Description and First Application of a New Technique to Measure the Gravitational Mass of Antihydrogen

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and the **ALPHA** Collaboration

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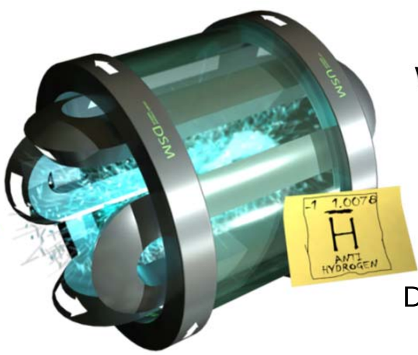
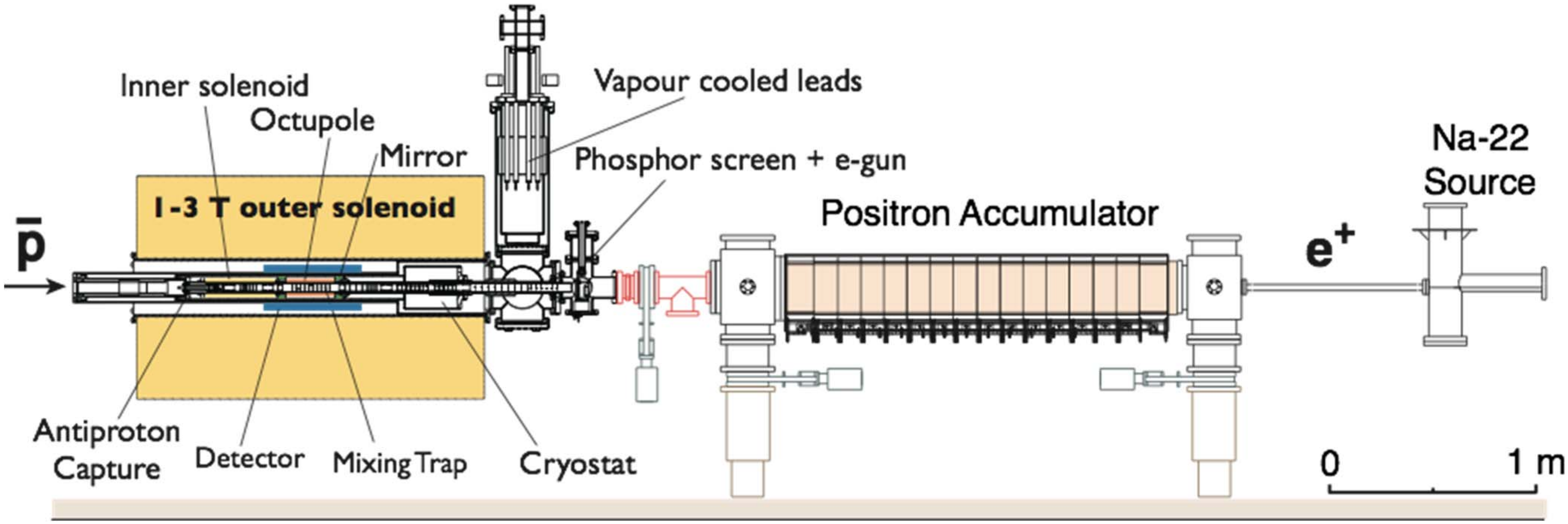
with A.E. Charman, H. Mueller, and P. Hamilton



Work supported by:
DOE/NSF Partnership in Basic Plasma Science,
DOE Office of High Energy Physics (Accelerator Science)
2011-2012 LBNL LDRD

Also supported by CNPq, FINEP/RENAFAE (Brazil), ISF (Israel), MEXT (Japan), FNU (Denmark), VR (Sweden), NSERC, NRC/TRIUMF AIF FQRNT(Canada), and EPSRC, the Royal Society and the Leverhulme Trust (UK).

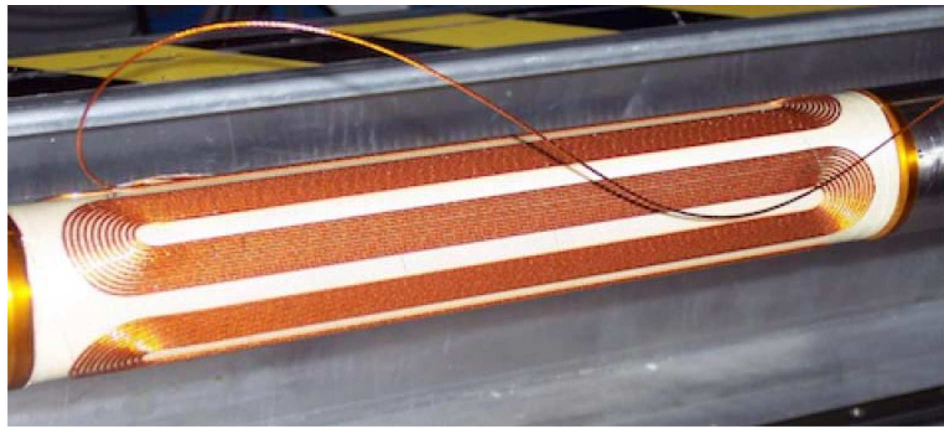
ALPHA Apparatus

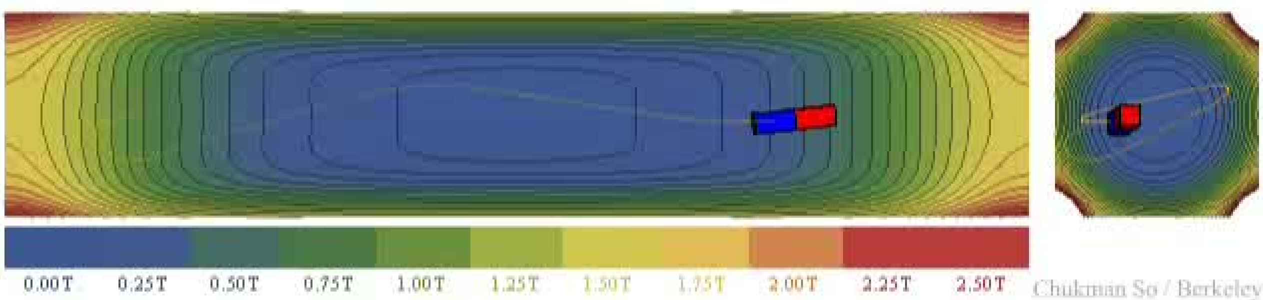


- Using the ALPHA antihydrogen apparatus, we have been able to set the first "freefall" limits on the gravitational mass of antihydrogen.
- Using extensions of our technique, we expect to be able to determine if antimatter falls up or down.
- With an atom interferometer, we may be able the measure the antimatter *g* to 0.0001%.

Antihydrogen Trap

- Alpha uses a minimum-B configuration to trap anti-atoms.
- The magnetic minimum is formed by two mirror coils and an octupole.

