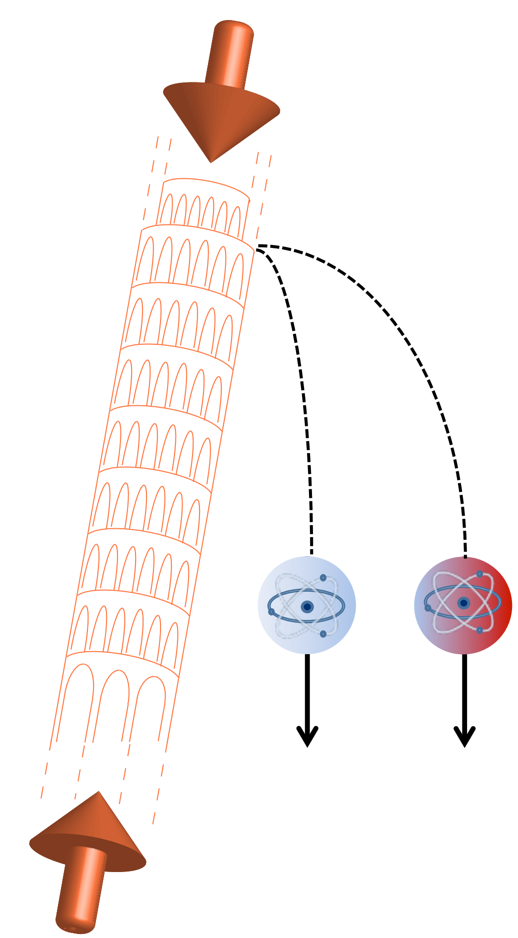
Verifiche sperimentali del principio di equivalenza con sistemi quantistici

Fiodor Sorrentino
INFN Genova



Istituto Nazionale di Fisica Nucleare

Testing the weak equivalence principle with quantum sensors

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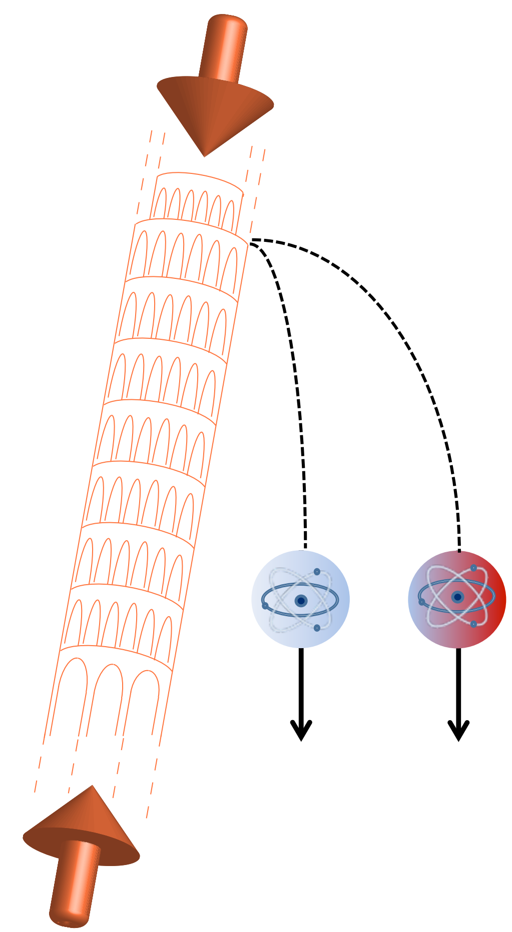
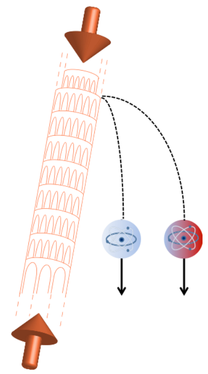
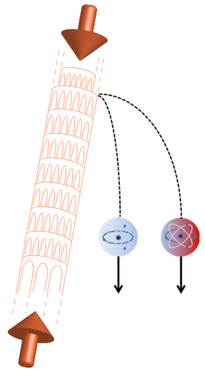


Istituto Nazionale di Fisica Nucleare

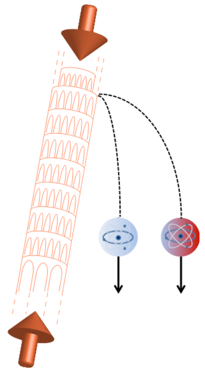


Outline

- Introduction
  - the weak equivalence principle: a pillar of general relativity
  - classical WEP tests: state of the art
- Atomic quantum sensors
  - Precision gravity measurements
  - Fundamental physics tests and applications
- WEP tests with atomic probes
  - recent results and ongoing experiments
  - WEP for anti-matter
  - spin-gravity coupling
  - a quantum test of the weak equivalence principle
- Prospects

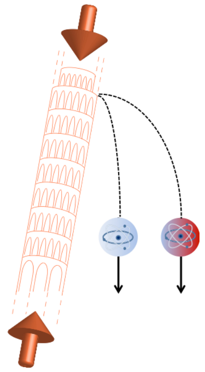


Tests of the weak equivalence principle



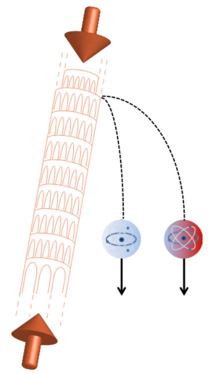
Limits of general relativity

- General Relativity provides a complete description gravity
- many predictions of GR were confirmed with amazing accuracy:
  - Geodetic Deviation
  - Frame Dragging
  - Gravitational Lensing
  - Black Holes
  - Gravitational Redshift
  - Gravity Waves
- So far, no direct experimental test identified any violation of GR principles
- However there are several reasons to look for theories beyond GR
  - GR is not sufficient to explain the modern cosmological observations
    - a standard cosmological model has to include dark matter and an expanding universe
  - hierarchy problem: why the weak force is 10^{32} times stronger than gravity?
  - GR is not compatible with quantum mechanics



Limits of general relativity

- GR experimental proofs are all related to the case of very weak limit
- Exploration of the strong regime has just started with Gravitational Waves detection
- Precision laboratory tests of gravity
  - one of the most rapidly growing subfields of modern physics
  - laboratory and space-based experiments are designed to test the foundations of General Relativity and to probe theories that predict deviations from General Relativity.
  - starting point: GR is a complete gauge theory based on the assumption of Einstein Equivalence Principle (EEP)
  - new physics can be hidden beyond the violation of this assumption

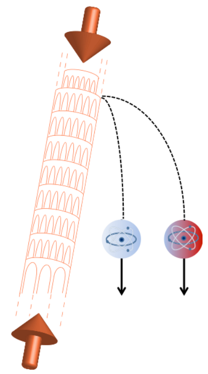


Beyond GR

- EEP tests are interpreted after two different approaches:

- **SME**: **Standard Model Extension** (domain of particle physicists)
    - generalization of the usual Standard Model and General Relativity allowing for violations of Lorentz and CPT symmetry
    - violation is controlled by a set of coefficients whose values can be determined or constrained by experiment
    - *Colladay, D., and V. A. Kostelecký , 1997, Phys. Rev. D 55, 6760. Colladay, D., and V. A. Kostelecký , 1998, Phys. Rev. D 58, 116002.*

- **PPN: Parameterized Post Newtonian** formalism (domain of gravitational physicists)
    - Einstein's equation of Gravity expressed in terms of lowest-order deviation from the Newton's law.
    - a set of parameters are defined, in which a general theory of gravity can differ from GR gravity
    - holds in the case of weak field limit
    - *Will, C. M. Theory and Experiment in Gravitational Physics, University Press, Cambridge, 1993*

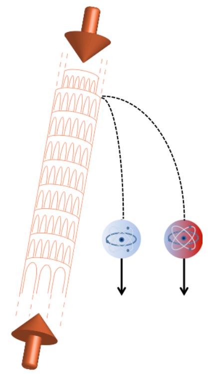


The Einstein Equivalence Principle (EEP)

- **Local Lorentz Invariance (LLI):**
  - The result of any non-gravitational experiment is independent of the speed of the apparatus (in free fall)
  - tested with great precision on a variety of experiments spanning from high energy physics to optical interferometry

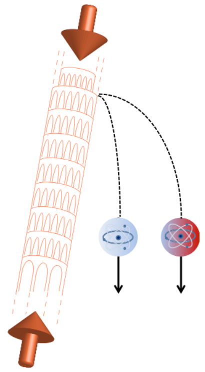
- **Local Position Invariance (LPI):**
  - The result of any non-gravitational experiment is independent of where and when it is brought to completion in the Universe
  - Tested by measuring the gravitational red shift

- **Universality of Free Fall (UFF or WEP):**
  - If an uncharged test body is placed at an initial event in space-time and given an initial velocity there, then its subsequent trajectory will be independent of its internal structure and composition



WEP and GR

- The two different definitions of mass (i.e. inertial, gravitational) are equivalent;
  - bodies of different constitution feel the same acceleration.
- in classical physics, it is not entirely clear why this is the case. Early experiments were already performed by Galileo, Newton, Bessel; much more accurate ones between1906-1909 by Eötvös
- in GR, gravity is explained geometrically: matter deforms space and time and all bodies are following the straightest lines in this distorted geometry
  - ‣ no need for different mass-definitions like Newton:
    - (a) force acting on a body depends on its gravitational mass
    - (b) but the reaction on this force depends on the body’s inertial mass
- in GR, all bodies feel the same acceleration because their motion is determined by the very same space-time around them



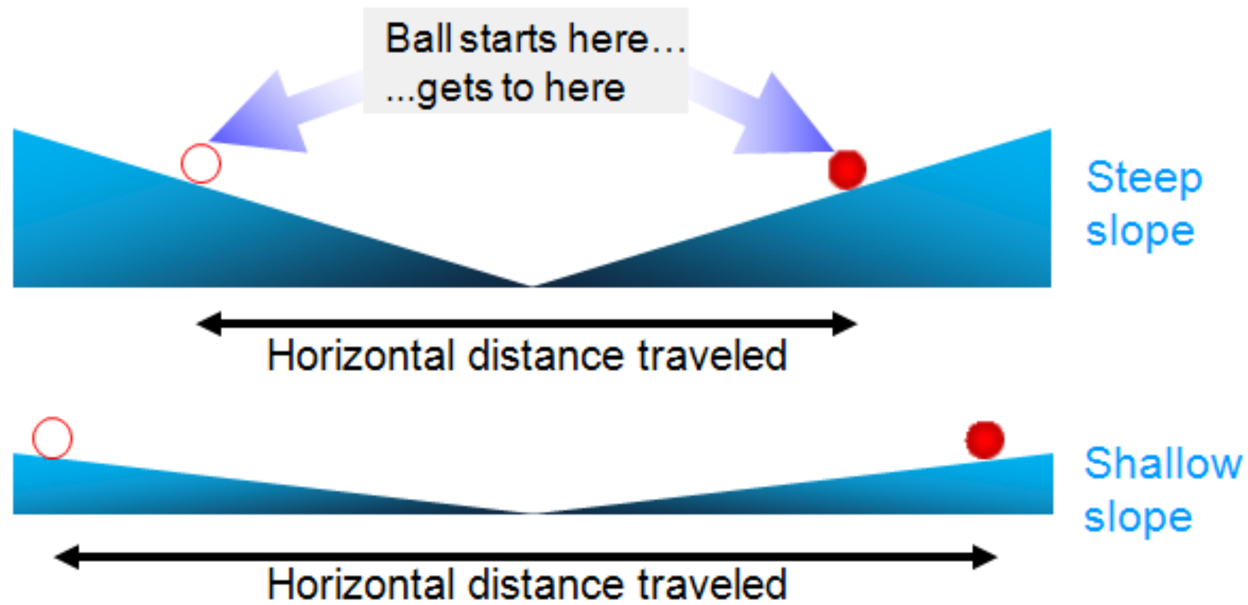
Classical WEP tests

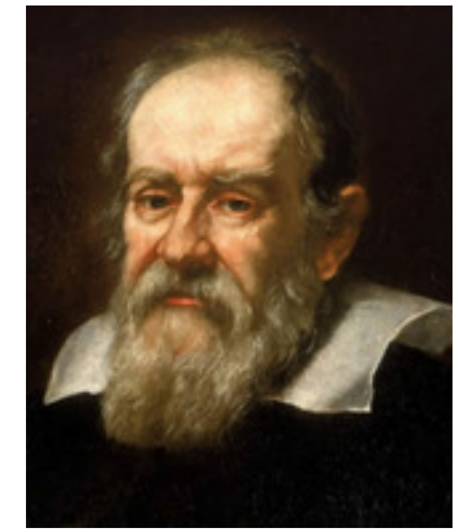
- Measure differential acceleration of two bodies with different composition
- Equivalent to test the equivalence of gravitational and inertial mass
- Null test: much higher precision than red shift measurements
- Experimental precision expressed in terms of the Eötvös-parameter

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

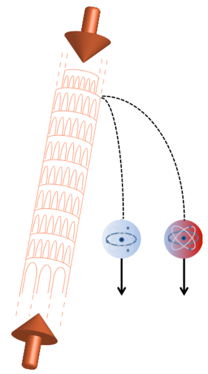
- Free fall experiments on Earth
- Torsion balances
- Astronomical observations
- Free fall experiments in microgravity

Free fall experiments

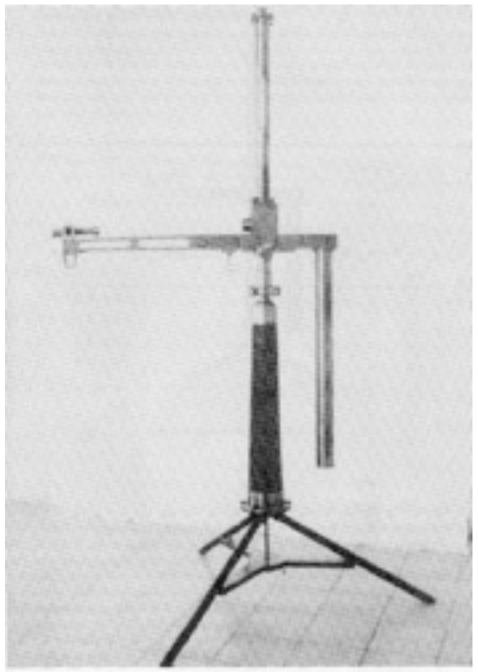


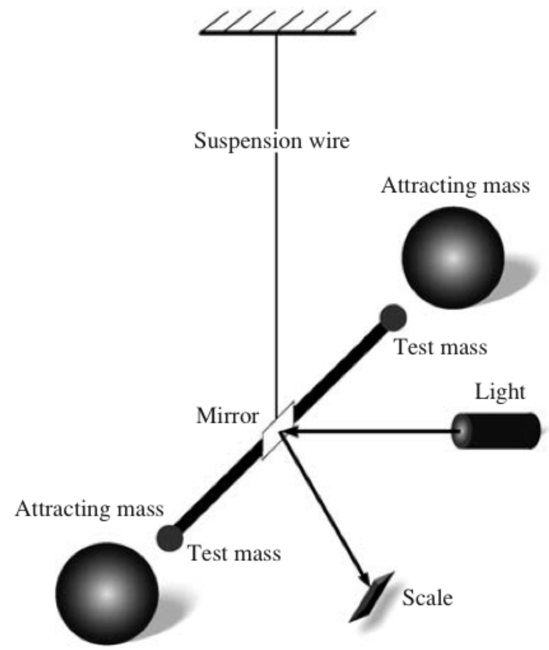


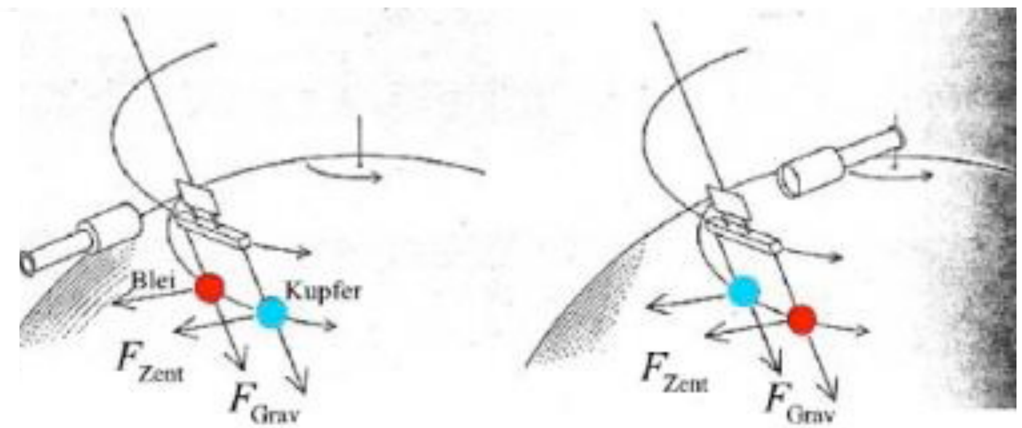
- First demonstration of UFF by Galileo, using both simple pendula and inclined planes
- Free fall experiments on Earth limited by the control of release velocity, and limited free fall time

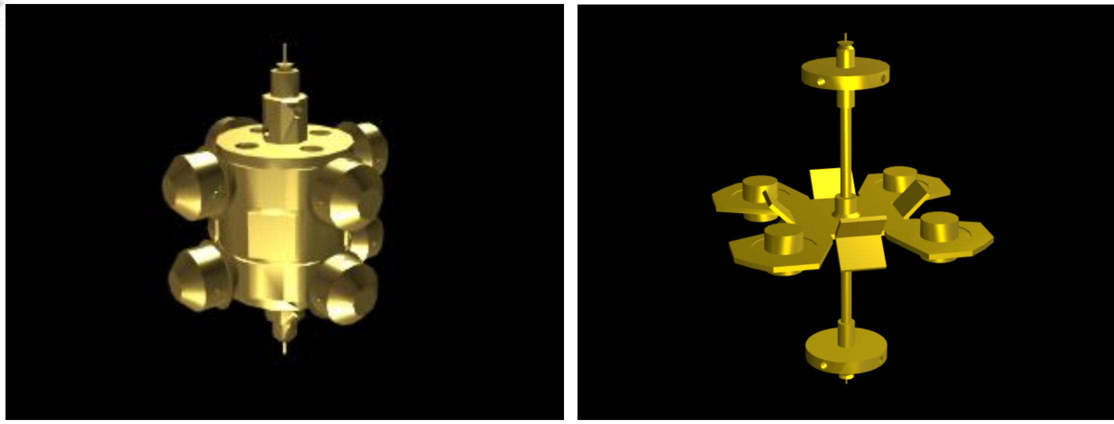


Torsion balances

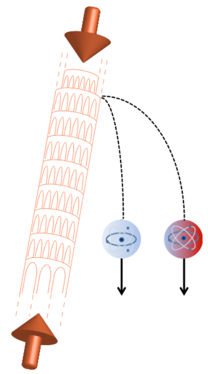






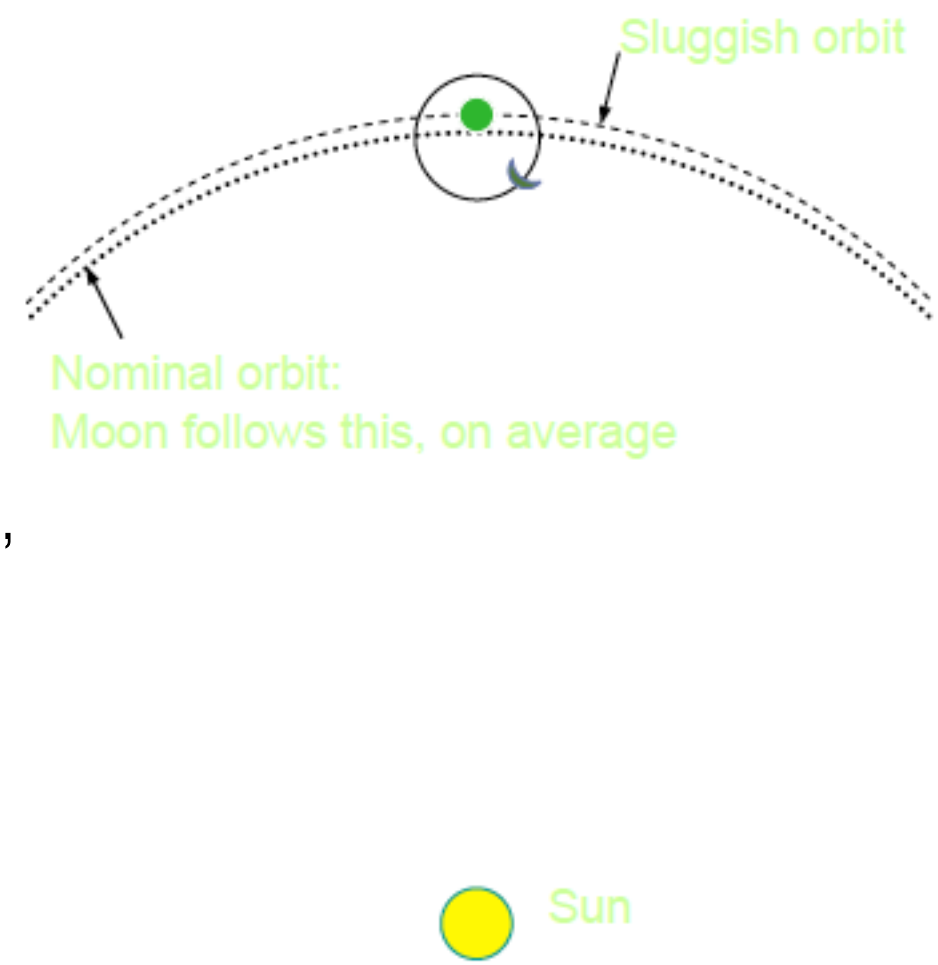


- two test-masses of different composition with equal weight -> equal gravitational mass
- a net torque will show up if the equivalence principle is violated
- original experiment by Eötvös in early 19th century reached 10^{-9} precision on Eötvös parameter
- refined versions improved over one century up to 10^{-13} precision
- limited by noise and biases from suspension and gravity gradient

