Antimatter Gravity Experiment at Fermilab

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The goal of the AGE collaboration is to make the first direct measurement of the gravitational force of the earth on antimatter. We can make this measurement, which has the potential to profoundly change the way we view the universe, to a precision exceeding 1% of g relatively quickly and at a modest cost.

Thomas Phillips
Duke University

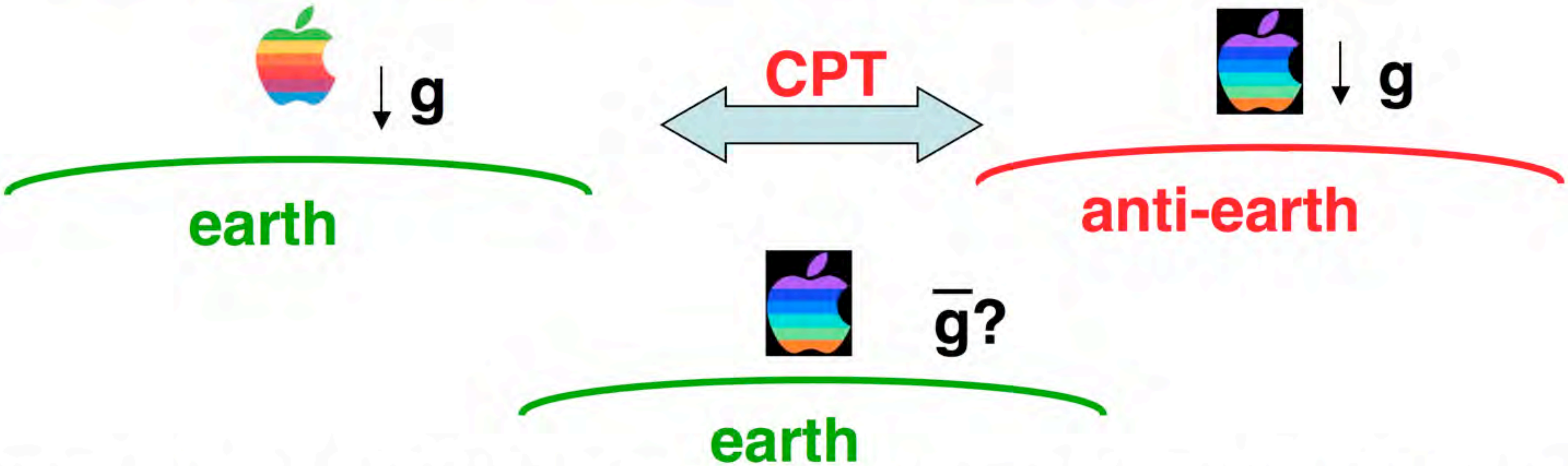
Outline

1. Motivation
2. Method
   A. Overview
   B. Background on techniques
   C. Preparing the antimatter
      - Gerry Jackson will provide details in his talk.
   D. Monte Carlo results
3. Schedule
4. Summary

Physics Motivation

$\bar{g}$ (the acceleration of antimatter towards the earth)

has never been directly measured!



CPT does not address how an antiapple falls on the earth.

General Relativity does predict that gravity is independent of composition, so this experiment will test GR in a new way: Does the equivalence principle apply to antimatter?

New forces, e.g., graviscalar and gravivector forces could cancel for matter but add for antimatter.

"Do we already know the answer?"

Equivalence Principle limits

- graviscalar and gravivector interactions can cancel for matter-matter and add for matter-antimatter Nieto & Goldman Phys. Rep. 205, 221.

Virtual antimatter (Schiff argument) Schiff PRL 1, 254; Proc.Natl.Acad.Sci. 45, 69.

- non renomalizable as presented; too small to see (10^{-16}) when using contribution to stress-energy tensor Nieto & Goldman Phys. Rep. 205, 221.

K_S regenerated in K_L beam (Good argument) Good Phys. Rev. 121, 311.

- Argument requires absolute potentials
  - with relative potentials, too small to have been seen Nieto & Goldman Phys. Rep. 205, 221.
- CP violation in Kaon system from antigravity Chardin & Rax Phys. Lett. B 282, 256.

Energy not conserved (Morrison argument) Morrison Am.J.Phys. 26, 358.

- Depends upon coupling of photons to forces Nieto & Goldman Phys. Rep. 205, 221.
- Antigravity gives Hawking radiation from normal bodies Chardin AIP CP643, 385.

Neutrinos from SN1987a

- Some uncertainty that both ν and $\bar{\nu}$ observed.
- Insensitive to forces with ranges much less than 1 pc Nieto & Goldman Phys. Rep. 205, 221.

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In a word, "No". Antimatter gravity is an empirical question.

Only a direct measurement can provide a definitive answer!

A Neutral Beam Experiment for Measuring $\bar{g}$

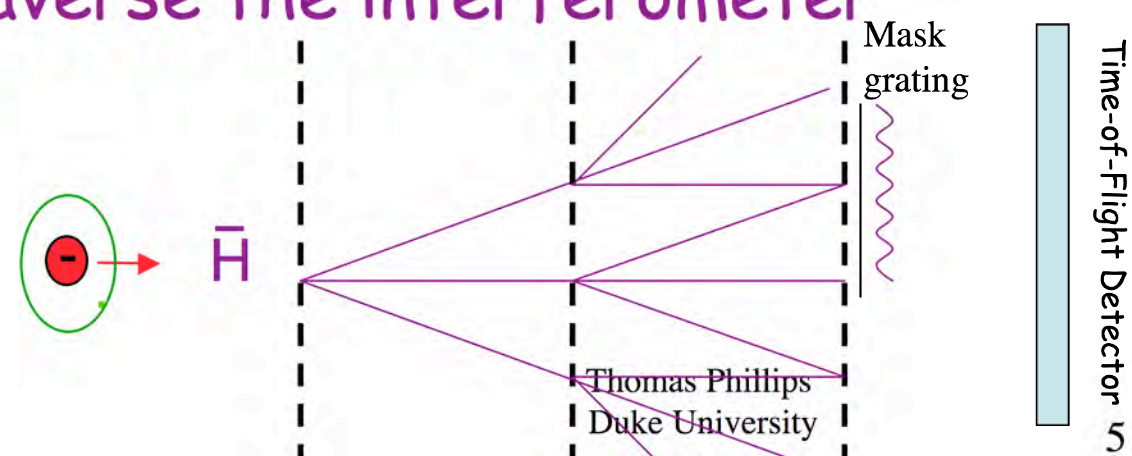
Make a low-velocity antihydrogen beam

- Trap and cool antiprotons
- Trap and cool positrons
- Accelerate antiprotons, direct through positron plasma to make antihydrogen

Direct the beam through a transmission-grating interferometer (Measure velocity with Time of Flight)

Measure $\bar{g}$ by observing the gravitational phase shift

- Interference pattern shifts by the same amount the atoms "fall" as they traverse the interferometer



