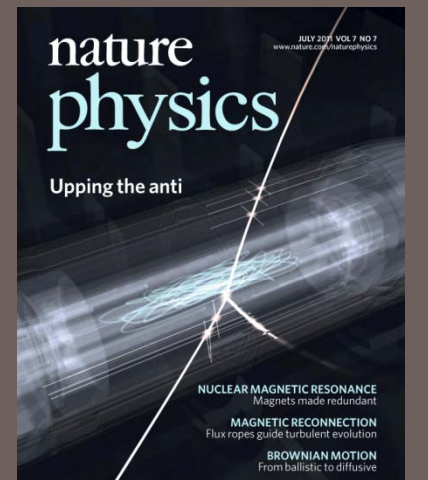
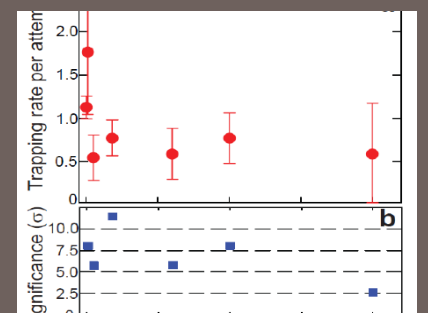
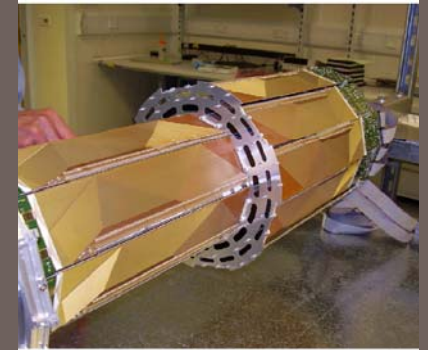


Trapped Antihydrogen, CPT and Gravity

Gbar 2011, Paris, Oct 10-11, 2011

Makoto C. Fujiwara
TRIUMF/Univ. of Calgary





10th International Conference on Low Energy Antiproton Physics

April 27 – May 1, 2011

TRIUMF, Vancouver, BC, Canada

leap2011.triumf.ca

- Antihydrogen and Antimatter Physics
- Fundamental Symmetries
- Exotic Atoms
- Hadron and Nuclear Physics with Antiprotons
- Antimatter in the Universe
- Applications of Antiprotons
- New Instrumentation and Facilities

Public Lecture: by John Ellis (CERN)

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Mary Alberg - Co-Chair (Seattle)

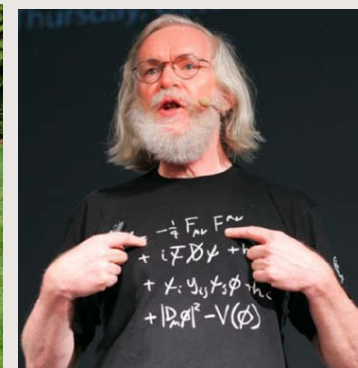


• 10th Int'l Conference on **Low Energy Antiproton Physics**

- Chair: Makoto Fujiwara
- Co-Chair: Mary Alberg
- Program Cmtt: Art Olin

• 1st LEAP in North America

• ~100 participants



Hosted by:



Makoto Fujiwara, TRIUMF



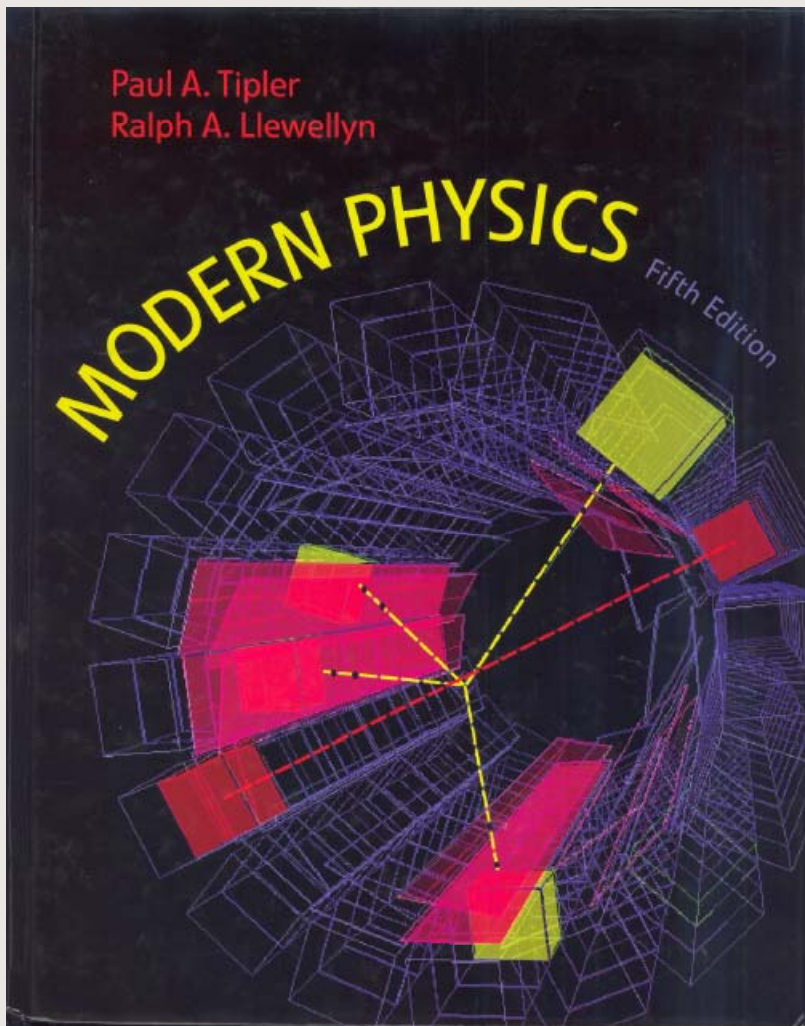
Background graphics courtesy of Chairmen Dr.

