GW detection by atom interferometry Status and prospects

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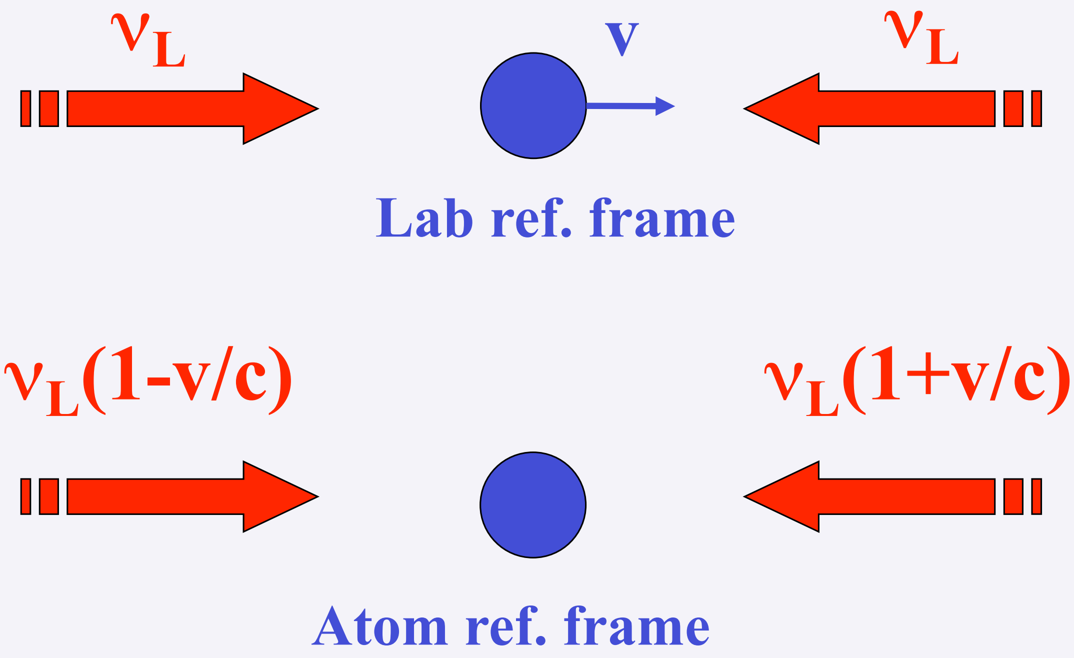
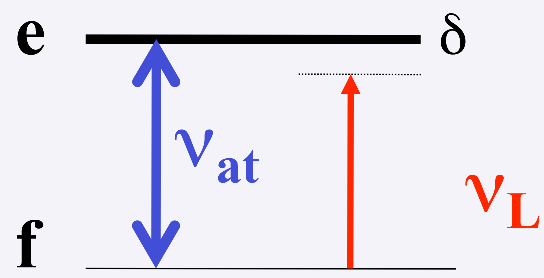
http://coldatoms.lens.unifi.it/

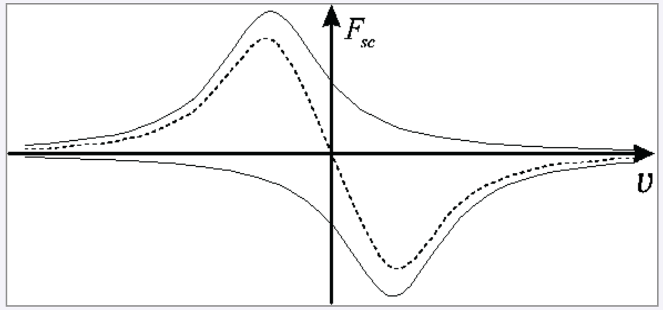
GWADW2019 - Isola d'Elba
24 May 2019

Laser cooling: Optical molasses





$\nu_{at} > \nu_L$



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

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

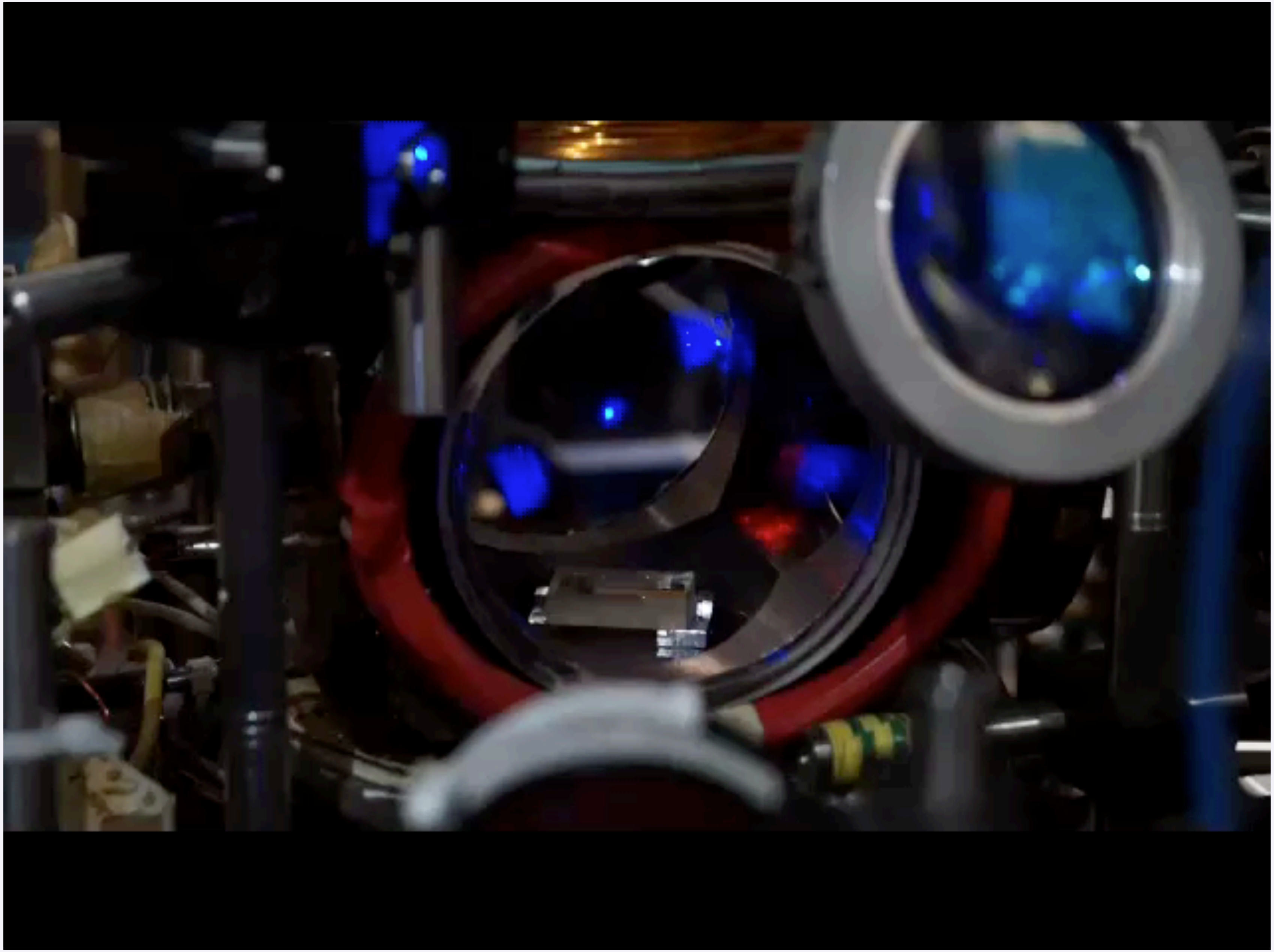
Recoil limit: $\boxed{k_B T_r = \frac{1}{M}\left(\frac{\hbar\nu_L}{c}\right)^2}$

Examples:

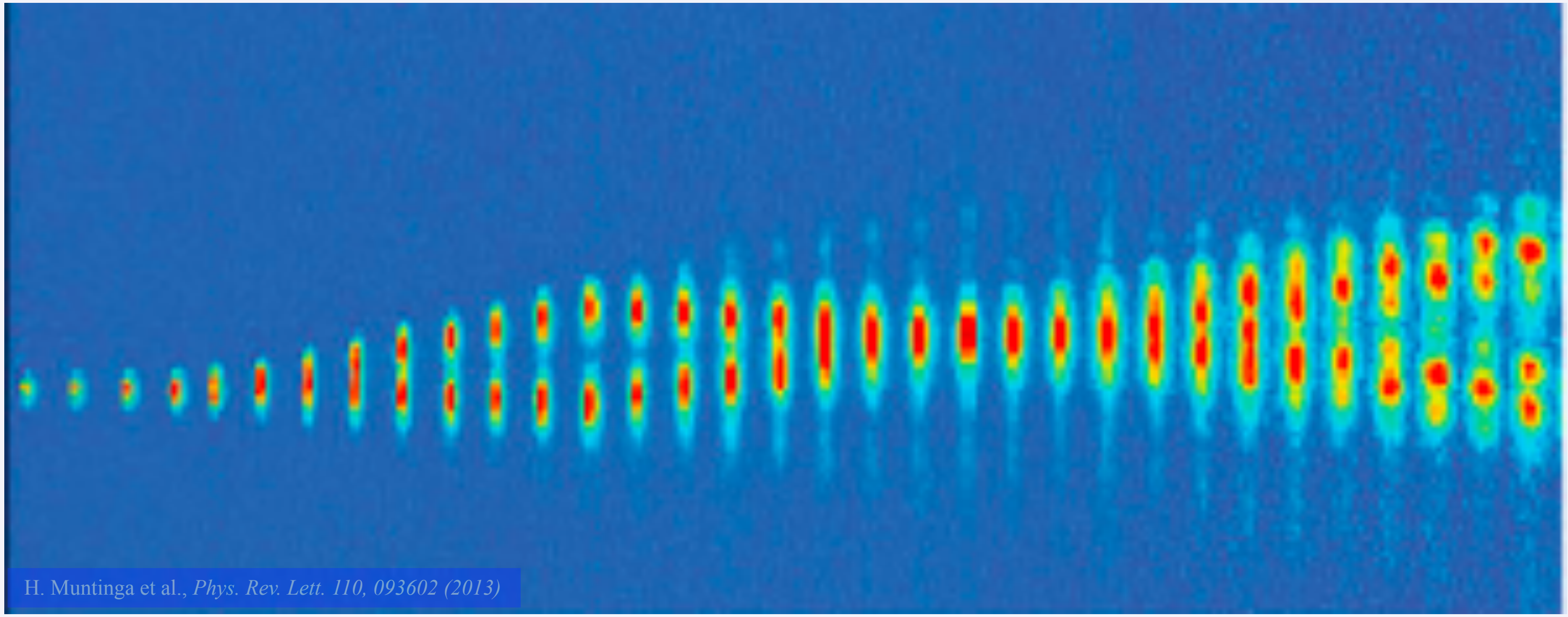
	T_D	T_r
Na	240 μK	2.4 μK
Rb	120 μK	360 nK
Cs	120 μK	200 nK
Sr	180 nK	460 nK

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

Sr Magneto-Optical Trap (MOT)
LENS - Firenze, 2004



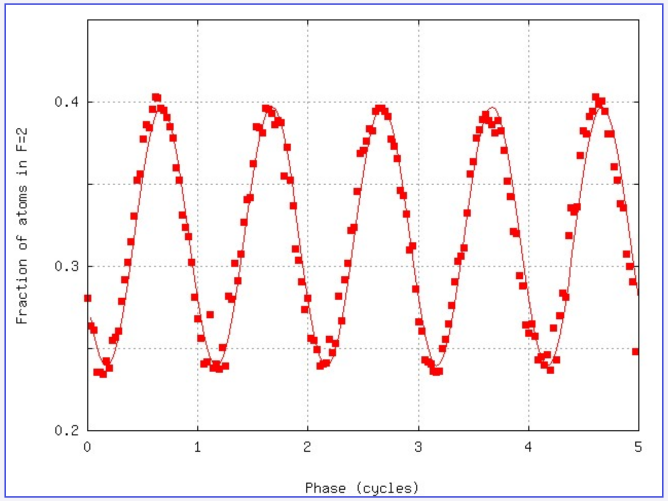
Atom interferometry



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

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

de Broglie wavelength

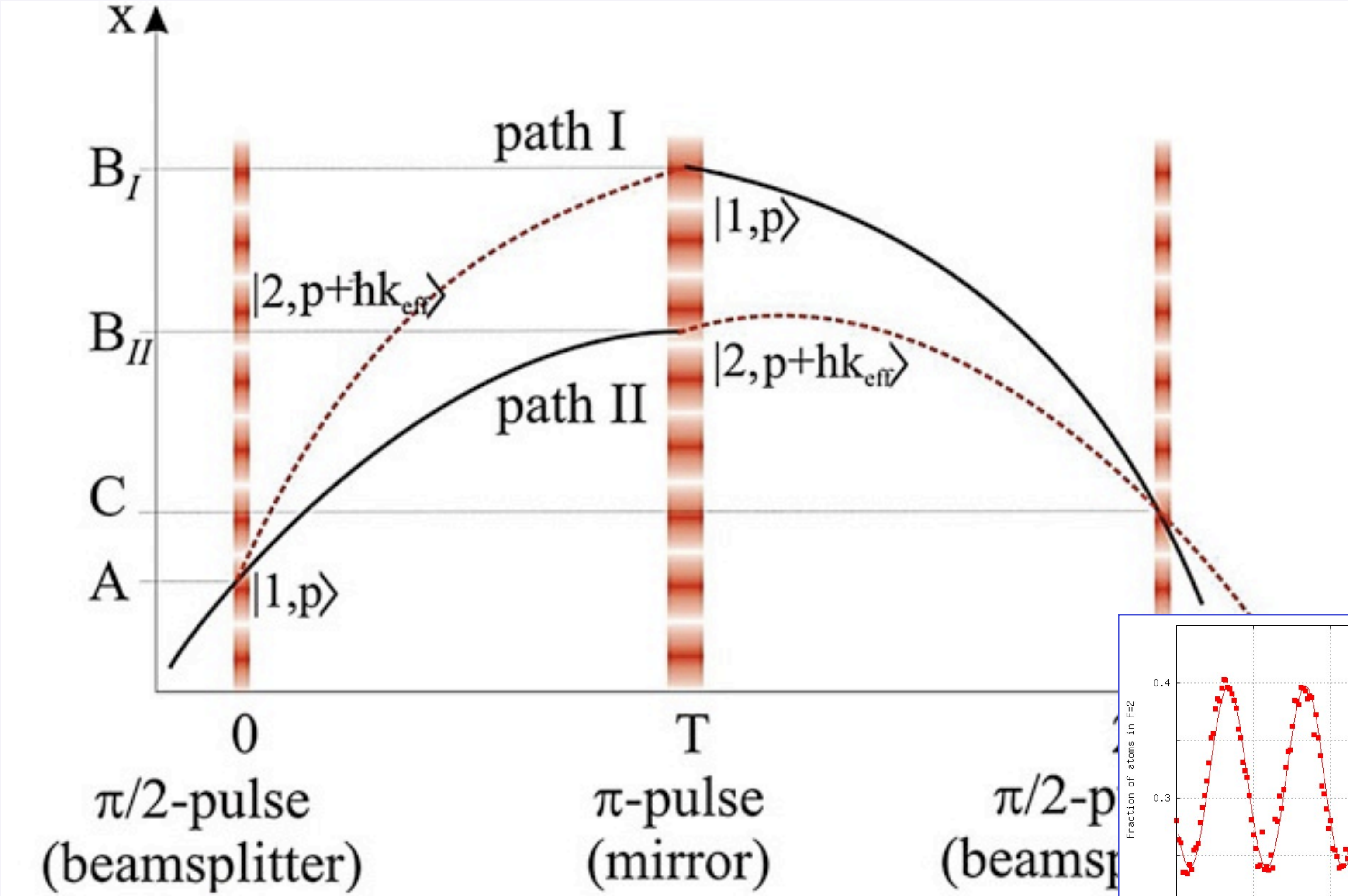


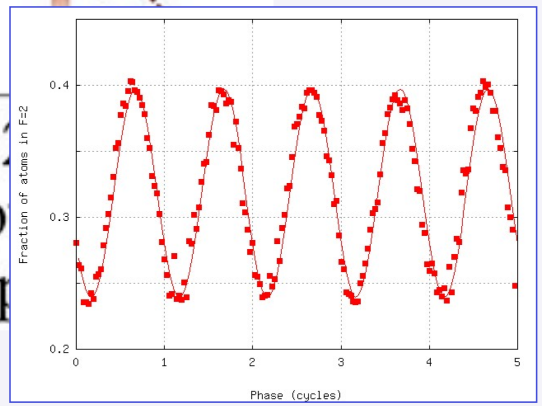
Atomic interference fringes – Firenze 2006

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

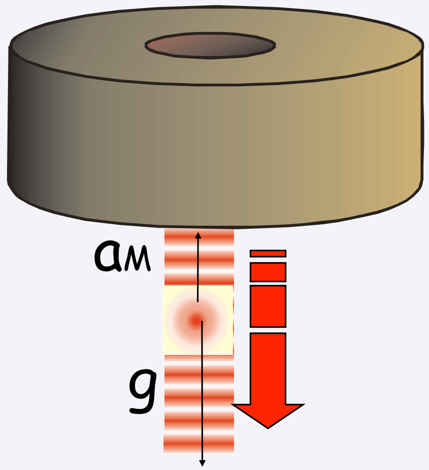




MAGIA

(Misura Accurata di G mediante Interferometria Atomica)

