Atom interferometry gyroscopes

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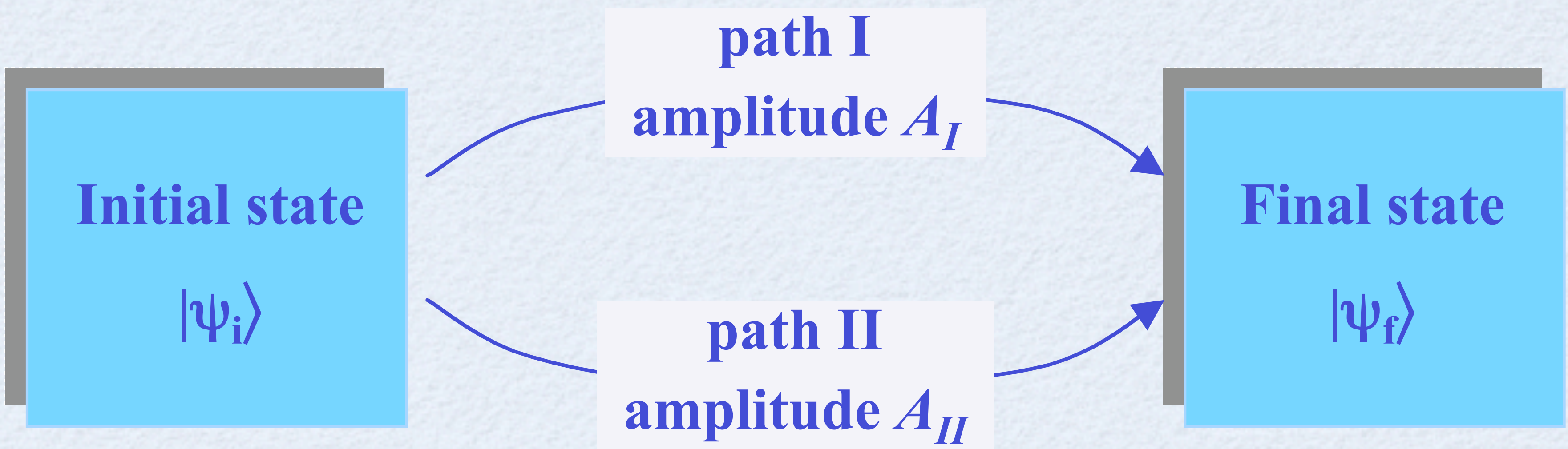
Outline

- Atom interferometry: basic principles
- AI inertial sensors: state of the art
- The MAGIA experiment
- Performance of current AI gyroscopes
- Future of AI inertial sensors
  - transportable systems
  - new applications
  - combination with "classical" sensors

Matter-wave interferometry

Quantum interference



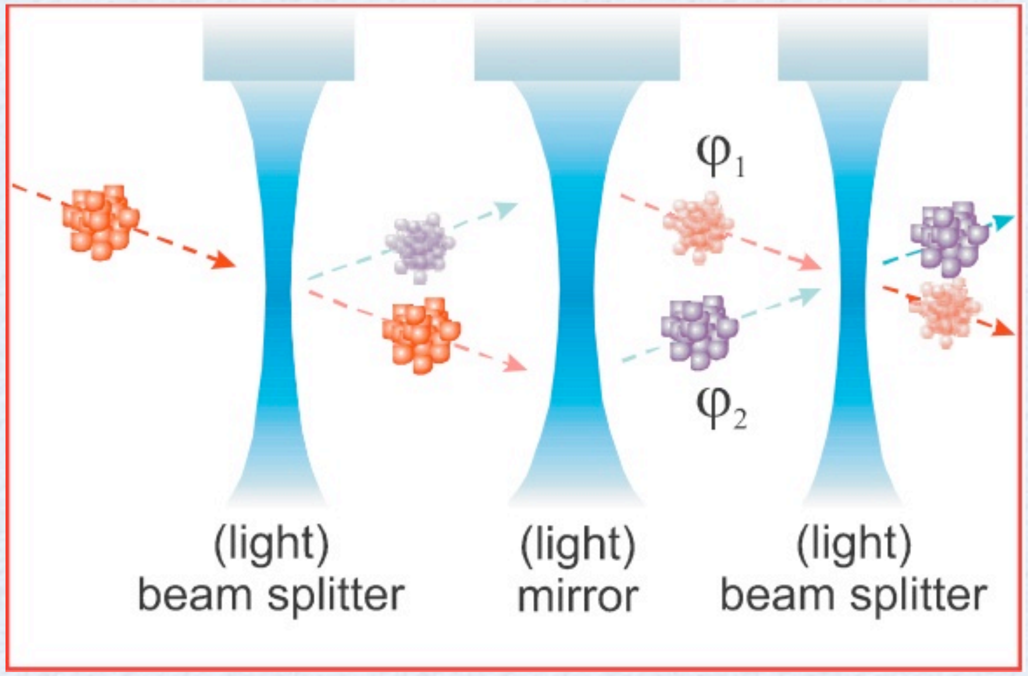
Interference of transition amplitudes

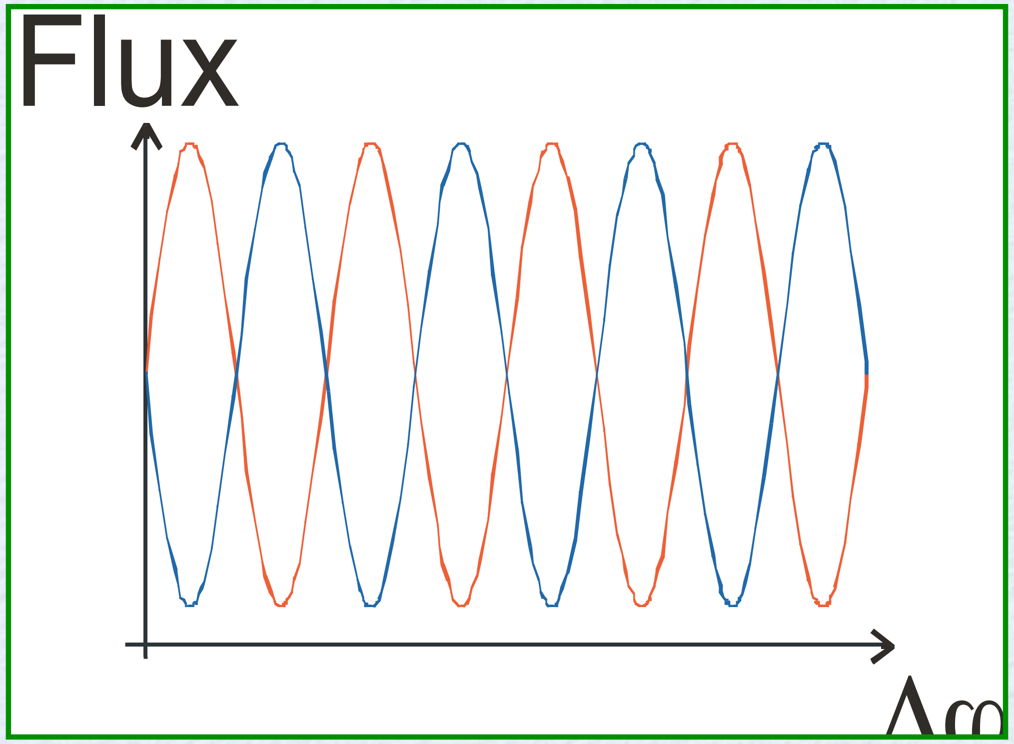
$$P(|\psi_i\rangle \rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2Re(A_I A_{II}^*)$$

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**

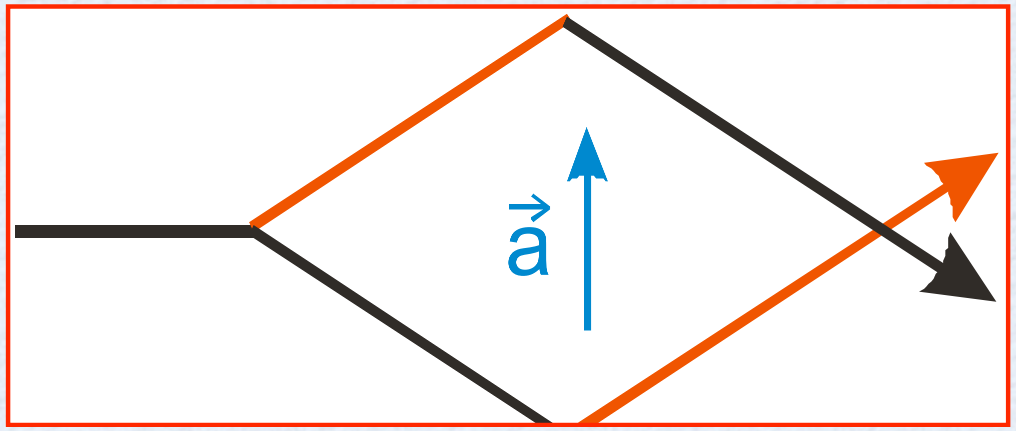
- atom optics
- different internal states/isotopes
- phase difference may depend on:
  - accelerations
  - rotations
  - photon recoil
  - laser phase
  - laser frequency detuning
  - electric/magnetic fields
  - interactions with atoms/molecules

Possible applications of AI

- Already achieved:
  - inertial sensing (accelerations, gravity gradients, rotations)
  - measuring fundamental constants (α, G)
- Proposed:
  - tests of GR (equiv. principle, limits on PPN parameters, Lense-Thirring, etc.)
  - GW detection
  - atom neutrality
  - testing Newton's $1/r^2$ law at short distance
  - realization of mass unit (Watt balance)

Matter-wave vs optical inertial sensors

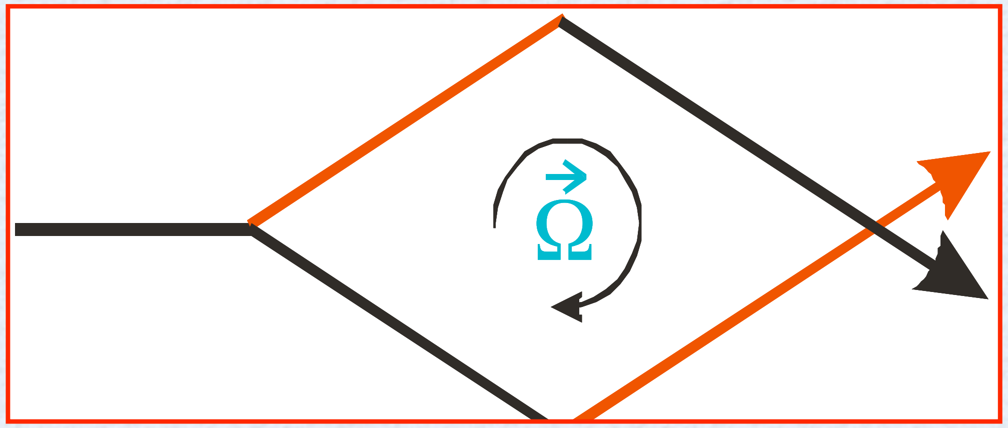
Accelerations



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

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

Rotations



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

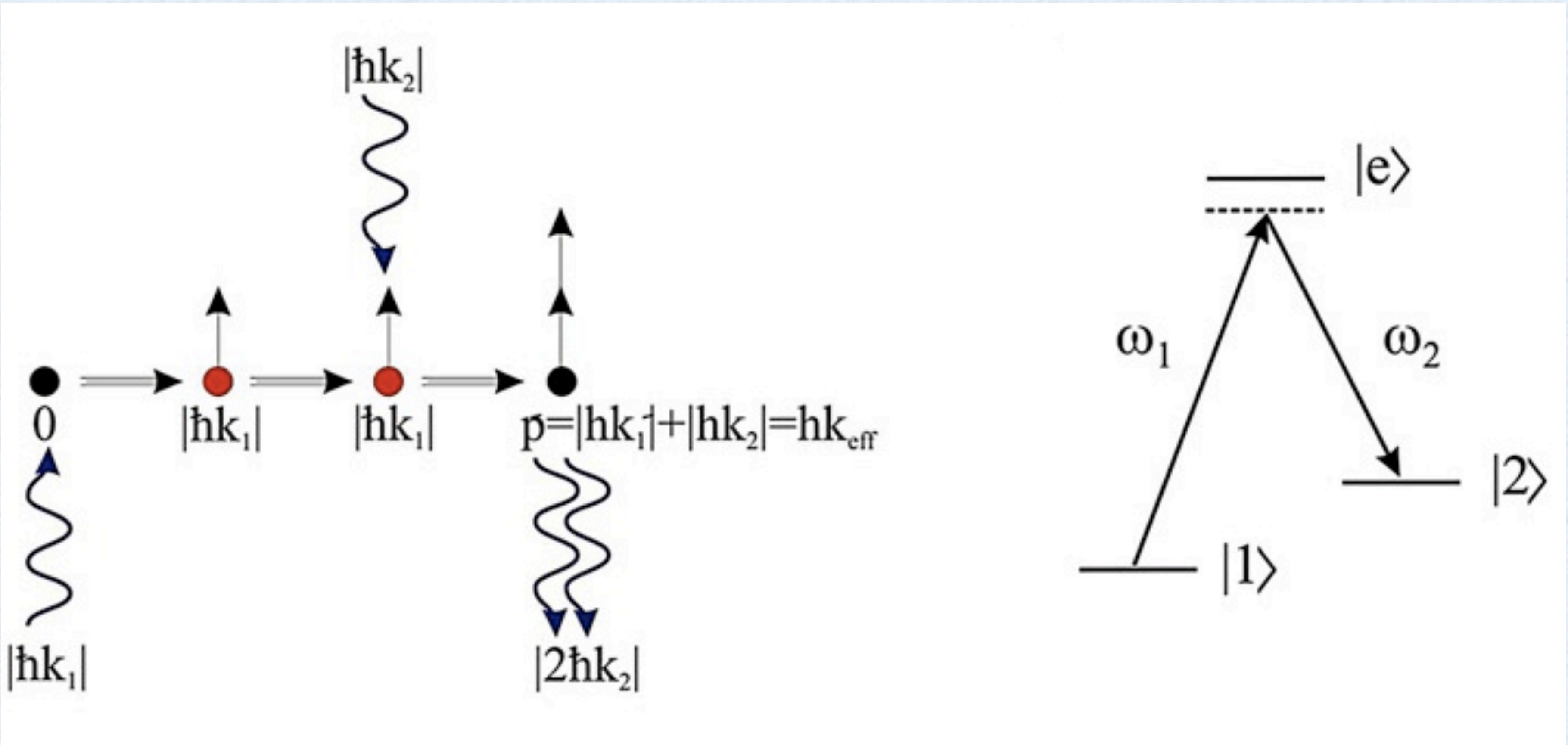
$$\frac{\Delta\phi_{mat}}{\Delta\phi_{ph}} \sim \frac{m_{at}\lambda c}{h} \approx 5 \cdot 10^{11}$$

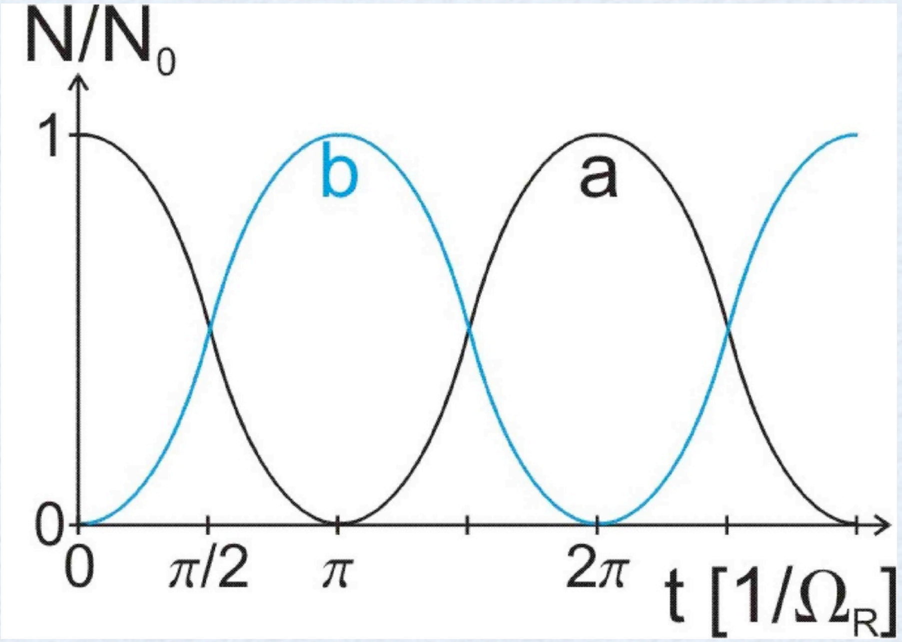
- in principle, excellent sensitivity
- good control over systematic effects
  - based on quantum matter-light interaction
  - many “knobs” to tune

