Experiments on trapped atomic antihydrogen and the ALPHA experiment at the Antiproton Decelerator

Simone Stracka, INFN Pisa

6 november 2023

The PS-AD/ELENA complex

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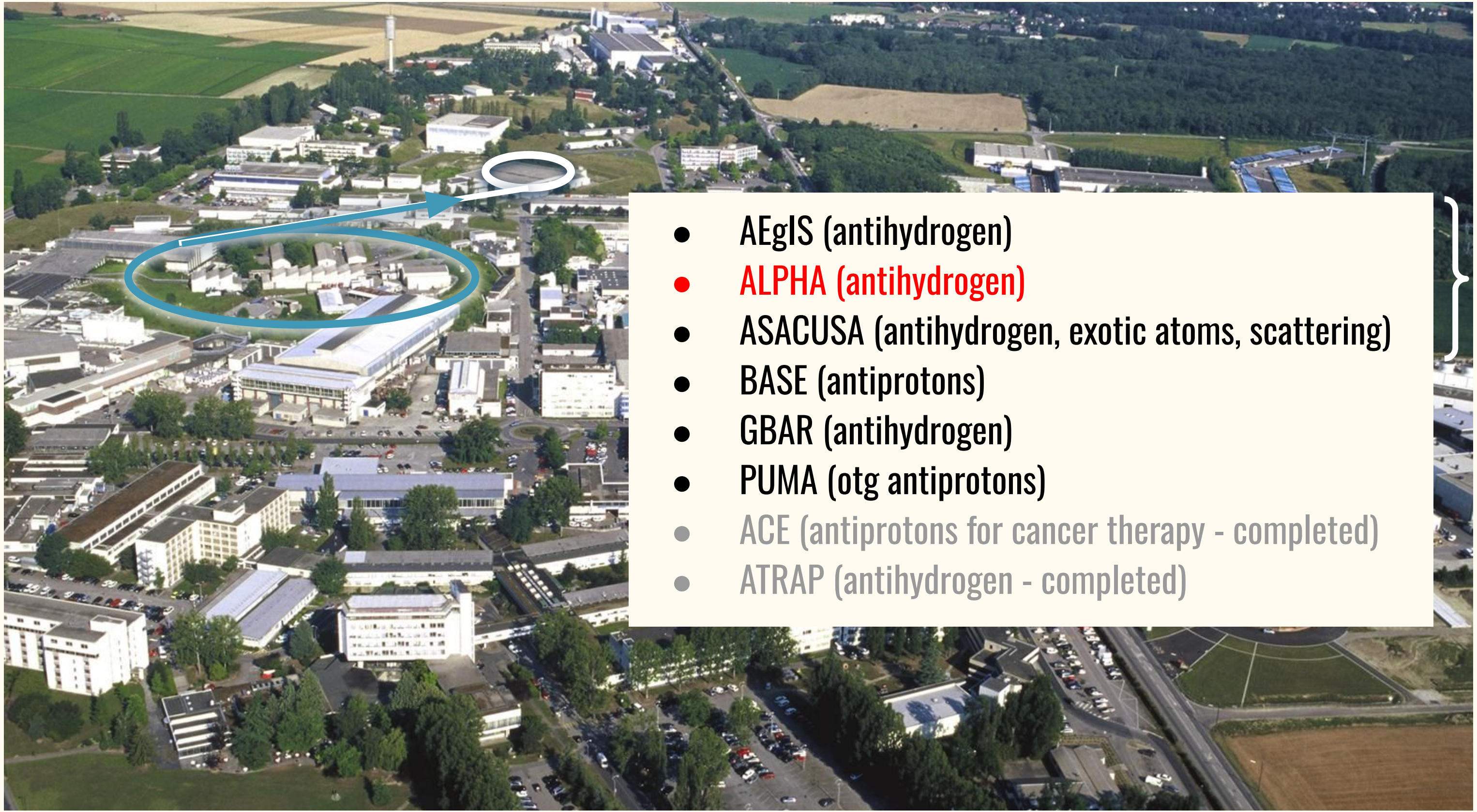


- AEgIS (antihydrogen)
- ALPHA (antihydrogen)
- ASACUSA (antihydrogen, exotic atoms, scattering)
- BASE (antiprotons)
- GBAR (antihydrogen)
- PUMA (otg antiprotons)
- ACE (antiprotons for cancer therapy - completed)
- ATRAP (antihydrogen - completed)

LEA (CSN3)
RN L. Venturelli

18 institutes, ~60 researchers

Aarhus University, Denmark

University of Brescia, Italy

University of British Columbia, Canada

University of California Berkeley, USA

University of Calgary, Canada

CERN

University of Liverpool, UK

University of Manchester, UK

NRCN - Nuclear Res. Center Negev, Israel

Purdue University, USA

Federal University of Rio de Janeiro, Brazil

INFN (Pavia, Pisa) Italy

G Bonomi, M Urioni,
A Del Vincio, SS

Stockholm University, Sweden

Simon Fraser University, Canada

TRIUMF, Canada

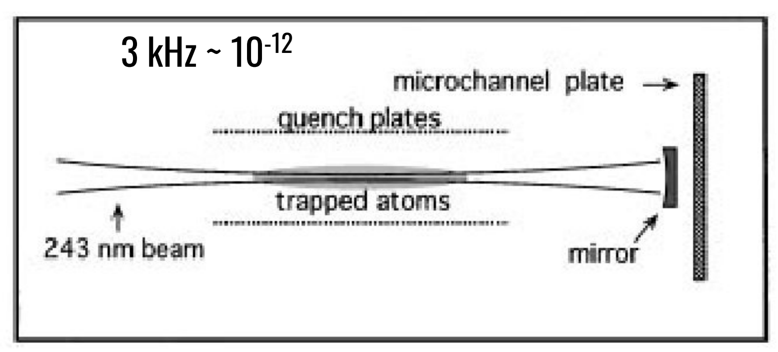
University of Wales Swansea, UK

Cockcroft Institute, UK

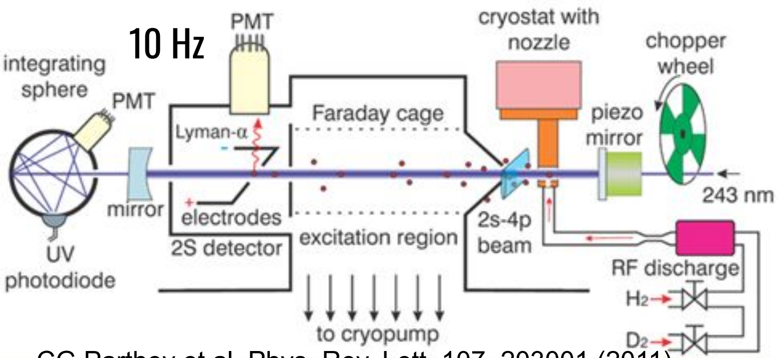
York University, Canada

ALPHA physics program: spectroscopy and gravity

- Repeat on antihydrogen the measurements done on hydrogen over time
  - As many as it is reasonable, and maybe a few more (we don't have a wide selection of anti-elements to choose from)
- With the best achievable precision
  - A mix of old and recent techniques
  - Using today's state of the art techniques, e.g., in metrology
- Taking into account the special environment constraints imposed by dealing with antimatter
  - Strong inhomogeneous magnetic fields to confine anti-atoms
  - To study anti-atoms, we must make them


3 kHz ~ 10^{-12}

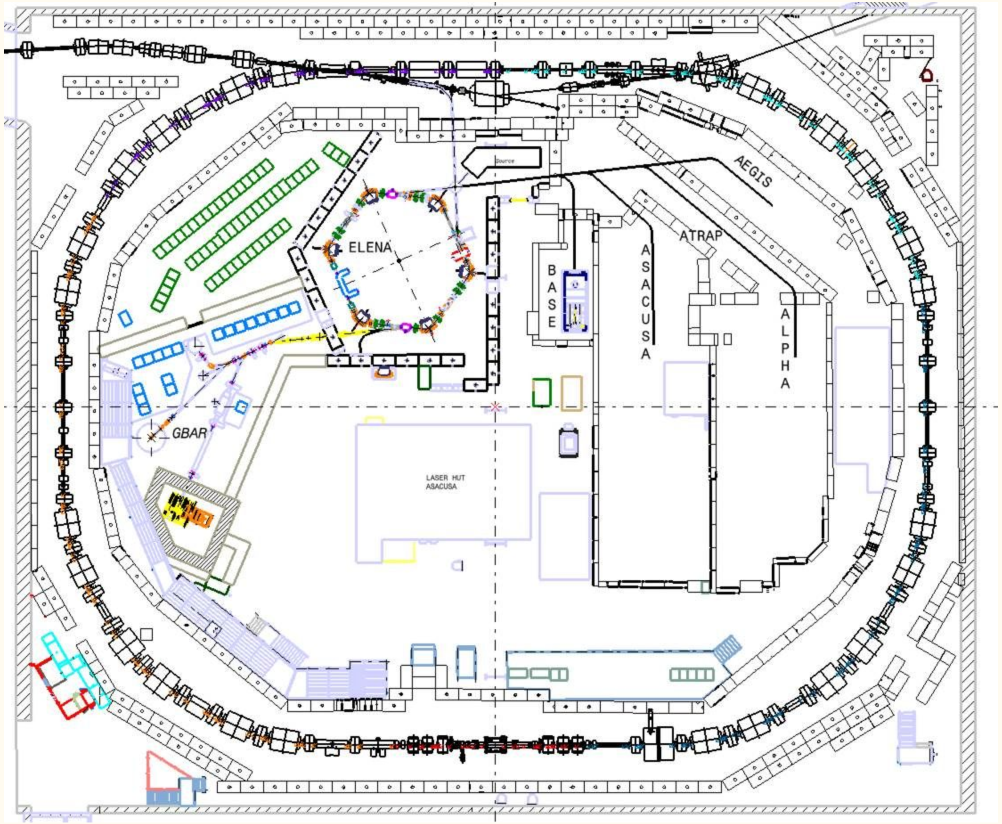
CL Cesar et al, Phys. Rev. Lett. 77, 255–258 (1996)


10 Hz

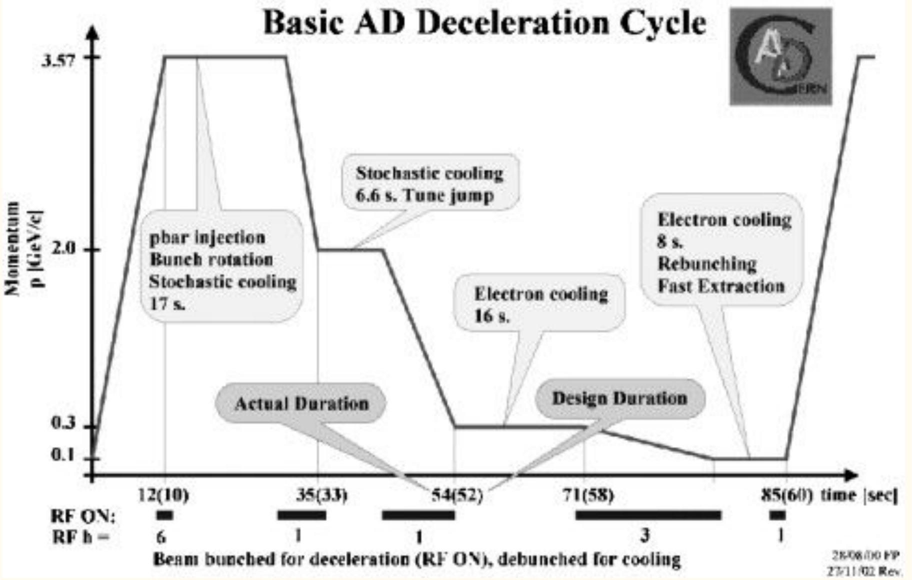
CG Parthey et al, Phys. Rev. Lett. 107, 203001 (2011)

Making antihydrogen

The “Antimatter Factory”: two accelerators in tandem

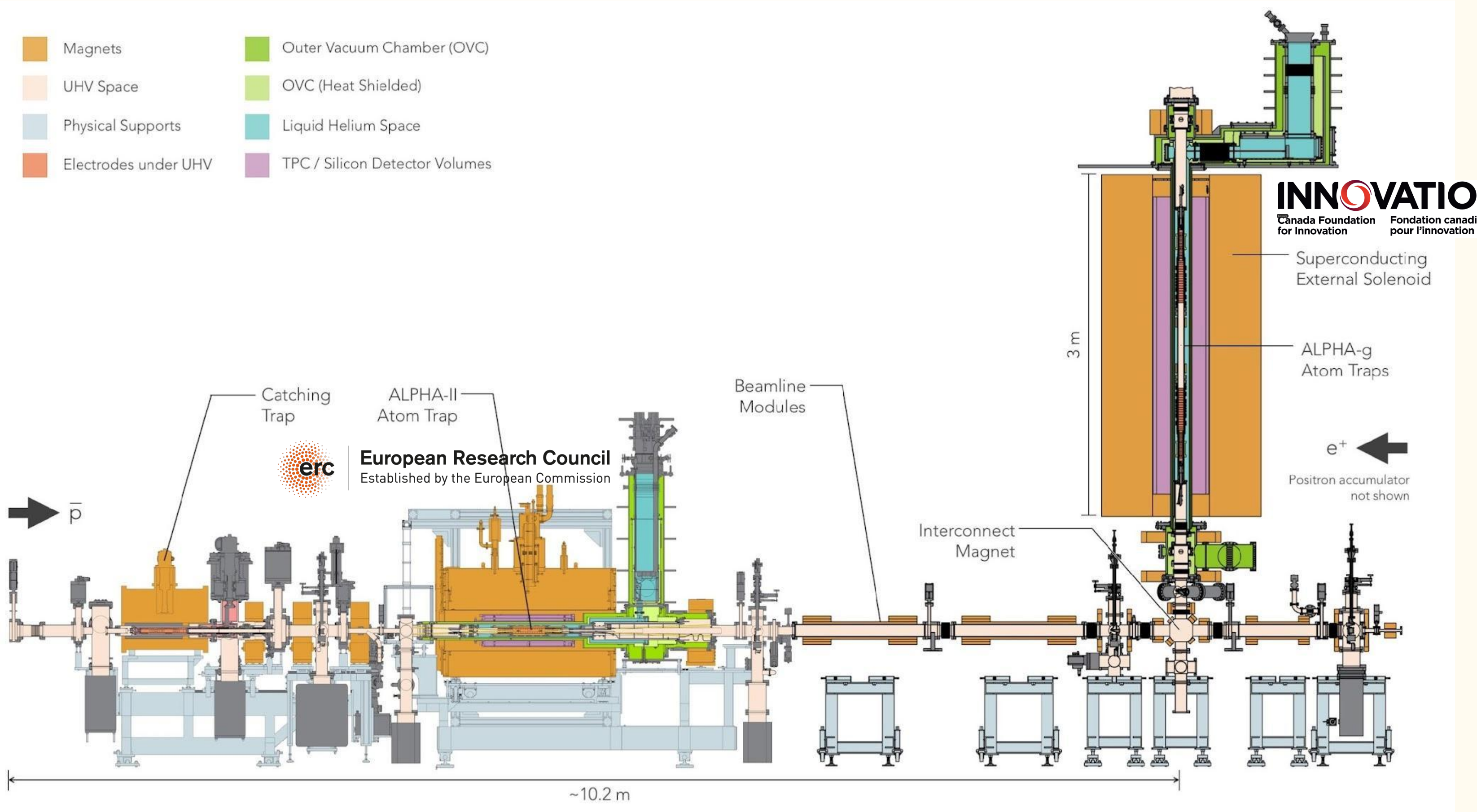


- AD (Antiproton Decelerator) since 2000
  - Decelerate to 5 MeV kinetic energy
- ELENA (Extra Low ENergy Antiproton) since 2018
  - 10^7 antiprotons at 100 keV per bunch



ALPHA-2 and ALPHA-g

INFN
PISA

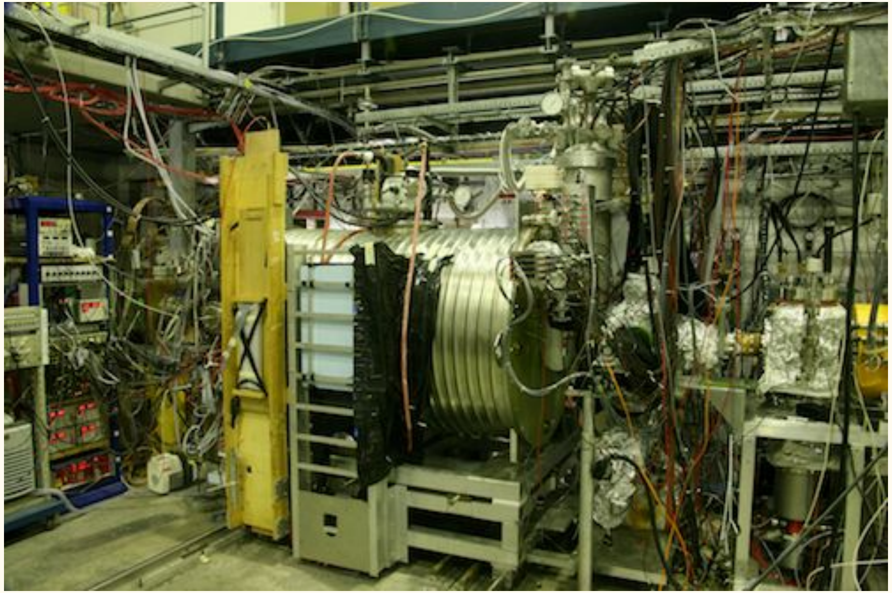


erc European Research Council
Established by the European Commission

INNOVATION
Canada Foundation for Innovation
Fondation canadienne pour l'innovation

ALPHA-1 (2005-2011) and ALPHA-2 (2012-)

- ALPHA-1 designed to establish anti-hydrogen confinement
- ALPHA-2: upgrade of ALPHA-1, with optical access added, optimized for laser spectroscopy
- I’ll refer to them interchangeably as ALPHA

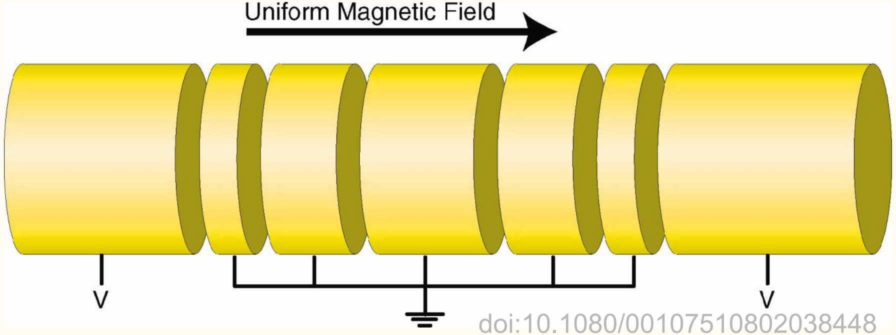


ALPHA-2 and ALPHA-g

- ALPHA-g (2018-) added to allow gravity studies
    - First mention of gravity studies in vertical ALPHA trap in 2008
      M. C. Fujiwara (TRIUMF), Pbar08 proc., arXiv:0805.4082
- Designed for 10 ppm control over the magnetic fields
- All the sections share the same working principles

