Antimatter Gravity with Muons?

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Physics Colloquium
IIT
29 August 2013

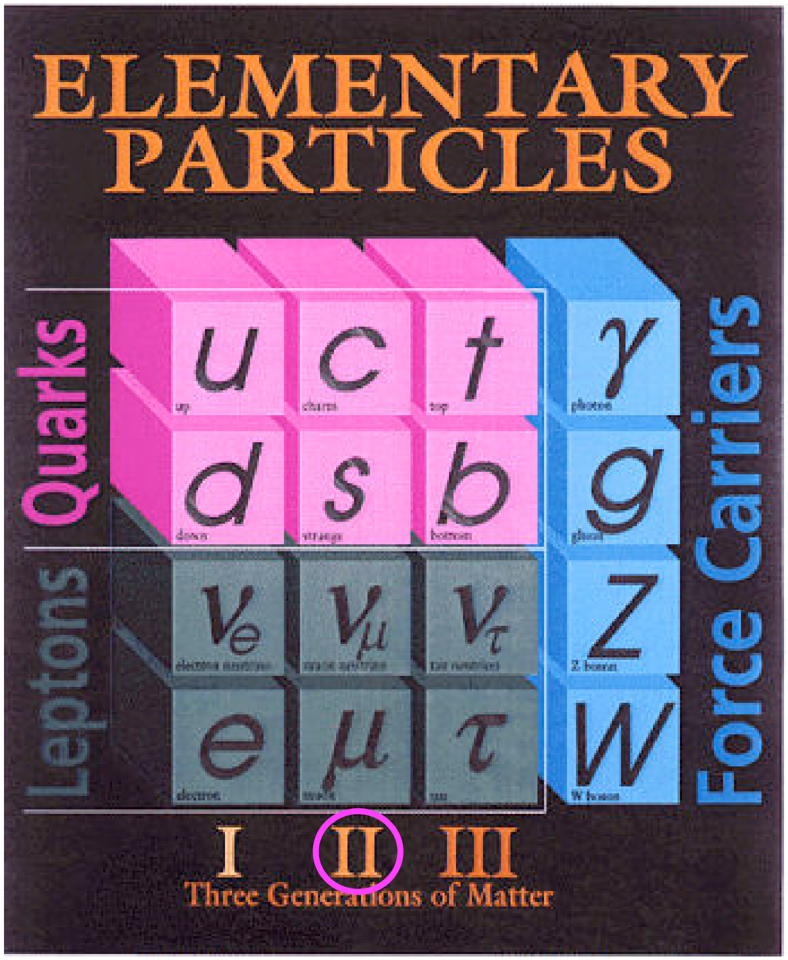
Outline

- 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:

