Probing gravity with atomic matter waves

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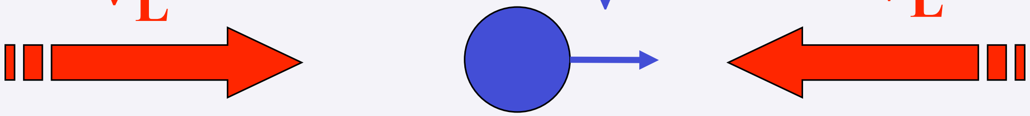
http://coldatoms.lens.unifi.it

Workshop on *Gravity and Entanglement*

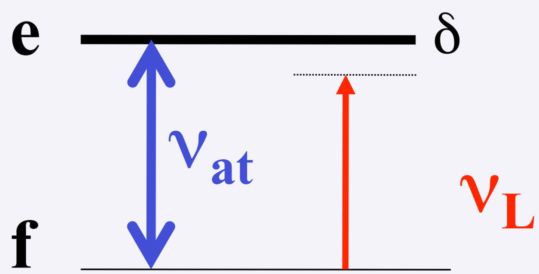
DESY, Hamburg - 7–9 October 2024

Laser cooling: Optical molasses

ν_L v ν_L

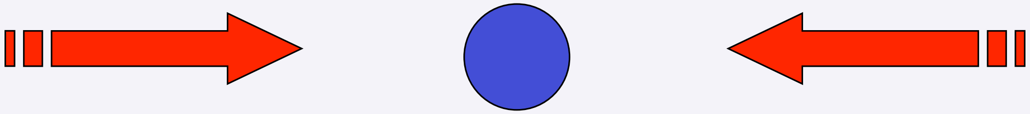


Lab ref. frame

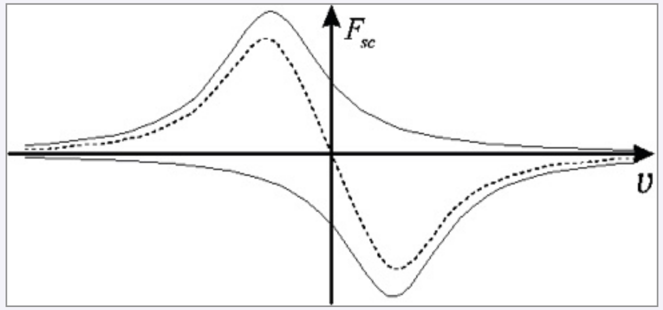


$\nu_{at} > \nu_L$

$\nu_L(1-v/c)$ $\nu_L(1+v/c)$



Atom ref. frame



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

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

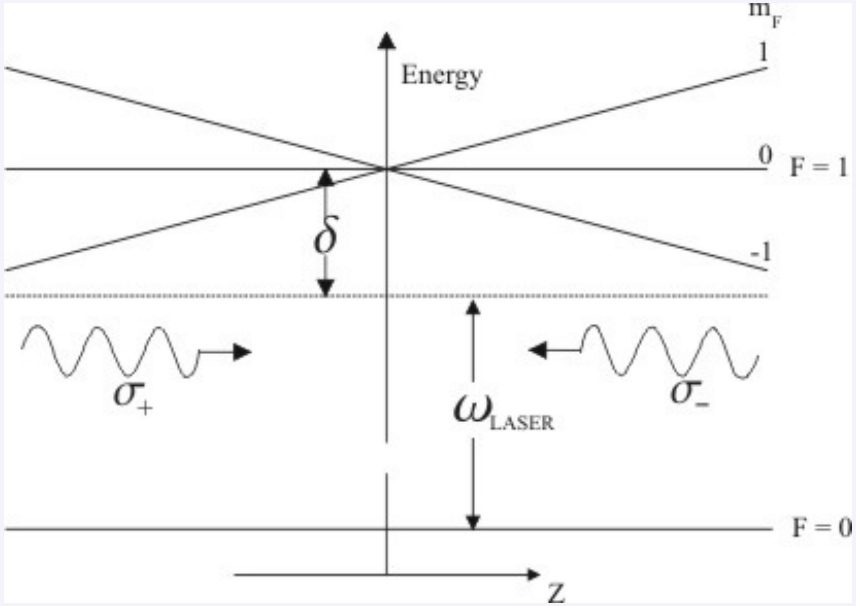
Recoil limit: $$k_B T_r = \frac{1}{M}\left(\frac{h\nu_L}{c}\right)^2$$

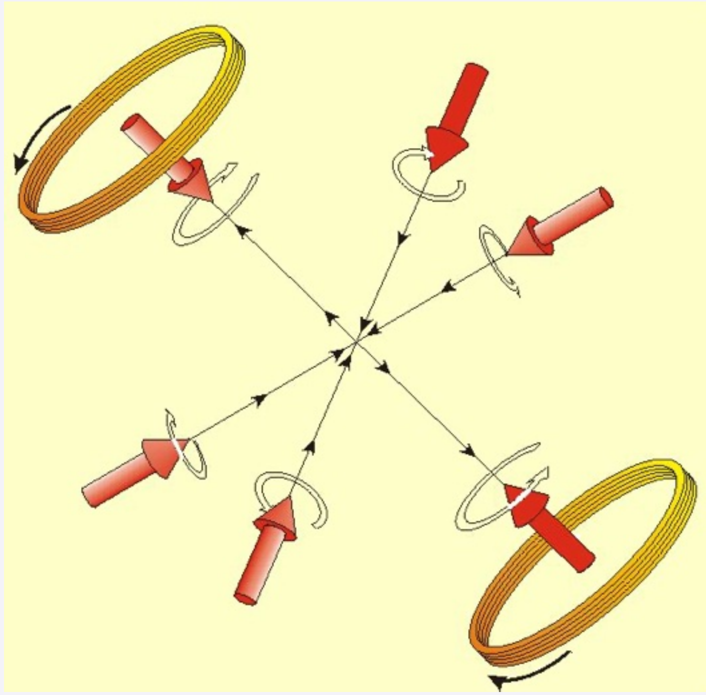
Examples:

	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

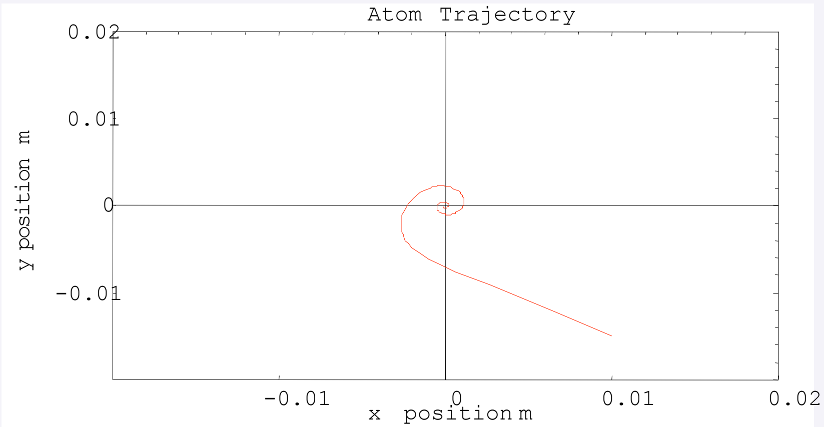
Idea: **T. W. Hänsch, A. Schawlow, 1975**
Exp. demonstration: **S. Chu et al., 1985**

Magneto-Optical Trap (MOT)





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



atom number ≈ 10^9 - 10^{10}

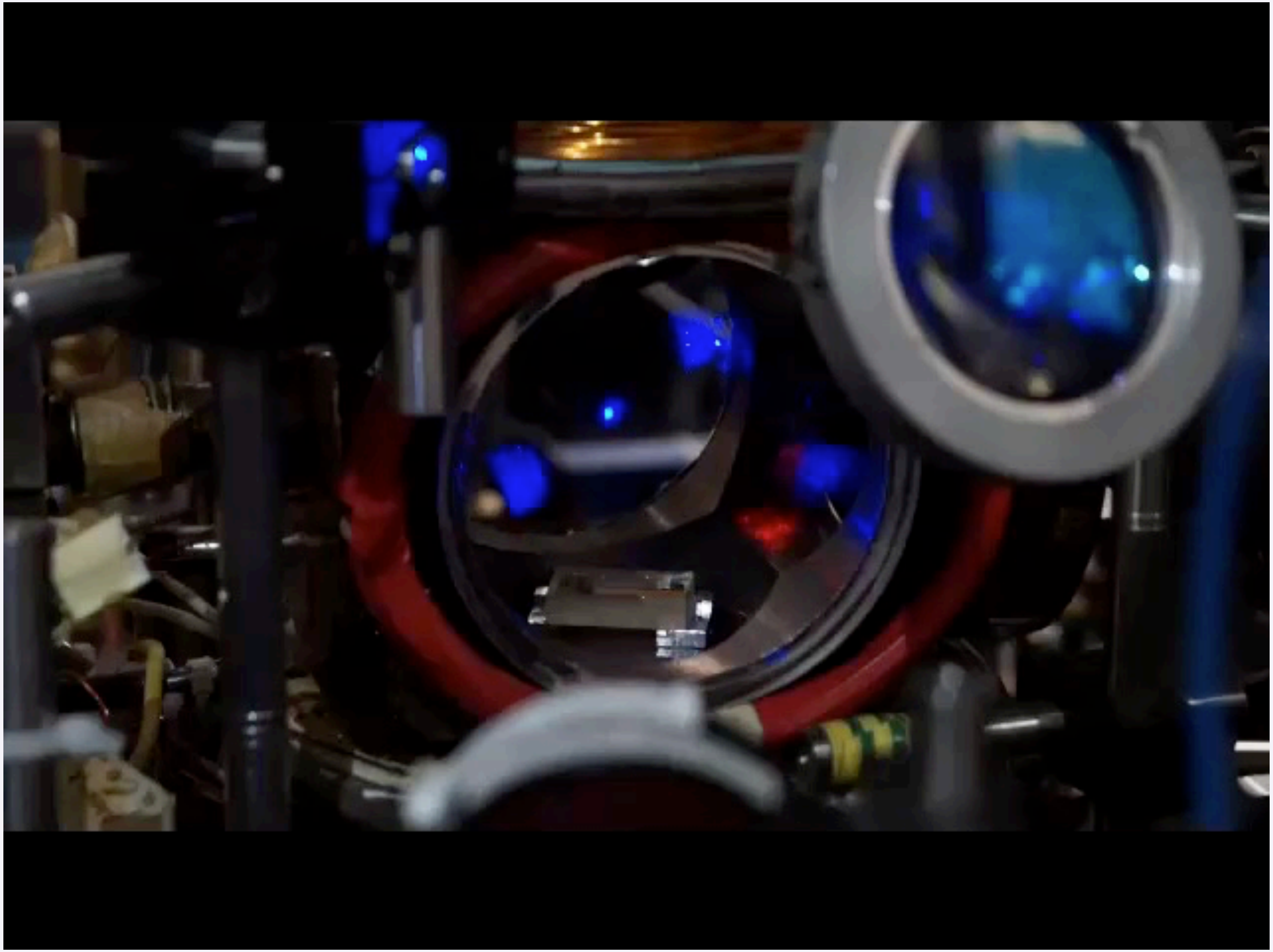
density n ≈ 10^{11} cm^{-3}

temperature T ≈ 100 μK

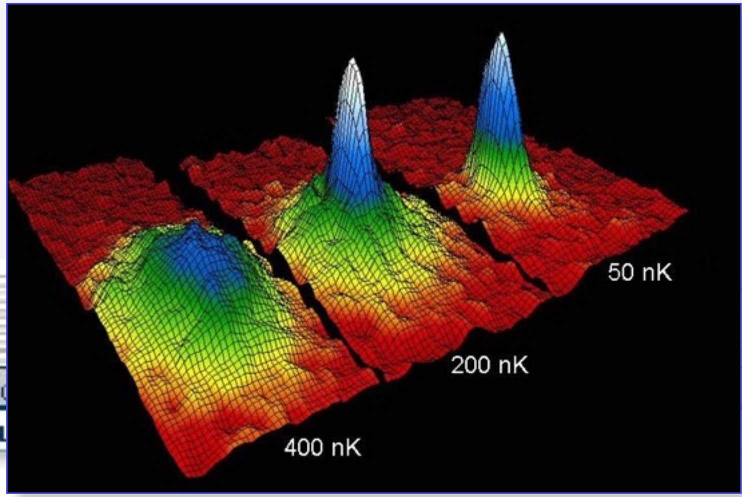
size Δx ≈ 1 mm

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

Cold Sr atoms in a Magneto-Optical Trap



Bose-Einstein condensation in dilute gases of atoms



NOBEL e-MUSEUM

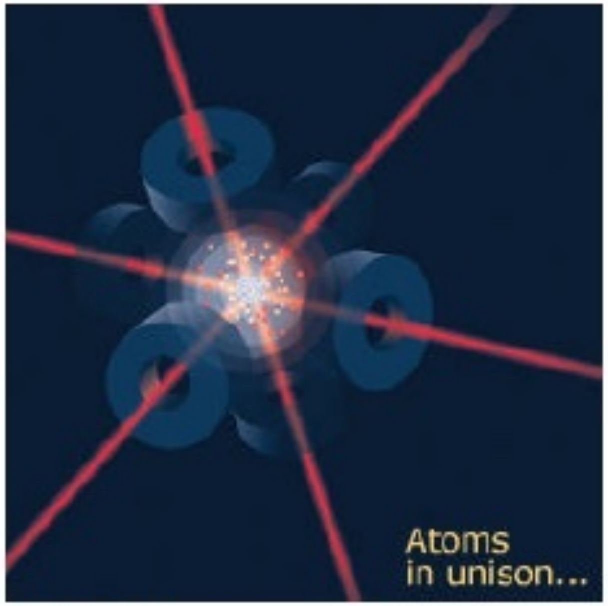
TE HELP ABOUT SEARCH

TURE PEACE ECONOMICS

BACK

The Nobel Prize in Physics 2001

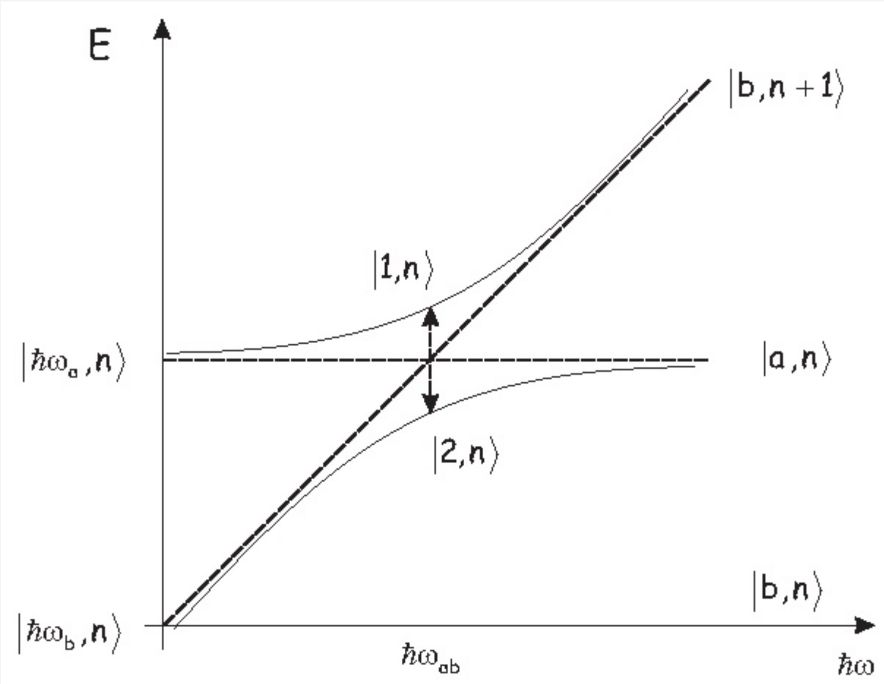
The Royal Swedish Academy of Sciences has awarded the Nobel Prize in Physics for 2001 jointly to Eric A. Cornell, Wolfgang Ketterle and Carl E. Wieman "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates".

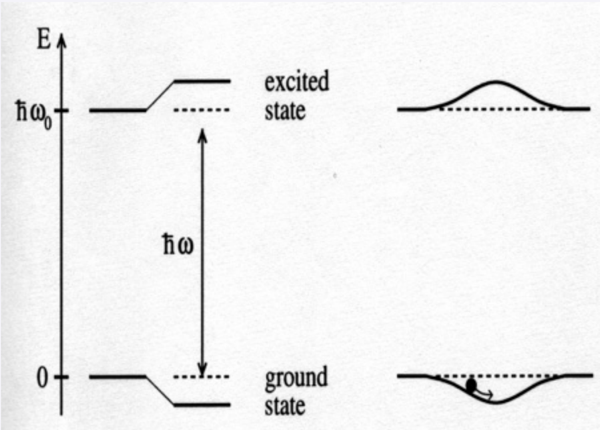


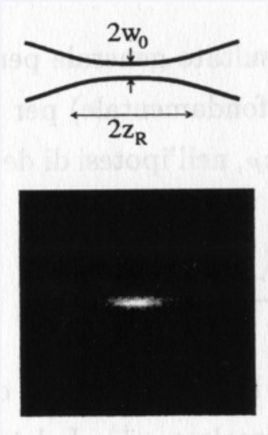
Eric A. Cornell	Carl E. Wieman	Wolfgang Ketterle
JILA and National Institute of Standards and Technology (NIST), Boulder, Colorado, USA.	JILA and University of Colorado, Boulder, Colorado, USA.	Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, USA.

Contents:

Light shifts and optical traps

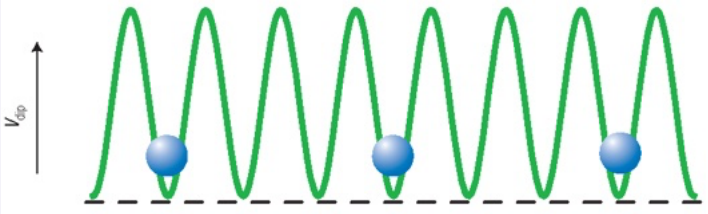




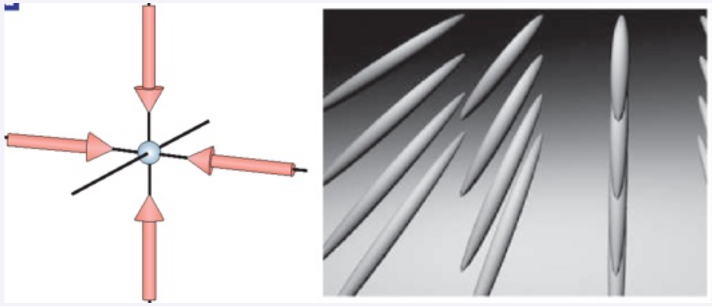


$$V_{dip}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)|\mathbf{E}(\mathbf{r})|^2$$

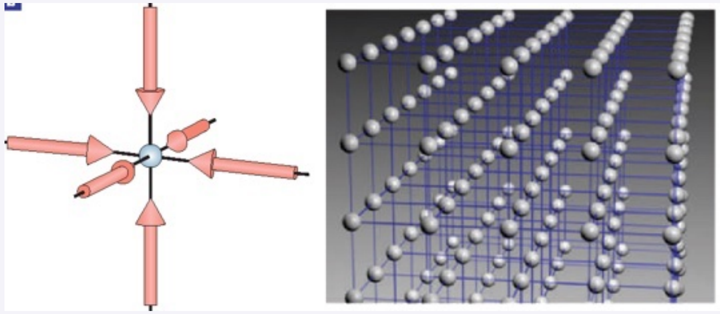
optical lattices



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



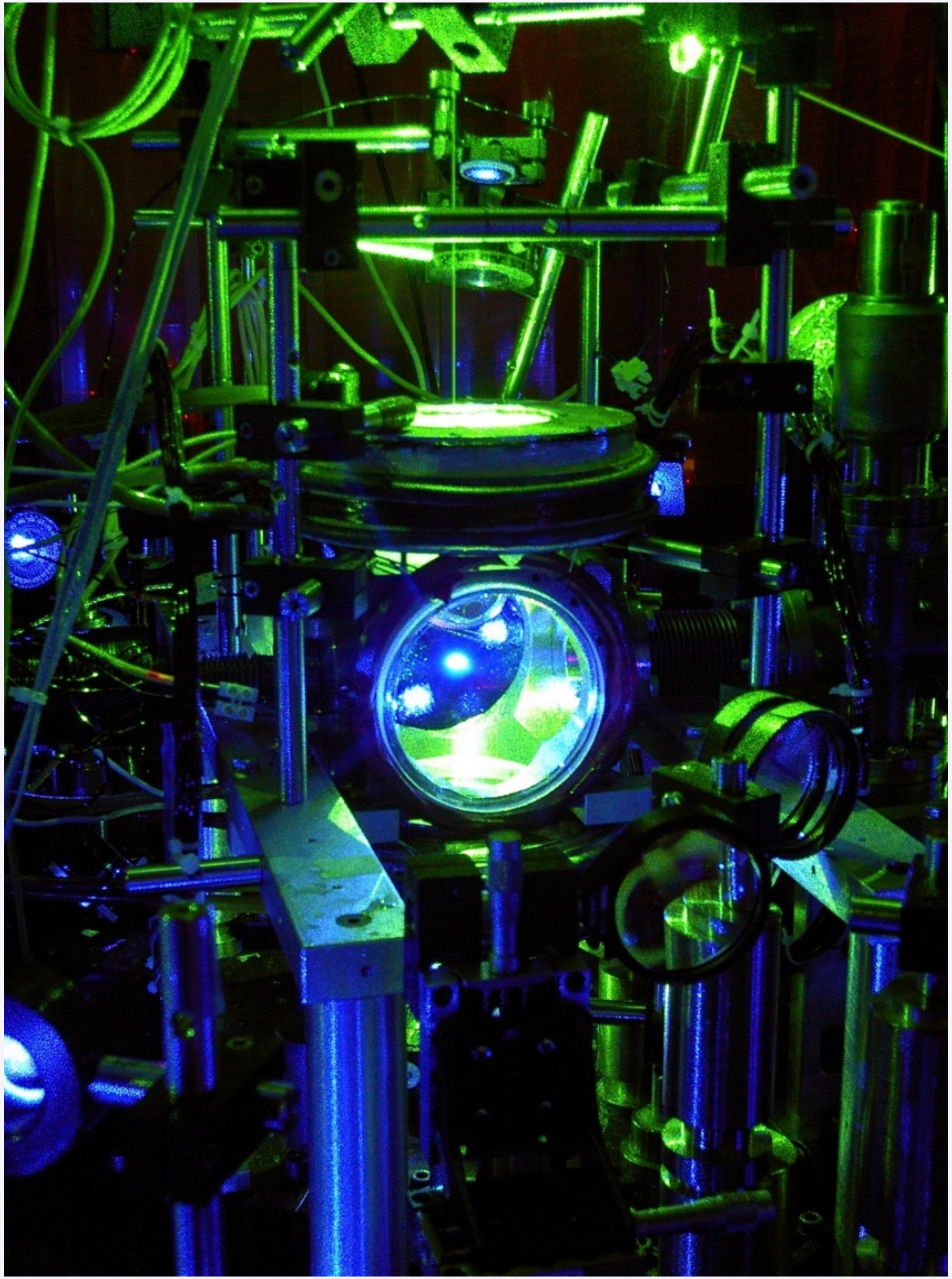
2 D optical lattice ⇒ array of 1D potential tubes



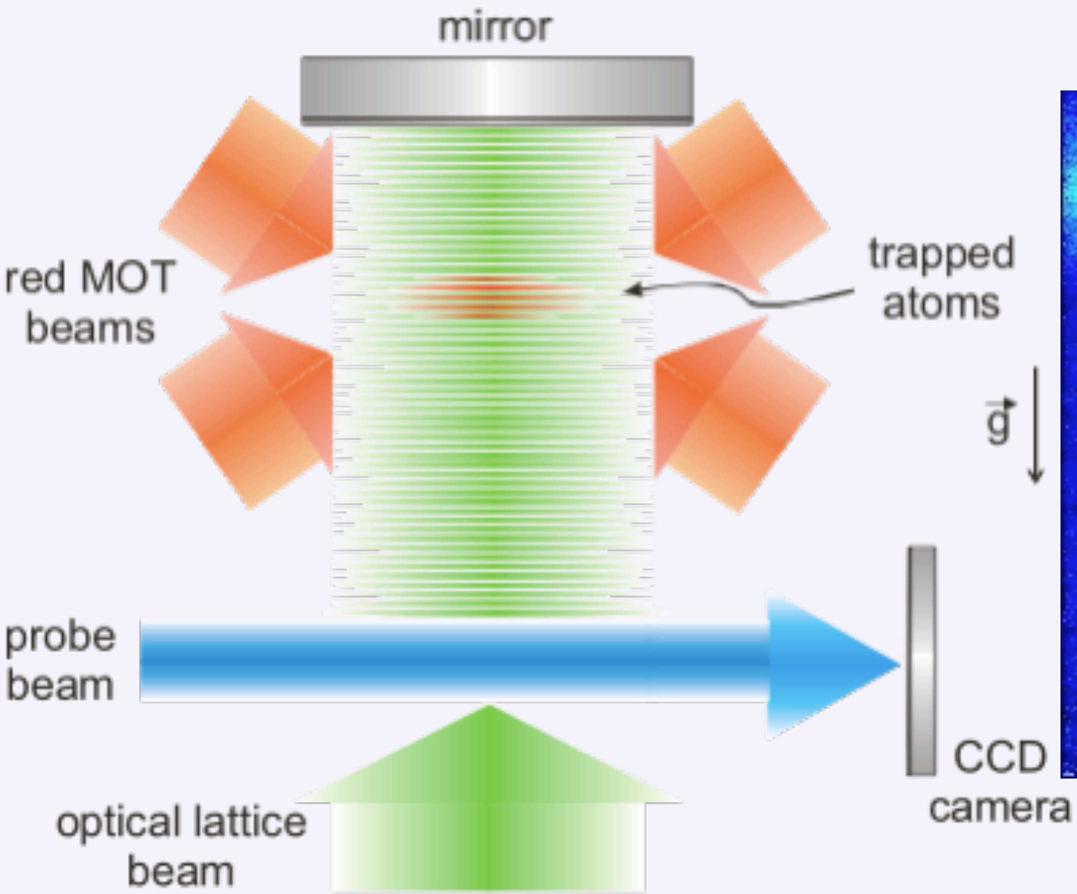
3 D optical lattice ⇒ 3D simple cubic array of h.o. potentials

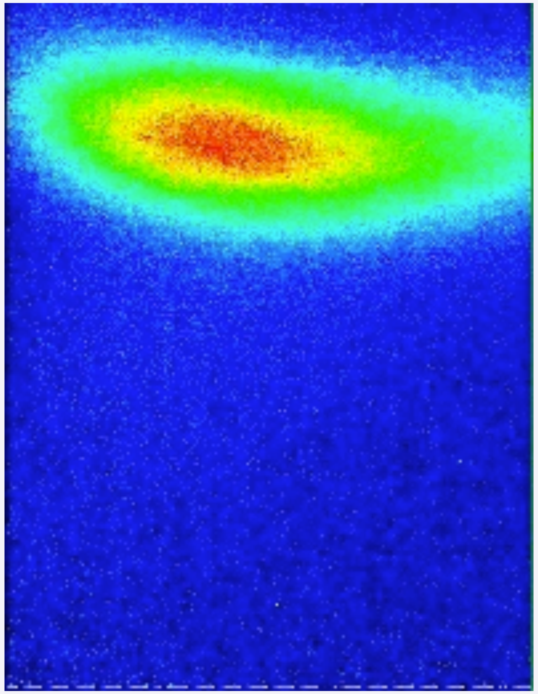
First exp. demonstration: **S. Chu et al., 1986**

Review: **I. Bloch, 2005**



Bloch oscillations of Sr atoms in an optical lattice





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

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

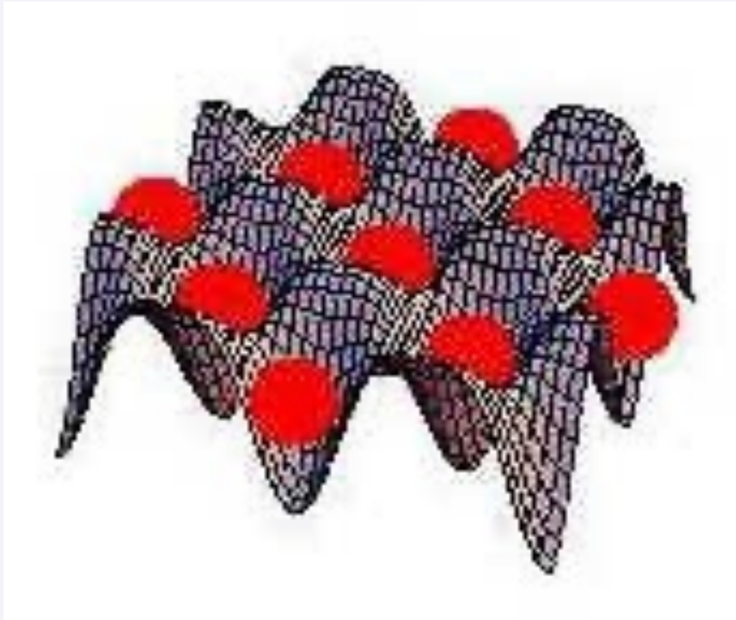
V. Ivanov, A. Alberti, M. Schioppo, G. Ferrari, M. Artoni, M. L. Chiofalo, G. M. Tino, *Coherent Delocalization of Atomic Wave Packets in Driven Lattice Potentials,* **Phys. Rev. Lett. 100, 043602 (2008)**

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

Optical clocks with neutral atoms

- 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)…

Optical clocks: Towards 10^{-20}

- **Narrow optical transitions**

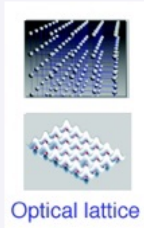
$\delta\nu_o \sim$ 1-100 Hz, $\nu_0 \sim 10^{14}$-10^{15} Hz