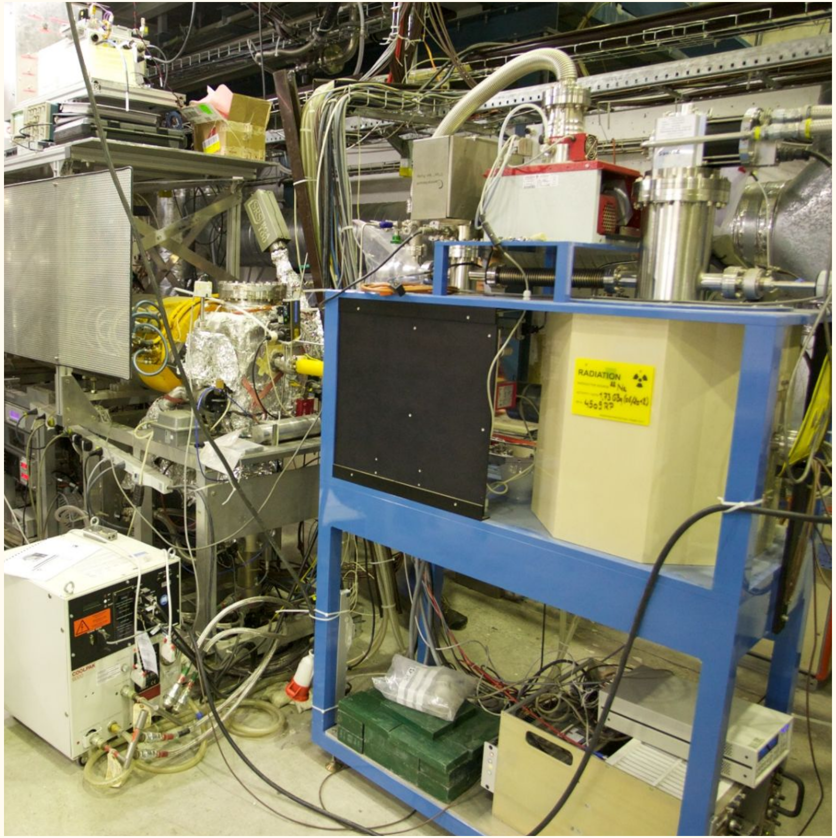
Catching antiprotons: Penning-Malmberg trap

- 100 keV antiprotons transverse a thin aluminum degrader
- Axial confinement from voltages applied to electrodes (up to 5 kV)
  - Trap ~2×10^5 per bunch
- Radial confinement from strong magnetic fields (3 to 5 T)
- Co-trap with electron for sympathetic cooling
- After initial cooling, may use lower fields

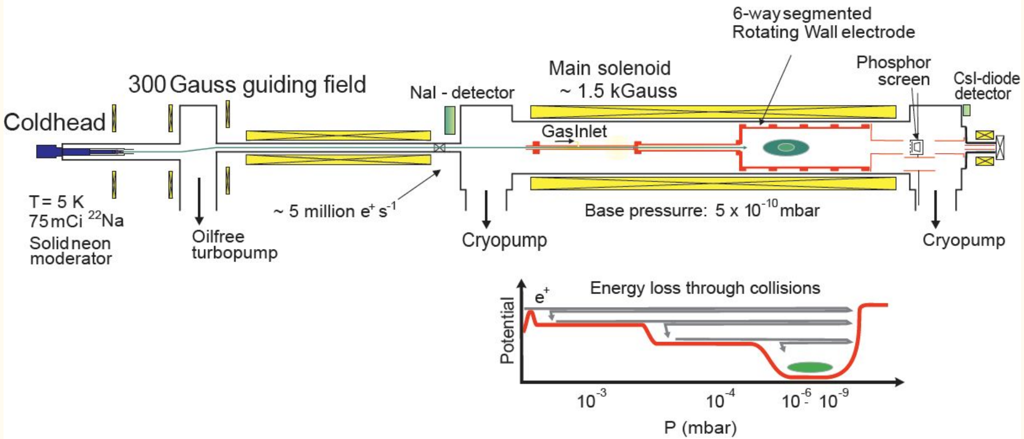


doi:10.1080/00107510802038448

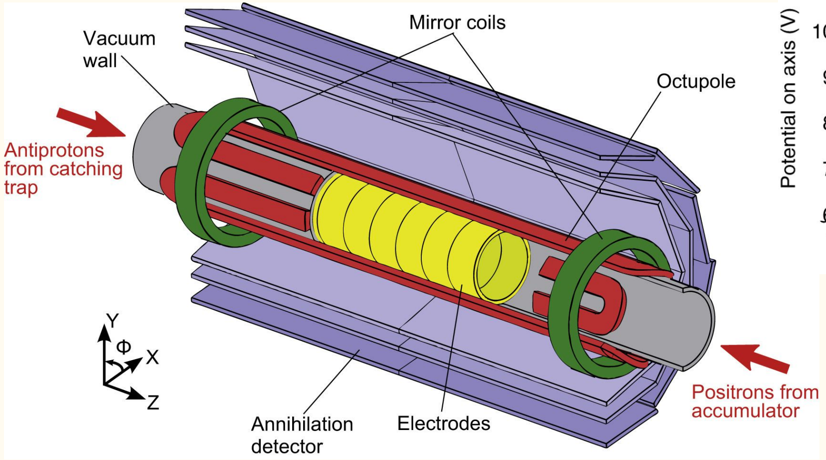
Accumulating positrons



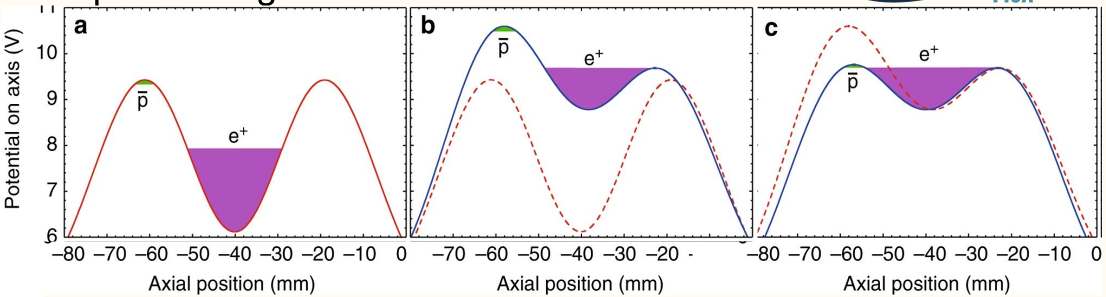
- e+ from ^{22}Na radioactive source (peak activity ~2.8 GBq)
- formed into a beam in vacuum using a solid neon moderator (0.5% efficiency)
- lose energy and become trapped through inelastic collisions with nitrogen molecules (25% efficiency)

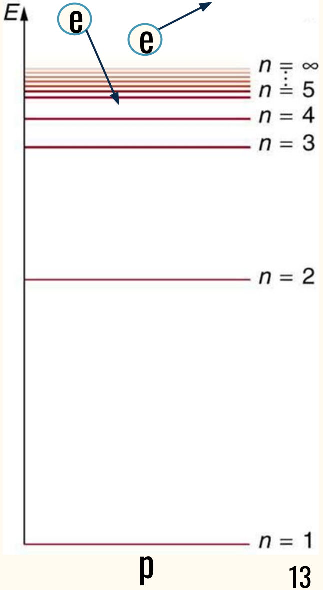


Mixing the two species



https://doi.org/10.1038/s41467-017-00760-9

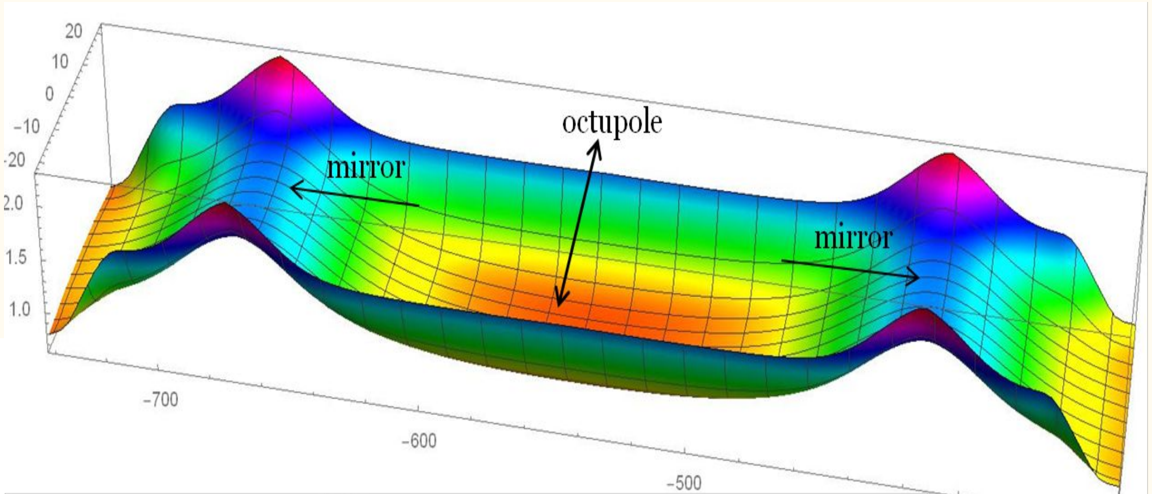


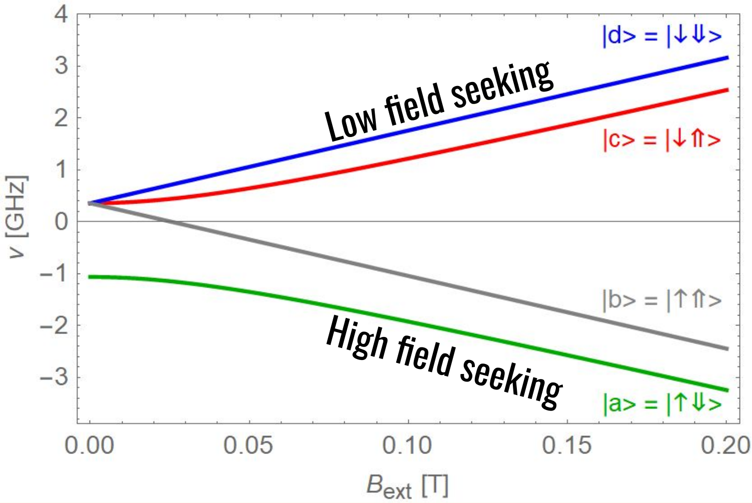


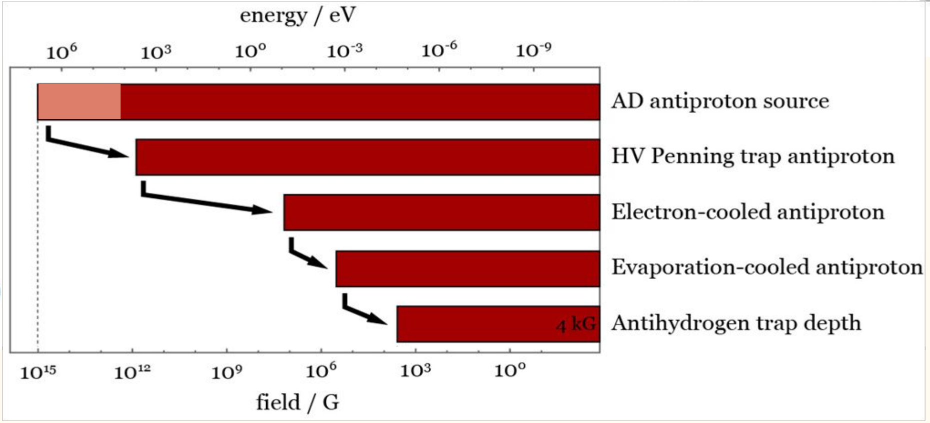
- Nested wells (a), with positrons separated from antiprotons
- Positrons are evaporatively cooled, then sit there waiting for antiprotons (b)
- Antiprotons are gradually moved closer to, and then into, the positron cloud (c)
- Anti-hydrogen is formed in a three-body recombination process (1 s mixing)
    - Then quickly cascade to the ground state ($\tau < 0.5$ s)
- The remaining positrons and antiprotons are then cleared by electric fields

Trapping antihydrogen

- Magnetic potential well $U = -\boldsymbol{\mu}\cdot\mathbf{B}$
    - 1T background field B_{ext}
- Well depth: 0.54 K / 50 μeV
- Good vacuum
    - can keep trapped Hbar for several hours

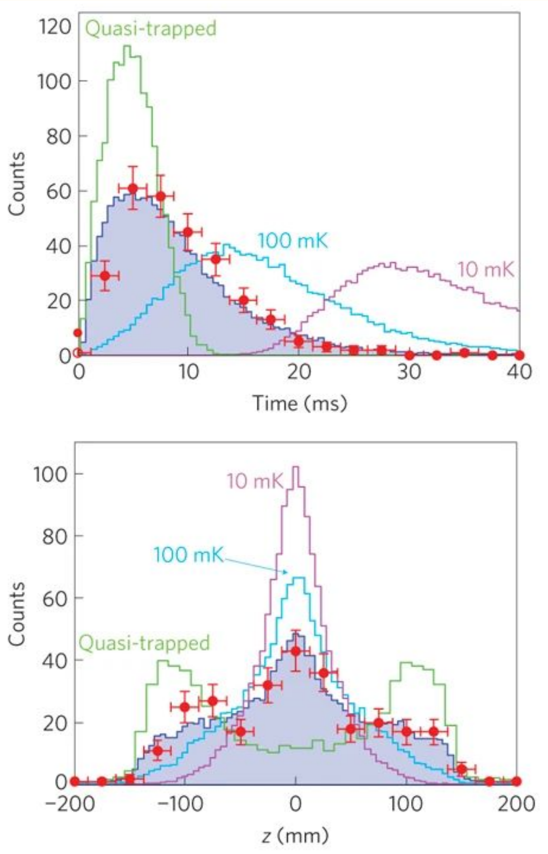


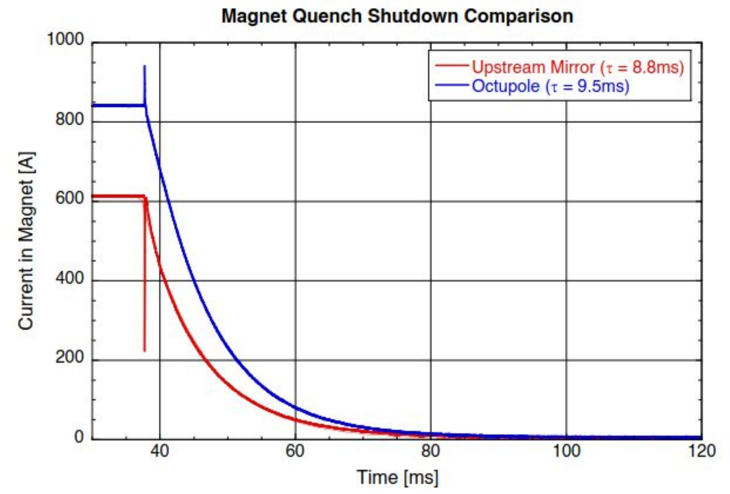




Releasing antihydrogen

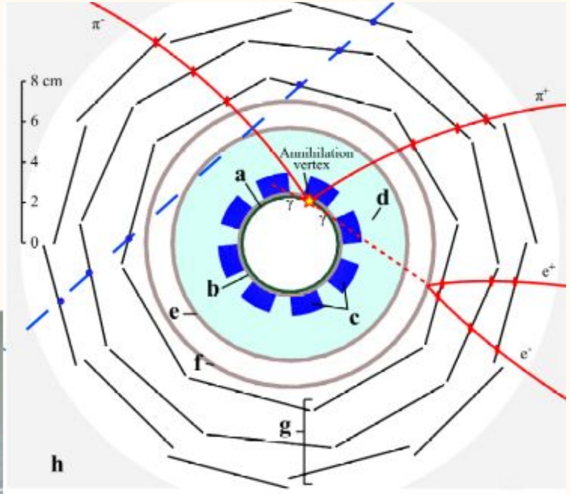
- As of today, antihydrogen is revealed only by its annihilation
  - No analog for hydrogen
- We can count the Hbar in the trap by lowering the magnetic fields
  - As the trap is lowered, hotter antihydrogen escapes first, then colder atoms
  - The time and z profile of annihilations provide means to estimate Hbar temperature
- Antihydrogen is imaged by position sensitive detectors





Detecting antihydrogen

- Track annihilation products in a silicon strip detector (ALPHA2) or a radial TPC (ALPHA-g), self-triggering
- Vertex position tells something about ejection mechanism
    - Hbar escaping the confining fields annihilates on electrodes
    - Confined Hbar also annihilates on residual gas in the trap
    - Main reducible background is cosmics
- Resolution limited by multiple scattering
    - octupole, trap walls, cryostat, vacuum chamber

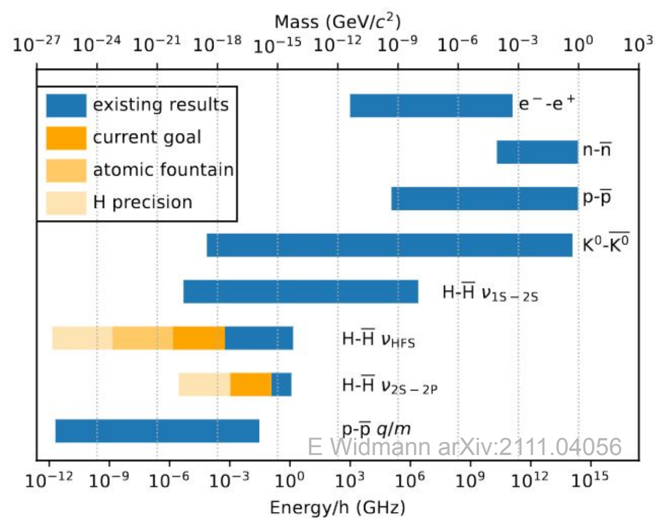


Petteri Pusa and Joseph McKenna (U. of Liverpool) with then TRIUMF grad student Andrea Gutierrez
P. Pusa et al, 2012 JINST 7 C01051
P. Pusa et al, NIM A 732 (2013) 134

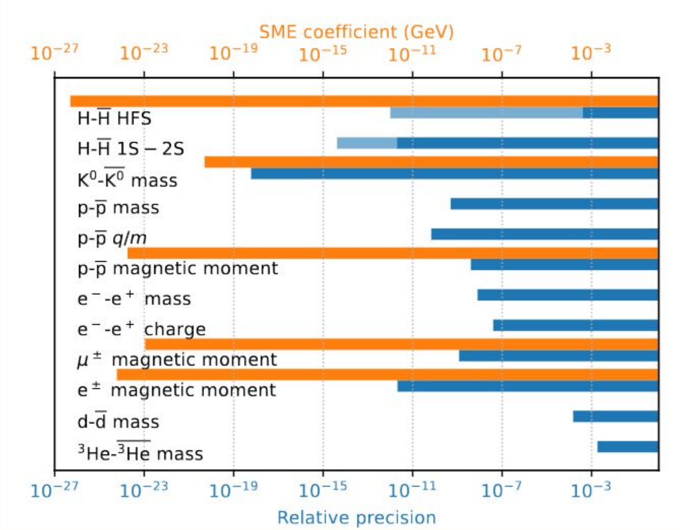
Antihydrogen spectroscopy

C Amole et al, Resonant quantum transitions in trapped antihydrogen atoms, **Nature 483, 439 (2012)**

What can we learn?



