UNIVERSITÀ DEGLI STUDI FIRENZE

Lens European Laboratory for Non-Linear Spectroscopy

INFN

Fundamental physics with space and ground atomic quantum sensors

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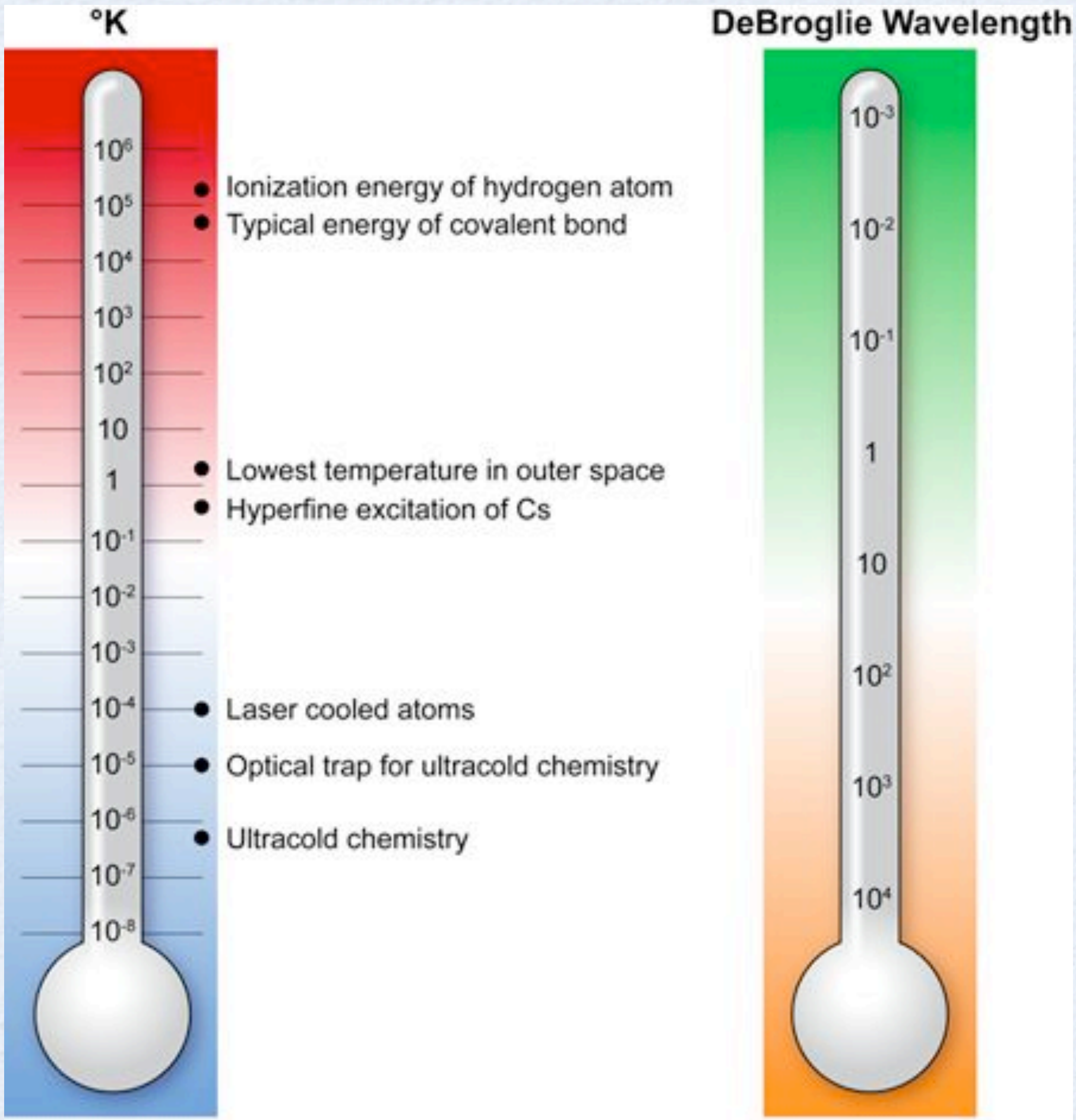
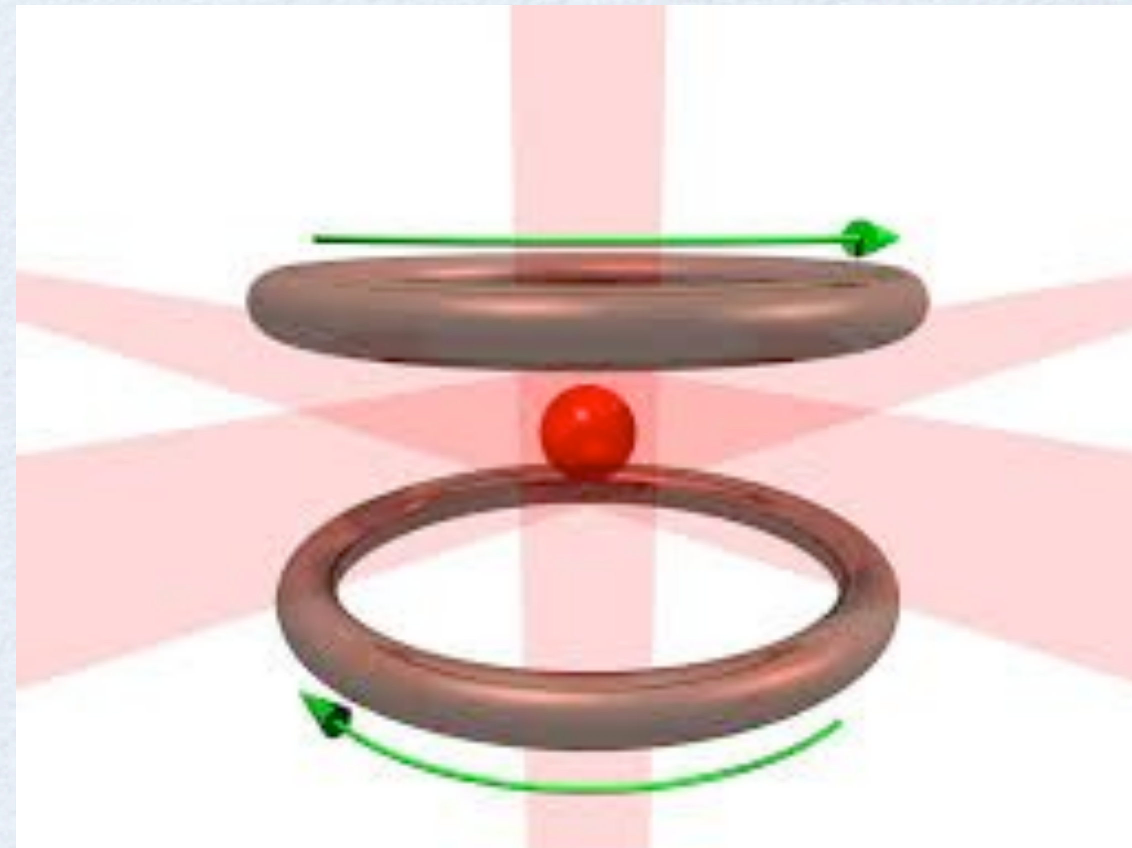
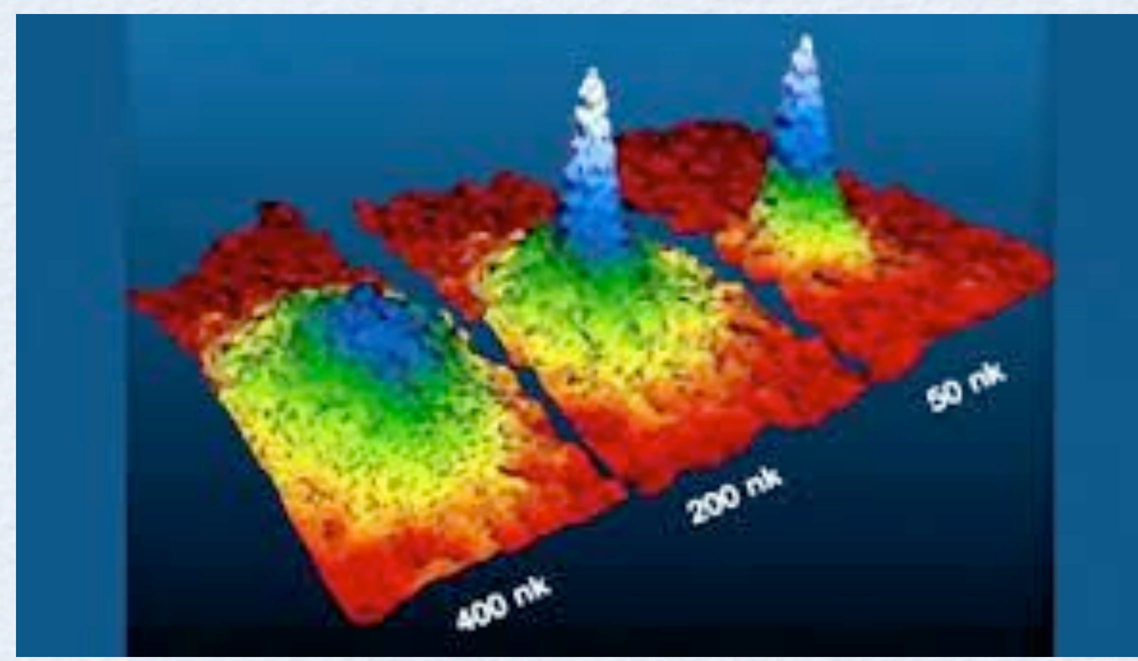
Outline

- Introduction to quantum sensors
  - atom optics and ultracold atoms
  - optical clocks and atom interferometers
- Precision measurements with quantum sensors
  - inertial sensing
  - fundamental constants: (e.g. G and α)
  - tests of fundamental physics (GR, quantum gravity)
  - other applications
- Future prospects on ground and in space
  - advanced atom interferometers
  - future space experiments

Ultracold atoms







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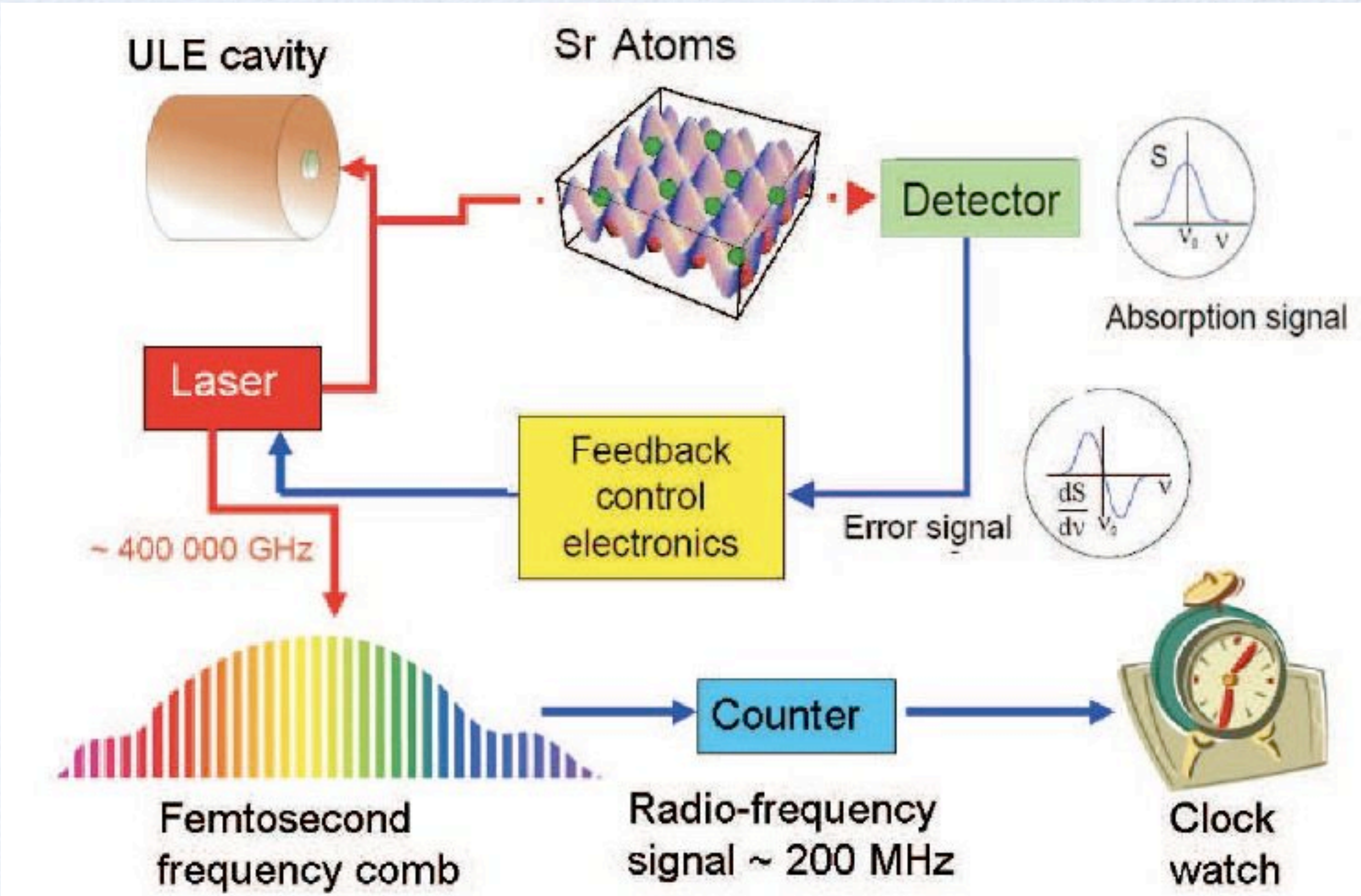
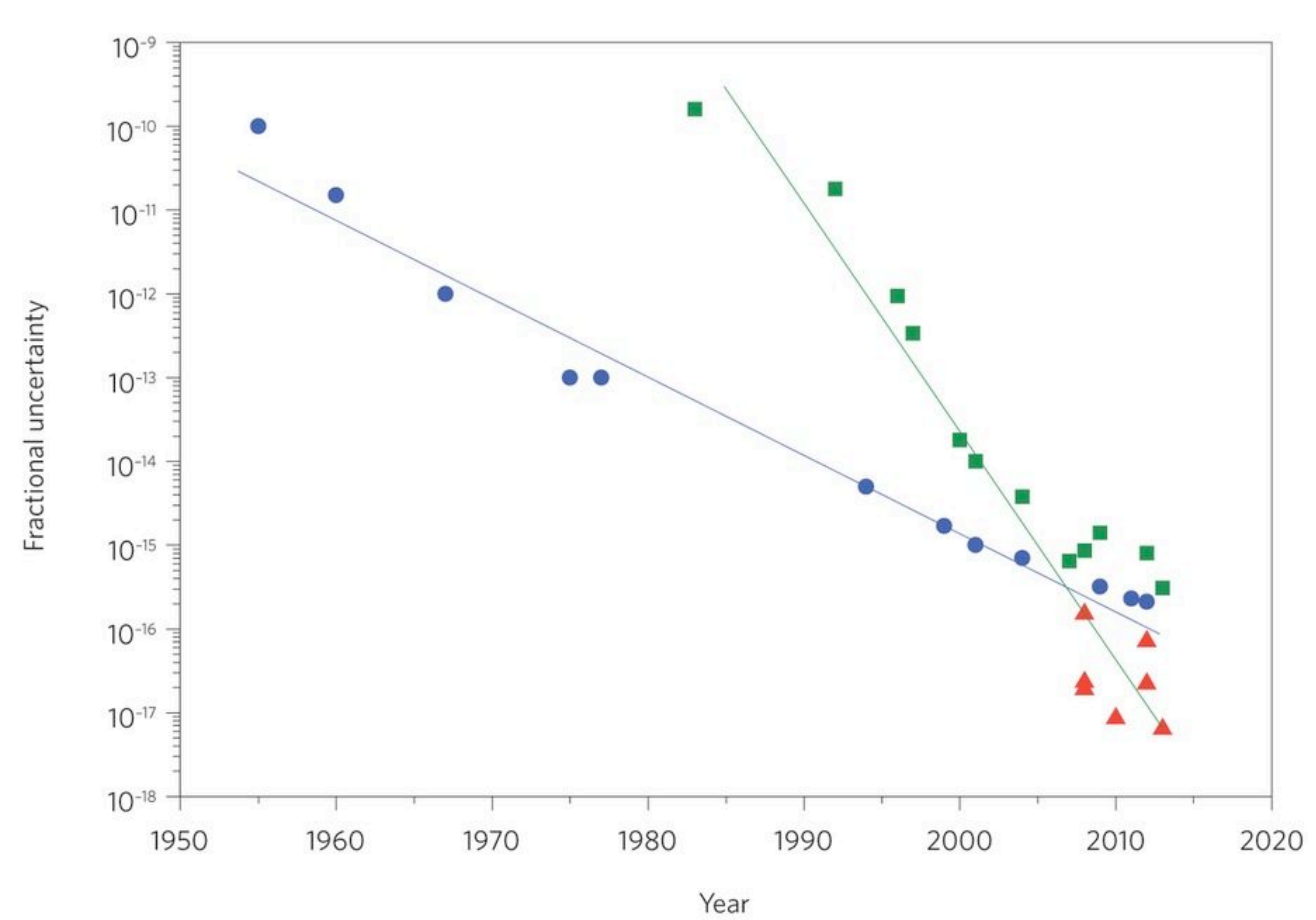
Atomic quantum sensor

Optical atomic clocks



Optical vs MW atomic clocks



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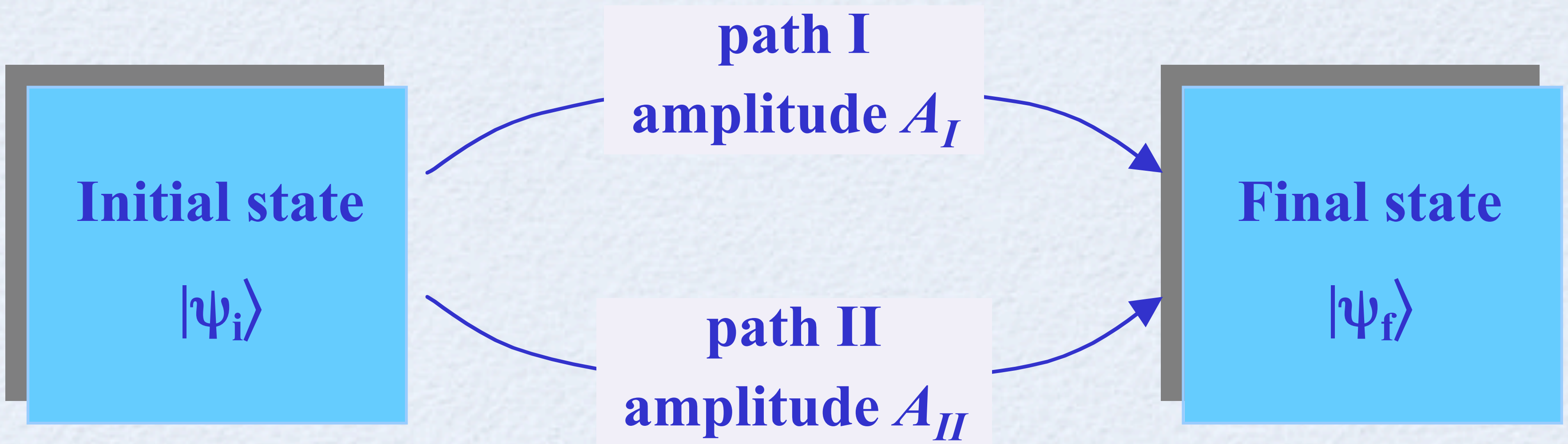
Applications of optical atomic clocks

- Metrology (definition of time and other units)
- Time keeping
- Telecommunication
- Positioning (Galileo & beyond)
- Fundamental physics
  - test of gravitational red-shift
  - time drift of fundamental constants
- Geophysics (relativistic geodesy)

Matter-wave interferometry

Quantum interference



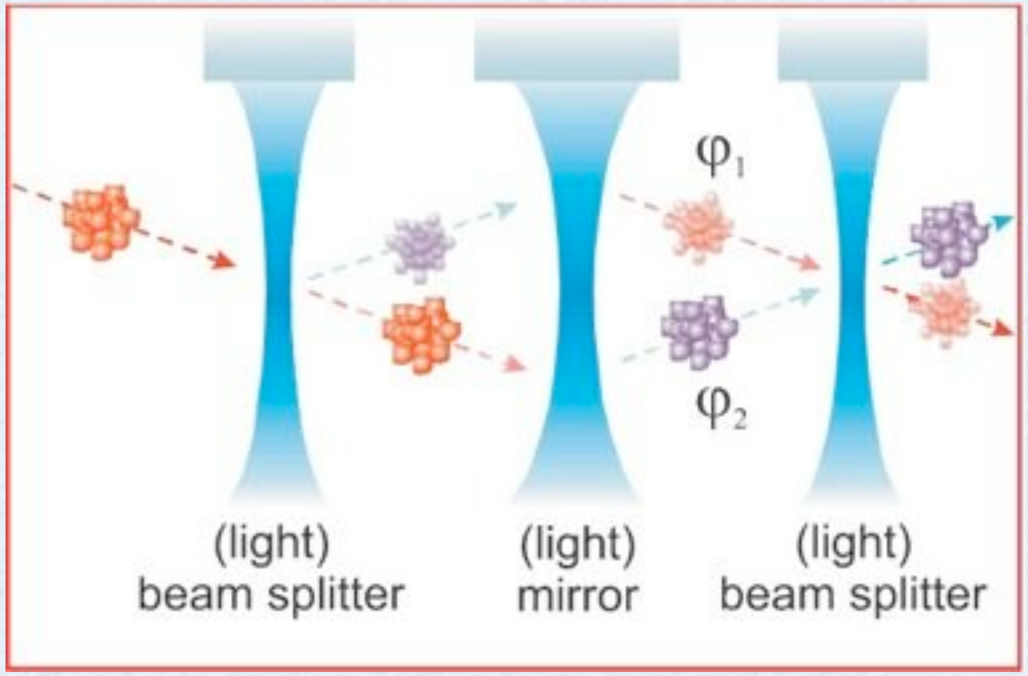
Interference of transition amplitudes

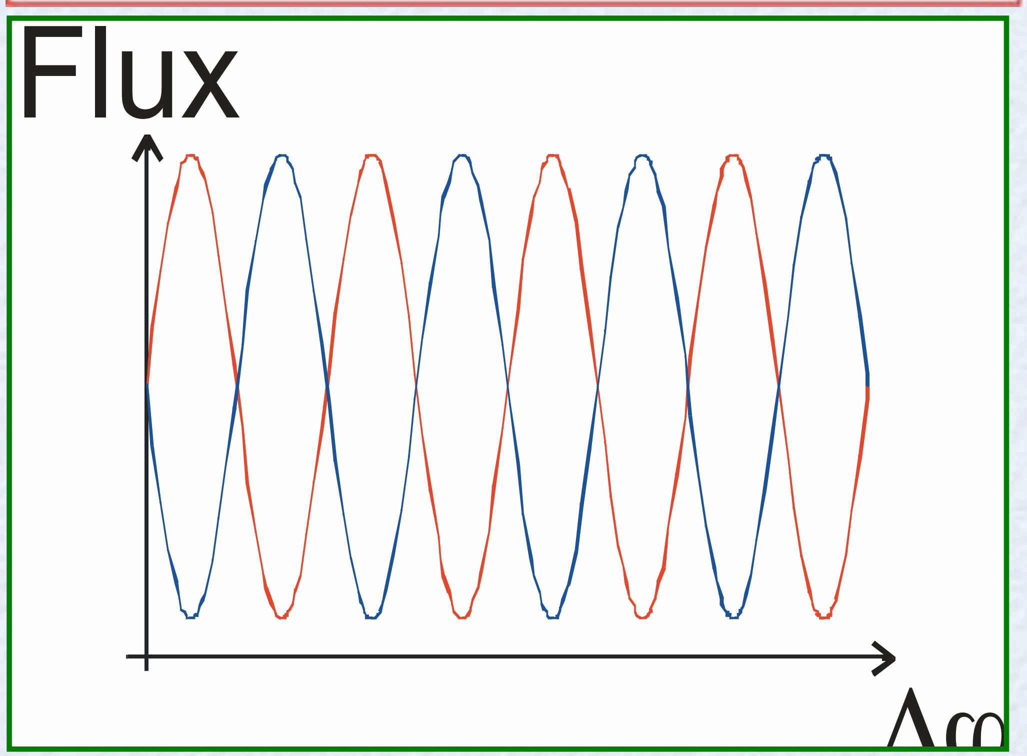
$$P(|\psi_i\rangle \rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2Re(A_I A_{II}^*)$$

de Broglie wave $\lambda_{dB} = h/mv$

- *with electrons since 1953*
- *with neutrons since 1974*
- *with atoms since 1991*

