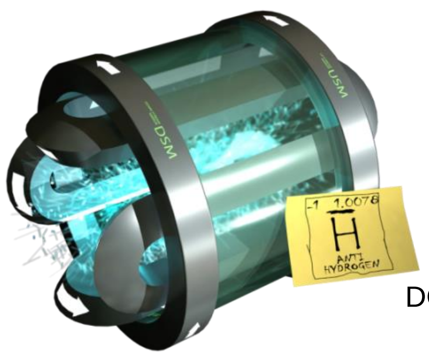
Description and First Application of a New Technique to Measure the Gravitational Mass of Antihydrogen

Joel Fajans
U.C. Berkeley

and the **ALPHA** Collaboration

C. Amole, M.D. Ashkezari, M. Baquero-Ruiz, W. Bertsche, E. Butler, A. Capra, C.L. Cesar, M. Charlton, S. Eriksson, T. Friesen, M.C. Fujiwara, D.R. Gill, A. Gutierrez, J.S. Hangst, W.N. Hardy, M.E. Hayden, C.A. Isaac, S. Jonsel, L. Kurchaninov, A. Little, N. Madsen, J.T.K. McKenna, S. Menary, S.C. Napoli, P. Nolan, A. Olin, P. Pusa, C.O. Rassmussen, F. Robicheaux, E. Sarid, D.M. Silveira, C. So, R.I. Thompson, D.P. van der Werf, J.S. Wurtele, and A.I. Zhmoginov
with A.E. Charman



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

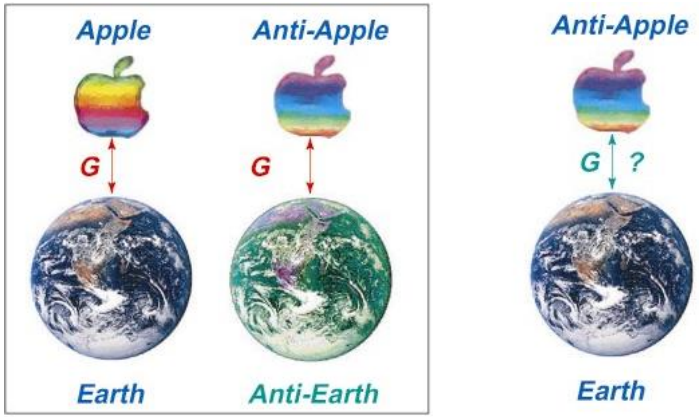
Also supported by CNPq, FINEP/RENAFAE (Brazil), ISF (Israel), MEXT (Japan), FNU (Denmark), VR (Sweden), NSERC, NRC/TRIUMF AIF FQRNT(Canada), and EPSRC, the Royal Society and the Leverhulme Trust (UK).

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

Antimatter Gravity

•Will antimatter fall under gravity the same way that normal matter falls?
•The weak equivalence principle asserts that it will.
•There have been many indirect test of the weak equivalence principle.
•The evidence from the indirect tests is compelling, but all such indirect tests have assumptions which just might not hold.
•There have been no “free fall” tests.

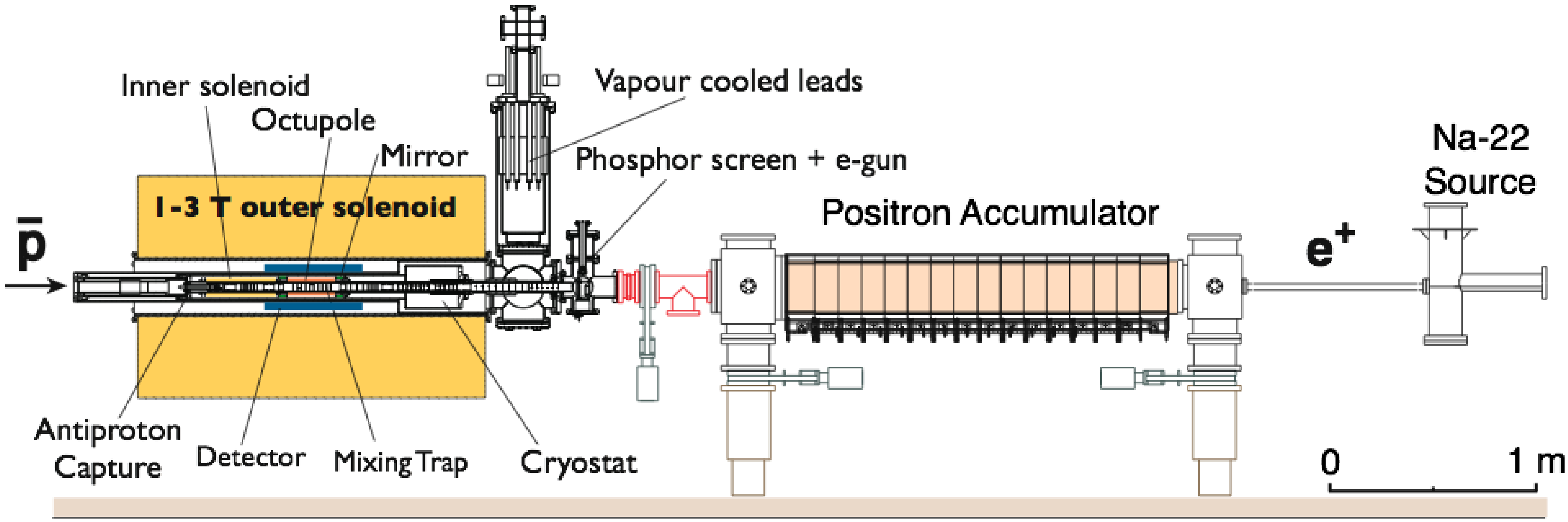
Weak Equivalence



After Thomas Phillips

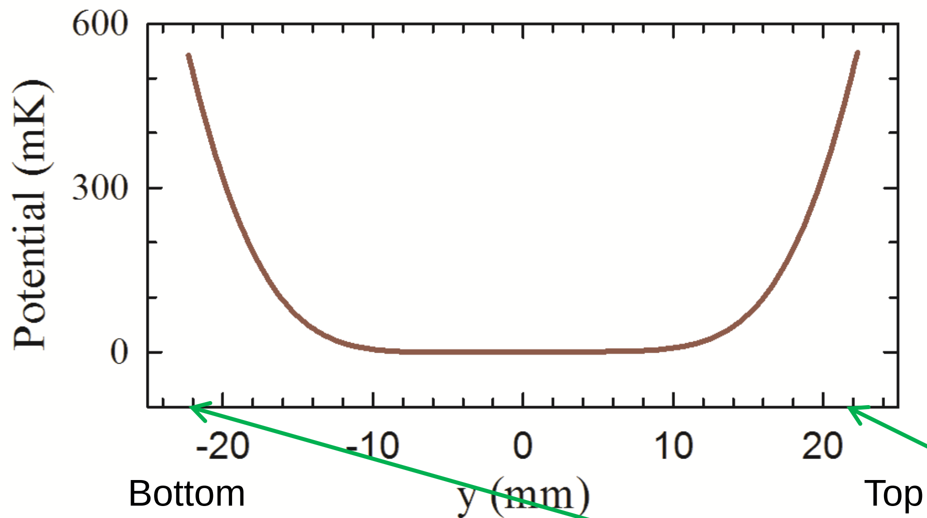
M. Fischler, J. Lykken, and T. Roberts, Direct observation limits on antimatter gravitation, Preprint at http://arxiv.org/abs/0808.3929 (2008).

