Atom interferometry gyroscopes

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Outline

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

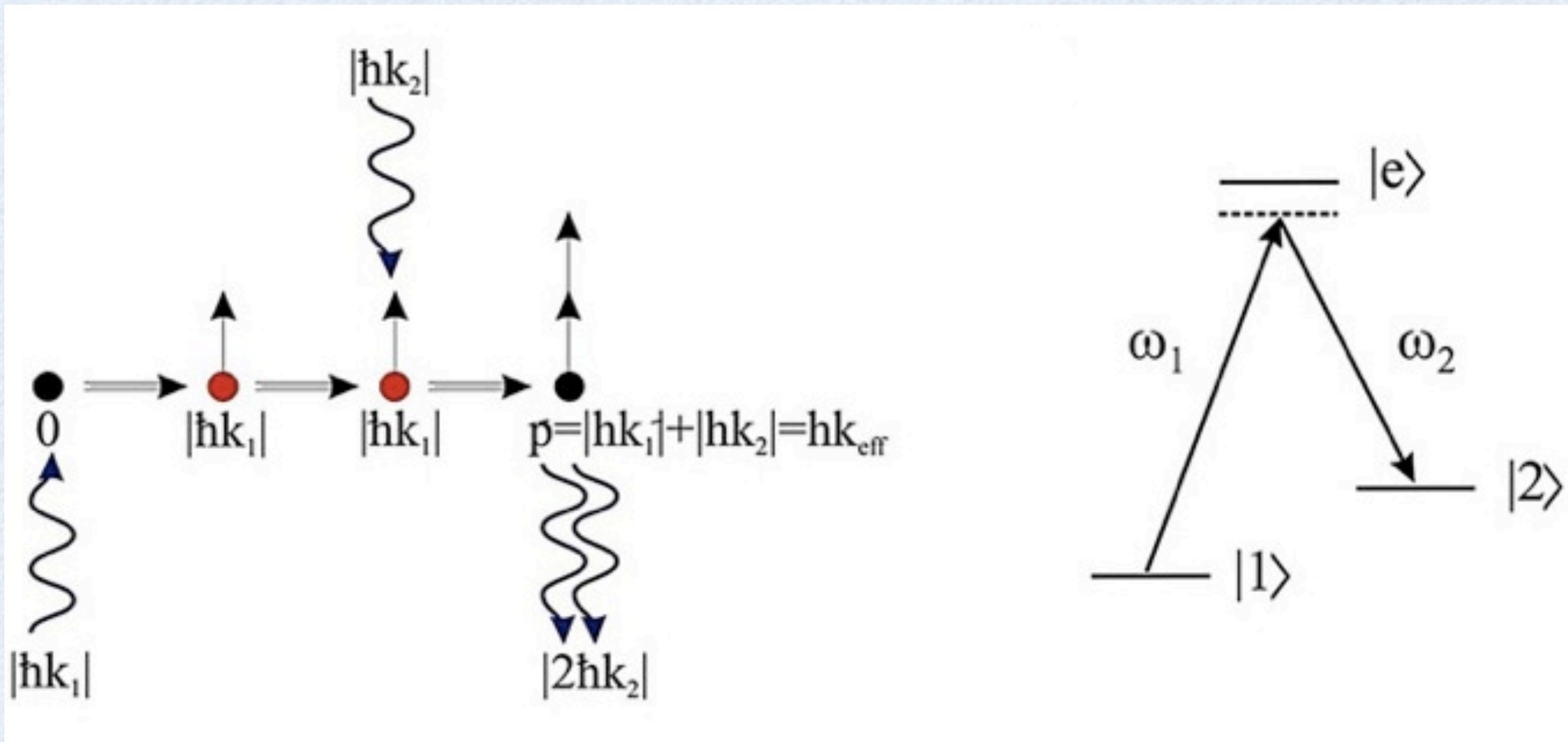
Atom interferometry sensors (I)

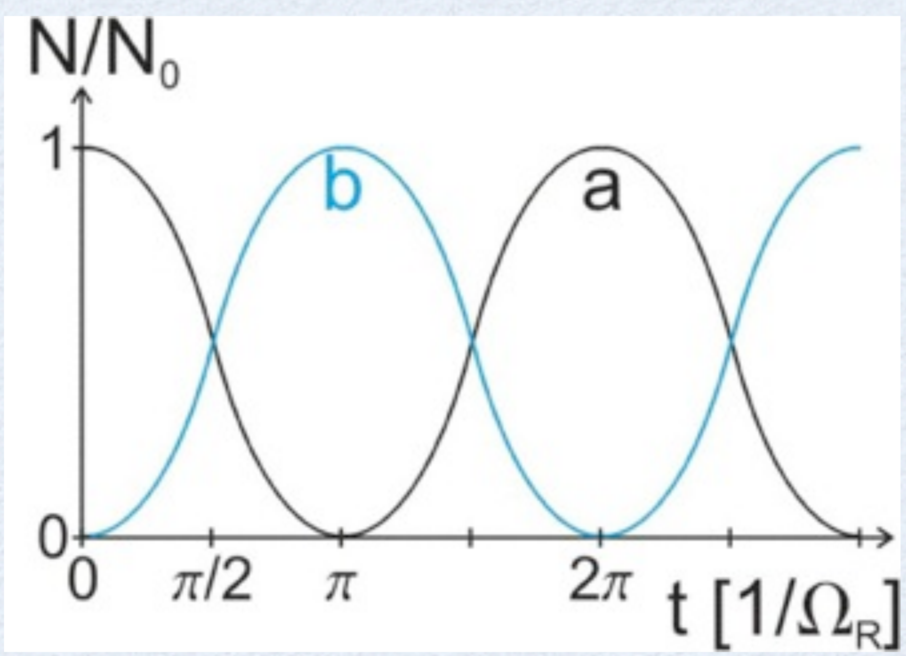
- Virtual sensitivity improvement of several orders of magnitude over optical interferometers.
- However, such advantage is currently reduced by
  - small particle flux (10^{10} for alkali, 10^{18} for H)
  - small separation of matter-wave paths (few photon recoils).
- Nevertheless, AI sensors already compete with optical counterparts.
- Already achieved: inertial sensing (acceleration, gravity gradient, rotations) measurement of fundamental constants (G, α).
- In progress/proposed: tests of GR (EP, Lense-Thirring, limits on PPN parameters); test of Newton's $1/r^2$ law at short length scale; atom neutrality; GW detection.
- Large progress are foreseen in the next future (LMT beam splitters, high flux atomic sources, sub-shot noise detection schemes, etc.)

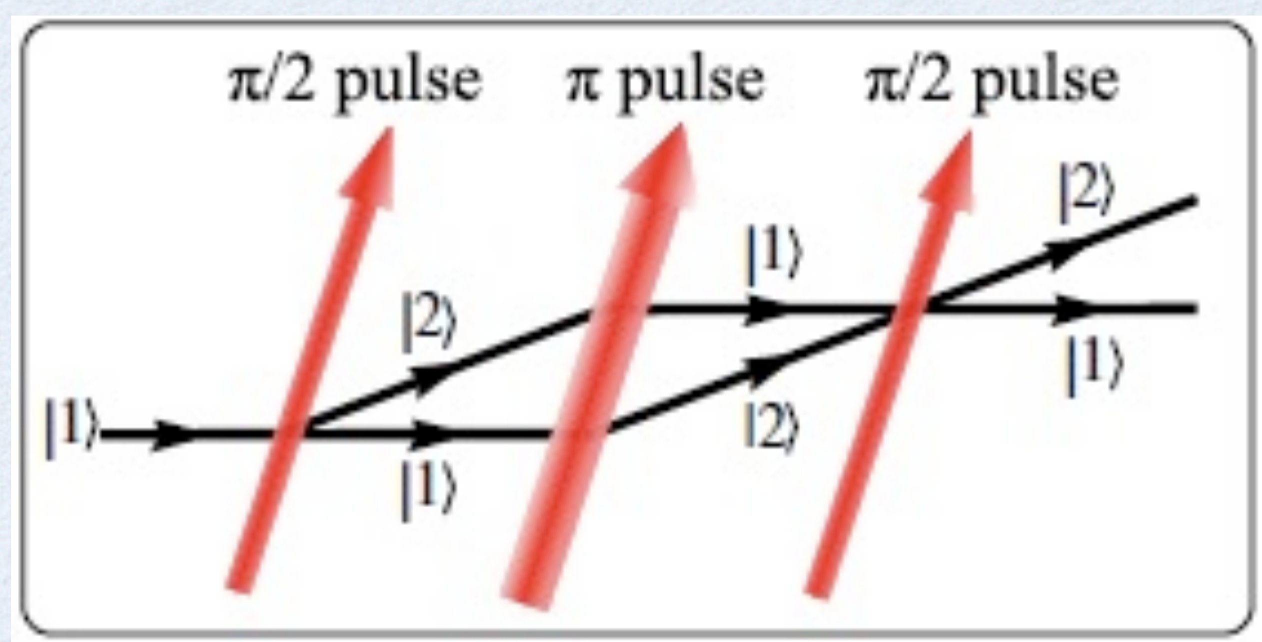
Atom interferometry sensors (II)

- AI inertial sensors feature very good long term stability and control over systematic effects
  - Differential configurations allow for very large CMRR of vibrations
  - Based on quantum atom-light interaction, which can be precisely modeled
  - The possible choice of different internal/external quantum states, as well as of different isotopic species, provides “knobs” to isolate, model and minimize several possible noise sources

Raman pulse atom interferometer







Light-pulse AI inertial sensors

TRANSVERSAL PULSES

-the interferometer encloses an area

-used to measure rotations (GYROSCOPES)

LONGITUDINAL PULSES

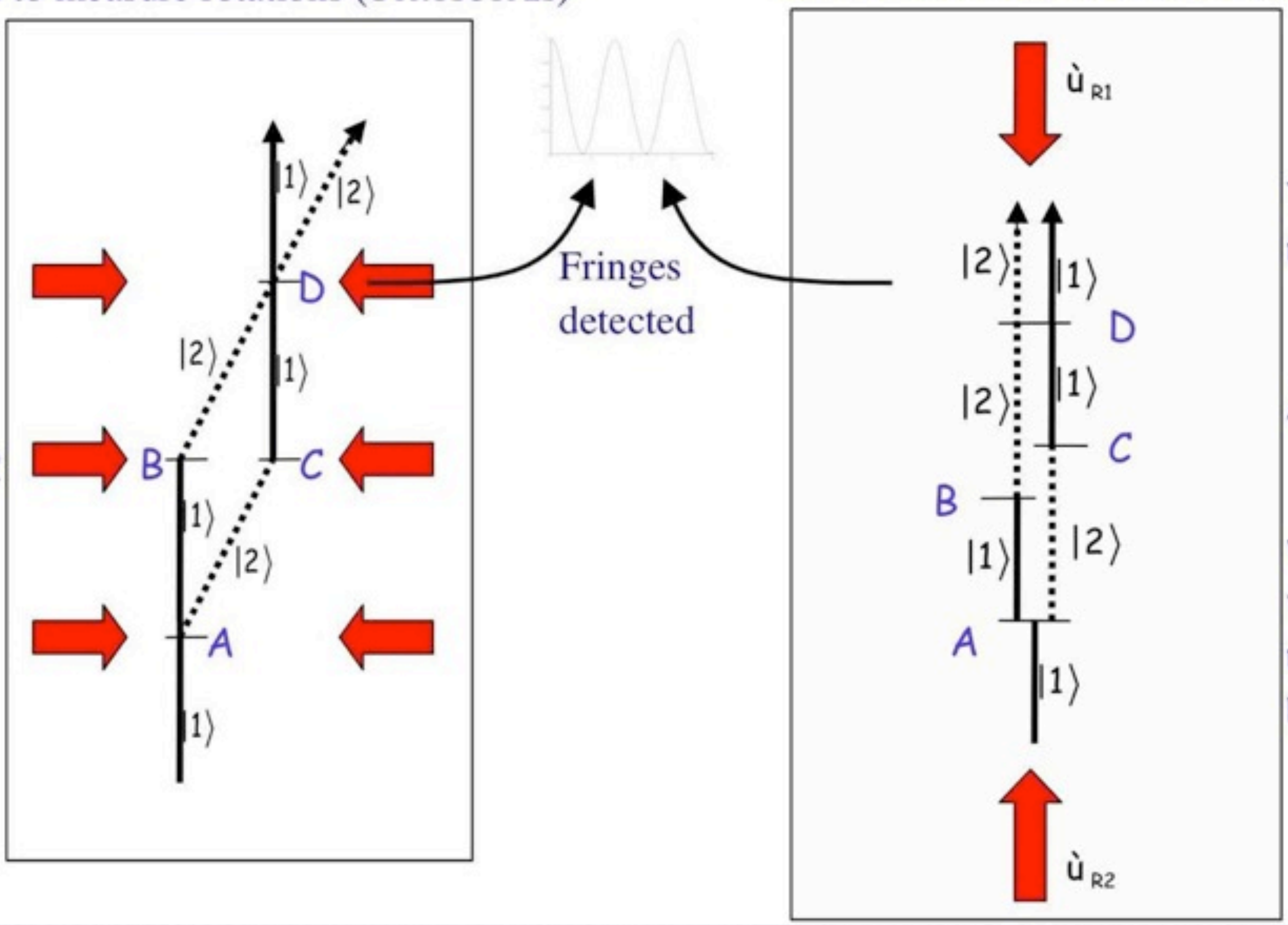
-no area enclosed

-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

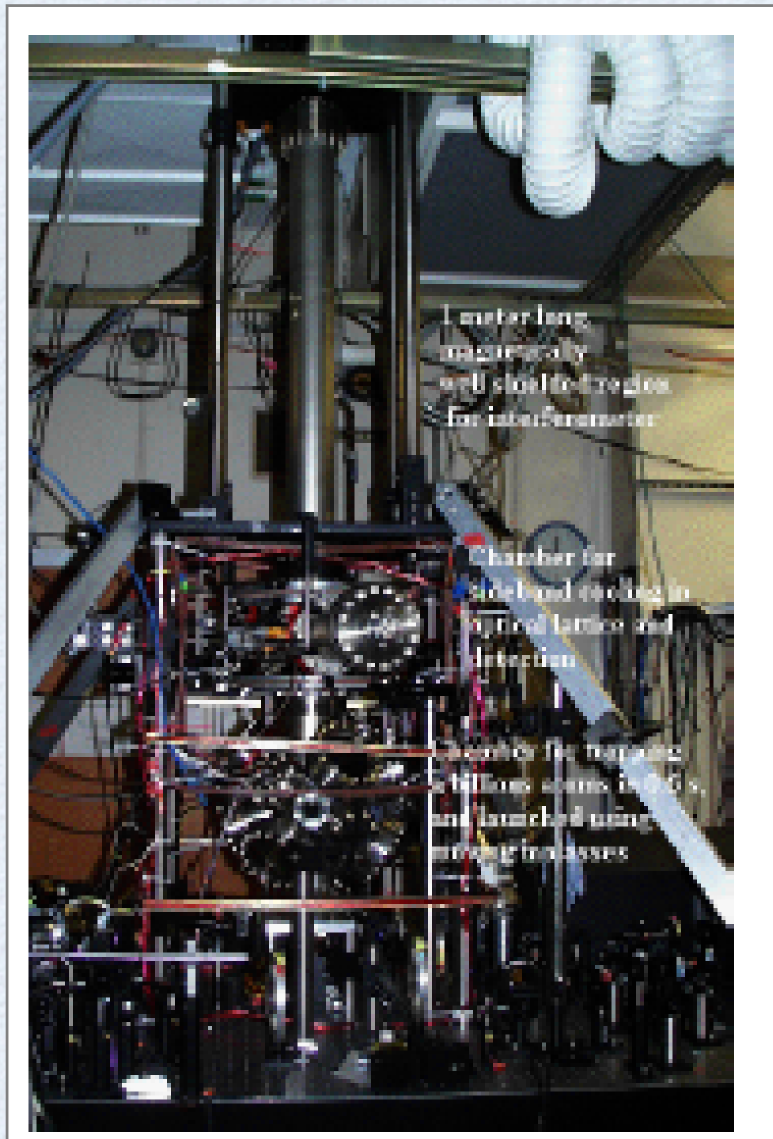


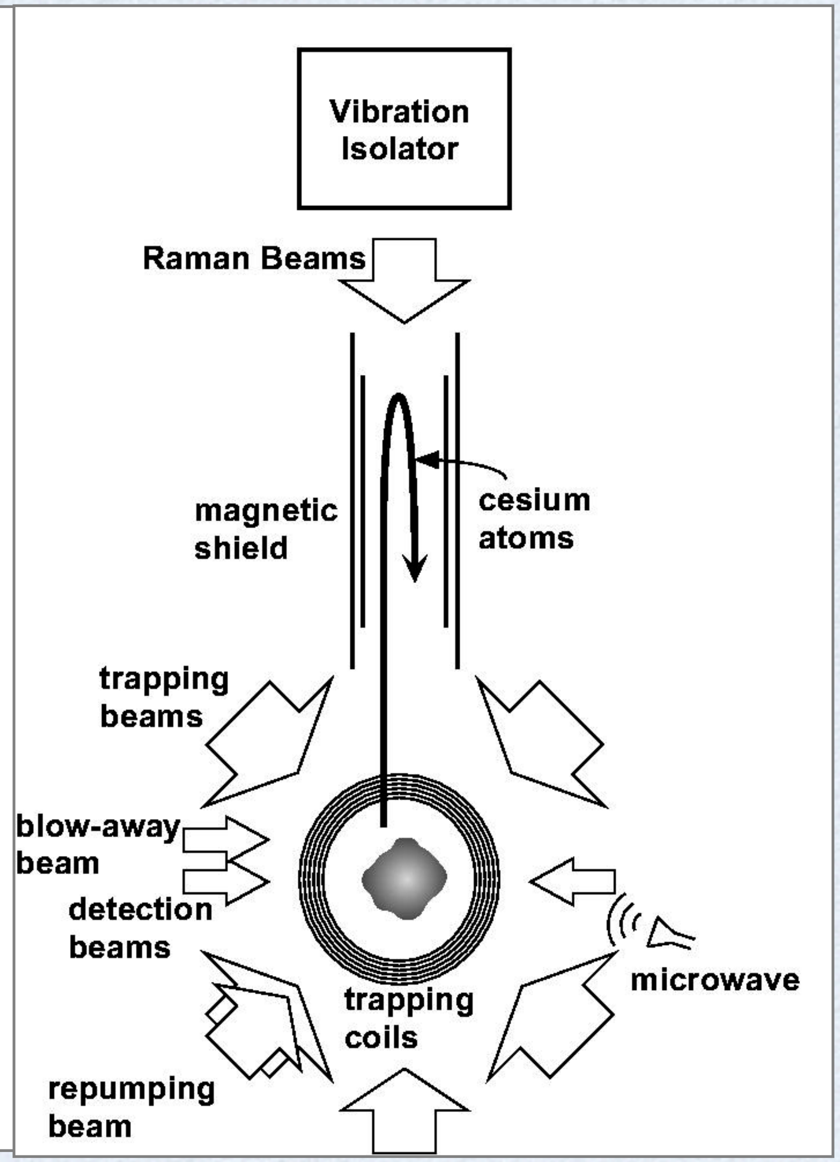
With an acceleration g, the phase difference

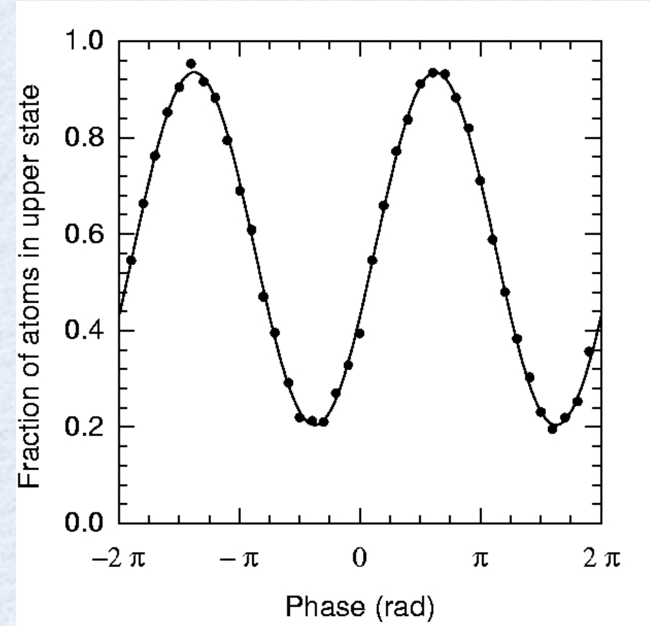
$\Delta\phi = k_{eff}\, g\, T^2$

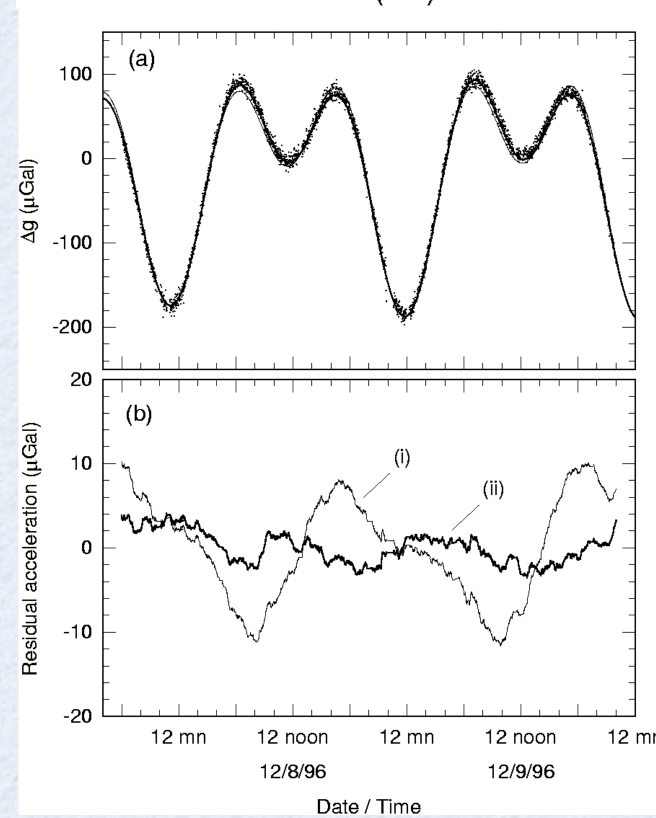
where $\boldsymbol{k}$ is the laser wavenumber and $\boldsymbol{T}$ the time interval between laser pulses

