Optical techniques for atom interferometry

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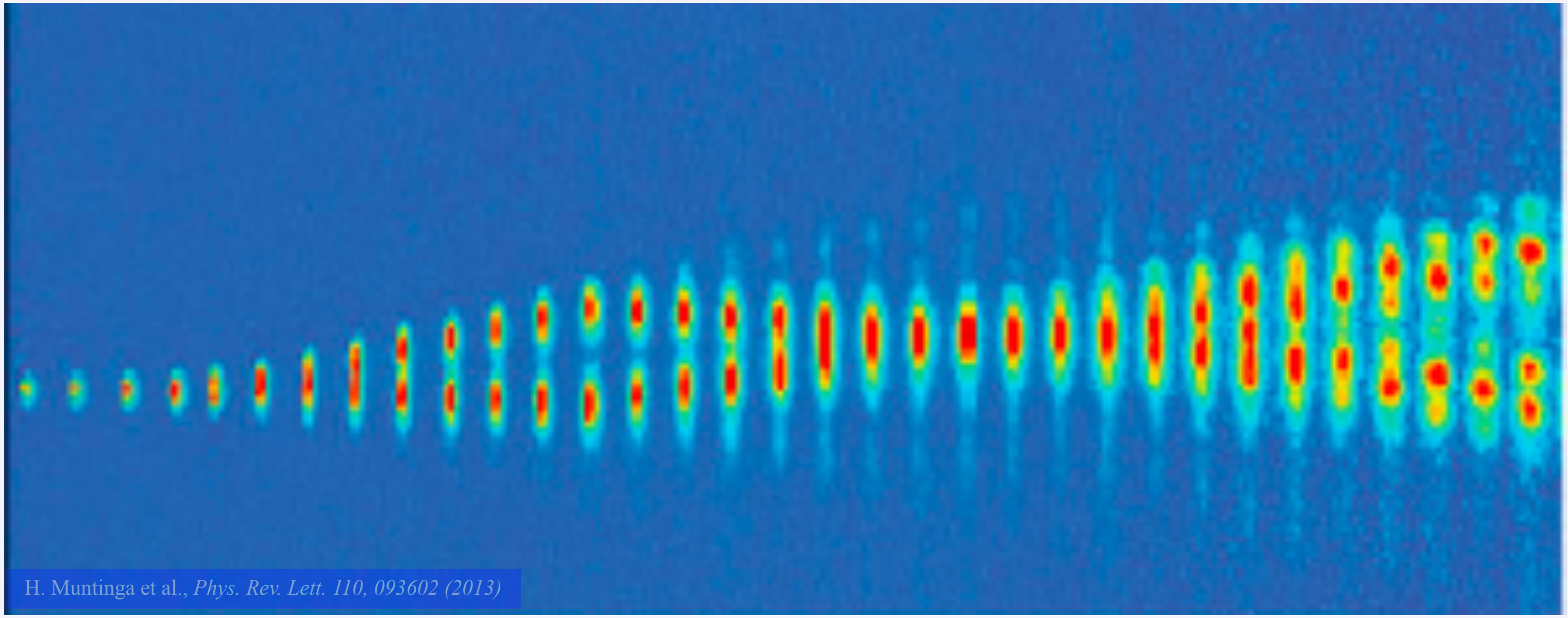
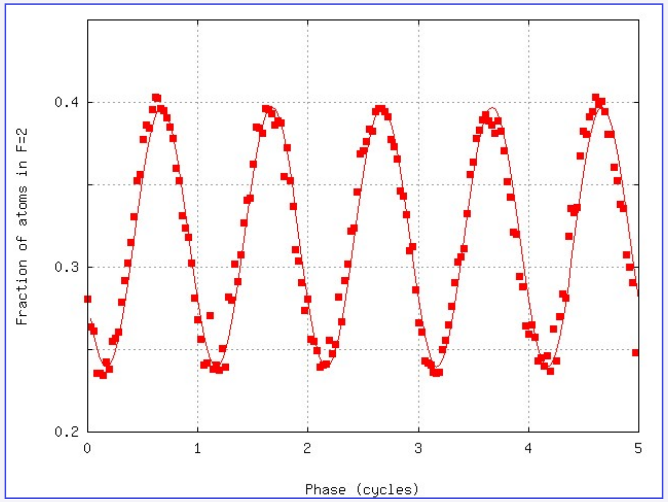
2nd PBC technology mini workshop: lasers & optics
10/12/2021 - Online

Atom interferometry
Wave-particle duality in quantum physics



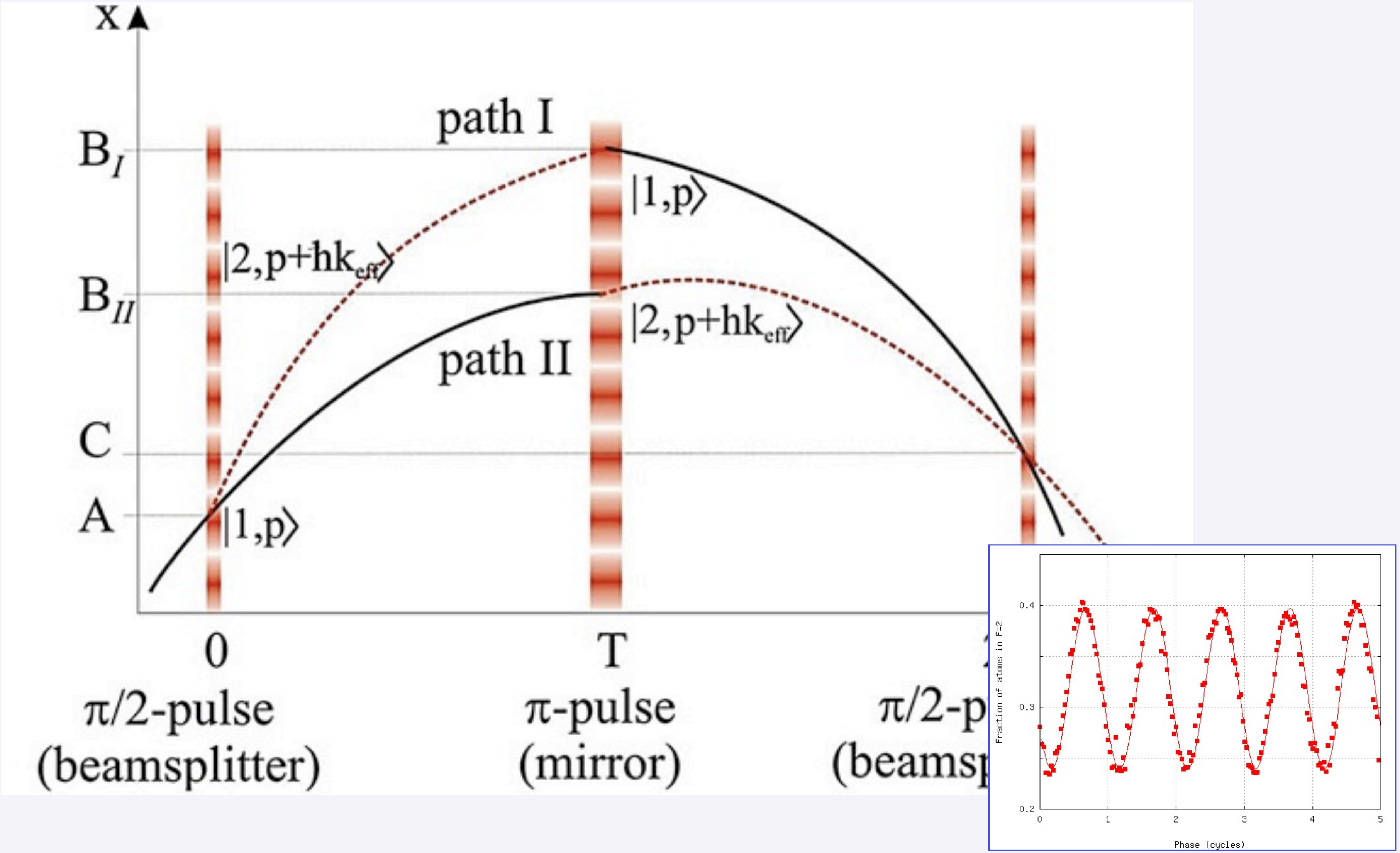


Atomic interference fringes – Firenze 2006

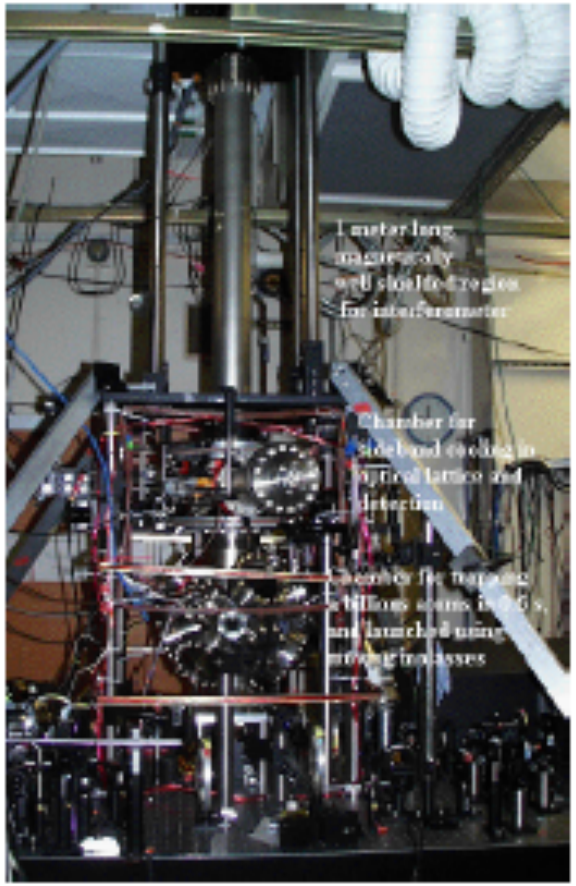
Alexander D. Cronin, Jörg Schmiedmayer, David E. Pritchard, *Optics and interferometry with atoms and molecules*, Rev. Mod. Phys., Vol. 81, No. 3 (2009)

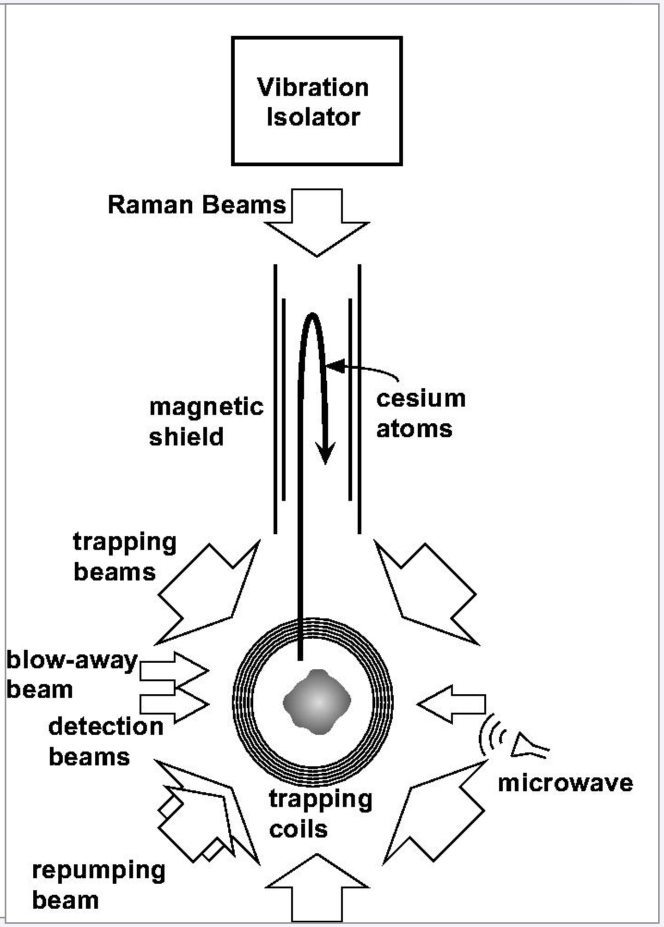
G. M. Tino, M. A. Kasevich (eds) *Atom Interferometry*, Proc. Int. School Phys. "Enrico Fermi", Course CLXXXVIII, Varenna 2013 (SIF and IOS Press, 2014).

