

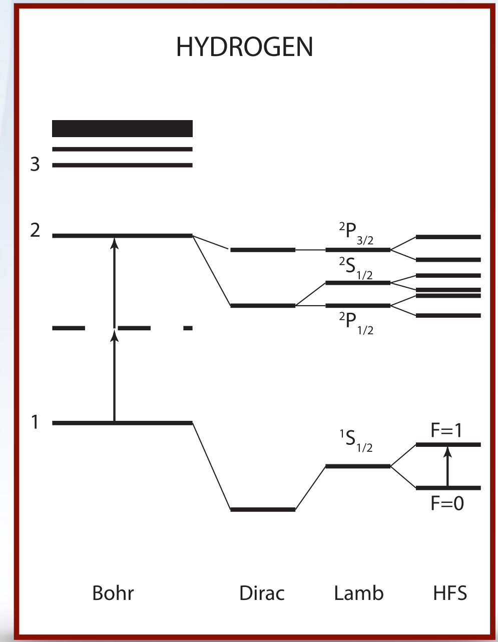
C_2- program at CERN *Phys. Rev. Lett* 114, 21300 (2015)

challenge: find suitable laser transitions for cooling of negative atoms/molecules



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** ==> ?