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

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

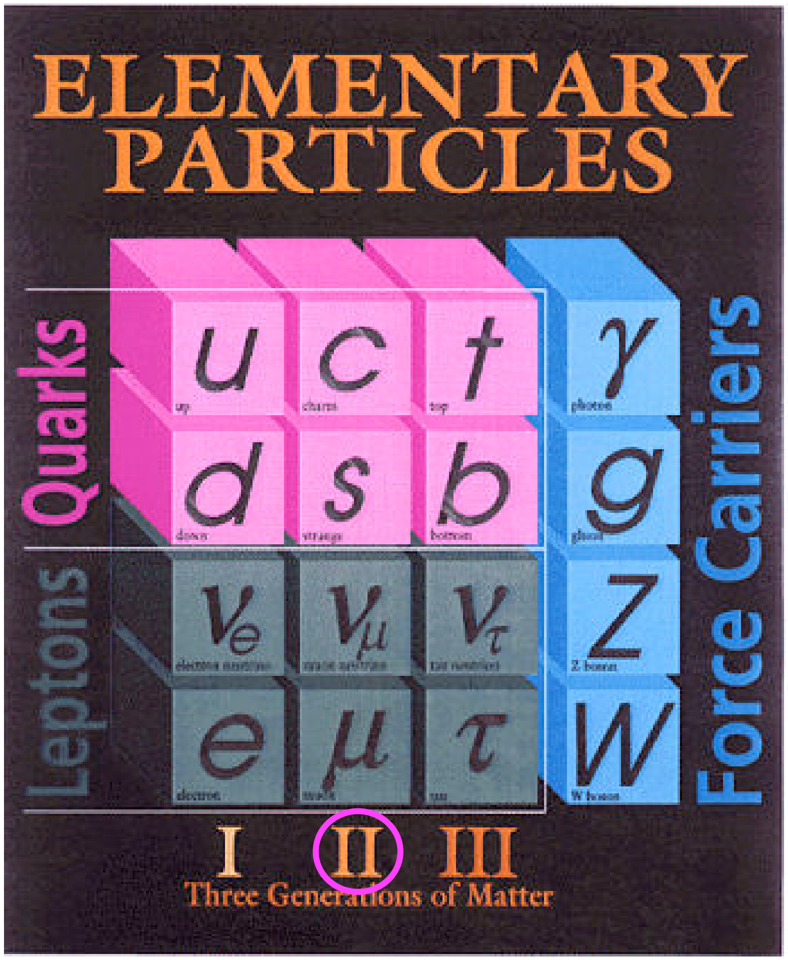
$B^+ = u\bar{b}$ & $B^- = \bar{u}b$

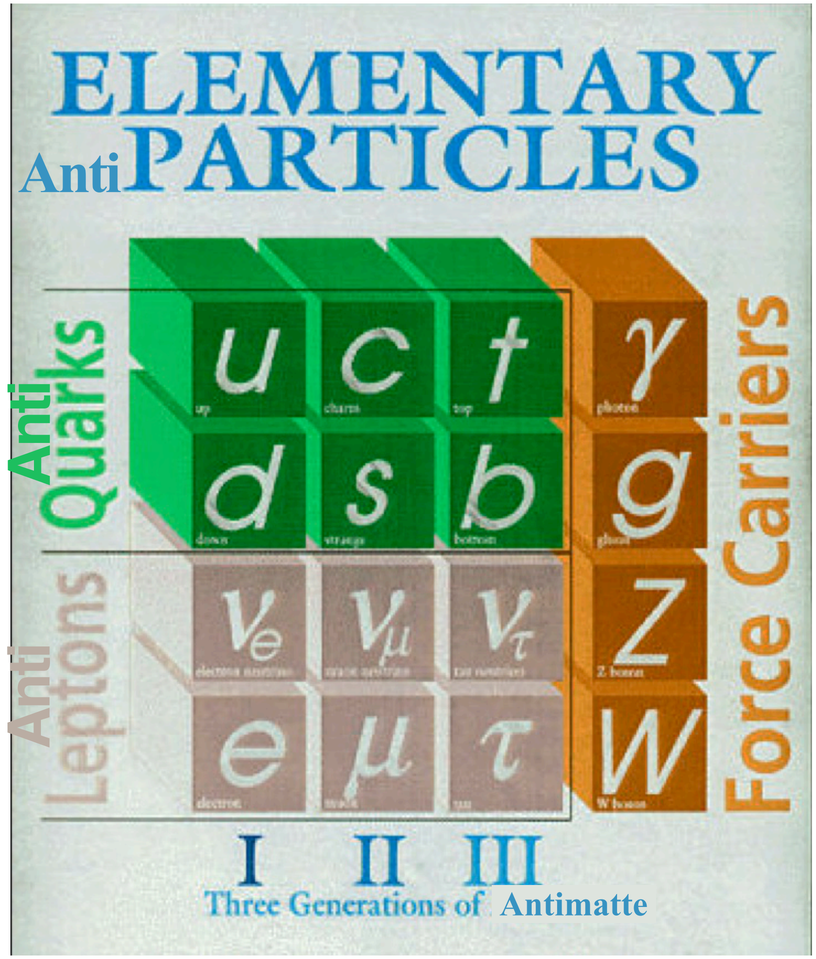
...

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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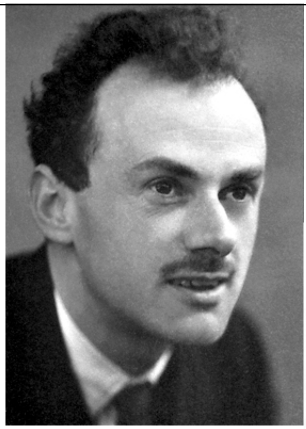
Our story begins with...

Antimatter!

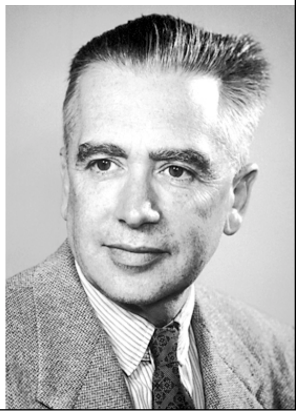
- Introduced by Dirac in 1928
  - Dirac equation (QM + relativity) described positrons in addition to electrons
  - positron discovered by Anderson in 1932
  - antiproton discovered by Chamberlain & Segrè in 1955
  - now well established that
    - all charged particles (and many types of neutrals) have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

Baryon Asymmetry

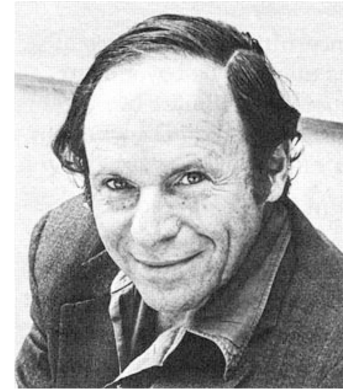
- Big Bang produced exactly equal amounts of matter and antimatter – a puzzle!

- 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

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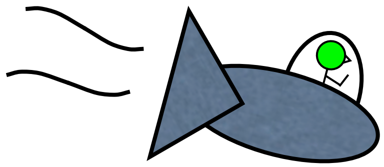
Baryon Asymmetry

- 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")

