Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

Measurement of Properties of Antihydrogen with the Alpha Trap

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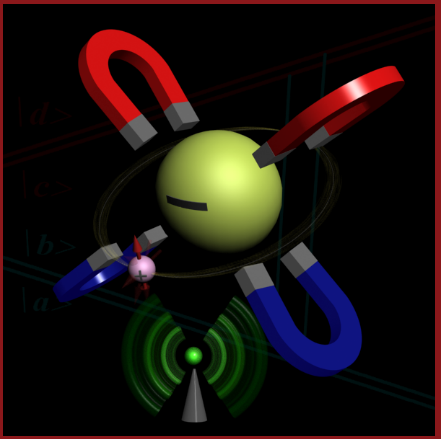

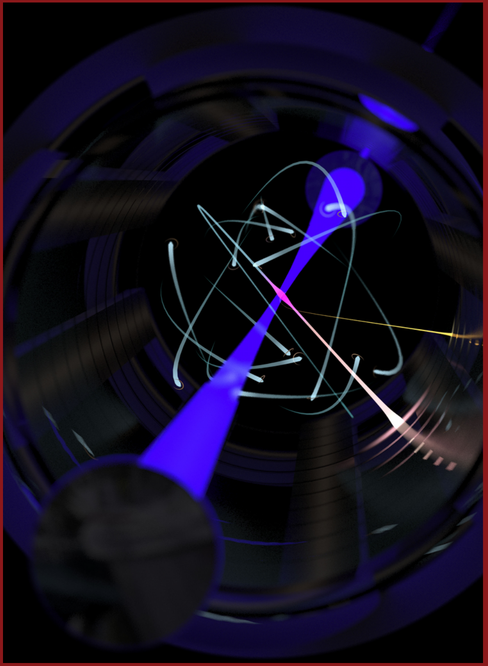

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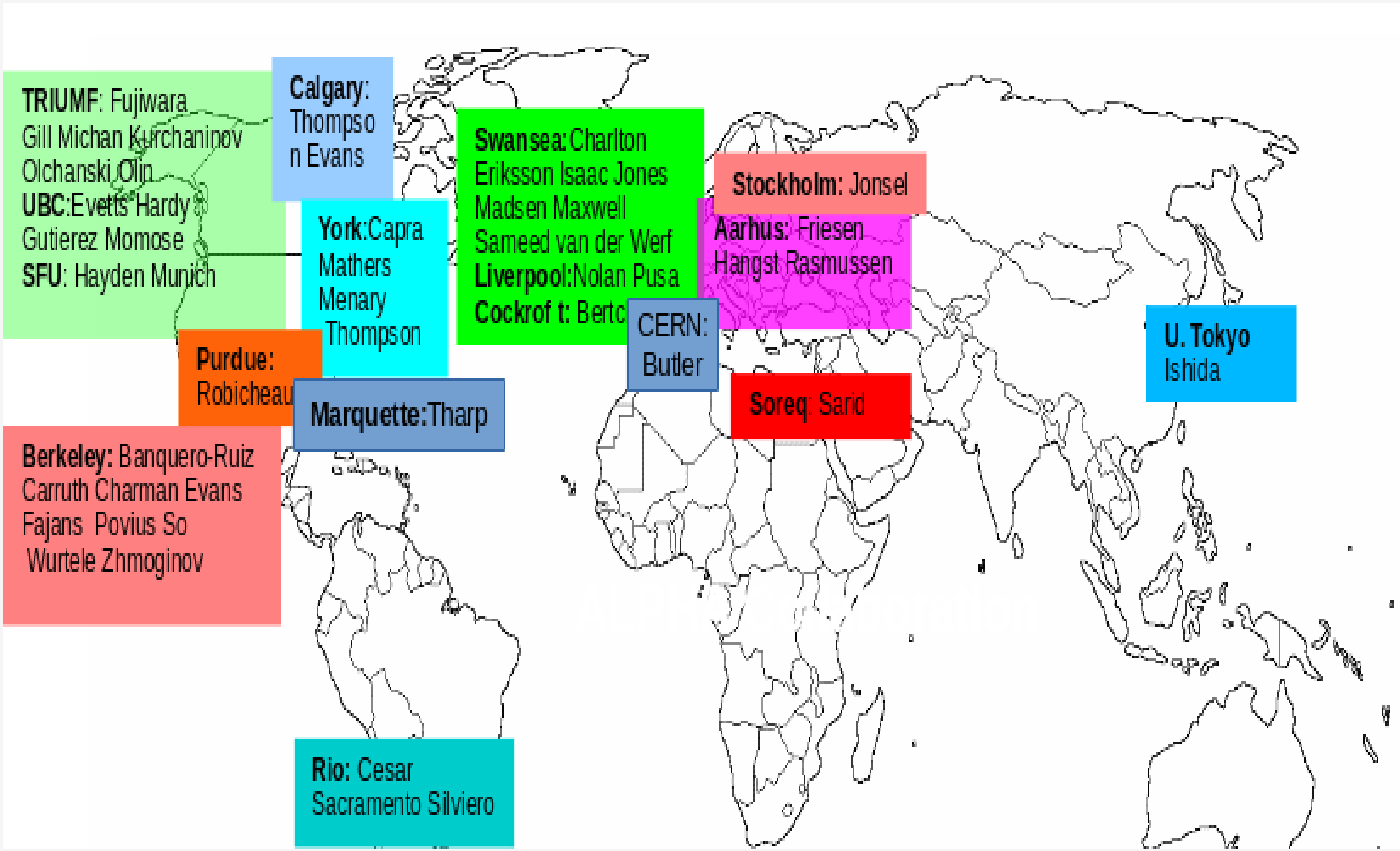
ALPHA Collaboration

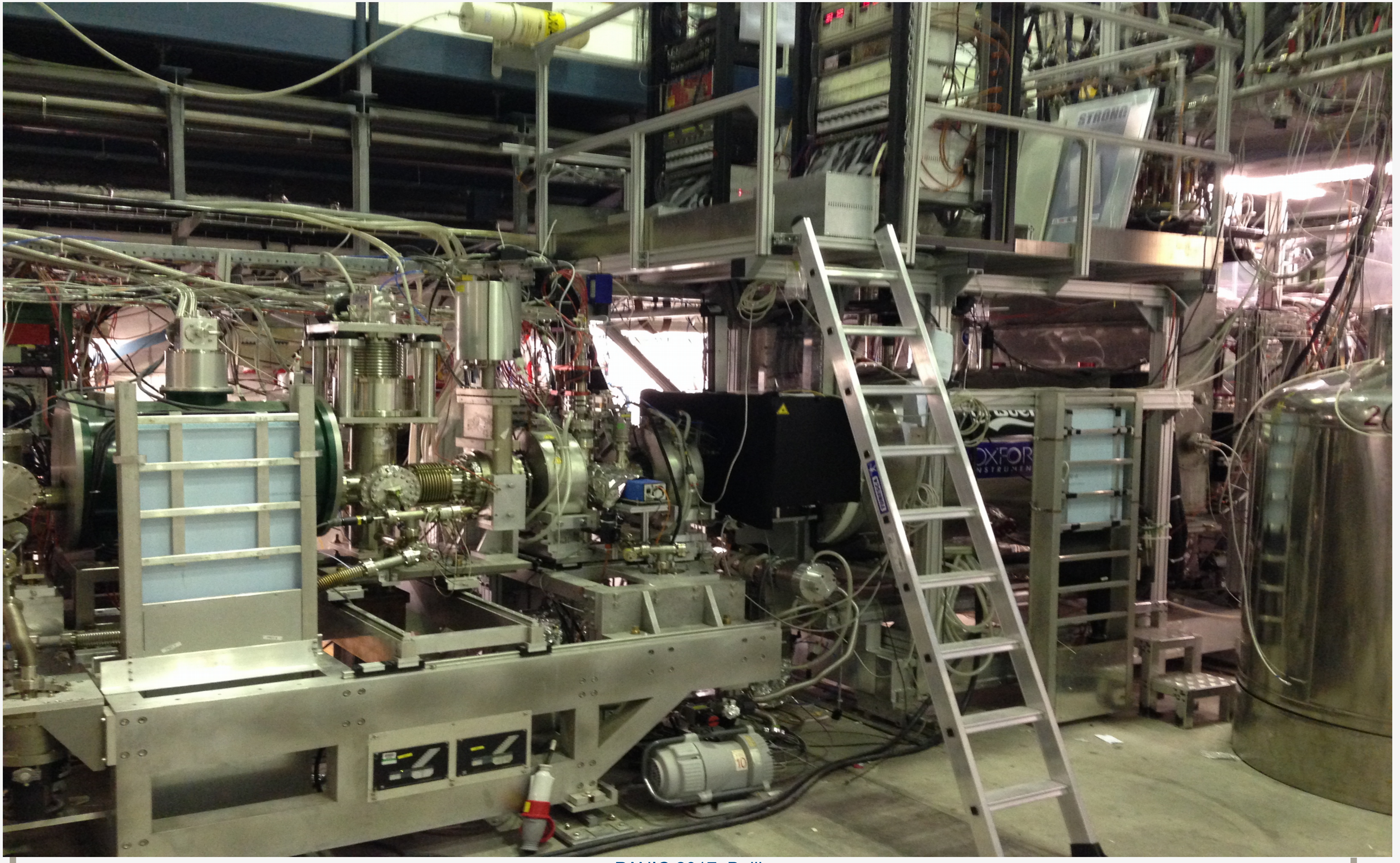


Outline

Our program is to contain antihydrogen ($\overline{\mathrm{H}}$) atoms in a magnetic trap and study their properties in a stable environment. Measurements of hydrogen atom properties are among the most precise in physics, and these comparisons test fundamental assumptions – CPT symmetry and principle of equivalence – which underlie modern theory.

