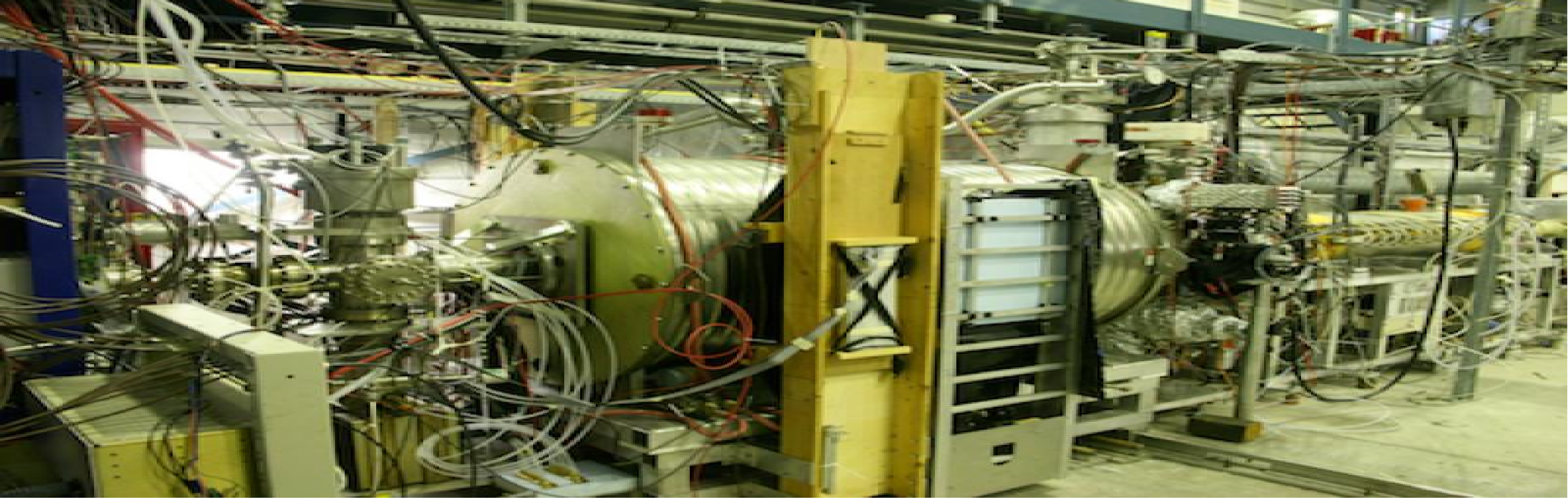

Spectroscopy of Trapped Atomic Antihydrogen in ALPHA

International Conference on New Frontiers in Physics, 2013

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(Anti-)hydrogen and CPT

- Very precise spectroscopic techniques can be used

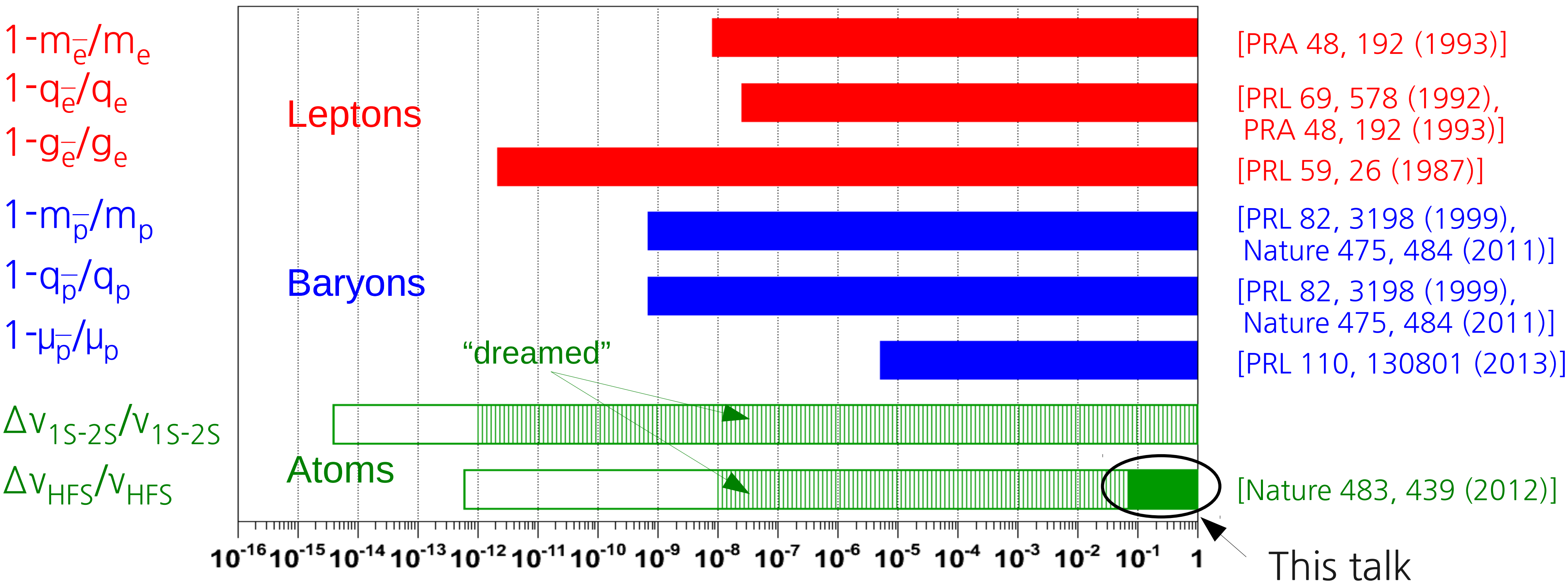
$$\nu_{1S-2S}(\mathrm{H}) = 2\,466\,061\,413\,187\,035\,(10)\ \mathrm{Hz}$$ [Nature 229, 110 (1971)]

$$\nu_{HFS}(\mathrm{H}) = 1\,420\,405\,751.7667\,(0.0010)\ \mathrm{Hz}$$ [PRL 107, 203001 (2011)]

- Quite well understood theoretically

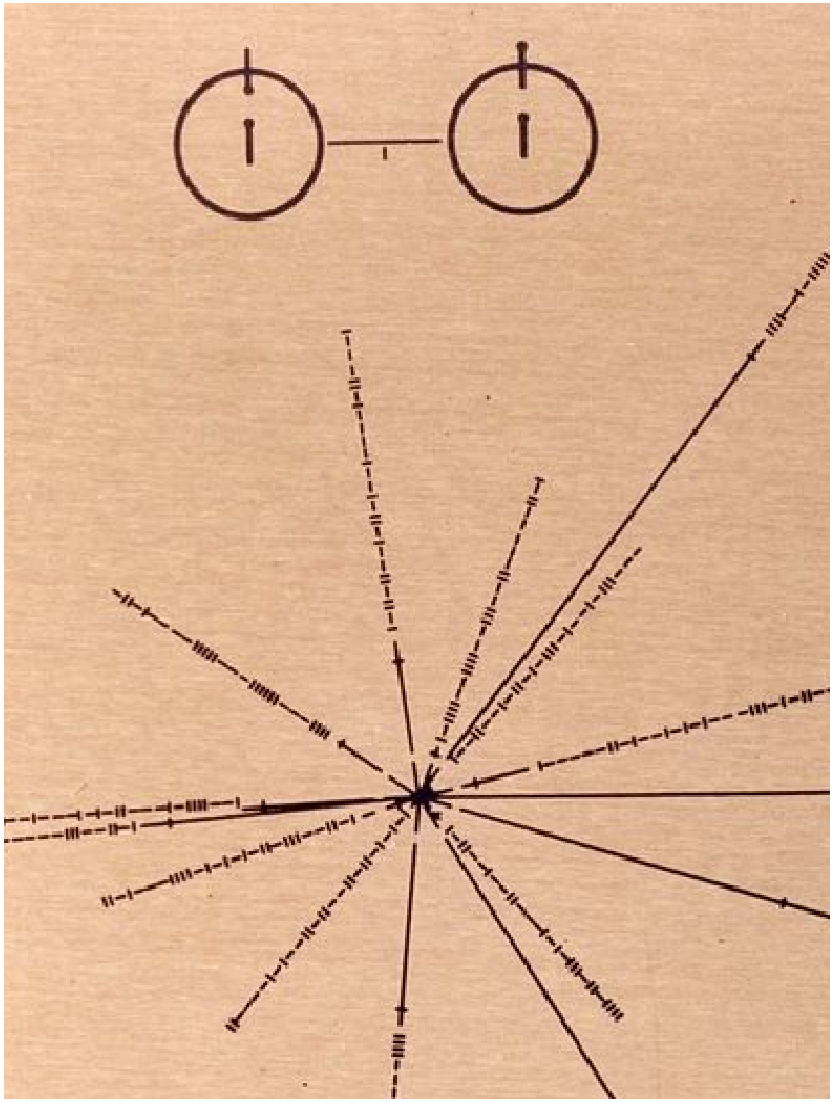
$$\nu_{1S-2S} \approx \frac{3}{4} Z^2 \frac{m_p}{m_e + m_p} cR_\infty, \quad \nu_{HFS} \approx \frac{16}{3}\alpha^2 Z^3 \left(\frac{m_p}{m_e + m_p}\right)^3 \frac{m_e}{m_p}\frac{\mu_p}{\mu_N}\frac{g_e}{2} cR_\infty$$

