# *Detecting gravitational waves with atomic sensors*

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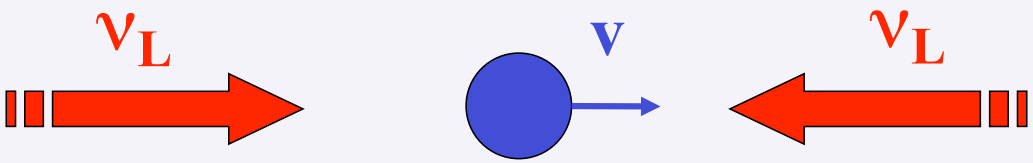
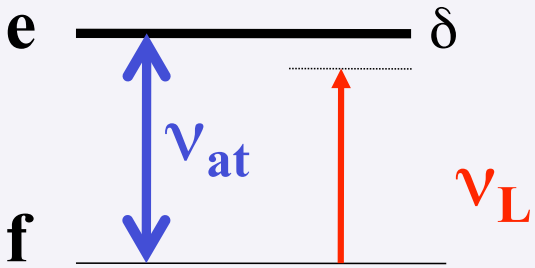
http://coldatoms.lens.unifi.it/

Les Rencontres de Physique de la Vallée d'Aoste
Results and Perspectives in Particle Physics
La Thuile, 26/2/2018

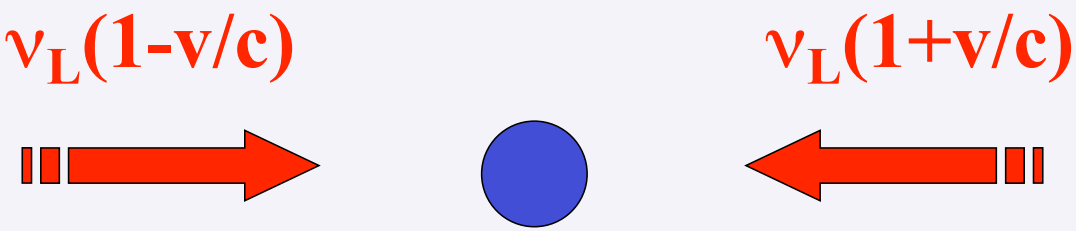
# Laser cooling: Optical molasses



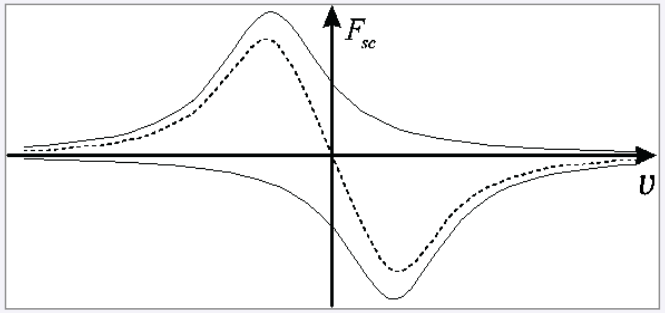

Lab ref. frame




$\nu_{at} > \nu_L$




Atom ref. frame




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

Doppler limit: $$k_B T_D = \frac{h\Gamma}{2}$$

Recoil limit: $$k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$$

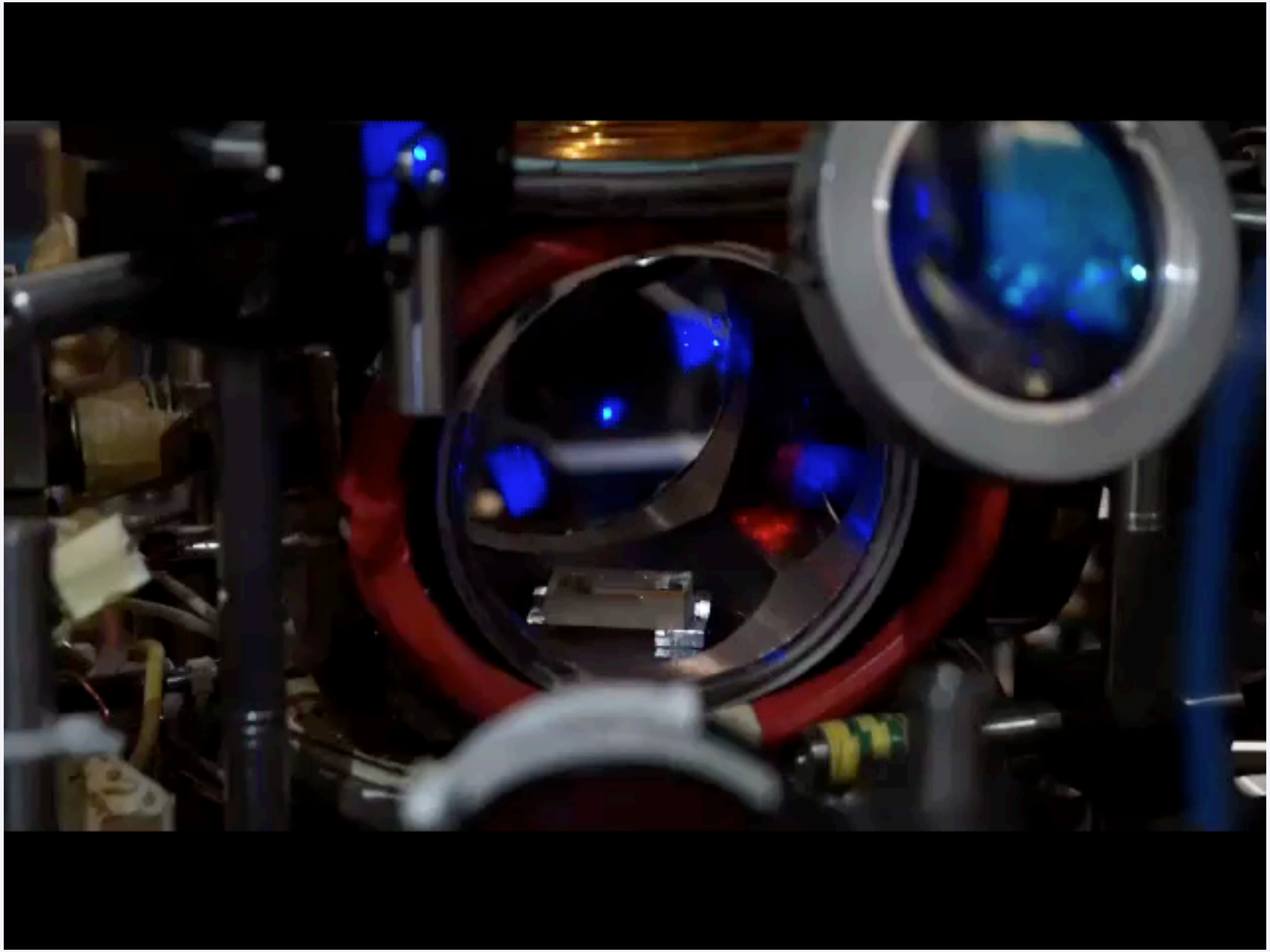
Examples:

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

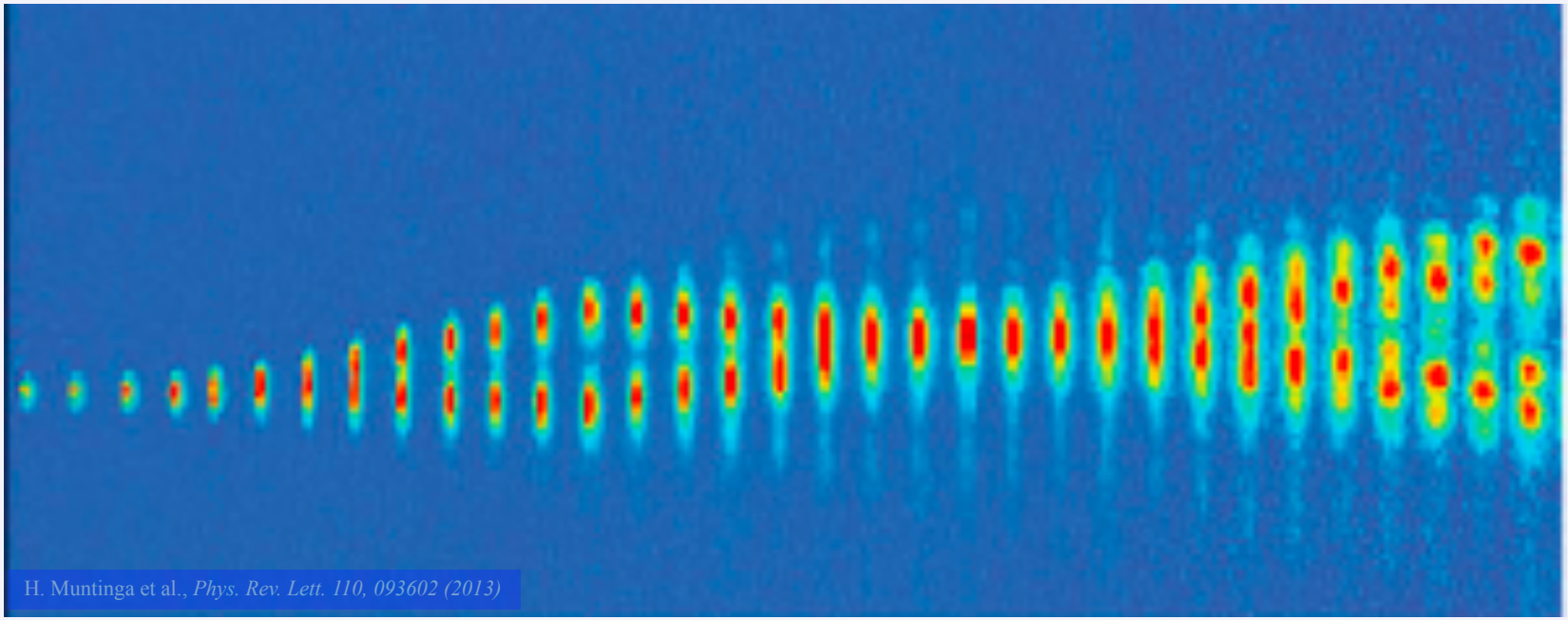
Idea: **T.W. Hänsch, A. Schawlow, 1975**

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

# Sr Magneto-Optical Trap (MOT)
# LENS - Firenze

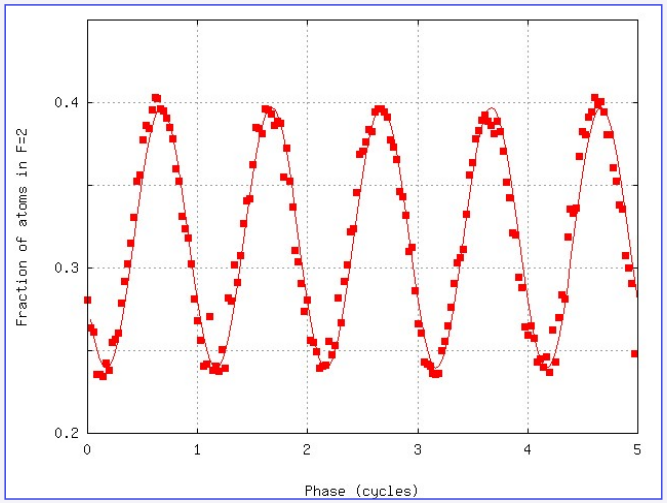


# *Atom interferometry*
# *Wave-particle duality in quantum physics*




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

de Broglie wavelength

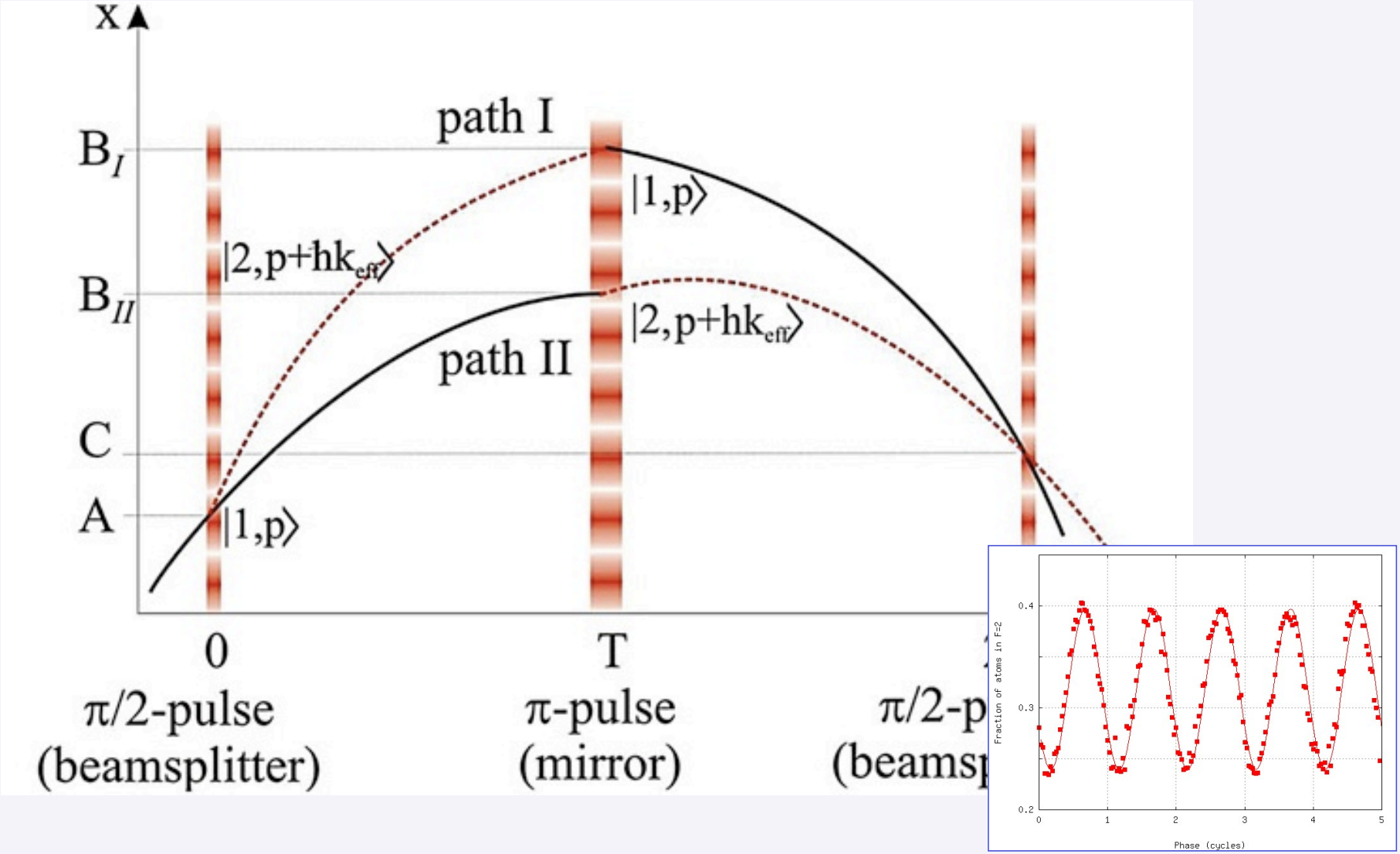



Atomic interference fringes – Firenze 2006


Alexander D. Cronin, Jörg Schmiedmayer, David E. Pritchard, *Optics and interferometry with atoms and molecules*, Rev. Mod. Phys., Vol. 81, No. 3 (2009)

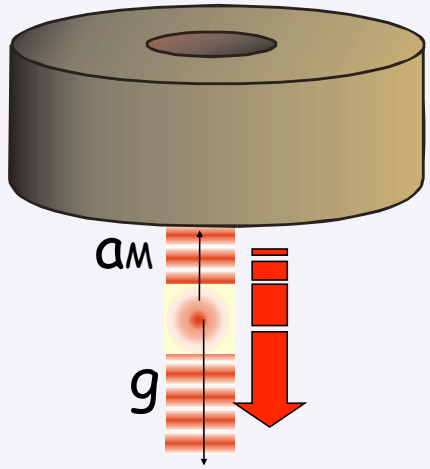
G. M. Tino, M. A. Kasevich (eds) *Atom Interferometry*, Proc. Int. School Phys. "Enrico Fermi", Course CLXXXVIII, Varenna 2013 (SIF and IOS Press, 2014).