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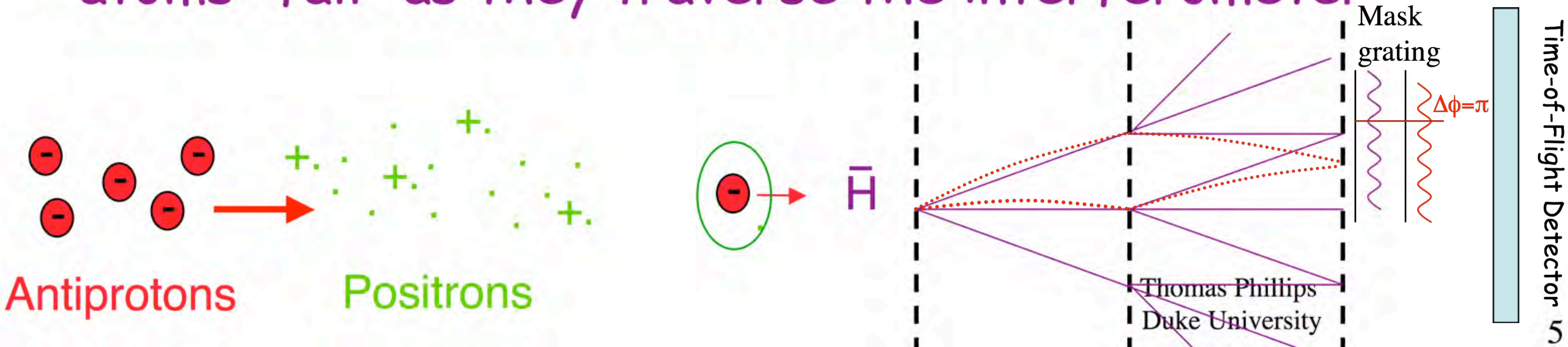
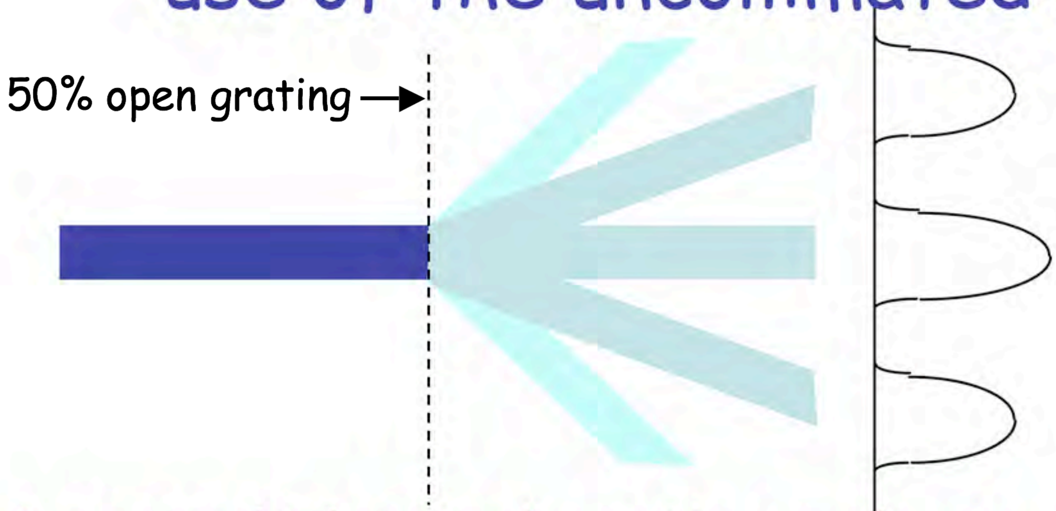


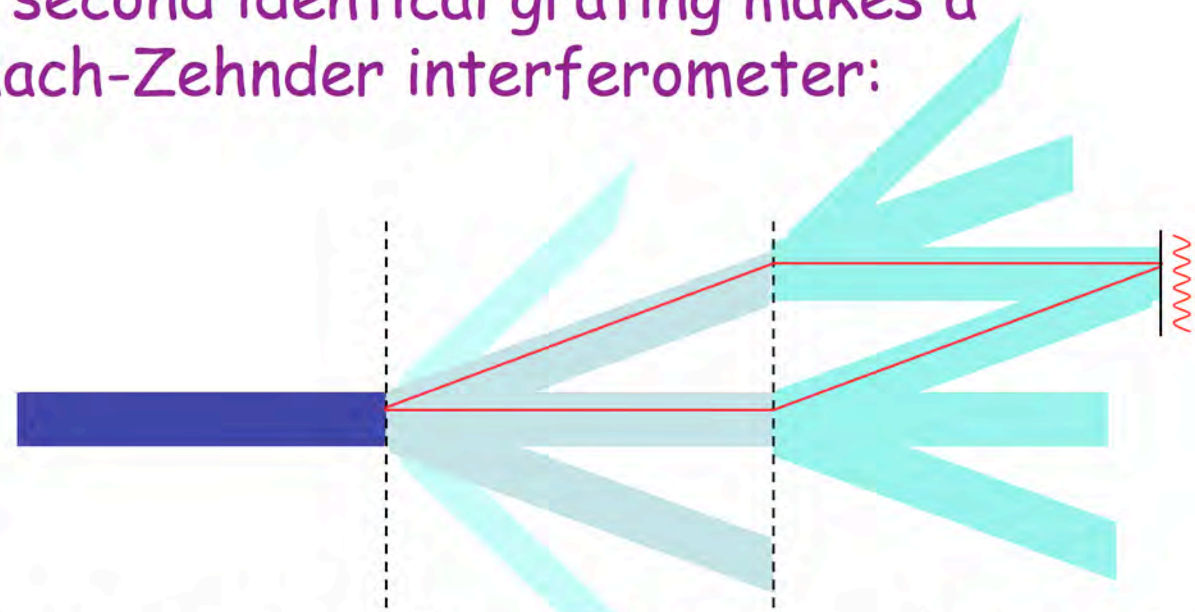
The Atomic Interferometer

This interferometer design can make efficient use of the uncollimated antihydrogen beam.



A single grating splits the beam and makes a diffration pattern.

A second identical grating makes a Mach-Zehnder interferometer:



The interference pattern has the same period as the gratings so a third identical grating can be used as a mask to analyze the phase of the pattern.

The gravitational phase shift will measure $\bar{g}$.

This is a "white-light" "extended source" interferometer

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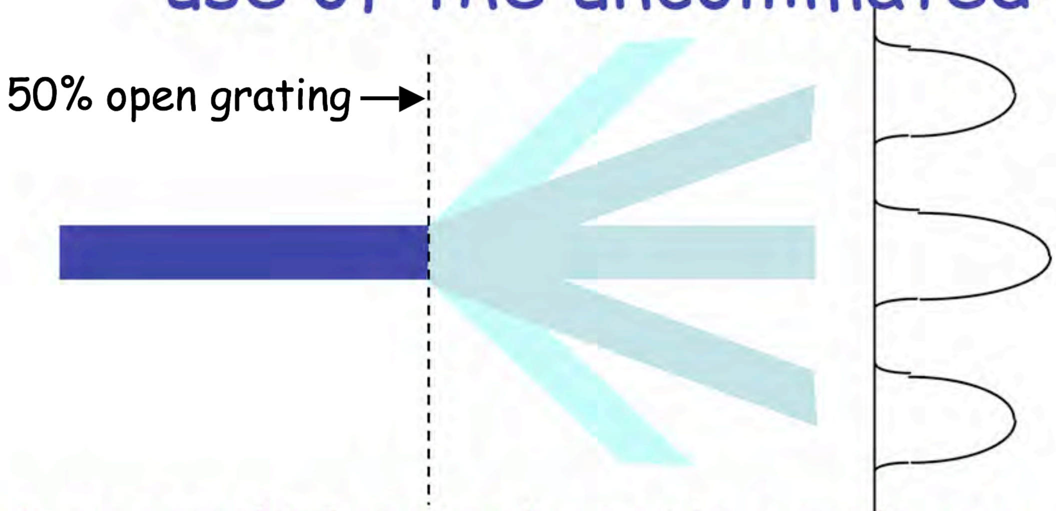

