Antimatter Gravity with Muonium

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Workshop: "Searching for Physics Beyond the Standard Model Using Charged Leptons"
Colegio de Física Fundamental e Interdiciplinaria de las Américas (COFI)
San Juan, PR
25 May 2018

Outline

- Motivation
- A bit of history
- Experimental approach
- Required R&D
- Conclusions

Motivation in a Nutshell

- Standard "ΛCDM" cosmology has several major anomalies – and introduces new effects to explain them!
  - horizon & flatness problems: inflation
  - cosmic acceleration & age problems: dark energy
  - galactic rotation curves: dark matter
  - baryon asymmetry: non-SM *CP* violation

Motivation in a Nutshell

- But what if matter and antimatter repel gravitationally?
  - leads to universe with separated matter and antimatter regions (and implies ∃ gravitational dipoles)

    [M. M. Nieto & T. Goldman, "The Arguments Against 'Antigravity' and the Gravitational Acceleration of Antimatter," Phys. Rep. 205 (1991) 221]

    - baryon asymmetry is local, not global ⇒ no need for new sources of CPV

      [A. Benoit-Lévy and G. Chardin, "Introducing the Dirac-Milne universe," Astron. & Astrophys. 537 (2012) A78]

  - repulsion changes expansion rate of universe
    - possible explanation for apparent acceleration – without dark energy

      [D. Hajdukovic, "Quantum vacuum and virtual gravitational dipoles: the solution to the dark energy problem?," Astrophys. Space Sci. 339 (2012) 1]

    - all regions of early universe causally connected & older than oldest stars

      [A. Benoit-Lévy and G. Chardin, *ibid.*]

  - virtual gravitational dipoles modify gravity at long distances
    - possible explanation for rotation curves – without dark matter

      [L. Blanchet, "Gravitational polarization and the phenomenology of MOND," Class. Quant. Grav. 24, 3529 (2007);
      L. Blanchet & A.L. Tiec, "Model of dark matter and dark energy based on gravitational polarization," PRD 78, 024031 (2008)]

Motivation in a Nutshell

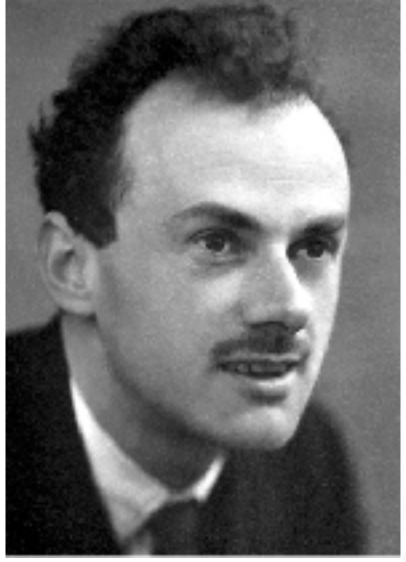
- Moreover, unclear whether Lorentz and CPT symmetry are perfect, or only approximate
  - many symmetries are only approximate:
    - isospin, parity, *CP*, *T*, lepton flavor,…
  - searching for and studying small violations has often been a fruitful way forward → "Standard Model Extension" (SME)
- Antimuon gravity can access unique SME coefficients

[V. A. Kostelecky & J. D. Tasson, "Matter-Gravity Couplings and Lorentz Violation," Phys. Rev. D 83, 016013 (2011)]

  - via small deviations from $\bar{g} = g$, or sidereal variation
- *Only way* to access gravitational coupling to 2nd gen.
- *And* generically sensitive to possible 5th forces

A bit of history…

- 1928: antimatter proposed by Dirac
  - Dirac equation (QM + relativity) described positrons in addition to electrons
  - positron discovered by Anderson in 1932
  - antiproton discovered by Chamberlain & Segrè in 1955
  - now well established that
    - all charged particles (and many types of neutrals) have antiparticles, of opposite electric charge
    - Big Bang produced exactly equal amounts of matter and antimatter


Paul A. M. Dirac

[photo credits: Nobelprize.org]


Carl Anderson


Owen Chamberlain


Emilio Segrè

Baryon Asymmetry

- Big Bang produced exactly equal amounts of matter and antimatter – a puzzle!

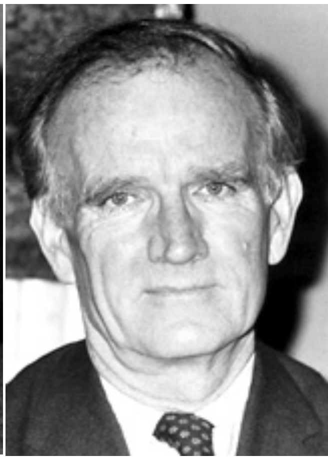
- Already in 1956, M. Goldhaber noted the "baryon asymmetry of the universe" (BAU) [M. Goldhaber, "Speculations on Cosmogeny," Science 124 (1956) 218]
  - universe seems to contain *lots* of mass in the form of baryons – protons and neutrons – but almost *no* antimatter! How could this be consistent with the BB?
  - now generally believed BAU arose through *CP violation* (discovered in 1964)
  - but, pre-1964, more plausible to postulate *gravitational repulsion* between matter and antimatter – "antigravity"!

Baryon Asymmetry

- now generally believed BAU arose through *CP violation* (discovered in 1964)

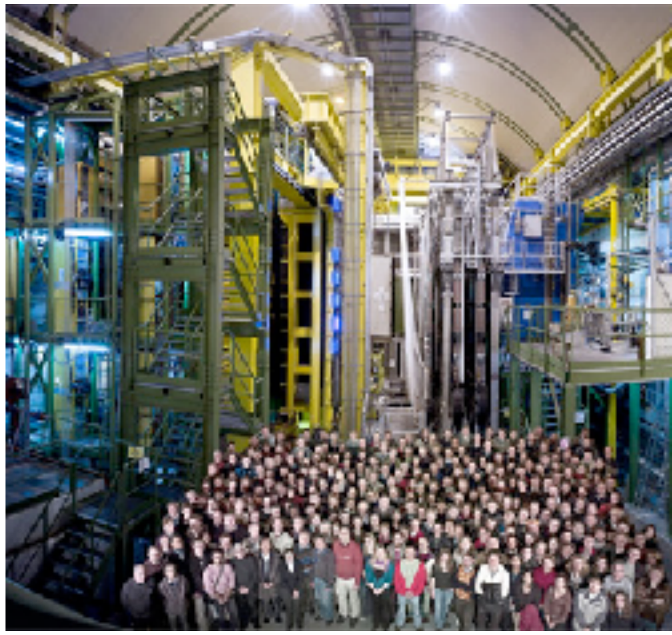
- But – where's the needed *CP* violation?
  - CPV discovery [Cronin, Fitch, et al., PRL 13 (1964) 138]: ~10^{-3} asymmetry in decays of K^0 vs $\overline{K}^0$ meson
    - too weak by *orders of magnitude* to account for observed ~1-in-10^8 BAU!
    - more *CP* violation to be discovered??
      - hot question: LHC*b*/Belle II/T2K/NOvA/DUNE… – but, so far, no experimental evidence for it

James Watson Cronin



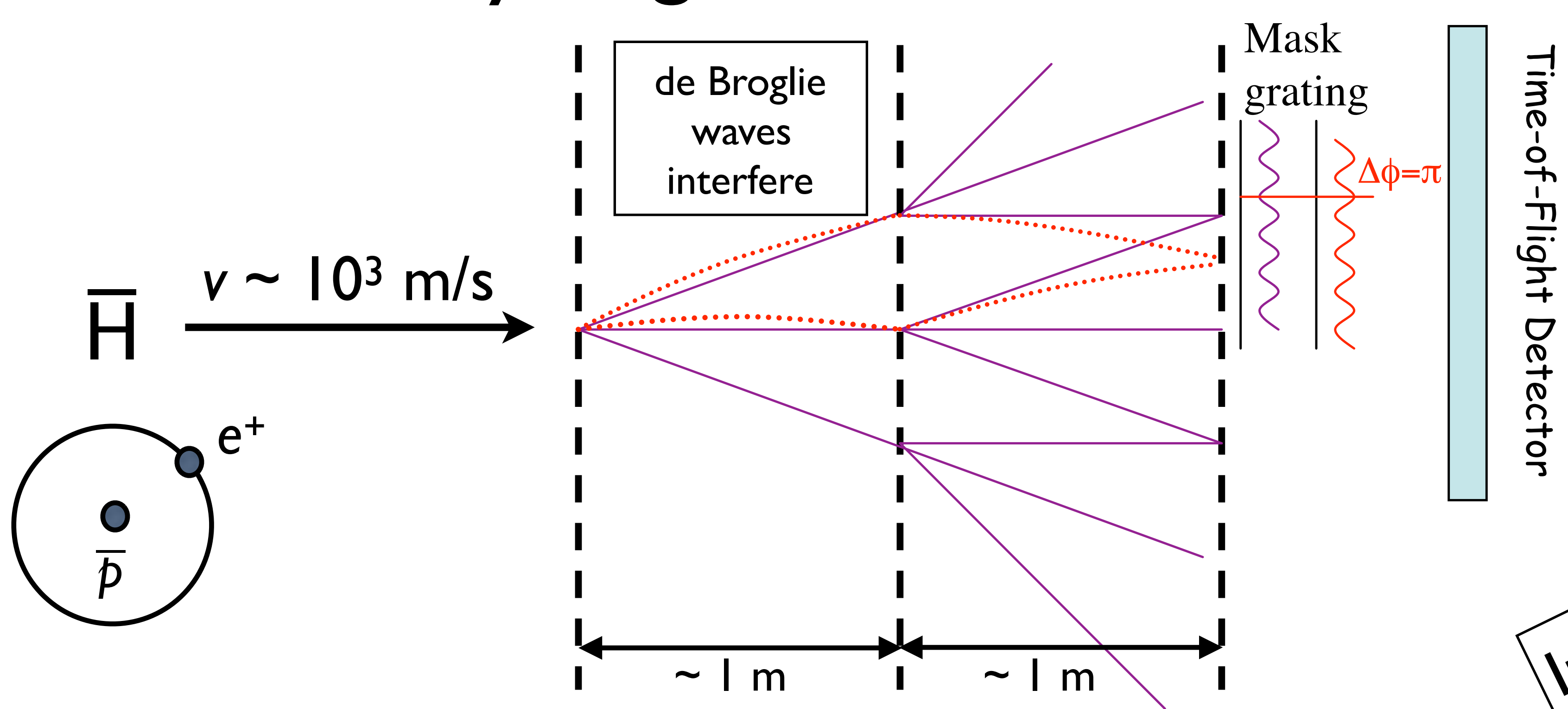
Val Logsdon Fitch

[photo credits: Nobelprize.org]



