# Antimatter Gravity Experiment

## An Opportunity for Fermilab to (potentially) Answer Three of the Big Questions of Particle Physics

**Thomas J. Phillips**
**Duke University**

Outline

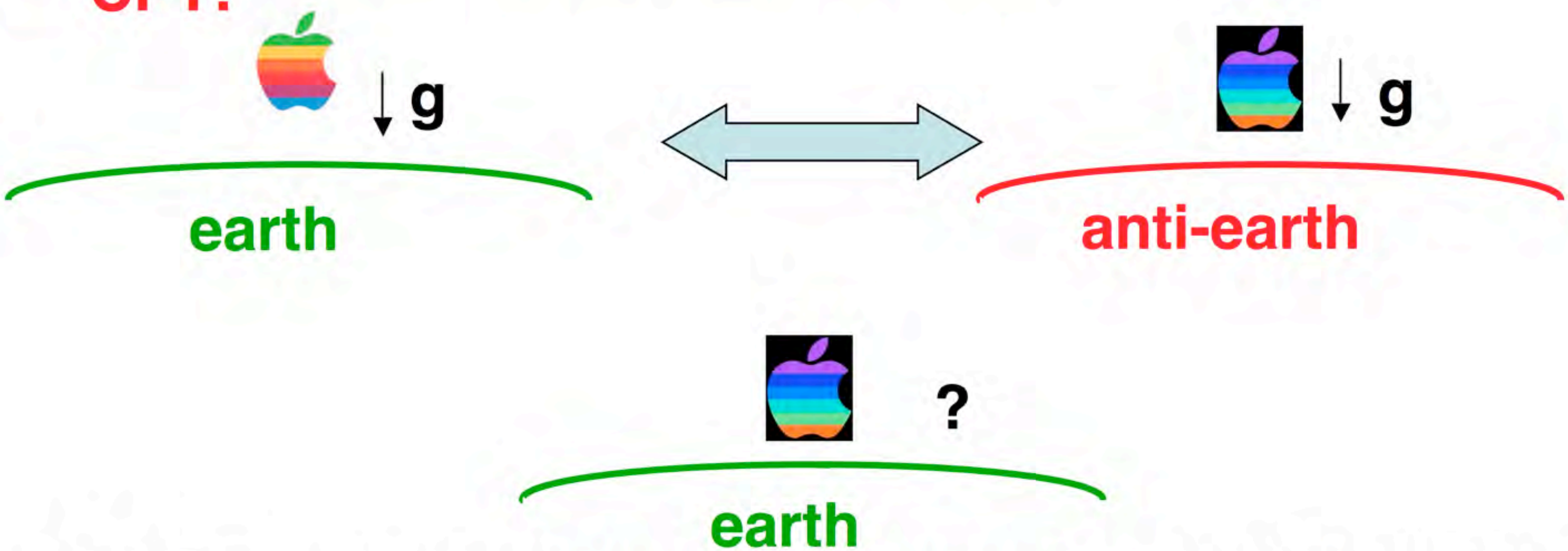
Motivation: Potentially BIG payoff

Method: Use proven technology

# Physics Motivation

## $\bar{g}$ has never been measured!

**CPT:**




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

**CPT theorem assumes <u>flat</u> spacetime.**

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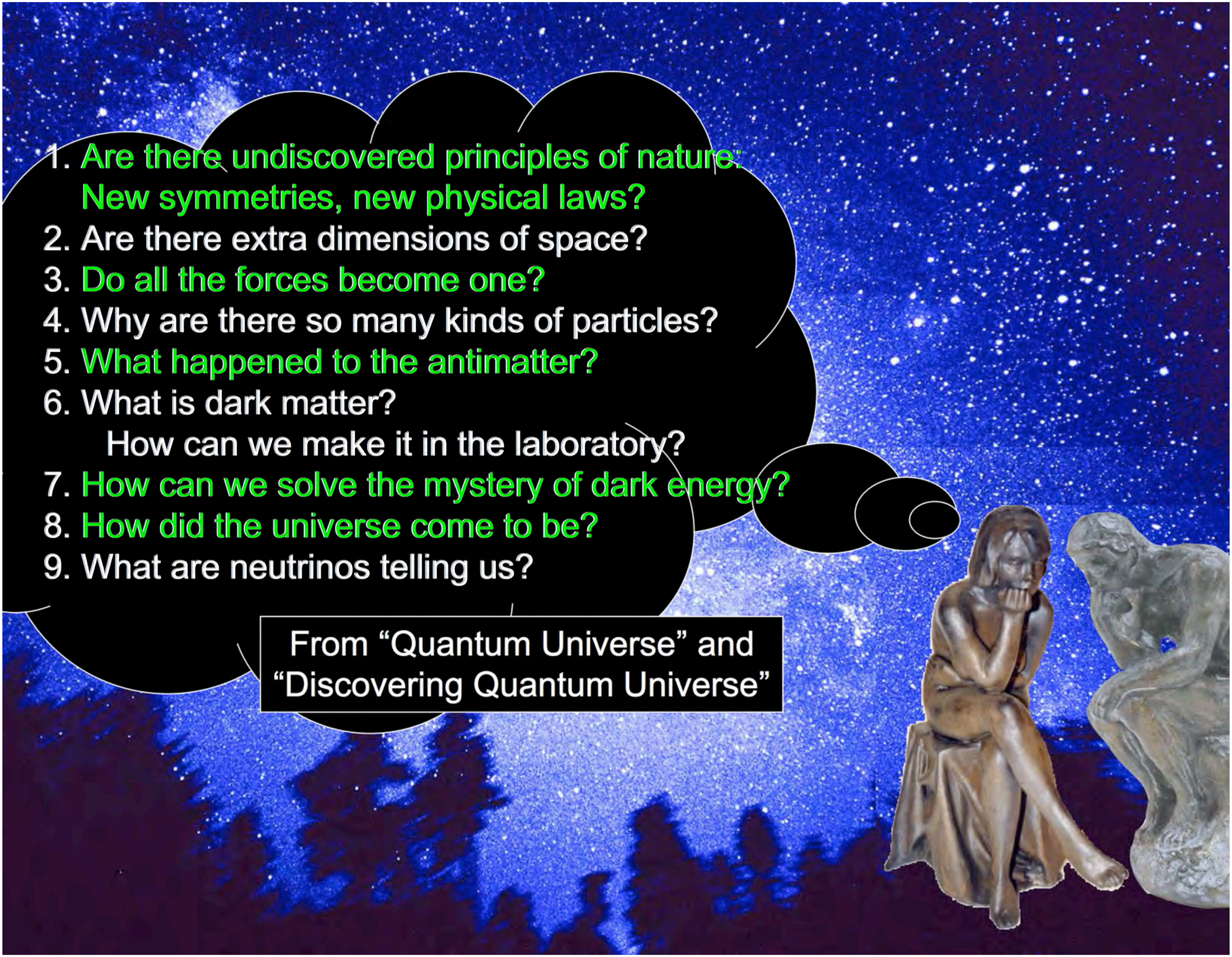
1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. Are there extra dimensions of space?
3. Do all the forces become one?
4. Why are there so many kinds of particles?
5. What happened to the antimatter?
6. What is dark matter? How can we make it in the laboratory?
7. How can we solve the mystery of dark energy?
8. How did the universe come to be?
9. What are neutrinos telling us?

From “Quantum Universe” and “Discovering Quantum Universe”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# This is a Dark Energy Experiment!

Suppose the gravitational force between matter and antimatter is repulsive

- This would **explain** "missing" antimatter!
  - matter and antimatter domains grow, separate
- This would also **explain** dark energy!
  - an equal mix of matter and antimatter domains would give a net repulsive force
    - analogous to an ionic crystal where opposite charges attract giving a net attraction
  - net repulsive force would lead to cosmic acceleration!
- Repulsion could power inflation!

# What About GR?

- Repulsive gravity for antimatter appears to be inconsistent with General Relativity, BUT
  - antimatter can be identified with negative-mass solution in Kerr-Newman Geometry
    - G. Chardin, AIP Conf. Proc. 643, 385 (2002)
  - Dirac antimatter is a negative energy "hole"
    - M. Kowitt, Int. J. Theoretical Phys. **35**, 605 (1996)
  - new forces i.e. Gravivector and Graviscalar
    - would ~ cancel for matter, add for antimatter
    - limits exist; need precise matter-antimatter difference
    - Nieto and Goldman, Phys. Rep. **205**, 221 (1991)
  - A different theory of gravity?
    - GR and QM incompatible by $10^{120}$, so we already need to revise our theories!

# Great 4 Public Relations!

The public loves antimatter!

- CERN's press release announcing they had made antihydrogen generated the biggest response they had ever gotten.

Particle physics needs good press!

