

# *MAGIA-Advanced*

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*Istituto Nazionale di Fisica Nucleare, Sezione di Firenze*

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

*Workshop on Atomic Experiments for DM and Gravity Exploration*  
CERN, 22 July 2019

# MAGIA-Advanced

## Advanced atomic quantum sensors for gravitational physics

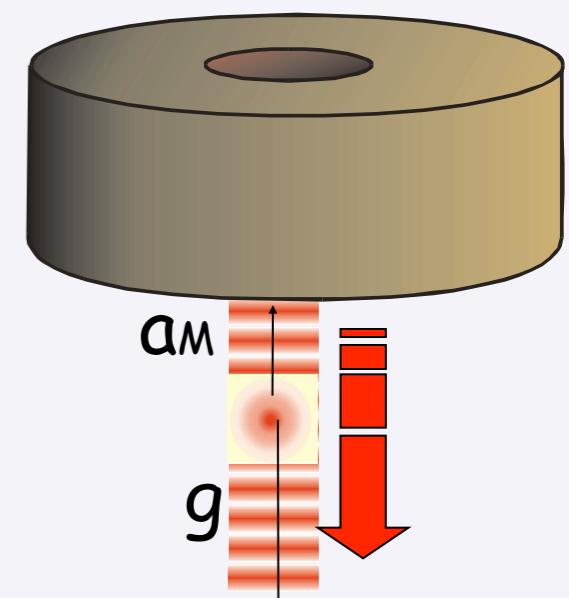
- Large-scale atom interferometer (Rb & Sr)
- New schemes for large momentum transfer
- High-flux atomic sources
- High-sensitivity detection schemes
- Squeezed atomic states



# MAGIA

(*MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA*)

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



➤ *Precision measurement of G*

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

PROCEEDINGS  
OF  
THE JOHNS HOPKINS WORKSHOP  
ON  
CURRENT PROBLEMS IN PARTICLE THEORY 25  
  
FIRENZE, 2001  
(September 3 – 5)

**2001:  
A RELATIVISTIC  
SPACETIME ODYSSEY**

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PROCEEDINGS

OF

THE JOHNS HOPKINS WORKSHOP

ON

CURRENT PROBLEMS IN PARTICLE THEORY 25

FIRENZE, 2001

(September 3 – 5)

HIGH PRECISION GRAVITY MEASUREMENTS BY ATOM  
INTERFEROMETRY

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Experiments in progress, planned or simply being considered to perform accurate measurements of gravitational field properties using new quantum devices based on ultracold atoms are presented.

1 Introduction

Matter-wave interference with neutral atoms was first demonstrated in 1991. In analogy to optical interferometers, atomic wave packets are split and recombined giving rise to an interference signal. Different schemes can be used for splitting, reflecting and recombining the atoms and the atom optics components can be either material structures or light fields.<sup>1</sup> In a particular class of interferometers, which is the one relevant for the experiments described in this paper, the separation of the atoms is achieved by inducing a transition between internal states of the atoms by an electromagnetic field. The spatial separation in this case is induced by the momentum recoil and the internal and external states of the atoms become entangled. The field is now mature both from the point of view of the understanding of the basic physics underlying laser cooling and laser manipulation of atoms and for the development of a solid technology for the experimental implementation of sensors. Atom interferometers are already competing with state-of-the-art optical interferometers in terms of sensitivity in the measurement, for example, of gravity acceleration<sup>2</sup> and rotations.<sup>3</sup> Already in 1975, a neutron interferometer was used to detect the phase shift caused by the Earth's gravitational field.<sup>4</sup> The inertial sensitivity of an atom interferometer can be much larger than the one of neutron interferometers because of the larger mass and the possibility of manipulating internal and external atomic degrees of freedom. Indeed, the sensitivity of atom interferometers as detectors of rotations and accelerations increases with the observation time so that it can be extremely high if slow laser-cooled atoms are used. Laser cooling of atoms has been one of the most active fields of research in physics in the last decade. Atoms from a room-temperature vapor can be cooled to temperatures as low as a few microkelvin by interacting with laser light. At such low temperatures, the wave properties

High Precision Gravity Measurements 149

and  $|2, p + \hbar k \rangle \rightarrow |1, p \rangle$  for the two parts of the atoms. This corresponds to the mirrors in an optical interferometer. 3) After another time T, the two parts of the atoms overlap again and a third pulse ( $\pi/2$  pulse) acts as a recombining beam splitter. 4) At the end of the pulse sequence the number of atoms in either of the states is detected.

For a proper arrangement of experimental parameters, it can be shown that the phase difference between the two arms of the interferometer is  $\Delta\phi = kgT^2$ . The sensitivity of the method therefore increases with the interrogation time and this is the reason to use an atomic fountain scheme. The expression also shows that an increase in sensitivity can be obtained if a shorter wavelength is used to induce the Raman transition. In the same way, a significative increase of the sensitivity can be achieved if each pulse of the sequence is replaced by a sequence of pulses,<sup>7</sup> thus increasing the spatial separation between the two parts of the atomic wavepacket. The Raman transition between two internal states can be induced using two laser beams whose frequency difference is phase-locked to a stable microwave source. This insures a precise control of the relative phase. Alternatively, optical modulators can be used to produce the required frequencies. Another crucial element of the interferometer is the mirror used to retroreflect the Raman laser beams. This mirror plays the role of an inertial reference during the measurement. The two laser beams can be arranged to travel along the same path and only vibrations of this mirror can affect the relative phase. Therefore this mirror needs to be stabilized using active low-frequency vibration isolation systems to reduce vibrations in the 0.1–10 Hz range. The better the mirror vibration isolation, the larger can be the time T between pulses and the resulting sensitivity.

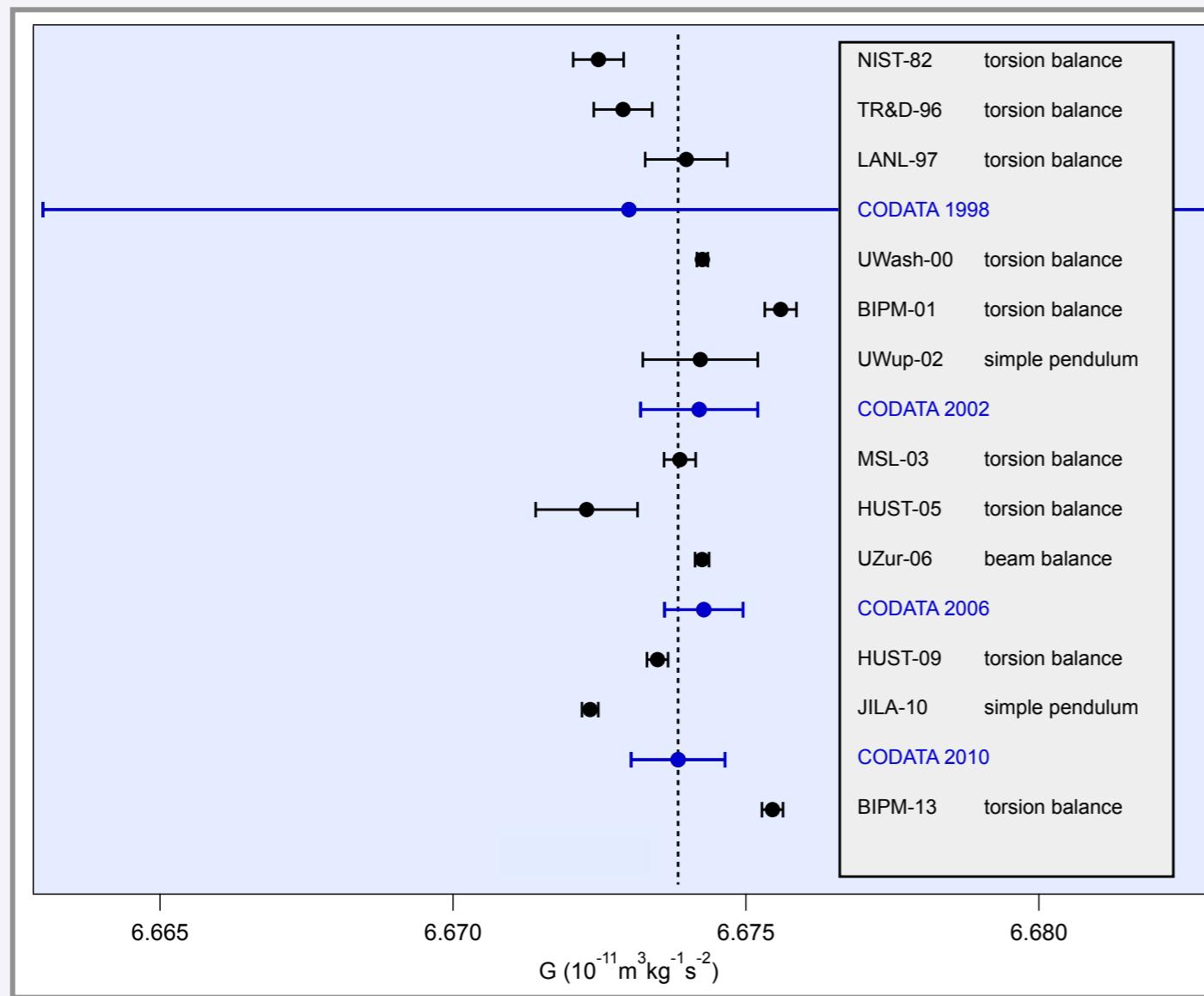
An important advantage of this atom interferometer scheme is that it is intrinsically free of instrumental drifts thus allowing integration over very long time intervals to increase sensitivity.

3 MAGIA: a new experiment to measure the gravitational constant

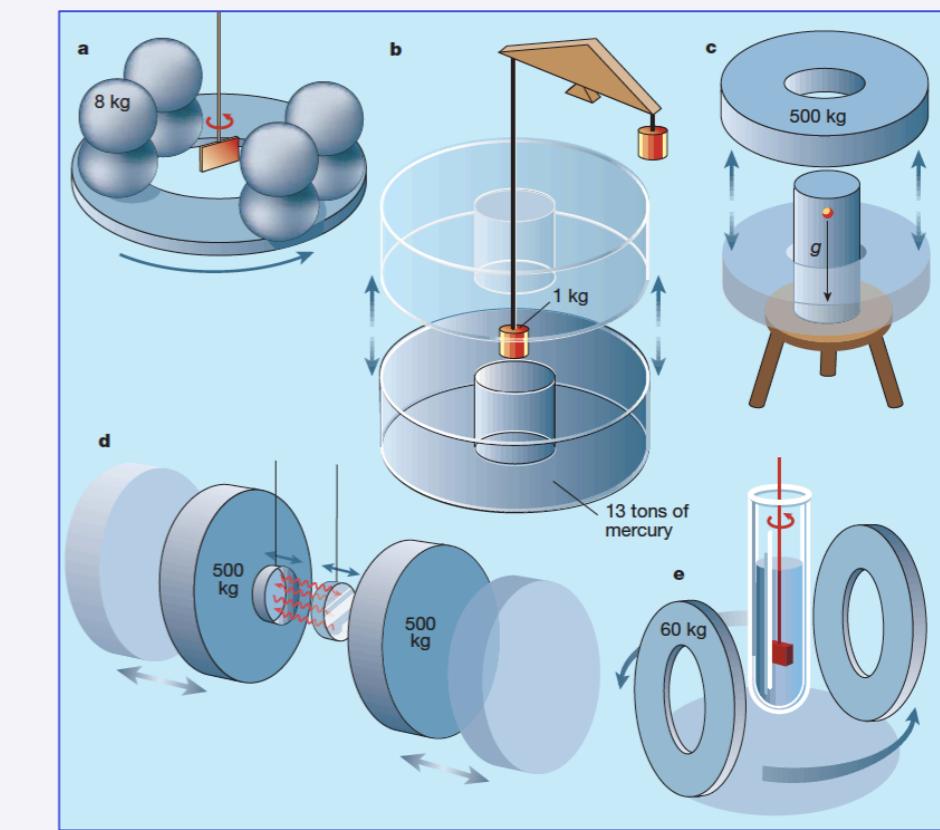
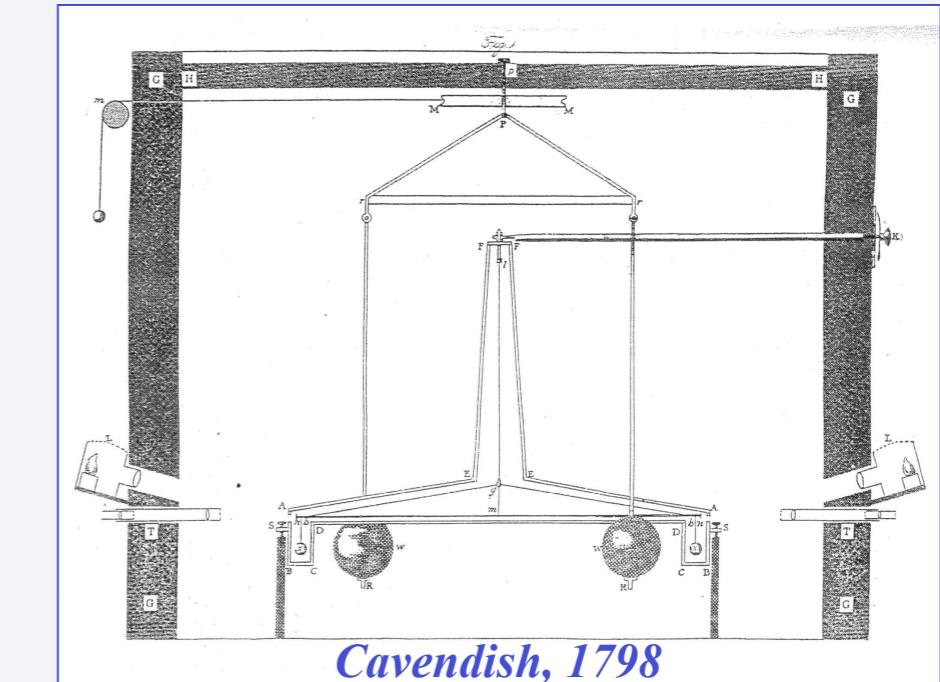
The Newtonian gravitational constant G is, with the Planck's constant h and the speed of light c, one of the most fundamental constants. While h is known with a relative uncertainty of about 80 ppb and the value of c was measured to 9 decimal digits before being defined as exact, in the last adjustment of the fundamental quantities of physics<sup>8</sup> the recommended value for the gravitational constant is  $G = (6.673 \pm 0.010) \times 10^{-11} \text{ m}^3 \text{kg}^{-1} \text{s}^{-2}$ , corresponding to a relative uncertainty of  $\pm 1500$  ppm. This is due to the weakness of gravity,

# Measurements of the Newtonian gravitational constant $G$

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



P.J. Mohr, B. N. Taylor, and D. B. Newell,  
*CODATA recommended values of the  
fundamental physical constants: 2010,*  
*Rev. Mod. Phys., Vol. 84, No. 4, (2012)*



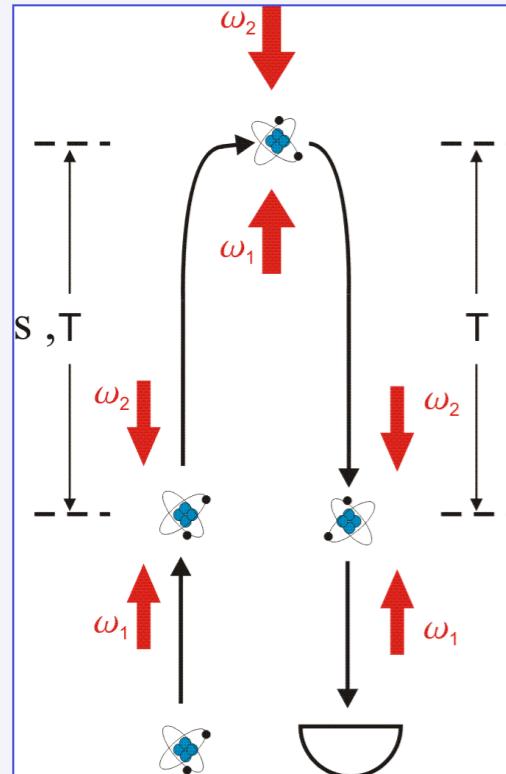
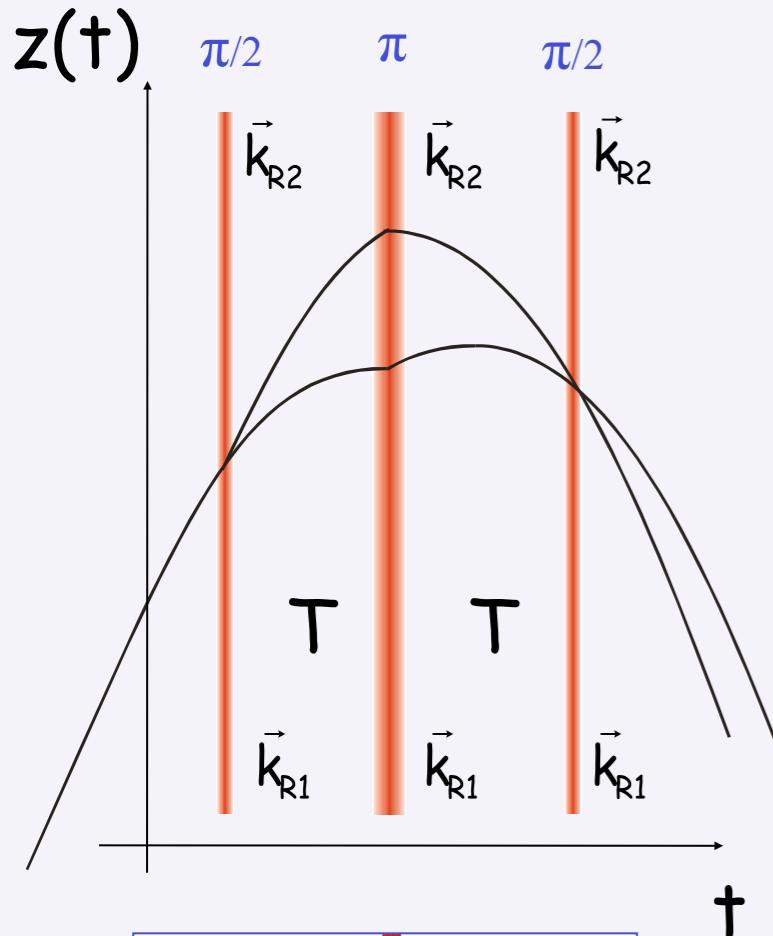
Terry Quinn. *Measuring big G*, NATURE, 408, 919 (2000)



# Why atoms?

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

# Raman interferometry in a Rb atomic fountain



Phase difference between the paths:

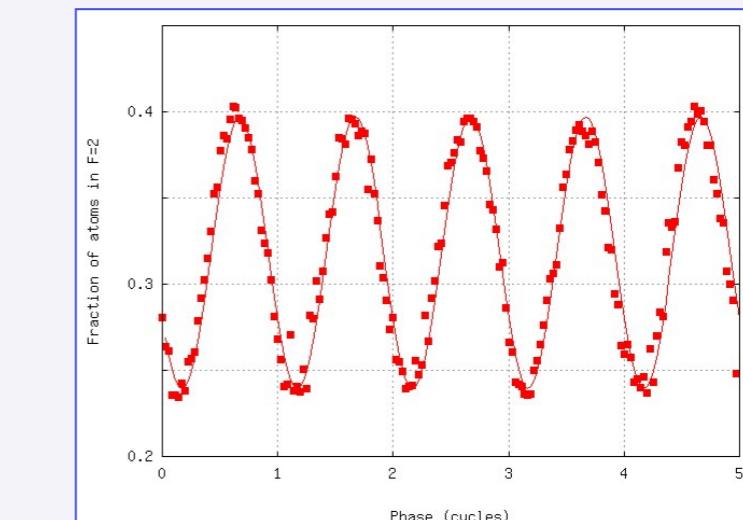
$$\Delta\Phi = k_e[z(0)-2z(T)+z(2T)] + \Phi_e \quad k_e = k_1 - k_2, \omega_e = c k_e$$

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

$$g = \Delta\Phi / k_e T^2$$

Final population:

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



Interference fringes – Firenze 2006

$10^6$  Rb atoms

S/N = 1000

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

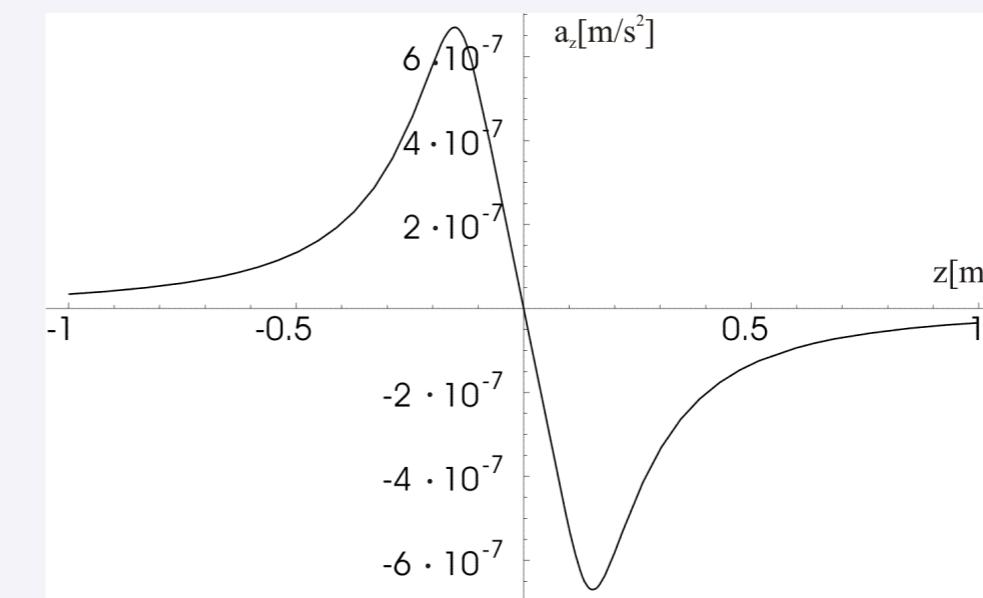
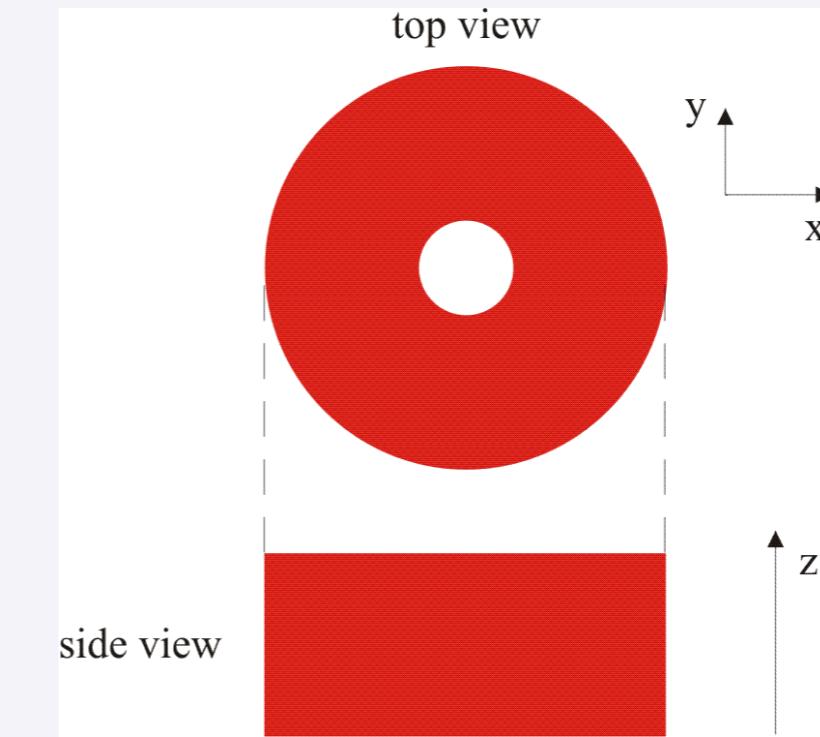
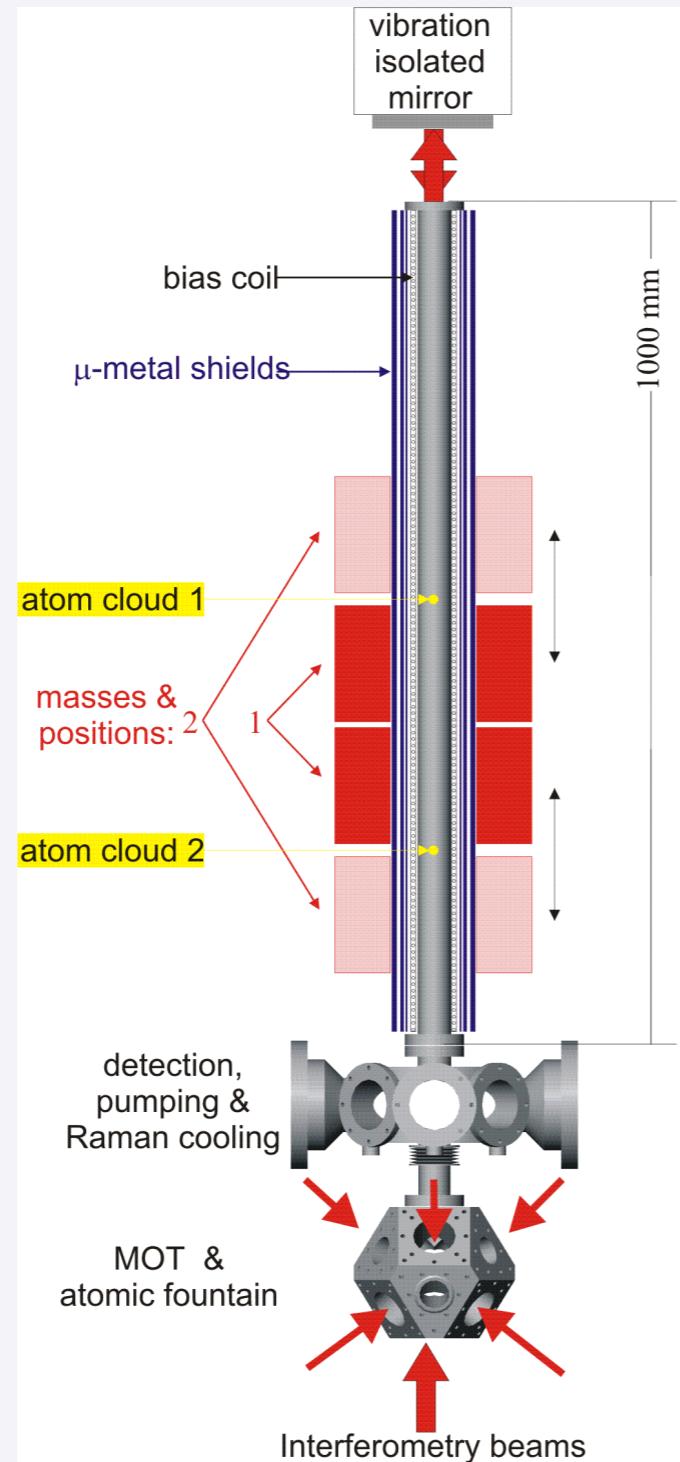
$\Rightarrow$  Sensitivity  $10^{-9} \text{ g/shot}$

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

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

# MAGIA

## Rb gravity gradiometer + source mass

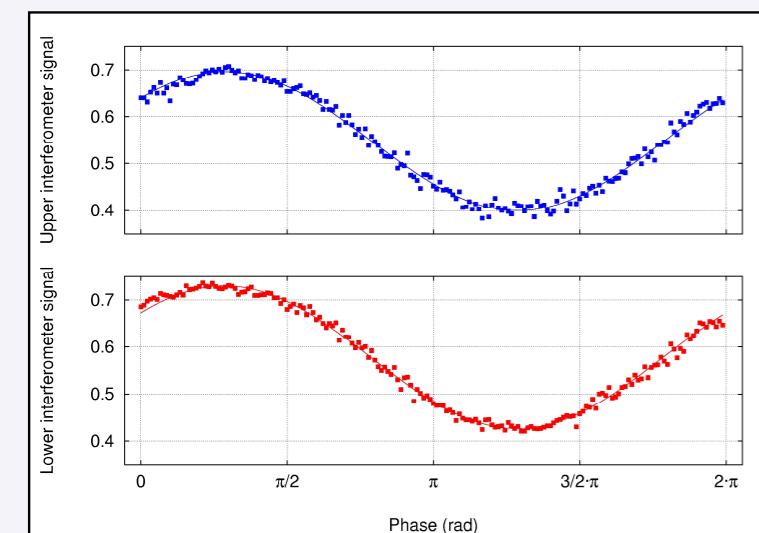


500 kg tungsten mass

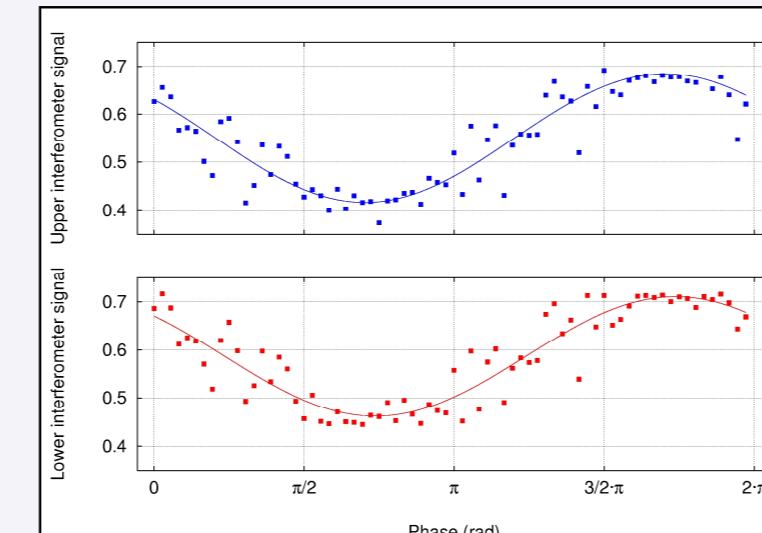
Sensitivity  $10^{-9}\text{g}/\text{shot}$   
one shot  $\Rightarrow \Delta G/G \approx 10^{-2}$

Peak mass acceleration  $a_G \approx 10^{-7}\text{g}$   
10000 shots  $\Rightarrow \Delta G/G \approx 10^{-4}$

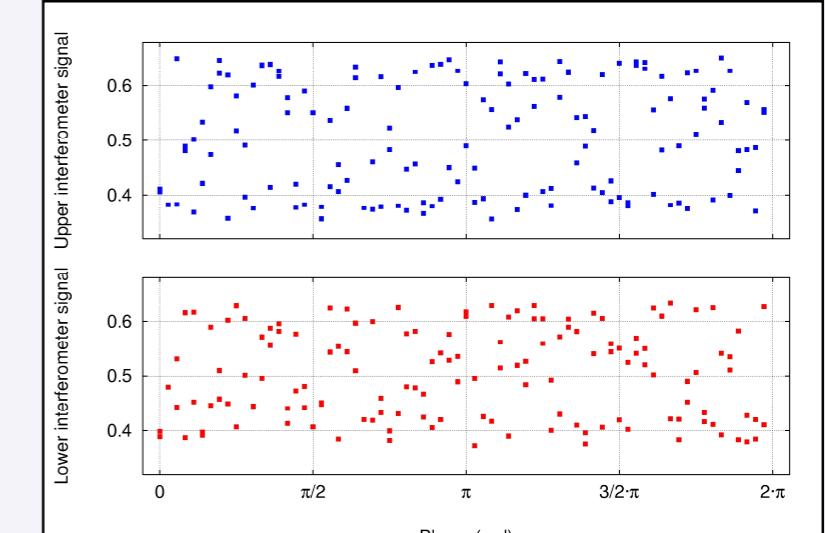
# Gravity gradiometer



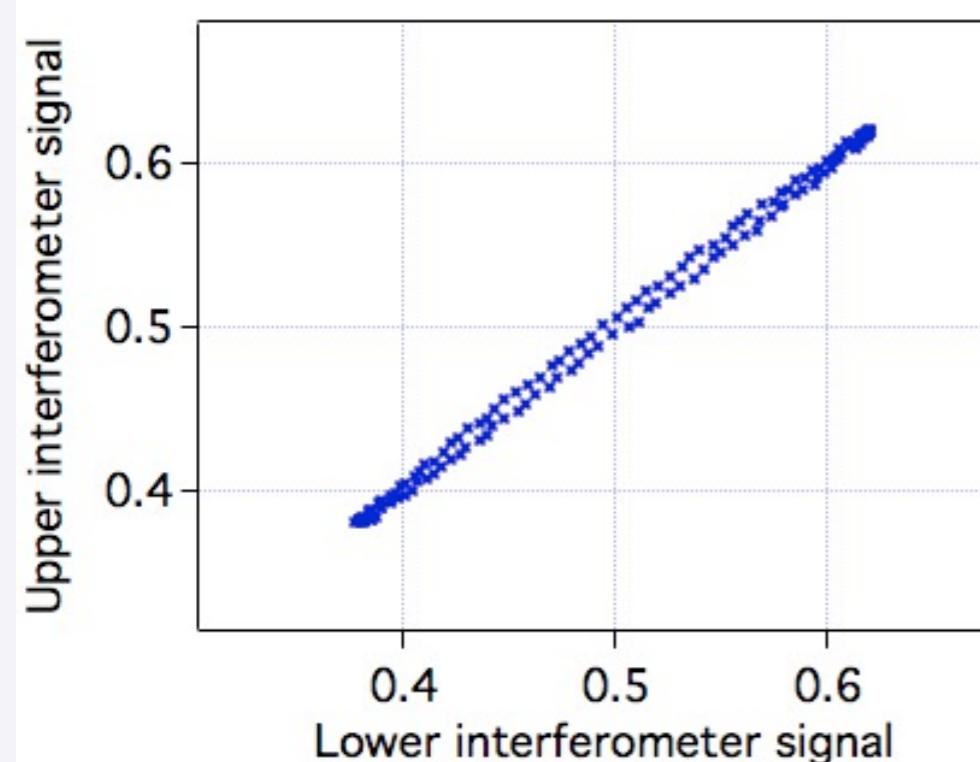
$T = 5 \text{ ms}$   
resol. =  $2.3 \times 10^{-5} \text{ g/shot}$



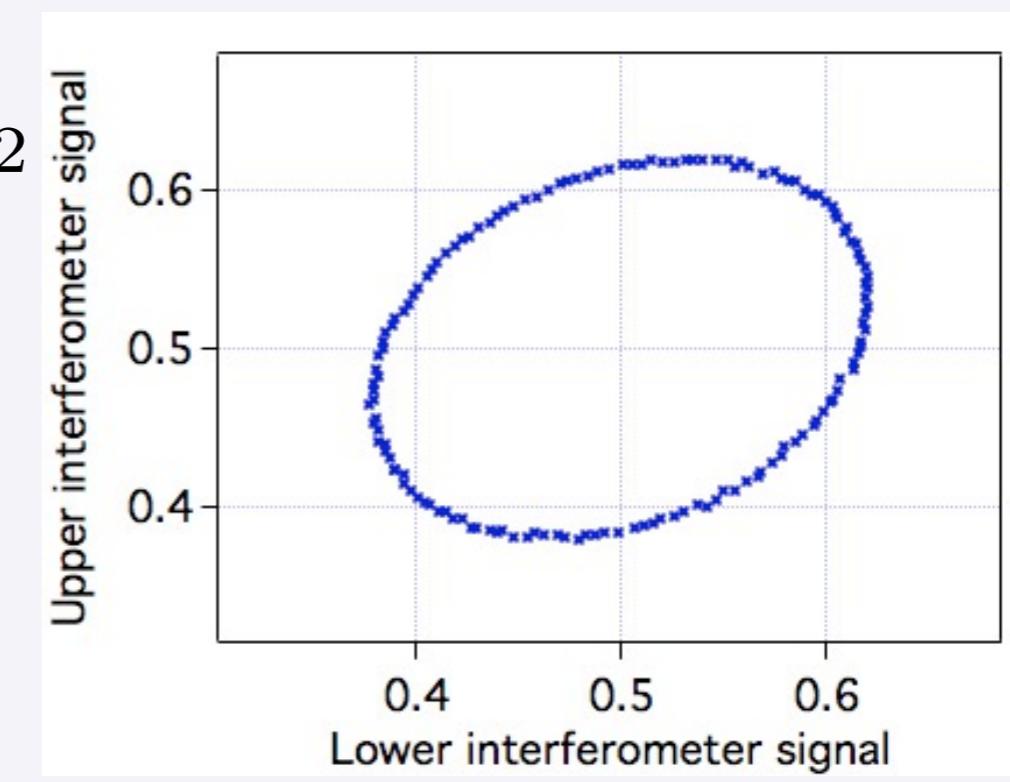
$T = 50 \text{ ms}$   
resol. =  $1.0 \times 10^{-6} \text{ g/shot}$