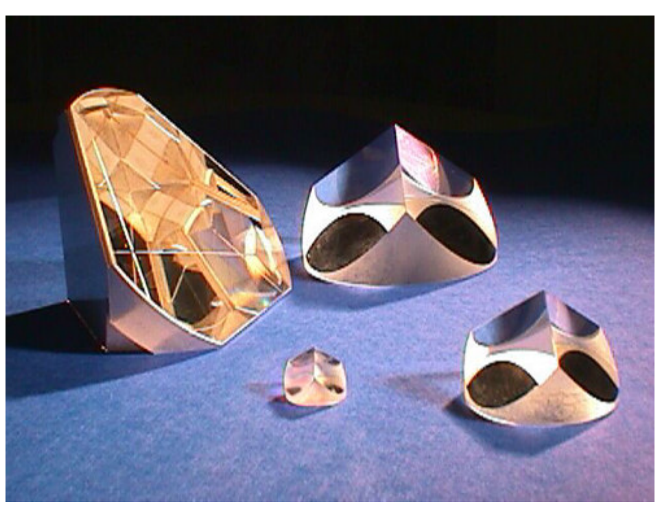


LLR

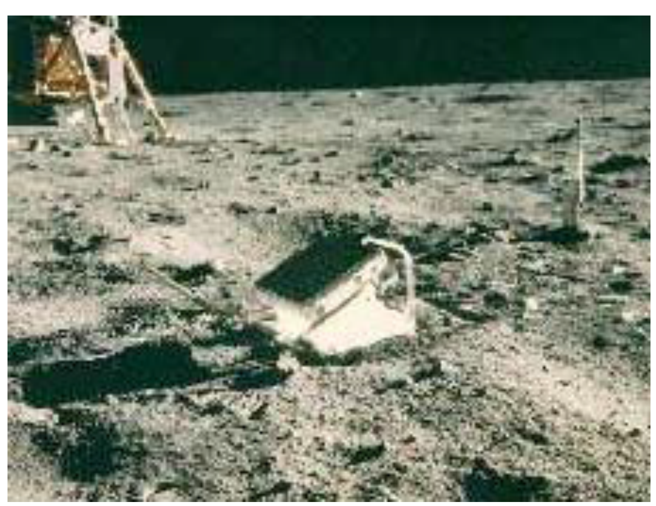
- Differential acceleration of Earth and moon
- Monitor the Earth-Moon distance with cm precision via laser ranging, using a set of corner-cube retroreflectors installed on Moon's surface



ground observatory

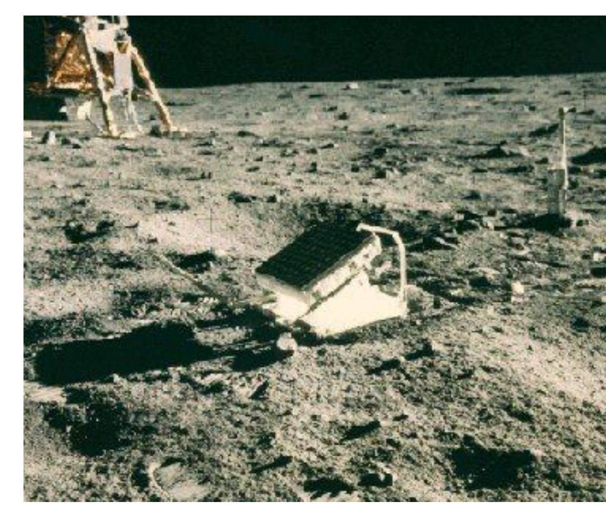


corner cubes

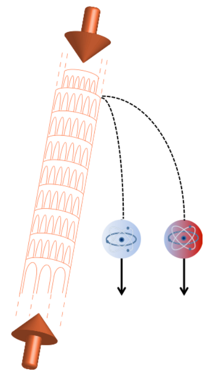


Apollo 11 retroreflectors

Apollo 14 retroreflectors



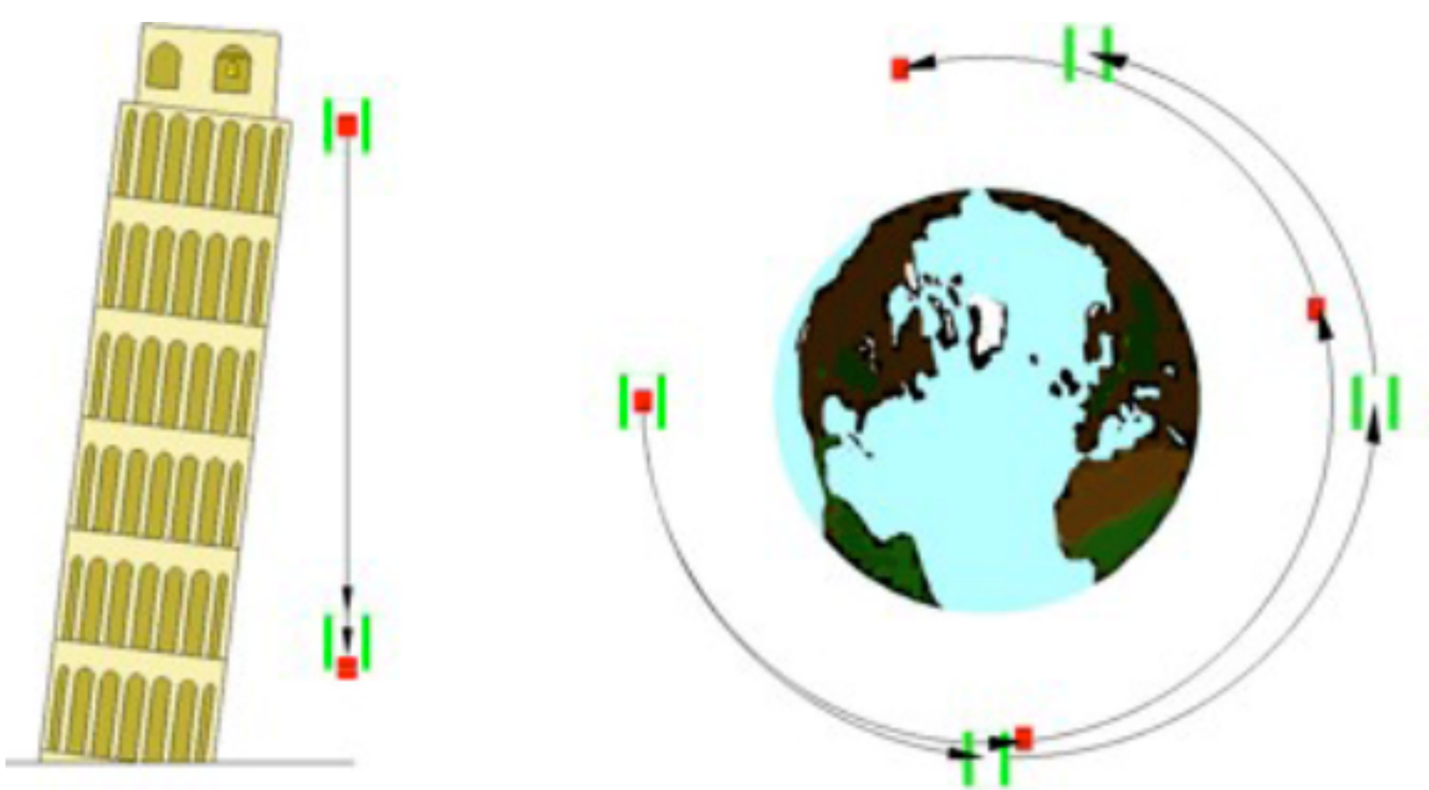
Apollo 15 retroreflectors

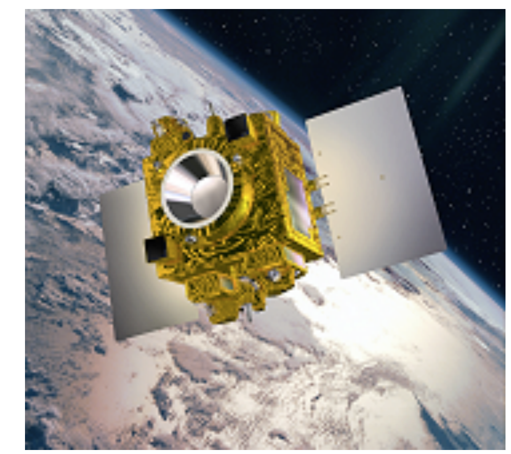


WEP tests in microgravity

- MICROSCOPE (CNES), now flying: target 10^{-15}
- GG proposal (ASI): target 10^{-17}

MICRO-Satellite a traînee Compensee pour l'Observation du Principe d'Equivalence





CHARACTERISTICS

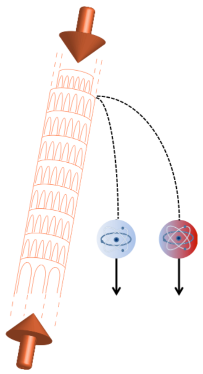
Micro-satellite of the CNES Myriade series equiped with field emission electric thrusters.

Instruments: Two differential accelerometers.

Equivalence Principle Test

Sun synchronous polar orbit at 700 km

Lifetime 1 year



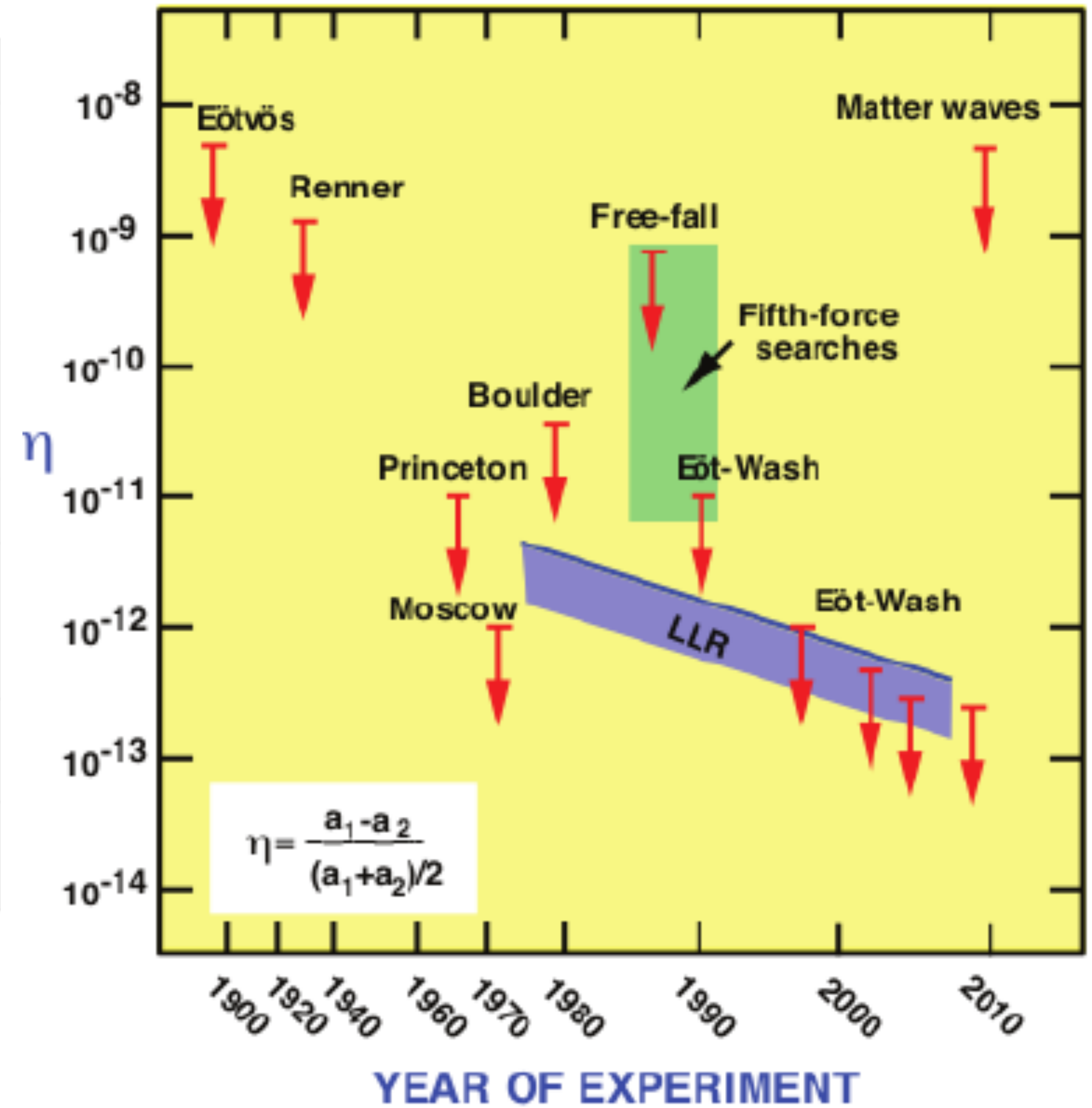
State of the art

36 yr

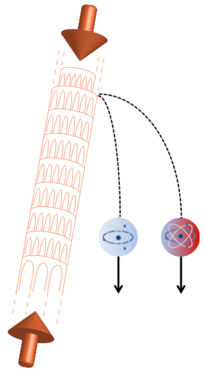
14 yr

Authors	Apparatus	Source mass	Materials	$\eta \equiv \Delta a / a$
Eötvös et al. ≈1900 collected in Ann. Phys. 1922	Torsion balance. Not rotating. No signal modulation	Earth	Many combinations	$10^{-8} \div 10^{-9}$
Roll, Krotkov & Dicke Ann. Phys. 1964	Torsion balance. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Au	$(1.3 \pm 1) \times 10^{-11}$
Braginsky & Panov JETP 1972	Torsion balance. 8TMs. Not rotating. 24hr modulation by Earth rotation	Sun	Al – Pt	$(-0.3 \pm 0.9) \times 10^{-12}$
E. Fischbach et al.: "Reanalysis of the Eötvös Experiment" PRL 1986				
Eöt-Wash, PRD 1994	Rotating torsion balance. ≈ 1hr modulation	Earth	Be – Cu	$(-1.9 \pm 2.5) \times 10^{-12}$
			Be – Al	$(-0.2 \pm 2.8) \times 10^{-12}$
Eöt-Wash, PRL 1999	Rotating torsion balance. 1hr to 36' modulation	Sun	Earthlike/ Moonlike	$\approx 10^{-12}$ (SEP 1.3×10^{-3})
Eöt-Wash, PRL 2008	Rotating torsion balance. 20' modulation	Earth	Be – Ti	$(0.3 \pm 1.8) \times 10^{-13}$

