What is the physical mechanism of the origin of the Universe?

@Univ. of Tokyo

July 7-8, 2026

Antimatter and Gravity

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藤原真琴

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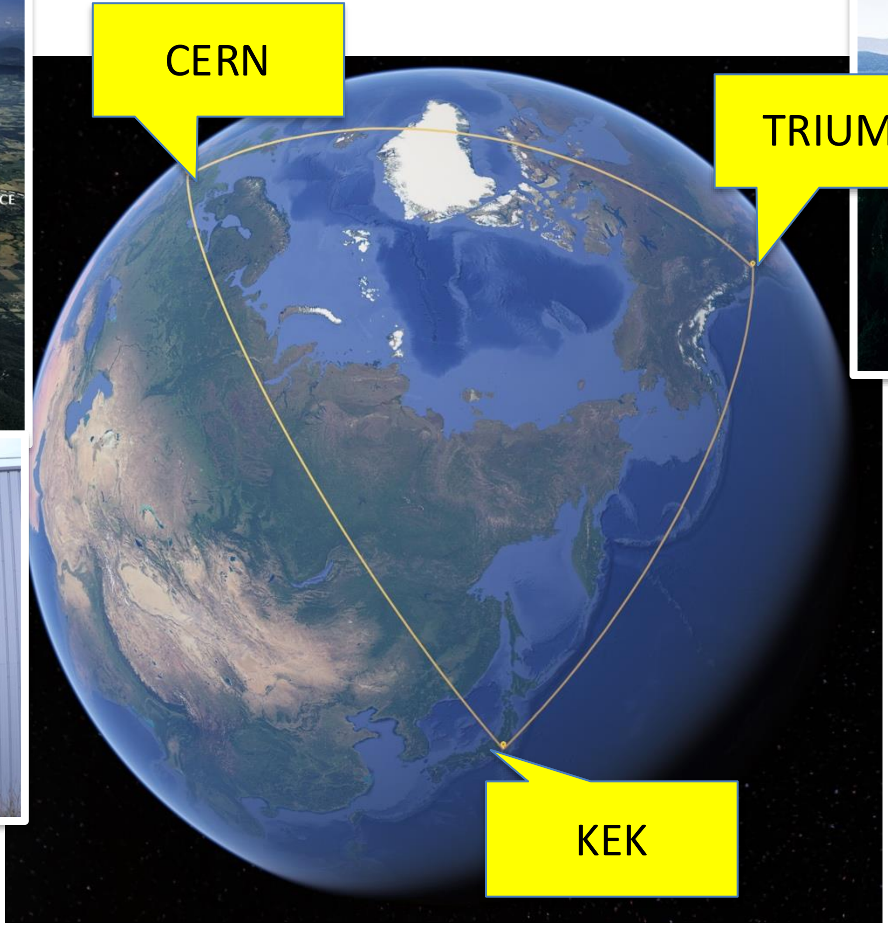
Senior Scientist, TRIUMF

Professor & PI, WPI-QUP, KEK

TRIUMF (Vancouver, Canada) & CERN (Geneva)

CERN's Antiproton Decelerator



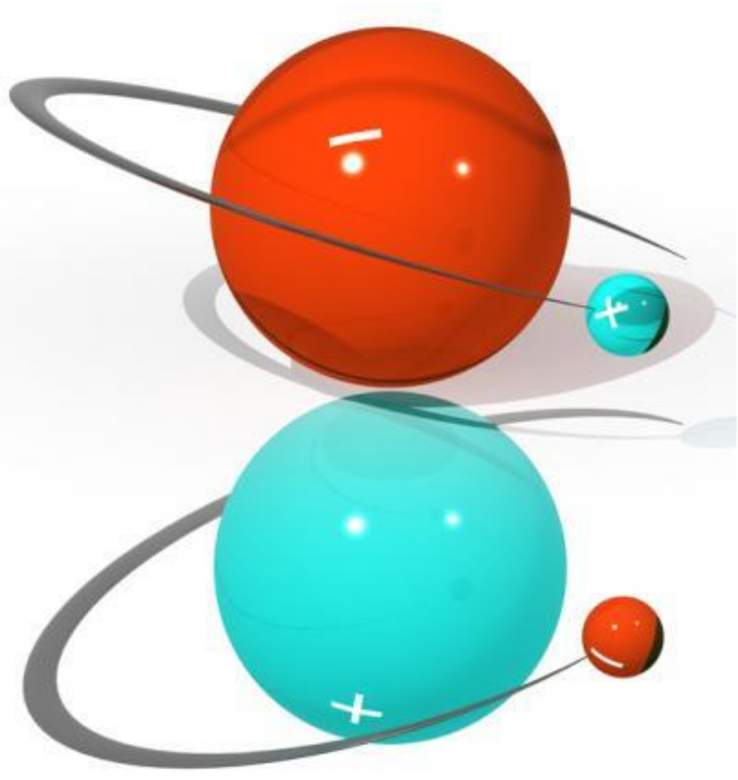
TRIUMF—Canada's National Lab for Particle & Nuclear Physics, Vancouver,
Located at Univ. British Columbia

TRIUMF

Please visit us!

QUP—Int'l Center for Quantum-field Measurement Systems for Studies of the Universe and Particles
WPI Center at KEK

Anti-H: bound state of antiproton & positron



Objective:

Test symmetries between anti-H and H at highest possible precision

Technology driven!

This will be a high-level talk

– Introduction
  - Motivations
  - ALPHA experiment at CERN
  (cf: ASACUSA, BASE, AEGIS, Gbar)
– Dropping antimatter – this was a dream!
  - ALPHA-g general ideas
  - ~~Detailed systematics~~
– Future
  - HAICU(俳句) & QUP: quantum sensing with (anti)hydrogen

絶賛発売中！
(2680円）

“Antimatte
「反物質
(E

Motivations: Fundamental Symmetries

Quantum Field Theory

↕

CPT Symmetry

↕

H & anti-H Spectra

Precision spectroscopy
Katori-san
Kawasaki-san et al.