Studying Antimatter Gravity

- Experimentally, still unknown whether antimatter falls up or down! Or whether $\bar{g} - g = 0$ or ε
  - in principle a simple interferometric measurement with slow antihydrogen beam [T. Phillips, Hyp. Int. 109 (1997) 357]:



$\frac{1}{2} gt^2 = 5\ \mu m$

In either case, Equivalence Principle must be modified!

  - if $\bar{g} = -g$, antigravity as discussed above
  - if $\bar{g} = g \pm \varepsilon$, need to modify theory of gravity (scalar + vector + tensor), or add "5th force" to the known 4

Studying Antimatter Gravity

- But that's not how anybody's doing it!

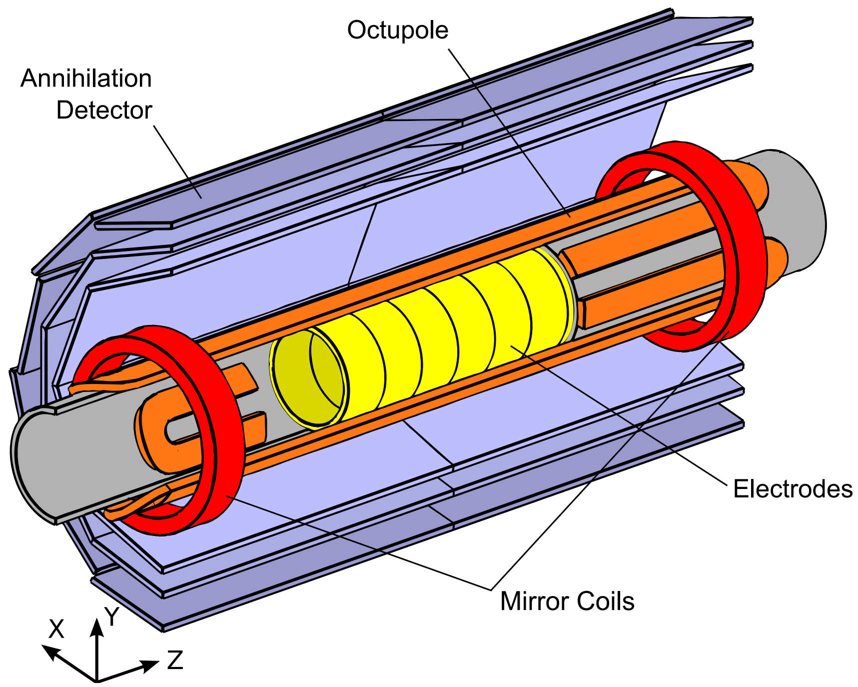
Studying Antimatter Gravity

- World leader: ALPHA* at CERN Antiproton Decelerator

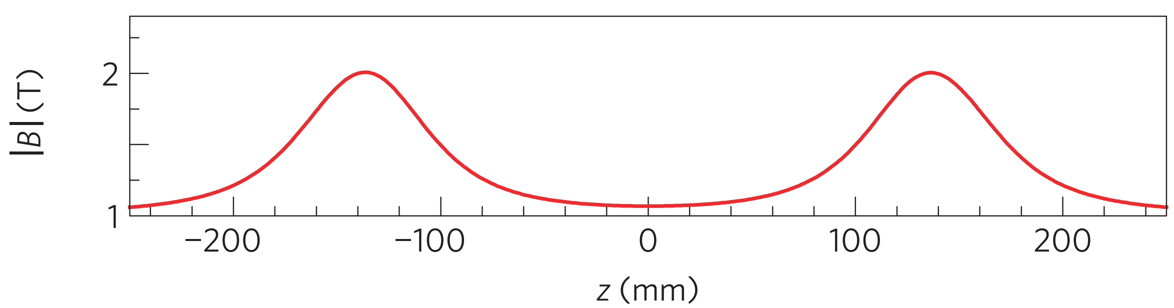
Aarhus Univ, Simon Fraser Univ, Berkeley, Swansea Univ, CERN, Univ Federal do Rio de Janeiro, Univ of Calgary, TRIUMF, Univ of British Columbia, Univ of Tokyo, Stockholm Univ, York Univ, Univ of Liverpool, Univ of Victoria, Auburn Univ, NRCN-Nuclear Research Center Negev, RIKEN

* Antihydrogen Laser Physics Apparatus

- Make antihydrogen from $\bar{p}$ and e^+ in a Penning trap, trap it with an octupole winding,



[G. B. Andresen et al., “Confinement of antihydrogen for 1,000 seconds,” Nature Phys. 7 (2011) 558]



- then shut off the magnet currents & see whether more $\bar{\mathrm{H}}$ annihilate on the top or on the bottom

[C. Amole et al., “Description and first application of a new technique to measure the gravitational mass of antihydrogen,” Nature Comm. 4 (2013) 1785]

Studying Antimatter Gravity

- The first published limit:
- Let $F = m_{\text{grav.}}/m_{\text{inert.}}$ of $\bar{\text{H}}$
- Then

  $-65 \leq F \leq 110$ @ 90% C.L.

  [ALPHA Collaboration, 2013]

- They propose improving sensitivity to $\Delta F \sim 0.5$
  - $\bar{\text{H}}$ laser-cooling (Lyman α)…
- May take ? more years?

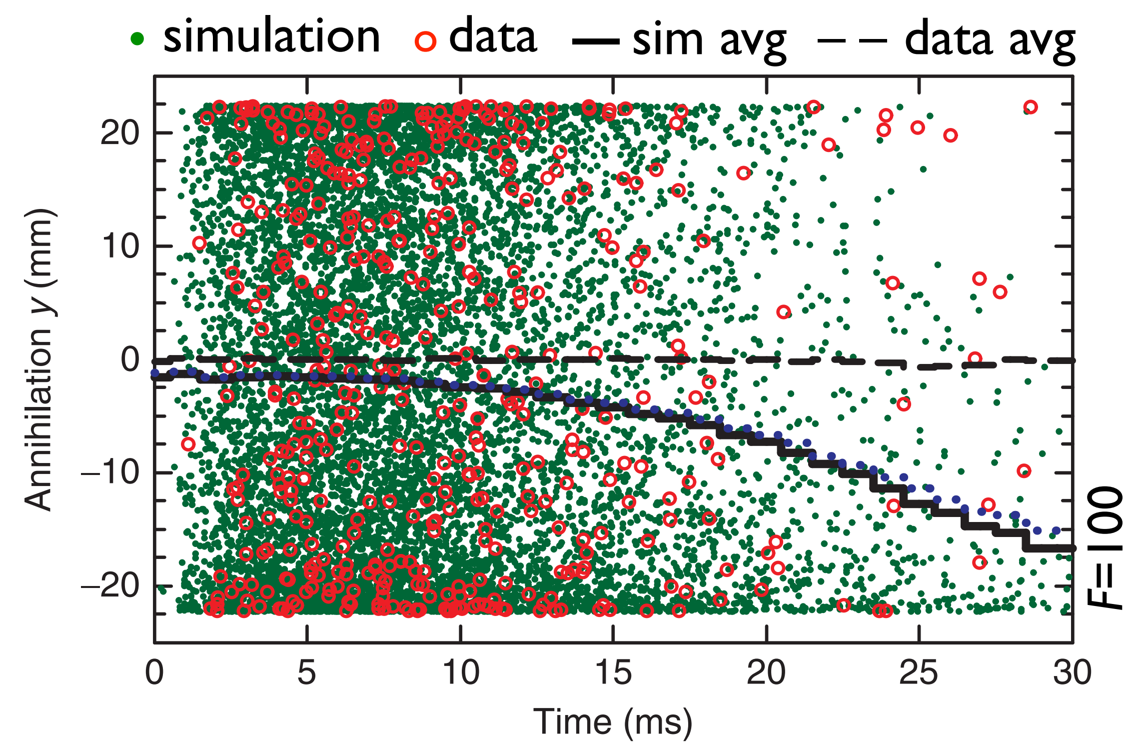


Figure 2 | Annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms in the decaying magnetic fields, as found by simulations of equation 1 with $F = 100$. Because $F = 100$ in this simulation, there is a tendency for the anti-atoms to annihilate in the bottom half ($y < 0$) of the trap, as shown by the black solid line, which plots the average annihilation locations binned in 1 ms intervals. The average was taken by simulating approximately 900,000 anti-atoms; the green points are the annihilation locations of a sub-sample of these simulated anti-atoms. The blue dotted line includes the effects of detector azimuthal smearing on the average; the smearing reduces the effect of gravity observed in the data. The red circles are the annihilation times and locations for 434 real anti-atoms, as measured by our particle detector. Also shown (black dashed line) is the average annihilation location for $\sim$840,000 simulated anti-atoms for $F = 1$.