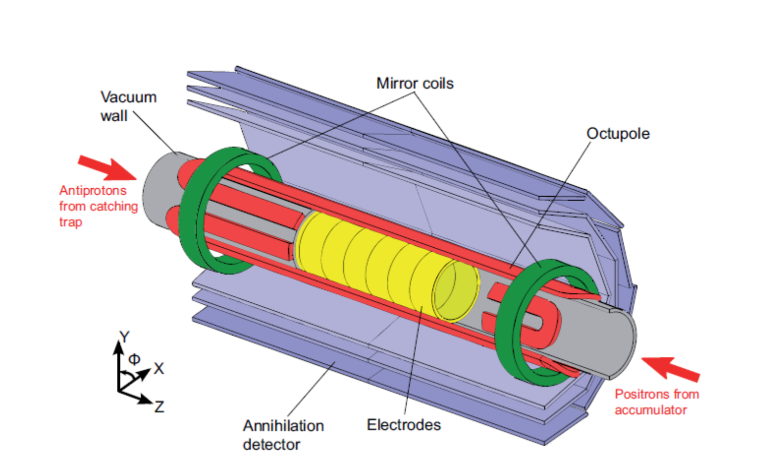
- Trapping methods and status
- Measurement of the $\overline{\mathrm{H}}$ Charge
- Measurement of the $\overline{\mathrm{H}}$ 1S-2S transition
- Measurement of the $\overline{\mathrm{H}}$ hyperfine interval

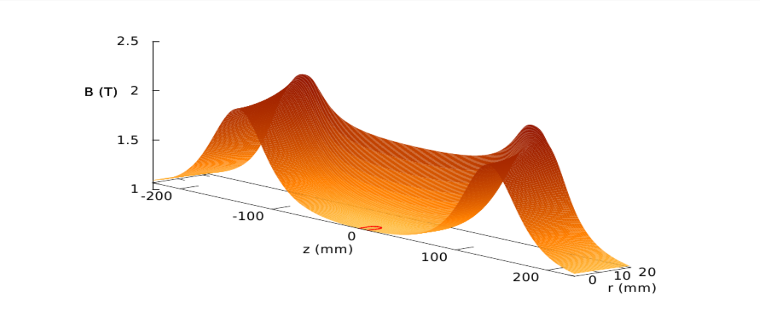
ALPHA apparatus



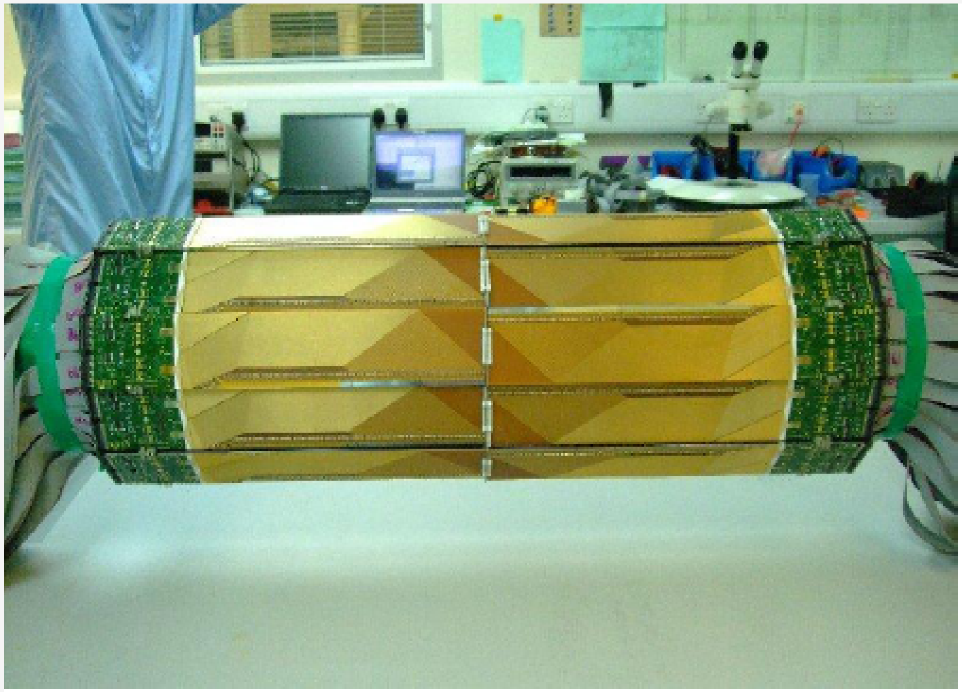
Making and Trapping $\overline{H}$

- Trap and cool antiprotons from the CERN AD to form a plasma of ~10^5 particles in a Penning trap.
- Trap and cool positrons accumulated from an ^{22}Na source to form a plasma of ~10^6 particles in a Penning trap.
- Bring them together from nested wells to form $\overline{H}$ s inside a magnetic neutral atom trap.
- $\overline{H}$ s produced at sufficiently low energy will be captured in the atom trap and interrogated.
- Time and position of $\overline{H}$ s annihilating on the trap walls are detected with a silicon vertex detector.

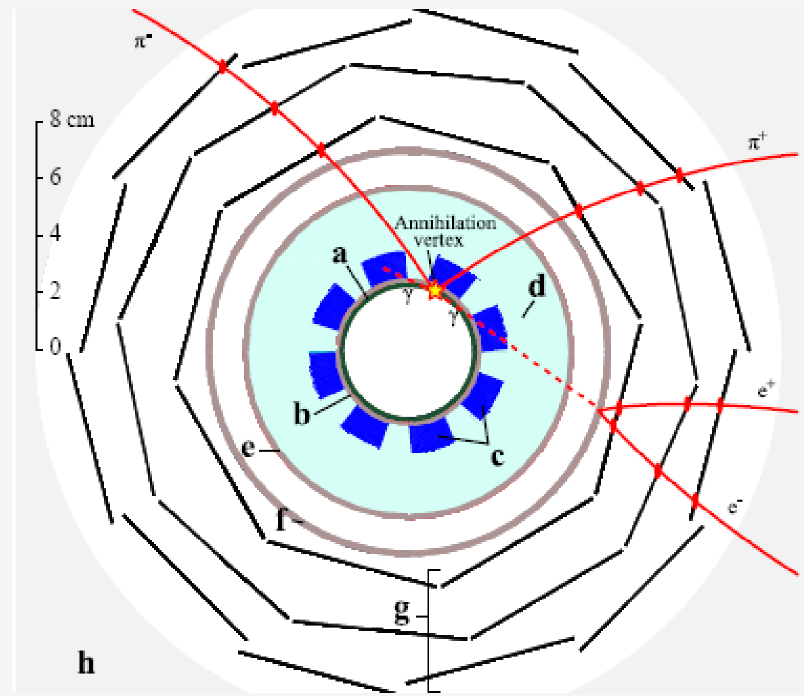




Si Vertex Detector

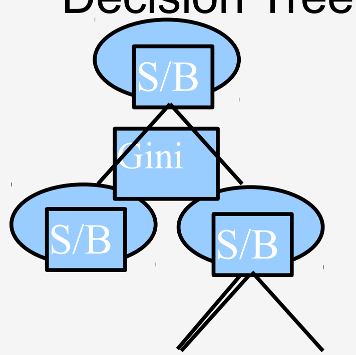


- Double sided silicon strips
- Vertex Resolution ~7mm
- Hit Efficiency > 95%. ~0.8 m^2 area
-
-



MVA tuned for maximum significance suppresses cosmic ray background.

Boosted Decision Tree



Trapping Challenges

Characteristic energy scales:

Antiprotons from AD: 5 MeV
Hydrogen atom binding energy: 13.6 eV
Plasma space charge energy: ≈ 10 eV
Neutral trap depth: 0.5K ≈ 50 μeV

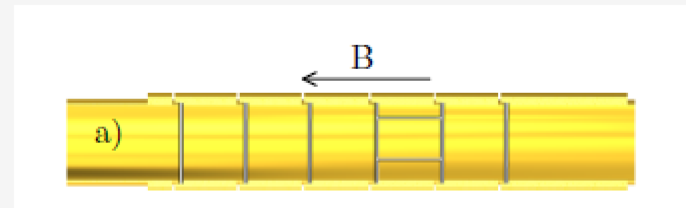
- Need 10^{-5} control of plasma to make trapped $\bar{H}$
- $\bar{H}$ production is much easier than trapping.
- Only a few atoms will be cold enough to be trapped, so very efficient low background detection is needed.
- The high gradients of the trapping field are challenging for atomic spectroscopy.