James Watson Cronin   Val Logsdon Fitch

[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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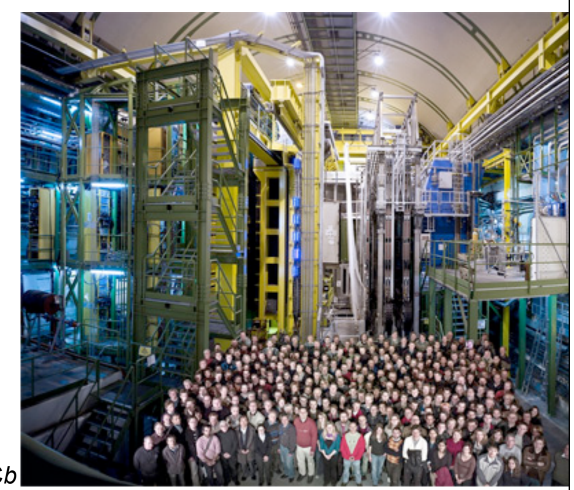
    - allows distinguishing matter from antimatter in an *absolute* sense ("annihilating an alien")
  - but too weak by orders of magnitude to account for observed ~1-in-10^8 BAU!
    - more *CP* violation to be discovered??
      - hot particle-physics topic (LHC*b*/Belle/LBNE...) – but, so far, no experimental evidence for it

James Watson Cronin Val Logsdon Fitch

[photo credits: Nobelprize.org]



LHC*b*

But there's *more*...

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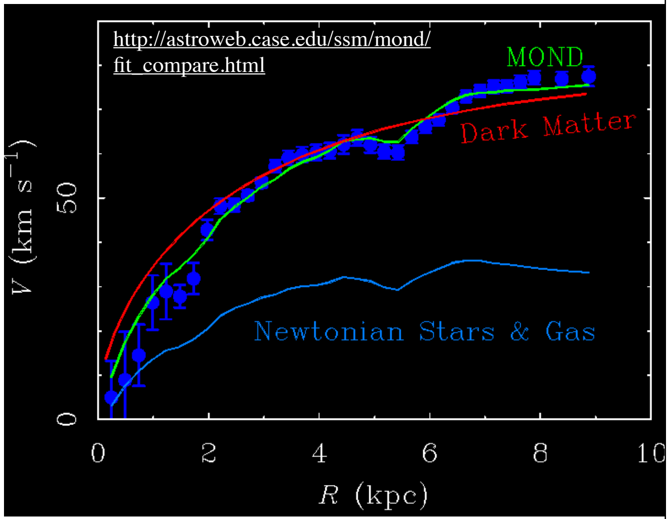
Three Cosmological Puzzles

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*
   - suggest existence of large amounts of "**dark matter**" (5 x normal matter) – but dark matter particles have yet to be found



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]
  - 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

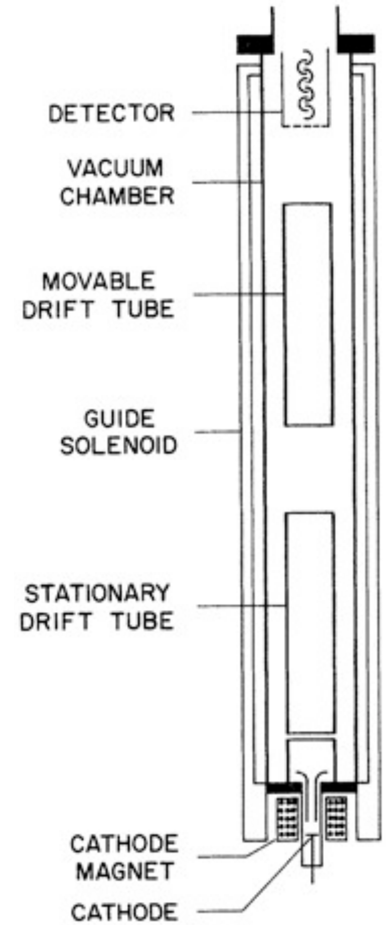
Whitteborn & Fairbanks Expt

[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

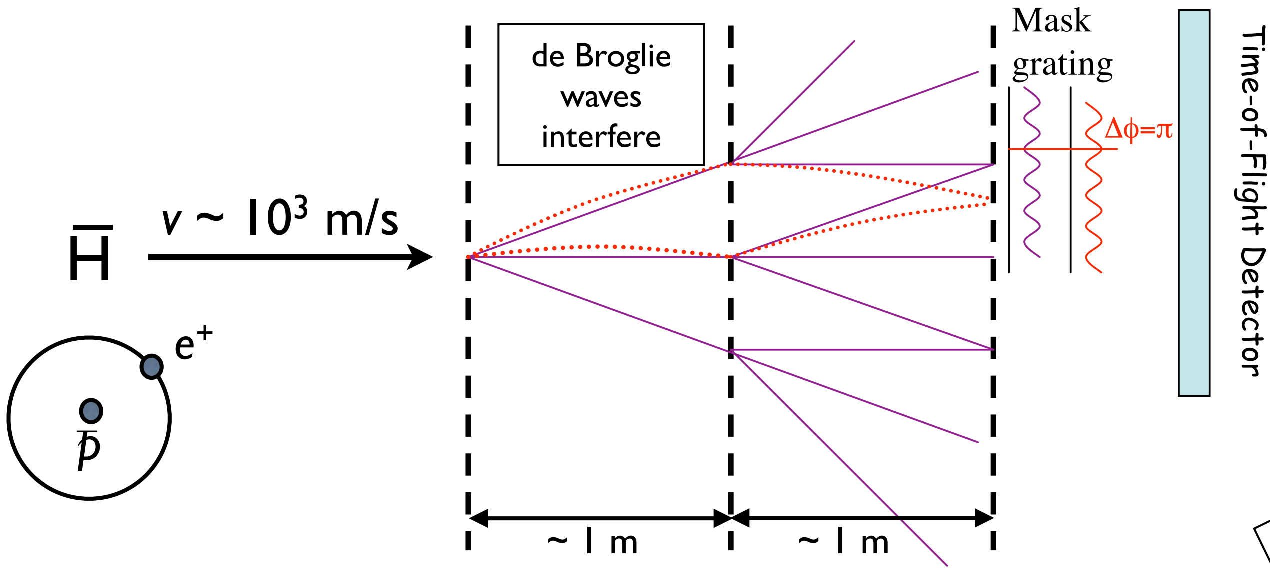
- Los Alamos-led team proposed (1986) to measure gravitational force on antiprotons at the CERN Low Energy Antiproton Ring (LEAR)
- Similar approach to Witteborn & Fairbank, but with 2000x greater *m*/*q* ratio
- Project ended inconclusively