- ALPHA currently focused on microwaves
- ALPHA2 being designed and constructed for laser access, improved uWaves, and atom manipulations
- ALPHA2 will be horizontal!
- No immediate plan for real gravity experiment
- Based on latest ALPHA paper [Nature Phys. June 2011], I'll give my personal view on gravity measurements with trapped antihydrogen

Antimatter Gravity

- Gravitational interaction of antimatter atoms:
“Textbook” experiment

Textbook Experiment



- ATHENA's anti-H annihilation event (Nature, 2002): now on the cover of textbook!
- \$107.28 on Amazon.com



Amazon.com: Modern Physics (97807... x Amazon.com: Modern Physics Studie... +

http://www.amazon.com/Modern-Physics-Paul-Tipler/dp/0716775506/ref=pd_sim_... Google

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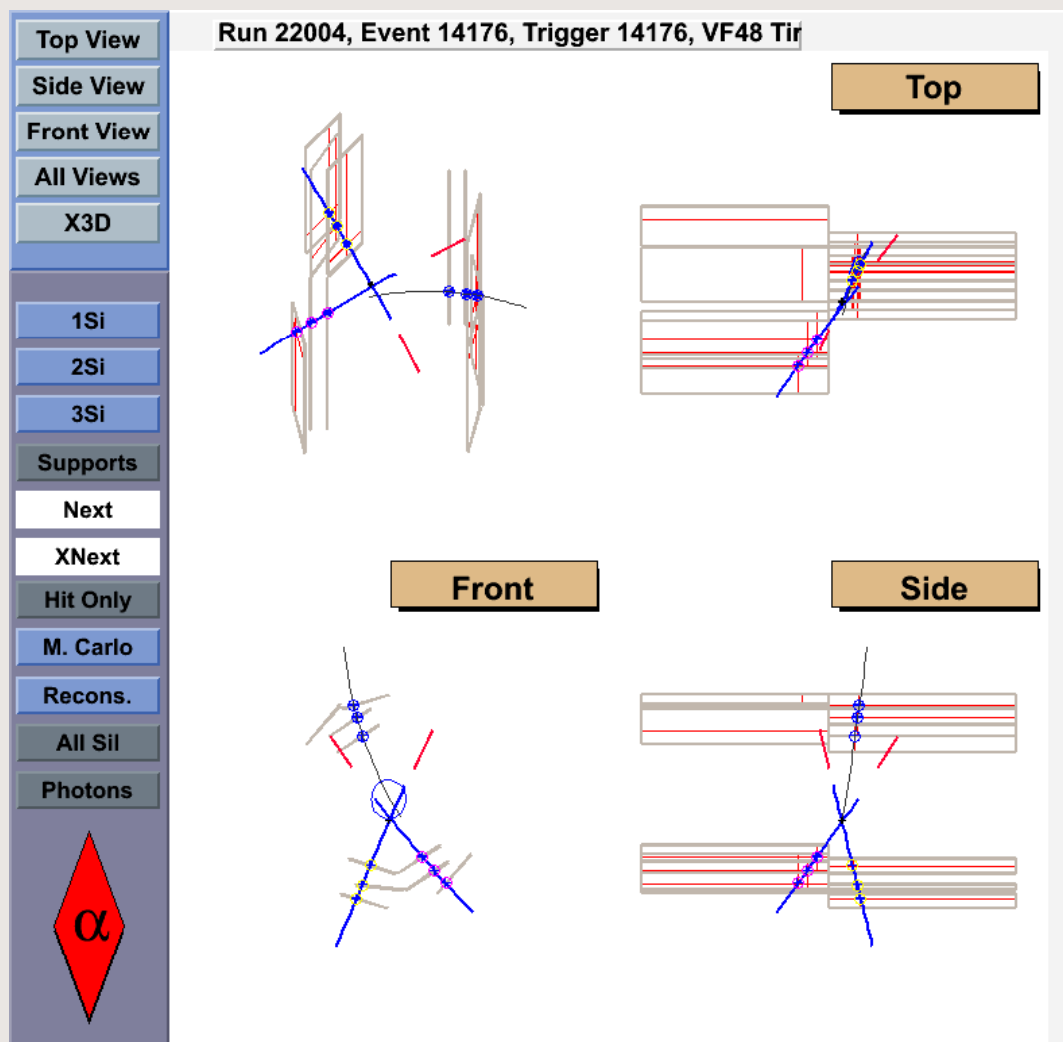
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Antimatter Gravity

- Gravitational interaction of antimatter:
“Textbook” experiment
- Ambitious efforts:
 - AEGIS, GBAR, AGE
- I have been scared of even thinking about gravity, because of its technical difficulties, until...

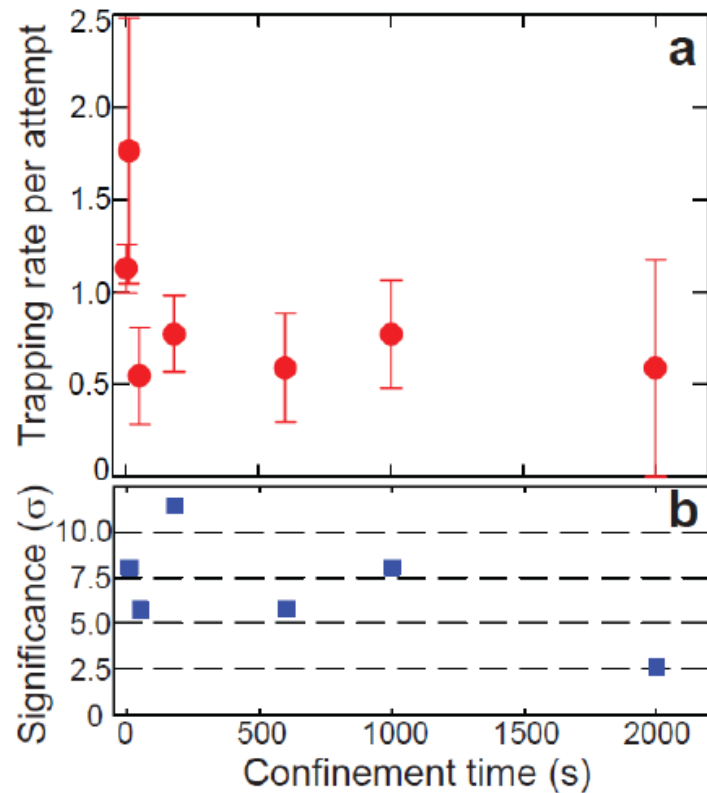
Annihilation event after 1000 s confinement