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

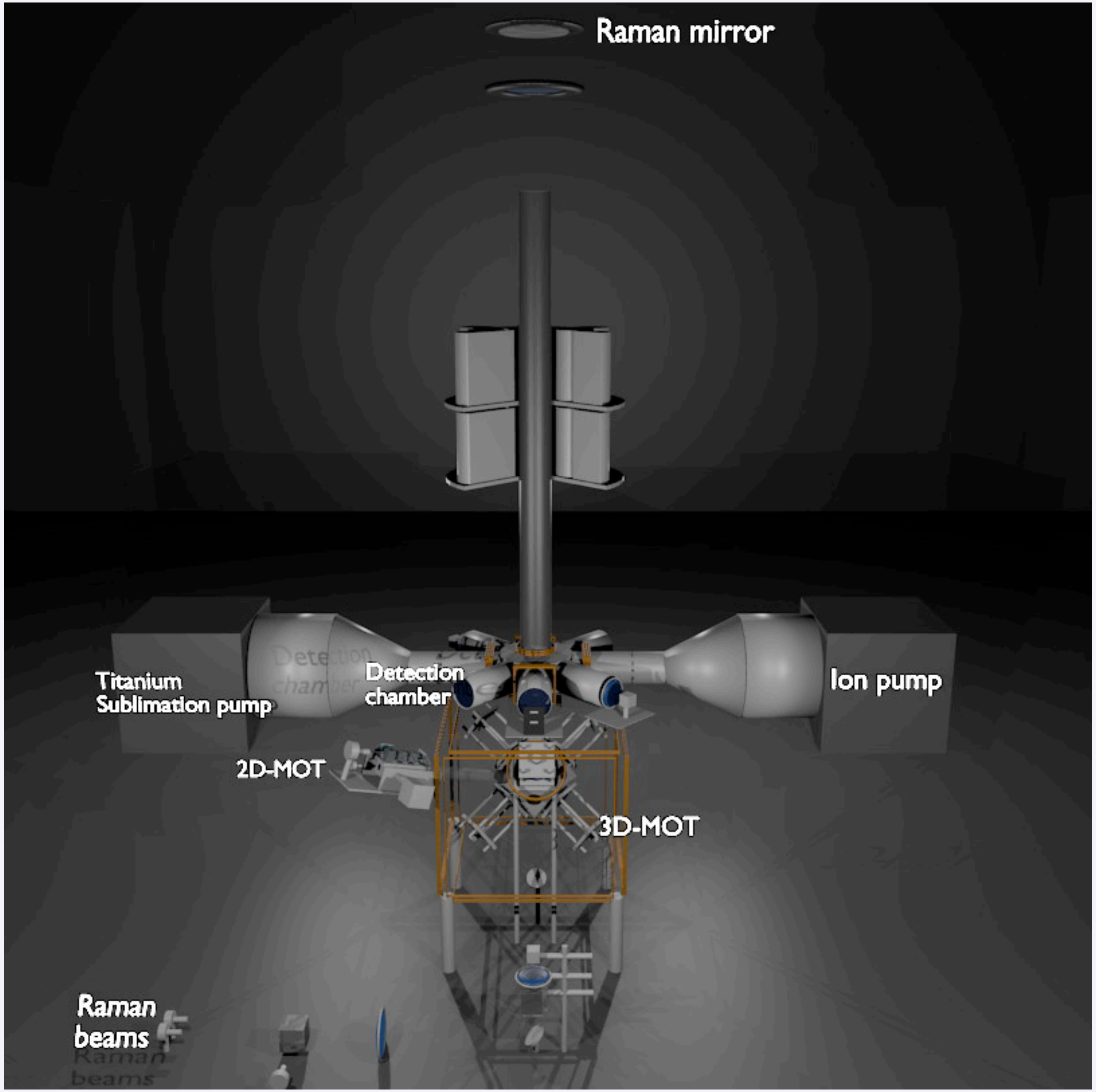


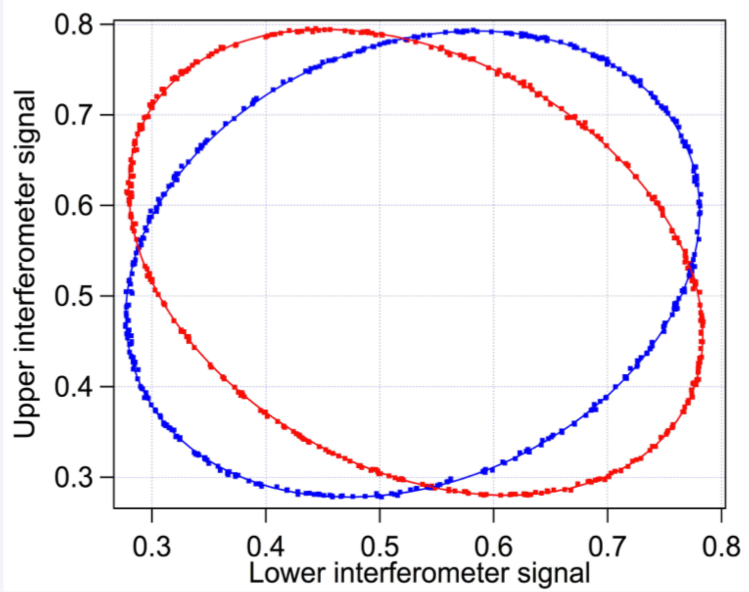
➢ ***Precision measurement of G***

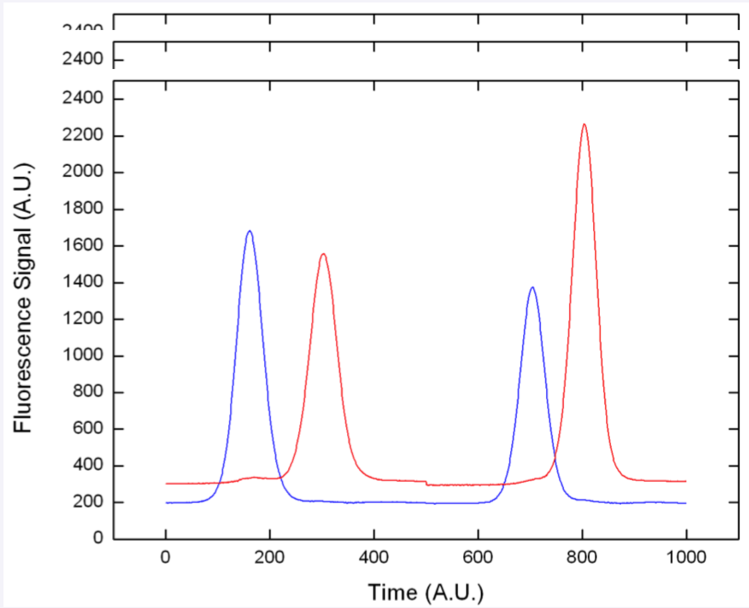
$$F(r) = G\frac{M_1 M_2}{r^2}$$

MAGIA

(Misura Accurata di G mediante Interferometria Atomica)







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.

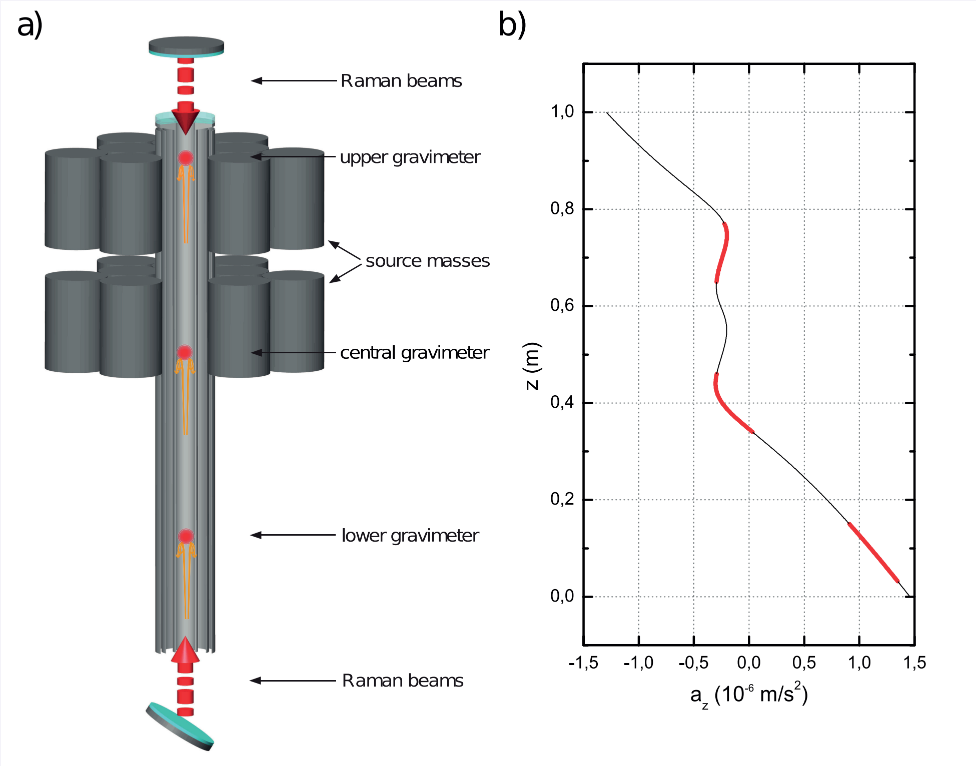
The atom interferometer is realized using light pulses to stimulate ^{87}Rb atoms at the two-photon Raman transition between the hyperfine

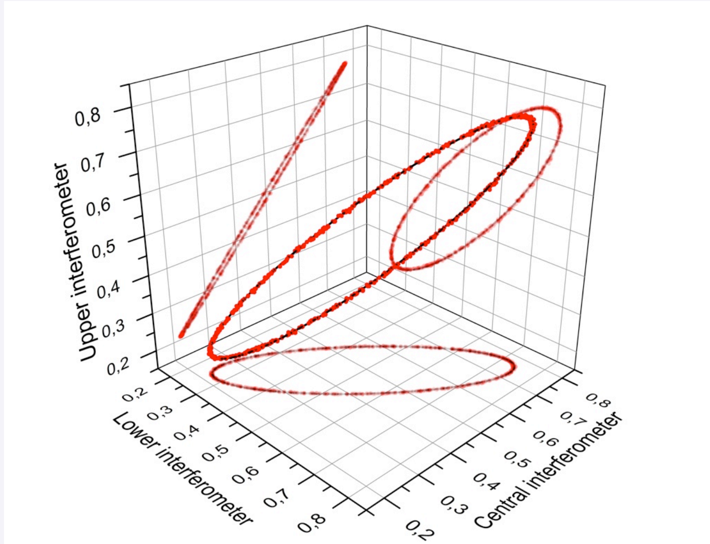
$$G = 6.67191(77)(62) \times 10^{-11}\ \mathrm{m^3\ kg^{-1}\ s^{-2}}$$

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)

Measurement of the Gravity-Field Curvature by Atom Interferometry





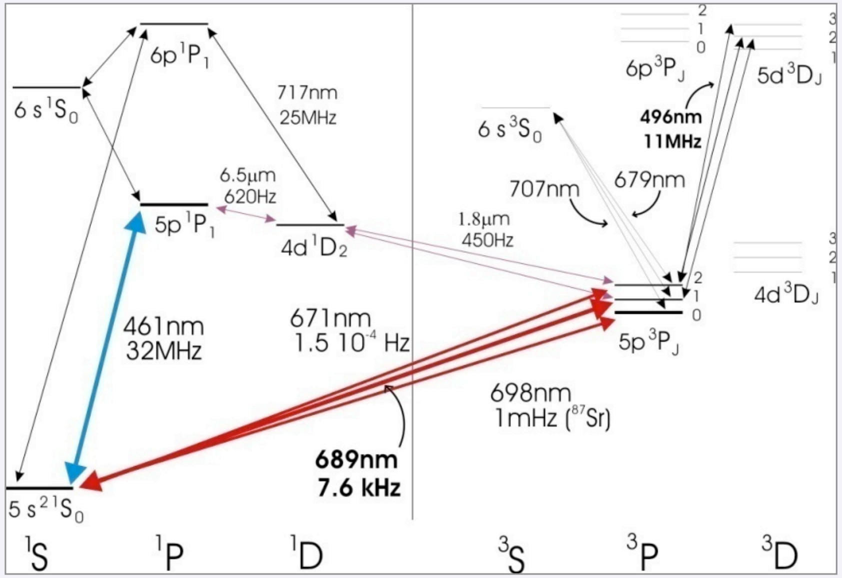
$$x(\theta) = A + B\sin\theta,$$

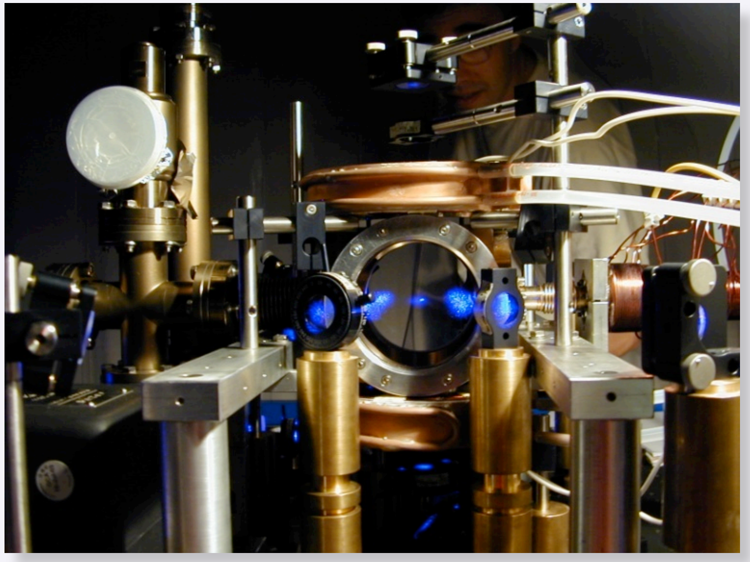
$$y(\theta) = C + D\sin(\theta + \varphi_1),$$

$$z(\theta) = E + F\sin(\theta + \varphi_1 + \varphi_2)$$

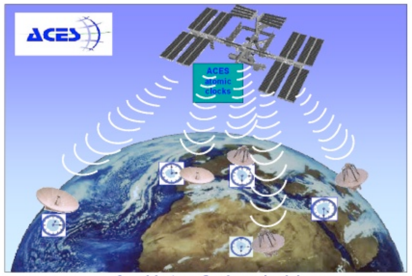
G. Rosi, L. Cacciapuoti, F. Sorrentino, M. Menchetti, M. Prevedelli, G. M. Tino, *Measurement of the Gravity-Field Curvature by Atom Interferometry,* **Phys. Rev. Lett. 114, 013001 (2015)**

Ultracold Sr - Experiments in Firenze





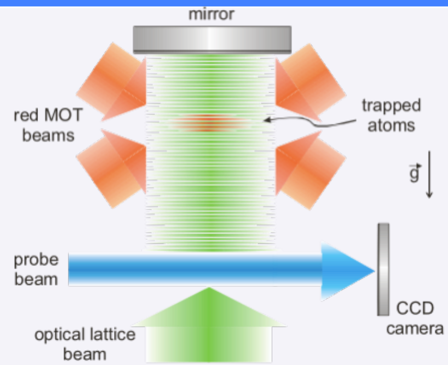
- Optical clocks using visible intercombination lines