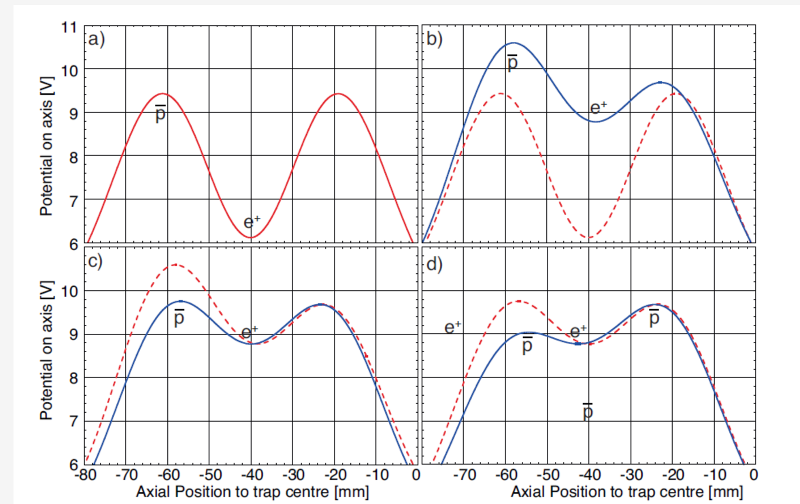
Plasma Techniques

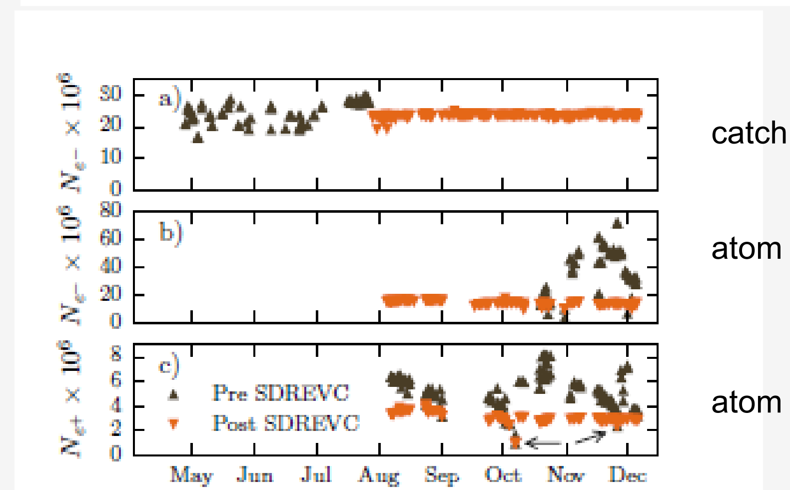
Improvements from our 2010 trapping rate of 0.2 $\overline{\mathrm{H}}$/trial come from improvements in our plasma techniques and cryogenics.

- New cryostat- stable environment.
- Rotating wall: Oscillating field applied to segmented electrode spins and compresses the plasma.
- Evaporative cooling of the plasma and slow merge enhances cold $\overline{\mathrm{H}}$ synthesis.
- Together these techniques allow us to robustly produce plasmas with the desired densities and sizes.

Nature Comm (In press) and PRL in preparation.

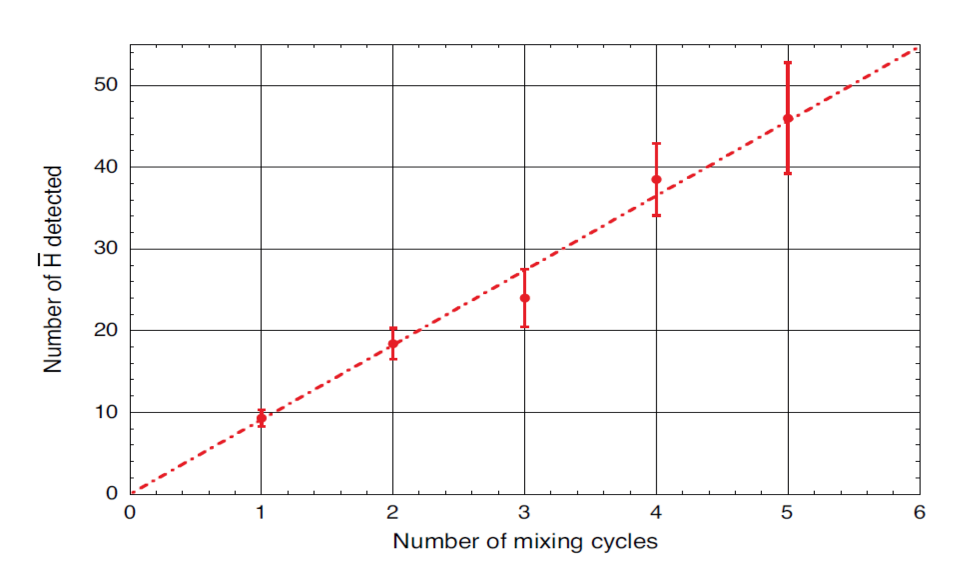


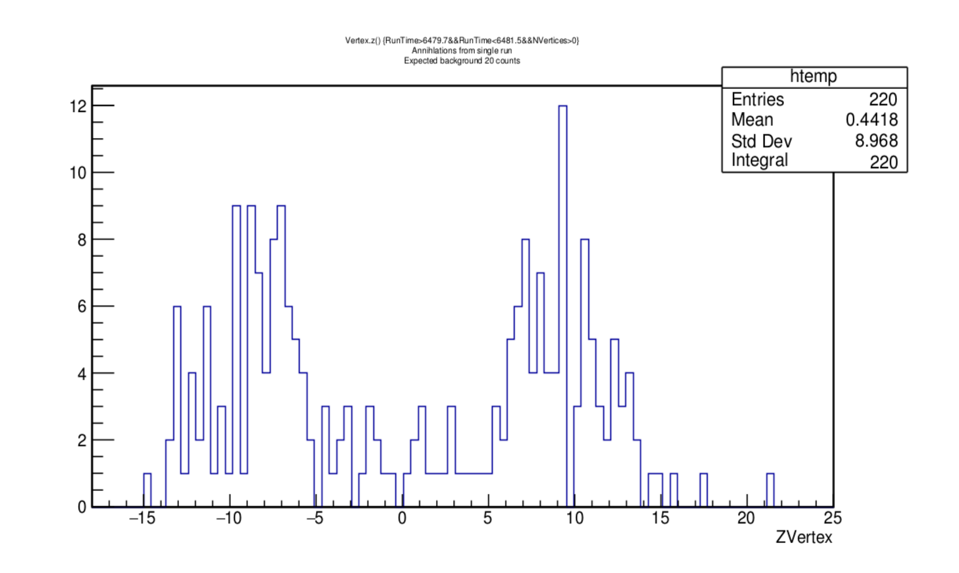




Trapping Status

- Current trapping rate is ~20 $\bar{H}$ / AD shot
- Rate increases when we accumulate p shots before mixing.
- $\bar{H}$ s can be stacked in the neutral trap with little loss and held for study. We have detected 200 $\bar{H}$ s in a trial accumulating 25 stacks.





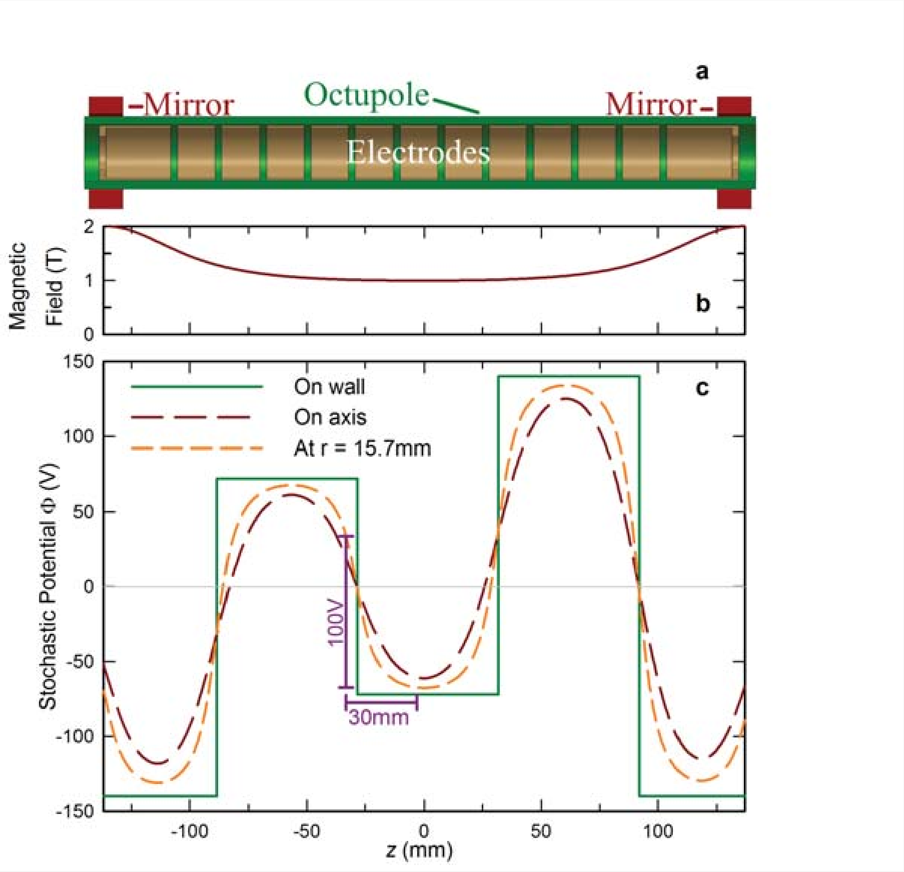
Charge Measurement: Stochastic heating of $\overline{\mathrm{H}}$

Trap antihydrogen.

Subject anti-atoms to stochastically varying electrostatic potentials for 119.4s.
Anti-atoms with a sufficiently large *Q* will be ejected.

Hold anti-atoms for 119.4s.

Quench and count surviving anti-atoms.



- $\overline{\mathrm{H}}$ held in magnetic well $\mu \bullet B$
- Transition gives a random kick $\Delta\Phi$ to each charge Q.
- Ejected from the 0.5K well unless

$$|Q|e\,\Delta\Phi\,\sqrt{N} < E_{well}$$

$$N=84900; \quad \Delta\Phi \simeq 100V$$

With these parameters
$|Q|/e \leq 1.6$ ppb
≤ 0.9 ppb taking account mean energy of the Hs in the trap.

