Towards comprehensive control of atomic motion: application to anti-hydrogen

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Ultra-Cold Atoms and Molecules

Laser cooling and trapping

Nobel Prize 1997

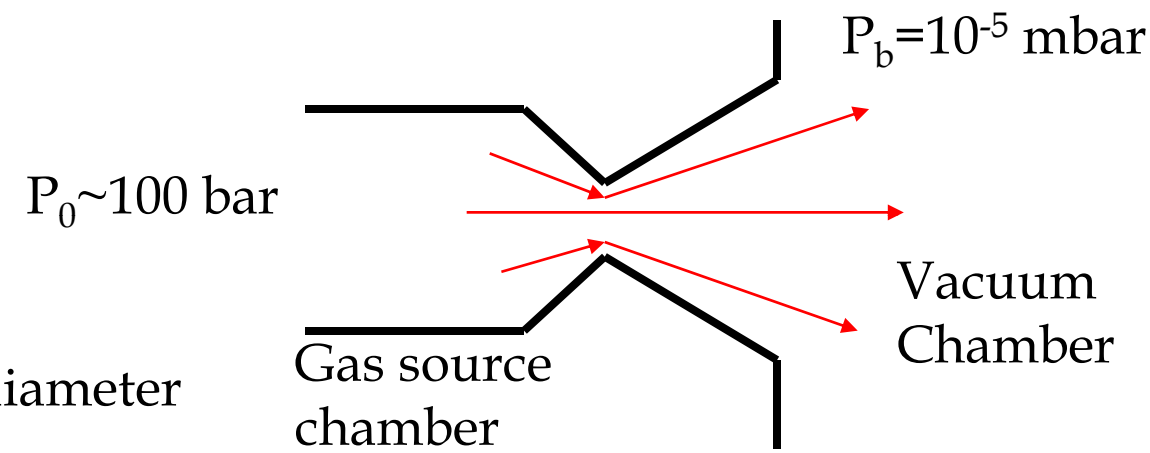
Stringent Requirements:

2-level cycling transition

Transition accessible with lasers

What about hydrogen?

Supersonic Beams



Mean free path < nozzle diameter

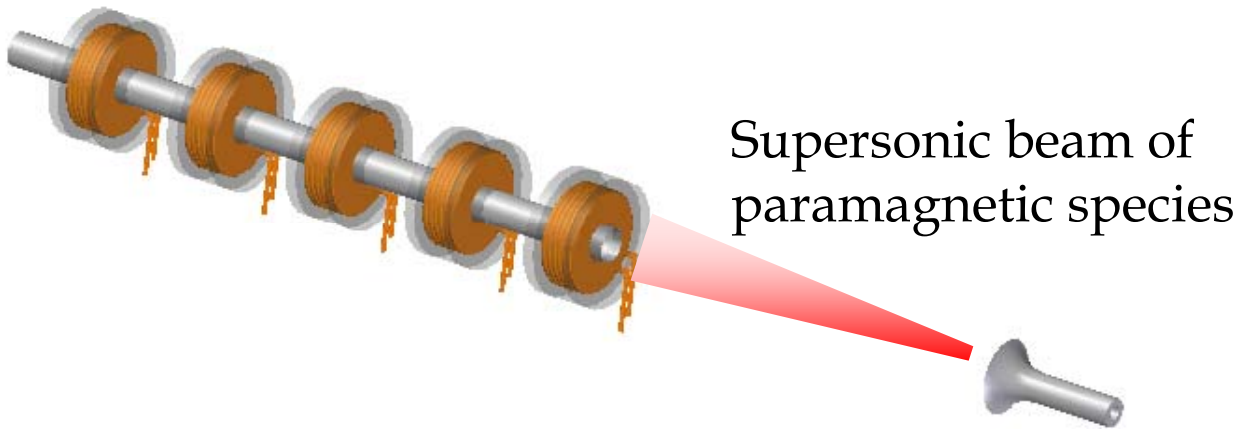
Speed ratio (average/standard deviation) can be 100 or higher.