ALPHA Apparatus

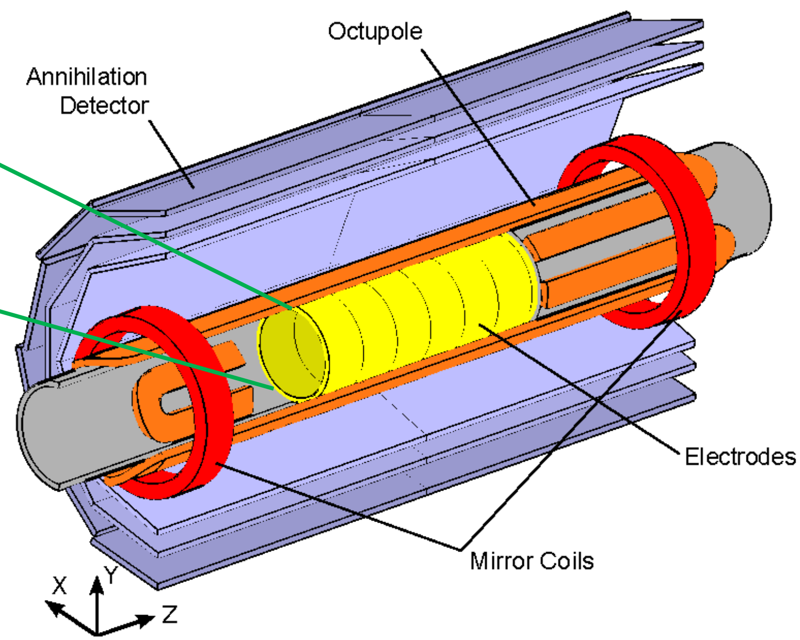


Effect of Gravity on the Anti-Atom Trapping Well

$F = M_G / M$=100



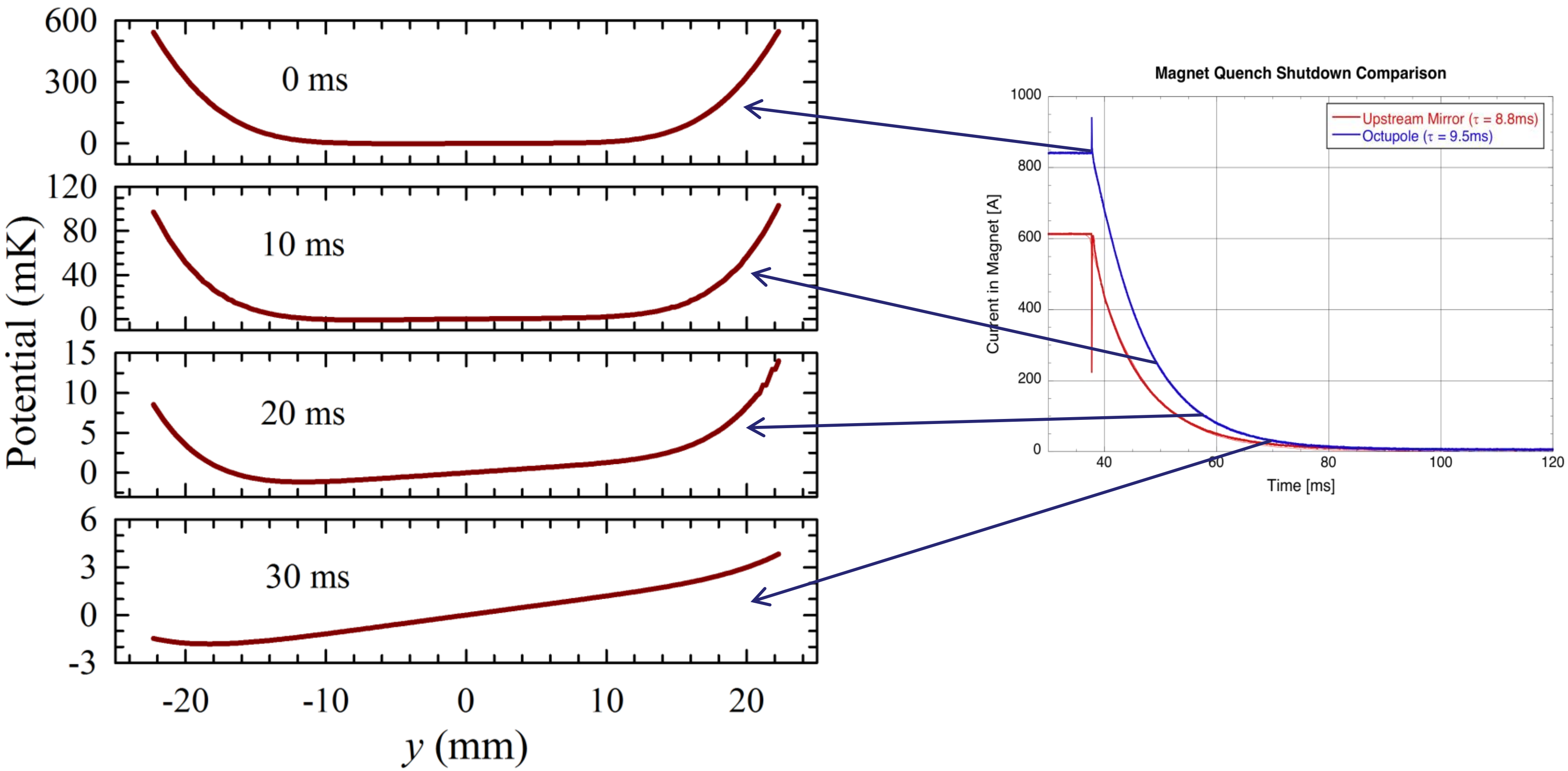
- F is the ratio of the gravitational mass to the inertial mass of antihydrogen.
- “Normal” gravity is $F = 1$.