[C. Amole et al., "Description and first application of a new technique to measure the gravitational mass of antihydrogen," Nature Comm. 4 (2013) 1785]

Studying Antimatter Gravity

- How else might it be done?
- Clearly need *neutral* antimatter –
  - or gravity's tiny effect swamped by residual EM forces (why early Fairbanks & LEAR experiments failed)
- *Many* $\overline{\mathrm{H}}$ efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)
  - too various to describe them all here…
    - but generally, $\overline{\mathrm{H}}$ hard to produce, manipulate, and cool!
    - and antiprotons required ⇒ possible only at AD
- Or see if Ps in metastable state levitates (UCL)?
- BUT – another approach may also be feasible...

Studying Antimatter Gravity

- Besides antihydrogen and positronium, only *one other* antimatter system conceivably amenable to gravitational measurement:
- Muonium (M or Mu) —
  - a hydrogenic atom with a positive (anti)muon replacing the proton
    - easy to produce but hard to study!
- Measuring muonium gravity — if feasible — could be the *first* (only?) gravitational measurement of a lepton, and of a 2nd-generation particle

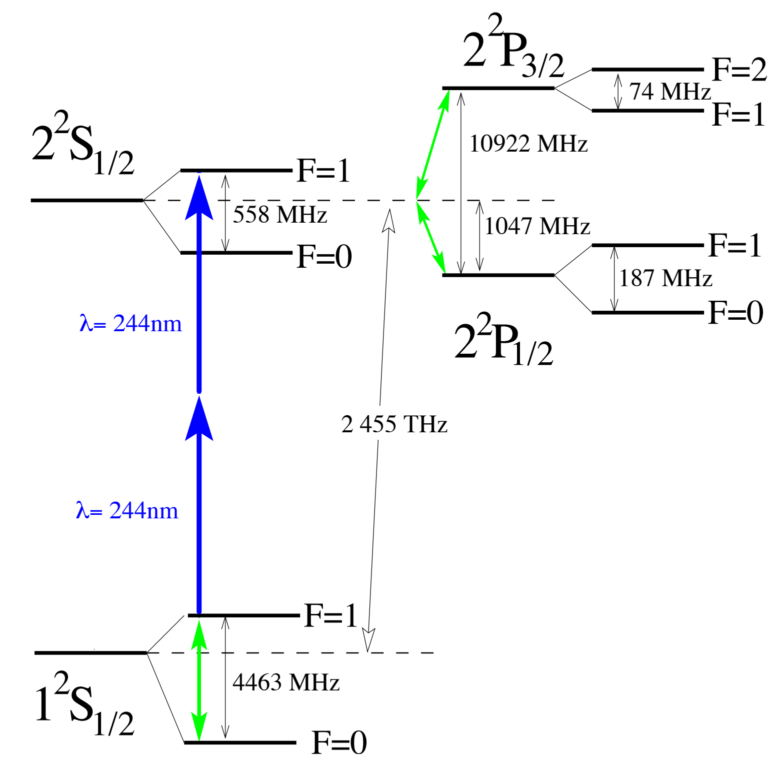
Muonium

- Much is known about muonium...
  - a *purely leptonic atom*, discovered in 1960

[V. W. Hughes et al., "Formation of Muonium and Observation of its Larmor Precession," Phys. Rev. Lett. 5, 63 (1960)]

$$\tau_M = \tau_\mu = 2.2\ \mu s$$

  - readily produced when μ^+ stop in matter
  - chemically, almost identical to hydrogen
  - atomic spectroscopy well studied
  - forms certain compounds (MuCl, NaMu,...)
  - "ideal testbed" for QED, the search for new forces, precision measurement of muon properties, etc.



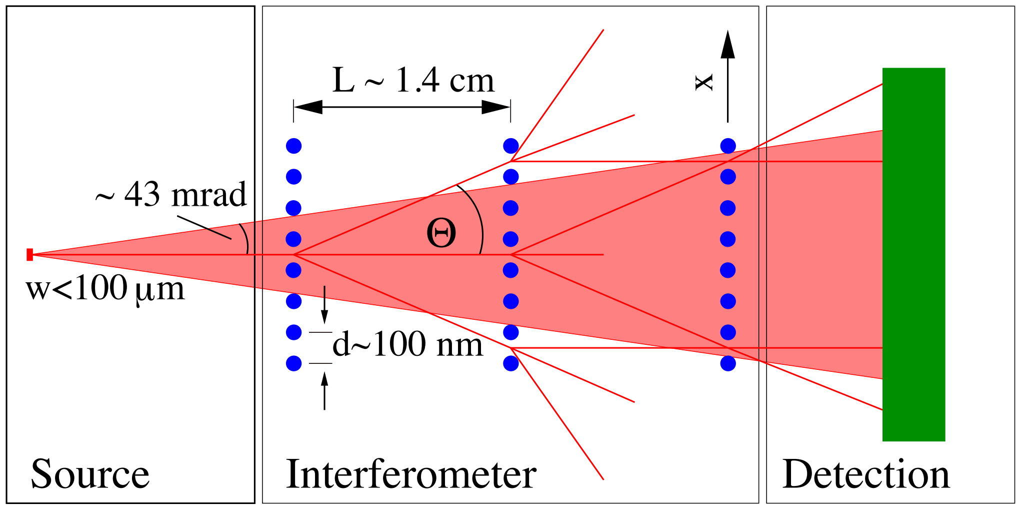
Studying Muonium Gravity

arXiv:physics/0702143v1 [physics.atom-ph]

Testing Gravity with Muonium

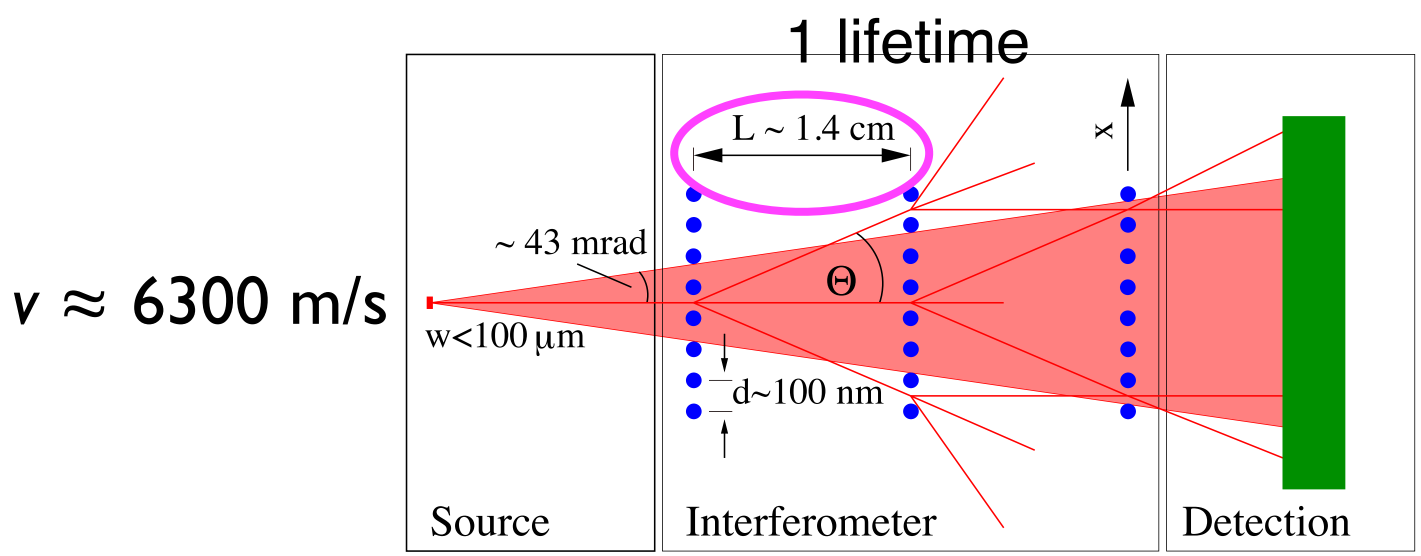
K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

Recently a new technique for the production of muon (μ^+) and muonium (μ^+e^-) beams of unprecedented brightness has been proposed. As one consequence and using a highly stable Mach-Zehnder type interferometer, a measurement of the gravitational acceleration $\bar{g}$ of muonium atoms at the few percent level of precision appears feasible within 100 days of running time. The inertial mass of muonium is dominated by the mass of the positively charged - antimatter - muon. The measurement of $\bar{g}$ would be the first test of the gravitational interaction of antimatter, of a purely leptonic system, and of particles of the second generation.



Studying Muonium Gravity

- Adaptation of T. Phillips' $\overline{\mathrm{H}}$ interferometry idea to an antiatom with a 2.2 μs lifetime! [T. Phillips, "Antimatter gravity studies with interferometry," Hyp. Int. 109 (1997) 357]



$\frac{1}{2}\,gt^2 = 24$ pm

Smaller than an *atom*!