Atom interferometry



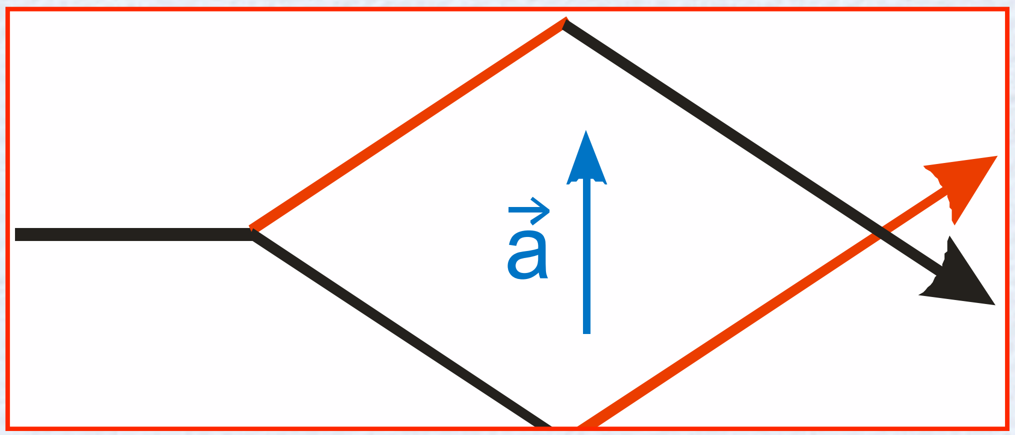


atomic flux at **exit** port **1**
at **exit** port **2**

- atom optics
- different internal states/isotopes
- phase difference may depend on:
  - accelerations
  - rotations
  - photon recoil
  - laser phase
  - laser frequency detuning
  - electric/magnetic fields
  - interactions with atoms/molecules

Matter-wave vs optical inertial sensors

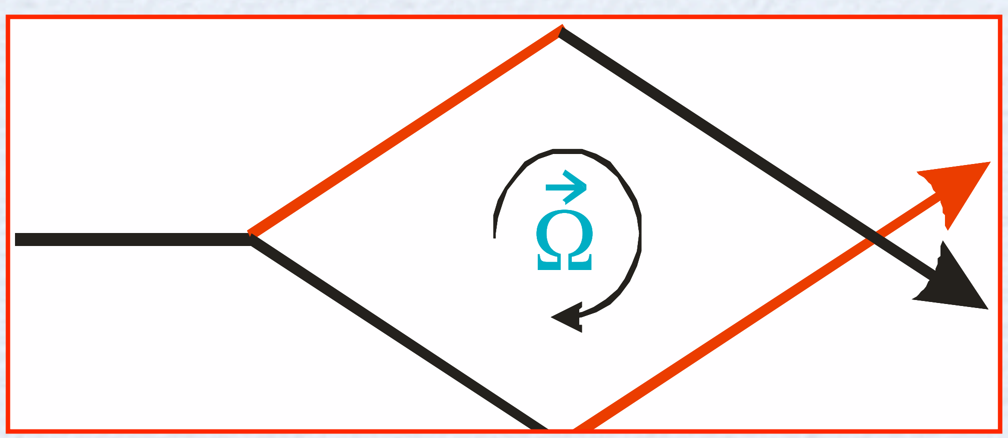
Accelerations



$$\Delta\Phi_{acc} = kT^2_{drift} \cdot a$$

$$\frac{\Delta\phi_{mat}}{\Delta\phi_{ph}} \sim \left(\frac{c}{v_{at}}\right)^2 \approx 10^{11} \div 10^{17}$$

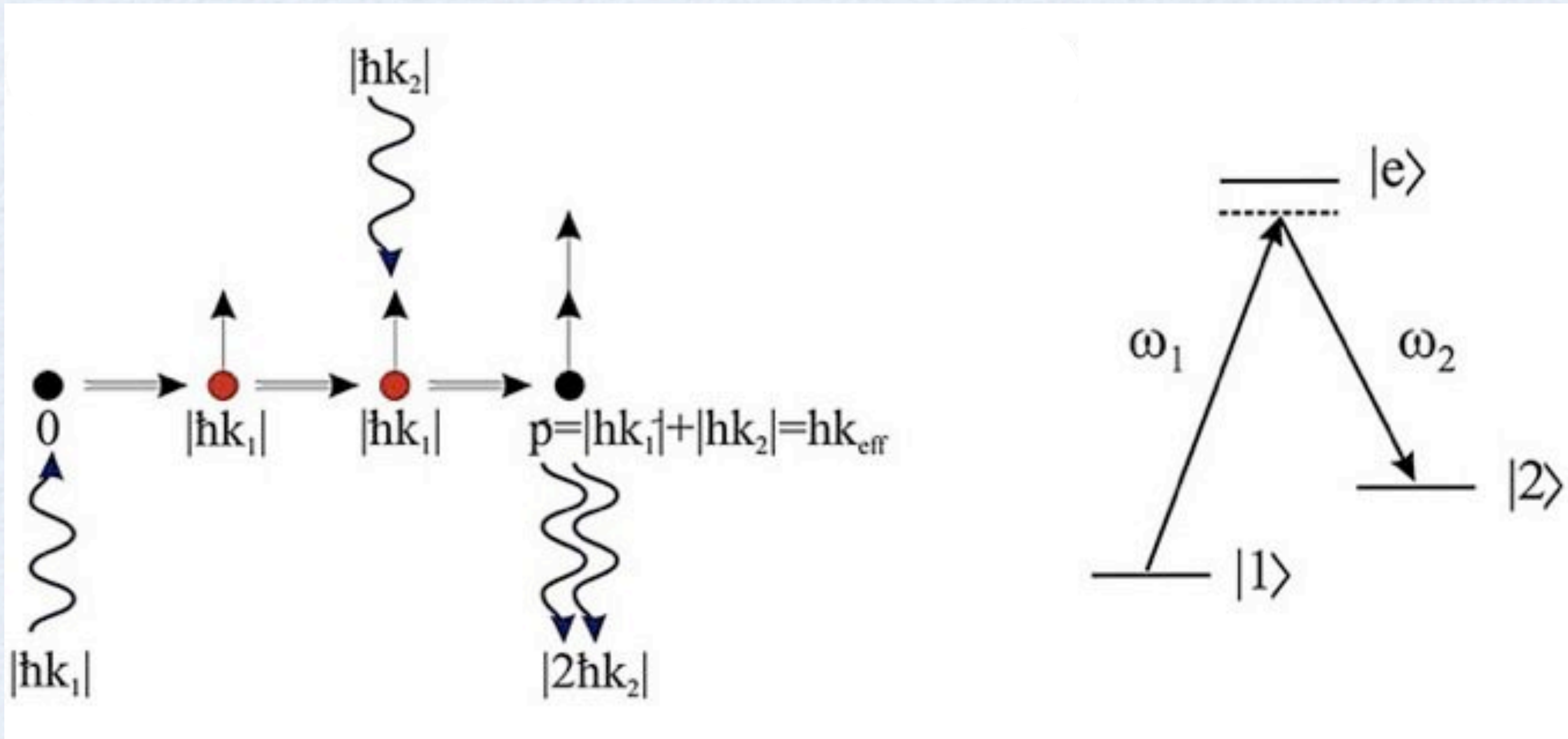
Rotations

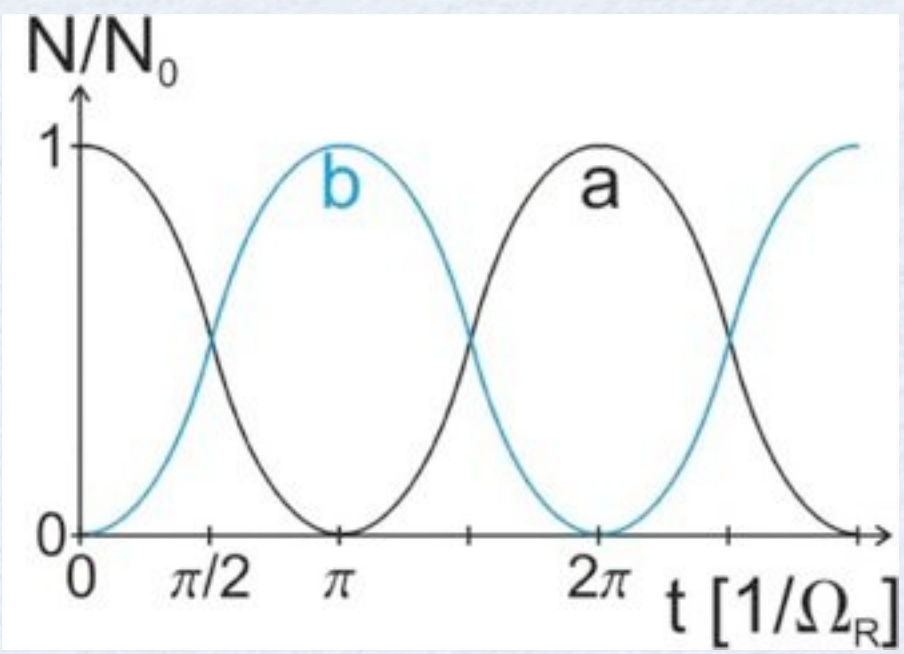


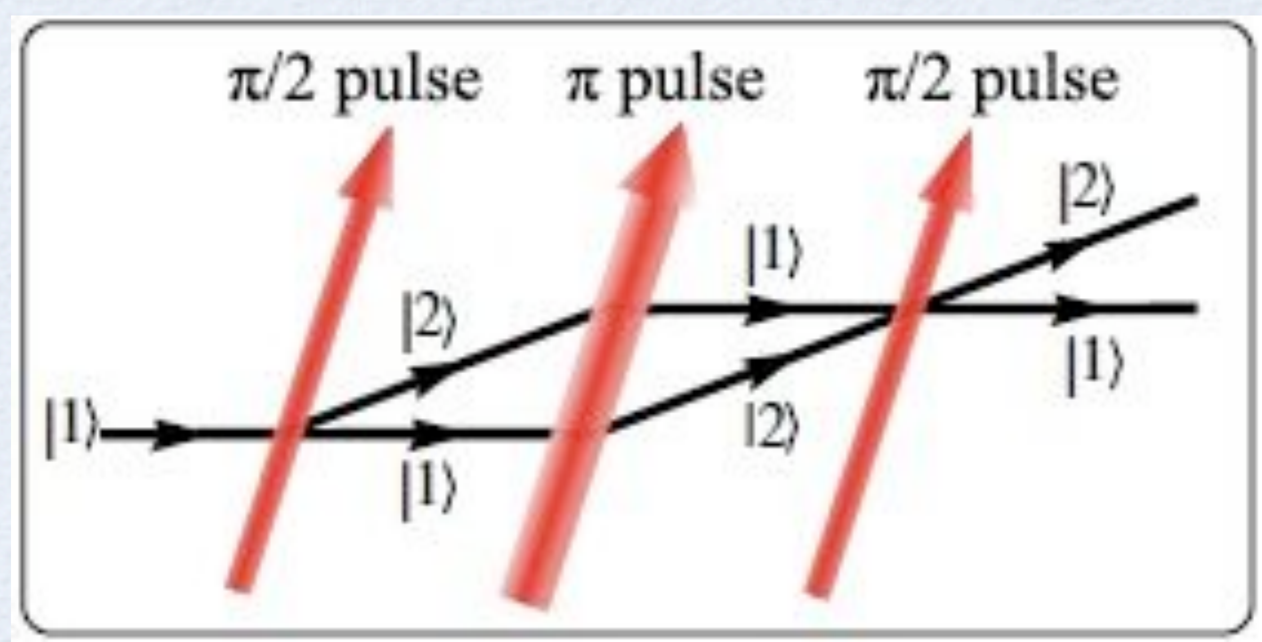
$$\Delta\Phi_{rot} = 2\pi\frac{2m_{at}}{h}A \cdot \Omega$$

$$\frac{\Delta\phi_{mat}}{\Delta\phi_{ph}} \sim \frac{m_{at}\lambda c}{h} \approx 5 \cdot 10^{11}$$

Raman pulse atom interferometer







Light-pulse AI inertial sensors

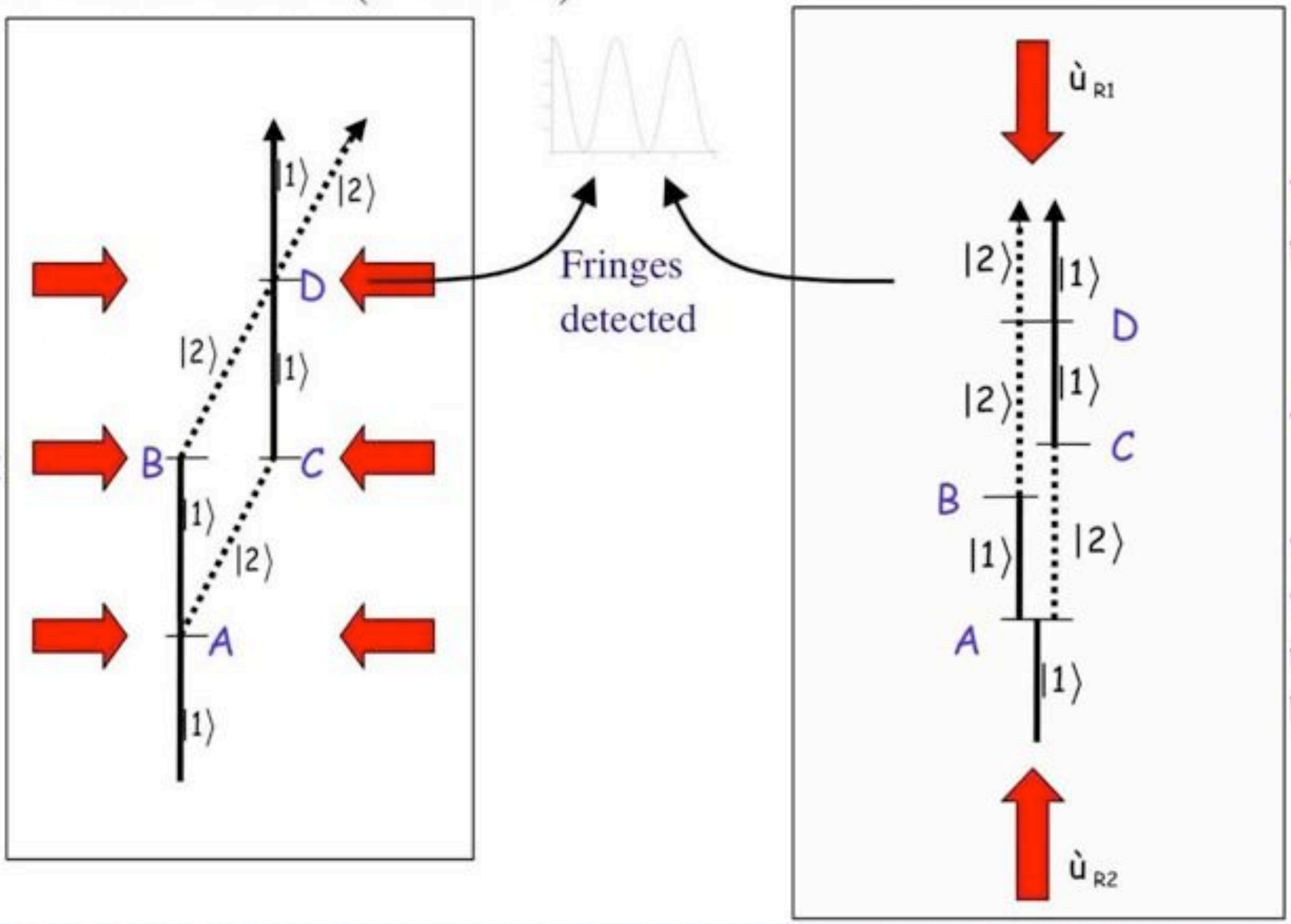
TRANSVERSAL PULSES
- the interferometer encloses an area
- used to measure rotations (GYROSCOPES)

LONGITUDINAL PULSES
- no area enclosed
- used to measure accelerations (GRAVIMETERS)

With an acceleration g, the phase difference

$\Delta\phi = 2k_{eff} \cdot (a - 2(\Omega \times v))\, T^2$

where ***k*** is the laser wavenumber and ***T*** the time interval between laser pulses

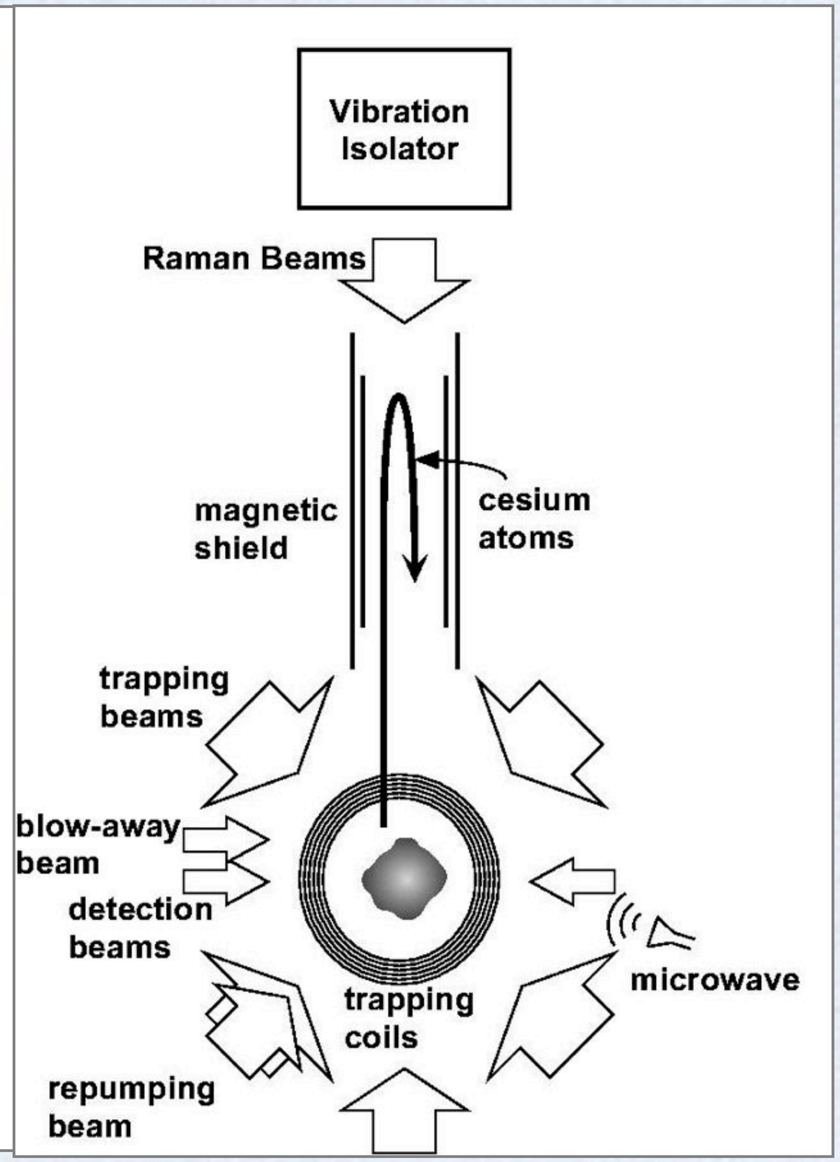


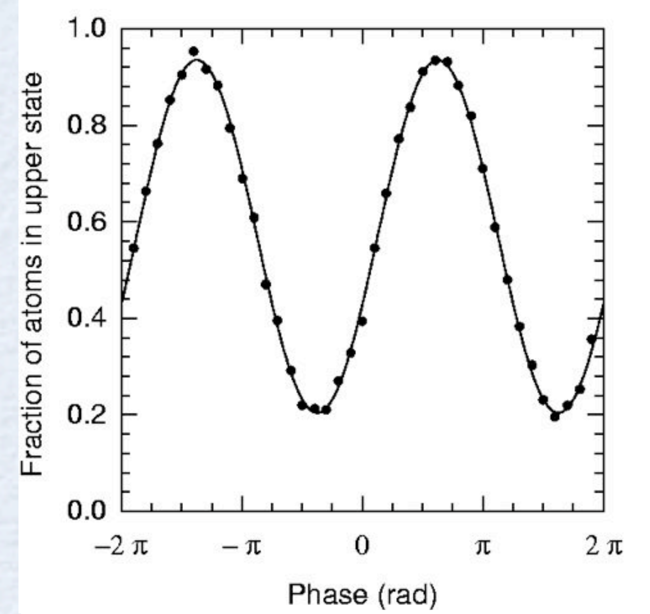
With an acceleration g, the phase difference

