- Light Waves and Matter Waves -
Atom Interferometers and Optical Clocks

Guglielmo M. Tino

Dipartimento di Fisica & Astronomia e LENS – Università di Firenze

Istituto Nazionale di Fisica Nucleare, Sezione di Firenze

http://coldatoms.lens.unifi.it/

International Centre for Theoretical Physics
Winter College on Optics:
Light: a bridge between Earth and Space
Trieste, 9 - 20 February 2015

Outline of the Lectures

- *Lecture I: Atom Interferometry*
  Light waves and matter waves, atom interferometry, methods, experiments on Earth and in space.

- *Lecture II: Optical Atomic Clocks*
  Atomic clocks, basics, methods, optical clocks, experiments on Earth and in space.

Lecture I: Atom Interferometry

- Introduction
- Basic concepts
- Experimental methods
- Atom interferometers
- Experiments on Earth and in space

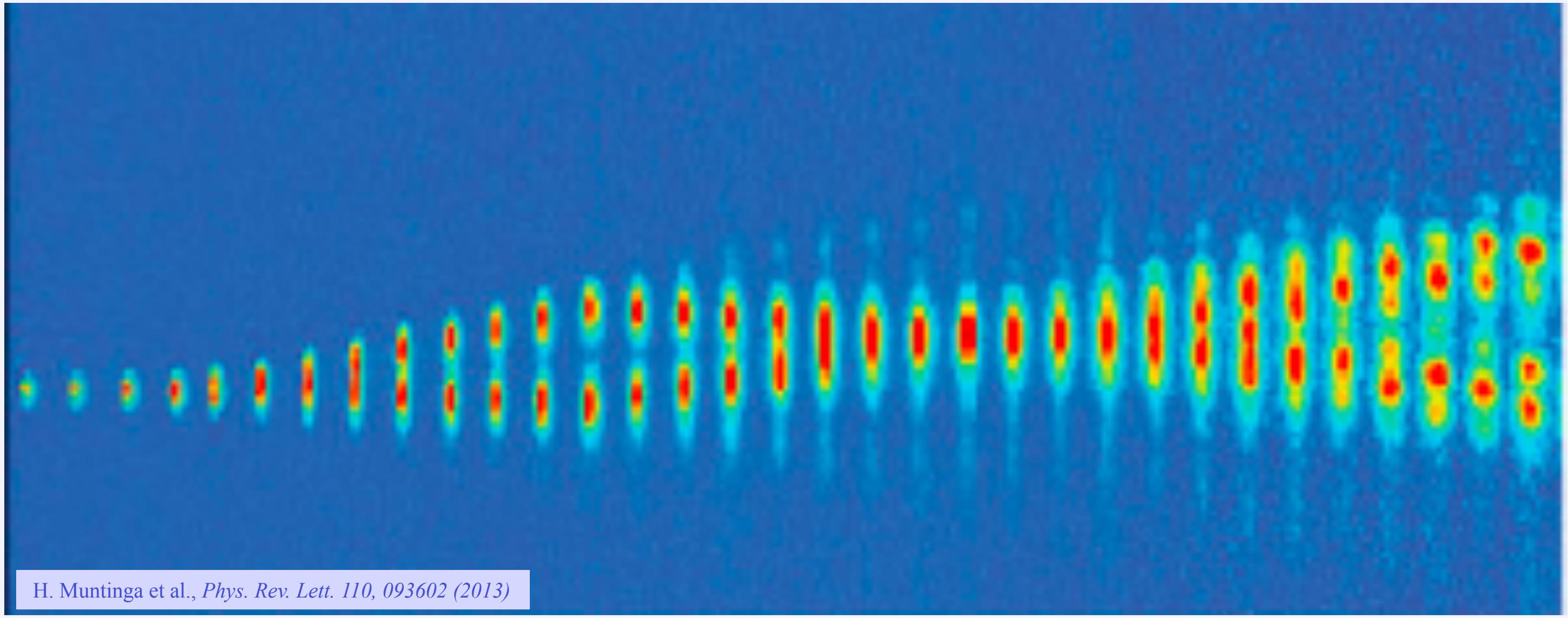
Main references

- A. D. Cronin, J. Schmiedmayer, D. E. Pritchard, *Optics and interferometry with atoms and molecules,* Rev. Mod. Phys. 81, 1051 (2009).

- J. Schmiedmayer, *Interferometry with atoms*, Lectures at the E. Fermi School on *Atom Interferometry*, Varenna (2013).

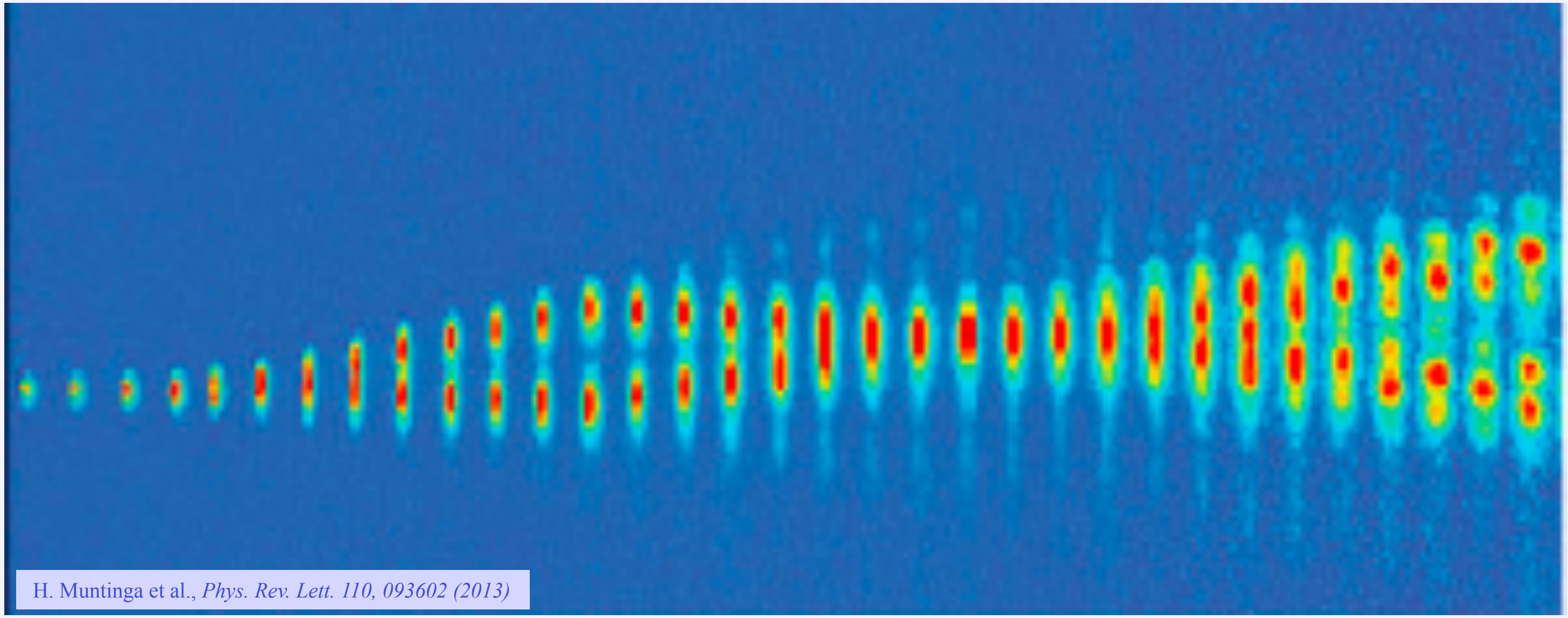
- G. M. Tino, M. A. Kasevich (eds). *Atom Interferometry*. Proc. International School of Physics 'Enrico Fermi', Course CLXXXVIII, Varenna 2013, SIF and IOS (2014).

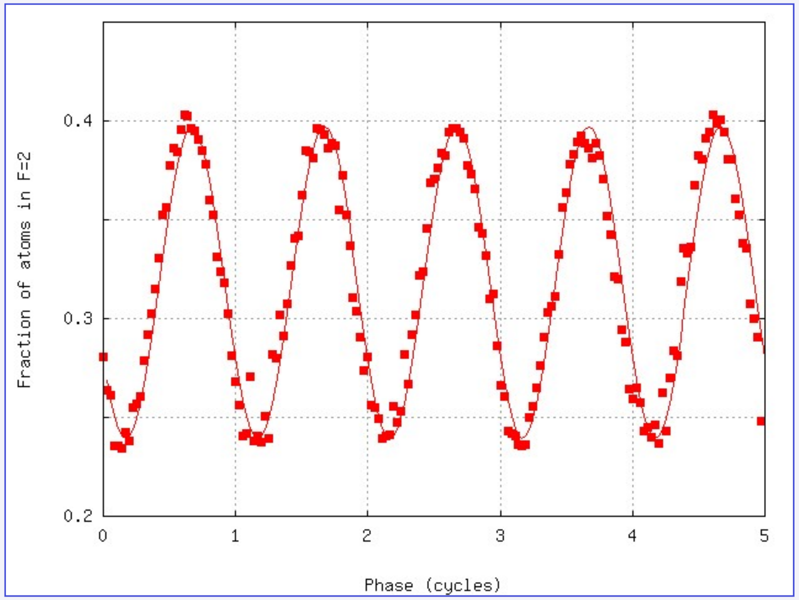
Atom Interferometry



H. Muntinga et al., *Phys. Rev. Lett. 110, 093602 (2013)*

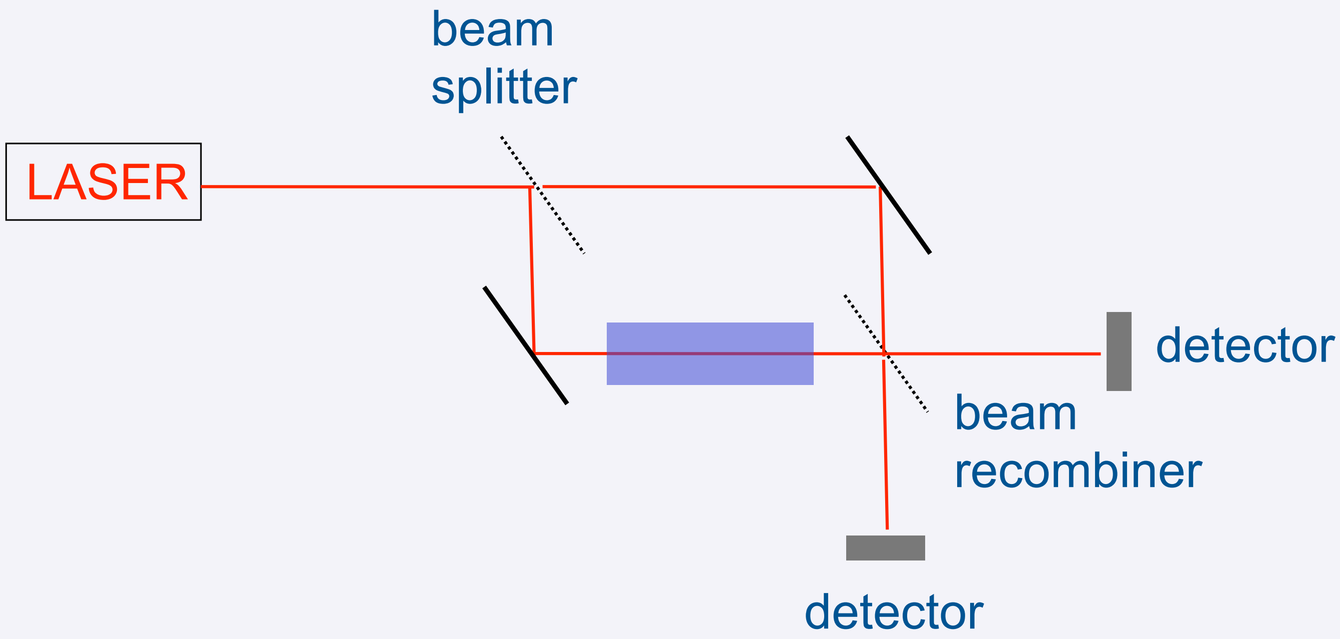
Atom Interferometry





Interference fringes – Firenze 2006

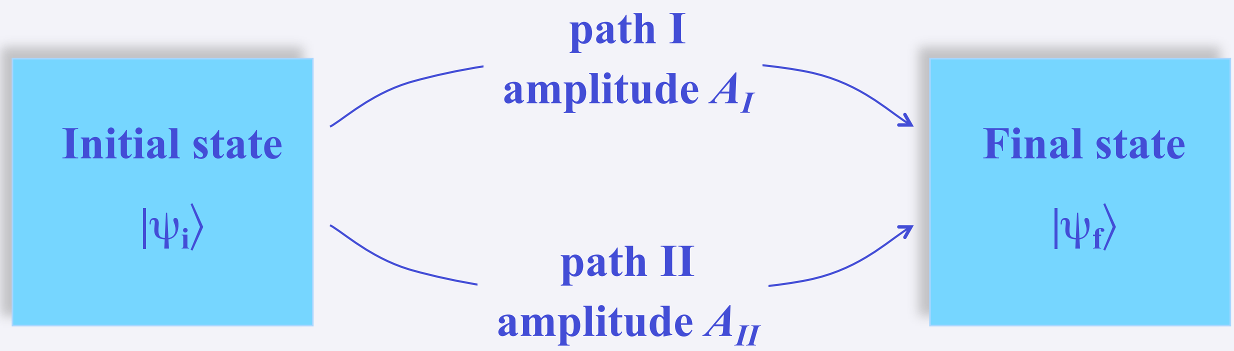
Optical interferometry



Change of optical path, length, pressure, temperature,… → Change of phase of interference pattern

From C. Salomon

Quantum interference



Interference of transition amplitudes

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

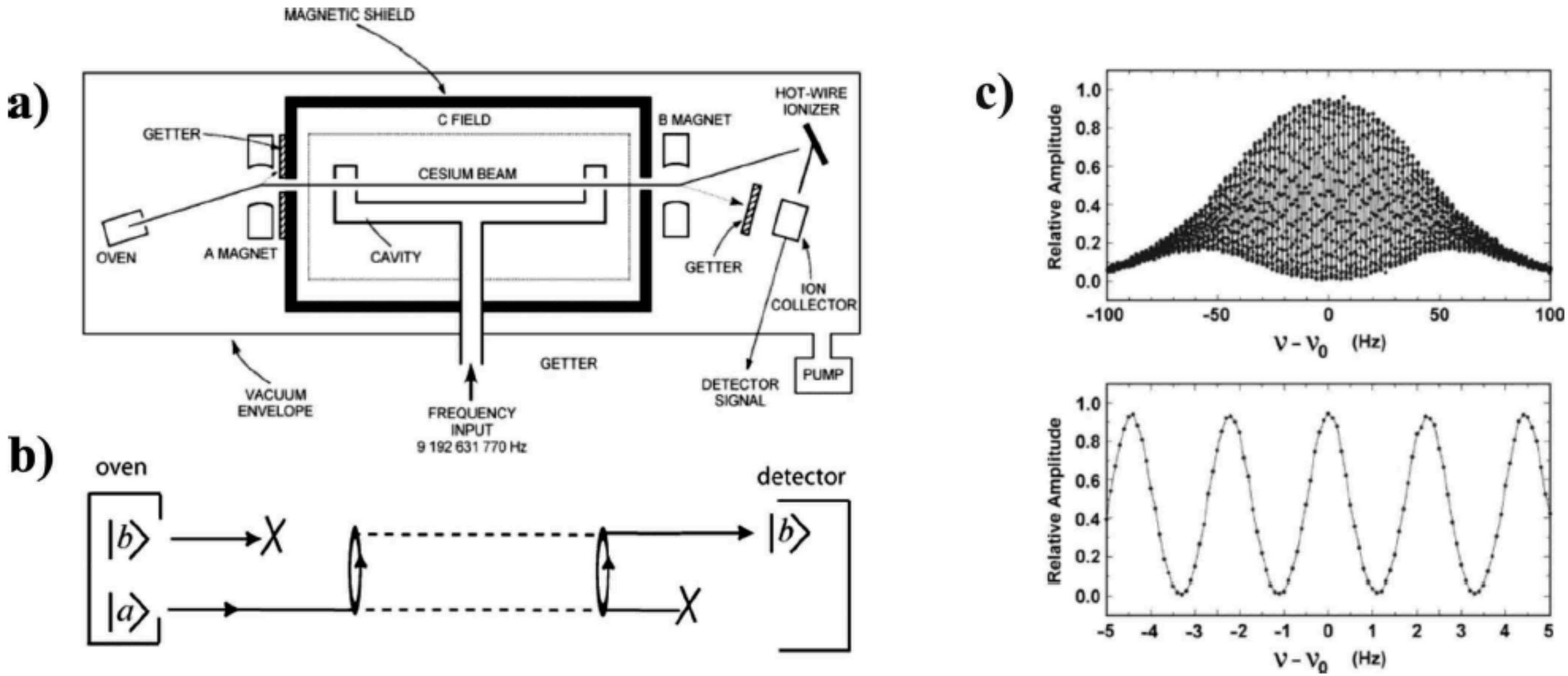


FIG. 1. Interferometry with internal quantum states of atoms. (a) Ramsey's separated oscillatory fields experiment. (b) The same experiment depicted as an interferometer for internal states. (c) The detected atom count rate exhibits interference fringes as a function of the applied rf frequency. These interference fringes, from the NIST-F1 fountain clock (Sullivan *et al.*, 2001), demonstrate the precision obtained with interference techniques. From Sullivan *et al.*, 2001.

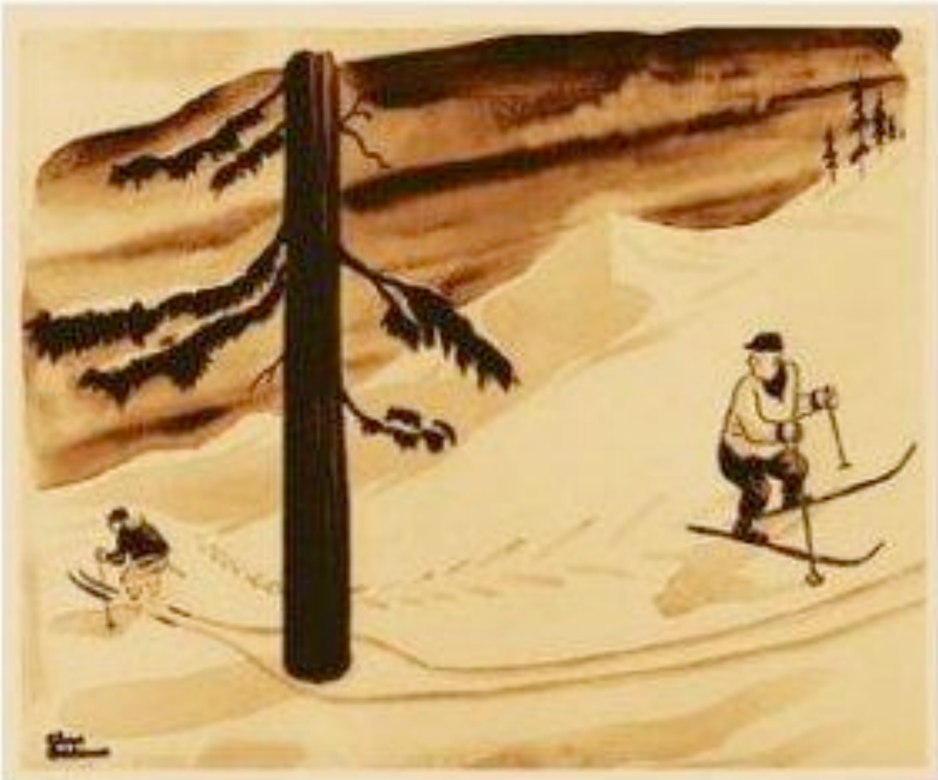
PHYSICS TEXTBOOK

Yakir Aharonov
Daniel Rohrlich

WILEY-VCH

Quantum Paradoxes

Quantum Theory for the Perplexed



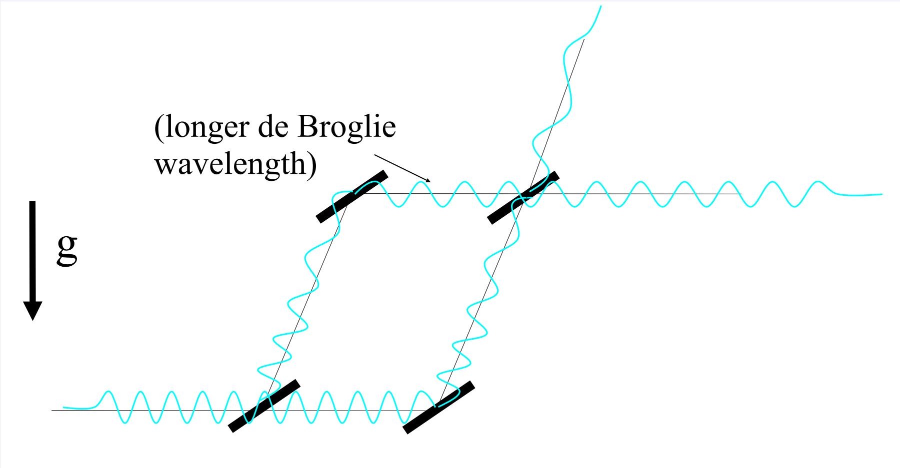
Atom interferometer force sensors

The quantum mechanical wave-like properties of atoms can be used to sense inertial forces.

$$\lambda_{DB} = \frac{h}{Mv}$$

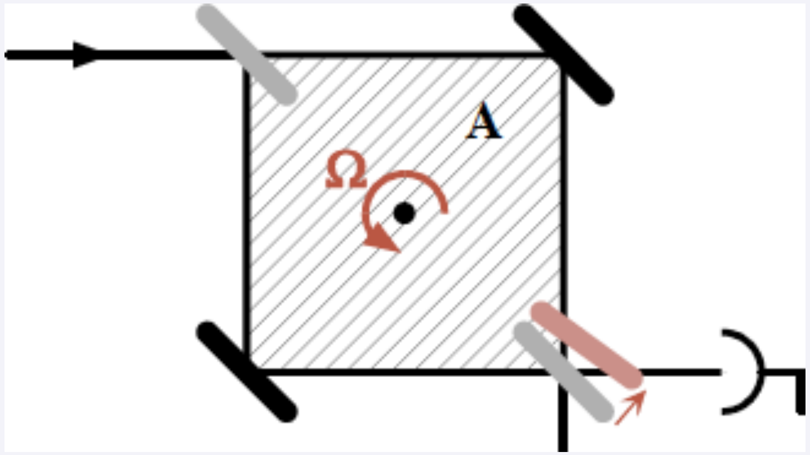
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases

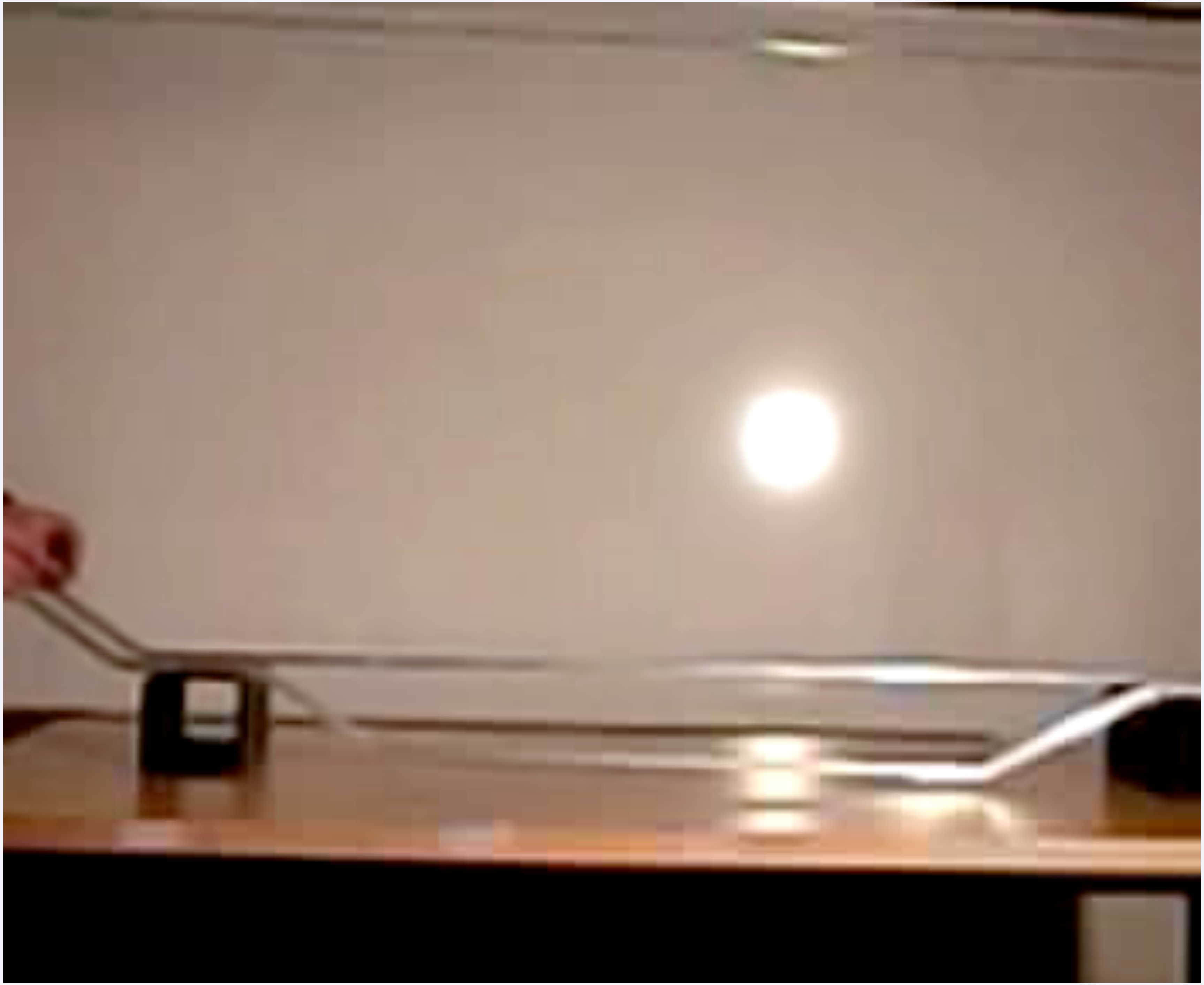


Rotations

Rotations induce path length differences by shifting the positions of beam splitting optics



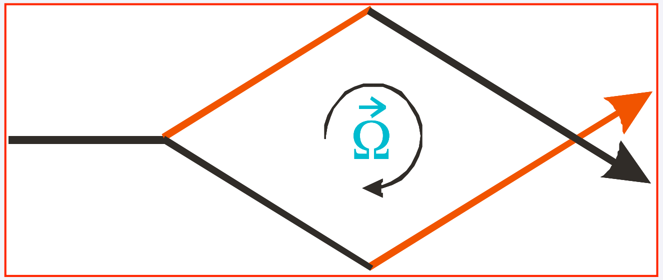
From M. Kasevich



Courtesy of M. Gisselbrecht

Matter wave sensors

rotations:



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

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

$\Delta\varphi$ *effects*

- Accelerations
- Rotations
- Laser frequency detuning
- Laser phase
- Photon recoil
- Electric/magnetic fields
- Interactions with atoms and molecules

Atomic vs optical interferometers

- The atoms move much more slowly in the interferometer compared to the photons. The interaction times are therefore much longer and the sensitivity can be much higher, for example to inertial effects (acceleration, rotation, gravitation).
- The actual size of optical interferometers can be much larger compared to atom interferometers. Examples are LIGO/Virgo interferometers and optical fiber gyroscopes.
- For the atoms, possibility to control the internal state and detection sensitive to internal state.
- For the atoms a larger variety of internal states compared to the photons which have only the two polarizations.
- Higher fragility of the atoms. In an atom interferometer it is important to avoid all processes of spontaneous emission or collisions that can destroy the atomic coherence.
- The flux of photons in a laser beam is typically much larger than the flux of atoms in a beam.