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

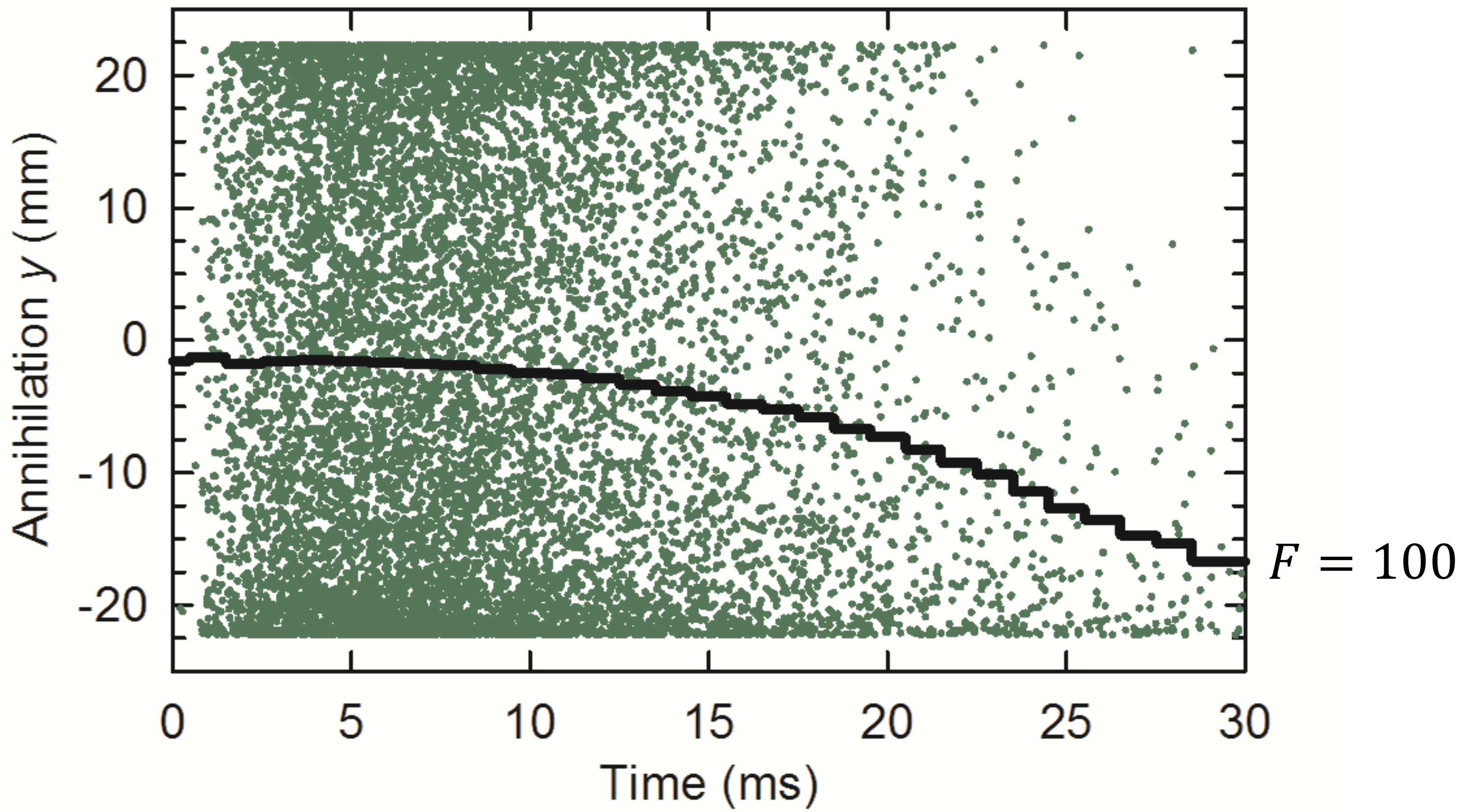
Antimatter Gravity

$F = M_G/M = 100$



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

$F = M_G/M = 100$



Green dots---simulated annihilations

Simulations

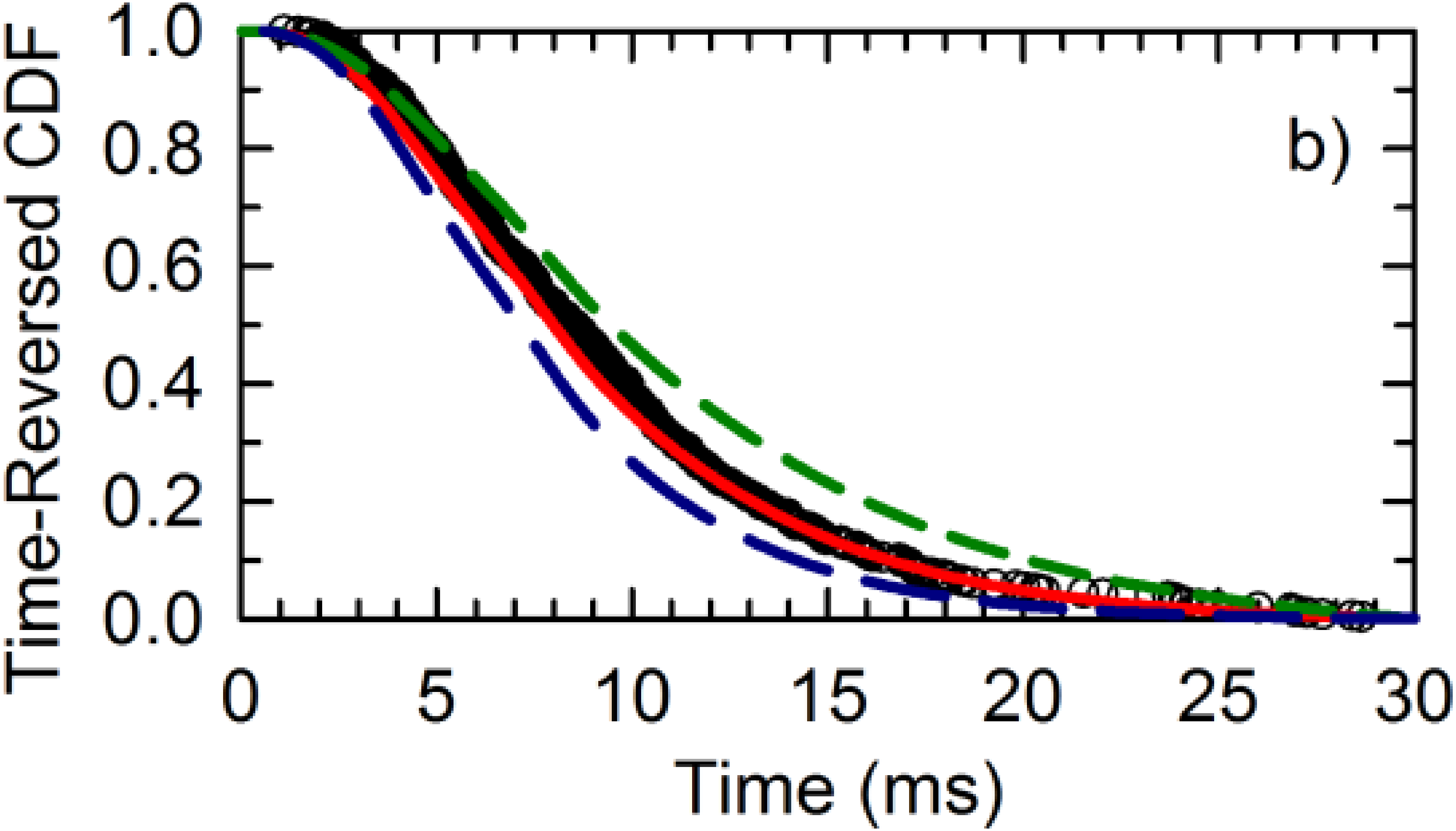
- Simulations follow:

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

- 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.