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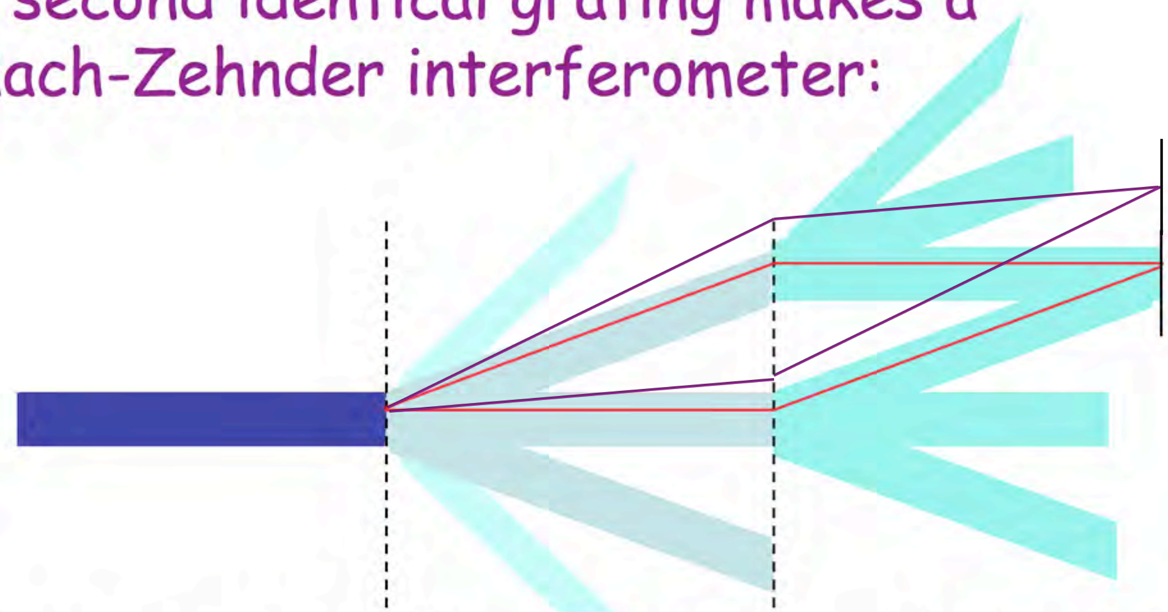

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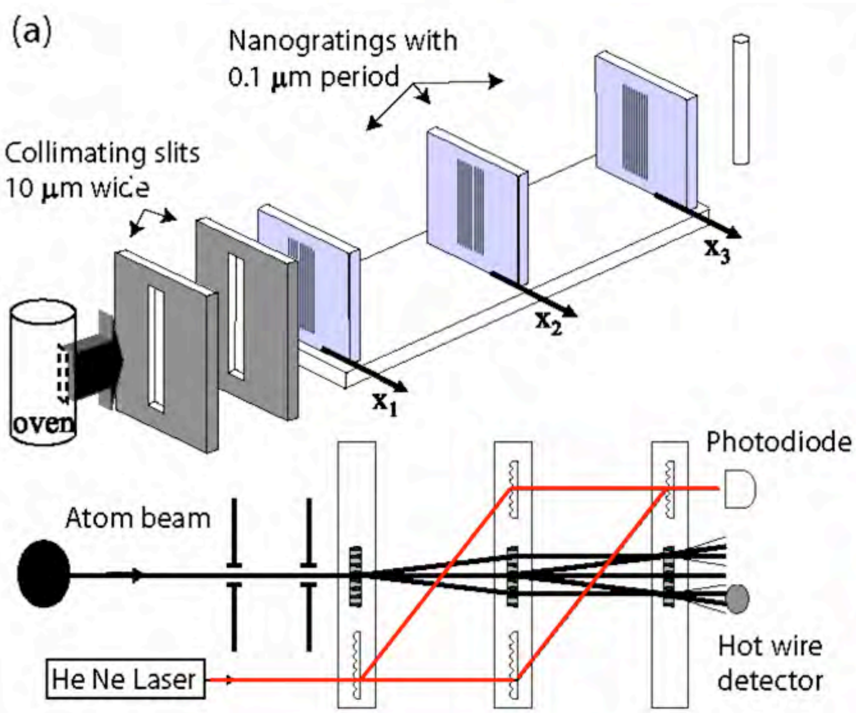
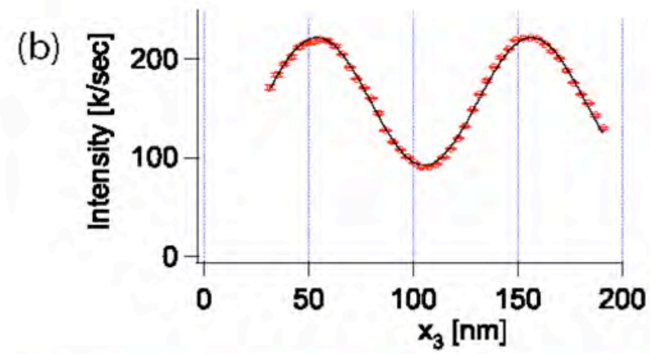
Atomic Interferometry Works!

Interference has been observed with the MIT/Arizona interferometer using an atomic Sodium beam

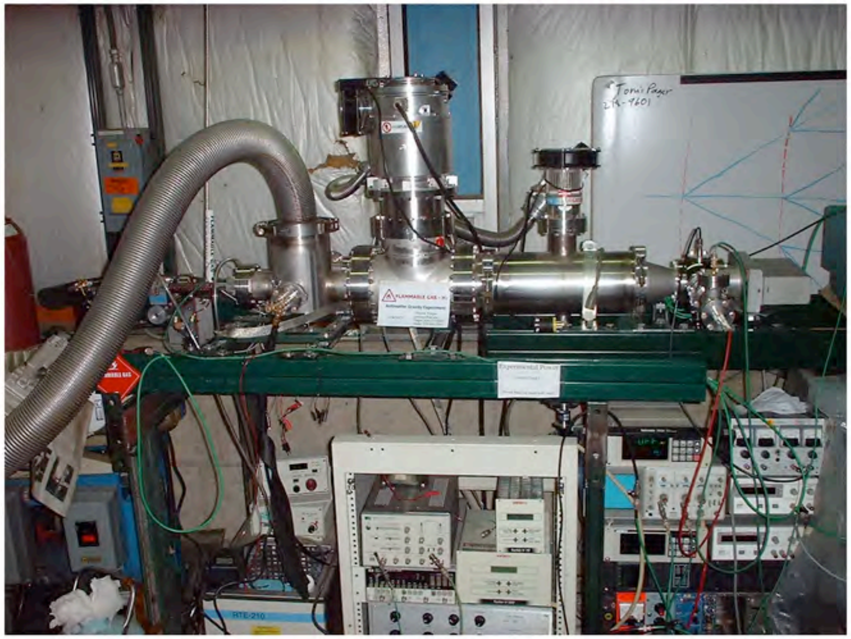




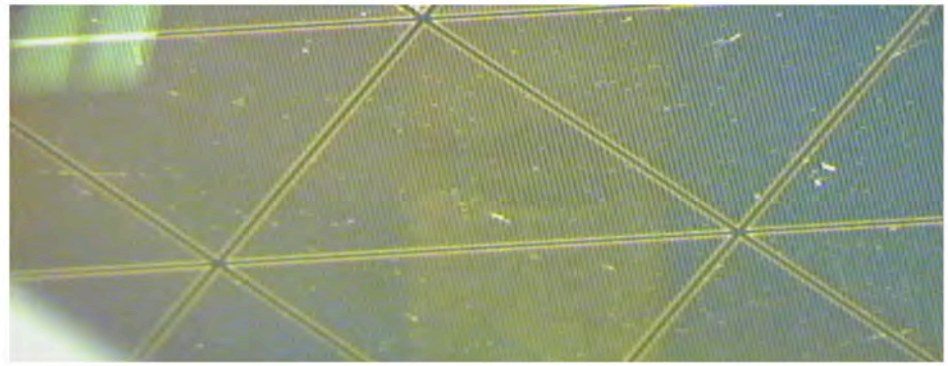
An atomic interferometer using sodium atoms and vacuum transmission gratings