Matter Waves

Luis de-Broglie 1924:
Particles with rest-mass $m_0>0$ (electrons, neutrons, atoms, molecules) are elementary quanta of a wave field $\Psi(x,t)$

relativistic:

$$\hbar\omega = E = mc^2 = \gamma m_0 c^2$$

$$\hbar\left|\vec{k}\right| = \frac{h}{\lambda} = \left|\vec{p}\right| = mv = \gamma m_0 v$$

non - relativistic:

$$\lambda_{dB} = \frac{h}{mv} \qquad \hbar k = mv$$

Optics with Matter Waves: Some numbers

Particle	Energy	Velocity	Wave length
Neutron	0.025 eV	2200 m/s	2.2 A
Electron	100 eV	$6\ 10^6$ m/s	1.2 A
Na (atomic beam)	0.11 eV	1000 m/s	0.17 A
Cs (laser cooled)	$7\ 10^{-11}$ eV	1 cm/s	3000 A

from J. Schmiedmayer, E. Fermi School on "Atom Interferometry", Varenna 2013

Wave Optics:
comparison
Light – Matter Waves

Light:
Maxwell equations

$$\left[\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right]\vec{A}(r,t) = 0$$

Matter waves:
Schrödinger equation

$$\left[-\frac{\hbar^2}{2m}\nabla^2 + V(r,t)\right]\Psi(r,t) = i\hbar\frac{\partial\Psi(r,t)}{\partial t}$$

Wave equation in
time independent formulation:

$$\left[\nabla^2 + k^2(r)\right]\Psi(r) = 0$$

Wave vector for matter waves:

$$k(r) = \frac{1}{\hbar}\sqrt{2m\left(E - V(r)\right)}$$

$$k = \frac{2\pi}{\lambda}$$

from J. Schmiedmayer, E. Fermi School on "Atom Interferometry", Varenna 2013

Coherence length
and
thermal de Broglie wavelength

Coherence length $$\xi \simeq \frac{\hbar}{\Delta p}$$

Thermal de Broglie wavelength $$\lambda_T = \frac{h}{\sqrt{2\pi m k_B T}}$$

Experimental Methods

Atomic Beams

Atom Sources

- Atoms enter the atomic beam machine from a (gaseous) reservoir through a small opening
- Velocity (wave length) of the atoms is given by the thermal distribution of the atoms passing through the opening.
  - Effusive sources
    wide thermal velocity distribution
  - Supersonic expansion
    cooling in the expansion leads to a narrow velocity distribution

$$\frac{\Delta v}{v} = \frac{\Delta\lambda}{\lambda} \approx 100\%$$

$$\frac{\Delta v}{v} = \frac{\Delta\lambda}{\lambda} \leq 10\%$$

Atom Beam

- For free propagation of atoms we need at least HV conditions: $p < 10^{-7}$ *torr*
- In the gravitational field of the earth propagation is in free fall
- Good collimation can be achieved with narrow slits
  (10µm slits separated 1m apart $\sim 10^{-5}$ rad)

from J. Schmiedmayer, E. Fermi School on "Atom Interferometry", Varenna 2013

Experimental Methods
Cold Atoms

Laser Cooling

Neutral atoms can be cooled by interacting with monochromatic light (~thermal equilibrium with the light)

- Temperature 1mK ⇨ 1μK
- Velocity 0.5m/s ⇨ 1mm/s
- deBroglie wavelength 10nm ⇨ 500nm
- Typical samples 10^8 atoms @ 10^{11} atoms/cm^3

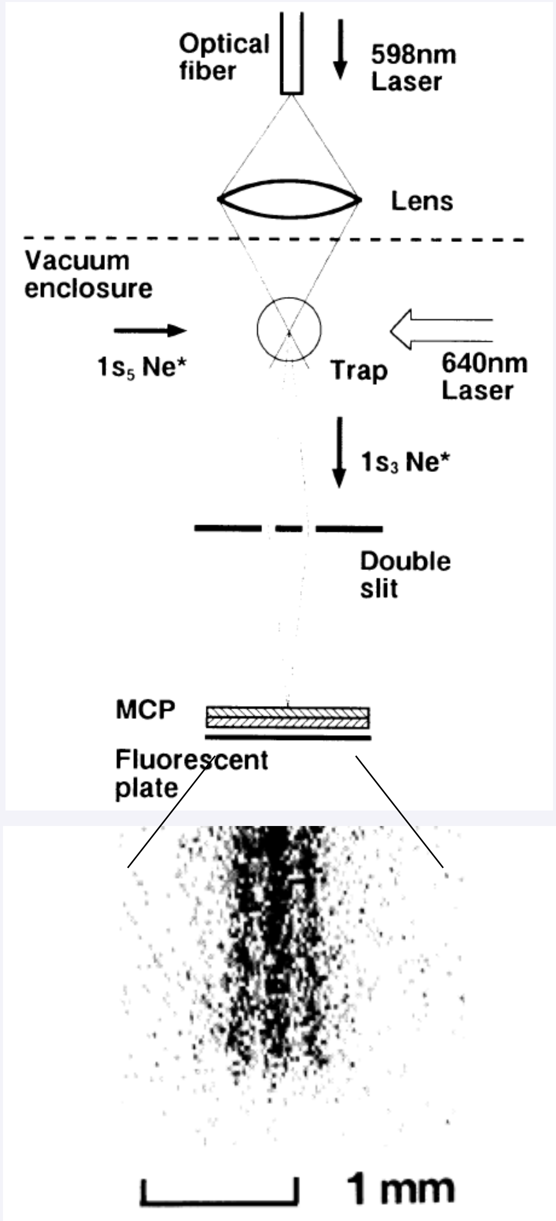
BEC

Cooling in a magnetic trap by removing the hottest atoms and thermal equilibration (evaporative cooling)

- Typical samples >10^5 atoms @ 10^{14} atoms/cm^3
- Temperature <1μK
- deBroglie wavelength >1μm

from J. Schmiedmayer, E. Fermi School on "Atom Interferometry", Varenna 2013

Young's double slit interference with cold metastable atoms



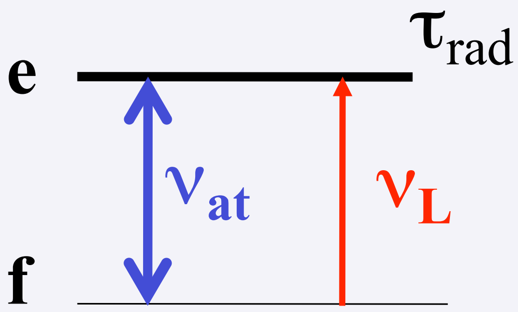
F. Shimizu et al.,
Phys. Rev. A 46, R17 (1992)

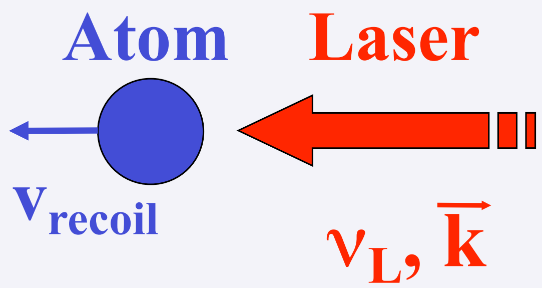
Cold atom source
$\rightarrow$ large λ_{dB}
$\rightarrow$ large fringe spacing

Metastable atoms
$\rightarrow$ single atom detection
$\rightarrow$ wave/particle duality for atoms

Laser cooling and manipulation of atoms

Radiation pressure





Momentum conservation $\rightarrow$ $\vec{v}_{recoil} = \hbar\,\vec{k}/M$

Isotropic emission $\rightarrow$ $\langle \vec{v}_{em} \rangle = 0$

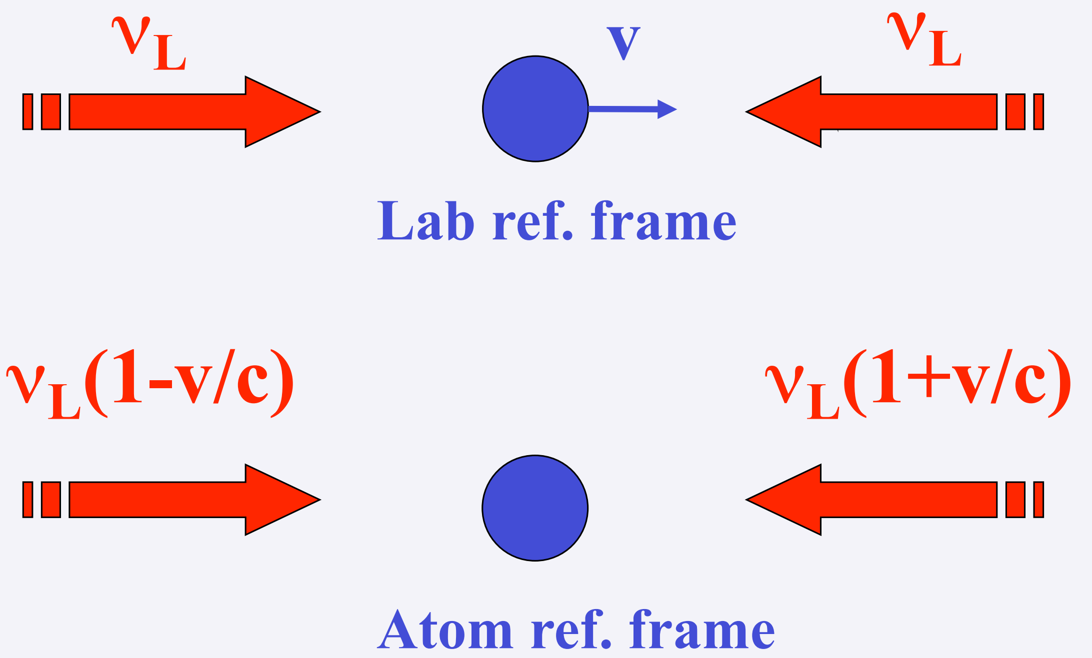
$\rightarrow$**Radiation pressure force:** $\vec{F} = \hbar\vec{k}/2\tau_{rad} = M\vec{a} \;\rightarrow\; a = \hbar k/2M\tau_{rad}$

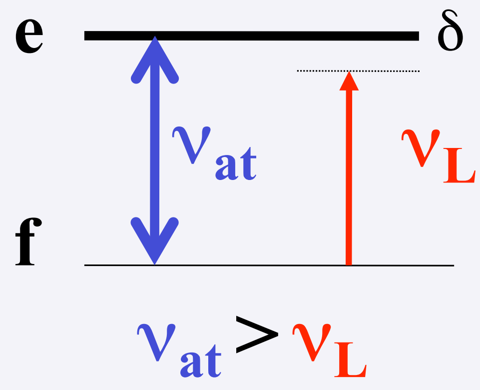
Example, Na atom : $\lambda \approx 589$ nm, M= 23 a.m.u., $\tau_{rad} \approx 16$ ns

$\rightarrow$ $v_{recoil} \approx 3$ cm/s, $a \approx 10^6\ m/s^2 \approx 10^5\ g$

$t_{stop} = v_{in}/a \approx 1$ ms, $L_{stop} = v_{in}^2/2a \approx 0.5$ m

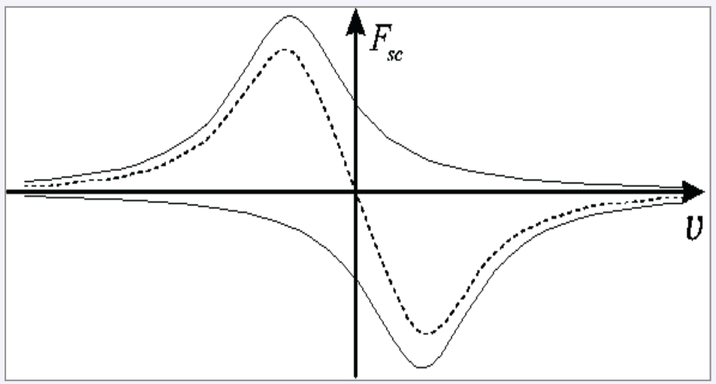
Optical molasses





$(I/I_0 \ll 1)$

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



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

Idea: **T.W. Hänsch, A. Schawlow, 1975**

Exp. demonstration: **S. Chu et al., 1985**

Laser cooling: atomic temperatures

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

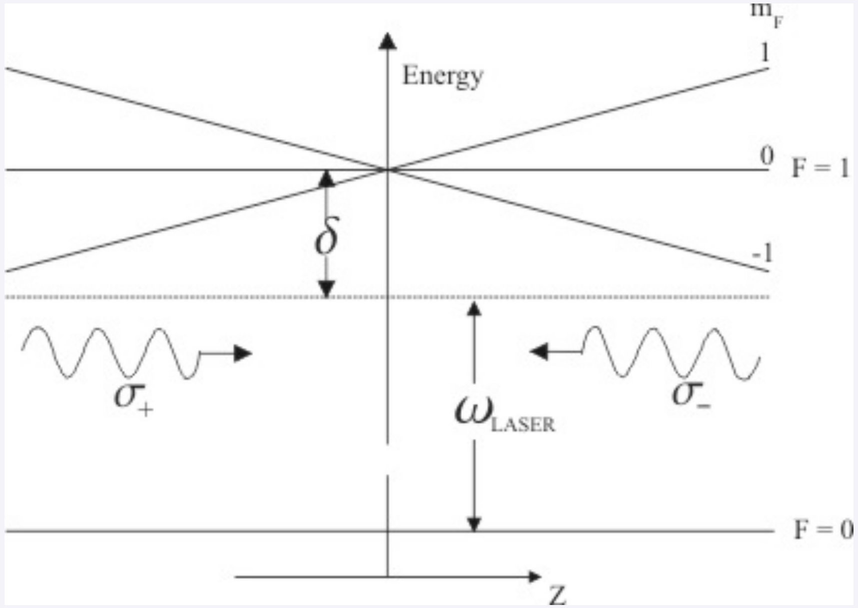
Minimum temperature for Doppler cooling: $k_B T_D = \frac{\hbar\Gamma}{2}$

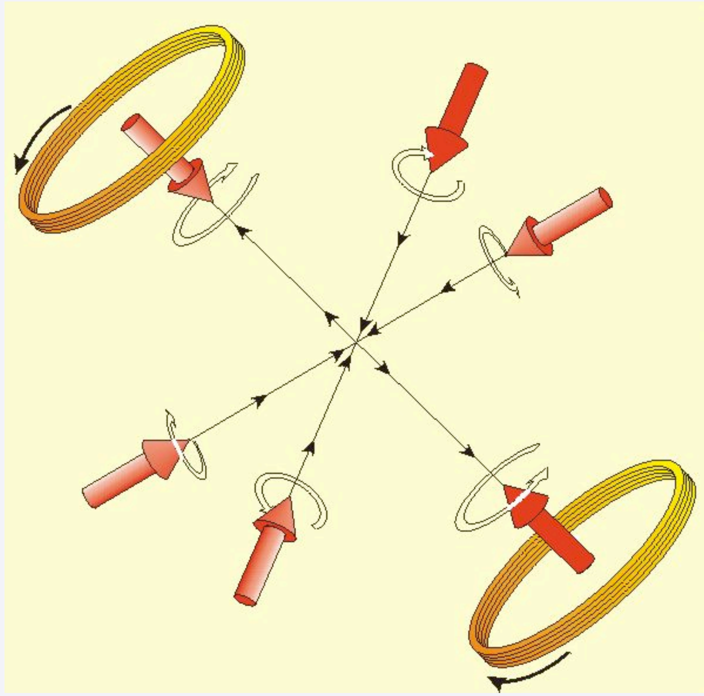
Single photon recoil temperature: $k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$

Examples:

	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK
Sr (intercombination transition)	180 nK	460 nK

Magneto-Optical Trap (MOT)



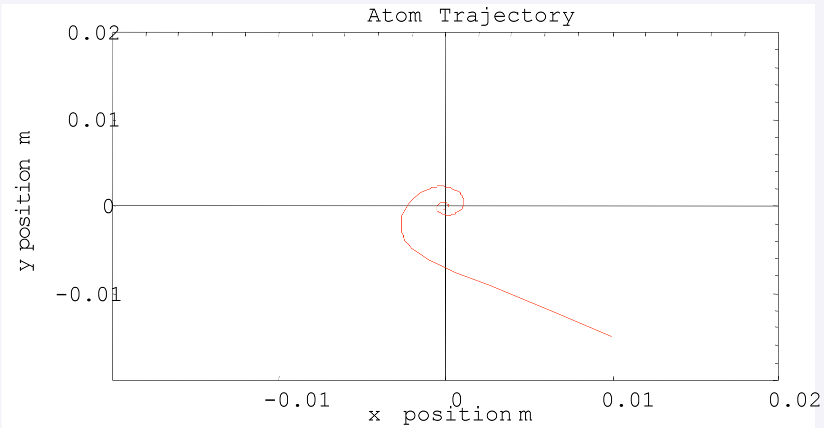


$$F(z,\mathrm{v}) \simeq \frac{4hk}{\pi}\,\frac{I}{I_0}\,\frac{\delta}{\Gamma}\,\frac{k\mathrm{v}+\beta z}{\left[1+\left(\frac{2\delta}{\Gamma}\right)^2\right]^2}$$

density n ≈ 10^{11} cm^{-3}

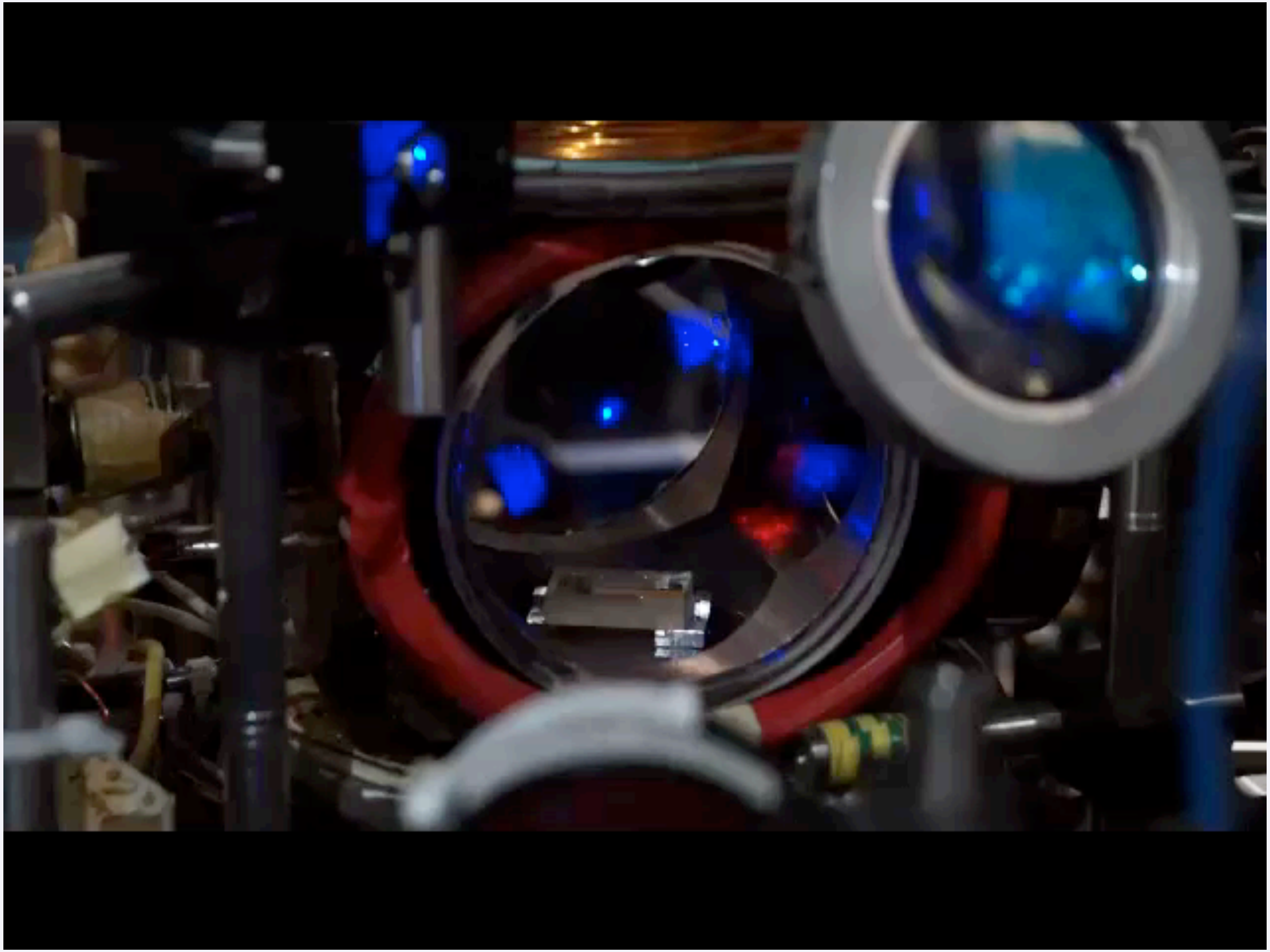
temperature T ≈ 100 μK

size Δx ≈ 1 mm

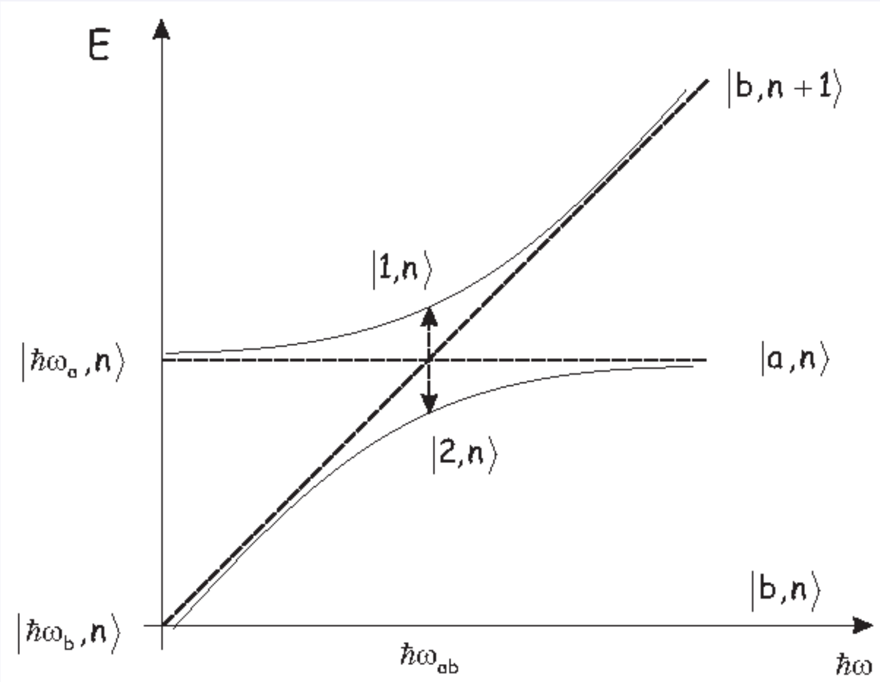


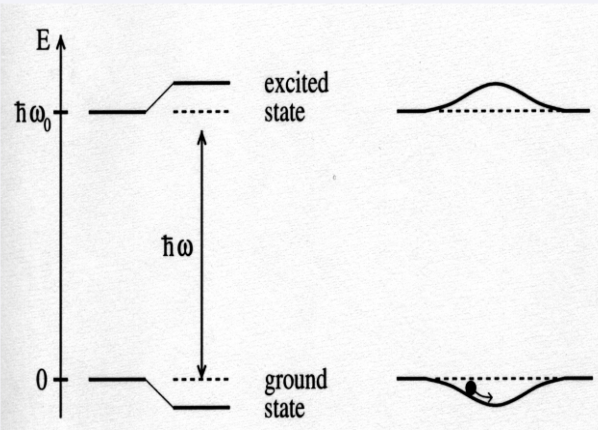
E. Raab *et al.*, Phys. Rev. Lett. 59, 2631 (1987)