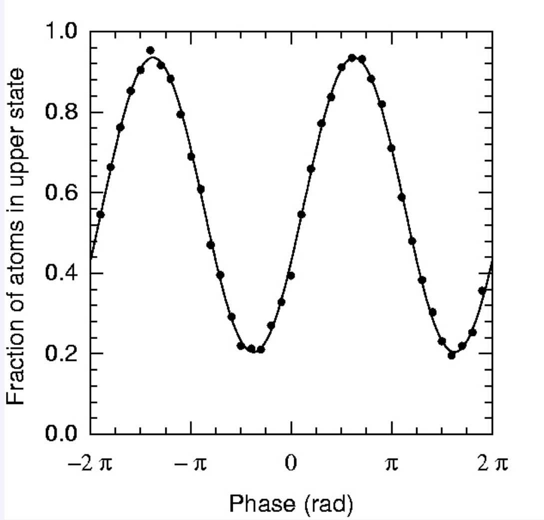
Atom interferometry and gravity

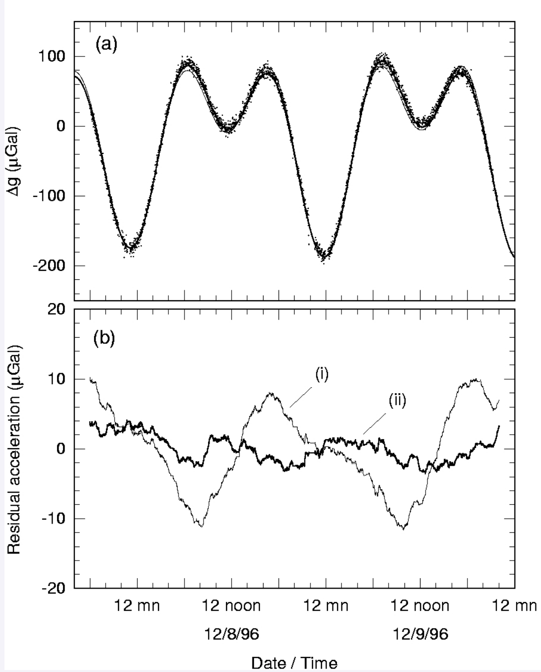


Stanford atom gravimeter









Resolution: 3×10^{-9} g after 1 minute

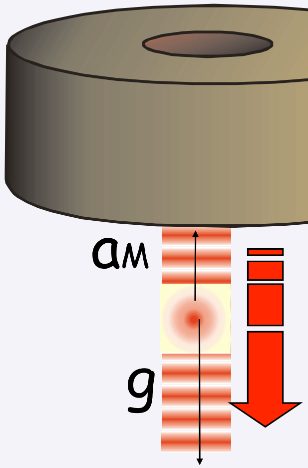
Absolute accuracy: $\Delta g/g < 3 \times 10^{-9}$

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

MAGIA

(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

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

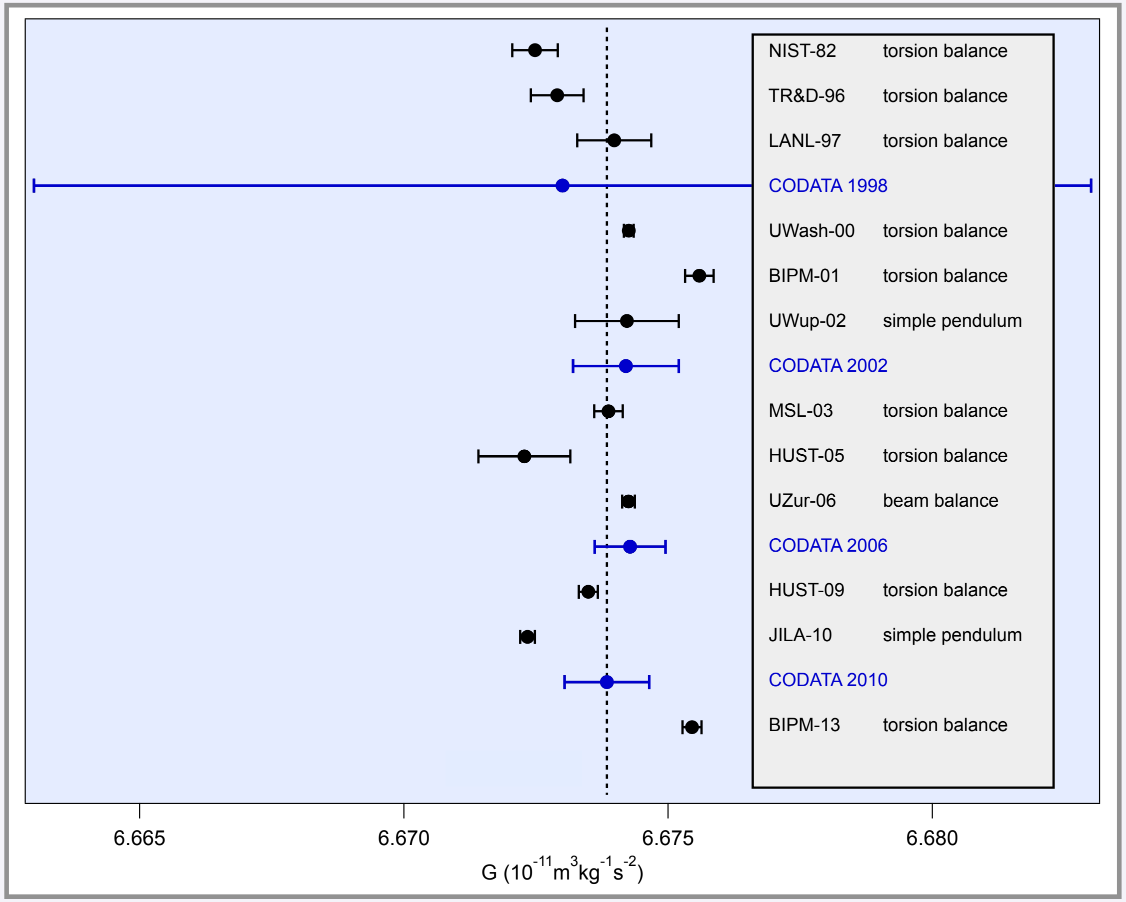


➤ ***Precision measurement of G***

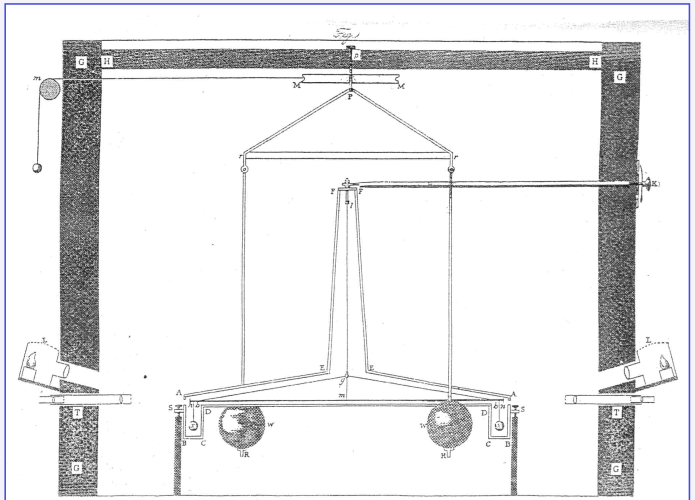
$$F(r) = G\frac{M_1 M_2}{r^2}$$

Measurements of the Newtonian gravitational constant G

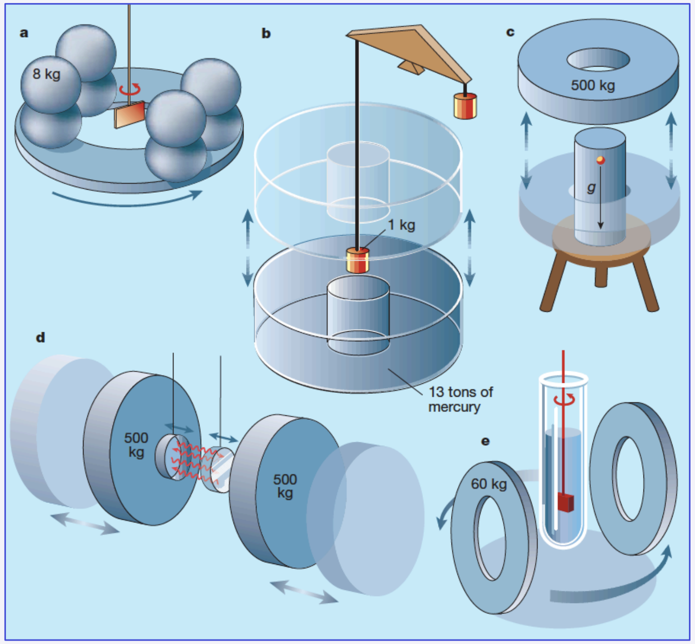
$$F(r) = G\frac{M_1 M_2}{r^2}$$



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)

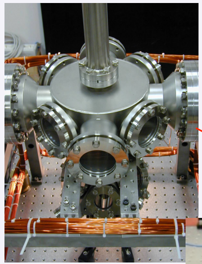
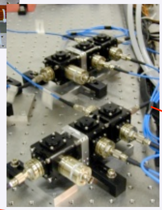
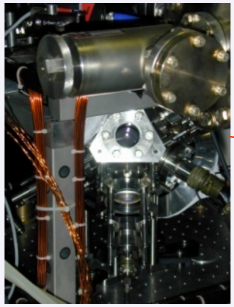
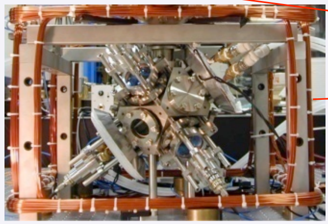
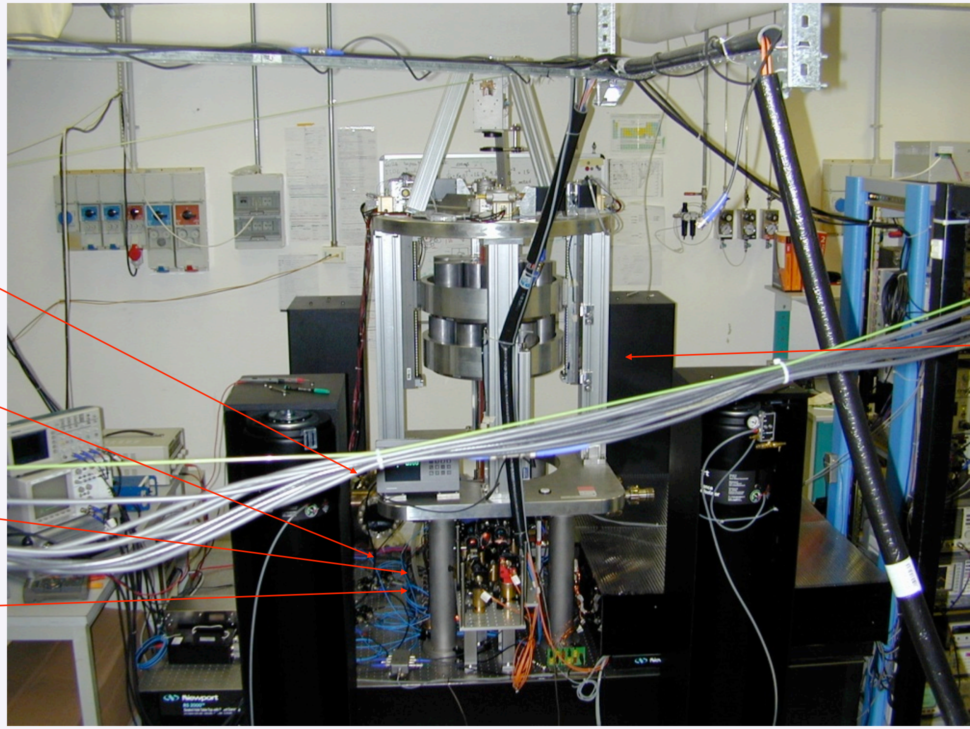


Cavendish, 1798



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

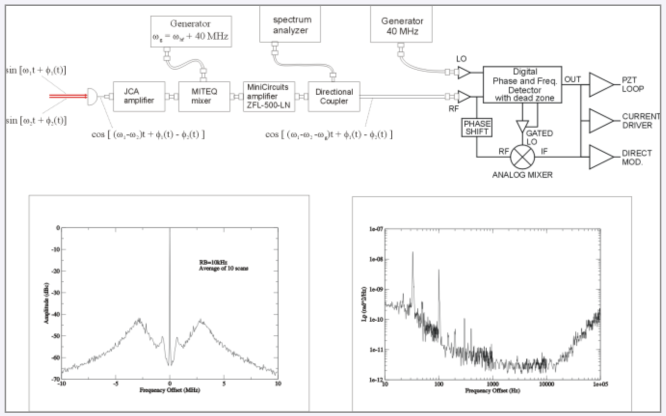
MAGIA apparatus

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)**

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.

