Precision tests of gravitational physics using atomic quantum sensors

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SIGRAV International School 2024 - *Measuring Gravity*

Vietri sul Mare - 19-23 February 2024

Outline of the Lectures

- *Laser cooling and manipulation of atoms*
- *Atom interferometry*
- *Optical atomic clocks*
- *Gravitational physics experiments on Earth and in space*

Main references

- C. Cohen-Tannoudji, D. Guery-Odelin, *Advances in Atomic Physics: An Overview*, World Scientific (2011).

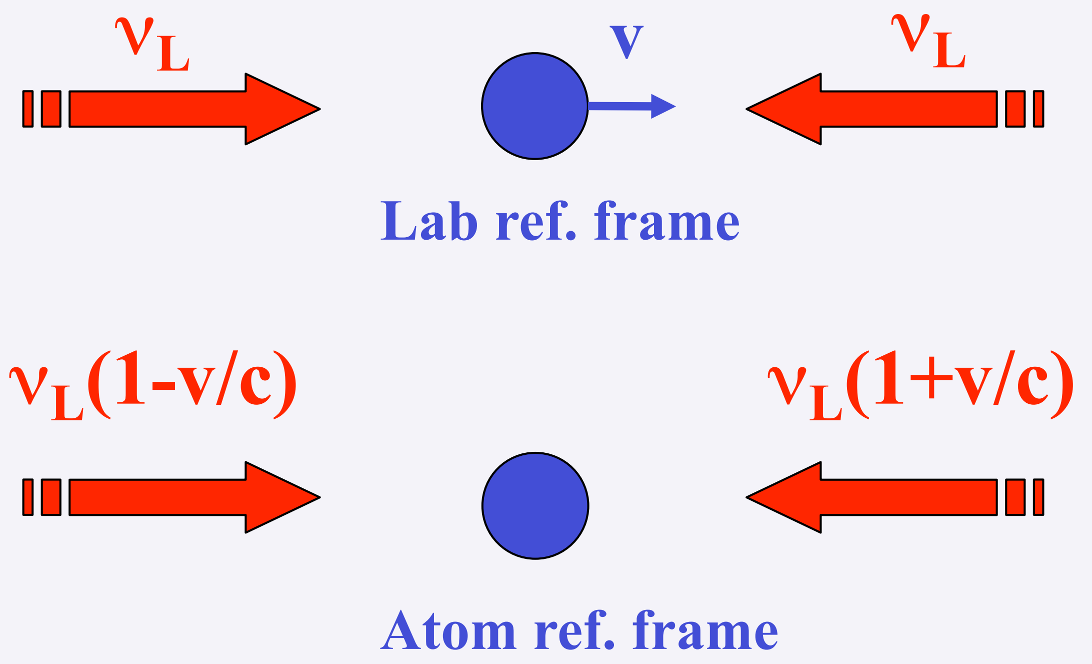
- G. M. Tino, M. A. Kasevich (eds). *Atom Interferometry*, SIF and IOS (2014).

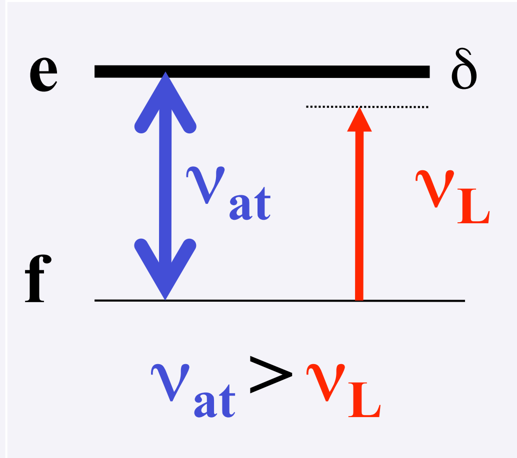
- N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks*, Rivista del Nuovo Cimento 36, n. 12, 555 (2013).

- G. M. Tino, *Testing gravity with cold atom interferometry: results and prospects*, Quantum Sci. Technol. 6, 024014 (2021).

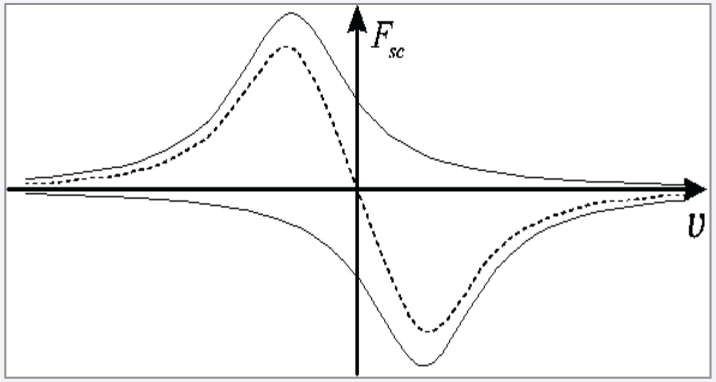
Introduction to laser cooling and manipulation of atoms

Laser cooling of atoms





$$(I/I_0 \ll 1) \longrightarrow \quad F(\mathrm{v}) \simeq \frac{h\nu_L}{c}\times\frac{1}{2\pi}\times\left[\frac{I/I_0}{1+I/I_0+\frac{4}{\Gamma^2}(\delta-\frac{\nu_L}{c}\mathrm{v})^2} - \frac{I/I_0}{1+I/I_0+\frac{4}{\Gamma^2}(\delta+\frac{\nu_L}{c}\mathrm{v})^2}\right]$$

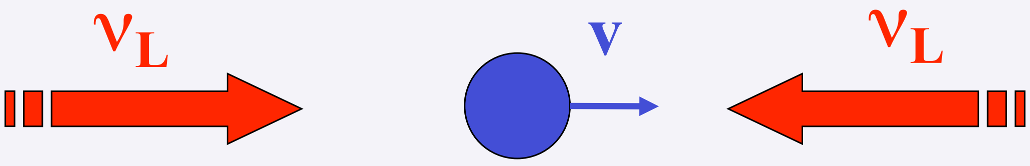


$$(\mathrm{v}\ll\frac{\Gamma c}{2\nu_L}) \longrightarrow F(\mathrm{v})\simeq \frac{h\nu_L^2}{c^2}\times\frac{8\delta}{\Gamma}\times\frac{I/I_0}{[1+(\frac{2\delta}{\Gamma})^2]^2}\,\mathrm{v} = -\alpha\,\mathrm{v}$$

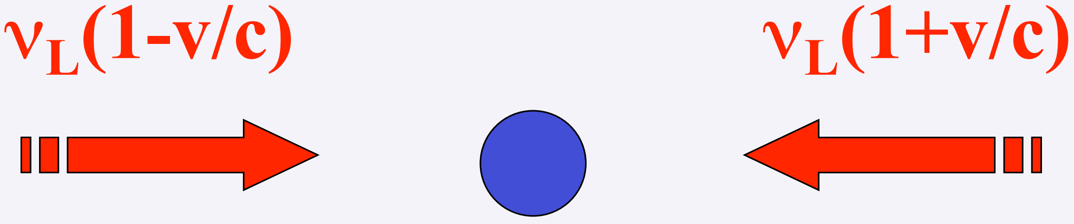
Idea: **T.W. Hänsch, A. Schawlow, 1975**

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

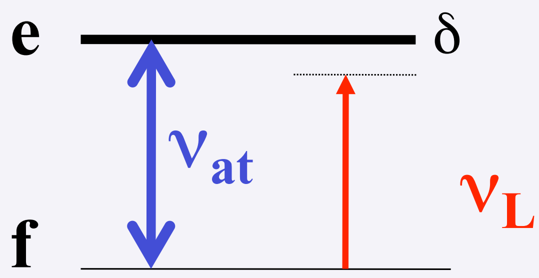
Laser cooling: Optical molasses



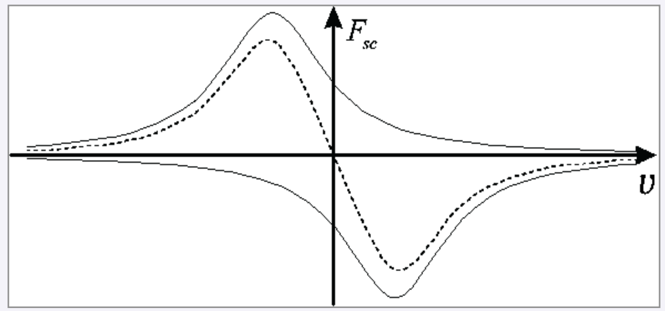
Lab ref. frame



Atom ref. frame



$\nu_{at} > \nu_L$



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

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

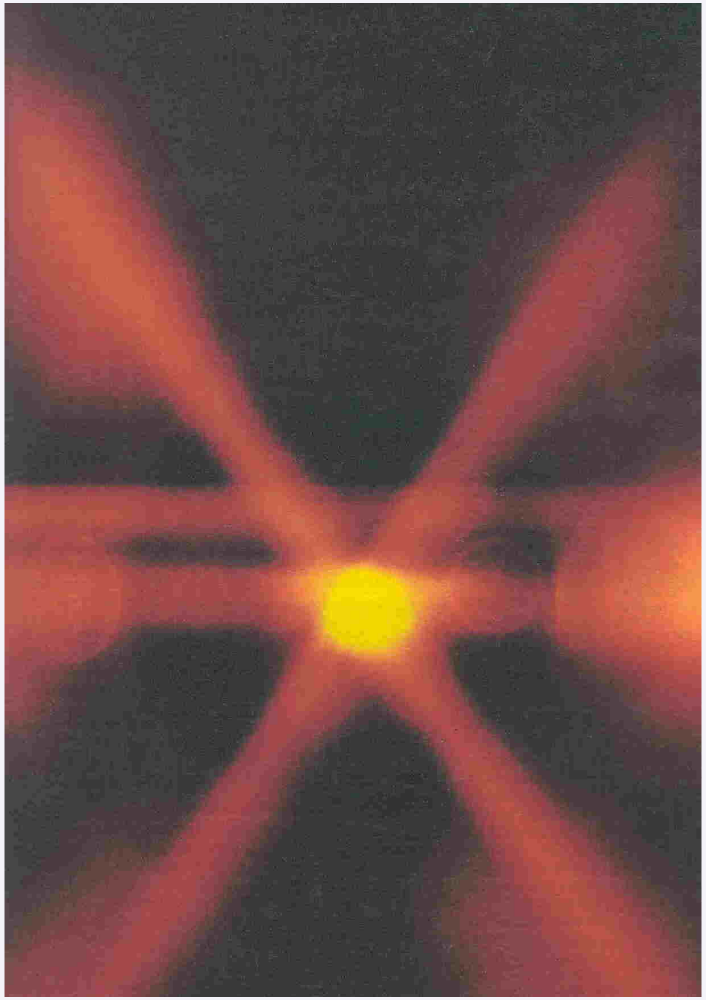
Recoil limit: $$k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$$

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

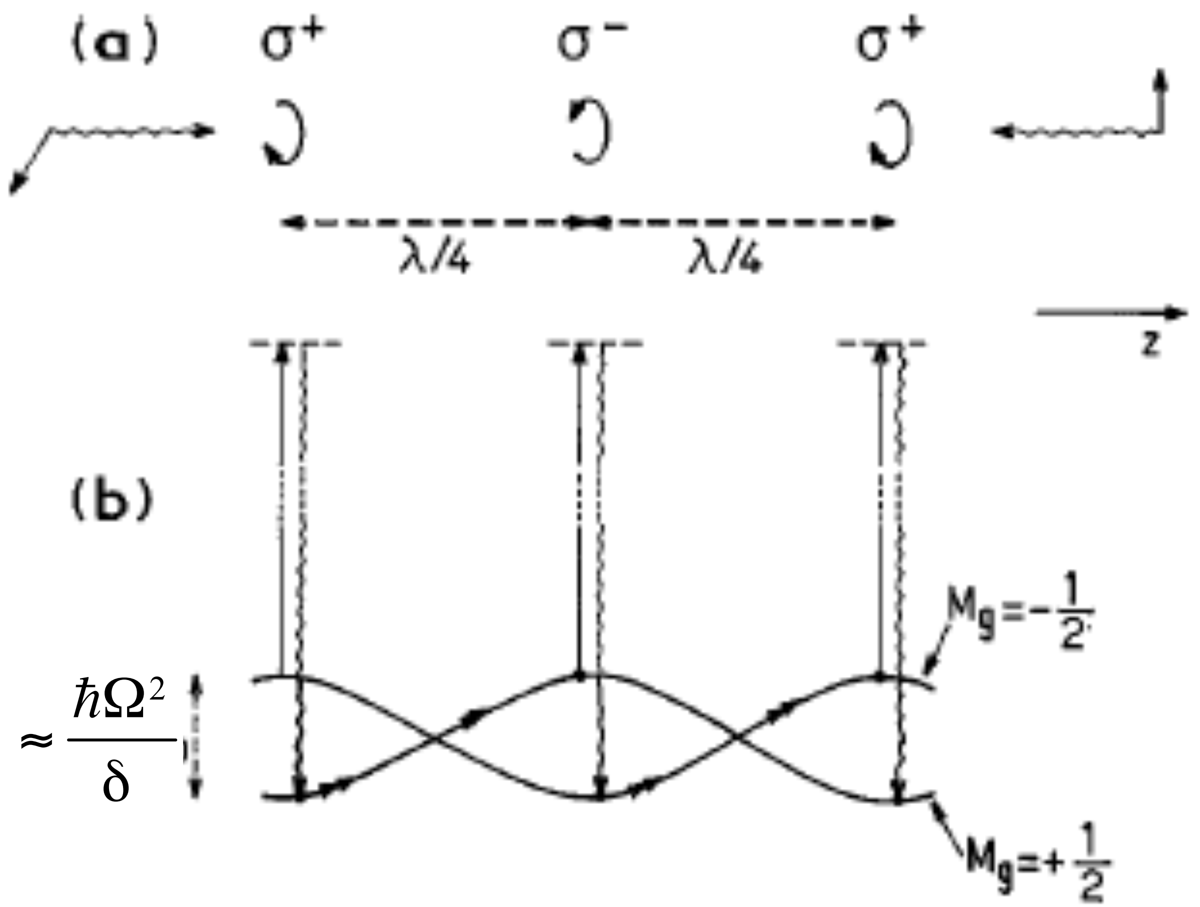
Idea: **T. W. Hänsch, A. Schawlow, 1975**
Exp. demonstration: **S. Chu et al., 1985**

3D molasses



Na molasses

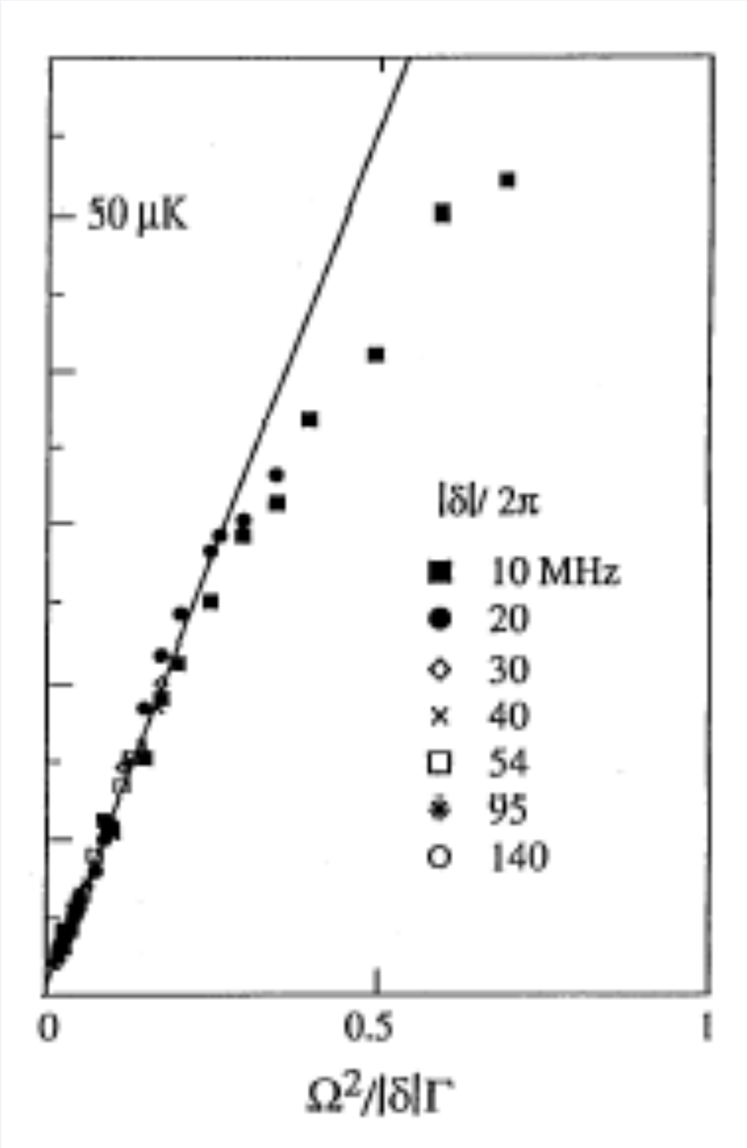
Sisyphus cooling



$U_0 \approx \frac{\hbar\Omega^2}{\delta}$

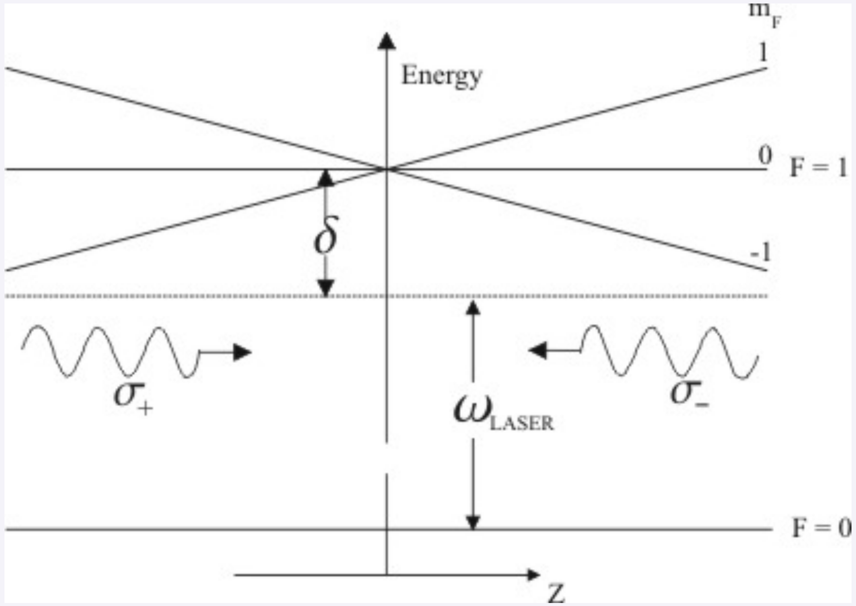
From C. Cohen-Tannoudji

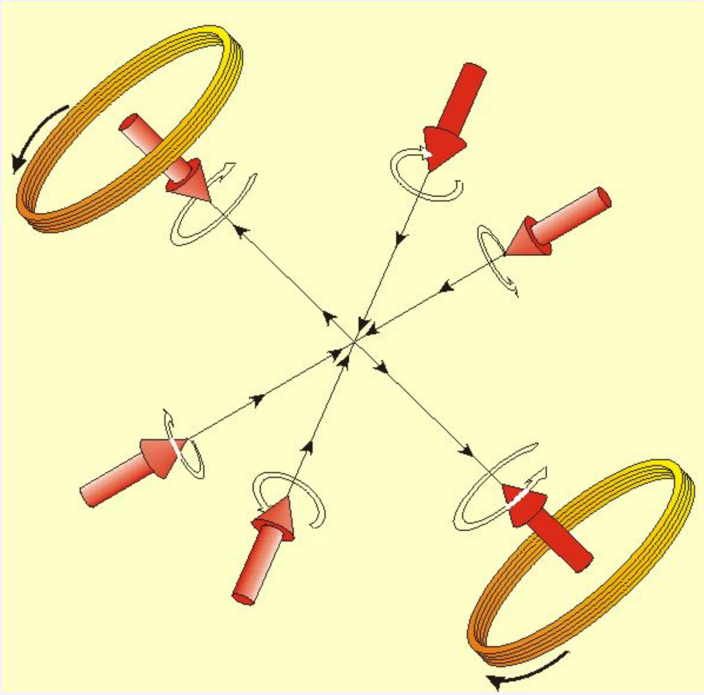
Sub-Doppler temperatures



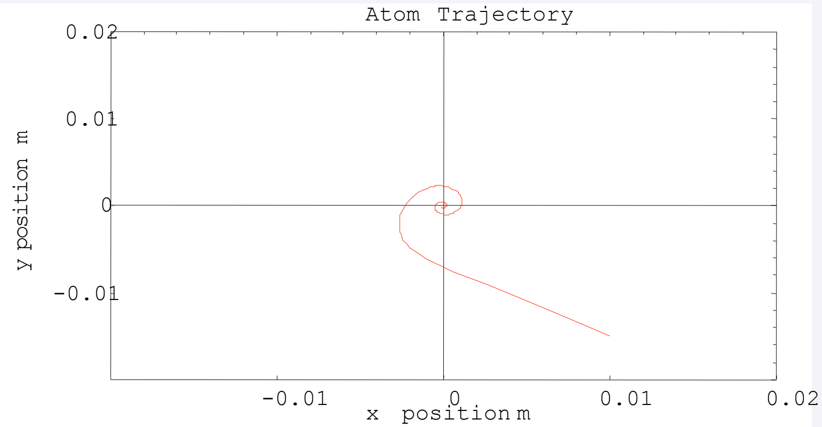
C. Salomon et al., 1990

Magneto-Optical Trap (MOT)





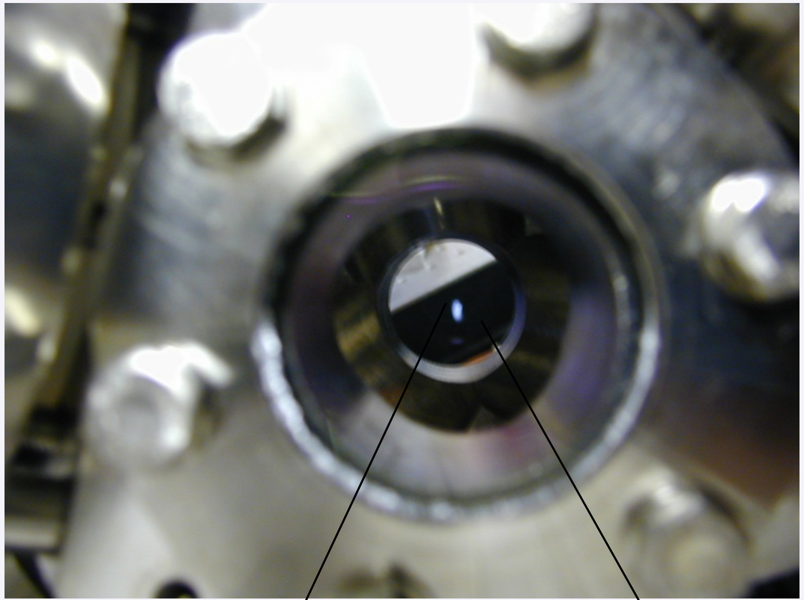
$$F(z,\mathrm{v}) \simeq \frac{4hk}{\pi}\frac{I}{I_0}\frac{\delta}{\Gamma}\frac{k\mathrm{v}+\beta z}{[1+(\frac{2\delta}{\Gamma})^2]^2}$$



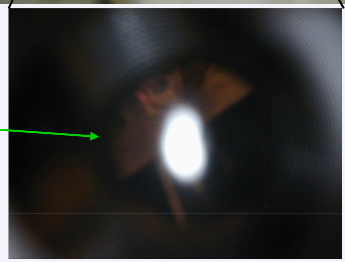
density n ≈ 10^{11} cm^{-3}
temperature T ≈ 100 μK
size Δx ≈ 1 mm

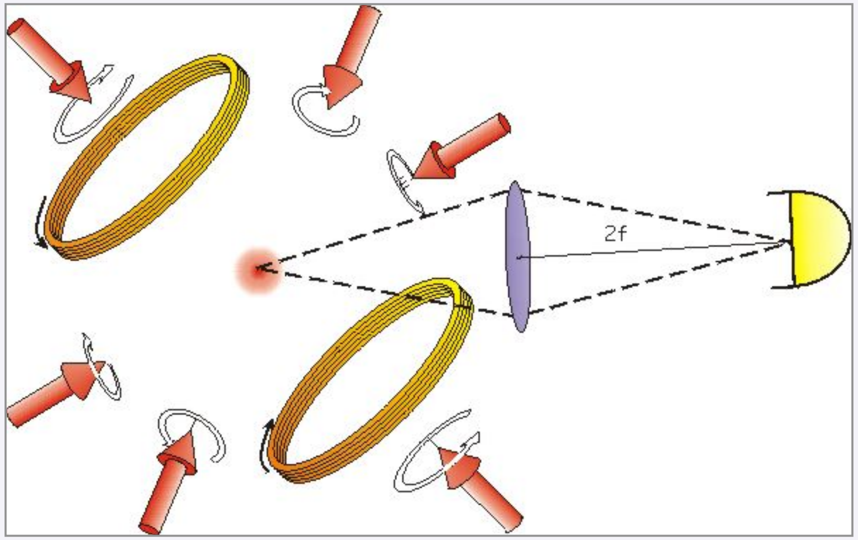
E. Raab *et al.*, Phys. Rev. Lett. 59, 2631 (1987)

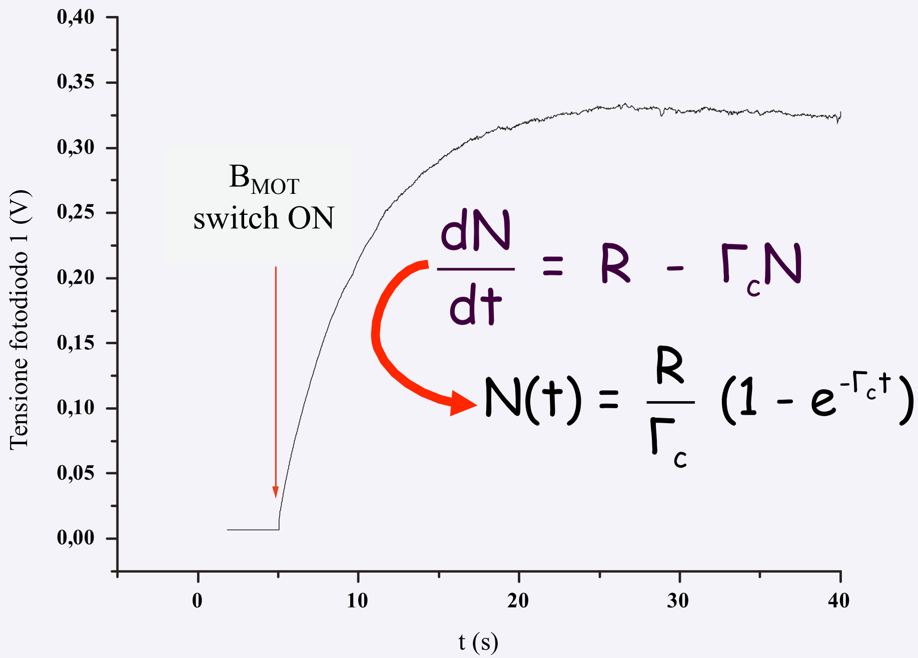
Rb MOT



Ø ≈ 4 mm

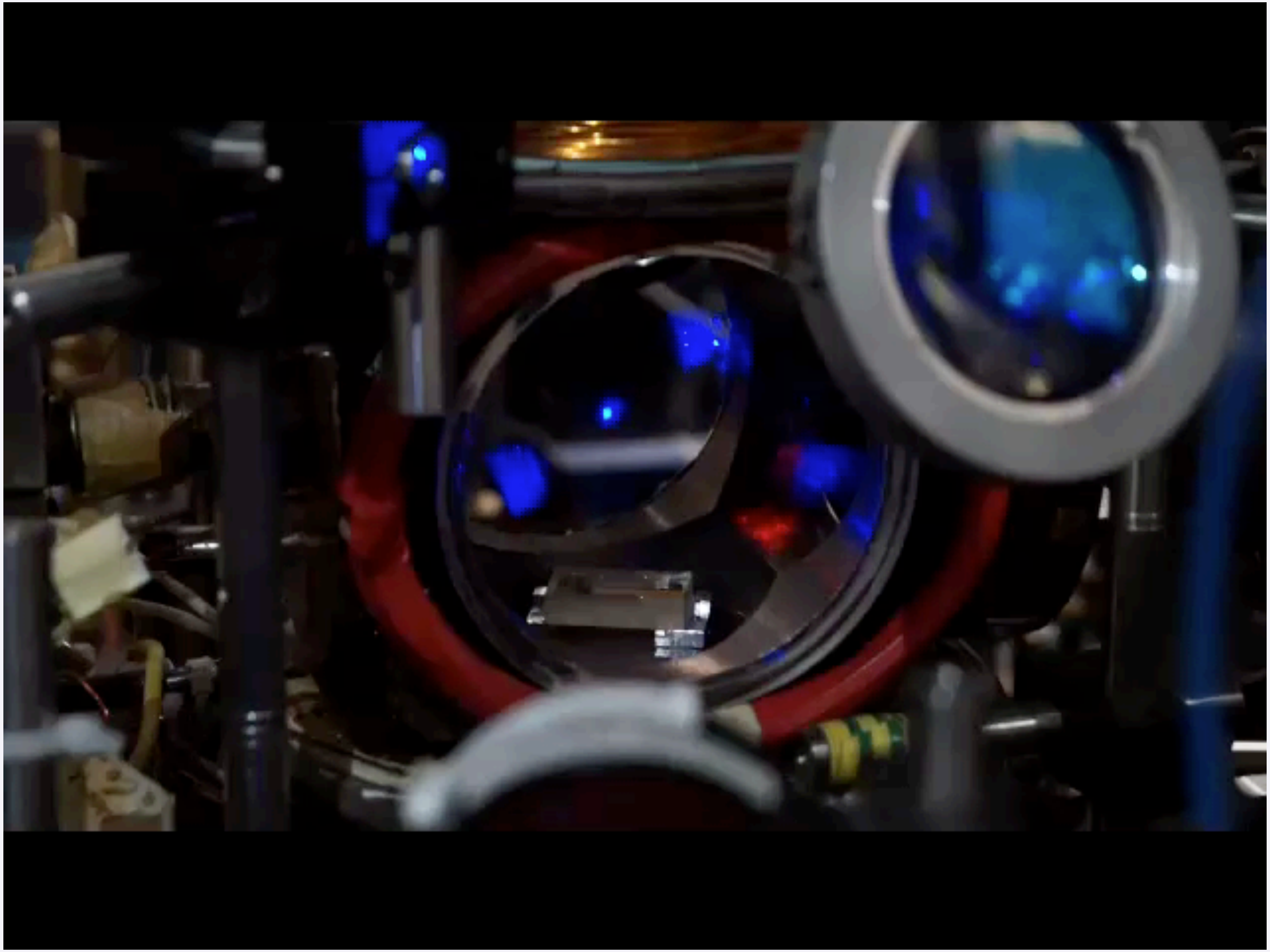




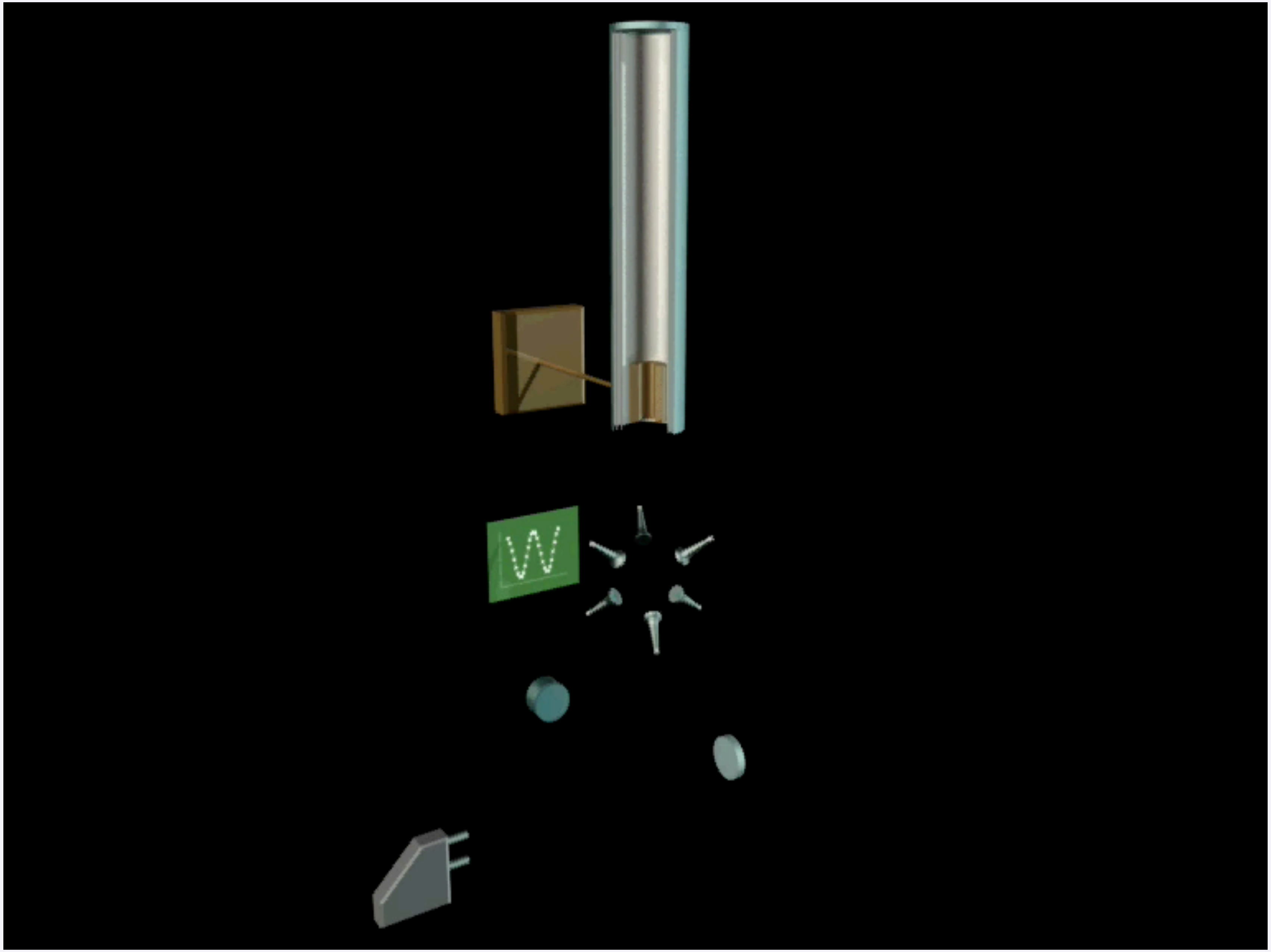


MOT	grad B: 7 G/cm detuning: -3Γ intensity: 2 I_S
MOLASSES	grad B: 0 G/cm detuning: -7Γ intensity: 0.5 I_S

Sr MOT

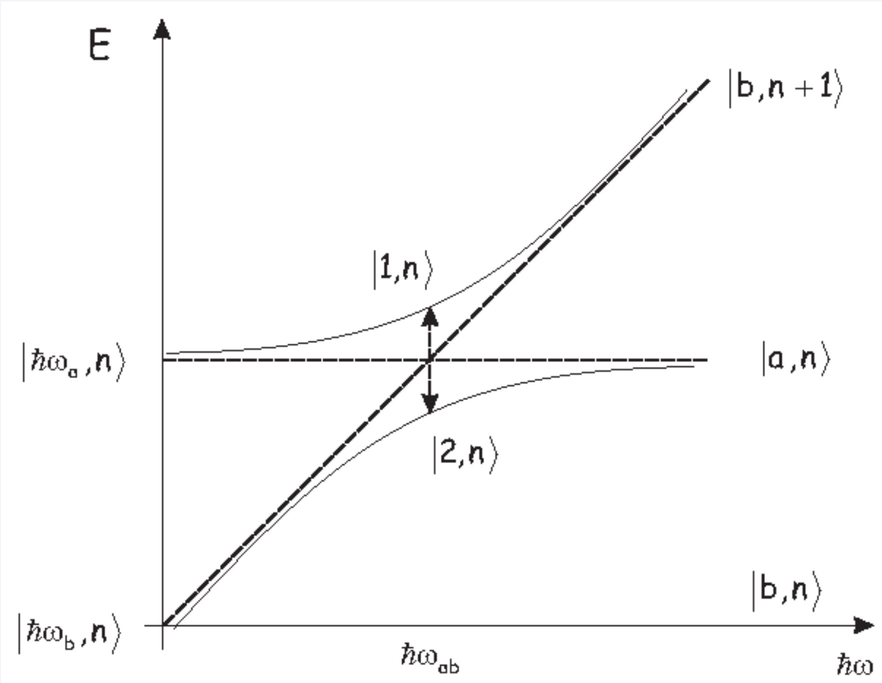


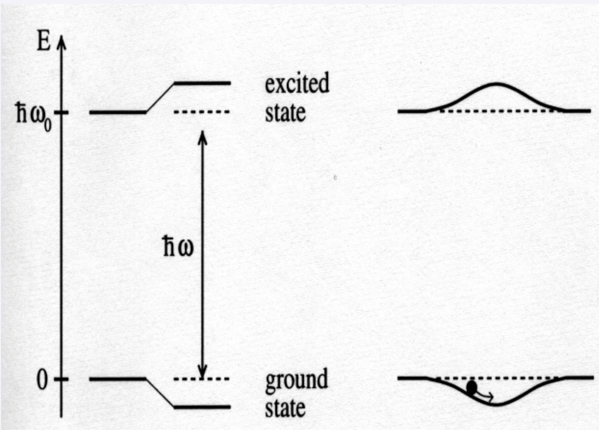
Atomic fountain

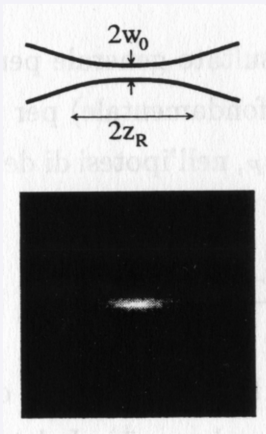


from C. Salomon

Light shifts and optical traps

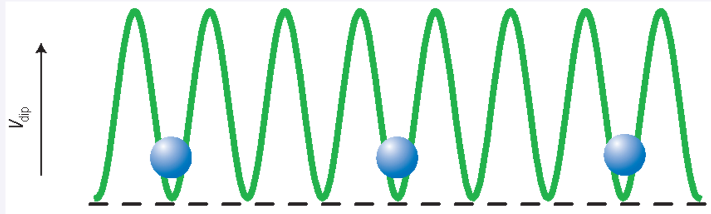




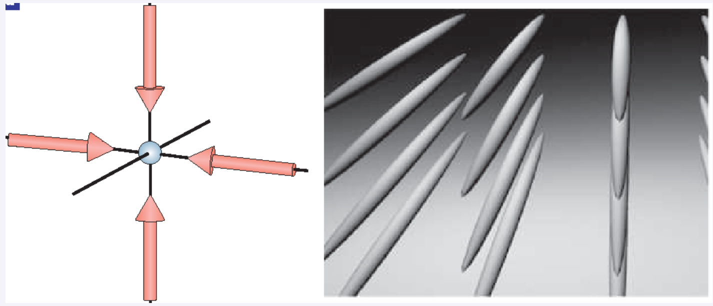


$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)\,|\mathbf{E}(\mathbf{r})|^2$$

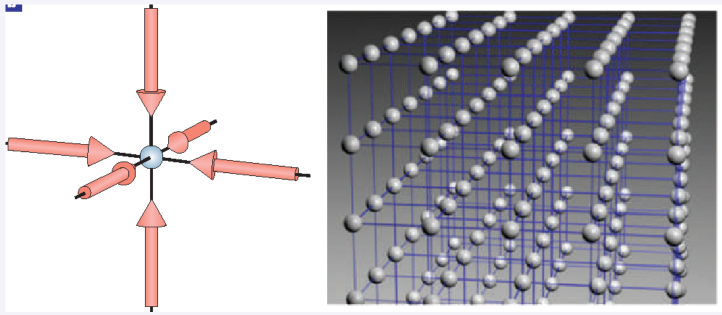
optical lattices



1D optical lattice ⇒ array of 2D disk-like trapping potentials



2 D optical lattice ⇒ array of 1D potential tubes

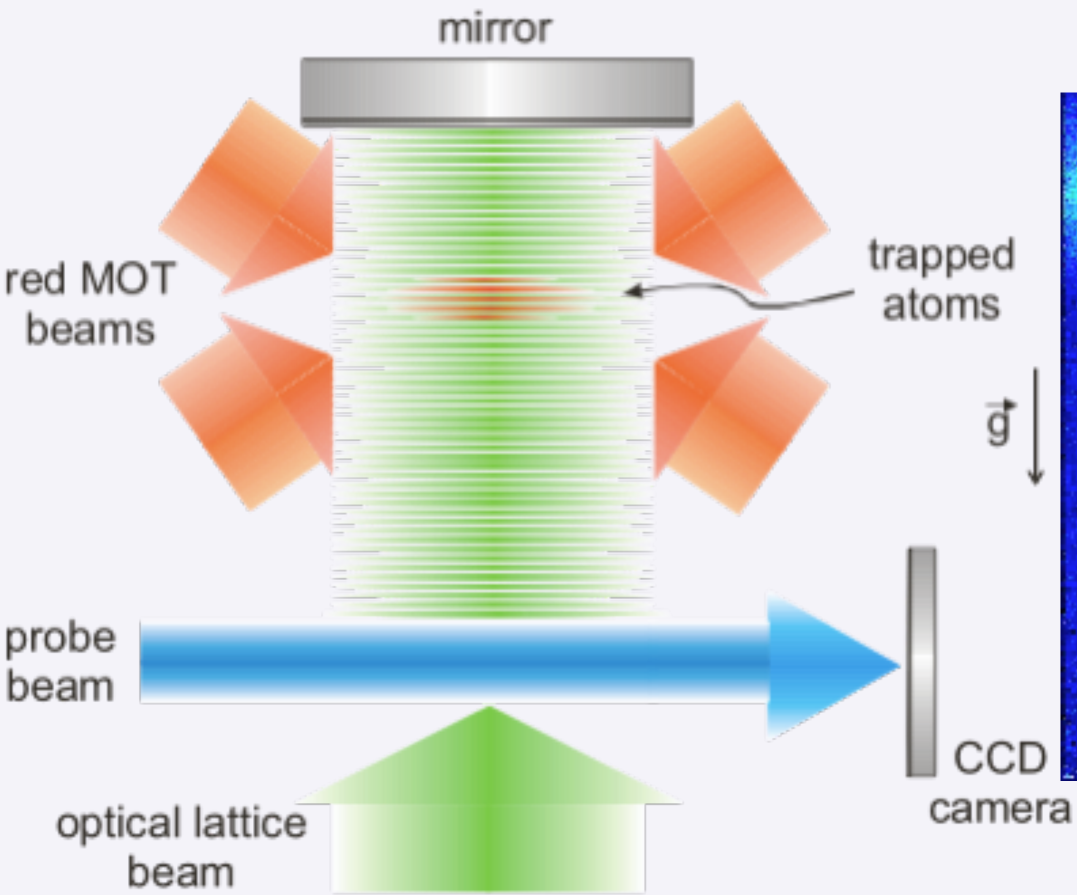


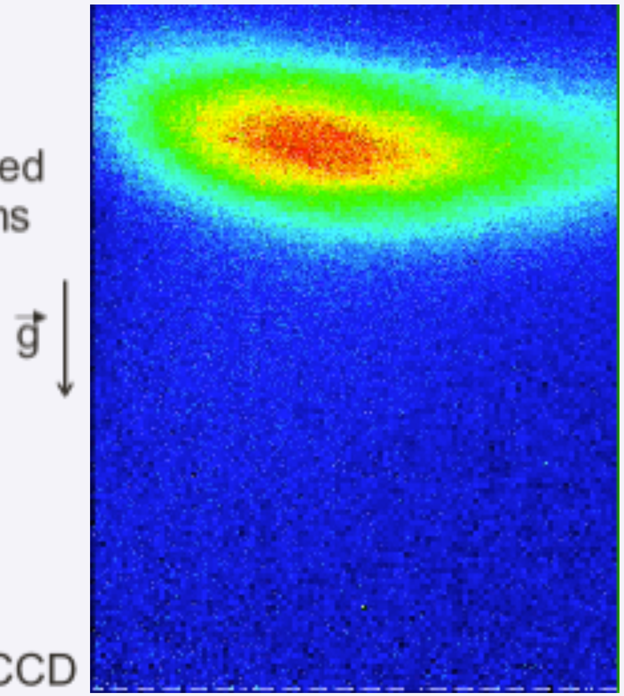
3 D optical lattice ⇒ 3D simple cubic array of h.o. potentials

First exp. demonstration: **S. Chu et al., 1986**

Review: **I. Bloch, 2005**

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





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

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

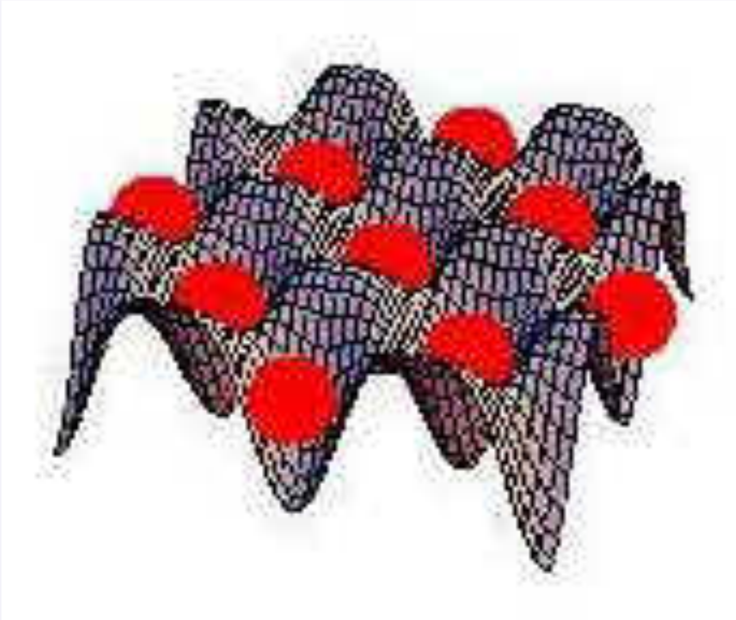
Sr optical clock

- **Method:**

Interrogate atoms in optical lattice without frequency shift

- Long interaction time
- Large atom number (10^8)
- Lamb-Dicke regime

Excellent frequency stability



- Small frequency shifts:
  - No collisions (fermion)
  - No recoil effect (confinement below optical wavelength)
  - Small Zeeman shifts (only nuclear magnetic moments)…

Under development:

Sr (Tokyo, JILA, PTB, SYRTE, Firenze)

Cooling and trapping atoms with laser light
The Nobel Prize in Physics 1997

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LAUREATES ARTICLES EDUCATIONAL

Web Adapted Version of the Nobel Poster from the Royal Swedish Academy of Sciences

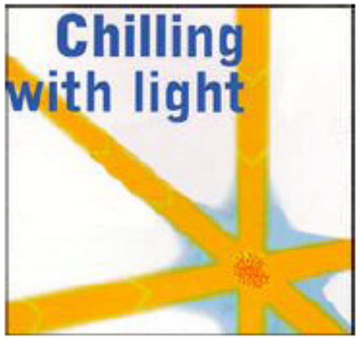
BACK

The Nobel Prize in Physics 1997

The Royal Swedish Academy of Sciences has awarded the 1997 Nobel Prize in Physics jointly to

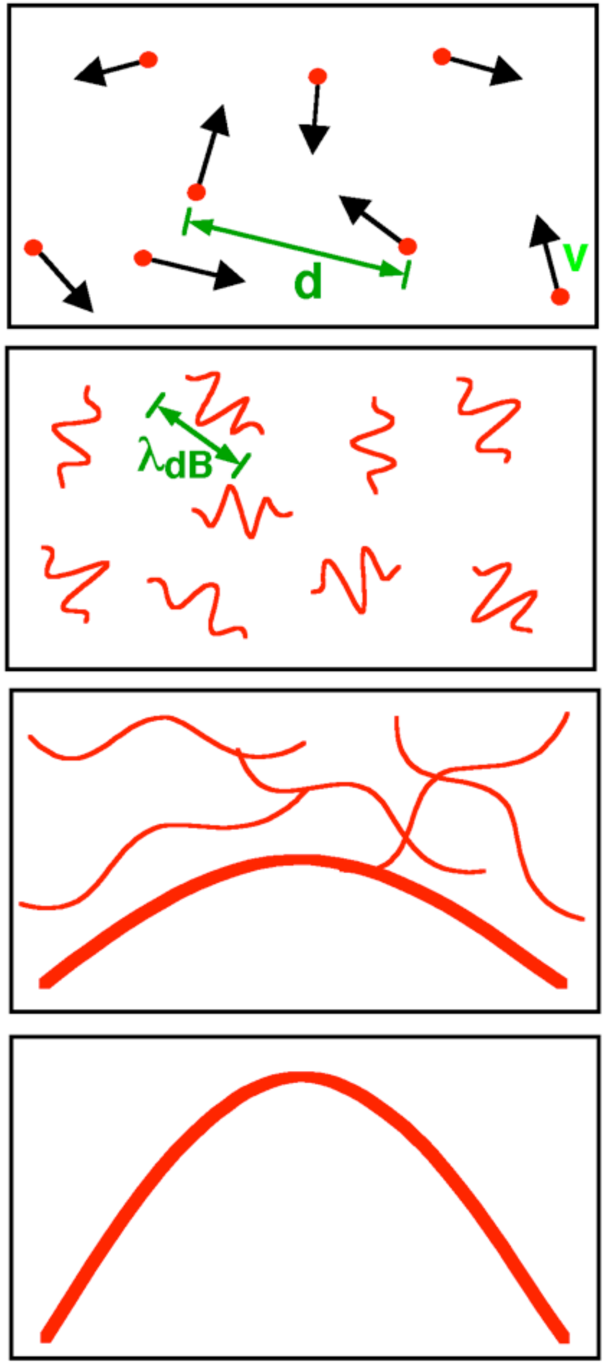
Steven Chu, Claude Cohen-Tannoudji and **William D. Phillips**

for their developments of methods to cool and trap atoms with laser light.



This year's Nobel laureates in physics have developed methods of cooling and trapping atoms by using laser light. Their research is helping us to study fundamental phenomena and measure important physical quantities with unprecedented precision.

What is Bose-Einstein condensation (BEC)?



High Temperature T:

thermal velocity v
density d^{-3}

"Billiard balls"

Low Temperature T:

De Broglie wavelength
$\lambda_{dB}=h/mv \propto T^{-1/2}$

"Wave packets"

$T=T_{crit}$:
Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

T=0:
Pure Bose condensate

"Giant matter wave"

from W. Ketterle

Bose-Einstein Condensation in dilute gases

$$\rho = n\lambda_{dB}^3 = 2.612$$

$T \approx 300$ K → $\rho \approx 10^{-20}$

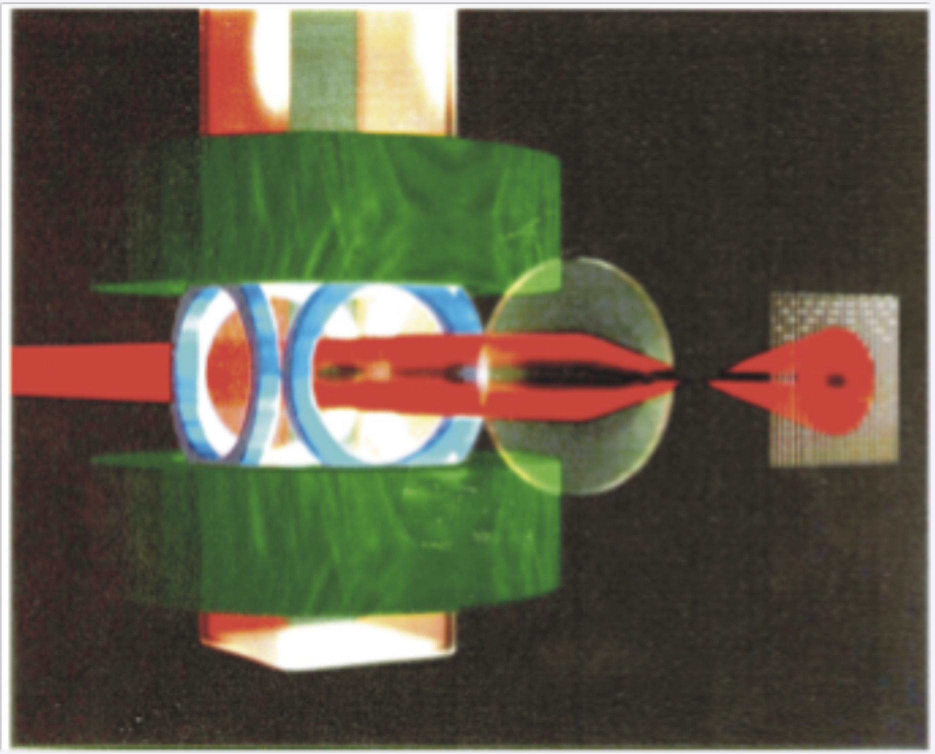
Laser cooling

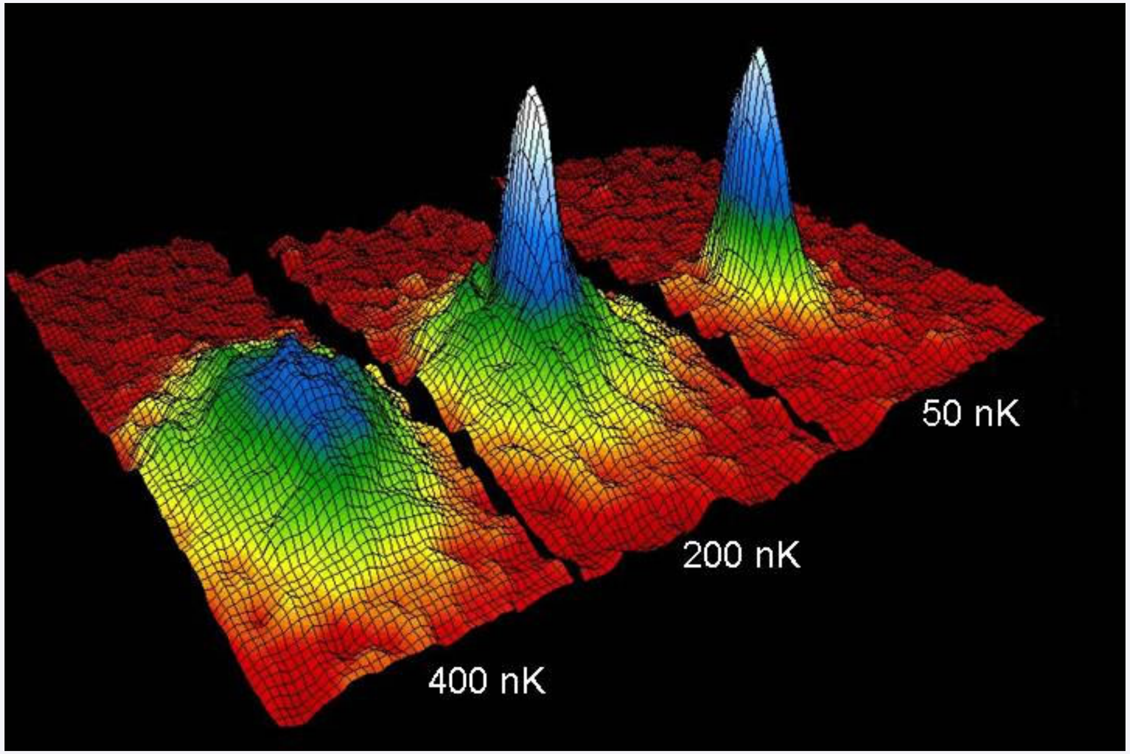
$T \approx 10\ \mu$K → $\rho \approx 10^{-5}$

Evaporative cooling

$T \approx 100$ nK → $\rho \approx 1$

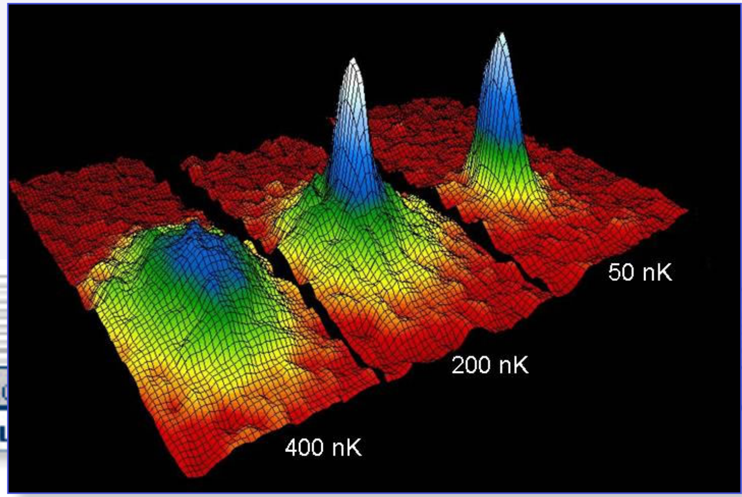
First BEC





Anderson *et al.*, Science 269, 198 (1995)

Bose-Einstein condensation in dilute gases of atoms
The Nobel Prize in Physics 2001



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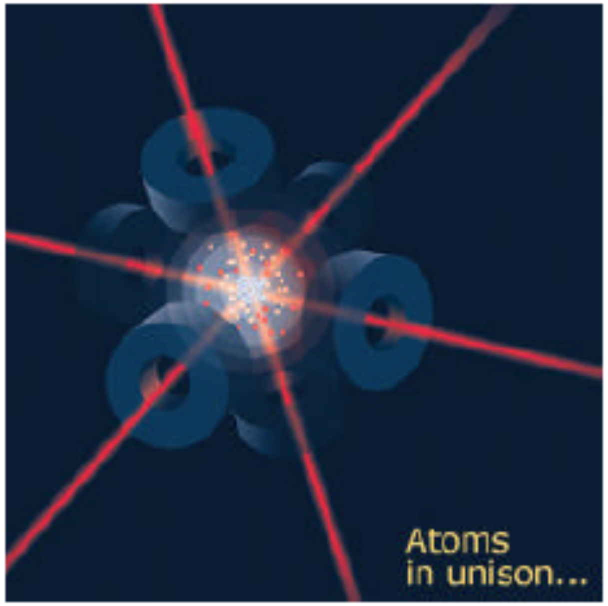
BACK

The Nobel Prize in Physics 2001

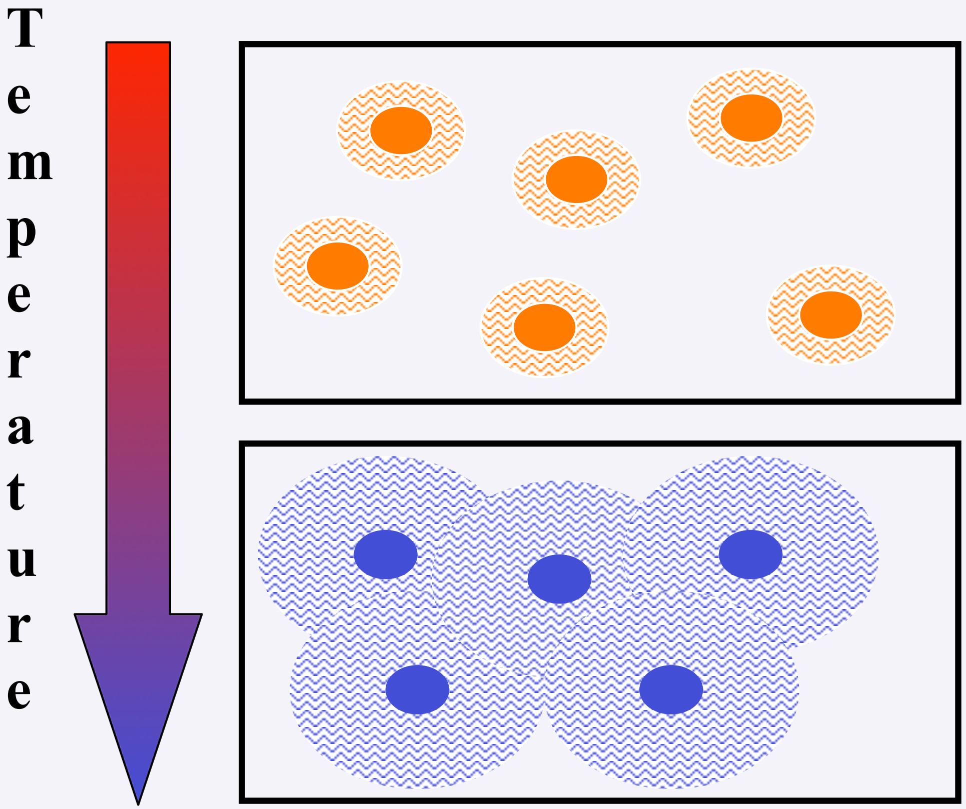
The Royal Swedish Academy of Sciences has awarded the Nobel Prize in Physics for 2001 jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".



Eric A. Cornell JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.	**Carl E. Wieman** JILA and University of Colorado, Boulder, Colorado, USA.	**Wolfgang Ketterle** Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

Contents:

Quantum degenerate gases

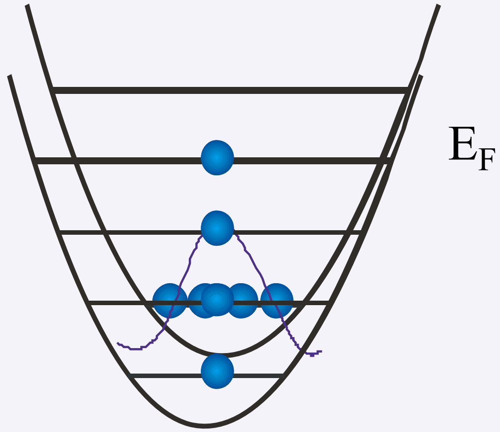


Fermions

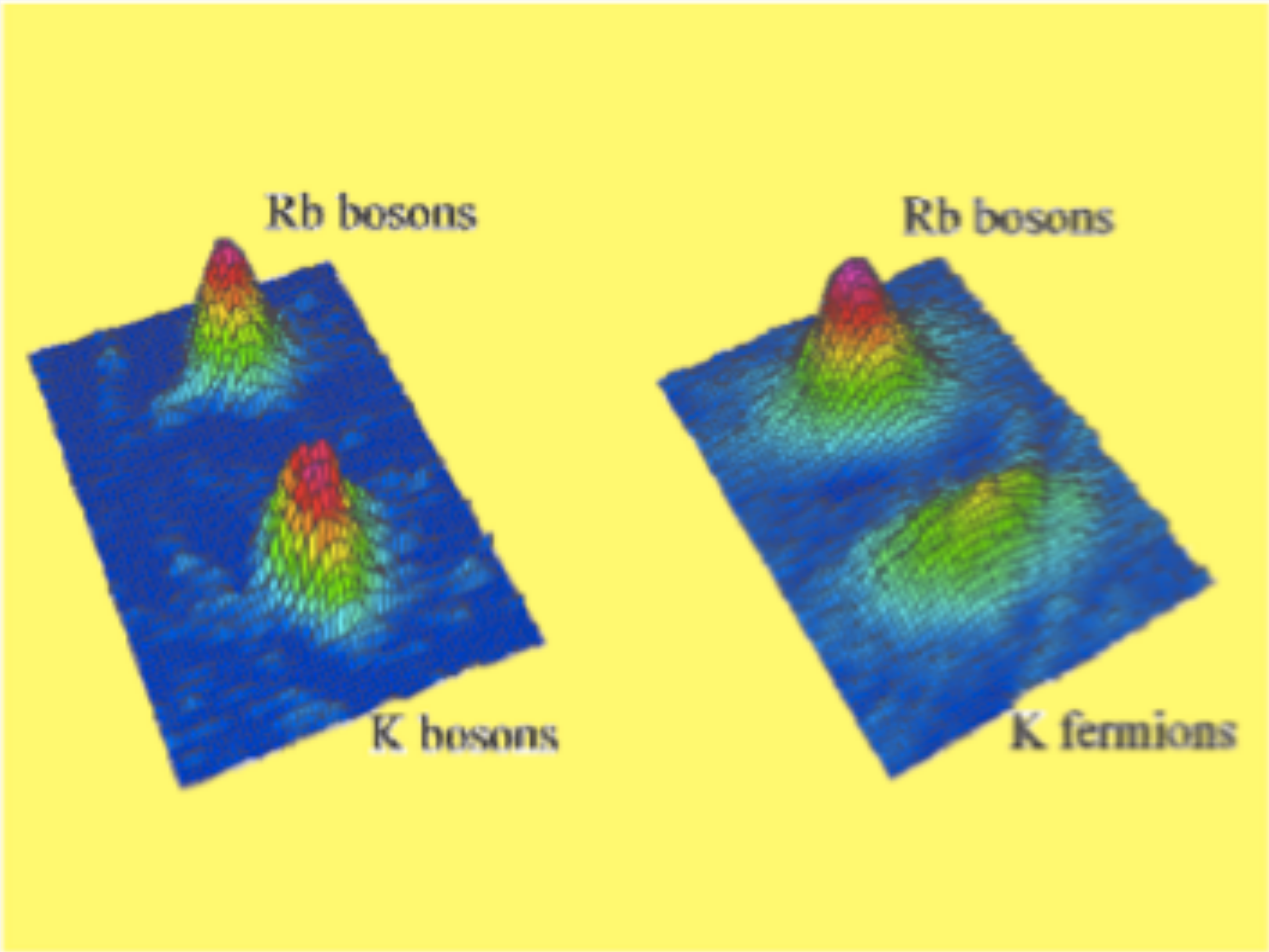
Bosons

$T < T_F$

$T < T_C$

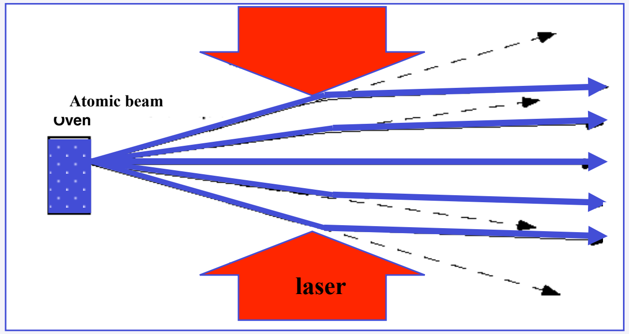


Bosons vs Fermions

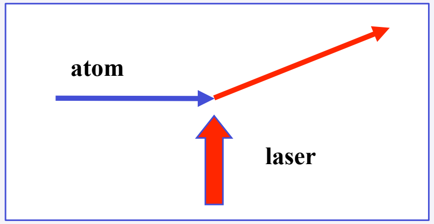


Atom optics

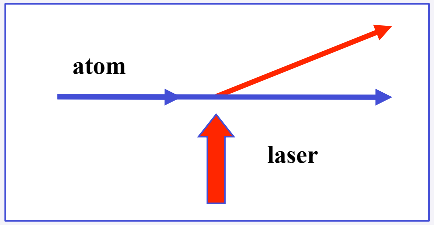
lenses



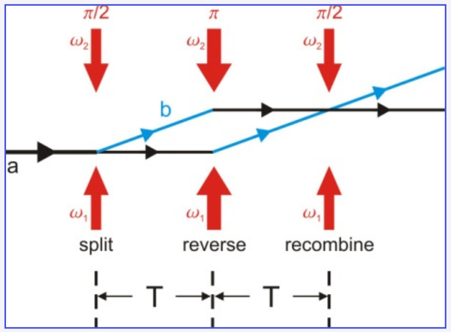
mirrors



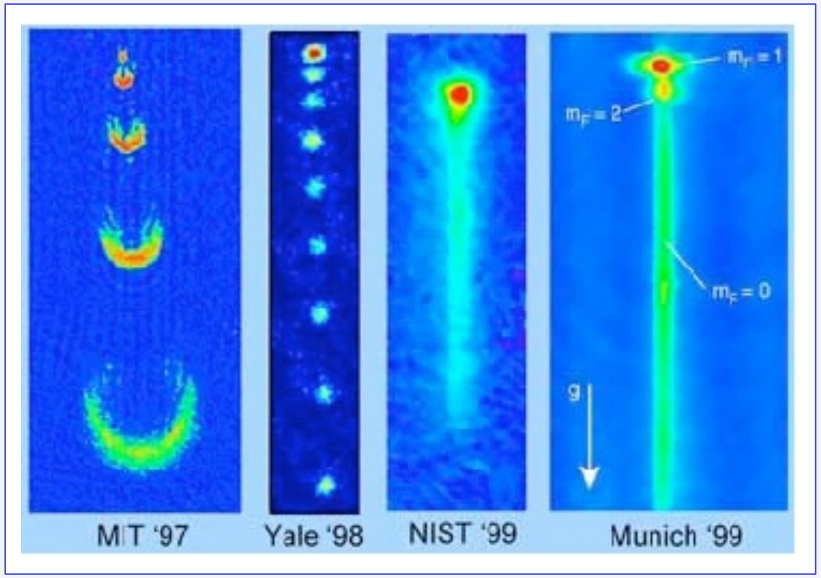
beam-splitters



interferometers

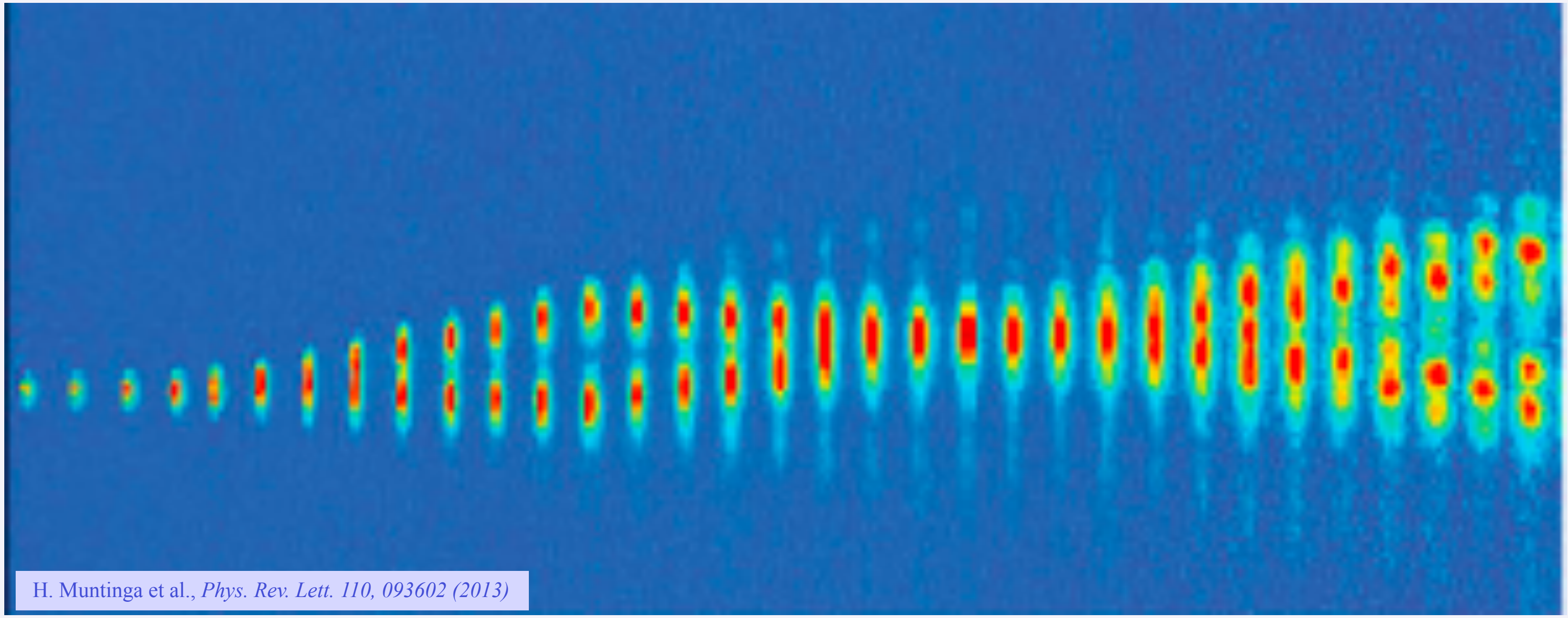


atom laser



Atom Interferometry

Atom Interferometry



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).

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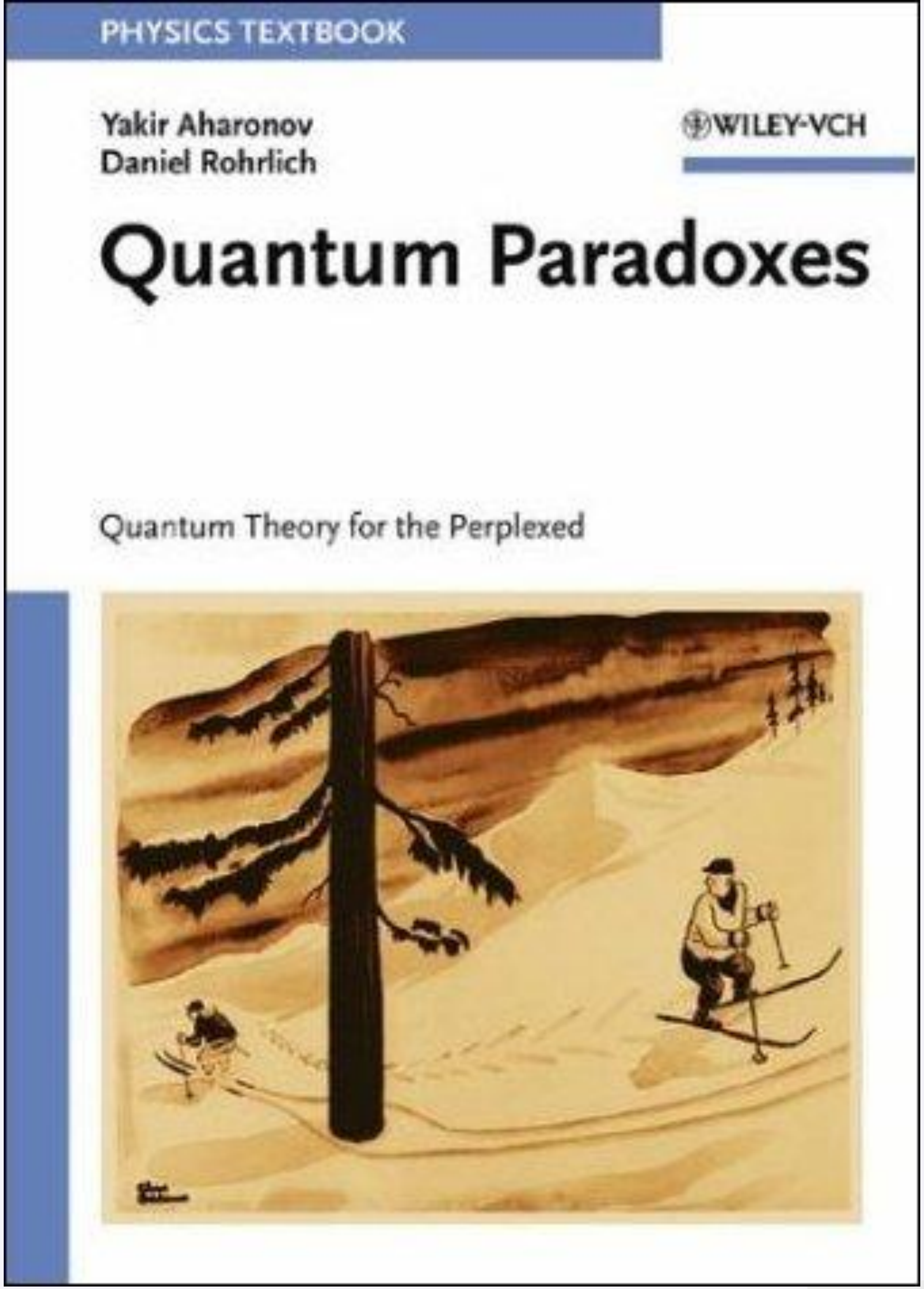
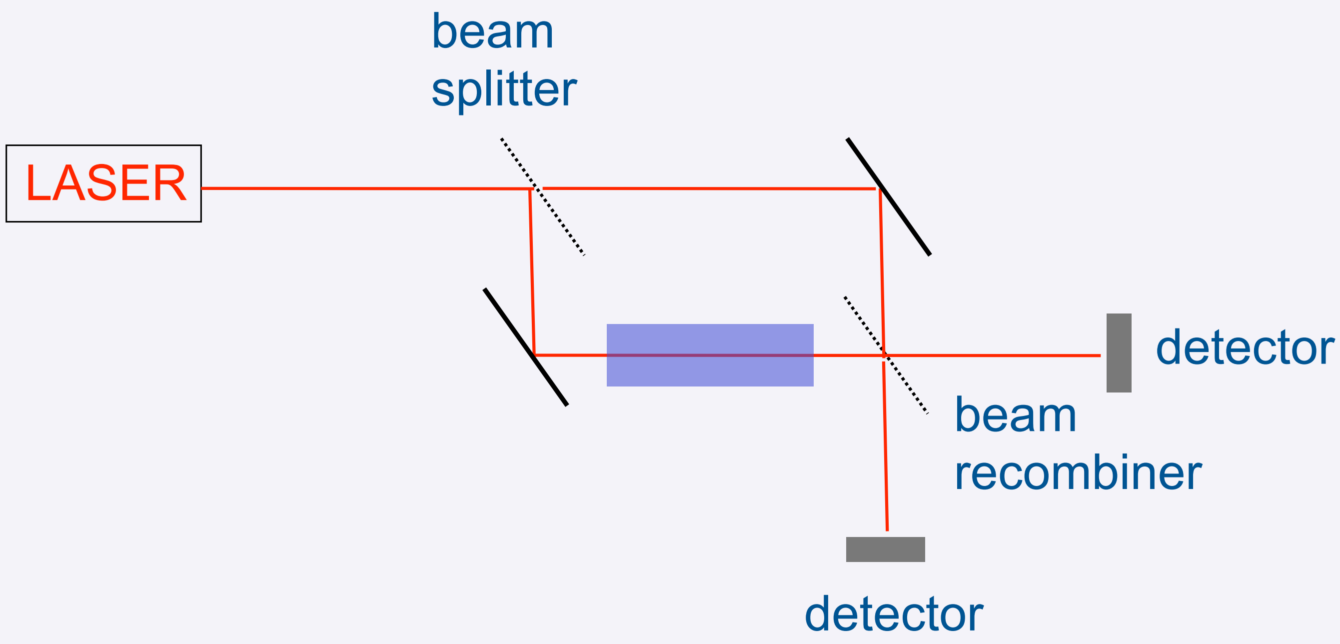


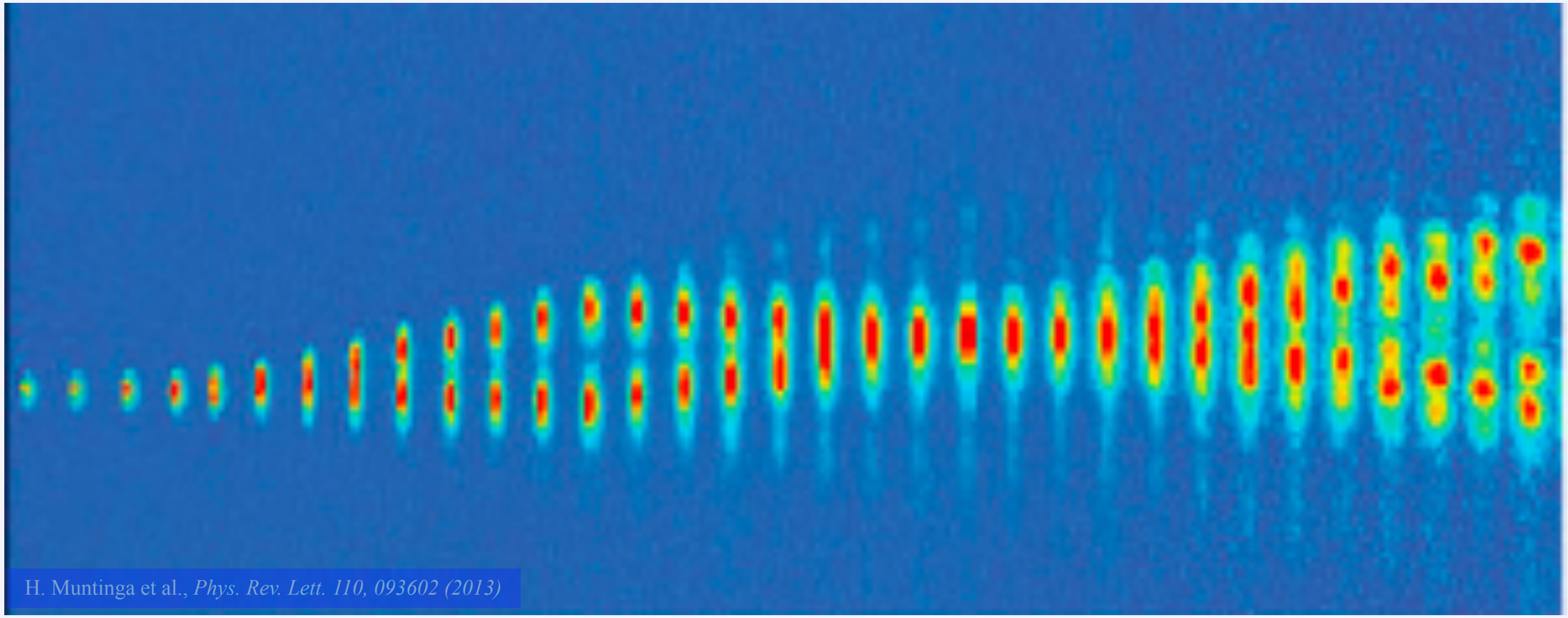
Optical interferometry



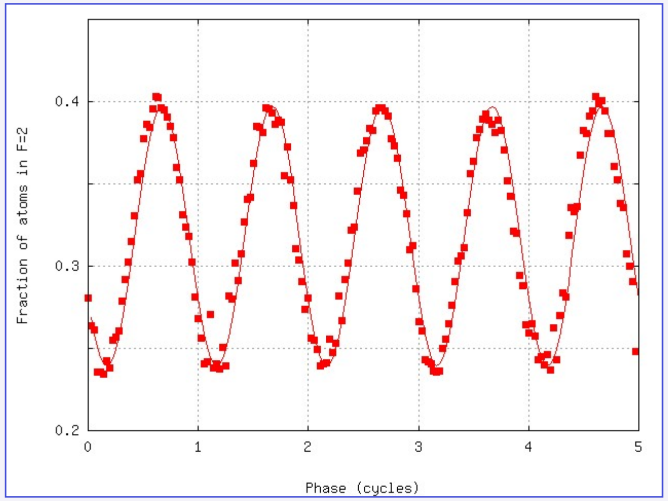
Change of optical path, length, pressure, temperature,… → Change of phase of interference pattern

From C. Salomon

Atom Interferometry



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

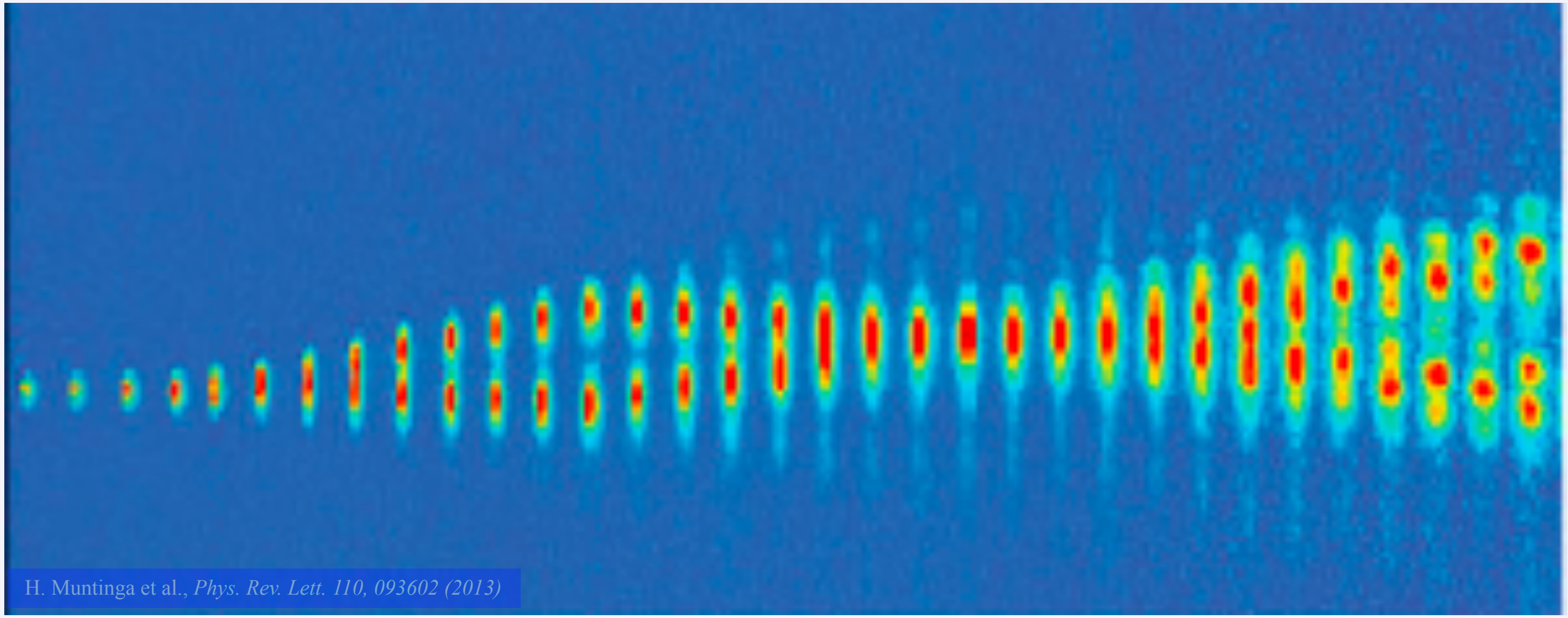


Atomic interference fringes – Firenze 2006

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

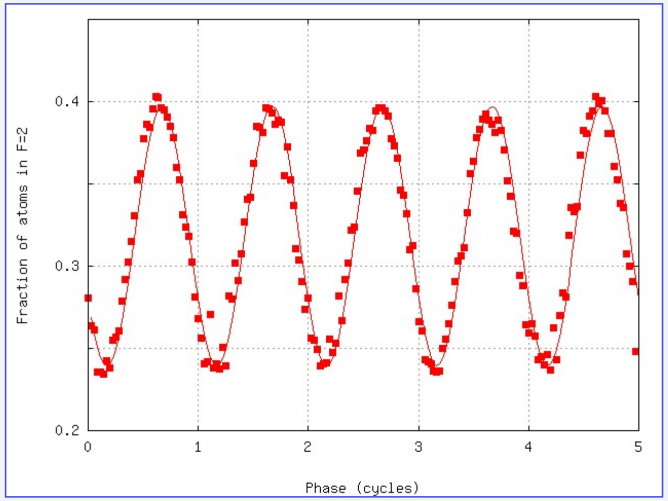
G. M. Tino, M. A. Kasevich (eds) *Atom Interferometry*, Proc. Int. School Phys. "Enrico Fermi", Course CLXXXVIII, Varenna 2013 (SIF and IOS Press, 2014).