Principal Observations and Outlook

	Number of Trials	Observed Antiatoms Surviving	Observed Antiatoms During 119s Heating
Stochastic Trials	10	12	**6**
Null Trials	10	12	**11**

Predicted cosmic ray background in heating period: 6.9 counts.

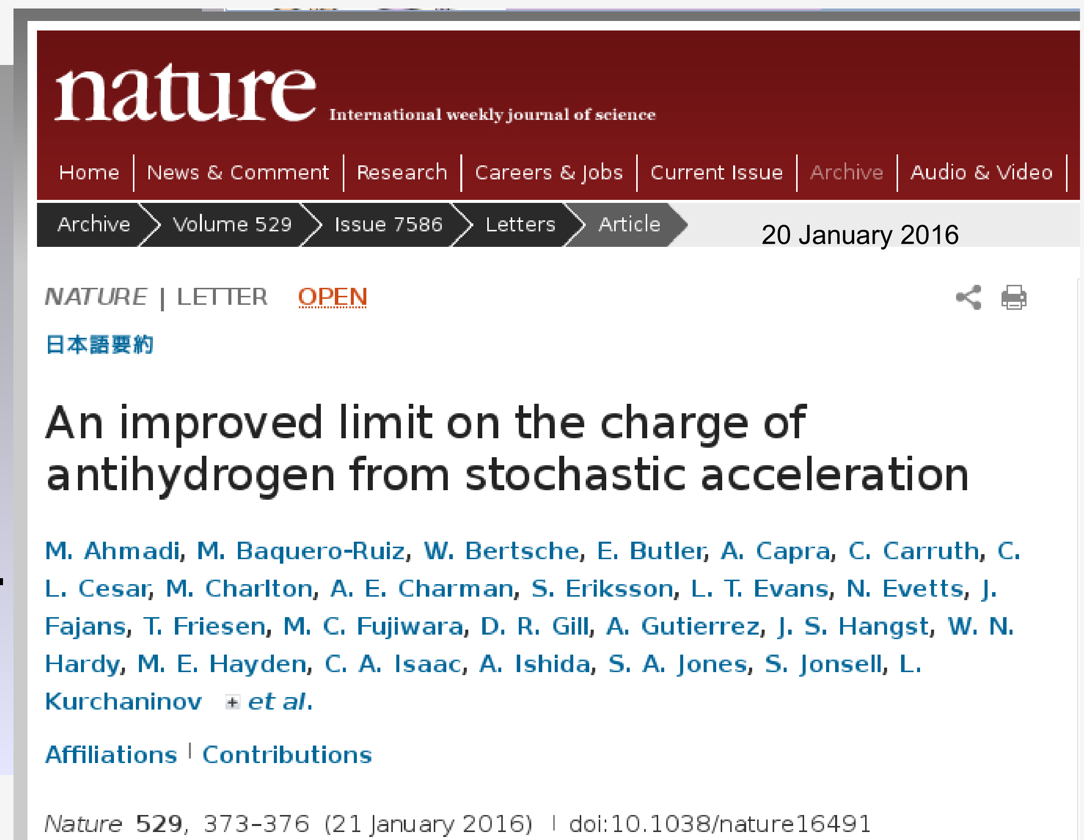
$|Q_H|/e< 0.7\ 10^{-9}$ (1σ)

Improvement of 20x from our first measurement.

This is a CPT test.

Prospects of improvement from more $\bar{H}$ s and longer heating.

$\sim\sqrt{NT}$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日本語要約

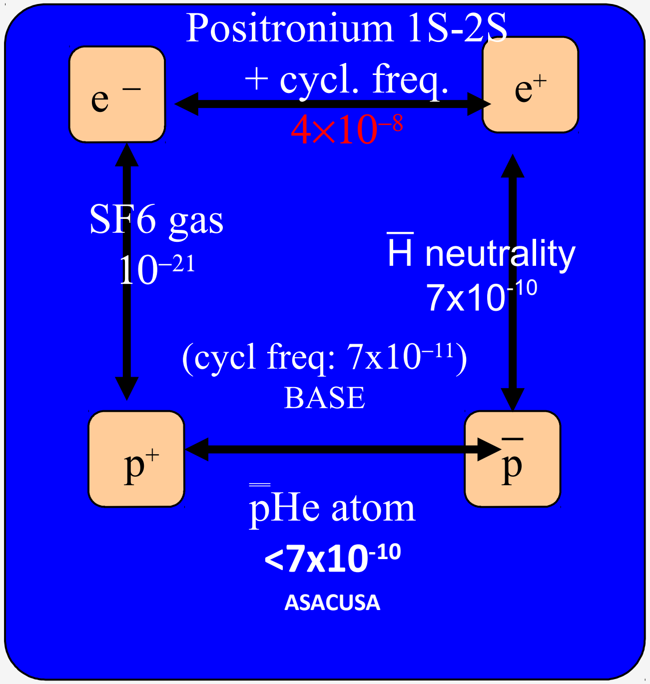
An improved limit on the charge of antihydrogen from stochastic acceleration

M. Ahmadi, M. Baquero-Ruiz, W. Bertsche, E. Butler, A. Capra, C. Carruth, C. L. Cesar, M. Charlton, A. E. Charman, S. Eriksson, L. T. Evans, N. Evetts, J. Fajans, T. Friesen, M. C. Fujiwara, D. R. Gill, A. Gutierrez, J. S. Hangst, W. N. Hardy, M. E. Hayden, C. A. Isaac, A. Ishida, S. A. Jones, S. Jonsell, L. Kurchaninov + *et al.*

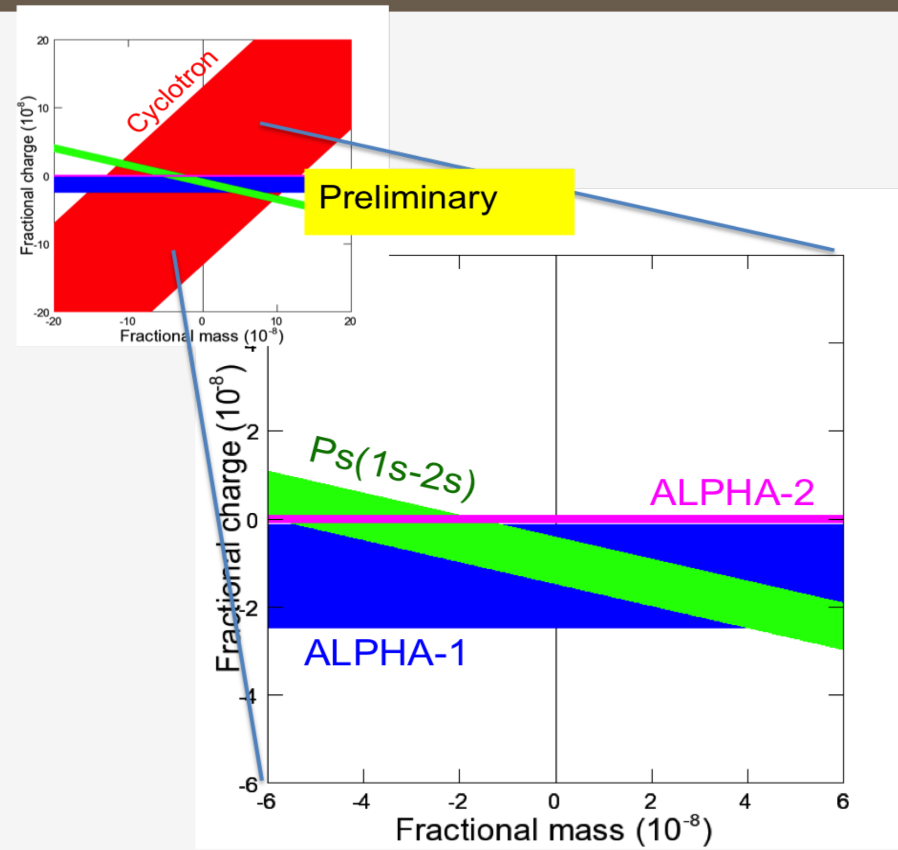
Affiliations | Contributions

Nature 529, 373-376 (21 January 2016) | doi:10.1038/nature16491

Experimental limits on anomalous positron charge and mass



"Weak link": e+ charge



$\Delta Q_{e+}/e \sim 7\text{x}10^{-10}$ (1σ), 40-fold improvement

$\Delta m_{e+}/m_{e+} \sim \pm 2\text{x}10^{-8}$, ~5 fold improvement

ALPHA-II Atom Trap

- Laser access and improvement in field homogeneity.
- Modular Design
- Reduced He useage.
- New Trap designed at TRIUMF.
- C. Marshall
-
- F MF.