# *Atom interferometry and gravity*



# MAGIA
## (Misura Accurata di G mediante Interferometria Atomica)

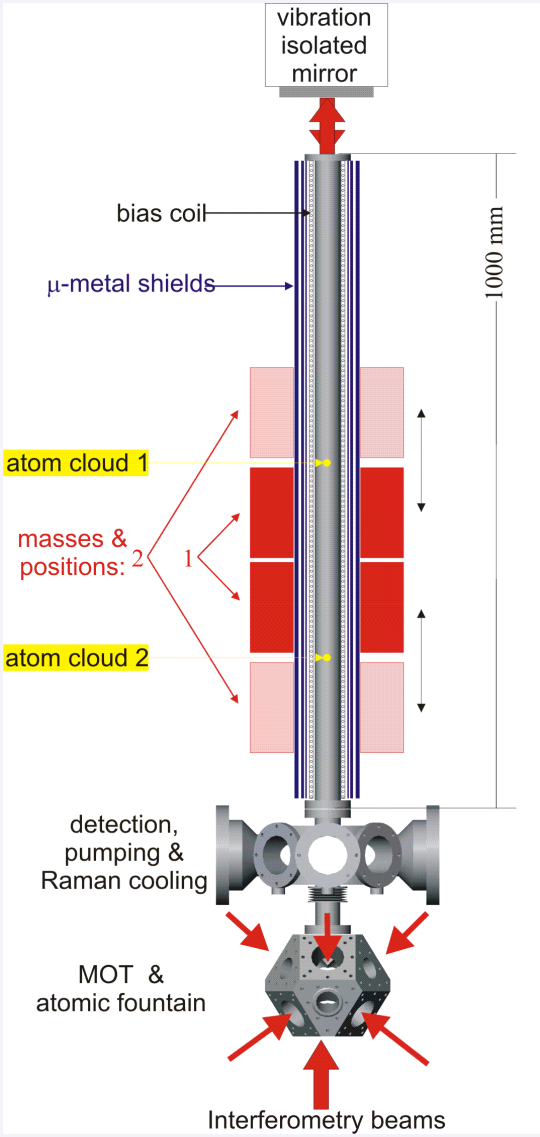
- Measure g by atom interferometry
- Add source mass
- Measure change of g

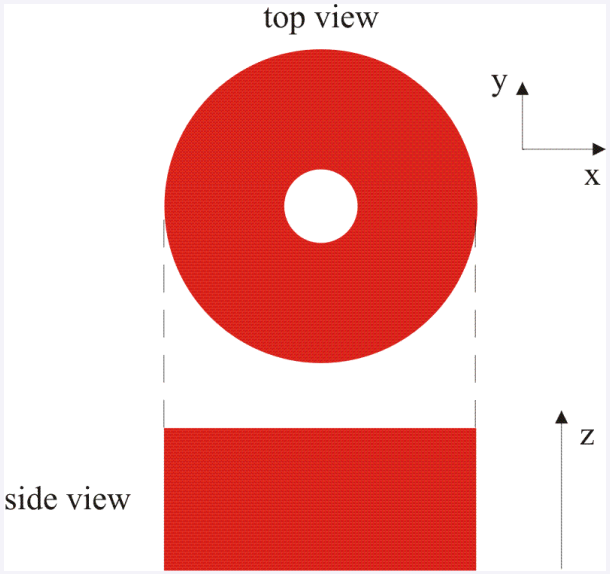


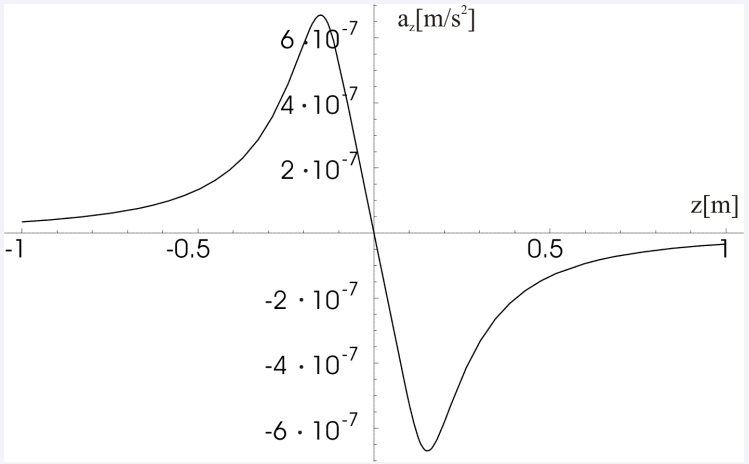

➢ ***Precision measurement of G***

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

# MAGIA
# Rb gravity gradiometer + source mass



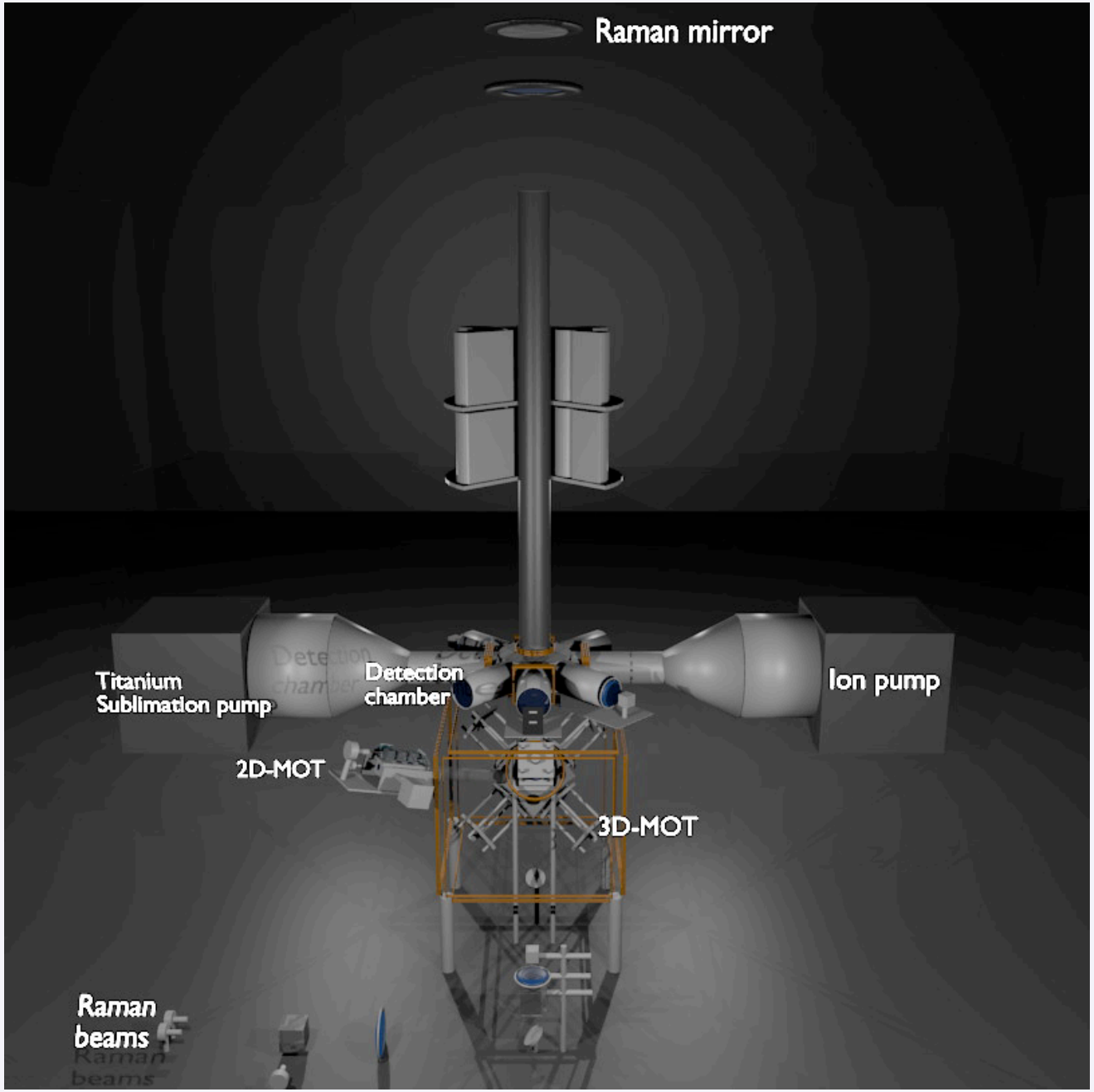

500 kg tungsten mass

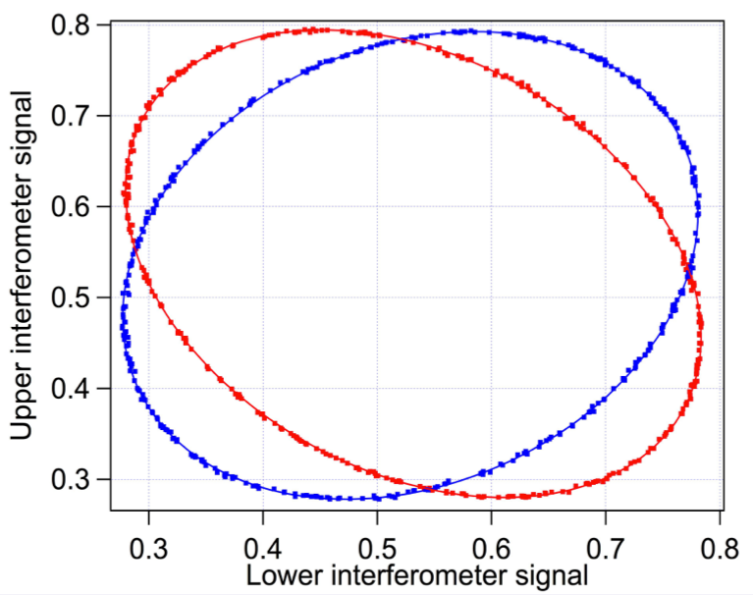
Sensitivity $10^{-9}$g/shot

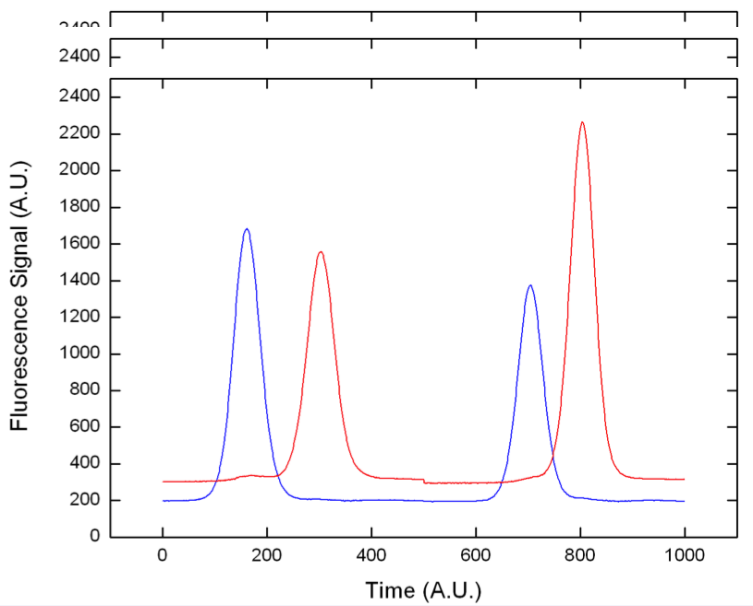
one shot $\Rightarrow \Delta G/G \approx 10^{-2}$

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

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


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


Upper interferometer signal
Lower interferometer signal
0.3
0.4
0.5
0.6
0.7
0.8


Fluorescence Signal (A.U.)
Time (A.U.)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400

UNIVERSITÀ DEGLI STUDI FIRENZE

LETTER

doi:10.1038/nature13433

# Precision measurement of the Newtonian gravitational constant using cold atoms

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

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

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

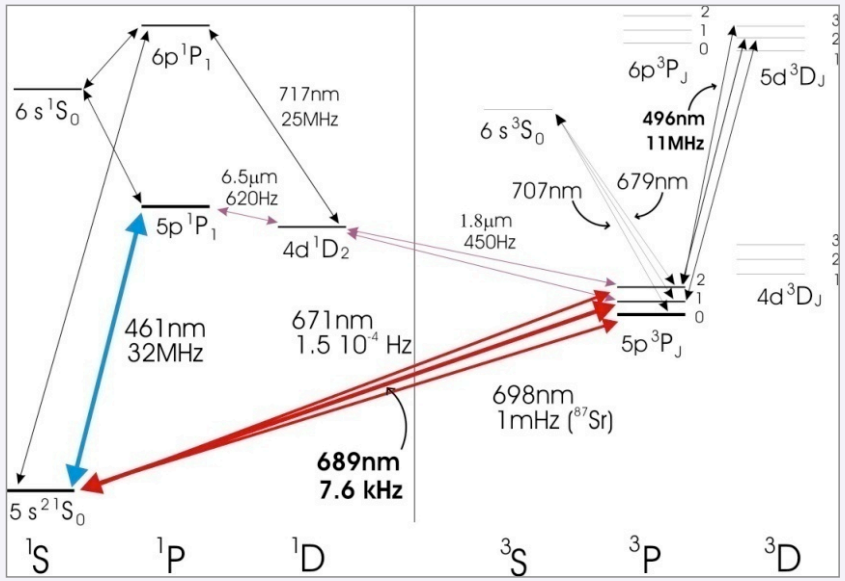
The atom interferometer is realized using light pulses to stimulate $^{87}$Rb atoms at the two-photon Raman transition between the hyperfine