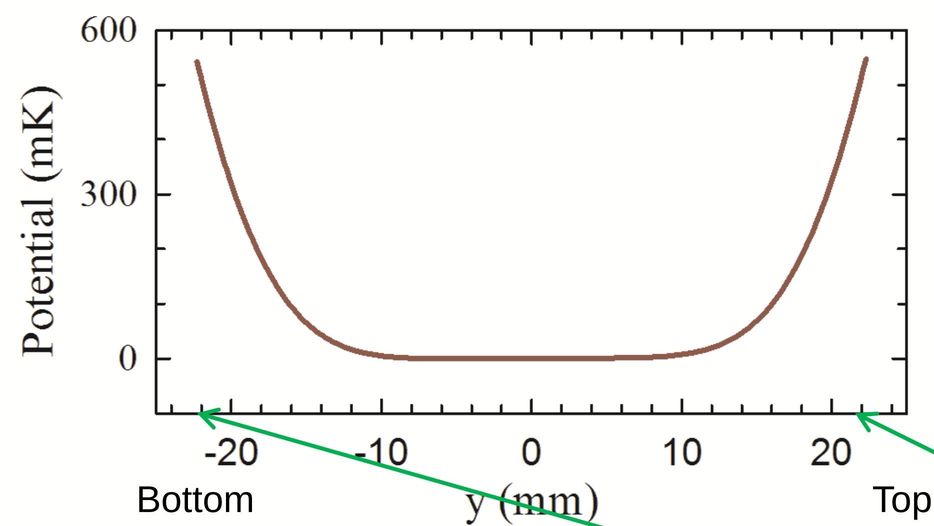




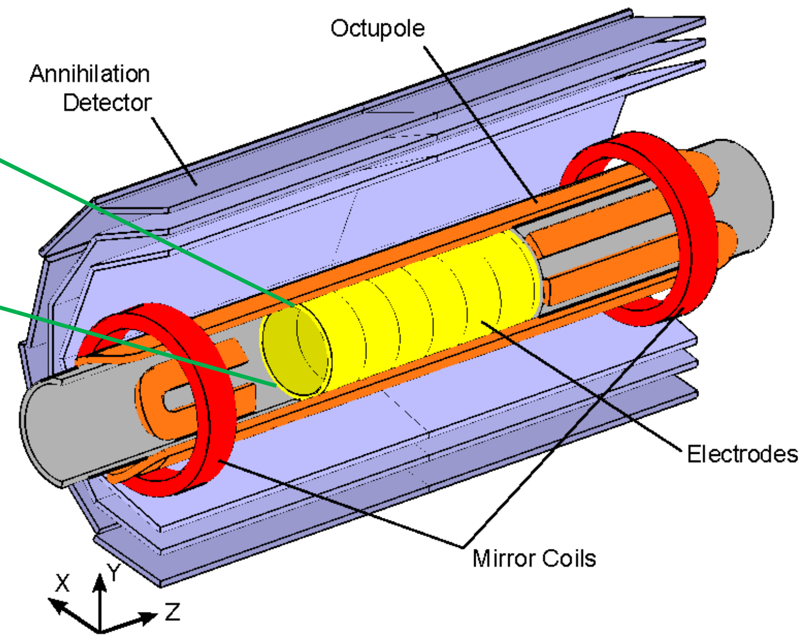
Magnetic Field Magnitude

Effect of Gravity on the Anti-Atom Trapping Well

$F = M_G / M$=100

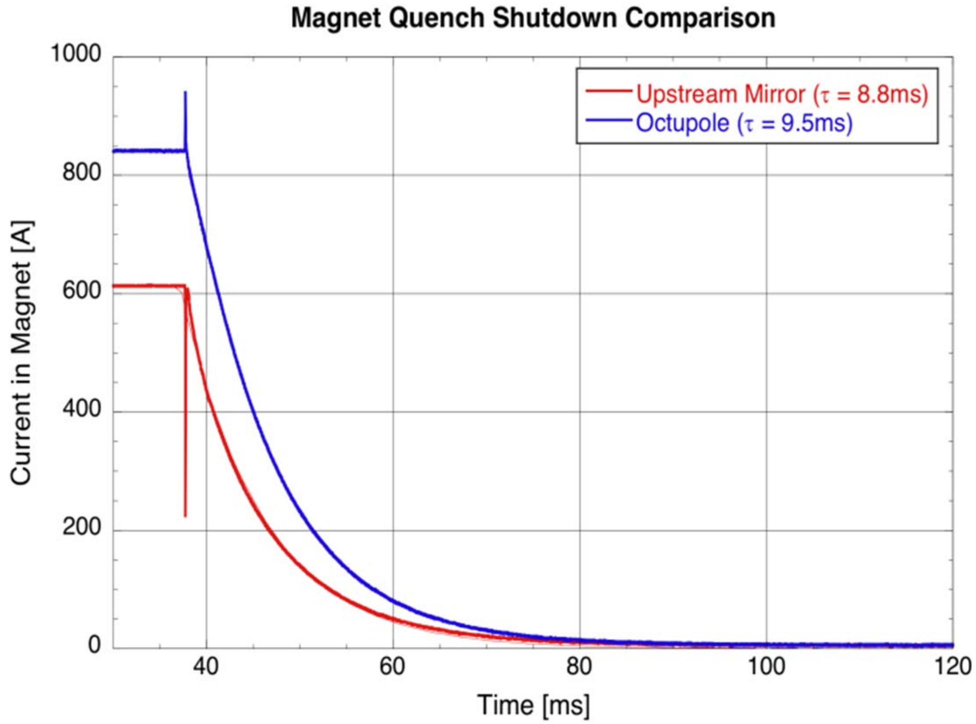


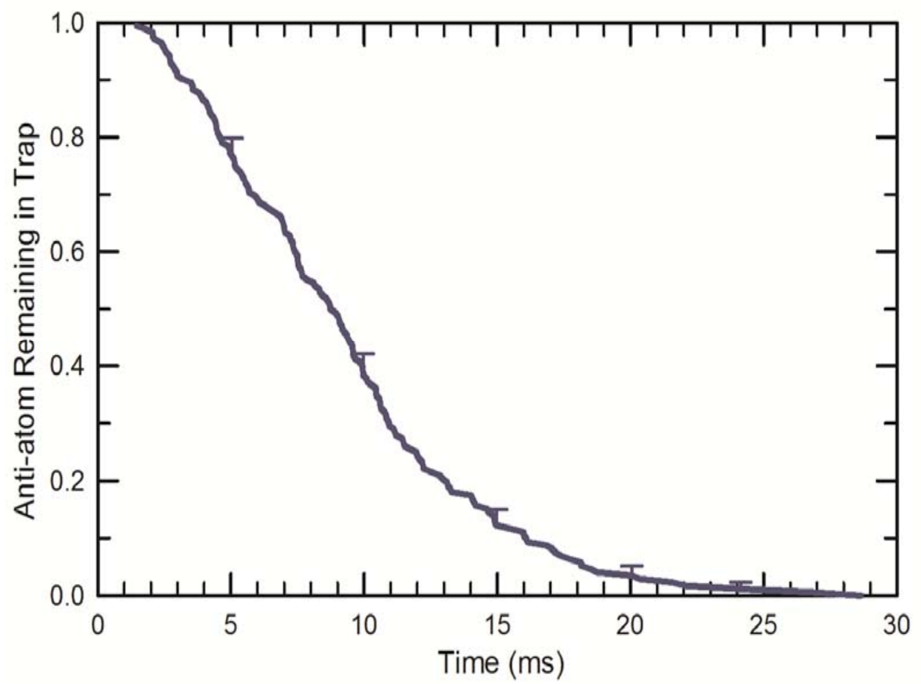
- F is the ratio of the gravitational mass to the inertial mass of antihydrogen.
- “Normal” gravity is $F = 1$.



- Potential includes effect from both the magnet system and gravity.
- The trap diameter is 44.55mm.

Anti-atoms Escape as Trap is Shut Off





Potential Well After Magnet Shutdown

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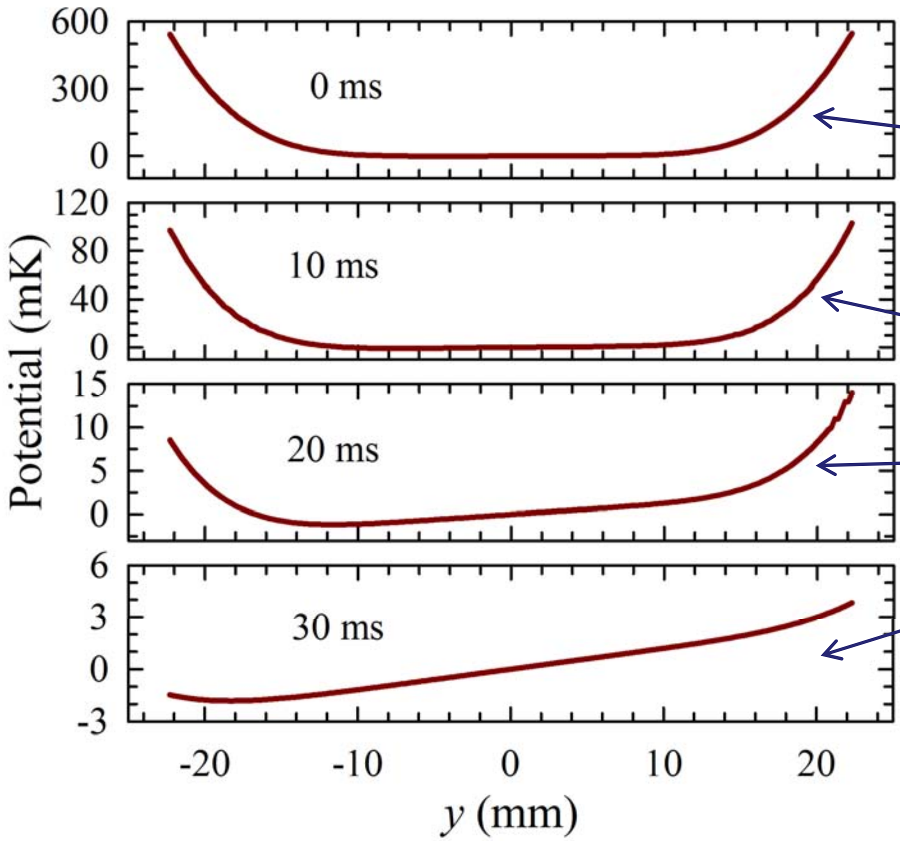
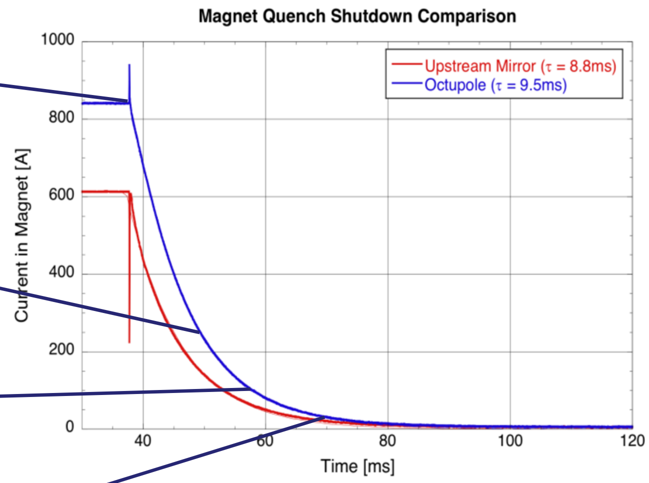
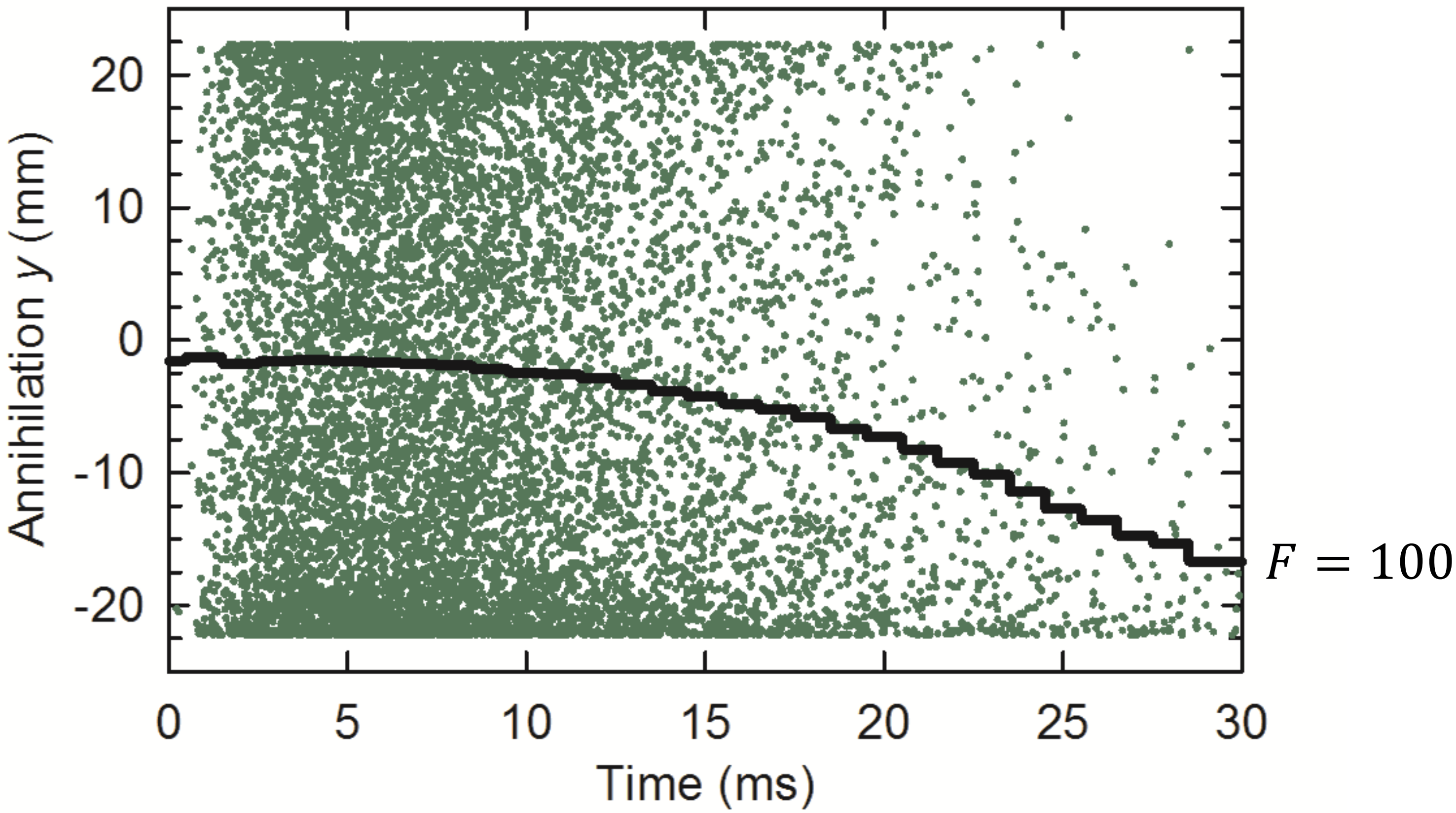




Effect of Gravity on Anti-Atoms in a Diminishing Minimum-B Potential Well

$F = M_G/M = 100$



Green dots---simulated annihilations

Simulations

- Simulations follow:

$$M\frac{d^2\rho}{dt^2} = \nabla\left[\boldsymbol{\mu}_{\mathrm{H}} \cdot \mathbf{B}(\rho, t)\right] - M_g g\hat{y}$$

- Employ a 4th order adaptive Runge-Kutta stepper.
  - Simulations have been benchmarked against other aspects of the data.
- Employ an accurate model of the magnetic fields.
  - Field model has been benchmarked with antiprotons.
- Typically, nearly one million trajectories are followed for a given condition.

ALPHA, Confinement of antihydrogen for 1000s, Nature Physics **7,** 558 (2011).
ALPHA, Discriminating between antihydrogen and mirror-trapped antiprotons in a minimum-B trap, New J. Phys., **14** 015010, (2012).

