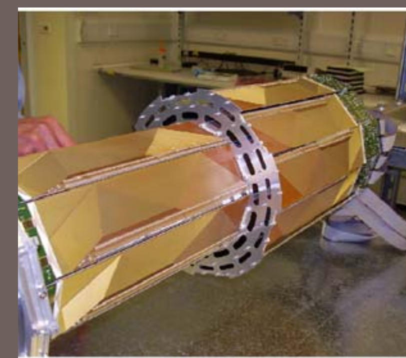
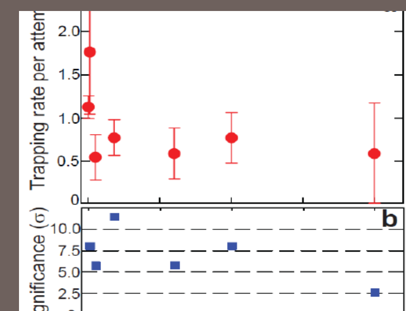
Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

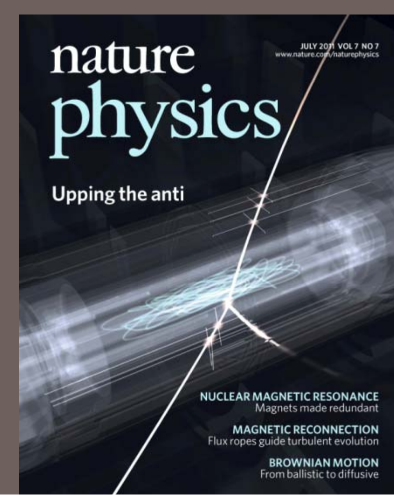
Trapped Antihydrogen, CPT and Gravity

Gbar 2011, Paris, Oct 10-11, 2011

Makoto C. Fujiwara
TRIUMF/Univ. of Calgary

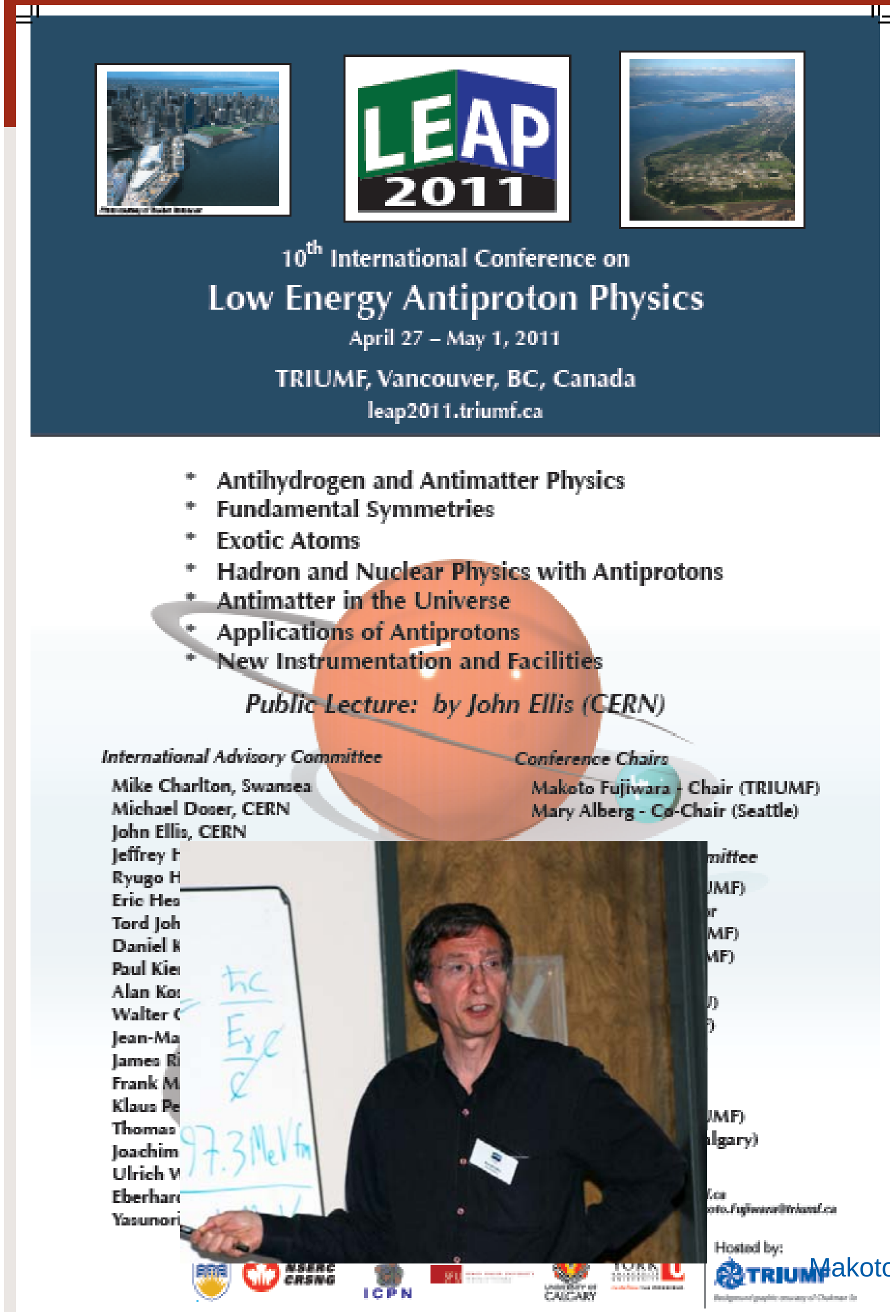




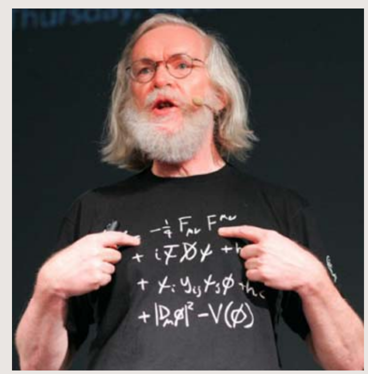