  - High order corrections: p($\bar{\mathrm{p}}$) charge and magnetic distributions



Summary

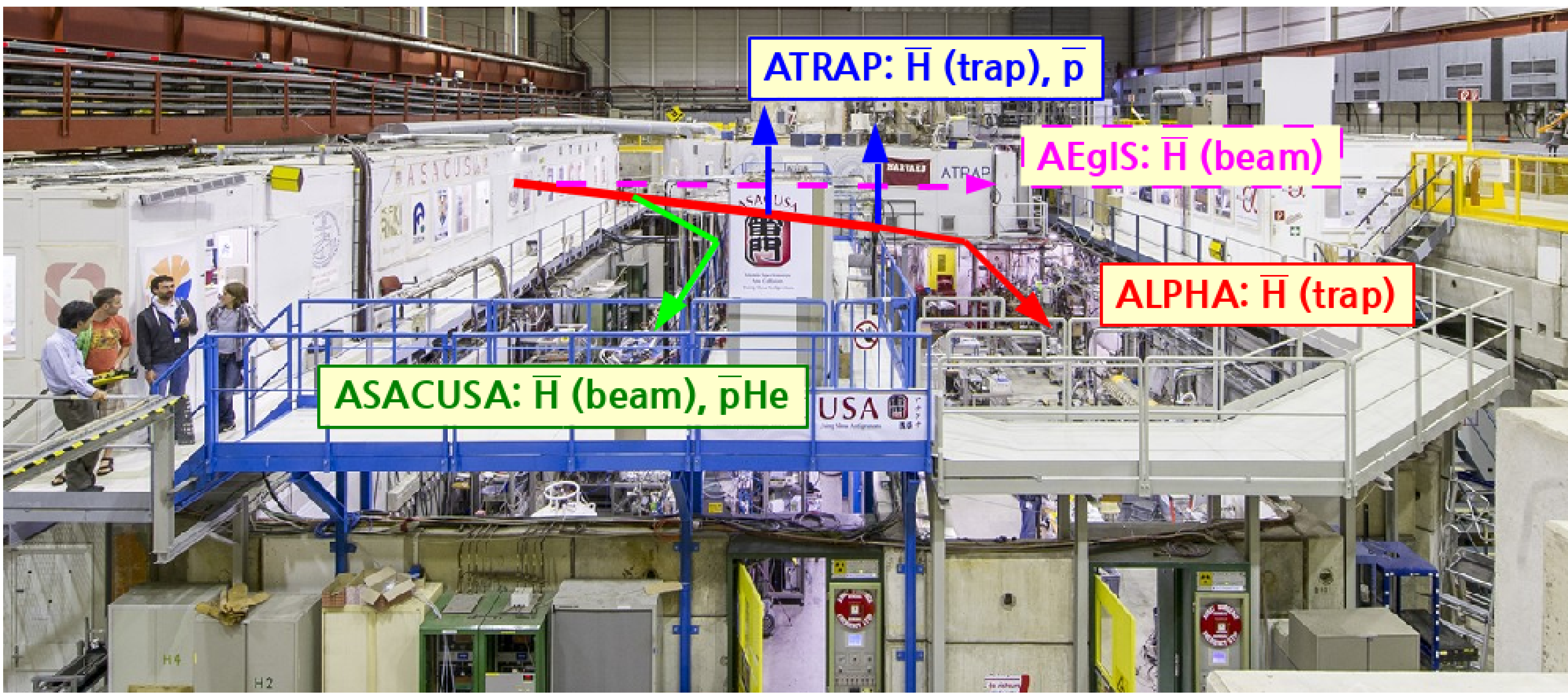
- The ALPHA/AD-5 experiment
- Positron spin resonance in trapped antihydrogen
- Applications and outlook



[Detail of the *Pioneer 10* plaque]