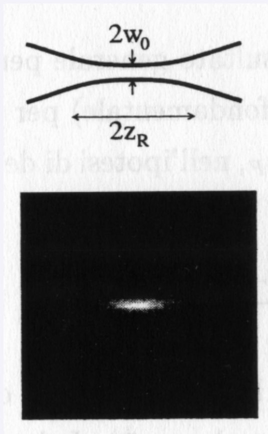
Sr Magneto-Optical Trap (MOT)
LENS - Firenze



Light shifts and optical traps



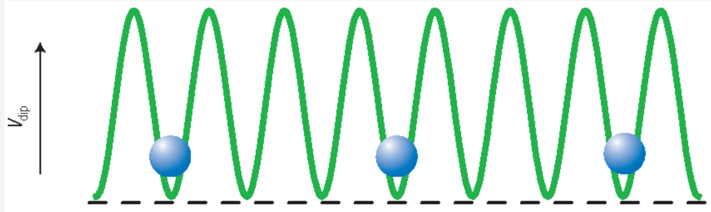




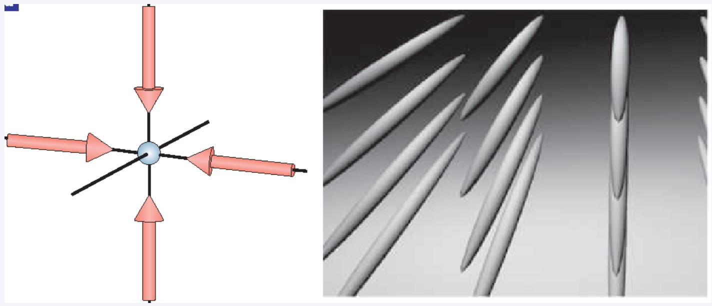
$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)|\mathbf{E}(\mathbf{r})|^2$$

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

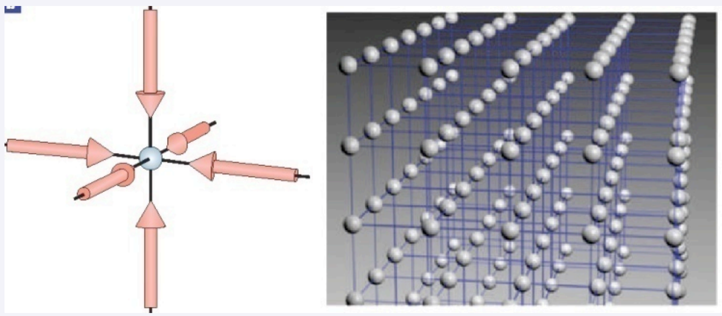
optical lattices



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

HOME SITE HELP ABOUT SEARCH

NOBEL e-MUSEUM

NOBEL | PHYSICS | CHEMISTRY | MEDICINE | LITERATURE | PEACE | ECONOMICS

LAUREATES ARTICLES EDUCATIONAL

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

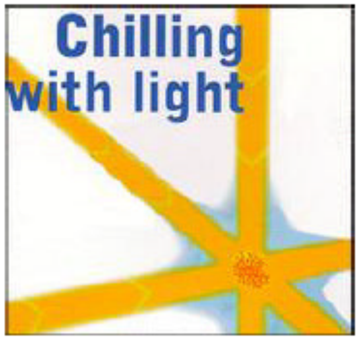
BACK

The Nobel Prize in Physics 1997

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

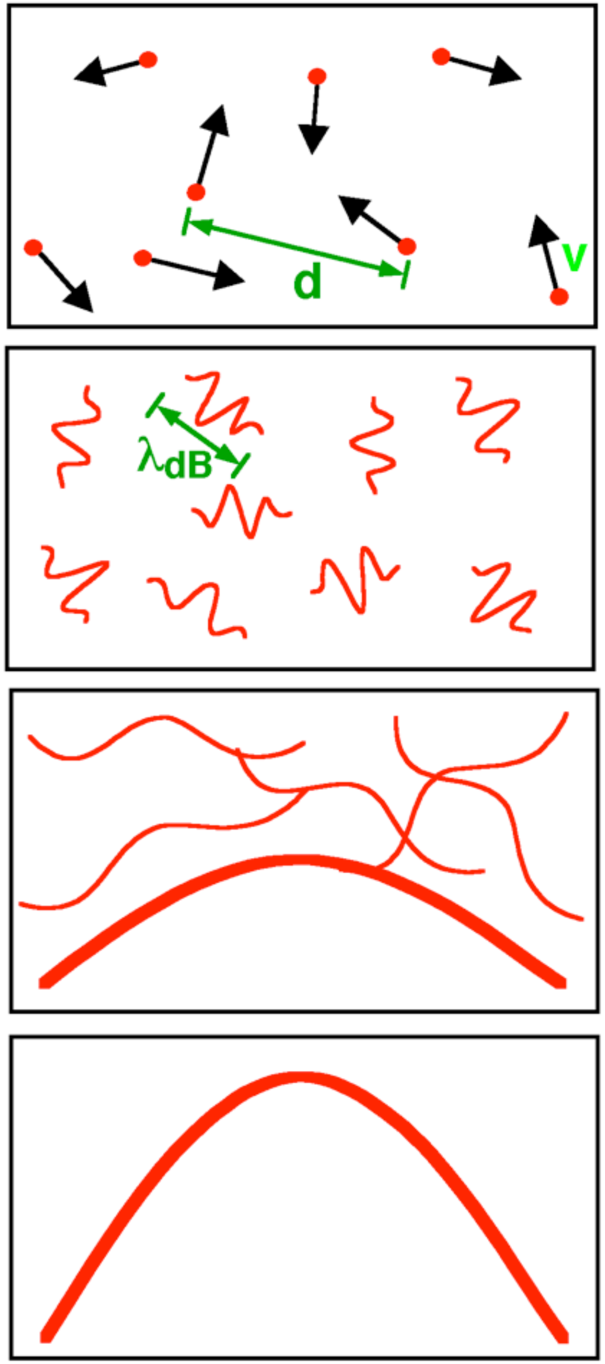
Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**

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.

What is Bose-Einstein condensation (BEC)?



High Temperature T:
thermal velocity v
density d^{-3}
"Billiard balls"

Low Temperature T:
De Broglie wavelength
$\lambda_{dB}=h/mv \propto T^{-1/2}$
"Wave packets"

$T=T_{crit}$:
Bose-Einstein Condensation
$\lambda_{dB} \approx d$
"Matter wave overlap"

T=0:
Pure Bose condensate
"Giant matter wave"

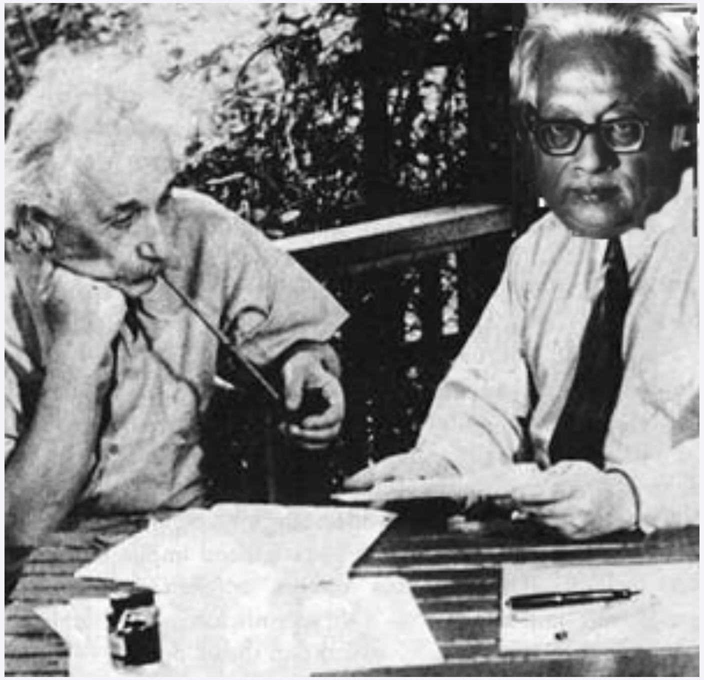
from W. Ketterle

Bose-Einstein condensation

The atoms with an <u>even</u> number of electrons + protons + neutrons at very low temperatures occupy all the ground state of the system.

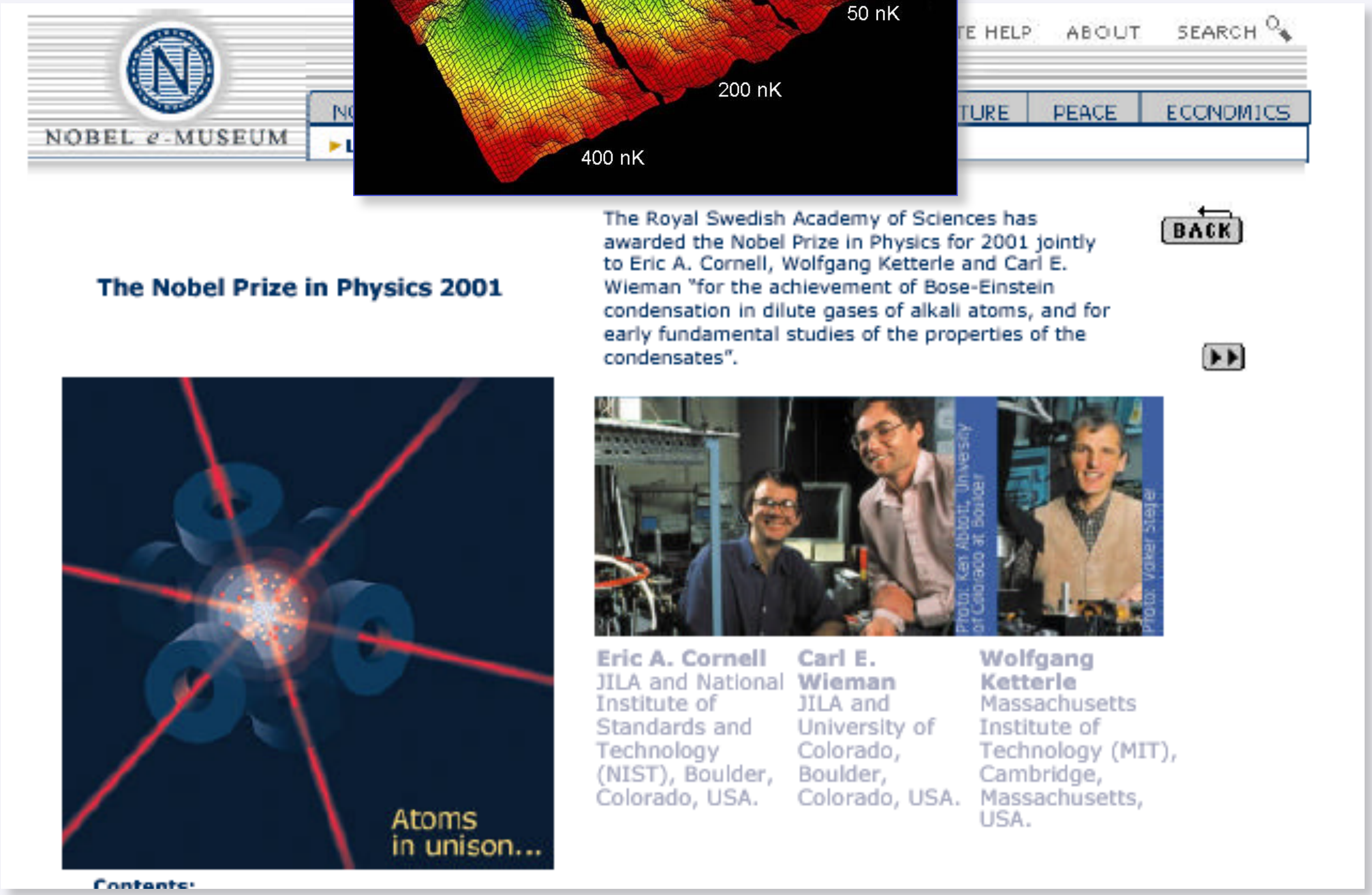
This new state of matter is called ***Bose-Einstein condensate***.

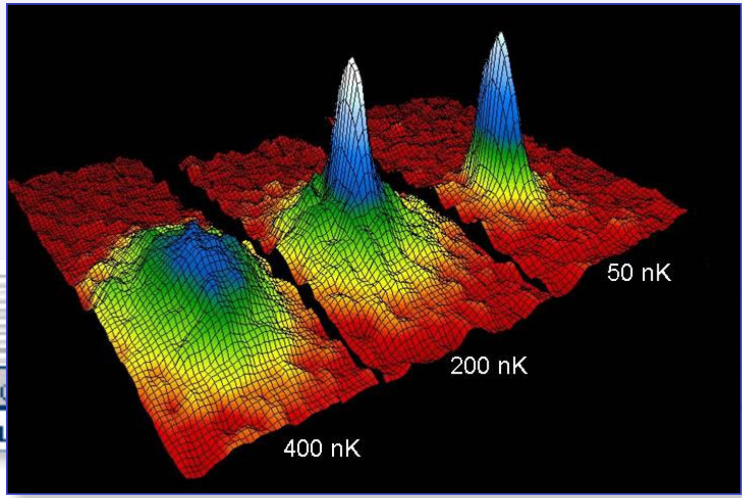
The atoms are called ***bosons***.



A. Einstein and S.N. Bose (1925)

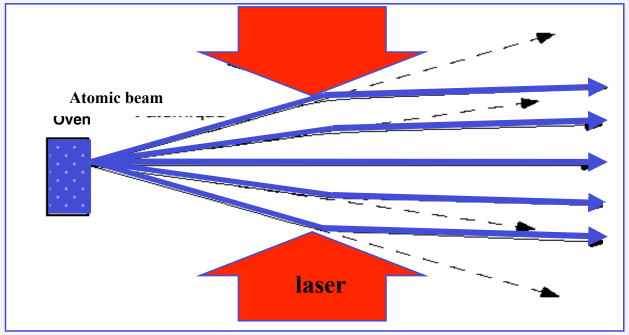
Bose-Einstein condensation in dilute gases of atoms



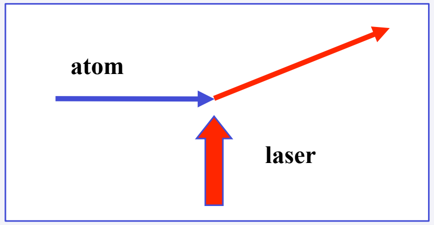


Atom optics

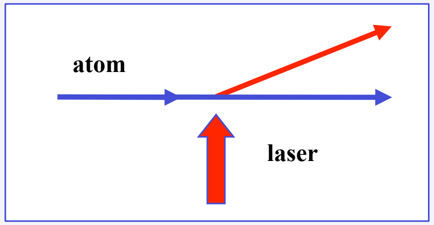
lenses



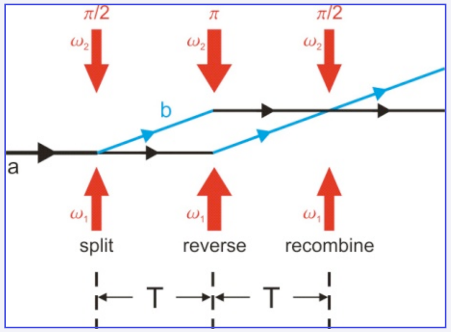
mirrors



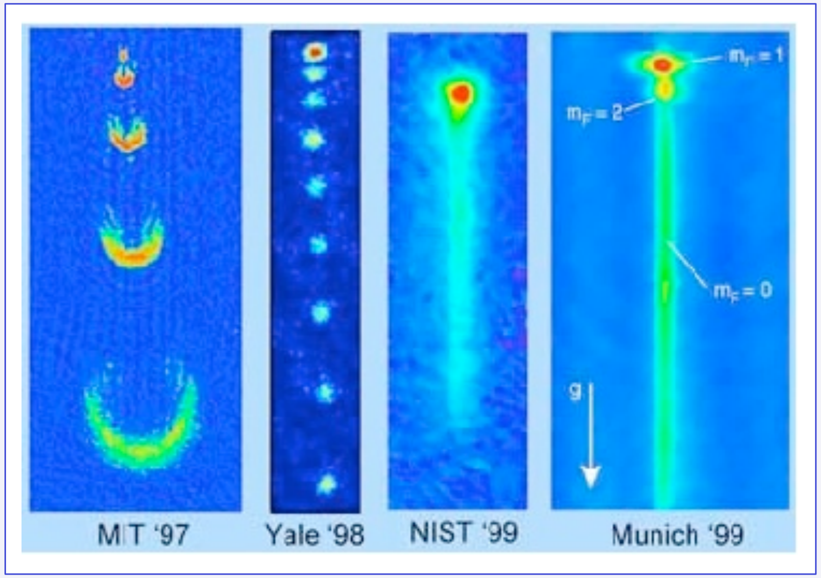
beam-splitters



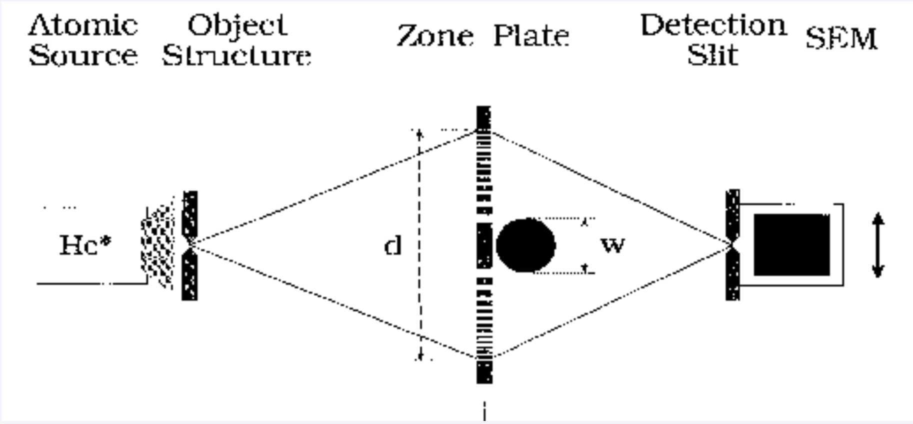
interferometers

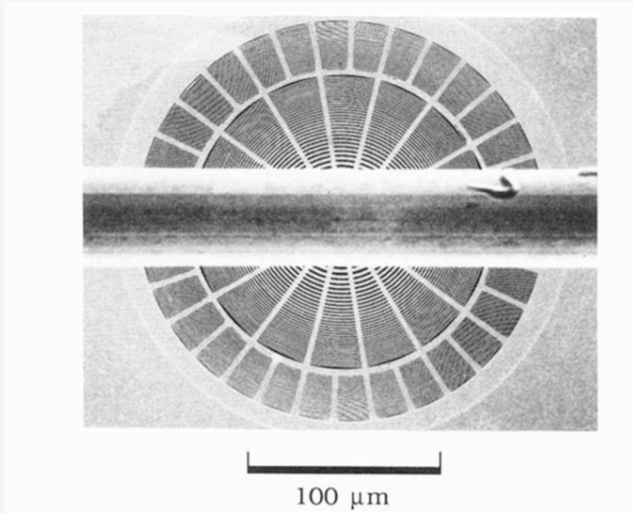


atom laser

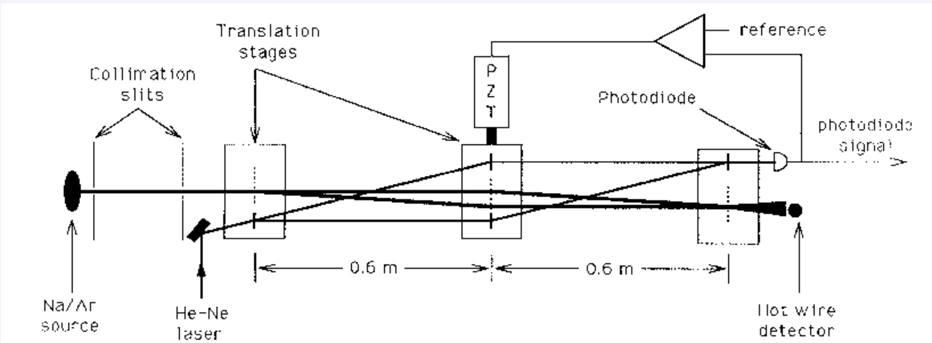


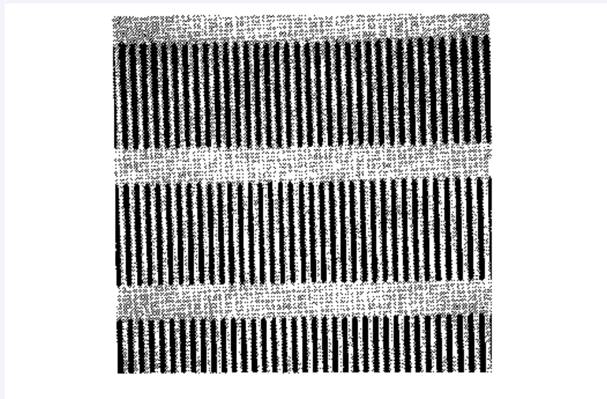
Microfabricated atom optics





O. Carnal, M. Sigel, T. Sleator, H. Takuma, J. Mlynek, Phys. Rev. Lett. 67, 3231 (1991)





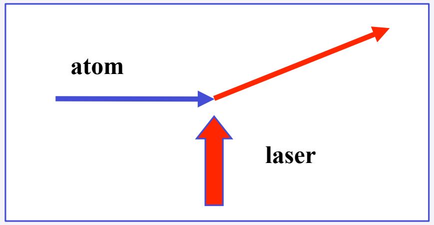
D. W. Keith, C. R. Ekstrom, Q. A. Turchette, D. E. Pritchard, Phys. Rev. Lett. 66, 2693 (1991)

Physics and applications of ultracold atoms

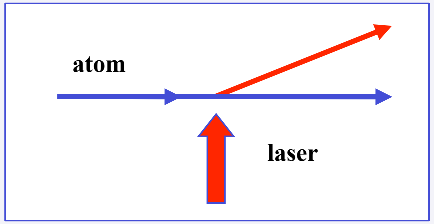
- **BEC, degenerate Fermi gases, collective quantum effects**
- **Ultracold interactions and collision dynamics**
- **Ultracold molecules**
- **Surface physics and quantum reflection**
- **Entanglement and quantum information**
- **Precision spectroscopy**
- **Ultrasensitive isotope trace analysis**
- **Atom optics and atom laser**
- **Atom lithography**
- **Atomic clocks**
- **Atom interferometers**