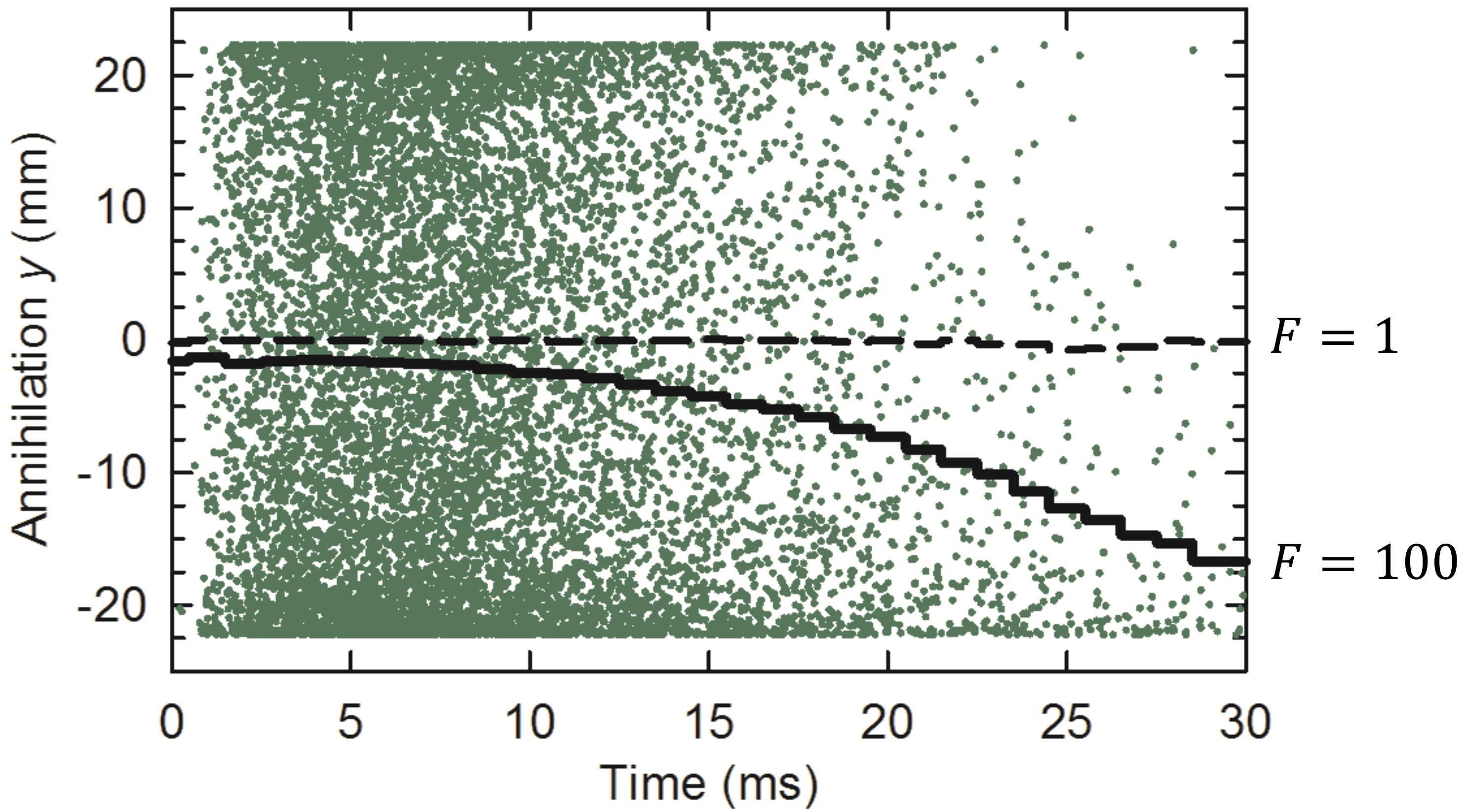
ALPHA, Confinement of antihydrogen for 1000s, Nature Physics **7,** 558 (2011).
ALPHA, Discriminating between antihydrogen and mirror-trapped antiprotons in a minimum-B trap, New J. Phys., **14** 015010, (2012).