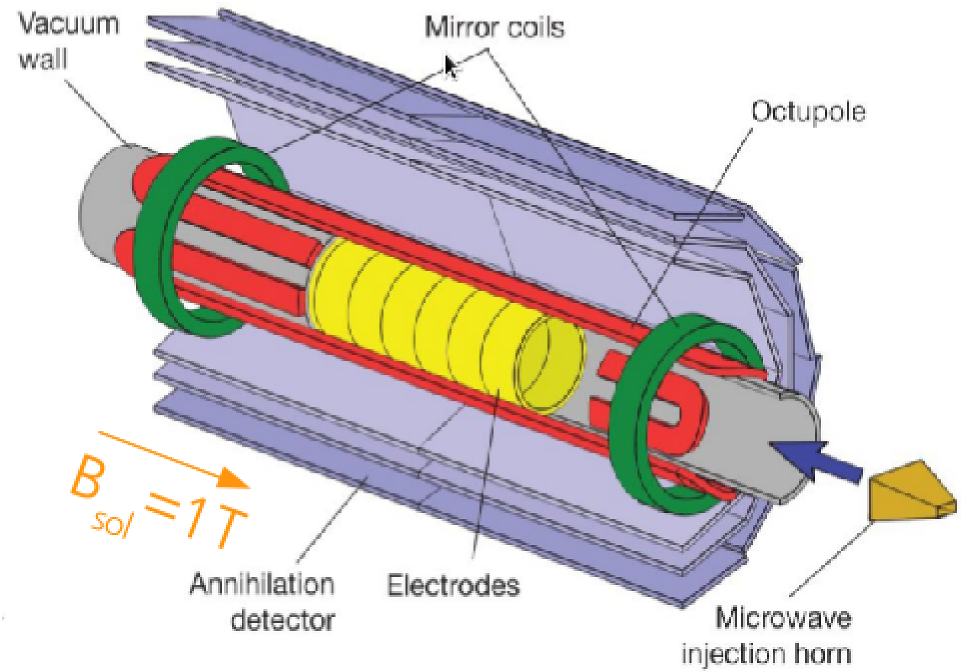
Antiproton Decelerator

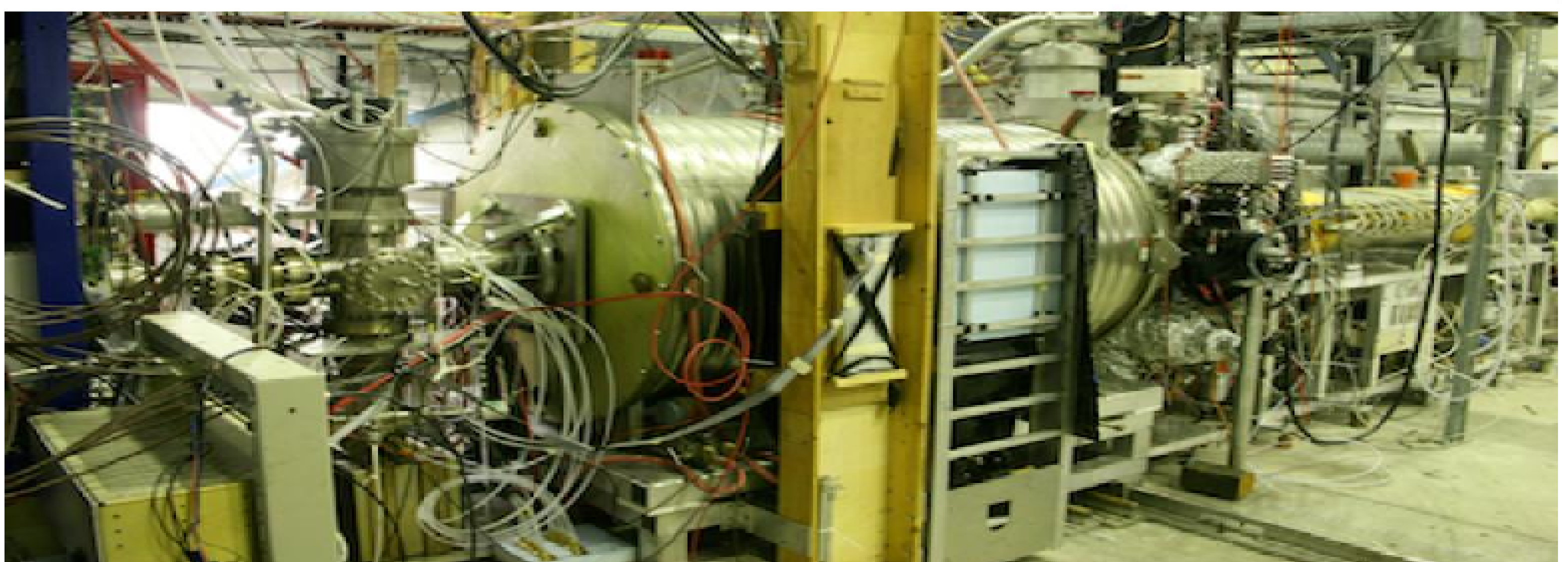
- Multiple experiments / technologies
  - $\bar{H}$ 1S-2S spectroscopy [ALPHA, ATRAP-$\bar{H}$]
  - $\bar{H}$ HFS spectroscopy [ALPHA, ASACUSA-$\bar{H}$ + AEgIS]
  - $\bar{H}$ gravitational fall [AEgIS, (GBAR)]
  - $\bar{p}$ magnetic moment [ATRAP-$\bar{p}$, (BASE)]
  - $\bar{p}$/e mass ratio [ASACUSA-$\bar{p}$He + theory]



The ALPHA apparatus

- Combined charged particles (Penning-) and neutral atoms (Ioffe-) trap @ $B_{min} = 1T$
  - $\bar{H}$ production via $\bar{p}+e^{+}+e^{+} \rightarrow \bar{H}^{*}+e^{+}$
    [G. Gabrielse et al., PLA 129, 38 (1988)]
  - Trap $\bar{H}$ in a 0.54K magnetic potential well ($U = -\boldsymbol{\mu} \cdot \mathbf{B}$)





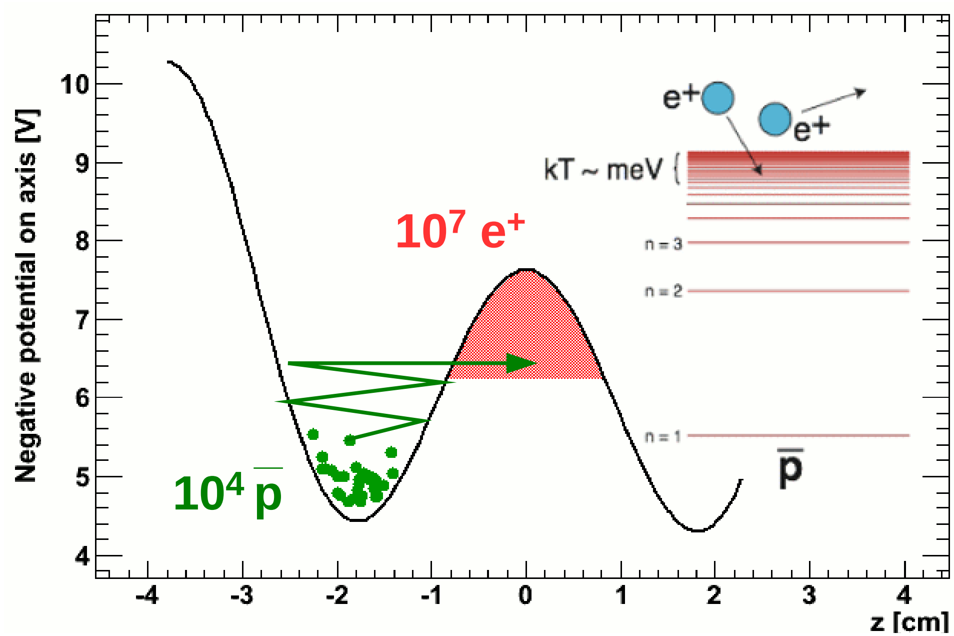
$\bar{p}$ AD extraction line (+ Al degrader)

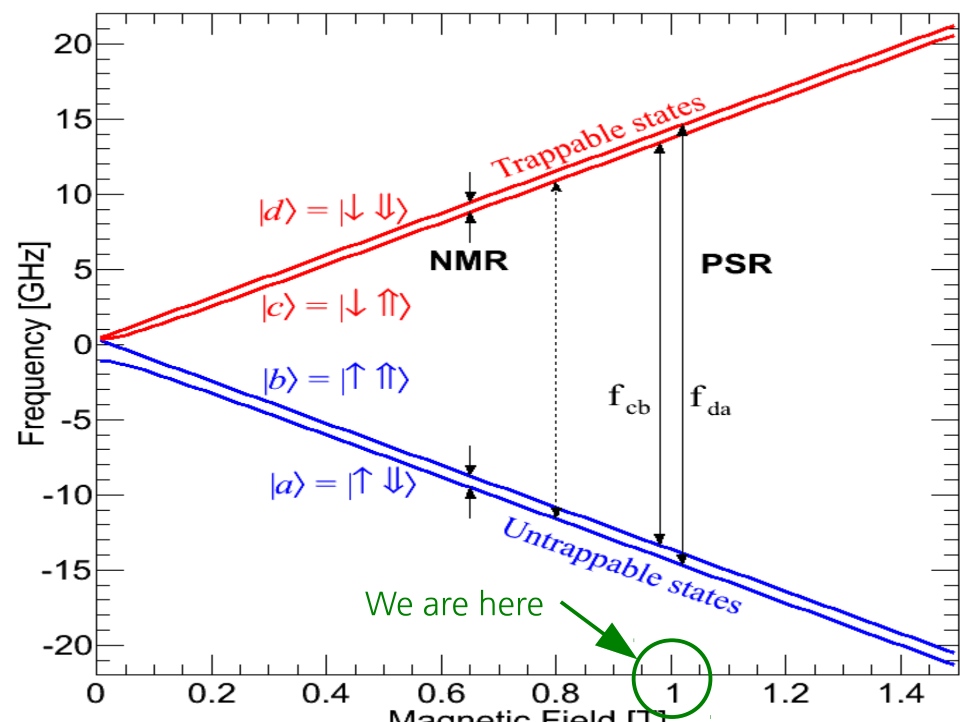
1T external solenoid

RF injection, e-gun, plasma diagnostics

^{22}Na source + e^{+} accumulator

Producing a sample of trapped $\bar{H}$





- $\bar{p}$ and e^+ gently mixed in nested Penning trap
- Three-body recombination mostly results in highly excited $\bar{H}$ atoms
  - Long confinement *should* allow $\bar{H}$ to cascade to ground state
  - $\tau_{cascade} \lesssim 0.5$ s in simulations