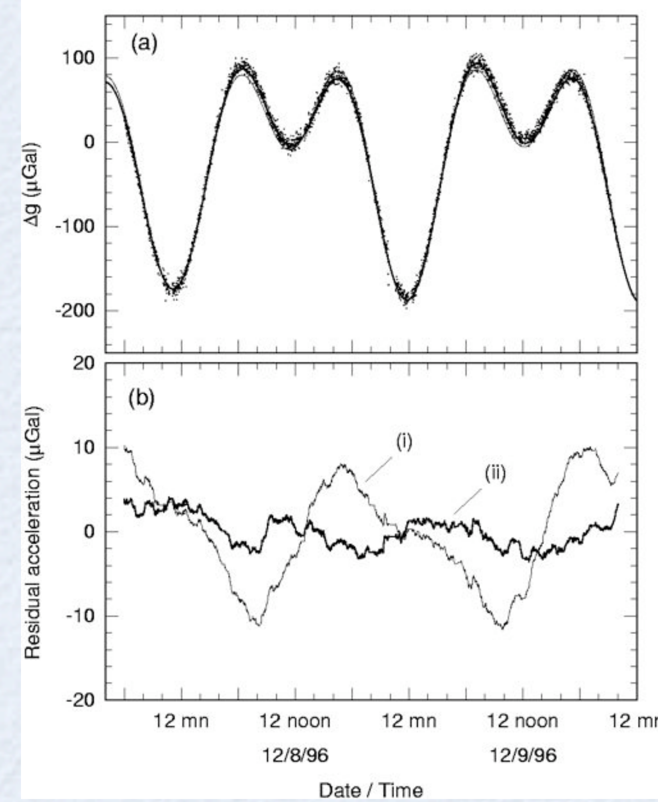
$\Delta\phi = k_{eff}\, g\, T^2$

where ***k*** is the laser wavenumber and ***T*** the time interval between laser pulses

Atom gravimeters (Stanford, Berlin, Paris)



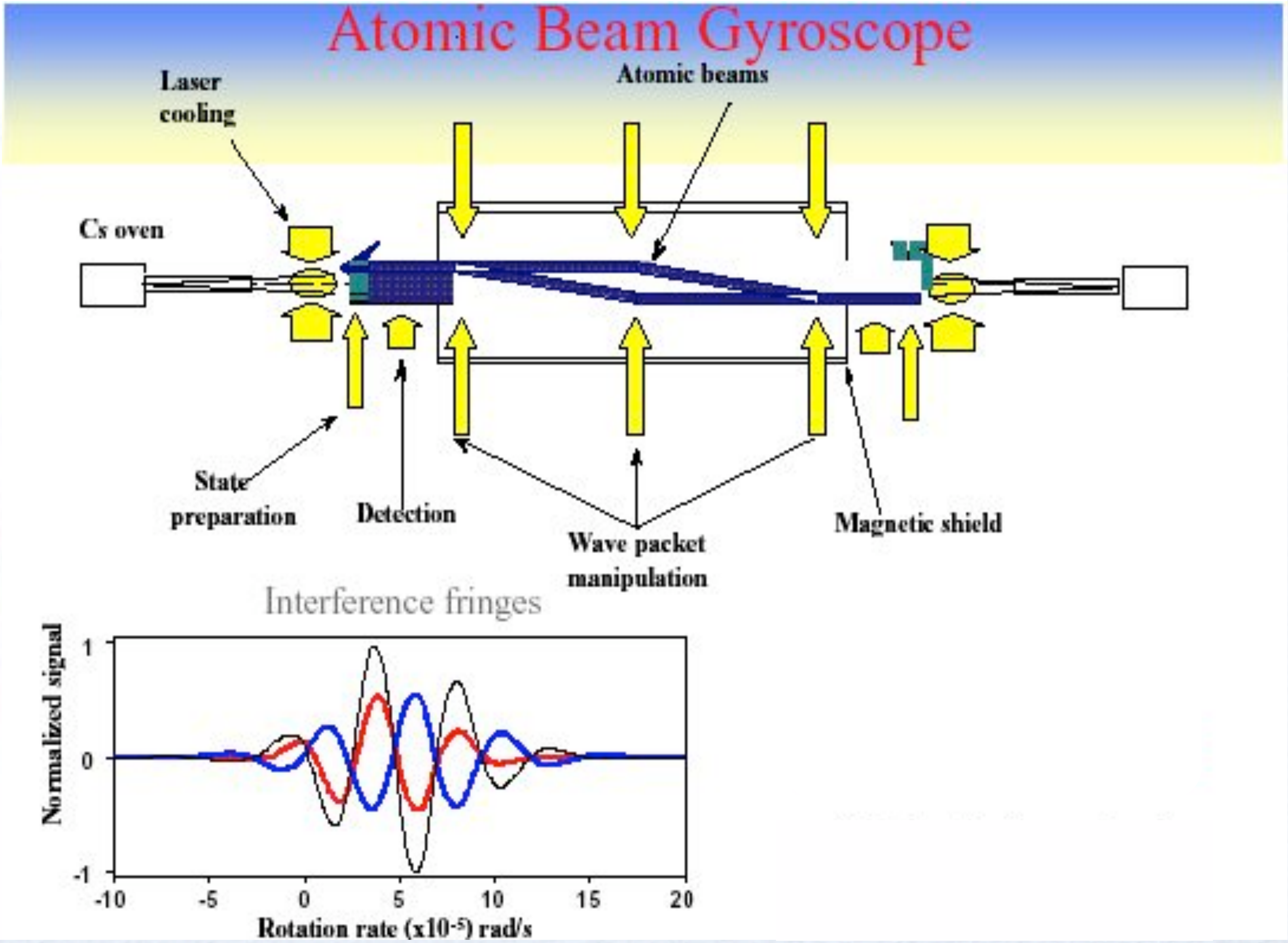




resolution: 8x10^{-9} g in 1 second (Stanford)
averaging down to 8x10^{-10} g after 10 min (Berlin)
accuracy: ~ 10^{-9} g, limited by tidal models

A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)
H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)

Gyroscopes (Stanford, Paris, Hannover)



sensitivity: 6×10^{-10} rad$\cdot$ s$^{-1}\sqrt{Hz}$

scale factor stability < 5 ppm

bias stability $< 70\,\mu$deg/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)

MAGIA

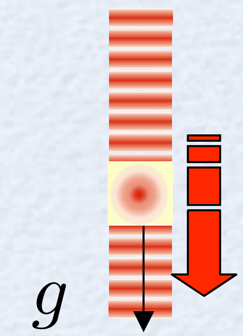
Misura Accurata di G mediante Interferometria Atomica

http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

MAGIA

Misura Accurata di G mediante Interferometria Atomica

- Measure g by atom interferometry

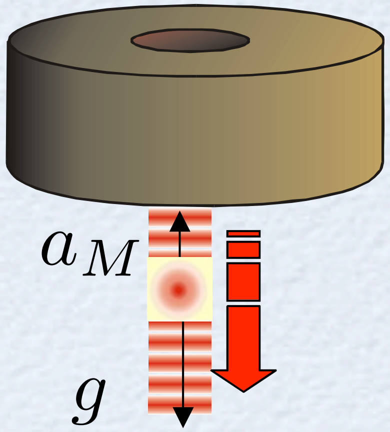


http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

MAGIA

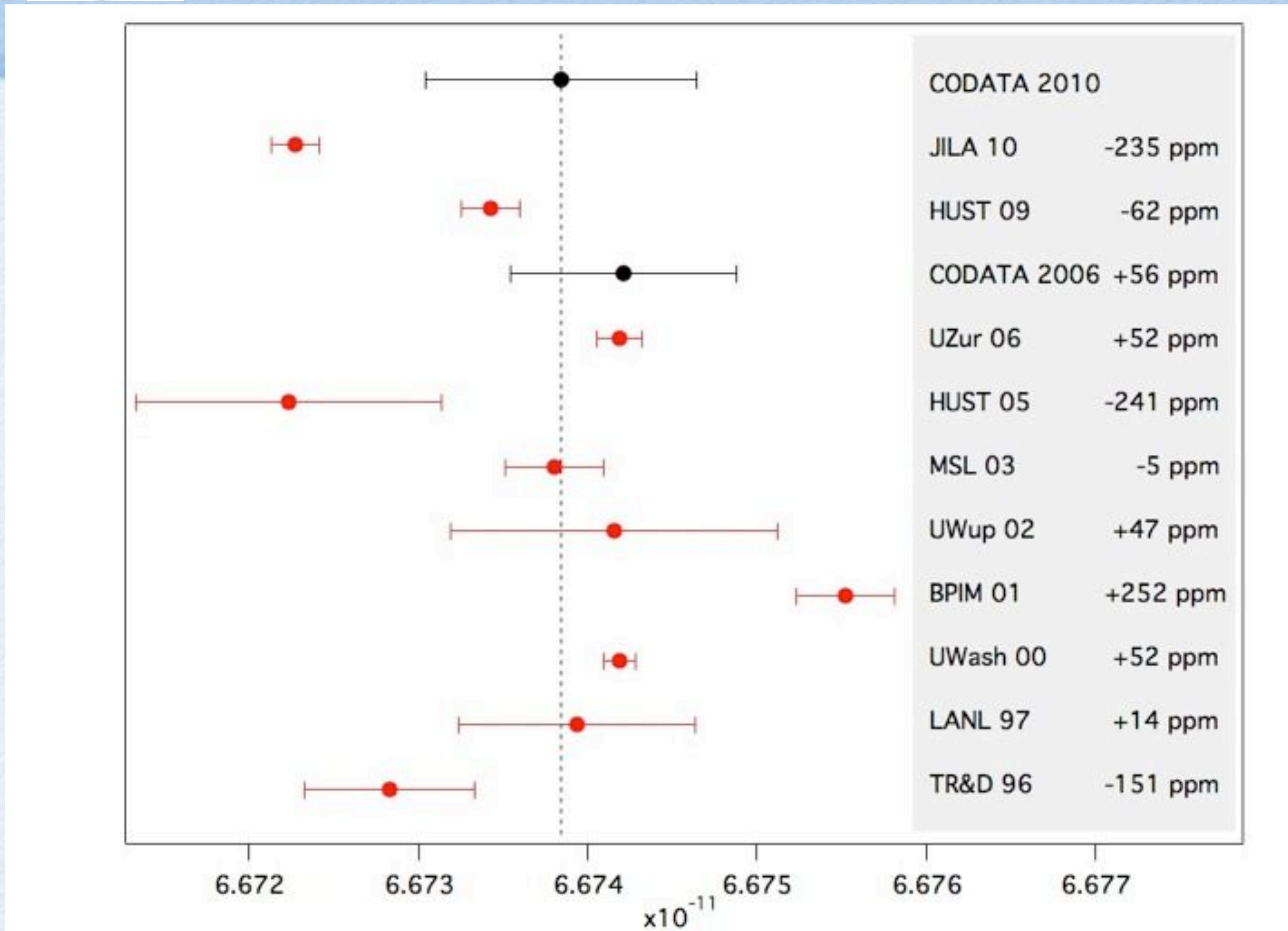
Misura Accurata di G mediante Interferometria Atomica

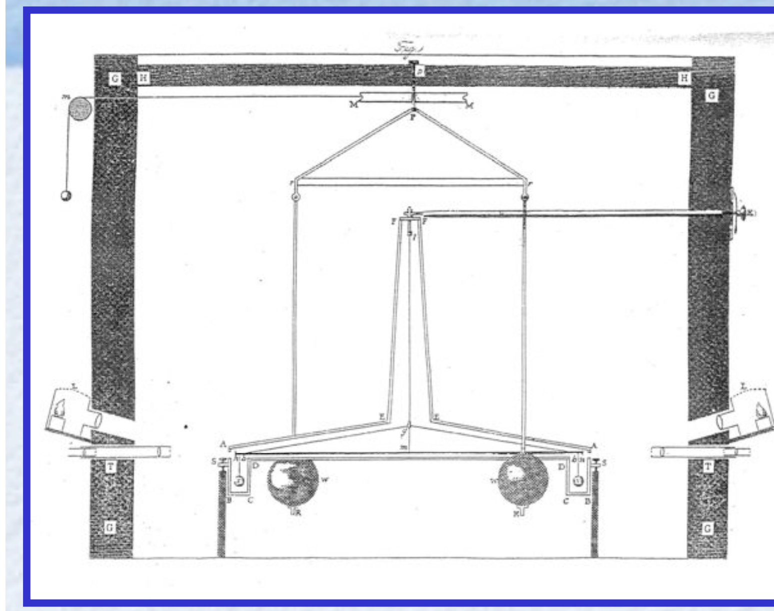
- Measure g by atom interferometry
- Add source masses
- Measure change of g



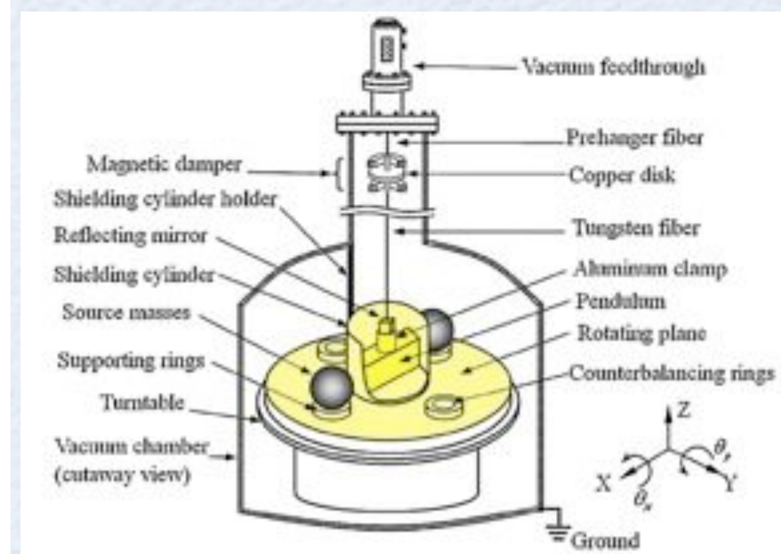
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Motivation





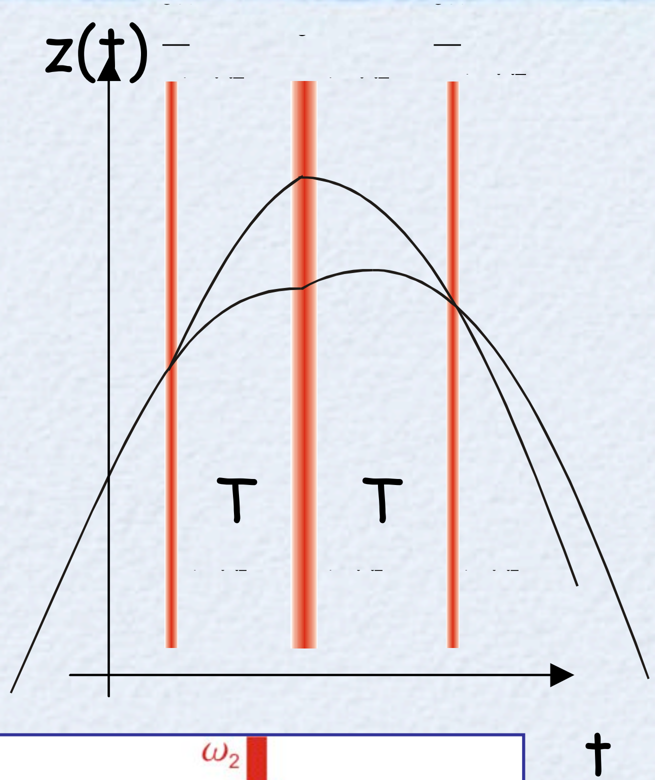
Cavendish 1798



Zang 2009

- Atomic probes
  - point-like test masses in free fall
  - virtually insensitive to stray fields
  - well know and reproducible properties
  - different states, isotopes

Raman interferometry in a ^{87}Rb atomic fountain



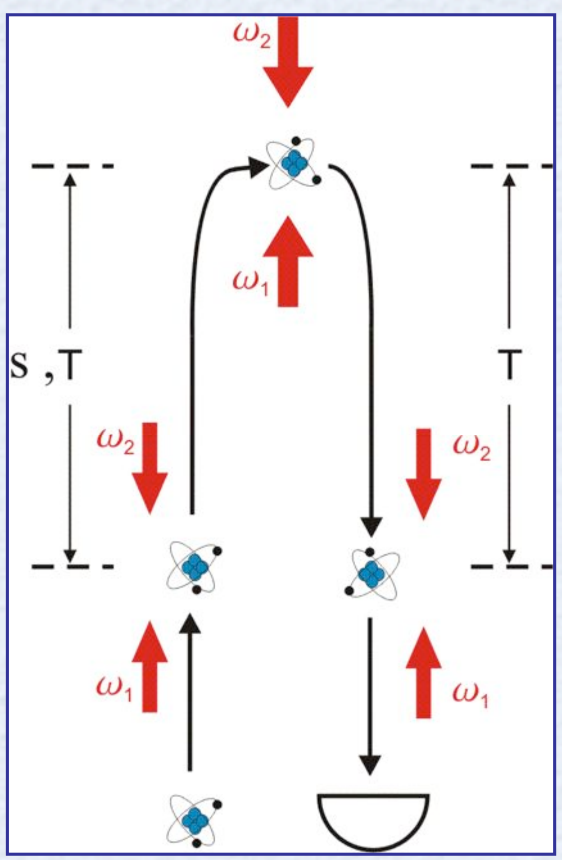
Phase difference between the paths:

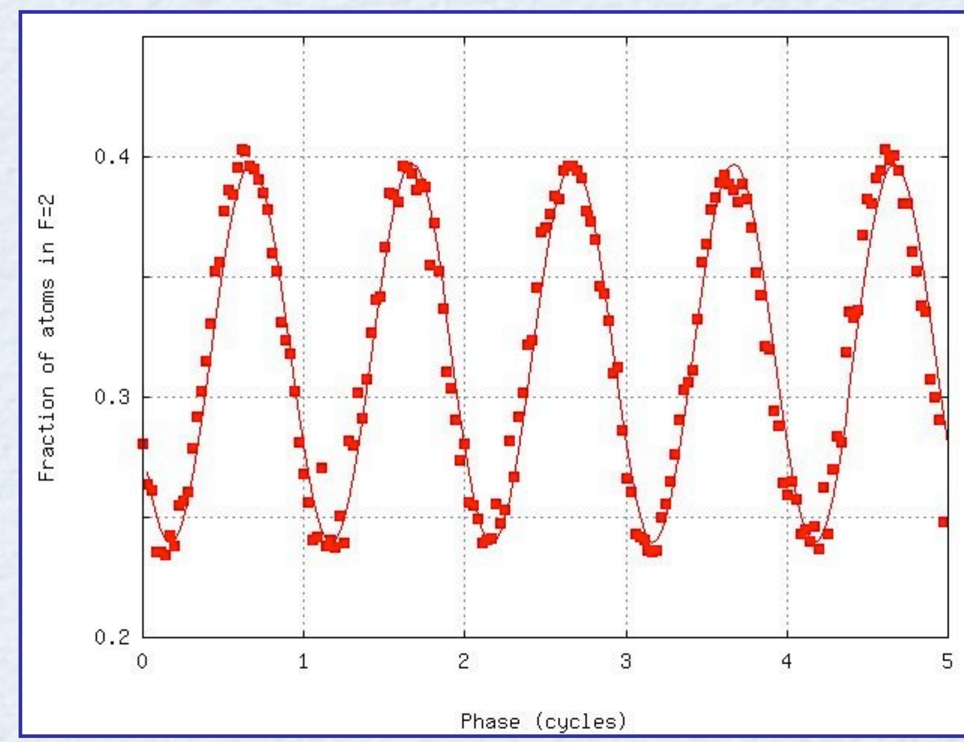
$$\Delta\Phi = k_c[z(0)]2z(T)] + \Phi_e$$

$$k_e = k_1 - k_2$$

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

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





Final population:

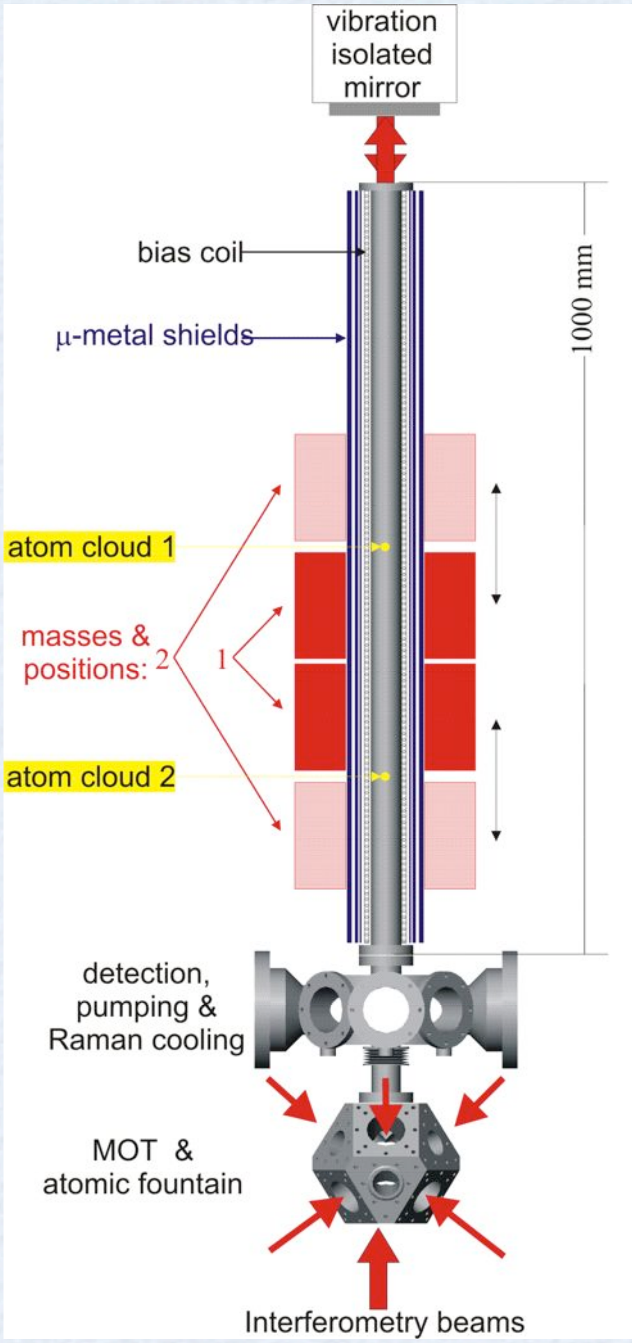
$$N_a = N/2(1 + cos[\Delta\Phi])$$

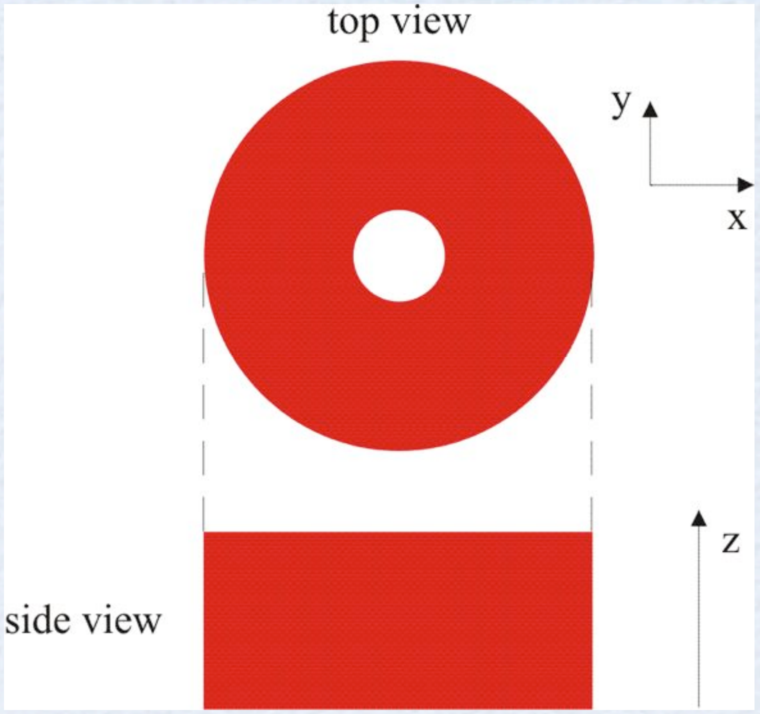
$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