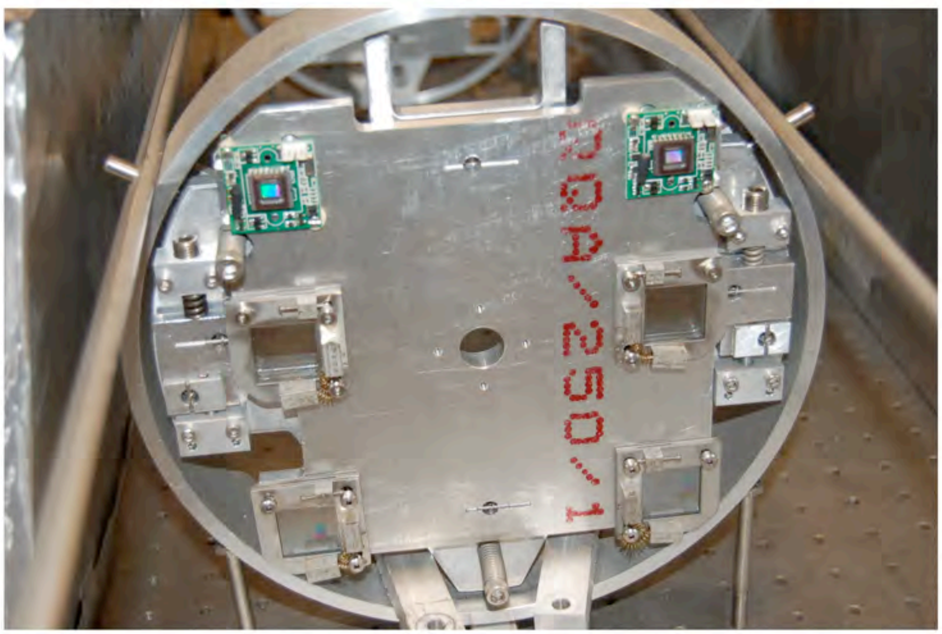
This resolution is an order of magnitude better than we need for the antimatter gravity experiment. If this interferometer were rotated 90°, gravity would cause a 200 π phase shift. Atom interferometers (using lasers rather than gratings) have measured g to 1:10^{10}

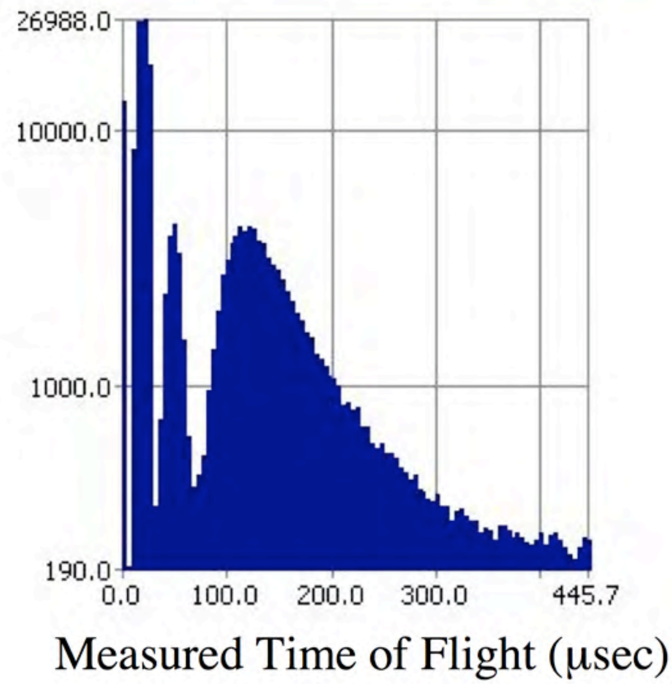
Prototype Interferometer (Hydrogen)



We are currently working on a prototype interferometer…







Prototype Interferometer (Hydrogen)

R&D in Progress

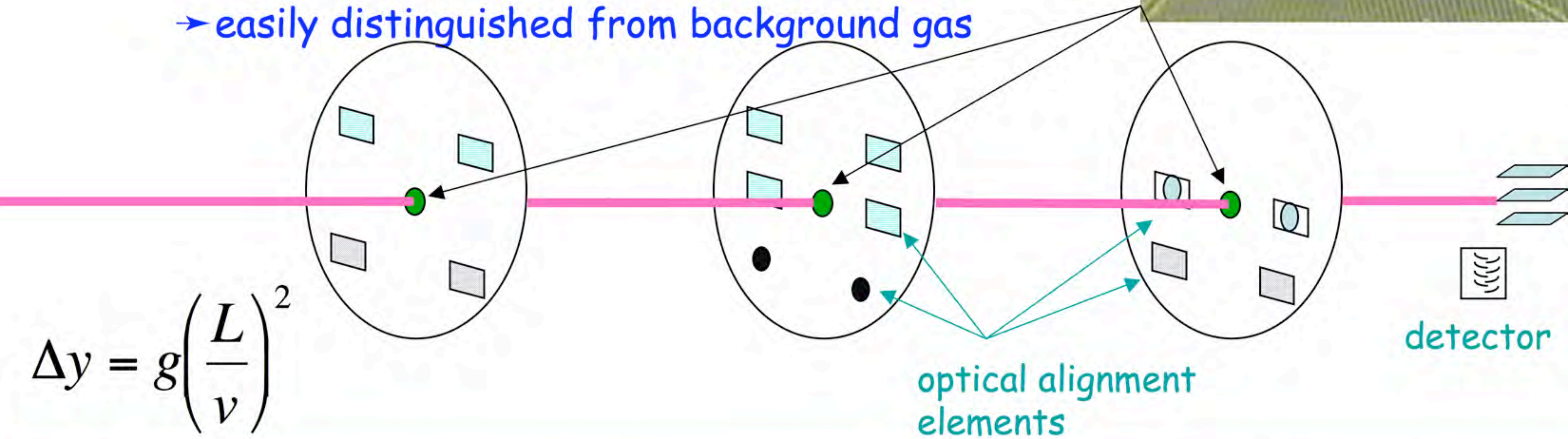
Transmission gratings have a 1 μm period

- Courtesy of Max Planck Institute for Extraterrestrial Physics

L = 62 cm between pairs of gratings

Uses a metastable H beam

- easily distinguished from background gas



$$\Delta y = g\left(\frac{L}{v}\right)^2$$

gravitational deflections: Δy=3.8 μm for v=1000 m/s => $\Delta\phi$=7.5 π radians
Δy=0.4 μm for v=3000 m/s => $\Delta\phi$=0.8 π radians
Δy=0.15 μm for v=5000 m/s => $\Delta\phi$=0.3 π radians

Antiprotons

This is a $0.5 billion experiment!

- The vast majority of this has already been spent
  - Antiproton Source
  - Main Injector
  - Recycler

Minimal operational impact

- use < 1% of antiprotons
- transfer from Recycler to Main Injector
  - already routine
- Decelerate in MI & extract to experiment

Antiprotons

The Antimatter Gravity Experiment will have negligible impact on the Tevatron program

can commission with small extractions of antiprotons from the Recycler (e.g. after Tevatron shots)

could also use occasional larger transfers when the antiprotons need to be dumped for an access.