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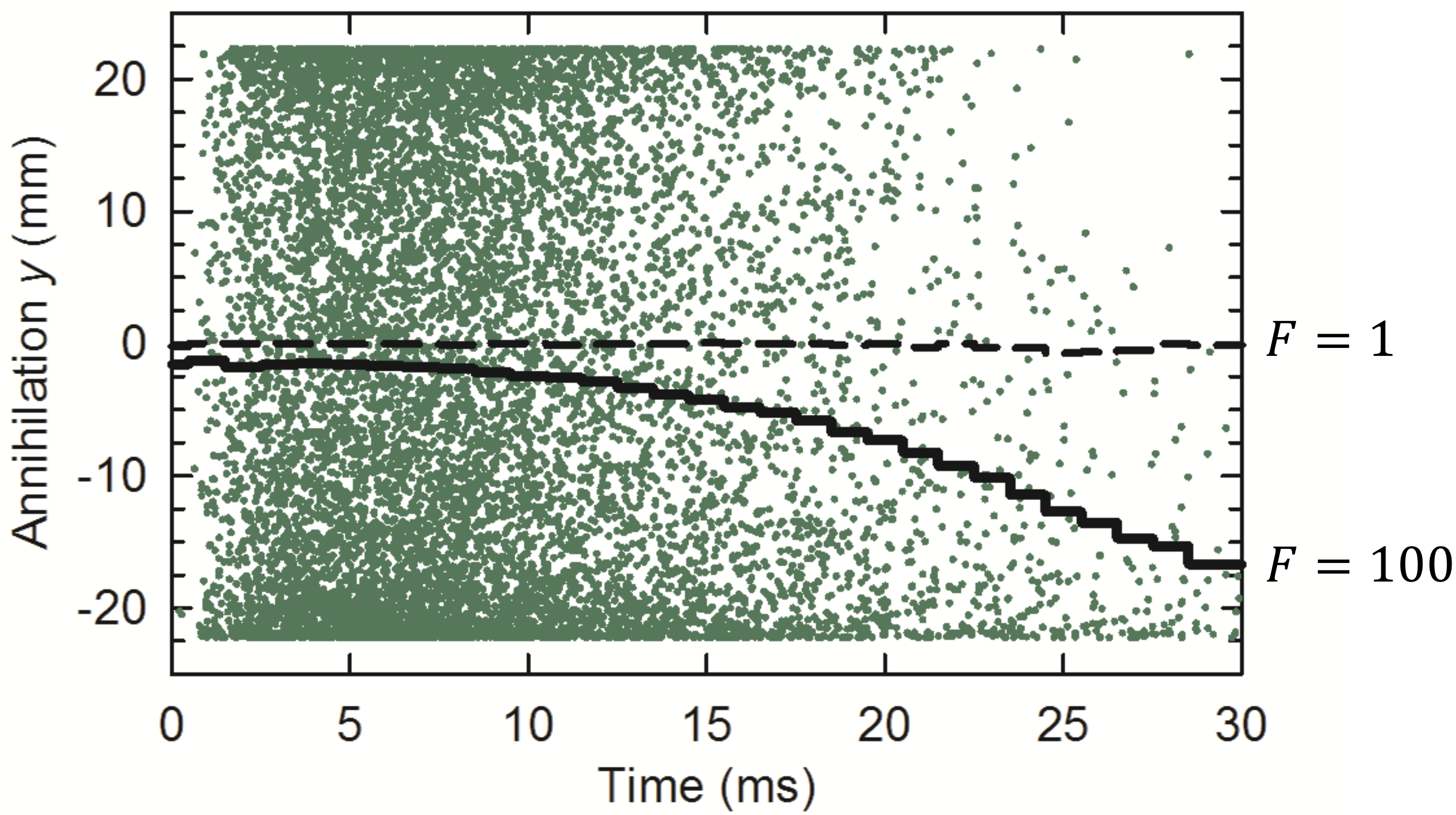

Green dots---simulated annihilations

Red circles---434 Observed annihilations

Data Set:

- All 434 observed antihydrogen atoms in 2010 and 2011 that were held for longer than 400ms.
- All atoms were in the ground state.

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Effect of Gravity on Anti-Atoms in a Diminishing Minimum-B Potential Well

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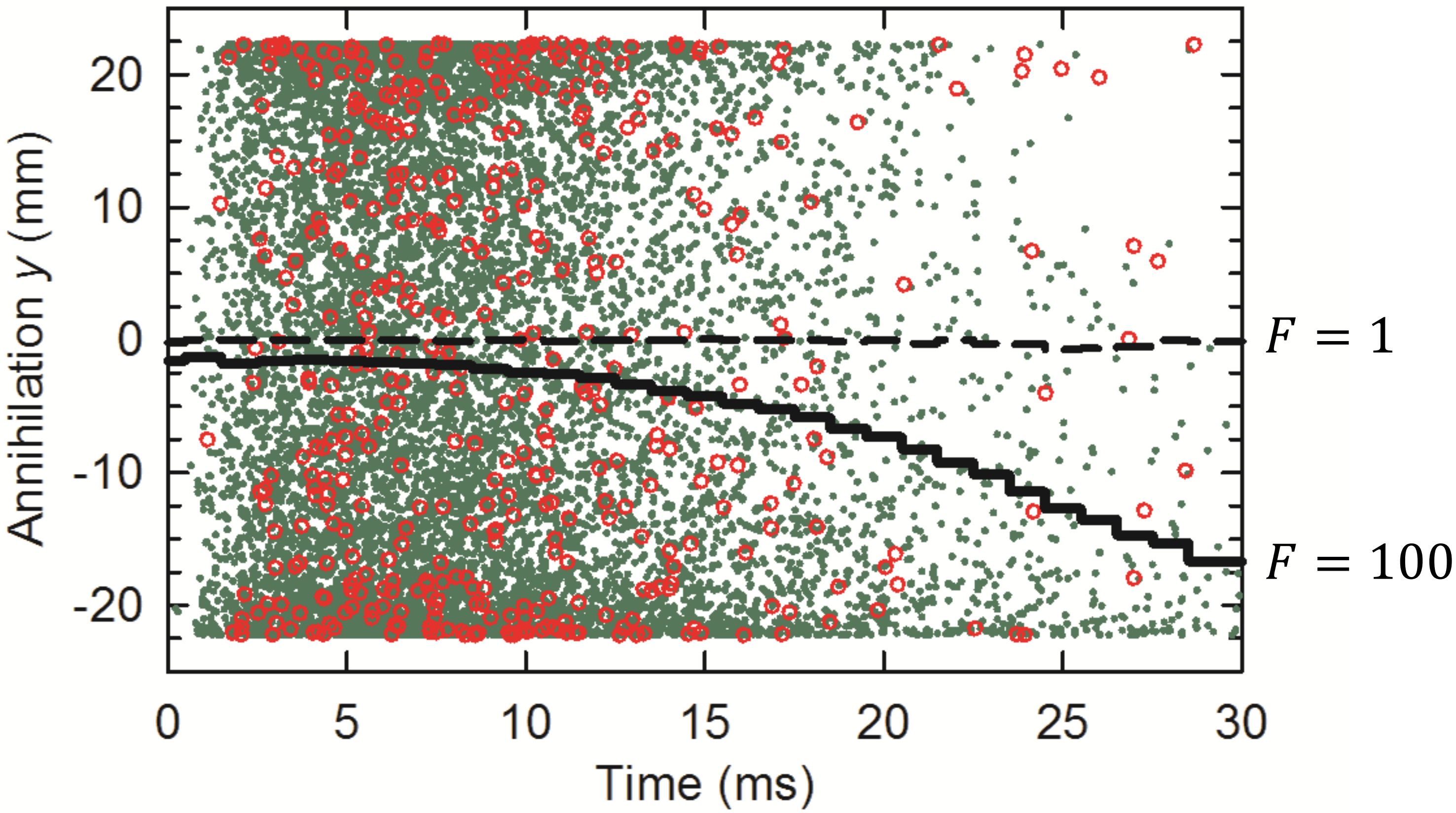


Green dots---simulated annihilations

Red circles---434 Observed annihilations

How do we establish that the observed annihilations are not compatible with some F, say $F = 100$?

Basic Dilemma:

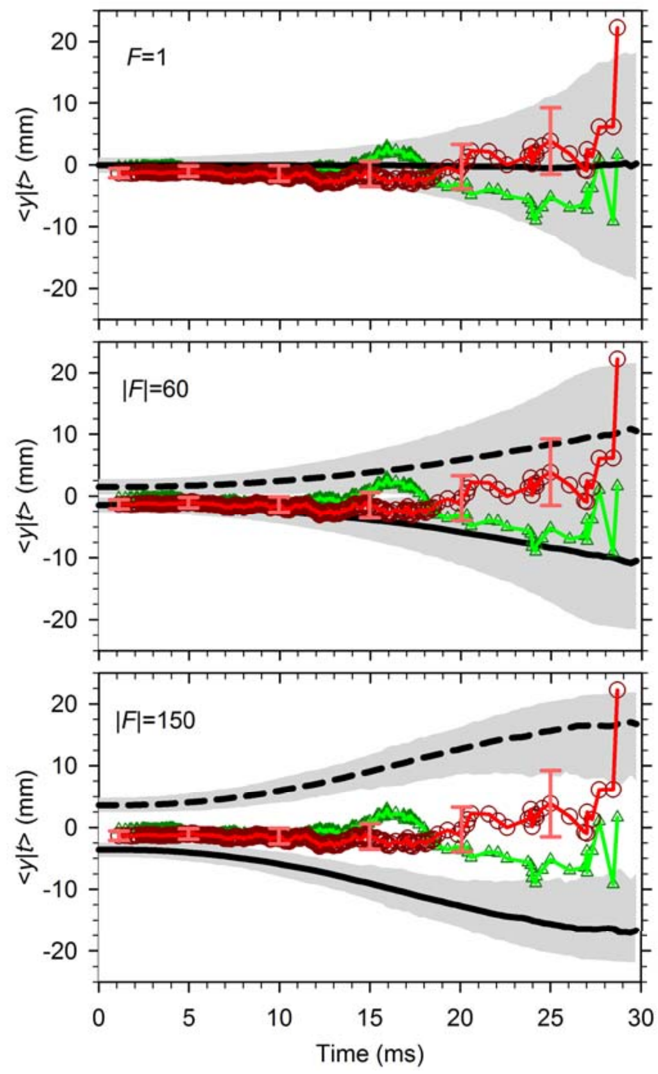
- The late escaping anti-atoms are most sensitive to gravity…
- But there are relatively few late escaping particles, so the statistics for these anti-atoms are poor.

Reverse Cumulative Average

- One way to analyze the data is with the reverse cumulative average:

$$\langle y|t\rangle = \frac{1}{N_t}\sum_{\tau>t} y_\tau$$

  where y_τ is annihilation locate of an event which occurs at time τ, and N_t is the number of events that occur after time t.
- Gray bands demark 90% confidence regions for 434 events around the simulations at each F.



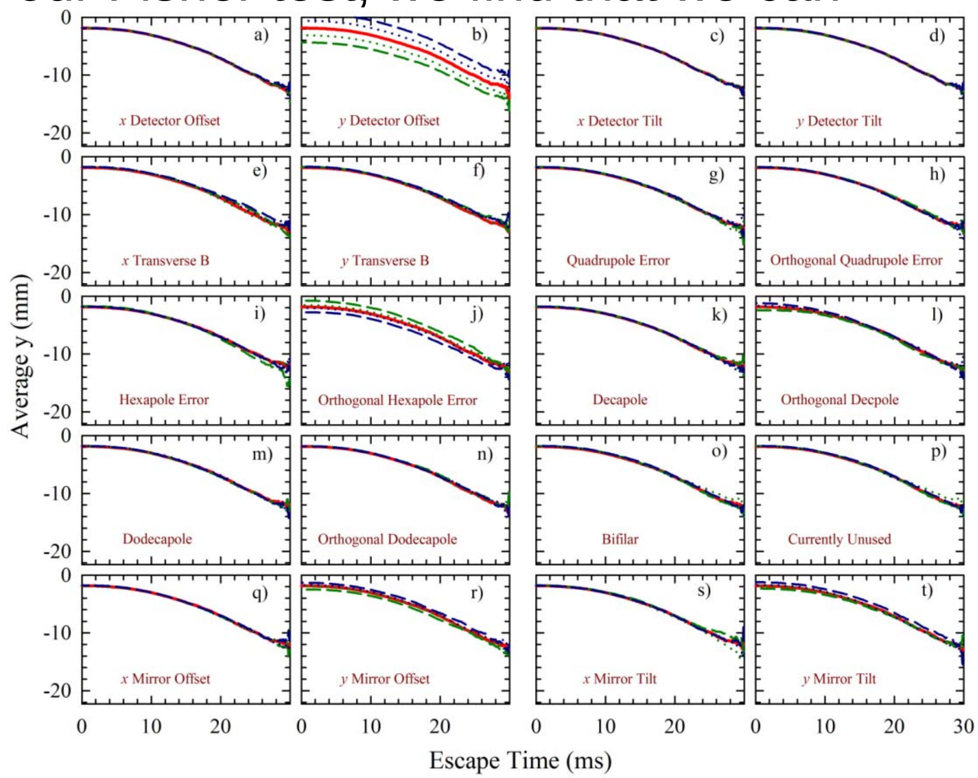
ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm **4**, 1785 (2013).

