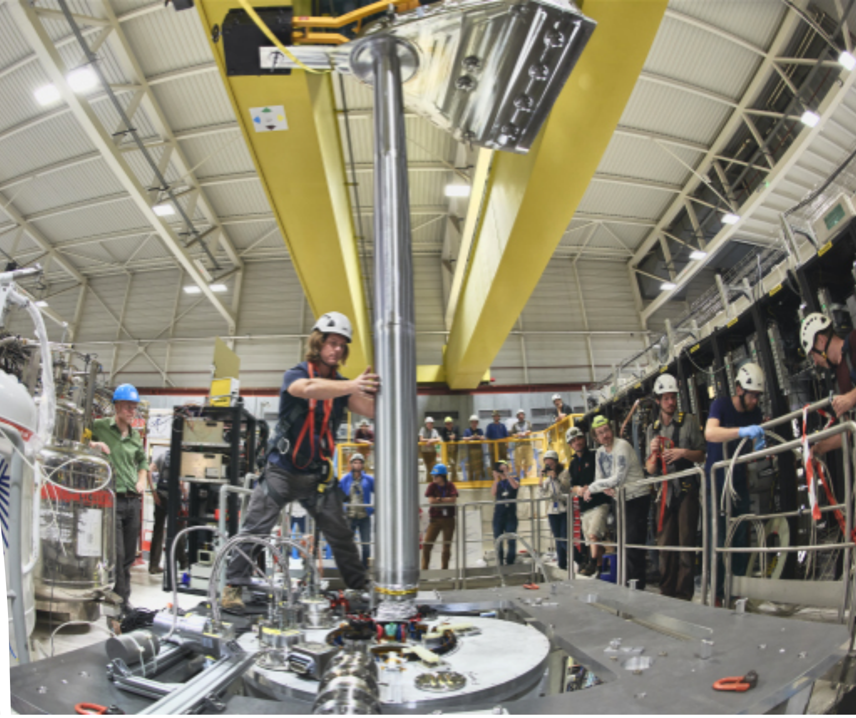
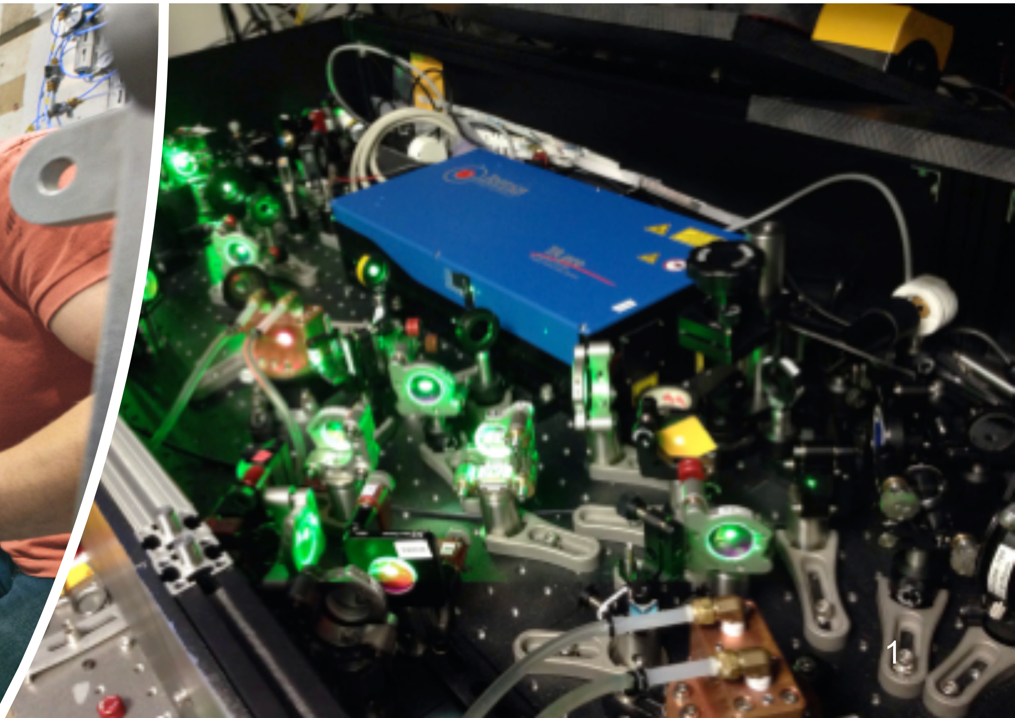
New techniques in precision measurements on simple atoms (and molecules)