Atom interferometry
Wave-particle duality in quantum physics



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

de Broglie wavelength



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

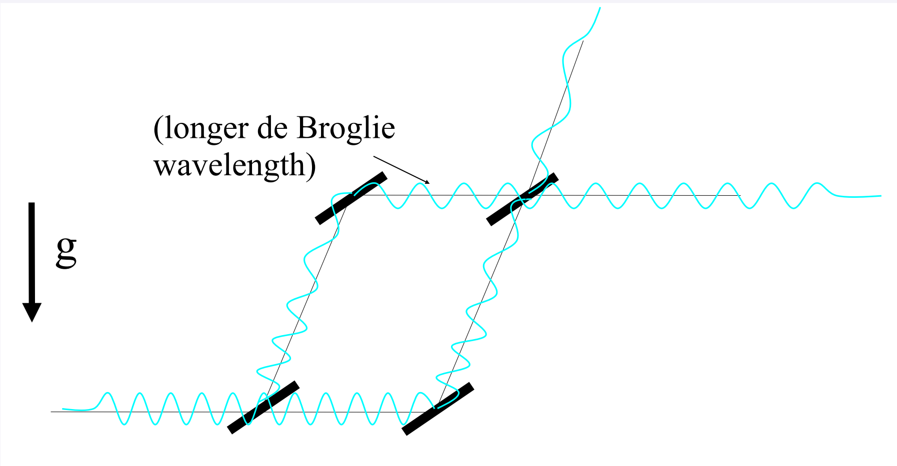
Atom interferometer force sensors

The quantum mechanical wave-like properties of atoms can be used to sense inertial forces.

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

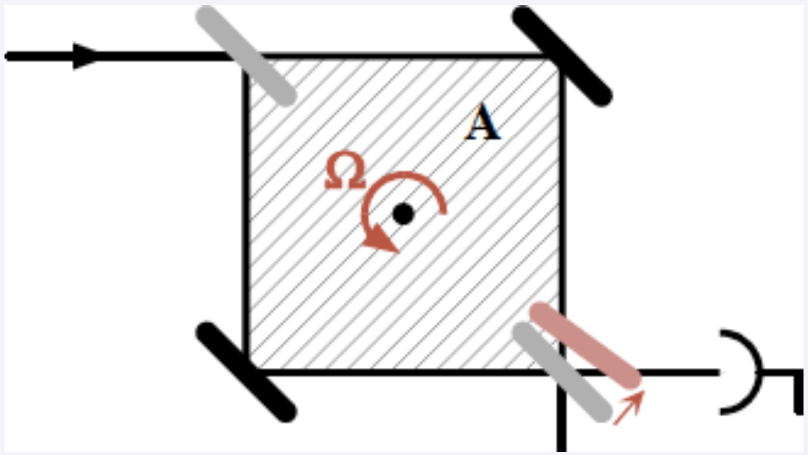
Gravity/Accelerations

As atom climbs gravitational potential, velocity decreases and wavelength increases



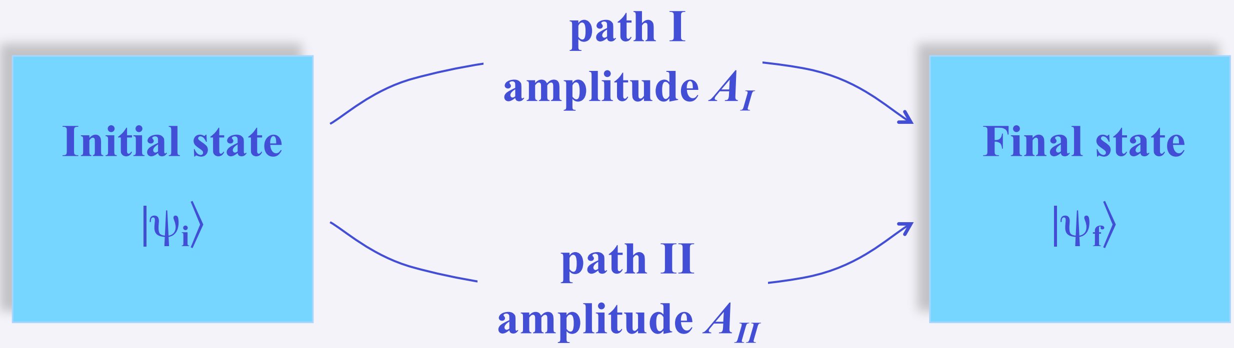
Rotations

Rotations induce path length differences by shifting the positions of beam splitting optics



From M. Kasevich

Quantum interference



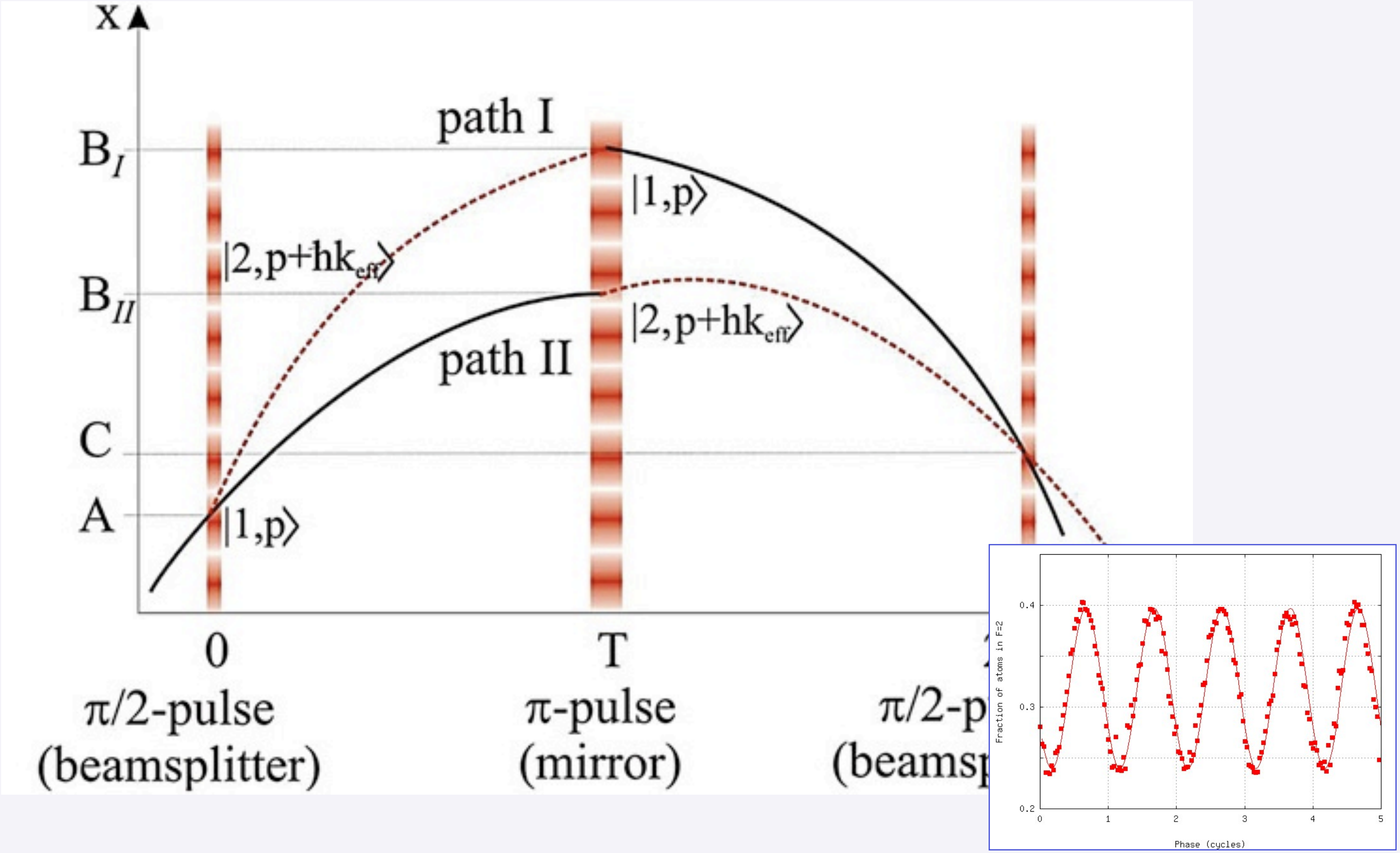
Interference of transition amplitudes

$$P(|\psi_i\rangle \Rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2\, Re(A_I A_{II}^*)$$

Atomic vs optical interferometers

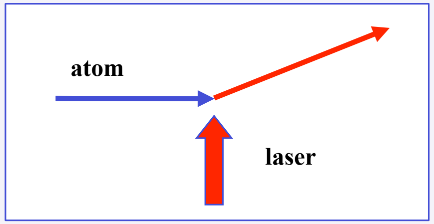
- The atoms move much more slowly in the interferometer compared to the photons. The interaction times are therefore much longer and the sensitivity can be much higher, for example to inertial effects (acceleration, rotation, gravitation).
- The actual size of optical interferometers can be much larger compared to atom interferometers. Examples are LIGO/Virgo interferometers and optical fiber gyroscopes.
- For the atoms, possibility to control the internal state and detection sensitive to internal state.
- For the atoms a larger variety of internal states compared to the photons which have only the two polarizations.
- Higher fragility of the atoms. In an atom interferometer it is important to avoid all processes of spontaneous emission or collisions that can destroy the atomic coherence.
- The flux of photons in a laser beam is typically much larger than the flux of atoms in a beam.

Atom interferometry and gravity

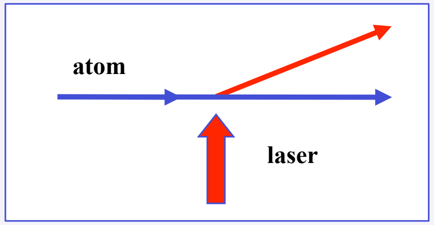


Optical pulse atom optics

mirror



beam-splitter



Optical pulse atom optics

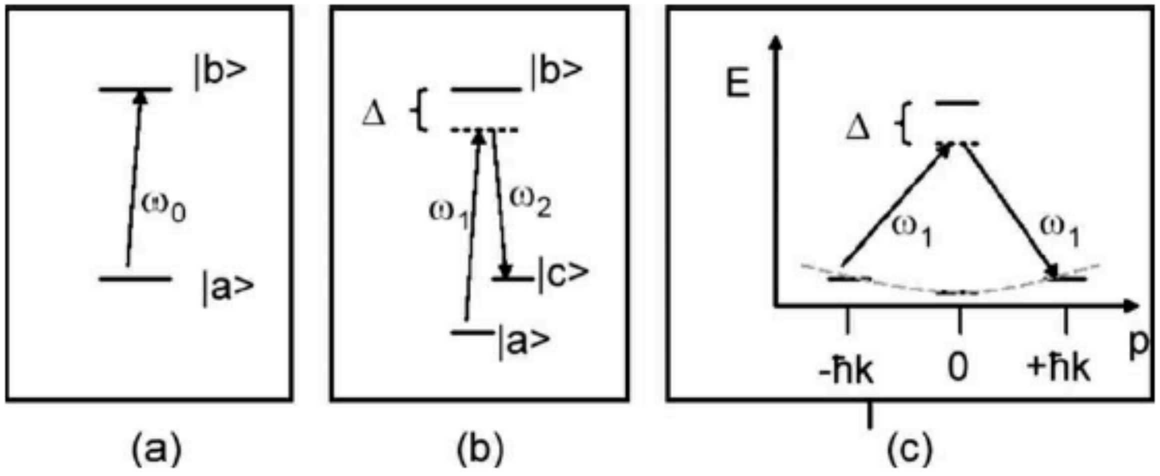
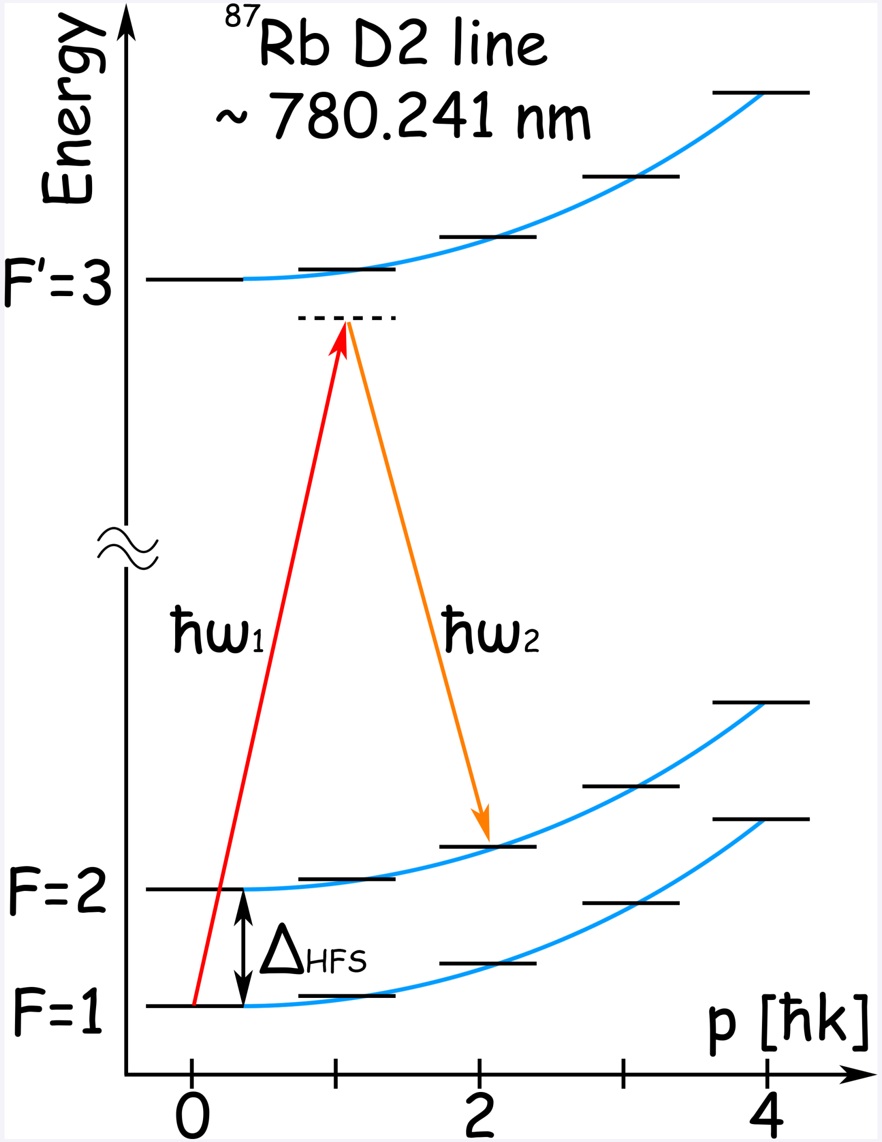


FIG. 25. Different schemes used to place atoms in a superposition of momentum states. (a) Superposition with a metastable state using a $\pi/2$ pulse. (b) Stimulated Raman transition with two light fields. (c) Bragg scattering with monochromatic light. Δ is the detuning from resonance. The dashed curve is the kinetic energy $p_{\text{light}}^2/2m$.

Alexander D. Cronin, Jörg Schmiedmayer, David E. Pritchard, *Optics and interferometry with atoms and molecules*, Rev. Mod. Phys. 81, 1051 (2009).

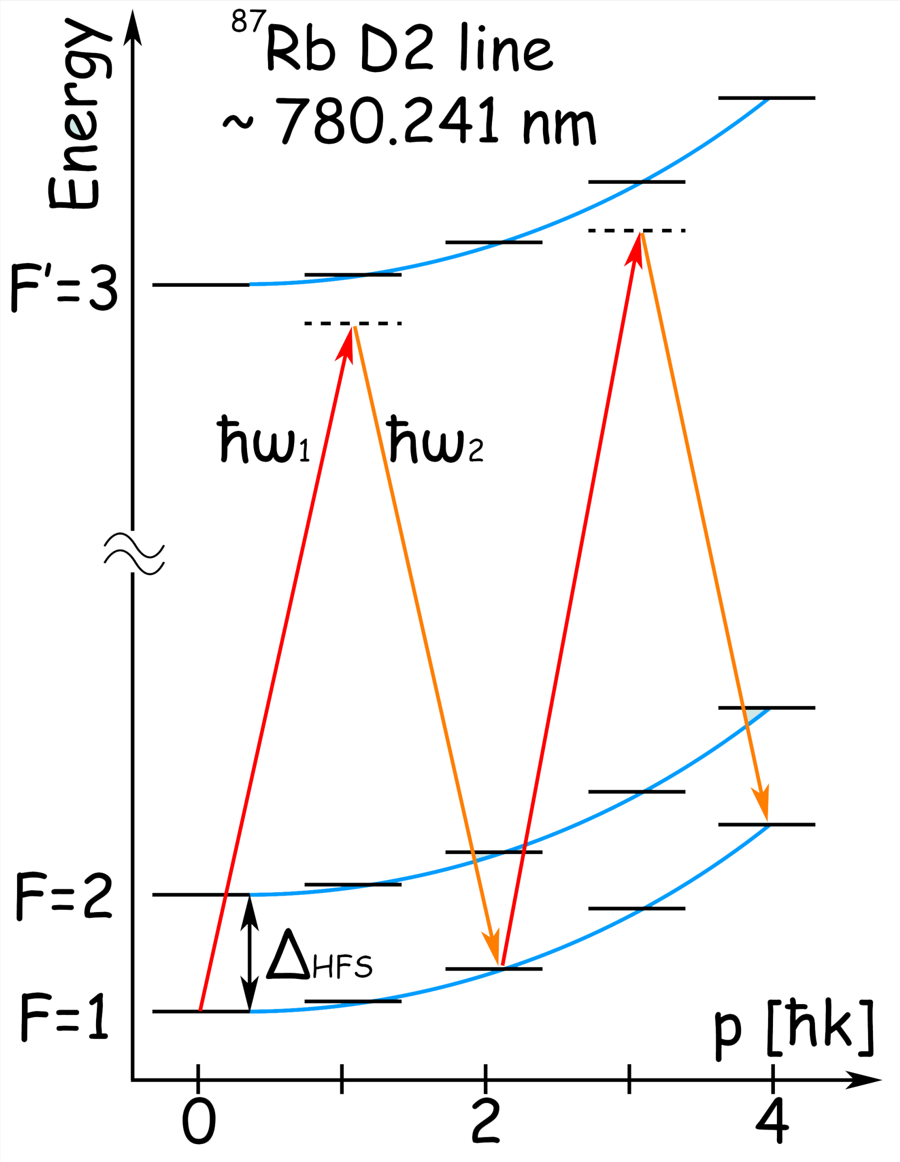
Raman transitions



$\omega_1 - \omega_2 = \Delta_{HFS}$ ~ 6,835 GHz

- Counter-propagating laser beams
- Change in atomic internal state
- Momentum transfer $\Delta p = 2\hbar k$ ($\mathbf{k} = \mathbf{k}_1 \approx -\mathbf{k}_2$)
- Required laser power provided by semiconductor LD technology.

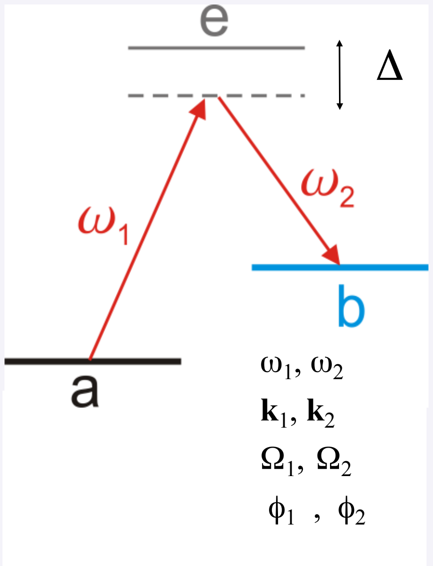
Bragg transitions

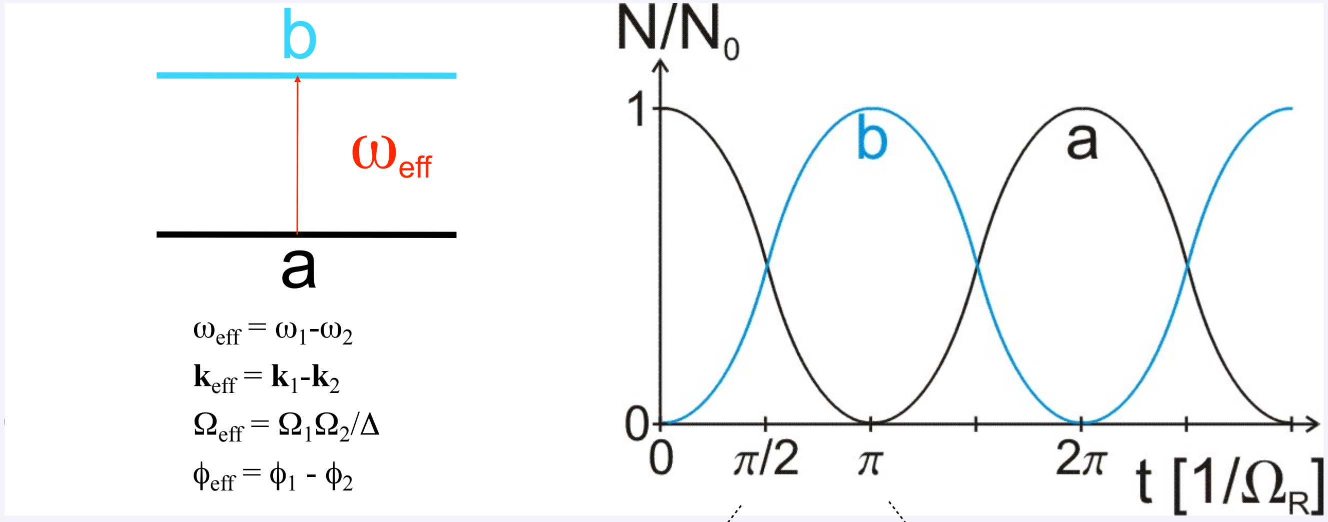


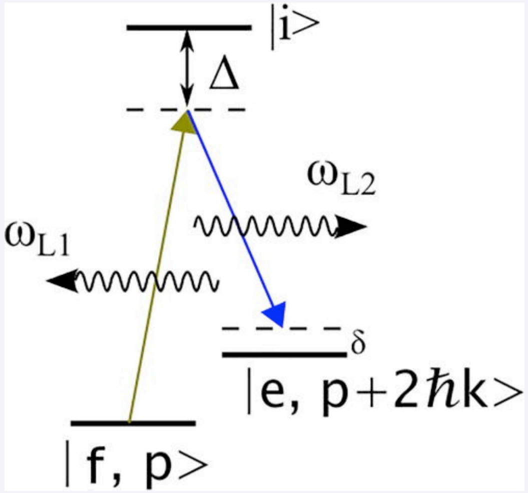
$\omega_1 - \omega_2 \sim$ MHz

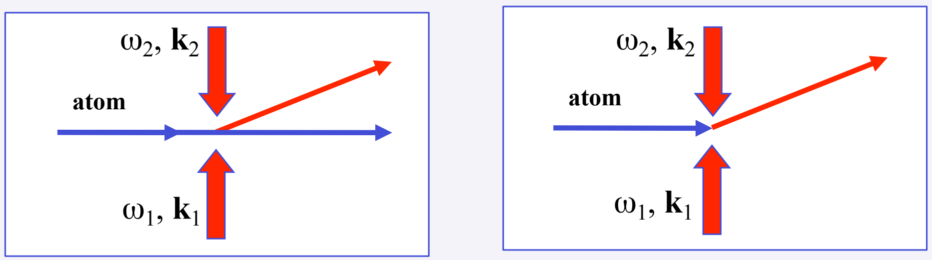
- Counter-propagating laser beams
- No change in atomic internal state
- Momentum transfer scales linearly with Bragg diffraction order n, $\Delta p = 2n\hbar k$
- High power laser beams (>1W) are required.

Raman pulses





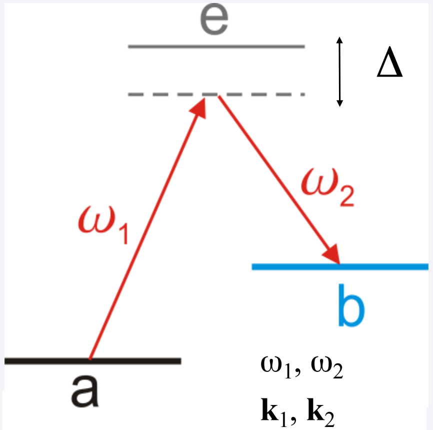




beam-splitter **mirror**

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

Raman pulse interferometer



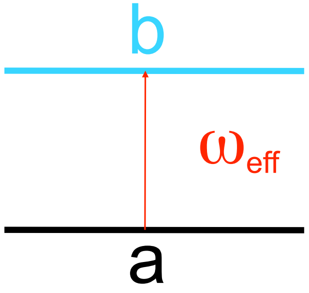
ω_1, ω_2

$\mathbf{k}_1$, $\mathbf{k}_2$

Ω_1, Ω_2

ϕ_1 , ϕ_2

$\Longrightarrow$

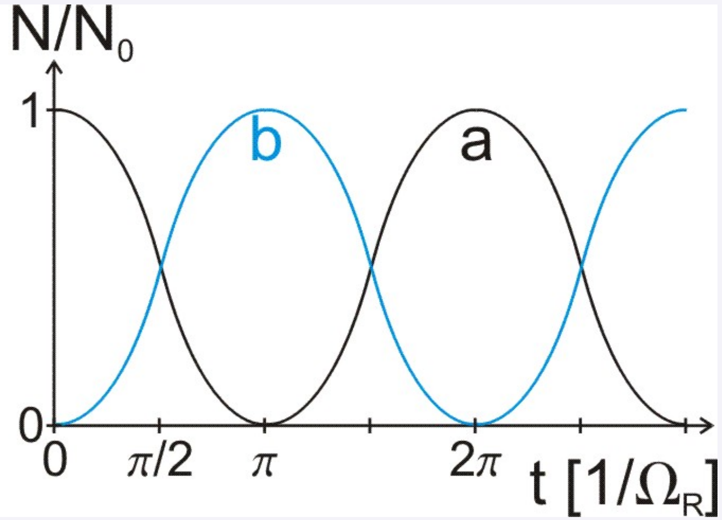


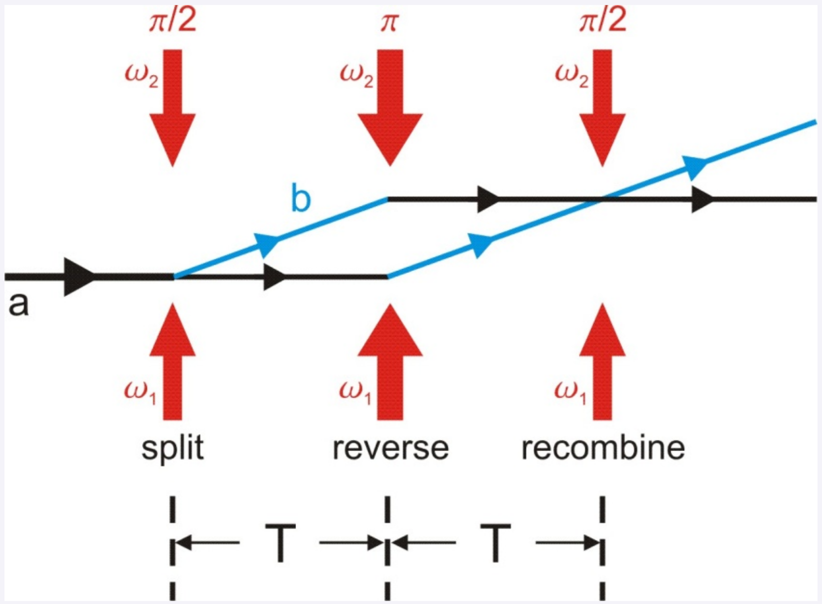
$\omega_{eff} = \omega_1 - \omega_2$

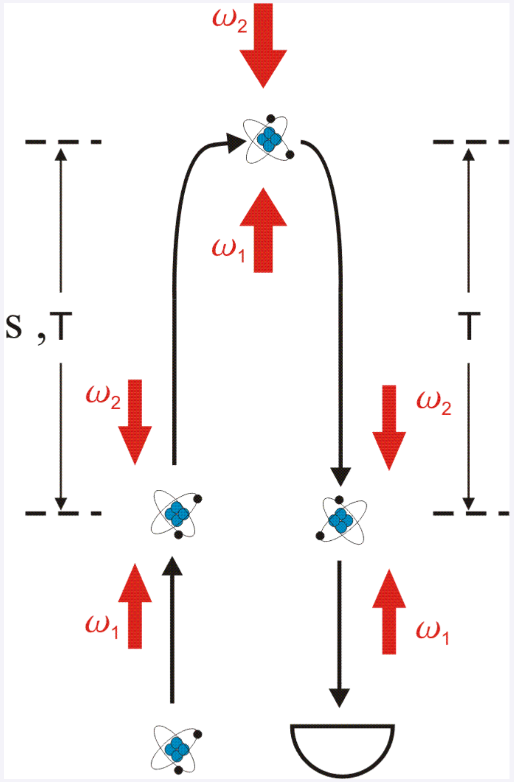
$\mathbf{k}_{eff} = \mathbf{k}_1 - \mathbf{k}_2$

$\Omega_{eff} = \Omega_1\Omega_2/\Delta$

$\phi_{eff} = \phi_1 - \phi_2$

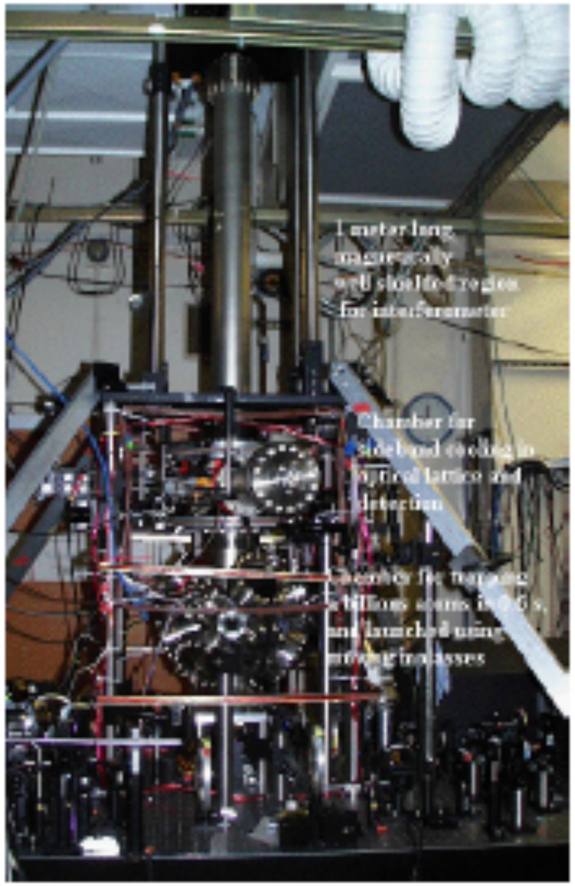


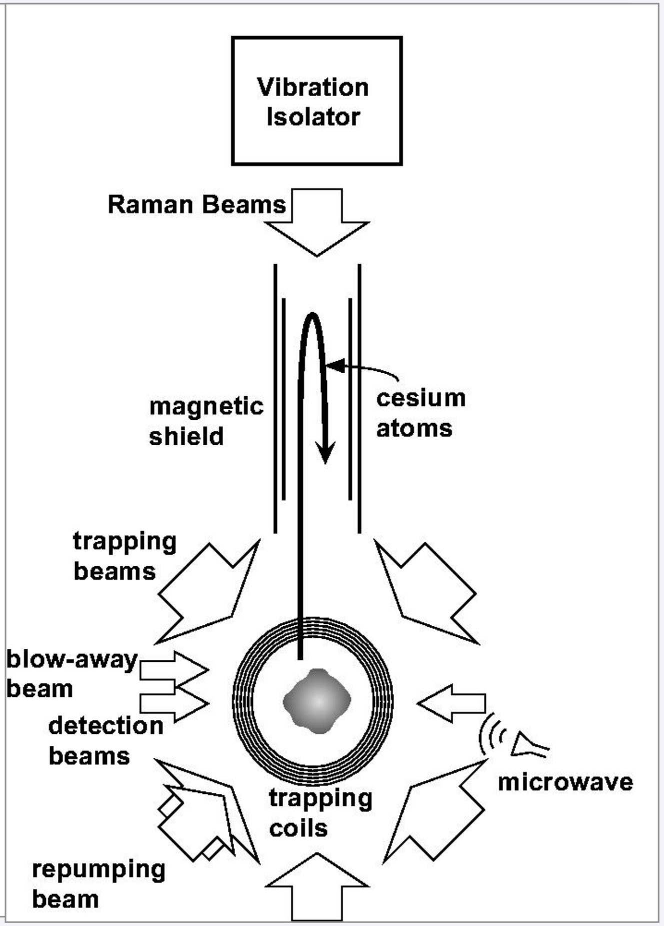


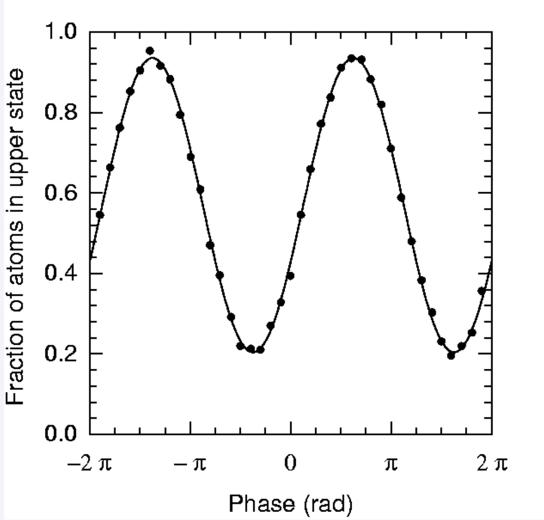


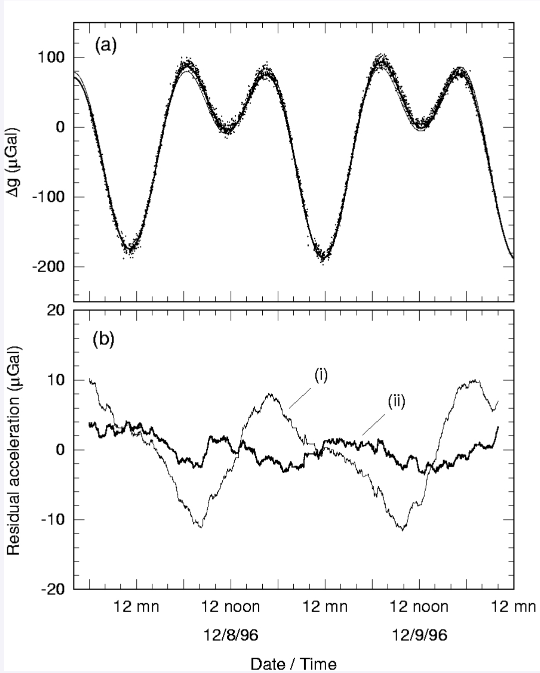
M. Kasevich, S. Chu, Appl. Phys. B 54, 321 (1992)

Stanford atom gravimeter







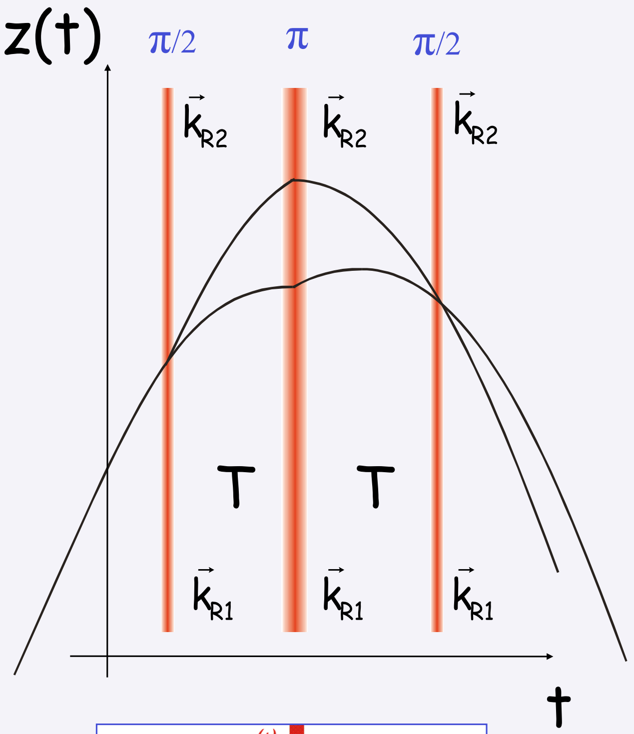


Resolution: 3×10^{-9} g after 1 minute

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

A. Peters, K.Y. Chung and S. Chu, *Measurement of gravitational acceleration by dropping atoms*, Nature **400**, 849 (1999)

Raman interferometry in a Rb atomic fountain

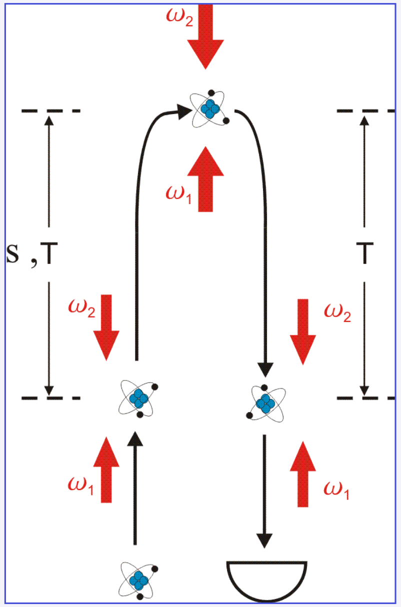


Phase difference between the paths:

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

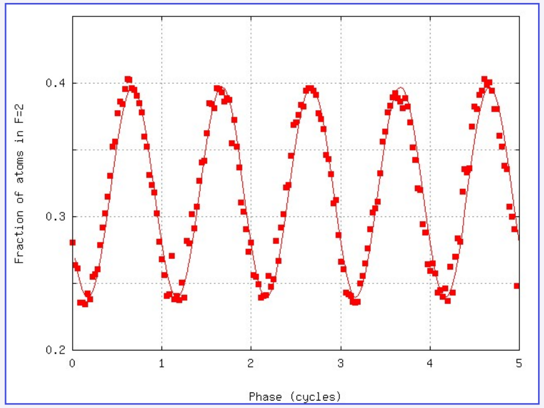
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0 \Longrightarrow \mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

10^6 Rb atoms

S/N = 1000

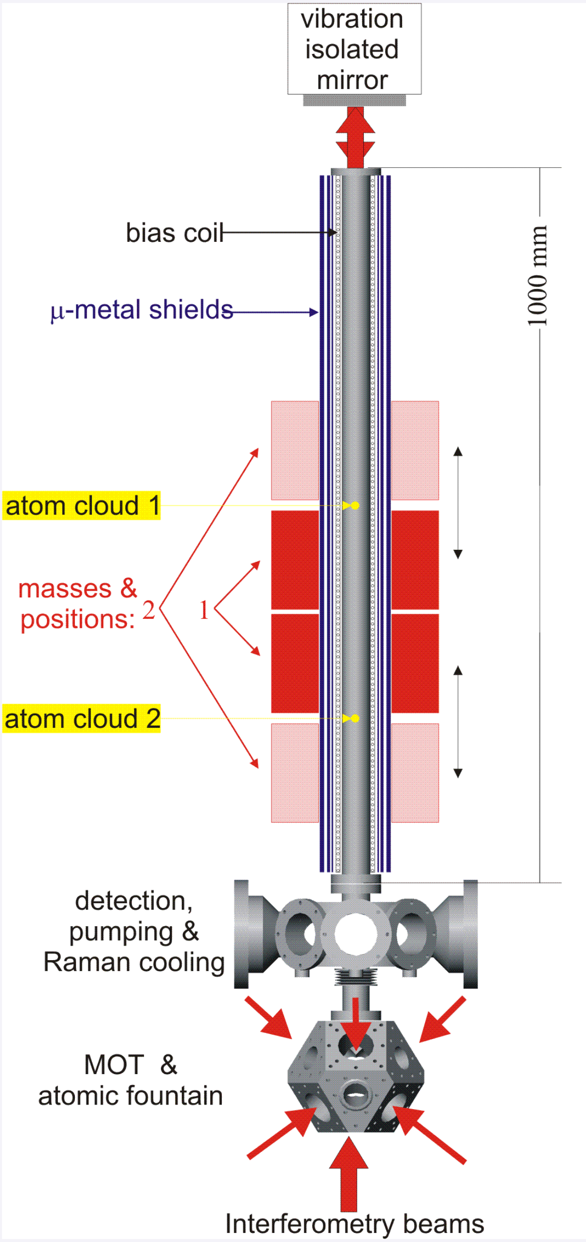
T = 150 ms ⇒ 2π = 10^{-6}g

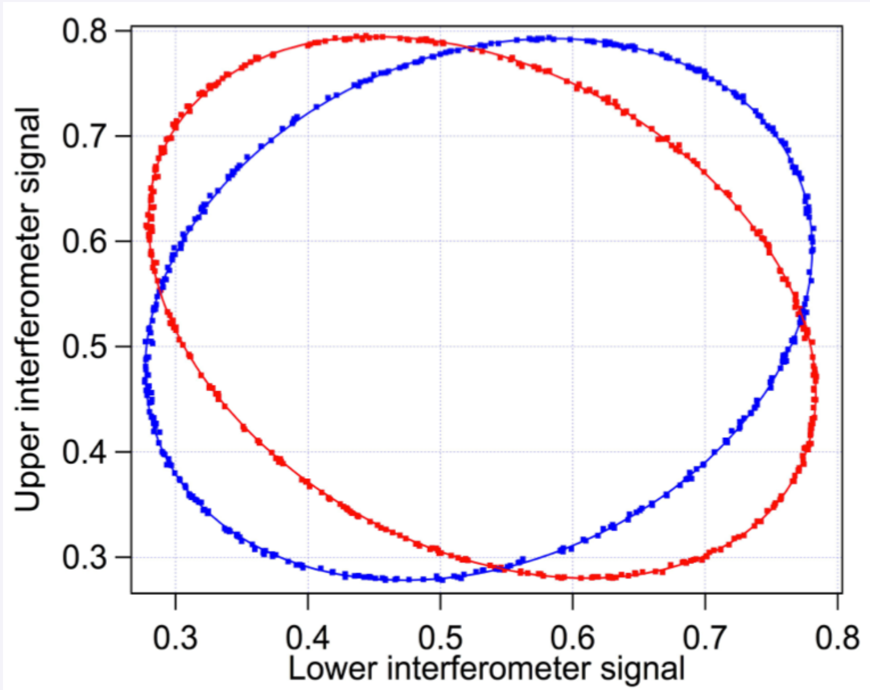
⟹ Sensitivity 10^{-9} g/shot

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

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

Florence Raman gravity gradiometer





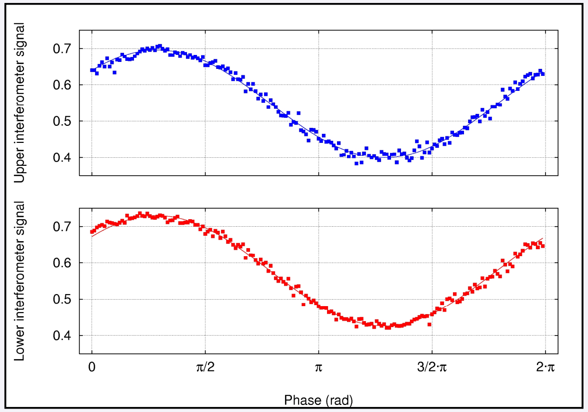
Differential acceleration sensitivity

$3 \times 10^{-9} g$ at 1 s

$5 \times 10^{-11} g$ after 8000 s

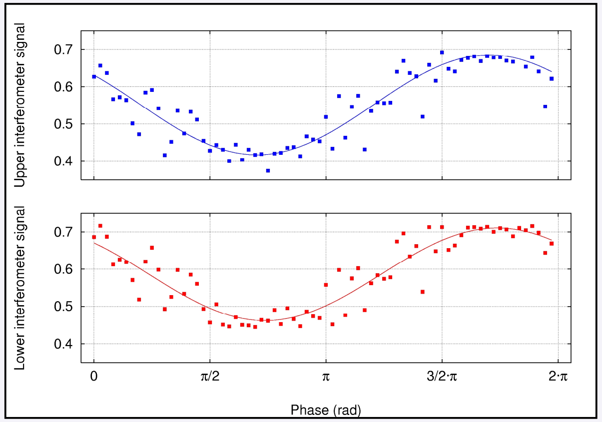
F. Sorrentino, Q. Bodart, L. Cacciapuoti, Y.-H. Lien, M. Prevedelli, G. Rosi, L. Salvi, G. M. Tino, *Sensitivity limits of a Raman atom interferometer as a gravity gradiometer,* Phys. Rev. A 89, 023607 (2014)

Gravity gradiometer



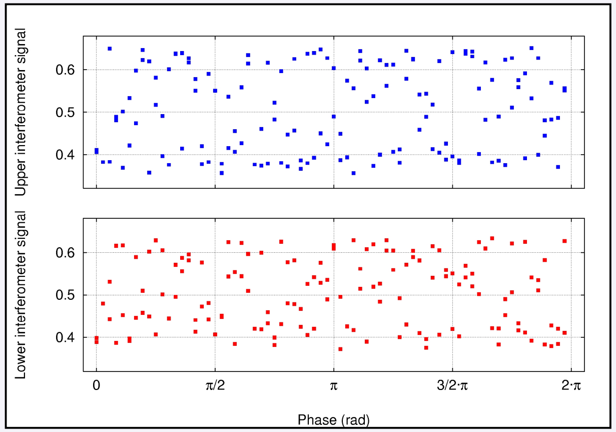
T=5 ms

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



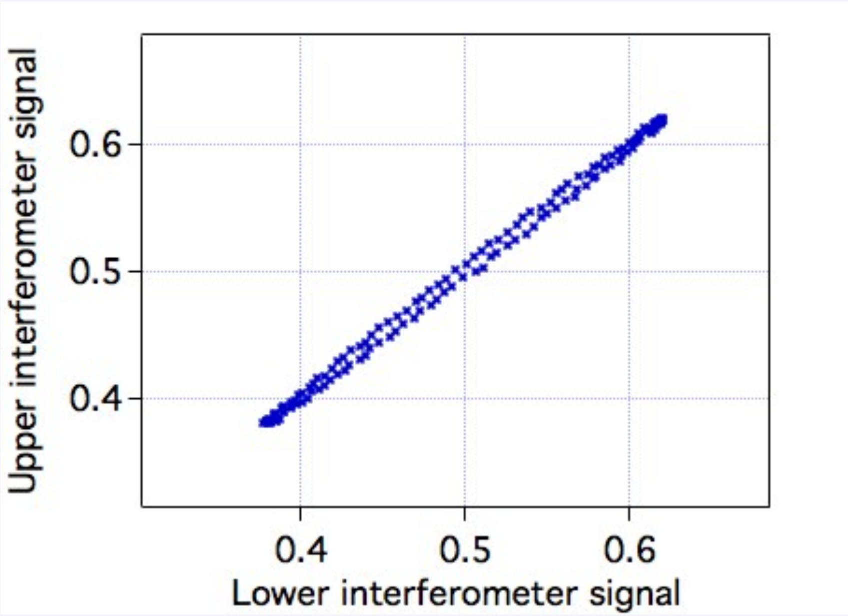
T=50 ms

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

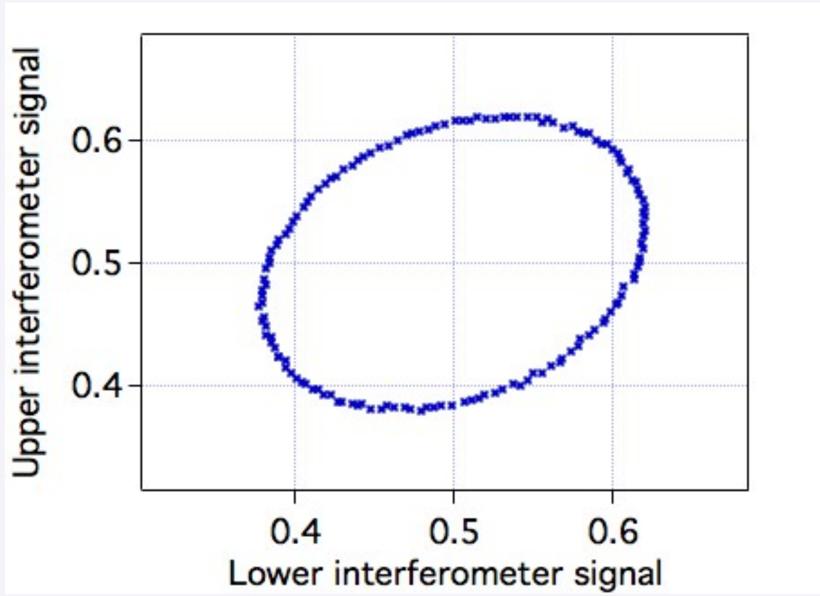


T=150 ms

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

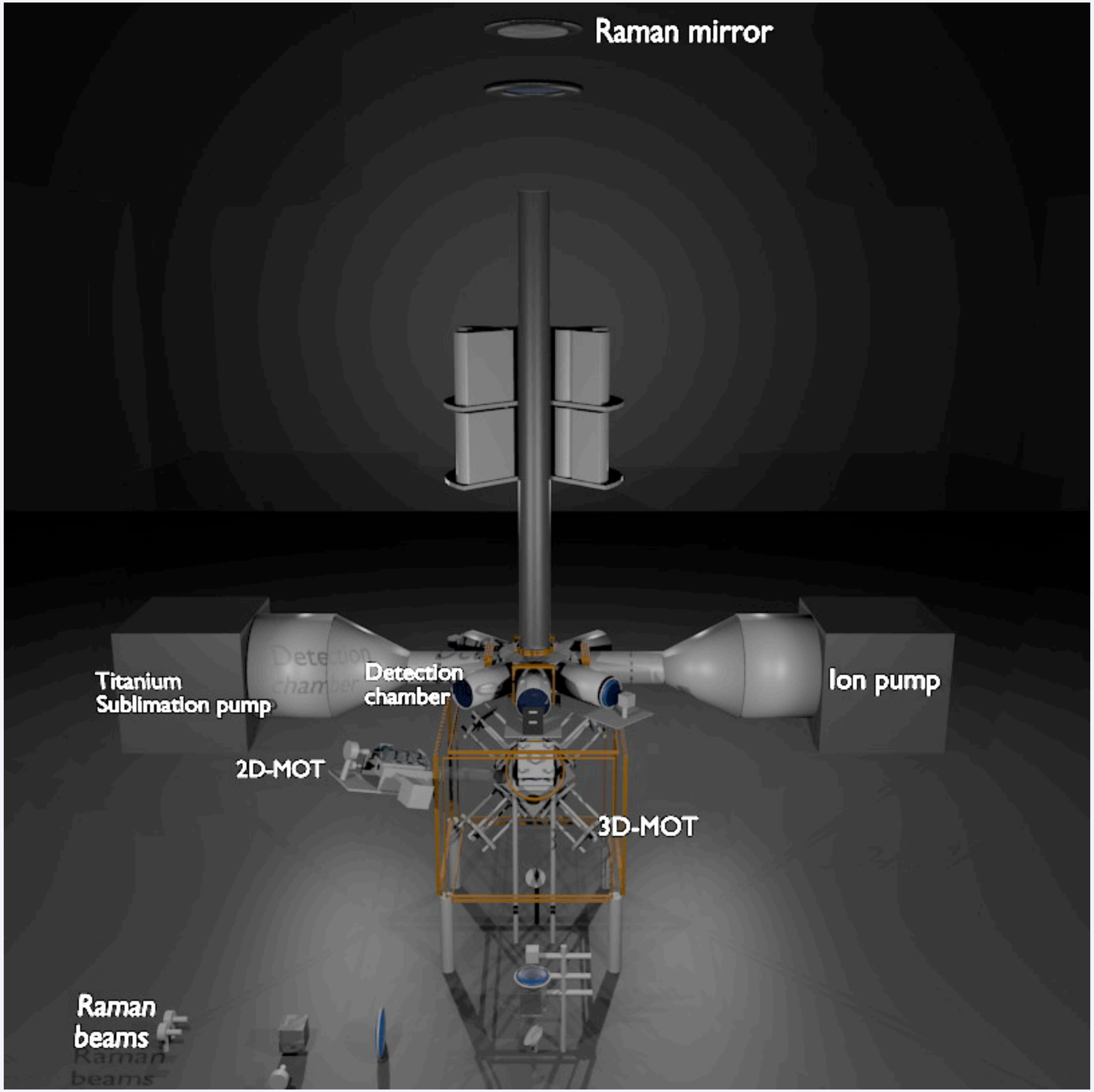


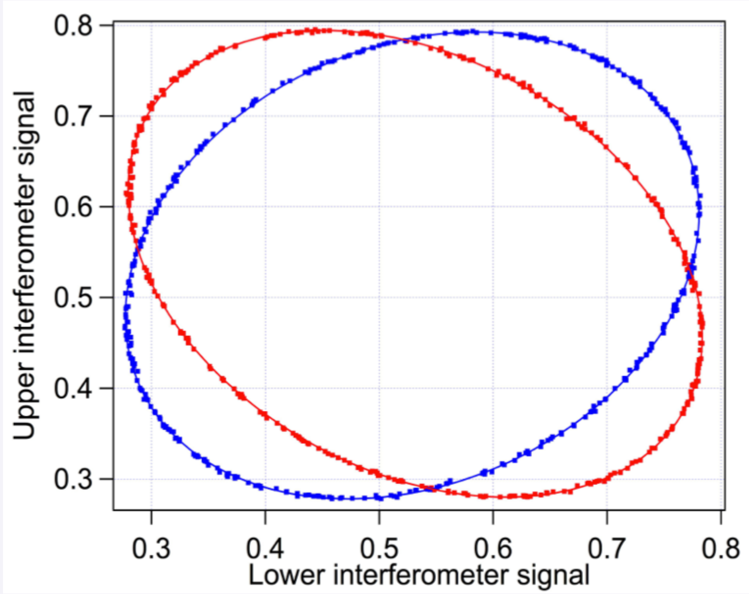
$$\Delta\Phi = k_e g T^2$$

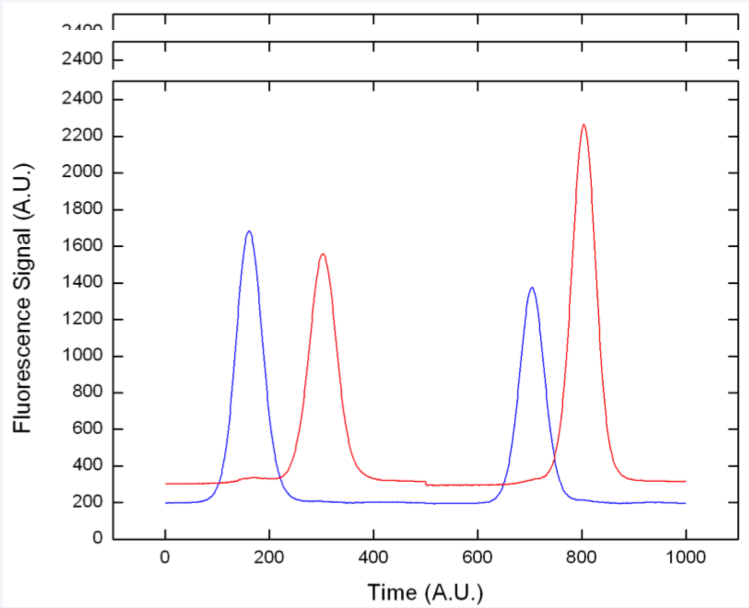


G. T. Foster et al., Opt. Lett **27**, 951 (2002)

Gravity gradiometer





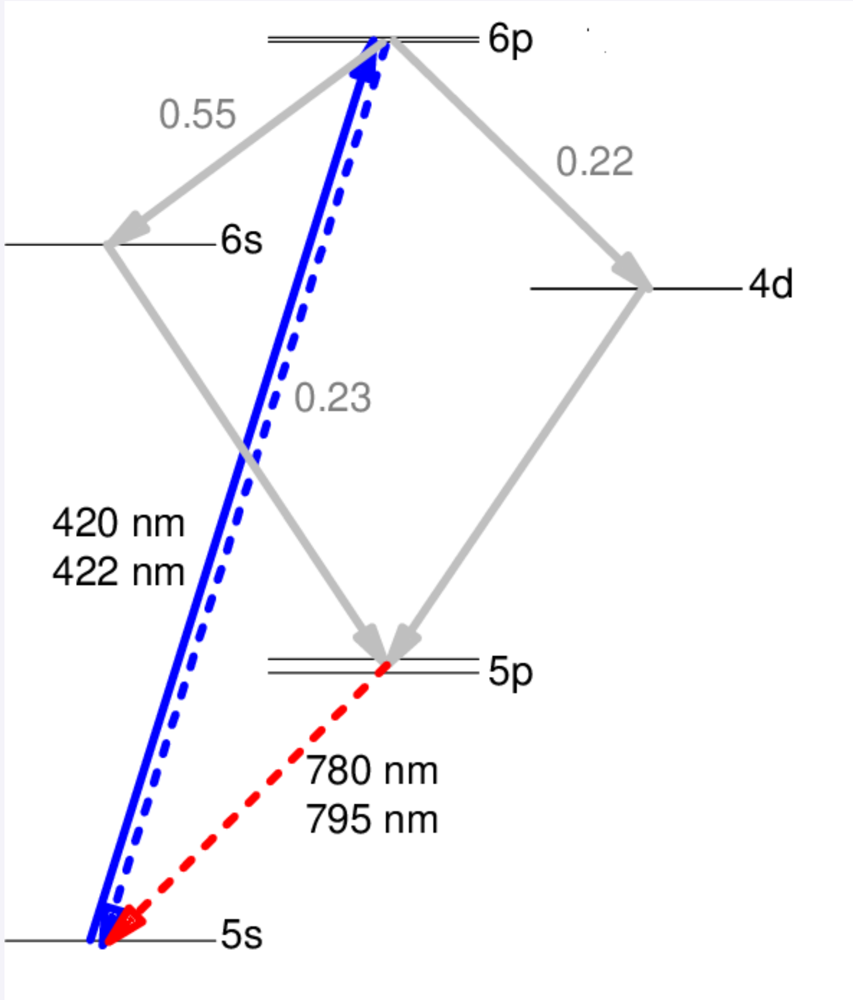


How do we improve sensitivity to gravity acceleration?

$$\Delta\phi = k_{\mathrm{eff}}\, g\, T^2$$

- $\Delta\phi$ → Large phase resolution
- k_{eff} → Large momentum transfer
- T^2 → Long interrogation times

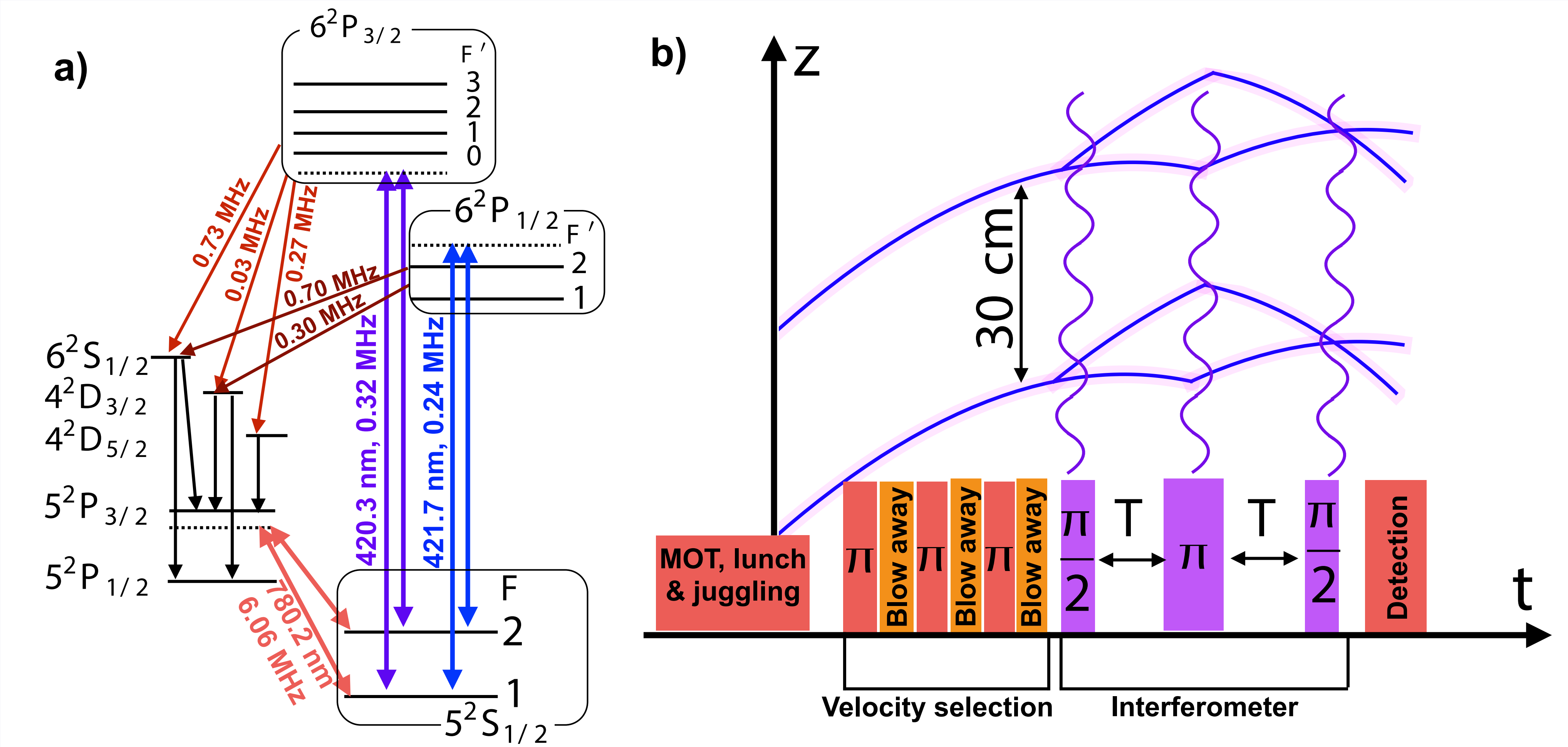
Atom Interferometry with Rb Blue Transitions



- In the previous experiment on G, 100 hours of integration were required to reach 100 ppm.
- To reach 10 ppm, the sensitivity must be improved.
- Enhancing the transferred momentum to the atomic wave packets
- Most LMT schemes require ultracold atomic samples (=> slow cycle rate, less atoms) and/or multi-pulse interferometric sequences (=> parasitic interferometers, reduced contrast)
- **A still unexplored possibility was to use Rb transitions on the 5S -> 6P manifold @ 420-422 nm instead of the D2 line @ 780 nm**
- **Even if the signal enhancement is only ~1.9 there are some major advantages:**
  - **Thermal cold atom samples can be used**
  - **The interferometric sequence is simple**
  - **Smaller diffraction, reduced systematic effects**

L. Salvi, L. Cacciapuoti, G. M. Tino, G. Rosi, *Atom Interferometry with Rb Blue Transitions*, Phys. Rev. Lett. **131**, 103401 (2023)

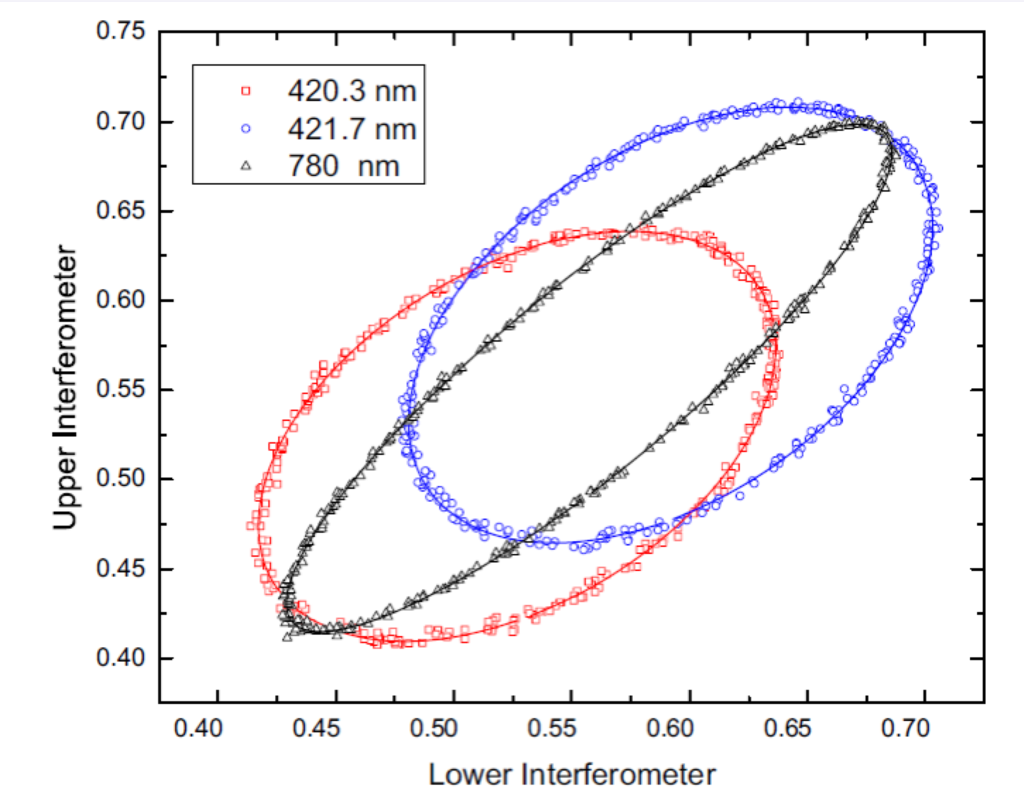
Atom Interferometry with Rb Blue Transitions

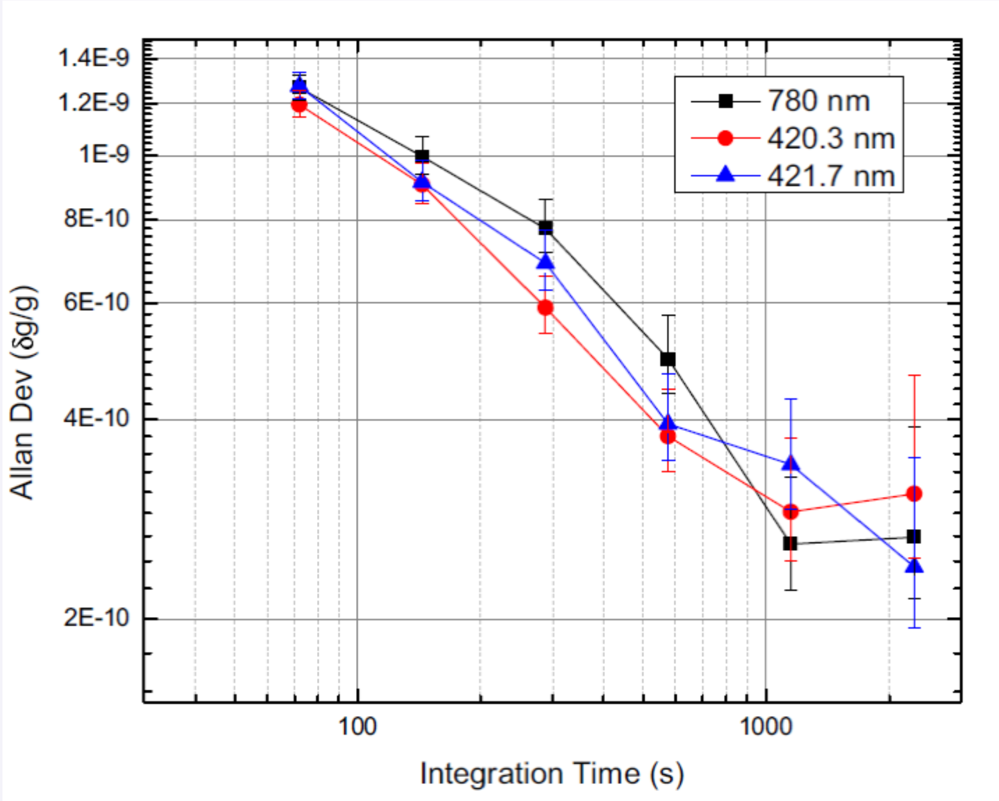


L. Salvi, L. Cacciapuoti, G. M. Tino, G. Rosi, *Atom Interferometry with Rb Blue Transitions*, Phys. Rev. Lett. **131**, 103401 (2023)

Raman Interferometry with Rb Blue Transitions

Both transitions $5S_{1/2} \rightarrow 6P_{1/2}$ @ 421.7 nm and $5S_{1/2} \rightarrow 6P_{3/2}$ @ 420.3 nm were tested (6 h data acquisition)





Sensitivity: 1×10^{-8} g/Hz$^{1/2}$

- Pulse duration: 48 us (instead of 24 us => narrower velocity interval selected)
- Detuning: 35-50 Γ (instead of 300 Γ => higher scattering rate, 14%)
- Beam waist: 9 mm (instead of 13 mm)
- Interferometer time T: 160 ms

- From the comparison with the 780 nm, the expected increase in the signal is observed (0.6 rad -> 1.1 rad)
- Sensitivity does not improve due to higher scattering:

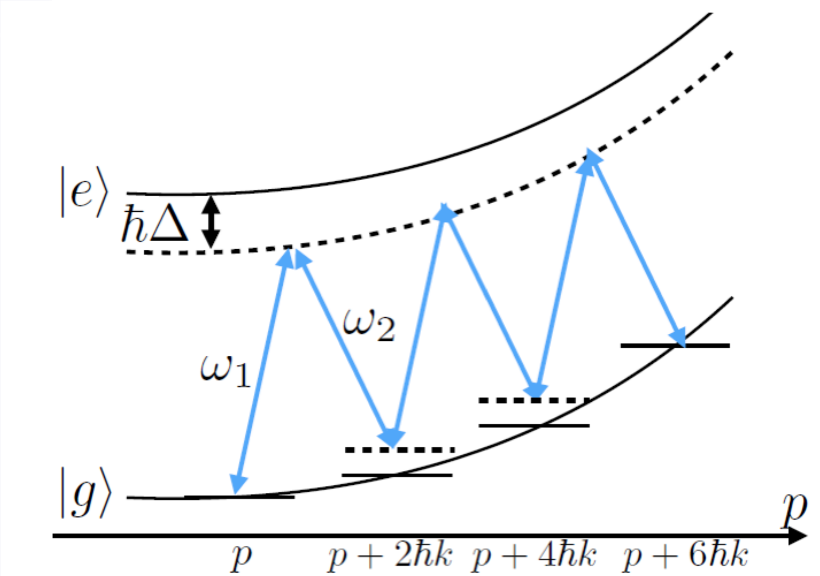
1×10^{-8} g/Hz$^{1/2}$ -> 2 $\times10^{-10}$ g after 2000 s integration time

- **Non-optimal conditions due to limited laser power (0.5 W)**

=> Technical upgrades required: Higher power lasers, e.g., additional amplification stages or Ti-Sa lasers.

L. Salvi, L. Cacciapuoti, G. M. Tino, G. Rosi, *Atom Interferometry with Rb Blue Transitions*, Phys. Rev. Lett. **131**, 103401 (2023)

Bragg Interferometry with Rb Blue Transitions



- Bragg diffraction: interferometer remains in the same internal state => Less sensitivity to external fields (e.g. magnetic fields)

- Multiphoton interaction, laser resonance condition: $\omega_1 - \omega_2 = 4n\omega_r$

- Improves sensitivity to Raman transitions by increasing the area of the interferometer at high orders

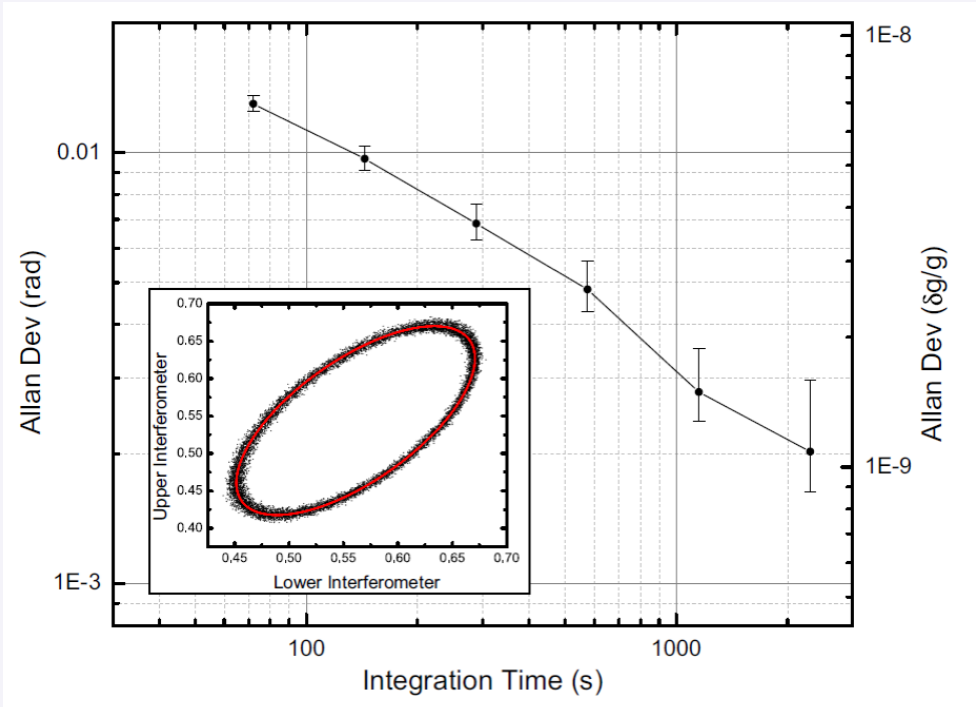
- Higher recoil speed => greater spacing between orders

- Bragg interferometry demonstrated for n = 1 on the $5S_{1/2}$ -> $6P_{3/2}$ transition at 420.3 nm

- Gaussian pulse duration: 21 us (sigma)
- Smaller beam size: 7 mm
- Detuning: 210 Γ (scattering rate 10%)
- Interferometer time T: 80 ms
- Frequency detuning of the Bragg π pulse changed by 40 MHz to introduce a differential phase shift.

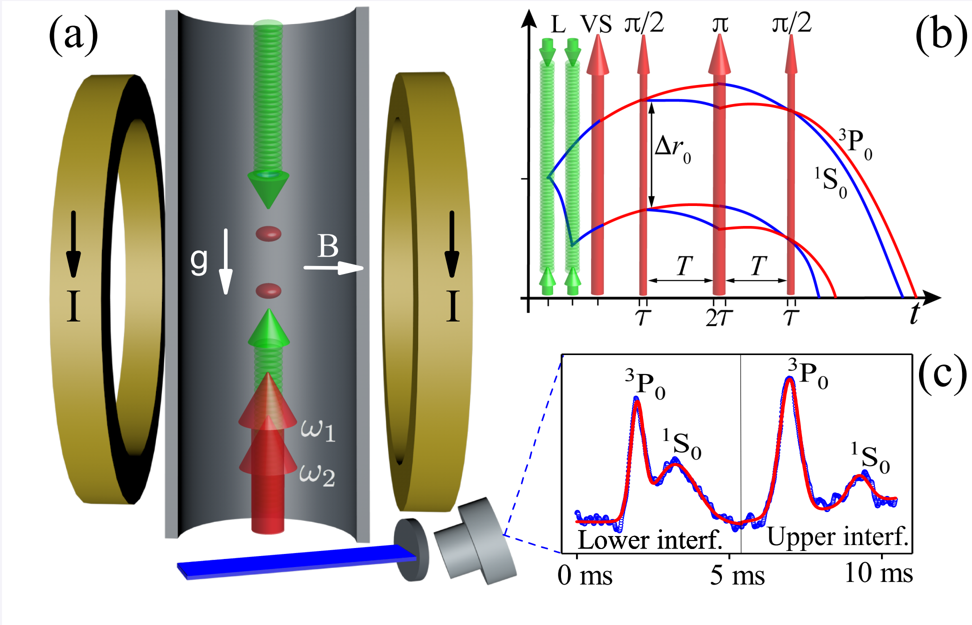
=> Sensitivity: 6 x10^{-8} g/$Hz^{1/2}$ -> 1 x10^{-9} g after 2000 s integration

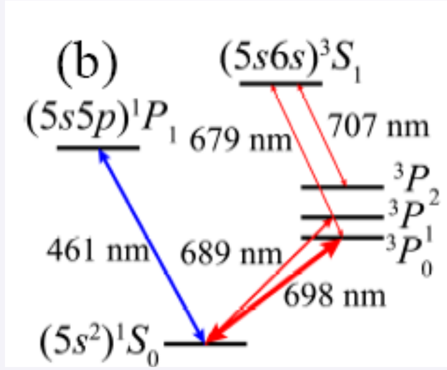
Possible technical improvements as for Raman Interferometry to reach optimal conditions.