General Relativity

↕

Equivalence Principle

↕

H & anti-H Free fall

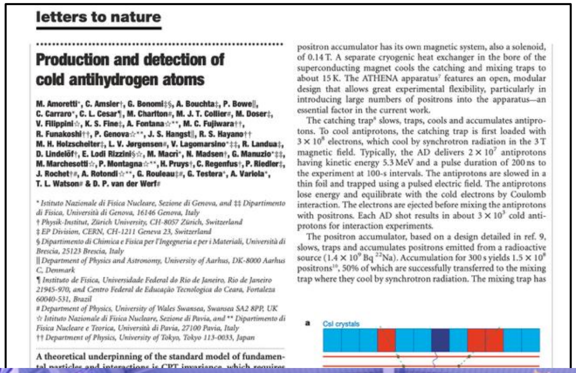
QFT and GR: no good reasons to believe they are invalid!
Still, they are among physical laws that govern the origin of the Universe

TRIUMF

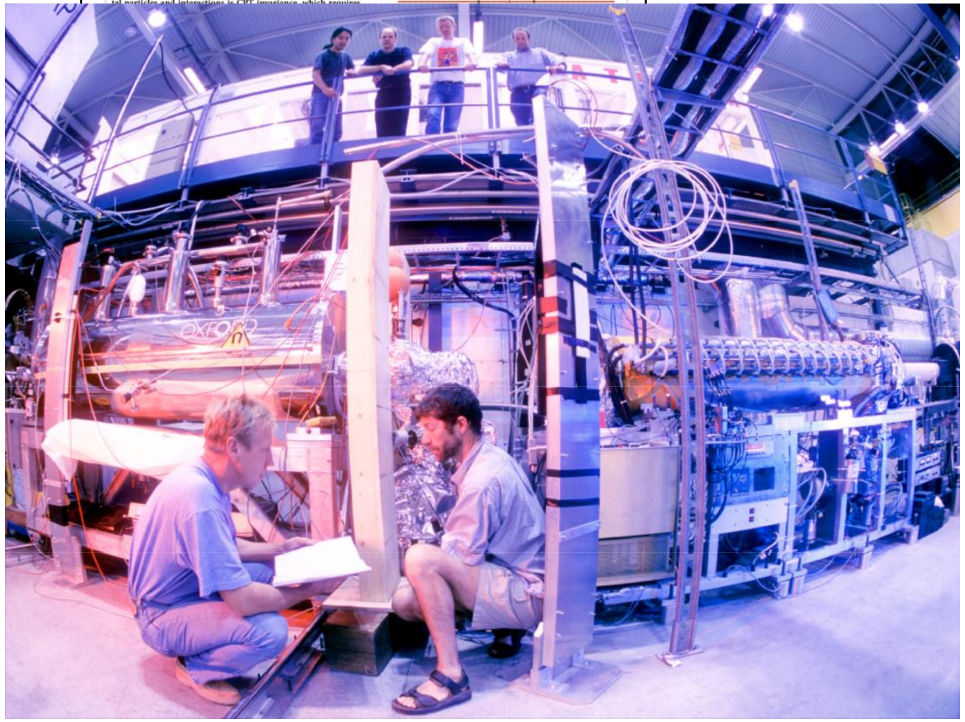
ALPHA Experiment at CERN

More than 2 decades of development for cold antihydrogen

Production of cold antihydrogen, Oct 3, 2002


letters to nature

Production and detection of cold antihydrogen atoms

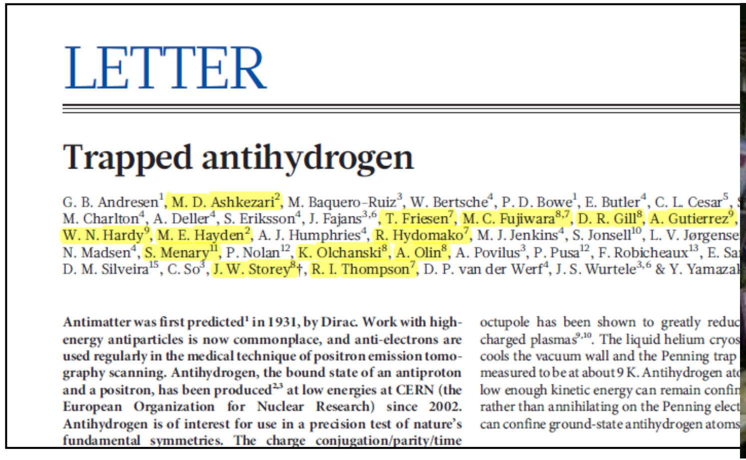


ATHENA at CERN AD

- ATHENA's anti-H not trapped
- Developed new experiment to trap anti-H for precision measurements in 2005

- ~~ALE —Antihydrogen Laser Experiment~~
- ALPHA: Antihydrogen Laser PHysics Apparatus

Trapped antihydrogen, Nov. 17, 2010


LETTER

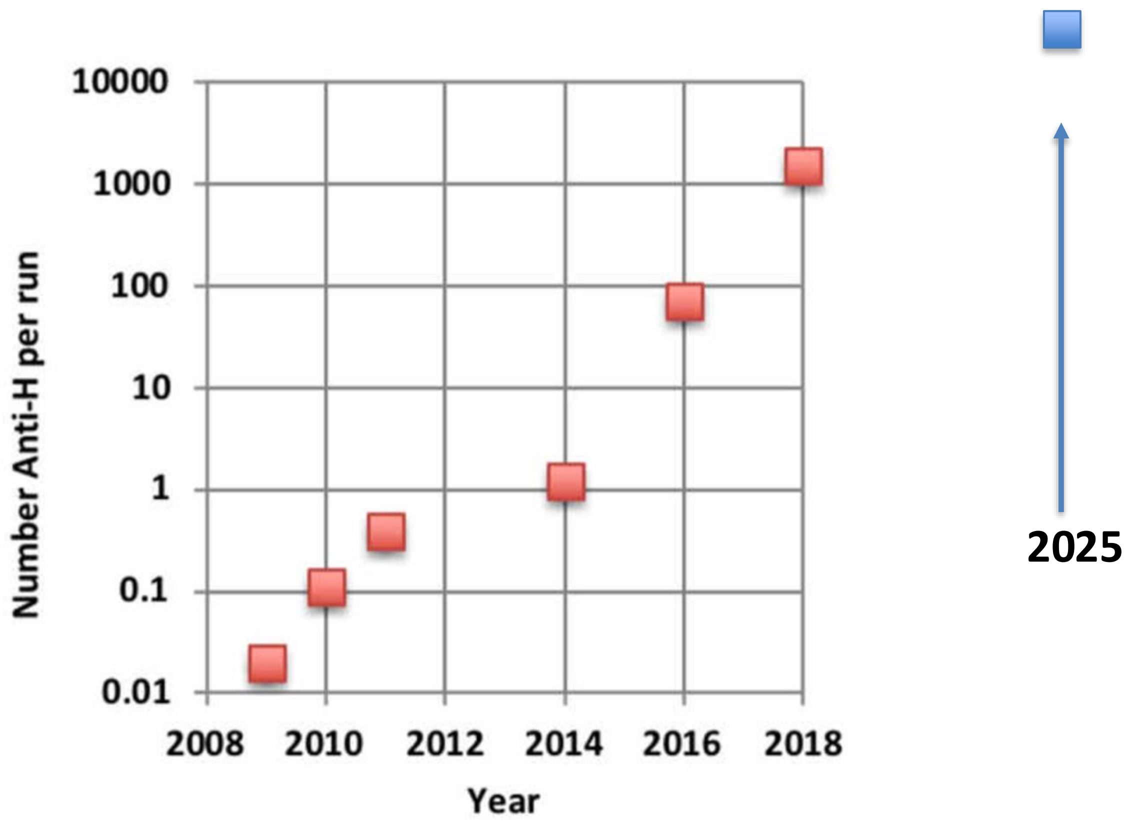
Trapped antihydrogen

G. B. Andresen[1], M. D. Ashkezari[2], M. Baquero-Ruiz[3], W. Bertsche[4], P. D. Bowe[1], E. Butler[4], C. L. Cesar[5], M. Charlton[4], A. Deller[4], S. Eriksson[4], J. Fajans[3,6], T. Friesen[7], M. C. Fujiwara[8,7], D. R. Gill[8], A. Gutierrez[9], W. N. Hardy[9], M. E. Hayden[2], A. J. Humphries[4], R. Hydomako[7], M. J. Jenkins[4], S. Jonsell[10], L. V. Jørgense N. Madsen[4], S. Menary[11], P. Nolan[12], K. Olchanski[8], A. Olin[8], A. Povilus[3], P. Pusa[12], F. Robicheaux[13], E. Sa D. M. Silveira[15], C. So[3], J. W. Storey[8]†, R. I. Thompson[7], D. P. van der Werf[4], J. S. Wurtele[3,6] & Y. Yamazak