LEAP 2011 at TRIUMF, Vancouver

April 27 – May 1, 2011



- 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



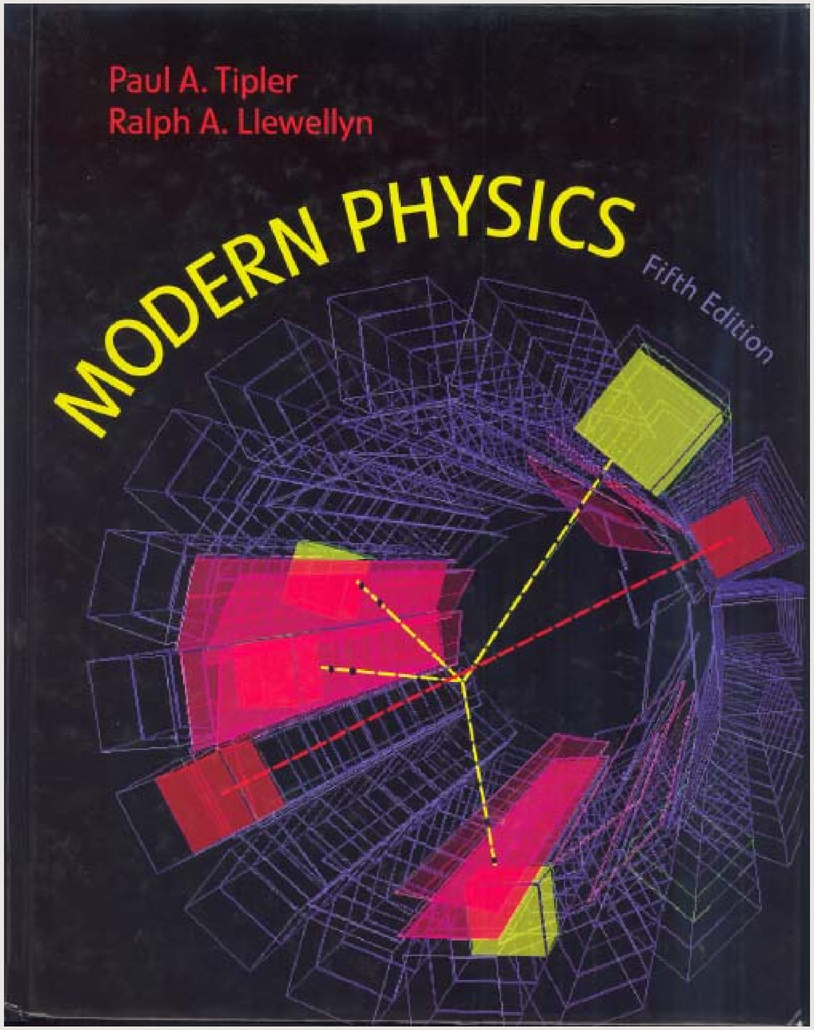
Introduction

- 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

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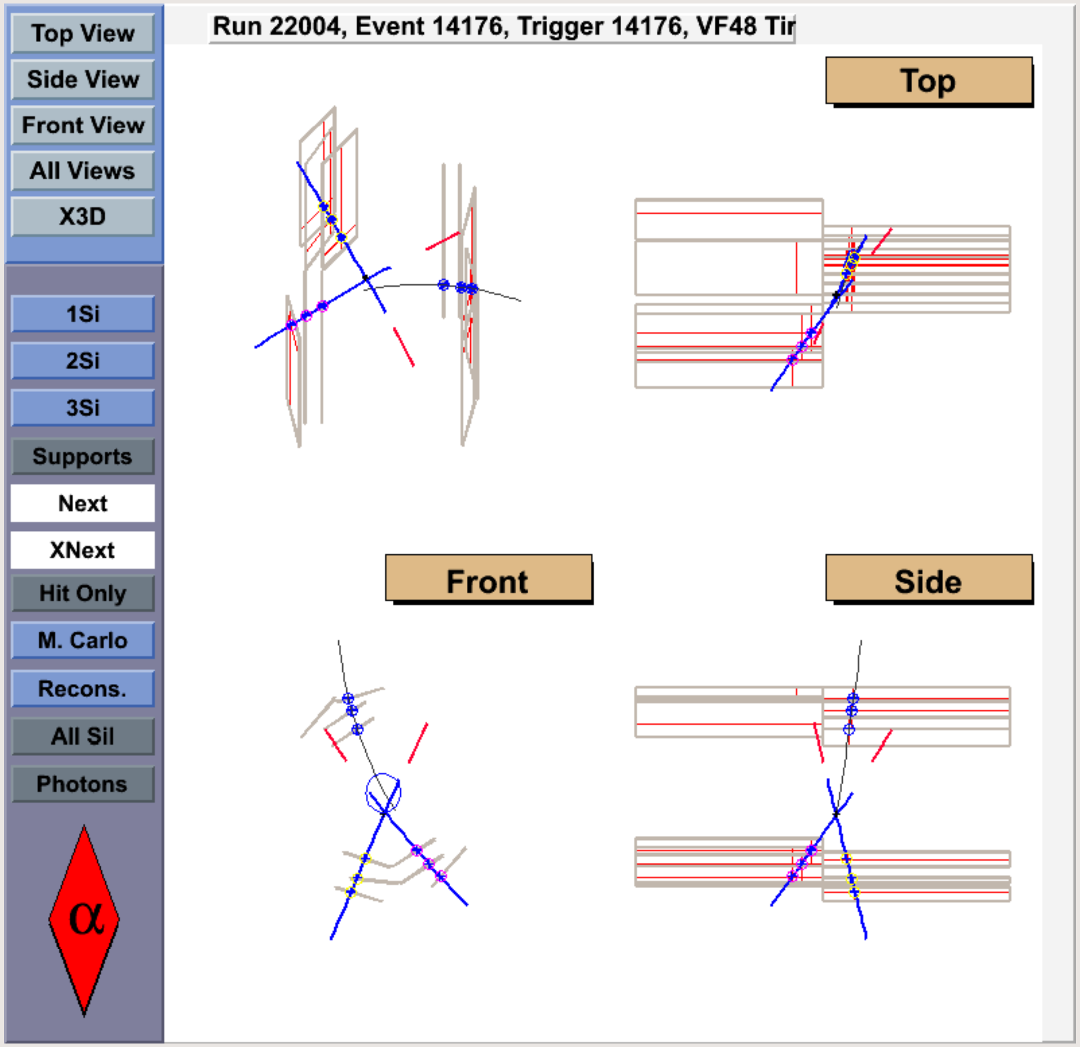
Antimatter Gravity