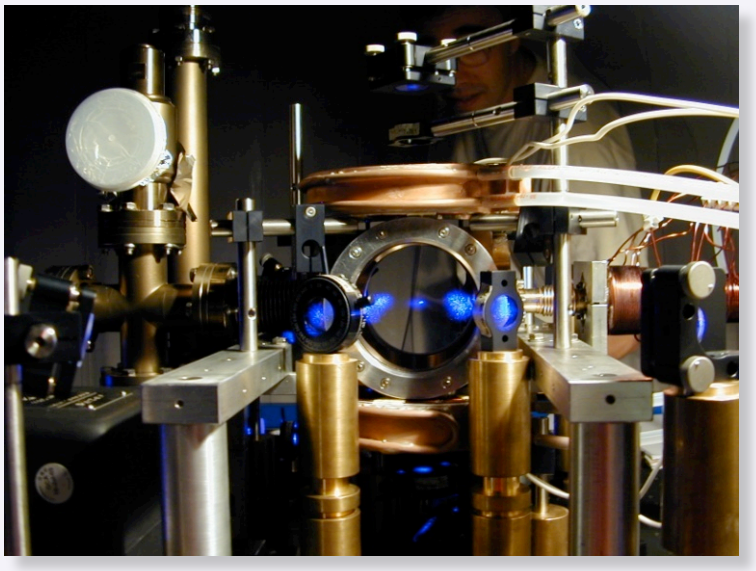
$$G = 6.67191(77)(62) \times 10^{-11}\ m^3\ kg^{-1}\ s^{-2}$$

Relative uncertainty: 150 ppm

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

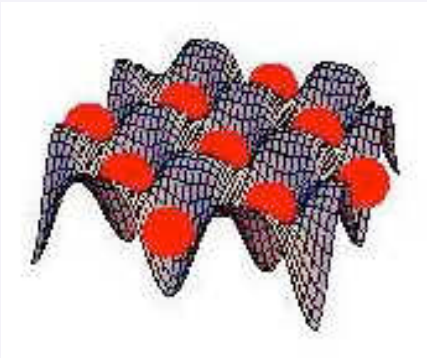
# Ultracold Sr - Experiments in Firenze

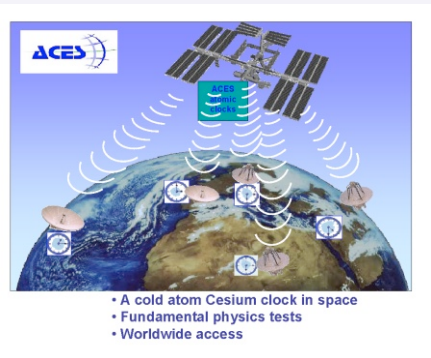


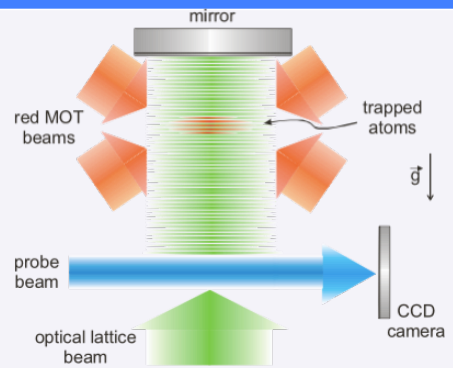



- Optical clocks using visible intercombination lines

- 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)

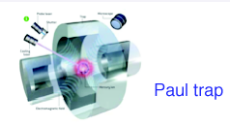
V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, *Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials*, Phys. Rev. Lett. 100, 043602 (2008) )

# Optical clocks: Towards $10^{-18}$

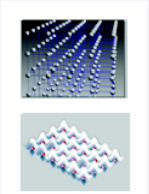
- **Narrow optical transitions**
  $\delta\nu_o \sim$ 1-100 Hz, $\nu_0 \sim 10^{14}$-$10^{15}$ Hz

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

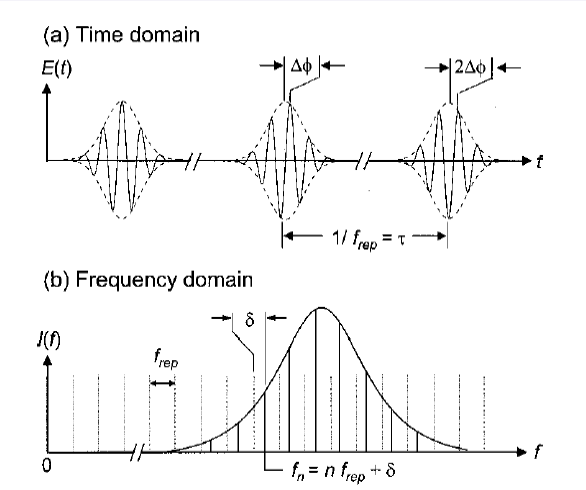
- **Candidate atoms**
  - **Trapped ions: $Hg^+$, $In^+$, $Sr^+$, $Yb^+$,…**