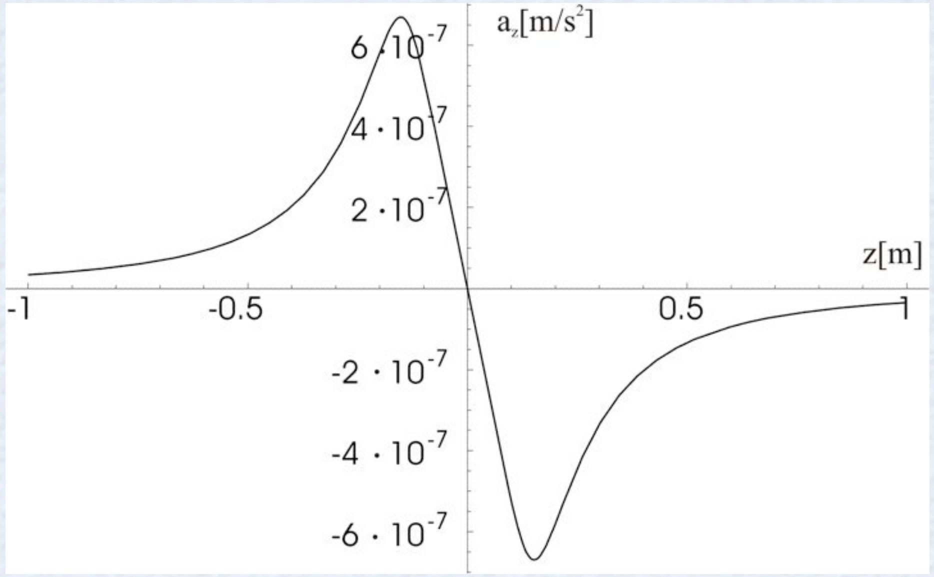
S/N=1000 $\rightarrow$ Sensitivity 10^{-9} g/shot

A. Peters et al., Nature **400**, 849 (1999)

Atom gravimeter + source masses







500 Kg tungsten mass

Peak mass acceleration $a_g \sim 10^{-7}$ g

10000 shots $\rightarrow \Delta G/G \sim 10^{-4}$

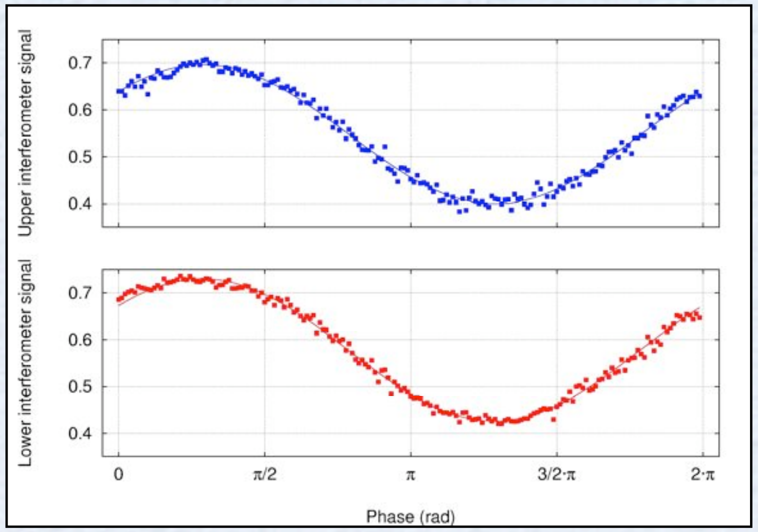
Sensitivity 10^{-9} g/shot

one shot $\rightarrow \Delta G/G \sim 10^{-2}$

Raman gravity gradiometer

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

Raman gravity gradiometer

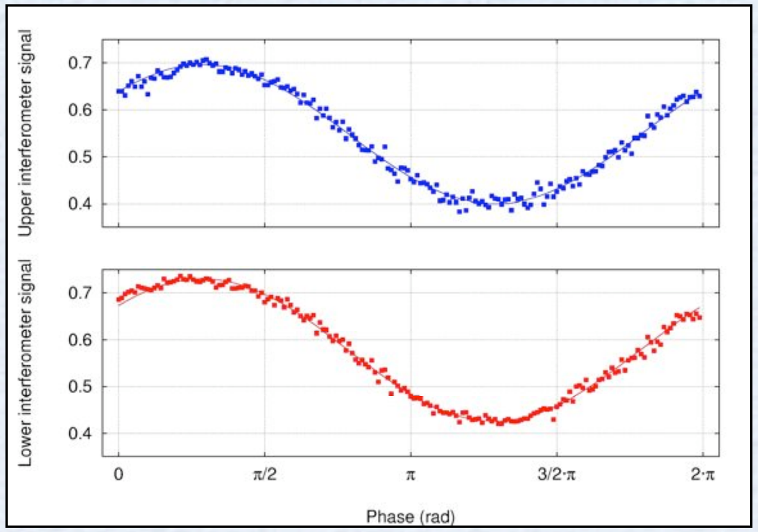


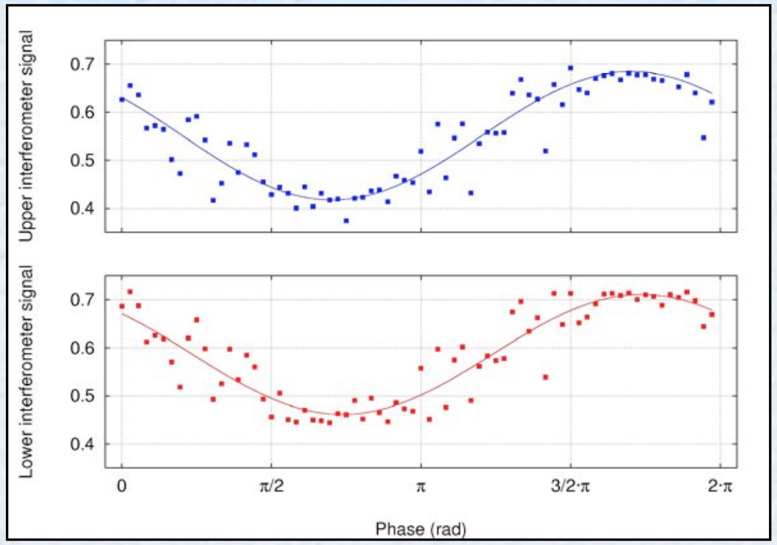
T=5 ms

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

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

Raman gravity gradiometer



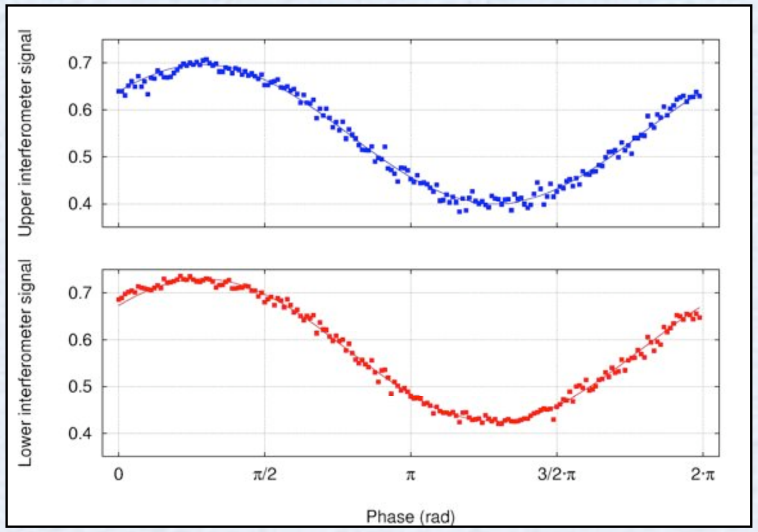


$$\mathrm{T}=5\ \mathrm{ms}$$
$$\mathrm{resol.}\ = 2.3 \times 10^{-5}\mathrm{g/shot}$$

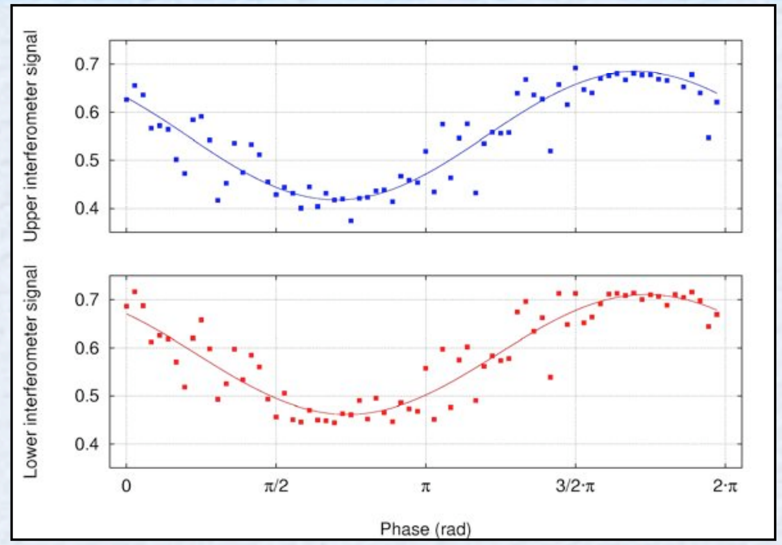
$$\mathrm{T}=50\ \mathrm{ms}$$
$$\mathrm{resol.}\ = 1.0 \times 10^{-6}\mathrm{g/shot}$$

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

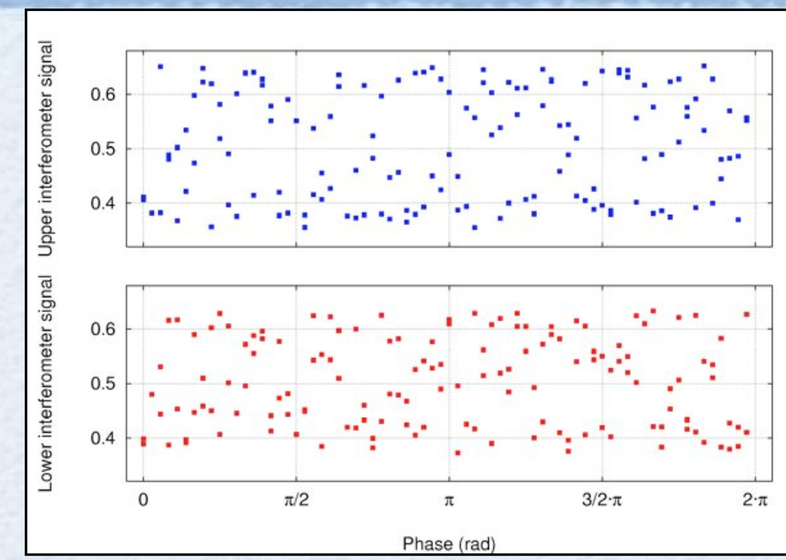
Raman gravity gradiometer



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



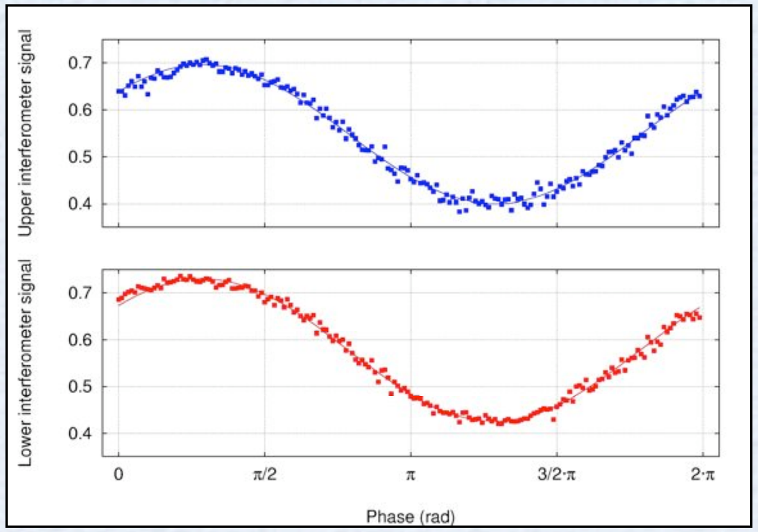
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot



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

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

Raman gravity gradiometer



T=5 ms
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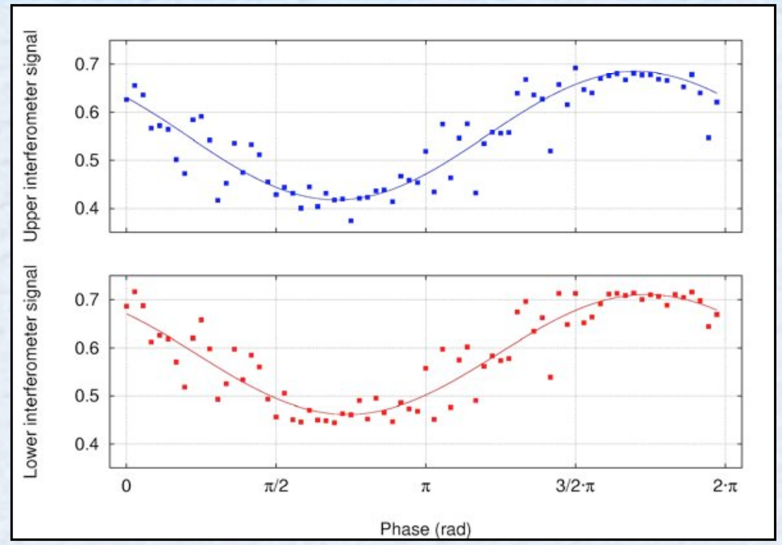

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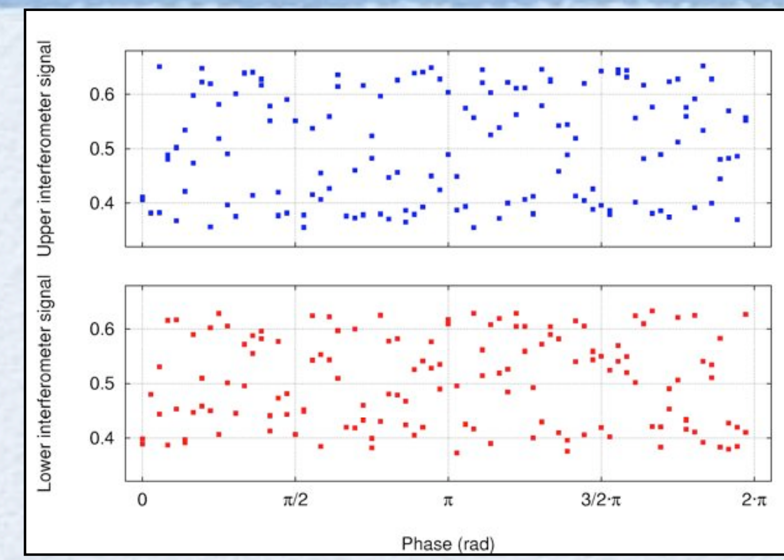

T=150 ms
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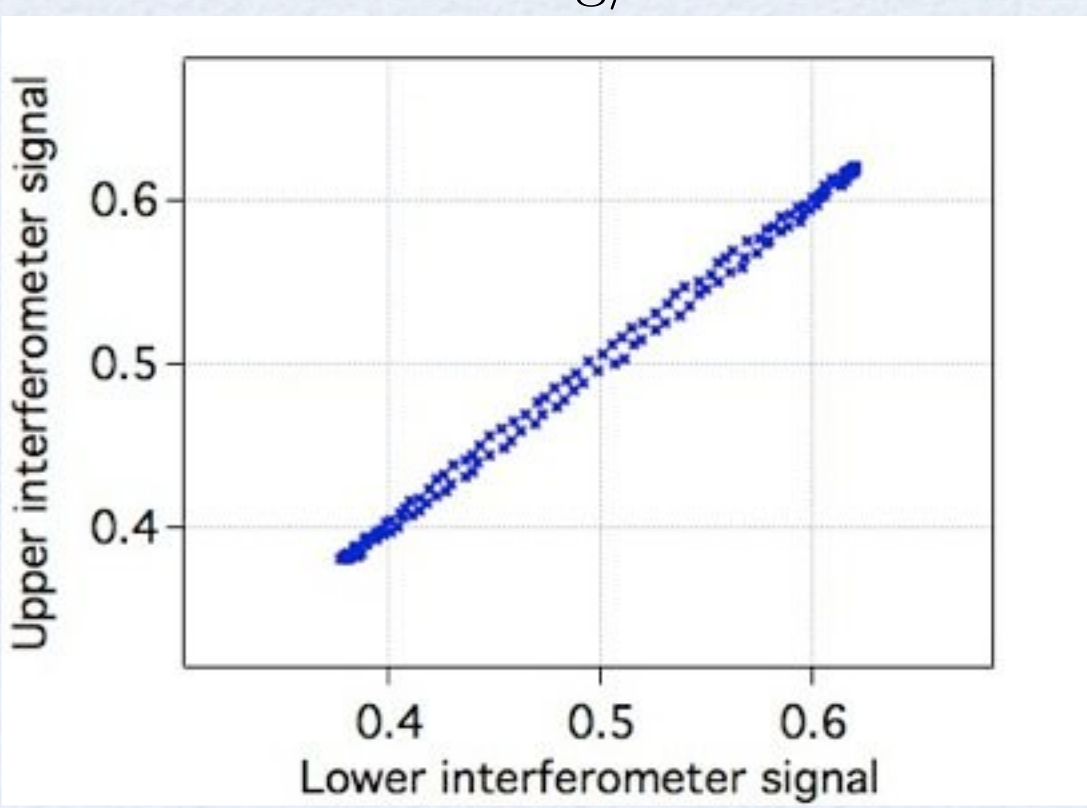
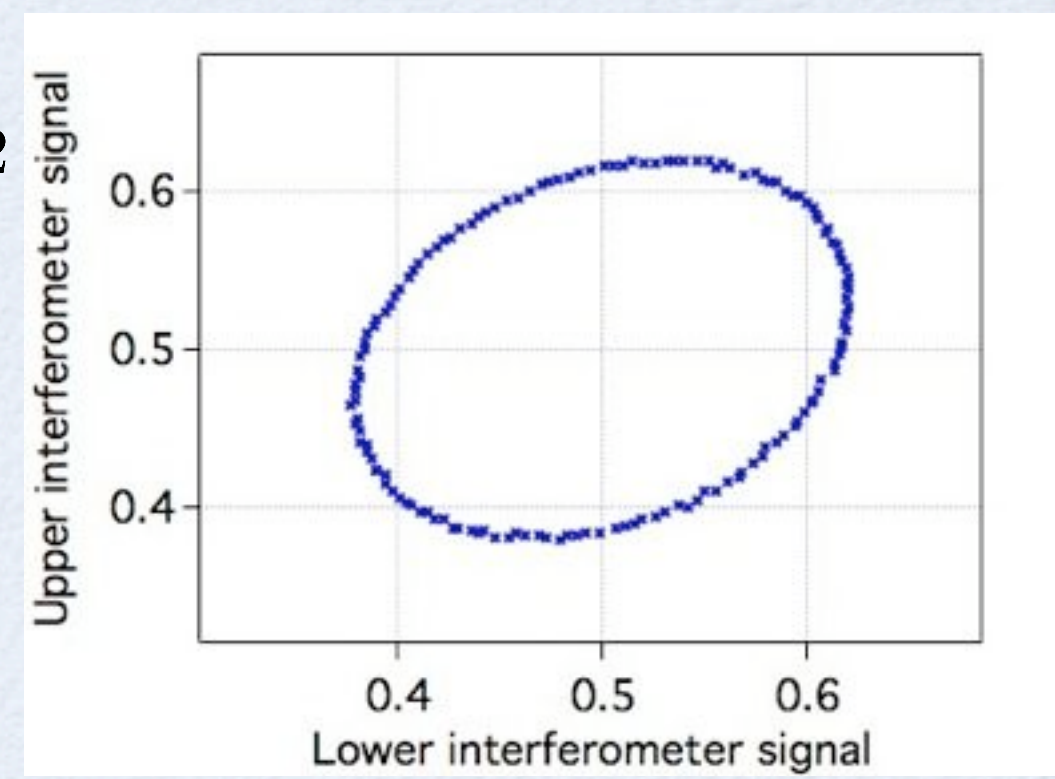
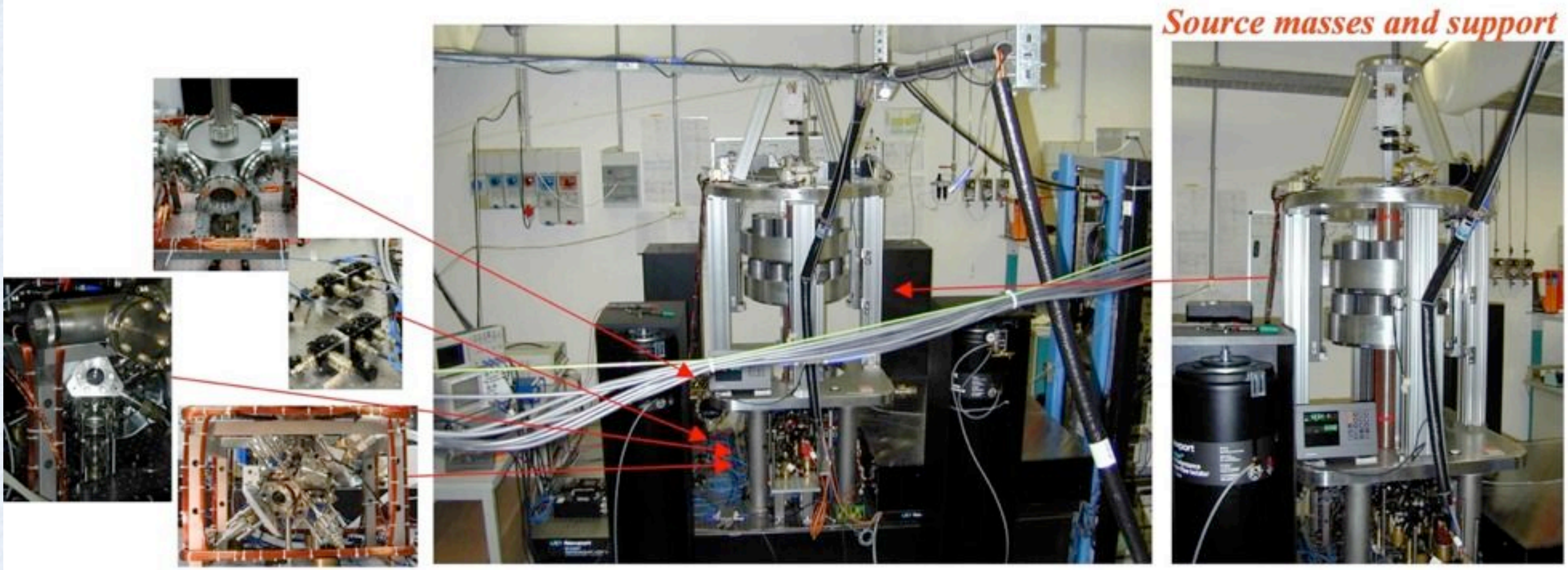