Developing New Directions in fundamental Physics 2020

Nov 5, 2020

Makoto Fujiwara, TRIUMF





UBC

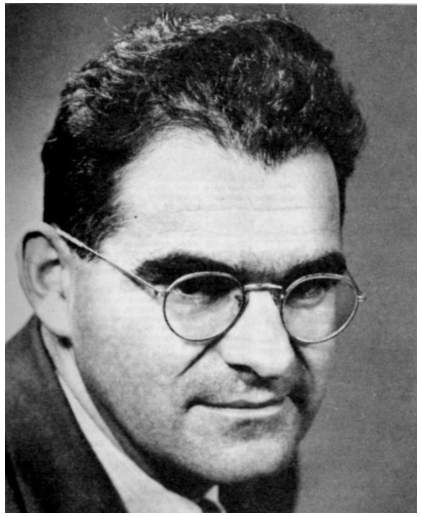
UNIVERSITY OF CALGARY

SFU SIMON FRASER UNIVERSITY

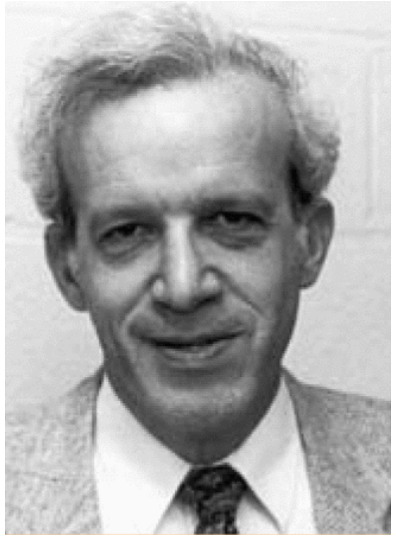
TRIUMF

YORK UNIVERSITÉ UNIVERSITY

"To understand hydrogen is to understand all of physics"



Victor Weisskopf



Dan Klepper

- Hydrogen
  - "Much of what we know about the Universe comes from looking at hydrogen"
  - 75% of *known* Universe
  - One of the most precisely measured physical systems
- Exotic hydrogen (TRIUMF/CENPA)
  - Muonium
  - Muonic Hydrogen
  - Hadronic Hydrogen
  - Antihydrogen
  - Positronium

Tests of QED, Quantum Field Theory, General Relativity
Fundamental Symmetries (CPT, Equiv. Principle etc)
"Are we asking the right question?" arXiv:1309.7468

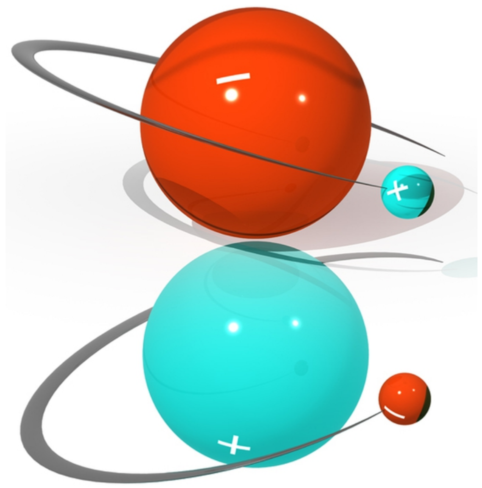
If we can improve the precisions of simple systems, we should!