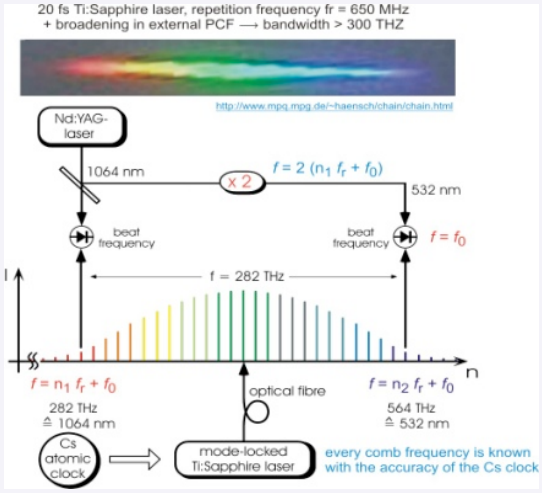


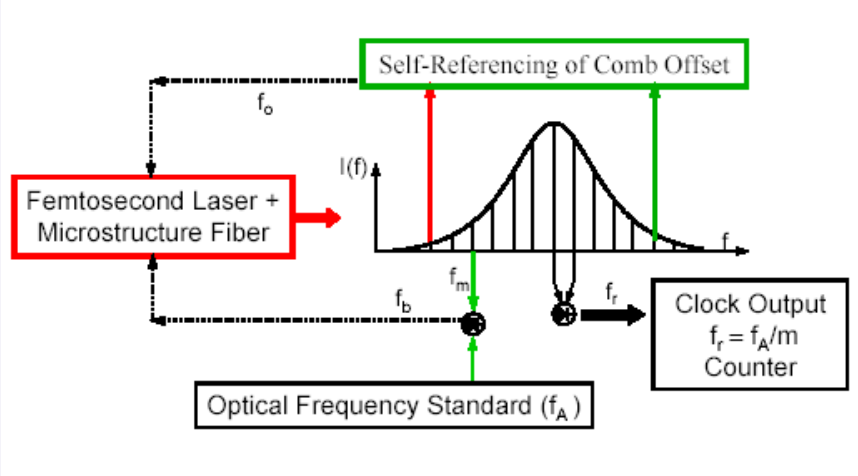

  - **Cold neutral atoms: H, Ca, Sr, Yb,…**




- **Direct optical-μwave connection by optical frequency comb**

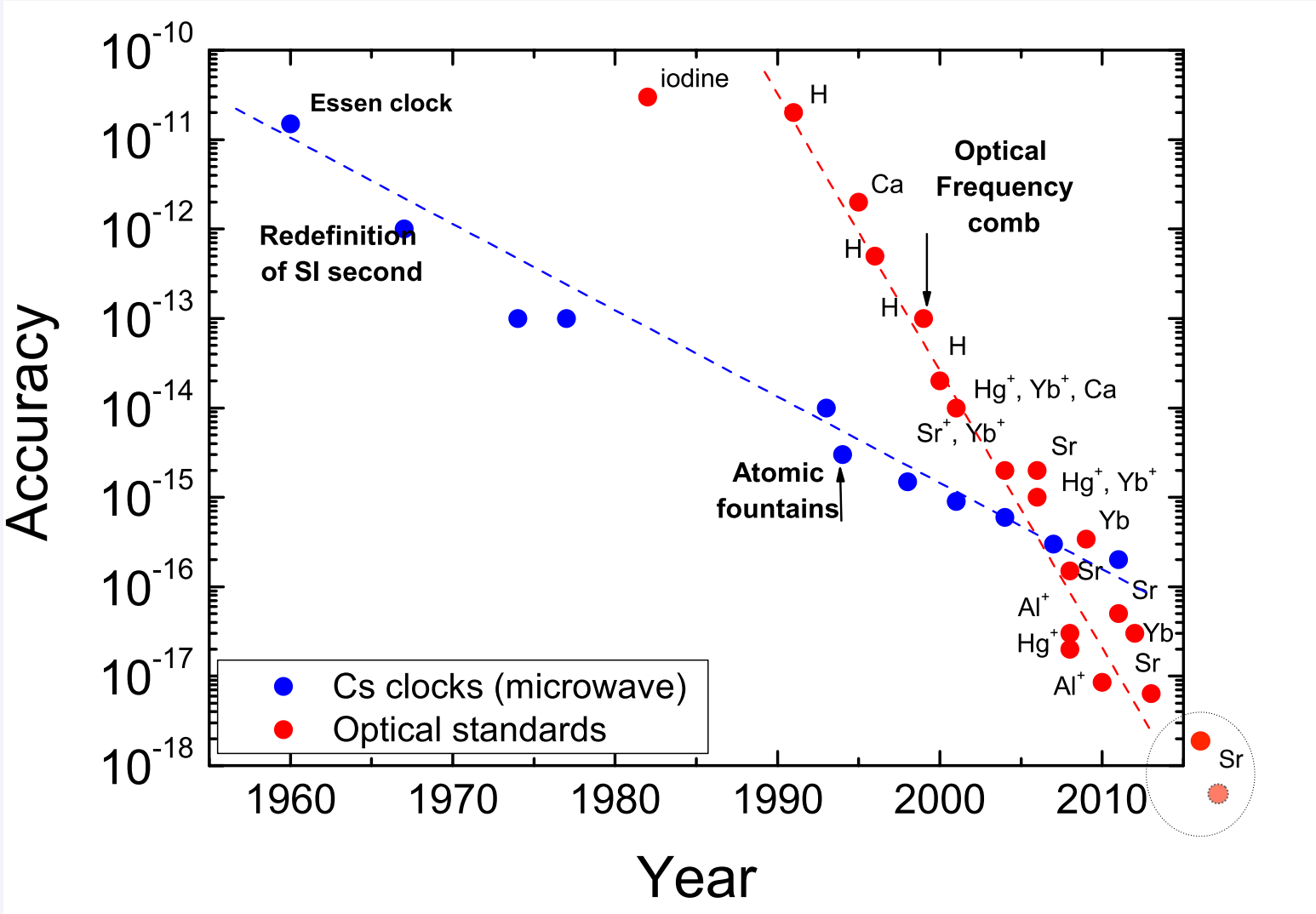


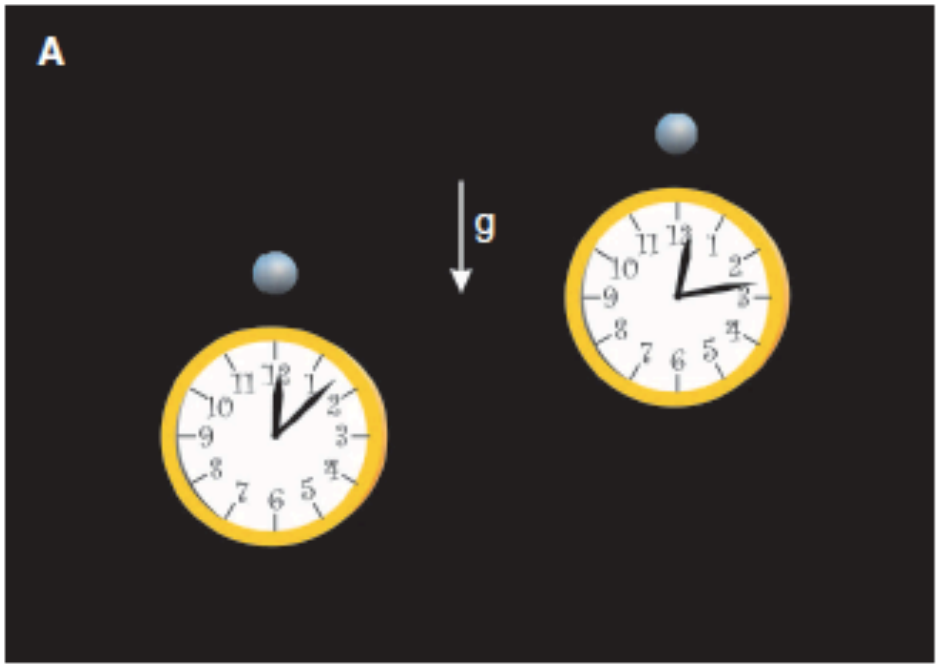

Th. Udem *et al.*, Nature 416 , 14 march 2002

# 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**

# *Measure gravitational red shift in the lab*



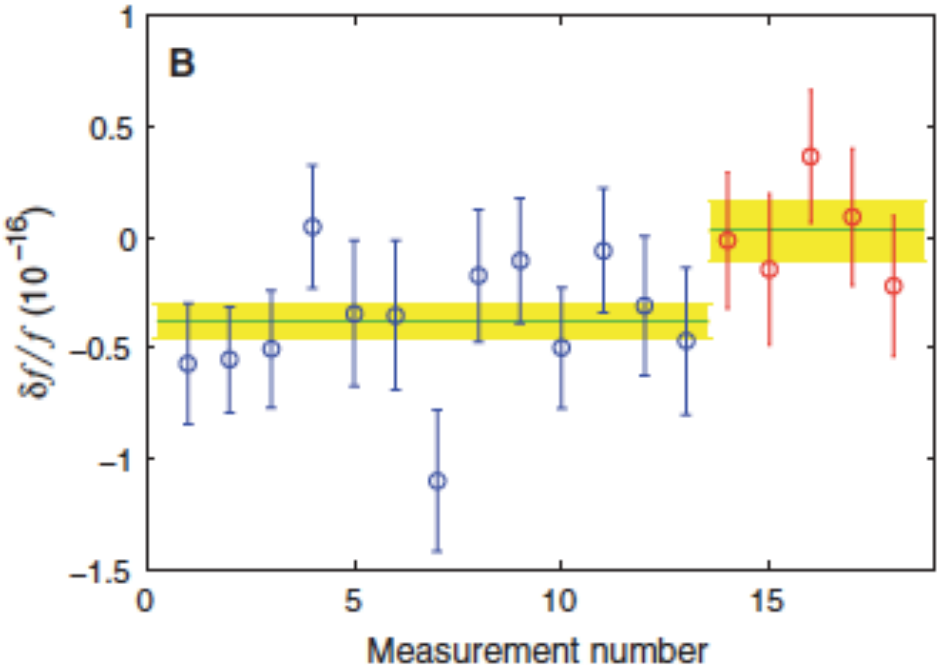
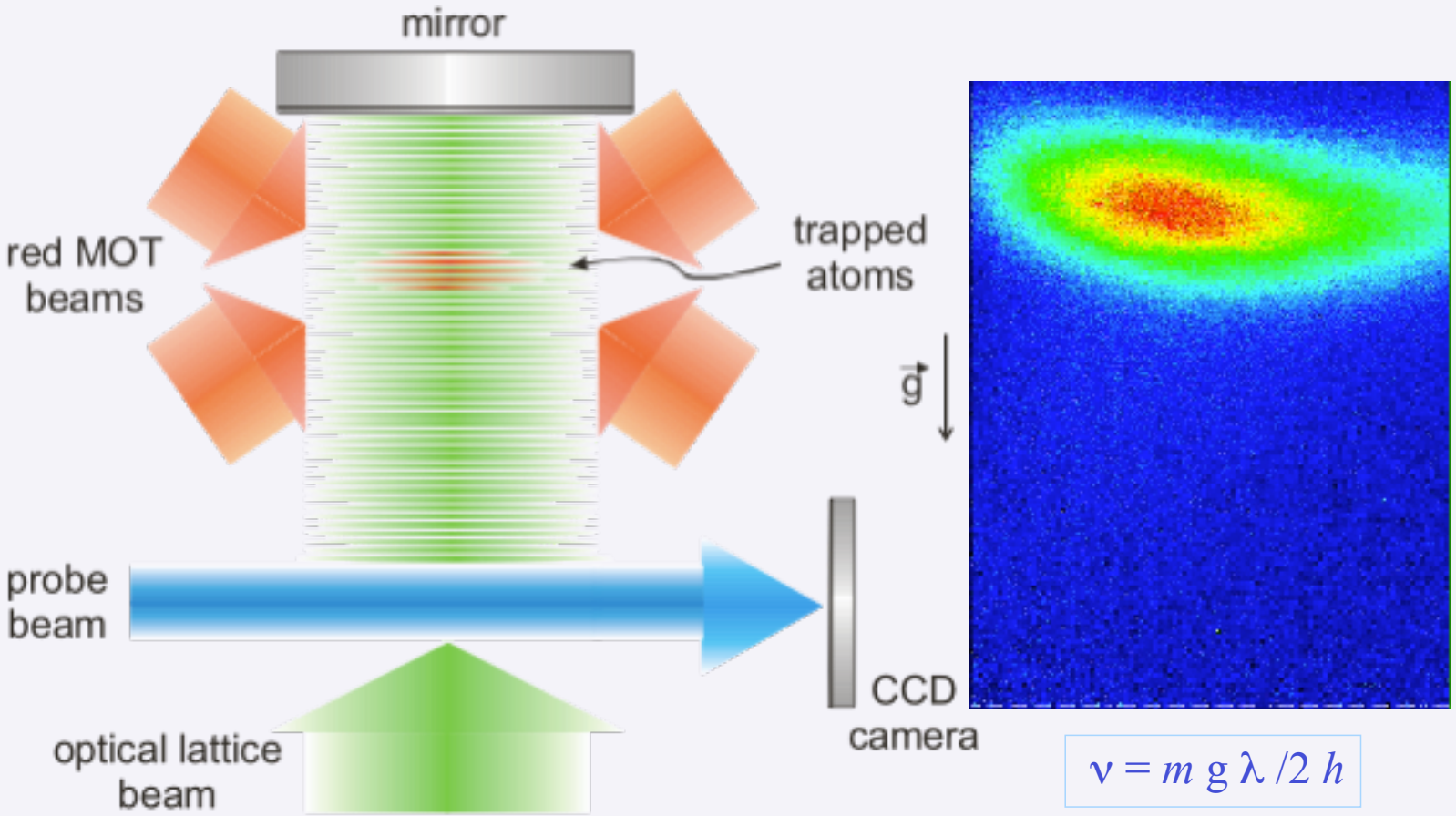




**Fig. 3.** Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two $Al^+$ optical clocks at different heights. The Al-Mg clock was initially 17 cm lower in height than the Al-Be clock, and subsequently, starting at data point 14, elevated by 33 cm. The net relative shift due to the increase in height is measured to be $(4.1 \pm 1.6) \times 10^{-17}$. The vertical error bars represent statistical uncertainties (reduced $\chi^2 = 0.87$). Green lines and yellow shaded bands indicate, respectively, the averages and statistical uncertainties for the first 13 data points (blue symbols) and the remaining 5 data points (red symbols). Each data point represents about 8000 s of clock-comparison data.

C. W. Chou*, D. B. Hume, T. Rosenband and D. J. Wineland , *Optical Clocks and Relativity,* Science Vol. 329 no. 5999 pp. 1630-1633 (2010)

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



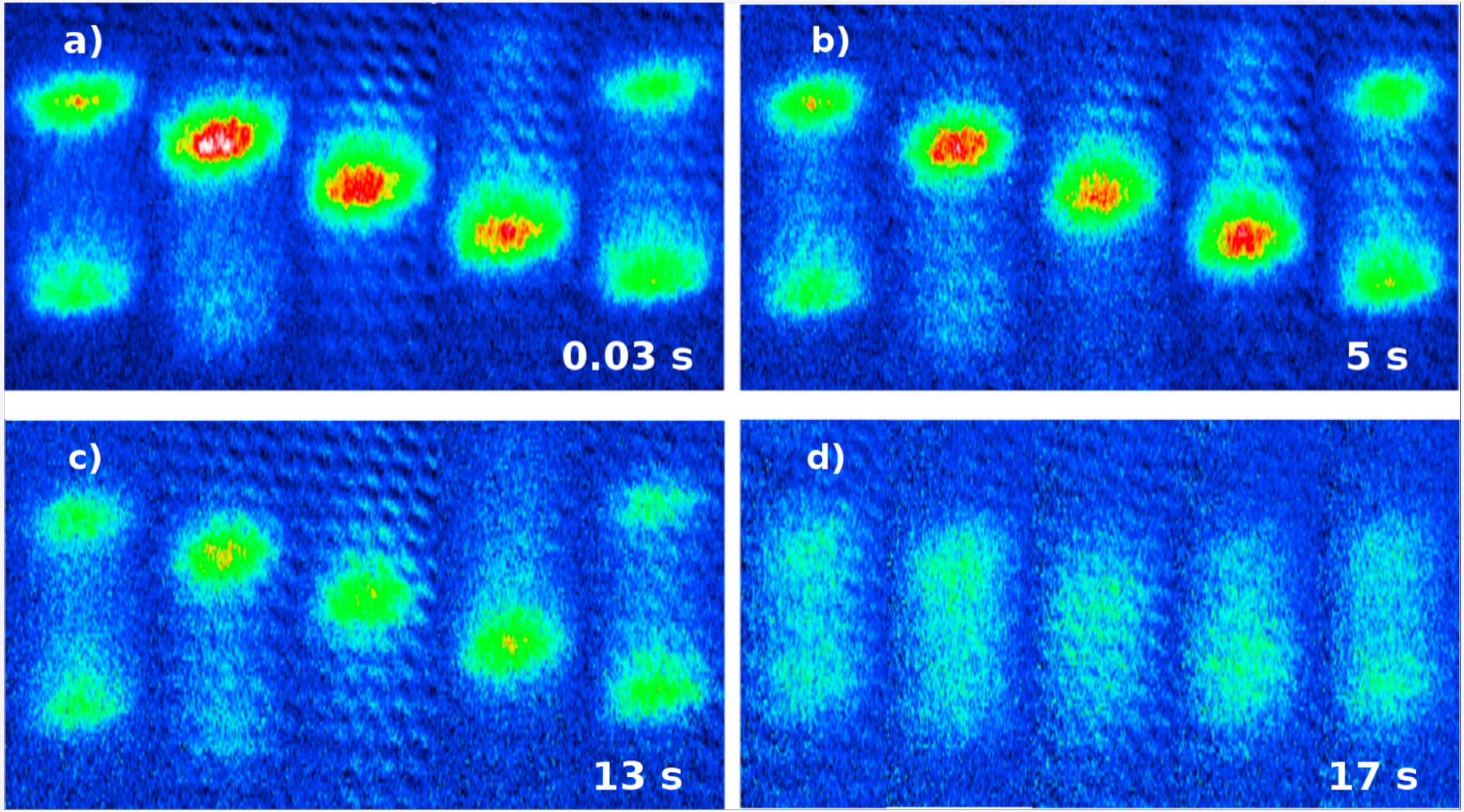

$$\nu = m\, g\, \lambda / 2\, h$$


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. 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)**

# Bloch oscillations of $^{88}Sr$ atoms



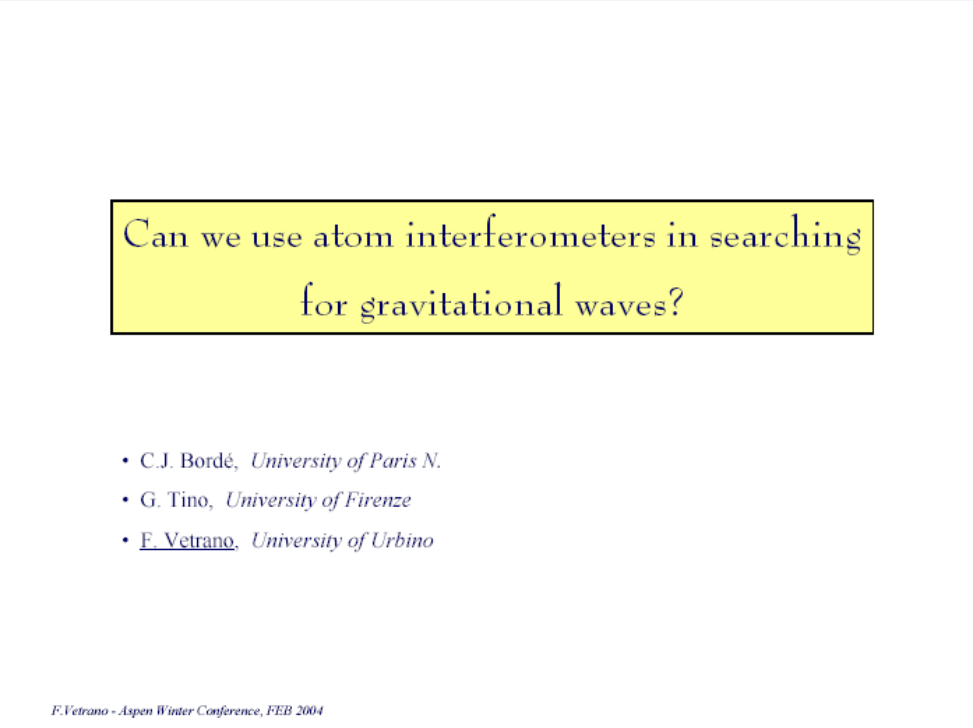

**N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino,**
*Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter,*
**Phys. Rev. Lett. 106, 038501 (2011)**

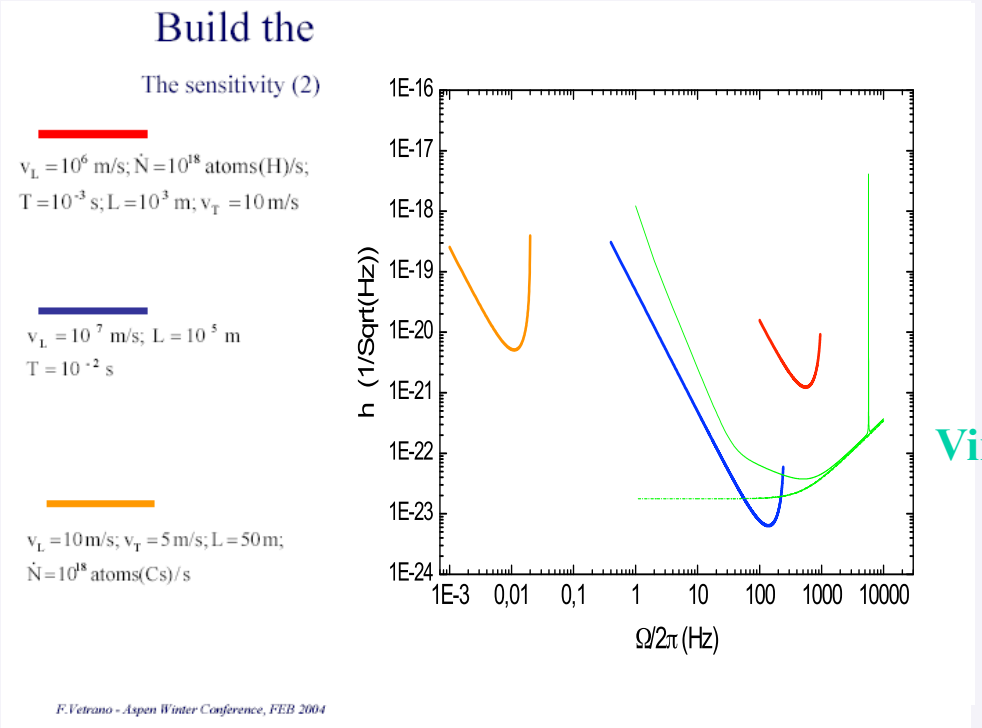
# *Detection of Gravitational Waves by Atom Interferometry*

## *Main ideas*

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

# *Gravitational waves detection with atom interferometry*





• R.Y. Chiao, A. D. Speliotopoulos, "Towards MIGO, the matter-wave interferometric gravitational-wave observatory, and the intersection of quantum mechanics with general relativity", Journal of Modern Optics (2004), 51(6-7), 861-899

• C. Bordè, G. M. Tino, F. Vetrano, "Can we use atom interferometers in searching for gravitational waves?", 2004 Aspen Winter College on Gravitational Waves. Available online at: http://www.ligo.caltech.edu/LIGO_web/Aspen2004/pdf/vetrano.pdf

• A. Roura, D.R. Brill, B. L. Hu, C.W. Misner, W.D. Phillips, "Gravitational wave detectors based on matter wave interferometers (MIGO) are no better than laser interferometers (LIGO)", Physical Review D: Particles and Fields (2006), 73(8), 084018/1-084018/14

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

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

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October 14, 2008

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## Gravitational Waves Detection with Atom Interferometry

Conference

Apply | Schedule

**Organizers:**

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

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

Deadline: 15-01-2009

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

**Abstract**

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

Special issue on

*Gravitational Waves Detection with Atom Interferometry*

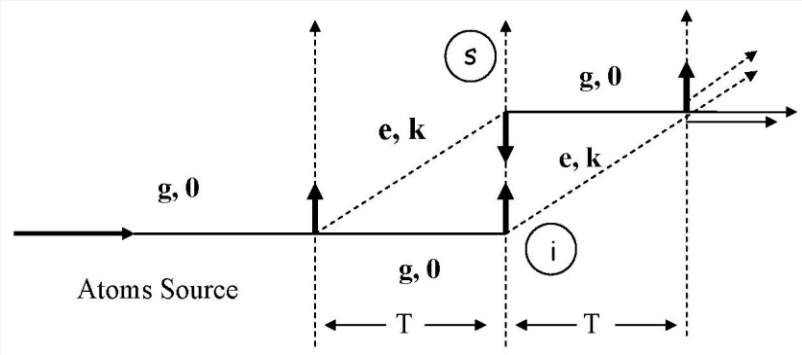
G.M. Tino, F. Vetrano, C. Laemmerzahl Editors,