from A. Nobili

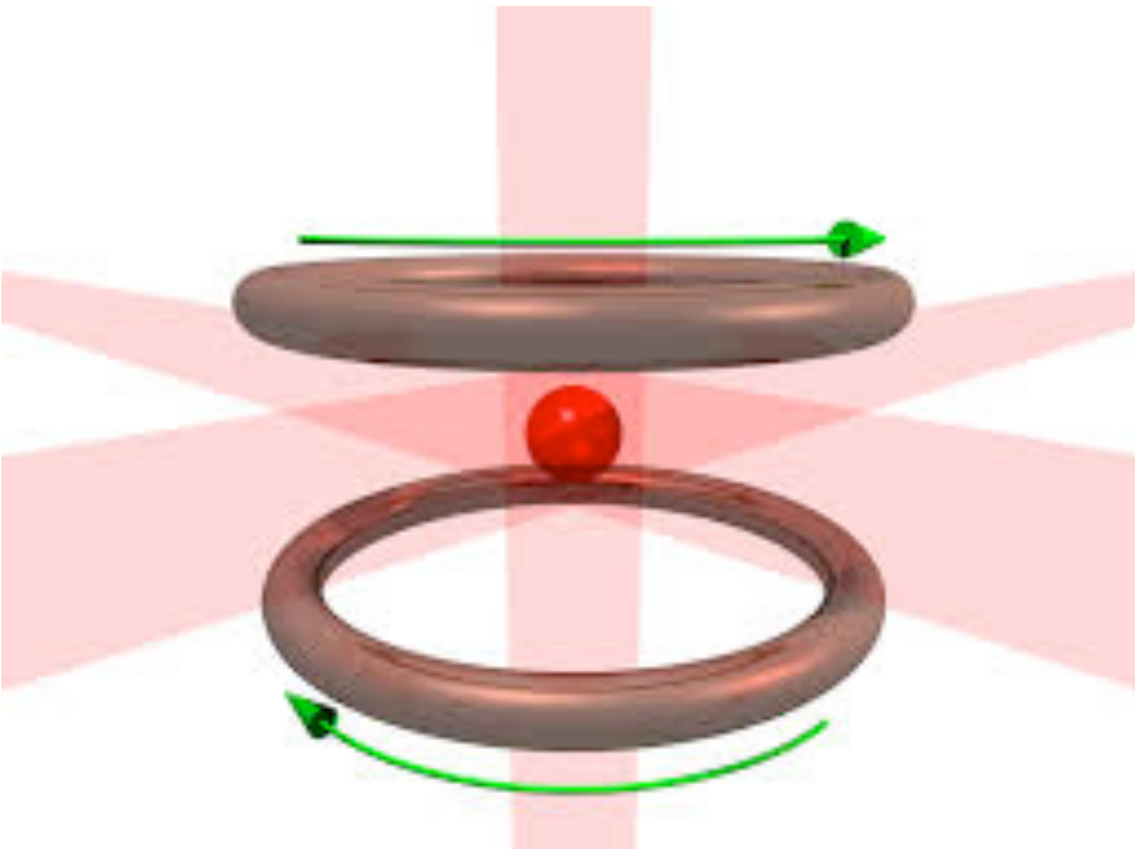


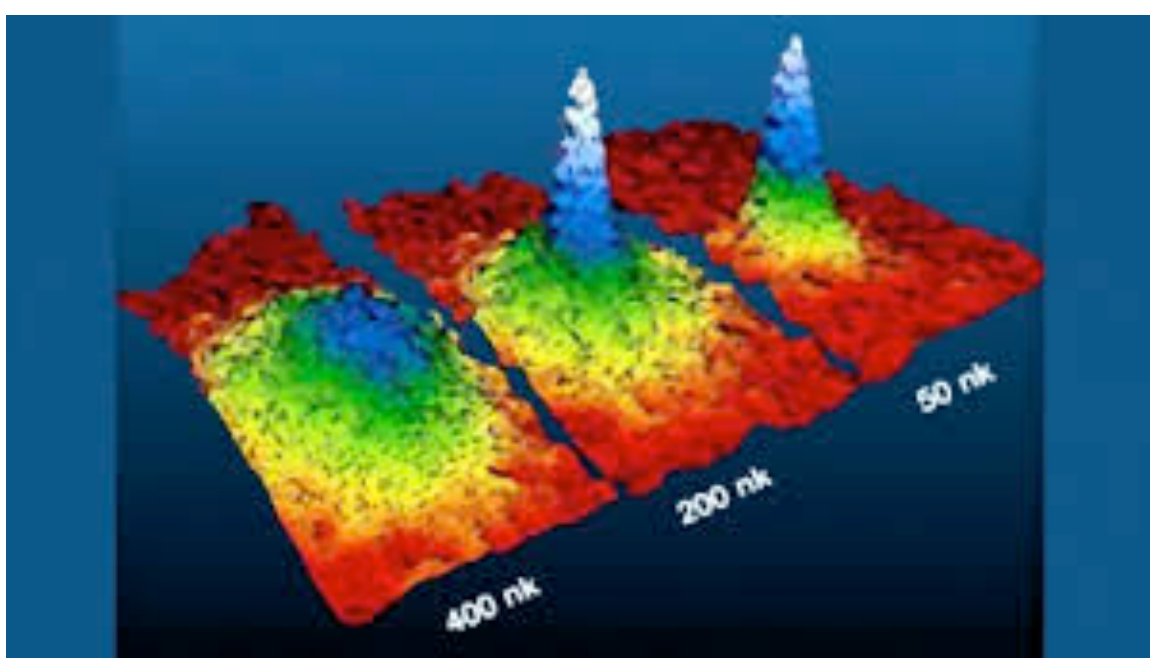
from Will 2014



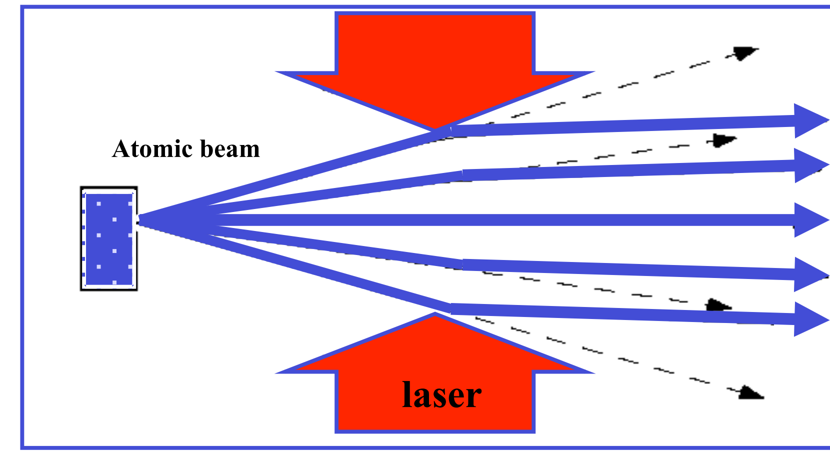
Atomic quantum sensors

Atom optics

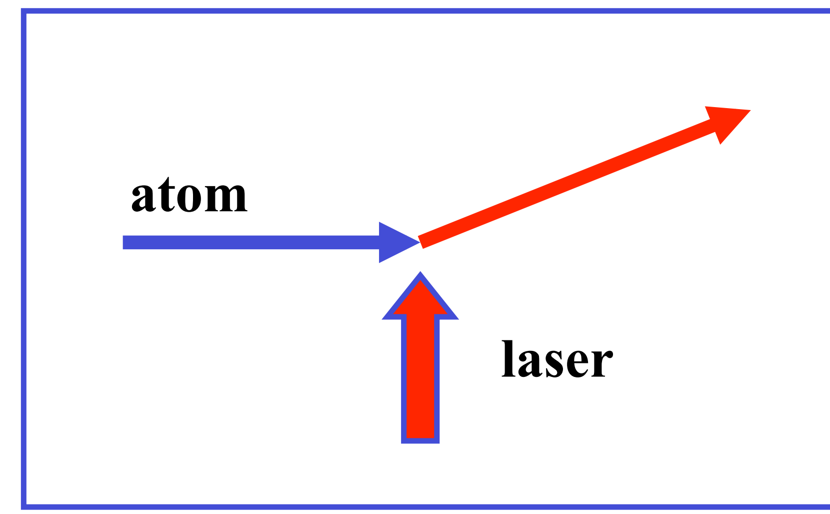




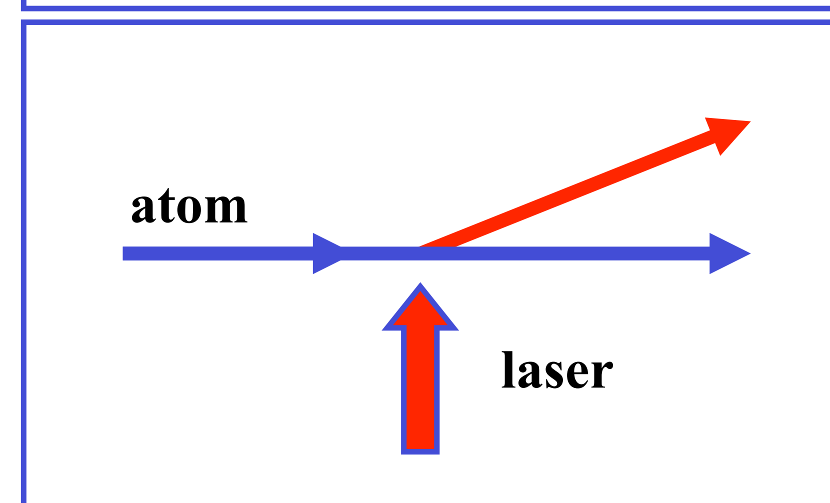
Lenses



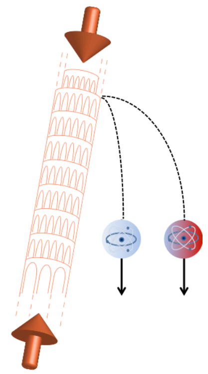
Mirrors

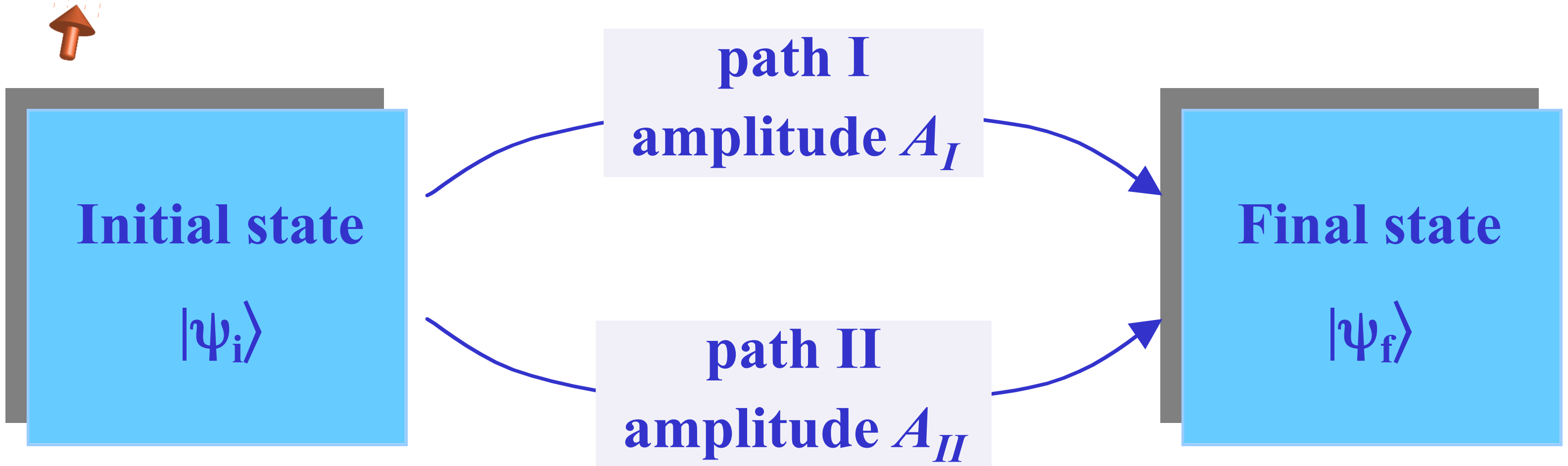


Beam splitters

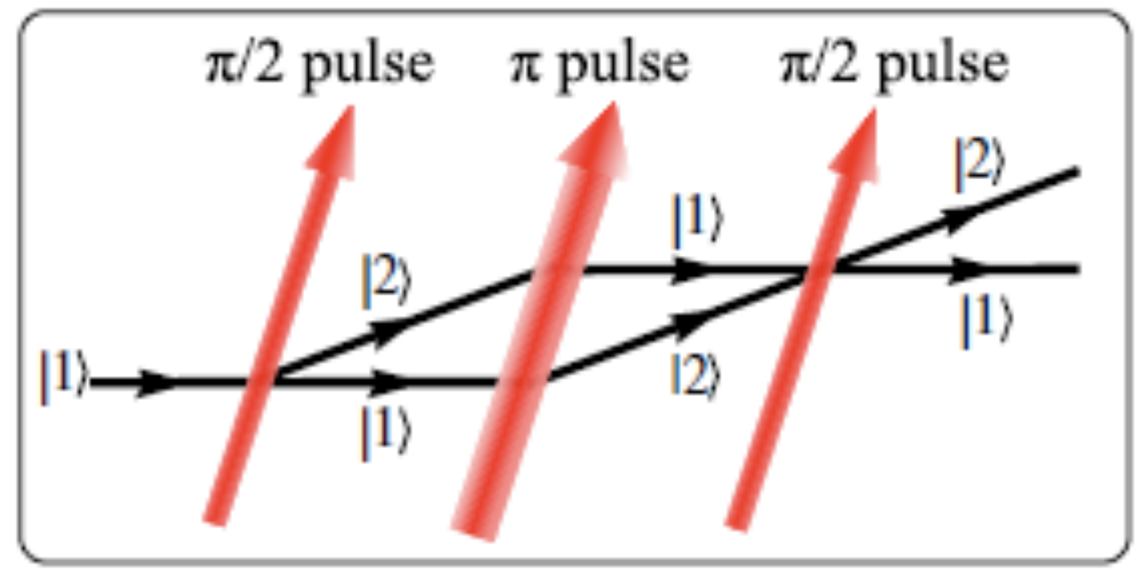


Atom interferometry

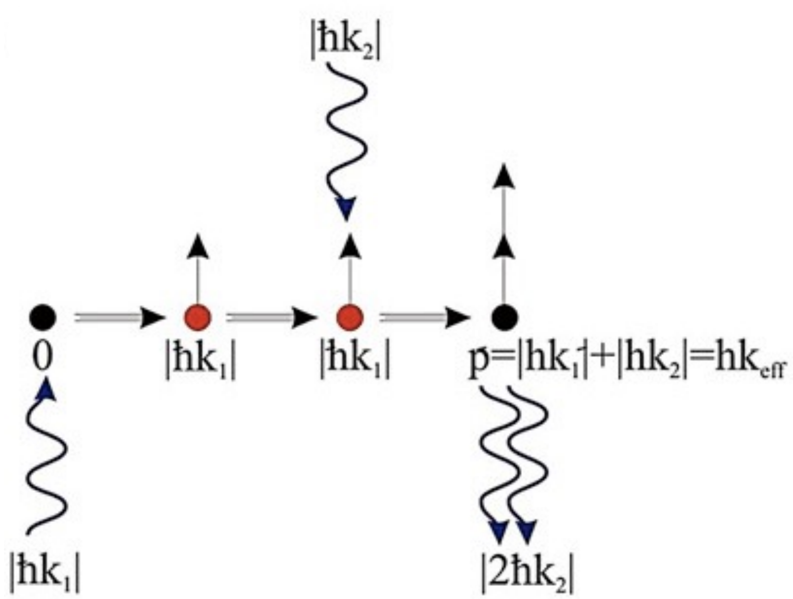


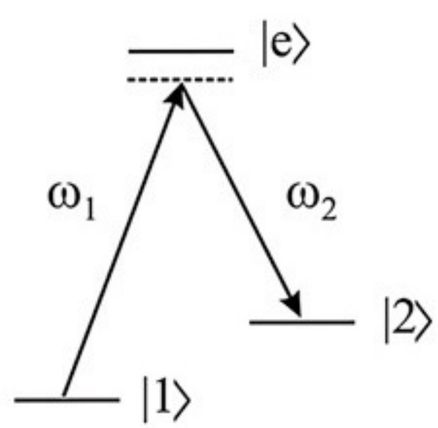


Interference of de Broglie amplitudes

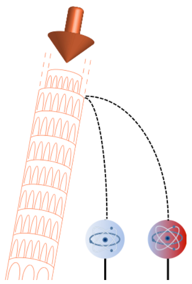


Light-pulse beam splitters + fluorescence detection

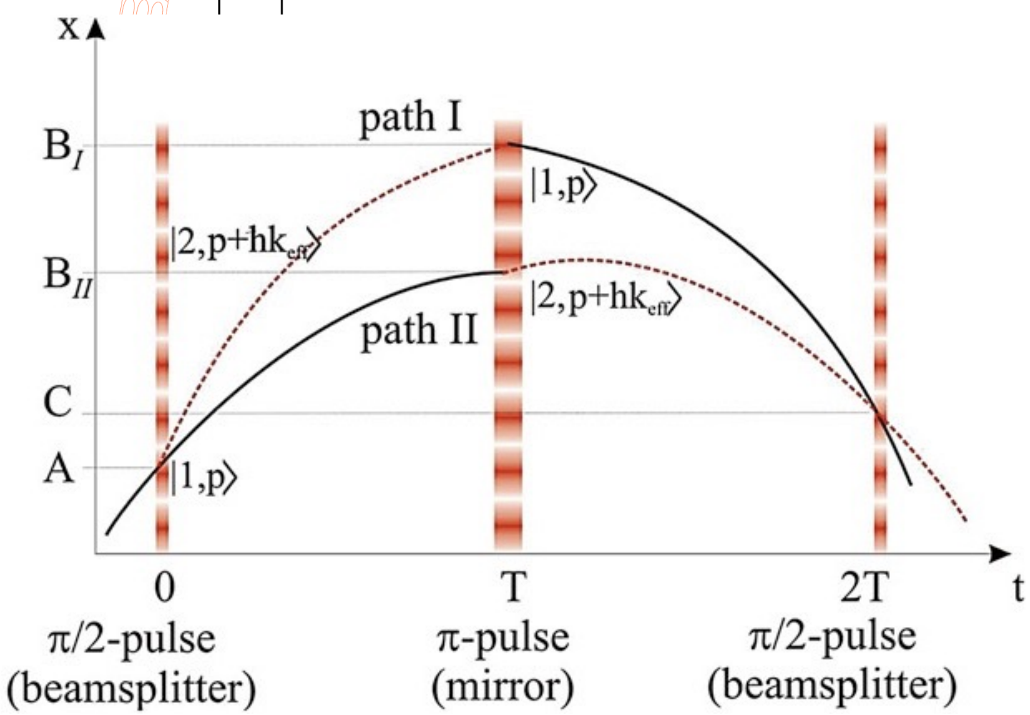




Output phase selectively sensitive to different effects (inertial, gravitational, external fields, laser phase/frequency, etc) via choice of quantum states



Quantum noise



Phase difference between the paths:

$\Delta\Phi = k_e[z(0) - 2z(T) + z(1T)] + \Phi_e$

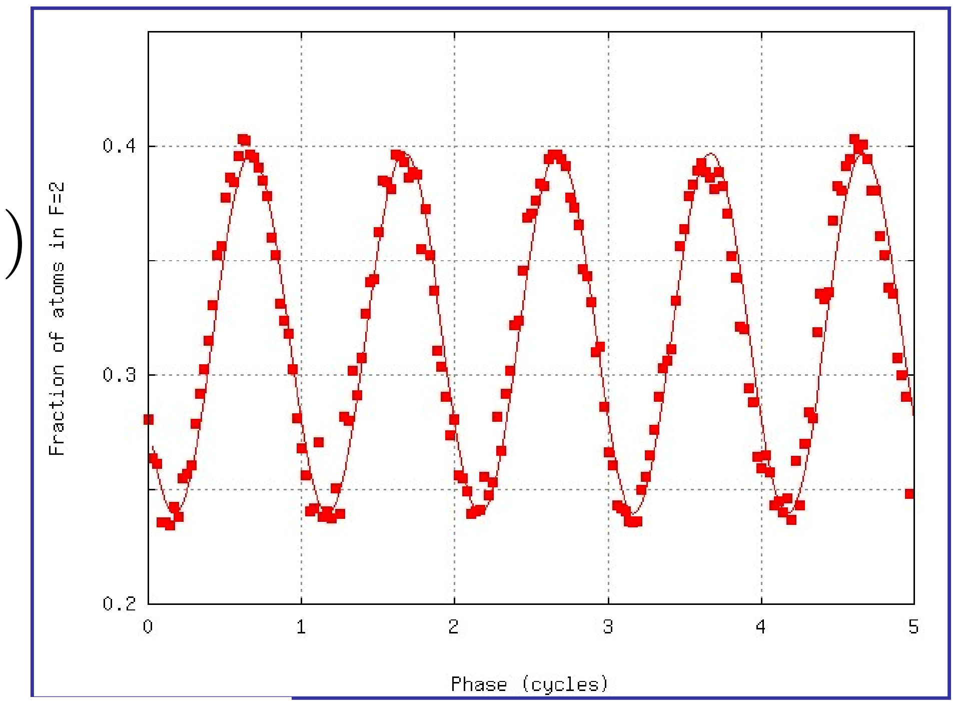
$k_e = k_1 - k_2$

with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

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

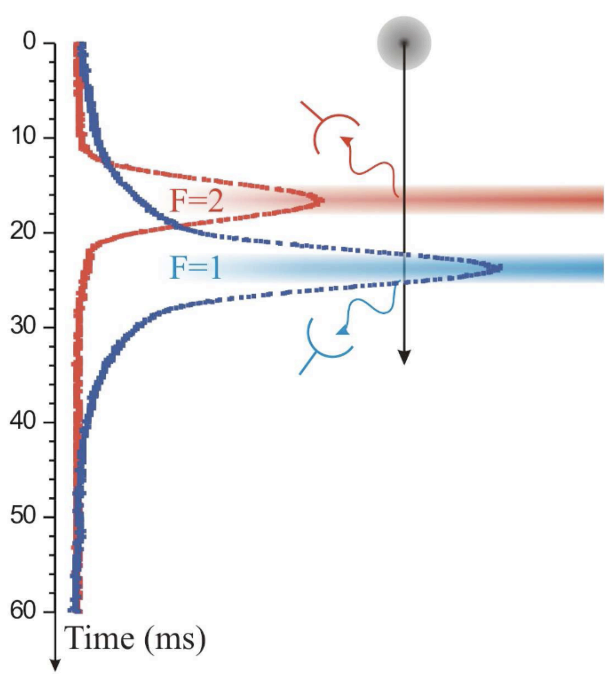
Final population:

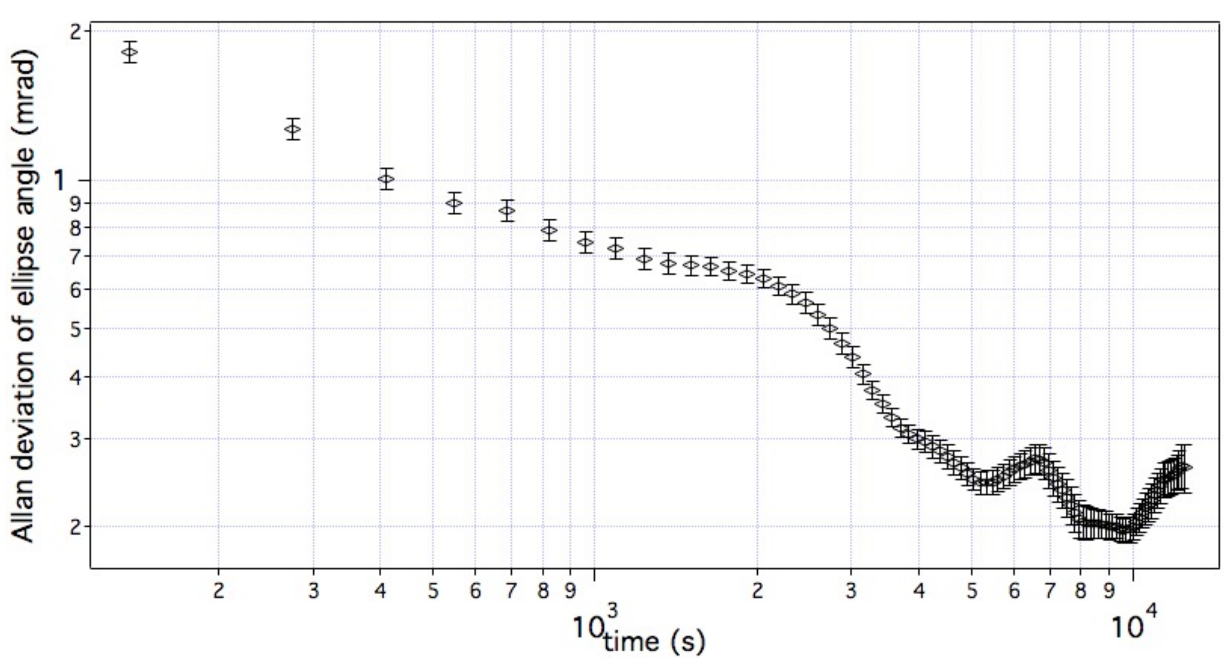
$N_a = N/2(1 + cos[\Delta\Phi])$



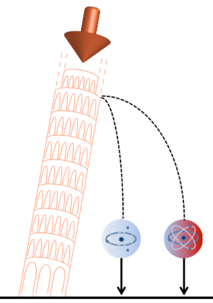
$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

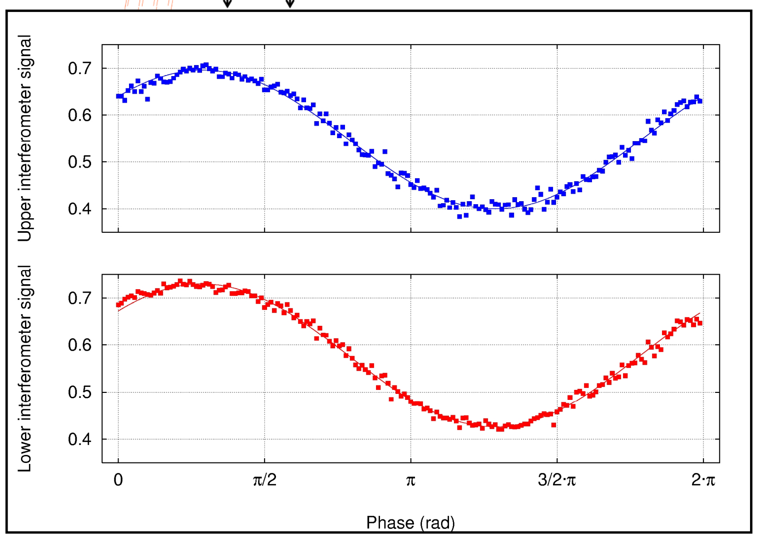
S/N=1000 $\rightarrow$ Sensitivity 10^{-9} g/shot



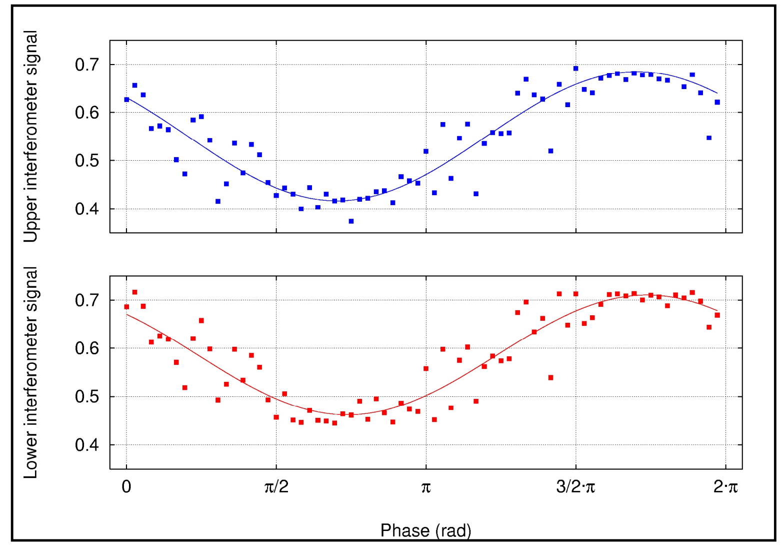


Acceleration noise

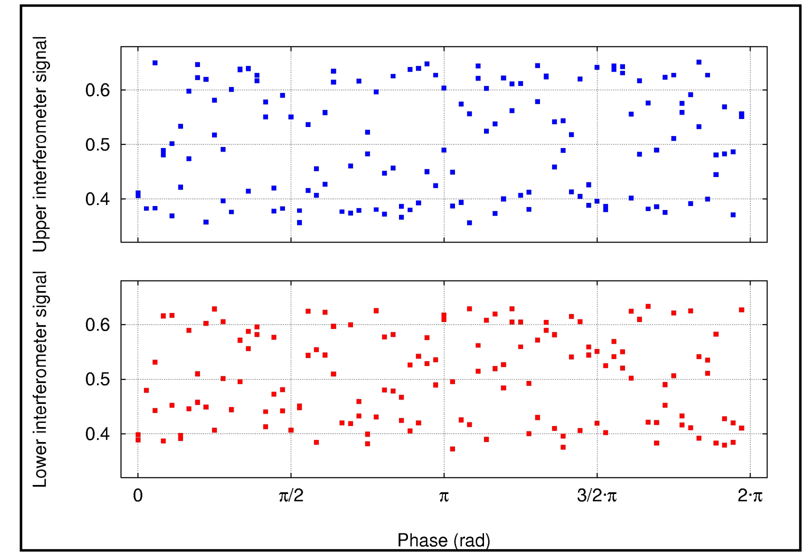




T=5 ms
resol. $= 2.3 \times 10^{-5}$g/shot

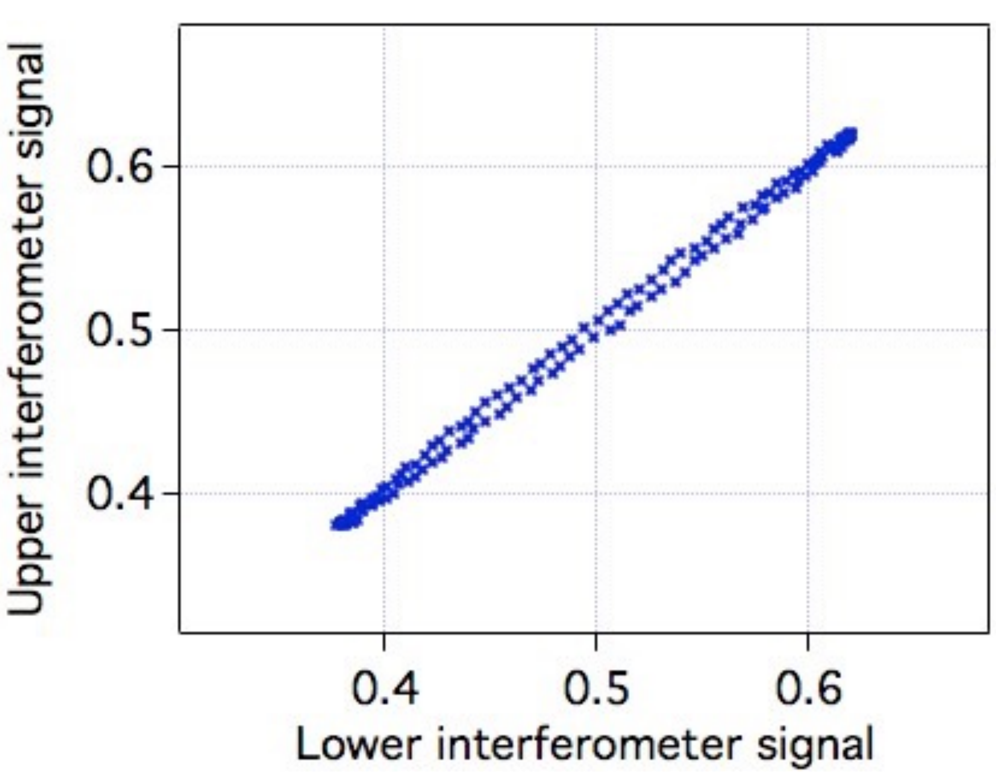


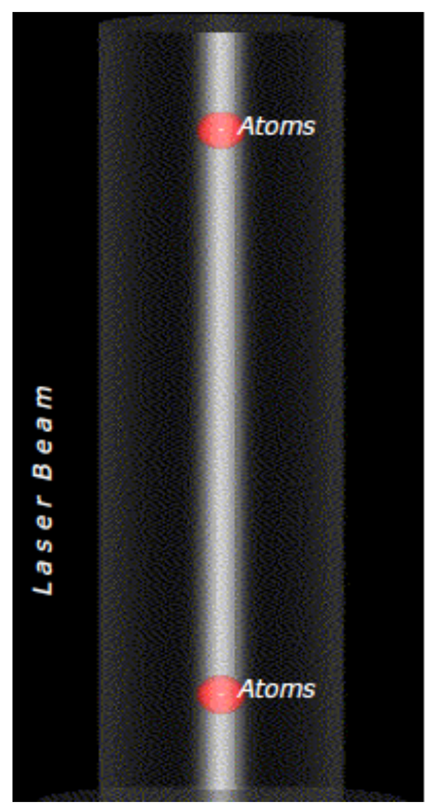
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot

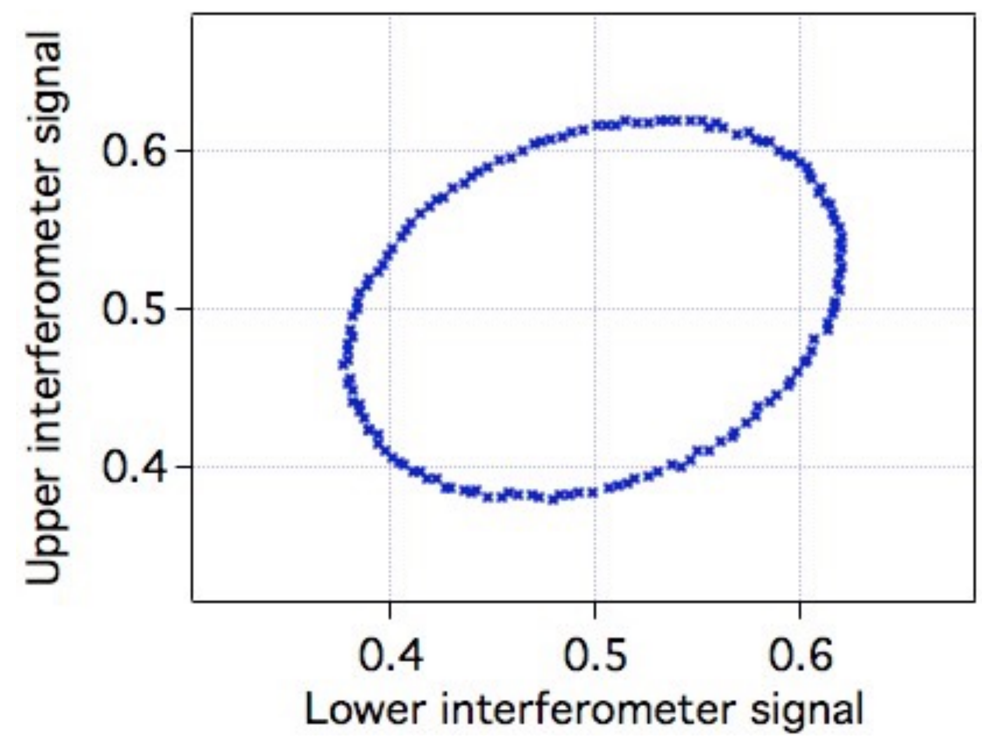


T=150 ms
resol. $= 3.2 \times 10^{-8}$g/shot

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



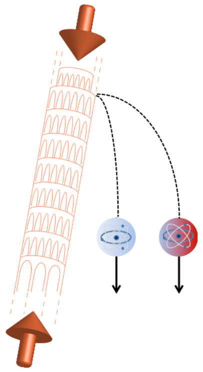




up to 140 dB CMRR with 1 m separation

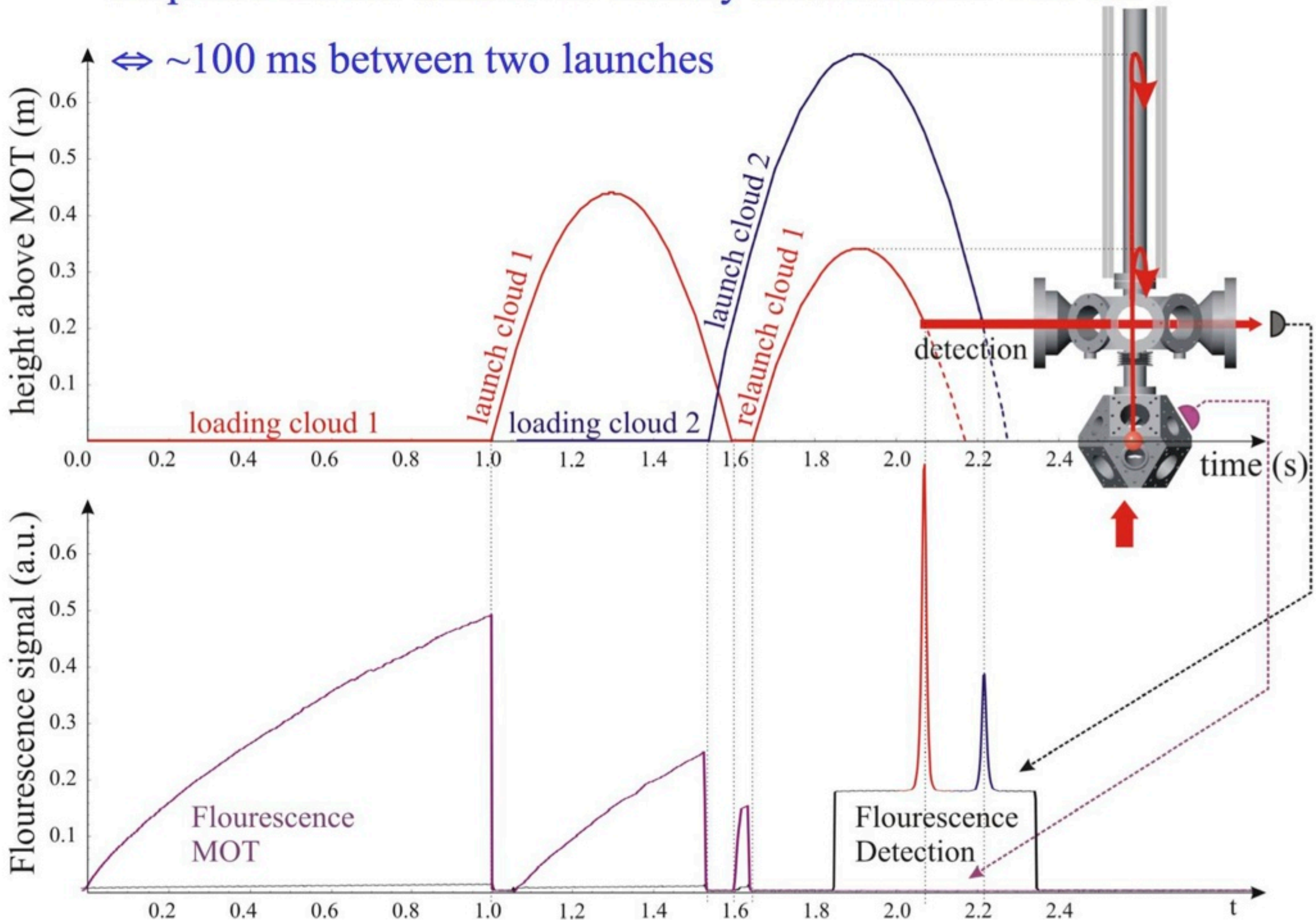
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

An AI gradiometer

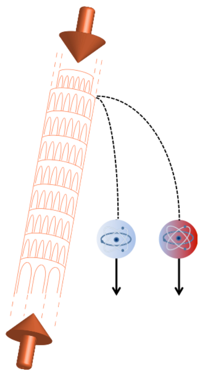


Goal: Prepare 2 clouds with same velocity at distance of ≈ 35 cm

⇔ ~100 ms between two launches



F. Sc

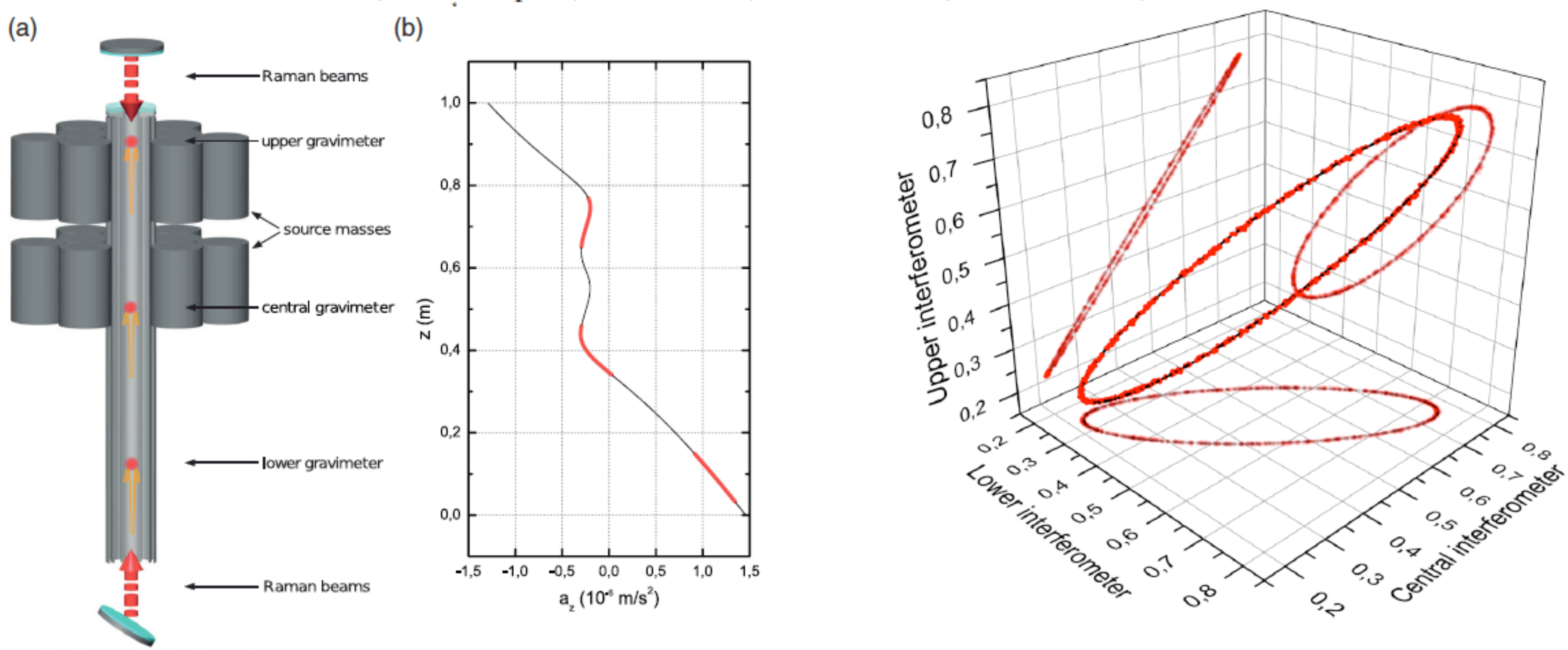


Multiple samples

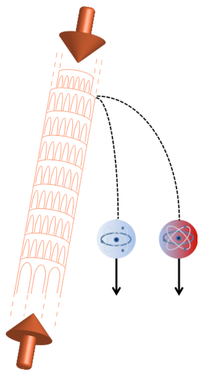
PRL 114, 013001 (2015) PHYSICAL REVIEW LETTERS week ending 9 JANUARY 2015

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,‡]

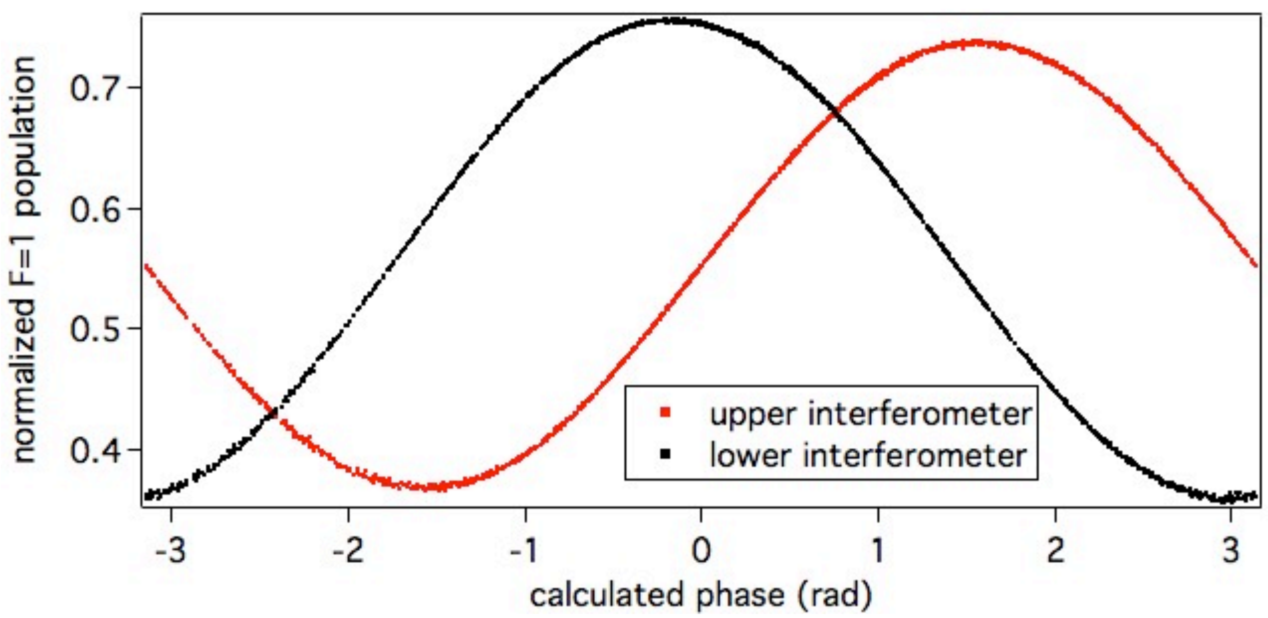


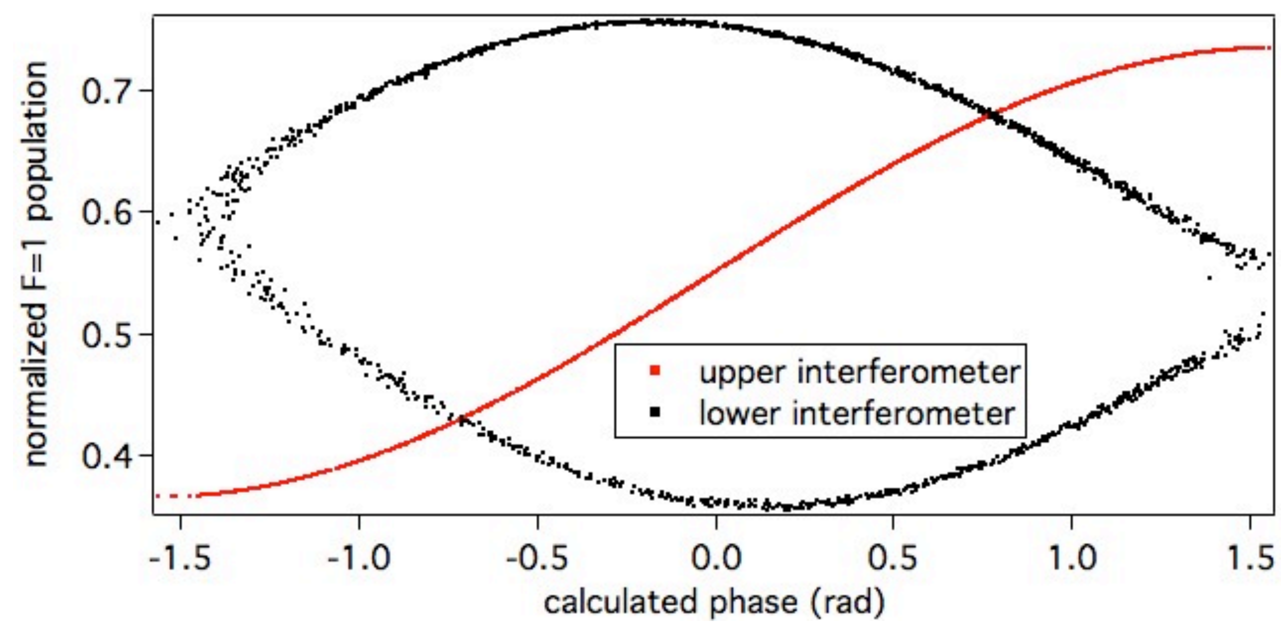
- Use three atomic clouds to measure the vertical derivative of vertical gravity gradient
  - *G. Rosi et al., Phys. Rev. Lett. 114, 013001 (2015)*
- Scalable to arbitrary large number of samples
- Simultaneous, correlated AI can improve g measurements as well
  - *F. Sorrentino et al., Appl. Phys. Lett. 101, 114104 (2012)*



g measure with 2 clouds

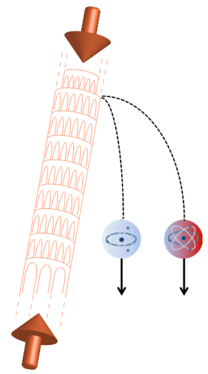
- Using a dual-cloud Raman interferometer for g measurements
- Simultaneous interferometers allow g measurements in the presence of larger phase noise because of
    - twice larger range for phase retrieval
    - suppressed conversion of amplitude noise into phase noise at the edges of the fringe





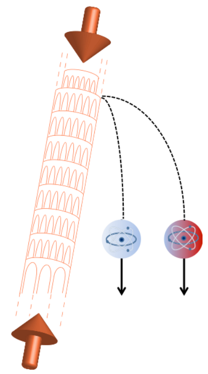
F. Sorrentino et al., Appl. Phys. Lett. **101**, 114104 (2012)

Somewhat similar to using a mechanical accelerometer to correct the phase shift from seismic noise, see J. Le Gouët et al., Appl. Phys B **92**, 133 (2008)



Examples

- **Measurement of fundamental constants**
  - G
  - fine structure
- **Inertial sensing** (acceleration, gravity gradient, rotations)
- **GR tests** (WEP, constraints on ppn parameters, gravito-magnetism, LLI)
- **Quantum gravity** (energy-momentum dispersion, short-range forces)
- Test of fundamental symmetries (e.g. atom neutrality)
- GW, DM, and more



G measurement

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International journal of science