Take home message

- Hydrogen–antihydrogen symmetry test with ALPHA@CERN likely limited by hydrogen precision in near future

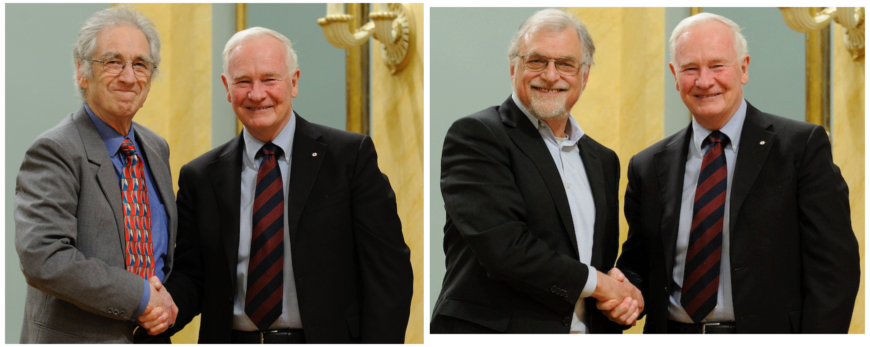
- HAICU@Canada (UBC, SFU, TRIUMF, Calgary, York): Developing novel "quantum sensing" techniques to push both antihydrogen AND hydrogen measurements

- These new techniques could be used for new types of exciting measurements at TRIUMF!



- This talk:
  - Introduction/motivation
  - ALPHA antihydrogen experiment
  - HAICU: proposed R&D platform
  - Future opportunities

15 Years of ALPHA



2013 NSERC Polanyi Award

2005
ALPHA, ALPHA-Canada started

2006
First beam in ALPHA

2010
Stable anti-H trapping
Nature

2011
1000 sec trapping
Nature Phys.

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 kHz
Nature

2018
10^{-12} laser spectr.
Nature

2018
Lyman-alpha transition
Nature

2020
Lamb shift & fine structure
Nature

2020
Hyperfine split. Δf =13 kHz
Submitted to Nature

2020
Laser cooling
Submitted

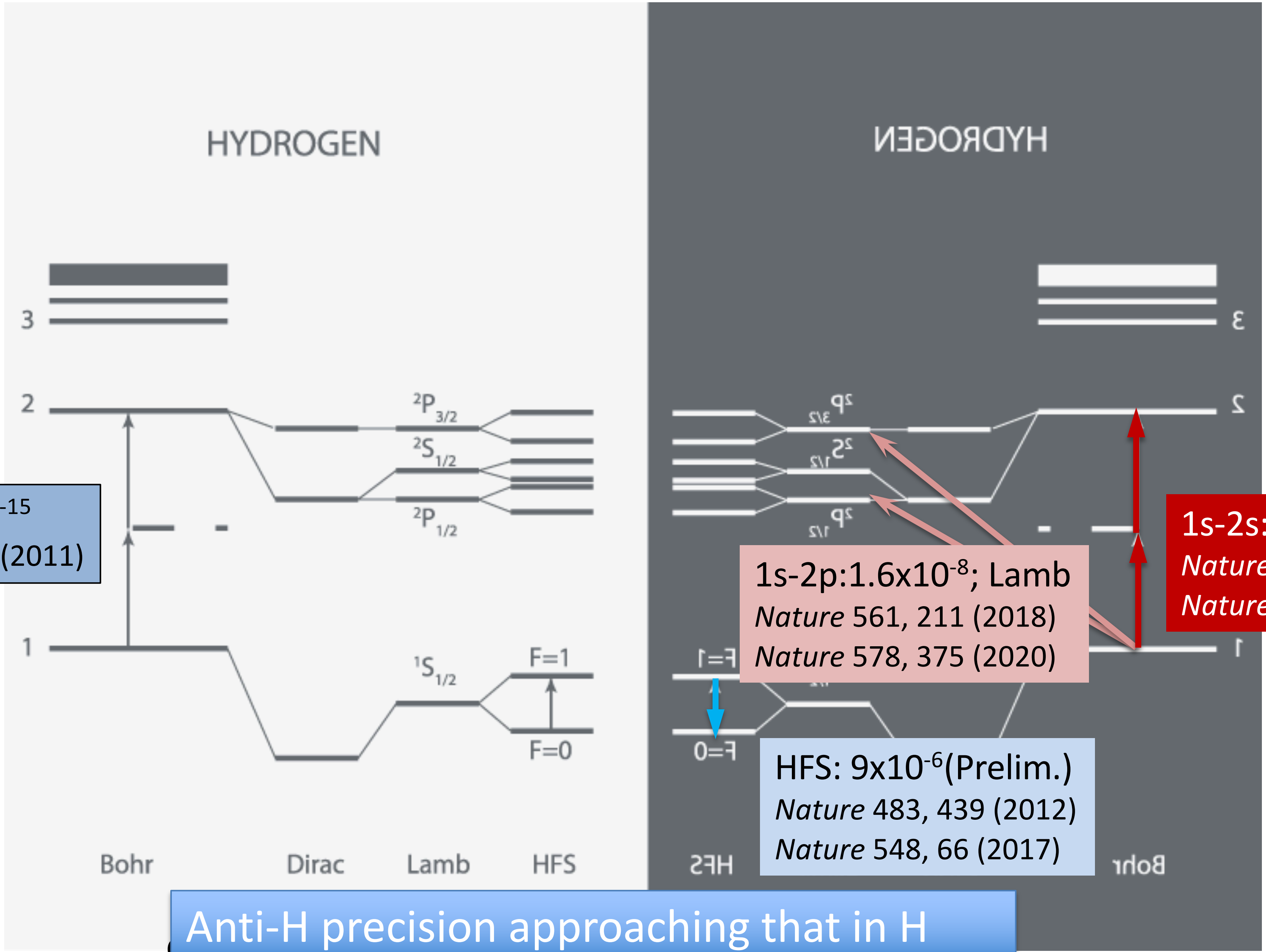
2020
Laser-cooled 1S-2S spectr.
Submitted

