Antimatter Gravity – with Muonium?

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Outline

- Motivation
- Experimental approach
- Required R&D
- Conclusions

Motivation in a Nutshell

- Standard cosmology has (at least) 4 major anomalies – and introduces a new effect to explain each!
  - horizon and flatness problems: inflation
  - cosmic acceleration: 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 – no need for inflation

      [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

Studying Antimatter Gravity

- How might it be tested experimentally?
- Clear that one needs *neutral* antimatter –
  - otherwise gravity's tiny effect swamped by residual EM forces
  - has led to multiple *antihydrogen* ($\overline{\mathrm{H}}$) gravity efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)
    - but $\overline{\mathrm{H}}$ hard to produce and manipulate!
    - antiprotons required ⇒ possible only at AD
- However – another approach may also be feasible...

Studying Antimatter Gravity

- Besides antihydrogen, only *one* (or 2?) *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* gravitational measurement of a lepton, and of a 2nd-generation particle

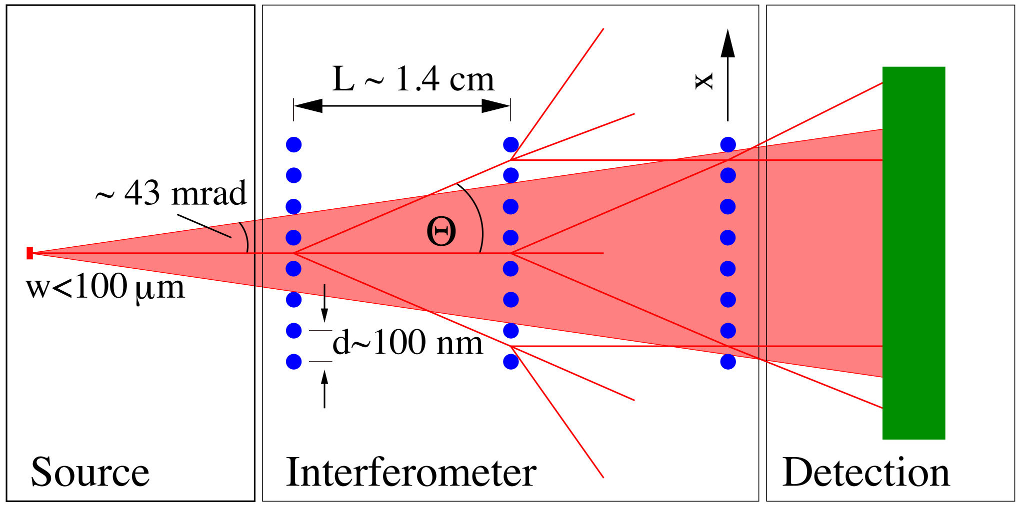
Studying Muonium Gravity

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

Testing Gravity with Muonium

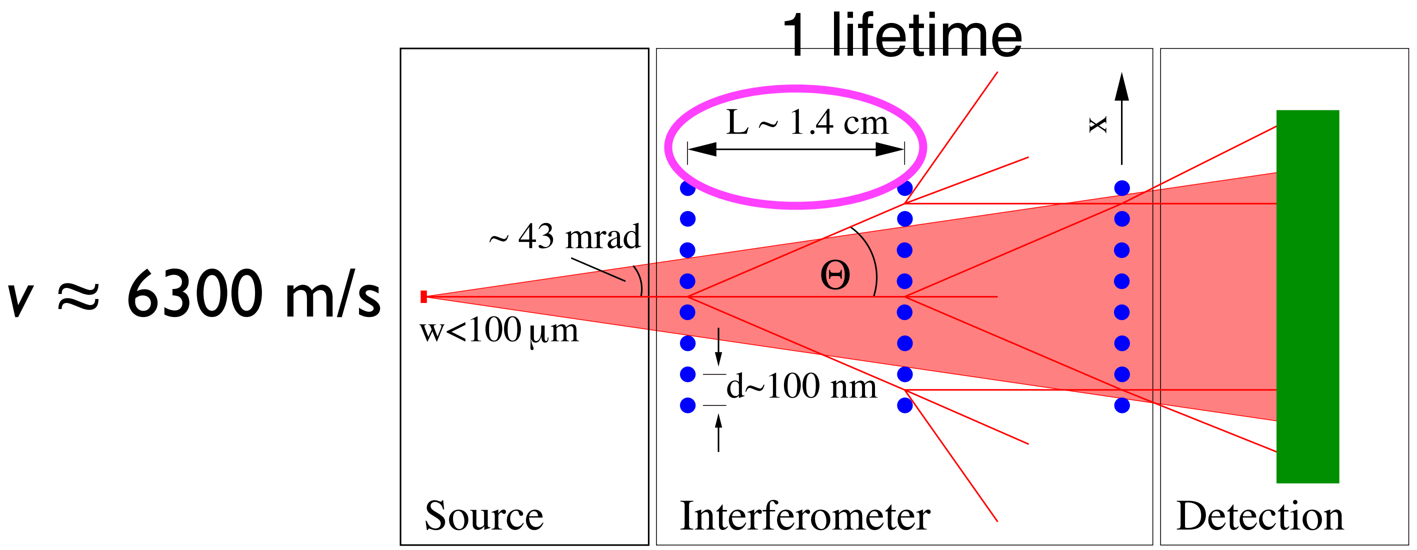
K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

