Testing gravity with free falling and trapped atom interferometry

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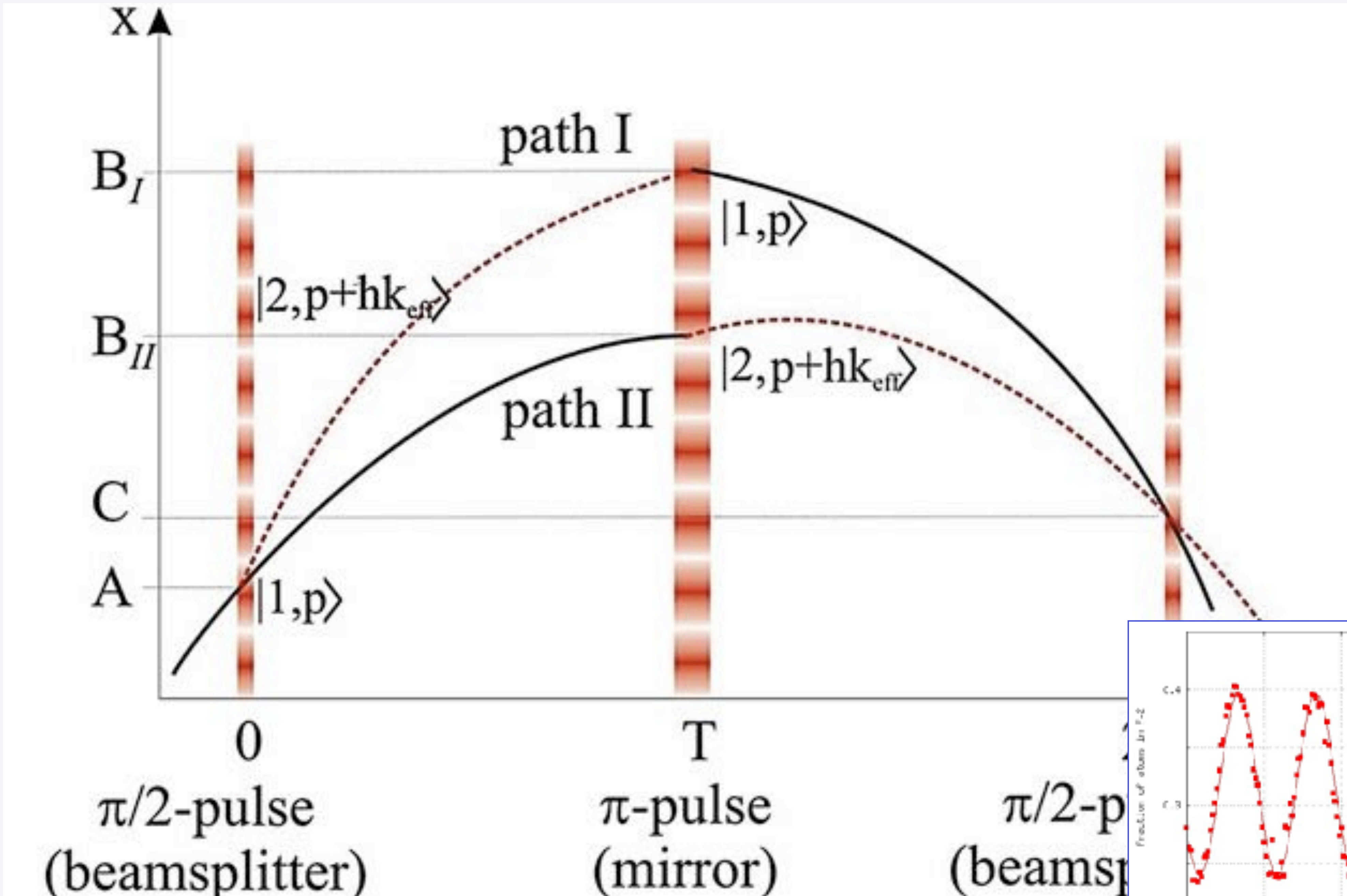
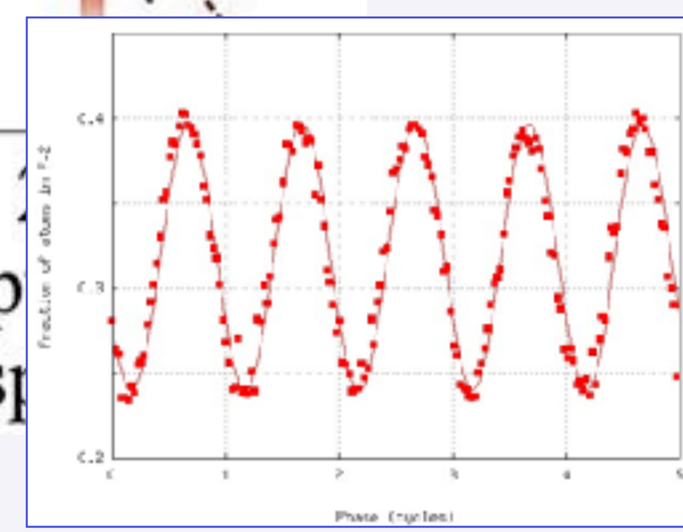
http://coldatoms.lens.unifi.it

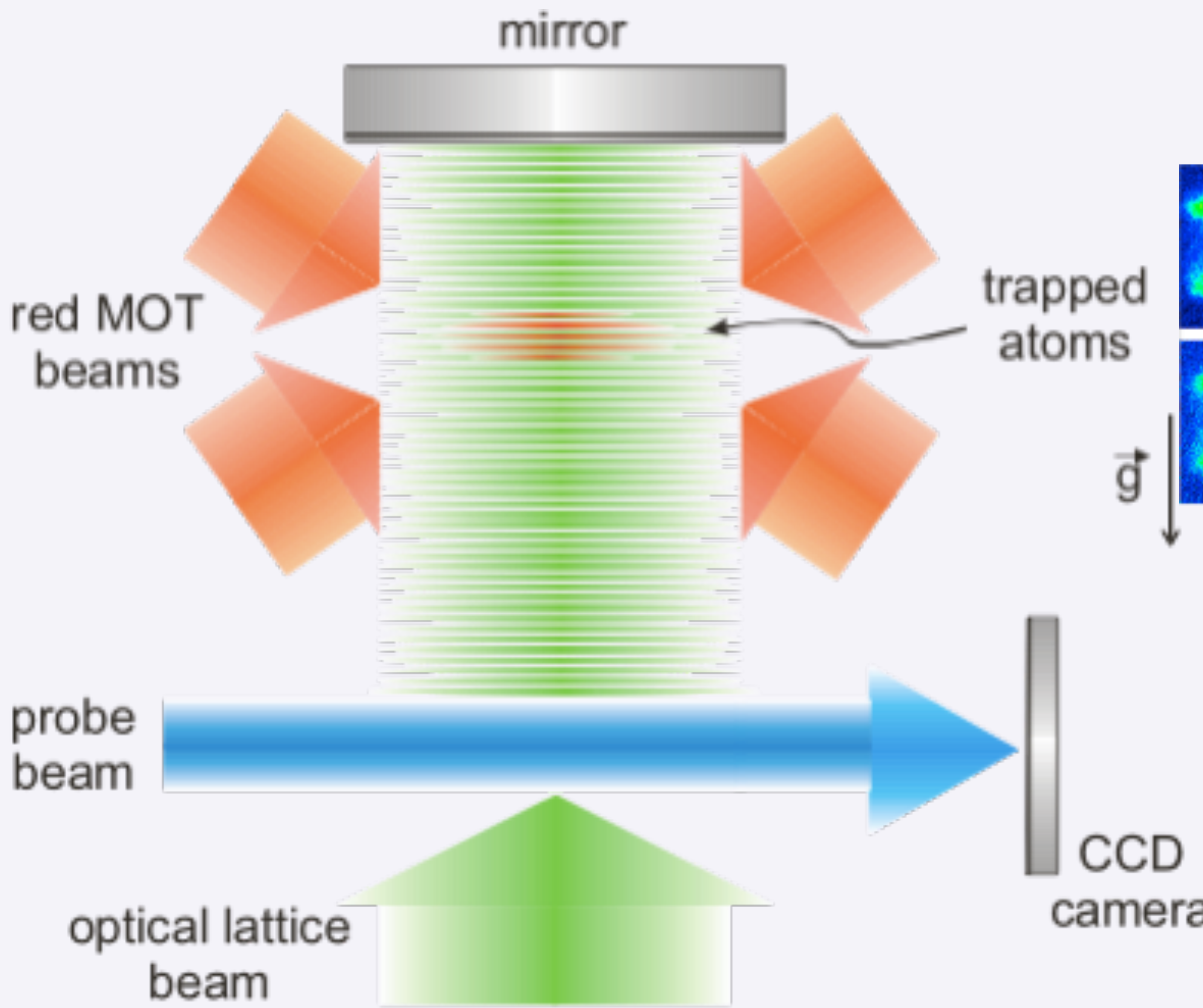
Workshop on matter-wave interferometry: From pioneering experiments to modern applications
Paris, 28 June 2019

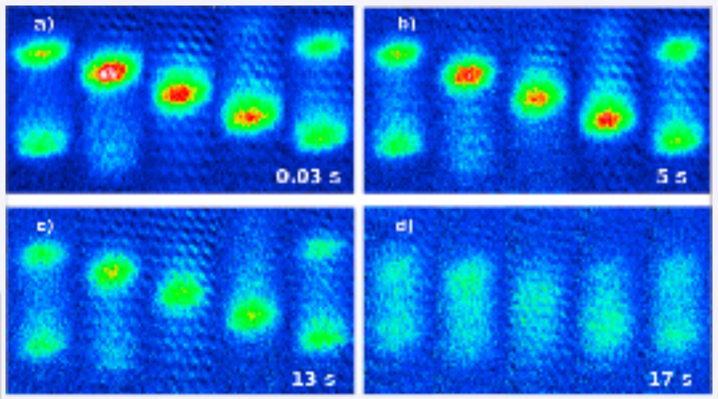
Atom interferometry and gravity





Bloch oscillations of Sr atoms in an optical lattice





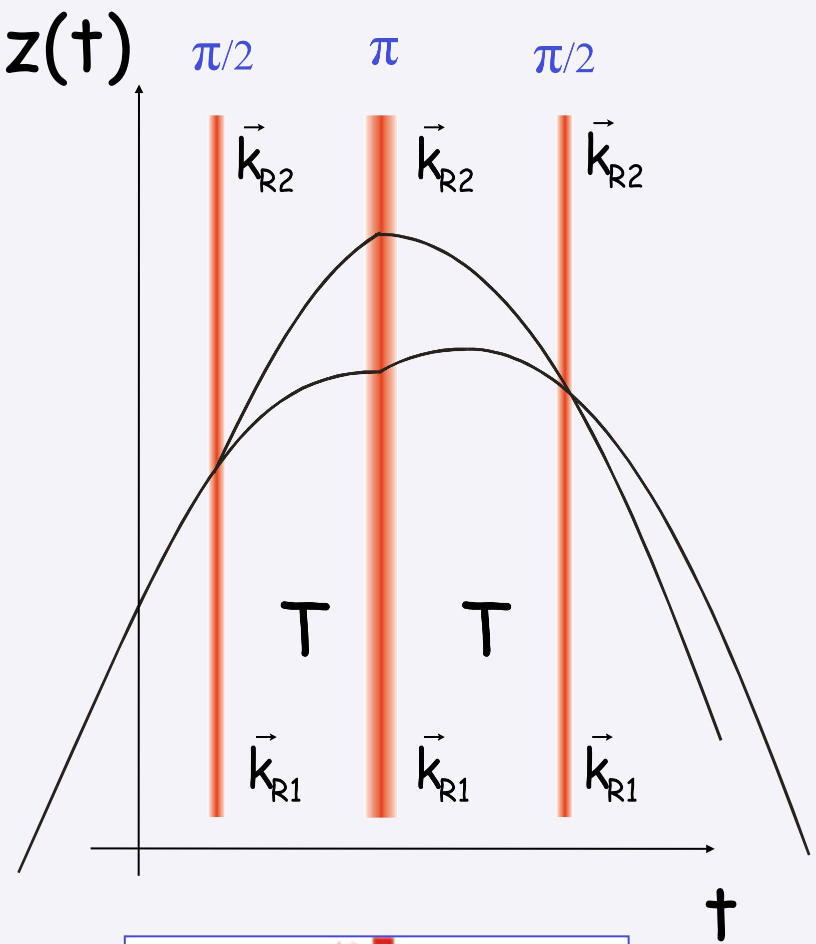
$$\nu = m\,g\,\lambda\,/2\,h$$

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)**

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)**

Raman interferometry in a Rb atomic fountain

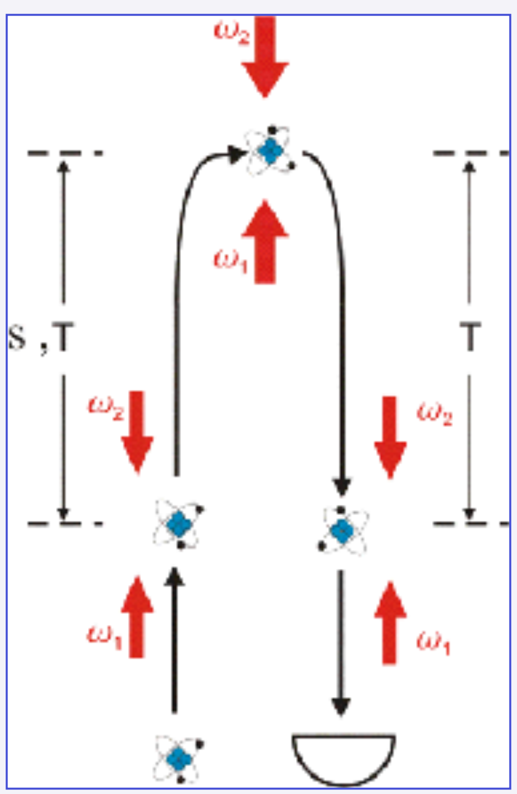


Phase difference between the paths:

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

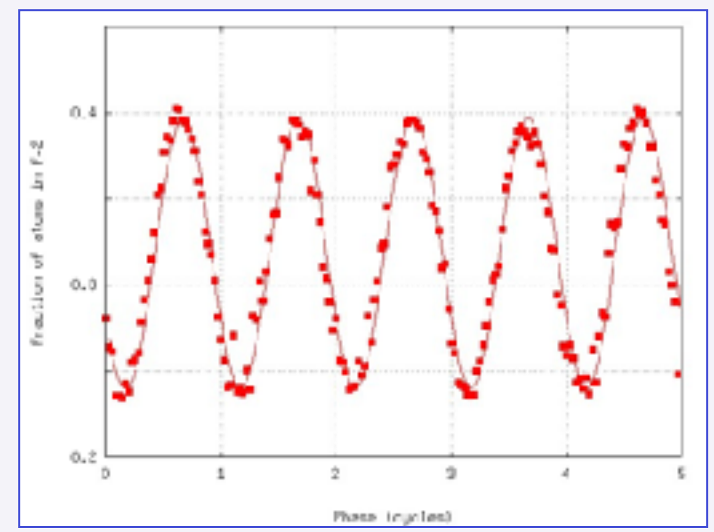
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0 \Rightarrow$ $\mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

10^6 Rb atoms

S/N = 1000 $\Rightarrow$ Sensitivity 10^{-9} g/shot

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

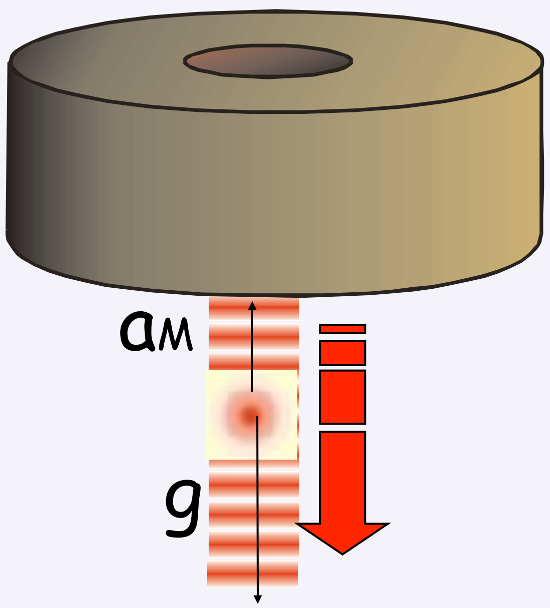
M. Kasevich, S. Chu, Appl. Phys. B <u>54</u>, 321 (1992)

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

MAGIA

(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

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



➤ ***Precision measurement of G***

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

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Towards an atom interferometric determination of the Newtonian gravitational constant

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Abstract

We report on progress towards an atom interferometric determination of the Newtonian gravitational constant. Free-falling laser-cooled atoms will probe the gravitational potential of nearby source masses. To reduce systematic errors, we will perform double differential measurements between two vertically separated atom clouds and with different source mass positions.

PACS: 04.80.-y; 39.20.+q; 03.75.Dg; 93.85

1. Introduction

The Newtonian gravitational constant G is—together with the speed of light—the most popular physical constant. Invented by Newton in 1686 to describe the gravitational force between two massive objects and first measured by Cavendish more than a hundred years later [1], "big G" became more and more subject of high precision measurements. There are many motivations for such measurements,[1] ranging from purely metrological interest over determinations of mass distributions of celestial objects to geophysical applications. In addition, many theoretical models profit from an accurate knowledge of G.

Despite these severe motivations and some 300 measurements in the past 200 years,[2] the 1998 CODATA [4] recommended value of $G = (6.673 \pm 0.010) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$ includes an uncertainty of 1500 parts per million (ppm). Thus, G is still the least accurately known fundamental physical constant. Recently, two measurements with much smaller uncertainties of 13.7 ppm [5] and 41 ppm [6] have been reported. However, the given values for G still disagree on the order of 100 ppm. Therefore, it is useful to perform high resolution G-measurements with different methods. This may help to identify possible systematic effects. It is worthwhile to mention that so far, only few conceptually different methods have resulted in G measurements on the level of 1000 ppm or better [3]. All these methods have in common that the masses,

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[1] A comprehensive listing of motivations for G measurements can be found in Ref. [2].

[2] For a recent review of the status of G measurements, see, e.g., Ref. [3].

0375-9601/$ – see front matter
doi:10.1016/j.physleta.2003.07.011

a more exhaustive description of these aspects refer to [12,21].

5. Conclusion

We presented a scheme that allows to measure the Newtonian gravitational constant G using a new method based on atom interferometry. In this scheme, free-falling atoms probe the gravitational potential of nearby source masses. Using two atom clouds in a gradiometer configuration and repeating measurements with different positions of the source masses reduce noise and systematic errors. We reported on the progress of our MAGIA experiment, which—based on the described scheme—aims at the high precision measurement of G. The experimental setup is in great part already functioning. We numerically analyzed the influence of atomic initial conditions and source mass locations on the measurement. The results are encouraging to determine G to the targeted accuracy of 100 ppm. Using modified configurations, atom interferometry can also be applied to prove the $1/r^2$-dependence of Newton's law of gravitation or to test the equivalence principle.

Acknowledgements

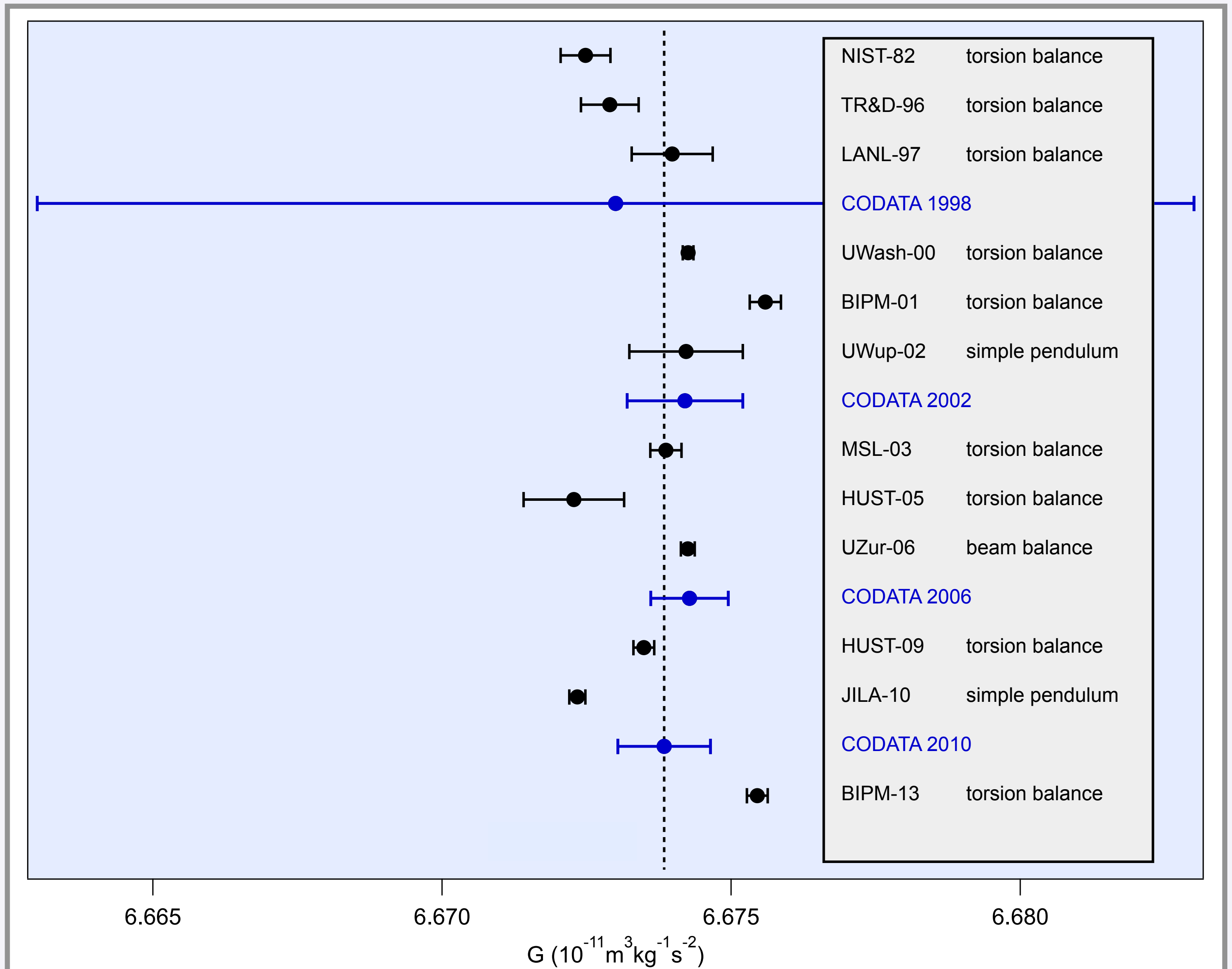
We thank Mark Kasevich for stimulating discussions and appreciate fruitful suggestions of Achim Peters and James Faller. J.S. and T.P. acknowledge support from the European Union under contract number HPRI/CT/1999/00111. This work is financed by the Istituto Nazionale di Fisica Nucleare (INFN).

References

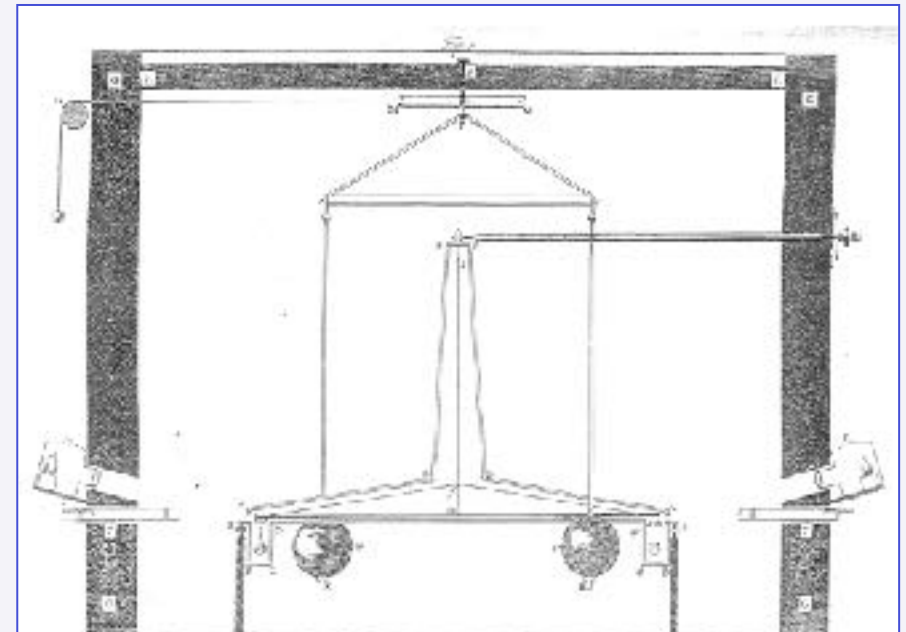
[1] H. Cavendish, Philos. Trans. R. Soc. 88 (1798) 467.
[2] G.T. Gillies, Rep. Prog. Phys. 60 (1997) 151.
[3] J. Luo, Z.-K. Hu, Class. Quantum Grav. 17 (2000) 2351.
[4] P.J. Mohr, B.N. Taylor, Rev. Mod. Phys. 72 (2000) 351, the values can also be found at http://physics.nist.gov/cuu/Constants/index.html.
[5] J.H. Gundlach, S.M. Merkowitz, Phys. Rev. Lett. 85 (2000) 2869.
[6] T.J. Quinn, C.C. Speake, S.J. Richman, R.S. Davis, A. Picard, Phys. Rev. Lett. 87 (2001) 111101.
[7] J.P. Schwarz, D.S. Robertson, T.M. Niebauer, J.E. Faller, Science 282 (1998) 2230.
[8] G.M. Tino, A relativistic space time odyssey, in: I. Ciufolini, et al. (Eds.), Experiments and Theoretical Viewpoints on General Relativity and Quantum Gravity, Proceedings of the 25th Johns Hopkins Workshop on Current Problems in Particle Theory, Firenze, Italy, 2001, World Scientific, Singapore, 2001.
[9] (a) P.R. Berman (Ed.), Atom Interferometry, Academic Press, New York, 1997;
(b) D.E. Pritchard, A.D. Cronin, S. Gupta, D.A. Kokorowski, Ann. Phys. (Leipzig) 10 (2001) 35.
[10] S. Chu, Rev. Mod. Phys. 70 (1998) 685;
C.N. Cohen-Tannoudji, Rev. Mod. Phys. 70 (1998) 707;
W.D. Phillips, Rev. Mod. Phys. 70 (1998) 721.
[11] B. Young, M. Kasevich, S. Chu, in: Atom Interferometry, Academic Press, New York, 1997, p. 363.
[12] A. Peters, Dissertation, Department of Physics, Stanford University, 1998;
A. Peters, K.Y. Chung, S. Chu, Metrologia 38 (2001) 25.
[13] D.S. Weiss, Dissertation, Department of Physics, Stanford University, 1993.
[14] A. Peters, K.Y. Chung, S. Chu, Nature 400 (1999) 849.
[15] M.J. Snadden, J.N. McGuirk, P. Bouyer, K.G. Haritos, M.A. Kasevich, Phys. Rev. Lett. 81 (1998) 971.
[16] J. Schurr, F. Nolting, W. Künding, Phys. Rev. Lett. 80 (1998) 1142.
[17] J. Stuhler, M. Fattori, T. Petelski, G.M. Tino, in preparation.
[18] G. Santarelli, A. Clairon, S.N. Lea, G.M. Tino, Opt. Commun. 104 (1994) 339.
[19] K. Gibble, S. Chu, Phys. Rev. Lett. 70 (1993) 1771, and references therein.
[20] P. Treutlein, K.Y. Chung, S. Chu, Phys. Rev. A 63 (2001) 051401.
[21] J.M. McGuirk, G.T. Foster, J.B. Fixler, M.J. Snadden, M.A. Kasevich, Phys. Rev. A 65 (2002) 033608.
[22] G. Santarelli, Ph. Laurent, P. Lemond, A. Clairon, A.G. Mann, S. Chang, A.N. Luiten, C. Salomon, Phys. Rev. Lett. 82 (1999) 4619.