Optical pulse atom optics

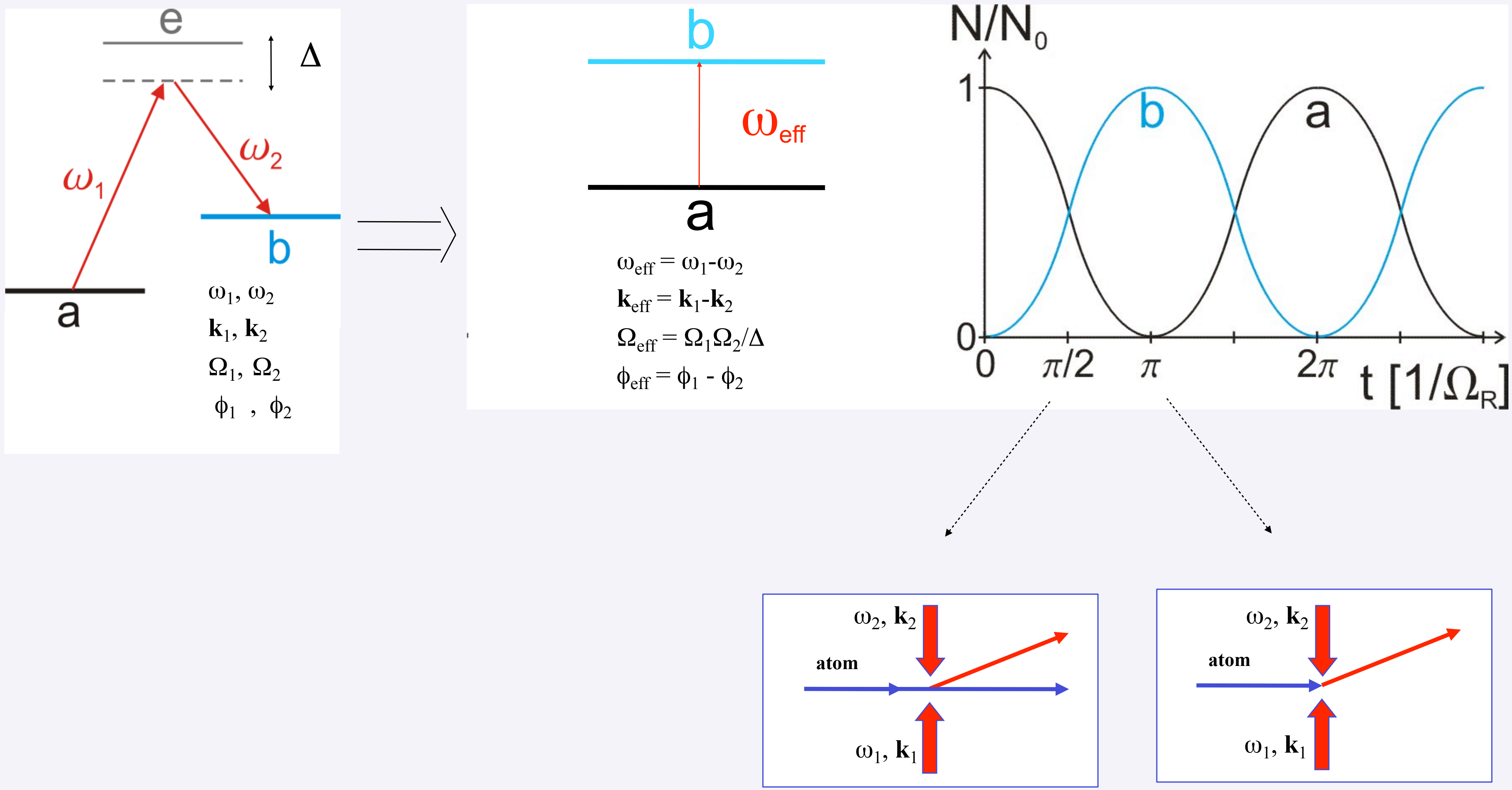
mirror



beam-splitter



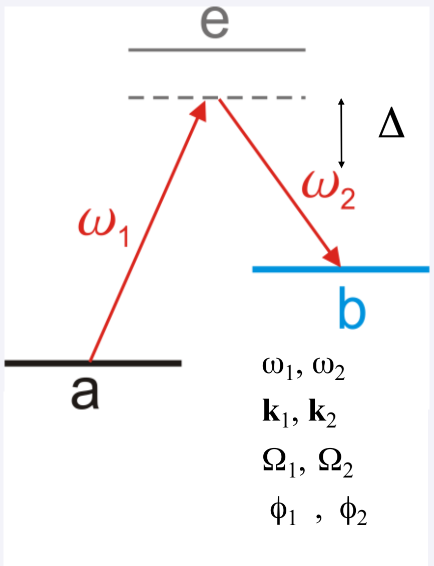
Raman pulses

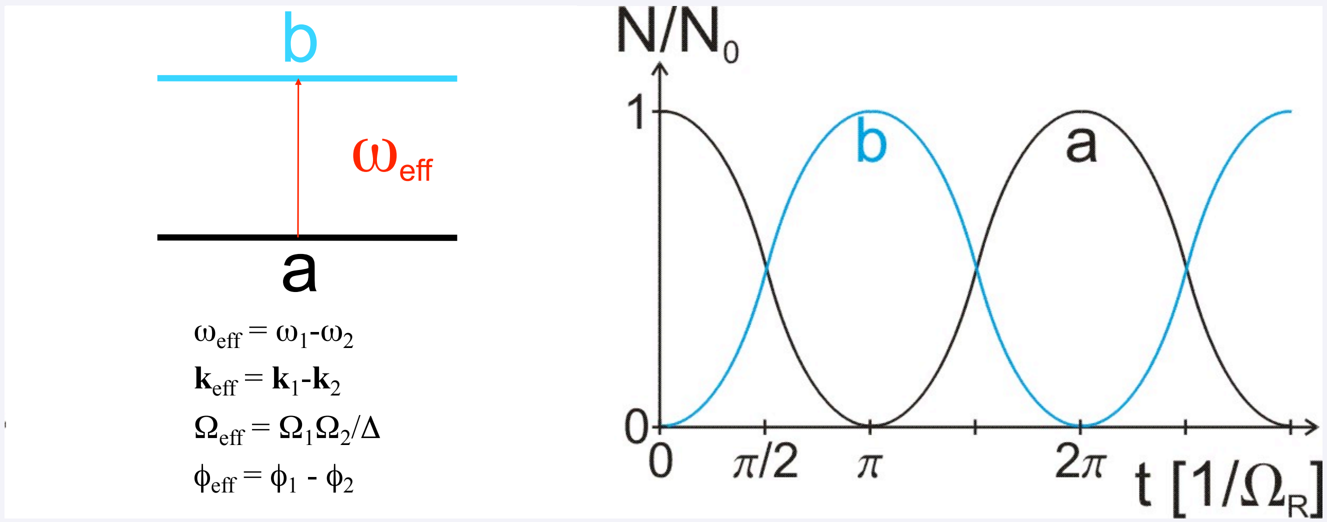


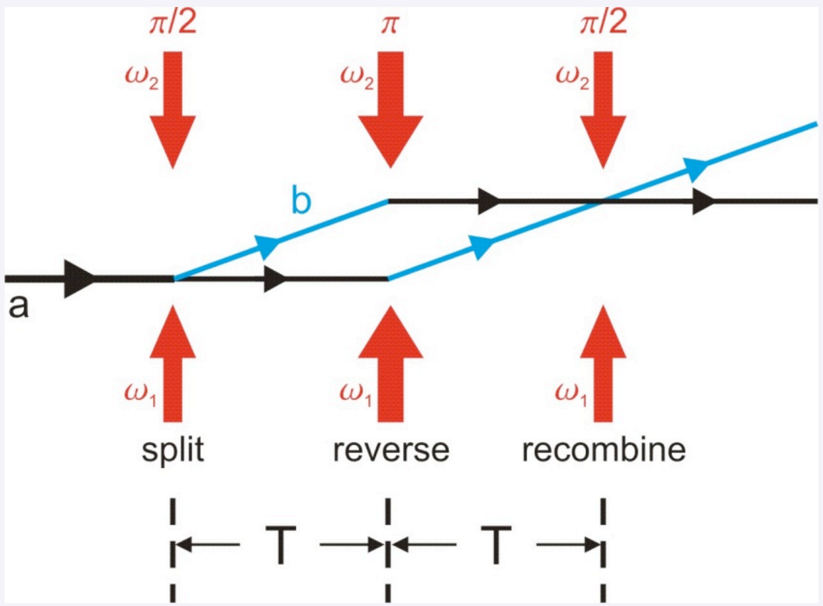
beam-splitter **mirror**

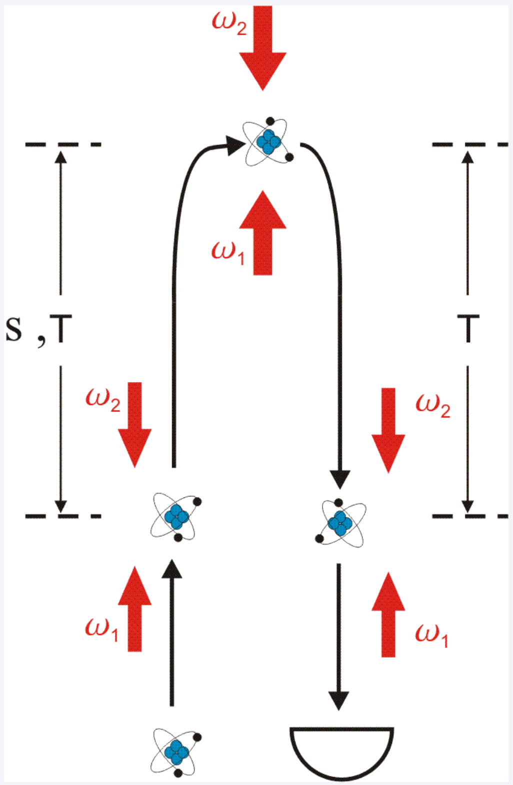
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

Raman pulse interferometer





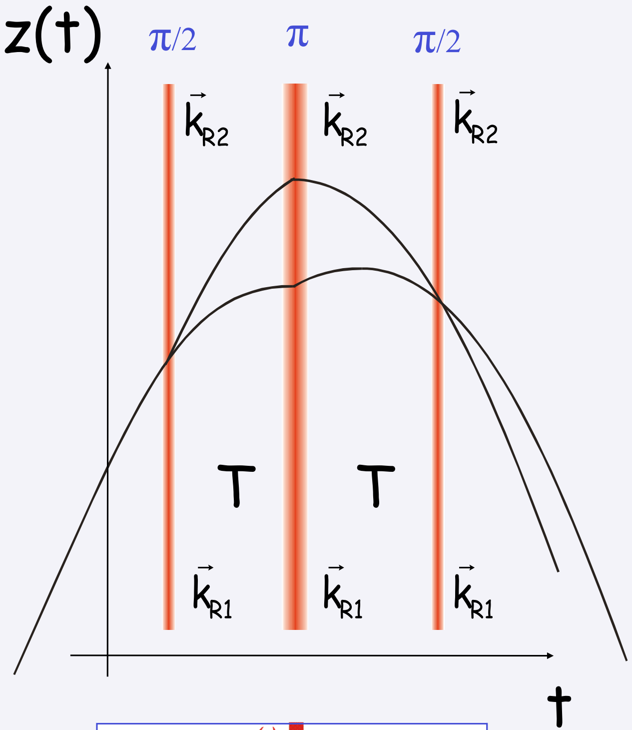


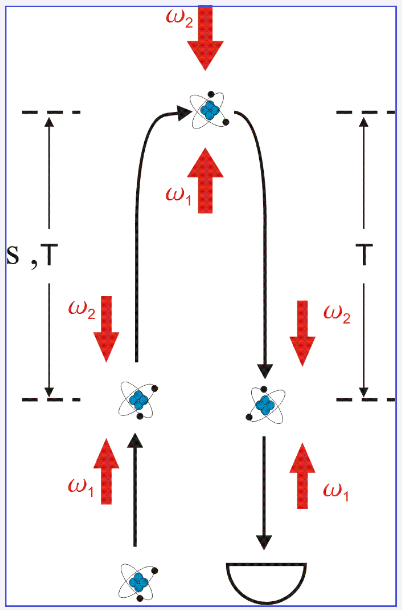


M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

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

Raman interferometry in an atomic fountain





Phase difference between the paths:

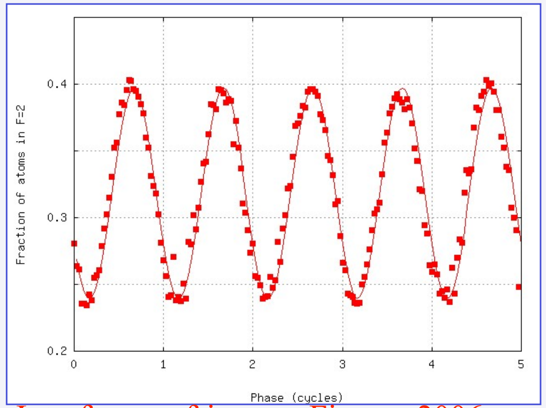
$\Delta\Phi = k_e[z(0)\text{-}2z(T)+z(2T)]+\Phi_e$ $\mathbf{k_e = k_1 - k_2}$, $\omega_e = c\,\mathbf{k_e}$

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

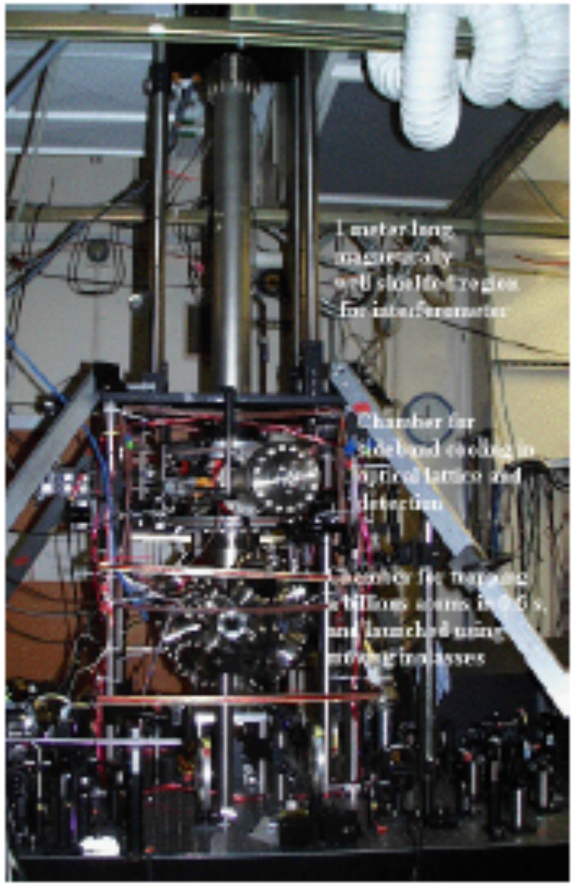
$S/N = 1000$

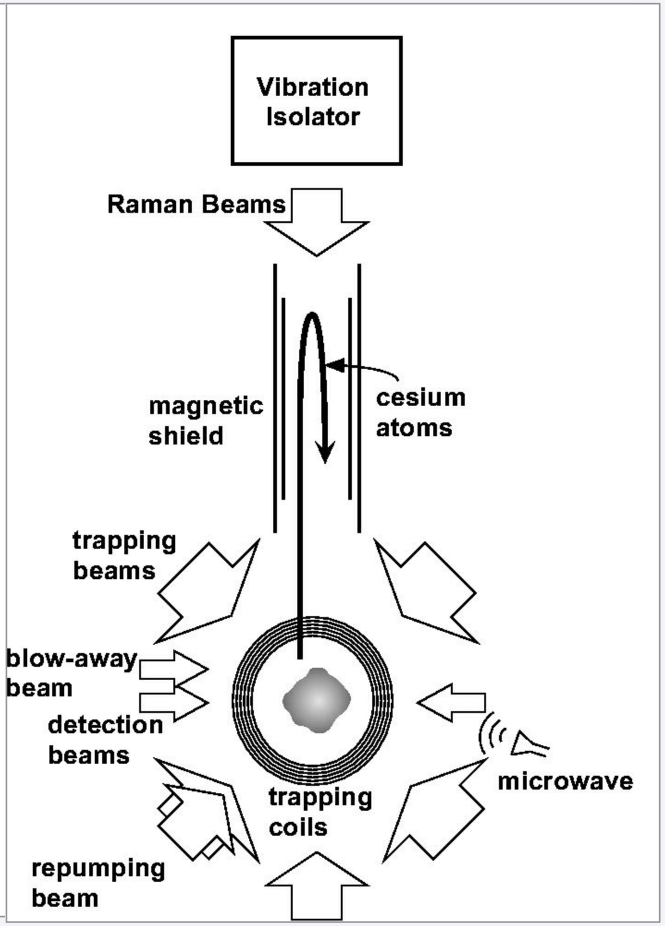
$\Rightarrow$ Sensitivity 10^{-9} g/shot

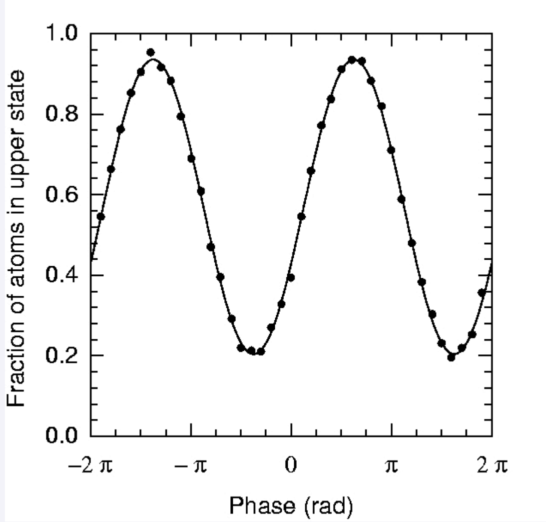
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

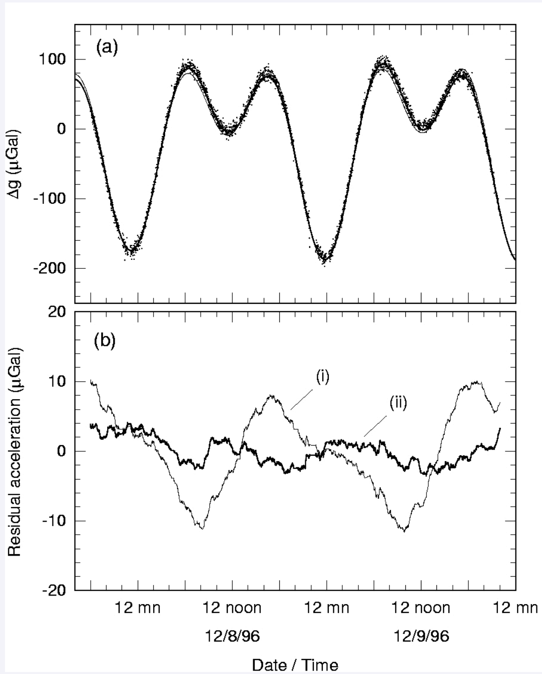
A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)

Stanford atom gravimeter









Resolution: $3x10^{-9}$ g after 1 minute

Absolute accuracy: $\Delta g/g<3x10^{-9}$

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

Atom interferometry – gravity measurements

- spatial gravity variations
  - gravity gradient ~ $3 \cdot 10^{-7}$ g / m
  - global scale ~ 10^{-3} g
  - regional scale ~ 10^{-6} g

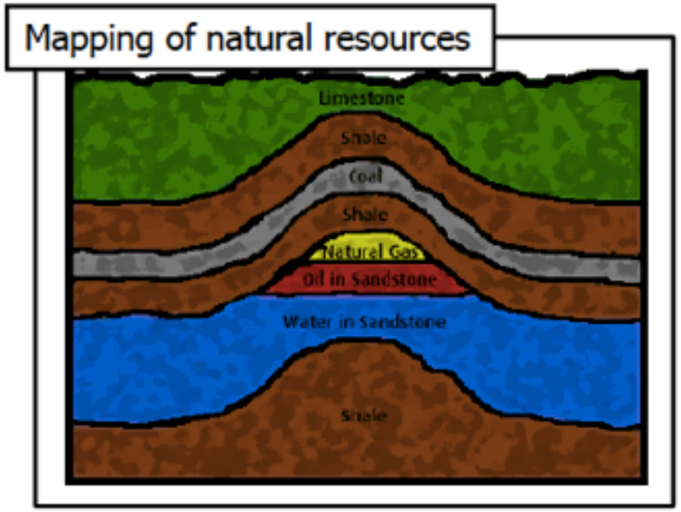
- navigation
- finding oil, water, minerals, archeological sites, ...

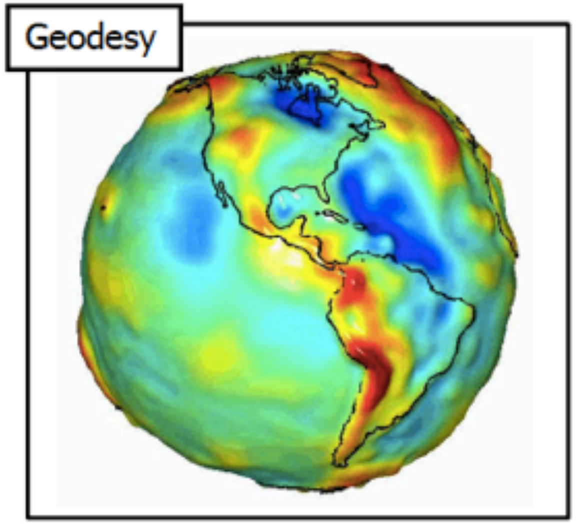
- temporal gravity variations
  - tides ~ 10^{-7} g
  - man-made changes ~ 10^{-9} g
  - atmospheric pressure ~ 10^{-10} g / mbar
  - local water table ~ 10^{-8} g
  - ... ~ 10^{-9} g

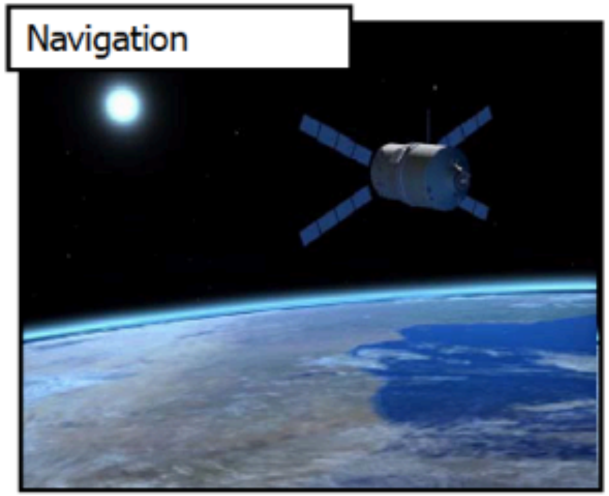
(1 Gal = 1 cm/s^2 → 1 μGal ≃ 10^{-9} g)

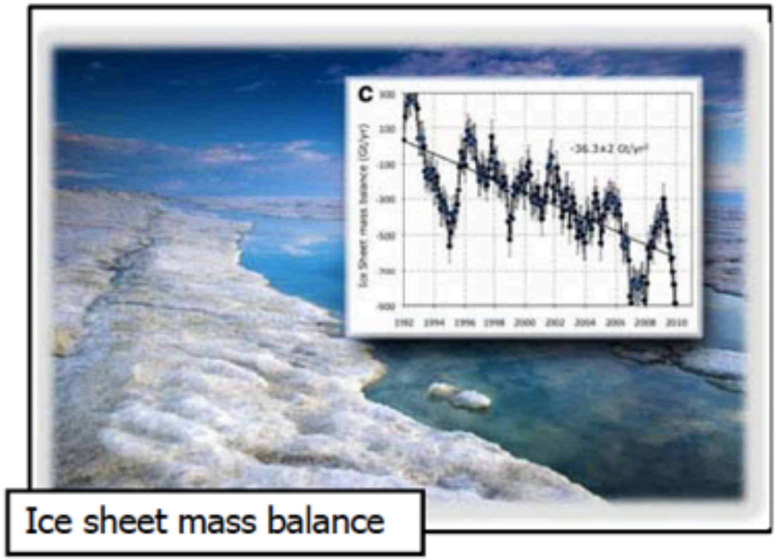
from A. Peters, E. Fermi School on "Atom Interferometry", Varenna 2013