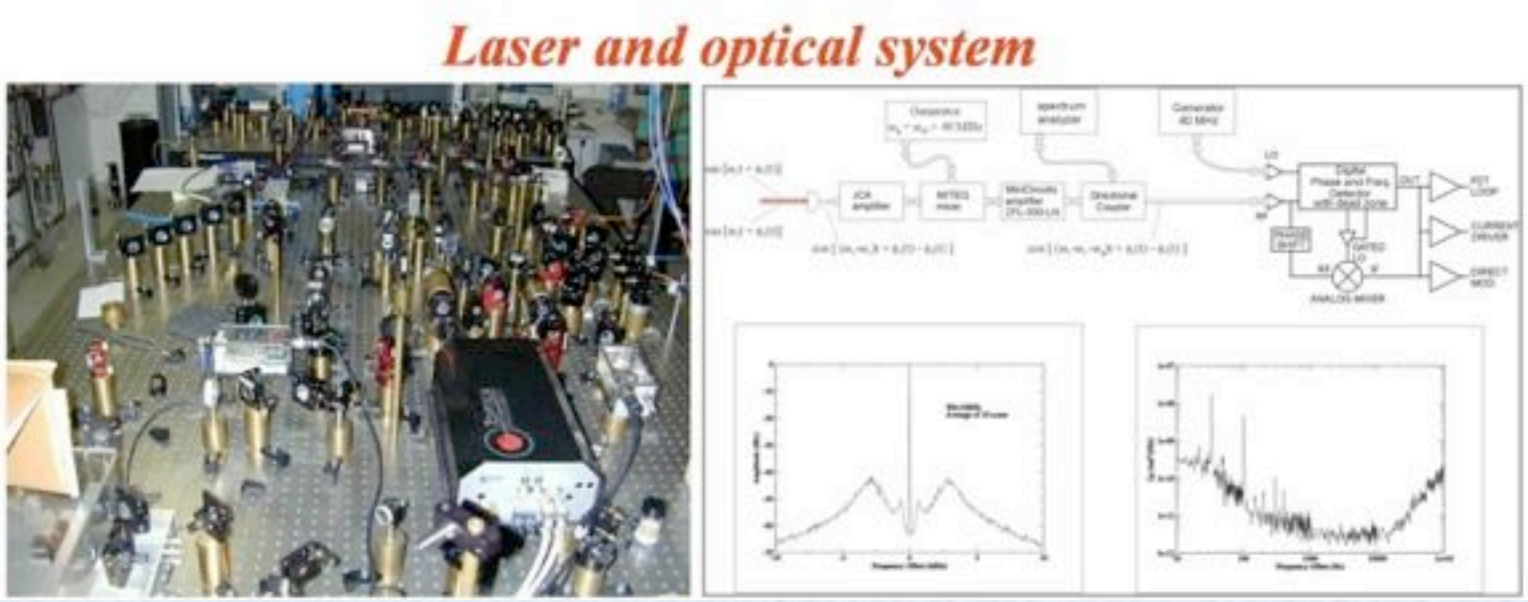
$$\Delta\Phi = k_e g T^2$$



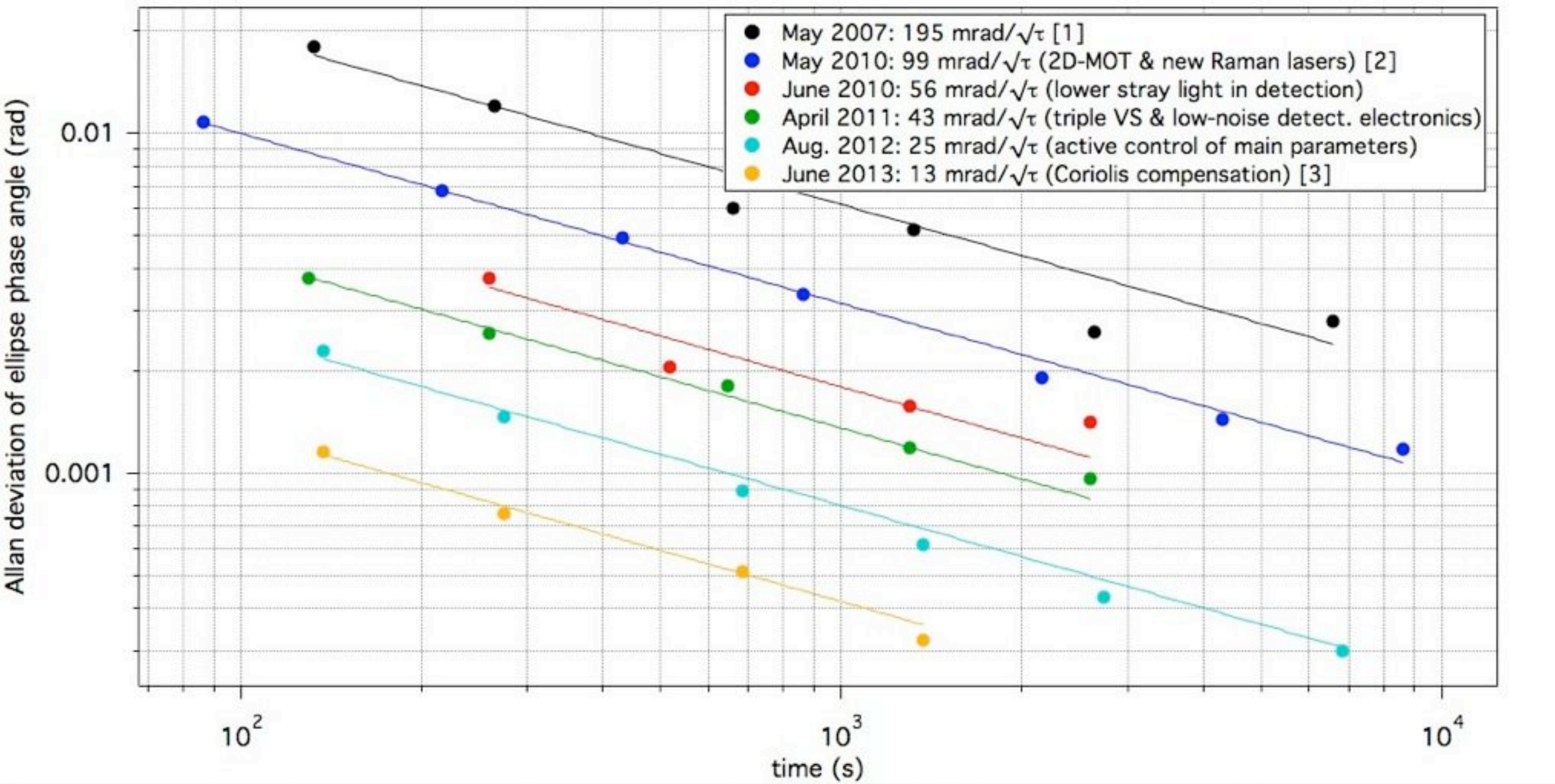
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

The MAGIA apparatus





Short-term sensitivity



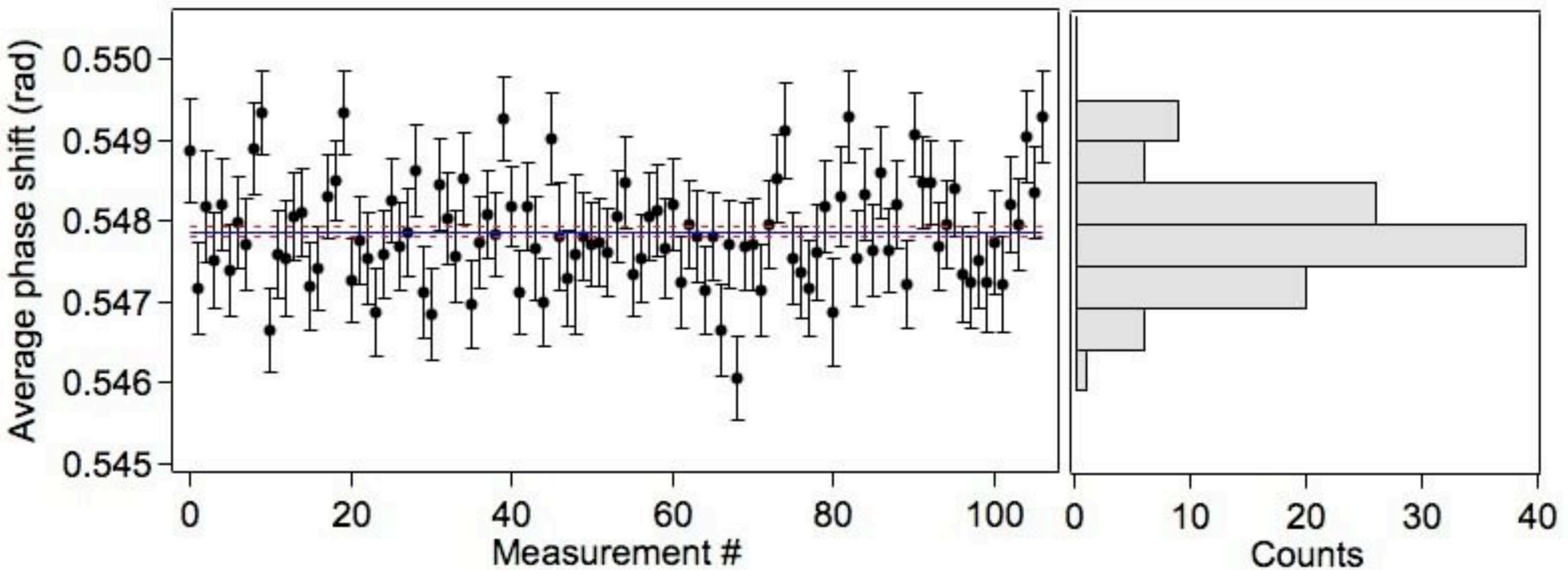
Current sensitivity to differential acceleration: 3×10^{-9} g @ 1s (=QPN for 4×10^{5} atoms)

[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)

[2] F. Sorrentino et al., New J. Phys. **12**, 095009 (2010)

[3] F. Sorrentino et al., Phys. Rev. A **89**, 023607 (2014)

G measurement



From our data we deduce G=6.67191(77)(65)$m^3kg^{-1}s^{-2}$

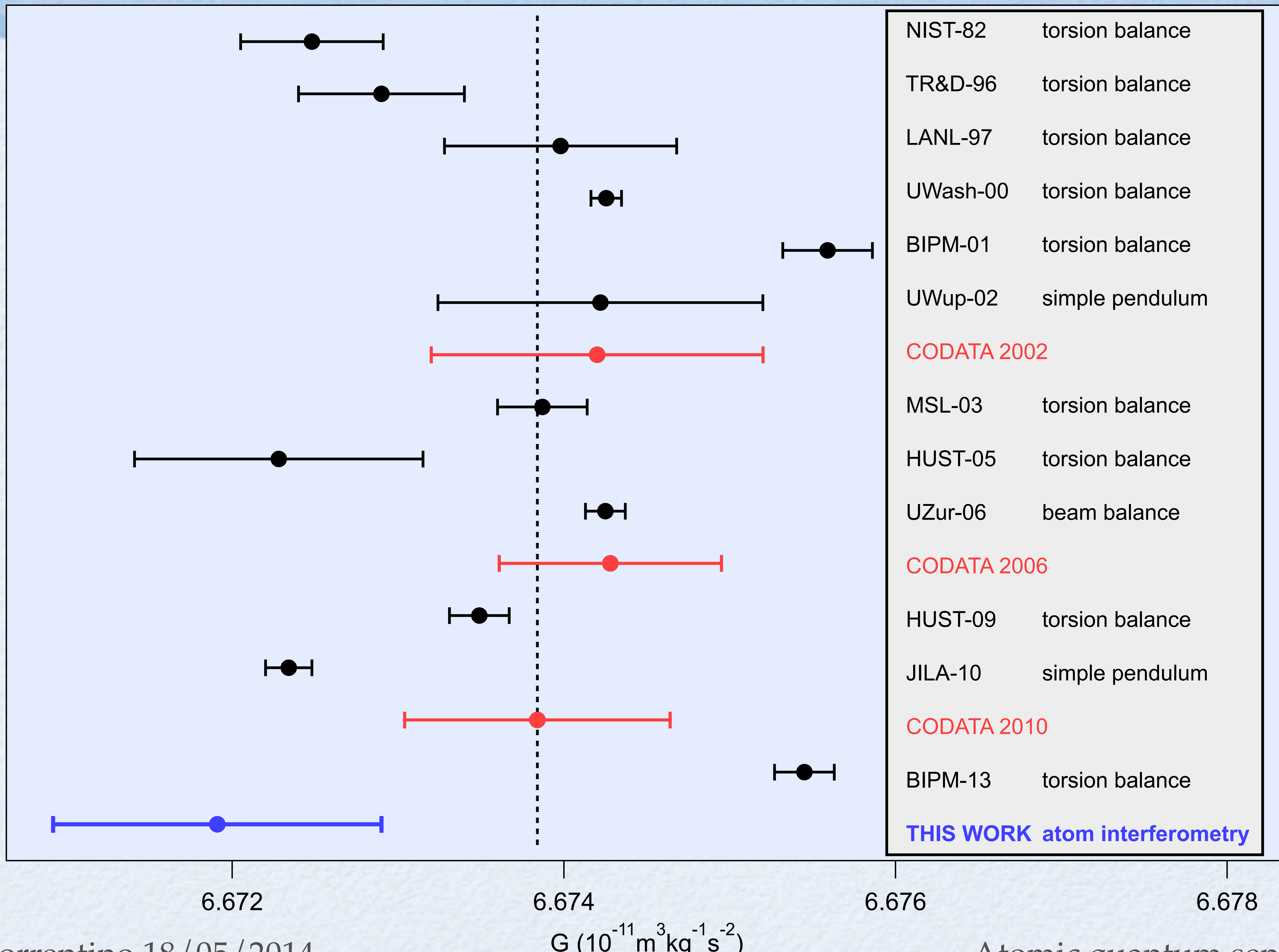
Statistical error 116 ppm

Systematic error 92 ppm

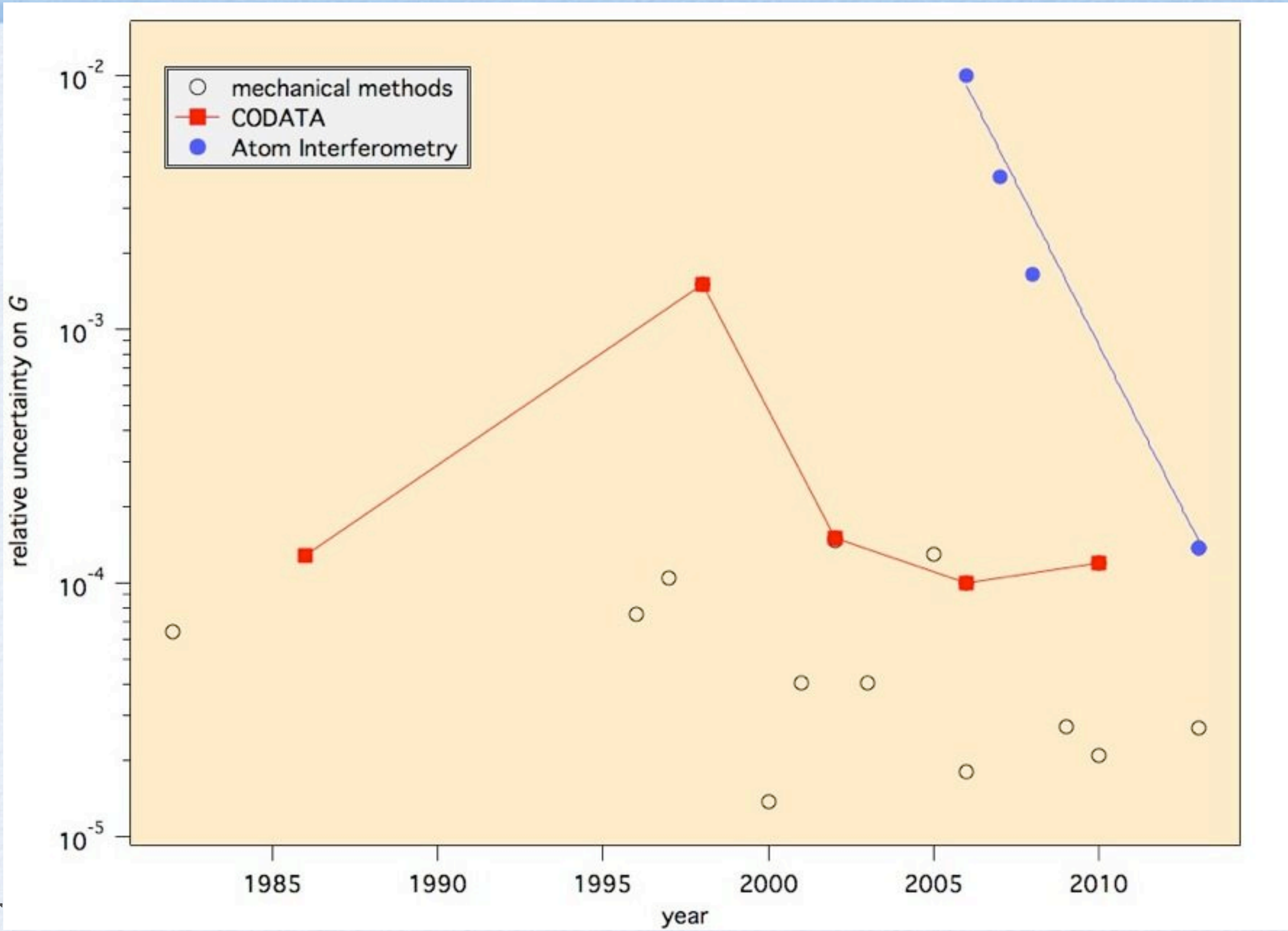
G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli and G. M. Tino, *Precision Measurement of the Newtonian Gravitational Constant Using Cold Atoms*, to be published on Nature

Under embargo until publication

G measurements: current status



From proof of principle to G measure

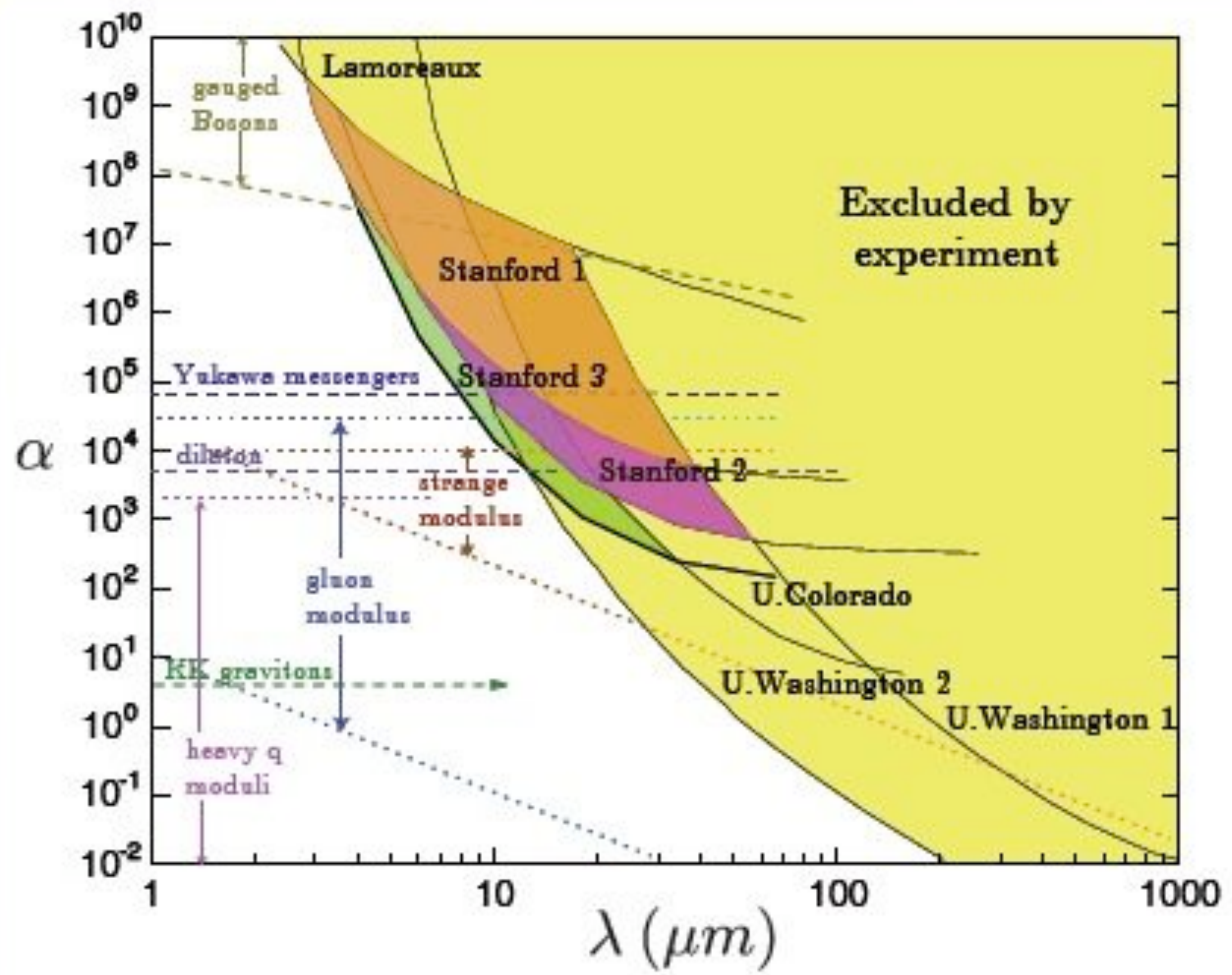


F. Sor

Other possible applications of AI

- Fundamental physics
  - measurement of fine-structure constant (through photon recoil)
  - test of equivalence principle (by dropping two atomic species)
  - test of atom neutrality
  - GW detection
  - quantum gravity
    - force measurements at micrometer scale
    - see also G. Amelino-Camelia,, C. Laemmerzahl,, F. Mercati, and G. M. Tino, *Constraining the energy-momentum dispersion relation with Planck-scale sensitivity using cold atoms*, Phys. Rev. Lett. **104**, 039901(E) (2010)
  - search for new physics beyond SM (see for example F. Terranova & G. M. Tino, *Testing the a_μ anomaly with a_e: experimental perspectives and the role of atom interferometry*, arXiv 1312.2346, to appear on Phys. Rev. A)
- Metrology
  - definition of mass unit through Watt balance
- Earth observations
  - ground (mineral & oil explor., volcano monitoring, earthquake forecast)
  - airborne (underground structures, cavities, mineral & oil exploration)
  - satellite (geoid mapping, inertial navigation)