Nov. 2010



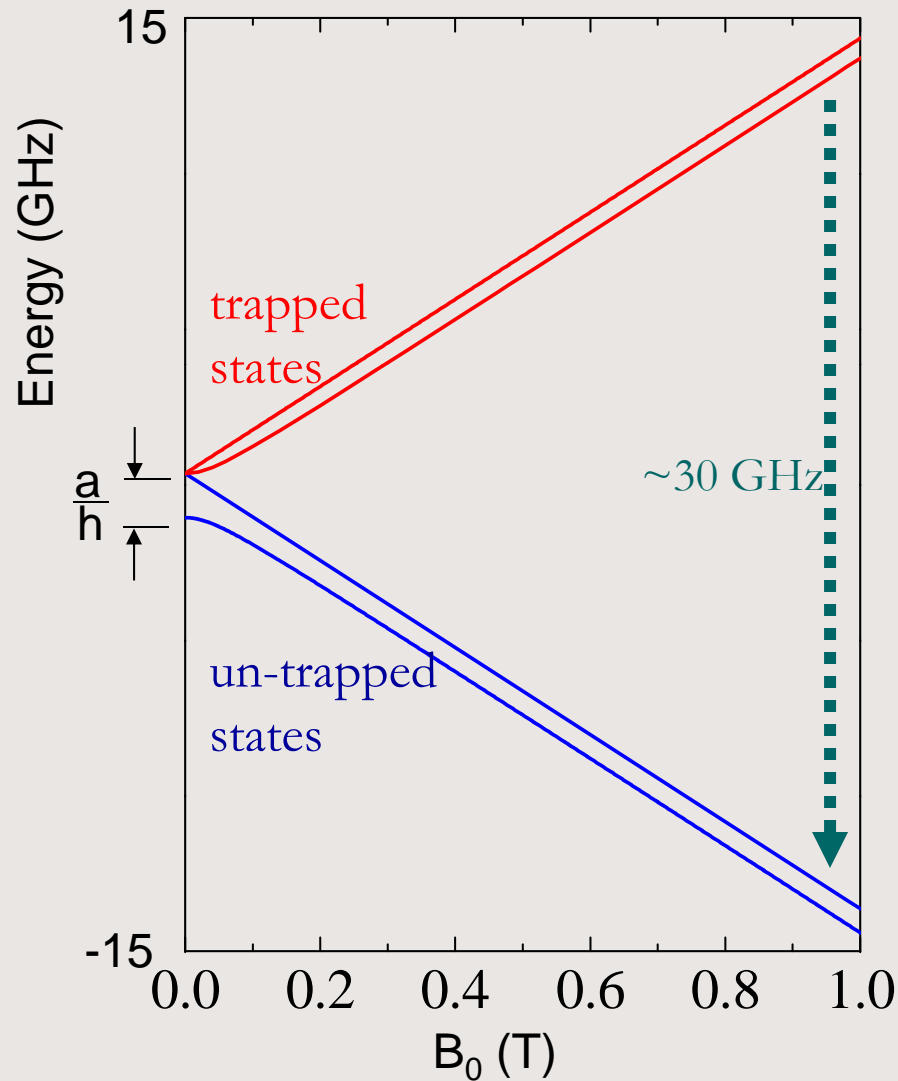
Confinement of antihydrogen for 1000 s

Nature Physics June, 2011



Confinement Time (s)	0.4	10.4	50.4	180	600	1000	2000
Number of attempts	119	6	13	32	12	16	3
Detected events	76	6	4	14	4	7	1
Estimated background	0.17	0.01	0.02	0.05	0.02	0.02	0.004
Statistical significance (σ)	>>20	8.0	5.7	11	5.8	8.0	2.6
Trapped antihydrogen per attempt	1.13 ± 0.13	1.76 ± 0.72	0.54 ± 0.26	0.77 ± 0.21	0.59 ± 0.29	0.77 ± 0.29	0.59 ± 0.59

CPT: μ Wave Spectroscopy with trapped antihydrogen



Positron Spin Resonance

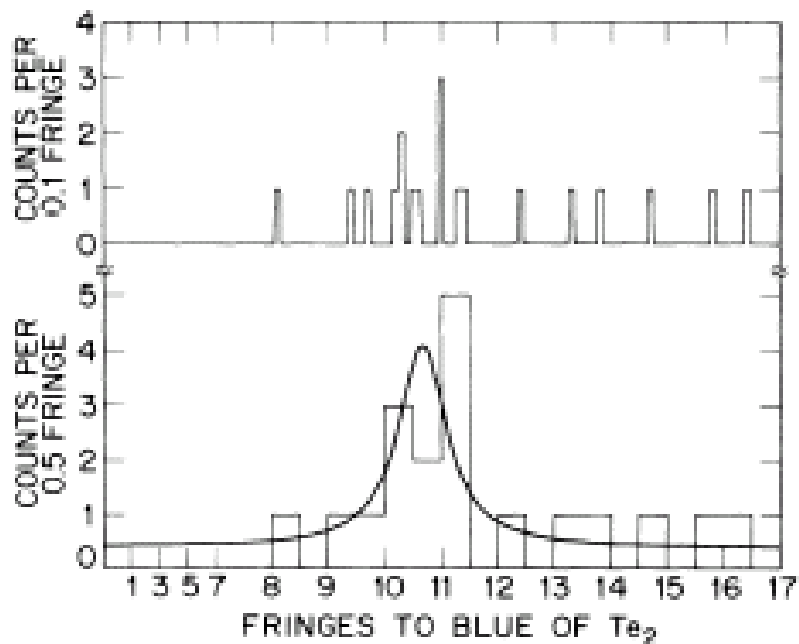
- Pulsed μ W at ~ 30 GHz
trapped \rightarrow **un-trapped**
- Look for annihilations
- Can start with a few atoms

