Antimatter Gravity with Muons

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Physics Seminar
Wichita State Univ.
June 16, 2017

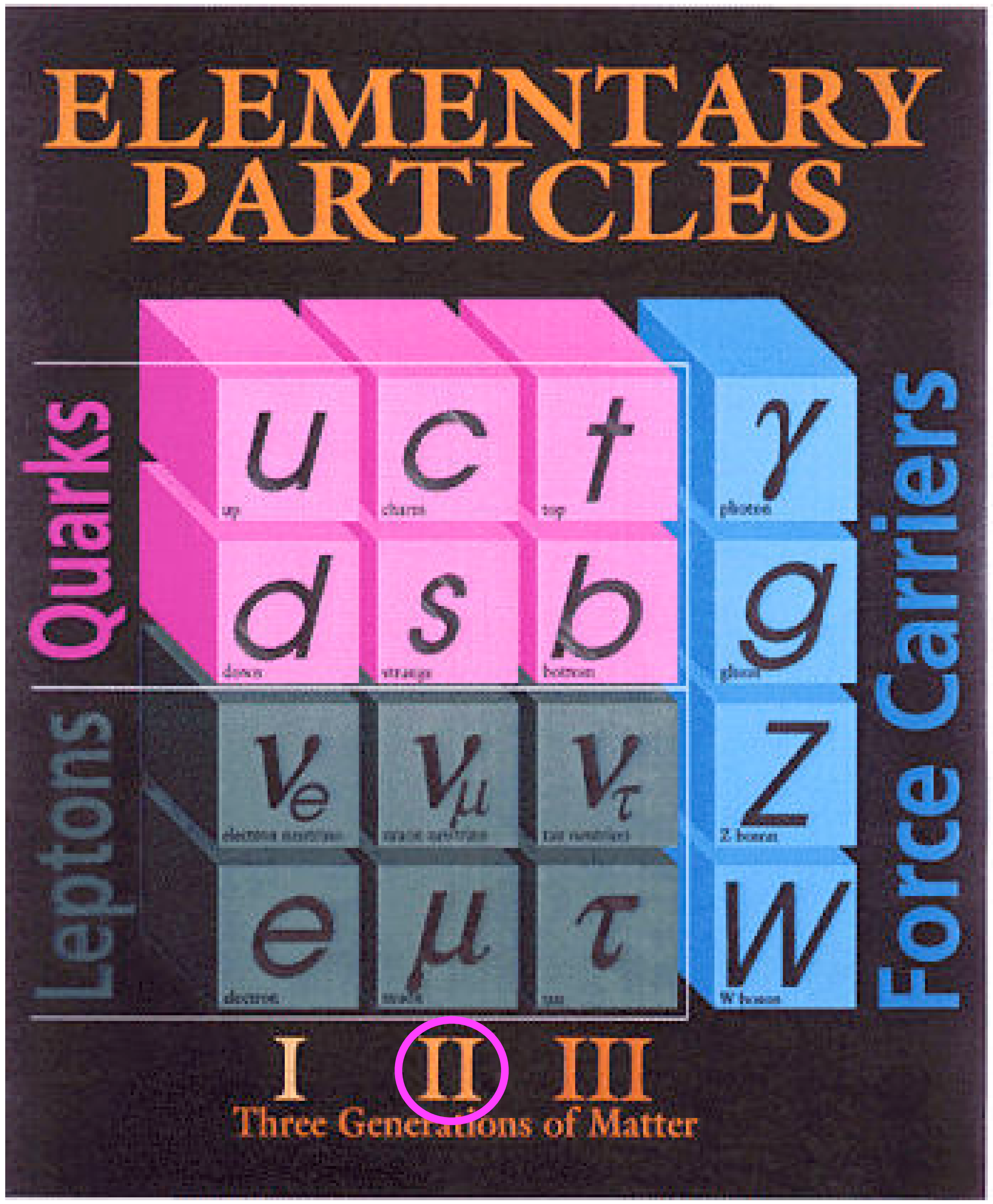
Outline

- Dramatis Personae
- A Bit of History
  - antimatter, the baryon asymmetry of the universe, and all that...
- The Ideas, The Issues, The Opportunities
- Required R&D
- Conclusions

Our story's a bit complicated, so please bear with me!

...and stop me if you have a question!

Dramatis Personae



Baryons & antibaryons :

$p = uud$ & $\bar{p} = \bar{u}\bar{u}\bar{d}$

$\Lambda = uds$ & $\bar{\Lambda} = \bar{u}\bar{d}\bar{s}$

...

Mesons :