Measurements of the Newtonian gravitational constant G

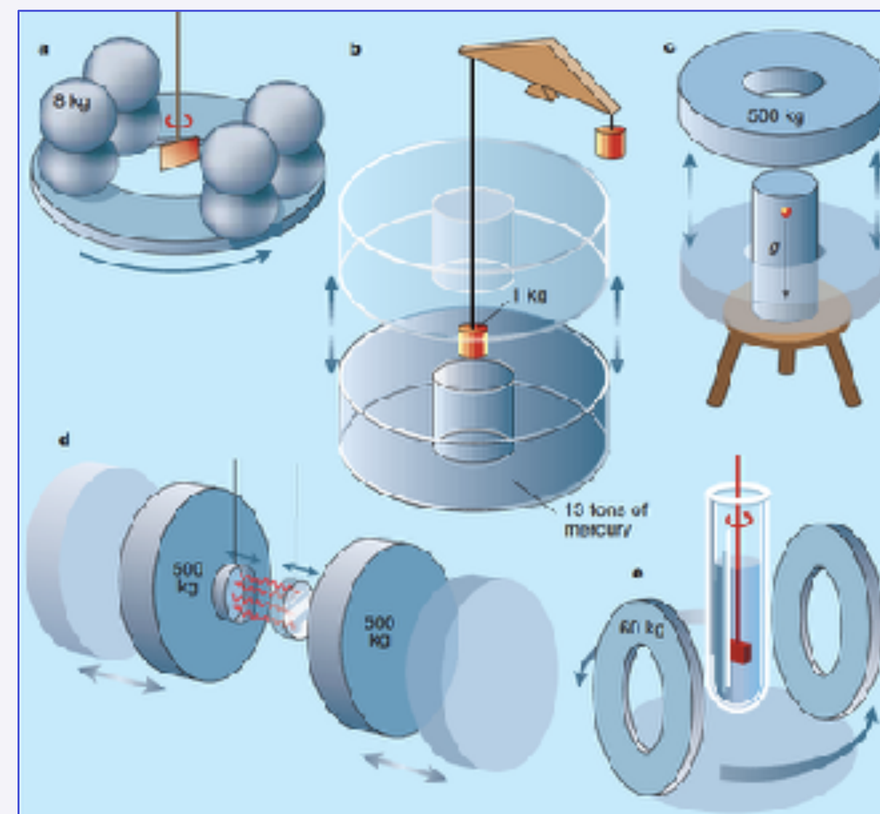
$$F(r) = G\frac{M_1 M_2}{r^2}$$



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)

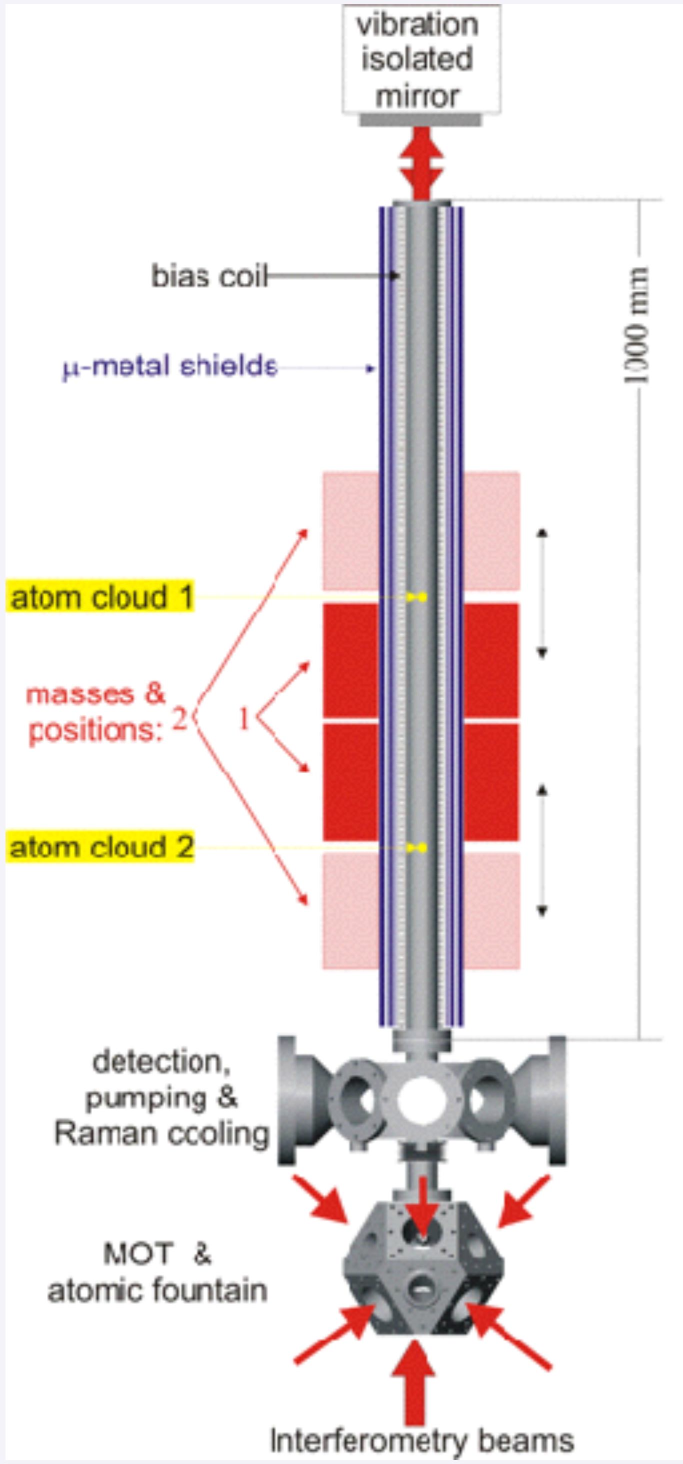


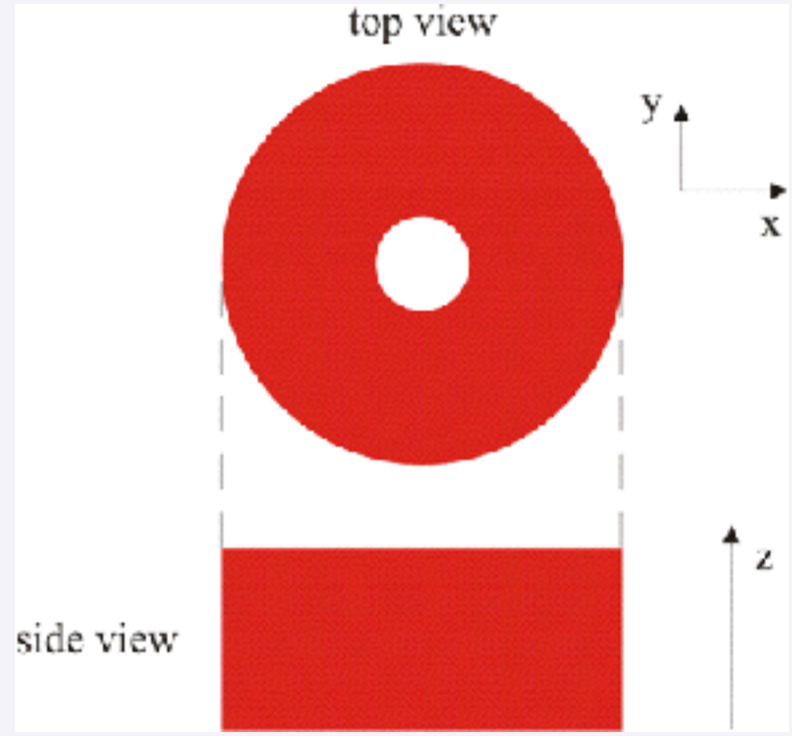
Cavendish, 1798

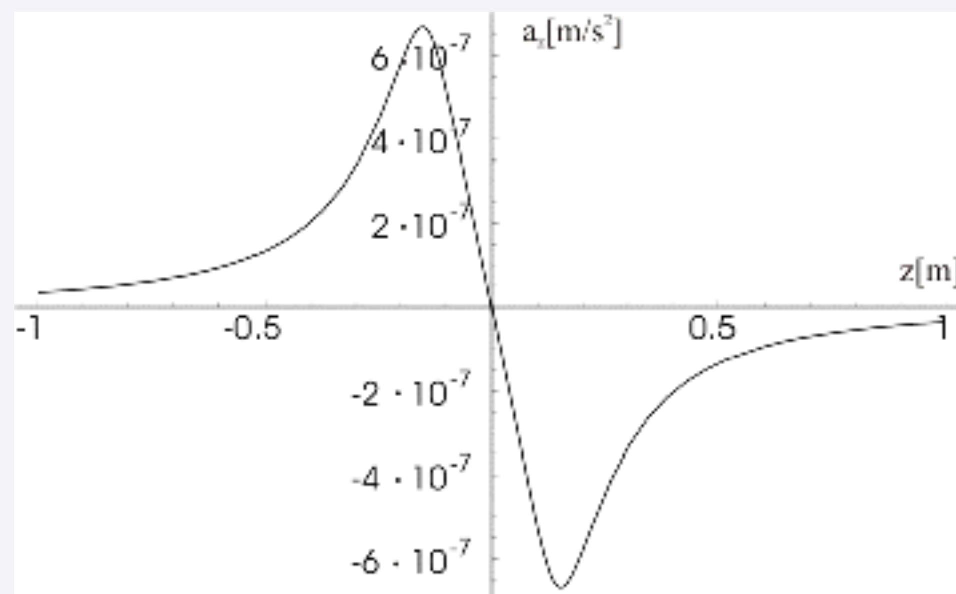


Terry Quinn. *Measuring big G*, NATURE, 408, 919 (2000)

MAGIA
Rb gravity gradiometer + source mass







500 kg tungsten mass

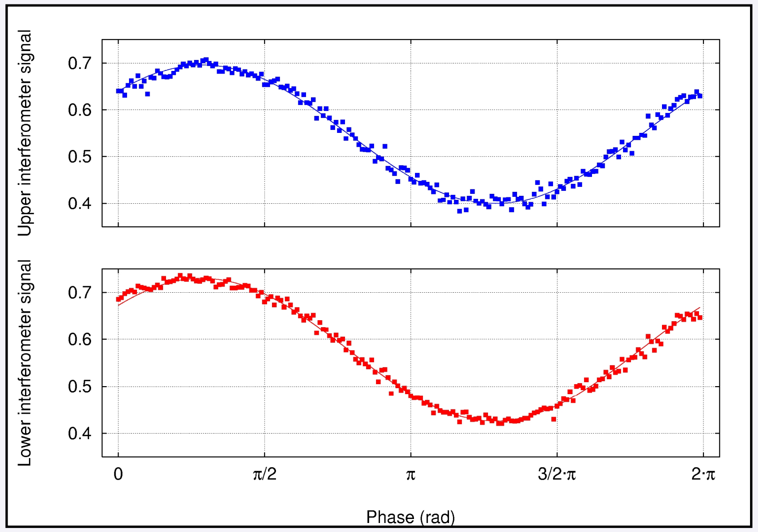
Sensitivity 10^{-9}g/shot

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

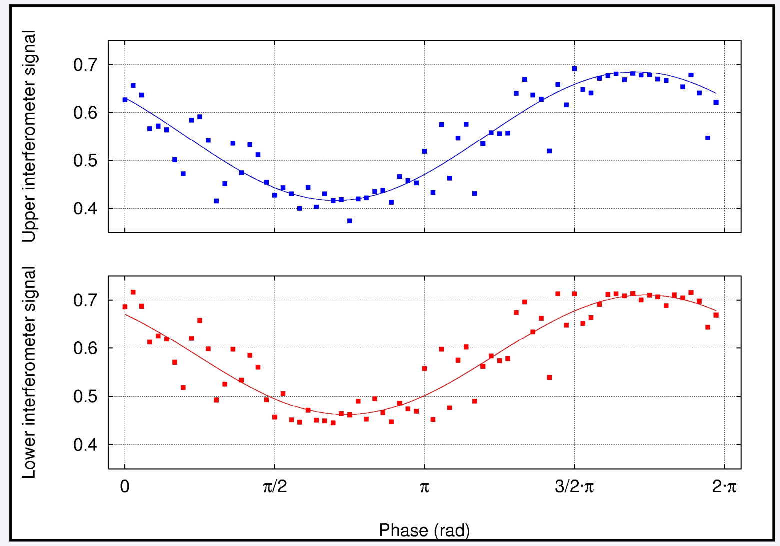
Peak mass acceleration $a_G \approx 10^{-7}$g

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

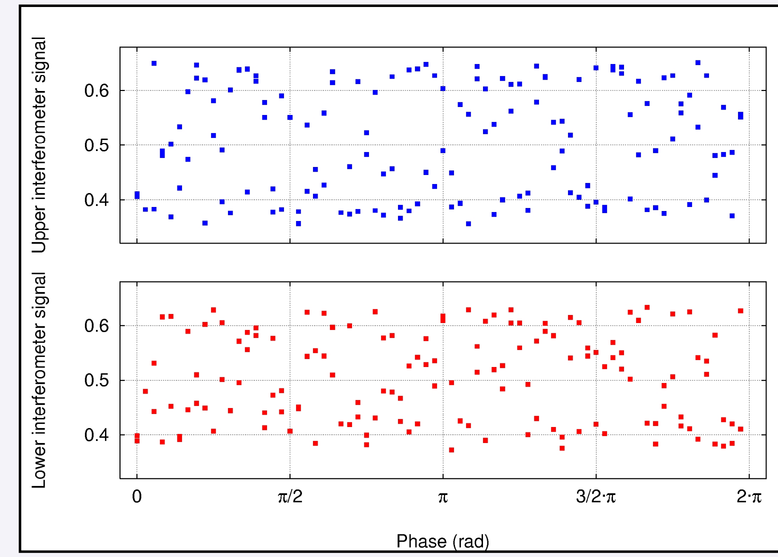
Gravity gradiometer



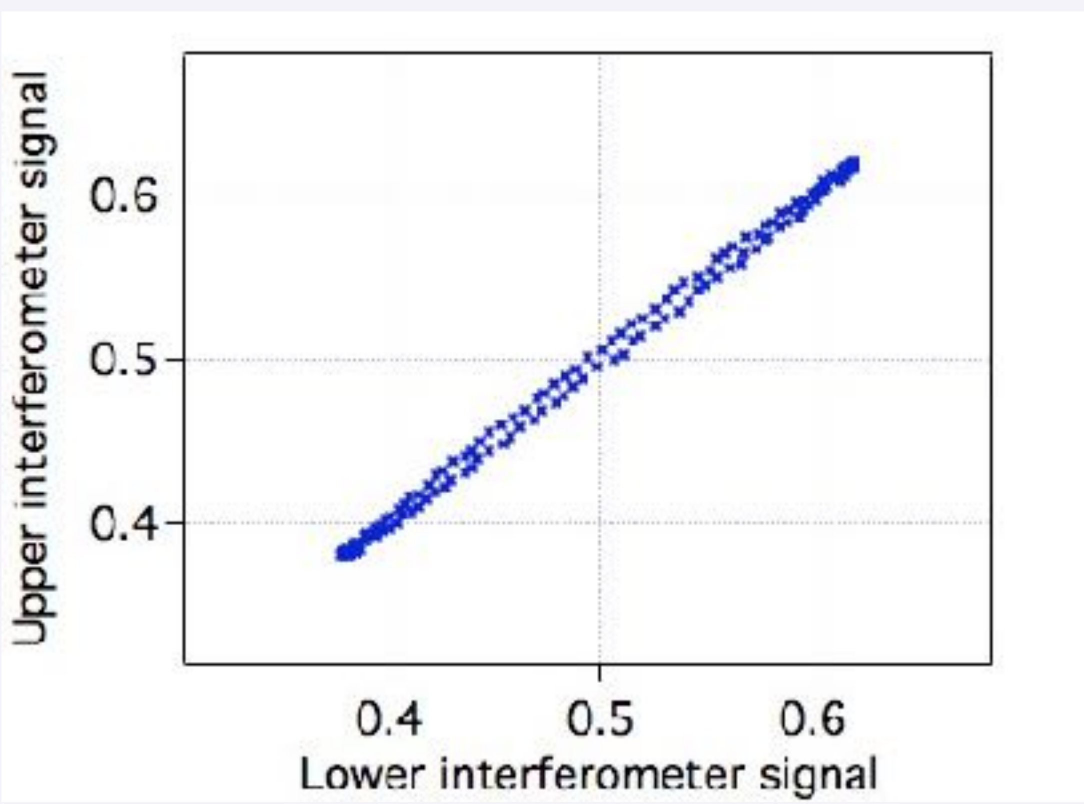
T=5 ms
resol. $= 2.3 \times 10^{-5}$g/shot



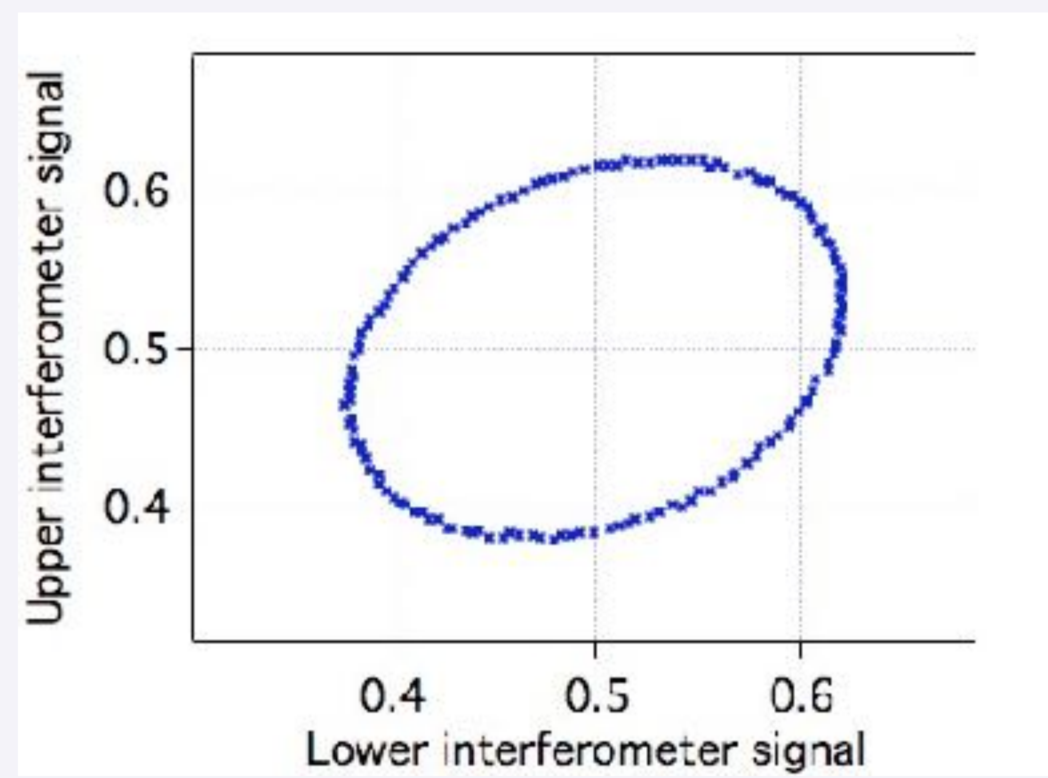
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot



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



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



G. T. Foster et al., Opt. Lett **27**, 951 (2002)

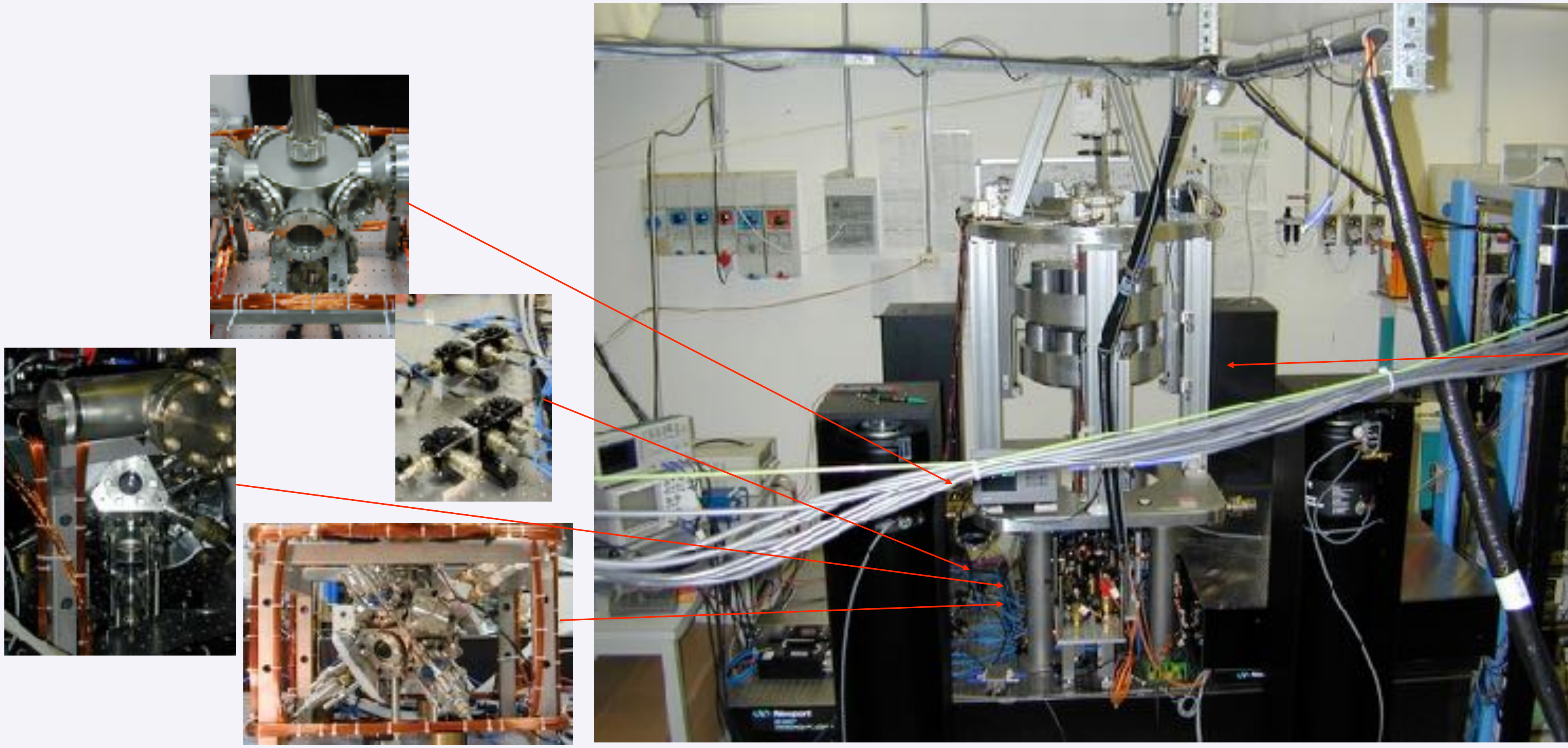
MAGIA apparatus

Cavendish 1798: “The apparatus is very simple”

MAGIA apparatus is not very simple

- Laser system
  - 6 frequency stabilized ECDL sources @ 780 nm (Reference, Cooling 2D-MOT, Cooling 3D-MOT, Repumper master, Raman master, Raman slave)
  - 3 optically injected diode lasers @ 780 nm (Repumper 2D-MOT, Repumper 3D-MOT, Probe)
  - 4 Tapered Amplifiers @ 780 nm (Cooling 2D-MOT, Cooling 3D-MOT, Raman master, Raman
  - ~20 AOMs
  - ~20 PM optical fibres
- Active stabilization loops
  - Intensity of 3D-MOT Cooling up and down laser beams, master and slave Raman laser beams and Probe laser
  - tilt of Raman retro-reflection mirror
  - Earth rotation compensation with tilt-tip Raman mirror
- Vacuum system
  - 2D-MOT chamber, steel, 10^{-7} torr Rb pressure
  - main chambers and interferometer tube, titanium, ~10^{-10} torr
- Electronic control system
  - real-time system for analog I/O and TTL signals, <5 μs jitter
  - ~20 shutter drivers
  - ~10 DDS for AOM and OPLL driving
  - 6 low-noise coil drivers
- Laboratory environment
  - temperature stability 0.1 °C
  - humidity stability 5%

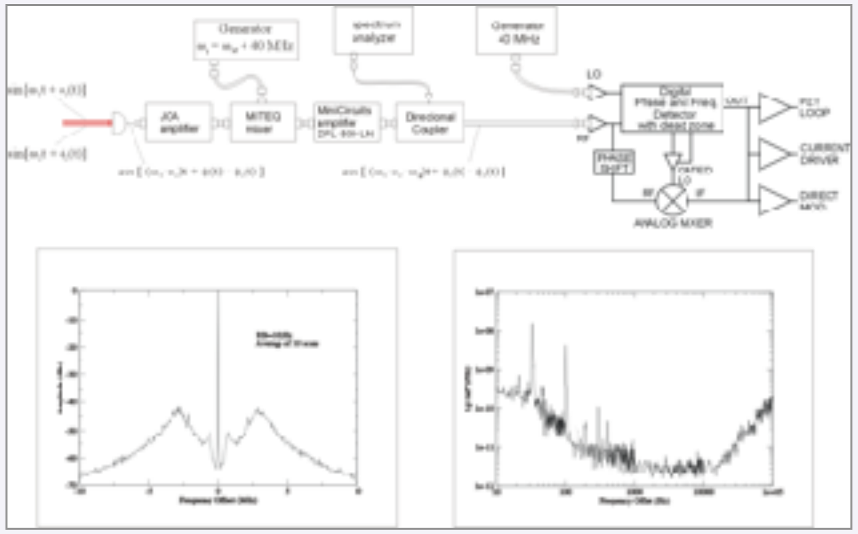
MAGIA apparatus



Source masses and support

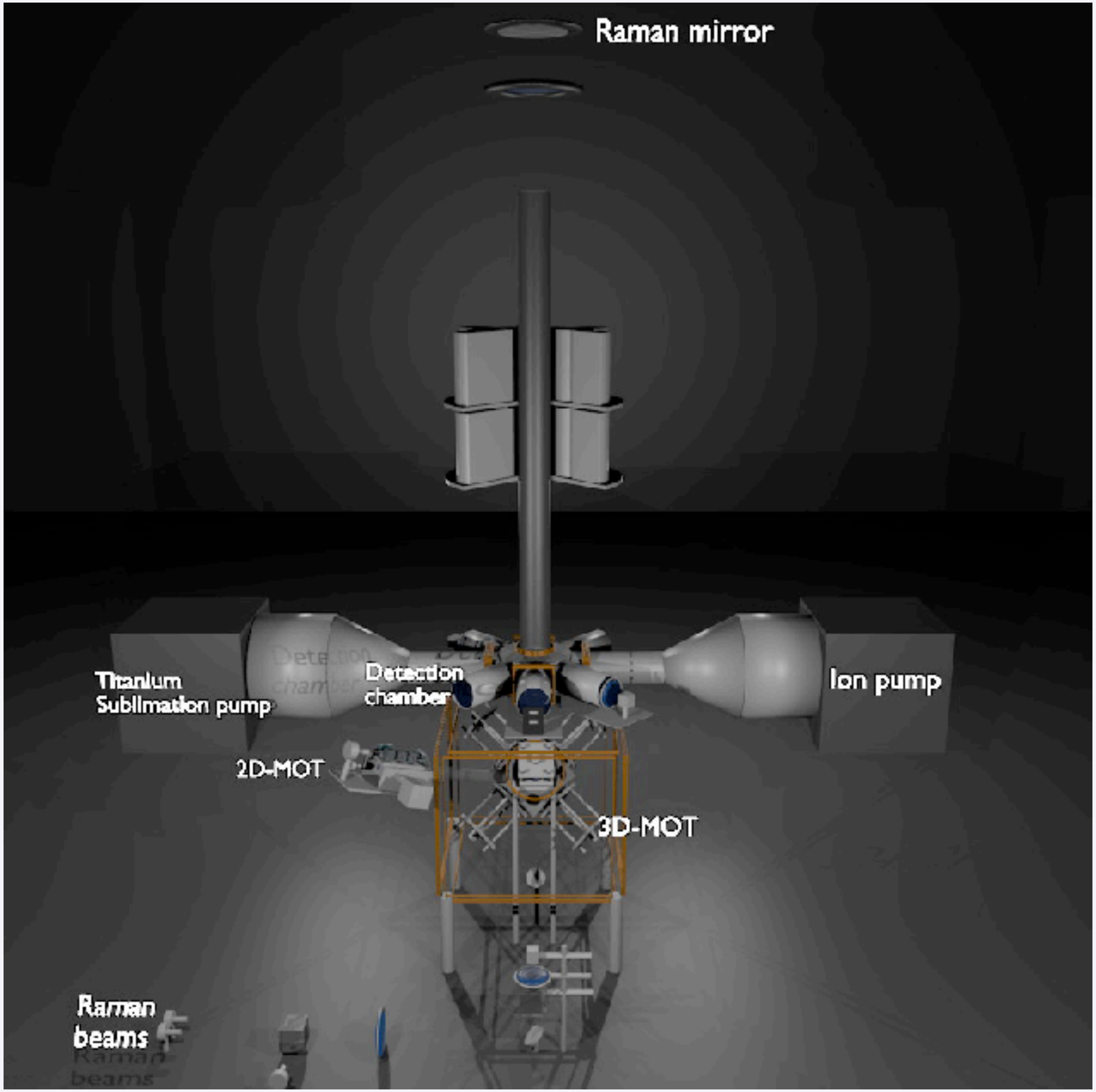
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino,
Source Masses and Positioning System for an Accurate Measurement of G, **Rev. Scient. Instr. 78, 075109 (2007)**

Laser and optical system

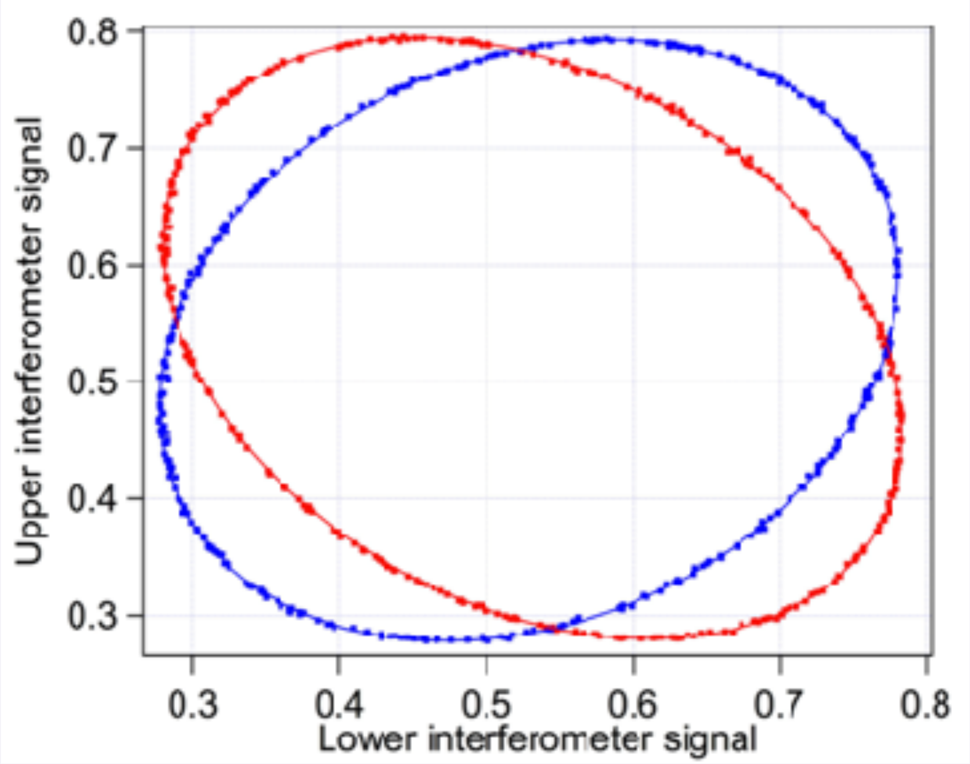


L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino,
Analog+digital phase and frequency detector for phase locking of diode lasers, **Rev. Scient. Instr. 76, 053111 (2005)**