First AI sensors @ Stanford: gravimeter









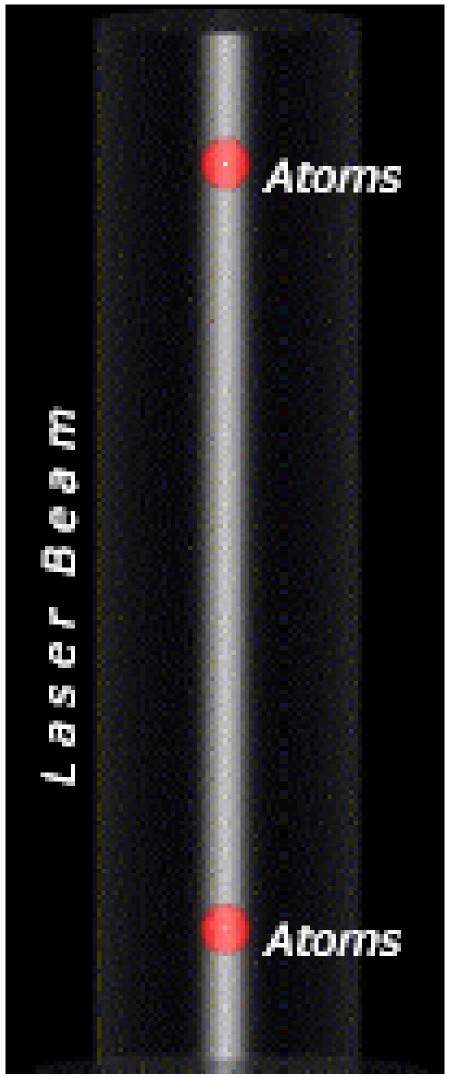
resolution: 8×10^{-9} g in 1 second

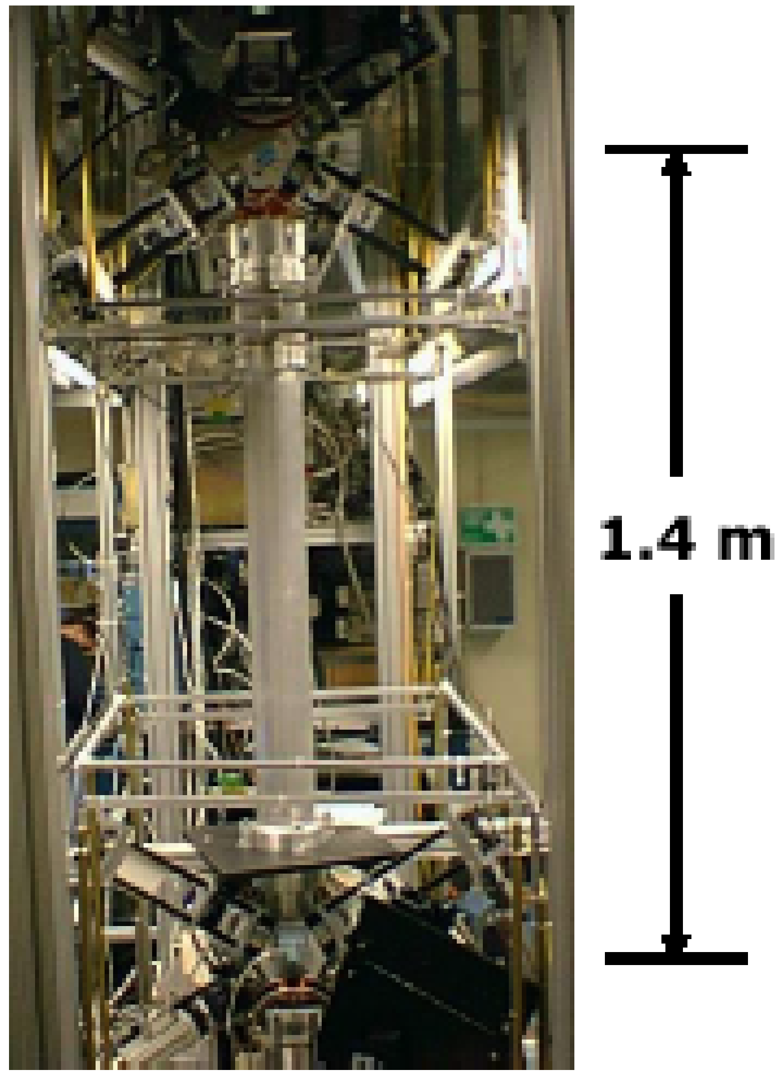
accuracy: $\Delta g/g \leq 3 \times 10^{-9}$ limited by tidal models

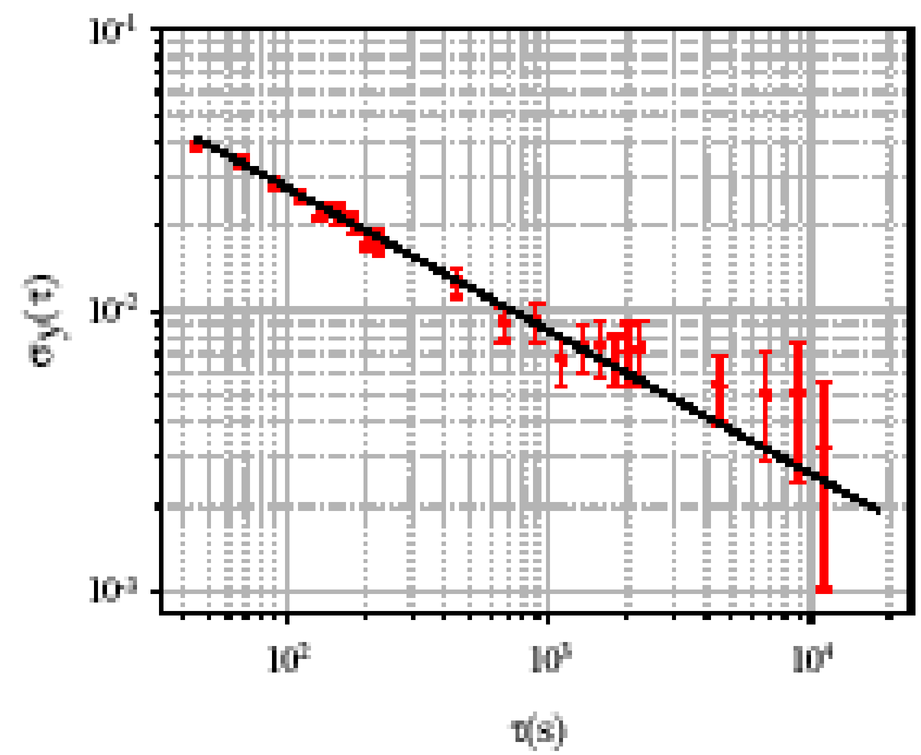
A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)

H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)

First AI sensors @ Stanford: gradiometer







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

Demonstrated diffential acceleration sensitivity:

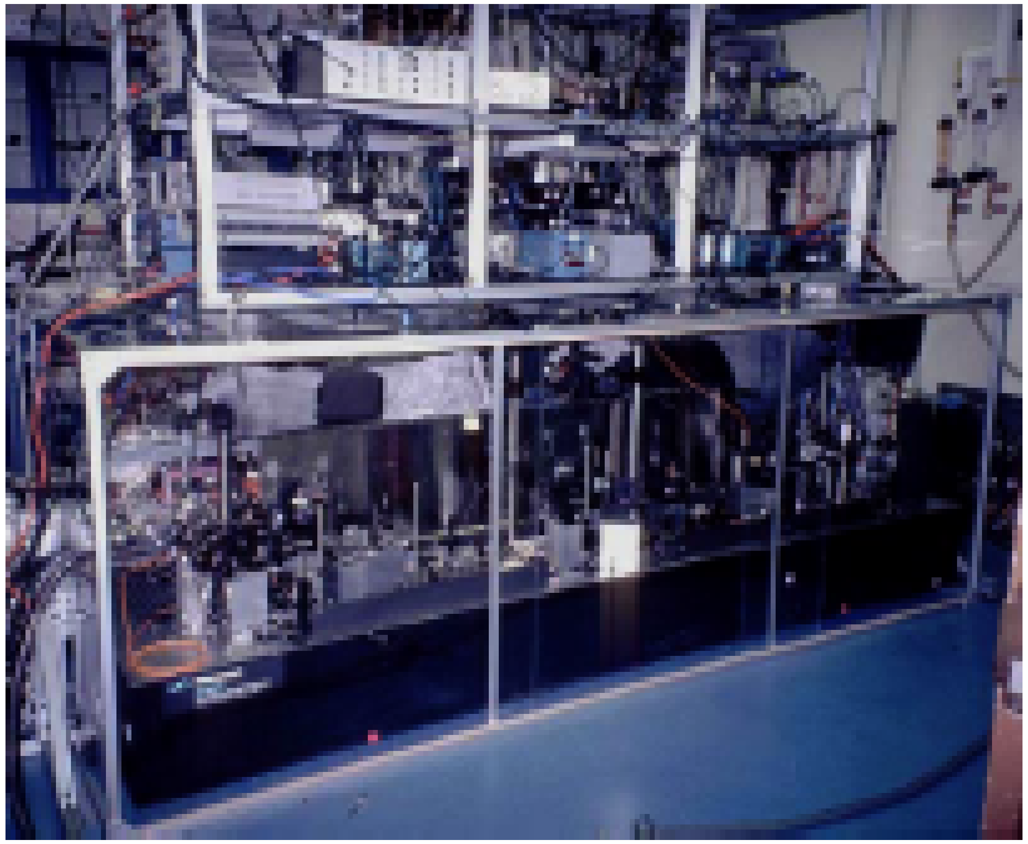
4×10^{-9} g/Hz$^{1/2}$

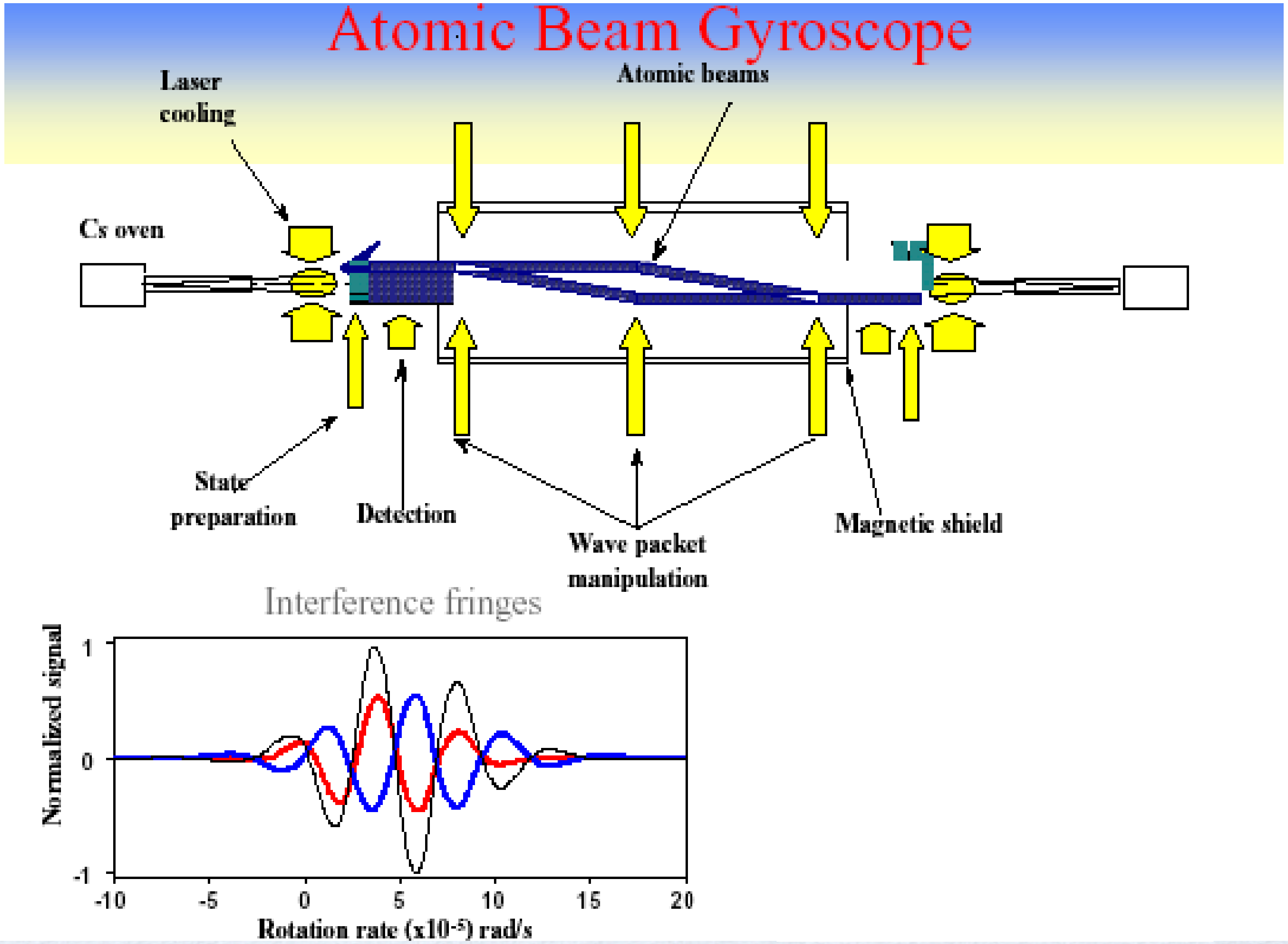
(2.8×10^{-9} g/Hz$^{1/2}$ per accelerometer)

limited by QPN

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

First AI sensors @ Stanford: gyroscope





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

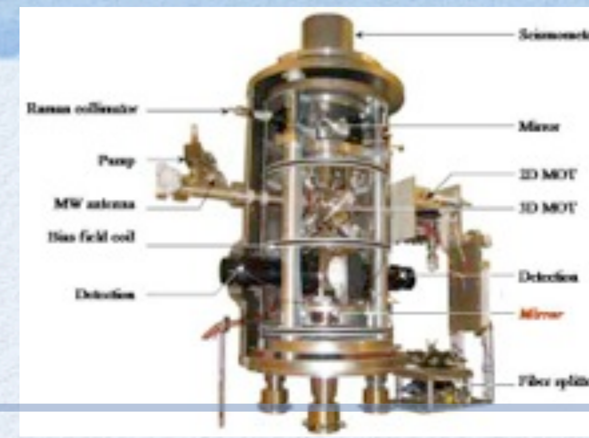
scale factor stability < 5 ppm

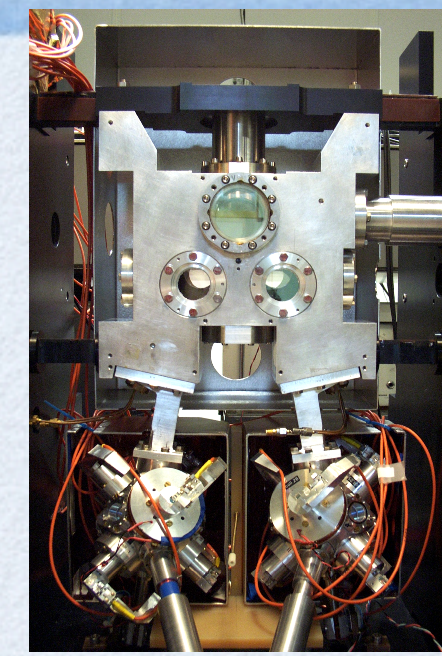
bias stability $< 70\,\mu$deg/h

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)

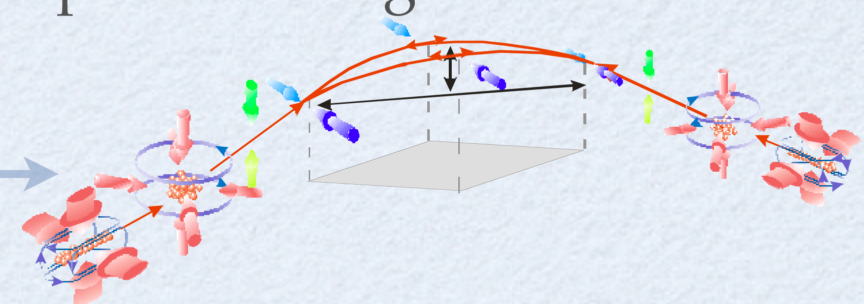
Other AI sensors

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

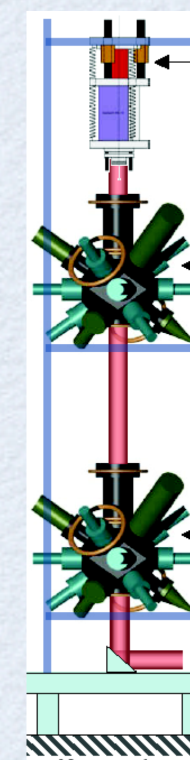




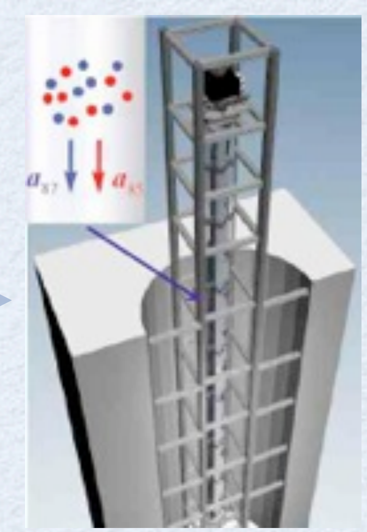
- IQO (D)
  - CASI gyroscope
  - QUANTUS drop-tower experiment



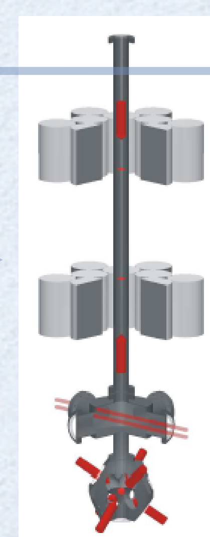
- JPL (USA)
  - gradiometer



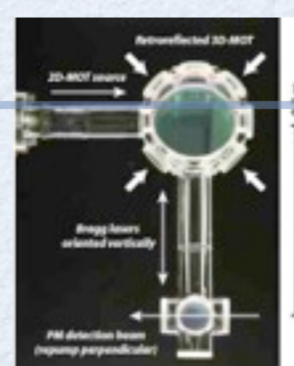
- STANFORD (U.S.A)
  - transportable multi-axis sensors
  - 10 m tower for WEP test