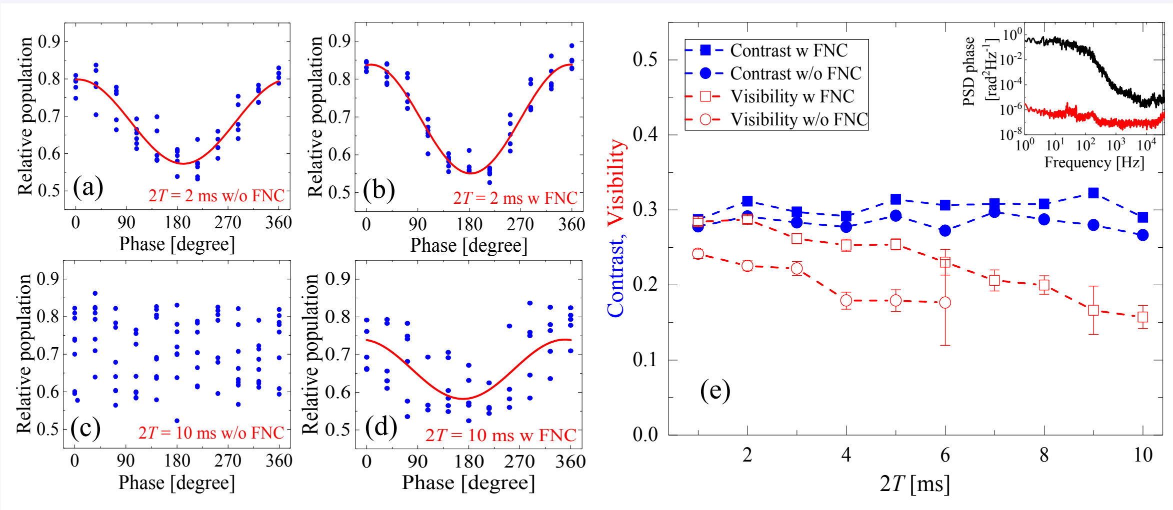
L. Salvi, L. Cacciapuoti, G. M. Tino, G. Rosi, *Atom Interferometry with Rb Blue Transitions*, Phys. Rev. Lett. **131**, 103401 (2023)

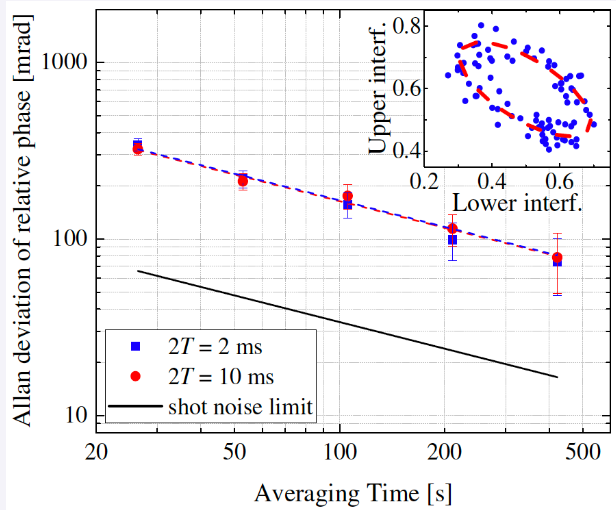
Atom interferometry with the Sr optical clock transition





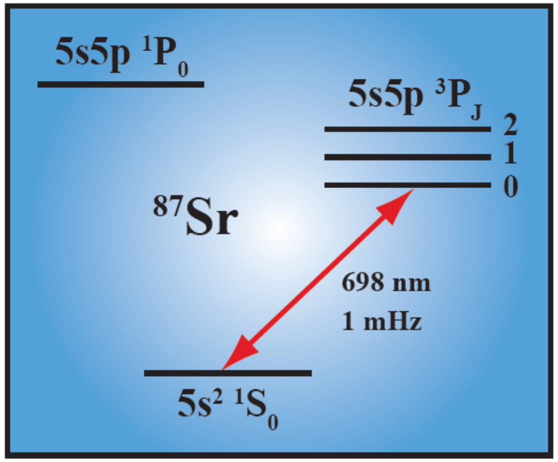
- ^{88}Sr isotope
- B=300 G -> Δν=20 μHz
- Rabi frequency Ω ~ 1kHz





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

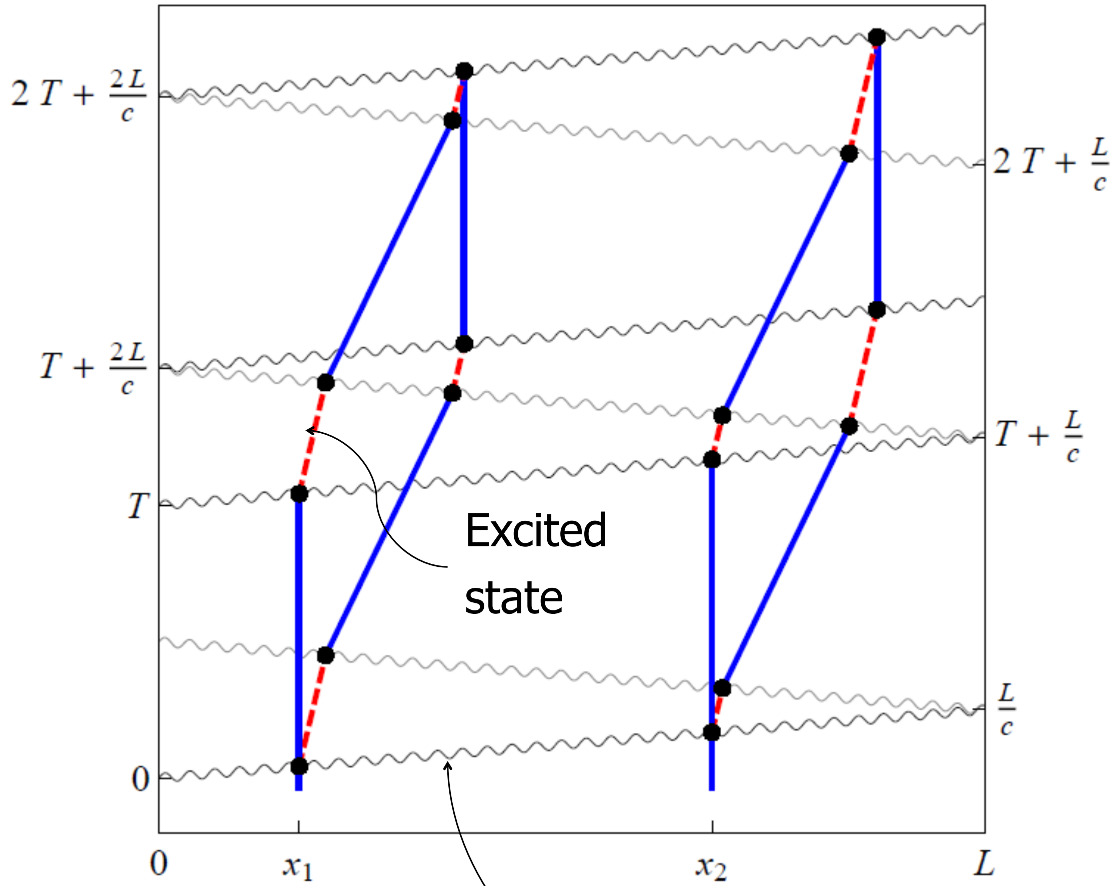
Laser frequency noise insensitive detector



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.

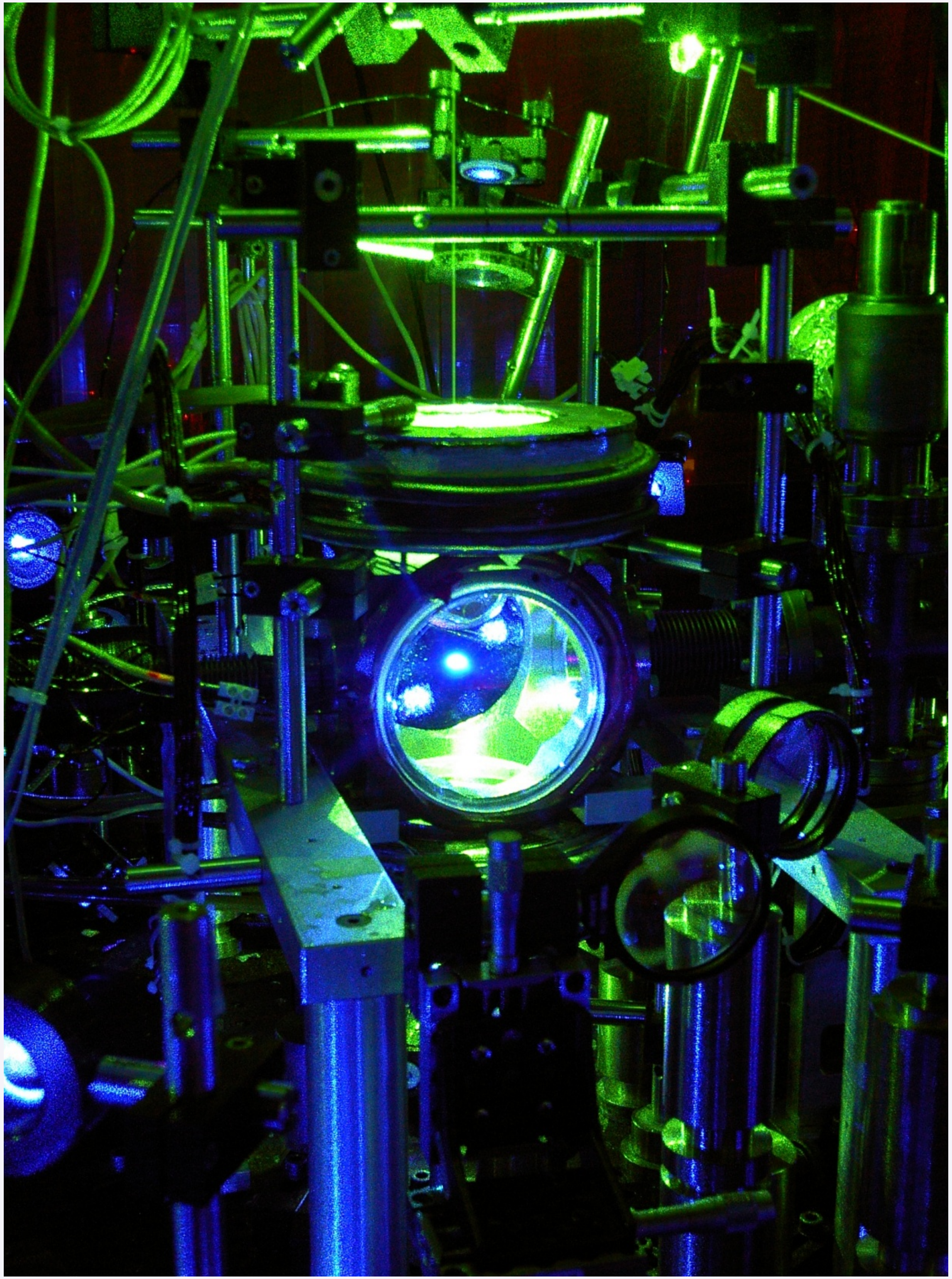
Enables 2 satellite configurations



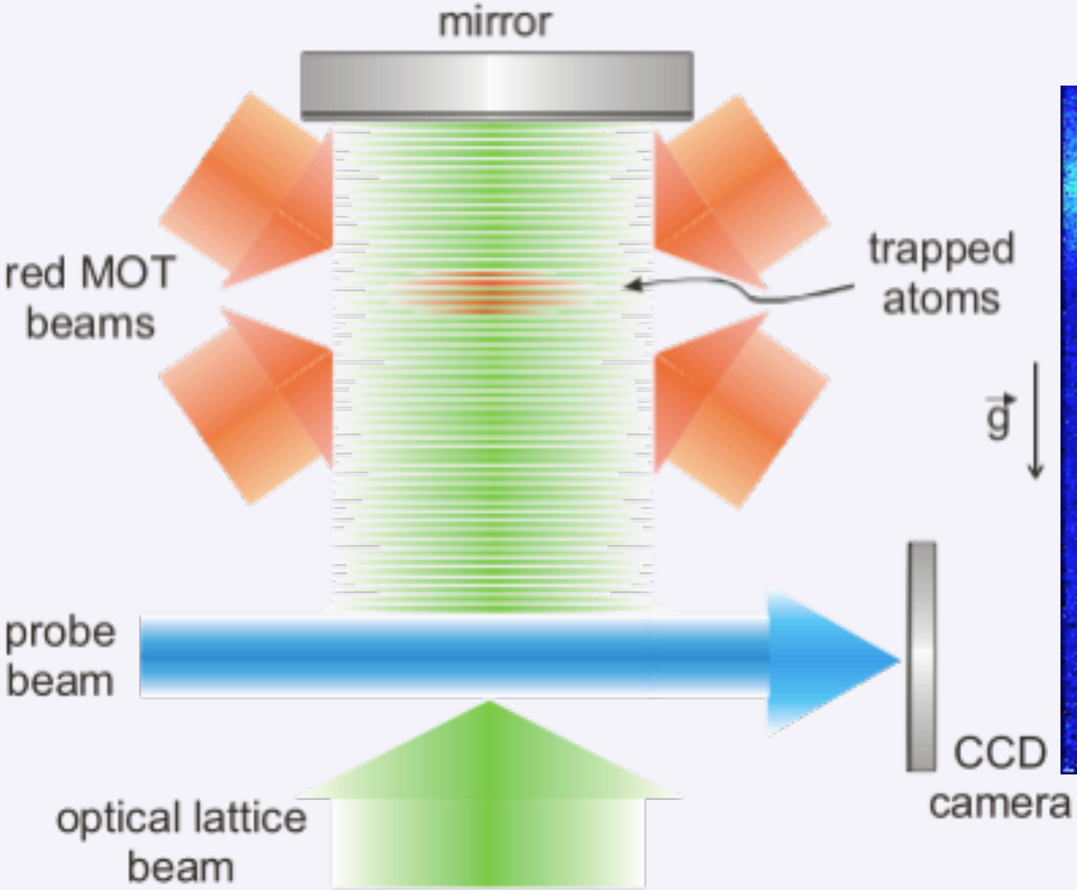
Graham, et al., arXiv:1206.0818, PRL (2013)

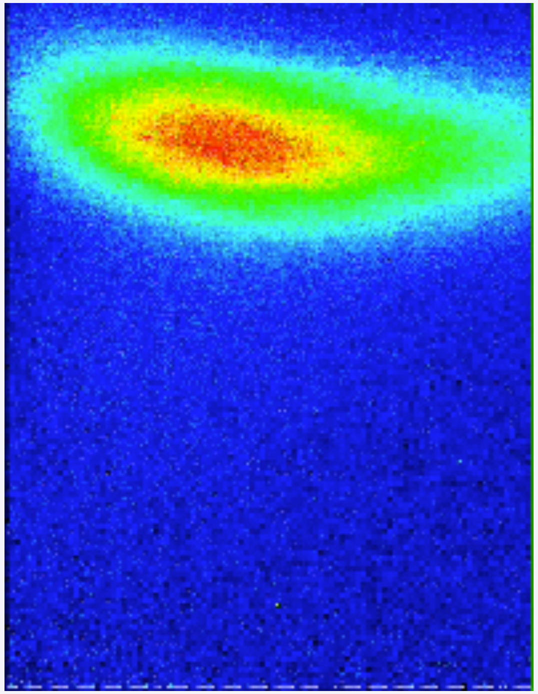
from M. Kasevich
STANFORD UNIVERSITY

UNIVERSITÀ DEGLI STUDI FIRENZE



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





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

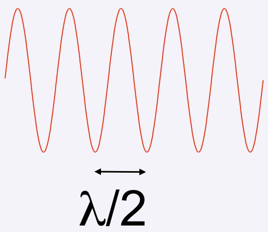
G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* **Phys. Rev. Lett. 97, 060402 (2006)**

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)**

Particle in a periodic potential: Bloch oscillations

periodic potential



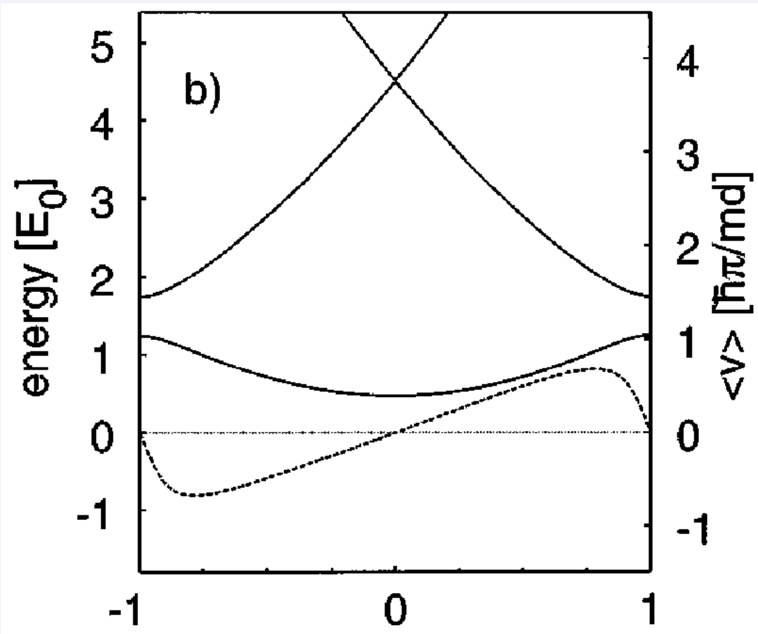
$$V(z+\lambda/2) = V(z)$$

$$\Psi(z) = e^{i\frac{q}{\hbar}z}\, u(z)$$

$$u(z+\lambda/2) = u(z)$$

Bloch's theorem

$$\Psi(z+\lambda/2) = e^{i\frac{q}{\hbar}\frac{\lambda}{2}}\, \Psi(z)$$



quasimomentum q [2π/λ]

$$\langle v\rangle_n(q(t)) = \frac{1}{\hbar}\frac{dE_n(R(q(t)))}{dq}$$

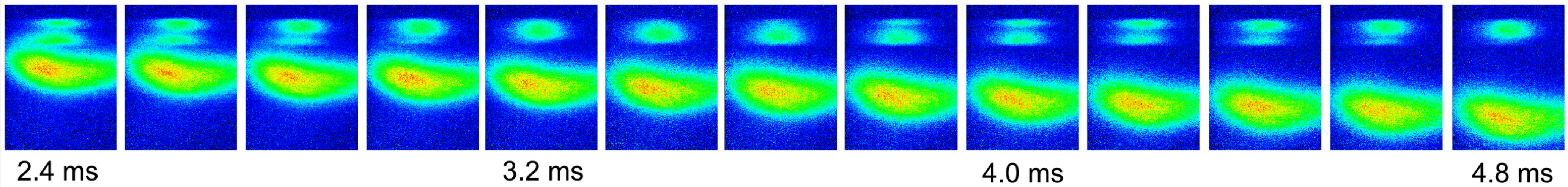
with a constant external force F

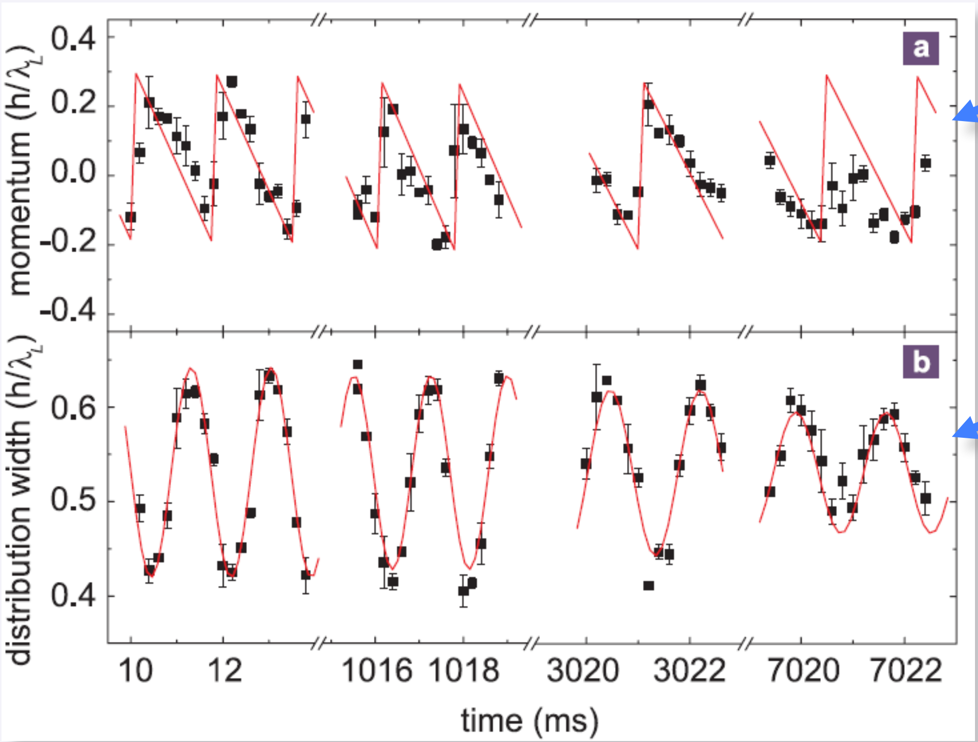
$$q(t) = q(0) + Ft/\hbar$$

Bloch oscillations

Quantum theory for electrons in crystal lattices: **F. Bloch, Z. Phys. 52, 555 (1929)**
Never observed in natural crystals (evidence in artificial superlattices)
Direct observation with Cs atoms: **M.Ben Dahan, E.Peik, J.Reichel, Y.Castin, C.Salomon, PRL 76, 4508 (1996)**

Persistent Bloch oscillations





average vertical momentum of the lower peak

width of the atomic momentum distribution

Bloch frequency ν_B = 574.568(3) Hz

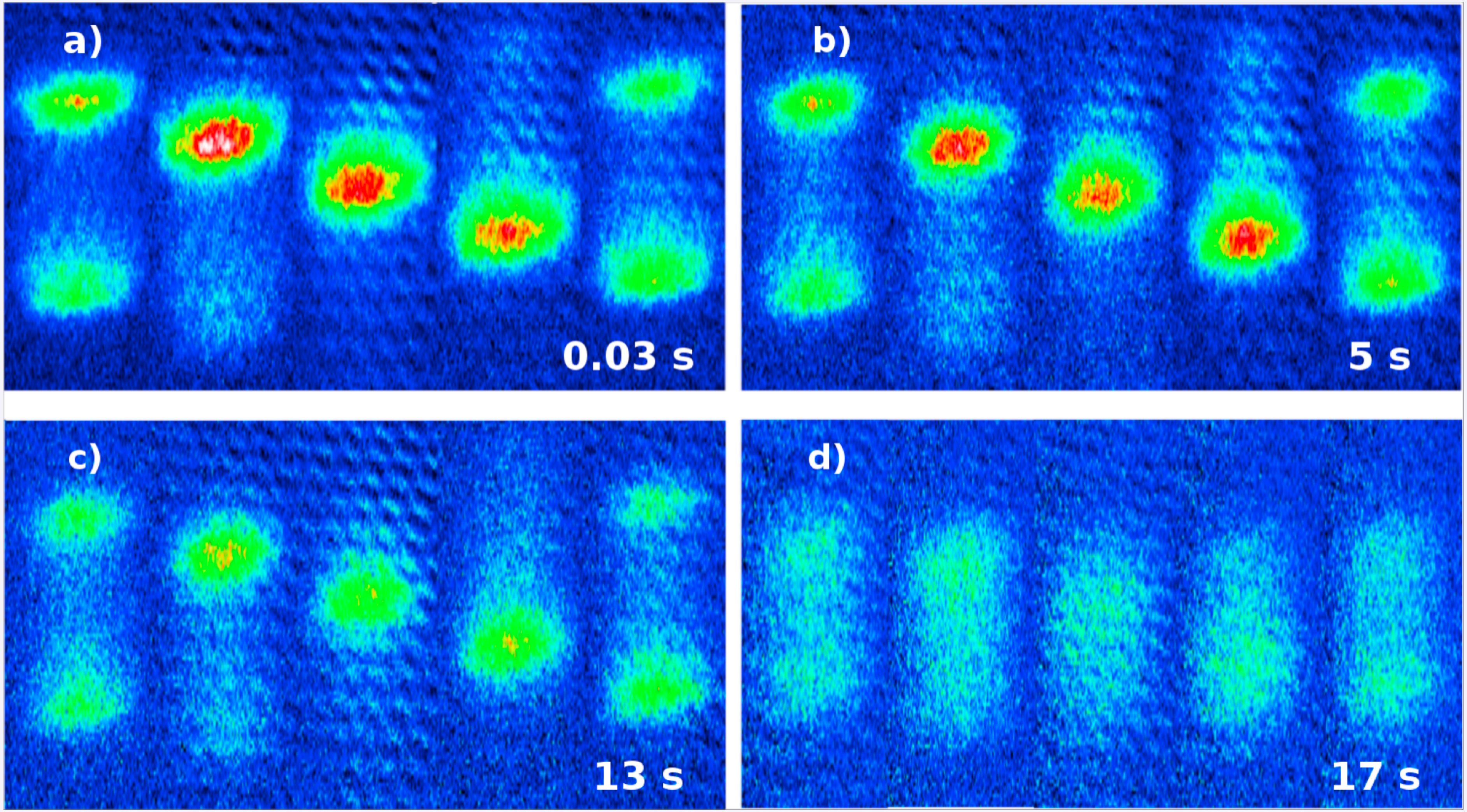
damping time τ = 12 s

8000 photon recoils in 7s

g_{meas} = 9.80012(5) ms^{-2}

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)**

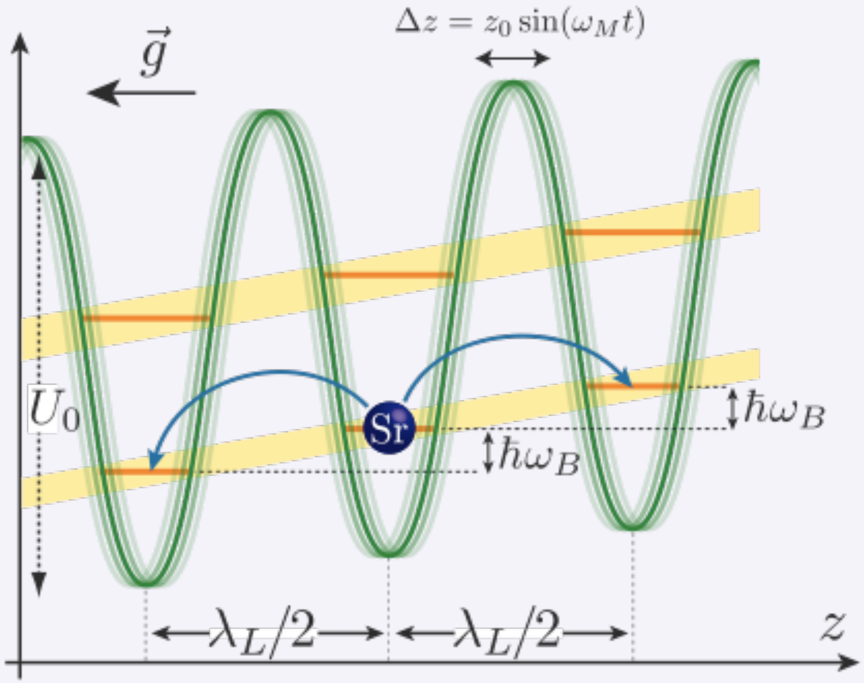
Bloch oscillations of ^{88}Sr atoms



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)

Modulation of optical lattices

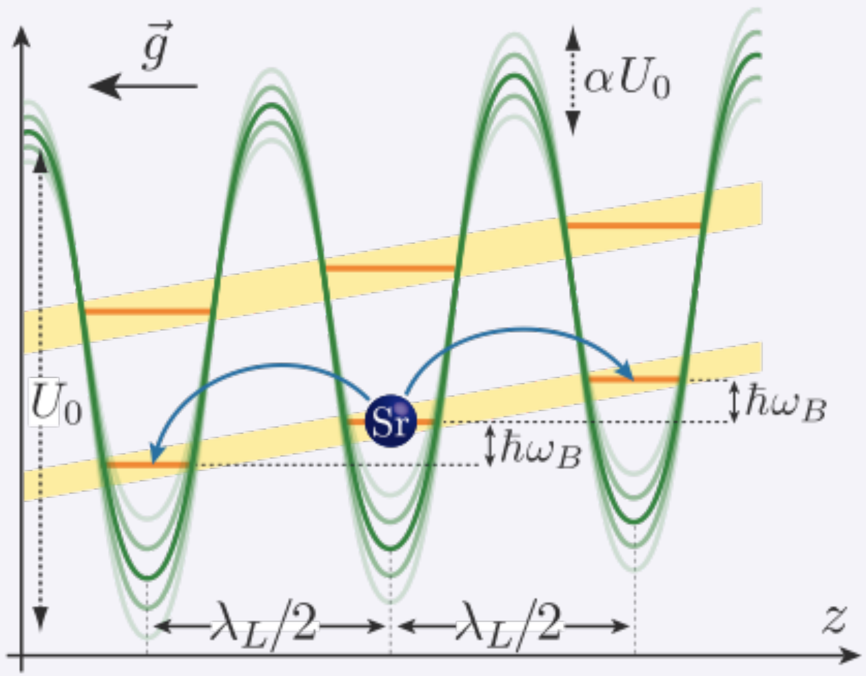
Phase modulation



$$\mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2}\cos\left\{2k_L[z - z_0\sin(\omega_M t)]\right\} + mgz$$

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)**

Amplitude modulation



$$\mathcal{H}_0 = \frac{p^2}{2m} - \frac{U_0}{2}\cos(2k_L z)[1 + \alpha\,\sin(\omega_M t)] + mgz$$

A. Alberti, G. Ferrari, V.V. Ivanov, M. L. Chiofalo, G. M. Tino, *Atomic wave packets in amplitude-modulated vertical optical lattices* **New Journal of Physics 12, 065037 (2010)**

M. G. Tarallo, A. Alberti, N. Poli, M. L. Chiofalo, F.-Y. Wang, G. M. Tino, *Delocalization-enhanced Bloch oscillations and driven resonant tunneling in optical lattices for precision force measurements,* **Phys. Rev. A 86, 033615 (2012)**

PRL 102, 240402 (2009) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2009

Large Momentum Beam Splitter Using Bloch Oscillations

Pierre Cladé, Saïda Guellati-Khélifa, François Nez, and François Biraben

Laboratoire Kastler Brossel, UPMC, Ecole Normale Supérieure, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, Fr

(Received 20 March 2009; published 18 June 2009)

The sensitivity of an inertial sensor based on an atomic interferometer is proportional to the velocity separation of atoms in the two arms of the interferometer. In this Letter we describe how Bloch oscillations can be used to increase this separation and to create a large momentum transfer (LMT) beam splitter. We experimentally demonstrate a separation of 10 recoil velocities. Light shifts during the acceleration introduce phase fluctuations which can reduce the fringes contrast. We precisely calculate this effect and demonstrate that it can be significantly reduced by using a suitable combination of LMT pulses. We finally show that this method seems to be very promising to realize a LMT beam splitter with several tens of recoils and a very good efficiency.

Eur. Phys. J. D **59**, 349–360 (2010)
DOI: 10.1140/epjd/e2010-00198-0

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Theoretical analysis of a large momentum beamsplitter using Bloch oscillations

P. Cladé[a], T. Plisson, S. Guellati-Khélifa, F. Nez, and F. Biraben

Laboratoire Kastler Brossel, UPMC, École Normale Supérieure, CNRS, 4 place Jussieu, 75252 Paris Cedex 05, France

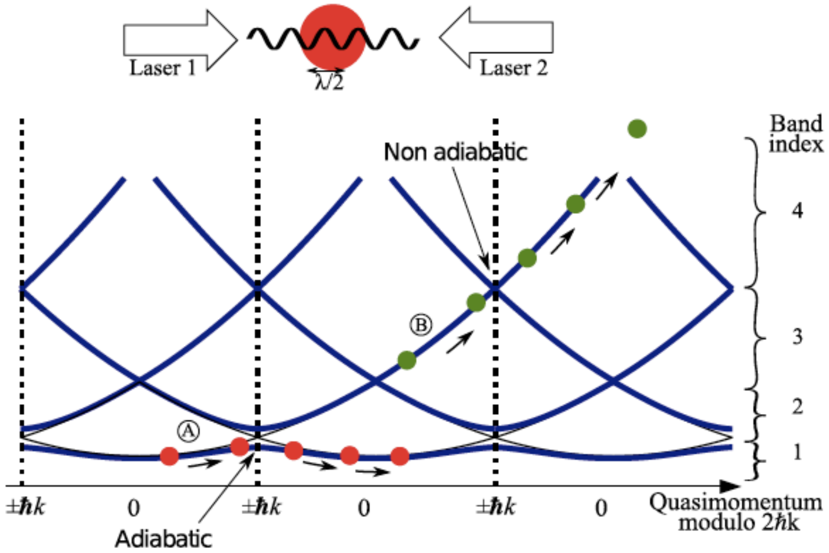
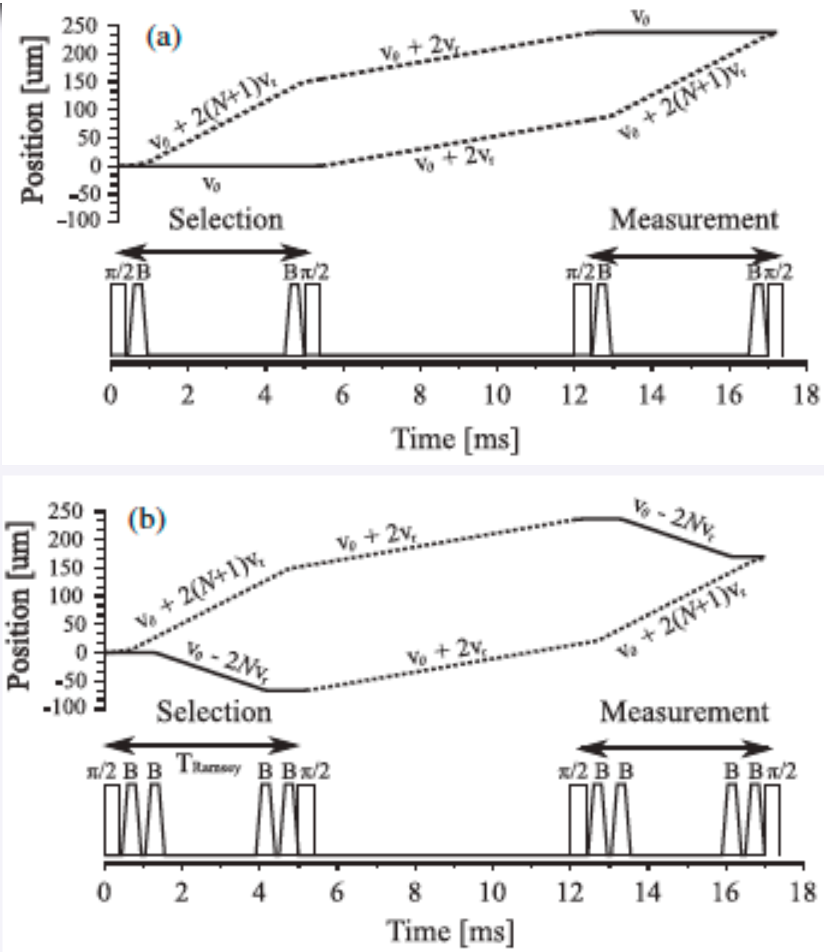


Fig. 1. (Color online) Band structure of the optical lattice. This graph represents the band energy in the frame of the lattice as a function of the quasi-momentum. Because quasi-momentum is defined modulo $2\hbar k$, one can think of this graph as an unrolled cylinder where the vertical dot-dashed lines are overlapping.



How do we improve sensitivity to gravity acceleration?

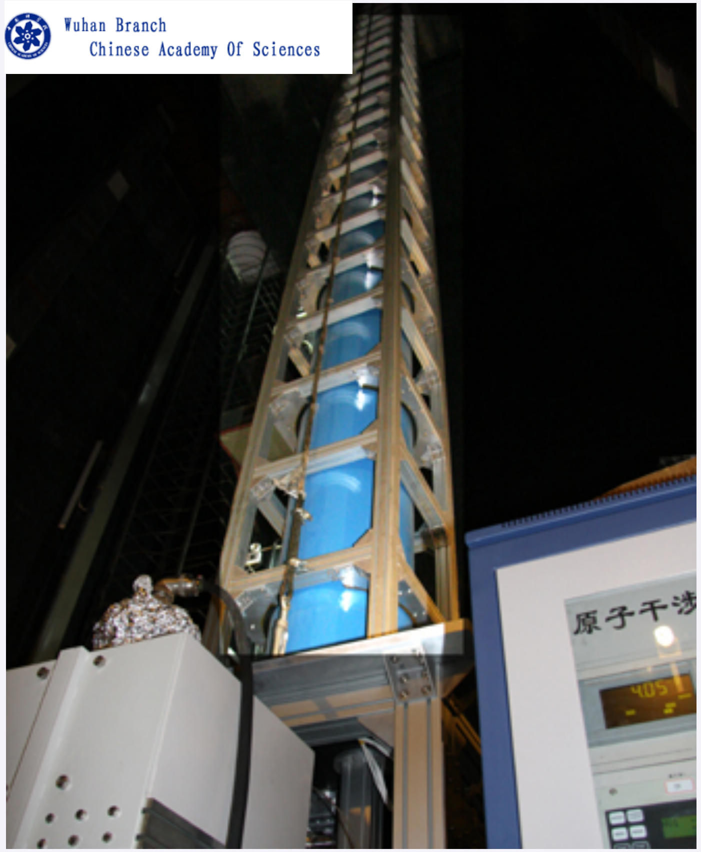
$$\Delta\phi = k_{\text{eff}}\, g\, T^2$$

- $\Delta\phi$ → Large phase resolution
- k_{eff} → Large momentum transfer
- T^2 → Long interrogation times

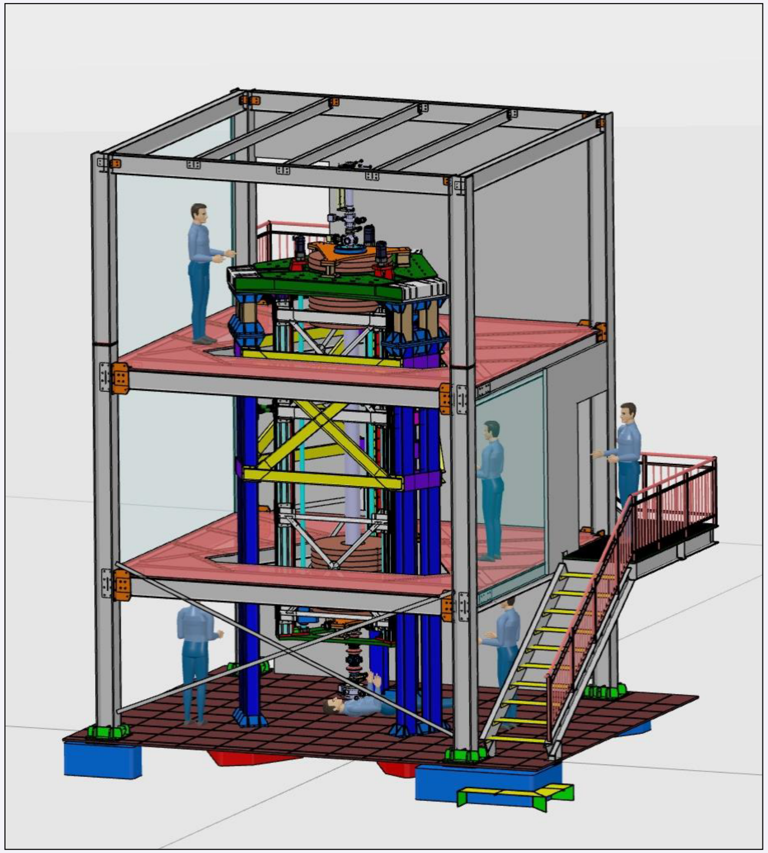
Large-scale atom interferometers

10 m fountain - Stanford

12 m fountain - Wuhan

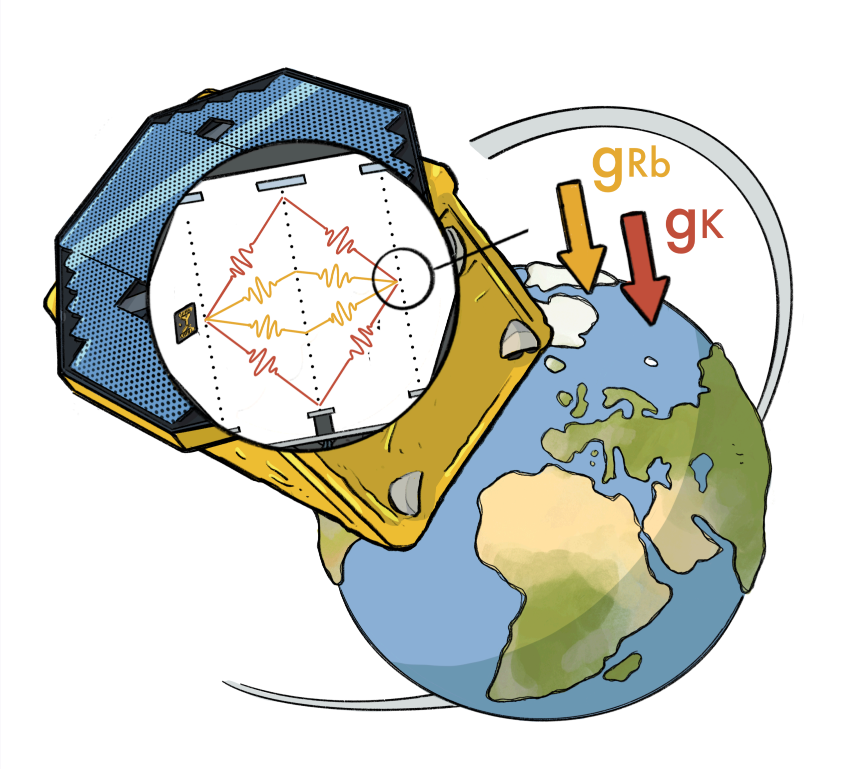


8 m fountain - Firenze
(under construction)



Towards Space

G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,* **Eur. Phys. J. D 73, 228 (2019)**



P. Wolf *et al.*, *STE-QUEST: Space Time Explorer and QUantum Equivalence Principle Space Test,* **arXiv:2211.15412 (2022)**

Atomic Squeezing

How do we improve sensitivity to gravity acceleration?

$$\Delta\phi = k_{\text{eff}}\, g\, T^2$$

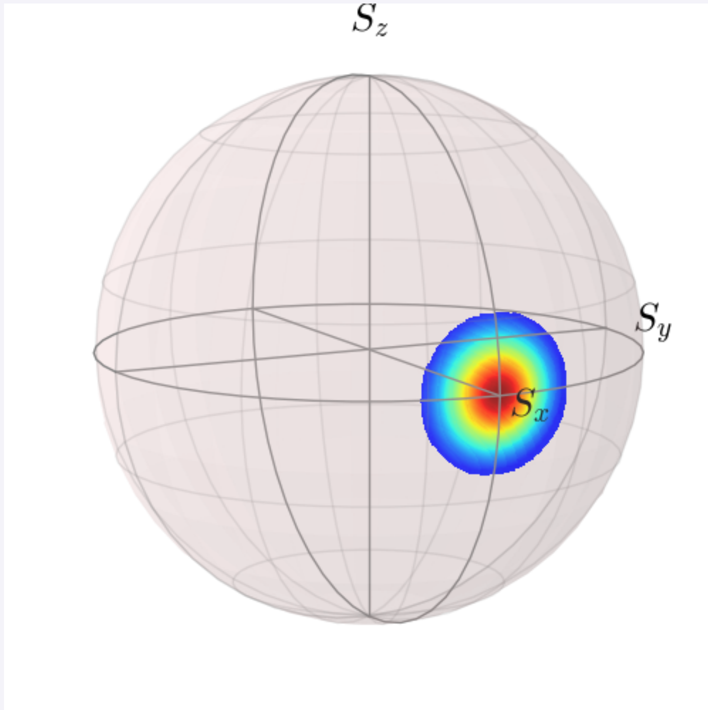
- $\Delta\phi$ → Large phase resolution
- k_{eff} → Large momentum transfer
- T^2 → Long interrogation times

Coherent spin state

$$|\psi_{\text{CSS}}\rangle = \otimes_{i=1}^{N}\left[\cos\left(\frac{\theta}{2}\right)|\uparrow\rangle_i + \sin\left(\frac{\theta}{2}\right)e^{i\varphi}|\downarrow\rangle_i\right]$$

$$\delta(\Delta\phi) = \frac{1}{\sqrt{N}}$$

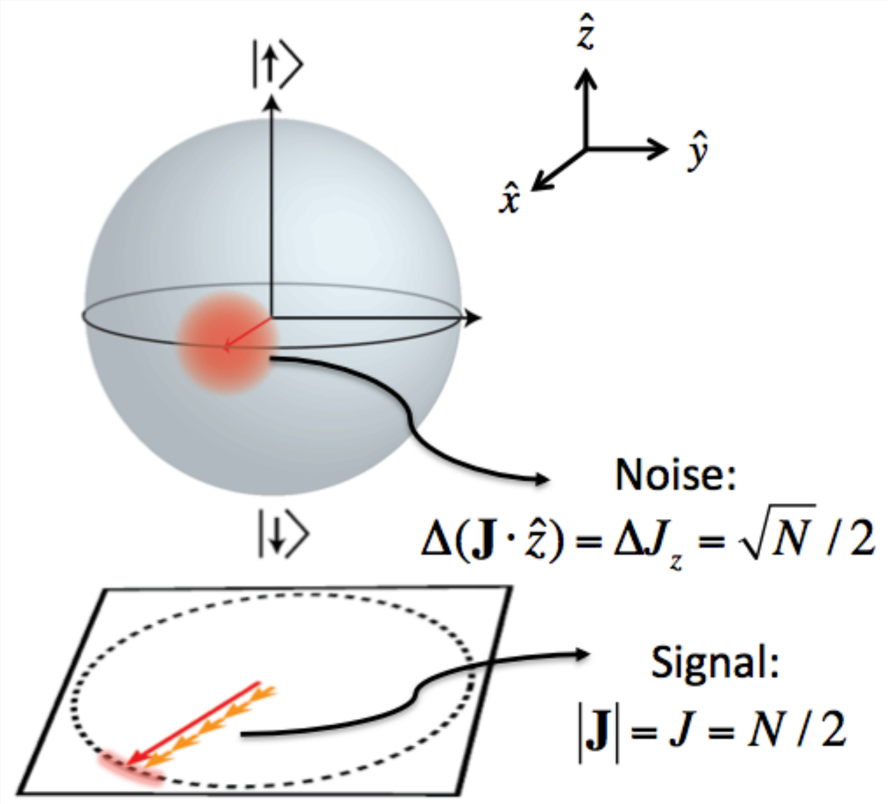
SQL



The Standard Quantum Limit and beyond

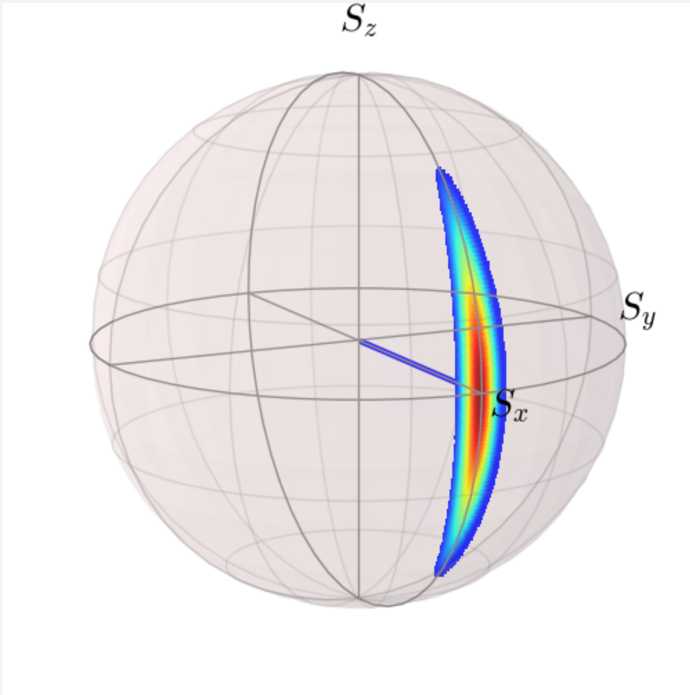
Shot noise limit

$$|\psi\rangle = \prod_{i=1}^{N} (c_\downarrow | \downarrow\rangle_i + c_\uparrow | \uparrow\rangle_i)$$



$$\Delta\theta_{\mathrm{SQL}} = \frac{1}{\sqrt{N}}$$

Beyond the shot noise limit: spin squeezed states



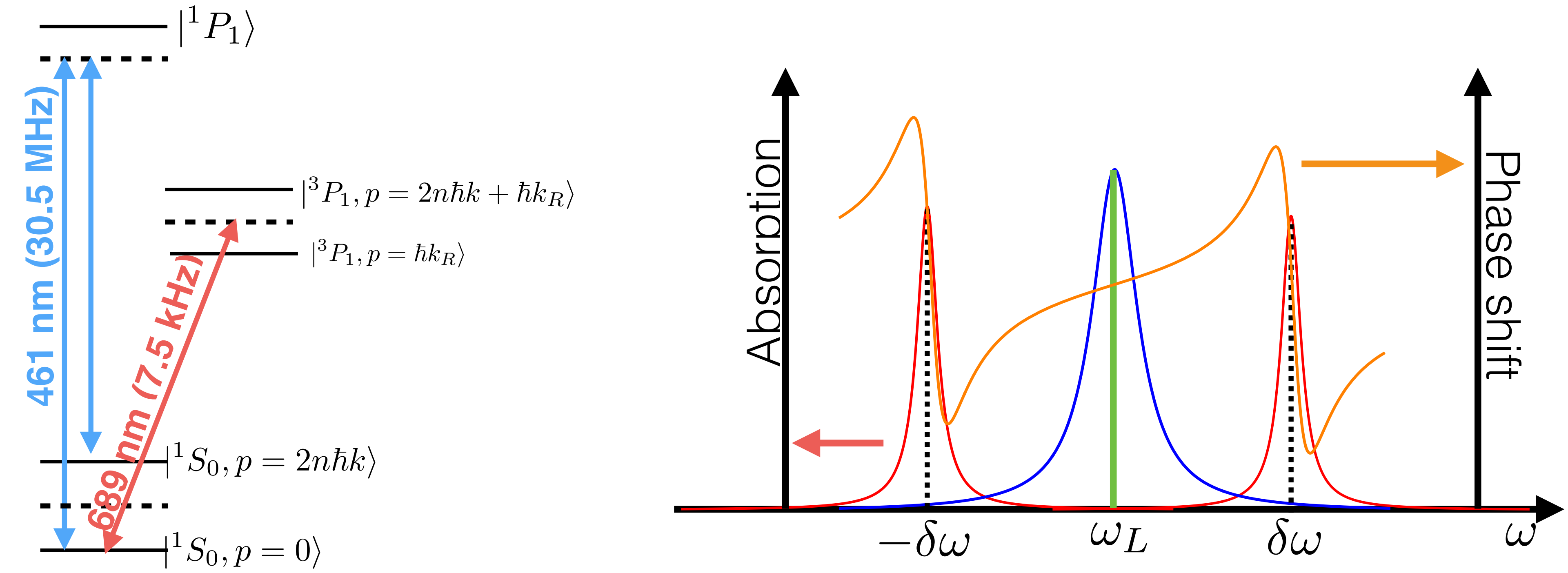
Requires correlations between particles

$$\Delta\theta_{\mathrm{HL}} = \frac{1}{N}$$

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

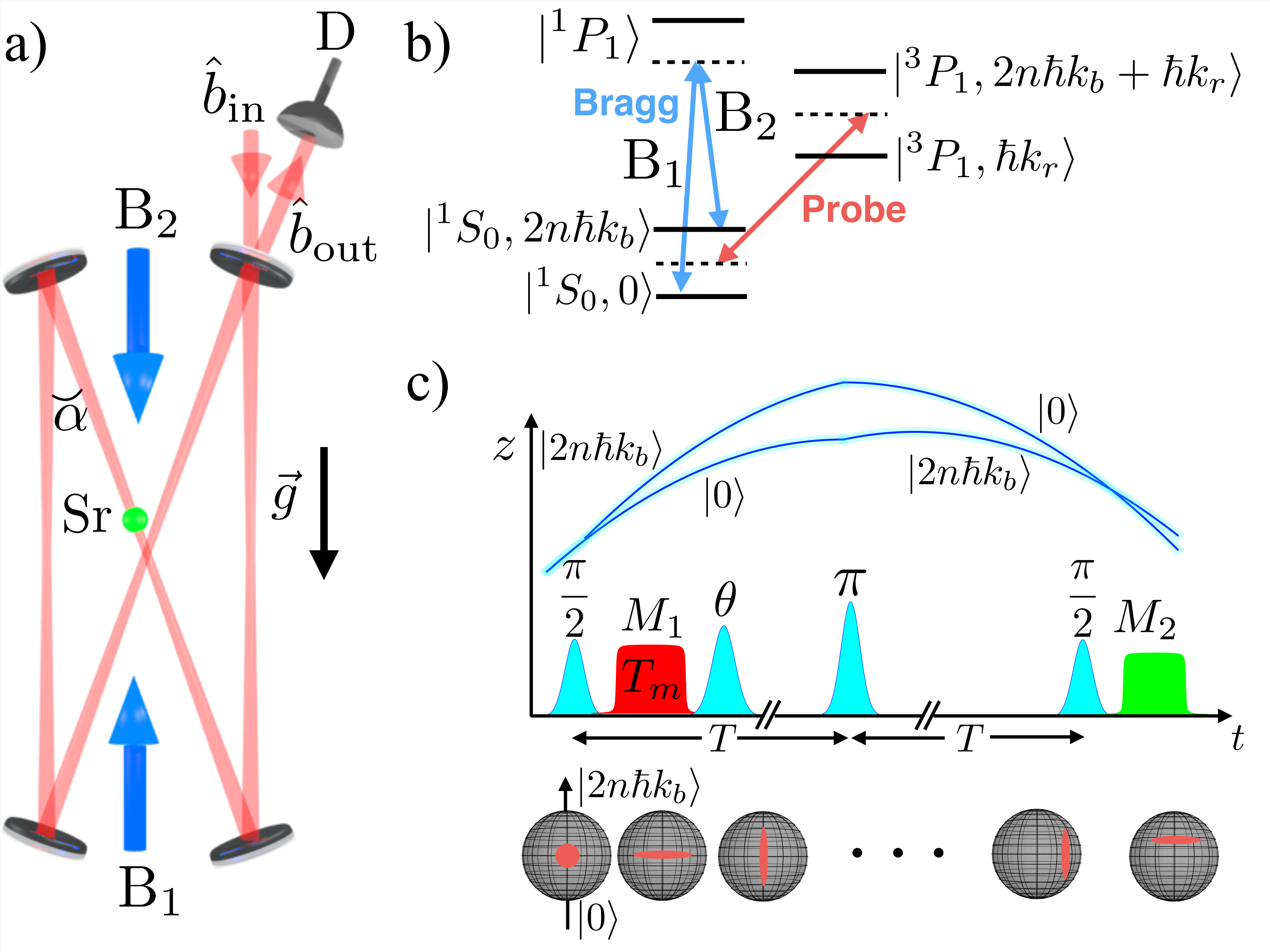
$$\delta\omega = 2\pi n \times 28.6 \text{ kHz}$$

Condition for dispersive regime:

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

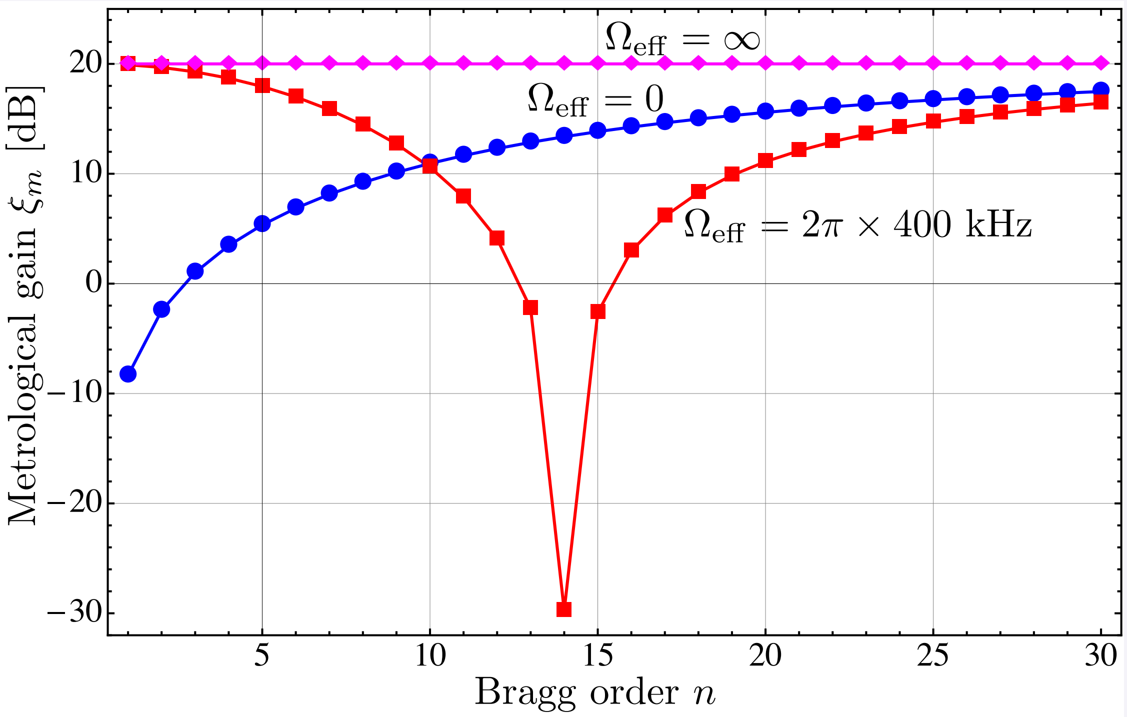
Leonardo Salvi, Nicola Poli, Vladan Vuletić, Guglielmo M. Tino, *Squeezing on Momentum States for Atom Interferometry,* **Phys. Rev. Lett. 120, 033601 (2018)**

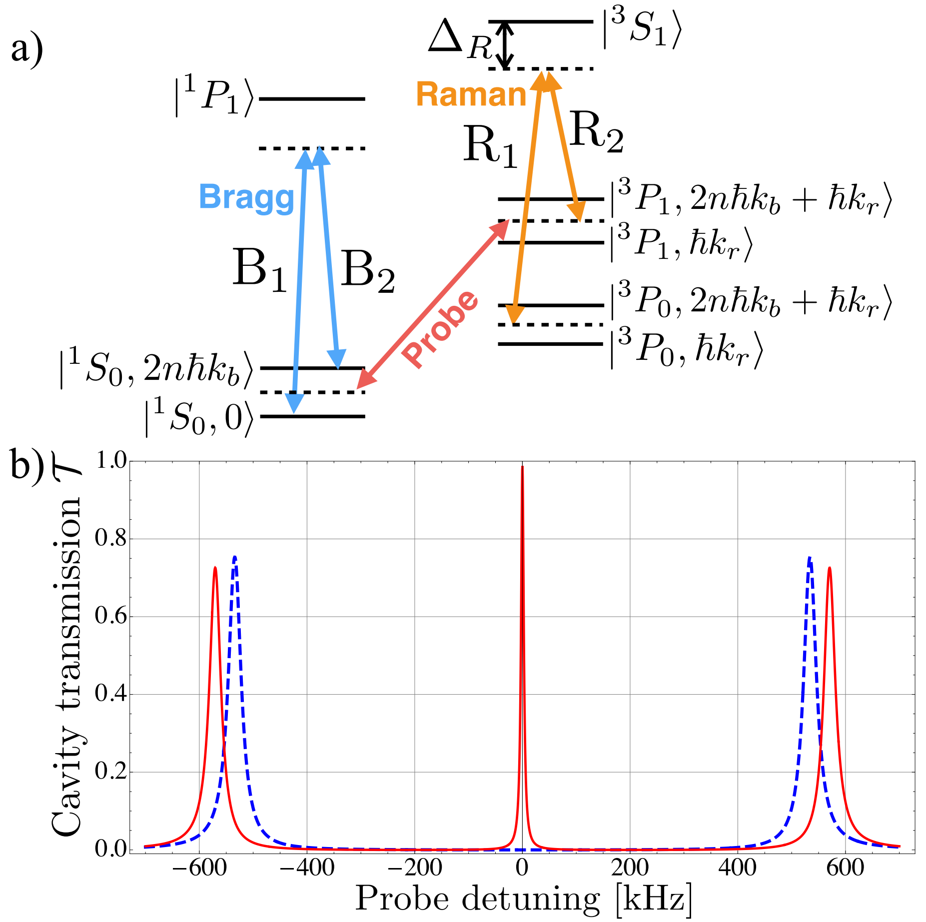
Squeezing on momentum states for atom interferometry



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

Squeezing on momentum states for atom interferometry

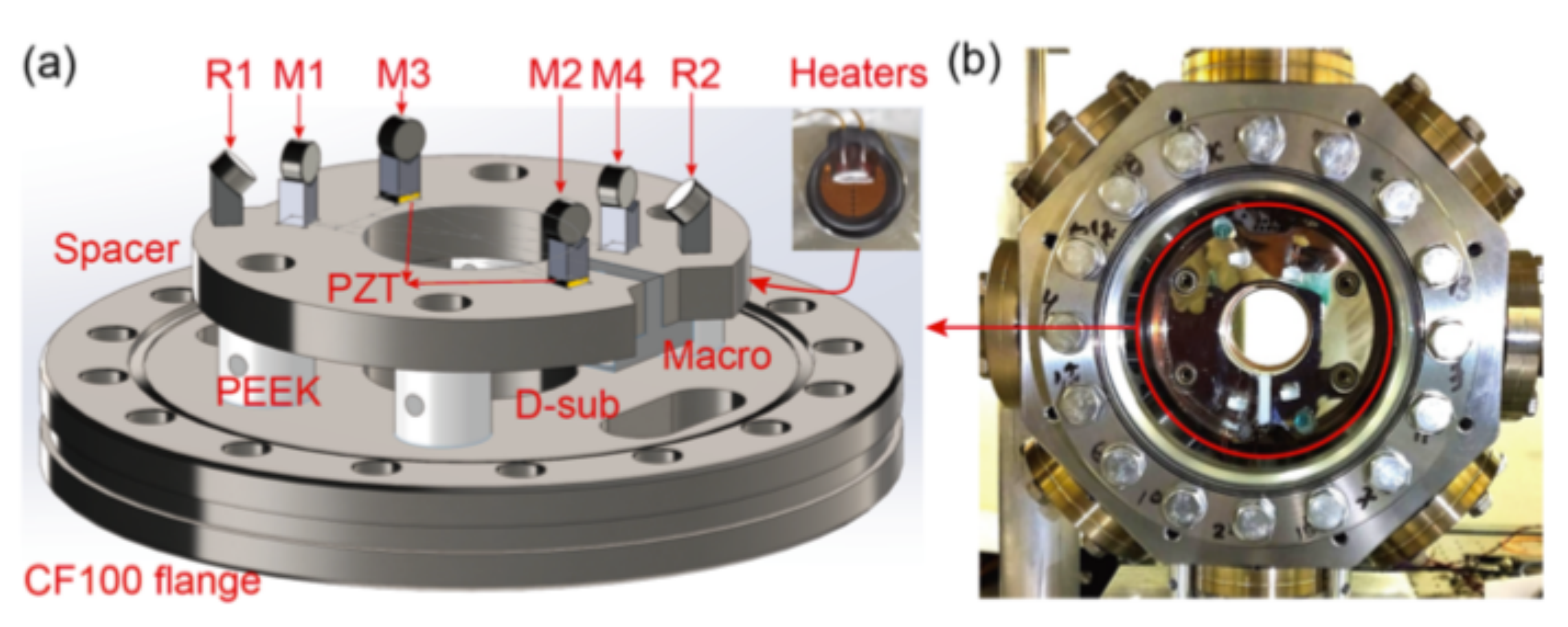




$$\xi_m = \frac{S}{2(\Delta S_z)^2}\mathcal{C}^2$$

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

Optical ring cavity in the vacuum chamber



Single-atom cooperativity

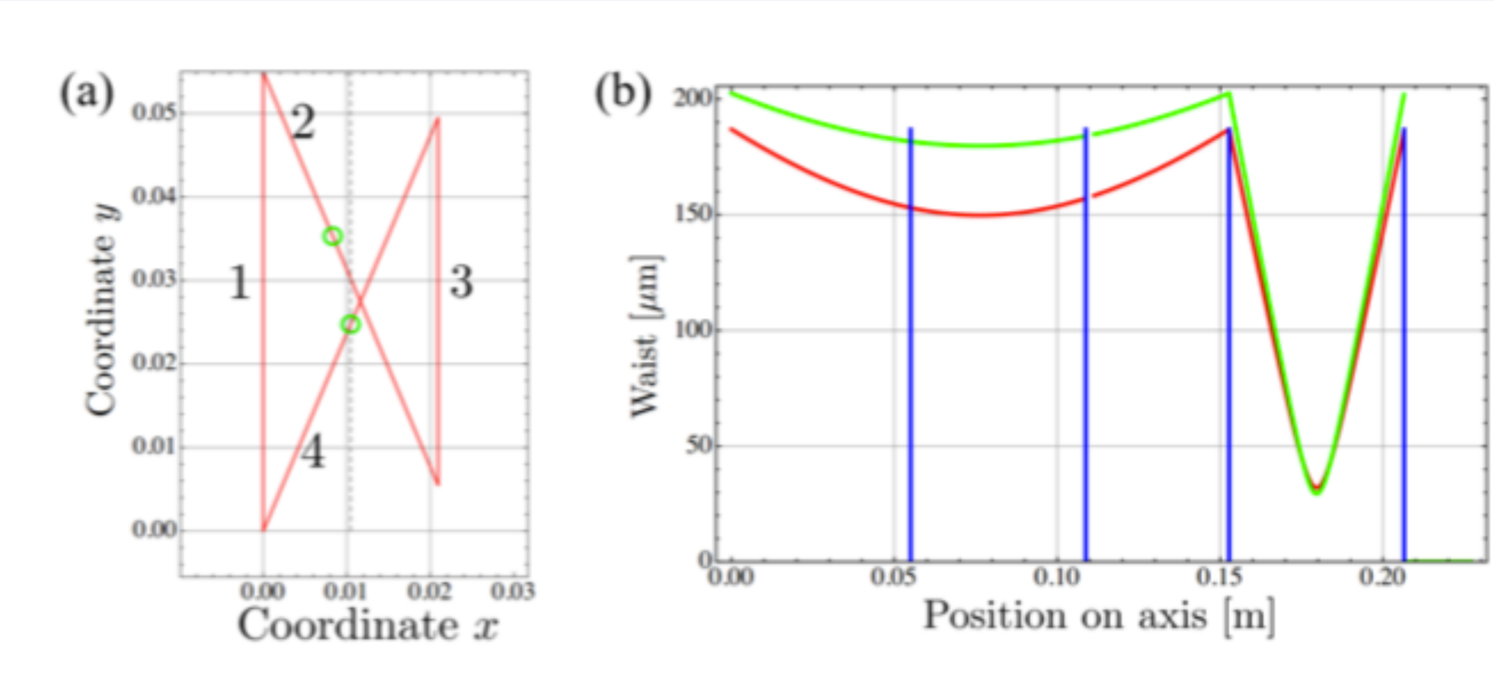
$$\eta = \frac{6F}{\pi k^2 w^2}$$

Large waist

$$\eta \simeq 0.02$$

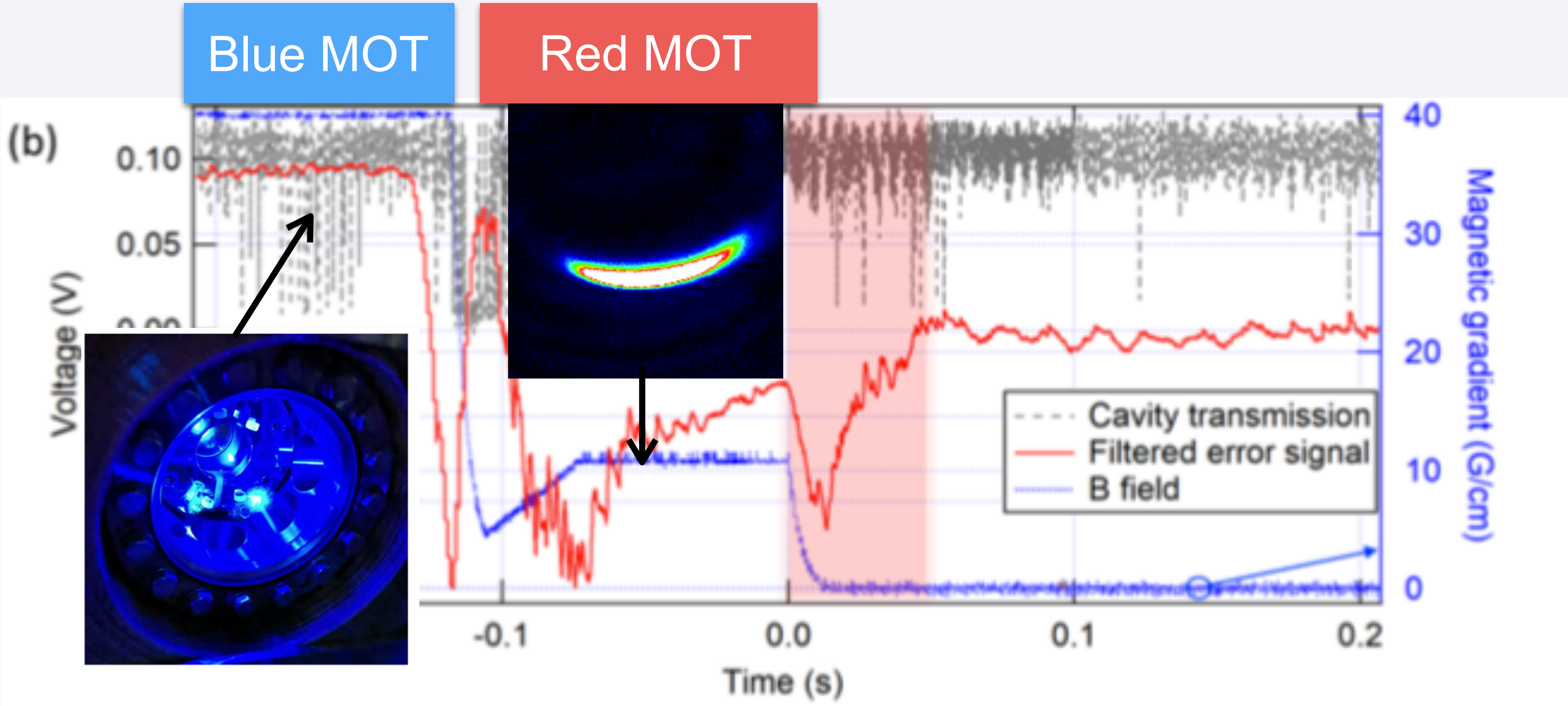
Small waist

$$\eta \simeq 0.6$$



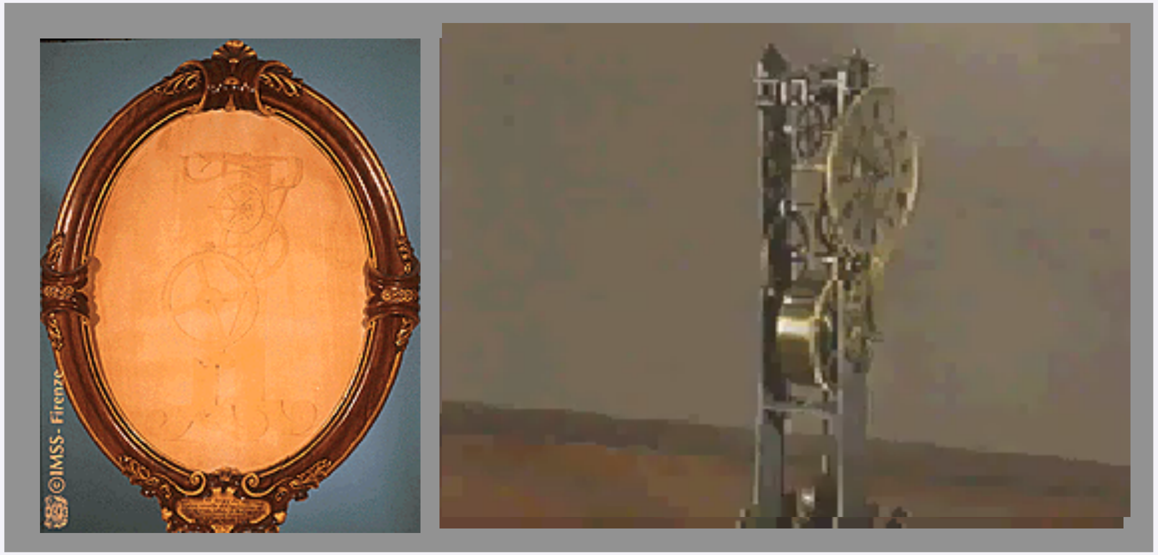
Squeezing on momentum states for atom interferometry

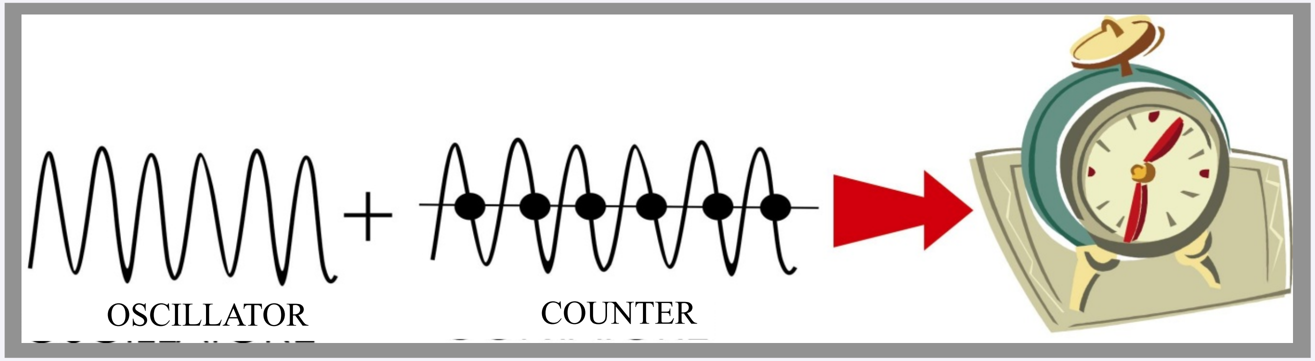
First signatures of atom-cavity coupling



Atomic clocks

The measurement of time

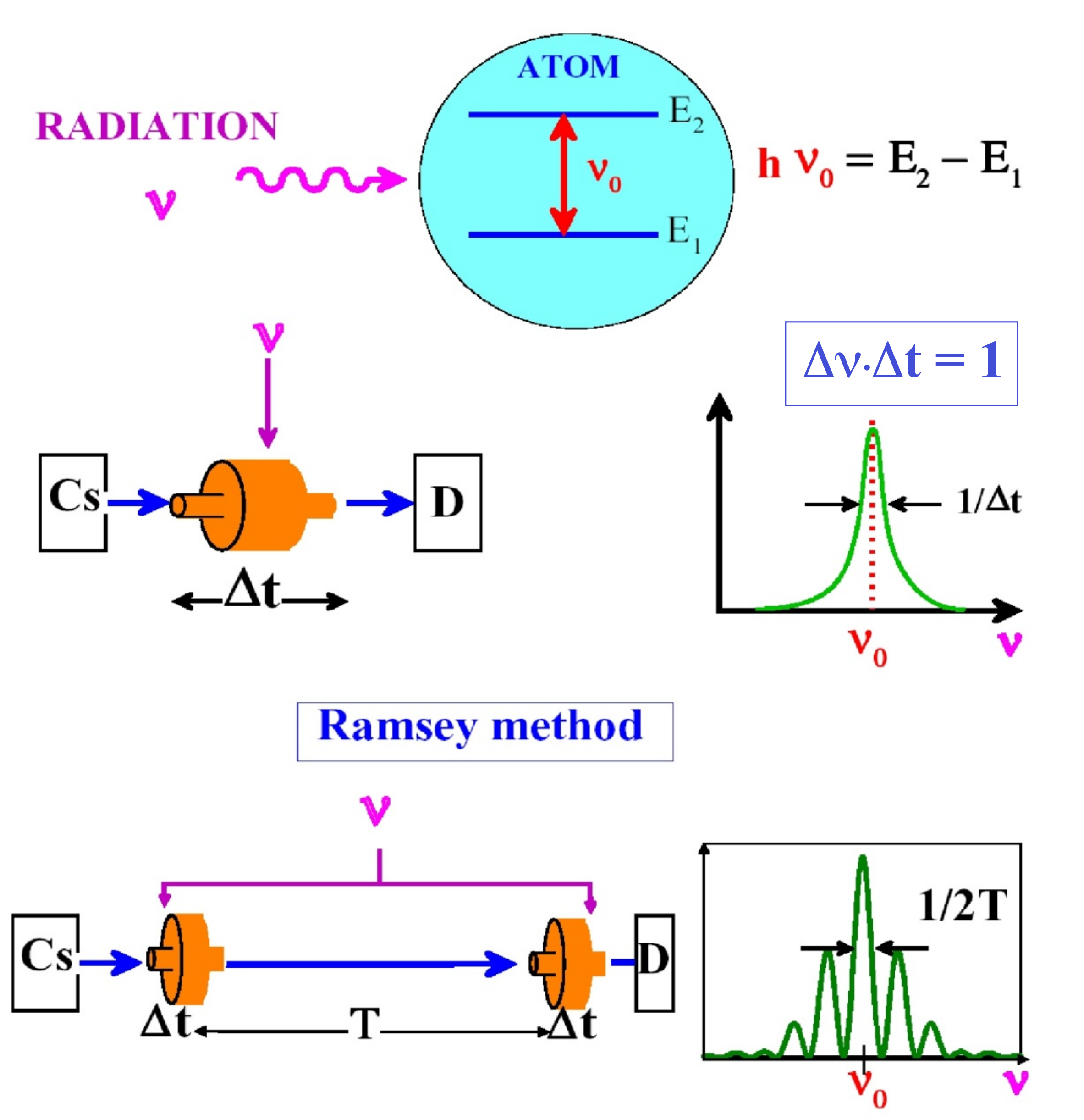




Accuracy → realization of the standard

Stability → stability of the frequency: depends on $\frac{\Delta\nu_0}{\nu_0}$ of the oscillator

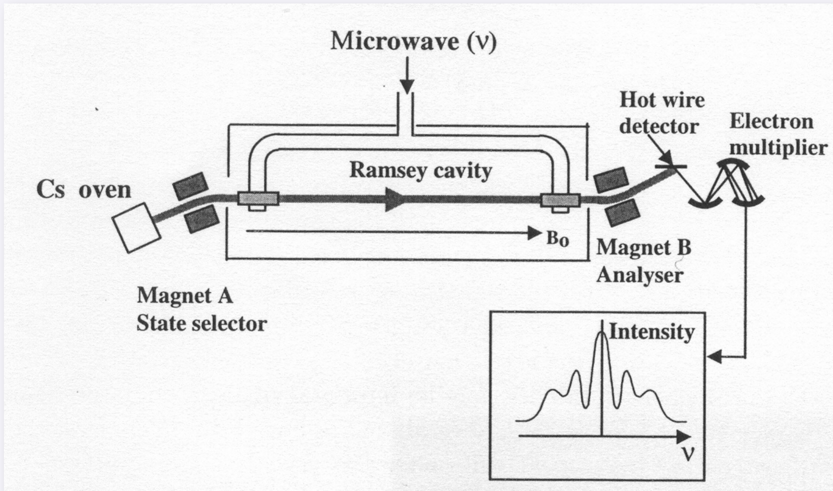
Atomic clocks



The definition of the second

The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the ^{133}Cs atom

(13th CGPM, 1967)



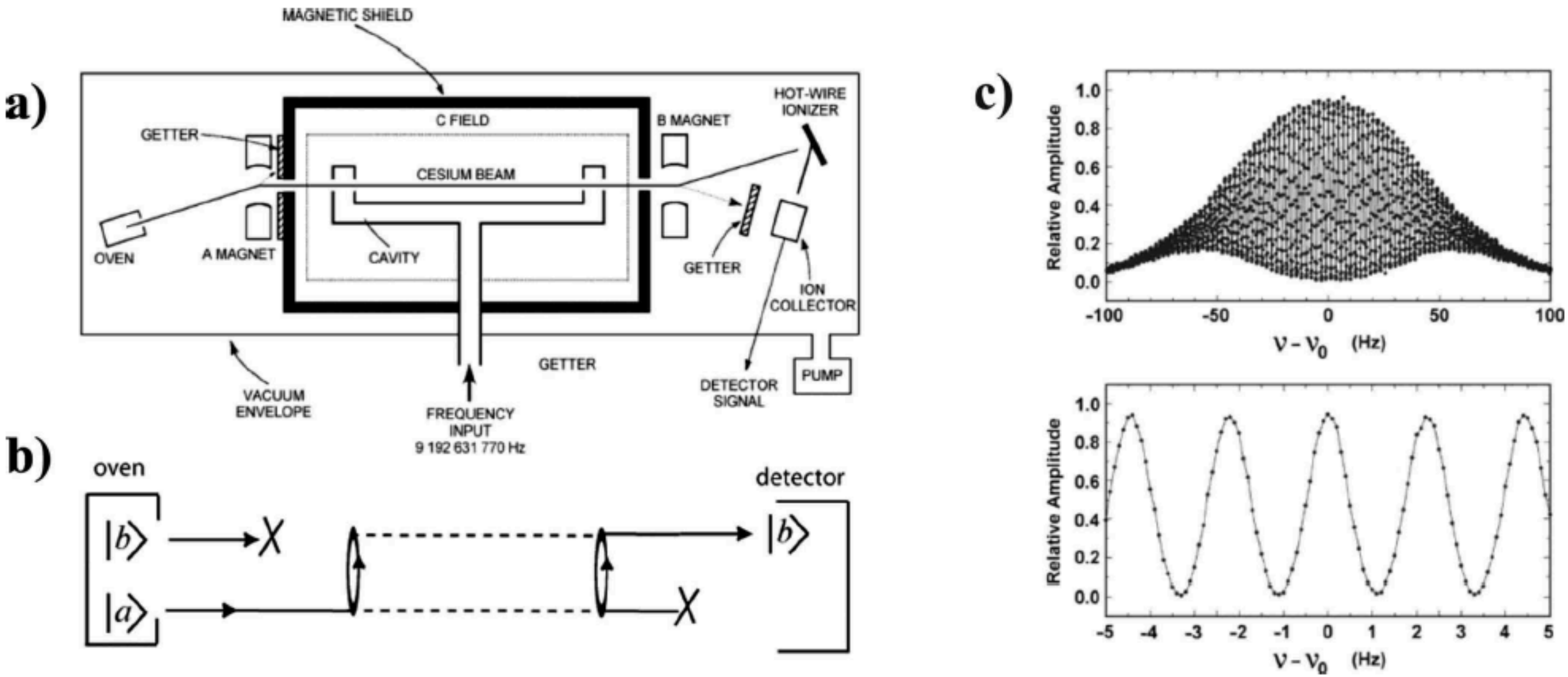
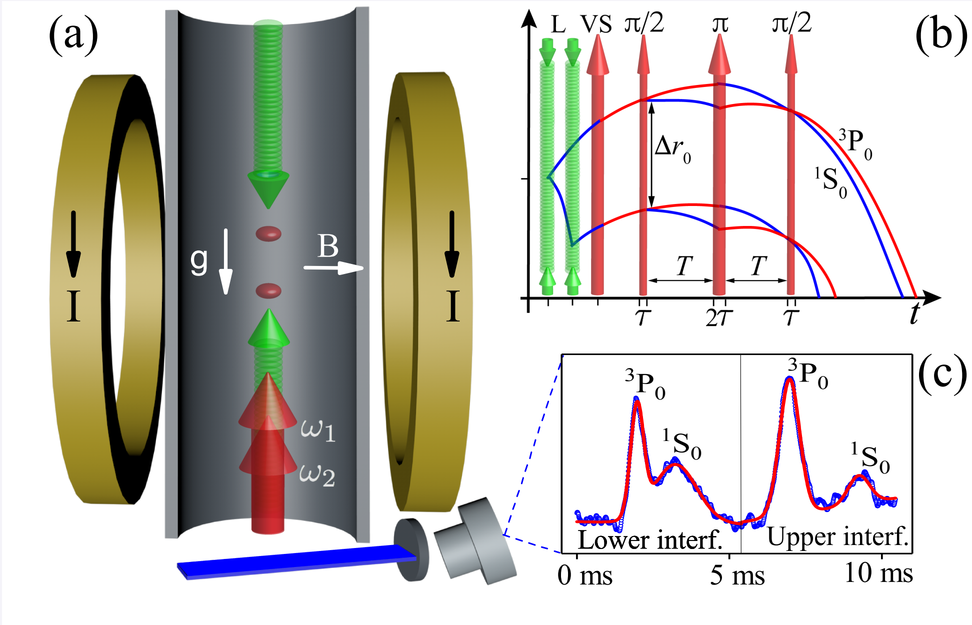
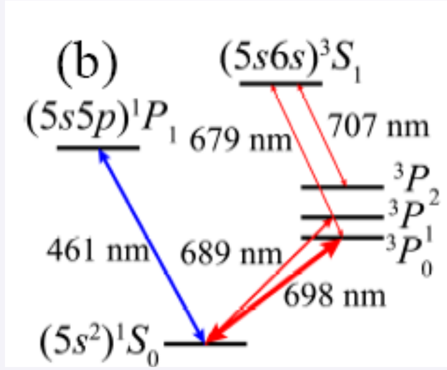


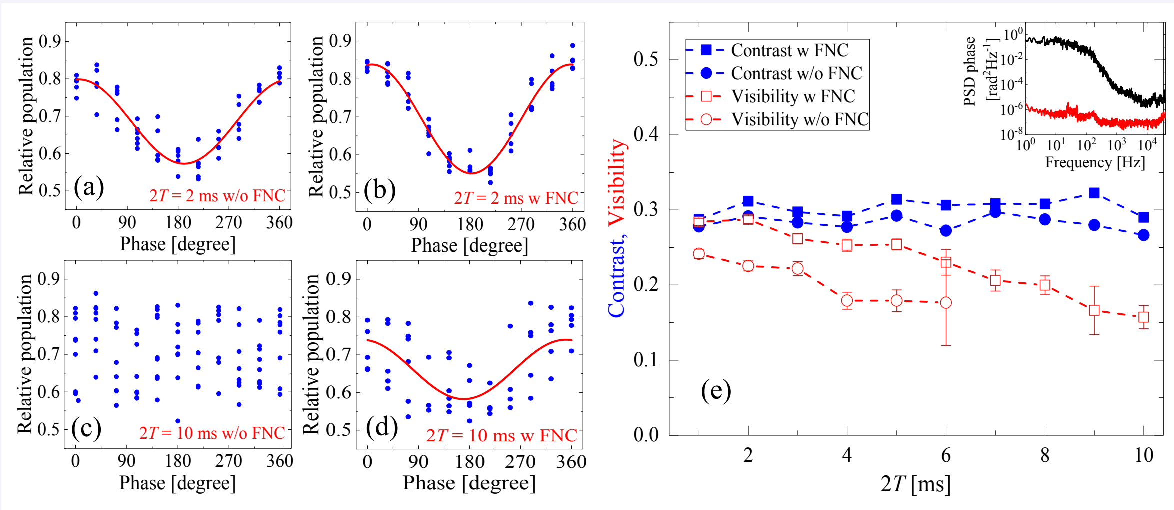
FIG. 1. Interferometry with internal quantum states of atoms. (a) Ramsey's separated oscillatory fields experiment. (b) The same experiment depicted as an interferometer for internal states. (c) The detected atom count rate exhibits interference fringes as a function of the applied rf frequency. These interference fringes, from the NIST-F1 fountain clock (Sullivan *et al.*, 2001), demonstrate the precision obtained with interference techniques. From Sullivan *et al.*, 2001.