Fermilab need physics results between the tevatron and Project X

# 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

Direct the beam through a transmission-grating interferometer

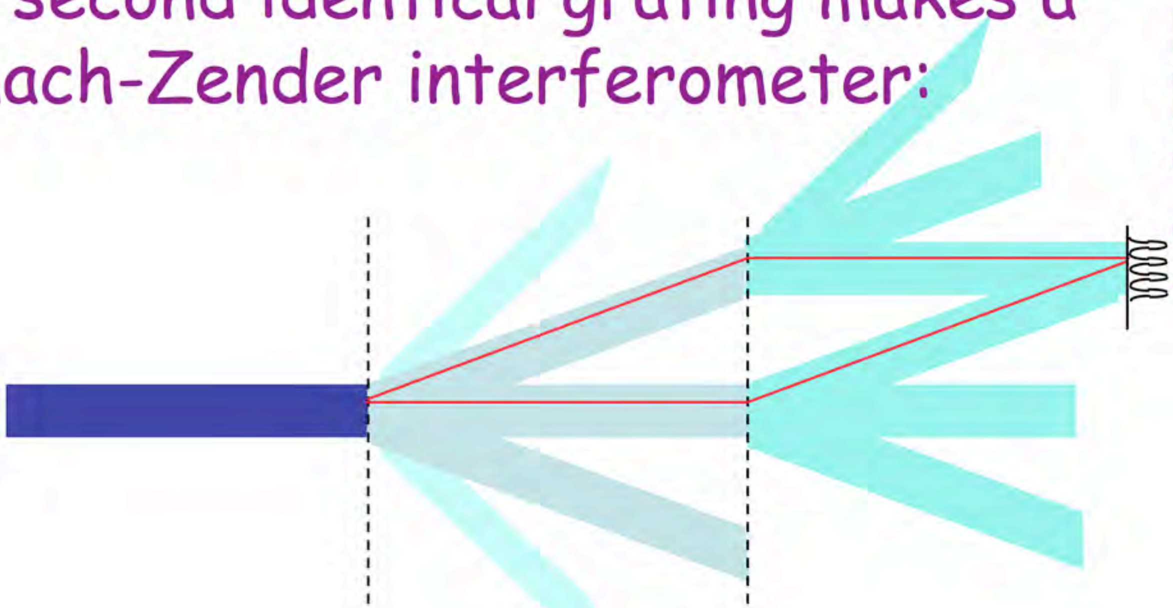
Measure $\bar{g}$ by observing the gravitational phase shift

- Interference pattern shifts by the same amount that the atoms fall

# Atomic Interferometer

A single grating makes a diffraction pattern:

A second identical grating makes a Mach-Zender interferometer:



The interference pattern has the same period as the gratings so a third identical grating can be used to analyze the phase of the pattern. The interference pattern "falls" by the same amount that the atoms fall as they traverse the inter-ferometer:

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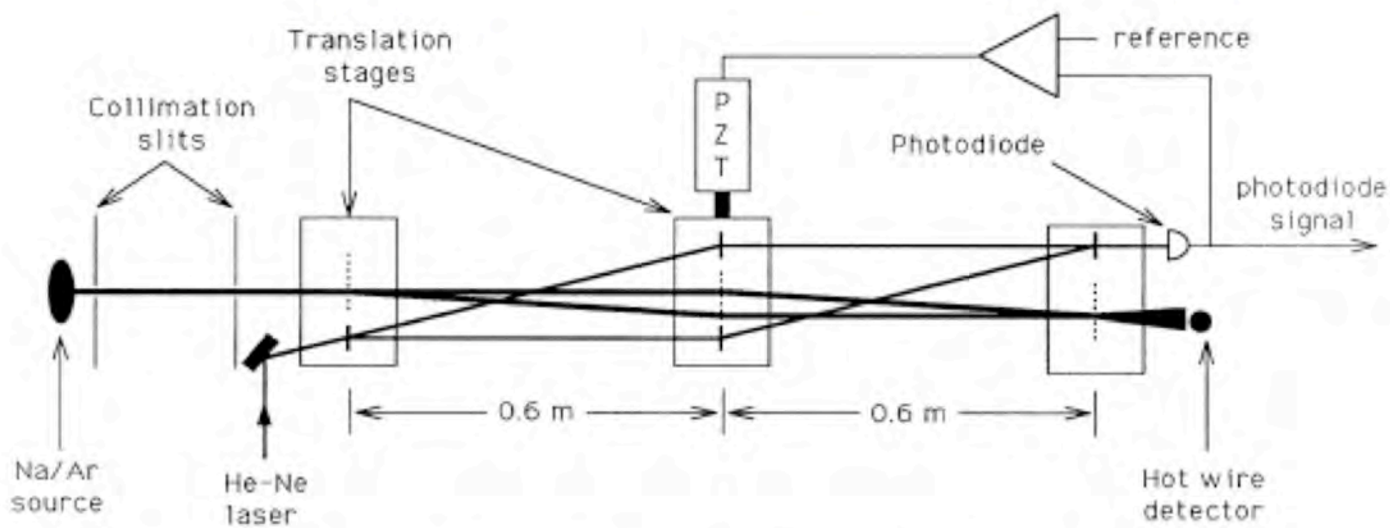
# Sodium Interferometer