Short-range force measurements

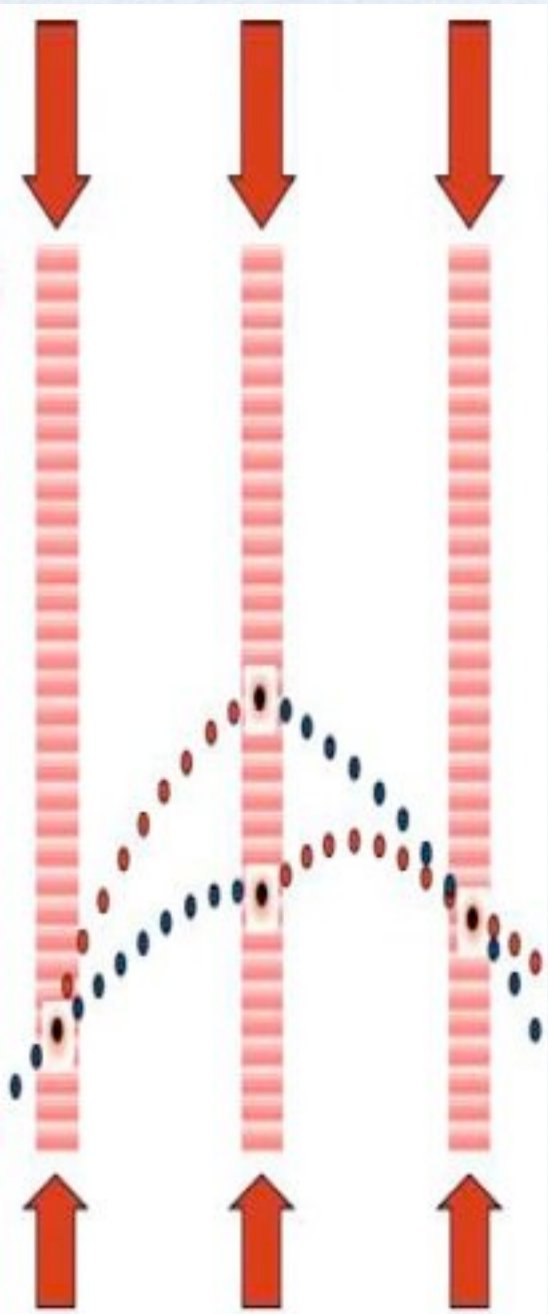


Geraci et al. Phys. Rev. D **78** 22002 (2008)

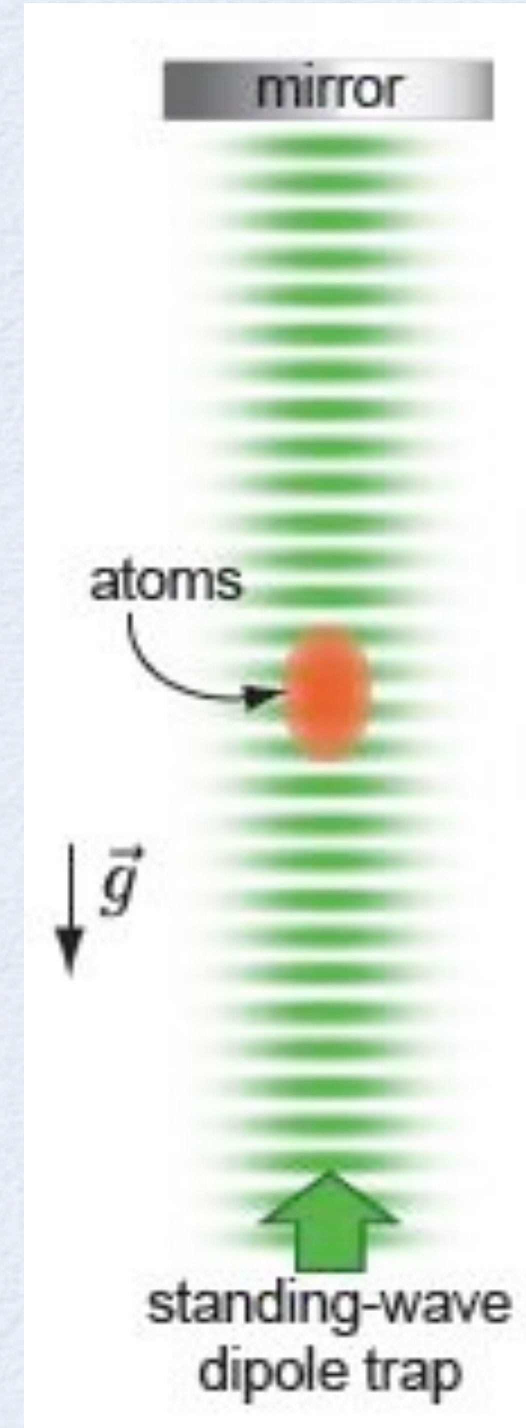
- Characterization of the Casimir-Polder effect
- Exotic theories predict violations of Newton's law on some length scale
- Effect parametrized through Yukawa potential
- experiment set limits in parameters space $(\alpha - \lambda)$

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

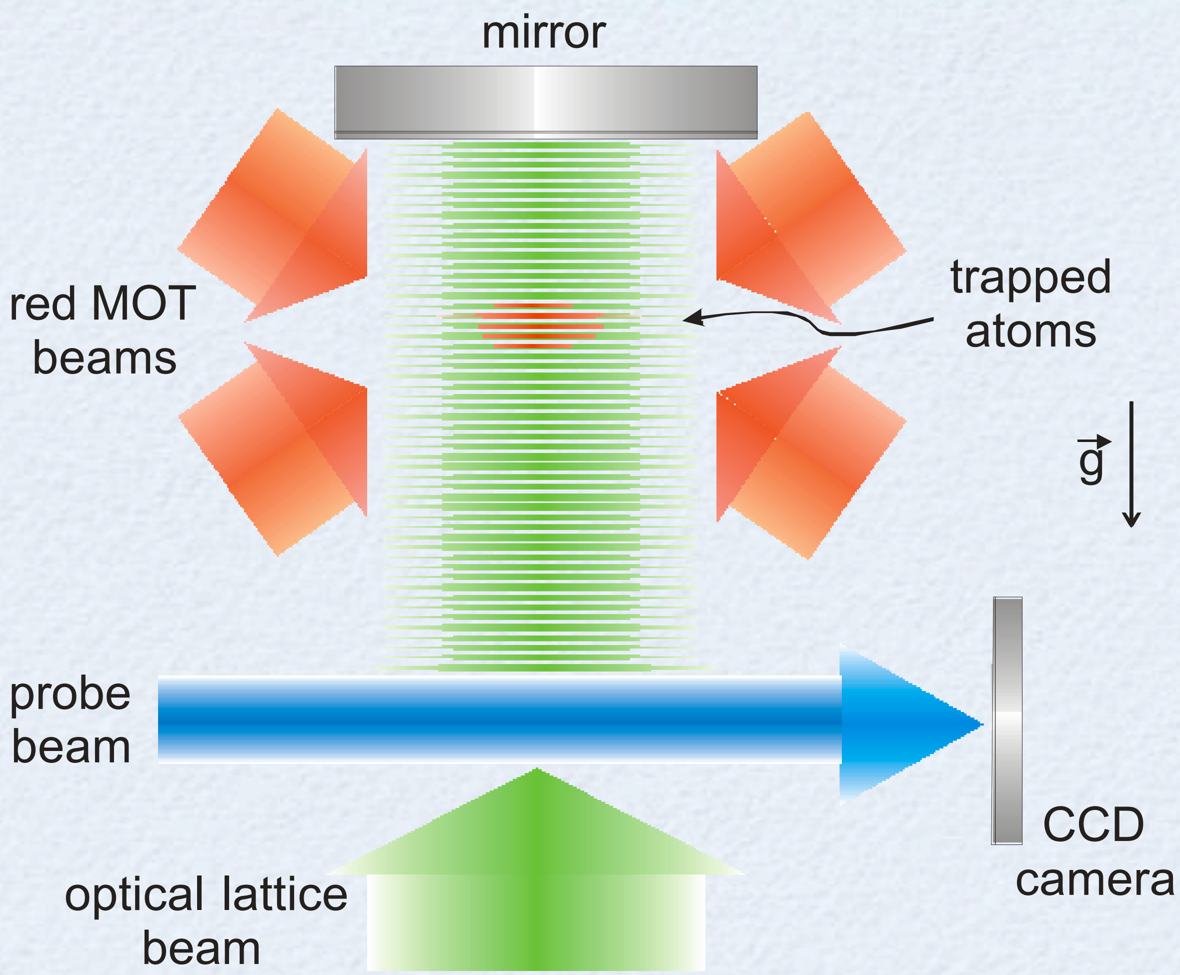
Freely falling vs trapped atoms

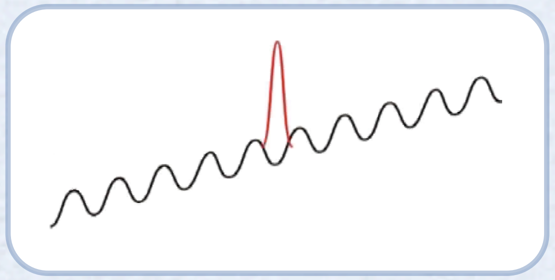


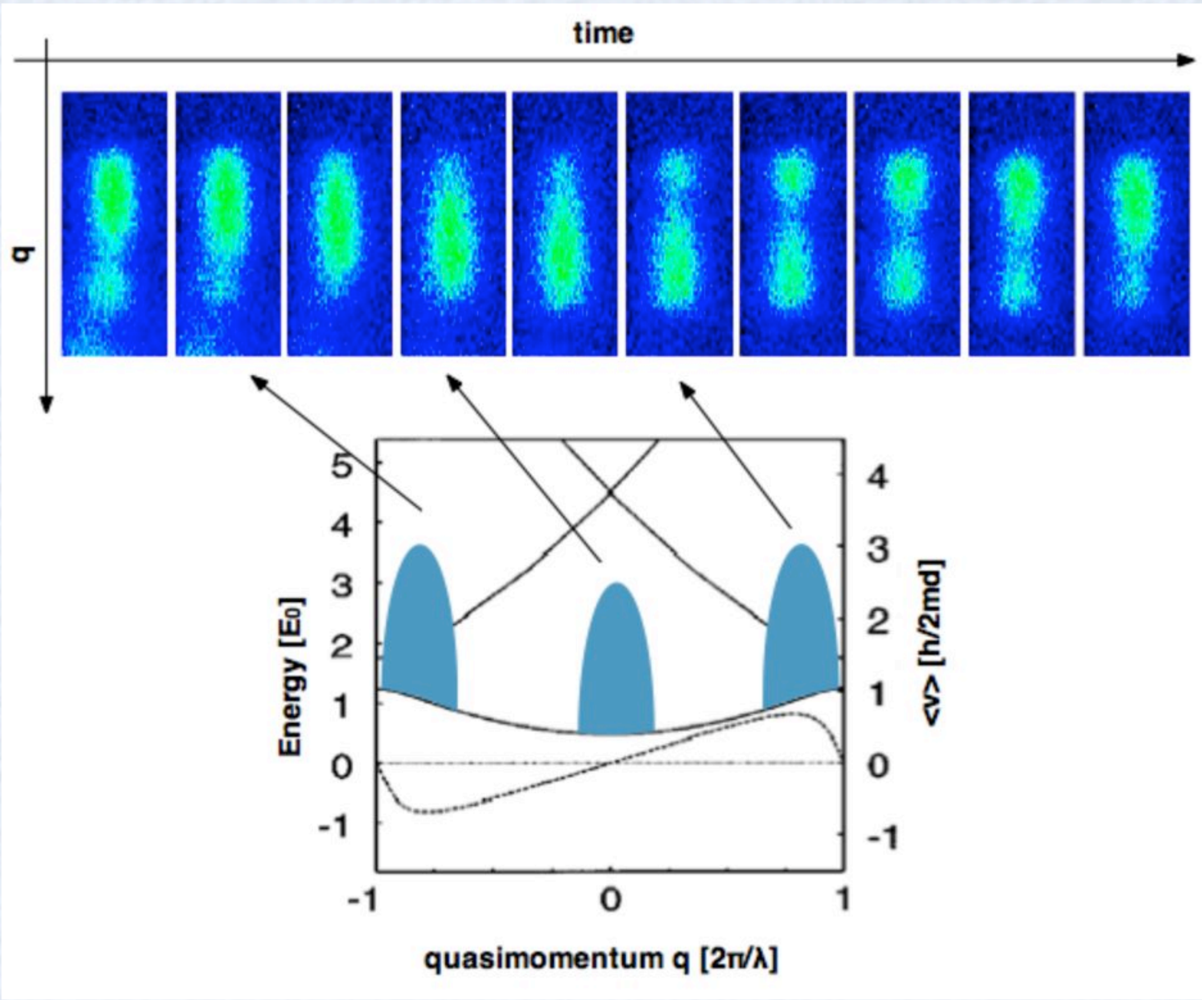
- Light-pulse (Raman or Bragg) atom interferometry
  - highest precision and highest accuracy so far demonstrated
  - atomic wave-function evolves in the absence of external fields
- AI in optical lattices
  - No free fall or free expansion
  - Small intrinsic size of the sensor
  - but... perturbation by laser field and by interatomic collisions



Bloch oscillations in optical lattice

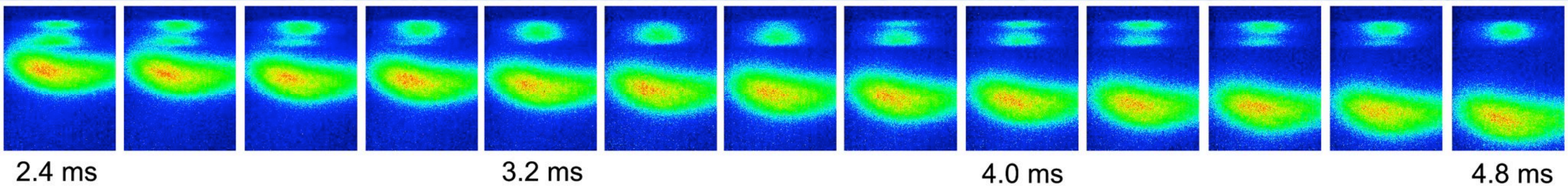


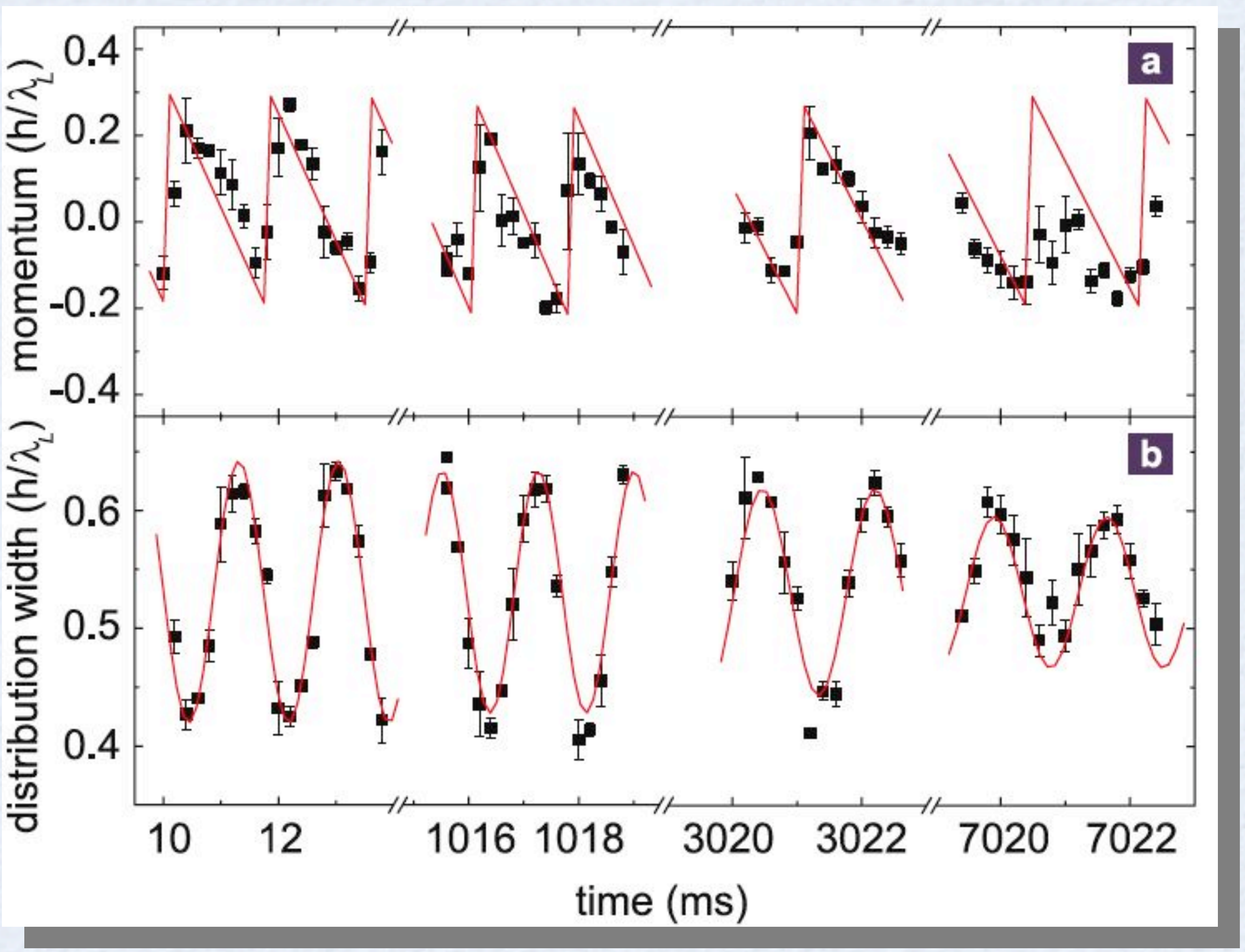




$$q(t) = q_0 + Ft/\hbar \quad \Rightarrow \quad \nu_B = \frac{F\lambda}{2h} = \frac{mg\lambda}{2h}$$

Bloch oscillations of ^{88}Sr





Bloch frequency 574.568(3) Hz

8000 photon recoils in 7 s

g_{meas}=9.80012(5) m/s^2

*G. Ferrari et al., PRL **97**, 060402 (2006)*

Decoherence time > 500 s

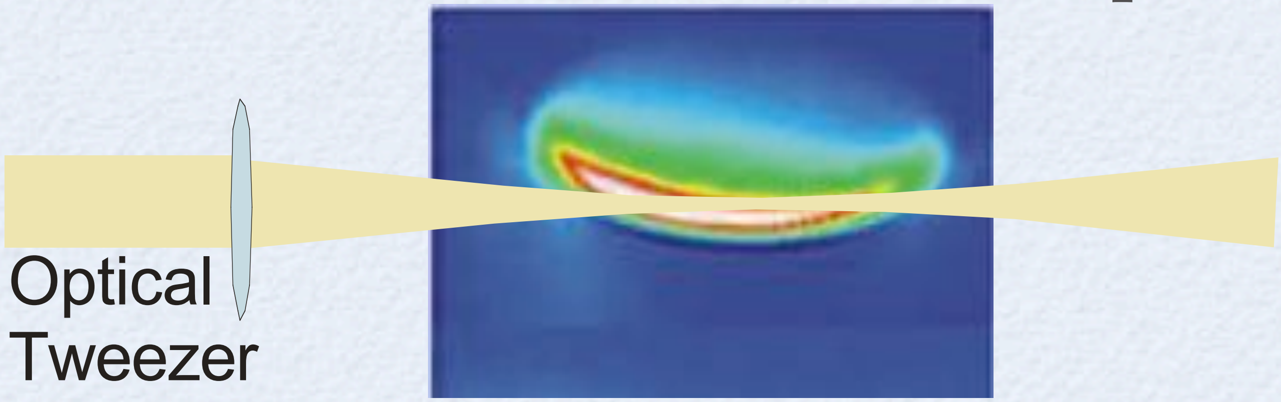
*M. Tarallo et al., PRA **86**, 033615 (2012)*