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

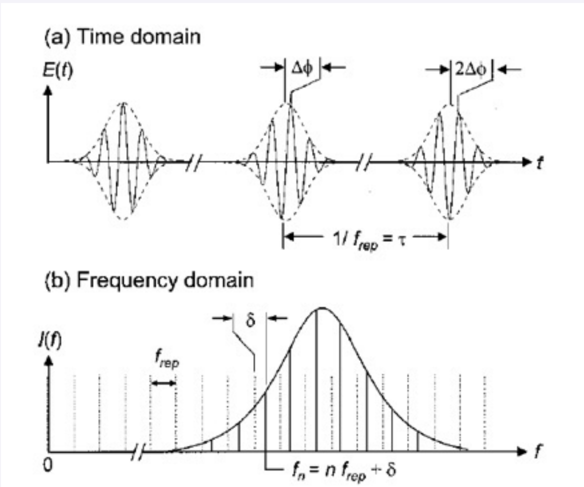
- **Candidate atoms**

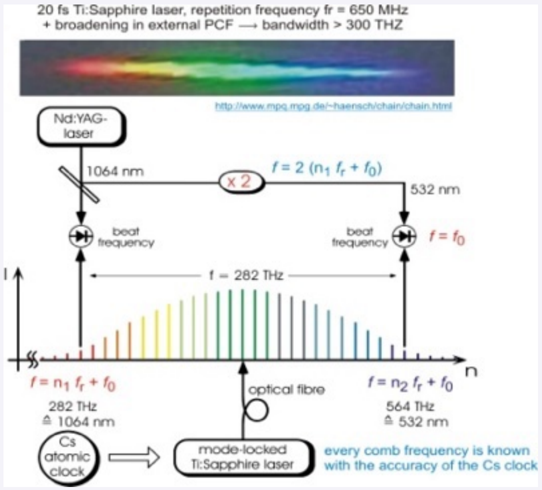
Trapped ions: Hg^+, In^+, Sr^+, Yb^+,…

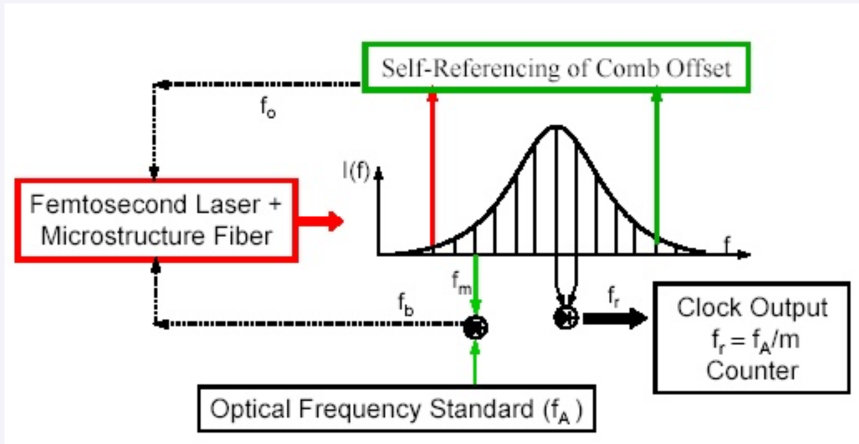
Cold neutral atoms: H, Ca, Sr, Yb,…



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







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

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

Gravitational redshift at millimetre scale

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

Resolving the gravitational redshift across a millimetre-scale atomic sample

https://doi.org/10.1038/s41586-021-04349-7
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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

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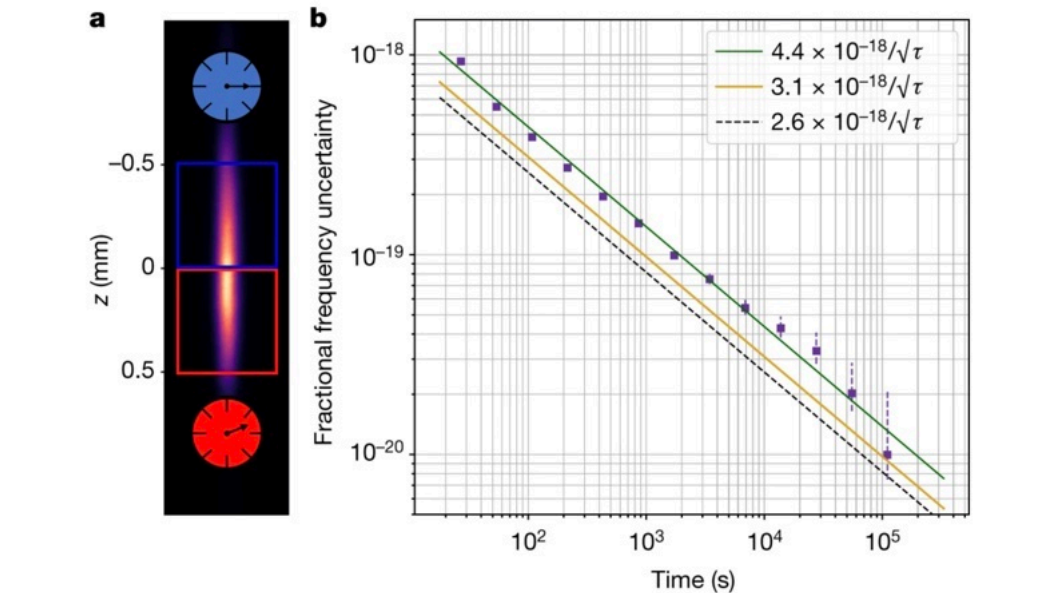
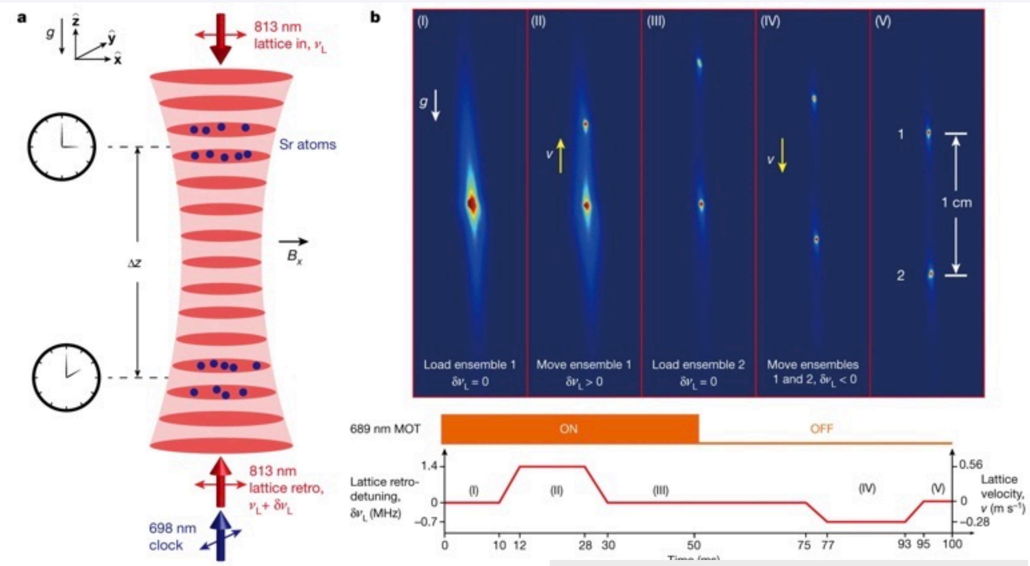
Received: 24 September 2021
Accepted: 14 December 2021
Published online: 16 February 2022
Check for updates

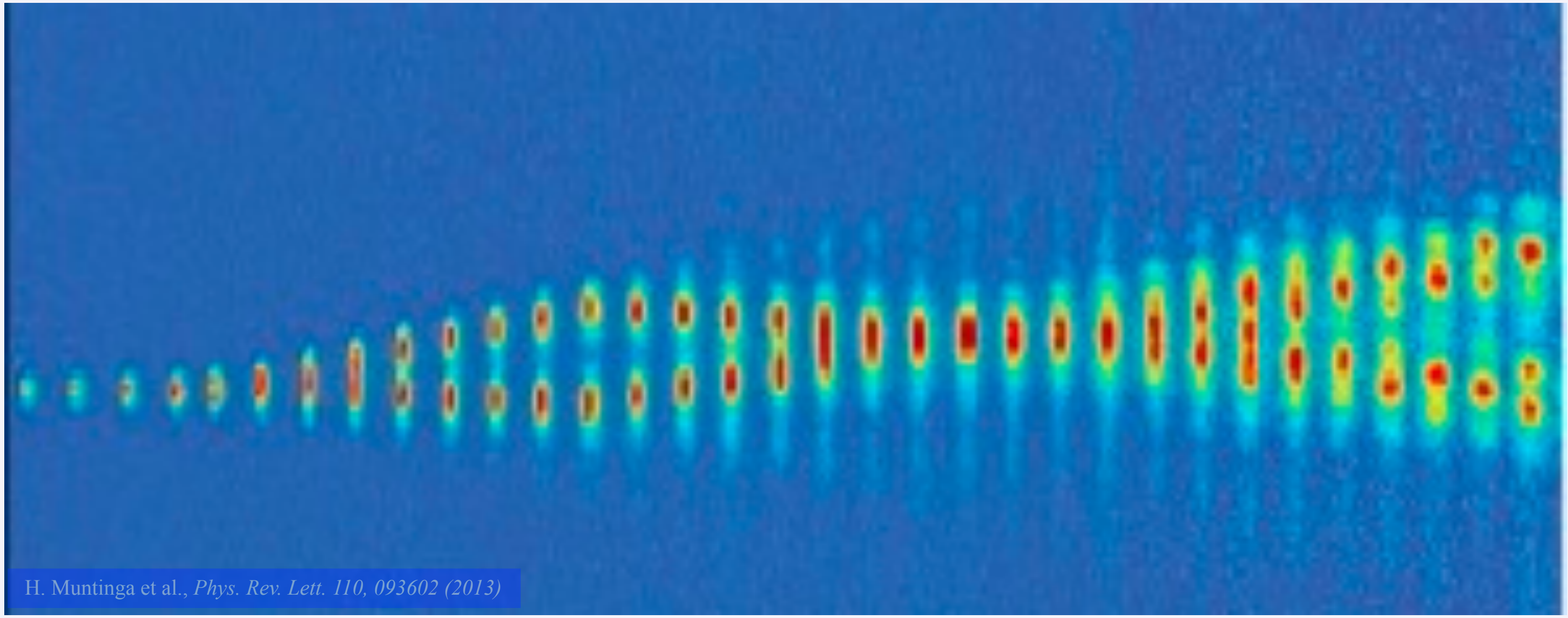
Xin Zheng[1], Jonathan Dolde[1], Varun Lochab[1], Brett N. Merriman[1], Haoran Li[1] & Shimon Kolkowitz[1✉]

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].

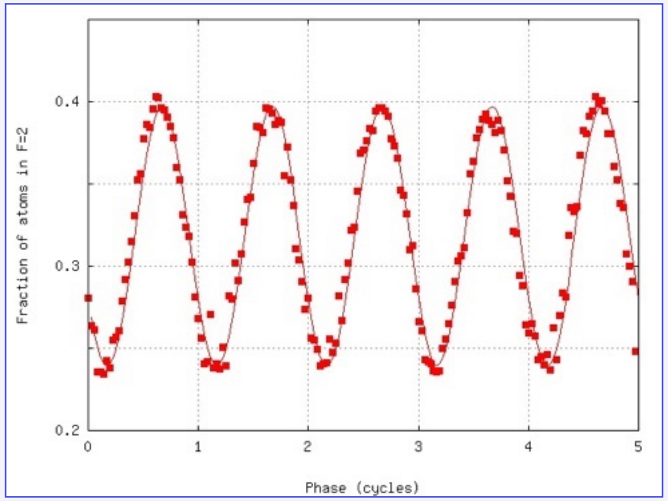




Atom Interferometry



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

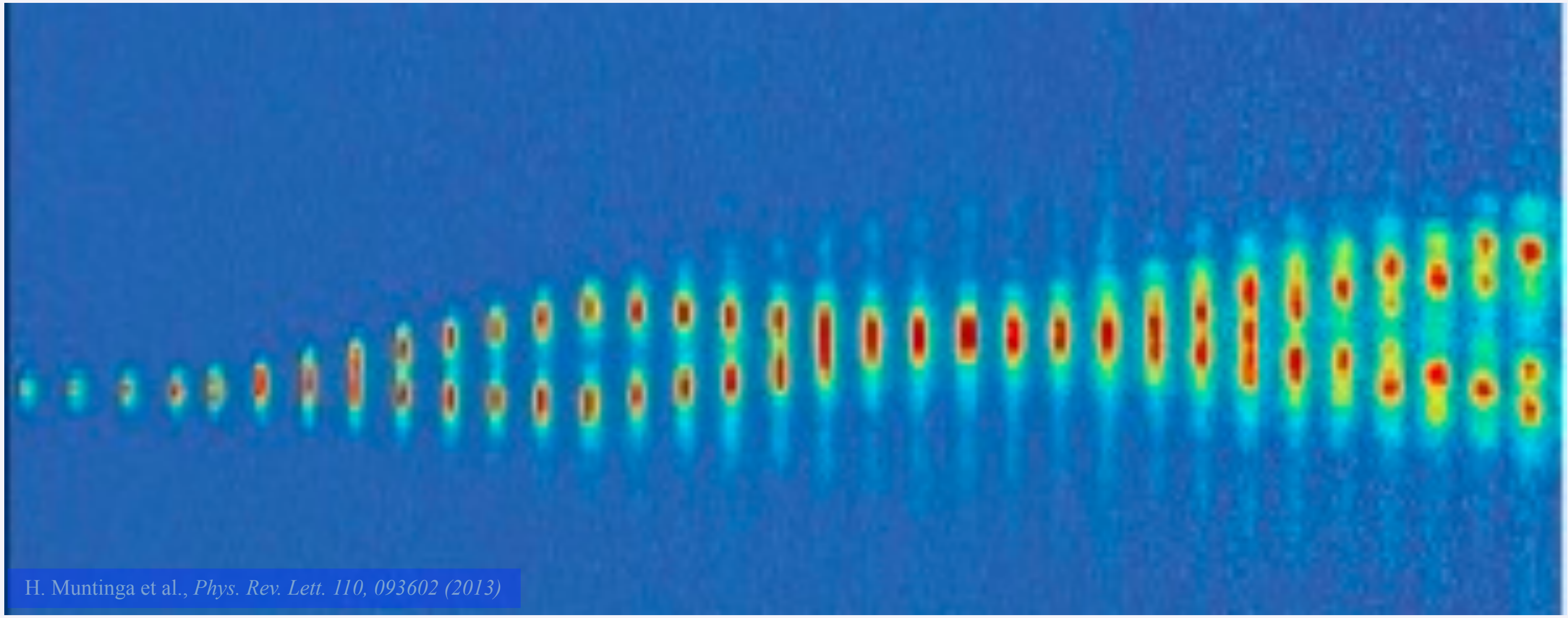


Atomic interference fringes – Firenze 2006

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

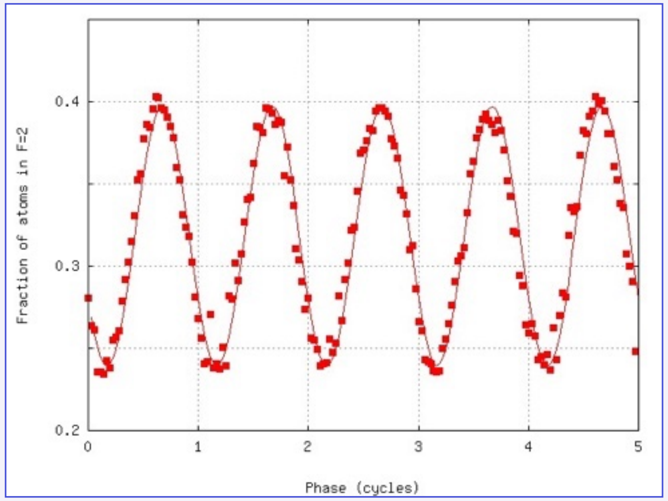
G. M. Tino, M. A. Kasevich (eds) *Atom Interferometry*, Proc. Int. School Phys. "Enrico Fermi", Course CLXXXVIII, Varenna 2013 (SIF and IOS Press, 2014).

Atom interferometry
Wave-particle duality in quantum physics



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

de Broglie wavelength



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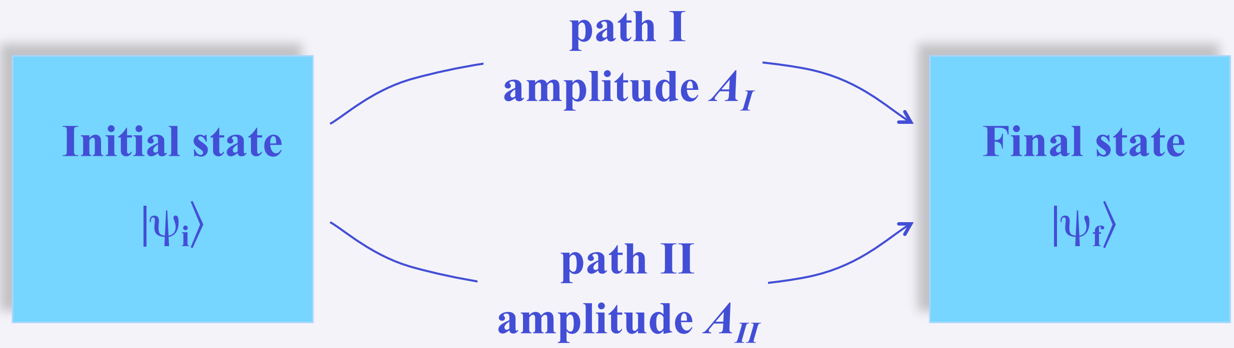
G. M. Tino, M. A. Kasevich (eds) *Atom Interferometry*, Proc. Int. School Phys. ''Enrico Fermi'', Course CLXXXVIII, Varenna 2013 (SIF and IOS Press, 2014).

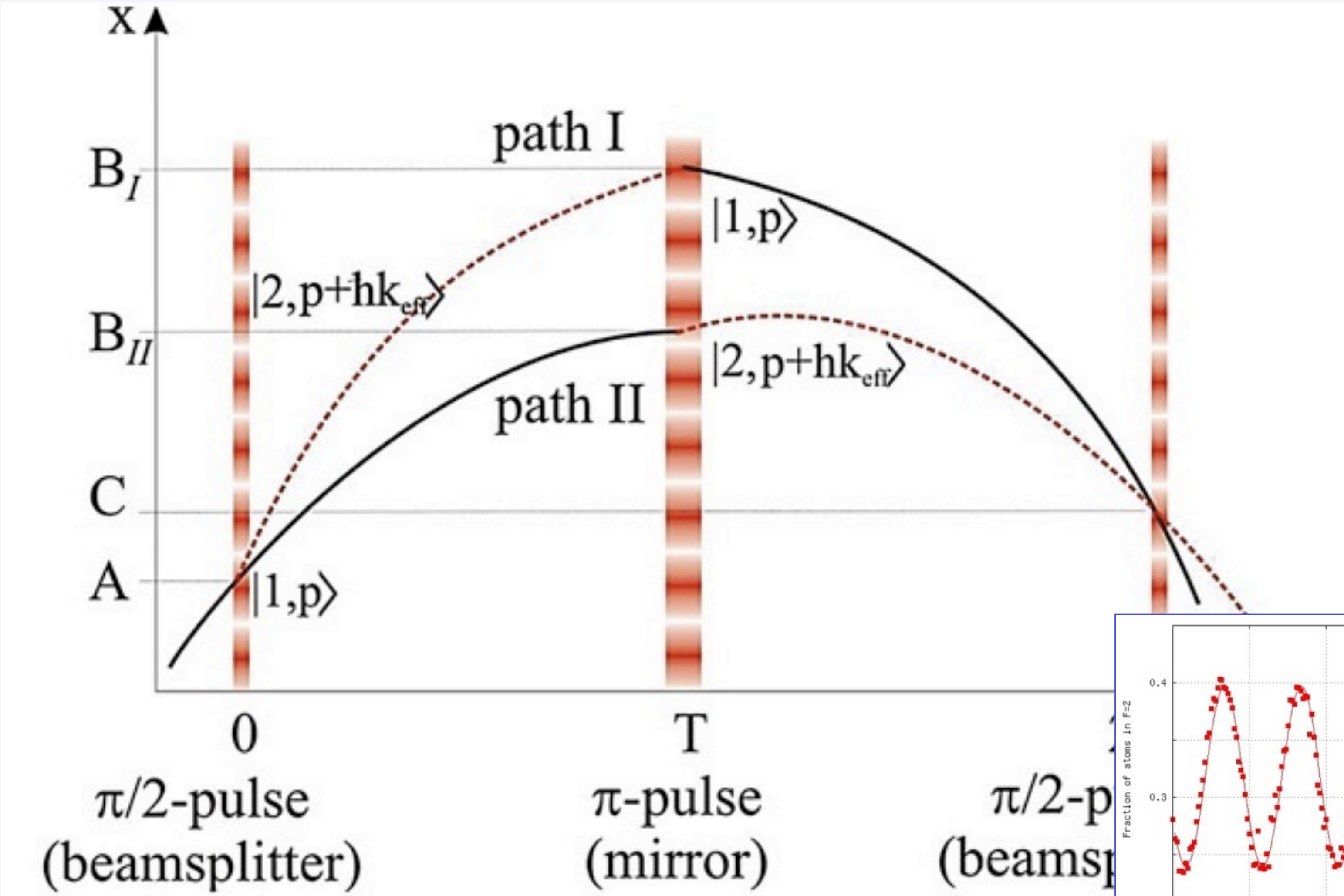
Quantum interference

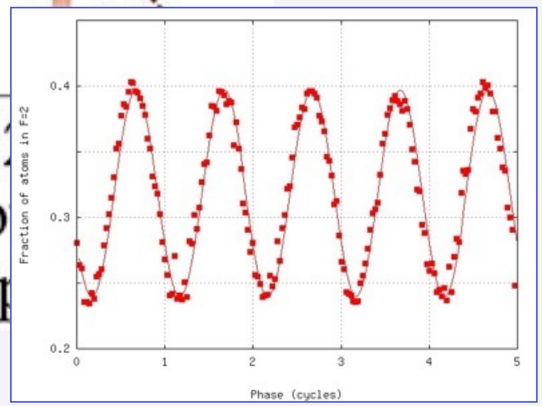


Interference of transition amplitudes

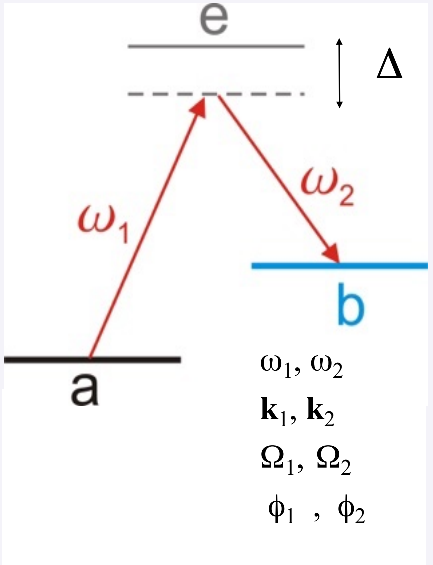
$$P(|\psi_i\rangle \Rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2\,Re(A_I A_{II}^*)$$

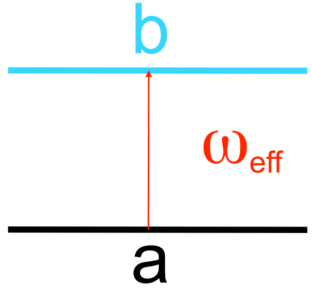
Atom interferometry and gravity





Raman pulses



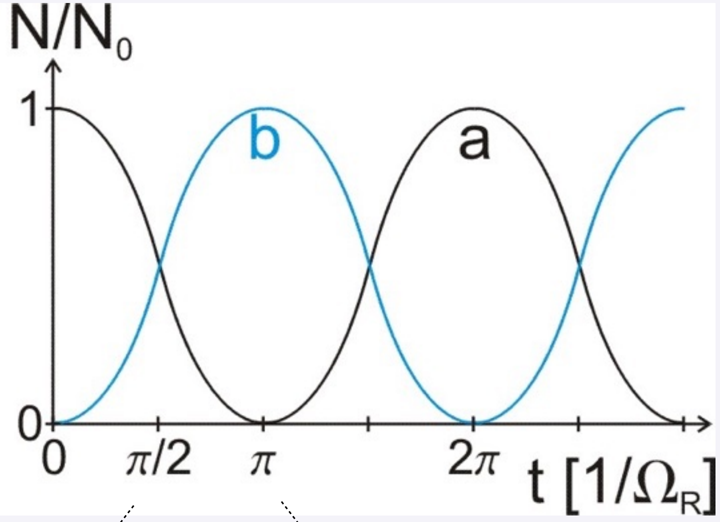


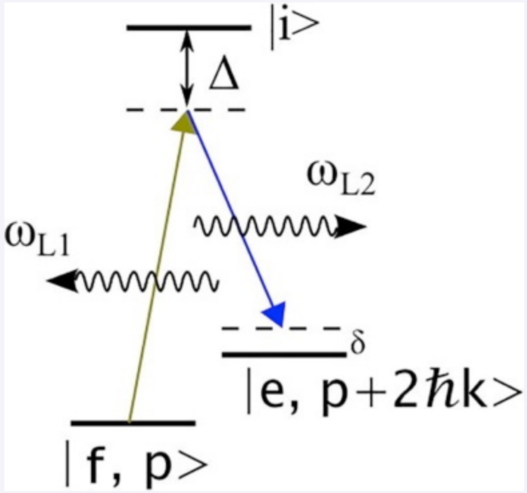
$\omega_{eff} = \omega_1 - \omega_2$

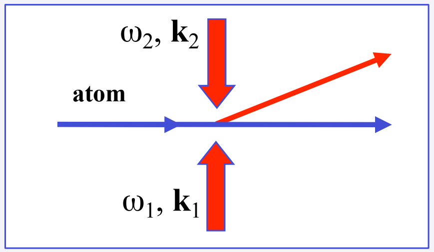
$\mathbf{k}_{eff} = \mathbf{k}_1 - \mathbf{k}_2$

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

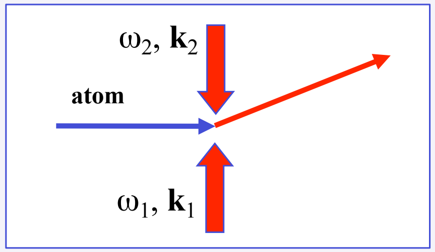
$\phi_{eff} = \phi_1 - \phi_2$







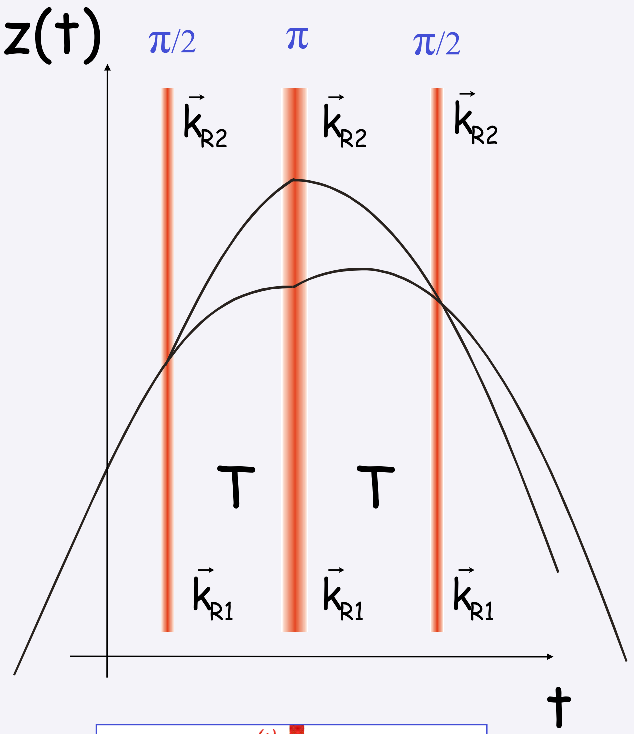
beam-splitter



mirror

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

Raman interferometry in a Rb atomic fountain

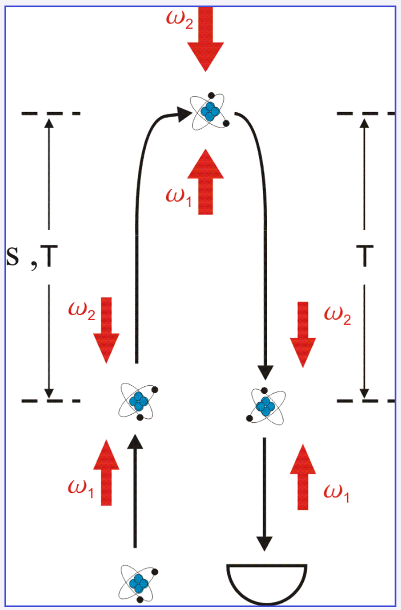


Phase difference between the paths:

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

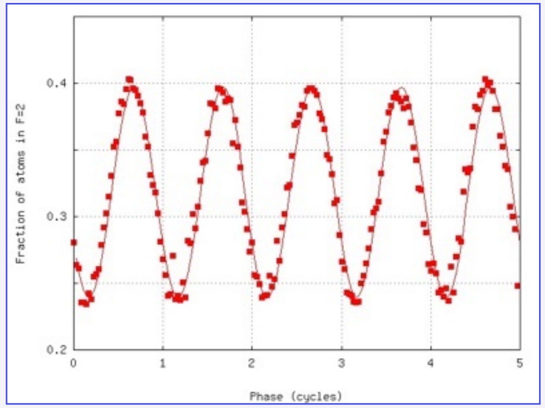
with $z(t) = -g\,t^2/2 + v_0 t + z_0$ & $\Phi_e = 0 \Longrightarrow$ $\mathbf{\Delta\Phi = k_e g T^2}$

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



Final population:

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



Interference fringes – Firenze 2006

10^6 Rb atoms

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

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

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

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

How do we improve sensitivity to gravity acceleration?

