Precision Measurement of Gravity at Micrometer Scale using Ultracold Atoms

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Outline

- *Motivation*
- *Previous experiments*
- *Measuring gravity with atoms*
- *Precision gravity measurement at μm scale with laser-cooled Sr atoms in an optical lattice*
- *Prospects*

Motivation

- **Physics beyond the standard model**

Extra space-time dimensions

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429, 263 (1998)
N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Rev. D 59, 086004 (1999)

Deviations from $1/r^2$ law
Hierarchy problem: why is gravity so weak?

New boson-exchange forces

Radion – low-mass spin-0 fields with gravitational-strength couplings
Moduli – massive scalar particles producing gravitylike forces

S. Dimopoulos and G. F. Giudice, Phys. Lett. B 379, 105 (1996)
I. Antoniadis, S. Dimopoulos, and G. Dvali, Nuc. Phys. B 516,70 (1998)

Dilaton – Light scalar in string theory, coupling to nucleons

T.R. Taylor, G. Veneziano, Phys. Lett. B 213, 450 (1988)
D. B. Kaplan, M. B. Wise, J. High Energy Phys. 8, 37 (2000)

Axion – pseudoscalar particles explaining smallness of CP violation in QCD for strong nuclear force

Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

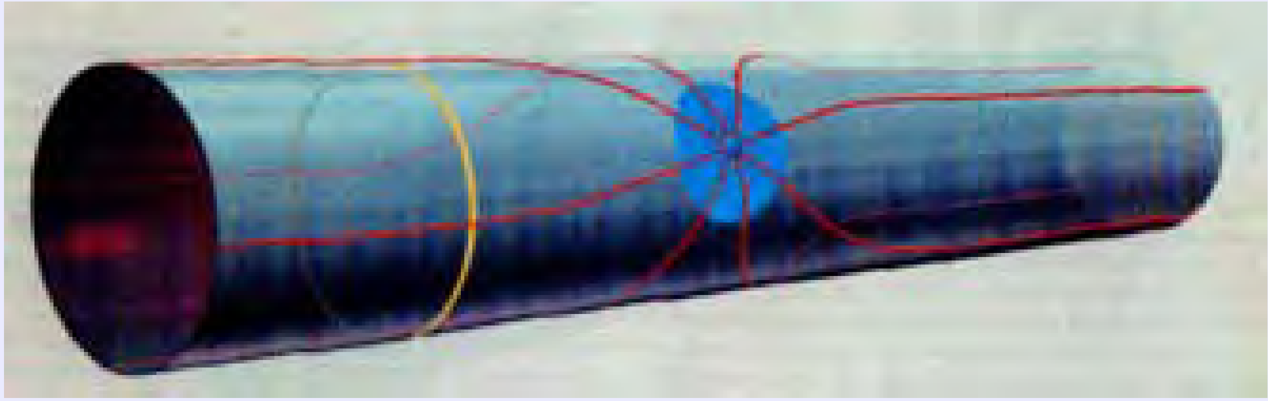
Multi-particle exchange forces

- **Small observed size of Einstein cosmological constant**

S.R. Beane, Gen. Rel. Grav. 29, 945 (1997)
R. Sundrum, Phys. Rev. D 69, 044014 (2004)

- **Experimental challenge**

Extra Dimensions



1 extra dimension	$\Rightarrow$	$F \propto 1/r^3$	size $\approx 10^{11}$ m
2 extra dimensions	$\Rightarrow$	$F \propto 1/r^4$	size $\approx 10^{-4}$ m
3 extra dimensions	$\Rightarrow$	$F \propto 1/r^5$	size $\approx 10^{-9}$ m
…			

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B 429, 263 (1998)

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *Phenomenology, astrophysics, and cosmology of theories with submillimiter dimensions and TeV scale quantum gravity*, Phys. Rev. D 59, 086004 (1999)

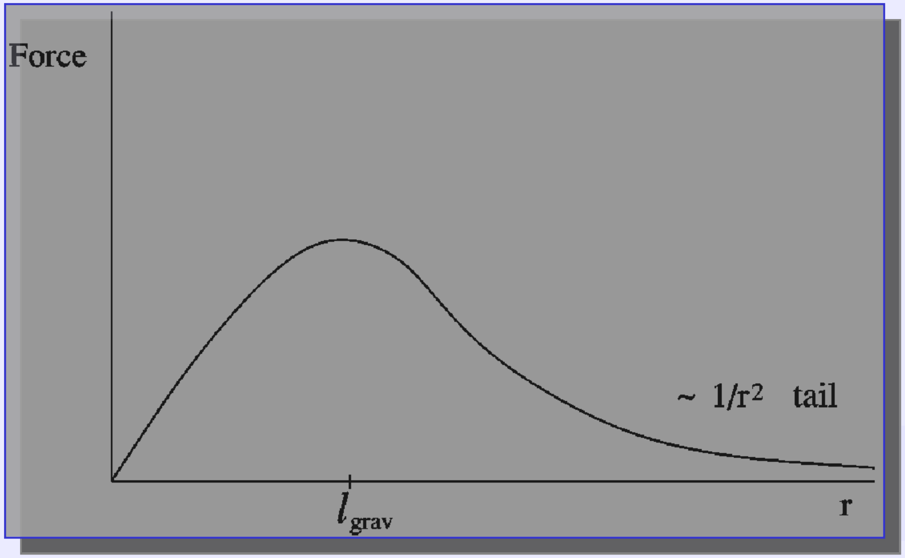
Cosmological constant problem and “fat” gravitons

Cosmological data $\Rightarrow$ vacuum-energy density $\rho_{vac} \sim 3 \cdot 10^3$ eV/cm^3

$$\Downarrow$$

$$l \sim (\hbar c/\rho_{vac})^{1/4} \sim 0.1 \text{ mm}$$

The graviton is “fat” at distances $\leq$ 1 mm ?
Solution to the CC Problem?



R. Sundrum, *Fat gravitons, the cosmological constant and submillimeter tests*, Phys. Rev. D 69, 044014 (2004)

$$20\ \mu\text{m} \leq l_{grav} \leq 0.2 \text{ mm}$$

Parametrizations for deviations from Newtonian gravity

- **Modification of power law in Newton-type force**

$$F(r) = G\frac{M_1 M_2}{r^{2+\delta}}$$

- **Newton+Yukawa potential**

$$V(r) = -G\frac{M_1 M_2}{r}\left[1+\alpha e^{-\frac{r}{\lambda}}\right]$$

→
- Exchange of a boson with m = ħ/λc
- Extra dimensions

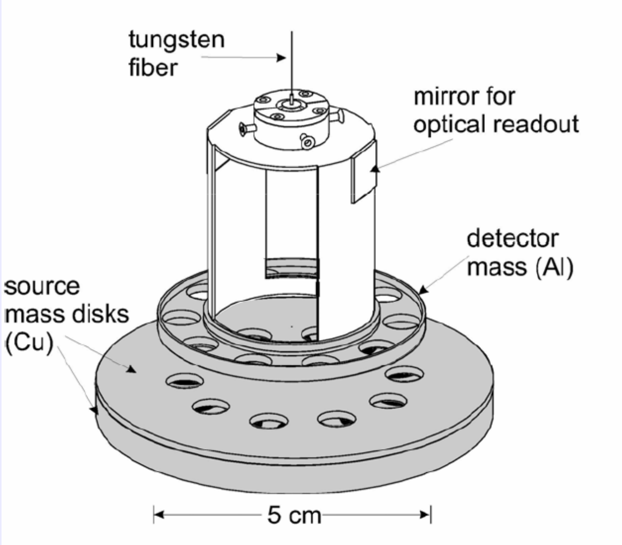
- **Modified power-law potential**

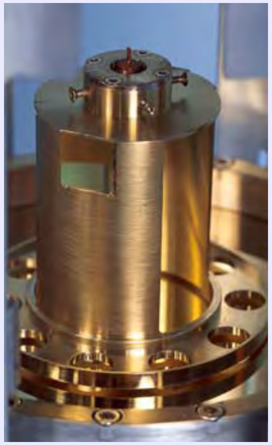
$$V(r) = -G\frac{M_1 M_2}{r}\left[1+\alpha_N\left(\frac{r_0}{r}\right)^{N-1}\right]$$

→ Exchange of 2 massless particles

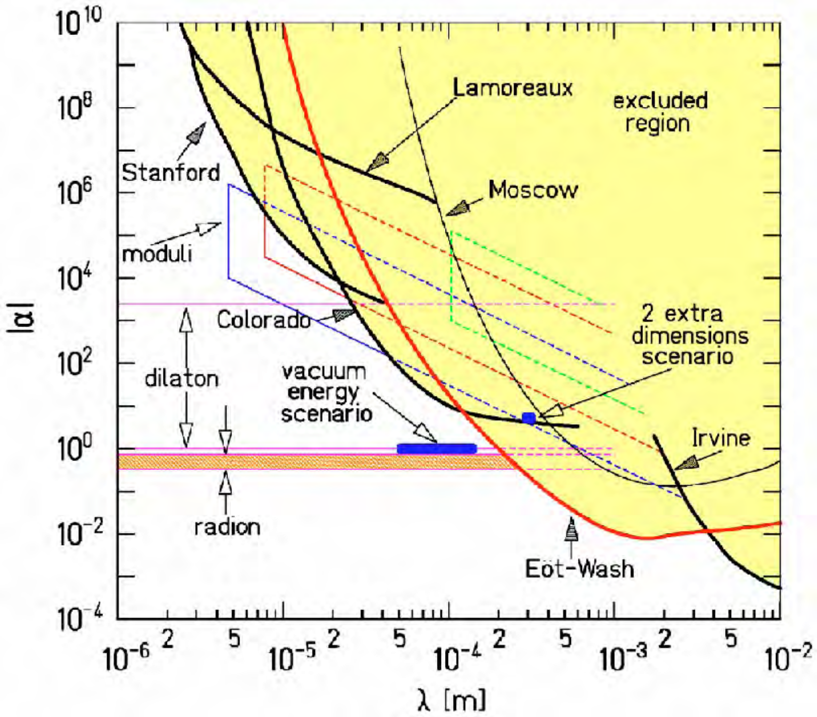
Experiments on gravity at small spatial scale

Torsion balance - Washington experiment





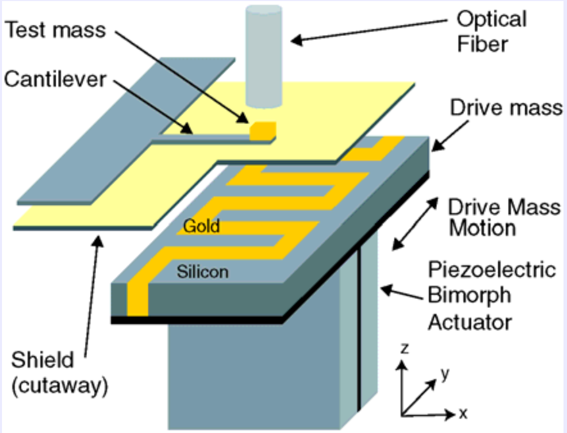
- **Test bodies: ‘‘missing masses’’ of holes bored into plates**
- **Torsion pendulum**
  7075 aluminum, gold coated
  disk height = 2 mm
  10 cylindrical holes evenly spaced about the azimuth
- **Attractor**
  high-purity copper disk
  top surface coated with gold
  10 cylindrical holes evenly spaced about the azimuth
  uniformly rotating
- **Electrostatic shield**
  tightly stretched 20-μm-thick BeCu foil

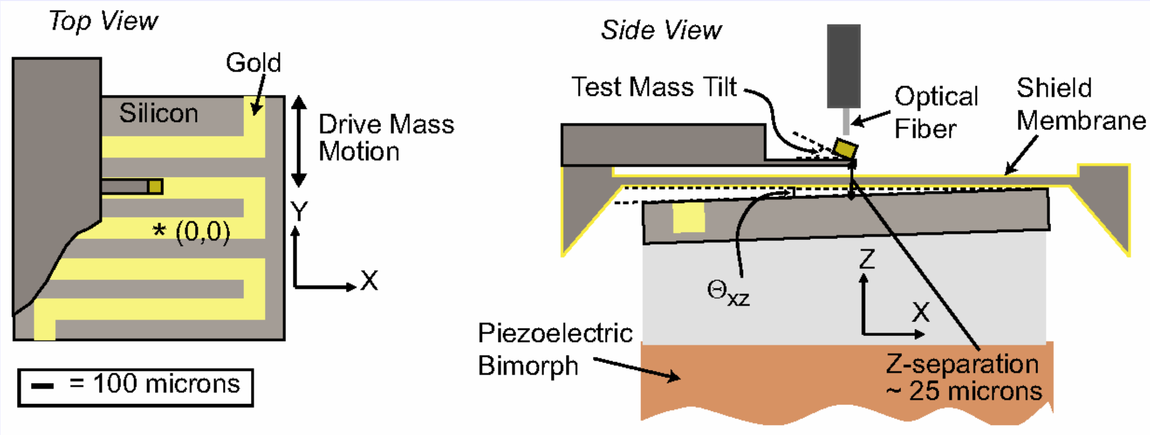


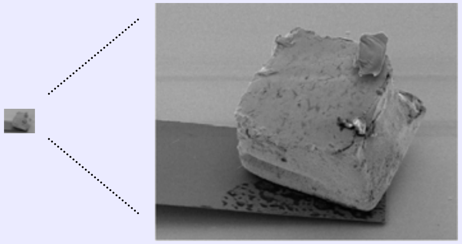
- **Distance from top of attractor to bottom of pendulum from 10.77 mm to 137 μm**

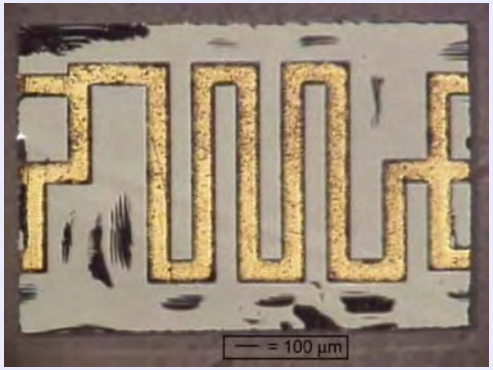
C. D. Hoyle, D. J. Kapner, B. R. Heckel, E. G. Adelberger, J. H. Gundlach, U. Schmidt, H. E. Swanson, *Submillimeter tests of the gravitational inverse-square law*, PRD 70, 042004 (2004)

Microcantilever - Stanford experiment







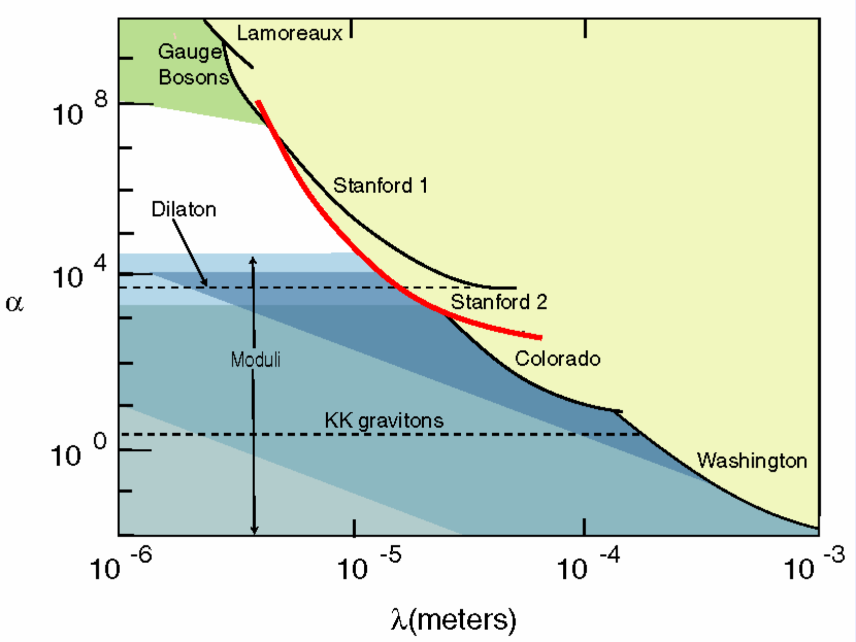


Probe mass (gold)
50 μm x 50 μm x 30 μm
$m_t \sim 1.6$ μg

Cantilever (<100> Si)
50 μm x 250 μm x 0.33 μm
Q ~ 80 000
$\omega_o \sim (k/m_t)^{1/2} \sim 300$ Hz

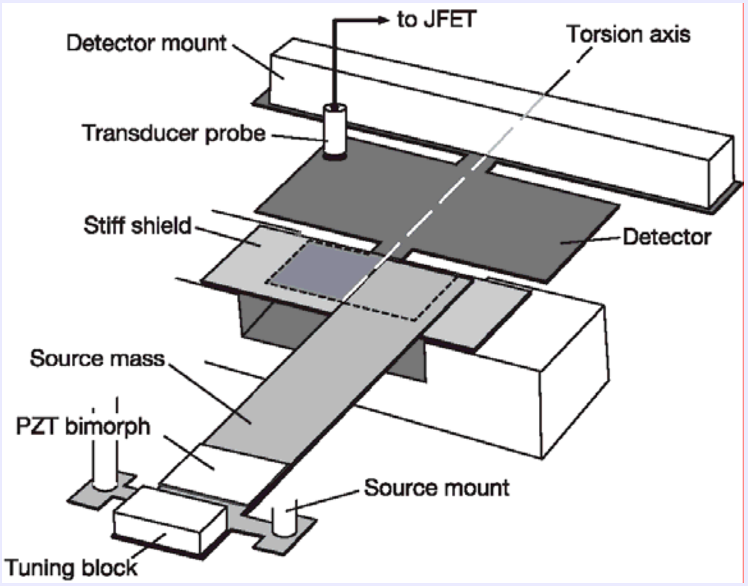
Source mass
5 sets of gold and silicon bars
100 μm x 1mm x 100 μm