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Letter

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino

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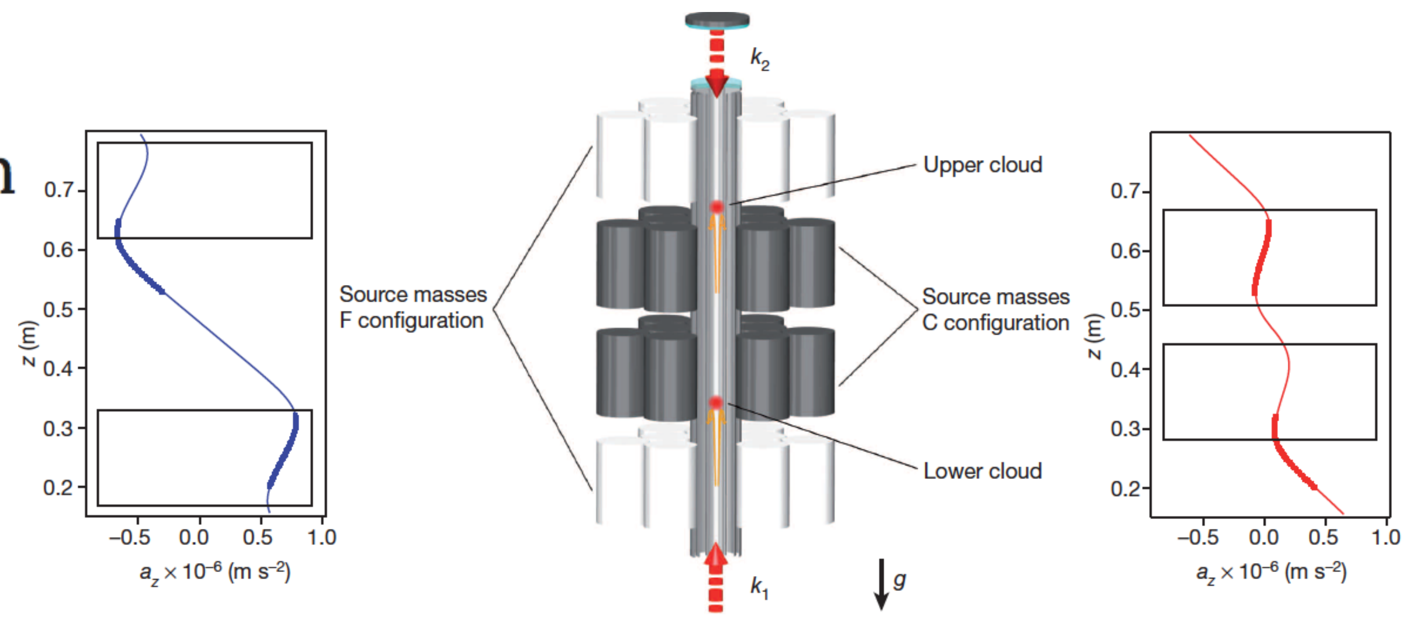
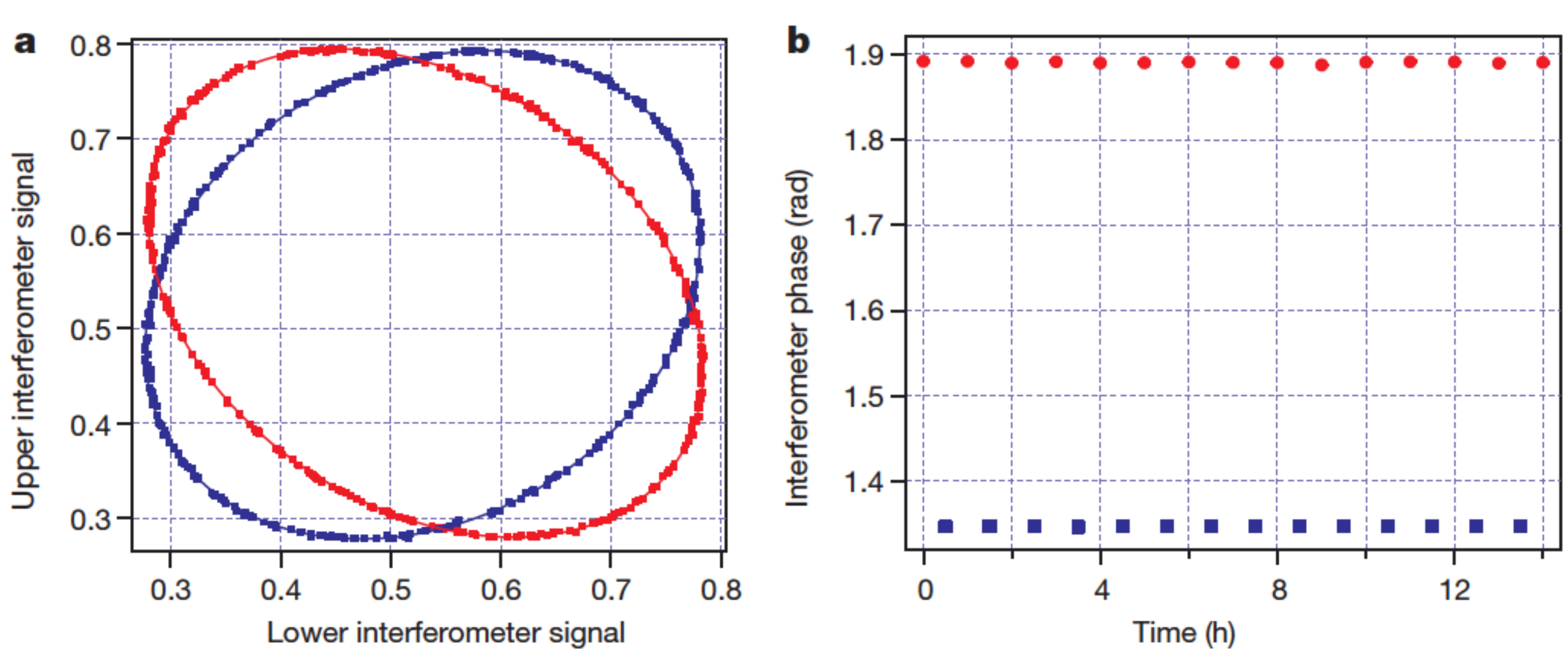
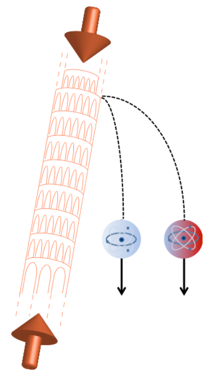
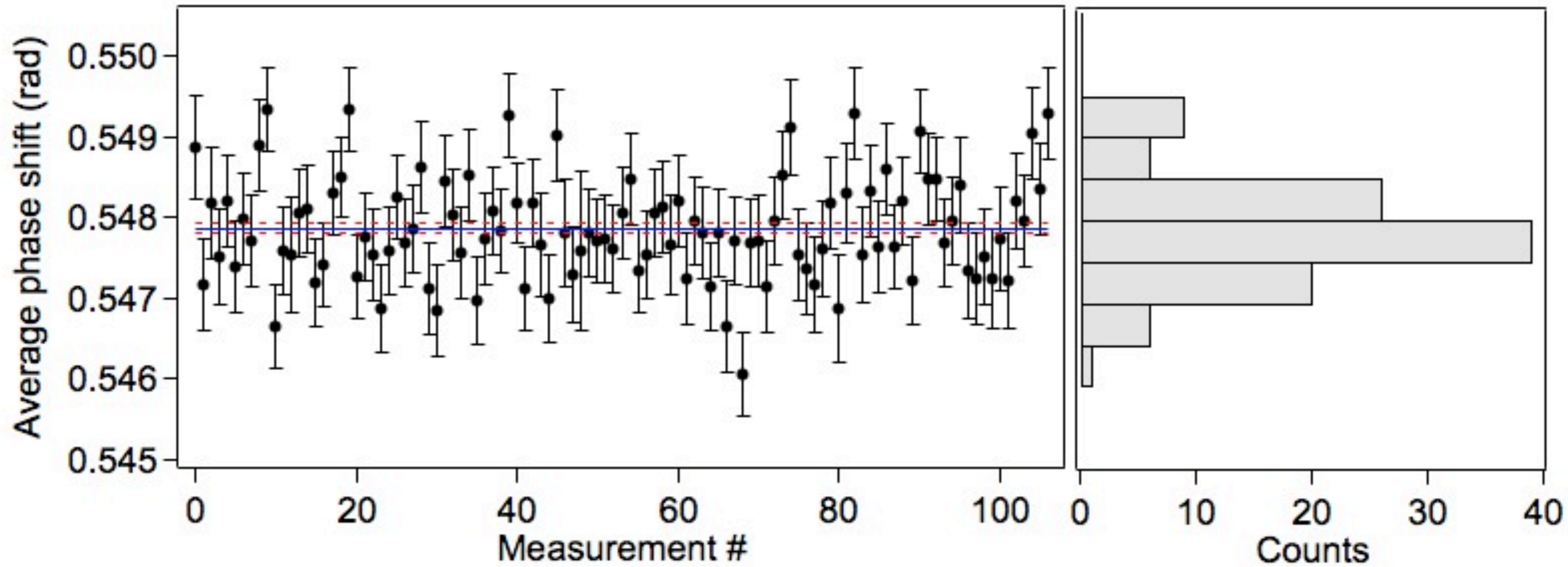


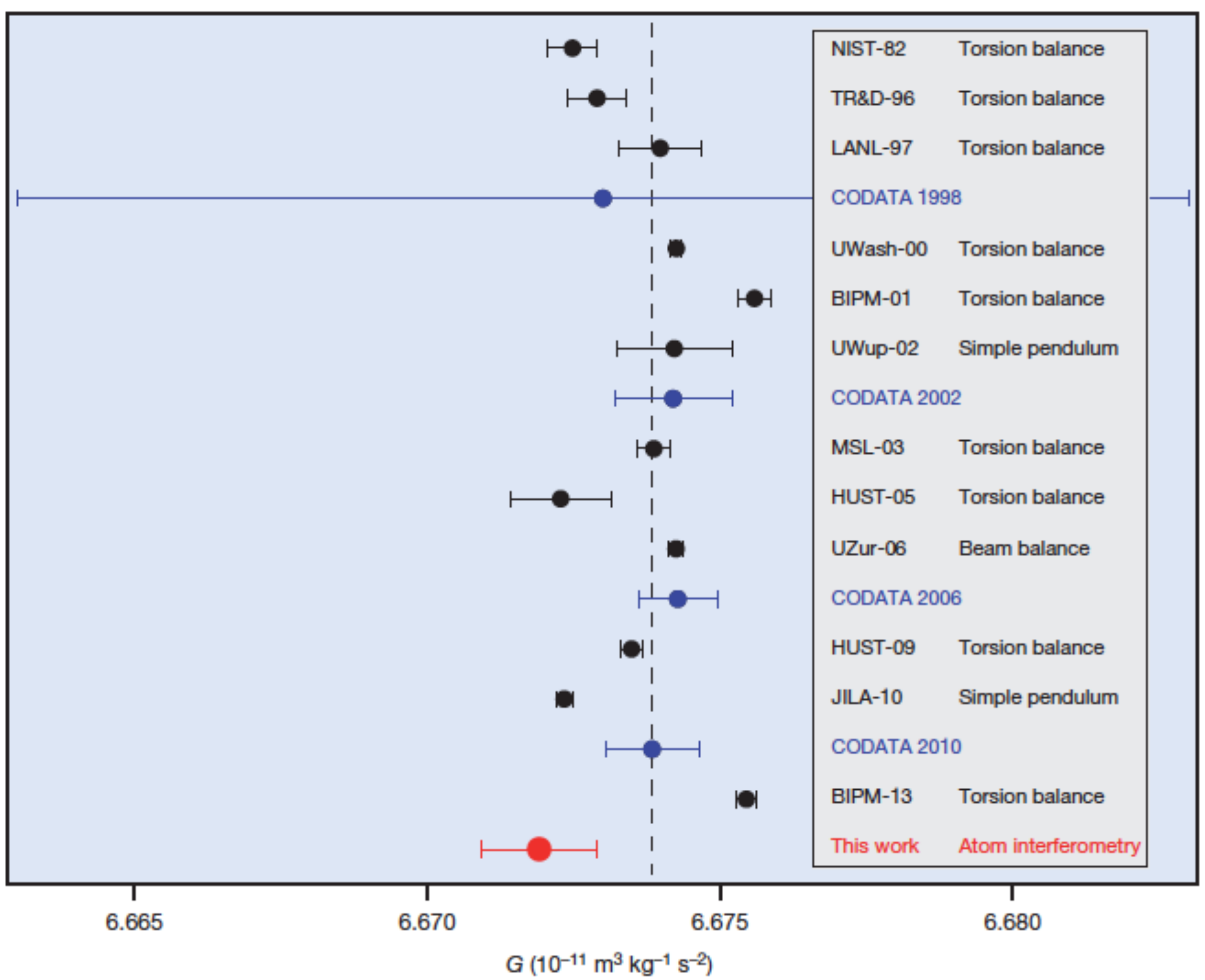


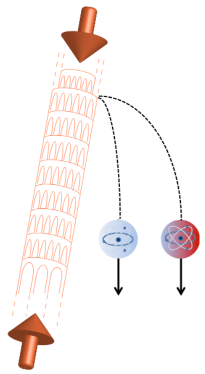
Testing the equivalence principle…



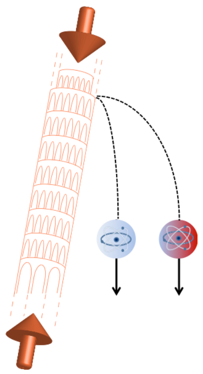
G measurement



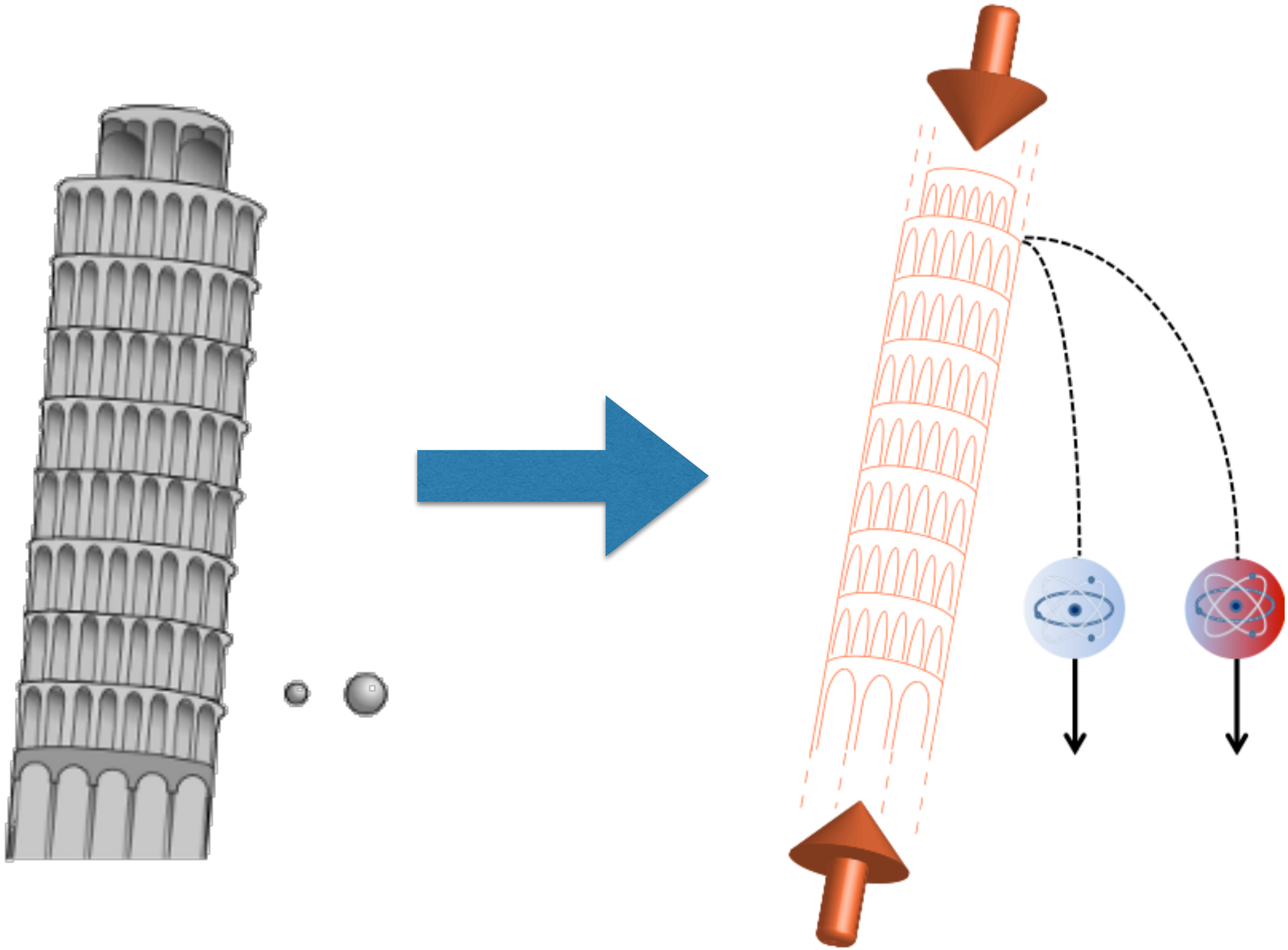


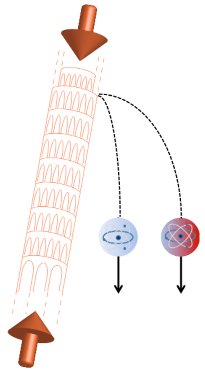


WEP tests with atomic probes



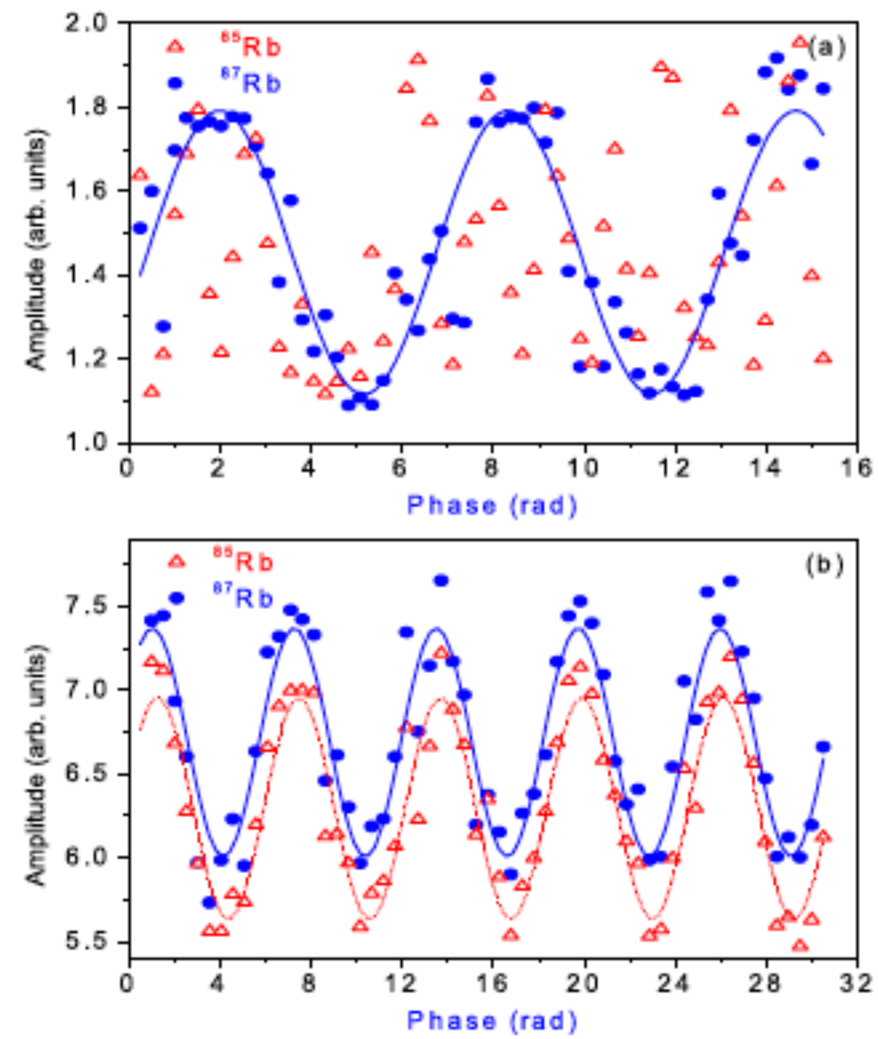
Free-fall experiments revisited

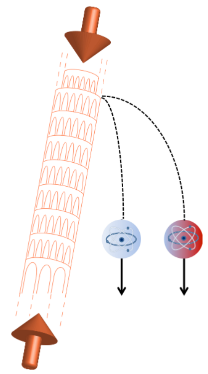




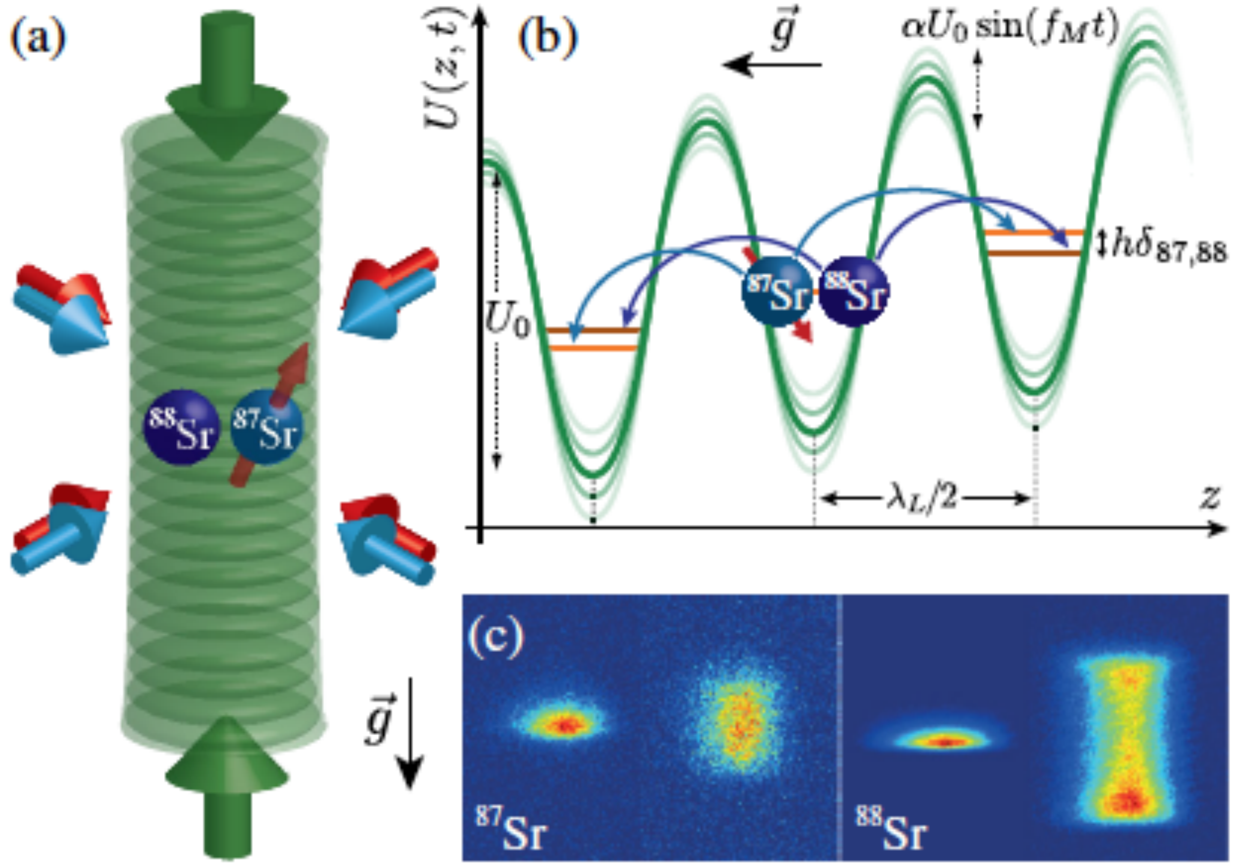
Different species/isotopes

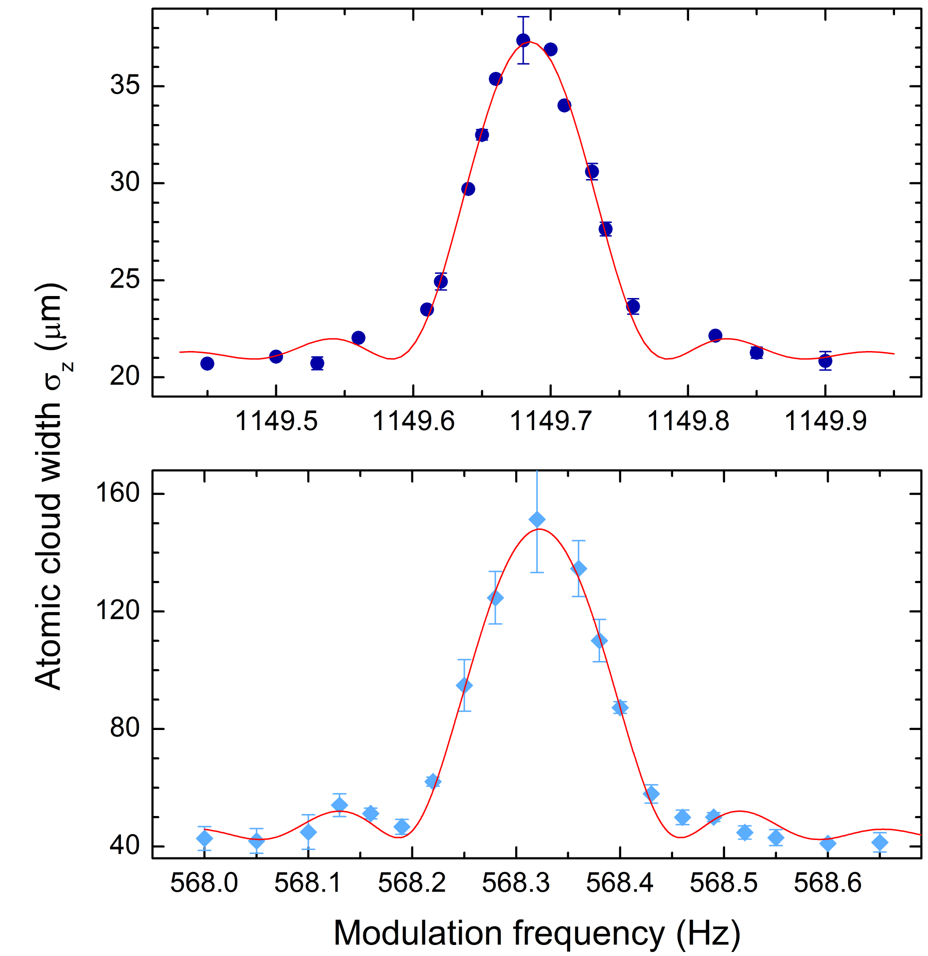
- Tests already achieved (at $10^{-7}\div10^{-8}$ level)
  - ^{87}Rb-^{85}Rb [*A. Bonnin et al., PRA 88, 043615 (2013)*]
  - K-Rb [*D. Schlippert et al., PRL 112, 203002 (2014)*]
  - ^{87}Sr-^{88}Sr [*M. G. Tarallo et al., PRL 113, 023005 (2014)*]
  - ^{87}Rb-^{85}Rb [*L. Zhou et al., PRL 115, 013004 (2015)*]
- Many other planned/ongoing