High contrast has been observed with the MIT interferometer using an uncollimated atomic Sodium beam




**An atomic interferometer using sodium atoms and vacuum transmission gratings**
**David W. Keith *et al.* PRL** 66 **2693.**

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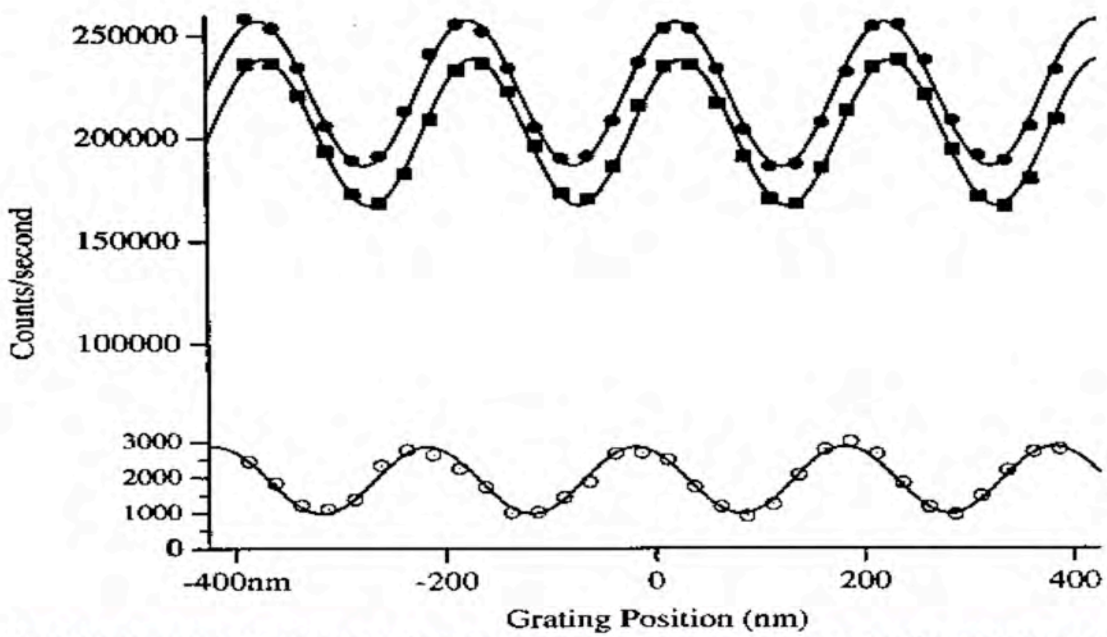



Atom Interferometry: Dispersive Index of Refraction and Rotation Induced Phase Shifts for Matter-Waves
Troy Douglas Hammond, Ph.D. Thesis, MIT, February 1997.

**Slow (1050 m/s) beam (upper)**
**Fast (3000 m/s) beam (lower)**
**uncollimated beams**

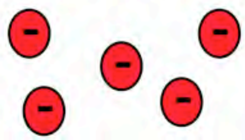
$10^4$ detected atoms enough to get this phase measurement

**Slow (1050 m/s) collimated beam**
**non-interfering diffraction orders do not contribute**

gravitational deflections: 19 μm for 1050 m/s
2 μm for 3000 m/s

# Making Antihydrogen

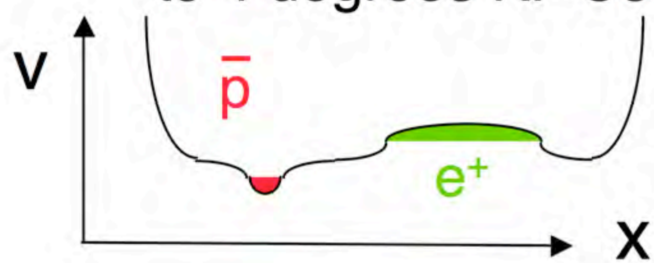
## Ingredients:



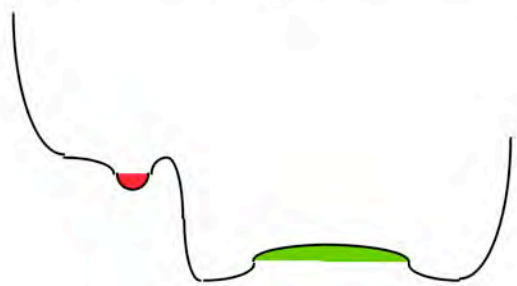
Antiprotons

Positrons

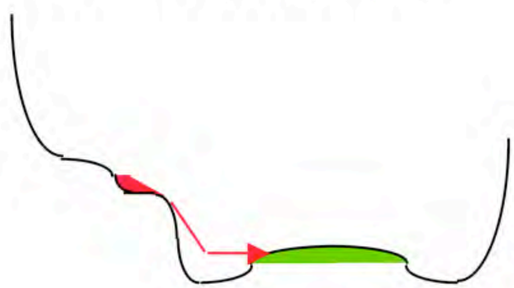
Collect antiprotons in a trap. Add electrons to cool to 4 degrees K. Collect positrons in an adjacent trap.



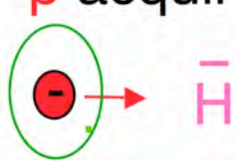

Then raise potential of $\bar{p}$ ...



...and drop barrier:



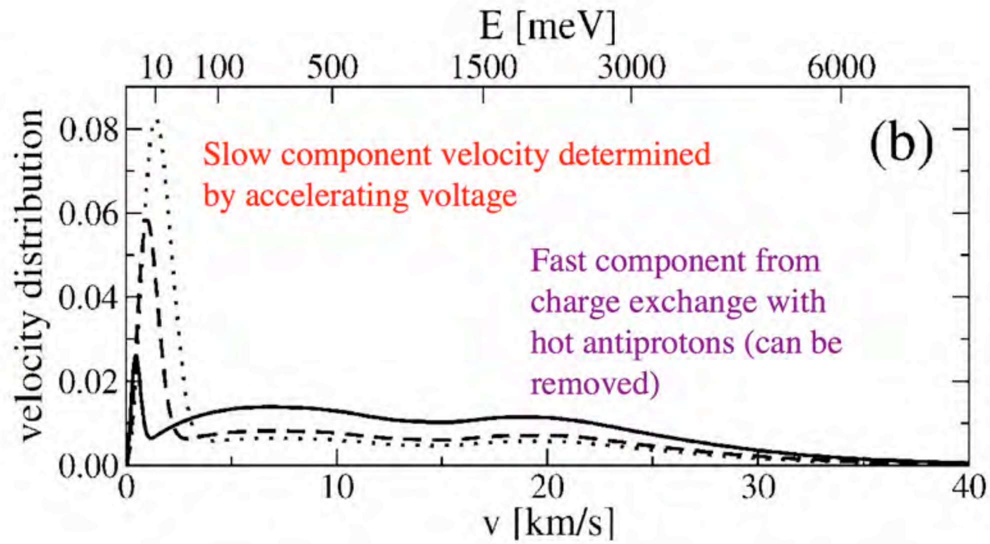
$\bar{p}$ acquires an $e^+$ and exits with $\bar{p}$'s momentum



# Antihydrogen Beam

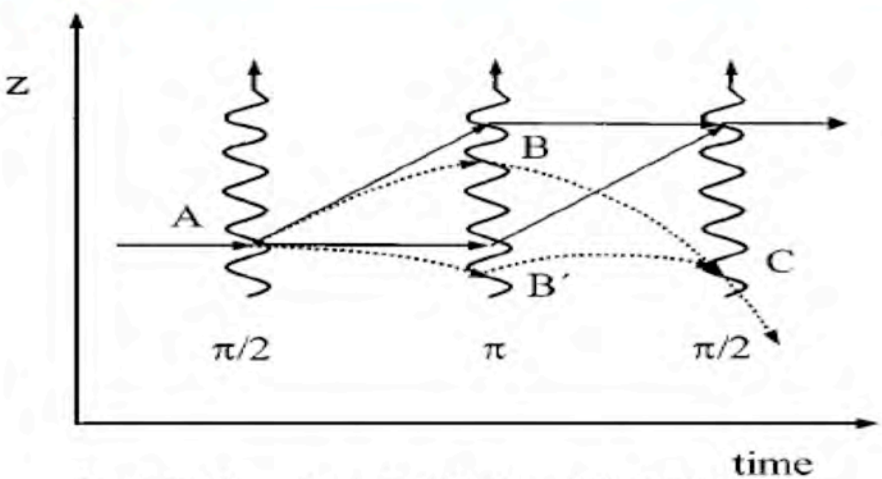
Cold Antihydrogen has been made by several groups at CERN