E Widmann arXiv:2111.04056

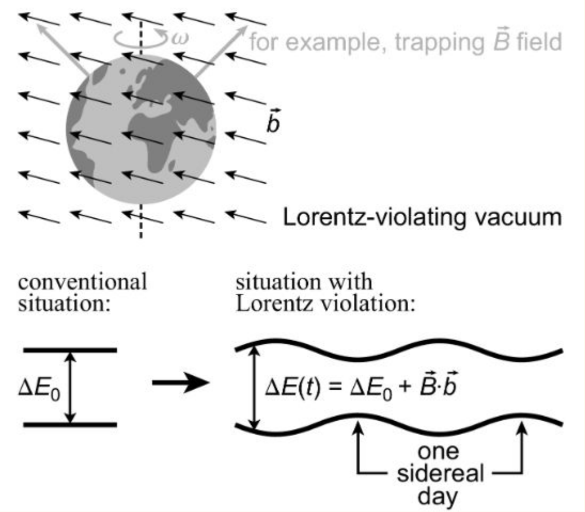


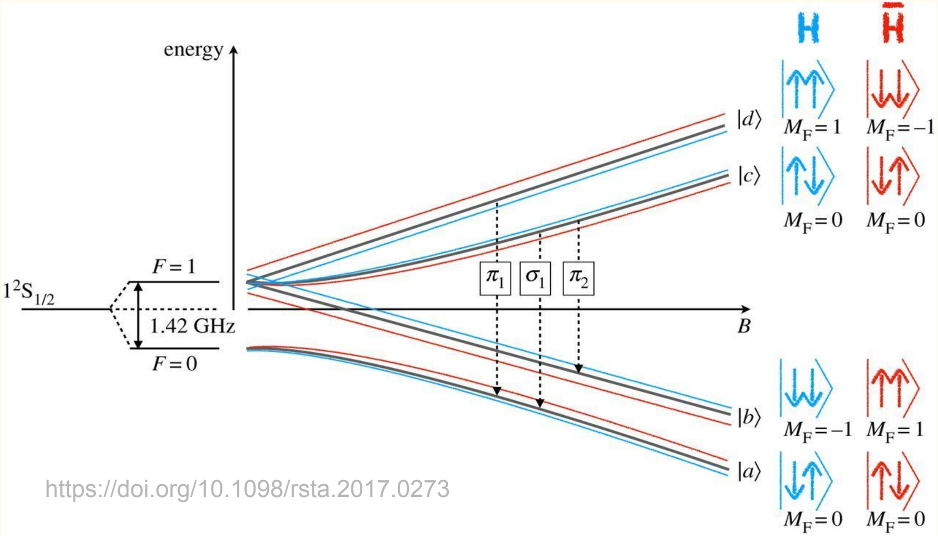
- Compare hydrogen and antihydrogen spectra: if CPT holds they should be the same
- CPT should hold in the usual (local, Lorentz invariant) QFT, but may be broken in other cases
    - e.g., when trying to introduce gravity, Lorentz invariance may be broken
    - or in non local theories [Physics Letters B 699, 177 (2011)]
- Standard Model Extension (SME): effective model with Lorentz violating terms (CPT and CPTV)
    - [arXiv:hep-ph/9810269]

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

Theoretical guidance

- Constraints to SME coefficients from
    - Single particle measurements in Penning trap (e.g., in the proton sector, BASE at the AD)
    - “Instantaneous” comparison of transition frequencies in H and Hbar
    - Sidereal variation of measured properties
- Framework to classify (and maybe compare and combine) different experiments
    - Different systems probe different combinations of (specie-dependent) operators
    - f_{da} - f_{cb} largely uninteresting

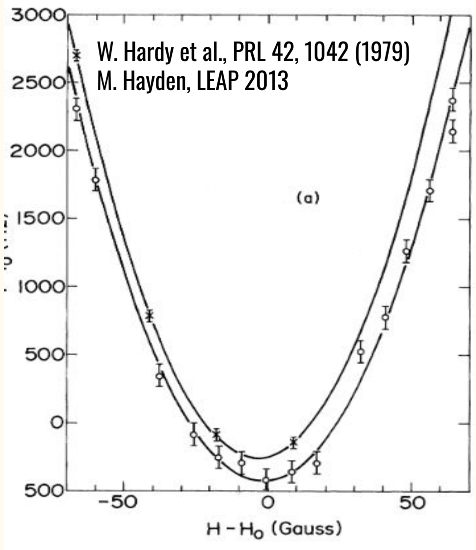




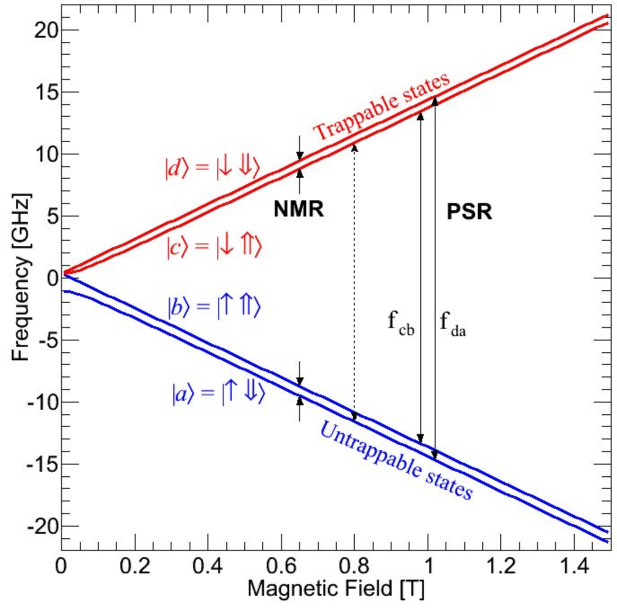
https://doi.org/10.1098/rsta.2017.0273

Studying the hyperfine structure of antihydrogen

- To study the hyperfine structure, the most promising approach is looking at the NMR d-c transition
  - Broad maximum at 0.65 T, 10^{-6}-10^{-7} precision within reach
    - Transit time broadening
  - Requires a resonator for 654.9 MHz microwave



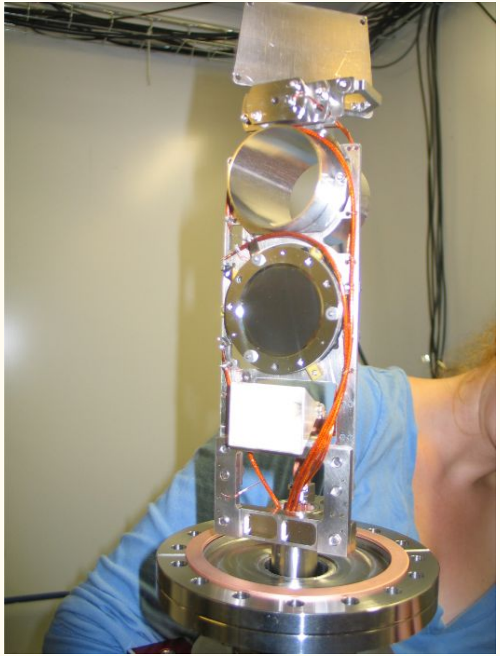
W. Hardy et al., PRL 42, 1042 (1979)
M. Hayden, LEAP 2013

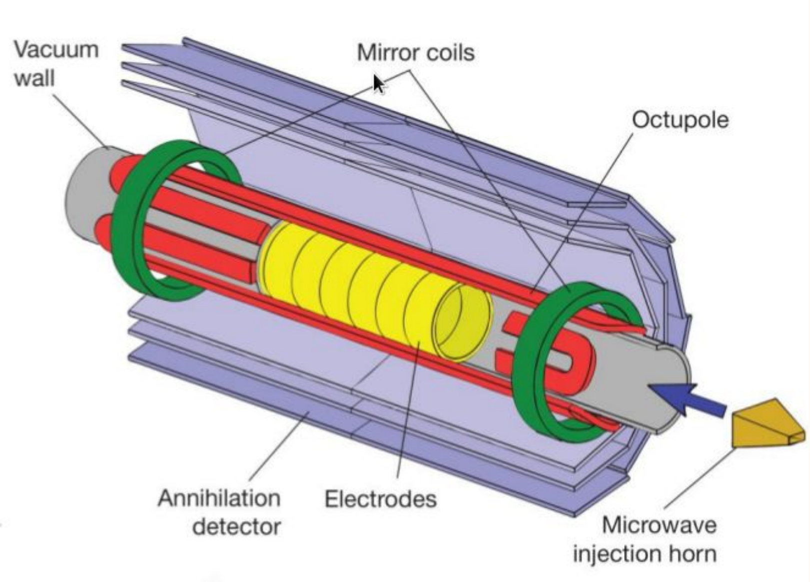


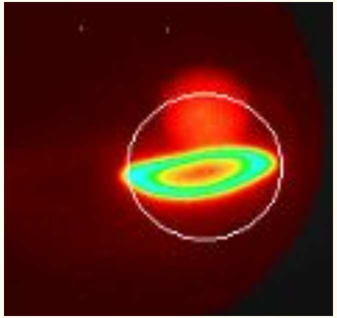
- c-b and d-a transitions are more easily accessible
  - difference of frequencies ~ constant with B
  - at high B, these transitions flip the positron spin and push the atom from the trap
  - microwave can travel down the stack of electrodes that act as a waveguide

Studying ground state hyperfine splitting of antihydrogen

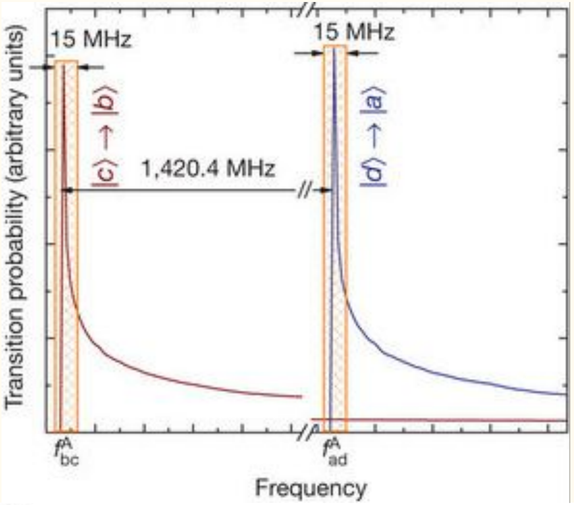
- Microwaves are injected from the diagnostic “stick”
- MCP with phosphor screen for imaging plasma

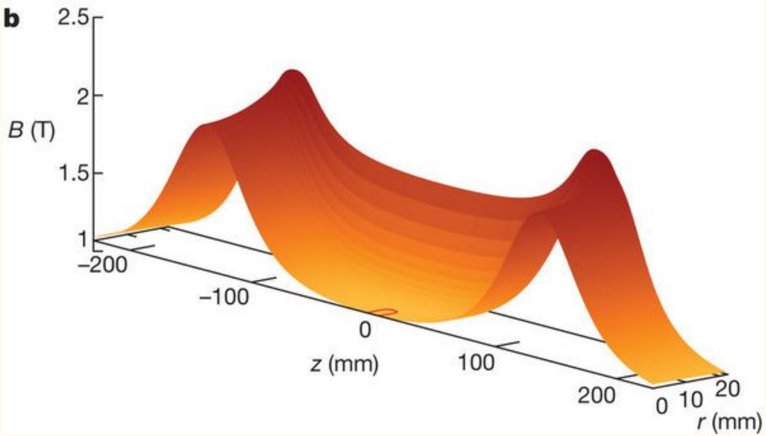






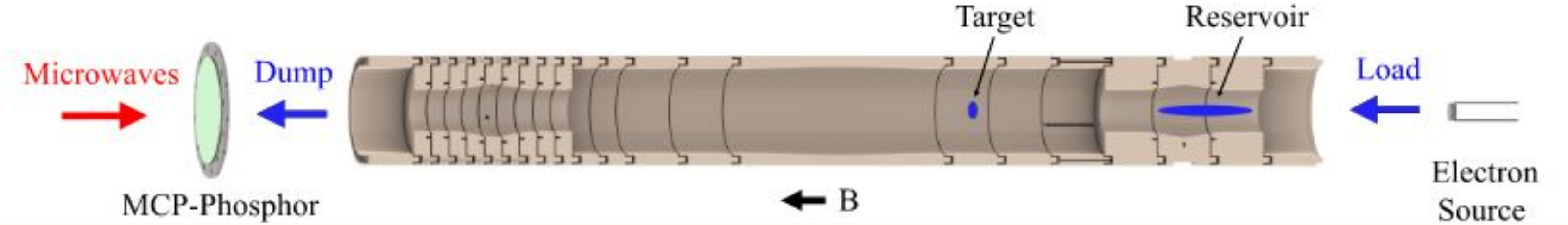
Anticipated PSR lineshape



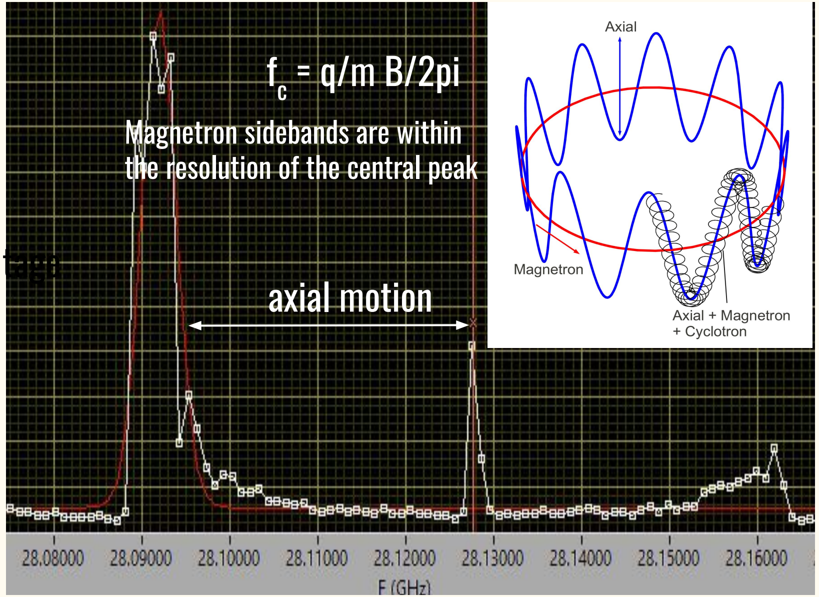


- Abrupt onset associated with minimum in magnetic field
  - The difference between onsets is the GSHF (21 cm line) frequency
  - The position of the onset can be used to monitor the B-field. Initially limited by statistics
- Long tail is related to temperature
  - Hotter Hbar travel to regions of higher B, where the transition frequency is larger than at the minimum
- The power at the two frequency may be different: the electrode stack is a waveguide with a frequency-dependent pattern of nodes
  - Lineshape need not be the same for the two transitions

Electron Cyclotron Resonance to measure magnetic field



- Load an electron plasma in measurement location
- Heat plasma with microwaves at given frequency
- Measure temperature
  - Look at time-development of MCP signal as the blocking voltage is gradually lowered to release the plasma, or
  - Use non-destructive methods calibrated on the former
- Wait for plasma to cool down (or load a new plasma, from a reservoir) and repeat at different frequency

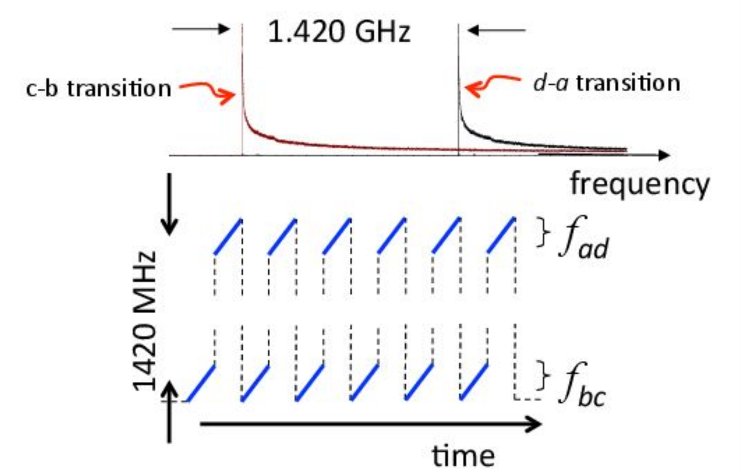

$f_c = q/m\ B/2pi$

Magnetron sidebands are within the resolution of the central peak

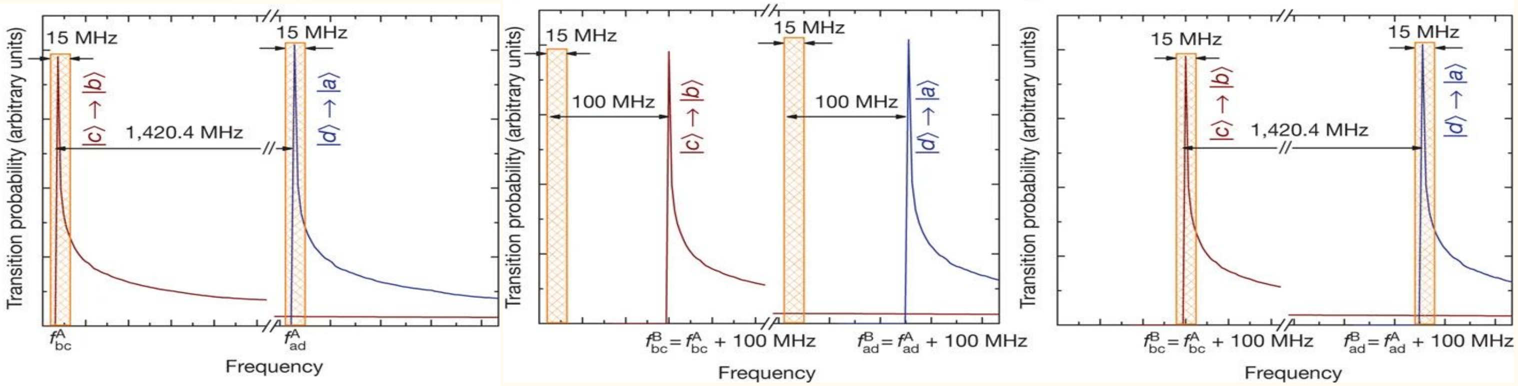
T Friesen et al, New Journal of Physics 16 (2014) 013037 doi:10.1088/1367-2630/16/1/013037
ED Hunter et al, Phys. Plasmas 27, 032106 (2020) doi:10.1063/1.5141999