$K^0 = d\bar{s}$ & $\bar{K}^0 = \bar{d}s$

$B^0 = d\bar{b}$ & $\bar{B}^0 = \bar{d}b$

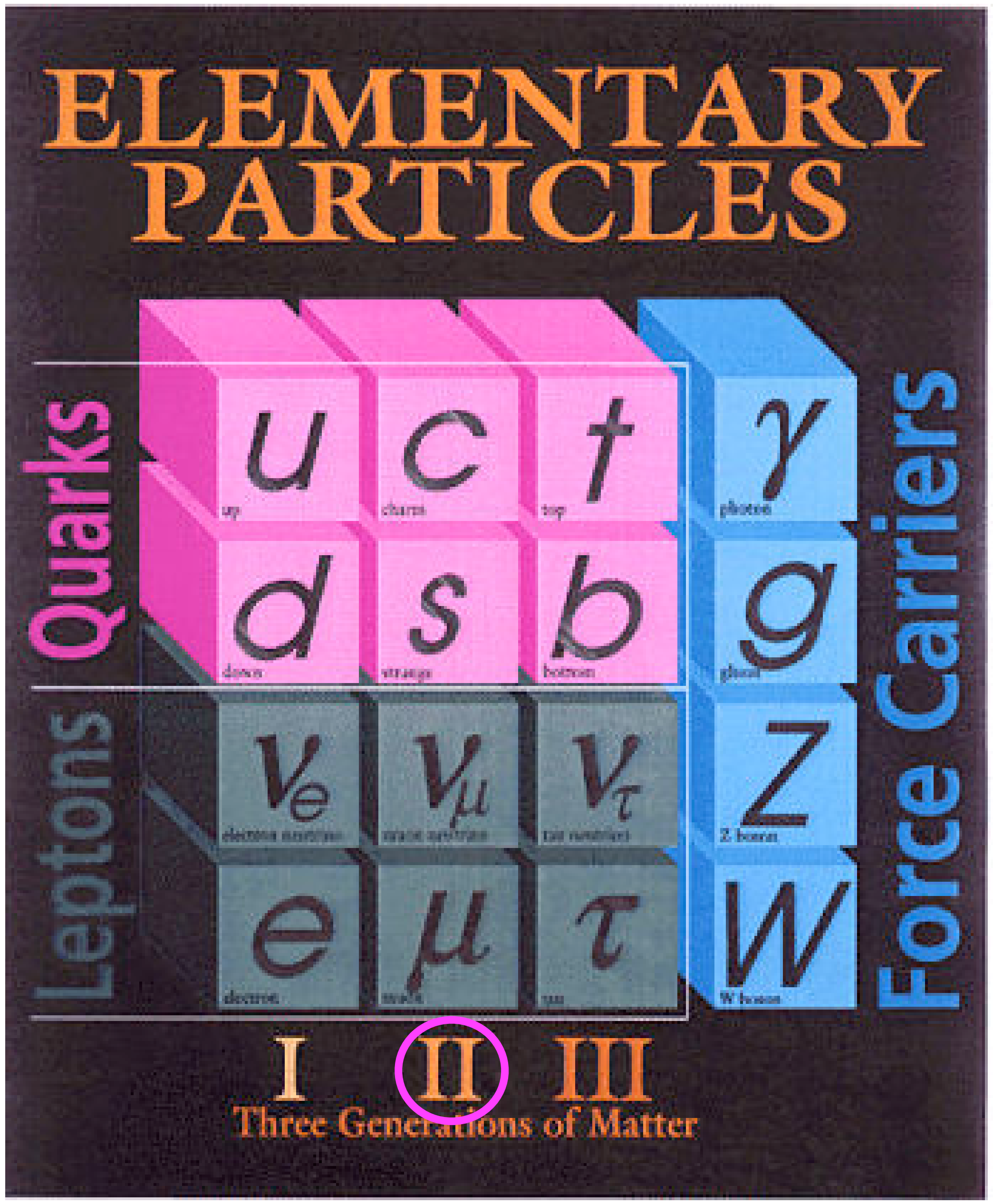
$B^+ = u\bar{b}$ & $B^- = \bar{u}b$

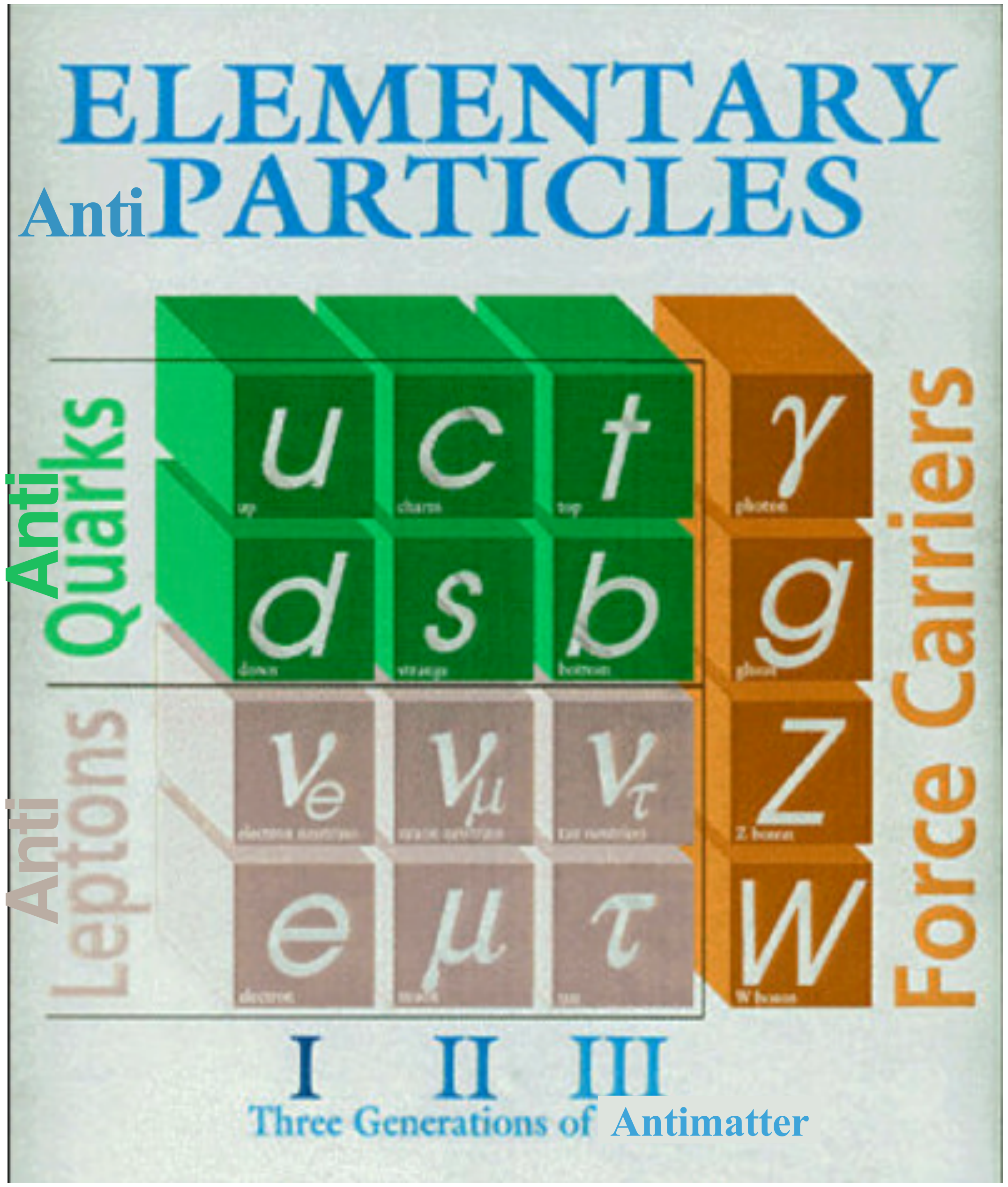
...

Leptons : $e^{\mp}$, $\mu^{\mp}$, $\tau^{\mp}$, ν's

Dramatis Personae

"Imperfect mirror"





- And, don't forget: antimatter and matter *annihilate* on contact

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Our story begins with…

Antimatter!

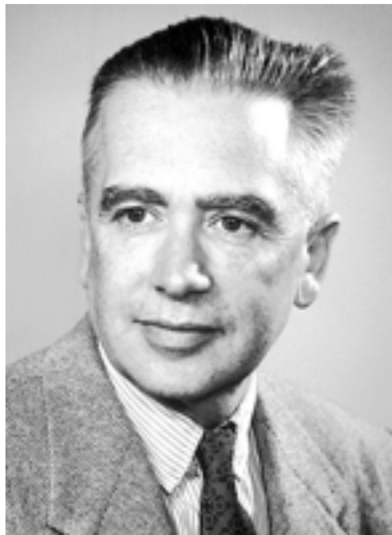
- Introduced by Dirac in 1928
  - Dirac equation (QM + relativity) described positrons in addition to electrons
  - positron discovered by Anderson in 1932
  - antiproton discovered by Chamberlain & Segrè in 1955
  - now well established that
    - all charged particles (and many types of neutrals) have 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

Antimatter!

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

Baryon Asymmetry

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

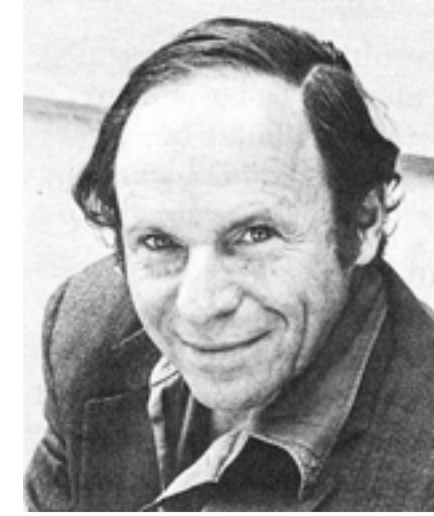
- Already in 1956, M. Goldhaber noted the "baryon asymmetry of the universe" (BAU) [M. Goldhaber, "Speculations on Cosmogeny," Science 124 (1956) 218]
  - universe seems to contain *lots* of mass in the form of baryons – protons and neutrons – but almost *no* antimatter! How could this be consistent 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"!

Am. J. Phys. **26** (1958) 358

Approximate Nature of Physical Symmetries*

P. Morrison
Cornell University, Ithaca, New York

(Received May 21, 1958)



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[...] For there is no more evident failure of symmetry in the world we see about us than the failure of charge conjugation. Matter made of particles, protons, electrons, and neutrons, is all about, but antimatter, made of antiparticles, is nowhere to be found. It is none the less possible to manufacture it, but only at great expense. If we committed the whole United States Federal Budget, Department of Defense and all, to the buying of antimatter at present prices, we could own a single microgram of the stuff only after we had paid off installments for a thousand years! [...]

Many have argued against the existence of antigravity, but they have all *postulated* the equivalence principle. It is evident that the Berkeley experiments prove the positive inertial mass of the antinucleon; it costs positive energy to make one. Then, if the gravitational mass is to be negative, the equivalence principle must break down. It will hold well enough as an approximation if test bodies and sources of field alike all are exclusively made of nucleons, and contain no antinucleons. That is our present situation. On this view a proton falls, but an antiproton *rises* in the earth's gravitational field. [...]

- Note: Eqivalence Principle is *fundamental* to General Relativity
  - if it doesn't apply to antimatter, at the very least, our understanding of GR must be modified

Baryon Asymmetry

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

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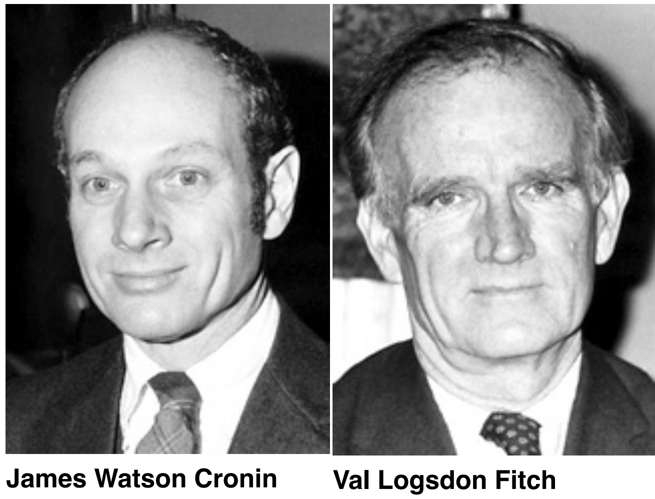
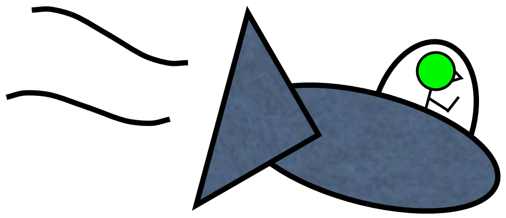
Baryon Asymmetry

- 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]: $\sim 10^{-3}$ asymmetry in decays of K^0 vs $\overline{K}^0$ meson
    - allows distinguishing matter from antimatter in an *absolute* sense ("annihilating an alien")



[photo credits: Nobelprize.org]



CPV and Alien Annihilation

- Imagine you're an alien from another galaxy approaching Earth in a spaceship.
- Is it safe to land or will you be annihilated on contact???
- Just radio Earth and ask:
  - "In the decay of the long-lived neutral kaon, is the more common lepton matter or antimatter?"
  - If you agree with their answer, it's safe to land!

Baryon Asymmetry

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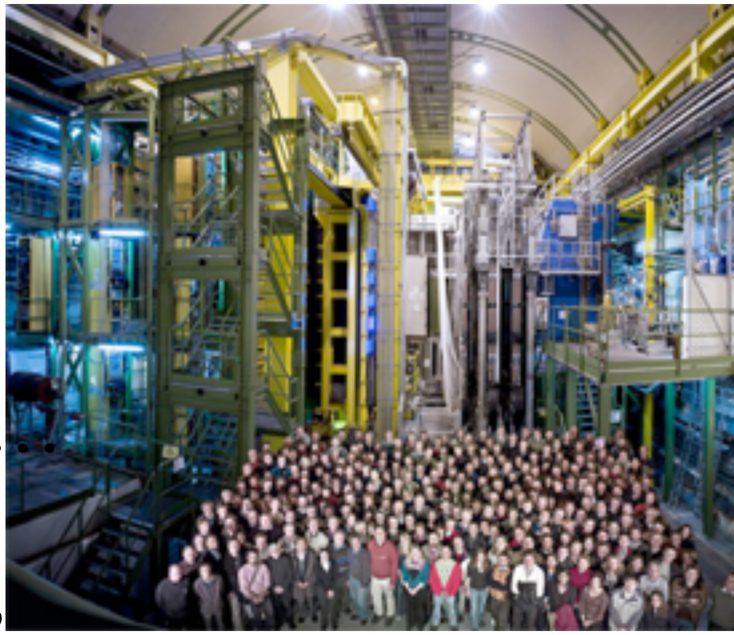
- But – where's the needed *CP* violation?
  - CPV discovery [Cronin, Fitch, et al., PRL 13 (1964) 138]: $\sim 10^{-3}$ asymmetry in decays of K^0 vs $\overline{K}^0$ meson
    - allows distinguishing matter from antimatter in an *absolute* sense ("annihilating an alien")
  - but too weak by *orders 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]



LHC*b*

But there's ***more***...