	Efficiency	Antiprotons
Daily yield		400×10^{10}
1% extracted		4×10^{10}
trapped	5×10^{-4}	2×10^{7}
$\overline{H}$ created*	10%	2×10^{6}
transmitted	10%	2×10^{5}
interfering	20%	4×10^{4}

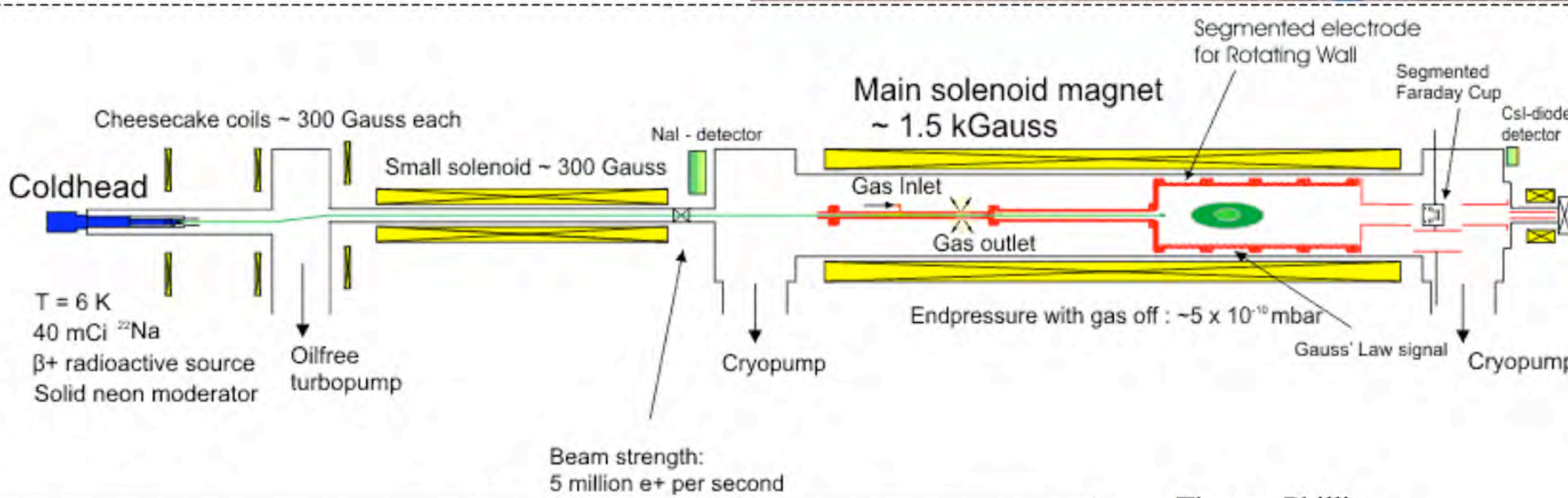
*Assumes ionizing collimator that can recycle $\overline{p}$.
Otherwise lose 10-50x to collimation.

Once antihydrogen production is established, the gravity measurement will be quick: only need ~10^6 $\overline{H}$ (1 km/sec) to measure $\overline{g}$ to 1% of g.

Positron Source

Commercial solution is available

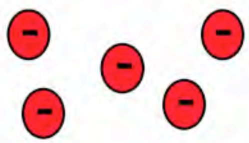
- up to 10^7 e^+/sec
- user supplies ^{22}Na
  - up to 150 mCi
- 5-11 month delivery
- \$212k + ^{22}Na source



ATHENA's positron accumulator (based upon same principle)

Making Antihydrogen

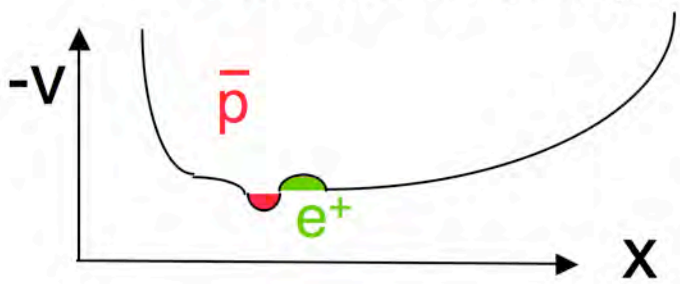
Ingredients:



Antiprotons

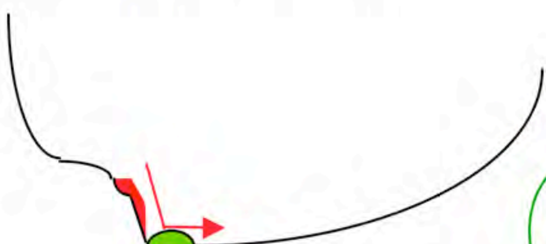
Positrons

Collect antiprotons in a trap. Add electrons to cool to 4 K. Collect positrons in an adjacent trap.

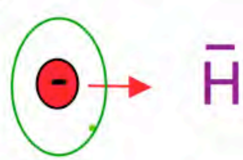


Then raise the potential of the $\bar{p}$ ...

...and drop barrier:



some $\bar{p}$ acquire an e^+ and make $\bar{H}$



which exit with $\bar{p}$'s momentum

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Antihydrogen Production

Antihydrogen Production

- Mechanisms:
  - 3-body: $\bar{p} + e^+ + e^+ \rightarrow \bar{H} + e^+$
  - radiative (re)combination $\bar{p} + e^+ \rightarrow \bar{H}$ + photon
  - 3-body $\bar{p} + \bar{p} + e^+ \rightarrow \bar{H} + \bar{p}$

- Rate estimate for first mechanism:

$$\Gamma = 6 \times 10^{-13} \left(\frac{4.2}{T} \right)^{\frac{9}{2}} n_e^2 \left[s^{-1} \right]$$

(Glinsky & O'Neil Phys. Fluids **B3** (1991) 1279.)

T in K

n_e in cm^{-3}

For $n_e \geq 10^7 / cm^3$ production rates ~ 1% of $\bar{p}$ converted to $\bar{H}$ per pass through a 10 cm positron plasma at 1 km/s

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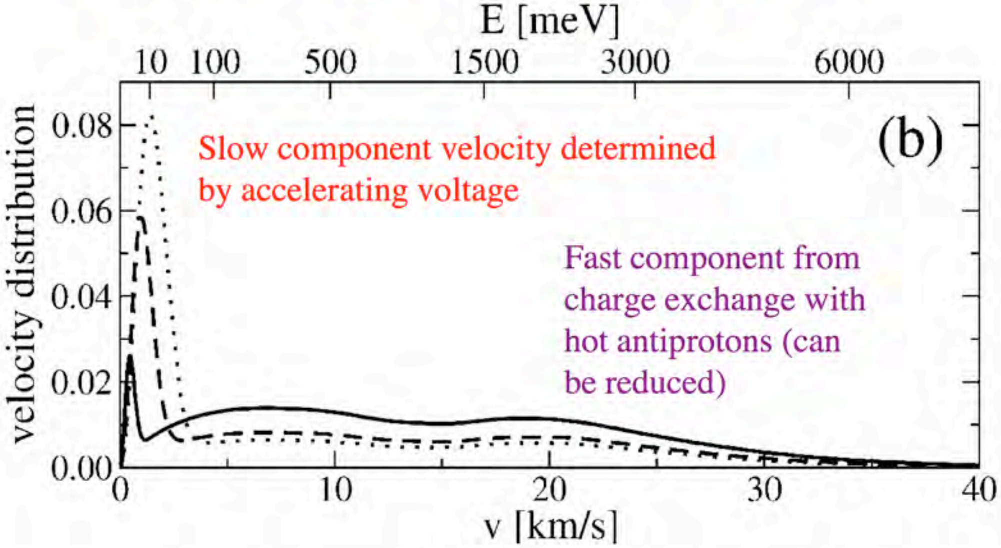
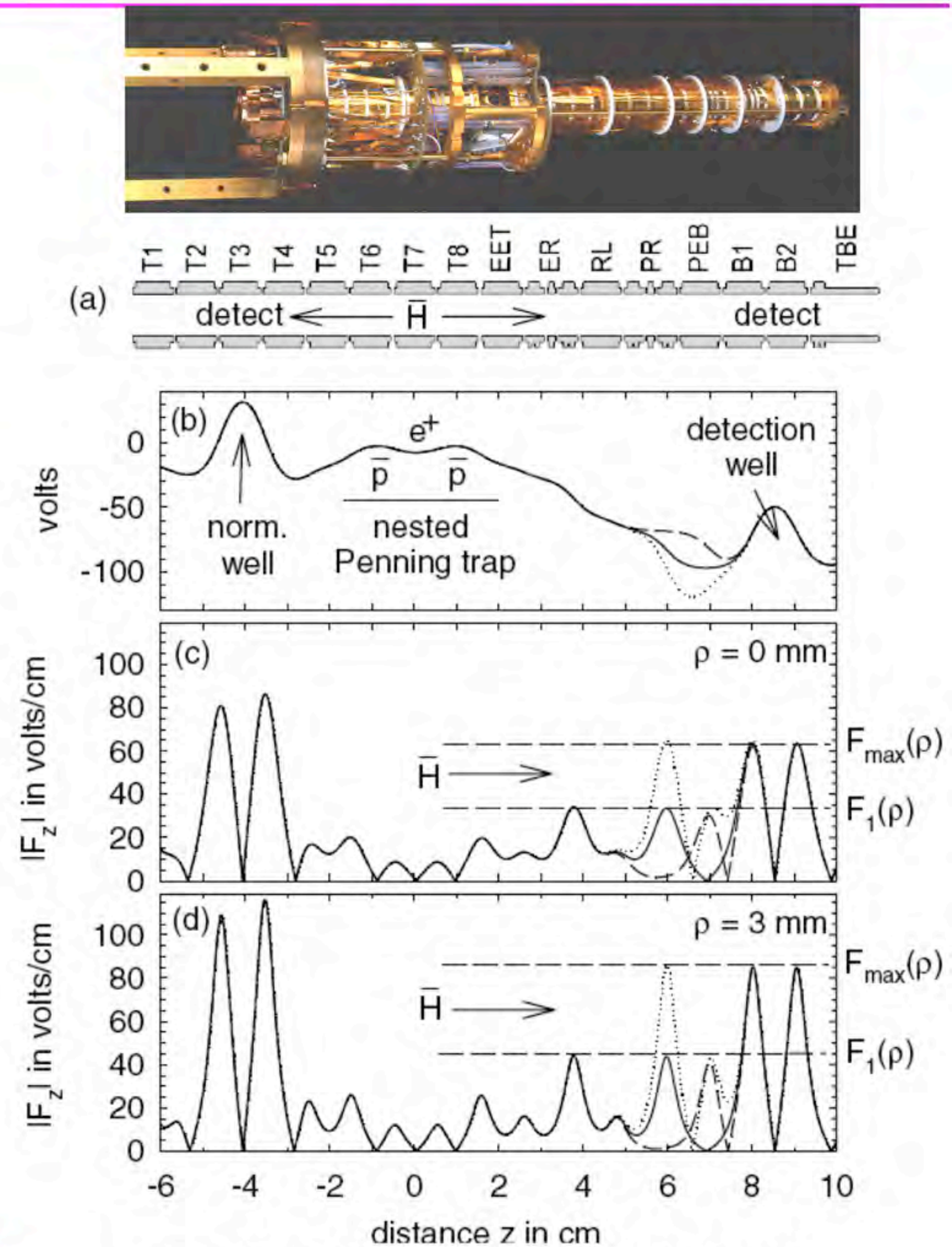
Antihydrogen Beam Proof-of-Principle