▶ 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 $g - \bar{g} = 0$ or ε
  - in principle a simple interferometric measurement with slow antihydrogen beam [T. Phillips, Hyp. Int. 109 (1997) 357]:



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

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!

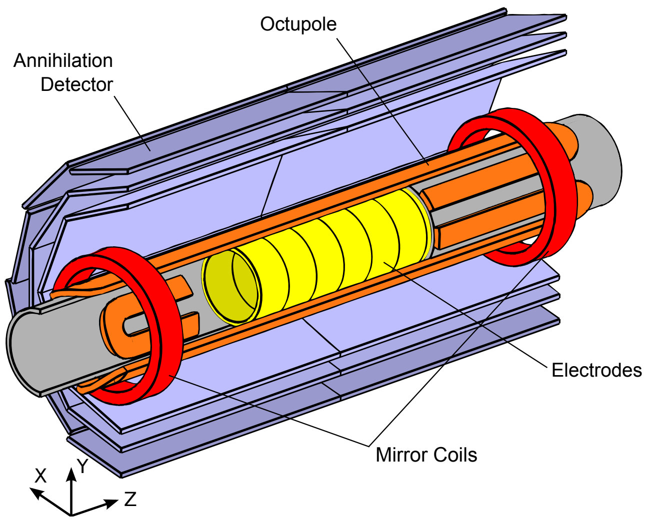
Studying Antimatter Gravity

- World leader: ALPHA* at CERN Antiproton Decelerator

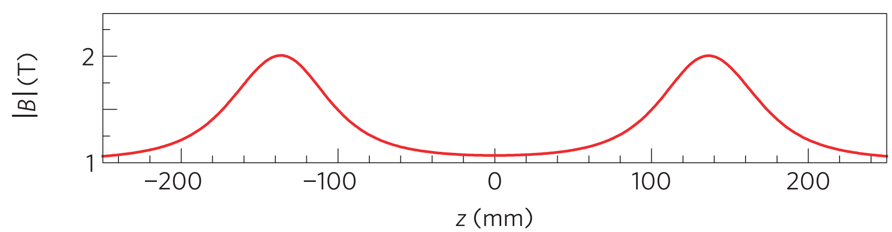
Aarhus Univ, Simon Fraser Univ, Berkeley, Swansea Univ, CERN, Univ Federal do Rio de Janeiro, Univ of Calgary, TRIUMF, Univ of British Columbia, Univ of Tokyo, Stockholm Univ, York Univ, Univ of Liverpool, Univ of Victoria, Auburn Univ, NRCN-Nuclear Research Center Negev, RIKEN

* Antihydrogen Laser Physics Apparatus

- 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]



- then shut off the magnet currents & see whether more $\overline{H}$ 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 $F = m_{grav.}/m_{inert.}$ of $\bar{H}$
- Then

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

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

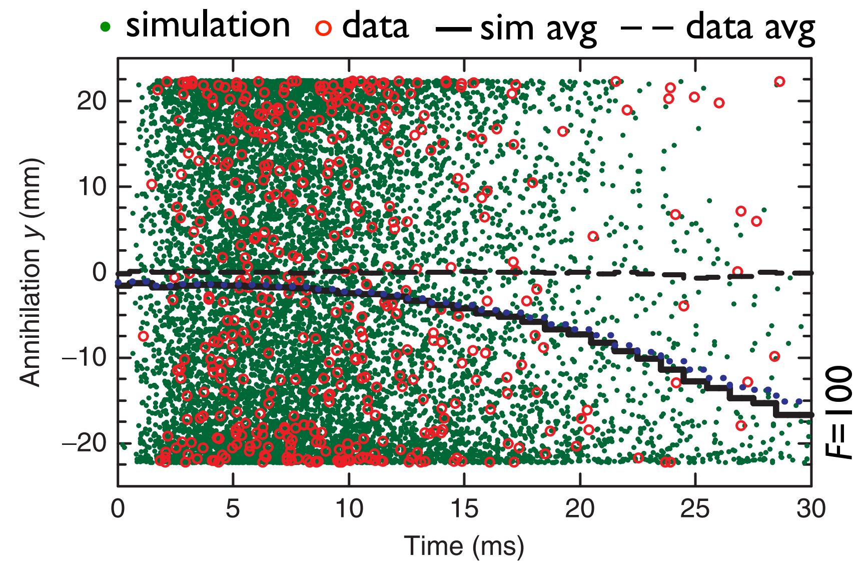


Figure 2 | Annihilation locations. The times and vertical (y) annihilation locations (green dots) of 10,000 simulated antihydrogen atoms in the decaying magnetic fields, as found by simulations of equation 1 with $F=100$. Because $F=100$ in this simulation, there is a tendency for the anti-atoms to annihilate 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 $\bar{H}$ 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, 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 – would be the *first* gravitational measurement of a lepton, and of a 2nd-generation particle