• Figure of merit:

- (trapped number) x
(**observation time**) x (laser or microwave power)
- Longtime confinement reduces dramatically power, number requirements

Rare Atom Physics: Rare Event Detection

- First measurements with trapped Hbar will be statistics limited
- Need best event characterizations, background rejections
 - Si vertex detector
- Position sensitivity provides unexpected physics potentials
 - e.g. Mirror trapped pbar background



Muonium 1S-2S
spectroscopy
S.Chu, et al.
Phys. Rev. Lett. (1988)



~8 events!

Antimatter Gravity with Trapped Hbars

- Gravity

- Never measured with antimatter
- Test of General Relativity

- Does antimatter fall down?

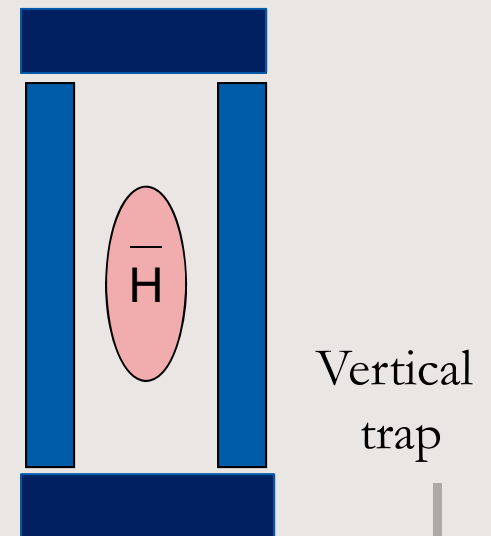
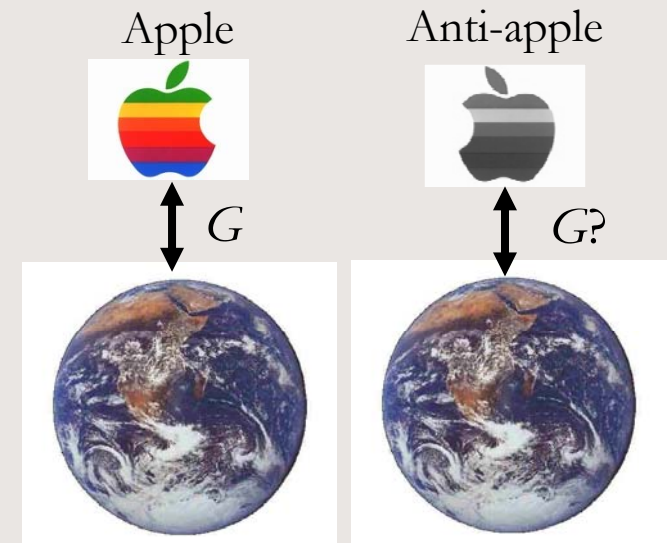
- Experimental question!
- If Hbar is cooled to mK

$$1/2kT - mgh$$

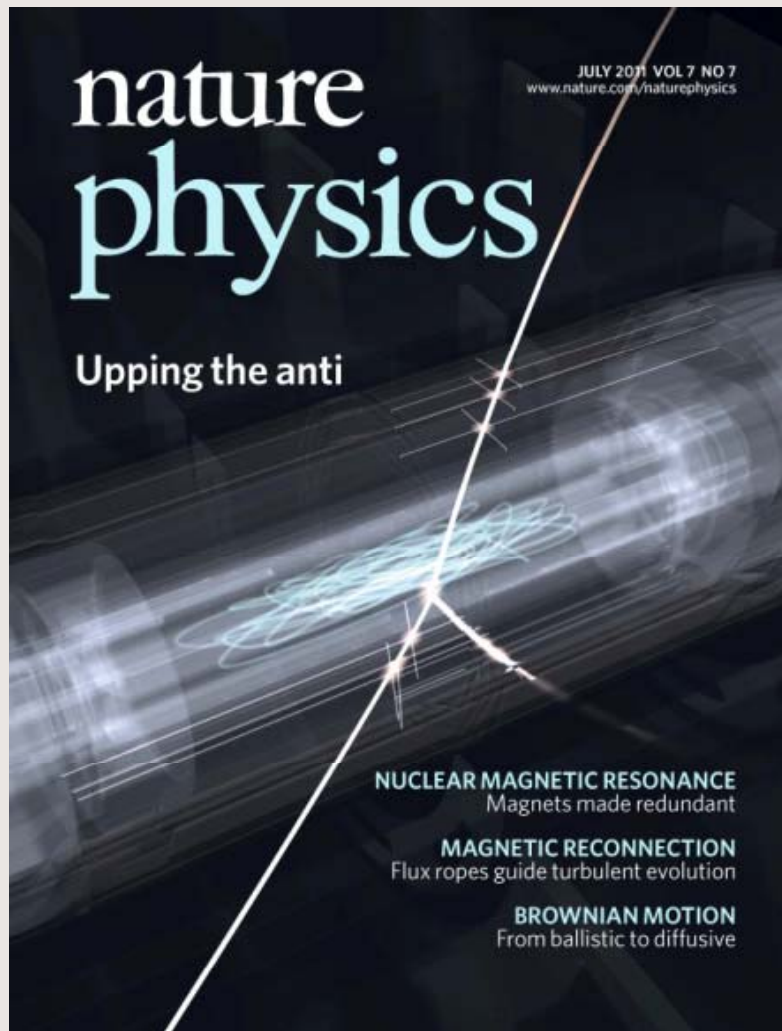
Vertical trap: $h \sim 1 \text{ m}$

- Laser cooling: Doppler limit 2.4 mK
- Adiabatic cooling: to sub mK?
 - Phillips; Walraven