Very fast beam of cold atoms (under 50 mK in the co-moving frame)

Universal platform: seed or entrain other species in flow

Atomic Coilgun

- Directly slow a beam of paramagnetic atoms



Analogy to Stark Decelerator: F. Merkt, ETH

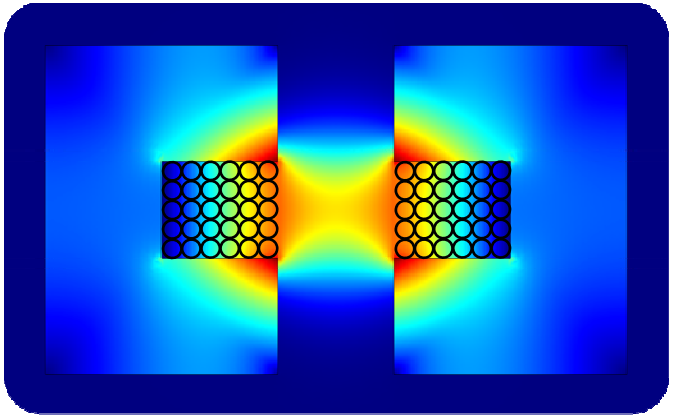
Most atoms in periodic table elements are paramagnetic

Experimental Challenge

- required field strength:

  B > 2 Tesla

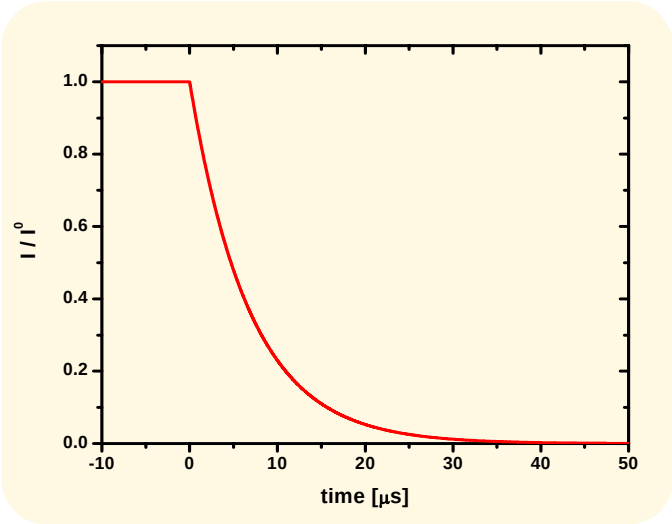
  Now 5.2 Tesla



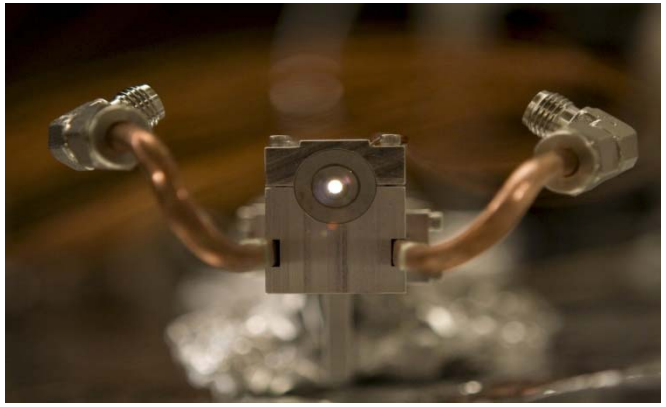
required switching time:

$\tau \leq 10\ \mu s$

Now 6 μs



Stopping Supersonic Beams with an Atomic Coilgun

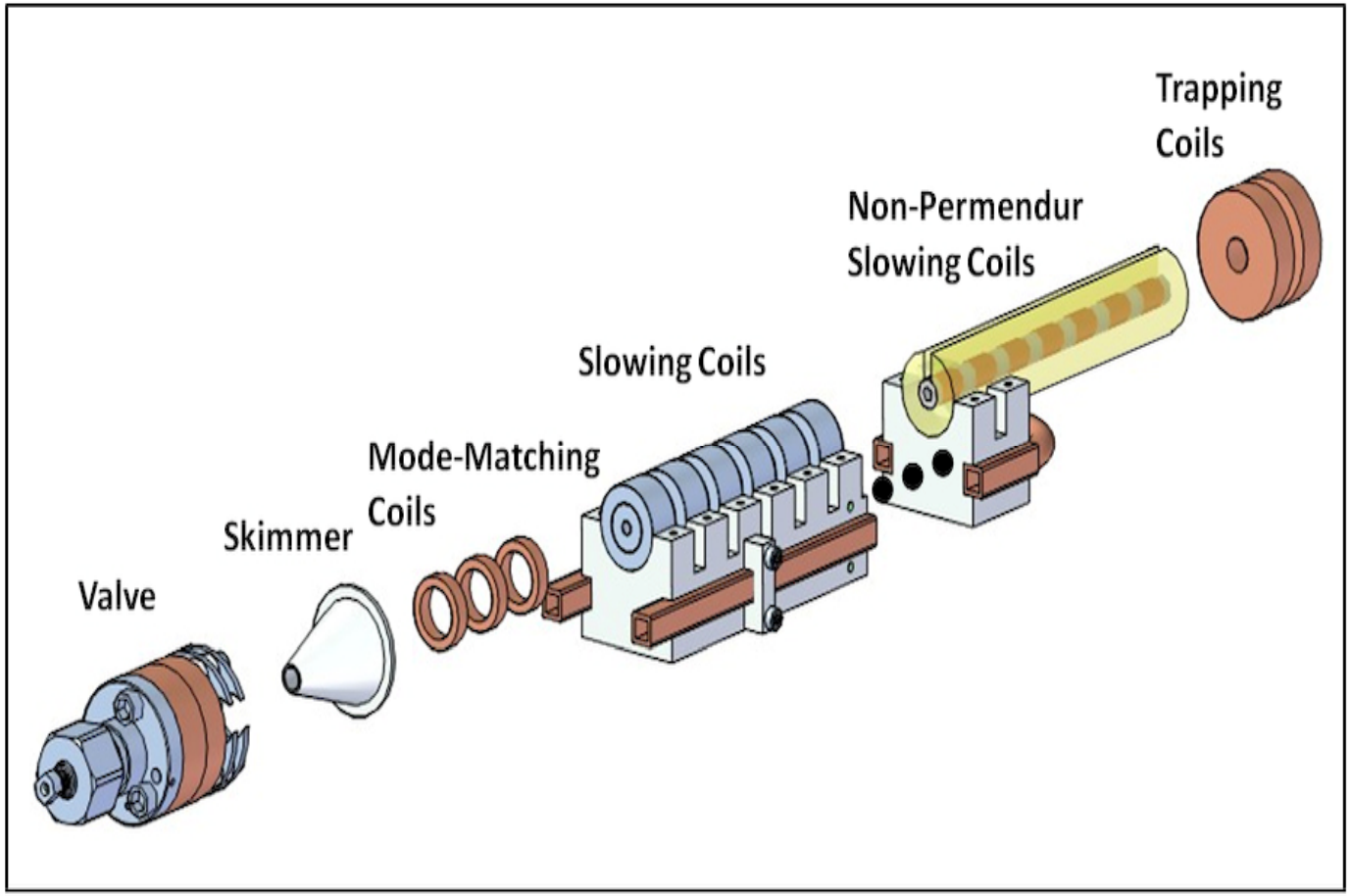


E. Narevicius, A. Libson, C. Parthey, I. Chavez, J. Narevicius, U. Even, and M. G. Raizen,
Phys. Rev. Lett. 100, 093003 (2008)

