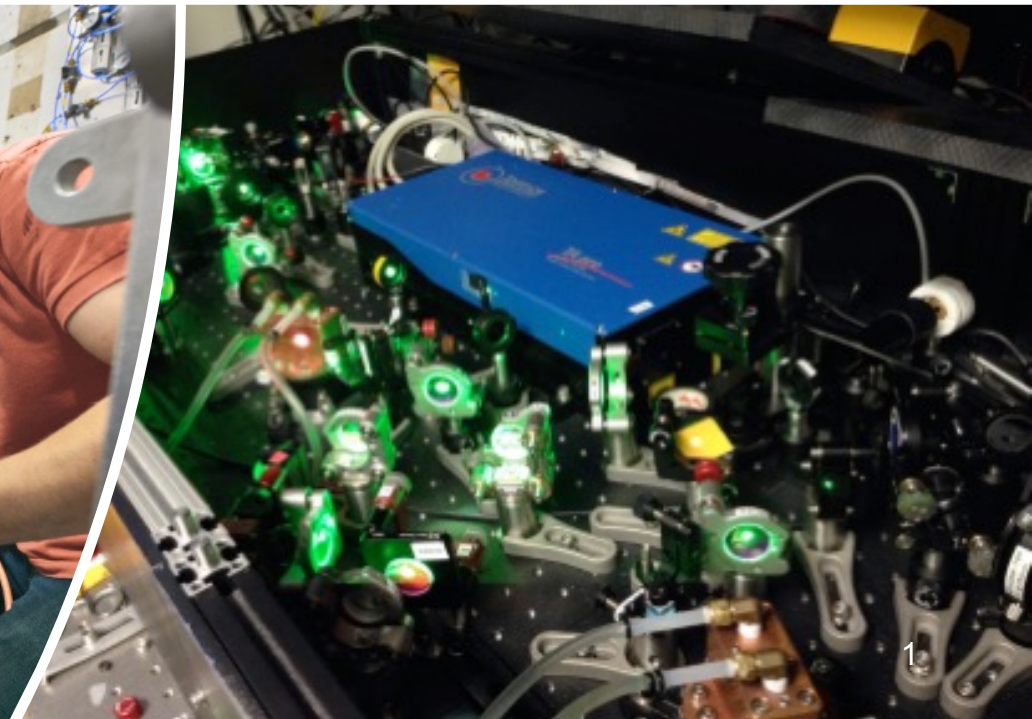
ALPHA/HAICU
TRIUMF FYP 2025-30

Particle Physics Dept Meeting

March, 2022

Makoto Fujiwara for ALPHA-Canada



ALPHA goal

To test fundamental symmetries
between H and anti-H atoms
at the highest precision possible

- Test of CPT, Quantum Field Theory
- Equivalence Principle

NB: QED tested only to 10^{-10} level

15 Years of Canadian Activities in ALPHA

FYP 2005 -2010

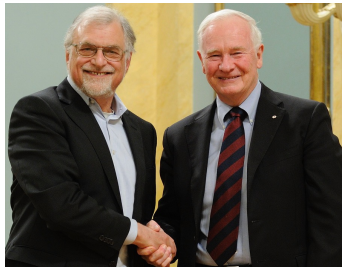
FYP 2010 - 2015

2005 ALPHA, ALPHA-Canada started

2006 First beam in ALPHA

2010 Stable anti-H trapping — Nature

2011 1000 sec trapping — Nature Phys.



2013 NSERC Polanyi Award

2012 microwave Spectroscopy — Nature

2013 Gravity test — Nature Comm.

2014 10^{-8} charge neutrality — Nature Comm.

2016 10^{-9} charge neutrality — Nature

2017 10^{-10} laser spectroscopy — Nature

2017 Hyperfine split. Δf=500 kH — Nature

2018 10^{-12} laser spectr. — Nature

2018 Lyman-alpha transitio — Nature

2020 Lamb shift & fine structu — Nature

2020 Hyperfine split. Δf =13 kH — Submitted

2021 Laser cooling — Nature

2022 Laser-cooled 1S-2S spectr. — To be submitted

Papers with Canadian principle author

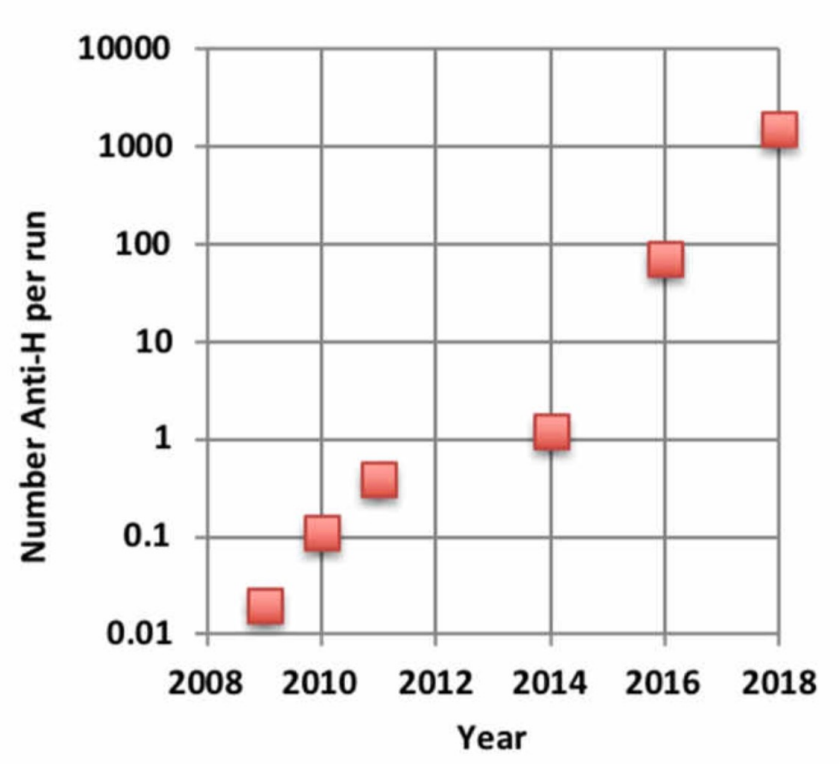
Canada > 1/3 of entire ALPHA

6 out of 11 Nature articles are Canadian-led

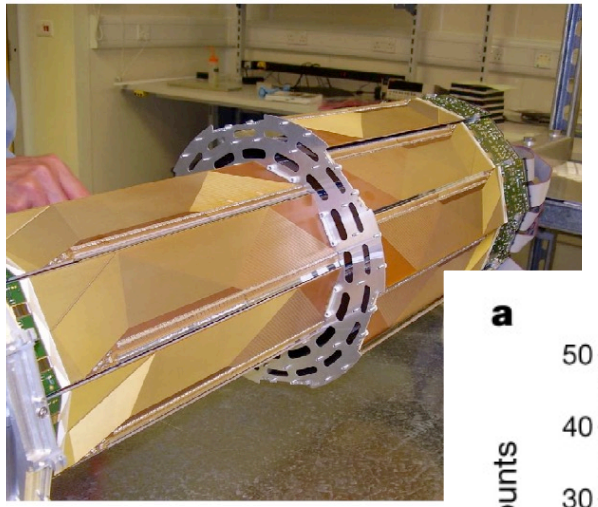
National and Int'l recognitions, e.g. NSERC Polanyi Award, APS Dawson Award

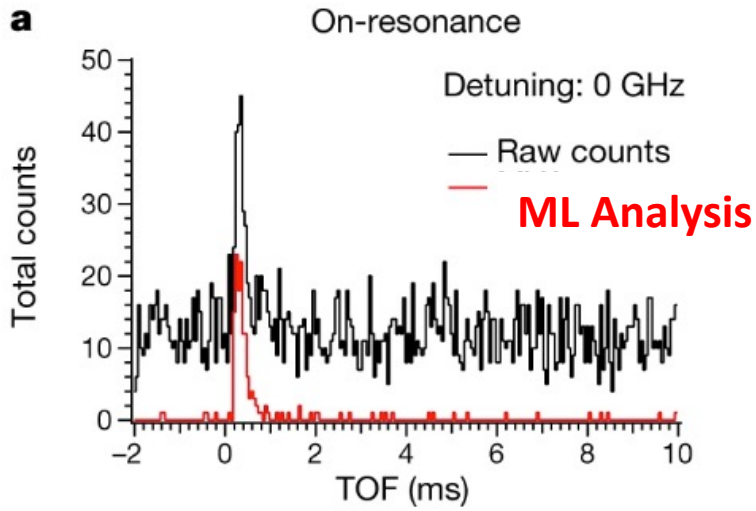
ALPHA is technologically driven experiment

- Challenge: anti-H must be synthesized!
- Improvements in trapping rates; now routinely accumulate >1000 anti-H



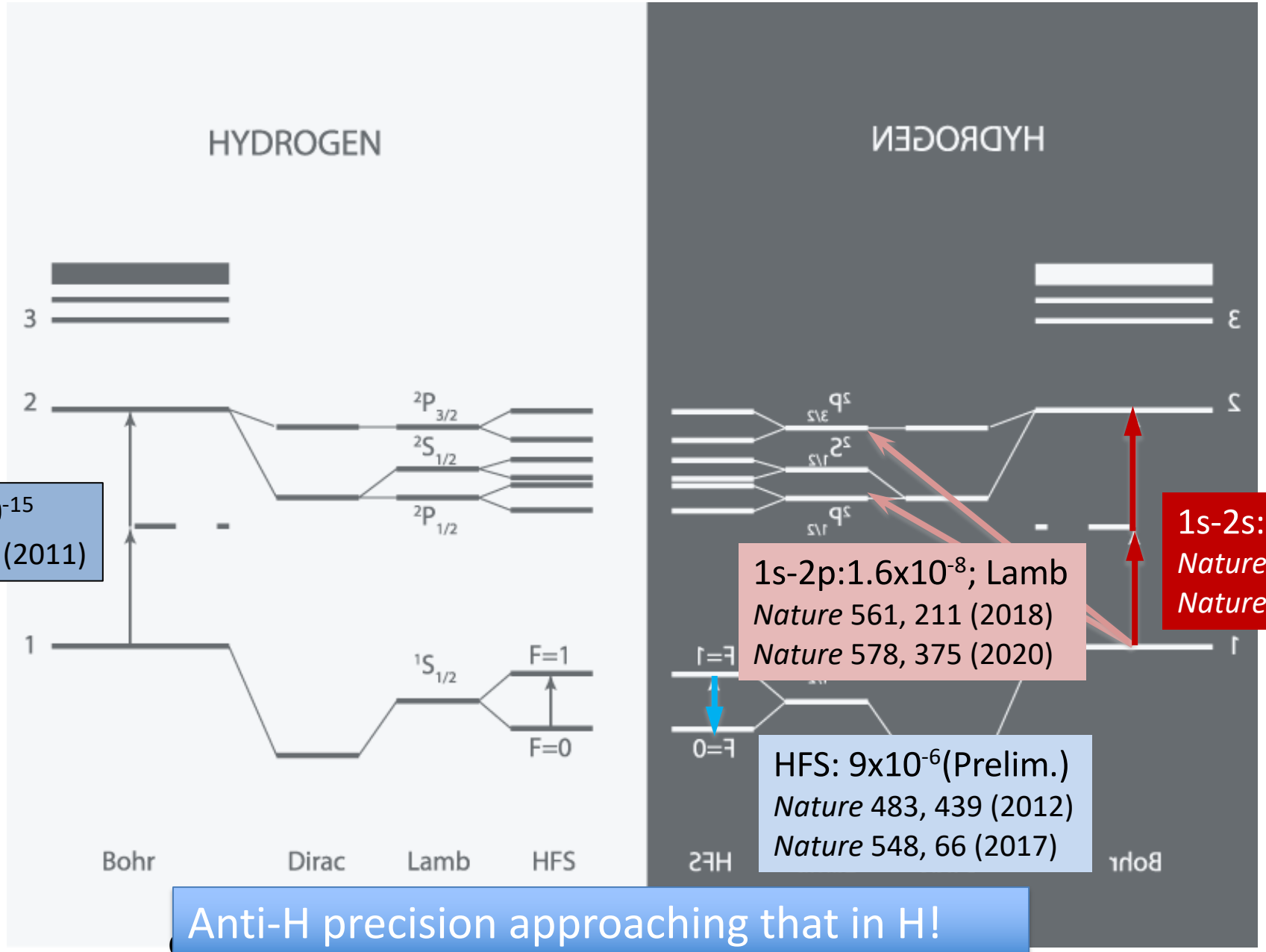
- Aggressive use of SAP techniques, e.g . Sophisticated detectors 37,000 channel Si tracker; machine-learning analysis





e.g. Nature 561, 211 (2018)