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

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

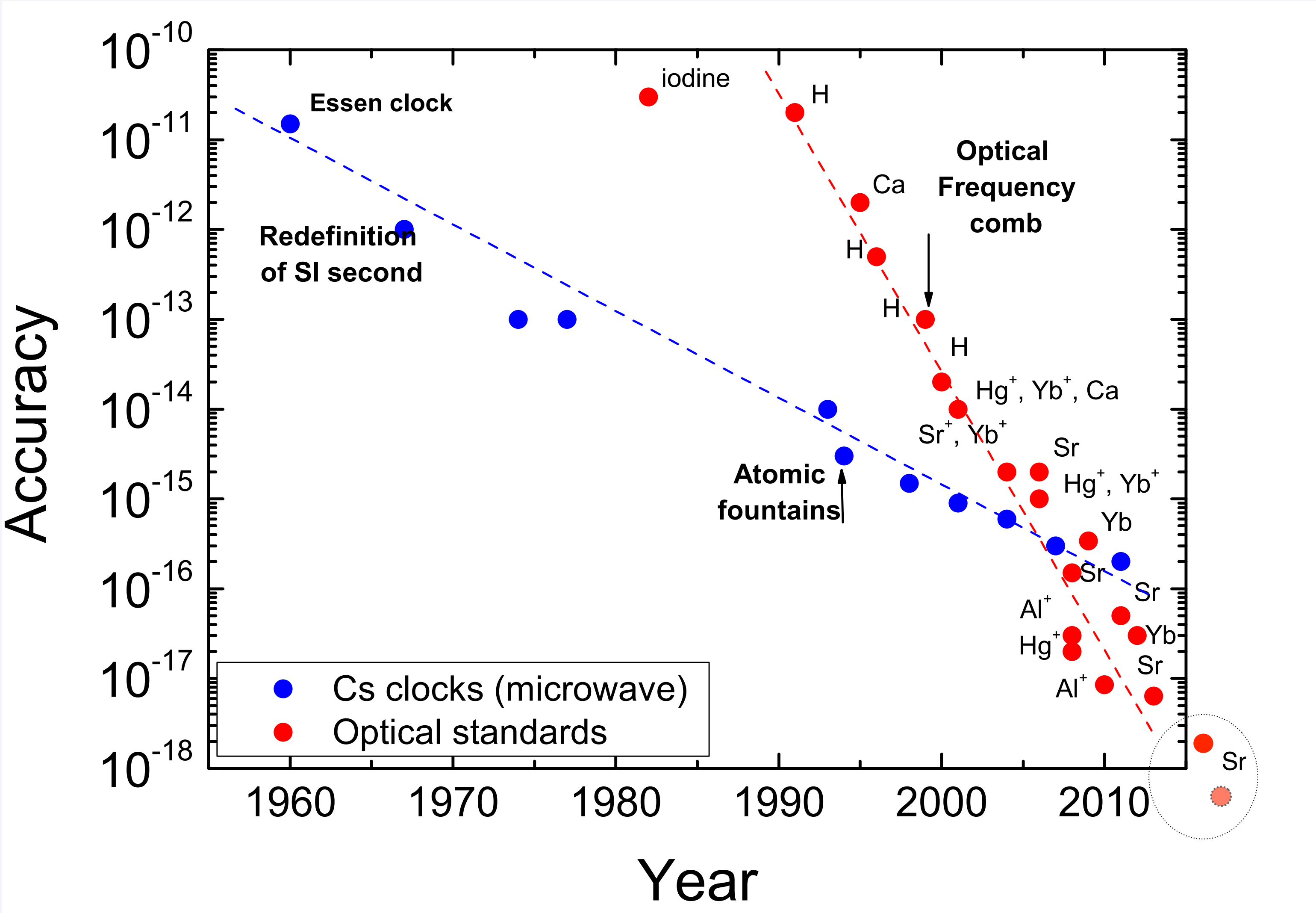
- New atomic sensors for fundamental physics tests



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

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

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

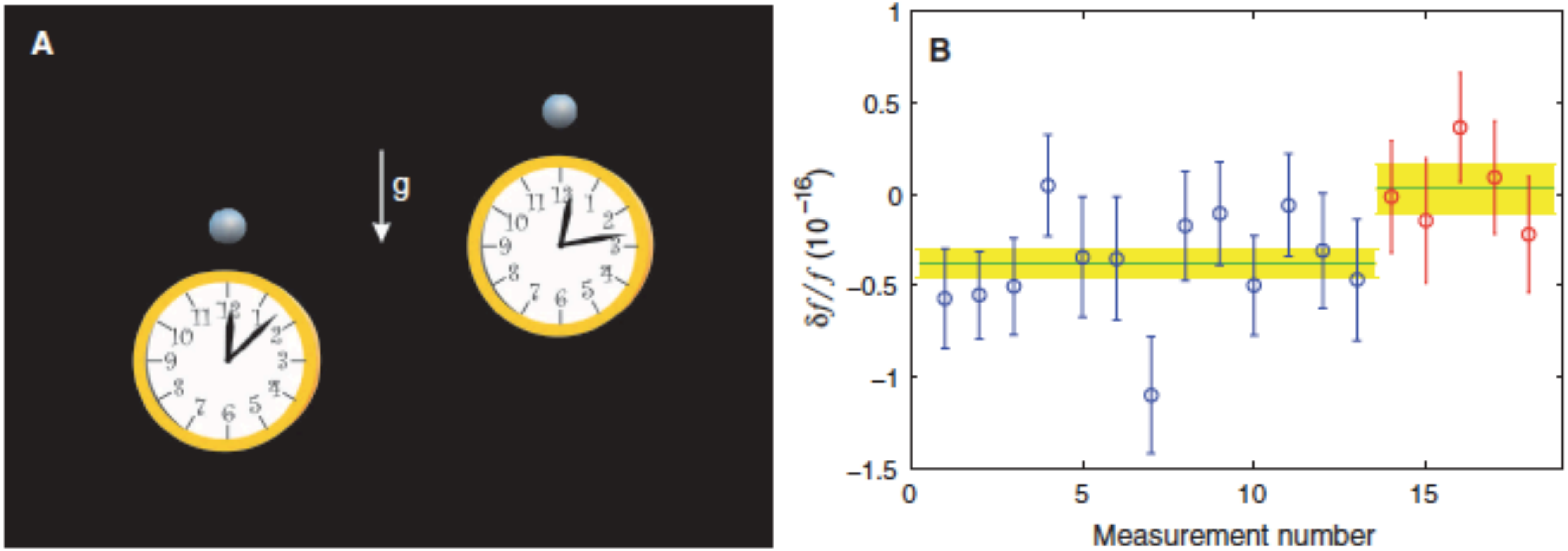
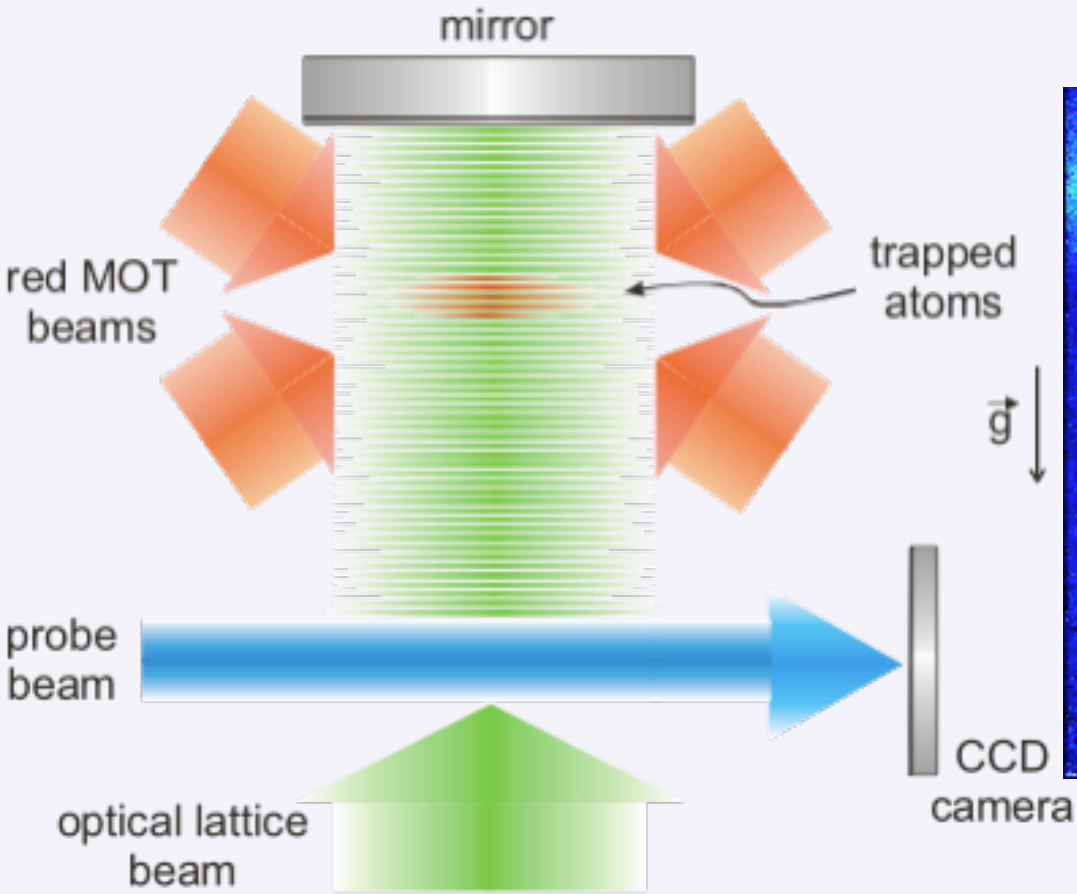
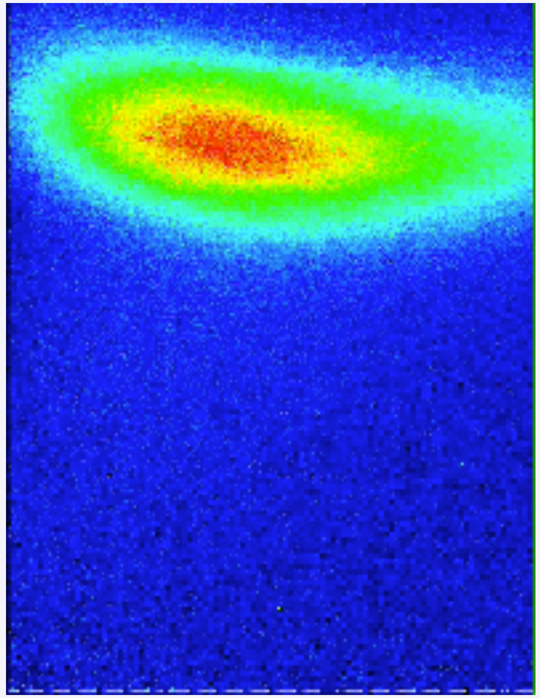


Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg 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

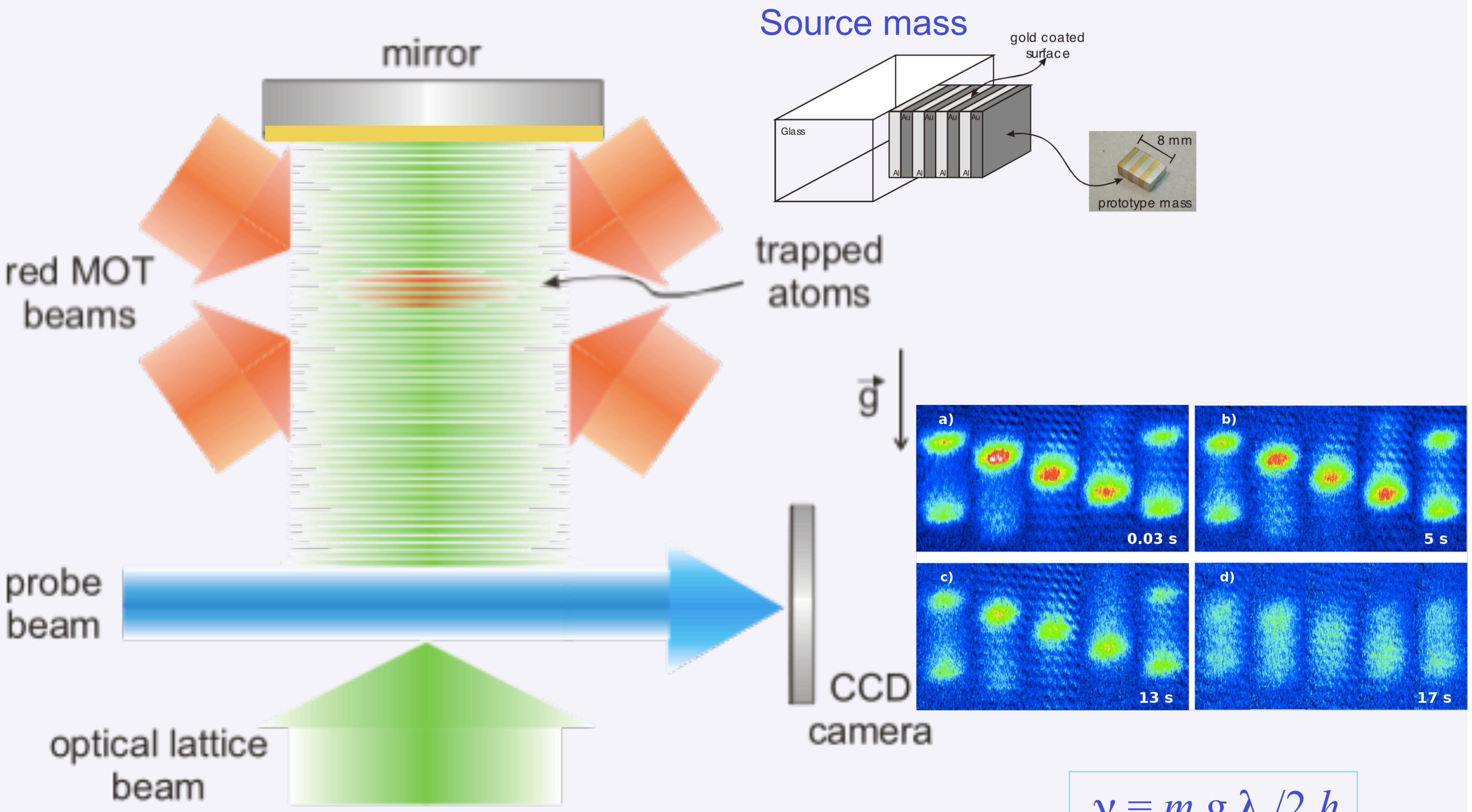




$\nu = m\,g\,\lambda\,/2\,h$

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)**

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 *=* 10^3*-*10^4**

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

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

Einstein Equivalence Principle
→ Universality of the Free Fall

The trajectory of a freely falling "test" body is independent of its internal structure and composition

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

^{88}Sr

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

^{87}Sr

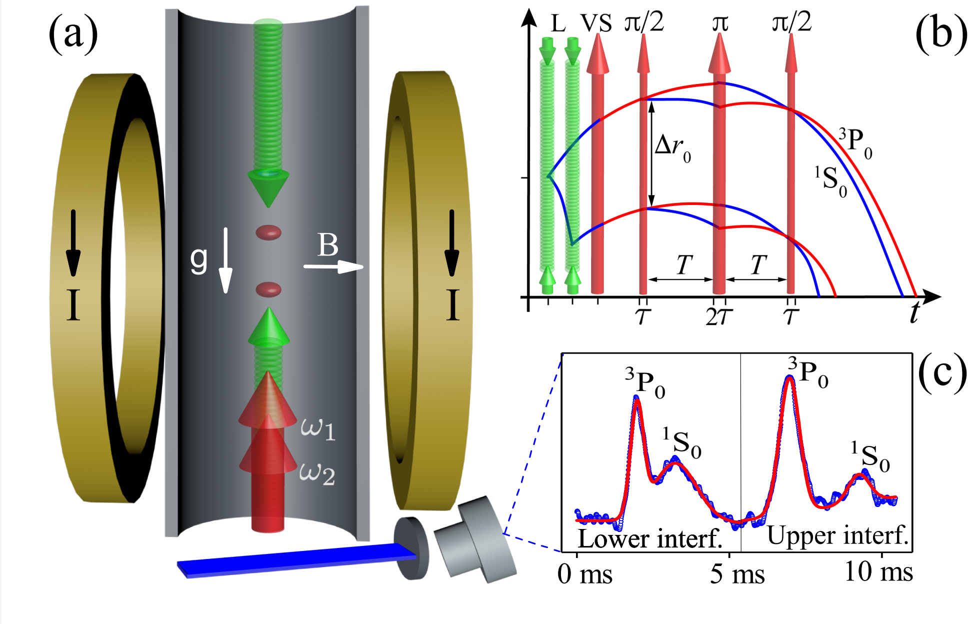
- **Total spin ≡ nuclear spin I = 9/2**
- **Fermion**

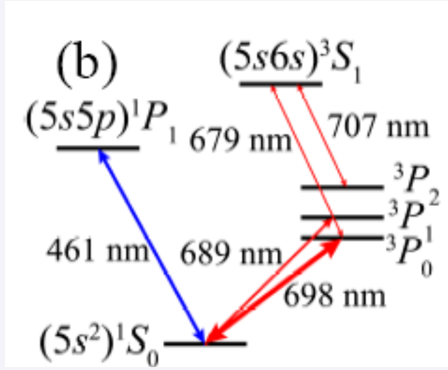
Comparison of the acceleration of ^{88}Sr and ^{87}Sr under the effect of gravity by measuring the Bloch frequencies in a vertical optical lattice

Search for EP violations due to spin-gravity coupling effects

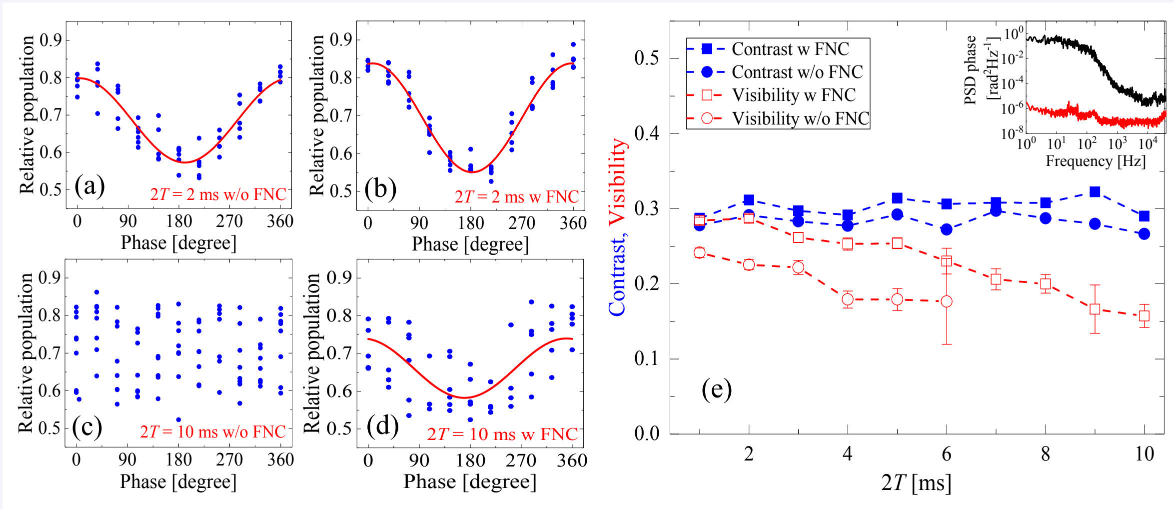
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects*, **Phys. Rev. Lett. 113, 023005 (2014)**