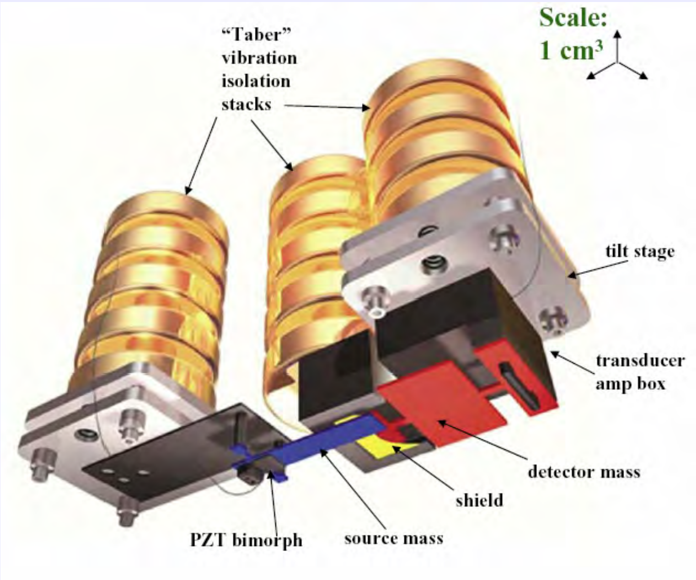
Separation 25 μm

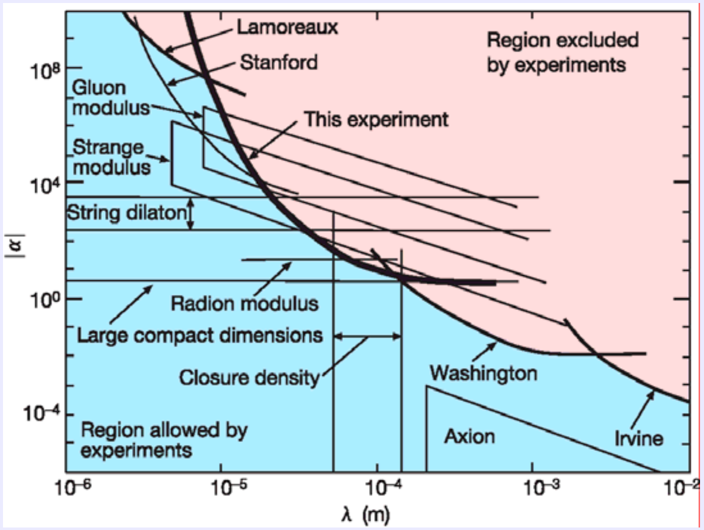


S. J. Smullin, A. A. Geraci, D. M. Weld, J. Chiaverini, S. Holmes, A. Kapitulnik, *Constraints on Yukawa-type deviations from Newtonian gravity at 20 microns*, Phys. Rev. D 72, 122001 (2005)

Microcantilever - Colorado experiment







Detector (tungsten)

11.455 mm x 5.080 mm x 195 μm

Q ~ 25 000

ω_o ~ 1173 Hz

Source mass (tungsten)

35 mm x 7 mm x 305 μm

Separation 108 μm

J.C. Long, H.W. Chan, A.B. Churnside, E.A. Gulbis, M.C.M. Varney, J.C. Price, *Upper limits to submillimetre-range forces from extra space-time dimensions*, Nature 421, 922 (2003)

Experiments on gravity at small spatial scale

Experiments based on torsion balances ($\lambda \leq 1$ mm)

J. Gundlach and E. Adelberger (Washington) – torsion balance

R. Newman and P. Boynton (Irvine, Washington) – cryogenic torsion balance

Experiments based on high-frequency oscillators ($\lambda \leq 0.1$ mm)

J. Long and J. Price group (Colorado) – torsional oscillator

A. Kapitulnik group (Stanford) - microcantilever

R. Decca and E. Fischbach group (Purdue, Indiana) – torsional oscillator

New experiments based on atomic probes ($\lambda \leq 0.01$ mm)

E.A. Cornell group (Colorado) – Oscillations of a Bose-Einstein condensate

G.M. Tino group (Firenze) – Atom interferometry

Also experiments on Casimir effect ($\lambda \leq 0.001$ mm)

Departures observed at ~70 μm?

(Washington, Stanford)

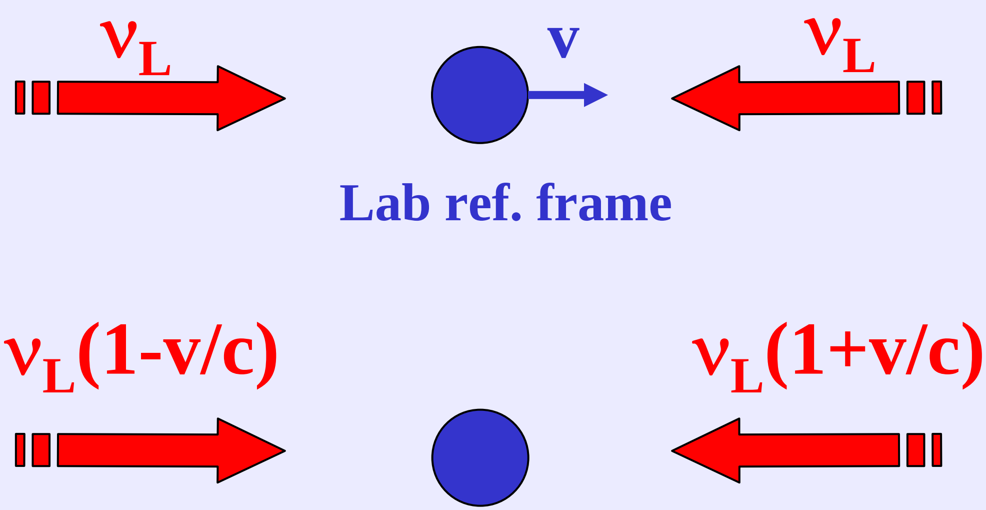
Experimental artifact?

Why atoms?

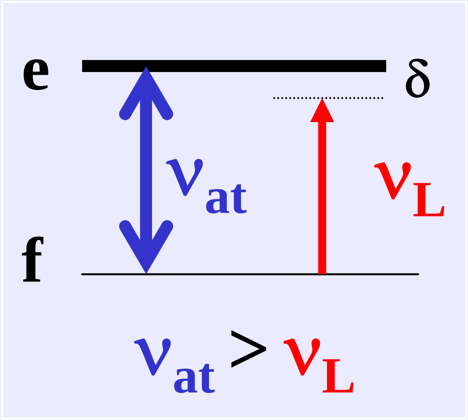
- Extremely small size
- Well known and reproducible properties
- Quantum systems
- Precision gravity measurement by atom interferometry
- Potential immunity from stray fields effects

Laser cooling and manipulation of atoms

Optical molasses

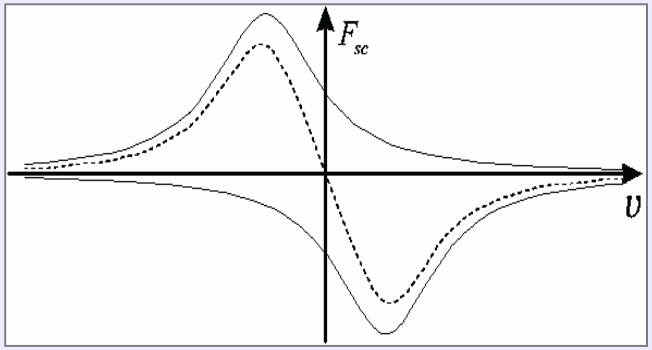


Atom ref. frame



$(I/I_0 \ll 1) \rightarrow$

$$F(\mathrm{v}) \simeq \frac{h\nu_L}{c}\cdot\frac{1}{2\tau}\cdot\left[\frac{I/I_0}{1+I/I_0+\frac{4}{\Gamma^2}(\delta-\frac{\nu_L}{c}\mathrm{v})^2}-\frac{I/I_0}{1+I/I_0+\frac{4}{\Gamma^2}(\delta+\frac{\nu_L}{c}\mathrm{v})^2}\right]$$



$$F(\mathrm{v}) \simeq \frac{h}{4\pi^2}\frac{\omega_L^2}{c^2}\frac{8\delta}{\Gamma}\frac{I/I_0}{[1+(\frac{2\delta}{\Gamma})^2]^2}\mathrm{v} = -\alpha \mathrm{v}$$

Idea: **T.W. Hänsch, A. Schawlow, 1975**
Exp. demonstration: **S. Chu et al., 1985**

Laser cooling: atomic temperatures

Atomic Temperature : $\boldsymbol{k_B T = Mv^2_{rms}}$

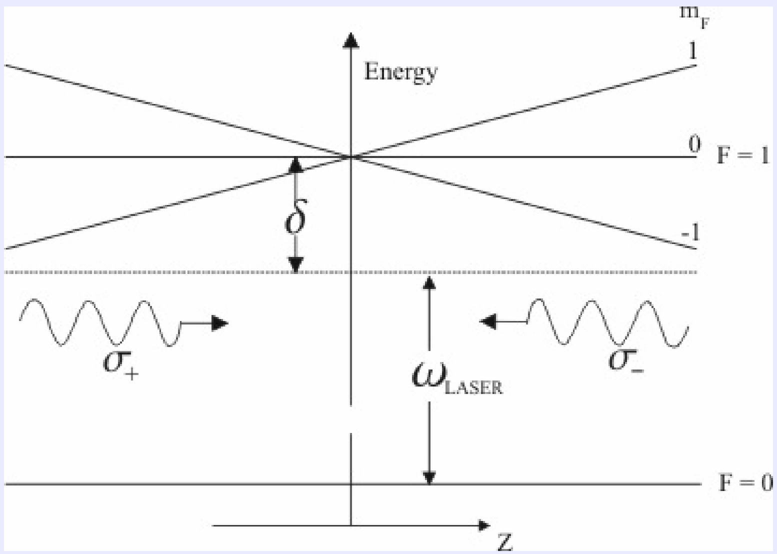
Minimum temperature for Doppler cooling: $\boxed{k_B T_D = \frac{h\Gamma}{2}}$

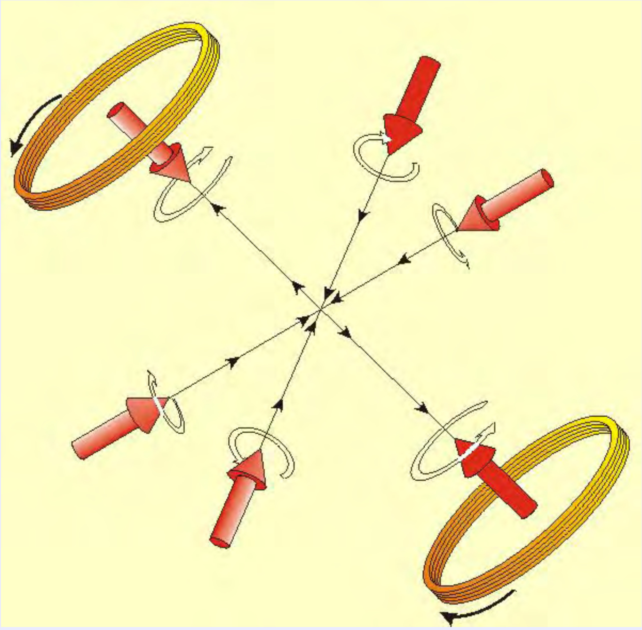
Single photon recoil temperature: $\boxed{k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2}$

Examples:

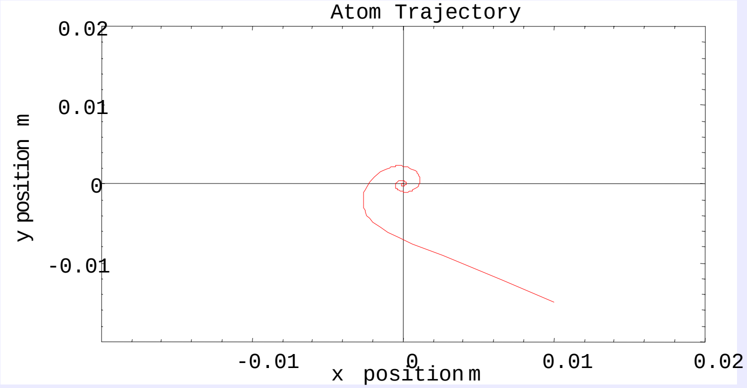
	T_D	T_r
Na	240 µK	2.4 µK
Rb	120 µK	360 nK
Cs	120 µK	200 nK
Sr	180 nK	460 nK

Magneto-Optical Trap (MOT)





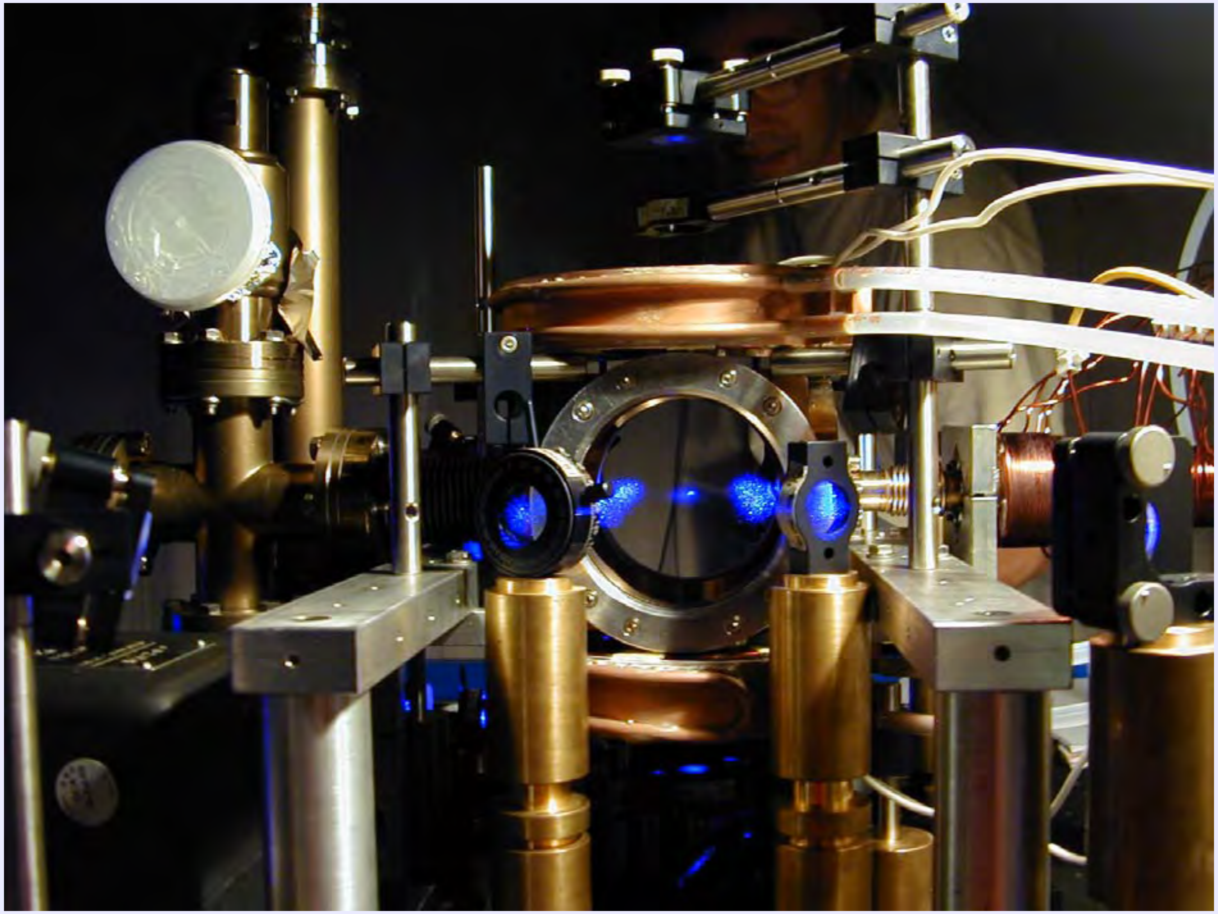
$$F(z,v) \simeq \frac{4hk}{\pi}\frac{I}{I_0}\frac{\delta}{\Gamma}\frac{kv+\beta z}{[1+(\frac{2\delta}{\Gamma})^2]^2}$$



density n $\approx 10^{11}$ cm^{-3}
temperature T $\approx 100\ \mu$K
size Δx ≈ 1 mm

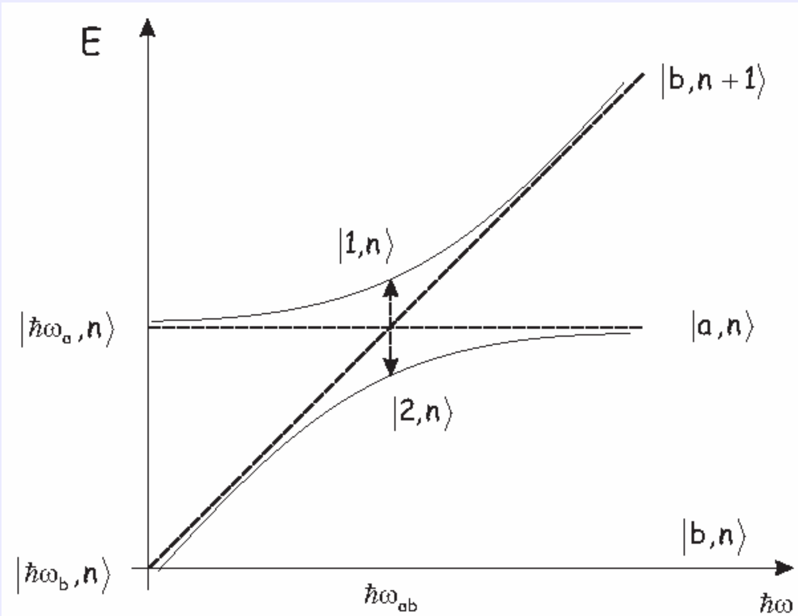
E. Raab *et al.*, Phys. Rev. Lett. 59, 2631 (1987)