Antihydrogen Spectroscopy with ALPHA at CERN



1s-2s: 4×10^{-15}
PRL 107, 203001 (2011)

1s-2p:1.6×10^{-8}; Lamb
Nature 561, 211 (2018)
Nature 578, 375 (2020)

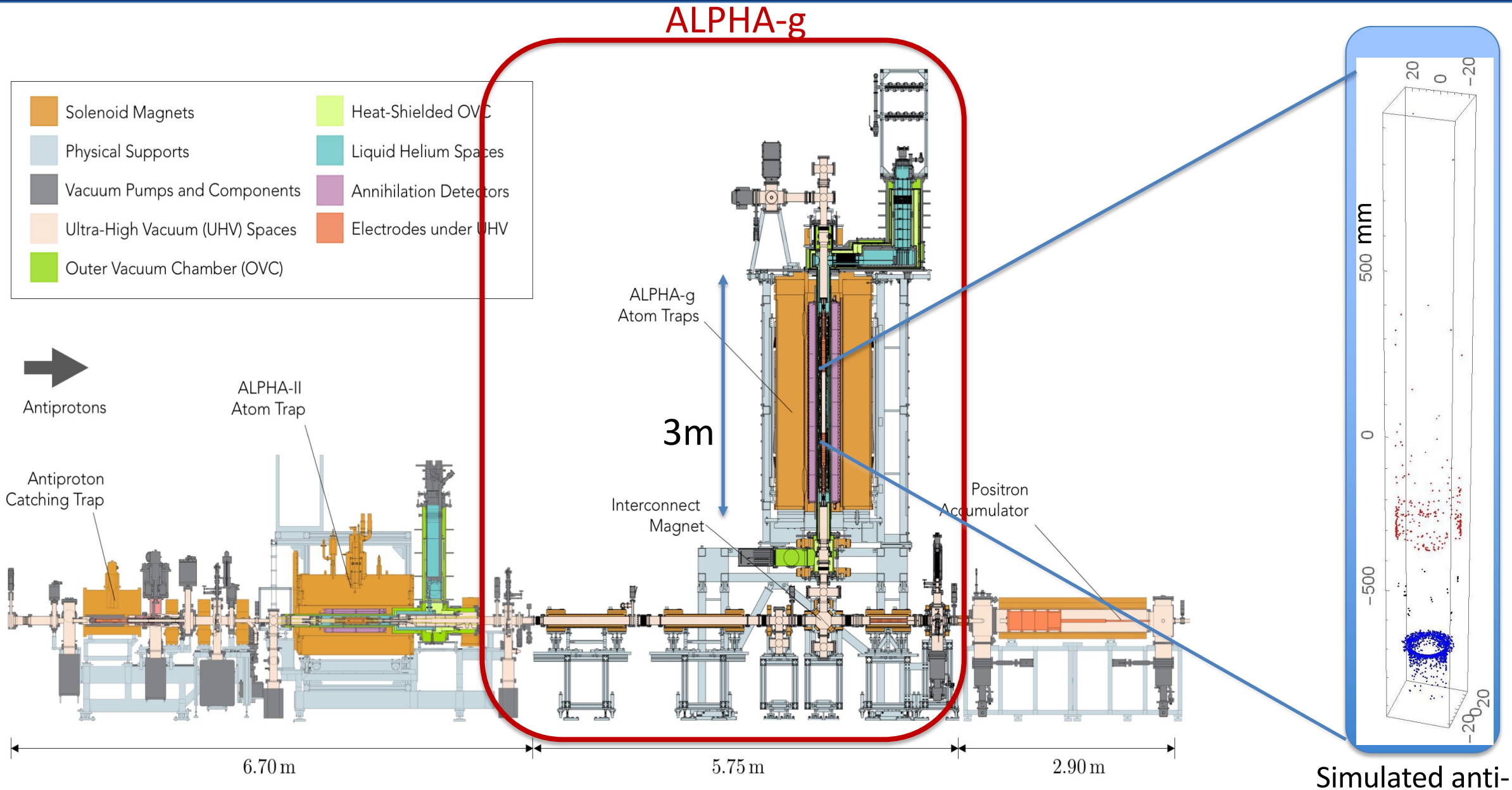
HFS: 9×10^{-6}(Prelim.)
Nature 483, 439 (2012)
Nature 548, 66 (2017)

1s-2s: 2×10^{-12}
Nature 541, 506 (2017)
Nature 557, 71 (2018)

Charge neutrality
Nature 539, 373 (2016)
Gravity (ongoing)

Anti-H precision approaching that in H!

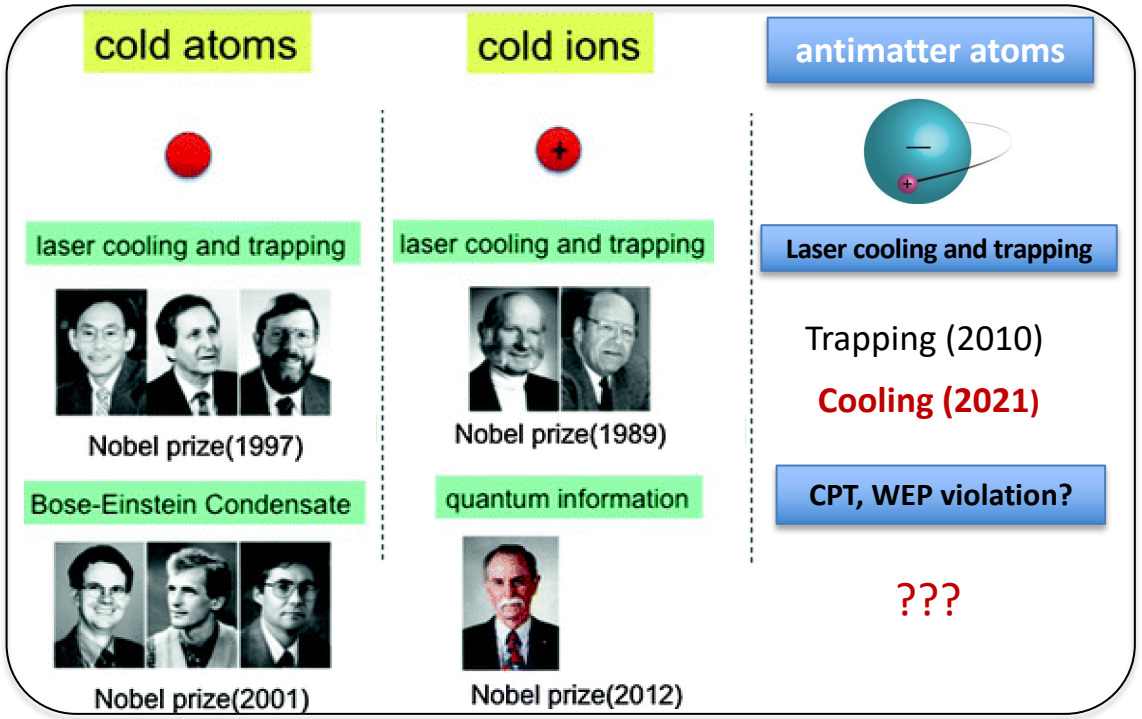
ALPHA-g: measuring gravity on anti-H (80% Canadian Funded)



Simulated anti-H free fall

Laser cooling of antihydrogen: a major breakthrough! (Canadian-led)

Laser cooling of atoms, ions revolutionized atomic physics in last 40 years



April 1st, 2021 Issue Cover

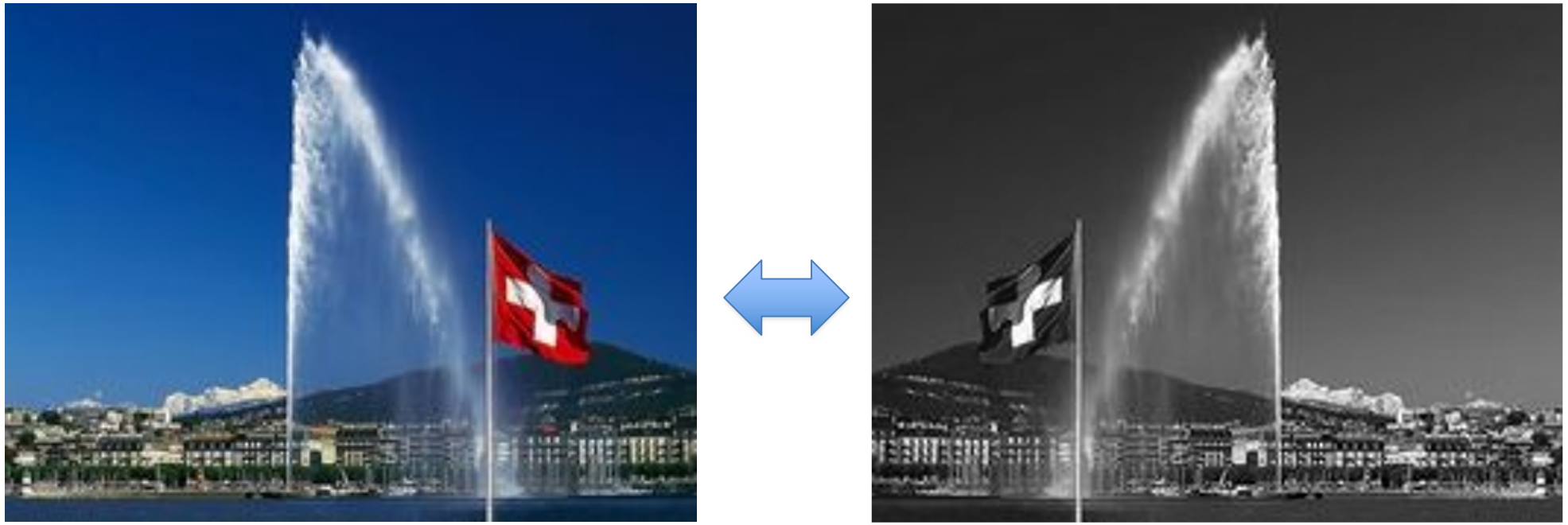
Taka Momose
UBC/TRIUMF

A game changer! Culmination of Canadian-led efforts in the past decade!