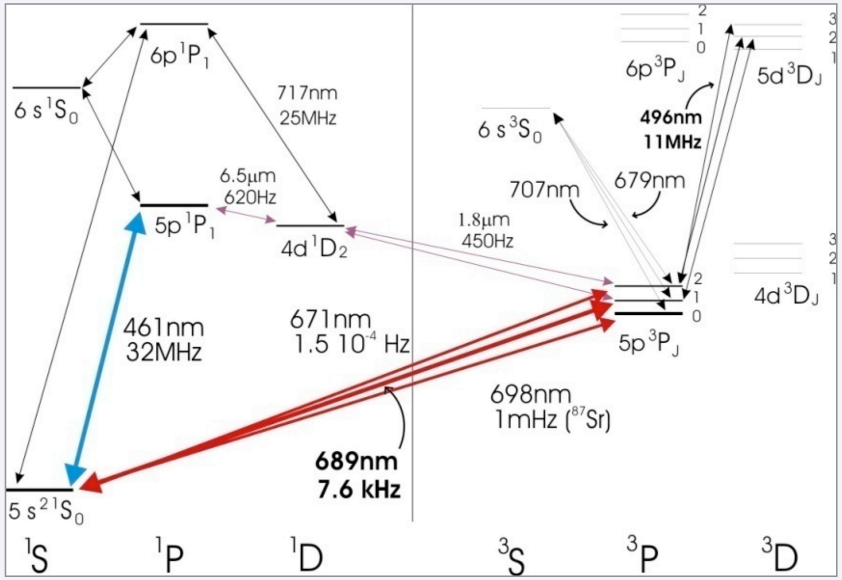
The atom interferometer is realized using light pulses to stimulate ^{87}Rb atoms at the two-photon Raman transition between the hyperfine

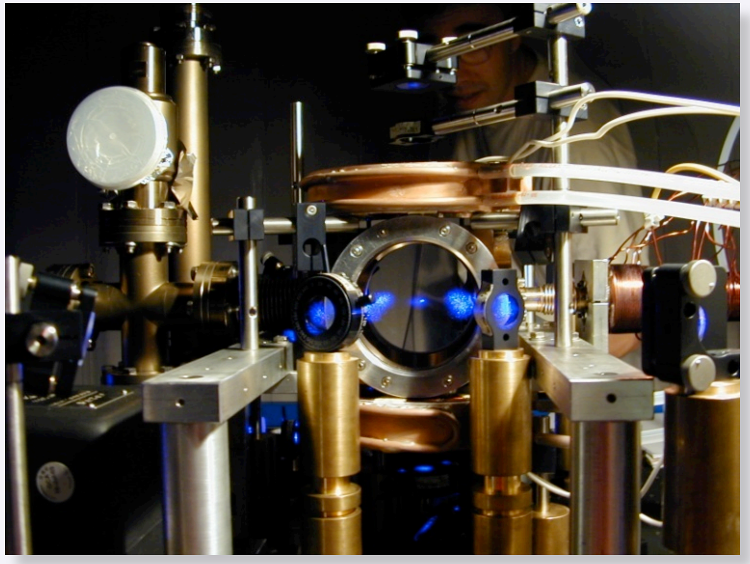
$$G = 6.67191(77)(62) \times 10^{-11}\ \mathrm{m^3\,kg^{-1}\,s^{-2}}$$

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)

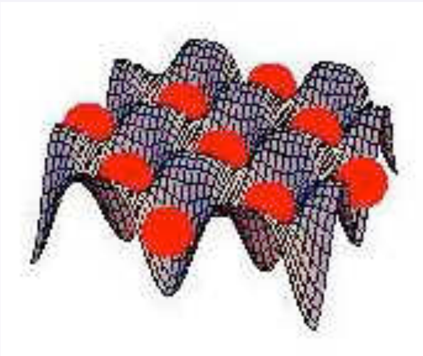
Ultracold Sr - Experiments in Firenze

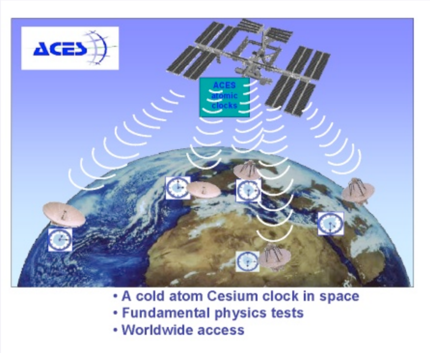


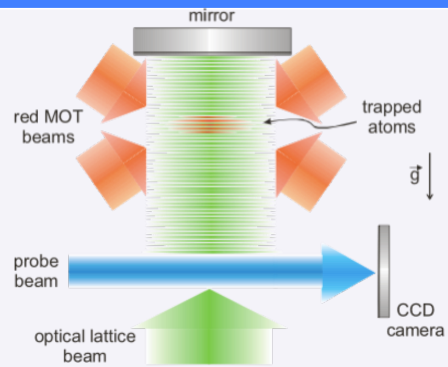


- Optical clocks using visible intercombination lines

- New atomic sensors for fundamental physics tests







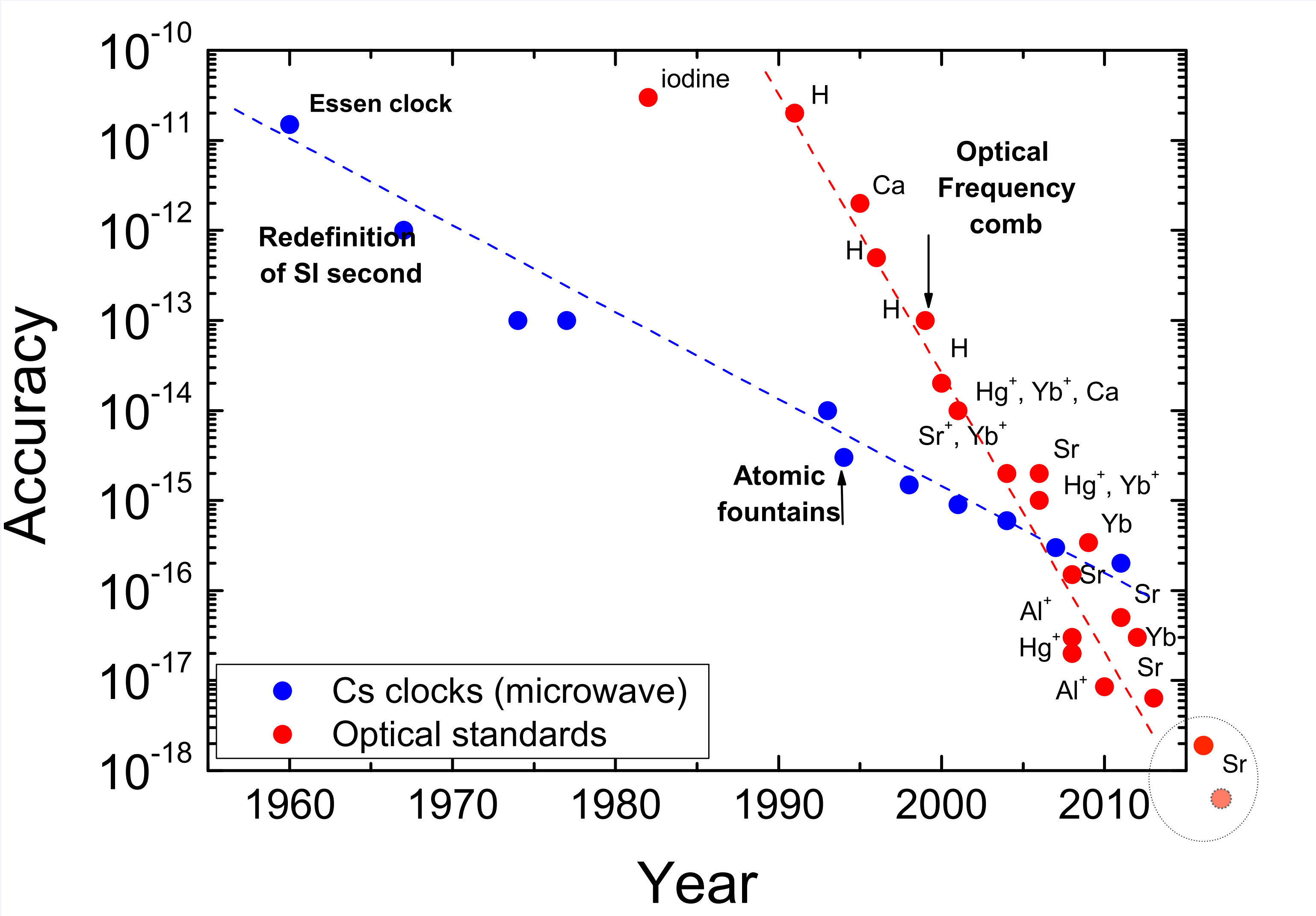
G. Ferrari, P.Cancio, R. Drullinger, G. Giusfredi, N. Poli, M. Prevedelli, C. Toninelli, G.M. Tino, *Precision Frequency Measurement of Visible Intercombination Lines of Strontium*, Phys. Rev. Lett. 91, 243002 (2003)

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)