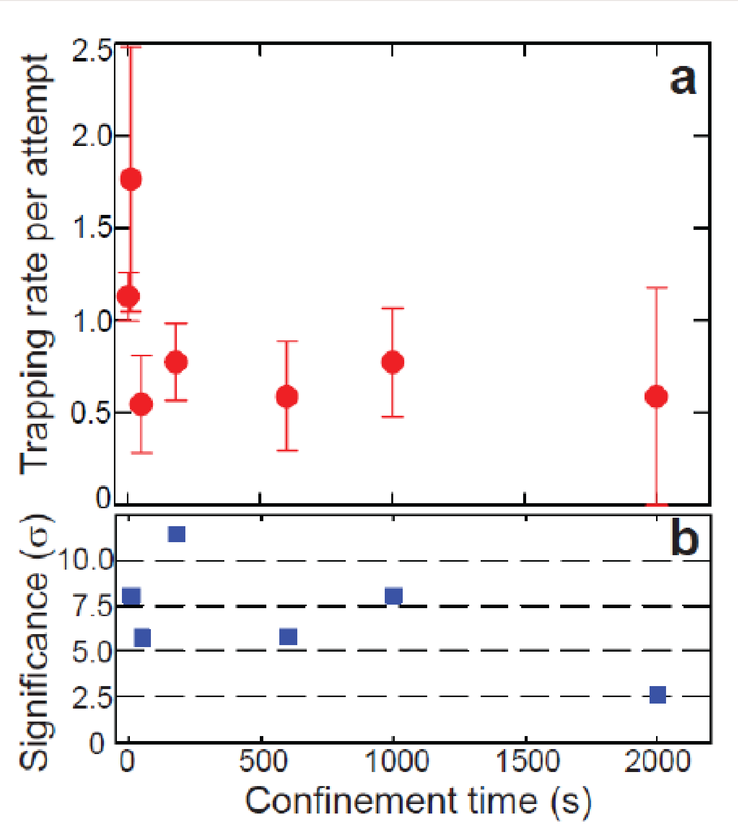
- Gravitational interaction of antimatter: "Textbook" experiment
- Ambitious efforts:
  - AEGIS, GBAR, AGE
- I have been scared of even thinking about gravity, because of its technical difficulties, until…