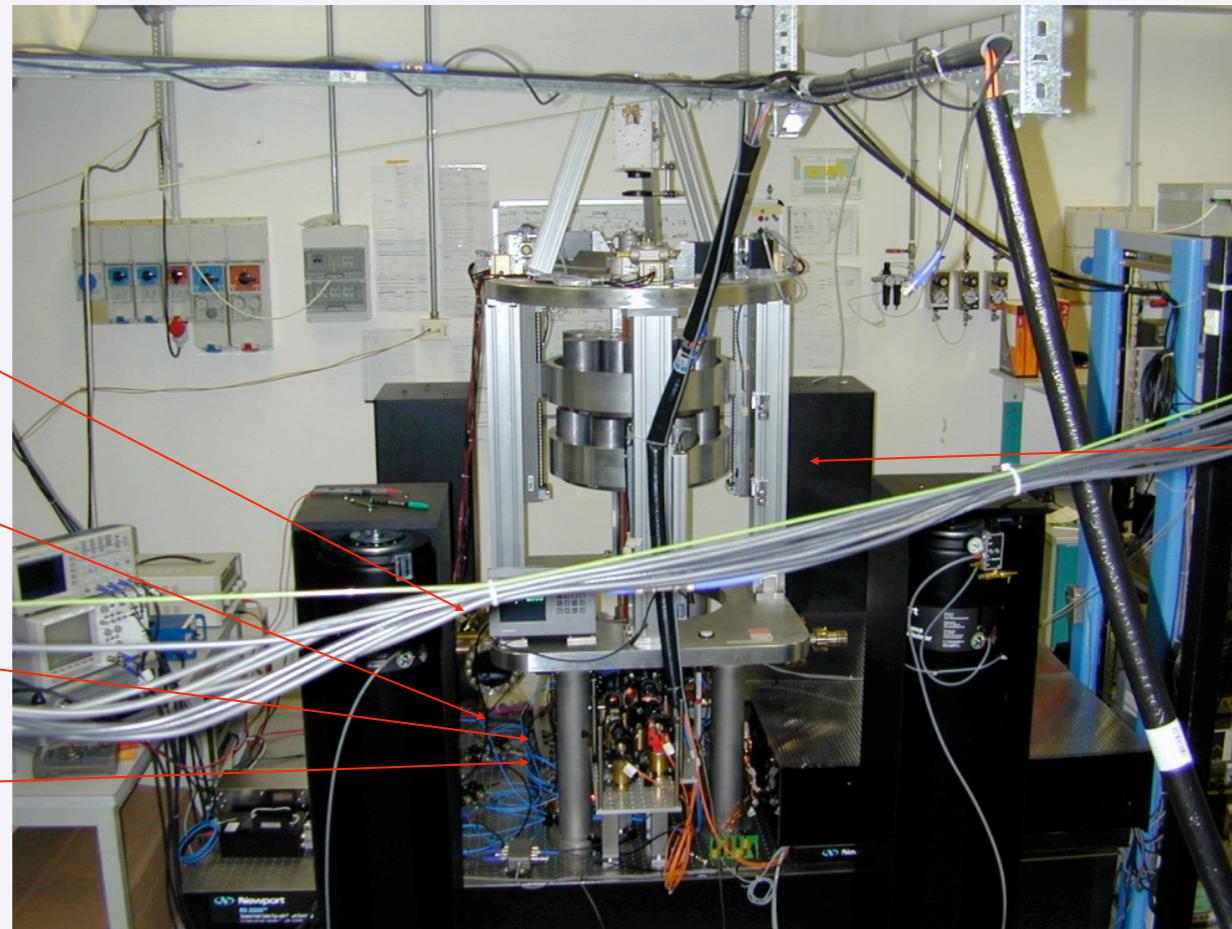
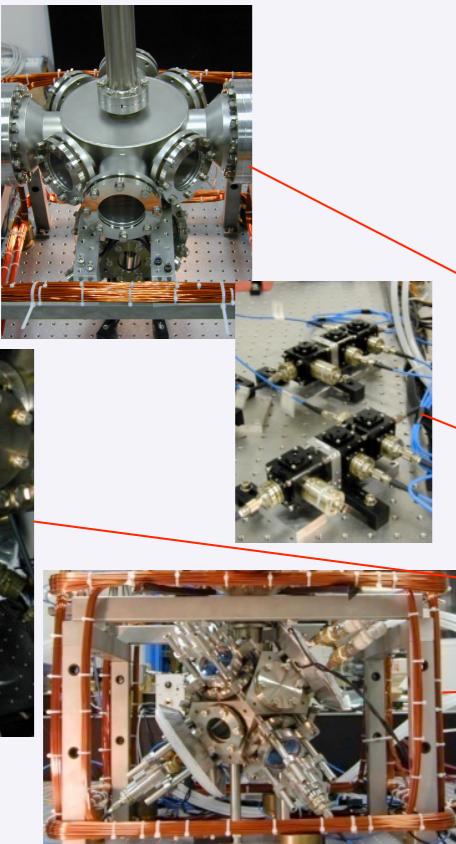
$T = 150 \text{ ms}$   
resol. =  $3.2 \times 10^{-8} \text{ g/shot}$



$$\Delta\Phi = k_e g T^2$$



# MAGIA apparatus

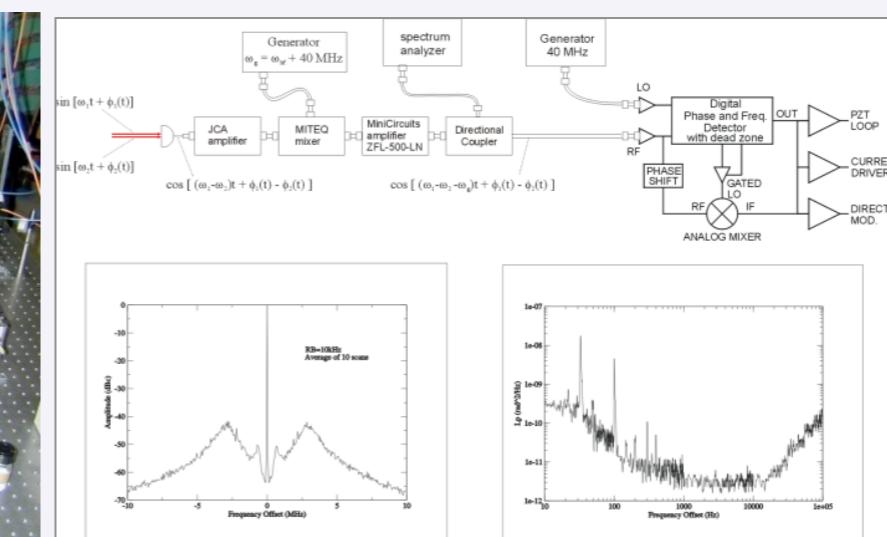


*Source masses and support*



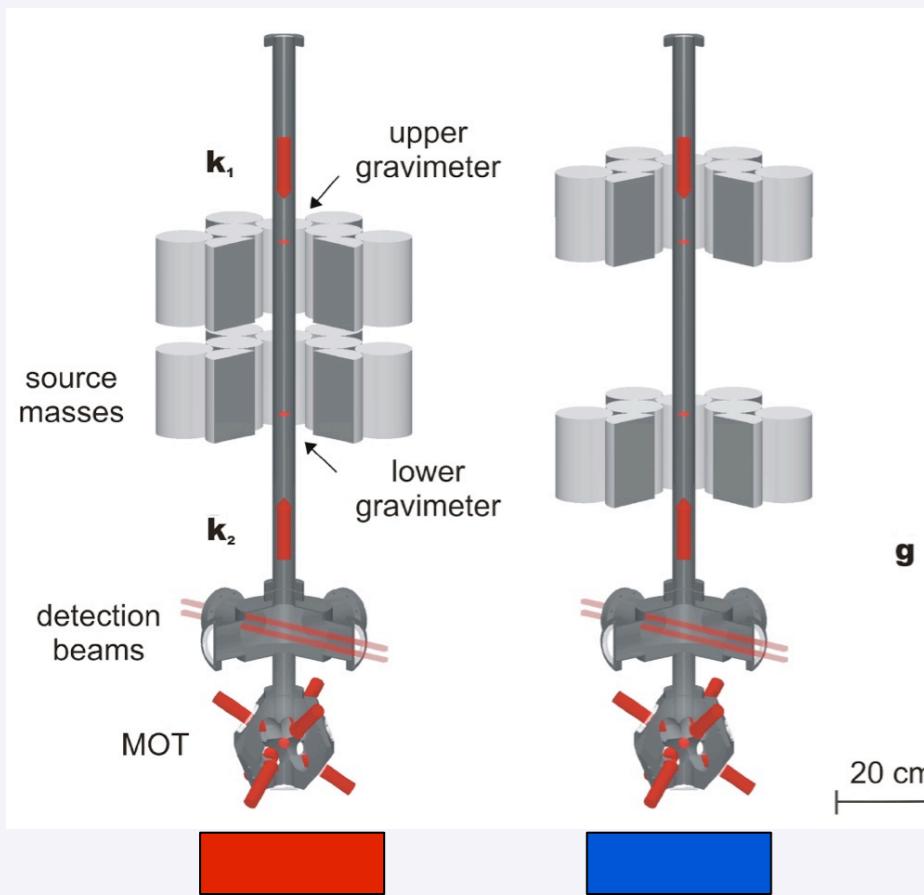
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettor Russo, M. Prevedelli, G.M. Tino,  
*Source Masses and Positioning System for an Accurate Measurement of G*, Rev. Scient. Instr. 78, 075109 (2007)

## Laser and optical system

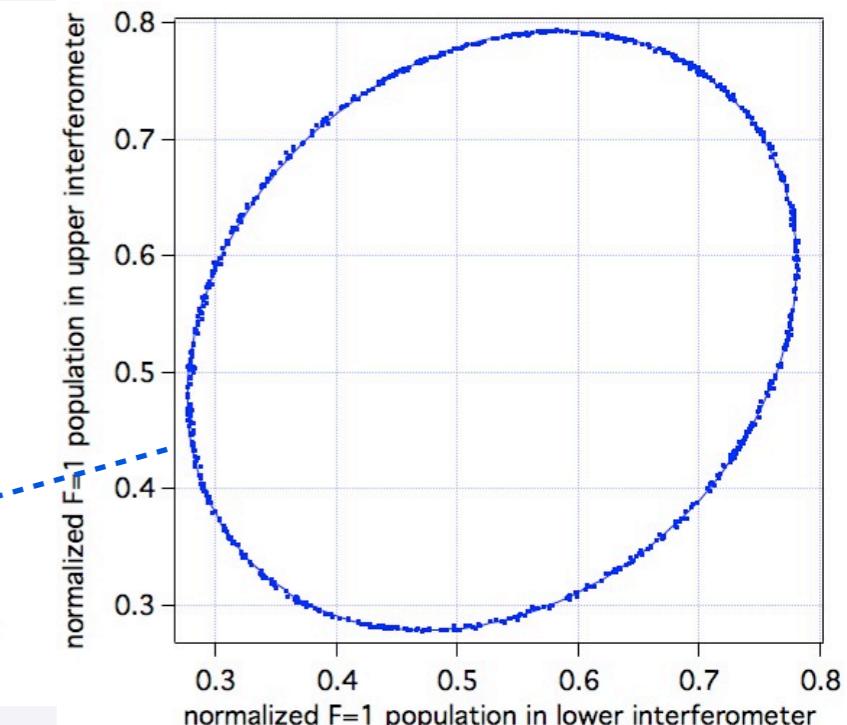
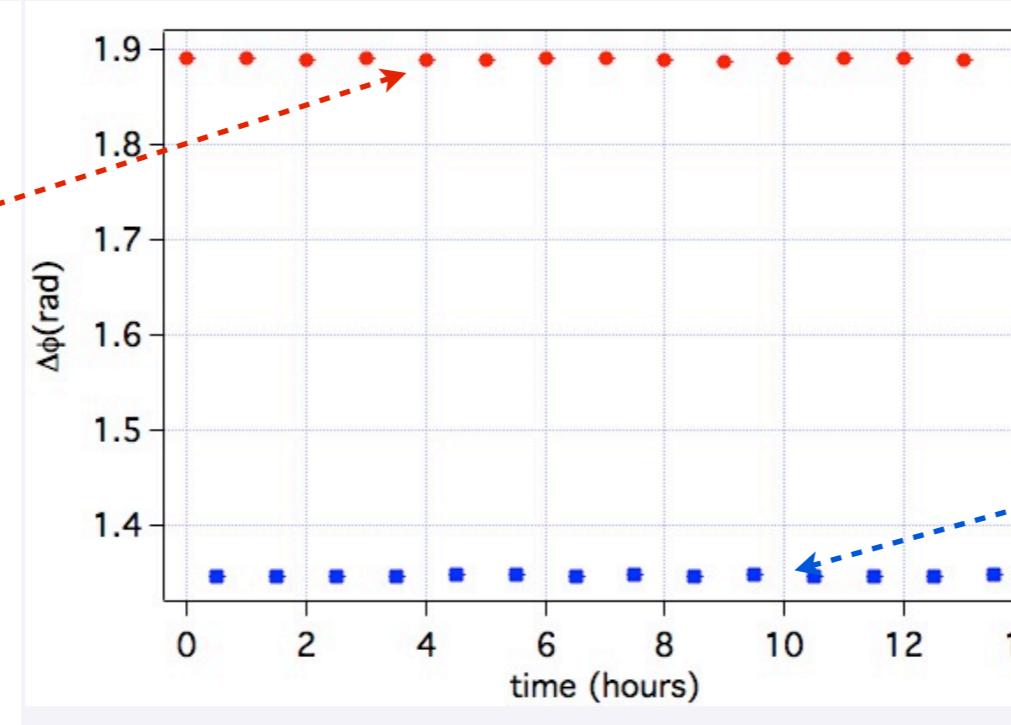
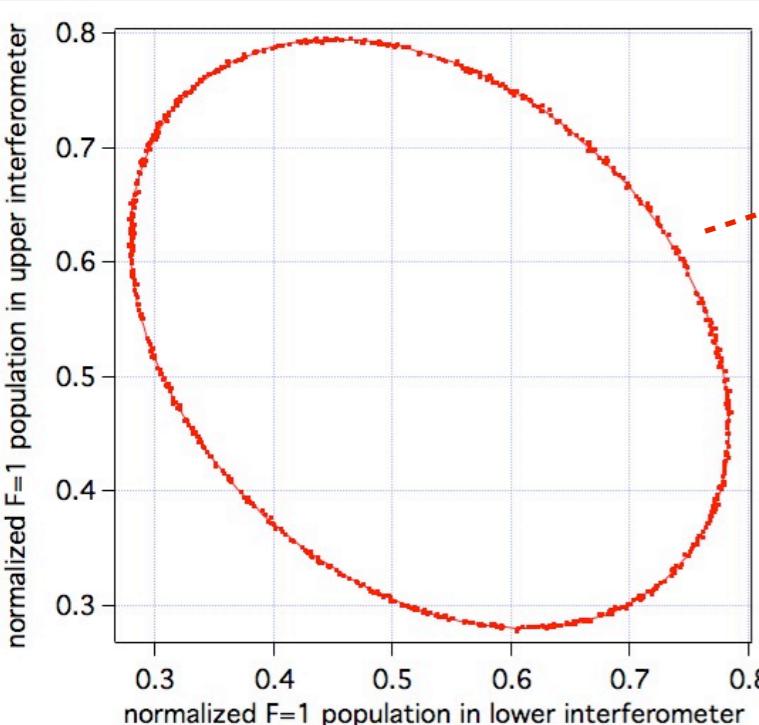


L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino,  
*Analog+digital phase and frequency detector for phase locking of diode lasers*, Rev. Scient. Instr. 76, 053111 (2005)

# MAGIA: Final sensitivity



- Repetition period of experimental cycle: 1.9 s
- Number of points per ellipse: 720 (23 min)
- Number of launched atoms:  $\sim 10^9$  per cloud
- Number of detected atoms:  $\sim 4 \times 10^5$  per cloud
- Sensitivity to ellipse angle:  $\sim 9$  mrad / shot
- Sensitivity to differential gravity:  $3 \times 10^{-9} g / \sqrt{\text{Hz}}$
- Sensitivity in  $G$  measurements:  $5.7 \times 10^{-2} / \sqrt{\text{Hz}}$
- Integration time to  $G$  at  $10^{-4}$ : 100 hours





# LETTER

doi:10.1038/nature13433

## Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi<sup>1</sup>, F. Sorrentino<sup>1</sup>, L. Cacciapuoti<sup>2</sup>, M. Prevedelli<sup>3</sup> & G. M. Tino<sup>1</sup>

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<sup>1</sup>. 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<sup>2</sup> 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  $G = 6.67191(99) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$  with a relative uncertainty of 150 parts per million (the combined standard

uncertainty). This value is in excellent agreement with the current best value of  $G$  obtained by the Cavendish balance method<sup>3</sup>. The new value is obtained by using a quantum interferometer to measure 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<sup>18</sup>. 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  $^{87}\text{Rb}$  atoms at the two-photon Raman transition between the hyperfine

$$G = 6.67191(77)(62) \times 10^{-11} \text{ m}^3 \text{ kg}^{-1} \text{ s}^{-2}$$

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)

Peter J. Mohr, David B. Newell, and Barry N. Taylor: CODATA recommended values of the fundamental ...

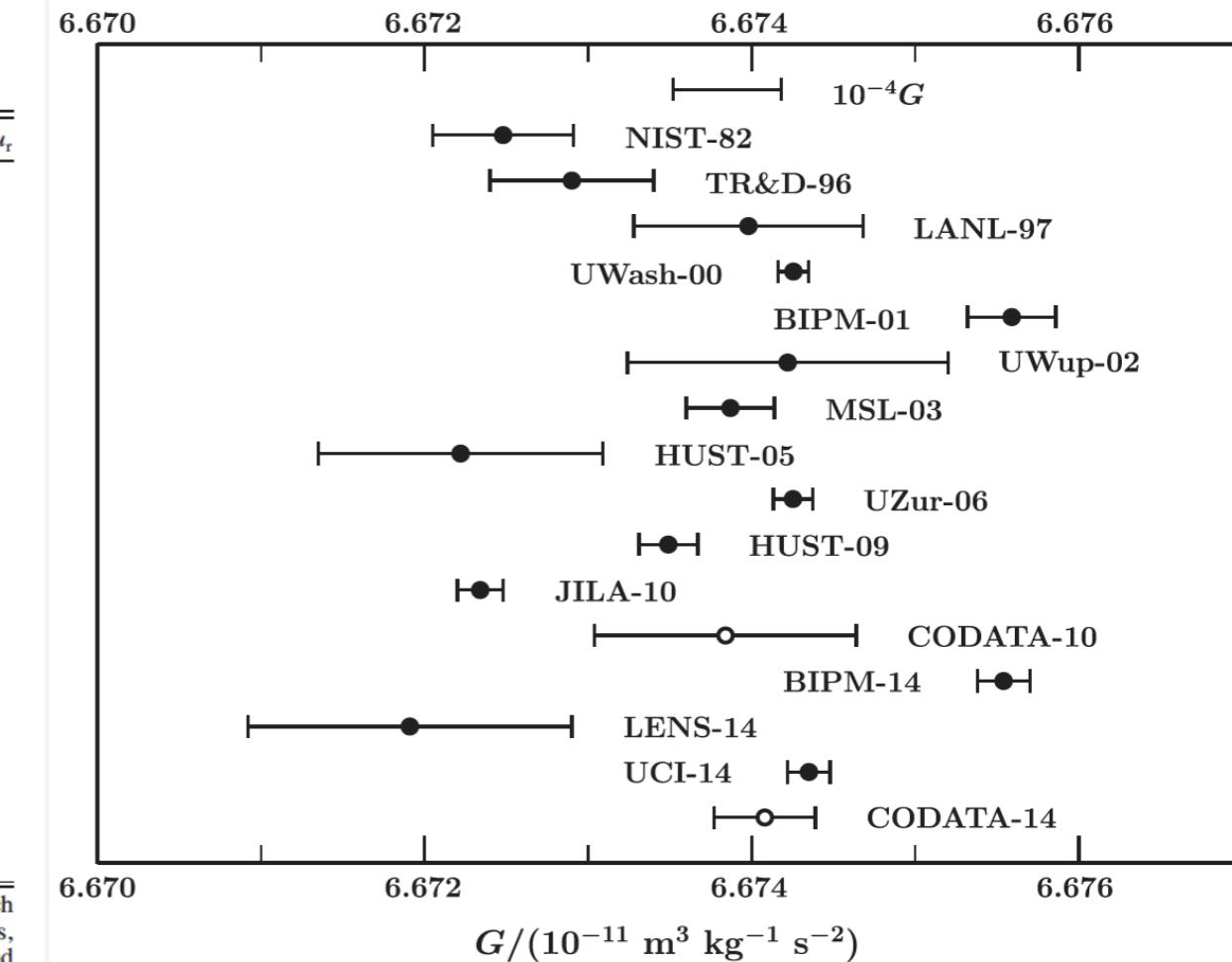
TABLE XV. Summary of the results of measurements of the Newtonian constant of gravitation relevant to the 2014 adjustment.