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

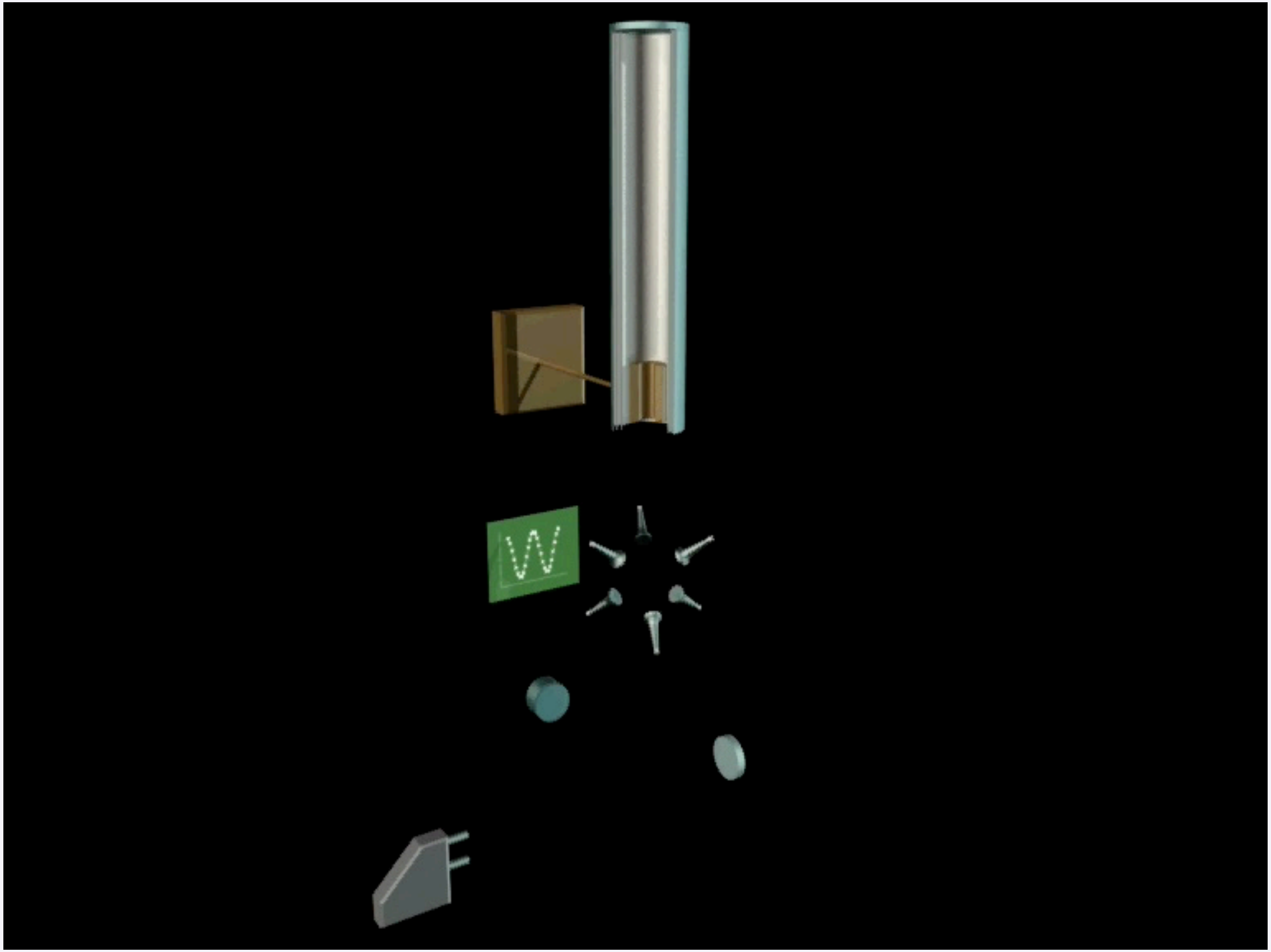
- $\Delta\phi$ → Large phase resolution
- k_{eff} → Large momentum transfer
- T^2 → Long interrogation times

How do we improve sensitivity to gravity acceleration?

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

Long interrogation times

Atomic fountain

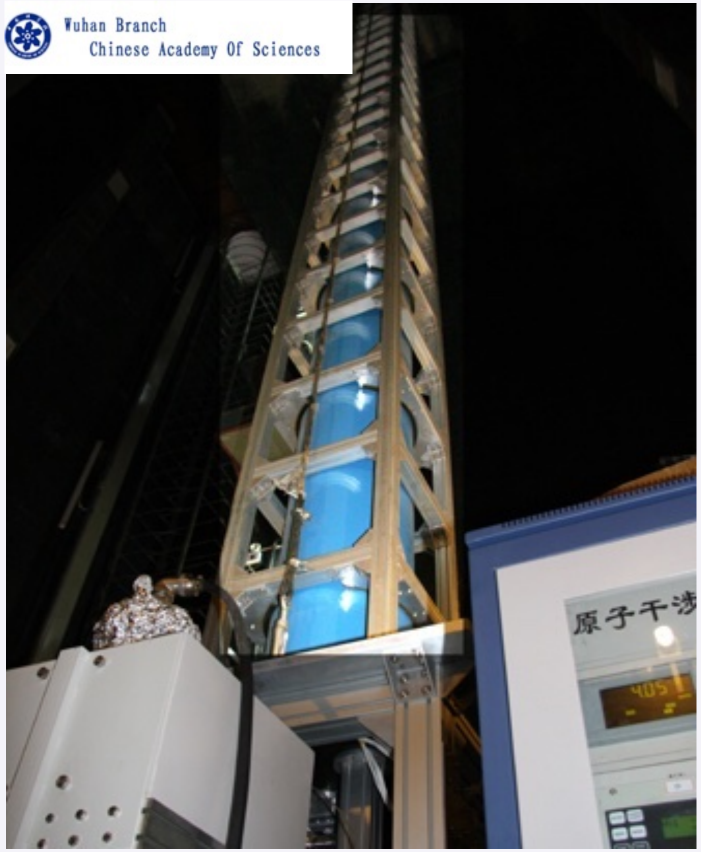


from C. Salomon

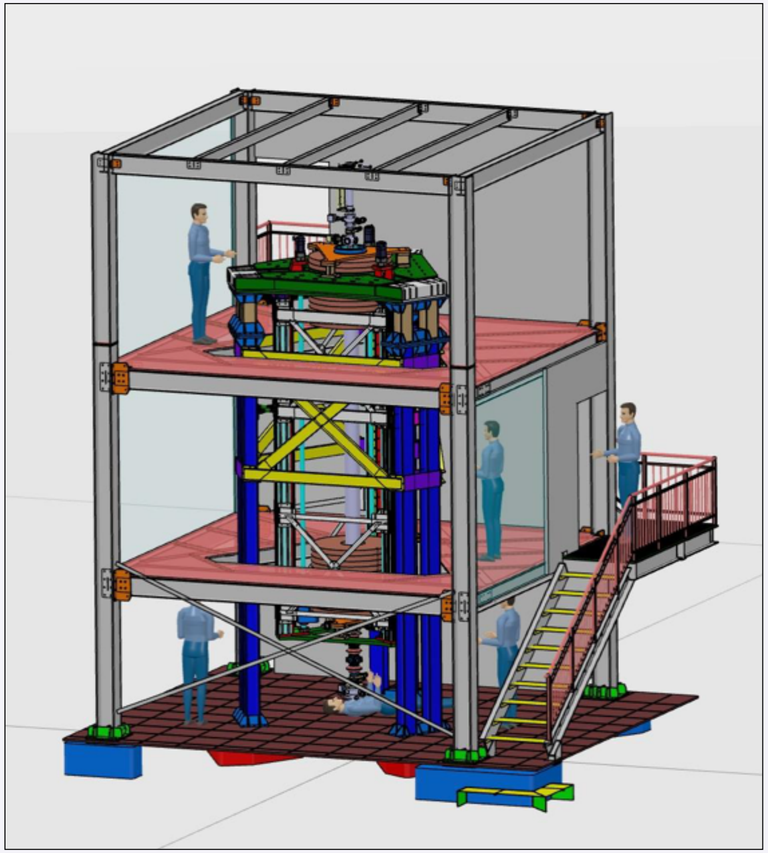
Large-scale atom interferometers

10 m fountain - Stanford

12 m fountain - Wuhan

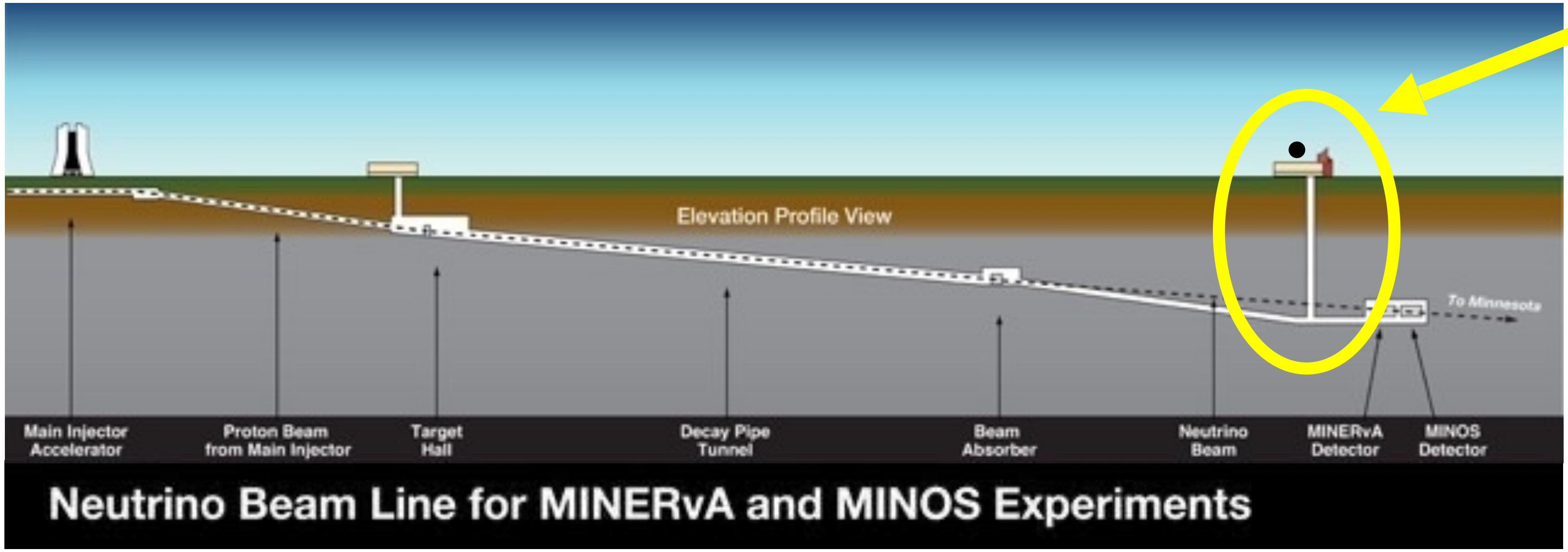


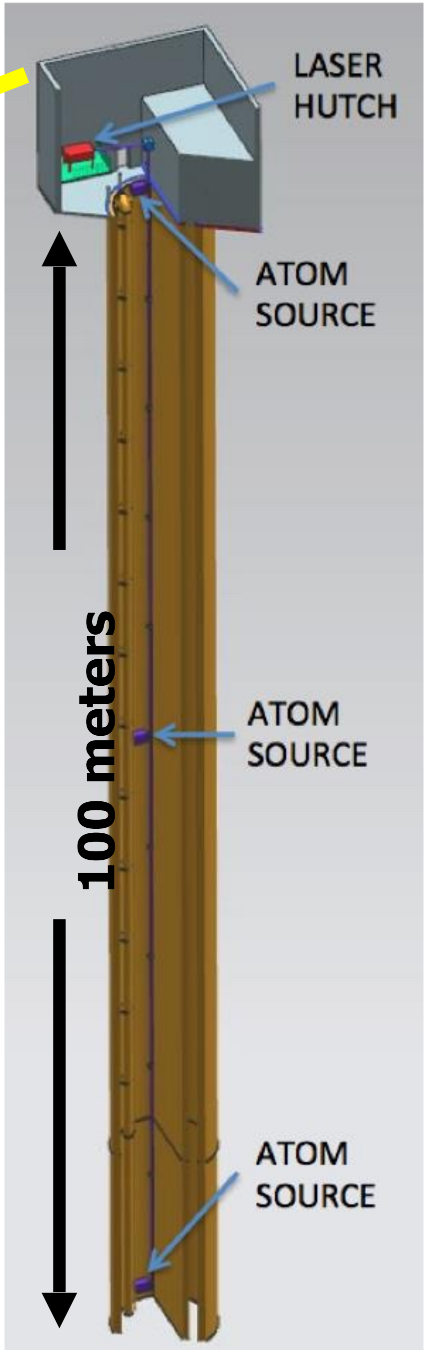
8 m fountain - Firenze
(under construction)



MAGIS-100: Detector prototype at Fermilab

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



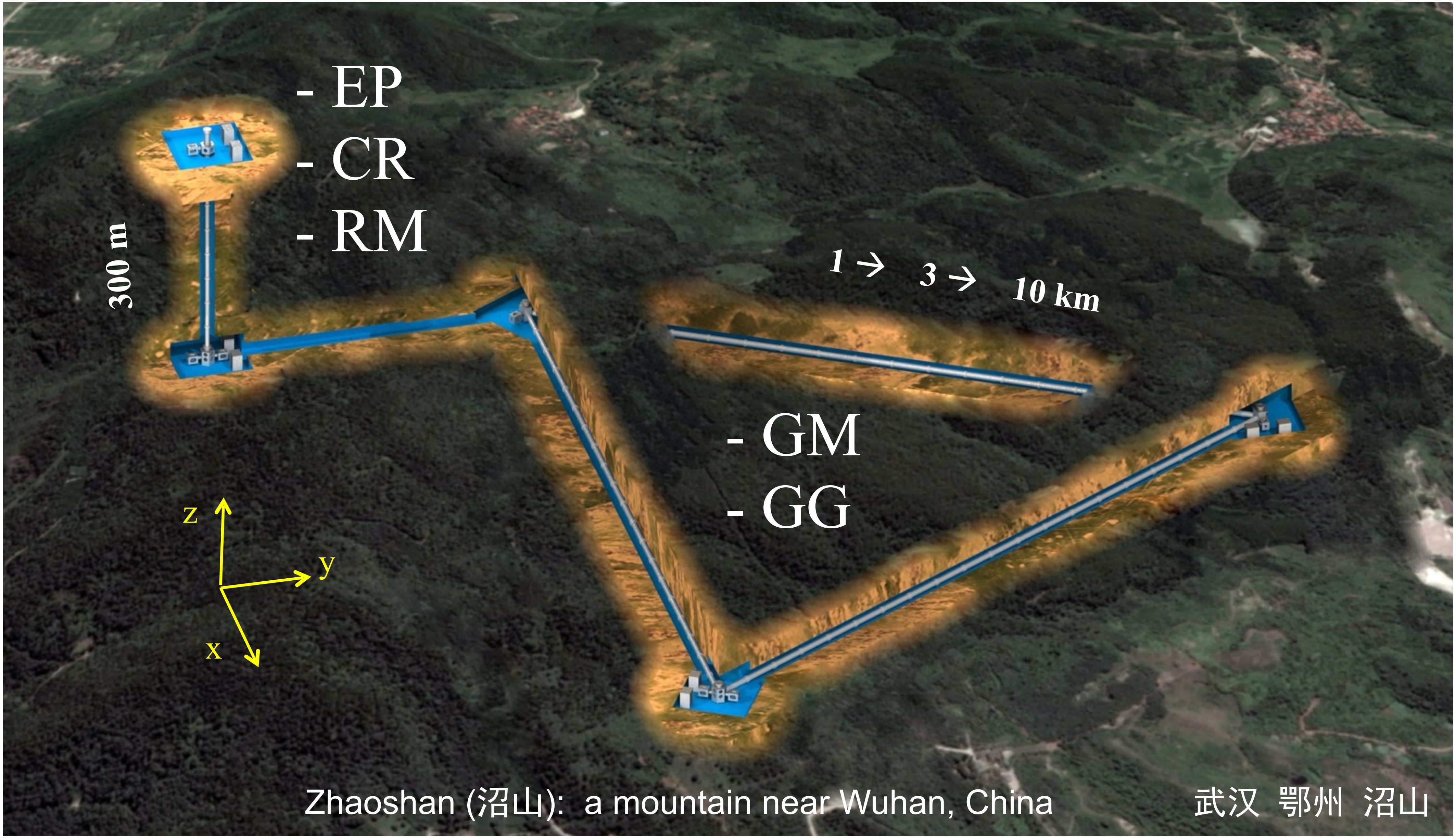


- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum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

STANFORD · Fermilab · Berkeley · University of Liverpool · Northwestern University · Northern Illinois University

from J. Hogan

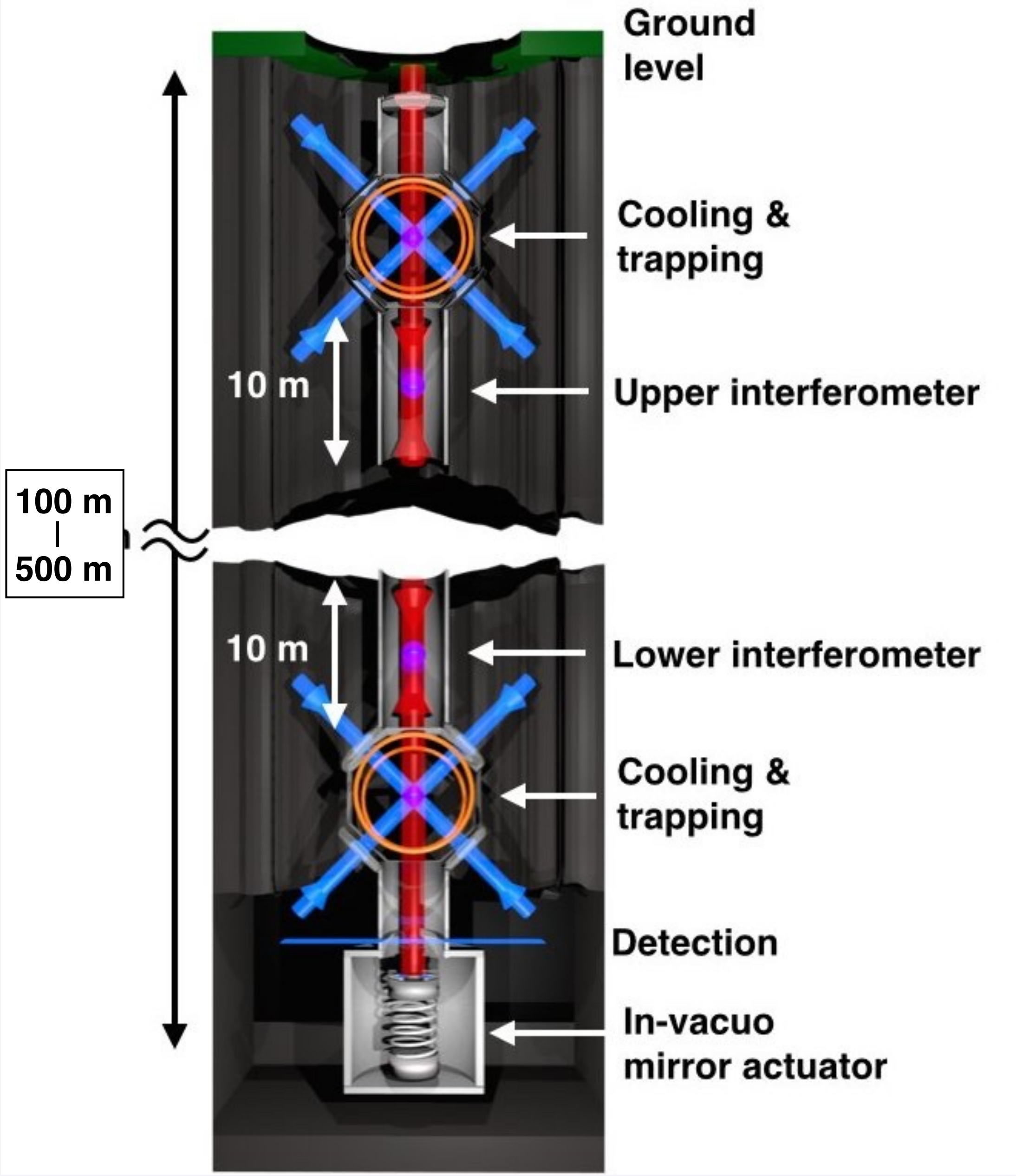
ZAIGA



from M. S. Zhan

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

MAGIA-Advanced ⇒ Sardegna (2016, Proposal)



Carbonia-Iglesias
ARIA/Darkside Lab

Sos Enattos
SAR-GRAV Lab

UNIVERSITÀ DEGLI STUDI FIRENZE

AVS Quantum Science

REVIEW ARTICLE | MAY 07 2024

Terrestrial very-long-baseline atom interferometry: Workshop summary

Special Collection: Large Scale Quantum Detectors

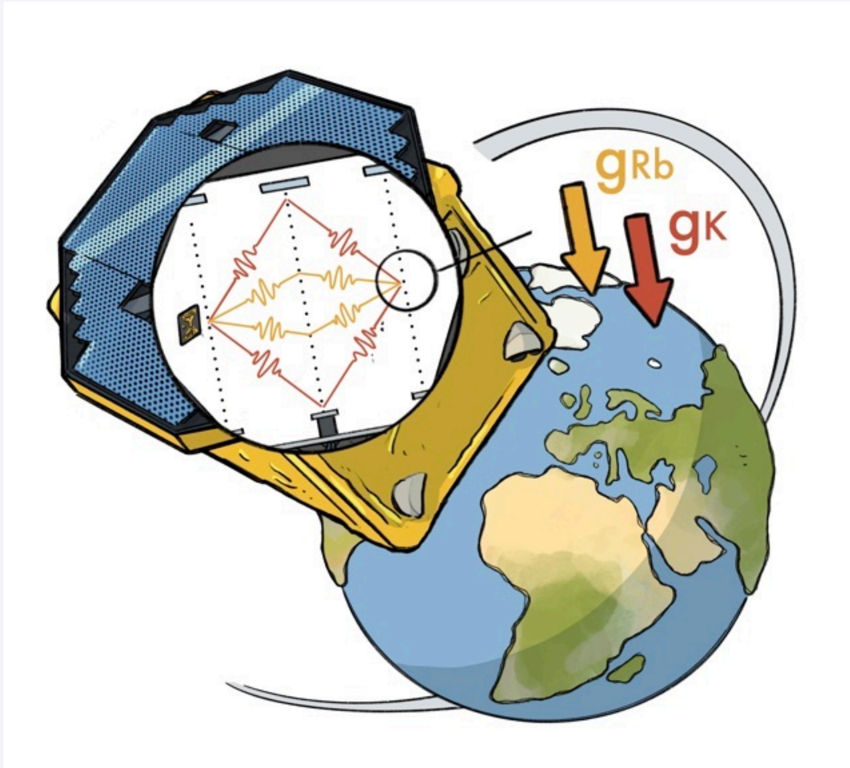
Sven Abend; Baptiste Allard; Iván Alonso; John Antoniadis; Henrique Araújo; Gianluigi Arduini; Aidan S. Arnold; Tobias Asano; Nadja Augst; Leonardo Badurina; Antun Balaž; Hannah Banks; Michele Barone; Michele Barsanti; Angelo Bassi; Baptiste Battelier; Charles F. A. Baynham; Quentin Beaufils; Aleksandar Belić; Ankit Beniwal; Jose Bernabeu; Francesco Bertinelli; Andrea Bertoldi; Ikbal Ahamed Biswas; Diego Blas; Patrick Boegel; Aleksandar Bogojević; 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 R. 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 S. Djordjevic; Babette Döbrich; 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 F. Giudice; Eric P. Glasbrenner; Mustafa Gündoğan; Martin Haehnelt; Timo Hakulinen; Klemens Hammerer; Ekim T. Hanımeli; Tiffany Harte; Leonie Hawkins; Aurelien Hees; Jaret Heise; Victoria A. Henderson; Sven Herrmann; Thomas M. Hird; Jason M. Hogan; Bodil Holst; Michael Holynski; Kamran Hussain; Gregor Janson; Peter Jeglič; Fedor Jelezko; Michael Kagan; Matti Kalliokoski; Mark Kasevich; Alex Kehagias; Eva Kilian; Soumen Koley; Bernd Konrad; Joachim Kopp; Georgy Kornakov; Tim Kovachy; Markus Krutzik; Mukesh Kumar; Pradeep Kumar; Claus Lämmerzahl; Greg Landsberg; Mehdi Langlois; Bryony Lanigan; Samuel Lellouch; Bruno Leone; Christophe Le Poncin-Lafitte; Marek Lewicki; Bastian Leykauf; Ali Lezeik; Lucas Lombriser; J. Luis Lopez-Gonzalez; Elias Lopez Asamar; Cristian López Monjaraz; Giuseppe Gaetano Luciano; M. A. Mahmoud; Azadeh Maleknejad; Markus Krutzik; Jacques Marteau; Didier Massonnet; Anupam Mazumdar; Christopher McCabe; Matthias Meister; Jonathan Menu; Giuseppe Messineo; Salvatore Micalizio; Peter Millington; Milan Milosevic; Jeremiah Mitchell; Mario Montero; Gavin W. Morley; Jürgen Müller; Özgür E. Müstecapl ioğlu; Wei-Tou Ni; Johannes Noller; Senad Odžak; Daniel K. L. Oi; Yasser Omar; Julia Pahl; Sean Paling; Saurabh Pandey; George Pappas; Vinay Pareek; Elizabeth Pasatembou; Emanuele Pelucchi; Franck Pereira dos Santos; Baptist Piest; Igor Pikovski; Apostolos Pilaftsis; Robert Plunkett; Rosa Poggiani; Marco Prevedelli; Julia Puputti; Vishnupriya Puthiya Veettil; John Quenby; Johann Rafelski; Surjeet Rajendran; Ernst M. Rasel; Haifa Rejeb Sfar; Serge Reynaud; Andrea Richaud; Tangui Rodzinka; Albert Roura; Jan Rudolph; Dylan O. Sabulsky; Marianna S. Safronova; Luigi Santamaria; Manuel Schilling; Vladimir Schkolnik; Wolfgang P. Schleich; Dennis Schlippert; Ulrich Schneider; Florian Schreck; Christian Schubert; Nico Schwersenz; Aleksei Semakin; Olga Sergijenko; Lijing Shao; Ian Shipsey; Rajeev Singh; Augusto Smerzi; Carlos F. Sopuerta; Alessandro D. A. M. Spallicci; Petruta Stefanescu; Nikolaos Stergioulas; Jannik Ströhle; Christian Struckmann; Silvia Tentindo; Henry Throssell; Guglielmo M. Tino; Jonathan N. Tinsley; Ovidiu Tintareanu Mircea; Kimberly Tkalčec; Andrew. J. Tolley; Vincenza Tornatore; Alejandro Torres-Orjuela; Philipp Treutlein; Andrea Trombettoni; Yu-Dai Tsai; Christian Ufrecht; Stefan Ulmer; Daniel Valuch; Ville Vaskonen; Verónica Vázquez-Aceves; Nikolay V. Vitanov; Christian Vogt; Wolf von Klitzing; András Vukics; Reinhold Walser; Jin Wang; Niels Warburton; Alexander Webber-Date; André Wenzlawski; Michael Werner; Jason Williams; Patrick Windpassinger; Peter Wolf; Lisa Woerner; André Xuereb; Mohamed E. Yahia; Emmanuel Zambrini Cruzeiro; Moslem Zarei; Mingsheng Zhan; Lin Zhou; Jure Zupan; Erik Zupanič

Check for updates

AVS Quantum Sci. 6, 024701 (2024)
https://doi.org/10.1116/5.0185291

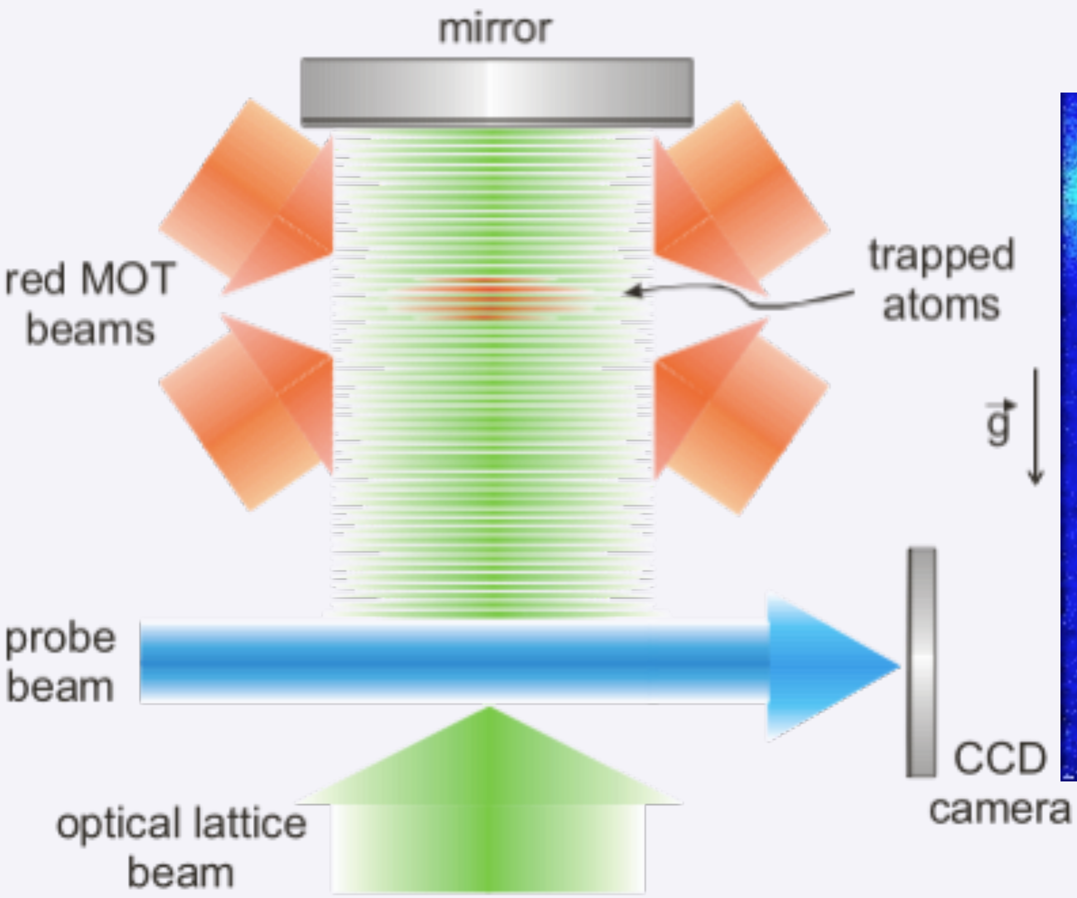
Towards Space

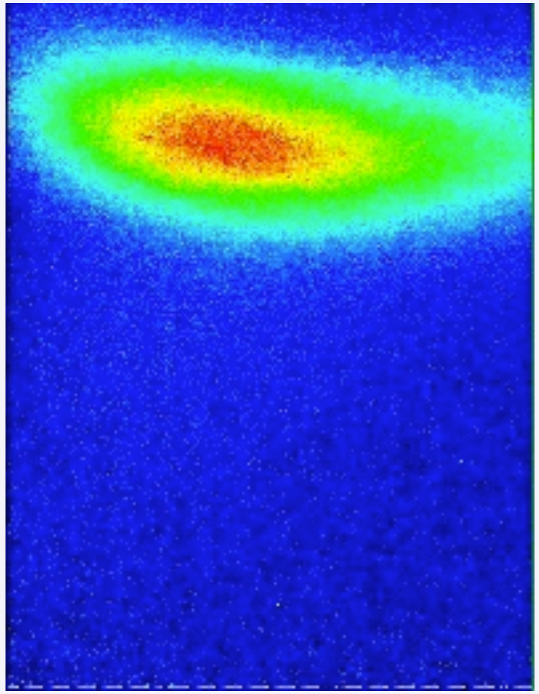
G. M. Tino *et al.*, *SAGE: A Proposal for a Space Atomic Gravity Explorer,* **Eur. Phys. J. D 73, 228 (2019)**