Vision

- Subatomic-style approach to tackle traditionally small-scale experiments
  - See e.g. recent cosmology experiments
- Tackling important, but technically challenging problems which are difficult at university labs
  - Nat'l Lab like TRIUMF has competitive advantage due to its expertise, infrastructure
- Of course, you have to have good ideas!

Future goal: anti-atomic fountain

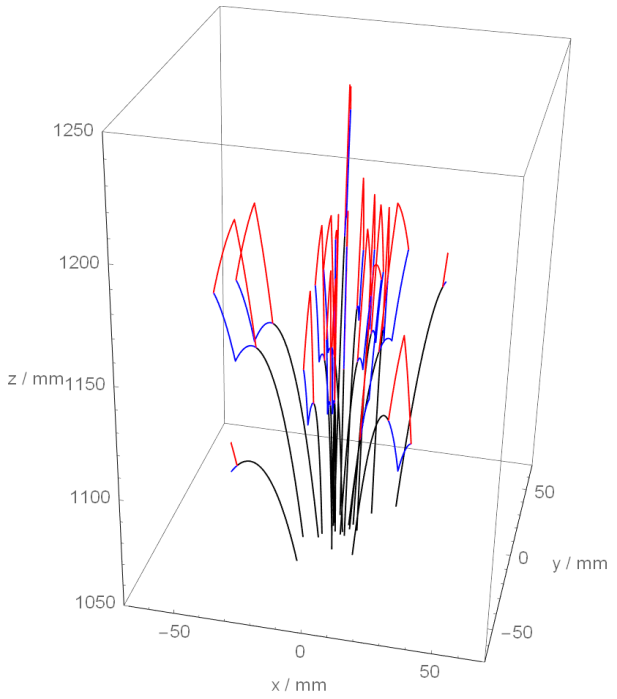


Objective: to make precision hydrogen–antihydrogen comparison
in the same apparatus
→ Need to improve both anti-H and H techniques!

HAICU: Hydrogen-Antihydrogen Infrastructure at Canadian Universities

- Pathfinding platform for development of "quantum sensing" techniques for anti-H (& H)
- Use H (and other cold atoms) as proxy
  - (Anti)atomic fountain
  - (Anti)Matter-wave interferometer
    With H. Mueller
  - Ramsey hyperfine spectroscopy
  - Optical trapping
  - Anti-molecular quantum logic clock
- Hydrogen difficult to handle
  - Difficult to trap
  - 1s-2p transition at 121 nm
  - No fountain made with H

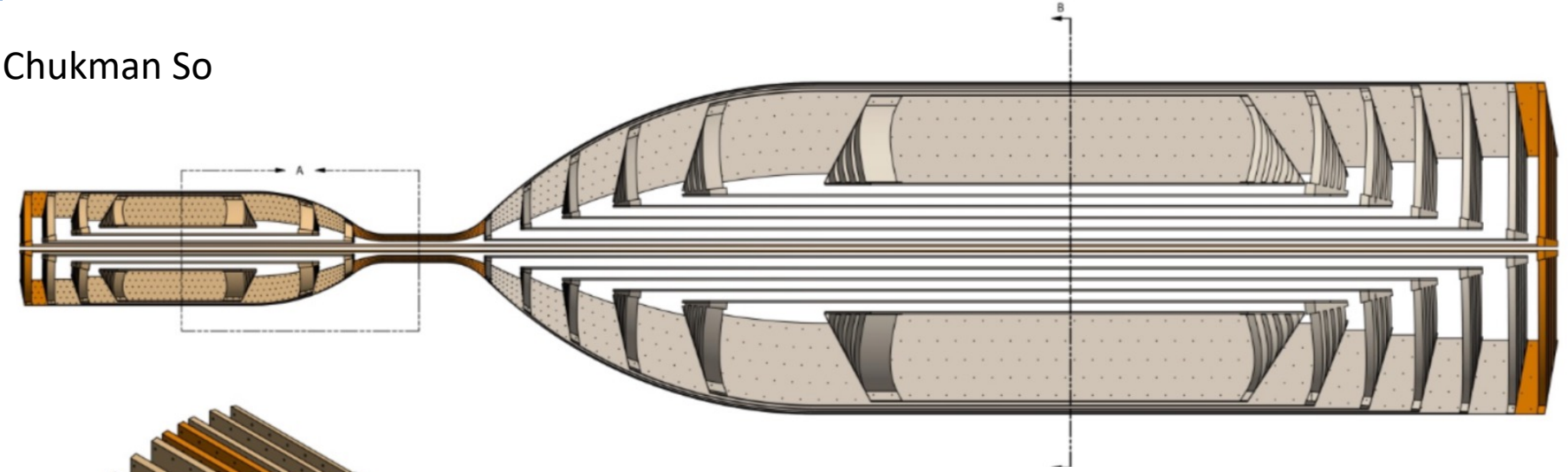
(Anti)atom Interferometer Simulation

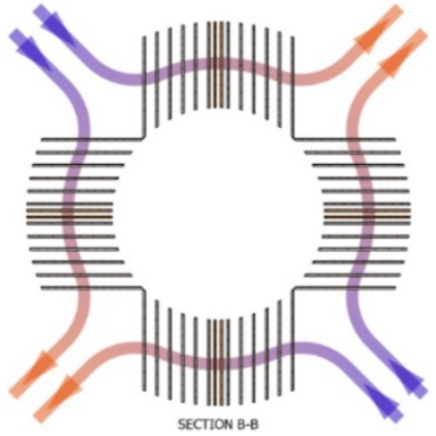


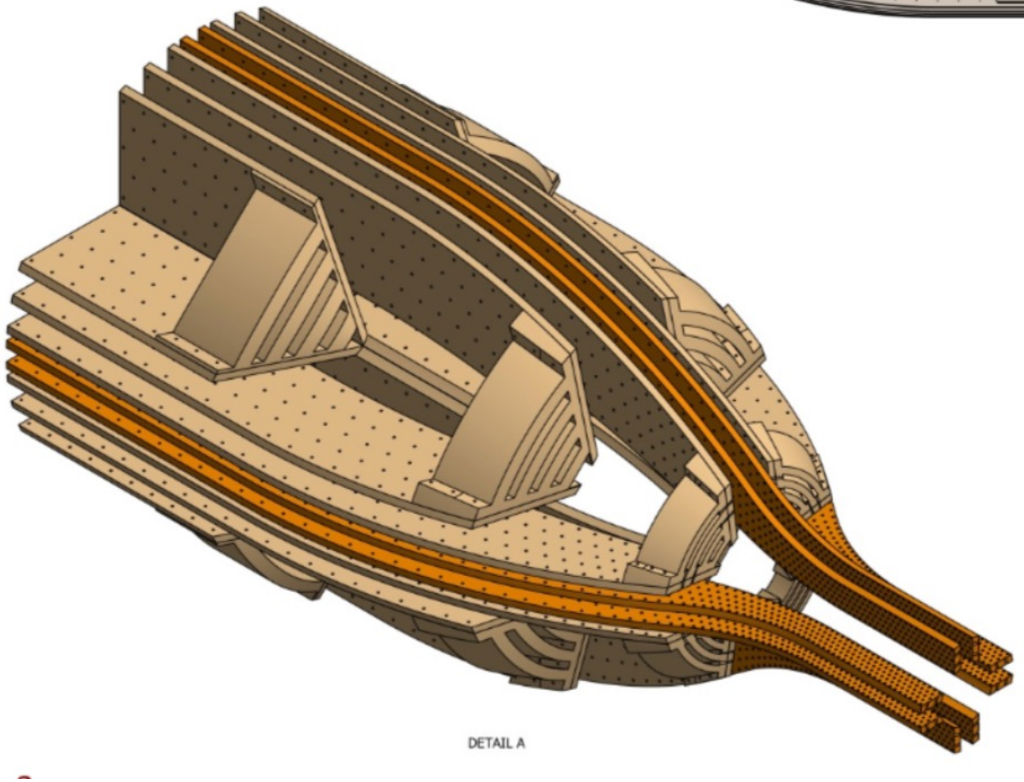
- Techniques needed for anti-H could be useful to improve H measurements

OCCAM: Optically-Cooled Compression with Advanced Magnets

Chukman So



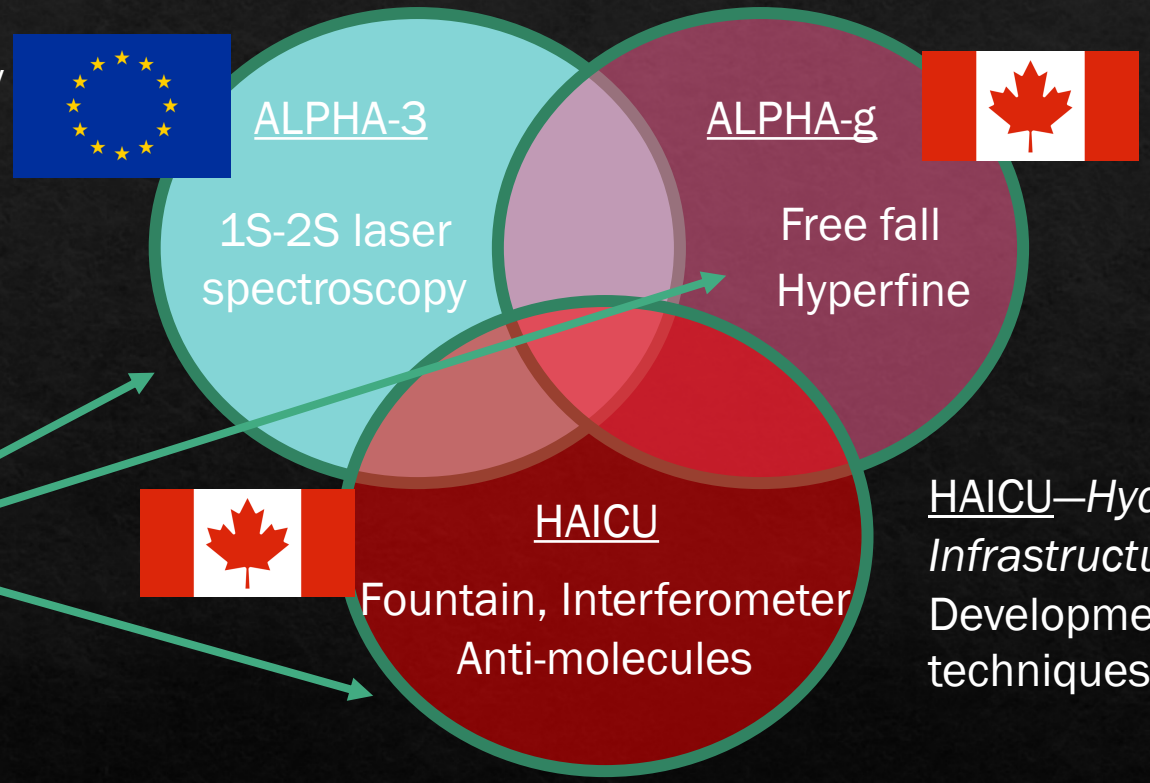




- Various magnet schemes being explored
  - "Bitter Magnet" configuration shown here
- Challenges:
  - High current densities
  - High power, high degree of cooling
  - Changing bore radius
  - Normal vs Superconducting
  - Space for coils, optical access, detectors
  - Manufacturing (alignment etc)
  - Cryogenics, vacuum

Vision (2022 – 26): Canadian perspective

ALPHA-3:
European-led laser&metrology upgrade to ALPHA-2 spectroscopy trap [Art Olin]



ALPHA-g:
Primarily CFI-funded vertical trap for gravity and microwave measurements

Unique technical contributions
Laser cooling
Detectors
MC/ML analysis
Microwaves
Magnetometry
Supercond. traps

HAICU—*Hydrogen-Antihydrogen Infrastructure at Canadian Universities*:
Development platform for "quantum sensing" techniques using H as proxy for anti-H

Flags represent leadership roles

ALPHA-Canada will focus on extracting the science out of ALPHA-g (gravity & hyperfine) at CERN, while developing new techniques for the next phases with HAICU in Canada. Meanwhile, we will make crucial technical contributions in the areas of unique Canadian expertise, such as laser cooling, detectors, and magnetometry.