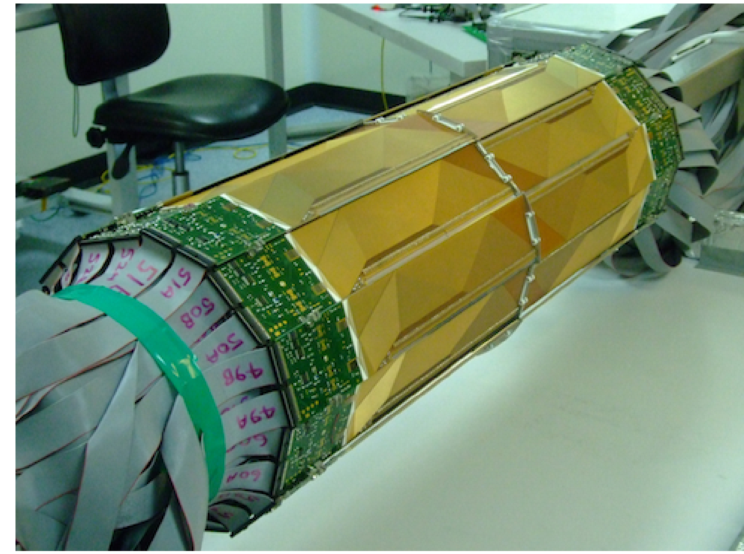
  [Topçu,and Robicheaux, PRA 73, 043405 (2006)]

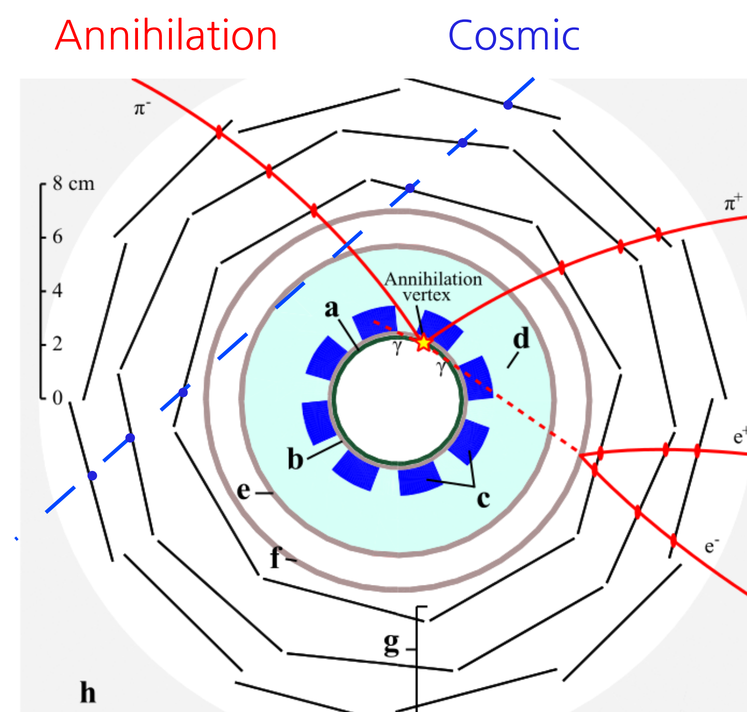
- "Low-field seeking" hyperfine states can be trapped ($E_{kin} \lesssim 50$ μeV)
  - "production + trapping" rate is low (and, so far, typically stable only over ~1-2 weeks timescale)
  - ~1 $\bar{H}$ *observed* /3 attempts (~1 $\bar{H}$/hr)

  [ALPHA Coll., Nature 468, 673 (2010)]

$\overline{\mathrm{H}}$ detection

- Self-triggering silicon detector
  - 60 double-sided strip modules (1 disconnected) in 3 layers
  - NIM-based logic combines AD- and e^+-side trigger information
- Identify $\overline{\mathrm{H}}$ from $\bar{p}$ annihilation products
  - We don't look for e^+ annihilation
  - Main bkg from cosmics (*reducible*)
    - Side effect: lack of good control samples for MC validation on data
- $\overline{\mathrm{H}}$ can made to annihilate:
  - on background gas: residual gas, e^+ buffer gas, gas desorbed by heat
  - on electrodes: **ramp down trap**
  - on electrodes: **transition to high-field seeking state (e^+ spin flip)**





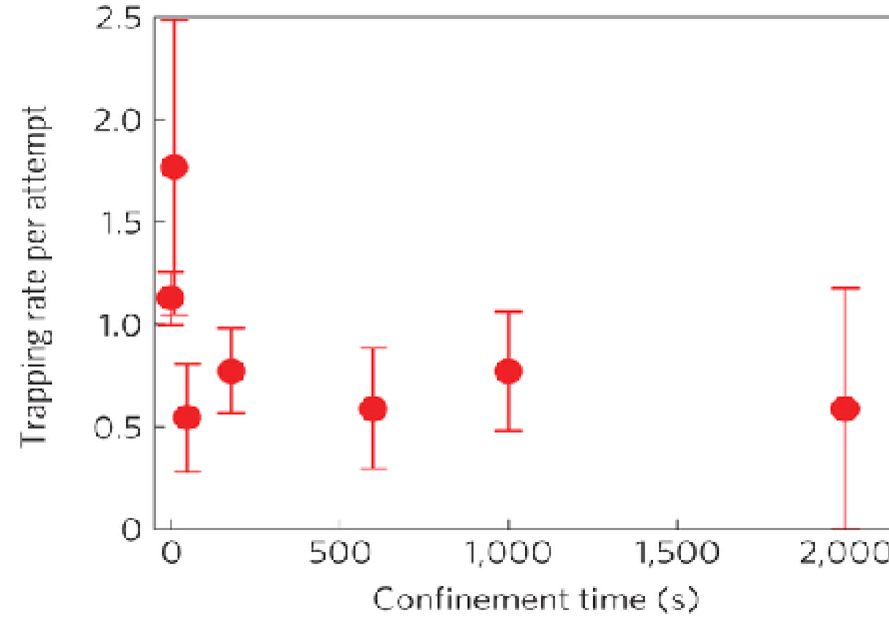
Demostration of quantum transition in trapped antihydrogen

[ALPHA Coll., Nature 483, 439 (2012)]

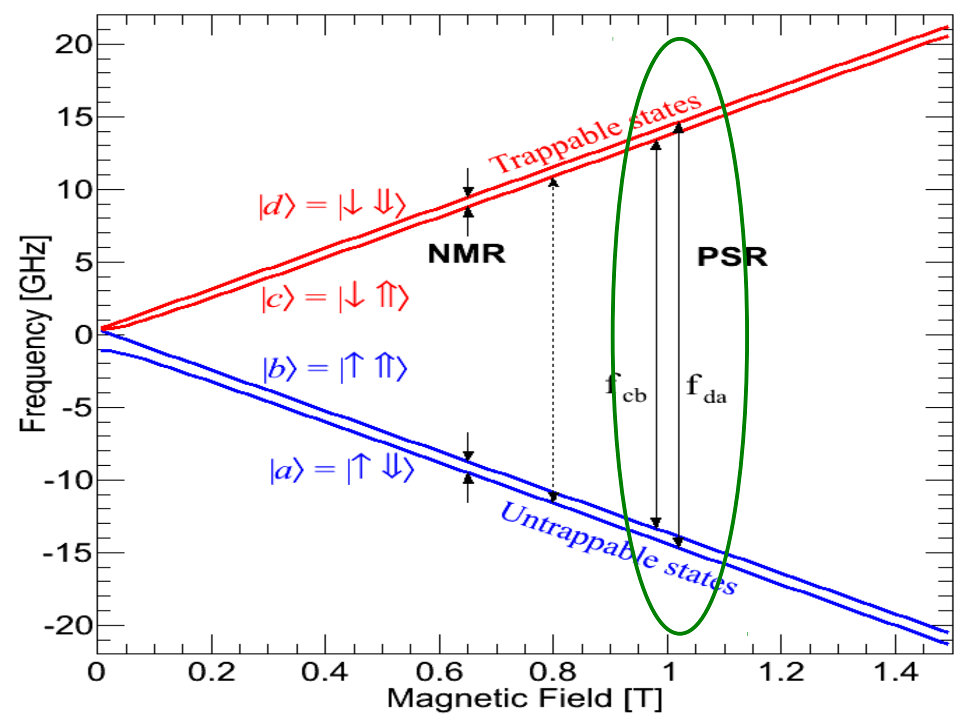
Waveguide for μ-wave injection (UBC, SFU)

Motivations

- Demonstrate ability to conduct spectroscopy measurements with few anti-atoms
  - Long confinement allows for longer irradiation time
  - Must cope with reproducibility of $\bar{H}$ production, apparatus, and environment
- No provision for laser access till 2014 ⇨ use microwaves
- **Positron spin resonance** in ground state anti-hydrogen
  - Two transitions (c-b, d-a)
  - Clear signature (trapped → untrapped: annihilation)