Measurement protocol

- Synthesize and trap antihydrogen
- Irradiate with microwaves, cycling between transitions
  - c-b transition tail may extend under the d-a peak
- Release and count surviving atoms
  - on/off-resonance measurements adjusting B and uw-frequency
  - turn off microwave to understand loss mechanisms other than positron spin-flips
- 100 MHz (30 Gauss) safe offset given B uncertainties

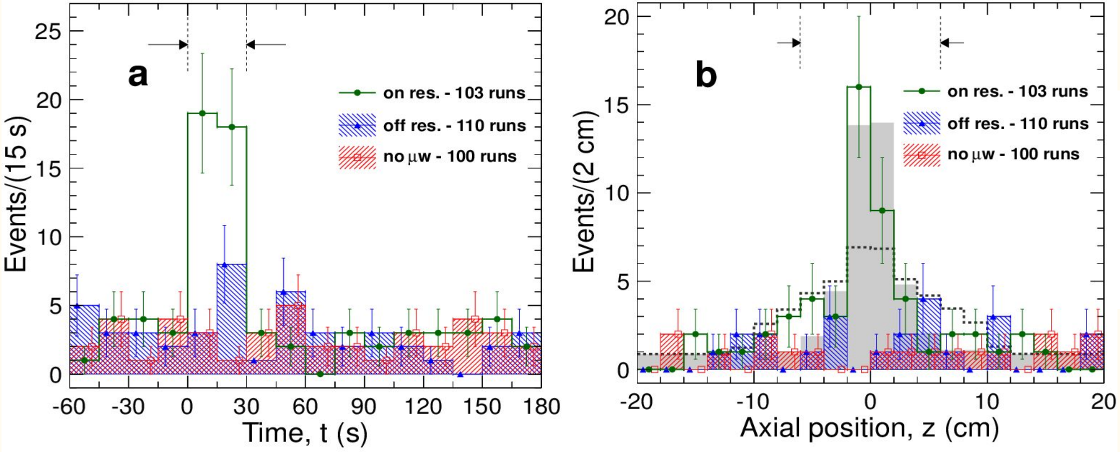


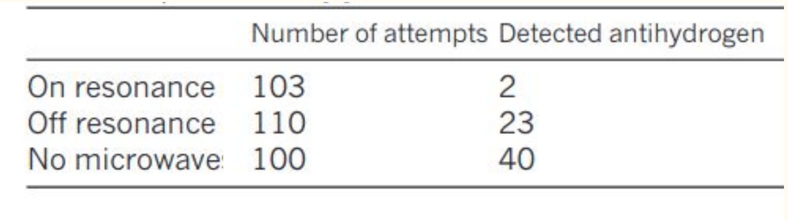
On-resonance ⇒ increase mag field ⇒ Off-resonance ⇒ increase frequency ⇒ On-resonance



Gateway to antihydrogen spectroscopy

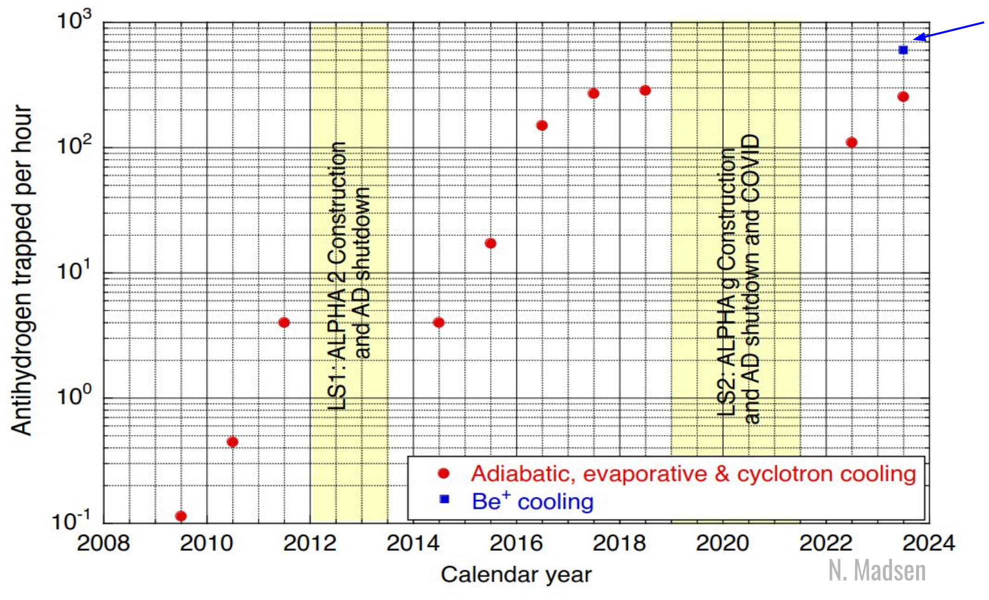
- We can count the residual Hbar after irradiation to show that we are hitting the resonance
  - Not an efficient way to run spectroscopy
- Looking at the distribution of annihilations as they happen is a better approach
  - Associate signal to frequency: can run a full scan in one go, avoiding normalization issues
  - Provides info about other mechanisms of Hbar losses
  - For PSR, obtain for free a real-time monitoring of the magnetic field variation at the center





	Number of attempts	Detected antihydrogen
On resonance	103	2
Off resonance	110	23
No microwave	100	40

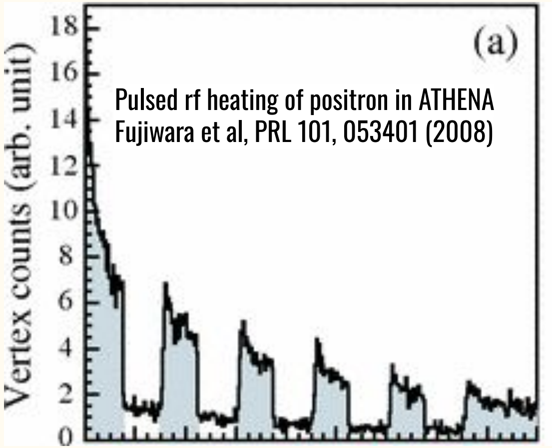
Antihydrogen production trends



N. Madsen

Be+ assisted, using techniques from Phys. Rev. A 67, 063406 (2003)

- Avoid depletion issues when scanning a spectrum by keeping power low
  - Smaller signal, longer scans, worse S/B
  - Improve background rejection
- Irradiate more Hbar
  - achieve precision with fewer iterations
  - larger signal for the same power, better S/B

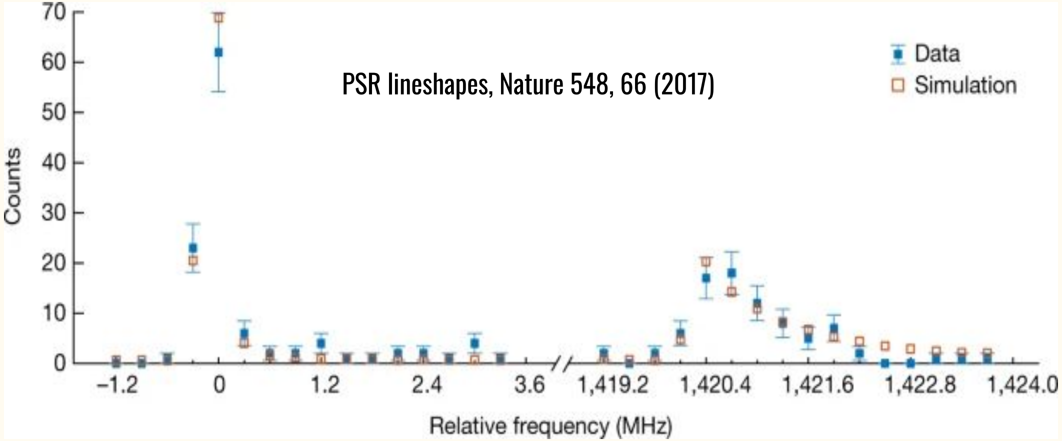


Pulsed rf heating of positron in ATHENA
Fujiwara et al, PRL 101, 053401 (2008)

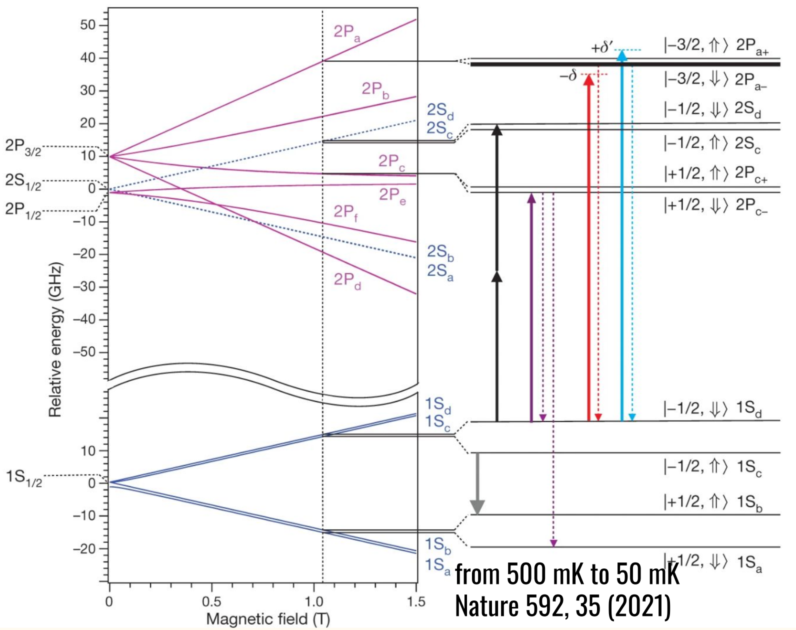
- Accumulate Hbar through several synthesis cycle before physics study (stacking)
- Improve Hbar production
  - E.g., by reducing positron temperature (20K to 7K)
    [CJ Baker et al, Nat. Comm. 12, 6139 (2021)]

Spectroscopy with ALPHA2

- PSR is a workhorse of spectroscopy in ALPHA
  - Monitor B field variations
  - Measure or select d or c population, and/or temperature
- Techniques used in virtually all spectroscopy results
  - E.g., two-photon 1S-2S spectroscopy
  - Used to select d-states
  - $f(1S\text{-}2S)_{d\text{-}d}$ = 2,466,061,103,079.4(5.4) kHz [Nature 557, 71 (2018)]



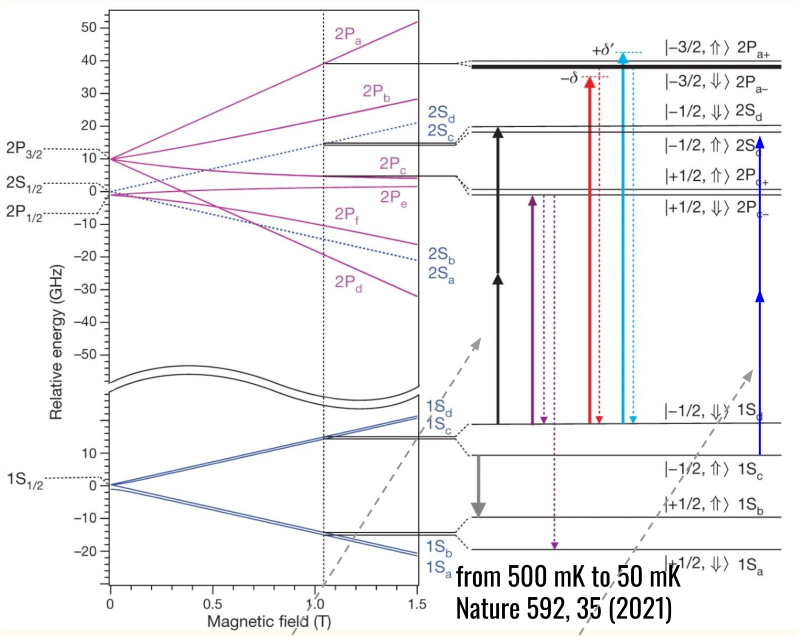
PSR lineshapes, Nature 548, 66 (2017)



from 500 mK to 50 mK
Nature 592, 35 (2021)

What lies ahead

- Study daily and annual variations of transition frequencies
  - need to speed-up “gear-up” phase at the beginning of the year
- Study (matter) hydrogen in the same apparatus
  - control systematics in H-$\underline{\text{H}}$ comparison
  - work in progress by several groups of the collaboration. However:
- Non-cancelling SME effects in [$f(1S\text{-}2S)_{d\text{-}d}$ - $f(1S\text{-}2S)_{c\text{-}c}$]
  - measure and compare this to hydrogen
  - could cancel many systematics without measuring H in ALPHA
  - maybe slightly worse reach than NMR
- NMR ($f_{d\text{-}c}$) is sensitive to roughly the same SME effects
  - Plans to add resonator in next Long Shutdown
- PSR can serve as control/calibration for NMR
  - Benefits from large volume of flat B field
  - Ability to shape B field helps

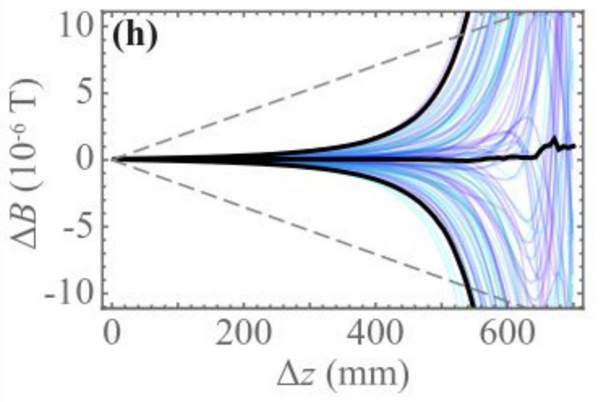


from 500 mK to 50 mK
Nature 592, 35 (2021)

$$\Delta^{H\text{-}\underline{H}}\ f(1S\text{-}2S)_{d\text{-}d} = O(\alpha^2)$$

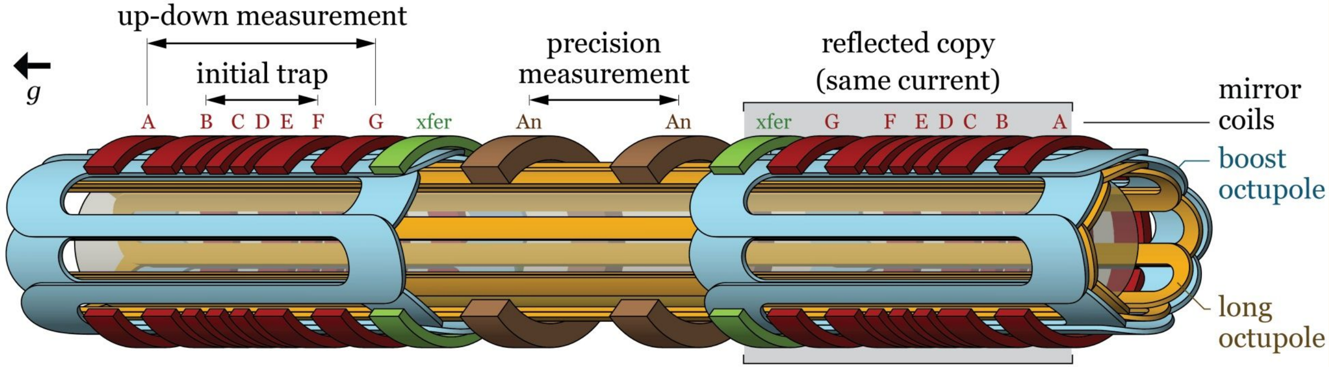
$$\Delta^{H\text{-}\underline{H}}\ f(1S\text{-}2S)_{c\text{-}c} = \cos(\tan^{-1}(51\ \mathrm{mT}/B_{ext}))\times O(1) + O(\alpha^2)$$

ALPHA-g

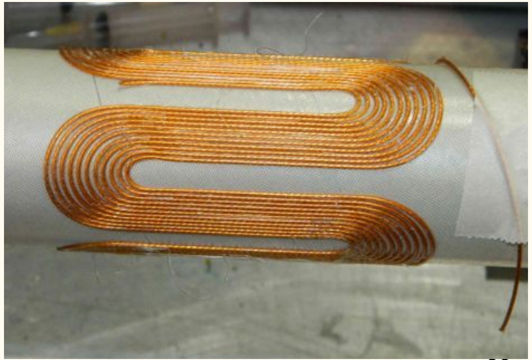


- Long+boost octupoles: minimise field errors due to fabrication tolerance in central (“precision”) region
- Symmetrise magnet history to mitigate effect of current loops induced by field changes
- Passive and active shimming to correct non-uniformity of background solenoid field
    - ~20 G non-uniformity to ~4 G non-uniformity, then further correction with coils

- A free-fall experiment for antihydrogen is an ideal testbed for magnetic field control



Chukman So (TRIUMF)



https://www.bnl.gov/magnets/alpha/

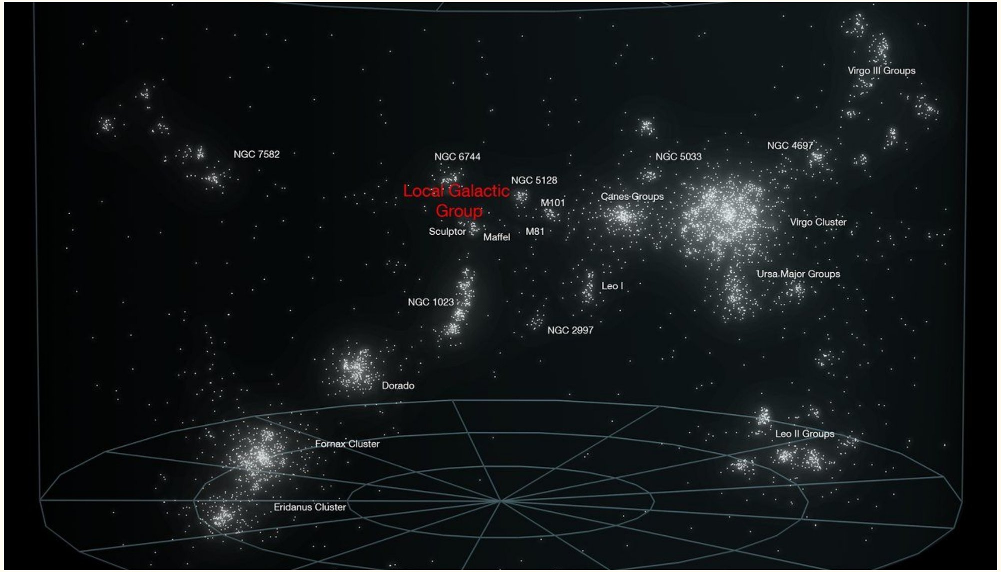
Free-falling antihydrogen

EK Anderson et al, Observation of the effect of gravity on the motion of antimatter, **Nature 621, 716 (2023)**