Quantitative Statistical Method

- To calculate the bounds on F quantitatively, we did a Monte Carlo study of a test statistic akin to Fisher's Combined Statistic which aggregates Kolmogorov-Smirnov tests.

$$\Phi = -\int_0^{30ms} \ln[P_{KS}(t;F)]dt\,.$$

- Considering counting statistics alone, we can reject $F > 75$ with at a statistical significance of 95%.
- Considering systematic effect with our Fisher test, we find that we can exclude, with 95% confidence:
  - $F > 110$ (Normal gravity)
  - $F < -65$ (Antigravity)



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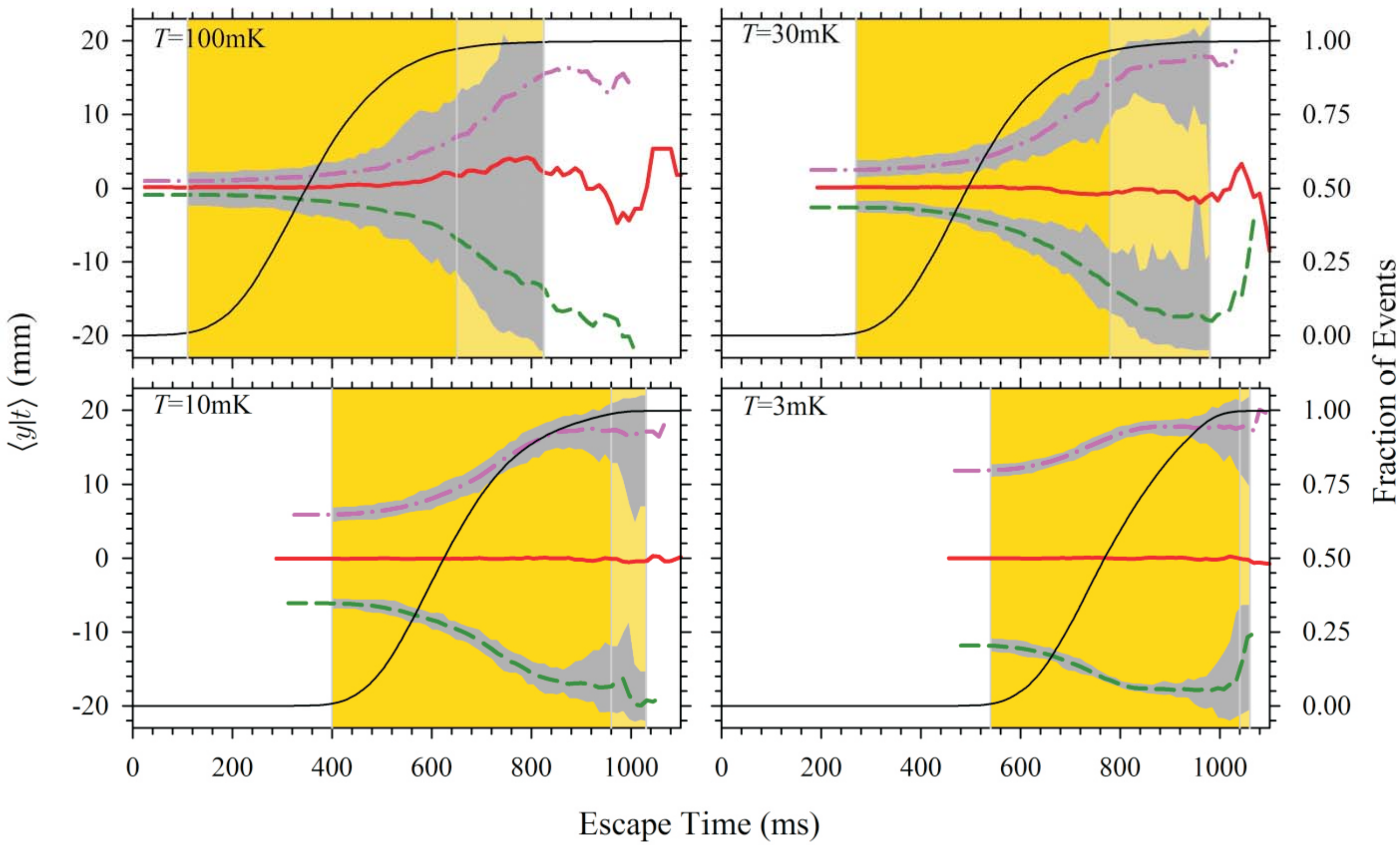
$F = \pm 1$?

- With an ALPHA style horizontal trap:
  - Use laser cooling.
  - Slow down the magnet turnoff by a factor of ten



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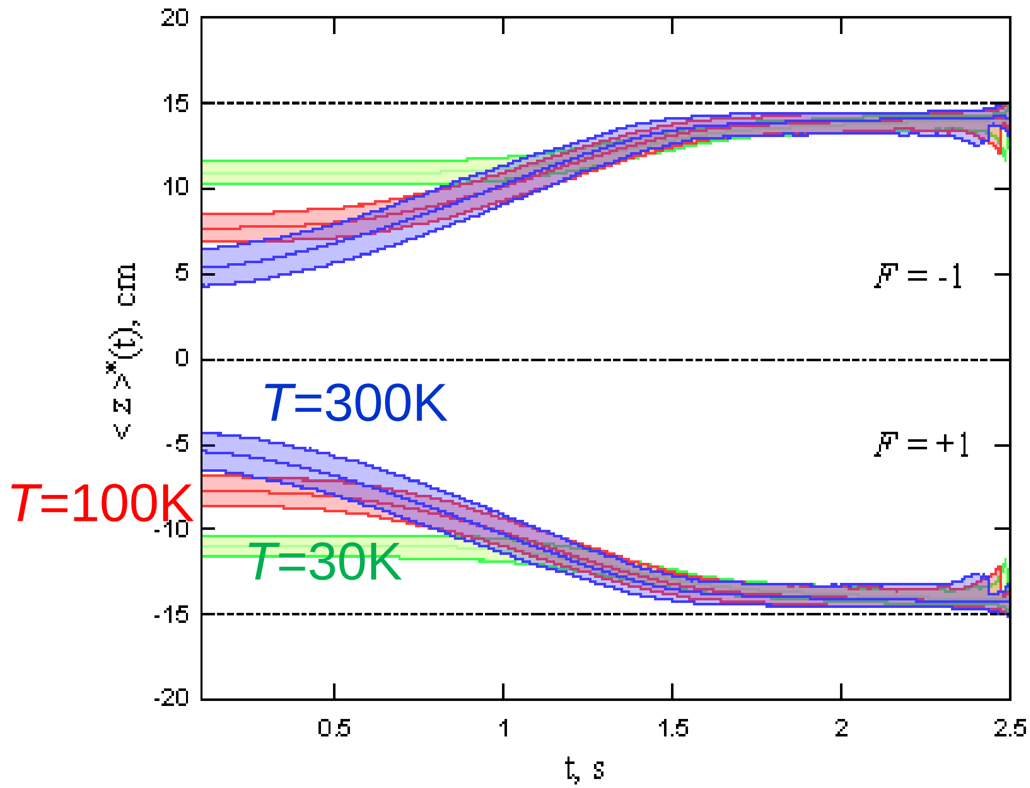
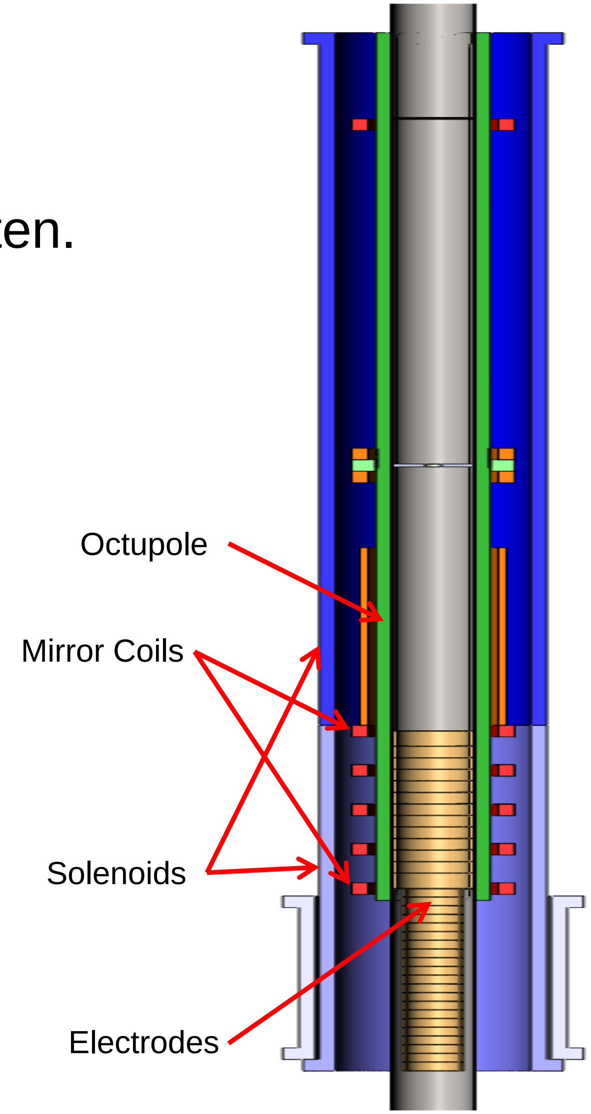
P.H. Donnan, M.C. Fujiwara, and F. Robicheaux, A proposal for laser cooling antihydrogen atoms, J. Phys. B **46**, 025302 (2013).

F beyond $\pm$ 1?

- Much easier in a vertical trap.
  - Laser cooling not necessary, though it helps.
  - Slow down the magnet turnoff by a factor of ten.
  - Turnoff the mirror coils only.