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

# *Gravitational waves detection with atom interferometry*

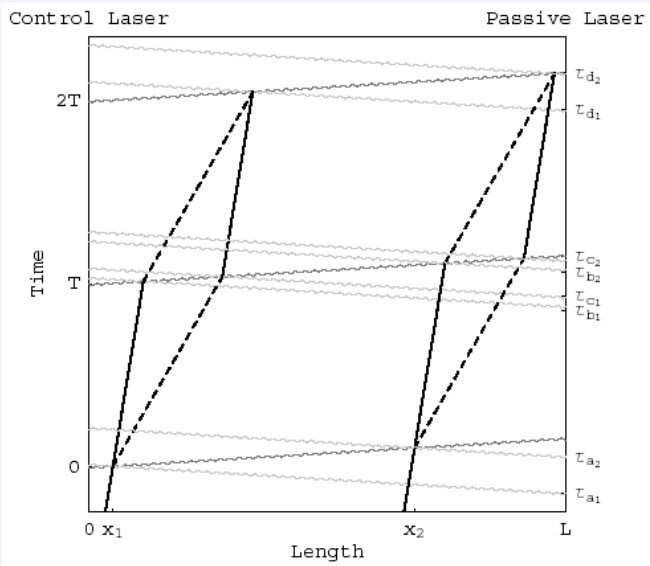
## • *Single atom interferometer*

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

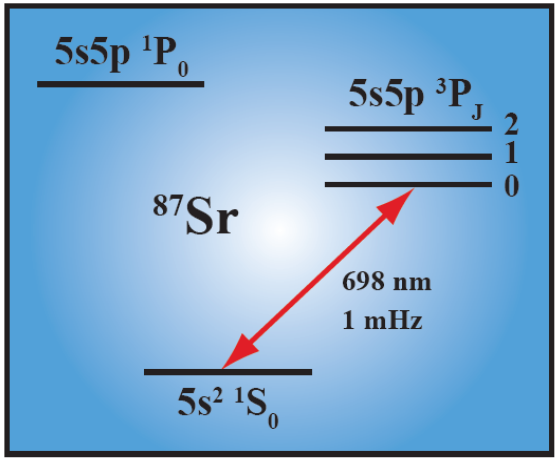



## • *Differential scheme*

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



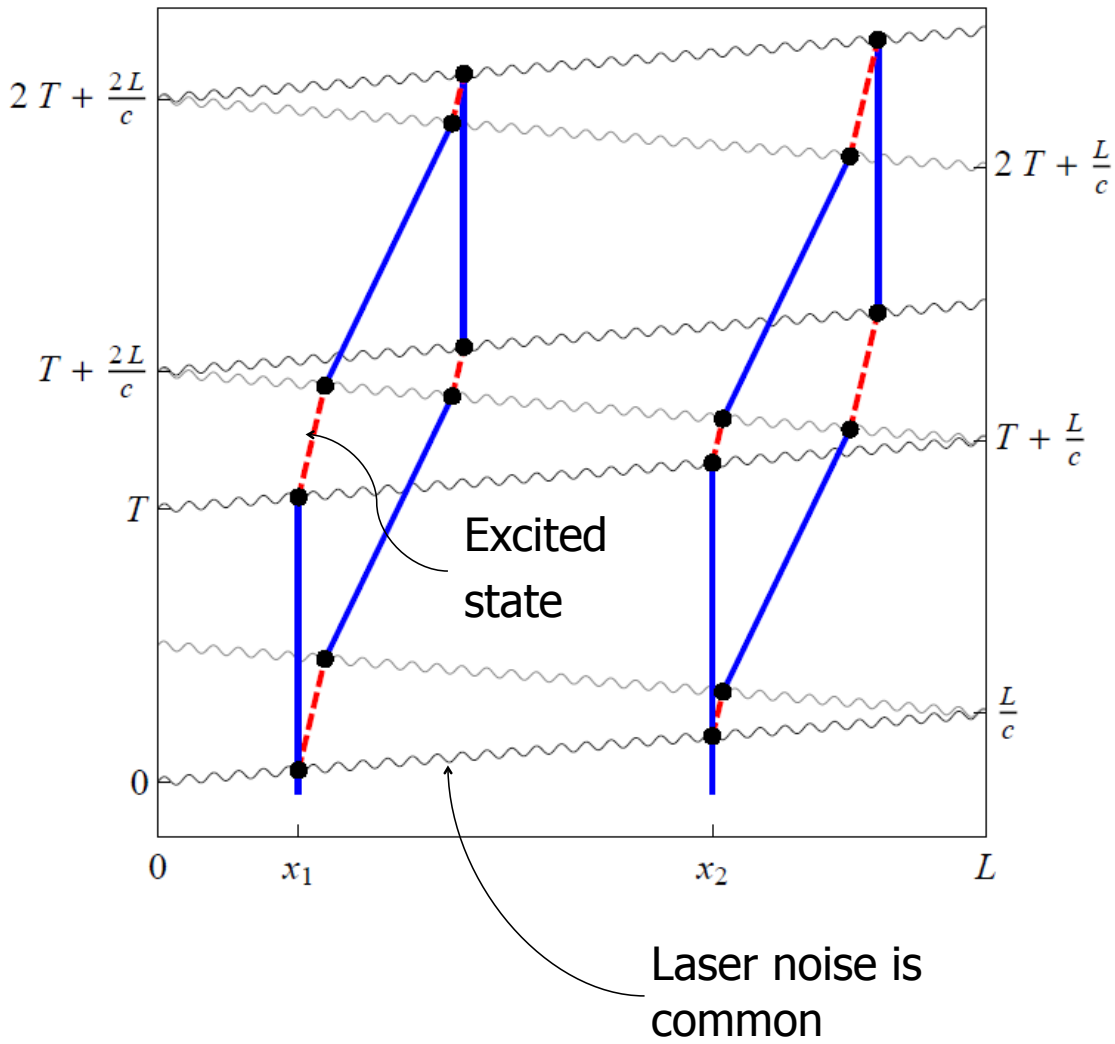
# Laser frequency noise insensitive detector




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

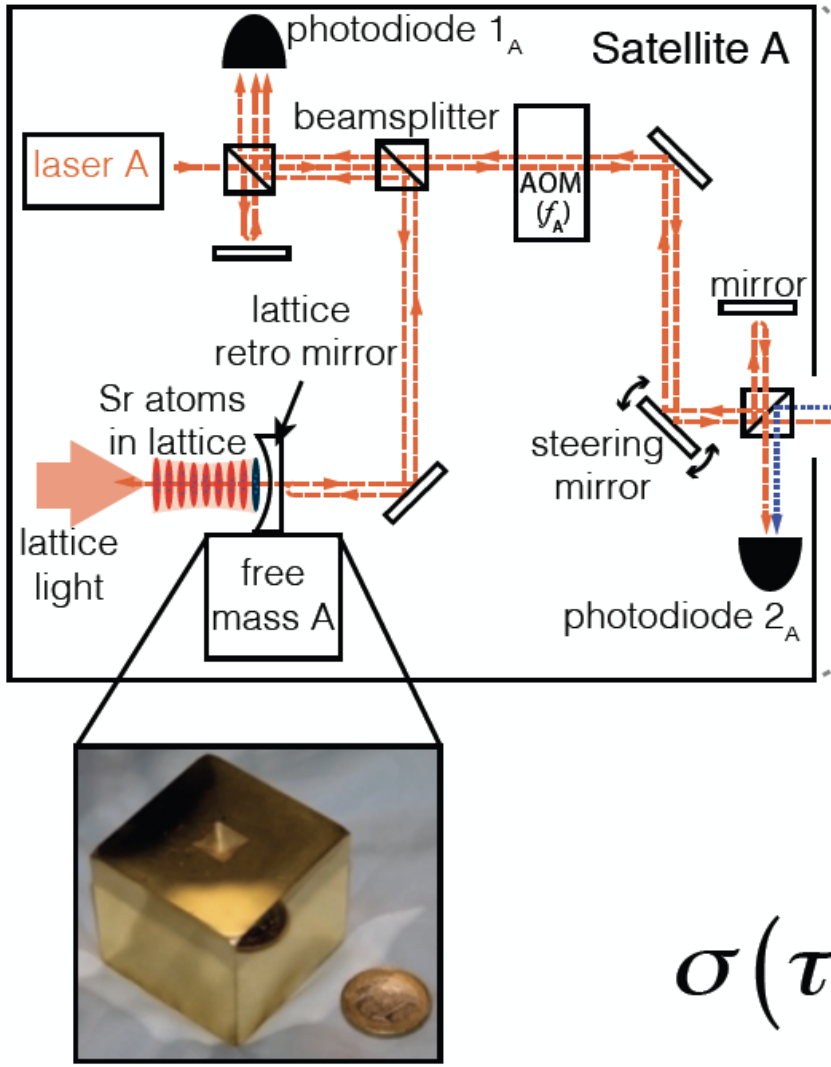
- Long-lived single photon transitions (e.g. clock transition in Sr, Ca, Yb, Hg, etc.).
- Atoms act as clocks, measuring the light travel time across the baseline.
- GWs modulate the laser ranging distance.

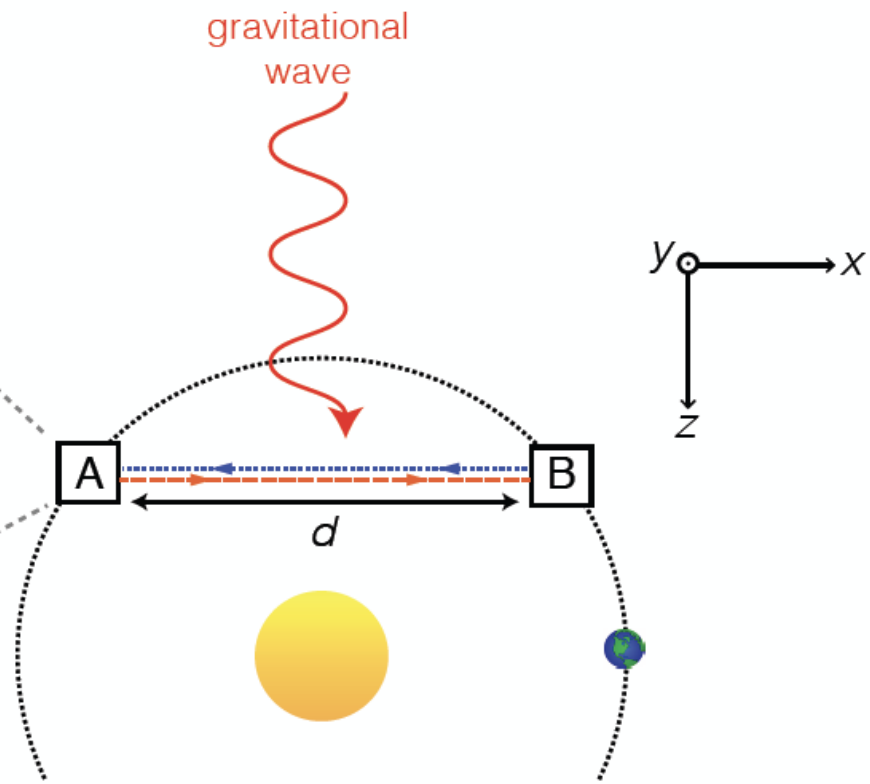
Enables 2 satellite configurations




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**

Dipartimento di Fisica e Astronomia and LENS Laboratory, Università di Firenze
Istituto Nazionale di Fisica Nucleare
Firenze (Italy)

In response to the Call for New Science Ideas in ESA's Science Programme

September 13, 2016

s in the field of Fundamental Physics. The scientific objective is to
al Waves and other fundamental aspects of gravity as well as the
ational physics and quantum physics using new quantum sensors,
namely, optical atomic clocks and atom interferometers based on ultracold Strontium atoms.

Combining quantum sensing and quantum communication, SAGE is based on recent impressive achievements in quantum technologies for optical clocks, atom interferometers, microwave and optical links. This call provides a unique opportunity to investigate in detail the fascinating idea of this ultimate multi-purpose gravity explorer based on all the most advanced achievements in the field.

We consider a multi-satellite configuration with payload/instruments including Strontium optical atomic clocks, Strontium atom interferometers and satellite-to-satellite/satellite-to-Earth laser links.

SAGE main scientific goals are:

PRIMARY GOAL:

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

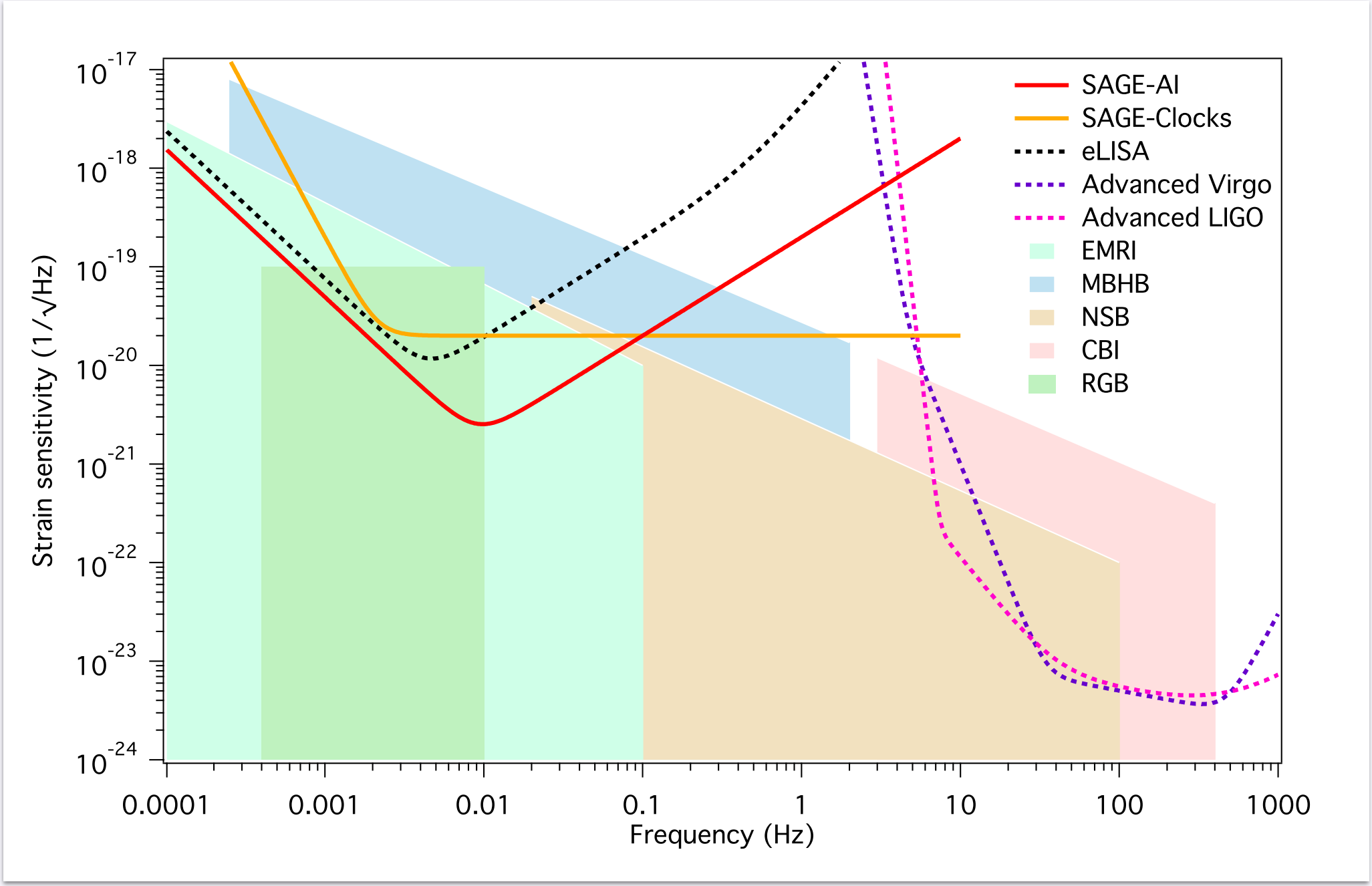
SECONDARY GOALS:

- 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 relative velocities
- Use clocks and links between satellites for optical VLBI in Space

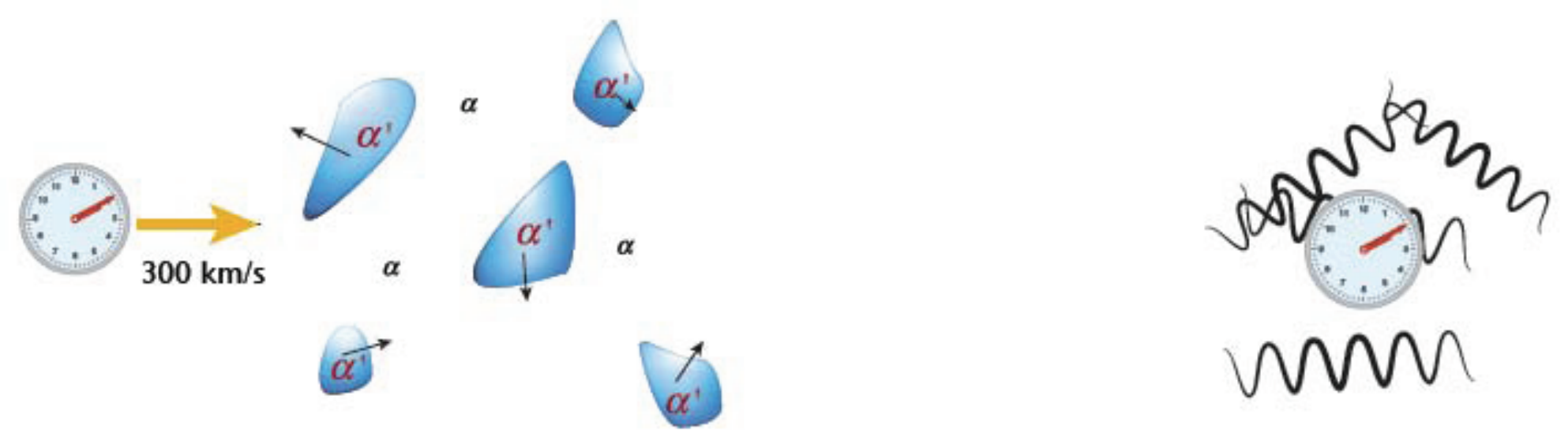
Although the technology for such a mission is not mature yet, it takes advantage of developments for the ACES (Atomic Clock Ensemble in Space) mission and the results of ESA studies for SOC (Space Optical Clock), SAI (Space Atom Interferometer), STE-QUEST, GOAT and ongoing national projects in this frame.

Supporting scientists and institutes from ESA member states as well as from USA, China, Japan, Singapore are listed in the final section of the proposal.

# SAGE: GW detection



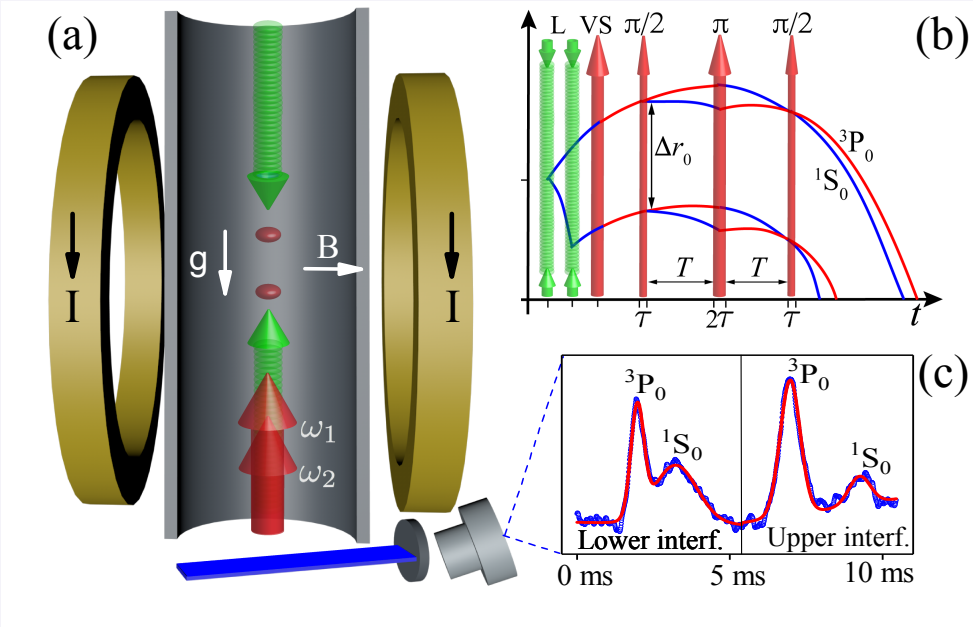
# SAGE: Search for Dark-Matter

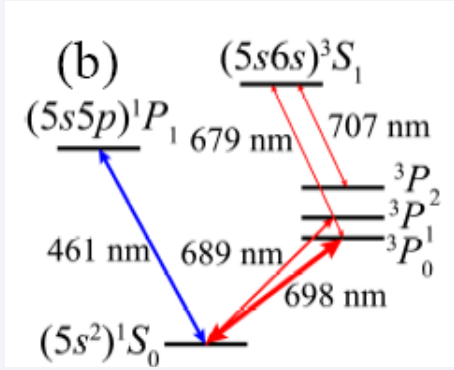



(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A.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

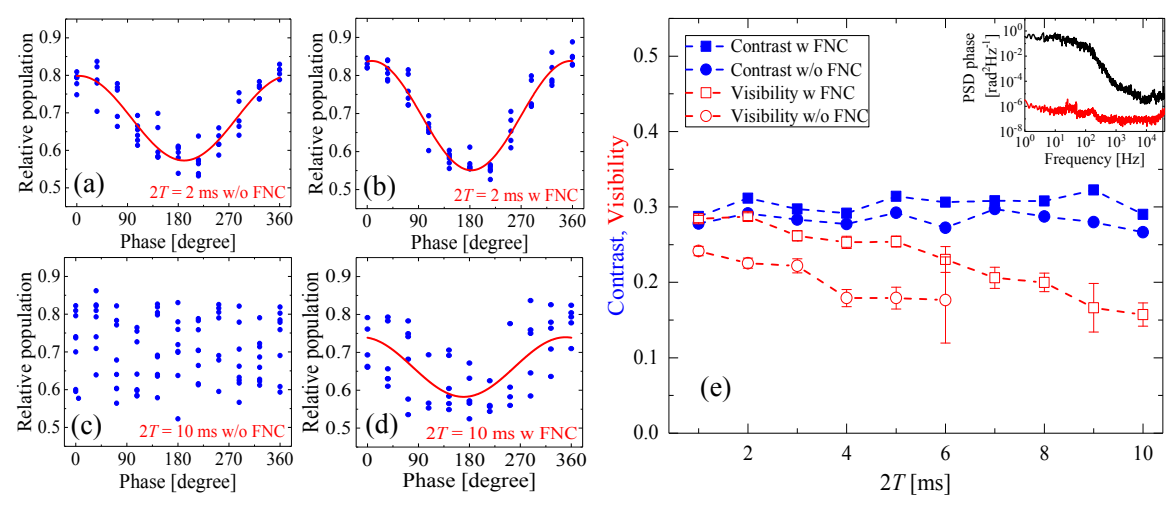
(Right) Ultralight fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [A. Arvanitaki, J. Huang, and K. Van Tilburg. 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]**

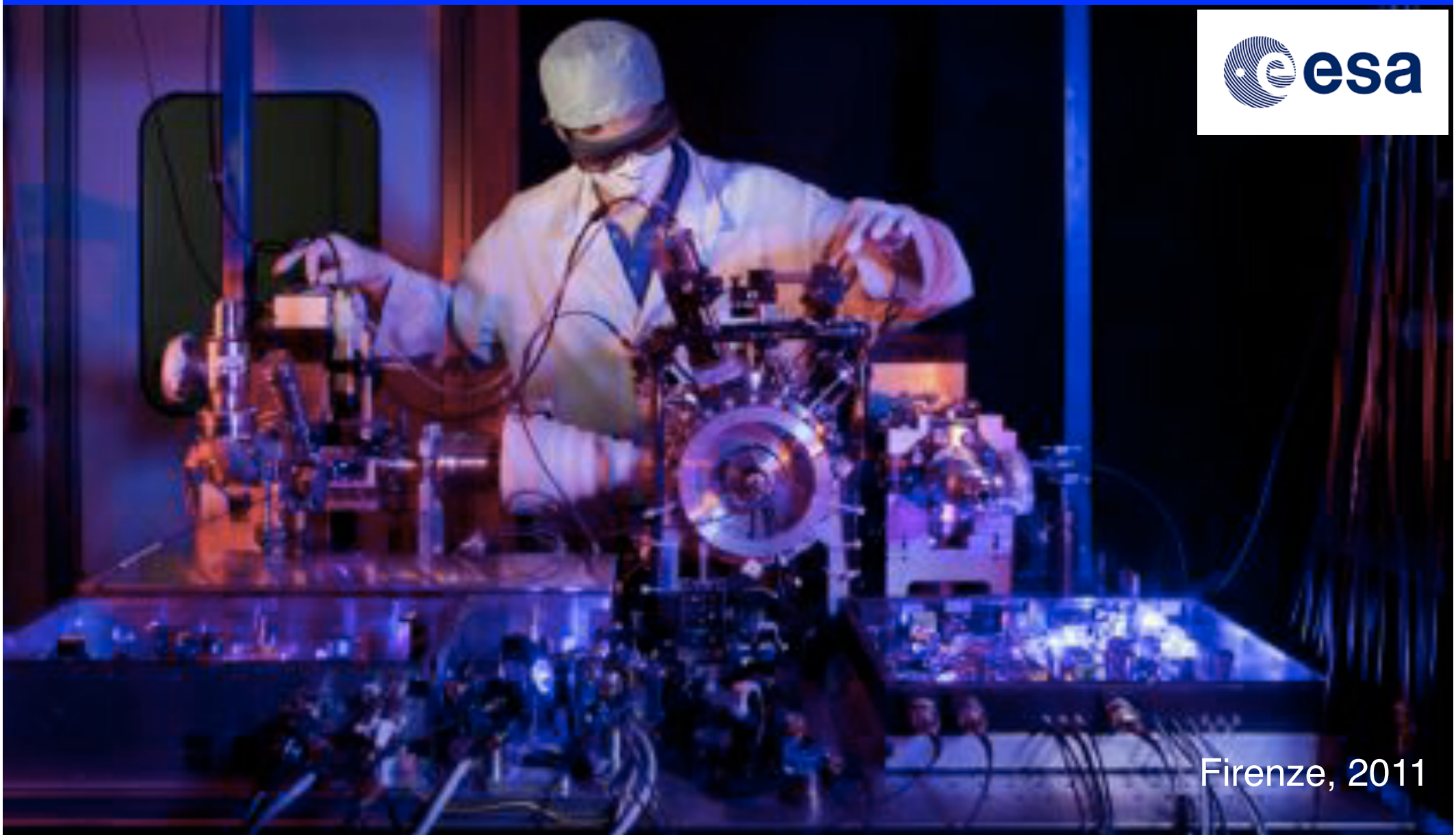
# *Atom interferometry with the Sr optical clock transition*

# SAGE Pathfinder

**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]**

# SAGE: SPACE ATOMIC GRAVITY EXPLORER

## Strontium Atomic Interferometers and Clocks in Space for Fundamental Physics and Applications



Firenze, 2011

# *MAGIA ➡ MAGIA-Adv*

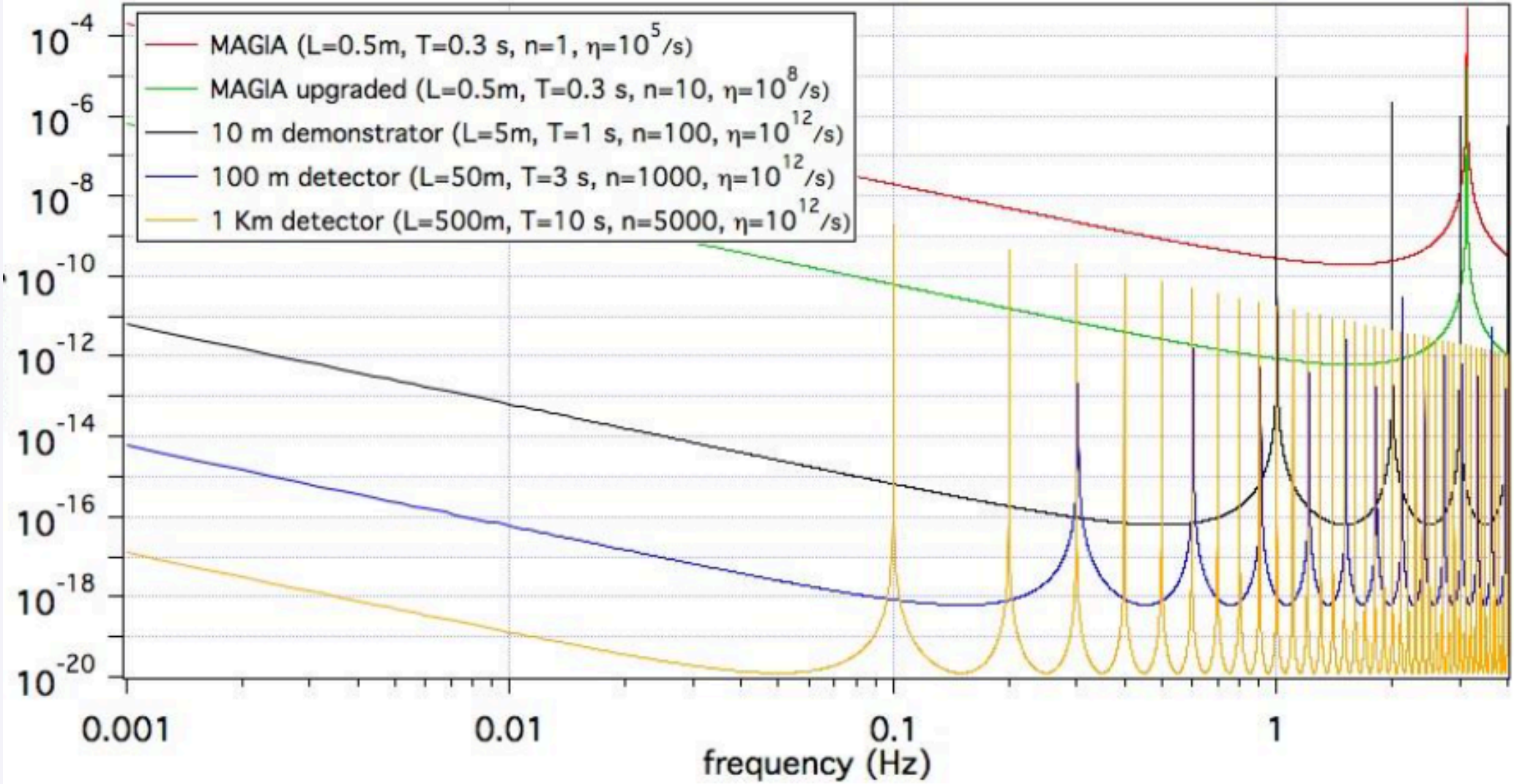
## Advanced atomic quantum sensors for gravitational physics