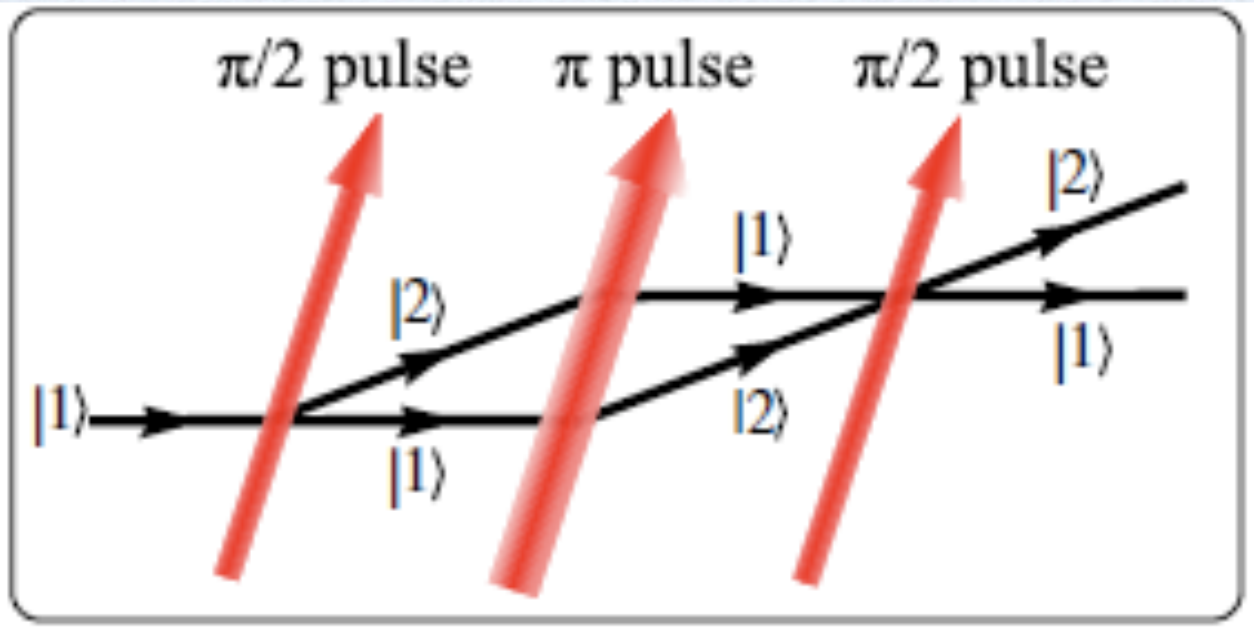
Present limitations of AI

- shot-noise limit to sensitivity ~ $1/\sqrt{\dot{N}}$
  - atomic flux ~ 10^{18} s^{-1} with H (~ 10^{11} s^{-1} with alkali)
  - in a 1-kW laser the photon flux is > 10^{22} s^{-1}
- much lower path difference than in optical interferometers
  - better beam splitters, optical cavities
- nevertheless AI inertial sensors are already competitive
  - long term stability (bias & scale factor) and accuracy
- future developments to improve sensitivity
  - large momentum beam splitters
  - high flux atomic sources
  - sub-shot noise detection (quantum degenerate gases, etc.)
  - large size AI, μ-gravity, ultracold atoms

Raman pulse atom interferometer







Light-pulse AI inertial sensors

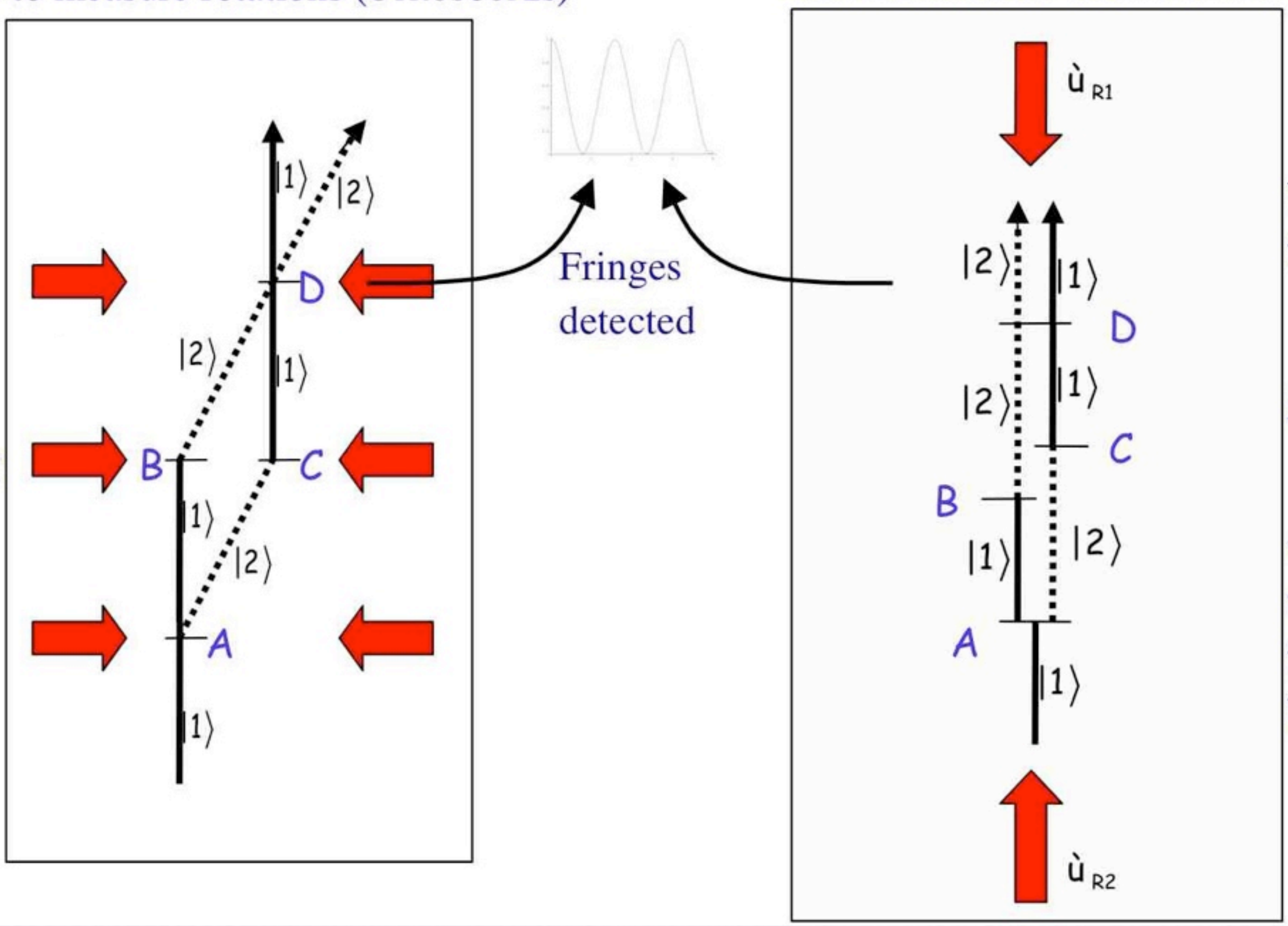
TRANSVERSAL PULSES
-the interferometer encloses an area
-used to measure rotations (GYROSCOPES)

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 $\boldsymbol{k}$ is the laser wavenumber and $\boldsymbol{T}$ the time interval between laser pulses

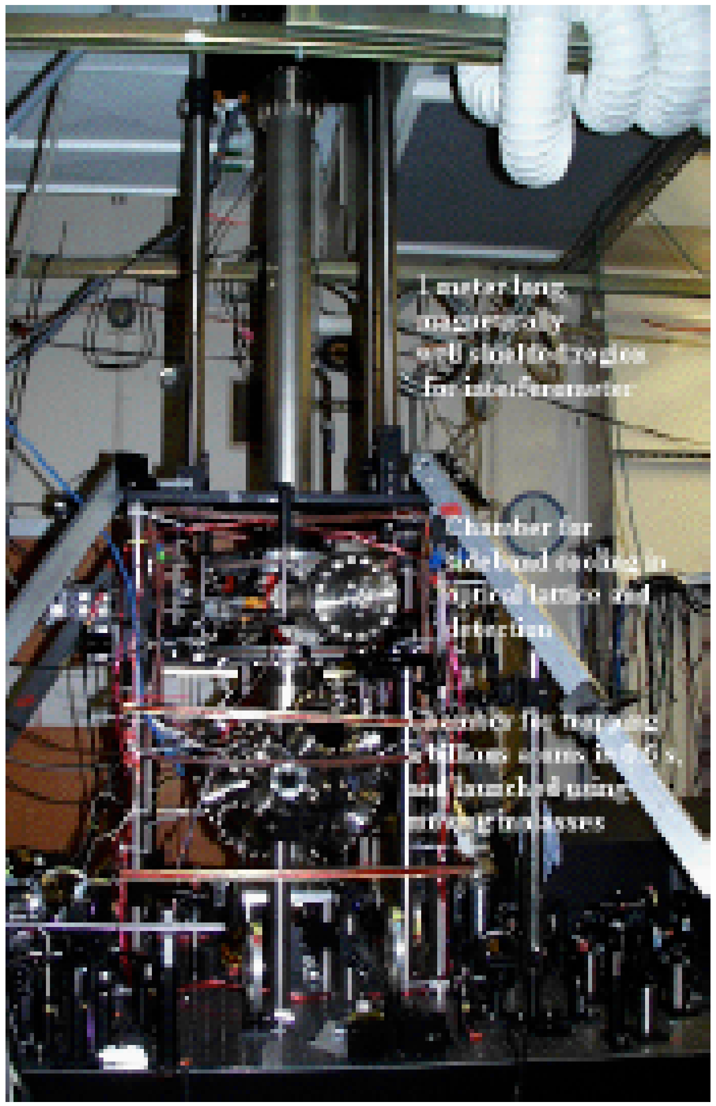


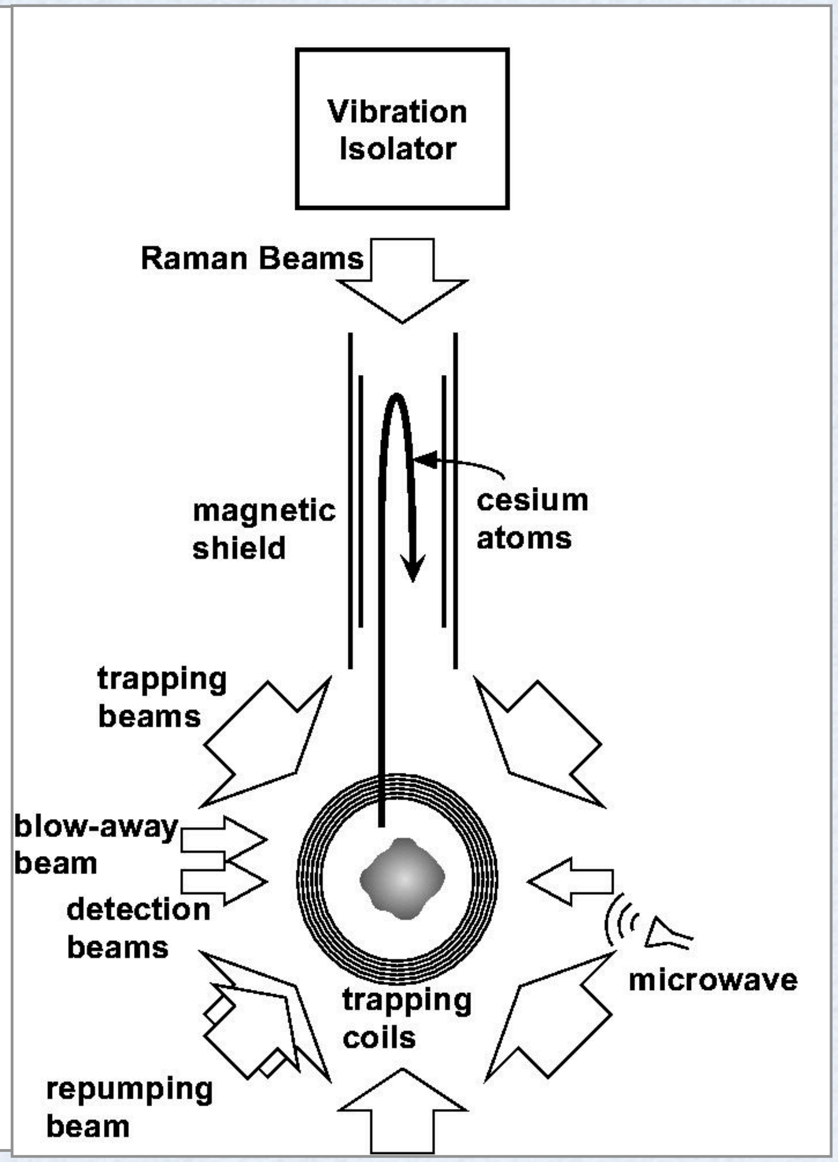
With an acceleration g, the phase difference

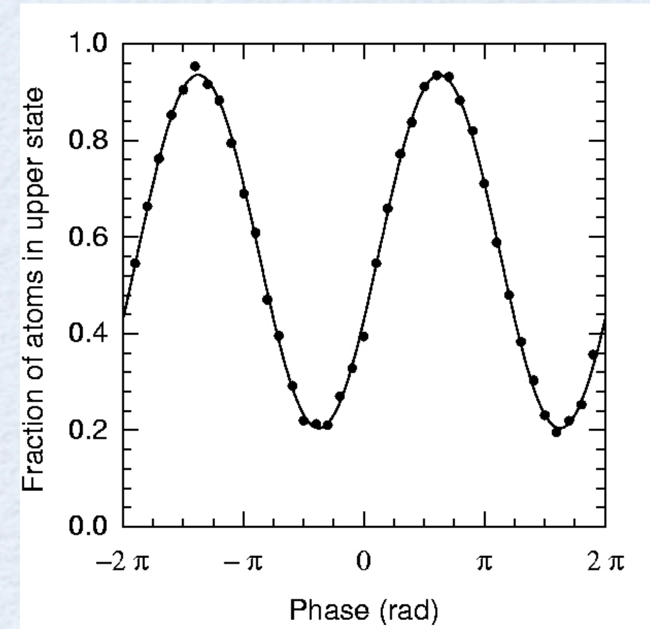
$$\Delta\phi = k_{eff}\, g\, T^2$$

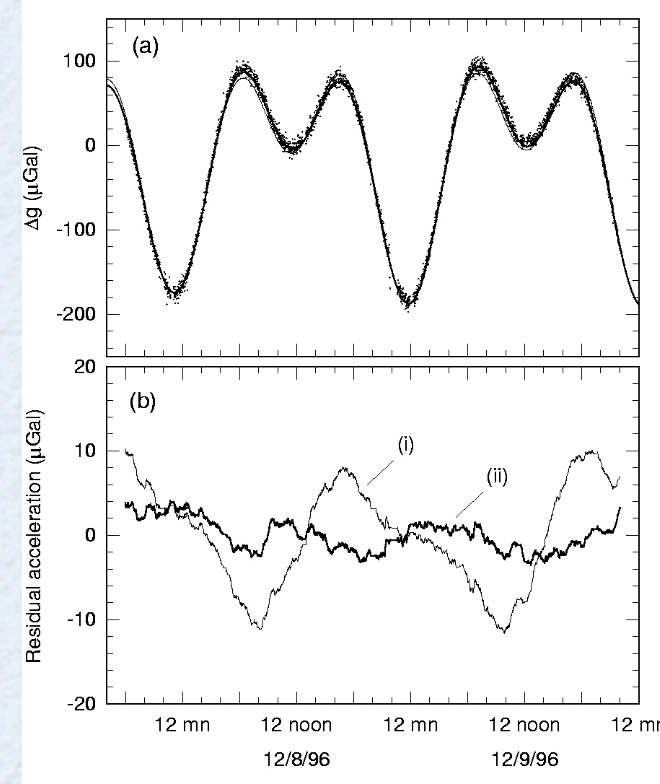
where $\boldsymbol{k}$ is the laser wavenumber and $\boldsymbol{T}$ the time interval between laser pulses