Direct and indirect measurements

- Force measurements with different elements
    - constrain WEP violations from varying binding energy
    - different proton-neutron fractions and kinetic energies
- Clock (gravitational redshift) measurements on antimatter (kaons, antiprotons)
    - specie dependence of fluctuations: do limits from kaons apply to antiprotons?
    - limits vary from 10^{-7} to 1% depending on the assumed gravitational potential (Earth, Sun, Local cluster?)

$$\frac{\nu_{c,\bar{p}}}{\nu_{c,p}} = \frac{m_p}{m_{\bar{p}}}\left(1 + \frac{3(\alpha_g - 1)}{c^2}U\right)$$

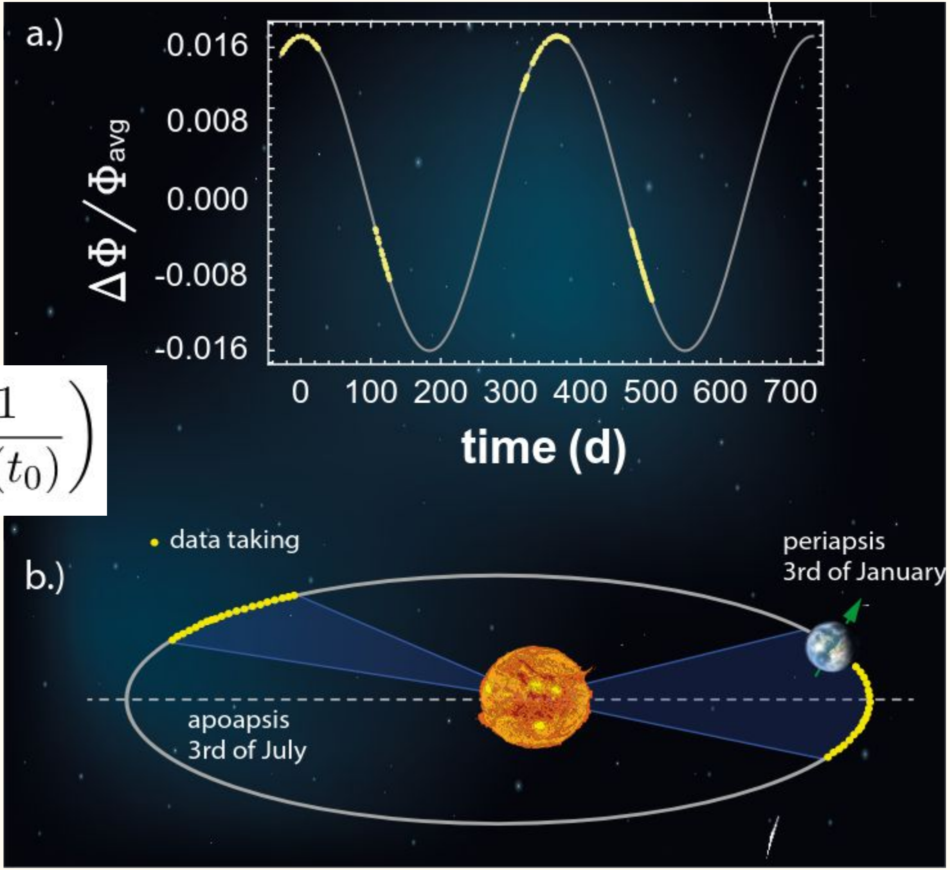


$$\frac{\nu_{c,\bar{p}} - \nu_{c,p}}{\nu_{c,\mathrm{avg}}} = \frac{3\Phi}{c^2}(\alpha_g - 1)$$

Property	Limit C.L. 0.68
$\alpha_g - 1$	$< 1.8 * 10^{-7}$
$\alpha_{g,D} - 1$	< 0.03

$$\frac{\Delta R(t)}{R_{\mathrm{avg}}} = \frac{3GM_{\mathrm{Sun}}}{c^2}(\alpha_{g,D} - 1)\left(\frac{1}{O(t)} - \frac{1}{O(t_0)}\right)$$

[S. Ulmer et al (BASE), Nature 601, 53 (2022)]

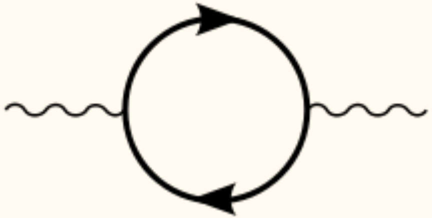


Virtual antimatter

- Virtual antimatter in elementary particles that are their own antiparticles [arXiv:1207.7358]
    - rely on a particular form of WEP-violating interactions (e.g., vector and scalar gravity-like forces, SME)
    - evaded by models in which corrections only depend on flavor but not on the mass (some limits of SME, fifth force)
- Virtual antimatter content of matter particles with structure combining force and clock measurements [arXiv:0907.4110, arXiv:1303.2747]
    - rely on CPT (to some extent, e.g., to model the behavior of antimatter in the system under study) and most (all?) of the above
- Indirect evidence suggests discrepancy between matter and antimatter is ≲1% [arXiv:0808.3929]
- With some assumptions these limits may reach the 10^{-6}-10^{-8} level

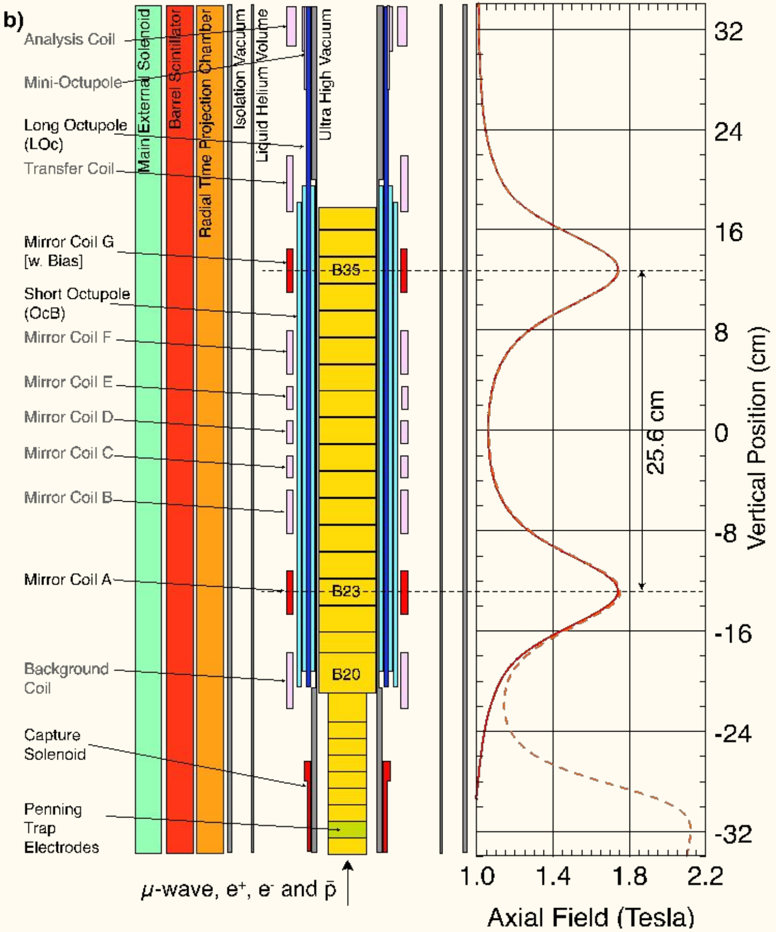
$$V = -\frac{G_\infty}{r} m_1 m_2 \left(1 \mp a\, e^{-r/v} + b\, e^{-r/s}\right)$$

[Phys. Rev. D 33 (2475) (1986)]



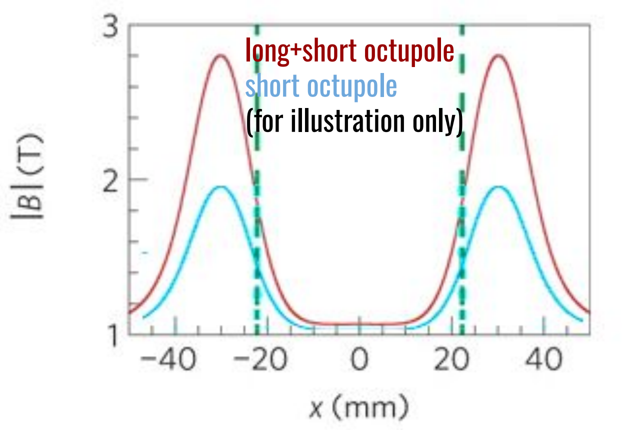
2022 experimental campaign

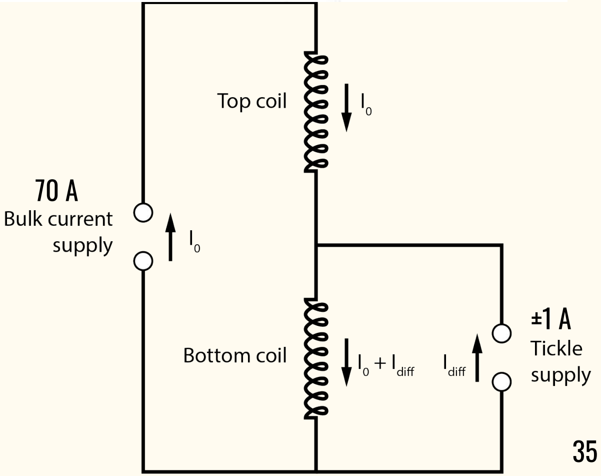
- Motion of antihydrogen is due to a combination of magnetic-trap and gravitational field
- Use the magnetic field difference between top and bottom mirrors to compensates gravity
- For hydrogen: $m_H\, g\, \Delta z / \mu_B \sim 4.53$ G
  - Compare to trap depth of ~ 4 kG
- In 2022 only the lower trap was used:
  - Deeper trap, fewer manipulations, larger statistics
  - Worse accuracy, larger history-related effects



Measuring the potential unbalance

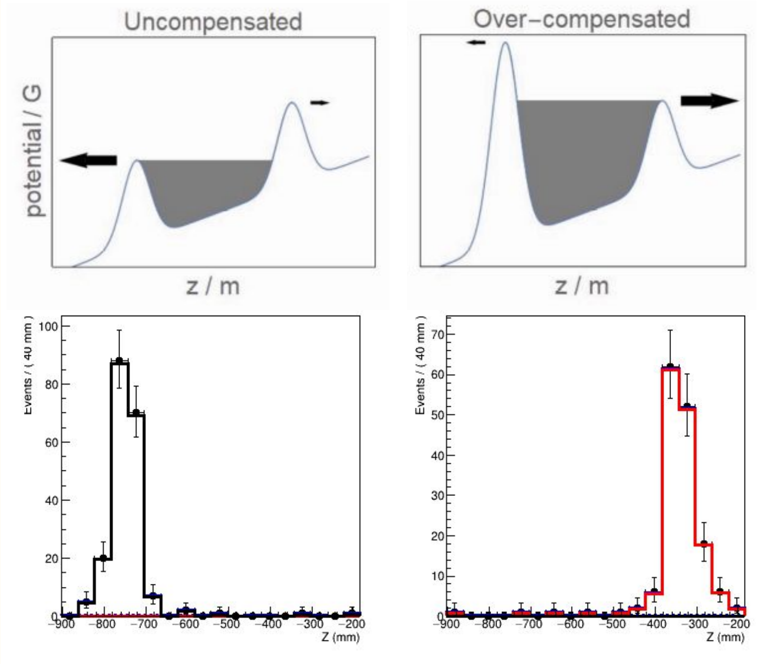
- After synthesis and trapping, the long octupole is ramped down, leaving only the shorter trap
  - Some fraction of antihydrogen is lost in this step
  - We assume this fraction is constant in all runs
- Set a difference between top and bottom mirror fields
- Mirrors gradually lowered to release antihydrogen
  - Common mode power supply to control the ramp
  - Second power supply to keep the difference between mirrors



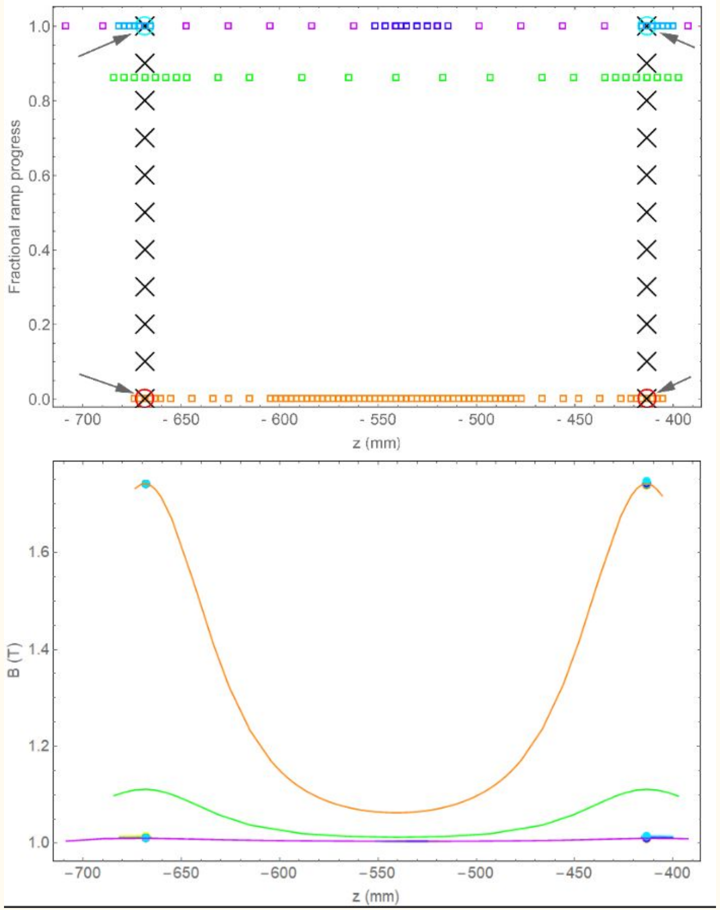


Measuring the potential unbalance

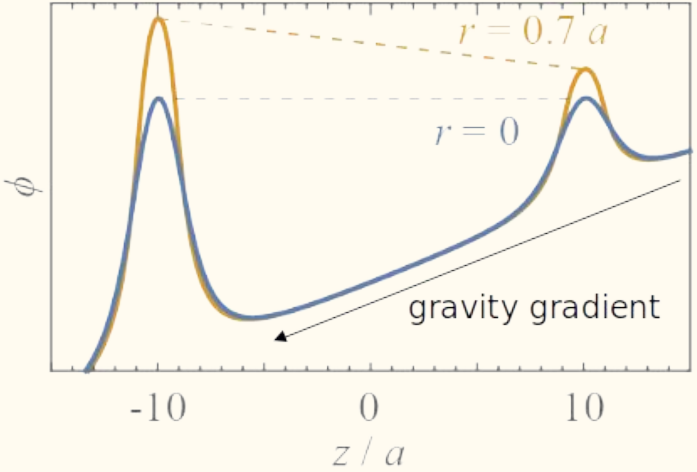
- Antihydrogen explores the trap until it finds a way out
    - Short octupole remains on: atoms escape from the axial ends
    - **Magnetic field at saddle points must be well characterized**
- If barrier is asymmetric they prefer escaping on one side
    - Relative proportion of atoms escaping up and down depends on **Hbar dynamics on the timescale of the mirror ramp-down**
- Study the asymmetry of annihilations
    - **Must correct yields for detection efficiencies**



Magnetometry

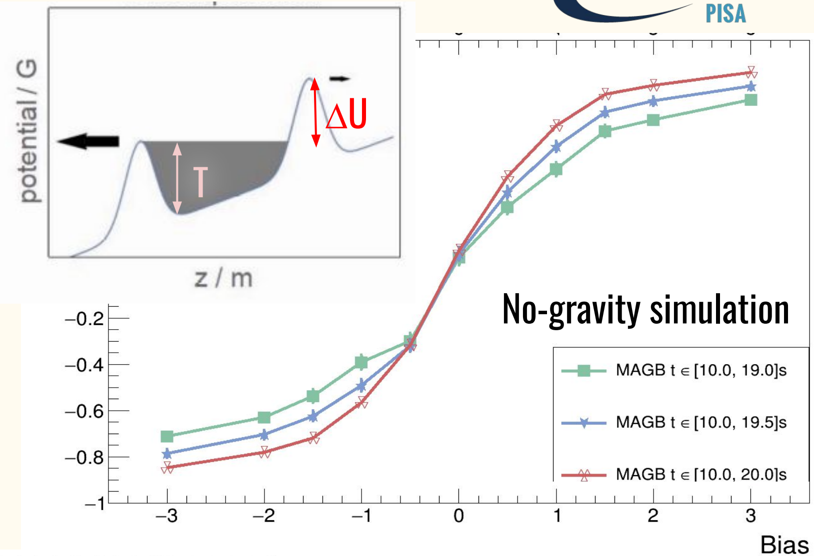


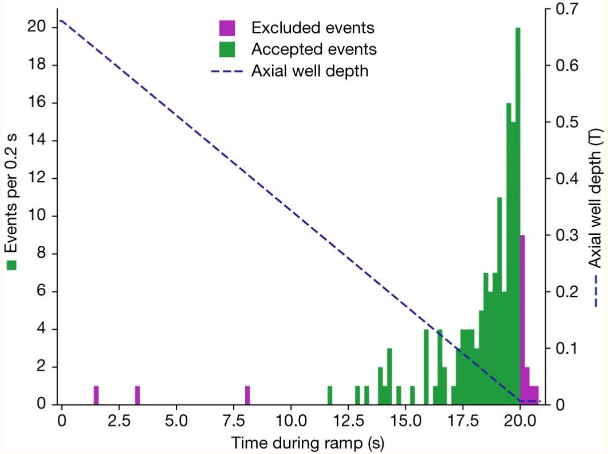
- Measure magnetic fields in dedicated control runs
  - rely on reproducibility
- ECR maps static field along axis (at different ramp stages)
- + method based on phase of ExB drift to study varying fields
  - less accurate, but faster, than ECR [A. Christensen, UCB]
- Results are integrated into a 3D field model

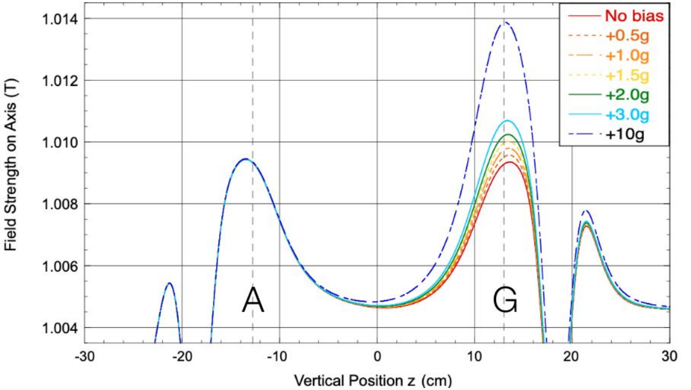


Temperature and simulation

- Simulate the trajectory of single atoms
- The asymmetry curve gets steeper
  - for slower ramps
  - for colder atoms
- Colder atoms exit last
- Features of B(z) prevent us from ramping to zero