- Manipulate Hbars, and detect annihilations



Confinement of antihydrogen for 1000 s: Implications



Nature Phys. 7, 558 (2011)
[arXiv:1104.4982]

- 30 pages in preprint format
- Please read the details! A lot of interesting atomic physics

Implications for gravity experiment

Nature Physics, June 2011

- Laser cooling plausible with existing laser technologies
- Temperature diagnosis of trapped antihydrogen (for future cooling studies)
- Direction-dependent temperature diagnosis
- First (but indirect) evidence of adiabatic cooling of antihydrogen
- Cold “beam” of antihydrogen

- In the absence of heating mechanism, even weak Lyman-alpha source can cool Hbars over long time
 - Laser cooling from 80 mK to 10 mK in 15 min with pulsed Lyman-alpha source

VOLUME 70, NUMBER 15

PHYSICAL REVIEW LETTERS

12 APRIL 1993

Optical Cooling of Atomic Hydrogen in a Magnetic Trap

I. D. Setija, H. G. C. Werij, O. J. Luiten, M. W. Reynolds, T. W. Hijmans, and J. T. M. Walraven
*Van der Waals-Zeeman Laboratory, Universiteit van Amsterdam,
Valckenierstraat 65/67, 1018 XE Amsterdam, The Netherlands*
(Received 28 December 1992)

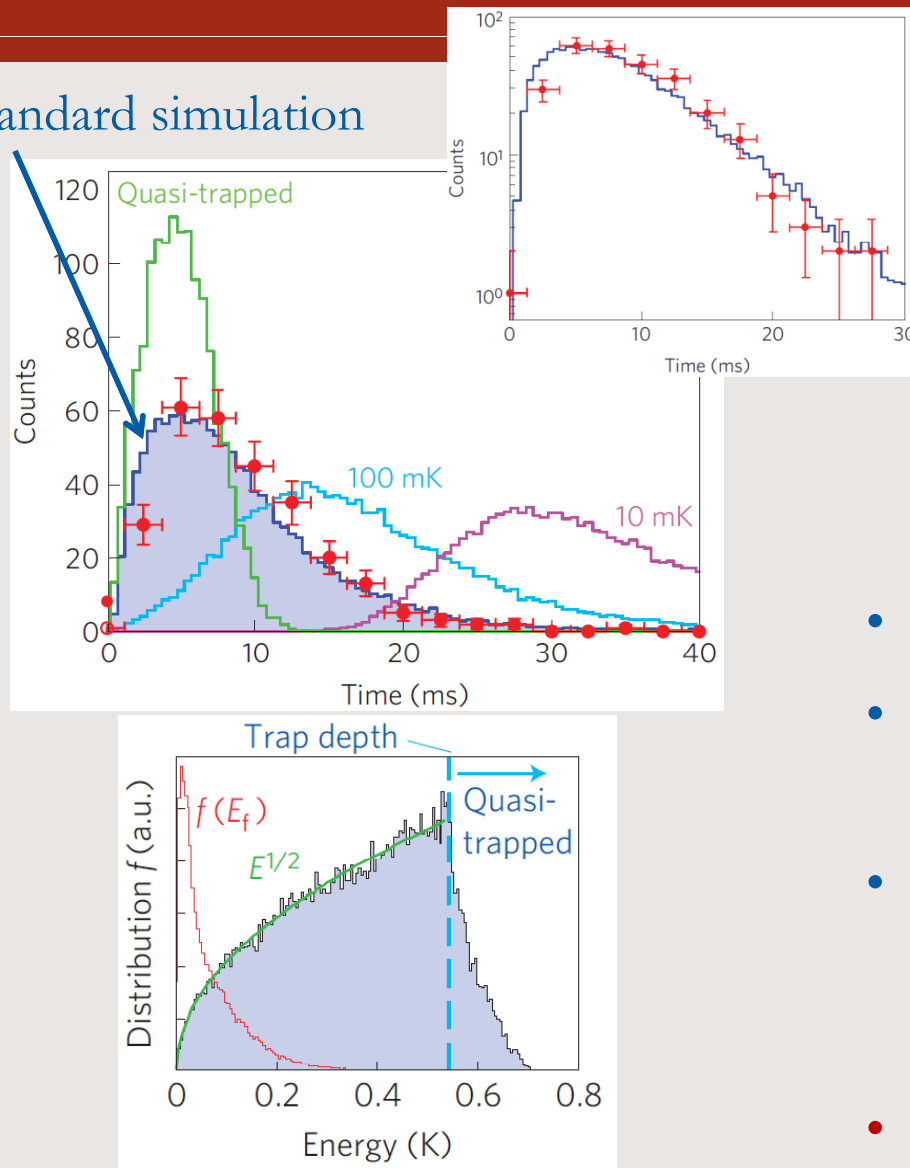
We present the first experimental demonstration of optical cooling of atomic hydrogen. Two methods are discussed: Doppler cooling, for which we report a minimum achieved temperature of 8 mK, and light-induced evaporation, a new cooling method by which we reached 3 mK.