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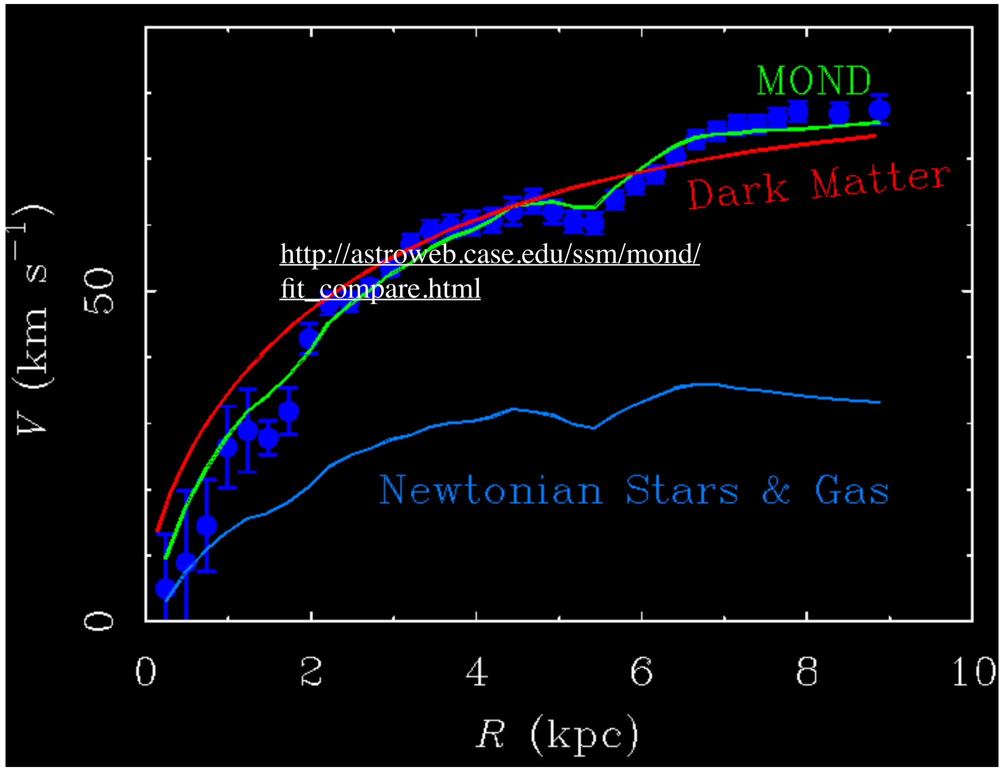
Four Cosmological Puzzles

(at least)

1. *Baryon asymmetry*
   - as we've seen, believed to be due to **CPV**, but insufficient CPV seen experimentally to support this
2. *Expansion of universe appears to be accelerating*
   - believed to be due to "**dark energy**," comprising 70% of total – but no direct observational evidence as to its nature or existence
3. *Galactic rotation curves and clusters*
   - suggest existence of large amounts of "**dark matter**" (5 x normal matter) – but dark matter particles yet to be found



4. *Flatness and Horizon problems*
   - Universe has same temperature in all directions – but photons just arriving from opposite directions are from regions that have not yet had time to communicate or equilibrate → "**inflation**"

Might there be a simpler explanation???

Antigravity?

- What if matter and antimatter repel gravitationally?
  - leads to universe with separated matter and antimatter regions, and makes gravitational dipoles possible
    - BAU 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 the expansion rate of the 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

      [A. Benoit-Lévy and G. Chardin, *ibid.*]
  - virtual gravitational dipoles can 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)]

Studying Antimatter Gravity

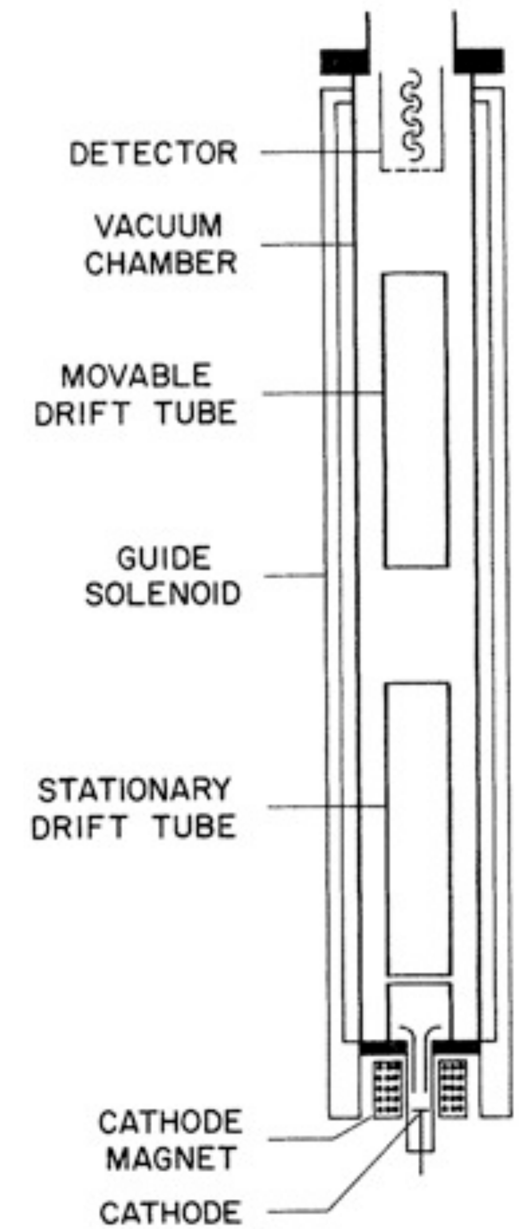
Whitteborn & Fairbanks Expt

[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)]

- 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:

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

- Indicated difficulty of a (never published) measurement with positrons



Next Attempt

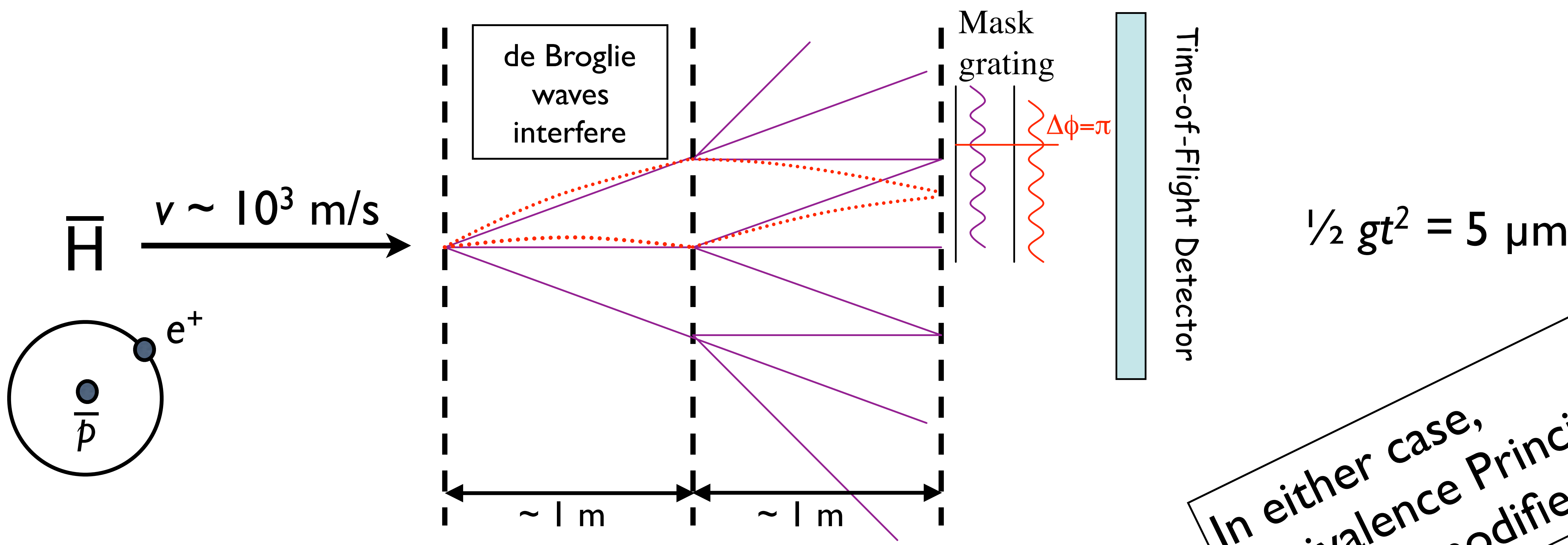
- Los Alamos-led team proposed (1986) to measure gravitational force on antiprotons at the CERN Low Energy Antiproton Ring (LEAR)
- Similar approach to Witteborn & Fairbank, but with 2000x greater *m*/*q* ratio
- Project ended inconclusively

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

➡ need to work with *neutral* antimatter

Studying Antimatter Gravity

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



In either case, Equivalence Principle must be modified!

  - if $\overline{g} = -g$, antigravity as discussed above
  - if $\overline{g} = g \pm \varepsilon$, 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!