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

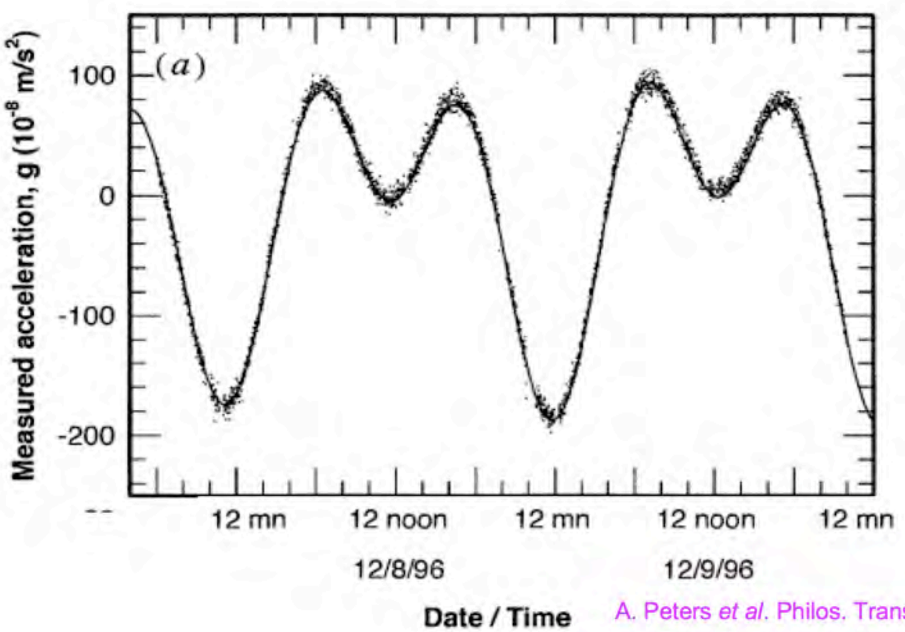



from Phys. Rev. Lett. 97, 143401 (2006)

# Long-Term Goal




from S. Chu, Rev. Mod.Phys. **70**, 685 (1998)




A. Peters *et al*. Philos. Trans. R. Soc. London Ser A **355,** 2223.

A longer-term goal of the antimatter gravity experiment is to make a precision matter-antimatter difference measurement

- local g precision 1:$10^{10}$
- can look for new ultra-weak forces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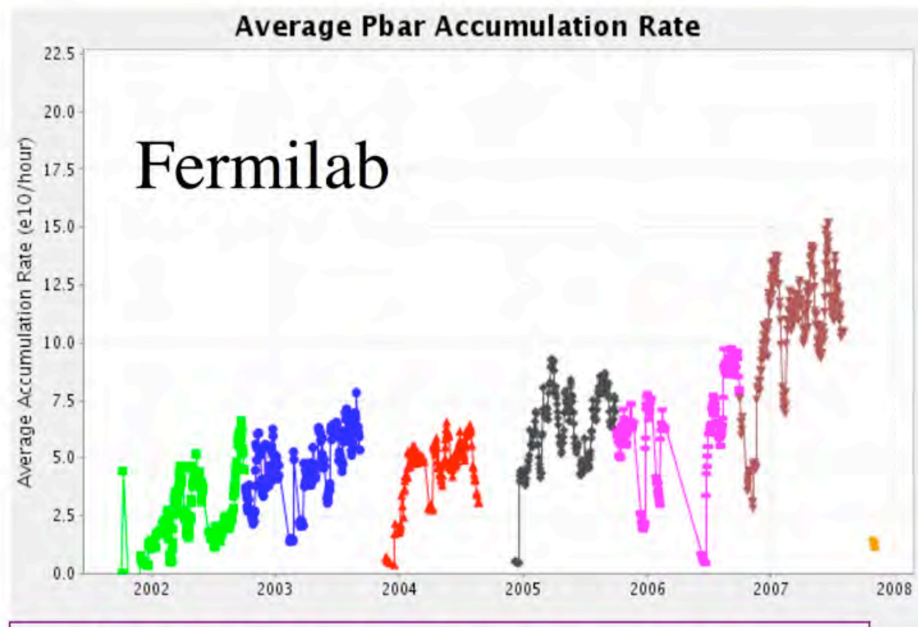
# Antiprotons

## Antiprotons are made at Fermilab and CERN

- CERN's AD cannot accumulate antiprotons
  - pulses of $3 \times 10^7$ every 90 seconds
  - 0.1% capture efficiency ($3 \times 10^4$ per pulse)
- Fermilab can accumulate antiprotons
  - stacking rate typically exceeds $10^{11}$/hour
  - no current ability to decelerate and trap




$10^4$ detected atoms enough to get a phase measurement. ~10% transmission efficiency: need $10^5$ antihydrogen in beam

# Conclusions

The Antimatter Gravity Experiment could Answer some BIG Questions:

- What happened to the Antimatter?
- What is the nature of Dark Energy?
- Are there New Laws, Principles, Symmetries?