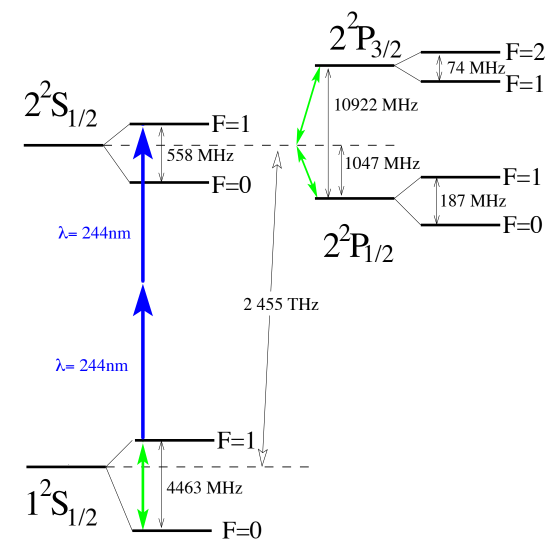
Muonium

- 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.

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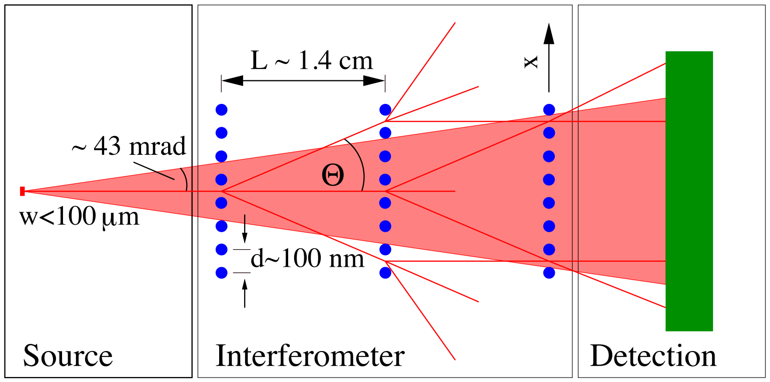
Studying Muonium Gravity

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)

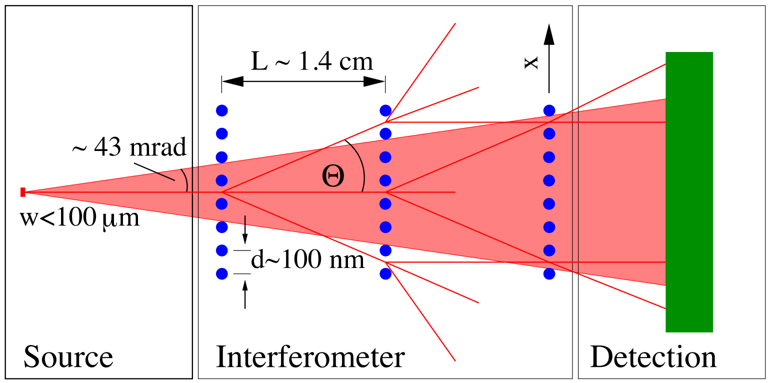
Recently a new technique for the production of muon (μ^+) and muonium (μ^+e^-) beams of unprecedented brightness has been proposed. As one consequence and using a highly stable Mach-Zehnder type interferometer, a measurement of the gravitational acceleration $\bar{g}$ of muonium atoms at the few percent 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!

v ~ 6300 m/s



$\frac{1}{2}gt^2 = 25$ 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 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, and the signal will be washed out

Monoenergetic Muonium?

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

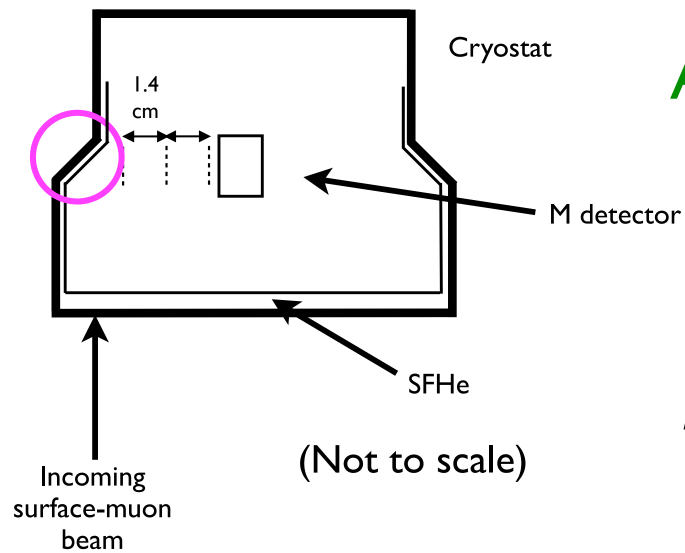
[D. Taqqu, "Ultraslow Muonium for a Muon beam of ultra high quality," Phys. Procedia 17 (2011) 216]

  - stop slow 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 (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!"