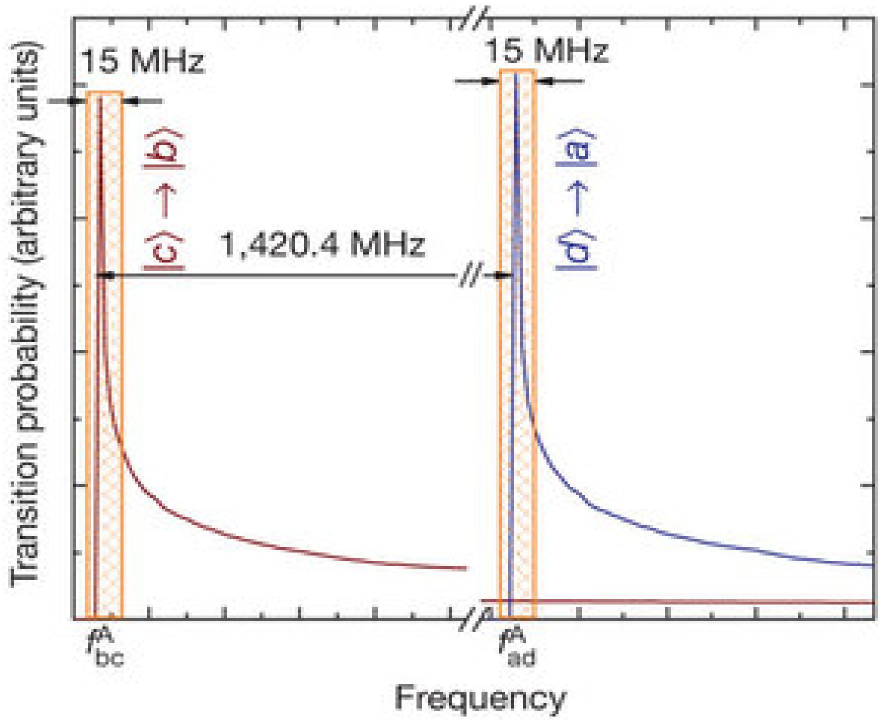
[Nature Physics 7, 558 (2011)]

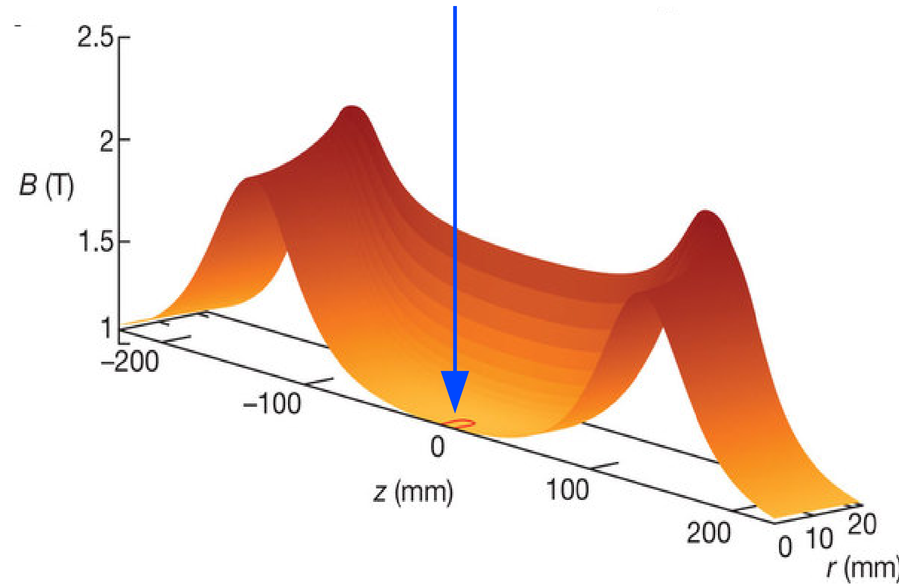


Measurement procedure

- Probability for each transition has an abrupt onset associated to minimum B field
  - Sit close to onset frequency ($\propto B_{min}$) to maximize spin-flip probability
  - Edges separation (CPT): 1420.4 MHz (~ independent of B_{min})
- Use Electron Cyclotron Resonance to characterize B stability *at trap center*
  - Run by run reproducibility: ±2 MHz
  - Background (solenoid) field value accurate to ±10 MHz (3 Gauss)
  - +40 MHz systematic uncertainty in B_{min}: discrepancy between measurement and model of magnetic trap contribution

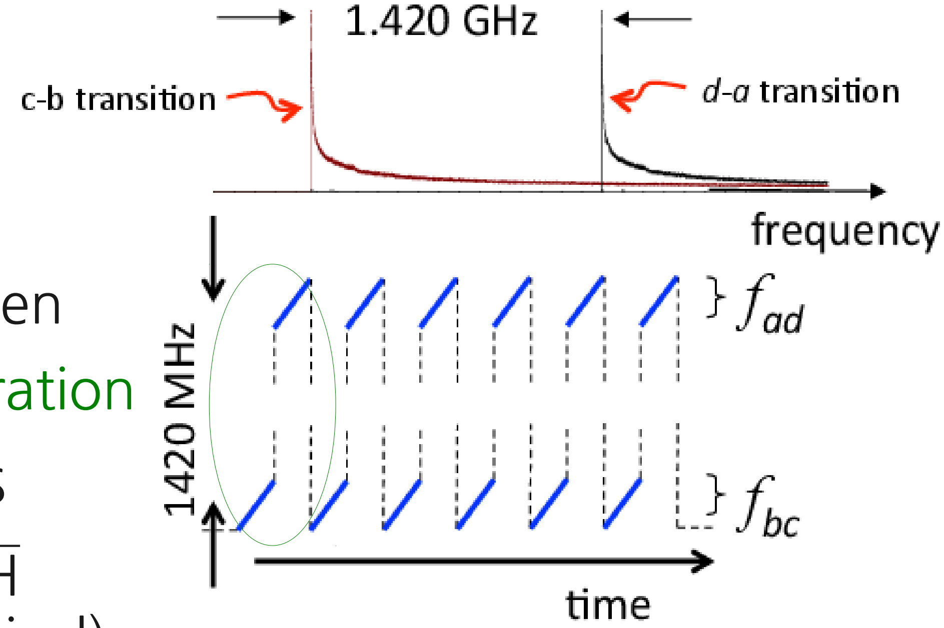
[T. Friesen et al., AIP Conf. Proc. 1521, 123 (2013); T. Friesen et al., submitted to NJP (2013)]

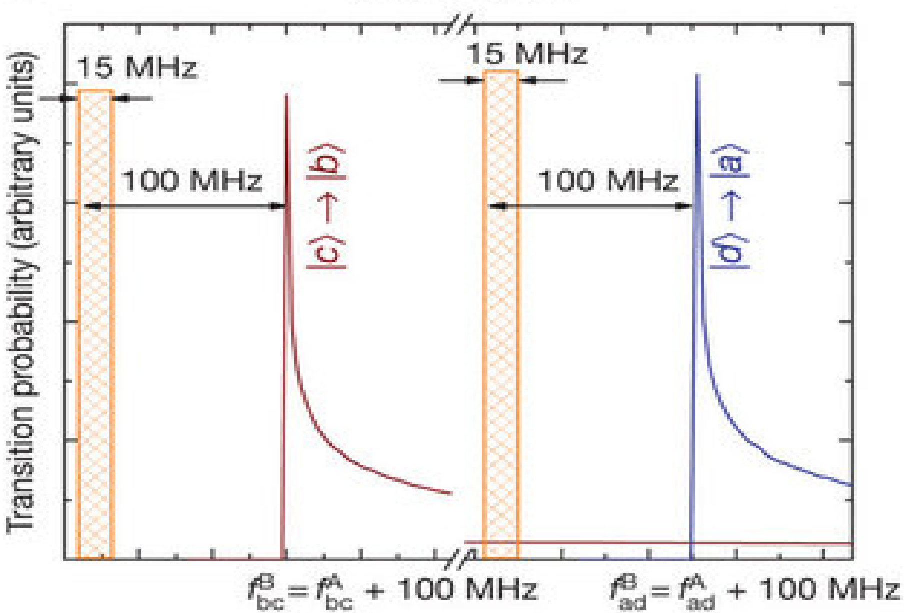




Experimental sequence

- Synthetize
- Trap & hold for 60s
- Irradiate for 30s (6x)
  - Observe annihilations as spin flips happen
  - Expect enough power to flip at first iteration
- Release $\overline{\text{H}}$ by quenching the magnets
  - Look for a deficit in count of surviving $\overline{\text{H}}$ (reproducibility of exp. conditions is critical)