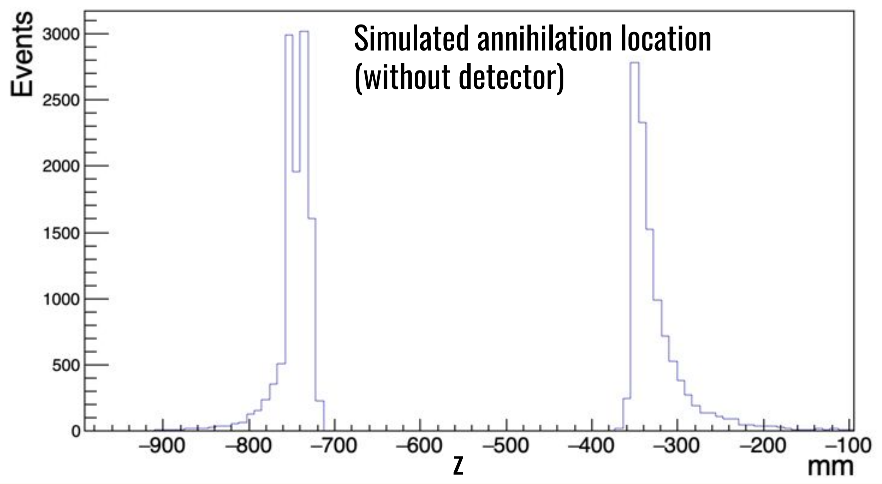


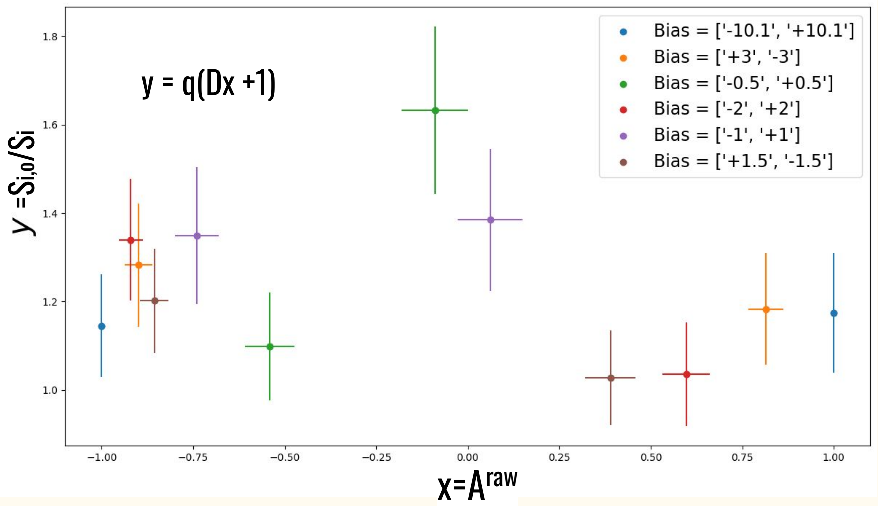




Detection efficiency asymmetry

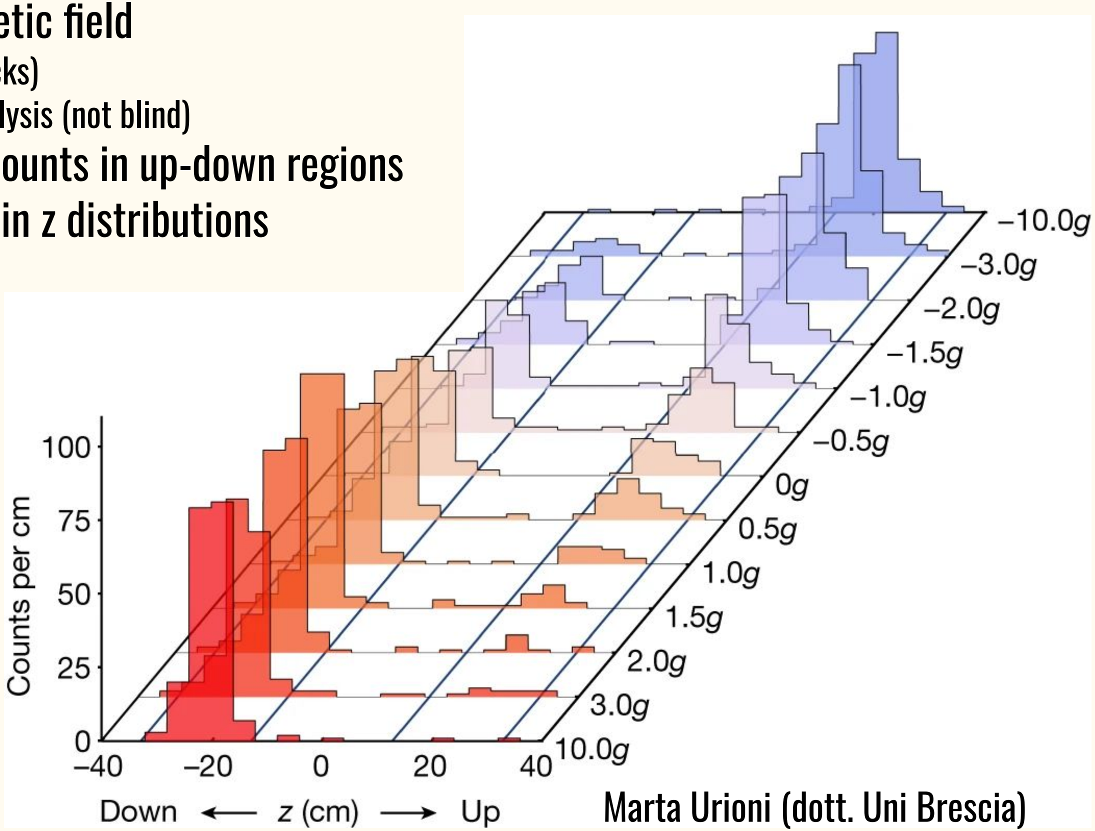
- Antihydrogen released during long-octupole ramp-down assumed to be a reproducible fraction of the total number of trapped atoms
- Assume all other losses are negligible/reproducible across all mirror-field configurations
- Derive efficiency from ratio of yields during long-octupole ramp-down and mirror-release
  - ○ Should exhibit a linear trend with the asymmetry observed during the mirror-release


Simulated annihilation location
(without detector)


$y = q(Dx + 1)$

Data

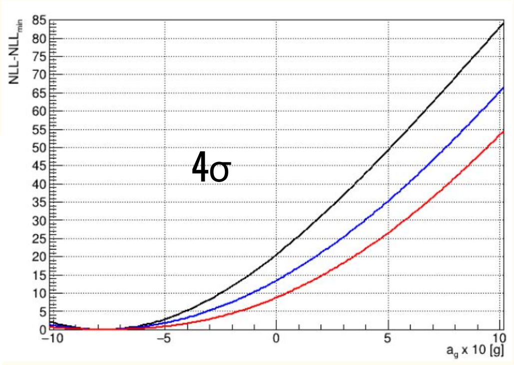
- 2 calibration sets with large mirror-field asymmetry in either direction
  - Force all antihydrogen to escape from a single side
- Physics data at 11 different values of magnetic field
  - ~200 events over 6-7 runs for each set (50 stacks)
  - Not fully chosen beforehand: feedback from analysis (not blind)
- Fit the efficiency-corrected asymmetry of counts in up-down regions
- No hint of annihilations on background gas in z distributions

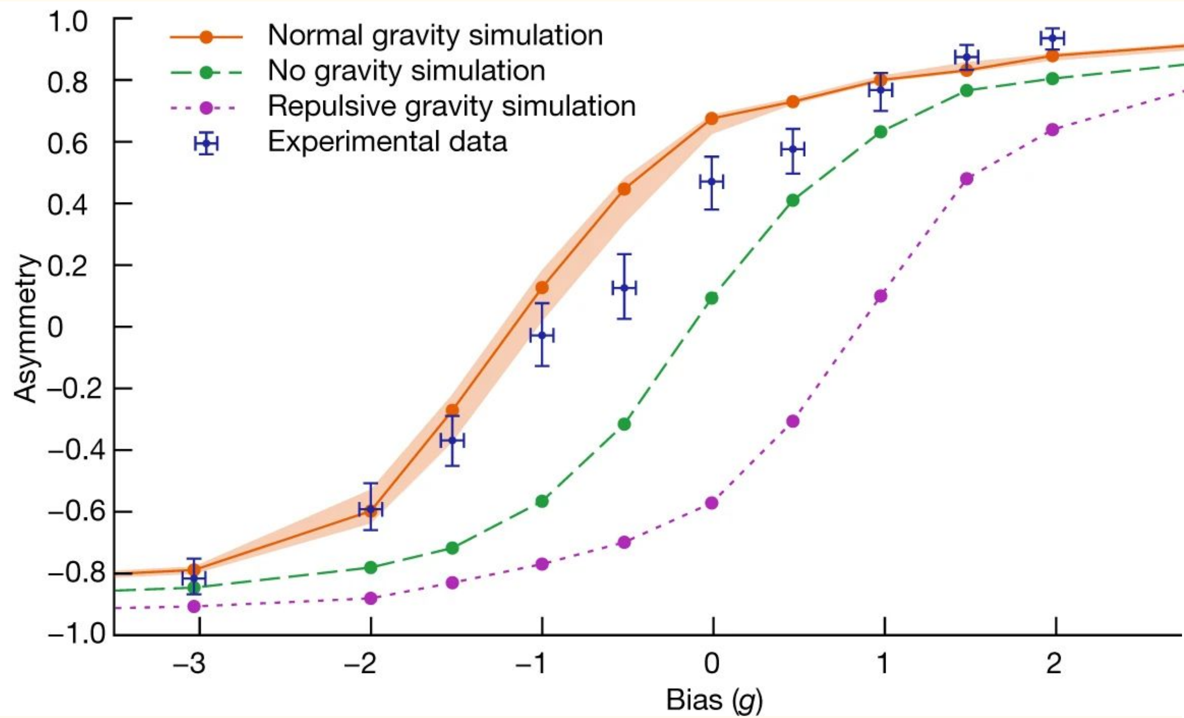


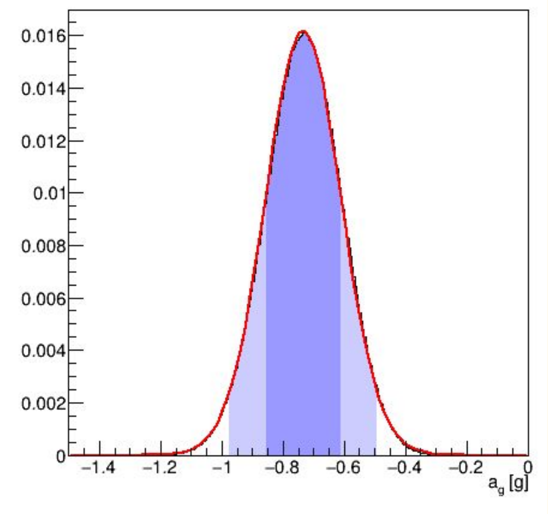
Marta Urioni (dott. Uni Brescia)

Fit to model from simulation

- a_g = [0.75 ± 0.13 (statistical + systematic) ± 0.16 (simulation)] g







Result

- Demonstrated sensitivity to gravity effects on antihydrogen in the magnetic trap
- Main systematic uncertainty from octupolar perturbations with zero component on axis
  - As much as allowed by tolerances of the winding, and critical current of NbTi
- Some systematics scale either with statistics, temperature, or improve in precision trap
  - Other will require improvement in the characterization of the apparatus, or a better technique

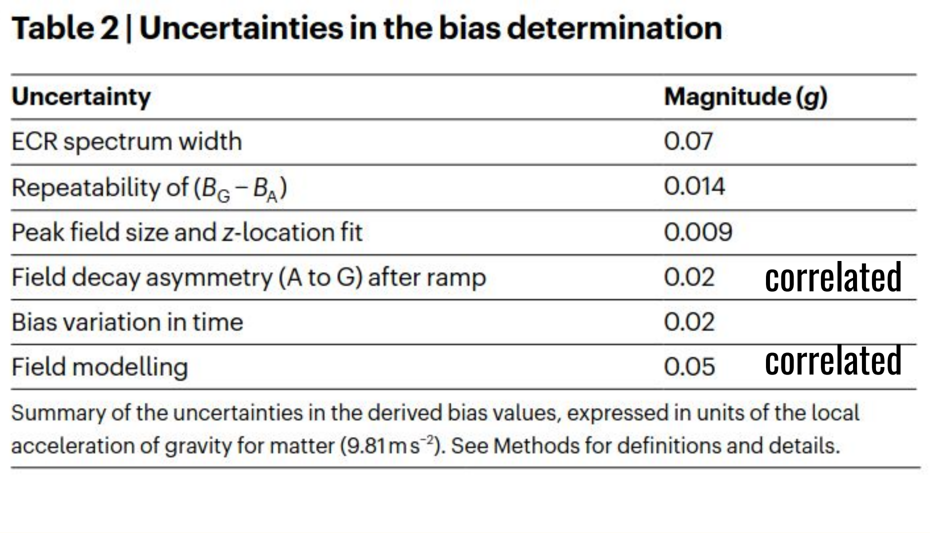


Table 2 | Uncertainties in the bias determination

Uncertainty	Magnitude (g)	
ECR spectrum width	0.07	
Repeatability of ($B_G - B_A$)	0.014	
Peak field size and z-location fit	0.009	
Field decay asymmetry (A to G) after ramp	0.02	correlated
Bias variation in time	0.02	
Field modelling	0.05	correlated

Summary of the uncertainties in the derived bias values, expressed in units of the local acceleration of gravity for matter (9.81 m s^{-2}). See Methods for definitions and details.

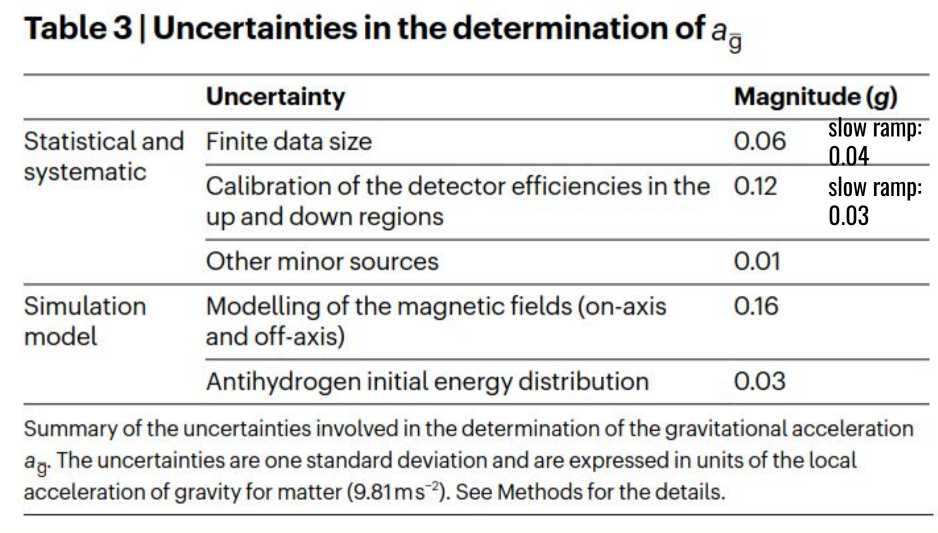
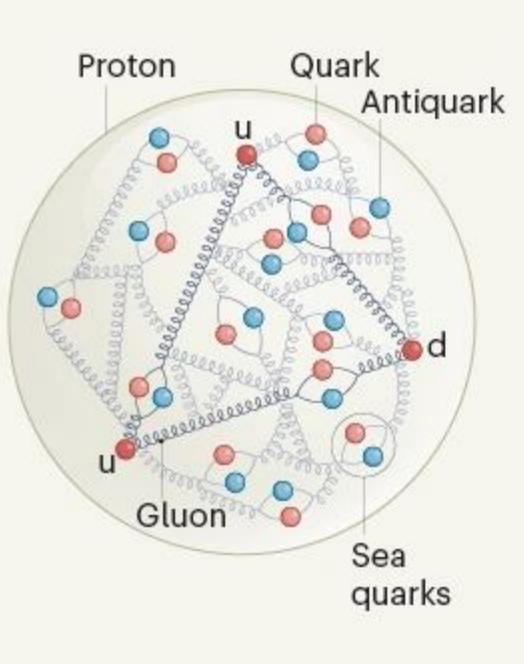


Table 3 | Uncertainties in the determination of $a_{\bar{g}}$

	Uncertainty	Magnitude (g)	
Statistical and systematic	Finite data size	0.06	slow ramp: 0.04
	Calibration of the detector efficiencies in the up and down regions	0.12	slow ramp: 0.03
	Other minor sources	0.01	
Simulation model	Modelling of the magnetic fields (on-axis and off-axis)	0.16	
	Antihydrogen initial energy distribution	0.03	

Summary of the uncertainties involved in the determination of the gravitational acceleration $a_{\bar{g}}$. The uncertainties are one standard deviation and are expressed in units of the local acceleration of gravity for matter (9.81 m s^{-2}). See Methods for the details.

Does it say anything about antimatter-matter gravity?



- Protons and antiprotons have a structure
  - Valence quarks account for a small fraction of the proton mass
  - Virtual quark-antiquark pairs is almost ~10x more
  - ¾ of the proton is kinetic energy of confined quarks and gluons

- Different forms of energy in (anti-) atoms and nuclei could gravitate differently. In each model:
  - How does gravity couple to binding energy? (constrained by torsion pendulum exp)
  - How does gravity couple to virtual particles? (inside the nucleon and in cosmology)
  - What's the role of flavor content of the valence particle?