Source	Identification <sup>a</sup>	Method	$10^{11} G(\text{m}^3 \text{kg}^{-1} \text{s}^{-2})$	Rel. stand. uncert. $u_r$
Luther and Towler (1982)	NIST-82	Fiber torsion balance, dynamic mode	6.672 48(43)	$6.4 \times 10^{-5}$
Karagioz and Izmailov (1996)	TR&D-96	Fiber torsion balance, dynamic mode	6.672 9(5)	$7.5 \times 10^{-5}$
Bagley and Luther (1997)	LANL-97	Fiber torsion balance, dynamic mode	6.673 98(70)	$1.0 \times 10^{-4}$
Gundlach and Merkowitz (2000, 2002)	UWash-00	Fiber torsion balance, dynamic compensation	6.674 255(92)	$1.4 \times 10^{-5}$
Quinn et al. (2001)	BIPM-01	Strip torsion balance, compensation mode, static deflection	6.675 59(27)	$4.0 \times 10^{-5}$
Kleinevoß (2002) and Kleinevoß et al. (2002)	UWup-02	Suspended body, displacement	6.674 22(98)	$1.5 \times 10^{-4}$
Armstrong and Fitzgerald (2003)	MSL-03	Strip torsion balance, compensation mode	6.673 87(27)	$4.0 \times 10^{-5}$
Hu, Guo, and Luo (2005)	HUST-05	Fiber torsion balance, dynamic mode	6.672 22(87)	$1.3 \times 10^{-4}$
Schlamminger et al. (2006)	UZur-06	Stationary body, weight change	6.674 25(12)	$1.9 \times 10^{-5}$
Luo et al. (2009) and Tu et al. (2010)	HUST-09	Fiber torsion balance, dynamic mode	6.673 49(18)	$2.7 \times 10^{-5}$
Parks and Faller (2010)	JILA-10	Suspended body, displacement	6.672 34(14)	$2.1 \times 10^{-5}$
Quinn et al. (2013, 2014)	BIPM-14	Strip torsion balance, compensation mode, static deflection	6.675 54(16)	$2.4 \times 10^{-5}$
Prevedelli et al. (2014) and Rosi et al. (2014)	LENS-14	Double atom interferometer gravity gradiometer	6.671 91(99)	$1.5 \times 10^{-4}$
Newman et al. (2014)	UCI-14	Cryogenic torsion balance, dynamic mode	6.674 35(13)	$1.9 \times 10^{-5}$

<sup>a</sup>NIST: National Institute of Standards and Technology, Gaithersburg, Maryland, and Boulder, Colorado, USA; TR&D: Tribotech Research and Development Company, Moscow, Russian Federation; LANL: Los Alamos National Laboratory, Los Alamos, New Mexico, USA; UWash: University of Washington, Seattle, Washington, USA; BIPM: International Bureau of Weights and Measures, Sèvres, France; UWup: University of Wuppertal, Wuppertal, Germany; MSL: Measurement Standards Laboratory, Lower Hutt, New Zealand; HUST: Huazhong University of Science and Technology, Wuhan, PRC; UZur: University of Zurich, Zurich, Switzerland; JILA: JILA, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado, USA; LENS: European Laboratory for Non-Linear Spectroscopy, University of Florence, Florence, Italy; UCI: University of California, Irvine, Irvine, California, USA.

The leading uncertainty components arise from the determination of the atomic cloud size, center, and launch direction, and the tungsten source mass position, and in parts in  $10^6$  are 61, 38, 36, and 38, respectively. Although the final uncertainty is not presently competitive, determinations of  $G$  using atom interferometry could be more competitive in the future.

vacuum dewar), thus greatly reducing the period-change signal of the torsion balance. The torsion balance test mass is a thin fused silica plate as pioneered by Gundlach and Merkowitz (2000) that, when combined with the ring source masses, minimizes the sensitivity to test mass shape, mass distribution, and placement.



**CODATA 2014**  
 $\mathbf{G = 6.67408(31) \times 10^{-11} \text{ m}^3 \text{kg}^{-1} \text{s}^{-2}}$   
 [Relative std. uncert.:  $4.7 \times 10^{-5}$ ]

Peter J. Mohr, David B. Newell, and Barry N. Taylor,  
*CODATA recommended values of the fundamental physical constants: 2014*  
 Rev. Mod. Phys., Vol. 88, No. 3 (2016)

# MEasuring the Gravitational constant with Atom interferometry for Novel fundamental physics TEsts

## **MEGANTE**

Principal investigator:



Gabriele Rosi

Host Institution:



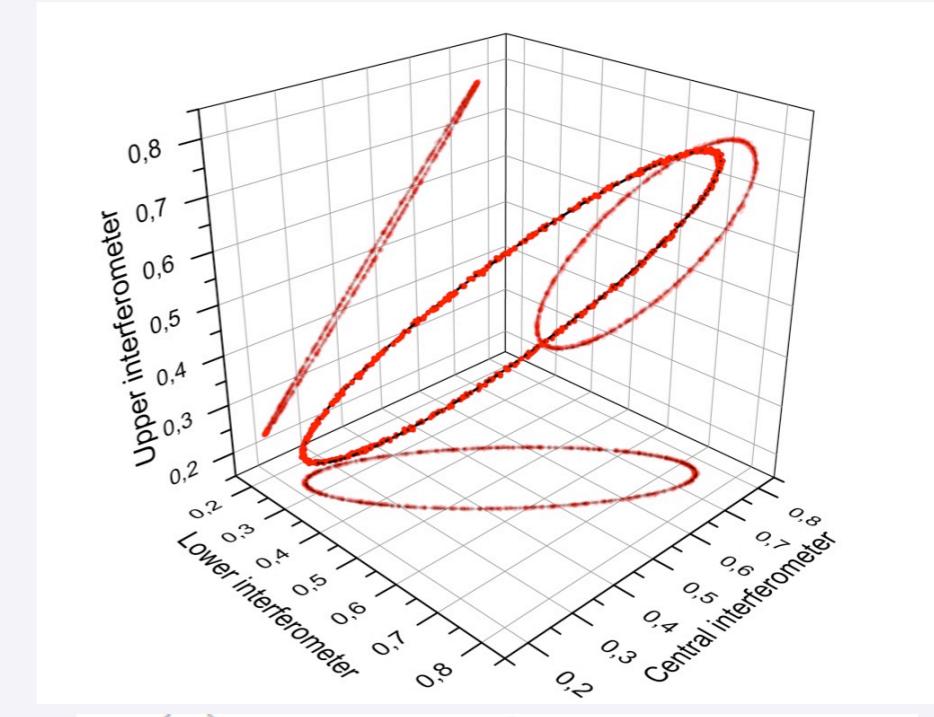
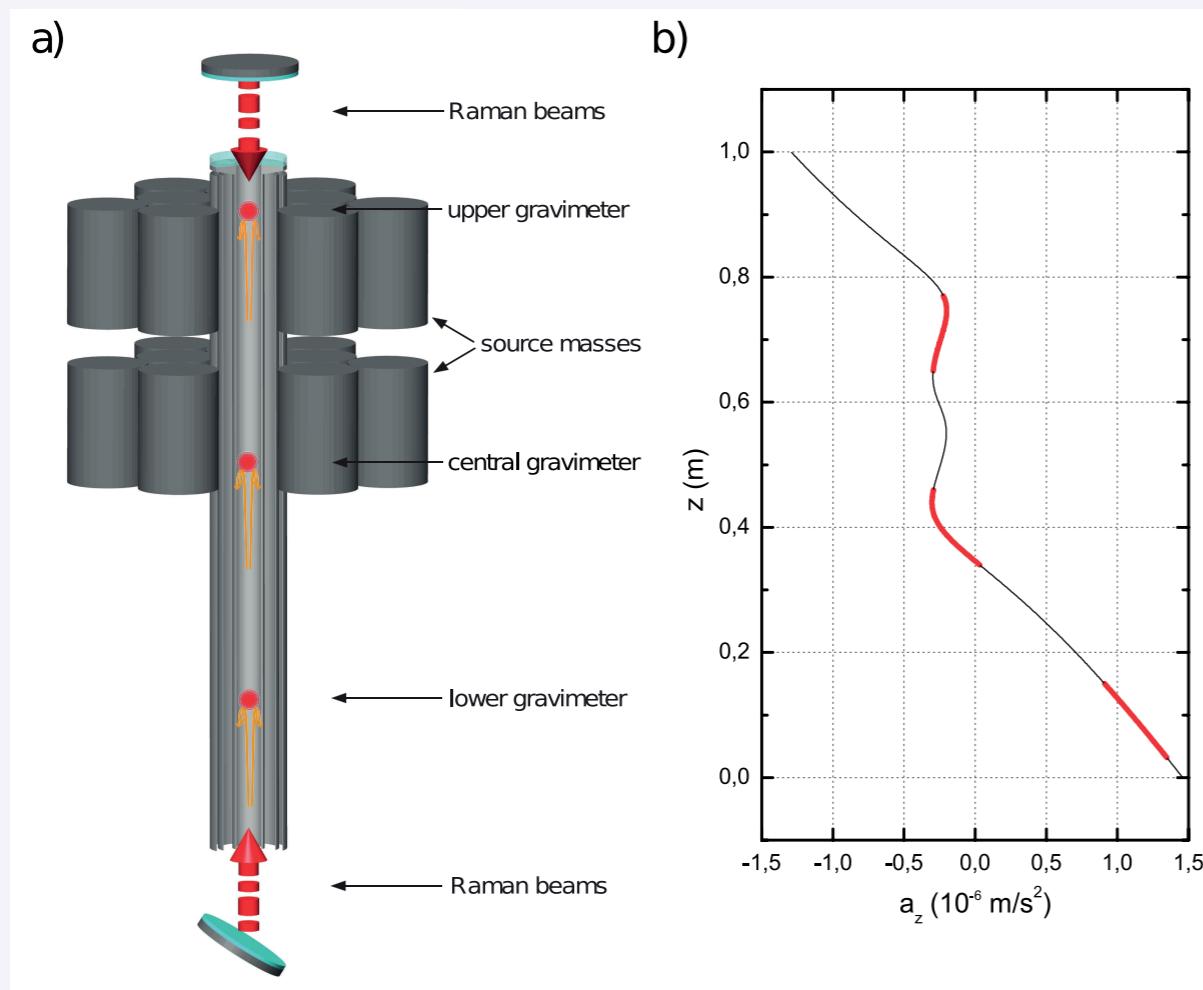
Firenze Division



Budget: 1.55 ME for  
5 years

A unique apparatus for precision measurements of G with cold atom towards the solution of puzzle

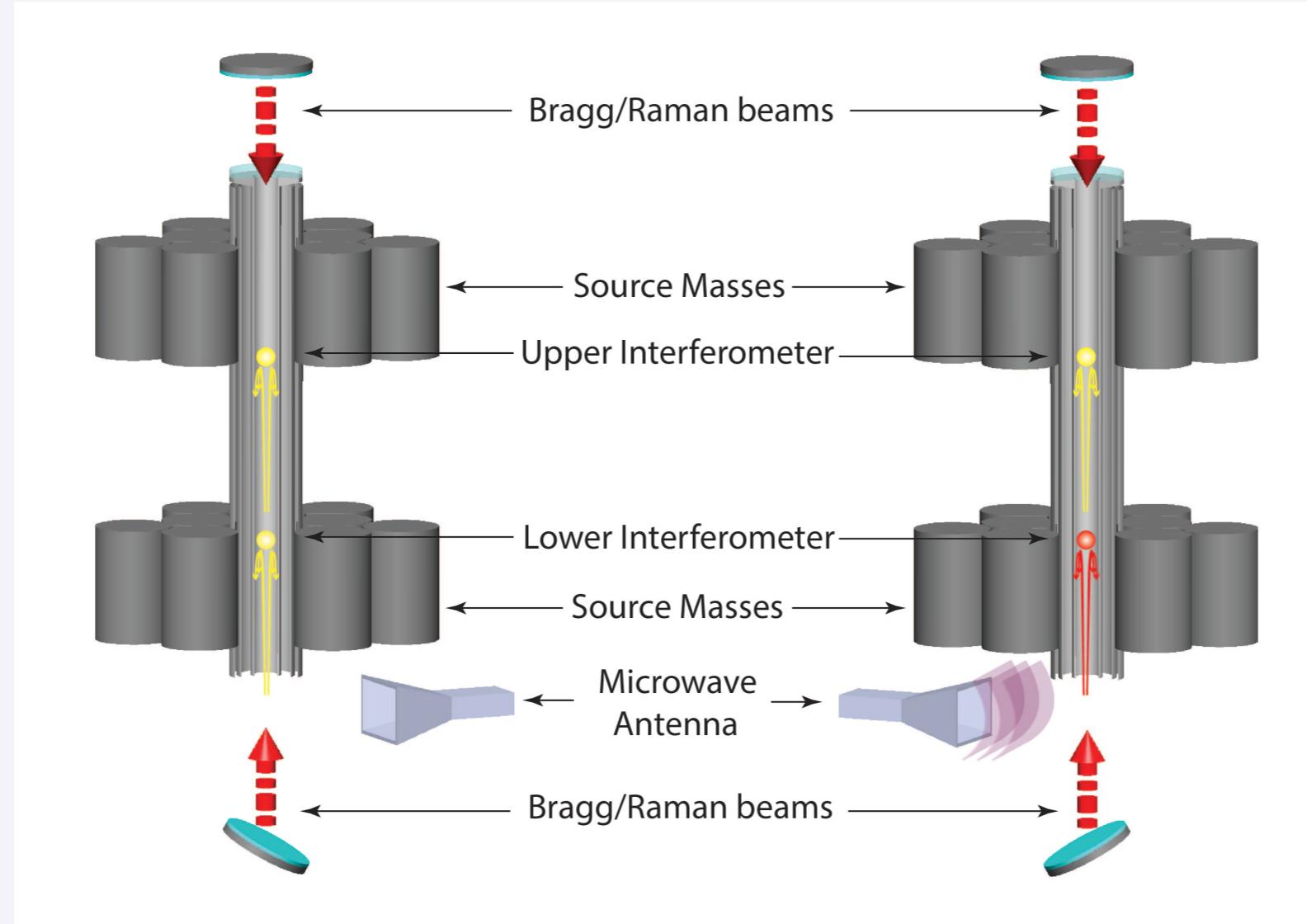
# Measurement of the Gravity-Field Curvature by Atom Interferometry



$$x(\theta) = A + B \sin \theta,$$
$$y(\theta) = C + D \sin(\theta + \varphi_1),$$
$$z(\theta) = E + F \sin(\theta + \varphi_1 + \varphi_2)$$

G. Rosi, L. Cacciapuoti, F. Sorrentino, M. Menchetti, M. Prevedelli, G. M. Tino, *Measurement of the Gravity-Field Curvature by Atom Interferometry*, Phys. Rev. Lett. 114, 013001 (2015)

# Quantum test of the equivalence principle for atoms in coherent superposition of internal energy states



$$|1\rangle = |F = 1, m_F = 0\rangle$$

$$|2\rangle = |F = 2, m_F = 0\rangle$$

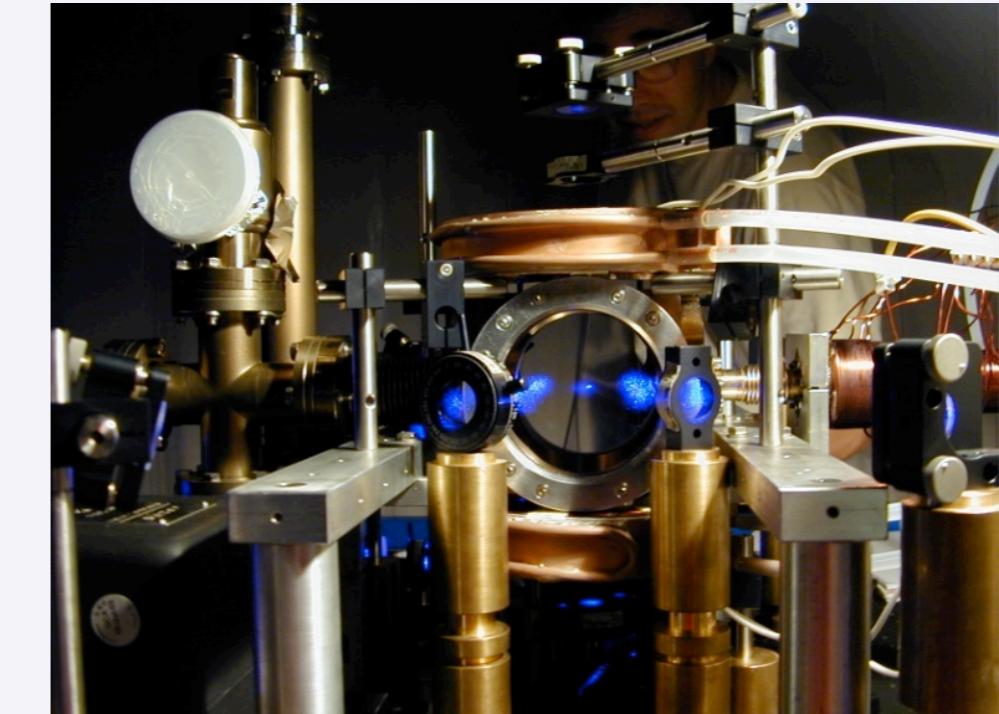
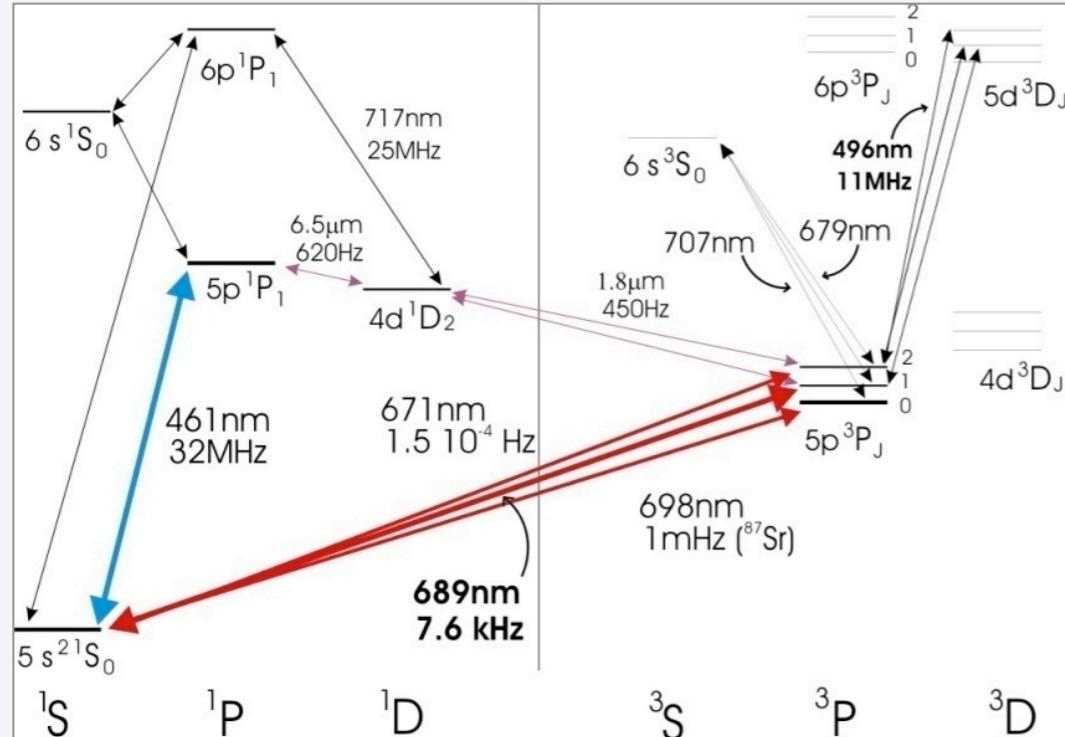
$$|s\rangle = (|1\rangle + e^{i\gamma}|2\rangle) / \sqrt{2}$$