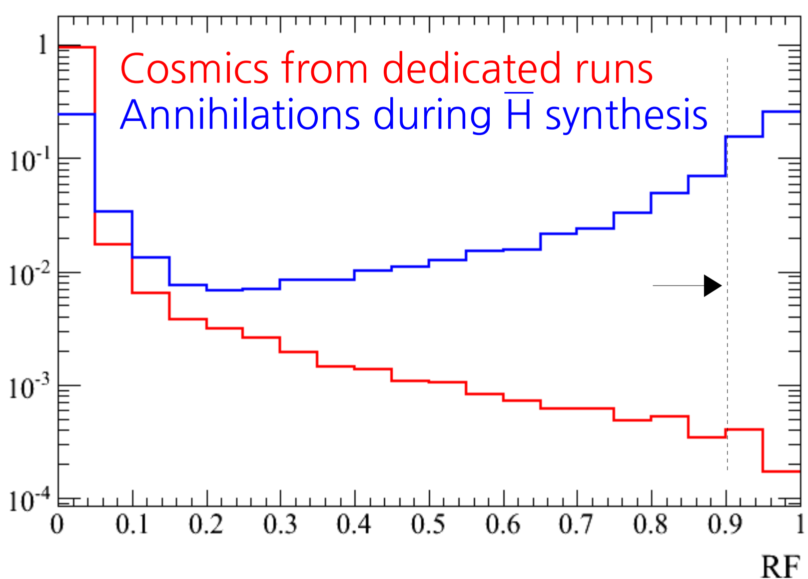


Frequency scan in off-resonance cycles

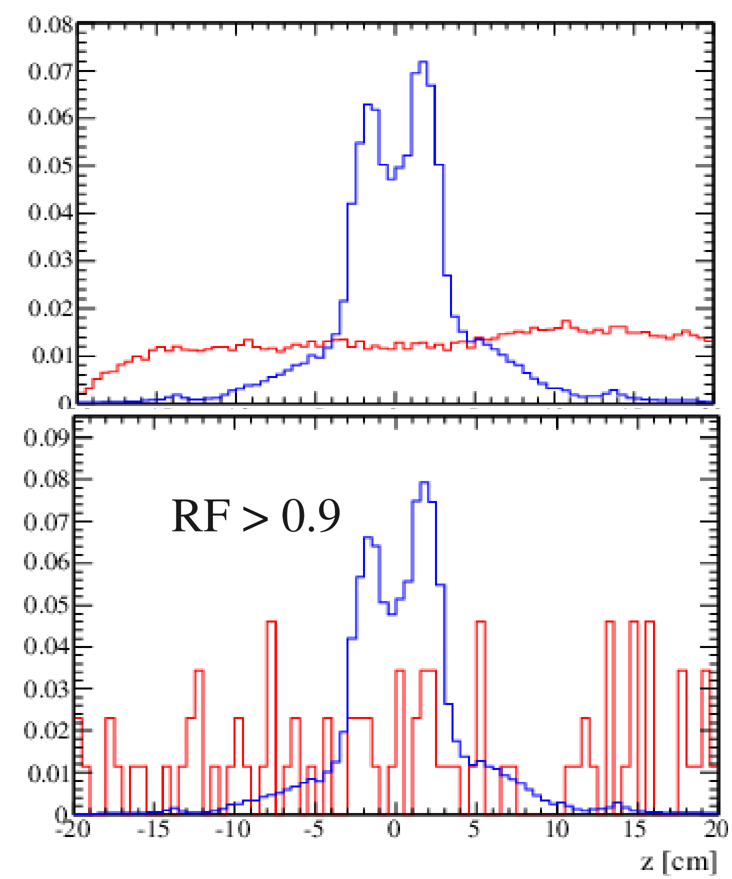
- Compare to *closely interspersed* off-resonance and no-microwaves cycles
  - Off-resonance: 100 MHz detuning (driven by syst.)
  - "Back-to-back" cycles, to decouple from varying experiment / environment conditions and intermittent detector funkiness

"Real time" study of $\overline{\text{H}}$ annihilations

- Long observation window: Random Forest to reject cosmics [I. Narsky, arXiv:physics/0507157 (2005)]
  - Trained on real data control samples
- Cuts on z,t to establish spin-flip signal (tuned on simulations)
  - t within first 30s sweep (f_{bc}, f_{ad})
  - z within 6 cm of trap center (smaller detuning ⇒ tighter z distribution, peaked at trap center)

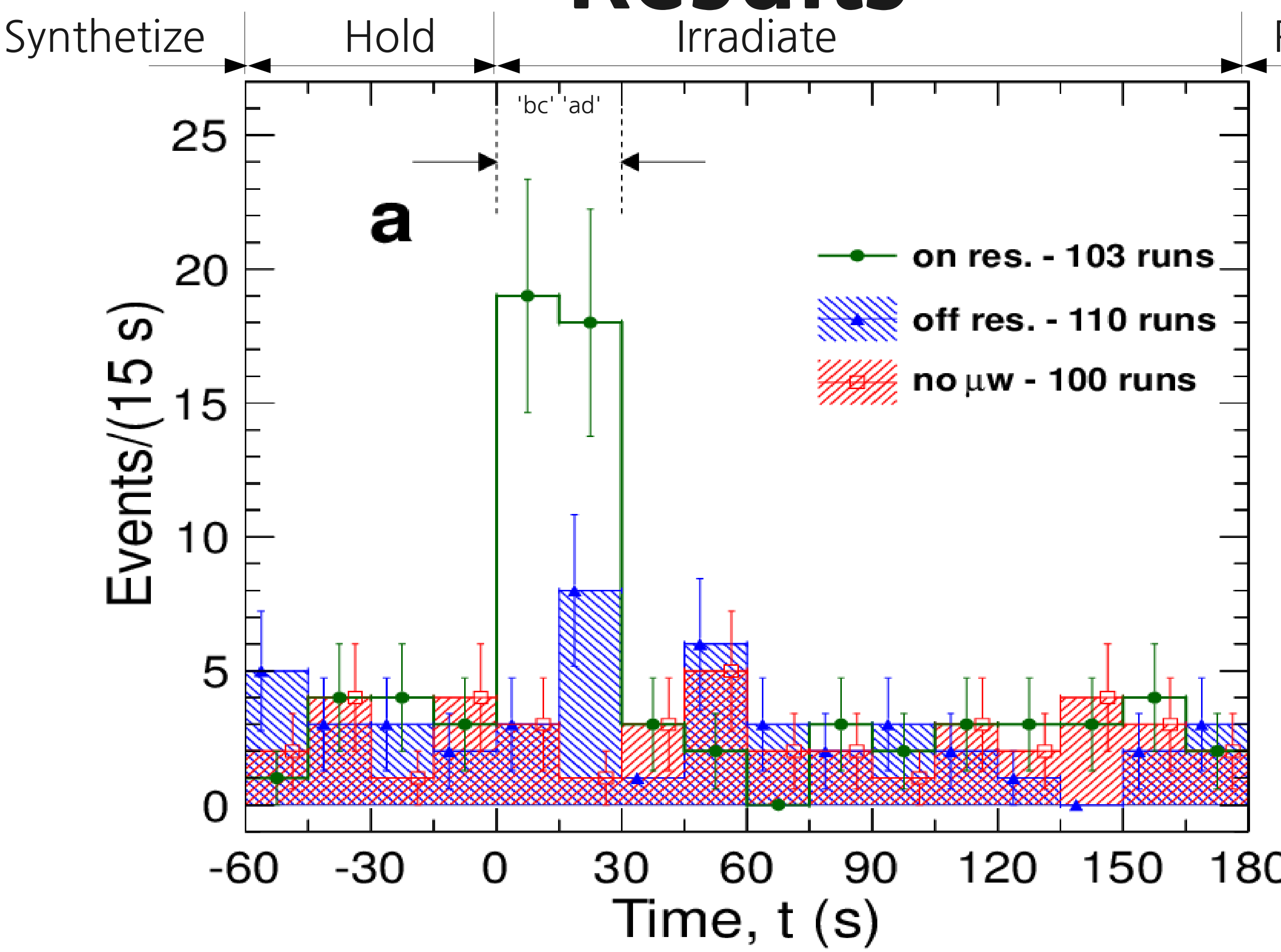


- Axial annihilation position z
  - *Qualitative* features of z-distribution shed light on mechanism causing annihilations
  - Less than 10% correlation between z and RF input variables