Personnel

Rob Thompson: now associate VPR, U Calgary

Dave Gill (TRIUMF): retired ~17 ys ago

Scott Menary (York): >60 yrs old

Walter Hardy (UBC):
retired ~18 ys ago;
stopped research
(Order of Canada)

Art Olin (TRIUMF): retired 7 ys ago

Mike Hayden (SFU):
Will retire in Sep 2022

Feb, 2014

- Taka Momose: joined 2012
- Tim Friesen (Calgary): hired 2018
- New BAE at TRIUMF

Despite new or planned hires, challenge remains for succession!

Resources & Infrastructure

- Technical support
  - Cryogenic, Mechanical, Electrical (high power magnets), Ultra-high vacuum
  - Laser, Microwaves, RF
  - DAQ, Detector experts
- Space, space, space!
  - Coordination with UCN & other projects
- Synergies
  - UCN: magnetometry, B shielding, traps, He liquefier etc.
  - Single VUV photon detection (121 nm, 102 nm…)
  - Cryogenic ion/charge detection (MCP@4K or superconducting sensors?)
  - AMO@ISAC (TRINAT, Radioactive molecules…)
  - Optical clocks & Metrology development at NRC Ottawa & U Toronto
  - Software/Analysis; tracking, machine learning
  - Exotic atoms studies, e.g. muonium interferometer, or neutrino studies with trapped tritium (Project 8)

Back up

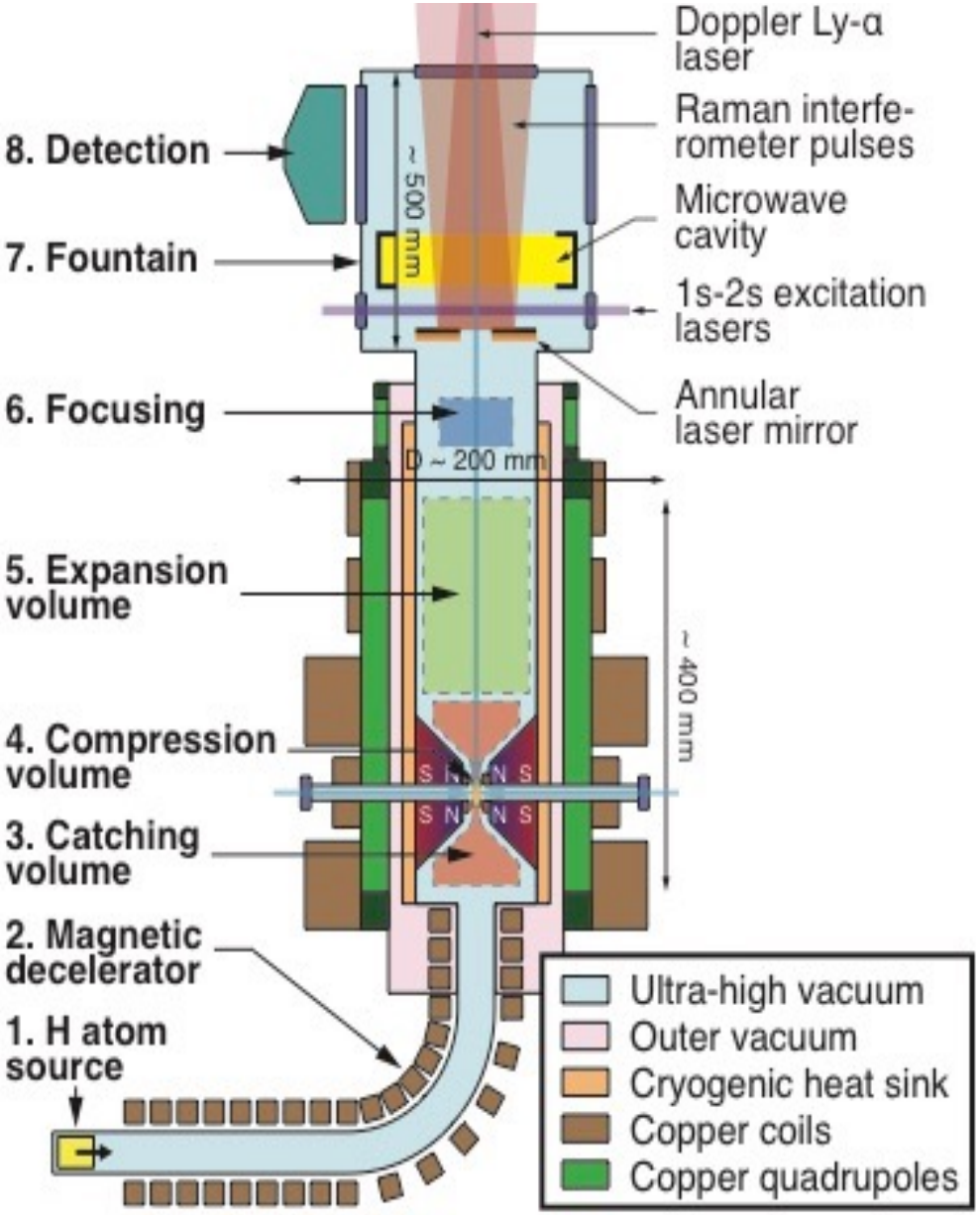
HAICU concept

Novel Concepts [paper in preparation]

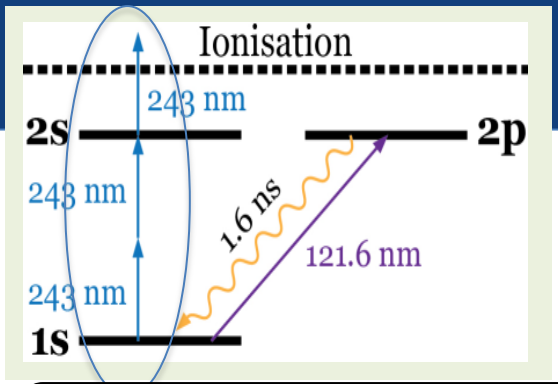
- **Deep Magnetic Compression** of atomic clouds in a small, high density quadrupole trap (~few mm radius)
  - Dynamically transferred from Octupole; now feasible due to laser cooling
  - Magnets are challenging!
- **Laser cooling** → high phase space density (~100 um radius, 2 mm length)
  - Allow densities 10^6 – 10^8 cm^{-3} (currently ~ 1 cm^{-3} in ALPHA)
  - This is a basis for antihydrogen molecular clock development [Myers PRA2018; Zammit et al PRA2019]
- **Expansion cooling**

  → Can create a (anti)H gas in micro-Kelvin regime!
  - Precision spectroscopy
- **Launch into free space** as fountain for informetric and other interrogations (~100 nK regime)

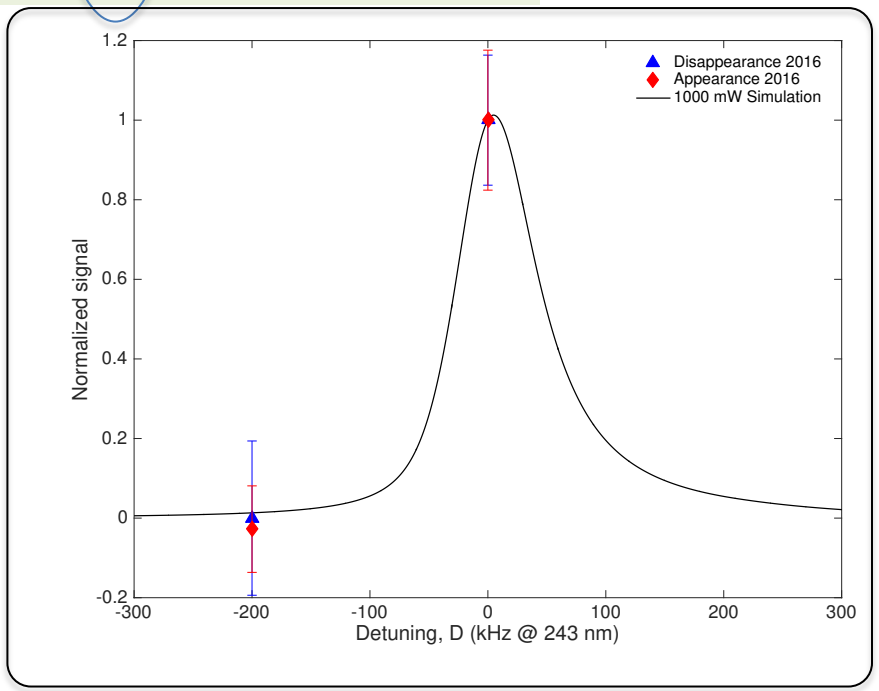
Up to 10^6 – 10^8 colder and/or denser anti-H cloud!