Annihilation event after 1000 s confinement Nov. 2010



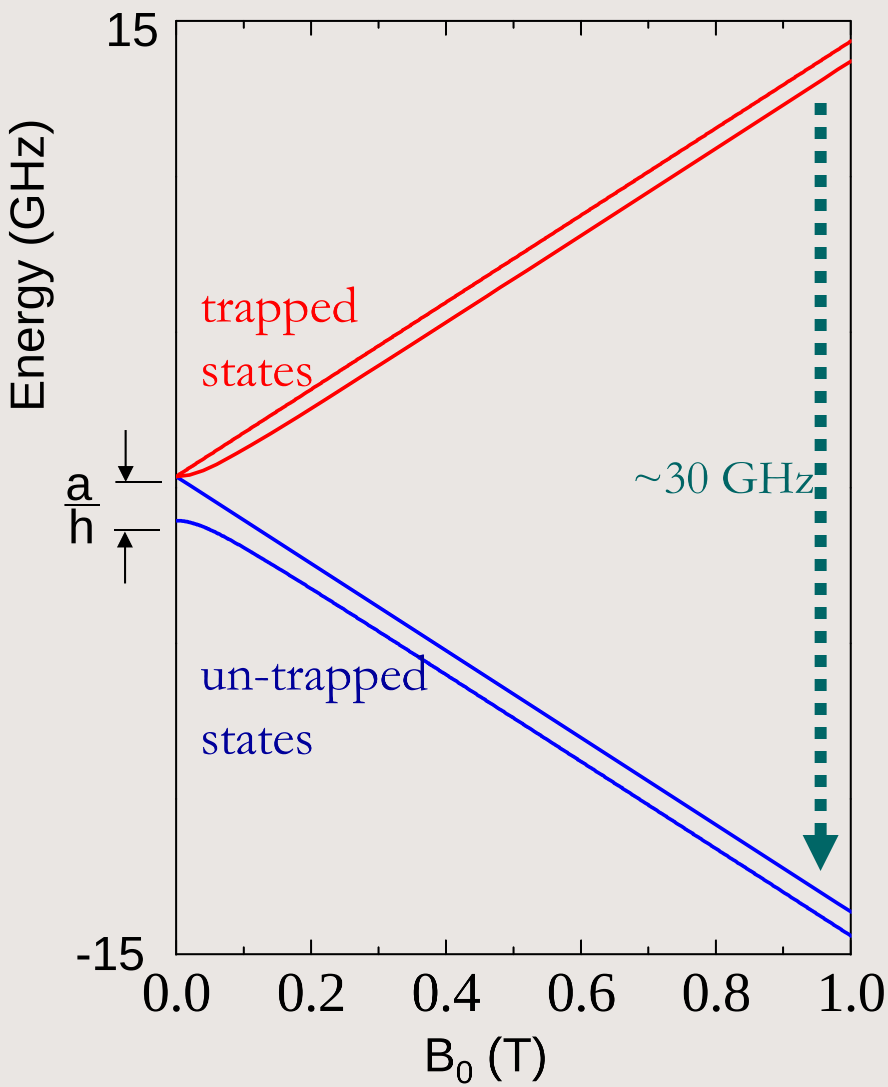
Confinement of antihydrogen for 1000 s

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: μWave Spectroscopy with trapped antihydrogen



(Anti)hydrogen energy diagram

Positron Spin Resonance

- Pulsed μW at ~30 GHz trapped → un-trapped
- Look for annihilations
- Can start with a few atoms

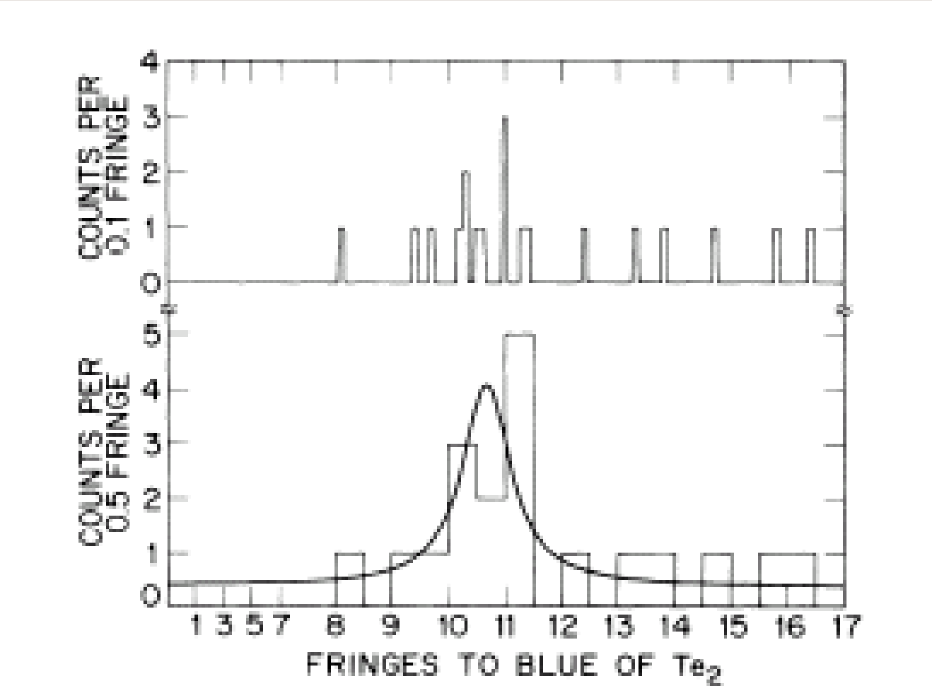
- **Figure of merit:**

  (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)

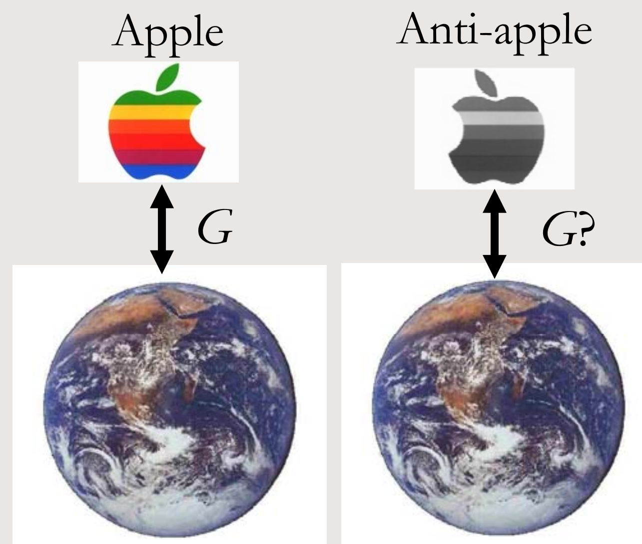
~8 events!