- UNIFI (IT)
  - MAGIA



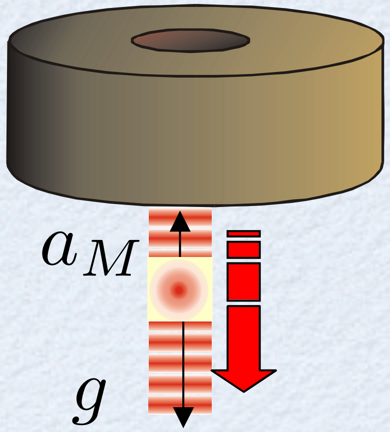
- CANBERRA
  - Bragg gravimeter



MAGIA

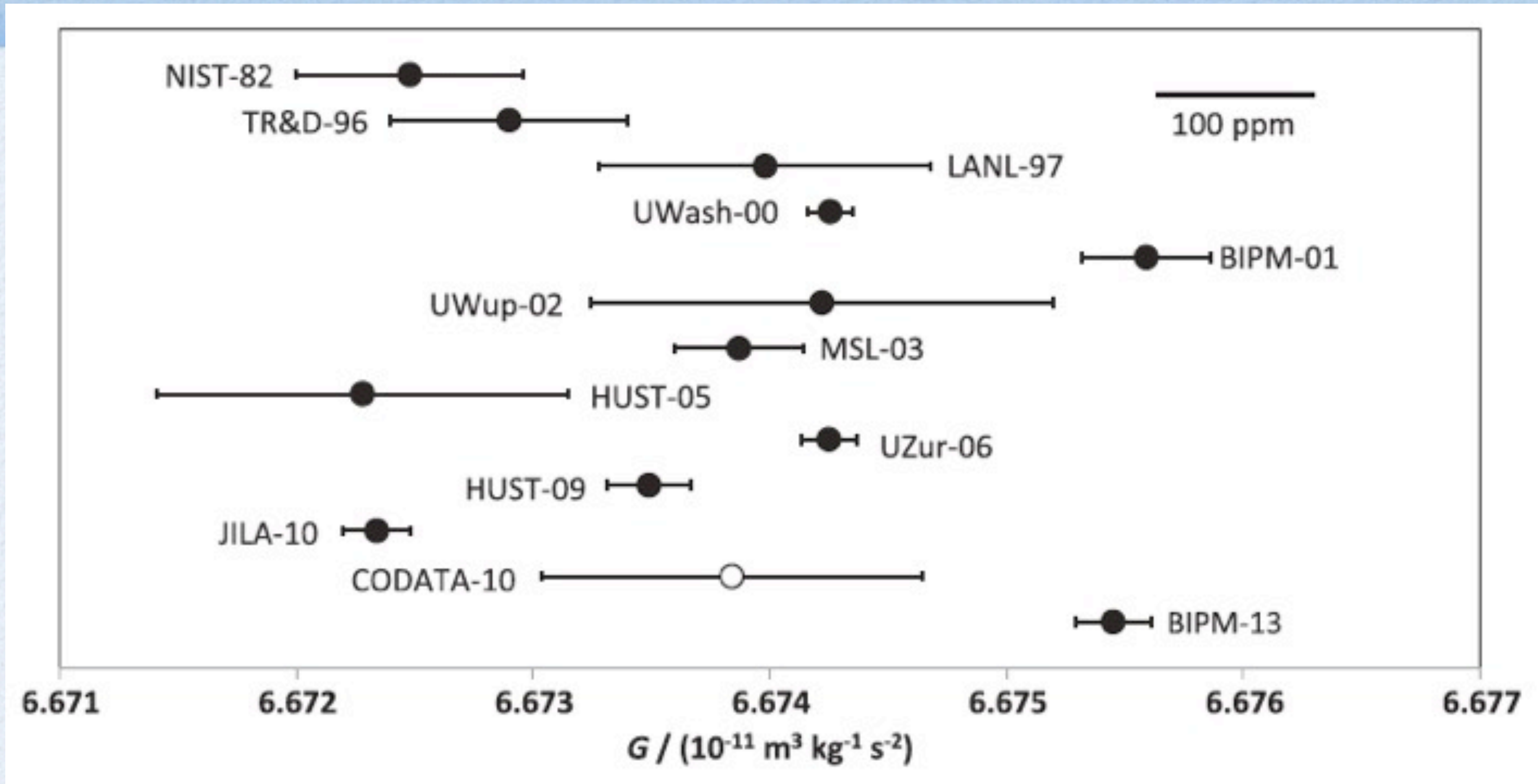
Misura Accurata di G mediante Interferometria Atomica

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



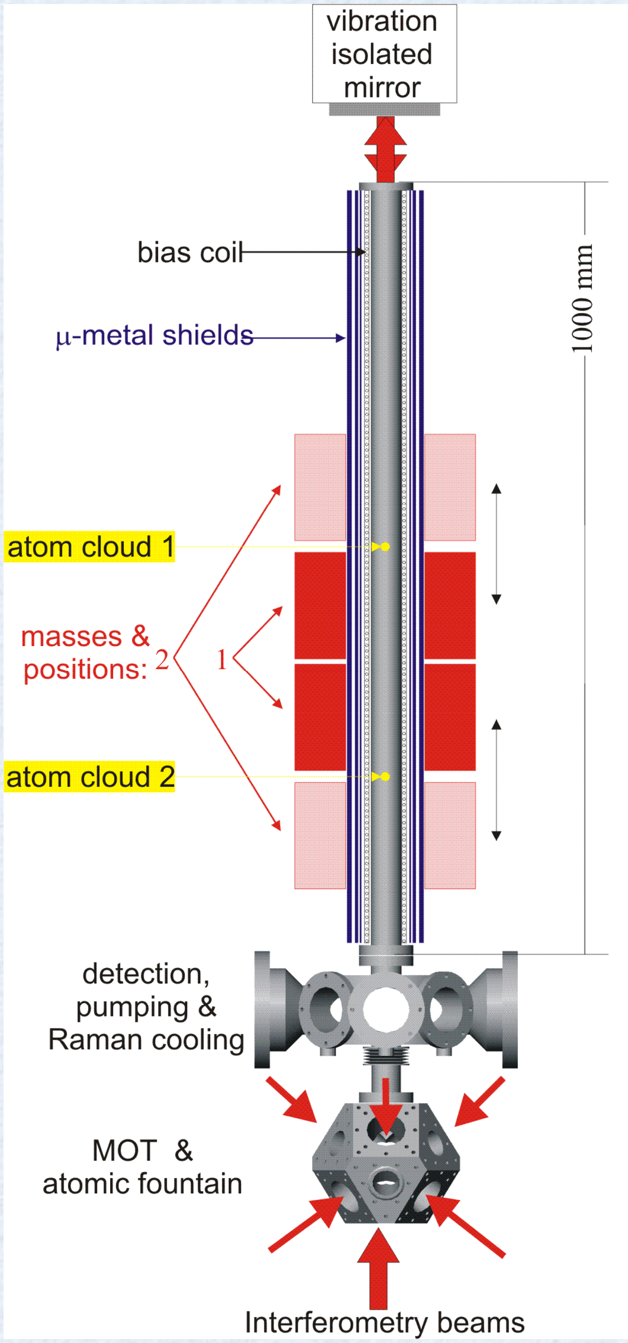
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

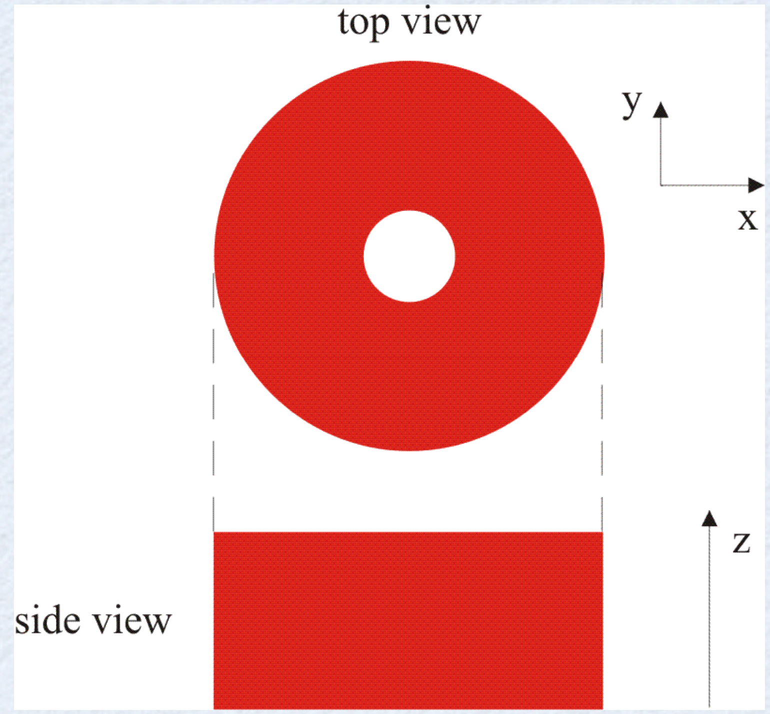
Using atomic probes

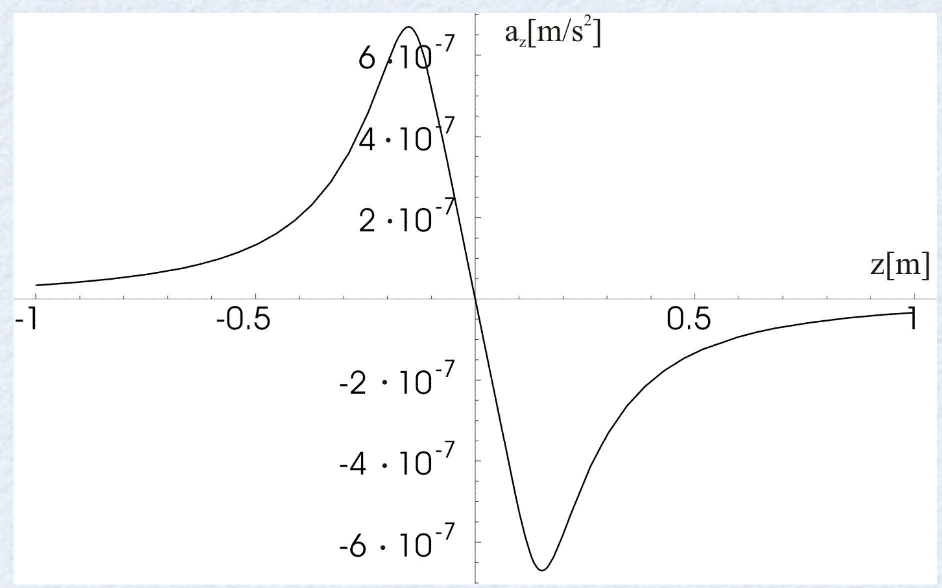


- Point-like test masses in free fall
- virtually insensitive to stray fields
- well know and reproducible properties
- different states, isotopes
- precision measurements by atom interferometry

Atom gradiometer + source masses



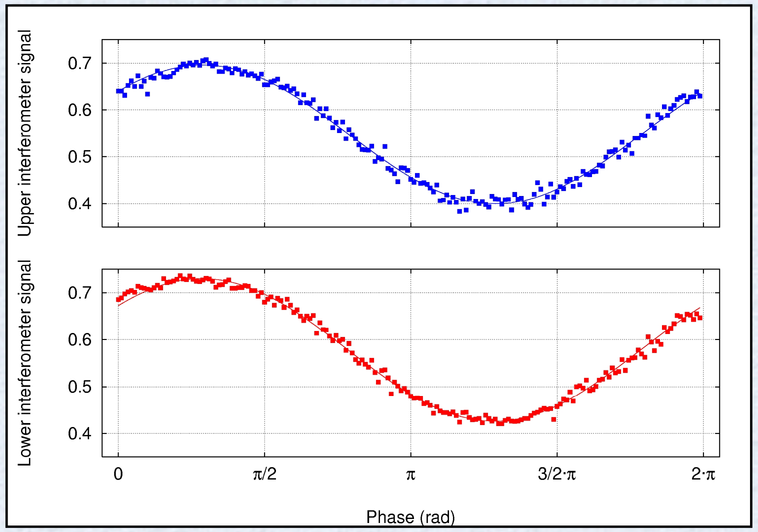




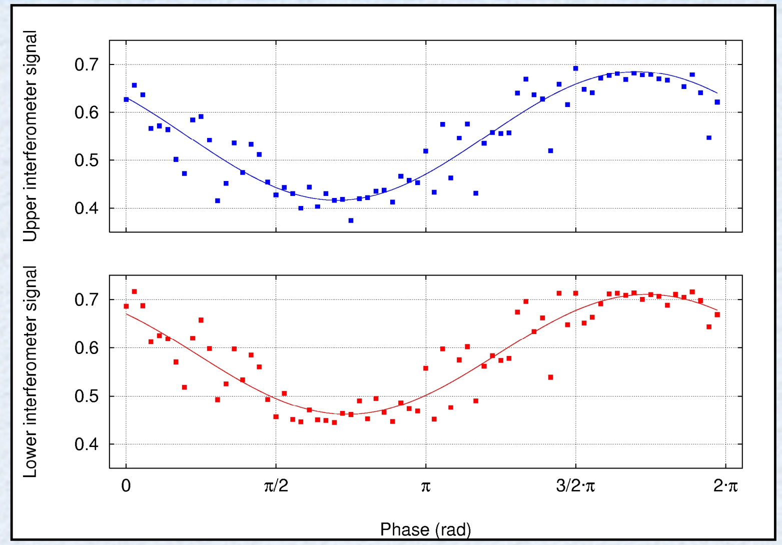
Sensitivity 10^{-9} g/shot
one shot $\rightarrow \Delta G/G \sim 10^{-2}$

500 Kg tungsten mass
Peak mass acceleration $a_g \sim 10^{-7}$ g
10000 shots $\rightarrow \Delta G/G \sim 10^{-4}$

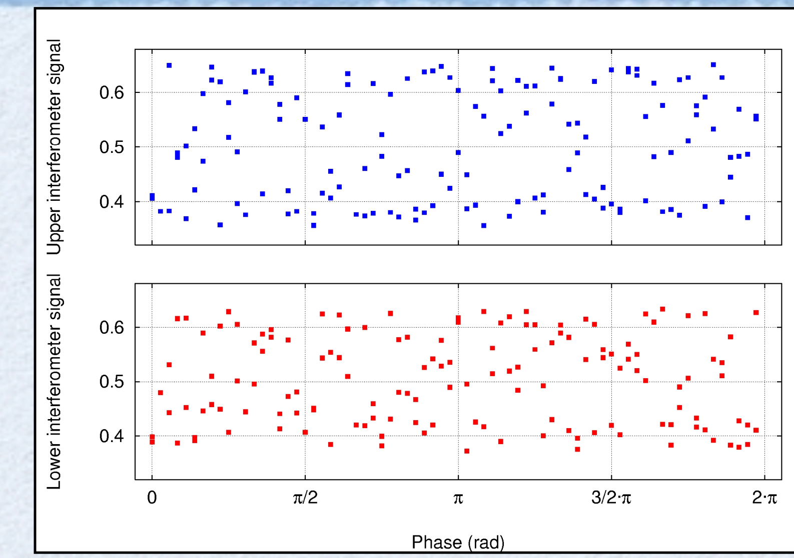
Differential gravity measurement



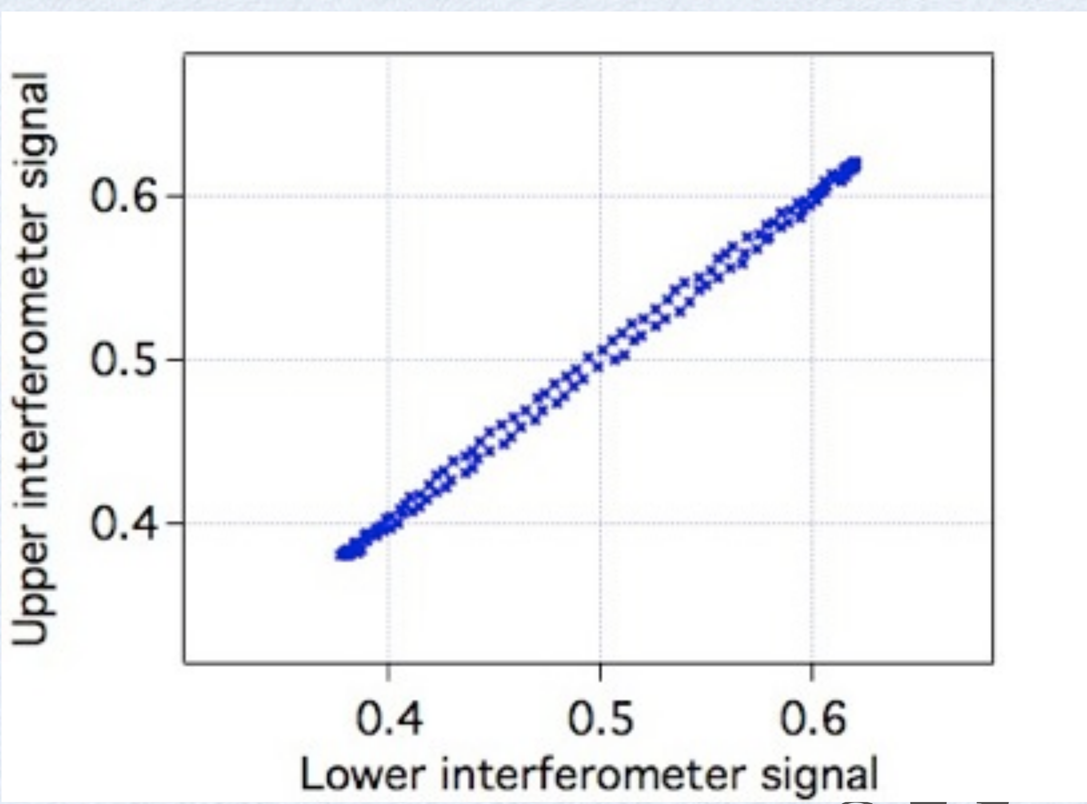
$T=5$ ms
resol. $= 2.3 \times 10^{-5}$g/shot



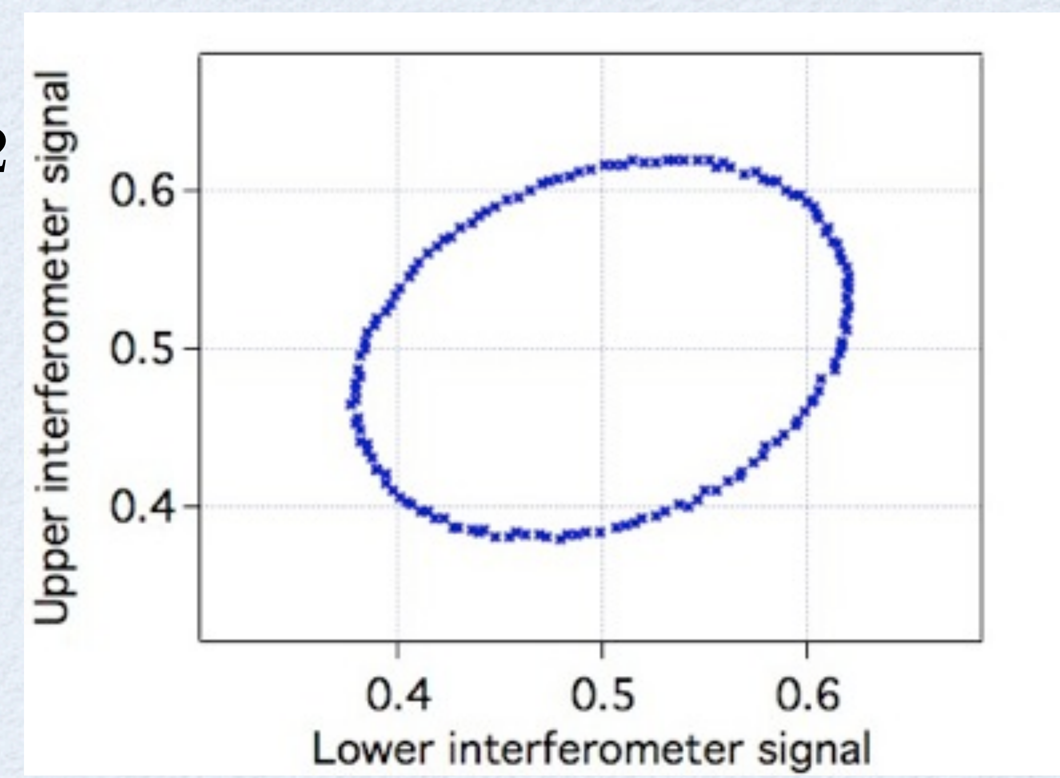
$T=50$ ms
resol. $= 1.0 \times 10^{-6}$g/shot