Papers with Canadian principle author

ALPHA-Canada: UBC, Calgary, SFU, TRIUMF, York
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

Antihydrogen Spectroscopy with ALPHA at CERN

TRIUMF



1s-2s: $4x10^{-15}$
PRL 107, 203001 (2011)

1s-2s: $2x10^{-12}$
Nature 541, 506 (2017)
Nature 557, 71 (2018)

1s-2p:$1.6x10^{-8}$; Lamb
Nature 561, 211 (2018)
Nature 578, 375 (2020)

HFS: $9x10^{-6}$(Prelim.)
Nature 483, 439 (2012)
Nature 548, 66 (2017)

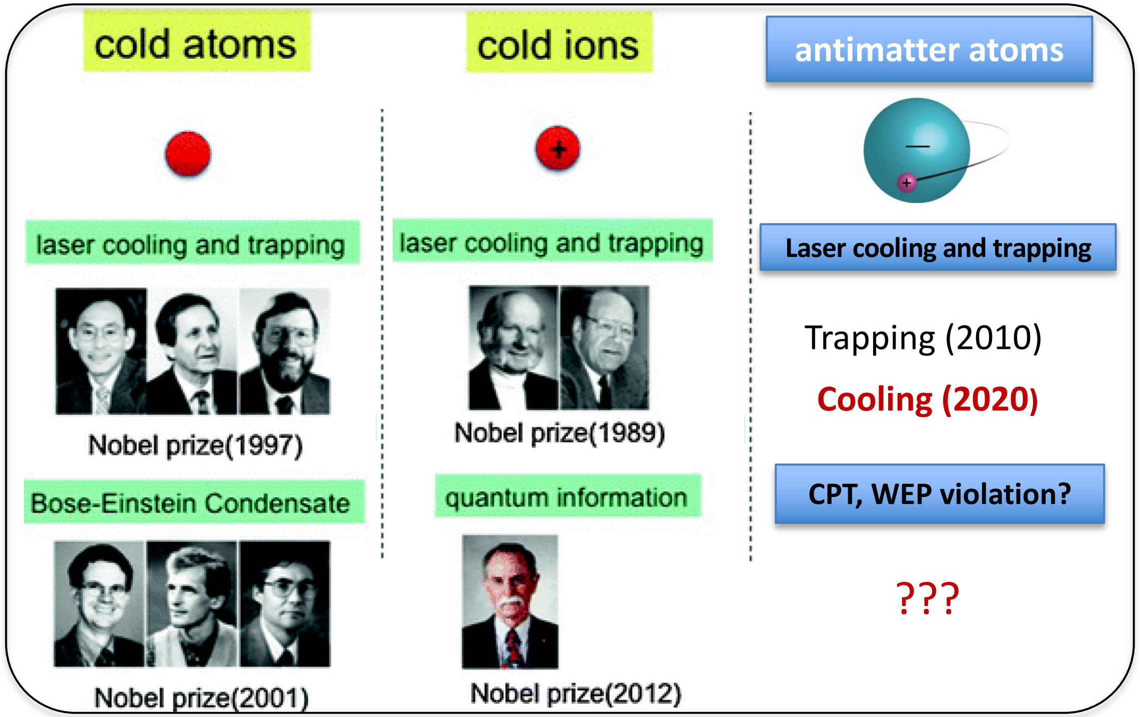
Charge neutrality
Nature 539, 373 (2016)
Gravity (ongoing)