Results

[ALPHA Coll., Nature 483, 439 (2012)]

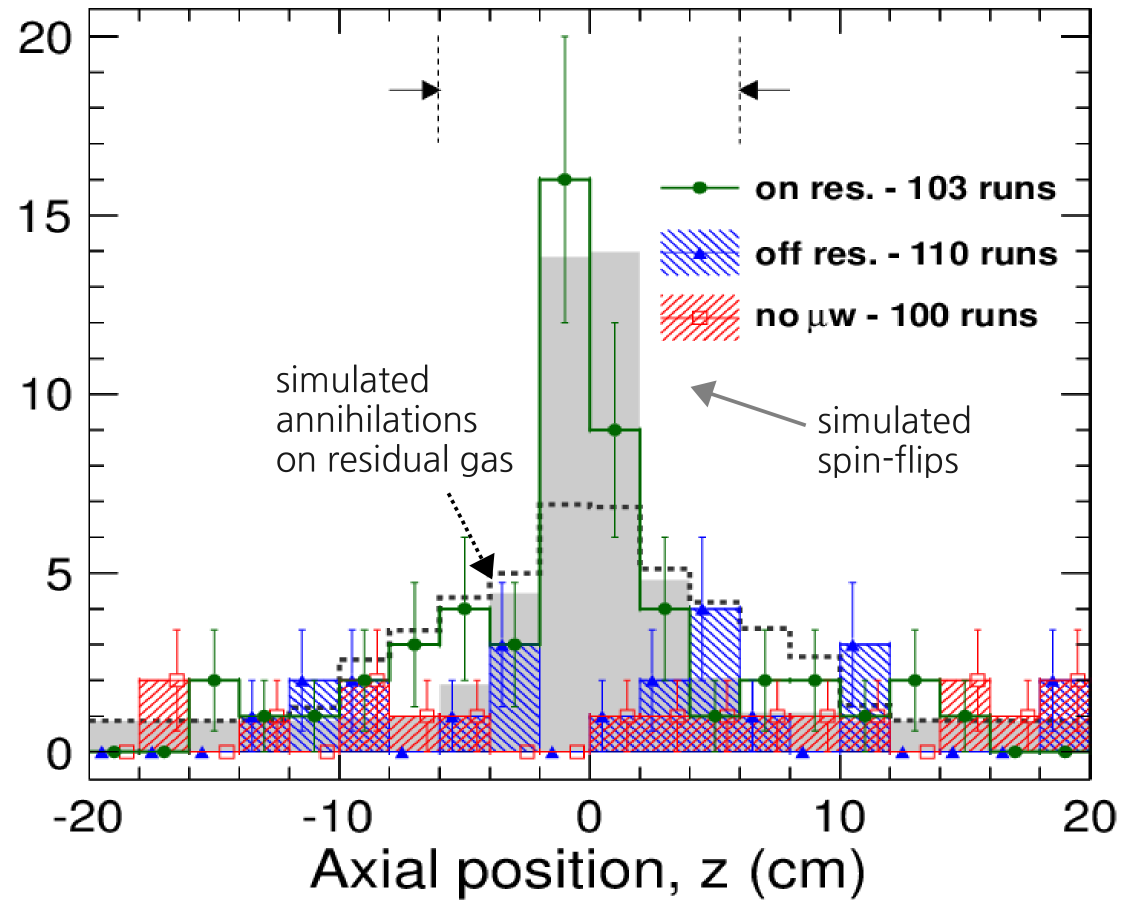


- 3.0σ excess on- vs. off-resonance
  - Agrees with count of surviving $\bar{H}$ at trap quench: 2 on-res, 23 off-res, 40 no-μw
- $|\nu_{HF}(\bar{H}) - \nu_{HF}(H)| < 100$ MHz
  - Consistent with transitions among ground state HF levels

Results

[ALPHA Coll., Nature 483, 439 (2012)]

- Positron Spin Resonance!
  - *On/off* z-distributions disfavor annihilations on desorbed gas
- Caveat: detector effects are *not* considered
  - MC model not reliable (material budget, energy loss model and secondaries)
  - Not a severe issue when just looking for an excess
  - *Mostly* relevant for analysis of properties (e.g.: width, mean) of broad z-distributions, as in quench data

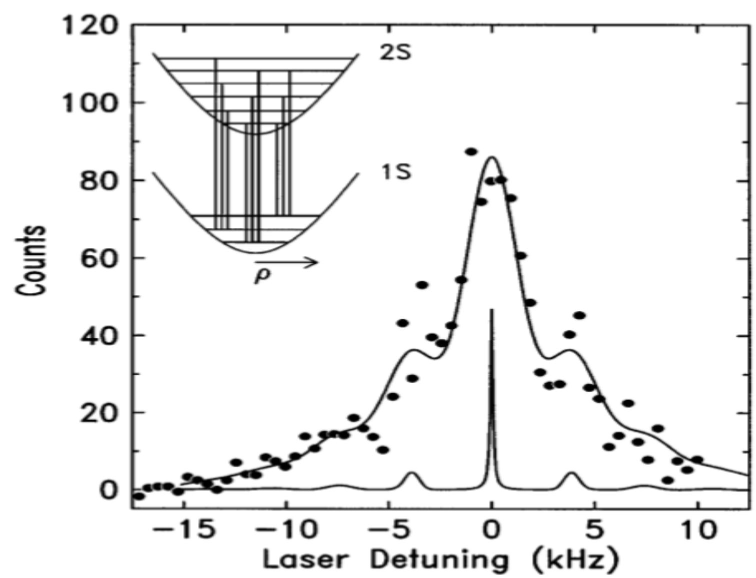


Applications

- Tested a mechanism for releasing $\bar{H}$ w/o lowering / quenching the magnetic trap
  - Could allow for a more efficient use of beam-time and increased stability
  - Results in localized annihilation z-distributions close to trap (and detector) center: more robust against detector effects w.r.t. trap-quench data
- Implications for $\bar{H}$ detection in laser spectroscopy

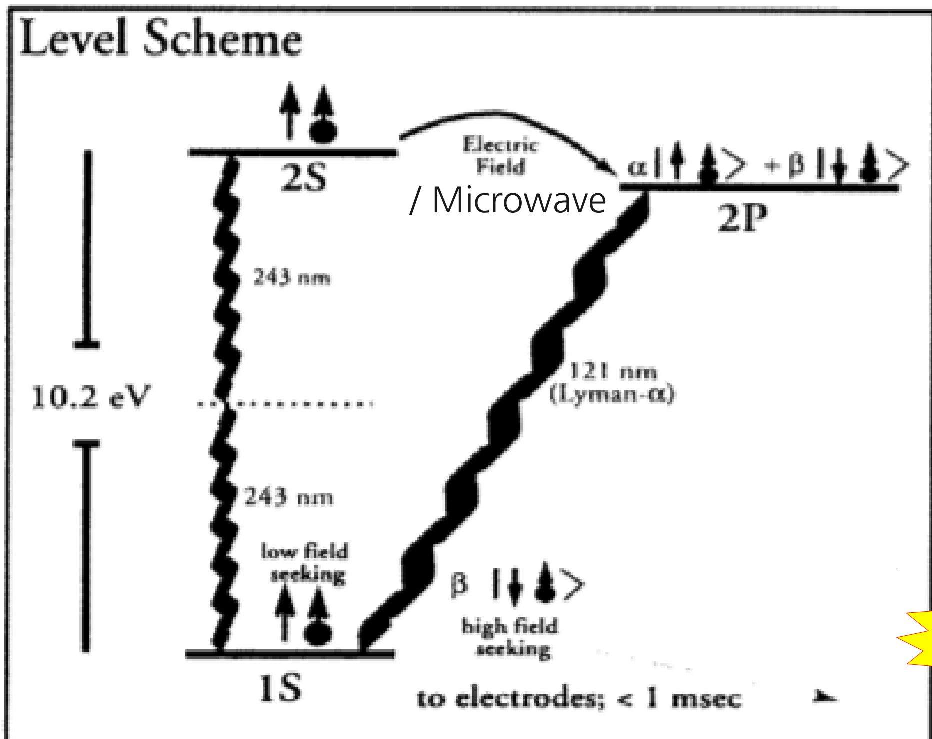
Measurement of ν(1S-2S)