Benchmarking Example: Antihydrogen Distribution



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

$F = M_G/M$=100



Green dots---simulated annihilations

Red circles---434 Observed annihilations

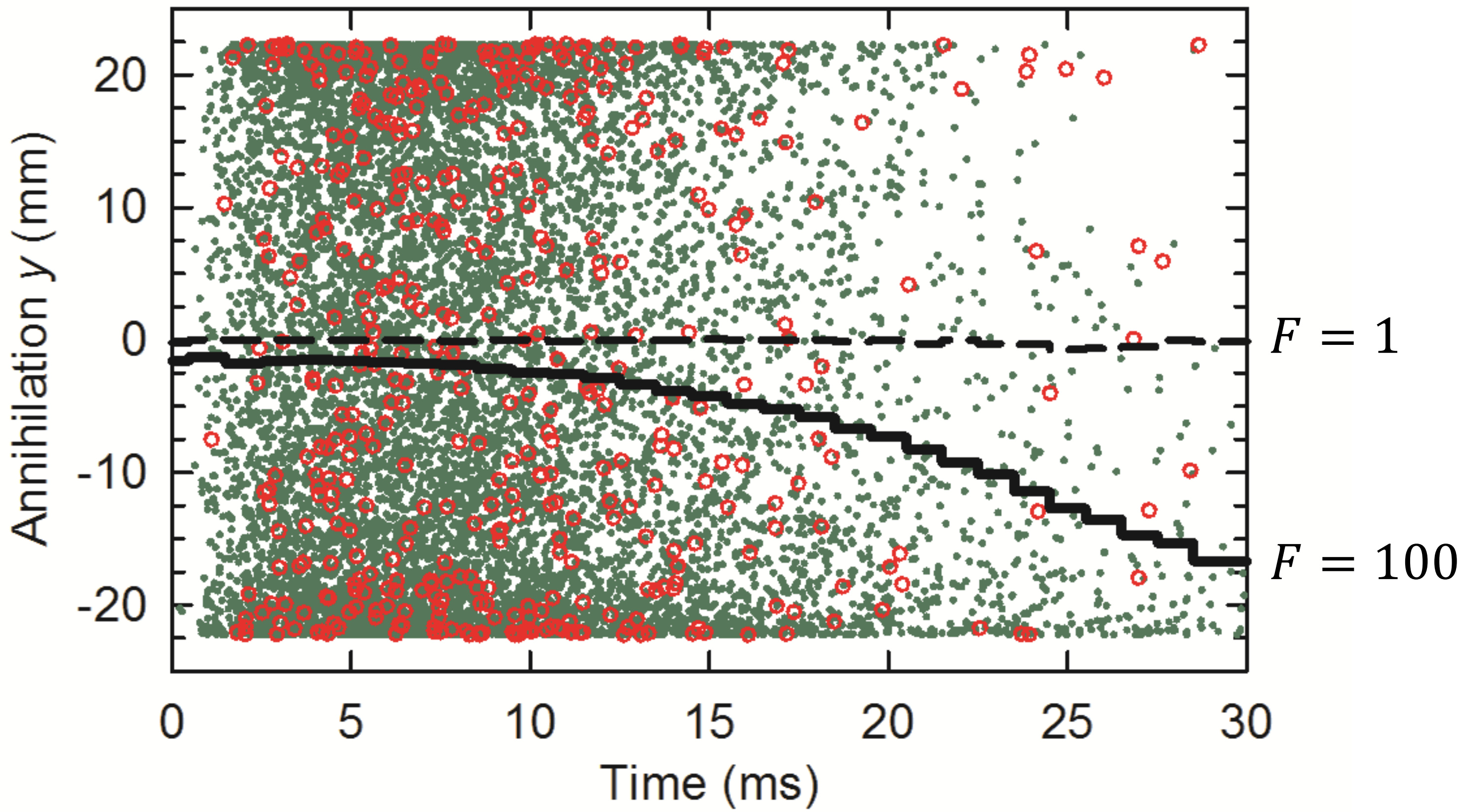
Data Set:

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

ALPHA, Confinement of antihydrogen for 1000s, Nature Physics **7,** 558 (2011).

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

$F = M_G/M$=100



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:

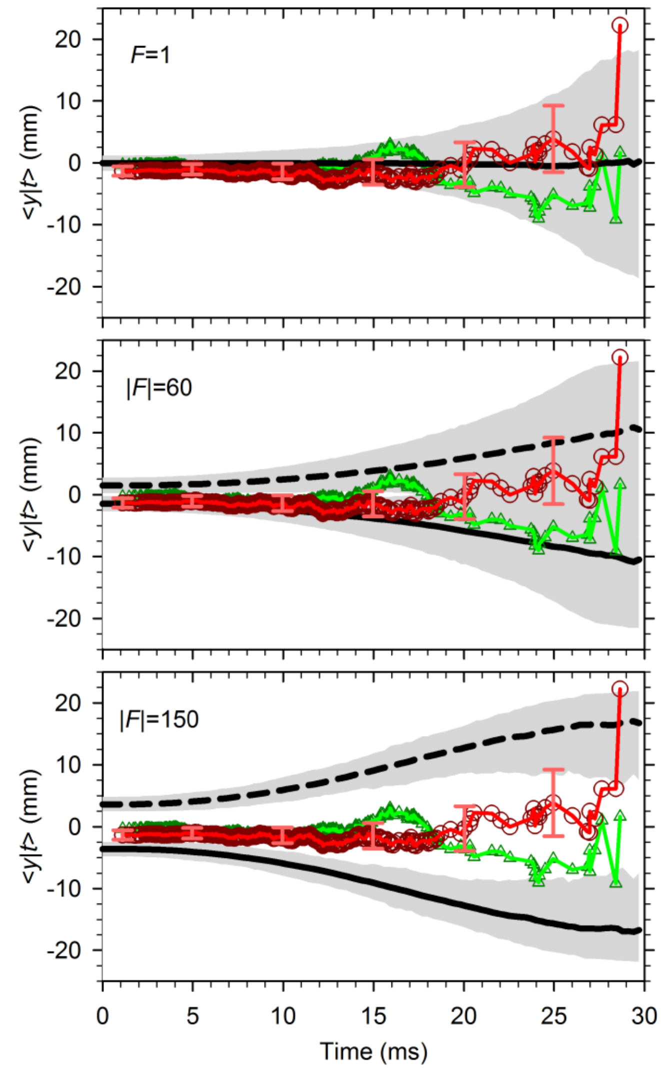
- The late escaping anti-atoms are most sensitive to gravity…
- But there are relatively few late escaping particles, so the statistics for these anti-atoms are poor.

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.



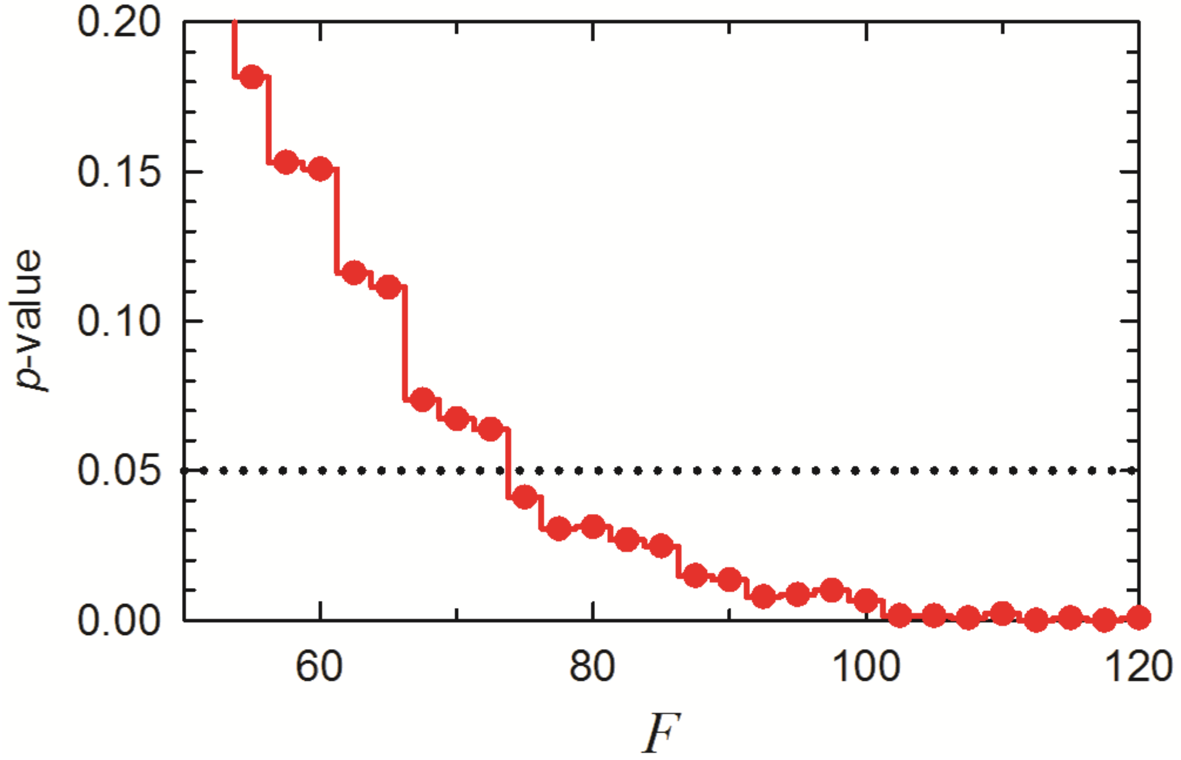
ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm **4**, 1785 (2013).