Antimatter was first predicted[1] in 1931, by Dirac. Work with high-energy antiparticles is now commonplace, and anti-electrons are used regularly in the medical technique of positron emission tomography scanning. Antihydrogen, the bound state of an antiproton and a positron, has been produced[2,3] at low energies at CERN (the European Organization for Nuclear Research) since 2002. Antihydrogen is of interest for use in a precision test of nature's fundamental symmetries. The charge conjugation/parity/time

octupole has been shown to greatly reduc charged plasmas[9,10]. The liquid helium cryos cools the vacuum wall and the Penning trap measured to be at about 9 K. Antihydrogen ato low enough kinetic energy can remain confin rather than annihilating on the Penning elect can confine ground-state antihydrogen atoms

ALPHA developments over past 25 years



6 orders of magnitude improvement in in anti-H trapping

Dropping Antimatter with ALPHA-g: First Result

[*Nature* **621**, 716 (2023)]

$$F = ma$$

Gravity

$$F = ma$$

Gravity force is given by

$$F = mg$$

g: Gravitational acceleration (9.8 m/s^2)

$$\cancel{m}a = \cancel{m}g$$

$$\boxed{a = g}$$

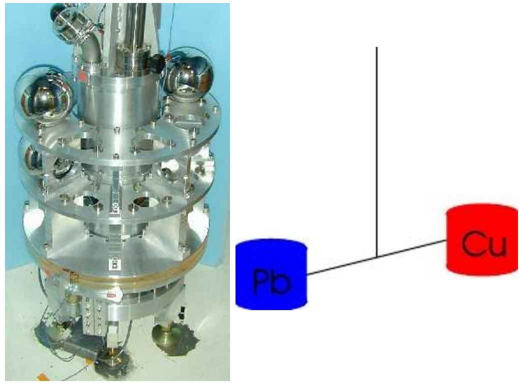
Gravity is universal!

$$m_{gravit} = m_{inert}\ ?$$

Test of Weak Equivalence Principle

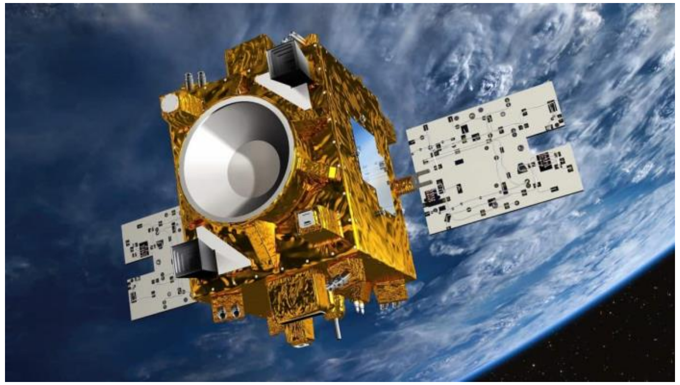
arXiv:2211.15412

Torsion Balance



Be vs Ti: 2 x 10^{-13}

MICROSCOPE satellite



Pt vs Ti: 3 x 10^{-15}

Stanford 10 m atom tower

^{85}Rb vs ^{87}Rb: 3.8 x 10^{-12}

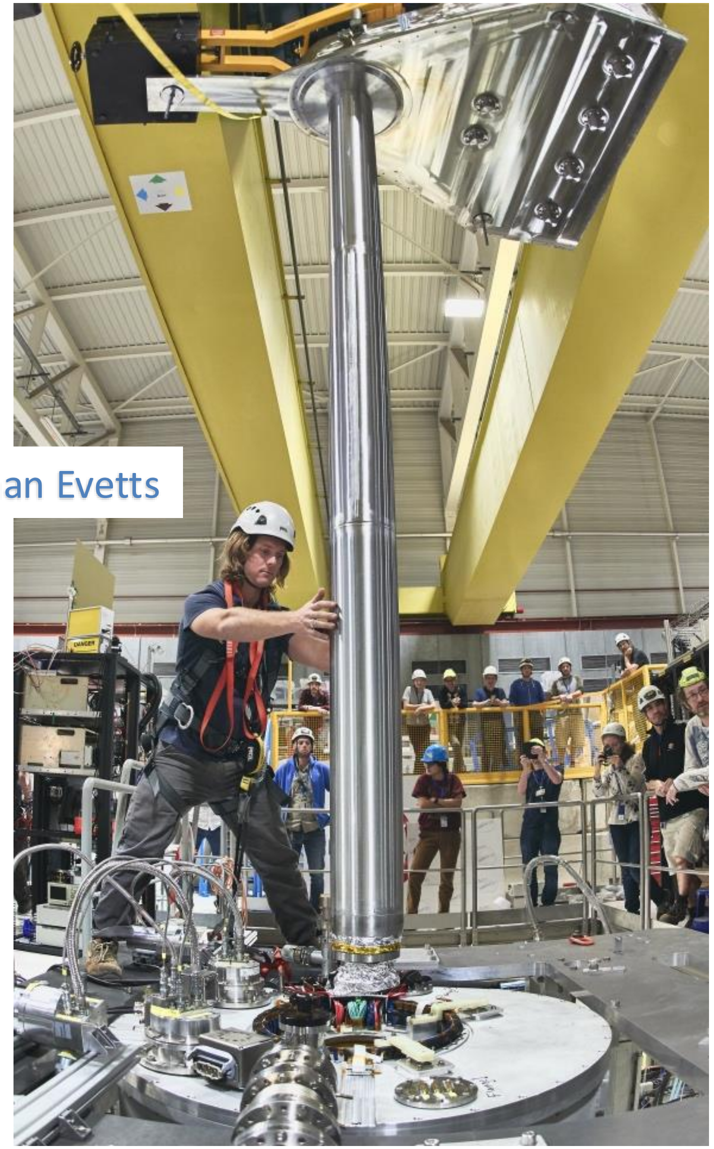
- No one had seen antimatter falls!
- Many arguments against Matter-Antimatter Gravitational Asymmetry—MAGA
  - Strong indirect limits exist, e.g. from 5th force searches, or clock comparions
- Asymmetry is not ruled out directly at the 1% level:
  - Joe Lykken et al, arXiv:0808.3929

Our ambition: to eventually match the precision of matter experiments!