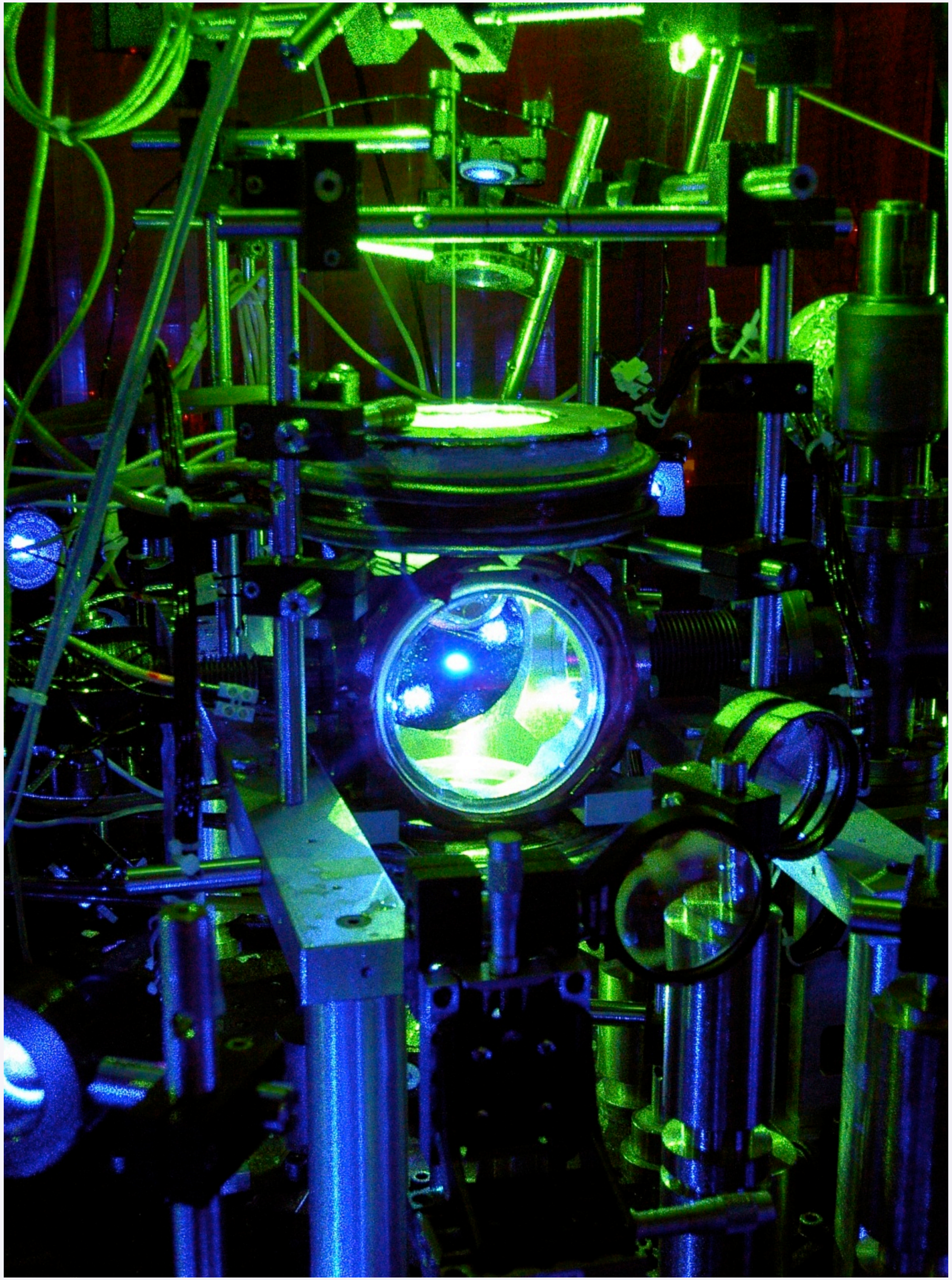
G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino, *Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at micrometer scale*, Phys. Rev. Lett. 97, 060402 (2006)

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))

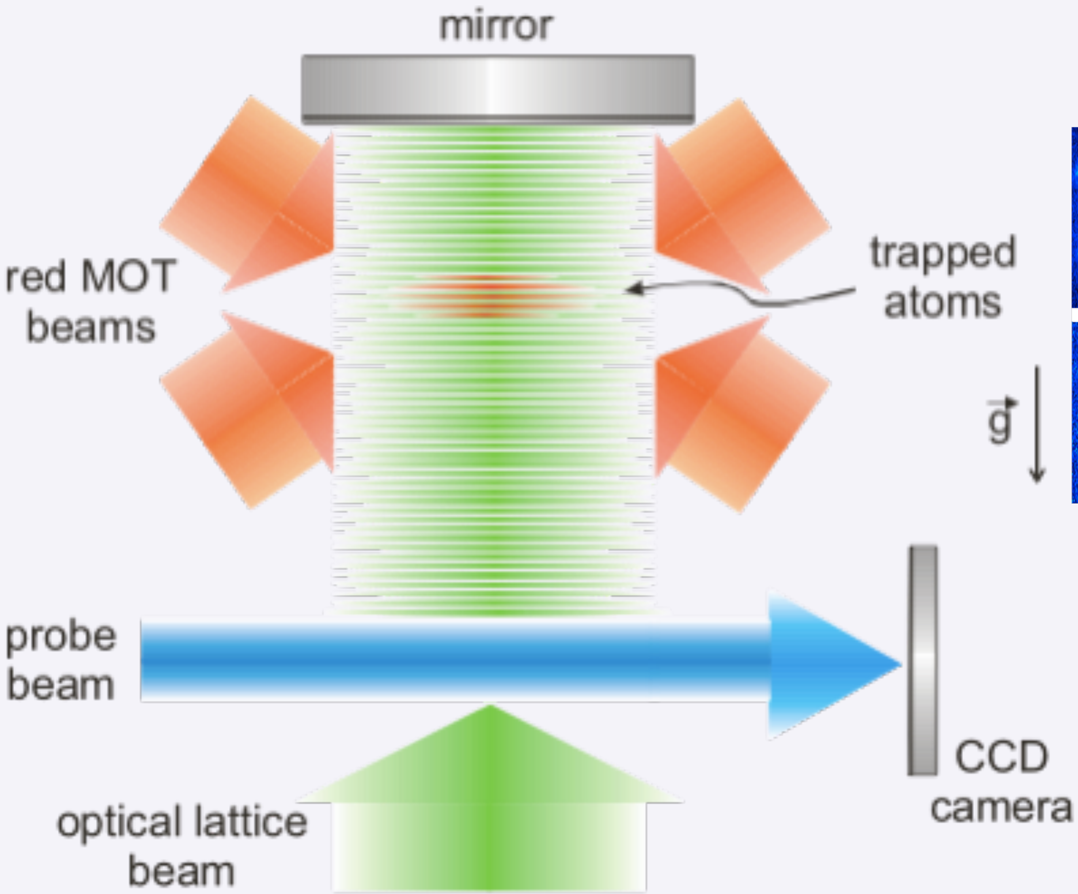
Microwave vs. optical clocks

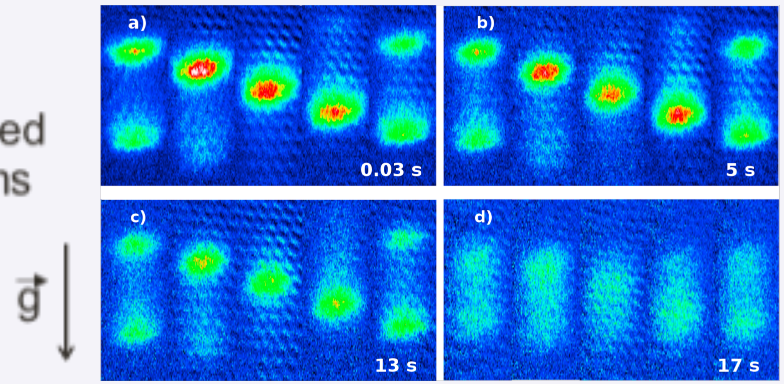


N. Poli, C. W. Oates, P. Gill and G. M. Tino, *Optical atomic clocks*,
Rivista del Nuovo Cimento Vol. 36, N. 12 (2013) - arXiv:1401.2378



Bloch oscillations of Sr atoms in an optical lattice
Precision gravity measurement at 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)**

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:

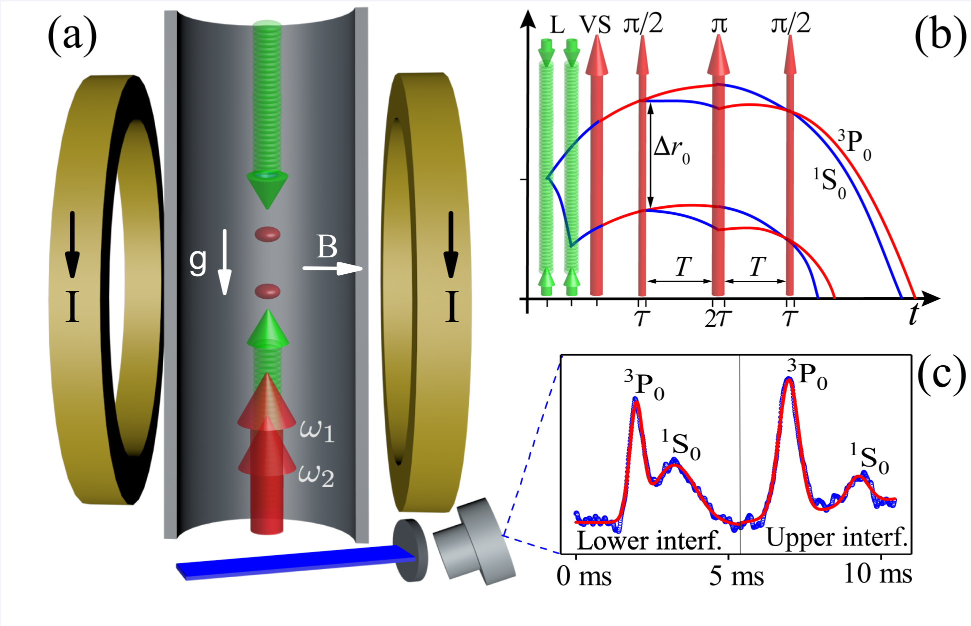
^{88}Sr	^{87}Sr
• Total spin = 0 • Boson	• Total spin ≡ nuclear spin I = 9/2 • Fermion

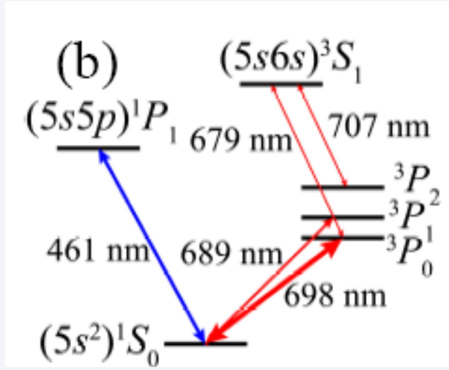
Comparison of the acceleration of ^{88}Sr and ^{87}Sr under the effect of gravity by measuring the Bloch frequencies in a vertical optical lattice

Search for EP violations due to spin-gravity coupling effects

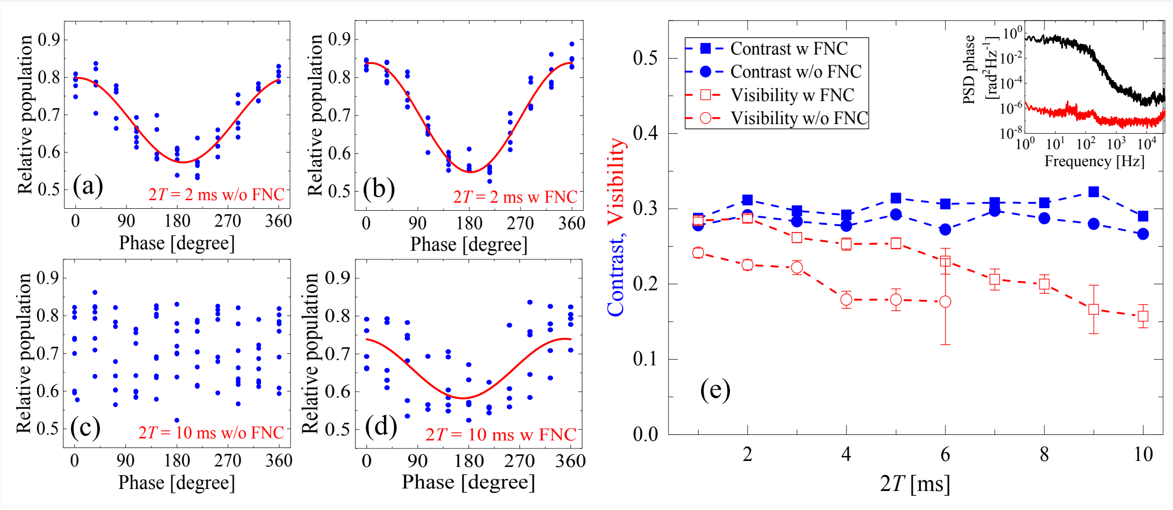
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects*, **Phys. Rev. Lett. 113, 023005 (2014)**