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

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

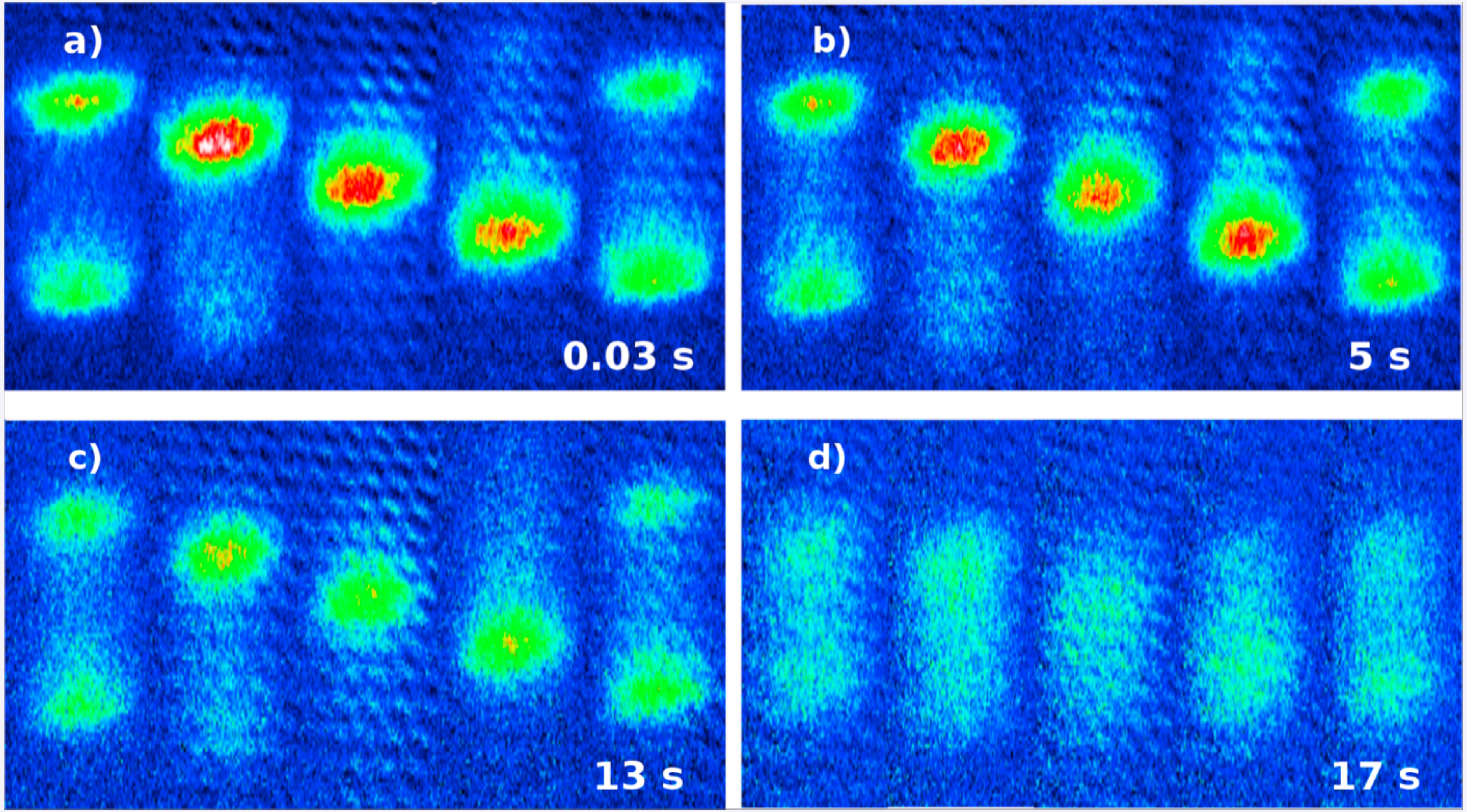




$\nu = m\, g\, \lambda / 2\, h$

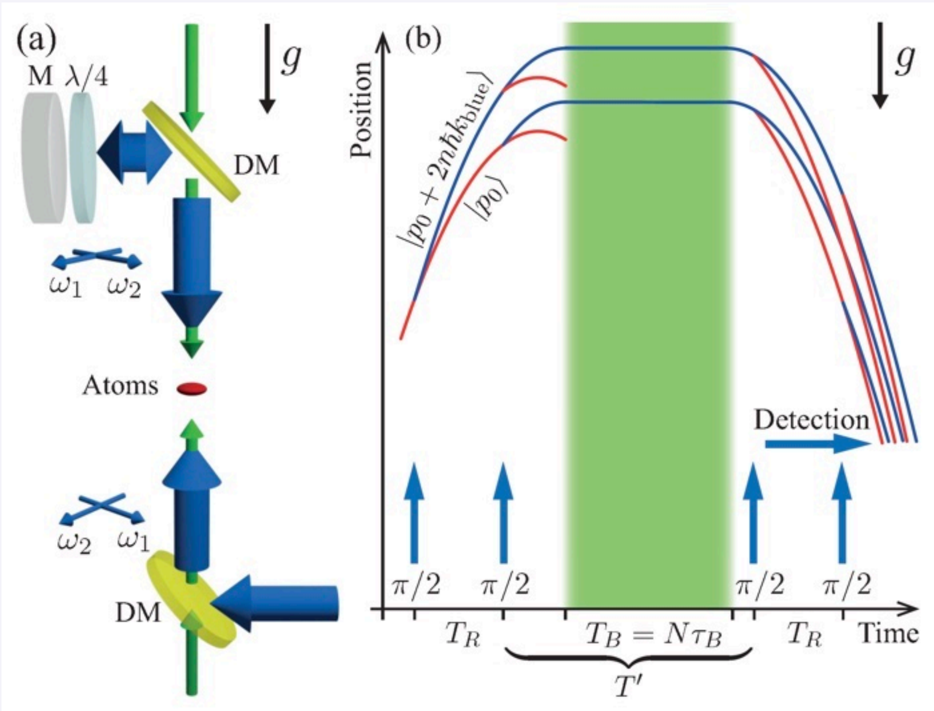
G. Ferrari, N. Poli, F. Sorrentino, G. M. Tino, *Long-Lived Bloch Oscillations with Bosonic Sr Atoms and Application to Gravity Measurement at the Micrometer Scale,* **Phys. Rev. Lett. 97, 060402 (2006)**

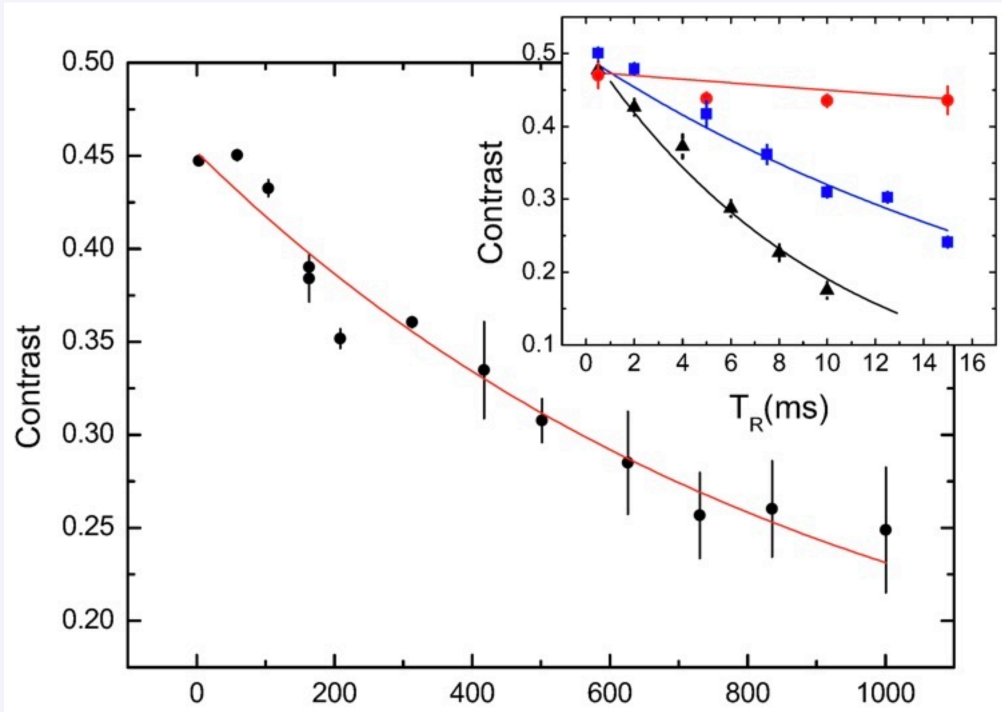
Bloch oscillations of ^{88}Sr atoms



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)

Trapped-atom interferometer with ultracold Sr atoms





- Ramsey–Bordé Bragg interferometer with ^{88}Sr atoms combined with Bloch oscillations

- We demonstrated a total interferometer time of 1 s, limited by technical issues, e.g., the atom lifetime in the lattice and geometry imperfections of the lattice beams.

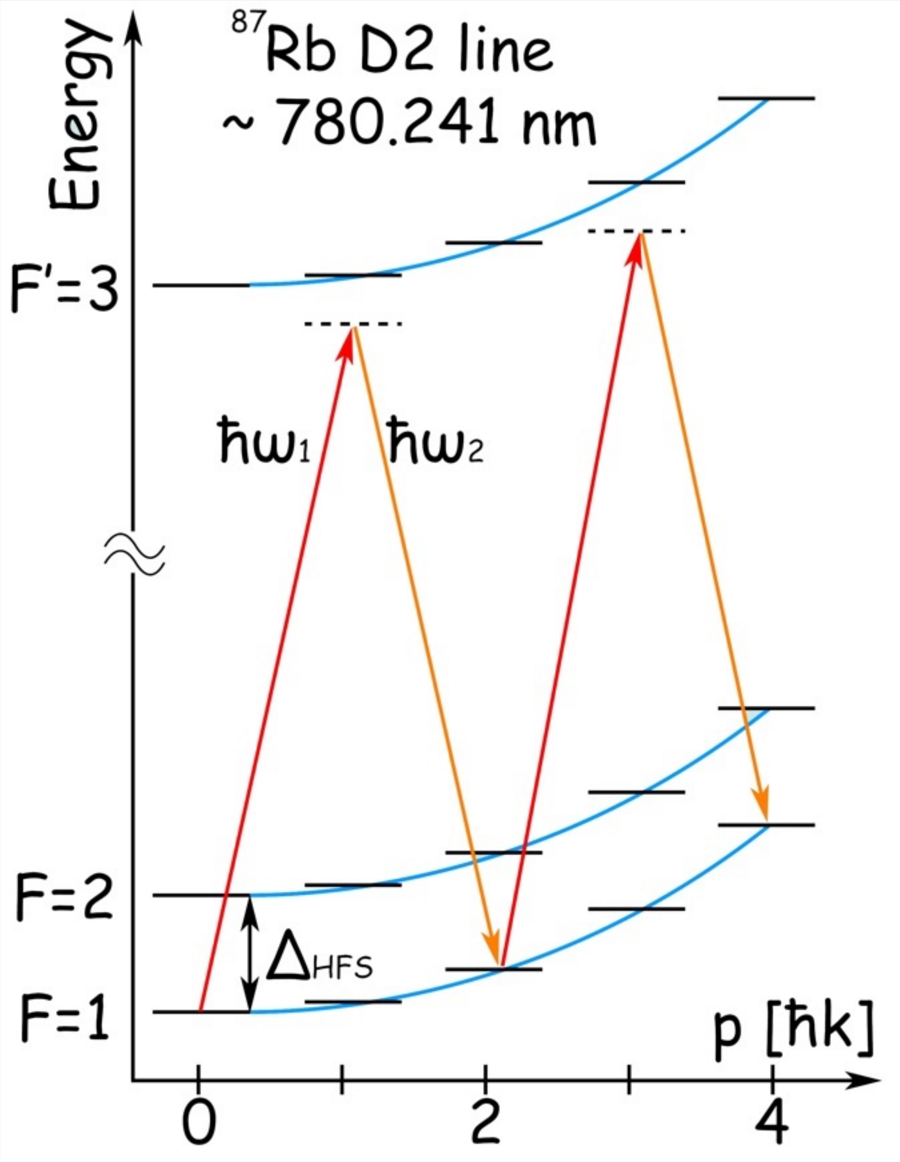
Xian Zhang, Ruben Pablo del Aguila, Tommaso Mazzoni, Nicola Poli, and Guglielmo M. Tino, *Trapped-atom interferometer with ultracold Sr atoms,* **Phys. Rev. A 94, 043608 (2016)**

How do we improve sensitivity to gravity acceleration?

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

k_{eff} → Large momentum transfer

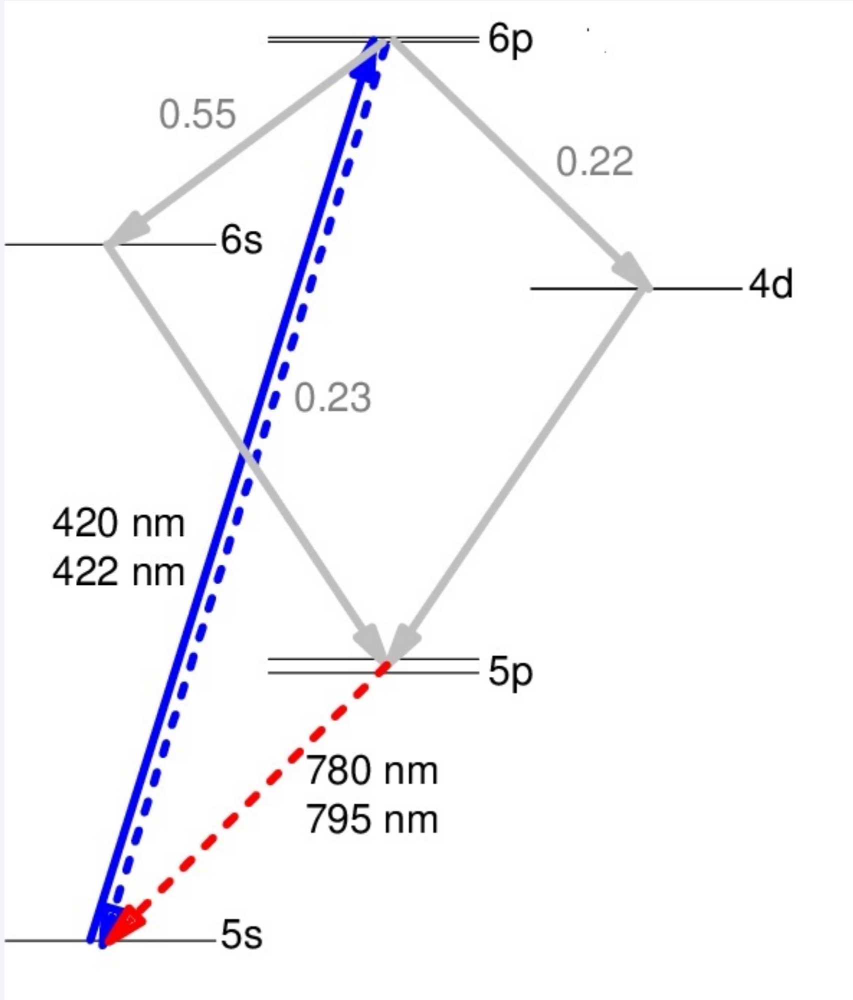
Bragg transitions



$\omega_1 - \omega_2 \sim$ 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.

Atom Interferometry with Rb Blue Transitions



- 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)

How do we improve sensitivity to gravity acceleration?

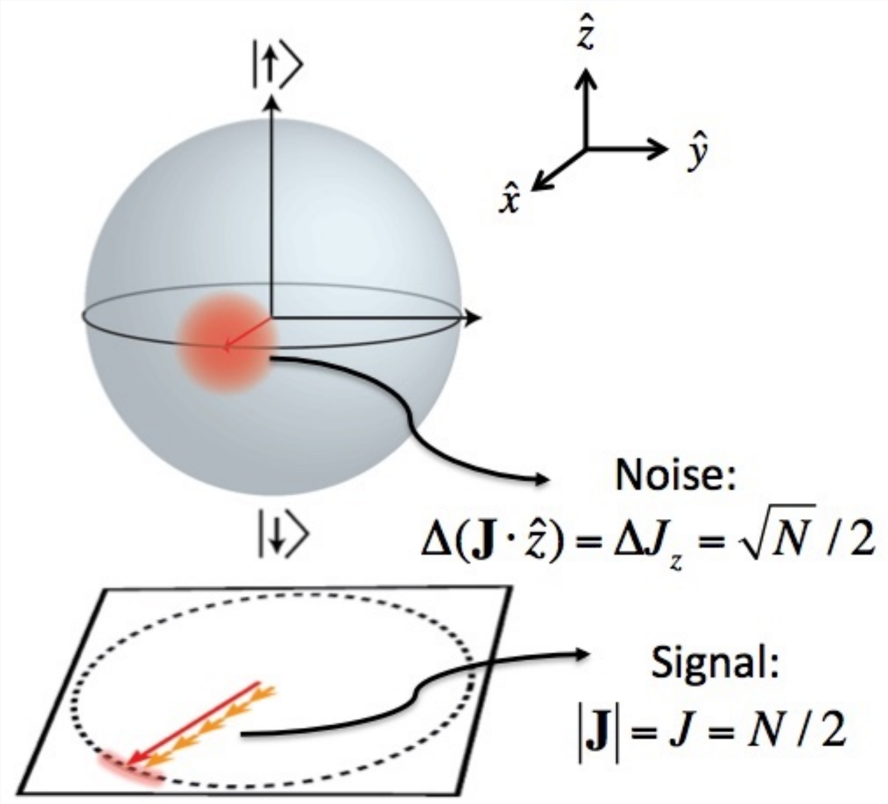
$$\Delta\phi = k_{\rm eff}\, g T^2$$

Large phase resolution

The Standard Quantum Limit and beyond

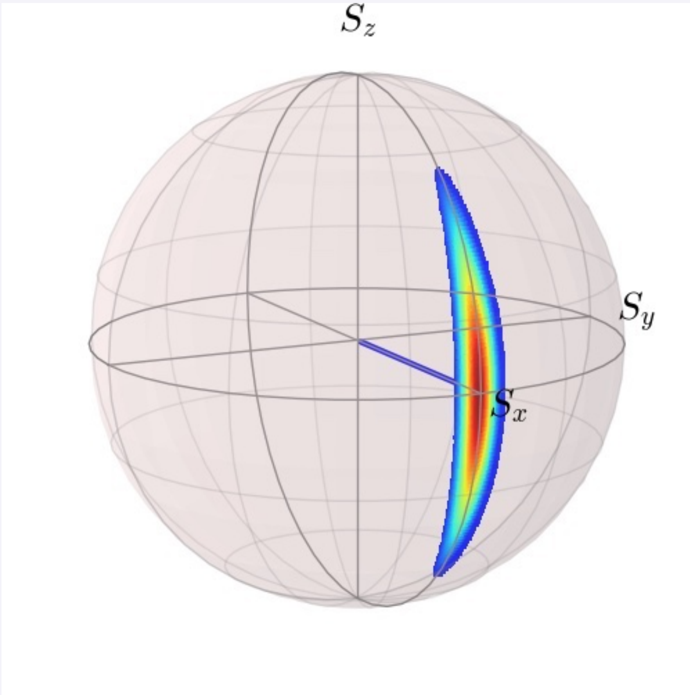
Shot noise limit

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



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

Beyond the shot noise limit: spin squeezed states



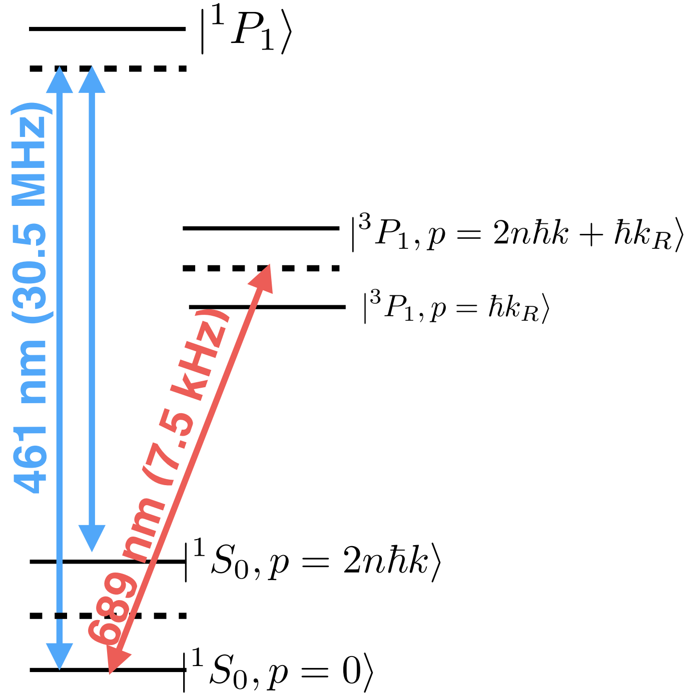
Requires correlations between particles

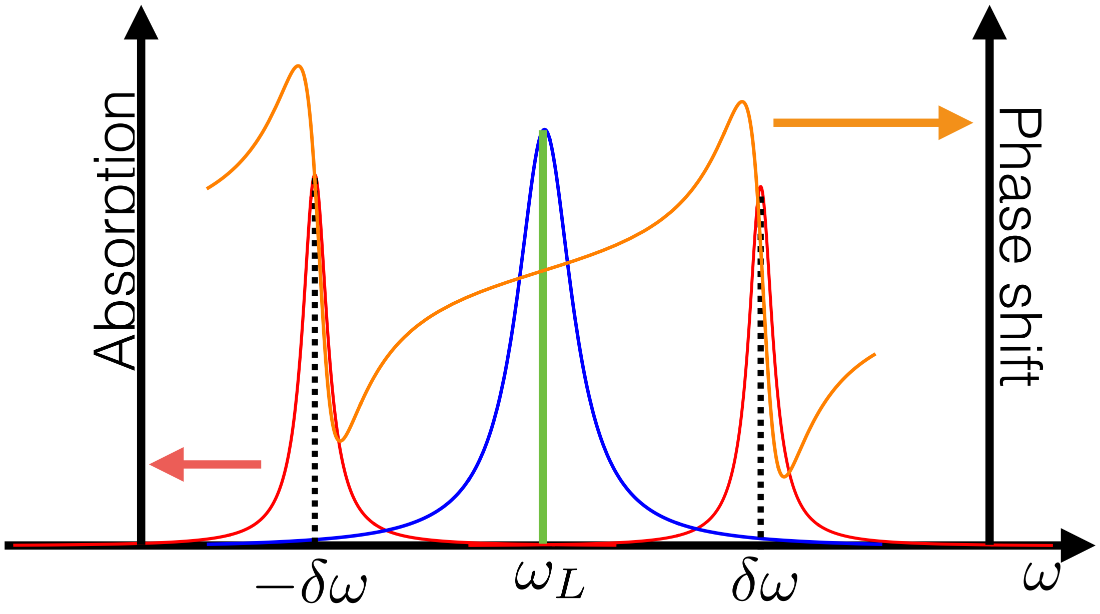
$$\Delta\theta_{\mathrm{HL}} = \frac{1}{N}$$

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

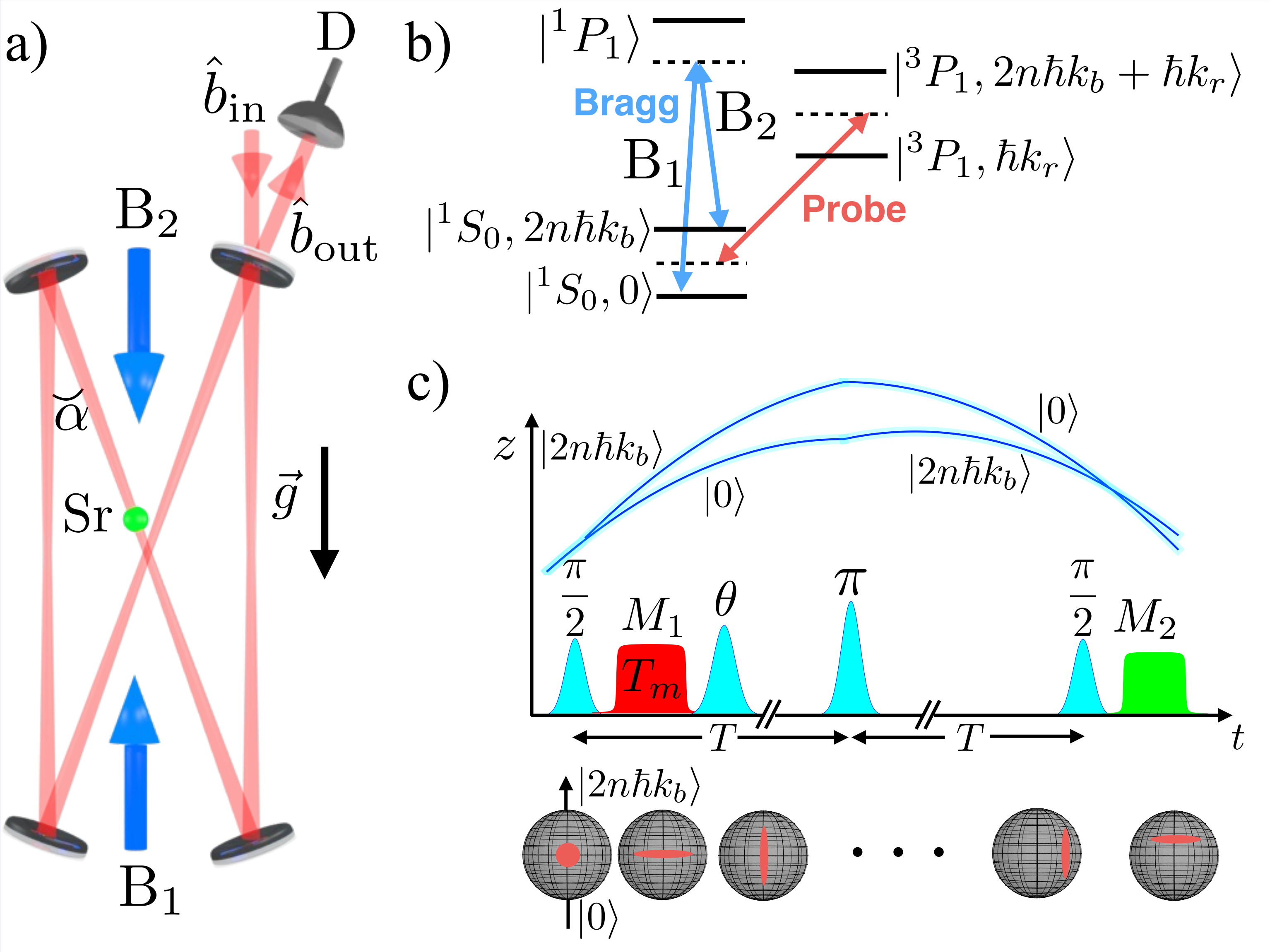
$$\delta\omega = 2\pi n \times 28.6\ \text{kHz}$$

Condition for dispersive regime:

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

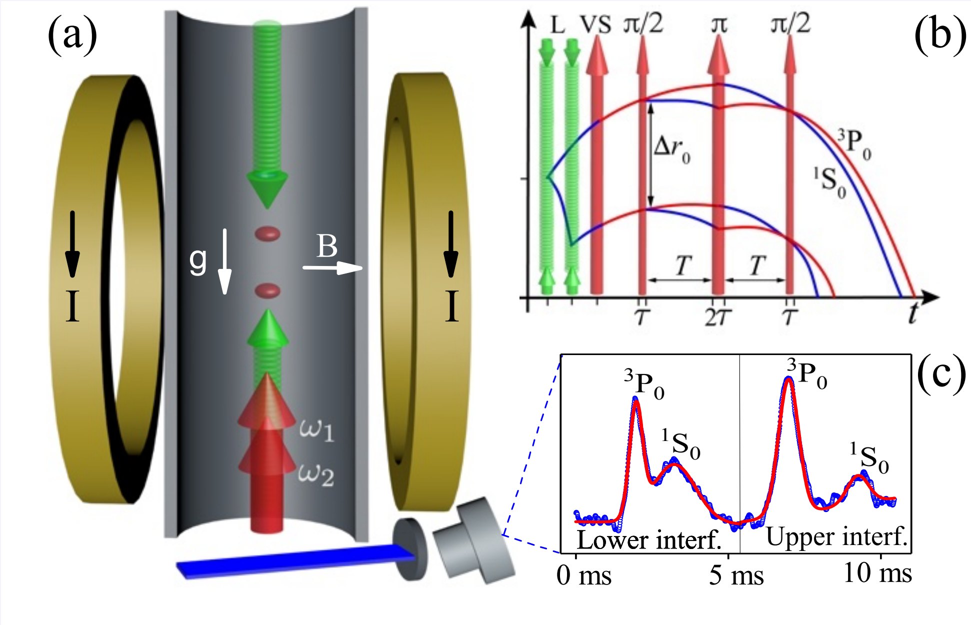
Leonardo Salvi, Nicola Poli, Vladan Vuletić, Guglielmo M. Tino, *Squeezing on Momentum States for Atom Interferometry,* Phys. Rev. Lett. 120, 033601 (2018)

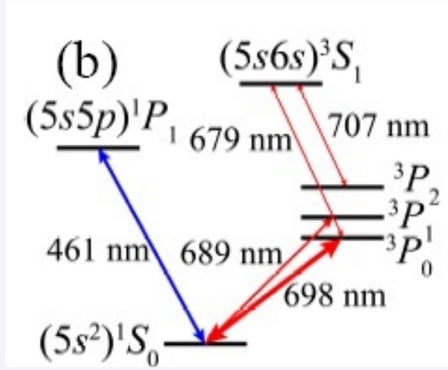
Squeezing on momentum states for atom interferometry



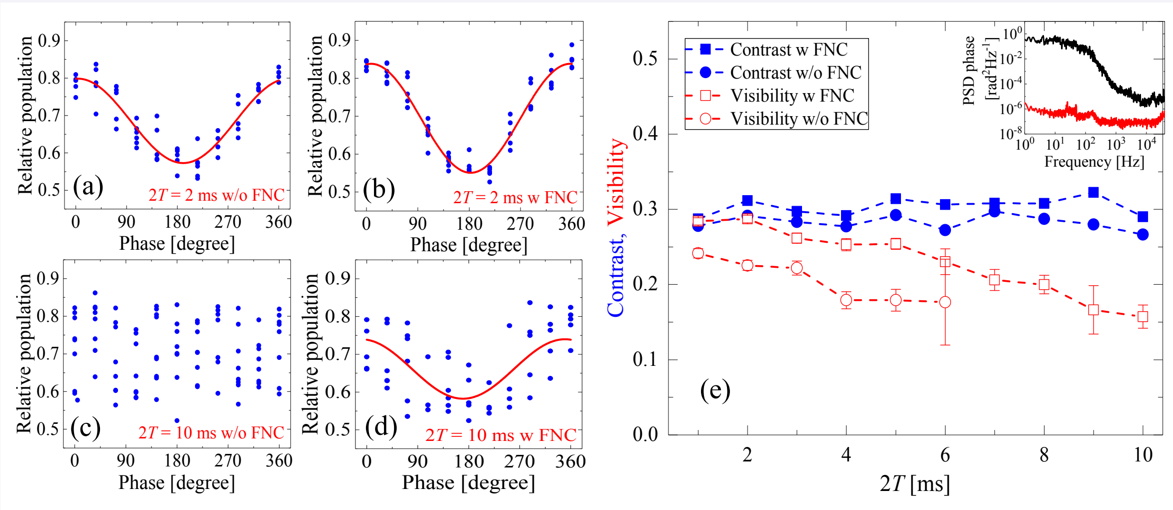
Leonardo Salvi, Nicola Poli, Vladan Vuletić, Guglielmo M. Tino, *Squeezing on Momentum States for Atom Interferometry,* Phys. Rev. Lett. 120, 033601 (2018)

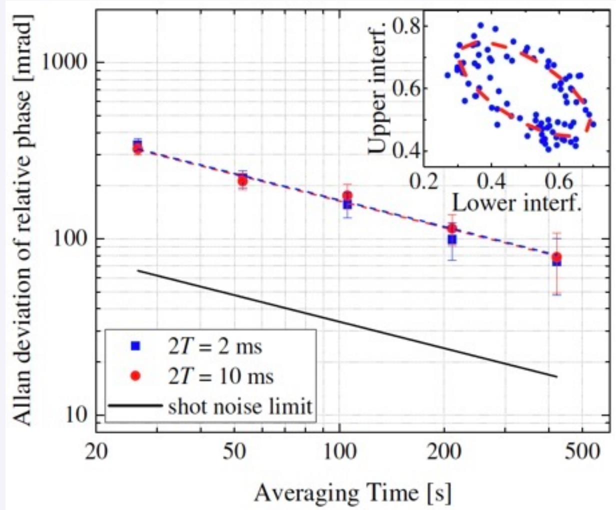
Atom interferometry with the Sr optical clock transition





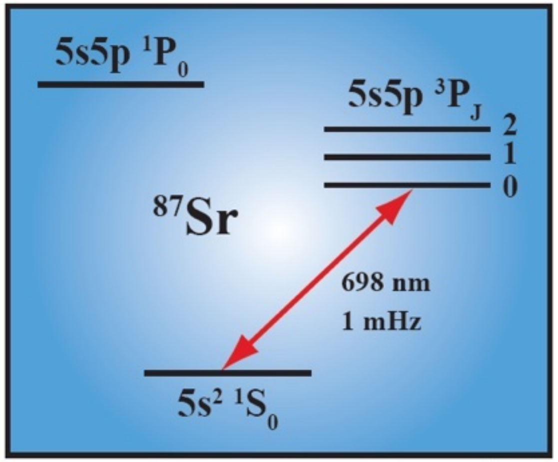
- ^{88}Sr isotope
- B=300 G -> Δν=20 μHz
- Rabi frequency Ω ~ 1kHz





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

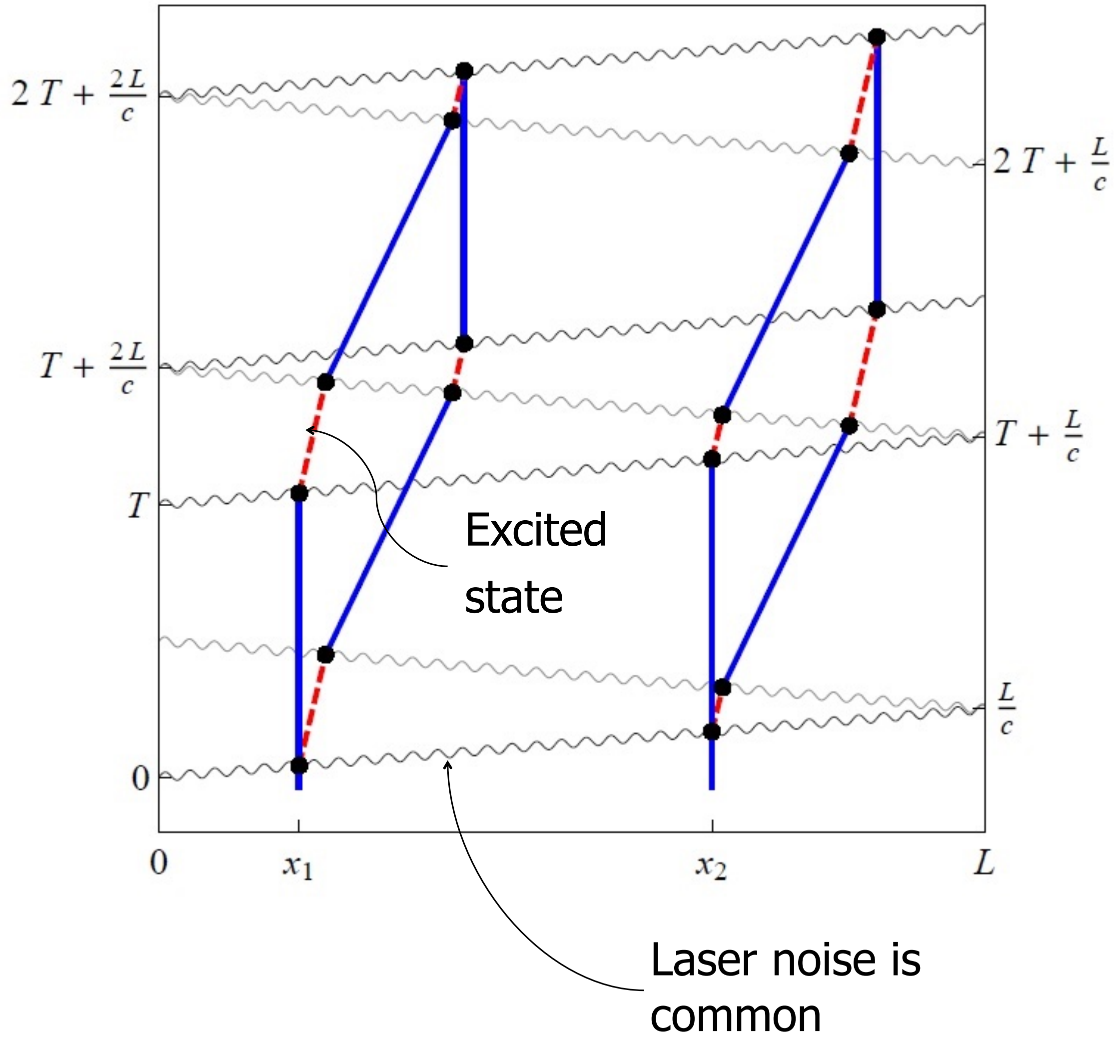
Laser frequency noise insensitive detector



Clock transition in candidate atom ⁸⁷Sr

- 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



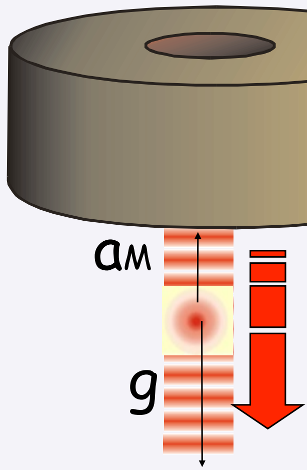
from M. Kasevich
STANFORD UNIVERSITY

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

MAGIA

(Misura Accurata di G mediante Interferometria Atomica)

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

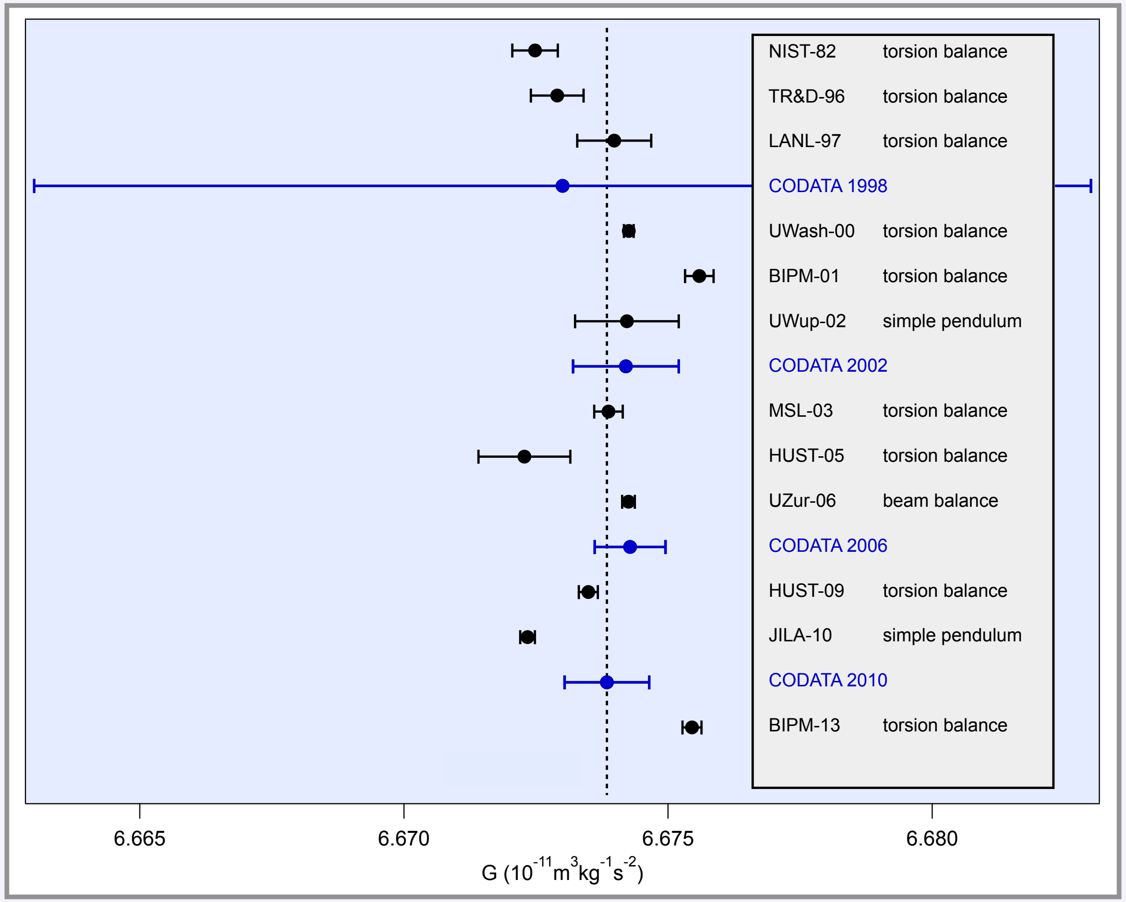


➢ ***Precision measurement of G***

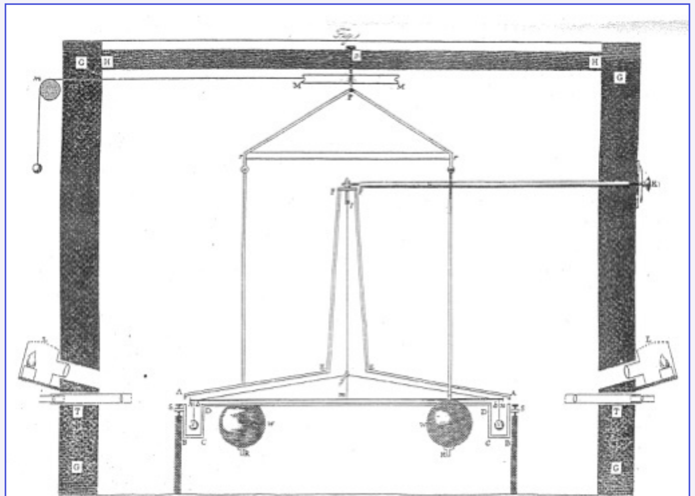
$$F(r) = G\frac{M_1 M_2}{r^2}$$

Measurements of the Newtonian gravitational constant G

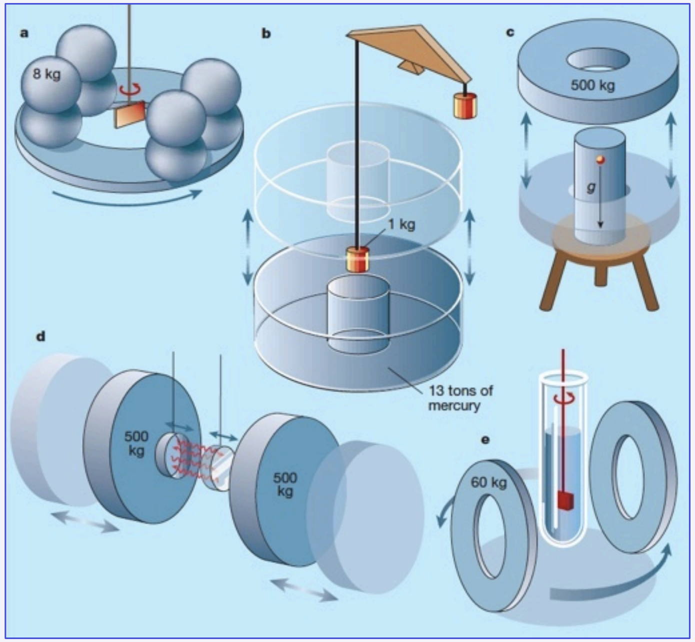
$$F(r) = G\frac{M_1 M_2}{r^2}$$



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)

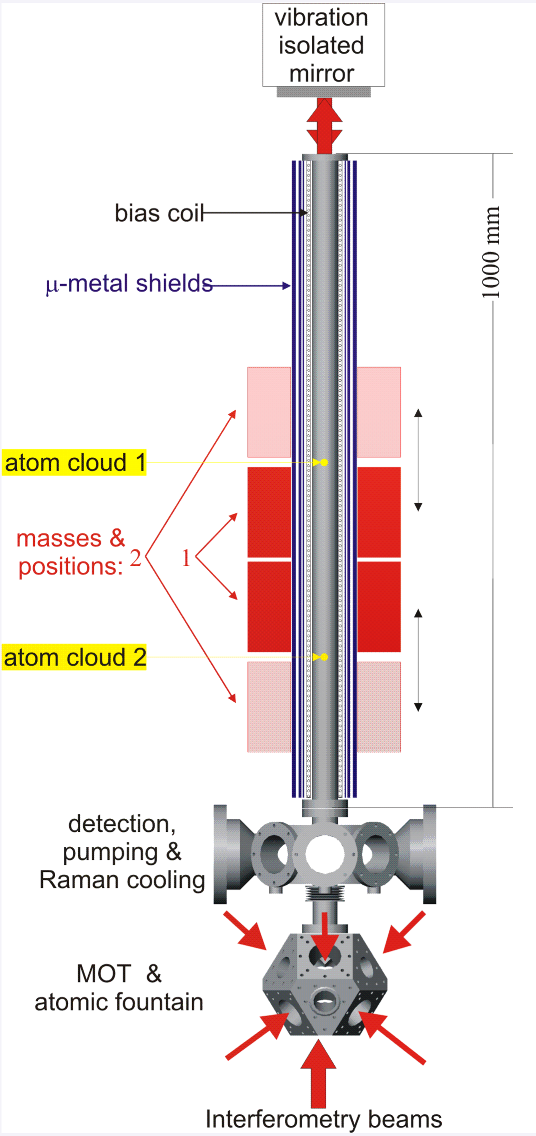


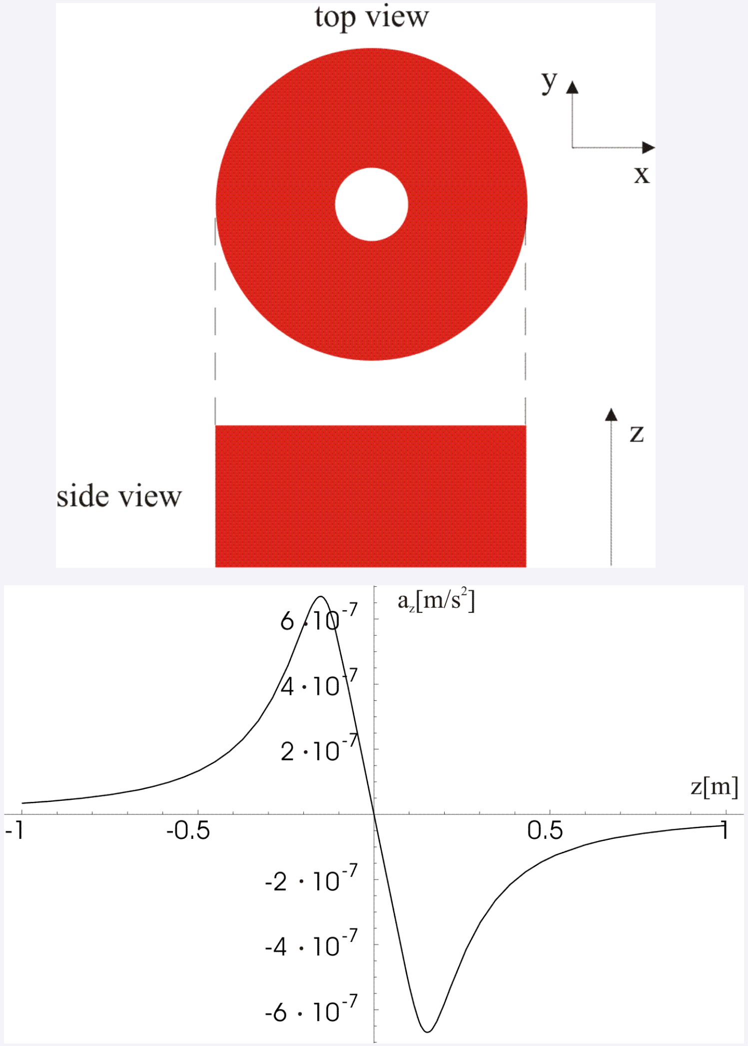
Cavendish, 1798



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

MAGIA
Rb gravity gradiometer + source mass





500 kg tungsten mass

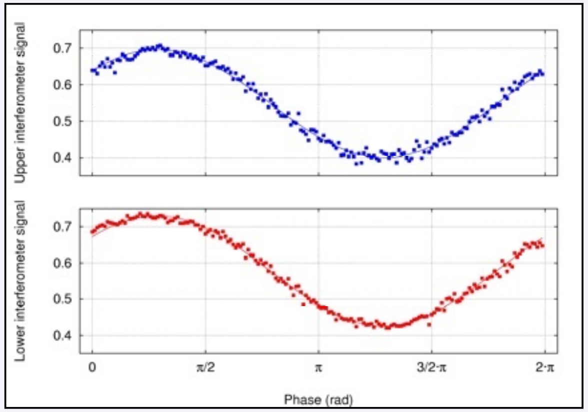
Sensitivity 10^{-9}g/shot

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

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

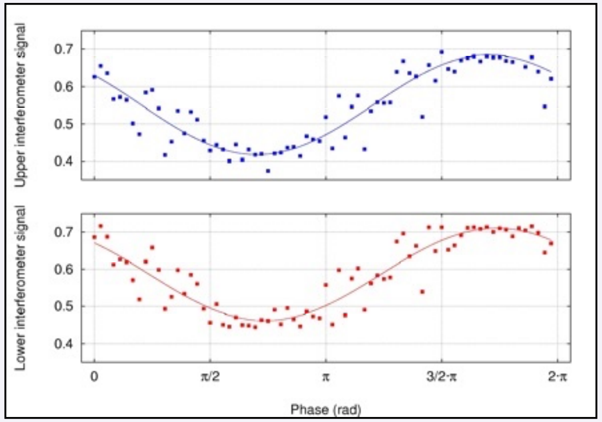
10000 shots $\Rightarrow$ **$\Delta G/G \approx 10^{-4}$**

Gravity gradiometer



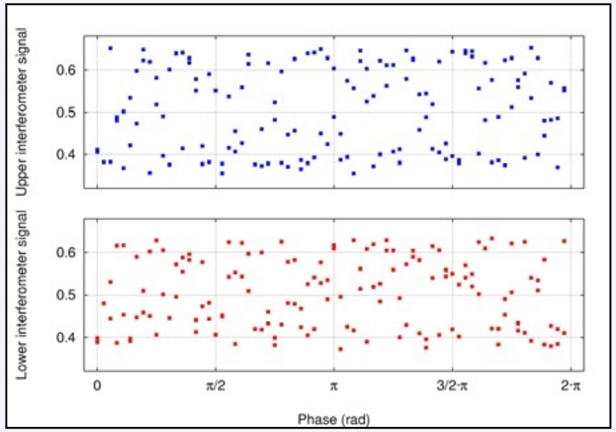
T=5 ms

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



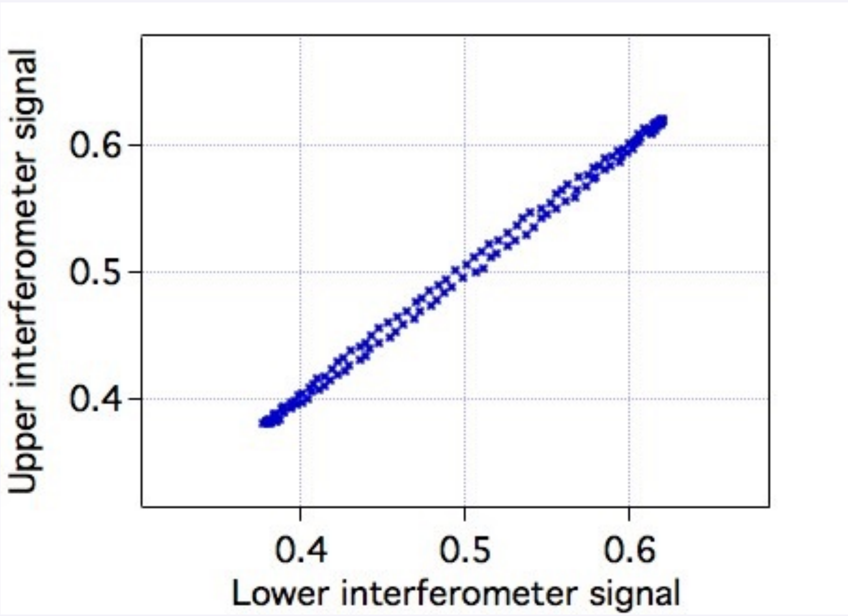
T=50 ms

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

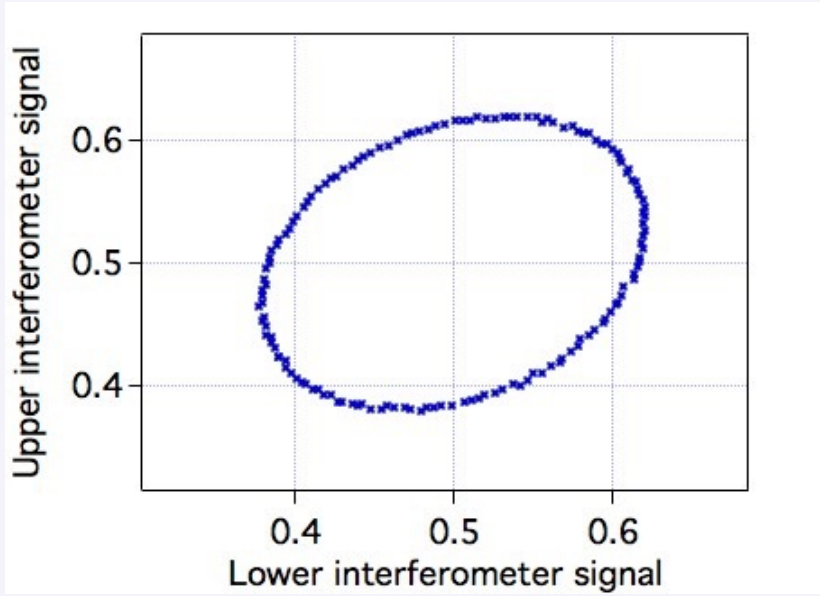


T=150 ms

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

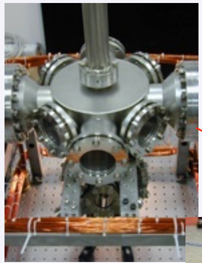


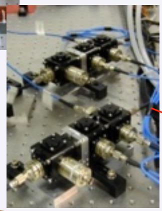
$$\Delta\Phi = k_e g T^2$$

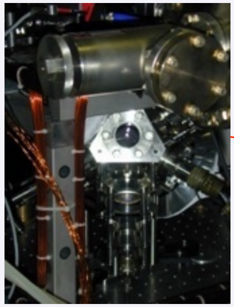


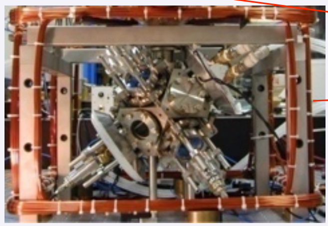
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