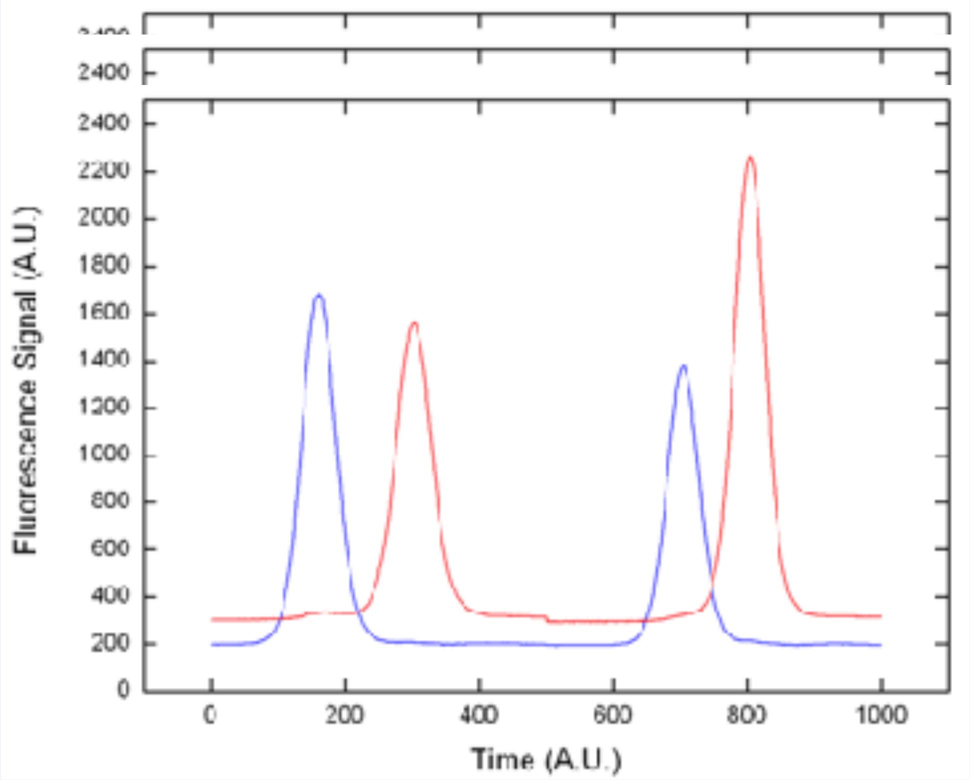
MAGIA



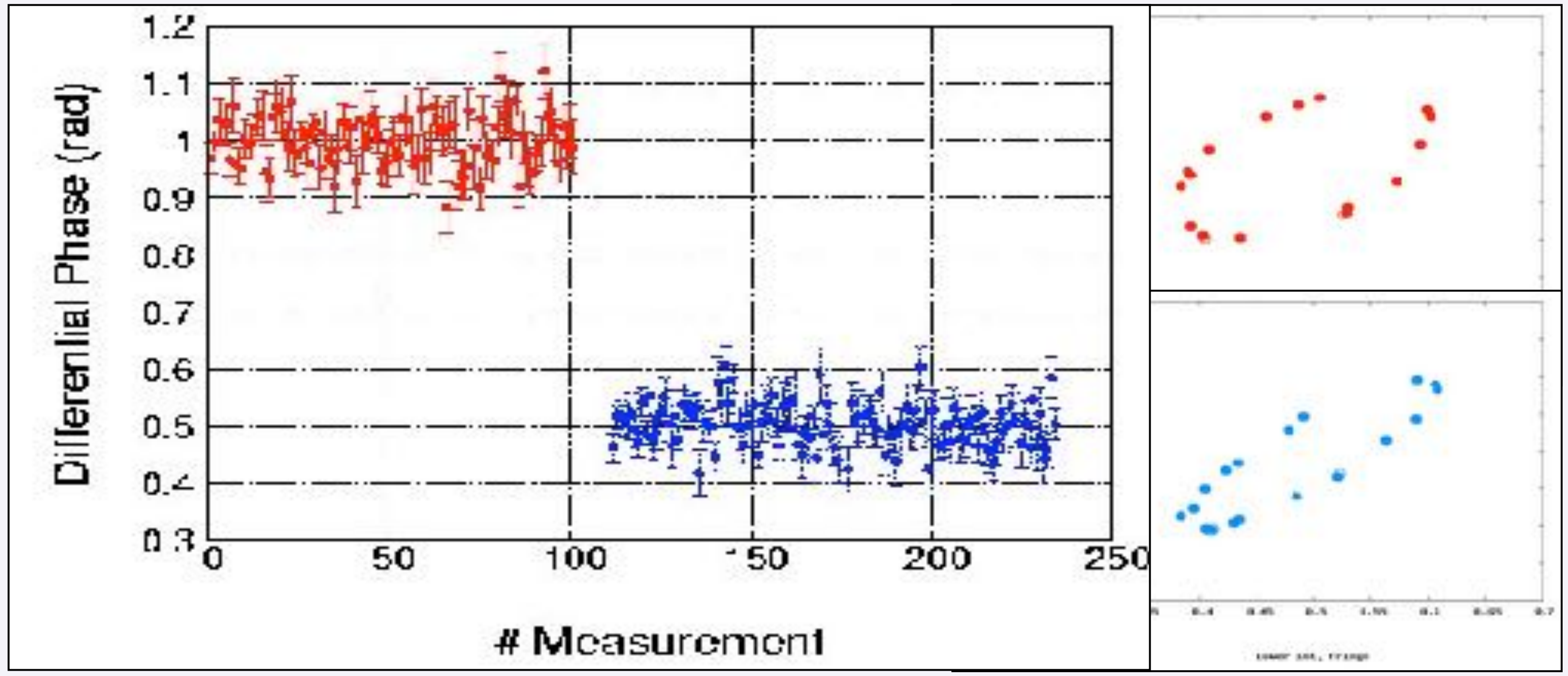
Raman mirror
Titanium Sublimation pump
Detection chamber
Ion pump
2D-MOT
3D-MOT
Raman beams



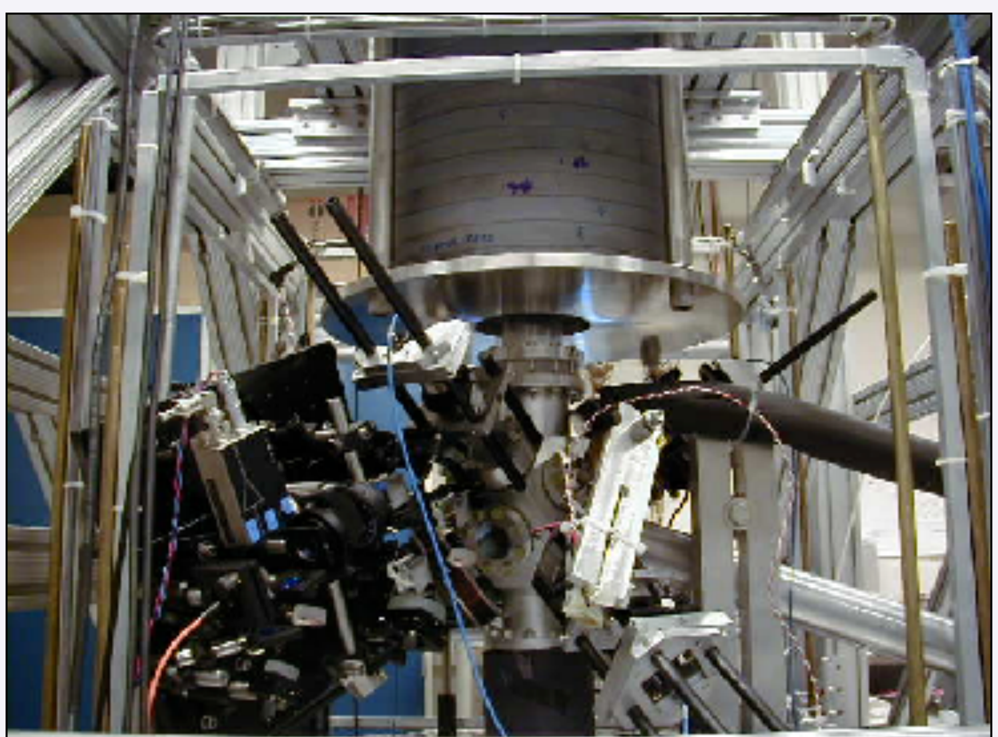
Upper interferometer signal
Lower interferometer signal

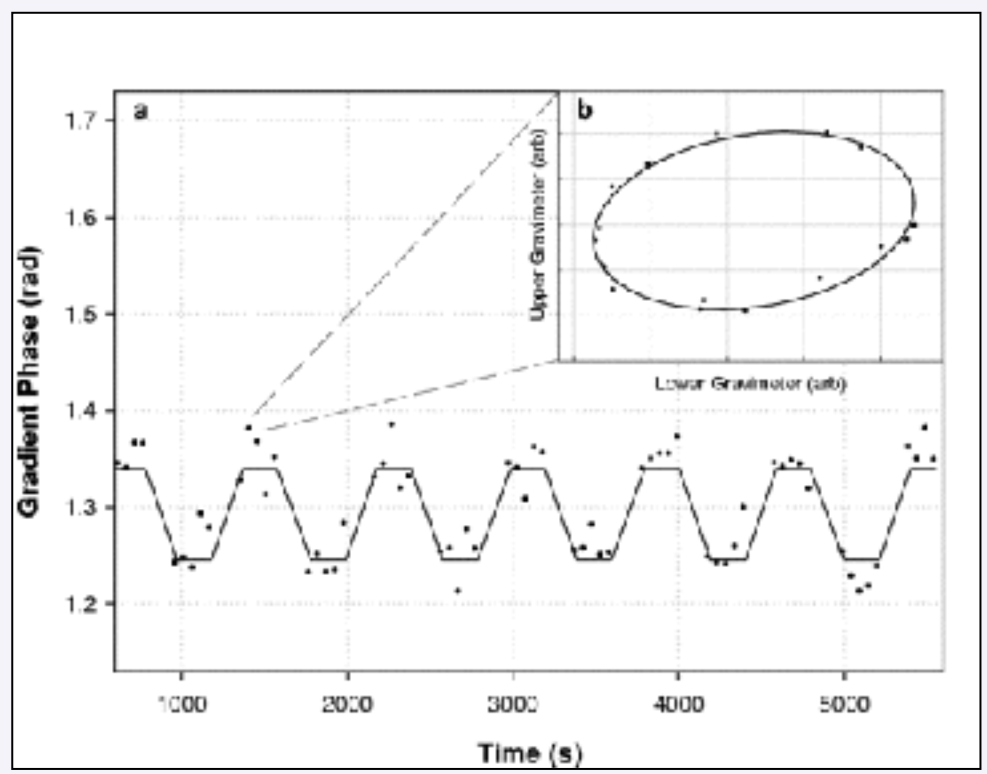


Fluorescence Signal (A.U.)
Time (A.U.)



A. Bertoldi G.Lamporesi , L. Cacciapuoti, M. deAngelis, M.Fattori, T.Petelski, A. Peters, M. Prevedelli, J. Stuhler, G.M. Tino,
Atom interferometry gravity-gradiometer for the determination of the Newtonian gravitational constant G,
Eur. Phys. J. D 40, 271 (2006)





J. B. Fixler, G. T. Foster, J. M. McGuirk and M. A. Kasevich,
Atom Interferometer Measurement of the Newtonian Constant of Gravity,
Science 315, 74 (2007)

MAGIA: From proof-of-principle to the measurement of G

- Sensitivity
  - 15-fold improvement of the instrument sensitivity from 2008 to 2013
  - integration time for the 100 ppm target reduced by more than a factor 200
- Accuracy
  - systematic uncertainty reduced by a factor ~10 since 2008, mostly due to
    - better characterization of source masses
    - control & mitigation of Coriolis acceleration
    - control of atomic trajectories
- Data analysis
  - developed a reliable model accounting for all of the relevant effects
    - gravitational potential generated by source masses along atomic path
    - quantum mechanical phase shift of atomic probes
    - detection efficiency
  - measured data compared with a Montecarlo simulation

Source mass

INTERMET IT 180
(PLANSEE)

COMPOSITION

W	95.3%
Ni	3.2%
Cu	1.5%

PROPERTIES

Density 18 kg/m^3
Resistivity 12×10^{-8} Ωm
Amagnetic
CTE 5×10^{-6} K^{-1}
Roughness 3 μm

REALIZATION

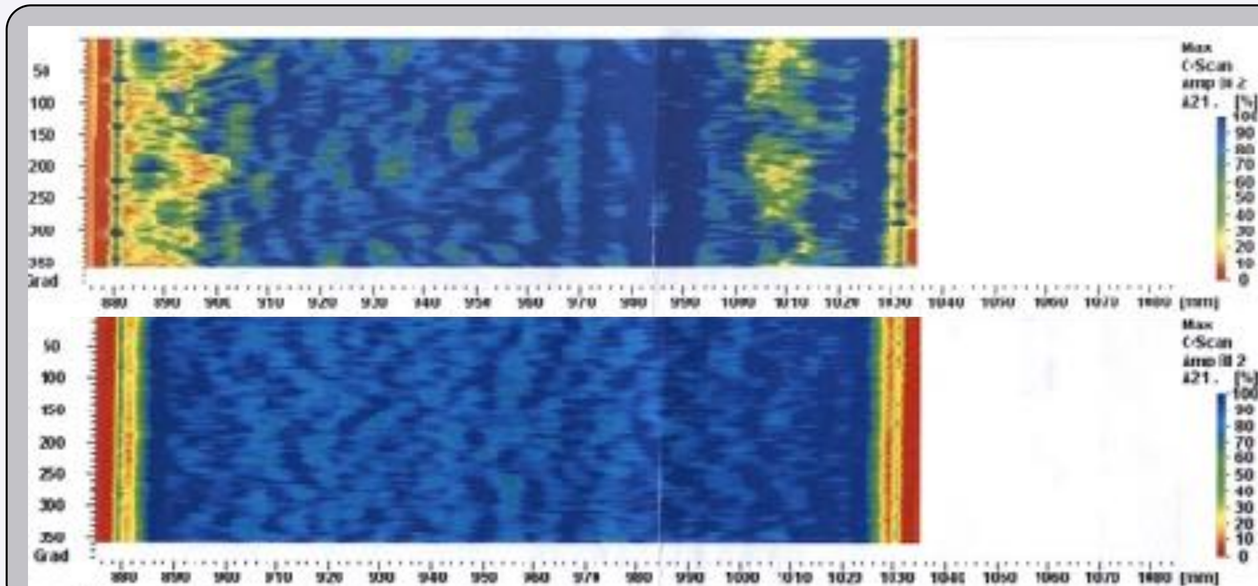
SINTERING
T=1500°C - P=1 bar

Hot Isostatic Pressing
T=1200°C - P=1000 bar

MICROSCOPE ANALYSIS

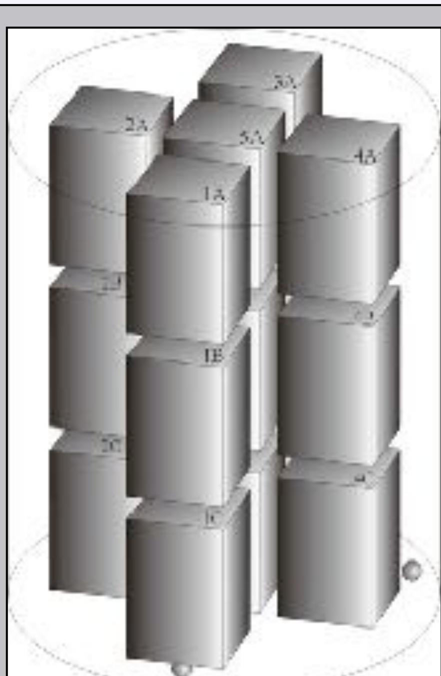
holes: Ø ~ 100 μ m

ULTRASONIC TEST



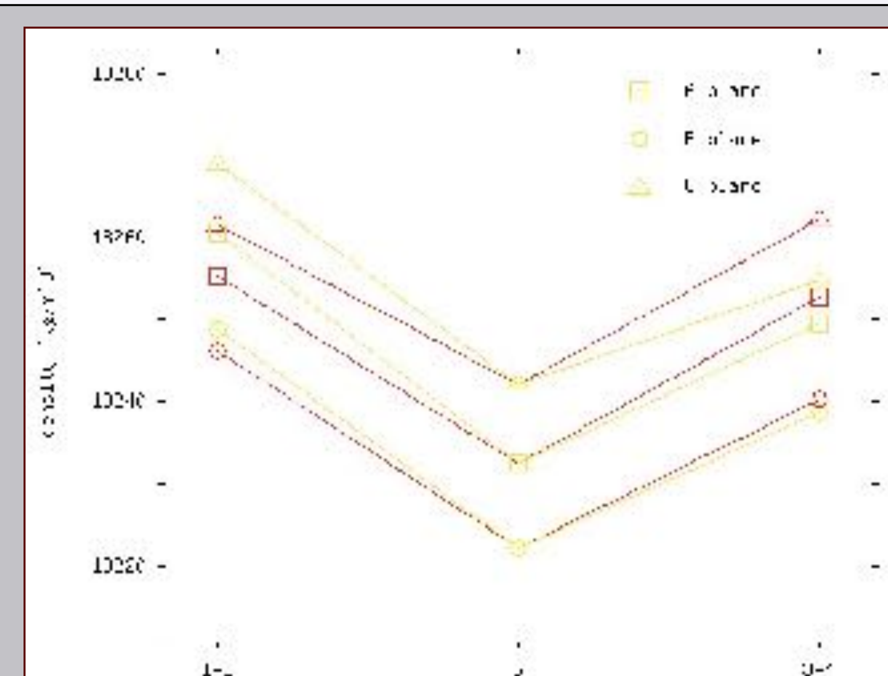
Before HIP

After HIP



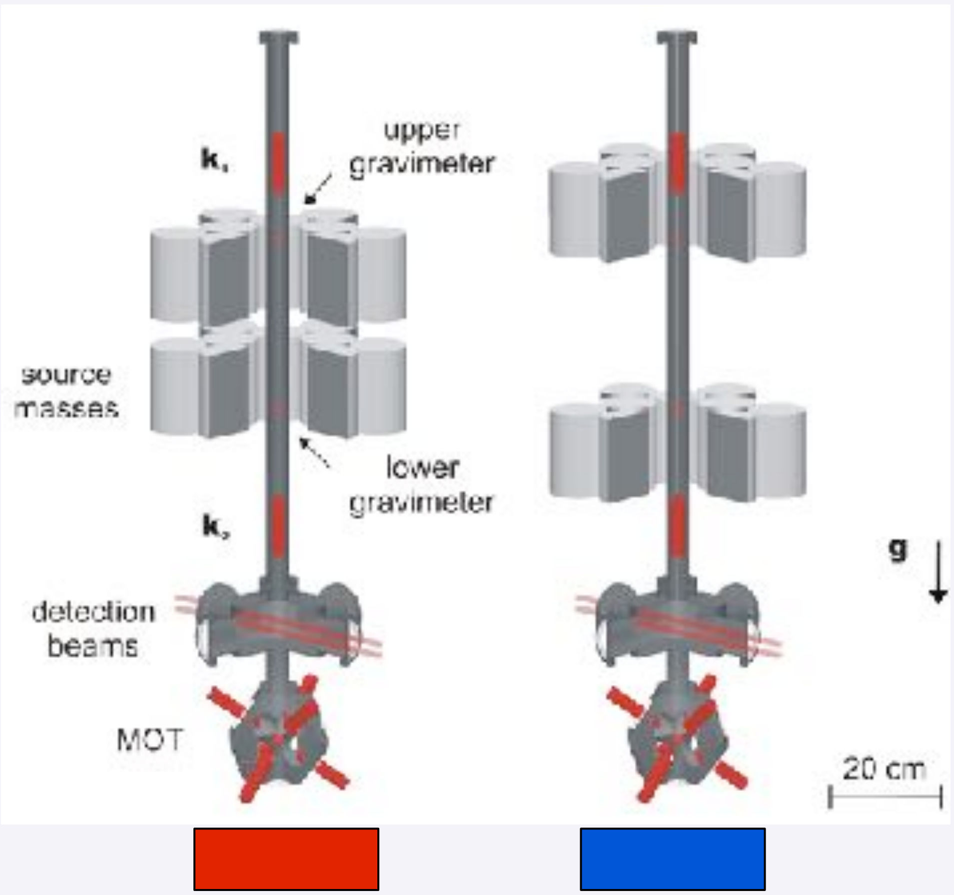
DENSITY TEST
(INRIM, Torino)

ρ = 18249 kg/m^3
res: 10 mg/m^3
σ_ρ = 12 kg/m^3 (6 10^{-4})
$\Delta\rho$ =47 kg/m^3 (2 10^{-3})

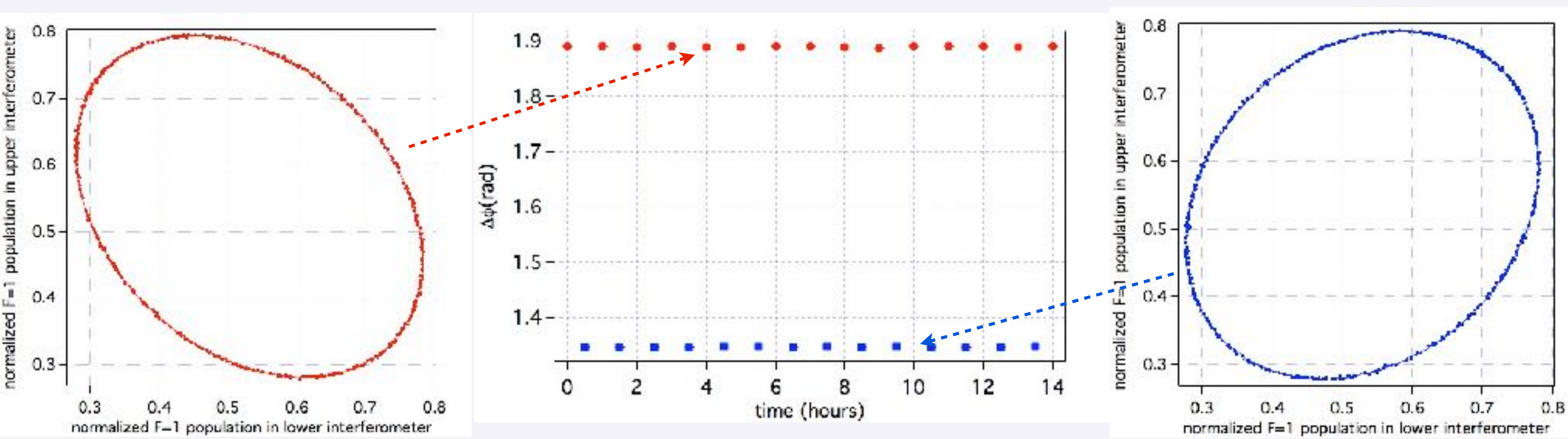


G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G*, Rev. Scient. Instr. 78, 075109 (2007)

MAGIA: Final sensitivity



- Repetition period of experimental cycle: 1.9 s
- Number of points per ellipse: 720 (23 min)
- Number of launched atoms: ~10^9 per cloud
- Number of detected atoms: ~4×10^5 per cloud
- Sensitivity to ellipse angle: ~ 9 mrad / shot
- Sensitivity to differential gravity: 3×10^{-9} g /√Hz
- Sensitivity in G measurements: 5.7×10^{-2}/√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[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 $G = 6.67191(99) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$ 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

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

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)

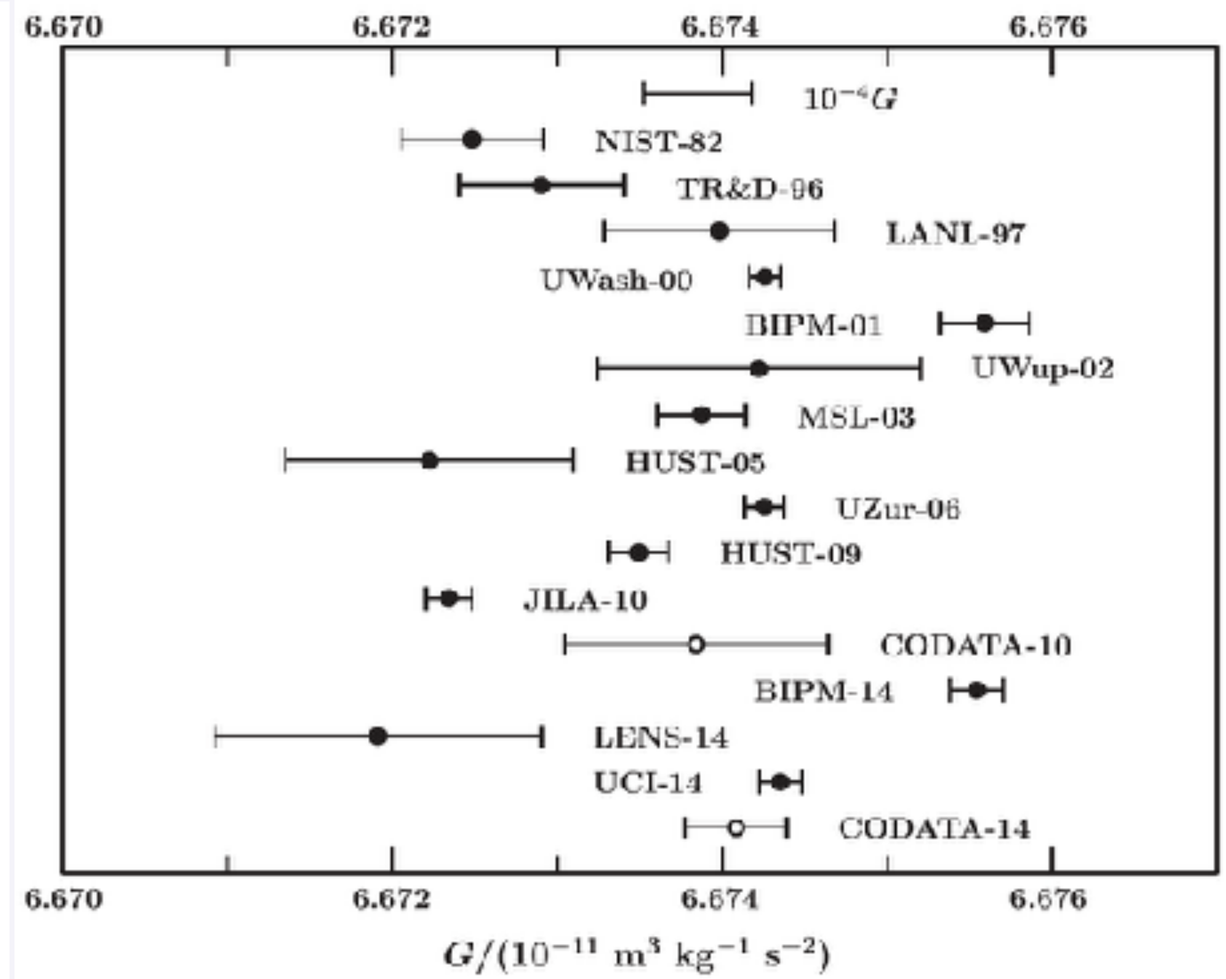
TABLE XV. Summary of the results of measurements of the Newtonian constant of gravitation relevant to the 2014 adjustment.

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

[a]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.



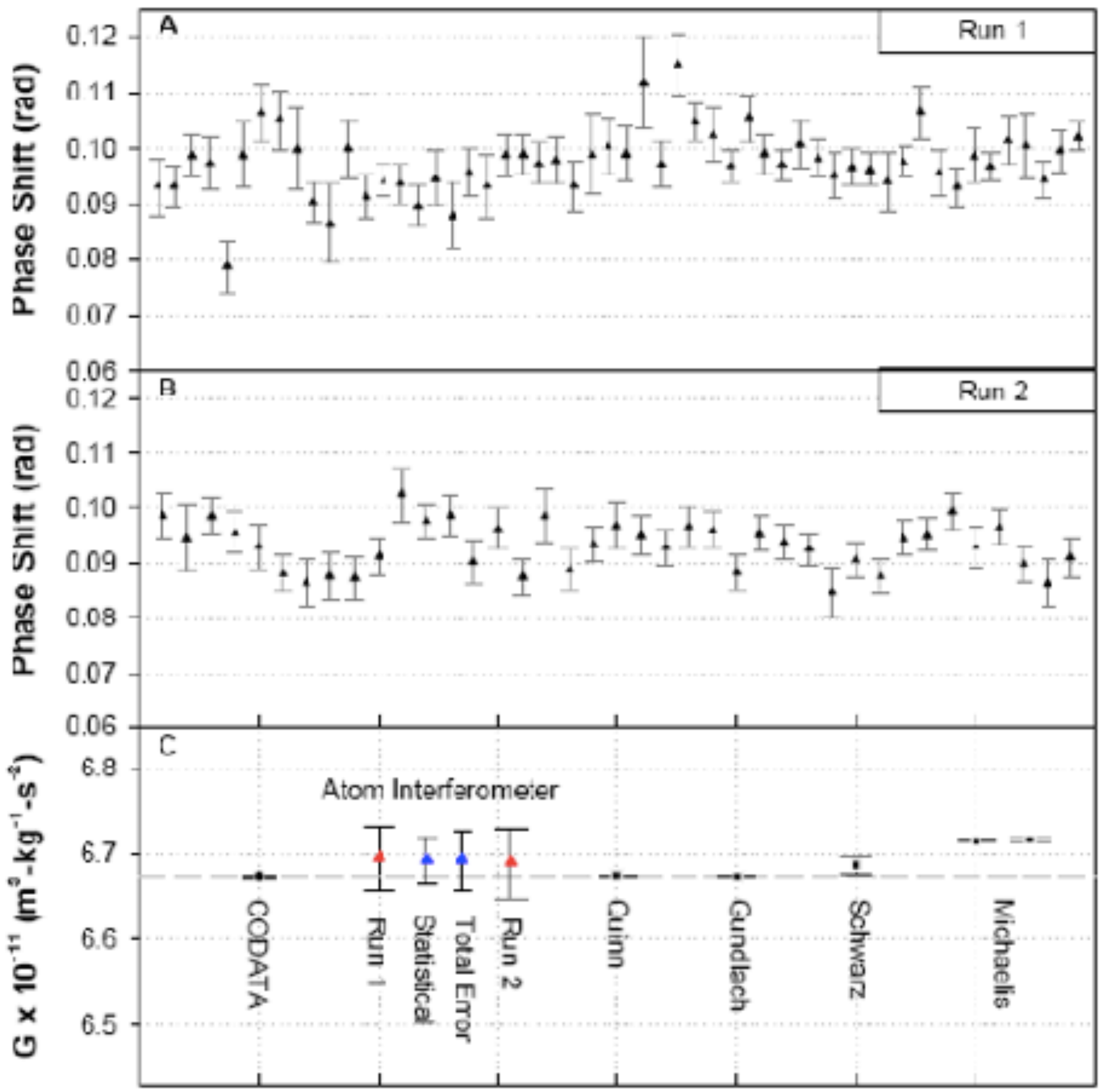
CODATA 2014

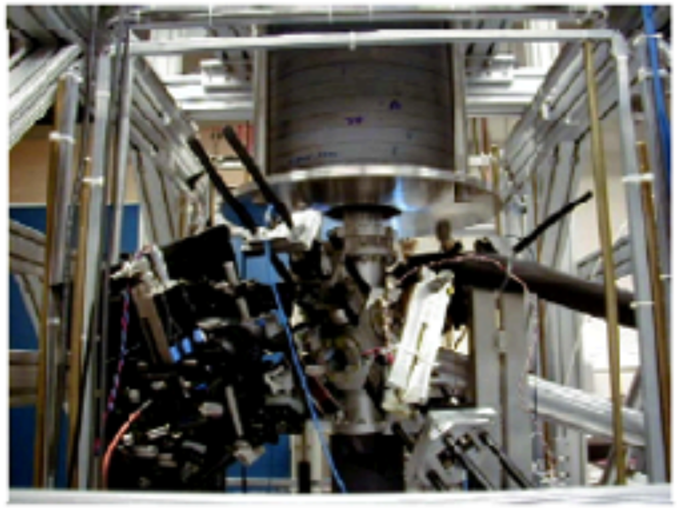
G = 6.67408(31)×10^{-11} $m^3\ kg^{-1}s^{-2}$

[Relative std. uncert.: 4.7×10^{-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)

Measurement of G





Systematic	$\delta G/G$
Initial Atom Velocity	1.88×10^{-3}
Initial Atom Position	1.85×10^{-3}
Pb Magnetic Field Gradients	1.00×10^{-3}
Rotations	0.98×10^{-3}
Source Positioning	0.82×10^{-3}
Source Mass Density	0.36×10^{-3}
Source Mass Dimensions	0.34×10^{-3}
Gravimeter Separation	0.19×10^{-3}
Source Mass Density inhomogeneity	0.16×10^{-3}
TOTAL	3.15×10^{-3}

Systematic error sources dominated by initial position/velocity of atomic clouds. $\delta G/G \sim 0.3\%$.