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

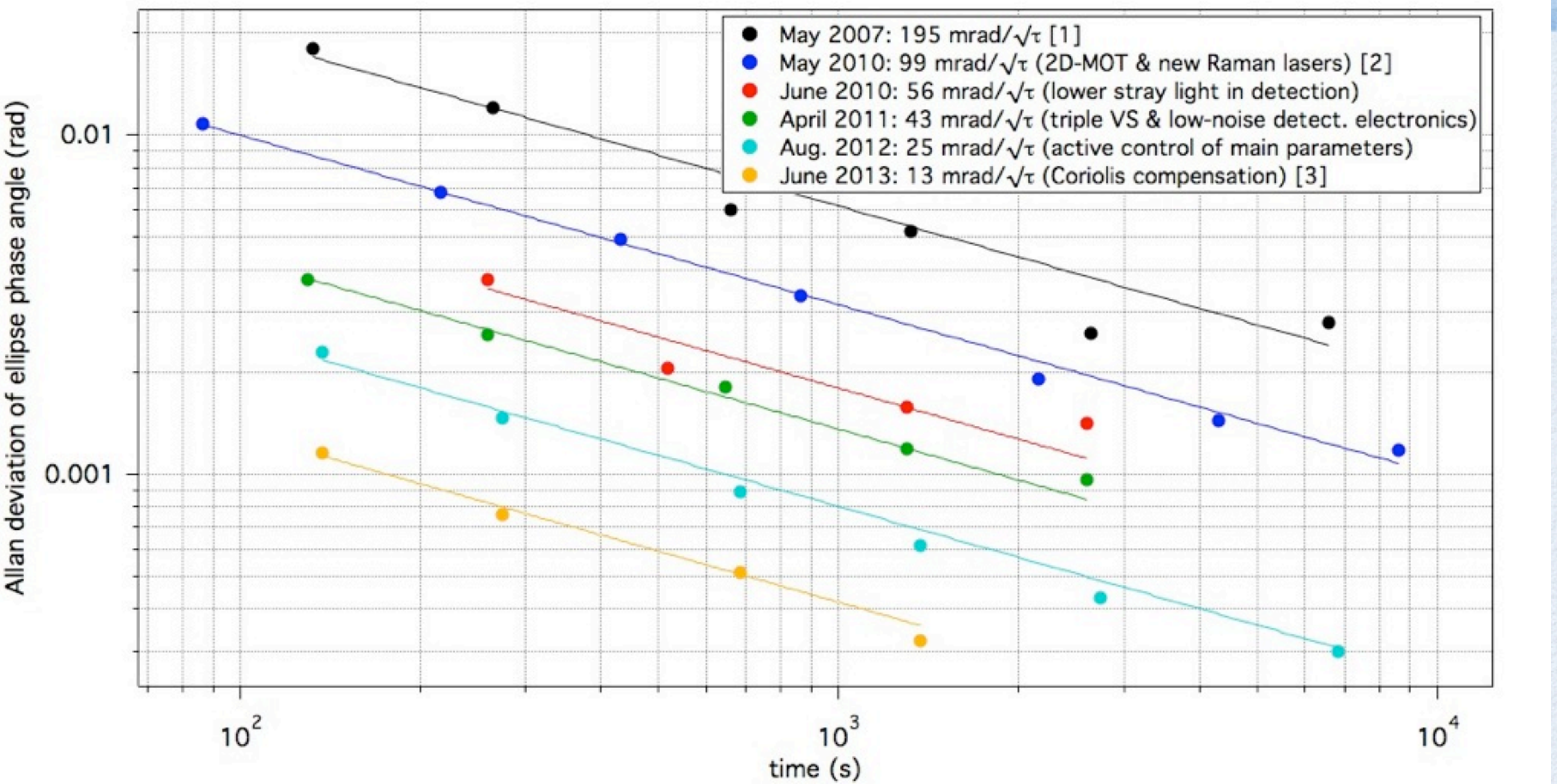


$$\Delta\Phi = k_e g T^2$$



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

MAGIA: short term sensitivity

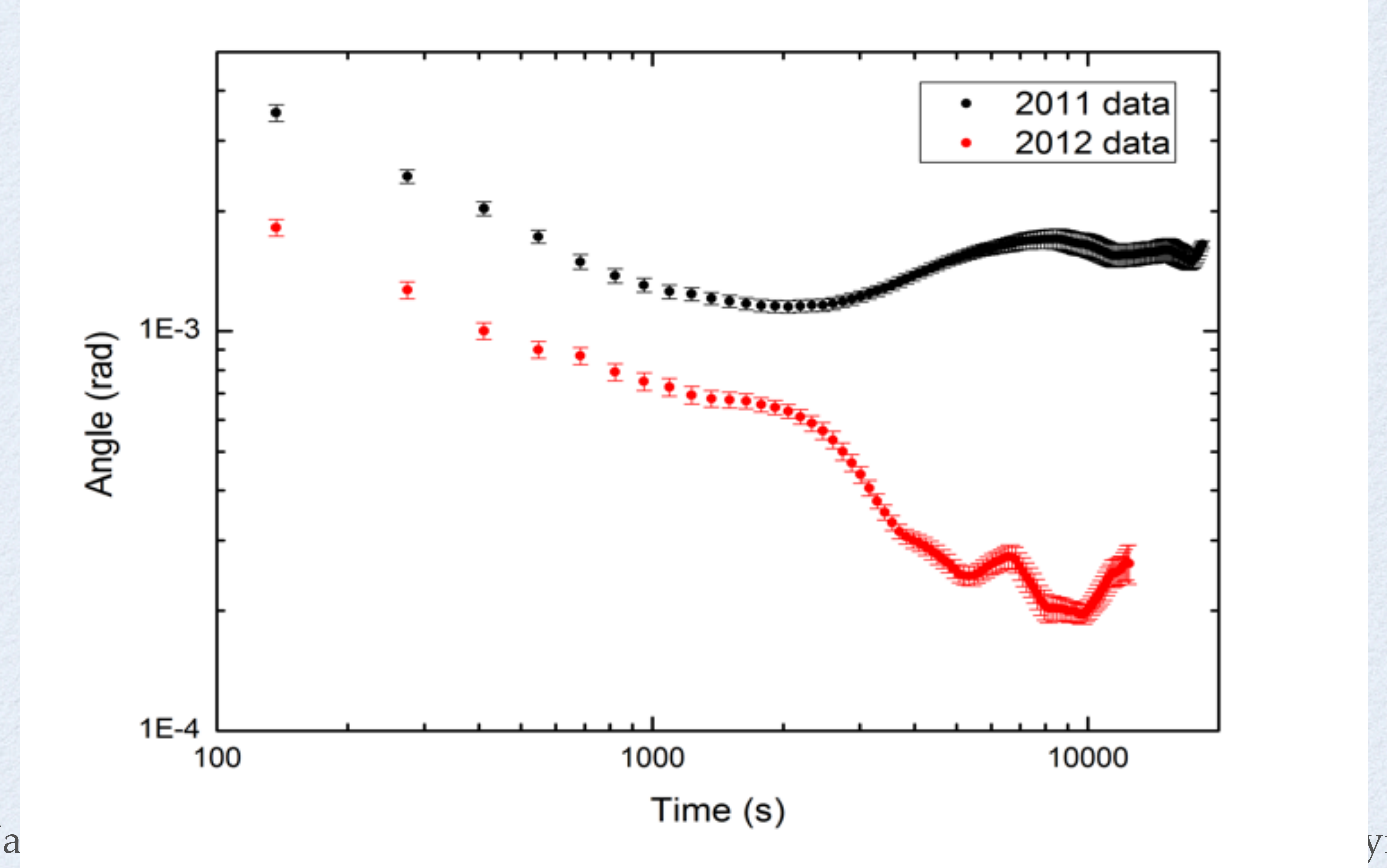


Current sensitivity to differential acceleration: $3x10^{-9}$ g @ 1s (=QPN for $4x10^5$ atoms)

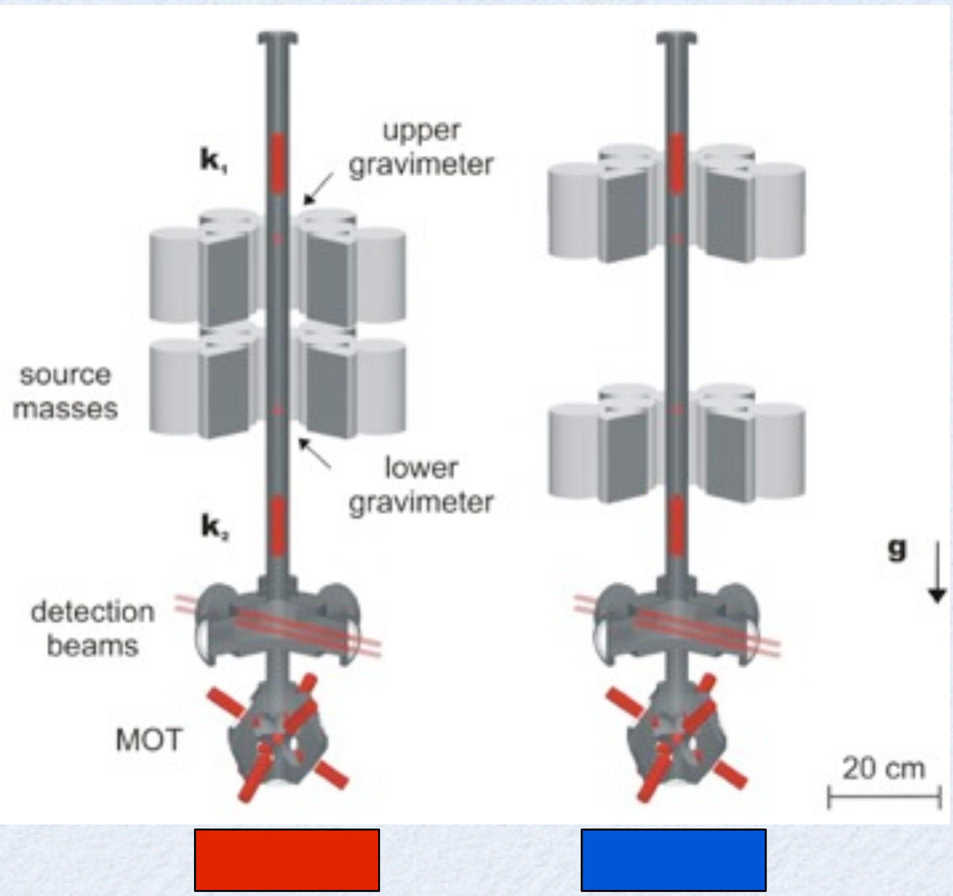
[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)
[2] F. Sorrentino et al., New J. Phys. **12**, 095009 (2010)
[3] F. Sorrentino et al., to be published

MAGIA: long term stability

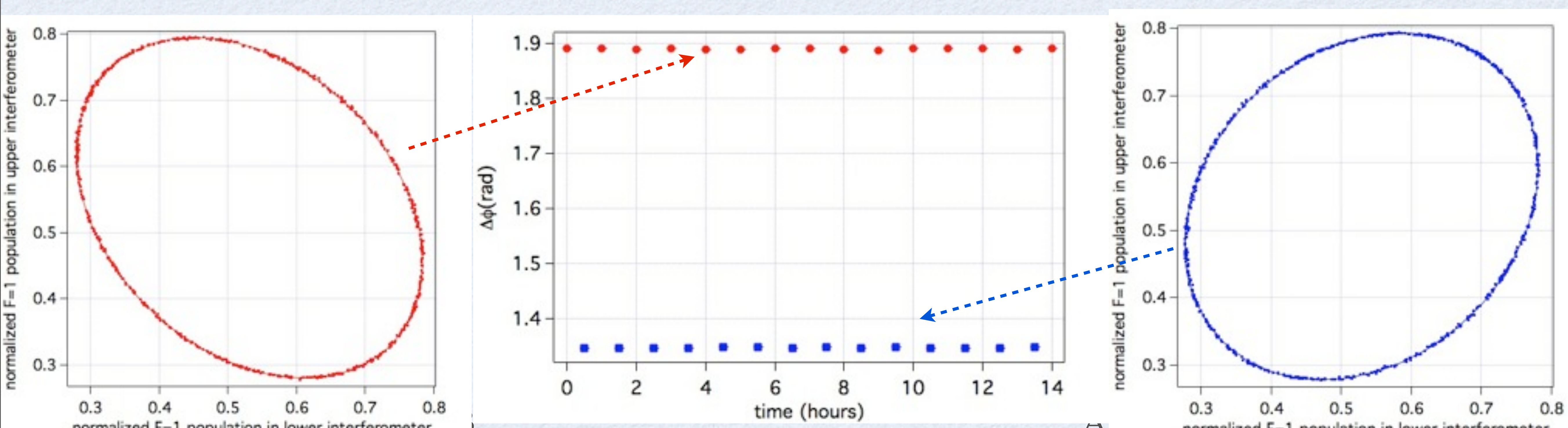
- Active intensity control of cooling and probe laser beams; tilt stabilization of Raman retro-reflecting mirror
- Coriolis compensation with tip-tilt mirror
- Allan variance on gravity gradient measurement ~0.2 mrad @ 10000 s, corresponding to 5×10^{-11} g (5x improvement from 2011)



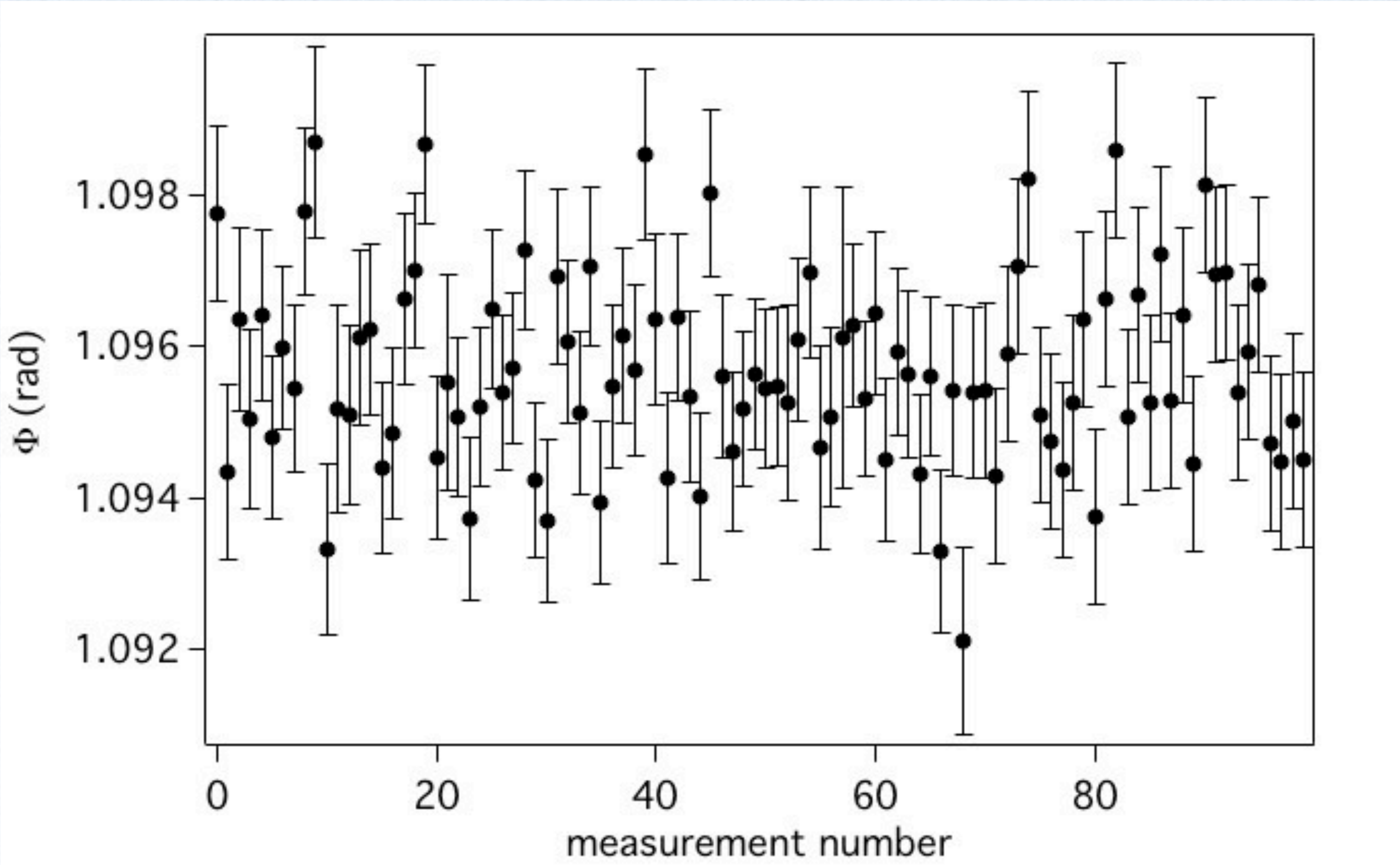
MAGIA current status



- Sensitivity to differential gravity: 5*10^{-9} g /√Hz
- Sensitivity in G measurements: 300 ppm in 12 hours



MAGIA: *G* measurement

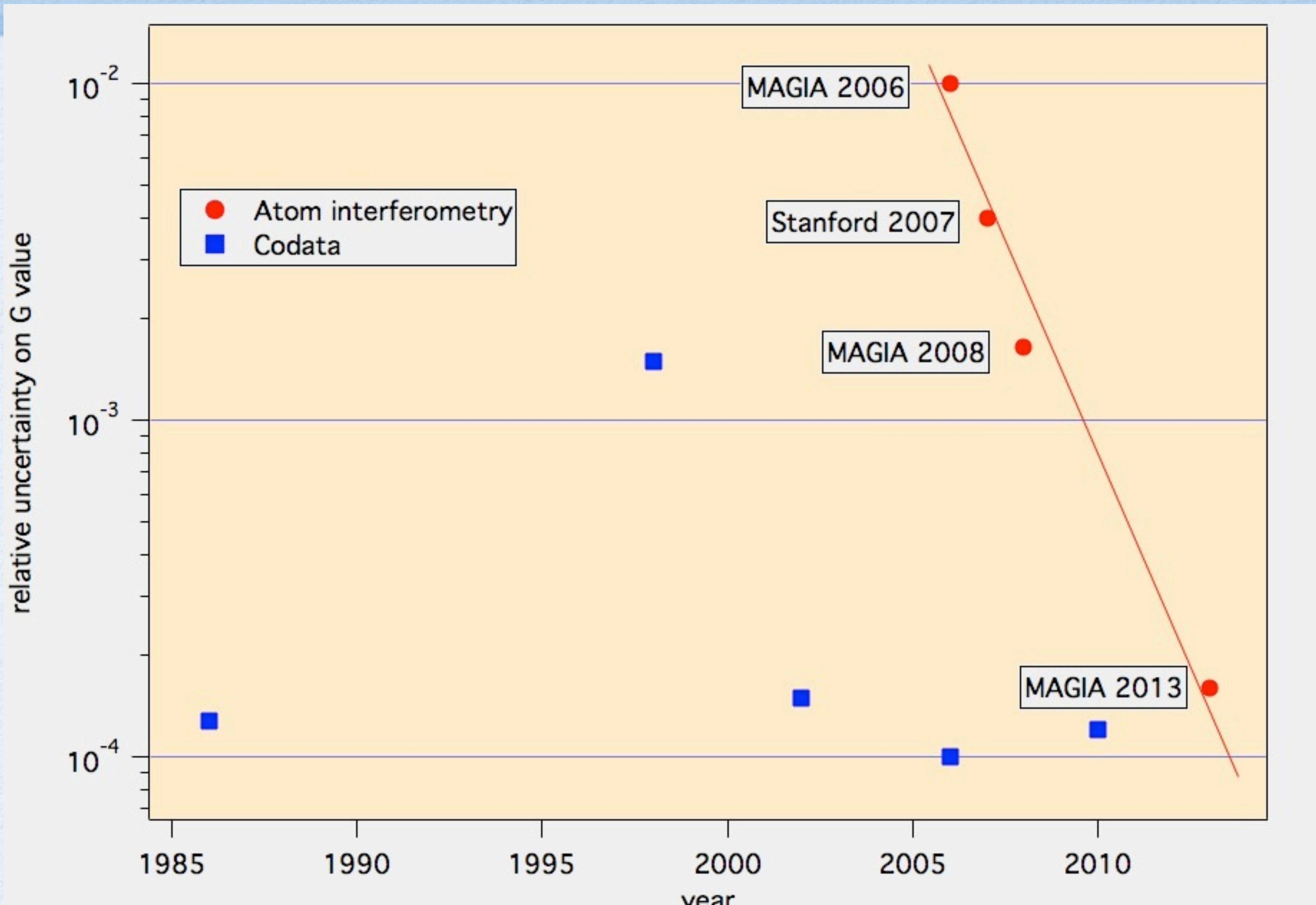


Statistical error 1×10^{-4} with 100 hrs integration time

MAGIA: error budget

Source	Uncertainty	$\Delta G/G(10^{-4})$
Cylinders radial position	$10\,\mu$m	0.5
Cylinders vertical position	$10\,\mu$m	0.5
Cylinder mass	10 mg	0.05
Radial density homogeneity	2×10^{-3}	0.01
Axial density homogeneity	0.5×10^{-3}	0.2
Support platforms' mass	10 g	0.1
Atomic vertical barycenter position	0.2 mm	0.1
Atomic horizontal barycenter position	0.5 mm	0.5
Atomic clouds vertical size	0.1 mm	0.7
Atomic clouds horizontal size	0.5 mm	0.9
Launch direction change C/F	$6\,\mu$rad	0.3
Raman mirror tilt C/F	100 nrad	0.005
Gravity gradient	$0.7 \times 10^{-8}\,\mathrm{s}^{-2}$	0.1
Total		1.5