(1) 1S-2S Spectroscopy (Strong Canadian Contributions)

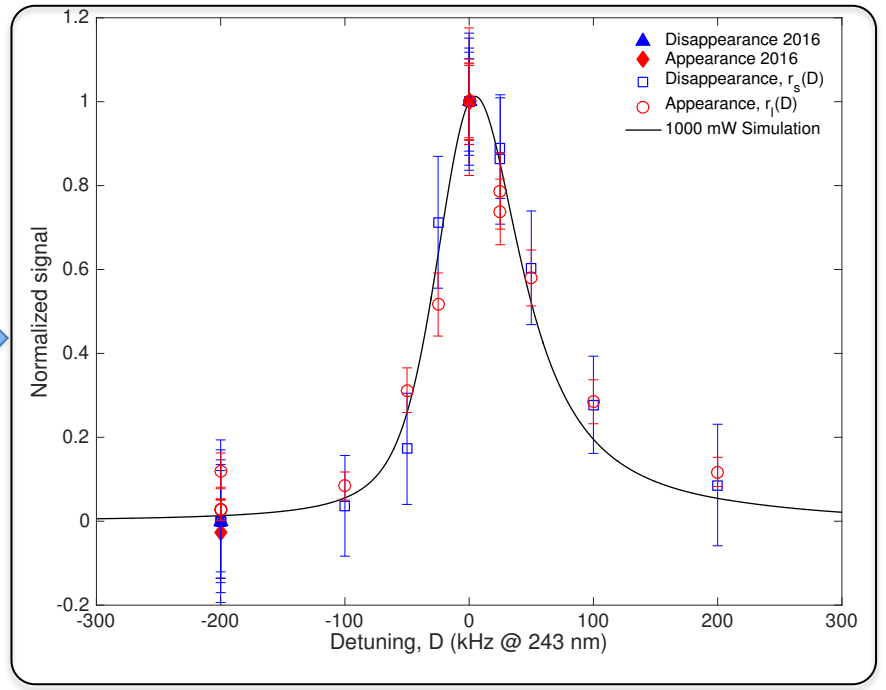


1S-2S transition: "golden mode", known to 4×10^{-15} in hydrogen



Nature 541, 596 (2017)

$\Delta f/f = 2 \times 10^{-10}$



Nature 557, 71 (2018) [Olin]

x 100 improvement! $\Delta f/f = 2 \times 10^{-12}$

Next few years

Laser cooled sample

10^{-13} precision

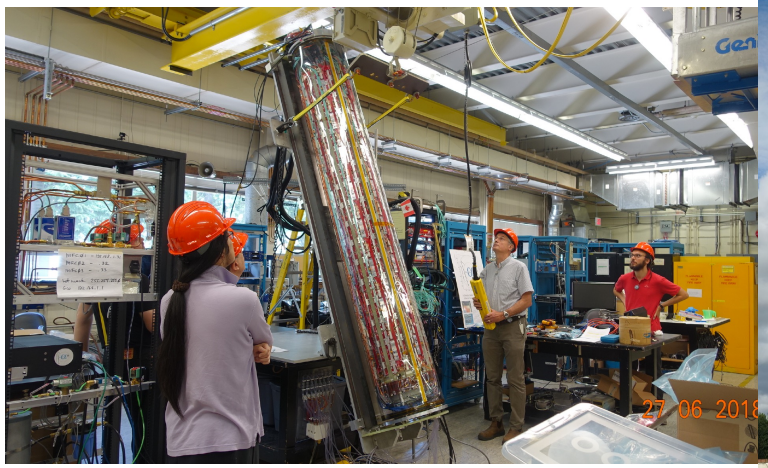
X10 improv.

f(1s-2s) = 2 466 061 103 079.4 (5.4) kHz

Most precise antimatter measurement to date

Within a factor of 500 wrt hydrogen

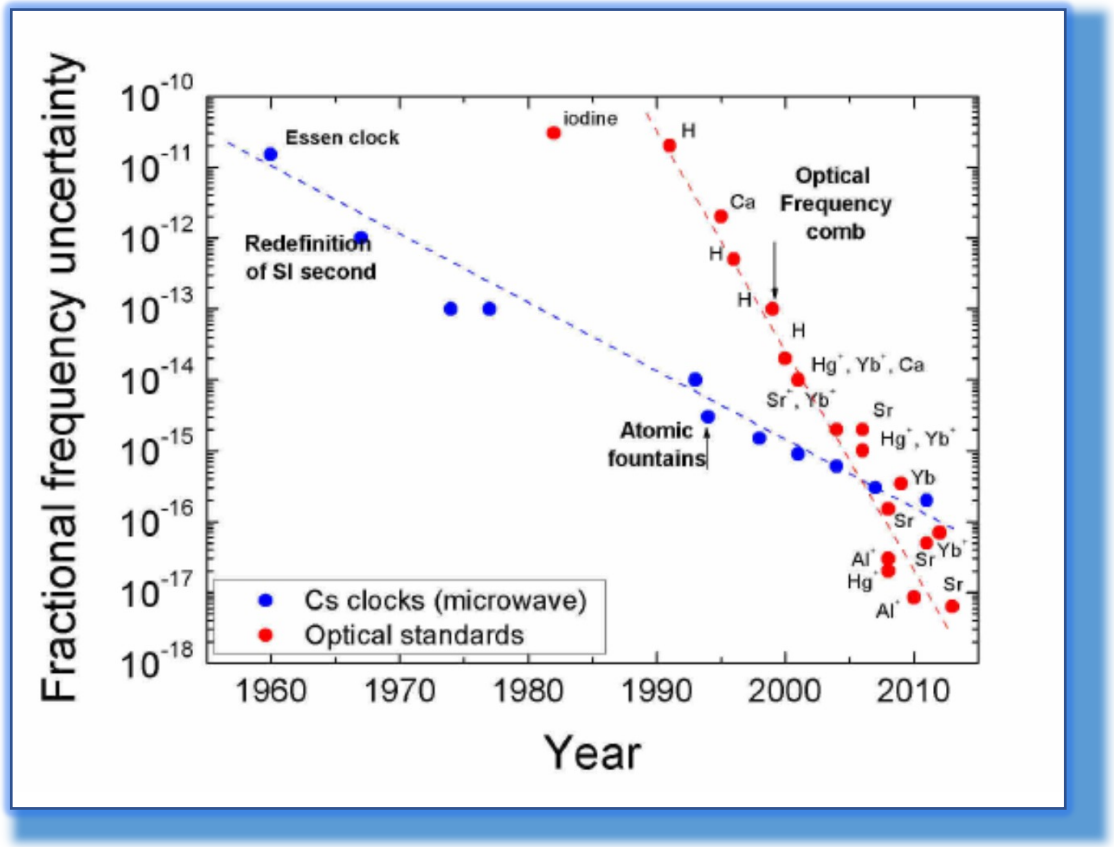
Radial-drift TPC built at TRIUMF



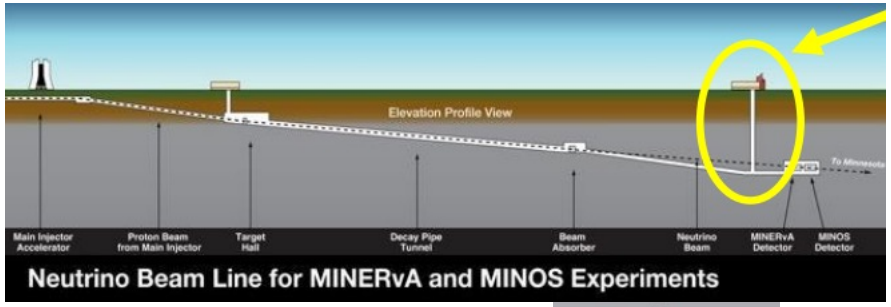
CERN

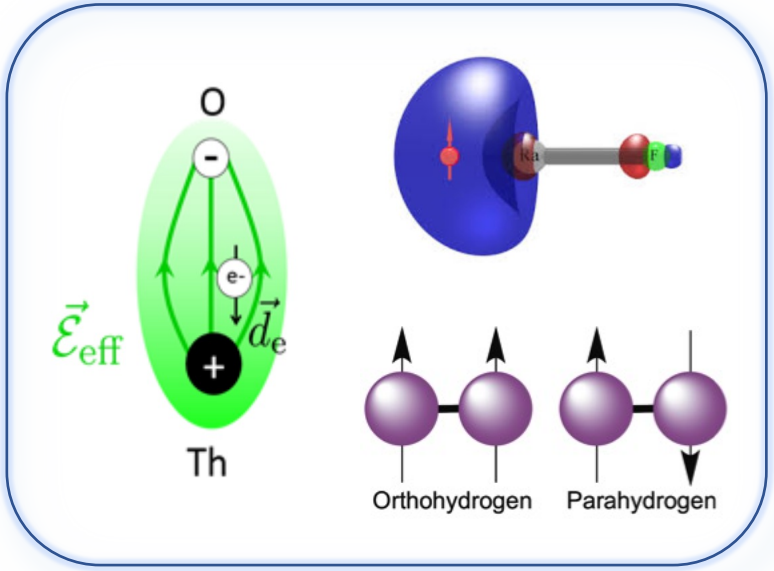
Mid-Term Future: "Quantum Sensing" with Antimatter

- Exploding interest world-wide in anything "Quantum"
- Tangible prospects: e.g. clocks, molecules, atomic fountain
- Applying these to antimatter

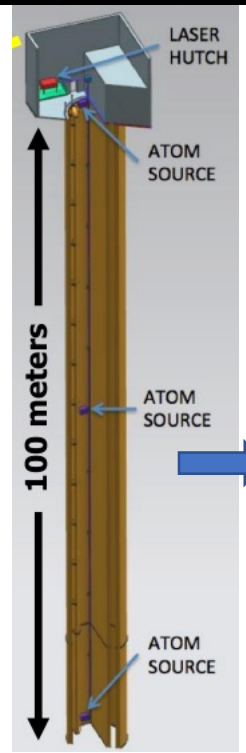


Atomic clocks: DM, QED, Lorentz, GR test…





Molecules: EDM, DM…



MAGIS @FNAL

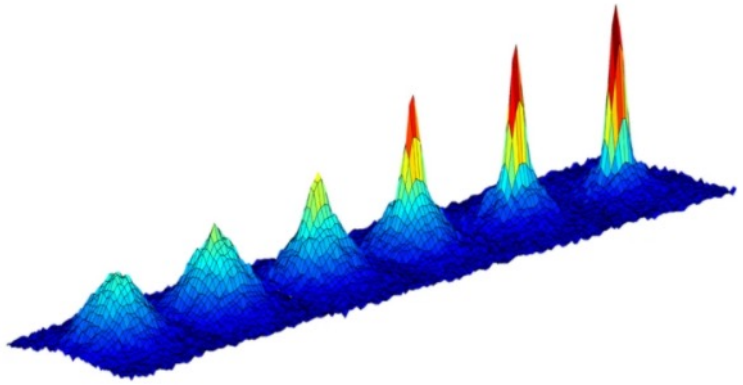
AION @Oxford

~1 km long at SURF?

Fountain: GW detection, DM, DE…

Personal Crazy Dream

Bose-Einstein condensates on Int'l Space Station
Nature June 11, 2020



Antimatter experiments in space?