Stanford atom gravimeter







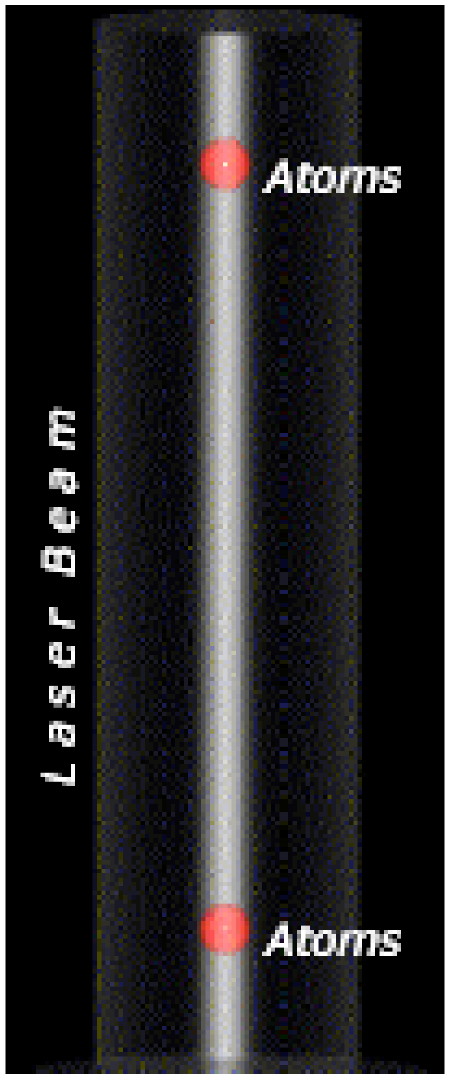


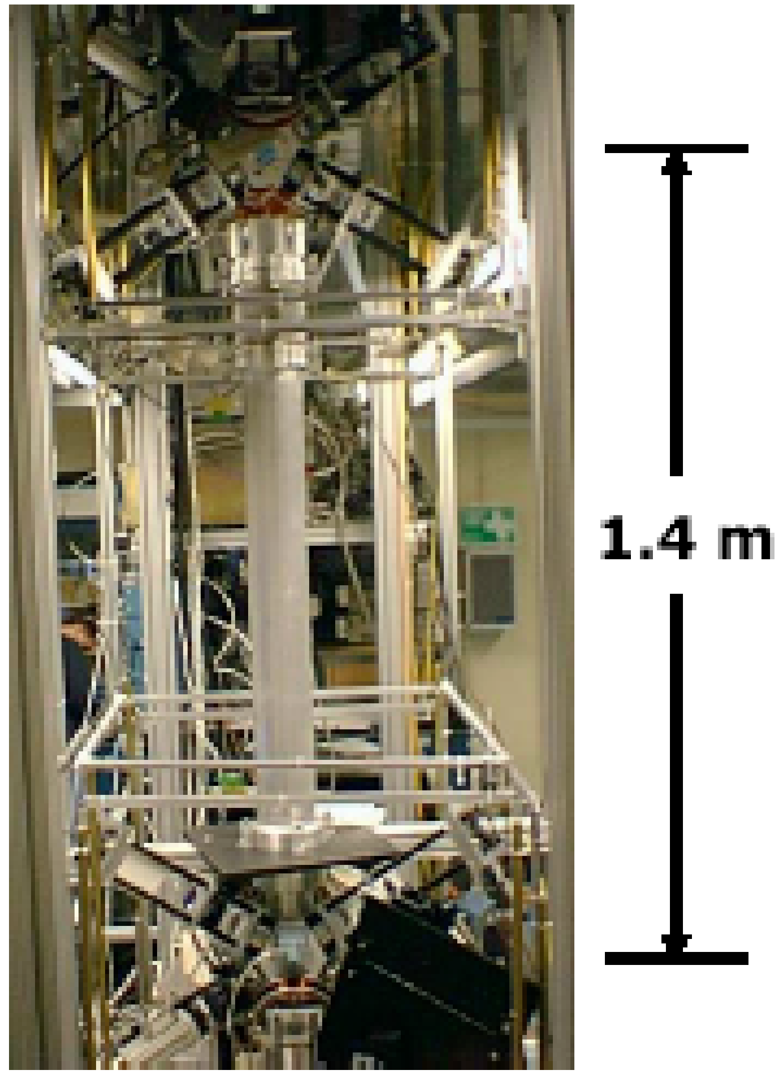
resolution: 8×10^{-9} g in 1 second

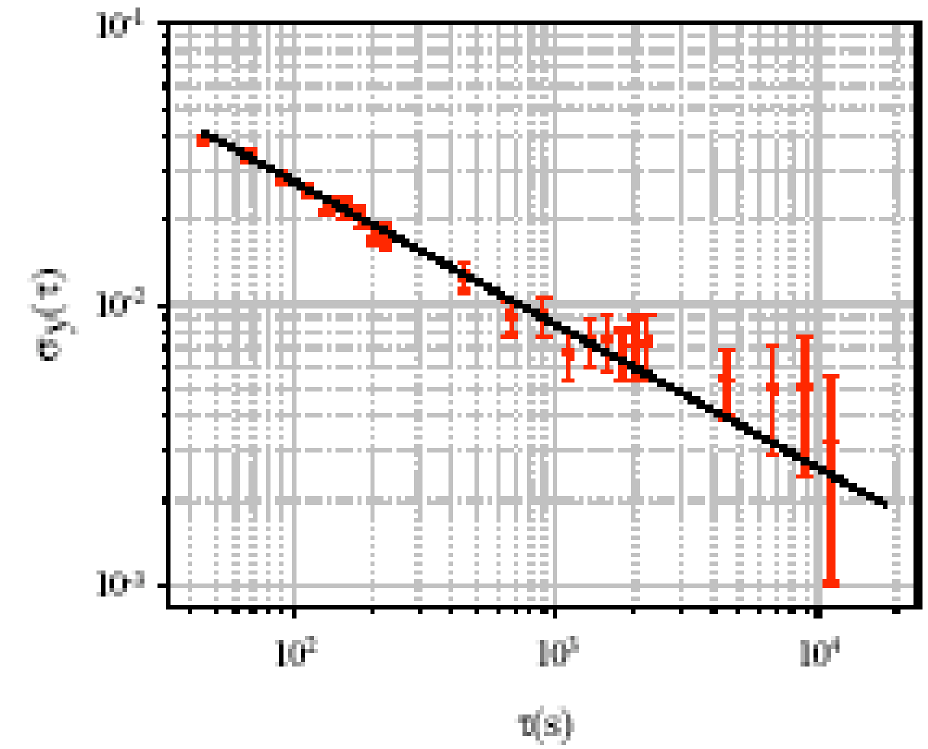
accuracy: $\Delta g/g \leq 3 \times 10^{-9}$ limited by tidal models

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

Sanford / Yale gravity gradiometer







Demonstrated diffential acceleration sensitivity:

4×10^{-9} g/Hz$^{1/2}$

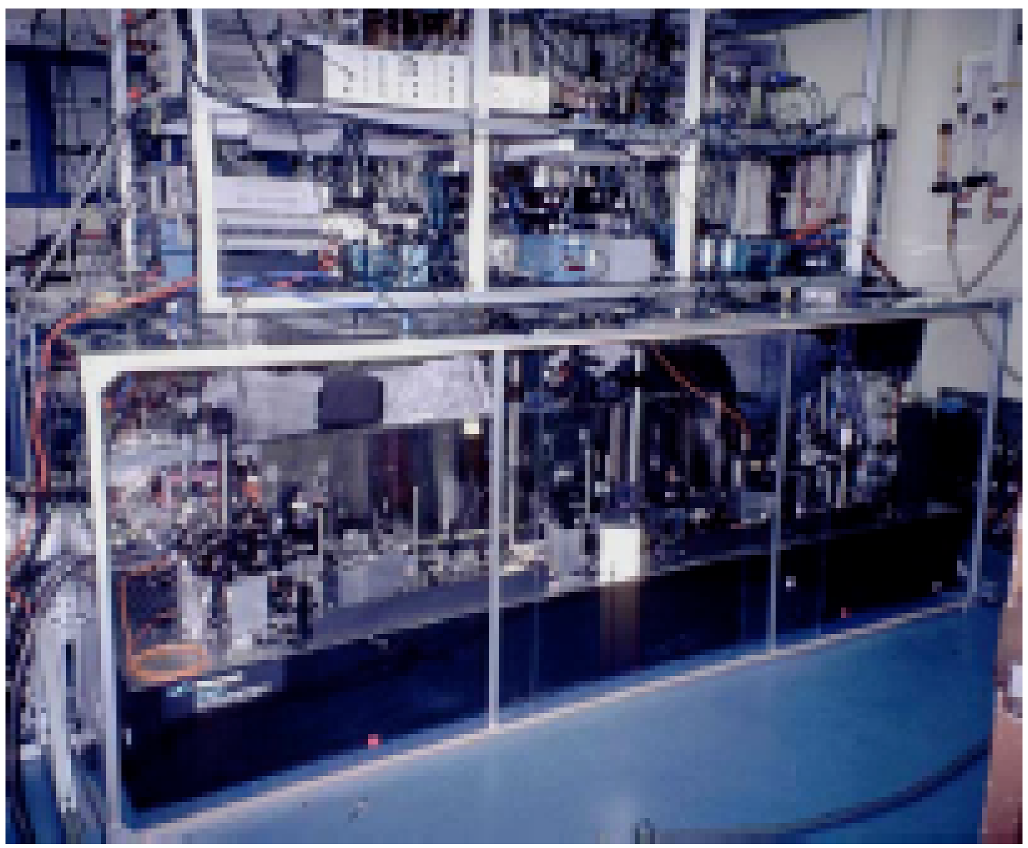
(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

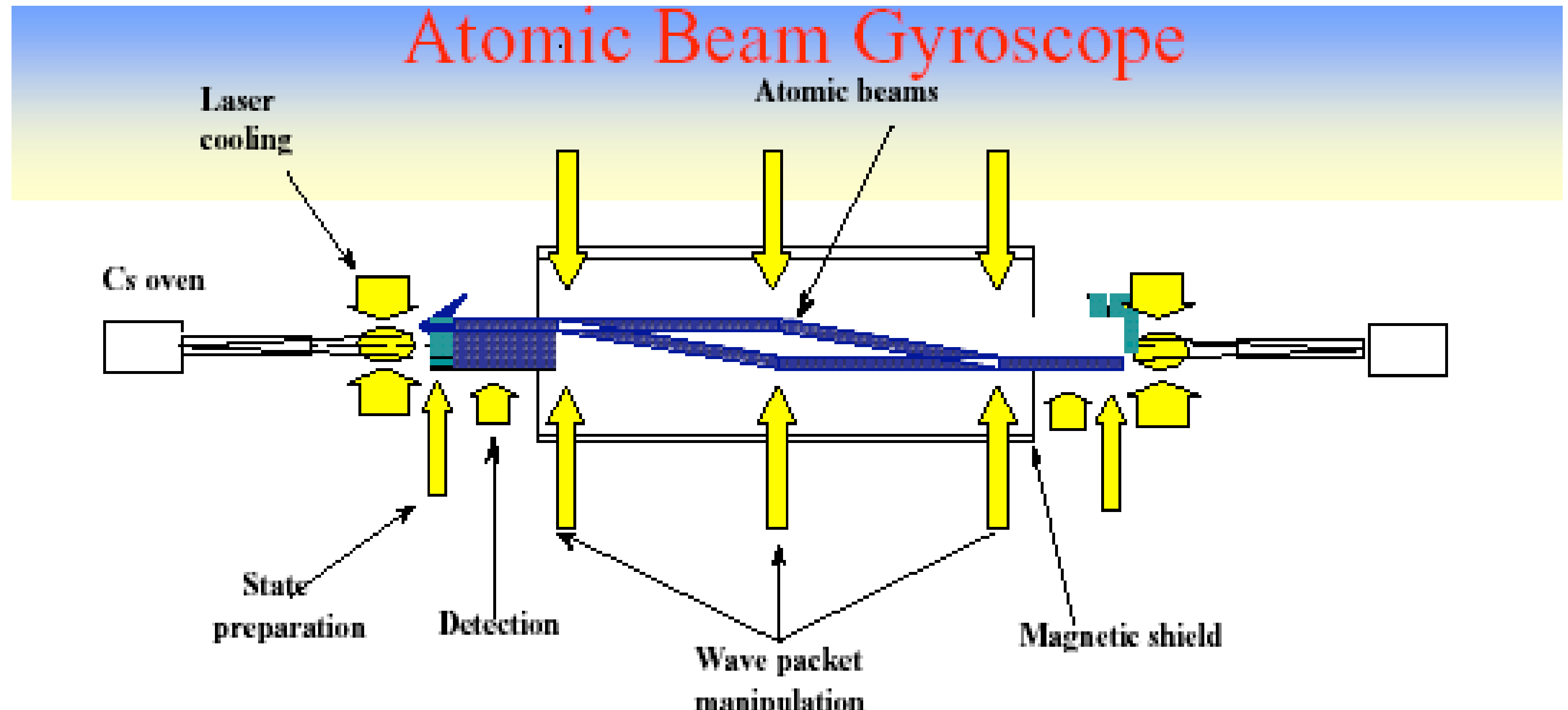
Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

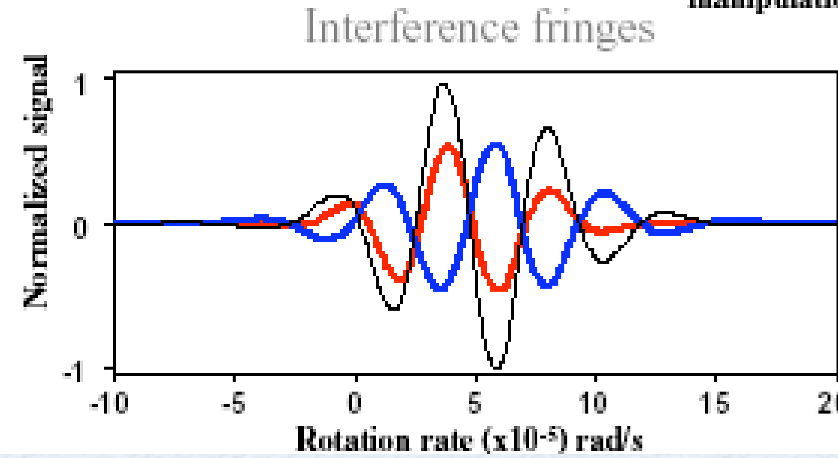
limited by QPN

J. M. McGuirk et al., Phys. Rev. A 65, 033608 (2002)

Stanford/Yale gyroscope







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

scale factor stability < 5 ppm

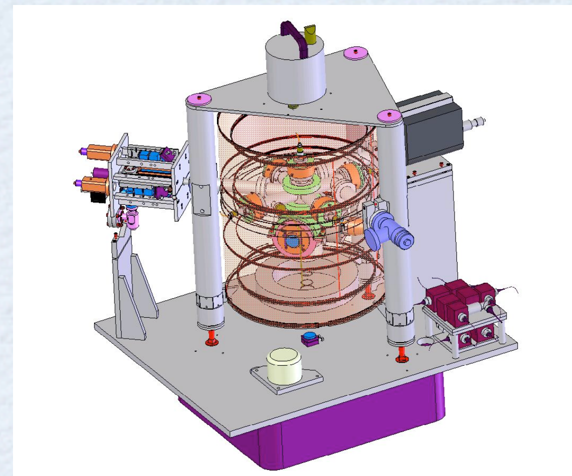
bias stability $< 70\,\mu$deg/h

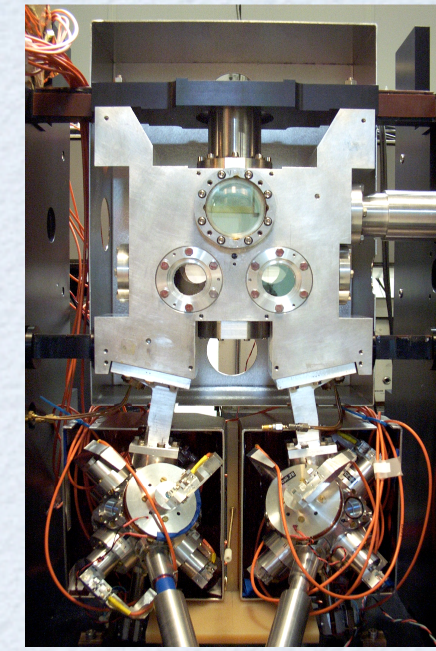
T.L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)

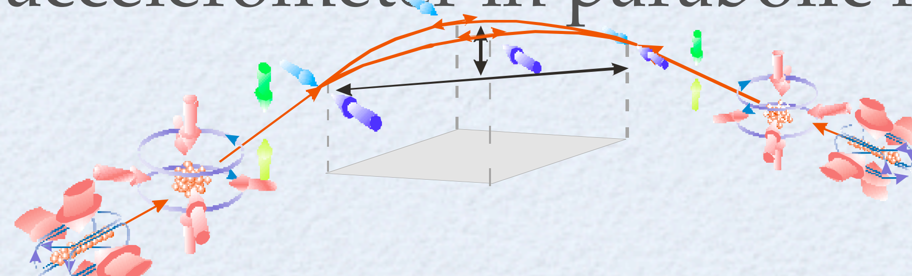
D. S. Durfee, Y. K. Shaham, M.A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006)

Other AI sensors

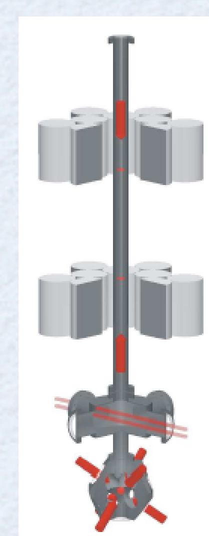
- SYRTE (FR)
  - absolute gravimeter
  - gyroscope
  - six-axis inertial sensor
  - I.C.E. AI differential accelerometer in parabolic flight

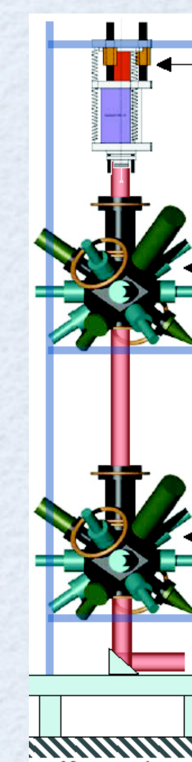






- IQO (D)
  - CASI gyroscope
  - QUANTUS drop-tower experiment
- JPL (USA)
  - gradiometer
- STANFORD (U.S.A)
  - transportable multi-axis sensors
- MAGIA (IT)