Com

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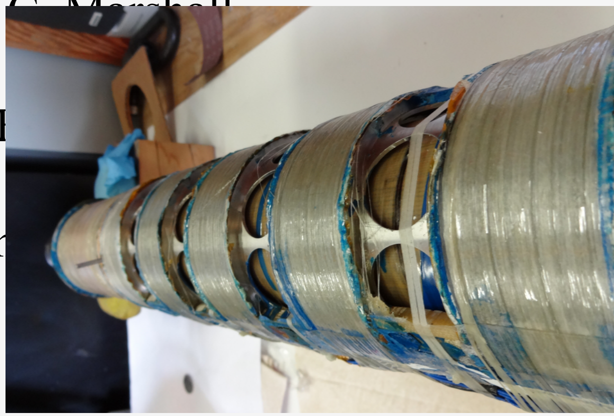
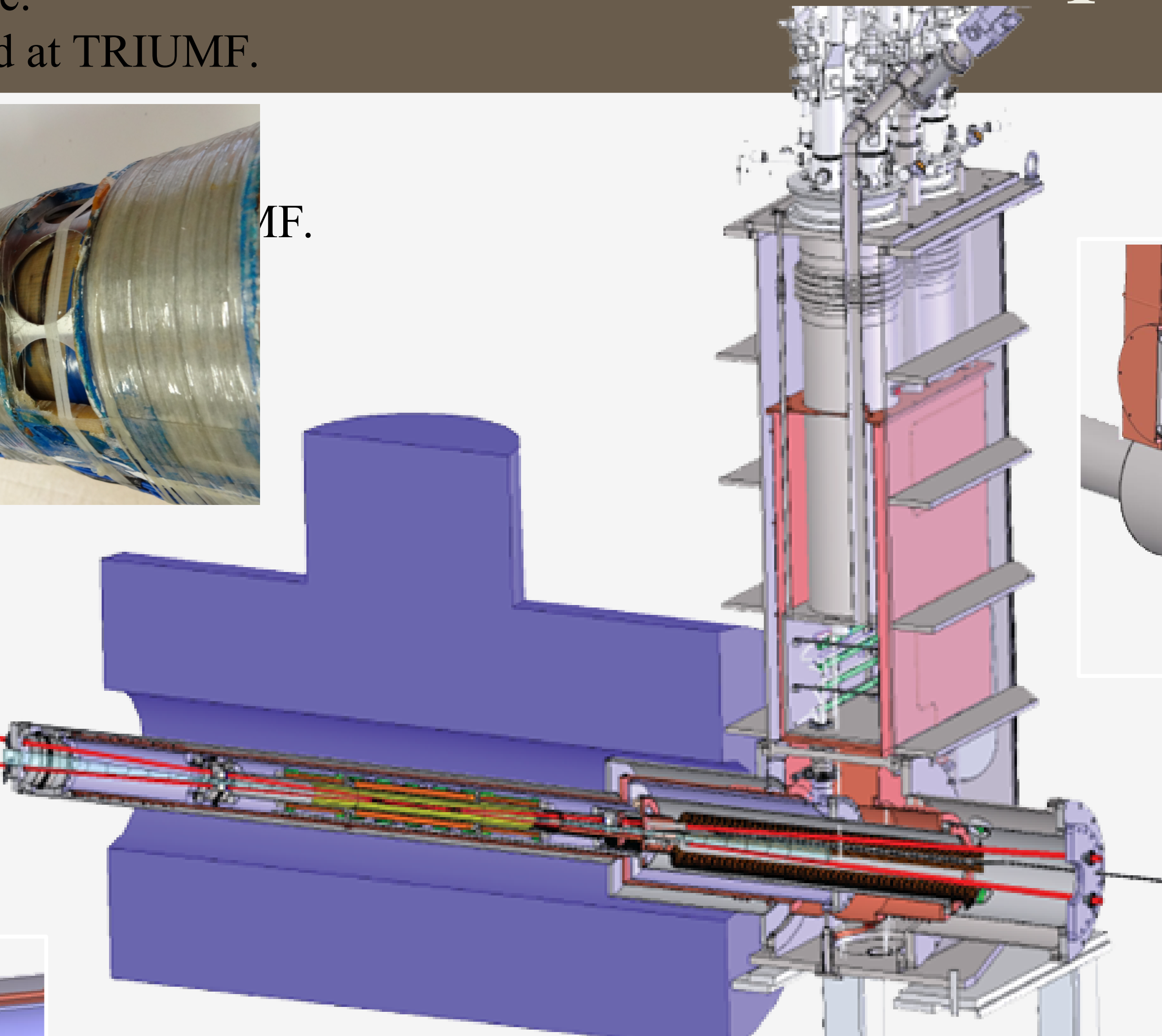
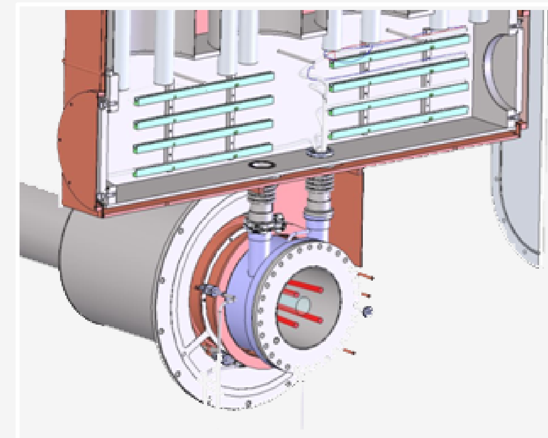
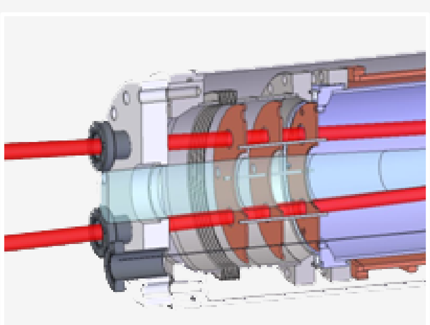
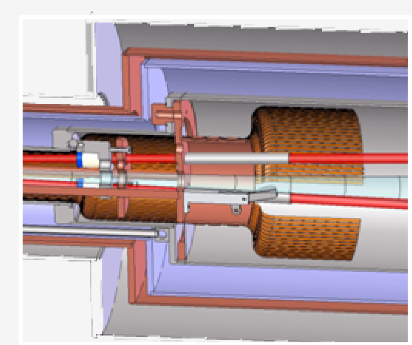