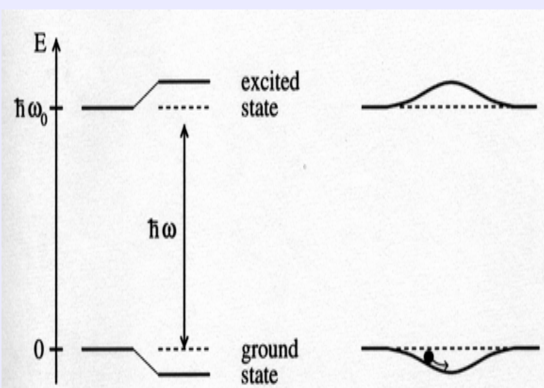
Sr MOT picture

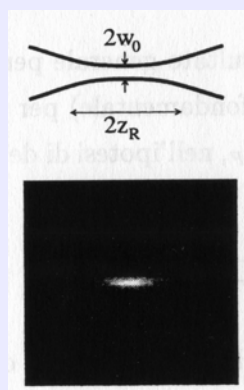


LENS, Firenze

Light shifts and optical traps



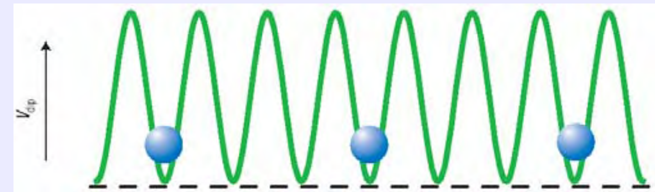




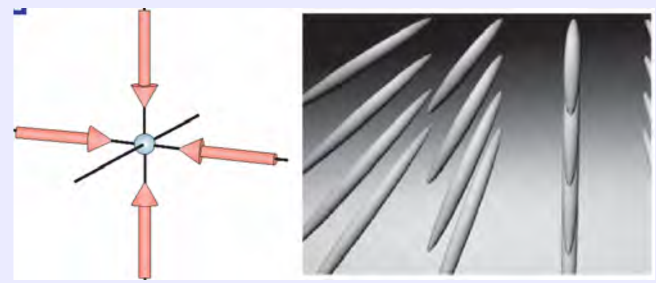
$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)\,|\,\mathbf{E}(\mathbf{r})\,|^2$$

First exp. demonstration: **S. Chu et al., 1986**

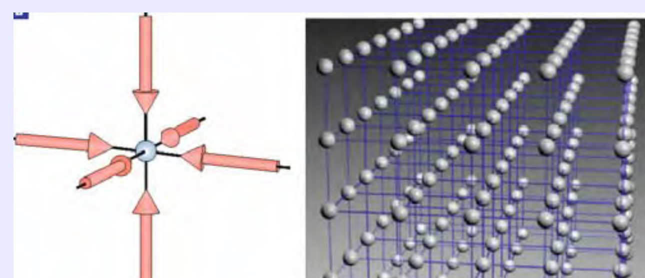
optical lattices



1D optical lattice ⇒ array of 2D disk-like trapping potentials



2 D optical lattice ⇒ array of 1D potential tubes



3 D optical lattice ⇒ 3D simple cubic array of h.o. potentials

Review: **I. Bloch, 2005**

Cooling and trapping atoms with laser light
The Nobel Prize in Physics 1997

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LAUREATES ARTICLES EDUCATIONAL

Web Adapted Version of the Nobel Poster from the Royal Swedish Academy of Sciences

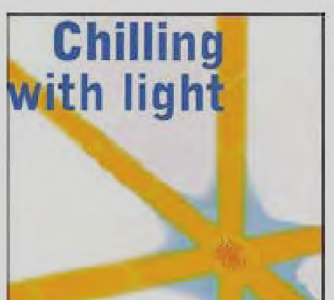
BACK

The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to

Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**

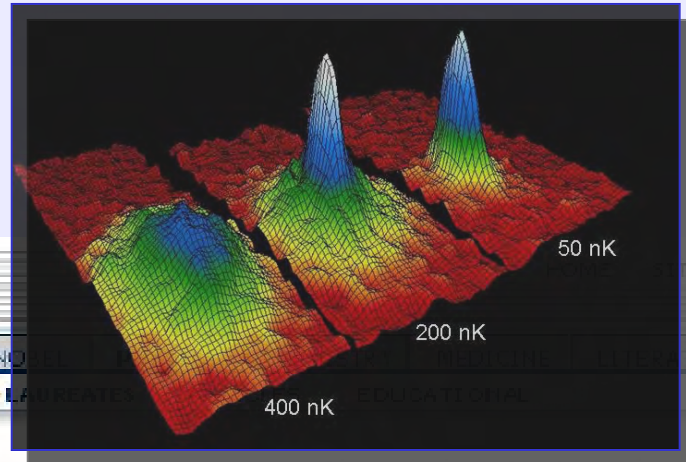
for their developments of methods to cool and trap atoms with laser light.

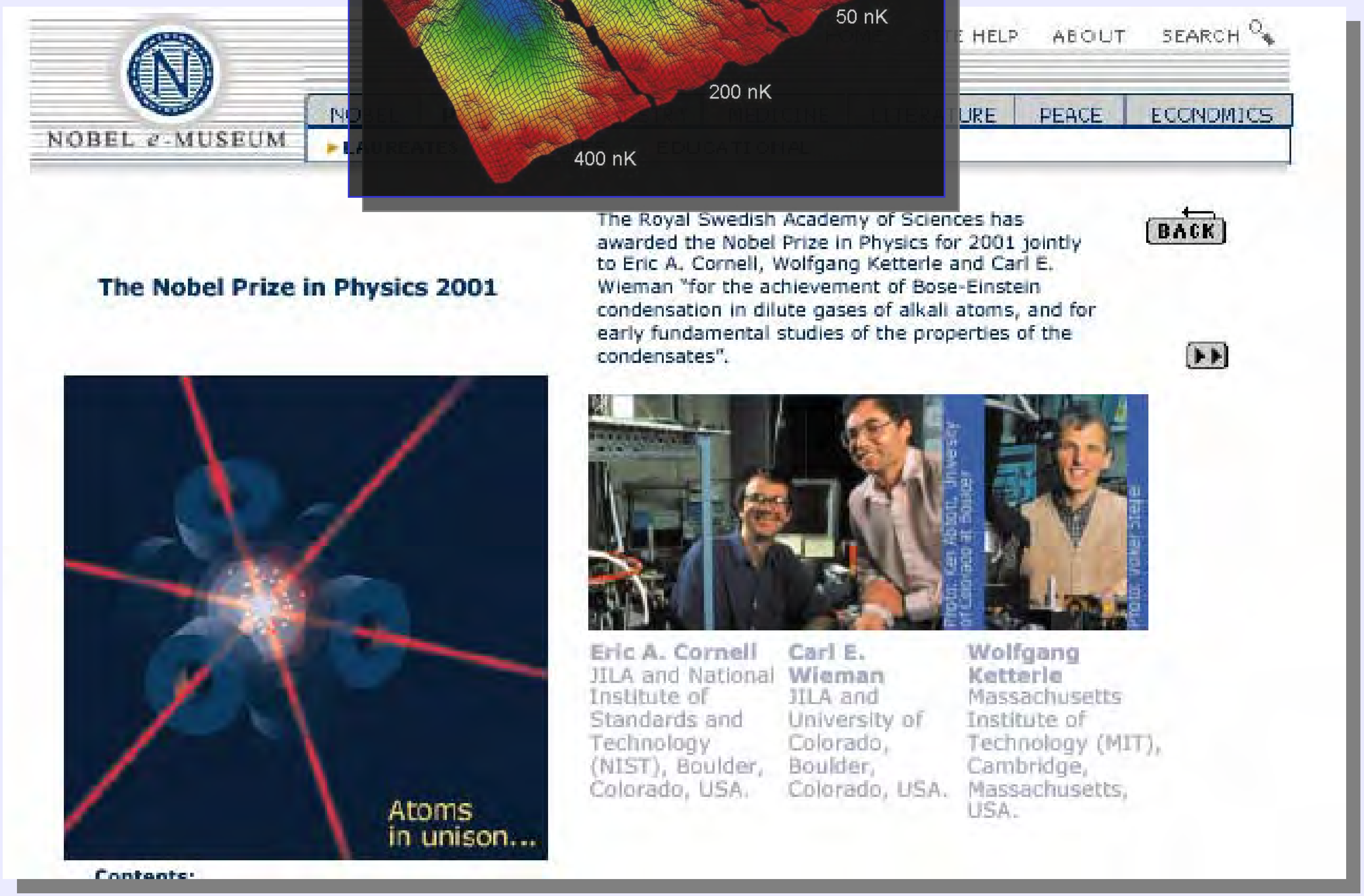


This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

Bose-Einstein condensation in dilute gases of atoms

The Nobel Prize in Physics 2001





The Nobel Prize in Physics 2001

The Royal Swedish Academy of Sciences has awarded the Nobel Prize in Physics for 2001 jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

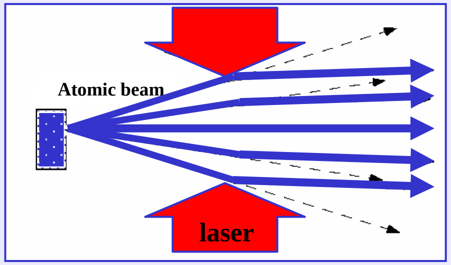
Eric A. Cornell JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.

Carl E. Wieman JILA and University of Colorado, Boulder, Colorado, USA.

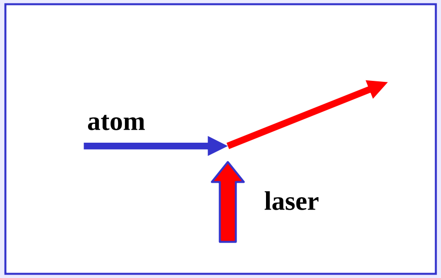
Wolfgang Ketterle Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

Atom optics

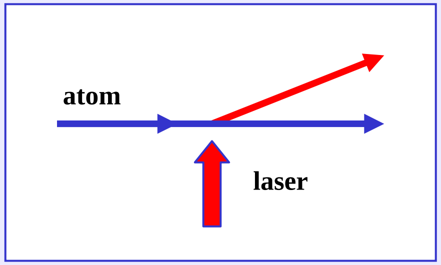
lenses



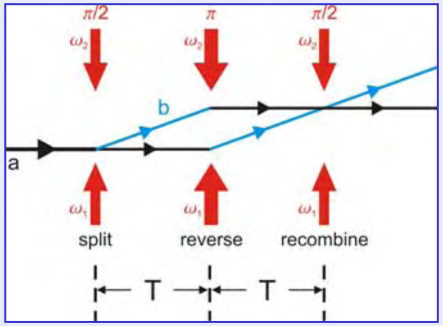
mirrors



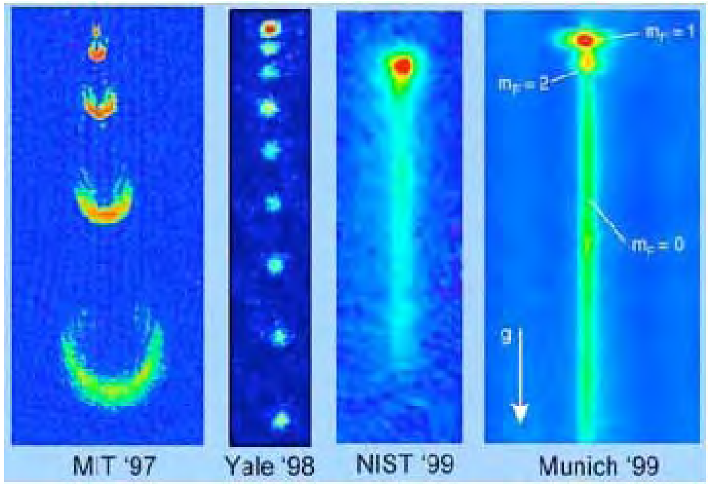
beam-splitters



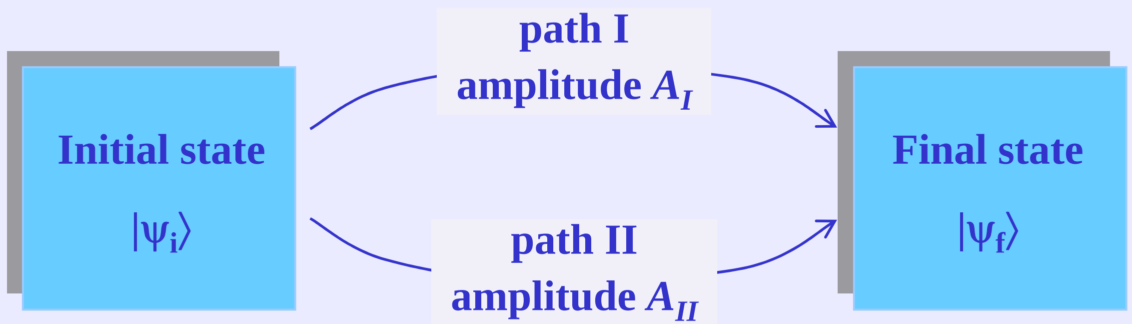
interferometers



atom laser



Quantum interference

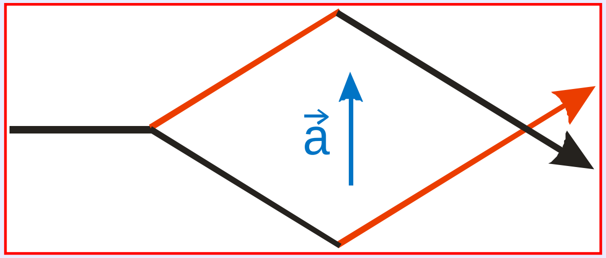


Interference of transition amplitudes

$$P\left(|\psi_i\rangle \Rightarrow |\psi_f\rangle\right) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2\,Re\left(A_I A_{II}^*\right)$$

Matter wave sensors

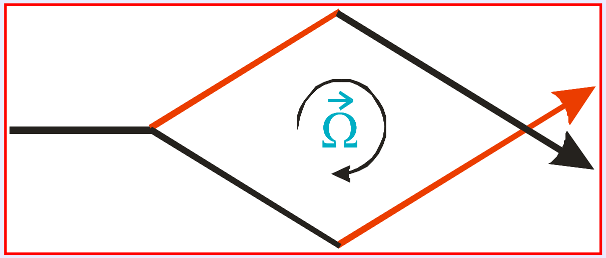
accelerations:



$$\Delta\Phi_{acc} = k\, T_{drift}^2 \cdot a$$

$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \left(\frac{c}{v_{at}}\right)^2 \approx 10^{11} - 10^{17}$$

rotations:



$$\Delta\Phi_{rot} = 2\pi \frac{2\, m_{at}}{h} A \cdot \Omega$$

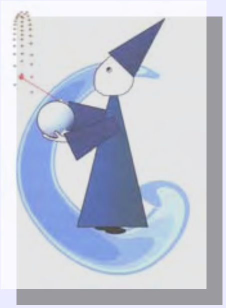
$$\frac{\Delta\varphi_{mat}}{\Delta\varphi_{ph}} \sim \frac{m_{at} \cdot \lambda \cdot c}{h} \approx 5 \cdot 10^{10}$$

MAGIA

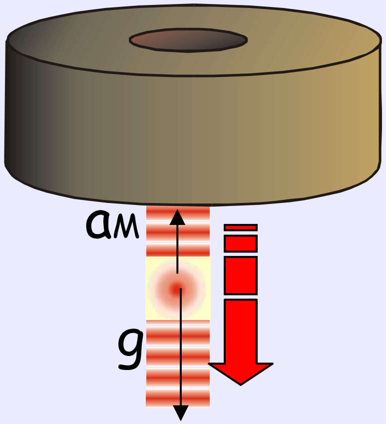
Misura Accurata di G mediante Interferometria Atomica

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

MAGIA



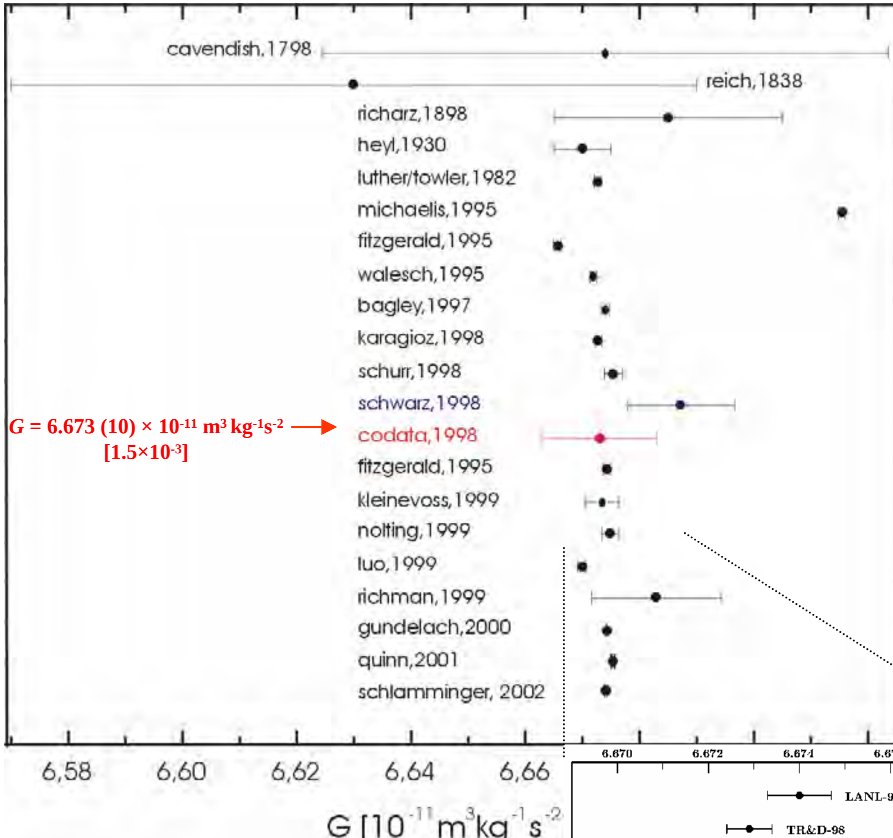
- Measure g by atom interferometry
- Add source masses
- Measure change of g



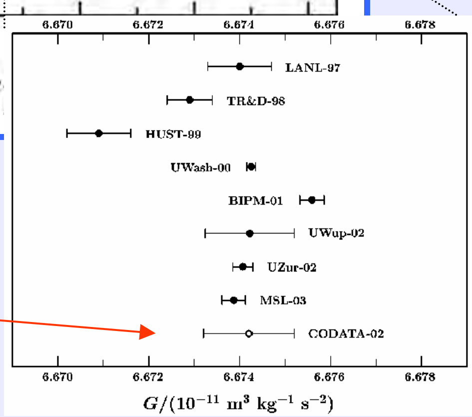
- *Precision measurement of G*
- *Measurement of G at sub-mm distances*

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

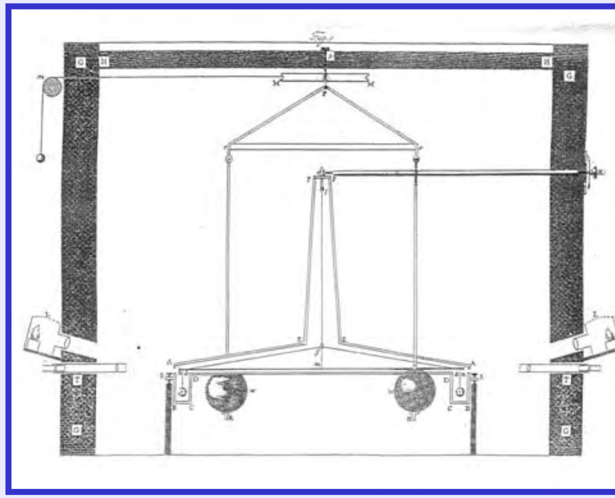
Why measuring G with atom interferometry?