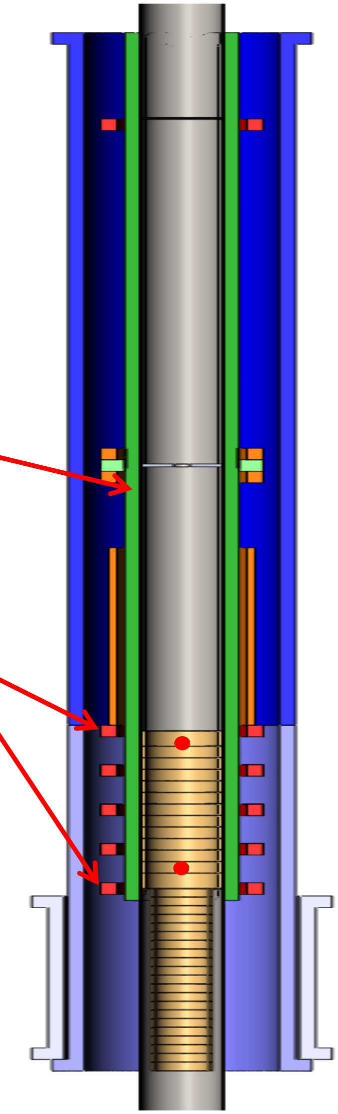


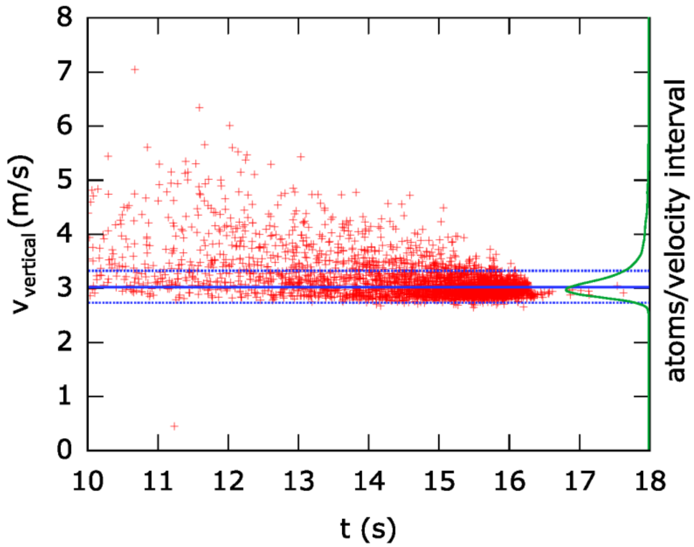
A. Zhmoginov, A. Charman, J. Fajans, and J.S. Wurtele Nonlinear dynamics of antihydrogen in magnetostatic traps: implications for gravitational measurements, Class. And Quantum Grav. **30** 205014 (2013).

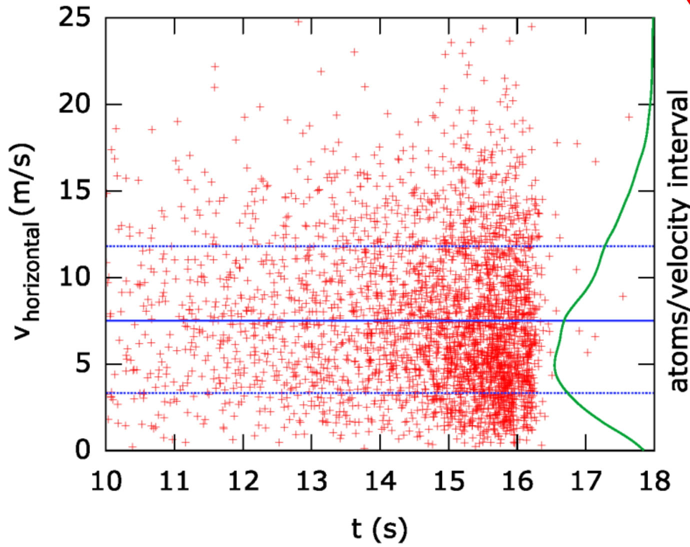
Fountain Measurement of F

- Let anti-atoms evaporate over a magnetic barrier.
  - Substantial parallel cooling results.
  - Some perpendicular cooling may also result.
    - Radially confining octupole magnet required over the entire drift region.

  - Fountain measurement: Do the anti-atoms annihilate on the top of the trap?
  - Accuracies to F 10% possible.



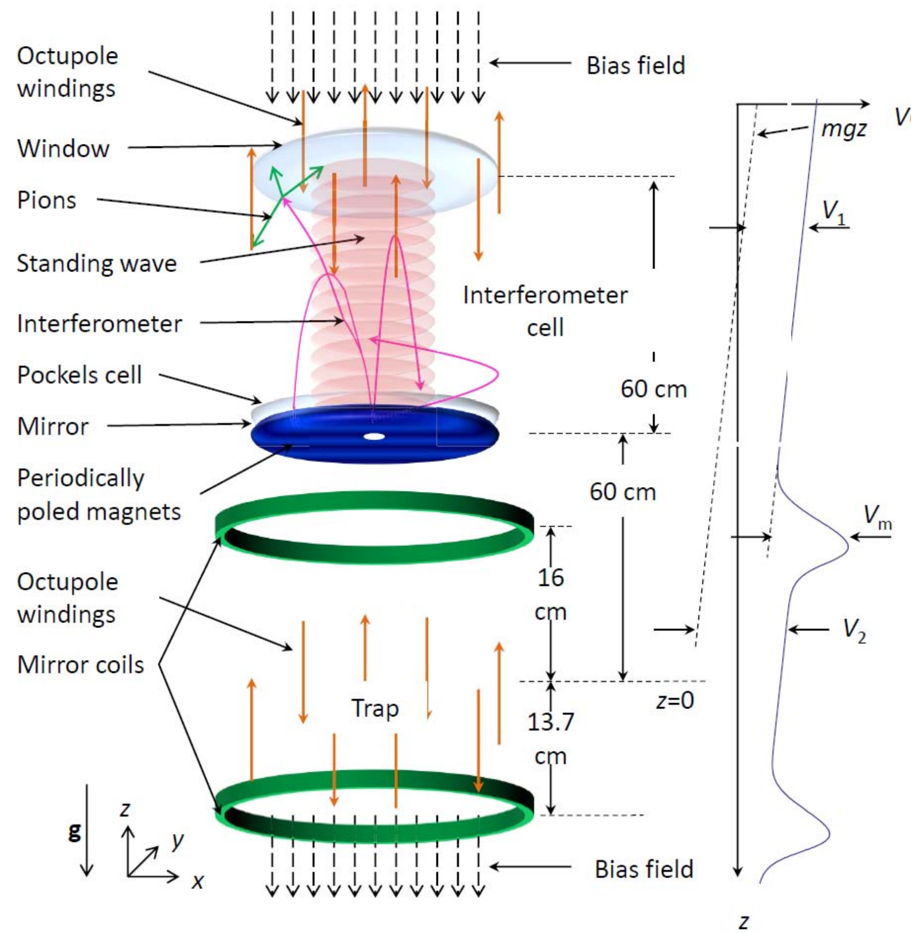


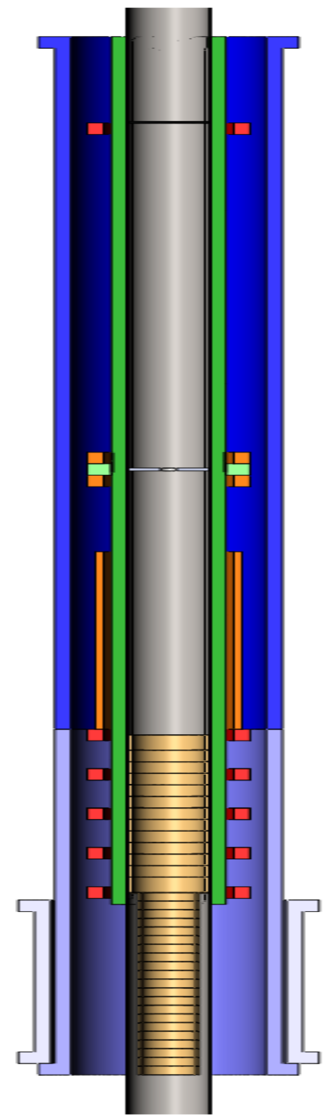


H. Mueller, P Hamilton, A. Zhmoginov, F. Robicheaux, J, Fajans and J.S. Wurtele, Antimatter interferometry for gravity measurements, arXiv:1308.107 (2013).

Interferometric Measurement of F

- More accurate gravity measurements can be made with a laser atom interferometer.
  - Initial results to 1%
  - Eventual result to perhaps 0.0001%.





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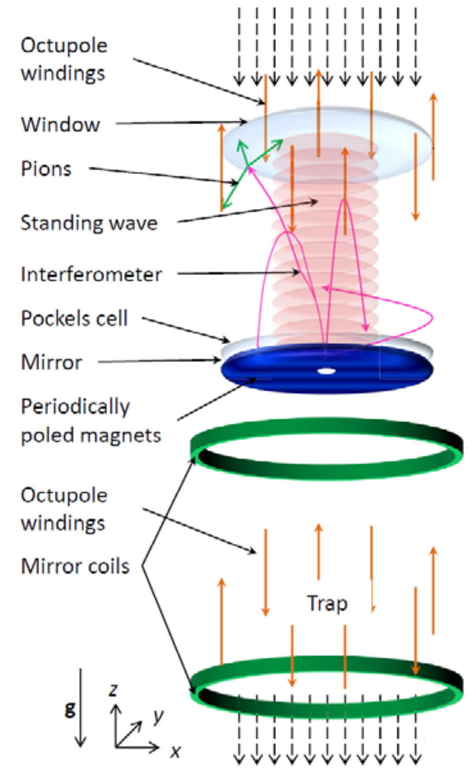
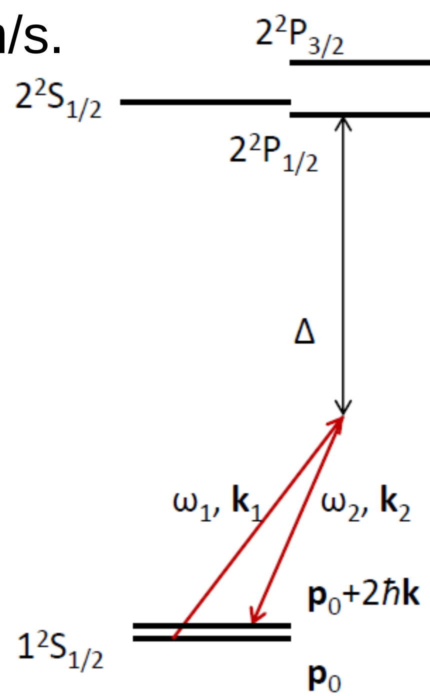
Interferometric Measurement of F

- Standard laser atom interferometer impossible as sufficiently powerful lasers are not available at the Lyman-alpha line.
- Use powerful (5J) off-resonant (1064nm) pulses in a Mach-Zehnder configuration.
- Anti-atom Bragg scatters in anti-propagating laser fields.
- Scattering event gives the anti-atom a momentum kick of $2\hbar k$…about 0.75m/s.