Atom interferometry with the Sr optical clock transition





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

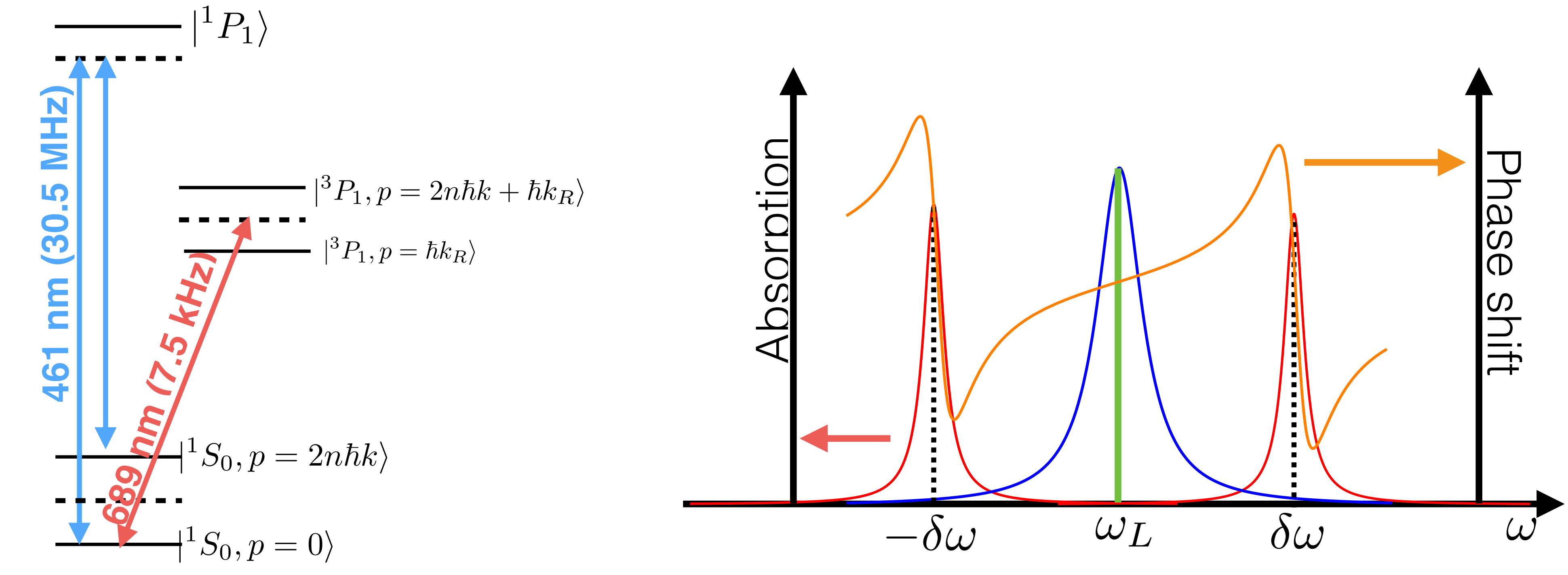


Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]

Squeezing on momentum states for atom interferometry

Goal: production of squeezed states of the atomic center-of-mass motion that can be injected into an atom interferometer.

Proposed method: dispersive probing in a ring resonator on a narrow transition for a collective measurement of the relative population of two momentum states.



Frequency splitting from Doppler effect

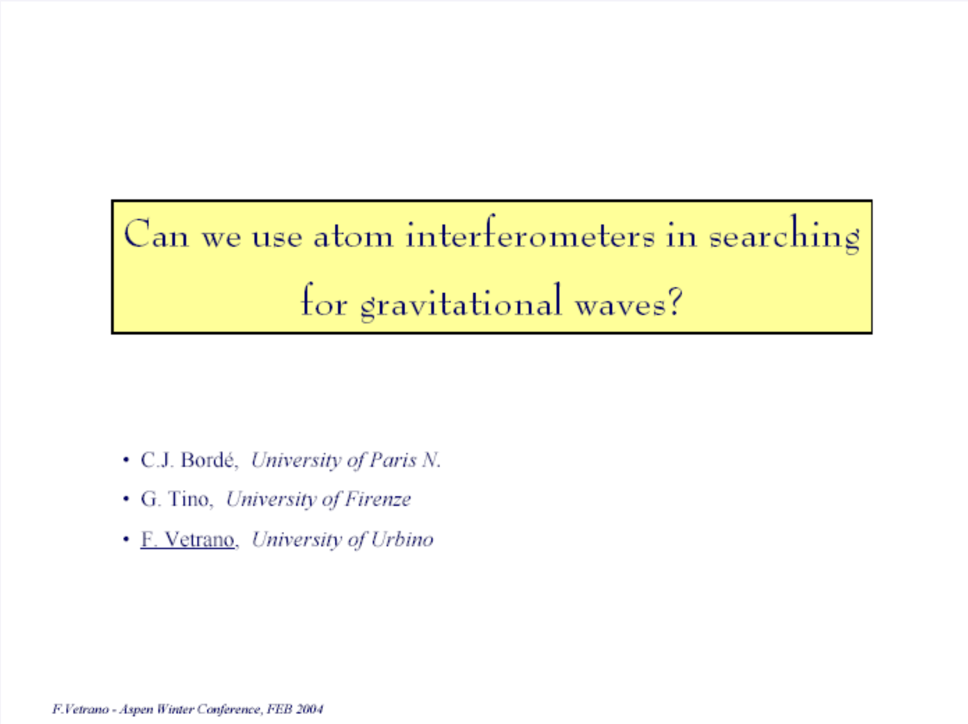
$$\delta\omega = 2\pi n \times 28.6 \text{ kHz}$$

Condition for dispersive regime:

$$\delta\omega \gg \Gamma$$

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

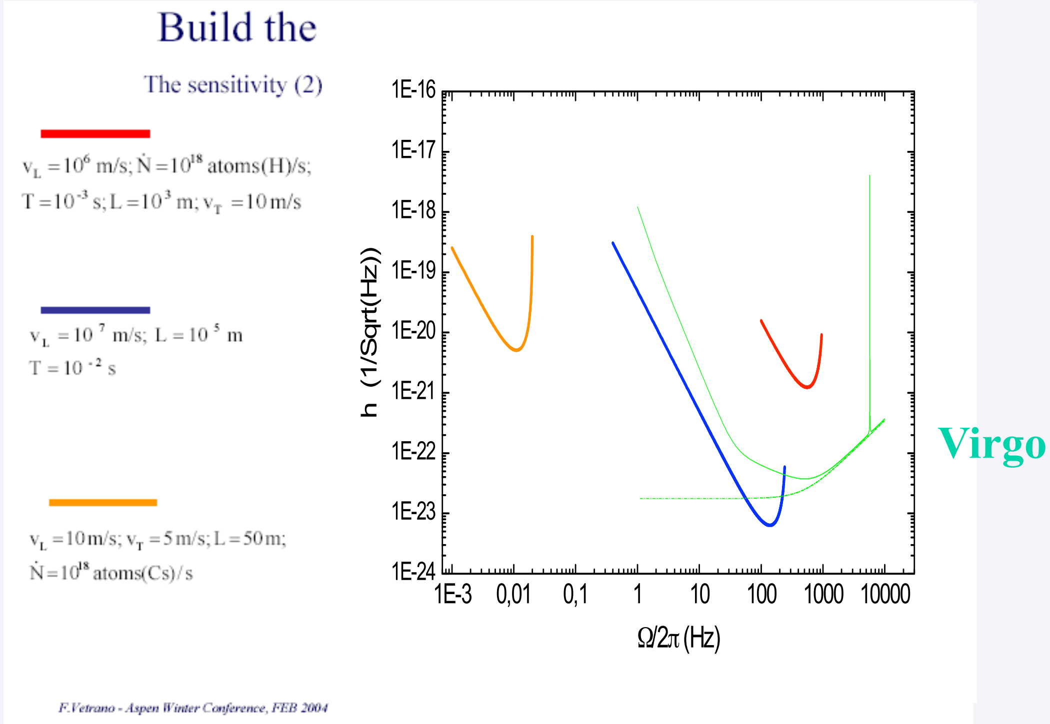
Gravitational waves detection with atom interferometry



Can we use atom interferometers in searching for gravitational waves?

- C.J. Bordé, *University of Paris N.*
- G. Tino, *University of Firenze*
- F. Vetrano, *University of Urbino*

F.Vetrano - Aspen Winter Conference, FEB 2004



- 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)

UNIVERSITÀ DEGLI STUDI FIRENZE

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)

Detection of Gravitational Waves by Atom Interferometry

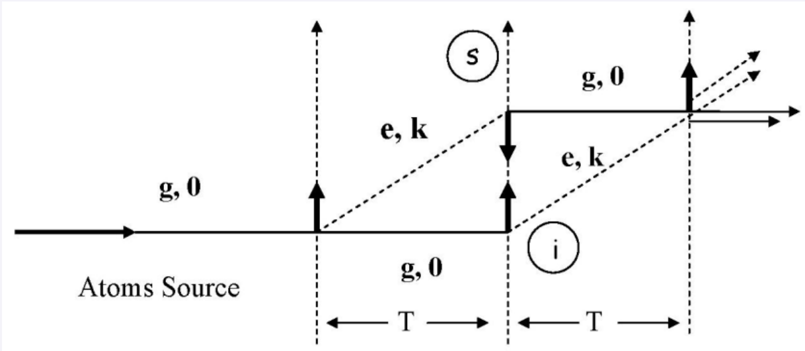
Main ideas

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

Gravitational waves detection with atom interferometry

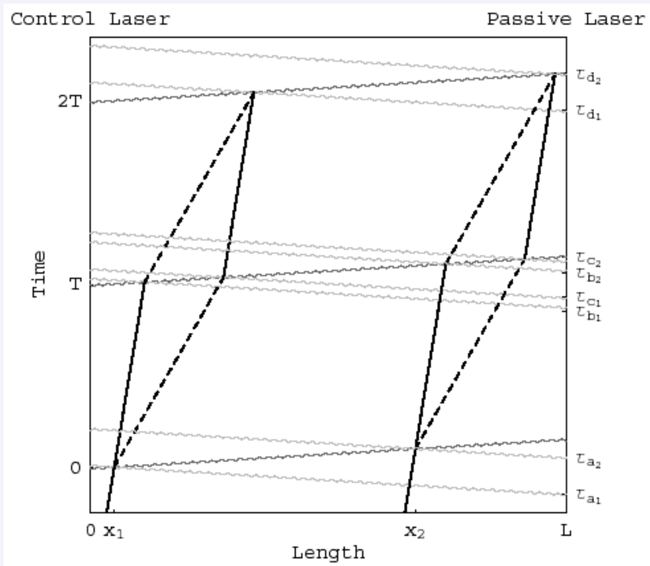
• Single atom interferometer

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

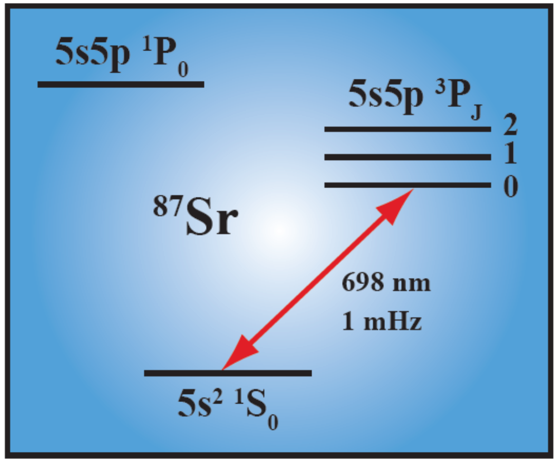


• Differential scheme

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



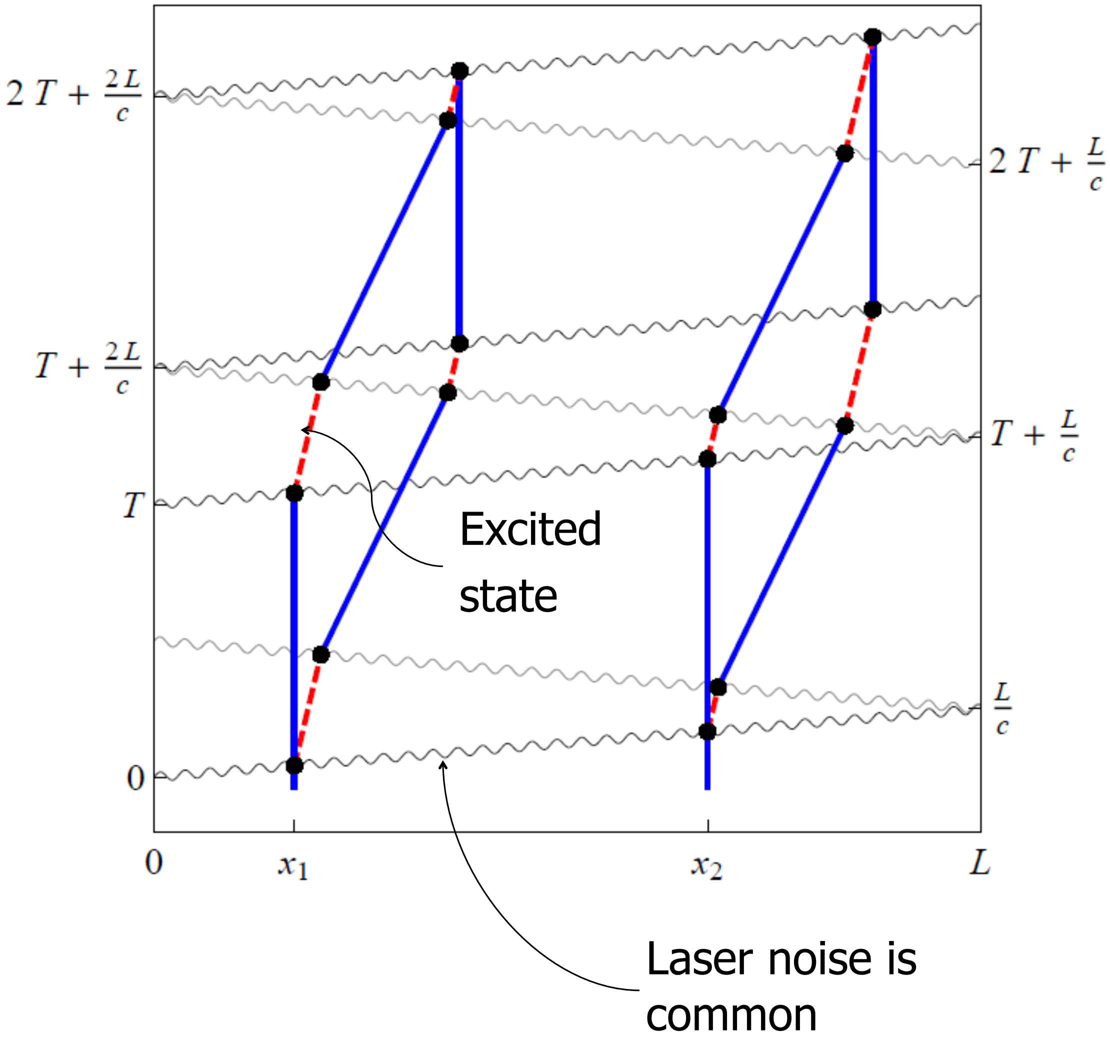
Laser frequency noise insensitive detector



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.