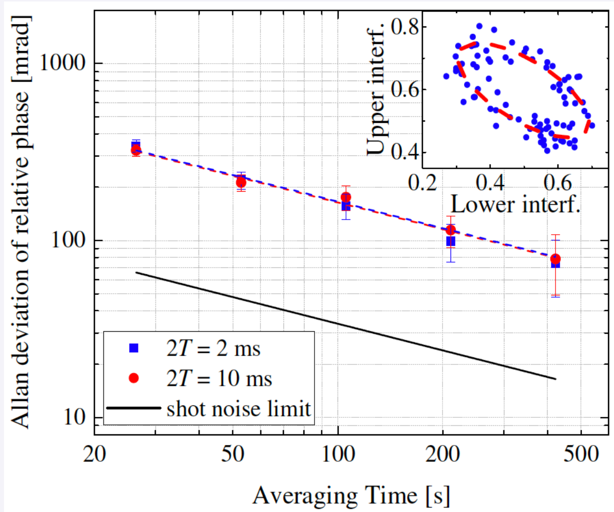
Atom interferometry with the Sr optical clock transition





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

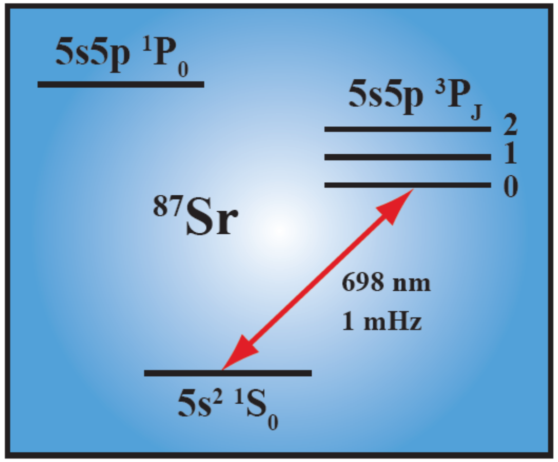




Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017)

From table-top experiments to large-scale detectors

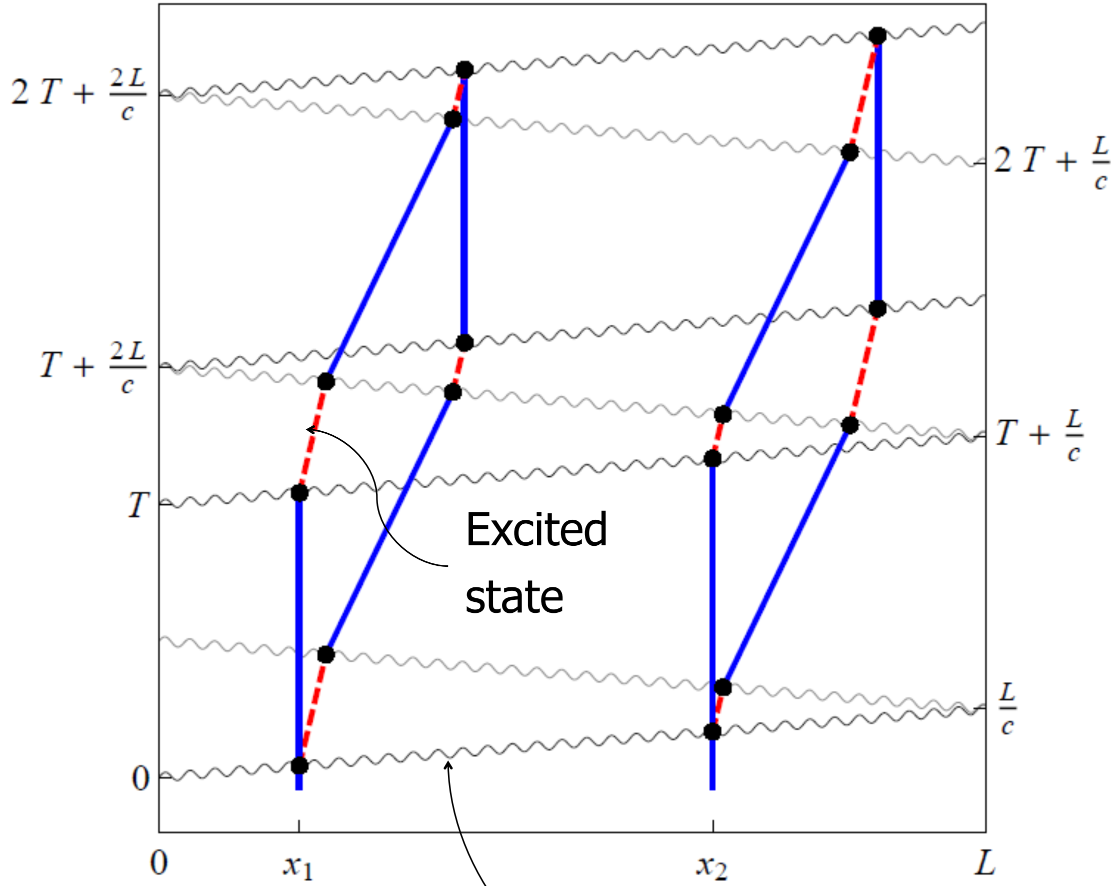
Laser frequency noise insensitive detector



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)

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

UNIVERSITÀ DEGLI STUDI FIRENZE · INFN · lens European Laboratory for Non-Linear Spectroscopy · UNIVERSITY OF BIRMINGHAM · UNIVERSITY OF AMSTERDAM · UNIVERSITÀ DEGLI STUDI DI PADOVA · FORTH INSTITUTE OF ELECTRONIC STRUCTURE AND LASER

NPL National Physical Laboratory · l'Observatoire de Paris SYRTE Systèmes de Référence Temps-Espace · HEINRICH HEINE UNIVERSITÄT DÜSSELDORF · cnrs · PTB Physikalisch-Technische Bundesanstalt Braunschweig und Berlin · Niels Bohr Institutet · ulm university universität ulm · IQ · Leibniz Universität Hannover

Stanford · NANYANG TECHNOLOGICAL UNIVERSITY · University of Nevada, Reno

...s in the field of Fundamental Physics. The scientific objective is to ...al Waves and other fundamental aspects of gravity as well as the ... gravitational 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.

AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration

AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration

Contact person: **Oliver Buchmueller** *(other authors listed on back cover)*

High Energy Physics Group, Blackett Laboratory, Imperial College, Prince Consort Road, London, SW7 2AZ, UK

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Abstract: We propose in this White Paper a concept for a space experiment using cold atoms to search for ultra-light dark matter, and to detect gravitational waves in the frequency range between the most sensitive ranges of LISA and the terrestrial LIGO/Virgo/KAGRA/INDIGO experiments. This interdisciplinary experiment, called Atomic Experiment for Dark Matter and Gravity Exploration (AEDGE), will also complement other planned searches for dark matter, and exploit synergies with other gravitational wave detectors. We give examples of the extended range of sensitivity to ultra-light dark matter offered by AEDGE, and how its gravitational-wave measurements could explore the assembly of super-massive black holes, first-order phase transitions in the early universe and cosmic strings. AEDGE will be based upon technologies now being developed for terrestrial experiments using cold atoms, and will benefit from the space experience obtained with, e.g., LISA and cold atom experiments in microgravity.

Submission in response to the Call for White Papers for the Voyage 2050 long-term plan in the ESA Science Programme

El-Neaj et al. *EPJ Quantum Technology* (2020) 7:6
https://doi.org/10.1140/epjqt/s40507-020-0080-0

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RESEARCH — Open Access

AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space

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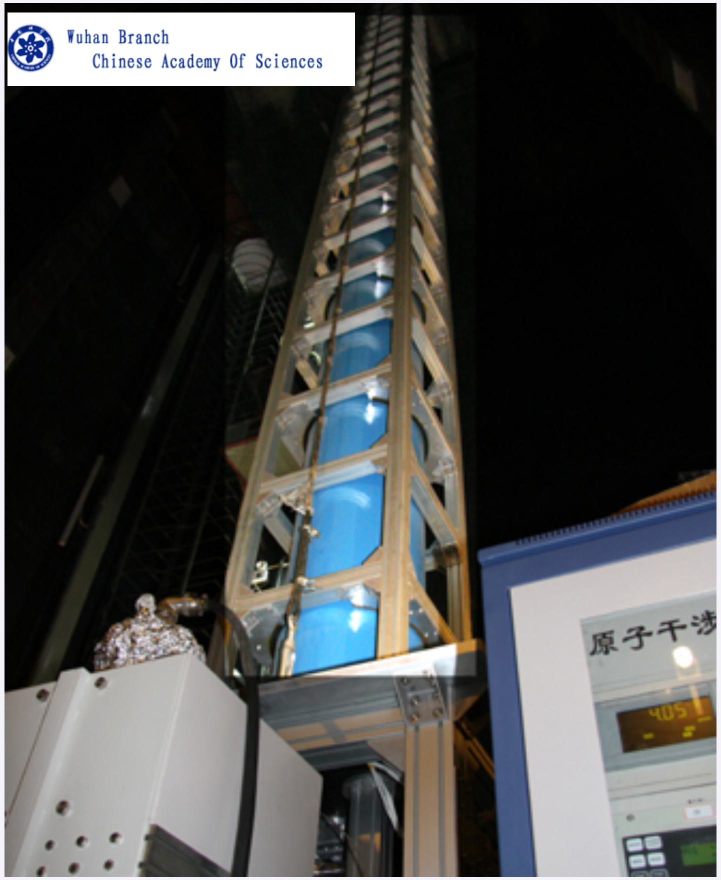
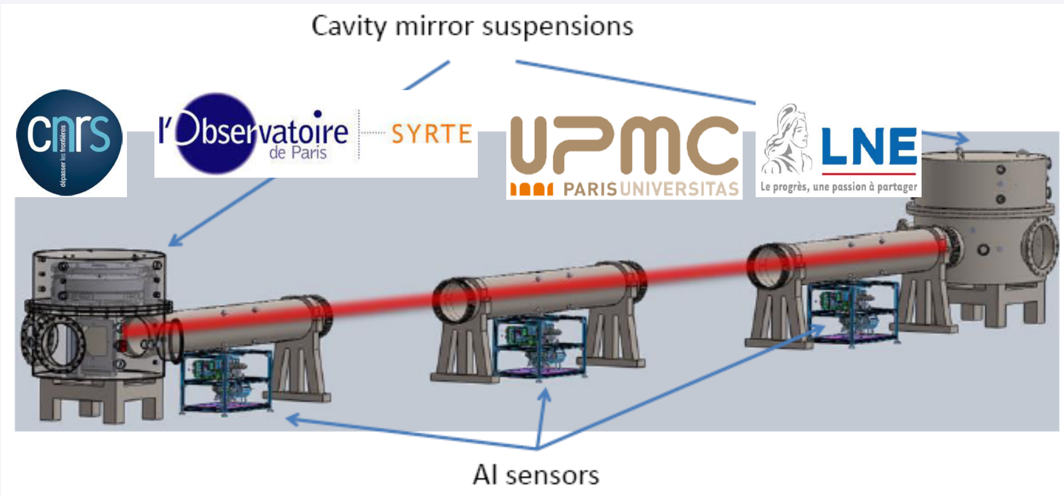
Full list of author information is available at the end of the article
†The White Paper authors are listed with a dagger sign.