Anti-H precision approaching that in H

TRIUMF

Laser cooling of antihydrogen: a major breakthrough!

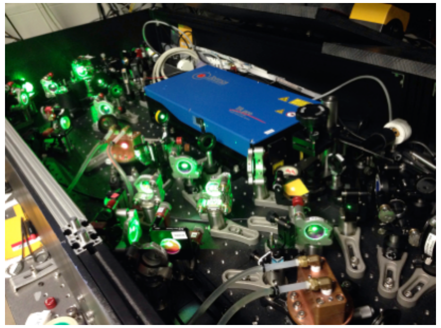
Laser cooling of atoms, ions revolutionized atomic physics in last 40 years



Inoue 2017

Laser at 121 nm (VUV)

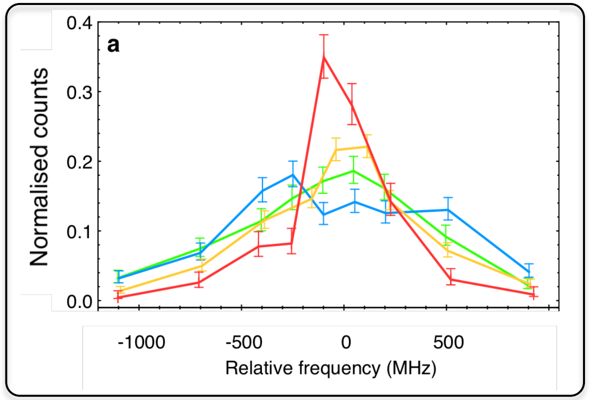
Extremely challenging!



UBC laser (Momose)

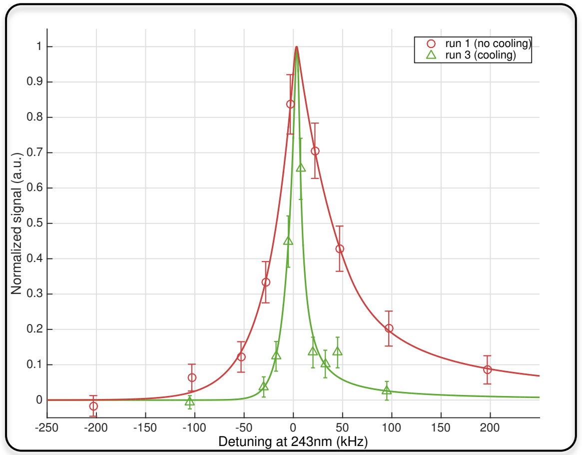
Preliminary results

Cooling demonstration



1S-2P lineshape

First application



1S-2S lineshape

Olin (TRIUMF)

A game changer! Culmination of efforts in the past decade!

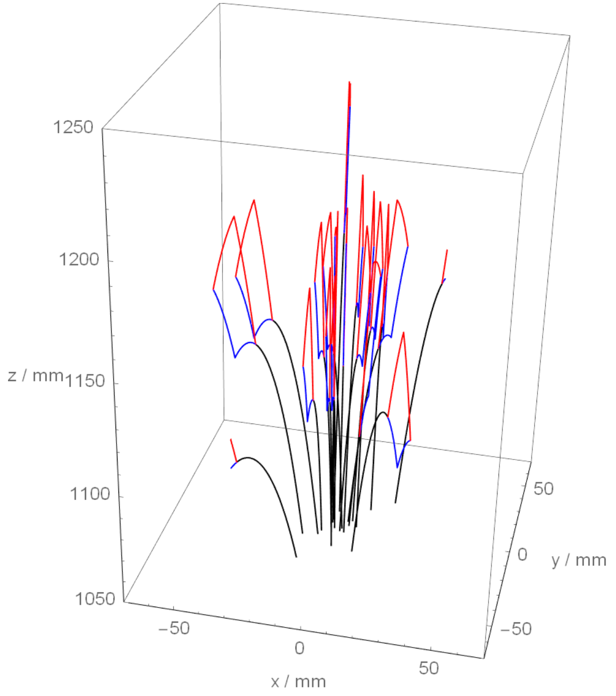
New opportunity: anti-atomic fountain!