- Heroic efforts by Walz, Ekima et al. for cw Lyman alpha
- Preparing Lyman-alpha laser in Vancouver: pulsed source first
- As long as not saturated, only ave. power matters for cooling rate: i.e. low duty factor not a problem: μW seems feasible
- Zeeman shift of 1s-2p an issue

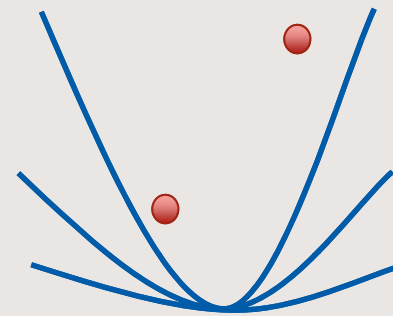
Kinetic energy of trapped Hbars:

Nature Phys. 2011

Standard simulation



Release of trapped Hbar at $t=0$



- Colder Hbars come out later
- Data agree with simulated energy distribution
- Consistent with theory assuming Hbar produced at thermalized with e^+ ($\gg 0.5$ K): $E^{1/2}$ scaling
- Temperature diagnosis for future cooling studies

Simulated kinetic energy distribution

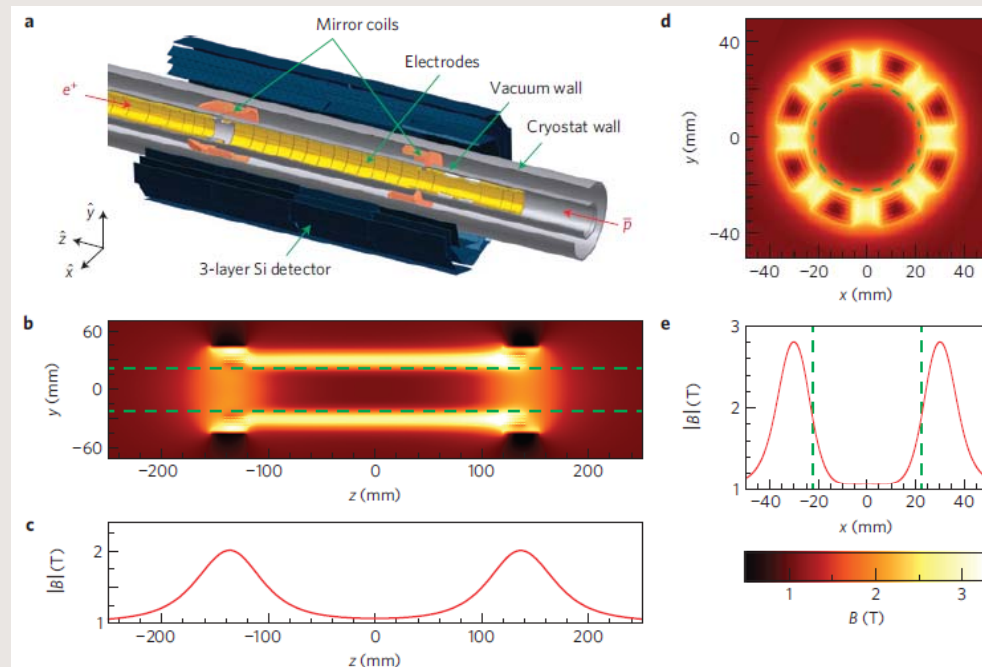
Trapped Antihydrogen Dynamics

Nature Phys. 2011

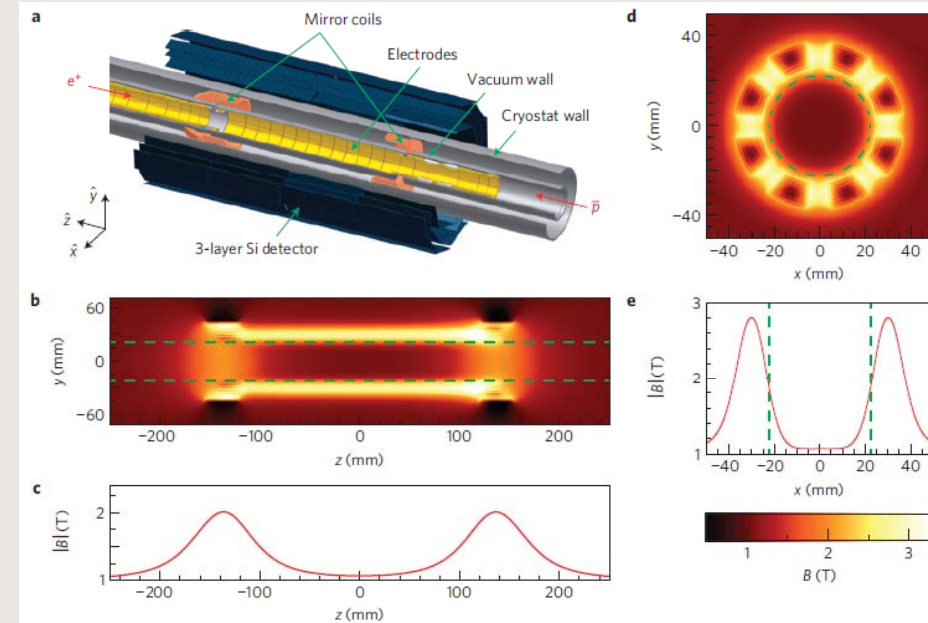
- Hierarchy of time scales:

$$\tau(\text{mix}) \gg \tau(\text{shutdown}) > \tau(\text{axial}) > \tau(\text{radial})$$