The ATRAP group has made antihydrogen in a beam with a velocity distribution nearly ideal for the gravity expt.



from Phys. Rev. Lett. 97, 143401 (2006)



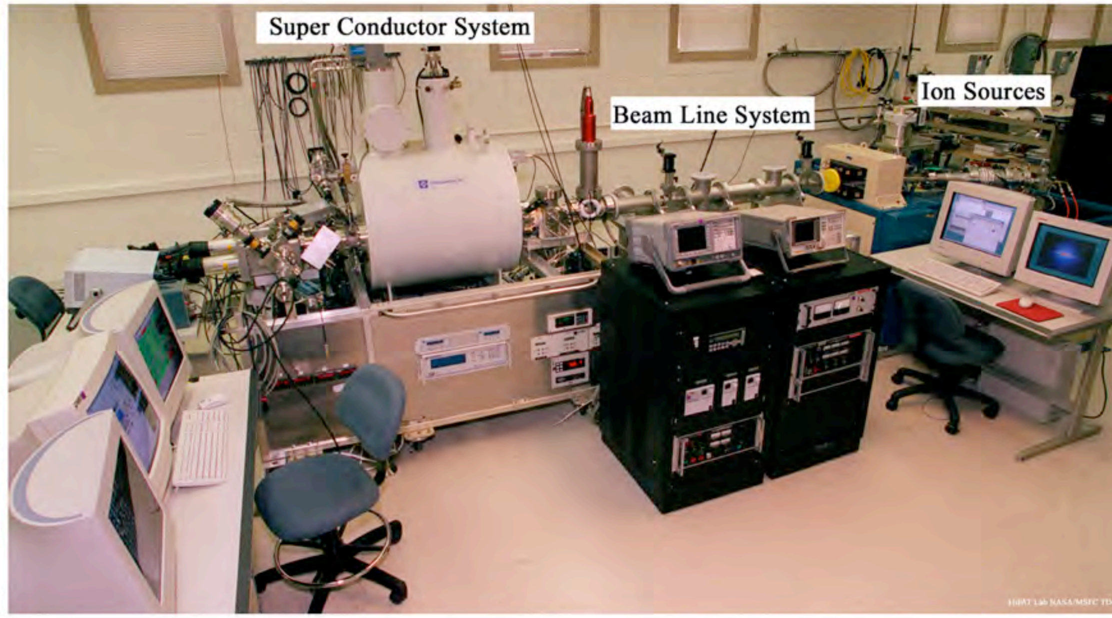
from Phys. Rev. Lett. 93, 073401 (2004)

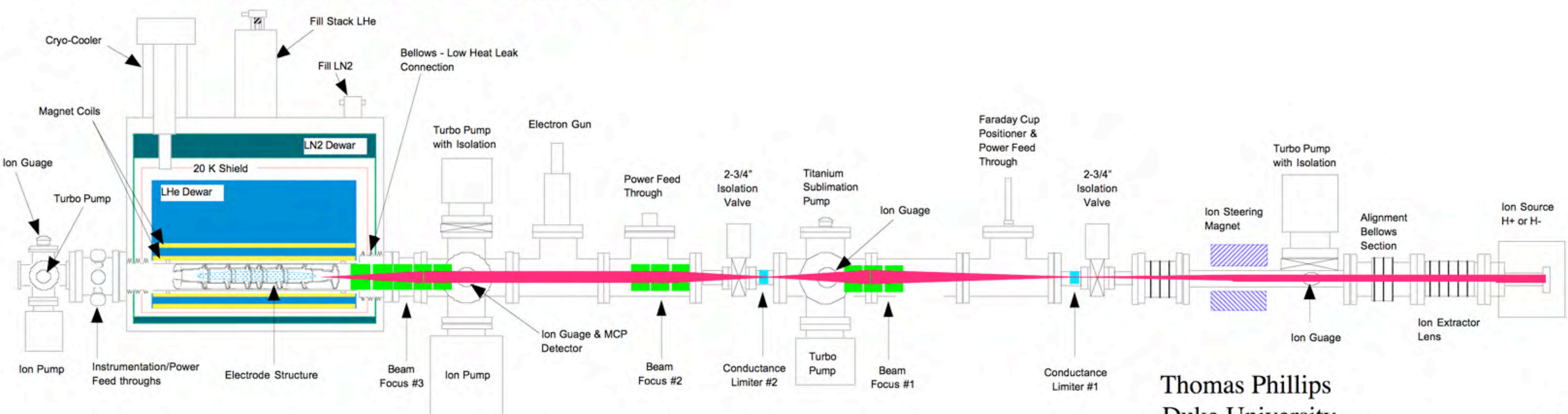
Beam would need to be gated to get TOF

High Performance Antiproton Trap

We will use NASA's HiPAT to make Hbar

- ➢4T solenoid
- ➢designed for 10^{12} $\bar{p}$
- ➢H^+, H^- beams
- ➢being crated for shipment here
- ➢will need a new electrode structure