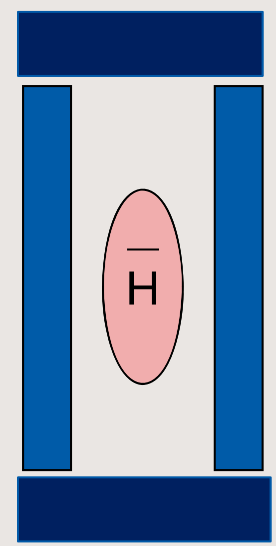
Antimatter Gravity with Trapped Hbars

- Gravity
  - Never measured with antimatter
  - Test of General Relativity
- Does antimatter fall down?
  - Experimental question!
  - If Hbar is cooled to mK

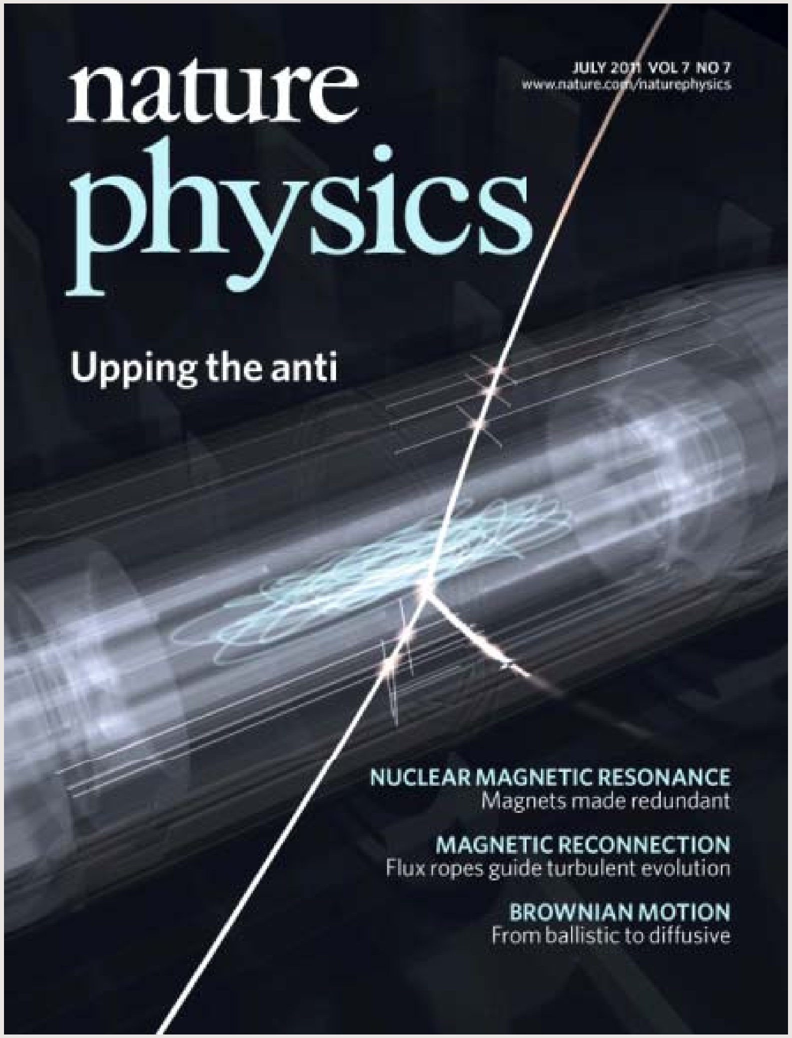
    $1/2kT=mgh$

    Vertical trap : $h \sim 1\ m$
  - 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

Laser Cooling

- 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 Laboratorium, Universiteit van Amsterdam,
Valckenierstraat 65/67, 1018 XE Amsterdam, The Netherlands
(Received 28 December 1992)

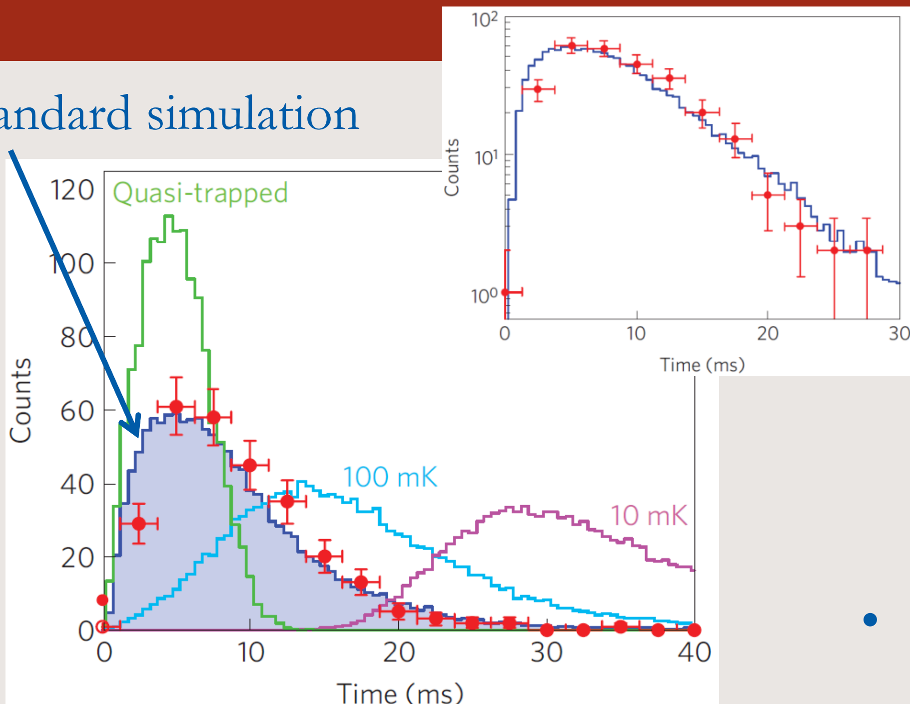
We present the first experimental demonstration of optical cooling of atomic hydrogen. Two methods are discussed: Doppler cooling, for which we report a minimum achieved temperature of 8 mK, and light-induced evaporation, a new cooling method by which we reached 3 mK.