G = 6.673 (10) × 10^{-11} $m^3\,kg^{-1}s^{-2}$ [1.5×10^{-3}]



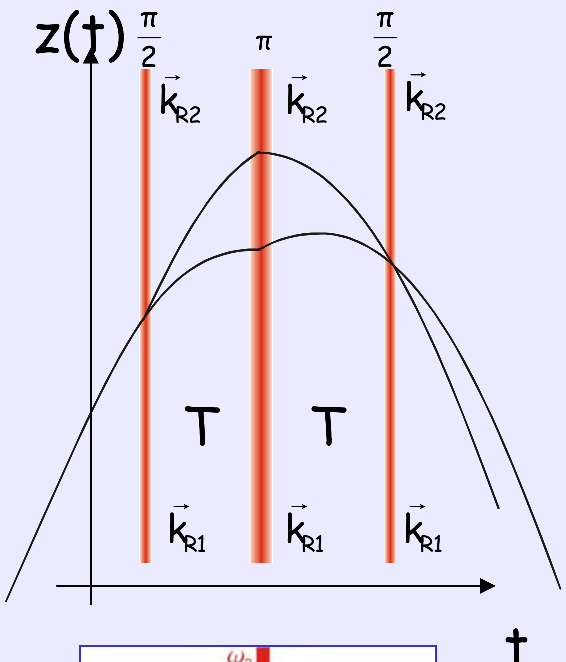
G = 6.6742 (10) × 10^{-11} $m^3\,kg^{-1}s^{-2}$ [1.5×10^{-4}]



Cavendish 1798

Quinn 2001

Raman interferometry in an atomic fountain

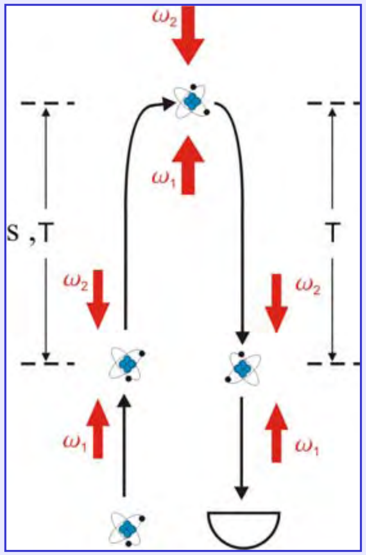


Phase difference between the paths:

$\Delta\Phi = k_e[z(0)-2z(T)+z(2T)]+\Phi_e$ $\quad \mathbf{k_e = k_1 - k_2}$, $\omega_e = c\,\mathbf{k_e}$

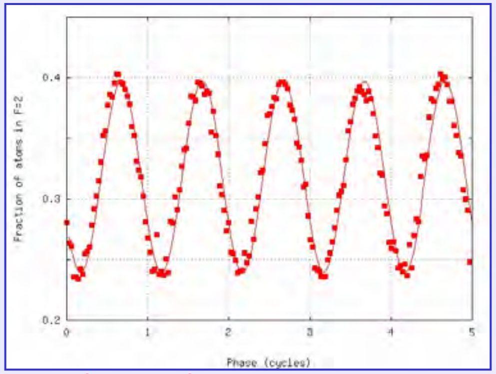
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0$ $\Rightarrow$ $\mathbf{\Delta\Phi = k_e g T^2}$

$$\mathbf{g = \Delta\Phi / k_e T^2}$$



Final population:

$\mathbf{N_a = N/2\ (1+\cos[\Delta\Phi])}$



Interference fringes – Firenze 2006

$T = 150$ ms $\Rightarrow 2\pi = 10^{-6}g$

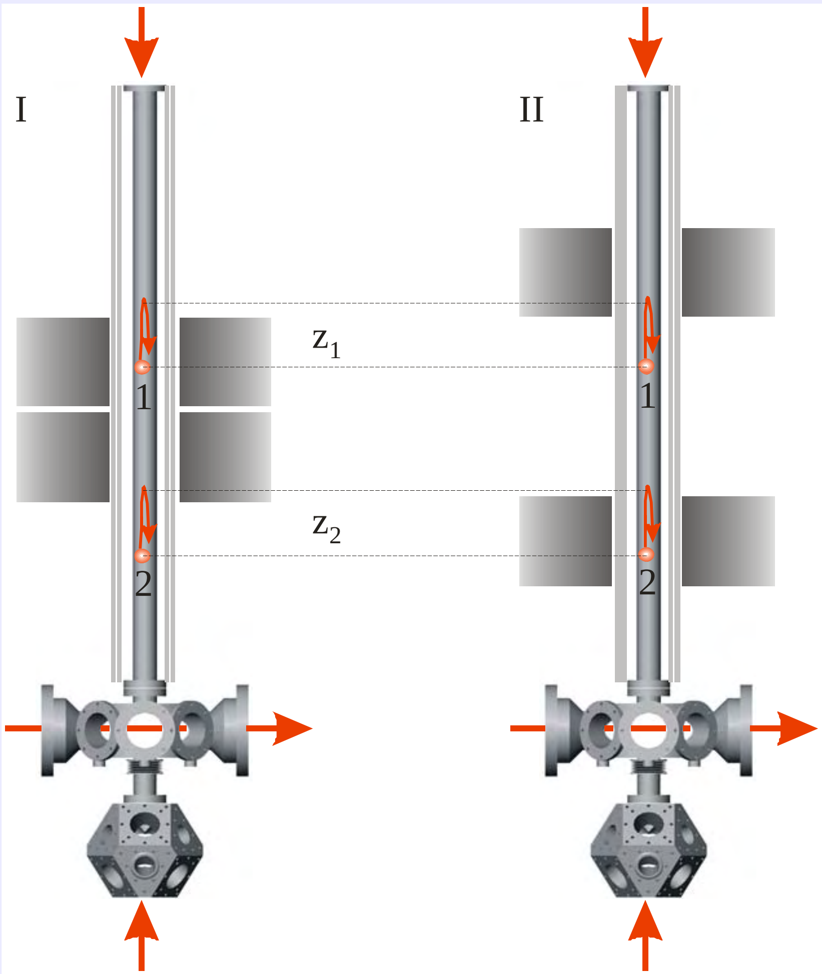
$S/N = 1000$

$\Rightarrow$ Sensitivity 10^{-9} g/shot

M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)

MAGIA: Experimental procedure



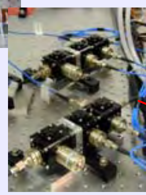
- trap, cool and launch 2 clouds of Rb atoms
- apply Raman light pulses
  masses in position 1
- detect atoms state selectively
- repeat several times
- plot N_a/N and fit the differential phase shift $\Delta\Phi_g$ between the clouds
- move masses to position 2
  repeat all procedure
- subtract the differential phase shifts for the two mass positions

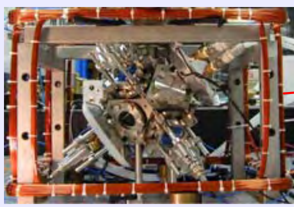
$$\phi_1^I - \phi_2^I = \phi_g(z_1) + \phi_{SM} + \phi_{Sys}(z_1, t_I) - \left(\phi_g(z_2) - \phi_{SM} + \phi_{Sys}(z_2, t_I)\right)$$

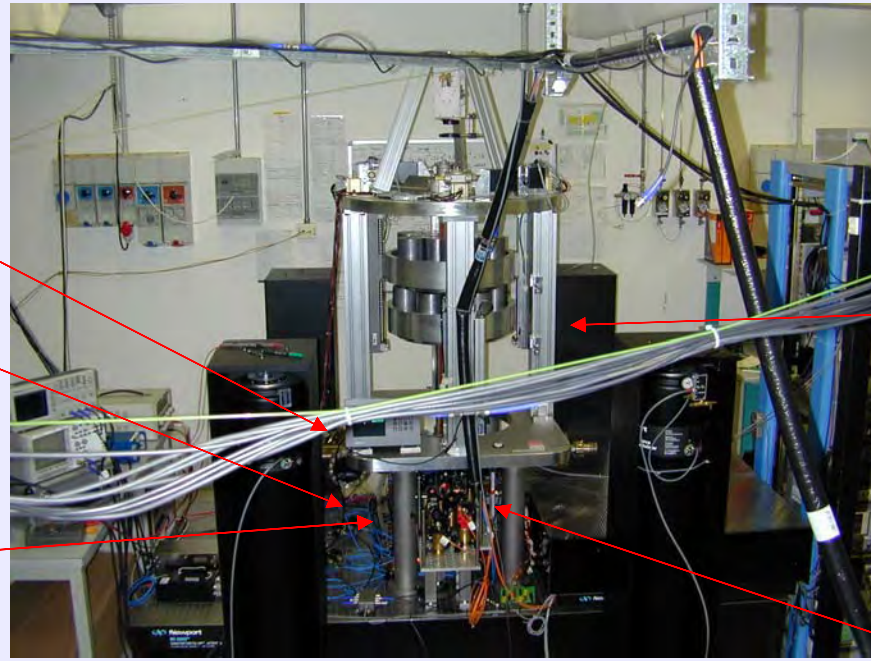
$$\phi_1^{II} - \phi_2^{II} = \phi_g(z_1) - \phi_{SM} + \phi_{Sys}(z_1, t_{II}) - \left(\phi_g(z_2) + \phi_{SM} + \phi_{Sys}(z_2, t_{II})\right)$$

$$\Rightarrow (\phi_1^I - \phi_2^I) - (\phi_1^{II} - \phi_2^{II}) = 4\phi_{SM} + \phi_{Sys}(\Delta z, \Delta t)$$

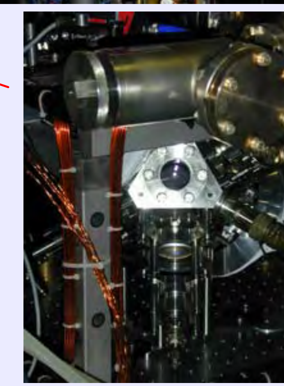
Atom gravity gradiometer apparatus



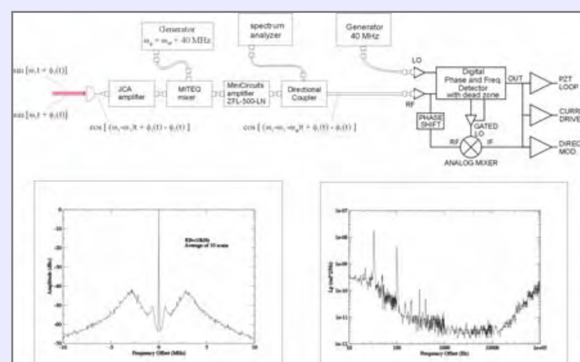




Source masses and support



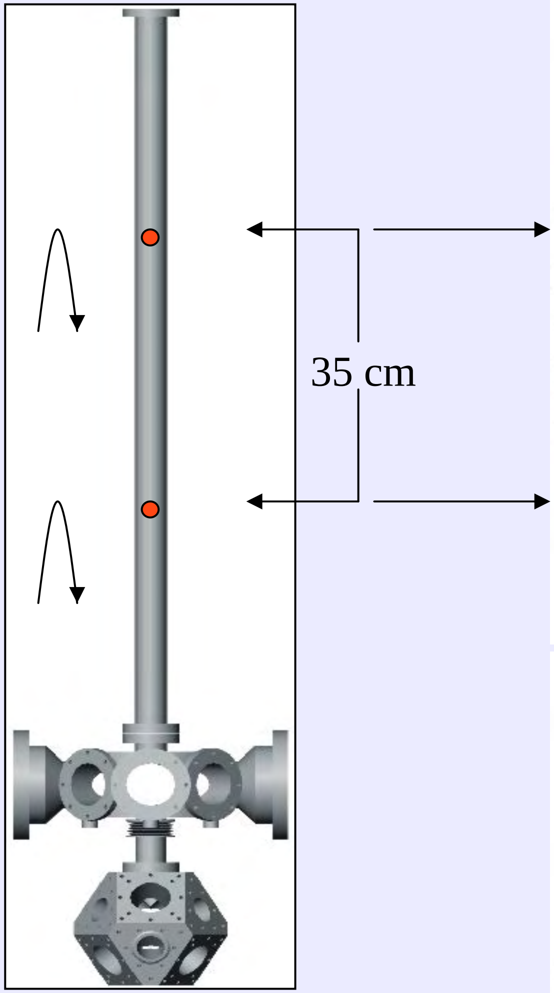
Laser and optical system

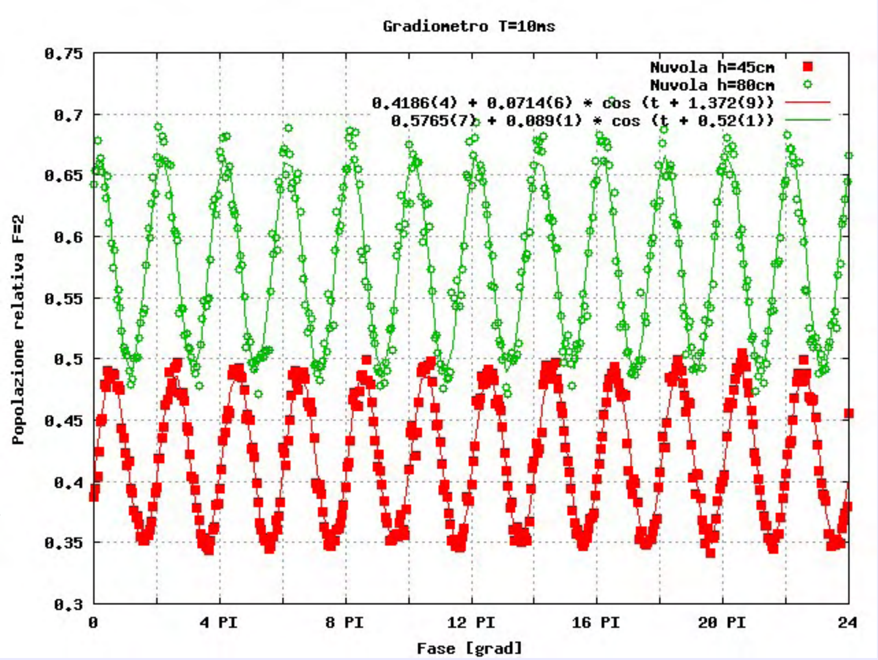


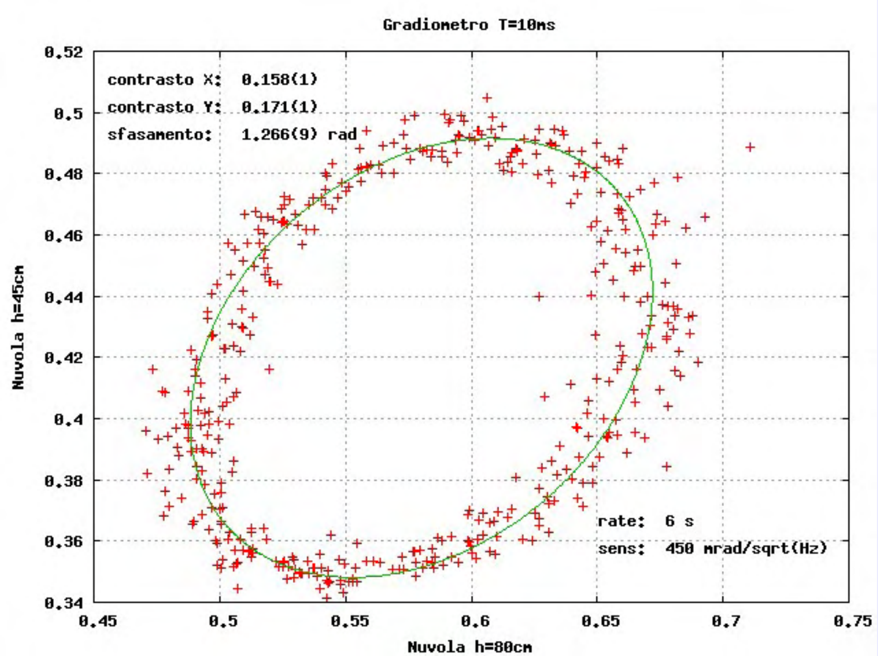
L. Cacciapuoti, M.de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M.Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* Rev. Scient. Instr. 76, 053111 (2005)