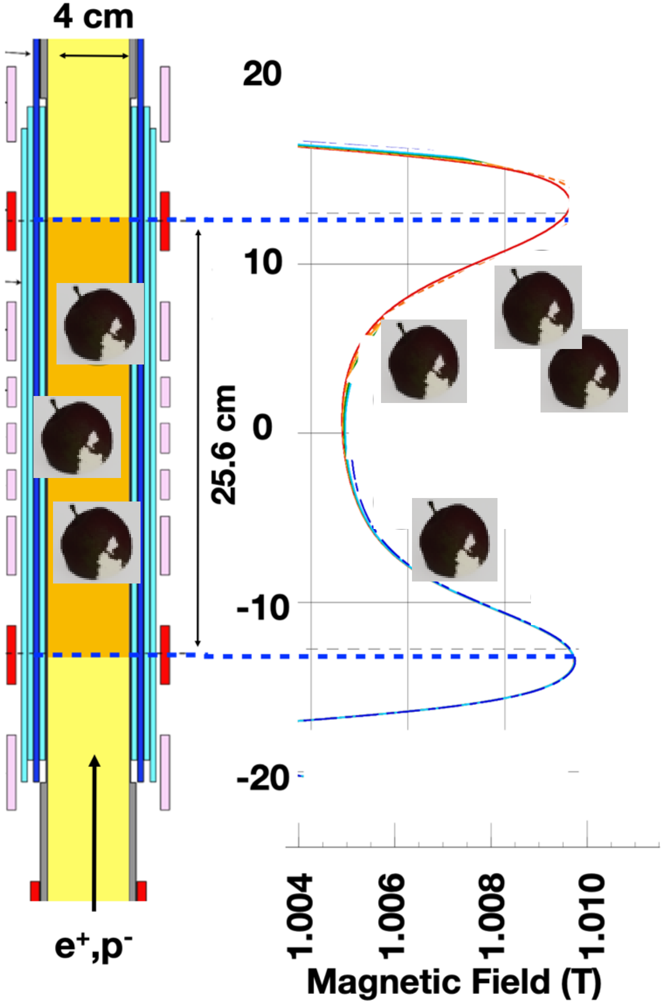
Release and detect anti-H

Annihilation position in 3D determined from trajectories

Event display: Gareth Smith



Nathan Evetts



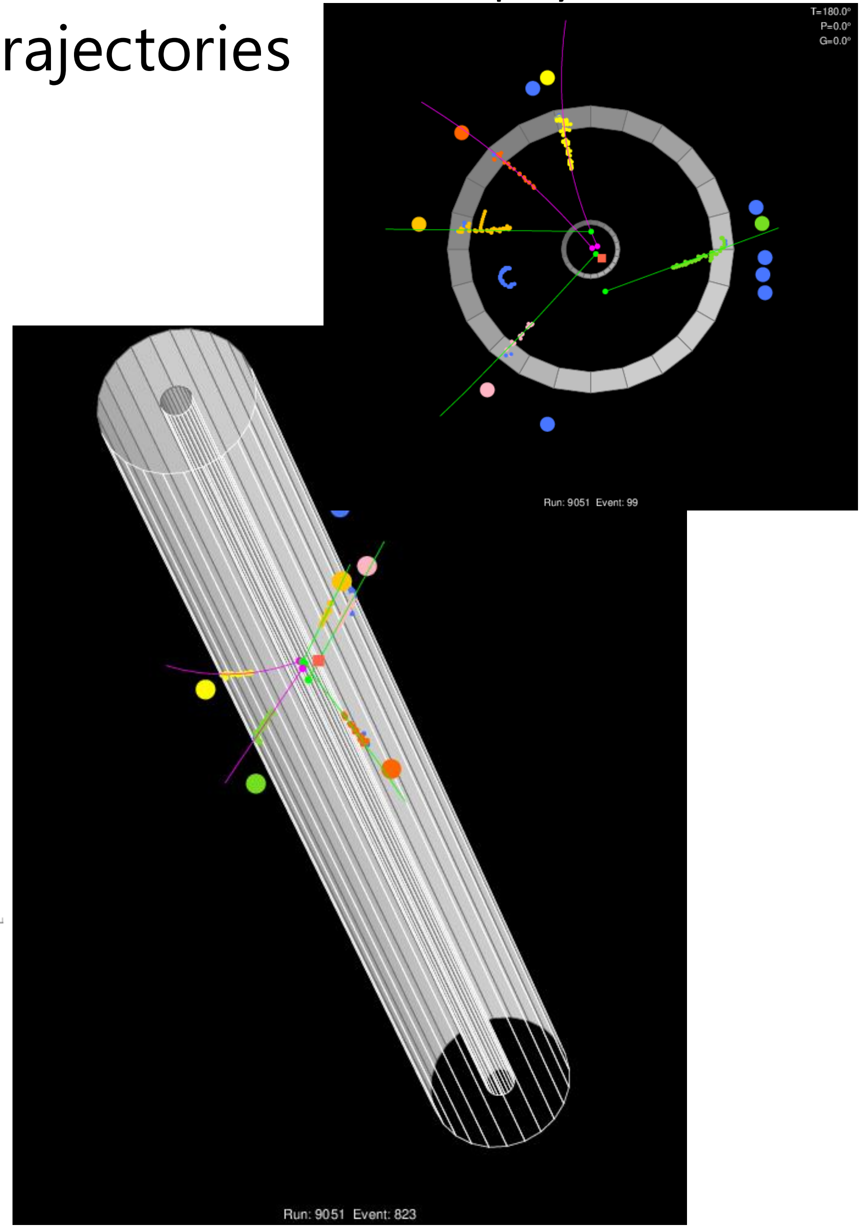
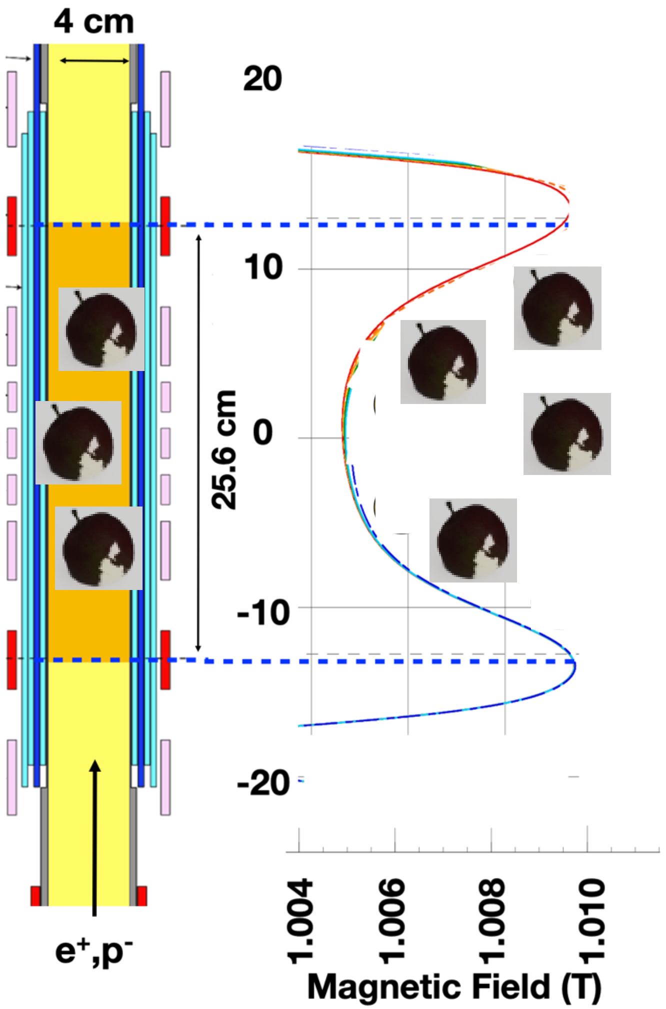