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

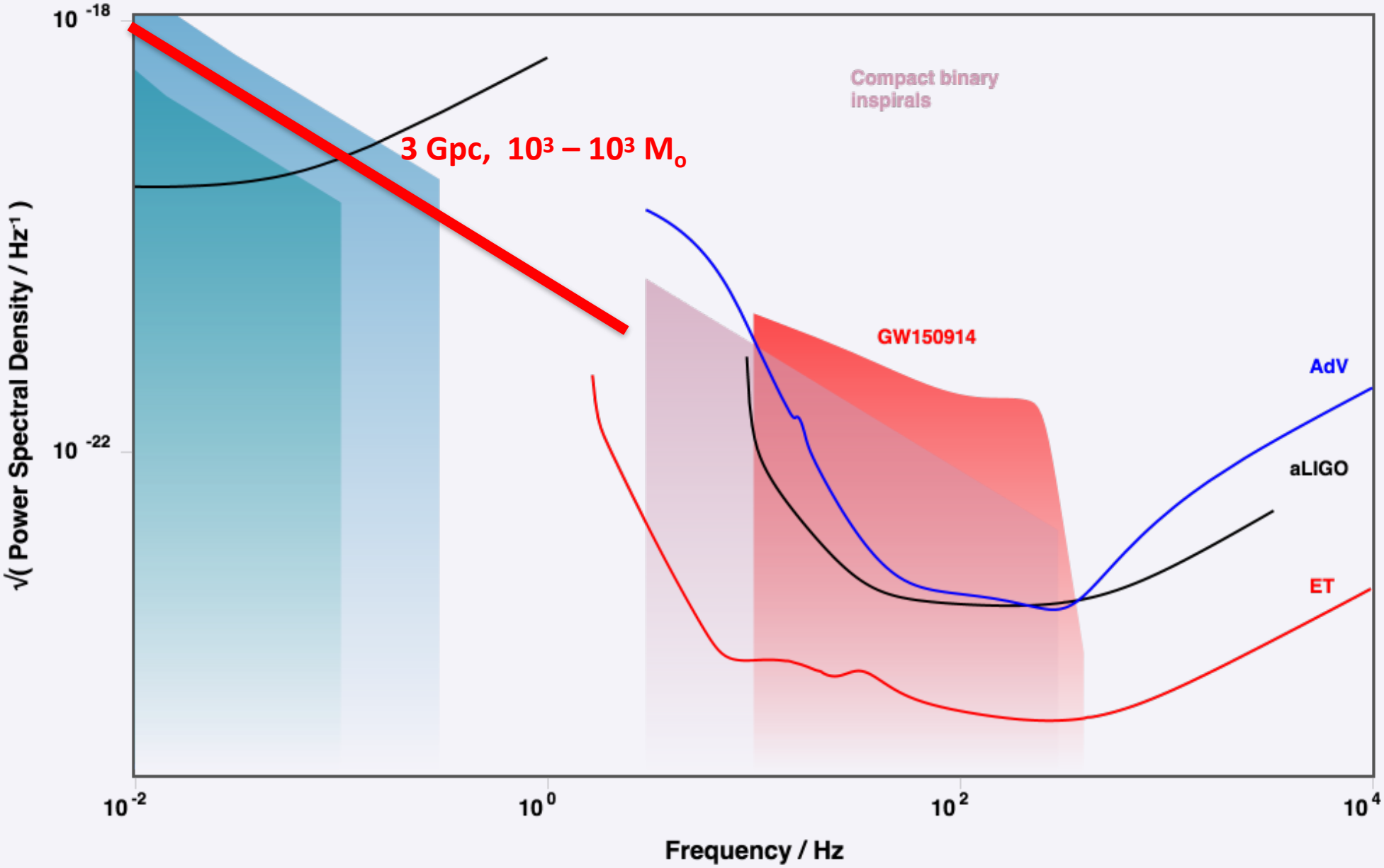
- **Sezioni: Firenze (+Urbino), Pisa**

$$h_{rms} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}}$$

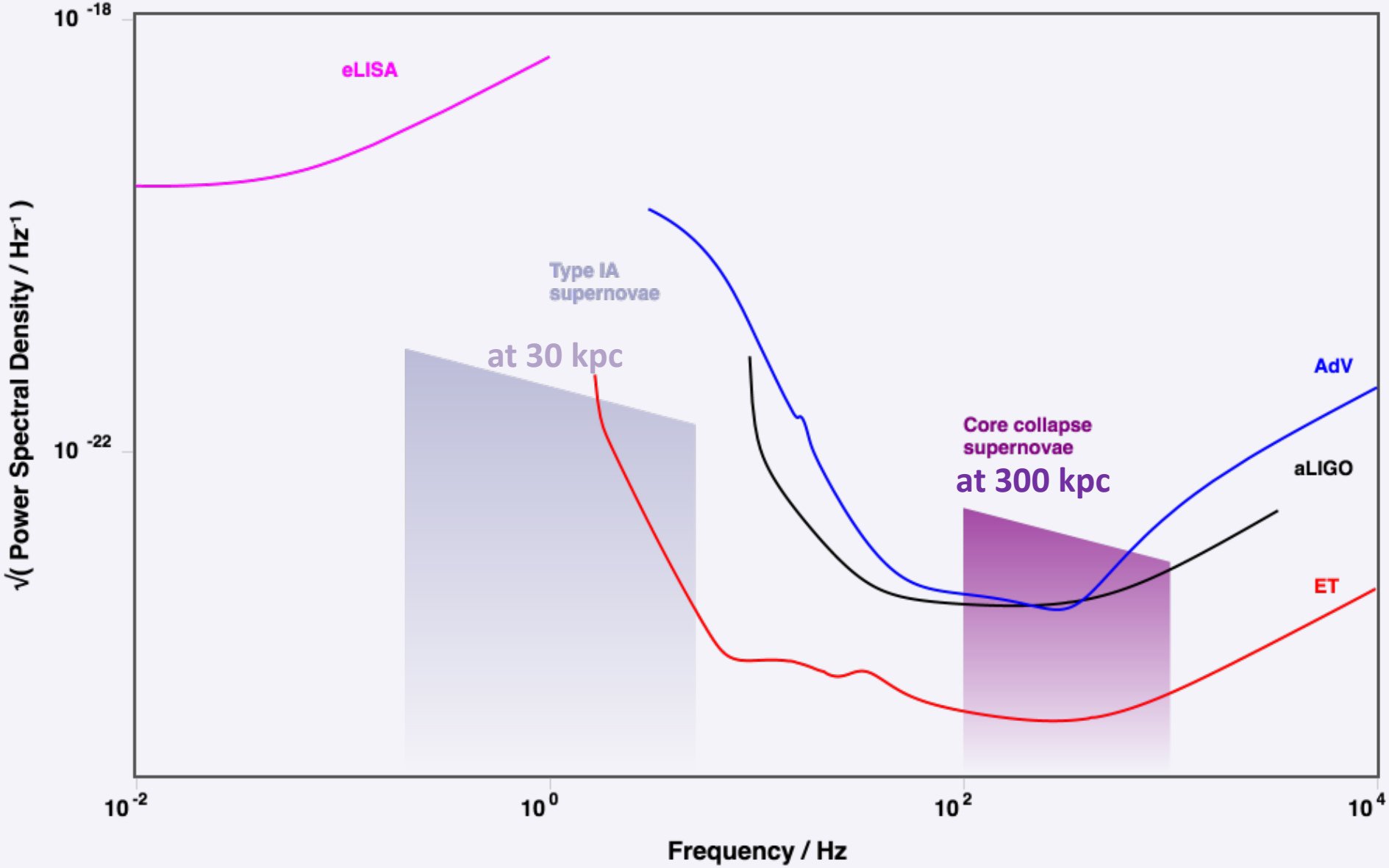
# Shot noise limited (diff. configuration)



# Example: IMBH $10^3 – 10^3$ $M_{sol}$

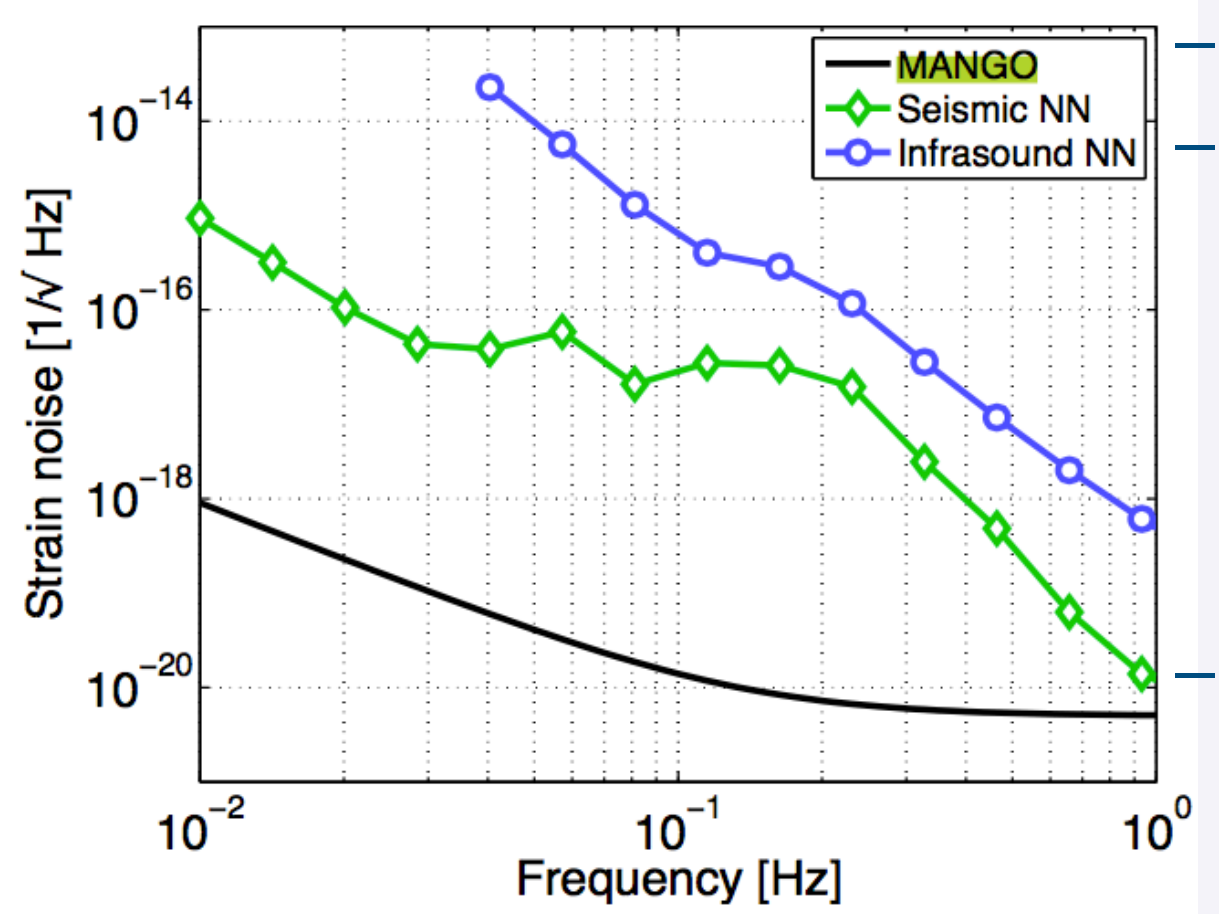


# *Supernovae Ia* and sensitivity




- *Possibly* visible within Milky Way, but infrequent (1/100 yr)

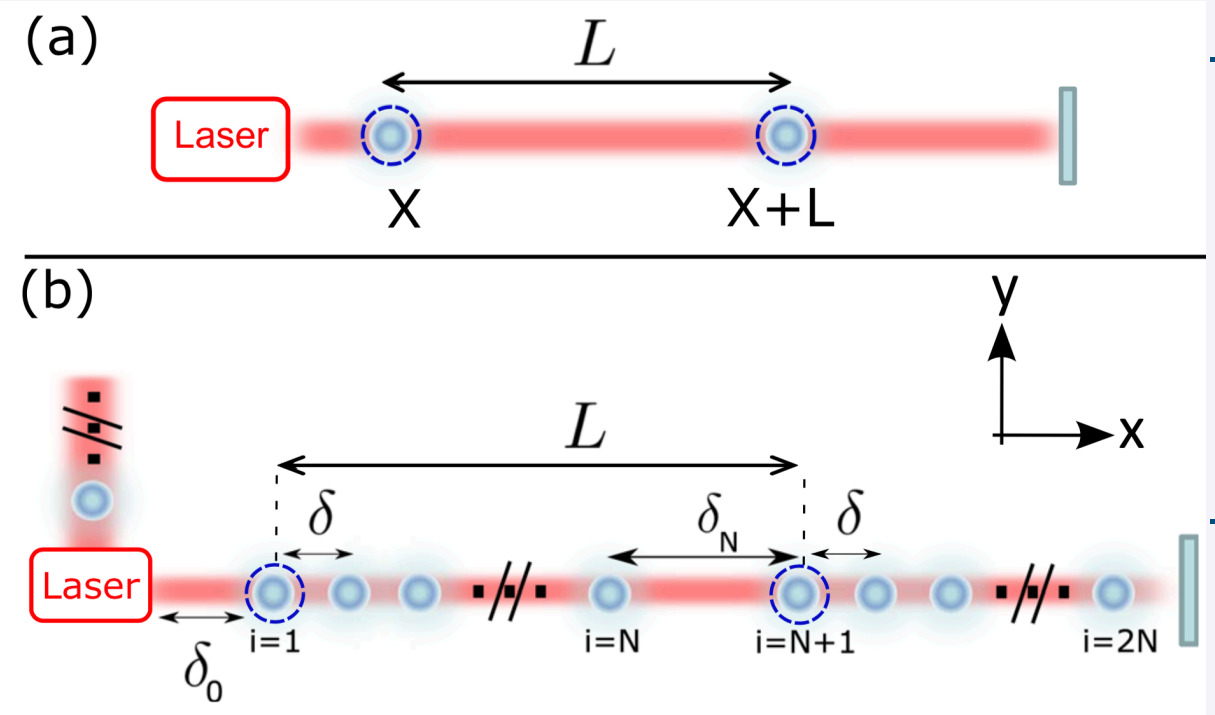
# What about Newtonian noise?