GRADIOMETER

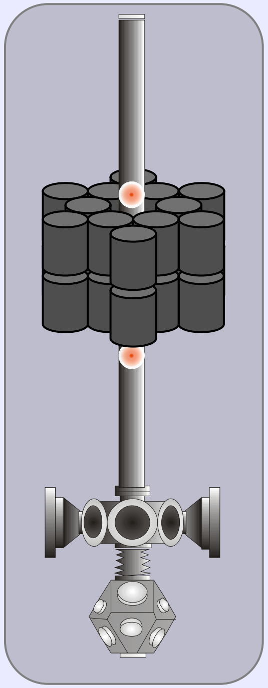
Atom interference fringes

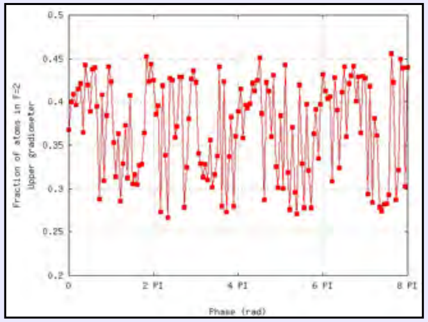


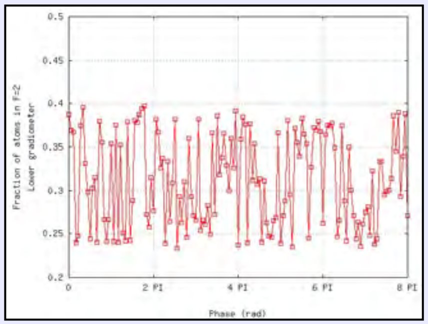


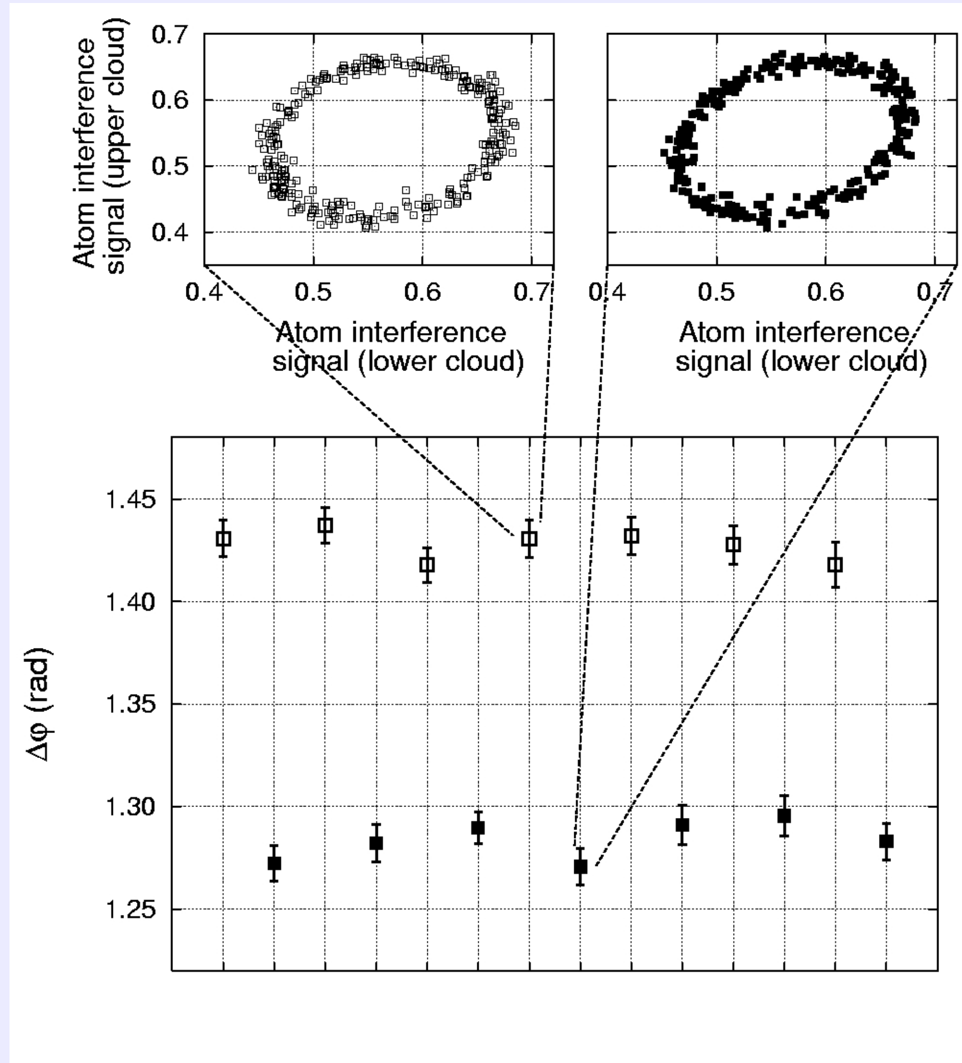


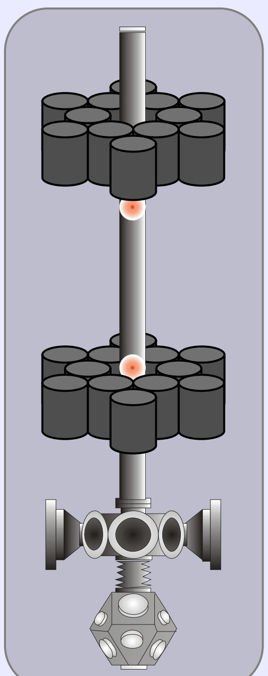
G: first results

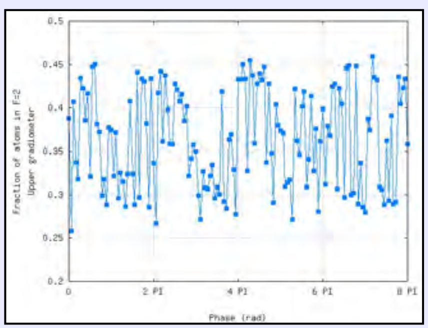


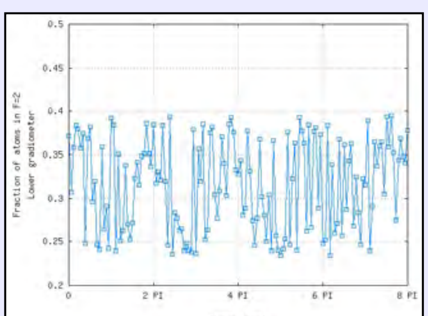












A. Bertoldi, G. Lamporesi , L. Cacciapuoti, M. de Angelis, M. Fattori, T. Petelski, A. Peters, M. Prevedelli, J. Stuhler, G. M. Tino (2006), submitted, arXiv:physics/0606126

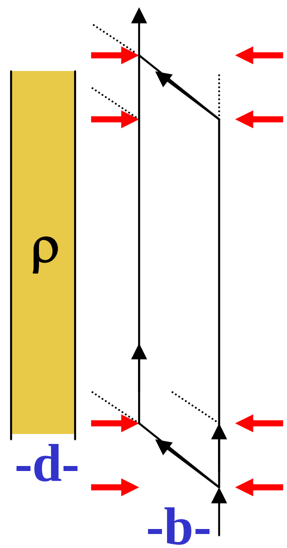
MAGIA – Relevant numbers

- time separation between pulses T=150 ms
- 10^6 atoms
- shot noise limited detection
- launch accuracy: 1 mm e $\Delta v \sim 5$ mm/s
- knowledge of the masses dimensions and relative positions: 10 μm
- 10000 measurements

$\Downarrow$

$$\Delta G/G \leq 10^{-4}$$

Possible test of the gravitational $1/r^2$ law in the sub-mm range with an atom interferometer



$a = 2\pi G\rho d$

Example:

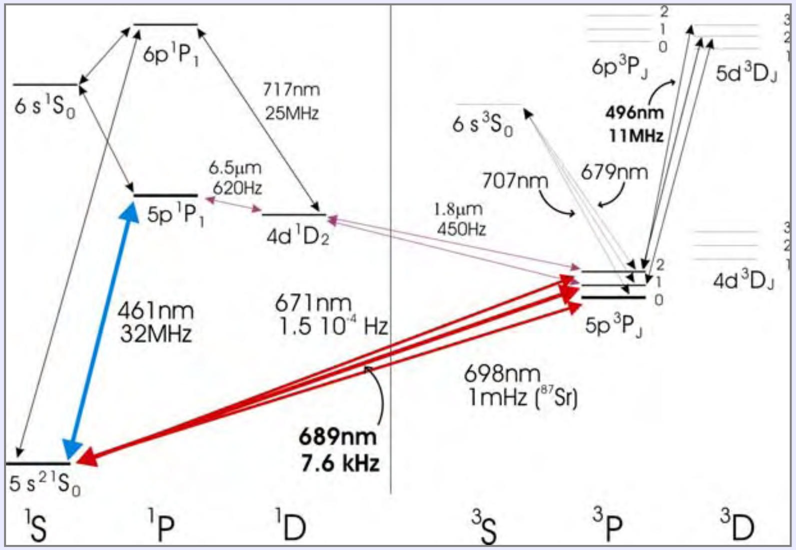
ρ_{Au} ~19 g/cm^3
d ~ 100 μm

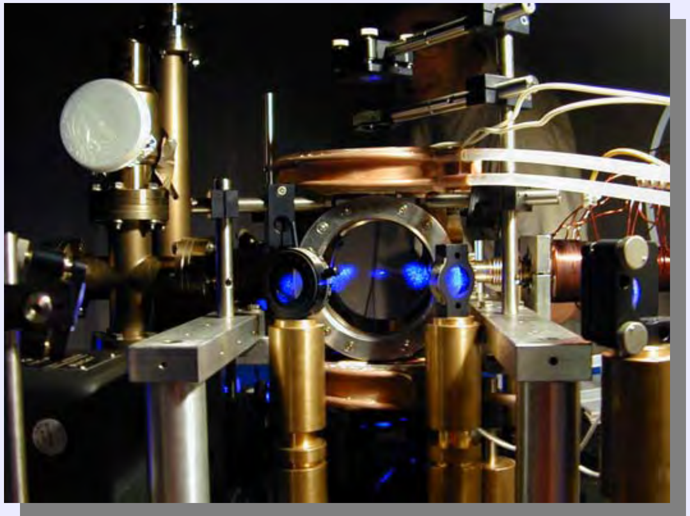
$\boxed{a \sim 10^{-9}\ \mathrm{ms}^{-2}}$

$$\Delta\phi = \frac{mab}{\hbar}T$$

- G.M. Tino, *in "2001: A Relativistic Spacetime Odyssey", Firenze, 2001*, World Scientific (2003)
- G.M. Tino, Nucl. Phys. B 113, 289 (2002)

Ultracold Sr – The experiment in Firenze

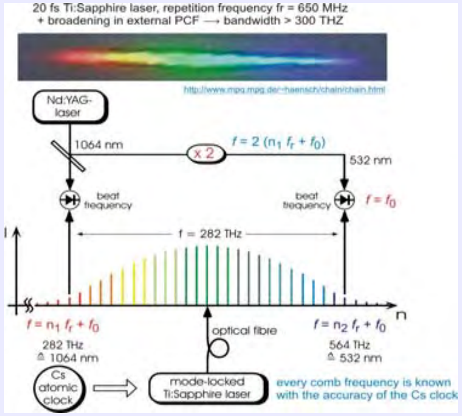


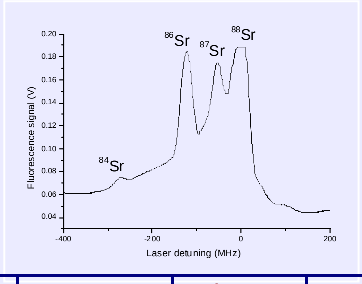


Firenze 2003, Magneto-optical trapping of all Sr isotopes

- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests





	Abundance
^{88}Sr	82.6%
^{86}Sr	9.9%
^{87}Sr	7.0%
^{84}Sr	0.6%

Isotope	I	transition	lifetime	λ	t_{int}	$\sigma_y\, t^{-1/2}$	abundance
^{88}Sr	0	$^1S_0$-$^3P_1$	20 µs	689 nm	10 µs	2 10^{-13}	83%
^{87}Sr	9/2	$^1S_0$-$^3P_0$	200 s	698 nm	0.5 s	10^{-17}	7%

G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

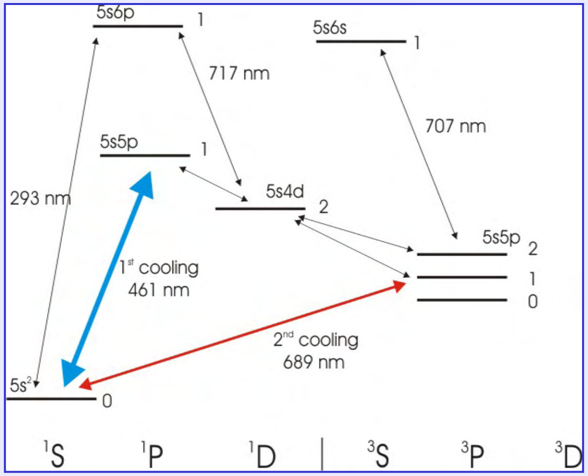
G. Ferrari, R.E. Drullinger, N. Poli, F. Sorrentino, G.M. Tino, *Cooling of Sr to high phase-space density by laser and sympathetic cooling in isotopic mixtures*, Phys. Rev. A 73, 023408 (2006)

Why Sr atom?

- New quantum sensors
  - J = 0 ground state
  - Small collisional cross section
  - Fermionic and bosonic atoms

- Optical clocks on visible intercombination lines
  - $^1S_0$ - $^3P_1$ (7.5 kHz) (this work)
  - $^1S_0$ - $^3P_0$ (1 mHz, ^{87}Sr)
  - $^1S_0$ - $^3P_2$ (<1 mHz)
  - Optical trapping in optical lattices with negligible change of clock frequency

- Physics of ultracold atoms
  - Simple 0 - 1 transitions
  - $T_D \approx T_{rec}$ for $^1S_0$ - $^3P_1$ transition
  - Two-stage optical cooling and trapping
  - All-optical cooling to quantum degeneracy
  - Degenerate Bose and Fermi gases



Sr Isotope	Nuclear Spin I	Atomic Mass (10^{-27} Kg)	Natural Abundance
88	0	145,97068	82,6 %
87	9/2	144,315568	7,0 %
86	0	142,65567	9,8 %
84	0	139,34150	0,56 %

Optical clocks: Towards 10^{-19}

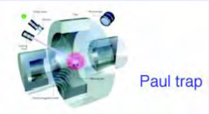
- **Narrow optical transitions**

$\delta\nu_0 \sim 1$ Hz, $\nu_0 \sim 10^{15}$ Hz

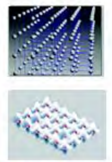
$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atom}}} \sqrt{\frac{T_{\text{cycle}}}{2\tau_{\text{average}}}} \frac{1}{C_{\text{fringe}}}$$

- **Candidate atoms**

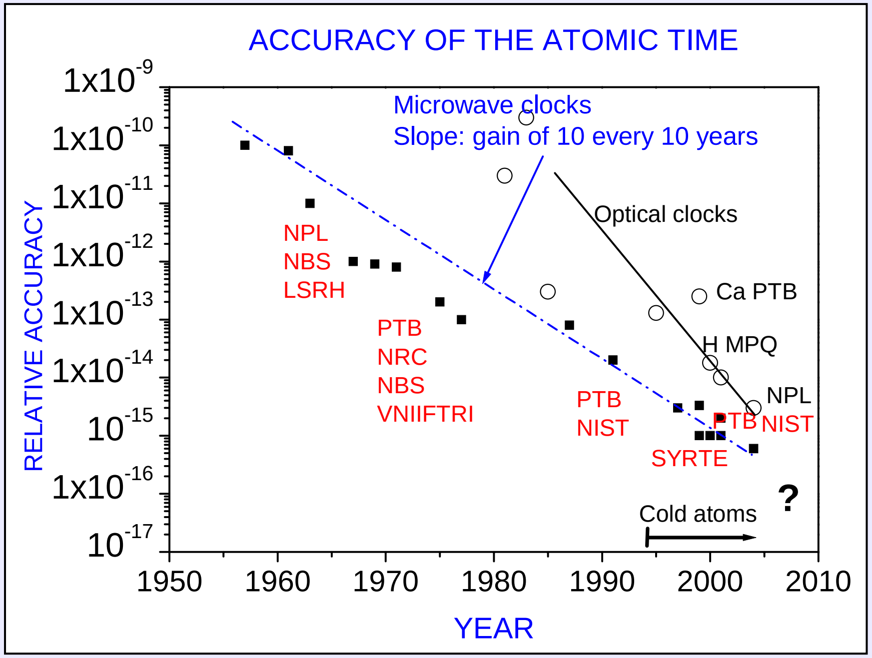
Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…



Cold neutral atoms: H, Ca, Sr, Yb,…



Optical lattice



Gravitational red shift at lab scale

G. M. Tino, GGI Colloquium, Arcetri 22/6/2006

HOM

Nobelprize.org

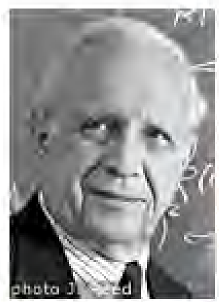
NOBEL PHYSICS CHEMISTRY MEDICINE LITERATURE PEACE ECONOMICS

LAUREATES ARTICLES EDUCATIONAL

The Nobel Prize in Physics 2005

"for his contribution to the quantum theory of optical coherence"

"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"



Roy J. Glauber

1/2 of the prize

USA

Harvard University
Cambridge, MA, USA

b. 1925

John L. Hall

1/4 of the prize

USA

University of Colorado, JILA; National Institute of Standards and Technology
Boulder, CO, USA

b. 1934

Theodor W. Hänsch

1/4 of the prize

Germany

Max-Planck-Institut für Quantenoptik
Garching, Germany;
Ludwig-Maximilians-Universität
Munich, Germany

b. 1941

The Nobel Prize in Physics 2005
Prize Announcement
Press Release
Advanced Information
Supplementary Information