Figure: T. Momose

Makoto Fujiwara/TRIUMF

Why is it difficult to measure gravity on antimatter?



Key Challenge

Anti-H thermal energy >>
Gravitational potential

kT (~30 μeV) >> *mgh* (~30 neV)

For 1 K anti-H:
$h \sim kT/mg$ ~ 800 m!

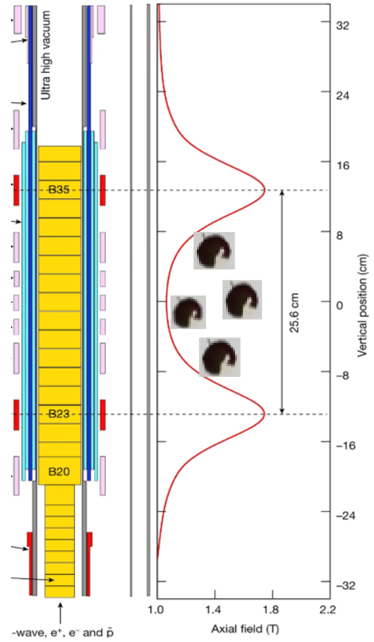
Tokyo Skytree: 634 m

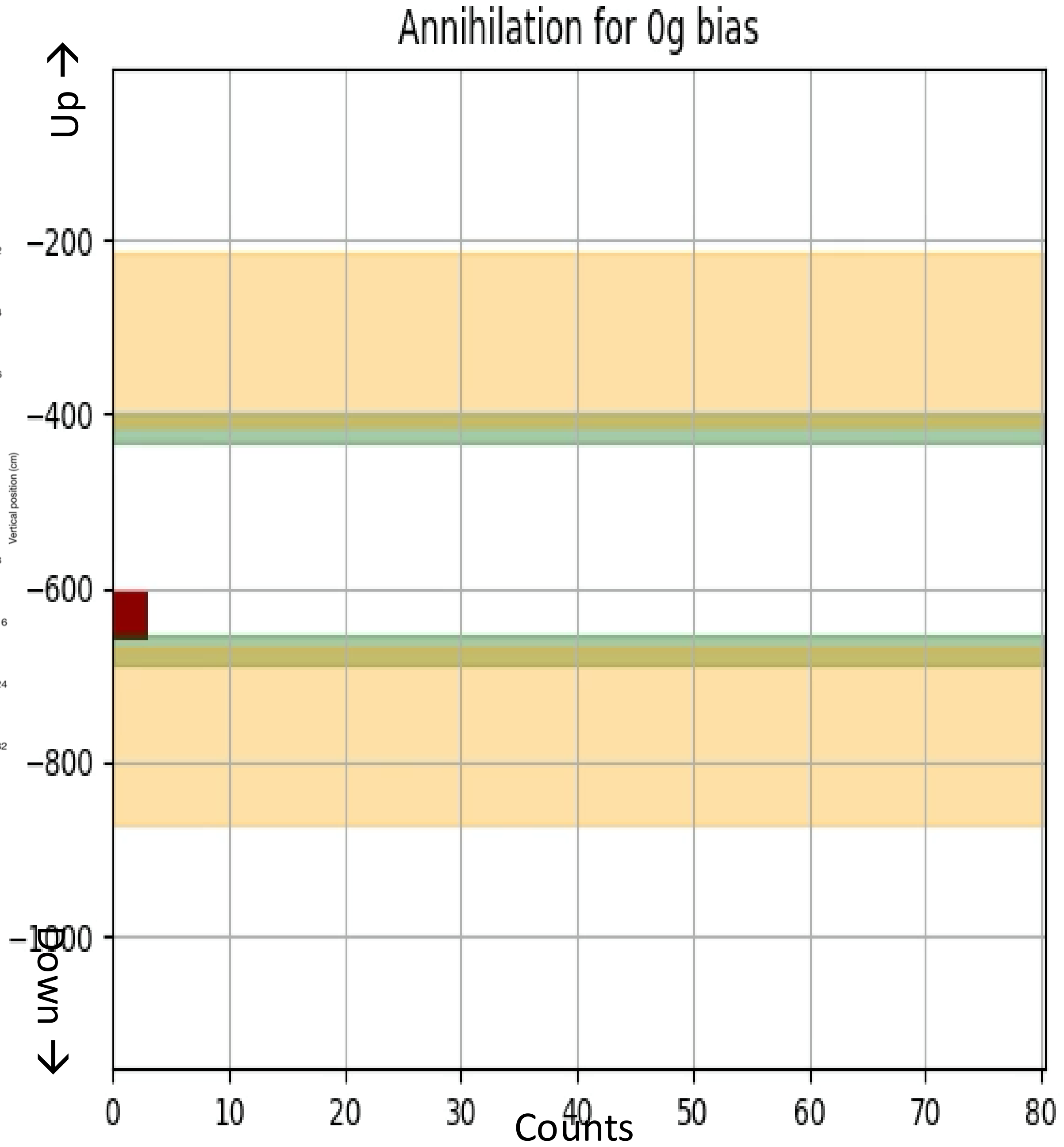
Requires exquisite control of systematics!