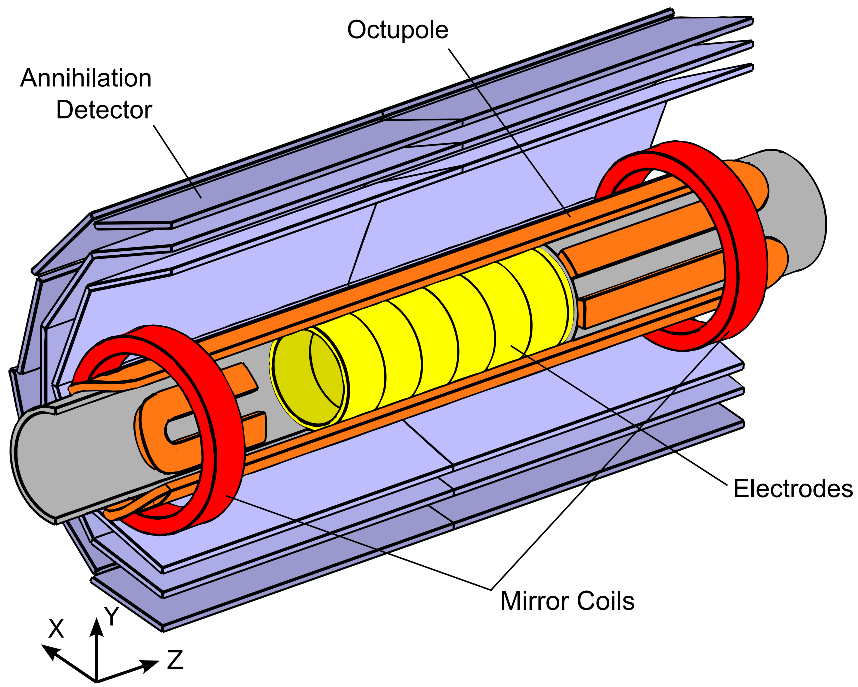
Studying Antimatter Gravity

- World leader: ALPHA* at CERN Antiproton Decelerator

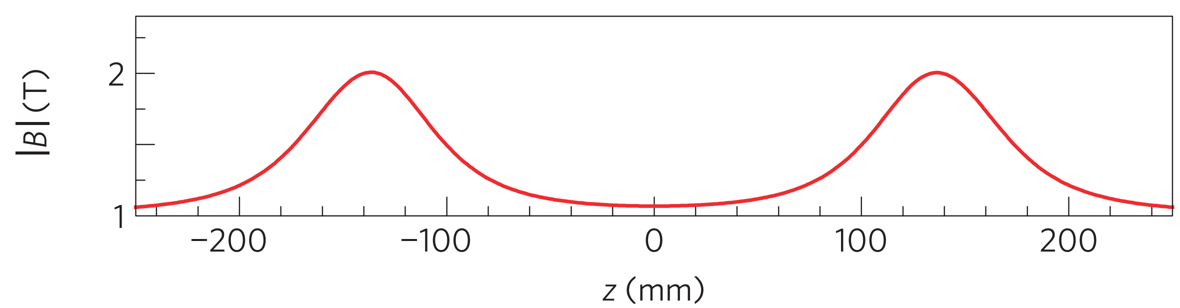
  * Antihydrogen Laser Physics Apparatus

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

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



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



- Shutting off the magnets, they then studied whether more $\overline{\mathrm{H}}$ 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 $\overline{\text{H}}$
- Then

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

  [ALPHA Collaboration, 2013]
- They propose improving sensitivity to $\Delta F \sim 0.5$
- May take another 5 years...?

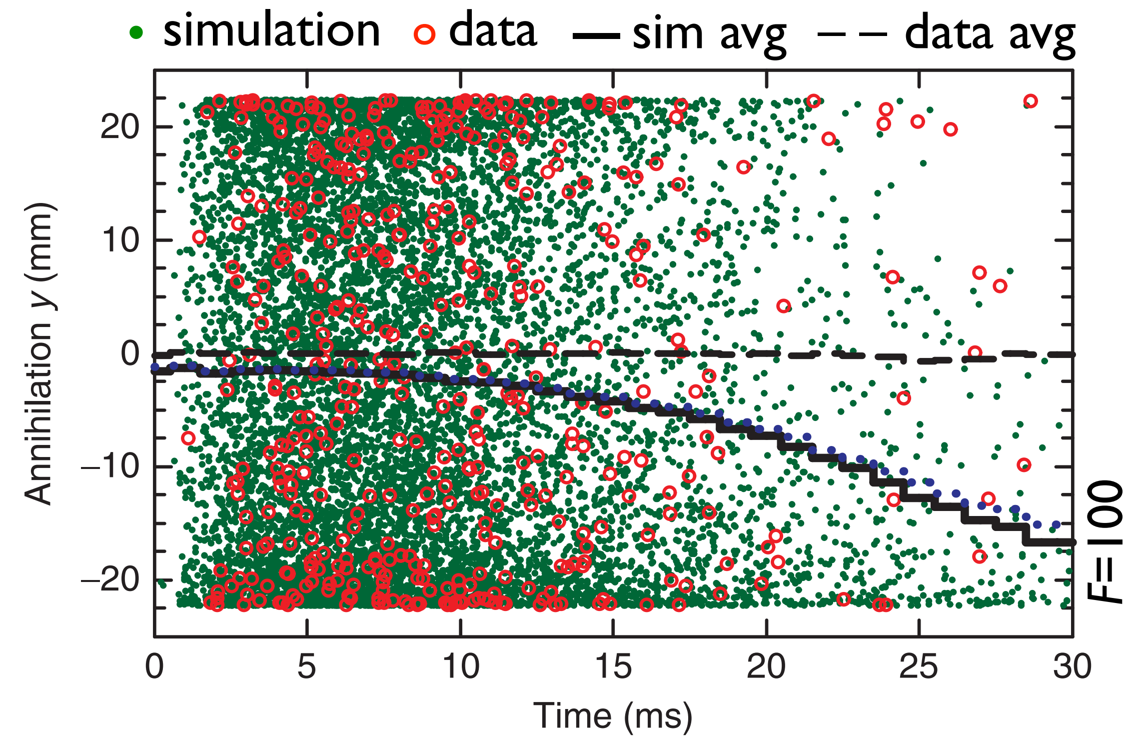


Figure 2 | Annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms in the decaying magnetic fields, as found by simulations of equation 1 with $F = 100$. Because $F = 100$ in this simulation, there is a tendency for the anti-atoms 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 ∼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?

- Many $\overline{\mathrm{H}}$ efforts in progress at CERN AD (ALPHA, ATRAP, ASACUSA, AEgIS, GBAR)
  - too various to describe here...
- All require antiprotons, so possible only at AD

- BUT – another approach may also be feasible...

Studying Antimatter Gravity

- Besides antihydrogen (and maybe 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

    (an object of study for more than 50 years)
- Measuring muonium gravity – if feasible – could be the *first* gravitational measurement of a lepton, and of a 2^{nd}-generation particle

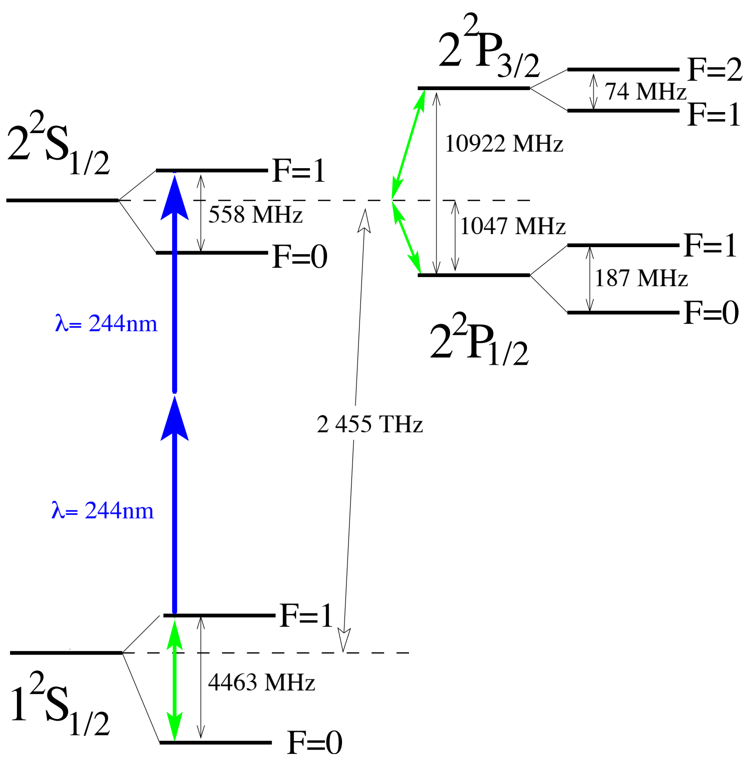
Muonium

- 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.