Next Generation: <1e-4, exp't in progress at AOSense, Inc. in colloboration with LLNL.

STANFORD UNIVERSITY

From M. Kasevich

G. W. Biedermann et al., *Testing Gravity with Cold-Atom Interferometers*, Phys. Rev. A 91, 033629 (2015)

Project of Measuring *G* with AI in HUST

HUST: Huazhong University of Science & Technology

Source masses:

24×10Kg spheres

Gravitational signal:

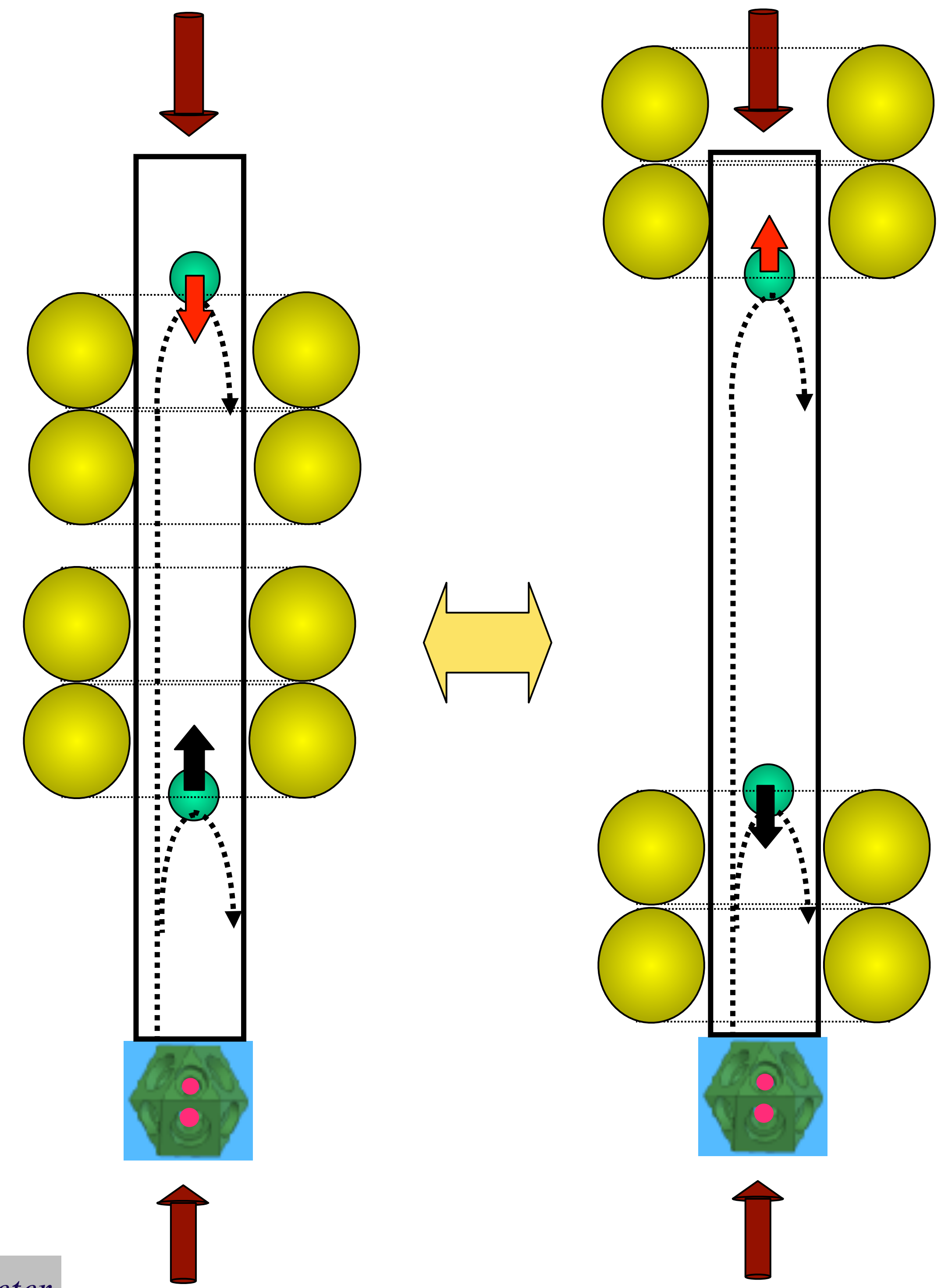
$$\Delta g = 120\,\mu Gal$$

Differential gravity sensitivity:

$$\sigma_{\Delta g} = 0.01\,\mu Gal @ 10^4\,s$$

Project target

$$\delta G / G \sim 100\text{ppm}$$



Xiao-Chun Duan et al., *Operating an atom-interferometry-based gravity gradiometer by the dual-fringe-locking method*, Phys. Rev. A 90, 023617 (2014)

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

MEGANTE

Principal investigator:

Gabriele Rosi

Budget: 1.55 ME for 5 years

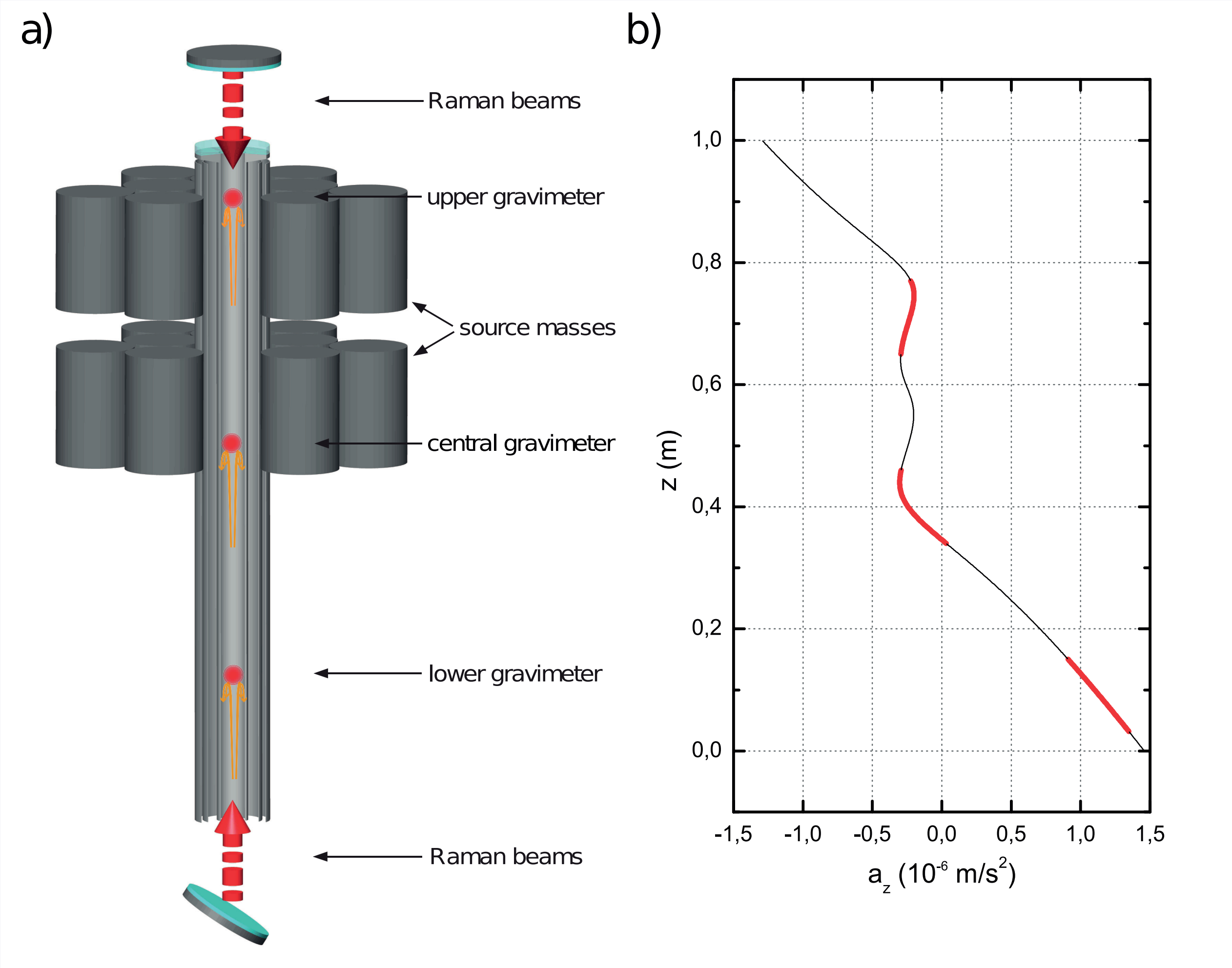
Host Institution:

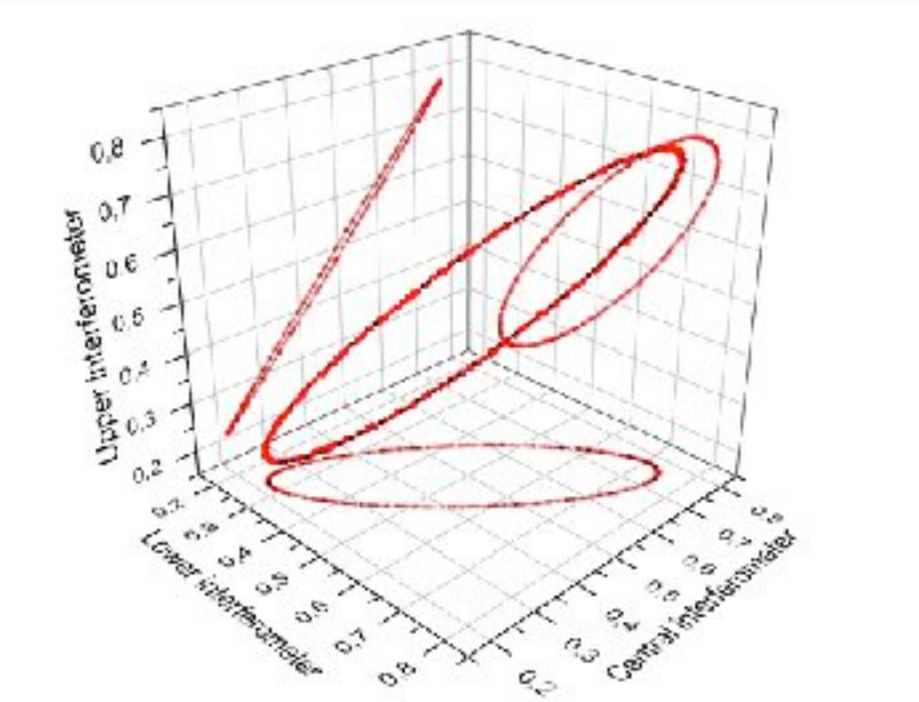
INFN

Firenze Division

<u>A unique apparatus for precision measurements of G with cold atom towards the solution of puzzle</u>

Measurement of the Gravity-Field Curvature by Atom Interferometry

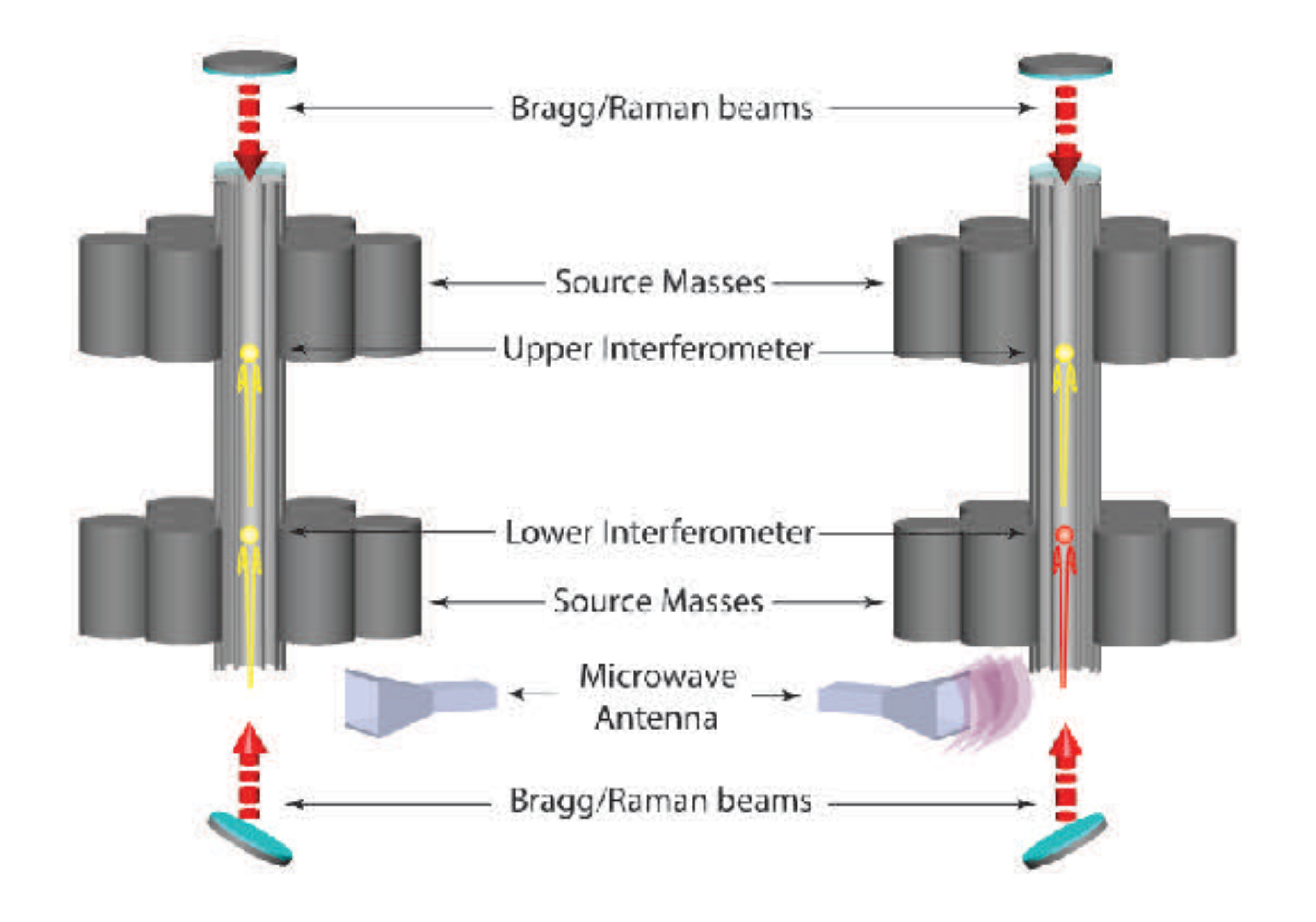




$$x(\theta) = A + B\sin\theta,$$
$$y(\theta) = C + D\sin(\theta + \varphi_1),$$
$$z(\theta) = E + F\sin(\theta + \varphi_1 + \varphi_2)$$

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



$$|1\rangle = |F=1, m_F=0\rangle \qquad a_1 = g\langle 1|\hat{M}_\mathrm{g}\hat{M}_\mathrm{i}^{-1}|1\rangle = gr_1$$

$$|2\rangle = |F=2, m_F=0\rangle \qquad a_2 = g\langle 2|\hat{M}_\mathrm{g}\hat{M}_\mathrm{i}^{-1}|2\rangle = gr_2$$

$$|\mathrm{s}\rangle = \left(|1\rangle + e^{i\gamma}|2\rangle\right)/\sqrt{2} \qquad a_s = g\langle \mathrm{s}|\hat{M}_\mathrm{g}\hat{M}_\mathrm{i}^{-1}|\mathrm{s}\rangle = g\left[\frac{r_1+r_2}{2} + |r|\cos(\varphi_r+\gamma)\right]$$

G. Rosi, G. D'Amico, L. Cacciapuoti, F. Sorrentino, M. Prevedelli, M. Zych, C. Brukner, G.M. Tino *Quantum test of the equivalence principle for atoms in coherent superposition of internal energy states,* **Nature Commun. 8, 15529 (2017)**

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

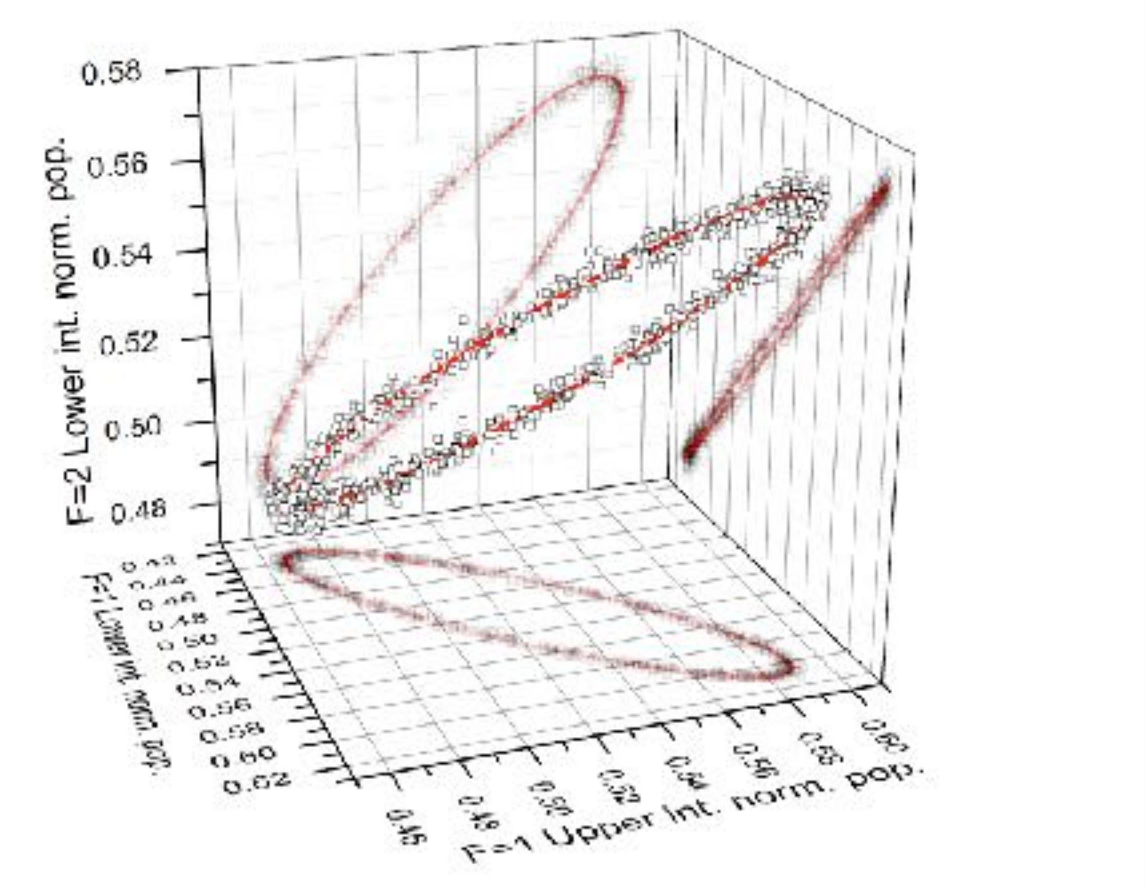


Table 1 | Measurement systematics.

Effect	**Uncertainty on $\delta g/g(\times 10^{-9})$**
Second order Zeeman shift	0.6
AC Stark shift	2.6
Ellipse fitting	0.3
Other effects	<0.1

Main error contributions affecting the differential acceleration measurement.

$$\eta_{1-2} = (1.0 \pm 1.4) \cdot 10^{-9}$$

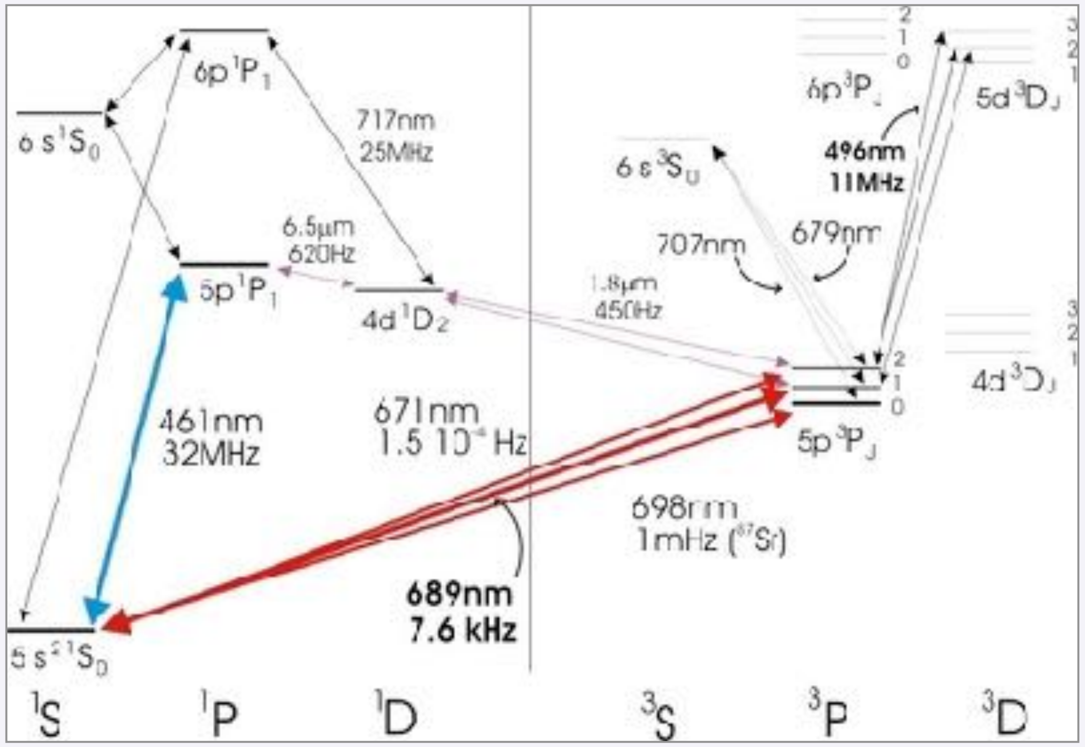
$$|\mathbf{r_1} - \mathbf{r_2}| \leq \mathbf{10^{-9}}$$

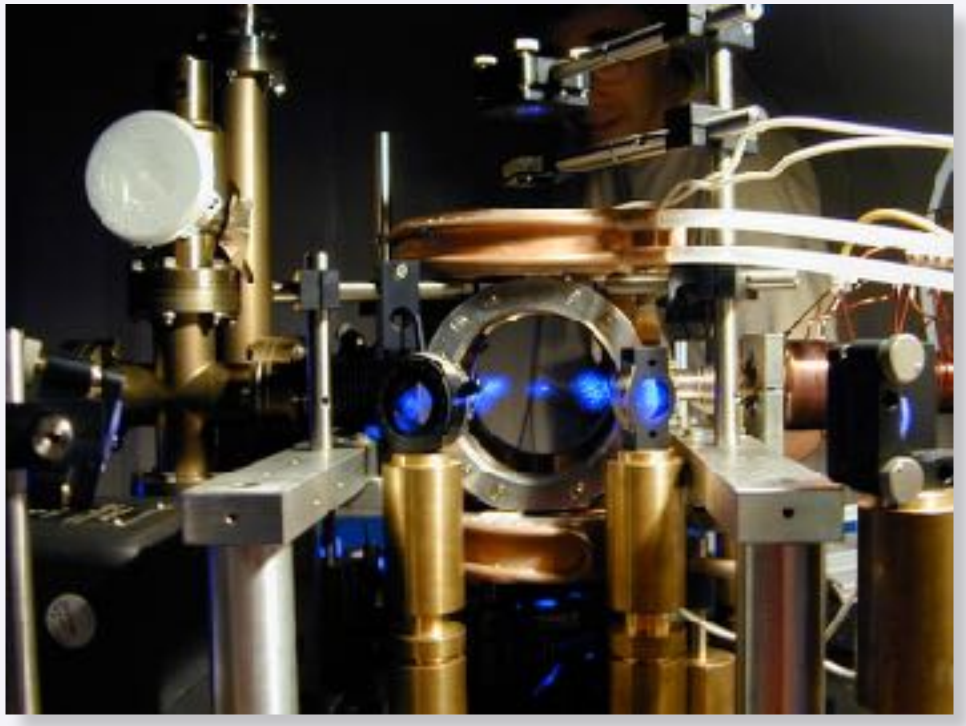
$$\eta_{1-\mathrm{s}} = (3.3 \pm 2.9) \cdot 10^{-9}$$

$$|\mathbf{r}| \leq \mathbf{5 \cdot 10^{-8}}$$

G. Rosi, G. D'Amico, L. Cacciapuoti, F. Sorrentino, M. Prevedelli, M. Zych, C. Brukner, G.M. Tino *Quantum test of the equivalence principle for atoms in coherent superposition of internal energy states,* **Nature Commun. 8, 15529 (2017)**

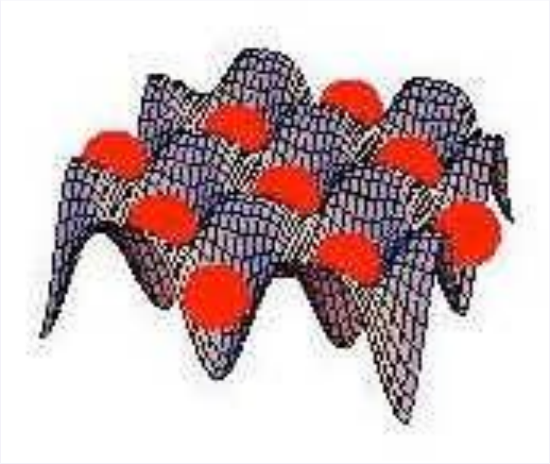
Ultracold Sr - Experiments in Firenze

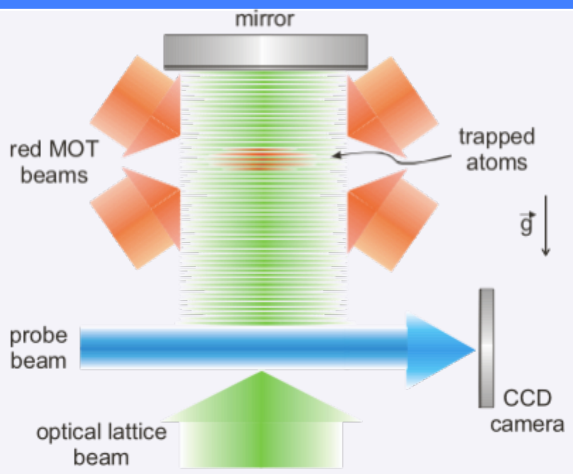




- Optical clocks using visible intercombination lines

- 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)

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)

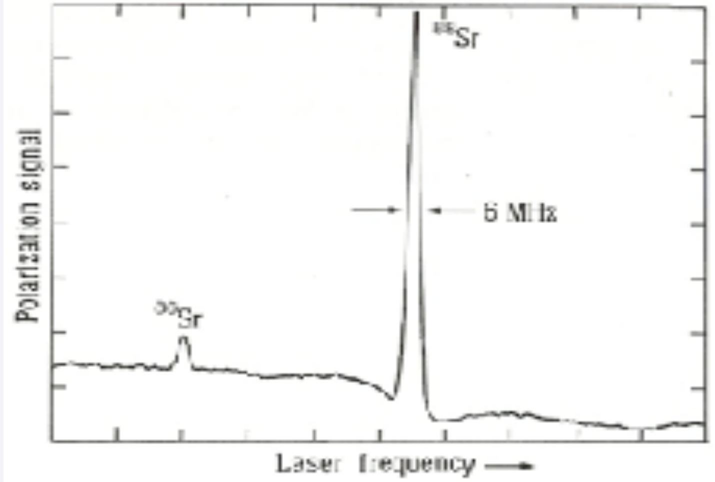
G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale*, Phys. Rev. Lett. 97, 060402 (2006)