Experimental Data

Animation by Andrea Capra

Vertical position



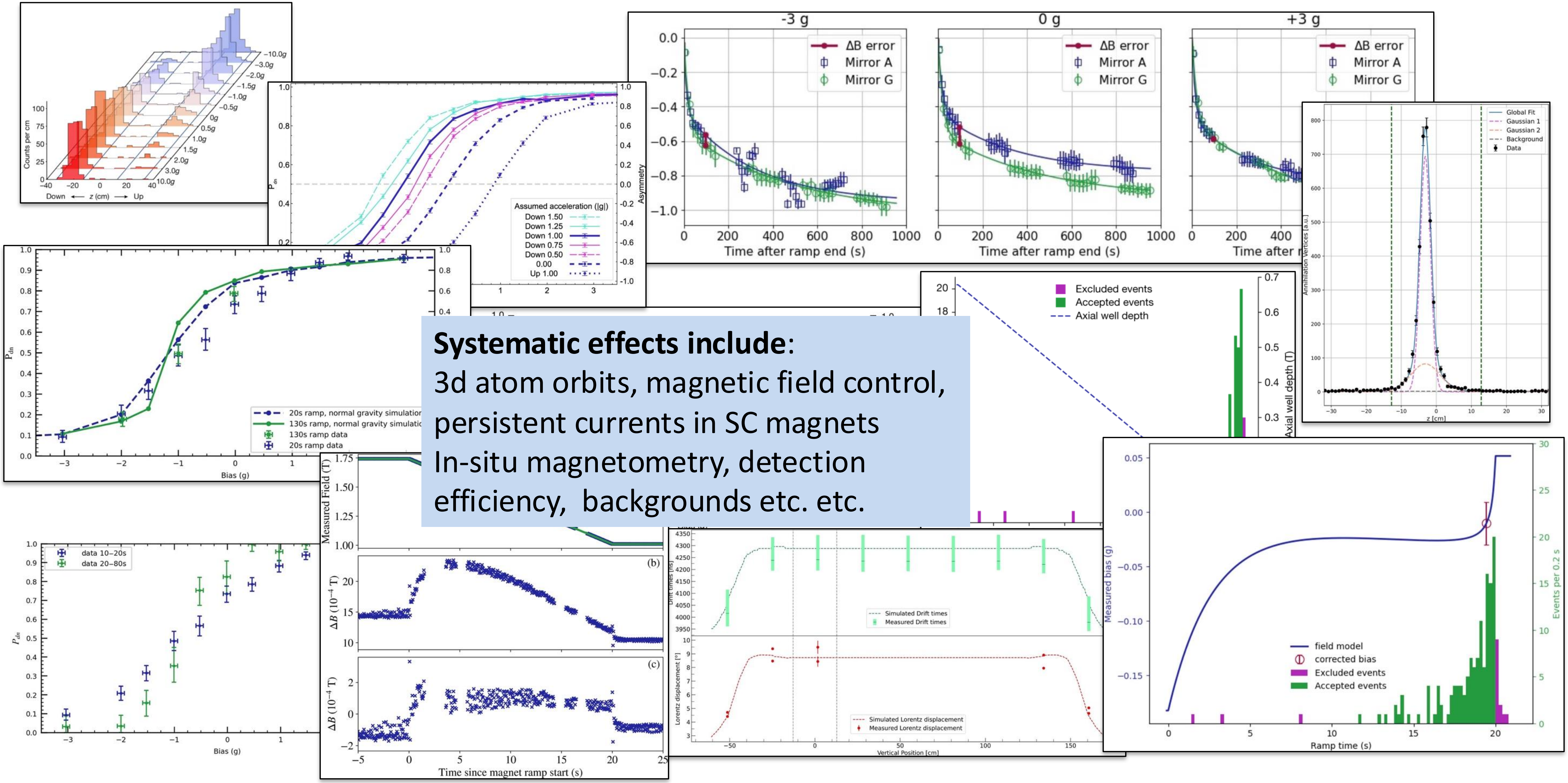


~75% of anti-H
released downwards
(as expected)

Antimatter falls down!

Does it?

Lots systematic studies!



Systematic effects include:
3d atom orbits, magnetic field control, persistent currents in SC magnets
In-situ magnetometry, detection efficiency, backgrounds etc. etc.

Result

nature

Sep 27, 2023

Article

Observation of the effect of gravity on the motion of antimatter

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Check for updates

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Einstein's general theory of relativity from 1915[1] remains the most successful description of gravitation. From the 1919 solar eclipse[2] to the observation of gravitational waves[3], the theory has passed many crucial experimental tests. However, the evolving concepts of dark matter and dark energy illustrate that there is much to be learned about the gravitating content of the universe. Singularities in the general theory of relativity and the lack of a quantum theory of gravity suggest that our picture is incomplete. It is thus prudent to explore gravity in exotic physical systems. Antimatter was unknown to Einstein in 1915. Dirac's theory[4] appeared in 1928; the positron was observed[5] in 1932. There has since been much speculation about gravity and antimatter. The theoretical consensus is that any laboratory mass must be attracted[6] by the Earth, although some authors have considered the cosmological consequences if antimatter should be repelled by matter[7–10]. In the general theory of relativity, the weak equivalence principle (WEP) requires that all masses react identically to gravity, independent of their internal structure. Here we show that

$$\frac{\bar{g}}{g} = 0.75 \pm 0.13\ (\text{Stat.} \pm \text{Syst.})\ \ \pm 0.16\ (\text{Simulation})$$

We have observed the gravitational free-fall of antihydrogen!

A first step towards precision measurements!
(current introducing laser cooling in ALPHA-g)

ANTIMATTER x GRAVITY x QUANTUM

High precision symmetry tests
via quantum control of antimatter

HAICU 俳句 at TRIUMF

Hydrogen-Antihydrogen Infrastructure at Canadian Universities for Quantum Innovations in Antimatter Science