Large-scale atom interferometers

10 m fountain at Stanford

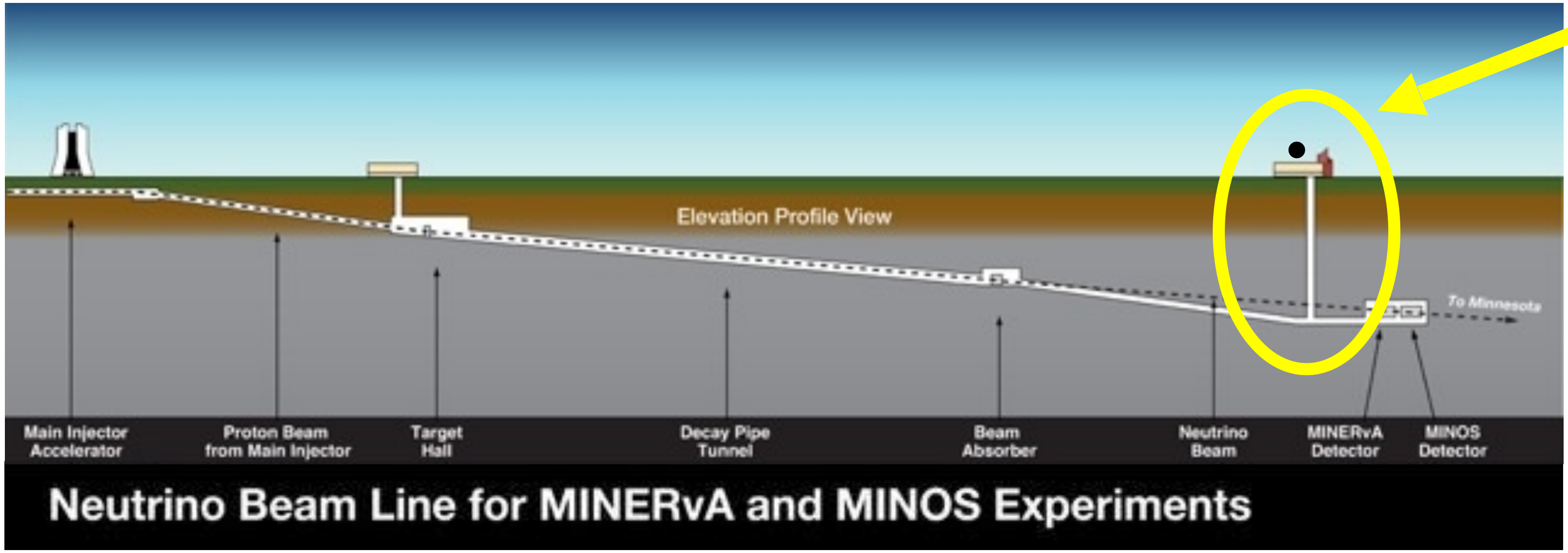
12 m fountain at Wuhan

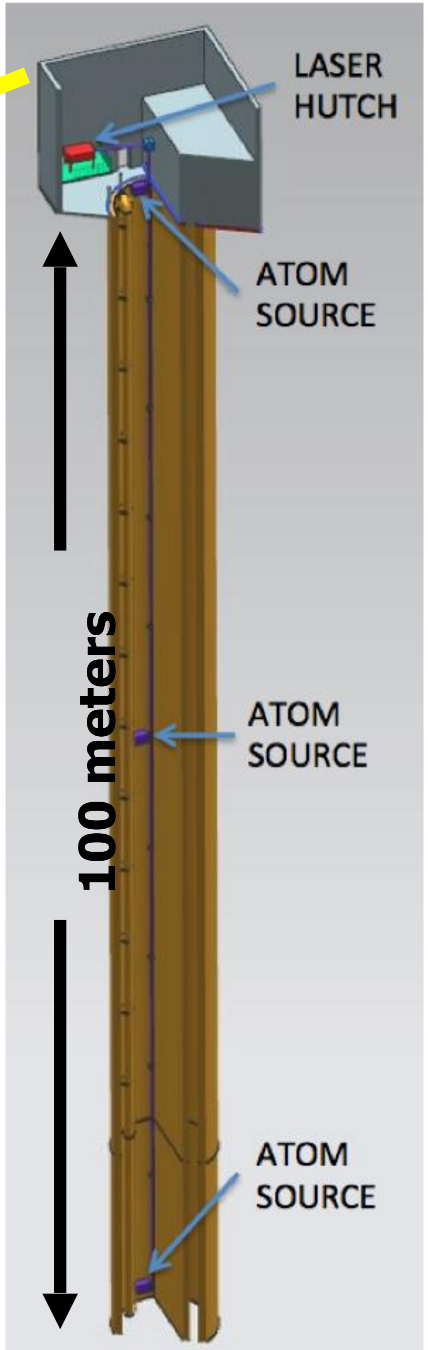




MAGIS-100: Detector prototype at Fermilab

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



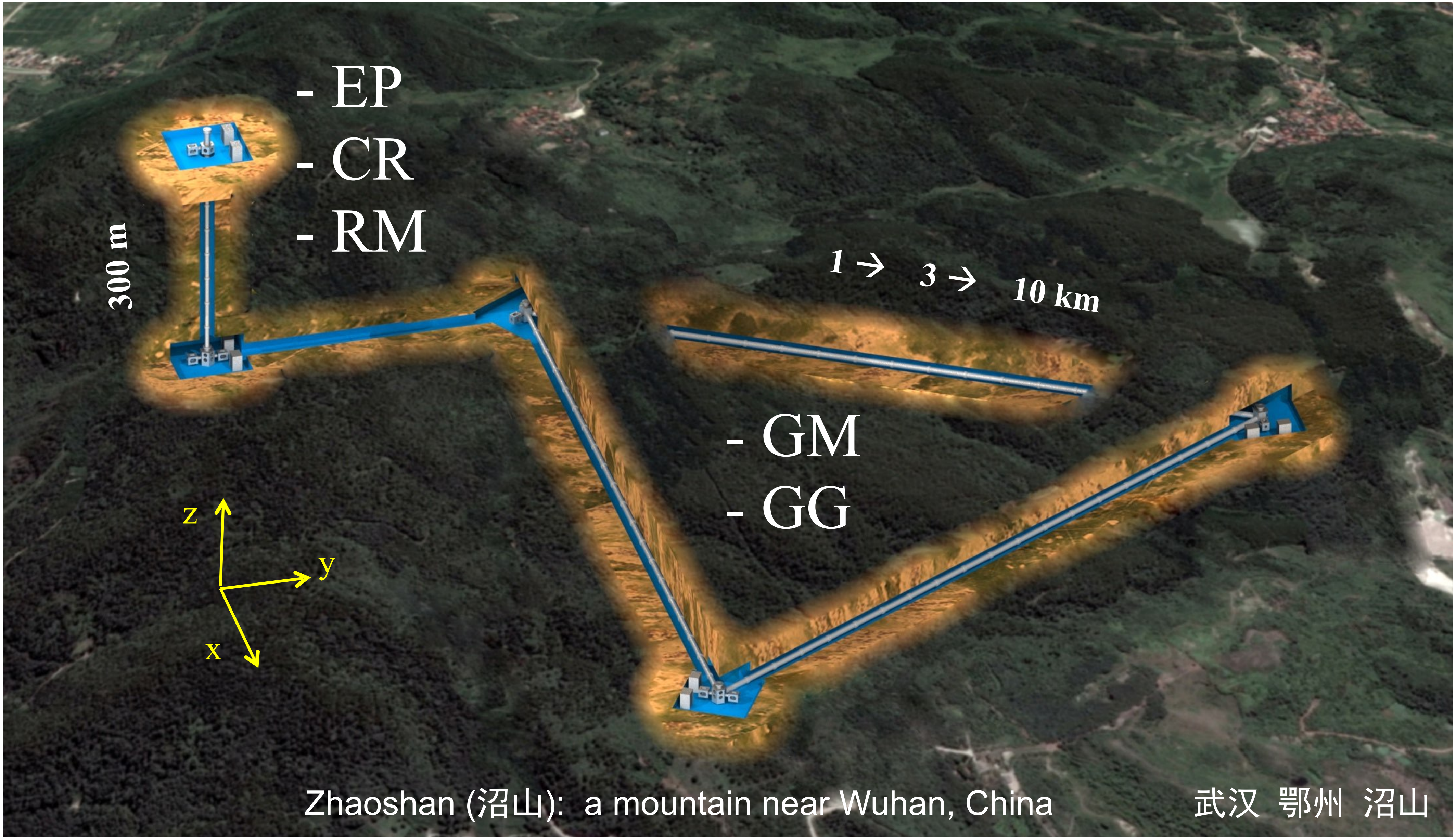


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum 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



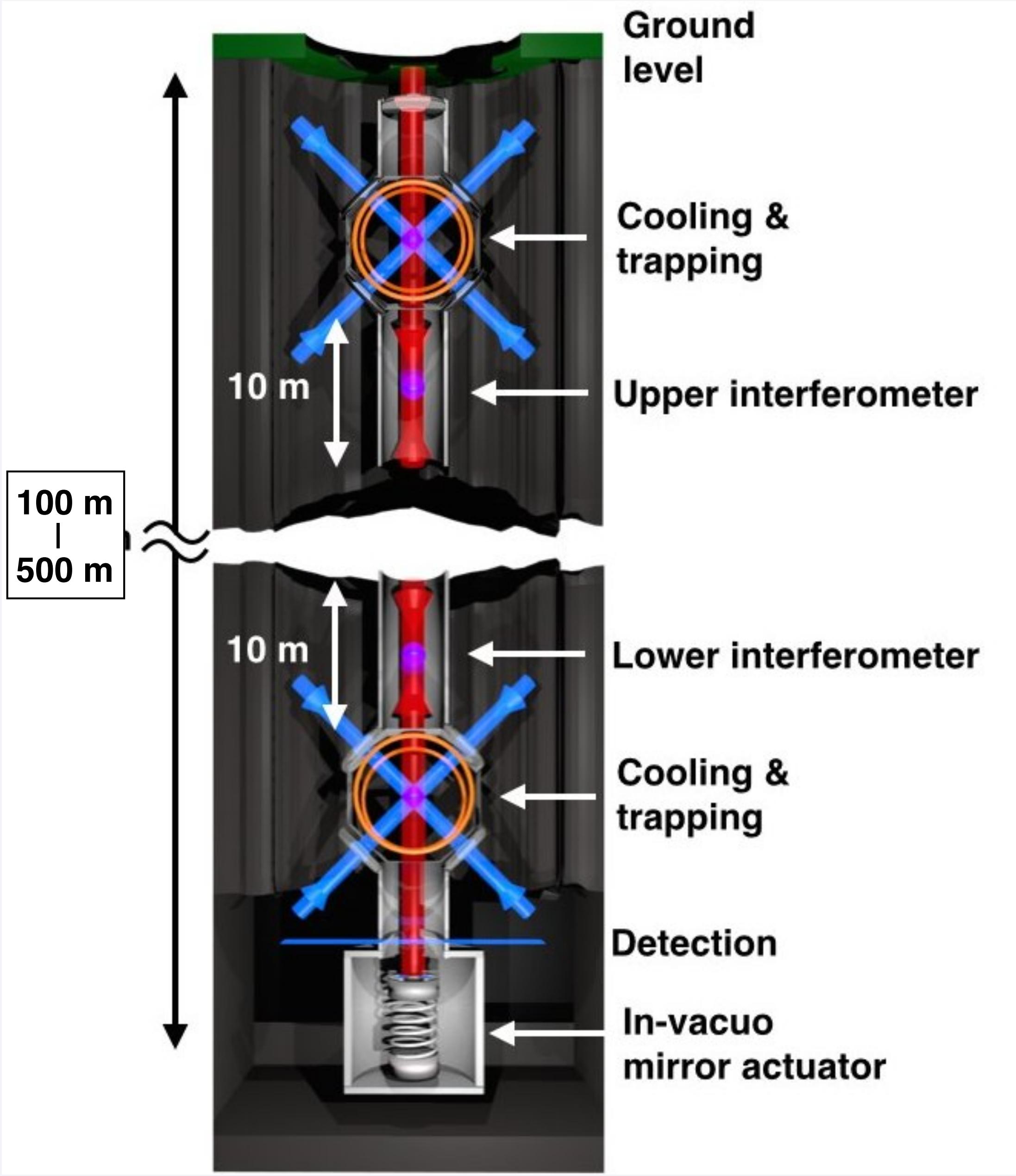
from M. S. Zhan

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

Large-scale atom interferometer
⇒ Sardegna?