- "Same experiment" as Phillips proposed — only harder!
- Is it feasible? How might it be done?

Studying Muonium Gravity

Part of the challenge: M production method:

- want *monoenergetic* M for uniform flight time
  - otherwise the interference patterns of different atoms will have differing relative phases,
    - so the signal could be washed out

      (although probably not a problem in practice, since the interference phase is so small…)
- want narrow, *parallel* M beam for good interferometer acceptance

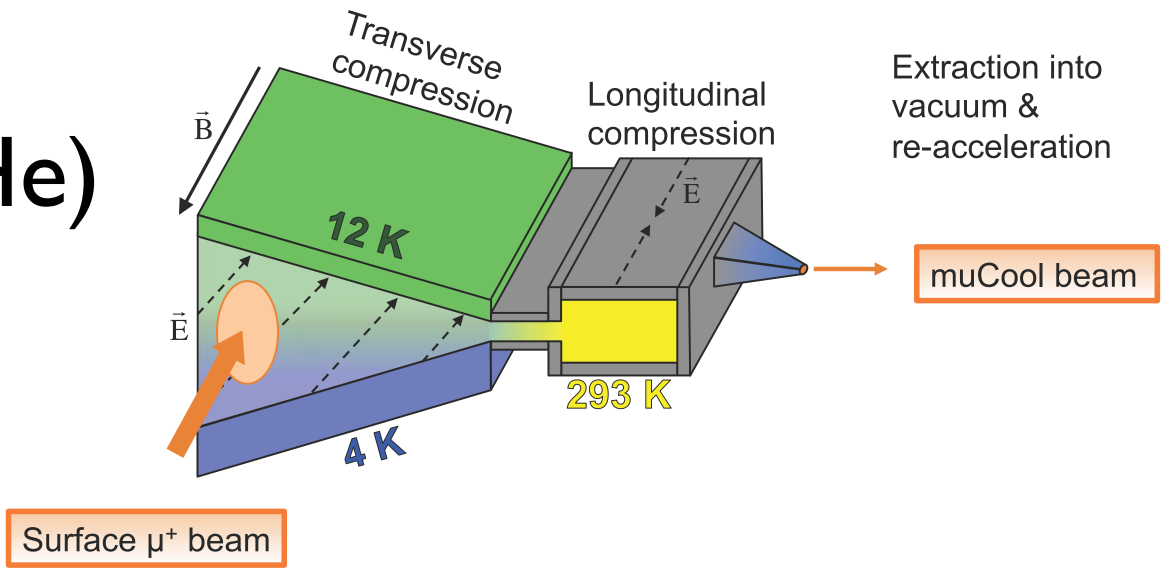
Monoenergetic Muonium?

- Proposal by D. Taqqu of Paul Scherrer Institute (Switzerland):

[D. Taqqu, "Ultraslow Muonium for a Muon beam of ultra high quality," Phys. Procedia 17 (2011) 216]

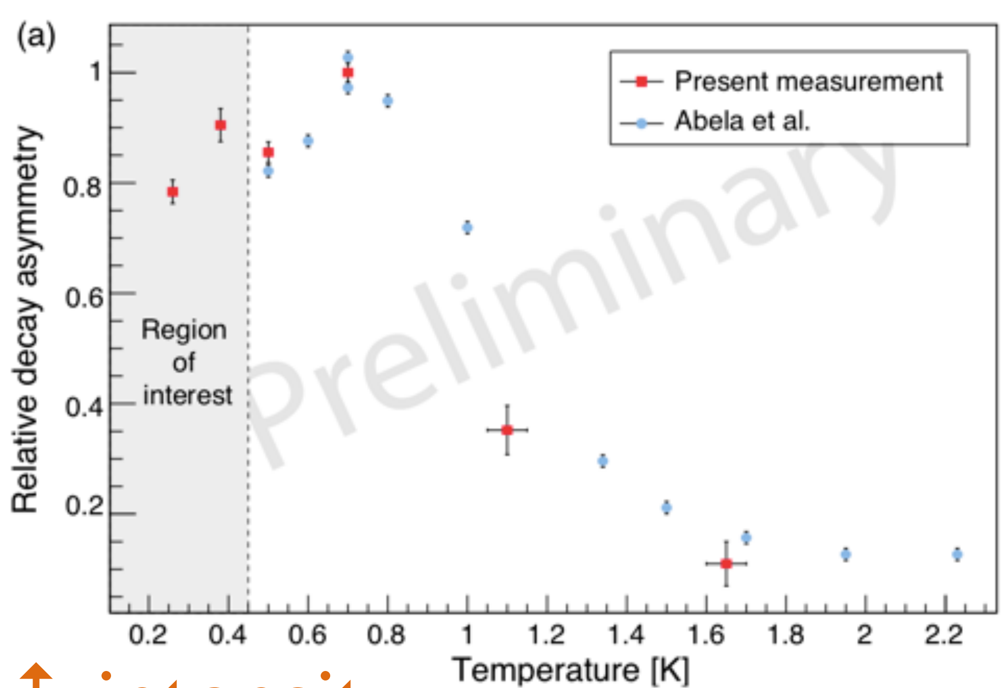
  - stop slow (keV) muons in ~ μm-thick layer of superfluid He (SFHe)

    ⇒ need "muCool" μ^+ beam upgrade



  - chemical potential of M in SFHe will eject M atoms at 6,300 m/s, ⊥ to SFHe surface
    - makes ≈ monochromatic, || beam!

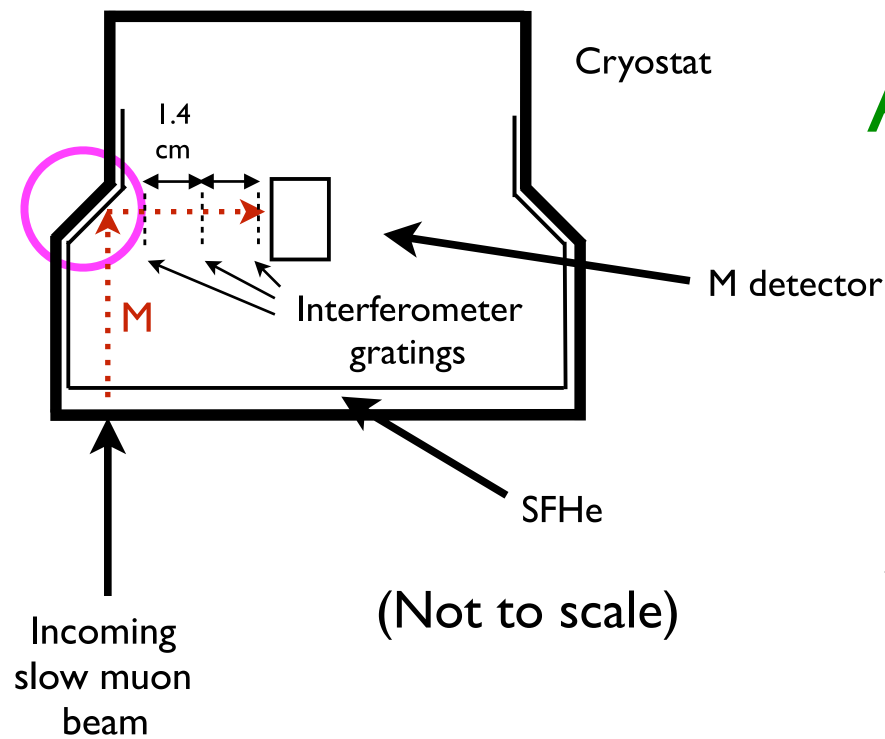
      $\Delta E/E \sim 0.1\%$



    - or use ~ 100 μm SFHe layer for ~ 10^2 ↑ intensity

Experiment Concept

- One can then imagine the following apparatus:



A "ship in a bottle!"

Sensitivity estimate @ 100 kHz:

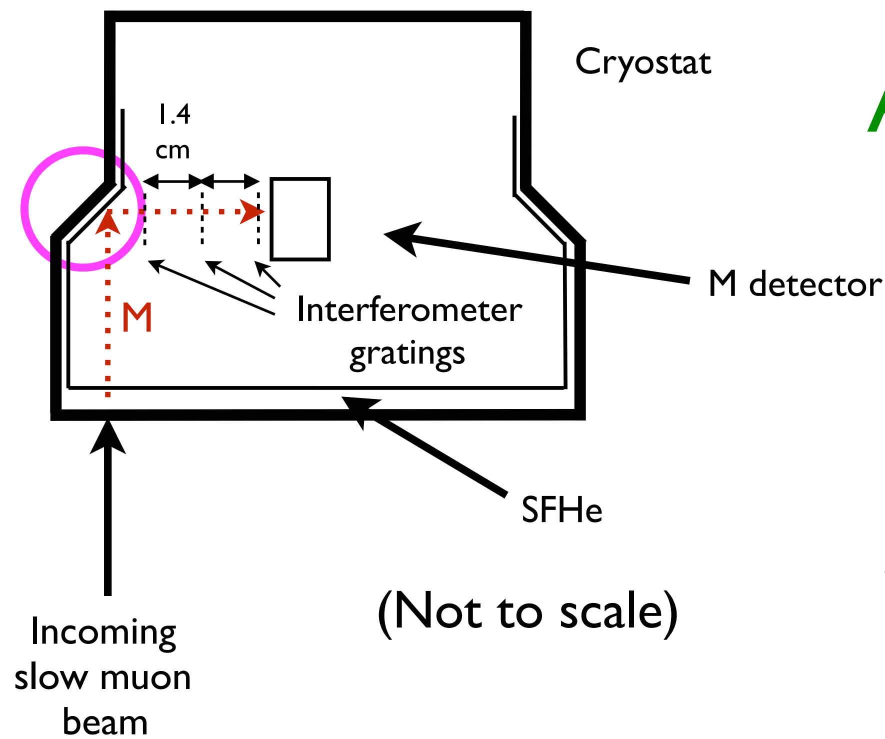
$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$

$$\approx \; 0.3\,\mathrm{g}\;\;\mathrm{per}\,\sqrt{\#\mathrm{days}}$$

- Well known property of SFHe to coat surface of its container
- 45° angled section of cryostat thus serves as reflector to turn vertical M beam emerging from SFHe surface into the horizontal

Experiment Concept

- One can then imagine the following apparatus:



A "ship in a bottle!"