- $\nu_{1S\text{-}2S}$(H) precision in magnetic trap: 10^{-12}
- Several possible signatures, but Ly-α detection challenging
  - Very few events
  - Very small solid angle



[C.L.Cesar et al., PRL 77, 255 (1996)]

[M.H. Holzscheiter et al., Rep.Prog.Phys. 62, 1 (1999)]

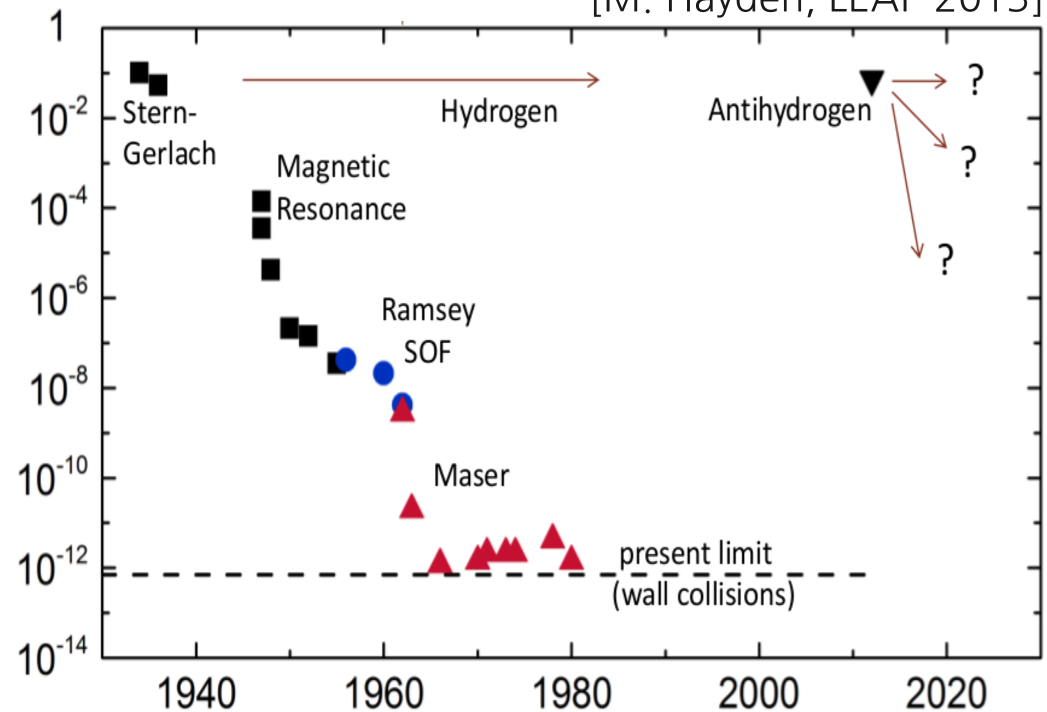


- ~~Ly-α (Stark quenching of 2S)~~
- ~~Ly-α ("closed cycle": μ-wave quenching to trapped state)~~
- $\bar{p}$ count ($\bar{p}$ retrapping after 2S photoionization)
- Annihilation (Stark quenching)
- NEW Annihilation (μ-wave quenching to high-field-seeking state)

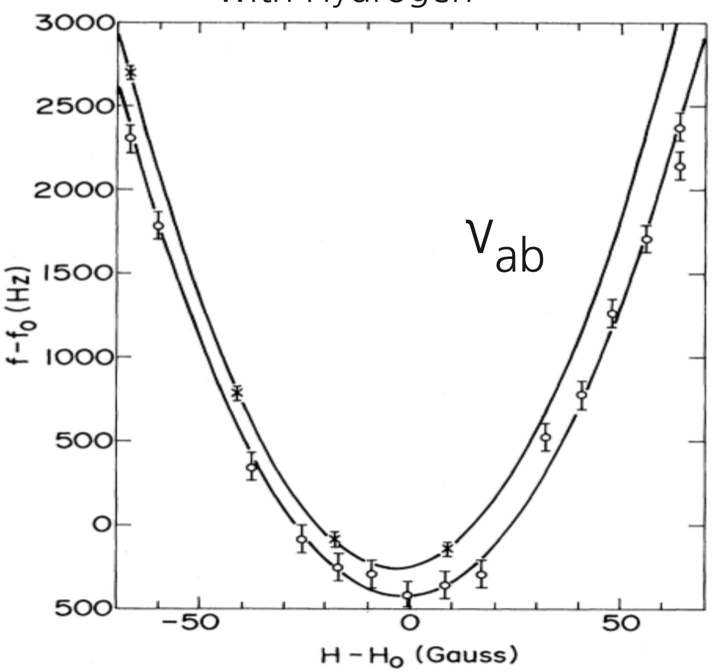
Outlook on HFS measurement

- NMR frequencies show broad $\min(\nu_{ab})/\max(\nu_{cd})$ at 0.65 T
  - suitable for magnetic trapped $\overline{\mathrm{H}}$
  - at 0.5K broadening limits precision on ν_{cd} to $\sim 2\times10^{-6}$
- R&D for NMR resonator in progress at UBC/TRIUMF + SFU

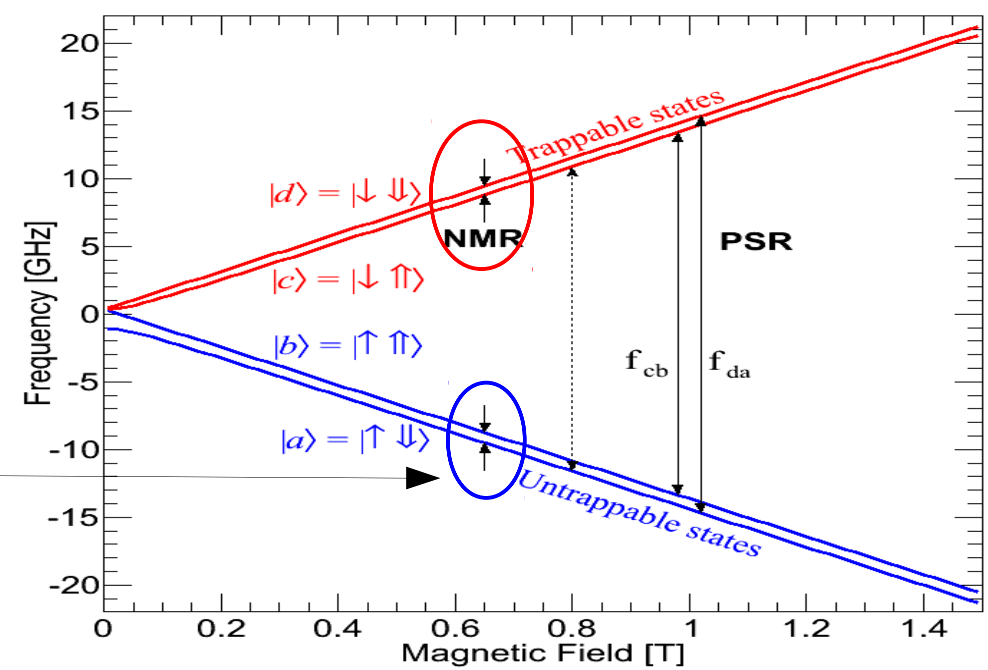
[M. Hayden, LEAP 2013]



with Hydrogen:



[W. Hardy et al., PRL 42, 1042 (1979)]



Summary

- Proof of principle experiment: controlled resonant interaction with $\overline{H}$
- Demonstrated viability of working with small numbers of trapped anti-atoms
- Procedures for forthcoming laser and microwave spectroscopy taking shape

Thank you!