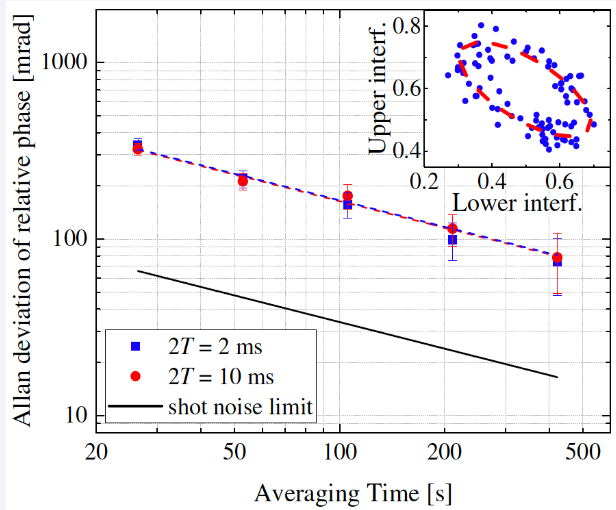
Atom interferometry with the Sr optical clock transition





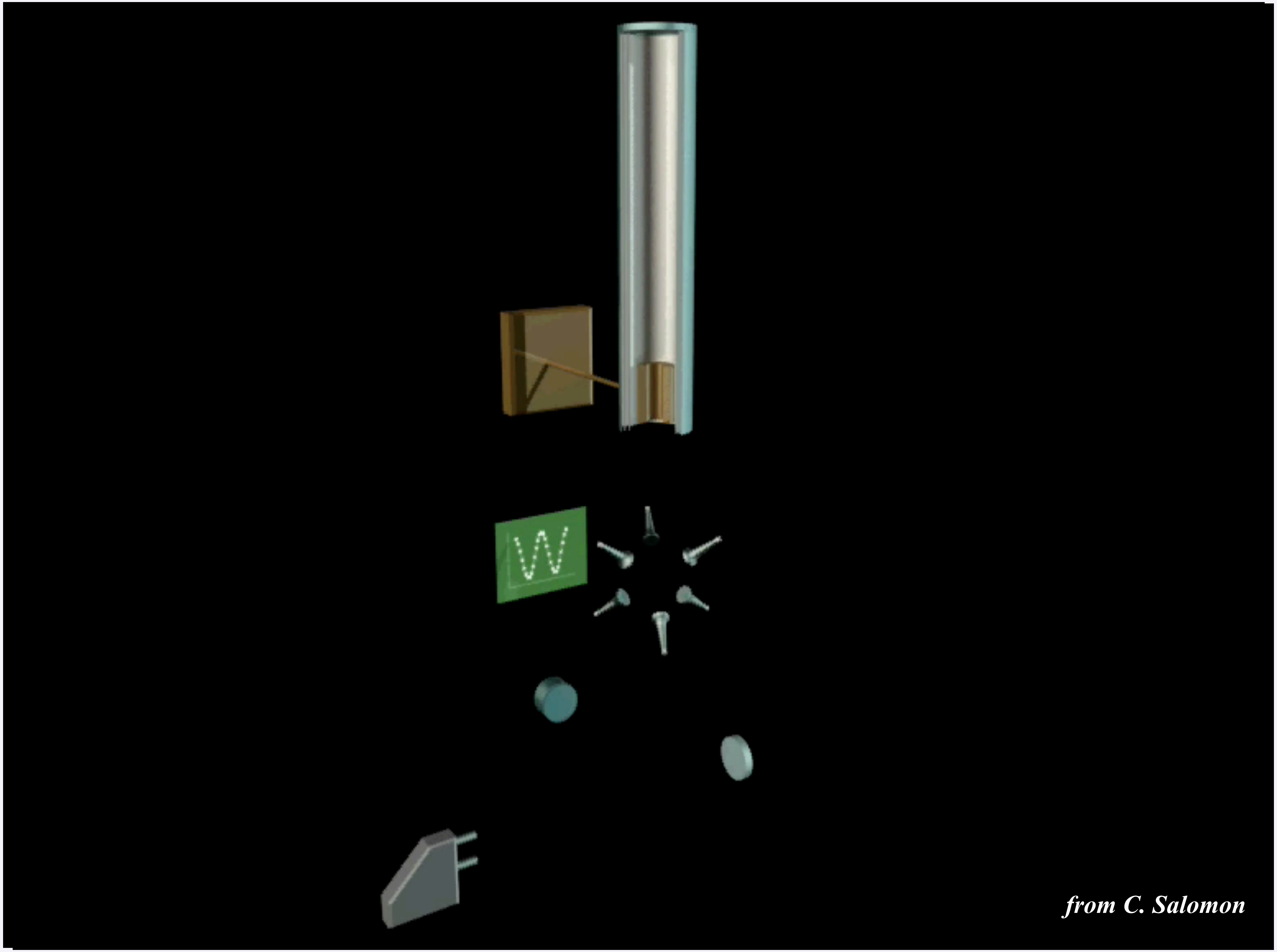
- ^{88}Sr isotope
- B=300 G -> Δν=20 μHz
- Rabi frequency Ω ~ 1kHz





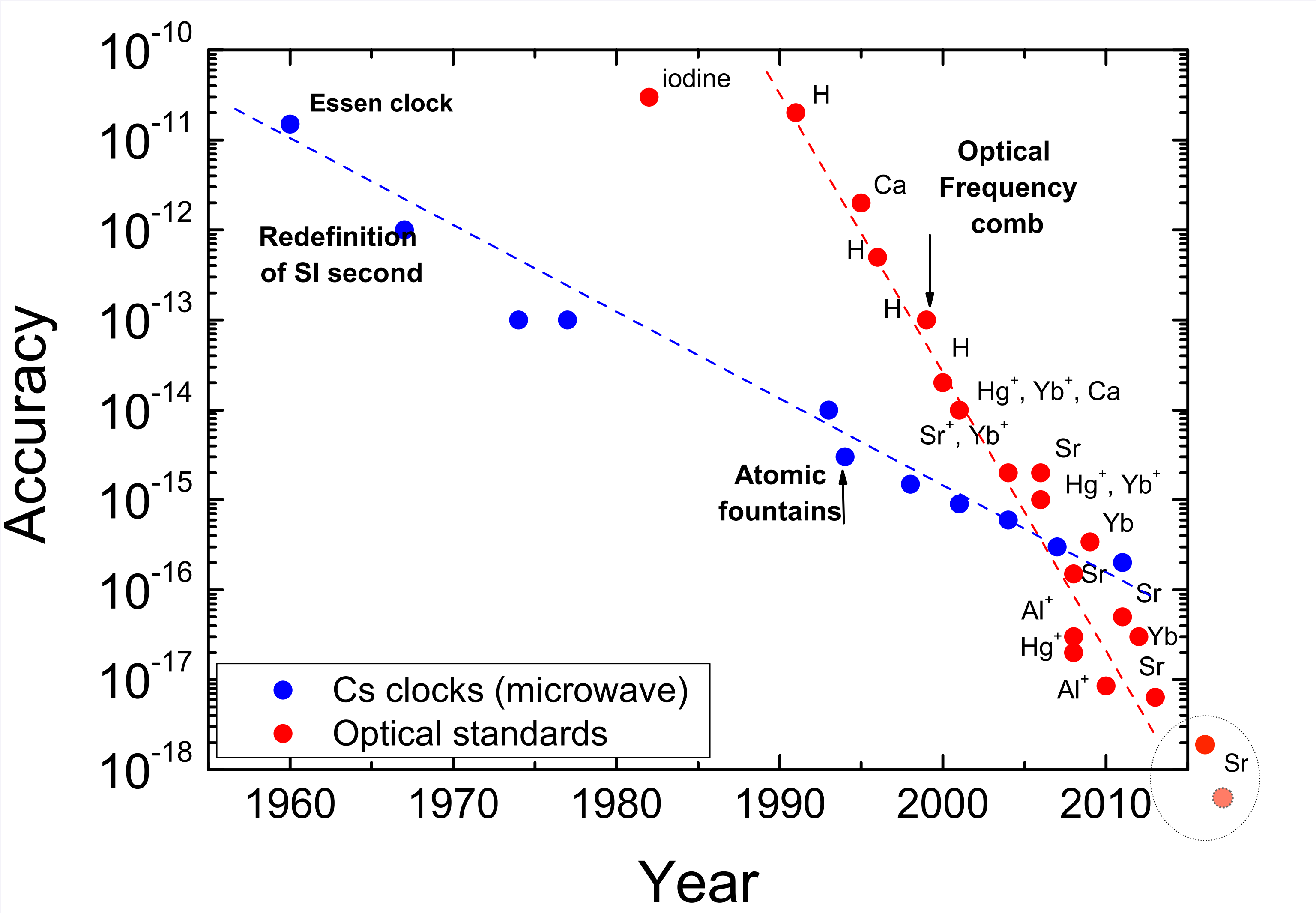
Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017)

Atomic fountain clock



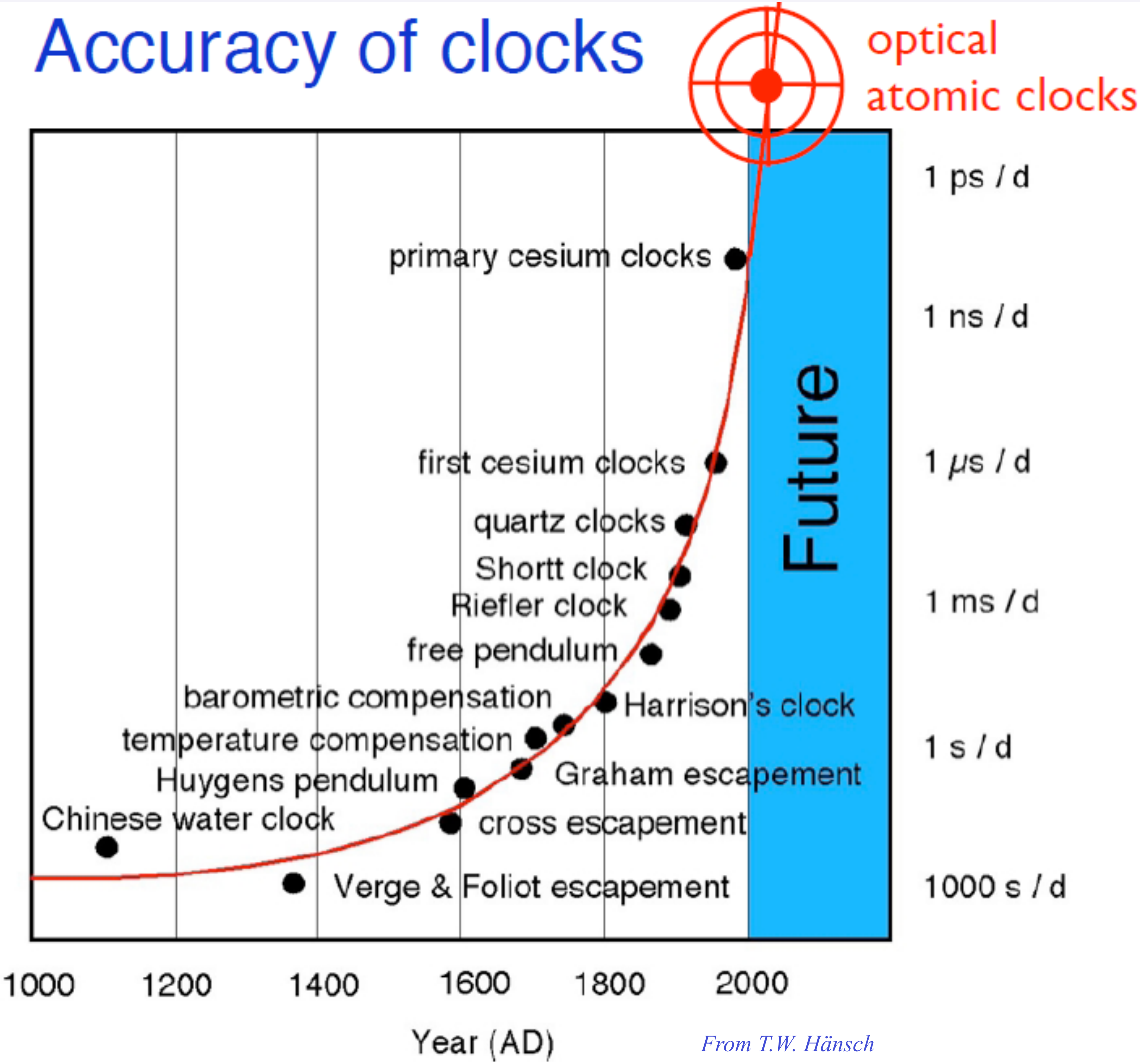
from C. Salomon

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)

Accuracy of clocks



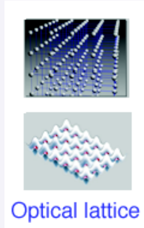
From T.W. Hänsch

Optical clocks: Towards 10^{-19}

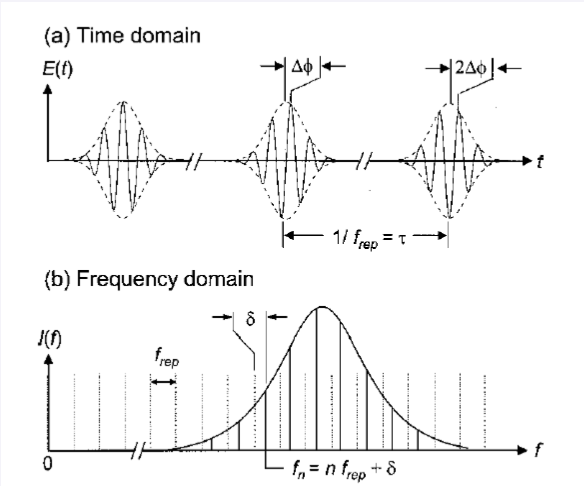
- **Narrow optical transitions**
  $\delta\nu_o \sim$ 1-100 Hz, $\nu_0 \sim 10^{14}$-10^{15} Hz

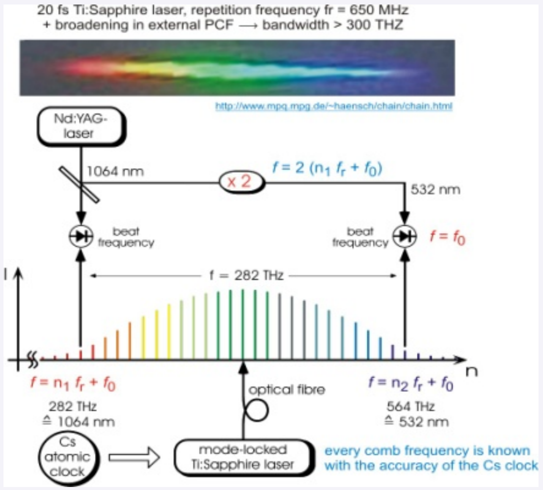
$$\sigma_y \simeq \frac{Noise}{\pi Q \bullet Signal} \simeq \frac{\Delta\nu}{\nu_0} \frac{1}{\sqrt{N_{atom}}} \sqrt{\frac{T_{\mathrm{cycle}}}{2\tau_{\mathrm{average}}}} \frac{1}{C_{\mathrm{fringe}}}$$

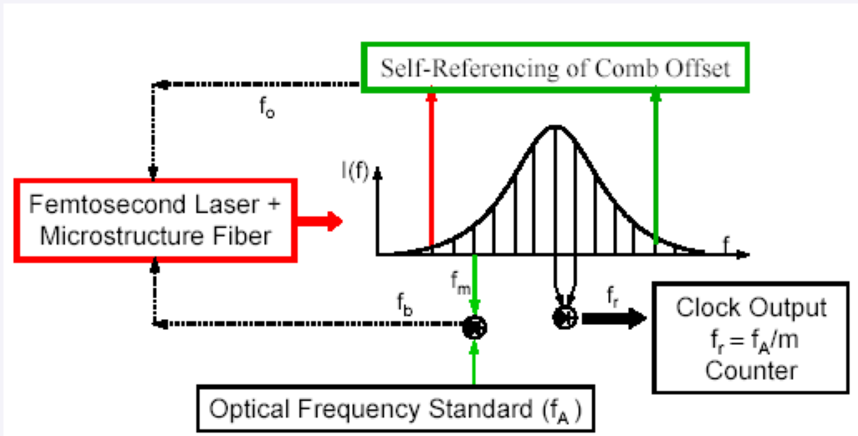
- **Candidate atoms**
  - **Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…**
  - **Cold neutral atoms: H, Ca, Sr, Yb,…**



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

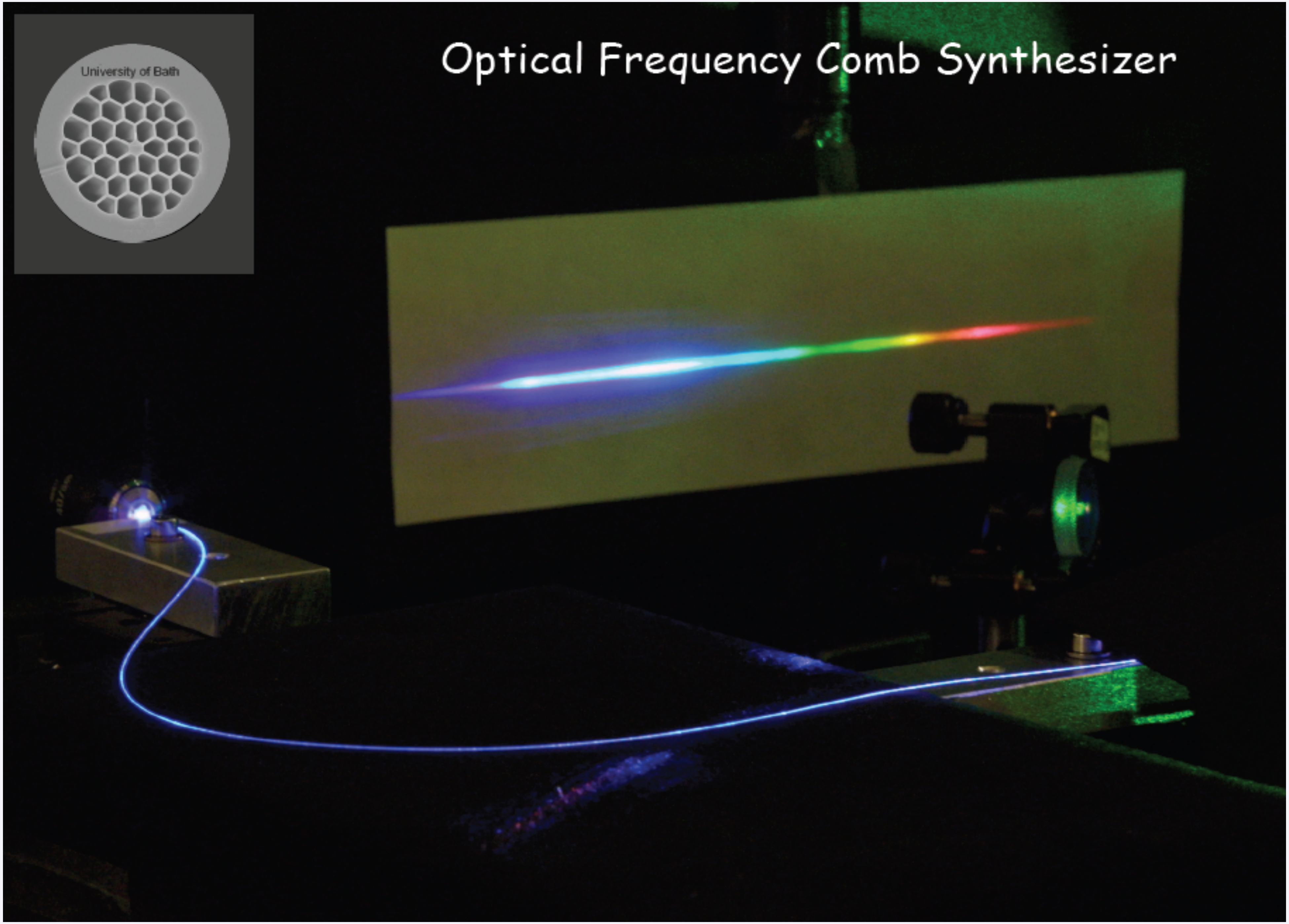






Th. Udem *et al.*, Nature 416 , 14 march 2002

N. Poli, C. W. Oates, P. Gill, G. M. Tino, *Optical Atomic Clocks*, La Rivista del Nuovo Cimento, 12, 555-624 (2013)



From T.W. Hänsch

The Nobel Prize in Physics 2005
Roy J. Glauber, John L. Hall, Theodor W. Hänsch

The Nobel Prize in Physics 2005

Nobel Prize Award Ceremony

Roy J. Glauber

John L. Hall

Theodor W. Hänsch

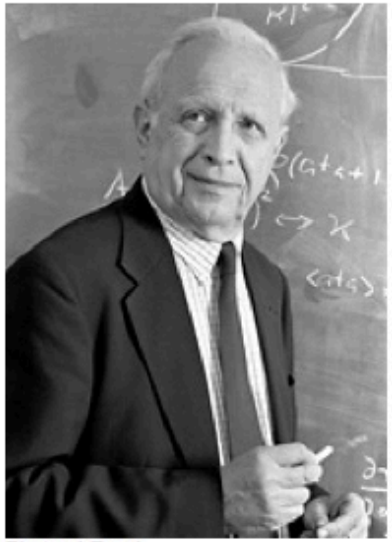


Photo: J.Reed

Roy J. Glauber


Photo: Sears.P.Studio

John L. Hall


Photo: F.M. Schmidt

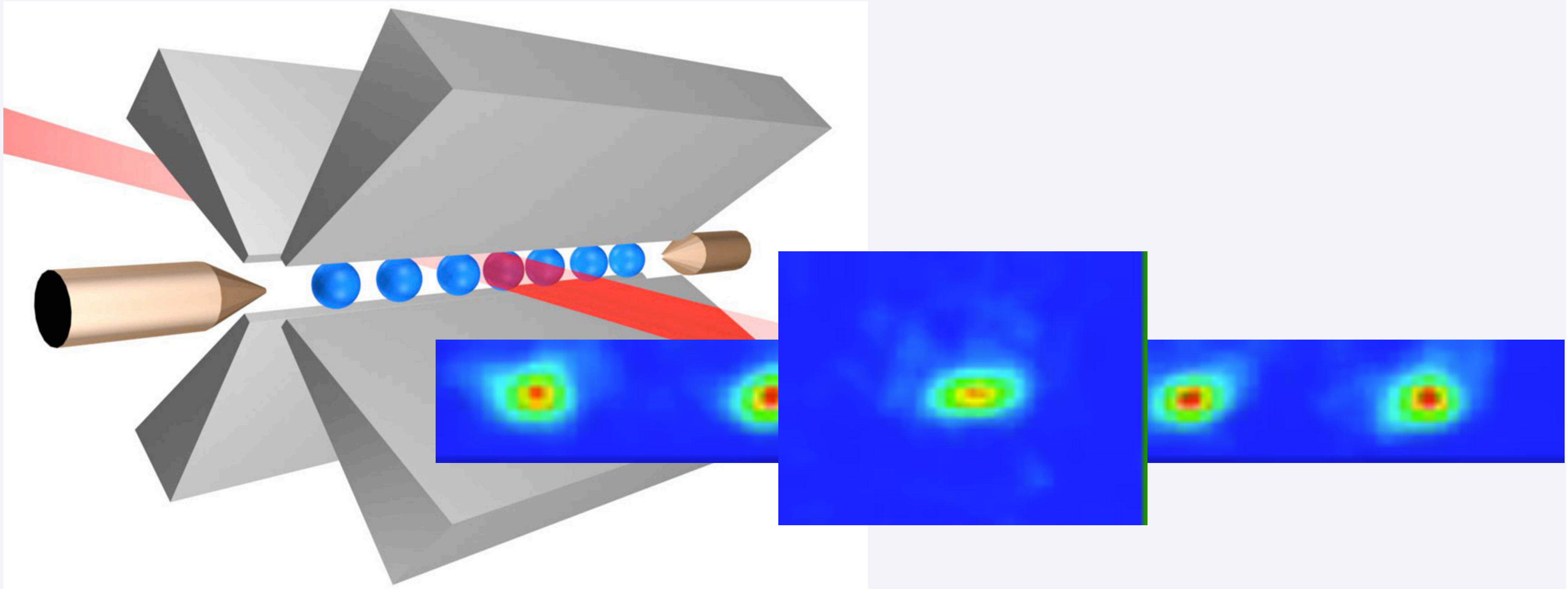
Theodor W. Hänsch

The Nobel Prize in Physics 2005 was divided, one half awarded to Roy J. Glauber *"for his contribution to the quantum theory of optical coherence"*, the other half jointly to John L. Hall and Theodor W. Hänsch *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*.

MLA style: "The Nobel Prize in Physics 2005". Nobelprize.org. 20 Oct 2012 http://www.nobelprize.org/nobel_prizes/physics/laureates/2005/

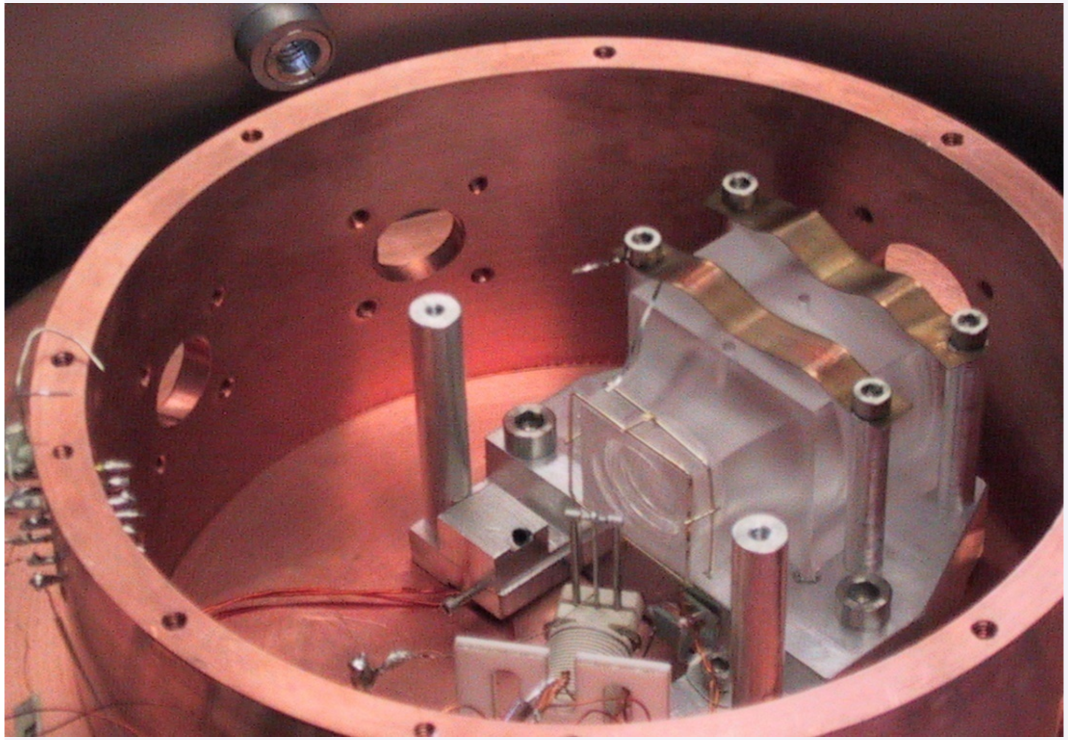
... The important contributions by John Hall and Theodor Hänsch have made it possible to measure frequencies with an accuracy of fifteen digits. Lasers with extremely sharp colours can now be constructed and with the frequency comb technique precise readings can be made of light of all colours. This technique makes it possible to carry out studies of, for example, the stability of the constants of nature over time and to develop extremely accurate clocks and improved GPS technology.

Trapped ions



From Michael Drewsen

Single ion Optical clock



Hg+, Al+, NIST (Bergquist et al.)

Yb+, PTB (Tamm, Peik...)

Other experiments: NPL : Yb^+, Sr^+, NRC : Sr^+,
MPQ : In^+…, Innsbruck: Ca+, ….

The Nobel Prize in Physics 2012
Serge Haroche, David J. Wineland

The Nobel Prize in Physics 2012

Serge Haroche

David J. Wineland

Photo: © CNRS Photothèque/Christophe Lebedinsky

Serge Haroche

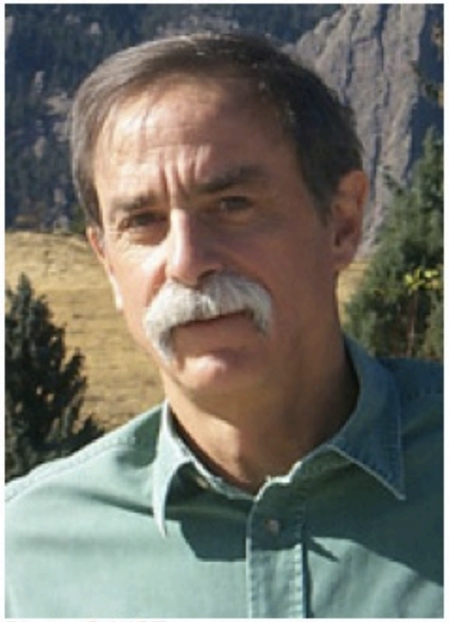


Photo: © NIST

David J. Wineland

MLA style: "The Nobel Prize in Physics 2012". Nobelprize.org.
20 Oct 2012 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/

The Nobel Prize in Physics 2012 was awarded jointly to Serge Haroche and David J. Wineland *"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"*

... Both Laureates work in the field of quantum optics studying the fundamental interaction between light and matter, a field which has seen considerable progress since the mid-1980s.

... The research has also ***led to the construction of extremely precise clocks*** *that could become the future basis for a new standard of time, with more than hundred-fold greater precision than present-day caesium clocks.*

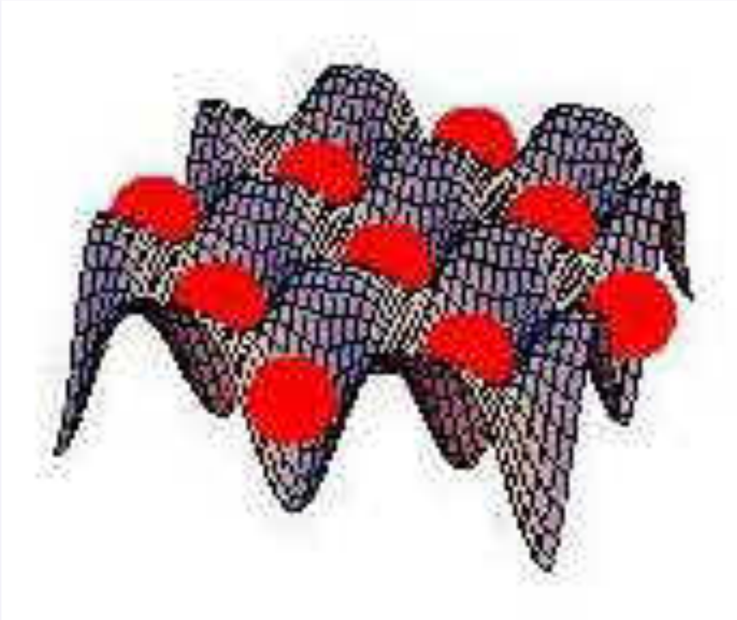
Sr optical clock

- **Method:**

Interrogate atoms in optical lattice without frequency shift

- Long interaction time
- Large atom number (10^8)
- Lamb-Dicke regime

Excellent frequency stability



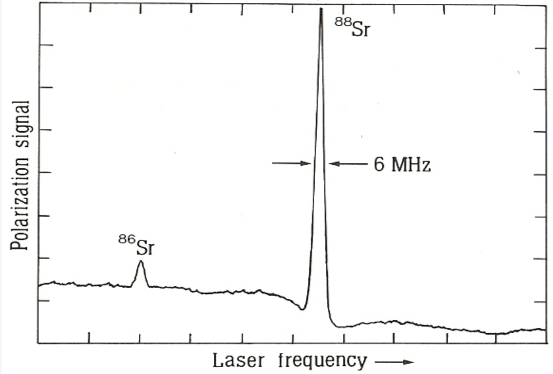
- Small frequency shifts:
  - No collisions (fermion)
  - No recoil effect (confinement below optical wavelength)
  - Small Zeeman shifts (only nuclear magnetic moments)…

Under development:

Sr (Tokyo, JILA, PTB, SYRTE, Firenze)

1992

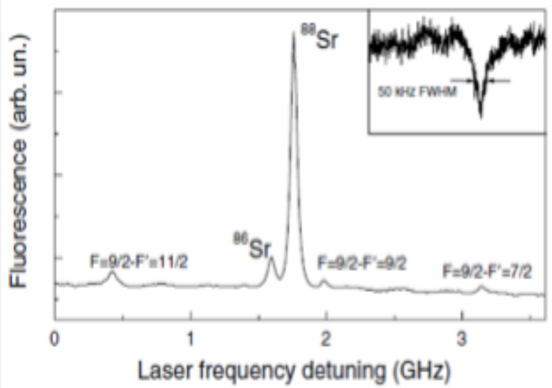
sub-Doppler laser spectroscopy
of Sr in a hollow cathode discharge
0 -> 1 intercombination line



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

2003

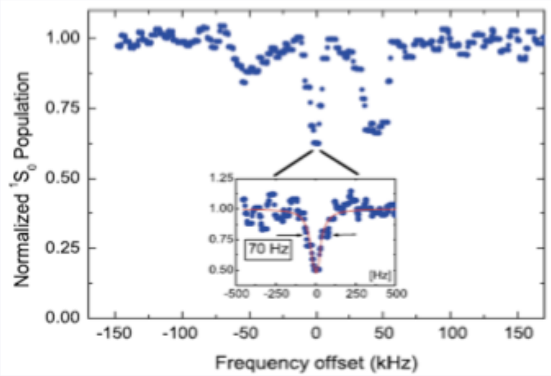
saturation spectroscopy
of Sr in a thermal atomic beam
0 -> 1 intercombination line



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

2009

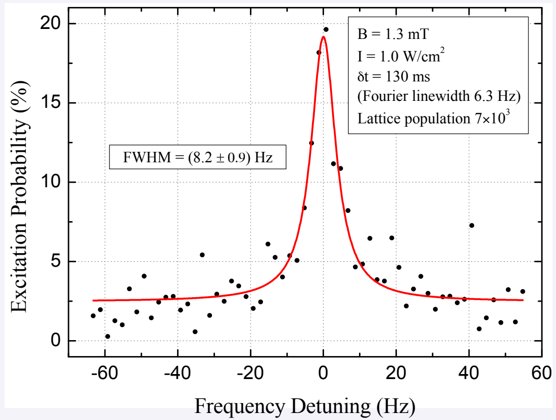
Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line



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

2012

Magnetic field induced spectroscopy
of cold Sr atoms in an optical lattice
0 -> 0 intercombination line



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

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

UNIVERSITÀ DEGLI STUDI FIRENZE · Lens European Laboratory for Non-Linear Spectroscopy · INFN

nature photonics

PUBLISHED ONLINE: 9 FEBRUARY 2015

Cryogenic optical lattice clocks

Ichiro Ushijima[1,2,3†], Masao Takamoto[1,2,4†], Manoj Das[1,2,4], Takuya Ohkubo[1,2,3]
and Hidetoshi Katori[1,2,3,4*]

The accuracy of atomic clocks relies on the superb reproducibility of atomic spectroscopy, which is accomplished by careful control and the elimination of environmental perturbations on atoms. To date, individual atomic clocks have achieved a 10^{-18} level of total uncertainties[1,2], but a two-clock comparison at the 10^{-18} level has yet to be demonstrated. Here, we demonstrate optical lattice clocks with ^{87}Sr atoms interrogated in a cryogenic environment to address the blackbody radiat... induced frequency sh...

larger susceptibility[7] than Al... clock, requiring deep-ultravio... and demonstrated[24] because ... Generally, atoms easily acces... lasers tend to show higher su... relatively large static polariza... celled out coincidentally. P...

nature COMMUNICATIONS

ARTICLE

Received 14 Jan 2015 | Accepted 11 Mar 2015 | Published 21 Apr 2015

DOI: 10.1038/ncomms7896 OPEN

Systematic evaluation of an atomic clock at 2×10^{-18} total uncertainty

T.L. Nicholson[1,2], S.L. Campbell[1,2], R.B. Hutson[1,2], G.E. Marti[1,2], B.J. Bloom[1,2,†], R.L. McNally[1,2], W. Z...
M.D. Barrett[1,3], M.S. Safronova[4,5], G.F. Strouse[6], W.L. Tew[6] & J. Ye[1,2]

The pursuit of better atomic clocks has advanced many research areas, providing better quantum state control, new insights in quantum science, tighter limits on fundamental constant variation and improved tests of relativity. The record for the best stability and accuracy is currently held by optical lattice clocks. Here we take an important step towards realizing the full potential of a many-particle clock with a state-of-the-art stable laser. Our ^{87}Sr optical lattice clock now achieves fractional stability of 2.2×10^{-16} at 1 s. With this improved stability, we perform a new accuracy evaluation of our clock, reducing many systematic uncertainties that limited our previous measurements, such as those in the lattice ac Stark shift, the atoms' thermal environment and the atomic response to room-temperature blackbody radiation. Our combined measurements have reduced the total uncertainty of the JILA Sr clock to 2.1×10^{-18} in fractional frequency units.

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Current Issue > Research Highlights > Article

NATURE | RESEARCH HIGHLIGHTS

METROLOGY

Atomic clock smashes records

Nature **520**, 589 (30 April 2015) | doi:10.1038/520589a
Published online 29 April 2015

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Subject terms: Physics

The world's best atomic clock has become even more accurate, neither gaining nor losing a second over 15 billion years — longer than the age of the Universe.

The clock keeps time using 2,000 ultracold strontium atoms trapped in a laser lattice. Its pendulum is a laser that has a frequency tuned to resonate with that of the photons that are released and absorbed by the atoms as they switch between two energy states. By using a more stable laser and by reducing the effects of environmental perturbations, Jun Ye at the JILA institute in Boulder, Colorado, and his team made the 'ticks' of the timepiece more uniform. This increased the clock's accuracy by three times compared with the previous record.

The result brings strontium-based optical clocks closer to replacing the current standard for time measurement, the caesium fountain clock, which makes lower-frequency atomic transitions.

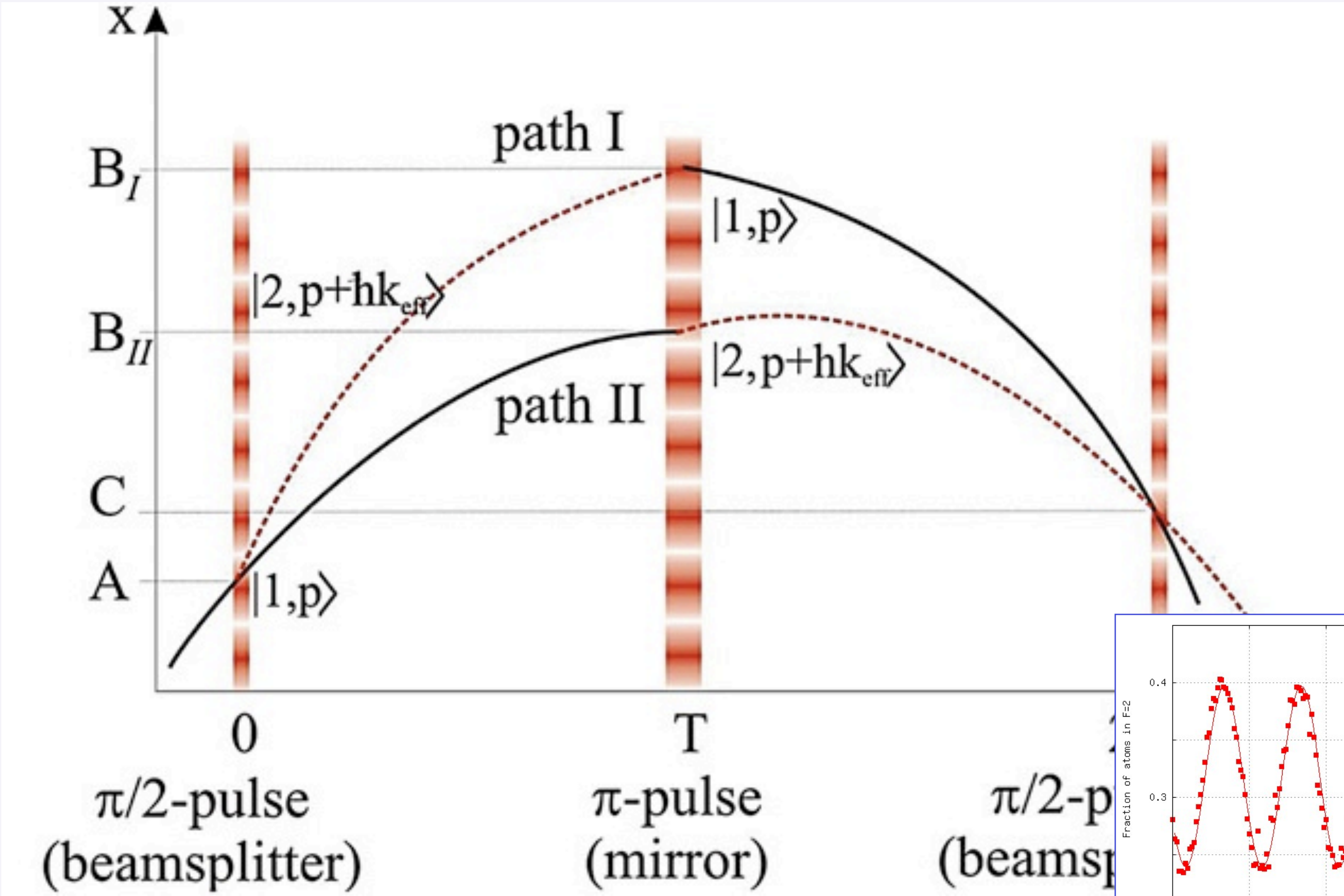
Nature Commun. **6**, 6896 (2015)

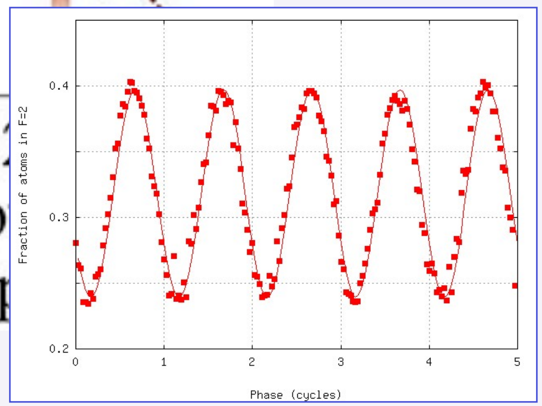
Testing gravity with atom interferometers

Why atoms?

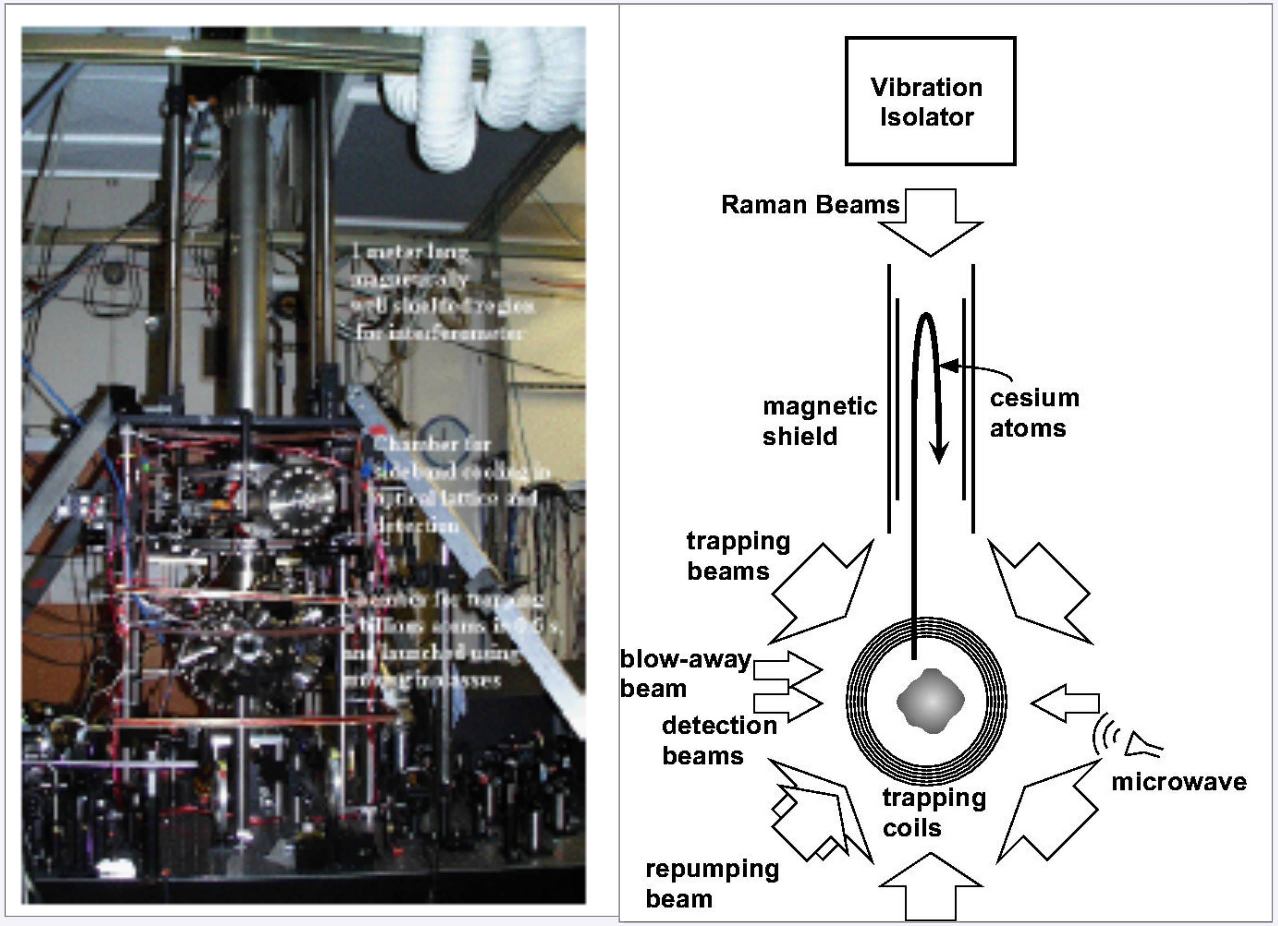
- Extremely small size
- Well known and reproducible properties
- Quantum systems
- Precision gravity measurement by atom interferometry
- Potential immunity from stray fields effects
- Different states, isotopes,…

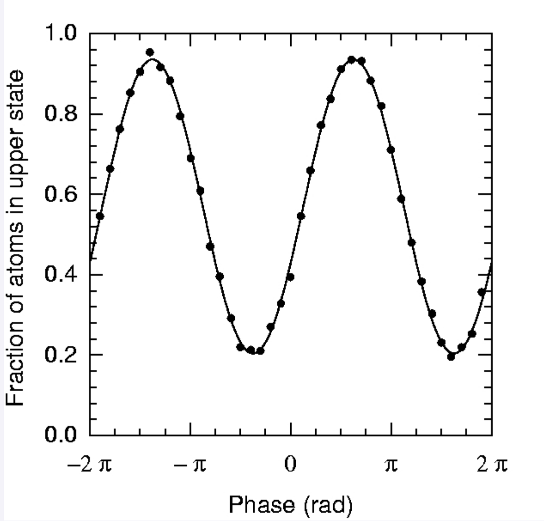
Atom interferometry and gravity

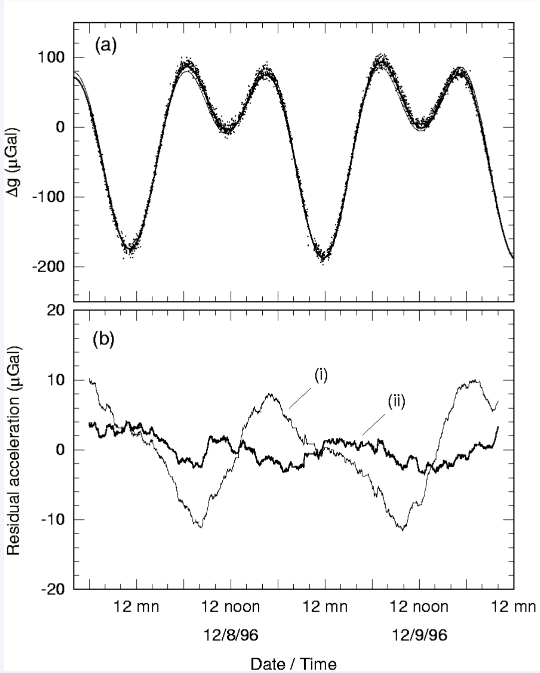




Stanford atom gravimeter







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

Absolute accuracy: $\Delta g/g<3\times10^{-9}$

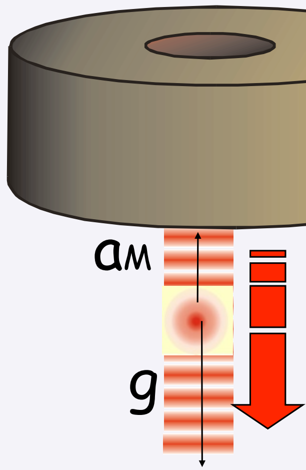
A. Peters, K.Y. Chung and S. Chu, *Measurement of gravitational acceleration by dropping atoms*, Nature **400**, 849 (1999)

Measuring G with atom interferometers

MAGIA

(MISURA ACCURATA di G MEDIANTE INTERFEROMETRIA ATOMICA)

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

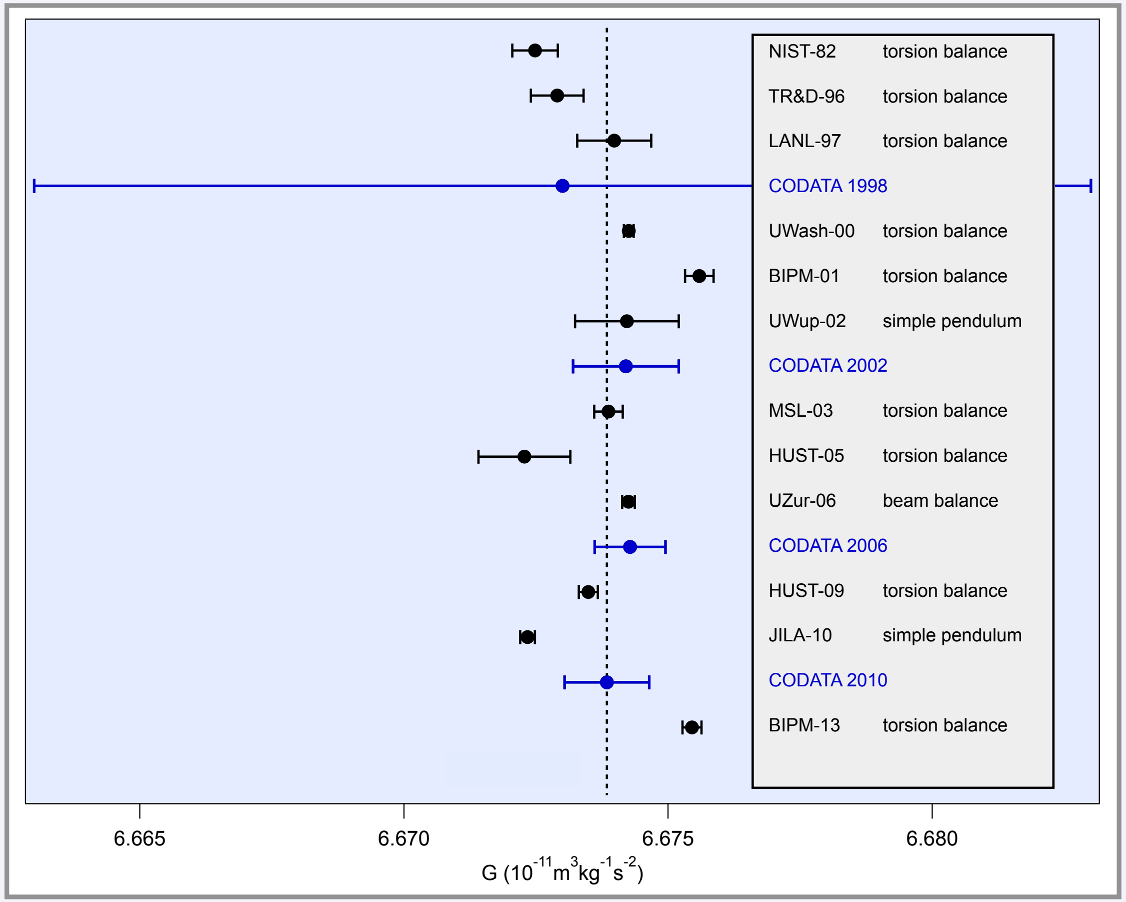


➤ ***Precision measurement of G***

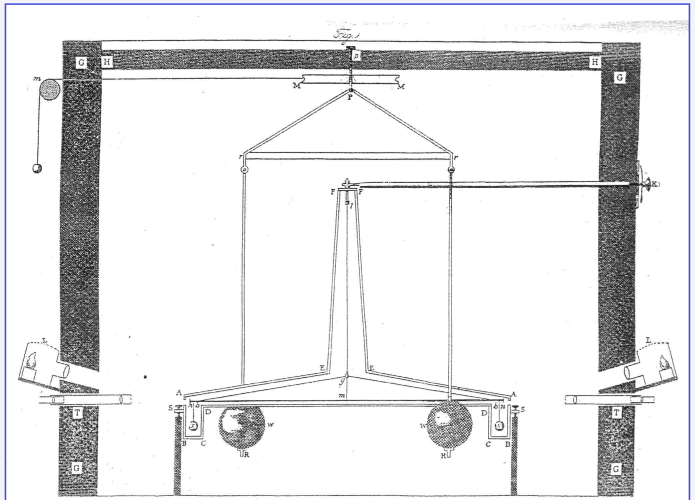
$$F(r) = G\frac{M_1 M_2}{r^2}$$

Measurements of the Newtonian gravitational constant G

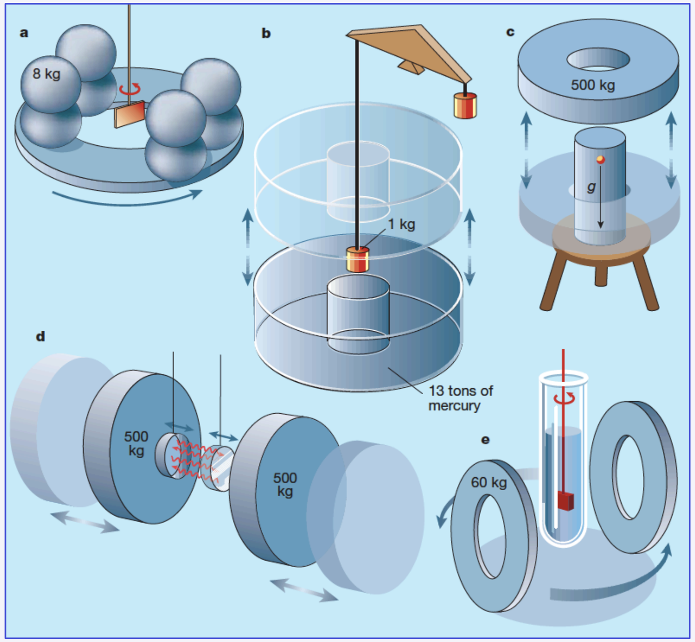
$$F(r) = G\frac{M_1 M_2}{r^2}$$



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)

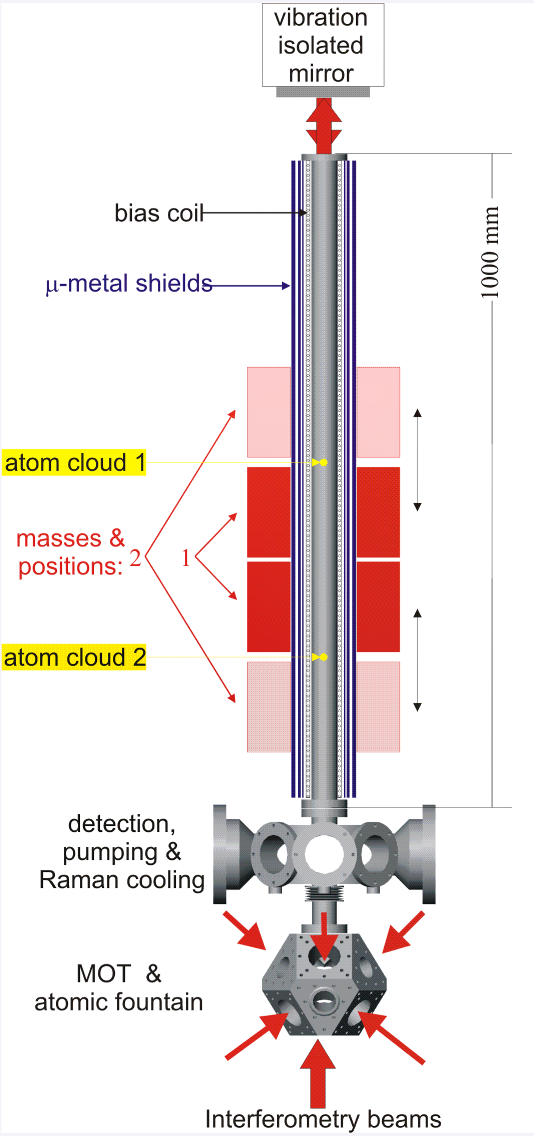


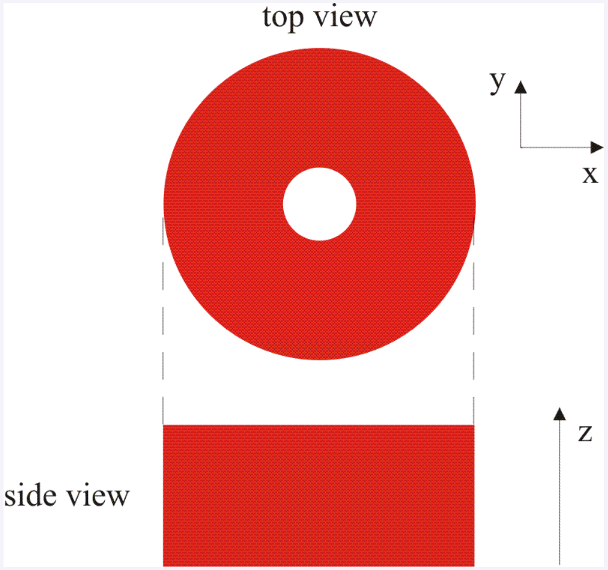
Cavendish, 1798

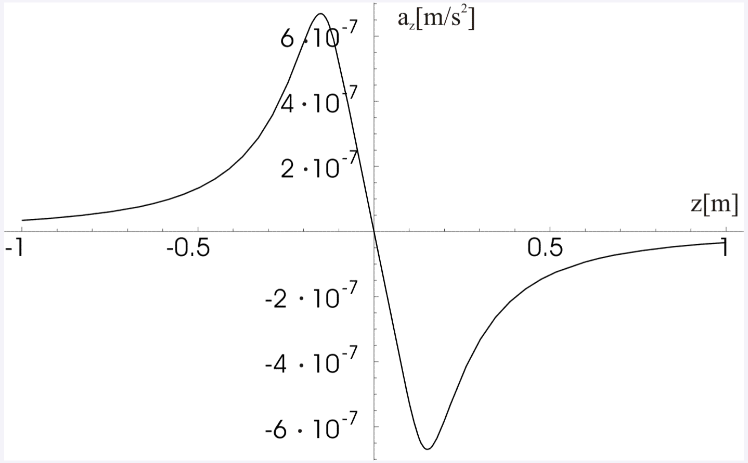


Terry Quinn. *Measuring big G*, NATURE, 408, 919 (2000)

MAGIA
Rb gravity gradiometer + source mass







500 kg tungsten mass

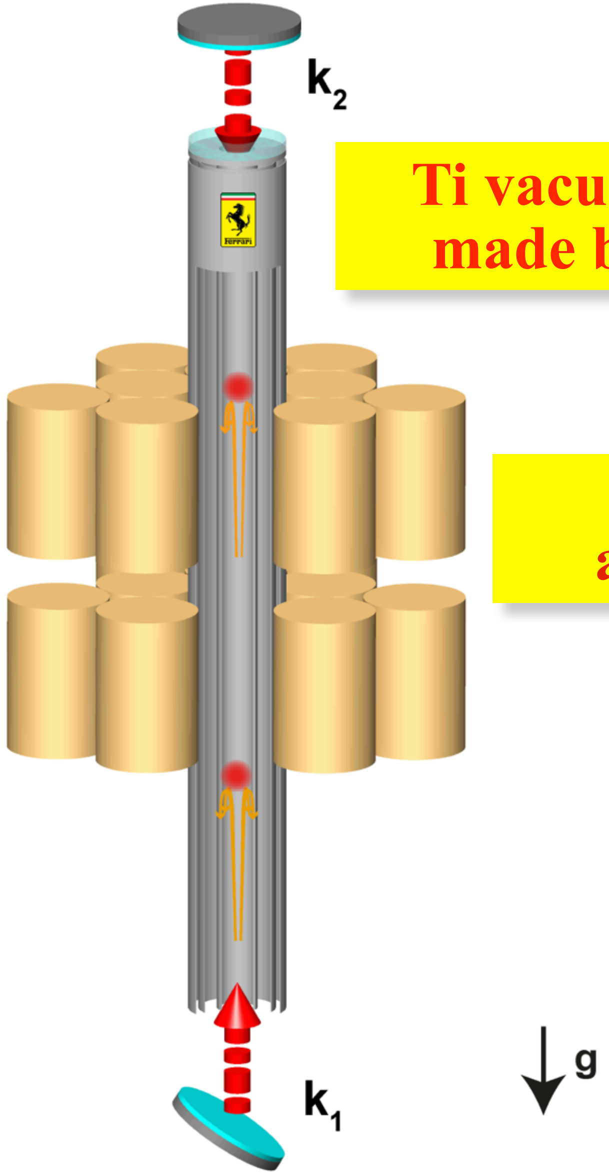
Sensitivity 10^{-9}g/shot

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

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

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

MAGIA: The dream



Ti vacuum system made by Ferrari

1 ton of gold as source mass

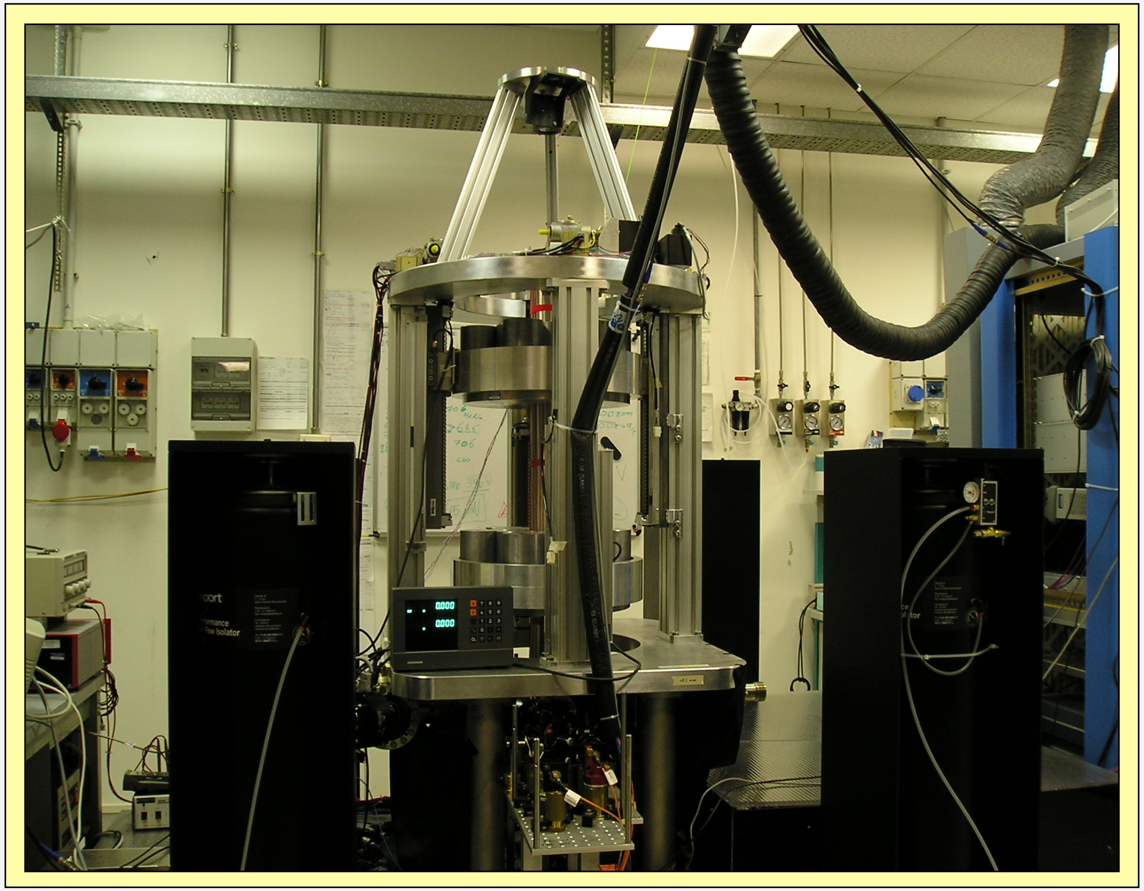
MAGIA apparatus

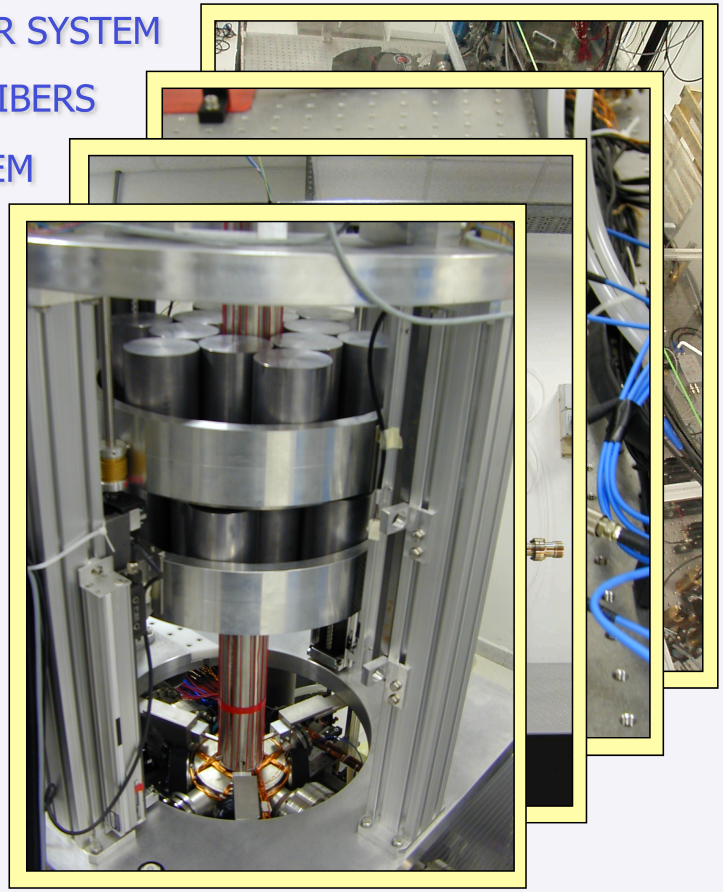
Manipulate ^{87}Rb atoms → LASER SYSTEM

Transport light → OPTICAL FIBERS

Long interaction times → Ti VACUUM SYSTEM

Gravitational field → W SOURCE MASSES

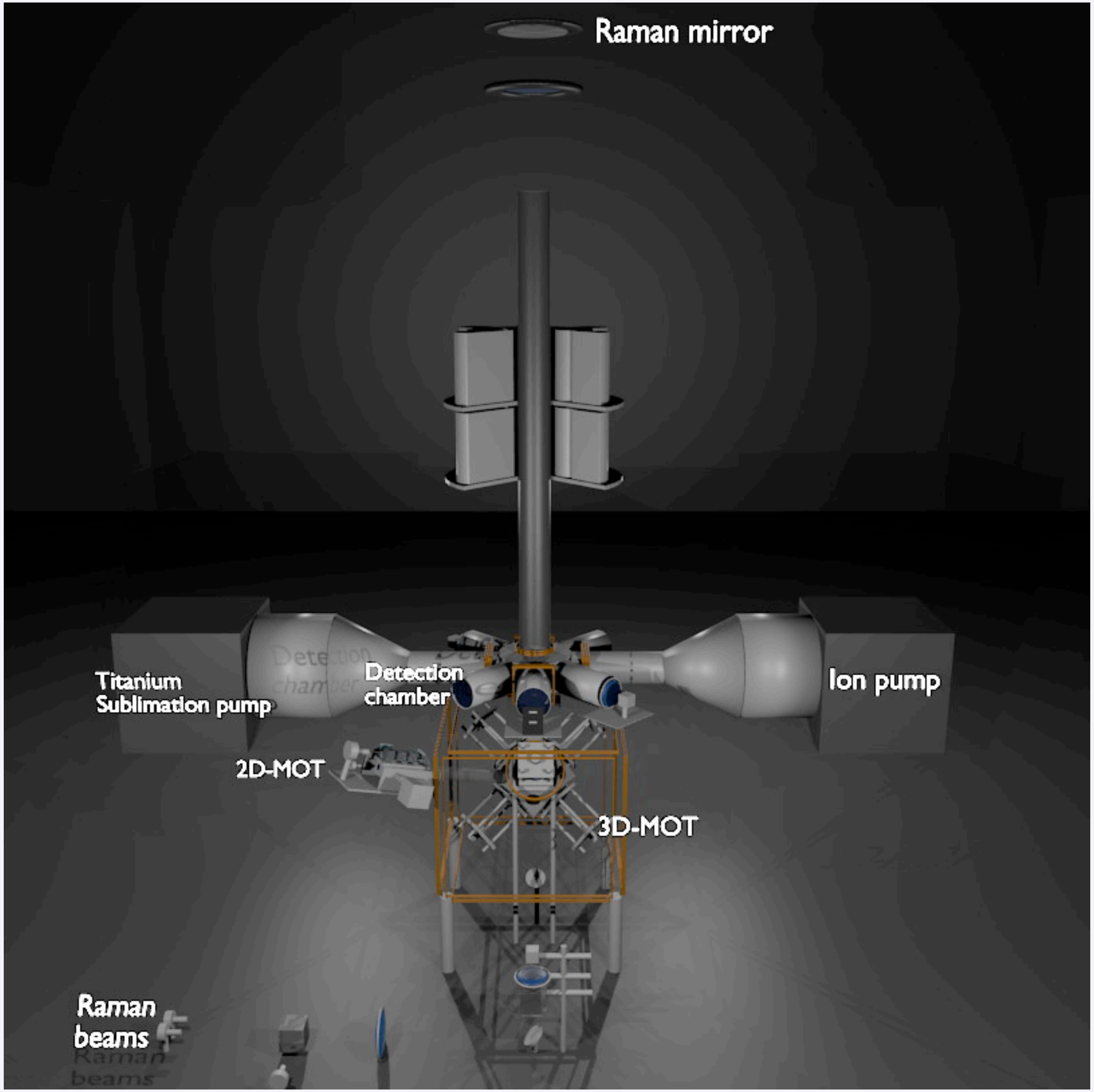




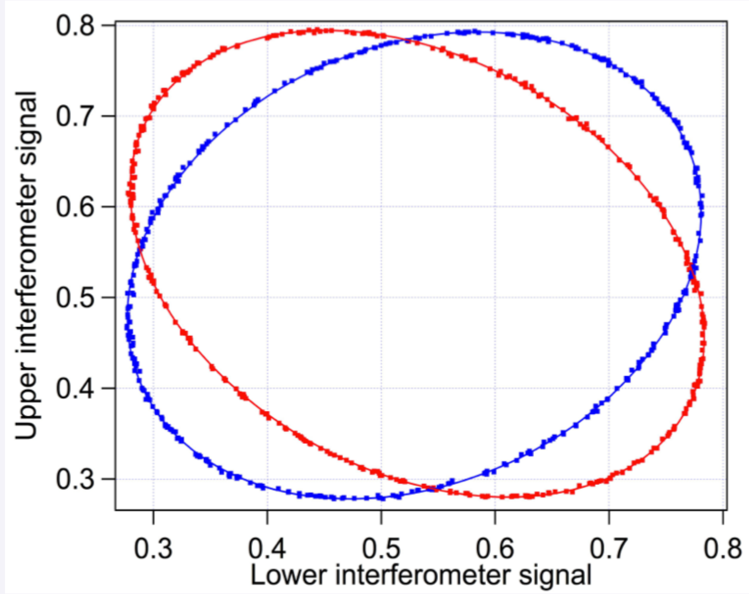
L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* **Rev. Scient. Instr. 76, 053111 (2005)**

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

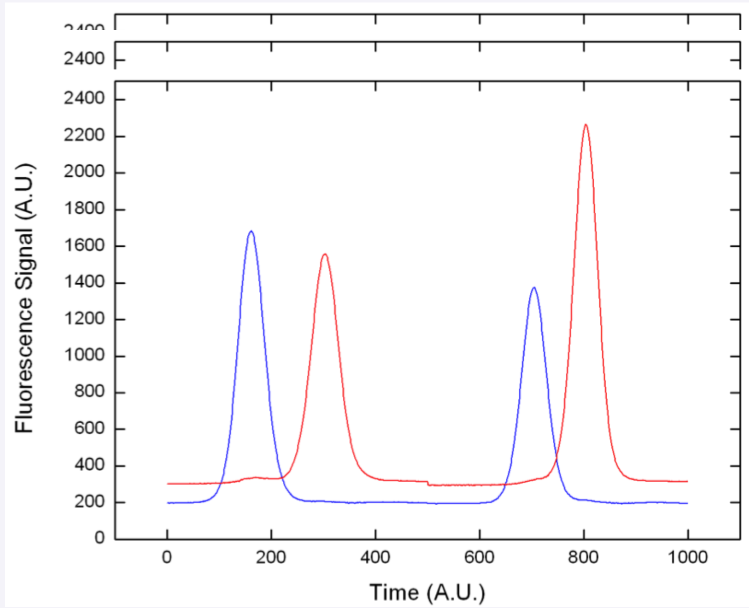
MAGIA



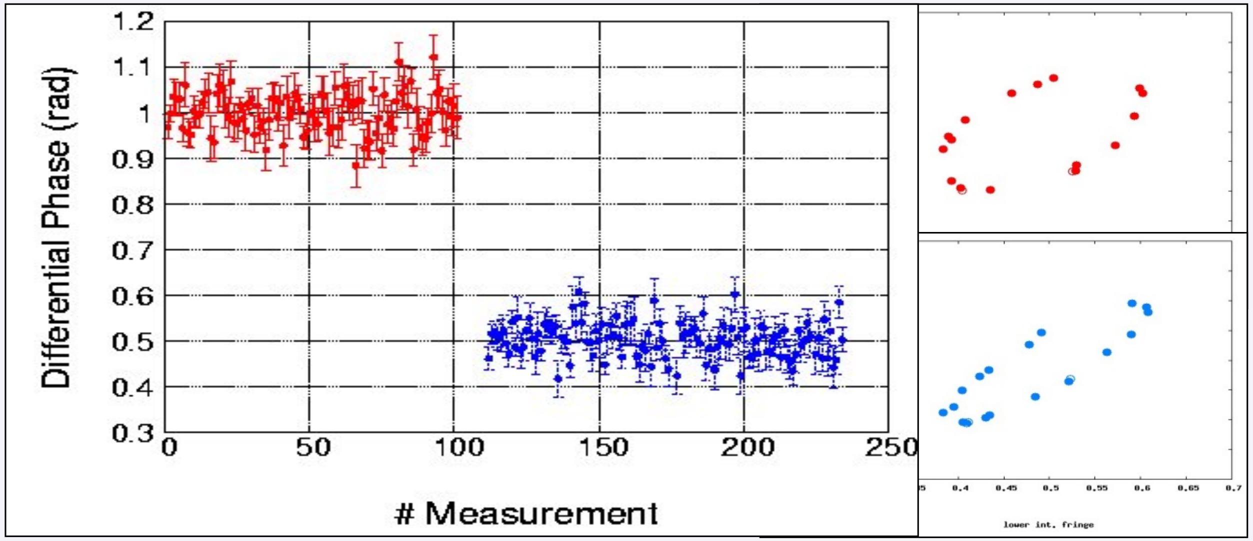
Raman mirror
Titanium Sublimation pump
Detection chamber
Ion pump
2D-MOT
3D-MOT
Raman beams