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$$S = \frac{1}{C\sqrt{N_0}} \frac{d}{2\pi} \frac{1}{\tau^2}$$
$$\approx 0.3\,\mathrm{g} \ \text{per} \sqrt{\#\text{days}}$$

where
C = 0.3 (est. contrast)
N_0 = # of events
d = 100 nm (grating pitch)
τ = M lifetime

➡ Muonium Antimatter Gravity Experiment (MAGE)

Focusing a Beam of Ultracold Spin-Polarized Hydrogen Atoms with a Helium-Film-Coated Quasiparabolic Mirror

V. G. Luppov
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
and Joint Institute for Nuclear Research, Dubna, Russia

W. A. Kaufman, K. M. Hill,* R. S. Raymond, and A. D. Krisch
Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan 48109-1120
(Received 7 January 1993)

We formed the first "atomic-optics" beam of electron-spin-polarized hydrogen atoms using a quasi-parabolic polished copper mirror coated with a hydrogen-atom-reflecting film of superfluid ^{4}He. The mirror was located in the gradient of an 8-T solenoidal magnetic field and mounted on an ultracold cell at 350 mK. After the focusing by the mirror surface, the beam was again focused with a sextupole magnet. The mirror, which was especially designed for operation in the magnetic field gradient of our solenoid, increased the focused beam intensity by a factor of about 7.5.

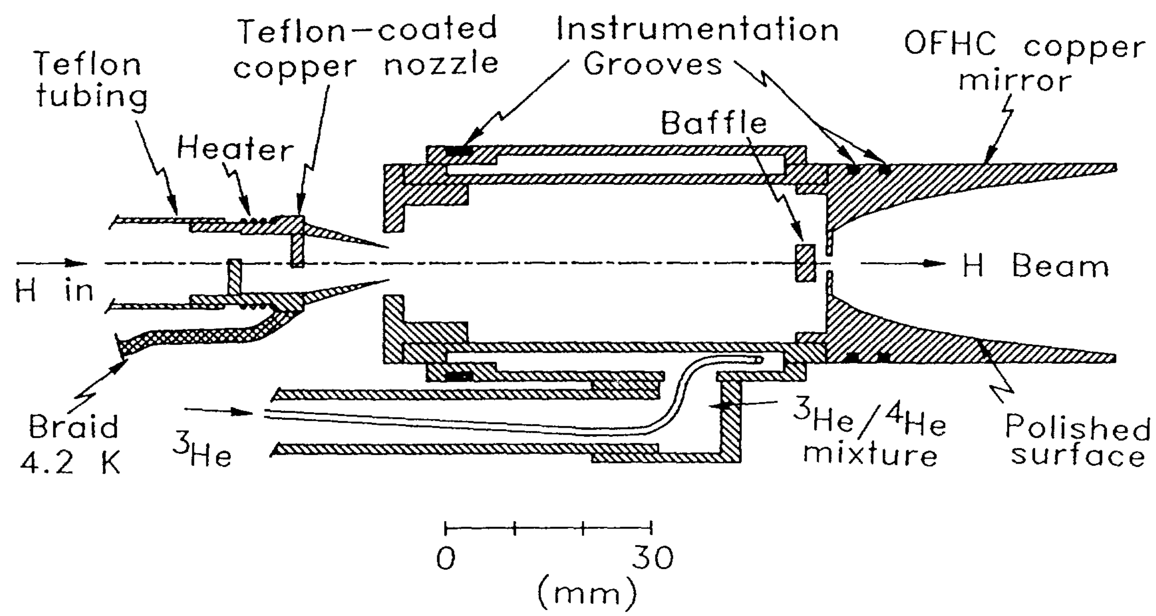


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

Muonium Gravity Experiment

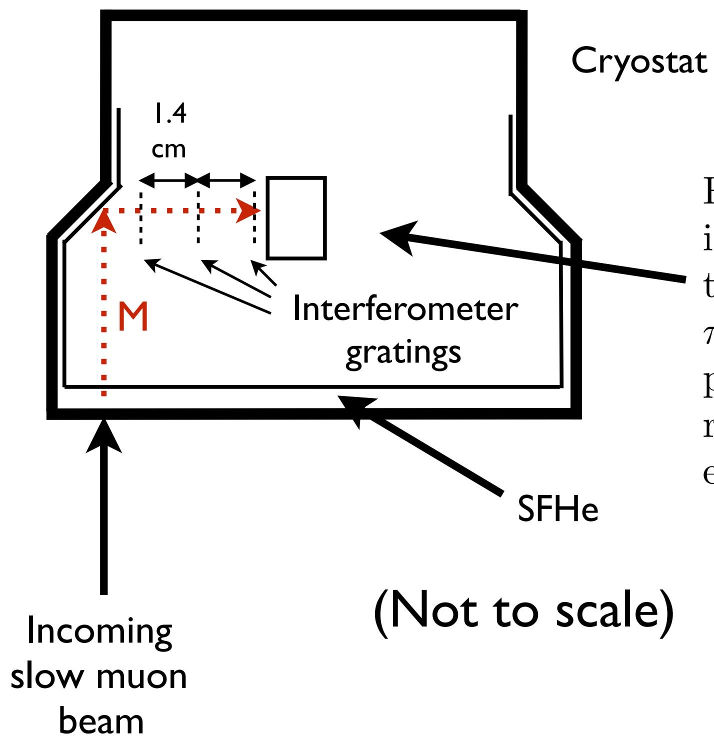
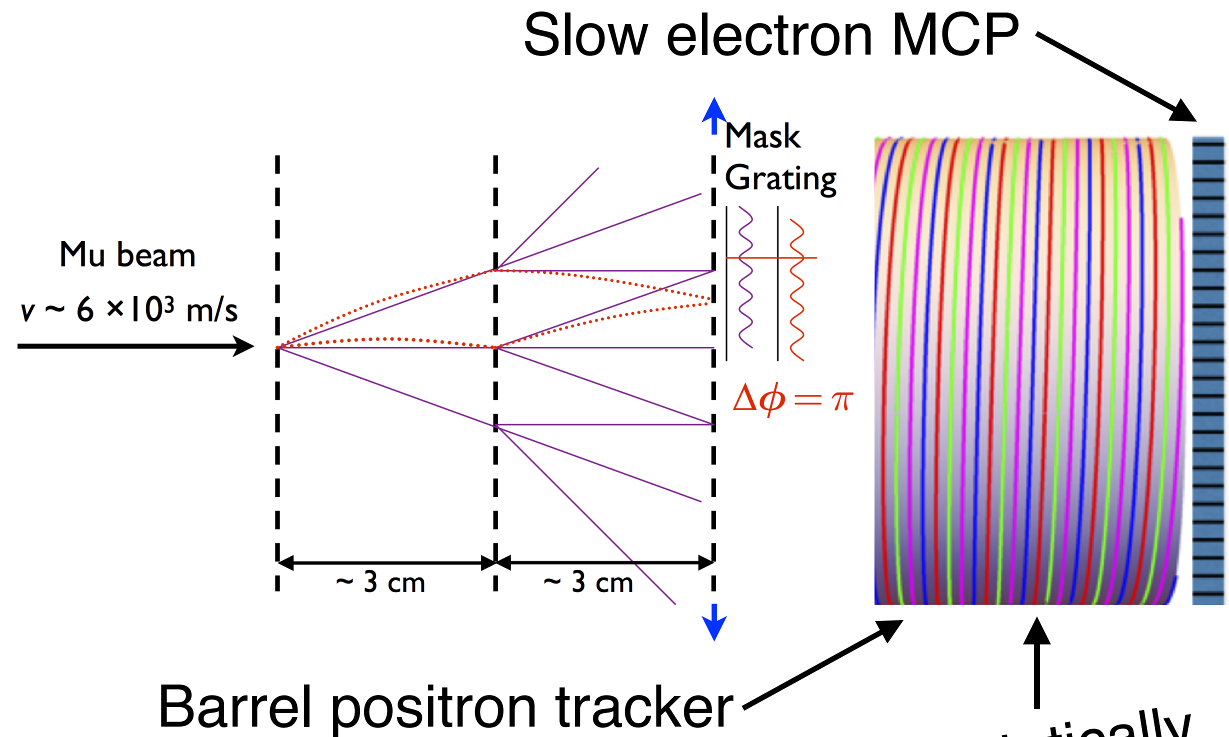


Figure 1: Principle of muonium interferometer, shown in elevation view (phase difference $\Delta\phi = \pi$ shown for illustrative purposes); Mu-decay detectors (barrel SciFi positron tracker and electron MCP) shown at right.