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

HAICU: **H**ydrogen-**A**ntihydrogen **I**nfrastructure at **C**anadian **U**niversities

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

(Anti)atom Interferometer Simulation



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

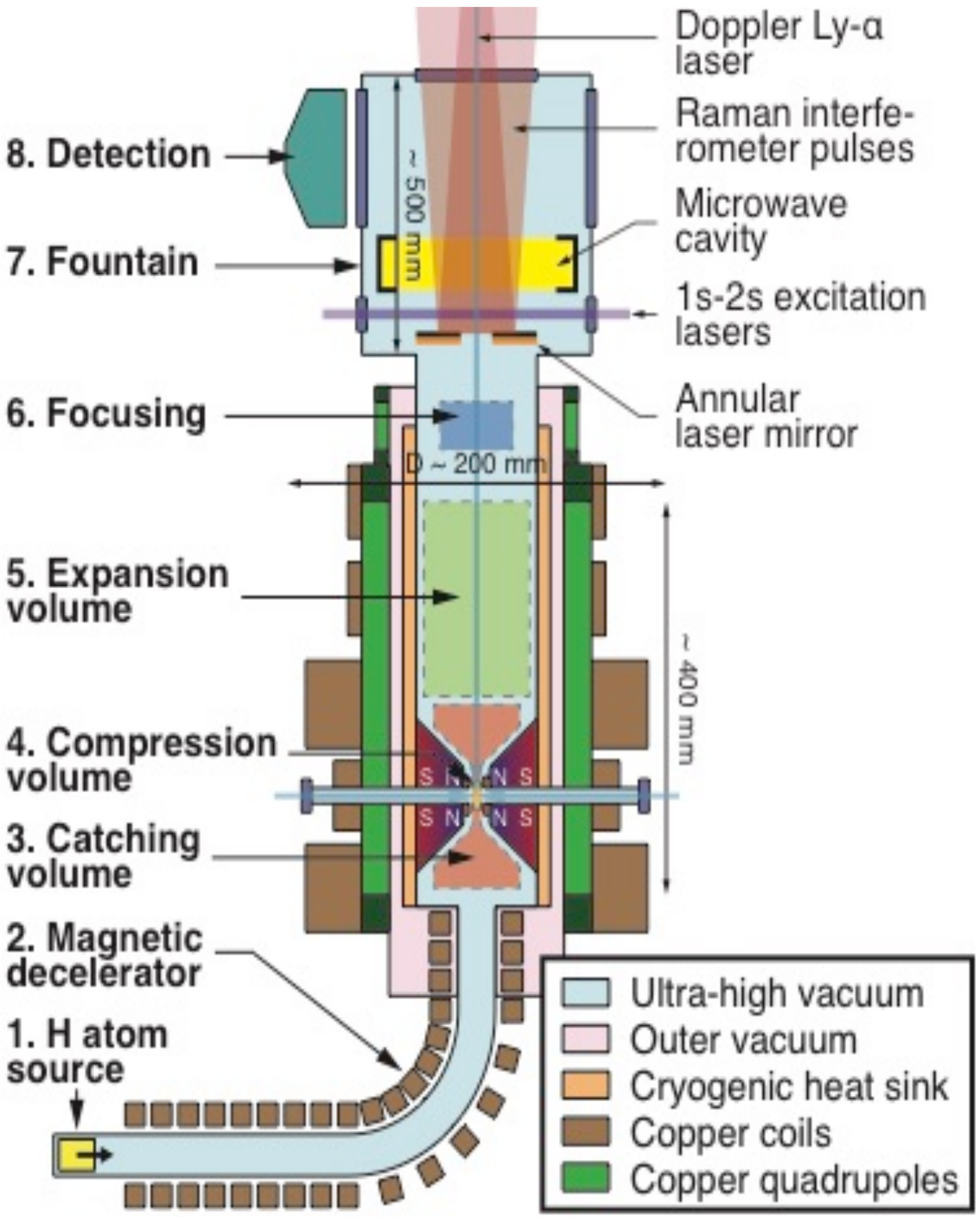
HAICU concept

Key Concept [paper in preparation]