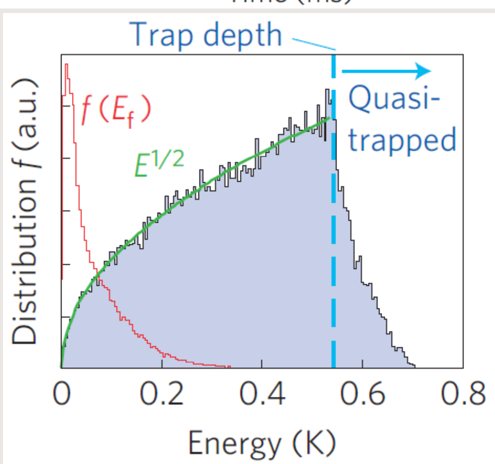
  - Heroic efforts by Walz, Ekima et al. for cw Lyman alpha
  - Preparing Lyman-alpha laser in Vancouver: pulsed source first
  - As long as not saturated, only ave. power matters for cooling rate: i.e. low duty factor not a problem: μW seems feasible
  - Zeeman shift of 1s-2p an issue

Kinetic energy of trapped Hbars:

Nature Phys. 2011

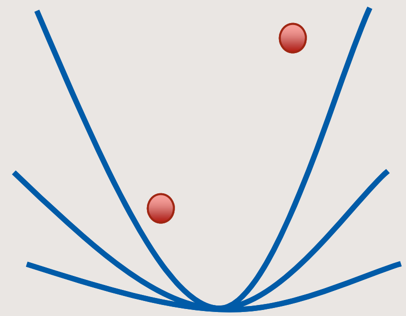
Standard simulation





Simulated kinetic energy distribution

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+ (>>0.5 K): $E^{1/2}$ scaling
- Temperature diagnosis for future cooling studies

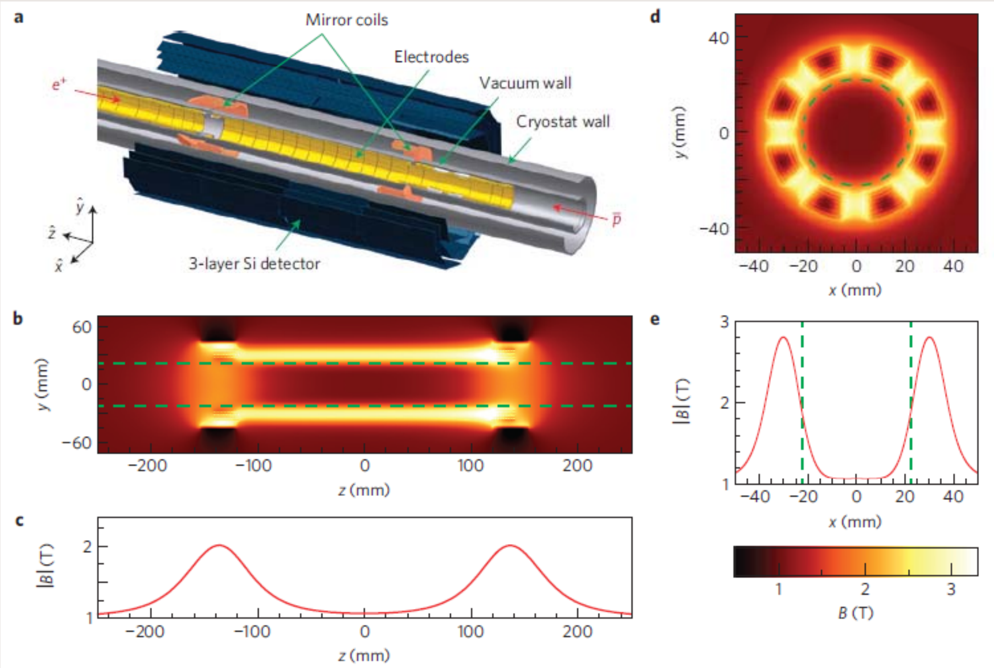
Trapped Antihydrogen Dynamics

Nature Phys. 2011

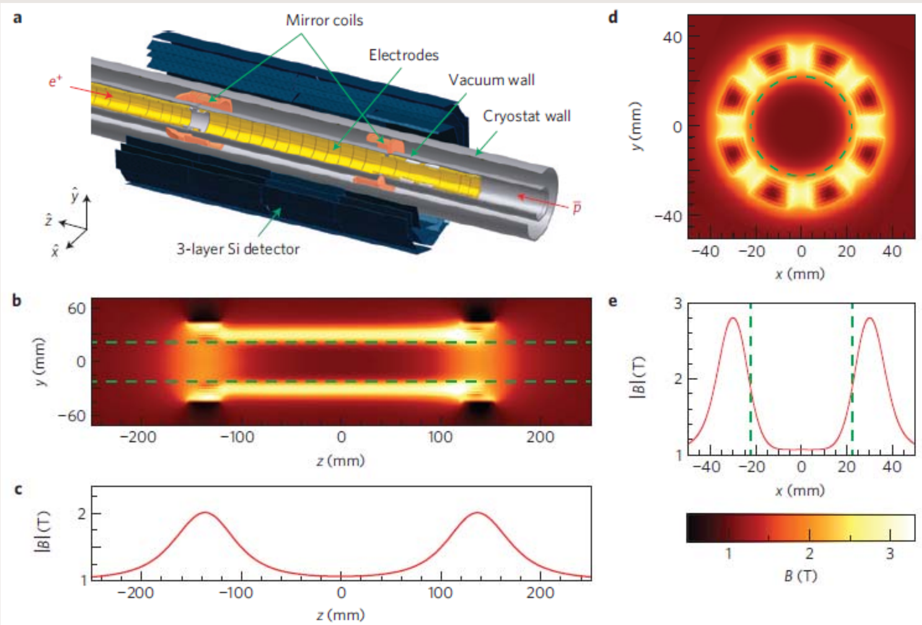
- Hierarchy of time scales:

  τ(mix) >> τ(shutdown) > τ(axial) > τ(radial)

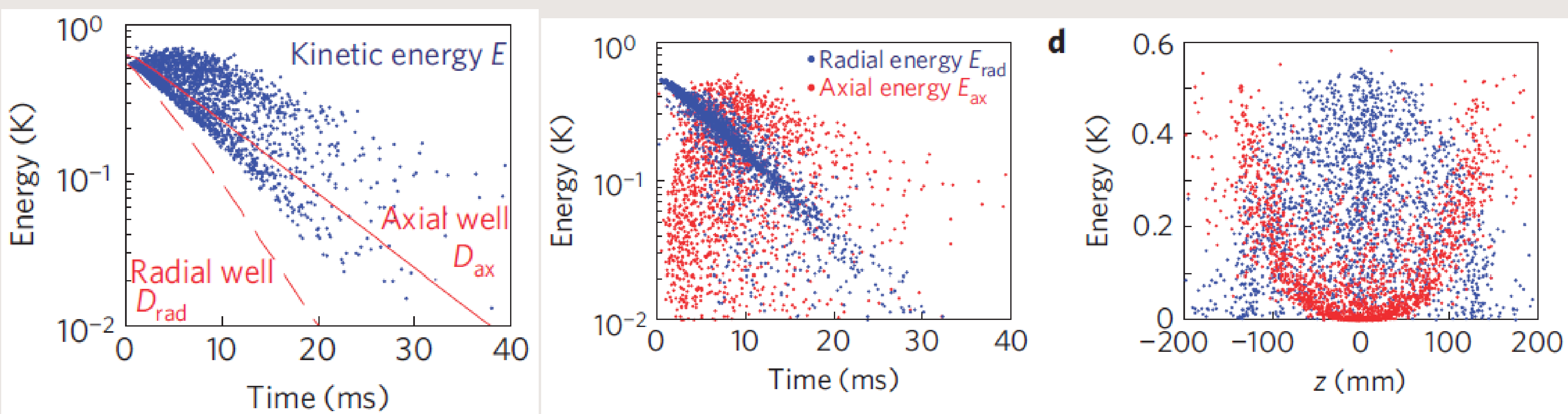
  - τ(shutdown) ~10 ms: trap shutdown time
  - τ(axial) ~ 1 ms: axial oscillation
  - τ(radial) ~ 0.1 ms: radial oscillation
  - τ(mix) > ~1 s: mixing of radial & axial deg of freedom



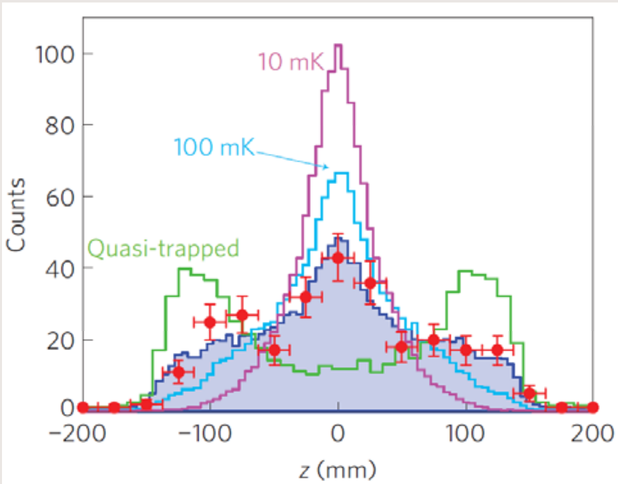
Trapped antihydrogen dynamics in magnetic trap

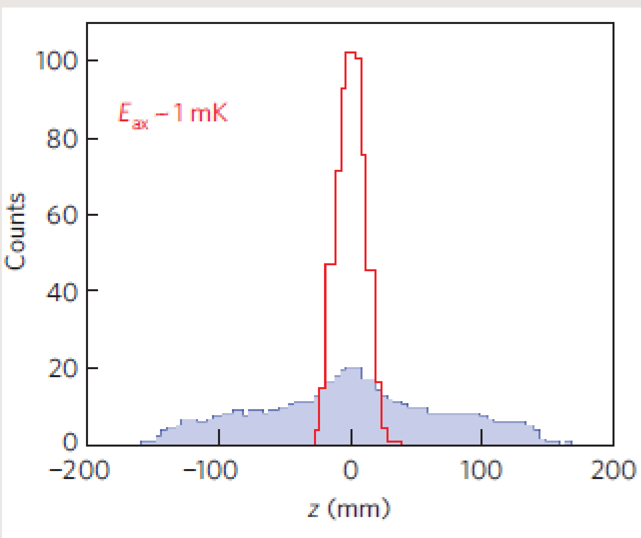


- Radial & axial deg. freedom largely decoupled
- Radial well decays faster than axial in trap shutdown
  → Hbar escapes radially
- *t* correlated with radial energy; *z* with axial energies: Orthogonal sensitivity