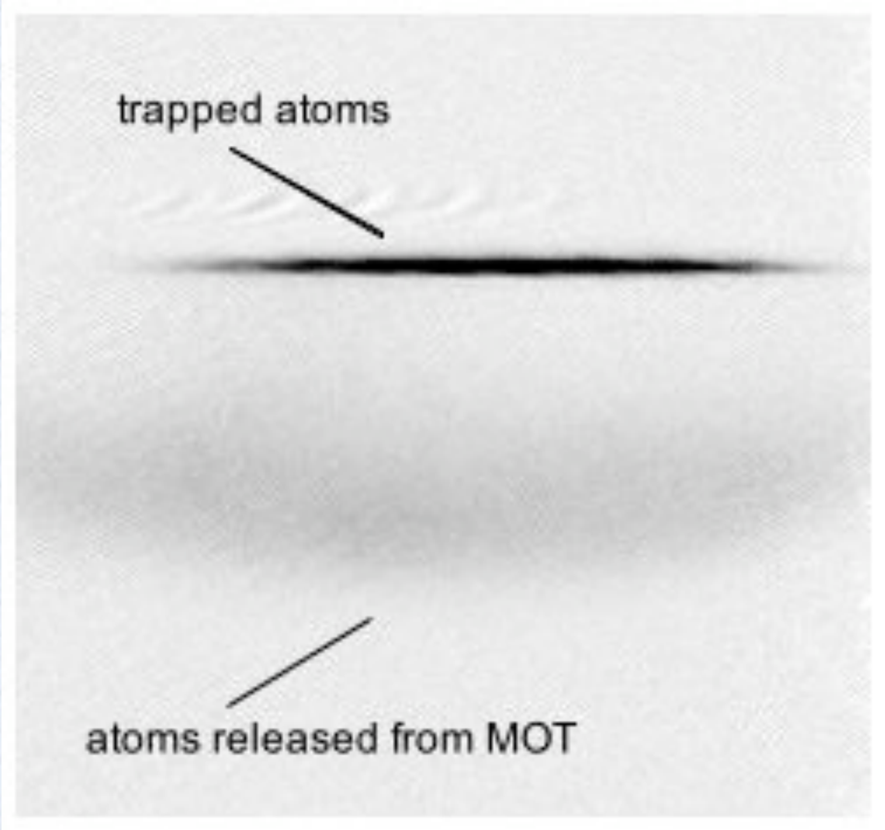
- Direct acceleration sensitivity limited by the small splitting (~1 μm)
- However, acceleration via BO already employed for LMT splitters in free-fall interferometers

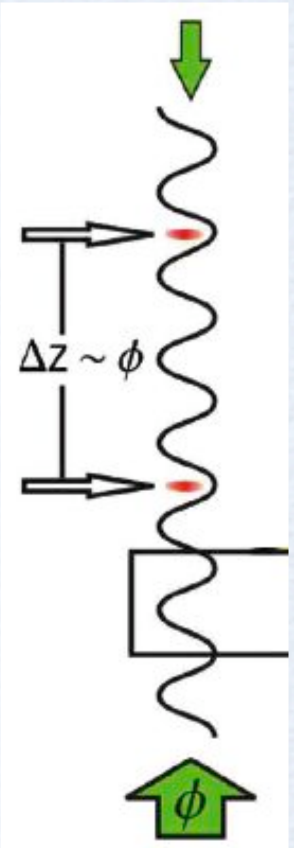
*H. Mueller et al., PRL **102**, 240403 (2009)*

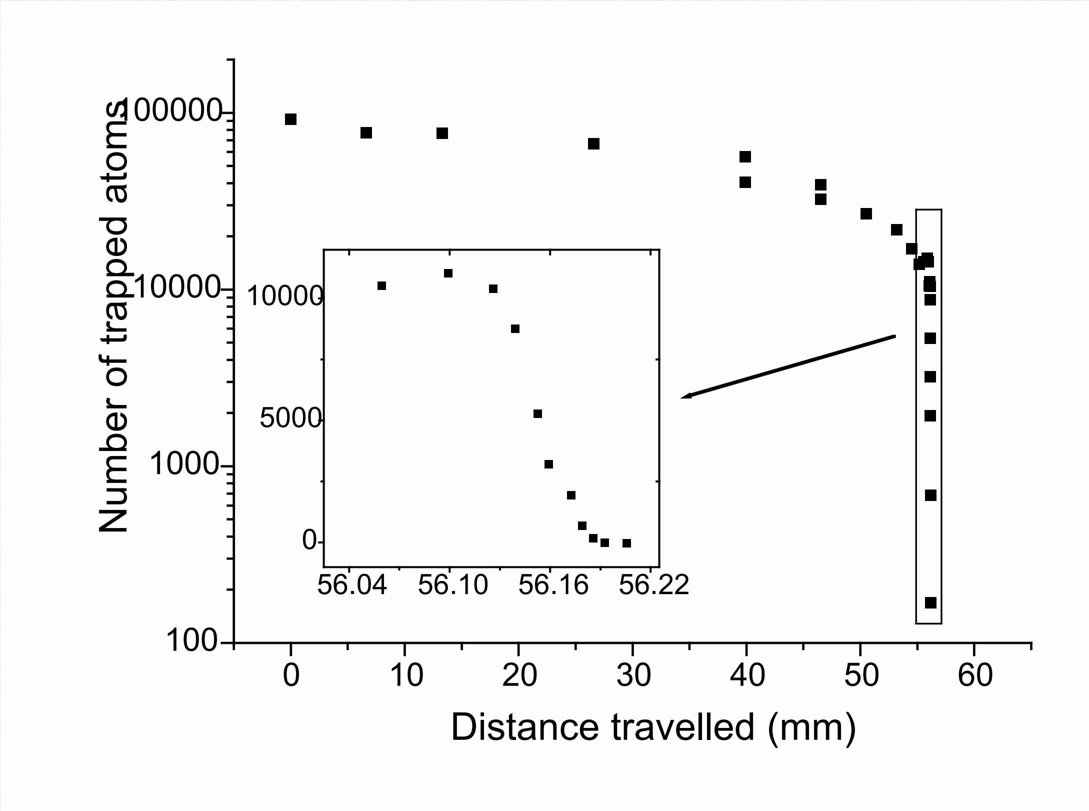
Sample manipulation at μm scale

- Vertical size in final MOT ≈ 12 μm rms
- We reduce it to 4 μm with an optical tweezer





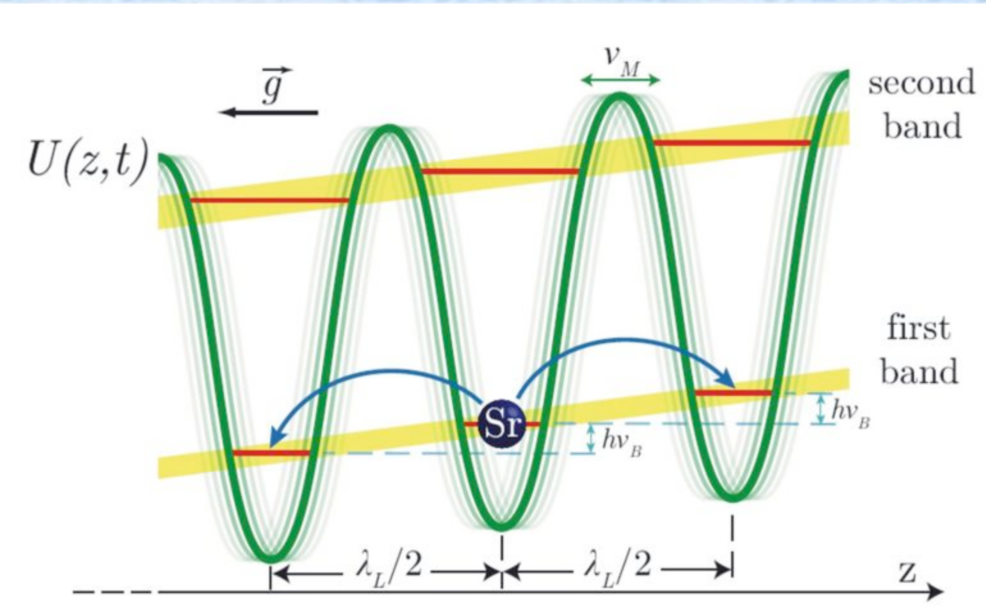


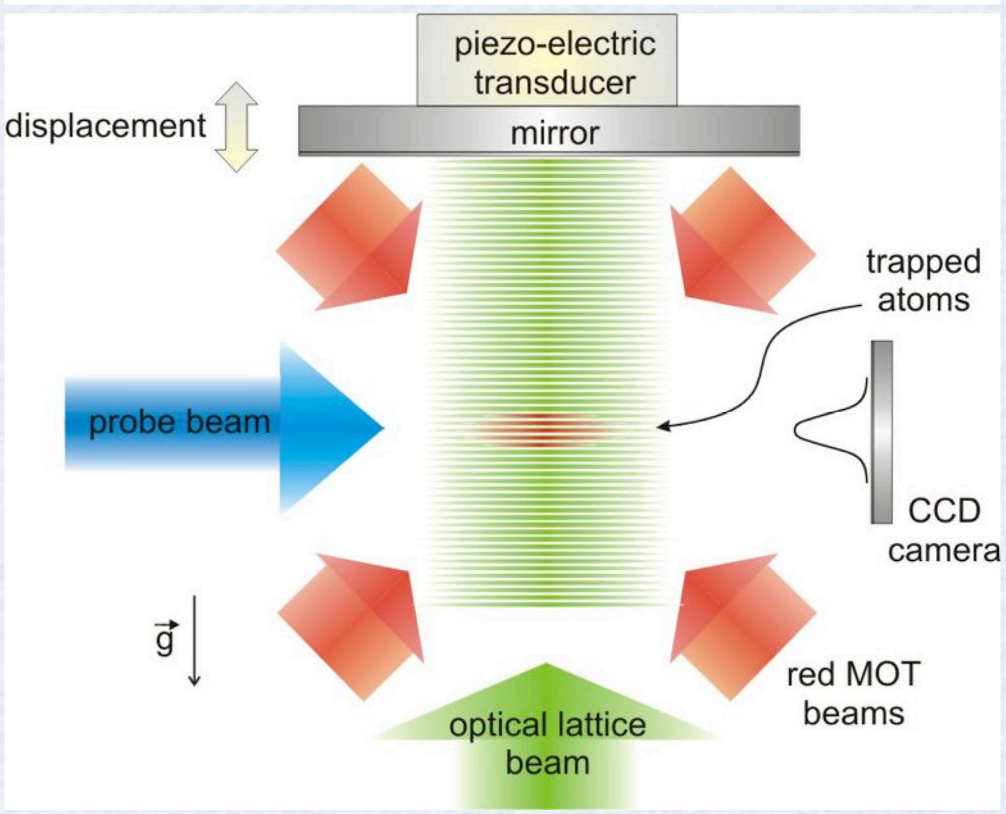


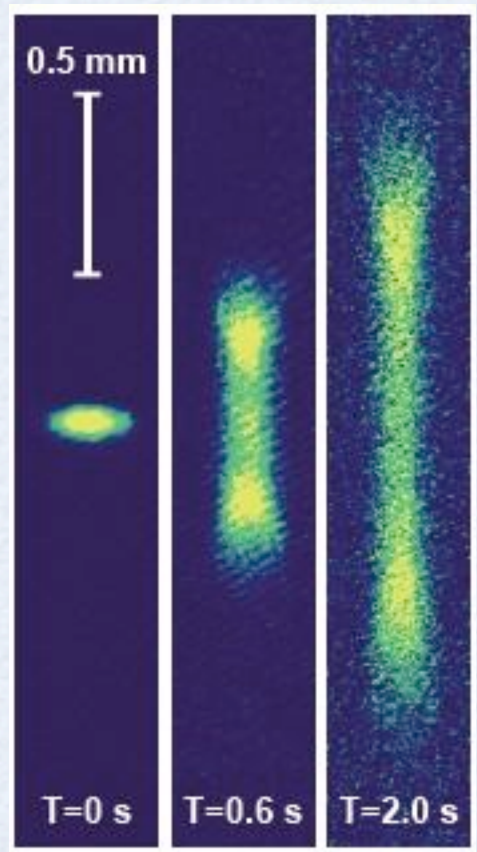
Atom-surface position jitter < 1 μm

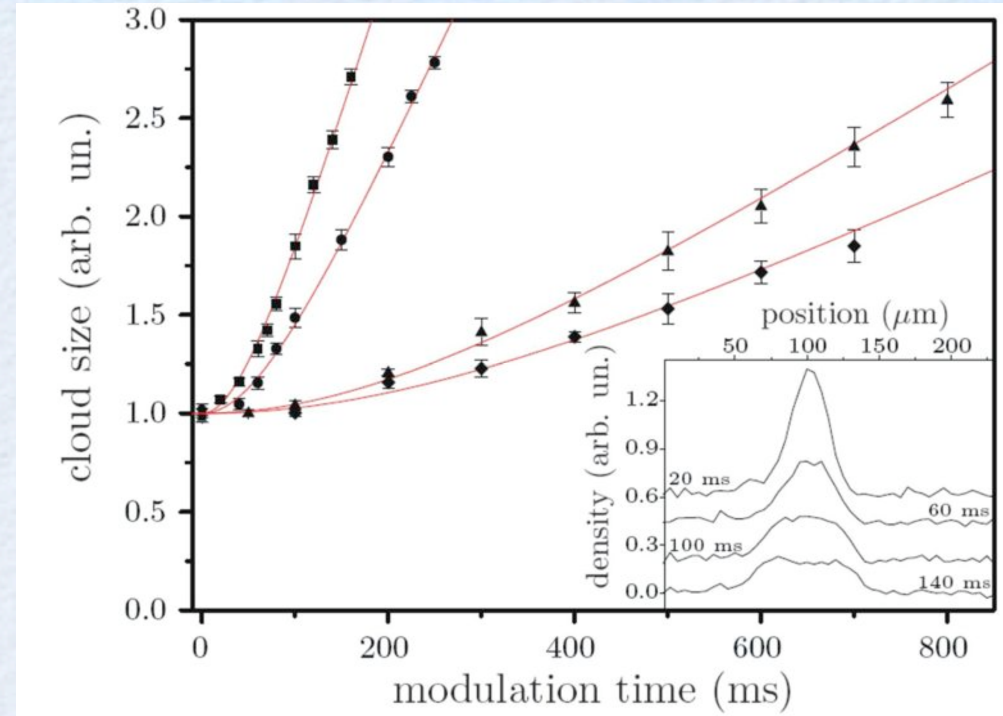
F. Sorrentino et al., Phys. Rev. A **79**, 013409 (2009)