Electrons electrostatically accelerated towards MCP

(electrodes not shown)

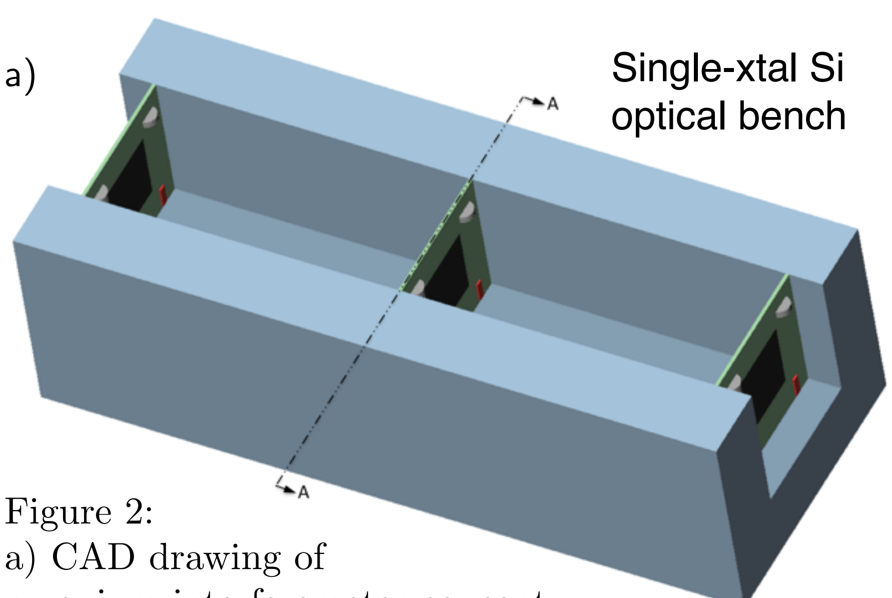
- Some important questions:

1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer be aligned to a few pm and adequately stabilized against vibration?
3. Can interferometer and detector be operated at cryogenic temperature?
4. How determine zero-degree line?
5. Does Taqqu's scheme work?

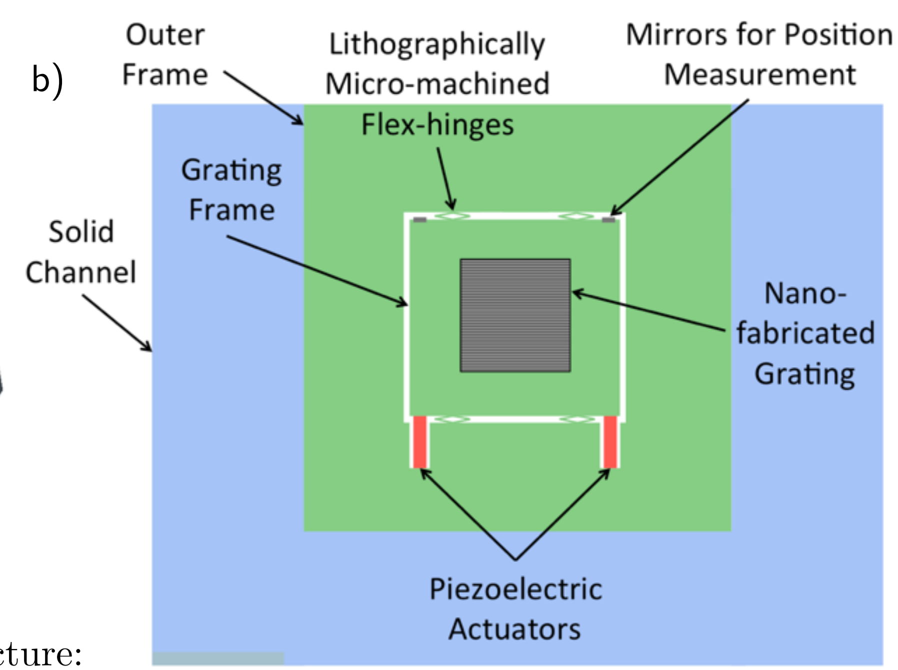
Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini, a founder of ANL Center for Nanoscale Materials (CNM), thinks so (CNM claims sub-nm precision) – proposal approved at CNM to try it (in progress)
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & POEM do much better than we need
   - we are operating a POEM distance gauge (TFG) at IIT

a)



b)



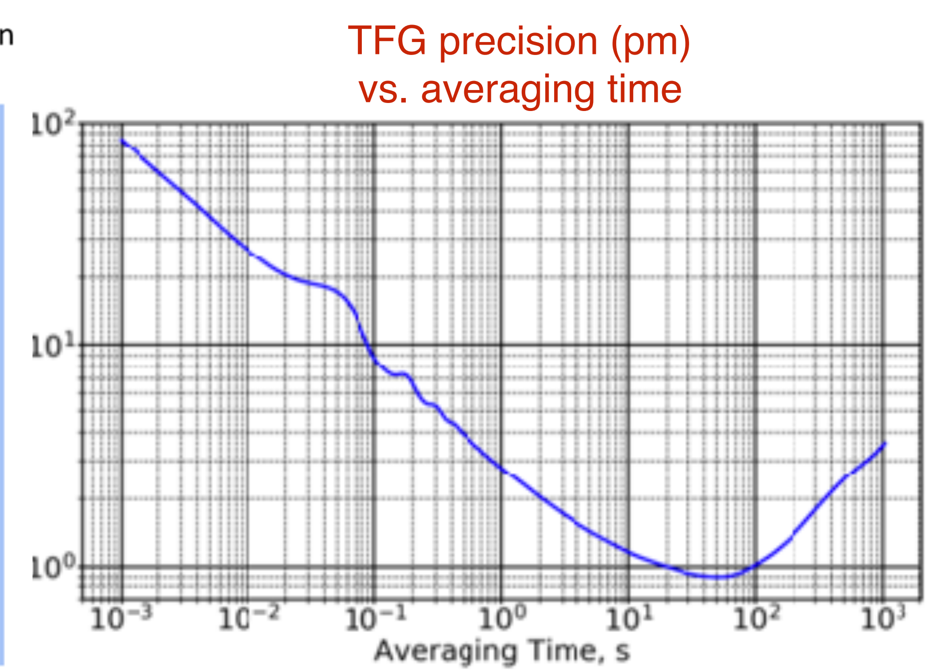
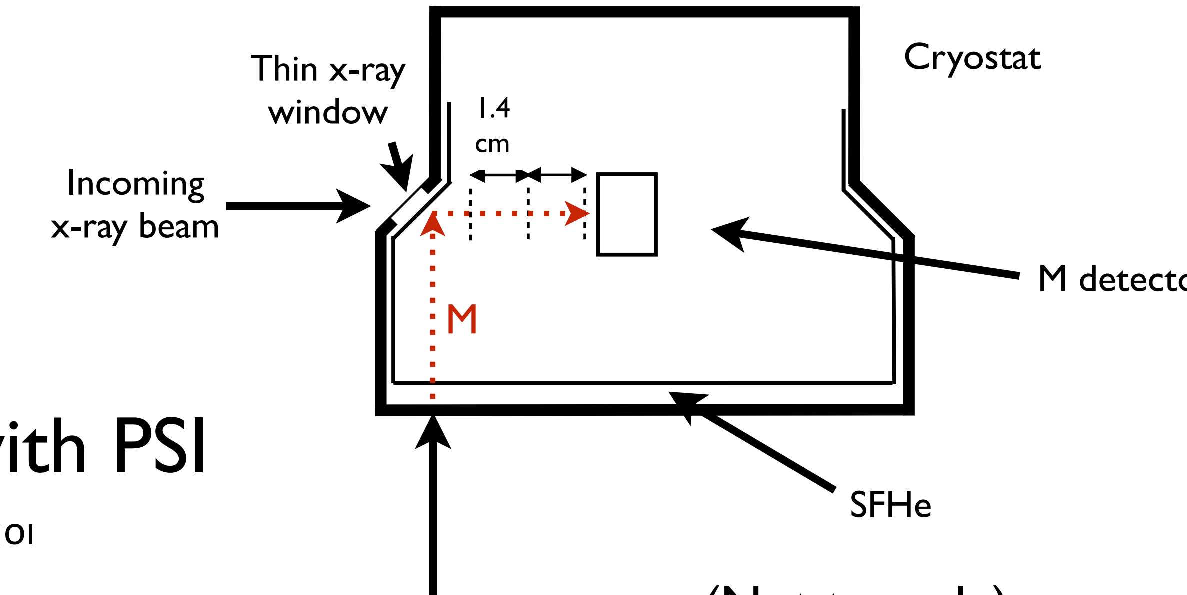


Figure 3. Allan deviation indicating TFG incremental-distance precision vs averaging time.

Figure 2:
a) CAD drawing of muonium interferometer concept;
b) Section A-A. In blue-gray is grating support structure: a U-channel machined out of a single-crystal silicon block. Each grating is mounted in a silicon frame connected to an outer frame by flex-hinges; piezo-actuator pair permits small rotations to align the gratings precisely in parallel, as well as scanning of grating 3. Grating frames have mirrors or corner-cube retroflectors at top corners that form part of the laser distance gauges (TFGs) used to measure their position.