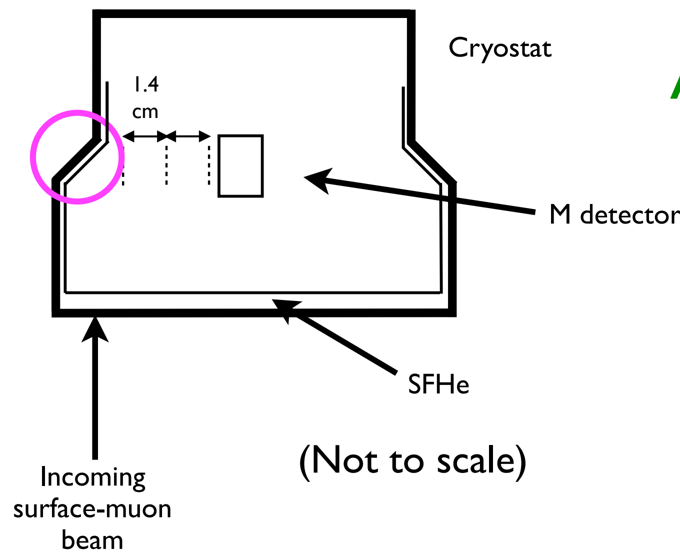
Sensitivity estimate
@ 100 kHz:

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

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

Muonium Gravity Experiment

- One can then imagine the following apparatus:



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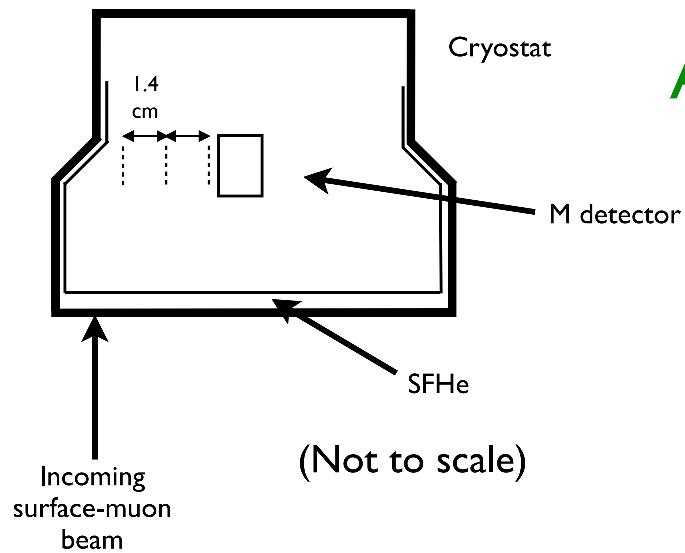
$$\approx 0.3\,\mathrm{g} \;\text{ per } \sqrt{\#\text{days}}$$

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

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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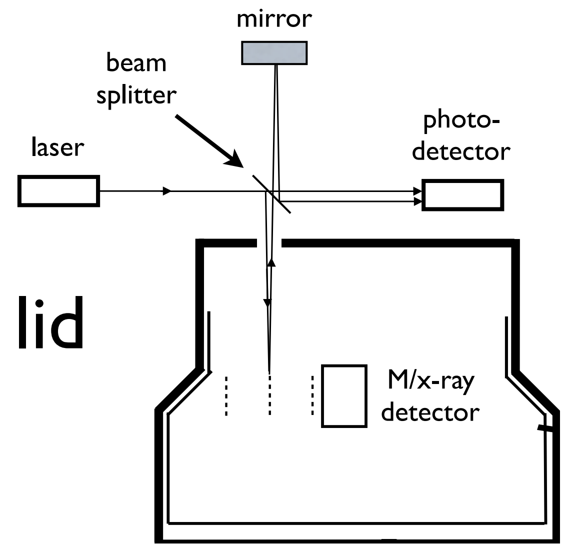
Answering the Questions:

1. Can sufficiently precise diffraction gratings be fabricated?
   - our collaborator, Derrick Mancini of the ANL Center for Nanoscale Materials (CNM) thinks so – proposal submitted to CNM to try it
2. Can interferometer and detector be aligned to a few pm and stabilized against vibration?
   - needs R&D, but LIGO does much 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 (can M detector detect x-rays?)
5. Does Taqqu's scheme work?
   - needs R&D; PSI working on it

Interferometer Alignment



- Could use 2 Michelson interferometers per grating
  - send laser beams in through cryostat lid
    - keeps instrumentation & heat external to cryostat & M detection path open
  - "natural" sensitivity ~ $\lambda/2$ ~ 300 nm; need ~ 3 pm $\Rightarrow 10^{-5}$ enhancement
    - enhance by sitting at a zero of the intensity, using SAW modulation, etc.
    - still lots of details to work out!