Quantitative Statistical Method

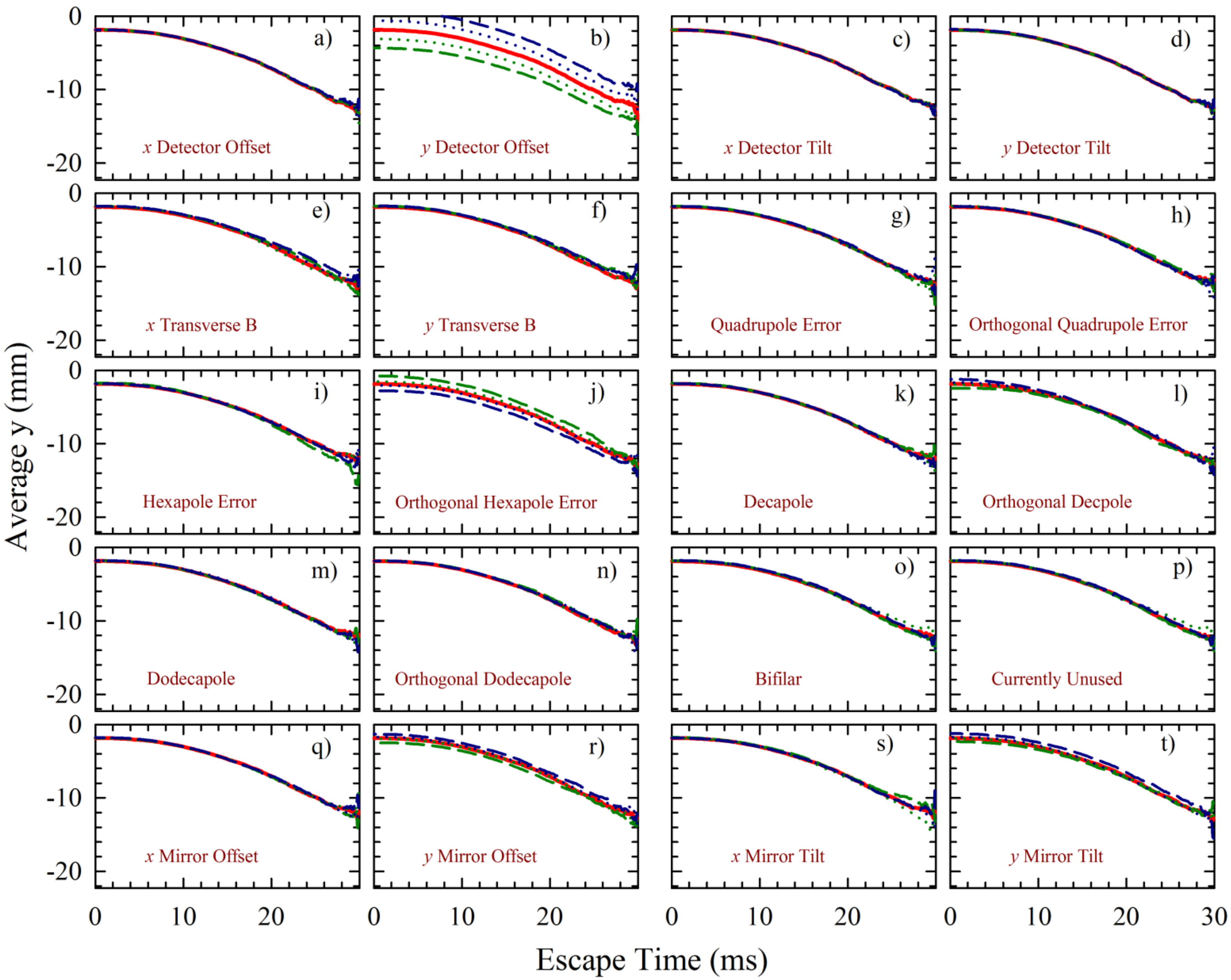
- To calculate the bounds on F quantitatively, we did a Monte Carlo study of a test statistic akin to Fisher's Combined Statistic which aggregates Kolmogorov-Smirnov tests.

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

- Considering counting statistics alone, we can reject $F > 75$ with at a statistical significance of 95%.