Search for spin-gravity couplings



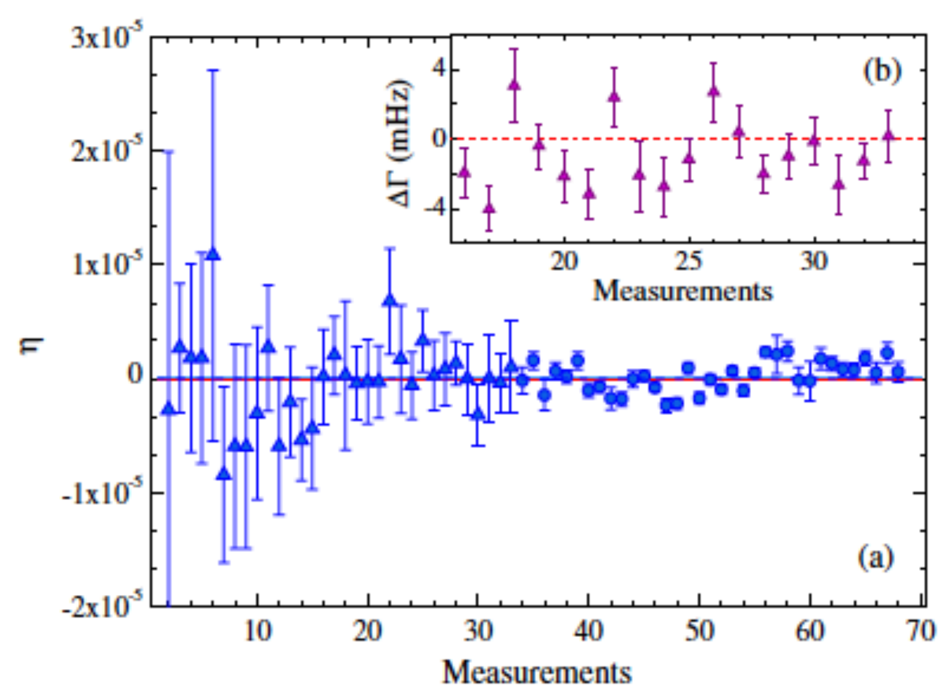


- differential gravimeter with Bloch oscillations
- Sr isotopes with different spin
- test possible spin-gravity coupling

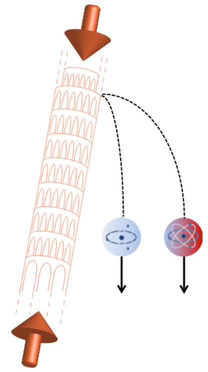
$$V_{g,A}(z) = (1 + \beta_A + kS_z)m_A gz$$

- measurement of the Eötvös ratio at the 10^{-7} level
- upper limit on spin-gravity coupling constant

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

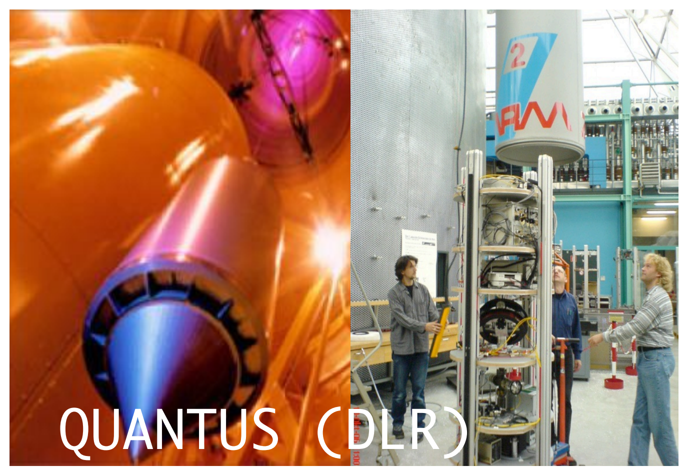


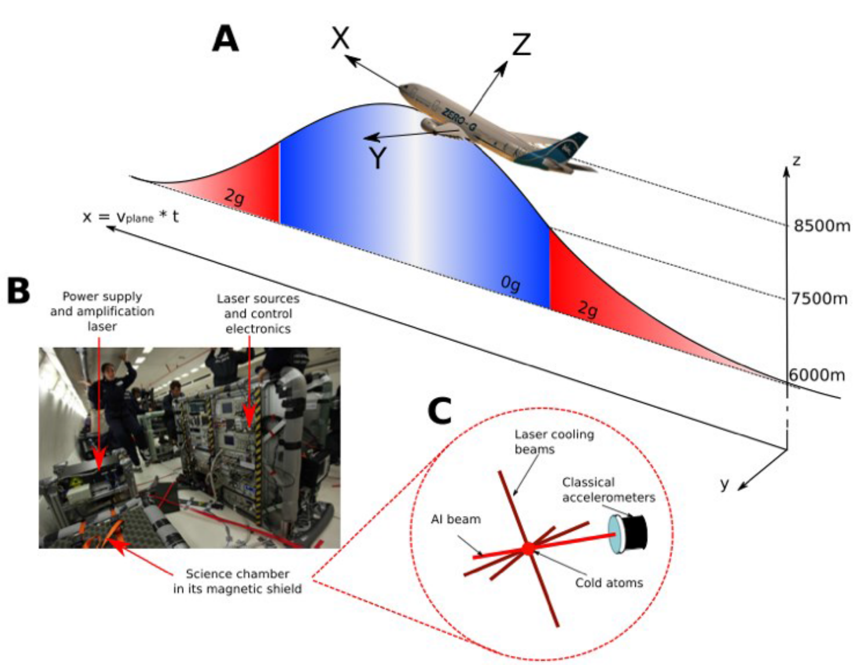
M. Tarallo et al., PRL 113, 023005-1 (2014)



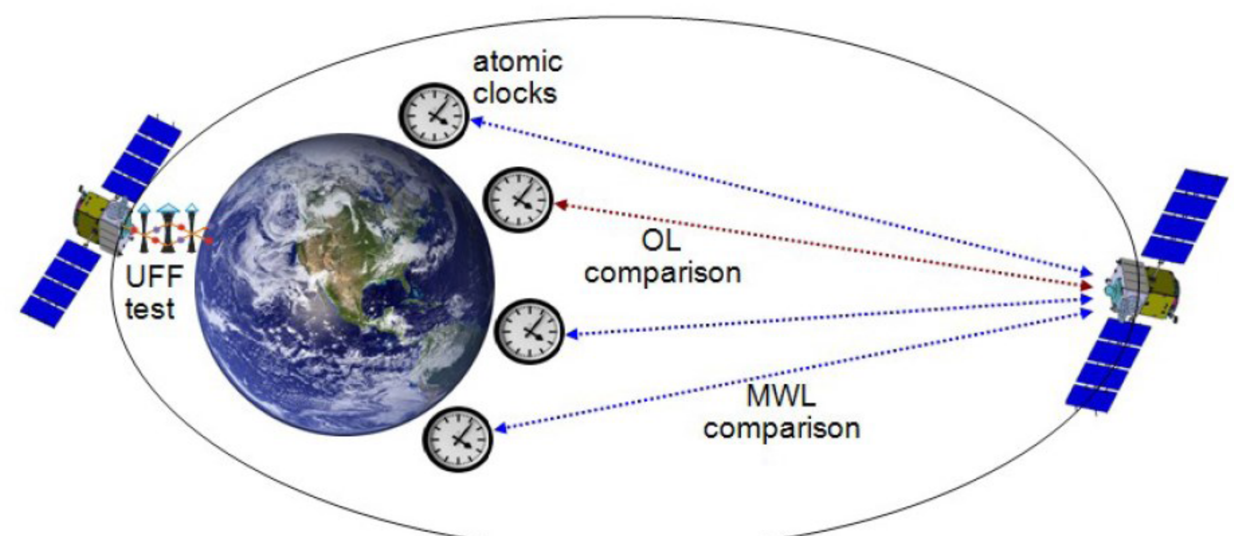
Tests in microgravity

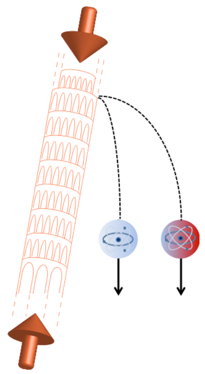
- Airborne: ICE (CNES)
- Sounding rocket: QUANTUS (DLR)



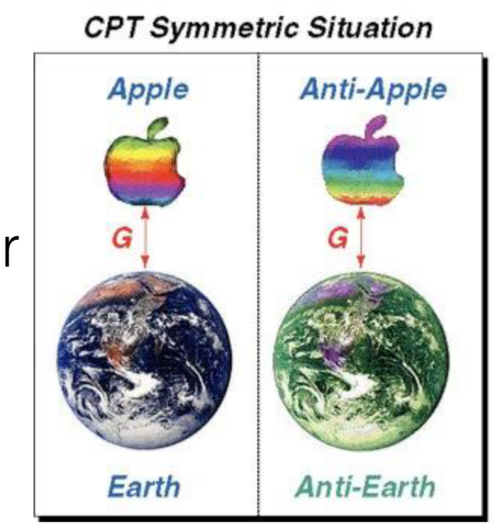


- STE-QUEST mission proposal
  - Primary Goal: UFF test and red shift measurement
  - Observables: Clock redshift measurements;
    - Differential acceleration measurements of freely falling atoms
  - Instruments:
    - A microwave clock based on laser cooled rubidium atoms;
    - A differential atom interferometer operating on the two rubidium isotopes;
    - Time and frequency transfer links in the microwave and optical domain for space-to-ground comparisons of clocks.
  - Orbit: Highly elliptical orbit around the Earth
  - Type: M-class mission





Tests with anti-matter: AEgIS

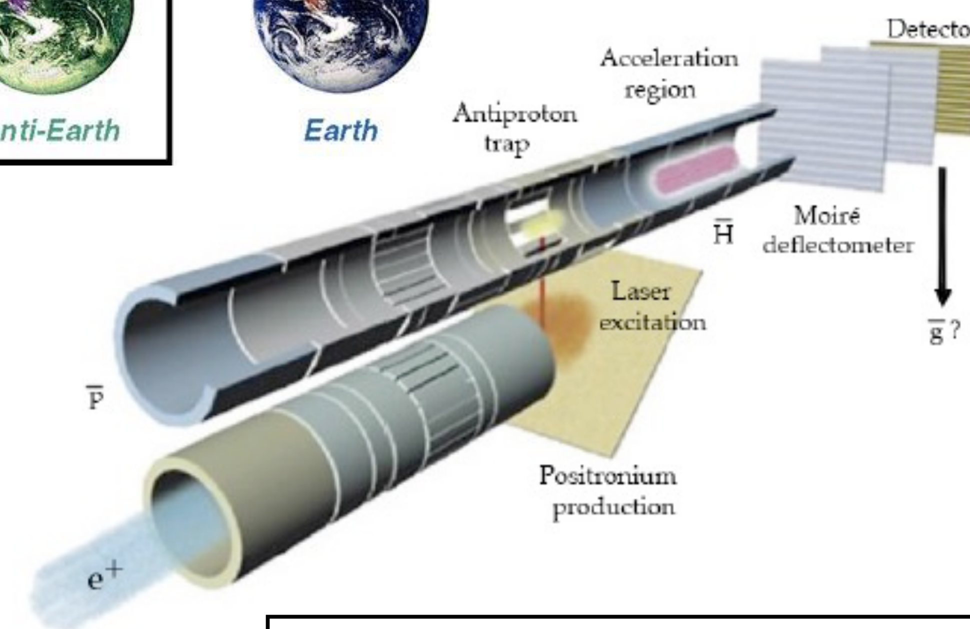


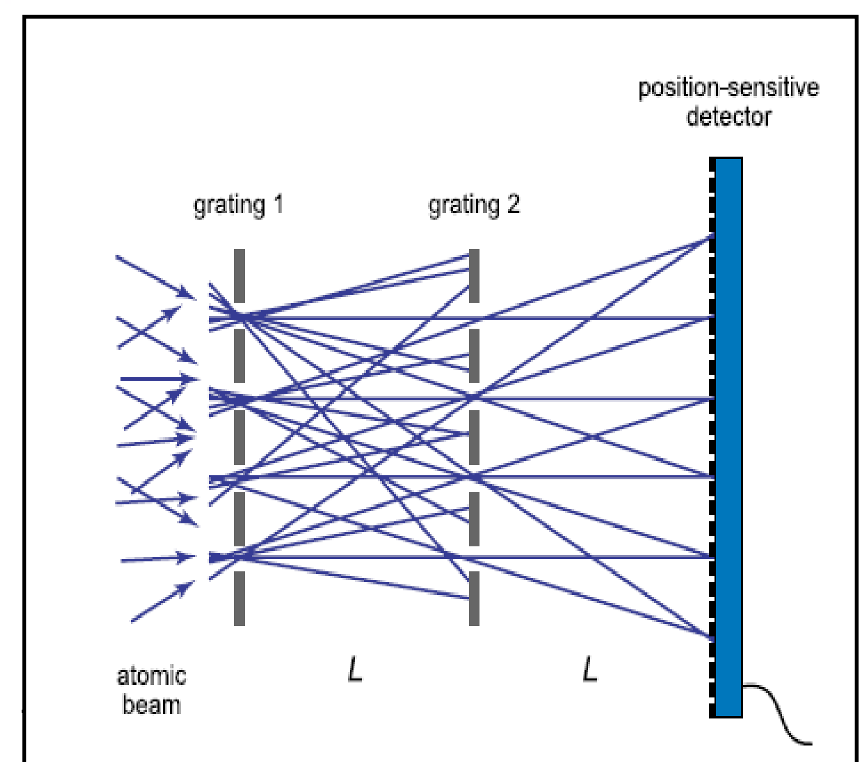
- No direct measurements with antimatter so far
- Can be done with a beam of anti-Hydrogen:

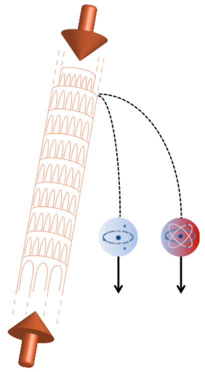
1) Produce ultracold antiprotons (100 mK)
2) Accumulate e+
3) Form Positronium (Ps) by e+ interaction with porous target
4) Laser excite Ps to get Rydberg Ps
5) Form Rydberg cold (100 mK) antihydrogen by charge exchange

$$\overline{p} + (Ps)^* \rightarrow \overline{H}^* + e^-$$

6) Form a beam using an inhomogeneous electric field to accelerate the Rydberg antihydrogen
7) The beam flies toward the deflectometer which introduces a spatial modulation in the distribution of the Hbar arriving on the detector
8) Extract g from this modulated distribution







A quantum WEP test

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ARTICLE

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OPEN

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

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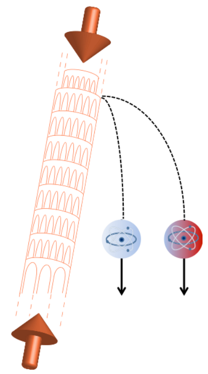


Quantum formulation of EEP

- The Einstein Equivalence Principle plays a crucial role in our understanding of gravity. It is based on three conditions:
  - Equivalence between the system's inertia and weight (WEP)
  - Independence of local non-gravitational experiments from the velocity of the free falling reference frame (LLI)
  - Independence of local non-gravitational experiments of their location (LPI)
- Implementing EEP in a non-relativistic quantum theory?

$$\hat{H}_{nr} = m_r c^2 + \frac{\hat{P}^2}{2m_i} + m_g \phi(\hat{Q})$$

← **Non-relativistic Hamiltonian with classical potential**

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

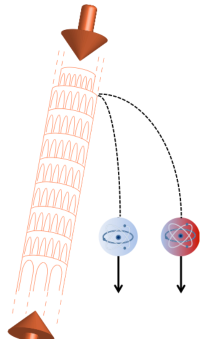
Developing to the first order:

Relativistic time dilation term

Gravitational time dilation term

$$\hat{H}^Q_{test} = m_r c^2 + \hat{H}_{int,r} + \frac{\hat{P}^2}{2m_i} + m_g \phi(\hat{Q}) - \hat{H}_{int,i} \frac{\hat{P}^2}{2m_i^2 c^2} + \hat{H}_{int,g} \frac{\phi(\hat{Q})}{c^2}$$

Zych et al. "Quantum formulation of the Einstein Equivalence Principle", arXiv:1502.00971 (2015)



Quantum formulation of WEP

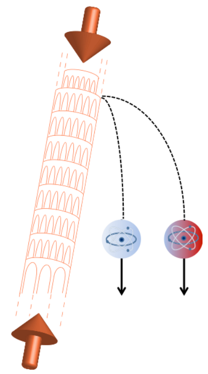
		EEP			
		WEP	**LLI**	**LPI**	**# param.**
Newtonian	classical & quantum	$m_i = m_g$	–	–	1
Newtonian + mass-energy equiv.	classical	$m_i c^2 + E_i = m_g c^2 + E_g$	$E_r = E_i$	$E_r = E_g$	$2n - 1$
	quantum	$m_i c^2 \hat{I} + \hat{H}_i = m_g c^2 \hat{I} + \hat{H}_g$	$\hat{H}_r = \hat{H}_i$	$\hat{H}_r = \hat{H}_g$	$2n^2 - 1$

- Acceleration operator in the Heisenberg picture:

$$\hat{a}_{\hat{H}^Q_{test}} := d^2\hat{Q}/dt^2 = -\frac{1}{\hbar^2}[[\hat{Q}, \hat{H}^Q_{test}], \hat{H}^Q_{test}] = -\hat{M}_g \hat{M}_i^{-1} \nabla\phi(\hat{Q}) + \frac{i}{\hbar}[\hat{H}_{int,i}, \hat{H}_{int,r}]\frac{\hat{P}}{m_i c^2} + \mathcal{O}(1/c^4)$$

$$\hat{M}_g \hat{M}_i^{-1} = \hat{I}_{int} - \hat{\eta} \quad \text{and} \quad \hat{\eta} \approx m_g/m_i(\hat{I} + \hat{H}_{int,g}/m_g c^2 - \hat{H}_{int,i}/m_i c^2)$$

- If $[\hat{H}_{int,i}, \hat{H}_{int,g}] \neq 0$ internal and external degrees of freedom can be entangled



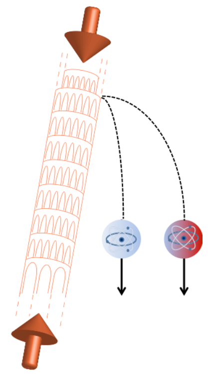
Quantum WEP test

- Quantum formulation of WEP requires
- In QM a state of internal energy can involve superpositions of states
  - validity of the quantum WEP implies equivalence between the off-diagonal elements of the operators
- Let us consider a two level systems (in our case F=1 and F=2 hyperfine ground state of ^{87}Rb:

$$\hat{M}_g \hat{M}_i^{-1} \approx \begin{pmatrix} r_1 & r \\ r^* & r_2 \end{pmatrix}$$

r_1 and r_2 are real numbers
r is complex: $r=|r|e^{i\phi}$

Classical WEP: $r_1 = r_2 = 1$
Quantum WEP: $r = 0$



Quantum WEP test

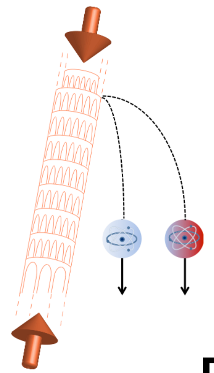
The AI sensor can measure:

$$a_1 = g\langle 1|\hat{M}_g \hat{M}_i^{-1}|1\rangle = g r_1 ,$$

$$a_2 = g\langle 2|\hat{M}_g \hat{M}_i^{-1}|2\rangle = g r_2 ,$$

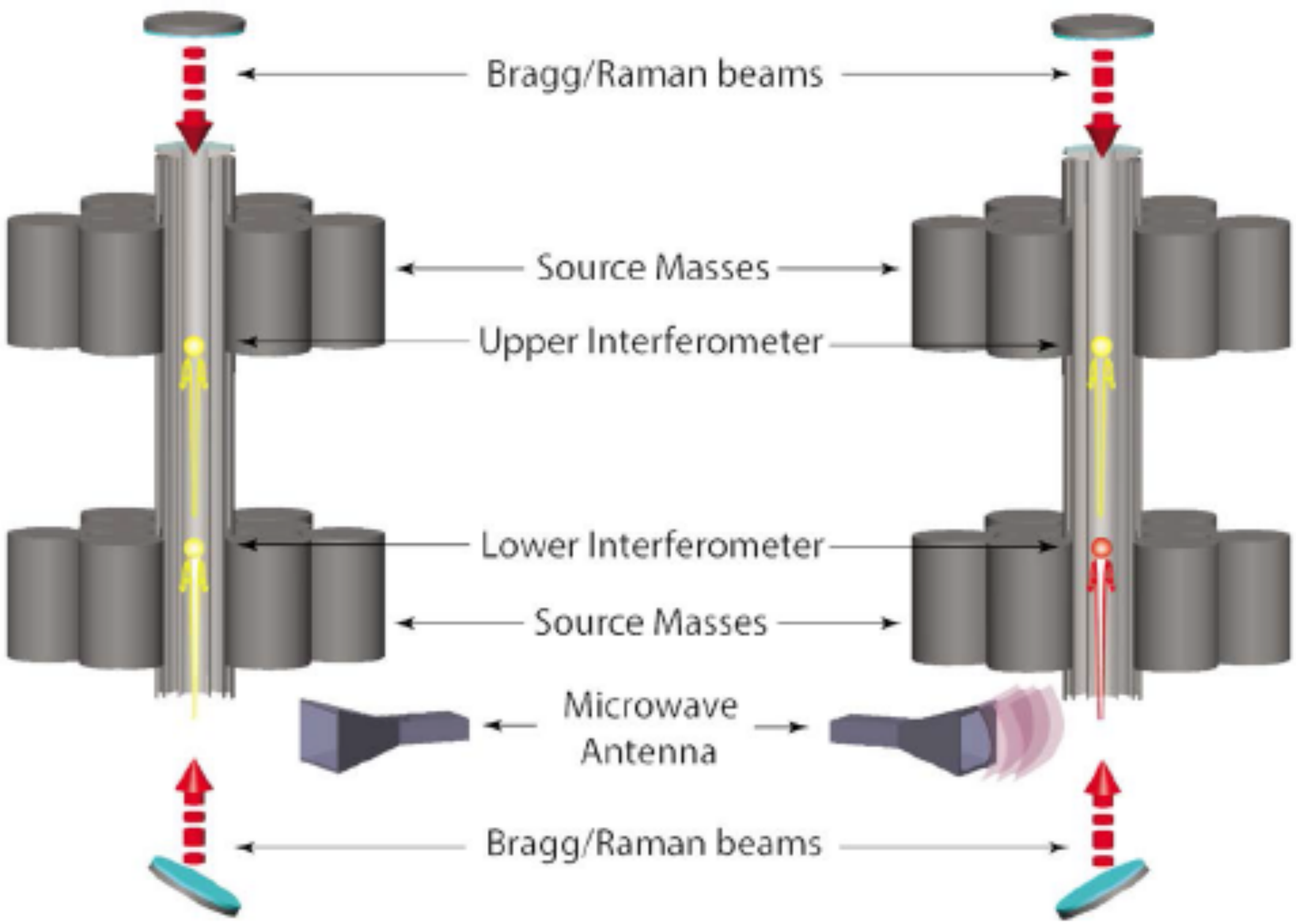
$$a_s = g\langle s|\hat{M}_g \hat{M}_i^{-1}|s\rangle = g\left[\frac{r_1 + r_2}{2} + |r|\cos(\varphi_r + \gamma)\right]$$

- A classical WEP violation (introduced by diagonal elements $r_{1,2}$) emerges as a differential acceleration proportional to $r_1 - r_2$.
- A quantum WEP violation would produce an excess phase noise on the acceleration measurements due to γ (random phase >> 2π).