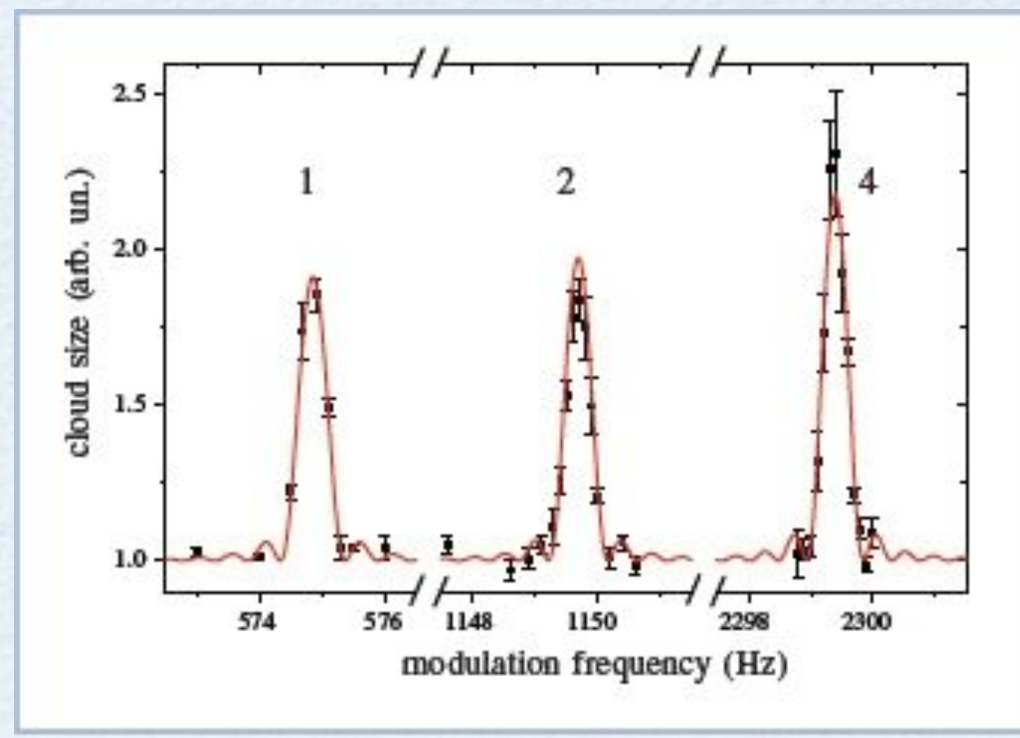
Resonant tunneling









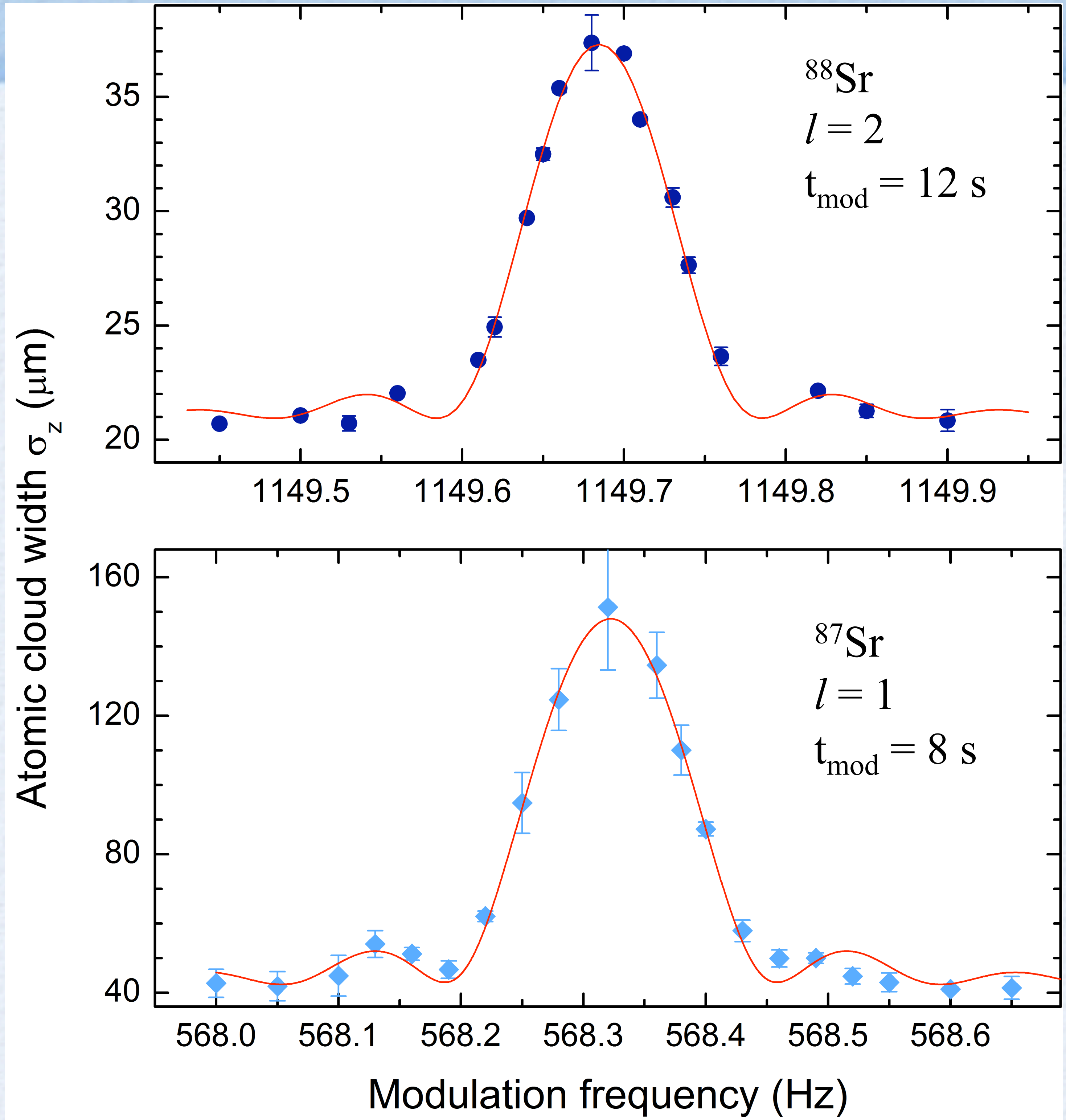


V. V. Ivanov et al., PRL **100**, 043602 (2008)

$\delta g/g \simeq 5 \times 10^{-7}$

Atomic quantum sensor

Test of EP with bosons & fermions

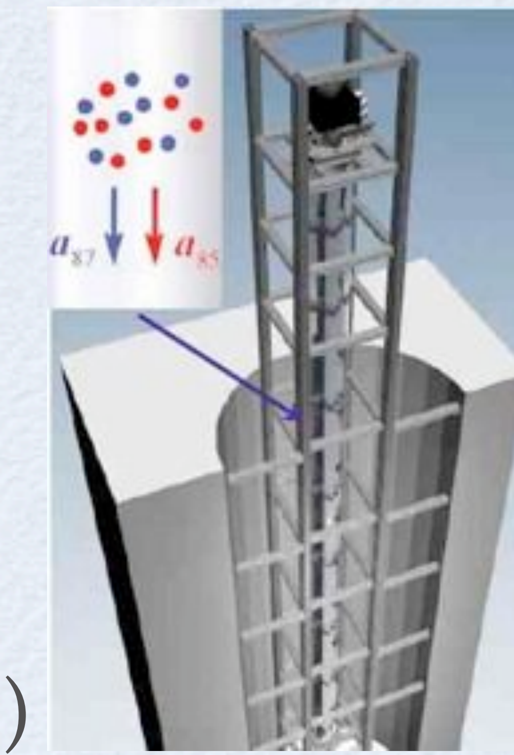


measurement of the Eötvös ratio at the 10^{-7} level

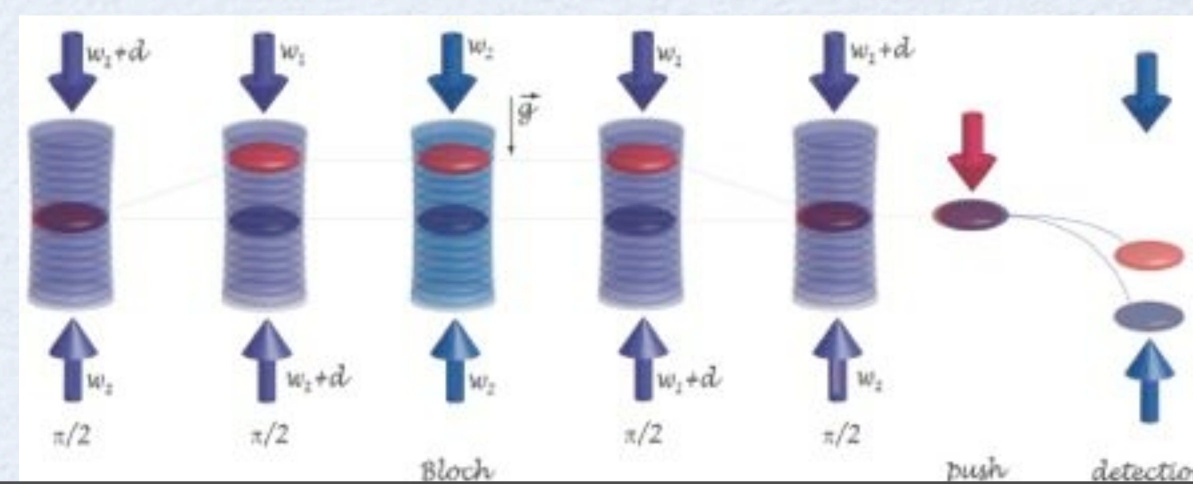
M. Tarallo et al., to be published

Future of AI sensors

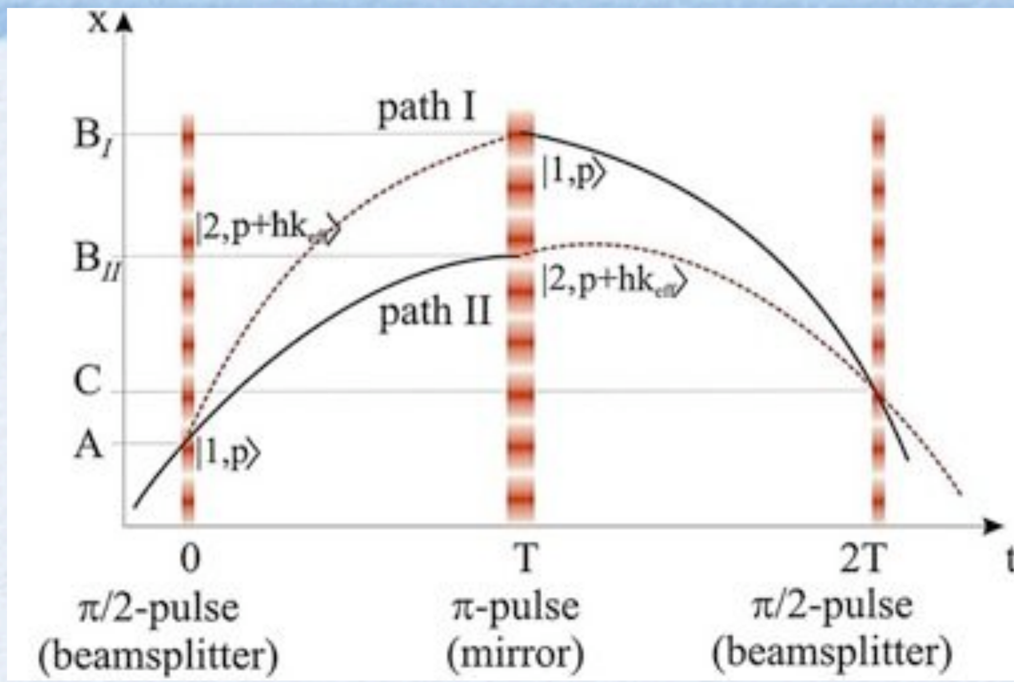
- Compact and transportable system without performance degradation
  - ground applications (geophysic)
  - space applications (satellite geodesy, inertial navigation, tests of fundamental physics): $\Delta\phi = kgT^2$
- Novel schemes to improve sensitivity/accuracy
  - high-momentum beam spitters (up to 100 hk demonstrated)
  - coherent/squeezed atomic states to surpass QPN detection
  - large size AI (some 10 m towers already developed)



- New applications
  - GR, GW, quantum gravity, etc.



AI measurements in space



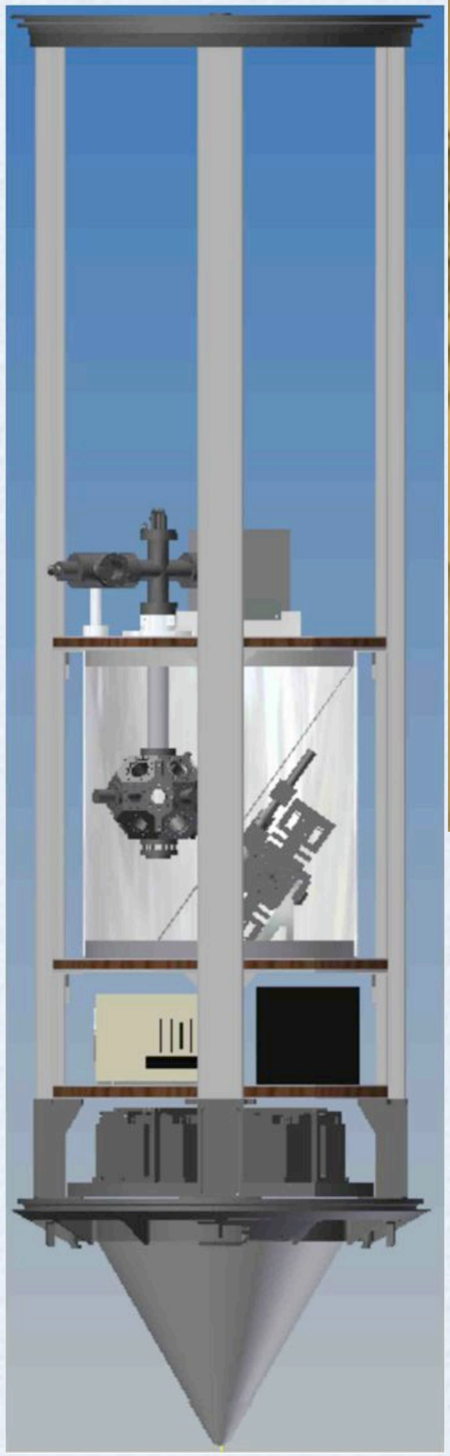
$$\Delta\phi = kgT^2$$

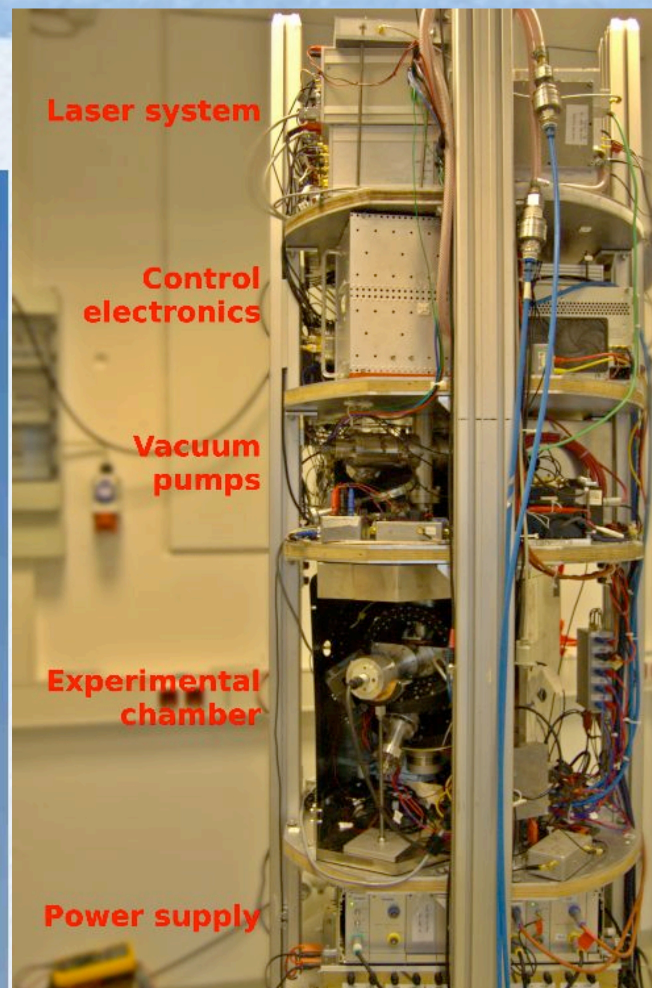
- W. Ertmer et al., Matter wave explorer of gravity (MWXG), Exp Astron 23, 611 (2009)
- F. Sorrentino, et al., A compact atom interferometer for future space missions, Microgravity Sci. Tech. J. 22, 551 (2010)
- F. Sorrentino et al., The Space Atom Interferometer project: status and prospects, Journal of Physics: Conference Series 327, 012050 (2011)
- G. M. Tino et al., Precision Gravity Tests with Atom Interferometry in Space, Nuclear Physics B - Proceedings Supplements 243-244, 203-217 (2013)

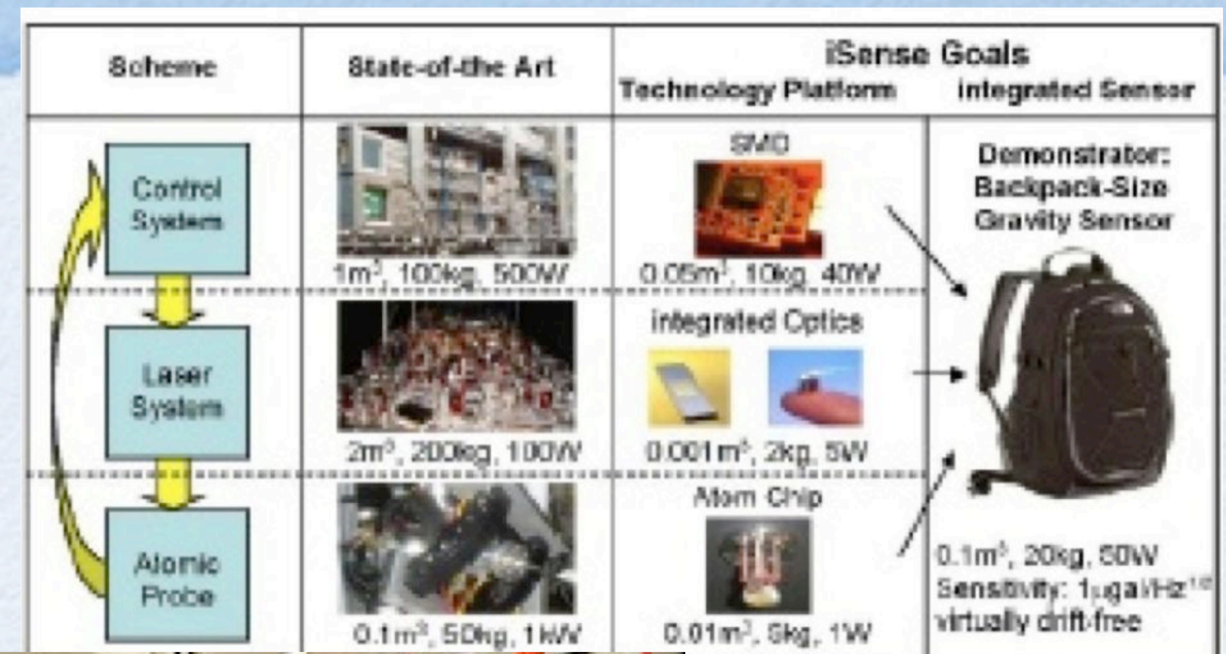
- Terrestrial AIs achieve differential gravity accuracy approaching ~10^{-11} g with T~0.1 s
- In space ~10^{-15} g or better is foreseen with T>>1s with same splitting
- Main issues to address for AI experiments in space:
  - TRL (lot of work in progress)
  - Motivation for space (on ground, large T requires long free-fall distance)
  - Understanding noise and error sources (test bench experiments on ground)

TRL of AI

SAI

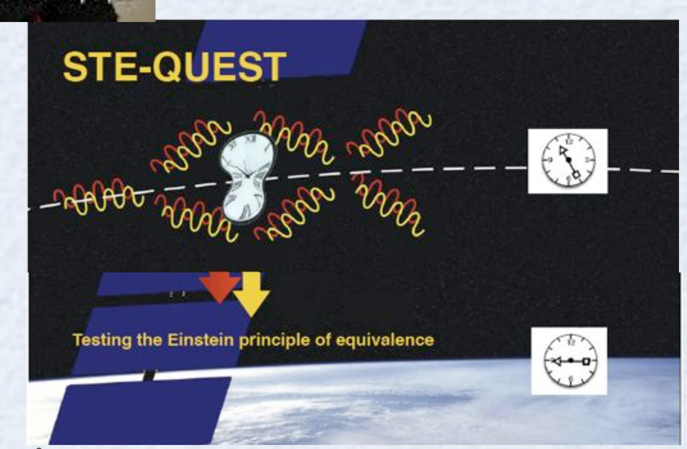






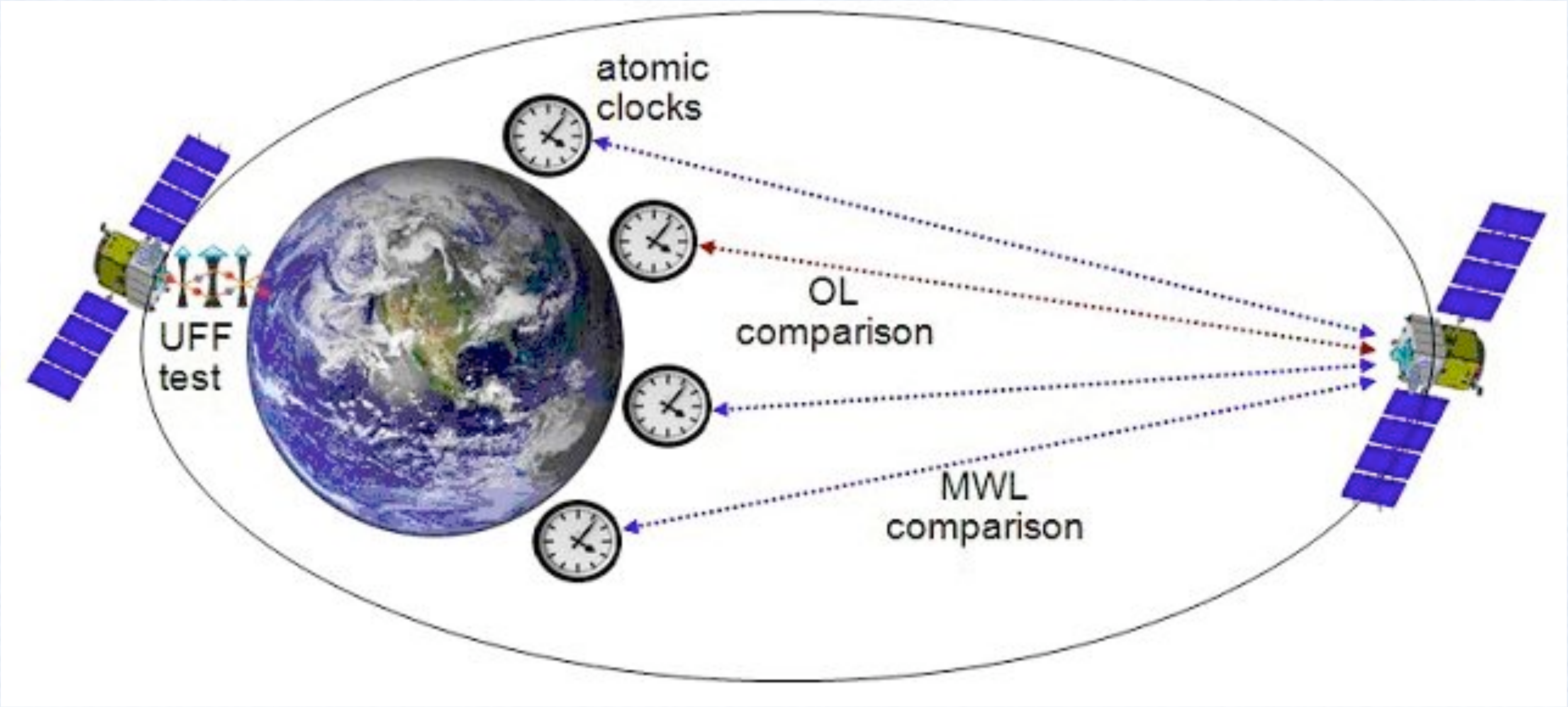
iSENSE

QUANTUS



Proposals for cold atoms in space

- ACES (atomic clock on the ISS)
- HYPER (test of Lense-Thirring)
- Q-WEP (testing WEP on ISS with AI using ^{87}Rb-^{85}Rb)
- STE-QUEST (atomic clock to measure red shift + AI to test WEP and mearu)

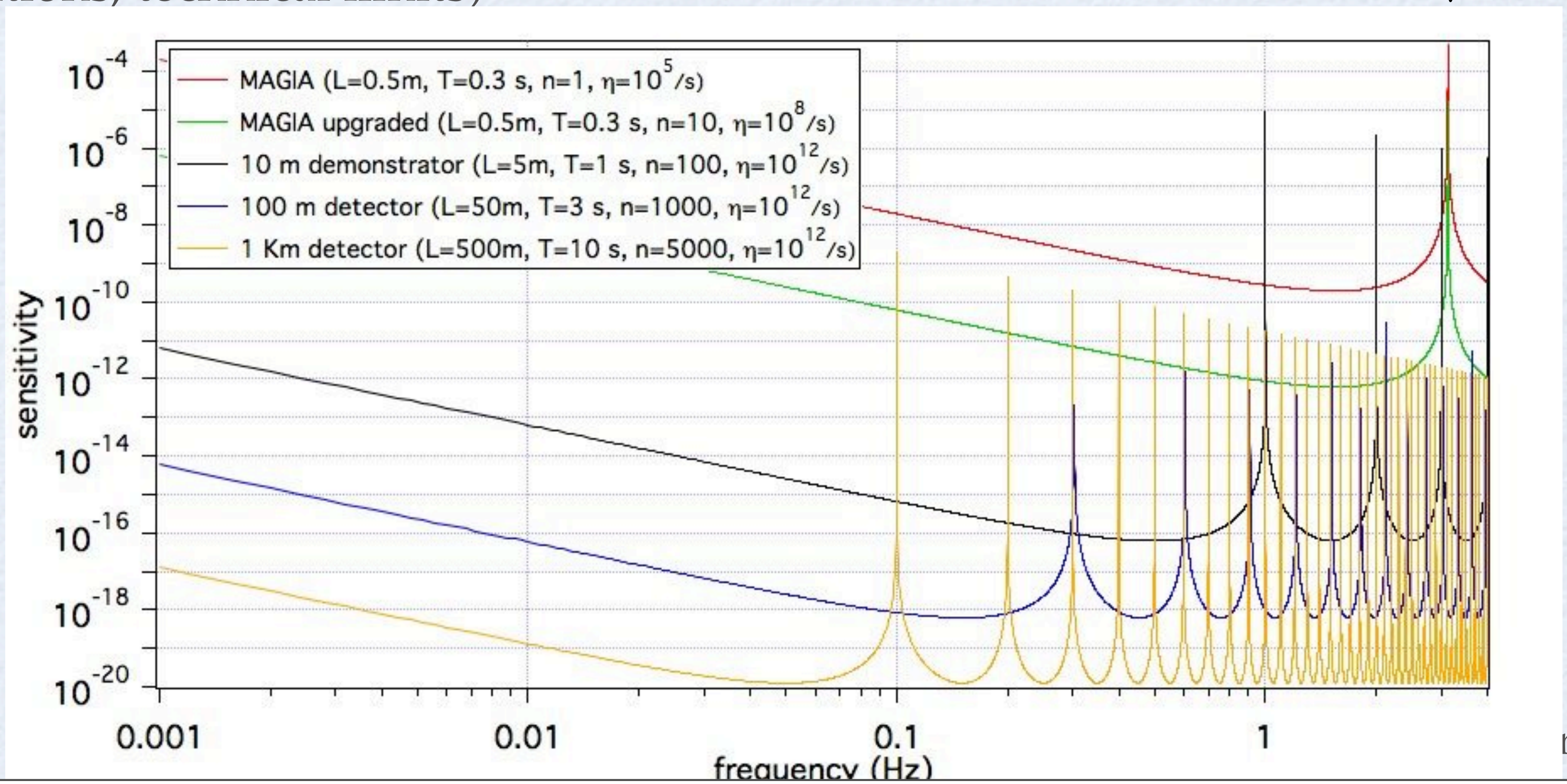


AI and GW detection

- excellent CMRR for vibration noise in differential configurations
- no thermal noise
- several “knobs” to tune sensitivity function and isolate noise sources
- potentially sensitive below 1 Hz (in between LIGO/Virgo and LISA)
- room for improvements (experimental configurations, technical limits)

G. M. Tino and F. Vetrano, Class. Quant. Grav. **24** (2007)
G. M. Tino and F. Vetrano, Gen. Relativ. Gravit. **43**, 2037 (2011)
S. Dimopoulot et al., Phys. Rev. D **78**, 122002 (2008)
G. M. Tino et al., Gen. Relativ. Gravit. **43**, 1901 (2011)
P. W. Graham et al., Phys. Rev. Lett. **110**, 171102 (2013)
F. Vetrano et al., Int. J. of Mod. Phys **23**, 135-143 (2013)

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



AI & GW detection in H2020

HORIZON 2020 – WORK PROGRAMME 2014-2015

European research infrastructures (including e-Infrastructures)

neutrino studies) and other interdisciplinary applications by simultaneously establishing common access procedures, promoting the common planning of experiments, and by coordinating technological efforts in order to optimise use and access to resources and to avoid duplication.

Integrating gravitational wave research. This activity aims at integrating the communities of researchers studying gravitational waves and their astrophysical sources: both laser and atom interferometers with their extreme technological requirements; observations of graviational-wave sources through electromagnetic waves and high-energy particles; numerical/theoretical studies of such sources. It should address also the computing and data handling needs of these communities.

Conclusions

- New atomic quantum devices have been developed with unprecedented sensitivity using ultracold atoms and atom optics
- Applications: fundamental physics, Earth science, space research
- Measurement of G with MAGIA at 10^{-4} level
- Atom interferometry with ultracold ^{88}Sr
  - Long coherence time up to 500 s
  - Optical atomic clock and gravity sensor in the same device
  - WEP test with quantum matter
- Well developed laboratory prototypes, work in progress for transportable/space-compatible systems
- Future prospects:
  - higher sensitivity (LMT splitters, high flux atomic sources, large size setups, microgravity)
  - larger interaction time within small size (interferometry with trapped atoms)
  - frontier physics (GR tests, GW detection, quantum gravity, etc.)

Guglielmo M. Tino's group web page:
http://coldatoms.lens.unifi.it