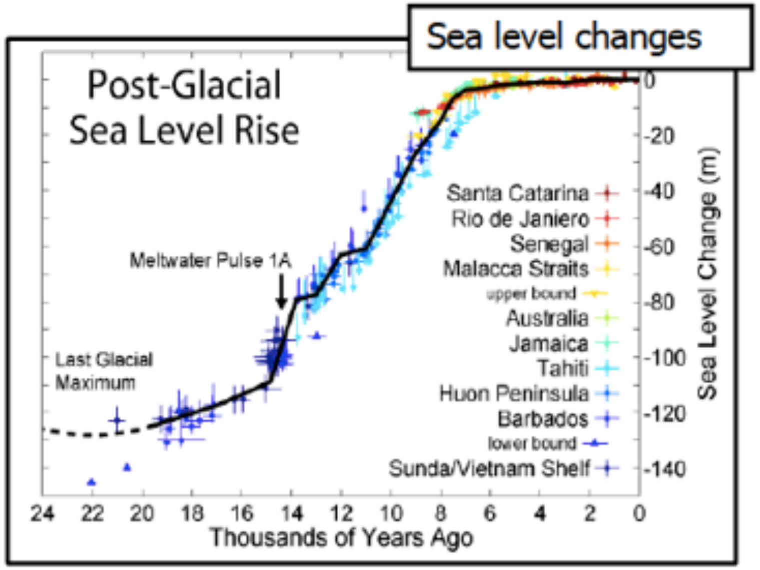
Gravimetry











Images: www.esa.int, Google Images

from A. Peters, E. Fermi School on "Atom Interferometry", Varenna 2013

IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY

Meas. Sci. Technol. **20** (2009) 022001 (16pp) doi:10.1088/0957-0233/20/2/022001

TOPICAL REVIEW

Precision gravimetry with atomic sensors

M de Angelis[1,2], A Bertoldi[3], L Cacciapuoti[4], A Giorgini[2,5], G Lamporesi[6], M Prevedelli[7], G Saccorotti[8], F Sorrentino[2] and G M Tino[2]

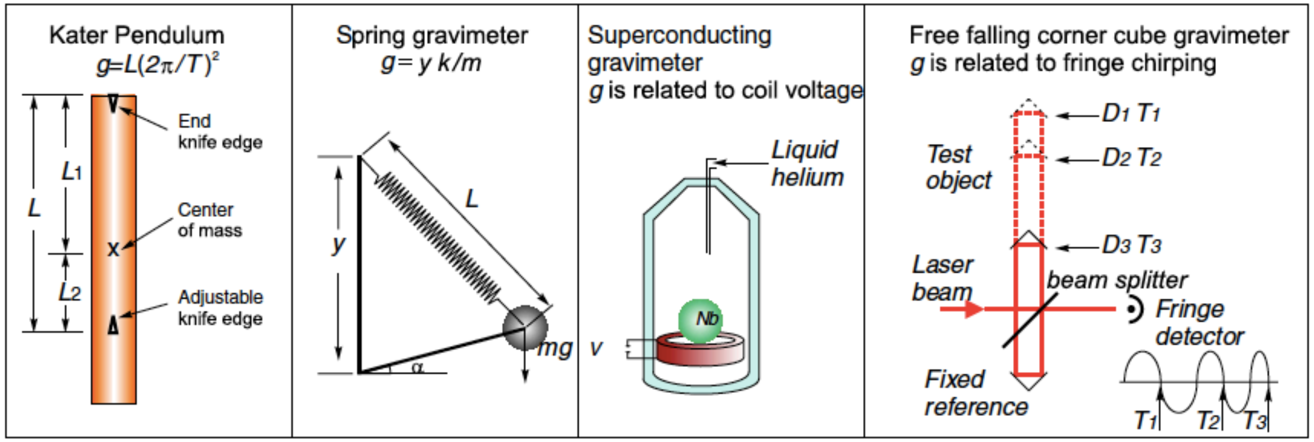
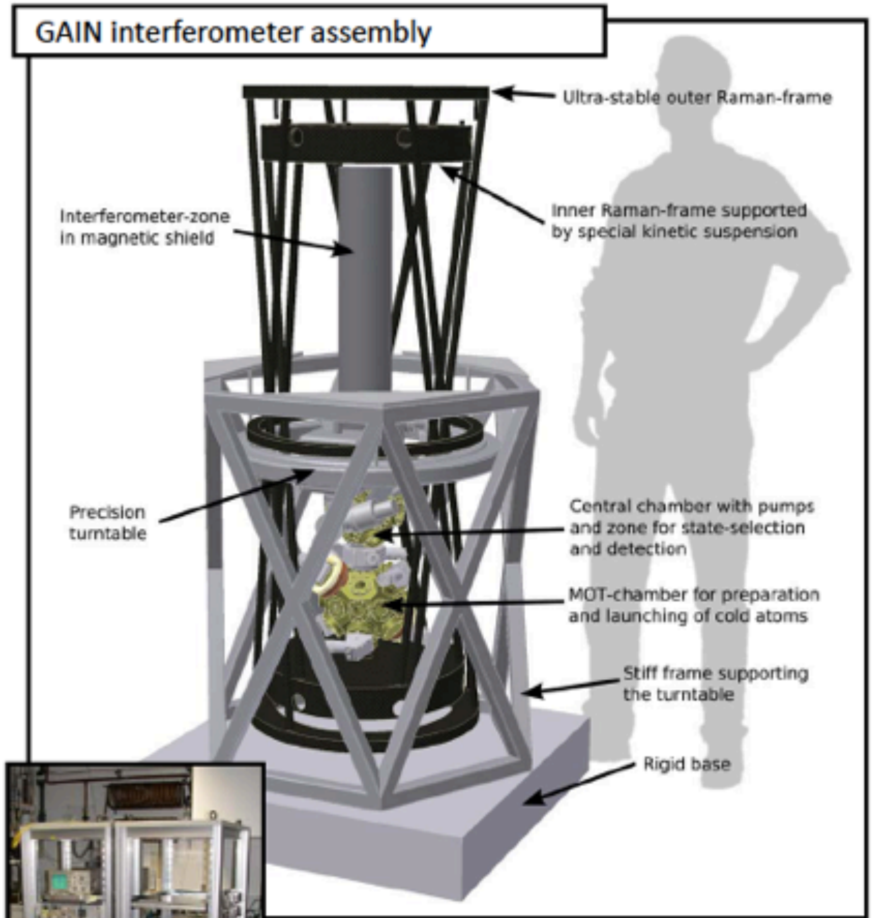


Table 1. Summary of error sources level and technical budgets for most used commercial gravimeters.

	Spring [94]	Superconducting [68, 95]	Free falling [69, 72]
Noise $(\Delta g/g)/\sqrt{Hz}$	5×10^{-9}	1×10^{-12}	5×10^{-8}
Drift $(\Delta g/g)$	1.5×10^{-6} per month	1×10^{-9} per year	–
Accuracy $\Delta g/g$	–	–	4×10^{-9}
Measurement	Relative	Relative	Absolute
Size (m^3)	0.04	~1.5	1.5
Weight (kg)	14	321	127
Power (W)	24	400	350
Error sources	Temperature and random seasonal drift. Calibration varies in time and position	No field operation. Magnetic and electrostatic effects	Thermal drift. Magnetic and electrostatic effects

Portable atomic quantum gravimeter GAIN



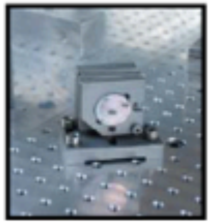
- Compact: three ~ 1 m³ Modules (interferometers assembly + two 19'' racks for laser system and electronics)
- Robust: critical components based on technology developed for the high g-loads in drop tower experiments
- Mobile: designed to be „truckable" and for use at a variety of interesting locations

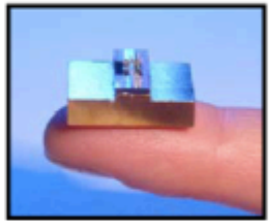
Targeted sensitivity:

$1 \cdot 10^{-9}$ g / sqrt(Hz) at a SNR of 300:1 (intrinsic noise only)

$1 \cdot 10^{-8}$ g / sqrt(Hz) at a SNR of 30:1 (under realistic vibration conditions)

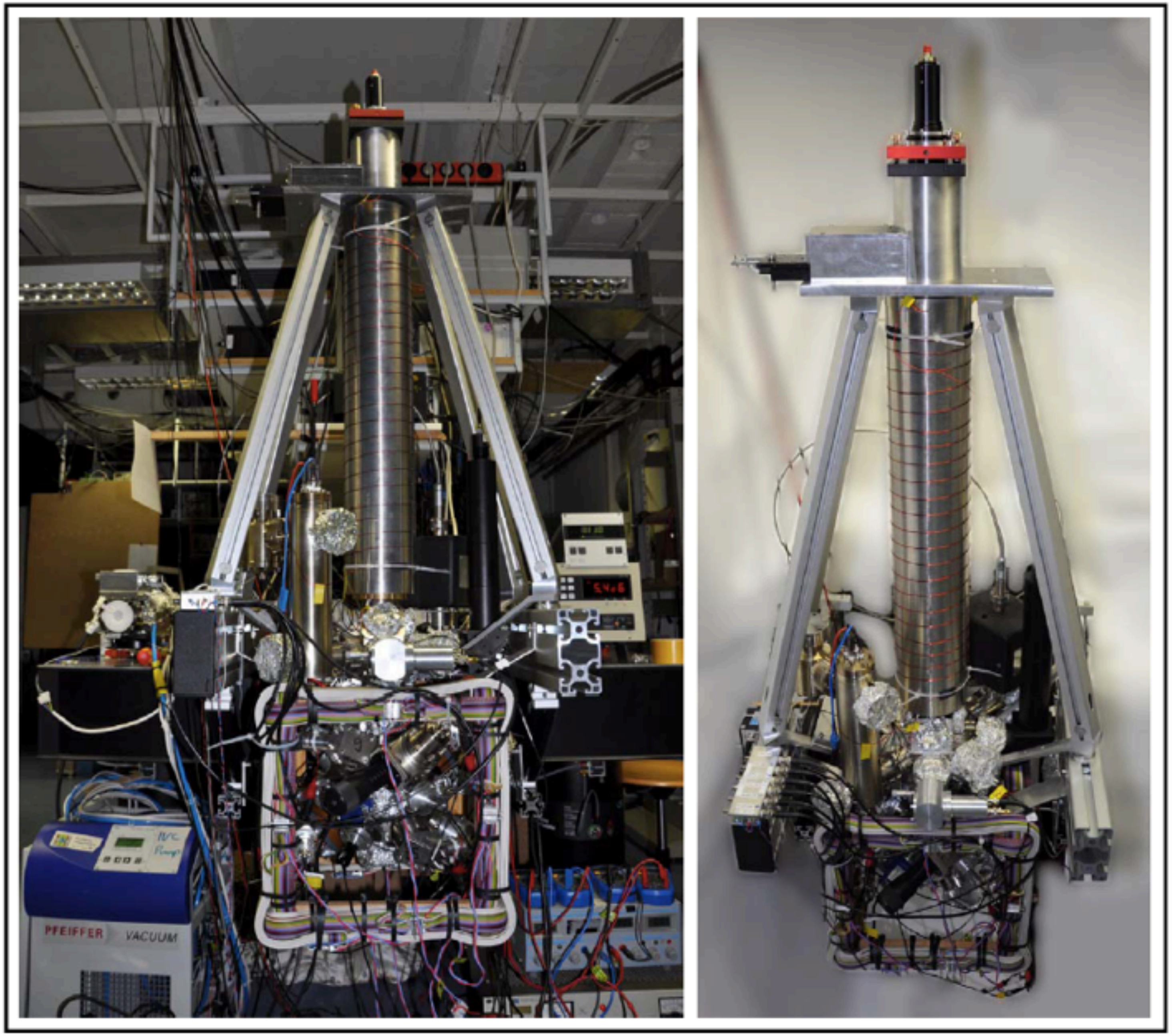
Targeted absolute accuracy: $5 \cdot 10^{-10}$ g

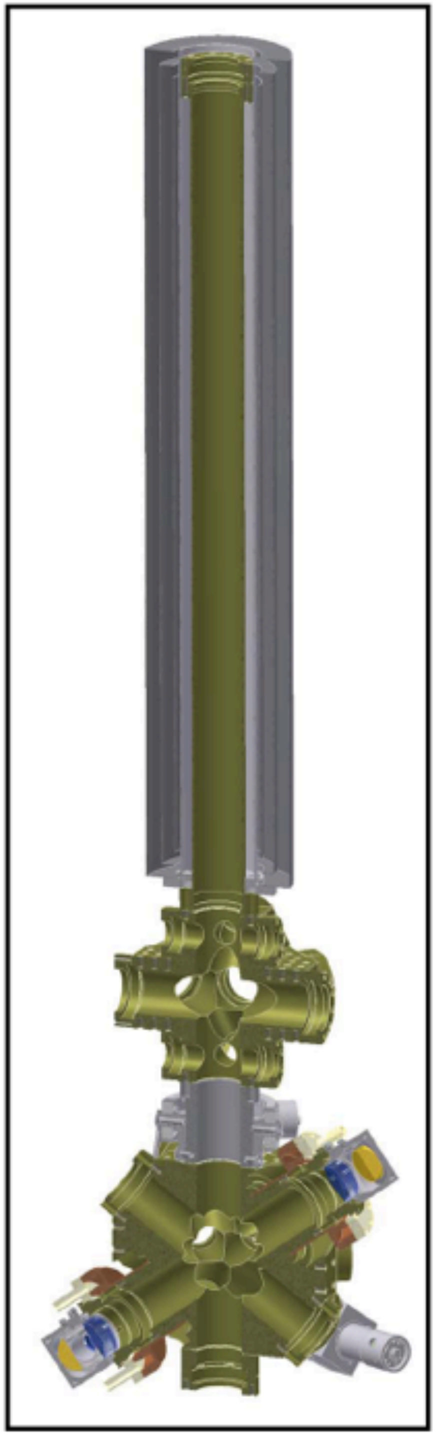




from A. Peters, E. Fermi School on "Atom Interferometry", Varenna 2013

GAIN – physics package





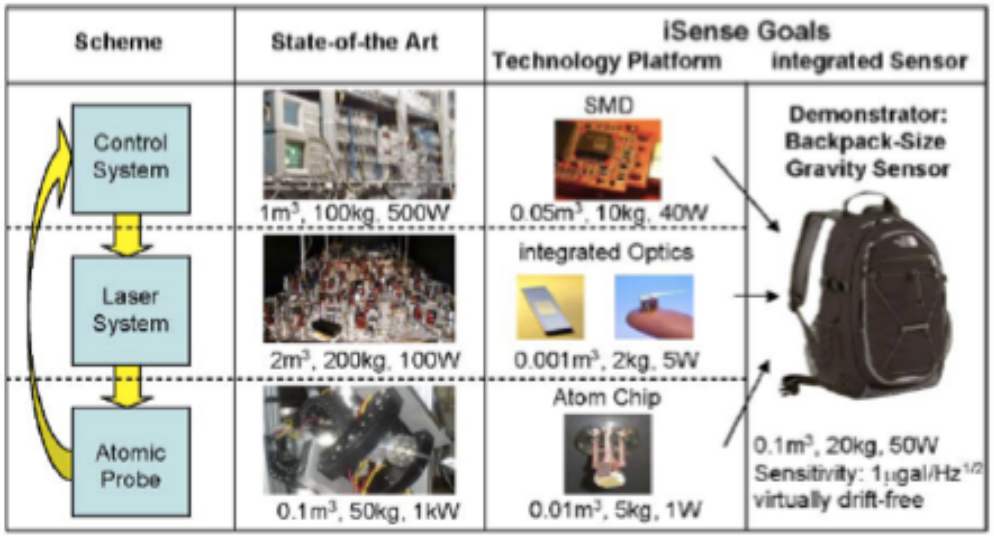
from A. Peters, E. Fermi School on "Atom Interferometry", Varenna 2013

EUROPEAN COMMISSION
Information Society and Media Directorate-General

Emerging Technologies and Infrastructures
Future and Emerging Technologies (FET) - Open

iSense – Integrated Quantum Sensors

7th Framework Programme - Theme 3 "Information and Communication Technologies"
Call identifier: FP7-ICT-2009- C FET-Open

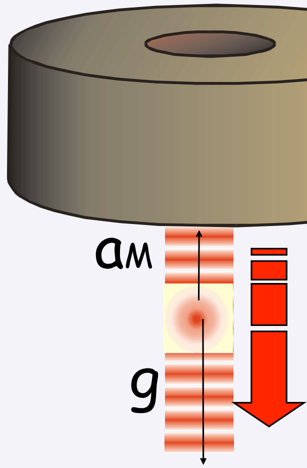


Participant no. *	Participant organisation name	Part. short name	Country
1 (Coordinator)	The University of Birmingham	Bham	UK
2	QinetiQ	QinetiQ	UK
3	University of Hamburg	UHH	D
4	Centre National de la Recherche Scientifique[1]	CNRS	F
5	University of Florence	UNIFI	I
6	Leibniz University Hannover	LUH	D
7	Institute for quantum optics and quantum information - Austrian Academy of Sciences	IQOQI-OEAW	A
8	Ferdinand-Braun-Institut für Höchstfrequenztechnik im Forschungsverbung Berlin e.V.	FBH	D
9	University of Nottingham	Nham	UK

MAGIA

(Misura Accurata di G mediante Interferometria Atomica)

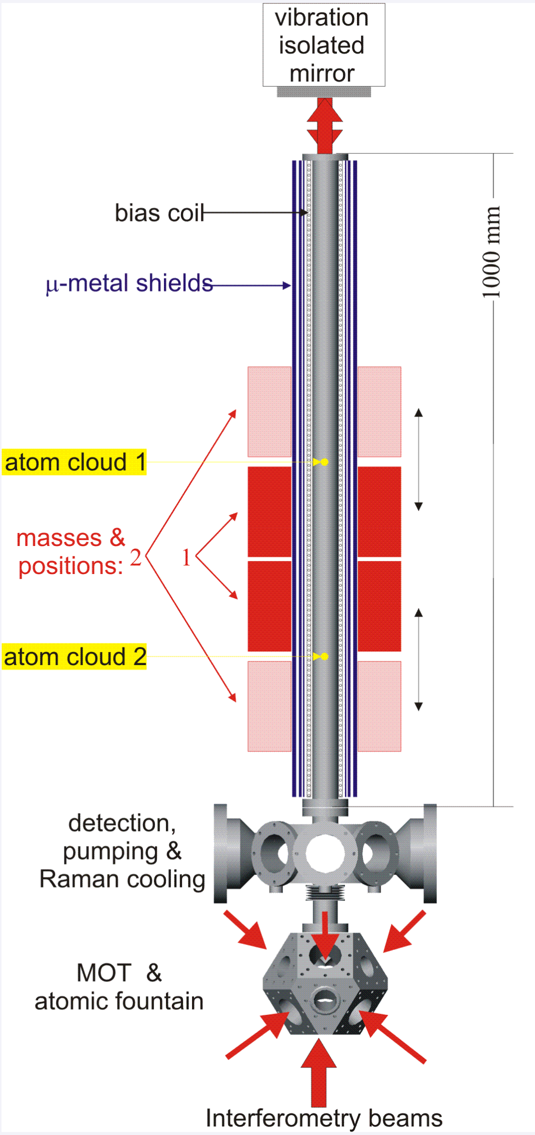
- **Measure g by atom interferometry**
- **Add source mass**
- **Measure change of g**

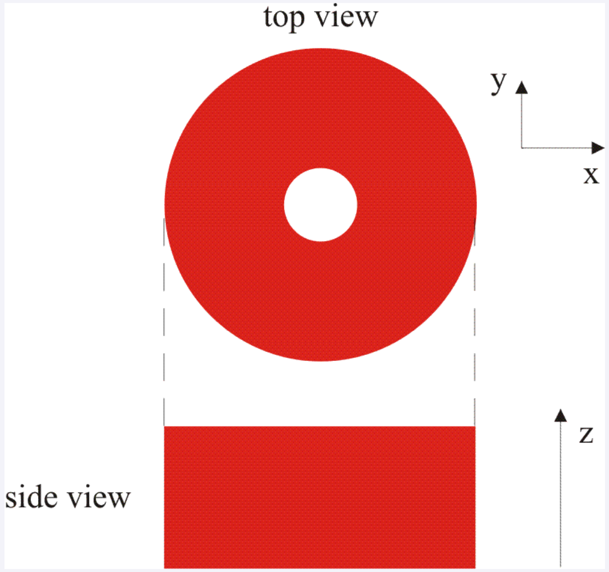


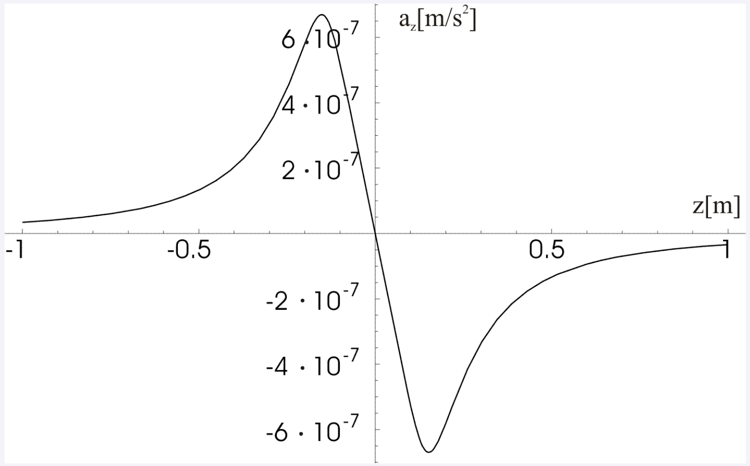
➢ ***Precision measurement of G***

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

MAGIA: atom gravimeter + source mass







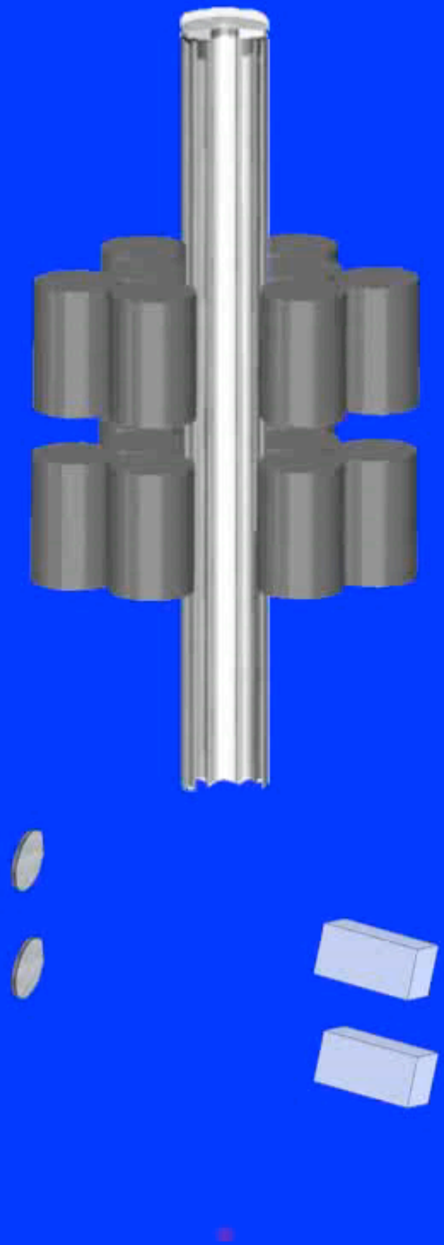
500 kg tungsten mass

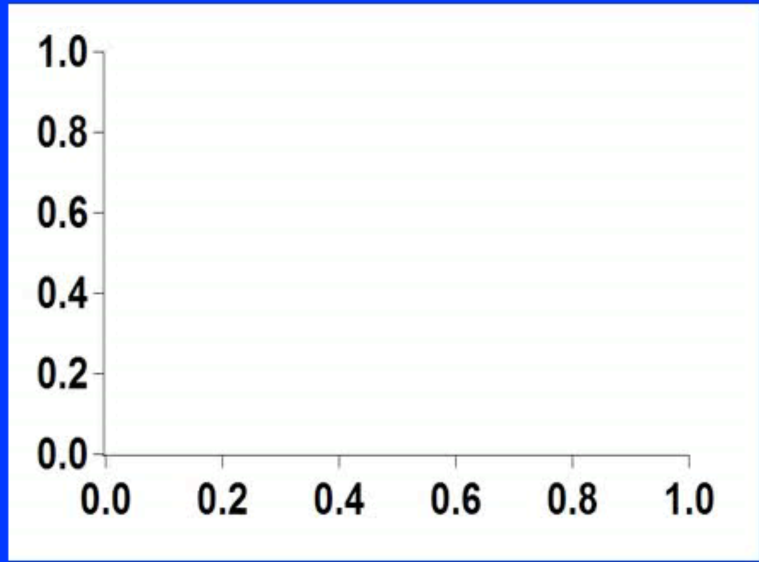
Sensitivity 10^{-9}g/shot

Peak mass acceleration $a_G \approx 10^{-7}$g

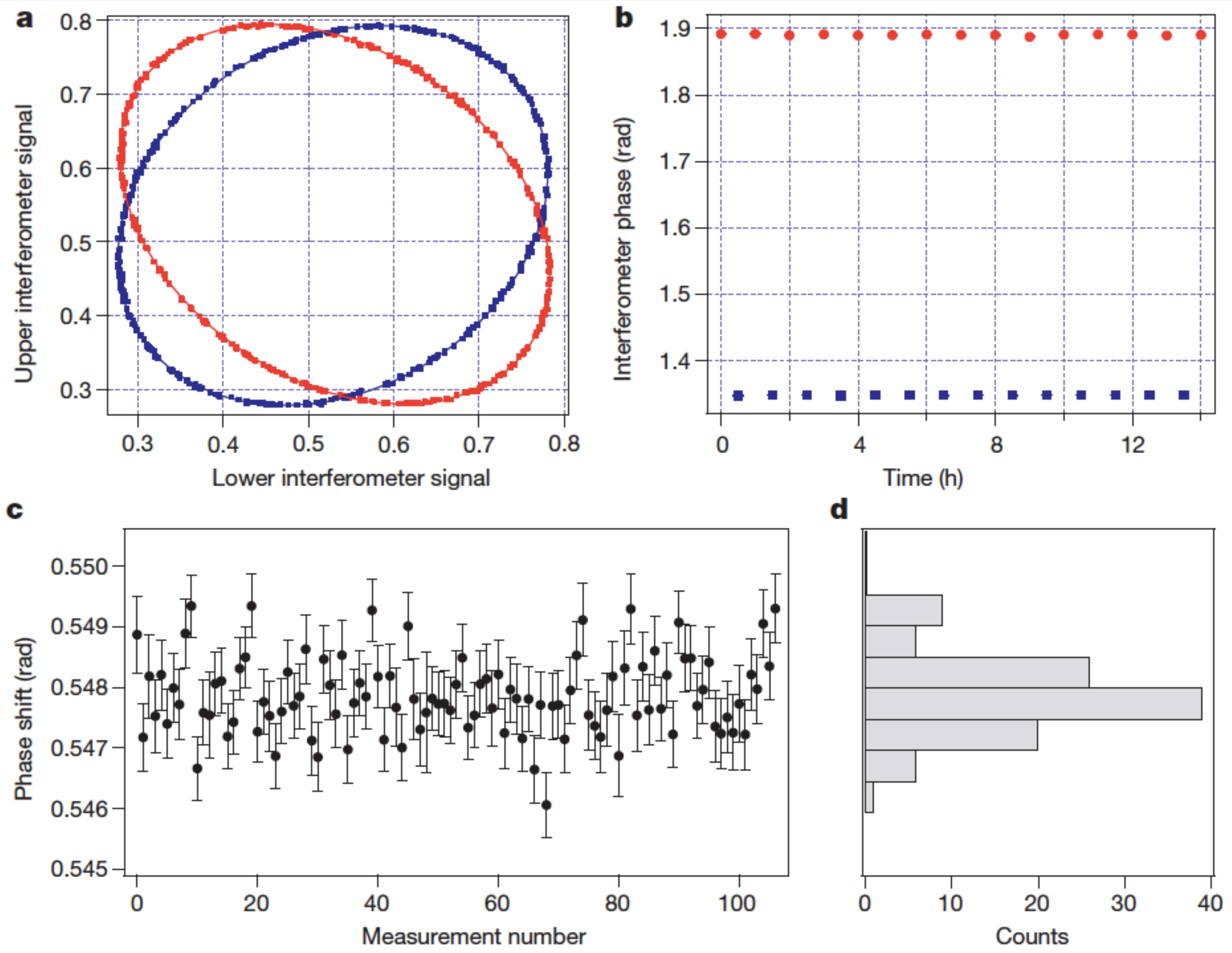
one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