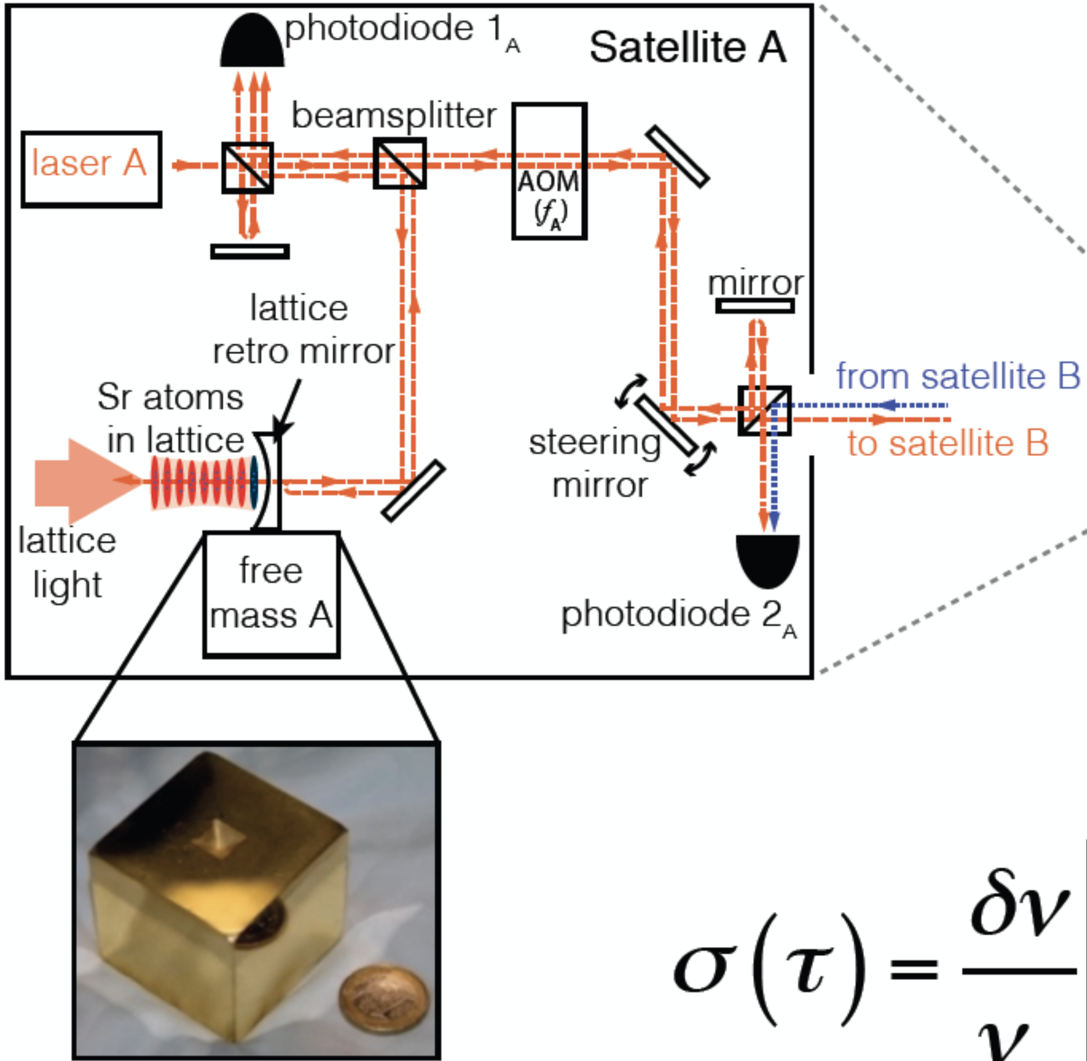
Enables 2 satellite configurations

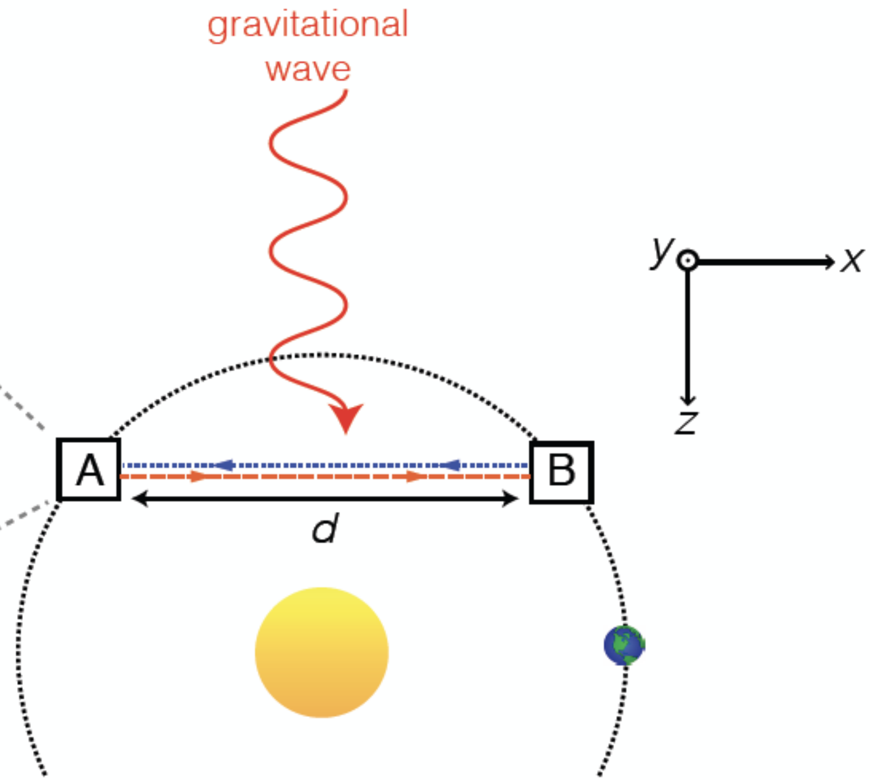


from M. Kasevich
STANFORD UNIVERSITY

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

Gravitational wave detection with clocks





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

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

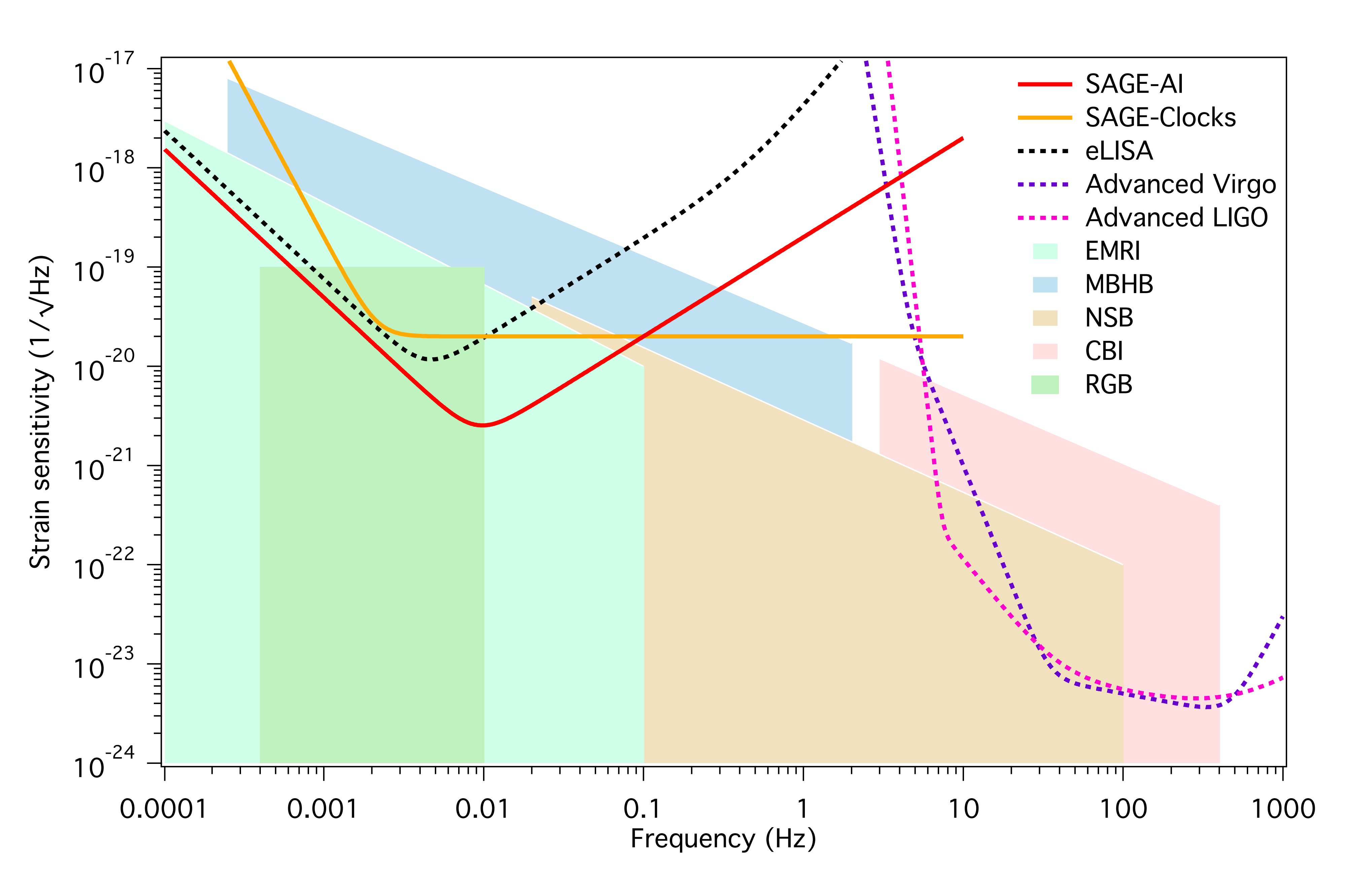
Lead Proposer
Prof. Guglielmo M. Tino

PRIMARY GOAL:
• Observe Gravitational Waves in new frequency ranges with atomic sensors.

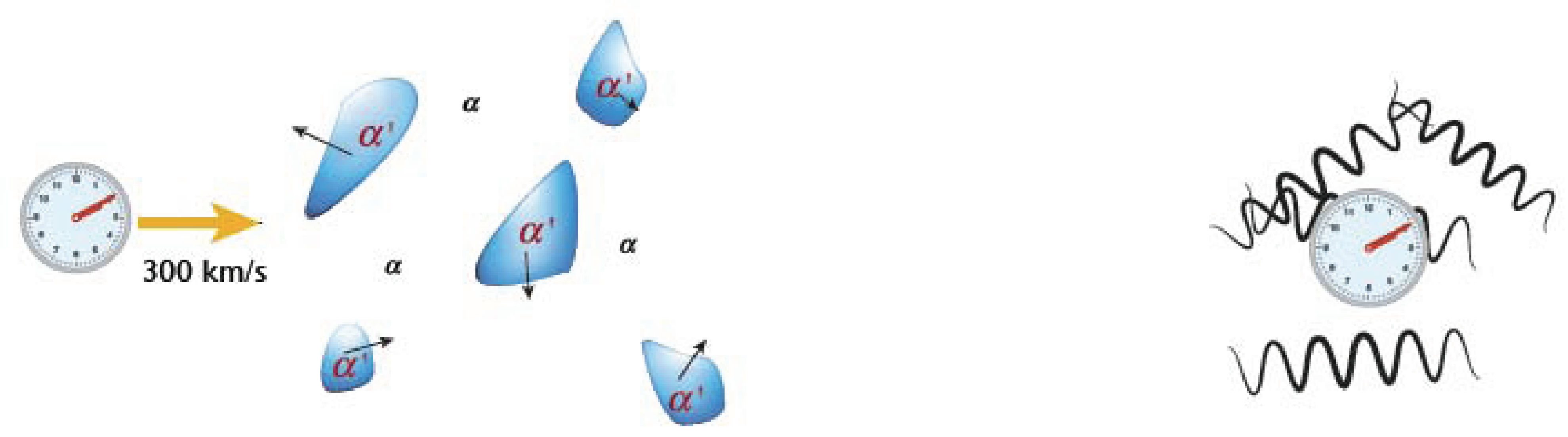
SECONDARY GOALS:
• Search for Dark-Matter
• Measure the Gravitational Red Shift
• Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
• Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
• Investigate quantum correlations 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



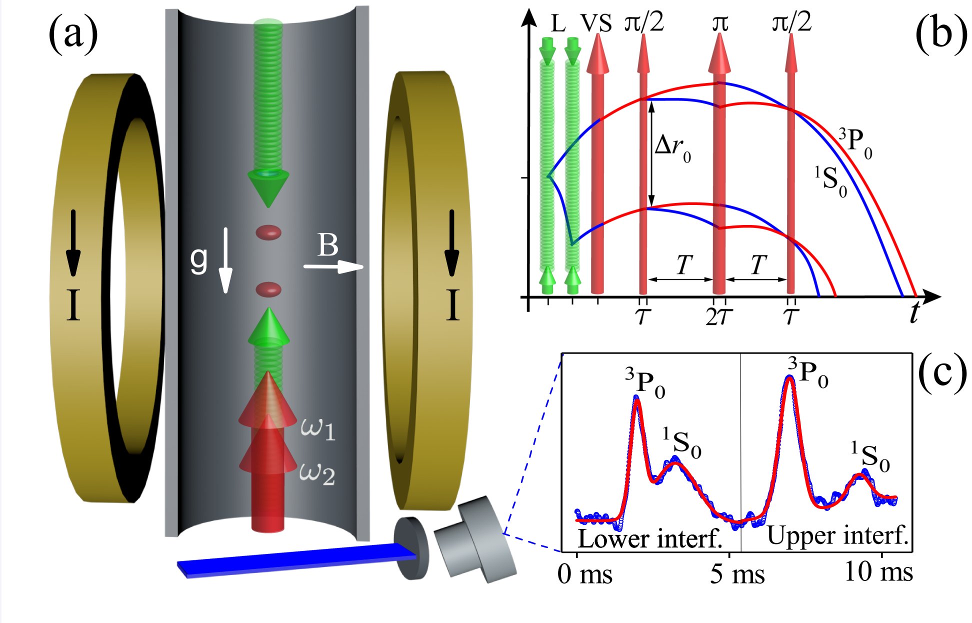
SAGE: Search for Dark-Matter

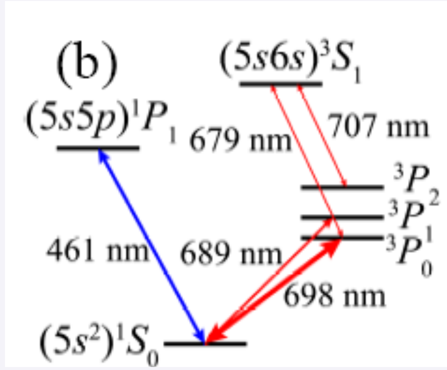


(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A.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

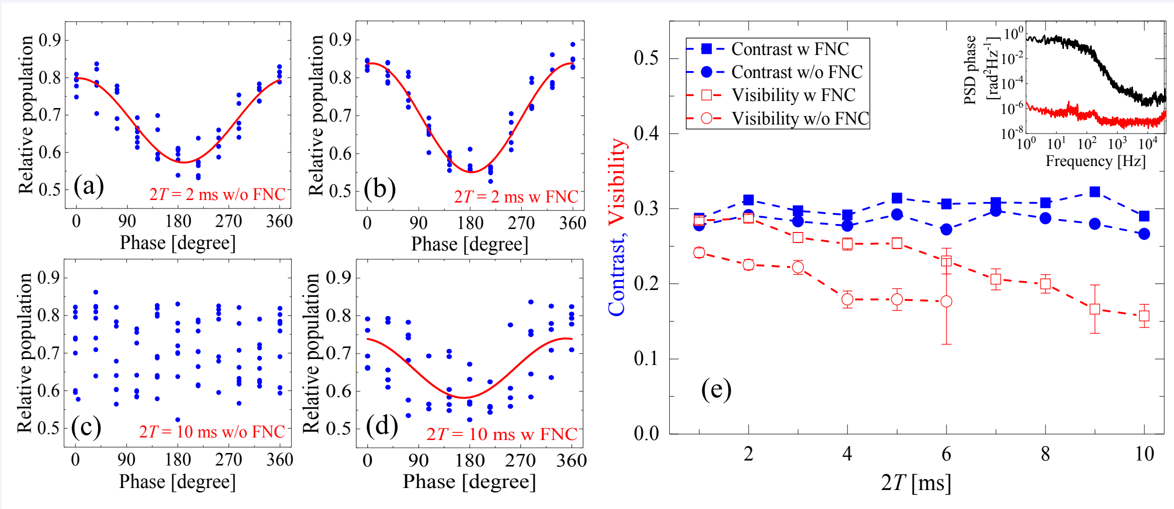
(Right) Ultralight fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [A. Arvanitaki, J. Huang, and K. Van Tilburg.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