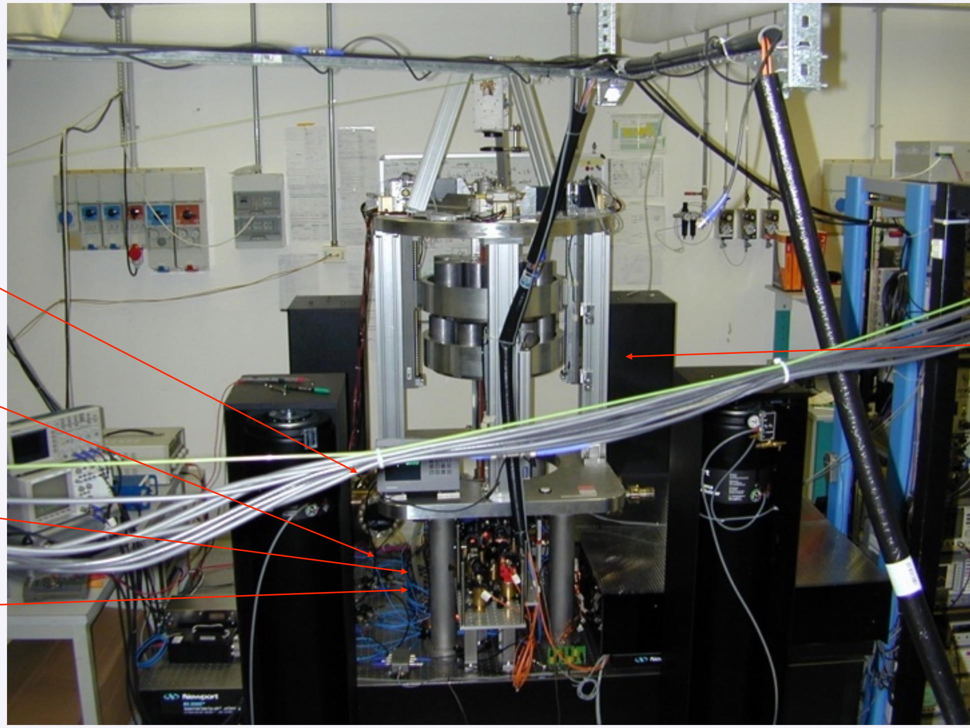
MAGIA apparatus







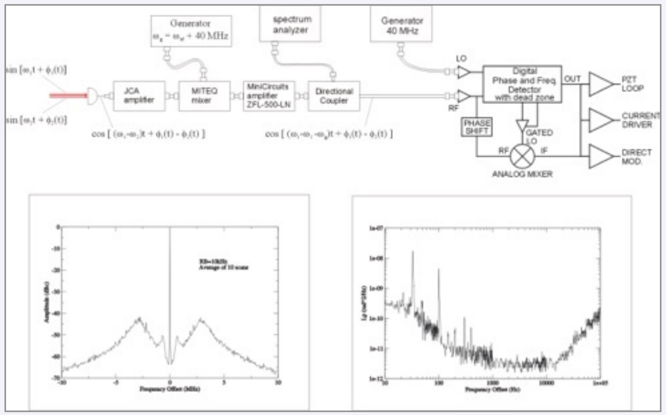




Source masses and support

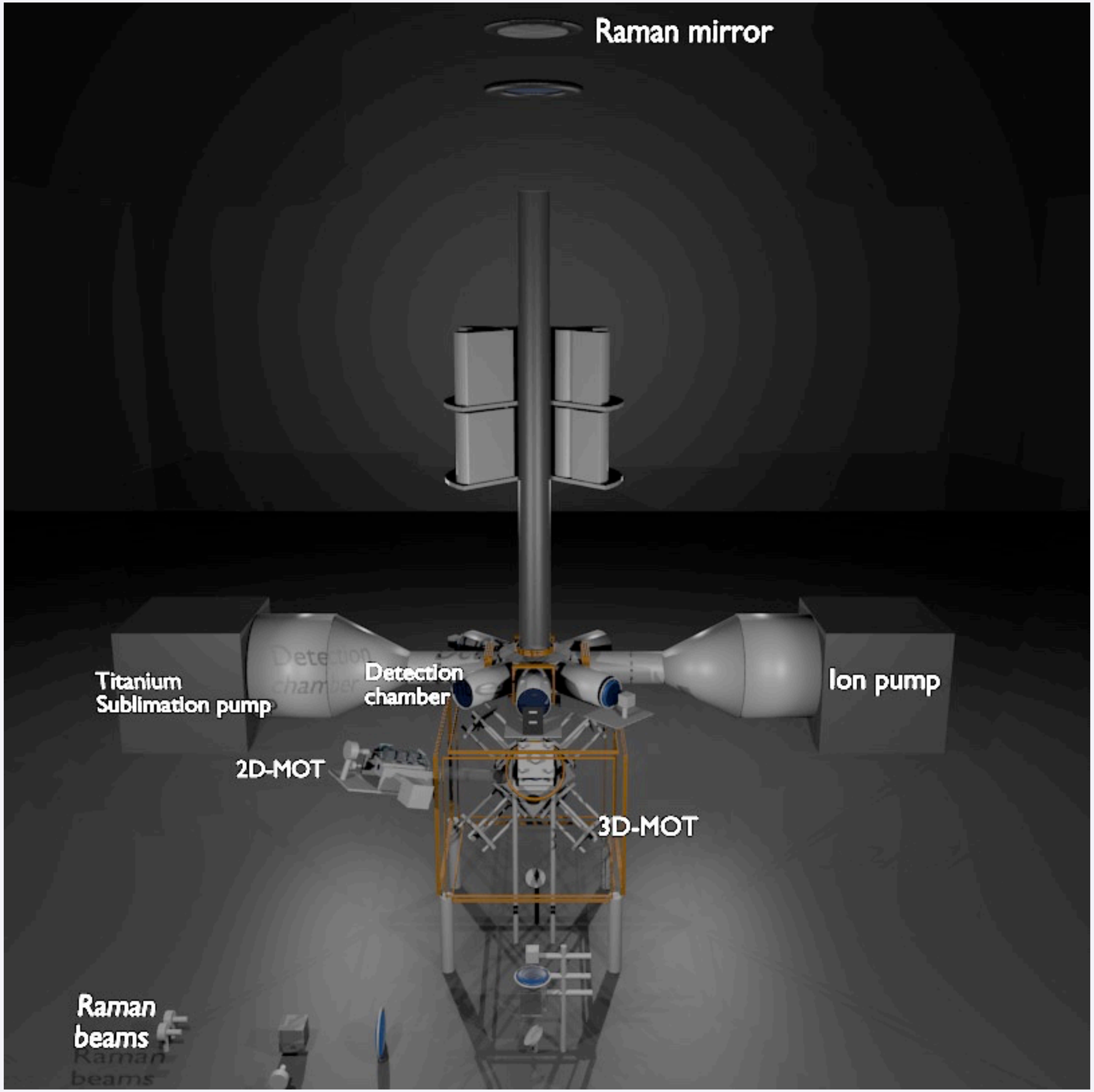
G. Lamporesi, A. Bertoldi, A. Cecchetti, B. Dulach, M. Fattori, A. Malengo,, S. Pettorruso, M. Prevedelli, G.M. Tino, *Source Masses and Positioning System for an Accurate Measurement of G,* **Rev. Scient. Instr. 78, 075109 (2007)**

Laser and optical system

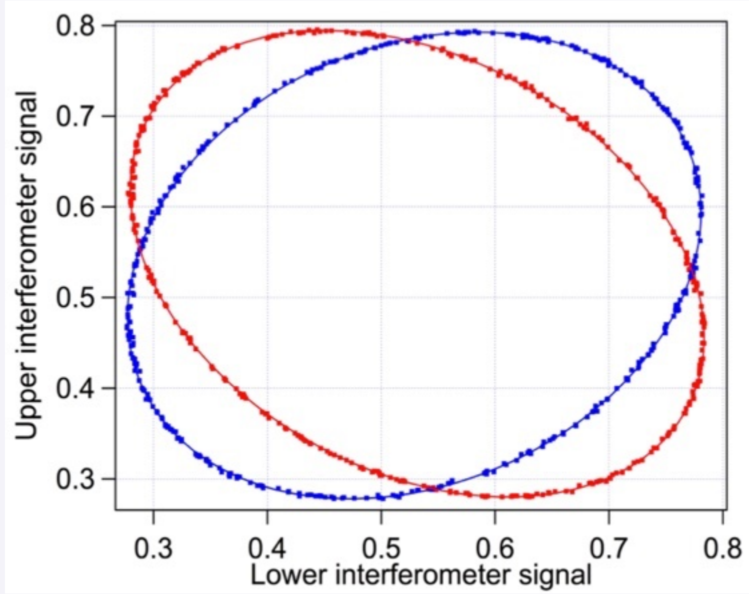


L. Cacciapuoti, M. de Angelis, M. Fattori, G. Lamporesi, T. Petelski, M. Prevedelli, J. Stuhler, G.M. Tino, *Analog+digital phase and frequency detector for phase locking of diode lasers,* **Rev. Scient. Instr. 76, 053111 (2005)**

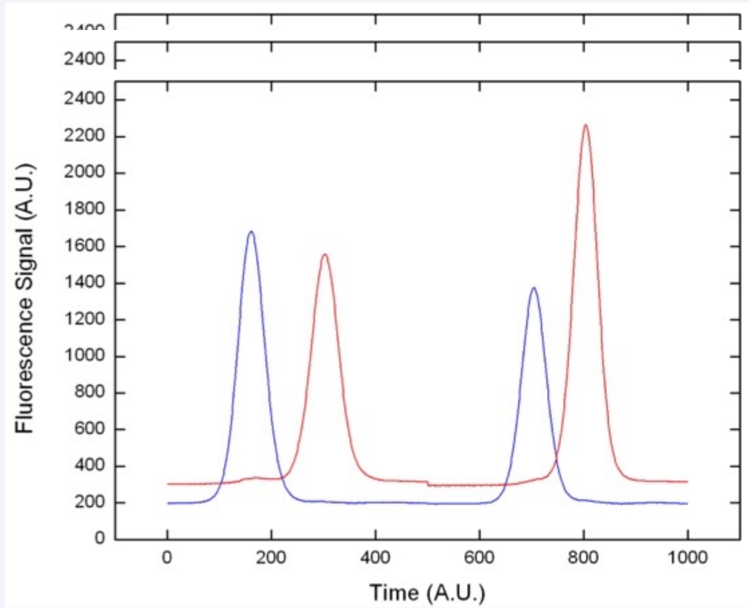
MAGIA



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



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

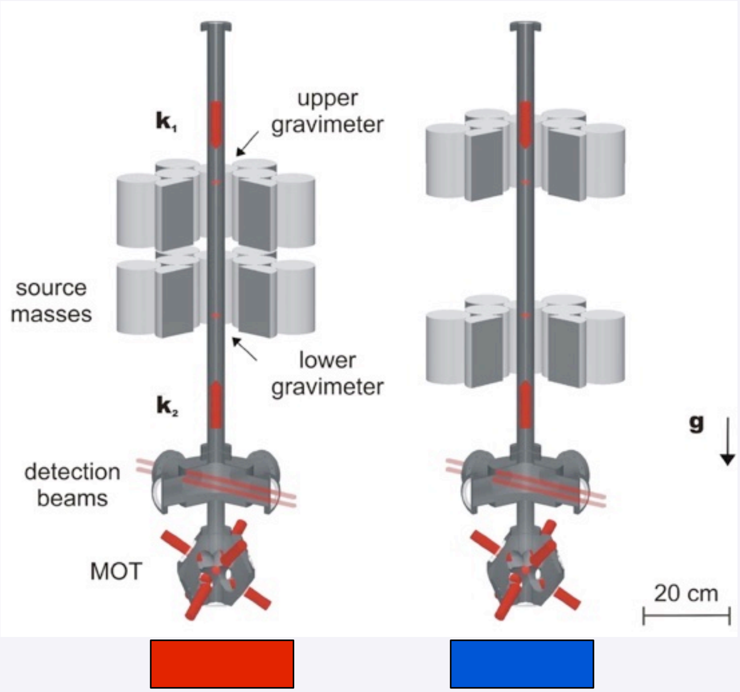


Fluorescence Signal (A.U.)
Time (A.U.)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400

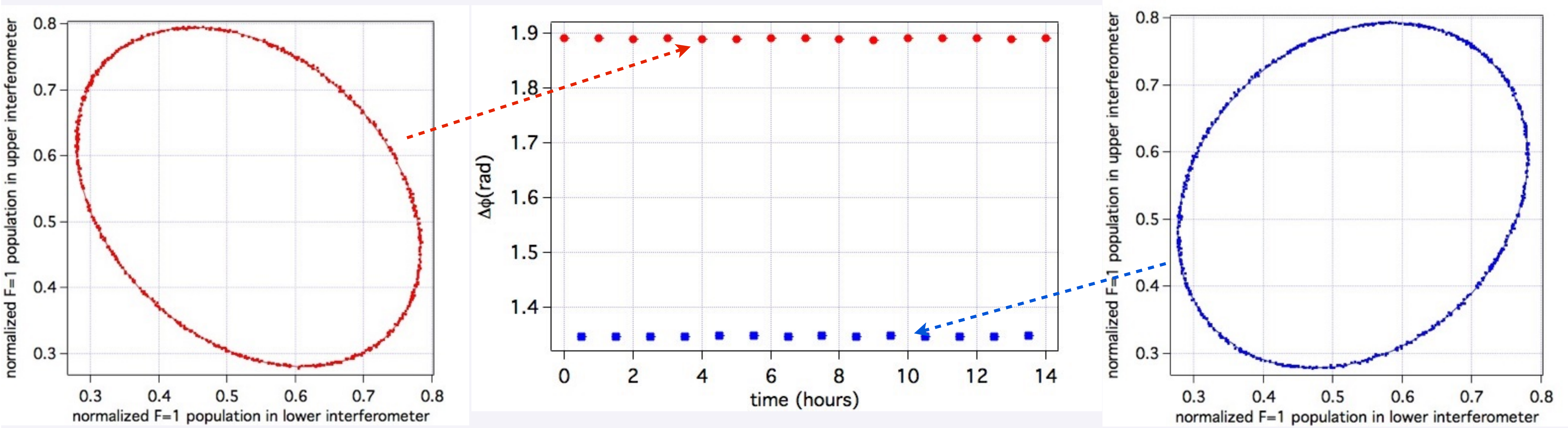
MAGIA: From proof-of-principle to the measurement of G

- 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: Final sensitivity



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



LETTER

doi:10.1038/nature13433

Precision measurement of the Newtonian gravitational constant using cold atoms

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

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

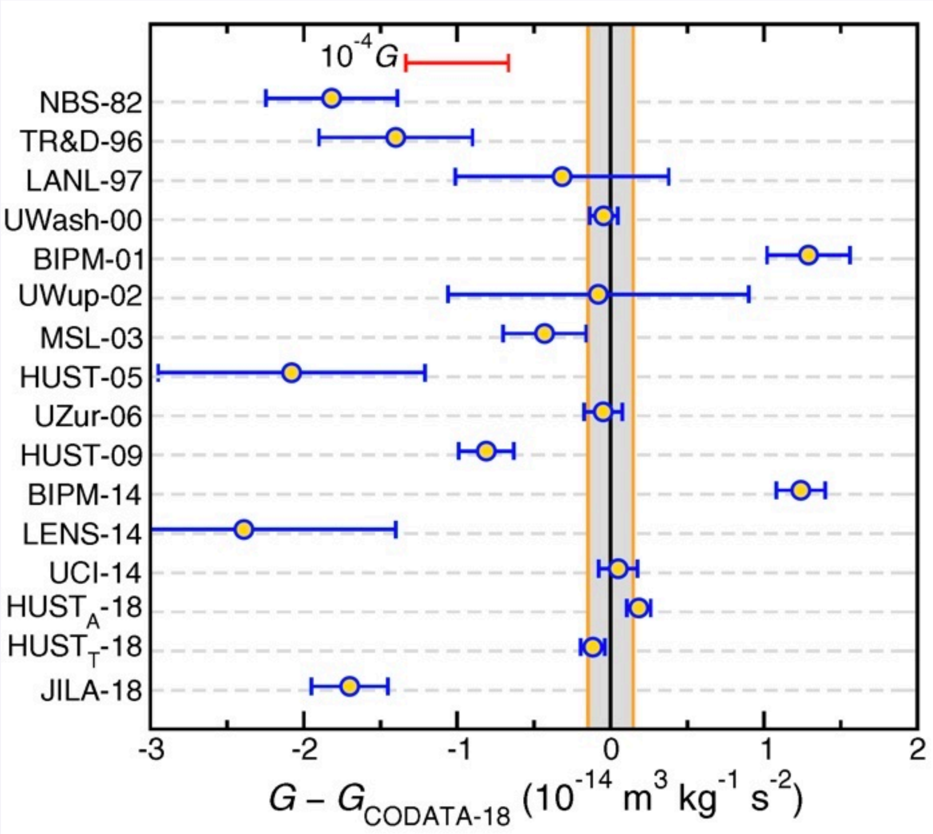
the relevant gravitational signal. An additional cancellation of common-mode spurious effects was obtained by reversing the direction of the two-photon recoil used to split and recombine the wave packets in the interferometer[18]. Efforts were devoted to the control of systematics related to atomic trajectories,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

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

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

Relative uncertainty: 150 ppm

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



Source	Identification	Method	$G(10^{-11}\ kg^{-1} \times m^3\ s^{-2})$	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}

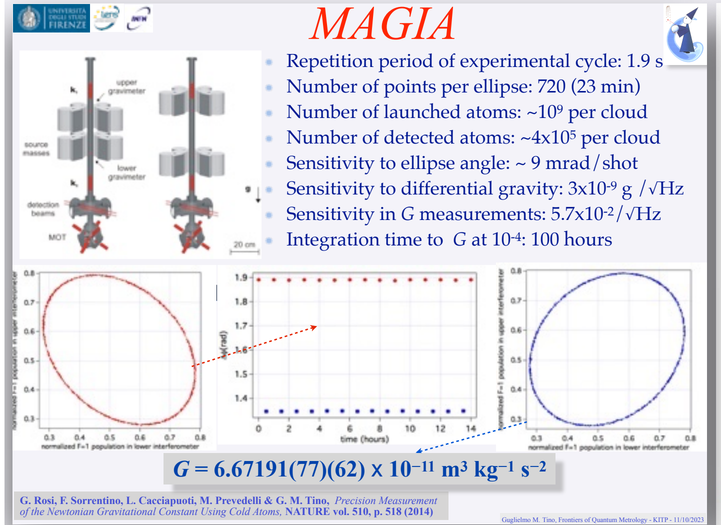
CODATA 2018

$G = 6.67430(15) \times 10^{-11}$ **m^3 kg^{-1}s^{-2}**

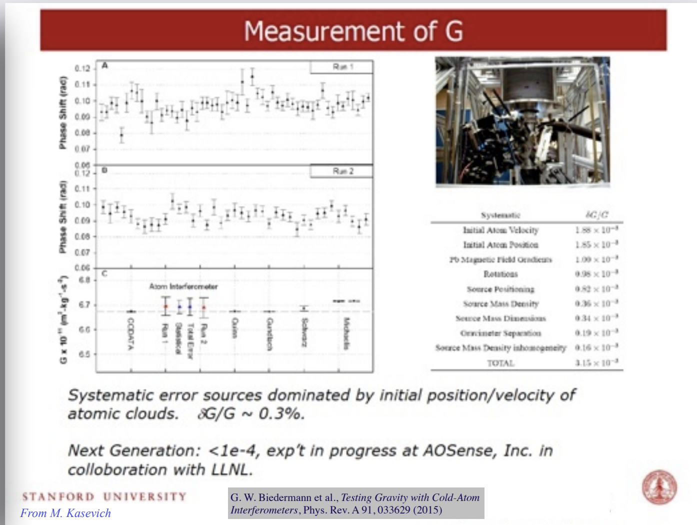
[Relative std. uncert.: 2.2×10^{-5}]

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)

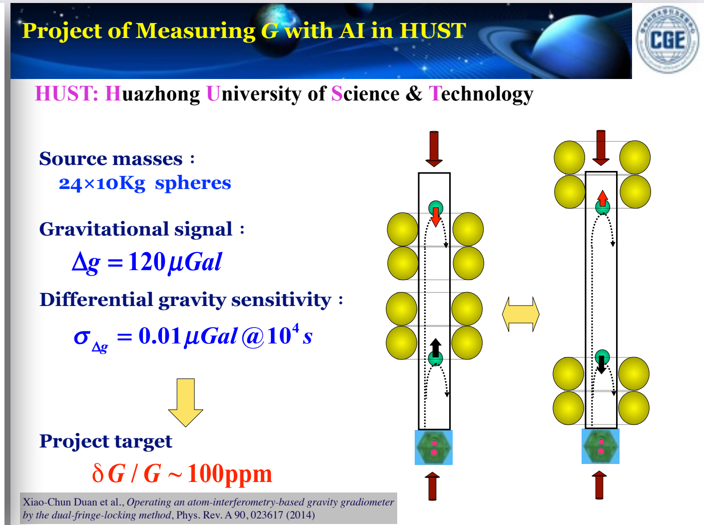
Measuring G with atom interferometry



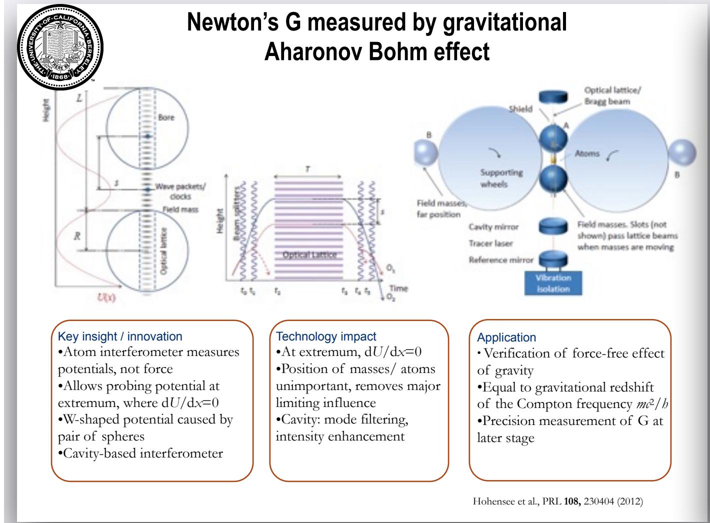
Florence



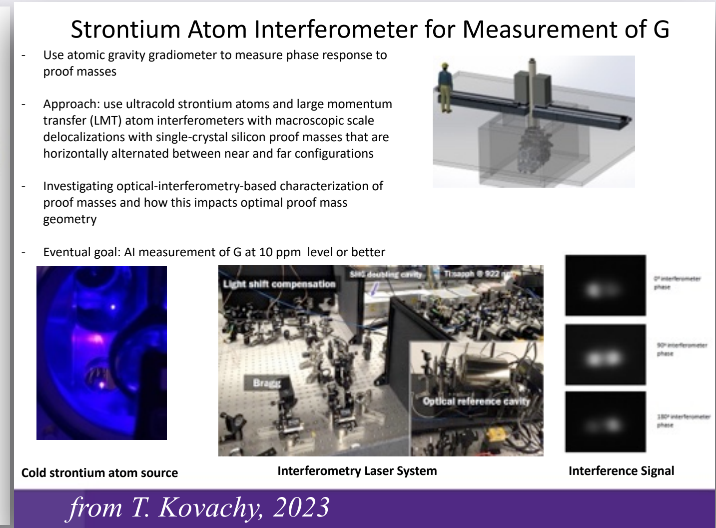
Stanford



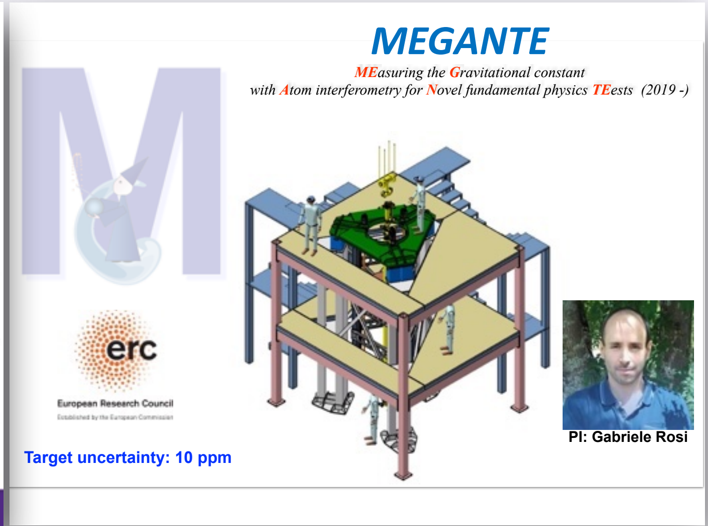
Wuhan



Berkeley

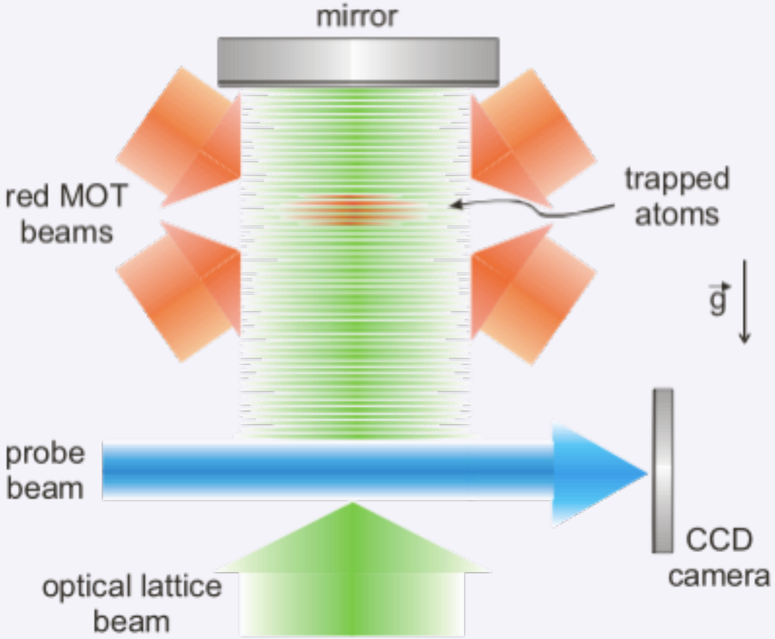


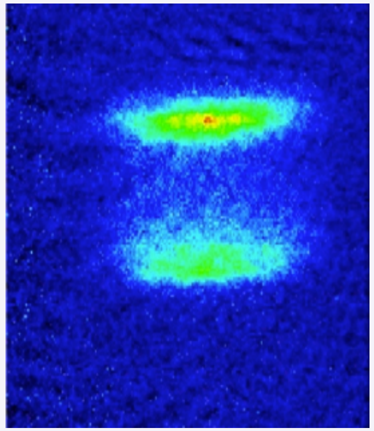
Northwestern University



Florence

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)

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 $\eta <$ **~10^{-13}**

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

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

Atoms $\eta <$ **~10^{-12} → ~ 10^{-14}-10^{-15}**

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

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

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305, USA

(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].

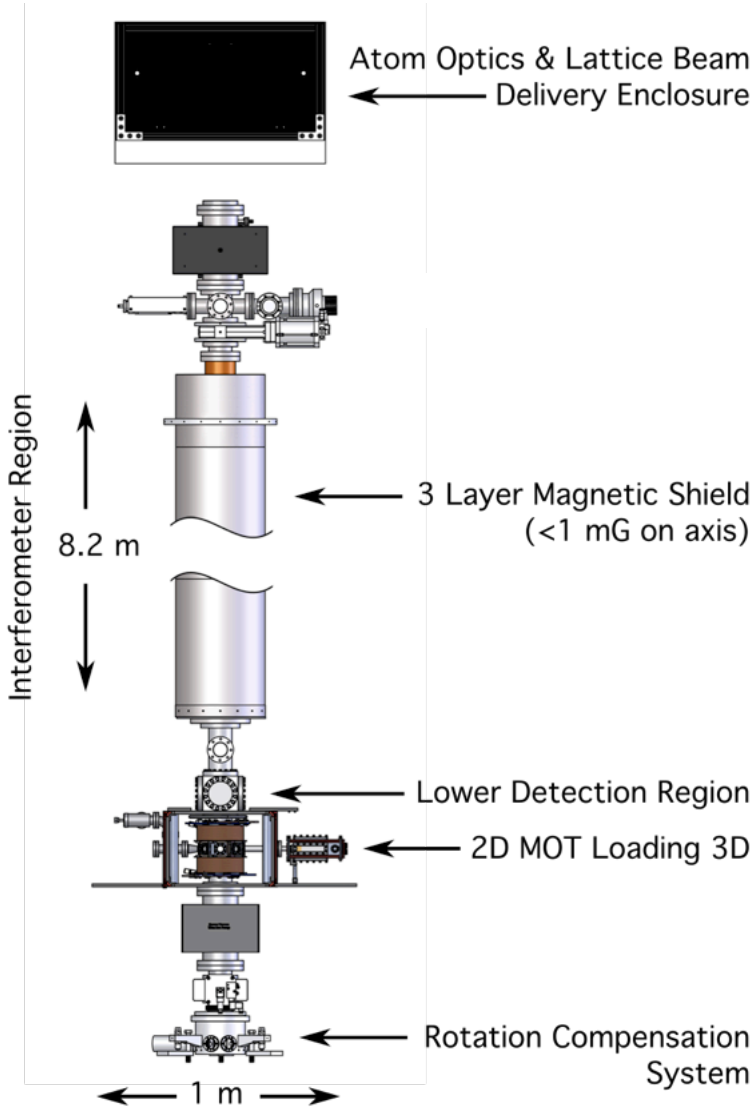
We perform an equivalence principle test by interferometrically measuring the relative acceleration of freely falling clouds of atoms. Atom clouds are well-suited test masses because they spend 99.9% of the interrogation time in free fall and the remainder in precisely controlled interactions with the 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.

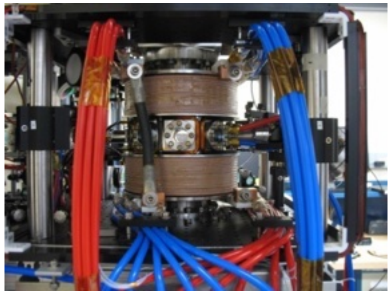
In this Letter, we report an atom-interferometric test of the equivalence principle between ^{85}Rb and ^{87}Rb with $\eta = [1.6 \pm 1.8(\mathrm{stat}) \pm 3.4(\mathrm{syst})] \times 10^{-12}$, consistent with zero violation at the 10^{-12} level. This result improves by four orders of magnitude on 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].