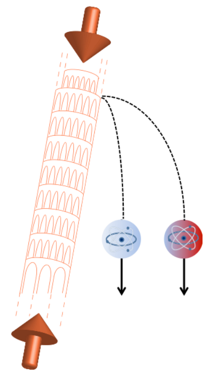


Quantum WEP test

- Bragg gradiometer to compare free fall accelerations of atoms
  - A. prepared in pure hyperfine states (F = 1, F = 2), and
  - B. atoms prepared in a coherent superposition of two different hyperfine states.



- Superposition state is prepared with RF pulse
- s = (|1> + |2> eiγ)/√2
- γ: random phase introduced with RF pulse



Quantum WEP test

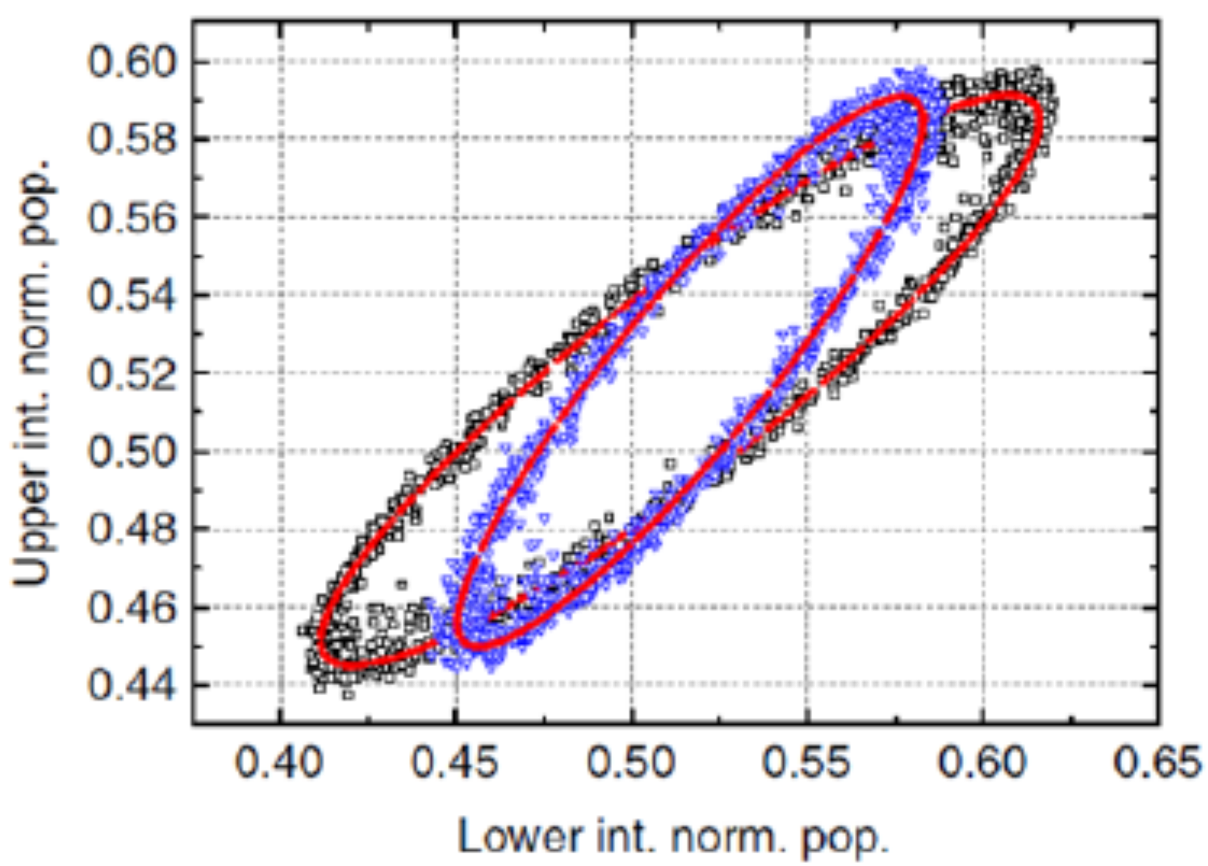
We realize three possible gradiometric configurations → $\Phi_{1\text{-}1}$, $\Phi_{1\text{-}2}$, $\Phi_{1\text{-}s}$

Classical WEP test → $\delta g_{1\text{-}2} \sim (\Phi_{1\text{-}1} - \Phi_{1\text{-}2})$ → $\eta_{1\text{-}2} = (1{,}4 \pm 2{,}8) \times 10^{-9}$

Quantum WEP test → Attributing all observed phase noise on 1-s ellipse to a WEP violation we estimate an upper limit for $|r|$ → $r \leq 5 \cdot 10^{-8}$.

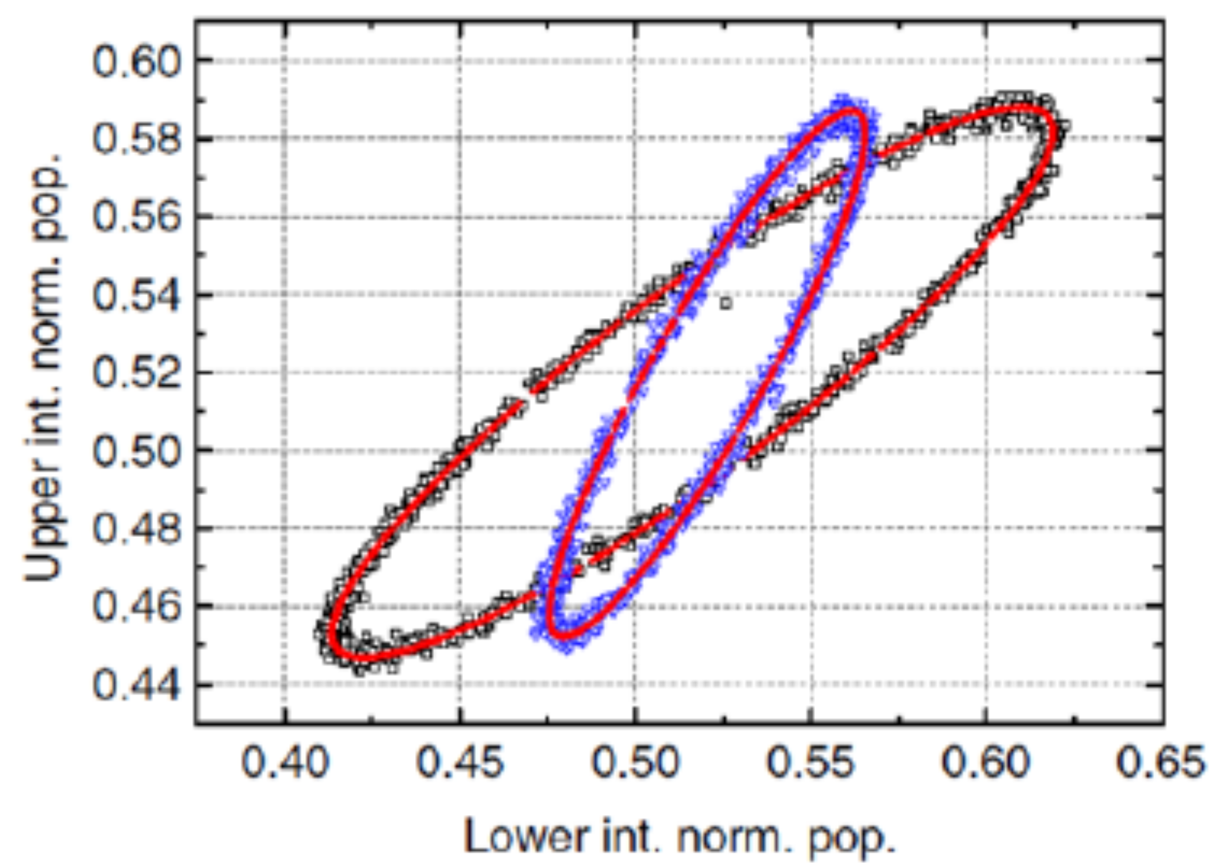
Black ellipse: 1 – 1 gradiometer

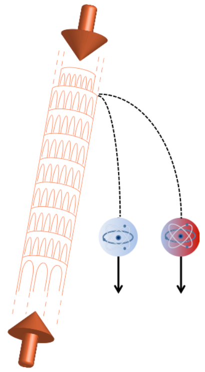
Blue ellipse: 1 – s gradiometer



Black ellipse: 1 – 1 gradiometer

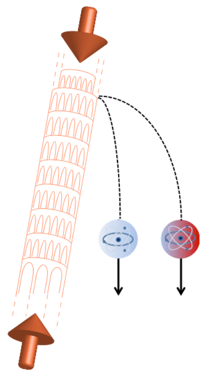
Blue ellipse: 1 – 2 gradiometer



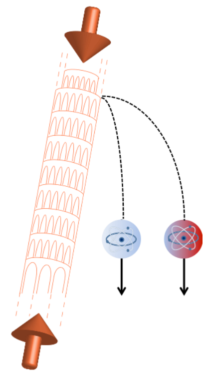


Next steps

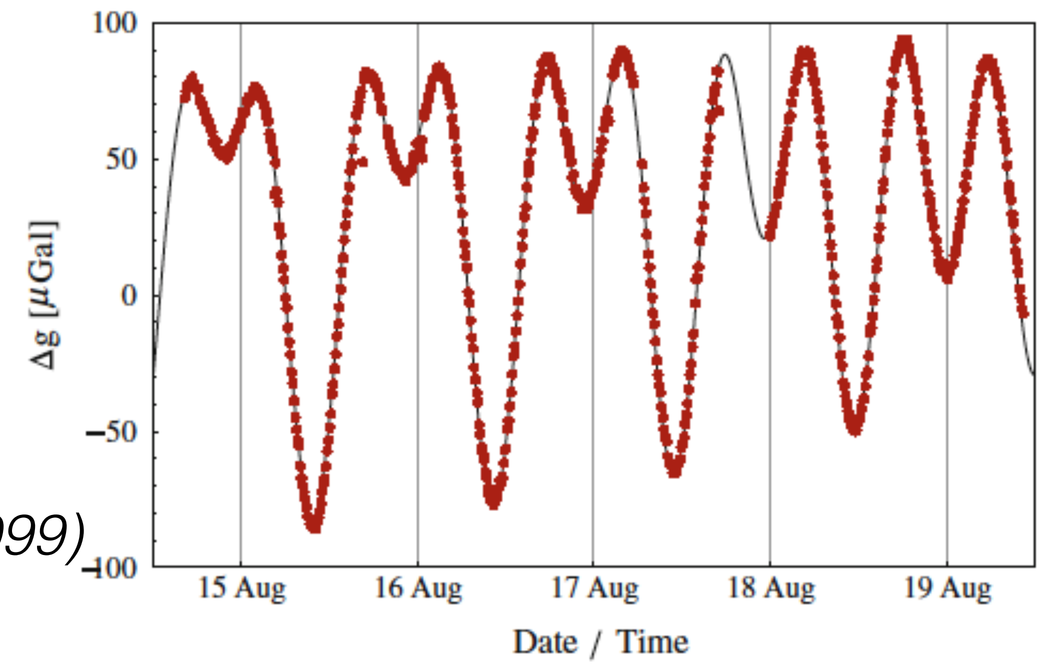
- Tiny energy difference between hyperfine states (28 μeV)
- Commutator $[\hat{H}_{int,i}, \hat{H}_{int,g}]$ expected to be proportional to the typical magnitude of H
    - larger ΔE yields to larger effects
- Example: Sr interferometer on clock transition ΔE= 1.8 eV [*L.Hu et al., submitted to PRL (2017)*]
- Additional configurations: entangled states between different isotopes



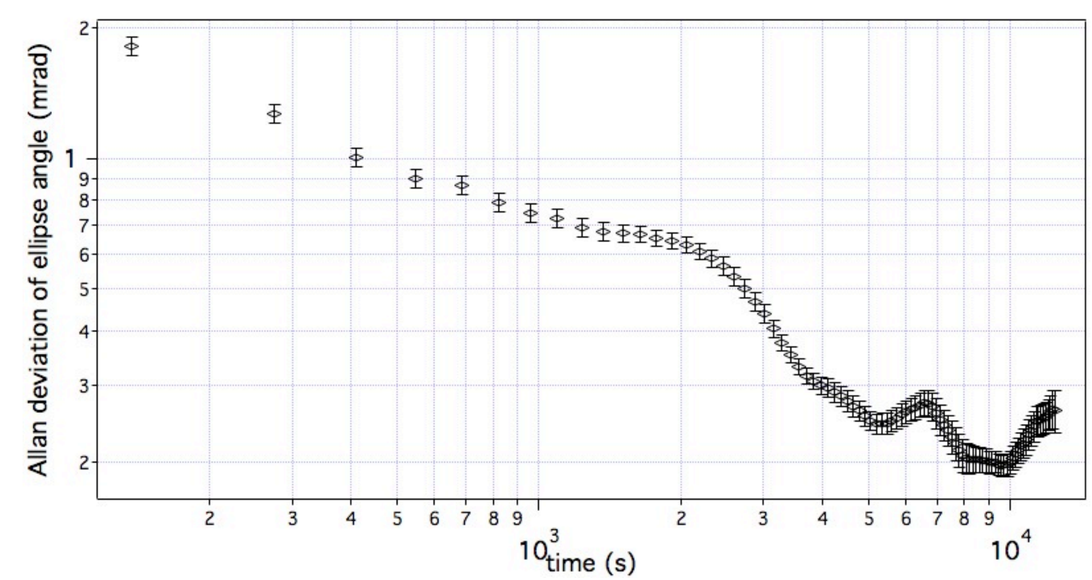
Prospects



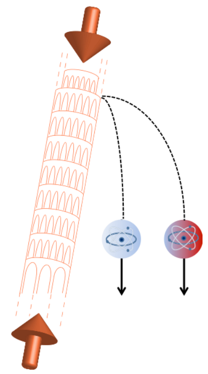
AI sensors: current performance



- Gravimeters
  - resolution: 3×10^{-9} g in 1 second (SYRTE)
  - averaging down to 2×10^{-10} g after 30 min (SYRTE)
  - accuracy: $10^{-9}\div10^{-10}$ g, limited by tidal models
    - *A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)*
    - *H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)*
    - *M. Hauth et el., Appl. Phys. B 113, 49 (2013)*
    - *P. Gillot et al., Metrologia 51, L15 (2014)*
- Gravity gradiometers
  - differential acceleration sensitivity: 5×10^{-9} g in1 s
  - 5×10^{-11} g after 10^4 s
    - *F. Sorrentino et al., Phys. Rev. A 89, 023607 (2014)*



- Rotation sensors
  - sensitivity: 6×10^{-10} rad/s/√Hz
  - scale factor stability <5 ppm
  - bias stability <70 μdeg/h
    - *T. L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)*
    - *D. S. Durfee, Y. K. Shaham, M.A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006)*

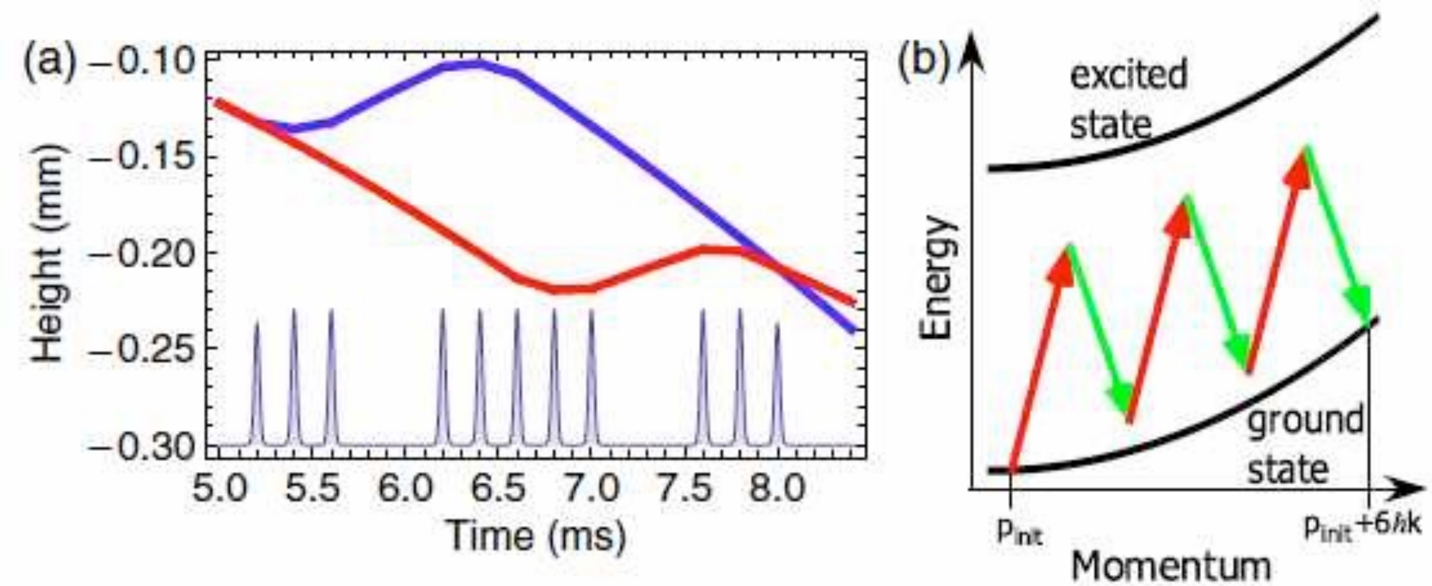


Potential improvements

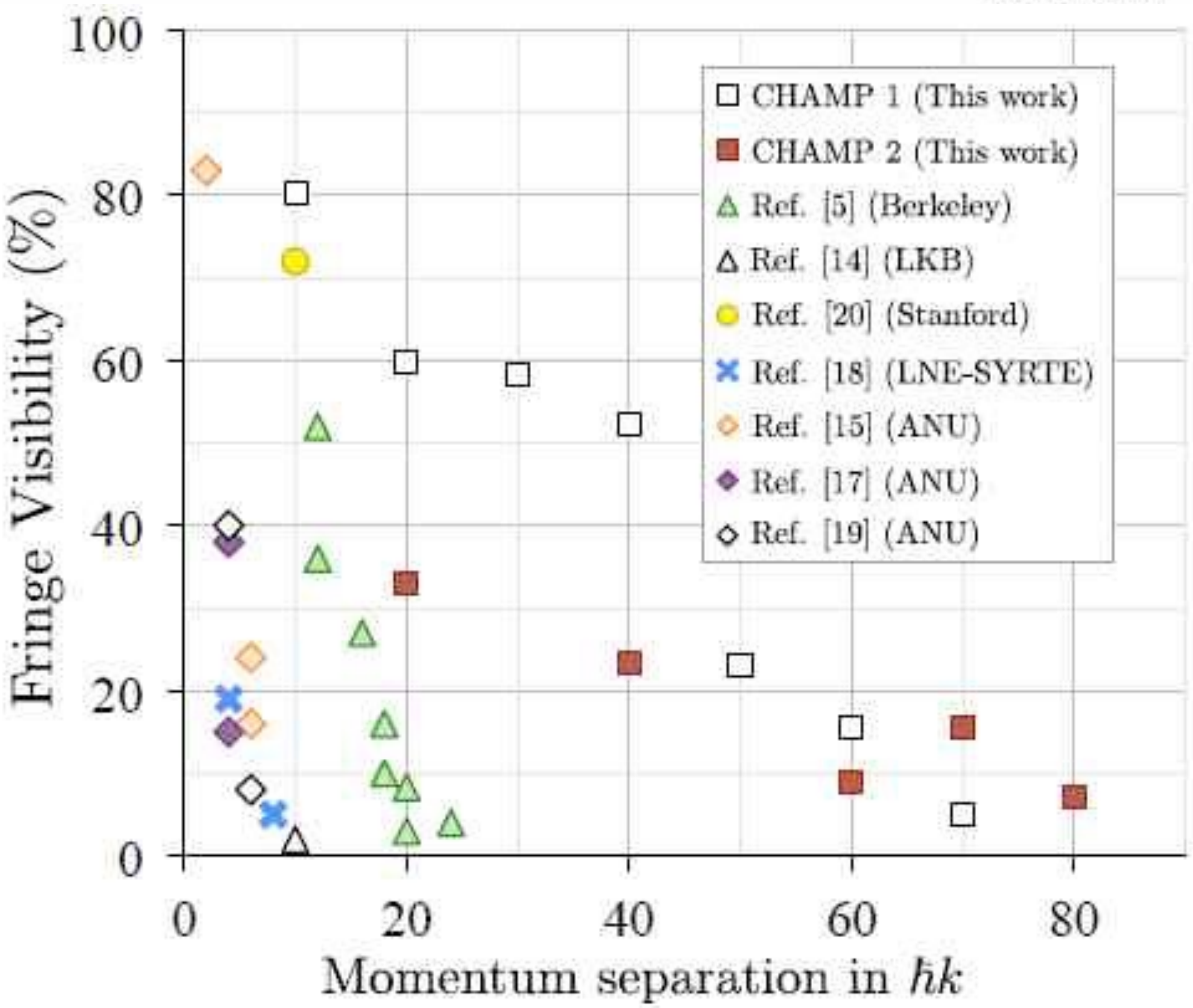
$$\Delta\Phi = nkgT^2$$

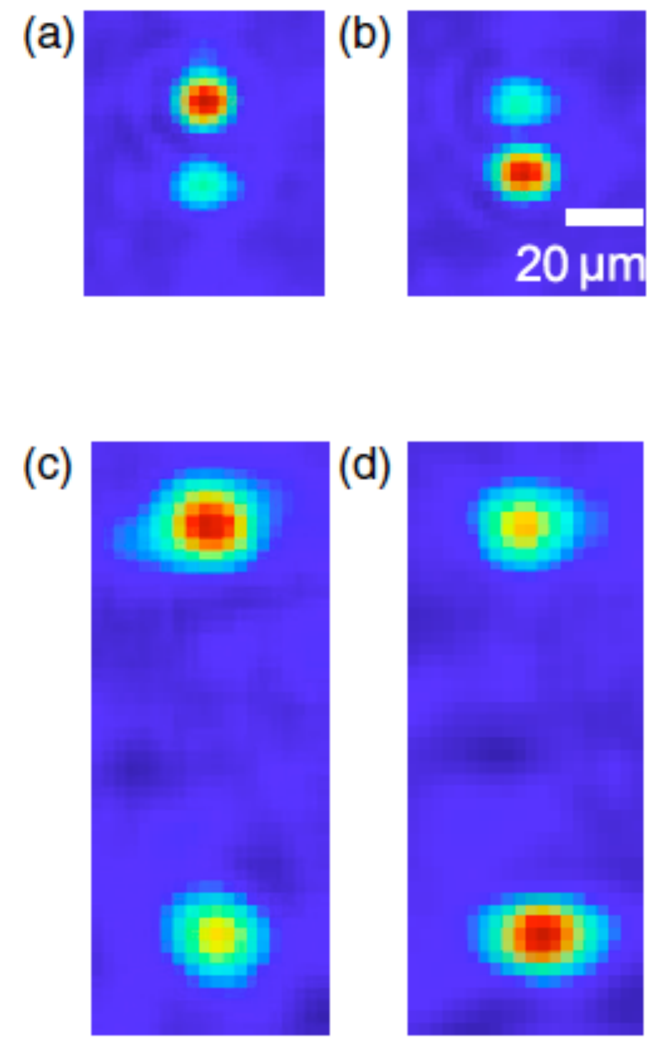
- Increasing the scale factor
  - Large momentum transfer splitters (increase *nk*)
  - Large scale AI, or microgravity (increase *T*)
- Reducing the phase noise
  - High flux atomic sources (reduce quantum noise)
  - Squeezing (phase noise below standard quantum limit)
- Choice of atomic species
- Interferometer topology