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 $4\ e^{-1} \approx 1.5$
  - tripling → x 1.2 improvement – diminishing returns
    - but 9 x bigger signal ⇒ easier calibration, alignment, & stabilization

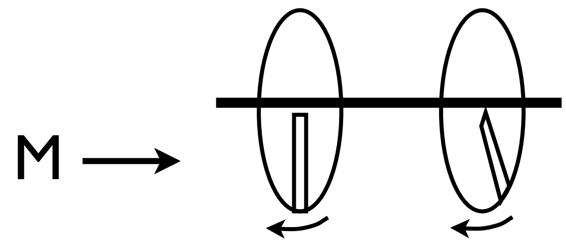
- Need simulation study to identify optimum, taking all effects into account

Additional Considerations

- Alternate solutions:
  - different M production scheme?
    - "monochromate" the beam by chopping?
  - laser interferometry instead of gratings?

Alternate Solutions

- Different M production scheme?
  - muonium production often employs SiO_2 powder or silica aerogel
  - thermal energy spectrum, not monochromatic
  - can monochromate using choppers
  - drawbacks:
    - flux reduction
    - rotating shaft & bearings in vacuum



Alternate Solutions

- Atomic-beam laser interferometry: gravimetry "gold standard"

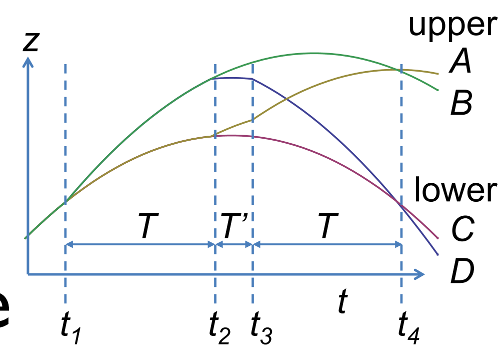
Selected for a Viewpoint in *Physics*
PRL **108,** 090402 (2012) PHYSICAL REVIEW LETTERS week ending 2 MARCH 2012

Influence of the Coriolis Force in Atom Interferometry

Shau-Yu Lan,[1,*] Pei-Chen Kuan,[1] Brian Estey,[1] Philipp Haslinger,[2] and Holger Müller[1,3]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*VCQ, Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria*
[3]*Lawrence Berkeley National Laboratory, One Cyclotron Road, Berkeley, California 94720, USA*
(Received 31 October 2011; published 27 February 2012)

In a light-pulse atom interferometer, we use a tip-tilt mirror to remove the influence of the Coriolis force from Earth's rotation and to characterize configuration space wave packets. For interferometers with a large momentum transfer and large pulse separation time, we improve the contrast by up to 350% and suppress systematic effects. We also reach what is to our knowledge the largest space-time area enclosed in any atom interferometer to date. We discuss implications for future high-performance instruments.

- technique good to $\Delta g/g \sim 10^{-9}$
- timed laser pulses make superposition of atomic hyperfine states, which interfere



Alternate Solutions

- Atomic-beam laser interferometry: gravimetry "gold standard"
- Evaluating feasibility for muonium will take some effort
  - many variables to consider, e.g.:
  - use ground-state muonium?
    - requires difficult "Lyman-alpha" VUV laser
    - likely impractical to get laser beams into cryostat without windows
  - or $n = 2$ muonium?
    - what fraction are produced in that state?

R&D Status

- Still early days...
- Seeking funding, students, and collaborators
  - collaboration so far:

IIT-CAPP-13-6
arXiv:1308.0878 [physics.ins-det]

Measuring Antimatter Gravity with Muonium

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Klaus Kirch
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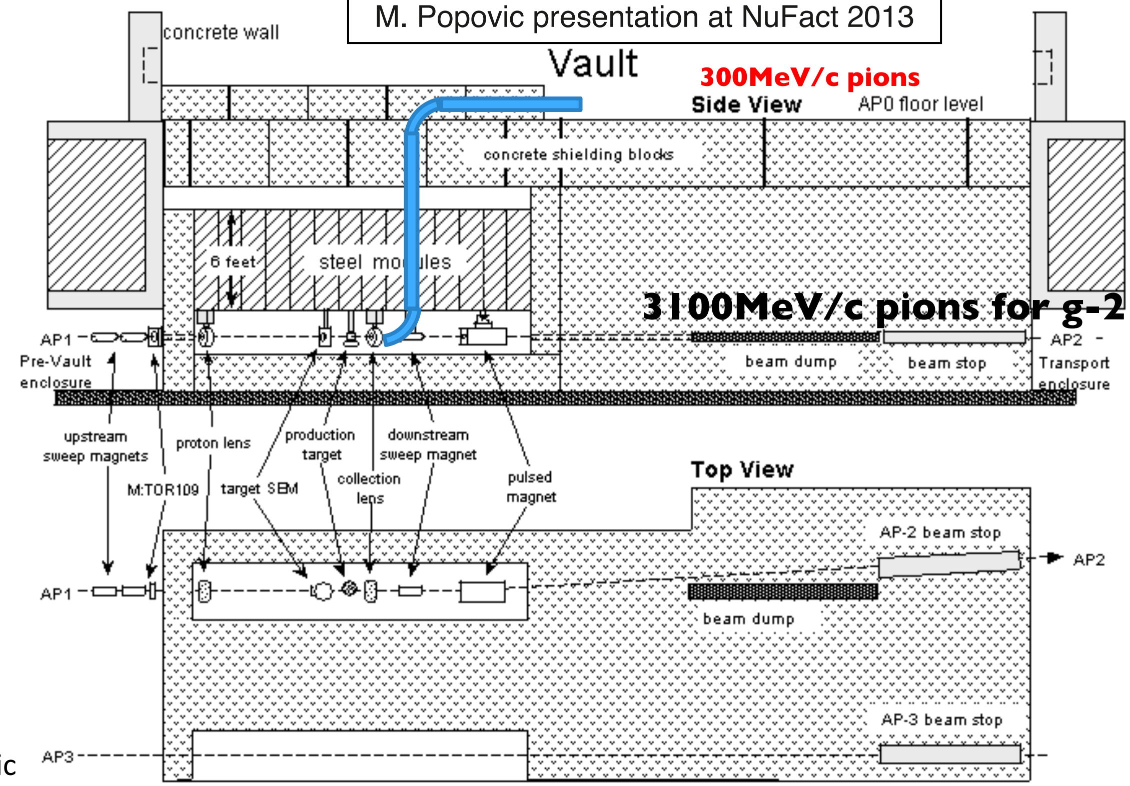
- Seeking venue at Fermilab
  - e.g., proposed new low-energy muon beam at AP0