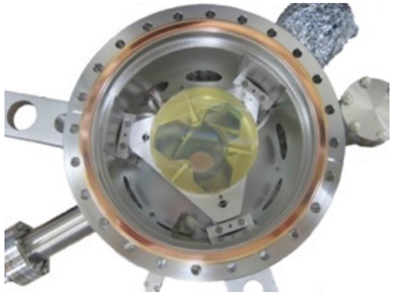
The relative acceleration between ^{85}Rb and ^{87}Rb is measured with a dual-species atom interferometer. The experimental apparatus is described in [16]. We prepare ultracold clouds of ^{85}Rb and ^{87}Rb by evaporative cooling in a magnetic trap. The subsequent magnetic lensing sequence lowers the 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

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**

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**

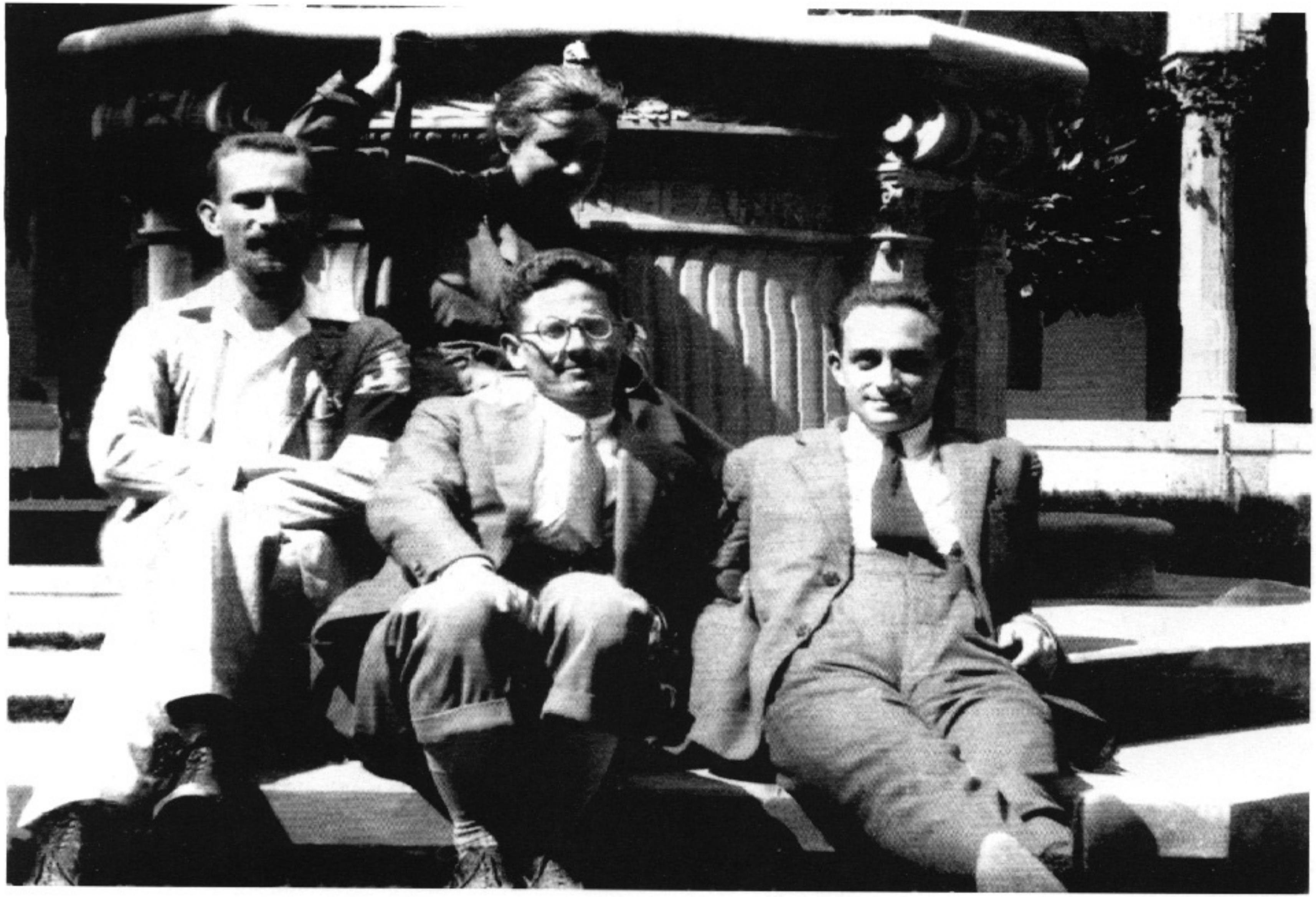
^{87}Sr

- **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

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 $R_m = \frac{m_{88}}{m_{87}}$ (*)

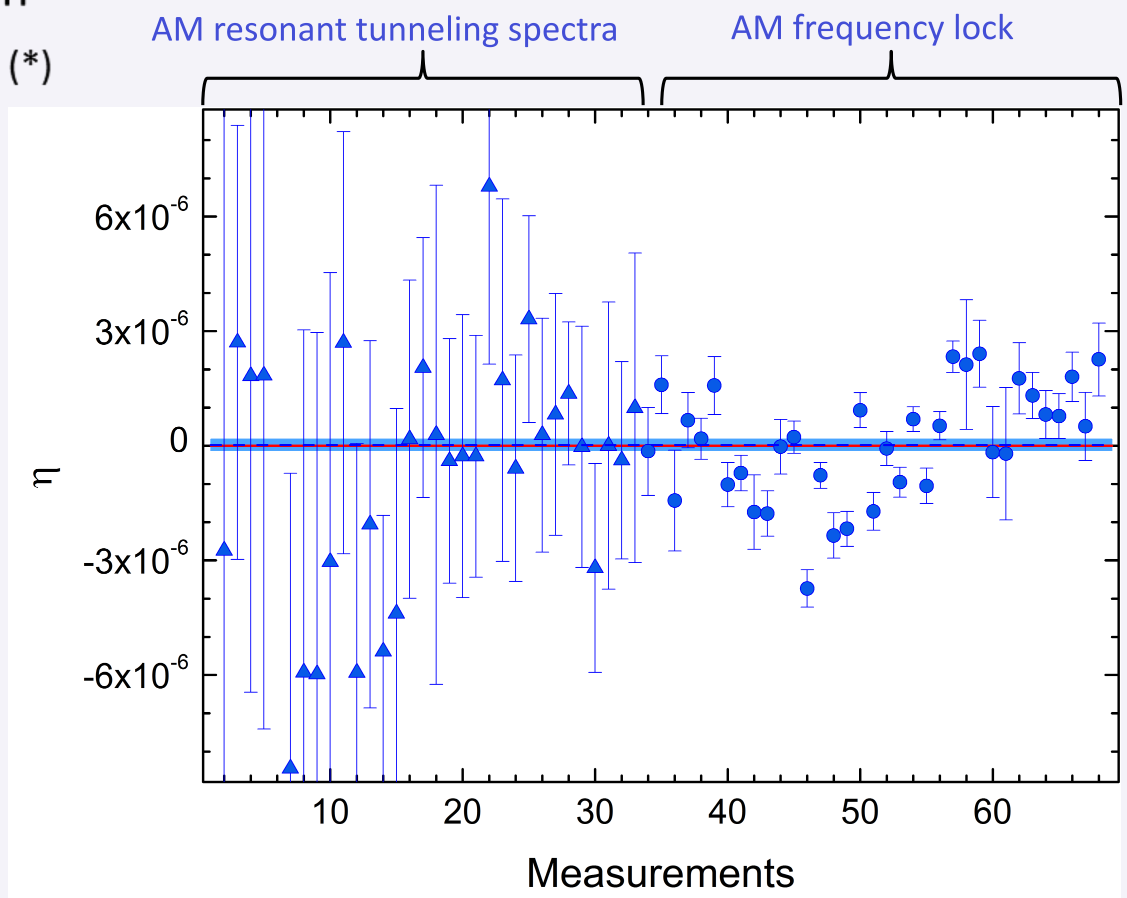
$$\eta = \frac{a_{88} - a_{87}}{(a_{88} + a_{87})/2} = \frac{\nu_{88} - R_m \nu_{87}}{(\nu_{88} + R_m \nu_{87})/2}$$

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

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

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

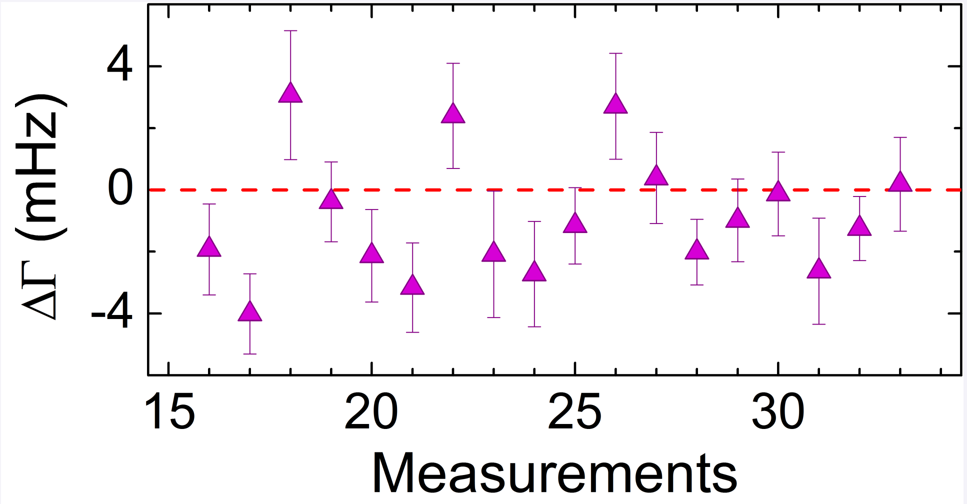
Each ^{87}Sr spin component $S_z = I_z$ will feel different gravitational forces due to different spin-gravity coupling. For unpolarized sample → broadening of the resonant tunneling spectra

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

$$\Delta\Gamma = 2I_{87}klv_{87}$$

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



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)

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

Eötvös ratio

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

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

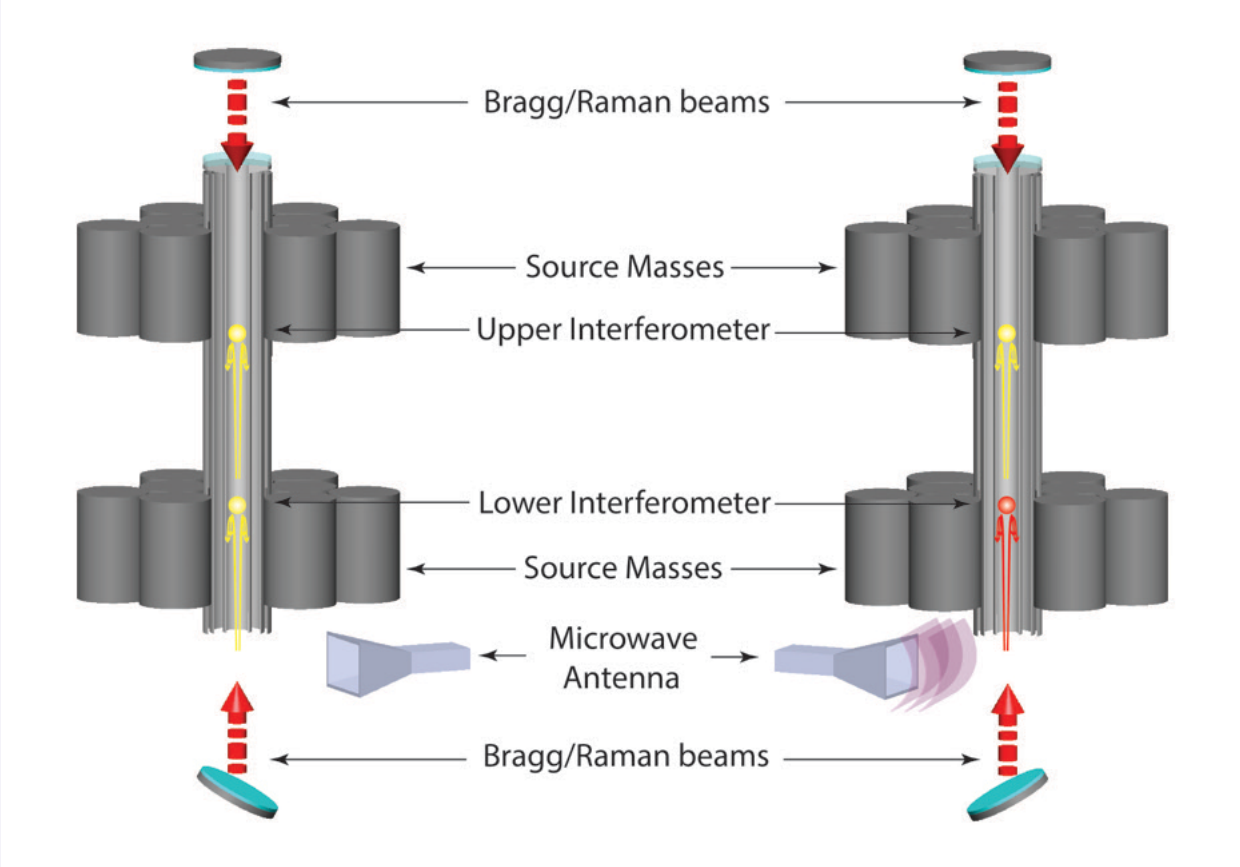
Quantum test theory with WEP violations $\Rightarrow \hat{M}_\mathrm{i} \neq \hat{M}_\mathrm{g} \Rightarrow \hat{a} = \hat{M}_\mathrm{g} \hat{M}_\mathrm{i}^{-1} g$

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

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



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

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

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

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

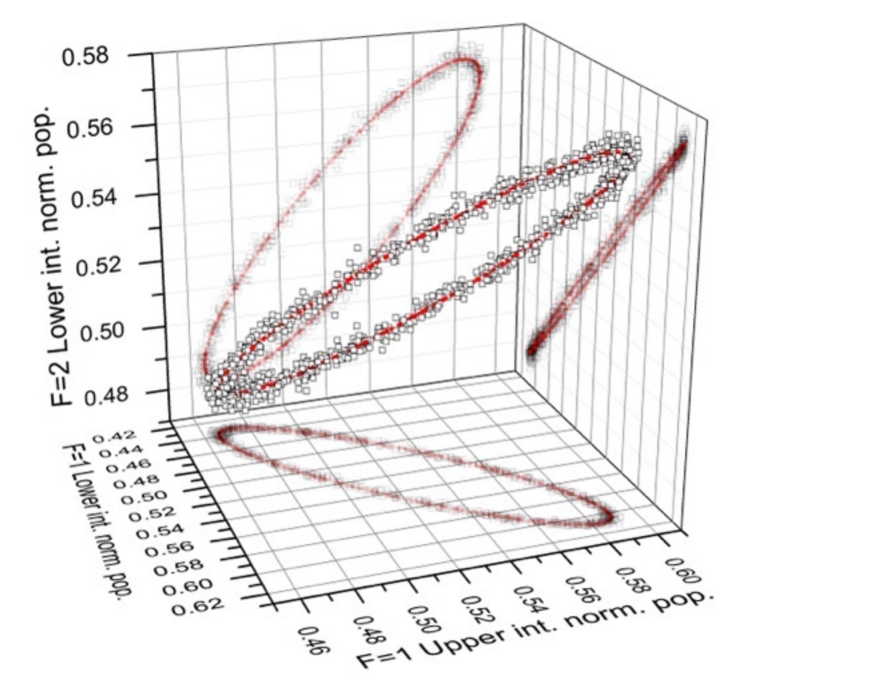


Table 1 | Measurement systematics.

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.

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

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

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

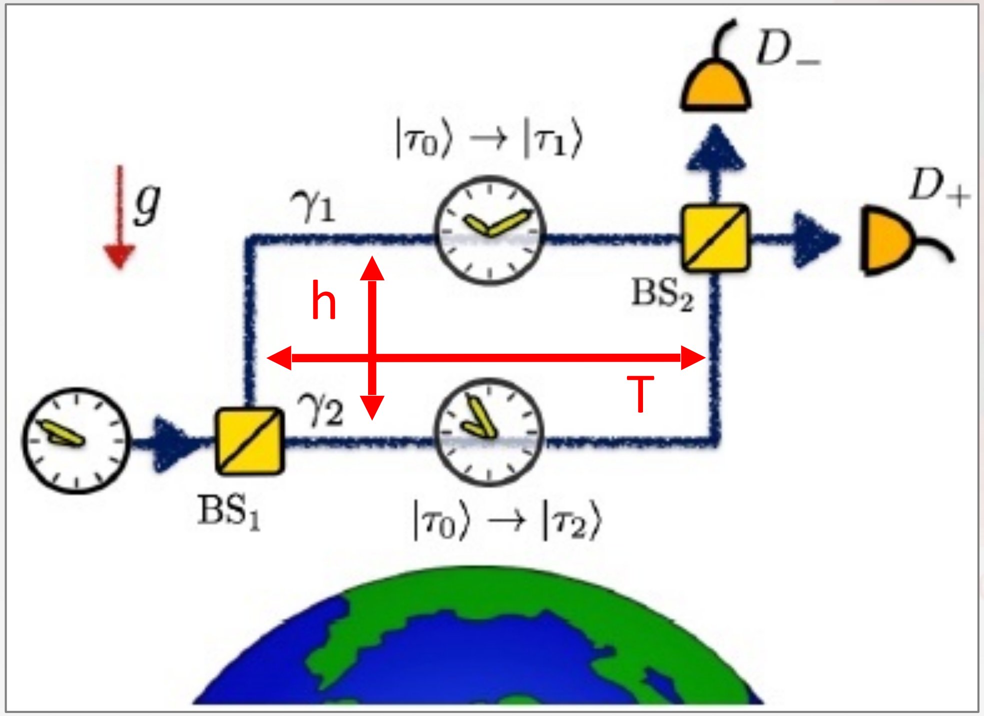
$$|\mathbf{r}| \leq \mathbf{5 \cdot 10^{-8}}$$

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

Quantum Interference of Clocks

TICTOC GRAV

Observe gravity induced "decoherence" in clock interferometers



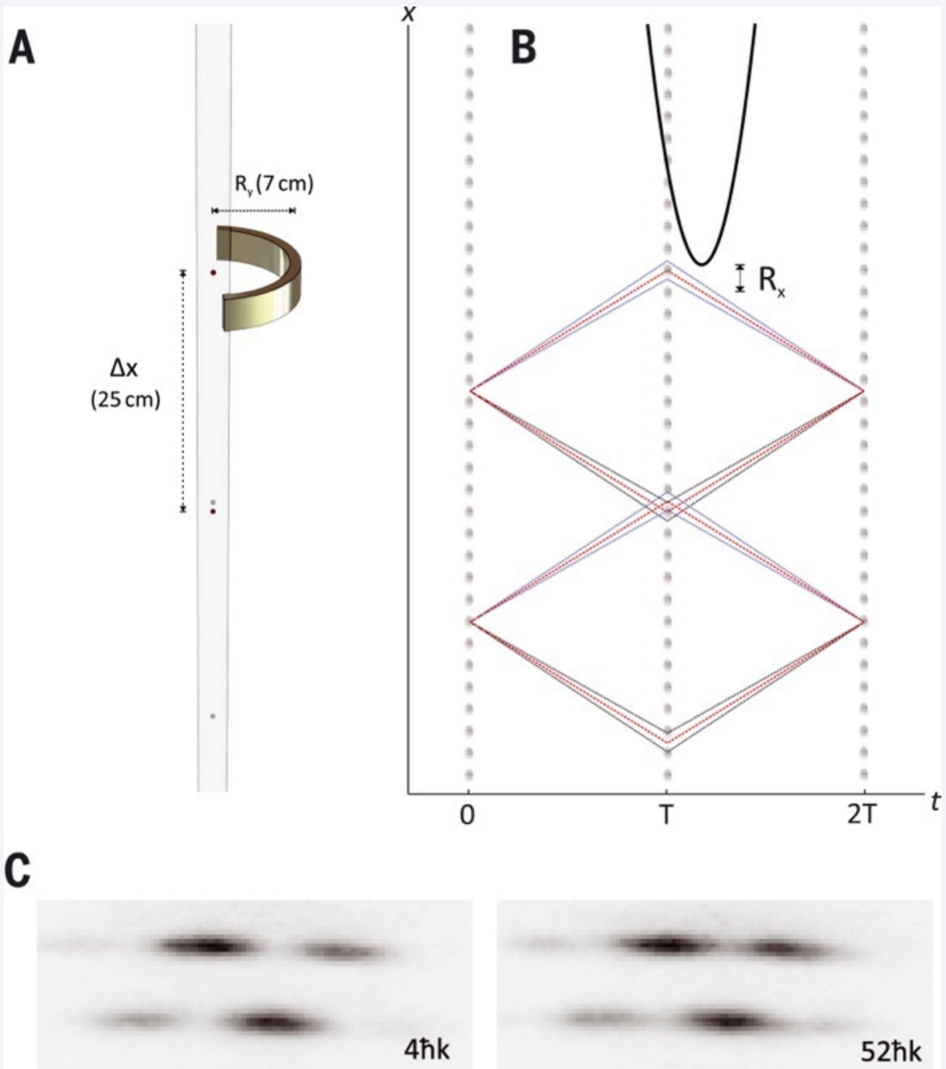
M. Zych et al. Nature Commun. 2(505), 1498 (2011)

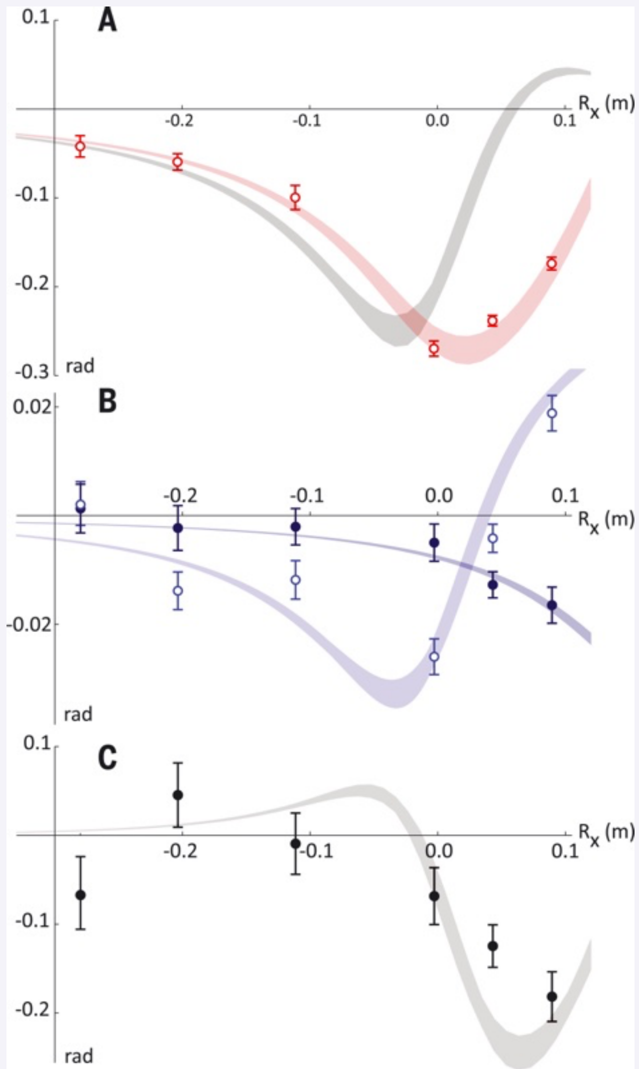
- ✓ Quantum superposition of clocks in different locations (h = height difference)
- ✓ Dephasing introduced by differential time dilation in the two different paths γ_1 and γ_2 (T=time)
- ✓ Interferometer contrast loss
- ✓ Decoherence induced by "which path" information from clock state

Test of foundation of quantum mechanics: quantum to classical transition

From N. Poli

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)

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

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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.

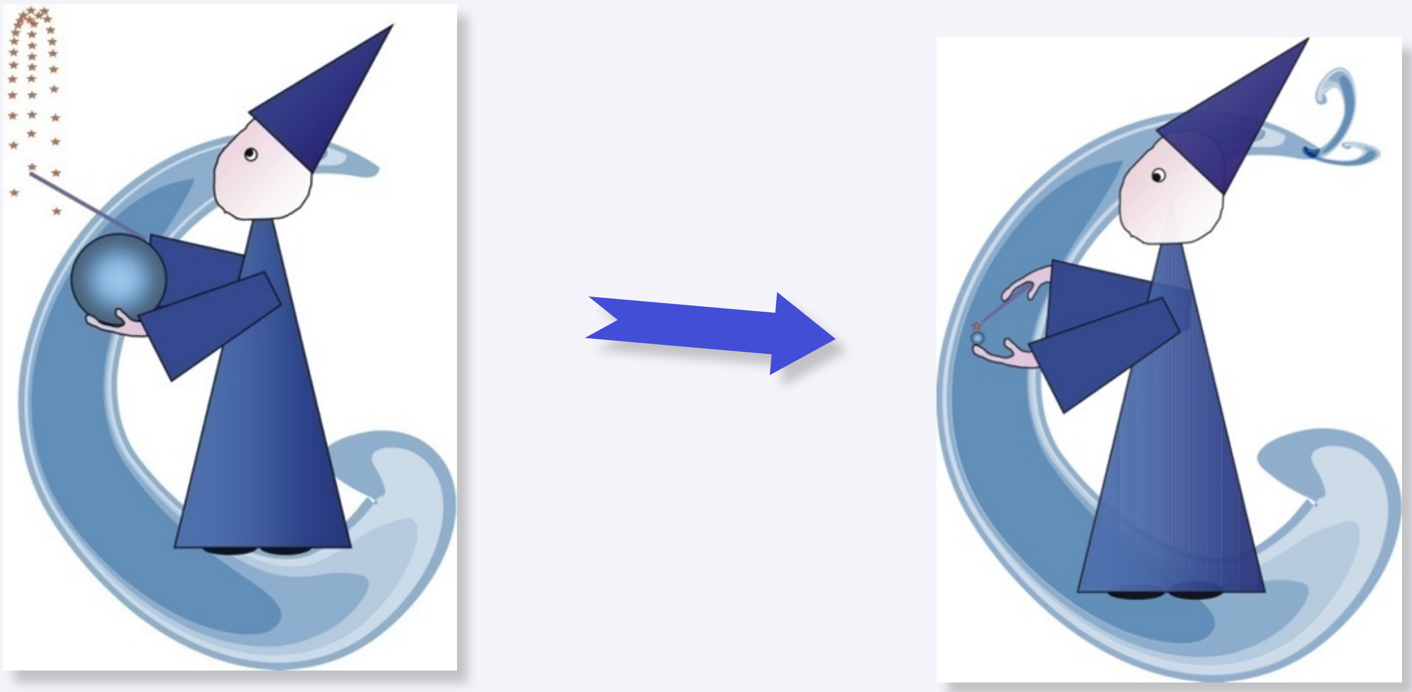
$$E = \sqrt{p^2 + m^2} + \Delta_{QG}(p, m, M_P)$$

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

$|\xi_1| \sim 1$ 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)
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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)

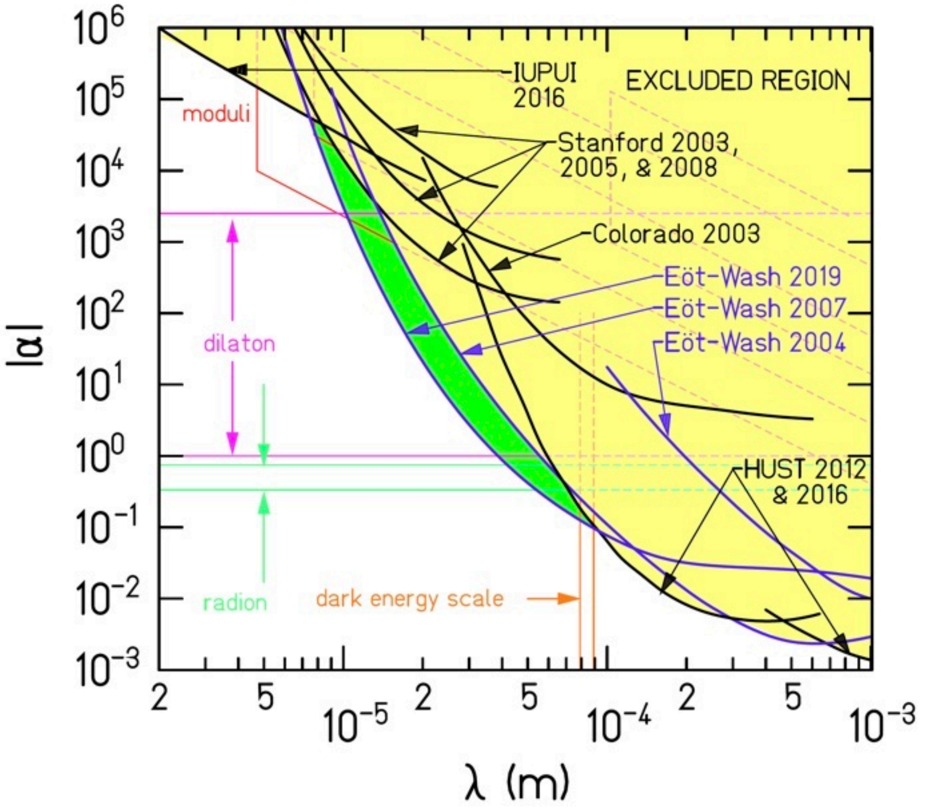
- **Experimental challenge**

Tests of the gravitational $1/r^2$ law at small distances

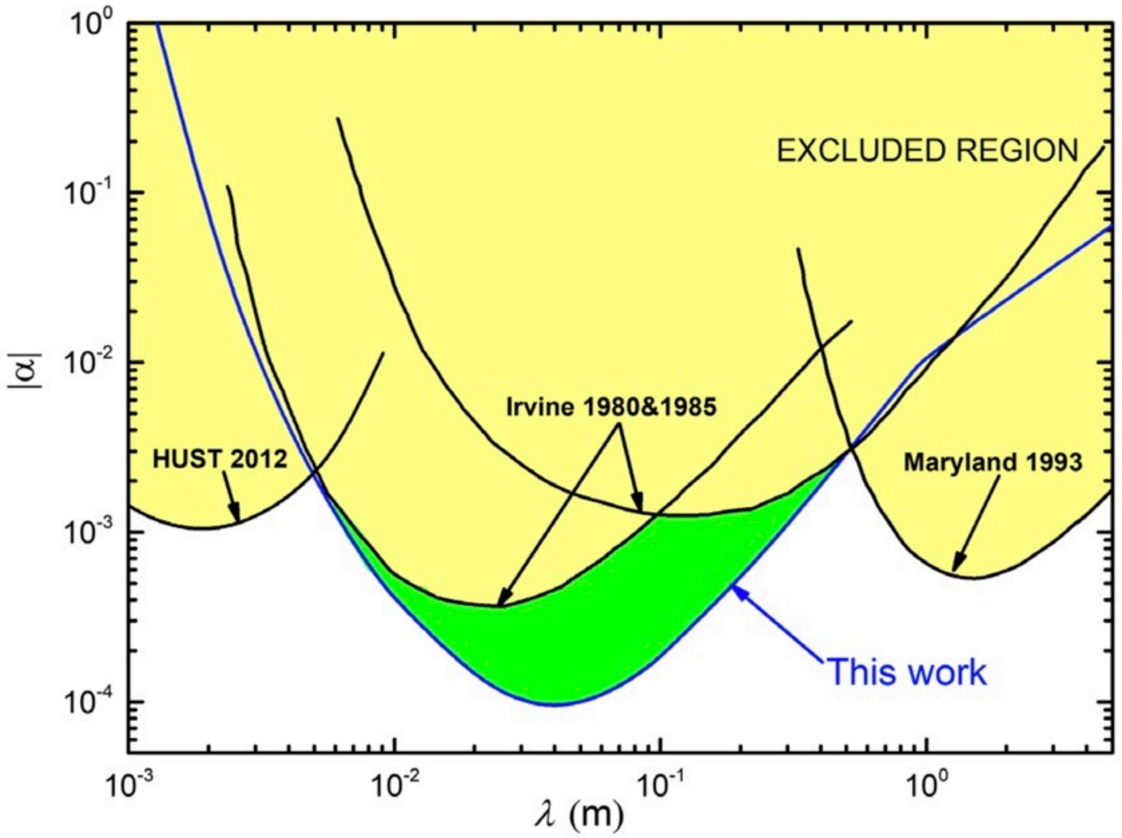
- **Newton+Yukawa potential**

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

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

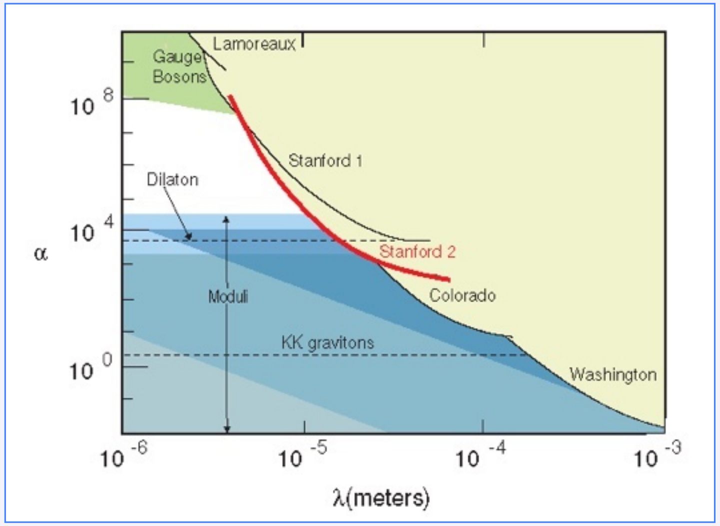


J. G. Lee, E. G. Adelberger, T. S. Cook, S. M. Fleischer, and B. R. Heckel, *New Test of the Gravitational $1/r^2$ Law at Separations down to 52 μm*, Phys. Rev. Lett. 124, 101101 (2020)