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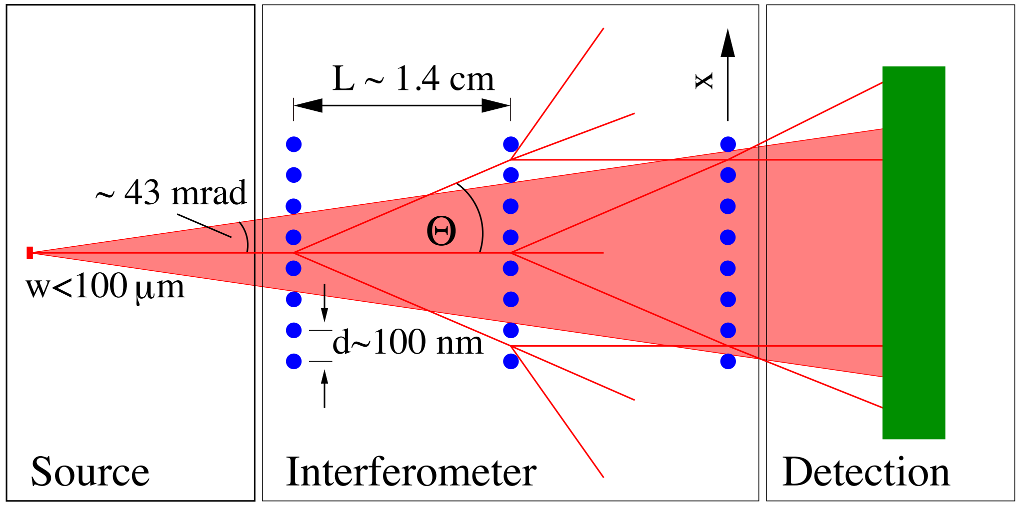
Studying Muonium Gravity

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

Testing Gravity with Muonium

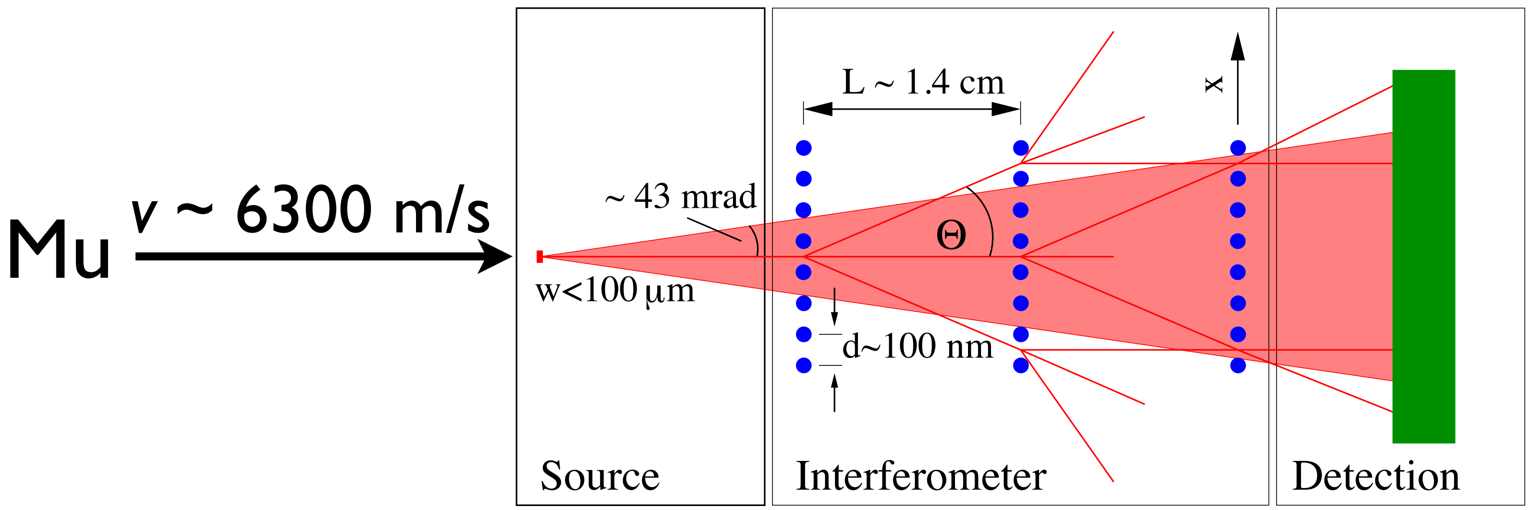
K. Kirch*
Paul Scherrer Institut (PSI), CH-5232 Villigen PSI, Switzerland
(Dated: February 2, 2008)

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 Phillips' interferometry idea to an antiatom with a 2.2 μs lifetime!



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

Smaller than an *atom*!

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

Studying Muonium Gravity

- Part of the challenge is the Mu production method:
  - want *monoenergetic* Mu so as to have uniform flight time
  - otherwise the interference patterns of different atoms would have differing relative phases, and the signal could be washed out

Monoenergetic Muonium?

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

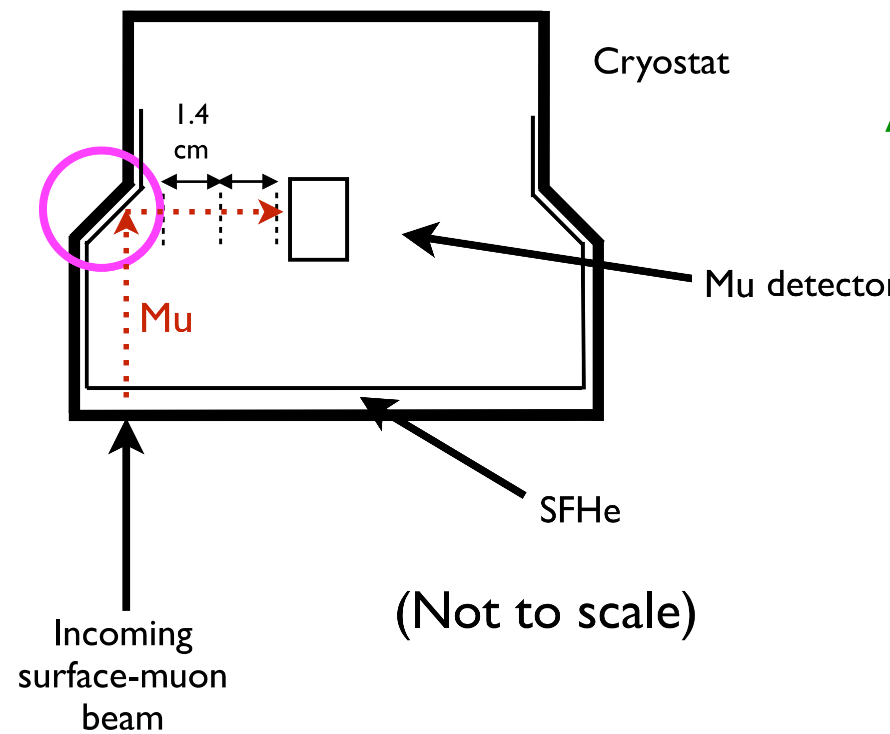
[D. Taqqu, “Ultraslow Muonium for a Muon beam of ultra high quality,” Phys. Procedia 17 (2011) 216]

  - stop slow muons in μm-thick layer of superfluid He (SFHe)
  - chemical potential of hydrogen in SFHe will eject Mu atoms at 6,300 m/s, perpendicular to SFHe surface
    - makes ~“monochromatic” beam (in the beam-physics jargon):

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

Muonium Gravity Experiment

- One can then imagine the following apparatus:



A "ship in a bottle!"

Sensitivity estimate @ 100 kHz:

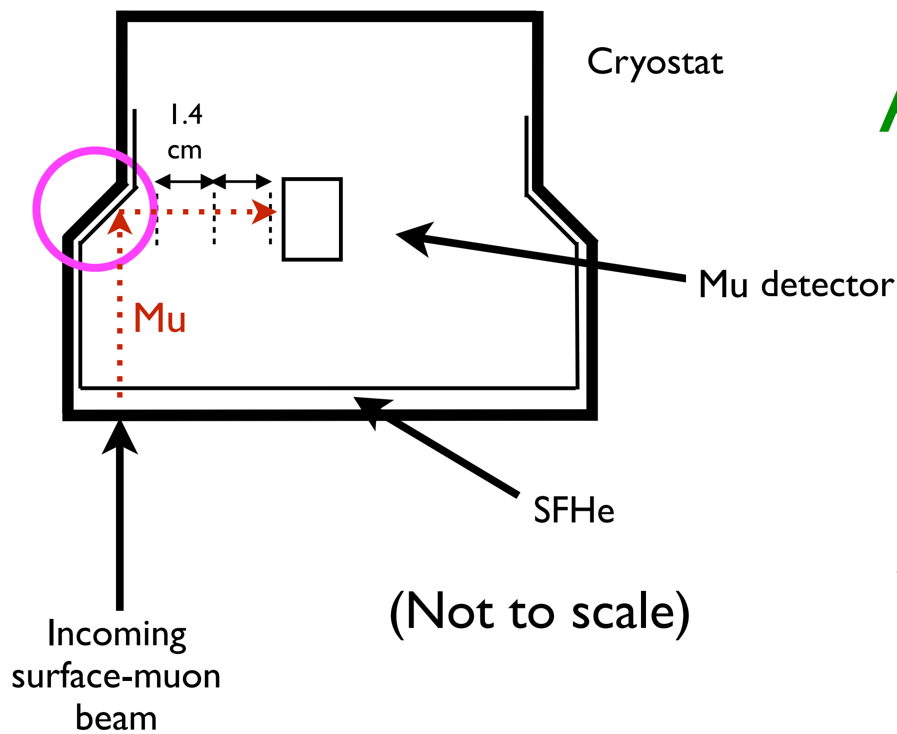
$$S = \frac{1}{C\sqrt{N_0}}\frac{d}{2\pi}\frac{1}{\tau^2}$$
$$\approx\ 0.3\,\mathrm{g}\ \text{per}\ \sqrt{\#\text{days}}$$

- Well known property of SFHe to coat surface of its container

- 45° section of cryostat thus serves as reflector to turn vertical Mu beam emerging from SFHe surface into the horizontal

Muonium Gravity Experiment

- One can then imagine the following apparatus:



(Not to scale)

A "ship in a bottle!"

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

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

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.