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' $\overline{\text{H}}$ 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 is the M production method:
  - need *monoenergetic* M so as to have uniform flight time
    - otherwise the interference patterns of different atoms will have differing relative phases,
      - so the signal will be washed out

Monoenergetic Muonium?

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

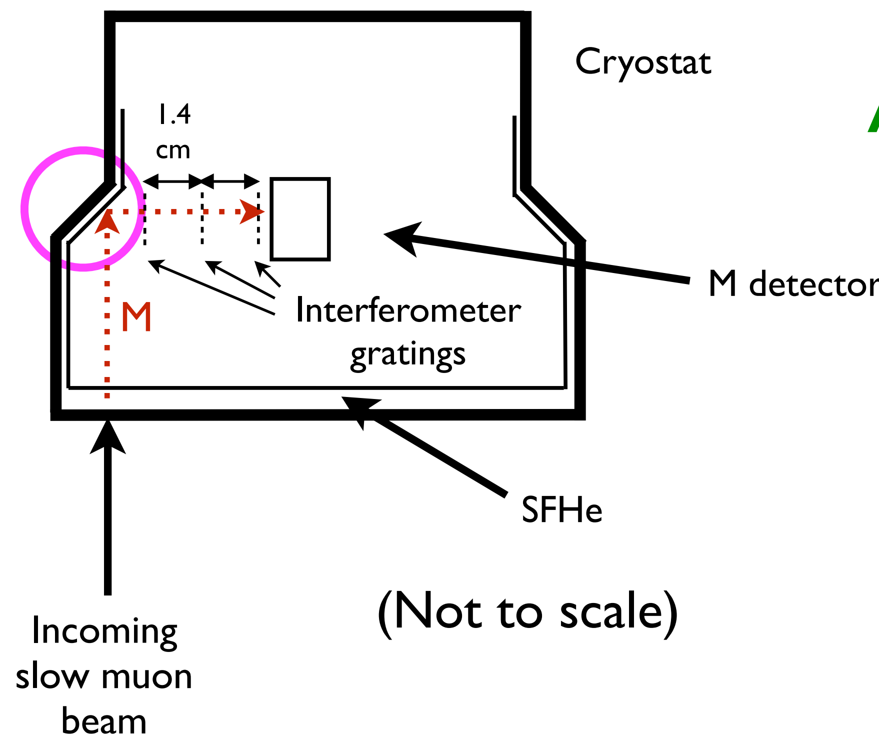
[D. Taqqu, "Ultraslow Muonium for a Muon beam of ultra high quality," Phys. Procedia 17 (2011) 216]

  - stop slow (keV) muons in μm-thick layer of superfluid He (SFHe)
  - chemical potential of hydrogen in SFHe will eject M atoms at 6,300 m/s, perpendicular to SFHe surface
    - makes ≈ monochromatic beam!

$$\Delta E/E \approx 0.2\%$$

Muonium Gravity Experiment

- One can then imagine the following apparatus:



A "ship in a bottle!"

Sensitivity estimate @ 100 kHz:

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

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

Muonium Gravity Experiment

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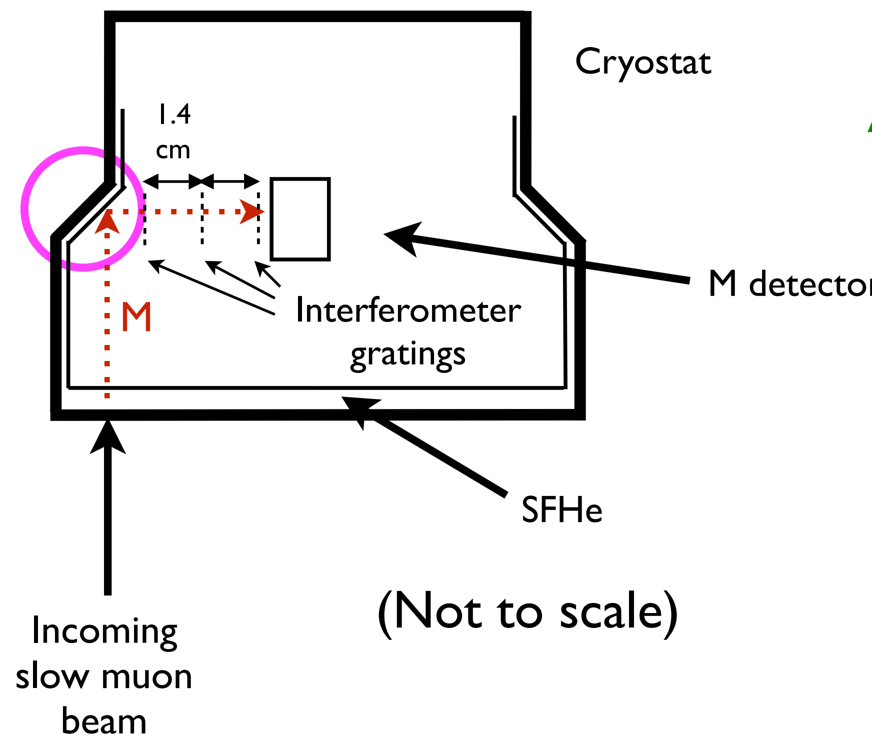

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Sensitivity estimate
@ 100 kHz:

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

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

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

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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.

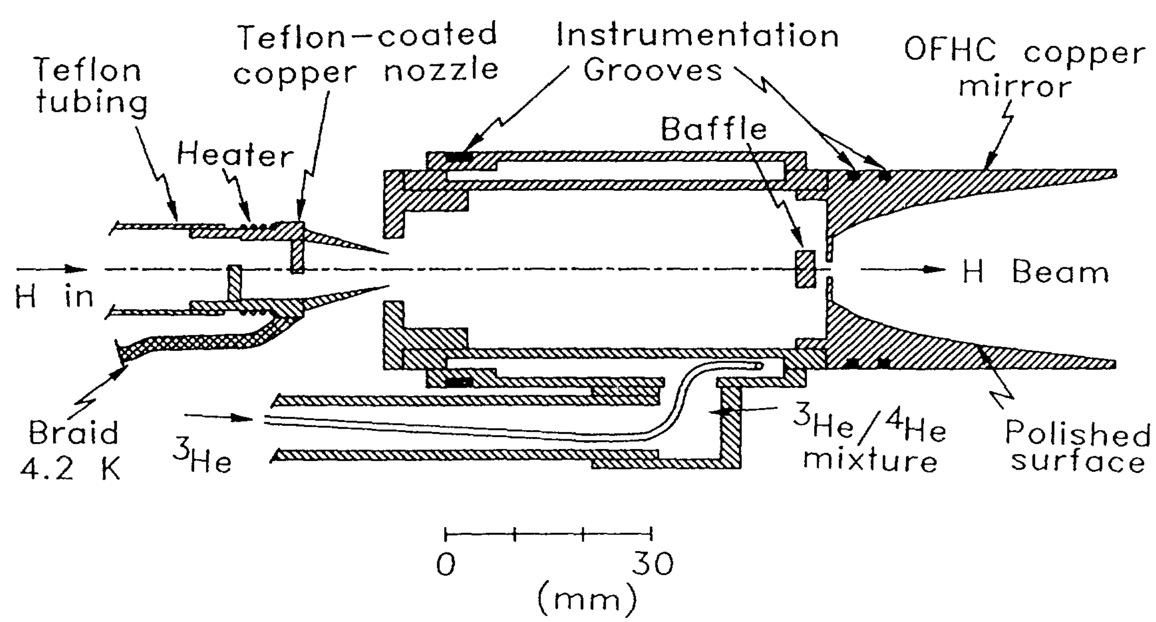
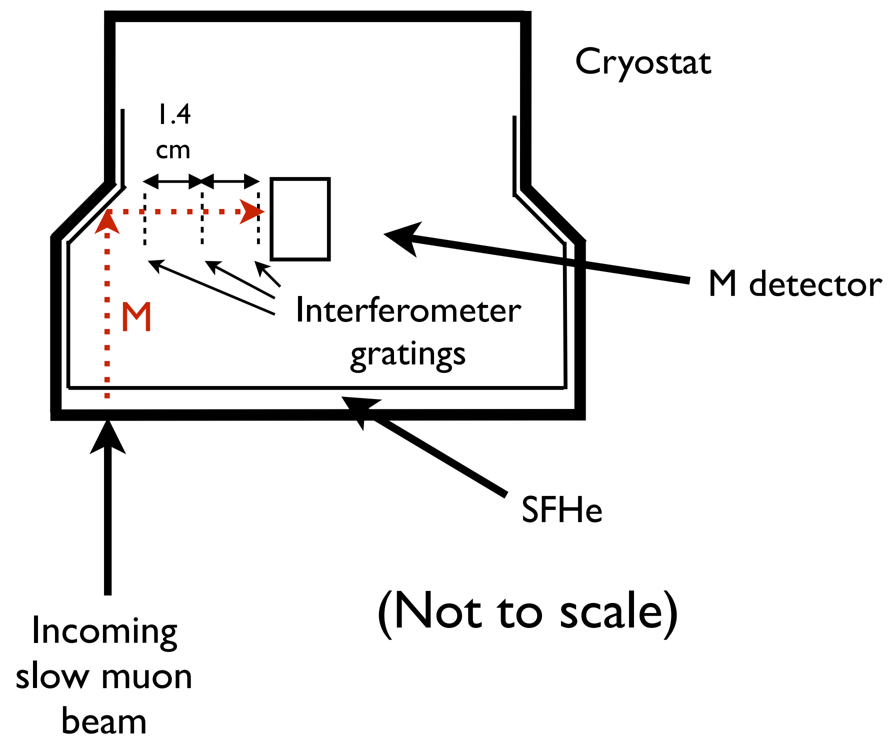