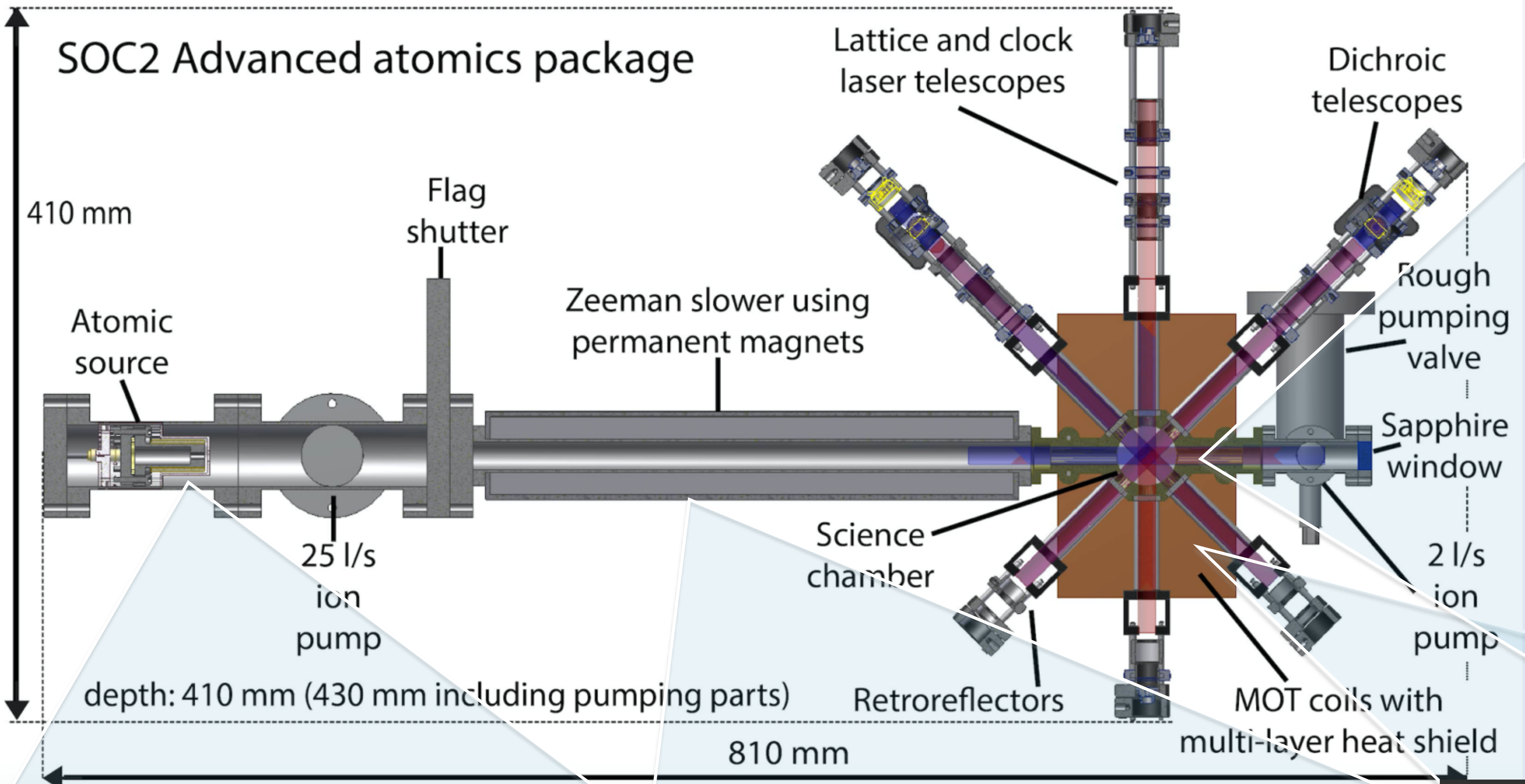
Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017) - [Editors' Suggestion]

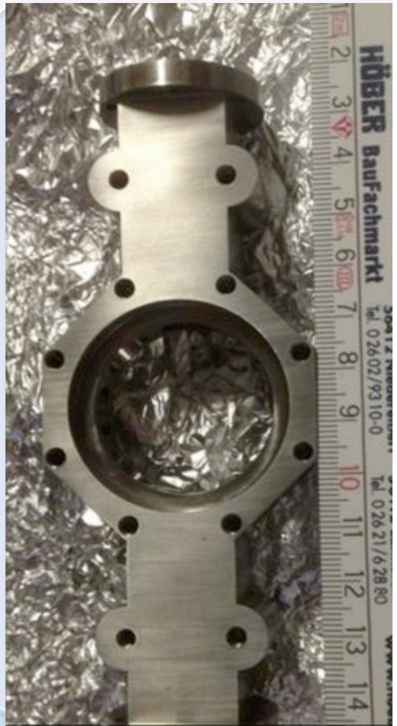
Atom interferometry with the Sr optical clock transition

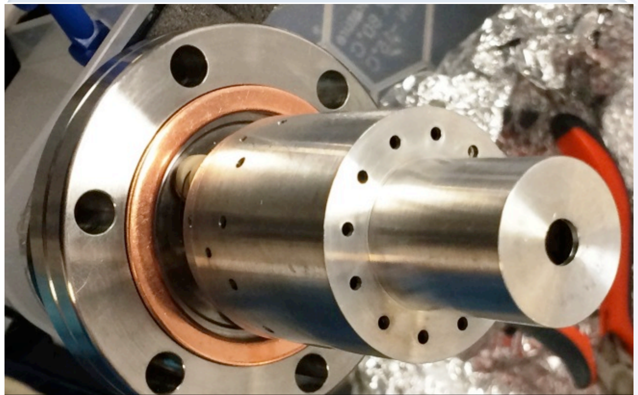
SAGE
Pathfinder
Successful !!

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]

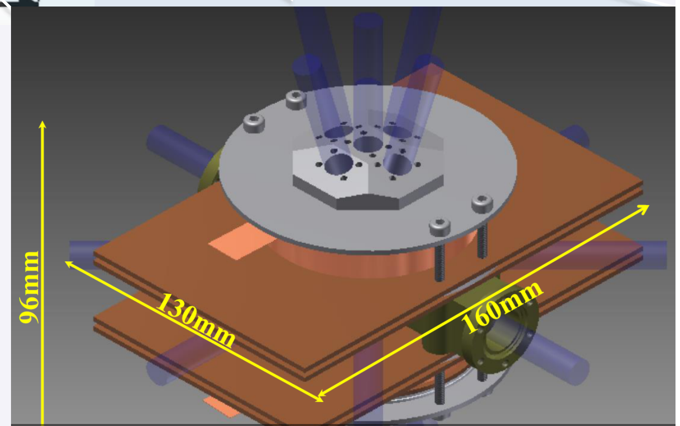
Development of a strontium optical lattice clock for the SOC mission on the ISS




Vacuum chamber


Low power (20W) atomic oven

Permanent-magnets Zeeman slower

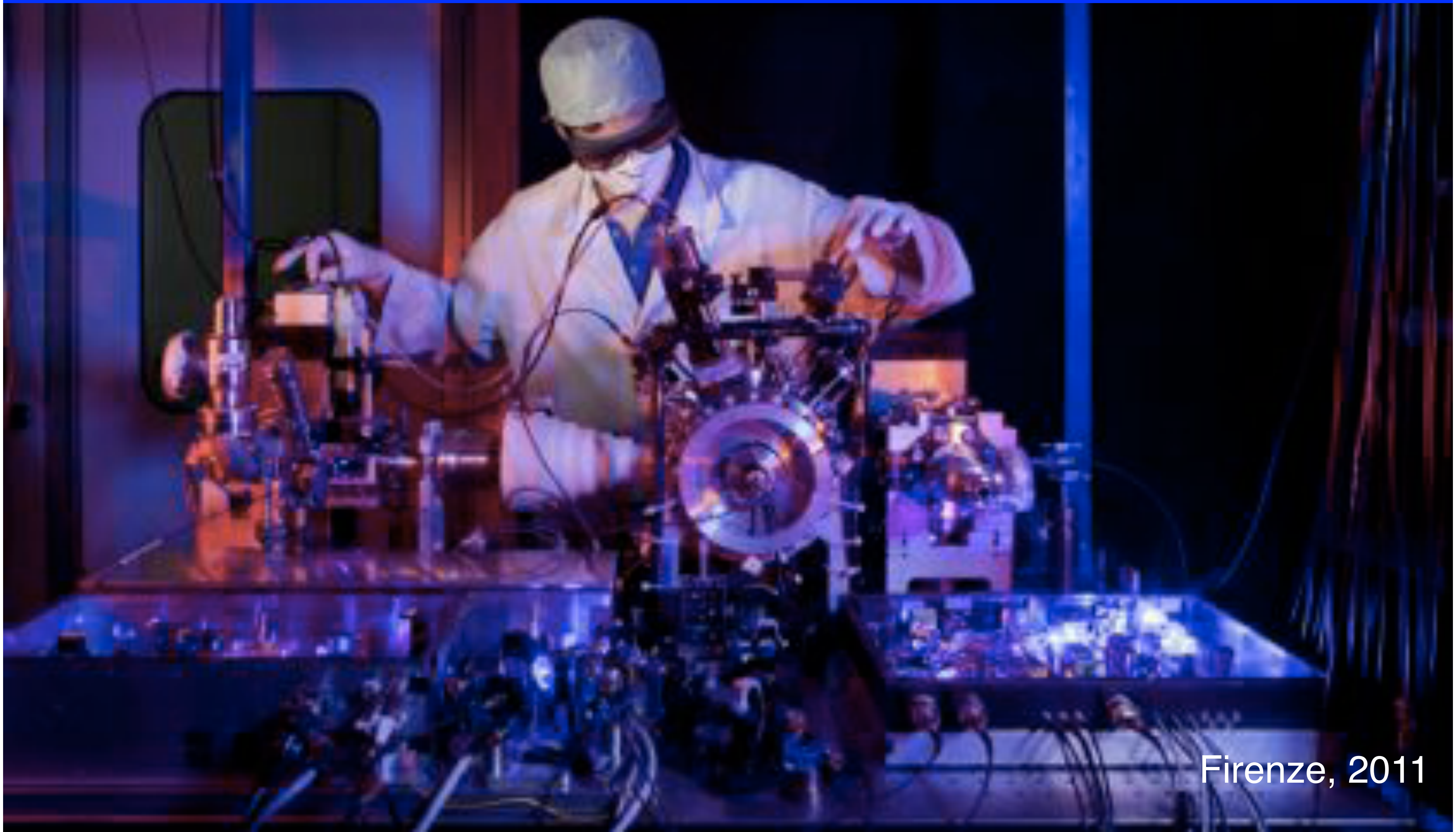


Small coils (no water cooling)

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)**

SAGE: SPACE ATOMIC GRAVITY EXPLORER

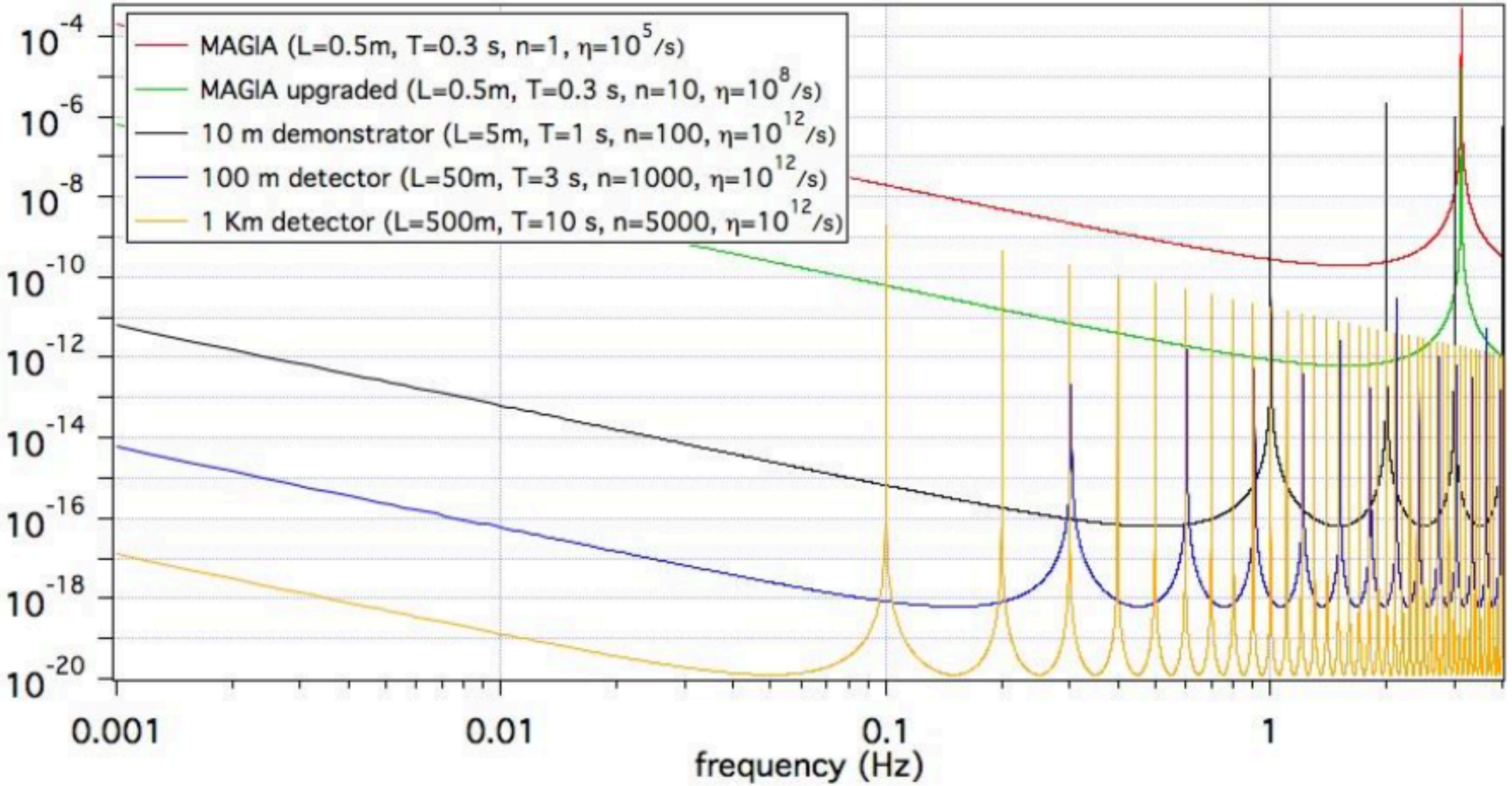
Strontium Atomic Interferometers and Clocks in Space for Fundamental Physics and Applications



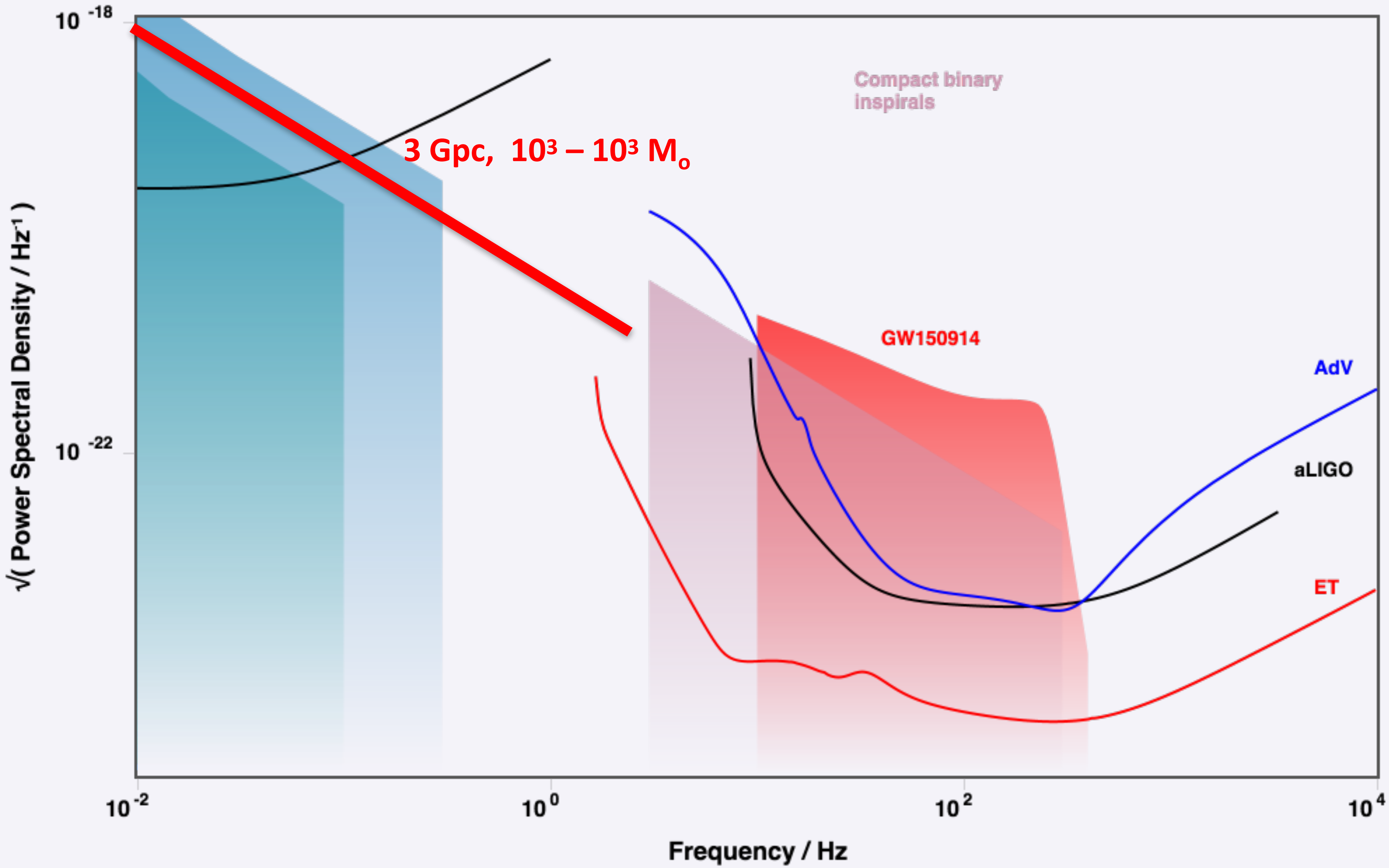
From table-top experiments to large-scale detectors

Shot noise limited (diff. configuration)