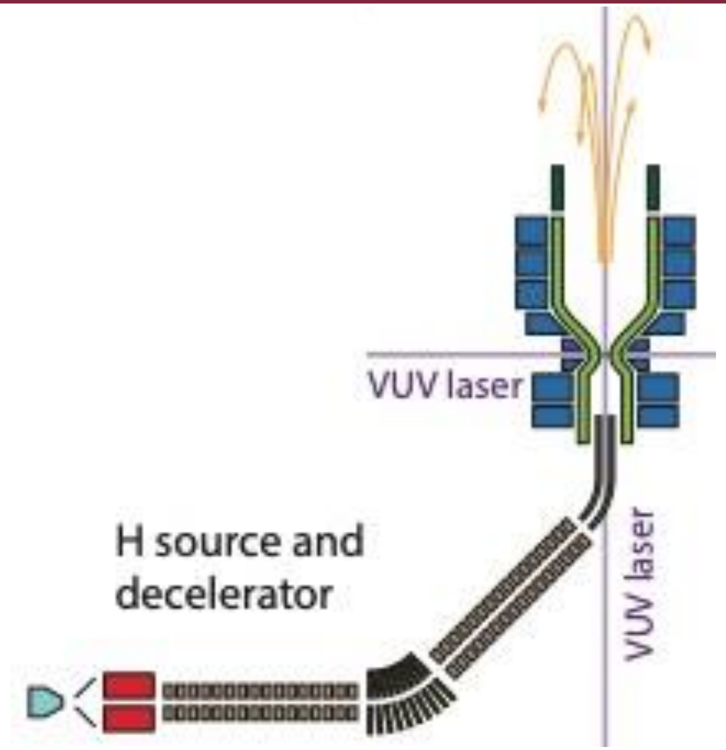
Hydrogen as anti-H proxy

QUP at KEK

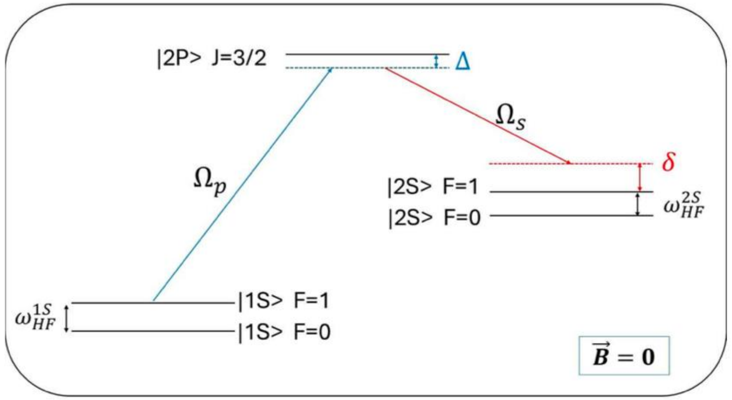
International Center for Qunatum-field Measurement Systems for the Studies of the Universe and Particles

Advanced laser development

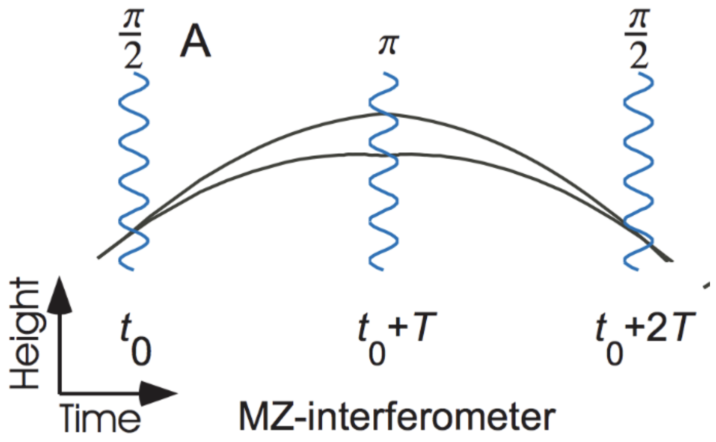
Quantum Measurements with (anti)hydrogen



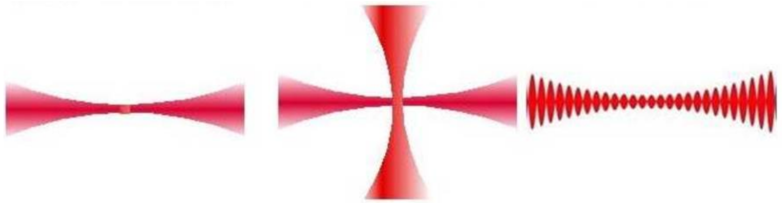
(Anti)atomic fountains



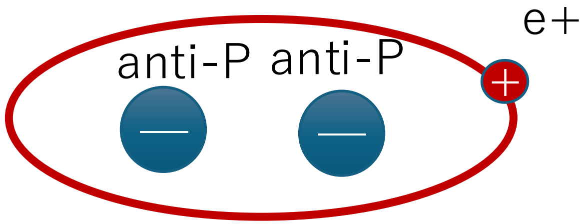
Coherent Manipulations (e.g. STIRAP)



(Anti)atomic Interferometers (GWs?)



Optical traps and clocks (Katori-san, Kawasaki-san)

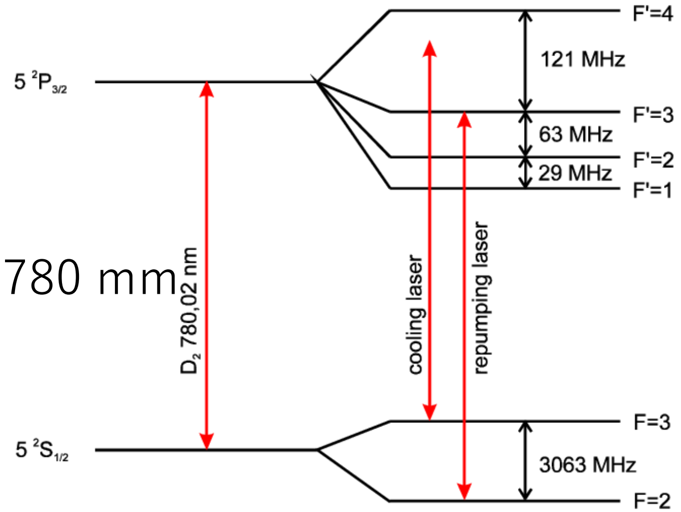


Antimatter molecules

Why is quantum manipulation of (anti)H so hard?

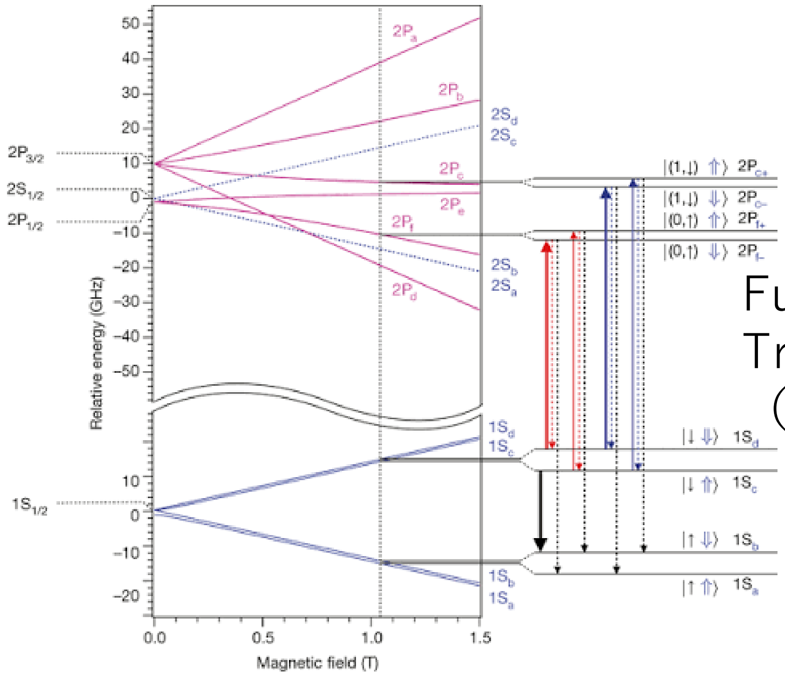
Normal atoms, e.g. Rb

Fundamental
Transitions ~ 780 mm
(1.6 eV)



Lasers, or even traps, commercially available

Antihydrogen / Hydrogen



Fundamental
Transitions 121 mm
(10.2 eV)

Vacuum-ultraviolet (VUV) light:

- Does not transmit in air
- No solid-state laser medium
- Optics; e.g. windows only 50% efficiency