- **Magnetic compression** of atomic clouds in a small, high density quadrupole trap (~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 $10^7 – 10^8$ 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 $10^7 – 10^8$ colder and/or denser anti-H cloud!

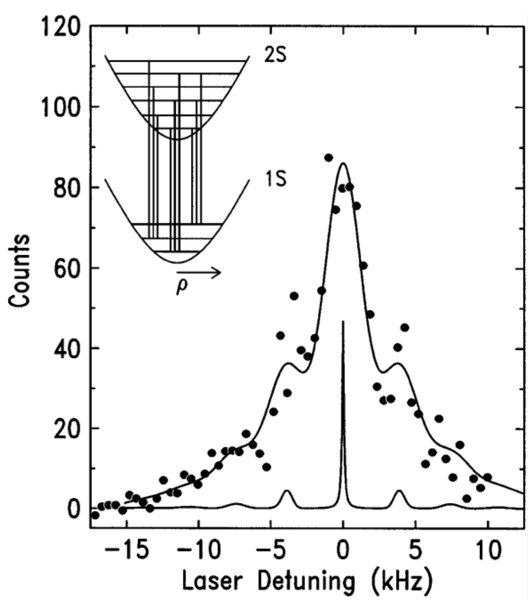


TRIUMF

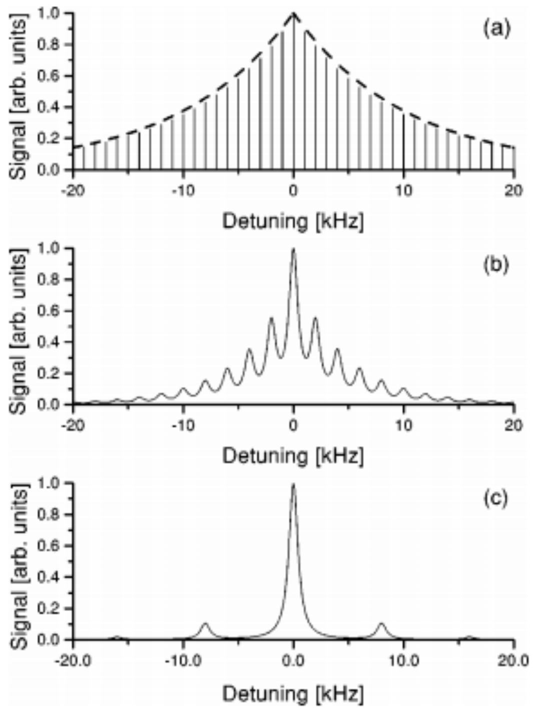
Applications to Hydrogen Studies

- Hydrogen spectroscopy with H in <μK regime
  - Note the current best H measurement uses 6 K atomic beam
  - Dominant errors
    - 2nd order Doppler broadening
    - Transit-time broadening

- Lamb-Dicke spectroscopy in harmonic trap



Cesar PRL 77, 255 (1996)



Cesar PRA 59, 4564 (1999)

Possible other applications??

- Fine structure const. via H fountain & interferometer
  - Larger recoils "signal" than Cs
  - QED test with g-2

  (Christian Panda)
- Optical trapping of H
- Muonium physics
- Positronium physics