Roy J. Glauber
Nobel Lecture
Interview
Other Resources

John L. Hall
Nobel Lecture
Interview
Other Resources

Theodor W. Hänsch
Nobel Lecture
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Other Resources

2004

The 2005 Prize in:
Physics
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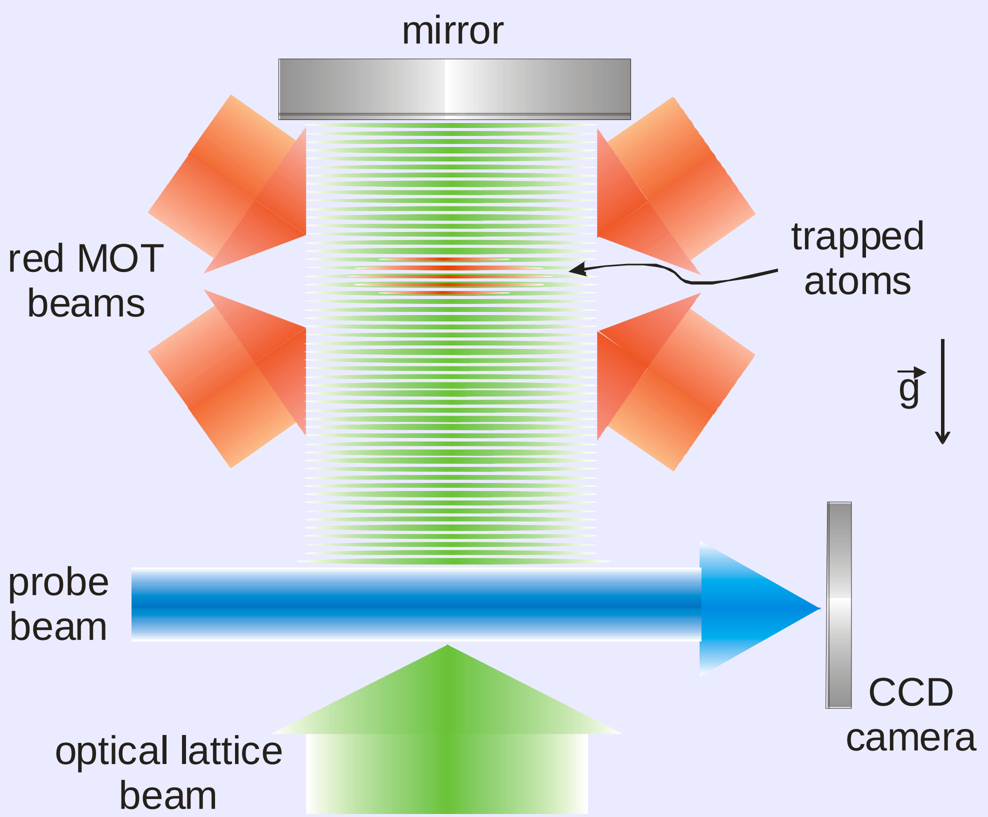
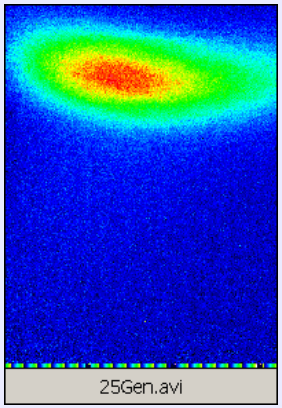
Precision gravity measurement at μm scale with Bloch oscillations of Sr atoms in an optical lattice

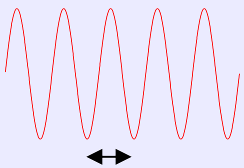




$$\nu = m\, g\, \lambda / 2\, h$$

G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale* (2006) to be published, arXiv:physics/0605018

Particle in a periodic potential: Bloch oscillations

periodic potential 

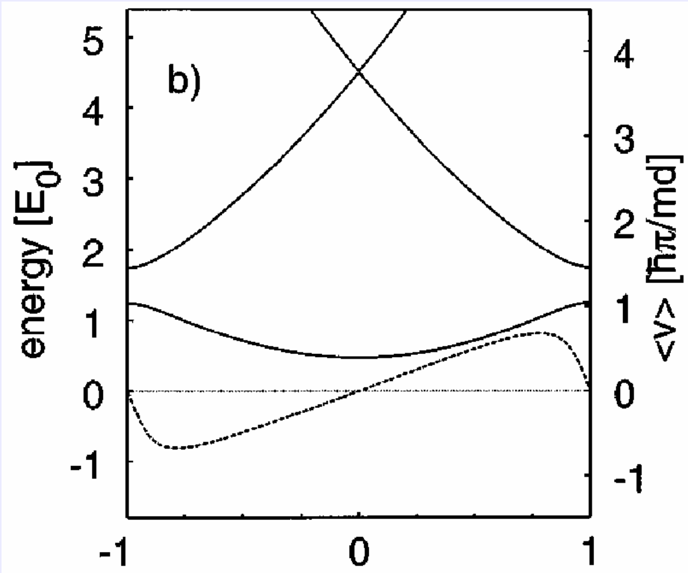
$V(z+\lambda/2) = V(z)$

$$\Psi(z) = e^{i\frac{\mathbf{q}}{\hbar}z}\,u(z)$$

$$u(z+\lambda/2) = u(z)$$

Bloch's theorem

$$\Psi(z+\lambda/2) = e^{i\frac{\mathbf{q}}{\hbar}\cdot\frac{\lambda}{\mathbf{2}}}\,\Psi(z)$$



quasimomentum q [2π/λ]

$$\langle v\rangle_n(q(t)) = \frac{1}{\hbar}\frac{dE_n(R(q(t)))}{dq}$$

with a constant external force F

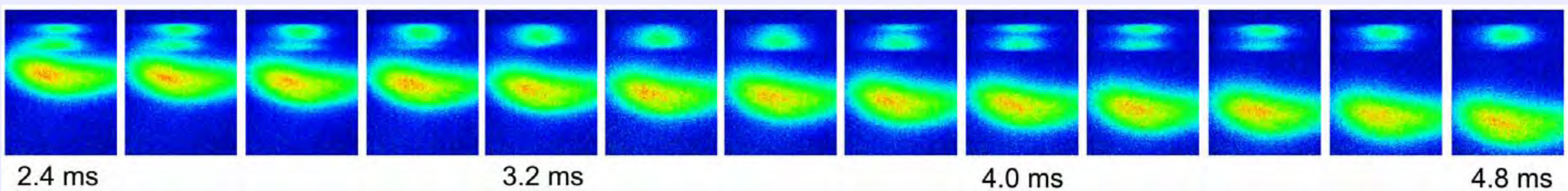
$$q(t) = q(0) + Ft/\hbar$$

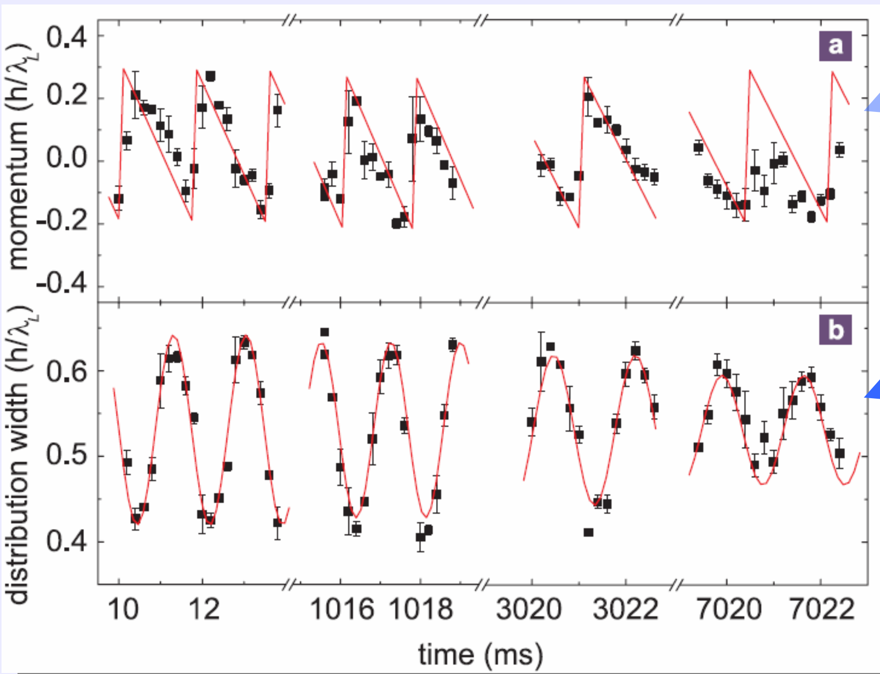
$\Downarrow$

Bloch oscillations

Quantum theory for electrons in crystal lattices: **F. Bloch, Z. Phys. 52, 555 (1929)**
Never observed in natural crystals (evidence in artificial superlattices)
Direct observation with Cs atoms: **M.Ben Dahan, E.Peik, J.Reichel, Y.Castin, C.Salomon, PRL 76, 4508 (1996)**

Persistent Bloch oscillations





average vertical momentum of the lower peak

width of the atomic momentum distribution

Bloch frequency ν_B = 574.568(3) Hz

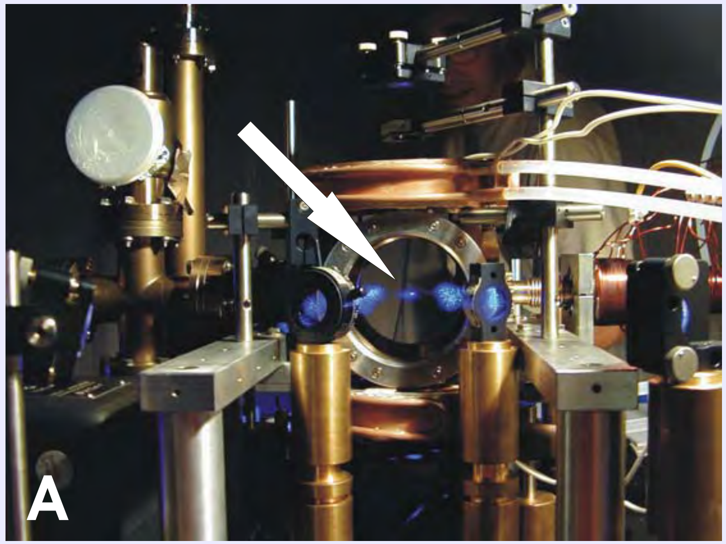
damping time τ = 12 s

8000 photon recoils in 7s

g_{meas} = 9.80012(5) ms^{-2}

G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale* (2006) to be published, arXiv:physics/0605018

Decoherence

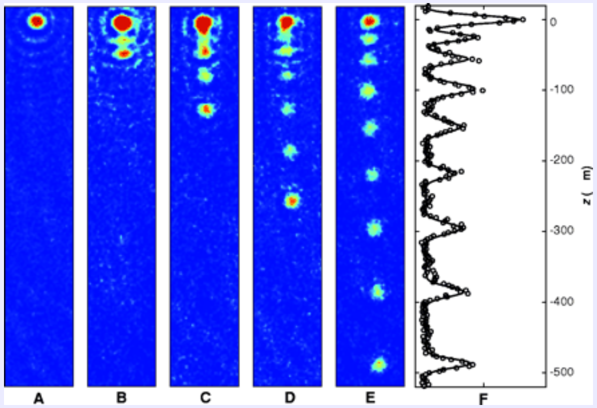


- ^{88}Sr: $\sigma_{88-88} = (3 \pm 1) \times 10^{-13}\ \mathrm{cm}^2$ $\Rightarrow$ $\tau_{coh} = 1\text{-}10\ \mathrm{s}$
- ^{87}Sr: suppressed collisions for fermions at low temperatures

• N. Poli, R.E. Drullinger, G. Ferrari, J. Leonard, F. Sorrentino, G.M. Tino, *Cooling and trapping of ultracold strontium isotopic mixtures*, Phys. Rev A 71, 061403 (R) (2005)

• G. Ferrari, R.E. Drullinger, N. Poli, F. Sorrentino, G.M. Tino, *Cooling of Sr to high phase-space density by laser and sympathetic cooling in isotopic mixtures*, Phys. Rev. A 73, 023408 (2006)

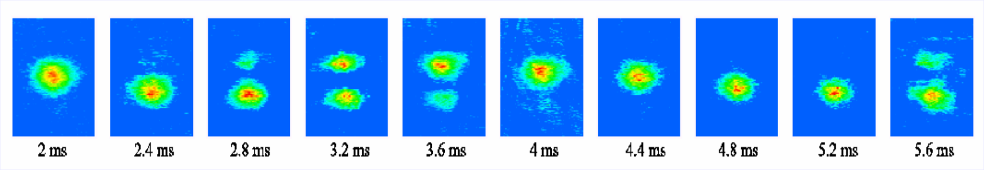
gravity measurement with quantum degenerate bosonic and fermionic atoms in optical lattices

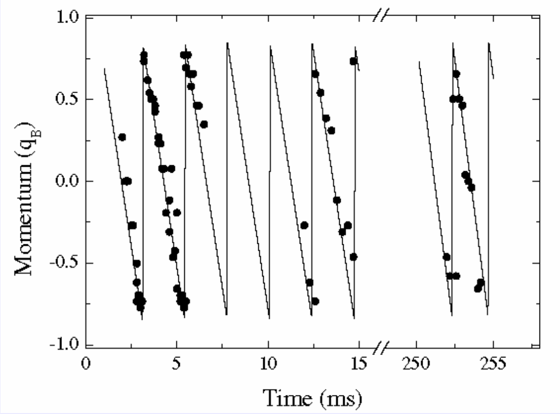


g = 9.6 (4) m/s^2

$\delta g/g \sim 10^{-4}$ in 10 ms

B. P. Anderson, M. A. Kasevich, *Macroscopic Quantum Interference from Atomic Tunnel Arrays*, Science 282, 1686 (1998)





g = 9.7372 (9) m/s^2

$\delta g/g \sim 10^{-4}$ in 250 ms

G. Roati, E. de Mirandes, F. Ferlaino, H. Ott, G. Modugno, M. Inguscio, *Atom Interferometry with trapped Fermi Gases*, PRL 92, 230402 (2004)

Precision gravity measurement with ultracold Sr atoms in an optical lattice:

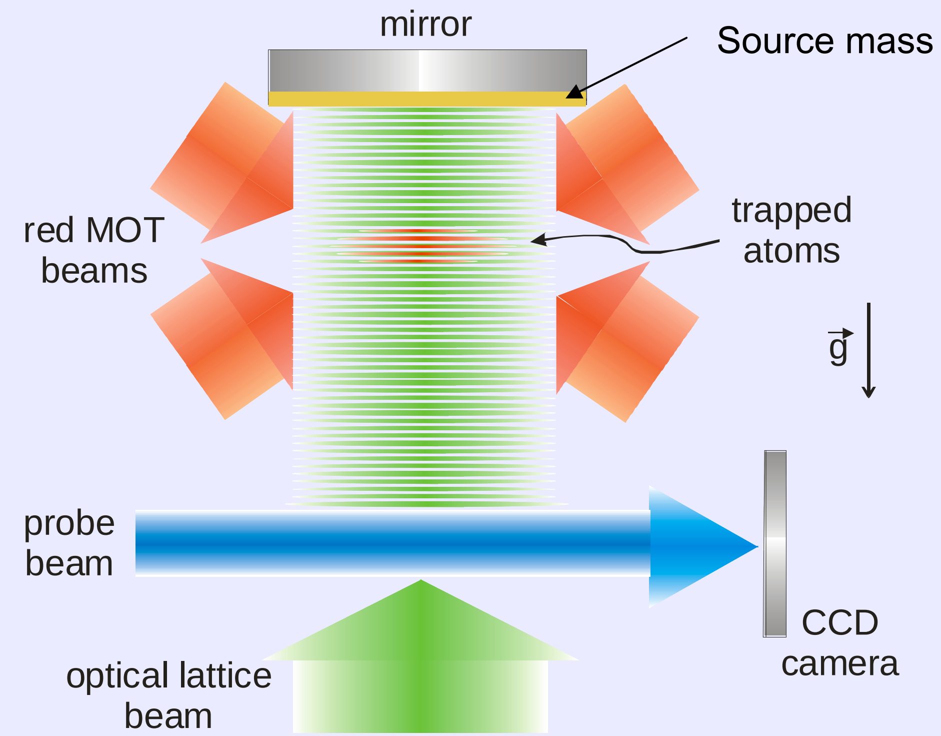
- **Measured gravity acceleration:** $g_{meas} = 9.80012\ (5)\ \mathrm{ms}^{-2}$