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 -> 1 intercombination line

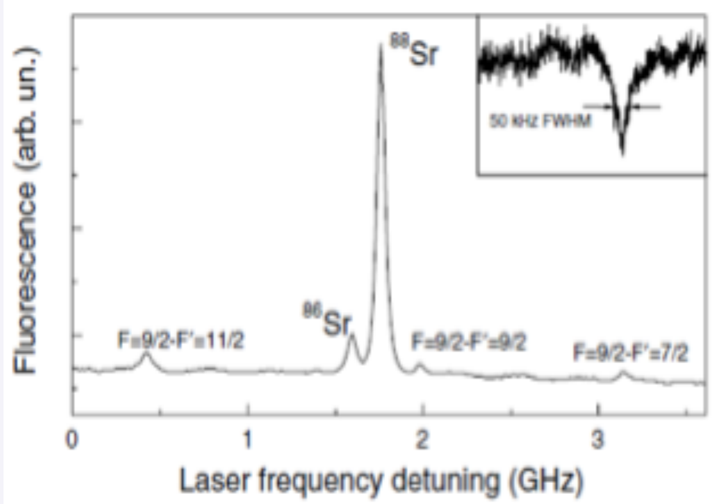


G.M. Tino, M. Barsanti, M. de Angelis, L. Gianfrani, M. Inguscio, *Spectroscopy of the 689 nm intercombination line of strontium using an extended cavity InGaP/InGaAlP diode laser*, Appl. Phys. B 55, 397 (1992)

2003

saturation spectroscopy of Sr in a thermal atomic beam

0 -> 1 intercombination line

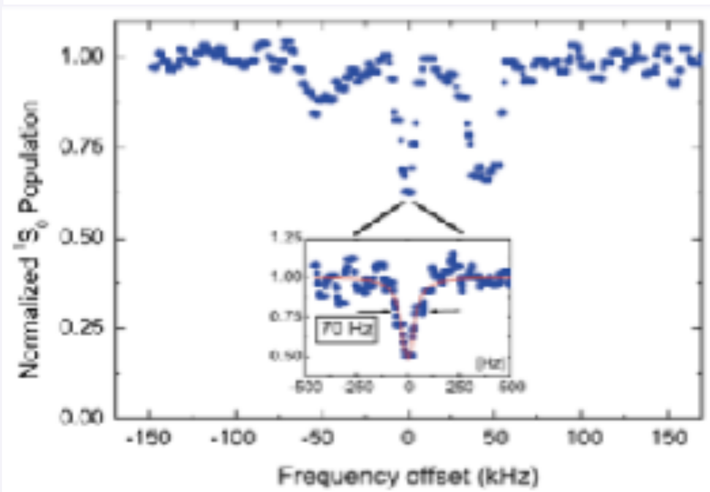


G. Ferrari, P. Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

2009

Magnetic field induced spectroscopy of cold Sr atoms in an optical lattice

0 -> 0 intercombination line

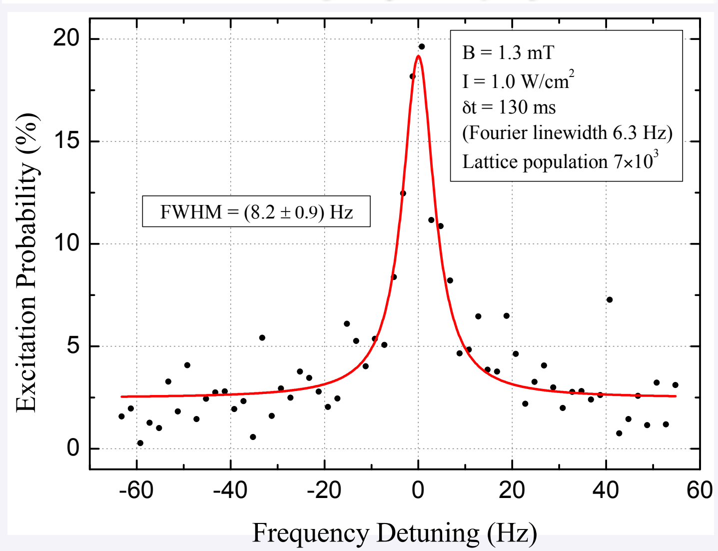


N. Poli, M.G. Tarallo, M. Schioppo, C.W. Oates, G.M. Tino, *A simplified optical lattice clock*, Appl. Phys. B 97, 27 (2009)

2012

Magnetic field induced spectroscopy of cold Sr atoms in an optical lattice

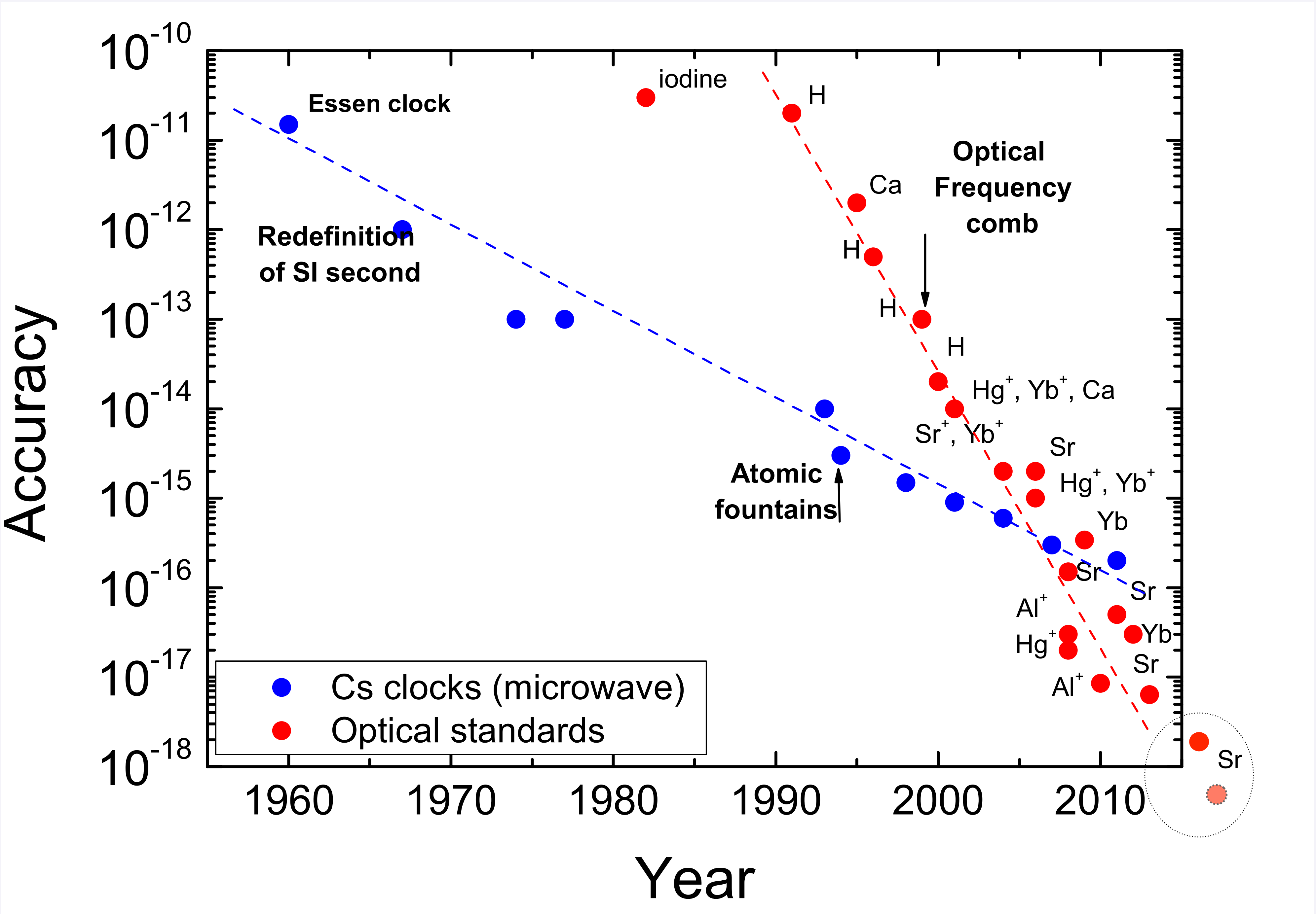
0 -> 0 intercombination line



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)

N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks,* Riv. Nuovo Cim. 36, n.12 (2013) arXiv:1401.2378

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

Towards BEC of Sr

2000: ^{88}Sr at phase-space density = 0.1

RAPID COMMUNICATIONS

PHYSICAL REVIEW A, VOLUME 61, 061403(R)

Optical-dipole trapping of Sr atoms at a high phase-space density

Tetsuya Ido,[1] Yoshitomo Isoya,[1] and Hidetoshi Katori[1,2]

2006: ^{88}Sr/^{86}Sr mixture (optical-sympathetic cooling + evaporative cooling) → phase-space density = 0.2

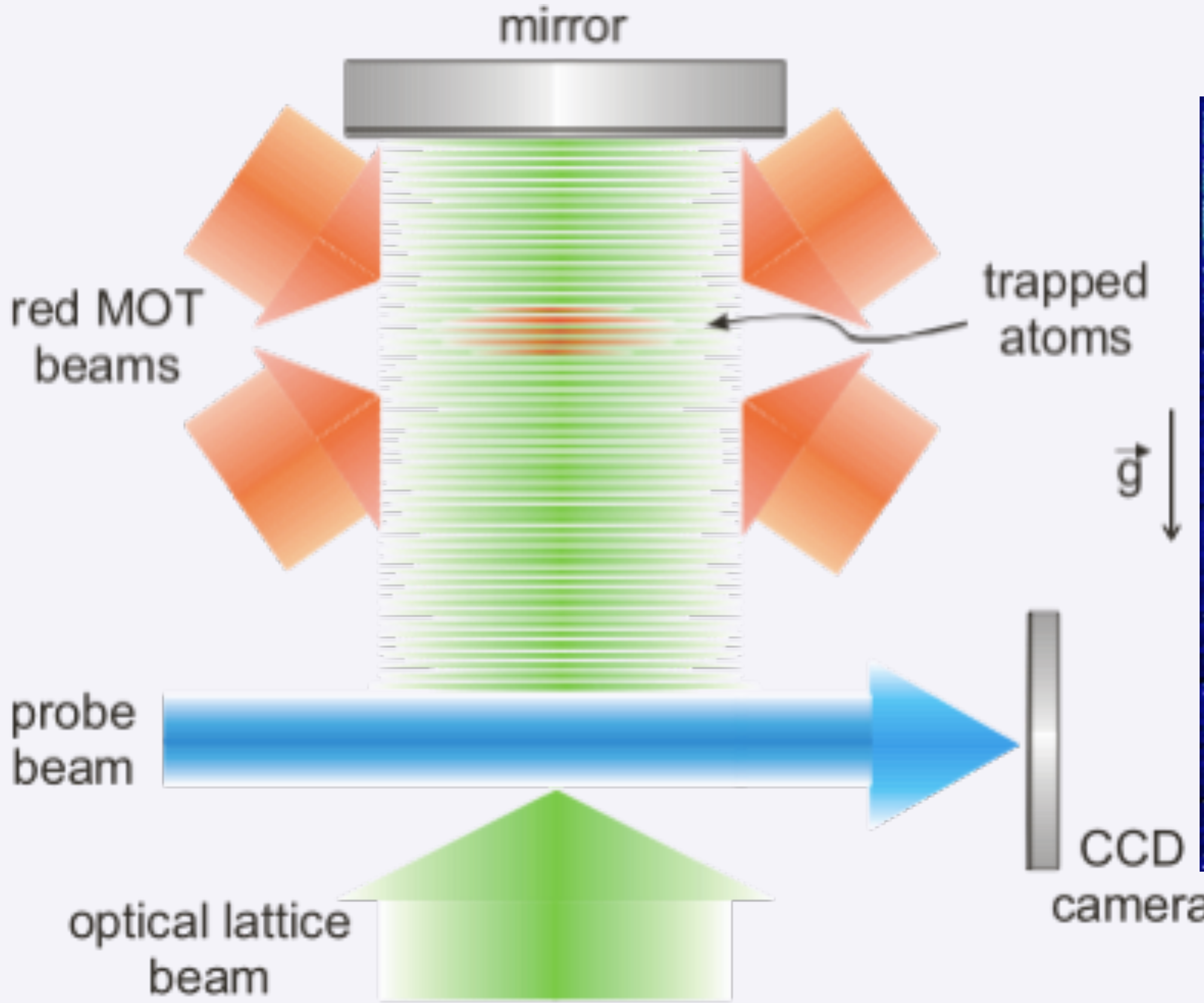
Modern Physics Letters B, Vol. 20, No. 21 (2006) 1287–1320

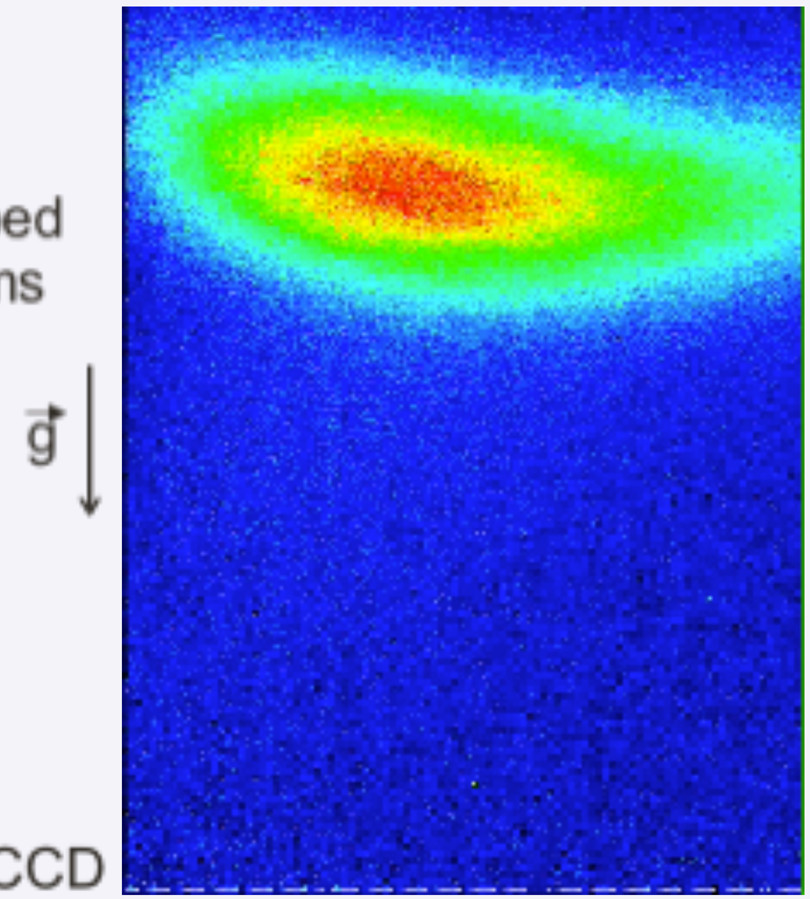
World Scientific
www.worldscientific.com

LASER COOLING AND TRAPPING OF ATOMIC STRONTIUM FOR ULTRACOLD ATOMS PHYSICS, HIGH-PRECISION SPECTROSCOPY AND QUANTUM SENSORS

F. SORRENTINO, G. FERRARI, N. POLI, R. DRULLINGER* and G. M. TINO†

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





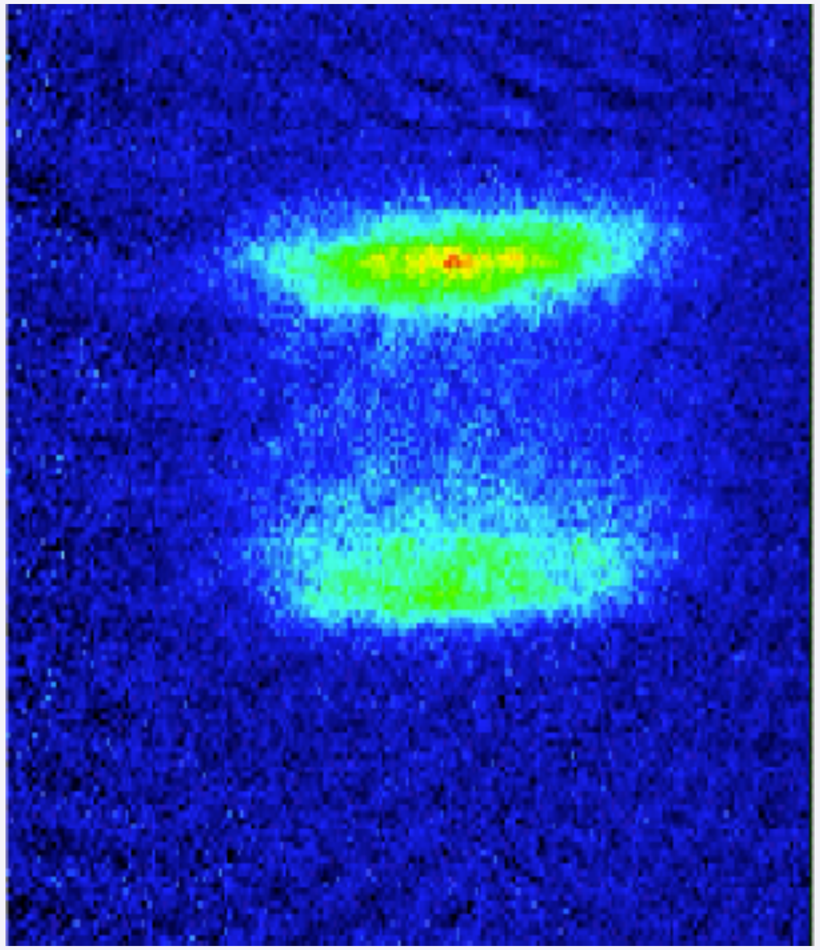
$$\nu = m\, g\, \lambda / 2\, h$$

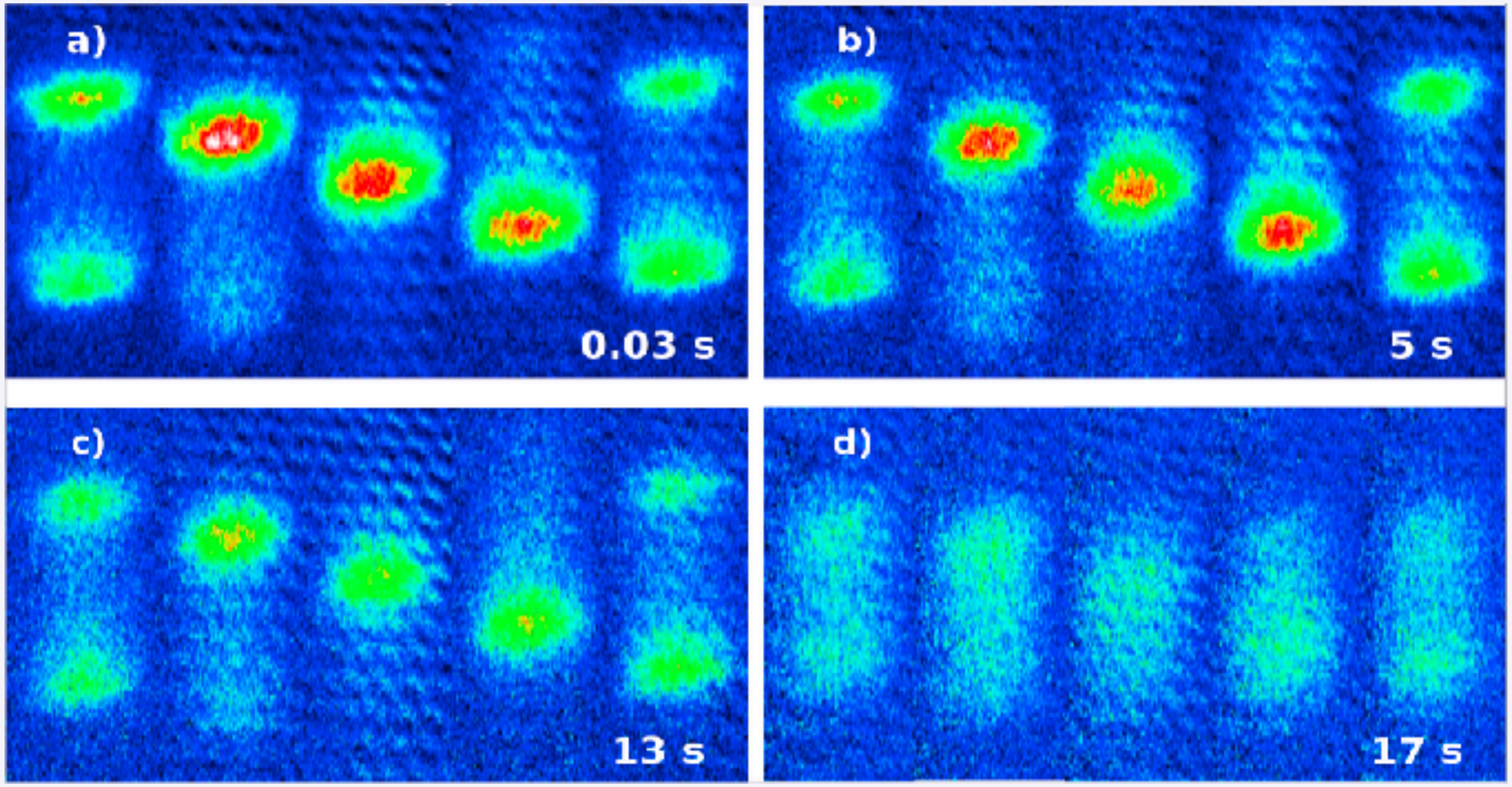
G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* **Phys. Rev. Lett. <u>97</u>, 060402 (2006)**

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)**

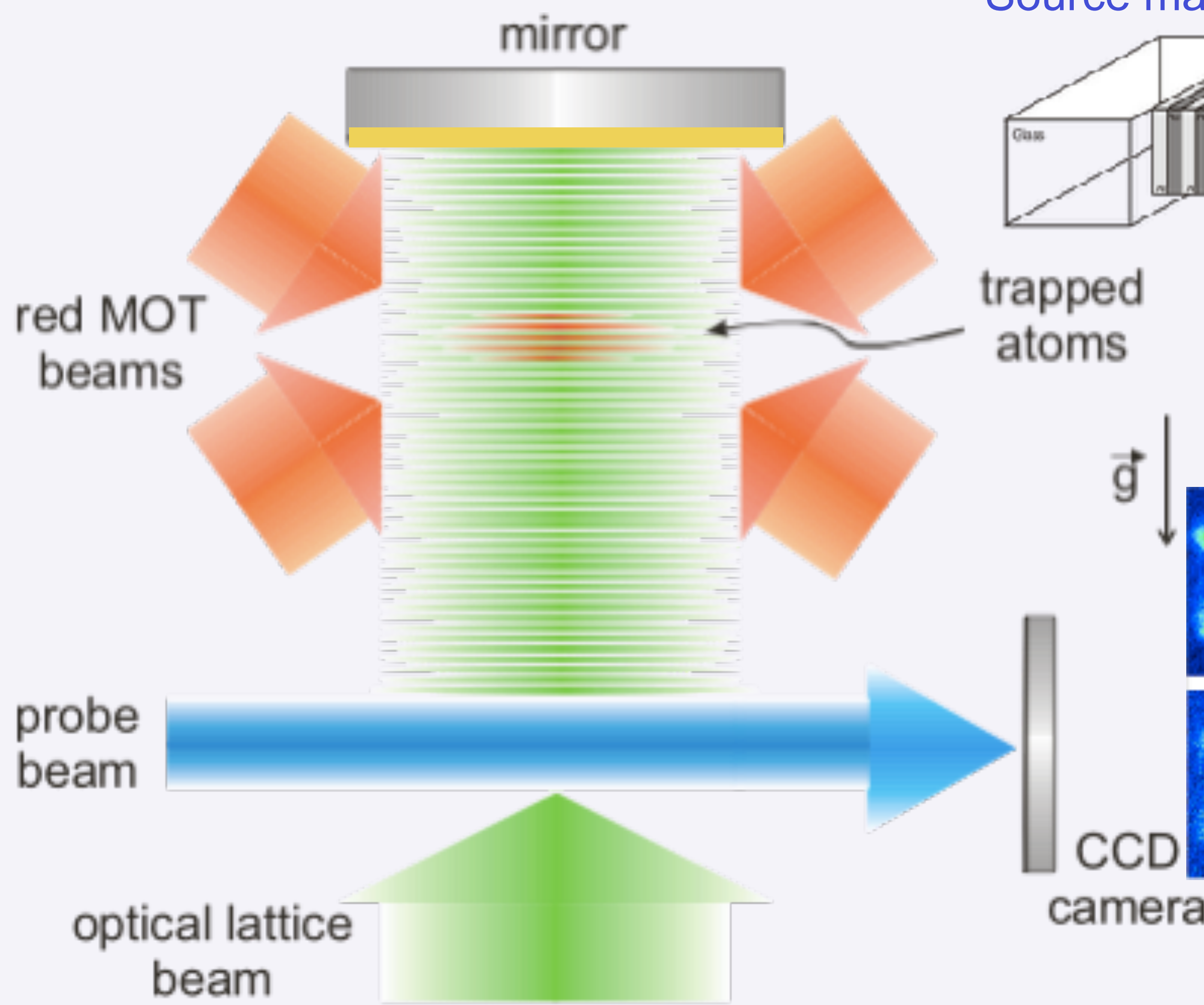
Bloch oscillations of ^{88}Sr atoms

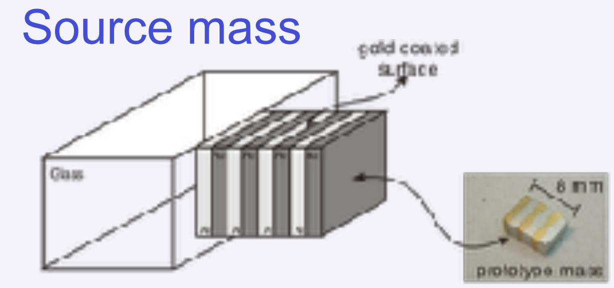


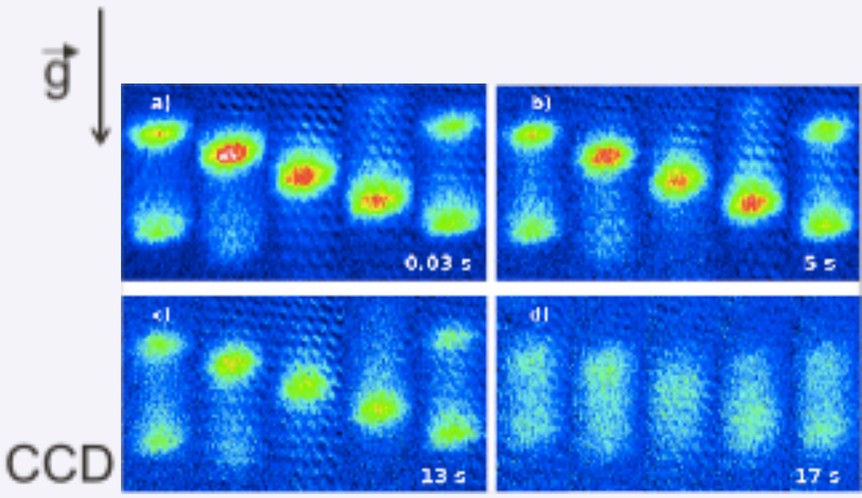


N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,
Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter,
Phys. Rev. Lett. 106, 038501 (2011)

Scheme for the measurement of small distance forces







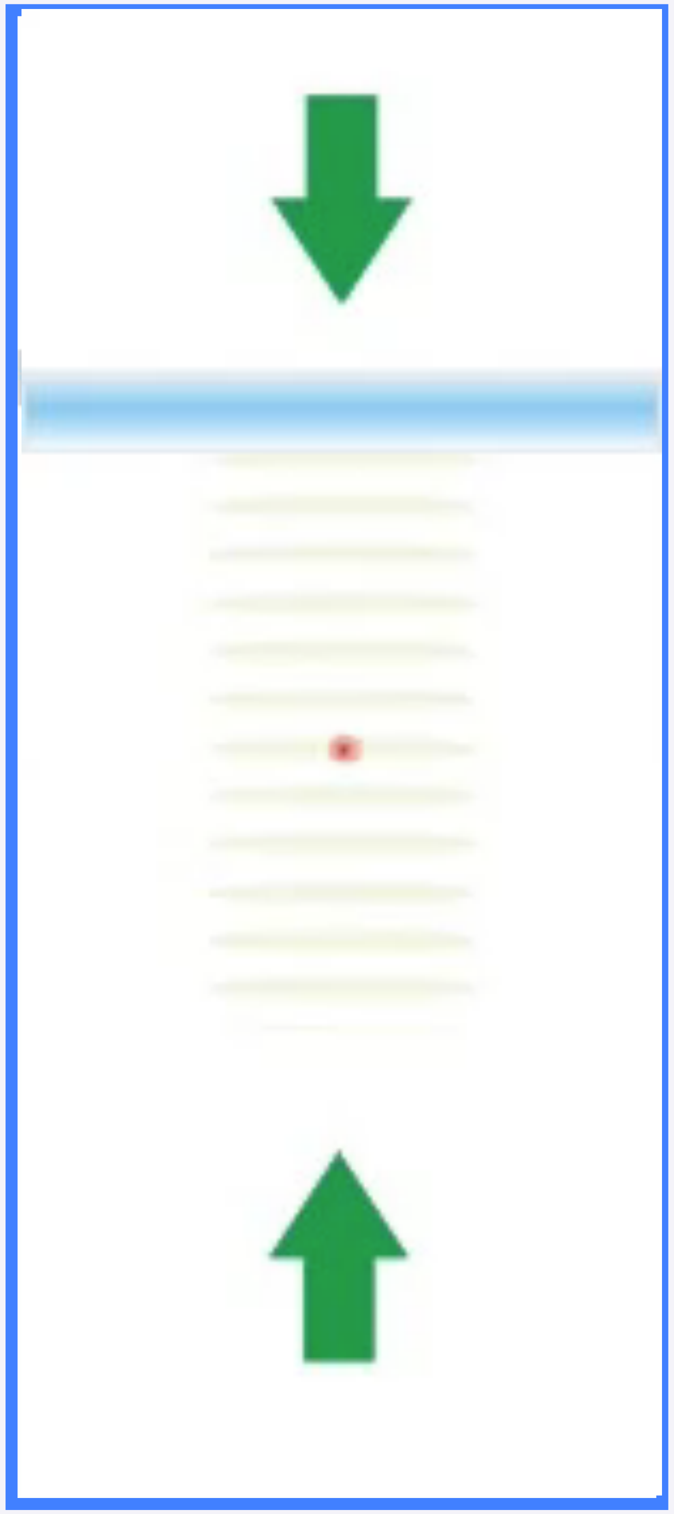
$\nu = m\, g\, \lambda /2\, h$

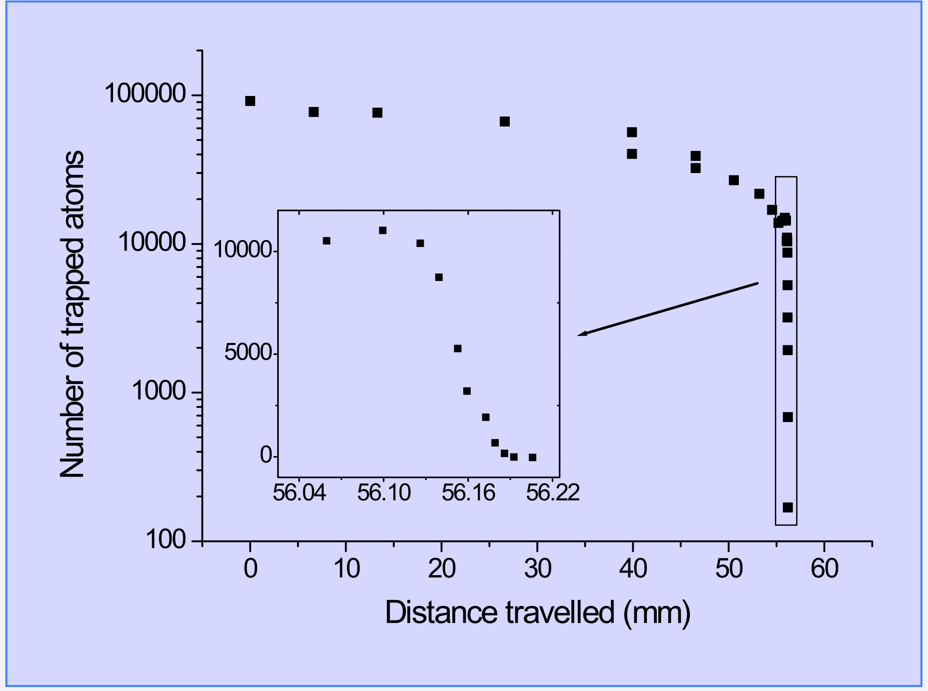
$\nu = m\, a\, \lambda /2\, h$

Objective: λ ***= 1-10*** **μ*m*****,** α ***= 10³-10⁴***

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* μ*m*, **Phys. Rev. A 79, 013409 (2009)**