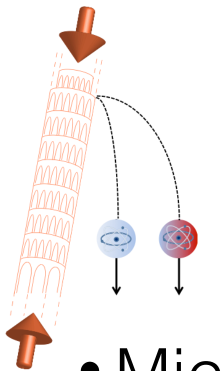
Large momentum transfer



- H. Müller et al., PRL **102**, 240403 (2009)
- S.-W. Chiow et al., PRL **107**, 130403 (2011)
- G. D. McDonald et al., PRA **88**, 053620 (2013)

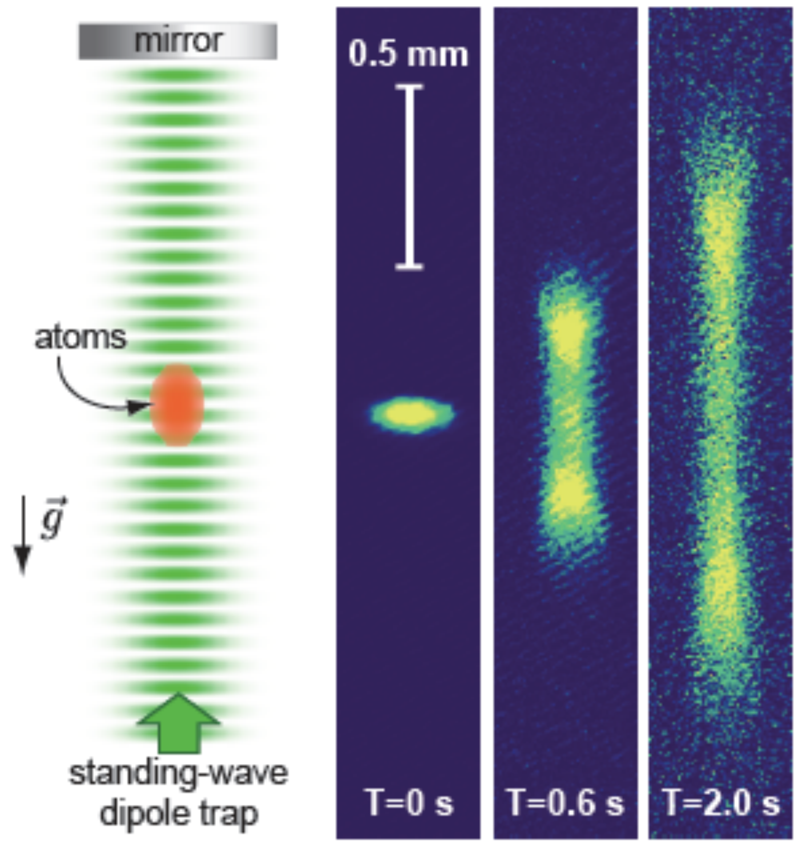


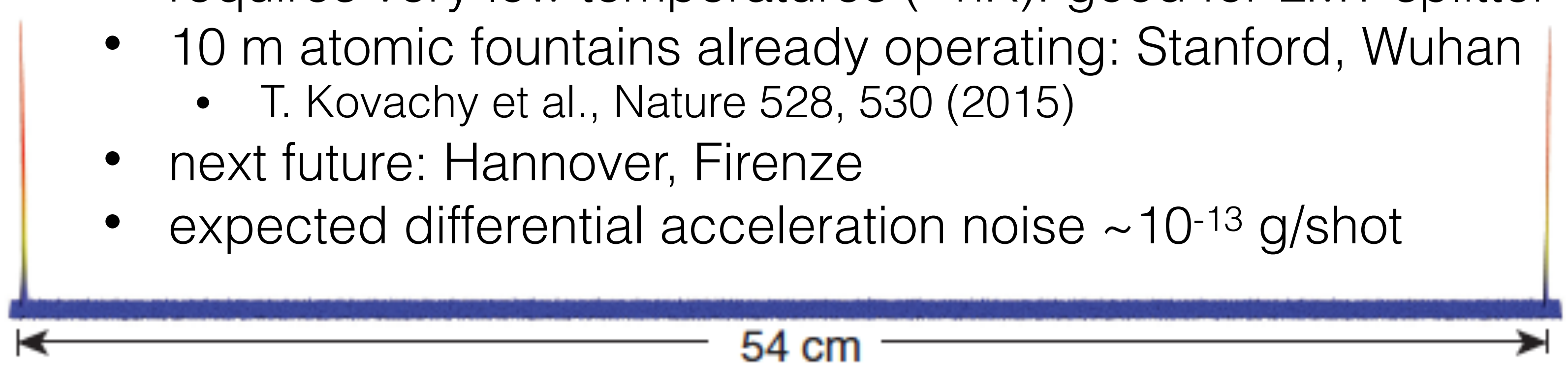


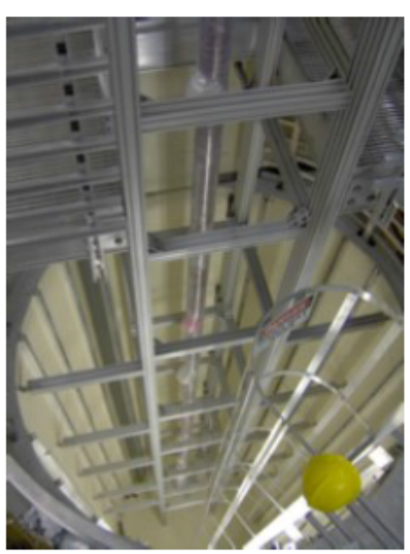


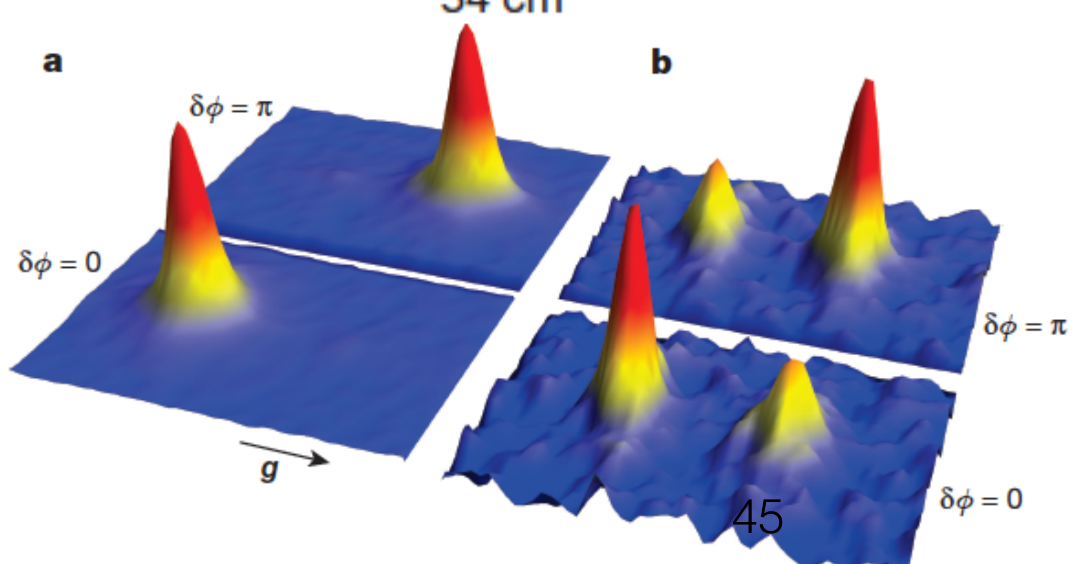
Long interaction time

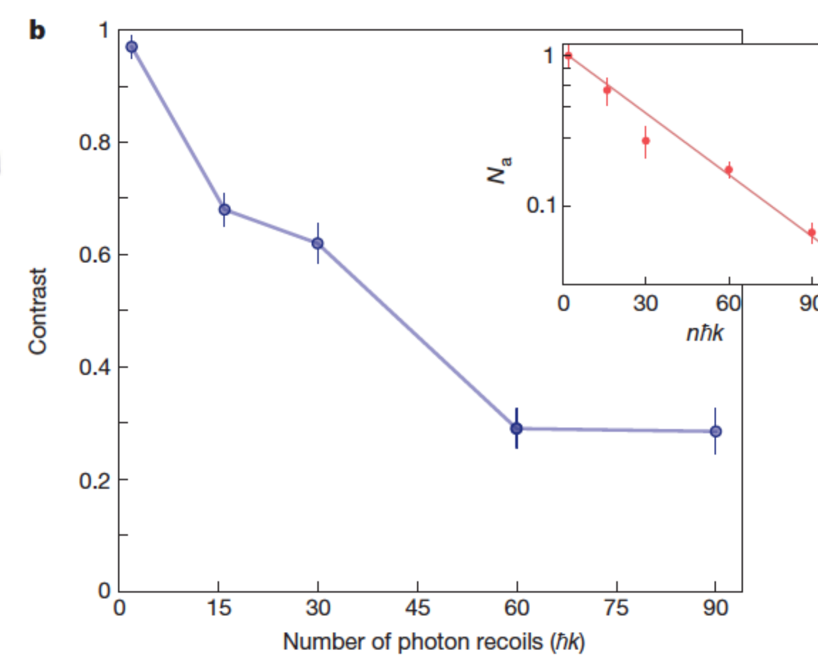
- Microgravity: in principle T>10 s
- Increasing T on Earth
  - trapped atoms (Sr)
    - up to 15000 coherent photon recoils
    - decoherence time >500 s
      - *G. Ferrari et al., PRL 97, 060402 (2006)*
      - *V. V. Ivanov et al., PRL 100, 043602 (2008)*
      - *F. Sorrentino et al., Phys. Rev. A 79, 013409 (2009)*
      - *M. Tarallo et al., PRA 86, 033615 (2012)*
  - free fall
    - requires large vertical size
    - requires very low temperatures (~nK): good for LMT splitter
    - 10 m atomic fountains already operating: Stanford, Wuhan
      - T. Kovachy et al., Nature 528, 530 (2015)
    - next future: Hannover, Firenze
    - expected differential acceleration noise ~10^{-13} g/shot



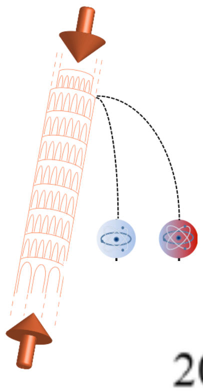




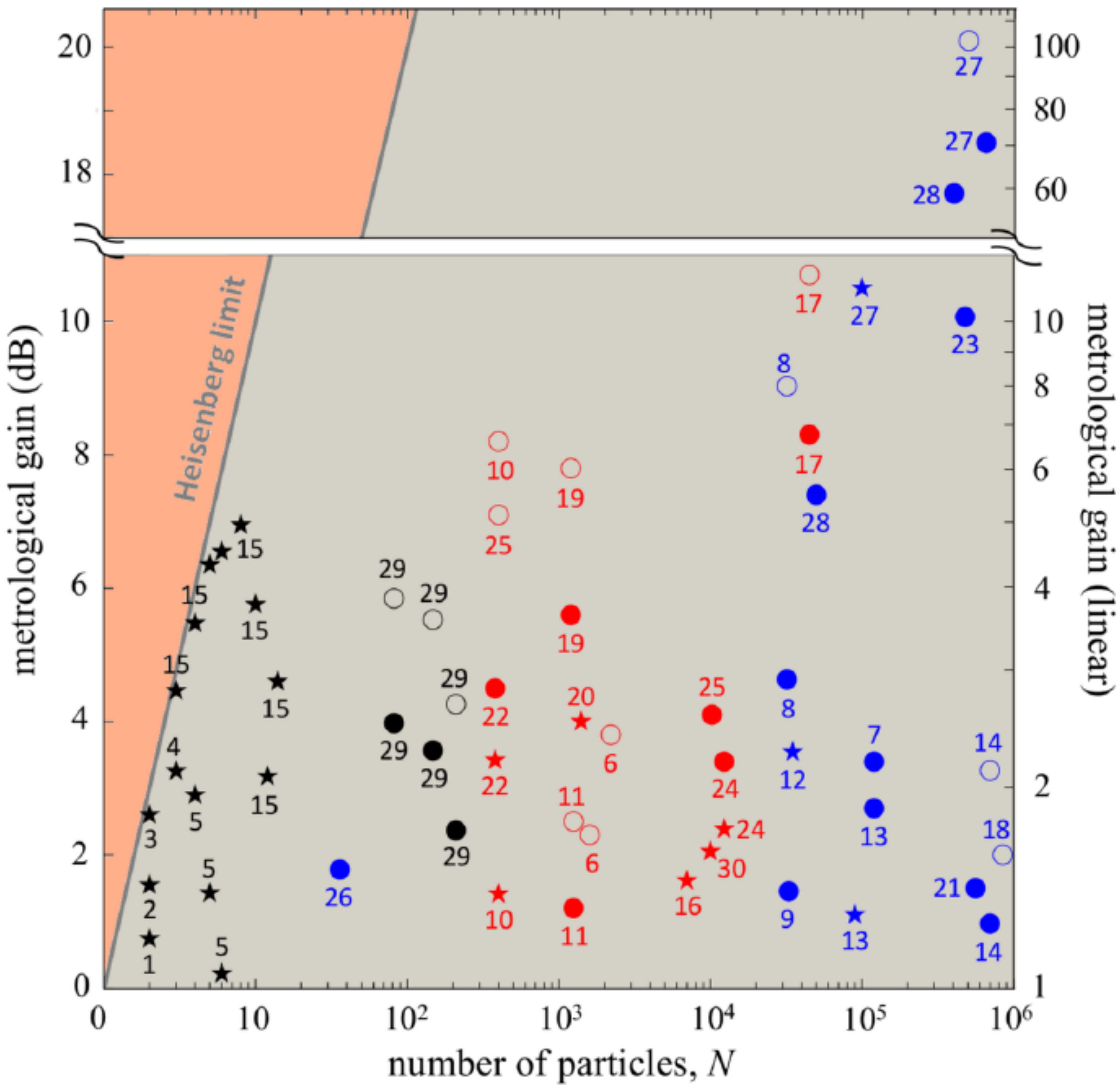




Testing the equivalence principle…



Squeezing

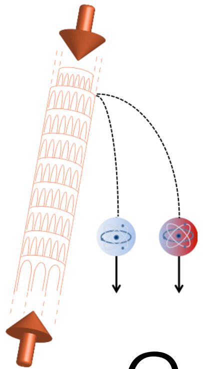


TRAPPED IONS
[1] Sackett *et al.*, 2000
[2] Meyer *et al.*, 2001
[3] Leibfried *et al.*, 2003b
[4] Leibfried *et al.*, 2004
[5] Leibfried *et al.*, 2005
[15] Monz *et al.*, 2011
[29] Bohnet *et al.*, 2016

BOSE-EINSTEIN CONDENSATES
[6] Estève *et al.*, 2008
[10] Gross *et al.*, 2010
[11] Riedel *et al.*, 2010
[16] Lücke *et al.*, 2011
[17] Hamley *et al.*, 2012
[19] Berrada *et al.*, 2013
[20] Ockeloen *et al.*, 2013
[22] Strobel *et al.*, 2014
[24] Muessel *et al.*, 2014
[25] Muessel *et al.*, 2015
[30] Kruse *et al.*, 2016

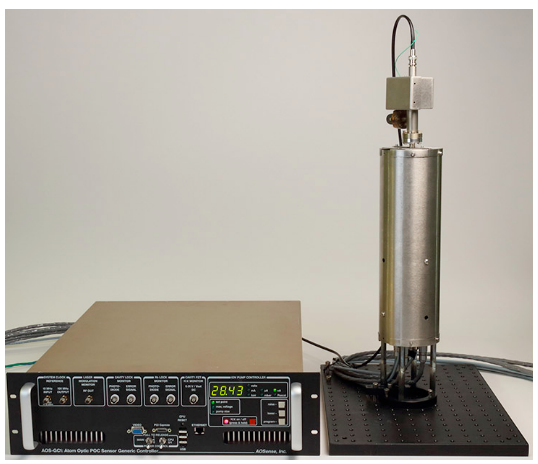
COLD THERMAL ATOMS
[7] Appel *et al.*, 2009
[8] Leroux *et al.*, 2010a
[9] Schleier-Smith *et al.*, 2010b
[12] Leroux *et al.*, 2010b
[13] Louchet-Chauvet *et al.*, 2010
[14] Chen *et al.*, 2011
[18] Sewell *et al.*, 2012
[21] Sewell *et al.*, 2014
[23] Bohnet *et al.*, 2014
[26] Barontini *et al.*, 2015
[27] Hosten *et al.*, 2016a
[28] Cox *et al.*, 2016

L. Pezzé and A. Smerzi, arXiv:1609.01609v2

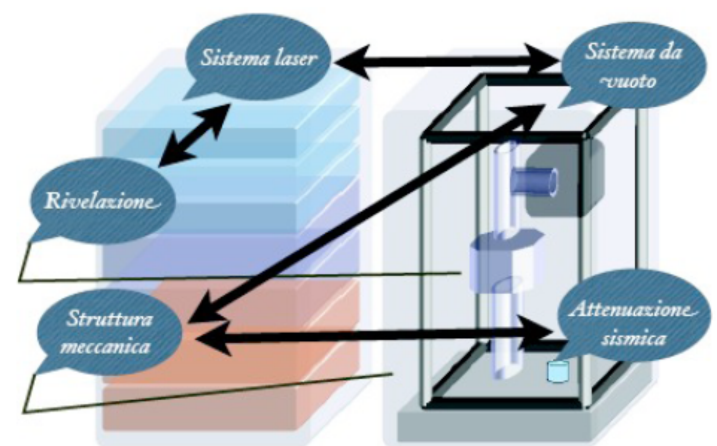


Technology readiness

- Commercial atomic gravimeters & gradiometers
  - MuQuans (France)
  - AOSense (USA)
  - AtomSensors (Italy)



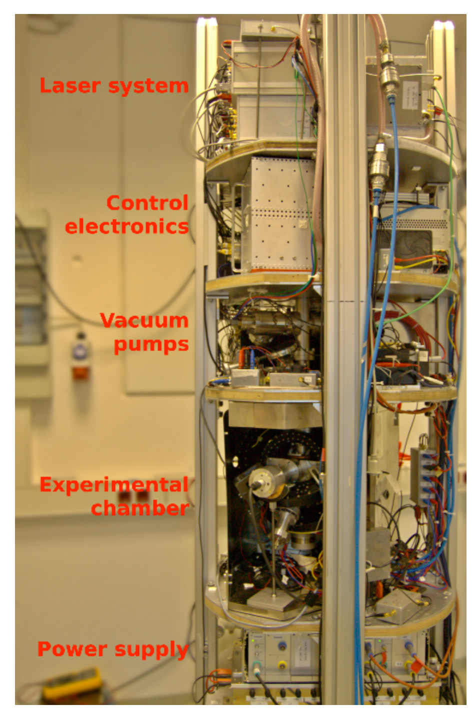
AOSense



AtomSensors

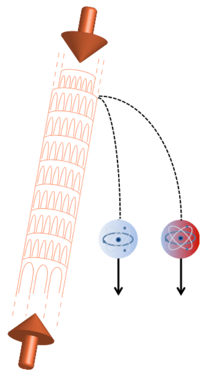
μQUANS

- Prototypes for microgravity
  - I.C.E. (CNES)
  - QUANTUS/MAIUS (DLR)
  - S.A.I. (ESA)



QUANTUS

G. Tino et al., Precision Gravity Tests with Atom Interferometry in Space, Nuclear Physics B 243, 203 (2013)



Conclusions

- Classical WEP tests reached 10^{-13} precision, aiming at 10^{-15} in the near future
- Precision gravity measurements with atomic quantum sensors
  - atoms are ideal test masses and clocks
  - allow to explore new physics
  - test genuine quantum features of WEP
- Next generation atomic sensors expected to attain extreme precision in the mid-term future