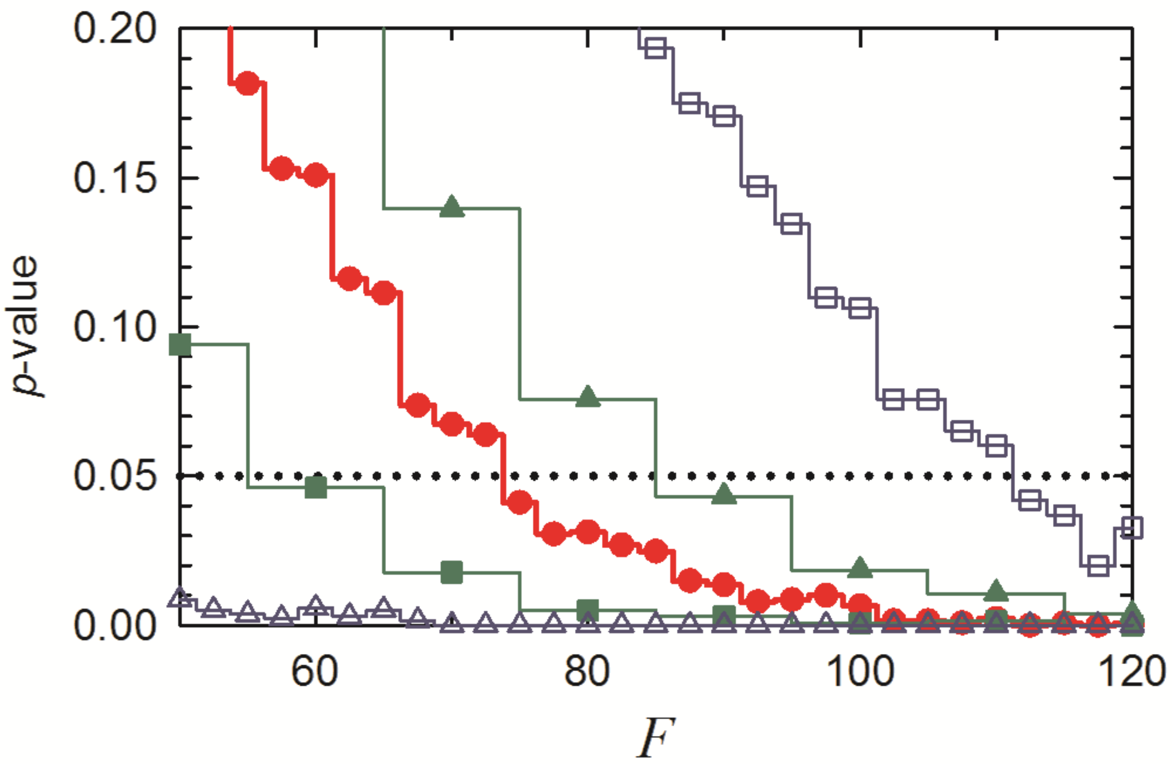


Systematic Effects



Systematic Effects

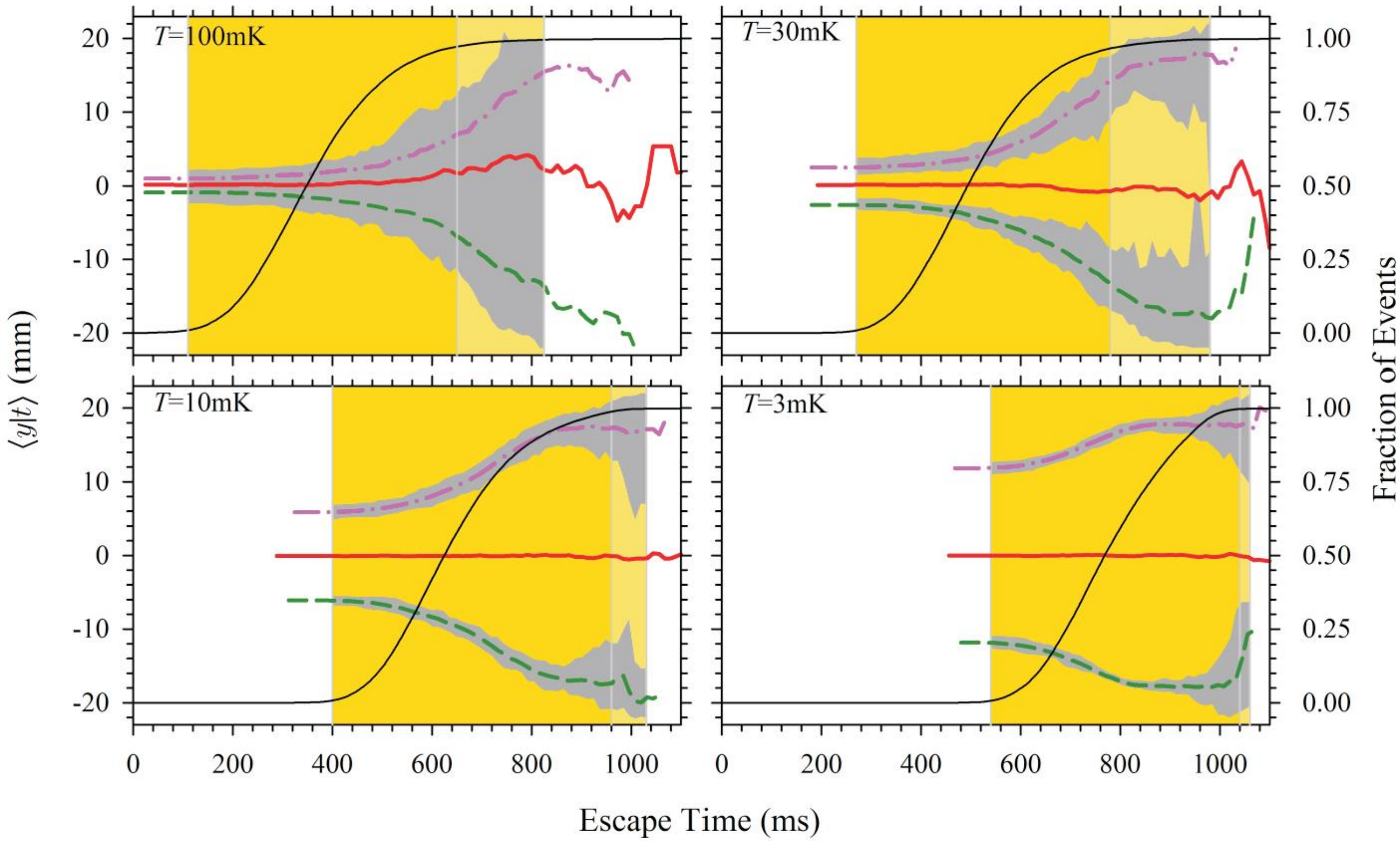
- Considering systematic effect with our Fisher test, we find that we can exclude, with 95% confidence:
  - $F > 110$ (Normal gravity)
  - $F < -65$ (Antigravity)



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

$F = \pm 1$?