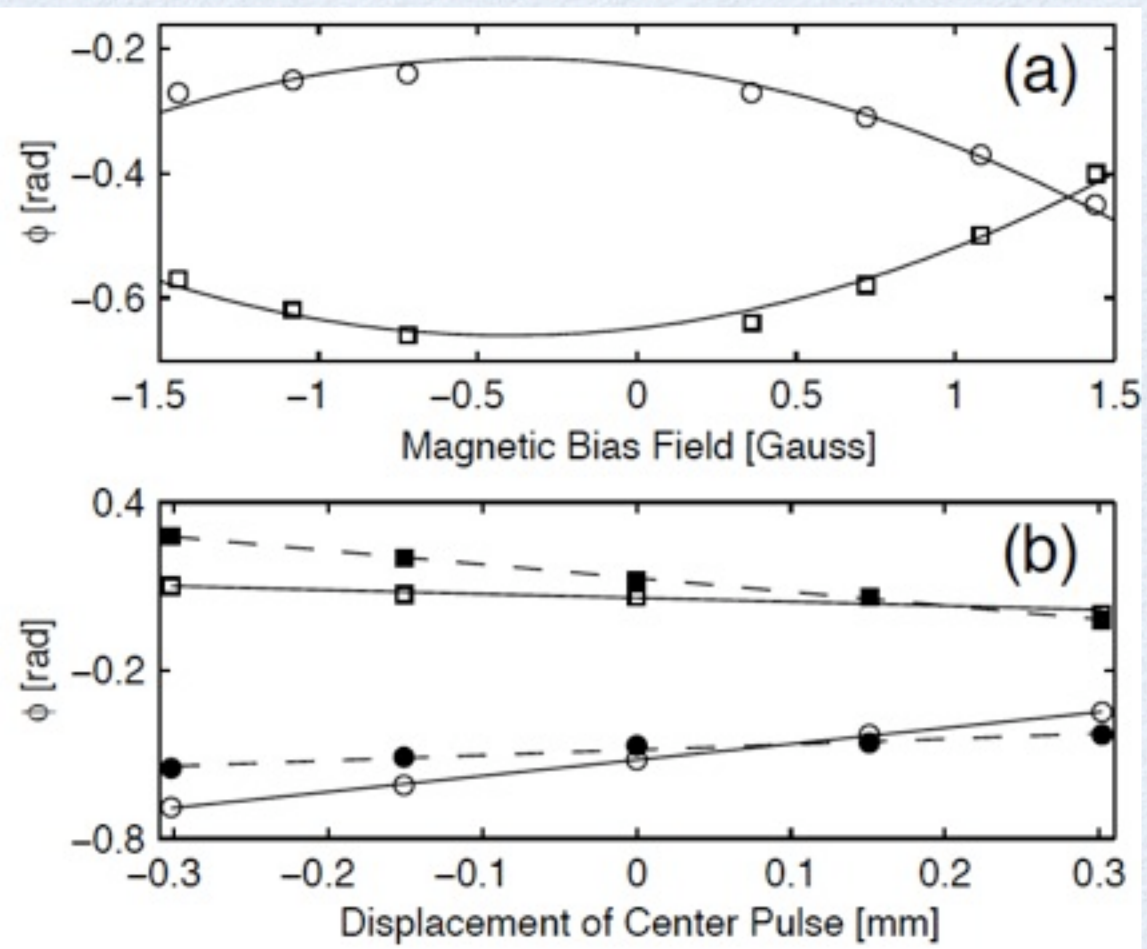
Uncertainty on G measurements

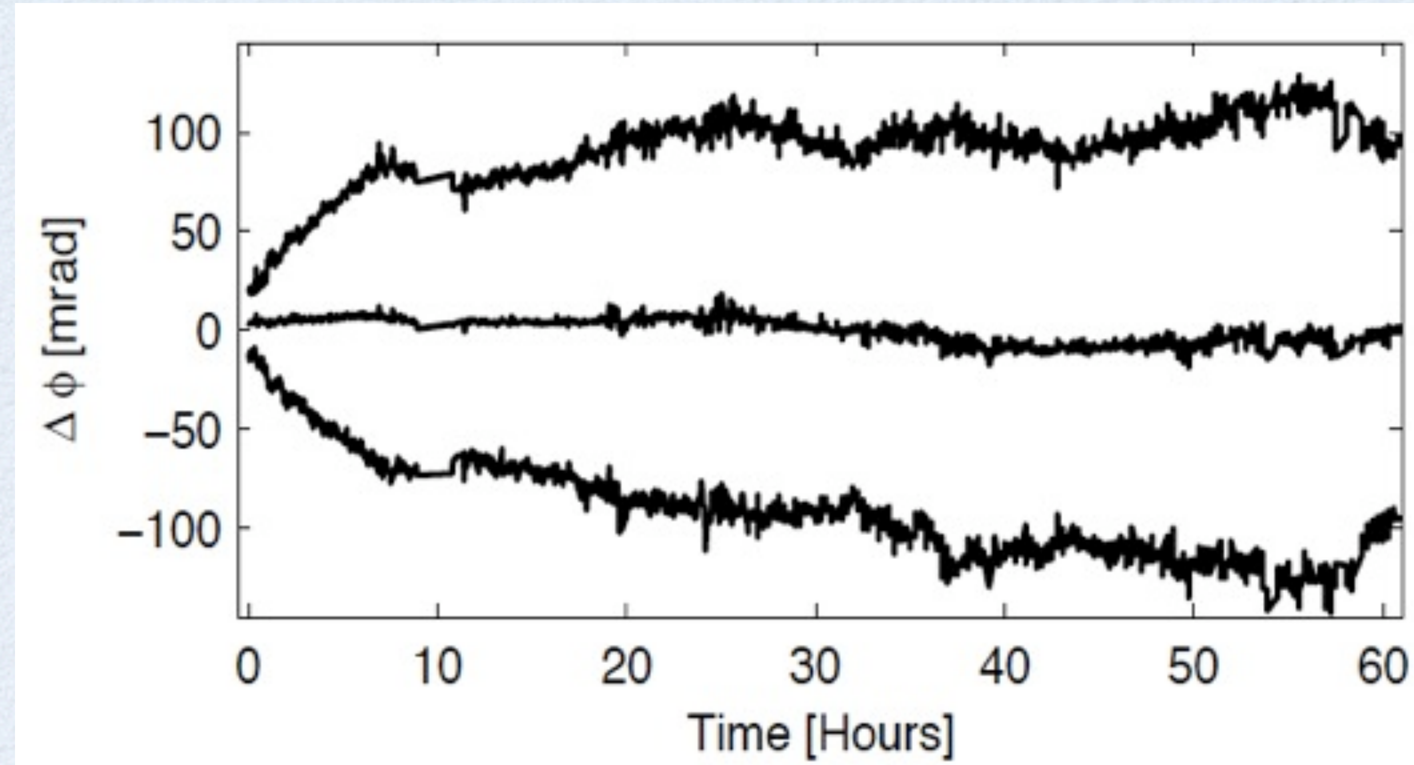


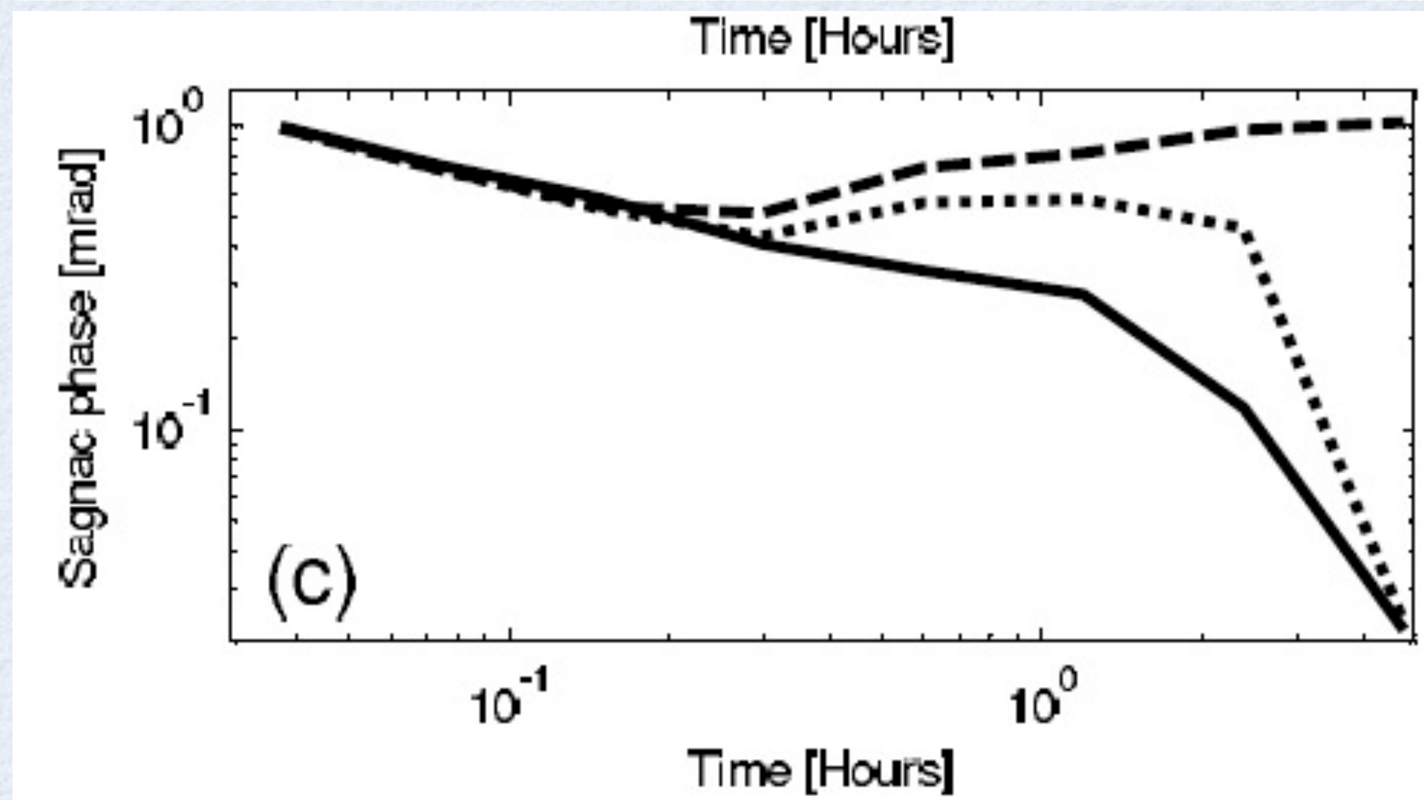
AI gyroscopes: long term stability

- Area reversal
- correlations removal

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







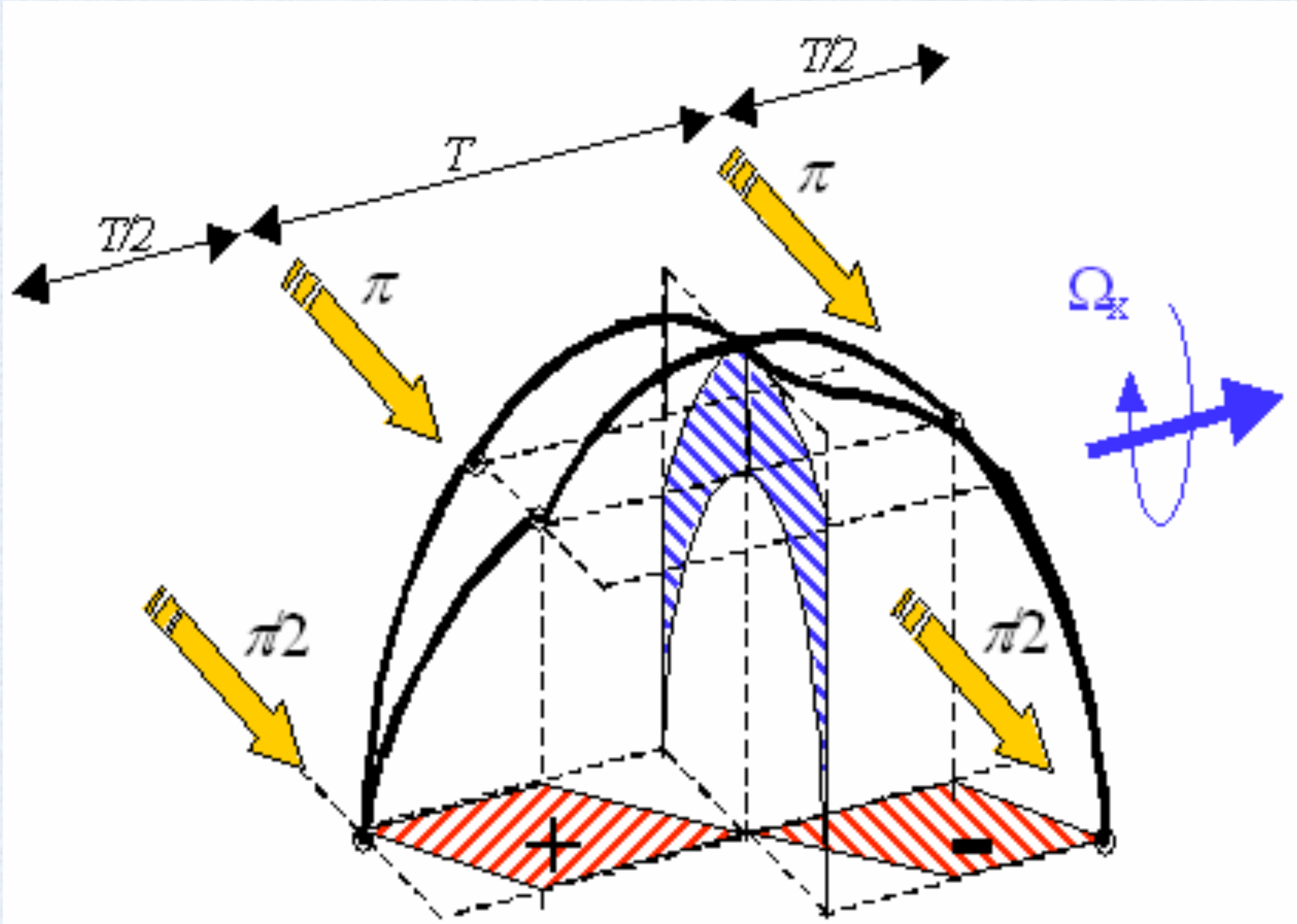
sensitivity: 6×10^{-10} rad$\cdot$ $s^{-1}\sqrt{Hz}$

scale factor stability < 5 ppm

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

Cold atoms AI gyroscopes (I)

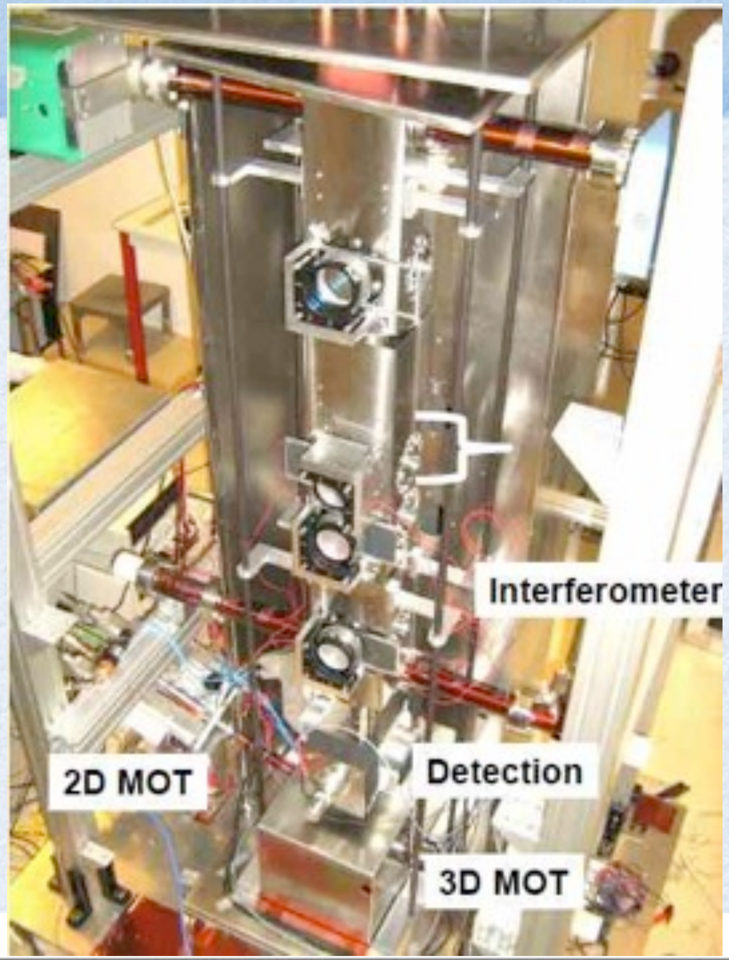
- Atomic fountain
  - Vertical @ SYRTE (Paris)
  - Tilted @ Stanford & IQO (Hannover)
- four Raman pulses
- no acceleration sensitivity
- Scale factor ~ $k_{\mathrm{eff}}T^3$
- larger area w.r.t. thermal beams
- large dynamic range

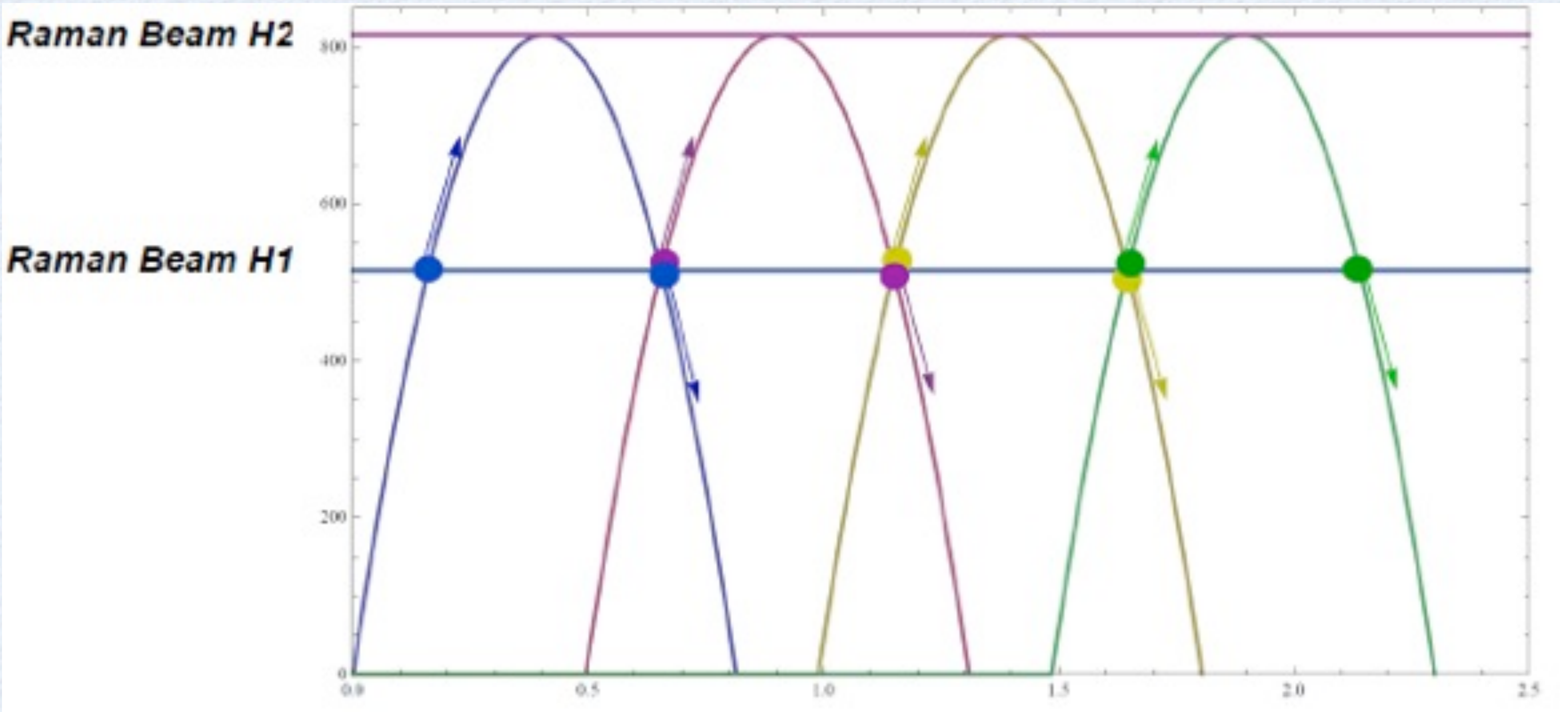


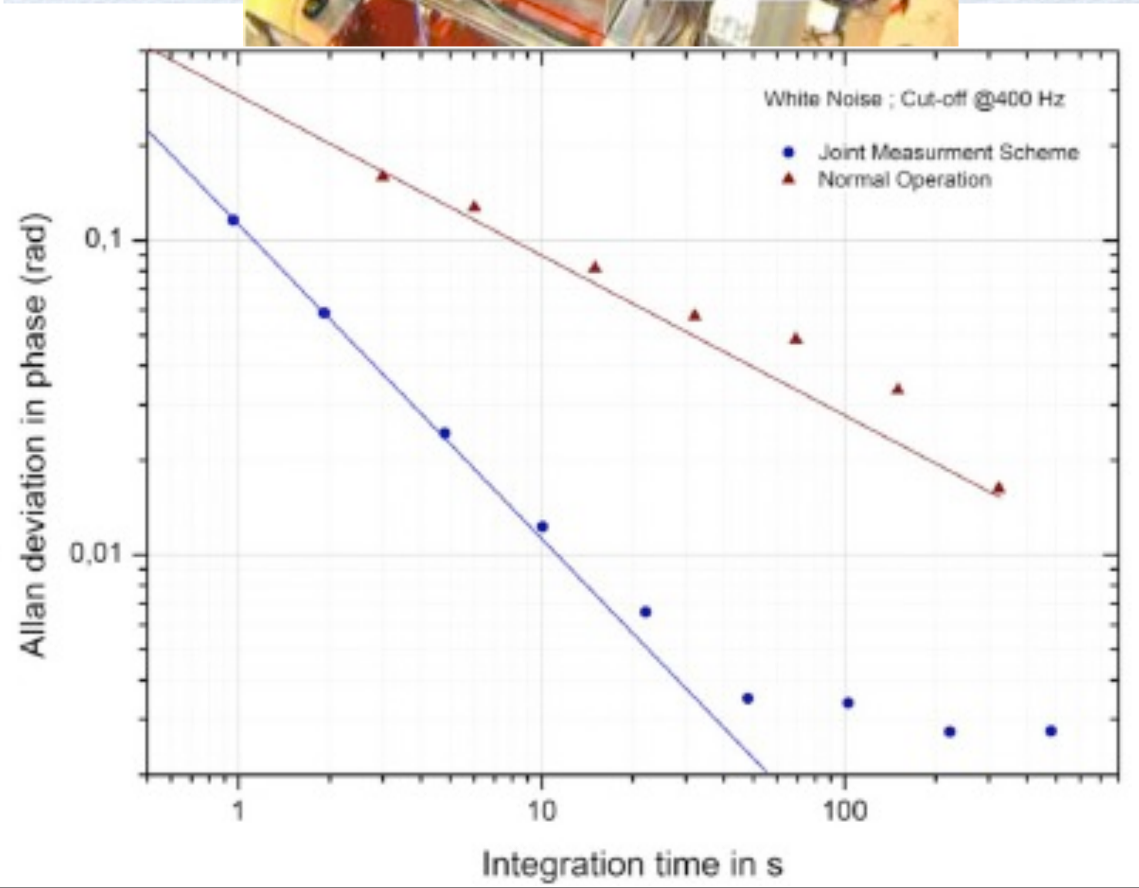
- A. Gauguet et al., PRA **80**, 063604 (2009)
- J. J. Stockton et al., PRL 107 (2011)