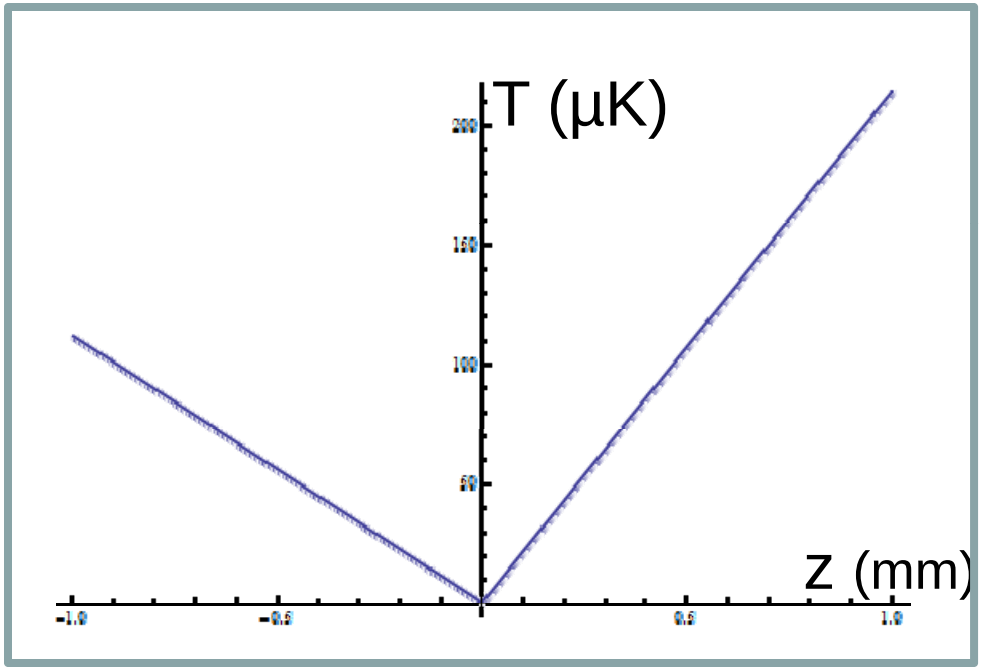
Molecular Coilgun: stopped O_2

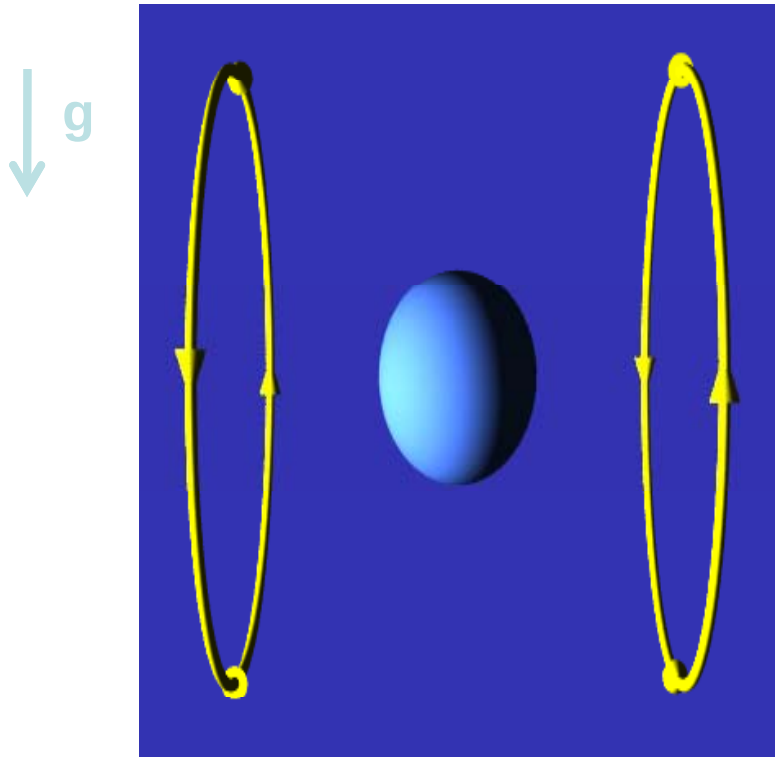
Parallel work Merkt group, ETH: stopped hydrogen

Toward magnetic trapping

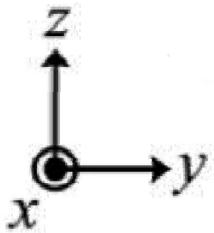


Quadrupole Potential



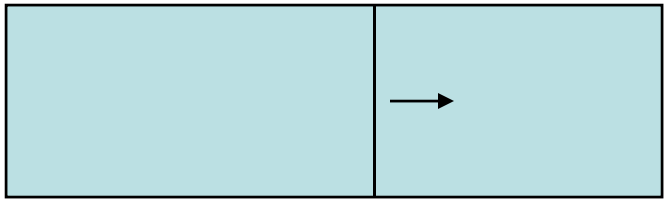


$$E = \mu_B |B| + mgz$$



Cooling

Goal is to reduce entropy S of gas (phase space compression)



Adiabatic wall (S=0)

permeable wall (S>0)

One way wall?