Scheme for the measurement of small distance forces



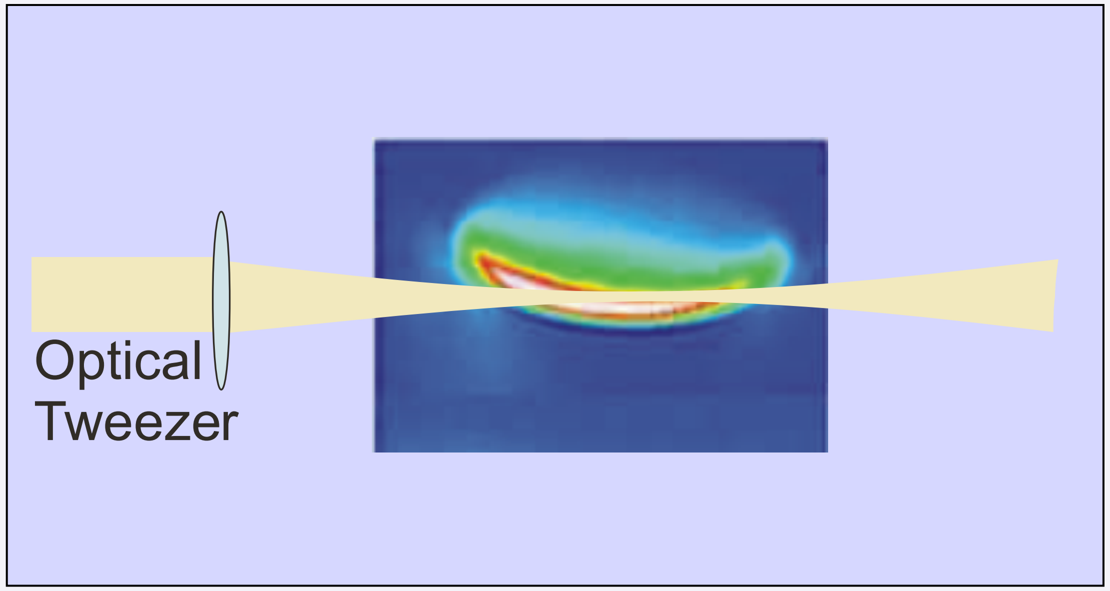


Vertical size of the atomic sample: 15 μm

Atom elevator:

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

Vertical position fluctuations: 3 μm rms



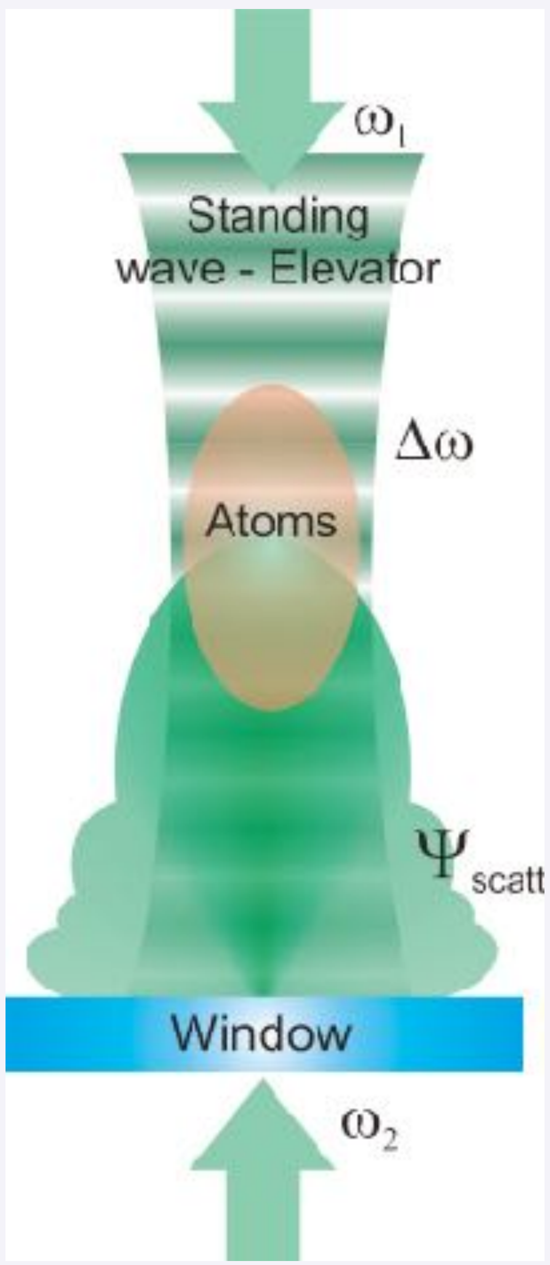
- **Vertical size reduced to 4 μm with an optical tweezer**

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)**

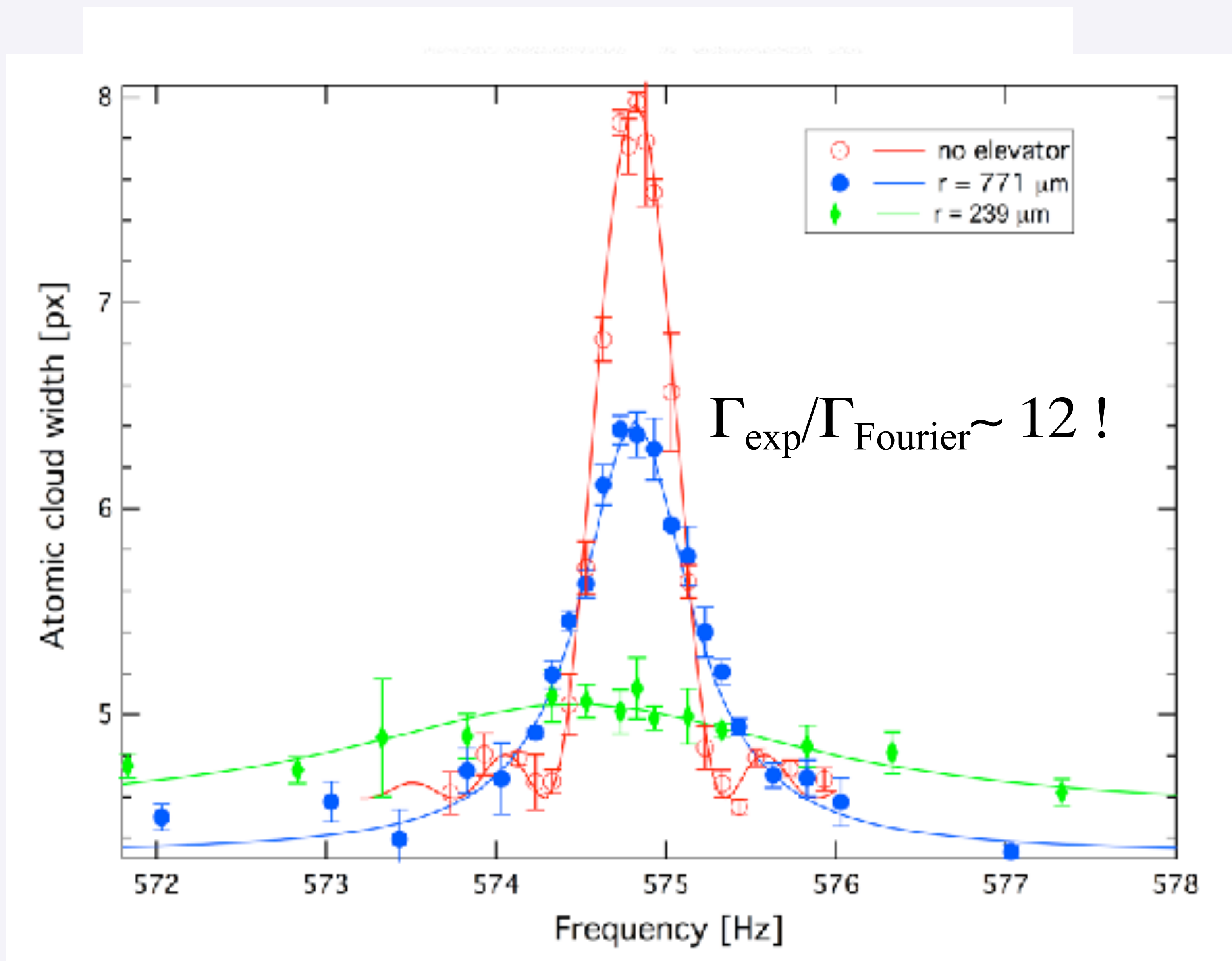
Short-distance measurements

- **Optical elevator** to bring atoms close to a sample surface: trying to measure Casimir-Polder force

⇒ AM measurement close to the surface (preliminary)



Getting closer:



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:

^{88}Sr

- **Total spin = 0**
- **Boson**

^{87}Sr

- **Total spin ≡ nuclear spin I = 9/2**
- **Fermion**

Comparison of the acceleration of ^{88}Sr and ^{87}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)**

Search for spin-gravity coupling

We consider possible EEP violation due to **spin-gravity coupling** generated by a gravitational potential of the form

$$V_{g,A}(z) = (1 + \beta_A + kS_z) m_A g z$$

m_A is the rest mass of the atom

S_z is the projection of the spin along gravity direction

k is the model-dependent spin-gravity coupling strength

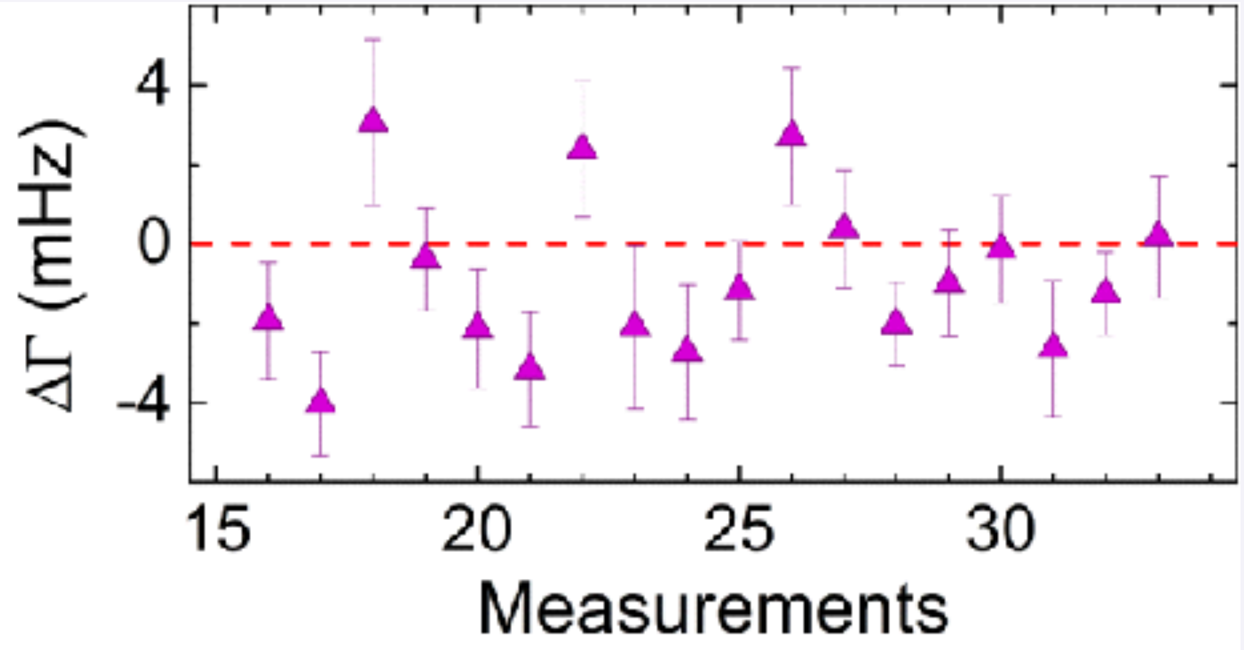
Each ^{87}Sr spin component $S_z = I_z$ will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

Deviations $\Delta\Gamma$ of measured linewidth from Fourier linewidth, corrected by systematics (two-body collisions, residual magnetic field)

→ Upper limit on spin-gravity coupling k

$$\Delta\Gamma = 2 I_{87} k l v_{87}$$

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



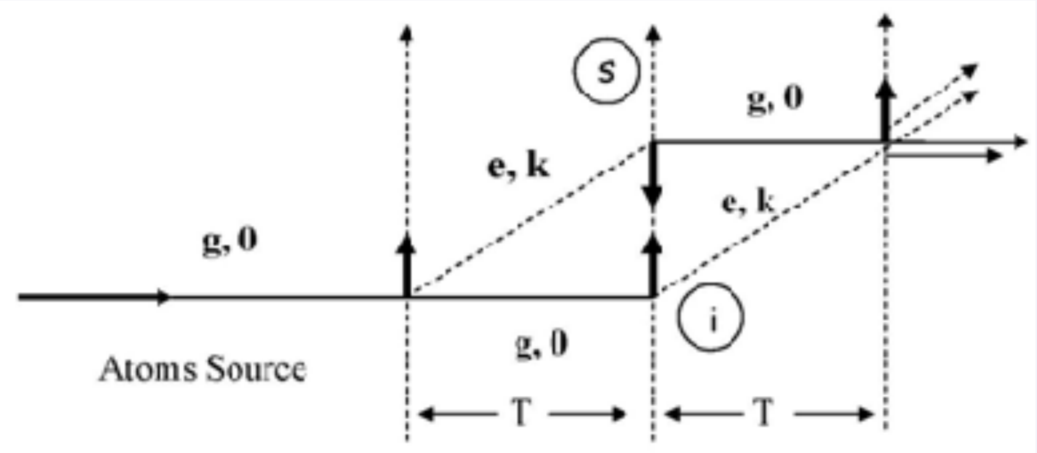
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects*, **Phys. Rev. Lett. 113, 023005 (2014)**

From table-top experiments to large-scale detectors

Gravitational wave detection with atom interferometry

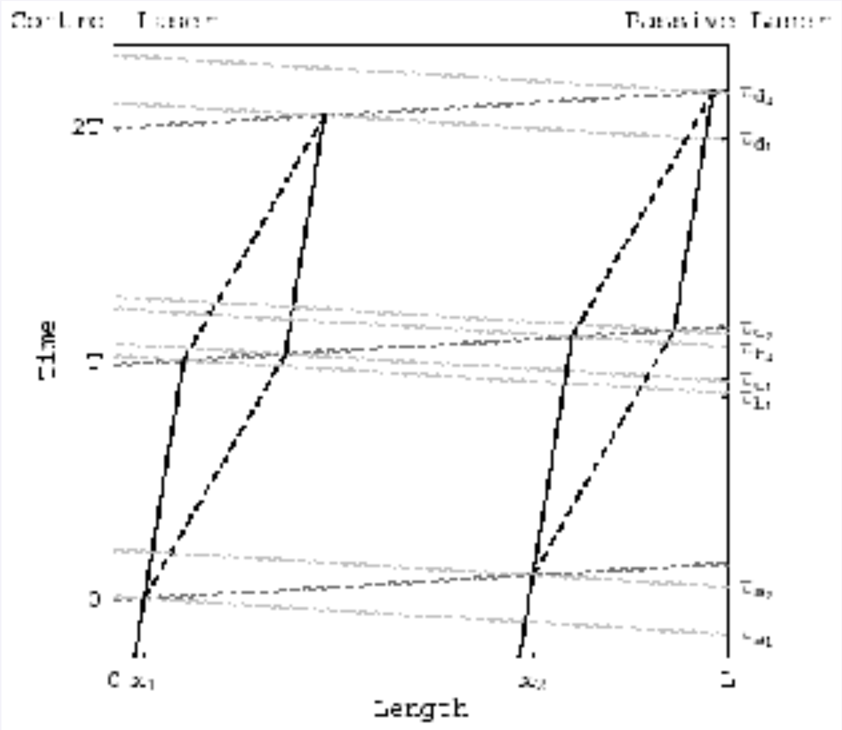
- *Single atom interferometer*

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

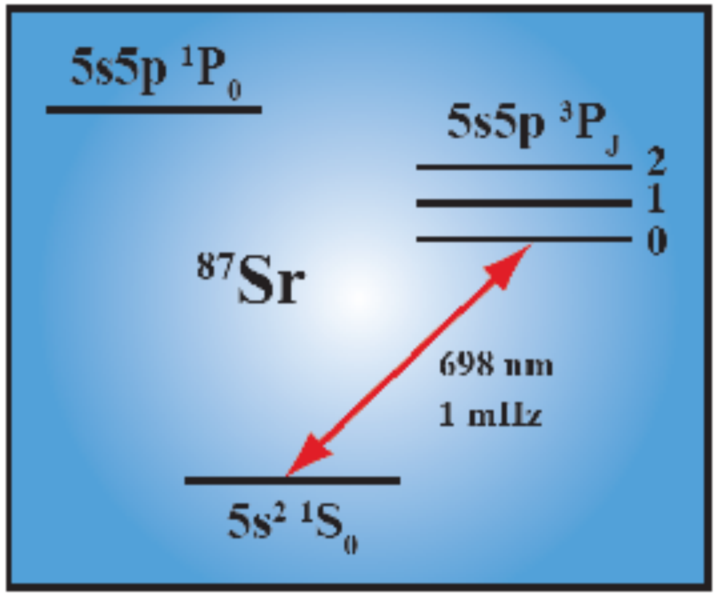


- *Differential scheme*

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



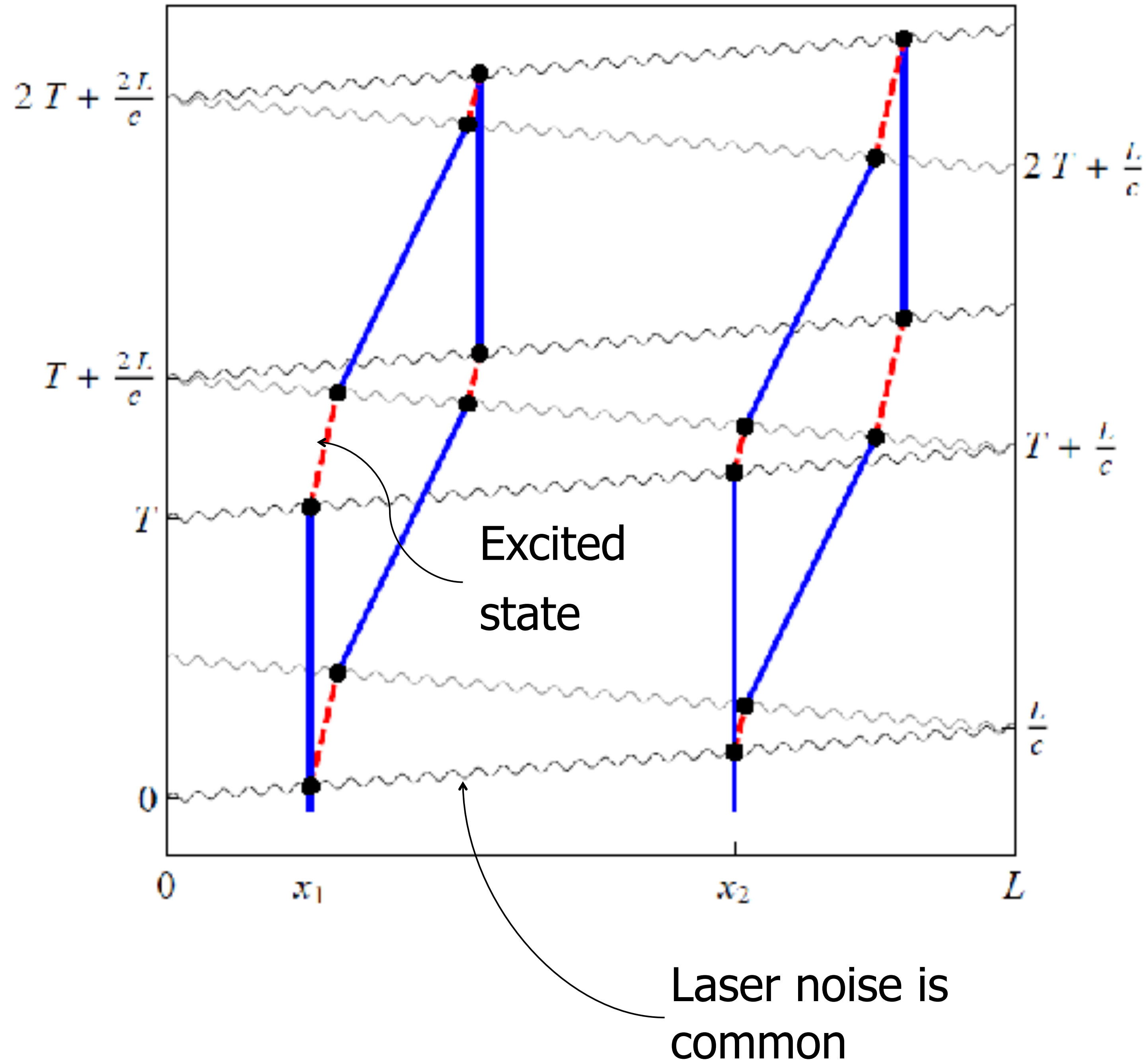
Laser frequency noise insensitive detector



Clock transition in candidate atom ^{87}Sr

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

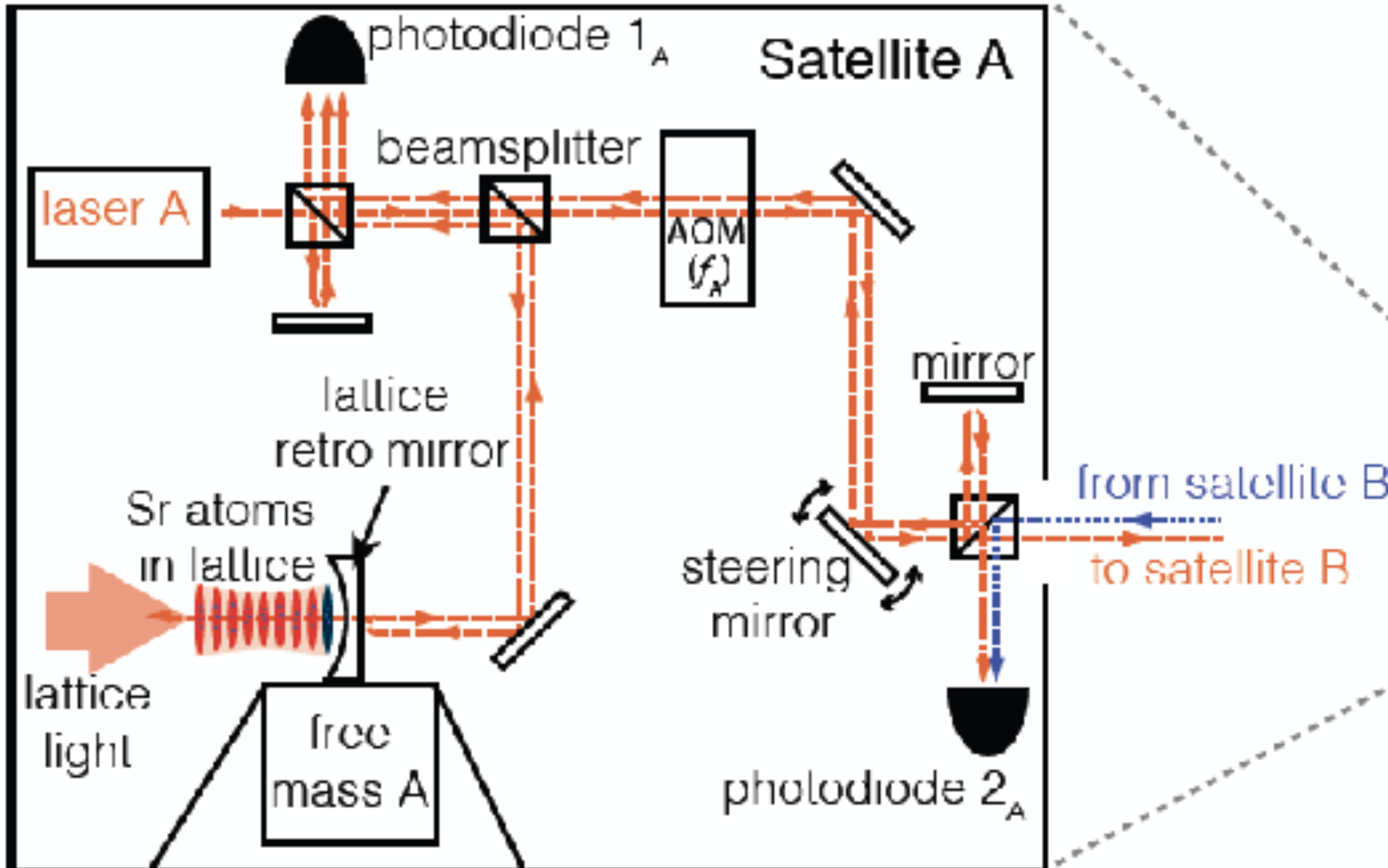
Enables 2 satellite configurations

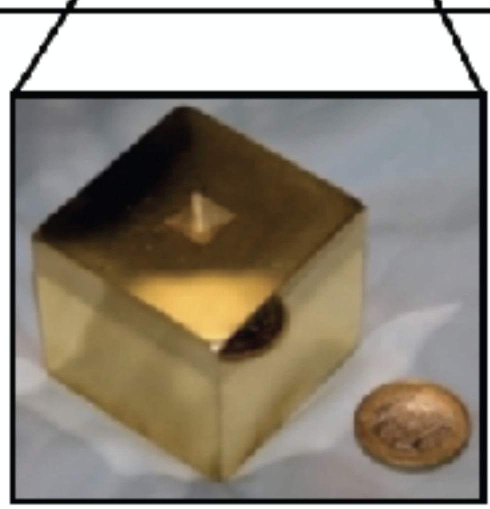


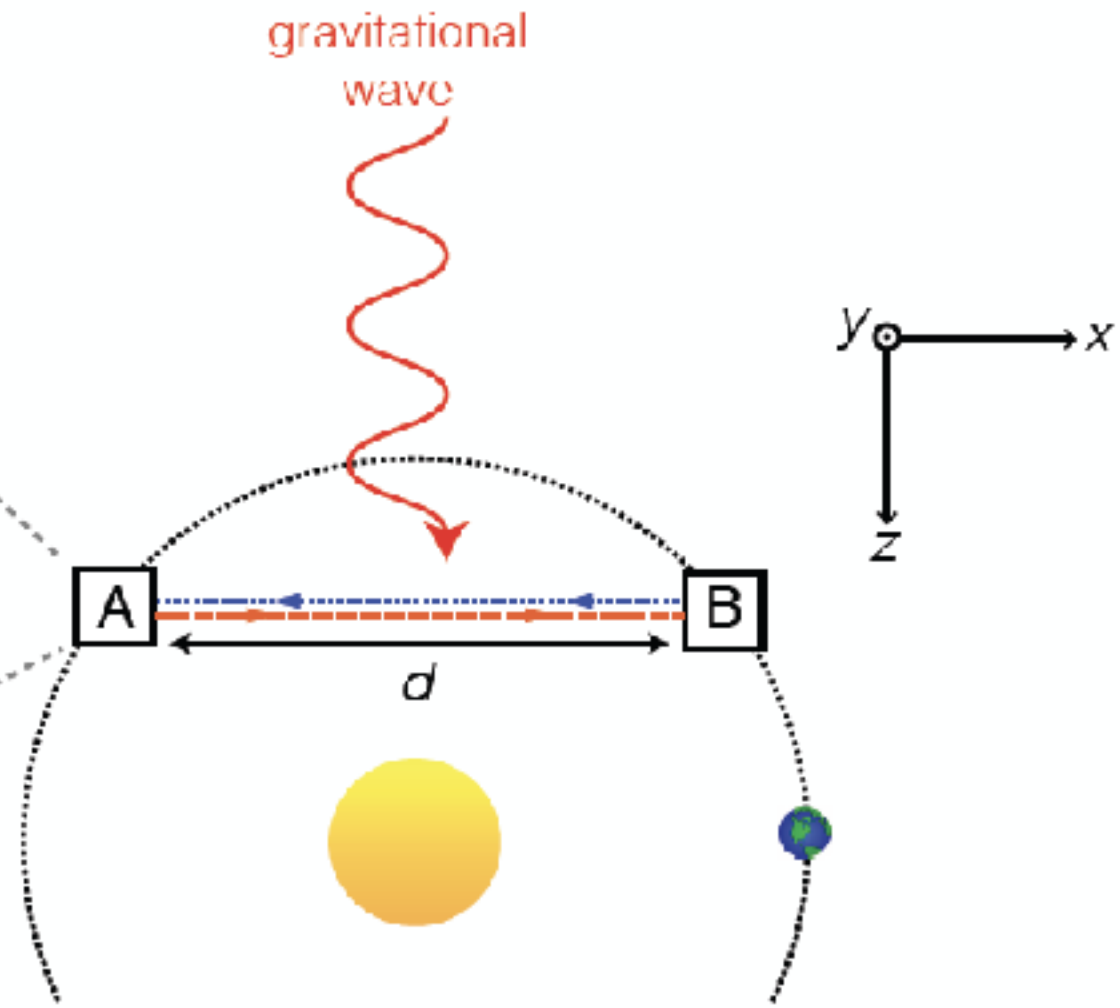
from M. Kasevich
STANFORD UNIVERSITY

Graham, et al., arXiv:1206.0818, PRL (2013)