The Antimatter Gravity Experiment can be done using Proven Technologies:

- Atomic Interferometry
- Antihydrogen Production

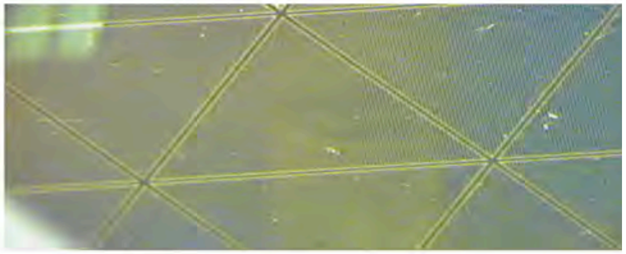
Fermilab should decelerate antiprotons!

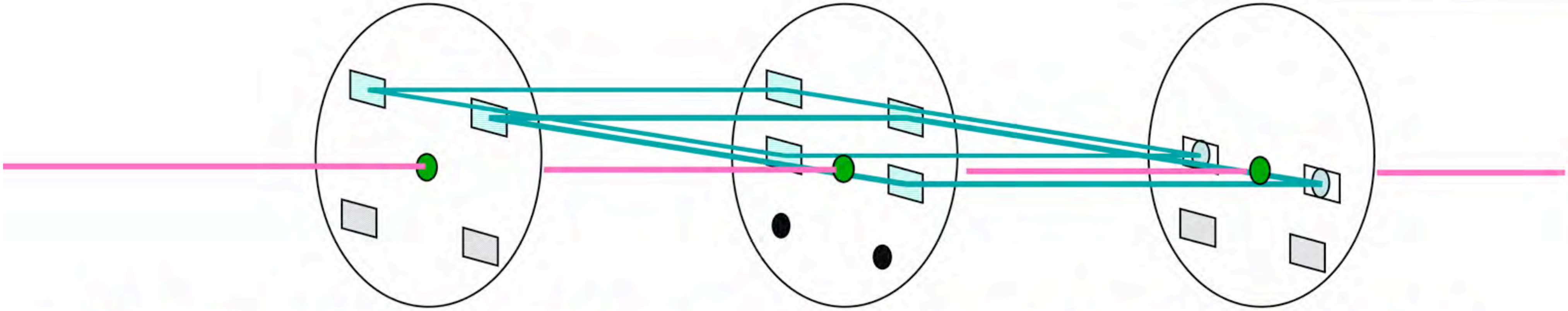
# Hydrogen Interferometer

Based upon MIT Design

Transmission gratings have a larger period

- Less sensitive to vibration, misalignment

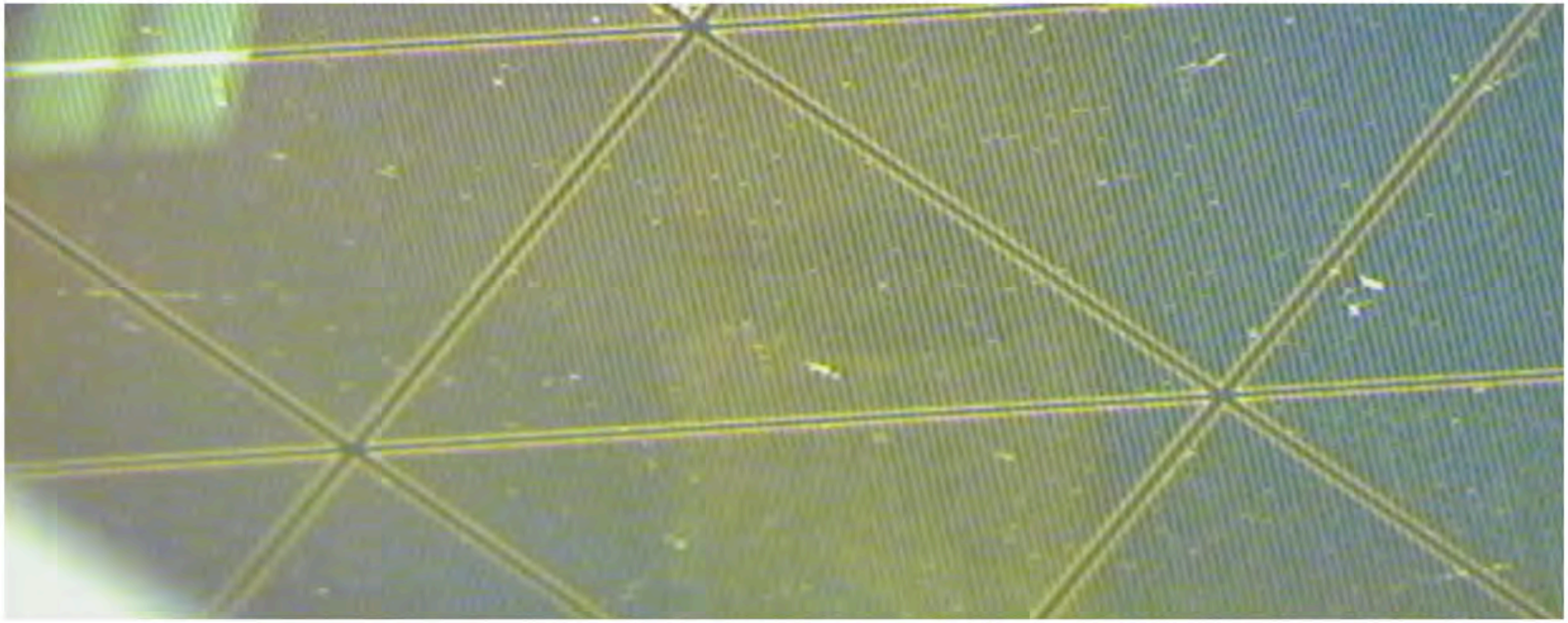




Atomic Transmission gratings mounted on floating aluminum plates along with optical gratings for alignment.

Floating aluminum plates are mounted on fixed plates with piezoelectric positioners.