$$a_1 = g\langle 1 | \hat{M}_g \hat{M}_i^{-1} | 1 \rangle = gr_1$$

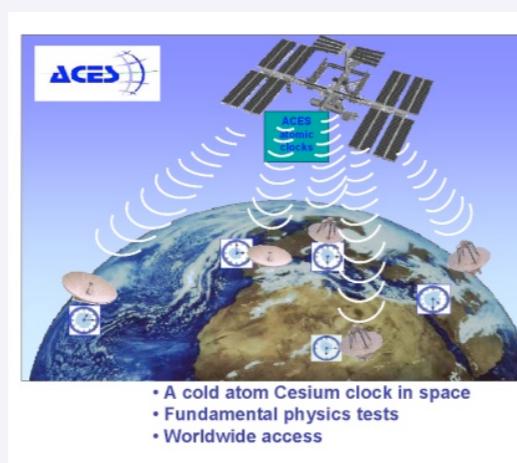
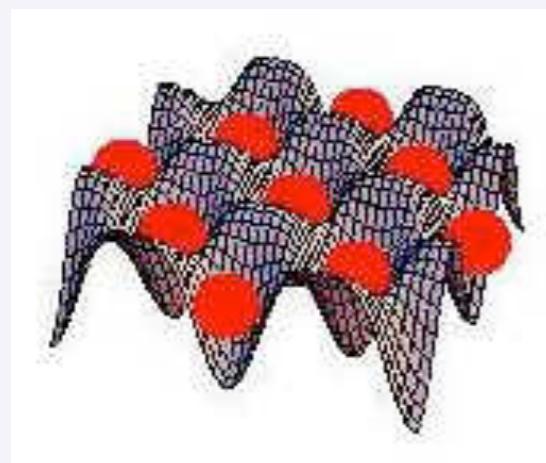
$$a_2 = g\langle 2 | \hat{M}_g \hat{M}_i^{-1} | 2 \rangle = gr_2$$

$$a_s = g\langle s | \hat{M}_g \hat{M}_i^{-1} | s \rangle = g \left[ \frac{r_1 + r_2}{2} + |r| \cos(\varphi_r + \gamma) \right]$$

# Ultracold Sr - Experiments in Firenze



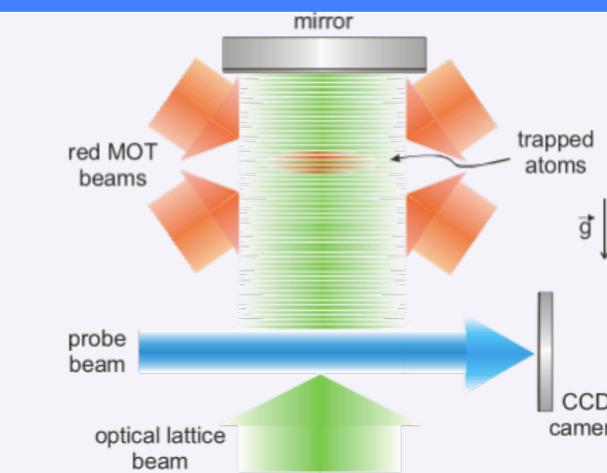
- Optical clocks using visible intercombination lines



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)

N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B 117, 1107 (2014)

- New atomic sensors for fundamental physics tests

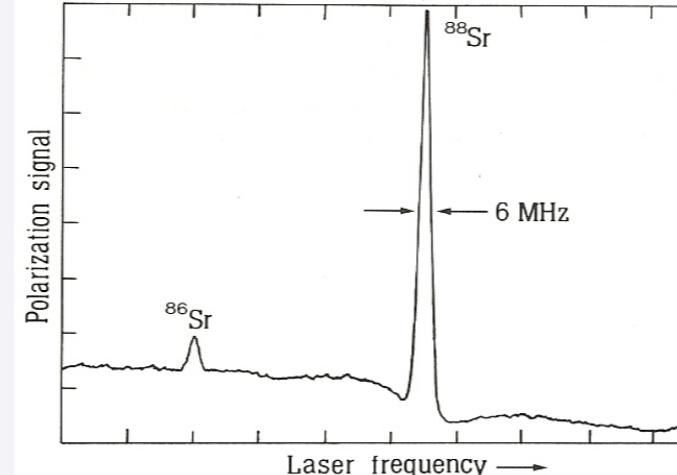


G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale*, Phys. Rev. Lett. 97, 060402 (2006)

V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, *Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials*, Phys. Rev. Lett. 100, 043602 (2008)

1992

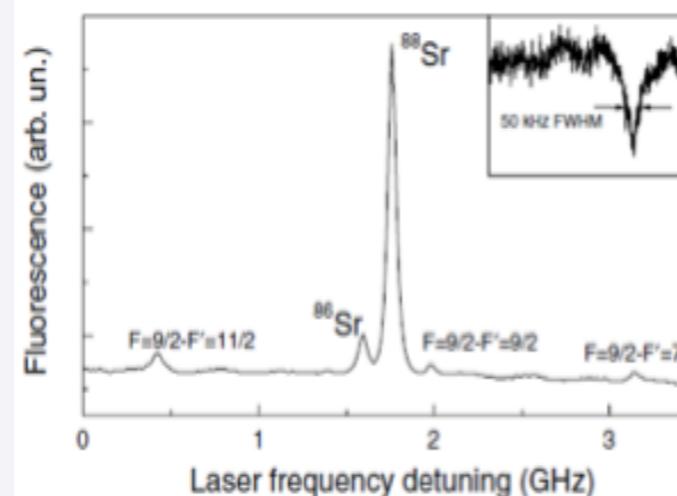
sub-Doppler laser spectroscopy  
of Sr in a hollow cathode discharge  
 $0 \rightarrow 1$  intercombination line



G.M. Tino, M. Barsanti, M. de Angelis, L. Gianfrani, M. Inguscio, *Spectroscopy of the 689 nm intercombination line of strontium using an extended cavity InGaP/InGaAlP diode laser*, Appl. Phys. B 55, 397 (1992)

2003

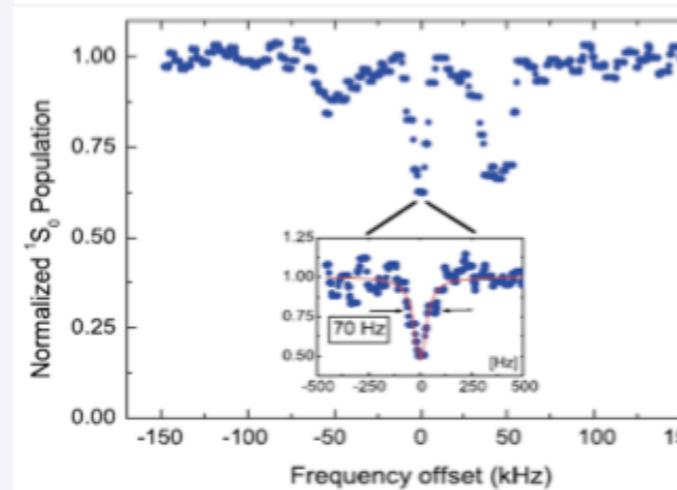
saturation spectroscopy  
of Sr in a thermal atomic beam  
 $0 \rightarrow 1$  intercombination line



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)

2009

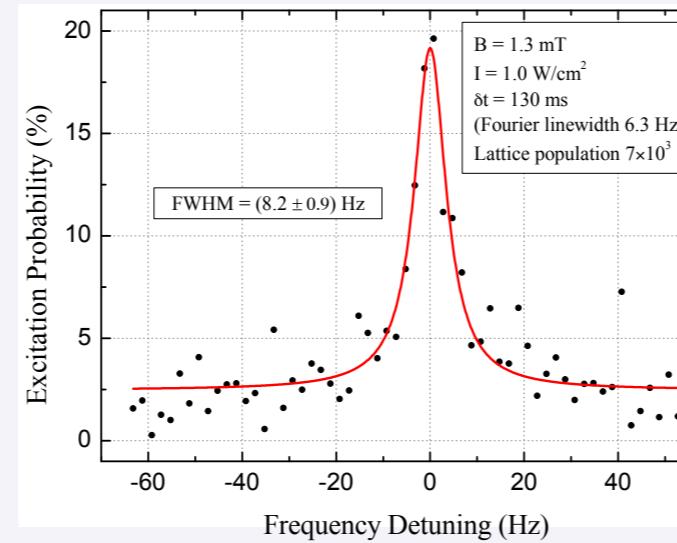
Magnetic field induced spectroscopy  
of cold Sr atoms in an optical lattice  
 $0 \rightarrow 0$  intercombination line



N. Poli, M.G. Tarallo, M. Schioppo, C.W. Oates, G.M. Tino, *A simplified optical lattice clock*, Appl. Phys. B 97, 27 (2009)

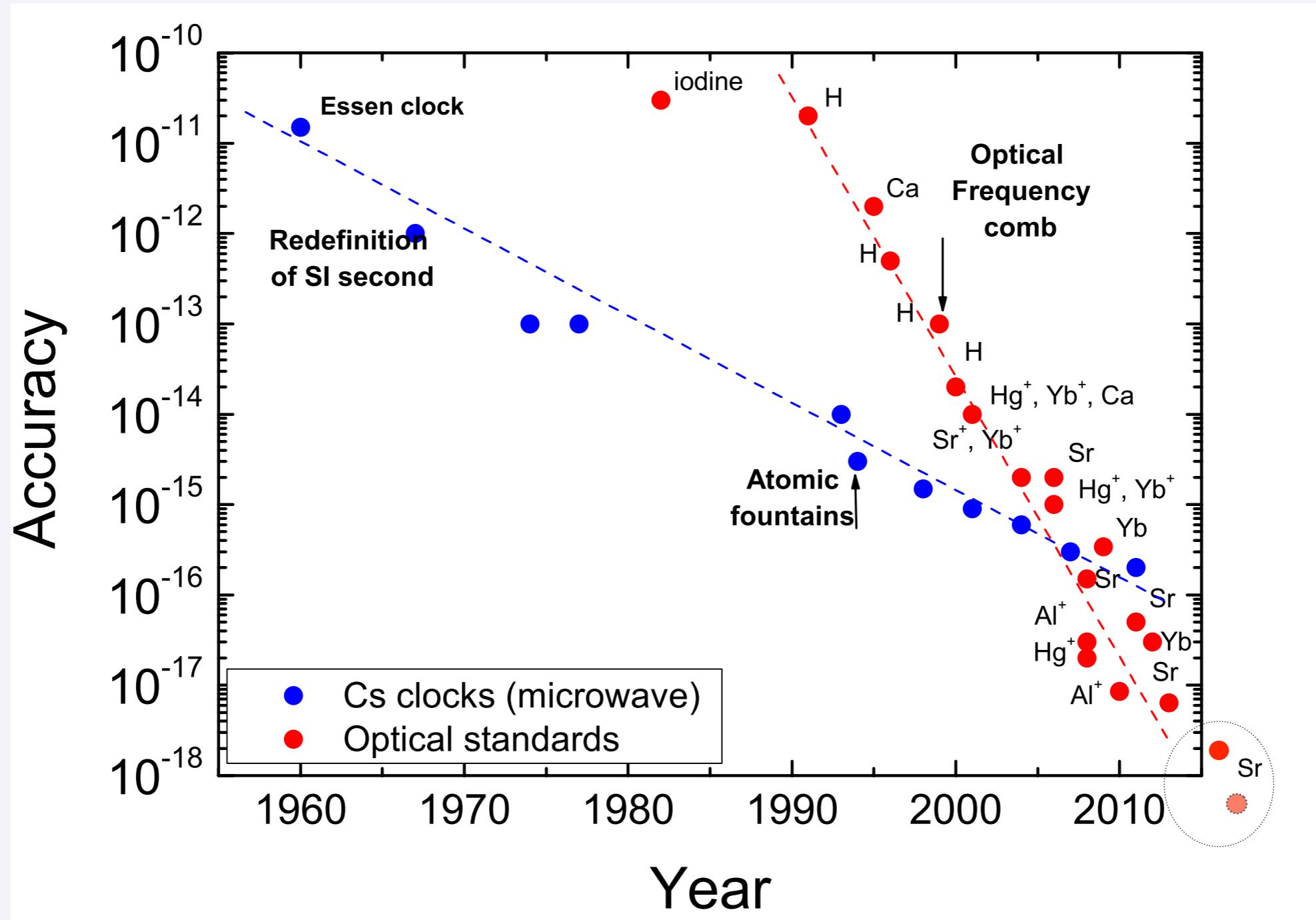
2012

Magnetic field induced spectroscopy  
of cold Sr atoms in an optical lattice  
 $0 \rightarrow 0$  intercombination line



N. Poli, M. Schioppo, S. Vogt, St. Falke, U. Sterr, Ch. Lisdat, G. M. Tino, *A transportable strontium optical lattice clock*, Appl. Phys. B 117, 1107 (2014)

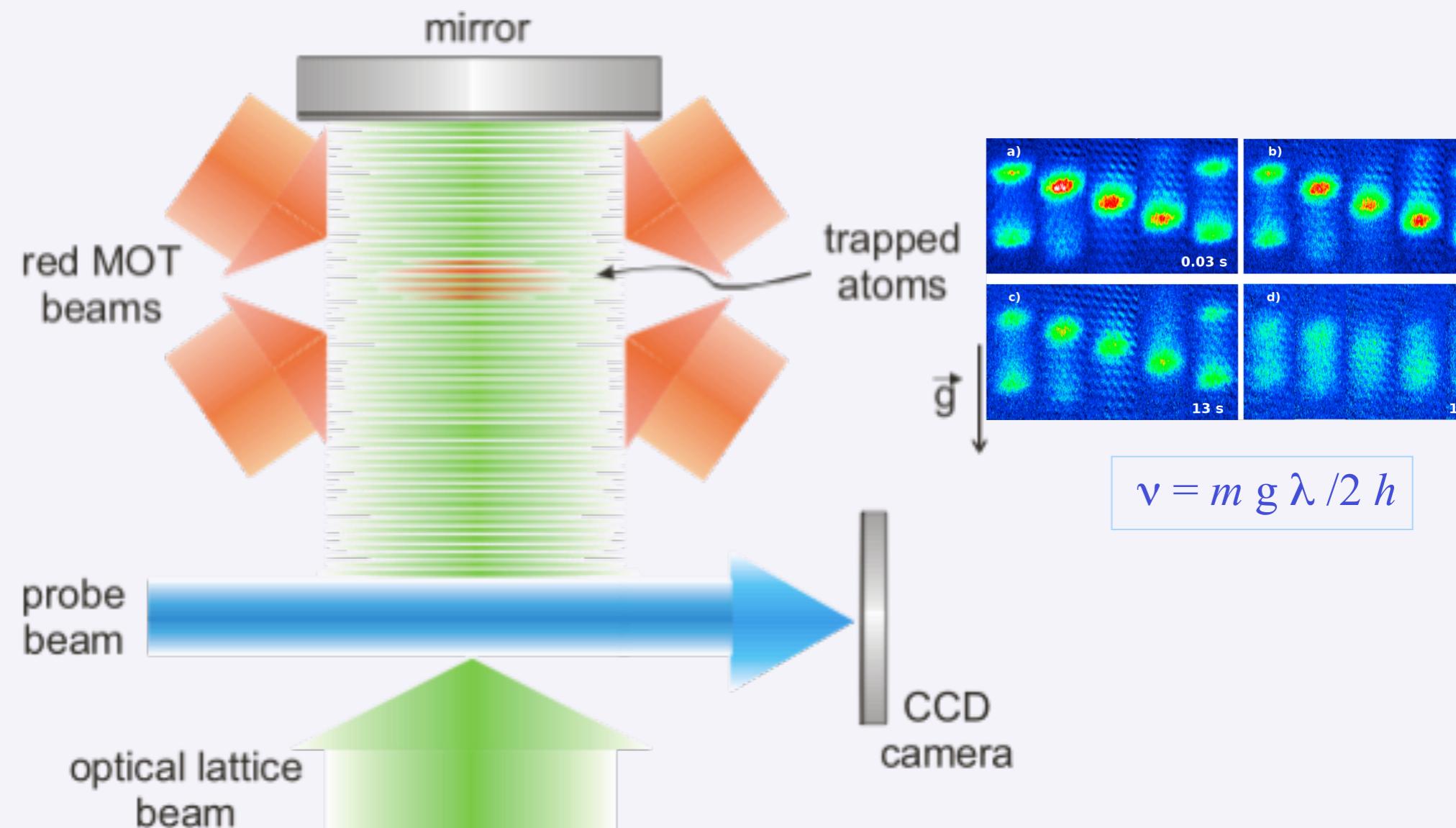
# Microwave vs. optical clocks



N. Poli, C. W. Oates, P. Gill and G. M. Tino, *Optical atomic clocks*,  
Rivista del Nuovo Cimento Vol. 36, N. 12 (2013) - arXiv:1401.2378