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

- SFHe H mirror an established technique

Muonium Gravity Experiment

- Some important questions:



1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer be aligned to a few pm and 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?

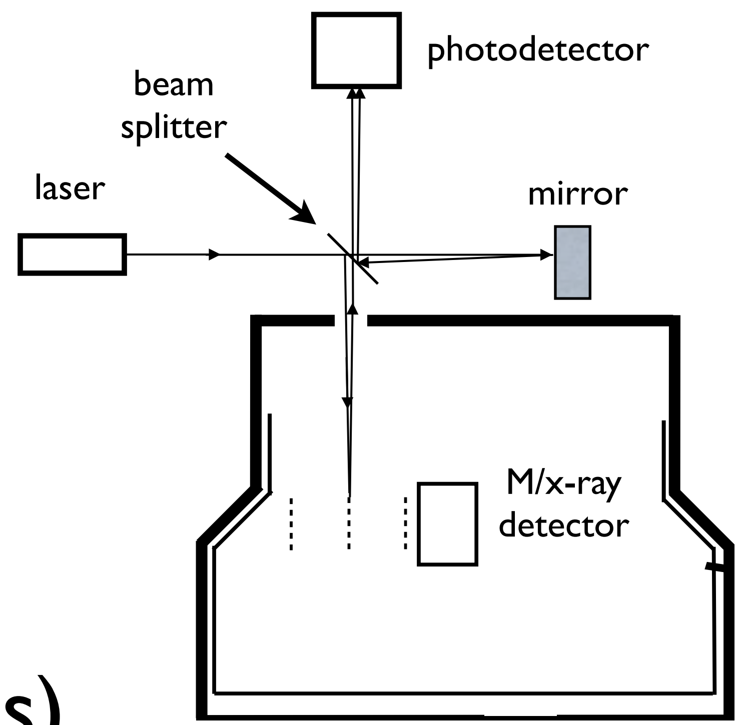
Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini, formerly of ANL Center for Nanoscale Materials (CNM), thinks so – 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 setting up a POEM distance gauge (TFG) at IIT to try it
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 (detected how well by M detector?)
5. Does Taqqu's scheme work?
   - needs R&D; we're working on it with PSI [next talk]

Interferometer Alignment

- Could use 2 laser interferometers per grating
  - @ λ = 1560 nm, need ~ 10 pm
    ⇒ ~ 10^{-5} x smaller
    - shot-noise limit (1 μW) = 0.04 pm
    - 3 pm demonstrated (averaging over 100 s)
    - To do:
      - reduce laser power
      - demonstrate in appropriate geometry
      - use TFG to demonstrate stability of muonium interferometer structure…

Concept:



"Laser 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, but diminishing returns
    - but 9 x bigger signal ⇒ easier calibration, alignment, & stabilization

- 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!
    - but nobody's ever done this before!