Gravitational wave detection with clocks







$$\sigma(\tau) = \left.\frac{\delta\nu}{\nu_o}\right|_{\tau} = \frac{\sqrt{\Delta_A}}{\nu_o\sqrt{2\pi\tau N}}$$

from J. Ye

S. Kolkowitz, I. Pikovski, N. Langellier, M.D. Lukin, R.L. Walsworth, J. Ye,
Gravitational wave detection with optical lattice atomic clocks, Phys. Rev. D 94, 124043 (2016)

Proposal title

SPACE ATOMIC GRAVITY EXPLORER

Acronym

SAGE

Lead Proposer

Prof. Guglielmo M. Tino

PRIMARY GOAL:

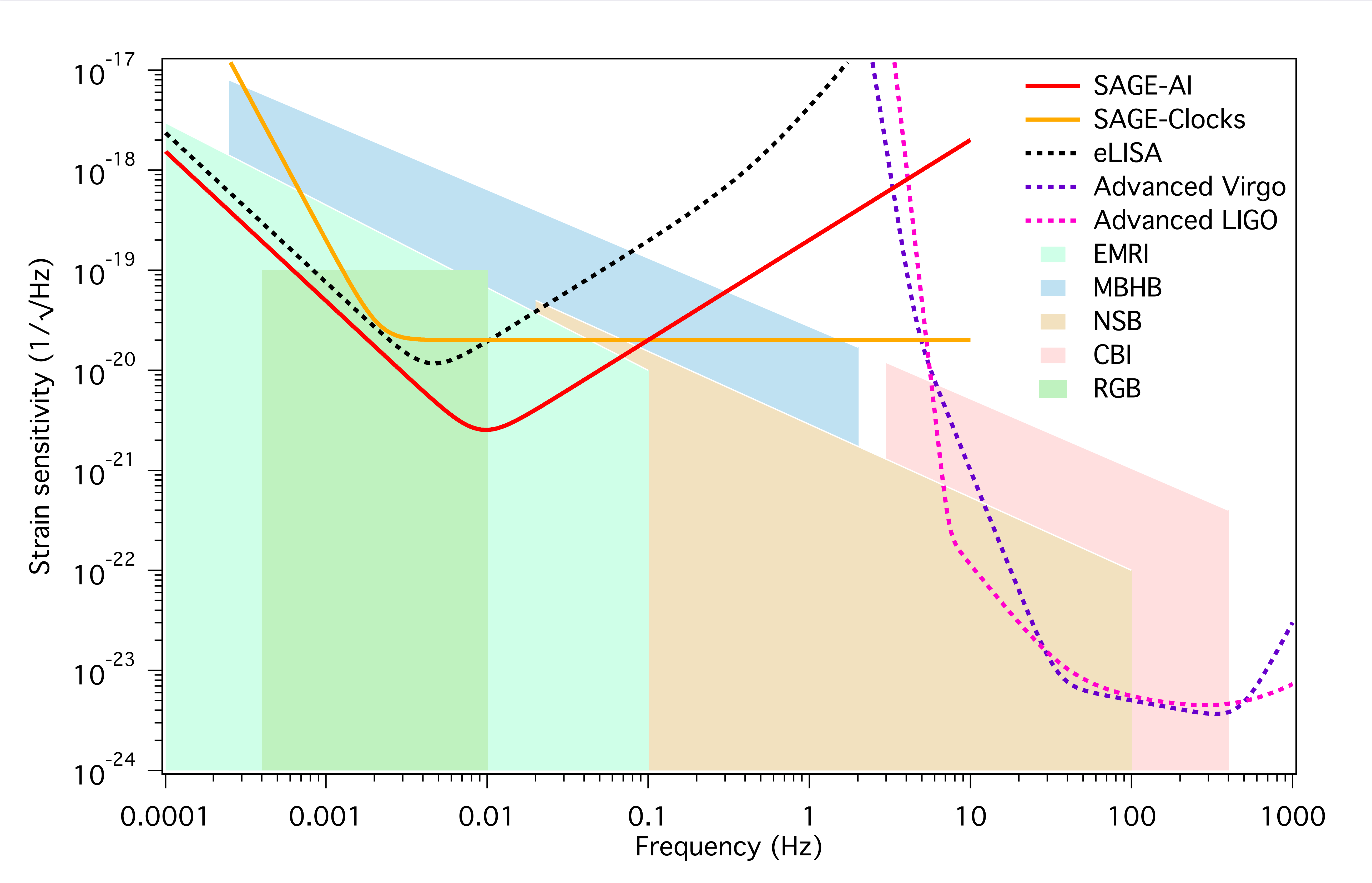
- Observe Gravitational Waves in new frequency ranges with atomic sensors.

SECONDARY GOALS:

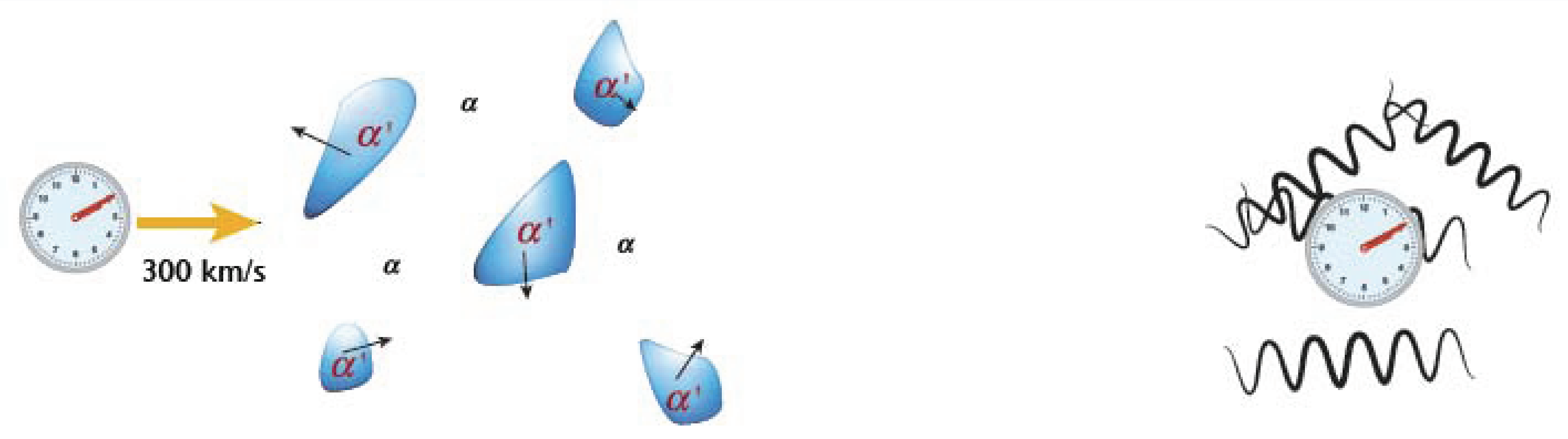
- Search for Dark-Matter
- Measure the Gravitational Red Shift
- Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
- Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
- Investigate quantum correlations and test Bell inequalities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

September 13, 2016

SAGE: GW detection



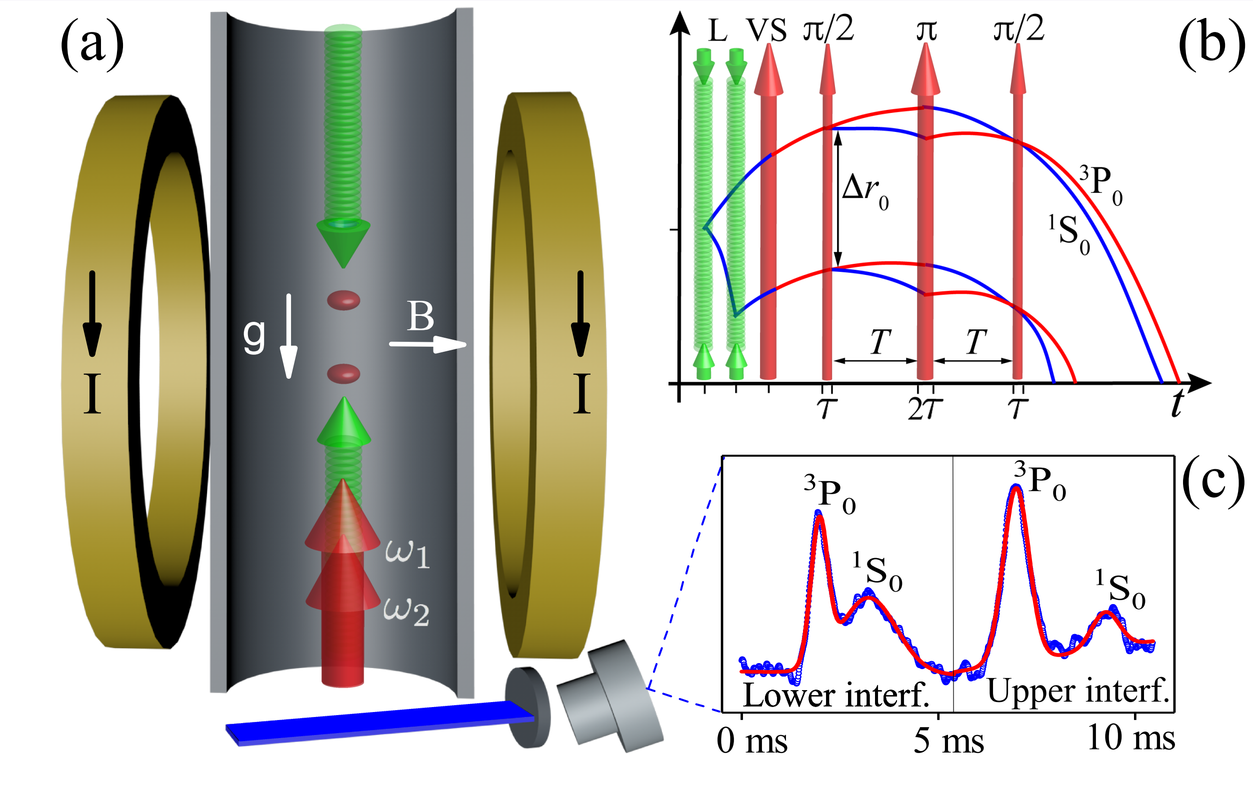
SAGE: Search for Dark-Matter

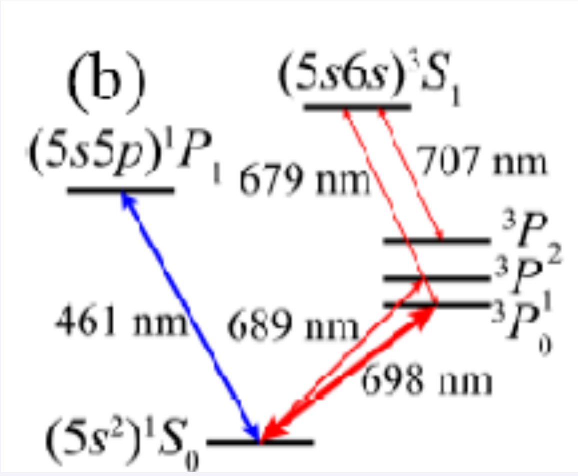


(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A.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

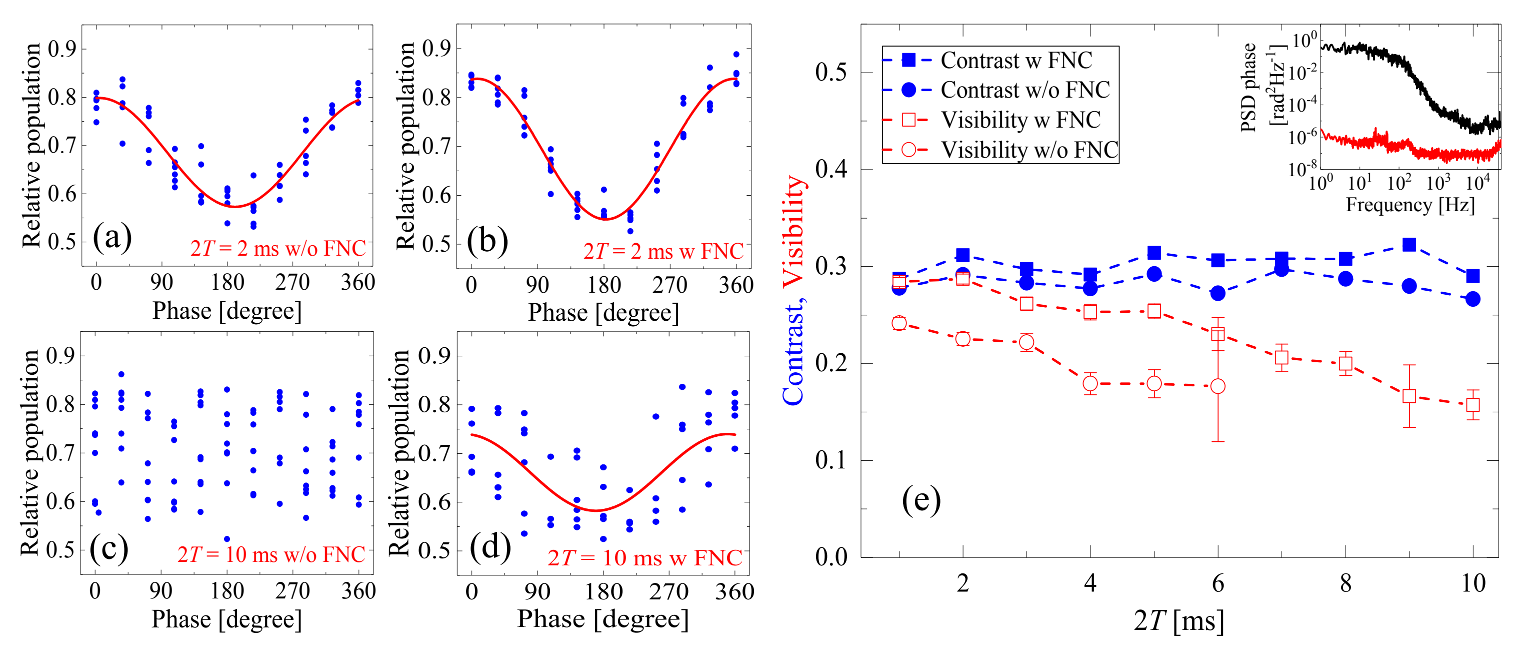
(Right) Ultralight fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [A. Arvanitaki, J. Huang, and K. Van Tilburg.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

Atom interferometry with the Sr optical clock transition





- ^{88}Sr isotope
- B=300 G -> Δν=20 μHz
- Rabi frequency Ω ~ 1kHz



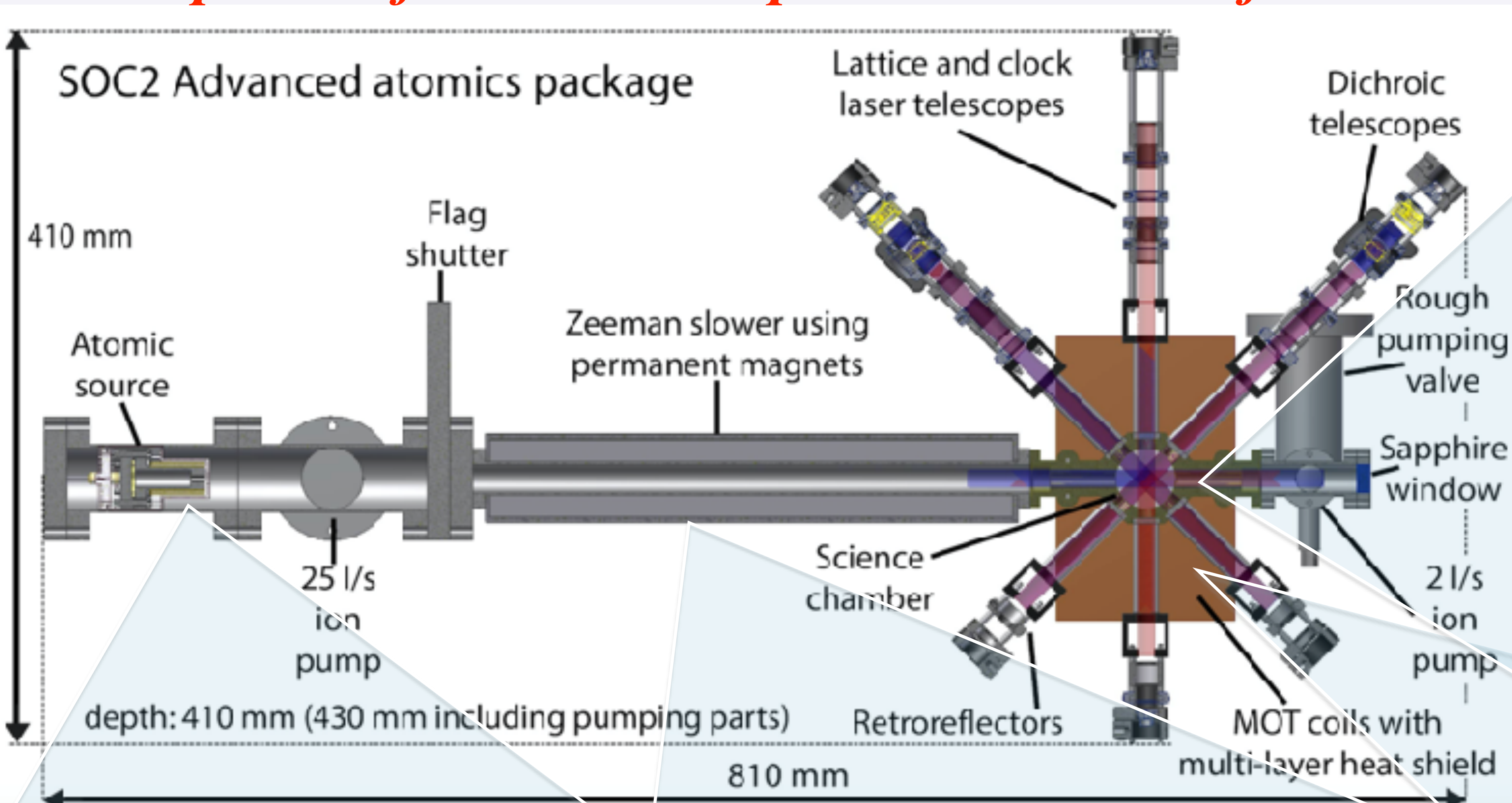
Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]

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]

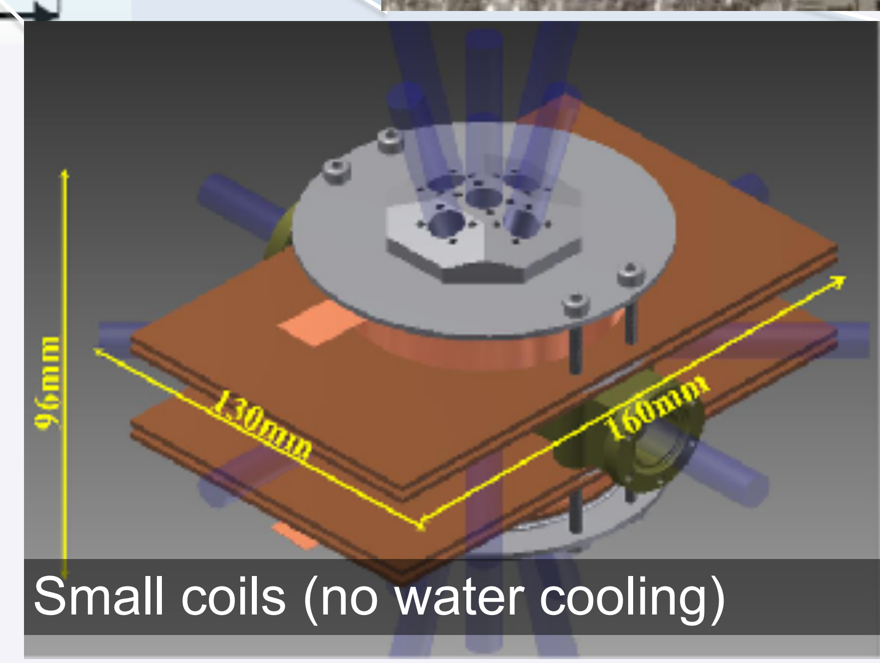
Development of a strontium optical lattice clock for the SOC mission on the ISS



Vacuum chamber


Low power (20W) atomic oven

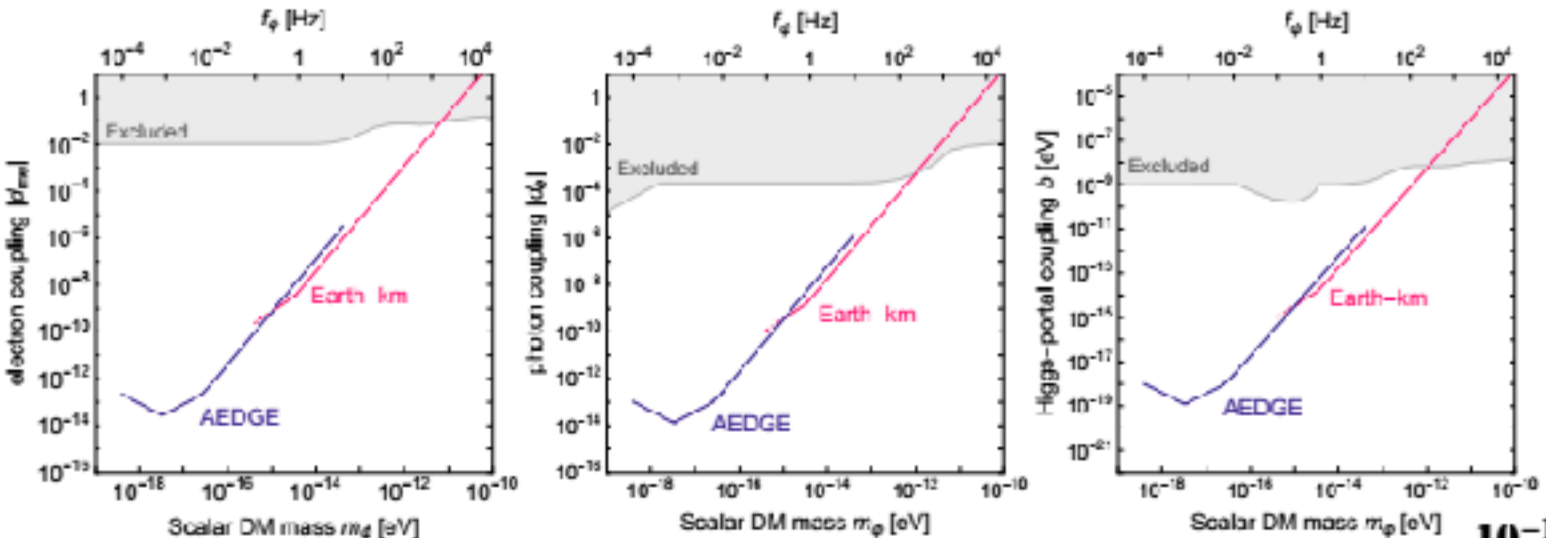
Permanent-magnets Zeeman slower



Small coils (no water cooling)

K. Bongs et al., *Development of a strontium optical lattice clock for the SOC mission on the ISS,* **C. R. Physique 16, 553–564 (2015)**

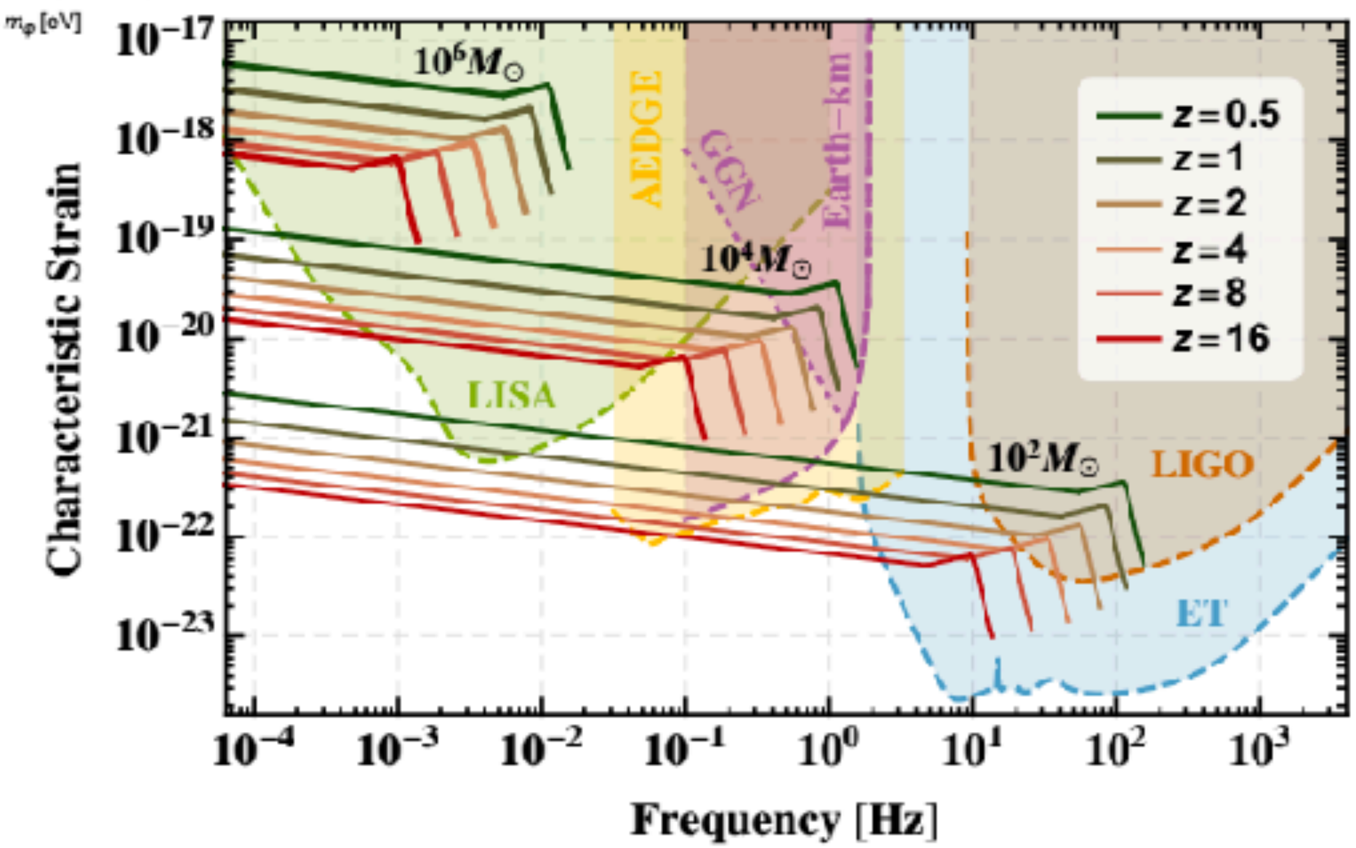
Atomic Experiment for Dark Matter and Gravity Exploration -- AEDGE



Currently preparing a White Paper for the ESA Voyager 2050 call:
https://www.cosmos.esa.int/web/voyage-2050
[Deadline August 8]
Focus on physics case!