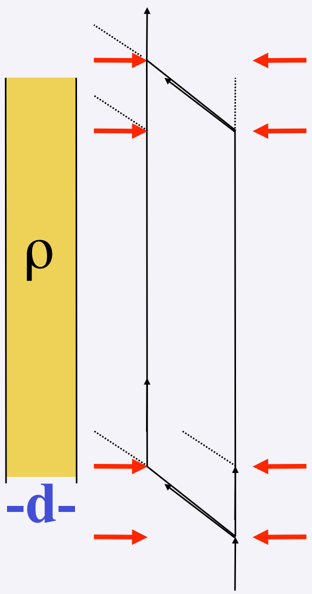
Jun Ke, Jie Luo, Cheng-Gang Shao, Yu-Jie Tan, Wen-Hai Tan, and Shan-Qing Yang, *Combined Test of the Gravitational Inverse-Square Law at the Centimeter Range,* Phys. Rev. Lett. 126, 211101 (2021)

Test of the gravitational $1/r^2$ law in the sub-mm range with atom interferometry sensors



95% confidence level constraints on a Yukawa violation of the gravitational inverse-square law. The vertical axis represents the strength of a deviation relative to that of Newtonian gravity while the horizontal axis designates its characteristic range. The yellow region has been excluded (From S. J. Smullin et al., 2005)

$$V(r) = -G\frac{m_1 m_2}{r}(1+\alpha e^{-r/\lambda})$$



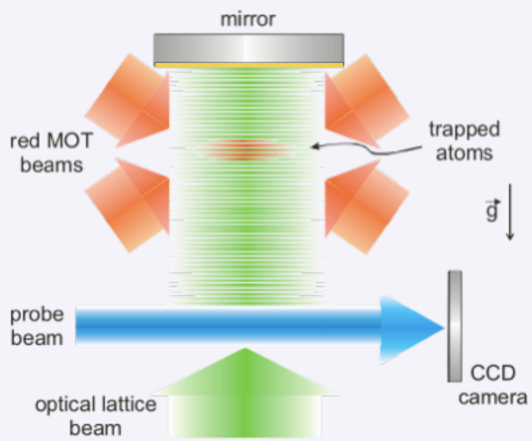
$a = 2\pi G\rho d$

Example:

$\rho_{Au} \sim 19$ g/cm^3

d ~ 200 μm

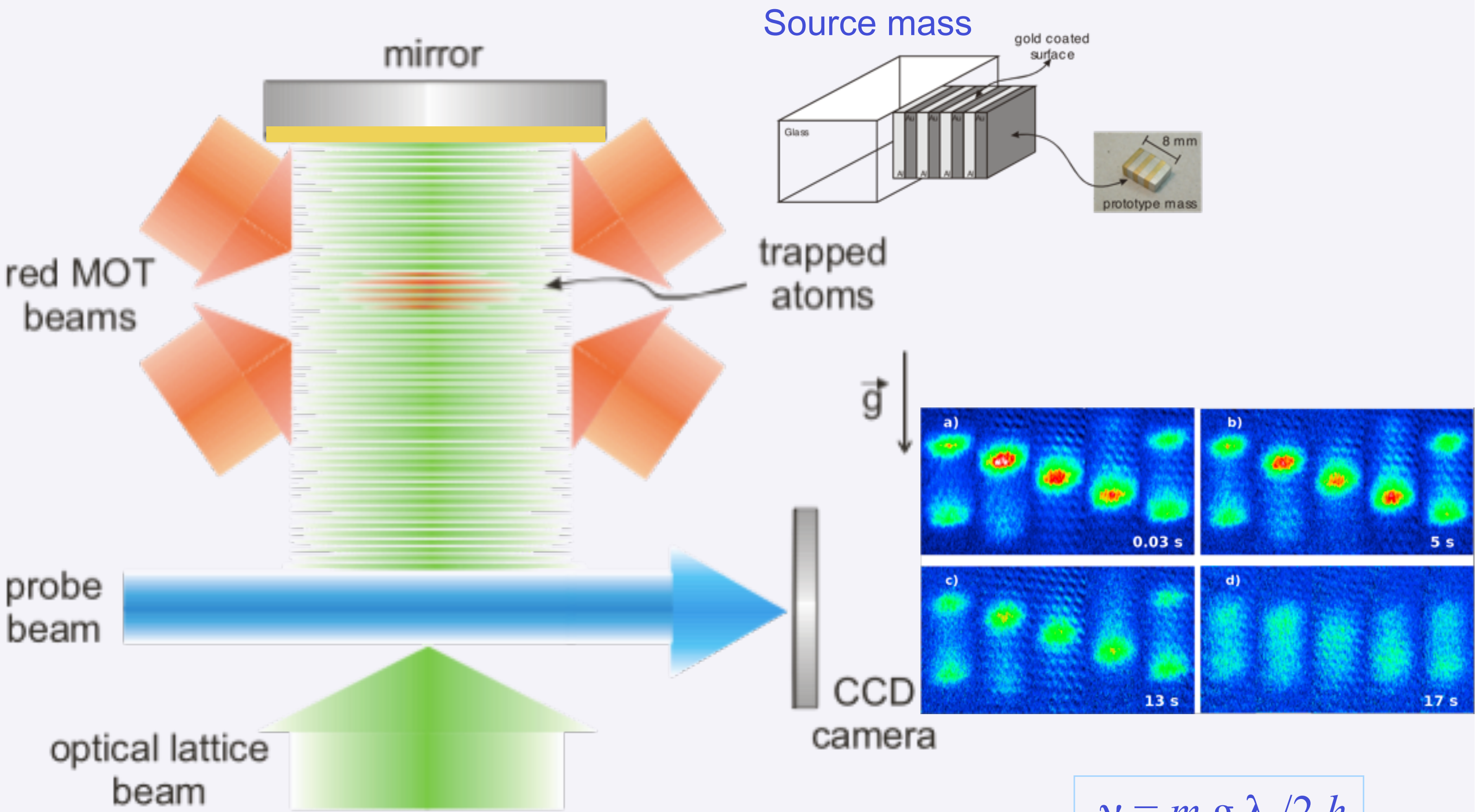
$a \sim 2 \times 10^{-9}$ ms^{-2}



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

- G.M. Tino, *in "2001: A Relativistic Spacetime Odyssey", Firenze, 2001,* World Scientific (2003)
- G.M. Tino, Nucl. Phys. B 113, 289 (2002)
- G. Ferrari, N. Poli, F. Sorrentino & G. M. Tino, PRL 97, 060402 (2006)

Scheme for the measurement of small distance forces



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

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

Objective: $\lambda = 1\text{-}10\ \mu m,\ \alpha = 10^3\text{-}10^4$

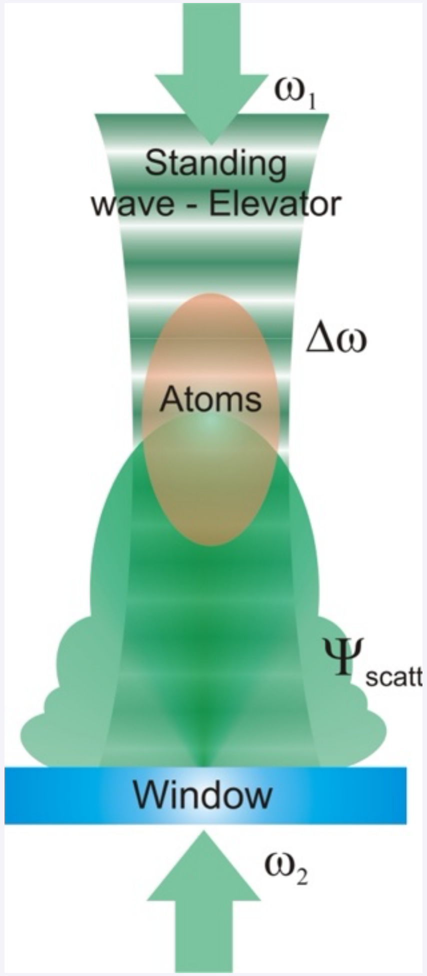
F. Sorrentino, A. Alberti, G. Ferrari, V. V. Ivanov, N. Poli, M. Schioppo, and G. M. Tino, *Quantum sensor for atom-surface interactions below 10 μm*, Phys. Rev. A 79, 013409 (2009)

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

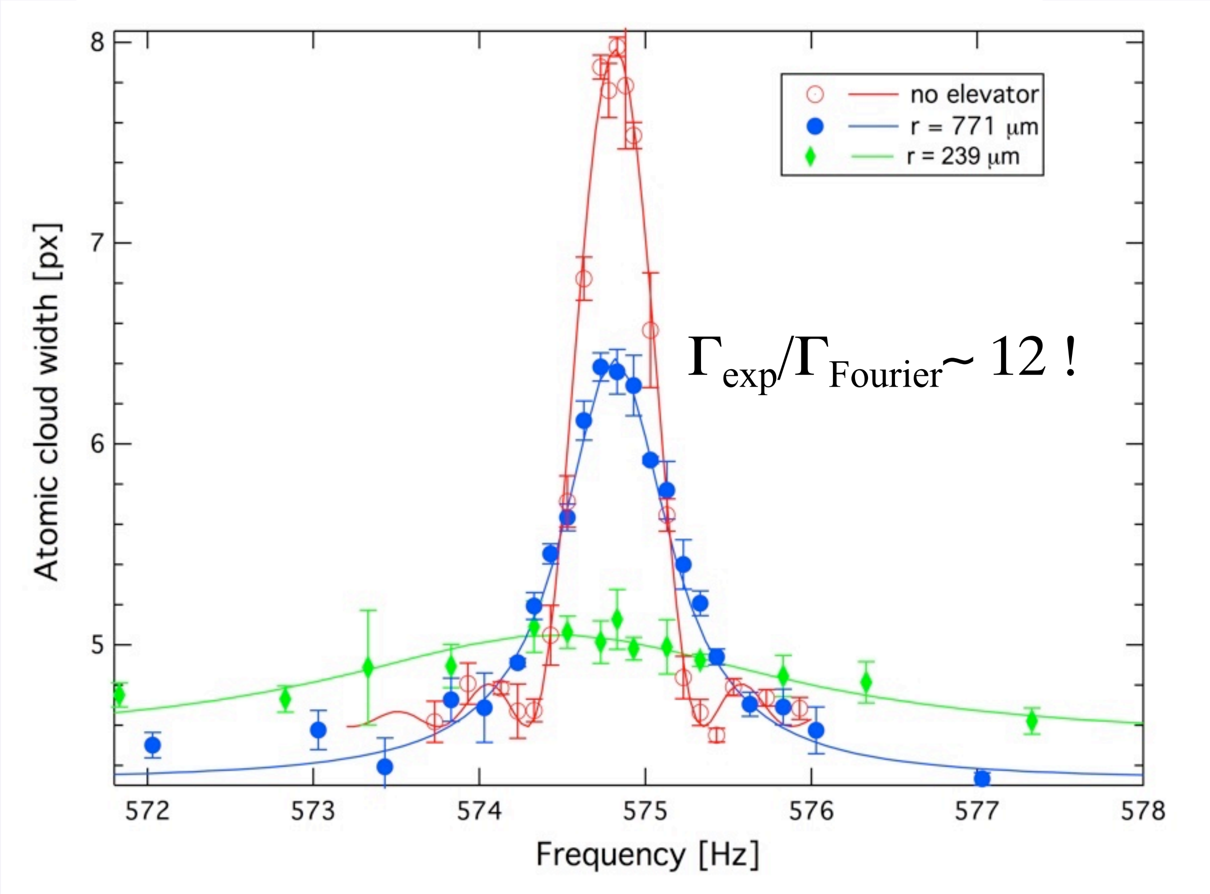
Short-distance measurements

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

⇒ AM measurement close to the surface (preliminary)

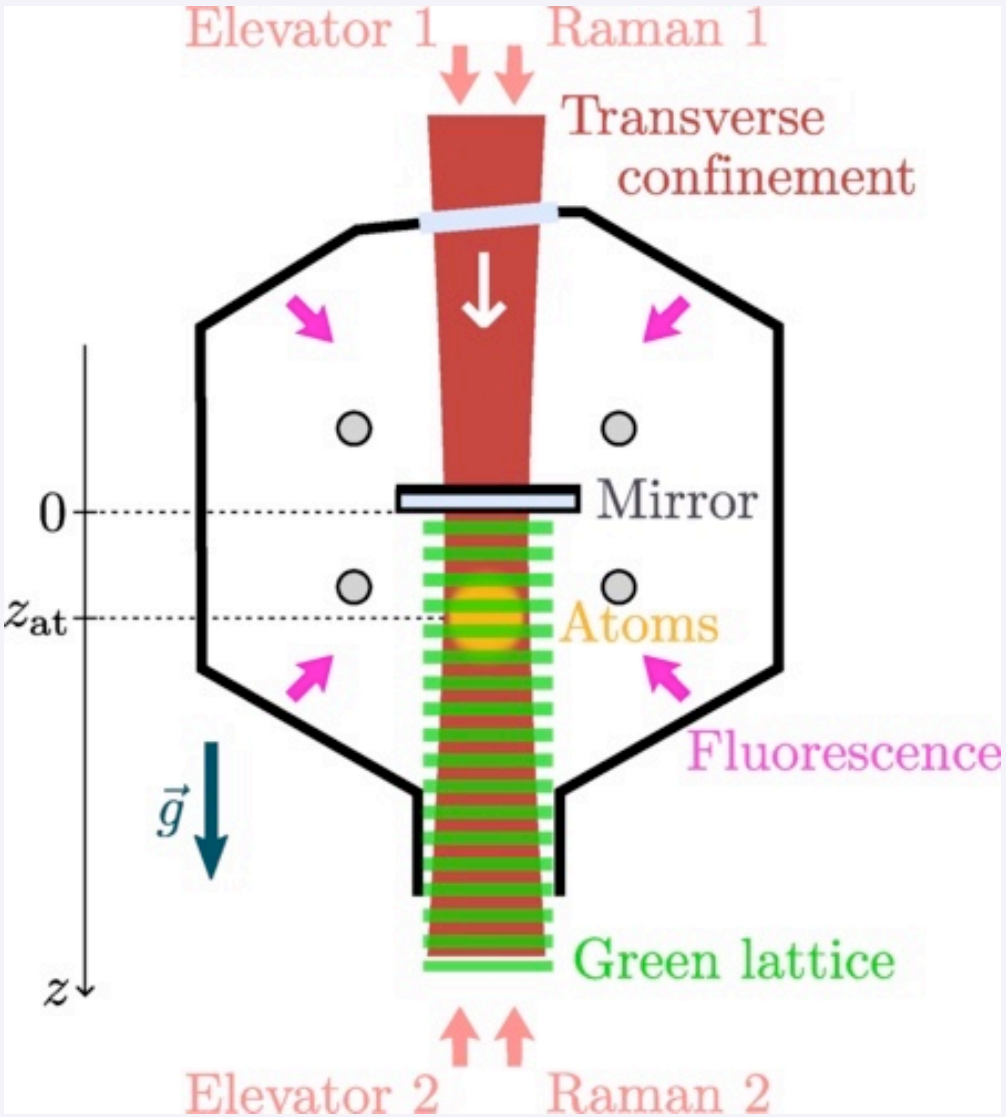


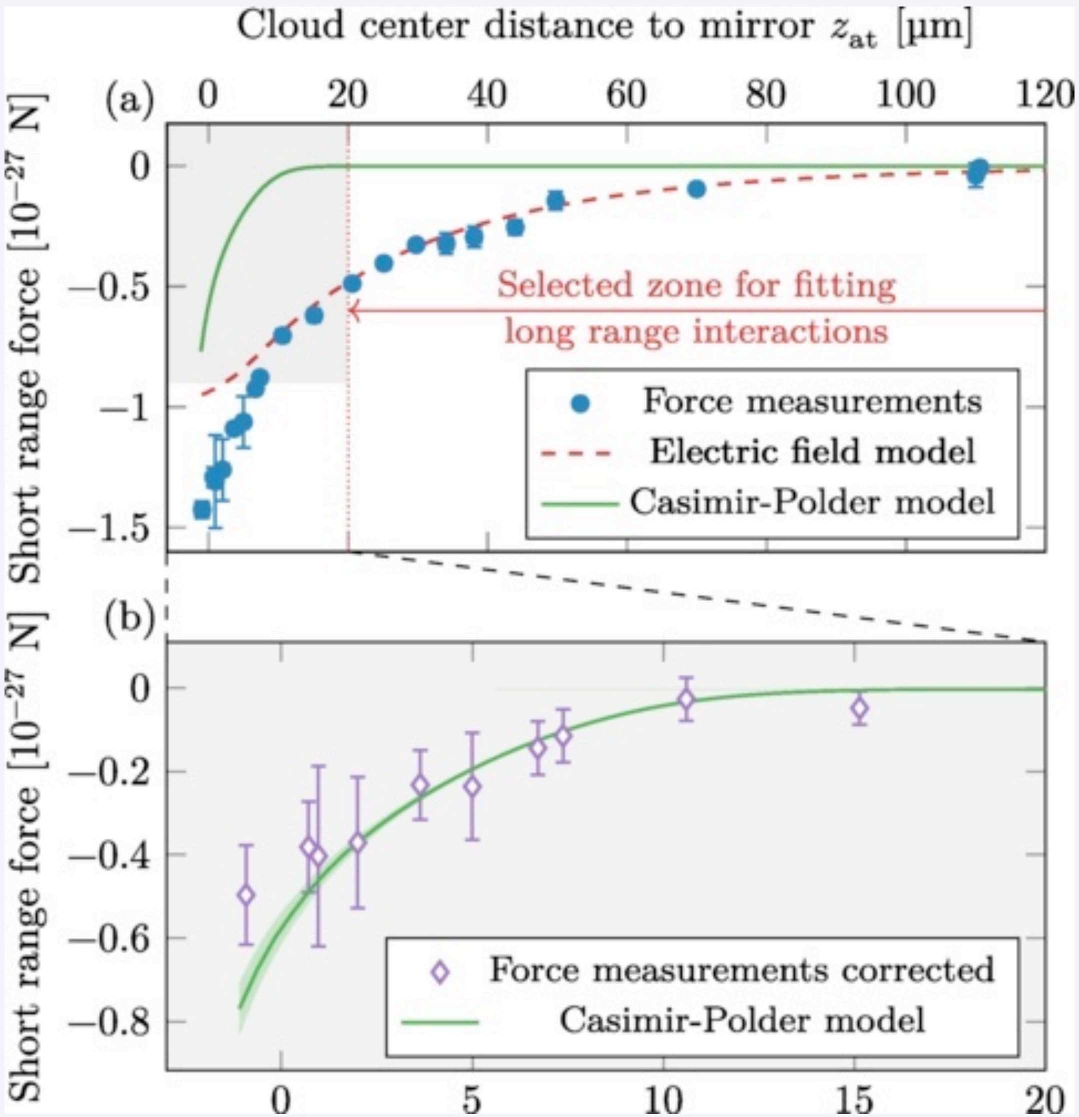
Getting closer:



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

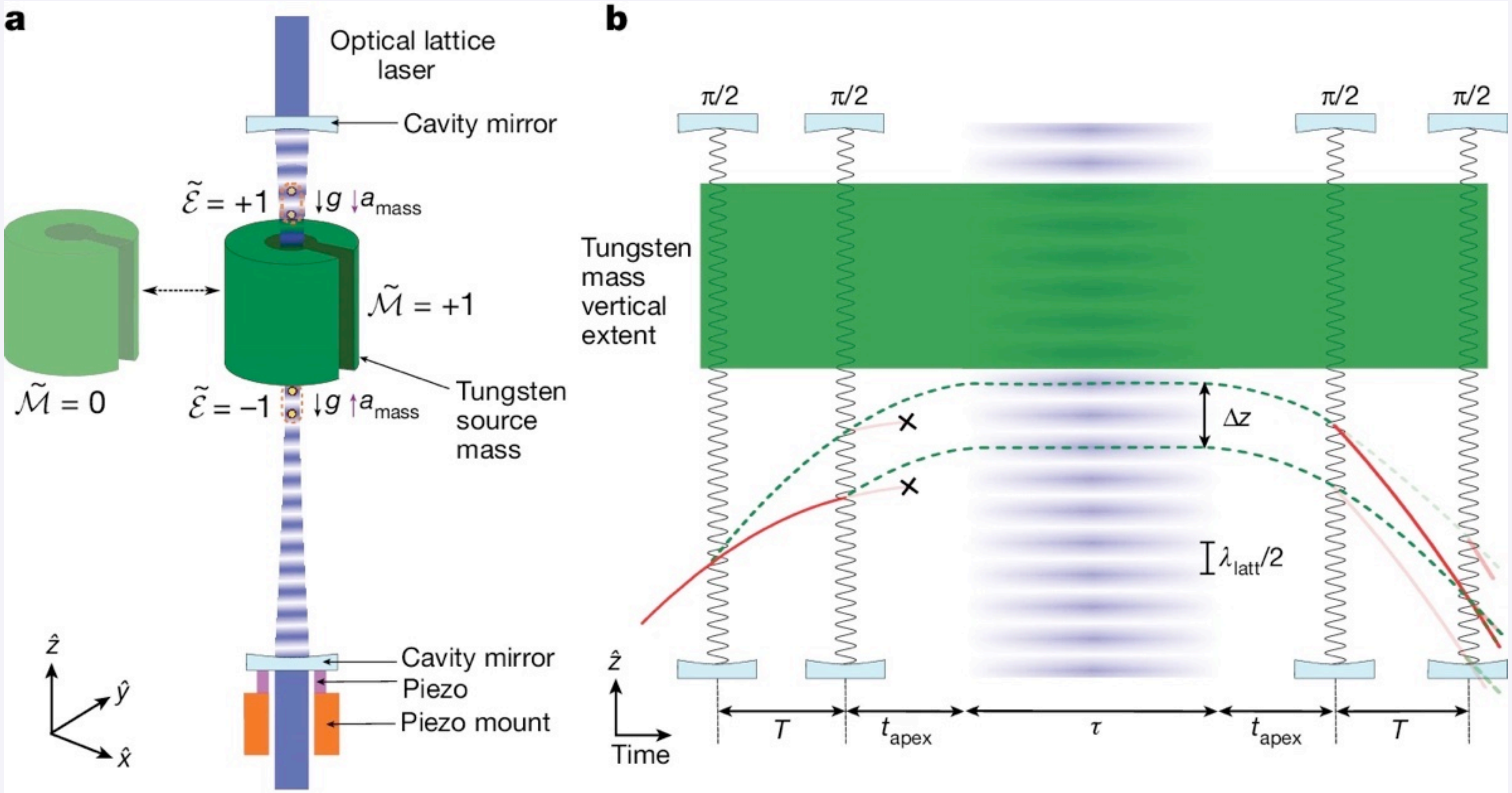
Measurement of small distance forces
The experiment at SYRTE, Paris





Yann Balland, Luc Absil, Franck Pereira Dos Santos,
Quectonewton local force sensor, PRL 133, 113403 (2024)

Measuring the gravitational attraction of a miniature source mass with a lattice atom interferometer



Cristian D. Panda, Matthew J. Tao, Miguel Ceja, Justin Khoury, Guglielmo M. Tino & Holger Müller,
Measuring gravitational attraction with a lattice atom interferometer, NATURE 631, 515 (2024)

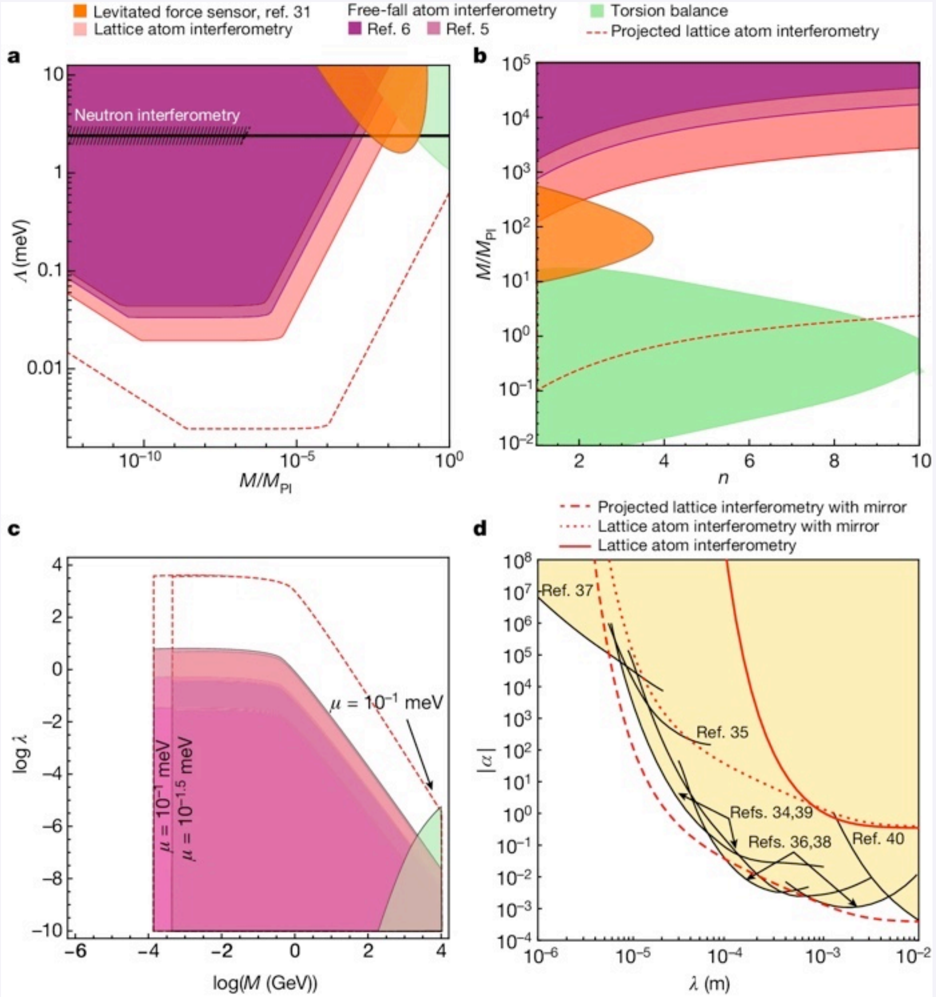
Measuring the gravitational attraction of a miniature source mass with a lattice atom interferometer

Chameleon fields

Chameleon fields

Symmetron fields

Yukawa-type deviation



Prospects:

- *probing forces at sub-millimeter ranges*
- *measuring the gravitational constant*
- *measuring the gravitational Aharonov-Bohm effect*
- *testing whether the gravitational field has quantum properties*

Cristian D. Panda, Matthew J. Tao, Miguel Ceja, Justin Khoury, Guglielmo M. Tino & Holger Müller, *Measuring gravitational attraction with a lattice atom interferometer*, NATURE 631, 515 (2024)

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- Istituto Nazionale Geofisica e Vulcanologia (INGV)
- ENI
- Ente Cassa di Risparmio di Firenze (CRF)

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Marco Fattori	Università di Firenze
Marco Prevedelli	Università di Bologna
Fiodor Sorrentino	INFN - Genova

Previous members and visitors

Andrea Alberti, PhD student
Andrea Bertoldi, Post-doc
Quentin Bodart, Post-doc
Filippo Borselli, Diploma student
Sergei Chepurov, Inst. Laser Physics, Novosibirsk, visitor
Robert Drullinger, NIST, Long term guest
Marco Fattori, PhD student
Gabriele Ferrari, Researcher, INFM/CNR
Antonio Giorgini, PhD and Post-doc
Jacopo Grotti, Diploma student, Università di Firenze
Vladyslav Ivanov, Post-doc
Marion Jacquey, Post-doc
Giacomo Lamporesi, PhD student
Yu-Hung Lien, Post-doc
Marco Marchetti, Diploma student
Marco Menchetti, Diploma student, Univ. di Bologna
Chris Oates, NIST, visitor
Torsten Petelski, PhD student
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Denis Sutyrin, Post-doc
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