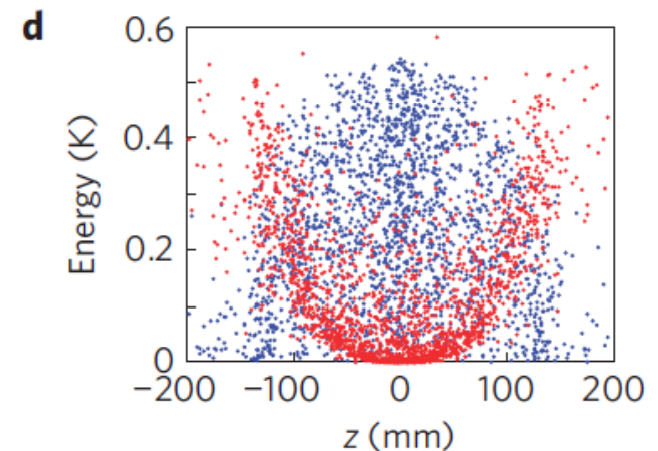
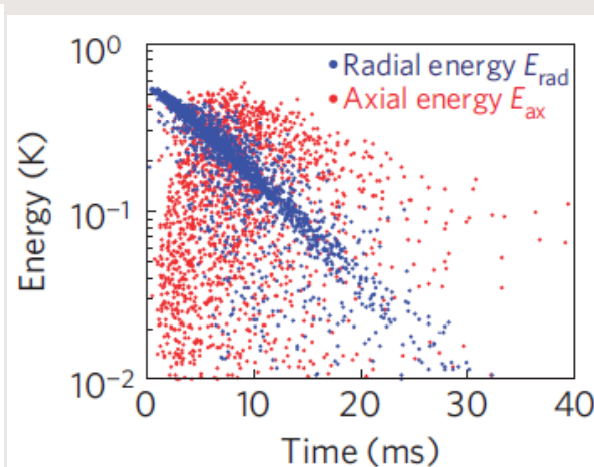
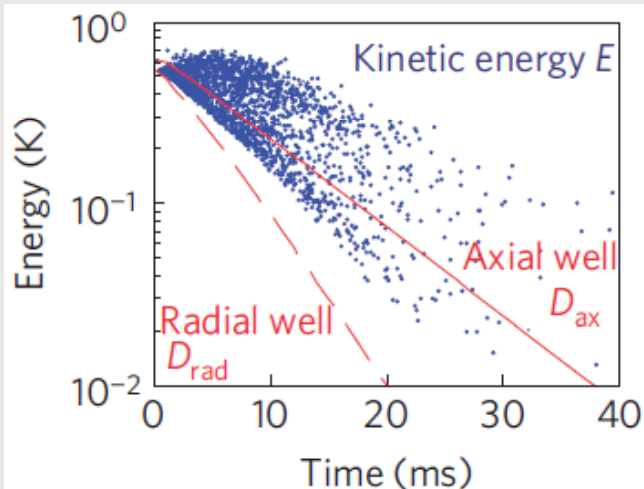
- $\tau(\text{shutdown}) \sim 10$ ms: trap shutdown time
- $\tau(\text{axial}) \sim 1$ ms: axial oscillation
- $\tau(\text{radial}) \sim 0.1$ ms: radial oscillation
- $\tau(\text{mix}) > \sim 1$ s: mixing of radial & axial deg of freedom



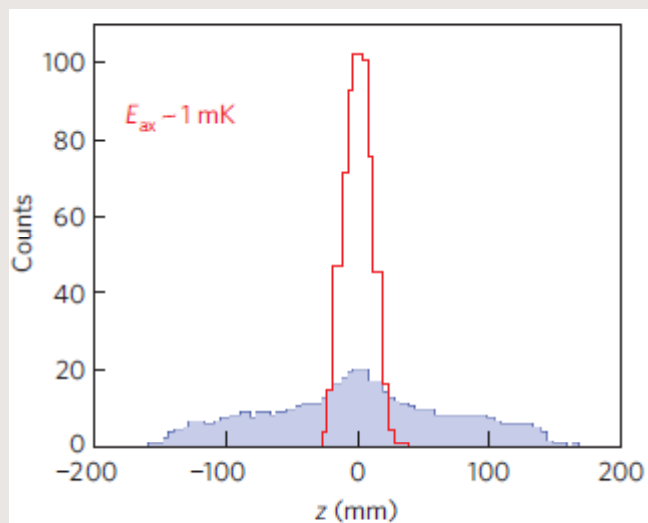
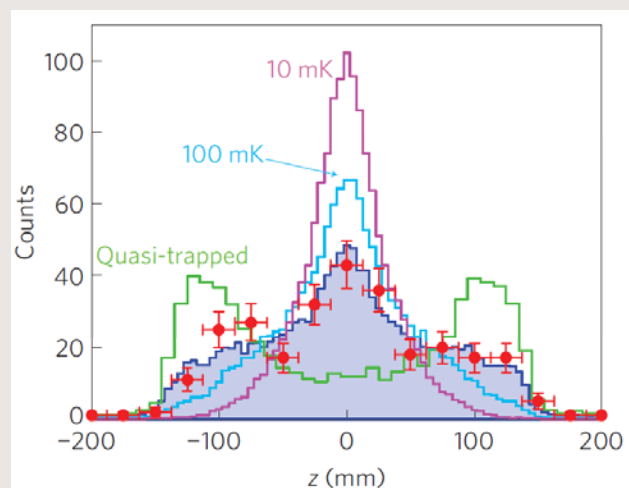
Trapped antihydrogen dynamics in magnetic trap



- Radial & axial deg. freedom largely decoupled
- Radial well decays faster than axial in trap shutdown
→ Hbar escapes radially
- t correlated with radial energy; z with axial energies:
Orthogonal sensitivity