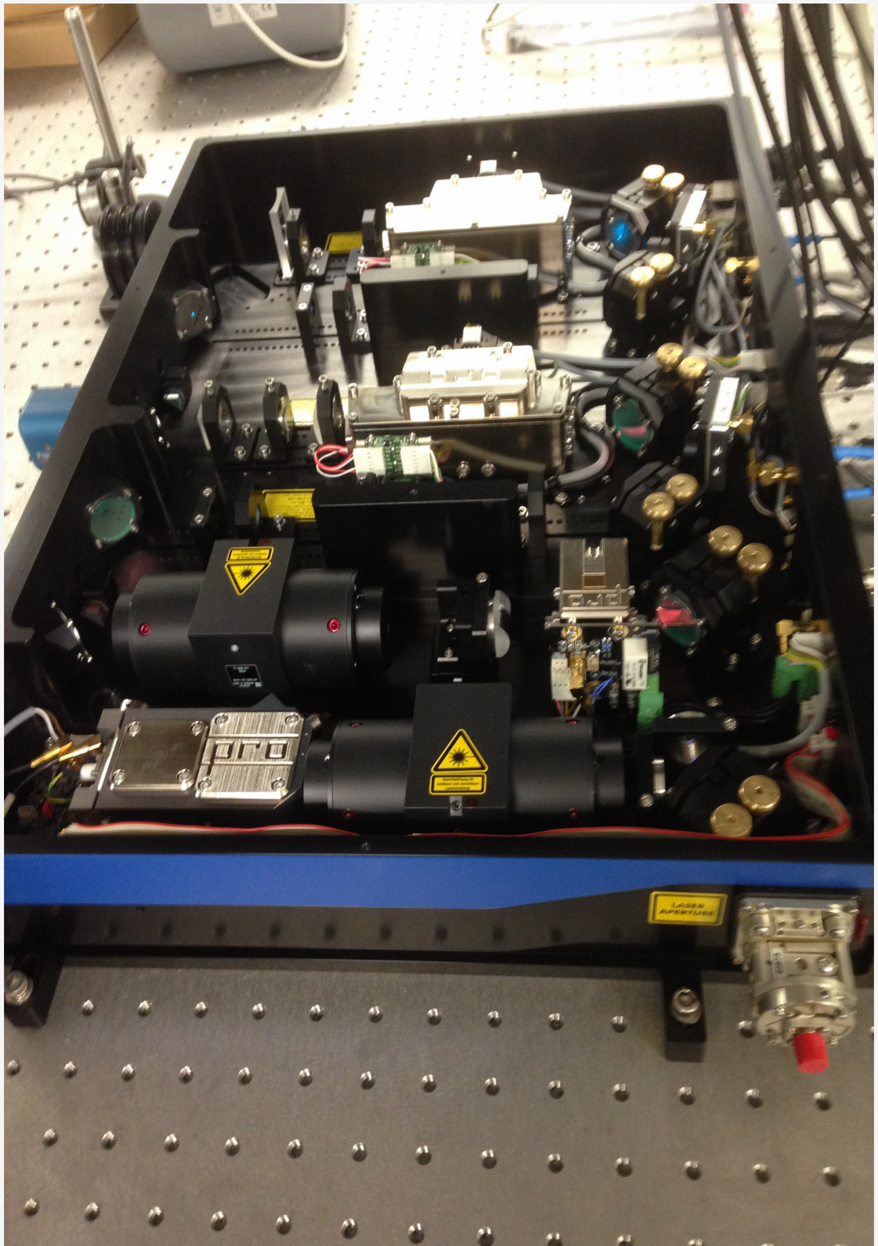


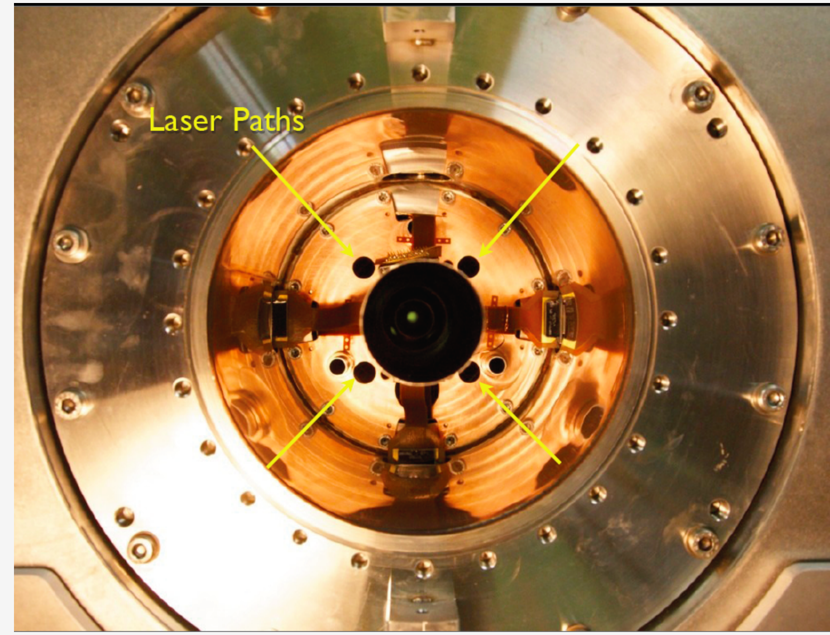


TRIUMF

ALPHA

243 nm Laser





- All solid state, fourth harmonic generation
- > 50 mW indefinitely; easily makes 200 mW
- Limited by UV damage to optical elements
- Manufactured by Toptica
- Financed by ERC Advanced Grant

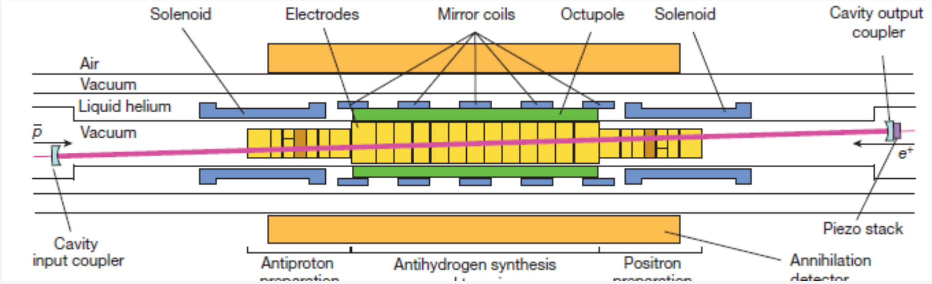
243 Laser Setup

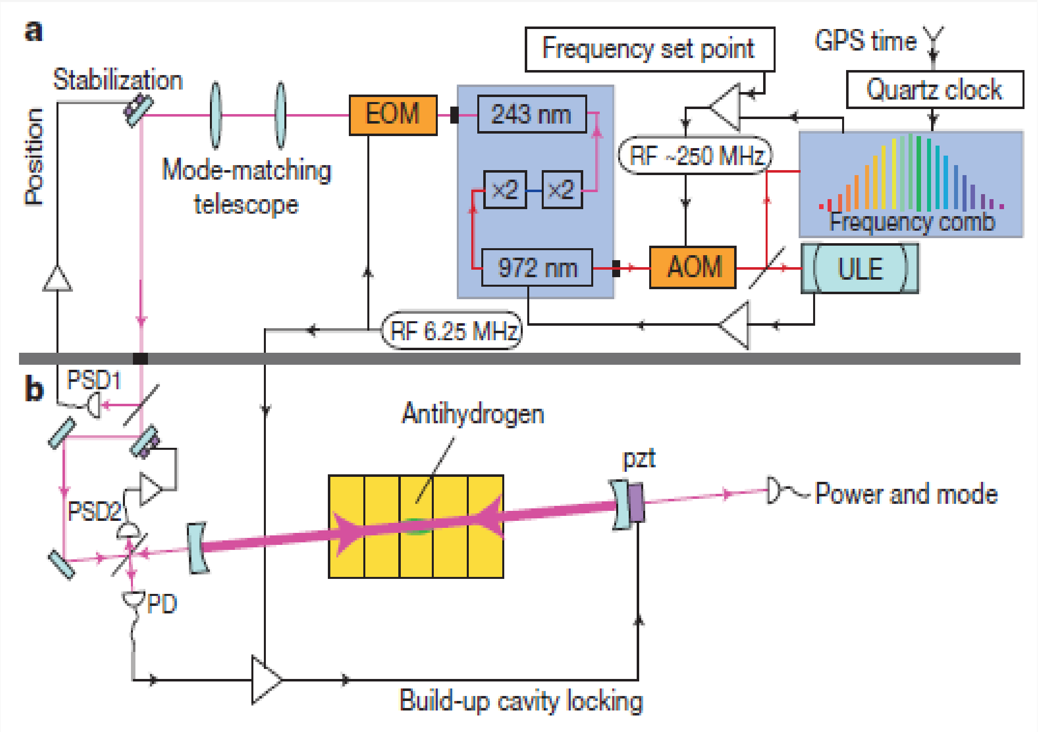
a) In laser hut

- AOM sets 972nm frequency stabilized to ULE and referenced by frequency comb to GPS time.
- 243nm produced by 2 doubling stages.

b) In zone

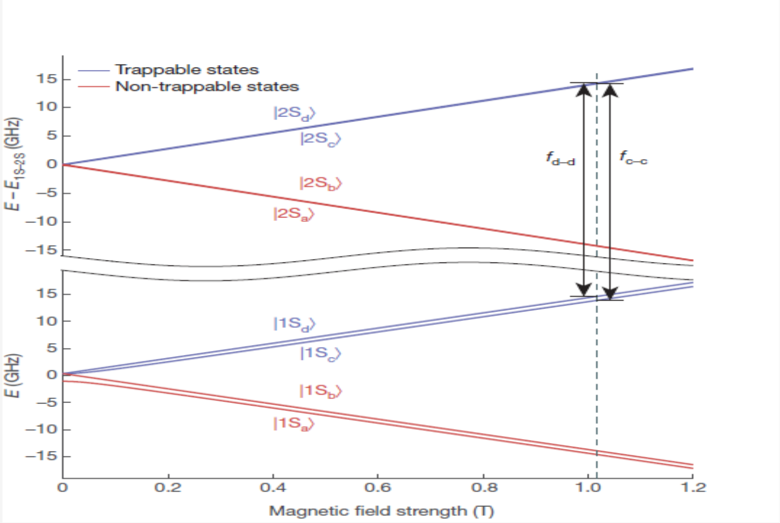
- Beam position/angle actively stabilized.
- Pound-Drever-Hall lock applied to piezzo-controlled mirror.
- Cryogenic buildup cavity has finesse of 250.
- Linewidth < 10kHz ((ULE lock excursions)
- Circulating power >1W.

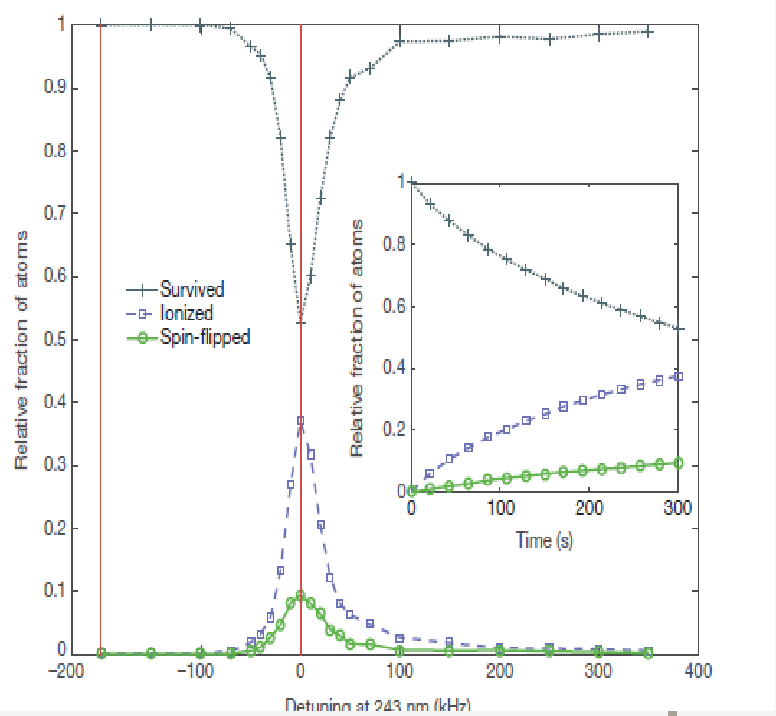




Experimental Procedure

- Fill trap with ~10 H atoms; Clear charged particles.
- 300s d→d (H) irradiation; 300s c→c (H) irradiation; clear charged particles; empty trap over 1.5 s.
- Alternate on-resonance, detuned -200kHz and no-laser runs
- Annihilations are produced by 1S-2S 2-photon excitation followed by decay to an untrapped level or by 2S state ionization by a subsequent photon. The ionized H then escapes from the trap radially.
-