- SFHe H mirror an established technique

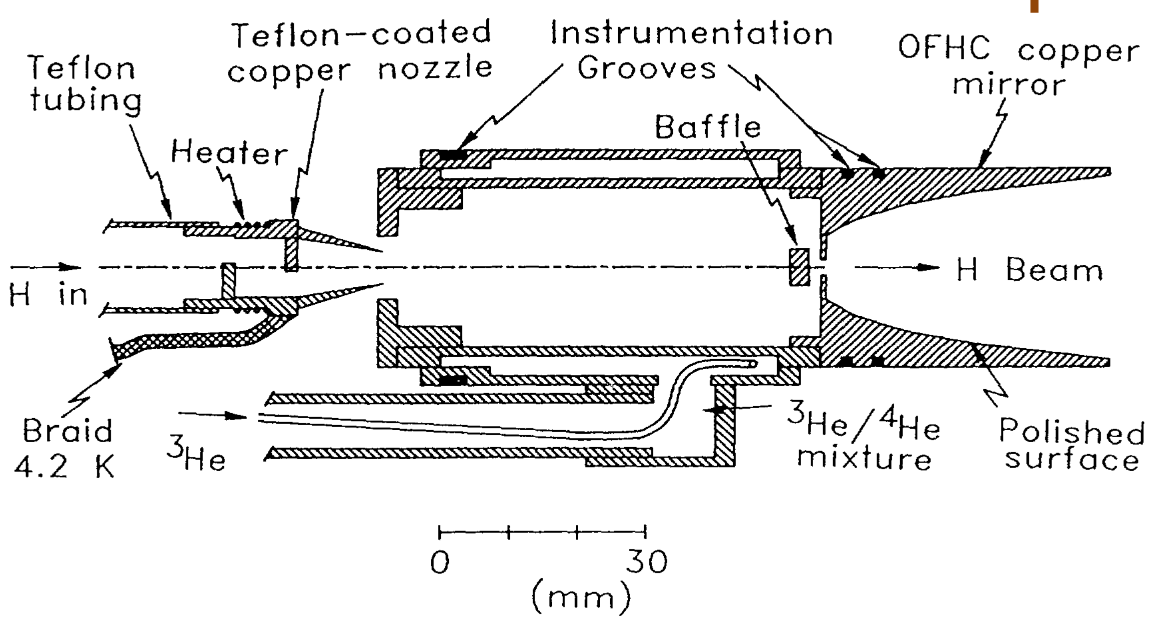
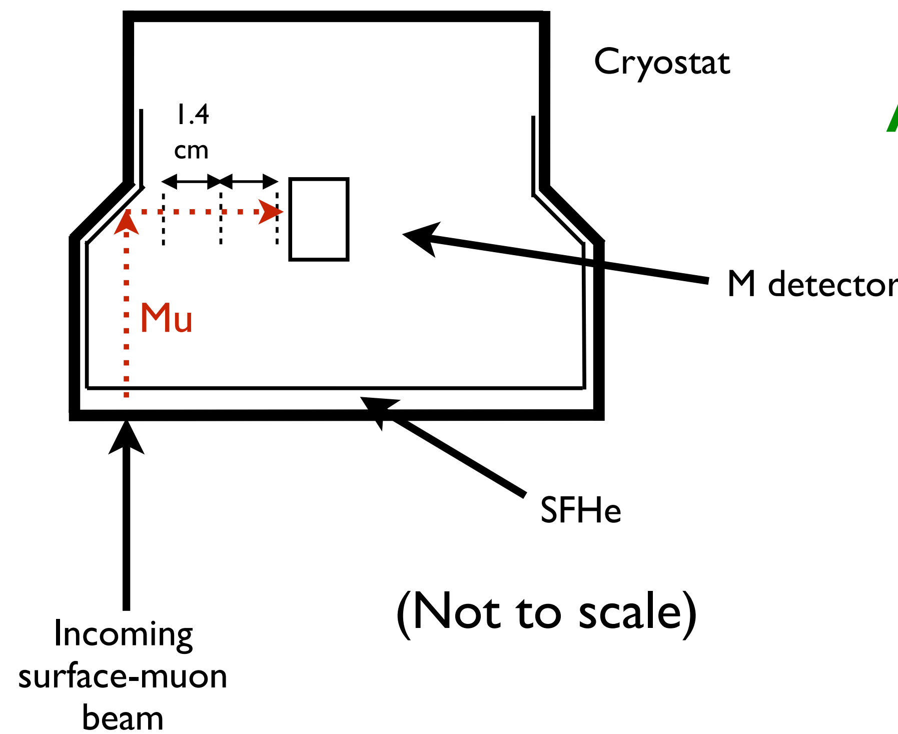


FIG. 2. Schematic diagram of the stabilization cell and mirror. The Teflon-coated copper nozzle is also shown.

Muonium Gravity Experiment

- Some important questions:



(Not to scale)

A "ship in a bottle!"

1. Can sufficiently precise diffraction gratings be fabricated?
2. Can interferometer and detector 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?

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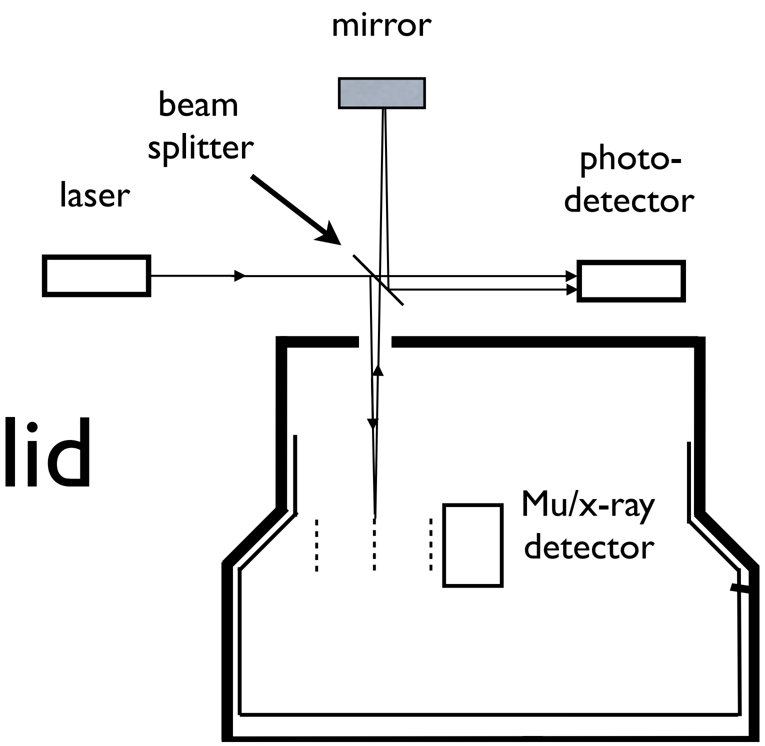
Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, D. Mancini, ex-ANL Center for Nanoscale Materials (CNM) director, thinks so – fabrication proposal approved at CNM (in progress with undergrad teams)
2. Can interferometer and detector be aligned to a few pm and stabilized against vibration?
   - R&D ongoing, looks OK (LIGO does better than we need)
3. Can interferometer and detector be operated at cryogenic temperature?
   - needs R&D; work at IPN Orsay implies at least piezos OK
4. How determine zero-degree line?
   - use cotemporal x-ray beam (Mu detector can detect x-rays)
5. Does Taqqu's scheme work?
   - needs R&D; PSI working on it with our collaborator T. Phillips

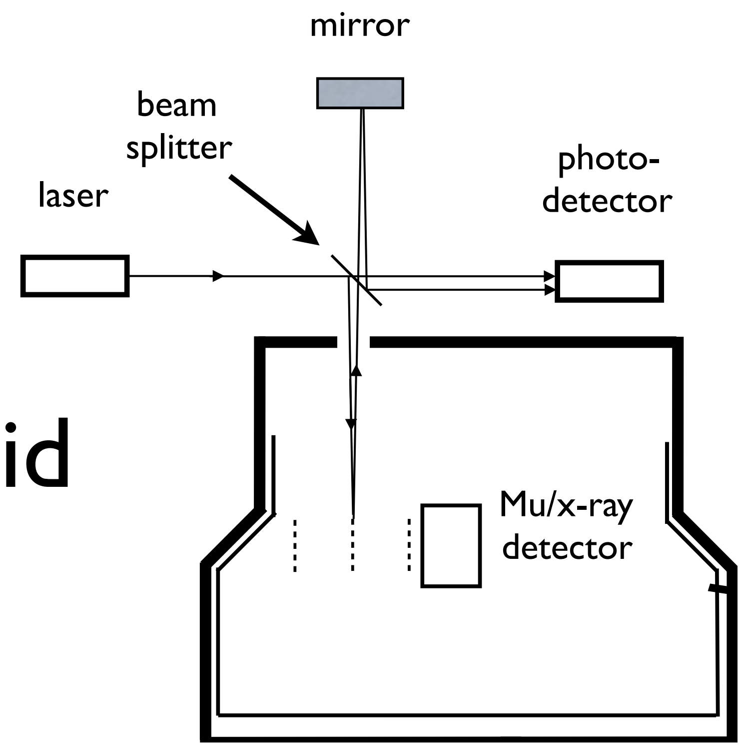
Interferometer Alignment



- Simplified concept: 2 Michelson interferometers per grating
  - send laser beams in through cryostat lid
    - keeps instrumentation & heat external to cryostat & Mu detection path open
  - "natural" sensitivity ~ $\lambda/2$ ~ 600 nm; need ~ 3 pm ⇒ 10^{-5} enhancement
    - enhance by sitting at a zero of the intensity, using heterodyne detection etc. → Laser Tracking Frequency Gauge
    - still some details to work out!