(micro-gravity environment)

BEC created on Earth: 1995

BEC created in space: 2020

(25 years later)

Trapped anti-H on Earth: 2010

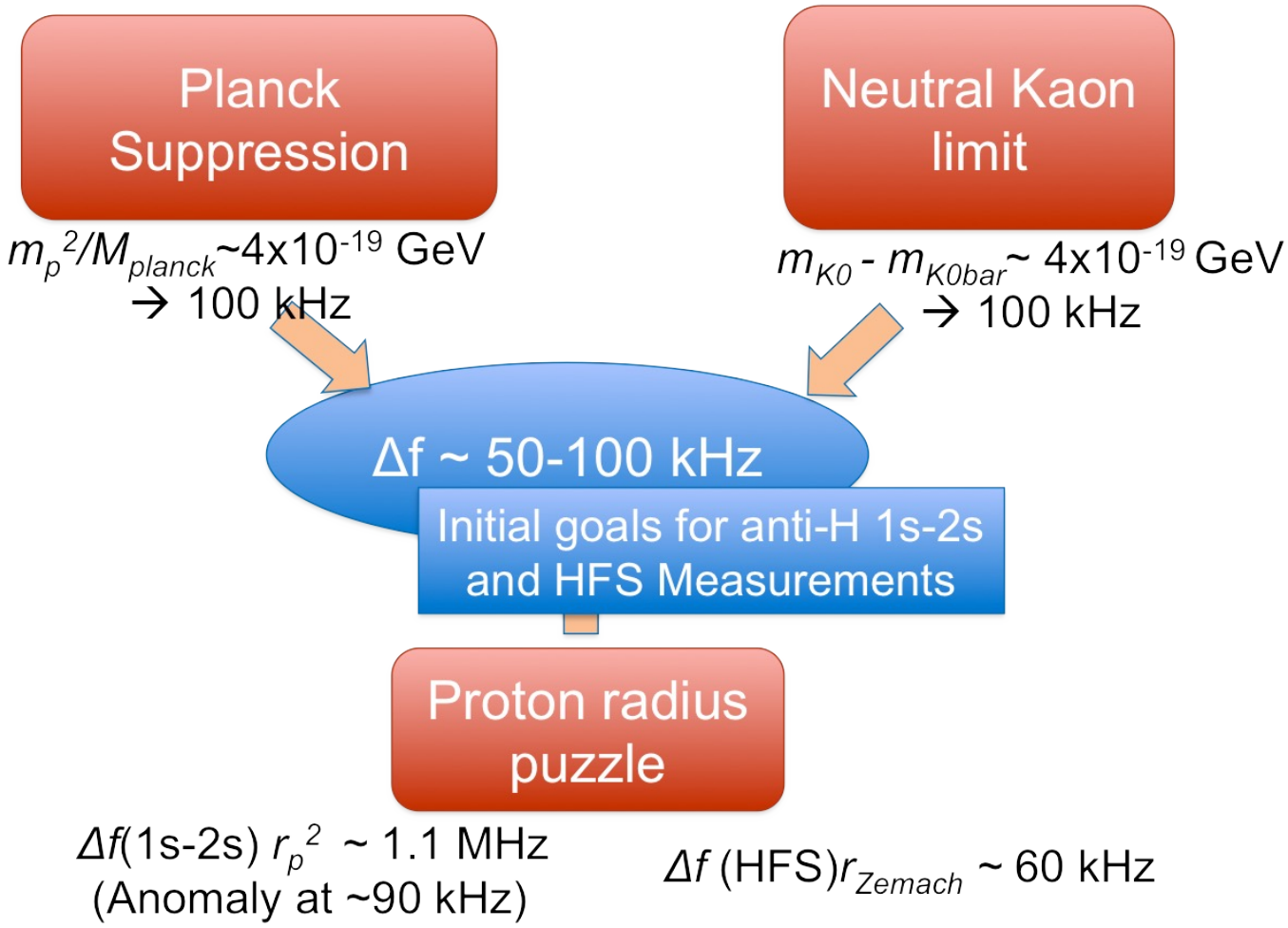
Trapped anti-H in space: 2035???

Motivation

- Most symmetries in Nature broken at some level
  - C, CP, #B, #L, EW, Chiral, GUT? SUSY?
  - Explicitly, spontaneously, or effectively (e.g. expanding Universe)
- How about CPT and Equivalence Principle?
  - Experimental question!
- At what level?

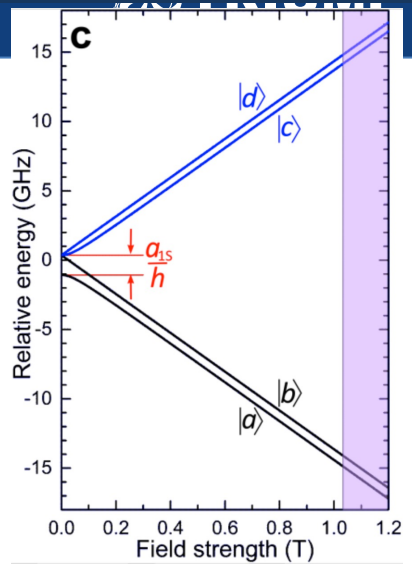
In 2017-20, we have achieved Δf ~ 5 to 13 kHz!

Possible Benchmark for CPT tests



Anti-H hyperfine level

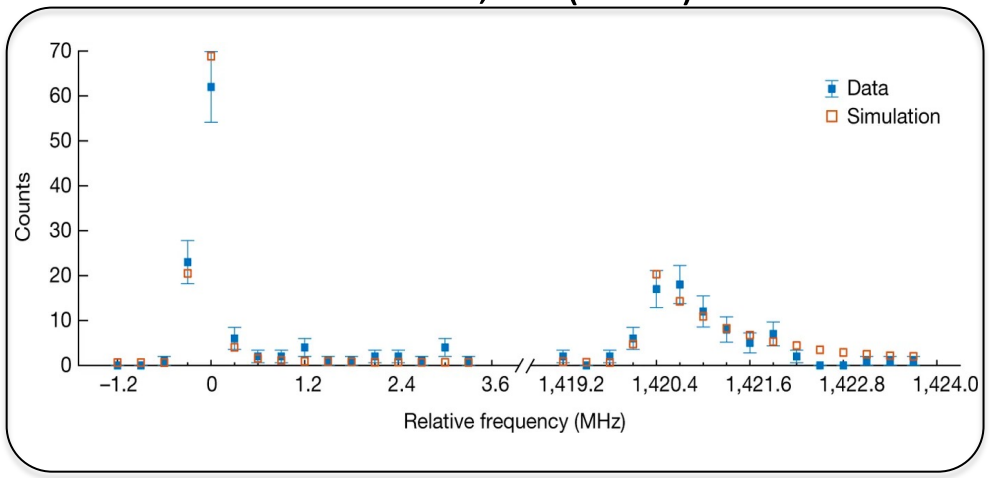
Hyperfine Spectroscopy via Microwaves (Canadian-led)



Hyperfine Splitting: a/h

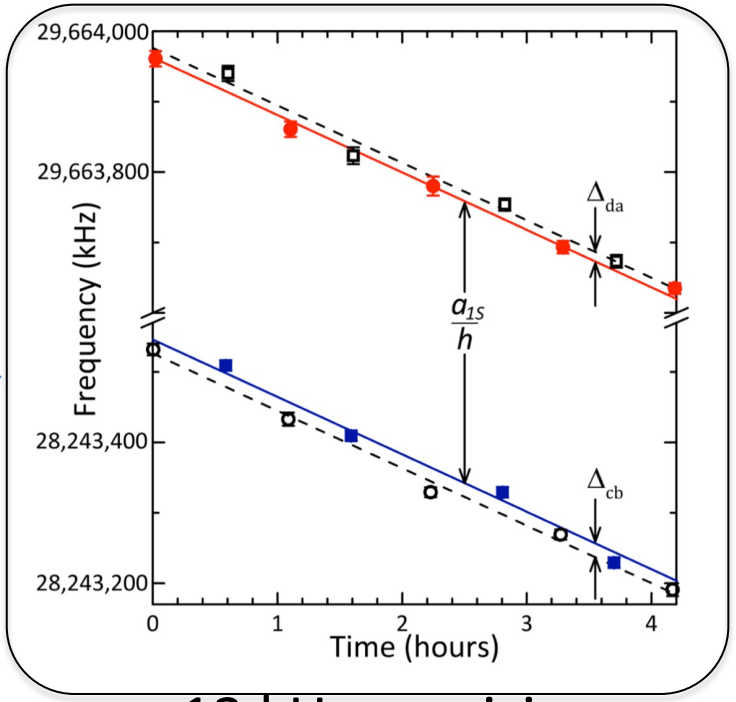
Contact interaction between e+ & anti-p spins
Sensitive to internal structure of anti-p
Complementary to laser spectroscopy

Nature 548, 66 (2017)



500kHz precision on a/h
x200 improvement over our 2012 result

Submitted to Nature



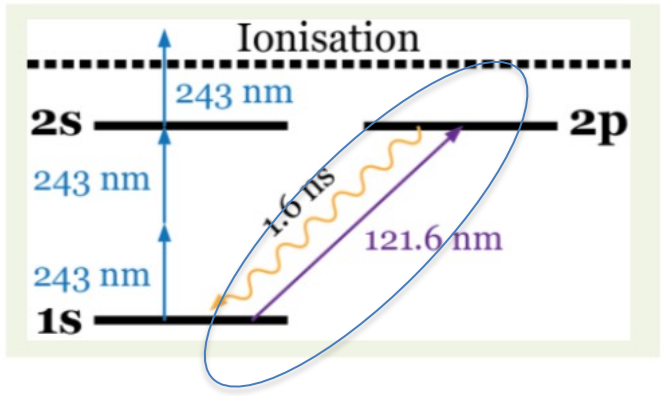
13 kHz precision
Another X40 improvement

Entirely new method

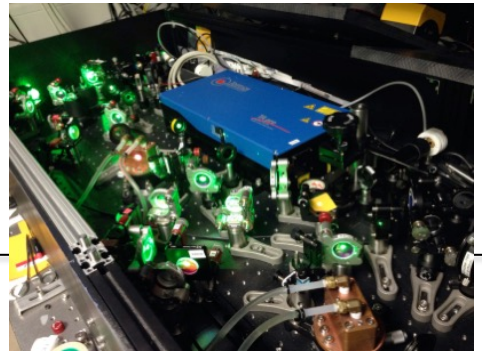
Next few years

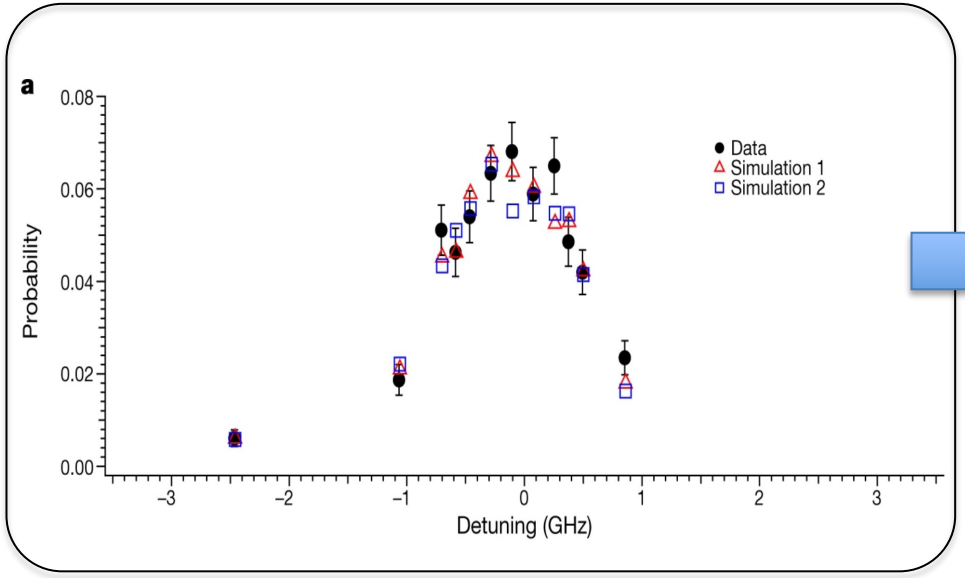
Antiproton NMR
100 Hz precision
X100 improv.