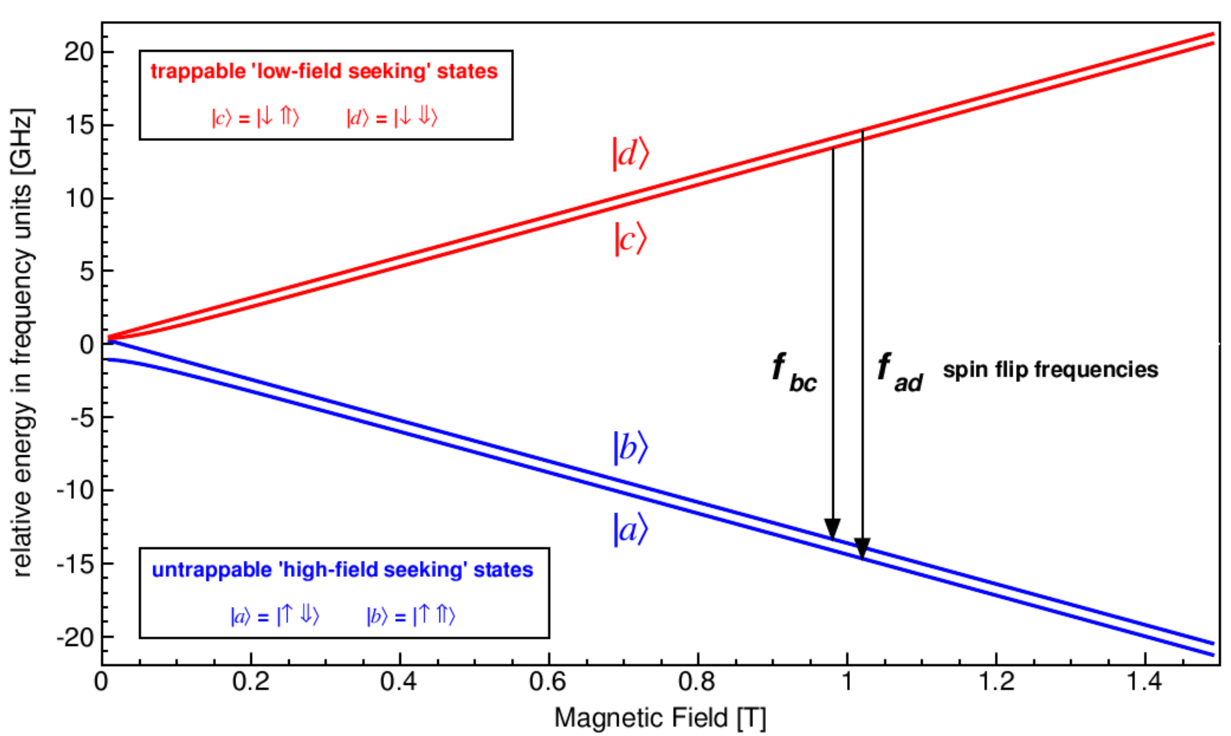
We saw it!

Series type	Surviving counts	Disappear-ance %	Appearance Counts	Appearance %	Power mW
Off Resonance	159	56±7 1100	7	71±16	1100
On Resonance	67				
No laser	142	-16±6	5	4±8	0

- Appearance: ratio of on-resonance/off-resonance counts observed during laser irradiation.
- Disappearance: 1 - ratio of on-resonance /off-resonance counts surviving the laser irradiation.
- Consistent with hydrogen transitions with 200 KHz bound.

- Attempting a lineshape measurement this year, aiming for ~10kHz precision.
- Stability of laser power and trapping rate will be systematic limits.

Hydrogen Hyperfine Energy Levels



- Hyperfine interval in hydrogen, $\boldsymbol{f}_{ad}$ - $\boldsymbol{f}_{bc}$, is measured to $\sim 10^{-12}$.
- A measurement in antihydrogen at this precision is a significant CPT test.
- Driving $\boldsymbol{f}_{bc}$ or $\boldsymbol{f}_{ad}$ expels $\overline{\mathrm{H}}$ from the trap.
-

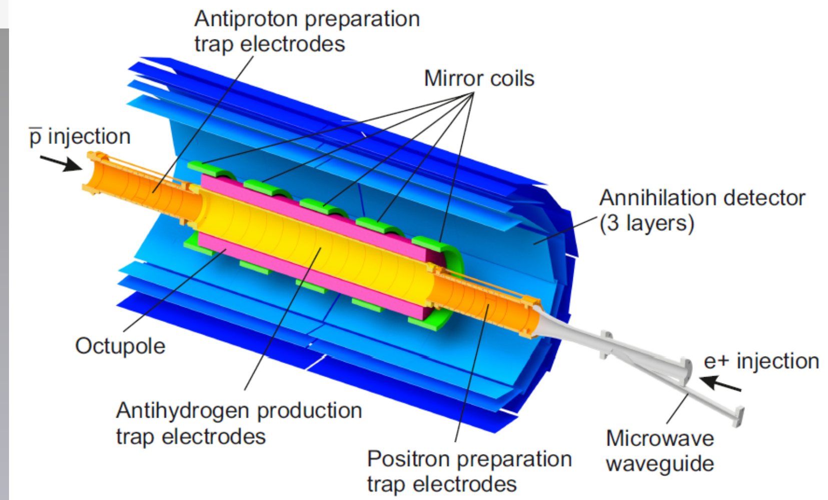
The Breit–Rabi diagram, showing the relative hyperfine energy levels of the ground state of the hydrogen (and antihydrogen, assuming CPT invariance) atom in a magnetic field. In the state vectors shown (for the high-field limit), the single arrow refers to the positron spin and the double arrow refers to the antiproton spin.

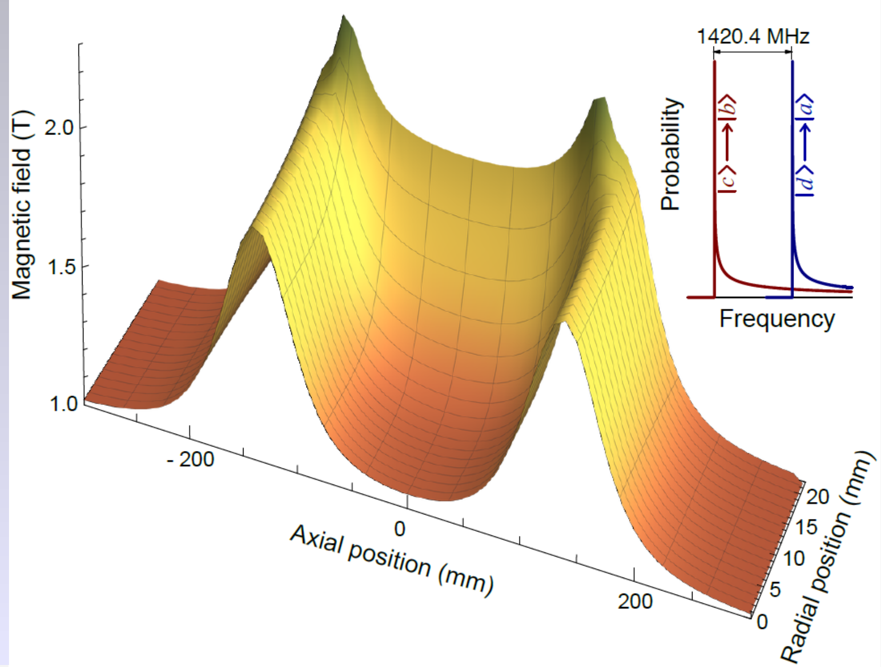
2017 Hyperfine Interval Measurement

Procedure

- Flattened trap field with central minimum produced using 5 mirror coils.
- Field at trap center measured daily to 0.3mT from ECR on electron plasma.
- ECR also determines uwave E field.
- Each measurement had ~14 $\bar{\mathrm{H}}$ s.
- Scan |c>→|b> in 16 300kHz intervals advancing every 4s with 160 mW microwaves.
- Scan |d>→|a> in 16 300kHz intervals advancing every 4s with 320 mW microwaves.
- Release the remaining trapped $\bar{\mathrm{H}}$ s over 2.1s.

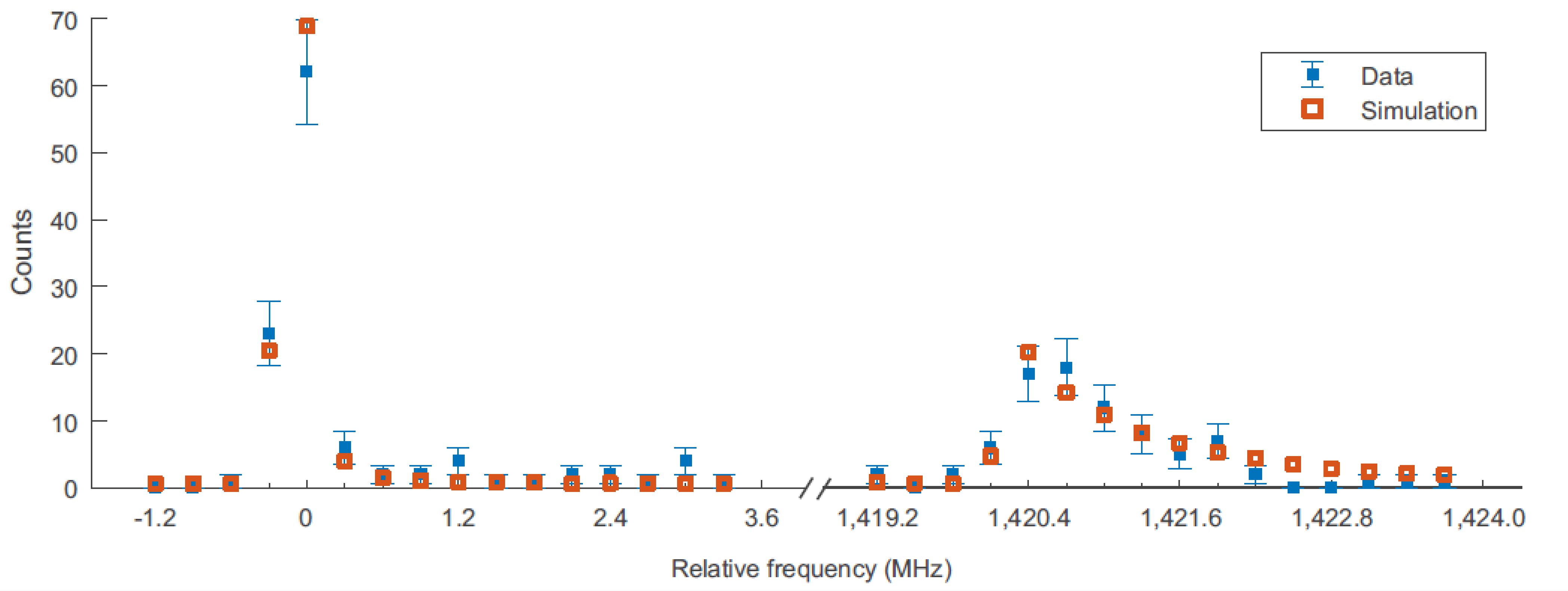
Both transitions are measured at the same magnetic field.