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

Interferometer Alignment



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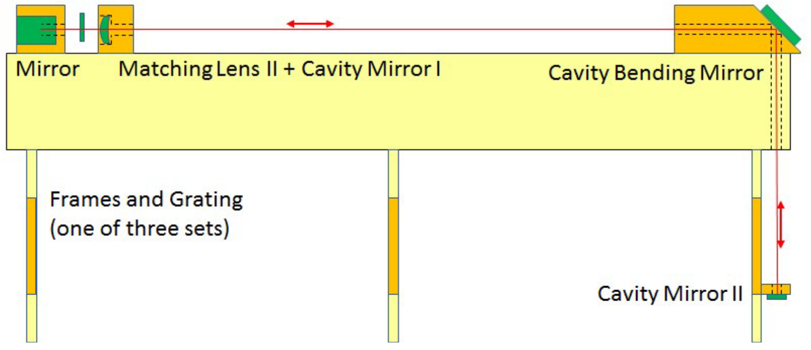
more miniaturized version



Additional Considerations

- What's the optimal muonium pathlength?
  - say muonium interferometer baseline doubled:

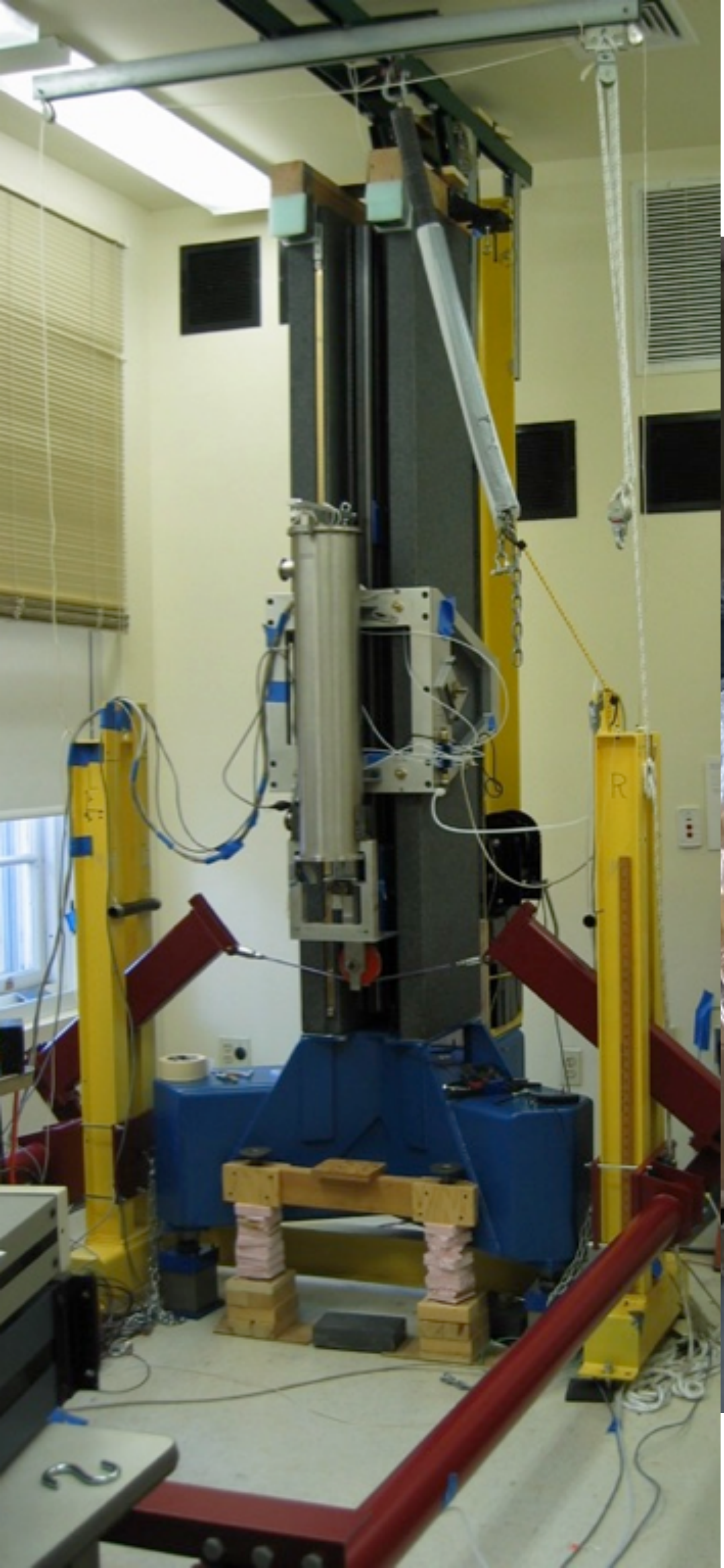
    costs e^{-2} = 1/7.4 in event rate, but gains x 4 in deflection
    - a net win by 4 $e^{-1} \approx 1.5$ → Statistically optimal
  - tripling → only x1.2 improvement – diminishing returns
    - but 9x bigger signal ⇒ easier calibration, alignment, & stabilization

- Need simulation study to identify optimum, taking all effects into account – gearing up for it (with undergrad teams)

Additional Considerations

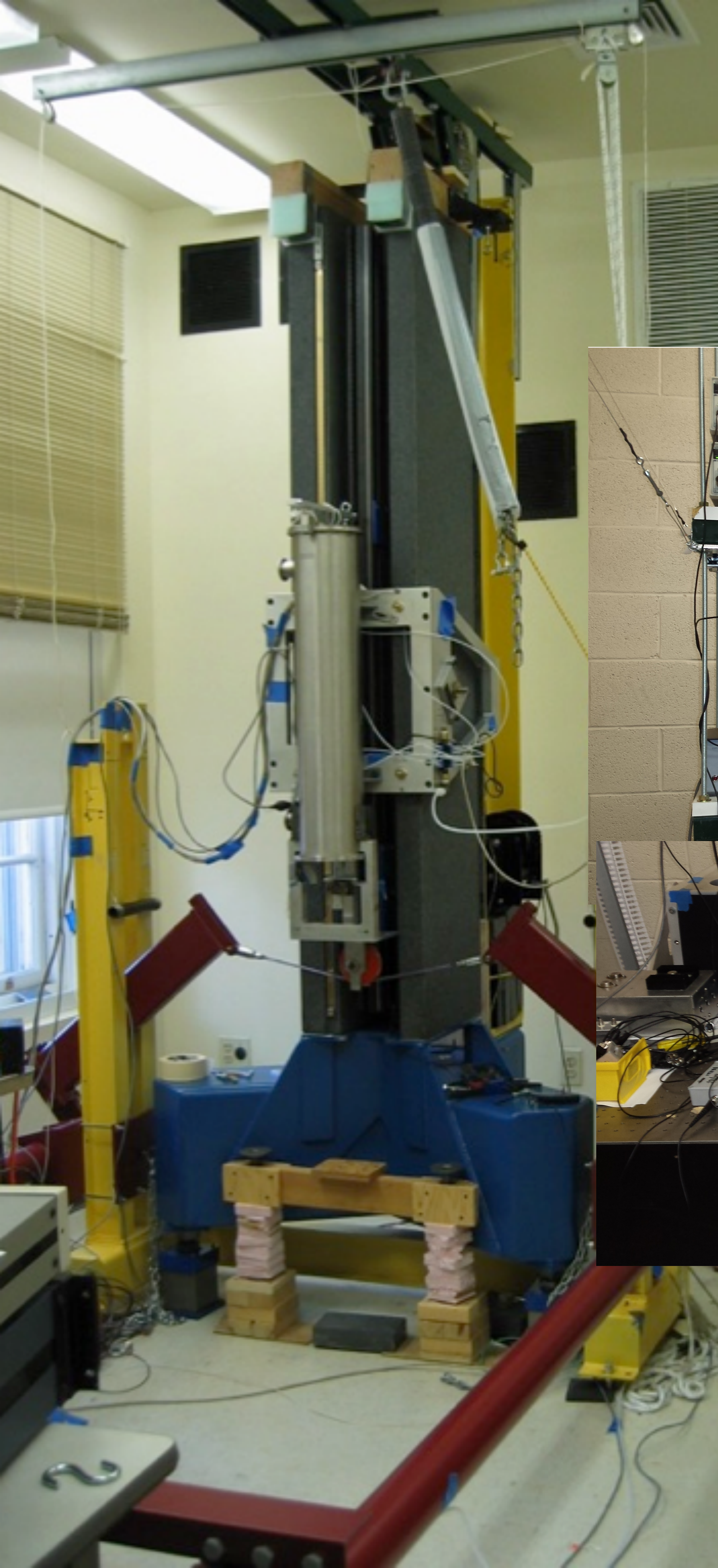
- Alternate solutions:
  - different M production scheme?
    - thick-film SFHe production

      → x100 or more higher rate!
    - proposed for R&D @ PSI along with thin-film scheme