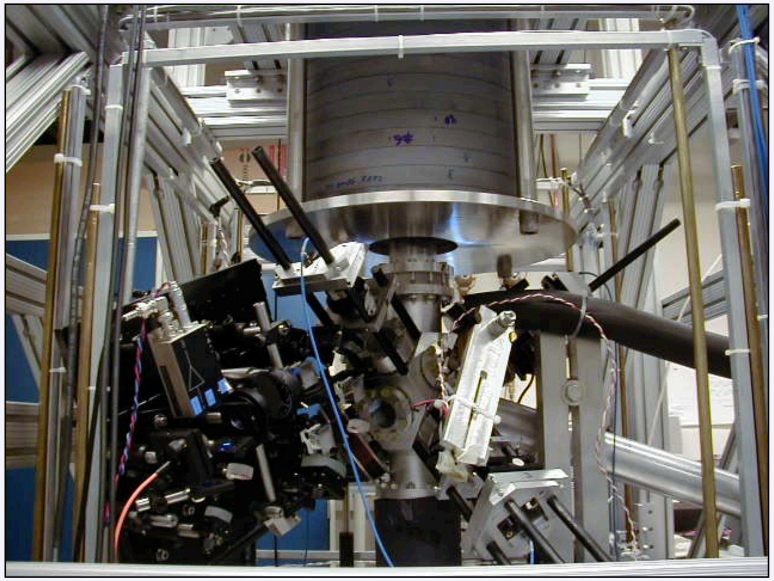
Upper interferometer signal
Lower interferometer signal
0.3
0.4
0.5
0.6
0.7
0.8

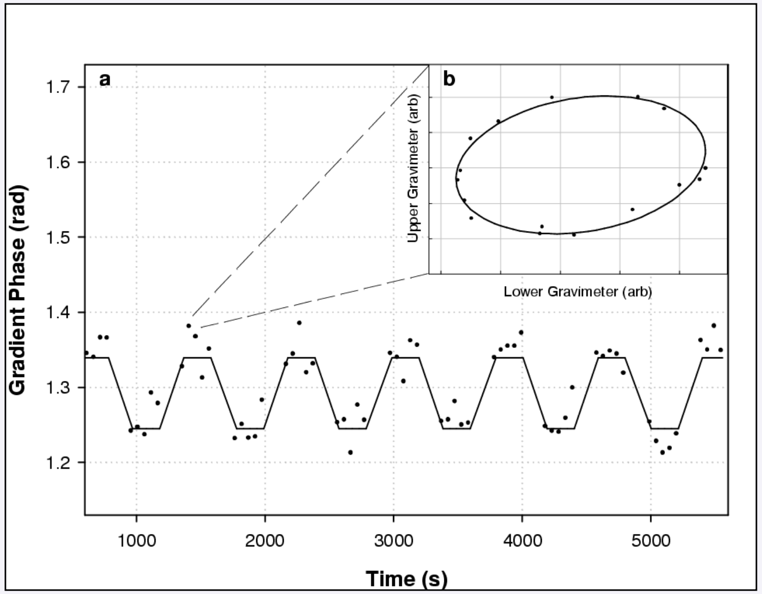


Fluorescence Signal (A.U.)
Time (A.U.)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400



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





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

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

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

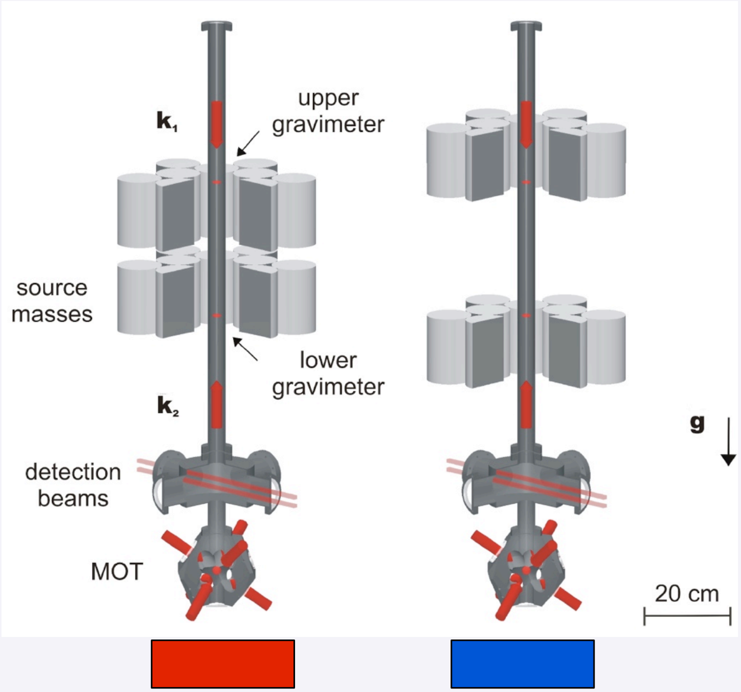
MAGIA apparatus

Cavendish 1798: "The apparatus is very simple"

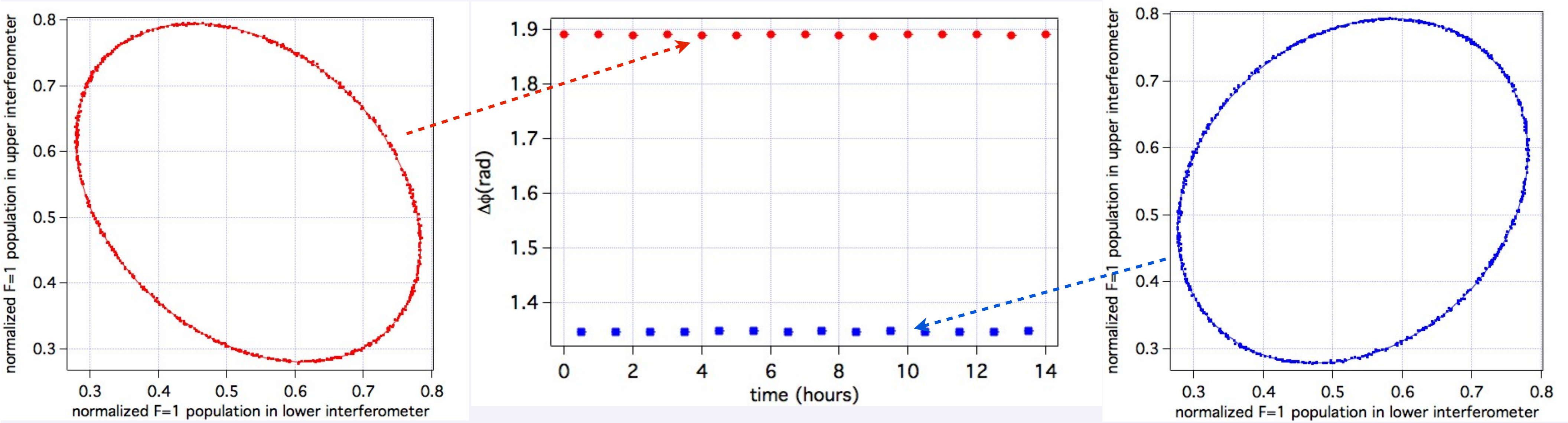
MAGIA apparatus is not very simple

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

MAGIA: Final sensitivity



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



LETTER

doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

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

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

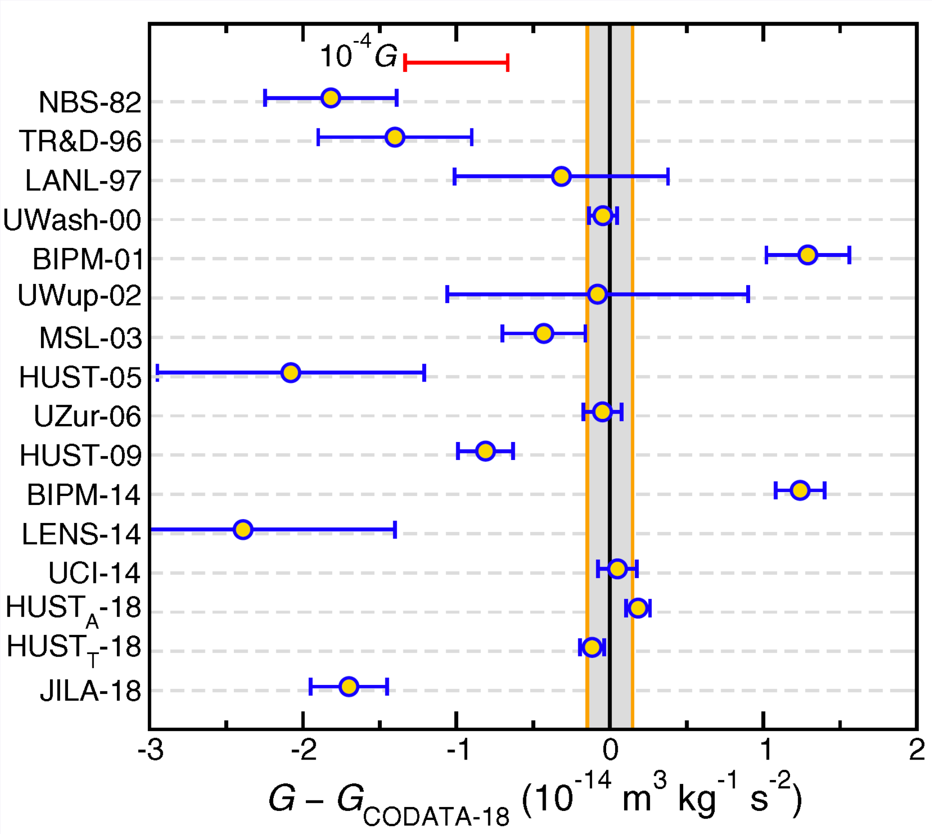
the relevant gravitational signal. An additional cancellation of common-mode spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer[18]. Efforts were devoted to the control of systematics related to atomic trajectories, 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)



Source	Identification	Method	$G(10^{-11}\ \mathrm{kg}^{-1} \times \mathrm{m}^3\ \mathrm{s}^{-2})$	Rel. stand. uncert. u_r
Luther and Towler (1982)	NIST-82	Fiber torsion balance, dynamic mode	6.672 48(43)	6.4×10^{-5}
Karagioz and Izmailov (1996)	TR&D-96	Fiber torsion balance, dynamic mode	6.672 9(5)	7.5×10^{-5}
Bagley and Luther (1997)	LANL-97	Fiber torsion balance, dynamic mode	6.673 98(70)	1.0×10^{-4}
Gundlach and Merkowitz (2000, 2002)	UWash-00	Fiber torsion balance, dynamic compensation	6.674 255(92)	1.4×10^{-5}
Quinn *et al.* (2001)	BIPM-01	Strip torsion balance, compensation mode, static deflection	6.675 59(27)	4.0×10^{-5}
Kleinevoß (2002) and Kleinevoß *et al.* (2002)	UWup-02	Suspended body, displacement	6.674 22(98)	1.5×10^{-4}
Armstrong and Fitzgerald (2003)	MSL-03	Strip torsion balance, compensation mode	6.673 87(27)	4.0×10^{-5}
Hu, Guo, and Luo (2005)	HUST-05	Fiber torsion balance, dynamic mode	6.672 22(87)	1.3×10^{-4}
Schlamminger *et al.* (2006)	UZur-06	Stationary body, weight change	6.674 25(12)	1.9×10^{-5}
Luo *et al.* (2009) and Tu *et al.* (2010)	HUST-09	Fiber torsion balance, dynamic mode	6.673 49(18)	2.7×10^{-5}
Quinn *et al.* (2013, 2014)	BIPM-14	Strip torsion balance, compensation mode, static deflection	6.675 54(16)	2.4×10^{-5}
Prevedelli *et al.* (2014) and Rosi *et al.* (2014)	LENS-14	Double atom interferometer, gravity gradiometer	6.671 91(99)	1.5×10^{-4}
Newman *et al.* (2014)	UCI-14	Cryogenic torsion balance, dynamic mode	6.674 35(13)	1.9×10^{-5}
Li *et al.* (2018)	$HUST_T$-18	Fiber torsion balance, dynamic mode	6.674 184(78)	1.2×10^{-5}
Li *et al.* (2018)	$HUST_A$-18	Fiber torsion balance, dynamic compensation	6.674 484(77)	1.2×10^{-5}
Parks and Faller (2019)	JILA-18	Suspended body, displacement	6.672 60(25)	3.7×10^{-5}

CODATA 2018

$\boldsymbol{G = 6.67430(15)\times10^{-11}\ \mathrm{m^3\,kg^{-1}s^{-2}}}$

[Relative std. uncert.: 2.2×10^{-5}]

Eite Tiesinga, Peter J. Mohr, David B. Newell, and Barry N. Taylor,
CODATA recommended values of the fundamental physical constants: 2018
Rev. Mod. Phys., 93, 025010 (2021)

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Physik: Forscher bestimmen Gravitationskonstante neu

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GRAVITATIONSKONSTANTE

Die Schwere der Schwerkraft

Von Frank Grotelüschen

Isaac Newton führte 1686 die Gravitationskonstante in die Physik ein. Wie sie genau lautet, ist bis heute umstritten. (dpa/picture alliance)

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Italiana la misura più precisa della costa...
gravitaziona...

Uno dei 5 numeri chiav...

18 giugno, 19:25

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0,0000000000667191: ecco il numero di Newton che tiene insieme il...

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EDIZIONE ITALIANA DI SCIENTIFIC AMERICAN

19 giugno 2014

Una misura atomica per la costante di gravitazione

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SCIENCE NEWS

014, 1:04 PM ET

New Value for Gravitational Consta... Could Blow Our Minds

NATURE | NEWS

Quantum method closes in on gravitational constant

Cold rubidium atoms provide fresh approach to measuring Newton's big *G*.

Ron Cowen

18 June 2014

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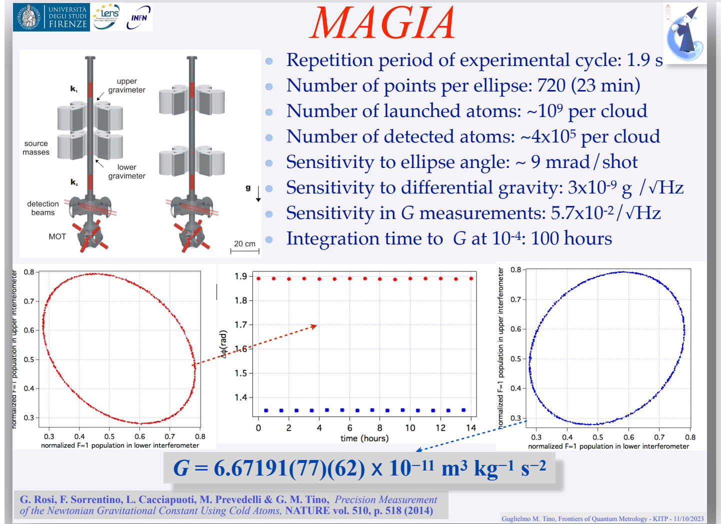
Dall'antimateria a Rosetta, la scienza del 2014

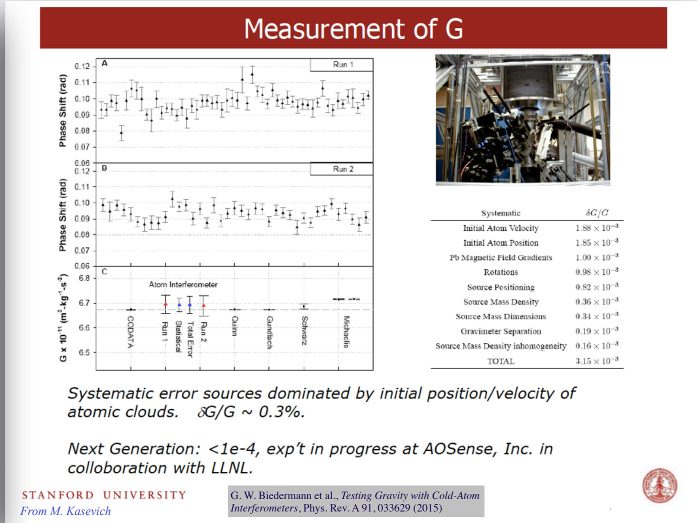
Gli avvenimenti principali, mese per mese

g+1 0 | Tweet 0 | Consiglia 0

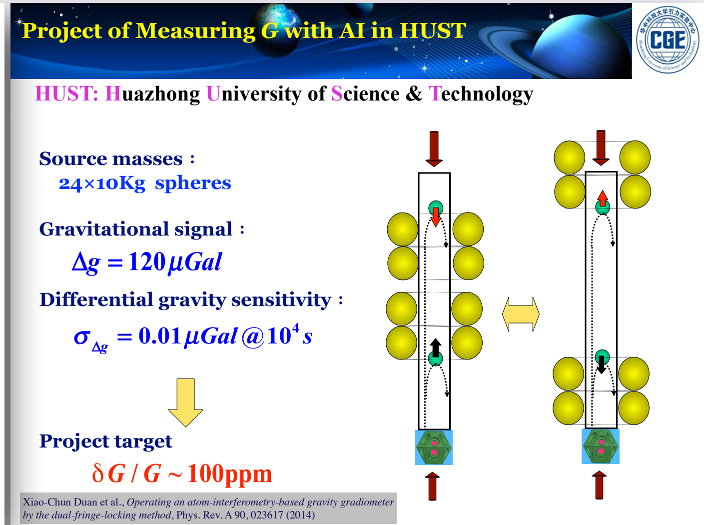
Measuring G with atom interferometry



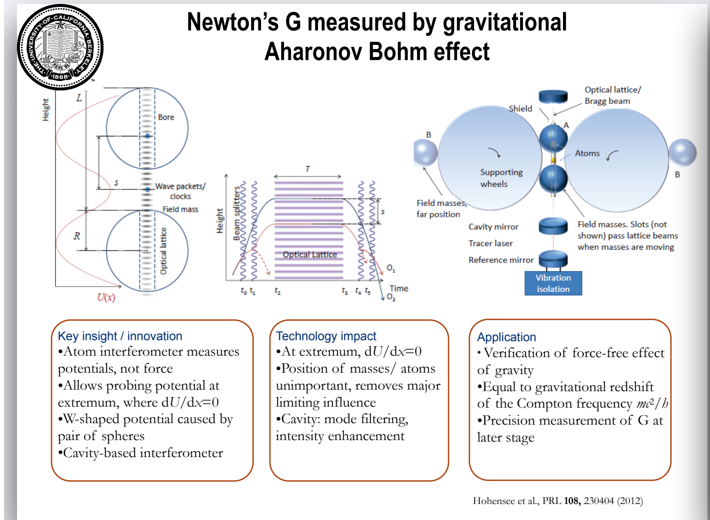
Florence



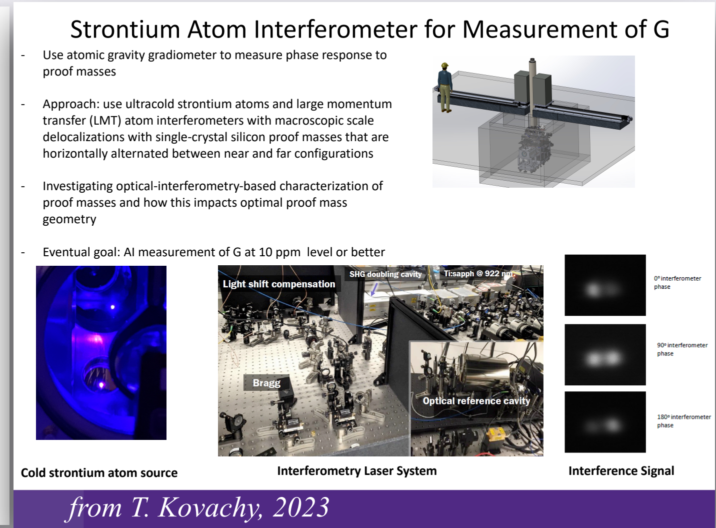
Stanford



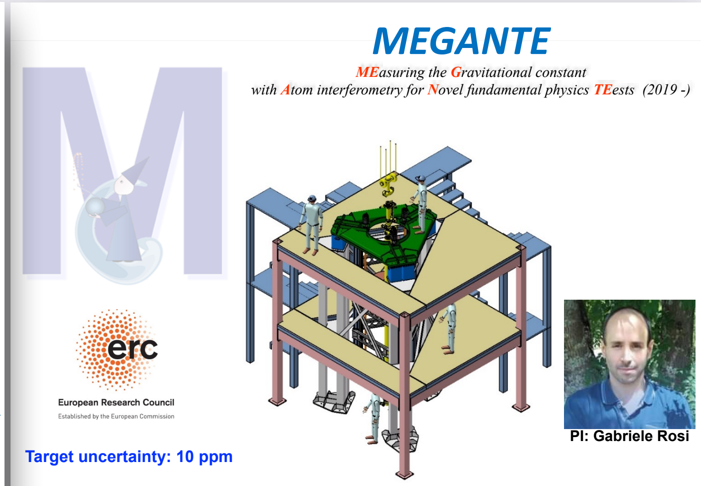
Wuhan



Berkeley



Northwestern University

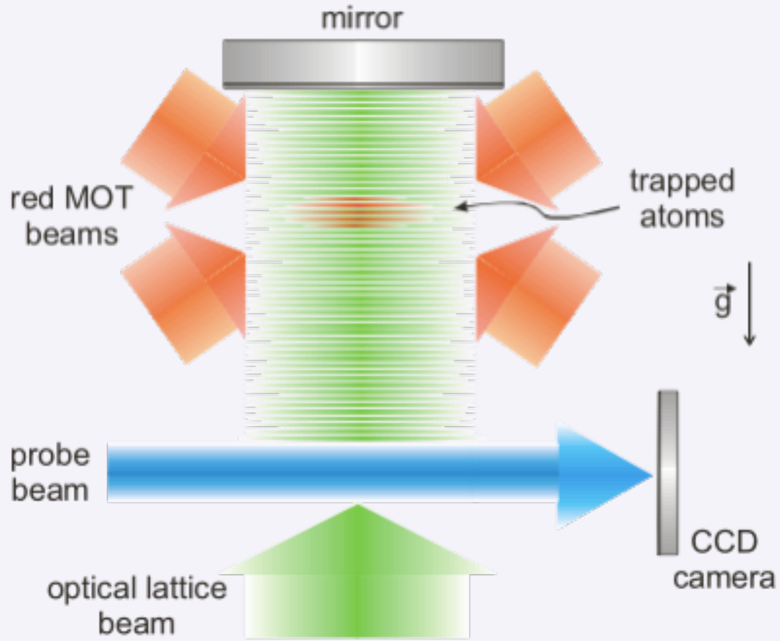


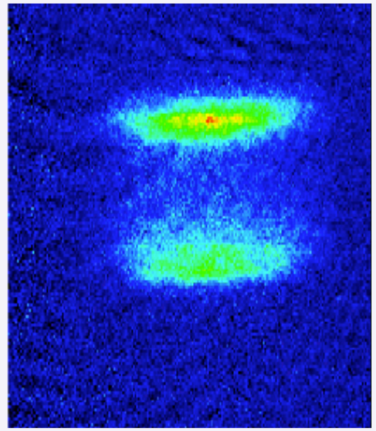
Florence

Future prospects to improve the measurement of G with atom interferometry

- Highly homogeneous (lower-density, e.g. silicon) source mass
- Higher sensitivity atom interferometer
- Different scheme with better definition of atomic velocities
- Smaller size of the atomic sensor
- Atom with lower sensitivity to magnetic fields

Idea for Advanced MAGIA:
Sr atoms in optical lattice and silicon crystal source mass





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

$\Delta G/G \approx 10^{-5}$

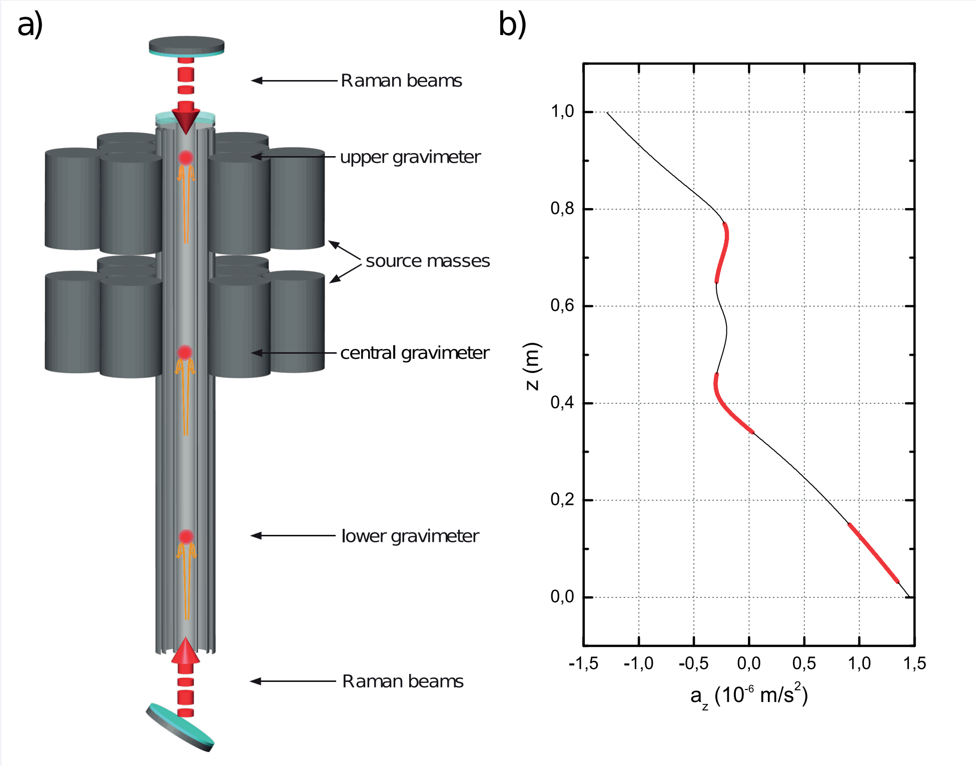
$\Delta G/G \approx 10^{-6}$?

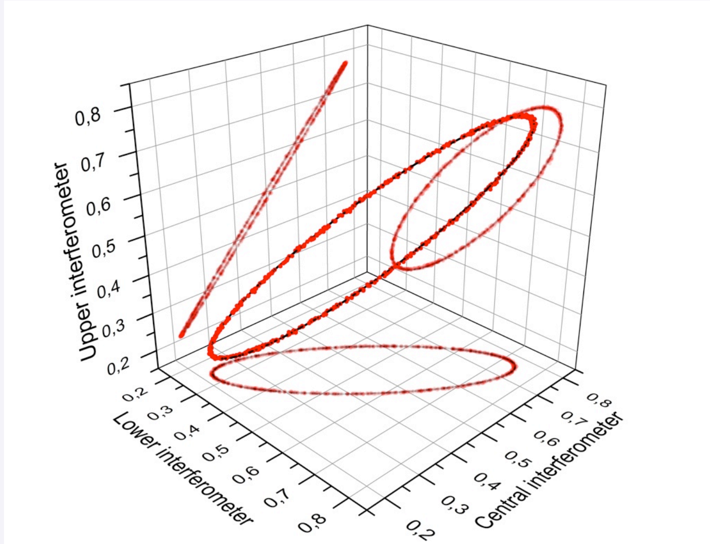
G. M. Tino, *Testing gravity with atom interferometry*, in "Atom Interferometry", G. M. Tino and M. A. Kasevich (eds), SIF and IOS (2014)

G. Rosi et al., *Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms,* NATURE vol. 510, p. 518 (2014)

Curvature

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)**

PRL 114, 013001 (2015) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2015

Measurement of the Gravity-Field Curvature by Atom Interferometry

G. Rosi,[1] L. Cacciapuoti,[2] F. Sorrentino,[1,*] M. Menchetti,[1,†] M. Prevedelli,[3] and G. M. Tino[1,‡]
[1]*Dipartimento di Fisica e Astronomia and LENS, Università di Firenze, INFN Sezione di Firenze, via Sansone 1, I-50019 Sesto Fiorentino, Firenze, Italy*
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(Received 21 October 2014; published 5 January 2015)

We present the first direct measurement of the gravity-field curvature based on three conjugated atom interferometers. Three atomic clouds launched in the vertical direction are simultaneously interrogated by the same atom interferometry sequence and used to probe the gravity field at three equally spaced positions. The vertical component of the gravity-field curvature generated by nearby source masses is measured from the difference between adjacent gravity gradient values. Curvature measurements are of interest in geodesy studies and for the validation of gravitational models of the surrounding environment. The possibility of using such a scheme for a new determination of the Newtonian constant of gravity is also discussed.

DOI: 10.1103/PhysRevLett.114.013001 PACS numbers: 37.25.+k, 03.75.Dg, 04.80.Cc, 37.10.Vz

In the last two decades, atom interferometry [1] has profoundly changed precision inertial sensing, leading to major advances in metrology and fundamental and applied physics. The outstanding stability and accuracy levels [2,3] combined with the possibility of easily implementing new measurement schemes [4–7] are the main reasons for the rapid progress of these instruments. Matter-wave interferometry has been successfully used to measure local gravity [8], gravity gradient [9–11], the Sagnac effect [12], the Newtonian gravitational constant [13–16], the fine structure constant [17], and for tests of general relativity [18,19]. Accelerometers based on atom interferometry have been developed for many practical applications including geodesy, geophysics, engineering prospecting, and inertial navigation [20–22]. Instruments for space-based research are being conceived for different applications ranging from used to detect short-wavelength density anomalies or in situations where the vibration noise seriously limits absolute gravity measurements. The second derivative of the gravity field can vary by several orders of magnitude when measured across shallow density anomalies, promising high spatial resolutions and sharp signals for their localization [27]. Simultaneous *in situ* measurements of the gravity acceleration and its derivatives can also be used for remote sensing to estimate the evolution of the gravitational field along the direction of the local plumb line. Such a method could find interesting applications in regional height systems to measure differences in the gravitational potential with respect to a reference station, e.g., located on the geoid [28]. Indeed, in the presence of shallow density anomalies, the knowledge of both the gravity gradient and the curvature can provide centimeter-level resolution

Selected for a Viewpoint in *Physics*
PRL **118,** 183602 (2017) PHYSICAL REVIEW LETTERS week ending 5 MAY 2017

Phase Shift in an Atom Interferometer due to Spacetime Curvature across its Wave Function

Peter Asenbaum,[1] Chris Overstreet,[1] Tim Kovachy,[1] Daniel D. Brown,[2] Jason M. Hogan,[1] and Mark A. Kasevich[1]
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(Received 13 October 2016; published 1 May 2017)

Spacetime curvature induces tidal forces on the wave function of a single quantum system. Using a dual light-pulse atom interferometer, we measure a phase shift associated with such tidal forces. The macroscopic spatial superposition state in each interferometer (extending over 16 cm) acts as a nonlocal probe of the spacetime manifold. Additionally, we utilize the dual atom interferometer as a gradiometer for precise gravitational measurements.

DOI: 10.1103/PhysRevLett.118.183602

A long-standing goal in matter-wave interferometry has been to resolve a phase shift associated with spacetime curvature across a particle's wave function [1–7]. The conceptual significance of such a tidal phase shift (ϕ_{tidal}) arises from the fact that acceleration and spacetime curvature have different physical origins in general relativity: Local acceleration arises from nongravitational forces, while curvature characterizes the spacetime manifold [2]. Unlike phase shifts arising from local acceleration, curvature-induced phase shifts have been described as representing the first true manifestation of gravitation in a quantum system [1–5].

In prior gravitational measurements exploiting de Broglie wave interference [8–15], the interferometer arm separation was small enough that the spacetime curvature across the wave function (i.e., gravity gradient across the interferometer arms) did not produce an identifiable tidal phase shift. For the purpose of understanding gravitational effects in these experiments, the trajectory of each interfering particle is well described by a single geodesic that is defined by that particle's initial position and velocity before the interferometer. The interferometer phase measures the local acceleration of this geodesic relative to the interferometer beam splitters and mirrors.

To clarify this distinction, we consider as an example the first case, the phase shift is zero. In the second case, the phase shift is $\phi_{\text{lab}} = nkg_iT^2 + nkv_iT_{zz}T^3 + (7/12)nkg_iT_{zz}T^4$ [16]. Since the phase shift is zero when the lasers move along the particle's geodesic, the entire phase shift ϕ_{lab} can be understood as arising from the relative motion of the lasers and this geodesic [17]. This phase shift includes the effect of the coupling of initial conditions to the gravity gradient [10] but does not include ϕ_{tidal}.

If the interferometer arm separation is made large enough that there are resolvable tidal forces across the spatial extent of the interferometer, then the wave function of an interfering particle can no longer be approximated as traveling along a single populated geodesic. Instead, the two arms follow separate trajectories that accelerate with respect to one another. A tidal phase shift can be observed in this regime—it appears as [16] $\phi_{\text{tidal}} = (\hbar/2m)n^2k^2T_{zz}T^3$ in this example regardless of whether the lasers are fixed in the lab frame or follow the geodesic defined by the particle's initial position and velocity. From these considerations, ϕ_{tidal} is a manifestation of gravitational curvature that cannot be interpreted as simply arising from the relative motion of a single atomic trajectory and the interferometer lasers.

In this Letter, we report the first observation of a tidal phase shift. In our experiment, this phase shift is induced by

Test of the Einstein Equivalence Principle

Test of the Einstein Equivalence Principle

Weak form of the Einstein Equivalence Principle → Universality of Free Fall

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

G. M. Tino, L. Cacciapuoti, S. Capozziello, G. Lambiase, F. Sorrentino, *Precision gravity tests and the Einstein Equivalence Principle,* **Progress in Particle and Nuclear Physics 112, 103772 (2020)**

Tests of the weak equivalence principle

Eötvös ratio $$\eta_{A-B} = 2 \cdot \frac{|a_A - a_B|}{|a_A + a_B|} = 2 \cdot \frac{|(m_i/m_g)_A - (m_i/m_g)_B|}{|(m_i/m_g)_A + (m_i/m_g)_B|}$$

Torsion balance $\eta < \sim 10^{-13}$

Lunar laser ranging $\eta < \sim 10^{-13}$

Test masses onboard a satellite (MICROSCOPE mission) $\eta < \sim 10^{-15}$

Atoms
- different isotopes
- different atoms
- bosons vs fermions
- different spins
- anti-matter

$\eta < \sim 10^{-12} \rightarrow \sim 10^{-14}$-$10^{-15}$

Tests of the weak Equivalence Principle with atoms

Atoms vs macroscopic mass	
A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)	**^{133}Cs atoms vs classical gravimeter**
S. Merlet, Q. Bodart, N. Malossi, A. Landragin, F. P. D. Santos, O. Gitlein, L. Timmen, Metrologia 47, L9 (2010).	**^{87}Rb atoms vs classical gravimeter**
N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino, Phys. Rev. Lett. 106, 038501 (2011)	**^{88}Sr atoms vs classical gravimeter**
Different atoms/isotopes	
S. Fray, C. A. Diez, T.W. Hänsch, and M. Weitz, Phys. Rev. Lett. 93, 240404 (2004).	**^{87}Rb vs ^{85}Rb**
A. Bonnin, N. Zahzam, Y. Bidel, and A. Bresson, Phys. Rev. A 88, 043615 (2013).	**^{87}Rb vs ^{85}Rb**
P. Asenbaum , C. Overstreet , M. Kim , J. Curti, M.A. Kasevich, Phys. Rev. Lett. 125, 191101 (2020)	**^{87}Rb vs ^{85}Rb**
L.Zhou, C.He, S.-T.Yan, X.Chen, W.-T.Duan, R.-D.Xu, C.Zhou, Y.-H.Ji, S.Barthwal, Q.Wang, Z.Hou, Z.-Y.Xiong, D.-F.Gao, Y.-Z.Zhang, W.-T.Ni, J.Wang, M.-S.Zhan, PRA 104, 022822 (2021)	**^{87}Rb vs ^{85}Rb**
D. Schlippert, J. Hartwig, H. Albers, L. L. Richardson, C. Schubert, A. Roura, W. P. Schleich, W. Ertmer, and E. M. Rasel, PRL 112, 203002 (2014)	**^{87}Rb vs ^{39}K**
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, Phys. Rev. Lett. 113, 023005 (2014)	**^{87}Sr vs ^{88}Sr**
The ALPHA collaboration, Nature 621, 716 (2023)	**anti-H**
Atoms in different internal states	
S. Fray, C. A. Diez, T.W. Hänsch, and M. Weitz, Phys. Rev. Lett. 93, 240404 (2004).	**^{85}Rb in two different hyperfine states**
M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, Phys. Rev. Lett. 113, 023005 (2014)	**^{87}Sr in different Zeeman states**
X.-C. Duan, X.-B. Deng, M.-K. Zhou, K. Zhang, W.-J. Xu, F. Xiong, Y.-Y. Xu, C.-G. Shao, J. Luo, Z.-K. Hu, Phys. Rev. Lett. 117, 023001 (2016)	**^{87}Rb in different Zeeman states**
G. Rosi, G. D'Amico, L. Cacciapuoti, F. Sorrentino, M. Prevedelli, M. Zych, C. Brukner, G.M. Tino, Nat. Commun. 8, 1 (2017)	**^{87}Rb in two different hyperfine states and in a coherent superposition**

PHYSICAL REVIEW LETTERS **125,** 191101 (2020)

Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

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(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

We use a dual-species atom interferometer with 2 s of free-fall time to measure the relative acceleration between ^{85}Rb and ^{87}Rb wave packets in the Earth's gravitational field. Systematic errors arising from kinematic differences between the isotopes are suppressed by calibrating the angles and frequencies of the interferometry beams. We find an Eötvös parameter of $\eta = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$, consistent with zero violation of the equivalence principle. With a resolution of up to 1.4×10^{-11} g per shot, we demonstrate a sensitivity to η of $5.4 \times 10^{-11}/\sqrt{\mathrm{Hz}}$.

DOI: 10.1103/PhysRevLett.125.191101

Does gravity influence local measurements? The equivalence principle (EP), which posits that all gravitational effects disappear locally [1], is the foundation of general relativity [2] and other geometric theories of gravity. Most theoretical unification attempts that couple gravity to the standard model lead to EP violations [3]. In addition, tests of the equivalence principle search for perturbations of geometric gravity and are sensitive to exotic interactions [4,5] that couple differently to the test masses. These tests are complementary to searches for large-scale variations of unknown fields [6] and are carried out with local probes that can be precisely controlled.

EP tests are often characterized by the Eötvös parameter η, which is the relative acceleration of the test masses divided by the average acceleration between the test masses and the nearby gravitational source. With classical accelerometers, EP violation has been constrained to $\eta < 1.8 \times 10^{-13}$ by torsion balances in a laboratory setting [7] and to $\eta < 1.3 \times 10^{-14}$ by the concluded space mission *MICROSCOPE* [8].

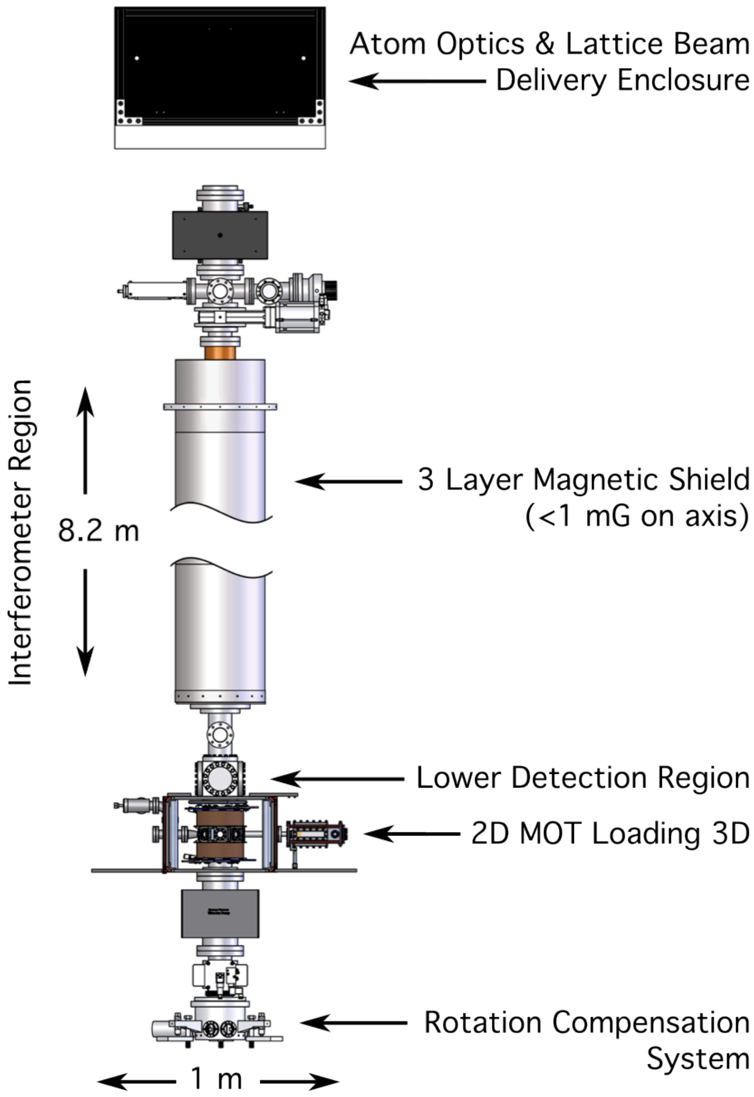
We perform an equivalence principle test by interferometrically measuring the relative acceleration of freely falling clouds of atoms. Atom clouds are well-suited test masses because they spend 99.9% of the interrogation time in free fall and the remainder in precisely controlled interactions with the interferometry lasers. In addition, atoms have uniform and well-characterized physical properties. Compared to classical tests, atom-interferometric (AI) EP tests are influenced by different sources of systematic error [9]. AI EP tests can be performed between isotopes that differ only in neutron number, and quantum tests are especially sensitive to particular violation mechanisms [10]. However, previous AI EP tests [11–14] have been limited to $\eta < 3 \times 10^{-8}$ in dual-species comparisons [14] and $\eta < 1.4 \times 10^{-9}$ in comparisons between ground states of a single species [15], largely due to a lack of sensitivity compared to classical experiments.

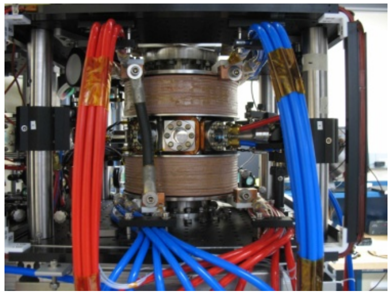
In this Letter, we report an atom-interferometric test of the equivalence principle between ^{85}Rb and ^{87}Rb with $\eta = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$, consistent with zero violation at the 10^{-12} level. This result improves by four orders of magnitude on the best previous dual-species EP test with atoms [14]. We achieve high sensitivity by utilizing a long interferometer time T and a large momentum splitting between interferometer arms. With a resolution of 1.4×10^{-11} g per shot and 15 s cycle time, the interferometer attains the highest sensitivity to η of any laboratory experiment to date [7].

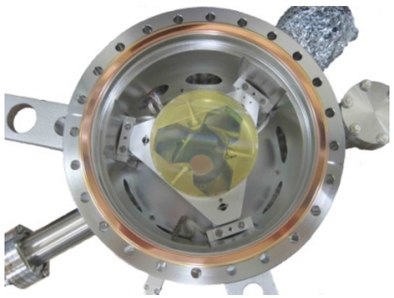
The relative acceleration between ^{85}Rb and ^{87}Rb is measured with a dual-species atom interferometer. The experimental apparatus is described in [16]. We prepare ultracold clouds of ^{85}Rb and ^{87}Rb by evaporative cooling in a magnetic trap. The subsequent magnetic lensing sequence lowers the horizontal kinetic energies to 25 nK but introduces a 1.8 mm vertical offset between the two isotopes. The other kinematic degrees of freedom (d.o.f.) remain matched. The clouds are then trapped in a vertical 1D optical lattice and accelerated to 13 m/s in 20 ms (launch height ~8.6 m). This laser lattice launch accelerates the atoms to approximately the final lattice velocity. Each isotope is accelerated to a distinct, even multiple of its recoil velocity $\hbar k/m$. We choose a final lattice velocity such that the vertical velocities of the two isotopes are overlapped to within 1 mm/s. To spatially overlap the clouds, we apply species-selective Raman transitions that kick the two isotopes in opposite directions. After a 77 ms drift time and removal of untransferred atoms, the Raman transitions are reversed, and the clouds are overlapped to within 65 μm. The Raman pulses also provide velocity selection, and the detunings of the Raman pulses allow the average vertical velocity of each isotope to be individually controlled, improving the velocity overlap to within 60 μm/s.

The interferometer beam splitters consist of sequences of two-photon Bragg transitions [16] that transfer $4\hbar k$, $8\hbar k$, or

Apparatus







Ultracold atom source

- $>10^6$ atoms at 50 nK
- 3e5 atoms at 1.6 nK

Optical Lattice Launch

- 13.1 m/s with 2372 photon recoils to 9 m

Atom Interferometry

- 2 cm $1/e^2$ radial waist
- 6 W total power
- Dynamic nrad control of laser angle with precision piezo-actuated stage

Detection

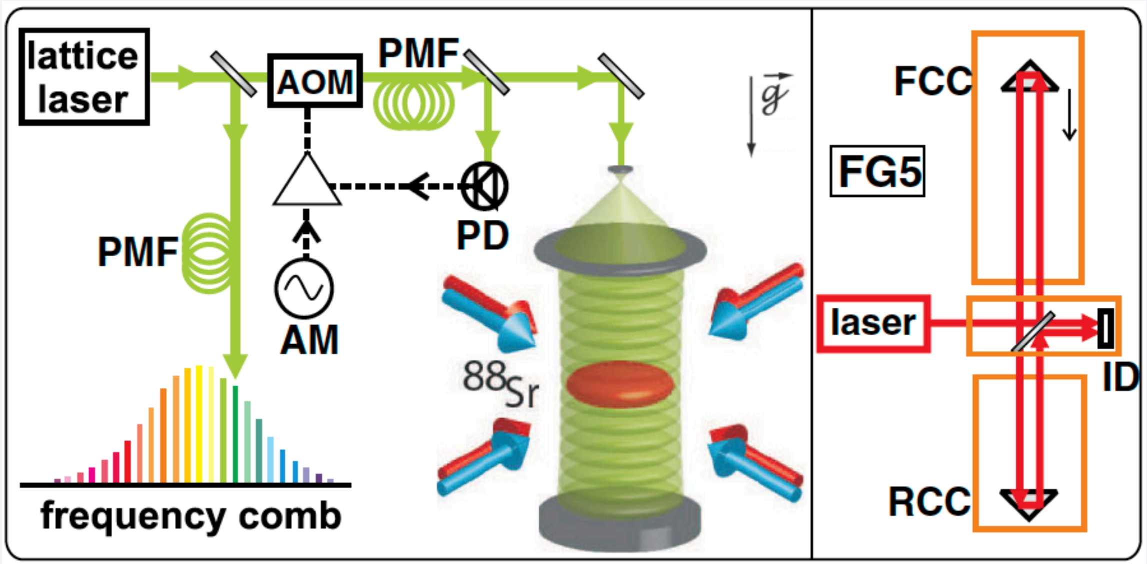
- Spatially-resolved fluorescence imaging
- Two CCD cameras on perpendicular lines of sight

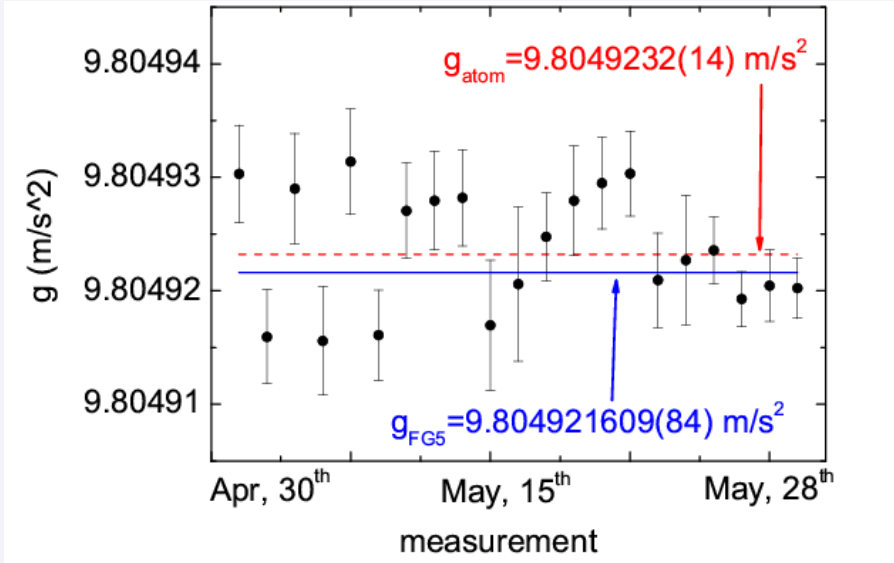
Current demonstrated statistical resolution, ~5e-13 g in 1 hr (87Rb)

STANFORD UNIVERSITY

From M. Kasevich, ICAP 2014

Precision measurement of gravity with cold atoms in an optical lattice and comparison with a classical gravimeter





140 ppb relative uncertainty

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

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

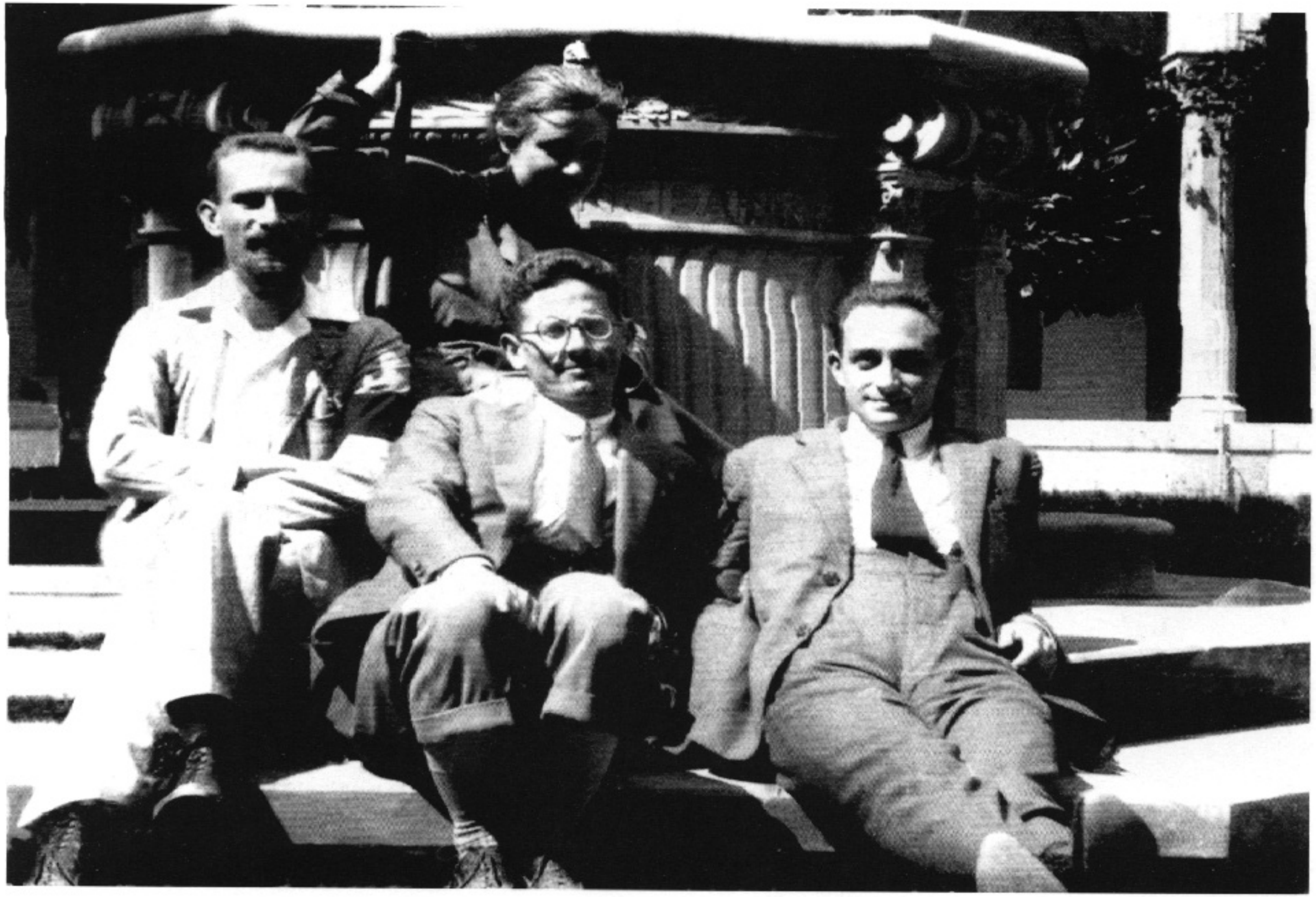
^{87}Sr

- **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)**

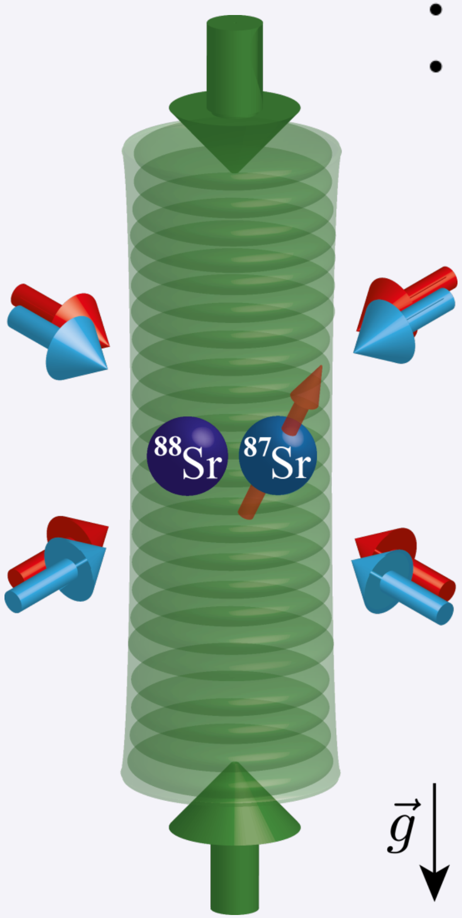


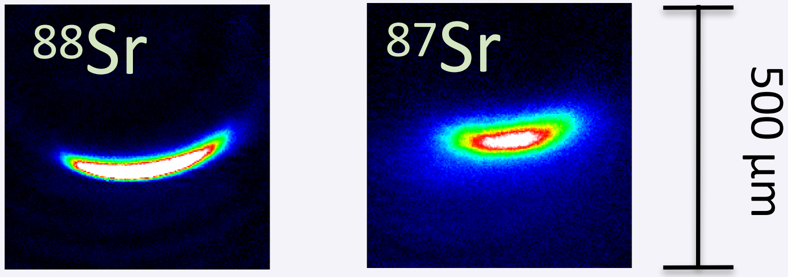
Ad Arcetri nel 1925: Franco Rasetti, Fermi e Nello Carrara con Rita Brunetti

Test of the equivalence principle with ^{88}Sr and ^{87}Sr atoms

- Atomic beam from an oven at 430°C
- Zeeman-slowed down to 50 m/s
- Two cooling stages sequence in MOT
  - Broad transition 461 nm, $\gamma = 32$ MHz
  - Narrow transition 689 nm, $\gamma = 7$ kHz

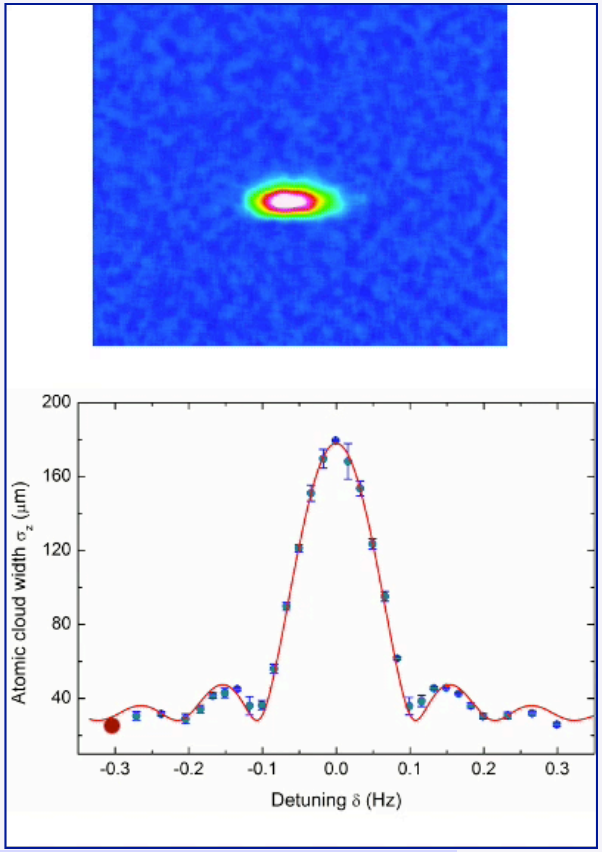
Loaded alternately in a vertical OL @ 532 nm
- waist 300 μm
- $U_0 = 6E_R$
- lifetime >10 s





8×10^6 atoms
T: 1 μK

1×10^6 atoms
T: 1.4 μK



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)**

Differential gravity measurements for ^{88}Sr and ^{87}Sr – Equivalence Principle test

Weak Equivalence Principle test with coherent probe masses with and without nuclear spin: ^{88}Sr ($I = 0$) and ^{87}Sr ($I = 9/2$)

Measuring **Eötvös ratio** that depends only on Bloch frequencies and mass ratio $R_m = \frac{m_{88}}{m_{87}}$ (*)

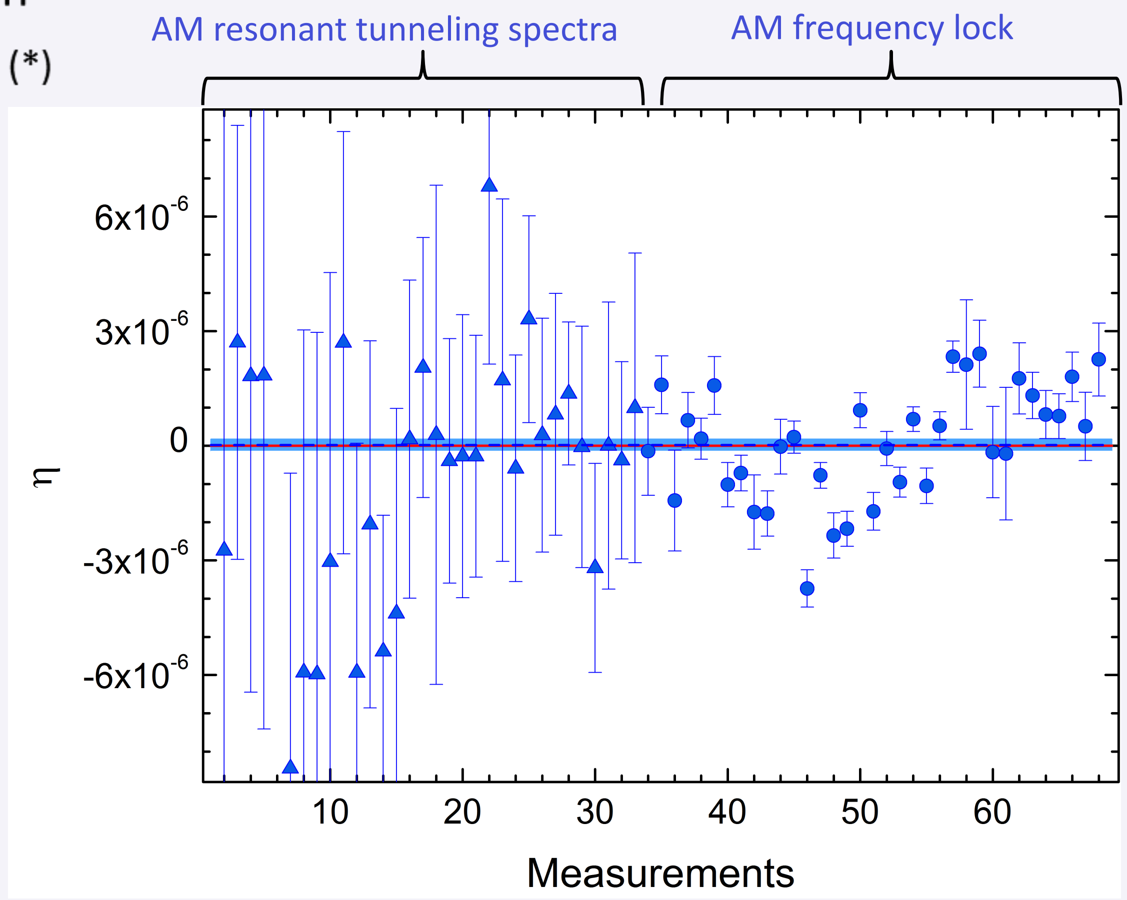
$$\eta = \frac{a_{88} - a_{87}}{(a_{88} + a_{87})/2} = \frac{\nu_{88} - R_m \nu_{87}}{(\nu_{88} + R_m \nu_{87})/2}$$

Uncertainty for each point is the quadratic sum of statistical error and systematics uncertainty

Final result:

$$\eta = (0.2 \pm 1.6) \times 10^{-7}$$

Where uncertainty corresponds to the standard error of the weighted mean



(*) known better than 10^{-10} : Rana *et al.*, PRA 86, 050502 (2012)

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

Search for spin-gravity coupling

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

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

m_A is the rest mass of the atom

S_z is the projection of the spin along gravity direction

k is the model-dependent spin-gravity coupling strength

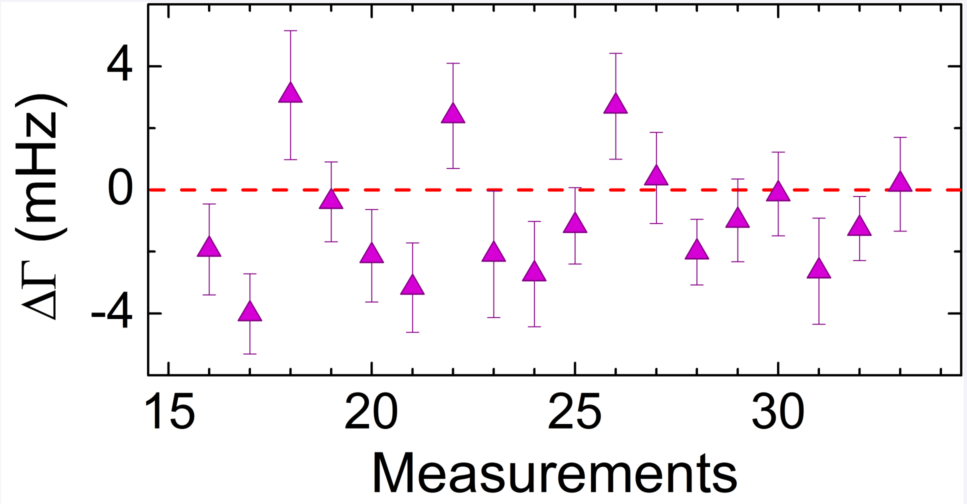
Each ^{87}Sr spin component $S_z = I_z$ will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

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

→ Upper limit on spin-gravity coupling k

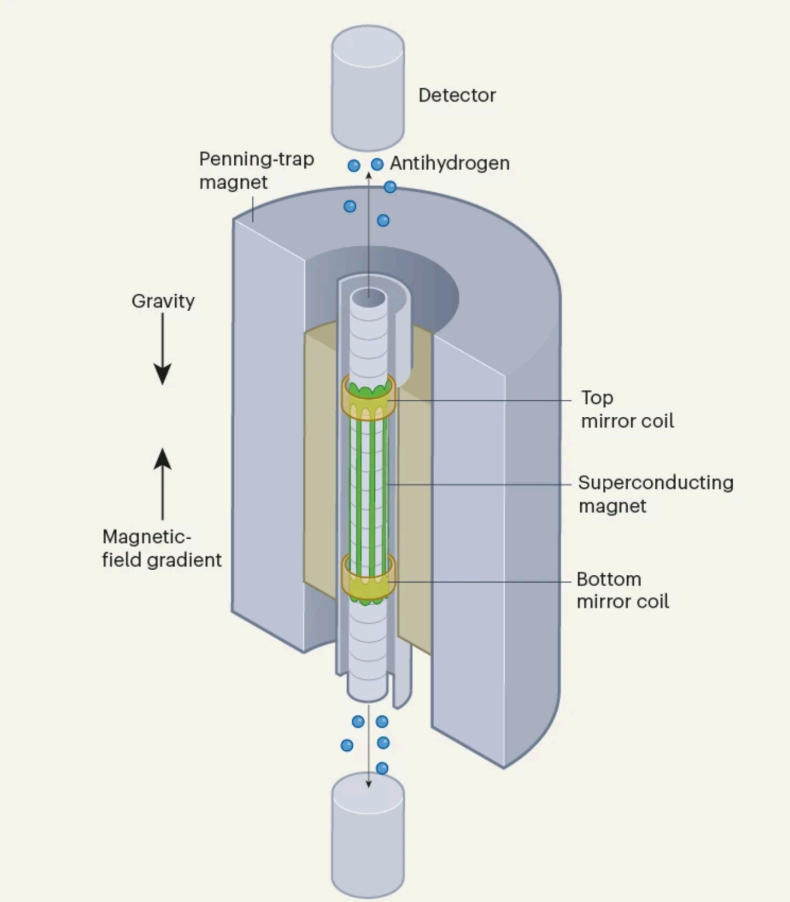
$$\Delta\Gamma = 2 I_{87} k l \nu_{87}$$

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

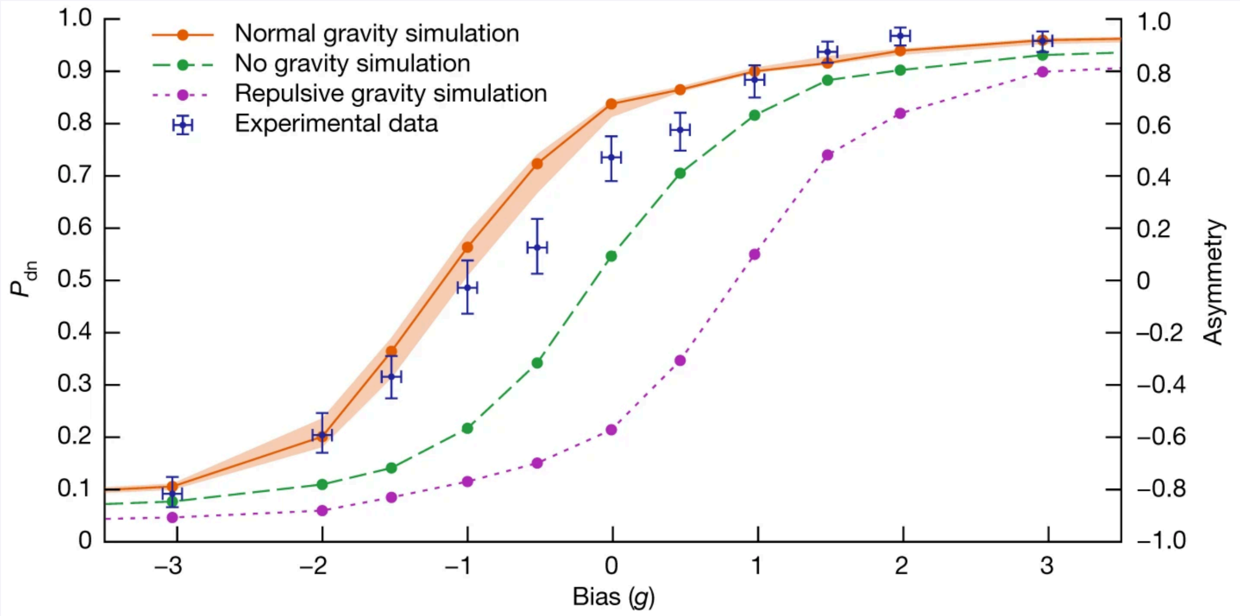


M.G. Tarallo, T. Mazzoni, N. Poli, D.V. Sutyrin, X. Zhang, G.M. Tino, *Test of Einstein Equivalence Principle for 0-Spin and Half-Integer-Spin Atoms:Search for Spin-Gravity Coupling Effects*, **Phys. Rev. Lett. 113, 023005 (2014)**

Observation of the effect of gravity on the motion of anti-H



Nature **621**, 699-700 (2023) - News and Views



Anderson, E.K., et al. (ALPHA collaboration), *Observation of the effect of gravity on the motion of antimatter,* **Nature** 621, 716 **(2023)**

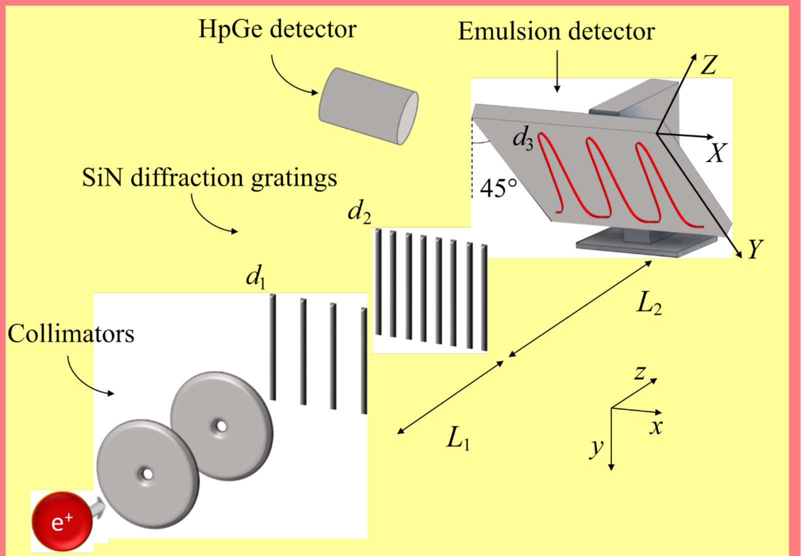
Gravitation with Positronium

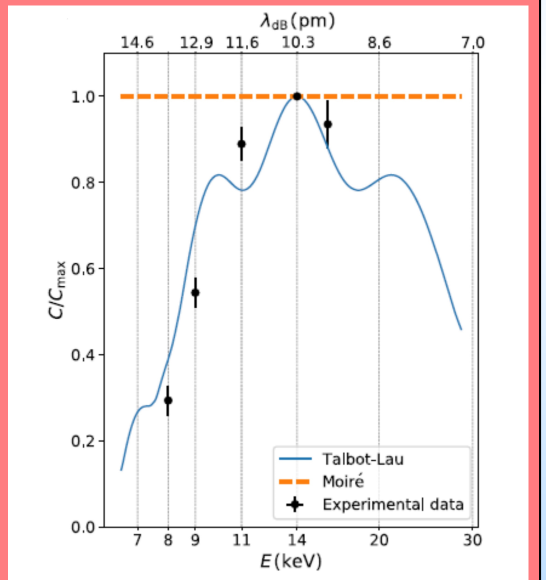
QUPLAS: Quantum interferometry and gravitation with Positrons and LASers

- QUPLAS-0: Positron interferometry (completed!)

S. Sala, A. Ariga, A. Ereditato, R. Ferragut, M. Giammarchi, M. Leone, C. Pistillo, P. Scampoli
Science Advances 5 eaav7610 (2019) doi: 10.1126/sciadv.aav7610

First Observation of Antimatter Quantum Interference – done with positrons in single-particle mode. This completes the first part of the program.





Positron interference in QUPLAS-0:

Talbot Lau mode with

-Positron E from 8 to 16 keV
-A material grating system
-Nuclear emulsion detector

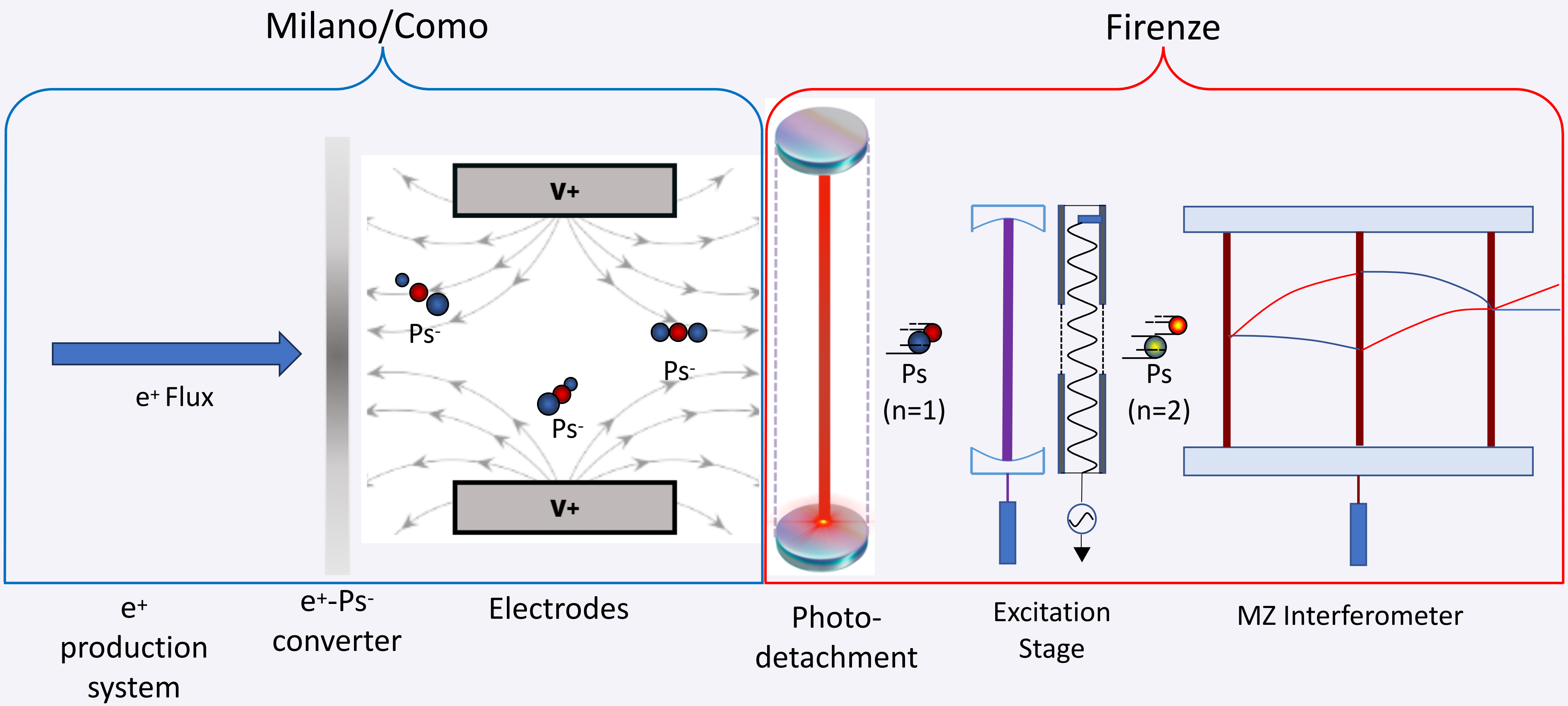
- QUPLAS-I: Positronium Interferometry
- QUPLAS-II: Positronium Gravitation

The next steps

from M. Giammarchi, 2020

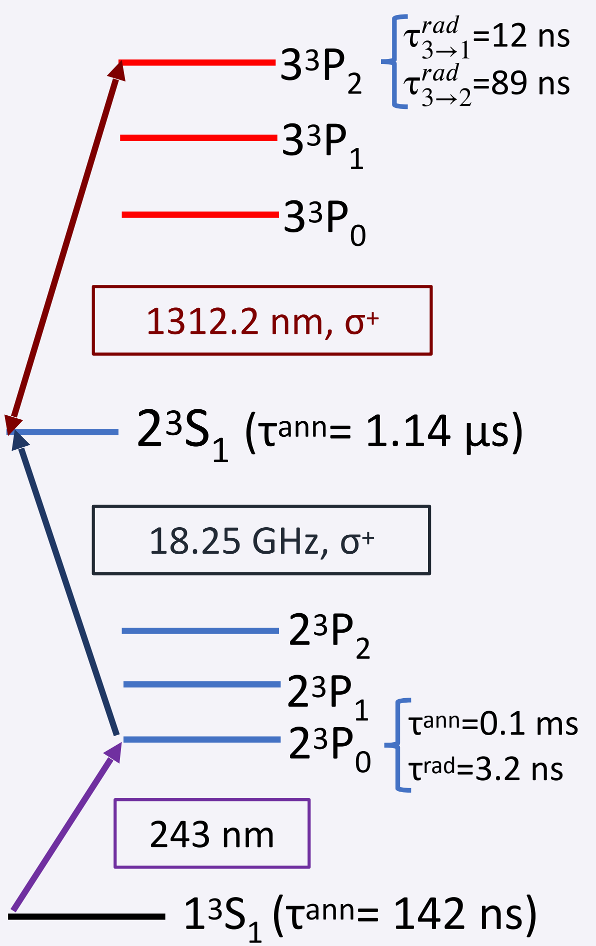
Gravitation with Positronium

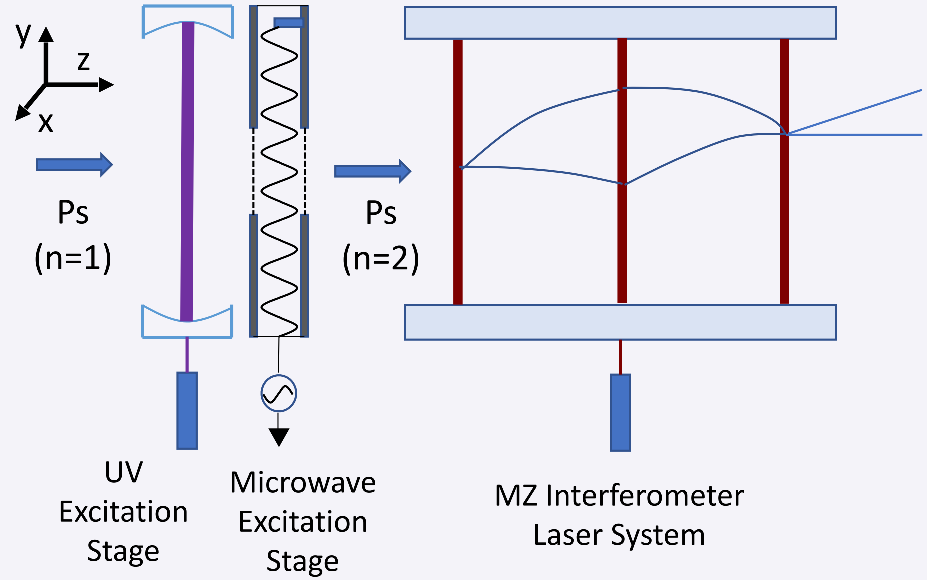
Experimental Setup Scheme

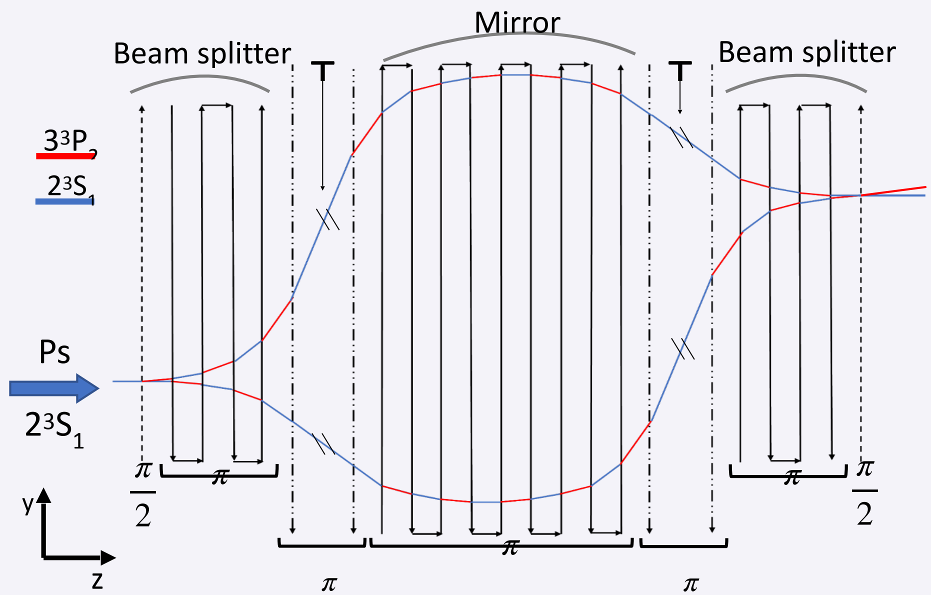


Giuseppe Vinelli, Fabrizio Castelli, Rafael Ferragut, Massimiliano Romé, Michele G. Sacerdoti, Leonardo Salvi, Valerio Toso, Marco G. Giammarchi, Gabriele Rosi and Guglielmo M. Tino, *A large-momentum-transfer matter-wave interferometer to measure the effect of gravity on positronium,* **Class. Quantum Grav. 40** 205024 **(2023)**

Gravitation with Positronium







K_{eff}=10k_l
v_{Ps}=6x10^6 m/s
L≈5 m
T≈0.4 μs
N_f/N_i≈27%

G. Vinelli, F. Castelli, R. Ferragut, M. Romé, M. G. Sacerdoti, L. Salvi, V. Toso, M. G. Giammarchi, G. Rosi, G. M. Tino, *A large-momentum-transfer matter-wave interferometer to measure the effect of gravity on positronium,* **Class. Quantum Grav. 40** 205024 **(2023)**

Tests of Gravitational Quantum Physics and Quantum Gravity models

UNIVERSITÀ DEGLI STUDI FIRENZE

nature COMMUNICATIONS

ARTICLE

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OPEN

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

G. Rosi[1], G. D'Amico[1], L. Cacciapuoti[2], F. Sorrentino[3], M. Prevedelli[4], M. Zych[5], Č. Brukner[6,7] & G.M. Tino[1]

The Einstein equivalence principle (EEP) has a central role in the understanding of gravity and space-time. In its weak form, or weak equivalence principle (WEP), it directly implies equivalence between inertial and gravitational mass. Verifying this principle in a regime where the relevant properties of the test body must be described by quantum theory has profound implications. Here we report on a novel WEP test for atoms: a Bragg atom interferometer in a gravity gradiometer configuration compares the free fall of rubidium atoms prepared in two hyperfine states and in their coherent superposition. The use of the superposition state allows testing genuine quantum aspects of EEP with no classical analogue, which have remained completely unexplored so far. In addition, we measure the Eötvös ratio of atoms in two hyperfine levels with relative uncertainty in the low 10^{-9}, improving previous results by almost two orders of magnitude.