An Antimatter Atomic Spectrum

The hyperfine interval is determined from the separation of the two onset bins.
The histogram shape is determined by the spin-flip rate and the number and trajectories of the remaining $\overline{H}$ s.
Good agreement with simulation using microwave power measured by ECR.

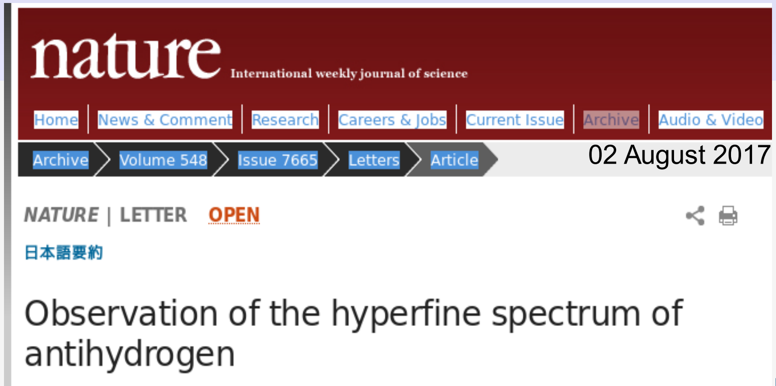


Hyperfine interval result

Antihydrogen a/h =1420.4 ±0.5 MHz in agreement with hydrogen.
Uncertainties:

- 300kHz (1 bin) uncertainty in difference of onset bins.
- 300 kHz uncertainty in magnetic field drift during the 128s measurement interval, based on a control measurement.
- 300kHz uncertainty in combining data over 3 days.

We anticipate an order of magnitude reduction in the uncertainties from 2017 data.



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02 August 2017

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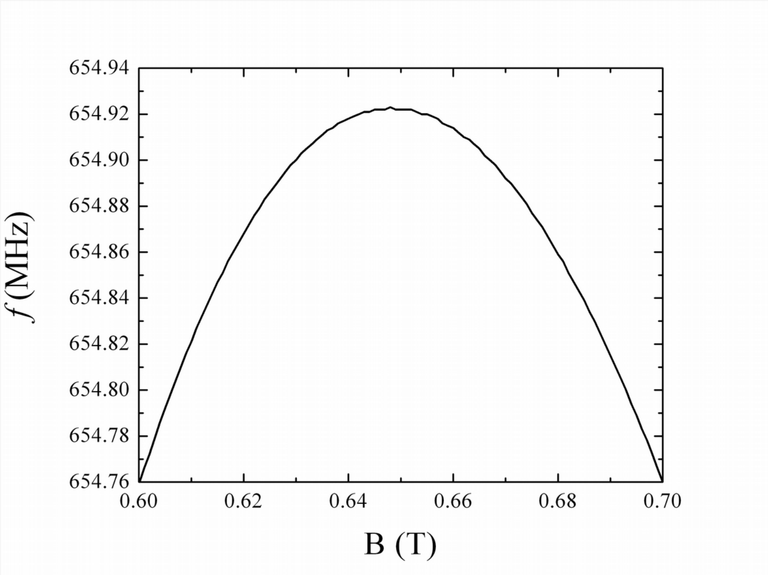
Observation of the hyperfine spectrum of antihydrogen



NMR (pbar spin flip)

655 MHz at magic 0.65T turning point: insensitive to 1st order B inhomogeneity

- Double resonance w/ PSR
- $\sim 10^{-7}$ possible with large number of H (like Asacusa)

Summary: ALPHA Physics Reach (model dep't!)

Possible CPTV shift (Pospelov)

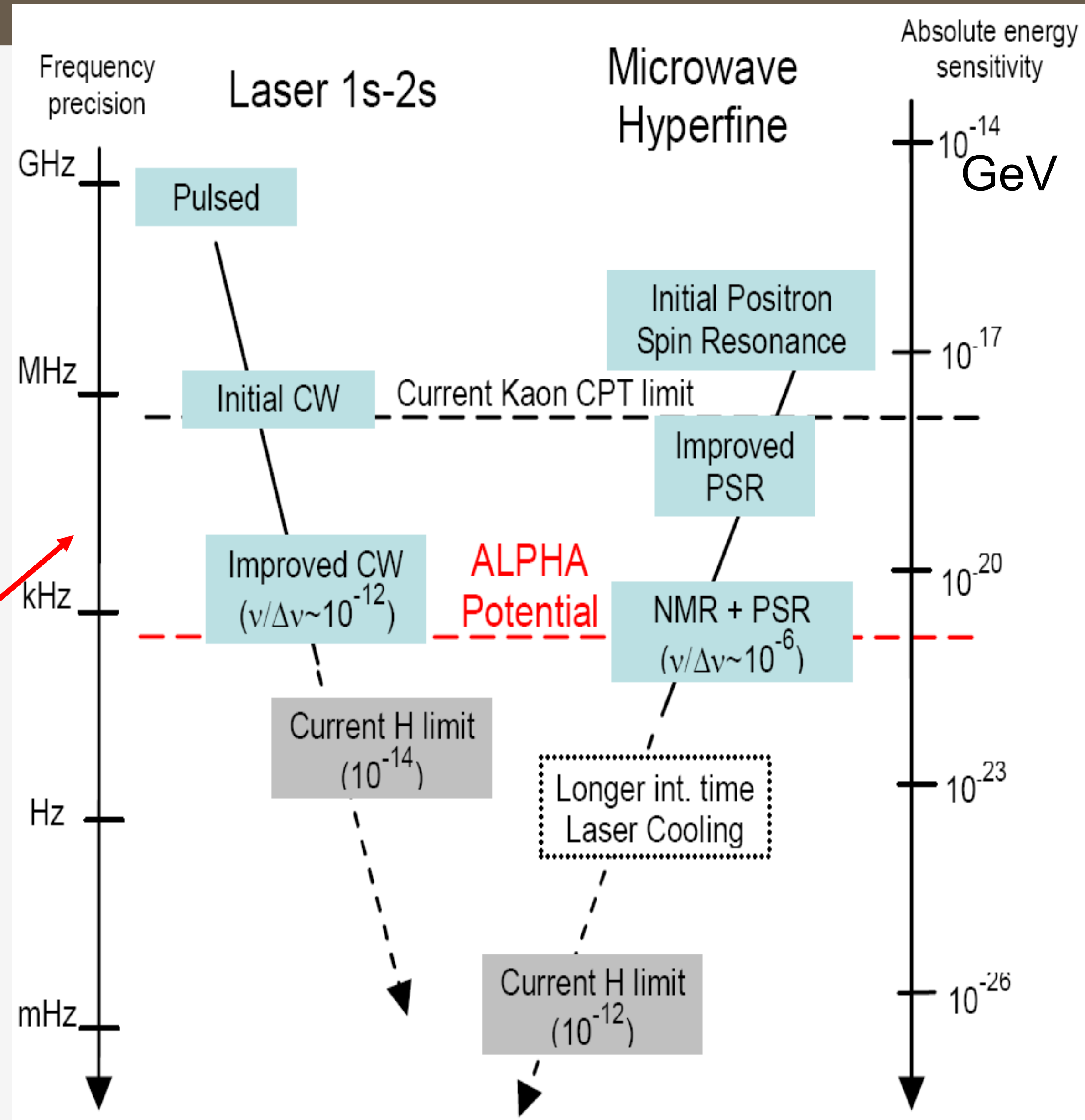
$$\Delta E \sim \frac{m^{n+1}}{\Lambda^n_{CPTV}}$$

Small absolute energy ΔE probes high energy scale

For $n=1$, $m=1$ GeV,
$\Lambda_{CPTV} = M_{Pl} \sim 10^{19}$ GeV

$\Delta E_{CPT} \sim 10^{-19}$ GeV
(~10 kHz in frequency)

Slide credit: Fujiwara 2008



Probing Planck scale physics

非常感谢你

Thank you

Extras

Bayesian Statistics Calculation

- Simulation of H trajectories with detailed trap fields and stochastic potentials.
- 1000 $\bar{H}$ trials for each Q.
- 1σ error band for survival probability.
- Q bounds are obtained from a Bayesian determination of the range of survival probability corresponding to a 1σ variation of our data.
- Dominant systematic is energy distribution in the trap.
- Consistent with assumption that trapped $\bar{H}$ distribution is Poisson.