Cold atoms AI gyroscopes (II)

- Joint Raman Ramsey gyroscope @ SYRTE
- improved sampling frequency
- 1/t scaling
- sensitivity ~10 nrad/s/√Hz with T~300 ms



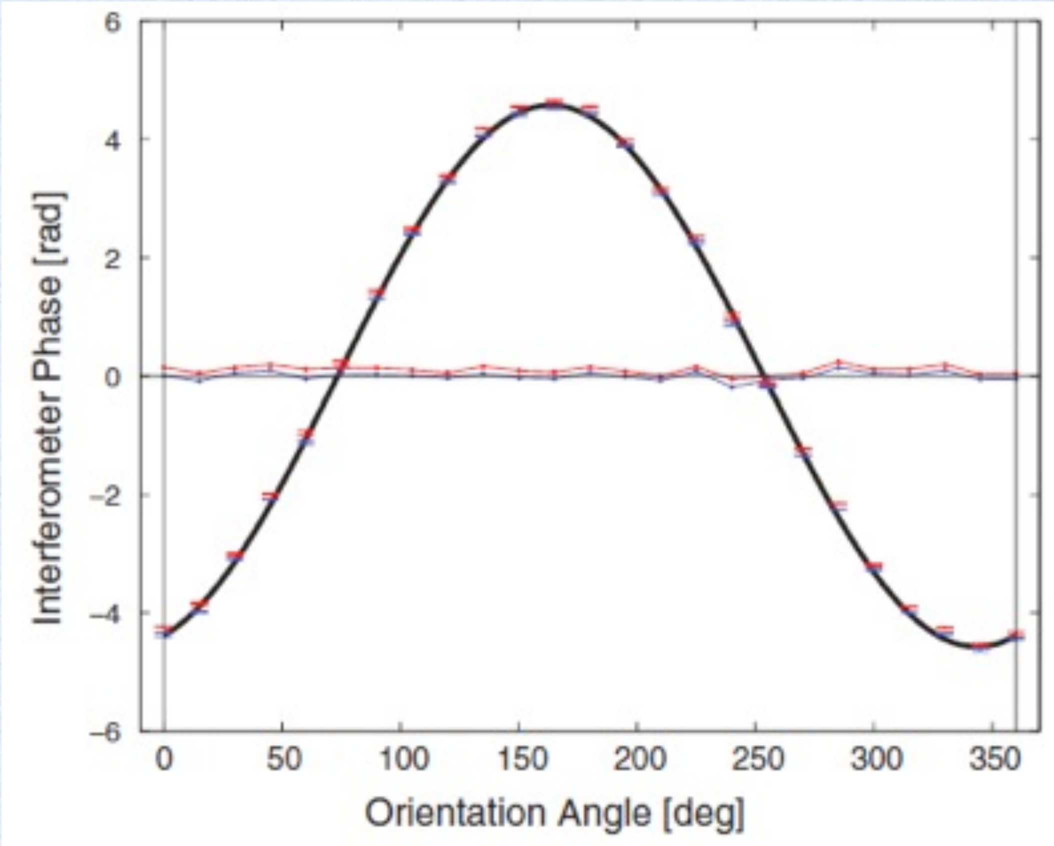


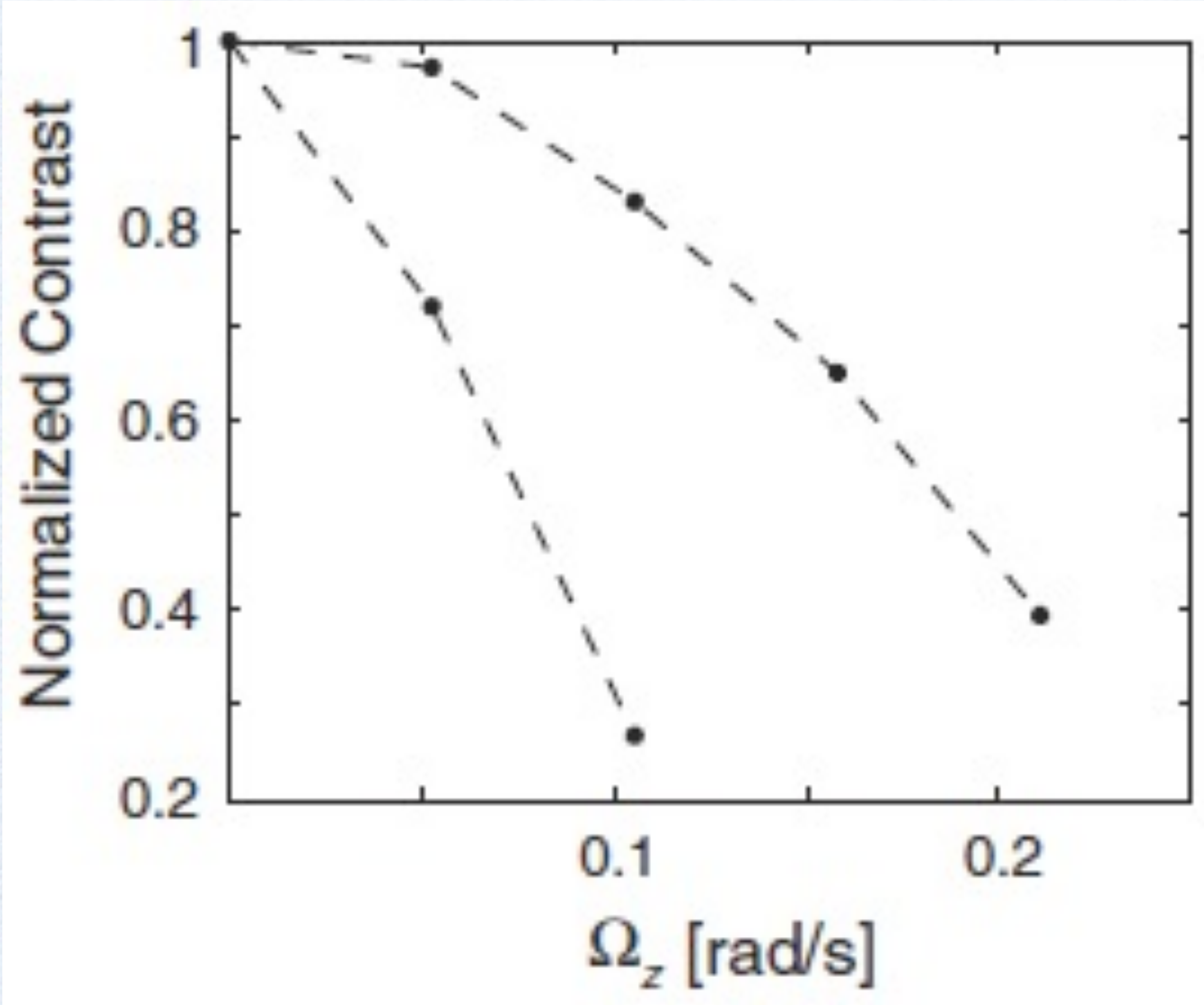


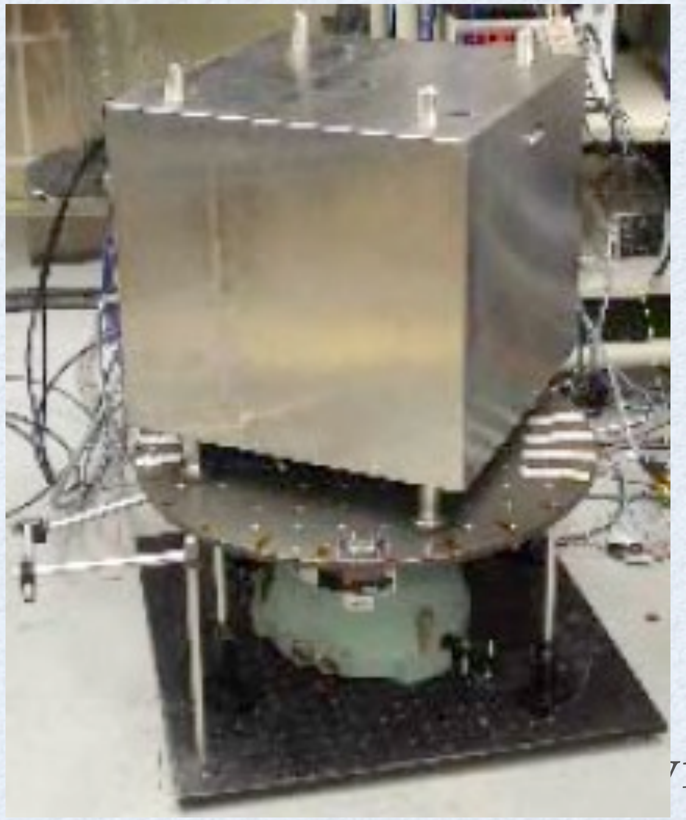
I. Dutta, Poster @ International School of Physycs "Enrico Fermi", Course CLXXXVIII, Varenna 2013

Cold atoms AI gyroscopes (III)

- Compact Raman gyroscope @ Stanford
- simultaneous determination of latitude, azimuth (true North) and Earth's rotation rate
- operating up to above 100 mrad/s
- sensitivity ~60 nrad/s/√Hz with T~50 ms
- scalable to ~1 prad/s/√Hz on a 10 m tower

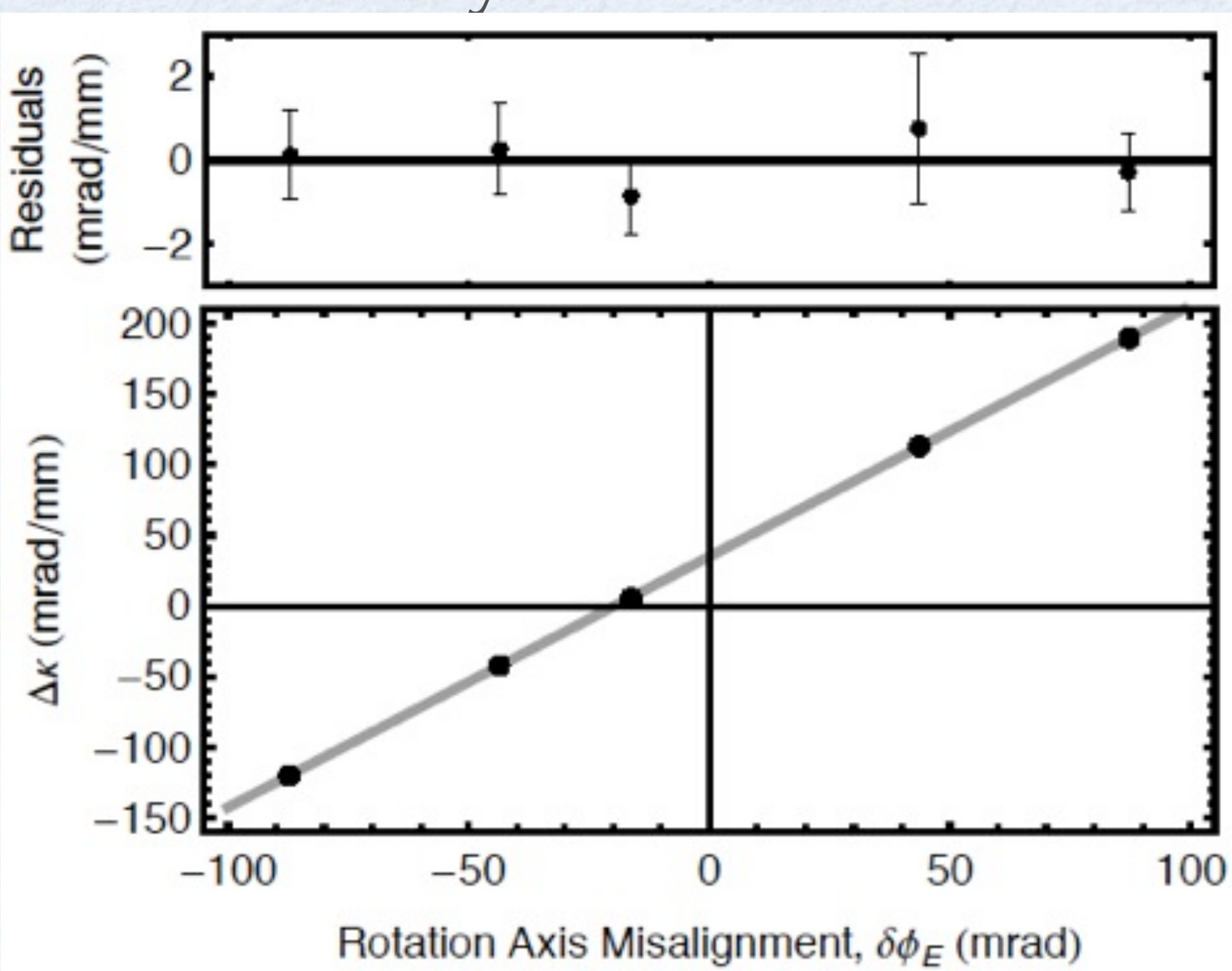


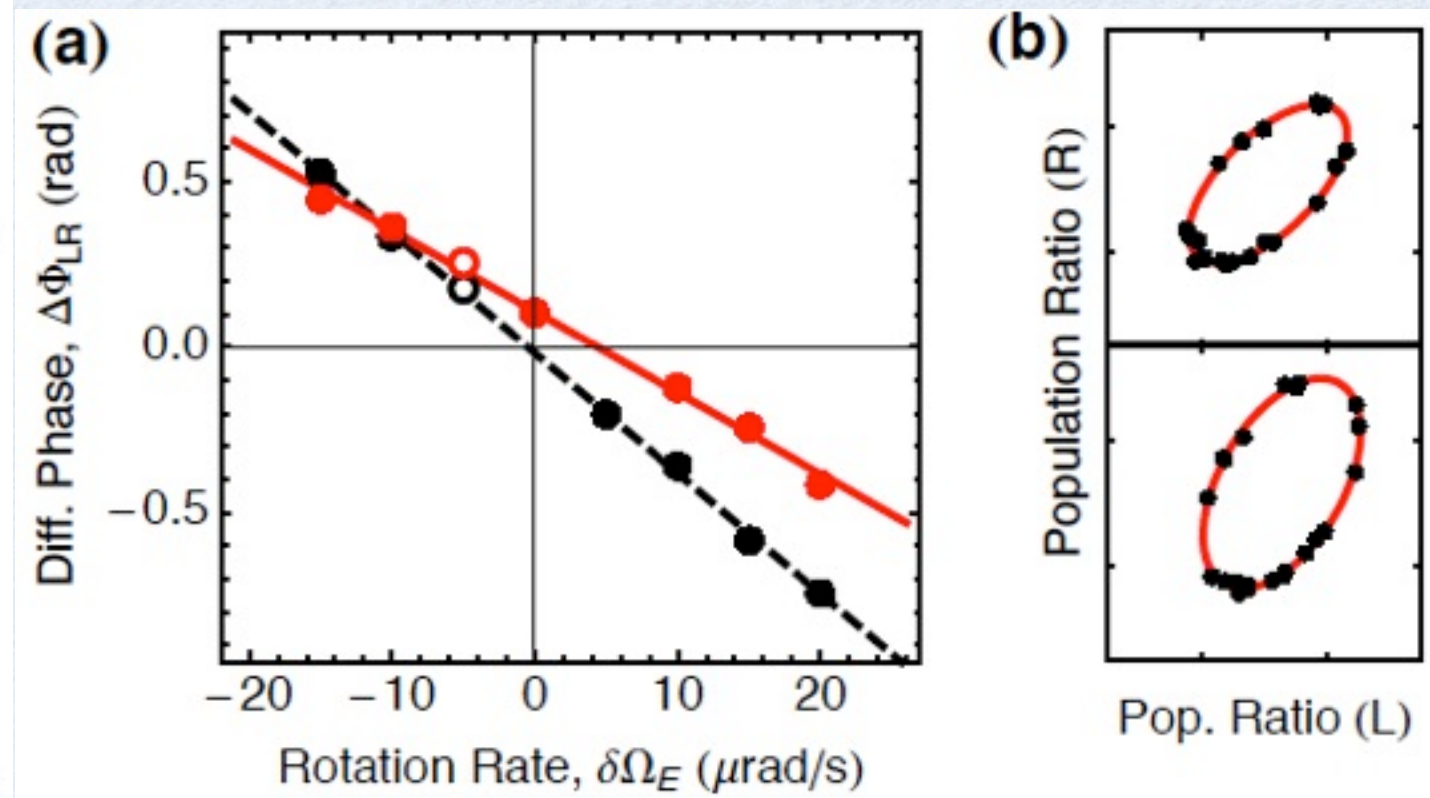




Cold atoms AI gyroscopes (IV)

- Measuring rotation rate and azimuth via the Coriolis effect
- sensitivity to rotation rate ~200 nrad/s/√Hz
- accuracy on North determination ~0.1 mrad



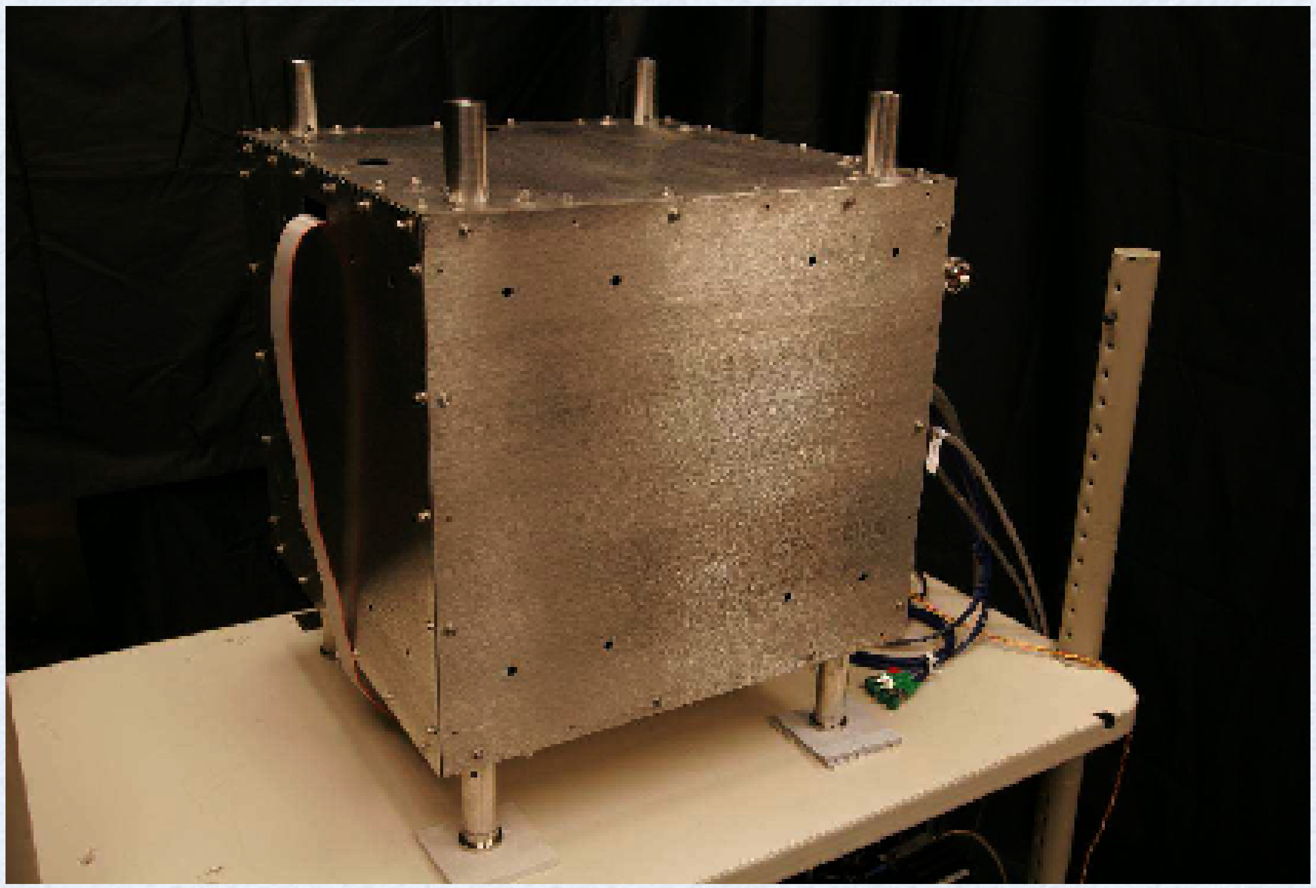


S. Dickerson et al., arXiv:1305.1700 (2013)

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
  - interferometry on trapped atoms
- New applications
  - GW, quantum gravity, etc.