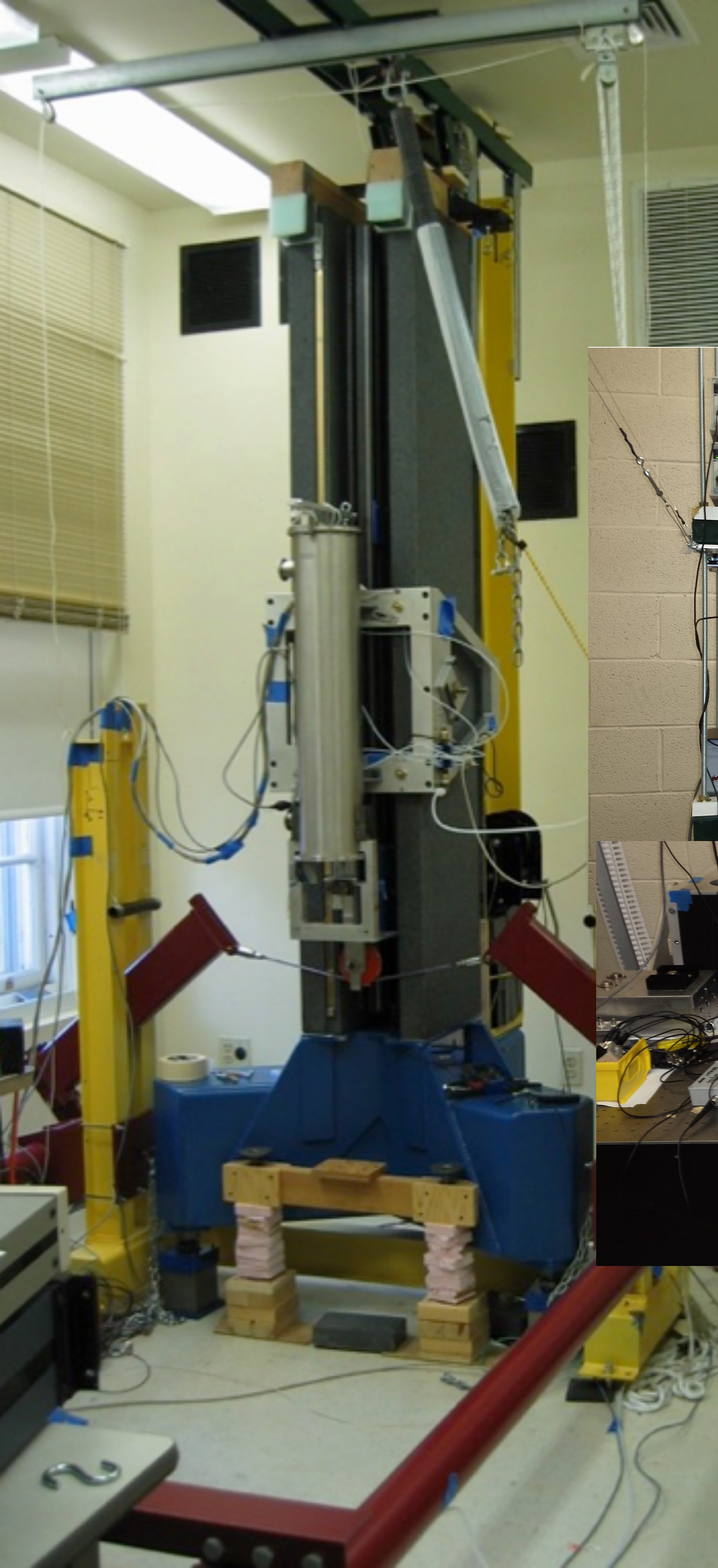


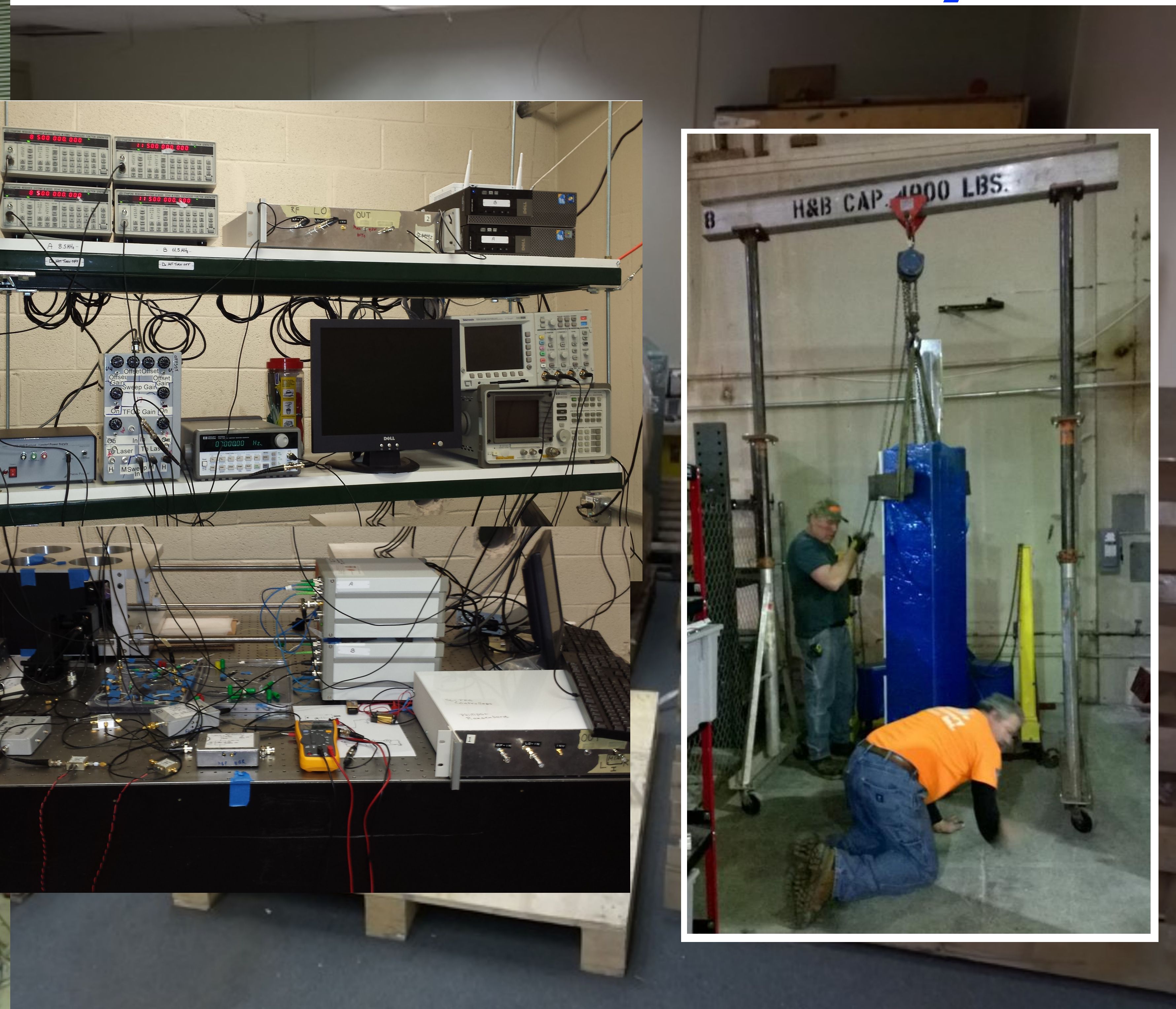
Picture Gallery

Picture Gallery

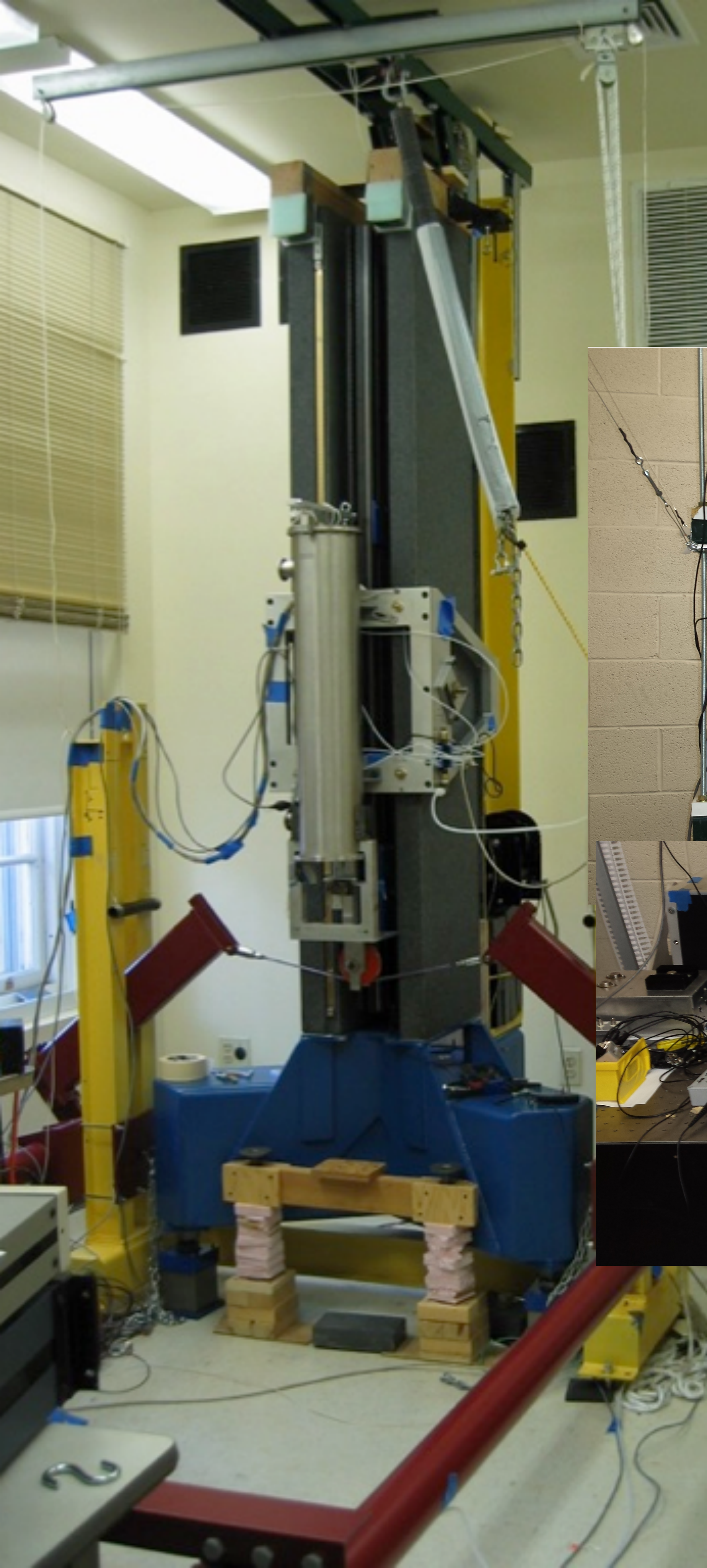


Picture Gallery





Picture Gallery



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 or muonium
  - if possible, *both* should be measured

➡ First measurement of muonium gravity would be a milestone!

- But first must determine feasibility

Final Remarks

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

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

Acknowledgments

- Thanks to my collaborators:

IIT:

Derrick Mancini

Jeff Terry

Tom Roberts

Jim Phillips

Tom Phillips

UCSD:

Bob Reasenberg

- …our ≈100 IPRO and BSMP undergrad students, and the IIT administration

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