Phys. Rev. Lett. 121, 212001 (2018)

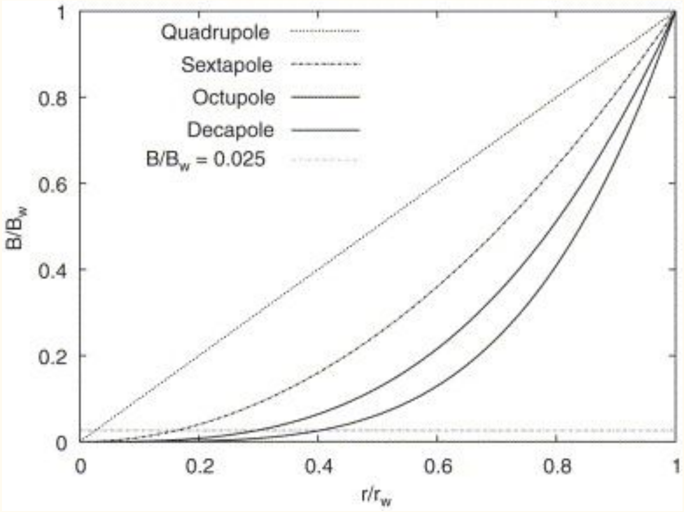
Outlook for gravity measurements

- Moving from antihydrogen to antimatter is not straightforward
  - Sensitivity to antimatter effects is reduced: require better precision
  - Requires a thorough analysis that could provide some light on these questions
  - Proposals to study lepton systems exist (e.g., muionium)

- 1% precision is a reasonable target for first measurements
  - Similar to initial AEgIS goal
- Further precision may require upgrade to allow fountain spectroscopy and atom interferometry
  - Could allow to address 10^{-6} range
- Also clock-tests with spectroscopy (e.g., annual variations) by pushing precision there
  - Need to setup the experiment quickly after long year-end shutdowns

Thank you

Trap field for radial confinement



- Run by run reproducibility: 2 MHz
- Background solenoid field value accurate to 10 Hz (3 Gauss)
- 40 MHz systematic uncertainty in B_{min}: discrepancy between measurement and model of magnetic trap contribution

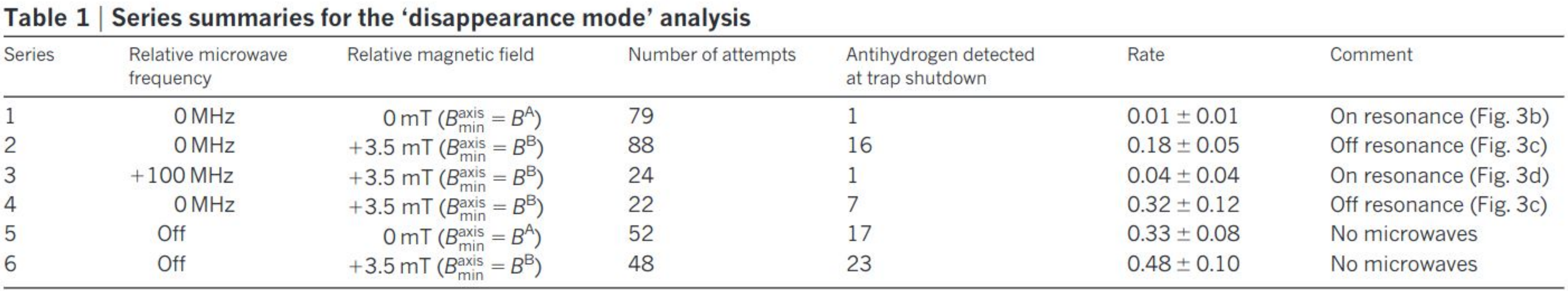
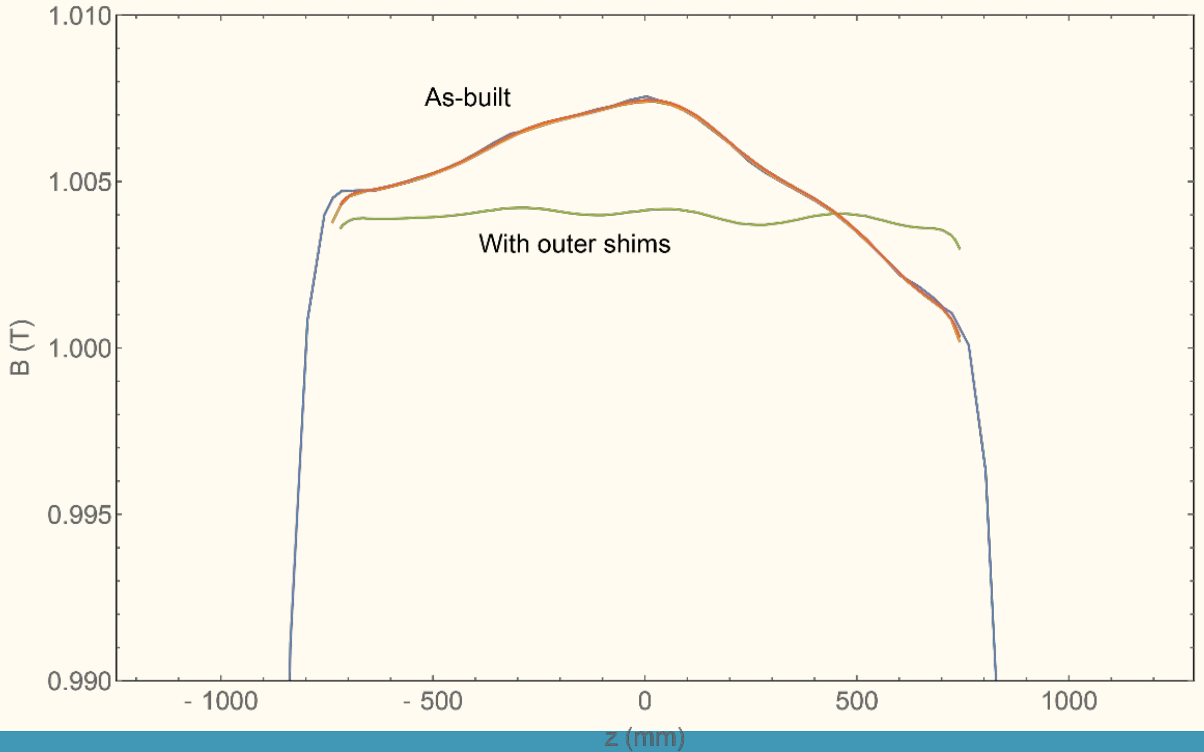


Table 1 | **Series summaries for the 'disappearance mode' analysis**

Series	Relative microwave frequency	Relative magnetic field	Number of attempts	Antihydrogen detected at trap shutdown	Rate	Comment
1	0 MHz	0 mT ($B_{\text{min}}^{\text{axis}} = B^{\text{A}}$)	79	1	0.01 ± 0.01	On resonance (Fig. 3b)
2	0 MHz	+3.5 mT ($B_{\text{min}}^{\text{axis}} = B^{\text{B}}$)	88	16	0.18 ± 0.05	Off resonance (Fig. 3c)
3	+100 MHz	+3.5 mT ($B_{\text{min}}^{\text{axis}} = B^{\text{B}}$)	24	1	0.04 ± 0.04	On resonance (Fig. 3d)
4	0 MHz	+3.5 mT ($B_{\text{min}}^{\text{axis}} = B^{\text{B}}$)	22	7	0.32 ± 0.12	Off resonance (Fig. 3c)
5	Off	0 mT ($B_{\text{min}}^{\text{axis}} = B^{\text{A}}$)	52	17	0.33 ± 0.08	No microwaves
6	Off	+3.5 mT ($B_{\text{min}}^{\text{axis}} = B^{\text{B}}$)	48	23	0.48 ± 0.10	No microwaves


1.010
1.005
1.000
0.995
0.990
B (T)
- 1000
- 500
0
500
1000
z (mm)
As-built
With outer shims

p = fractional ramp progress

Magnetometry results are integrated into a 3D field model

$$B(z,p) = B_{\mathrm{babcock}}(z) + B_{\mathrm{SOct}}(z) + B_{\mathrm{MAB}}(z) I_{\mathrm{MAB}}(p) + B_{\mathrm{MGB}}(z) I_{\mathrm{MGB}}(p)$$

Wire model field, from currents we provide

$$+ A(z)(1 - \exp(-p/0.1346))$$

Exponentially saturating component from magnetron results

$$+ B_{\mathrm{res0}}(z)(1-p) + B_{\mathrm{res1}}(z)p$$

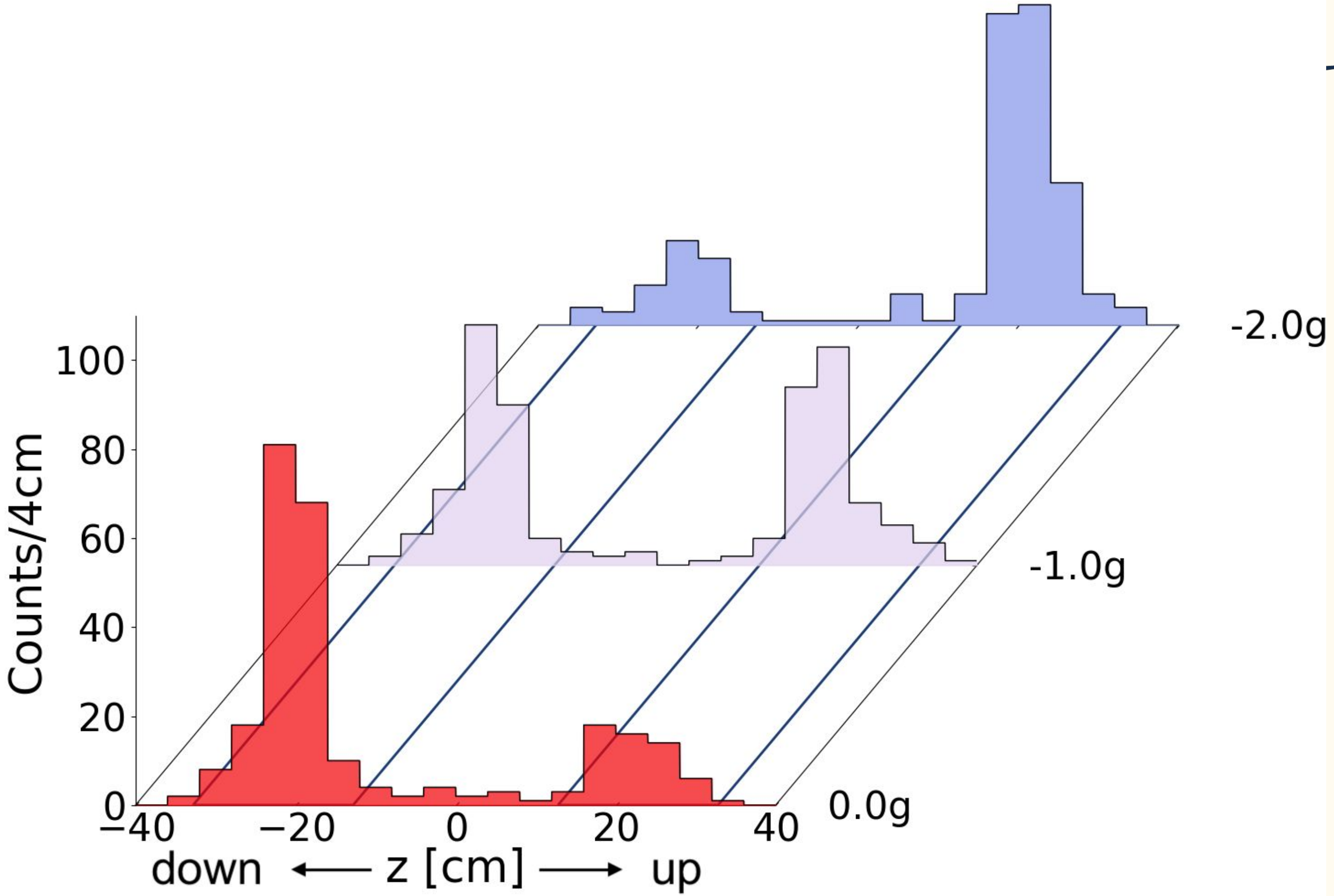
Residual to account for ECR

Field we don't control

O(1 Gauss) precision, much better around the saddle points

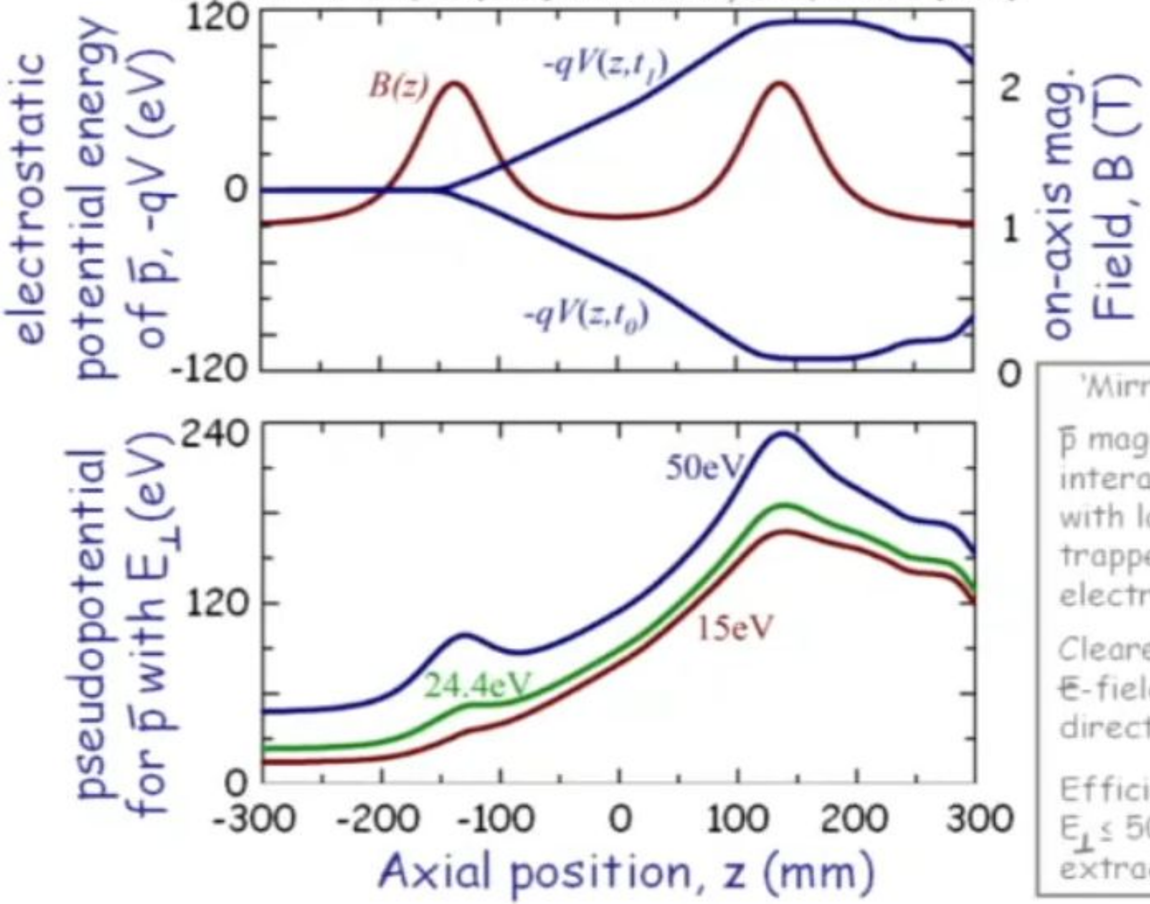
Particle pusher uses field to evolve anti-atoms through the entire experimental sequence

- Obtain the expected escape bias as a function of gravitational acceleration
- Field model is critical as antiatoms escape off-axis


Counts/4cm
0
20
40
60
80
100
−40
−20
0
20
40
down ⟵ z [cm] ⟶ up
0.0g
-1.0g
-2.0g

Electrostatic clearing of antiprotons

Phys. Lett. B **695**, 95 (2011) & *New J. Phys.* **14**, 015010 (2012)

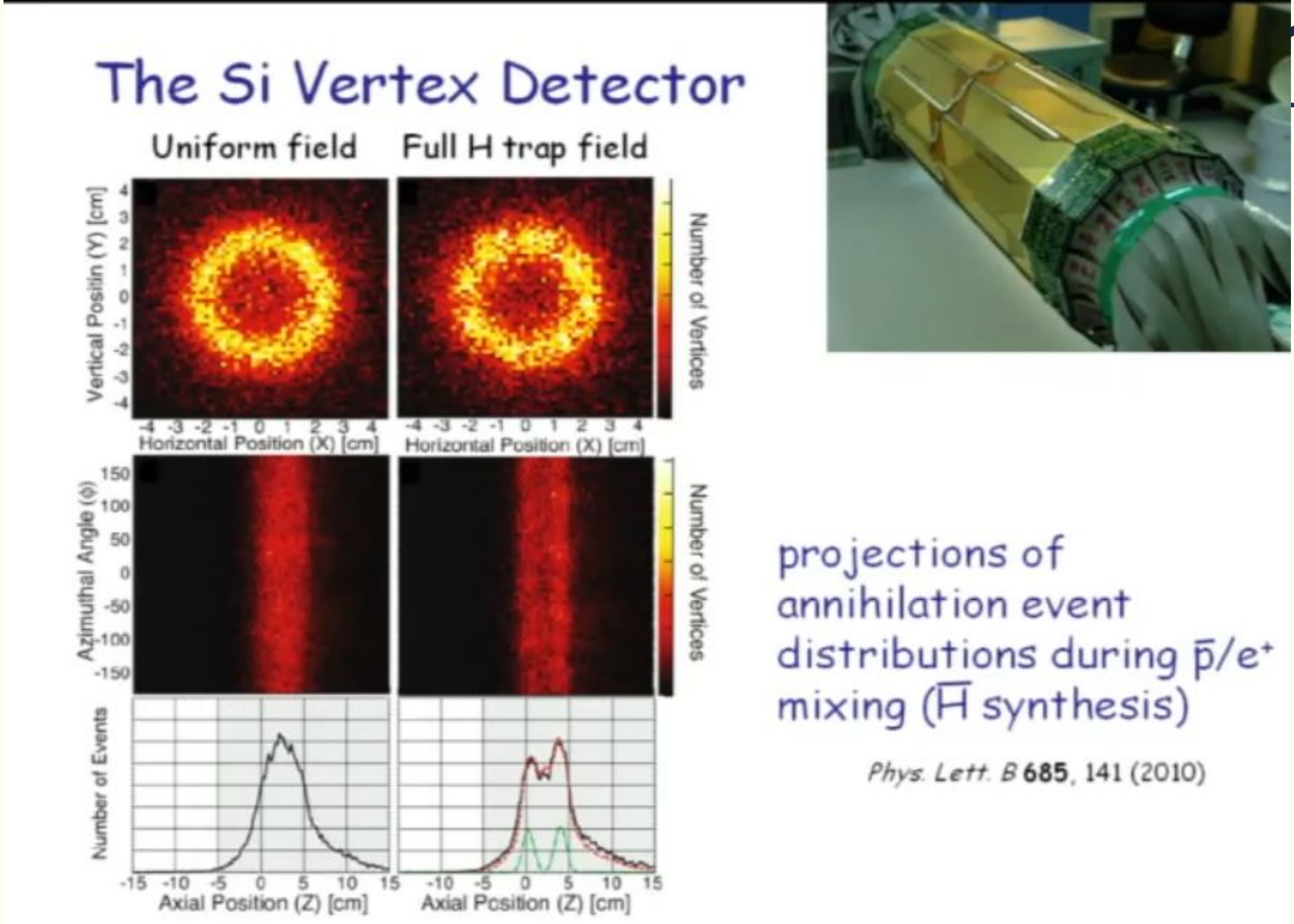


'Mirror Trapping'

p̄ magnetic moment interacts with $\vec{B}$: those with large $E_\perp$ can be trapped, even when all electrodes are grounded