  From geophysical data: $g_{ref} = 9.805046\ (9)\ \mathrm{ms}^{-2}$

- **Present sensitivity:** $5 * 10^{-6}\ g$

- **Achievable sensitivity:** $\sim 10^{-7}\ g$

Scheme for the measurement of small distance forces

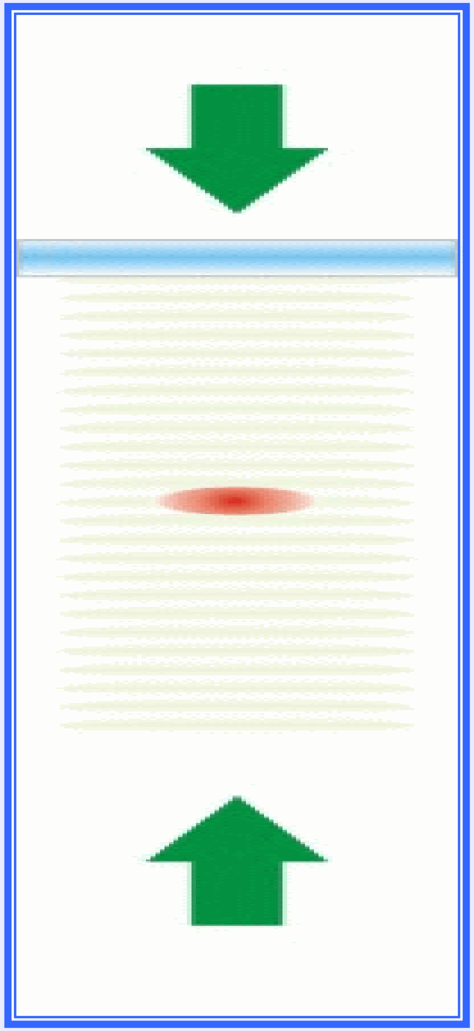


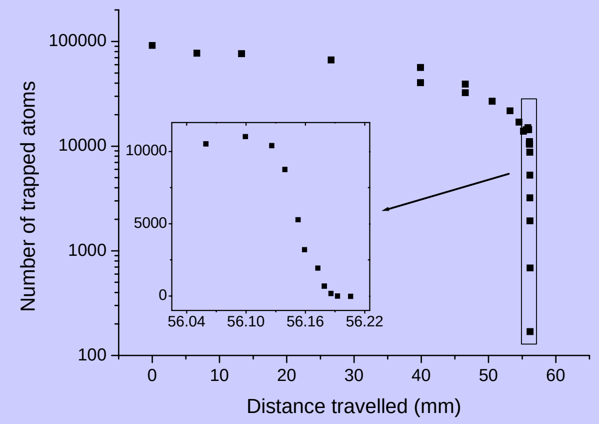
$$\nu = m\, \mathrm{a}\, \lambda / 2\, h$$

Objective: λ = 1- 10 μm, α = 10^3-10^4

G. Ferrari, G.M. Tino, INFN note, 2005
G. Ferrari, N. Poli, F. Sorrentino & G. M. Tino, 2006, to be published

Preliminary experiment



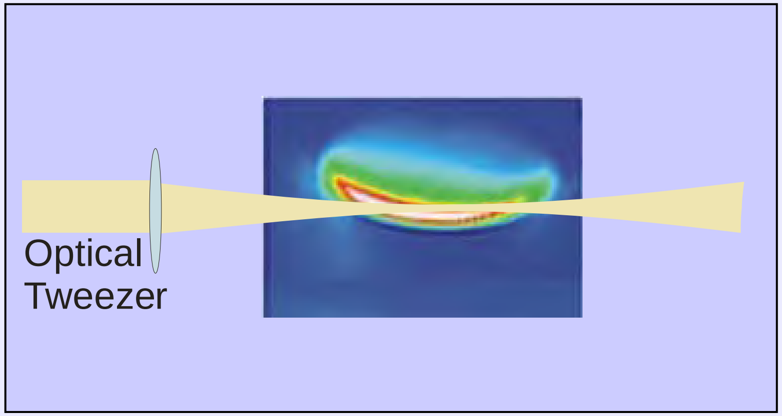


Vertical size of the atomic sample: 15 μm

Atom elevator:

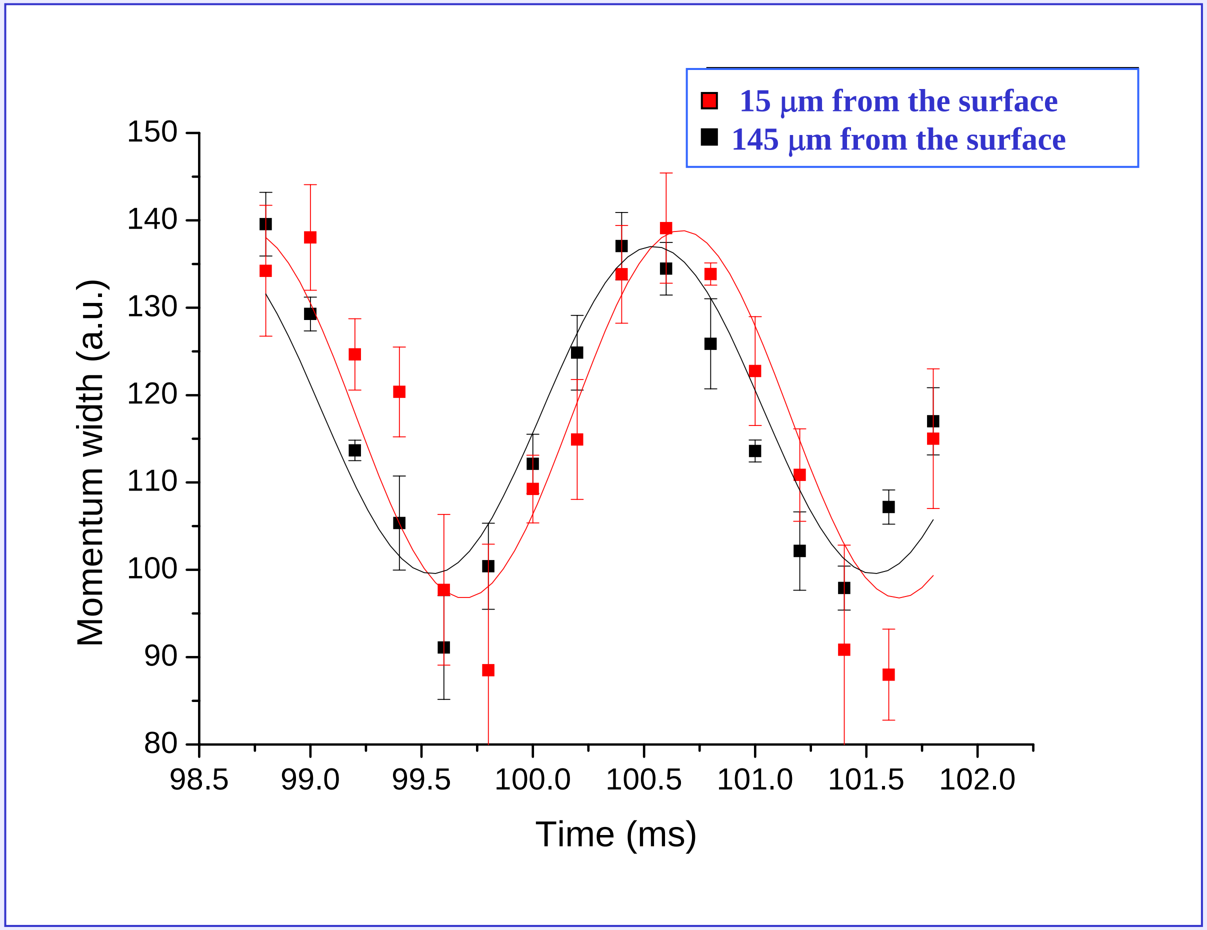
- **upward acceleration (1.35 g) for 10 ms**
- **uniform velocity (133 mm/s) for variable time**
- **downward acceleration (-1.35 g) for 10 ms**
- **rest for 470 ms**
- **reverse motion back to the starting point**

Vertical position fluctuations: 3 μm rms



•Vertical size reduced to 4 μm with an optical tweezer

Surface effect? (Preliminary)



Atom position varied by changing the duration of uniform velocity motion

Phase shift between 145 μm and 15 μm: 0.4 rad in 235 oscillations

$\Delta F \approx 10^{-3}$ gravity

Other experiments on atom-surface force

Hinds (1993)

Aspect-Westbrook (1997)

Vuletic (2004): effect of Casimir-Polder on atoms on chip

Shimuzu, Ketterle (2001,2005): effect of Casimir-Polder on quantum reflection

Cornell (2005): measurement of the Casimir-Polder force by oscillations of a BEC

Casimir-Polder and surface effects

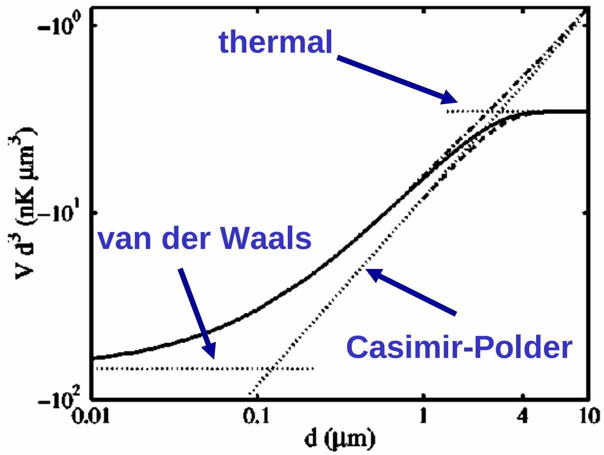


FIG. 3. The atom-surface potential is shown using the exact formula of Eq. (17) (solid line), the short-range approximation (21) (dash-dotted line), and the static approximation (26) (dashed line). The asymptotic van der Waals–London ($\sim 1/d^3$), Casimir-Polder ($\sim 1/d^4$), and high-T ($\sim 1/d^4$) potentials are also shown (dotted lines). The curves were obtained for a sapphire substrate at 300 K and for ^{87}Rb atoms in the condensate.

thermal

$$F_T = -\frac{3kT\alpha_0(\varepsilon_0-1)}{4z^4(\varepsilon_0+1)} \qquad z \gg \lambda_T$$

Casimir-Polder

$$F_{CP} = -\frac{3\hbar c\alpha_0(\varepsilon_0-1)\phi(\varepsilon_0)}{2\pi z^5(\varepsilon_0+1)} \qquad \lambda_{opt} \ll z \ll \lambda_T$$

^{87}Rb atoms
Sapphire substrate at 300 K
$\lambda_T = \hbar c/k_B T \sim 7.6$ μm
$\lambda_{opt} \sim 0.1$ μm

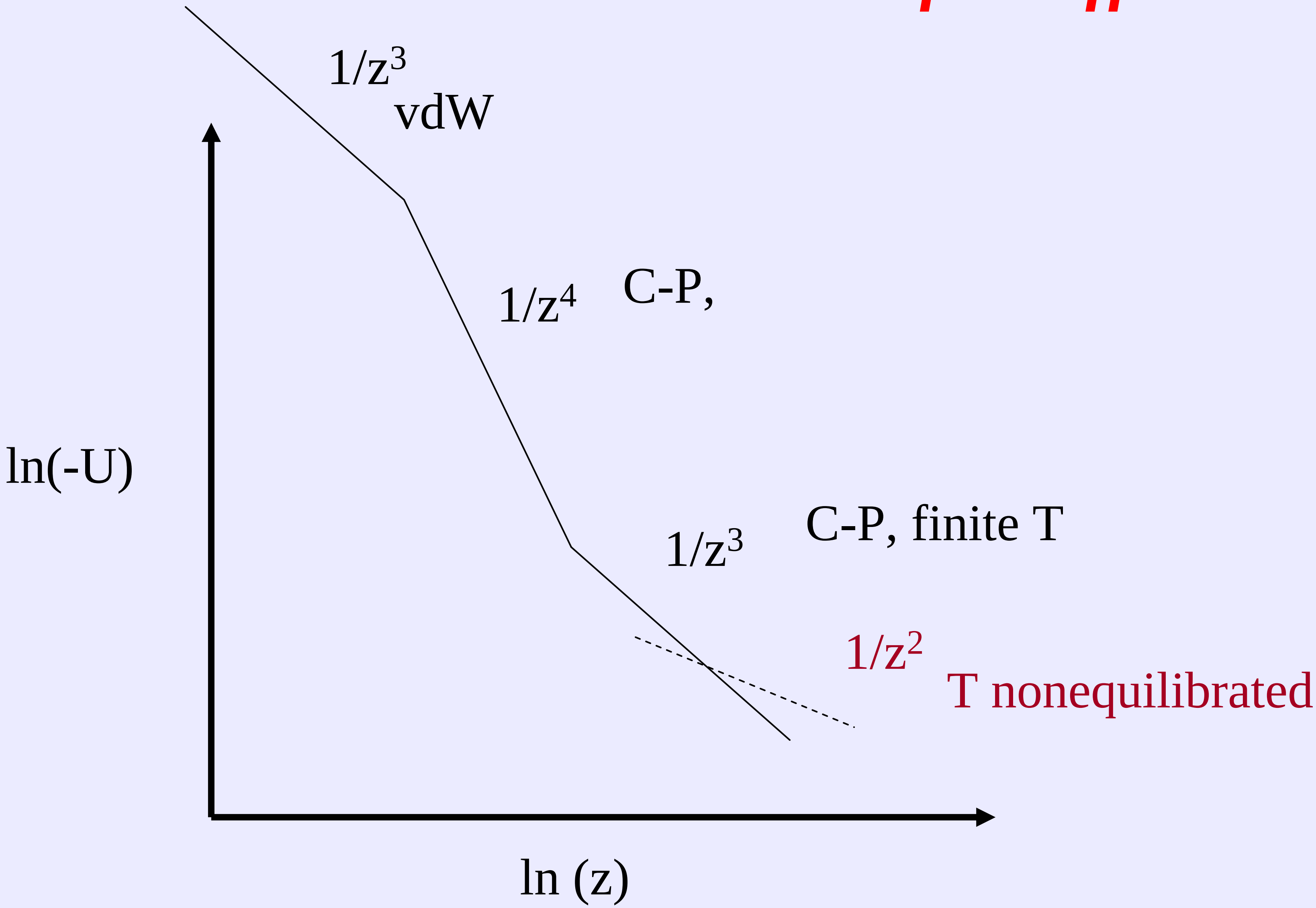
From M. Antezza et al., *Effect of the C-P force on the collective oscillations of a trapped BEC*, PRA 70, 053619 (2004)

surface-atom force
out of thermal equilibrium

$$F^{neq} = -\frac{\pi}{6}\frac{\alpha_0 k_B^2(T_{Surface}^2 - T_{Envir}^2)}{z^3 c\hbar}\frac{\varepsilon_0+1}{\sqrt{\varepsilon_0-1}}$$

M. Antezza et al., *New Asymptotic Behavior of the Surface-Atom Force out of Thermal Equilibrium* PRL 95, 113202 (2005)

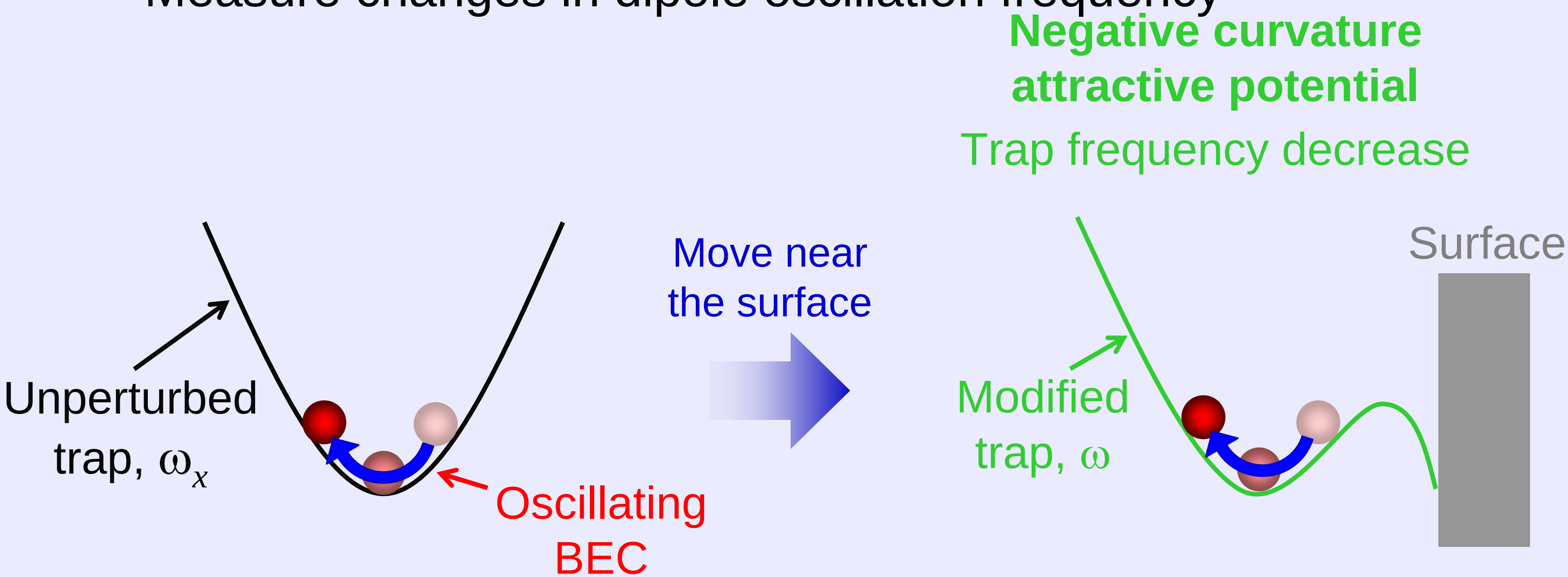
Casimir-Polder and surface effects



Measuring atom-surface forces

Use trapped BEC as a mechanical oscillator

Measure changes in dipole oscillation frequency

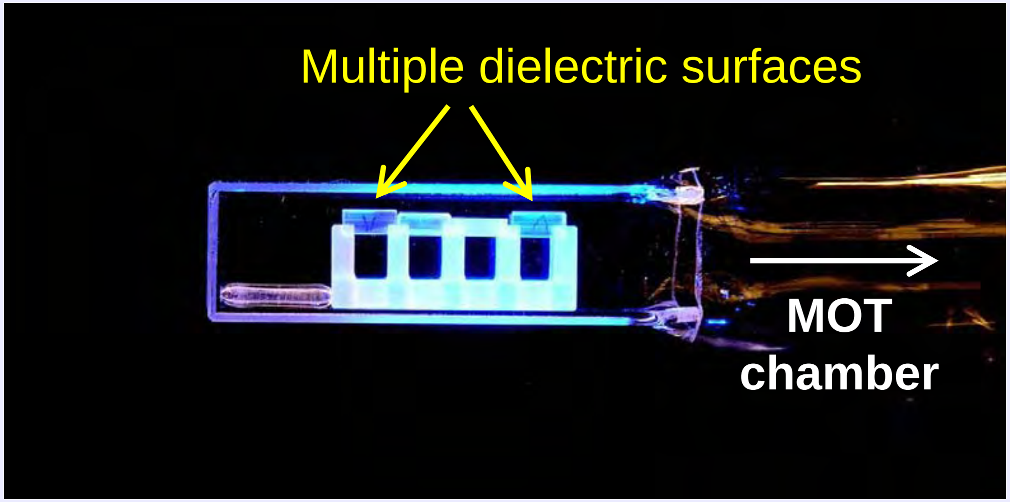


Express trap frequency changes as normalized frequency shifts:

$$\frac{\omega_x - \omega}{\omega_x} \approx -\frac{1}{2\omega_x^2 m}\frac{d^2U}{dx^2}$$