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

Eötvös ratio

$$\eta_{\mathrm{A-B}} = 2 \cdot \frac{|a_{\mathrm{A}} - a_{\mathrm{B}}|}{|a_{\mathrm{A}} + a_{\mathrm{B}}|} = 2 \cdot \frac{|(m_{\mathrm{i}}/m_{\mathrm{g}})_{\mathrm{A}} - (m_{\mathrm{i}}/m_{\mathrm{g}})_{\mathrm{B}}|}{|(m_{\mathrm{i}}/m_{\mathrm{g}})_{\mathrm{A}} + (m_{\mathrm{i}}/m_{\mathrm{g}})_{\mathrm{B}}|}$$

Mass–energy operators

$$\hat{M}_\alpha = m_\alpha \hat{I} + \frac{\hat{H}_\alpha}{c^2} \qquad \alpha = \mathrm{i}, \mathrm{g}$$

$\hat{H}_{\mathrm{i}}$, $\hat{H}_{\mathrm{g}}$ contributions of the internal energy to the inertial and gravitational mass

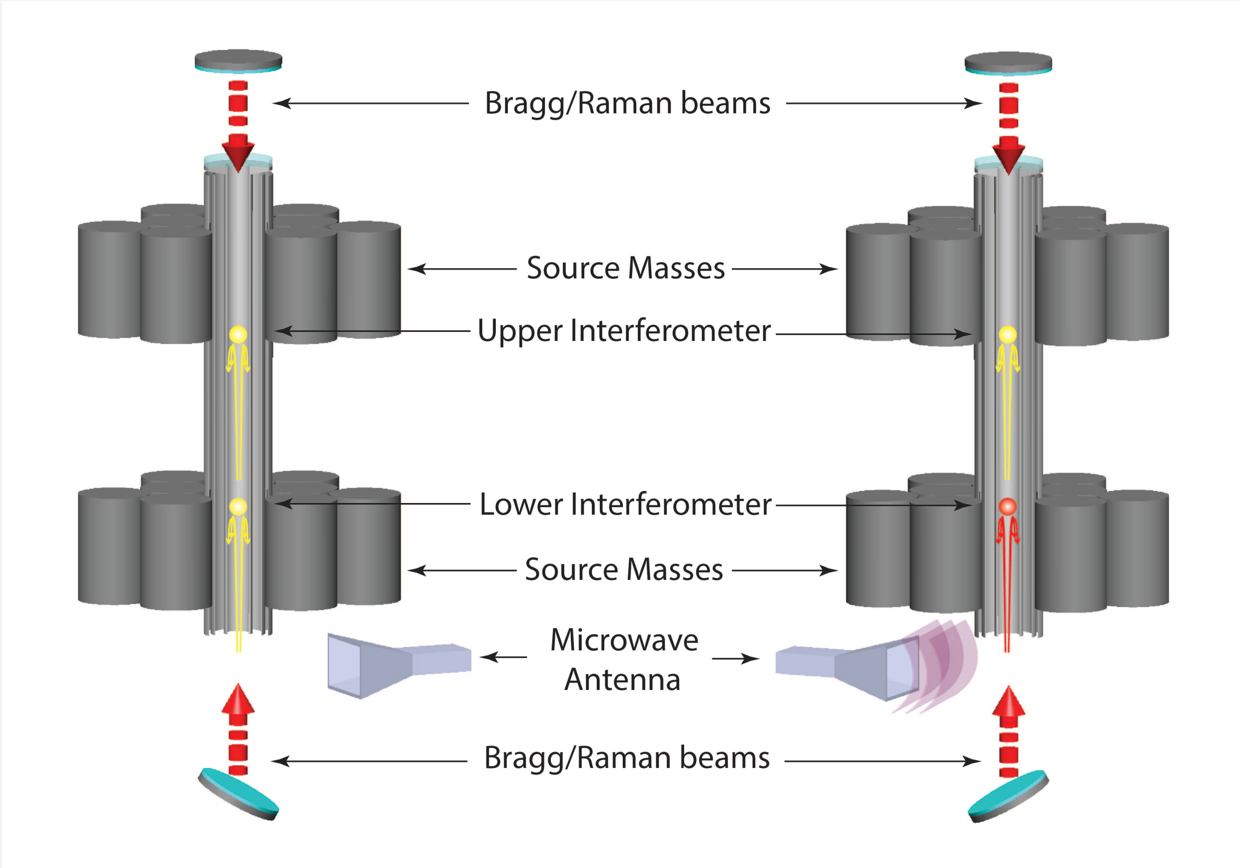
Quantum test theory with WEP violations $\Rightarrow \hat{M}_{\mathrm{i}} \neq \hat{M}_{\mathrm{g}} \Rightarrow \hat{a} = \hat{M}_{\mathrm{g}} \hat{M}_{\mathrm{i}}^{-1} g$

$$\hat{M}_{\mathrm{g}} \hat{M}_{\mathrm{i}}^{-1} \approx \begin{pmatrix} r_1 & r \\ r^* & r_2 \end{pmatrix} \qquad r = |r| e^{i\varphi_r}$$

Zych, M. & Brukner, C. Quantum formulation of the Einstein equivalence principle, https://arxiv.org/abs/1502.00971 (2015)

Orlando, P. J., Mann, R. B., Modi, K. & Pollock, F. A. A test of the equivalence principle(s) for quantum superpositions. Class. Quantum Grav. 33, 19LT01 (2016)

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



$$|1\rangle = |F=1, m_F=0\rangle \qquad a_1 = g\langle 1|\hat{M}_{\rm g}\hat{M}_{\rm i}^{-1}|1\rangle = g r_1$$

$$|2\rangle = |F=2, m_F=0\rangle \qquad a_2 = g\langle 2|\hat{M}_{\rm g}\hat{M}_{\rm i}^{-1}|2\rangle = g r_2$$

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

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

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

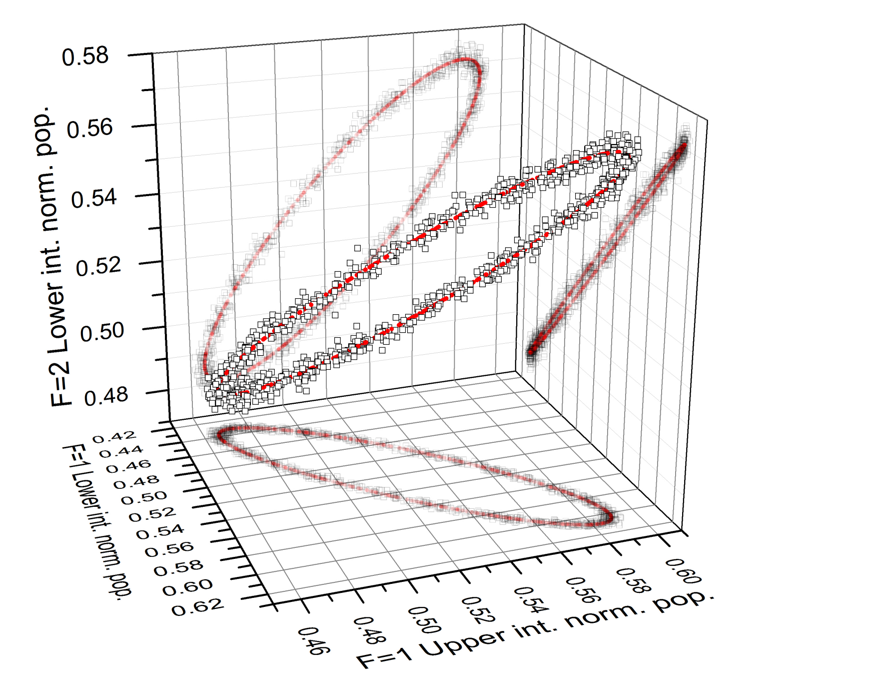


Table 1 | Measurement systematics.

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

Main error contributions affecting the differential acceleration measurement.

$$\eta_{1-2} = (1.0 \pm 1.4) \cdot 10^{-9} \qquad |\mathbf{r_1} - \mathbf{r_2}| \leq \mathbf{10^{-9}}$$

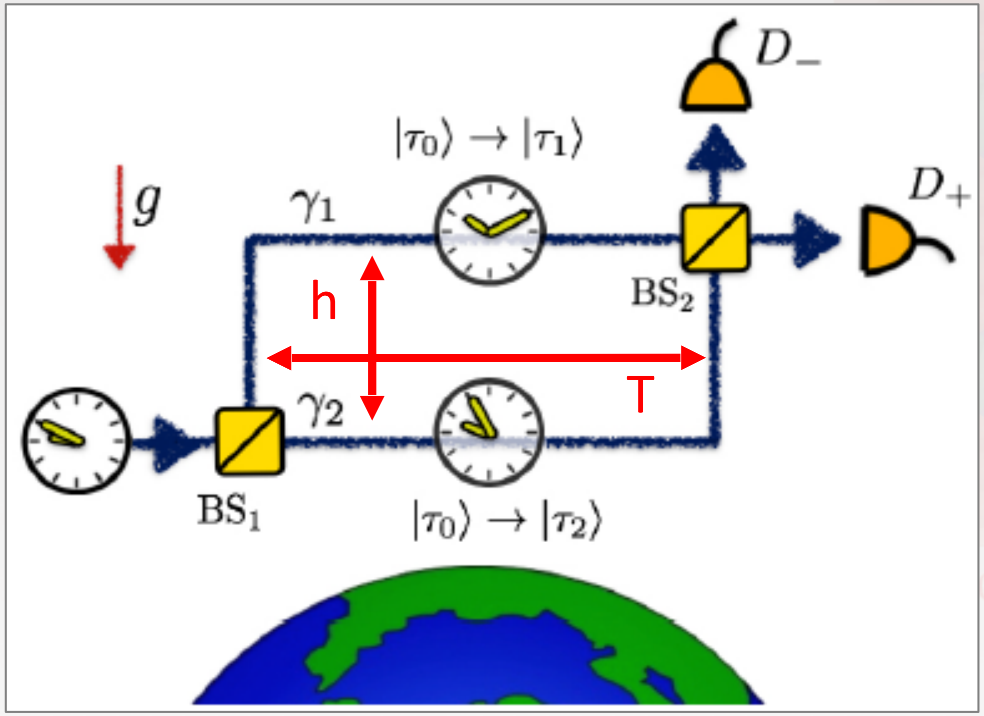
$$\eta_{1-s} = (3.3 \pm 2.9) \cdot 10^{-9} \qquad |\mathbf{r}| \leq \mathbf{5 \cdot 10^{-8}}$$

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

Quantum Interference of Clocks

TICTOC GRAV

Observe gravity induced "decoherence" in clock interferometers

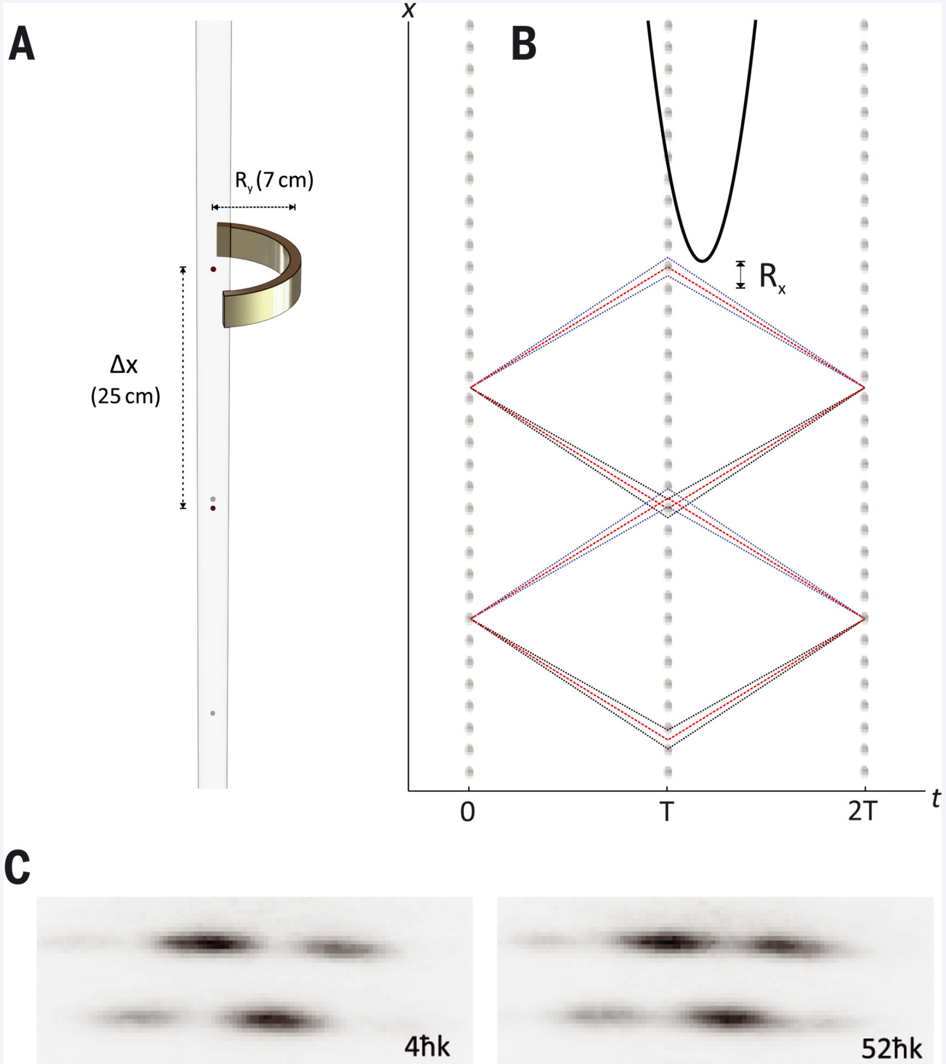


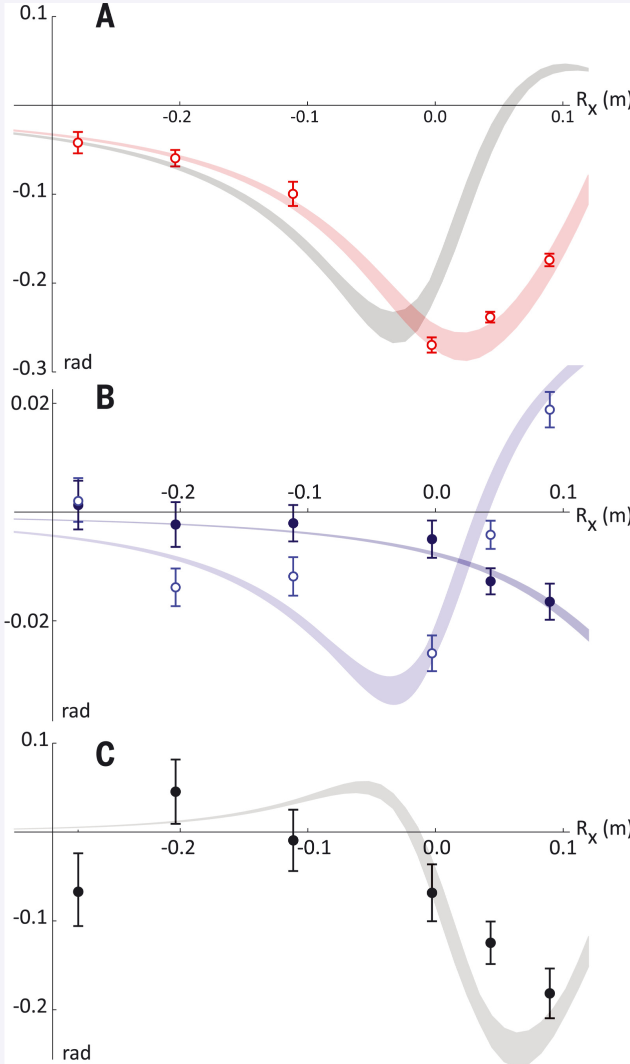
M. Zych et al. Nature Commun. 2(505), 1498 (2011)

- ✓ Quantum superposition of clocks in different locations
  (h = height difference)
- ✓ Dephasing introduced by differential time dilation in the two different paths γ_1 and γ_2
  (T=time)
- ✓ Interferometer contrast loss
- ✓ Decoherence induced by "which path" information from clock state

Test of foundation of quantum mechanics: quantum to classical transition

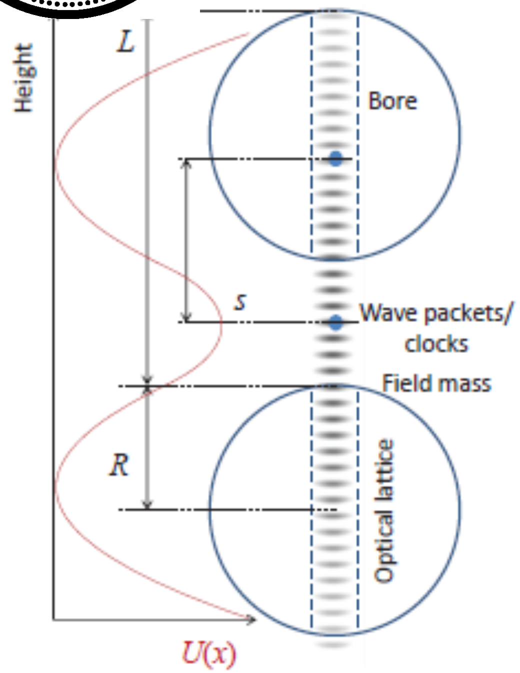
Observation of a gravitational Aharonov-Bohm effect

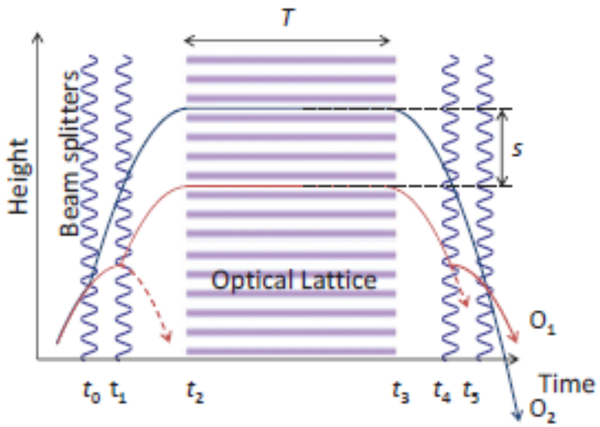


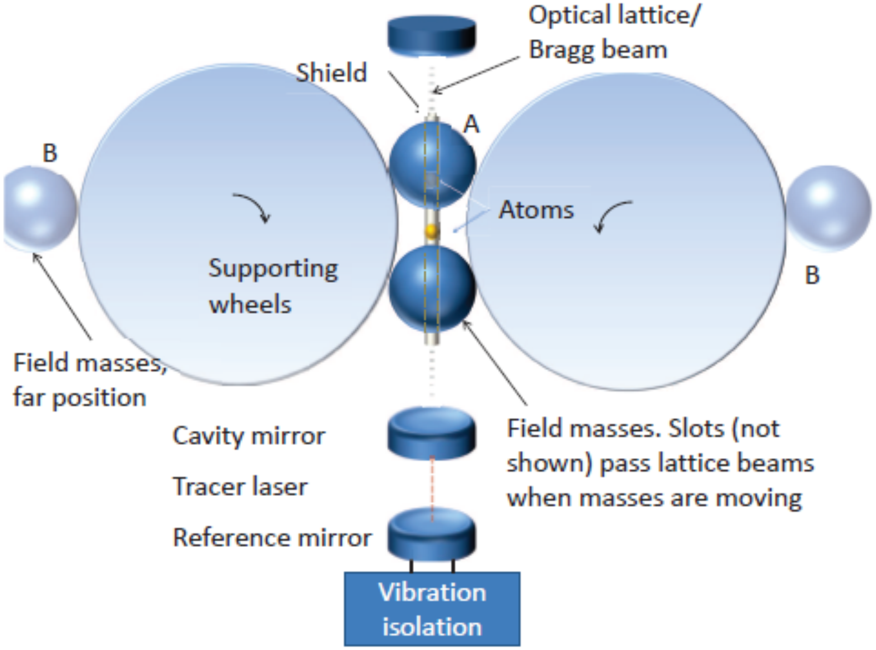


Chris Overstreet, Peter Asenbaum, Joseph Curti, Minjeong Kim, Mark A. Kasevich, *Observation of a gravitational Aharonov-Bohm effect,* Science 375, 226–229 (2022)

Newton's G measured by gravitational Aharonov Bohm effect







Key insight / innovation

- Atom interferometer measures potentials, not force
- Allows probing potential at extremum, where $dU/dx=0$
- W-shaped potential caused by pair of spheres
- Cavity-based interferometer

Technology impact

- At extremum, $dU/dx=0$
- Position of masses/ atoms unimportant, removes major limiting influence
- Cavity: mode filtering, intensity enhancement

Application

- Verification of force-free effect of gravity
- Equal to gravitational redshift of the Compton frequency mc^2/h
- Precision measurement of G at later stage

Hohensee et al., PRL **108,** 230404 (2012)

PHYSICAL REVIEW D **108,** 084038 (2023)

Inference of gravitational field superposition from quantum measurements

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Flaminia Giacomini
Perimeter Institute for Theoretical Physics, 31 Caroline St. N, Waterloo, Ontario, N2L 2Y5, Canada
and Institute for Theoretical Physics, ETH Zürich, 8093 Zürich, Switzerland

(Received 5 September 2022; accepted 19 September 2023; published 17 October 2023)

Experiments are beginning to probe the interaction of quantum particles with gravitational fields beyond the uniform-field regime. In nonrelativistic quantum mechanics, the gravitational field in such experiments can be written as a superposition state. We empirically demonstrate that semiclassical theories of gravity can avoid gravitational superposition states only by decoupling the gravitational field energy from the quantum particle's time evolution. Furthermore, such theories must specify a preferred quantum reference frame in which the equations of motion are valid. To the extent that these properties are theoretically implausible, recent experiments provide indirect evidence that gravity has quantum features. Proposed experiments with superposed gravitational sources would provide even stronger evidence that gravity is nonclassical.

DOI: 10.1103/PhysRevD.108.084038

IOP PUBLISHING — CLASSICAL AND QUANTUM GRAVITY

Class. Quantum Grav. **25** (2008) 105012 (10pp) doi:10.1088/0264-9381/25/10/105012

Metric fluctuations and the weak equivalence principle

Ertan Göklü and Claus Lämmerzahl

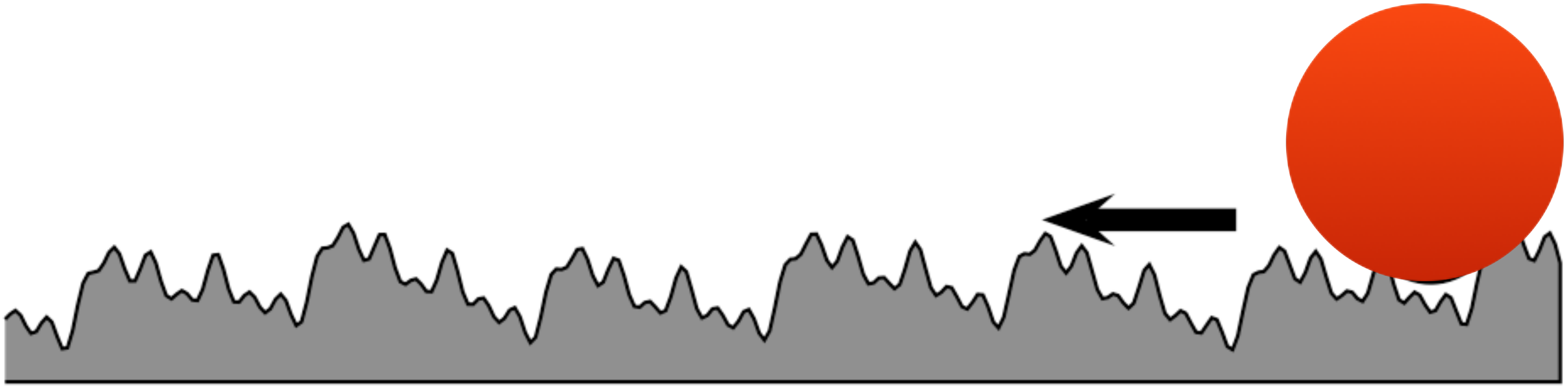
depends on the type of particle and the fluctuation scenario. The scenario considered in this paper is a most simple picture of spacetime fluctuations and gives an existence proof for an apparent violation of the weak equivalence principle and, in general, for a violation of Lorentz invariance.

$$\left(\frac{m_{\rm g}}{m_{\rm i}}\right)_p^i = 1 + \alpha_p^i .$$

$$\alpha_p^i = \left(\frac{l_{\rm Pl}}{\lambda_p}\right)^\beta a^{ii} .$$

from E. Rasel

Equivalence principle for quantum matter



different masses respond differently to the same space–time fluctuations

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu} \qquad g^{(0)} \leftrightarrow \text{background}\,, \quad h \leftrightarrow \text{fluctuations}$$

model: Klein–Gordon equation with mass m in fluctuating space–time leads effectively to a Schrödinger equation with a mass term which depends nonlinearly on the bare mass $m^* = m^*(m)$

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m^*}\Delta\psi + mU(x) \qquad \text{with} \qquad \frac{m^*(m)}{m} = f(m)$$

where $U(x)$ is the Newton potential contained in the background metric leads to mass–dependent, nonvanishing Eötvös coefficient

from E. Rasel

Test of quantum gravity

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]*Dipartimento di Fisica and LENS, Università di Firenze, Sezione INFN di Firenze, Via Sansone 1, 50019 Sesto Fiorentino, Italy*

(Received 22 June 2009; published 21 October 2009)

We use the results of ultraprecise cold-atom-recoil experiments to constrain the form of the energy-momentum dispersion relation, a structure that is expected to be modified in several quantum-gravity approaches. Our strategy of analysis applies to the nonrelativistic (small speeds) limit of the dispersion relation, and is therefore complementary to an analogous ongoing effort of investigation of the dispersion relation in the ultrarelativistic regime using observations in astrophysics. For the leading correction in the nonrelativistic limit the exceptional sensitivity of cold-atom-recoil experiments remarkably allows us to set a limit within a single order of magnitude of the desired Planck-scale level, thereby providing the first example of Planck-scale sensitivity in the study of the dispersion relation in controlled laboratory experiments.

$$E = \sqrt{p^2 + m^2} + \Delta_{QG}(p, m, M_P)$$

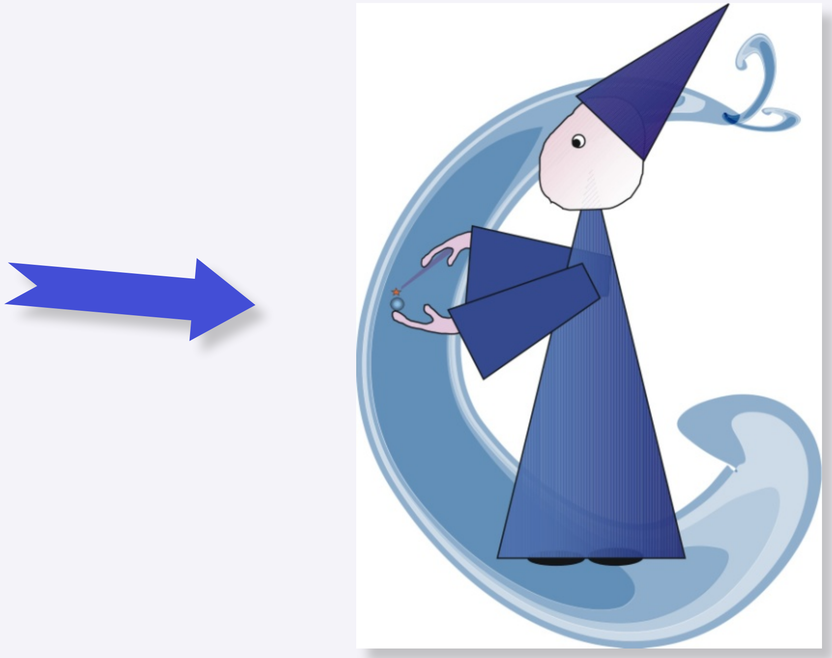
$$E \simeq m + \frac{p^2}{2m} + \frac{1}{2M_P}\left(\xi_1 m p + \xi_2 p^2 + \xi_3 \frac{p^3}{m}\right)$$

$|\xi_1| \sim 1$ to $|\xi_1| \sim 10^3$

$$-6.0 < \xi_1 < 2.4$$

$$|\xi_2| \lesssim 10^9$$

Experiments on gravity at small spatial scale



Motivation

- **Physics beyond the standard model**

Extra space-time dimensions

Deviations from $1/r^2$ law
Hierarchy problem: why is gravity so weak?

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B 429, 263 (1998)
N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Rev. D 59, 086004 (1999)

New boson-exchange forces

Radion – low-mass spin-0 fields with gravitational-strength couplings
Moduli – massive scalar particles producing gravitylike forces
Dilaton – Light scalar in string theory, coupling to nucleons
Axion – pseudoscalar particles explaining smallness of CP violation in QCD for strong nuclear force
Multi-particle exchange forces

S. Dimopoulos and G. F. Giudice, Phys. Lett. B 379, 105 (1996)
I. Antoniadis, S. Dimopoulos, and G. Dvali, Nuc. Phys. B 516,70 (1998)

T.R. Taylor, G. Veneziano, Phys. Lett. B 213, 450 (1988)
D. B. Kaplan, M. B. Wise, J. High Energy Phys. 8, 37 (2000)

Moody and Wilczek, Phys Rev. D 30, 130 (1984)
R. Barbieri, A. Romanino, A. Strumia, Phys. Lett. B 387, 310 (1996)
L.J. Rosenberg, K.A. van Bibber, Phys. Rep. 325, 1 (2000))

- **Small observed size of Einstein cosmological constant**

S.R. Beane, Gen. Rel. Grav. 29, 945 (1997)
R. Sundrum, Phys. Rev. D 69, 044014 (2004)

- **Experimental challenge**

Deviations from Newtonian gravity

- **Modification of power law in Newton-type force**

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

- **Newton+Yukawa potential**

$$V(r) = -G\frac{M_1 M_2}{r}\left[1+\alpha e^{-\frac{r}{\lambda}}\right]$$

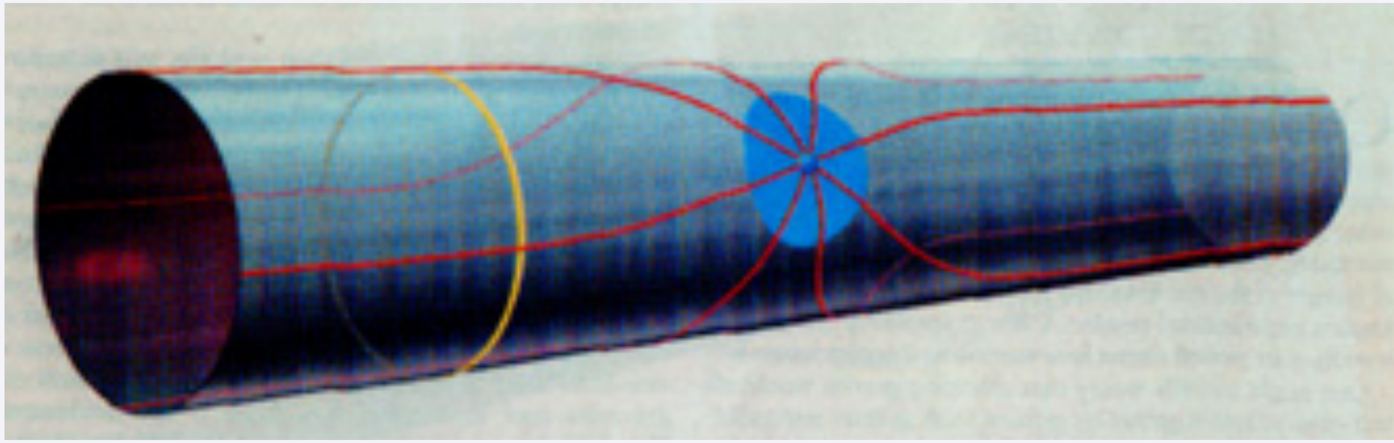
→
- Exchange of a boson with m = ħ/λc
- Extra dimensions

- **Modified power-law potential**

$$V(r) = -G\frac{M_1 M_2}{r}\left[1+\alpha_N\left(\frac{r_0}{r}\right)^{N-1}\right]$$

→ Exchange of 2 massless particles

Extra Dimensions

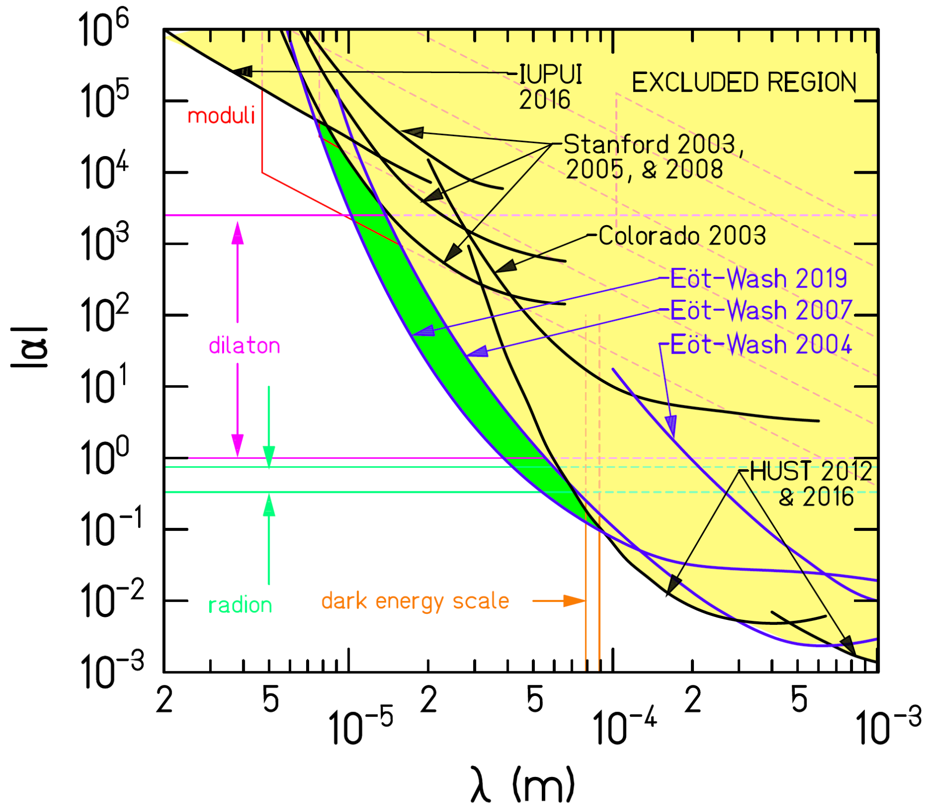


1 extra dimension	$\Rightarrow$	$F \propto 1/r^3$	size $\approx 10^{11}$ m
2 extra dimensions	$\Rightarrow$	$F \propto 1/r^4$	size $\approx 10^{-4}$ m
3 extra dimensions	$\Rightarrow$	$F \propto 1/r^5$	size $\approx 10^{-9}$ m
…			

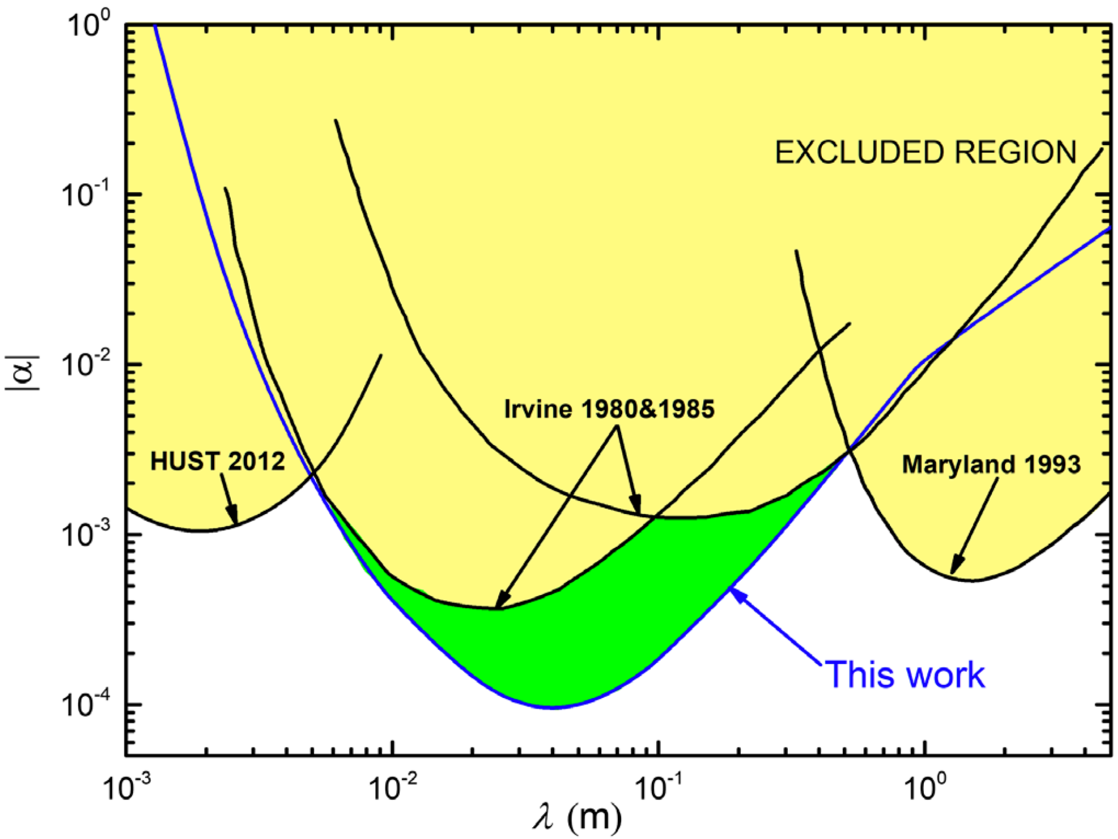
N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *The hierarchy problem and new dimensions at a millimeter*, Phys. Lett. B 429, 263 (1998)

N. Arkani-Hamed, S. Dimopoulos, G. Dvali, *Phenomenology, astrophysics, and cosmology of theories with submillimiter dimensions and TeV scale quantum gravity*, Phys. Rev. D 59, 086004 (1999)

Tests of the gravitational 1/r² law at small distances



J. G. Lee, E. G. Adelberger, T. S. Cook, S. M. Fleischer, and B. R. Heckel, *New Test of the Gravitational 1/r² Law at Separations down to 52 μm*, Phys. Rev. Lett. 124, 101101 (2020)



Jun Ke, Jie Luo, Cheng-Gang Shao, Yu-Jie Tan, Wen-Hai Tan, and Shan-Qing Yang, *Combined Test of the Gravitational Inverse-Square Law at the Centimeter Range,* Phys. Rev. Lett. 126, 211101 (2021)

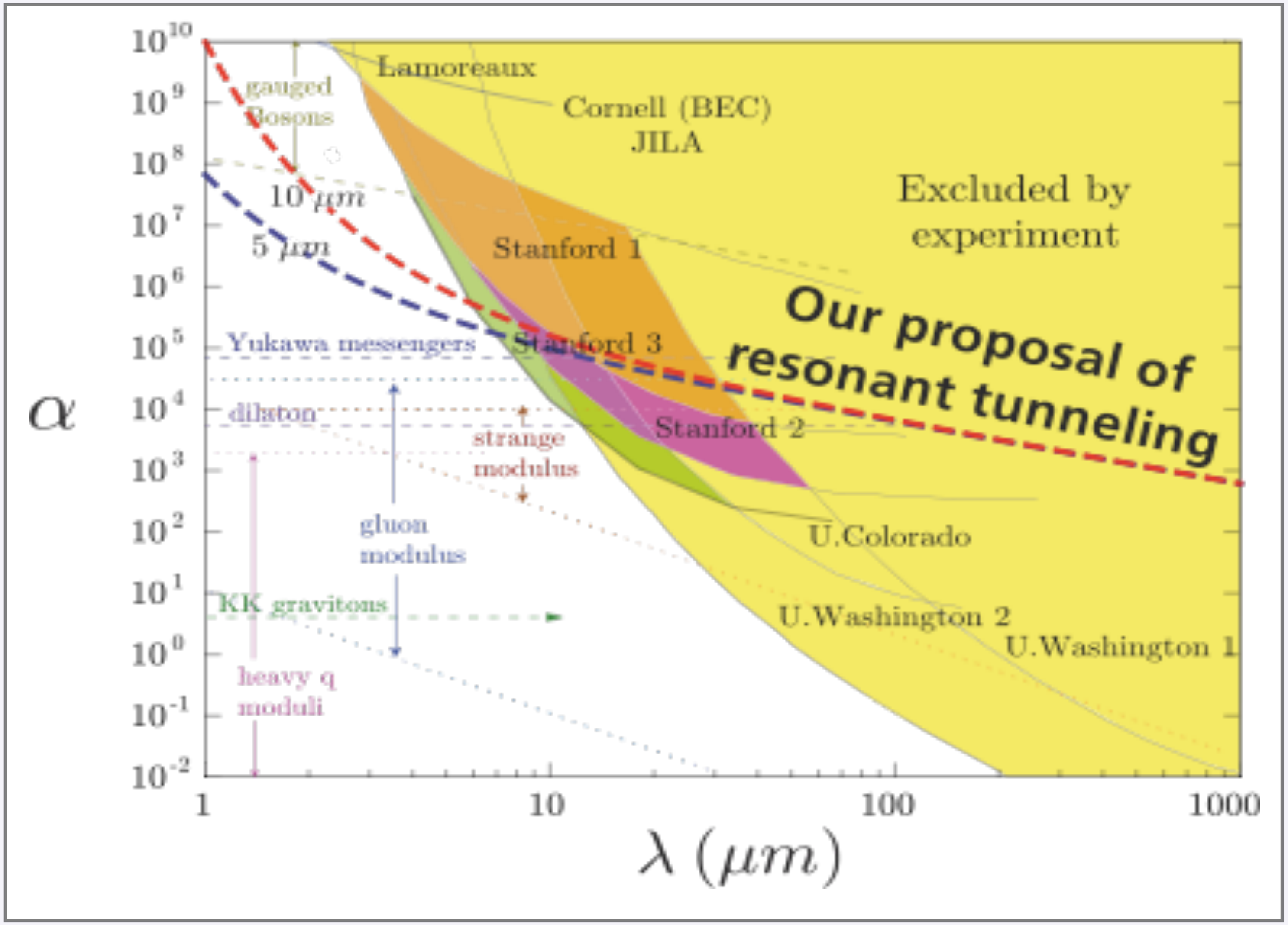
Accessible region with atomic probes

- **Newton+Yukawa potential**

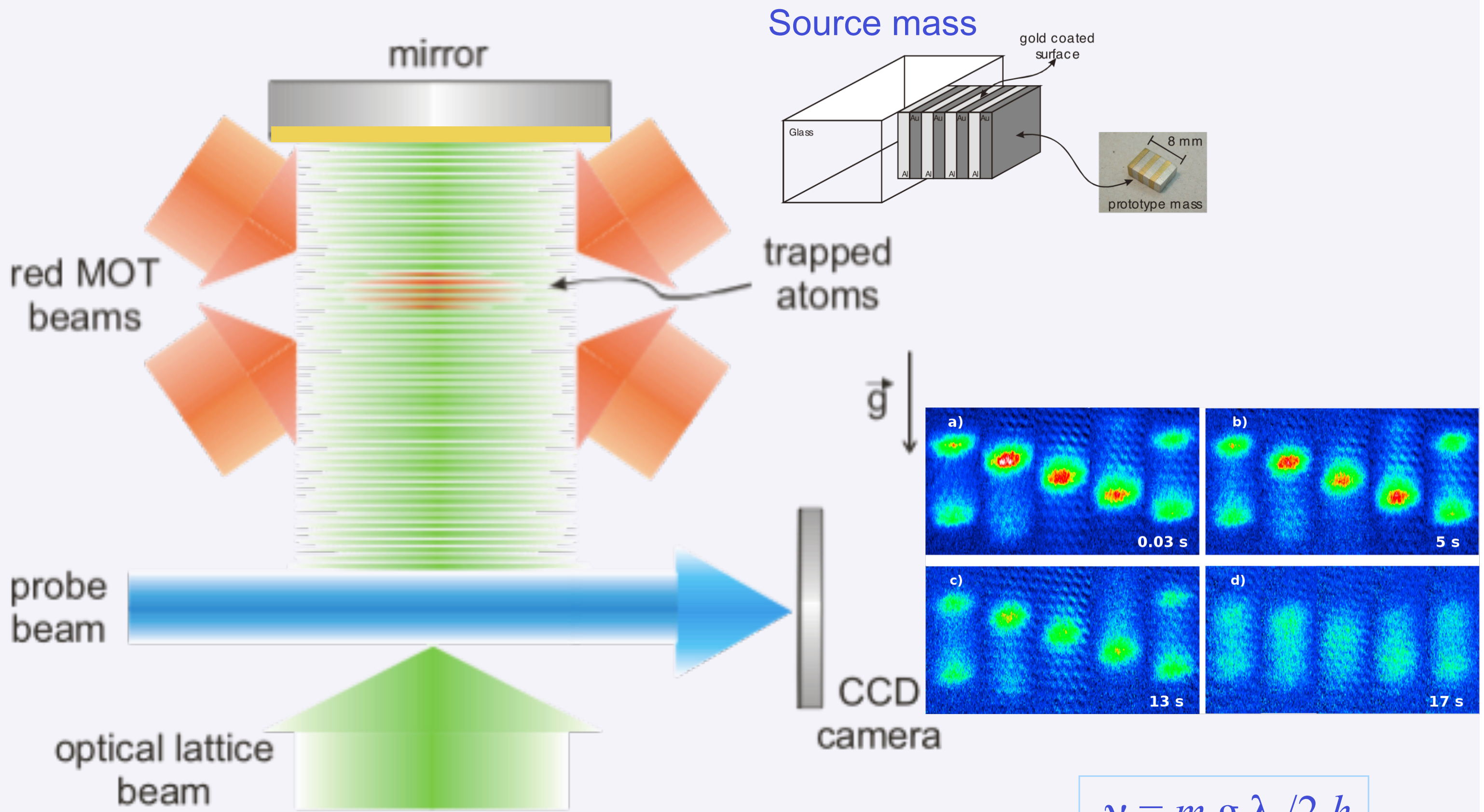
$$V(r) = -G\frac{M_1 M_2}{r}\left[1+\alpha e^{-\frac{r}{\lambda}}\right]$$

→

- Exchange of a boson with m = ħ/λc
- Extra dimensions



Scheme for the measurement of small distance forces



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

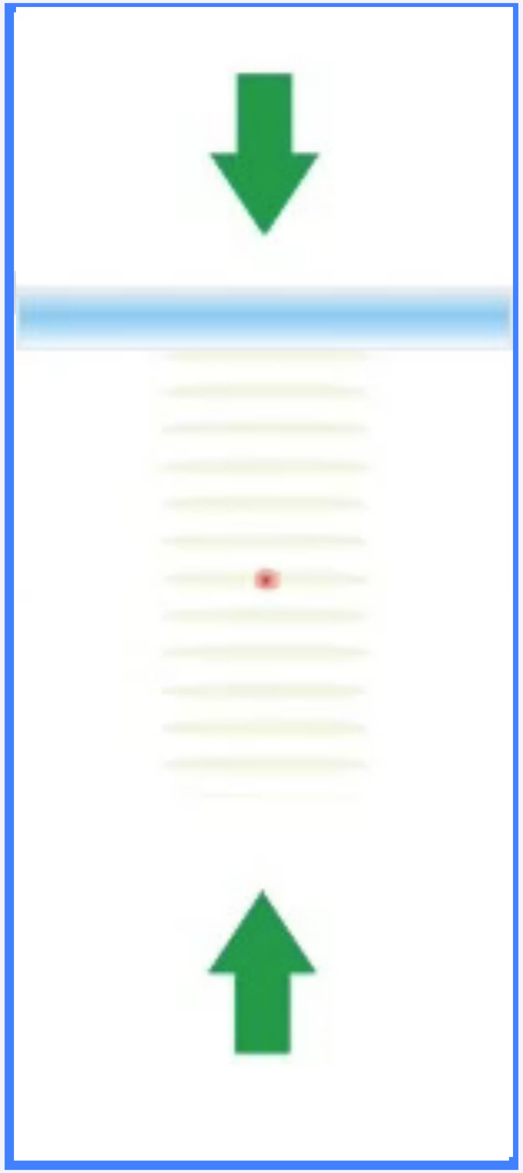
$\nu = m\, a\, \lambda / 2\, h$

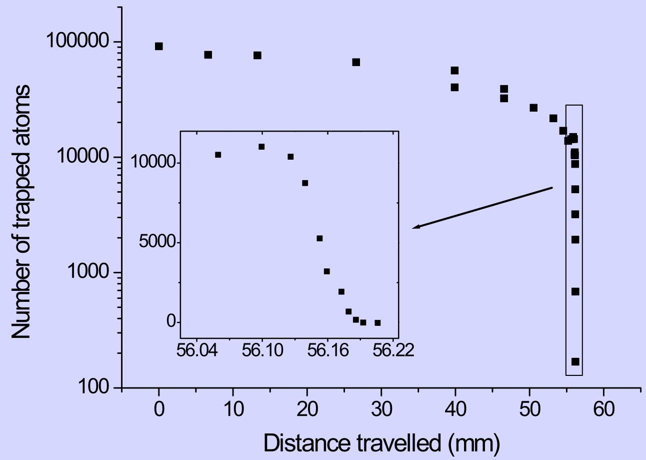
Objective: λ ***= 1-10*** μ***m,*** α ***= 10***^{3}***-10***^{4}

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)

G. M. Tino, *Testing gravity with atom interferometry*, in “Atom Interferometry”, G. M. Tino and M. A. Kasevich (eds), SIF and IOS (2014)

Scheme for the measurement of small distance forces



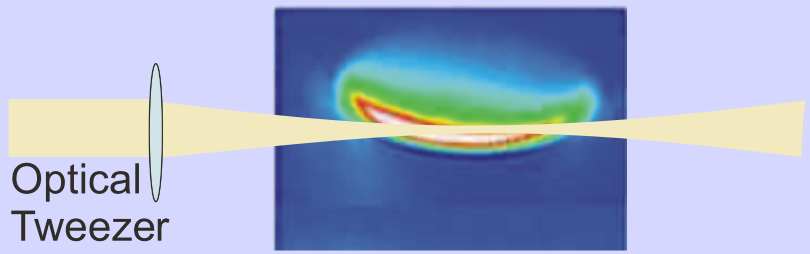


Vertical size of the atomic sample: 15 μm

Atom elevator:

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

Vertical position fluctuations: 3 μm rms



•Vertical size reduced to 4 μm with an optical tweezer

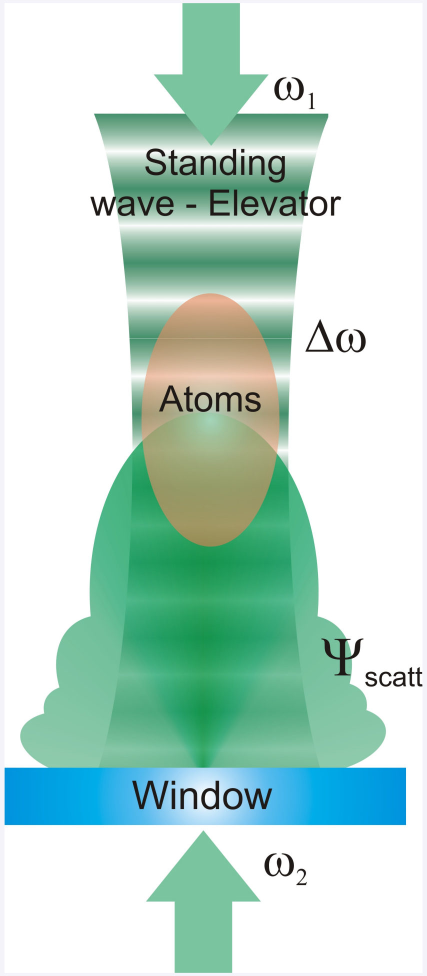
F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 μm*, **Phys. Rev. A 79, 013409 (2009)**

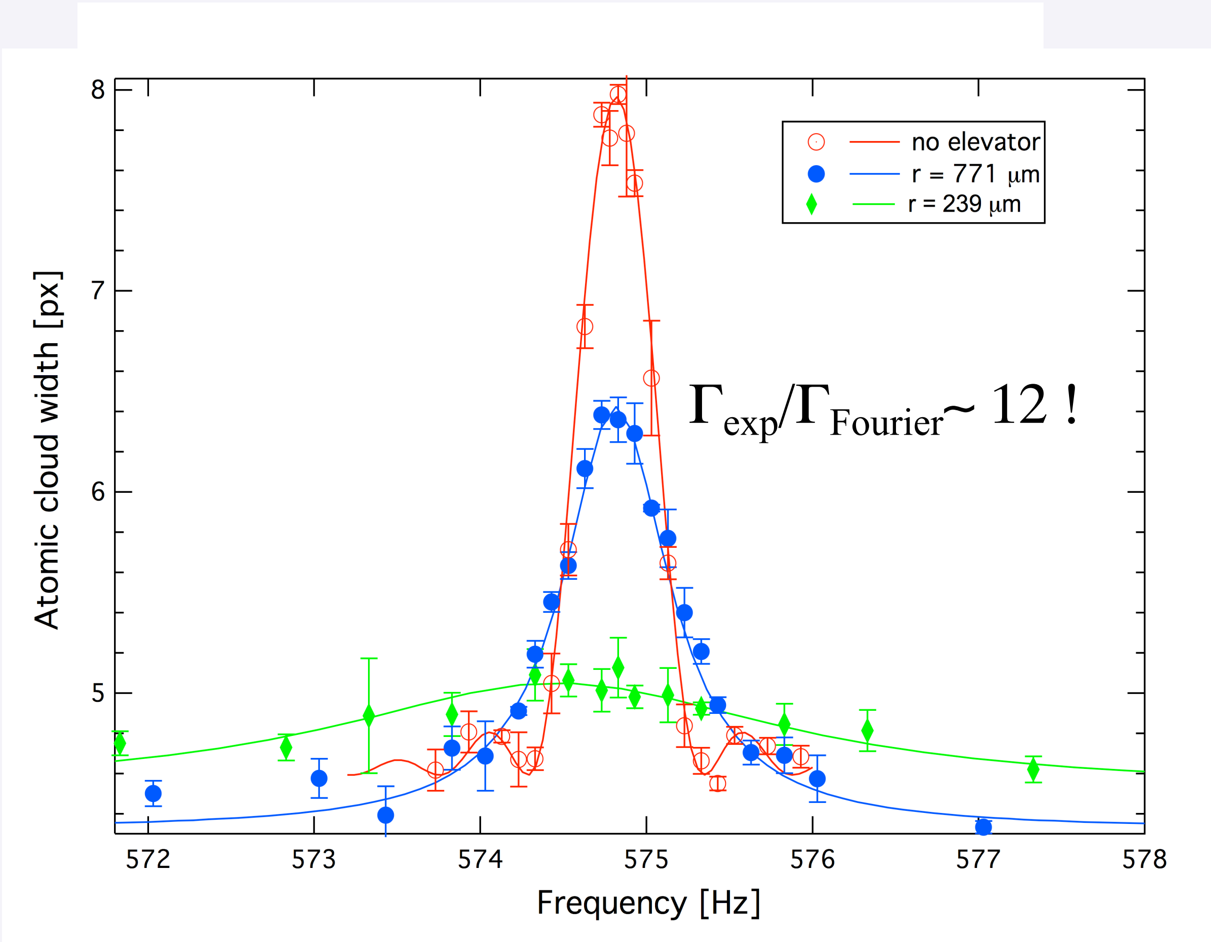
Short-distance measurements

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

⇒ AM measurement close to the surface (preliminary)

Getting closer:





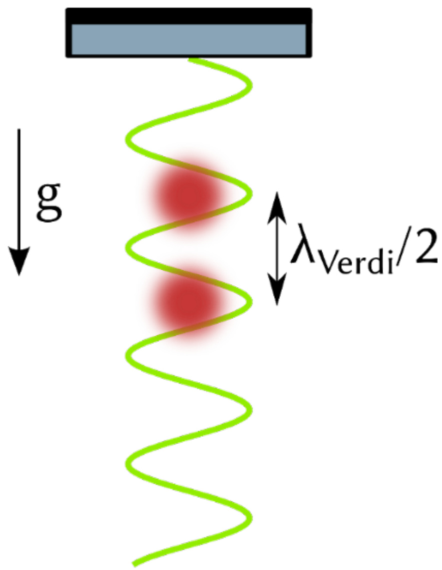
G. M. Tino, *Testing gravity with atom interferometry*, in "Atom Interferometry", G. M. Tino and M. A. Kasevich (eds), SIF and IOS (2014)

Experiment at SYRTE, Paris

Principle of our experiment

l'Observatoire de Paris | SYRTE — Systèmes de Référence Temps-Espace

Atoms trapped in a optical lattice
Lattice created by a laser beam retroreflected on a mirror



Interferometer :
Separate onto neighbouring wells/let evolve/recombine

- Interferometer phase shift:

$$\Delta\Phi \propto \Delta U$$

- **1st case :** far from the mirror $\Delta U = \Delta U_{grav}$
- **2nd case : close to the mirror** $\Delta U = \Delta U_{grav} + \Delta U_{CP} + \Delta U_{Yuk}$

Interest of the lattice:

- excellent control of the atom/surface distance (linked to the wavelength)

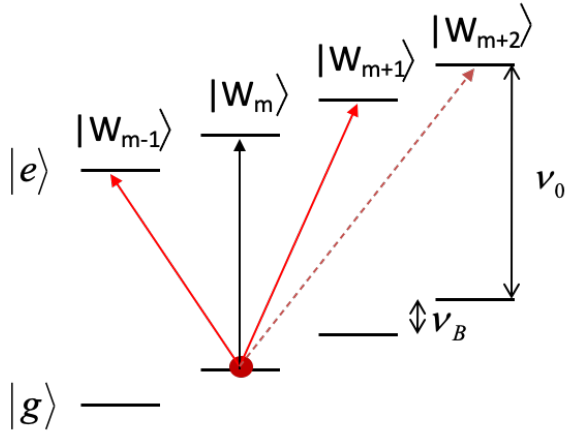
From Franck Pereira Dos Santos, 2024

Yann Balland, Luc Absil, and Franck Pereira Dos Santos, *Quectonewton local force sensor*, arXiv:2310.14717 (2023)

Experiment at SYRTE, Paris

Transitions between Wannier-Stark states

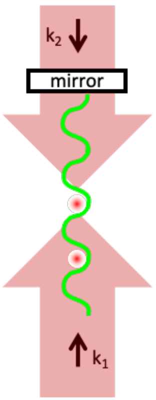
Two electronic states coupled with a laser : **"Laser induced tunneling"**

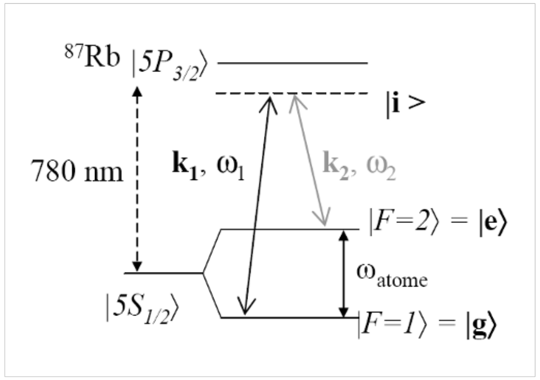


Laser :

$$k_s \sim k_L \Rightarrow |g,m\rangle \rightarrow |e,m+\Delta m\rangle$$

Laser frequency : $\nu = \nu_0 \pm \Delta m \times \nu_B$





2 photon transitions

2 conterpropagating lasers λ = 780 nm

$$k_s \Rightarrow k_{eff} = k_2 - k_1 \sim 2k_{780nm}$$

$$\nu_0 \Rightarrow \nu_R = \nu_{F=2} - \nu_{F=1}$$

From Franck Pereira Dos Santos, 2024

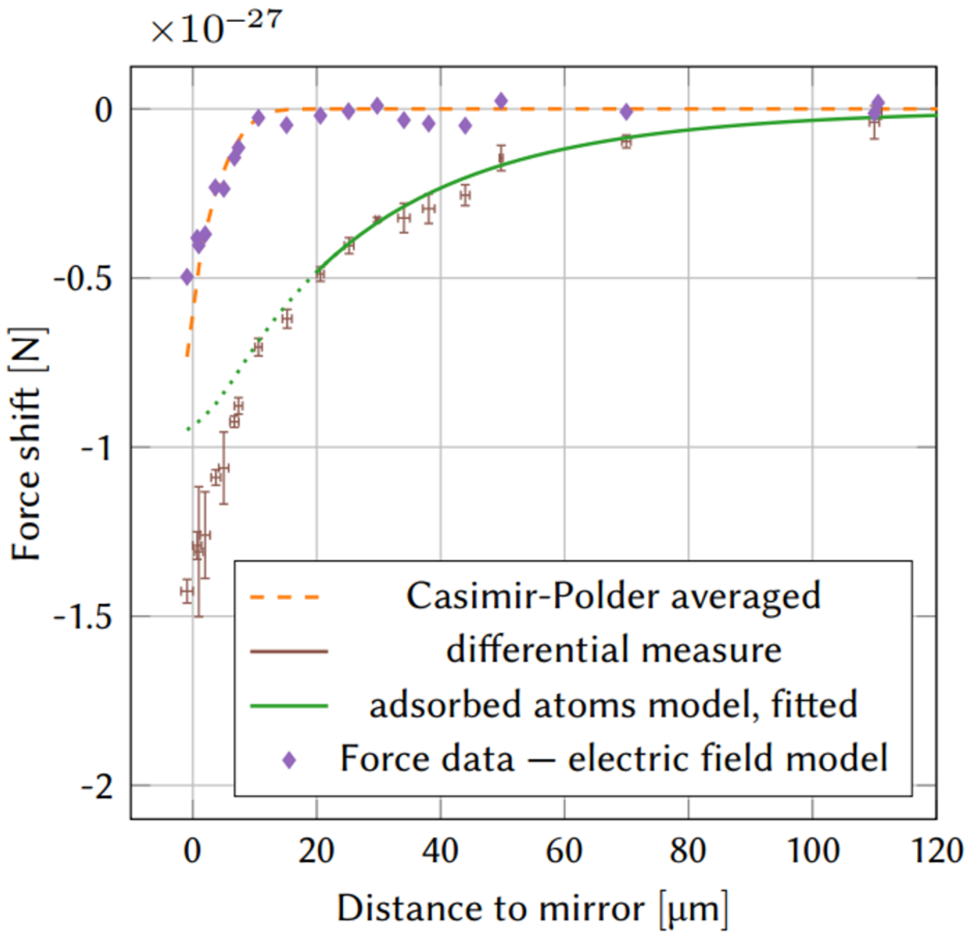
Yann Balland, Luc Absil, and Franck Pereira Dos Santos, *Quectonewton local force sensor*, arXiv:2310.14717 (2023)

Experiment at SYRTE, Paris

Correcting for adsorbed atoms

Unknown N, σ_m
$\Rightarrow$ fit over signal

$N = 2 \times 10^{10}$ atoms,
$\sigma_m = 88\ \mu\text{m} \simeq 2\sigma_x$



Clear evidence for Casimir Polder force

Reasonable agreement with expectations

Few % residuals

From Franck Pereira Dos Santos, 2024

Yann Balland, Luc Absil, and Franck Pereira Dos Santos, *Quectonewton local force sensor*, arXiv:2310.14717 (2023)

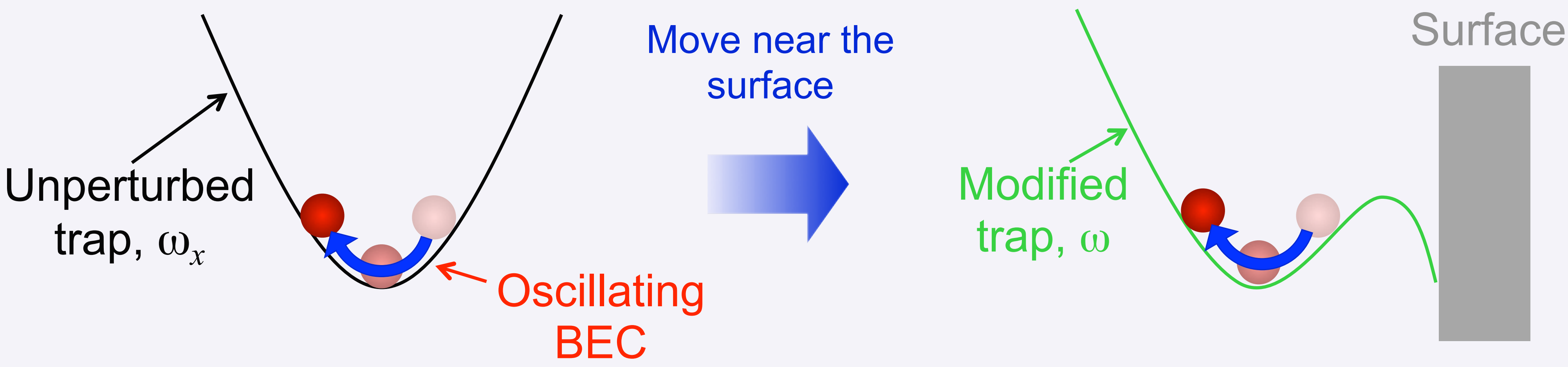
Measuring atom-surface forces

Use trapped BEC as a mechanical oscillator

Measure changes in dipole oscillation frequency

Negative curvature attractive potential

Trap frequency decrease

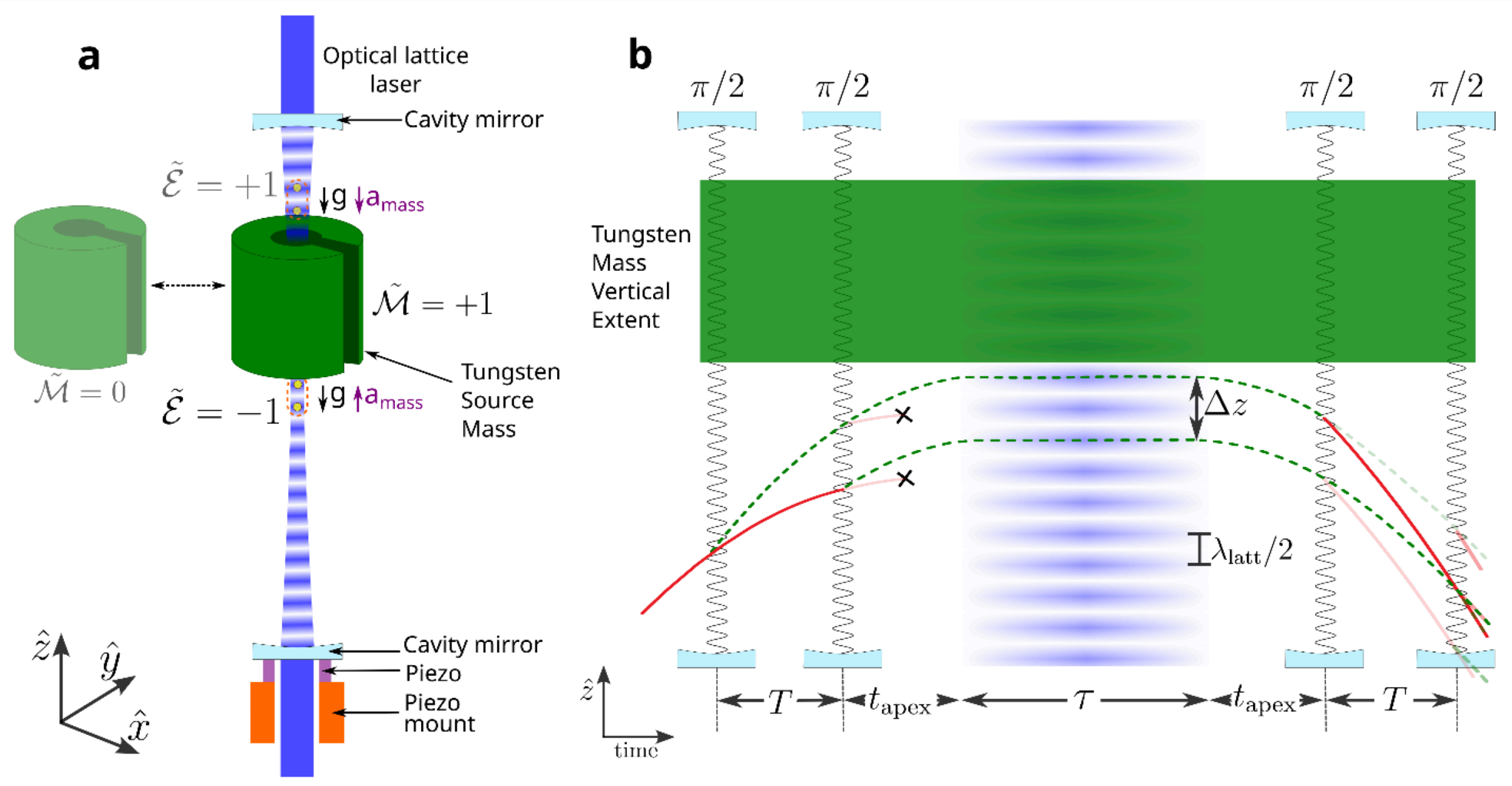


Express trap frequency changes as normalized frequency shifts:

$$\frac{\omega_x - \omega}{\omega_x} \approx -\frac{1}{2\omega_x^2 m} \frac{d^2U}{dx^2}$$

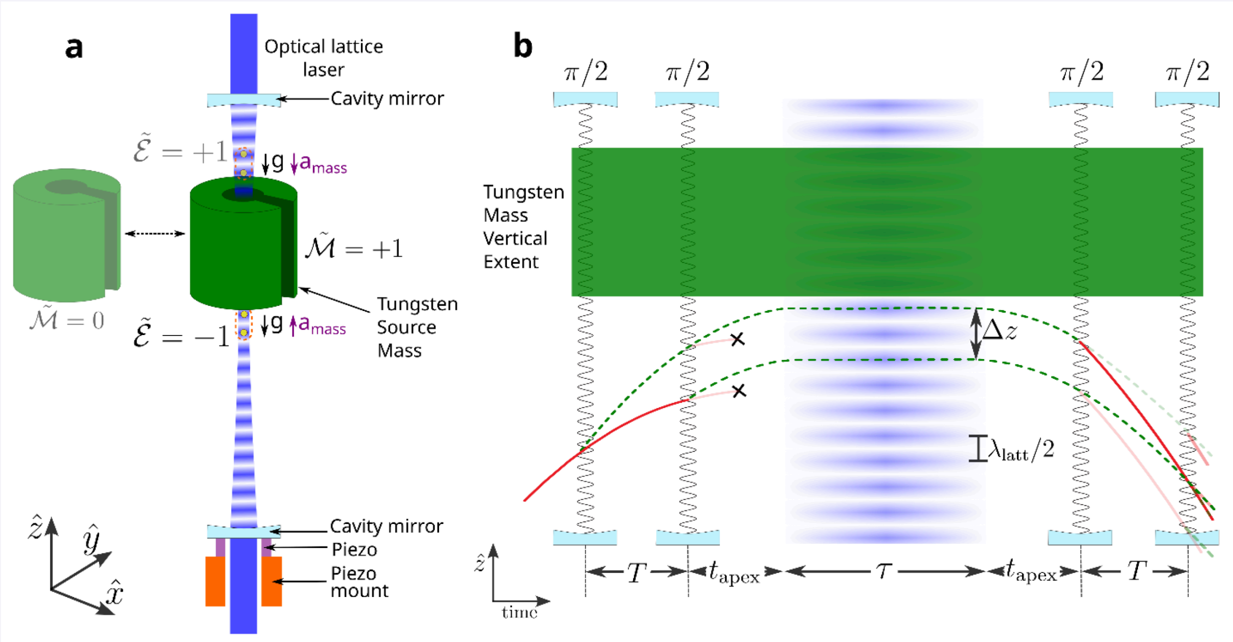
From E.A. Cornell, San Feliu Conference, 2005

D. M. Harber, J. M. Obrecht, J. M. McGuirk, E. A. Cornell, *Measurement of the Casimir-Polder force through center-of-mass oscillations of a Bose-Einstein condensate*, PRA 72, 033610 (2005)



Cristian D. Panda, Matthew J. Tao, Miguel Ceja, Holger Müller,
Measuring gravity by holding atoms, arXiv:2310.01344 (2023)

Search for dark energy



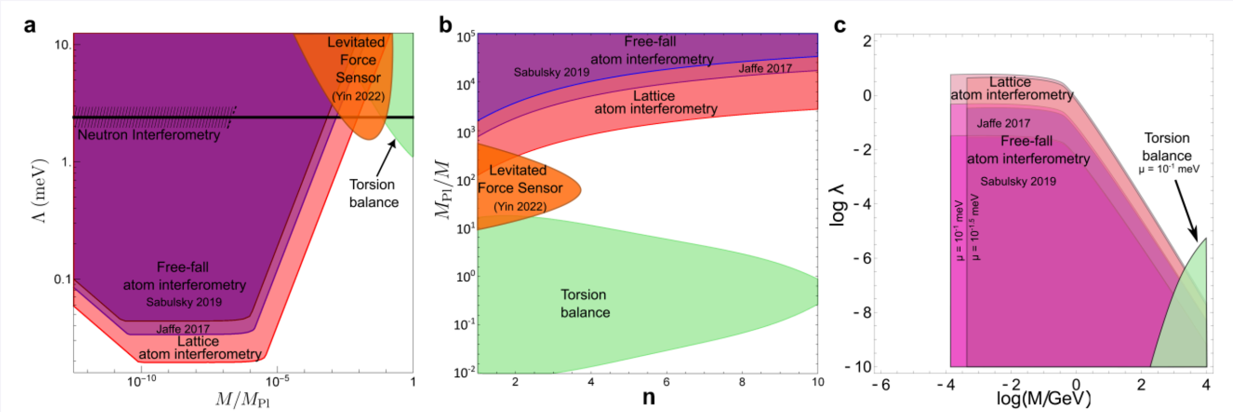
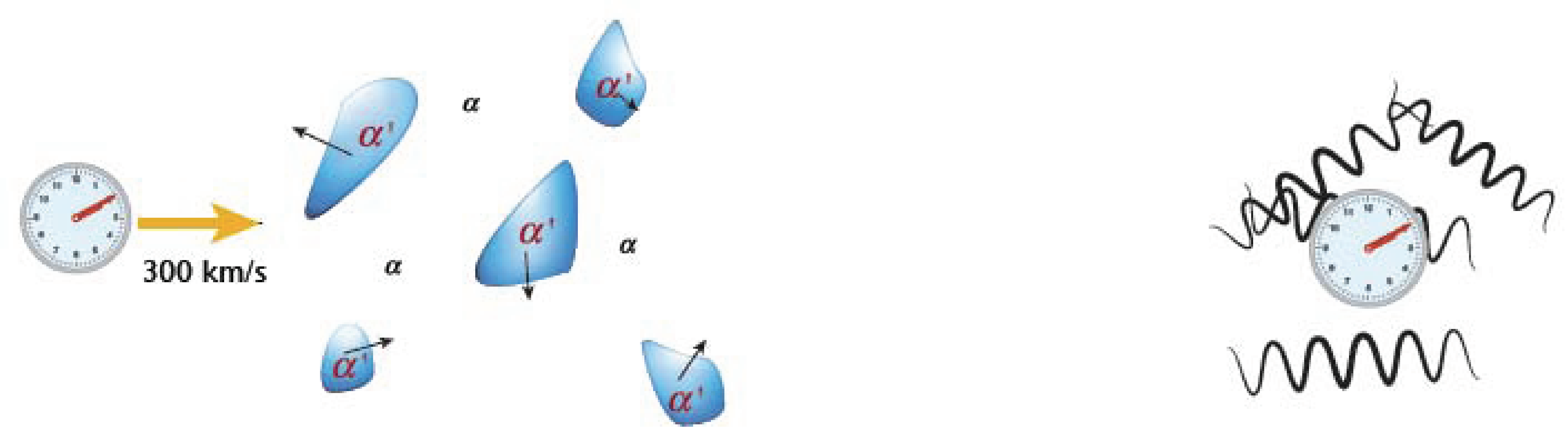


Figure 4. Constraints on chameleon and symmetron dark energy fields. a. Chameleon fields. Shaded areas in the $M - \Lambda$ parameter plane of chameleon field are ruled out (see Ref [4] for definitions). $\Lambda \approx 2.4$ meV (black line) is the dark energy level required to drive cosmic acceleration today. Limits from previous experiments are shown: interferometry with atoms in free-fall[4,5], neutron interferometry[30,31], levitated force sensors[32], and torsion balances[33,34]. **b. Chameleon limits for n>1.** Bounds with $\Lambda \approx 2.4$ meV showing the narrowing gap in which chameleon gap remains viable. n is the power law index describing the shape of the chameleon potential. **c. Symmetron fields.** Constraints from atom interferometers and torsion balance experiments are shown. All shaded areas are ruled out at 95% confidence level.

Cristian D. Panda, Matthew J. Tao, Miguel Ceja, Holger Müller,
Measuring gravity by holding atoms, arXiv:2310.01344 (2023)

Search for dark matter

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].