Annihilation position distribution

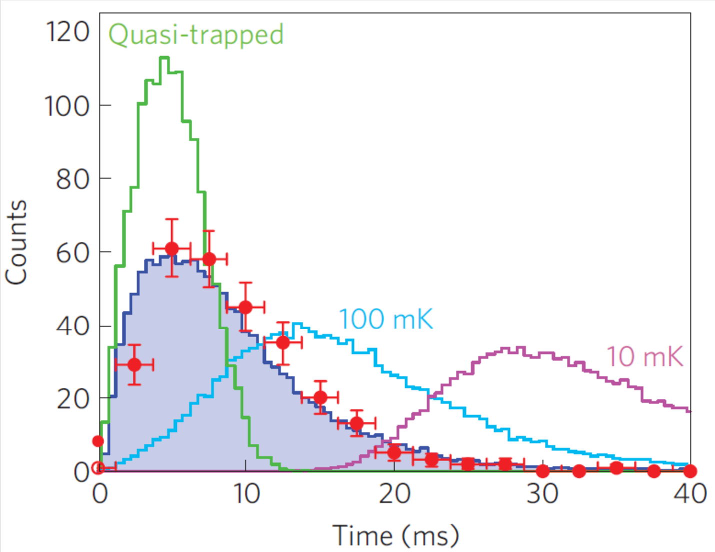


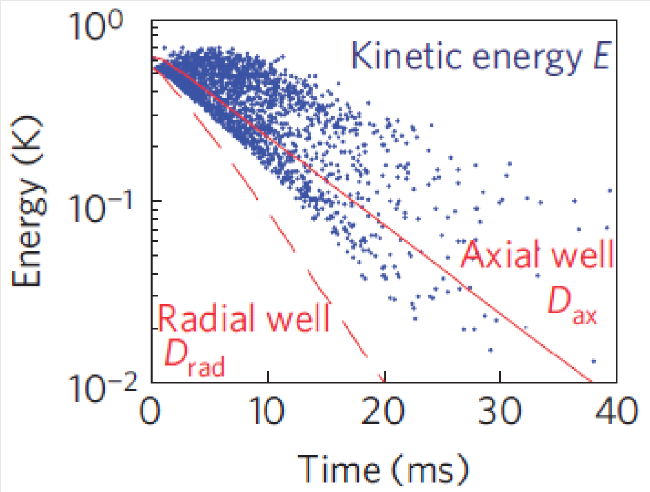


- Sensitivity of position to energy comes from that of axial energy
- t, z: Sensitivity to direction dependent (anisotropic) energy distribution
- Erad ~ 0.5 K, Eax ~ 1 mK (could be possible by 1-d adiabatic or laser cooling)
- Position sensitive detection, feature of anti-atoms, giving unexpected information!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

Indirect Evidence for Hbar adiabatic cooling

Nature Phys. 2011

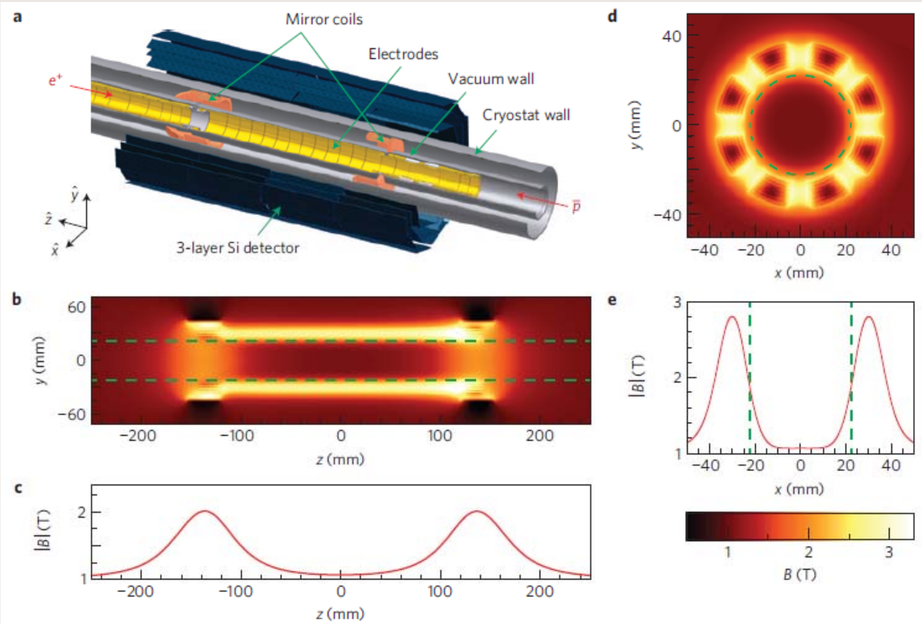


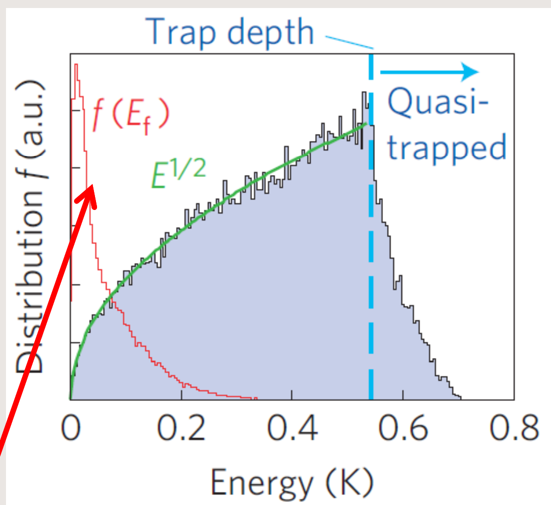


- Filled histogram
  - Assumed initial energy distribution, AND
  - Simulated release process incl. adiabatic cooling

    → 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 ~10s 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?

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Summary

- 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 Resslova