# Bloch oscillations of Sr atoms in an optical lattice

## Precision gravity measurement at $\mu\text{m}$ scale

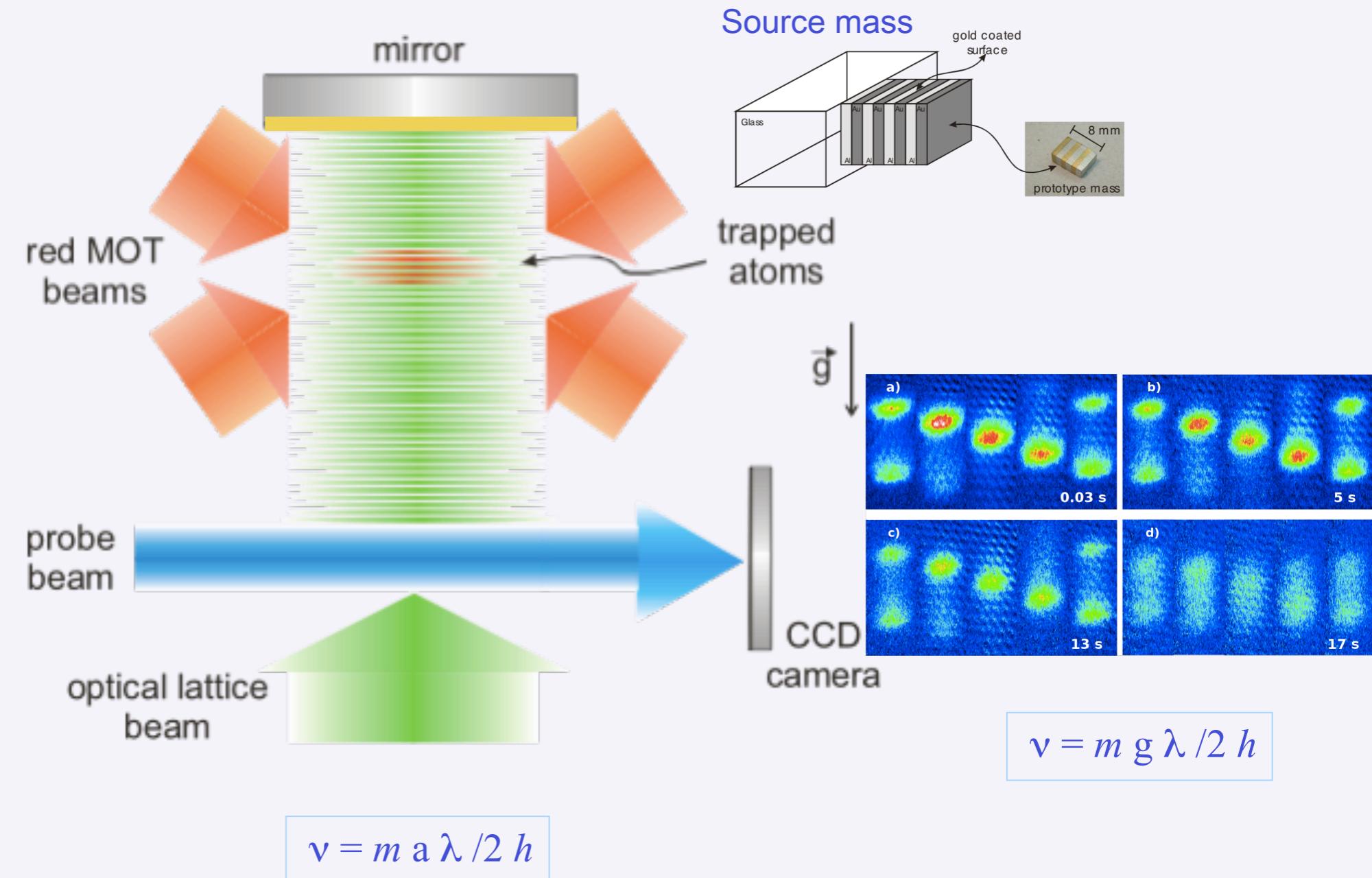


G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale*, Phys. Rev. Lett. **97**, 060402 (2006)

V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, *Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials*, Phys. Rev. Lett. **100**, 043602 (2008)

N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino, *Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter*, Phys. Rev. Lett. **106**, 038501 (2011)

# Experiments on gravity at small spatial scale



**Objective:**  $\lambda = 1\text{-}10 \mu\text{m}$ ,  $\alpha = 10^3\text{-}10^4$

F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino,  
*Quantum sensor for atom-surface interactions below 10 μm*, Phys. Rev. A 79, 013409 (2009)

# *Test of the EP for 0-spin and half-integer-spin atoms: Search for spin-gravity coupling effects*

Einstein Equivalence Principle

→ Universality of the Free Fall

*The trajectory of a freely falling “test” body  
is independent of its internal structure  
and composition*



Test of the equivalence principle with two isotopes of strontium atom:

**88Sr**

- Total spin = 0
- Boson

**87Sr**

- Total spin  $\equiv$  nuclear spin  $I = 9/2$
- Fermion

Comparison of the acceleration of  $^{88}\text{Sr}$  and  $^{87}\text{Sr}$  under the effect of gravity  
by measuring the Bloch frequencies in a vertical optical lattice

Search for EP violations due to spin-gravity coupling effects

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)

# *From table-top experiments to large-scale detectors*

# MAGIA $\rightarrow$ MAGIA-Adv

## Advanced atomic quantum sensors for gravitational physics

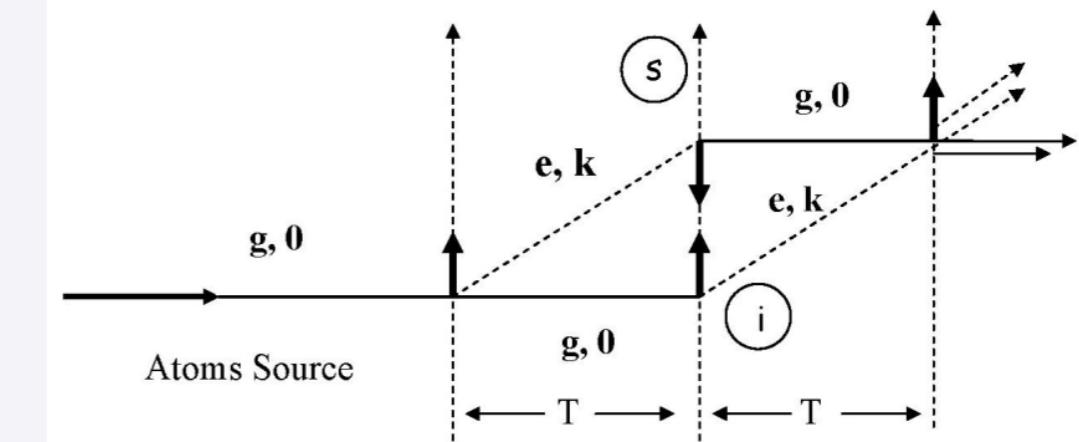
- Large-scale atom interferometer (Rb & Sr)
- New schemes for large momentum transfer
- High-flux atomic sources
- High-sensitivity detection schemes
- Squeezed atomic states

Firenze, Urbino, Pisa

# Gravitational wave detection with atom interferometry

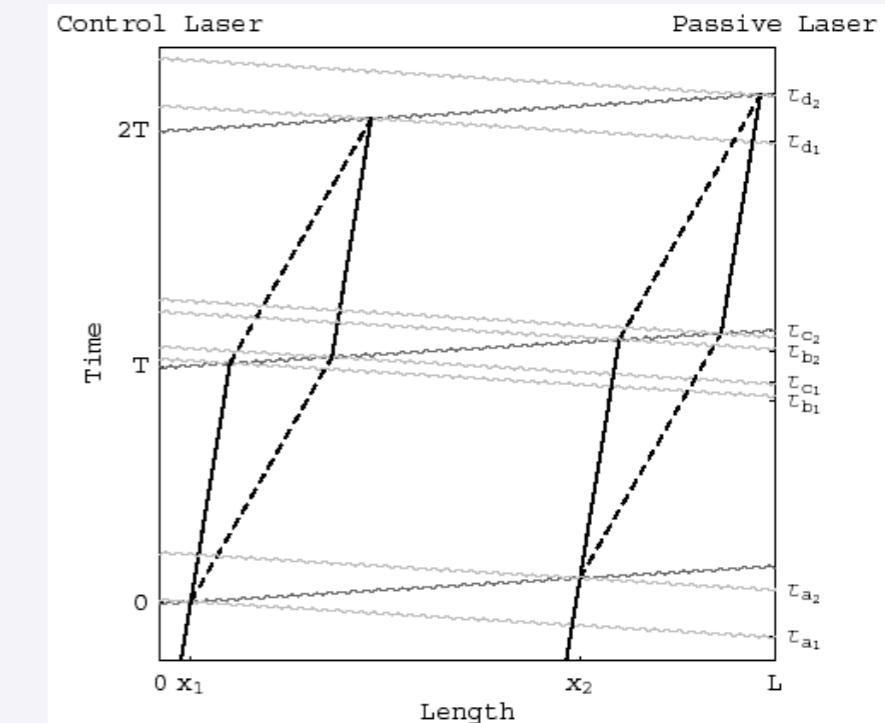
- Single atom interferometer

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

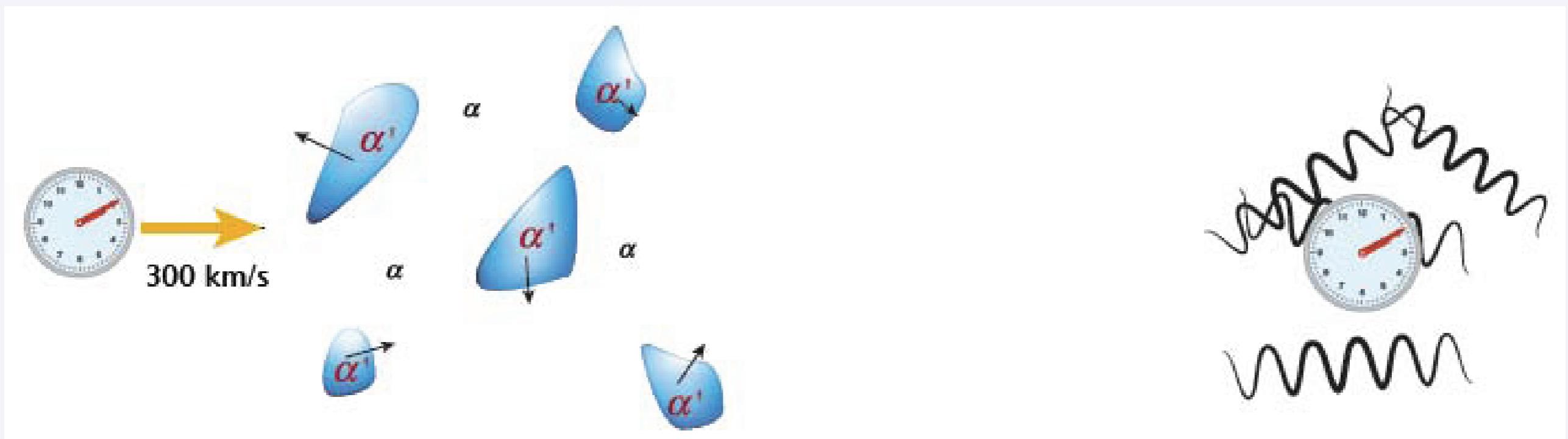


- Differential scheme

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



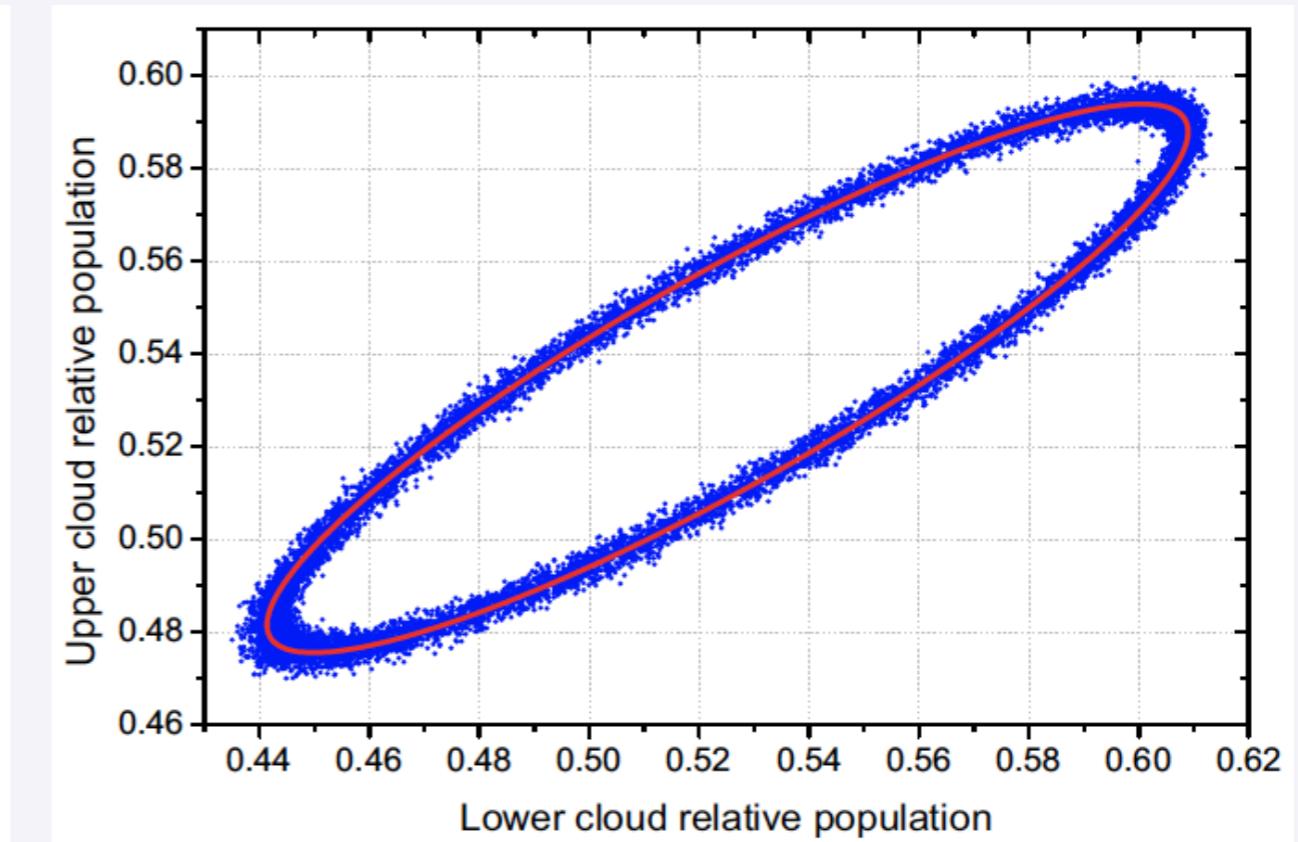
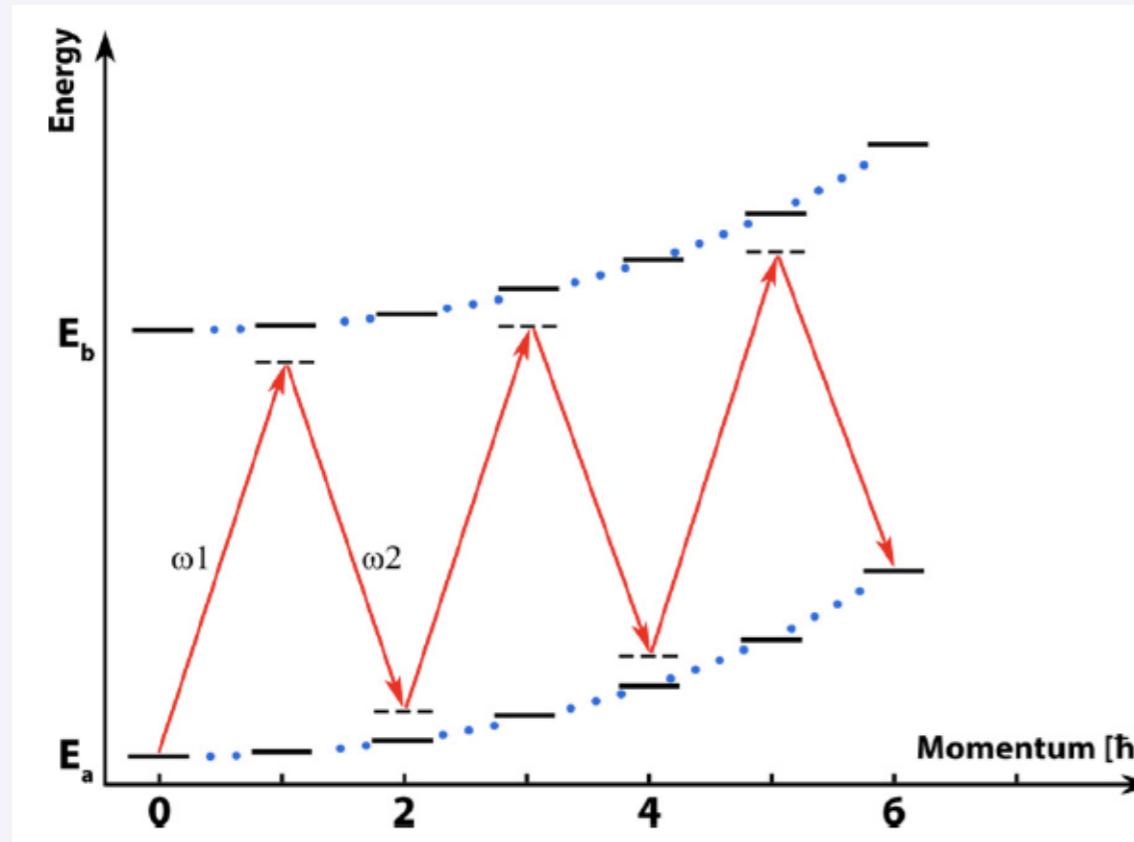
# Search for Dark-Matter



(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A. Derevianko and M. Pospelov. Hunting for topological dark matter with atomic clocks. *Nature Phys.*, 10:933, 2014].

(Right) Ultralight fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [A. Arvanitaki, J. Huang, and K. Van Tilburg. Searching for dilaton dark matter with atomic clocks. *Phys. Rev. D*, 91(1):015015, 2015].