Portable AI sensors

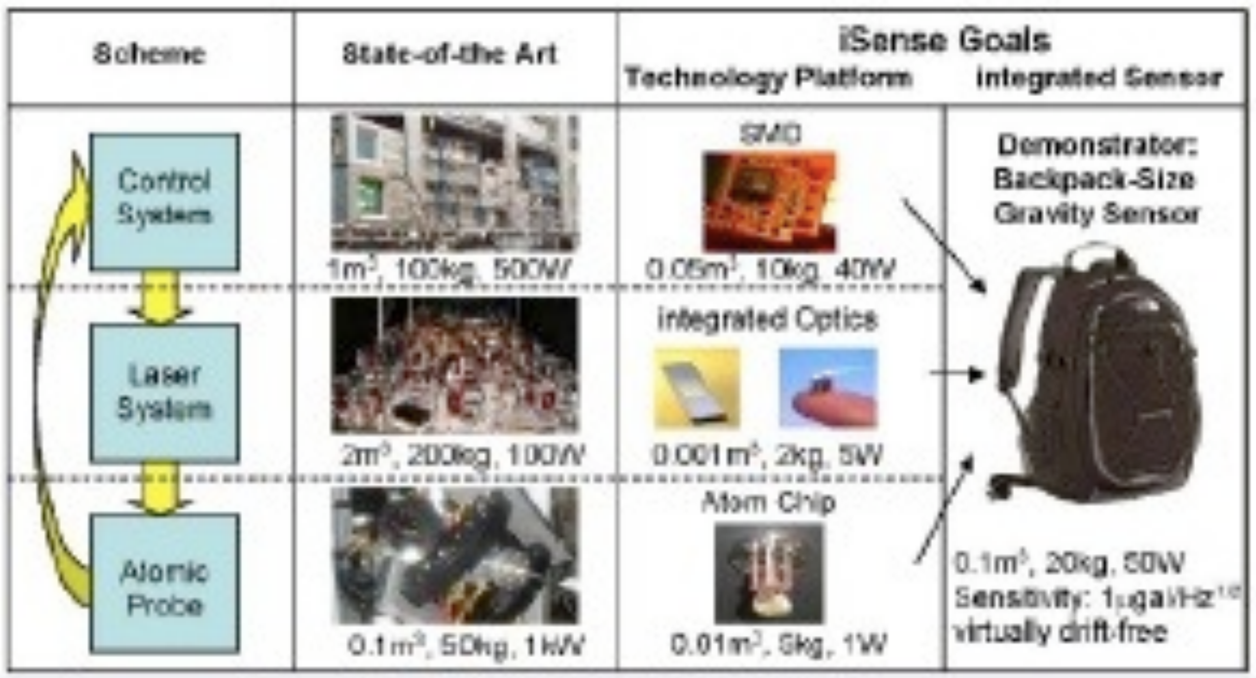


STANFORD

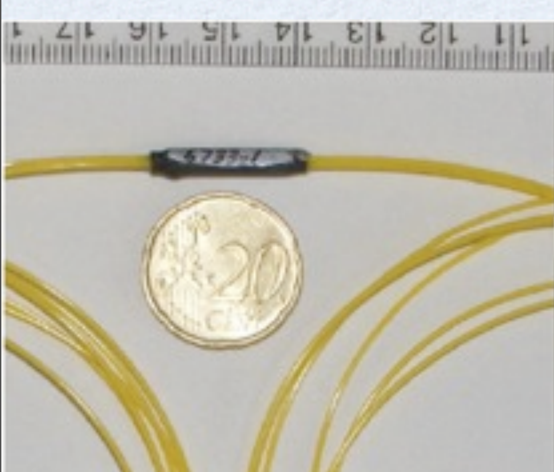
μ-QUANS (SYRTE-CNRS)

Future compact AI: iSense

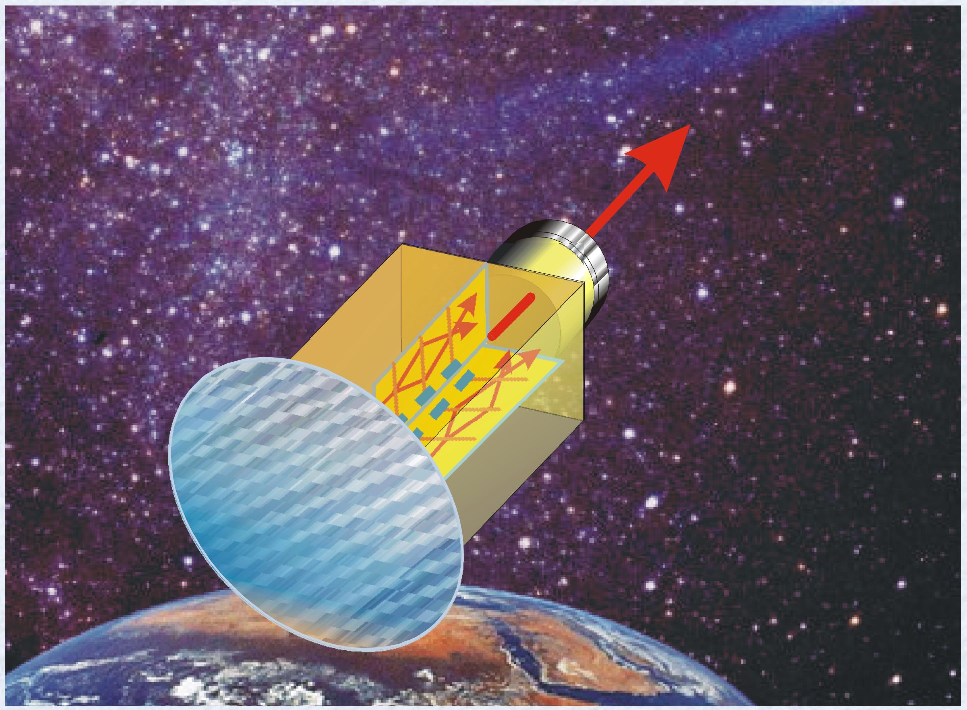
7th Framework Programme - Theme 3 "Information and Communication Technologies"
Call identifier: FP7-ICT-2009- C FET-Open



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



The HYPER project

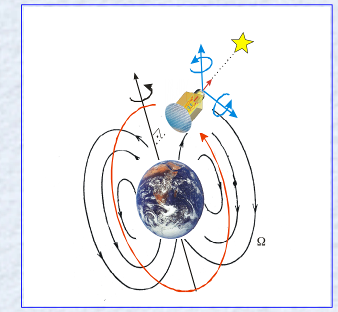


Differential measurement between two atom gyroscopes and a star tracker orbiting around the Earth

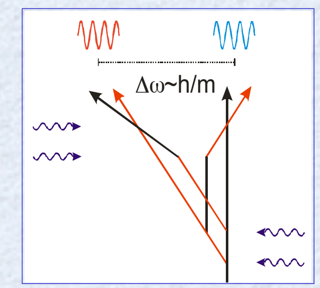
Resolution: 3×10^{-12}rad/s /√Hz

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

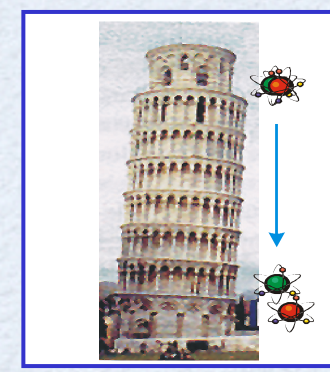
Mapping Lense-Thirring effect close to the Earth



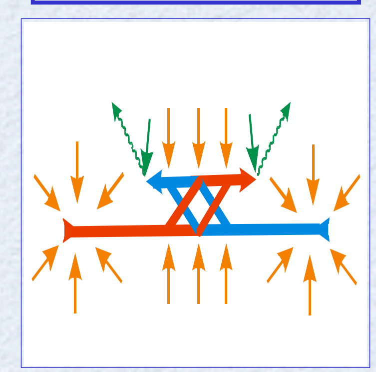
Improving knowledge of fine-structure constant



Testing EP with microscopic bodies



Atomic gyroscope control of a satellite

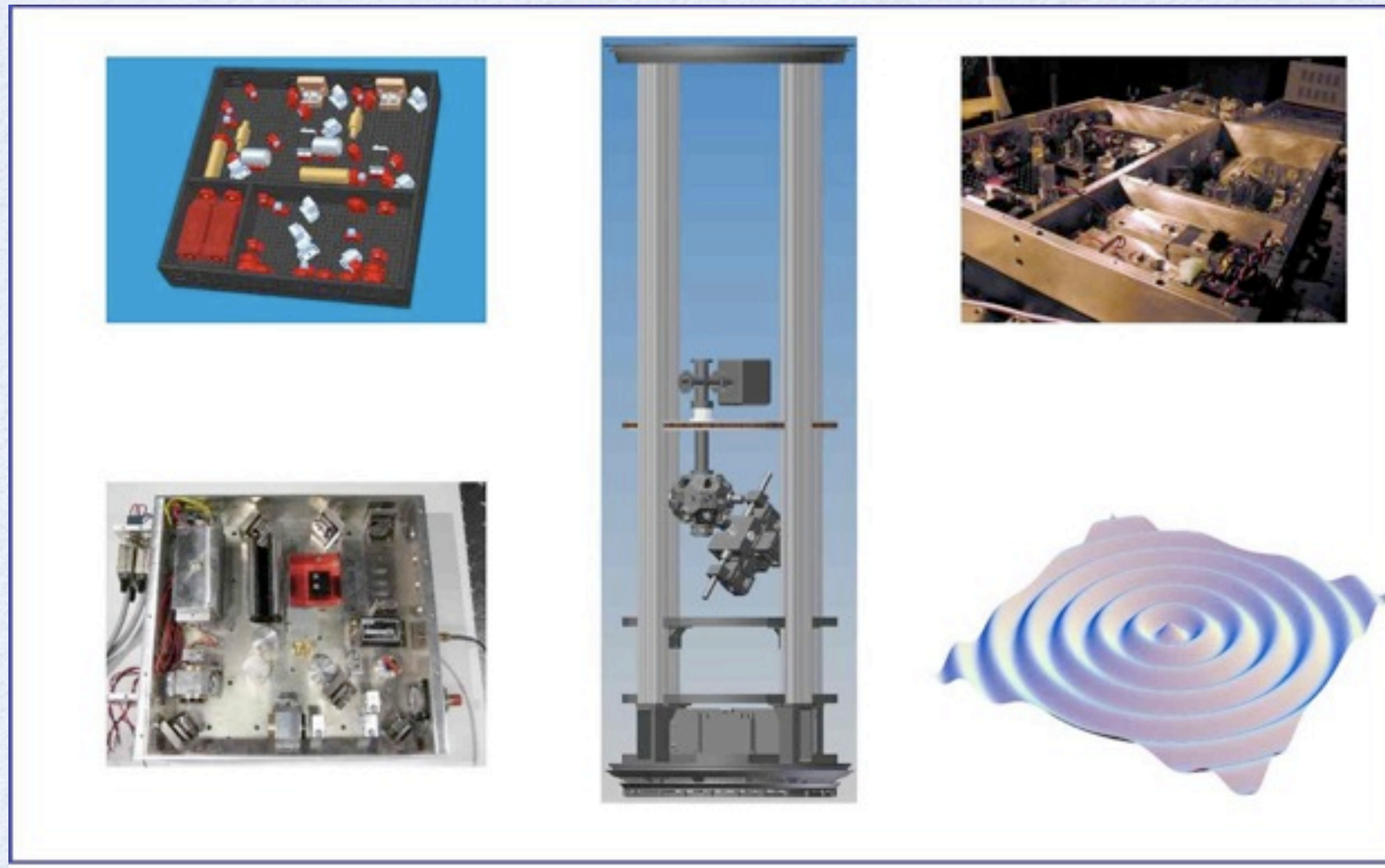


ESA-SCI (2000) 10
July 2000

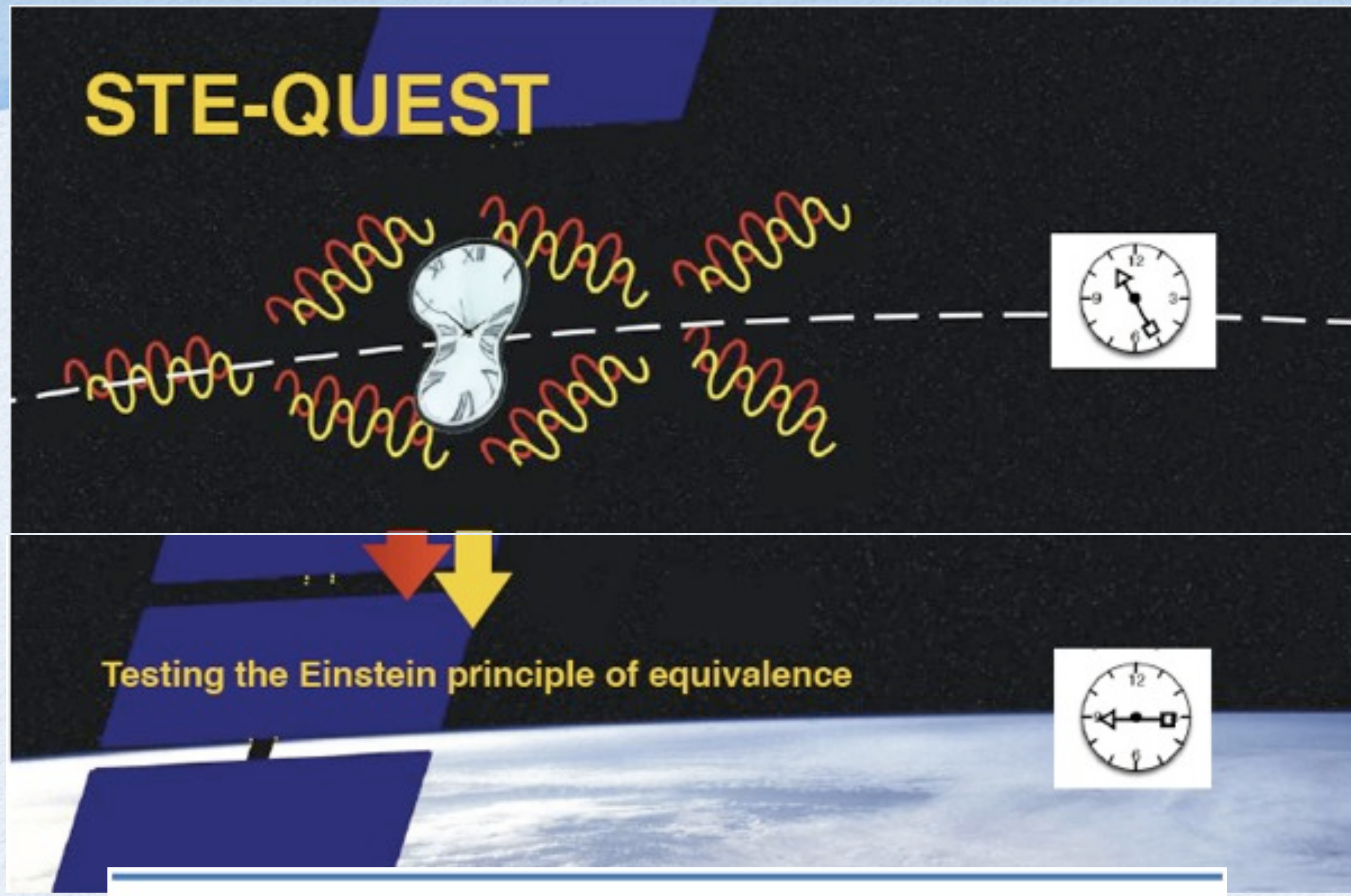
http://sci.esa.int/home/hyper/index.cfm

Space Atom Interferometers

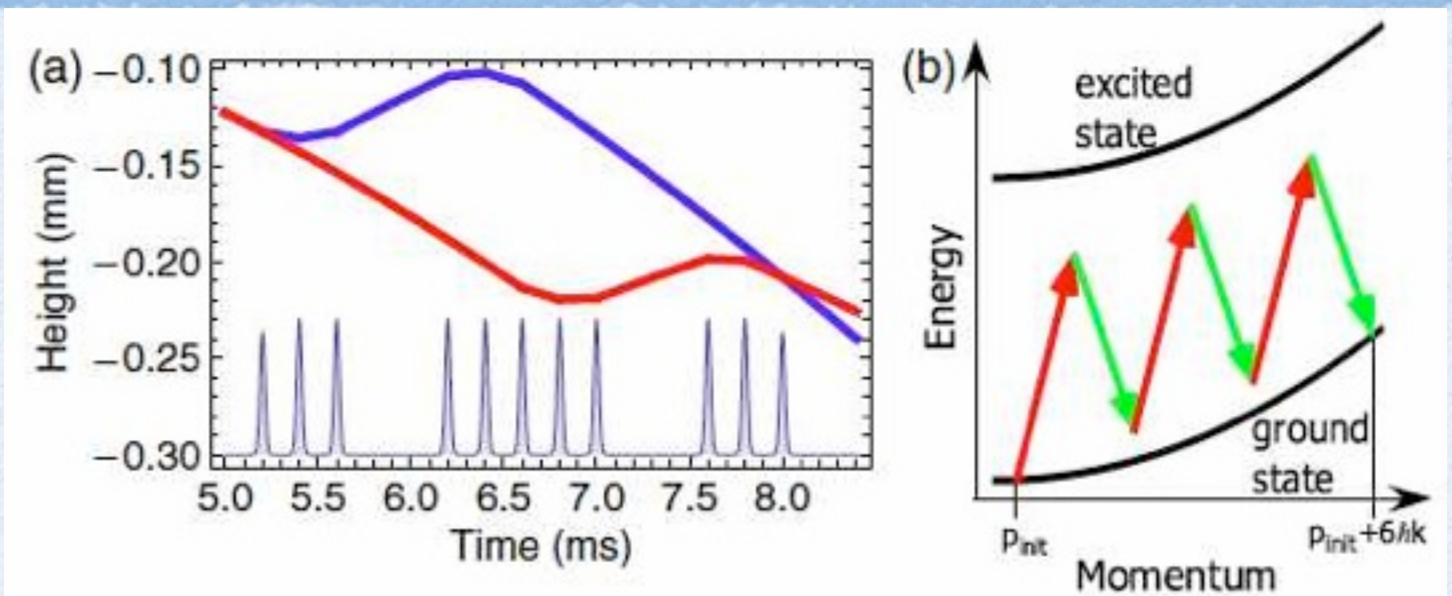
- Sensitivity of AI interferometry sensors scale as the square of T
- In microgravity possible sensitivity ~ 10^{-13} m/s^2 @ 1 s or better
- Main goals:
  - ground demonstrator to test technology readiness of atom interferometry sensors for space applications
  - Investigation of novel schemes based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