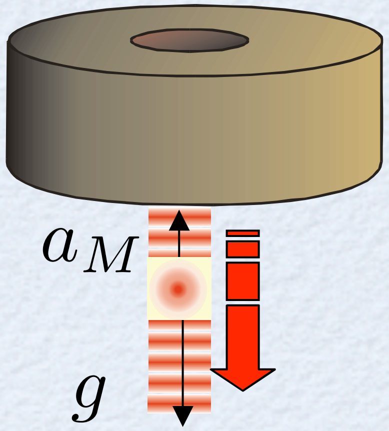




MAGIA

Misura Accurata di G mediante Interferometria Atomica

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

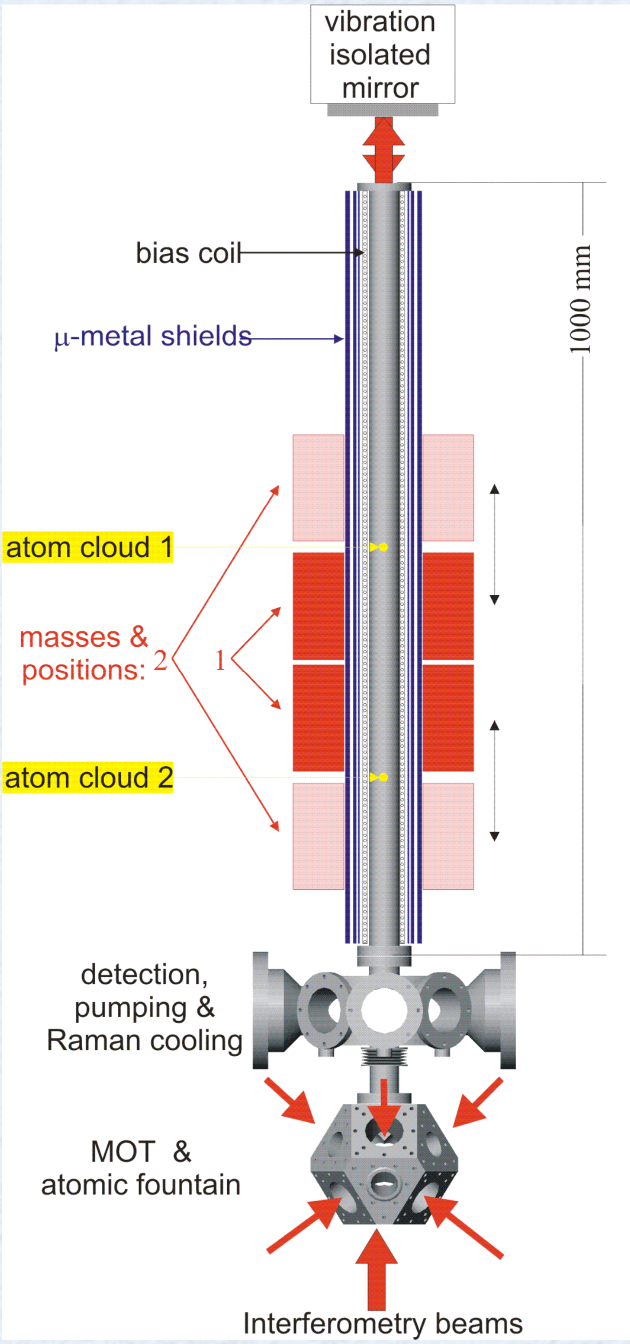


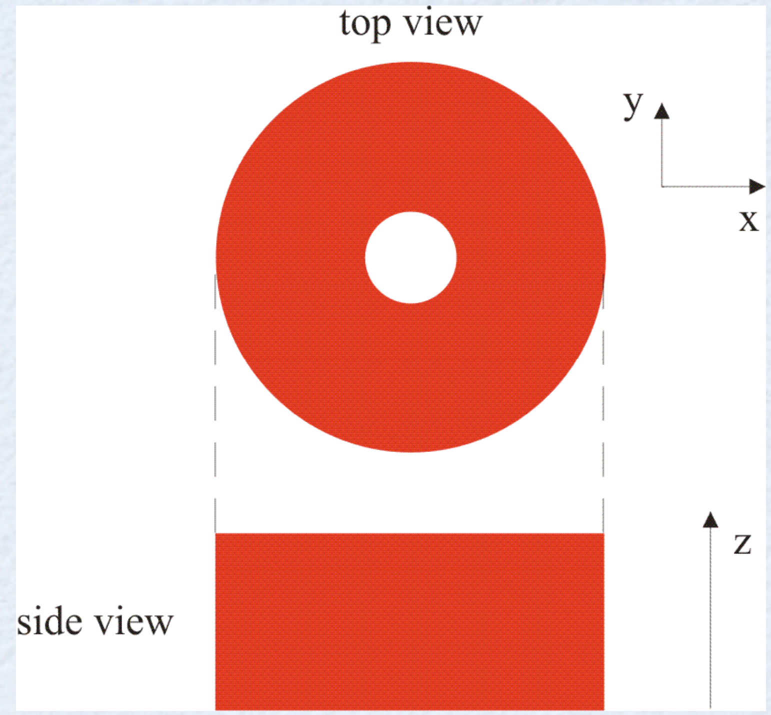
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

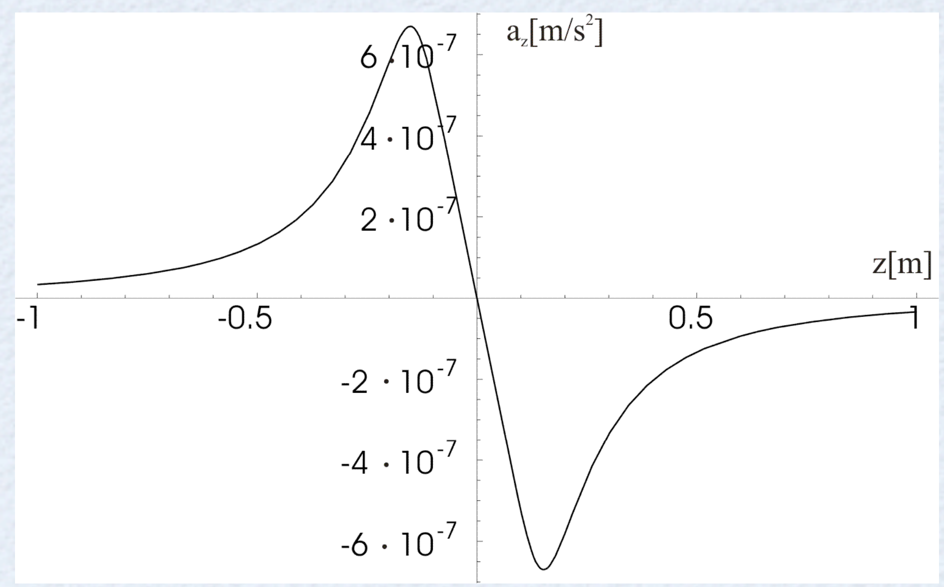
Using atomic probes

- Point-like test masses in free fall
- virtually insensitive to stray fields
- well know and reproducible properties
- different states, isotopes
- precision measurements by atom interferometry

Atom gradiometer + source masses







Sensitivity 10^{-9} g/shot

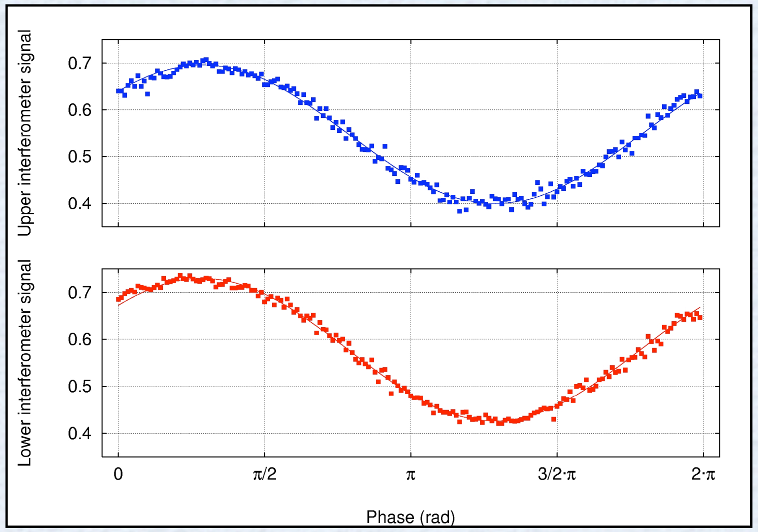
one shot $\rightarrow \Delta G/G \sim 10^{-2}$

500 Kg tungsten mass

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

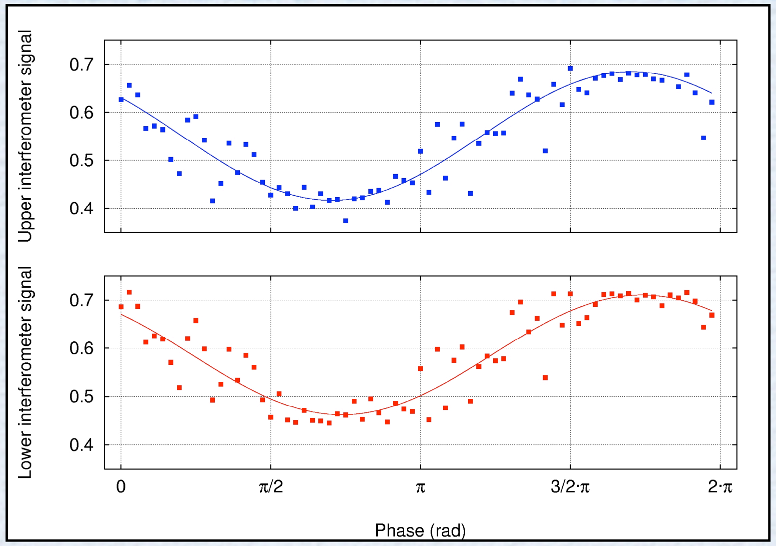
10000 shots $\rightarrow \Delta G/G \sim 10^{-4}$