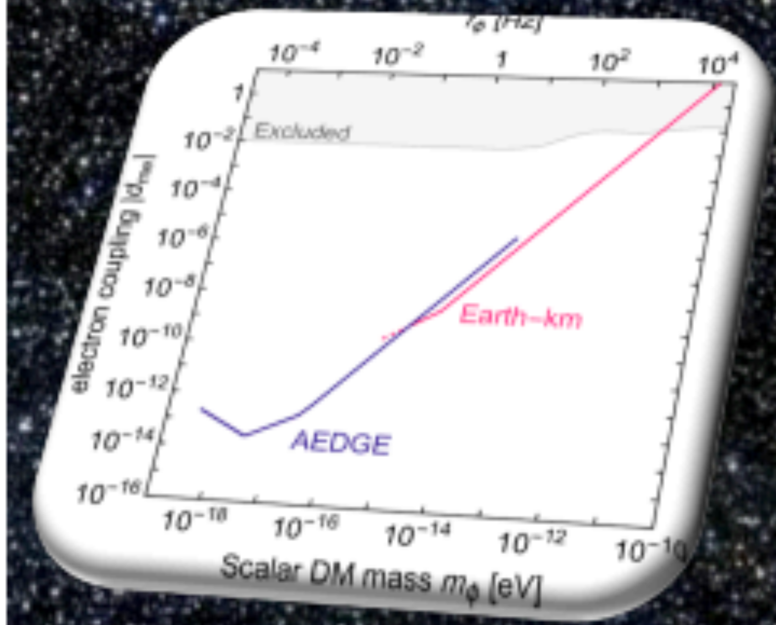
AEDGE Main Physics Goals:

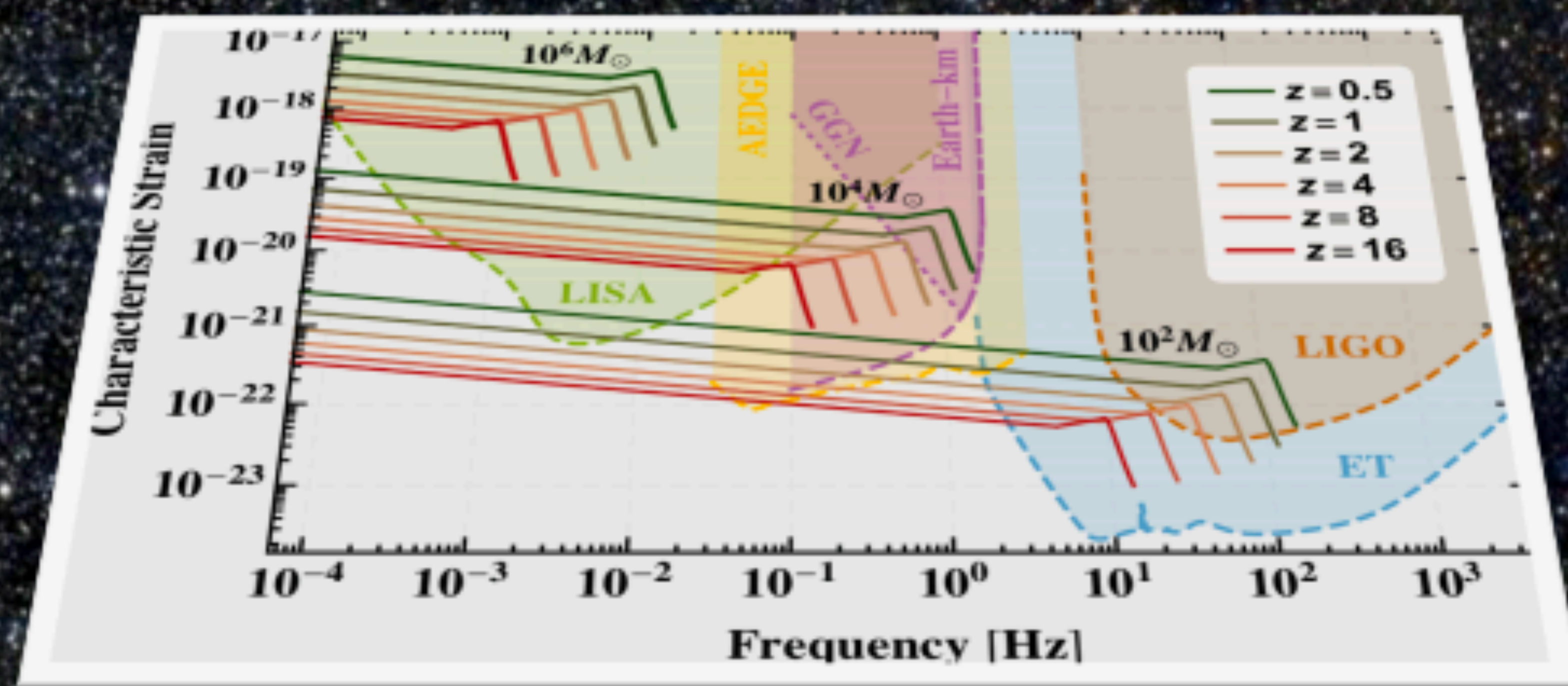
- **Search for Ultra-Light Dark Mater**
  - Complement and expand parameter space for DM searches
  - Main focus on scalar DM, but pseudoscalar and vector DM might be possible too.
- **Measurement of GW signals in mid-frequency band**
  - Measure GW in the frequency range between the most sensitive ranges of LISA and the LIGO/Virgo, KAGRA and Einstein Telescope experiments.



AEDGE:

Atomic Experiment for Dark Matter and Gravity Exploration





Informal Workshop

CERN, July 22/23 2019

https://indico.cern.ch/event/830432/

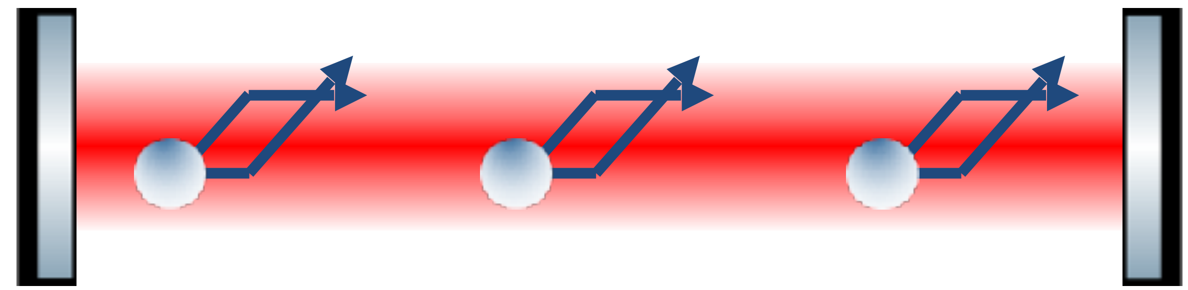
Large-scale atom interferometers

10 m fountain at Stanford

12 m fountain at Wuhan

MIGA Project

A new large instrument combining matter-wave and laser interferometry



- Gravitational wave physics
  - **Demonstrator for future sub-Hz ground based GW detectors**
- Geoscience
  - **Gravity sensitivity of 10^{-10} g/Sqrt(Hz) @ 2Hz**
  - **Gradient sensitivity of 10^{-13} s^{-2}/Sqrt(Hz) @ 2Hz: geology, hydrogeology…**

A Large research infrastructure hosted in a low noise laboratory

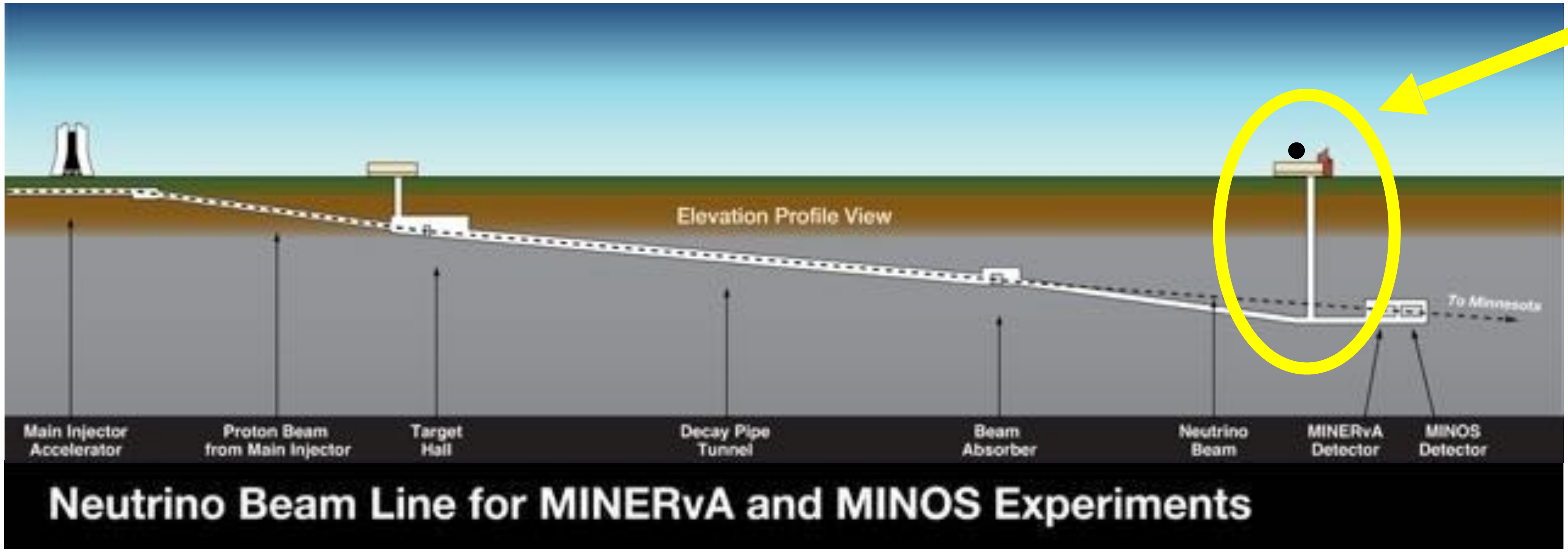
LSBB
Laboratoire Souterrain à Bas Bruit

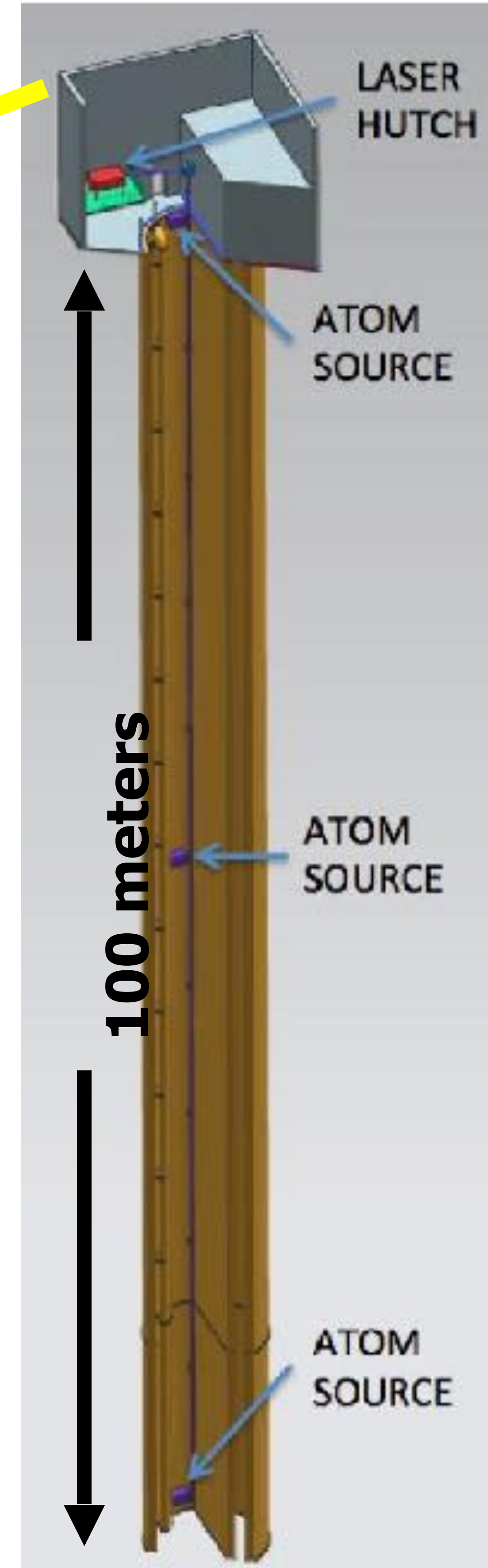
- Two 200 m horizontal optical cavity coupled with 3 AI
- Possible evolutions towards 2D or 3D instrument on site

from P. Bouyer

MAGIS-100: Detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



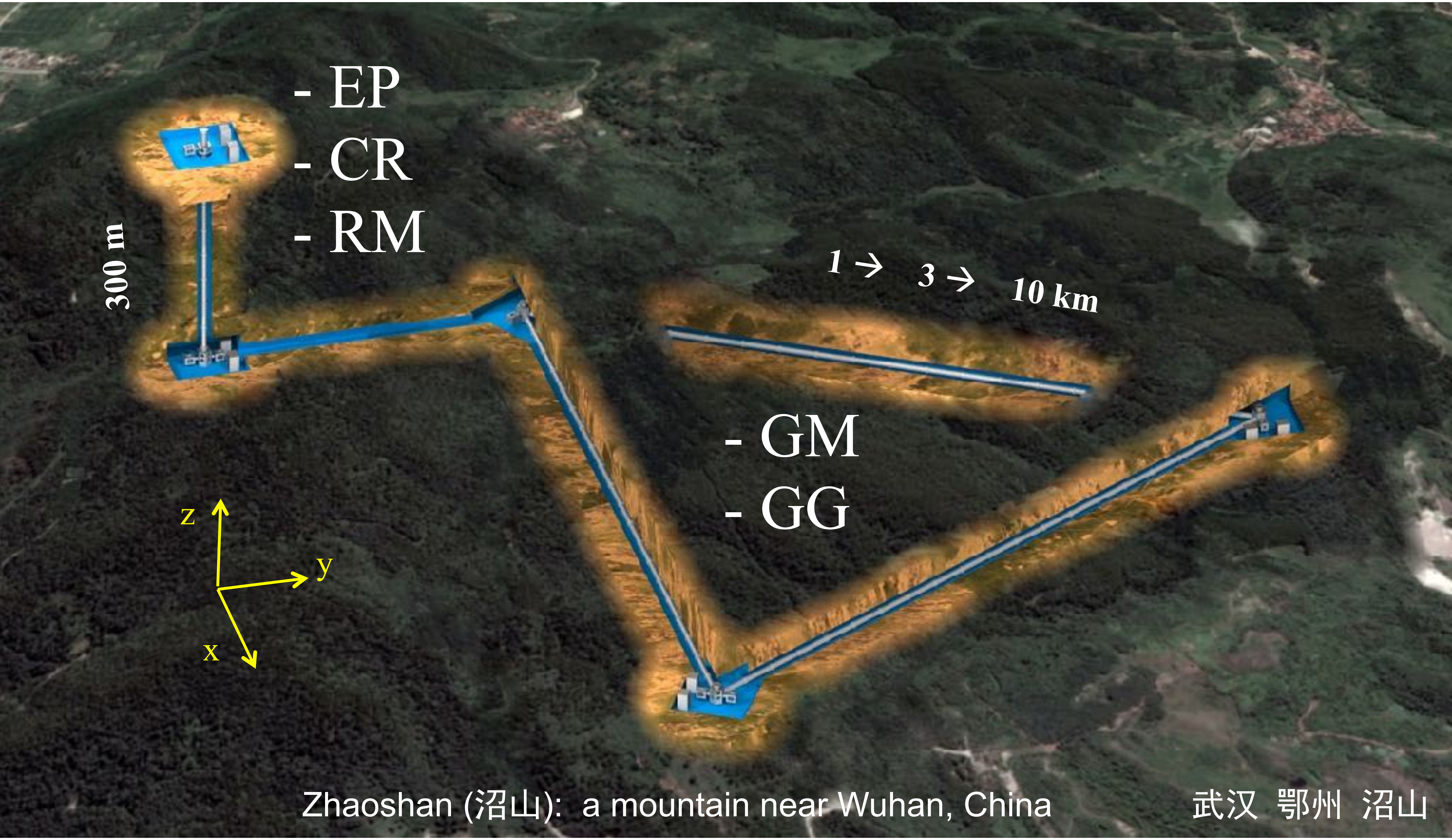


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

STANFORD Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University

from J. Hogan

ZAIGA



from M. S. Zhan

arXiv:1903.09288v2, accepted for publication in Int.J.Mod.Phys.B

Imperial College London

AION Project: Core Team

O. Buchmueller AION Seminar

UK

- 8 Institutes
- 21 Core Members
- Many Associates

Birmingham
Kai Bongs*
M. Holynski*
Y. Singh*

Cambridge
V. Gibson**
U. Schneider*

Imperial College London
O. Buchmueller** [co-coord.]
M. Tarbutt*
B. Sauer*

Kings College London
J. Ellis*

Liverpool
T. Bowcock**
J. Coleman** [co-coord.]

National Physical Lab.
W. Bowden*
P. Gill*
R. Hobson*

Oxford
E. Bentine*
C. Foot*
J. March-Russell**
I. Shipsey**

Rutherford Appleton Lab.
P. Majewski**
T. Valenzuela**
I. Willmut**

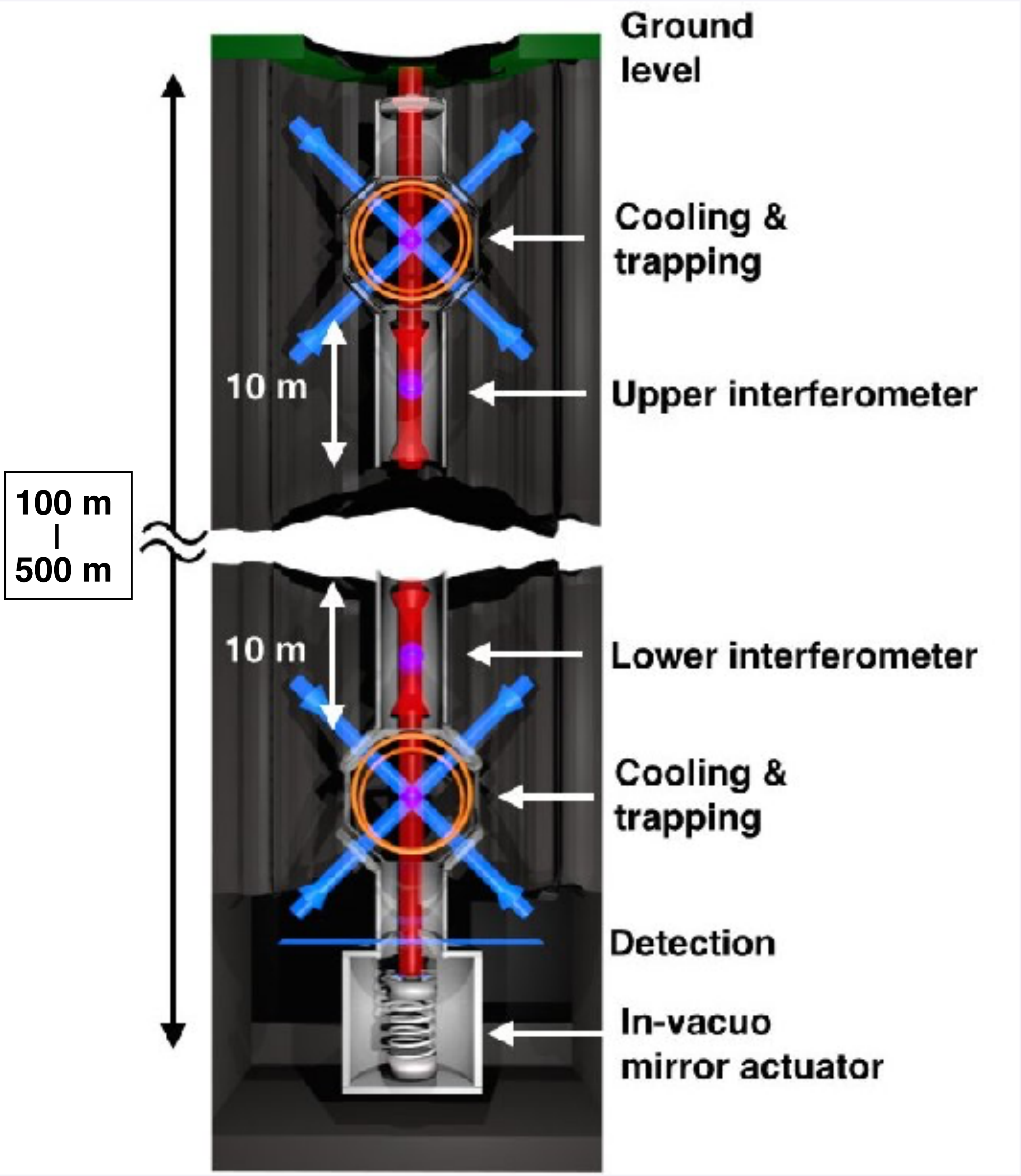
Main UK funding source:
**EPSRC; **STFC*

from O. Buchmueller

Large-scale atom interferometer
⇒ Sardegna?

Carbonia-Iglesias
ARIA/Darkside Lab

Sos Enattos
SAR-GRAV Lab?

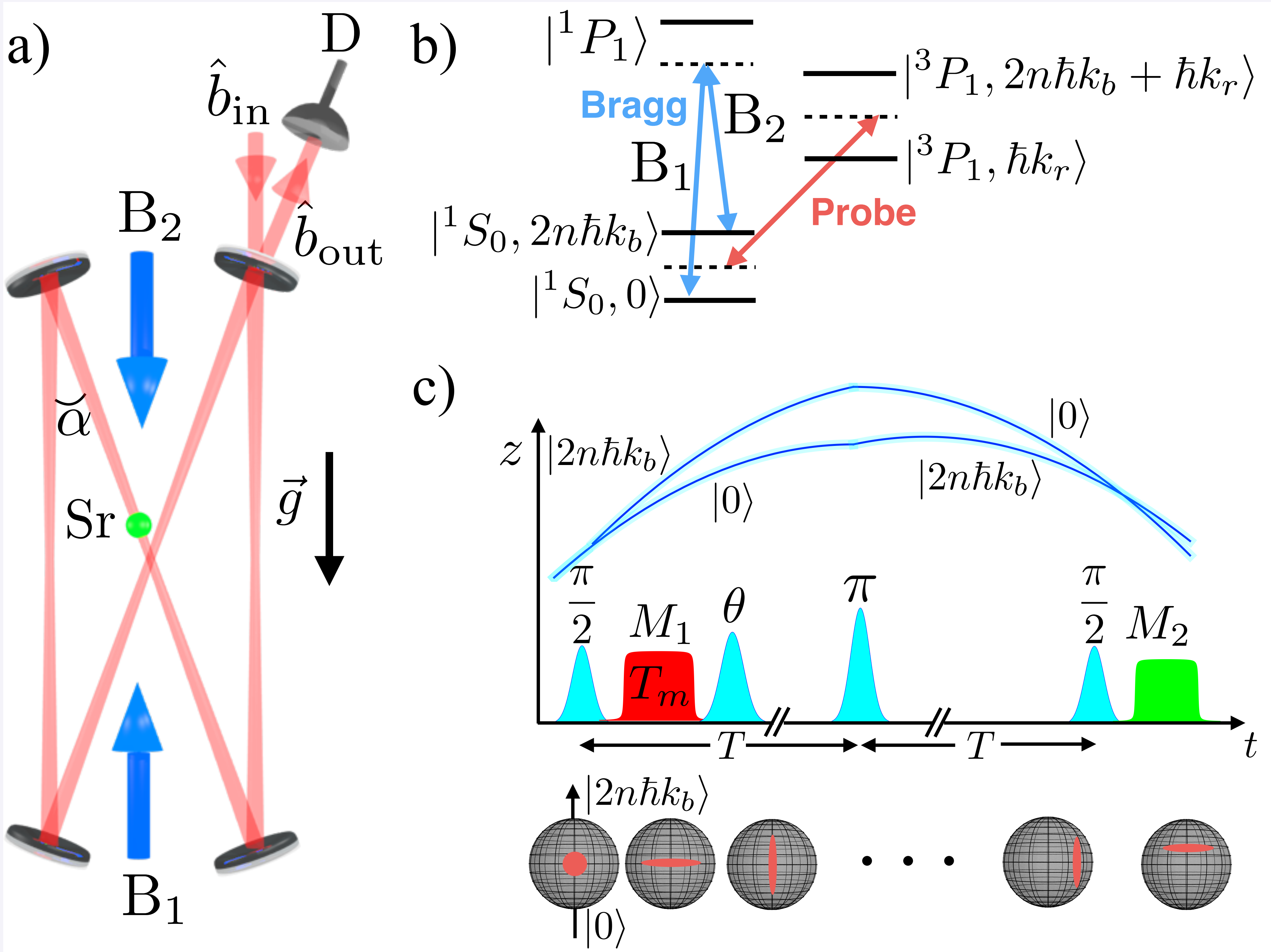


MAGIA ➟ *MAGIA-Adv*

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**

Squeezing on momentum states for atom interferometry

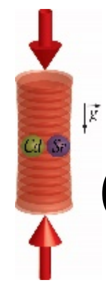


Leonardo Salvi, Nicola Poli, Vladan Vuletić, Guglielmo M. Tino, *Squeezing on Momentum States for Atom Interferometry,* **Phys. Rev. Lett. 120, 033601 (2018)**

ERC - TICTOCGRAV

European Research Council
Established by the European Commission

TICTOC



GRAV

ERC-2017-CoG

Exploring Gravity with Ultra-cold Cadmium and Strontium Optical Clocks and Atom Interferometers

Sr and Cd atom interferometers for fundamental physics test

WEP test/spin gravity test

Quantum interference of “clocks” in different gravitational potential

PI: Prof. Nicola Poli

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

The team

Nicola Poli	Associate professor, Università di Firenze
Gabriele Rosi	Researcher, INFN-Firenze
Leonardo Salvi	Post-doc, Università di Firenze
Gunjan Verma	Post-doc, CNR/ICTP
Jonathan Tinsley	Post-doc, Università di Firenze
Wang Enlong	PhD student, LENS
Manan Jain	PhD student, Università di Firenze
Giulio D'Amico	PhD student, Università di Firenze (now at GEM)
Liang Hu	Post-doc, Università di Firenze/ICTP (now at at Shanghai Jiao Tong University)
Tommaso Mazzoni	Post-doc, Università di Firenze (now at Muquans)
Xian Zhang	Post-doc, LENS/ICTP (now at Zhejiang Un.)
Ruben del Aguila	PhD student, Università di Firenze (now in London)
Jacopo Grotti	Diploma student, Università di Firenze (now at PTB)
Marco Menchetti	Diploma student, Università di Bologna (now at NPL)

PhD & post-doc positions available

Long-term collaborators

Luigi Cacciapuoti	ESA-Noordwijk
Marella de Angelis	CNR - Firenze
Marco Fattori	Università di Firenze
Marco Prevedelli	Università di Bologna
Fiodor Sorrentino	INFN - Genova

Previous members and visitors

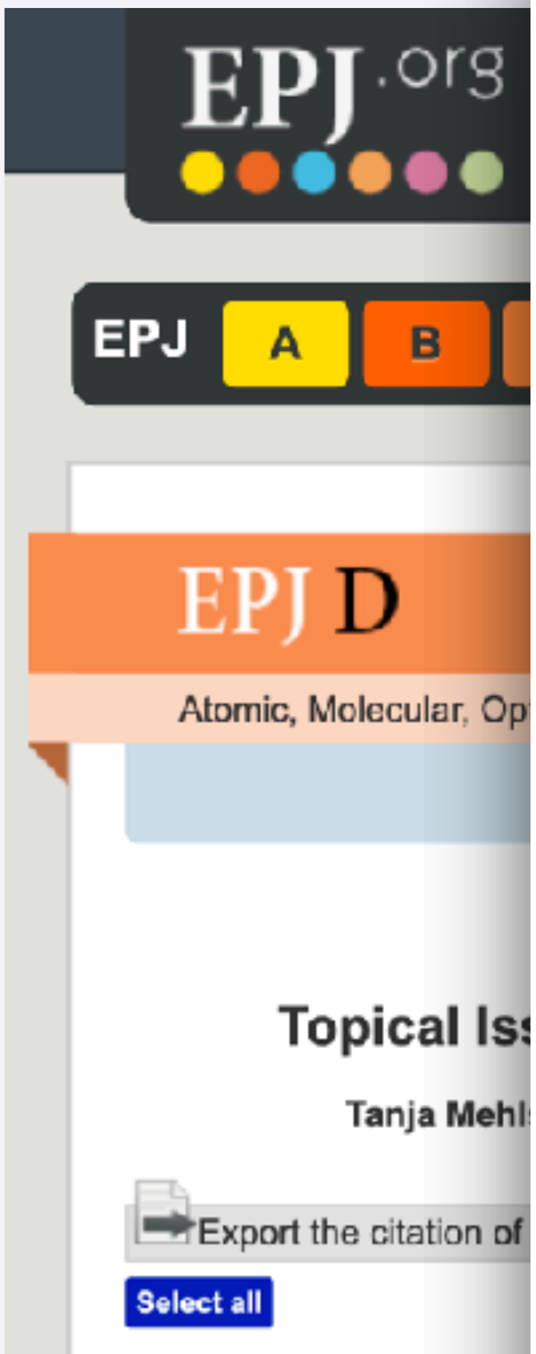
Andrea Alberti, PhD student
Andrea Bertoldi, Post-doc
Quentin Bodart, Post-doc
Filippo Borselli, Diploma student
Sergei Chepurov, Institute of Laser Physics, Novosibirsk, visitor
Robert Drullinger, NIST, Long term guest
Marco Fattori, PhD student
Gabriele Ferrari, Researcher, INFM/CNR
Antonio Giorgini, PhD and Post-doc
Vladyslav Ivanov, Post-doc
Marion Jacquey, 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

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)**

erc

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



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EPJ D Topical Issue:
Quantum Technologies for Gravitational Physics

Submissions are invited for a Topical Issue of EPJD on *Quantum Technologies for Gravitational Physics*.

Quantum technologies have pushed the sensitivity of both light and atom gravity sensors to a level where they have surpassed classical instruments in laboratory experiments but also in some first portable devices. Exploiting quantum properties of light and atoms new applications appear at the horizon, but also novel tests of Einstein's General Relativity and quantum gravity become possible.

The Guest Editors welcome theoretical and experimental papers on all aspects of research investigating and applying quantum metrology and technologies on the field of gravity tests and gravitational measurements, ranging from purely abstract considerations to commercial applications. **Topics of interest include, but are not limited to: quantum tests of gravity theories, atomic sensors or clocks for gravimetry and gravity potential determination, quantum technologies for gravitational wave detection - e.g. squeezed sources.**

This issue is prepared in response to the challenges and visions outlined in the European Commission Quantum Technologies Flagship strategic document, and the commitment of the EC to support research in quantum technologies.

The issue is open to everyone working in the field. We invite contributors to communicate their intention to submit manuscripts for this Topical Issue to the Guest Editors as soon as possible. Please provide the tentative title of the paper and a short abstract. The full manuscripts should be submitted before the deadline directly to the EPJD Editorial Office at https://articlestatus.edpsciences.org/is/epjd/.

Deadline for submission: **September 30, 2019**

Submissions should be clearly identified as intended for the Topical Issue "*Quantum Technologies for Gravitational Physics*". Papers will be published continuously and will appear (as soon as accepted) on the journal website. The electronic version of the Topical Issue will contain all accepted papers in the order of publication. All submitted papers will be refereed according to the usual high standards of the journal. More general information about EPJD including instructions for authors is available at http://epjd.epj.org/.

Guest Editors of the Topical Issue:

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