M. Popovic presentation at NuFact 2013



R&D Status

- Still early days...
- Seeking funding, students, and collaborators
  - collaboration so far:
- Seeking venue at Fermilab
  - e.g., proposed new low-energy muon beam at AP0
  - ultimately, Project X

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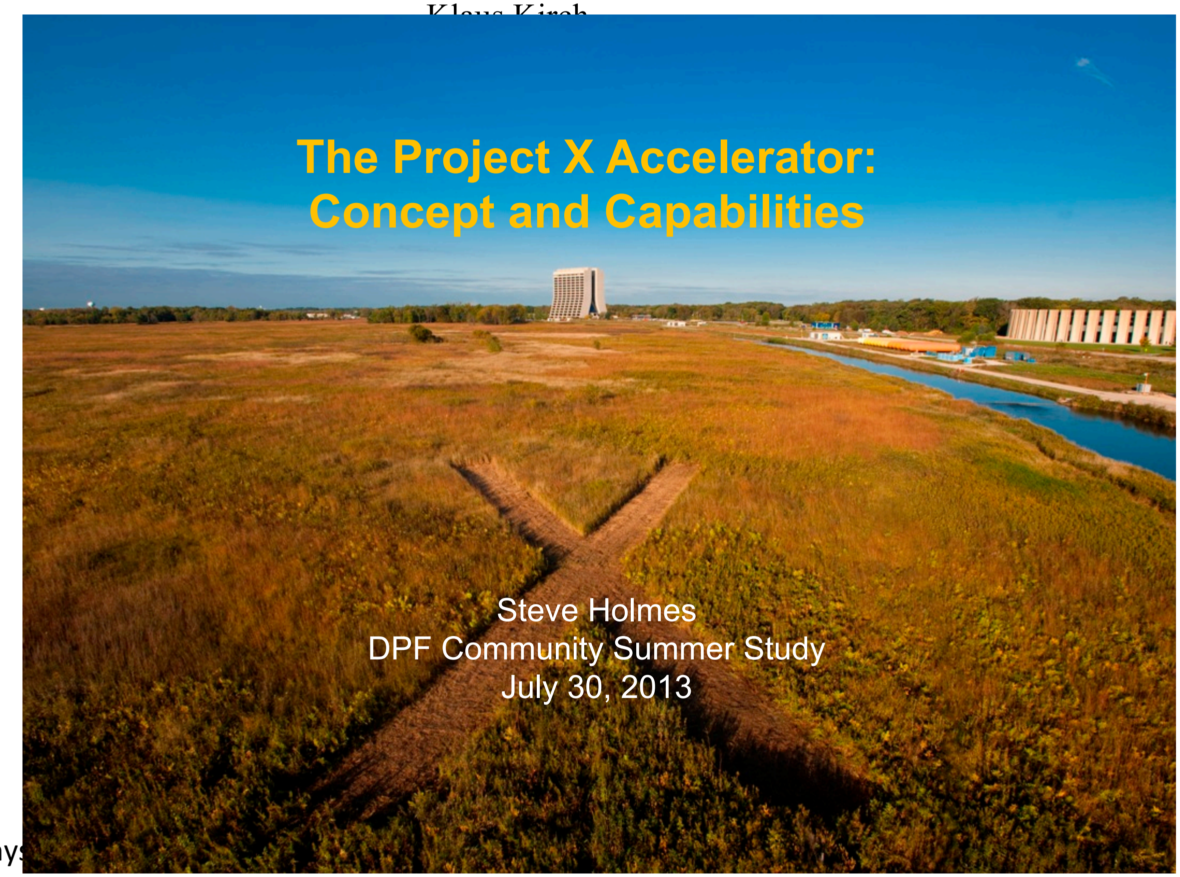

Conclusions

- Antigravity hypothesis might neatly solve several vexing problems in physics and cosmology
- In principle, testable with antihydrogen or muonium
  - if possible, *both* should be measured

➡ First measurement of muonium gravity would be a milestone!

- But first we must determine feasibility

Final Remarks

- These measurements are an obligatory homework assignment from Mother Nature!
- Whether $\bar{g} = -g$ or not, if they are successfully carried out, the results will certainly appear in future textbooks.