# Rb LMT gravity gradiometer

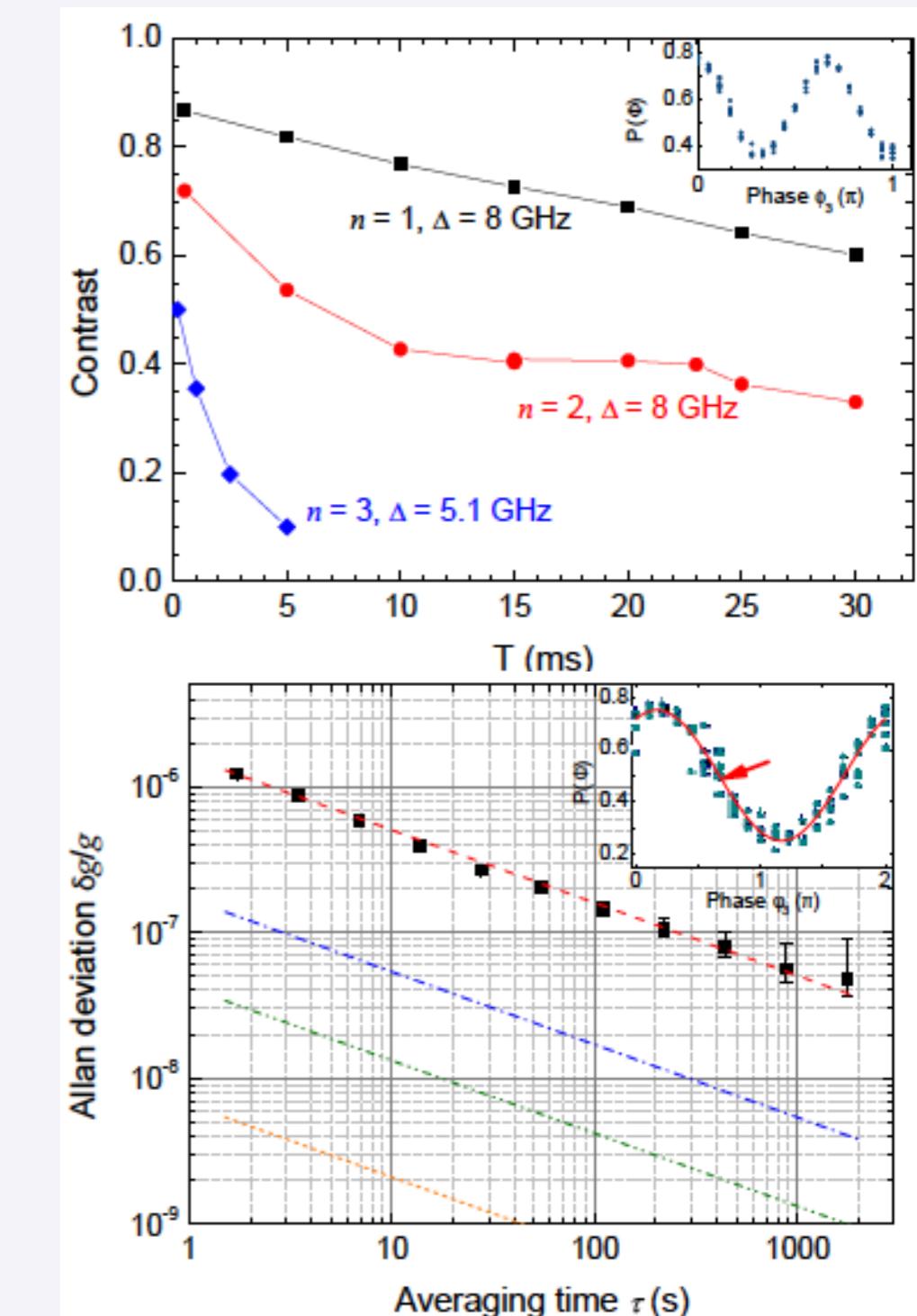
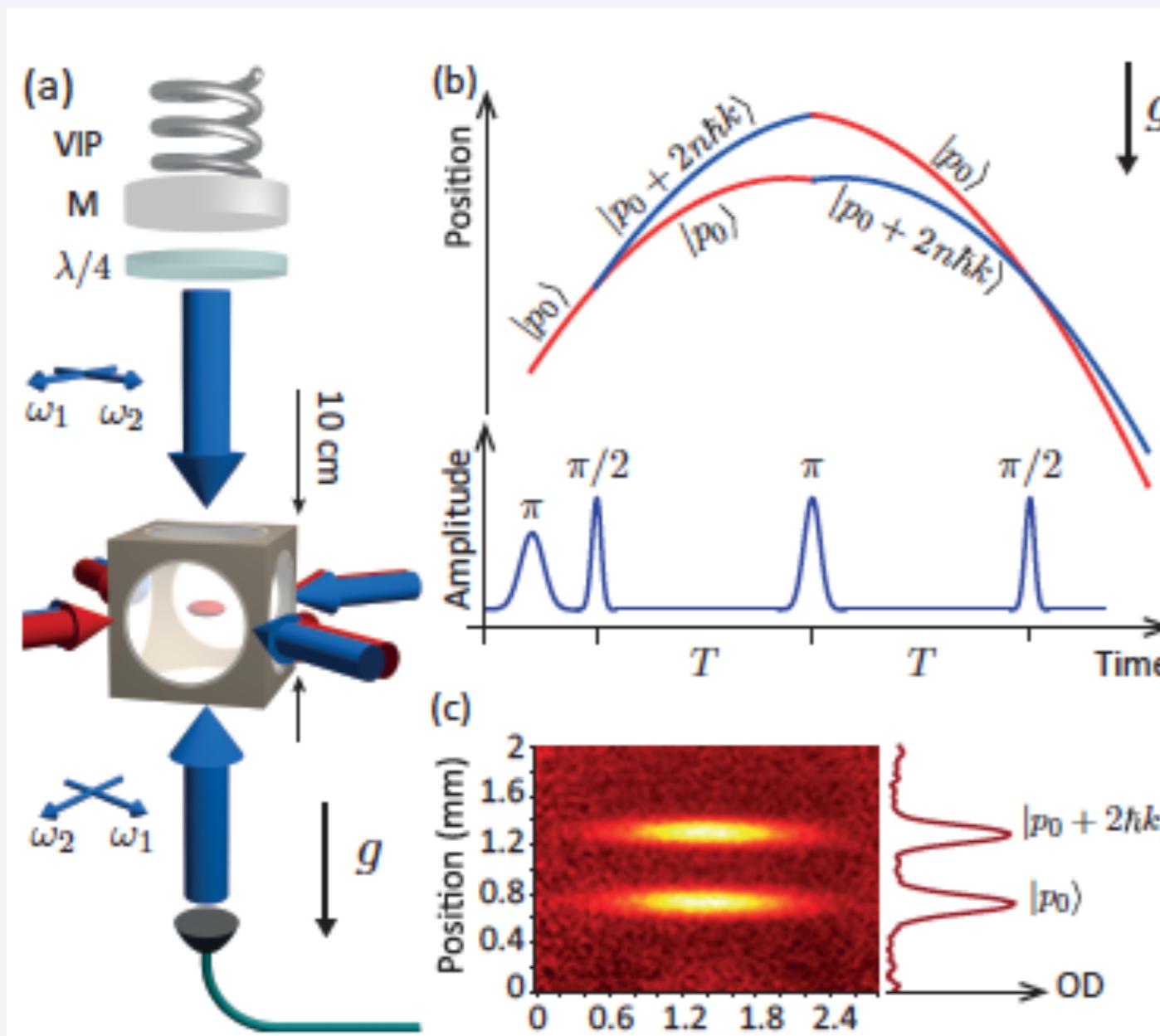


Experimental conditions: 3<sup>rd</sup> Bragg order, T = 80 ms, state F=1, detuning 4.8 GHz, Gaussian pulses ( $\sigma=12 \mu\text{s}$ ), vertical velocity spread  $0.15 \hbar k$ , peak intensity  $0.2 \text{ W/cm}^2$

- Need high-power lasers
- Increasing the order n => loss in contrast at large T
- Bragg transitions need narrow vertical ( $0.1 \hbar k$ ) momentum spread => severe velocity selection => low atomic flux
- Same internal state at the interferometer output => separate interferometer outputs

G. D'Amico, F. Borselli, L. Cacciapuoti, M. Prevedelli, G. Rosi, F. Sorrentino, G. M. Tino,  
*Bragg interferometer for gravity gradient measurements, Phys. Rev. A 93, 063628 (2016)*

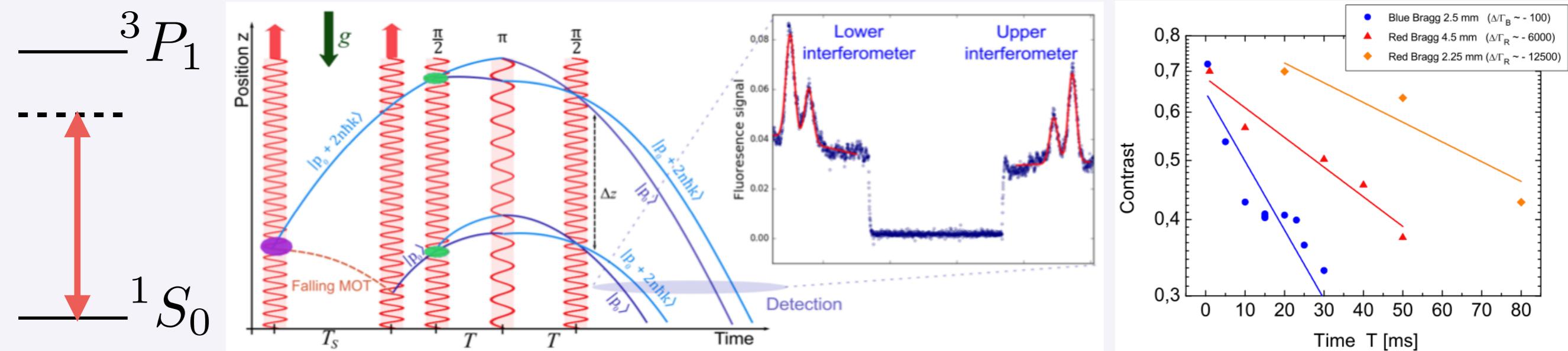
# Sr LMT Bragg interferometer



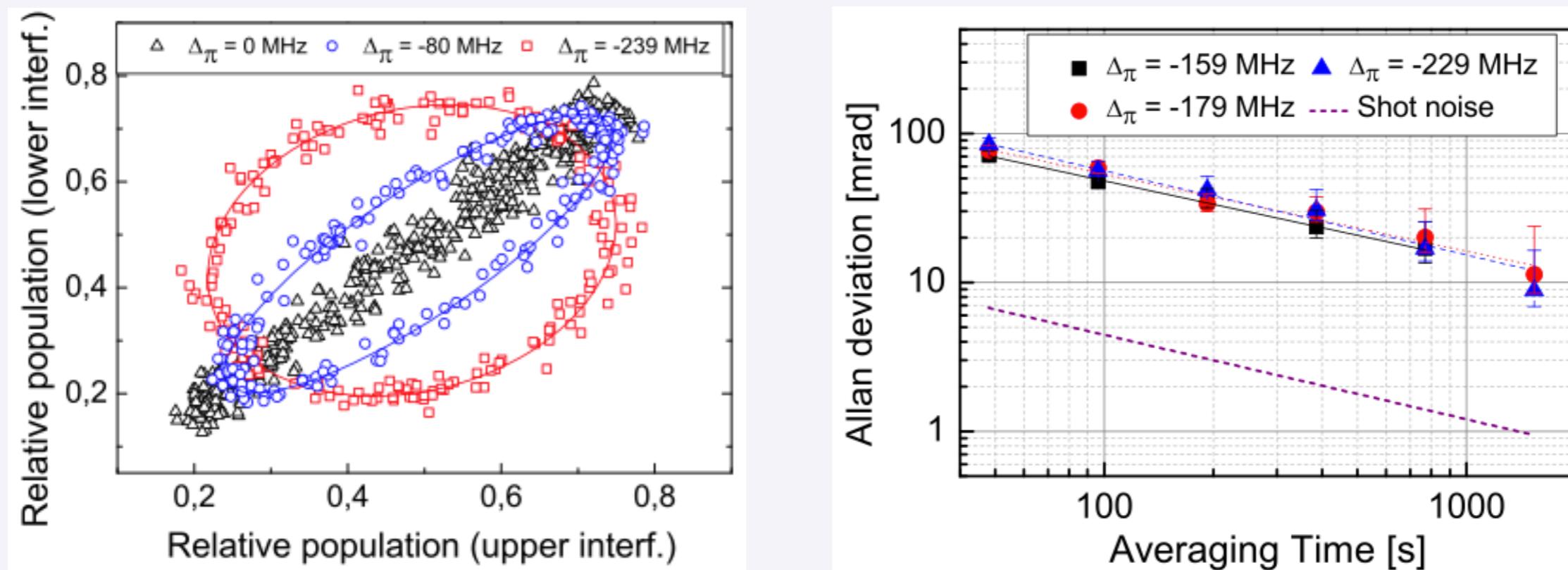
T. Mazzoni, X. Zhang, R. Del Aguila, L. Salvi, N. Poli, and G. M. Tino, *Large-momentum-transfer Bragg interferometer with strontium atoms*, Phys. Rev. A 92, 053619 (2015)

Xian Zhang, Ruben Pablo del Aguila, Tommaso Mazzoni, Nicola Poli, and Guglielmo M. Tino, *Trapped-atom interferometer with ultracold Sr atoms*, Phys. Rev. A 94, 043608 (2016)

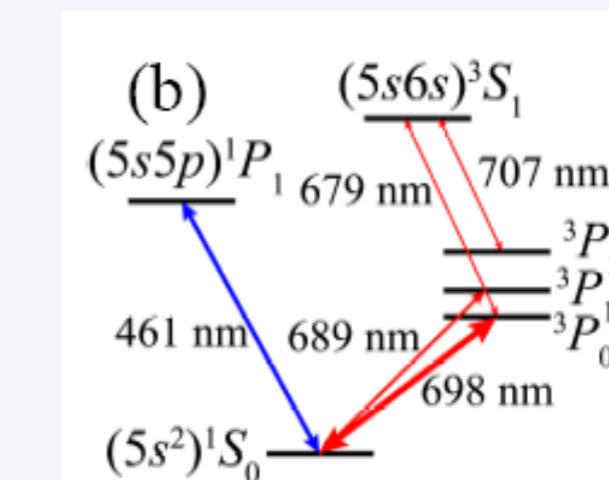
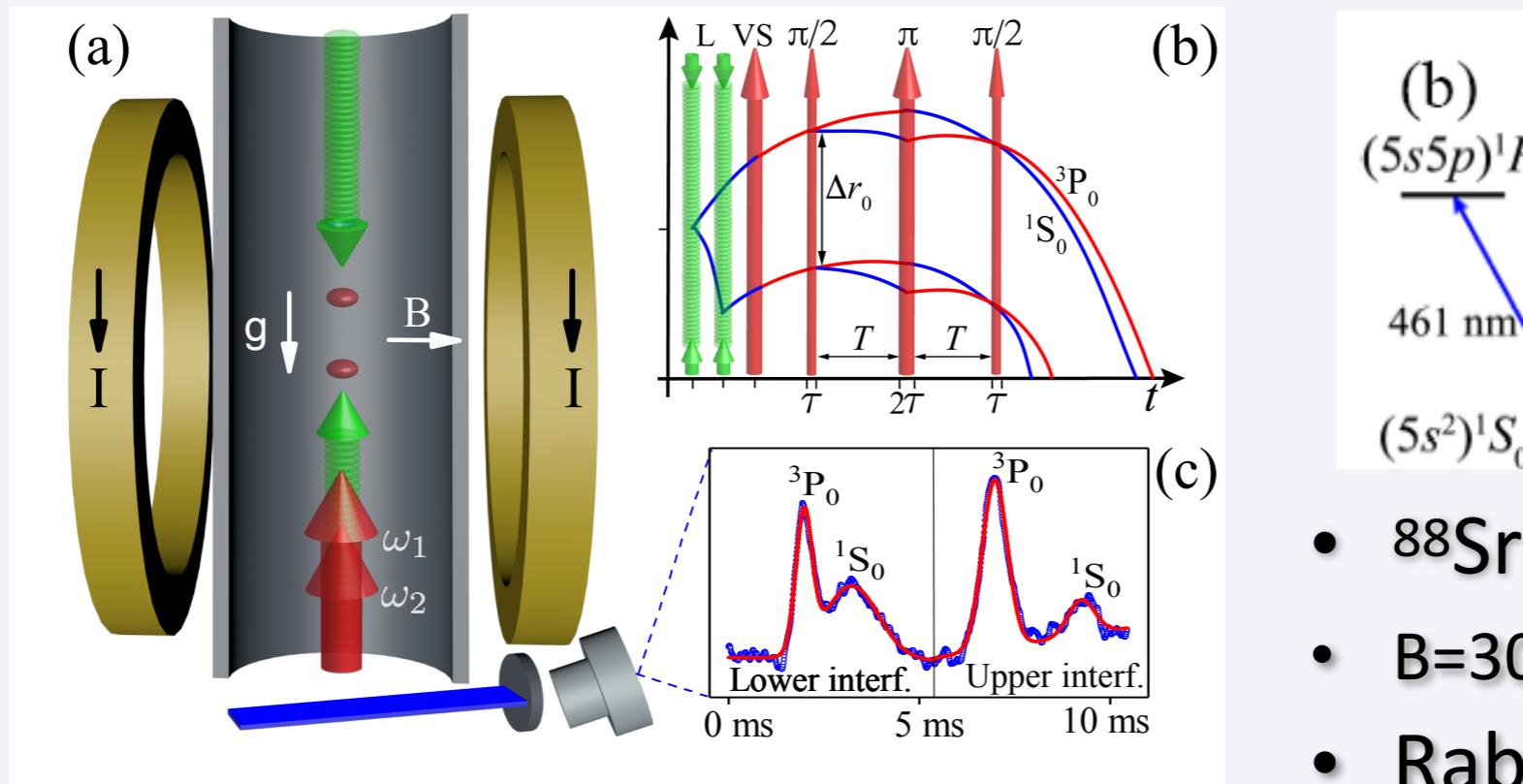
# Atom Interferometry on the red intercombination transition