One-way wall for atoms

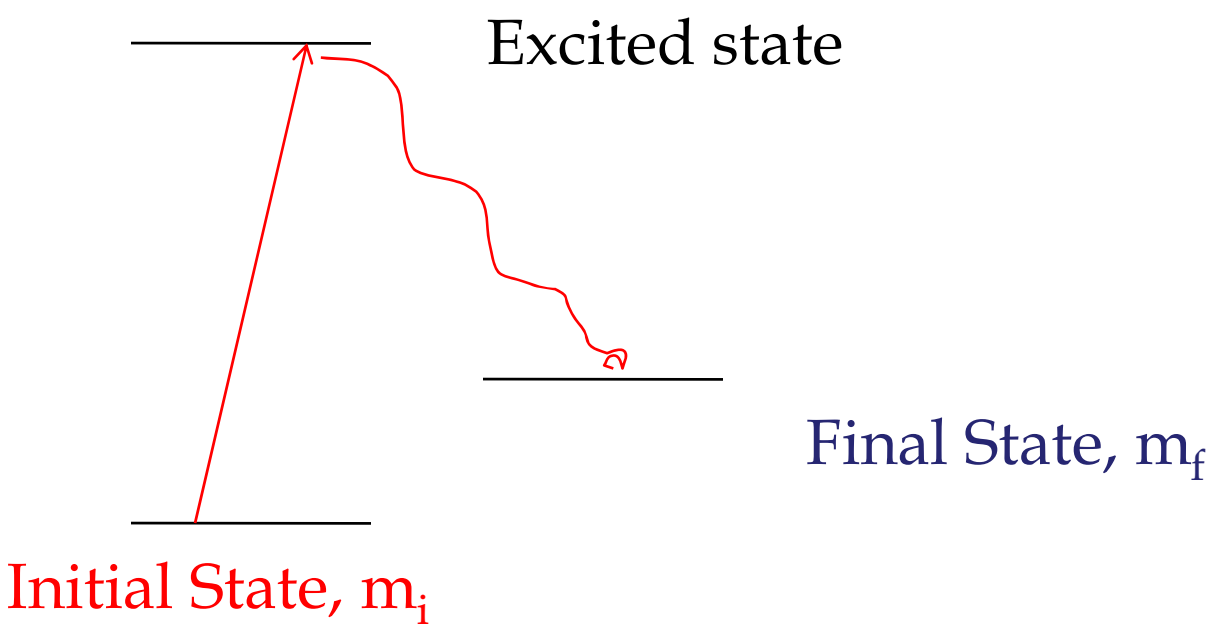
M.G. Raizen, A.M. Dudarev, N.J. Fisch, Q. Niu,
Phys. Rev. Lett. **94**, 053003 (2005).

A.M. Dudarev, M.P. Marder, Q. Niu, N.J. Fisch, M. G. Raizen,
Europhys. Lett. **70**, 761 (2005).

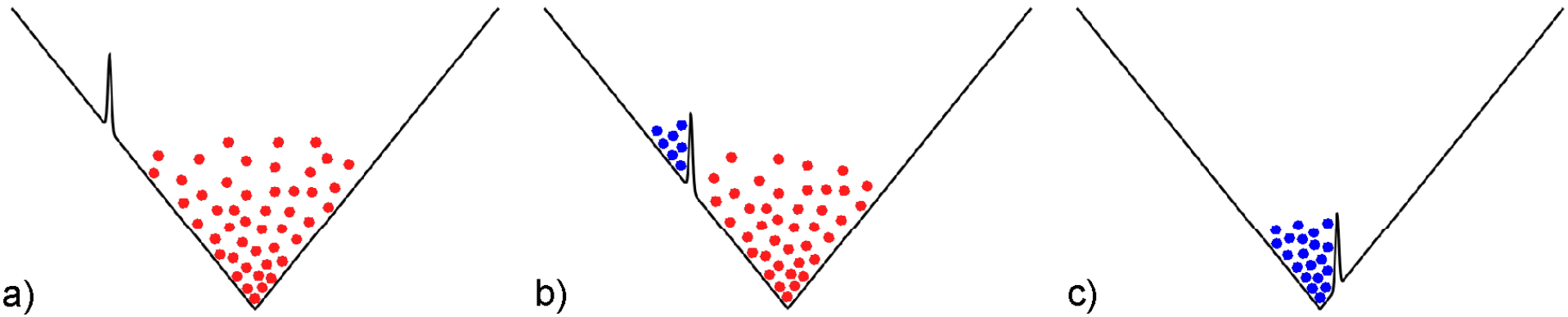
Combination of conservative trap + irreversible step
First Generation: All-Optical (demonstrate one-way wall)
Second Generation: Hybrid Magnetic/Optical (cooling)
Third Generation: All-Magnetic (improved cooling in progress)