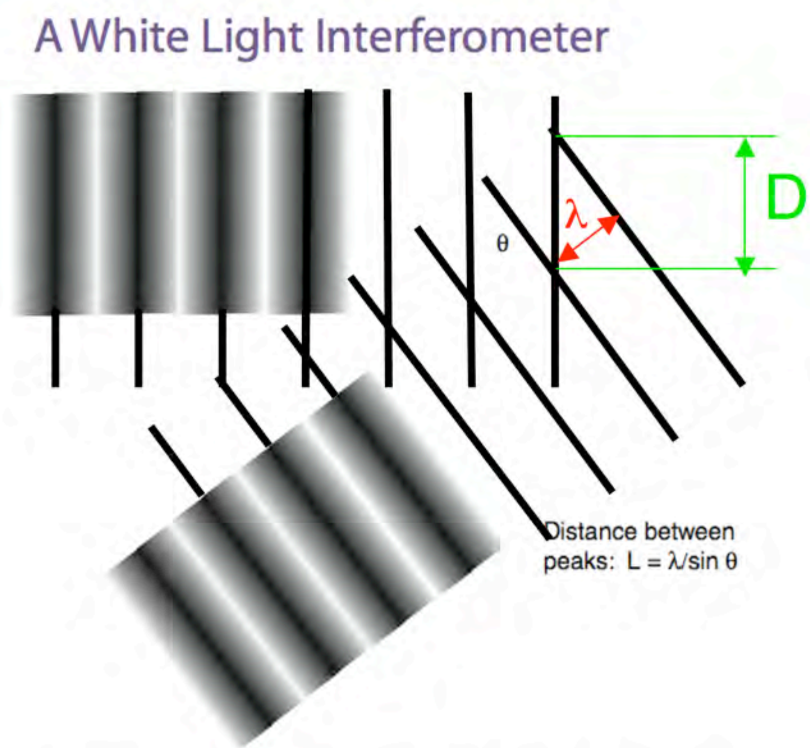
# Vacuum Transmission Gratings



Atomic gratings from Max Planck Institute for Extraterrestrial Physics

- ➤Spares from Chandra X-ray telescope low-energy spectrometer
  - ➢1 micron period

The interference pattern has a period equal to the grating period because longer wavelengths diffract more and the larger crossing angle cancels the longer wavelength




Crossing angle θ determined by diffraction angle: sin θ = λ/D where D is the grating period

Distance between interference pattern peaks
L= λ/sin θ = λ/( λ/D ) = D is independent of wavelength