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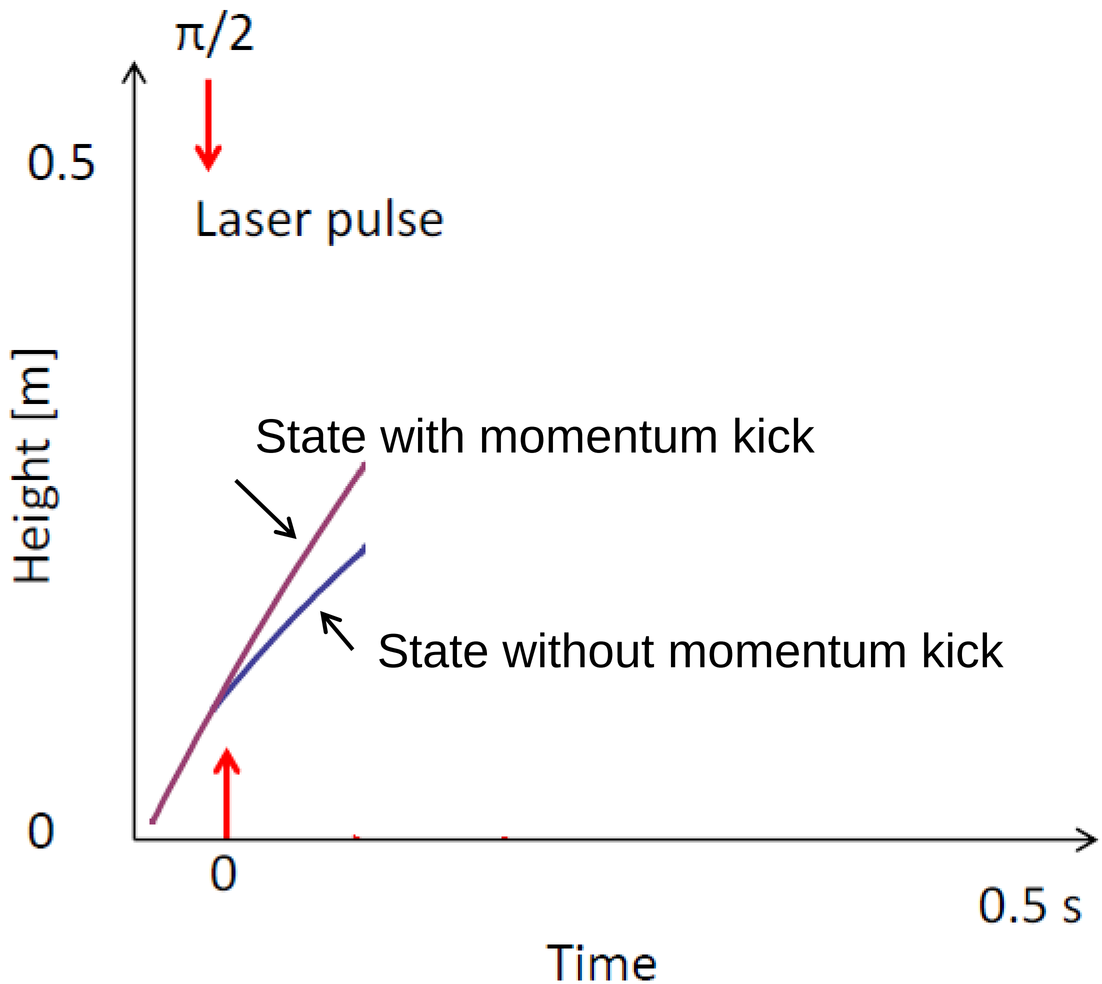
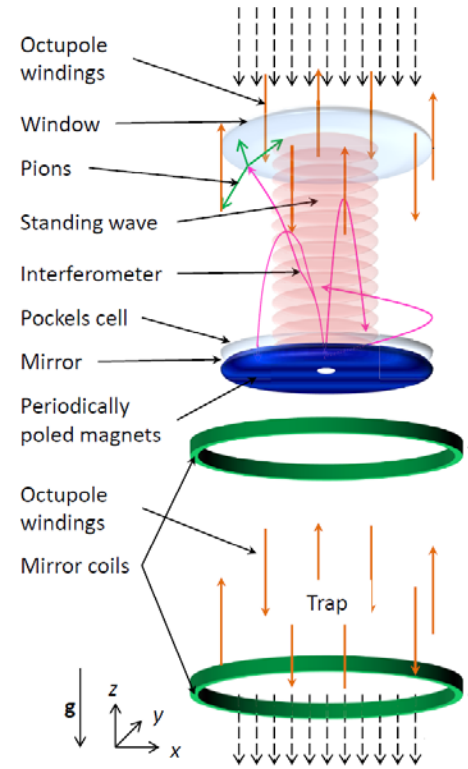
Interferometric Measurement of F

- $^{\pi}/_{2}$, π, $^{\pi}/_{2}$ laser pulse train.





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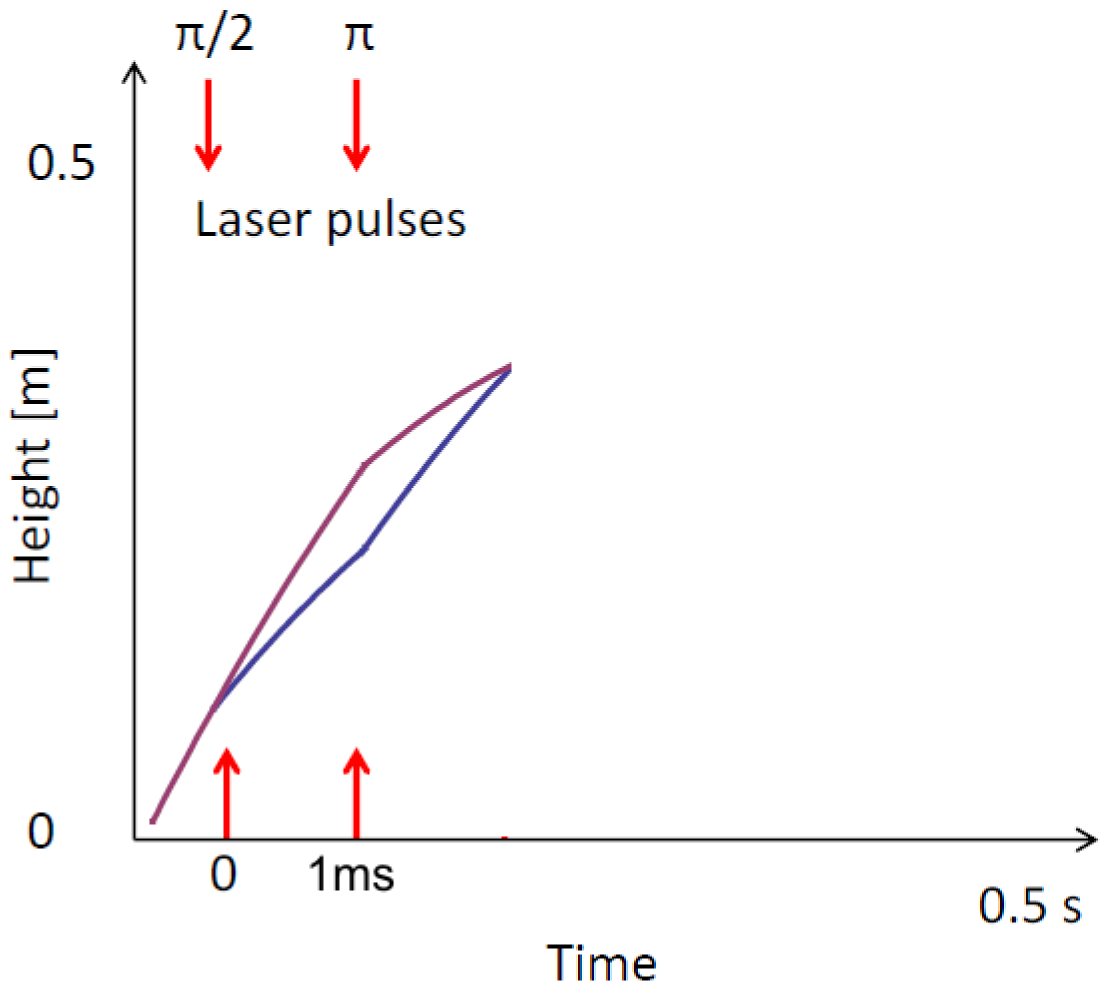

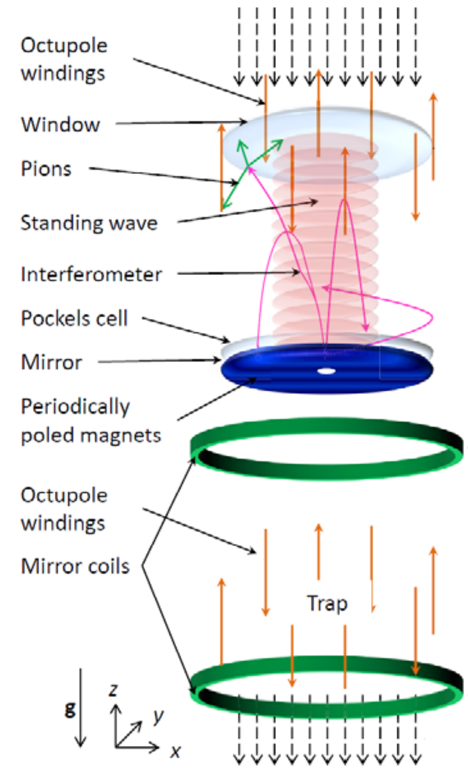

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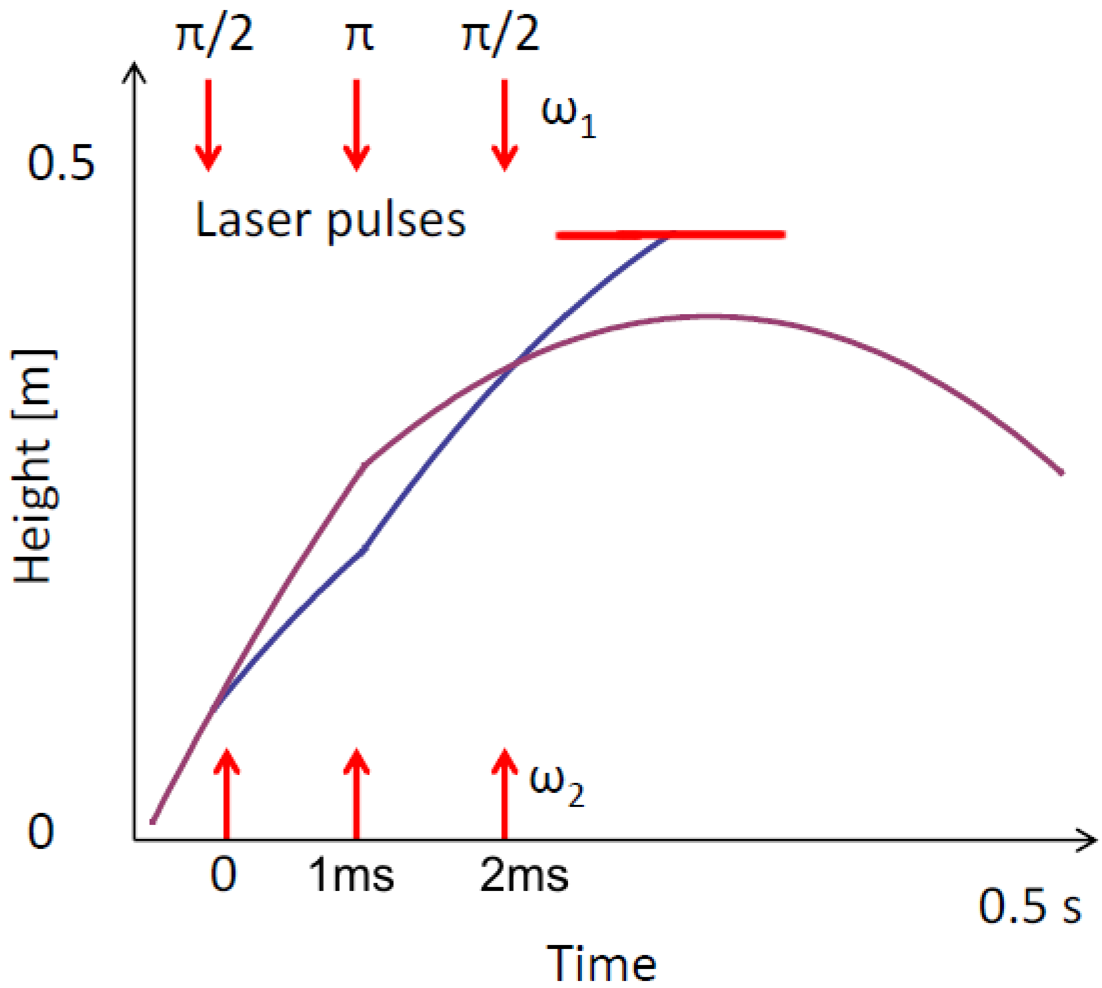
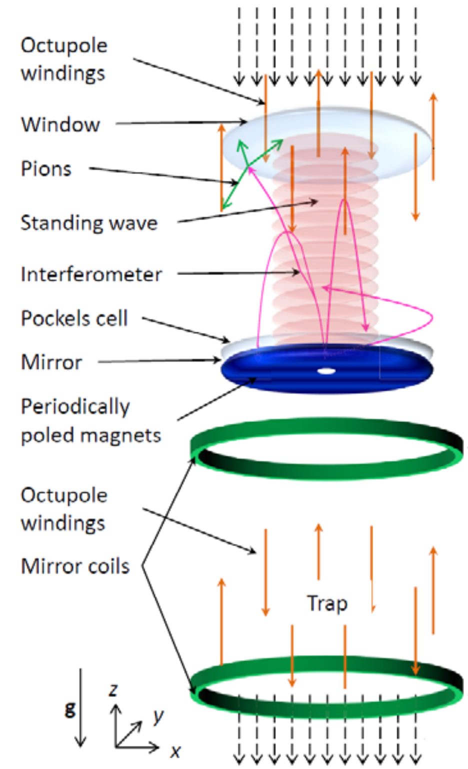
- $\pi/_2$, π, $\pi/_2$ laser pulse train.