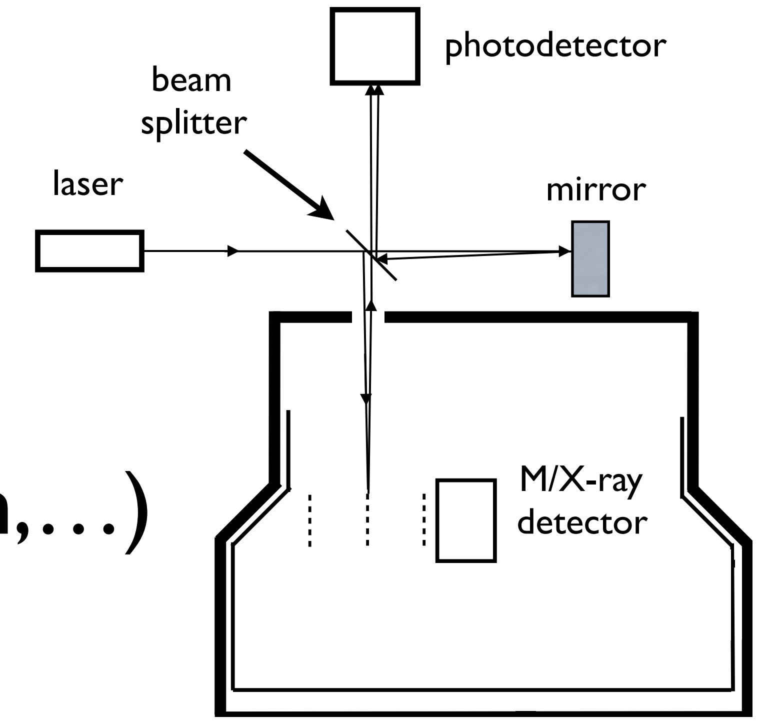
Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini, a founder of ANL Center for Nanoscale Materials (CNM), thinks so (CNM claims sub-nm precision) – proposal approved at CNM to try it (in progress)
2. Can interferometer be aligned, and stabilized against vibration, to several pm?
   - needs R&D, but LIGO & POEM do much better than we need
   - we are operating a POEM distance gauge (TFG) at IIT
3. Can interferometer and detector be operated at cryogenic temperature?
   - needs R&D; at least piezos OK; material properties favorable
4. How determine zero-degree line?
   - use cotemporal X-ray beam
5. Does Taqqu's scheme work?
   - needs R&D; we're working on it with PSI



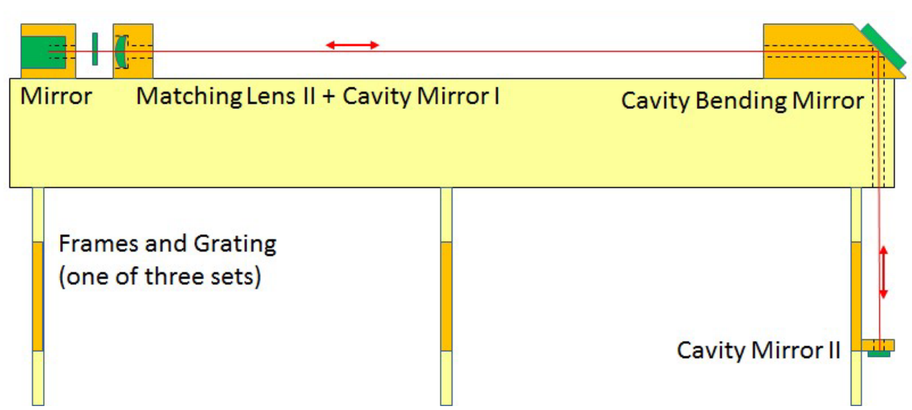
Interferometer Alignment

- Concept: 2 laser interferometers per grating
  - using λ = 1560 nm, need ~ 3 pm sensitivity ⇒ ~ $10^{-6}\,\lambda$
    - use PDH locking à la LIGO (resonance, interferometer null, heterodyne detection,…)
      – shot-noise limit (1 μW) = 0.04 pm
      – 1 pm demonstrated (averaging over 100 s)
    - To do:
      – reduce laser power
      – demonstrate in appropriate geometry
      – use TFG to demonstrate stability of muonium interferometer structure…



"Tracking Frequency Gauge" (TFG)

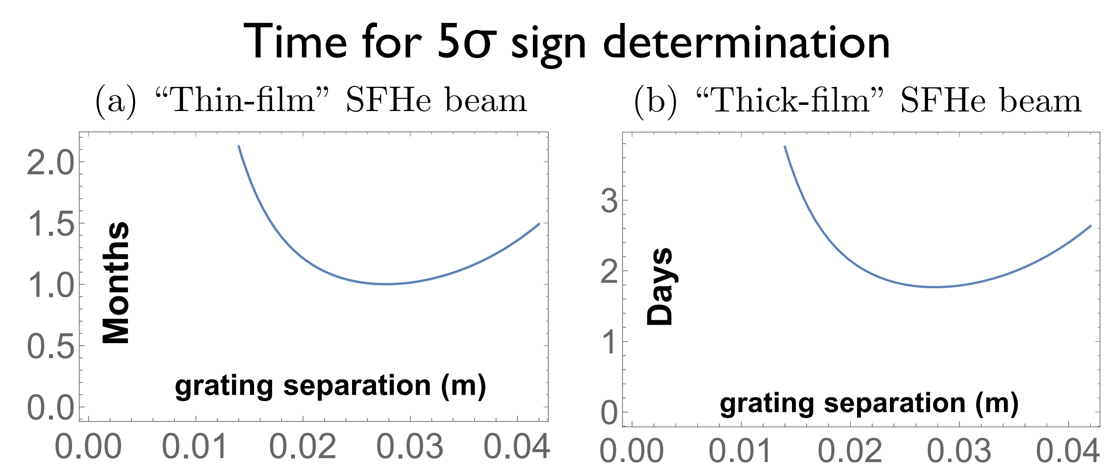
[R. Thapa et al., "Subpicometer length measurement using semiconductor laser tracking frequency gauge," Opt. Lett. **36**, 3759 (2011)]



Additional Considerations

- What's the optimal muonium pathlength?
  - say muonium interferometer baseline doubled: costs e^{-2} = 1/7.4 in event rate, but gains x 4 in deflection
    - a net win by $4\,e^{-1} \approx 1.5$ → Statistically optimal!
  - OTOH, tripling baseline → x 1.2 improvement
    - still better than 1 lifetime, though returns diminishing
    - but 9x bigger signal ⇒ easier calibration, alignment, & stabilization

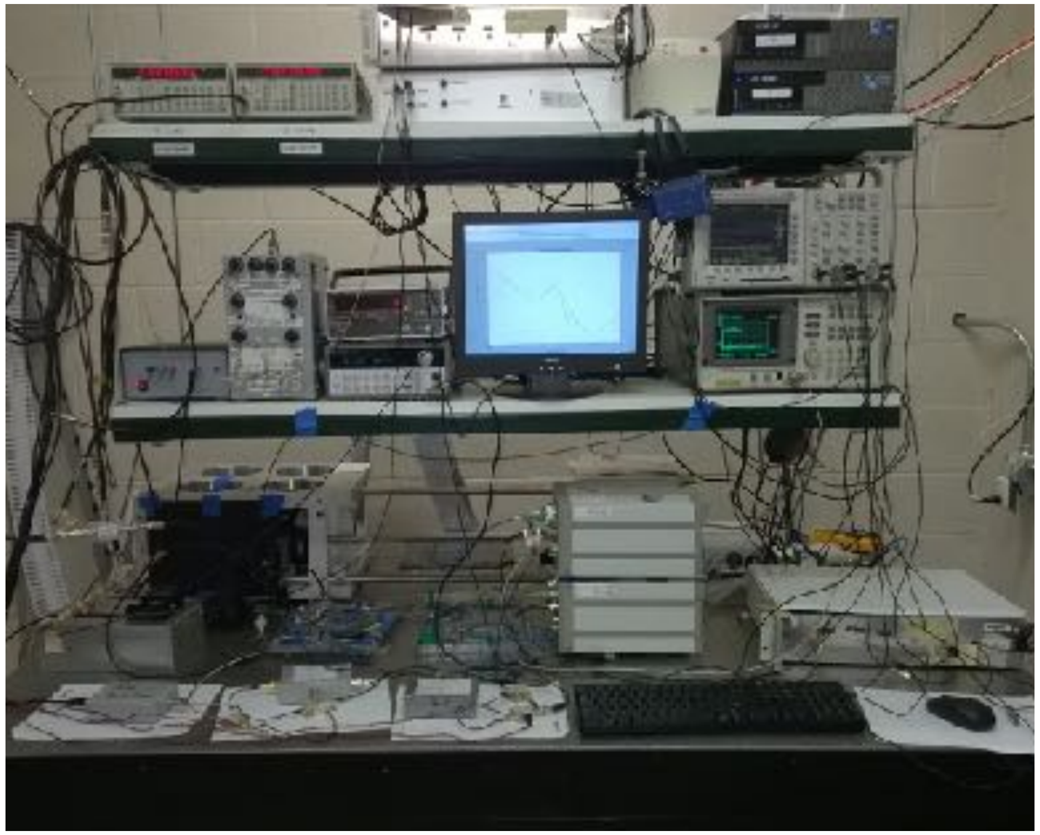
Figure 4: Representative MAGE sensitivity estimates vs. grating separation for beam options described in text, with 0.5 μm-thick gratings of 100 nm pitch, assuming 10% contrast and that the dominant error is statistical; shown is beam time required for 5σ determination of the sign of $\bar{g}$ (i.e., $\delta\bar{g}/g = 0.4$).[5]



- Need simulation study to identify *practical* optimum, taking all effects into account

Prospects

- To do the experiment we need a grant!
  - to get a grant we need a track record of accomplishment!
- We're the beneficiaries of the POEM program at Harvard–Smithsonian CfA
  - including 2 TFGs
  - so we have opportunity to demonstrate expertise!