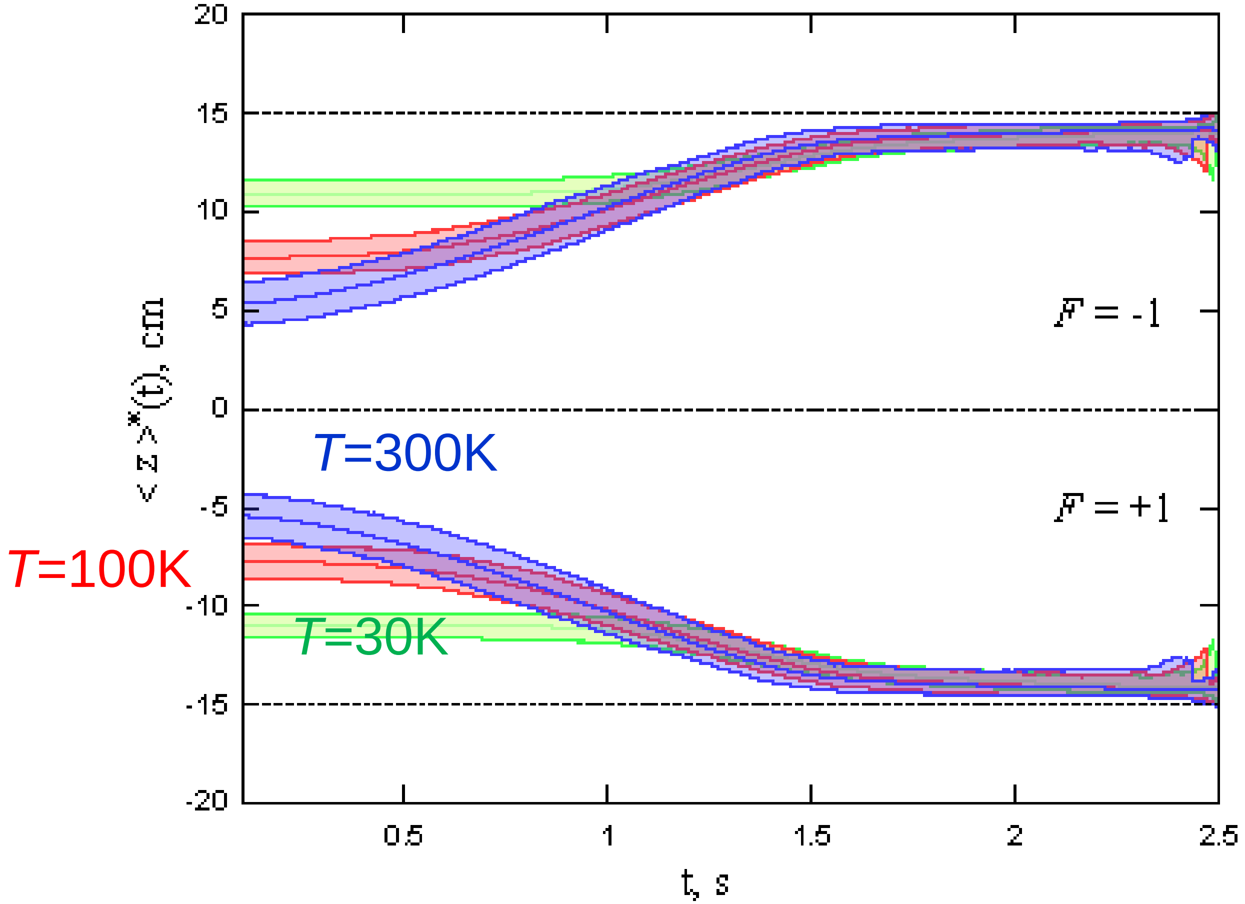
- With an ALPHA style horizontal trap:
  - Use laser cooling.
  - Slow down the magnet turnoff by a factor of ten



ALPHA, Description and first application of a new technique to measure the gravitational mass of antihydrogen, Nature Comm **4**, 1785 (2013).
P.H. Donnan, M.C. Fujiwara, and F. Robicheaux, A proposal for laser cooling antihydrogen atoms, J. Phys. B **46**, 025302 (2013).

$F = \pm 1$?

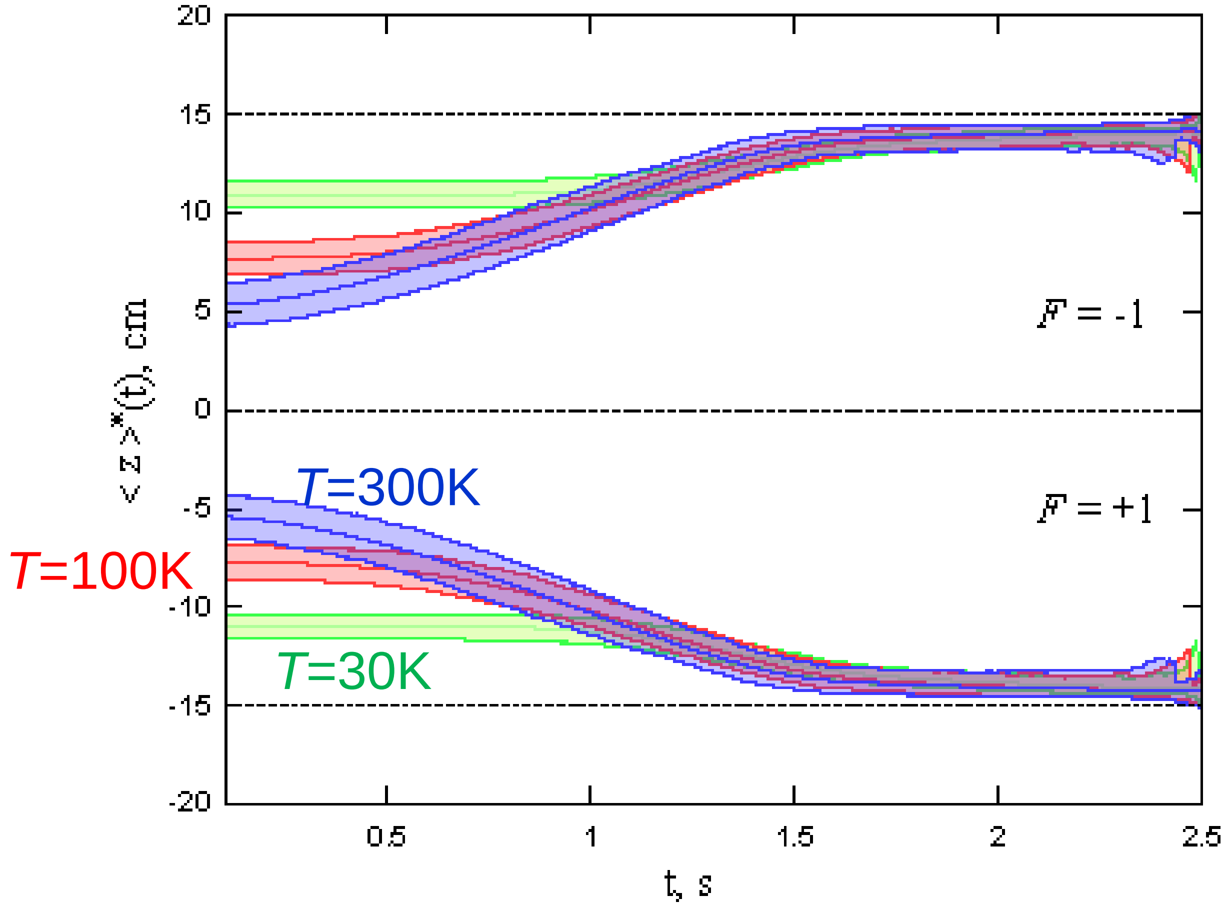
- With an ALPHA style *vertical* trap and 500 anti-atoms:
  - Laser cooling not necessary, though it helps.
  - Slow down the magnet turnoff by a factor of ten.
  - Turn of the mirror coils only.



A. Zhmoginov, A. Charman, J. Fajans, and J.S. Wurtele Nonlinear dynamics of antihydrogen in magnetostatic traps: implications for gravitational measurements, arXiv:1303.2738 (2013).

Beyond $F = \pm 1$?

- The slow release of trapped anti-atoms cools their axial motion substantially.
- Interferometric methods may yield ppm level precisions.



A. Zhmoginov, A. Charman, J. Fajans, and J.S. Wurtele Nonlinear dynamics of antihydrogen in magnetostatic traps: implications for gravitational measurements, arXiv:1303.2738 (2013).

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.