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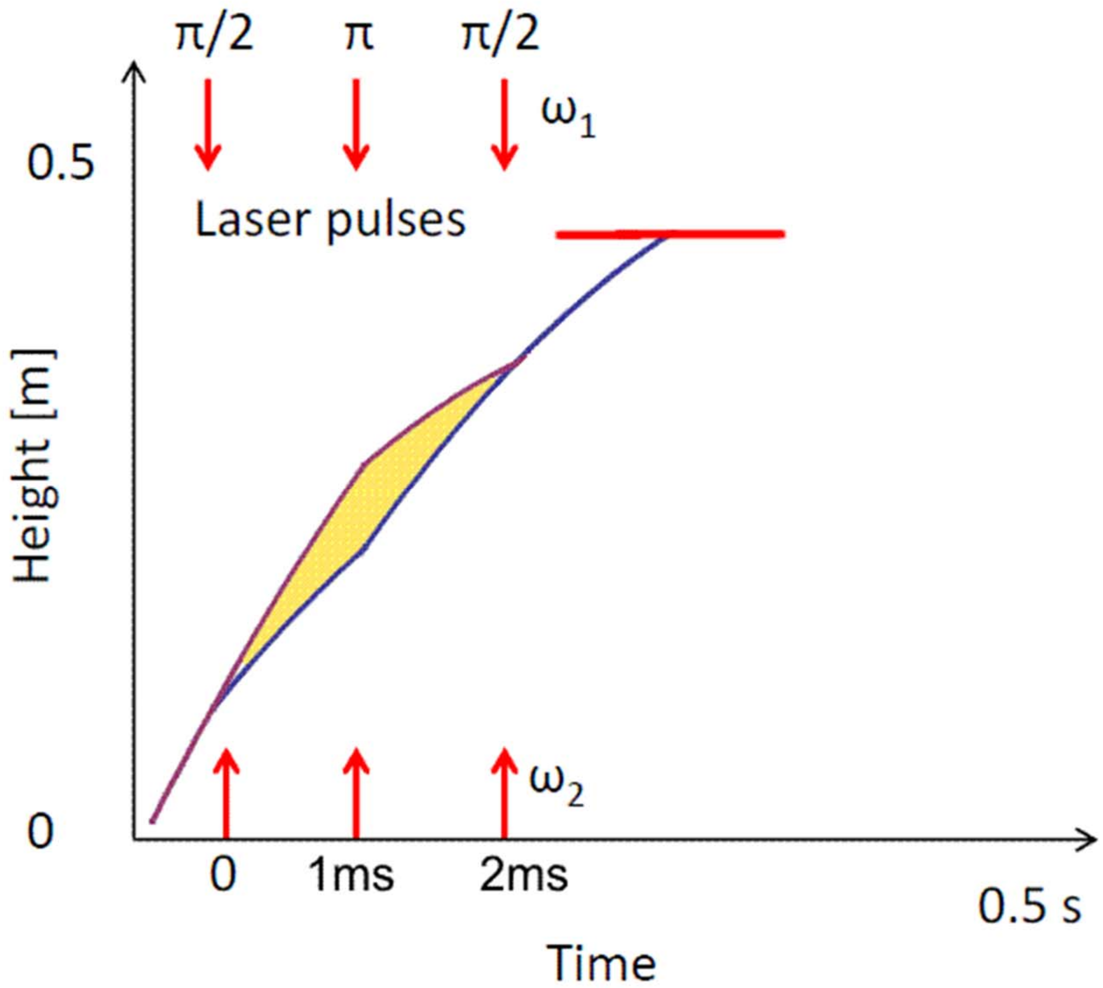

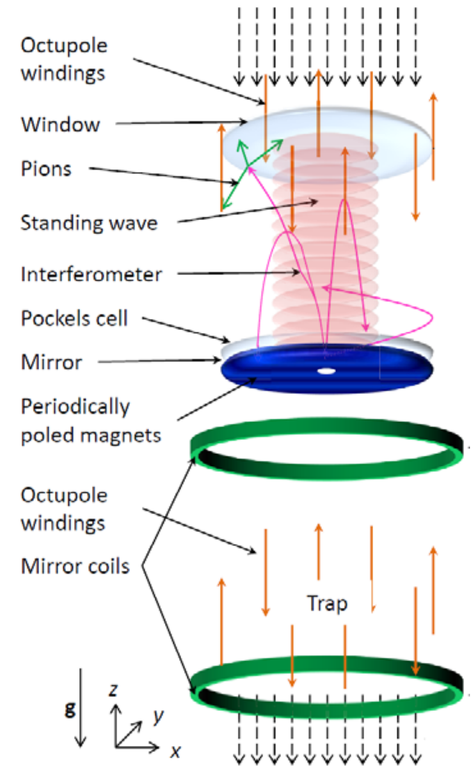

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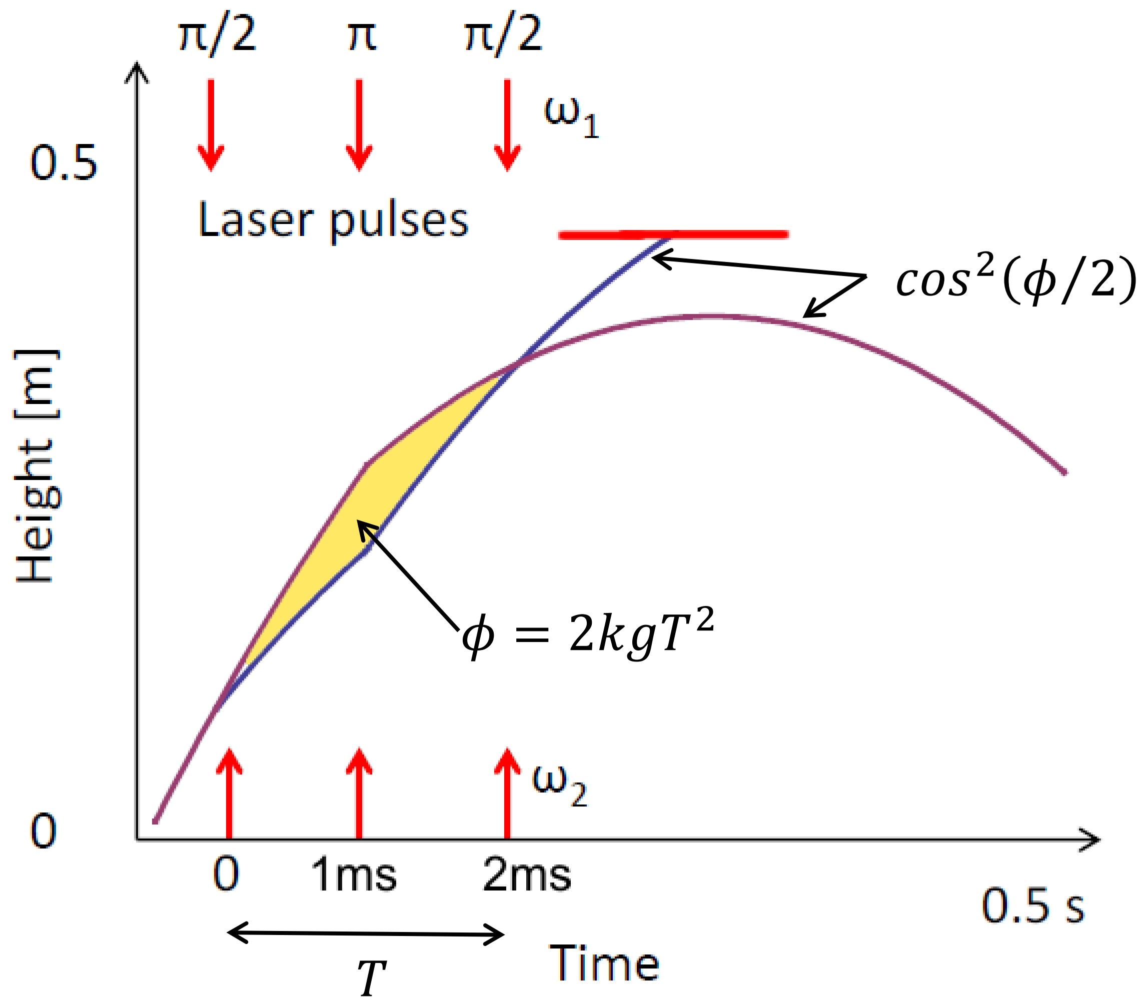