10000 shots $\Rightarrow$ **$\Delta G/G \approx 10^{-4}$**




1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.2
0.4
0.6
0.8
1.0

Measurement of G



(July 2013)

Relative uncertainty ~ 116 ppm (statistical)

LETTER

doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi[1], F. Sorrentino[1], L. Cacciapuoti[2], M. Prevedelli[3] & G. M. Tino[1]

About 300 experiments have tried to determine the value of the Newtonian gravitational constant, *G*, so far, but large discrepancies in the results have made it impossible to know its value precisely[1]. The weakness of the gravitational interaction and the impossibility of shielding the effects of gravity make it very difficult to measure *G* while keeping systematic effects under control. Most previous experiments performed were based on the torsion pendulum or torsion balance scheme as in the experiment by Cavendish[2] in 1798, and in all cases macroscopic masses were used. Here we report the precise determination of *G* using laser-cooled atoms and quantum interferometry. We obtain the value $G = 6.67191(99) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$ with a relative uncertainty of 150 parts per million (the combined standard

the relevant gravitational signal. An additional cancellation of common-mode spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer[18]. Efforts were devoted to the control of systematics related to atomic trajectories, the positioning of the atoms and effects due to stray fields. The high density of tungsten was instrumental in maximizing the signal and in compensating for the Earth's gravitational gradient in the region containing the atom interferometers, thus reducing the sensitivity of the experiment to the vertical position and size of the atomic probes.

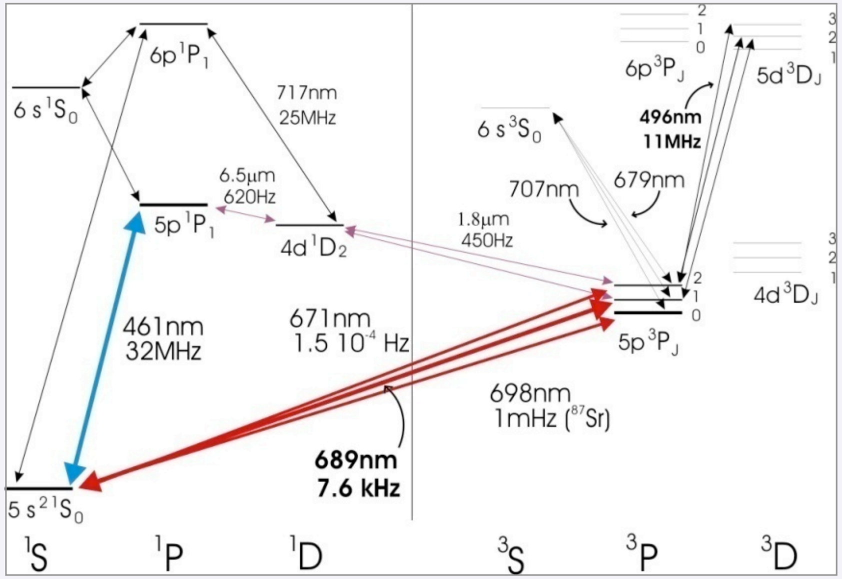
The atom interferometer is realized using light pulses to stimulate ^{87}Rb atoms at the two-photon Raman transition between the hyperfine

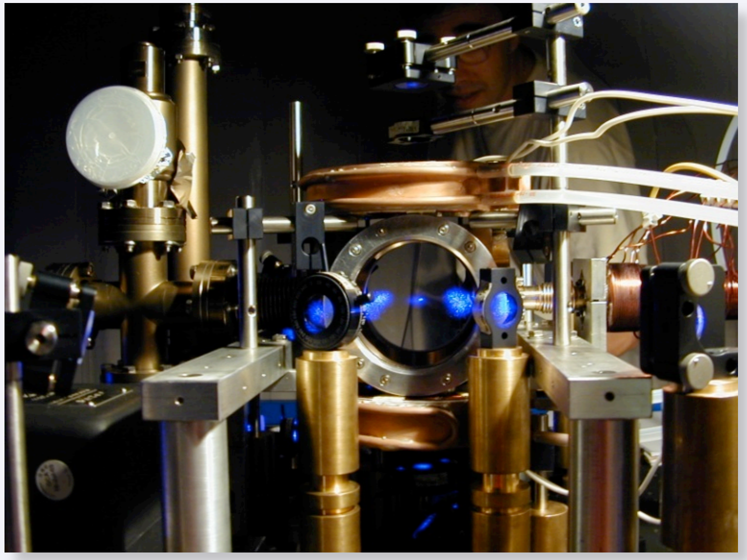
$$G = 6.67191(99) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$$

Relative uncertainty: 150 ppm

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino,
Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms
NATURE vol. 510, p. 518 (2014)

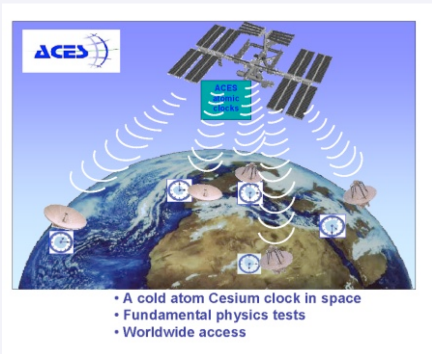
Ultracold Sr – The experiment in Firenze

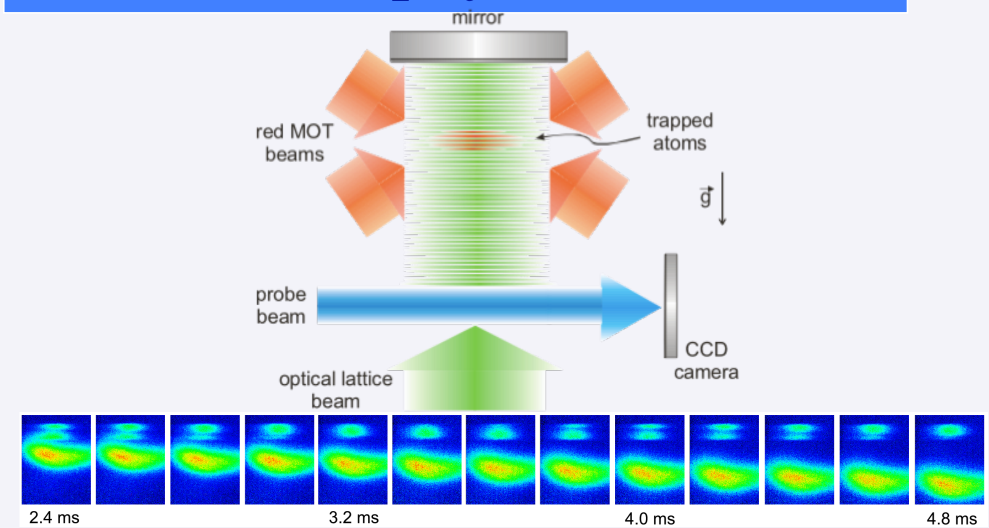




- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests

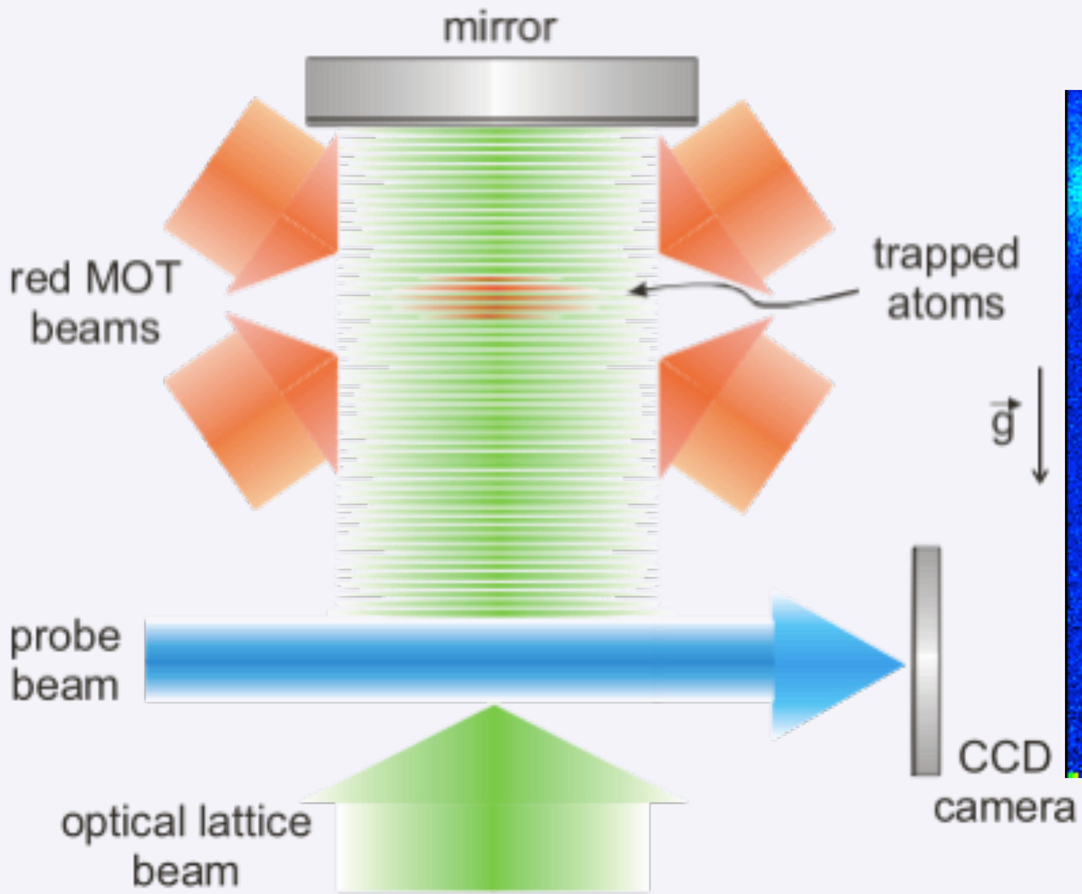


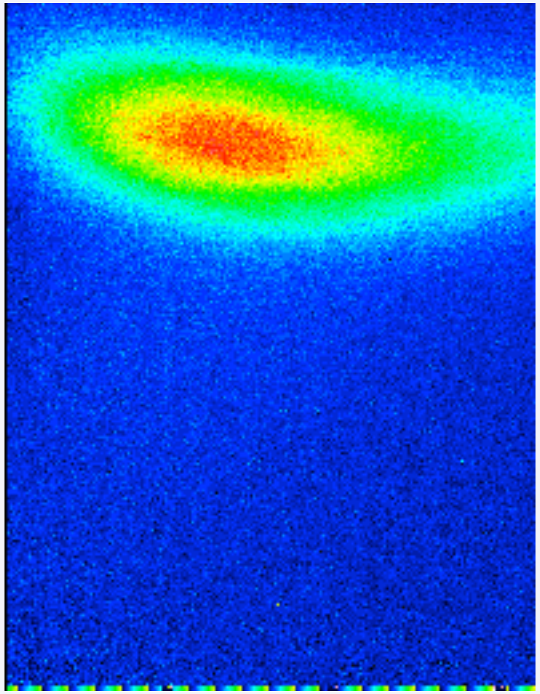


G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale*, Phys. Rev. Lett. 97, 060402 (2006)

Precision gravity measurement at μm scale with Bloch oscillations of Sr atoms in an optical lattice

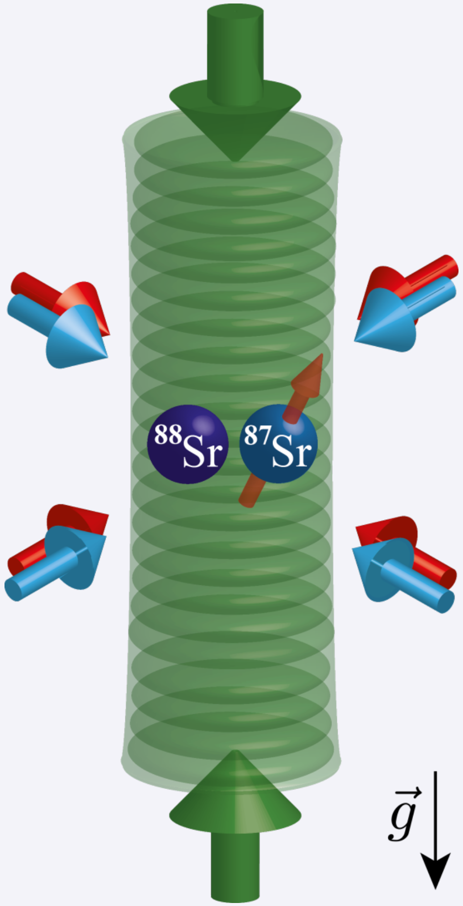


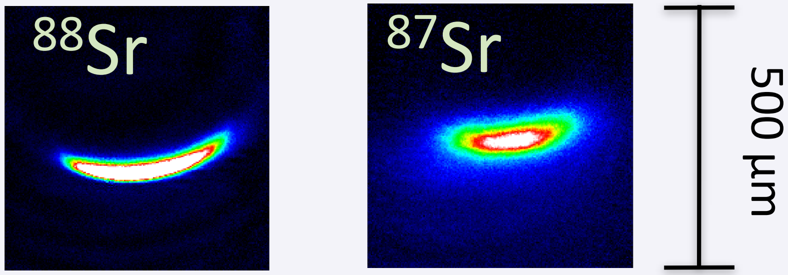


$$\nu = m\, g\, \lambda\, /2\, h$$

G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* **Phys. Rev. Lett. 97, 060402 (2006)**

Test of Einstein equivalence principle for 0-spin and half-integer-spin Sr atoms: Search for spin-gravity coupling effects

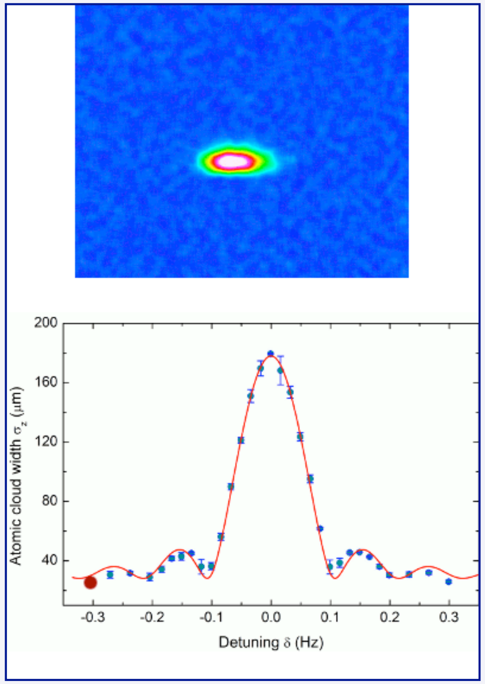




8×10^6 atoms
T: 1 μK

1×10^6 atoms
T: 1.4 μK

$\vec{g}$

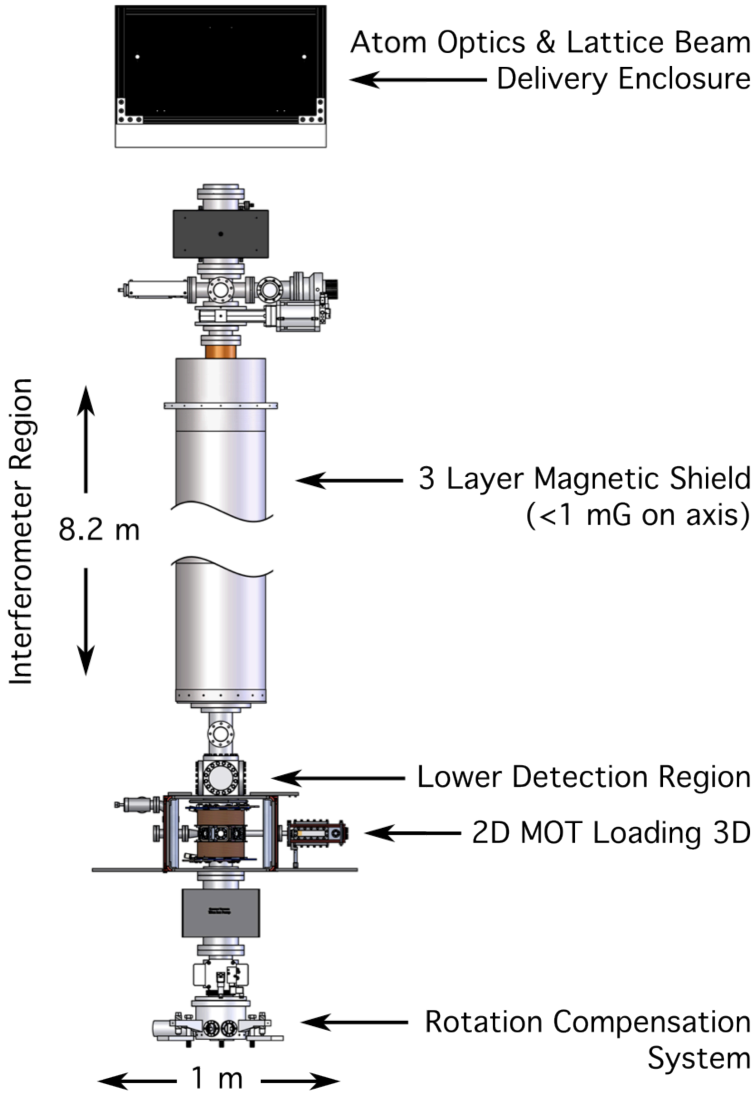


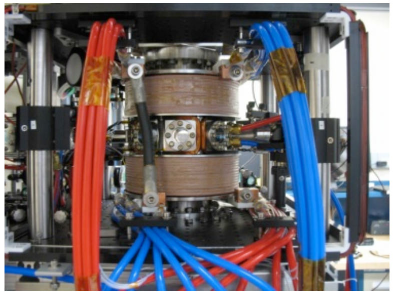
Final result:
$$\eta = (0.2 \pm 1.6) \times 10^{-7}$$

$$\Longrightarrow \quad k = (0.5 \pm 1.1) \times 10^{-7}$$

M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects,*
Phys. Rev. Lett. 113, 023005 (2014)

Apparatus





Ultracold atom source

$>10^6$ atoms at 50 nK

3e5 atoms at 1.6 nK

Optical Lattice Launch

13.1 m/s with 2372 photon recoils to 9 m

Atom Interferometry

2 cm $1/e^2$ radial waist

6 W total power

Dynamic nrad control of laser angle with precision piezo-actuated stage

Detection

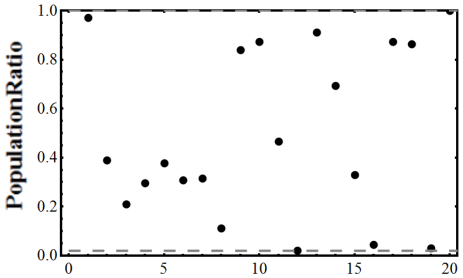
Spatially-resolved fluorescence imaging

Two CCD cameras on perpendicular lines of sight

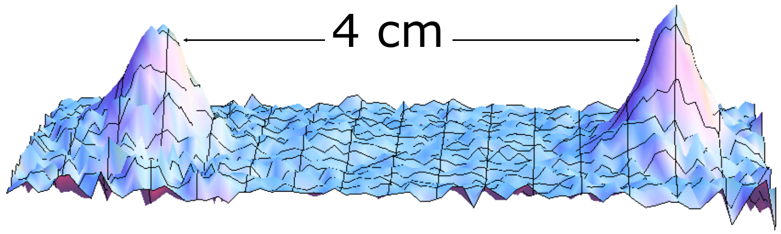
Current demonstrated statistical resolution, ~5e-13 g in 1 hr (87Rb)

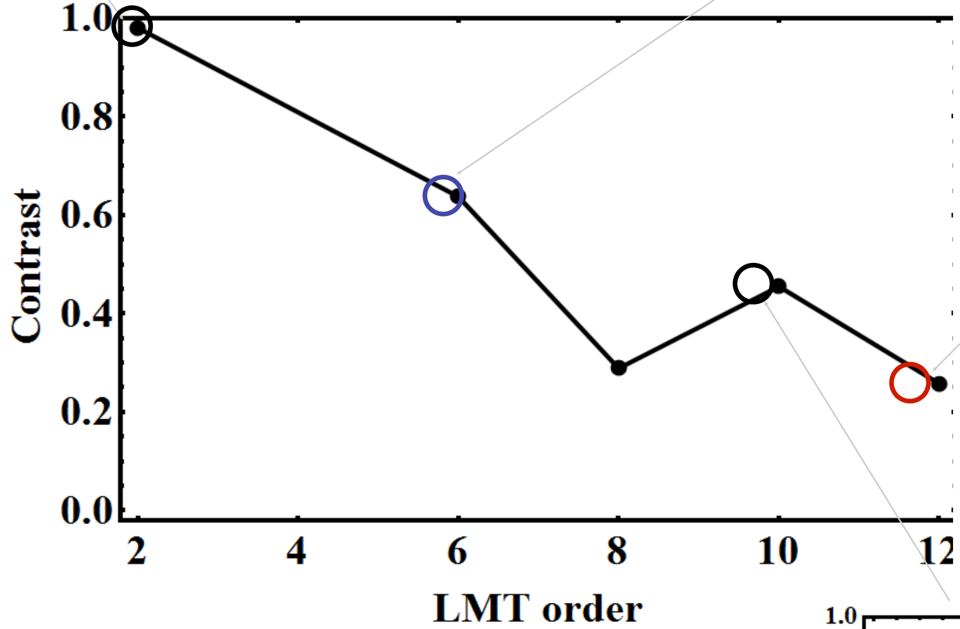
From M. Kasevich, ICAP 2014

Contrast vs. momentum recoil at 2T = 2.3 s

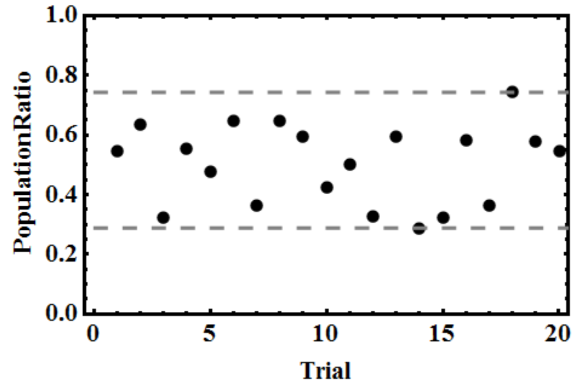


>98% contrast (!)