(3) 1S-2P Lyman-alpha Spectroscopy (Canadian-led)



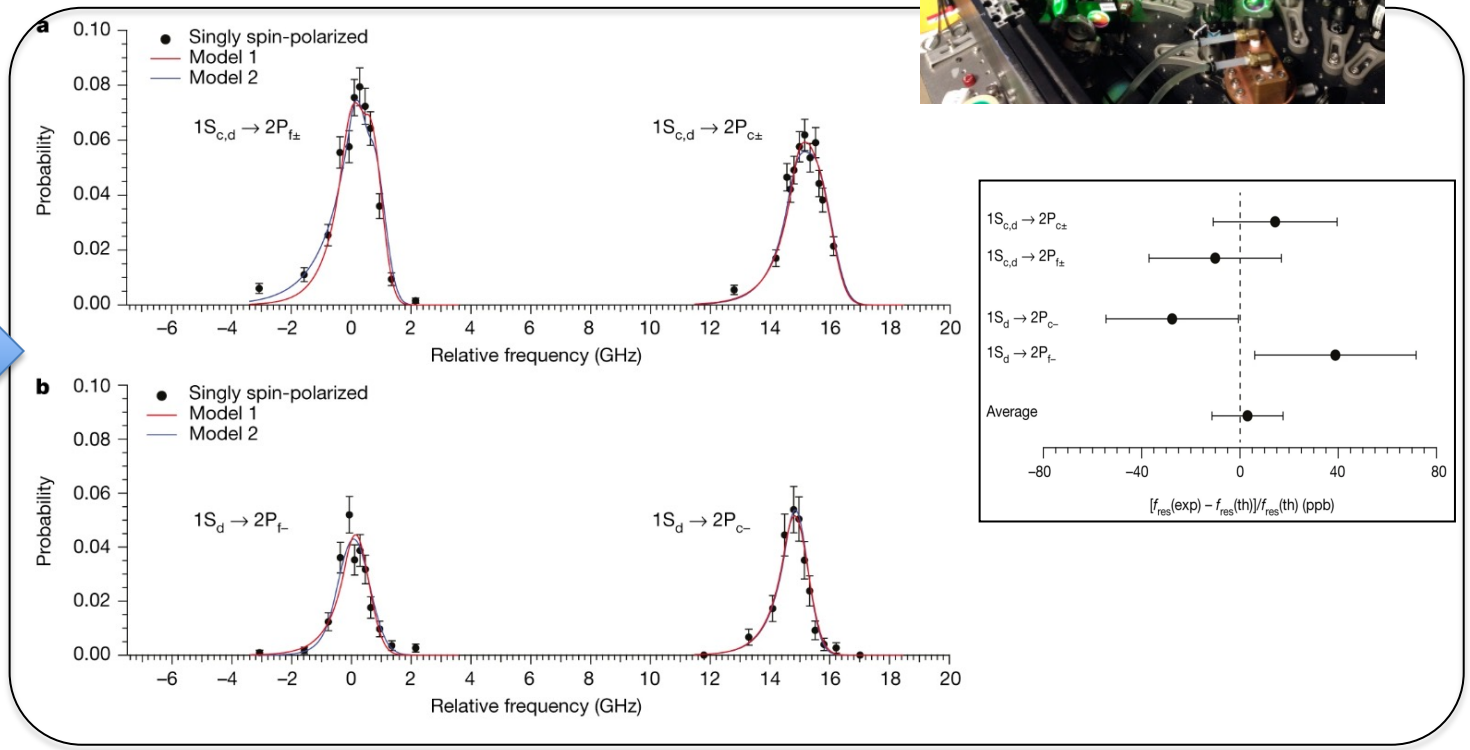
1S-2P: important atomic transition
Laser at 121 nm (VUV) challenging





First observation of 1S-2P transition

Nature 561, 211 (2018)

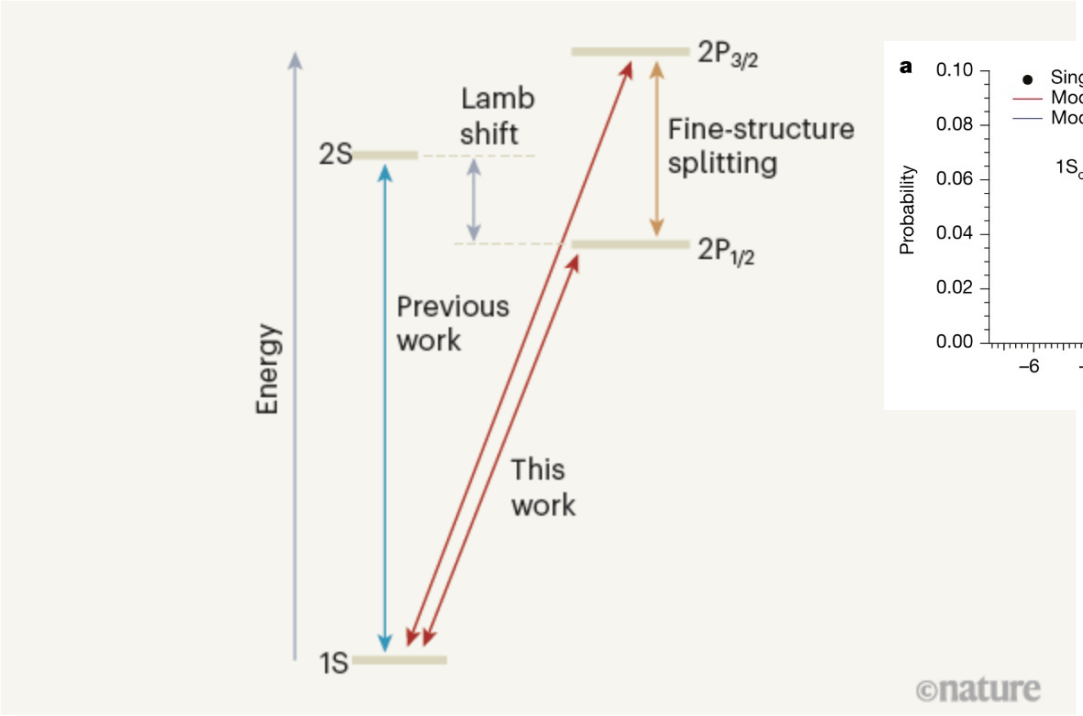


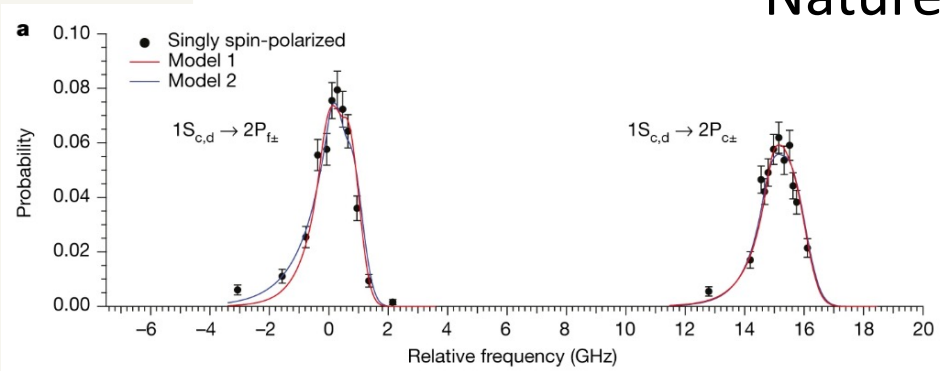
1.6×10^{-8} CPT test

Nature 578, 375 (Feb. 19, 2020)

Lamb shift in antihydrogen (Canadian-led)

Nature 578, 375, Feb. 19, 2020





- UBC built Lyman-alpha laser
- Microwave induced spin polarization
- Detection with Machine Learning analysis
- Fine structure splitting measured to 2%
- Lamb shift to 11%

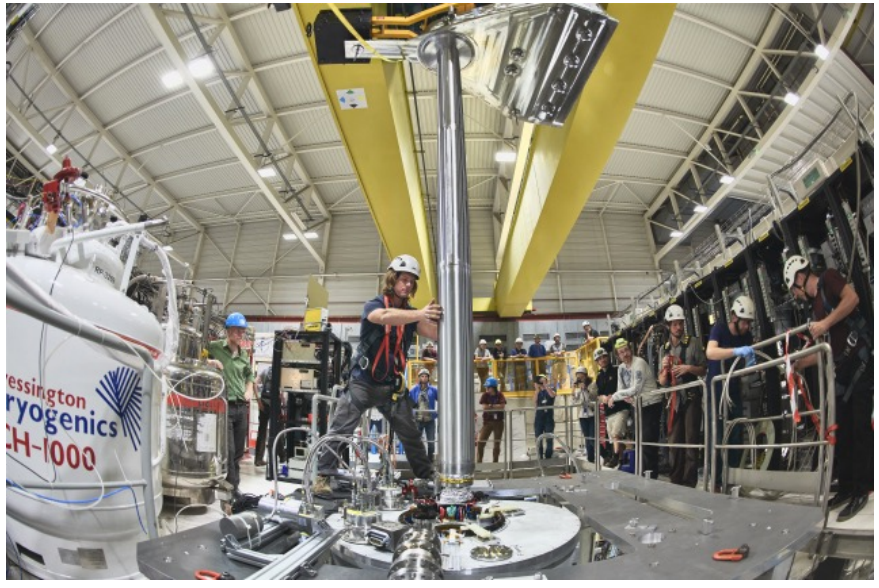
Next few years

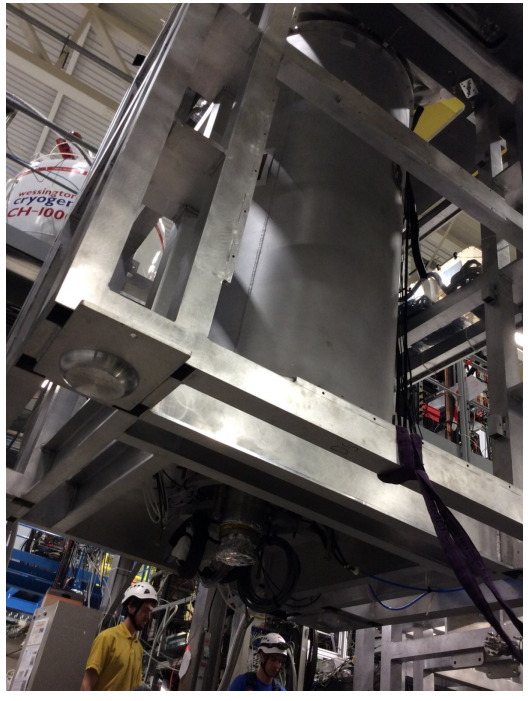
Direct Lamb shift meas. via microwaves (Friesen)