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



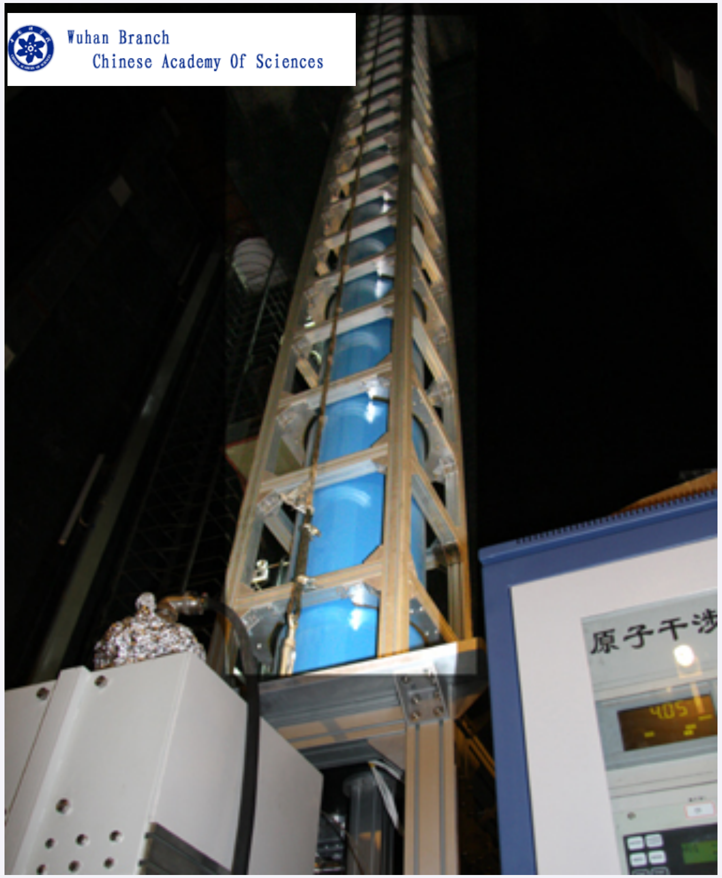
Example: IMBH $10^3 - 10^3\ M_{sol}$

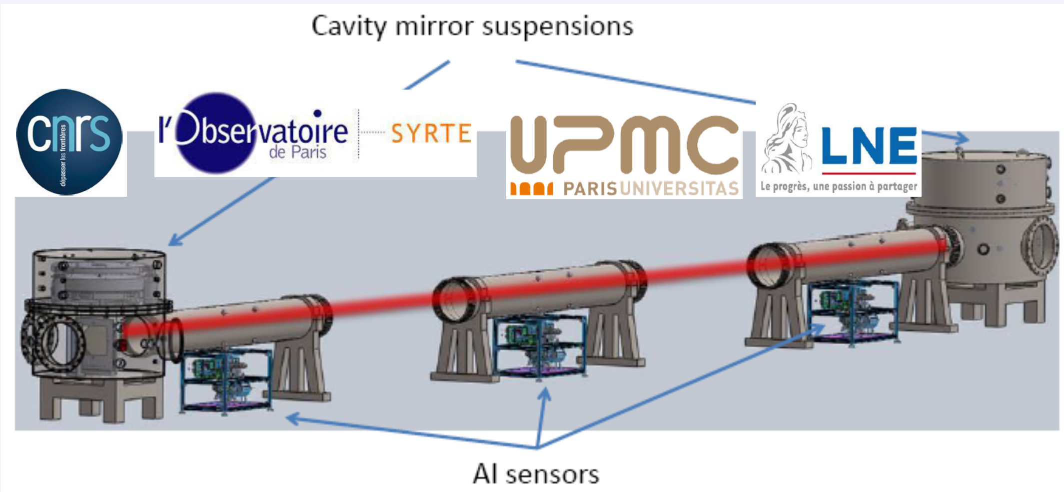


Large-scale atom interferometers

10 m fountain at Stanford

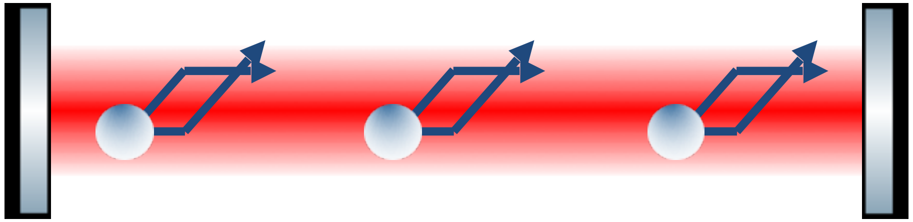
12 m fountain at Wuhan





MIGA Project

A new large instrument combining matter-wave and laser interferometry



- <u>Gravitational wave physics</u>
  - Demonstrator for future sub-Hz ground based GW detectors
- <u>Geoscience</u>
  - 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
Low Noise Inter Disciplinary Underground Science & Technology

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

MIGA Project - Status

Article "Characterizing Earth gravity field fluctuations with the MIGA antenna for future Gravitational Wave detectors" accepted in Physical Review D - https://arxiv.org/pdf/1902.05337.pdf

-*from P. Bouyer, May 2019* http://miga-project.org/

MAGIS Collaboration

Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

Phil Adamson[1], Swapan Chattopadhyay[1,2], Jonathon Coleman[5], Peter Graham[3], Steve Geer[1], Roni Harnik[1], Steve Hahn[1], Jason Hogan[†3], Mark Kasevich[3], Tim Kovachy[6], Jeremiah Mitchell[2], Rob Plunkett[1], Surjeet Rajendran[4], Linda Valerio[1] and Arvydas Vasonis[1]

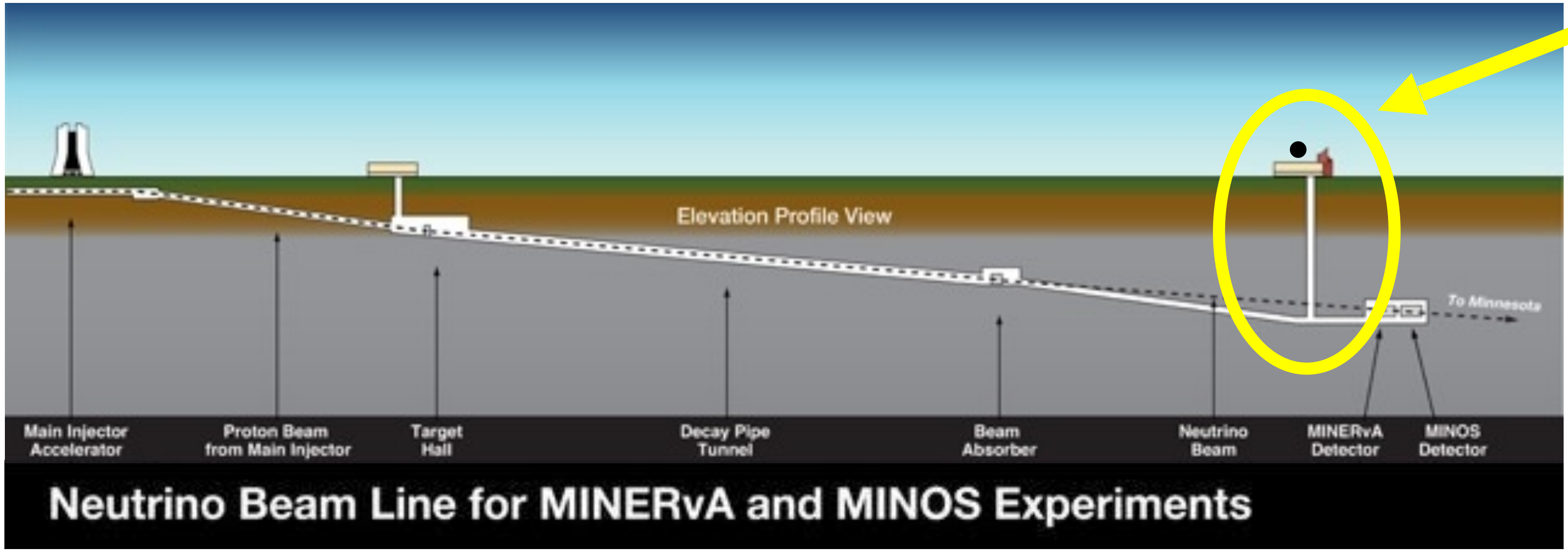
[1] *Fermi National Accelerator Laboratory; Batavia, Illinois 60510, USA*
[2] *Northern Illinois University; DeKalb, Illinois 60115, USA*
[3] *Stanford University; Stanford, California 94305, USA*
[4] *University of California at Berkeley; Berkeley, CA 94720, USA*
[5] *University of Liverpool; Merseyside, L69 7ZE, UK*
[6] *Northwestern University; Evanston, Illinois, USA*

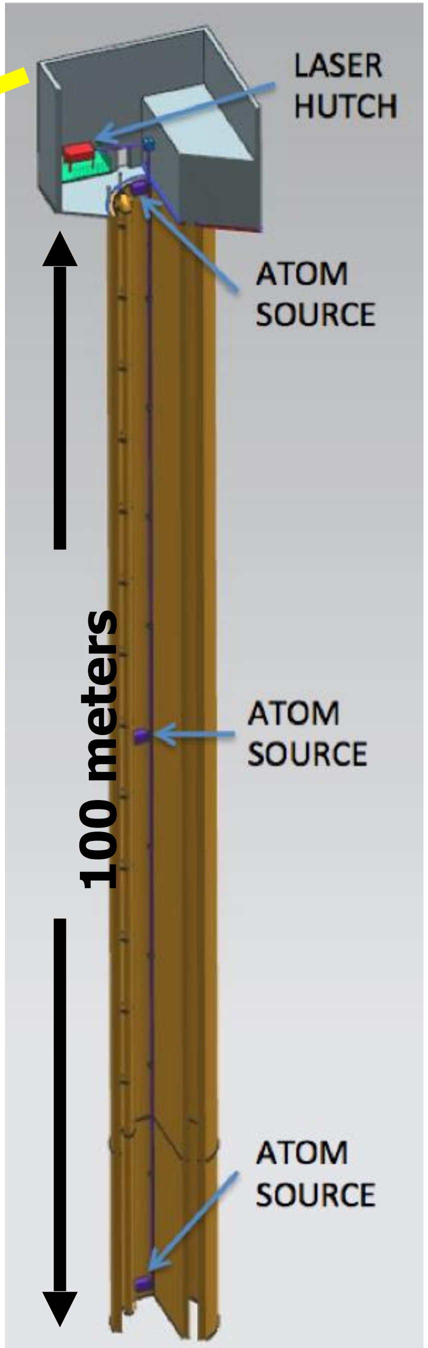
Part of the proposed Fermilab Quantum Initiative:
http://www.fnal.gov/pub/science/particle-detectors-computing/quantum.html#magis

from J. Hogan

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

MAGIS-100 - Status and plan

Received funding from the Gordon and Betty Moore Foundation for the project, beginning in January 2019.

Received Stage I approval from the Fermilab directorate to proceed with the experiment. Beginning preliminary designs.

The goal is to begin commissioning the detector in about two years.

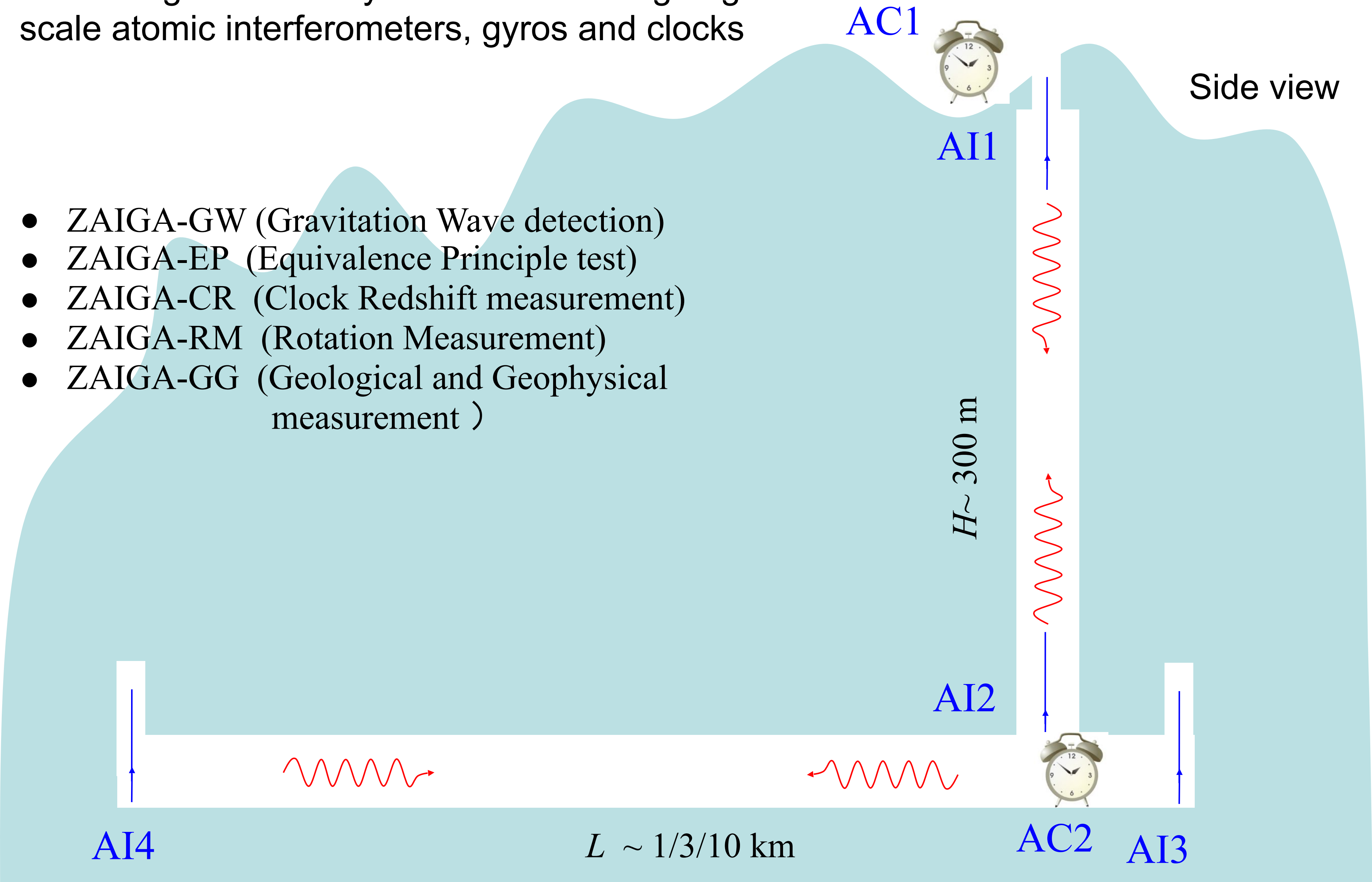
(From J. Hogan, May 2019)

ZAIGA

Zhaoshan long-baseline Atom Interferometer Gravitation Antenna

An underground facility for GR tests using large scale atomic interferometers, gyros and clocks

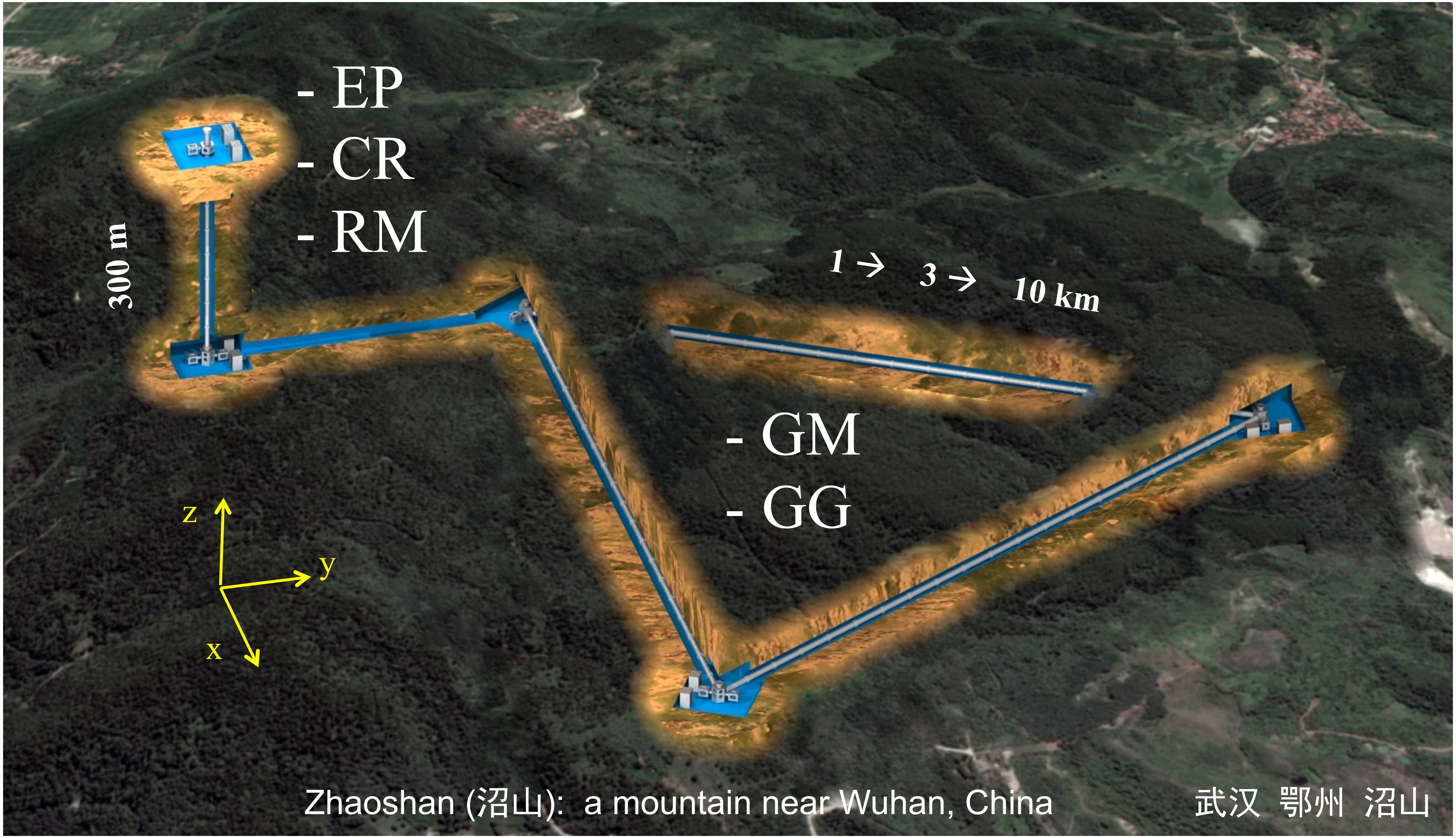
- ZAIGA-GW (Gravitation Wave detection)
- ZAIGA-EP (Equivalence Principle test)
- ZAIGA-CR (Clock Redshift measurement)
- ZAIGA-RM (Rotation Measurement)
- ZAIGA-GG (Geological and Geophysical measurement)



from M. S. Zhan

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

ZAIGA



from M. S. Zhan

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

ZAIGA -Status and plan

Completed site exploration with tunnel excavation starting in 2019.