Differential gravity measurement



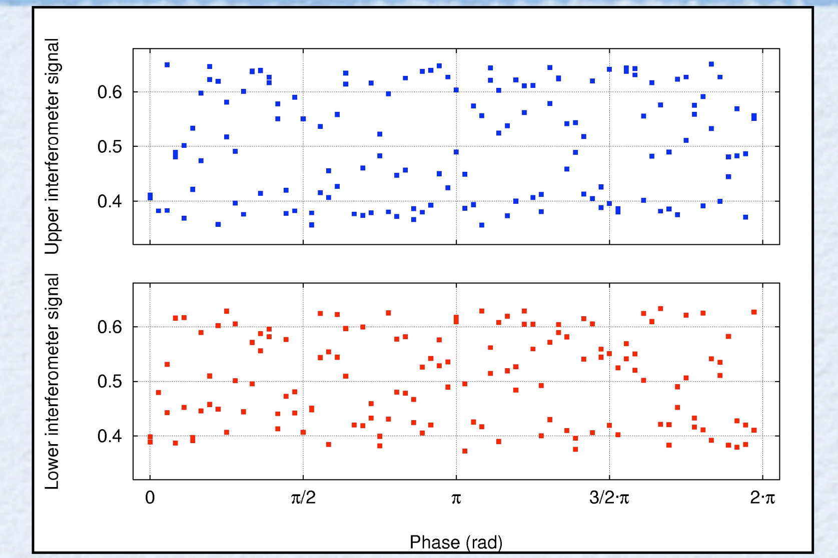
T=5 ms

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



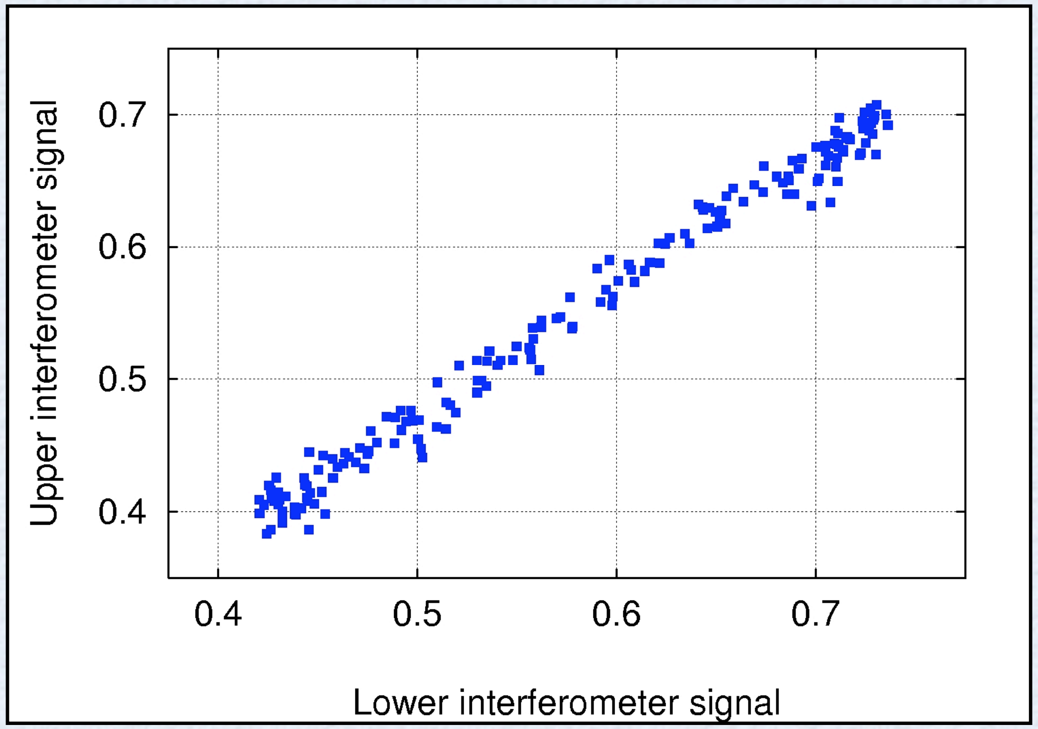
T=50 ms

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

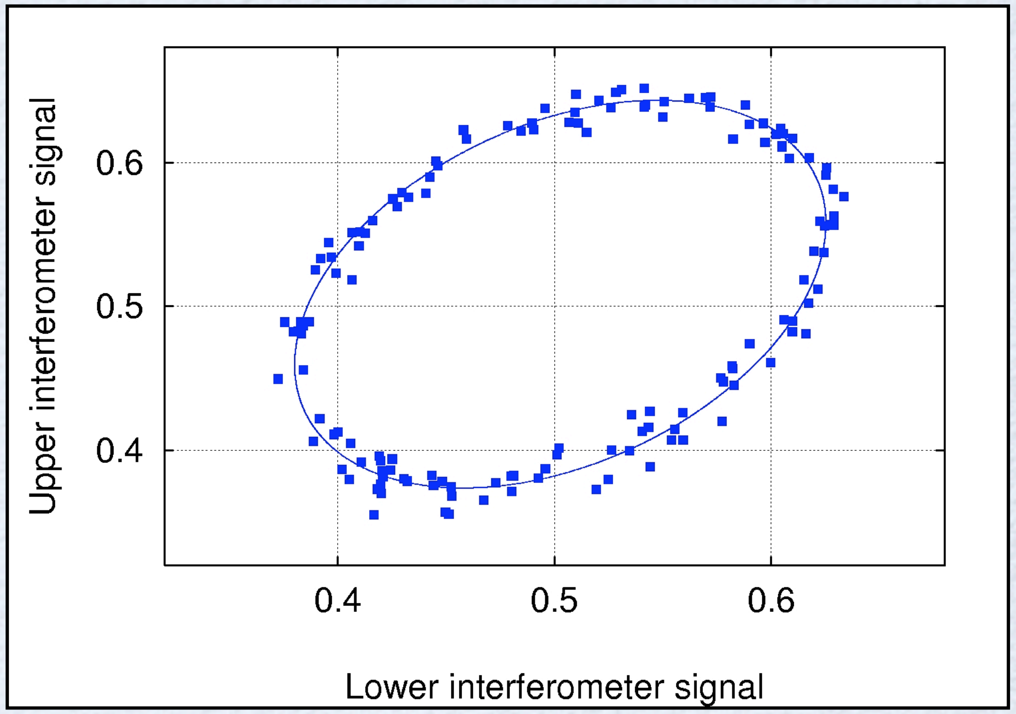


T=150 ms

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



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

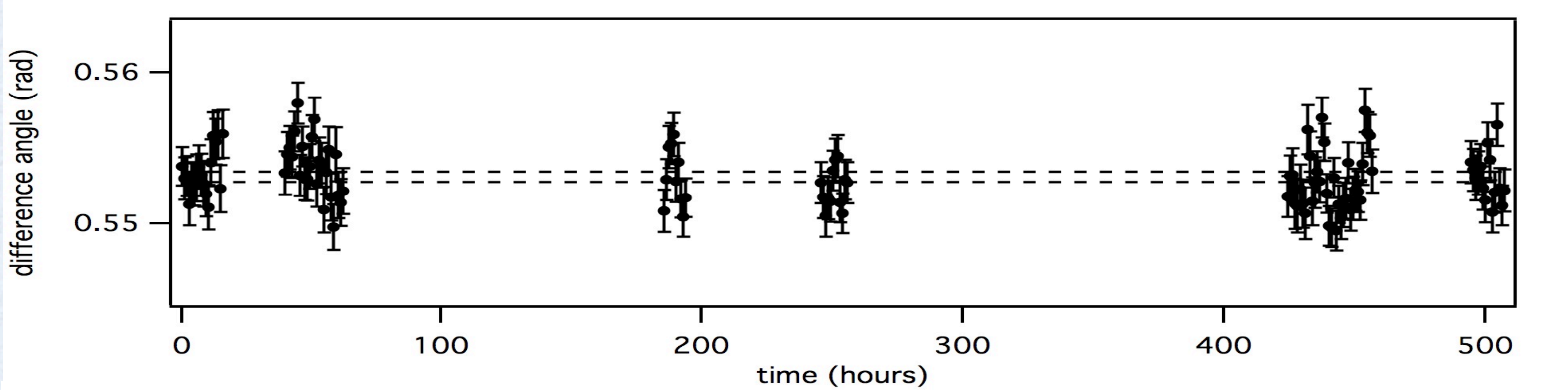


G. T. Foster et al., Opt. Lett **27**, 951 (2002)

Test of *G* measure & long term stability

First G measurement with 1500 ppm precision,

G. Lamporesi et al., Phys. Rev. Lett ***100****, 050801 (2008)*

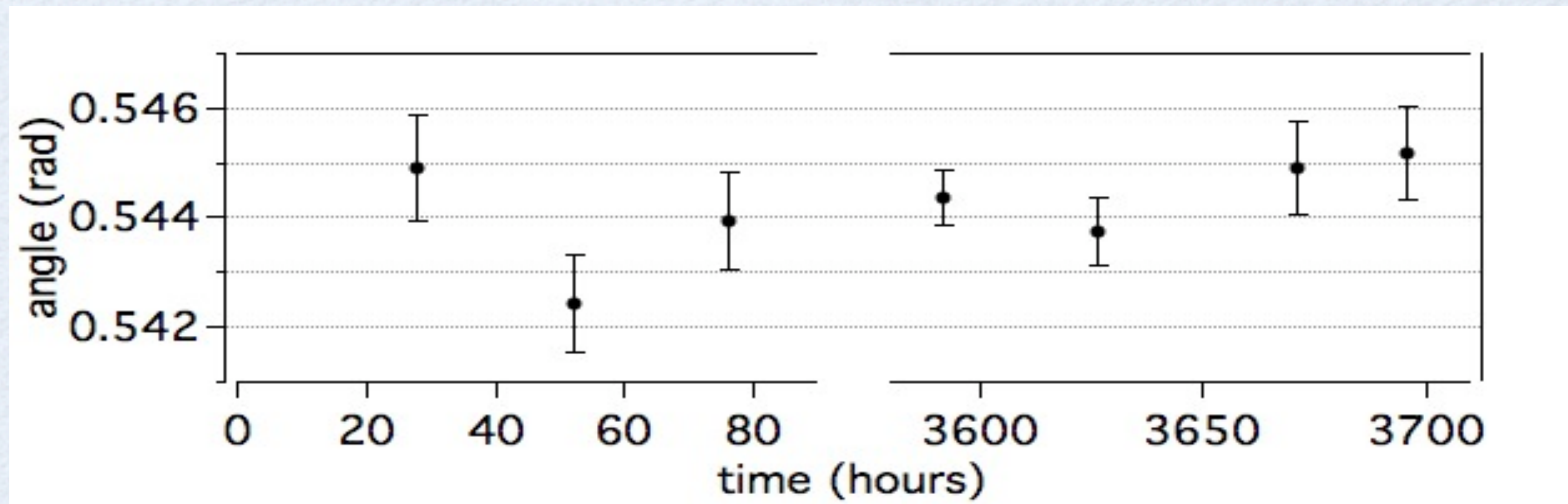


$$\Phi = 0.553065 \pm 0.00017 \text{ rad}$$

Corresponding to a statistical uncertainty of 300 ppm on *G*

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

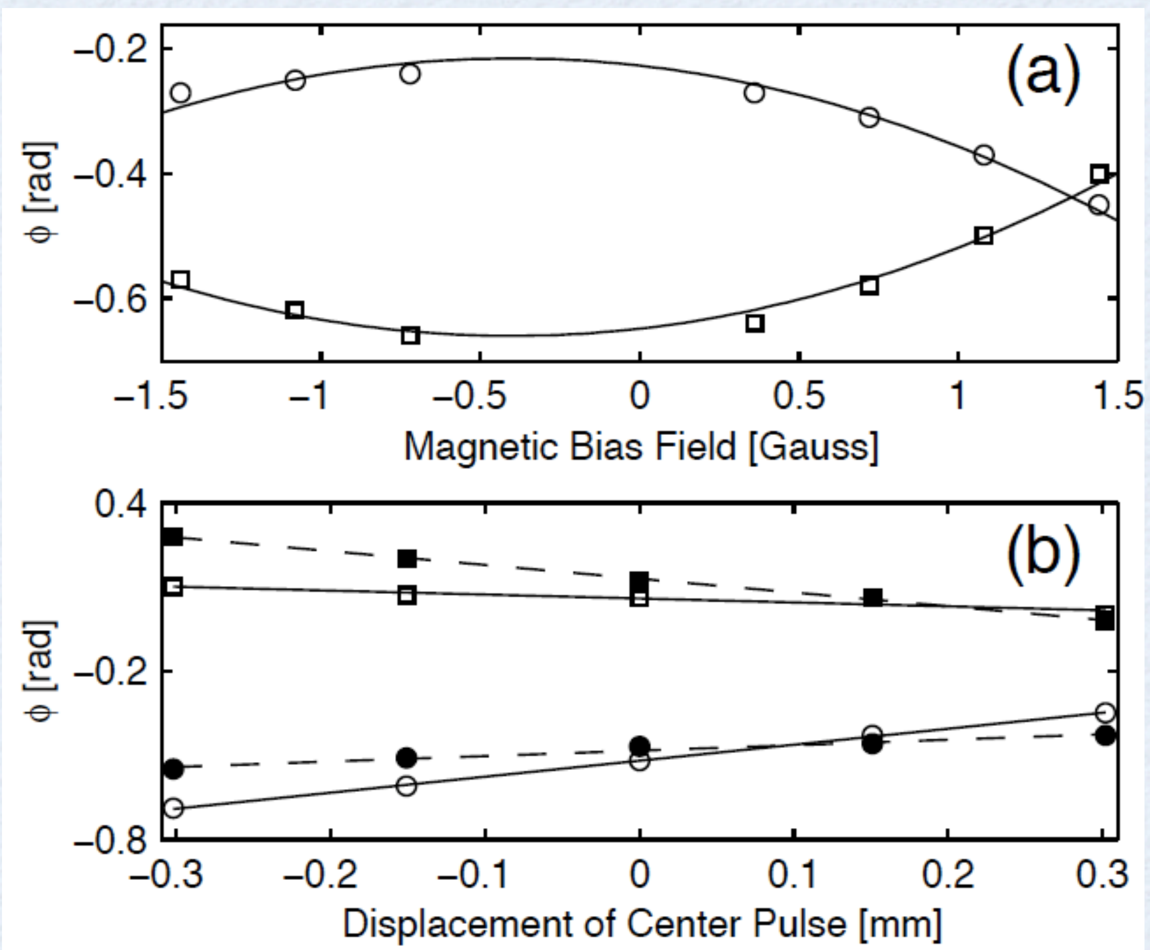
Comparison between two runs in December 2009 and May 2010

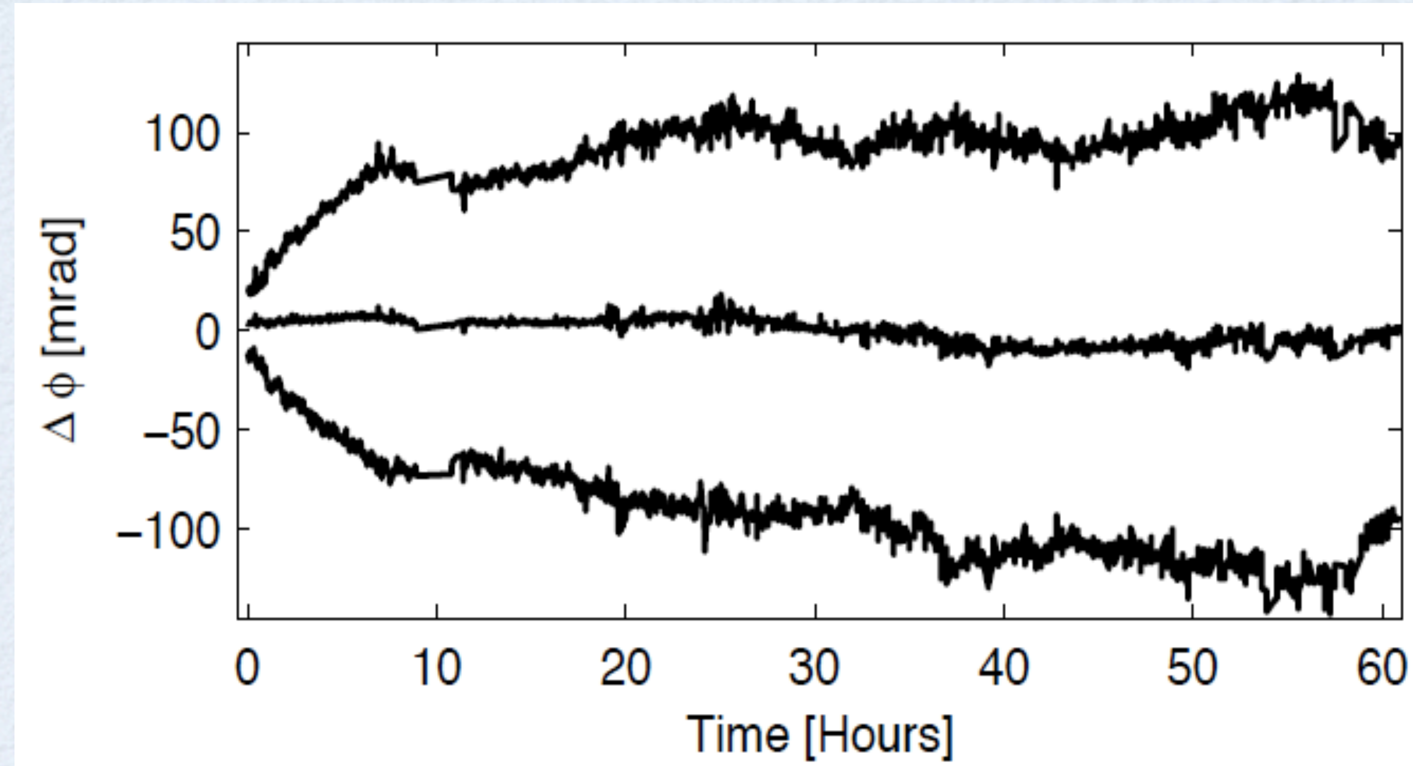


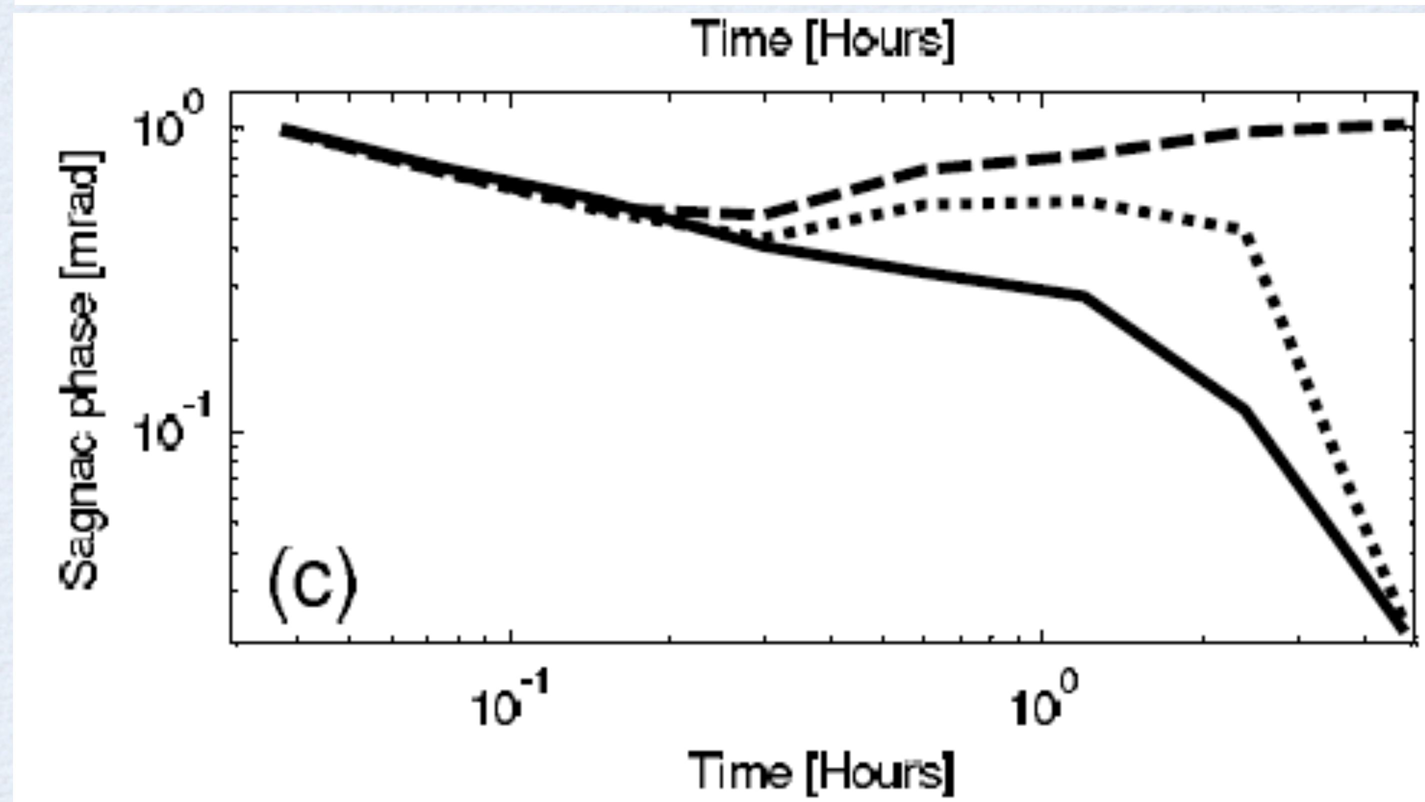
AI gyroscopes: long term stability

- Area reversal
- correlations removal

D. S. Durfee, Y. K. Shaham, M.A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006)





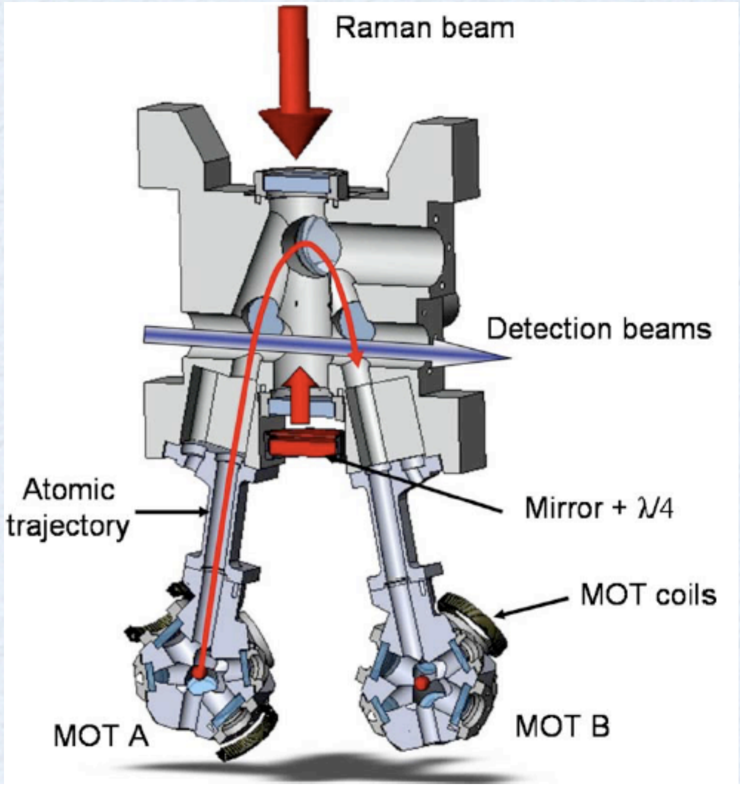


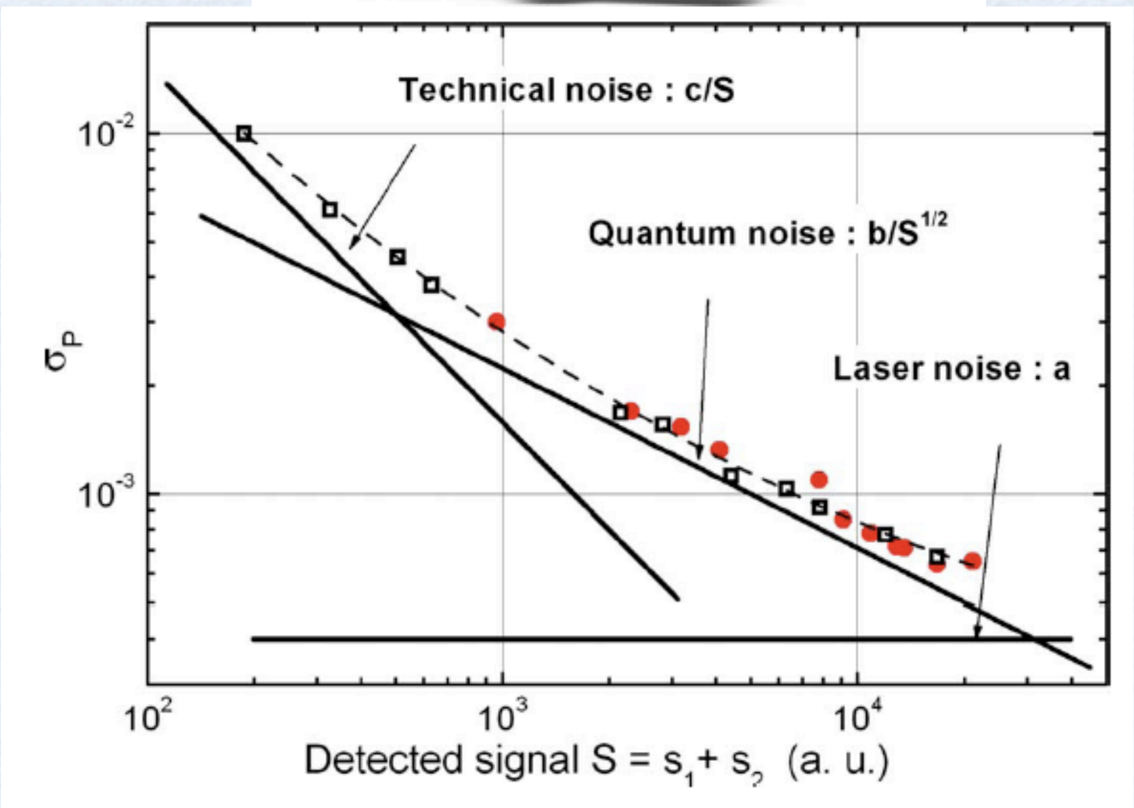
sensitivity: 6×10^{-10} rad$\cdot$ s$^{-1}\sqrt{Hz}$