Cleared with 8 × 12 ms $\vec{E}$-field pulses; alternating directions, $|\vec{E}| \sim 5$ V/cm

Efficient for p̄ with $E_\perp \lesssim 50$ eV; several dozen extracted, each run

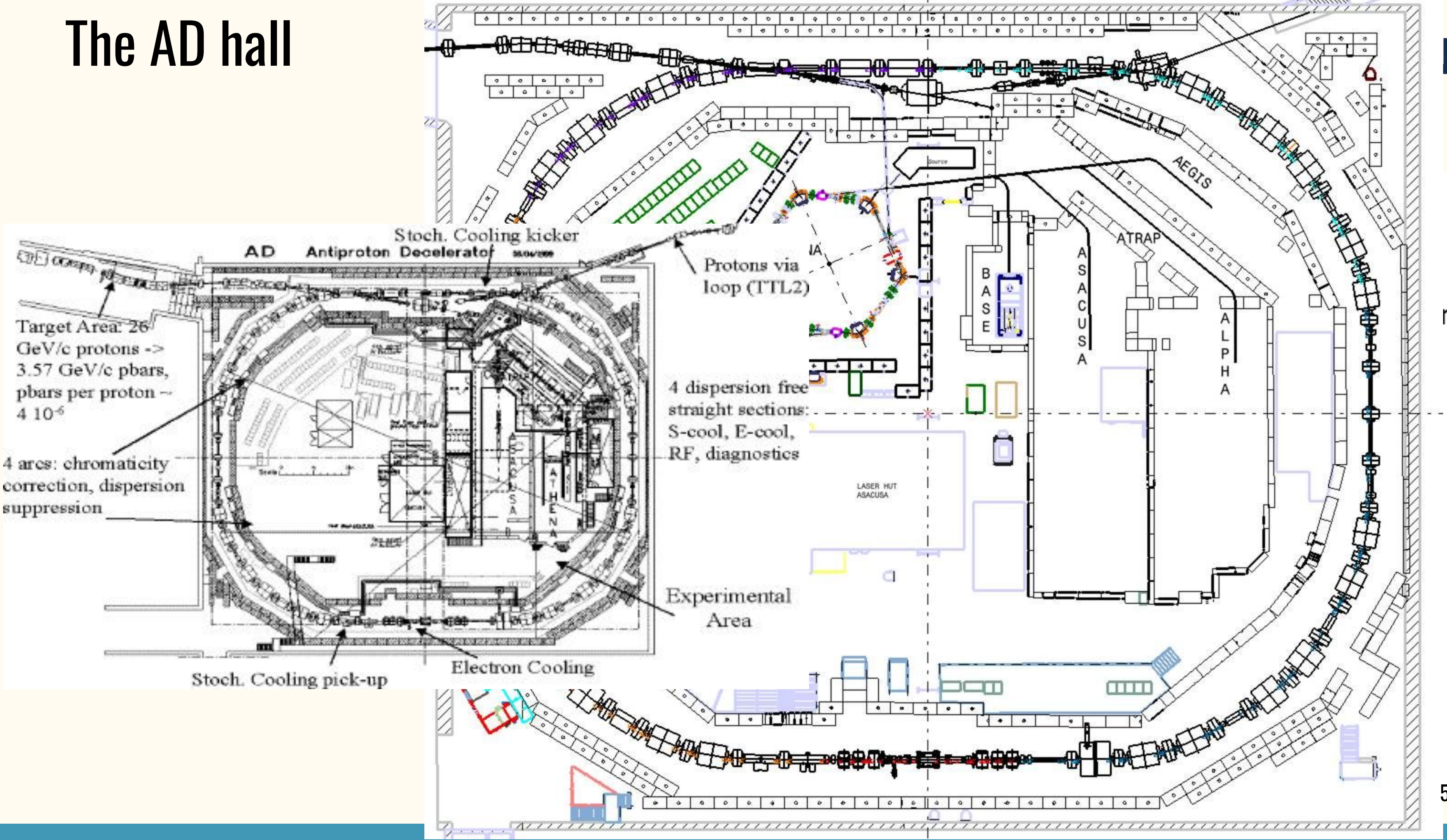


The Si Vertex Detector

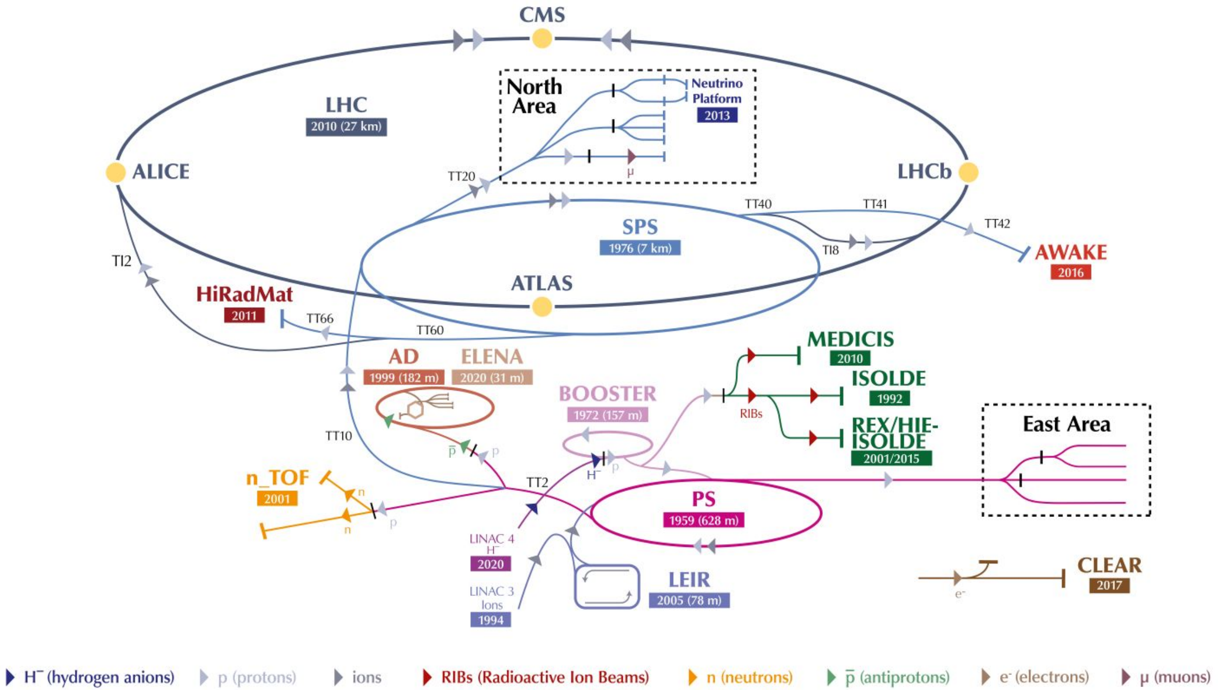
projections of annihilation event distributions during $\bar{p}/e^+$ mixing ($\overline{H}$ synthesis)

Phys. Lett. B **685**, 141 (2010)

The AD hall


AD Antiproton Decelerator
Stoch. Cooling kicker
Protons via loop (TTL2)
Target Area: 26 GeV/c protons -> 3.57 GeV/c pbars, pbars per proton ~ 4 10-6
4 arcs: chromaticity correction, dispersion suppression
4 dispersion free straight sections: S-cool, E-cool, RF, diagnostics
Experimental Area
Electron Cooling
Stoch. Cooling pick-up
ASACUSA
ATHENA
Source
AEGIS
ATRAP
BASE
ASACUSA
ALPHA
LASER HUT ASACUSA

The CERN accelerator complex
Complexe des accélérateurs du CERN



LHC - Large Hadron Collider // **SPS** - Super Proton Synchrotron // **PS** - Proton Synchrotron // **AD** - Antiproton Decelerator // **CLEAR** - CERN Linear Electron Accelerator for Research // **AWAKE** - Advanced WAKefield Experiment // **ISOLDE** - Isotope Separator OnLine // **REX/HIE-ISOLDE** - Radioactive EXperiment/High Intensity and Energy ISOLDE // **MEDICIS** // **LEIR** - Low Energy Ion Ring // **LINAC** - LINear ACcelerator // **n_TOF** - Neutrons Time Of Flight // **HiRadMat** - High-Radiation to Materials // **Neutrino Platform**

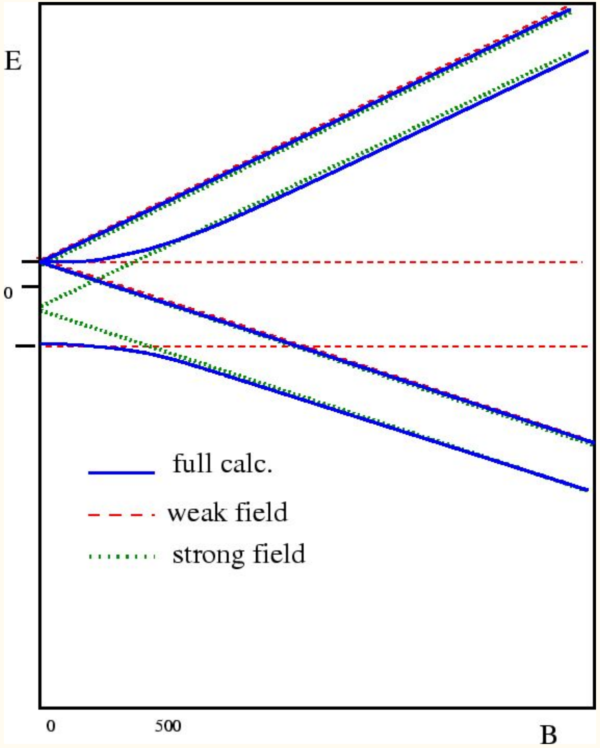
January 2022

- To first order f_{ad}-f_{bc} does not depend on the magnetic field
- Equal to the ground state hyperfine splitting (21 cm line)
- We can compare our measurement to the value in hydrogen
    - or any other feature of the spectrum
- If CPT holds they should be the same

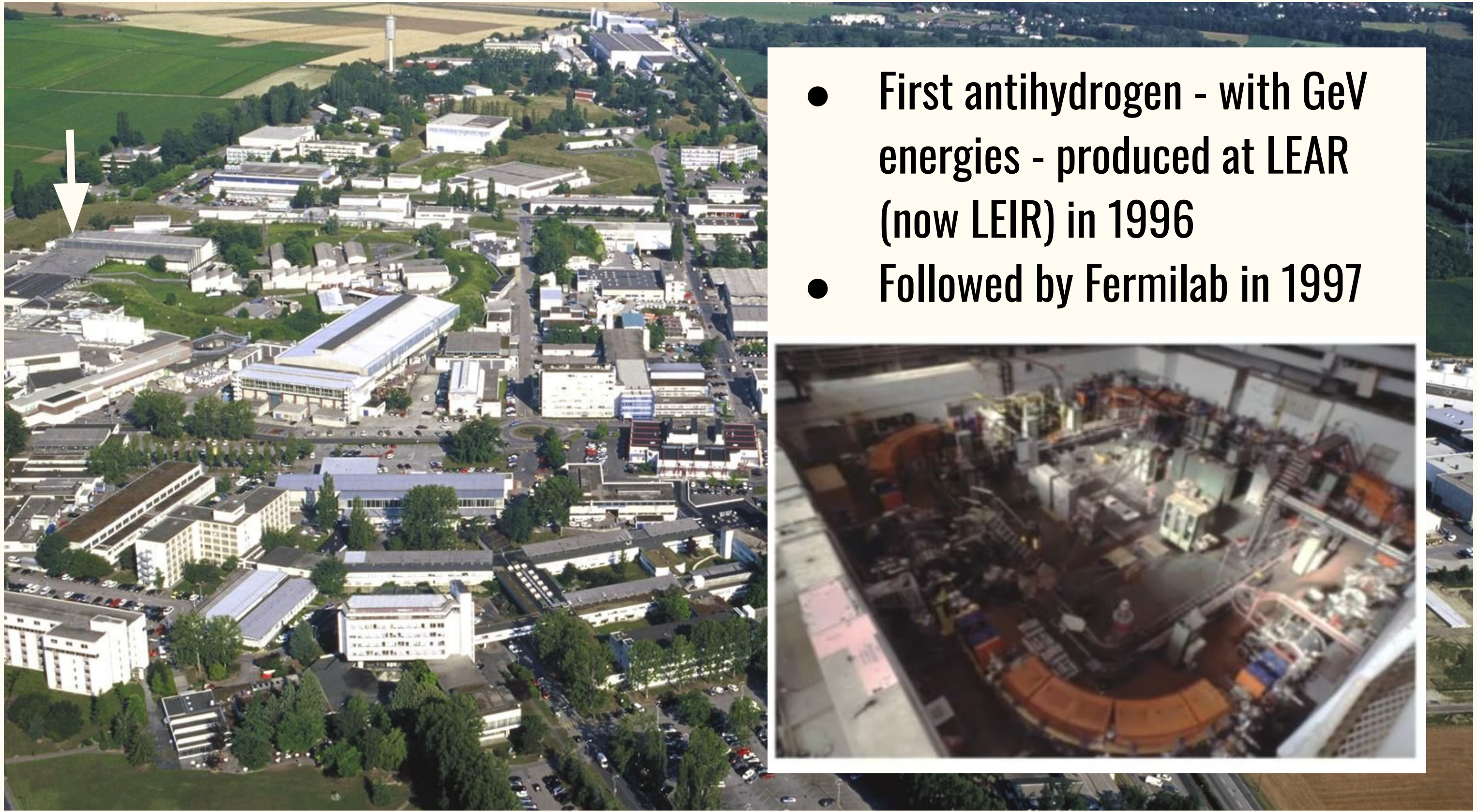
$$E = E_{n00} - \frac{\mathcal{A}}{4} \pm \sqrt{\left(\frac{\mathcal{A}}{2}\right)^2 + (\mu_B B)^2}.$$

A

$$E = E_{n00} + \frac{\mathcal{A}}{4} \pm \mu_B B$$

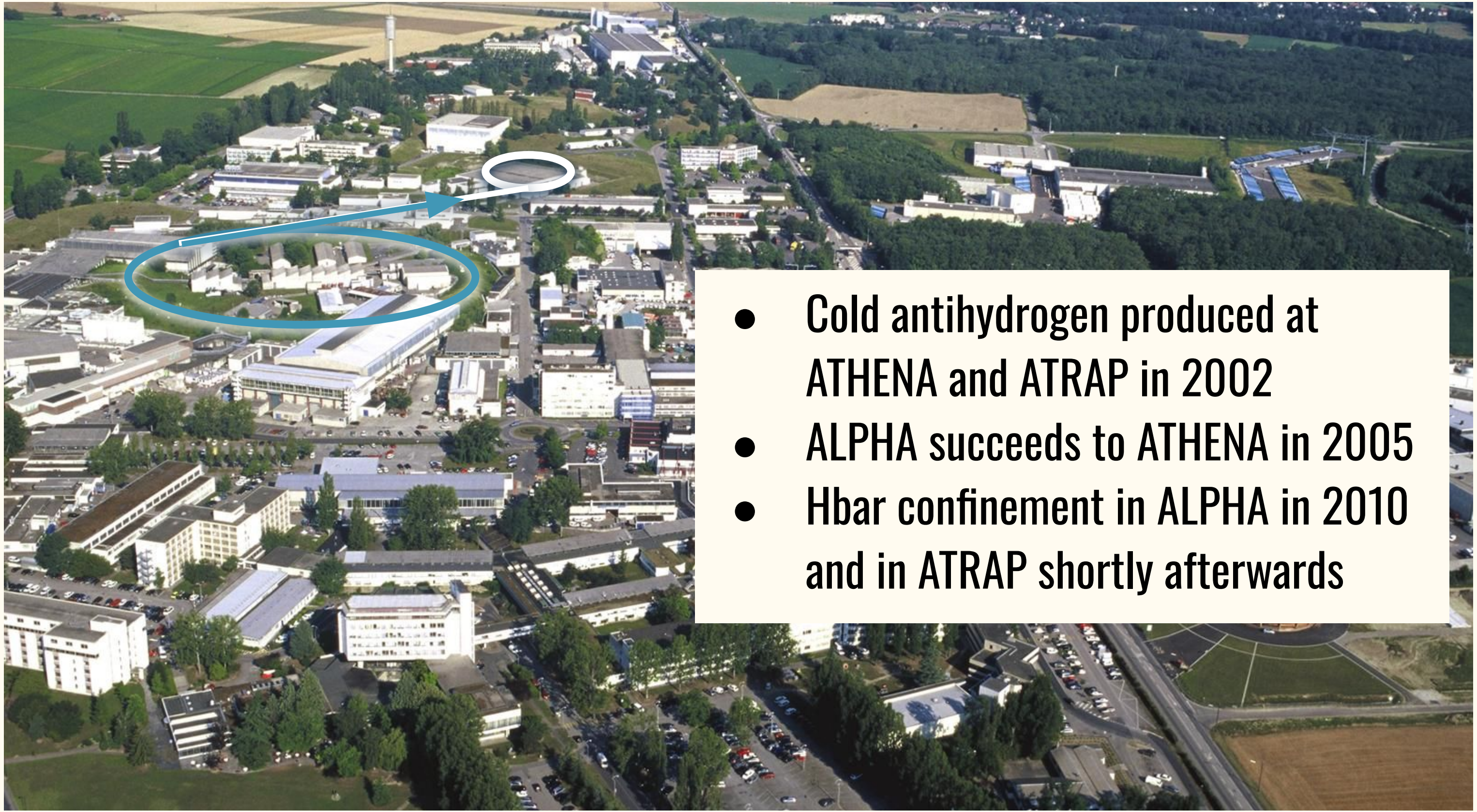


Brief history



- First antihydrogen - with GeV energies - produced at LEAR (now LEIR) in 1996
- Followed by Fermilab in 1997

The PS-AD/ELENA complex



- Cold antihydrogen produced at ATHENA and ATRAP in 2002
- ALPHA succeeds to ATHENA in 2005
- Hbar confinement in ALPHA in 2010 and in ATRAP shortly afterwards

ELENA

- Kinetic energy goes from 5 MeV to 100 keV, efficiently
  - 10^7 antiprotons per bunch (every 2 minutes)
  - Concurrently provide beam to several experiments
  - Allow 24/7 operations over the full beam season

- Increase number of experiments:
  - AEgIS (antihydrogen)
  - ALPHA (antihydrogen)
  - ASACUSA (antihydrogen, exotic atoms, scattering)
  - BASE (antiprotons)
  - GBAR (antihydrogen)
  - PUMA (otg antiprotons)
  - ACE (antiprotons for cancer therapy - completed)
  - ATRAP (antihydrogen - completed

- INFN (2 staff + 2 junior) participates under the umbrella of sigla LEA in CSN3