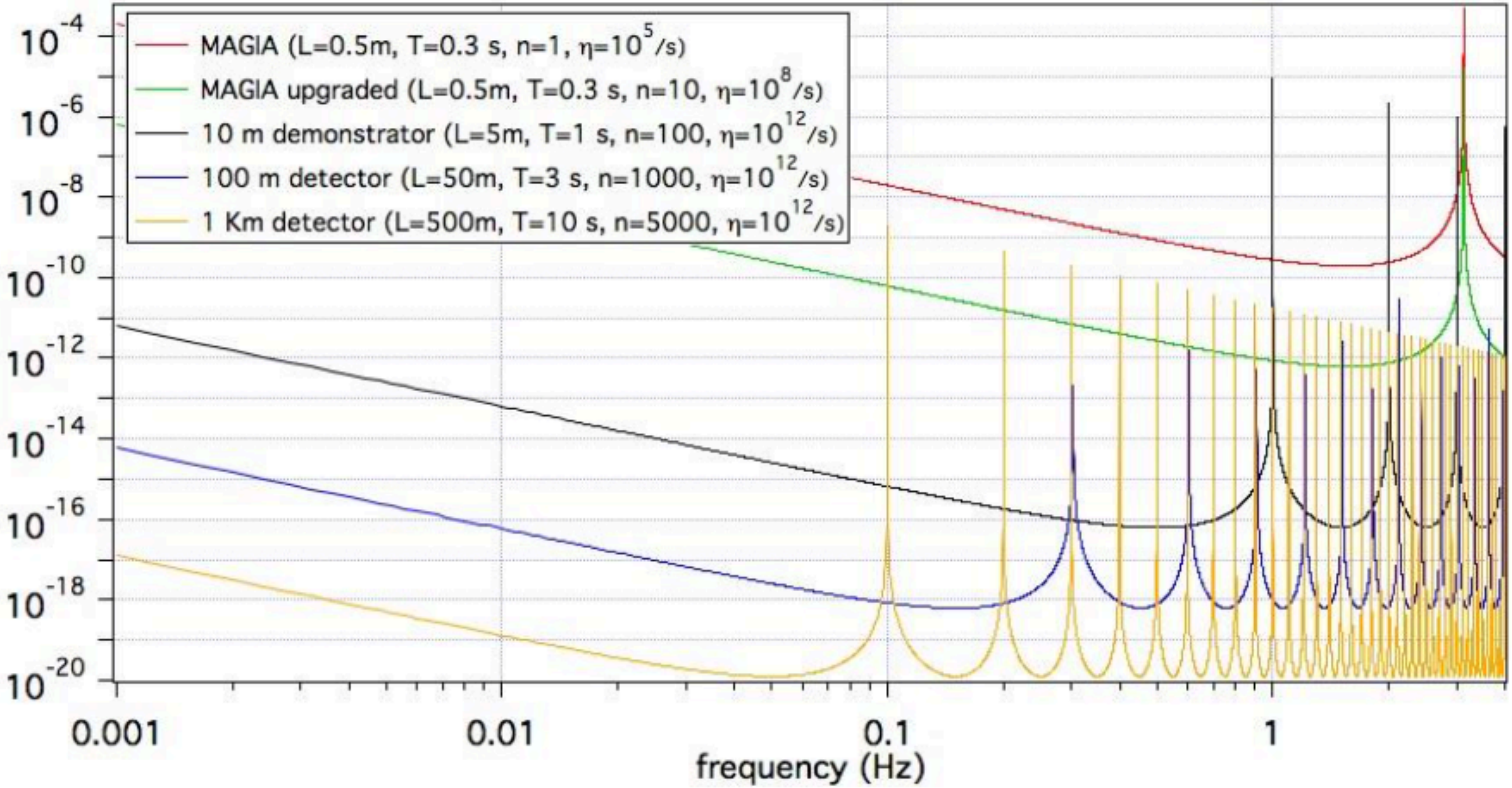
(Right) Ultralight fields can lead to oscillating fundamental constants at the field Compton frequency. By Fourier-transforming a time series of clock frequency measurements, one could search for peaks in the power spectrum and potentially identify DM presence [A. Arvanitaki, J. Huang, and K. Van Tilburg.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

G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,*
Eur. Phys. J. D 73, 228 (2019)

Toward atomic gravitational wave detectors

Shot noise limited (diff. configuration)

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



Gravitational wave detection with atom interferometry

Main ideas

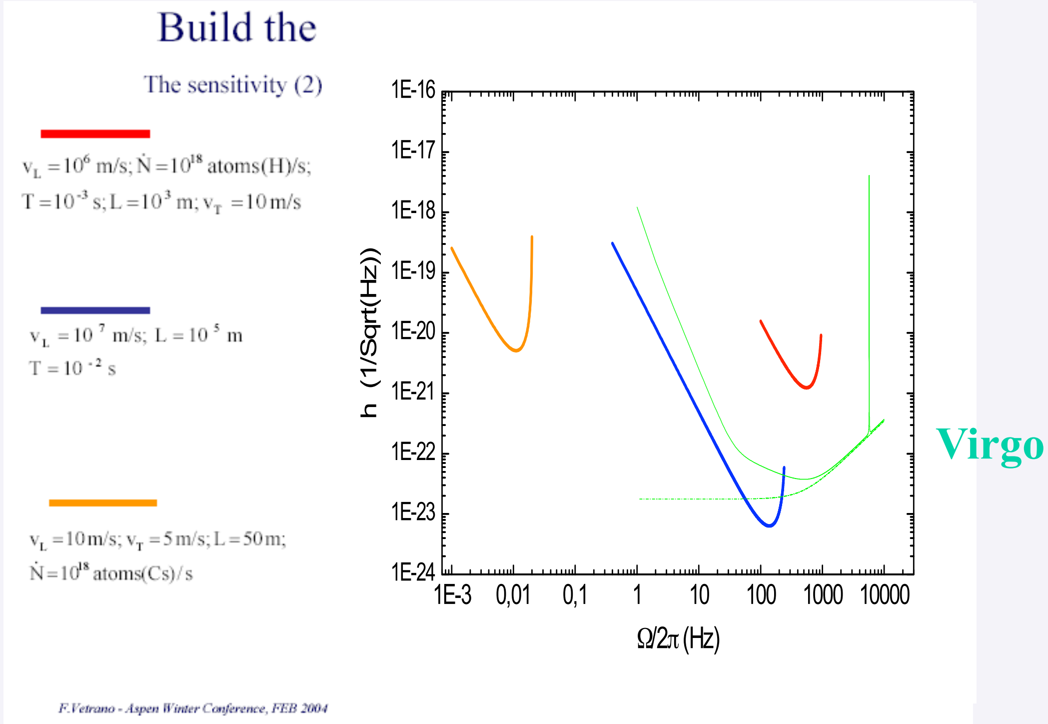
- Detection of GWs by matter waves
- Drastic reduction of critical noise sources
- Addressing new interesting frequency ranges

Gravitational wave 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



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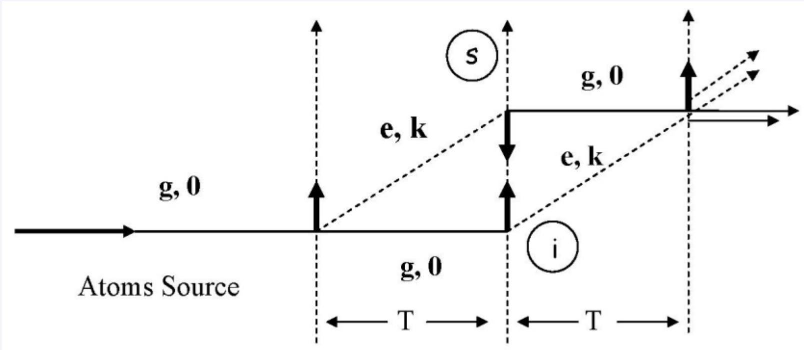
- C. Bordè, G. M. Tino, F. Vetrano, "Can we use atom interferometers in searching for gravitational waves?", 2004 Aspen Winter College on Gravitational Waves. Available online at: http://www.ligo.caltech.edu/LIGO_web/Aspen2004/pdf/vetrano.pdf
- A. Roura, D.R. Brill, B. L. Hu, C.W. Misner, W.D. Phillips, "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)

Gravitational wave detection with atom interferometry

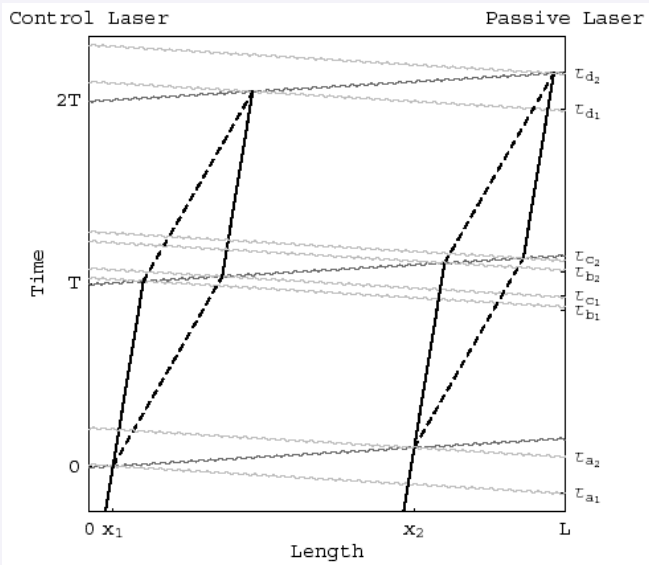
• *Single atom interferometer*

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



• *Differential scheme*

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



UNIVERSITÀ DEGLI STUDI FIRENZE

October 14, 2008

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Gravitational Waves Detection with Atom Interferometry

Conference

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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

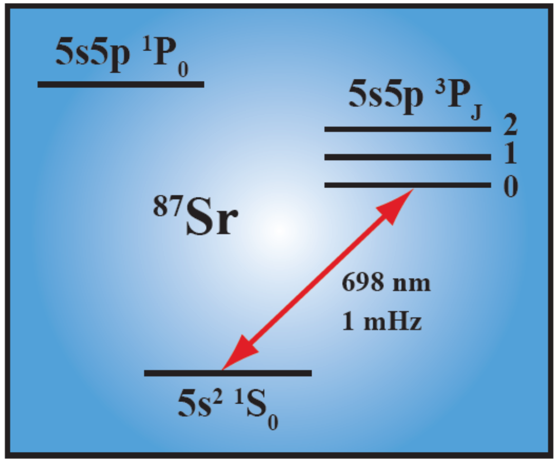
Note: The number of participants is limited to 50 The participation fee for the Workshop is 150 Euros including registration, coffee-breaks, lunches and the social dinner. The fee should be paid cash on arrival at the registration desk

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)

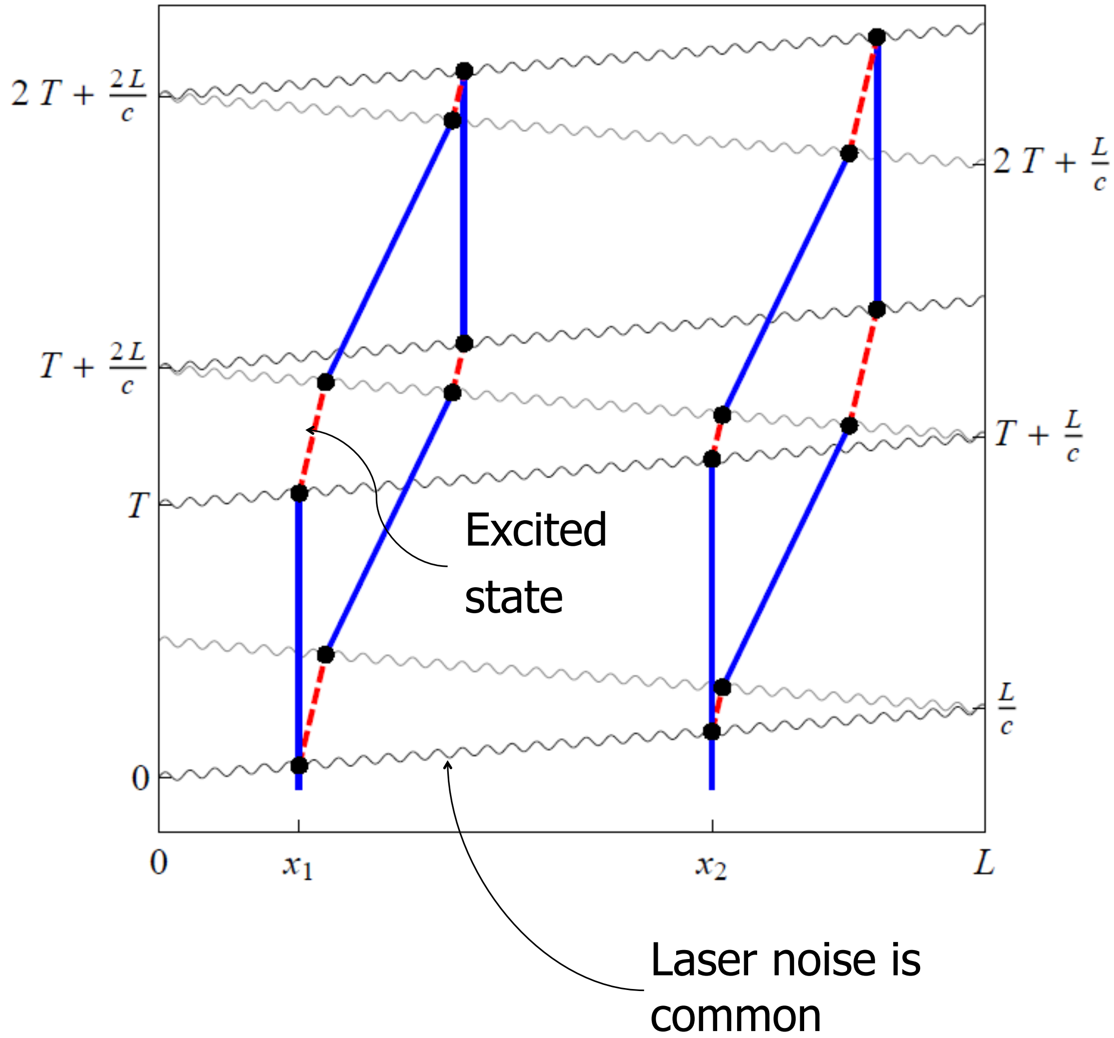
Laser frequency noise insensitive detector



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)

Testing gravity with atomic clocks

Gravitational red shift

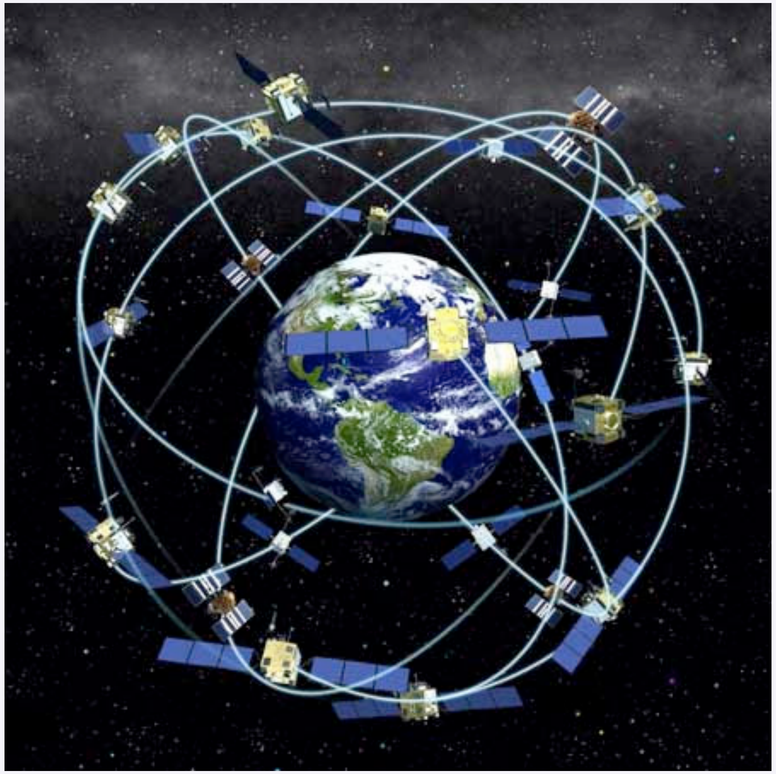
A clock close to a massive body runs slower

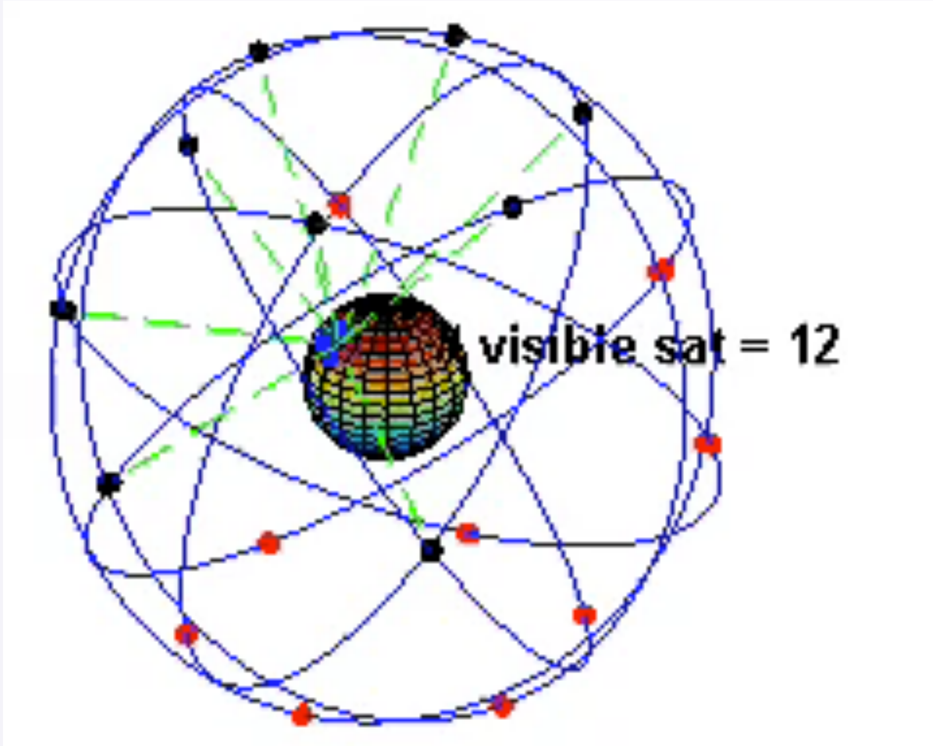
$$\frac{\nu - \nu_0}{\nu_0} = -\frac{GM}{c^2 r}$$

At a distance h from the surface of the Earth $\rightarrow$

$$\frac{\nu_h - \nu_T}{\nu_T} = \frac{gh}{c^2} \cong 10^{-16} / m$$

GPS (→ GALILEO)





The current GPS configuration consists of a network of 24 satellites in high orbits around the Earth. Each satellite in the GPS constellation orbits at an altitude of about 20,000 km from the ground, and has an orbital speed of about 14,000 km/hour (the orbital period is roughly 12 hours). Each satellite carries with it an atomic clock.

Because an observer on the ground sees the satellites in motion relative to them, Special Relativity predicts that we should see their clocks ticking more slowly. Special Relativity predicts that the on-board atomic clocks on the satellites should fall behind clocks on the ground by about 7 microseconds per day because of the slower ticking rate due to the time dilation effect of their relative motion.

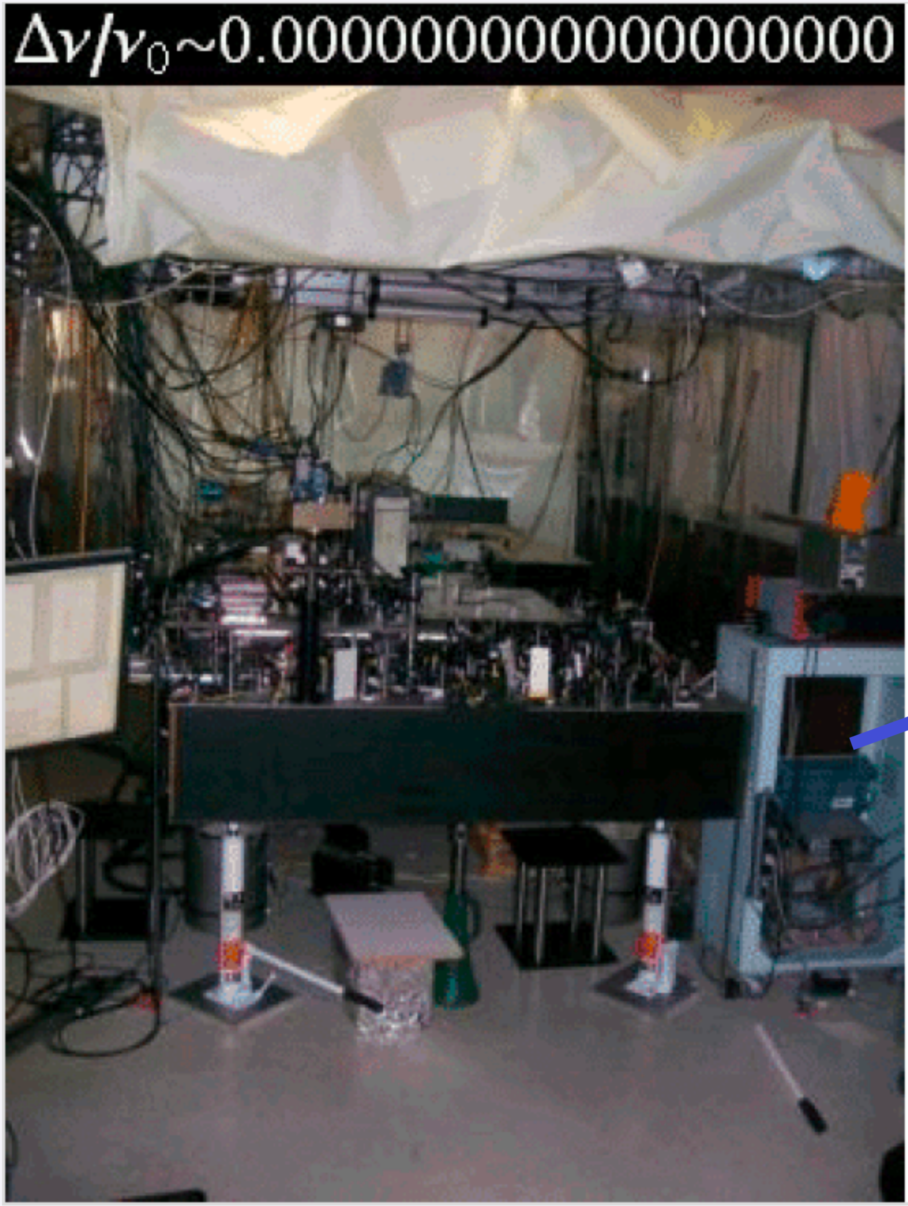
The satellites are in orbits high above the Earth, where the curvature of spacetime due to the Earth's mass is less than it is at the Earth's surface. As such, when viewed from the surface of the Earth, the clocks on the satellites appear to be ticking faster than identical clocks on the ground. A calculation using General Relativity predicts that the clocks in each GPS satellite should get ahead of ground-based clocks by 45 microseconds per day.

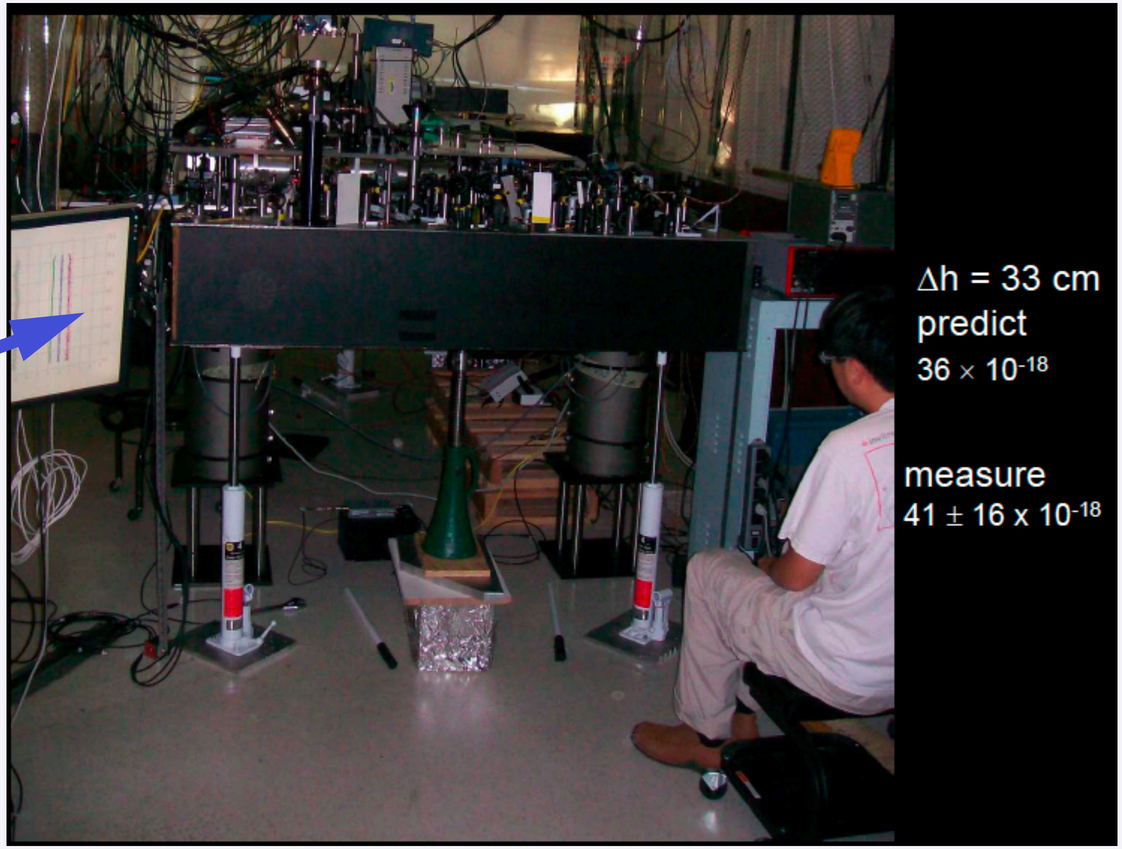
The combination of these two relativitic effects means that the clocks on-board each satellite should tick faster than identical clocks on the ground by about 38 microseconds per day

→ **If these effects were not properly taken into account, errors in global positions would continue to accumulate at a rate of about 10 km/day.**

From Wikipedia

Measure gravitational red shift in the lab





"David J. Wineland - Nobel Lecture: Superposition, Entanglement, and Raising Schroedinger´s Cat". Nobelprize.org. 7 Feb 2013 http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/wineland-lecture.html

Measure gravitational red shift in the lab

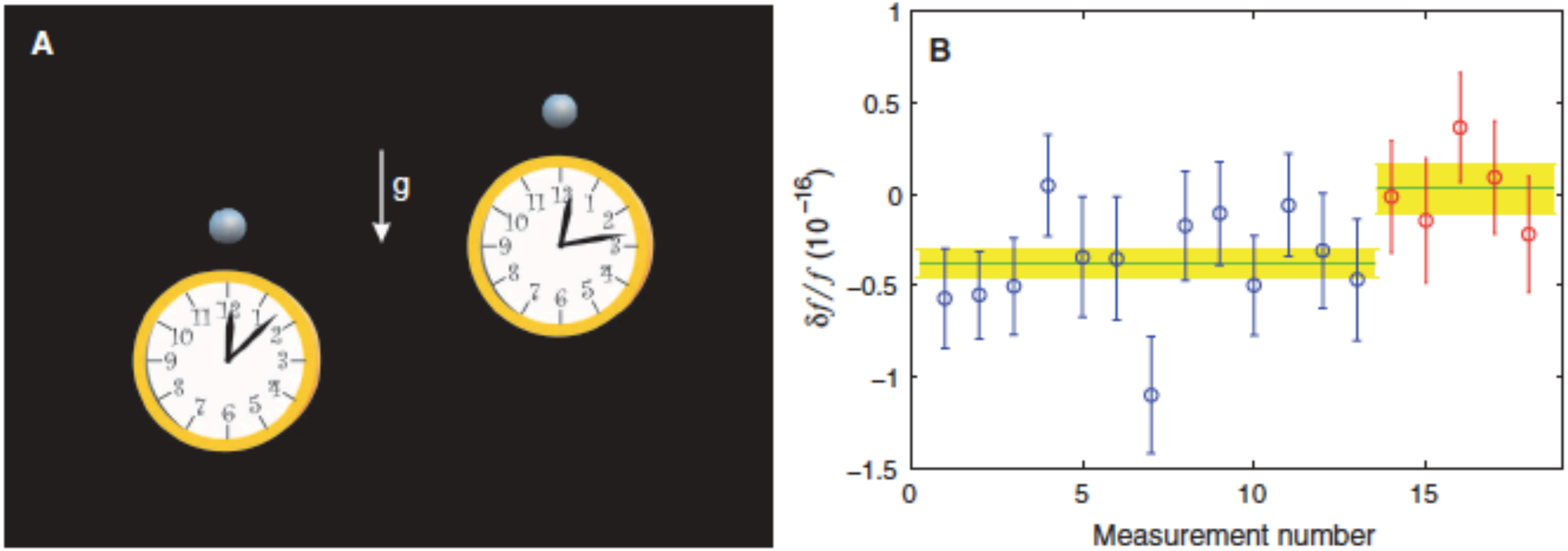


Fig. 3. Gravitational time dilation at the scale of daily life. **(A)** As one of the clocks is raised, its rate increases when compared to the clock rate at deeper gravitational potential. **(B)** The fractional difference in frequency between two Al^+ optical clocks at different heights. The Al-Mg 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 329, 1630 (2010)

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LENS European Laboratory for Non-Linear Spectroscopy

INFN

nature photonics

PUBLISHED ONLINE: 9 FEBRUARY 2015

Cryogenic optical lattice clocks

Ichiro Ushijima[1,2,3†], Masao Takamoto[1,2,4†], Manoj Das[1,2,4], Takuya Ohkubo[1,2,3] and Hidetoshi Katori[1,2,3,4*]

The accuracy of atomic clocks relies on the superb reproducibility of atomic spectroscopy, which is accomplished by careful control and the elimination of environmental perturbations on atoms. To date, individual atomic clocks have achieved a 10^{-18} level of total uncertainties[1,2], but a two-clock comparison at the 10^{-18} level has yet to be demonstrated. Here, we demonstrate optical lattice clocks with ^{87}Sr atoms interrogated in a cryogenic environment to address the blackbody radiation induced frequency ...

larger susceptibility[7] than Al clock, requiring deep-ultravio... and demonstrated[24] because ... Generally, atoms easily acces... lasers tend to show higher s... relatively large static polariz... celled out coincidentally. ...

nature COMMUNICATIONS

ARTICLE

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DOI: 10.1038/ncomms7896

OPEN

Systematic evaluation of an atomic clock at 2×10^{-18} total uncertainty

T.L. Nicholson[1,2], S.L. Campbell[1,2], R.B. Hutson[1,2], G.E. Marti[1,2], B.J. Bloom[1,2,†], R.L. McNally[1,2], W. Z... M.D. Barrett[1,3], M.S. Safronova[4,5], G.F. Strouse[6], W.L. Tew[6] & J. Ye[1,2]

The pursuit of better atomic clocks has advanced many research areas, providing better quantum state control, new insights in quantum science, tighter limits on fundamental constant variation and improved tests of relativity. The record for the best stability and accuracy is currently held by optical lattice clocks. Here we take an important step towards realizing the full potential of a many-particle clock with a state-of-the-art stable laser. Our ^{87}Sr optical lattice clock now achieves fractional stability of 2.2×10^{-16} at 1 s. With this improved stability, we perform a new accuracy evaluation of our clock, reducing many systematic uncertainties that limited our previous measurements, such as those in the lattice ac Stark shift, the atoms' thermal environment and the atomic response to room-temperature blackbody radiation. Our combined measurements have reduced the total uncertainty of the JILA Sr clock to 2.1×10^{-18} in fractional frequency units.

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NATURE | RESEARCH HIGHLIGHTS

METROLOGY

Atomic clock smashes records

Nature **520**, 589 (30 April 2015) | doi:10.1038/520589a
Published online 29 April 2015

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Subject terms: Physics

The world's best atomic clock has become even more accurate, neither gaining nor losing a second over 15 billion years — longer than the age of the Universe.

The clock keeps time using 2,000 ultracold strontium atoms trapped in a laser lattice. Its pendulum is a laser that has a frequency tuned to resonate with that of the photons that are released and absorbed by the atoms as they switch between two energy states. By using a more stable laser and by reducing the effects of environmental perturbations, Jun Ye at the JILA institute in Boulder, Colorado, and his team made the 'ticks' of the timepiece more uniform. This increased the clock's accuracy by three times compared with the previous record.

The result brings strontium-based optical clocks closer to replacing the current standard for time measurement, the caesium fountain clock, which makes lower-frequency atomic transitions.

Nature Commun. **6**, 6896 (2015)

Gravitational redshift at millimetre scale

Article — *Nature* **volume 602**, pages 420–424 (2022)

Resolving the gravitational redshift across a millimetre-scale atomic sample

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Received: 24 September 2021
Accepted: 13 December 2021
Published online: 16 February 2022
Check for updates

Tobias Bothwell[1]✉, Colin J. Kennedy[1,2], Alexander Aeppli[1], Dhruv Kedar[1], John M. Robinson[1], Eric Oelker[1,3], Alexander Staron[1] & Jun Ye[1]✉

Einstein's theory of general relativity states that clocks at different gravitational potentials tick at different rates relative to lab coordinates—an effect known as the gravitational redshift[1]. As fundamental probes of space and time, atomic clocks have long served to test this prediction at distance scales from 30 centimetres to thousands of kilometres[2–4]. Ultimately, clocks will enable the study of the union of general relativity and quantum mechanics once they become sensitive to the finite wavefunction of quantum objects oscillating in curved space-time. Towards this regime, we measure a linear frequency gradient consistent with the gravitational redshift within a single millimetre-scale sample of ultracold strontium. Our result is enabled by improving the fractional frequency measurement uncertainty by more than a factor of 10, now reaching 7.6×10^{-21}. This heralds a new regime of clock operation necessitating intra-sample corrections for gravitational perturbations.

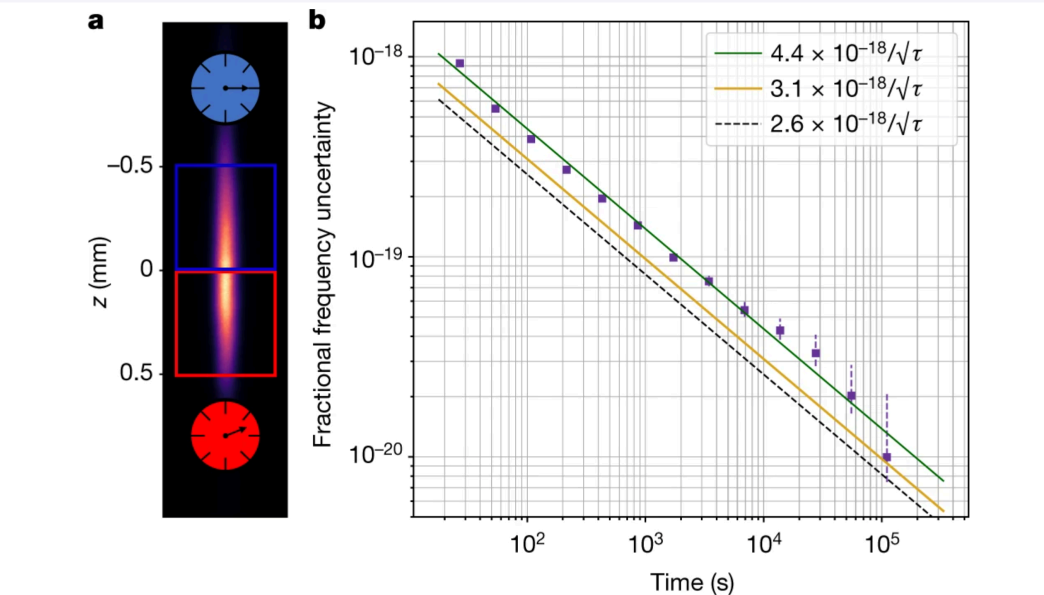
Article — *Nature* **volume 602**, pages 425–430 (2022)

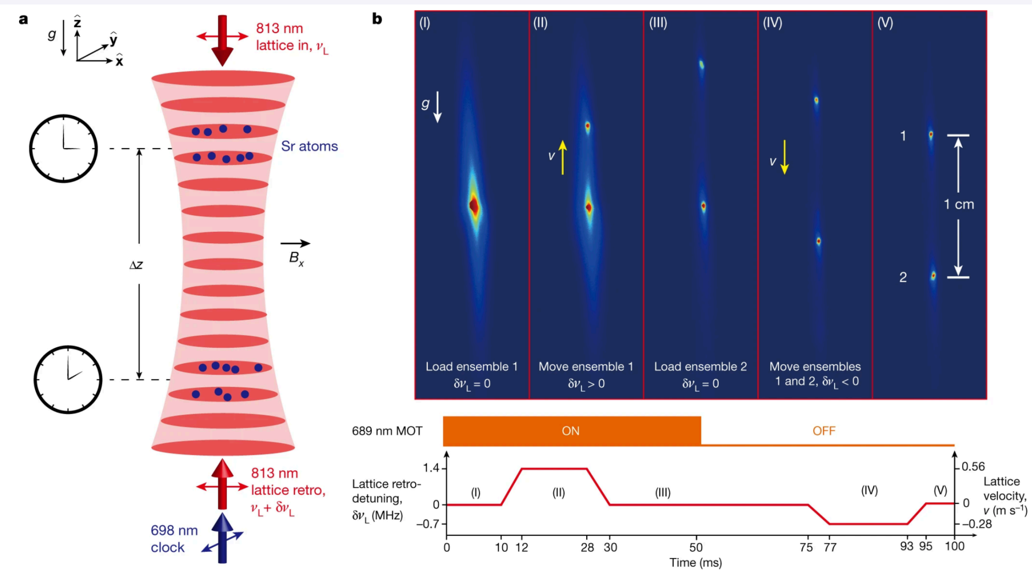
Differential clock comparisons with a multiplexed optical lattice clock

https://doi.org/10.1038/s41586-021-04344-y
Received: 24 September 2021
Accepted: 14 December 2021
Published online: 16 February 2022
Check for updates

Xin Zheng[1], Jonathan Dolde[1], Varun Lochab[1], Brett N. Merriman[1], Haoran Li[1] & Shimon Kolkowitz[1]✉

Rapid progress in optical atomic clock performance has advanced the frontiers of timekeeping, metrology and quantum science[1–3]. Despite considerable efforts, the instabilities of most optical clocks remain limited by the local oscillator rather than the atoms themselves[4,5]. Here we implement a 'multiplexed' one-dimensional optical lattice clock, in which spatially resolved strontium atom ensembles are trapped in the same optical lattice, interrogated simultaneously by a shared clock laser and read-out in parallel. In synchronous Ramsey interrogations of ensemble pairs we observe atom–atom coherence times of 26 s, a 270-fold improvement over the measured atom–laser coherence time, demonstrate a relative instability of $9.7(4) \times 10^{-18}/\sqrt{\tau}$ (where τ is the averaging time) and reach a relative statistical uncertainty of 8.9×10^{-20} after 3.3 h of averaging. These results demonstrate that applications involving optical clock comparisons need not be limited by the instability of the local oscillator. We further realize a miniaturized clock network consisting of 6 atomic ensembles and 15 simultaneous pairwise comparisons with relative instabilities below $3 \times 10^{-17}/\sqrt{\tau}$, and prepare spatially resolved, heterogeneous ensemble pairs of all four stable strontium isotopes. These results pave the way for multiplexed precision isotope shift measurements, spatially resolved characterization of limiting clock systematics, the development of clock-based gravitational wave and dark matter detectors[6–12] and new tests of relativity in the lab[13–16].





Gravitational redshift at millimetre scale

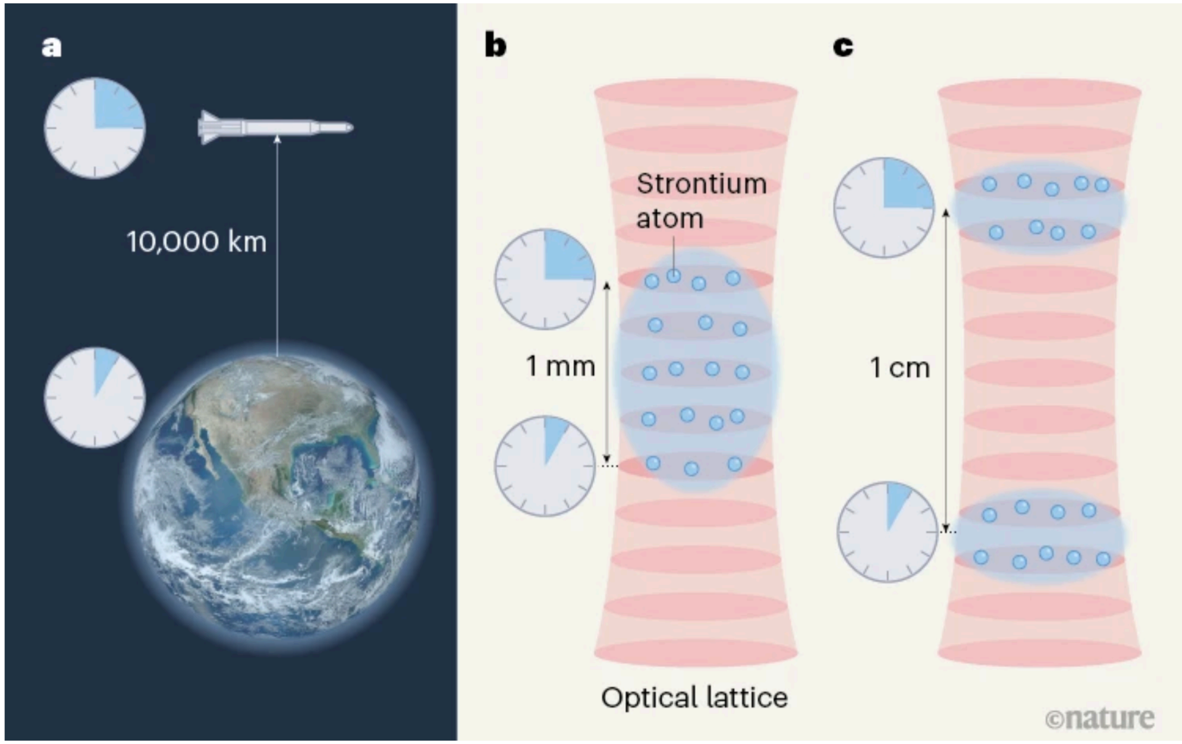


Figure 1 | Measuring time differences in vertically separated clocks. a, The Gravity Probe A experiment[3] measured gravitational redshift (a metric for how gravity changes time) using two clocks separated by a vertical distance of 10,000 kilometres — one was on a spacecraft and the other remained on Earth's surface. The clock on the spacecraft ran faster than the clock on Earth. **b**, Bothwell *et al.*[1] showed that it is possible to measure gravitational redshift even on the submillimetre scale, by probing the timing of electronic transitions in a single cloud of strontium atoms trapped in an optical lattice (formed by the interference pattern of lasers). This required the team to measure an effect that was 20 billion times less pronounced than that detected in the Gravity Probe A experiment. **c**, Zheng *et al.*[2] demonstrated a similar set-up for such measurements using clouds of strontium atoms separated by one centimetre.

1. Bothwell, T. *et al*. *Nature* **602**, 420–424 (2022)
2. Zheng, X. *et al*. *Nature* **602**, 425–430 (2022)
3. Vessot, R. F. C. *et al*. *Phys. Rev. Lett*. **45**, 2081–2084 (1980)

Ksenia Khabarova, *Atomic clouds stabilized to measure dilation of time*, Nature 602, 391-392 (2022) - News and Views

nature photonics

LETTERS

https://doi.org/10.1038/s41566-020-0619-8

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Test of general relativity by a pair of transportable optical lattice clocks

Masao Takamoto[1,2], Ichiro Ushijima[3], Noriaki Ohmae[1,2], Toshihiro Yahagi[4], Kensuke Kokado[4], Hisaaki Shinkai[5] and Hidetoshi Katori[1,2,3] ✉

A clock at a higher altitude ticks faster than one at a lower altitude, in accordance with Einstein's theory of general relativity. The outstanding stability and accuracy of optical clocks, at 10^{-18} levels[1–5], allows height differences[6] of a centimetre to be measured. However, such state-of-the-art clocks have been demonstrated only in well-conditioned laboratories. Here, we demonstrate an 18-digit-precision frequency comparison in a broadcasting tower, Tokyo Skytree, by developing transportable optical lattice clocks. The tower provides the clocks with adverse conditions to test the robustness and a 450 m height difference to test the gravitational redshift at $(1.4 \pm 9.1) \times 10^{-5}$. The result improves ground-based clock comparisons[7–9] by an order of magnitude and is comparable with space experiments[10,11]. Our demonstration shows that optical clocks resolving centimetres are technically ready for field applications, such as monitoring spatiotemporal changes of geopotentials caused by active volcanoes or crustal deformation[12] and for defining the geoid[13,14], which will have an immense impact on future society.

Einstein formulated general relativity (GR) as the theory of gravity in 1915, in which he explained the origin of gravity is the curvature of space and time. Over the century since then, alternative theories of gravity have been proposed, and they have been tested in many ways[15]. Although GR is believed to be the best theory of gravity, there are aspects that are not completely satisfactory. First, although special relativity has been integrated with quantum theory as quantum field theory, GR is not yet unified, preventing a single ultimate theory. Second, the current standard cosmological model based on GR has to introduce unknown 'dark energy' to explain the accelerating Universe[16]. Plausible solutions to the 'dark energy' problem are to throw away the cosmological principle (a homogeneous and isotropic Universe) or to modify GR. Thus, the precise measurement of the validity of GR is an important step towards understanding fundamental physics, even in the classical regime.

GR predicts the dilation of time in a deeper gravitational potential; this is referred to as gravitational redshift. The gravitational redshift between clocks ($\Delta\nu = \nu_2 - \nu_1$) located at positions 1 and 2 is given by their gravitational potential difference $\Delta U = U_2 - U_1$ as

$$\frac{\Delta\nu}{\nu_1} = (1+\alpha)\frac{\Delta U}{c^2} \qquad (1)$$

to first order of ΔU, where $\nu_{1(2)}$ is the clock frequency at location 1 (2), c is the speed of light and α denotes the violation from GR ($\alpha = 0$ for GR). The measurement of α at different locations serves as a test of local position invariance (LPI), which describes the result of a non-local gravitational experiment being independent of place and time, which is at the heart of Einstein's equivalence principle, the starting principle of GR.

The first redshift measurement was carried out in the series of Pound–Rebka–Snider experiments[7] in the early 1960s, in which they obtained $|\alpha| < \mathcal{O}(10^{-2})$ with a height difference of $\Delta h = 23$ m. Later, the Gravity Probe A mission[17] obtained $|\alpha| \approx 1.4 \times 10^{-4}$ using a hydrogen maser in a spacecraft launched to $\Delta h = 10{,}000$ km. Recently, using two Galileo satellites that accidentally took elliptic orbits with a height difference of $\Delta h \approx 8{,}500$ km, new constraints were reported as $\alpha = (0.19 \pm 2.48) \times 10^{-5}$ (ref. [10]) and $\alpha = (4.5 \pm 3.1) \times 10^{-5}$ (ref. [11]). The uncertainty of α is mainly given by $\frac{c^2}{\Delta U}\frac{\delta\nu}{\nu_1}$, suggesting that accurate frequency measurement of clocks ($u_c = \delta\nu/\nu_1$) is at the heart of the endeavour, in particular, for ground experiments with Δh less than a kilometre, as ΔU is nearly four orders of magnitude smaller than the space experiments. A comparison of optical lattice clocks at RIKEN and The University of Tokyo[8] with $\Delta h \approx 15$ m has so far demonstrated $\alpha = (2.9 \pm 3.6) \times 10^{-3}$, limited by $u_c = 5.7 \times 10^{-18}$. Constraining α to better than 10^{-3} on the ground has remained uninvestigated, as it requires outstanding clock accuracy or height differences.

Transportable optical clocks with uncertainties below 10^{-16} (refs. [18–20]) and laboratory-based clocks with uncertainties of 10^{-18} (refs. [1–3,5]) or below[4] offer new possibilities for testing fundamental physics on the ground, for example, a test of Lorentz symmetry[21] or a search for dark matter[22–27]. The Physikalisch-Technische Bundesanstalt (PTB) and Istituto Nazionale di Ricerca Metrologica (INRiM) team has reported $\alpha \approx 10^{-2}$ by comparing a transportable clock in the middle of a mountain and a laboratory clock, with $\Delta h \approx 1{,}000$ m (ref. [9]). Here, we demonstrate a test of the gravitational redshift of $\alpha = (1.4 \pm 9.1) \times 10^{-5}$ by developing a pair of transportable optical lattice clocks and operating them with a height difference of $\Delta h \approx 450$ m at Tokyo Skytree.

To operate Sr-based optical lattice clocks at 10^{-18} uncertainty, reducing the blackbody radiation (BBR) shifts[1–3] and the higher-order light shifts[28,29] is of prime concern. Applying a small-sized BBR shield as depicted in Fig. 1a, the ambient temperature in the spectroscopy region is controlled at 245 K by a four-stage Peltier cooler. In addition, we reduce the total lattice light shift to 1×10^{-18} by tuning the lattice laser to frequency $\nu_L = 368{,}554{,}470.4 \pm 0.2$ MHz, with polarization parallel to the bias magnetic field (Fig. 1a), and by setting the lattice depth to $81E_R$, where E_R is the lattice photon recoil energy[29], compensating the multipolar- and hyperpolarizability-induced light shift with the electric-dipole light shift[28]. To

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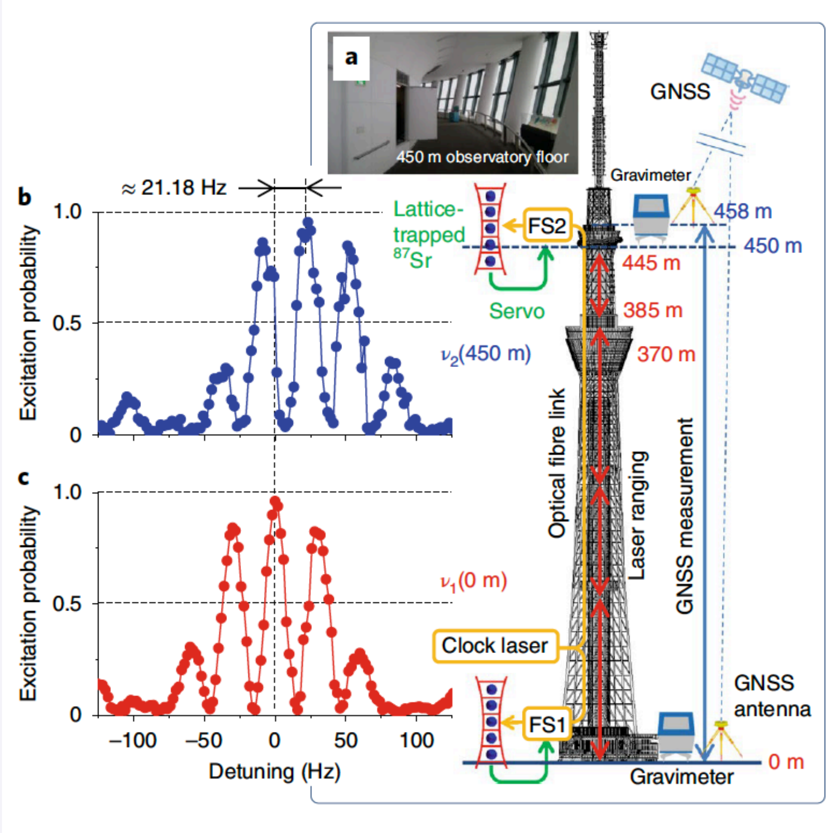
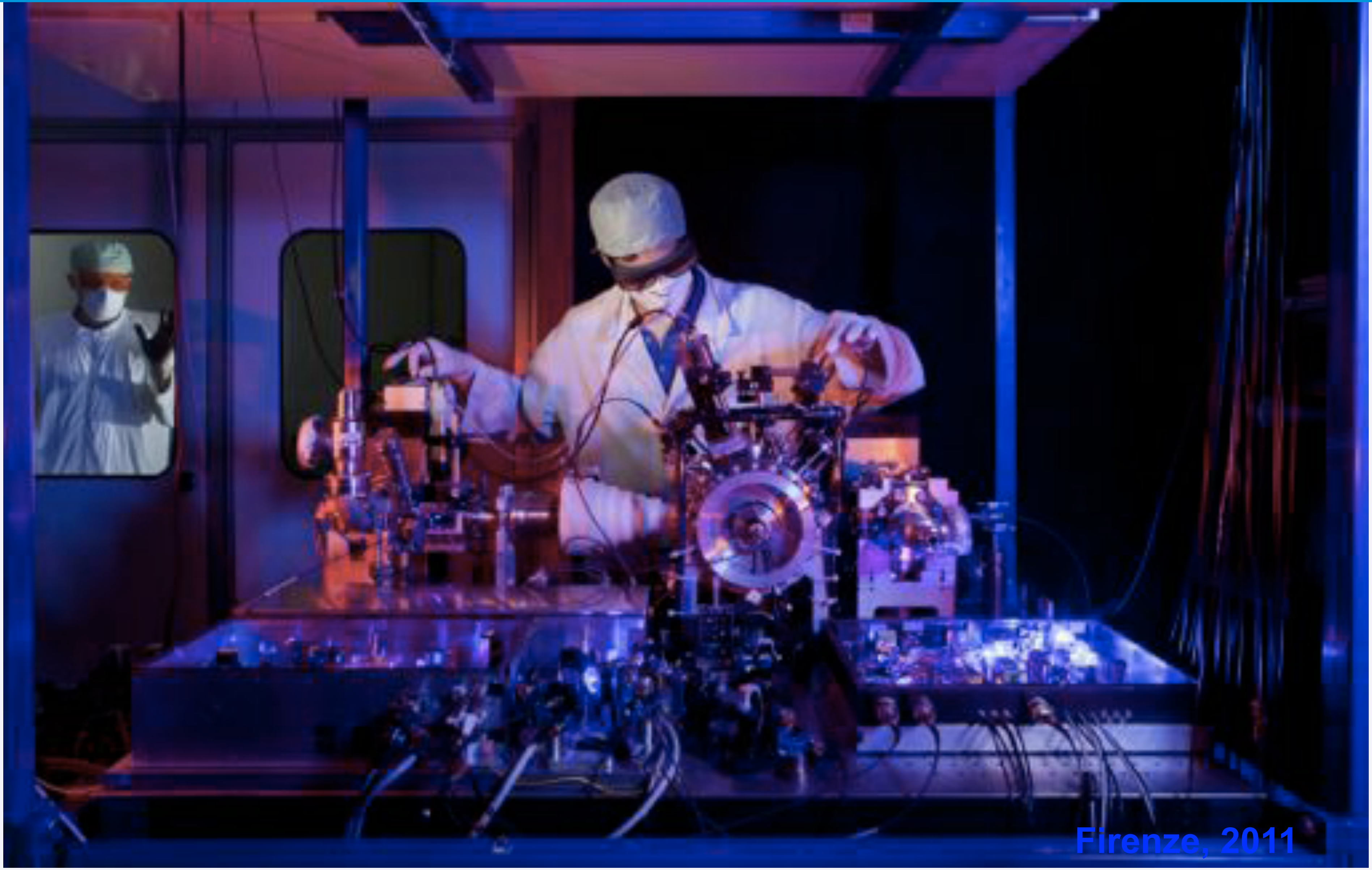


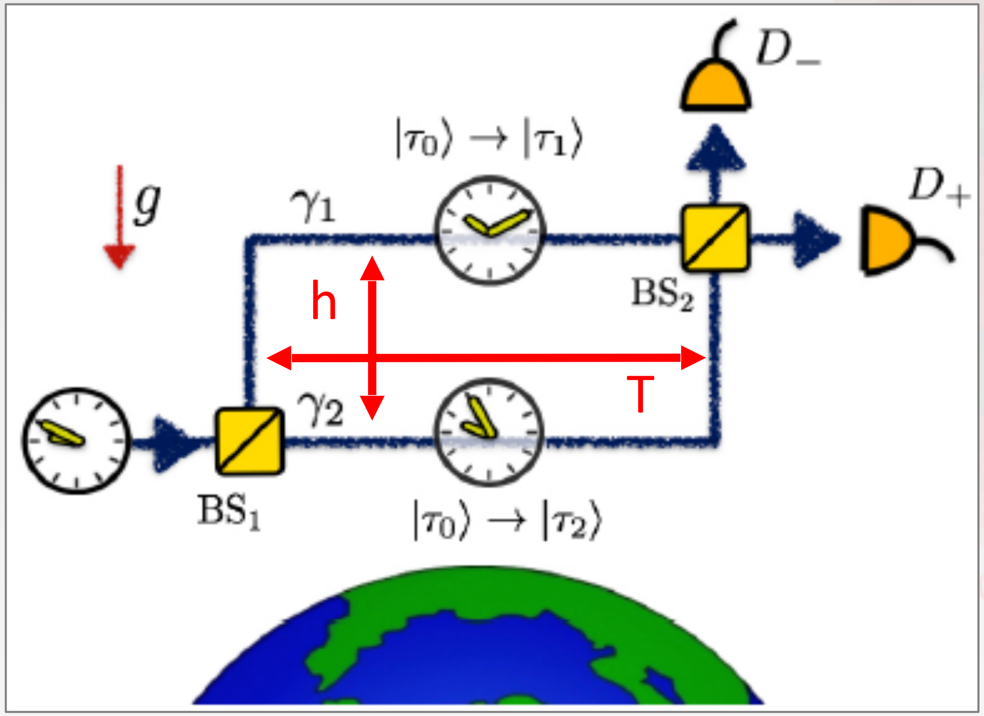
Space Optical Clock



Quantum Interference of Clocks

TICTOC GRAV

Observe gravity induced "decoherence" in clock interferometers



M. Zych et al. Nature Commun. 2(505), 1498 (2011)

- ✓ Quantum superposition of clocks in different locations (h = height difference)
- ✓ Dephasing introduced by differential time dilation in the two different paths γ_1 and γ_2 (T=time)
- ✓ Interferometer contrast loss
- ✓ Decoherence induced by "which path" information from clock state

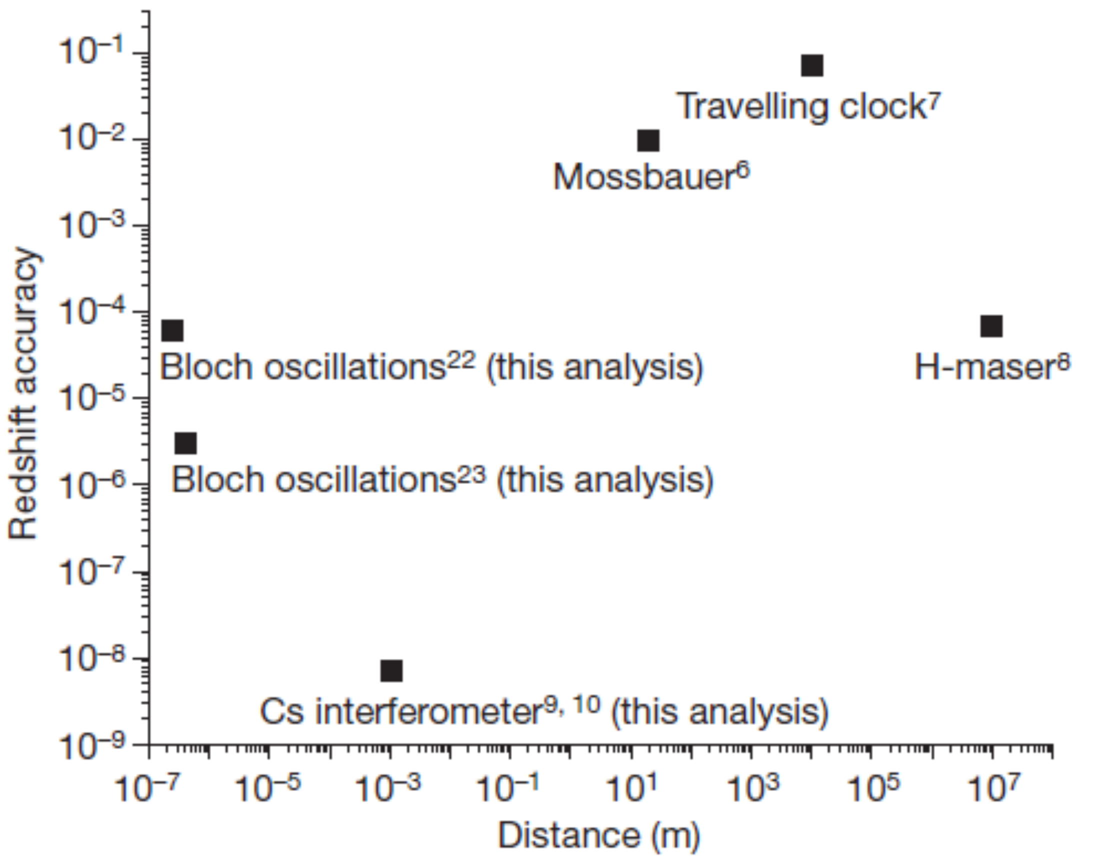
Test of foundation of quantum mechanics: quantum to classical transition

nature Vol 463|18 February 2010|doi:10.1038/nature08776

LETTERS

A precision measurement of the gravitational redshift by the interference of matter waves

Holger Müller[1,2], Achim Peters[3] & Steven Chu[1,2,4]



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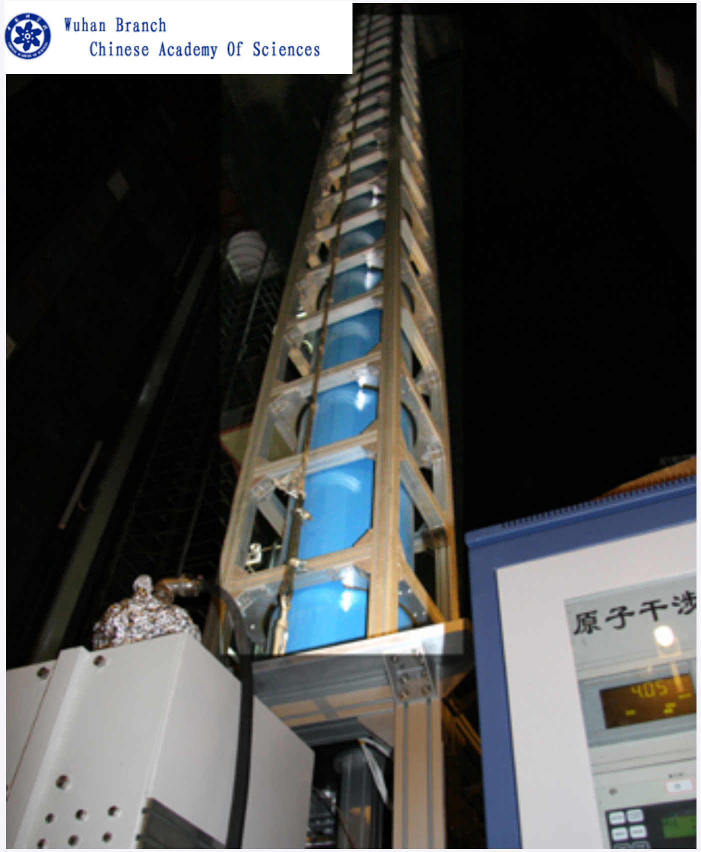
From table-top experiments to large-scale detectors

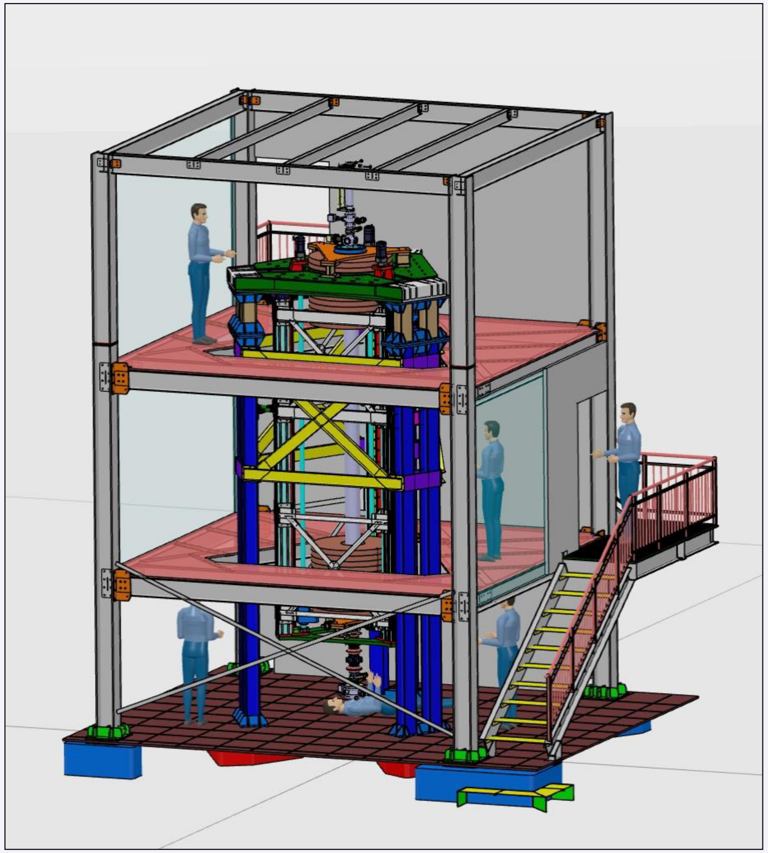
Large-scale atom interferometers

10 m fountain - Stanford

12 m fountain - Wuhan



8 m fountain - Firenze
(under construction)



The VLBAI facility

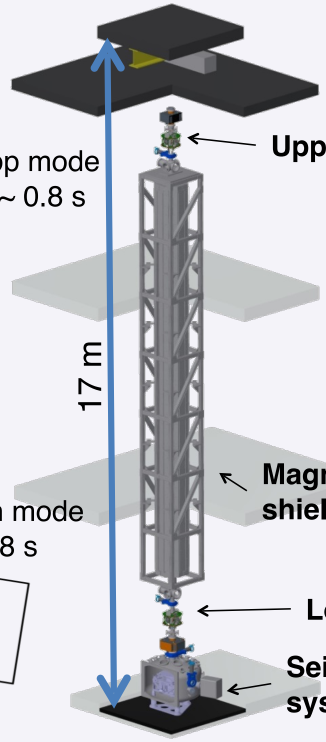
Atomic sources

- ➢ Rubidium & ytterbium (quantum-degenerate)
- ➢ Drop/launch mode

Inertial reference

- ➢ Geometric anti-spring system ($f_0 \sim 320$ mHz) with active stabilization
- ➢ Rotation compensation system (cf. Kasevich, Müller groups)

[DS et al., arXiv:1909.08524]



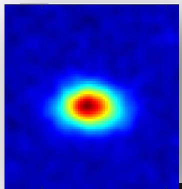
Al-zone & magnetic shield

- ➢ 10.5 m CF 200 Al tube
- ➢ Dual-layer mu-metal (octagonal geometry; collaboration with P. Fierlinger, TU München)

Rubidium source @10m facility

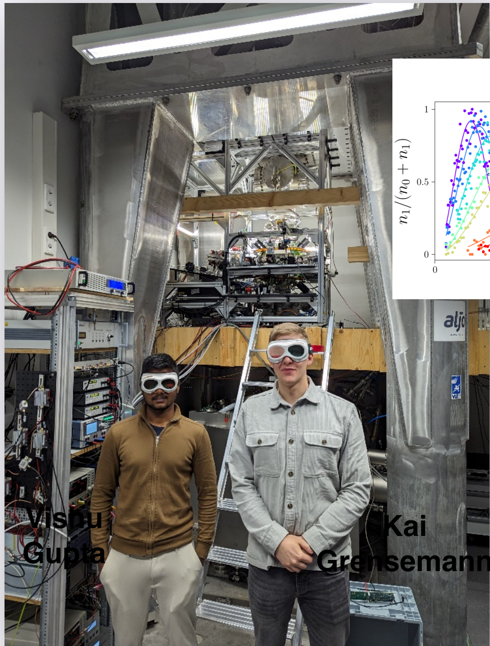
Recent progress

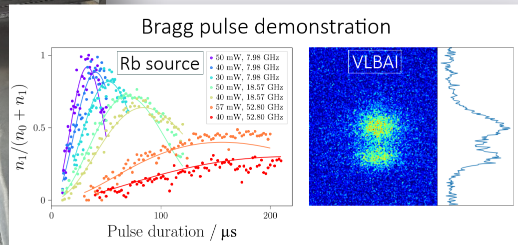
- Migration of Rb source 04/23
- Vibration isolation 07/23
- Optical dipole trap ~09/23
- Evaporated ensembles 11/23

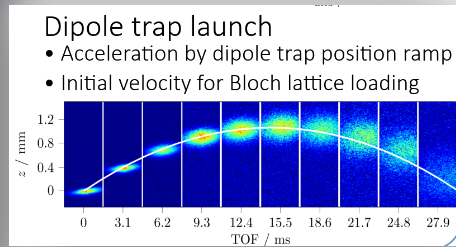


2×10^7 at → 3×10^4 at @~100 nK

- Atom optics lasers operational at the top lab
- Dipole trap launch for initial velocity → subsequent Bloch lattice launch

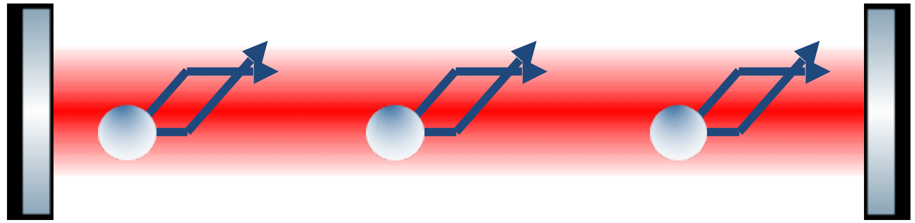






MIGA Project

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

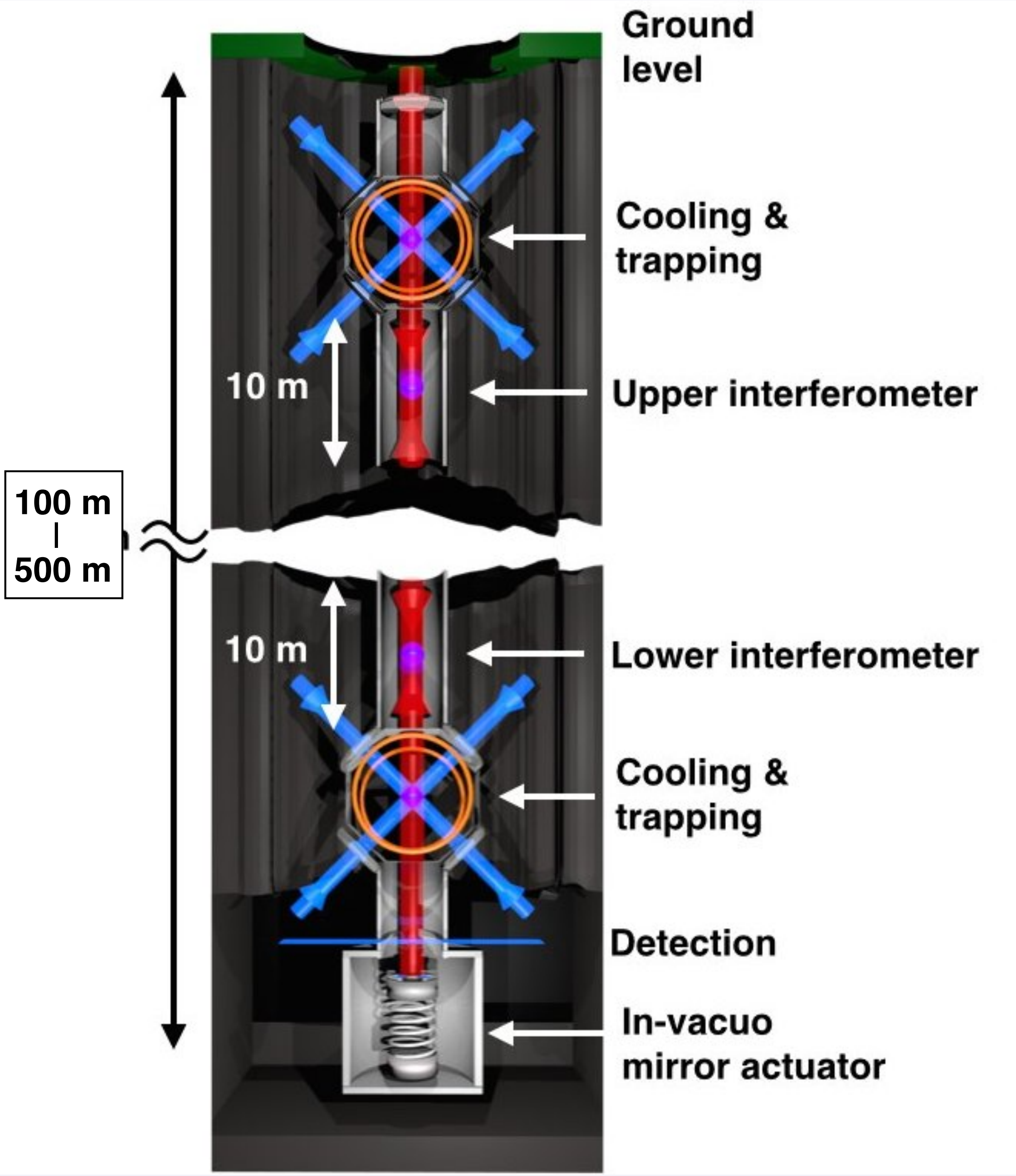
- Two 200 m horizontal optical cavity coupled with 3 AI
- Possible evolutions towards 2D or 3D instrument on site

from P. Bouyer

MAGIA-Advanced ⇒ Sardegna (2016, Proposal)

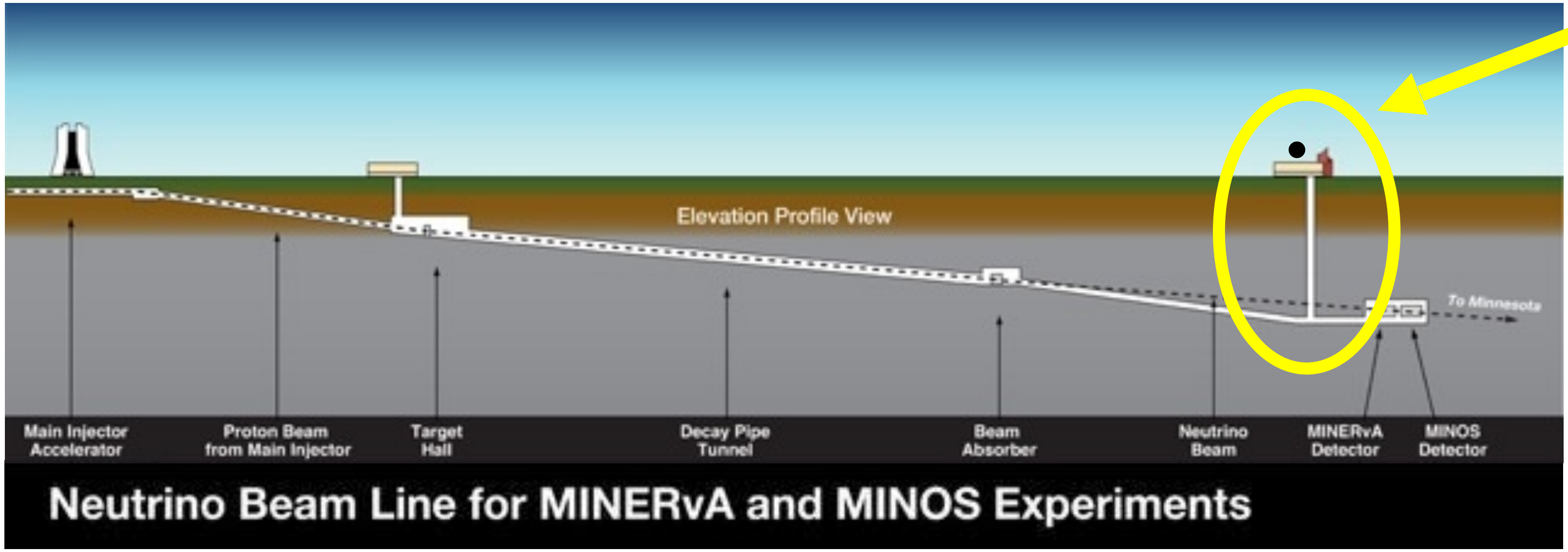
Carbonia-Iglesias
ARIA/Darkside Lab

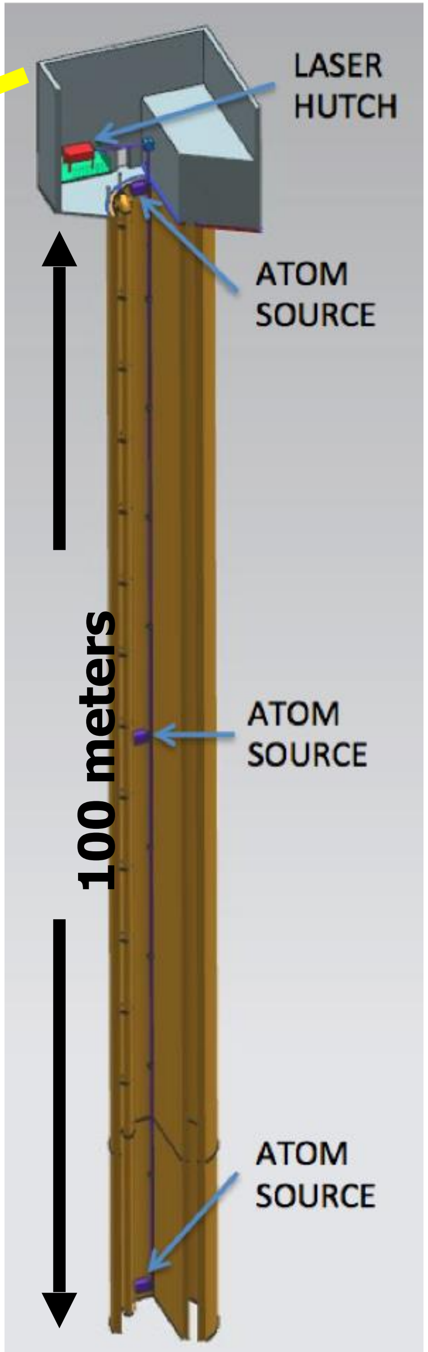
Sos Enattos
SAR-GRAV Lab



MAGIS-100: Detector prototype at Fermilab

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



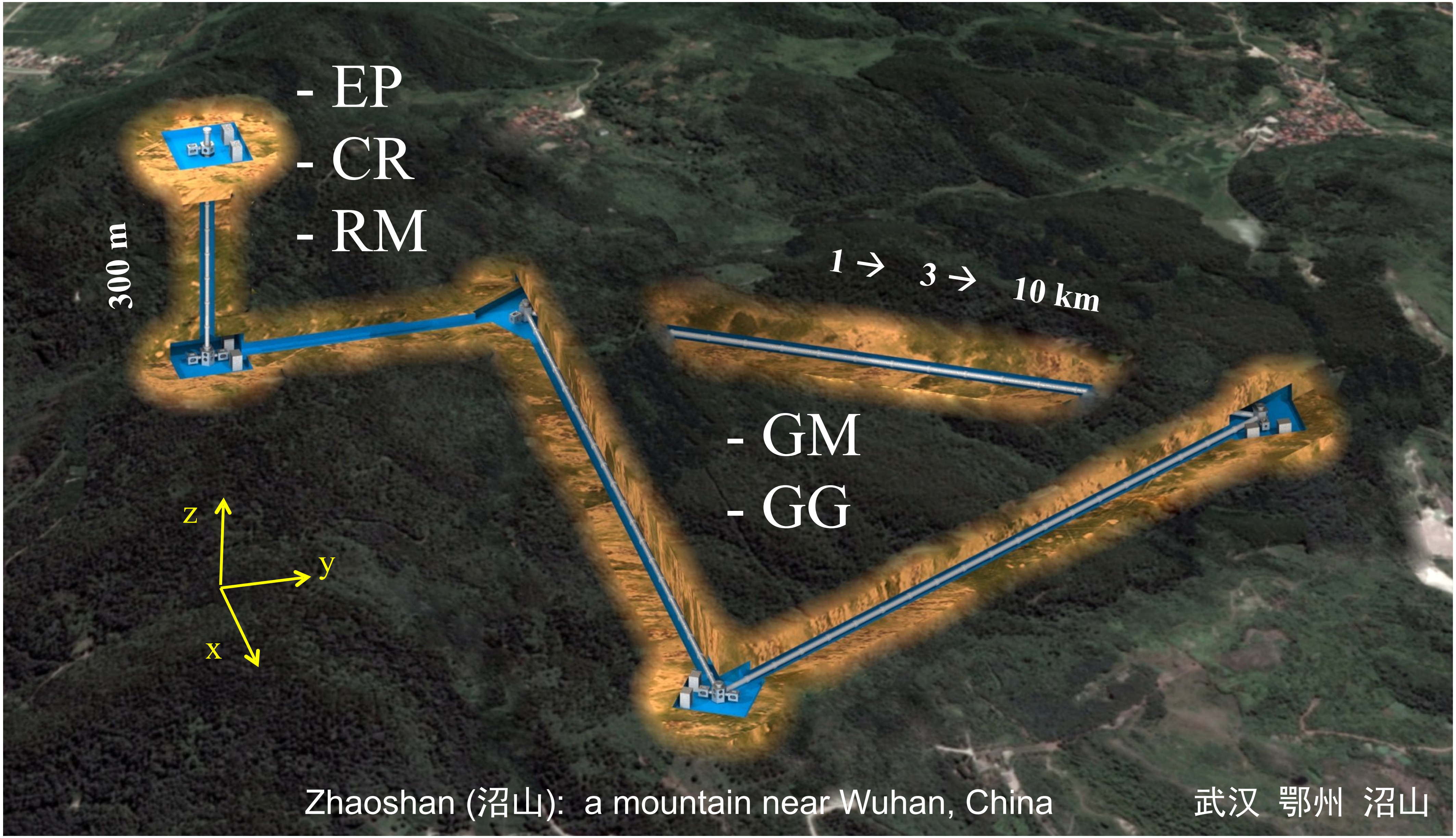


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

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*

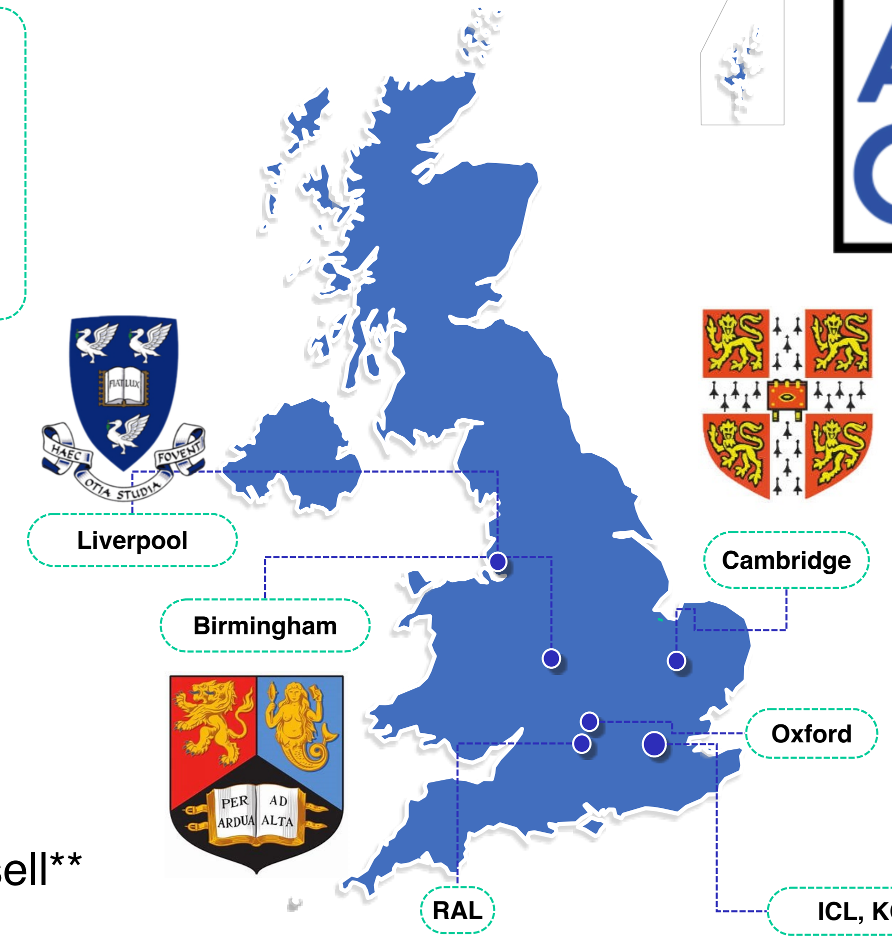
Kings College London
J. Ellis*

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

Mar 13 – 14, 2023 > CERN

Terrestrial Very-Long-Baseline Atom Interferometry

WORKSHOP

arXiv > hep-ex > arXiv:2310.08183

Search...