8 cm wavepacket separation (!!)



Large momentum transfer demonstration at 2T = 2.3 s (unpublished).

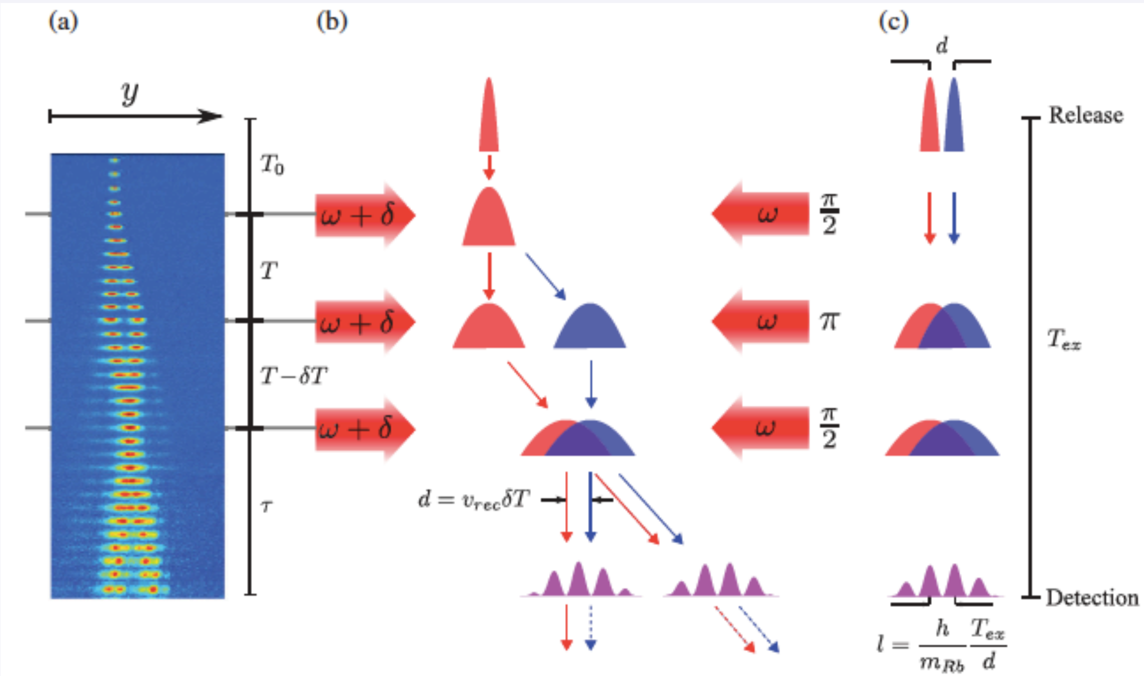
From M. Kasevich, ICAP 2014

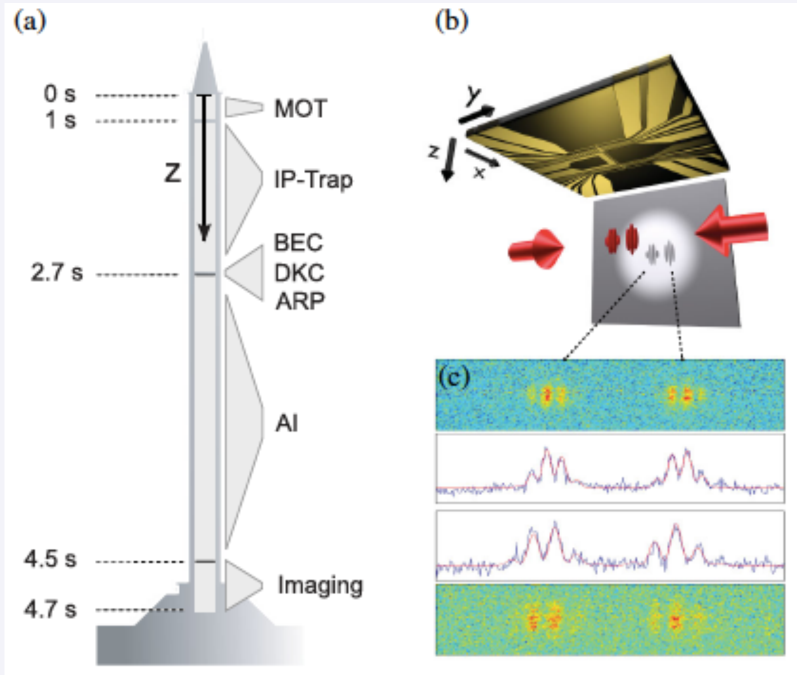
Selected for a Viewpoint in *Physics*
PRL **110,** 093602 (2013) PHYSICAL REVIEW LETTERS week ending 1 MARCH 2013

Interferometry with Bose-Einstein Condensates in Microgravity

H. Müntinga,[1] H. Ahlers,[2] M. Krutzik,[3] A. Wenzlawski,[4] S. Arnold,[5] D. Becker,[2] K. Bongs,[6] H. Dittus,[7] H. Duncker,[4] N. Gaaloul,[2] C. Gherasim,[8] E. Giese,[5] C. Grzeschik,[3] T. W. Hänsch,[9] O. Hellmig,[4] W. Herr,[2] S. Herrmann,[1] E. Kajari,[5,10] S. Kleinert,[5] C. Lämmerzahl,[1] W. Lewoczko-Adamczyk,[3] J. Malcolm,[6] N. Meyer,[6] R. Nolte,[8] A. Peters,[3,11] M. Popp,[2] J. Reichel,[12] A. Roura,[5] J. Rudolph,[2] M. Schiemangk,[3,11] M. Schneider,[8] S. T. Seidel,[2] K. Sengstock,[4] V. Tamma,[5] T. Valenzuela,[6] A. Vogel,[4] R. Walser,[8] T. Wendrich,[2] P. Windpassinger,[4] W. Zeller,[5] T. van Zoest,[7] W. Ertmer,[2] W. P. Schleich,[5] and E. M. Rasel[2,*]

Atom interferometers covering macroscopic domains of space-time are a spectacular manifestation of the wave nature of matter. Because of their unique coherence properties, Bose-Einstein condensates are ideal sources for an atom interferometer in extended free fall. In this Letter we report on the realization of an asymmetric Mach-Zehnder interferometer operated with a Bose-Einstein condensate in microgravity. The resulting interference pattern is similar to the one in the far field of a double slit and shows a linear scaling with the time the wave packets expand. We employ delta-kick cooling in order to enhance the signal and extend our atom interferometer. Our experiments demonstrate the high potential of interferometers operated with quantum gases for probing the fundamental concepts of quantum mechanics and general relativity.





Towards an Atom Interferometer in Space

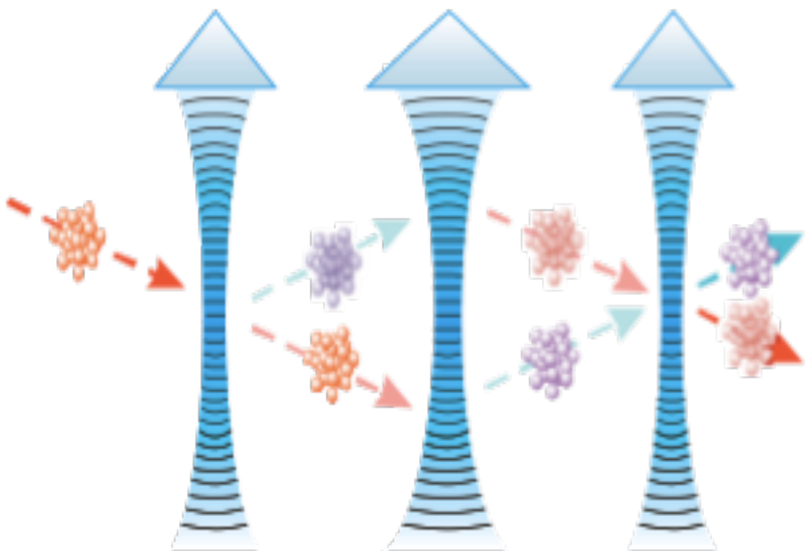
Space Atom Interferometer - SAI

Space Atom Interferometer: Pre-phase A study of a space instrument based on matter-wave interferometry for inertial sensing in space

Team: Firenze Univ. (I), IOTA (F), IQ (D), Hamburg Univ. (D), HU Berlin (D), SYRTE (F), LENS (I), Ulm Univ. (D), ZARM (D)

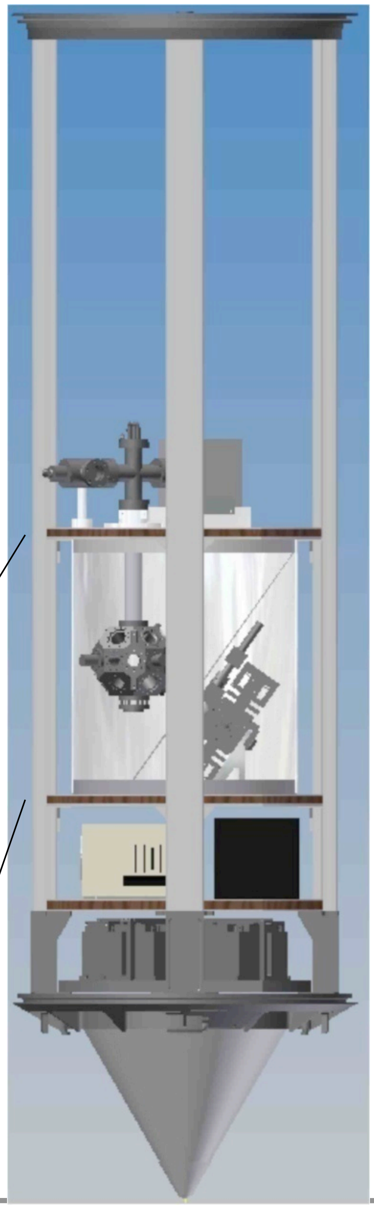
Objective: Ground based prototype of an atom interferometer for precision measurements

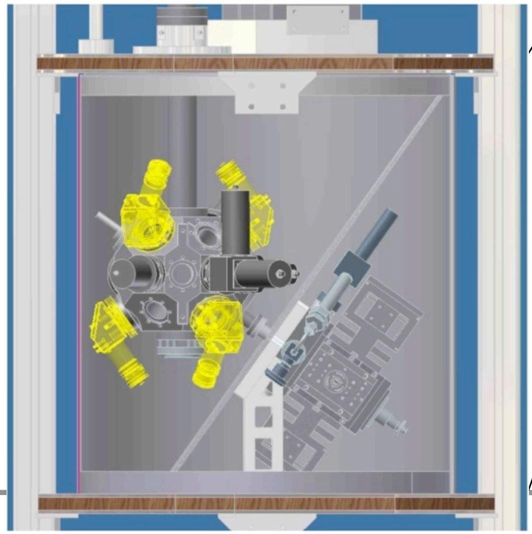
Duration: 3 years, funded within the ELIPS-2 Programme



SAI - Space Atom Interferometer

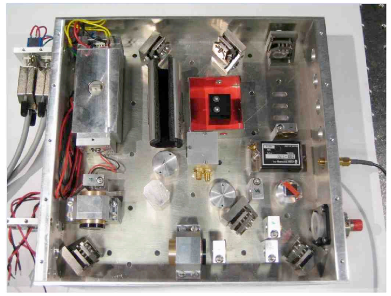
- Single-axis accelerometer
- Sensitivity target 10^{-7} m/s^2 @1s
- Repetition rate ≈ 2 Hz
- Modular laser system + optical fibers
- MOT + atomic fountain
- Same chamber for MOT and detection
- Load from 2D-MOT
- **Compatible with drop-tower capsule**



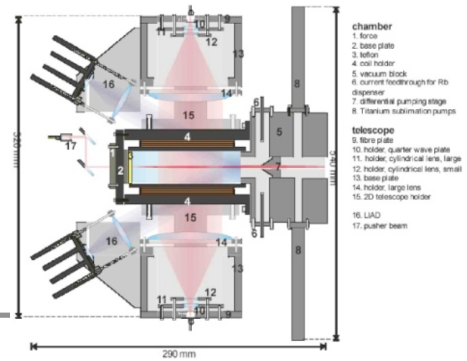


Raman laser system

Modular laser system

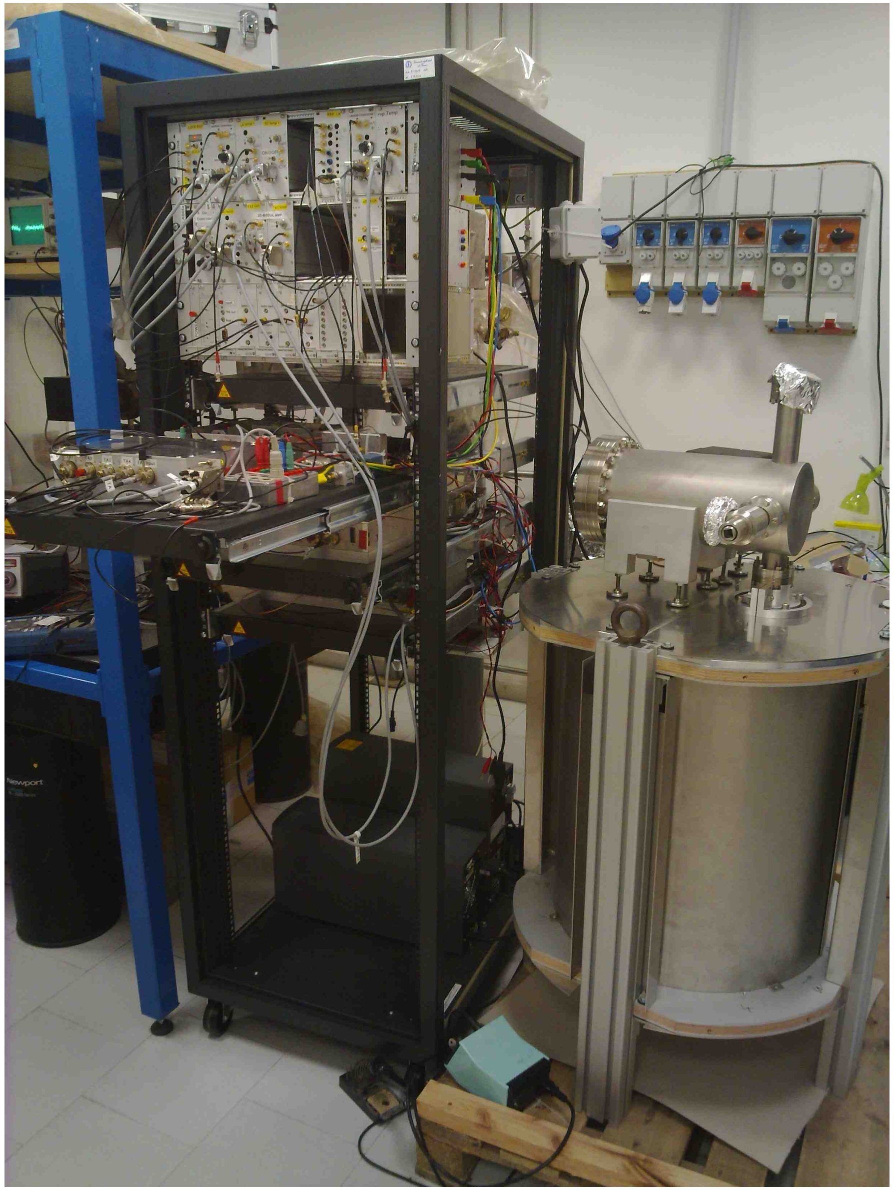


2D-MOT



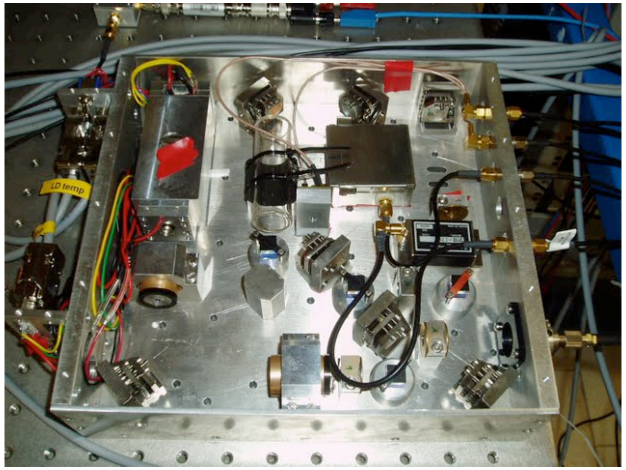
SAI - Space Atom Interferometer

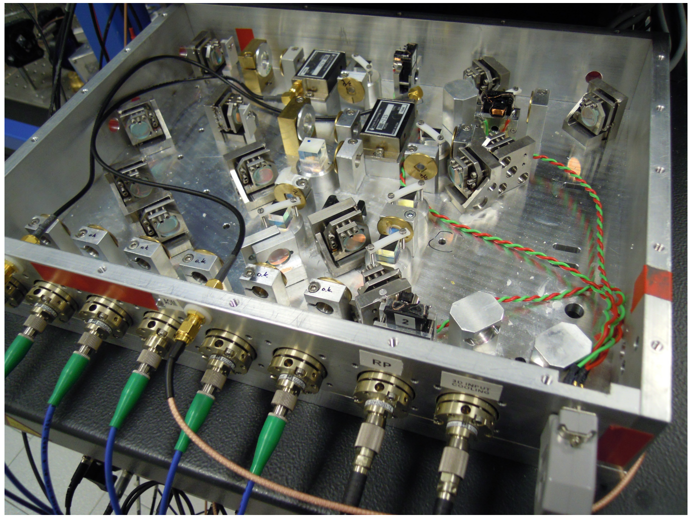
- Sensor hardware assembled
- Main subcomponents
  - Raman laser module
  - Modular laser system
  - 6.8 GHz source
  - High-flux atomic source (2D-MOT)
  - Vacuum system
  - Mechanical structure & magnetic shield
  - Electronic control system
- Theoretical investigations

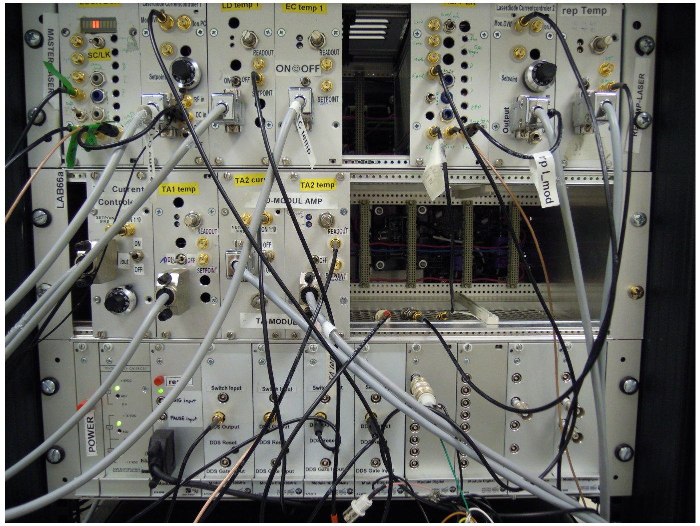


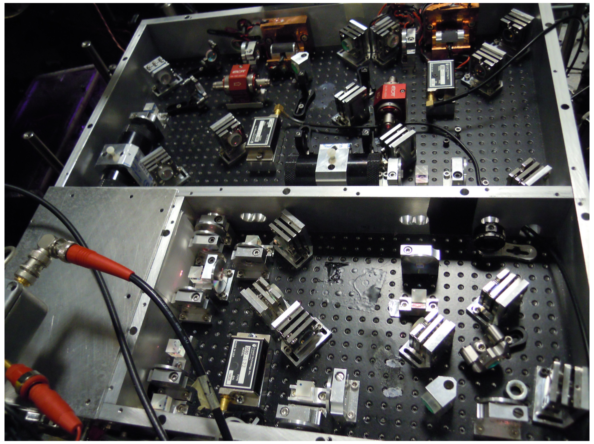
F. Sorrentino et al., *A compact atom interferometer for future space missions*,
Microgravity Sci. Technol. **22**, 551 (2010)