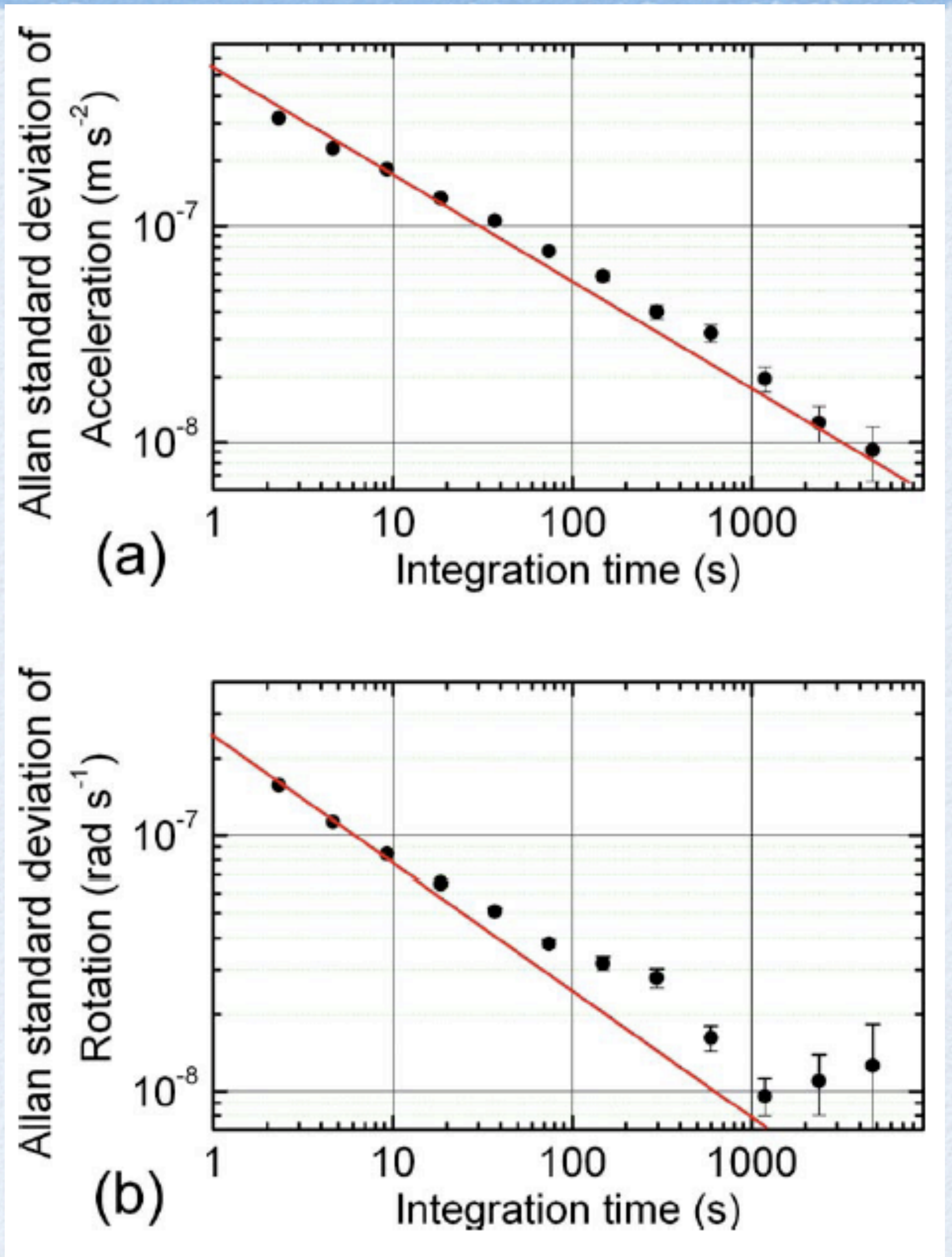
scale factor stability < 5 ppm

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

Cold atoms gyroscope (SYRTE)



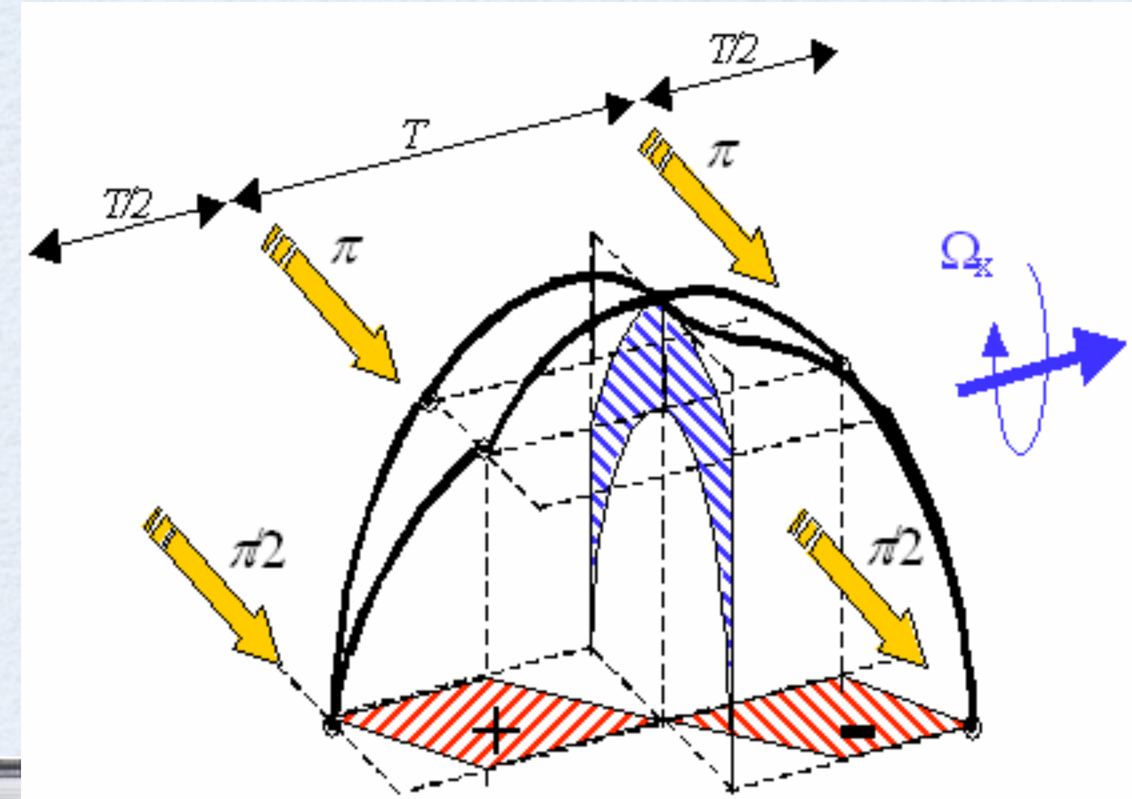


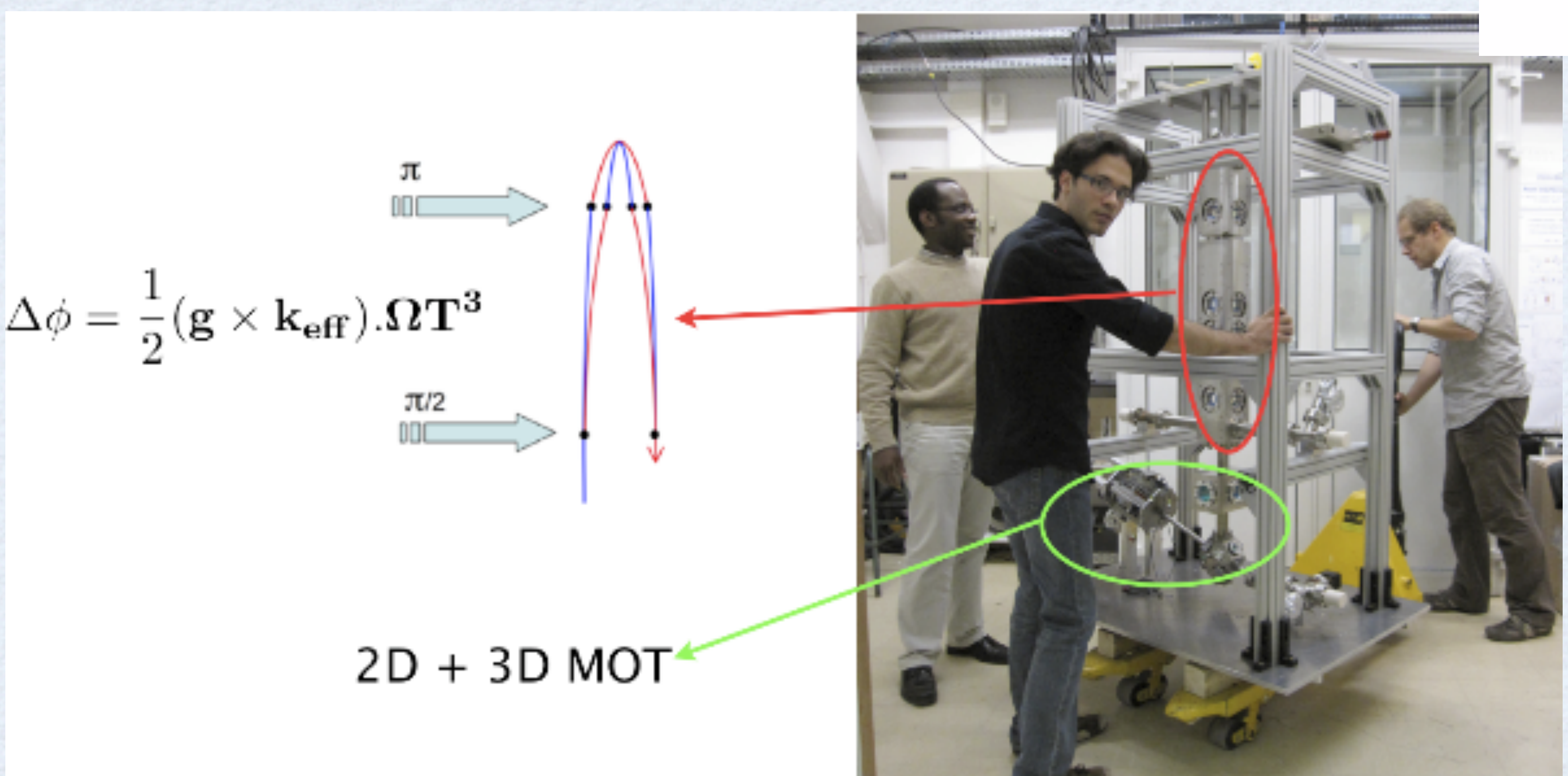


 A. Gauguet et al. PRA 80**, 063604 (2009)**

New AI gyro at SYRTE

- Vertical fountain
- four Raman pulses
- no acceleration sensitivity
- large area (11 cm2)



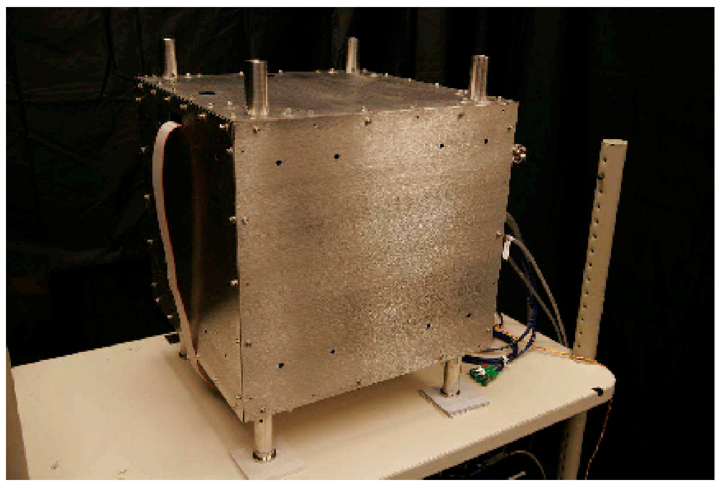


Future of AI inertial sensors

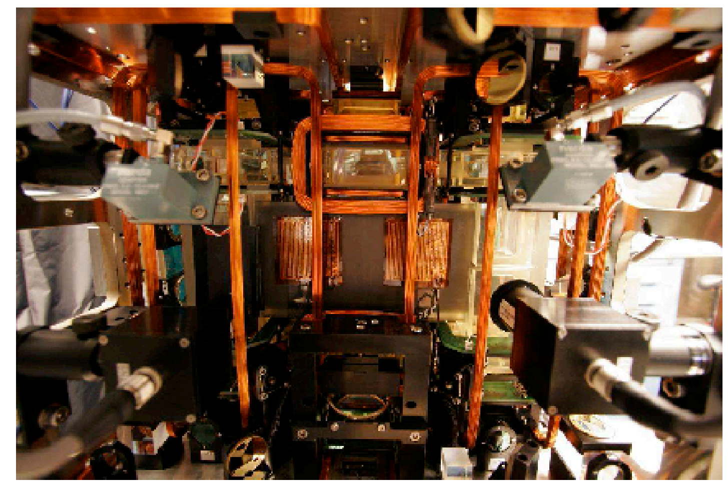
- Compact and transportable system without performance degradation
  - ground applications (geophysics)
  - space applications (satellite geodesy, inertial navigation, tests of fundamental physics): $\Delta\phi = kgT^2$
- Novel schemes to improve sensitivity/accuracy
  - high-momentum beam spitters
  - coherent/squeezed atomic states to surpass QPN detection
  - large size AI
- New applications
  - GW, quantum gravity, etc.

Portable AI sensors

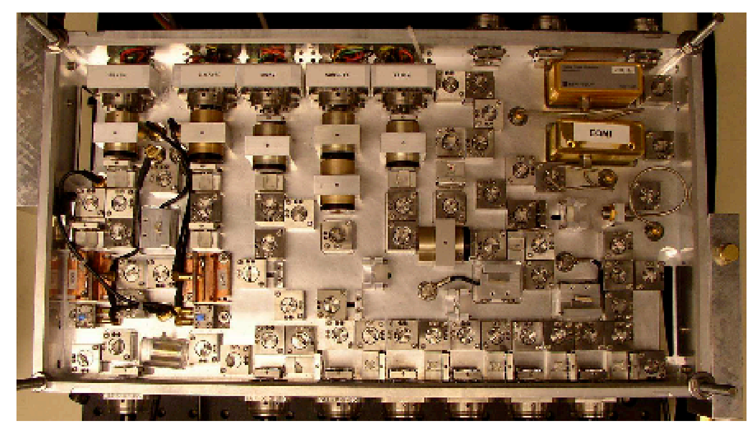
Compact gravity gradiometer/gyroscope/accelerometer



Multi-function sensor measures gravity gradient, rotation and linear acceleration along a single input axis.



Interior view



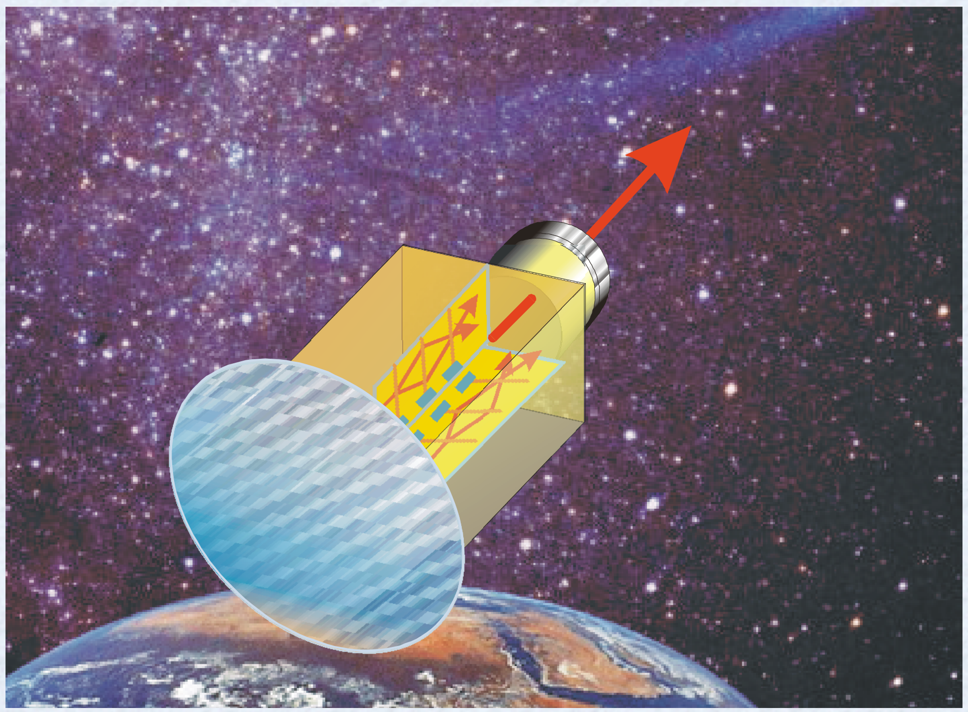
Laser system

PINS
PRECISION INERTIAL NAVIGATION SYSTEMS

STANFORD UNIVERSITY

from M. Kasevich, Talk at the International Workshop on Advances in Precision Tests and Experimental Gravitation in Space, Firenze, September 2006

The HYPER project

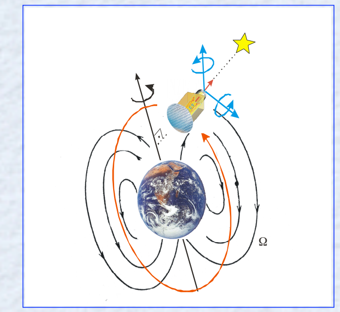


Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

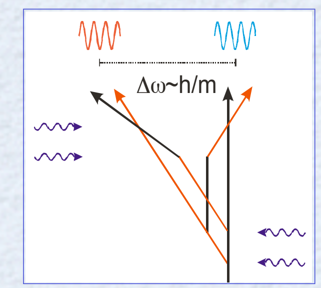
Resolution: 3x10^{-12}rad/s /√Hz

- Expected Overall Performance: 3x10^{-16}rad/s over one year of integration i.e. a S/N~100 at twice the orbital frequency

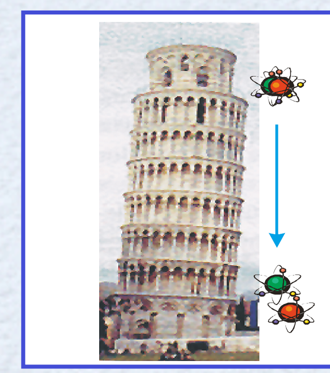
Mapping Lense-Thirring effect close to the Earth