Help | Advanced Se

High Energy Physics – Experiment

[Submitted on 12 Oct 2023]

Terrestrial Very-Long-Baseline Atom Interferometry: Workshop Summary

Sven Abend, Baptiste Allard, Iván Alonso, John Antoniadis, Henrique Araujo, Gianluigi Arduini, Aidan Arnold, Tobias Aßmann, Nadja Augst, Leonardo Badurina, Antun Balaz, Hannah Banks, Michele Barone, Michele Barsanti, Angelo Bassi, Baptiste Battelier, Charles Baynham, Beaufils Quentin, Aleksandar Belic, Ankit Beniwal, Jose Bernabeu, Francesco Bertinelli, Andrea Bertoldi, Ikbal Ahamed Biswas, Diego Blas, Patrick Boegel, Aleksandar Bogojevic, Jonas Böhm, Samuel Böhringer, Kai Bongs, Philippe Bouyer, Christian Brand, Apostolos Brimis, Oliver Buchmueller, Luigi Cacciapuoti, Sergio Calatroni, Benjamin Canuel, Chiara Caprini, Ana Caramete, Laurentiu Caramete, Matteo Carlesso, John Carlton, Mateo Casariego, Vassilis Charmandaris, Yu-Ao Chen, Maria Luisa Chiofalo, Alessia Cimbri, Jonathon Coleman, Florin Lucian Constantin, Carlo Contaldi, Yanou Cui, Elisa Da Ros, Gavin Davies, Esther del Pino Rosendo, Christian Deppner, Andrei Derevianko, Claudia de Rham, Albert De Roeck, Daniel Derr, Fabio Di Pumpo, Goran Djordjevic, Babette Dobrich, Peter Domokos, Peter Dornan, Michael Doser, Giannis Drougakis, Jacob Dunningham, Alisher Duspayev, Sajan Easo, Joshua Eby, Maxim Efremov, Tord Ekelof, Gedminas Elertas, John Ellis, David Evans, Pavel Fadeev, Mattia Fanì, Farida Fassi, Marco Fattori, Pierre Fayet, Daniel Felea, Jie Feng, Alexander Friedrich, Elina Fuchs, Naceur Gaaloul, Dongfeng Gao, Susan Gardner, Barry Garraway, Alexandre Gauguet, Sandra Gerlach, Matthias Gersemann, Valerie Gibson, Enno Giese, Gian Francesco Giudice, Eric Glasbrenner, Mustafa Gündogan, Martin G. Haehnelt, Timo Hakulinen, Klemens Hammerer, Ekim Taylan Hanımeli et al. (153 additional authors not shown)

This document presents a summary of the 2023 Terrestrial Very-Long-Baseline Atom Interferometry Workshop hosted by CERN. The workshop brought together experts from around the world to discuss the exciting developments in large-scale atom interferometer (AI) prototypes and their potential for detecting ultralight dark matter and gravitational waves. The primary objective of the workshop was to lay the groundwork for an international TVLBAI proto-collaboration. This collaboration aims to unite researchers from different institutions to strategize and secure funding for terrestrial large-scale AI projects. The ultimate goal is to create a roadmap detailing the design and technology choices for one or more km-scale detectors, which will be operational in the mid-2030s. The key sections of this report present the physics case and technical challenges, together with a comprehensive overview of the discussions at the workshop together with the main conclusions.

Comments: Summary of the Terrestrial Very-Long-Baseline Atom Interferometry Workshop held at CERN: this https URL

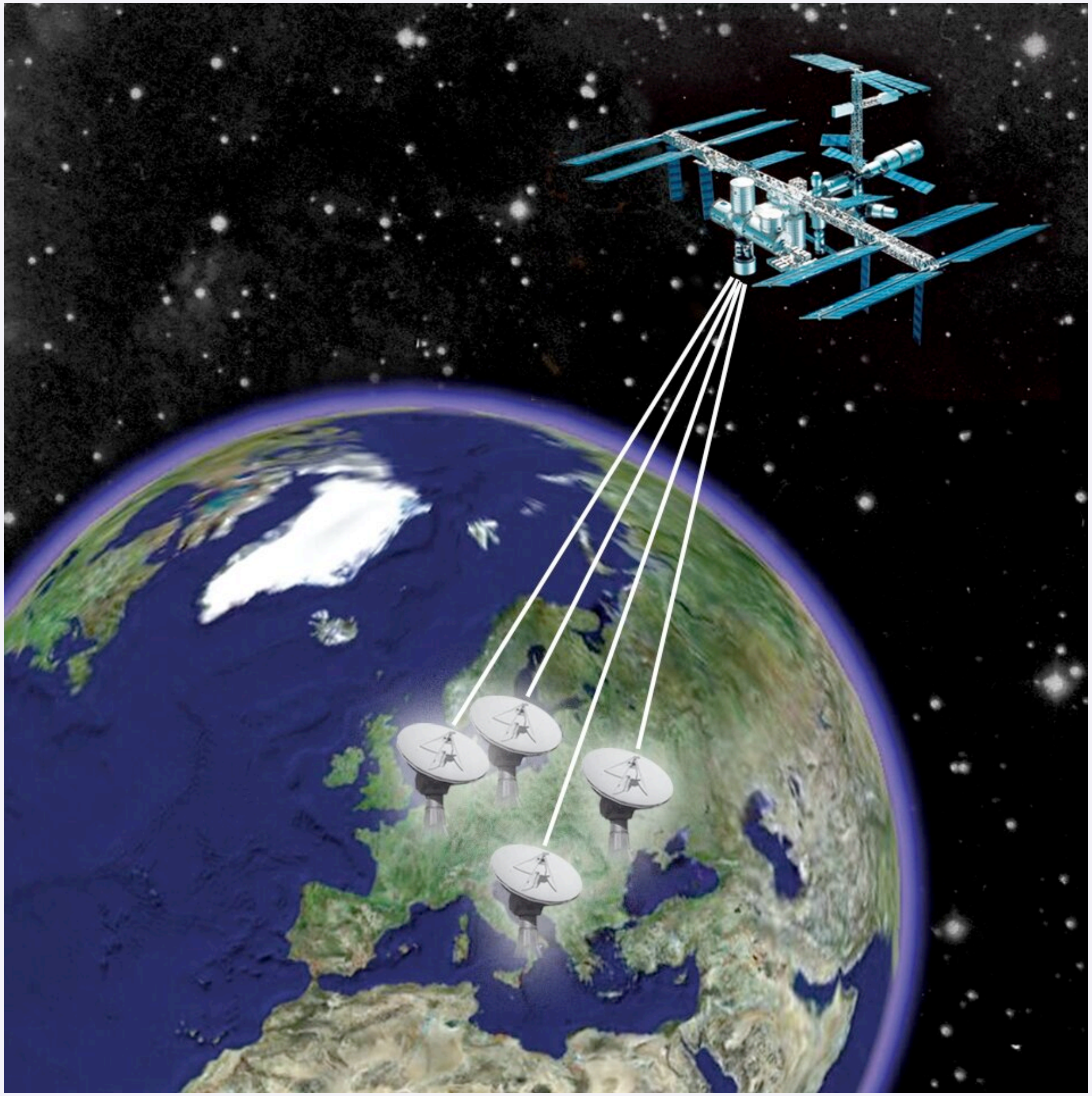
https://arxiv.org/abs/2310.08183

Accepted for publication in AVS Quantum Science

https://indico.cern.ch/event/1369392/

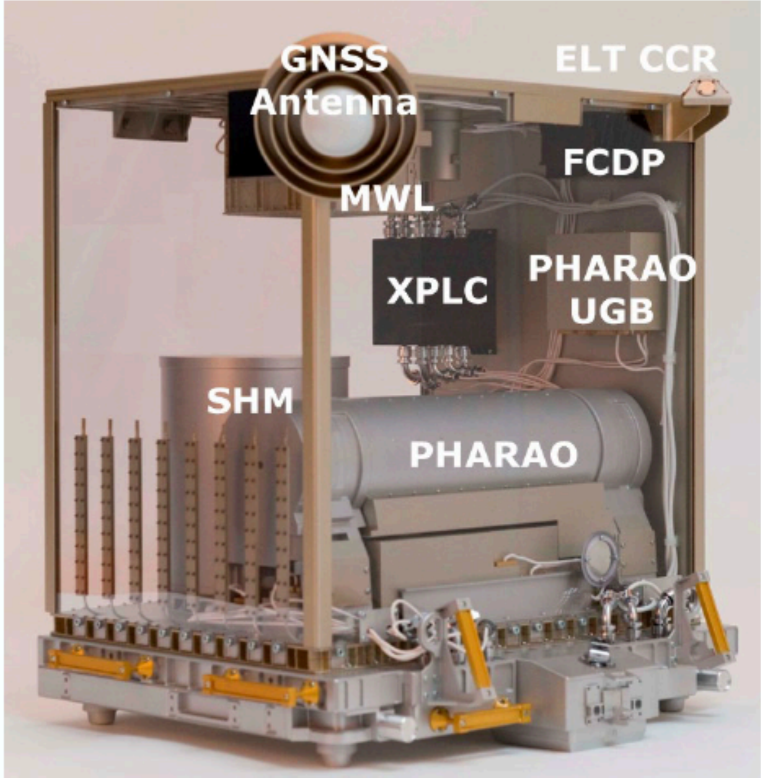
Towards space

ACES - Atomic Clock Ensemble in Space



The ACES payload

- **PHARAO** (CNES): Atomic clock based on laser cooled Cs atoms
- **SHM**: Active hydrogen maser
- **FCDP**: Clocks comparison and distribution
- **MWL** : T&F transfer link
- **GNSS** receiver
- **ELT**: Optical link
- **Support subsystems**
  - **XPLC**: External PL computer
  - **PDU**: Power distribution unit,
  - Mechanical, thermal subsystems
  - **CEPA**: Columbus External PL Adapter

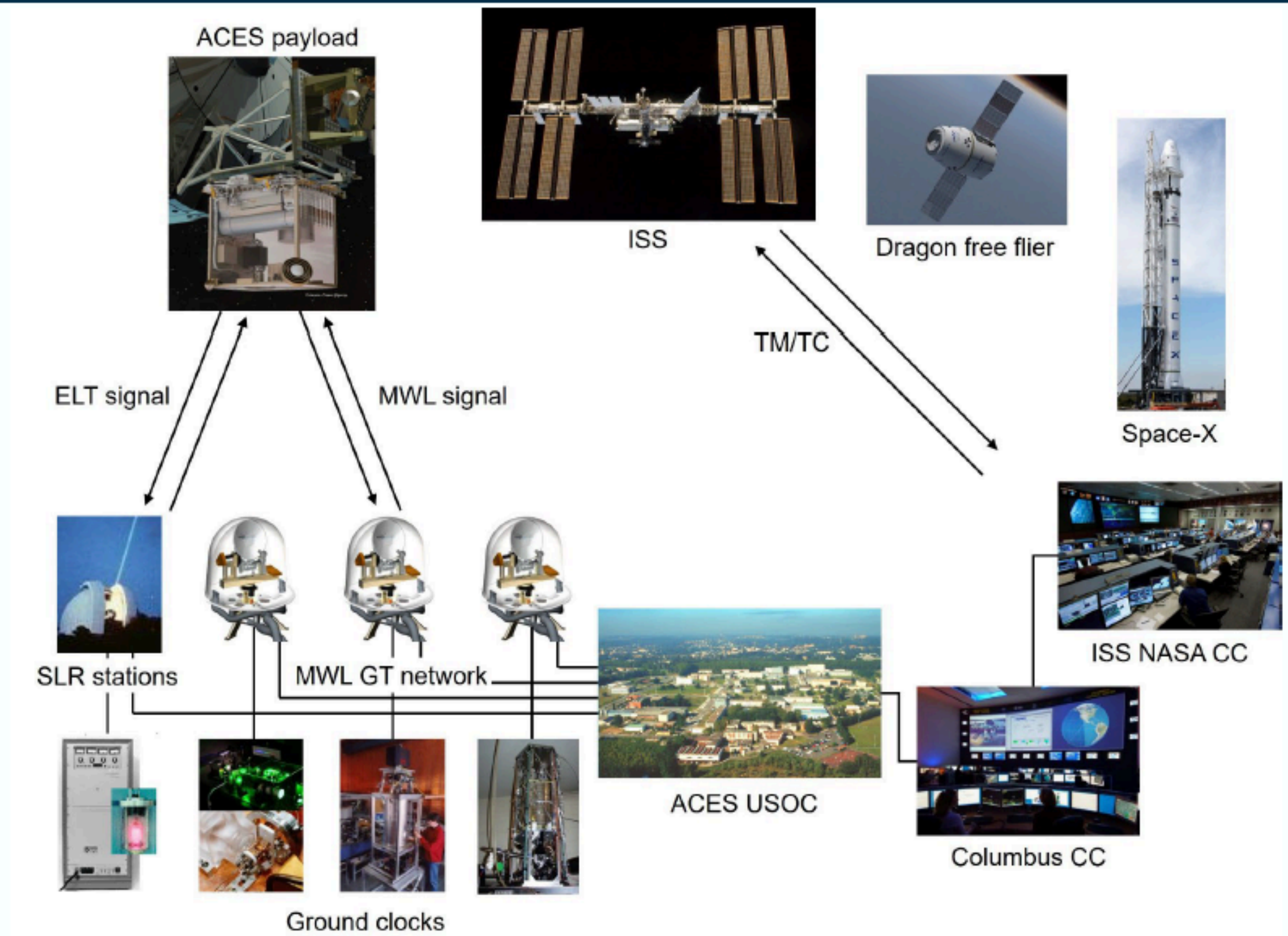


Volume: 1172x867x1246 mm^3
Mass: 240 kg (w/o CEPA)
Power: 600 W

→ THE EUROPEAN SPACE AGENCY

From Luigi Cacciapuoti, 2024

ACES mission concept



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From Luigi Cacciapuoti, 2024

ACES – Fundamental Physics tests

ACES Mission Objectives	ACES performances	Scientific background and recent results
Gravitational red-shift	Absolute measurement of the gravitational red-shift to < $2 \cdot 10^{-6}$ after 10 days of integration time.	Factor 70 improvement over the GPA experiment and factor 10 over tests involving Galileo 5 and 6 satellites.
Time drifts of fundamental constants	Time variations of α constrained to $\alpha^{-1} \cdot d\alpha/dt$ < $3 \cdot 10^{-18}\ yr^{-1}$ after 3 years of mission.	Comparisons of clocks based on different atoms and atomic transitions on a worldwide scale to constrain α, m_e/Λ_{QCD} and m_q/Λ_{QCD}.
Dark matter search with atomic clocks	Establish bounds on topological dark matter models based on the comparisons of clocks in the ACES network.	Comparisons via the ACES network imposing limits on the three coupling constants Λ_α, Λ_e, and Λ_q in the model lLagrangian. Measurements over an interval T between encounters of 20 d. Simultaneous observation with several clocks along different baselines providing ways to confirm any observation above the sensitivity threshold and control the measurement systematics. Screening effect on the dark matter field due to the Earth mass reduced to about 0.06 on the space clock PHARAO with respect to ground clocks (~ 10^{-7}).

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From Luigi Cacciapuoti, 2024

Way-forward to the ACES launch

- Acceptance status of ACES:
  - SHM PFM: getters have been replaced and acceptance tests completed.
  - PHARAO, ELT PFM, ACES GNSS system and FCDP PFM have also completed their tests.
  - PHARAO, SHM, FCDP, GNSS system are integrated in the ACES payload.
  - MWL PFM qualification tests are progressing towards final acceptance: TV tests have been completed, vibration tests are planned for this week, final performance tests will follow.
  - ACES payload IST (Integrated System Test) campaign started before the Christmas break.
    - PHARAO tested in Evaluation mode and permanently compared to SYRTE clocks via GPS link.
    - MWL tested outside the ACES payload in common clock and dual clock configuration.
  - ACES payload acceptance planned for summer 2024.
- ACES PFM delivered for launch on SpaceX in end 2024 – beginning 2025.
- MWL GTs deployment will start in mid 2024 (SYRTE, PTB and Wettzell); the other institutes will follow.

→ THE EUROPEAN SPACE AGENCY

From Luigi Cacciapuoti, 2024

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-05219-z OPEN

In-orbit operation of an atomic clock based on laser-cooled ^{87}Rb atoms

Liang Liu[1], De-Sheng Lü[1], Wei-Biao Chen[2], Tang Li[1], Qiu-Zhi Qu[1], Bin Wang[1], Lin Li[1], Wei Ren[1], Zuo-Ren Dong[2], Jian-Bo Zhao[1], Wen-Bing Xia[2], Xin Zhao[1], Jing-Wei Ji[1], Mei-Feng Ye[1], Yan-Guang Sun[2], Yuan-Yuan Yao[1], Dan Song[1], Zhao-Gang Liang[1], Shan-Jiang Hu[2], Dun-He Yu[2], Xia Hou[2], Wei Shi[2], Hua-Guo Zang[2], Jing-Feng Xiang[1], Xiang-Kai Peng[1] & Yu-Zhu Wang[1]

Atomic clocks based on laser-cooled atoms are widely used as primary frequency standards. Deploying such cold atom clocks (CACs) in space is foreseen to have many applications. Here we present tests of a CAC operating in space. In orbital microgravity, the atoms are cooled, trapped, launched, and finally detected after being interrogated by a microwave field using the Ramsey method. Perturbing influences from the orbital environment on the atoms such as varying magnetic fields and the passage of the spacecraft through Earth's radiation belt are also controlled and mitigated. With appropriate parameters settings, closed-loop locking of the CAC is realized in orbit and an estimated short-term frequency stability close to $3.0 \times 10^{-13}\tau^{-1/2}$ has been attained. The demonstration of the long-term operation of cold atom clock in orbit opens possibility on the applications of space-based cold atom sensors.

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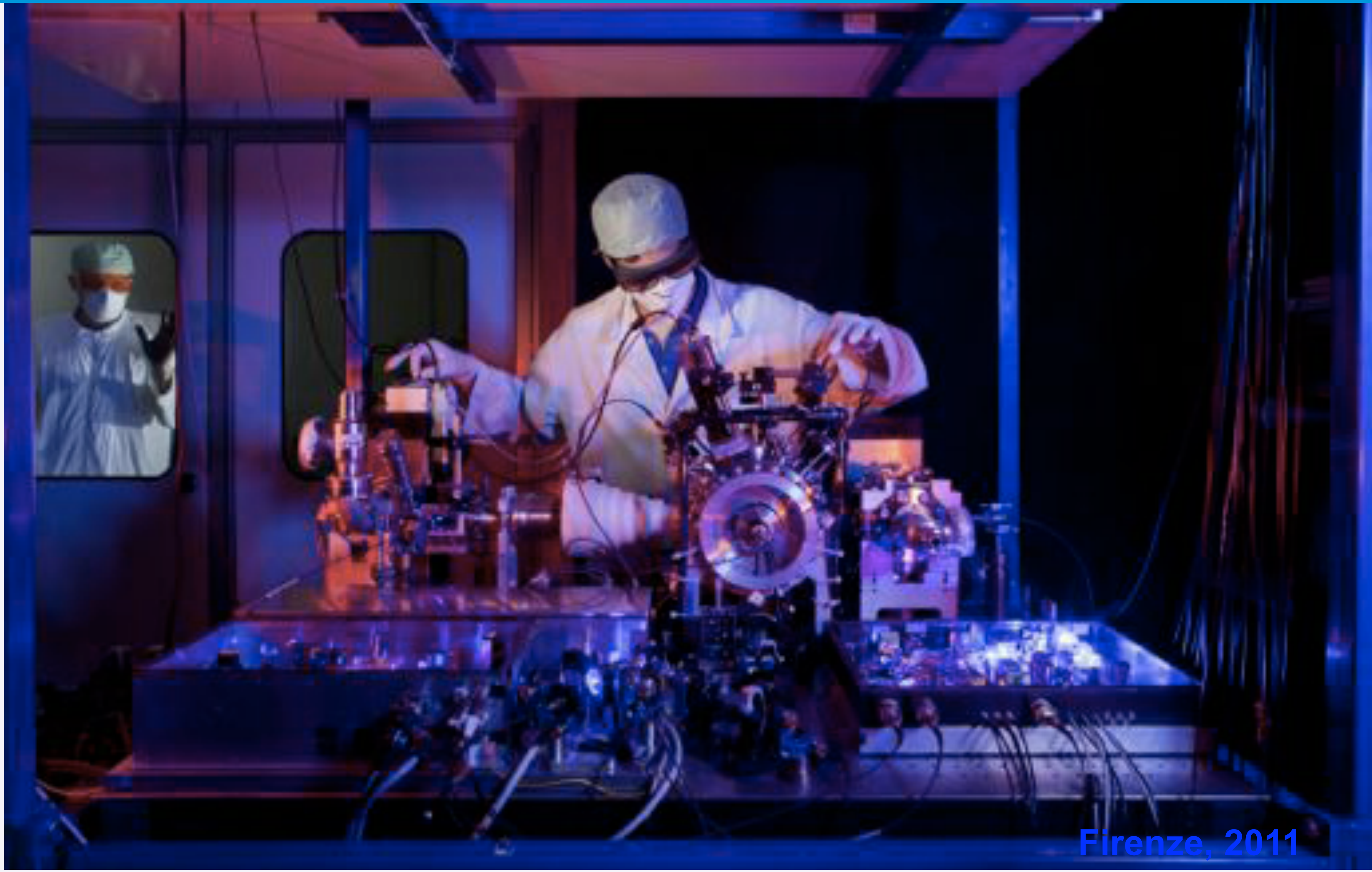
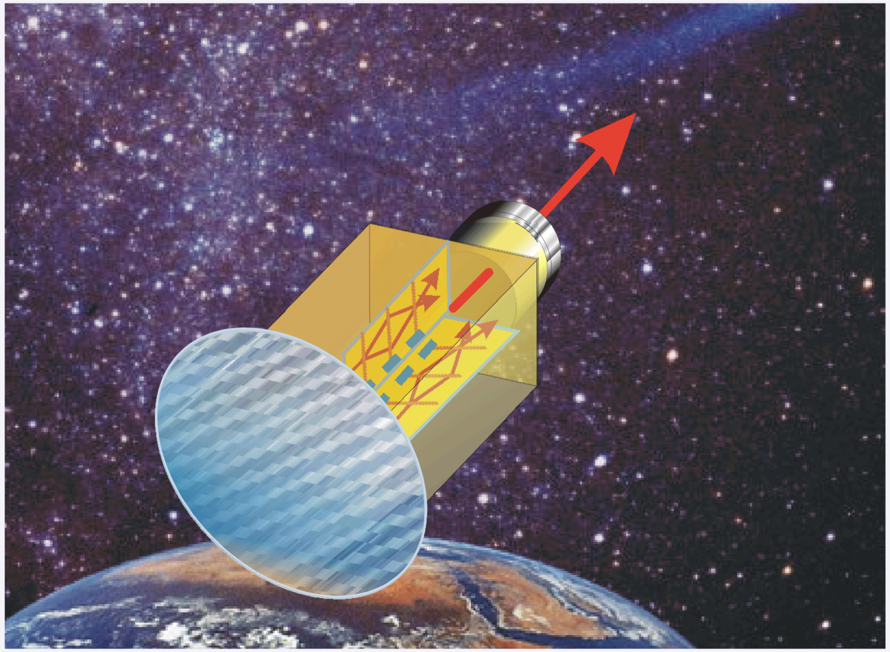
Space Optical Clock



HYPER

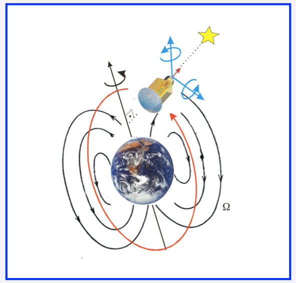


Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

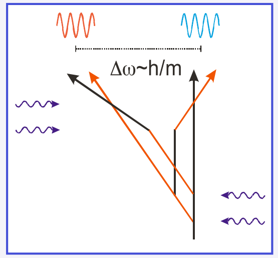
Resolution: 3×10^{-12} rad/s /√Hz

- Expected Overall Performance: 3×10^{-16} rad/s over one year of integration i.e. a S/N~100 at twice the orbital frequency

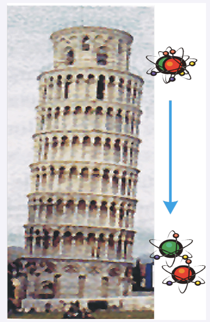
Mapping Lense-Thirring effect close to the Earth



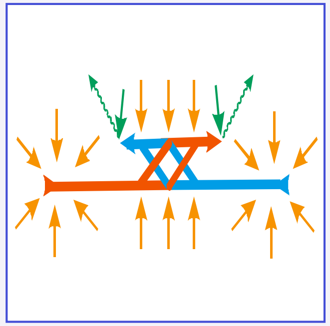
Improving knowledge of fine-structure constant



Testing EP with microscopic bodies



Atomic gyroscope control of a satellite



http://sci.esa.int/home/hyper/index.cfm

Space Atom Interferometer - SAI

Space Atom Interferometer: Pre-phase A study of a space instrument based on matter-wave interferometry for inertial sensing in space

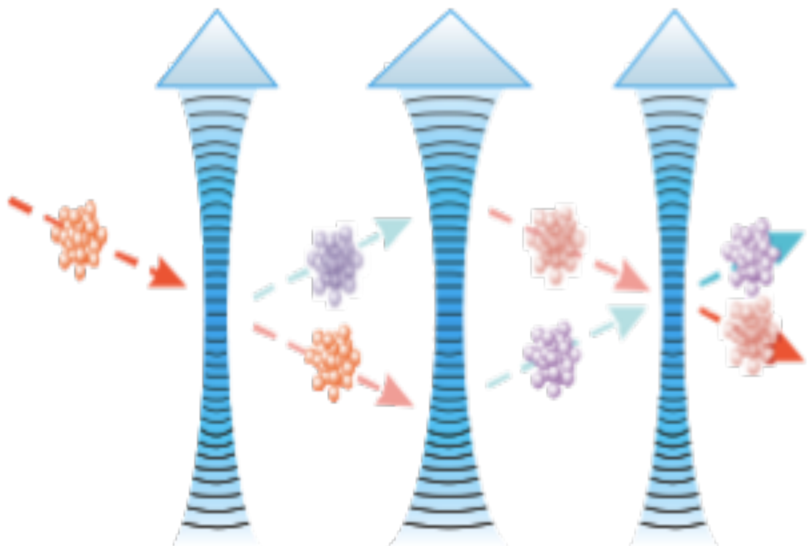
Team: Firenze Univ. (I), IOTA (F), IQ (D), Hamburg Univ. (D), HU Berlin (D), SYRTE (F), LENS (I), Ulm Univ. (D), ZARM (D)

Objective: Ground based prototype of an atom interferometer for precision measurements

Duration: 3 years, funded within the ELIPS-2 Programme

ESA AO-2004 peered review: Outstanding

From M. Kasevich

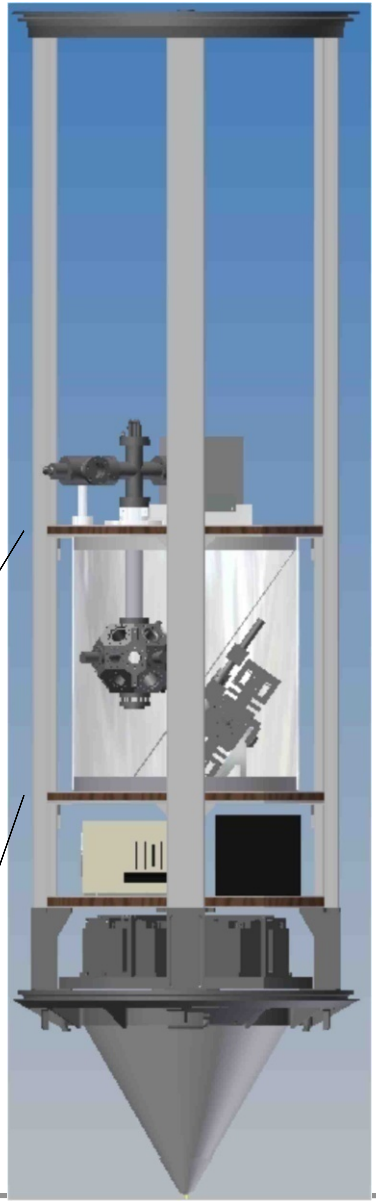


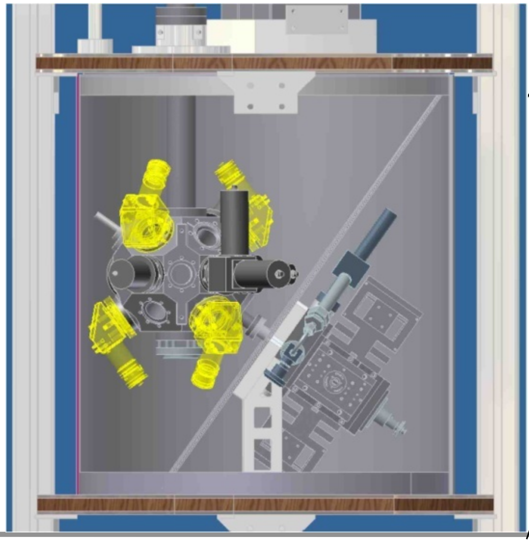
	Demonstrated on ground	Anticipated on ground	Projected in space
Gyroscope			
ARW Bias stability Scale factor	$2x10^{-6}$ deg/hr$^{1/2}$ $6x10^{-5}$ deg/hr 5 ppm	$<1x10^{-6}$ deg/hr$^{1/2}$ $<10^{-5}$ deg/hr <1 ppm	$<10^{-8}$ deg/hr$^{1/2}$ $<10^{-7}$ deg/hr <1 ppm
Accelerometer			
Sensitivity Bias stability Scale factor	10^{-9} g/Hz$^{1/2}$ $<10^{-10}$ g $<10^{-10}$	$<10^{-10}$ g/Hz$^{1/2}$ $<10^{-10}$ g $<10^{-10}$	$<10^{-13}$ g/Hz$^{1/2}$ $<10^{-16}$ g ? $<10^{-12}$

F. Sorrentino et al., *A Compact Atom Interferometer for Future Space Missions*, Microgravity Sci. Technol. 22, 551 (2010)

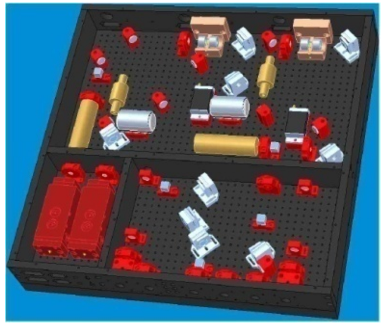
SAI - Space Atom Interferometer

- Single-axis accelerometer
- Sensitivity target 10^{-7} m/s^2 @1s
- Repetition rate ≈ 2 Hz
- Modular laser system + optical fibers
- MOT + atomic fountain
- Same chamber for MOT and detection
- Load from 2D-MOT
- **Compatible with drop-tower capsule**



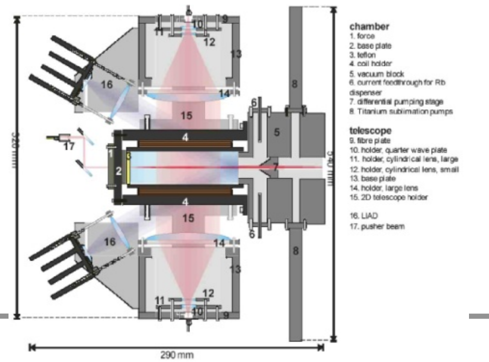


Raman laser system



Modular laser system

2D-MOT

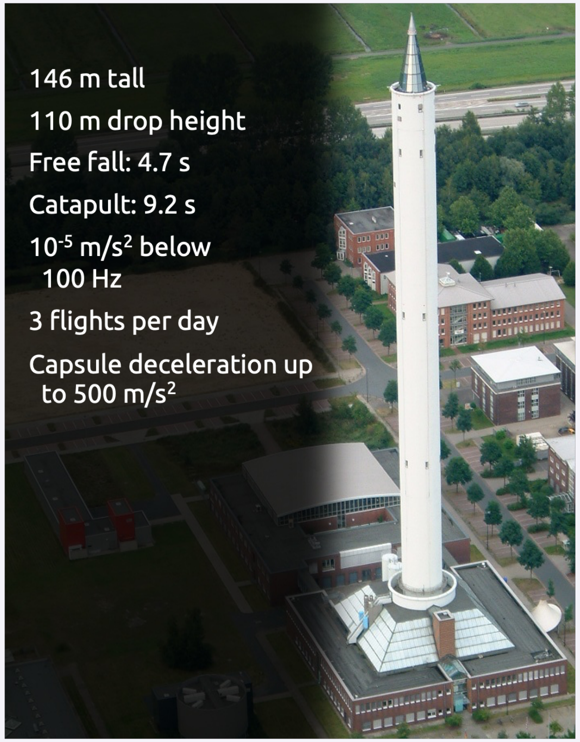


F. Sorrentino et al., *A Compact Atom Interferometer for Future Space Missions*, Microgravity Sci. Technol. 22, 551 (2010)

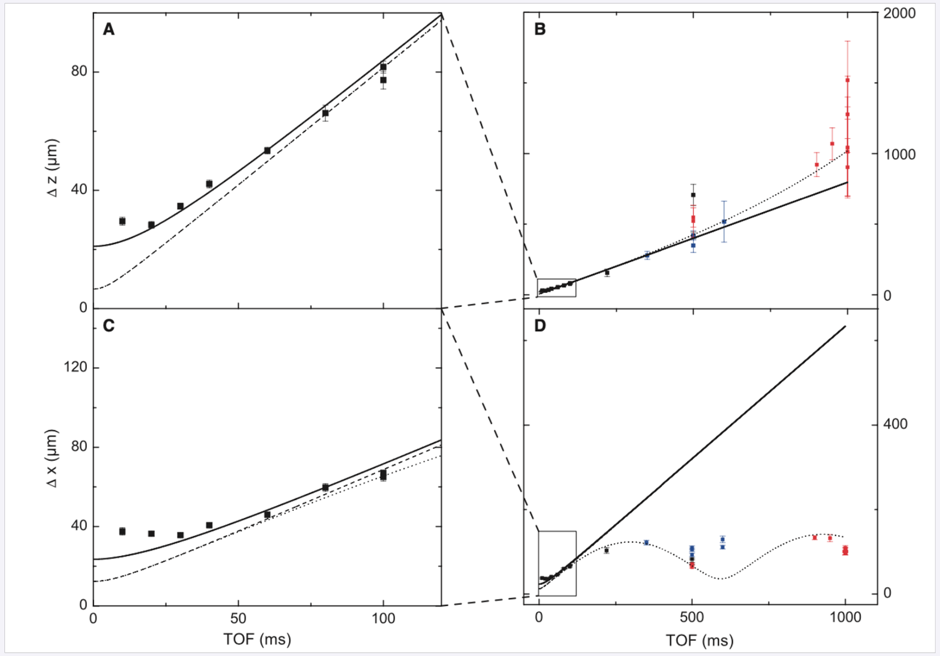
µg Platforms

Scaling methods for quantum dynamics

T. van Zoest, et al . Bose-Einstein Condensation in Microgravity, *Science* **328**, 1540 – 1543 (2010)



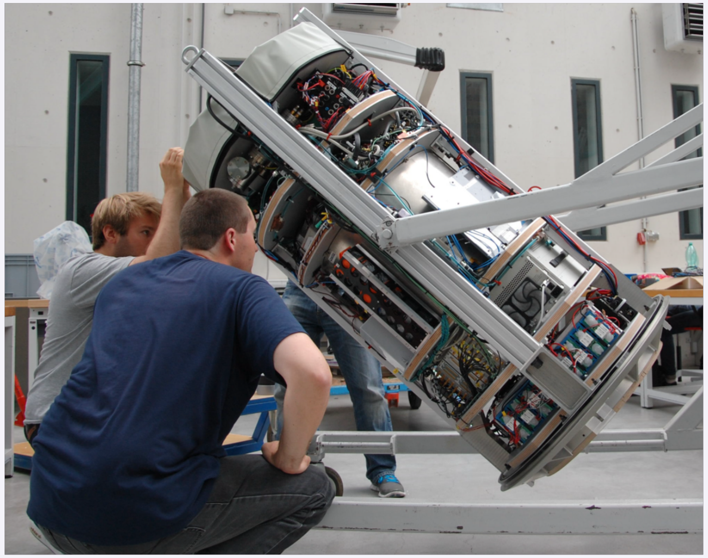
The numerical grid is rescaled to follow the cold gas size



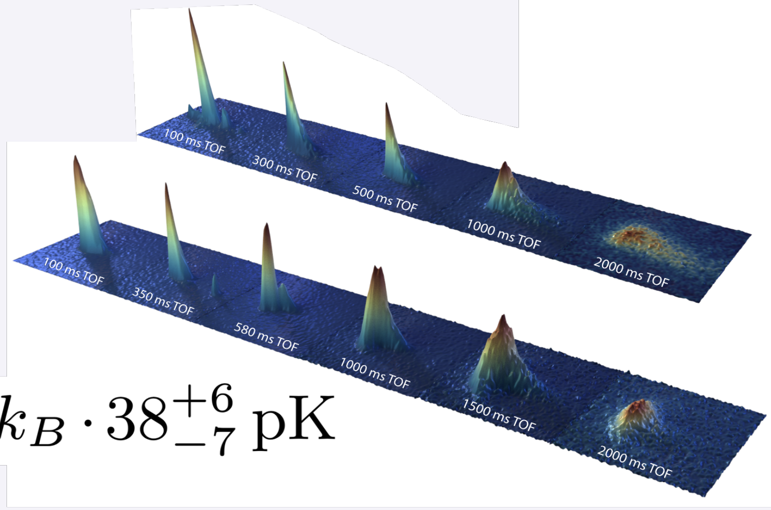
M. Meister et al., Efficient Description of Bose–Einstein Condensates in Time-Dependent Rotating Traps », Advances In Atomic, Molecular, and Optical Physics, 66, 375 (2017)

Quantum engineering of many-body systems

QUANTUS



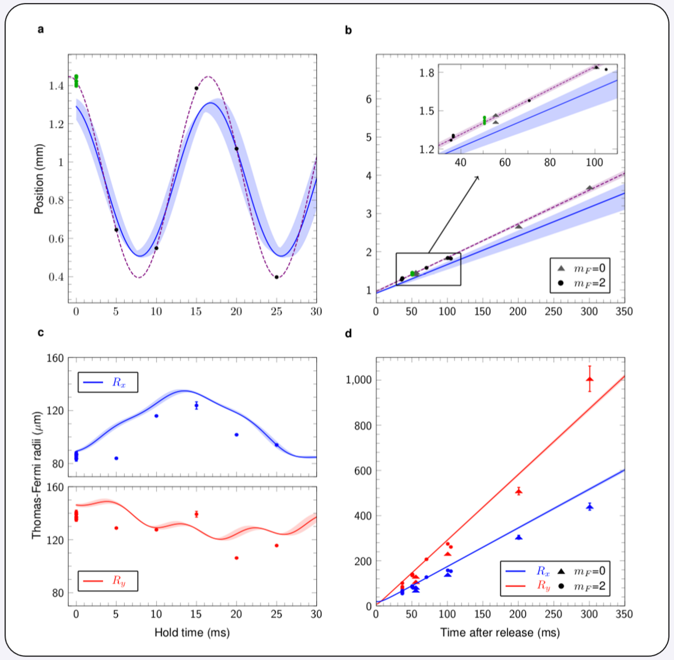
C. Deppner et al. Collective-Mode Enhanced Matter-Wave Optics, Phys. Rev. Lett. 127, 100401 (2021)

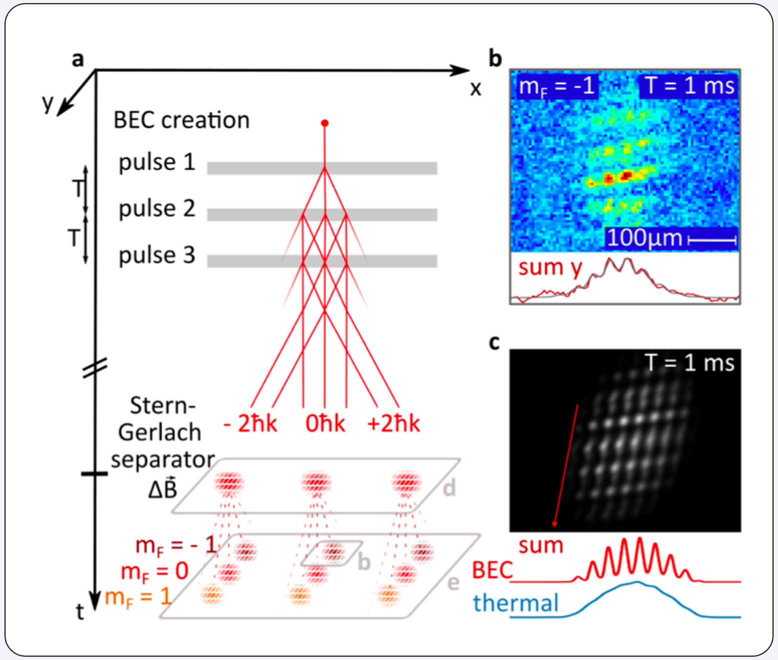


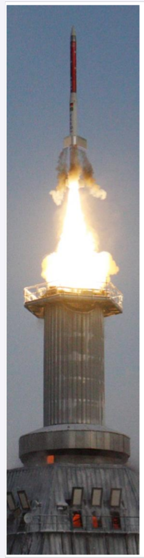
$$^3/_2\, k_B \cdot 38^{+6}_{-7}\,\mathrm{pK}$$

+ proposal for mixtures in Robin Corgier, et al., Interacting quantum mixtures for precision atom interferometry, New J. Phys. 22 123008 (2020).

Sounding rocket MAIUS-1





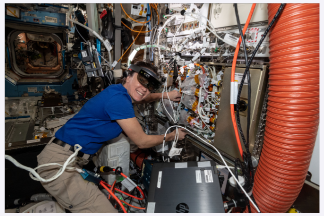


D. Becker et al., Space-borne Bose–Einstein condensation for precision interferometry, *Nature* **562**, 391 (2018)

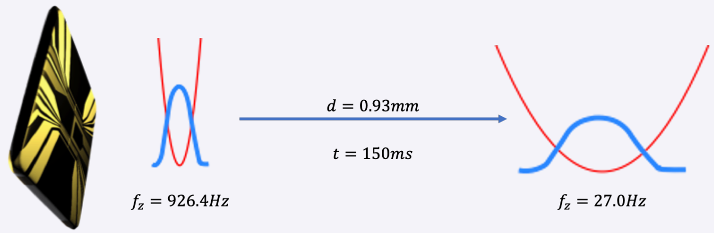
M. Lachmann, et al., « Ultracold atom interferometry in space », *Nature Comm.* **12,** 1317 (2021)

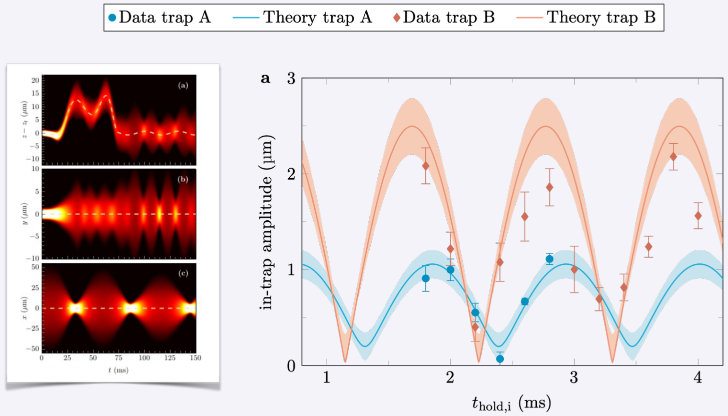
Quantum engineering of many-body systems

Cold Atom Lab. (CAL), NASA



- Transport of a quantum gas at a velocity of **6 mm/s** using the magnetics of the atom-chip-based BEC machine
- Manipulation of quantum gases over distances roughly **1000 times their sizes**
- Position control at the **70 nm accuracy level**
- Comparable to state-of-the-art ion shuttling experiments!





N. Gaaloul, et al. Nature Communications (2022)

npj | microgravity

www.nature.com/npjmgrav

ARTICLE OPEN

Check for updates

The space cold atom interferometer for testing the equivalence principle in the China Space Station

Meng He[1,2], Xi Chen[1✉], Jie Fang[1], Qunfeng Chen[1], Huanyao Sun[1], Yibo Wang[1], Jiaqi Zhong[1,3], Lin Zhou[1,3], Chuan He[1], Jinting Li[1,2], Danfang Zhang[1,2], Guiguo Ge[1,2], Wenzhang Wang[1,2], Yang Zhou[1,2], Xiao Li[1], Xiaowei Zhang[1], Lei Qin[1], Zhiyong Chen[1], Rundong Xu[1], Yan Wang[1], Zongyuan Xiong[1], Junjie Jiang[1,2], Zhendi Cai[1,2], Kuo Li[4], Guo Zheng[4], Weihua Peng[4], Jin Wang[1,3,5✉] and Mingsheng Zhan[1,3,5✉]

The precision of the weak equivalence principle (WEP) test using atom interferometers (AIs) is expected to be extremely high in microgravity environment. The microgravity scientific laboratory cabinet (MSLC) in the China Space Station (CSS) can provide a higher-level microgravity than the CSS itself, which provides a good experimental environment for scientific experiments that require high microgravity. We designed and realized a payload of a dual-species cold rubidium atom interferometer. The payload is highly integrated and has a size of 460 mm × 330 mm × 260 mm. It will be installed in the MSLC to carry out high-precision WEP test experiment. In this article, we introduce the constraints and guidelines of the payload design, the compositions and functions of the scientific payload, the expected test precision in space, and some results of the ground test experiments.

npj Microgravity (2023)9:58 ; https://doi.org/10.1038/s41526-023-00306-y

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.

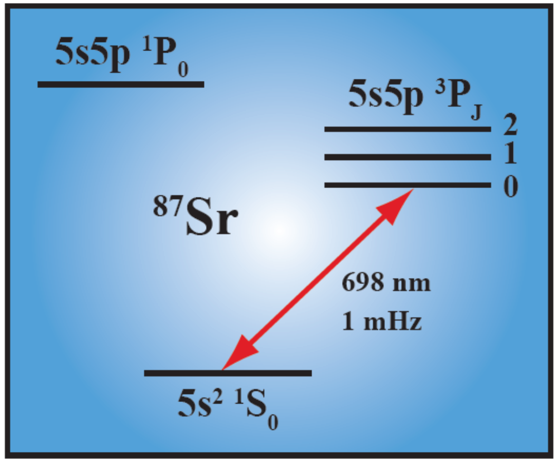
SECONDARY GOALS:

• 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

G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,* **Eur. Phys. J. D 73, 228 (2019)**

September 13, 2016

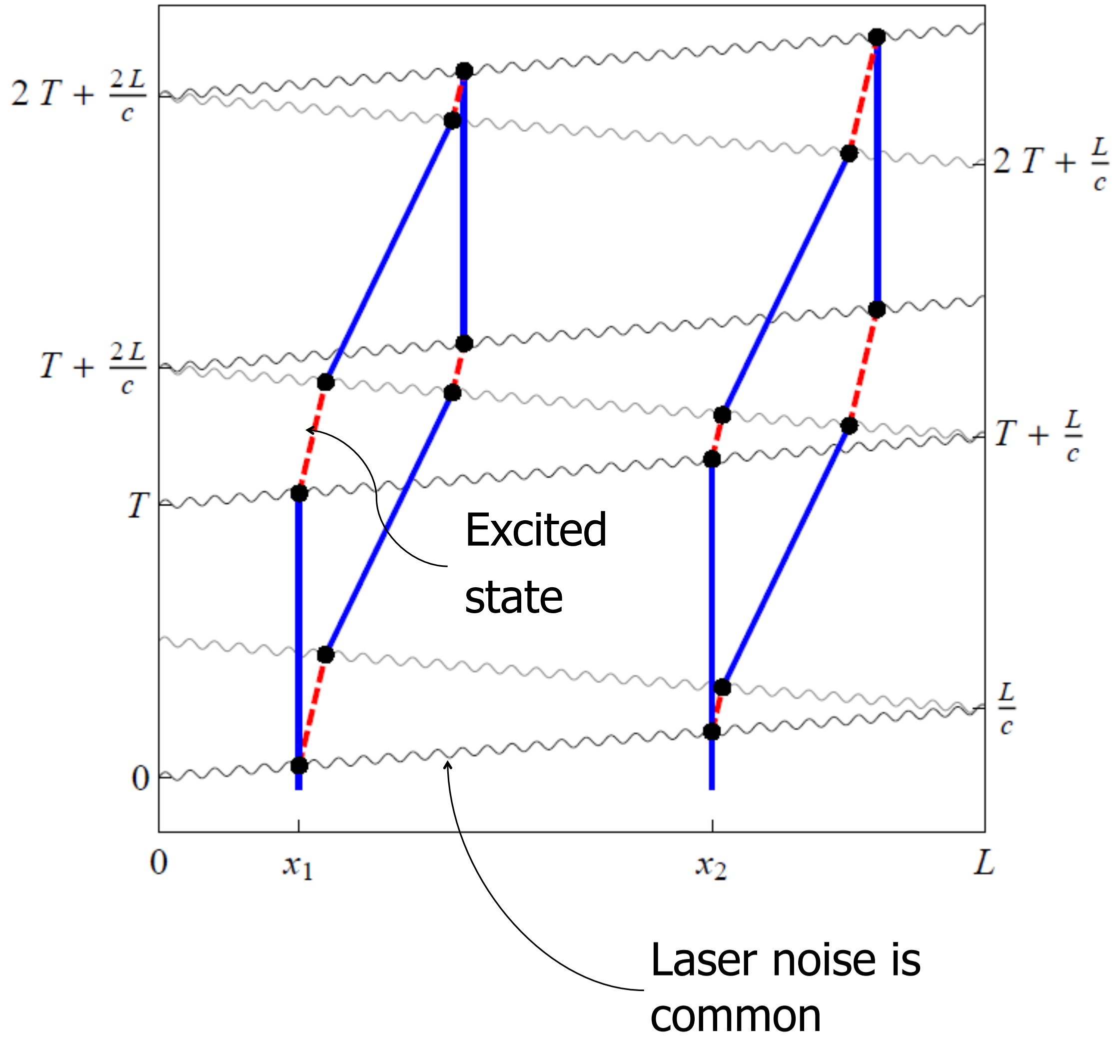
Laser frequency noise insensitive detector



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.

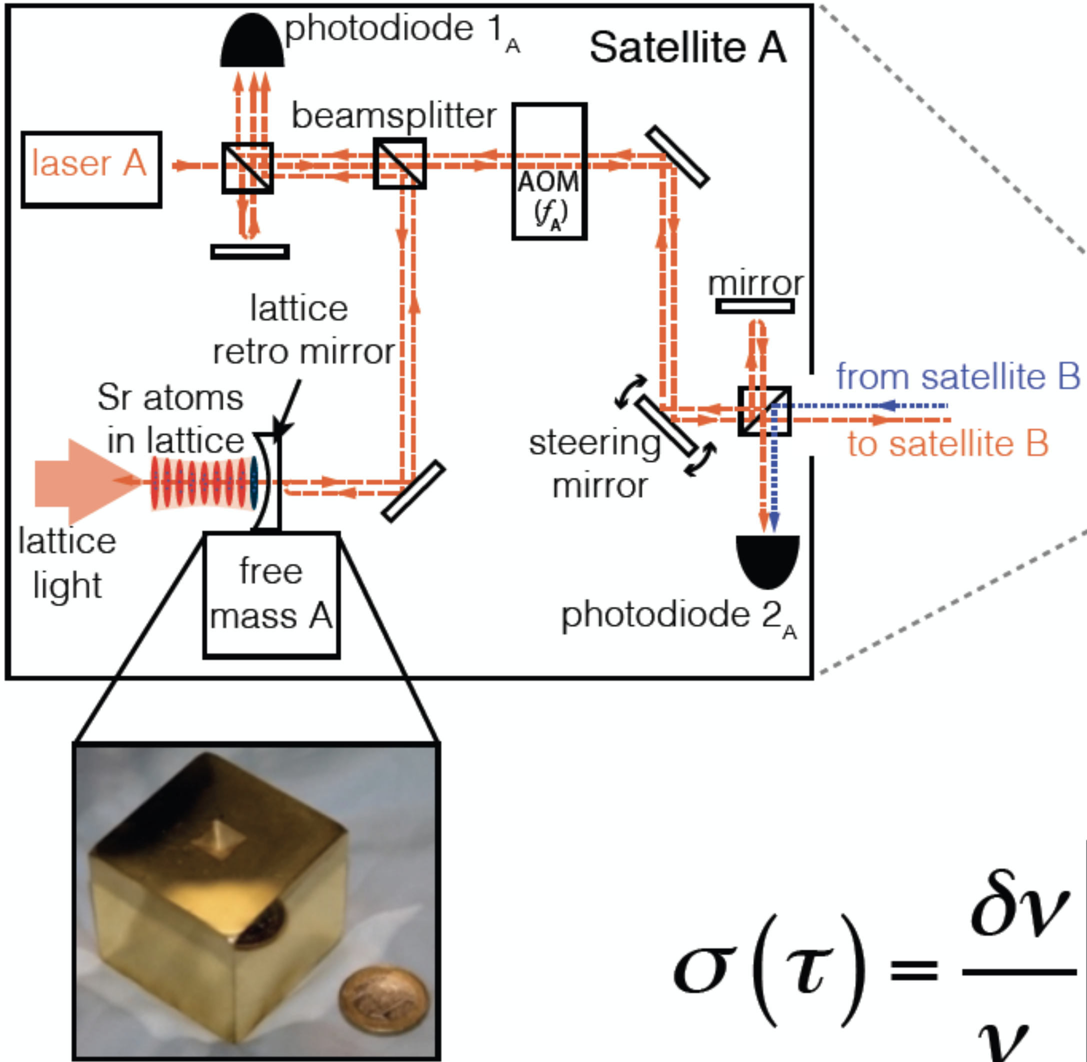
Enables 2 satellite configurations

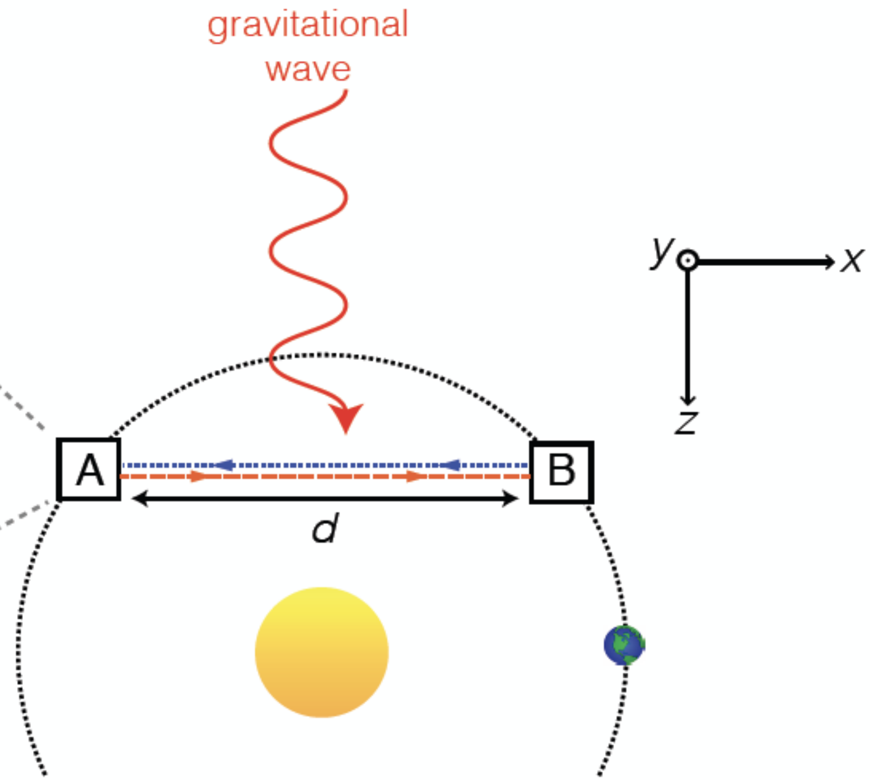


Graham, et al., arXiv:1206.0818, PRL (2013)

from M. Kasevich
STANFORD UNIVERSITY

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)

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 uulm · IQ · Leibniz Universität Hannover · Stanford · NANYANG TECHNOLOGICAL UNIVERSITY · University of Nevada, Reno

...s in the field of Fundamental Physics. The scientific objective is to ...nal Waves and other fundamental aspects of gravity as well as the ...itational physics and quantum physics using new quantum sensors.

Space Atomic Gravity Explorer (SAGE)

Submitted to ESA in response to the call for New Science Ideas (2016)

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:

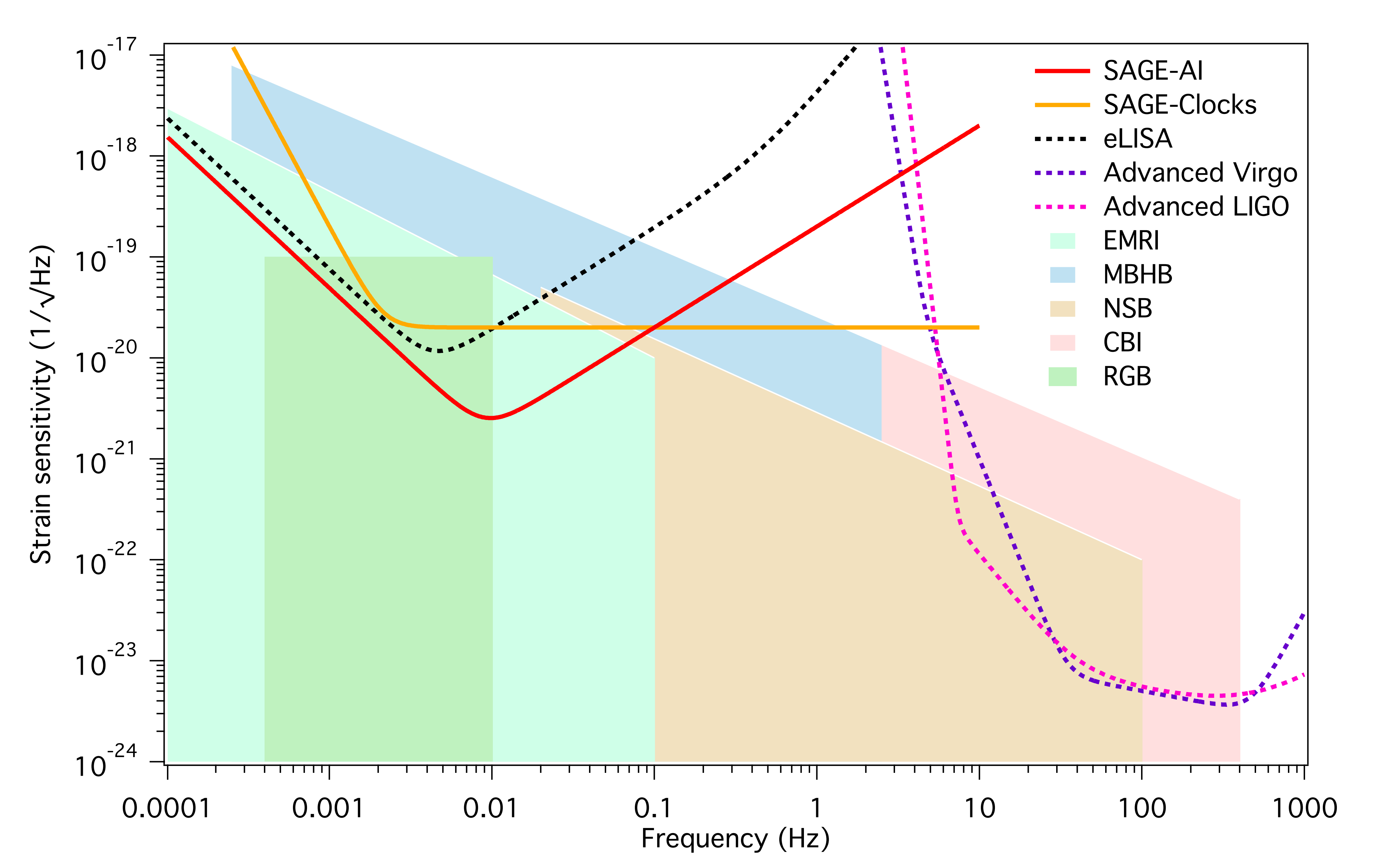
- Search for Dark-Matter
- Measure the Gravitational Red Shift
- Test the Equivalence Principle of General Relativity and search for spin-gravity coupling
- Define an ultraprecise frame of reference for Earth and Space and compare terrestrial clocks
- Investigate quantum correlations and test Bell inequalities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

...A member states as well as from USA, China, ...on of the proposal.

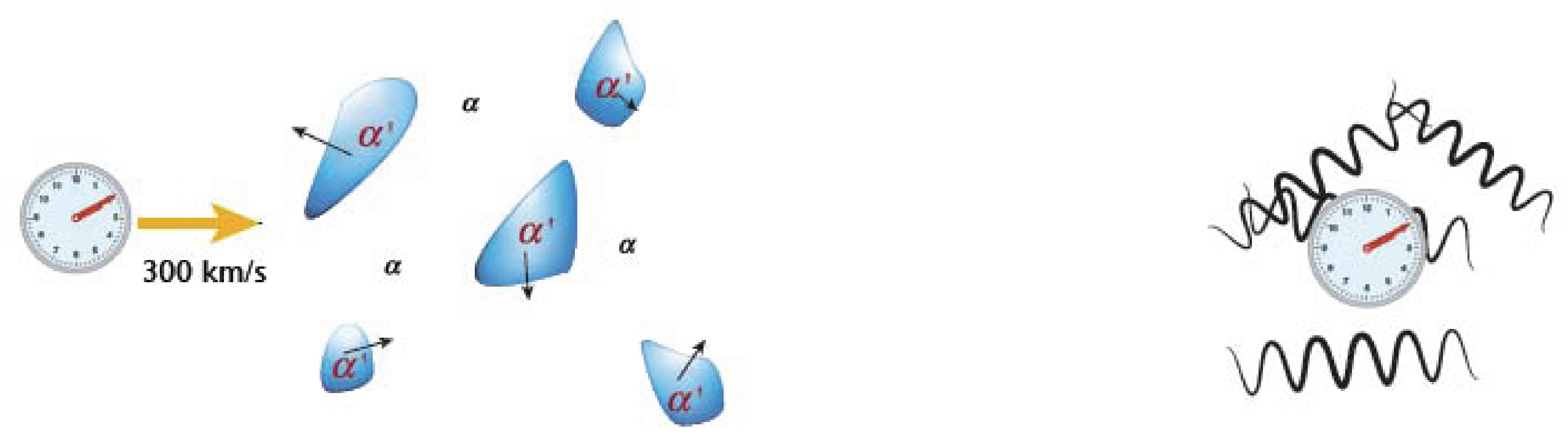
G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,* **Eur. Phys. J. D 73, 228 (2019)**

SAGE: GW detection



G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,*
Eur. Phys. J. D 73, 228 (2019)

SAGE: Search for Dark-Matter

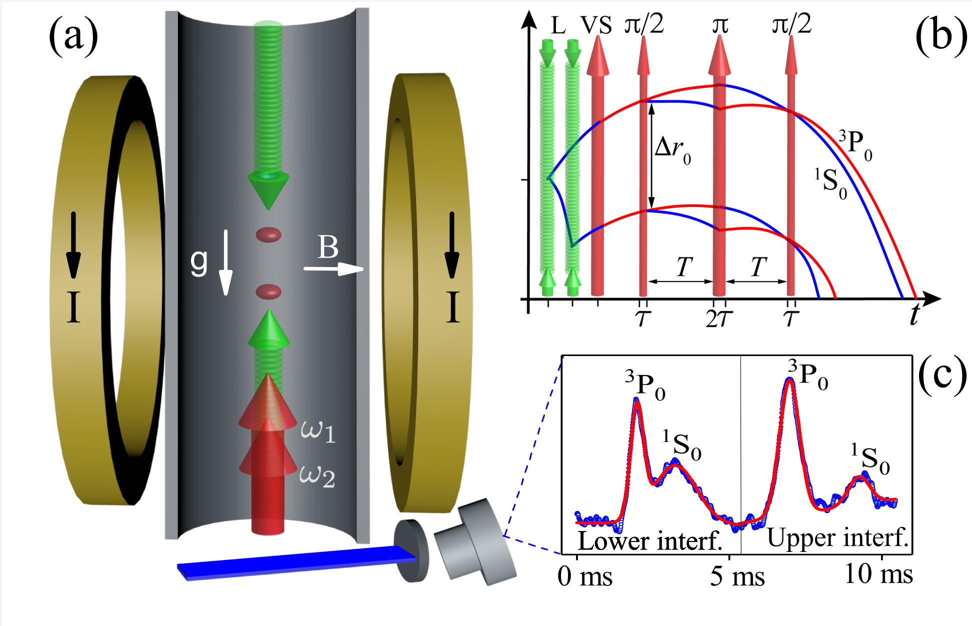


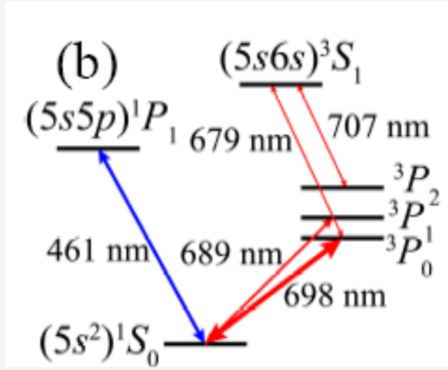
(Left) An atomic clock sweeps through the DM. DM is assumed to be composed of extended objects (or clumps). If there is a difference of fundamental constants (such as the fine-structure constant in the figure) inside and outside the clumps, the clumps can cause the clock to slow down or speed up [A. 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].

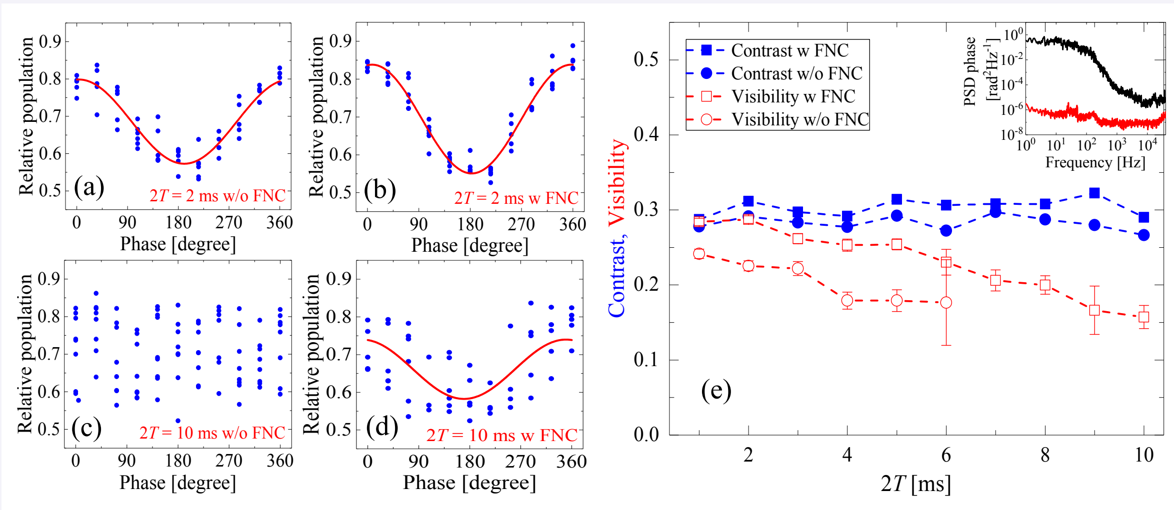
G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,*
Eur. Phys. J. D 73, 228 (2019)

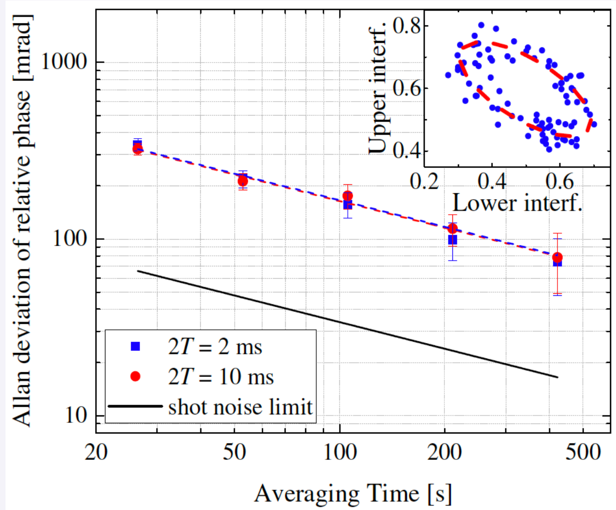
Atom interferometry with the Sr optical clock transition





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





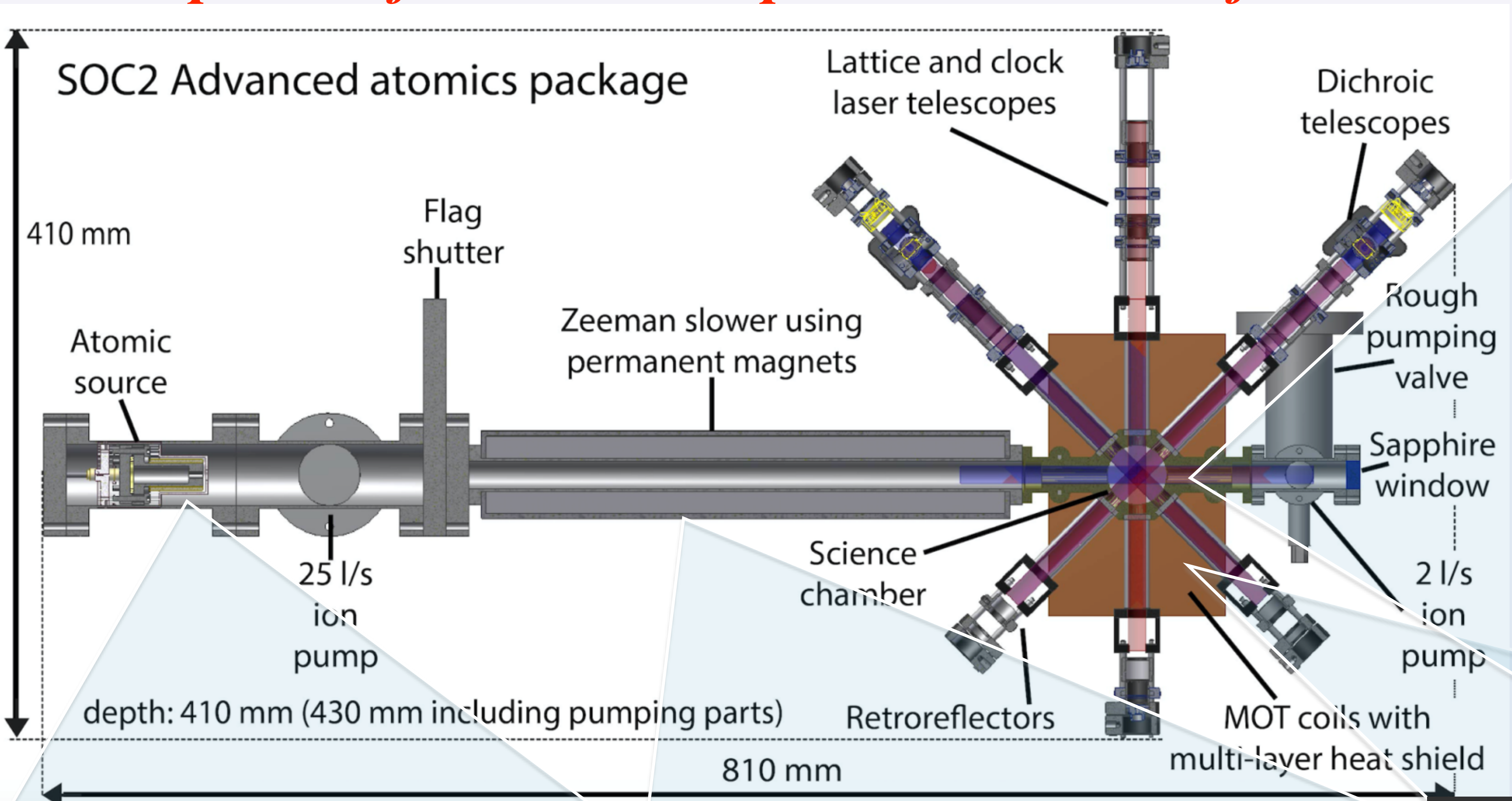
Liang Hu, Nicola Poli, Leonardo Salvi, Guglielmo M. Tino,
Atom interferometry with the Sr optical clock transition,
Phys. Rev. Lett. 119, 263601 (2017)

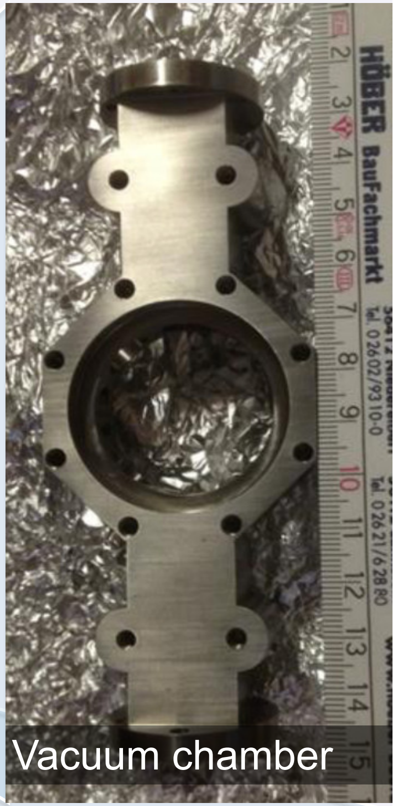
SAGE Pathfinder Successful !!

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]

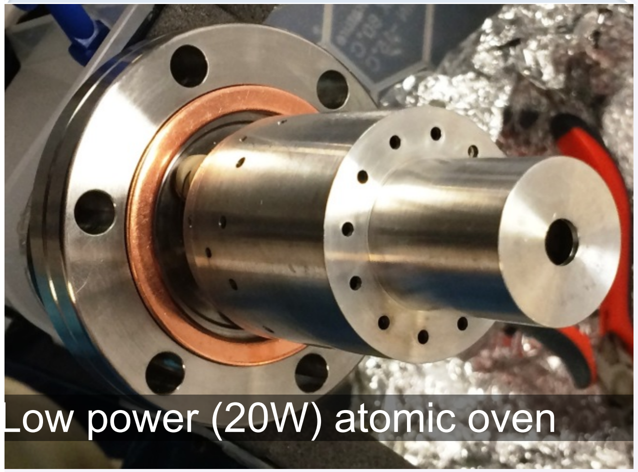
UNIVERSITY OF BIRMINGHAM | UNIVERSITÀ DEGLI STUDI FIRENZE | HEINRICH HEINE UNIVERSITÄT DÜSSELDORF | l'Observatoire de Paris – SYRTE | NPL National Physical Laboratory | Leibniz Universität Hannover | TOPTICA PHOTONICS | PTB

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



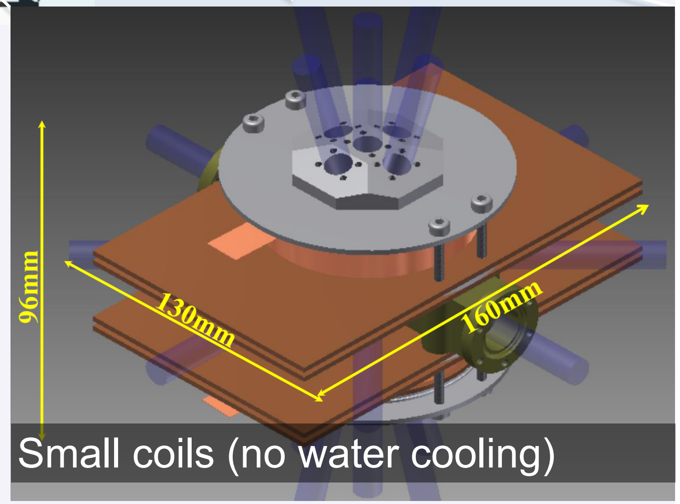


Vacuum chamber



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)**

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

E-mail: o.buchmueller@imperial.ac.uk

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

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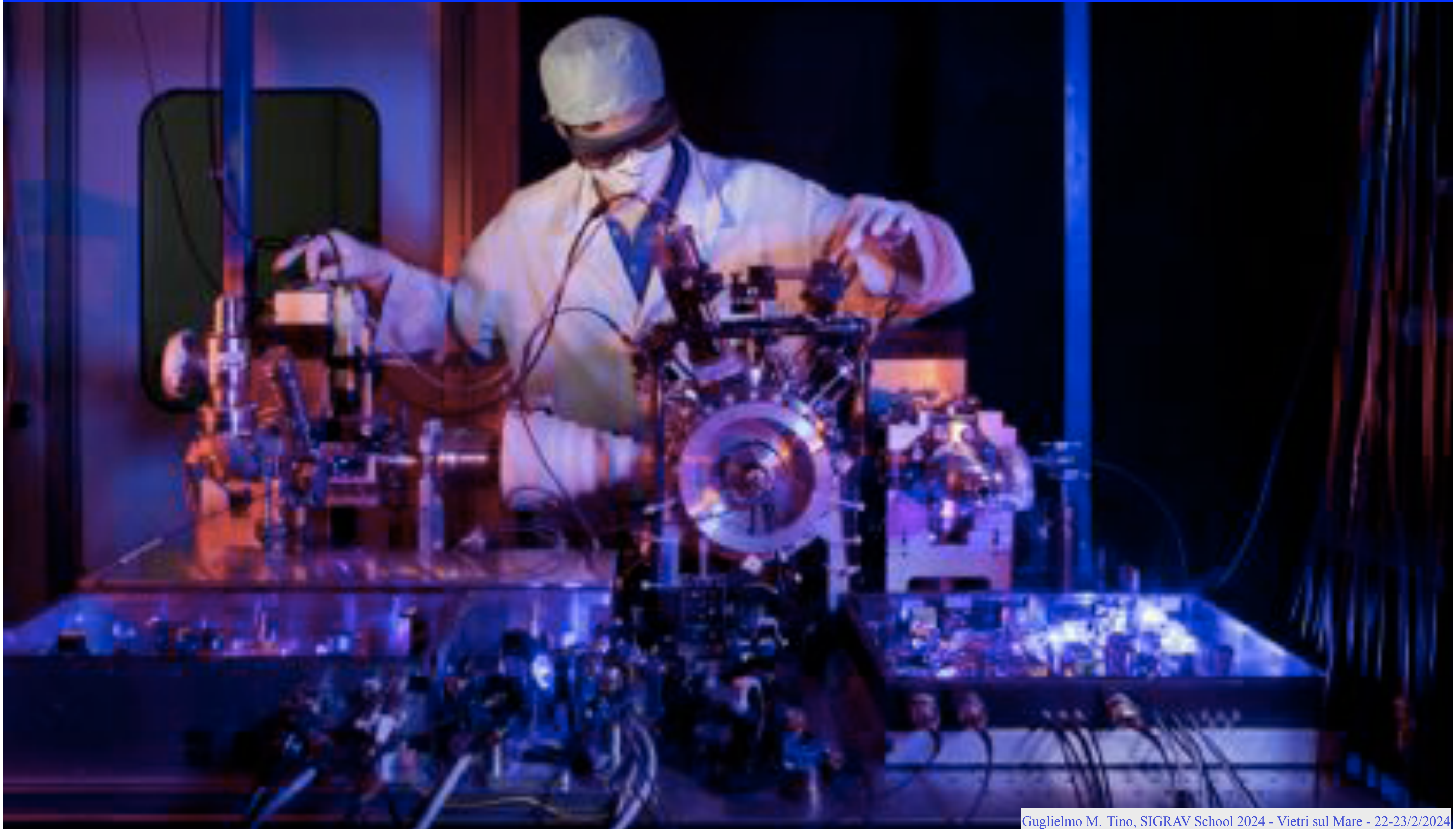

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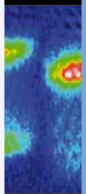

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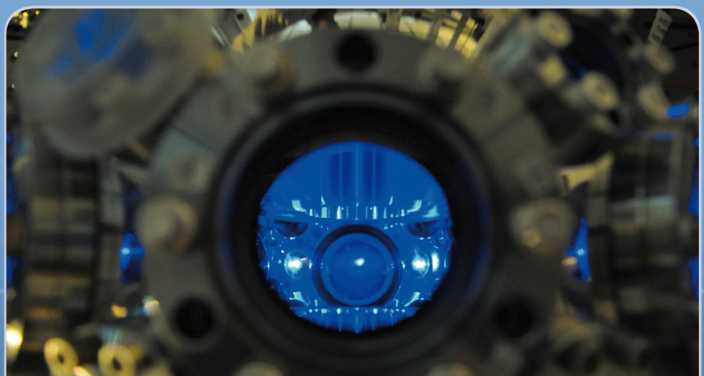

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Review

Precision gravity tests and the Einstein Equivalence Principle

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ABSTRACT

General Relativity is today the best theory of gravity addressing a wide range of phenomena. Our understanding of physical laws, from cosmology to local scales, cannot be properly formulated without taking into account its concepts, procedures and formalism. It is based on one of the most fundamental principles of Nature, the Equivalence Principle, which represents the core of the Einstein theory of gravity describing, under the same standard, the metric and geodesic structure of the spacetime. The confirmation of its validity at different scales and in different contexts represents one of the main challenges of modern physics both from the theoretical and the experimental points of view.

A major issue related to this principle is the fact that we actually do not know if

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PAPER

Testing gravity with cold atom interferometry: results and prospects

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Keywords: atom interferometry, experimental tests of gravity, new physics, cold atoms, atomic clocks

Abstract

Atom interferometers have been developed in the last three decades as new powerful tools to investigate gravity. They were used for measuring the gravity acceleration, the gravity gradient, and the gravity-field curvature, for the determination of the gravitational constant, for the investigation of gravity at microscopic distances, to test the equivalence principle of general relativity and the theories of modified gravity, to probe the interplay between gravitational and quantum physics and to test quantum gravity models, to search for dark matter and dark energy, and they were proposed as new detectors for the observation of gravitational waves. Here I describe past and ongoing experiments with an outlook on what I think are the main prospects in this field and the potential to se

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