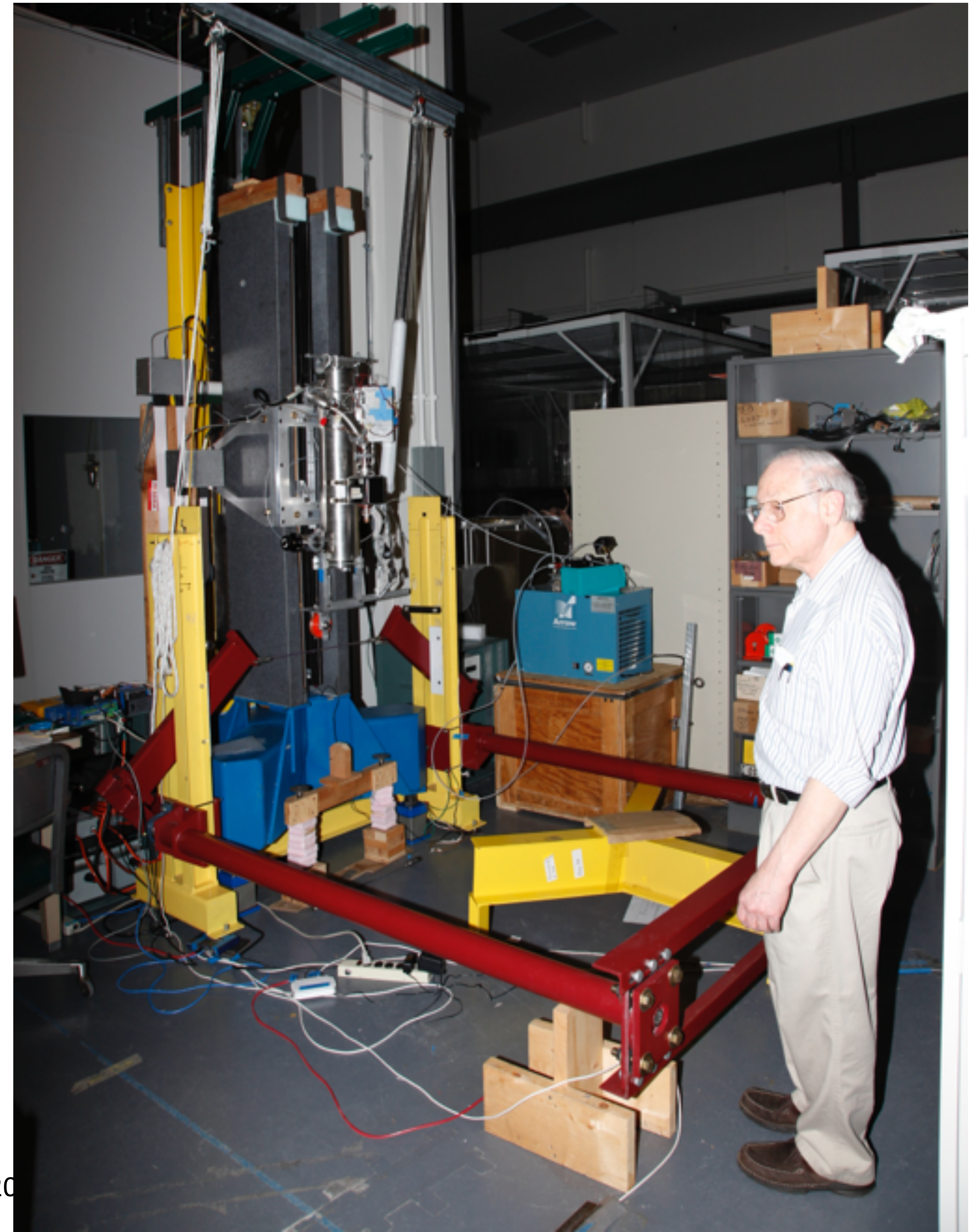
➡ how break out of the loop?

- IIT IPRO & BSMP programs

Prospects

- Moreover, we're the beneficiaries of the POEM program at Harvard-Smithsonian CfA
  - including 2 TFGs
  - so we have opportunity to demonstrate expertise!
  - as well as to continue to develop G-POEM with teams of undergrads

G-POEM @ CfA



G-POEM @ IIT

Progress

- IPROs (as well as Brazilian Scientific Mobility Program summer students) have been productive
  - accomplishments:
    - Mathematica and C 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
    - prototype grating layouts ready for e-beam litho @ CNM
    - setup of new lab space @ IIT begun

Collaborators

- Jim Phillips, ex-Harvard-Smithsonian CfA
- Bob Reasenberg, ex-Harvard-Smithsonian CfA
- Derrick Mancini, ex-ANL CNM, adjunct at IIT
- Tom Phillips, ex-Duke, adjunct at IIT
- Tom Roberts, Muons, Inc., adjunct at IIT
- Jeff Terry, IIT
- Klaus Kirch, PSI and ETH Zurich
- Ephraim Fischbach, Purdue

Conclusions

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

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