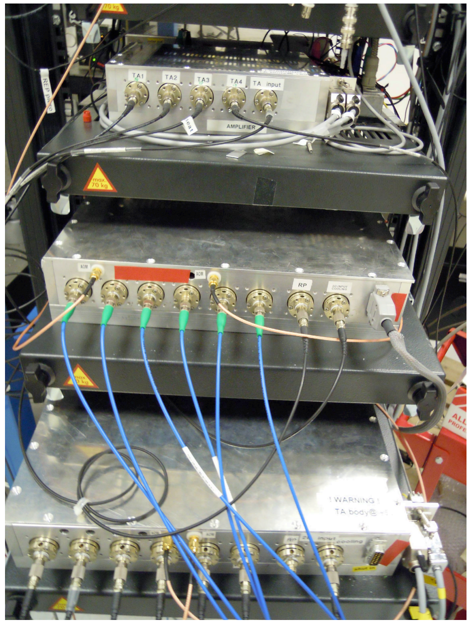
SAI - Space Atom Interferometer

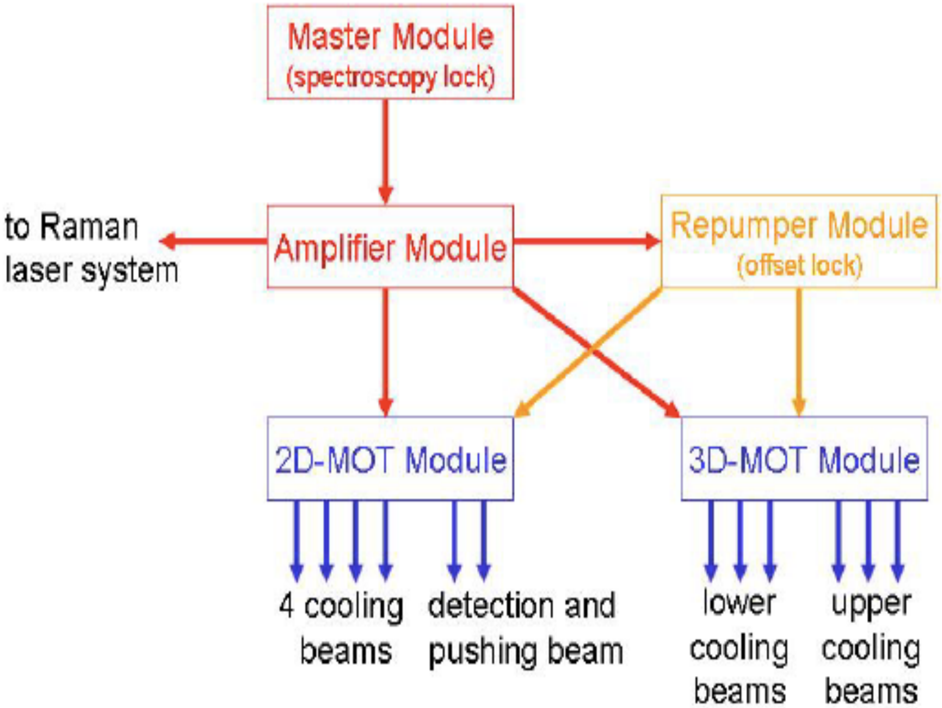




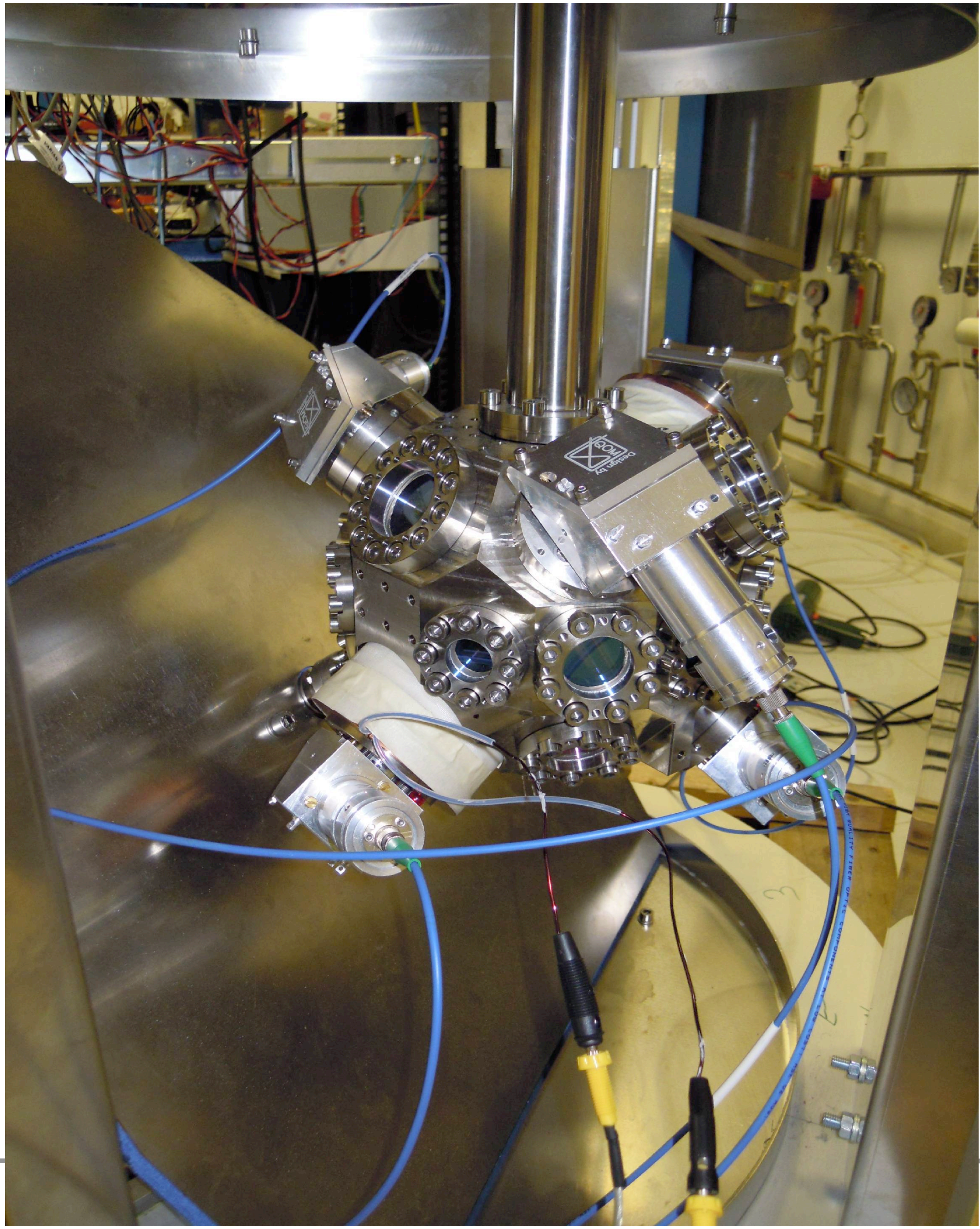








SAI - Space Atom Interferometer

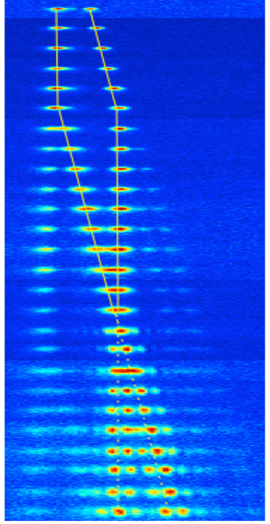


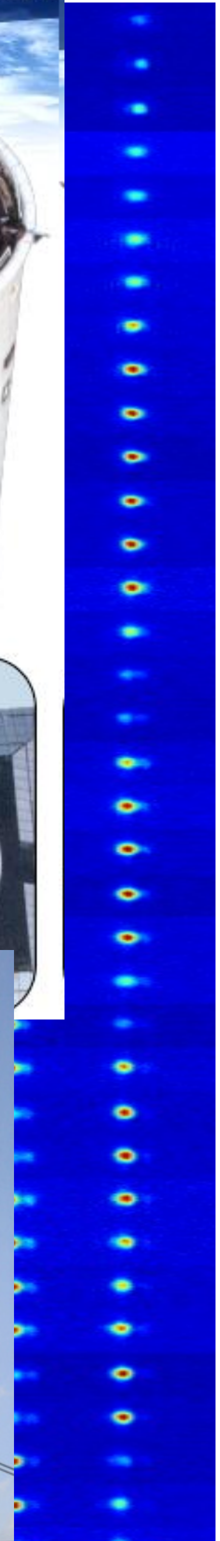
- SAI design compatible with all-optical evaporation to BEC
- Two viewports dedicated to 1560 nm FORT with two crossed beams of waist 150 μm and 30 μm

QUANTUS III

DRL-funded program until 2014

Experiments at the drop tower and catapult





QUANTUS I:

Drop experiments on chip-based interferometry

Physics with ultra cold gases

QUANTUS II

Drop & catapult experiments on dual species sources and interferometry

MAIUS

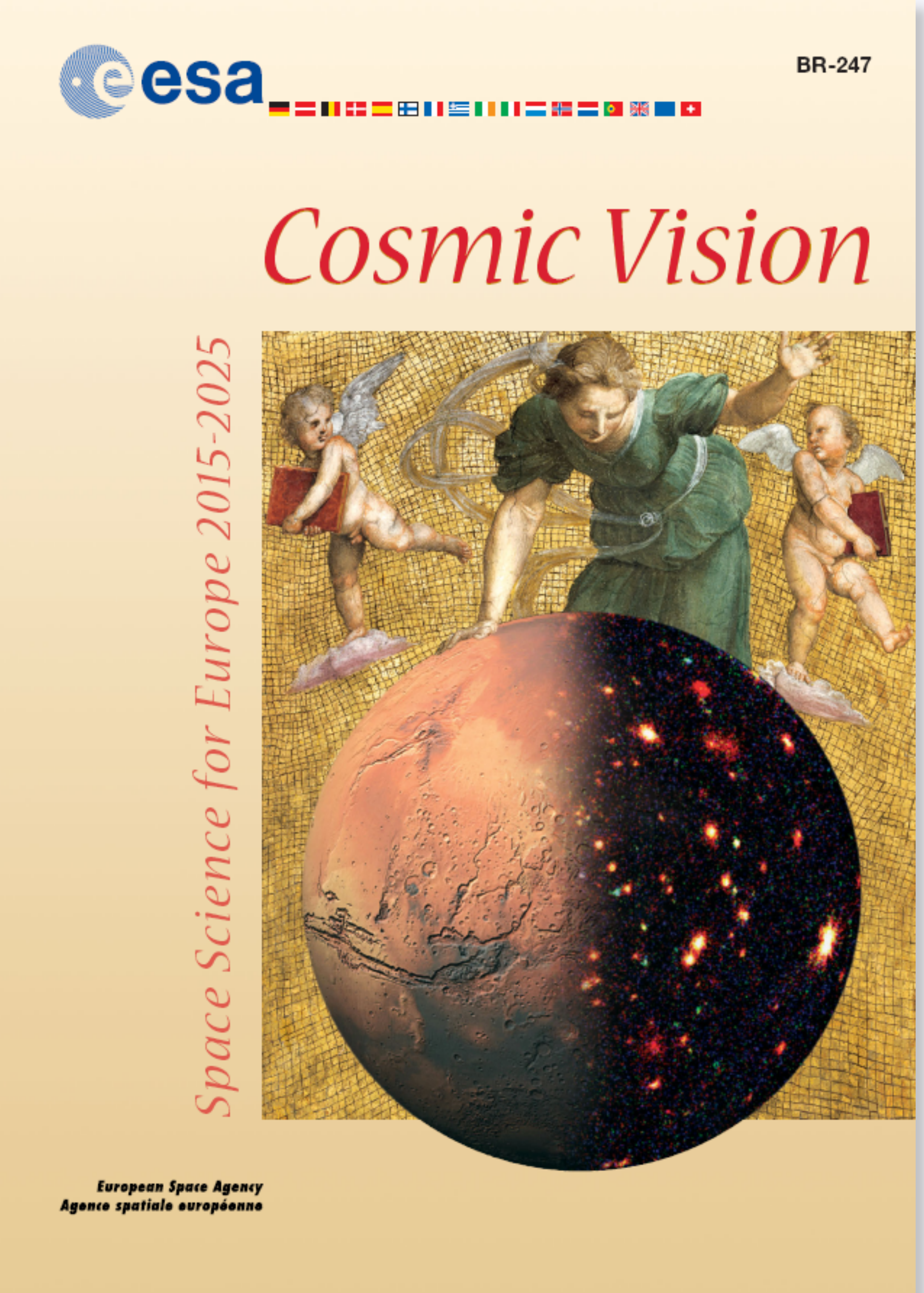
Atom interferometer hosted on a rocket

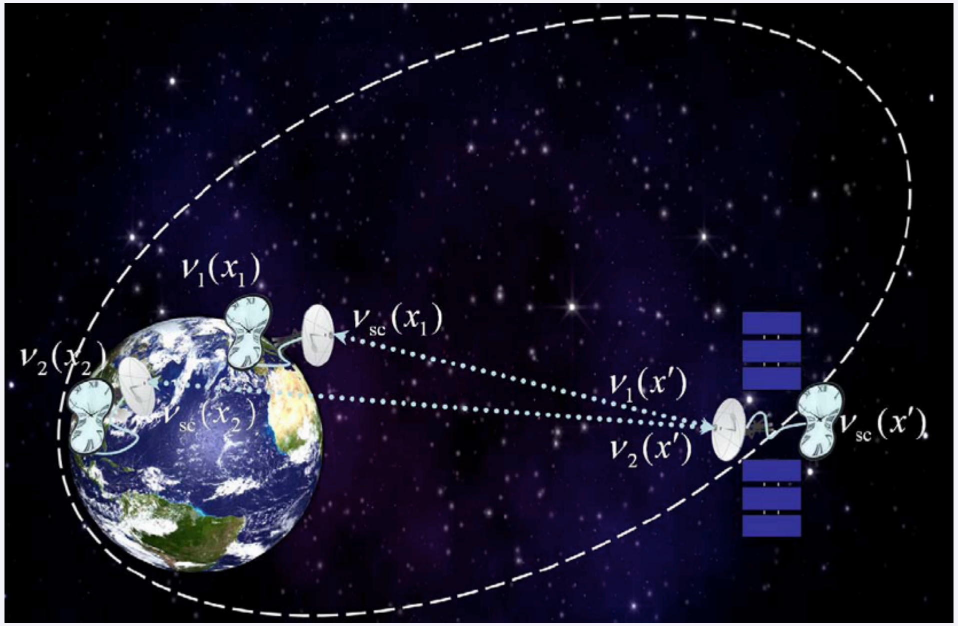
UNIVERSITÀ DEGLI STUDI FIRENZE

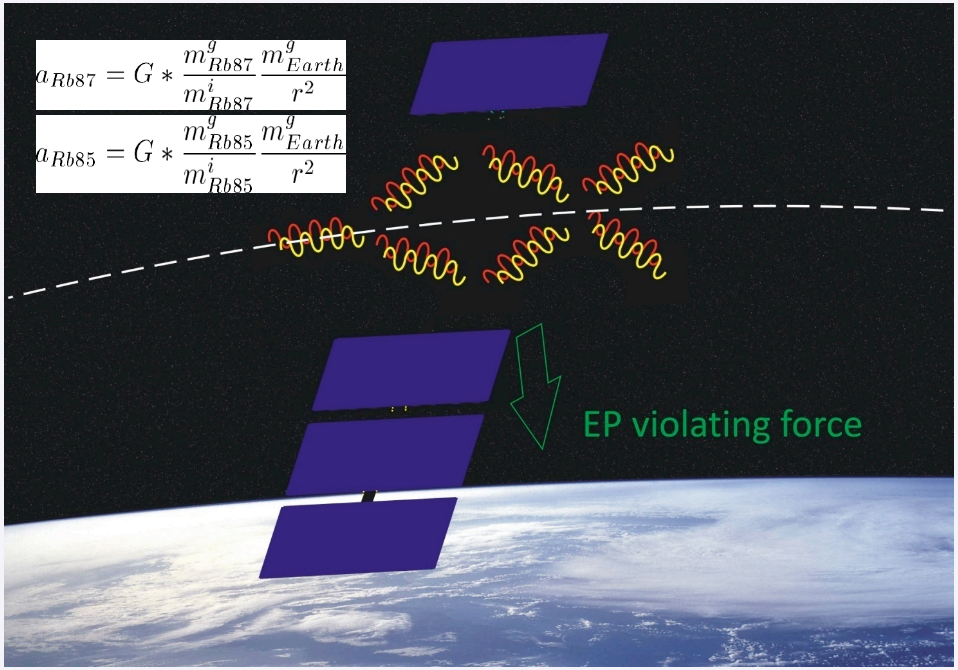
Q-WEP: towards a mission on the ISS

- Two studies in competition (1 year, funded to Astrium & Thales Alenia Space) for designing a mission architecture and addressing the design drivers imposed by the ISS-specific environment
- June 2012: joint ESR document delivered from scientific teams with definition of mission objectives with associated performance figures and derivation of the driving scientific requirements
  - **Primary objective**: WEP test at 10^{-14} on the Eötvös ratio in less than 4 months integration time
  - **Secondary objectives**: demonstration of atom interferometry differential acceleration measurement with sensitivity better than $2*10^{-10}$ $m/s^2/\sqrt{Hz}$; demonstration of long interaction time (1 s$<T<$5 s) with > 50% contrast.
  - **Baseline design**: double diffraction Raman differential interferometer on ^{85}Rb-^{87}Rb with T=1 s; CMRR for vibration noise up to 10^8 with scale factor compensation using equal k-vectors; tip-tilt mirror to compensate for ISS rotation @ 0.1%.
  - **Driving instrument requirements**: average relative displacement of atomic clouds < 4 nm; average relative velocity < 0.5 nm/s; atomic temperature ~1 nK with 10^6 atoms; retro-reflection mirror rotation < 10^5 rad/s; radius of curvature of Raman laser beams ~250 km
- …for a mission opportunity on the ISS in the 2018-2020 time frame

- STE-QUEST Mission -
Test of Gravitational Red Shift and Equivalence Principle







Detection of Gravitational Waves by Atom Interferometry

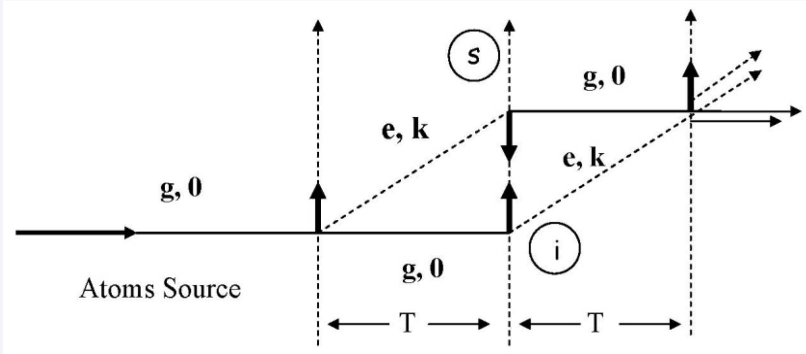
Main ideas

- Detection of GWs by matter waves
- Drastic reduction of critical noise sources
- Addressing new interesting frequency ranges

Two possible schemes

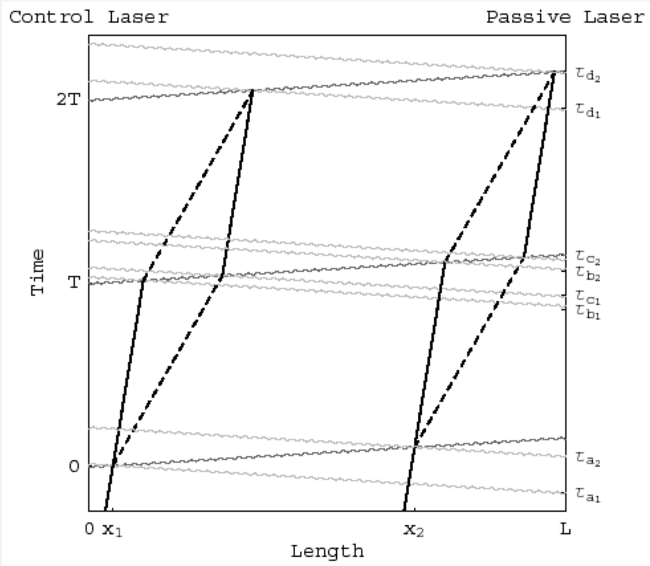
- *Single atom interferometer*

G.M. Tino and F. Vetrano, *Is it possible to detect gravitational waves with atom interferometers?* Class. Quantum Grav. 24, 2167 (2007)

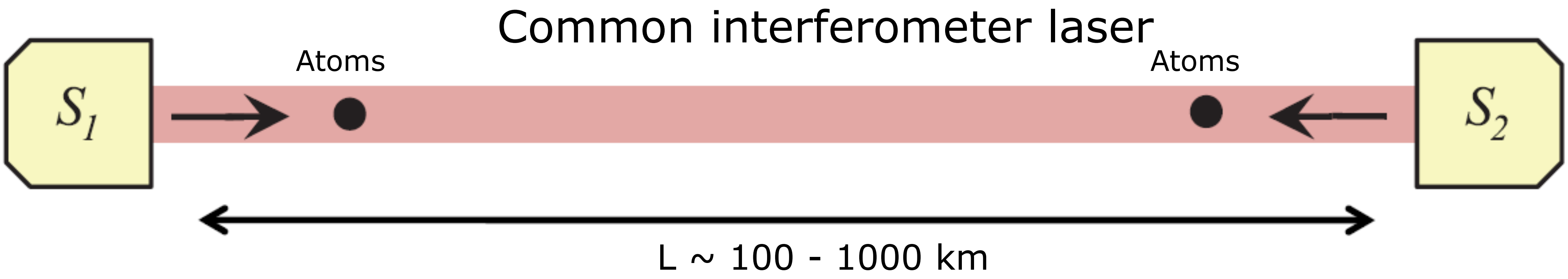


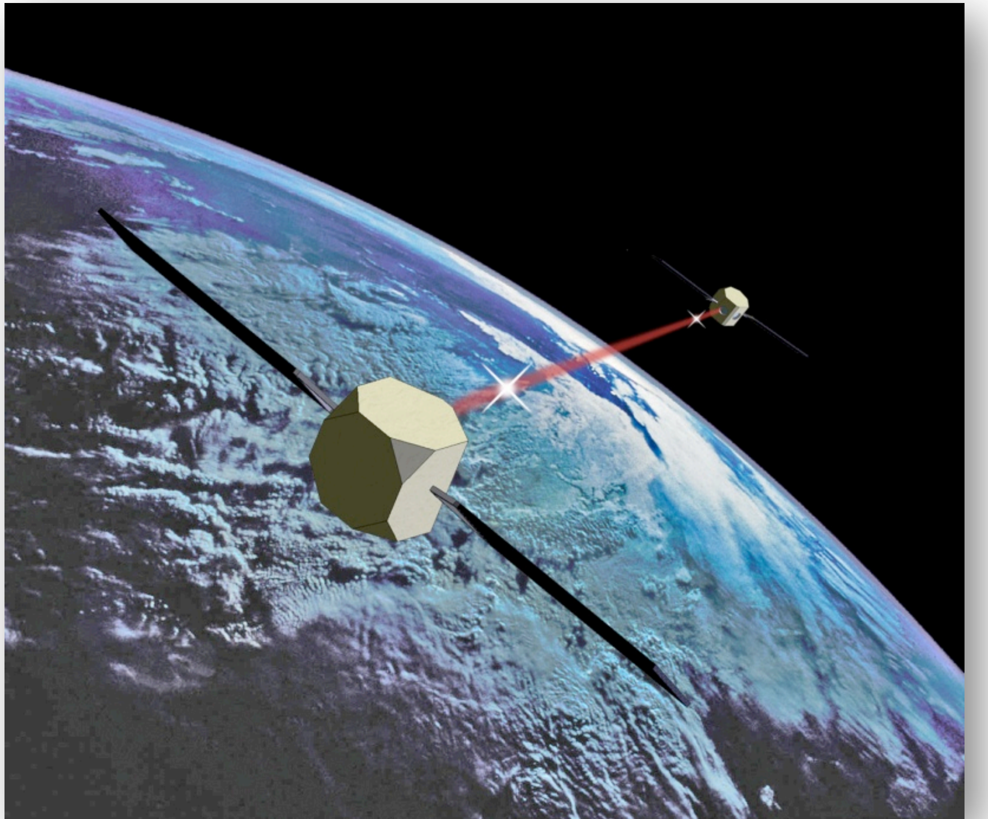
- *Differential scheme*

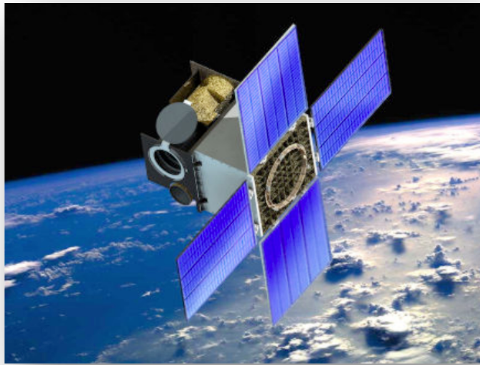
S. Dimopoulos, P. W. Graham, J. M. Hogan, M. A. Kasevich, S. Rajendran, *Atomic gravitational wave interferometric sensor,* Phys. Rev. D 78, 122002 (2008)

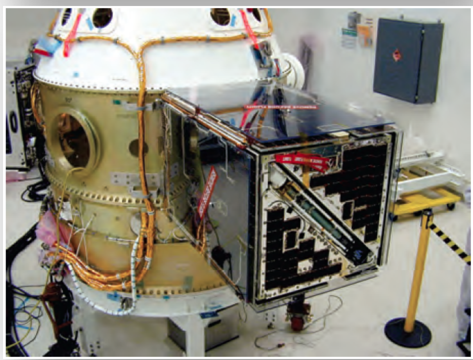


Satellite GW Antenna









JMAPS bus/ESPA deployed

From M. Kasevich Lectures at "E. Fermi" School on *Atom Interferometry*, Varenna, July 2013

UNIVERSITÀ DEGLI STUDI FIRENZE

October 14, 2008

- home
- events
- calls
- opportunities
- visit info
- weekly participants
- staff
- computing

Gravitational Waves Detection with Atom Interferometry

Conference

Apply   Schedule

Organizers:

Guglielmo M. Tino, University of Firenze, Italy Flavio Vetrano, University of Urbino, Italy

Period: from 23-02-2009 to 24-02-2009

Deadline: 15-01-2009

Note: The number of participants is limited to 50 The participation fee for the Workshop is 150 Euros including registration, coffee-breaks, lunches and the social dinner. The fee should be paid cash on arrival at the registration desk

Abstract

The possibility of using atom interferometers to detect gravitational waves is attracting increasing interest as an alternative to other detectors. Several papers were published discussing theoretical and experimental aspects. Although the results show that dedicated technological developments are still needed to achieve the required sensitivity values which are beyond those presently available, newschemes for atom interferometers, beam splitters and high flux coherent atomic sources could lead to an increase in sensitivity and make atom interferometers competitive with other gravitational wave detectors. The Workshop on "Gravitational Waves Detection with Atom Interferometry" will bring together scientists interested in theoretical and experimental

Special issue on

Gravitational Waves Detection with Atom Interferometry

G.M. Tino, F. Vetrano, C. Laemmerzahl Editors,

General Relativity and Gravitation **43**, 1901 (2011)

Applications of new quantum sensors based on atom interferometry

- Measurement of fundamental constants → ***G***, → α
- New definition of kg
- Test of equivalence principle
- Measurement of the gravitational redshift
- Tests of quantum gravity
- Short-distances forces measurement
- Search for electron-proton charge inequality
- New detectors for gravitational waves ?
- Development of transportable atom interferometers → geophysics, → space


COURSE 188
PROCEEDINGS
INTERNATIONAL SCHOOL OF PHYSICS «ENRICO FERMI»
COURSE 188
Atom Interferometry
edited by G. M. Tino and M. A. Kasevich
15-20 July 2013
Villa Monastero
Varenna, Lake Como
SOCIETÀ ITALIANA DI FISICA
Atom Interferometry
edited by G. M. Tino and M. A. Kasevich
IOS Press