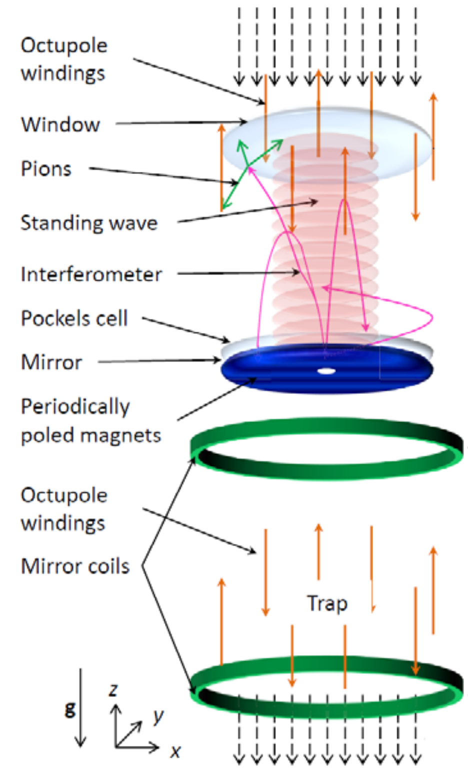

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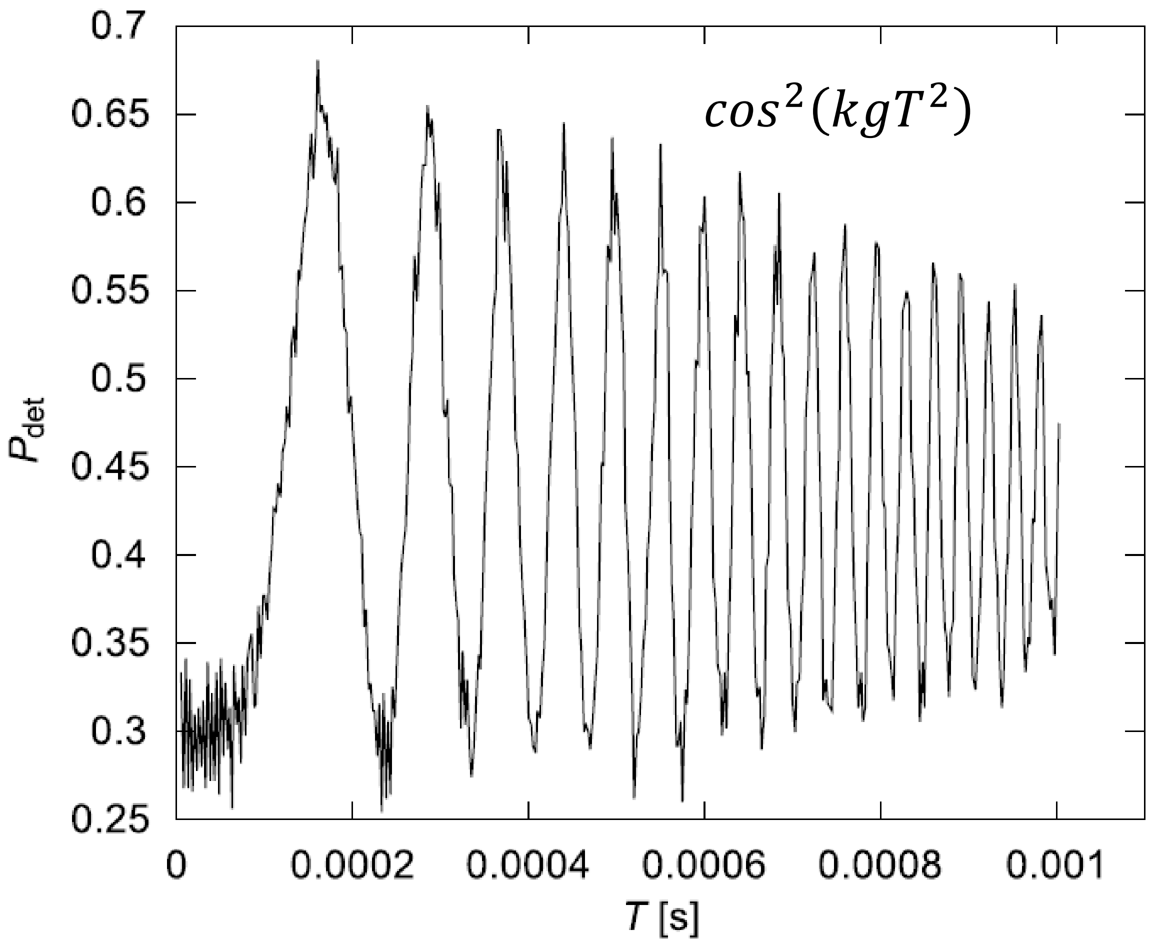

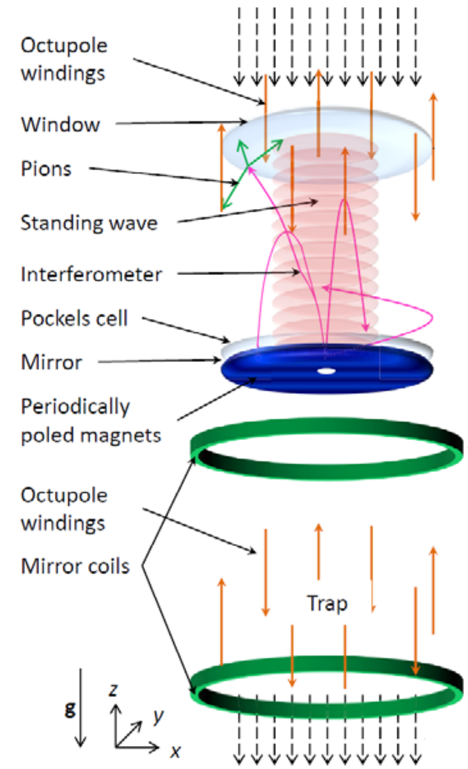

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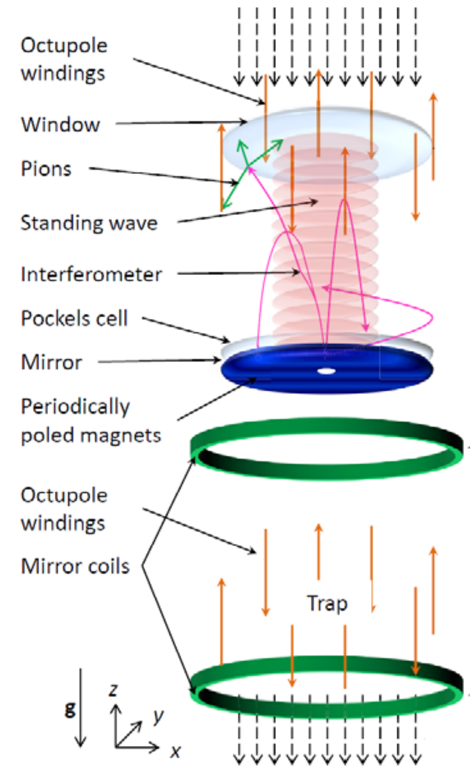
Interferometric Measurement of F

- Advantages of laser interferometric technique:
  - ALPHA has demonstrated sufficient anti-atom trapping.
  - Resonant interferometric techniques have been proven to work for gravitational measurements on single atoms.
  - Only new technology is off-resonant technique.
- Disadvantages of laser interferometric technique:
  - Requires a new apparatus.
  - 0.0001% sensitivity requires extraordinary control of external magnetic field gradients.
  - Laser has a lot of energy for a cryogenic environment.



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Conclusions

- ALPHA has set limits in the neighborhood of $F = \pm 100$ for the gravitational interactions between matter and antimatter.
- These are the first free fall style, model independent measurements of antimatter gravity.
- The route to the more interesting $F = \pm 1$ regime is clear, but will take either laser cooling or a vertical trap.
- Interferometric measurements of escaping trapped antihydrogen atoms could achieve ppm level precision.

Quantitative Statistical Method

- To calculate the bounds on F quantitatively, we did a Monte Carlo study of a test statistic akin to Fisher's Combined Statistic which aggregates Kolmogorov-Smirnov tests.

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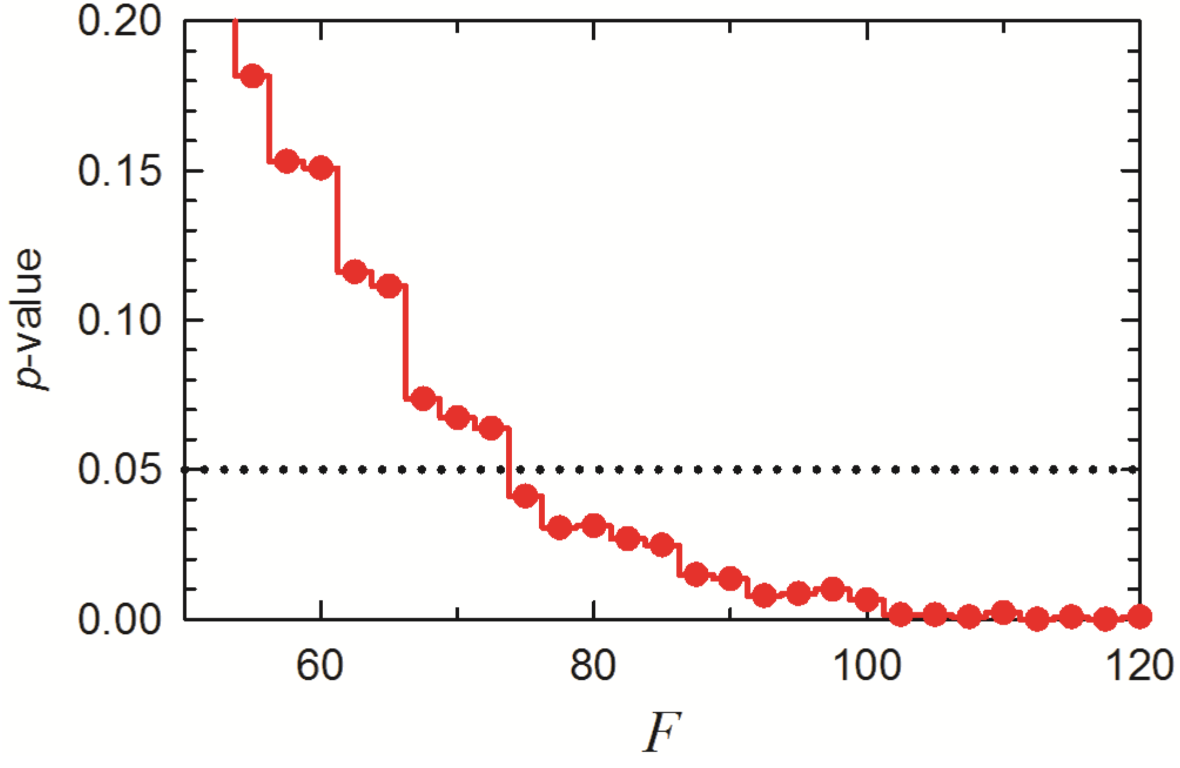

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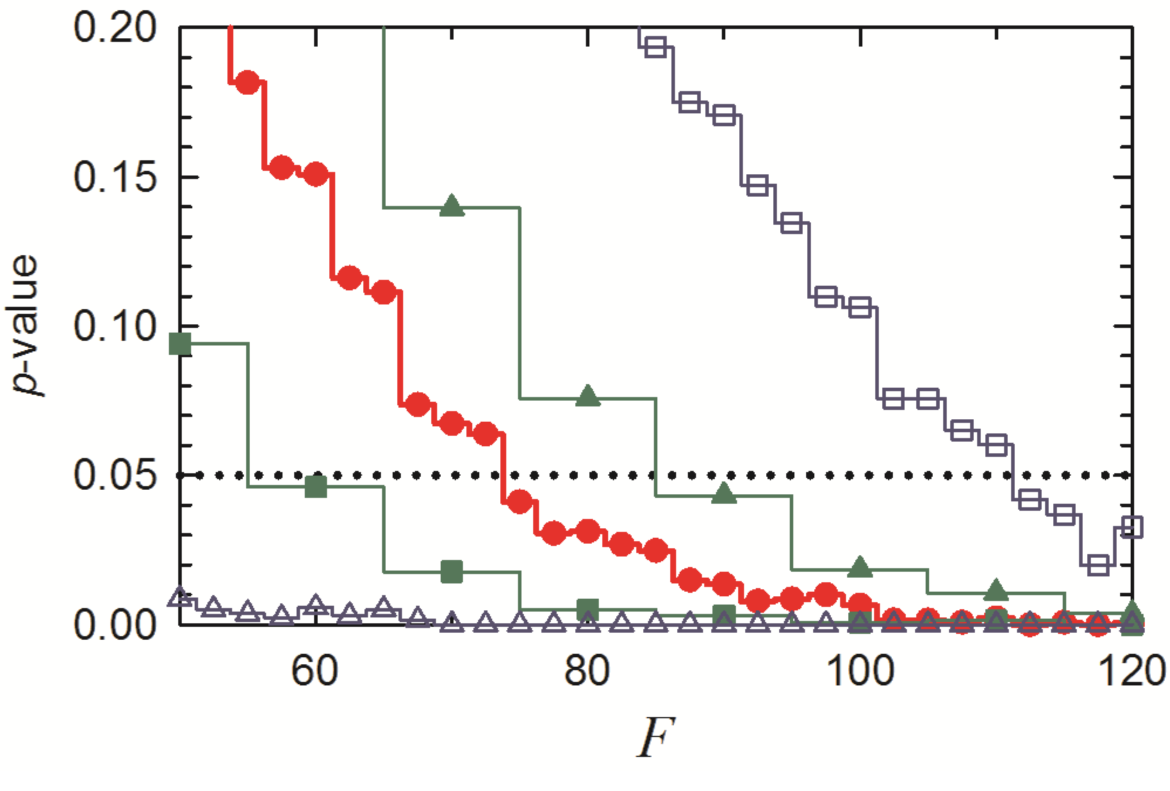

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