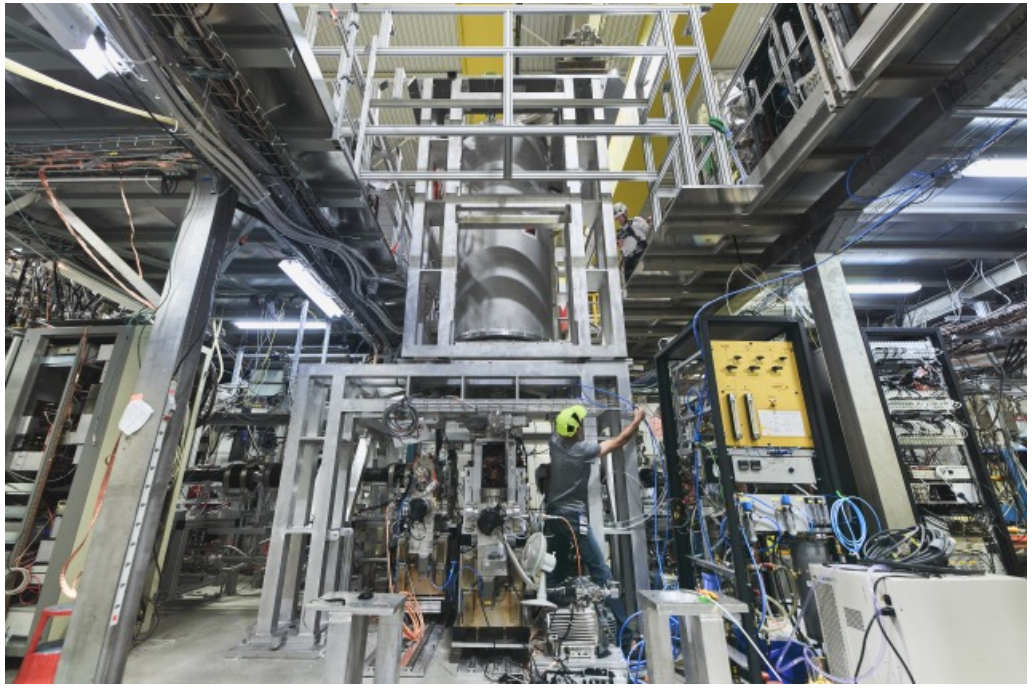
Shelter Island Conference 1948

Re-living history of modern physics with antimatter

ALPHA-g construction at CERN

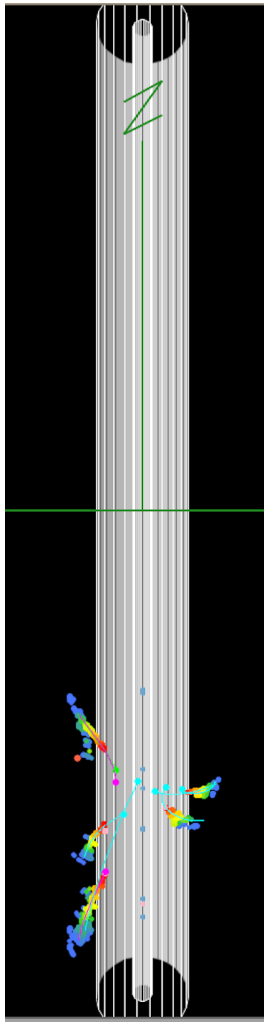


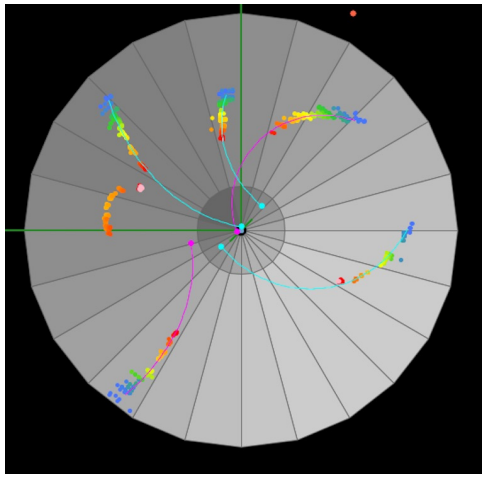




Antihydrogen Gravity Measurements with ALPHA-g

First antiproton annihilations
Oct/Nov. 2018 (before Shut Down)

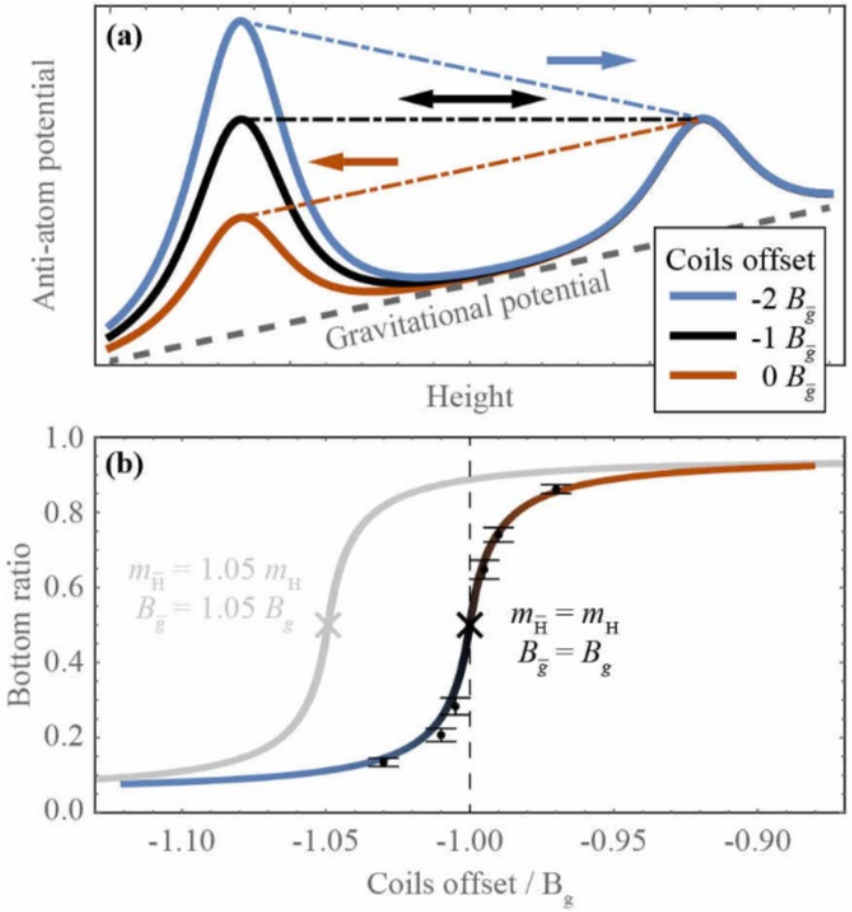




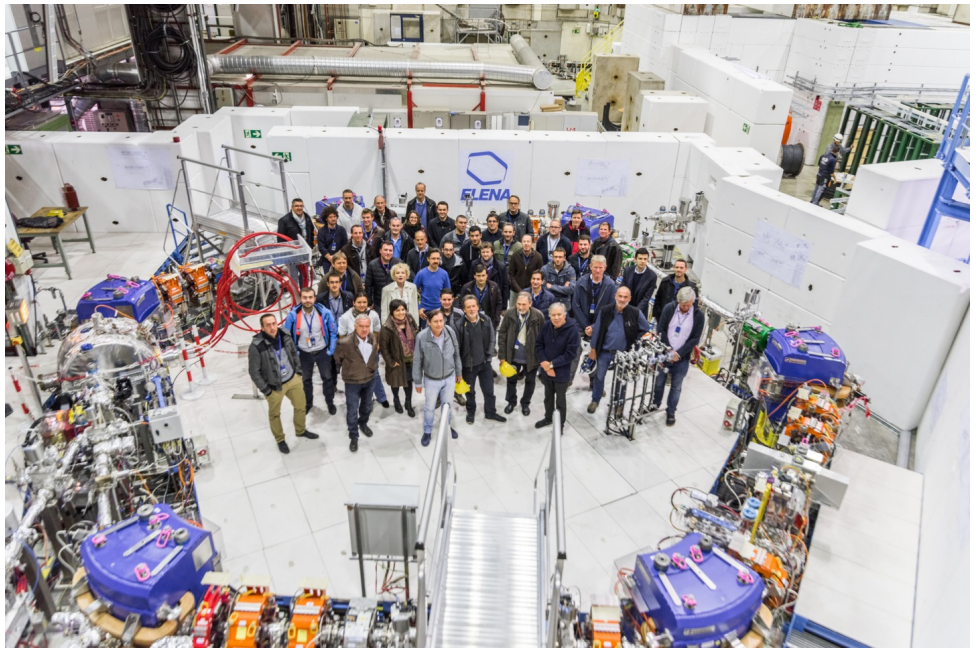
Next few years

First Physics Meas.:
Anti-H free fall
10% meas. of g

Extracting Physics (concept)



ELENA upgrade online in 2021



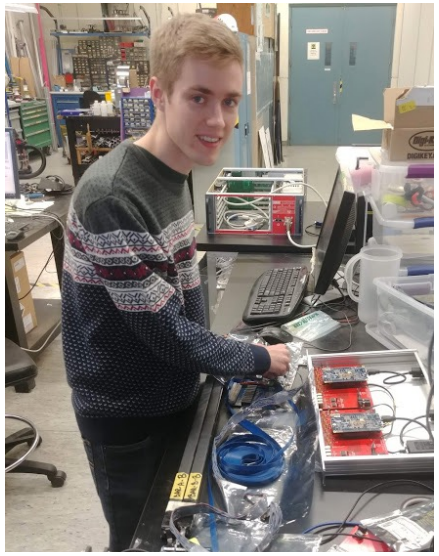
- Decelerate & cool anti-p: 5 MeV → 100 keV
  - Should increase anti-p trapping efficiency by up to x 100
  - New beam lines; trap modifications
- Simultaneous beams to expt's 24/7
  - Instead of 8 h/day/expt shift
  - Increased demand on human power
- Increased Competition
  - Gravity: AEGIS, GBAR
  - Hyperfine: ASACUSA
  - Lamb shift: GBAR

Personnel : some recent hires

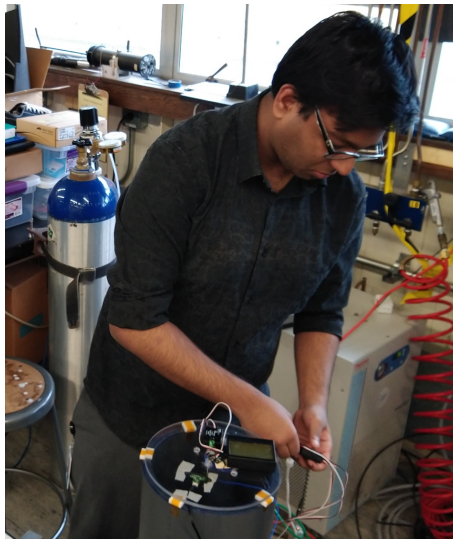
Maryam Mostamand
(Laser PDF)

Some new students

Gareth Smith (MSc)

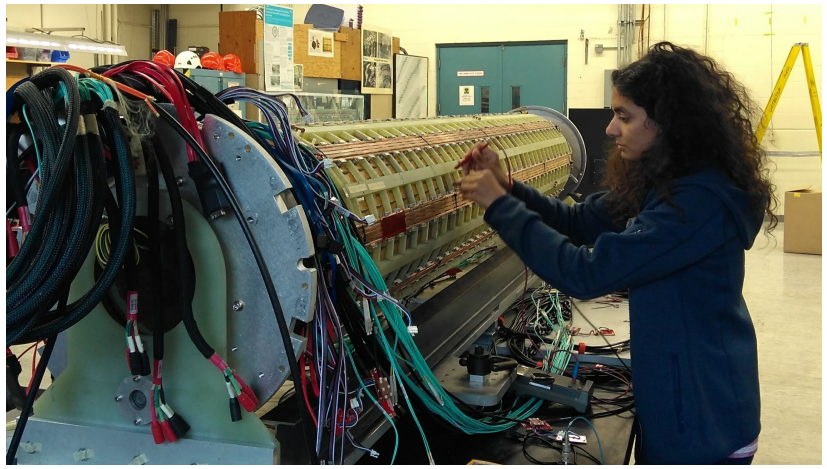


Janukan Sivajeyan (UG)



Adam Powell (PhD)

Pooja Woosaree (PhD)



Layla Haddad (UG)

ALPHA-g: Dropping antihydrogen