- Potential **show-stopper**
- Cancellation *possible* with additional information from seismometers and microphones [to reject seismic and infrasound noise respectively]
- Require high sensitivity [SNR=O($10^3$) at micro-seismic peak]
- **Getting below $10^{-20}$ at $10^{-1}$ Hz is *plausible*.**
- **10 mHz is a hard limit**

- J.Harms, H.J.Paik, PRD 92 (2015) 022001
- Harms, J. Living Rev Relativ (2015) 18: 3.

# "Internal" NN cancelling schemes




Chaibi *et al*, PRD 93, 021101(R) (2016)

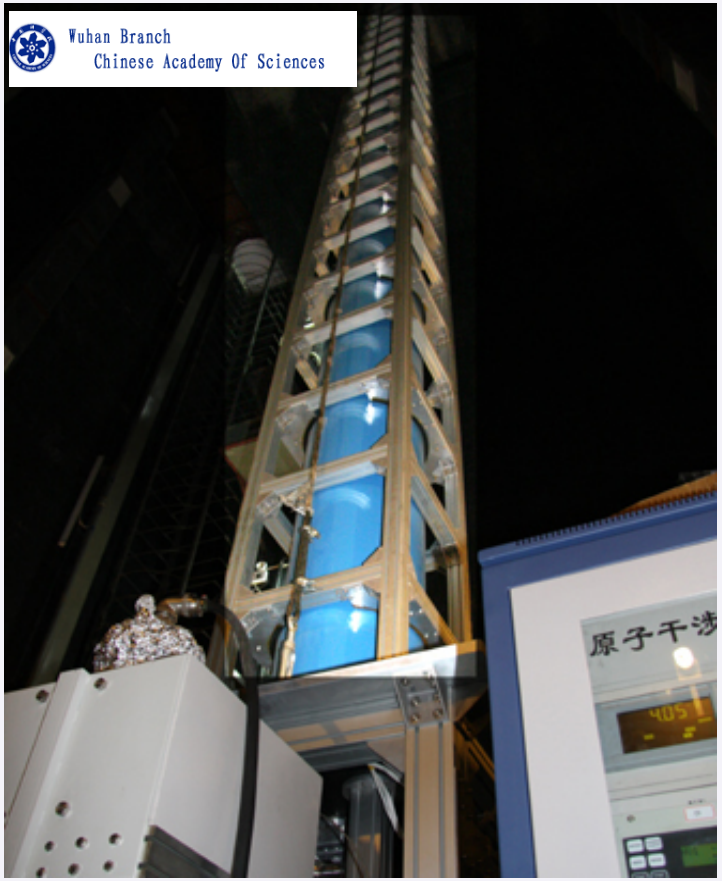
- Use an array of AI gradiometers to sample spatial variations of NN and subtract
- Promising, but claimed rejection factors [ O(10) ] still insufficient to achieve required sensitivity

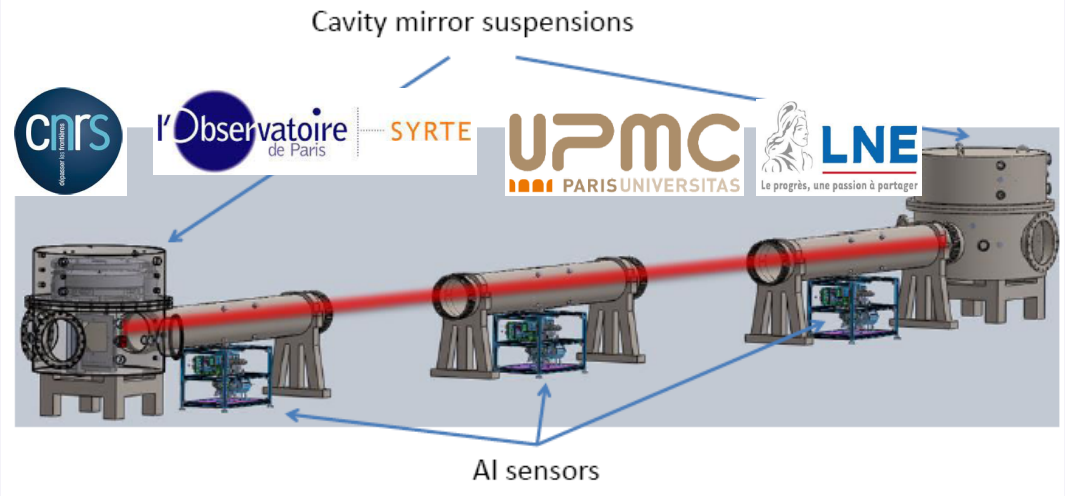
**R&D and dedicated facilities are required to test and demonstrate subtraction/ cancellation schemes for Newtonian Noise**

# Large-scale atom interferometers

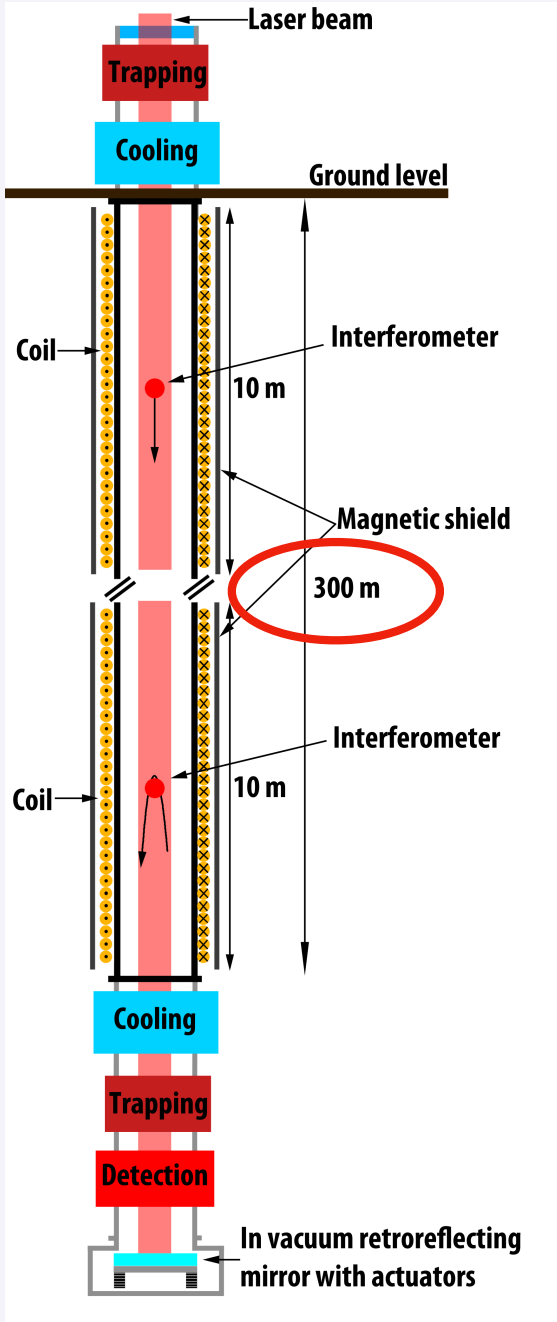
10 m fountain at Stanford

12 m fountain at Wuhan




# Large-scale atom interferometer
# ⇒ Sardegna?



# Possible experiments with the new apparatus

PRL 113, 023005 (2014) PHYSICAL REVIEW LETTERS week ending 11 JULY 2014

**Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms: Search for Spin-Gravity Coupling Effects**

M. G. Tarallo,* T. Mazzoni, N. Poli, D. V. Sutyrin, X. Zhang,† and G. M. Tino‡
*Dipartimento di Fisica e Astronomia and LENS—Università di Firenze, INFN—Sezione di Firenze, Via Sansone 1*
(Received 24 Feb

PRL 103, 171302 (2009) PHYSICAL REVIEW LETTERS week ending 23 OCTOBER 2009

**Constraining the Energy-Momentum Dispersion Relation with Planck-Scale Sensitivity Using Cold Atoms**

Giovanni Amelino-Camelia,[1] Claus Laemmerzahl,[2] Flavio Mercati,[1] and Guglielmo M. Tino[3]
[1]*Dipartimento di Fisica, Università di Roma "La Sapienza" and Sezione Roma1 INFN, Piazzale Moro 2, 00185 Roma, Italy*
[2]*ZARM, Universität Bremen, Am Fallturm, 28359 Bremen, Germany*
[3]*ne INFN di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy*
published 21 October 2009)

coil experiments to constrain the form of the energy-
expected to be modified in several quantum-gravity
nonrelativistic (small speeds) limit of the dispersion
ogous ongoing effort of investigation of the dispersion
tions in astrophysics. For the leading correction in the

PHYSICAL REVIEW A 89, 052118 (2014)

**Testing the $a_\mu$ anomaly in the electron sector through a precise measurement of $h/M$**

F. Terranova[1] and G. M. Tino[2,*]
[1]*Department of Physics, University of Milano-Bicocca and INFN, Sezione di Milano-Bicocca, Milano, Italy*
[2]*Department of Physics and Astronomy and LENS Laboratory, University of Florence, INFN Sezione di Firenze, Sesto Fiorentino (FI), Italy*
(Received 13 April 2014; published 19 May 2

The persistent $a_\mu \equiv (g-2)/2$ anomaly in the muon sector could be due t
sector through a sub-ppb (parts per $10^9$) measurement of the anomalous m
Driven by recent results on the electron mass [S. Sturm *et al.*, Nature 506, 46
of uncertainties that limit our knowledge of $a_e$ including current advances in a
that it is possible to attain the level of precision needed to test $a_\mu$ in the naiv
similar to next-generation $g-2$ muon experiments at Fermilab and JPAR
precision, knowledge of the quotient $h/M$, i.e., the ratio between the Planck
employed in the interferometer, will play a crucial role. We identify the m
overall relative precision below $10^{-10}$.

DOI: 10.1103/PhysRevA.89.052118 PACS numbe

I. INTRODUCTION

In the last 40 years, the experimental accuracy of the anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$

the atom emplo
and the ratio between the Planck constant and the atom mass ($h/M$; Sec. III E). For each of these observables we determine the best current accuracy and the improvements that are needed

IOP PUBLISHING MEASUREMENT SCIENCE AND TECHNOLOGY
Meas. Sci. Technol. 20 (2009) 022001 (16pp) doi:10.1088/0957-0233/20/2/022001

TOPICAL REVIEW

**Precision gravimetry with atomic sensors**

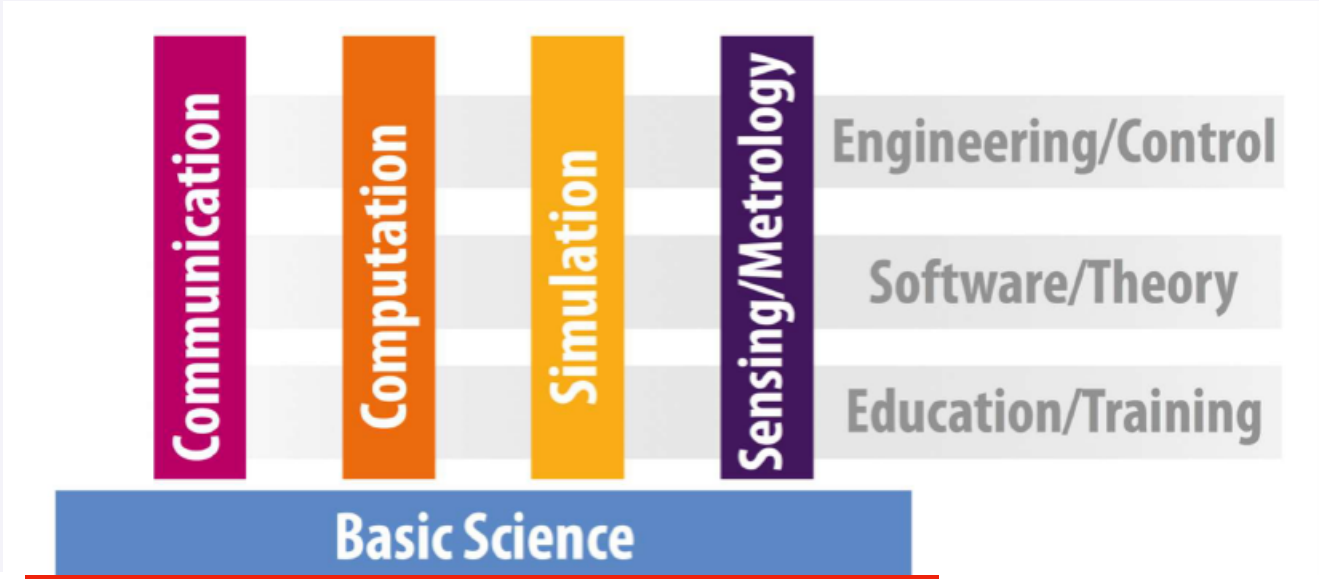
M de Angelis[1,2], A Bertoldi[3], L Cacciapuoti[4], A Giorgini[2,5], G Lamporesi[6], M Prevedelli[7], G Saccorotti[8], F Sorrentino[2] and G M Tino[2]

# EUROPEAN QUANTUM FLAGSHIP PROGRAM

European Commission

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020




## "Gravity Quantum Sensors"


| Participant | Participant organisation name | Country |
|---|---|---|
| 1 (Coordinator) | CNRS | FR |
| 2 | LUH IQO | DE |
| 3 | MUQUANS | FR |
| 4 | LENS | IT |
| 5 | IOTA | FR |
| 6 | FORTH | EL |
| 7 | LUH IFE | DE |
| 8 | LUH IMPT | DE |
| 9 | INFN | IT |
| 10 | INGV | IT |
| 11 | THALES | FR |
| 12 | ATOM SENSORS | IT |
| 13 | LIONIX | NL |
| 14 | ULM | DE |
| 15 | TU WIEN | AT |
| 16 | CNR-INO | IT |
| 17 | GFZ | DE |