Carbonia-Iglesias
ARIA/Darkside Lab

Sos Enattos
SAR-GRAV Lab



AION Project: Core Team

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 and John Ellis

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

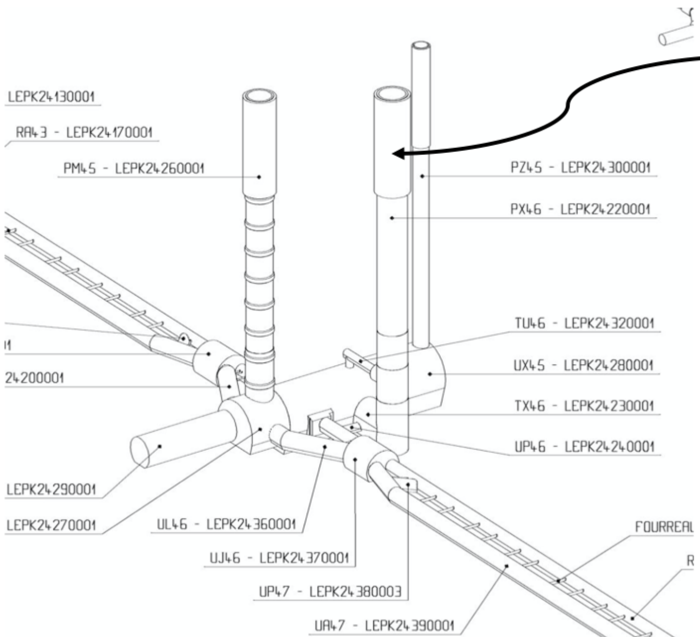
AION-SPACE: Stage 4 [after AION-KM]

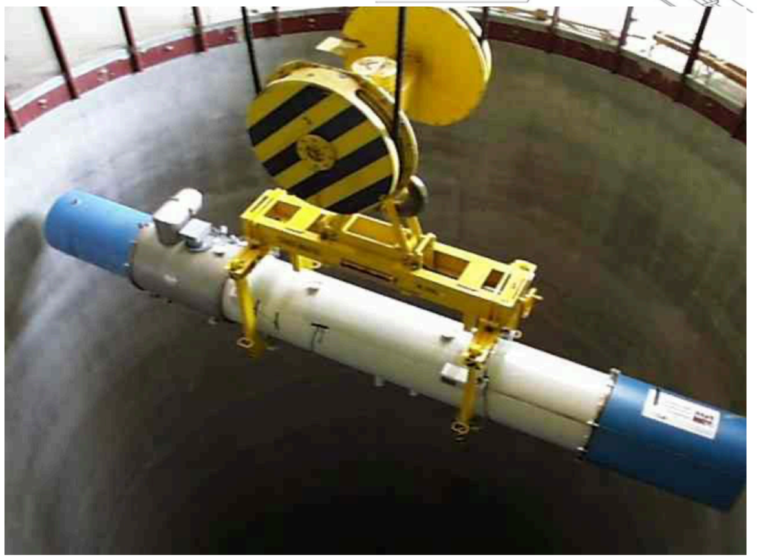
- Space based version

from O. Buchmueller and John Ellis

Possible CERN Location of AION-100m

AION Project: Physics Beyond Colliders Annual Workshop





PX46 – P4 Support shaft

Lengths 143m

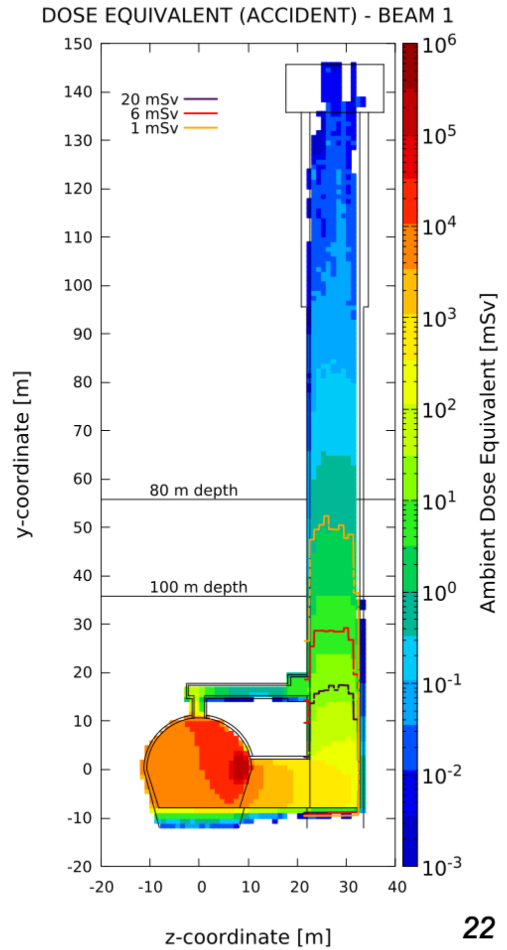
D = 10.10m

- **Ideal basic parameters for AION100**

First radiation studies are also Looking promising but more work is needed to determine if PX46 could be a valid option for AION 100.

We are working with PBC Team (Gianluigi Arduini et al) on feasibility study:

Seismology
Temperature
Ventilation
Radiation protection
Electromagnetic interference

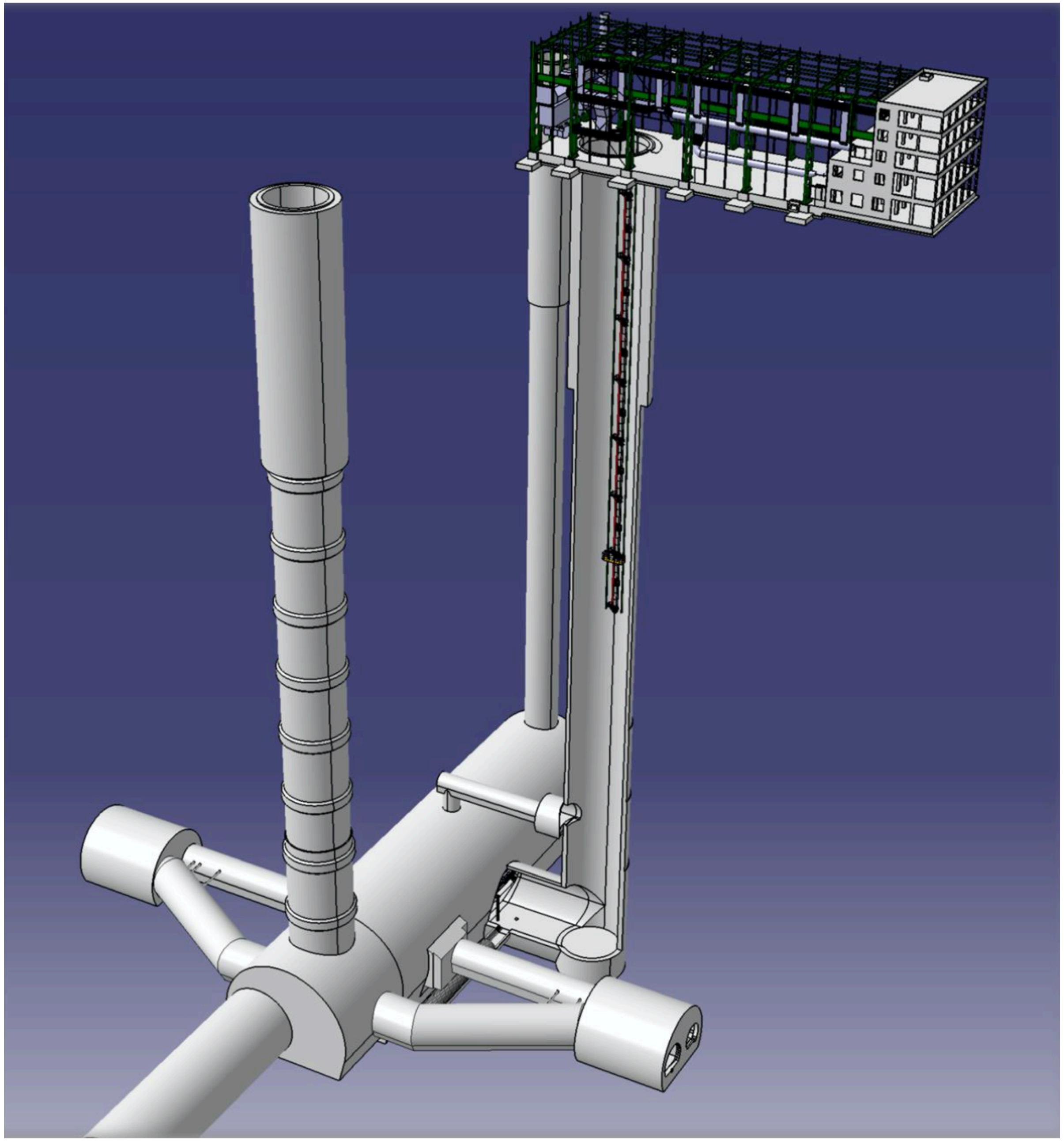


Kincsö Balazs, Angelo Infantino

from O. Buchmueller and John Ellis

Mini-Workshop at CERN

AION



AION-100 @ CERN (26 October 2021) · Indico 08.11.21, 10:06

AION-100 @ CERN

Tuesday 26 Oct 2021, 14:00 → 18:30 Europe/Zurich

Gianluigi Arduini (CERN), John Ellis (Kings College London), Jonathan R. Ellis (University of London (GB)), Kincso Balazs (CERN), Oliver Buchmuller (Imperial College (GB))

Videoconference AION-100 @ CERN

Registration *You are registered for this event.*

14:00 → 14:20 **Introduction** 20m

- o Why AION
- o What is AION
- o Why AION-100 at CERN
- o Present status

Speakers: John Ellis (Kings College London), Oliver Buchmuller (Imperial College (GB))

AIONatCERN.pdf

14:30 → 14:50 **AION-100 Challenges** 20m

- o Systematics
- o Sensitivity to environmental parameters (vibrations, pressure and temp differences, EM interferences, radiation

Speaker: Jeremiah Mitchell (University of Cambridge)

aion100-cern-work...

15:00 → 15:20 **Siting options and required civil engineering** 20m

Speaker: Kincso Balazs (CERN)

2021 10 26 AION1... 2021 10 26 AION1...

15:30 → 15:50 **Radiation protection considerations** 20m

- o access constraints
- o Radiation levels to equipment

Speaker: Angelo Infantino (CERN)

20211006_AION10...

16:00 → 16:20 **Cooling and ventilation** 20m

- o Expected parameters
- o Impact of modifications

Speakers: Olivier Crespo-Lopez (CERN), Raphael Langlois (CERN)

PX46 Ventilation.pdf

16:30 → 16:50 **Vibration and seismic noise** 20m

- o Expected levels
- o Measurement campaign (what are we going to measure in the forthcoming campaign?)

Speaker: Michael Guinchard (CERN)

Seismic measurem... Seismic measurem...

17:00 → 17:20 **EM noise** 20m

- o What is known?
- o What are the frequencies/characteristics
- o What can we measure?