From E.A. Cornell
San Feliu Conference, 2005

Casimir-Polder force near a dielectric surface



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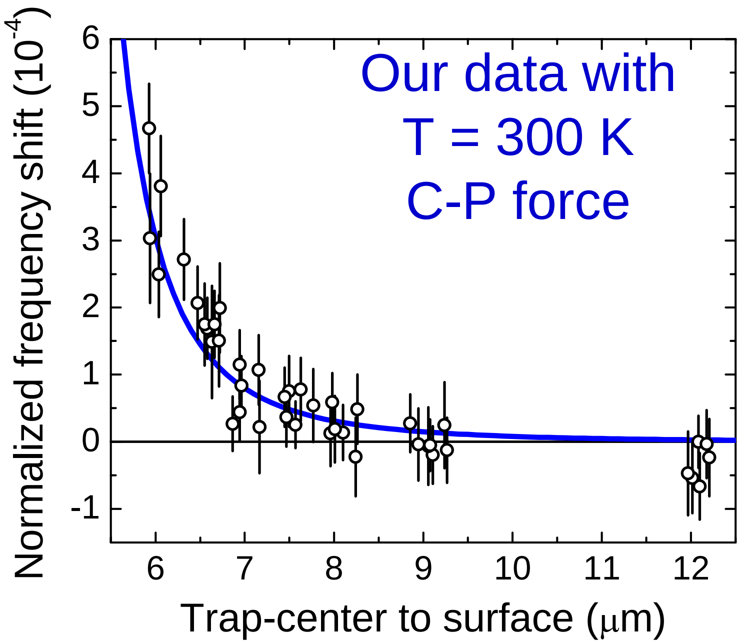
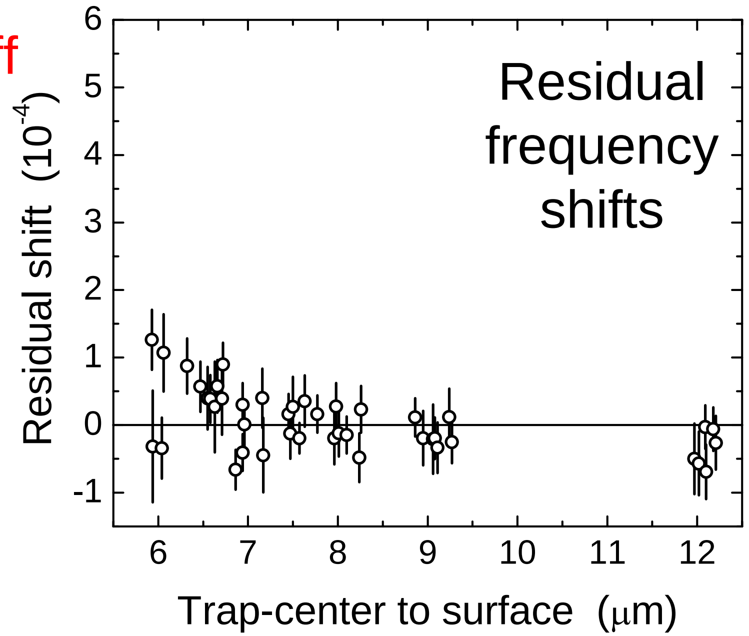
The *absence* of forces in addition to C-P force allows us to obtain limits from our data:



Subtract off C-P force



Use residuals to obtain a limit on the presence of additional forces

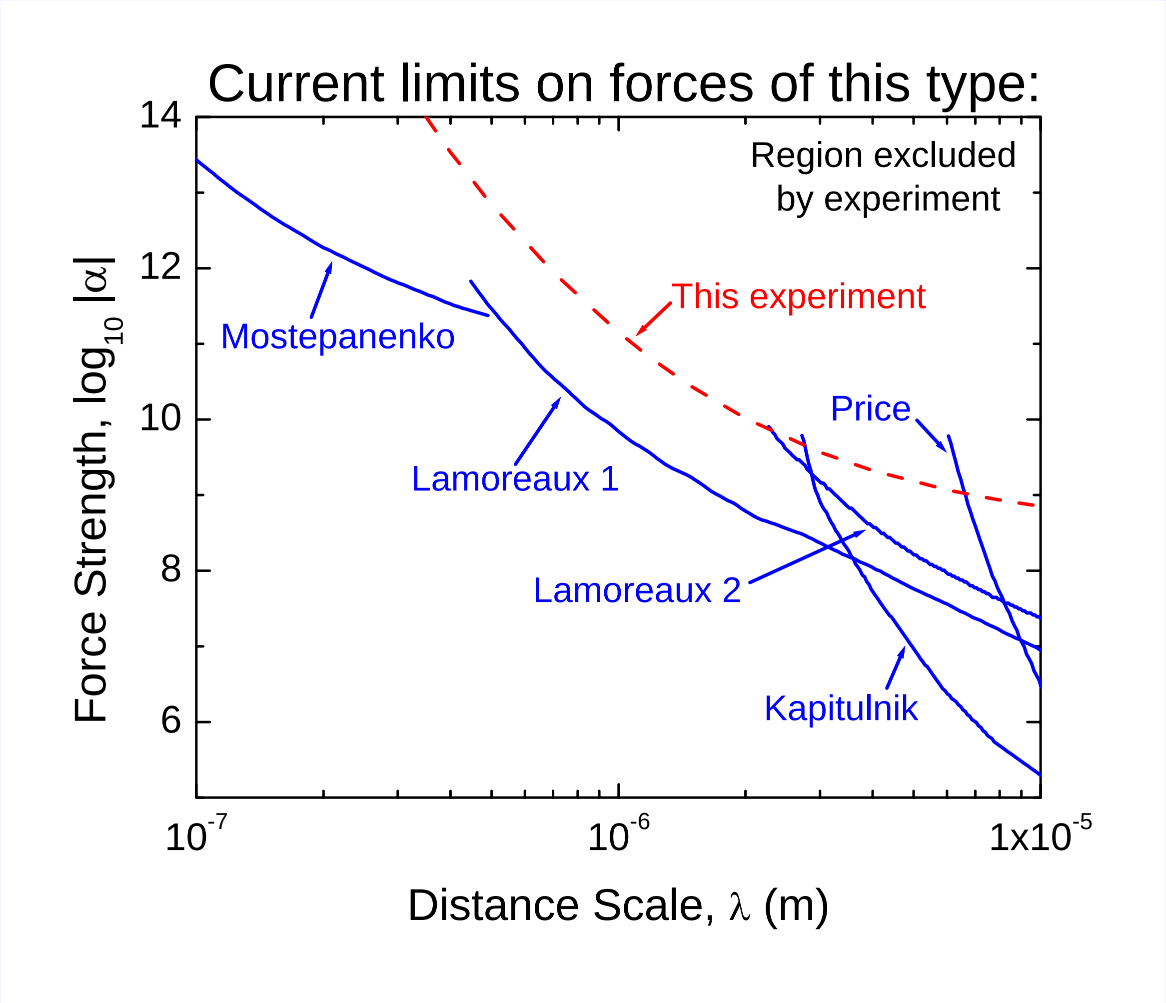
Residuals to the C-P force

From E.A. Cornell
San Feliu Conference, 2005

Limits on exotic forces

$$U = \int_V \frac{Gm\rho\, dV}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

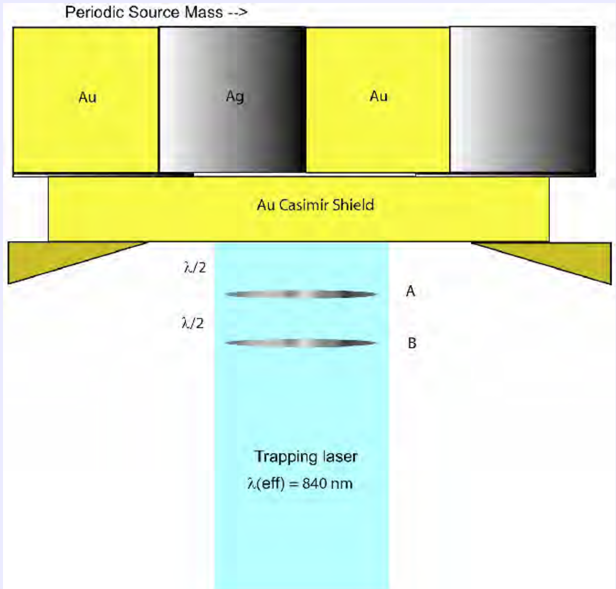
- Very different type of measurement (atom-bulk vs. bulk-bulk)
- Our experiment does not reach the current best limits in 1-10 μm range
- Experimental modifications could improve sensitivity by over an order of magnitude

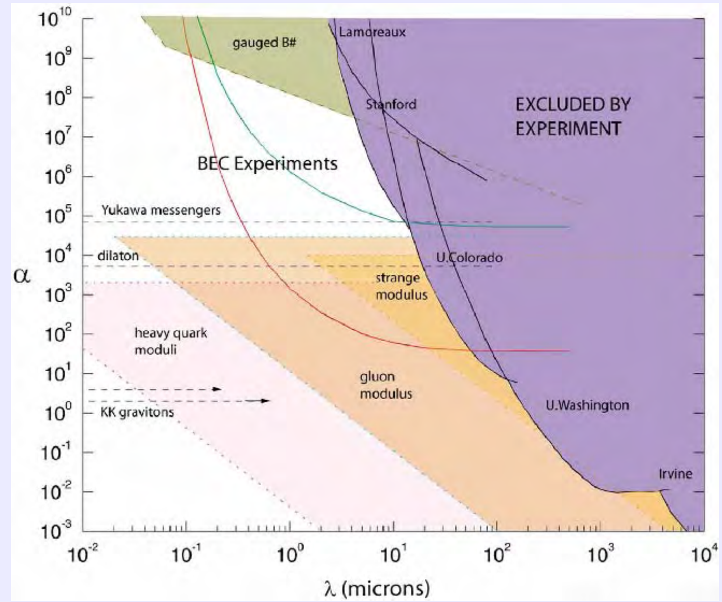


From E.A. Cornell, San Feliu Conference, 2005

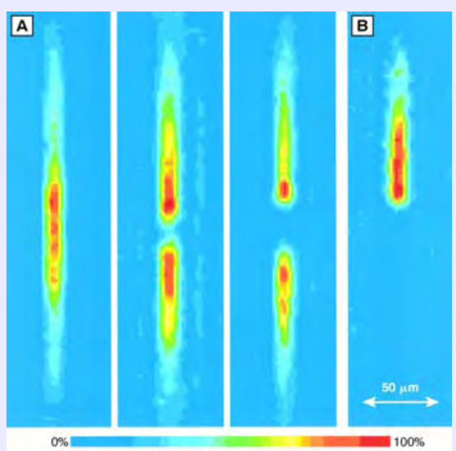
D. M. Harber, J. M. Obrecht, J. M. McGuirk, E. A. Cornell, ***Measurement of the Casimir-Polder force through center-of-mass oscillations of a Bose-Einstein condensate*****, PRA 72, 033610 (2005)**

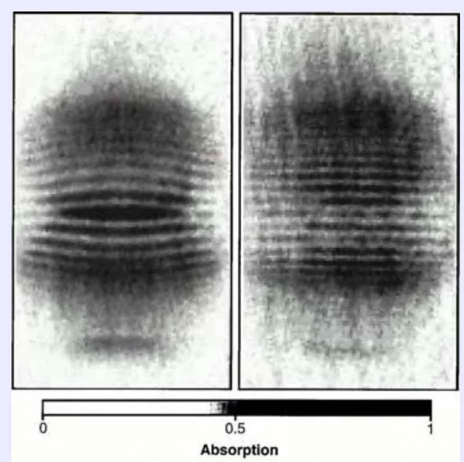
Interferometry with BEC - Proposal





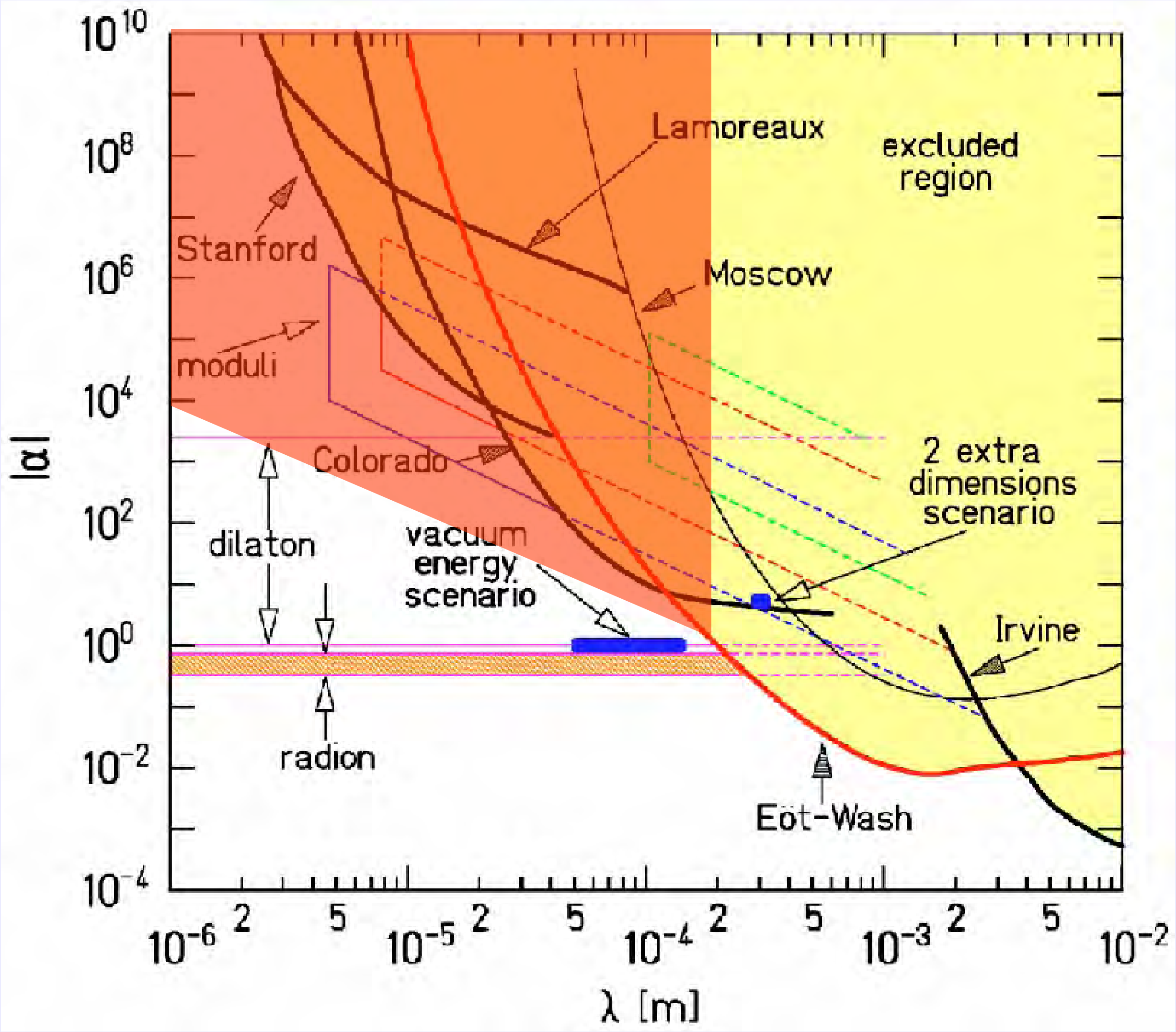
S. Dimopoulos, A. A. Geraci, *Probing submicron forces by interferometry of Bose-Einstein condensed atoms,* PRD 68, 124021 (2003)





M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, W. Ketterle, *Observation of Interference Between Two Bose Condensates,* Science, 275, 637 (1997)

Accessible region with atomic probes



Conclusions and Prospects

The small size and high sensitivity of atomic sensors enable the investigation of small spatial-scale forces as in atom-surface interactions, surface-induced decoherence, Casimir-Polder interaction, and for the search of recently predicted deviations from the Newtonian gravitational law at micrometer scale

We observed persistent Bloch oscillations of weak-interacting bosonic Sr atoms in a vertical optical lattice for a time longer than 7 s, with more than 8000 photon momenta coherently transferred to the atoms

Longer coherence time and reduced complexity compared to alternative approaches based on degenerate Bose or Fermi gases

The new scheme can be used for a force sensor with micrometric size and sensitivity ~ 10^{-7} g

Gravity can be investigated in new unexplored regions (λ ~ 1-10 μm, α ~ 10^3-10^4) with no need for modeling and extrapolation as in the case of macroscopic probes

Applications of new quantum sensors based on atom interferometry

- Measurement of fundamental constants → α, → G
- New definition of kg
- Test of equivalence principle
- Short-distances forces measurement
- Search for electron-proton charge inequality
- New detectors for gravitational waves ?
- Transportable sensors → geophysics, → space

School & Workshop

http://www.fi.infn.it/GGI/

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M. Prevedelli	Long term guest, Università di Bologna
M. Fattori	ex-PhD student, now in Stuttgart
T. Petelski	ex-PhD student, now in Munich
J. Stuhler	ex-Post-doc, now in Stuttgart

Collaborations

- **IEN, Torino**
- **IMGC, Torino**
- **Humboldt-Universitaet zu Berlin**
- **IQO, Hannover**
- **ENS and SYRTE, Paris**

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- ✓ **Agenzia Spaziale Italiana (ASI)**
- ✓ **Istituto Nazionale per la Fisica della Materia (INFM)**
- ✓ **Istituto Nazionale Geofisica e Vulcanologia (INGV)**