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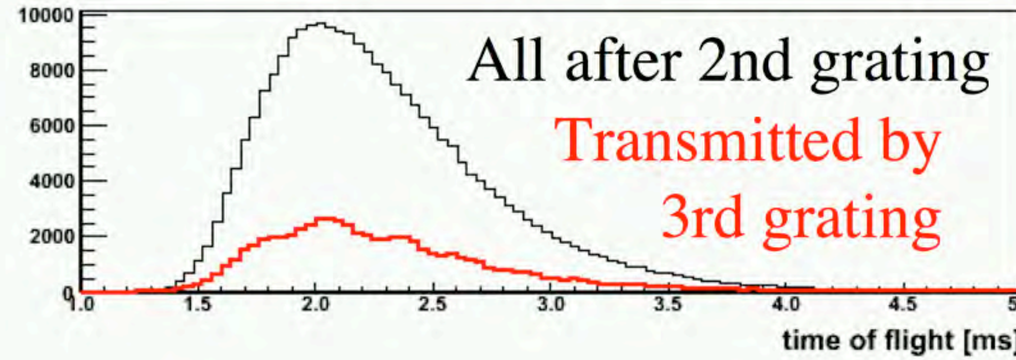
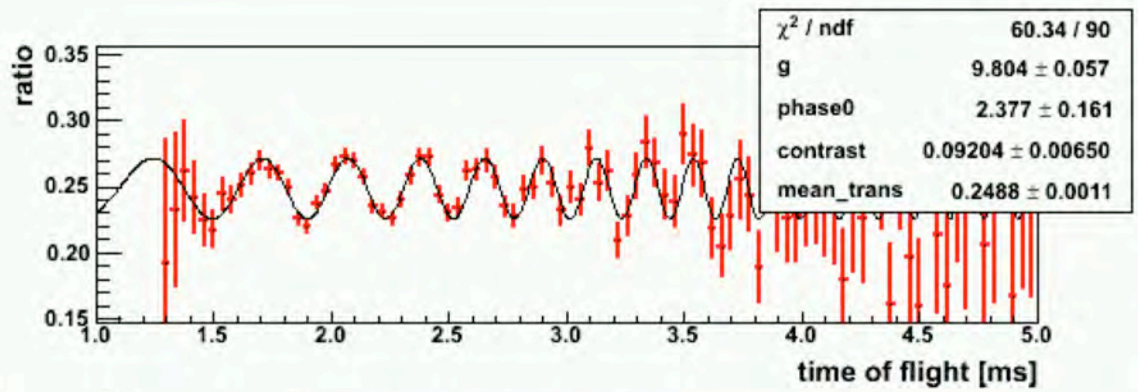
Monte Carlo Results

Simple MC shows what our data will look like.

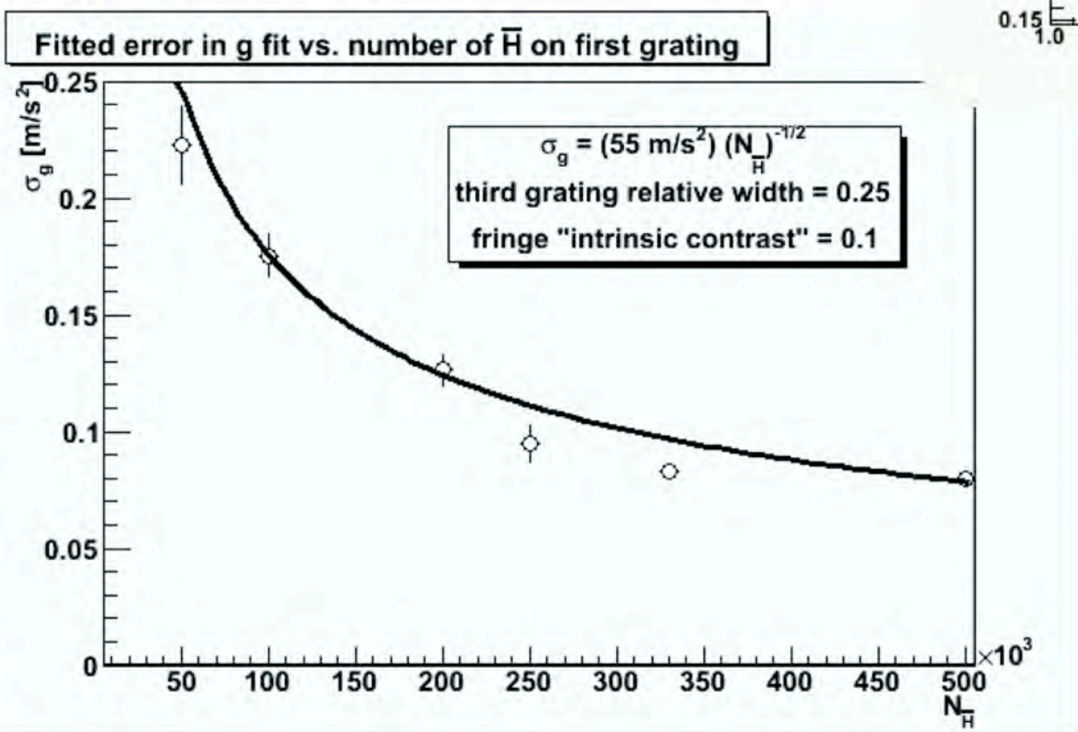


Phase shift is a function of time-of-flight: slower particles have larger gravitational phase shift

Get more transmission when interference peaks line up with gaps in mask



Time of Flight (msec)



Half a million antihydrogen will measure $\bar{g}$ to 1% of g.

Technically Driven Schedule I

This fiscal year

- demonstration experiment with H (3 FTE)
  - interferometer assembly requires use of a CMM
- additional deceleration studies (a few shifts)
- construct magnets for transfer line (10 FTE)
- build enclosure
- order positron source
- optimize designs (4 FTE)
- modify HiPAT for $\overline{\text{H}}$ production (3 FTE)

Technically Driven Schedule II

Next fiscal year & beyond

- Install & commission transfer line
- move HiPAT to enclosure
  - establish antiproton trapping
  - establish positron accumulation & transfer
  - establish antihydrogen production
- construct & commission interferometer
  - align & commission with a matter beam
- Measure $\overline{g}$
  - direct the antihydrogen through the interferometer and measure the gravitational phase shift

Conclusions

The Antimatter Gravity Expt will directly measure the force between antimatter and the earth for the first time

- direct test of the equivalence principle for antimatter
- sensitive to new forces with gravitational-scale couplings

The Antimatter Gravity Experiment will be done using proven technologies:

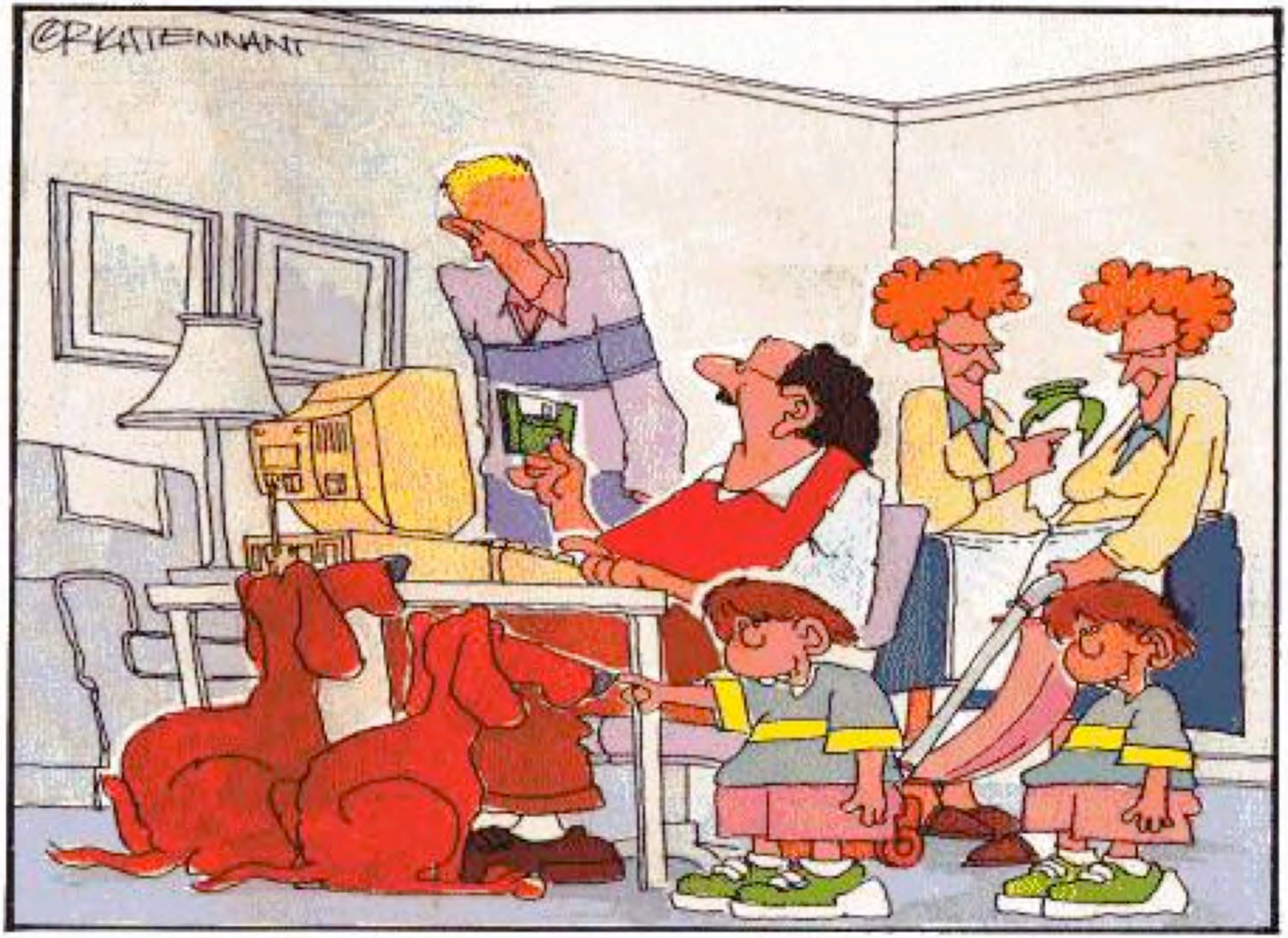
- antiproton production, trapping, & cooling
- antihydrogen production
- atomic interferometry

Much of the necessary equipment already exists

- antiproton source is operational (already built & paid for!)
- reduces cost and time required for the experiment

We believe this experiment is feasible, timely, and inexpensive, and we want to do it!

Backup



"I ALWAYS BACK UP EVERYTHING."

picture from http://comedy.glowport.com

Additional Motivation

- The Antimatter Gravity Experiment will provide an excellent opportunity for graduate students
- This program could be producing physics results between the Tevatron and Project X
  - Follow-on high precision experiment:
    - techniques used to measure local *g* with a resolution of a part in 10^{10} should work for (anti)hydrogen
    - considerable R&D needed

Public Relations!

The public loves antimatter!

- CERN's press release announcing they had made antihydrogen generated the biggest response they had ever gotten.
- The public can understand this experiment!

Particle physics needs good press!

Quantum Gravity

"a quantum-mechanically consistent construction of gravity requires a violation of the weak principle of equivalence" Nieto & Goldman, Phys.Rep. 205, 221 citing Kleinert Mod.Phys.Lett.A 4, 2329.

The spin-2 graviton generically has spin-1 (gravivector) and spin-0 (graviscalar) partners

- gravivector force is:
  - repulsive for matter-matter interactions
  - attractive for matter-antimatter interactions
- graviscalar force is always attractive
- gravivector and graviscalar forces can cancel for matter-earth and add for antimatter-earth:
  - e.g. $a \approx b, v \approx s$ in simplified potential below

$$V = -Gm_1 m_2 \left(1 \mp a e^{-r/v} + b e^{-r/s}\right)/r$$

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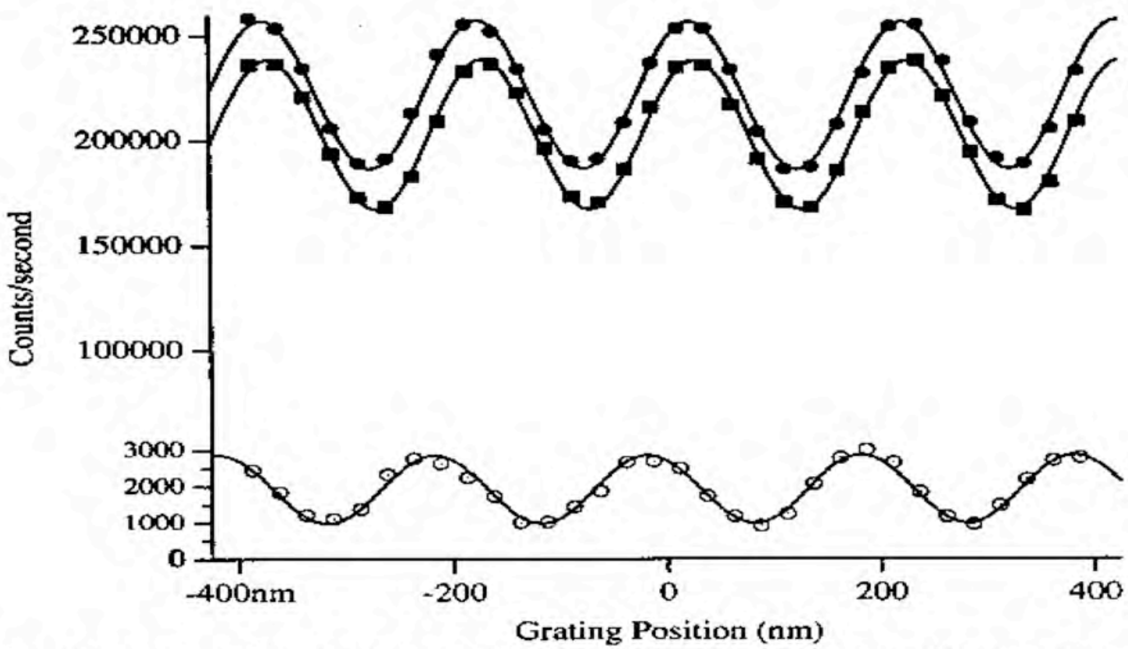
Uncollimated Beam Interferometry

Interference has been observed with the MIT interferometer using an <u>uncollimated</u> atomic Sodium beam

- Note much higher rate for uncollimated beams



<u>Uncollimated Beams</u>

Slow (1050 m/s) beam (upper)

Fast (3000 m/s) beam (lower)

<u>Collimated Beam</u>

Slow (1050 m/s)

non-interfering diffraction orders do not contribute

Atom Interferometry: Dispersive Index of Refraction and Rotation Induced Phase Shifts for Matter-Waves Troy Douglas Hammond, Ph.D. Thesis, MIT, February 1997.

Antiprotons

Antiprotons are made at Fermilab and CERN

- CERN's AD cannot accumulate antiprotons
  - pulses of 3×10^{7} antiprotons every 90 s
  - only runs part of year; future schedule uncertain
  - 10^{-3} capture efficiency (3×10^{4} per pulse)
- Fermilab can accumulate antiprotons
  - stacking rate typically exceeds 2×10^{11}/hour
  - runs year-round
  - 5×10^{-4} capture efficiency with degrader
    - 100x higher potential trapping rate than CERN
    - could be improved with decelerator ring
  - accumulating really helps!
    - antihydrogen production not tied to 90 sec. cycle
    - $\overline{H}$ from charge exchange goes as ($\bar{p}$ density)^2

Bottom line: Much easier to do the expt. at Fermilab