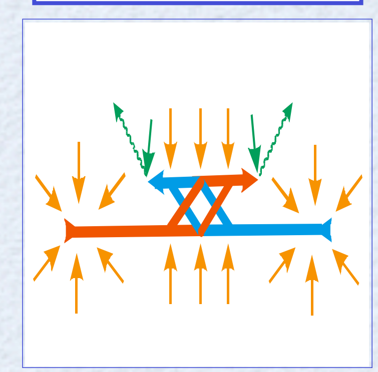
Improving knowledge of fine-structure constant



Testing EP with microscopic bodies



Atomic gyroscope control of a satellite

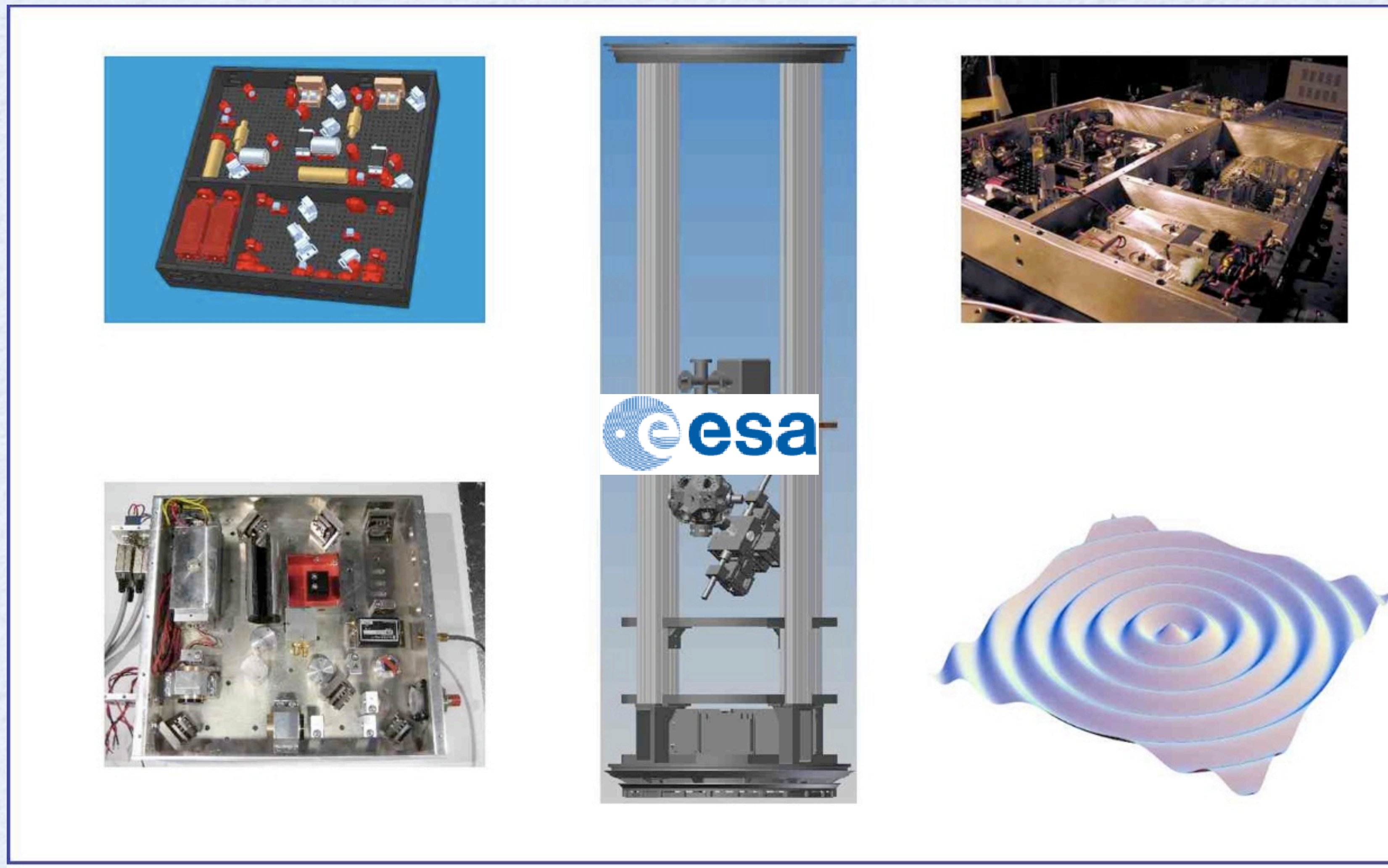


ESA-SCI (2000) 10
July 2000

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

Space Atom Interferometers

- Sensitivity of AI interferometry sensors scale as the square of T
- In microgravity possible sensitivity ~ 10^{-13} m/s^2 @ 1 s or better
- Main goals:
  - ground demonstrator to test technology readiness of atom interferometry sensors for space applications
  - Investigation of novel schemes based on quantum degenerate gases
- Space-based geodesy, inertial navigation, fundamental physics

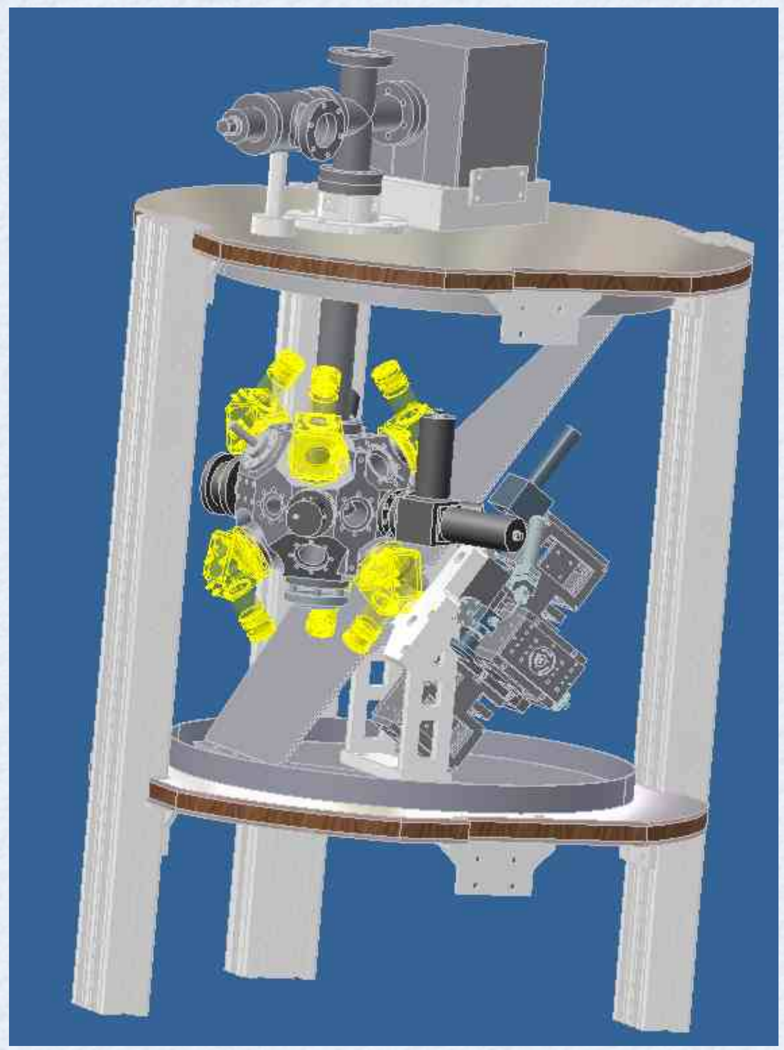


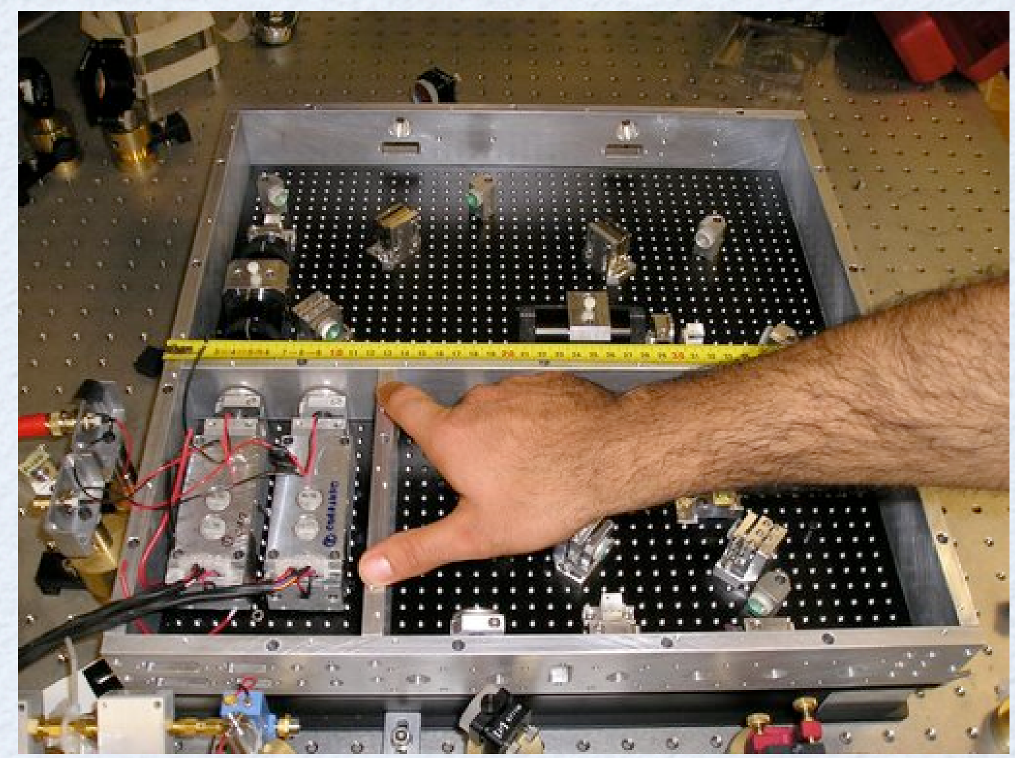
The SAI project

Pre-Phase-A project
ESA contract n. 20578/07/NL/VJ
AO-2004-064/082
Contract officer: Dr. L. Cacciapuoti

Project coordinator: Prof. G. M. Tino
Dipartimento di Fisica and LENS
Università di Firenze, Italy

SAI team:
Dipartimento di Fisica, Università di Firenze
Institut für Quantenoptik, Universität Hannover
Universität Hamburg
Humboldt-Universität zu Berlin
SYRTE, Observatoire de Paris
LENS, Firenze
Universität Ulm
ZARM, University of Bremen

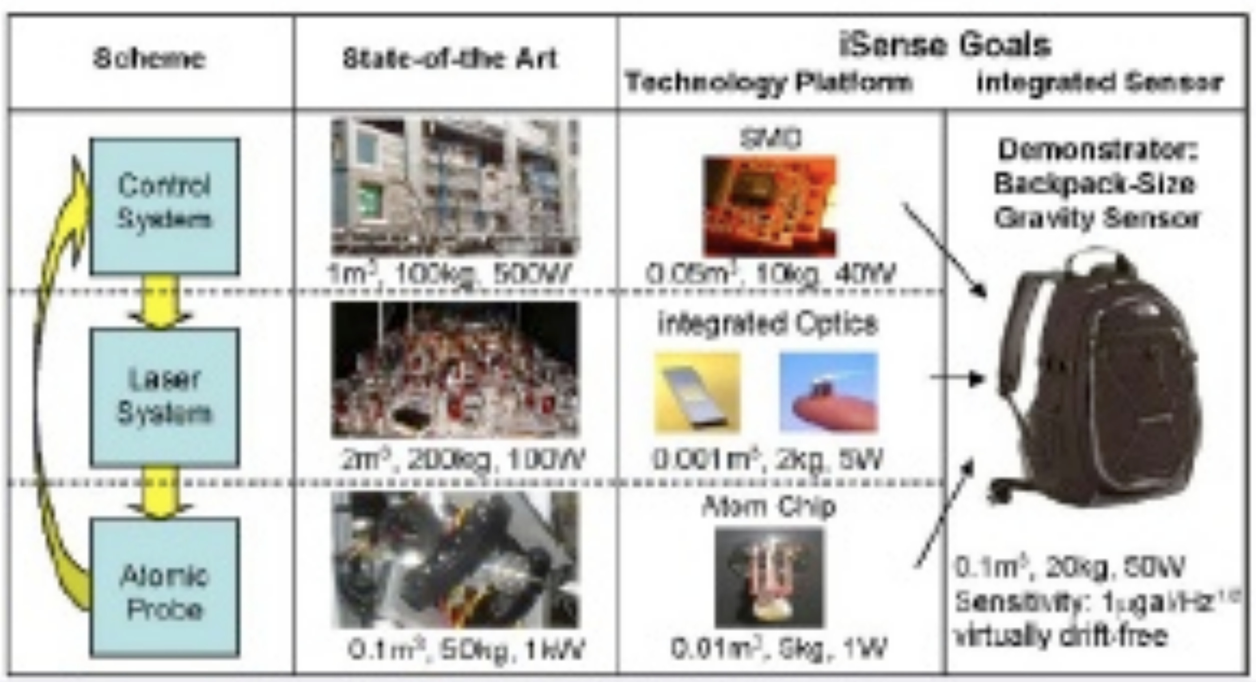




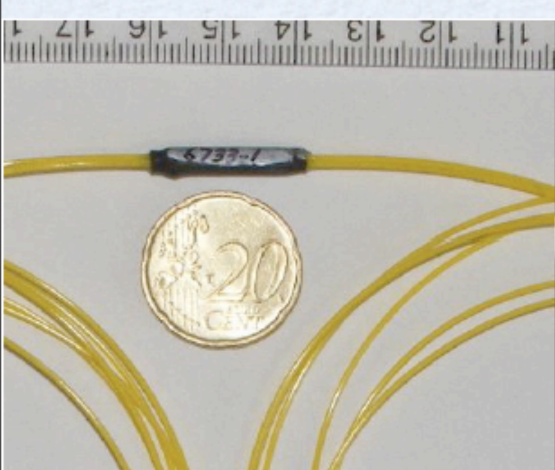
F. Sorrentino et al., *A compact atom interferometer for future space missions*, Microgravity Sci. Technol. **22**, 551 (2010)

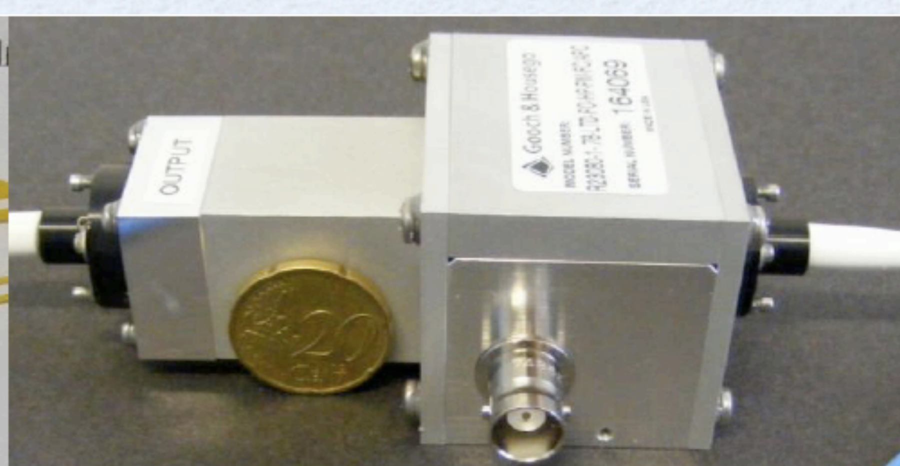
The iSense project

7th Framework Programme - Theme 3 "Information and Communication Technologies"
Call identifier: FP7-ICT-2009- C FET-Open