  - & develop MAGE & G-POEM with teams of undergrads (thanks to IIT IPRO program)

G-POEM @ CfA

Reasenberg&Phillips CfA lab packed into 53′ semi trailer

G-POEM @ CfA

Unpacked @ IIT

G-POEM @ CfA

Unpacked @ IIT

Latest Papers

Journal of Instrumentation

Improved performance of semiconductor laser tracking frequency gauge

D.M. Kaplan[a], T.J. Roberts[a], J.D. Phillips[a] and R.D. Reasenberg[b]

Published 14 March 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab
Journal of Instrumentation, Volume 13, March 2018

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MAGE Collaboration

Abstract

We describe new results from the semiconductor-laser tracking frequency gauge, an instrument that can perform sub-picometer distance measurements and has applications in gravity research and in space-based astronomical instruments proposed for the study of light from extrasolar planets. Compared with previous results, we have improved incremental distance accuracy by a factor of two, to 0.9 pm in 80 s averaging time, and absolute distance accuracy by a factor of 20, to 0.17 μm in 1000 s. After an interruption of operation of a tracking frequency gauge used to control a distance, it is now possible, using a nonresonant measurement interferometer, to restore the distance to picometer accuracy by combining absolute and incremental distance measurements.

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Atoms 2018, 6(2), 17; doi:10.3390/atoms6020017 (registering DOI)

Open Access Feature Paper Article

Studying Antimatter Gravity with Muonium

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Received: 13 February 2018 / Revised: 23 March 2018 / Accepted: 26 March 2018 / Published: 9 April 2018

(This article belongs to the Special Issue Measuring Gravity in the Lab)

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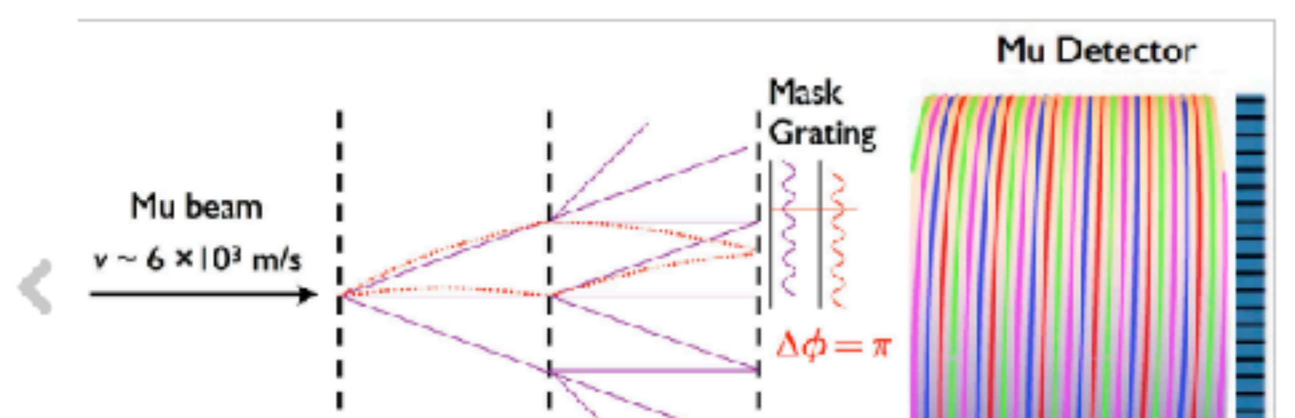
Abstract

The gravitational acceleration of antimatter, $\bar{g}$, has yet to be directly measured; an unexpected outcome of its measurement could change our understanding of gravity, the universe, and the possibility of a fifth force. Three avenues are apparent for such a measurement: antihydrogen, positronium, and muonium, the last requiring a precision atom interferometer and novel muonium beam under development. The interferometer and its few-picometer alignment and calibration systems appear feasible. With 100 nm grating pitch, measurements of $\bar{g}$ to 10%, 1%, or better can be envisioned. These could constitute the first gravitational measurements of leptonic matter, of 2nd-generation matter, and possibly, of antimatter. View Full-Text

Keywords: gravity; antimatter; muonium; atom interferometer; tracking frequency gauge

▼ Figures



Conclusions

- Antigravity hypothesis might neatly solve several vexing problems in physics and cosmology
  - or $\bar{g} = g \pm \varepsilon$ may point the way to a deeper theory
- In principle, testable with antihydrogen, positronium, or muonium
  - if possible, *all* 3 should be measured — *especially* if $\bar{\mathrm{H}}$ found anomalous

➡ First measurement of muonium gravity would be a milestone!

- But 1st must determine feasibility — in progress!

Final Remarks

- These measurements are a required homework assignment from Mother Nature!

- Whether $\overline{g} = -g$ or not, if successfully carried out, the results will certainly appear in future textbooks.

BACKUPS

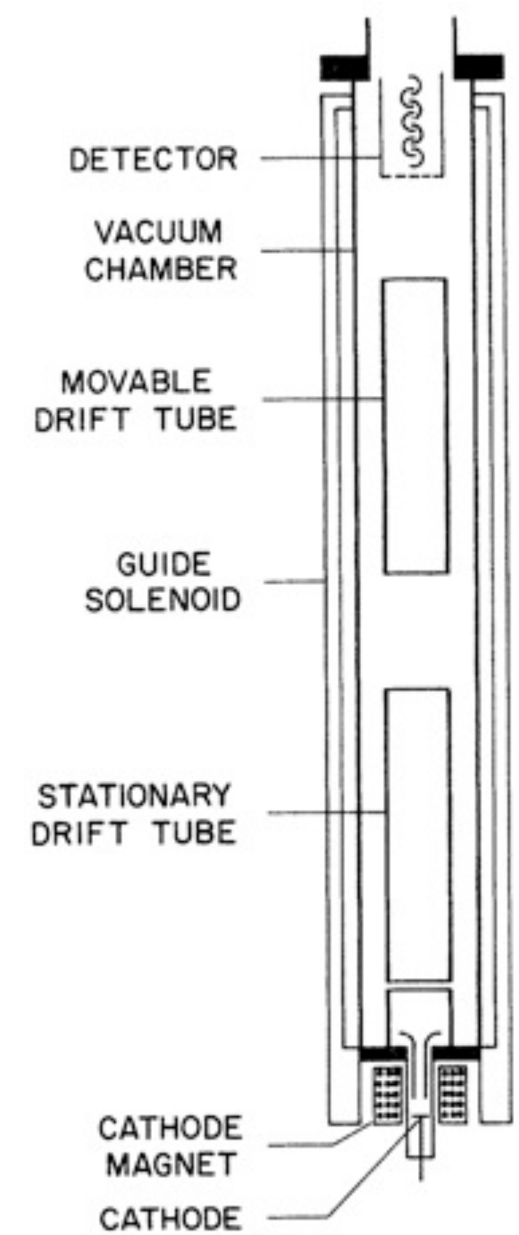
Studying Antimatter Gravity

- First attempt to address the question!
- Famous experiment, intended to measure gravitational force on positrons
- Started with *electrons* in copper drift tube; measured maximum time of flight
- Managed only to set an upper limit:

$$F < 0.09\ mg \Rightarrow \textit{electrical levitation?}$$

  - and what about patch effect…?
- Indicated difficulty of a (never-published) measurement with positrons

[F. C. Witteborn & W. M. Fairbank, "Experimental Comparison of the Gravitational Force on Freely Falling Electrons and Metallic Electrons," Phys. Rev. Lett. 19,1049 (1967)]



Next Attempt

- Los Alamos-led team proposed (1986) to measure gravitational force on antiprotons at the CERN Low Energy Antiproton Ring (LEAR)
- Similar approach to Witteborn & Fairbank, but with 2000x greater *m*/*q* ratio
- Project ended inconclusively

▸ Generally taken as evidence that gravitational measurements on *charged* antimatter are hopeless

➡ need to work with *neutral* antimatter

Progress

- IPROs and Brazilian Scientific Mobility Program summer students have been productive
  - accomplishments (so far):
    - Mathematica, C, and Python codes to model 3-grating interferometer (signal)
    - G4beamline code to model interferometer and detector geometry and materials (backgrounds)
    - FEA modeling of thermo-mechanical properties of interferometer bench and gratings begun
    - flex-hinges designed and FEA-analyzed
    - prototype grating layouts for e-beam litho @ CNM
    - setup of new lab space @ IIT
    - world's best TFG performance demonstrated

Do we need to test the POE?

- Many argue not – Eötvös/Eöt-Wash, earth-moon-sun system,…"set limits $\mathcal{O}(10^{-[7-9]})$"*
- But these arguments *all* rest on *untested assumptions* – e.g. [Alves, Jankowiak, Saraswat, arXiv:0907.4110v1]

  "We then make the assumption that any deviation of g_{H} from $g_{\bar{\mathrm{H}}}$ would manifest itself as a violation of the equivalence principle in these forms of energy† at the same level."

- Aren't such assumptions worth testing???

☞ especially when doing so costs ⋘ LHC?

☞ and so much is potentially at stake?

* in any case, these don't apply to muons

† i.e., fermion loops and sea antiquarks