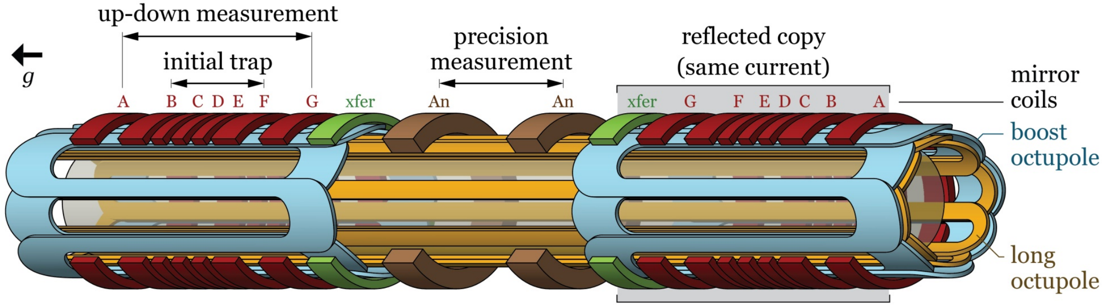
  ~4 σ discrepancy with QED
- Colder tritium atoms for Project-8 (Elise Novitski)

- Dark photon with para-H_2
  - J. Bramante et al, PRD 101, 0550540 (2020)
- Molecular fountain
- Radioactive molecules

- Our cooling scheme may be useful for other systems

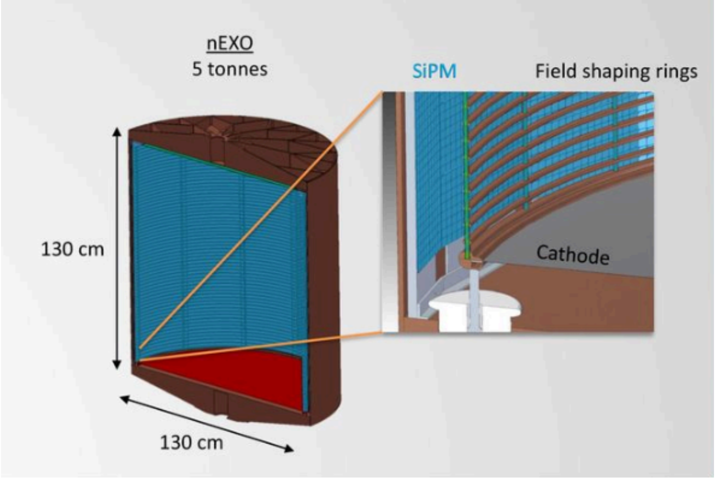
Technical challenges / synergies

- VUV lasers
- Superconducting magnetic trap
- Cryogenics
- Magnetic deceleration beamline
- Magnetometry



ALPHA-g magnetic trap: ~20 S.C. magnets

- Detection of H
  - Anti-H is easy to detect!
- VUV photon detection
  - SiPM at low temperatures
  - Synergies with Dark Matter/Neutrino expt's

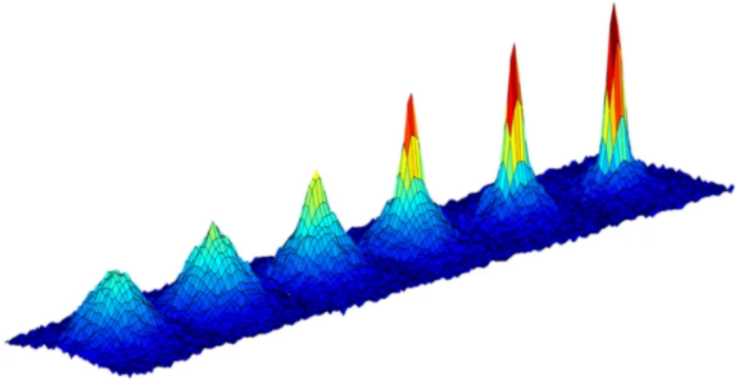


nEXO
SiPM "wall"

Requires national lab infrastructure!

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???

Summary & Outlooks

- New techniques for studies of anti-H & H atoms (molecules) proposed
  - 10^6 - 10^8 times colder and/or denser than existing expt's
  - Fountain, interferometer, Optical trapping, Ramsey spectroscopy, molecular ion clocks…
- CFI proposal under review

- Next few years
  - Will focus on ALPHA related R&D
- Beyond ~2025
  - Opportunities for H, Mu, Ps, Radioactive molecules etc.

Aiming at ambitious goals!

O snail
Climb Mount Fuji
But slowly, slowly!
— Issa Kobayashi

Result to be announced any day!

Stay tuned for the next DND!