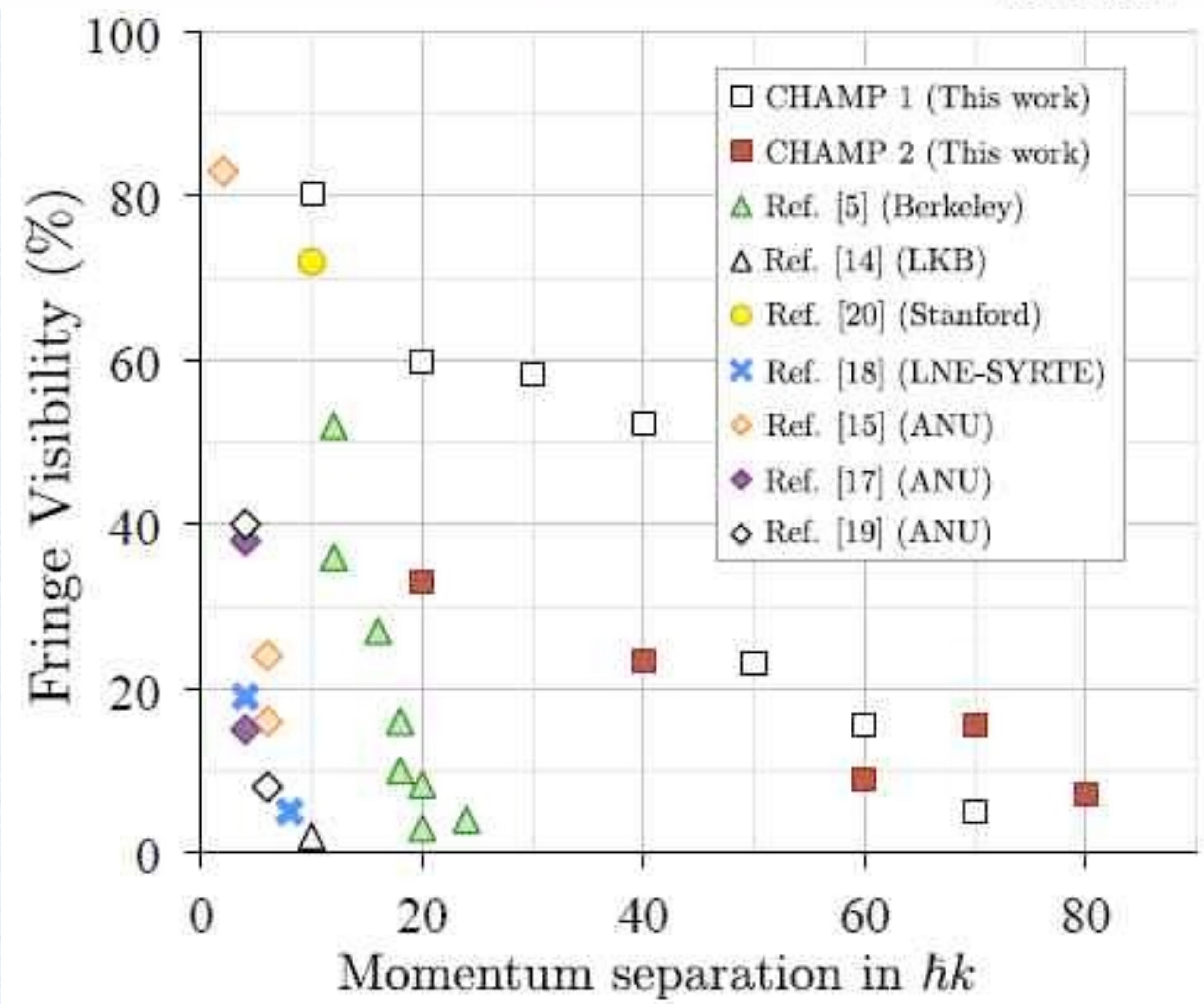
ESA Cosmic Vision: STE-QUEST

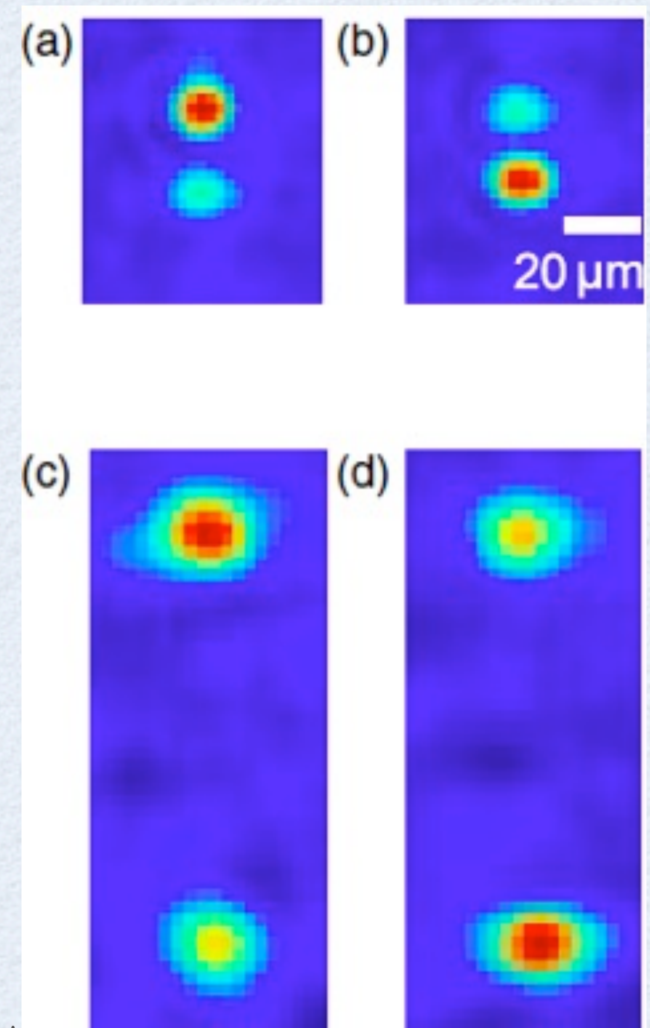


LMT beam splitters

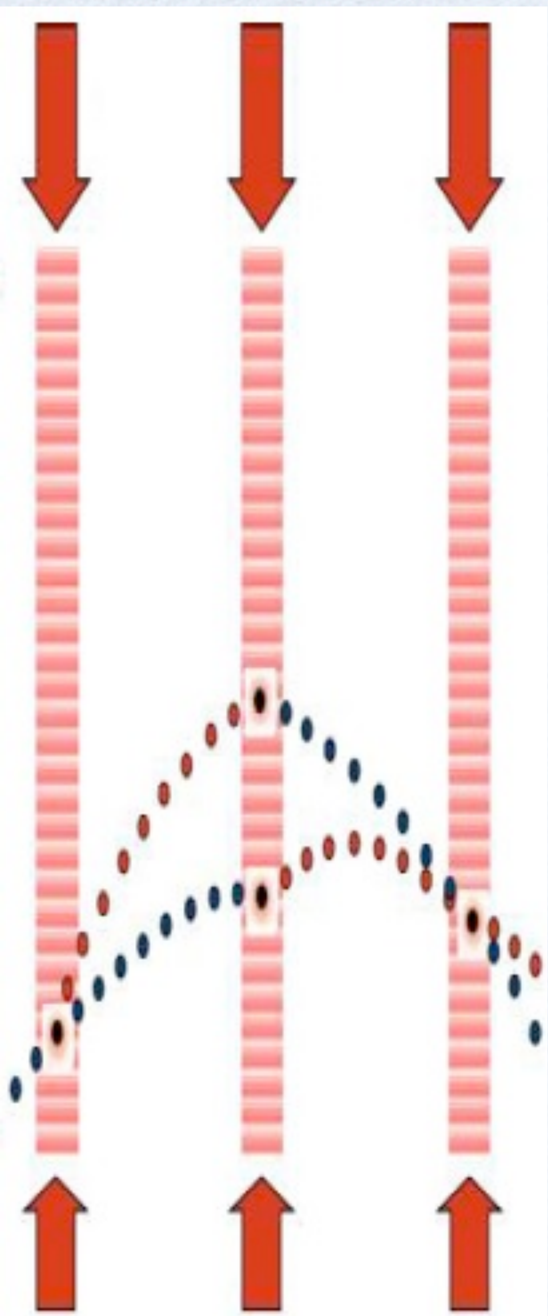


- H. Müller et al., PRL **102**, 240403 (2009)
- S.-W. Chiow et al., PRL **107**, 130403 (2011)
- G. D. McDonald et al., PRA **88**, 053620 (2013)

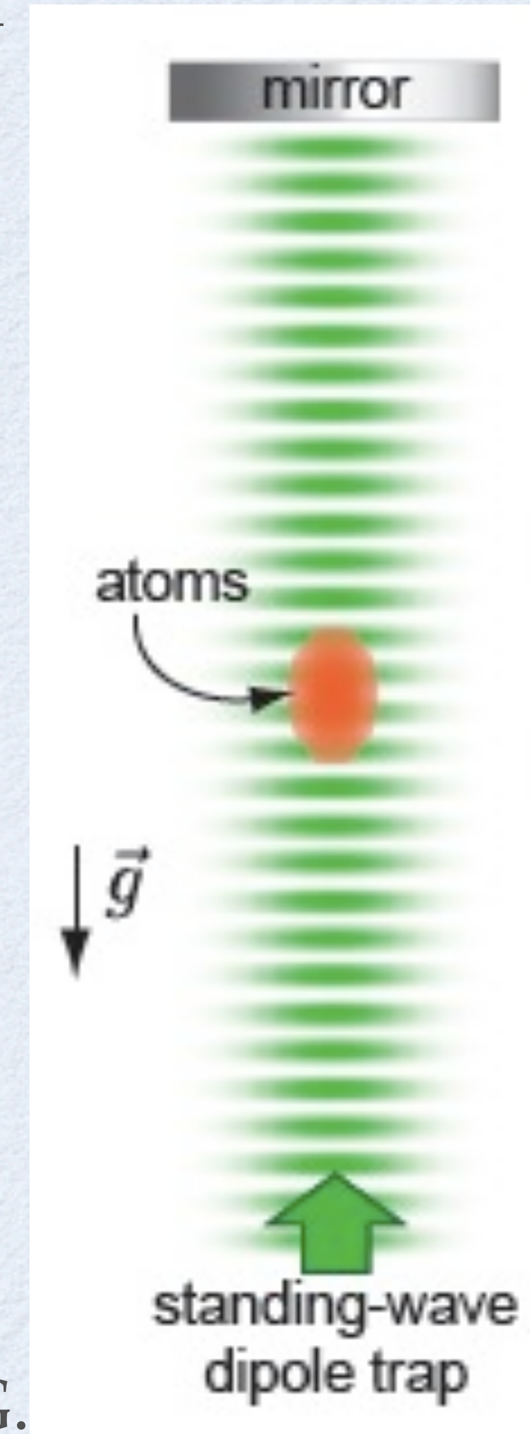




Free falling vs trapped atoms

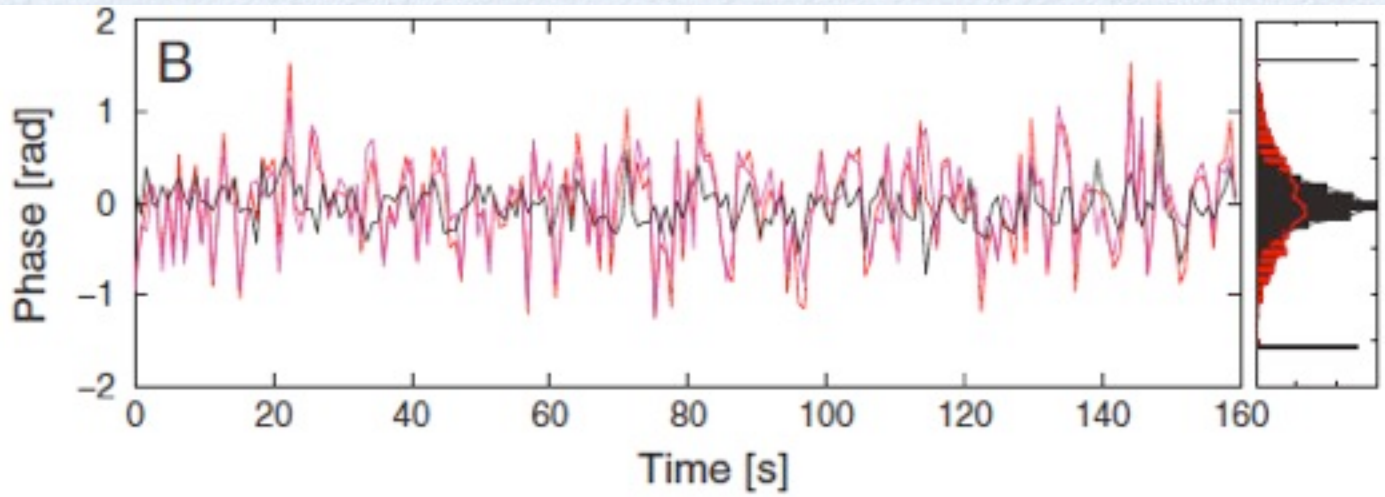


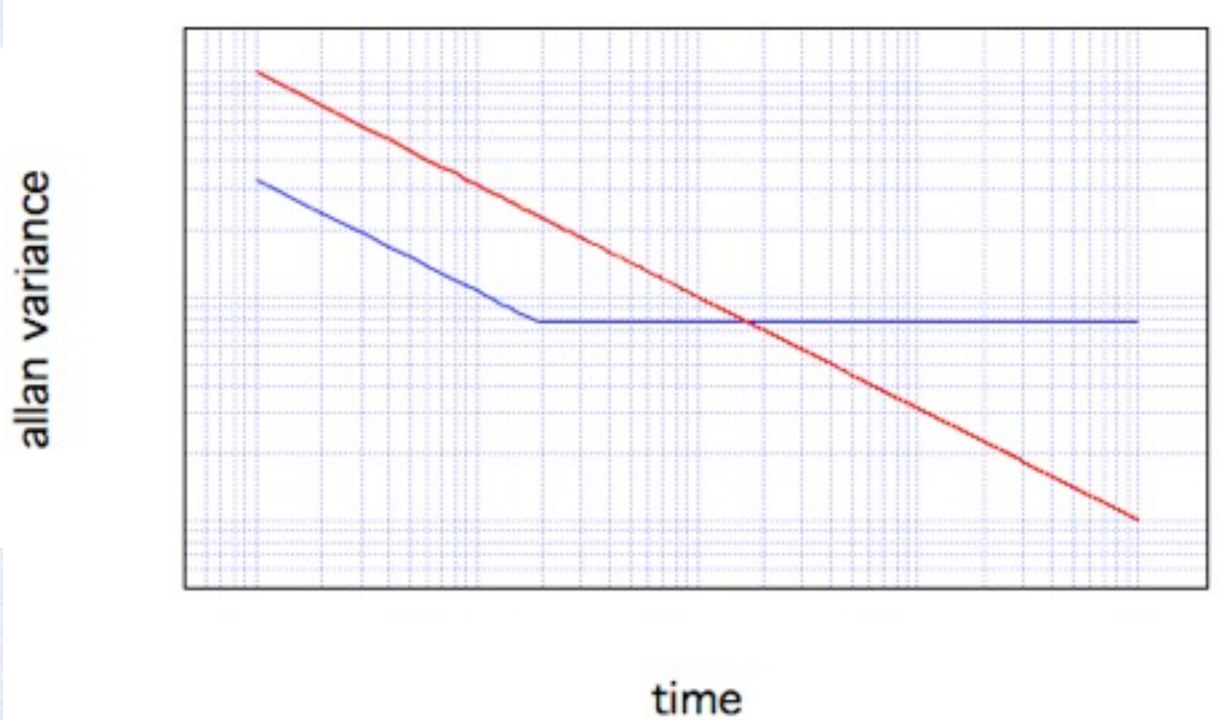
- Light-pulse (Raman or Bragg) atom interferometry
  - highest precision and highest accuracy so far demonstrated
  - atomic wave-function evolves in the absence of external fields
- AI in optical traps
  - No free fall or free expansion
  - Small intrinsic size of the sensor
  - but... perturbation by laser field
  - 1D optical lattice for acceleration measurements
  - toroidal traps for gyroscopes (see talk by G. Gori)



Combination of atom & optical gyros

- Optical gyro to improve AI sensors
  - Using optical gyro for high frequency noise cancellations in AI sensor
- AI to improve optical gyro
  - Using AI gyrocompass for absolute orientation of optical gyro
- Combination of AI and optical devices
  - optimal detection bands
  - Tests of quantum gravity?





J. J. Stockton et al., PRL 107 (2011)

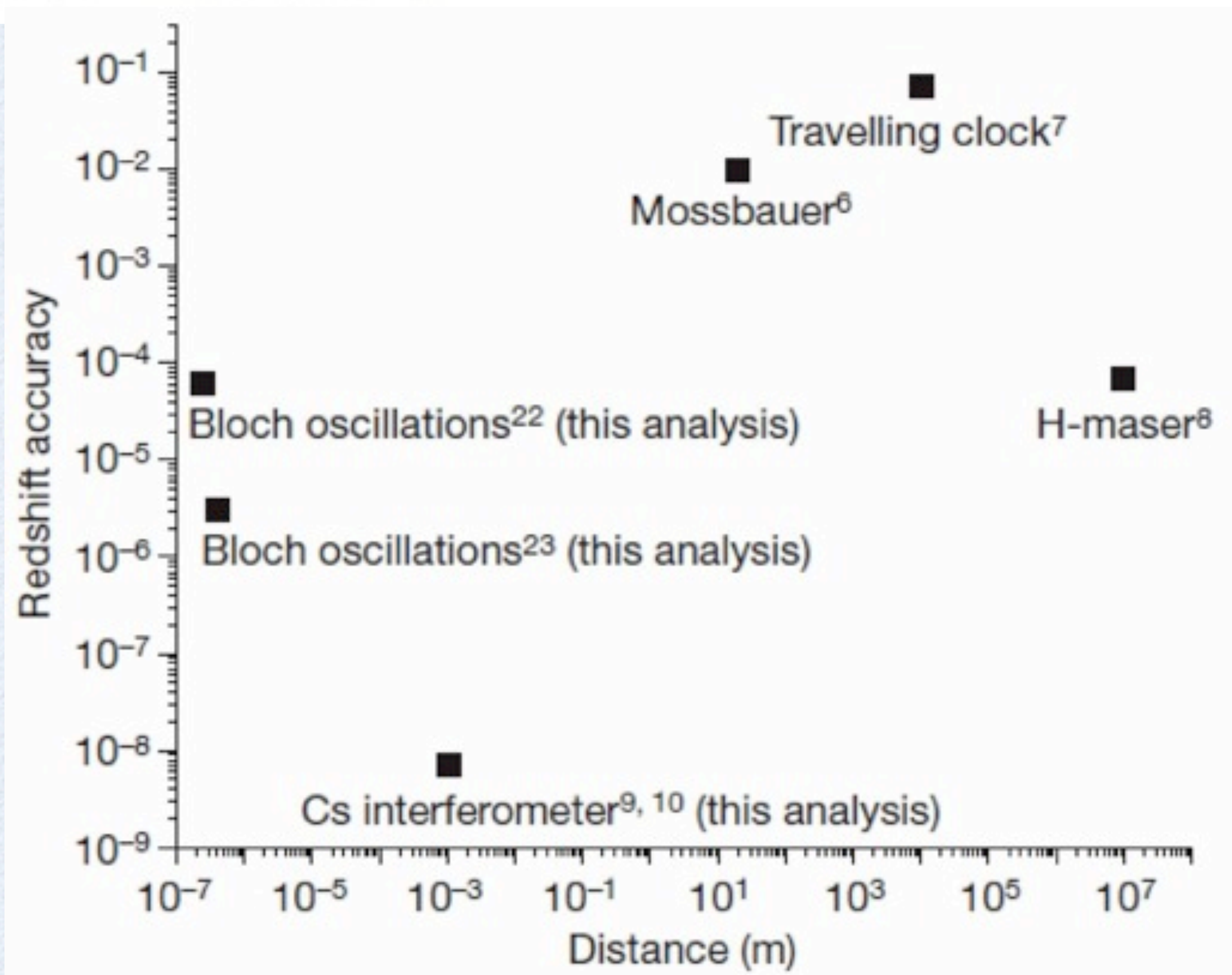
Red-shift measure with atomic probes

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^{-4} level
    - highly sensitive gyroscopes with thermal atoms, improved devices based on ultracold atoms still to reach ultimate performance
- 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

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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)
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- ✓ Istituto Nazionale Geofisica e Vulcanologia (INGV)

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