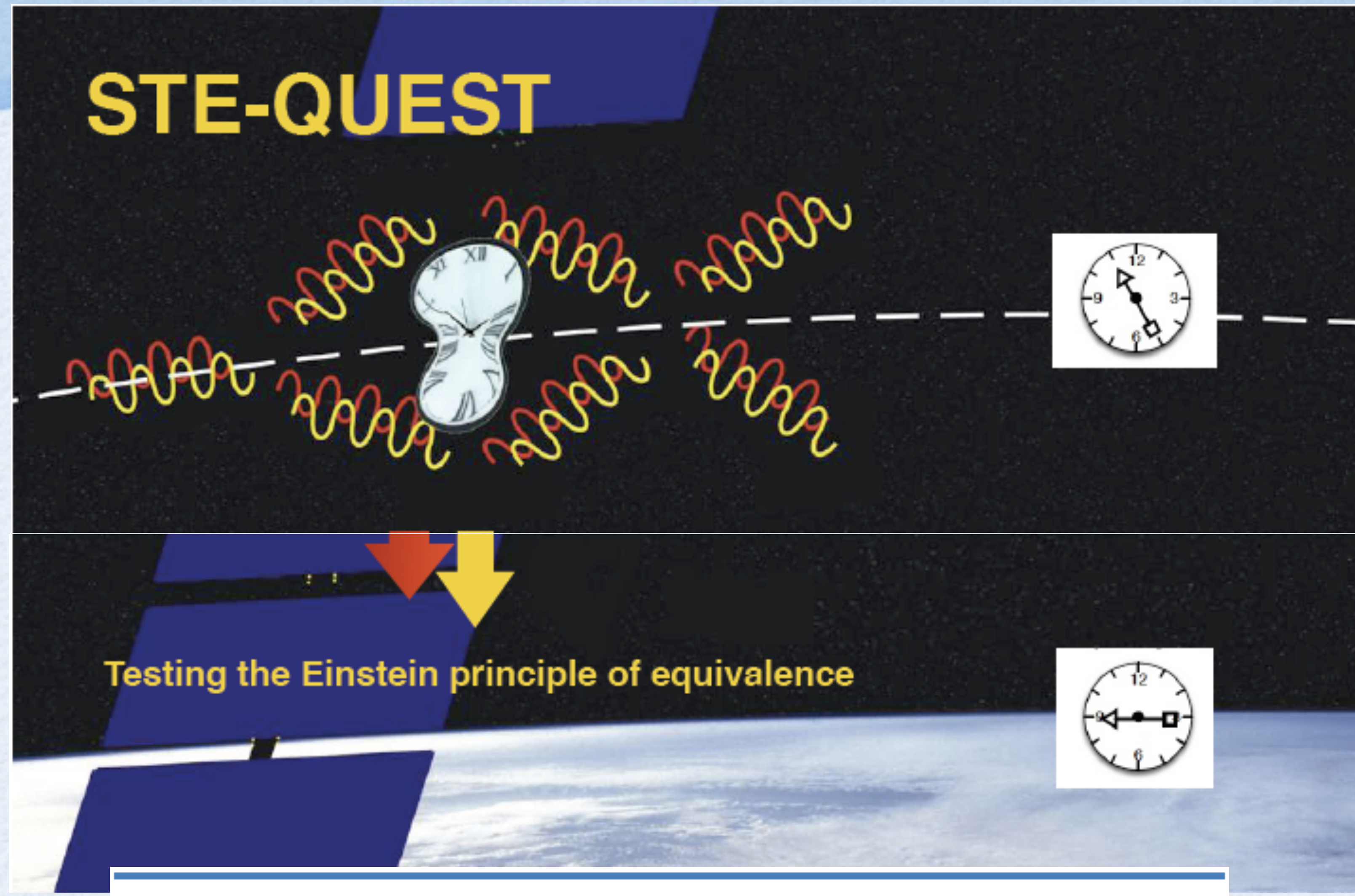


Participant no. *	Participant organisation name	Part. short name	Country
1 (Coordinator)	The University of Birmingham	Bham	UK
2	QinetiQ	QinetiQ	UK
3	University of Hamburg	UHH	D
4	Centre National de la Recherche Scientifique[1]	CNRS	F
5	University of Florence	UNIFI	I
6	Leibniz University Hannover	LUH	D
7	Institute for quantum optics and quantum information - Austrian Academy of Sciences	IQOQI-OEAW	A
8	Ferdinand-Braun-Institut für Höchstfrequenztechnik im Forschungsverbung Berlin e.V.	FBH	D
9	University of Nottingham	Nham	UK





ESA Cosmic Vision: STE-QUEST



LMT beam splitters

PRL 102, 240403 (2009) PHYSICAL REVIEW LETTERS week ending 19 JUNE 2009

Atom Interferometers with Scalable Enclosed Area

Holger Müller,[1,2,*] Sheng-wey Chiow,[3] Sven Herrmann,[3] and Steven Chu[1,2]

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Bloch oscillations (i.e., coherent acceleration of matter waves by an optical lattice) and Bragg diffraction are integrated into light-pulse atom interferometers with large momentum splitting between the interferometer arms, and hence enhanced sensitivity. Simultaneous acceleration of both arms in the same internal states suppresses systematic effects, and simultaneously running a pair of interferometers suppresses the effect of vibrations. Ramsey-Bordé interferometers using four such Bloch-Bragg-Bloch beam splitters exhibit 15% contrast at 24$\hbar k$ splitting, the largest so far ($\hbar k$ is the photon momentum); single beam splitters achieve 88$\hbar k$. The prospects for reaching 100 s of $\hbar k$ and applications such as gravitational wave sensors are discussed.

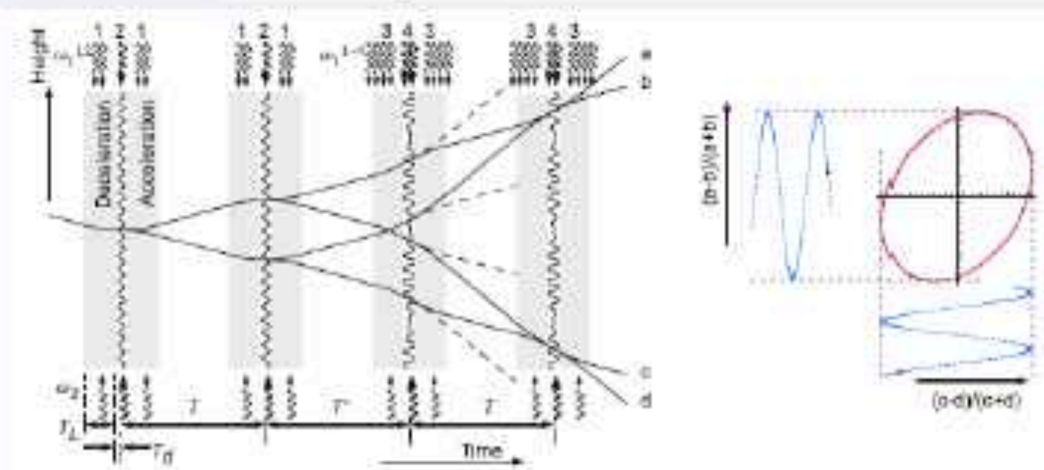
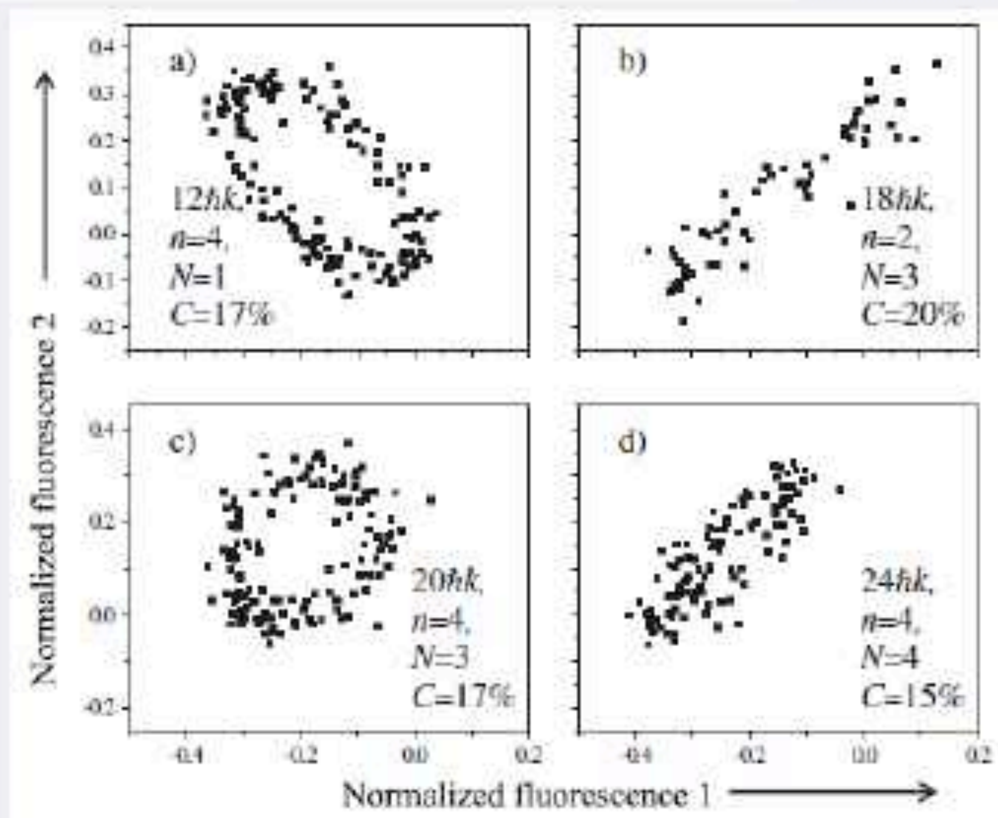
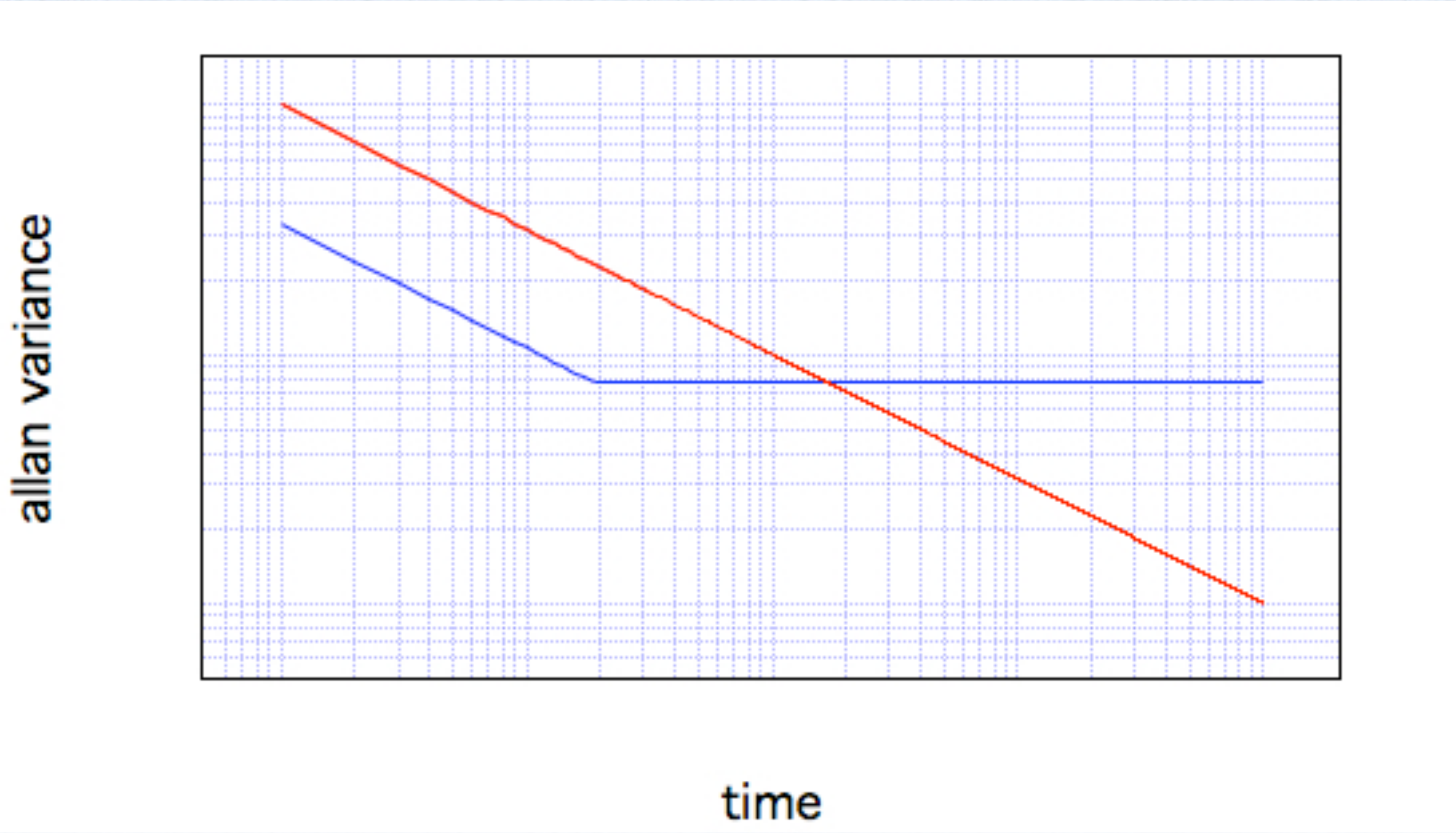


FIG. 1 (color online). Left: space-time diagram of simultaneous conjugate Ramsey-Bordé BBB-interferometers. 1: Dual optical lattice; 2: single Bragg beam splitter; 3: quadruple optical lattice; 4: dual Bragg beam splitter; (a)–(d): outputs. The dashed lines indicate trajectories that do not interfere. Right: plotting the outputs of the interferometers versus one another draws an ellipse.



Combination of atom & optical gyros

- Combination of optimal detection bands
- Tests of quantum gravity



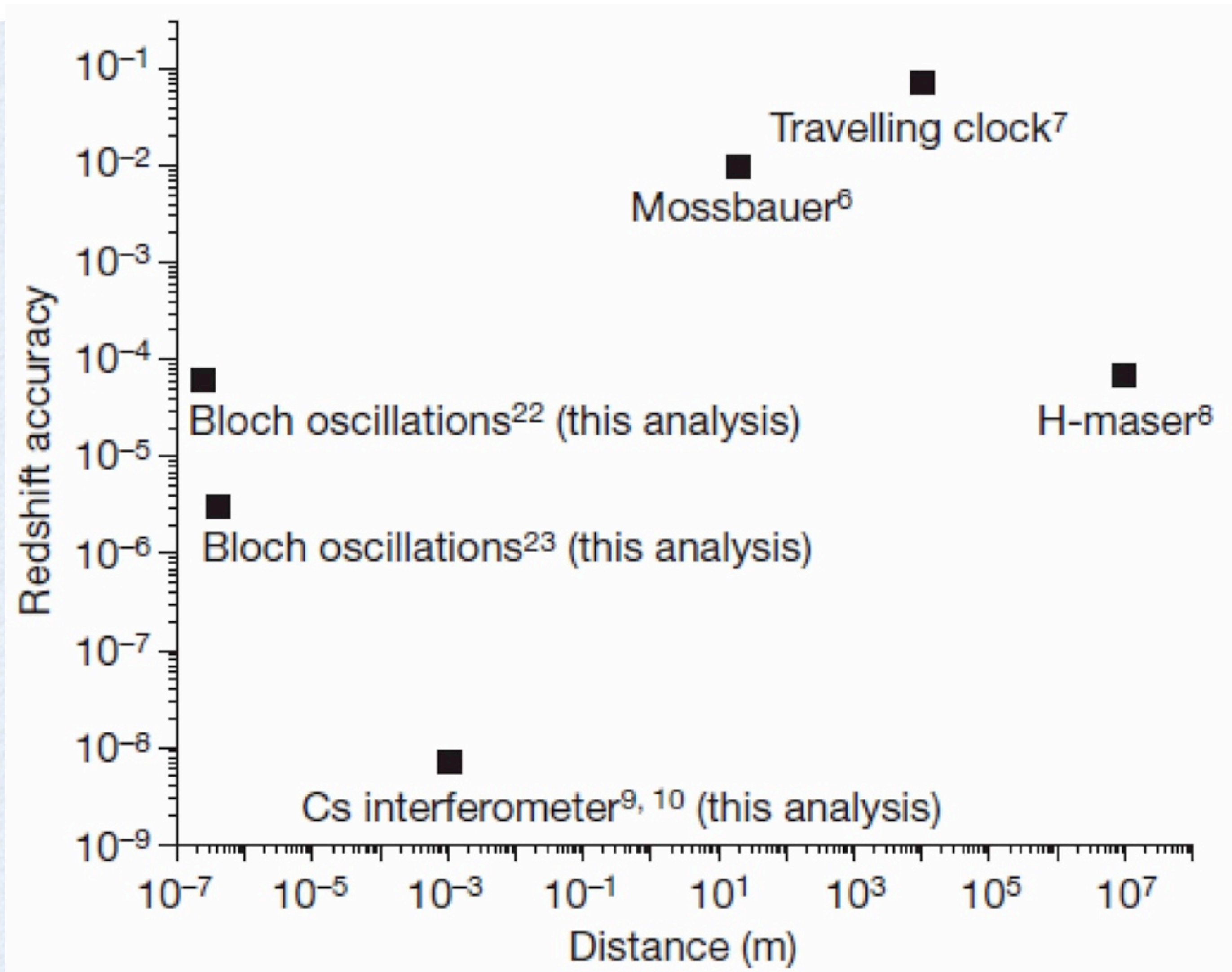
Red-shift measure with atomic probes

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

LETTERS

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

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



Conclusions

- Novel quantum inertial sensors have been developed using ultracold atoms and atom optics
- Particularly promising for long term stability and accuracy
  - MAGIA: *G* measured at 10^{-3} level, new measurement at 10^{-4} in progress
  - highly sensitive gyroscopes with thermal atoms, improved devices based on ultracold atoms under development
- Transportable systems have been already demonstrated, space-compatible ones are being developed
- Expected large improvements in next future, exp. in microgravity
- Combination/comparison with classical sensors may give rise to new schemes for applications of tests of fundamental physics

Our team

G.M. Tino team members

Nicola Poli	Researcher, Università di Firenze
Fiodor Sorrentino	Post-doc, CNR and Università di Firenze
Yu-Hung Lien	Post-doc, Università di Firenze/ICTP
Antonio Giorgini	Post-doc, LENS
Marco Tarallo	Post-doc, LENS
Fu-Yuan Wang	Post-doc, Università di Firenze/ICTP
Marco Schioppo	PhD student, Università di Firenze
Gabriele Rosi	PhD student, Università di Pisa
Denis Sutyrin	PhD student, Università di Pisa
Luigi Cacciapuoti	Long term guest, ESA-Noordwijk
Marella de Angelis	Long term guest, CNR
Marco Prevedelli	Long term guest, Università di Bologna

Previous members and visitors

Andrea Alberti, PhD student
Andrea Bertoldi, Post-doc
Sergei Chepurov, Institute of Laser Physics, Novosibirsk, visitor
Robert Drullinger, NIST, Long term guest
Marco Fattori, PhD student
Gabriele Ferrari, Researcher, INFM/CNR
Vladyslav Ivanov, Post-doc
Marion Jacquey, Post-doc
Giacomo Lamporesi, PhD student
Chris Oates, NIST, visitor
Torsten Petelski, PhD student
Juergen Stuhler, Post-doc

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- ✓ Agenzia Spaziale Italiana (ASI)
- ✓ Istituto Nazionale per la Fisica della Materia (INFM)
- ✓ Istituto Nazionale Geofisica e Vulcanologia (INGV)

http://coldatoms.lens.unifi.it/