Irreversible step

Requirement: $\mathbf{m_f < m_i}$



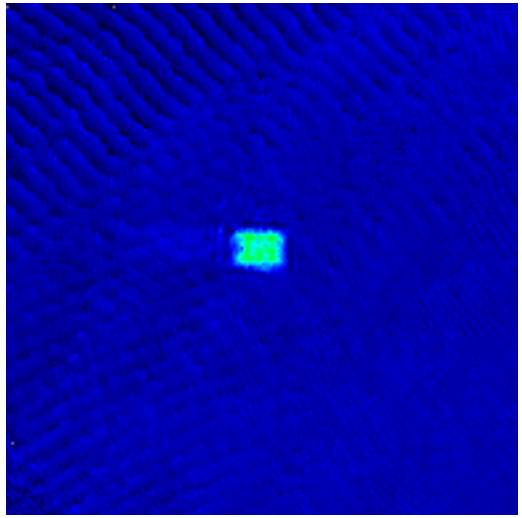
Single-Photon Cooling



Maxwell's Demon (1871)

Leo Szilard, Information entropy (1929)

Single-Photon Atomic Cooling



23x increase in phase space density from magnetic trap!

G. Price et al., Phys. Rev. Lett. 100, 093003 (2008)

Now 350x increase, submitted

Comprehensive Control of Atomic and Molecular Motion

Two-step solution

1. **Atomic and Molecular Coilgun**

2. **Single-Photon Cooling**
(Cooling of molecules: ArXiv:0808.1383)

Experiments with Hydrogen isotopes I

Trap and cool H, D, T, in room temp. apparatus
precision spectroscopy of 1S-2S transition

BEC of H and T

Raman Interferometry of H, T to test
weak equivalence principle

Experiments with Hydrogen isotopes II

Precision test of beta decay of ultracold tritium (neutrino mass)
arXiv:0901.3111

Trapping and cooling of anti-hydrogen (g-bar, test of CPT)
New collaboration at Fermilab: AGE

Application to Anti-Hydrogen

(Anti-)Atomic coilgun, single-photon cooling of H-bar

Optimization of H-bar beam

Precision measurement of g-bar/g

Precision measurement of 1S-2S of H-bar relative to H

Optimization of H-bar beam

Penning trap design

p-bar and positron cooling

Transverse cooling of H-bar as Rydberg state decays

Optimize capture

Can all be tested with matter!

Precision measurement of g-bar/g

Excite H-bar to 2S state (lifetime 120 ms)

Raman interferometry between hyperfine states of 2S (177 MHz)

Raman laser beams at 657 nm (near 2S-3P transition)

Phase shift proportional to T^2

But…. S/N proportional to sqrt(N)

1000 atoms, T=30 ms: g-bar/g=2×10^{-7} per shot
Averaging over one year @ 40 shots per day
Reach 5×10^{-9}

Precision Spectroscopy

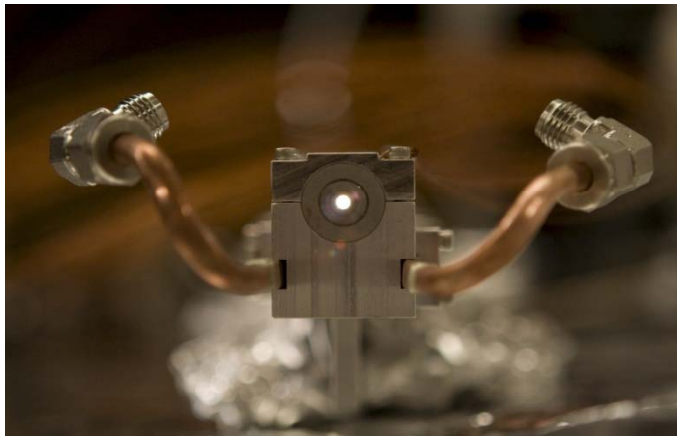
Collaborating with Jim Bergquist (NIST) and JunYe (JILA)

Compare H to H-bar **(not absolute measurement!)**

1000 atoms held in magic wavelength optical tweezer
resolve 10^{-15} per shot

In one year resolve 10^{-17}

Raizen Group



Travis Bannerman, Isaac Chavez, Melissa Jerkins, Hrishi Kelkar, Tongcang Li, Adam Libson, Julia Majors, Thomas Mazur, David Medellin, Dr. Ed Narevicius (Weizmann Institute) , Gabriel Price, Charlotte Sanders, Christoph Schaeff, Kirsten Viering