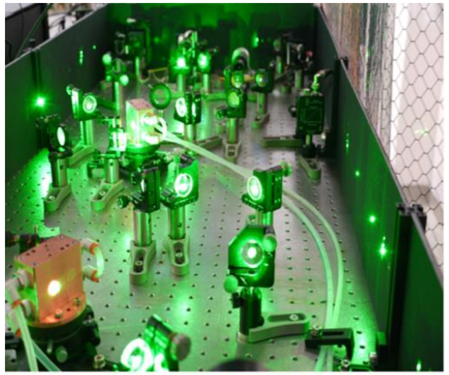
World's unique laser development

KEK/J-PARC

- >30 yrs of laser development for muon physics
- 121 nm via 4 wave mixing Broad linewidth ~ 100 GHz
- High power: ~ 30 micro-J/pulse

X

UBC/TRIUMF



- >25 yrs of anti-H experience
- Laser cooling on anti-H
- 121 nm via 3rd Harmonic Generation
- Narrow line 121 nm via cw seeding

=

QUP

10 uJ/pulse
100 MHz width
5 ns pulse length

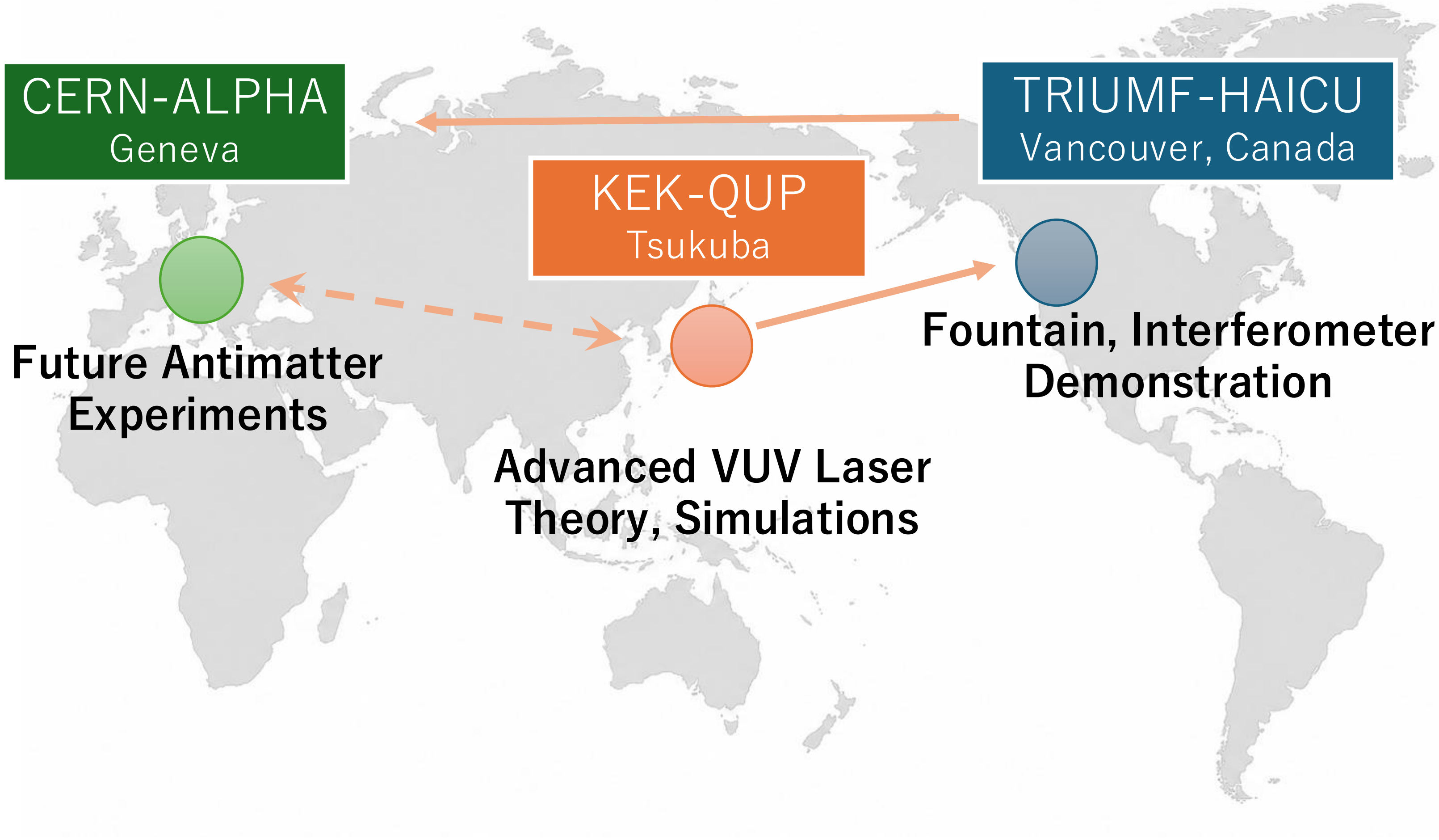
World's Highest Power Narrow Line Pulse Laser at 121 nm

New VUV technologies (phase & time shape control of ns pulses)

International Platform Driven by QUP Laser Technology

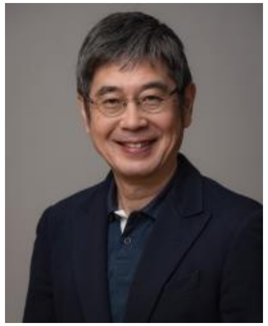
Antimatter Symmetry Test

ANTIMATTER x GRAVITY x QUANTUM



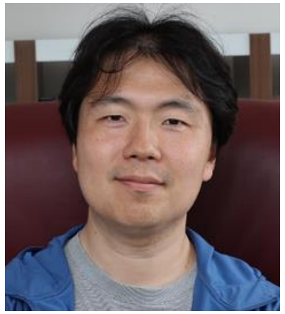
KEK QUP: Antimatter Gravity Group

Fujiwara:PI
(Apr 26 -)



Momose, QUP
Researcher
(Sep 26: tbd)

Oishi, QUP
Researcher
(June 26-)



Imai, QUP
Postdoc (Jul
26 -)

Lyman-alpha laser

Azuma, QUP
Director

Kuma*
Rikkyo U

Hydrogen source

Tokushuku
Admin Director

Mibe
Dep. Director

Shimomura*
Former Muon Head

QUP, KEK, J-PARC infrastructure

Amer, QUP Postdoc
(Aug 26-)

Theory, Simulations

Looking for Postdocs!

* not formally part of QUP

Summary

- Anti-H studies, technically-driven field, addressing fundamental questions;
  - **Past**: 25^{+} years since the start of AD at CERN, tremendous technical developments in antimatter physics
  - **Present**: we achieved one of our dreams: dropping antimatter to observe the effect of gravity
    - New results coming with ALPHA-2
  - **Future**: Exciting future is ahead for us: new era of anti-H studies, e.g. HAICU & QUP projects!

Looking forward to synergies & collaborations!