Speakers: Daniel Valuch (CERN), Richard Hobson (Imperial College London), Richard Hobson

AION100_EM_nois... Magnetic field requ... Magnetic field requ...

https://indico.cern.ch/event/1084435/?print=1 Page 1 of 2

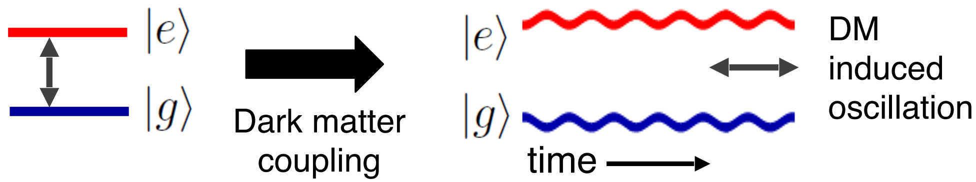
from O. Buchmueller and John Ellis

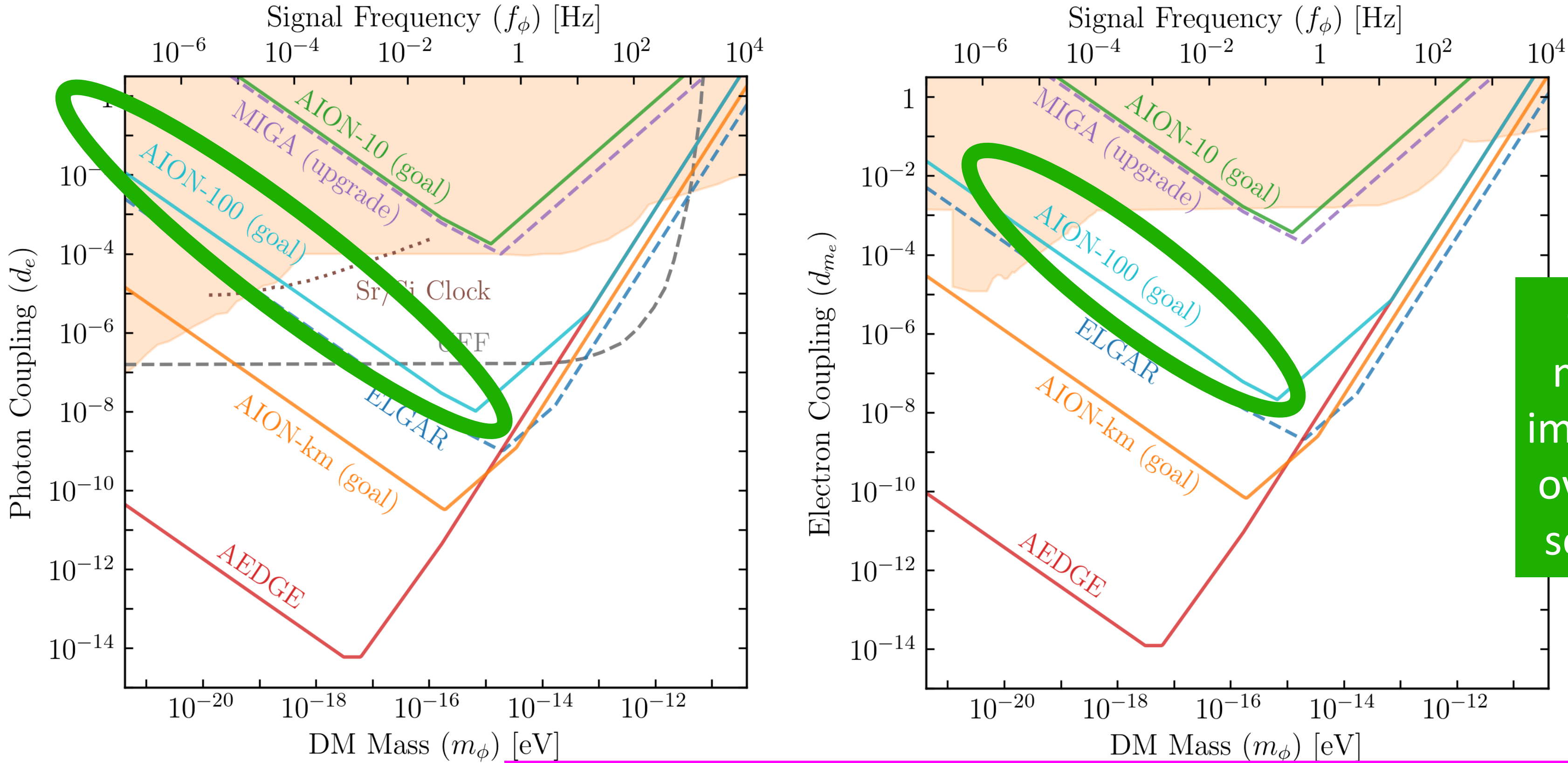
Searches for Light Dark Matter

AION

Linear couplings to gauge fields and matter fermions

$$\mathcal{L}_{\mathrm{int}\phi} = \kappa\phi \left[+\frac{d_e}{4e^2} F_{\mu\nu}F^{\mu\nu} - \frac{d_g \beta_3}{2g_3} F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=e,u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$$



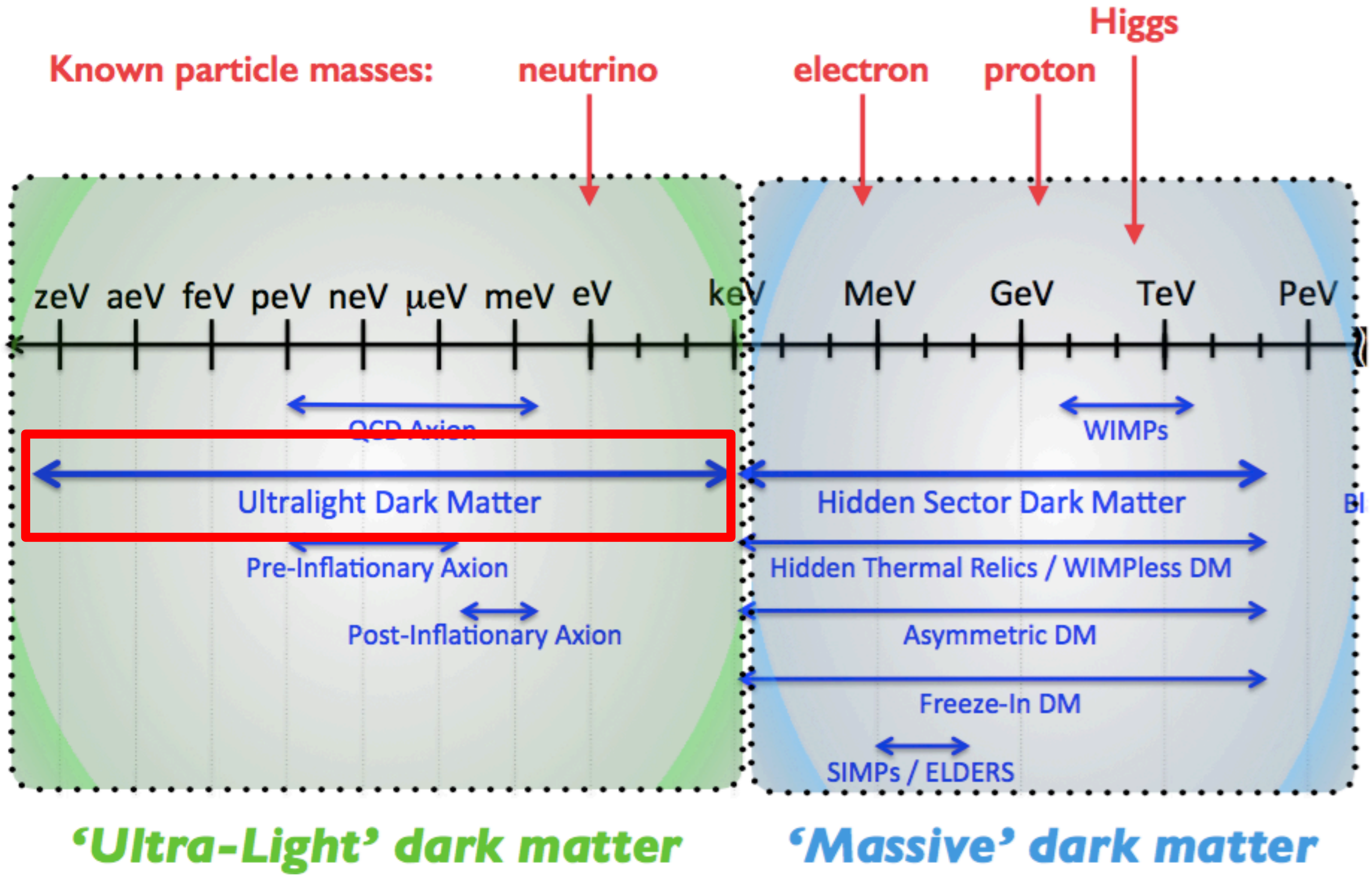


Orders of magnitude improvement over current sensitivities

AION Collaboration (Badurina, ..., JE et al): arXiv:1911.11755; Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

from O. Buchmueller and John Ellis

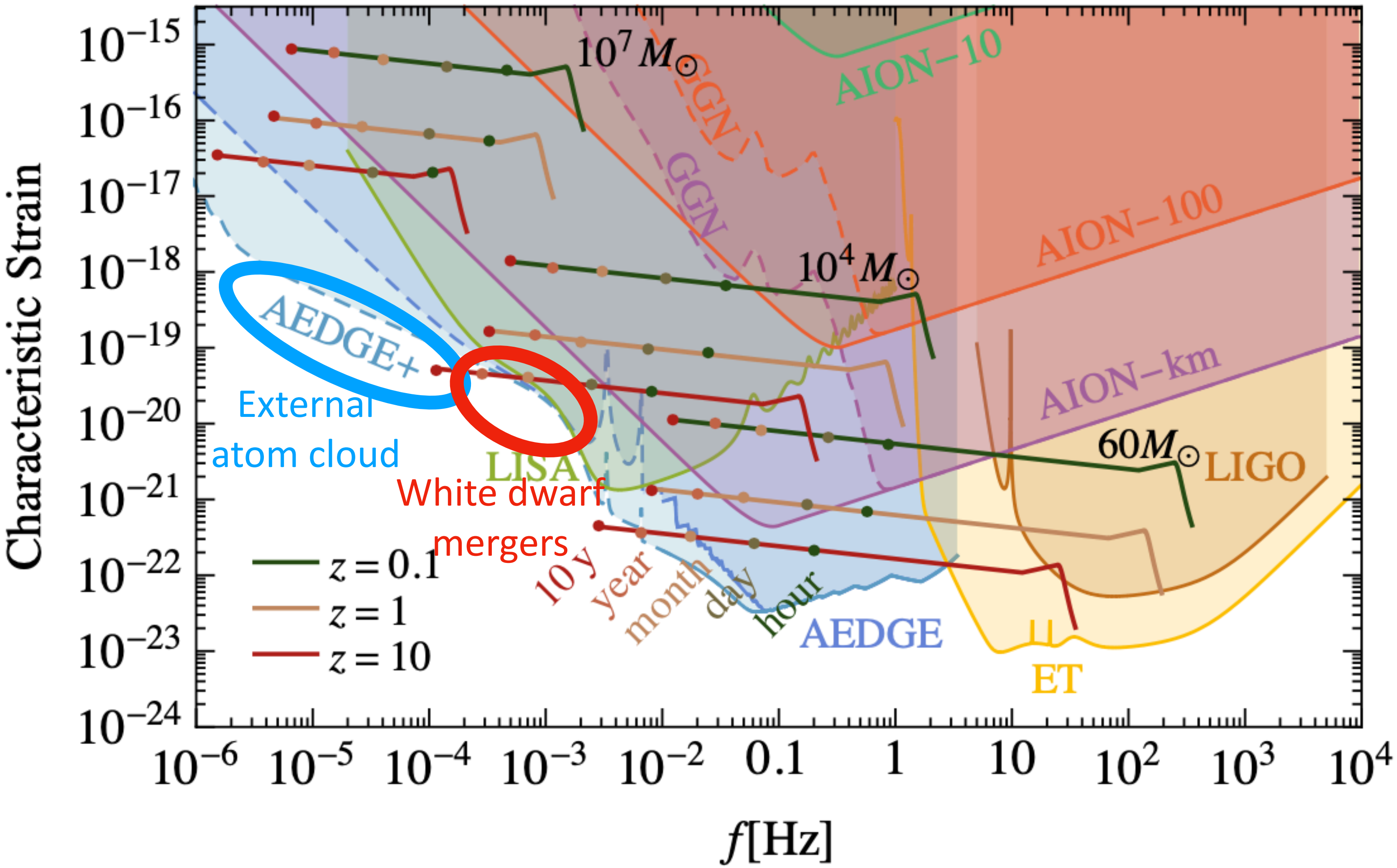
Search for Ultra-Light Dark Matter



from O. Buchmueller and John Ellis

AION Collaboration (Badurina, …, JE et al): arXiv:1911.11755

More on Gravitational Waves



Probe formation of SMBHs

Synergies with other GW experiments (LIGO, LISA), test GR

Badurina, Buchmueller, JE, Lewicki, McCabe & Vaskonen: arXiv:2108.02468

from O. Buchmueller and John Ellis

Advanced atomic quantum sensors for gravitational physics

- **Large-scale atom interferometer**
- **New schemes for large momentum transfer**
- **Higher power lasers**
- **High-flux atomic sources**
- **High-sensitivity detection schemes**
- **Squeezed atomic states**