The first phase of ZAIGA should be complete by the end of 2020.
300 m vertical tunnel to test the weak equivalence principle of GR.

If the project is fully funded, it could be operational by 2025.

(From Mingsheng Zhan, May 2019)

AION Project: Core Team

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*

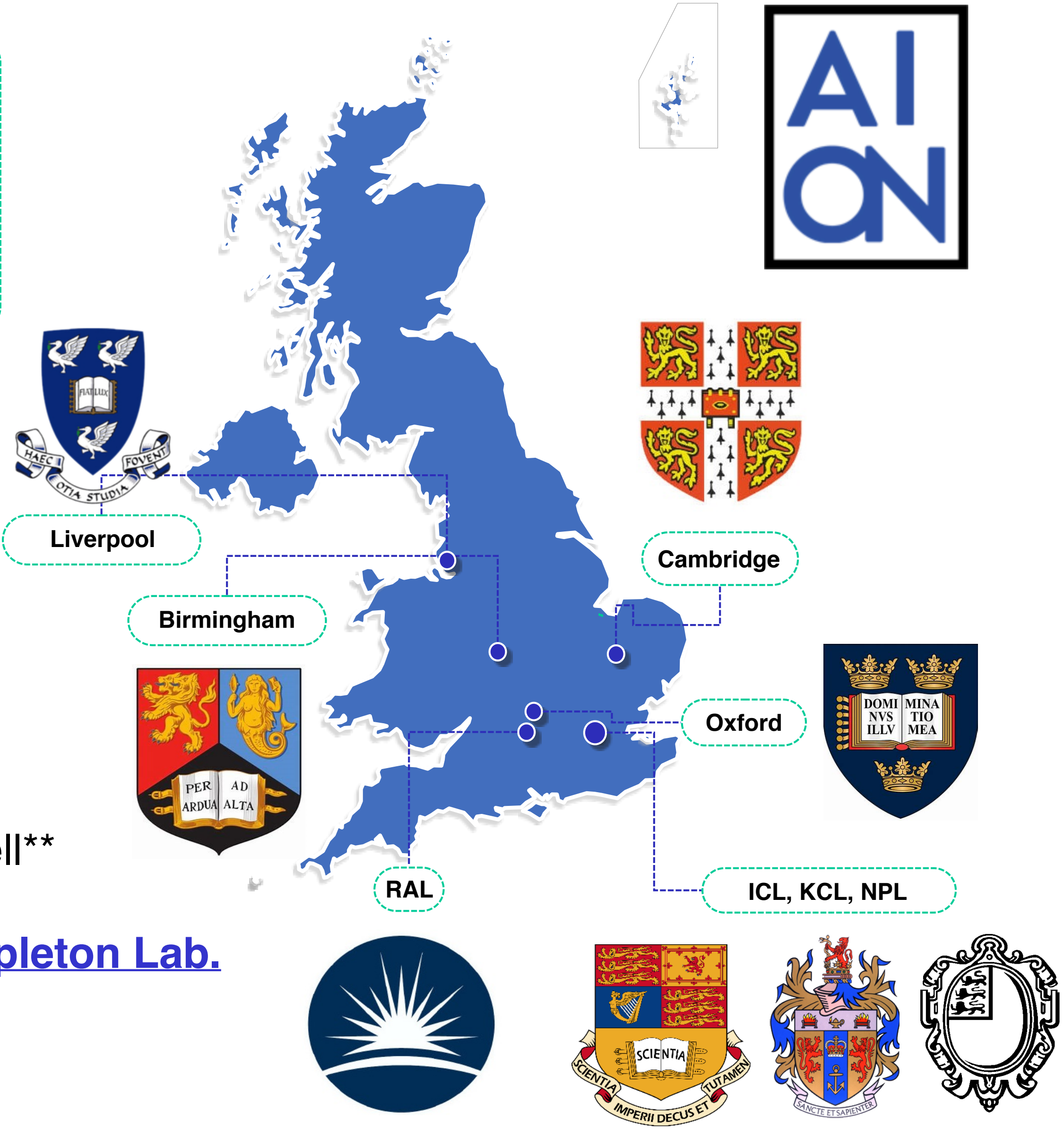
Liverpool
T. Bowcock**
J. Coleman** [co-coord.]

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

UK
- 8 Institutes
- 21 Core Members
- Many Associates

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

What is AION (in a nutshell)?

- The proposal is to construct and operate a next generation Atomic Interferometric Observatory and Network (AION) in the UK that will enable the exploration of properties of dark matter as well as searches for new fundamental interactions.
- It will provide a pathway for detecting gravitational waves from the very early universe in the, as yet mostly unexplored, mid-frequency band, ranging from several milliHertz to a few Hertz.
- The proposed project spans several science areas ranging fundamental particle physics over astrophysics to cosmology and, thus, connects these communities.
- Following the “Big Ideas” call, the project was selected by PAAP and STFC as a high priority for the community. It was provisionally classified as a medium scale project.
- AION is also a Work Package of the QSFP proposal

from O. Buchmueller

AION – A Staged Programme**

AION-10: Stage 1 [year 1 to 3]

- 1 & 10 m Interferometers & Site Development for 100m Baseline

AION-100: Stage 2 [year 3 to 6]

- 100m Construction & Commissioning

AION-KM: Stage 3 [> year 6]

- Operating AION-100 and planning for 1 km & Beyond

AION-SPACE: Stage 4 [after AION-KM]

- Space based version

**outlined in Big Ideas proposal

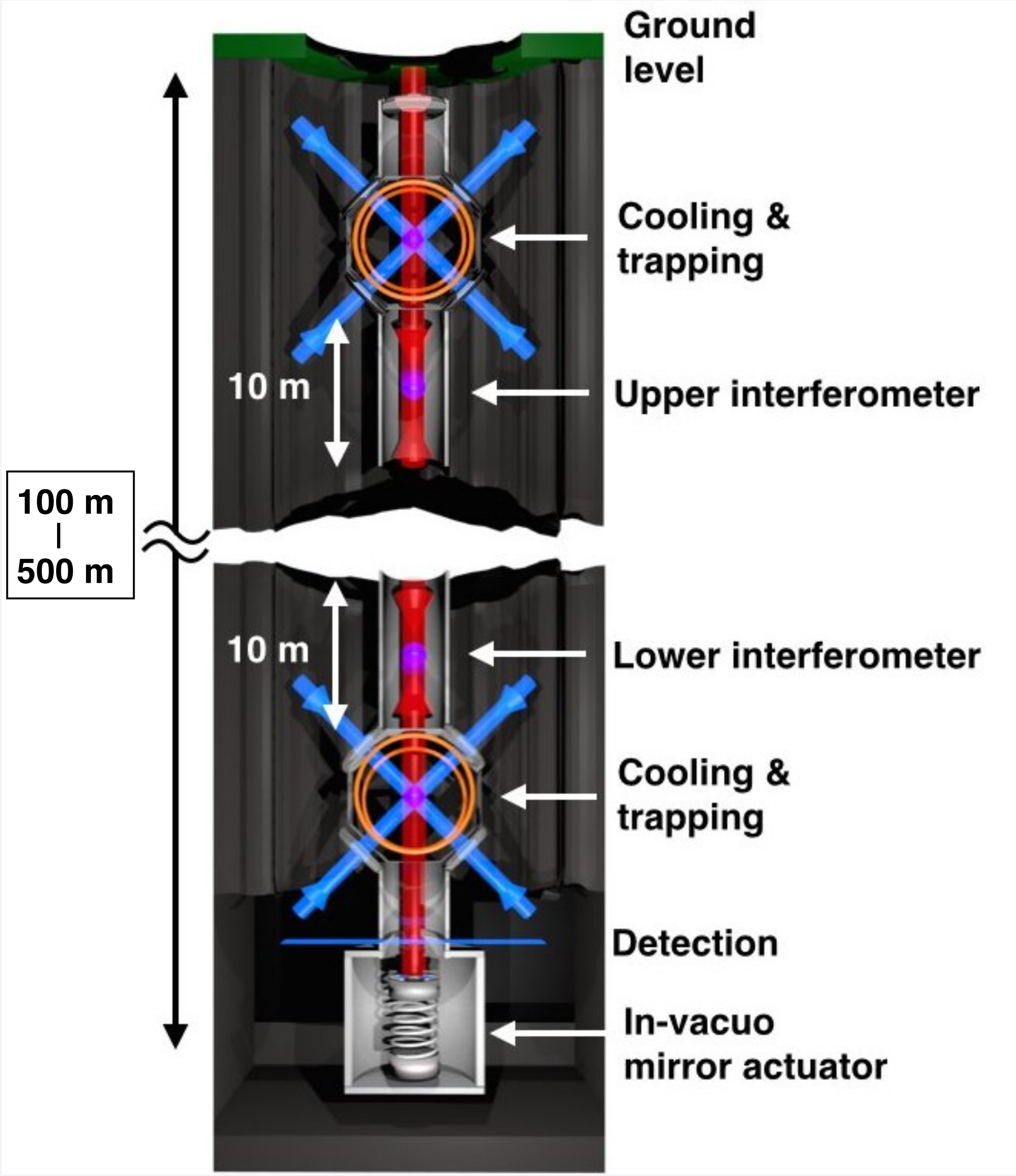
from O. Buchmueller

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

Large-scale atom interferometer ⇒ *Sardegna?*



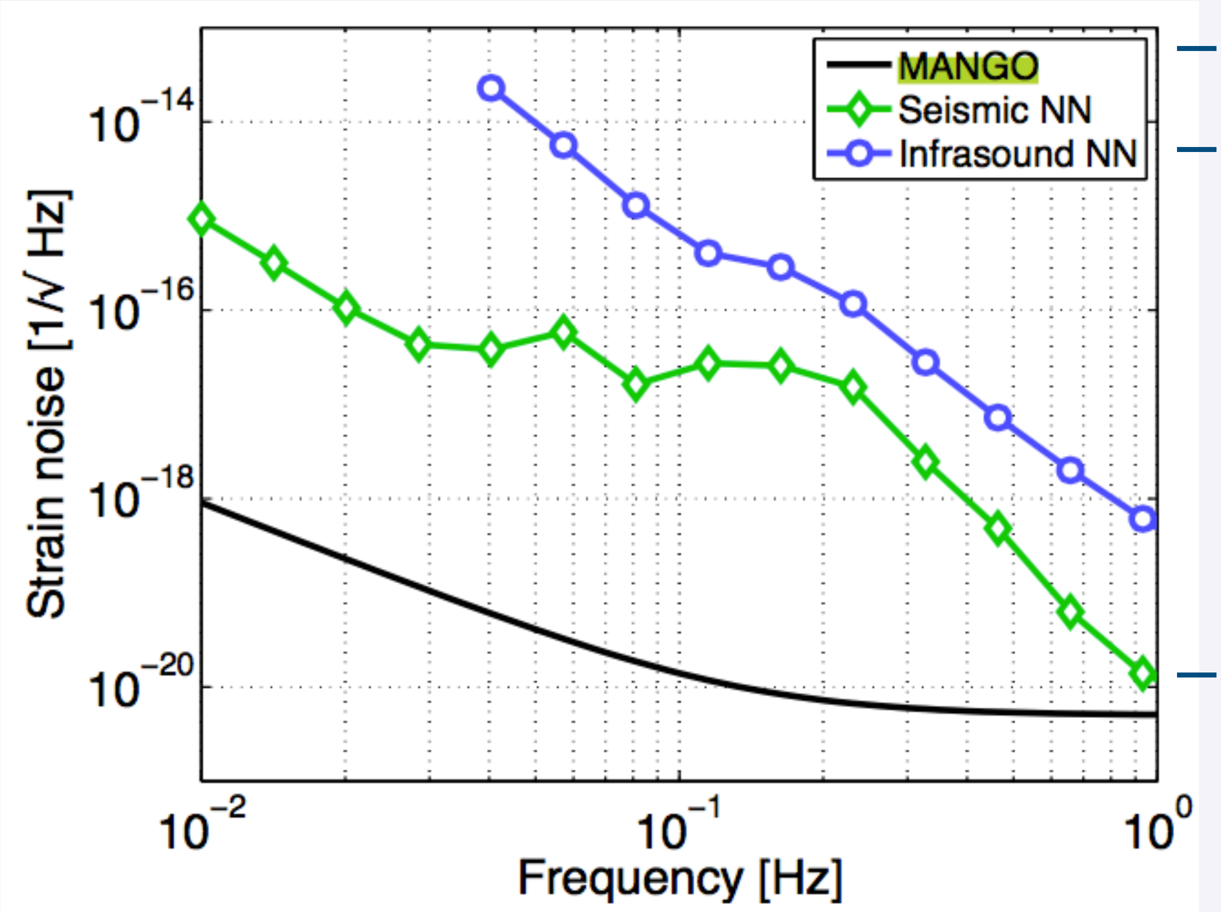
Carbonia-Iglesias
ARIA/Darkside Lab

Sos Enattos
SAR-GRAV Lab?

The end

The Beginning

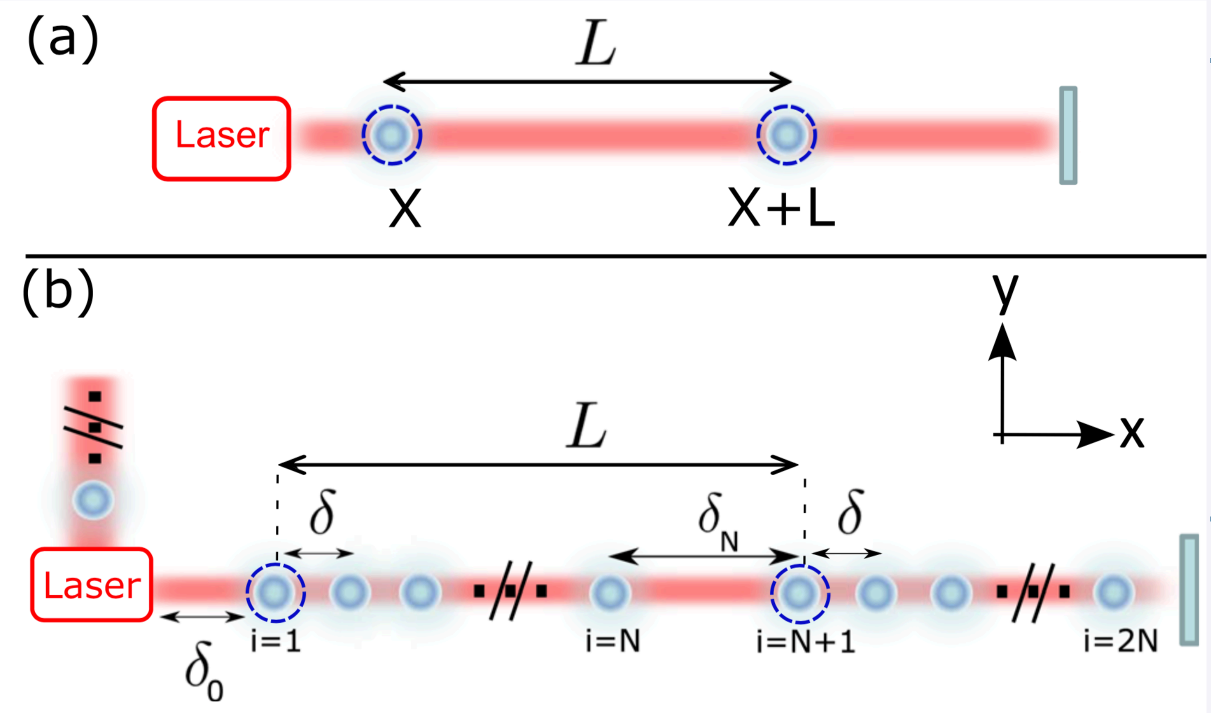
What about Newtonian noise?



- 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