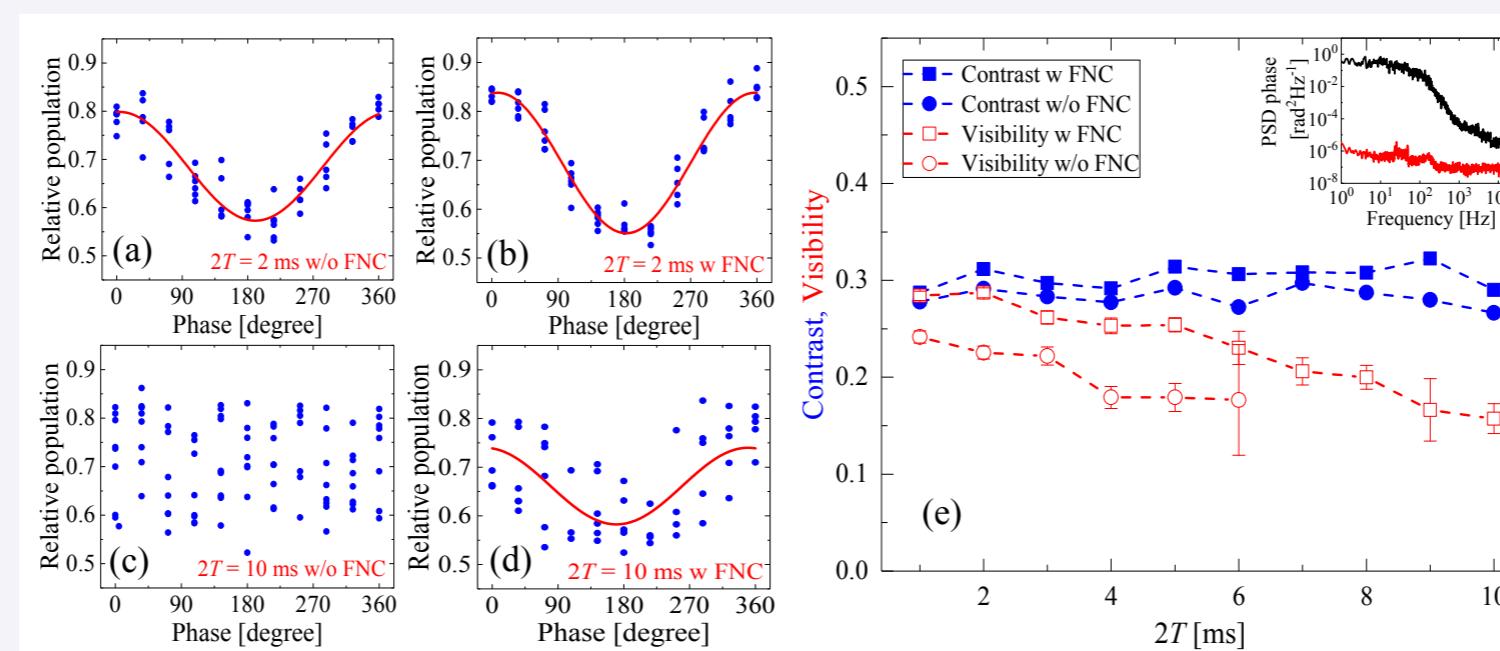
## Gradiometer with artificial gradient



# Atom interferometry with the Sr optical clock transition

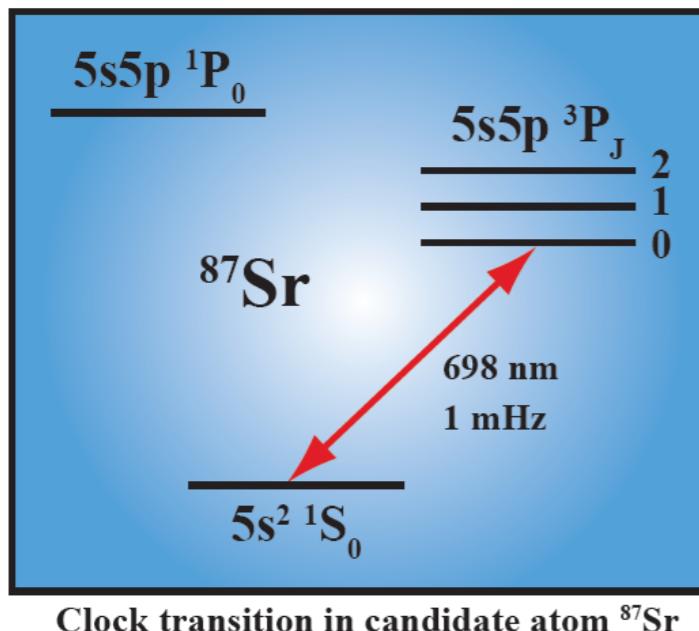


- $^{88}\text{Sr}$  isotope
- $B=300\text{ G} \rightarrow \Delta\nu=20\text{ }\mu\text{Hz}$
- Rabi frequency  $\Omega \sim 1\text{kHz}$



Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,  
Atom interferometry with the Sr optical clock transition,  
Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]

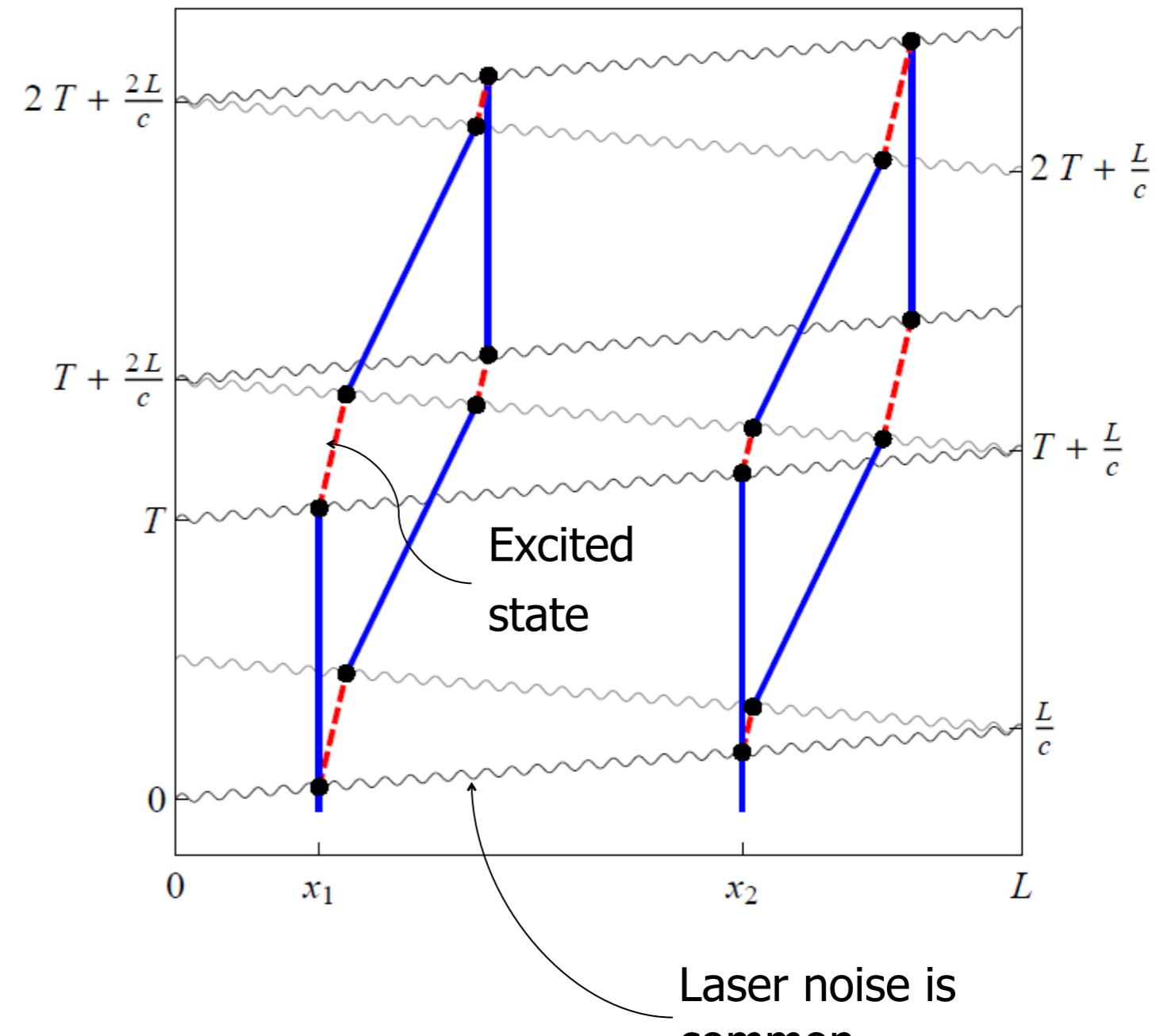
# Laser frequency noise insensitive detector



Clock transition in candidate atom  $^{87}\text{Sr}$

- Long-lived single photon transitions (e.g. clock transition in  $\boxed{\text{Sr}}$ , Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

Enables 2 satellite configurations





Proposal title

# SPACE ATOMIC GRAVITY EXPLORER

Acronym

SAGE

Lead Proposer  
**Prof. Guglielmo M. Tino**

## PRIMARY GOAL:

- Observe Gravitational Waves in new frequency ranges with atomic sensors.

## SECONDARY GOALS:

- Search for Dark-Matter
- Measure the Gravitational Red Shift
- Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
- Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
- Investigate quantum correlations and test Bell inequalities for different gravitational potentials and velocities
- Use clocks and links between satellites for optical VLBI in Space

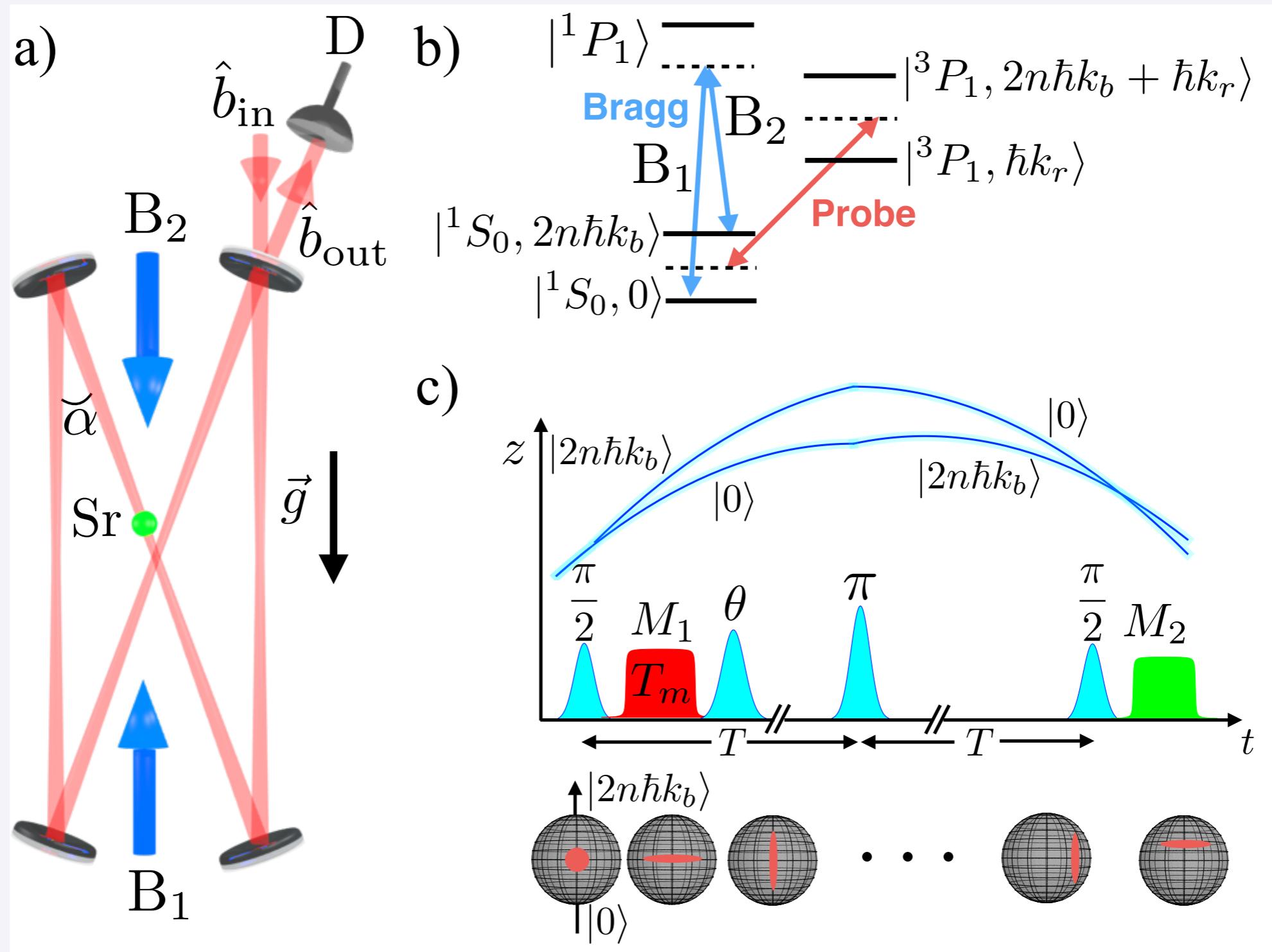
September 13, 2016

# *Atom interferometry with the Sr optical clock transition*

**SAGE  
Pathfinder  
Successful !!**

**Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,**  
*Atom interferometry with the Sr optical clock transition,*  
**Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]**

# Squeezing on momentum states for atom interferometry



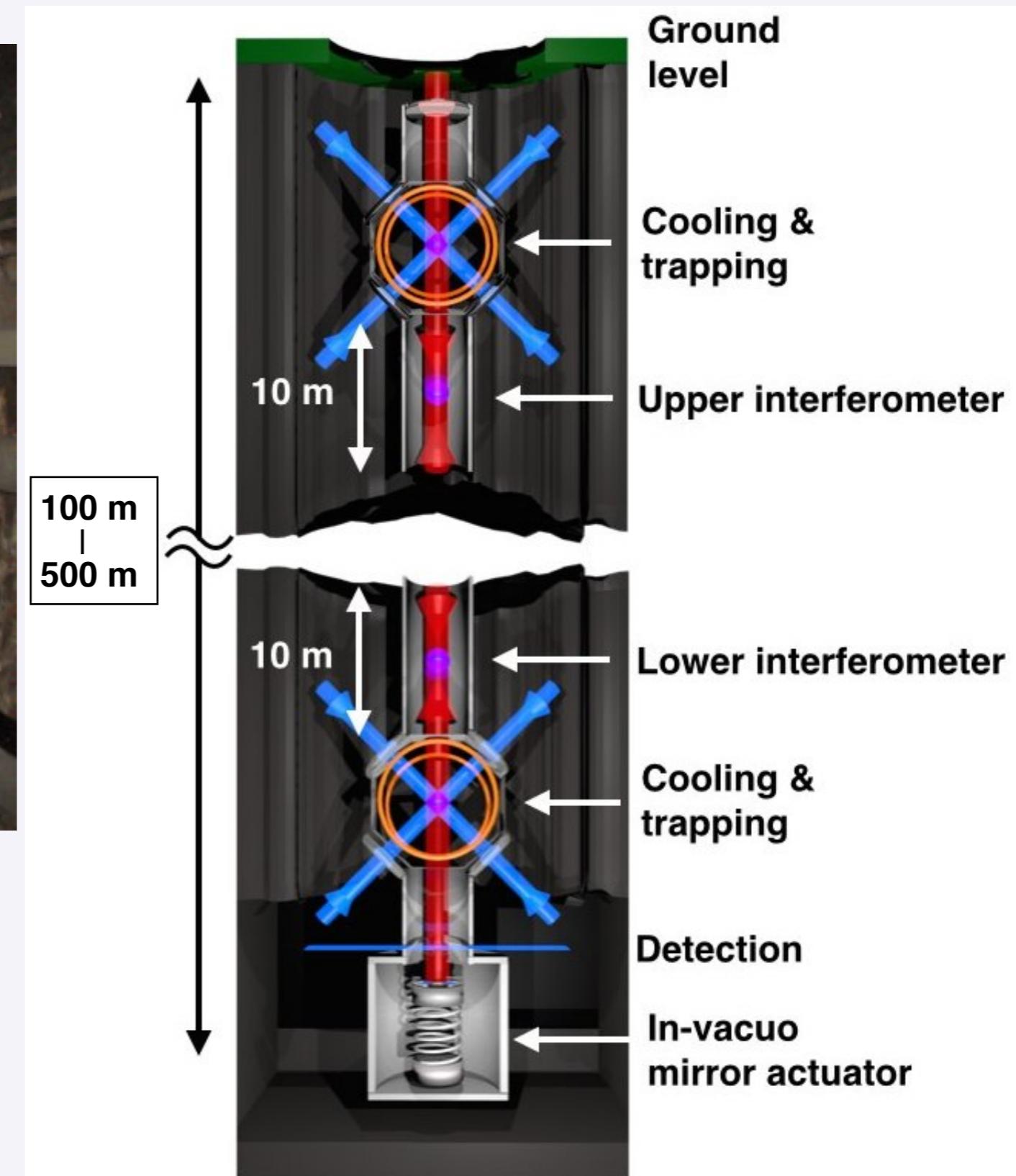
Leonardo Salvi, Nicola Poli, Vladan Vuletić, Guglielmo M. Tino, *Squeezing on Momentum States for Atom Interferometry*, Phys. Rev. Lett. 120, 033601 (2018)

# Large-scale atom interferometer ⇒ Sardegna?



**Carbonia-Iglesias  
ARIA/Darkside Lab**

**Sos Enattos  
SAR-GRAV Lab?**



## The team

**Nicola Poli**  
**Gabriele Rosi**  
**Leonardo Salvi**  
**Gunjan Verma**  
**Jonathan Tinsley**  
**Wang Enlong**  
**Manan Jain**  
**Giulio D'Amico**  
**Liang Hu**  
**Tommaso Mazzoni**  
**Xian Zhang**  
**Ruben del Aguila**  
**Jacopo Grotti**  
**Marco Menchetti**

## Long-term collaborators

**Luigi Cacciapuoti**  
**Marella de Angelis**  
**Marco Fattori**  
**Marco Prevedelli**  
**Fiodor Sorrentino**

## Previous members and visitors

**Andrea Alberti**, PhD student  
**Andrea Bertoldi**, Post-doc  
**Quentin Bodart**, Post-doc  
**Filippo Borselli**, Diploma student  
**Sergei Chepurov**, Institute of Laser Physics, Novosibirsk, visitor  
**Robert Drullinger**, NIST, Long term guest  
**Marco Fattori**, PhD student  
**Gabriele Ferrari**, Researcher, INFM/CNR  
**Antonio Giorgini**, PhD and Post-doc  
**Vladyslav Ivanov**, Post-doc  
**Marion Jacquay**, Post-doc  
**Giacomo Lamporesi**, PhD student  
**Yu-Hung Lien**, Post-doc  
**Marco Marchetti**, Diploma student  
**Chris Oates**, NIST, visitor  
**Torsten Petelski**, PhD student  
**Marco Schioppo**, PhD and Post-doc  
**Juergen Stuhler**, Post-doc  
**Zhan Su**, Post-doc  
**Denis Sutyrin**, Post-doc  
**Marco Tarallo**, PhD and Post-doc  
**Fu-Yuan Wang**, Post-doc

Associate professor, Università di Firenze  
Researcher, INFN-Firenze  
Post-doc, Università di Firenze  
Post-doc, CNR/ICTP  
Post-doc, Università di Firenze  
PhD student, LENS  
PhD student, Università di Firenze  
PhD student, Università di Firenze (now at GEM)  
Post-doc, Università di Firenze/ICTP (now at Shanghai Jiao Tong University)  
Post-doc, Università di Firenze (now at Muquans)  
Post-doc, LENS/ICTP (now at Zhejiang Un.)  
PhD student, Università di Firenze (now in London)  
Diploma student, Università di Firenze (now at PTB)  
Diploma student, Università di Bologna (now at NPL)

ESA-Noordwijk  
CNR - Firenze  
Università di Firenze  
Università di Bologna  
INFN - Genova

# PhD & post-doc positions available

## Support and funding

- ✓ Istituto Nazionale di Fisica Nucleare (INFN)
- ✓ European Commission (EC)
- ✓ ENI
- ✓ Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR)
- ✓ European Laboratory for Non-linear Spectroscopy (LENS)
- ✓ Ente Cassa di Risparmio di Firenze (CRF)
- ✓ European Space Agency (ESA)
- ✓ Agenzia Spaziale Italiana (ASI)
- ✓ Istituto Nazionale per la Fisica della Materia (INFM)
- ✓ Istituto Nazionale Geofisica e Vulcanologia (INGV)