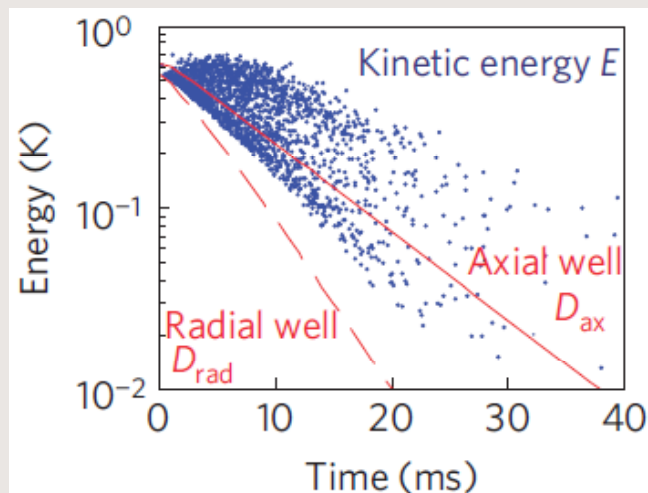
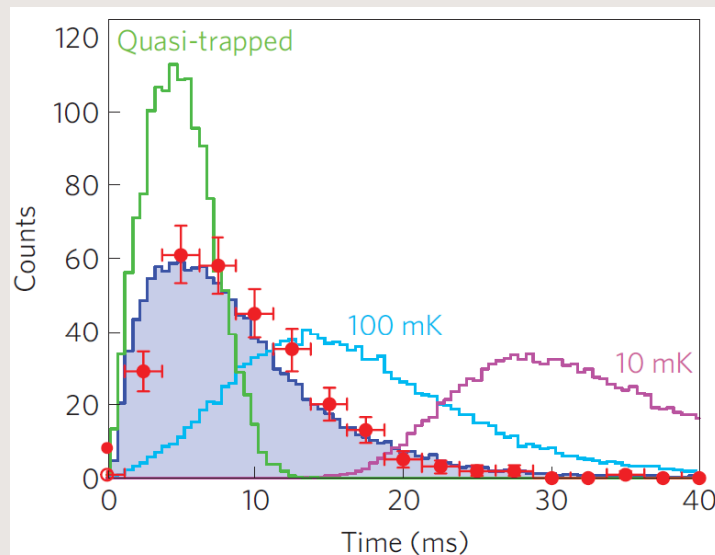
Annihilation position distribution



- Sensitivity of position to energy comes from that of axial energy
- t, z : Sensitivity to direction dependent (anisotropic) energy distribution
- $E_{rad} \sim 0.5$ K, $E_{ax} \sim 1$ mK (could be possible by 1-d adiabatic or laser cooling)
- Position sensitive detection, feature of anti-atoms, giving unexpected information!
- Note: low temperature in 1D is sufficient in some cases

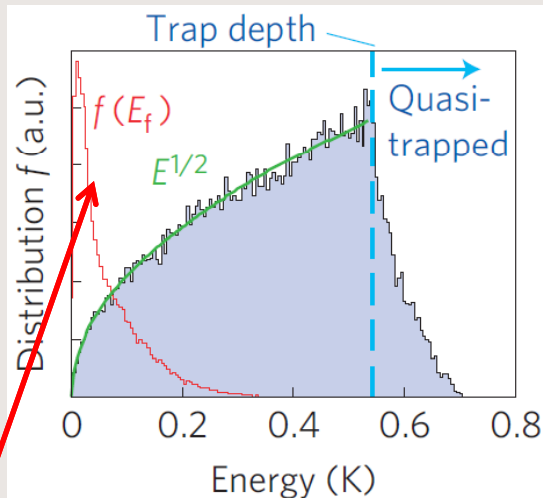
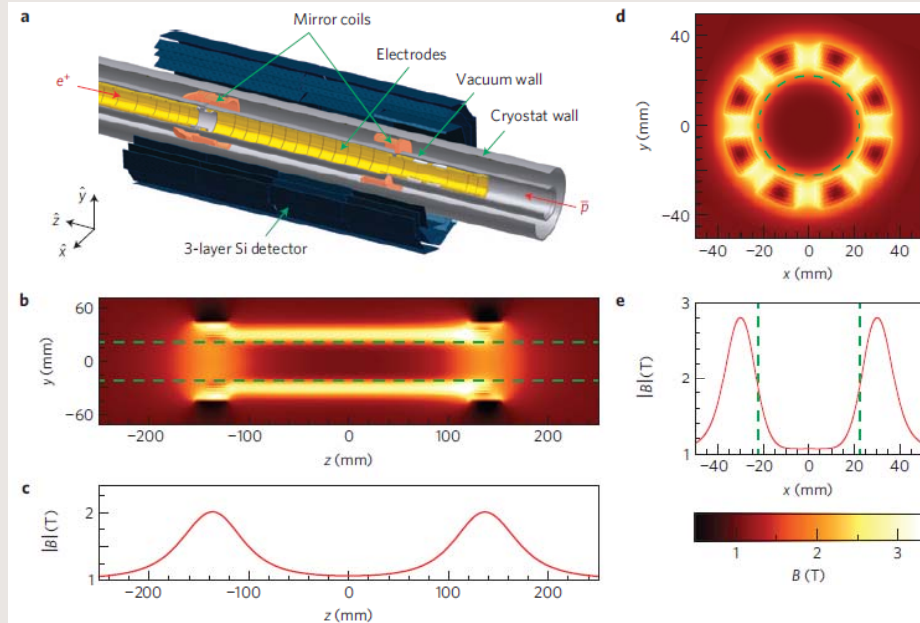
Indirect Evidence for Hbar adiabatic cooling

Nature Phys. 2011



- Filled histogram
 - Assumed initial energy distribution, AND
 - Simulated release process incl. adiabatic cooling
 - consistent with data
- Want to experimentally study more systematically (but so far no time)

Ultra-cold beam: Nature Phys. 2011



Release energies

- Hbar released with very low energies: at ~ 10 s mK
 - Hbar claiming the potential hill
 - Adiabatic cooling
 - Note: this wasn't optimized for a beam
- Hope to study in ALPHA2
 - Several mirror coils
- Anti-atomic fountain?

- ALPHA recent results: implications for gravity
- Trapped antihydrogen: significant potential for gravity test
- ALPHA currently occupied with CPT tests: microwaves@ALPHA1 and lasers@ALPHA2
- CPT measurements likely require all the beam time one can get
- Need a separate experiment for gravity?
 - Requirements may be compatible for precision microwaves and gravity: good B field, long trap
 - Separate traps for precision laser, gravity/microwaves?
- ELEAN will be great help!

Thank you!

Merci!

Acknowledgements: Local Organizing Committee,
Tereza Ressler