E-GRAAL kick-off meeting

Atom interferometry gravity gradiometers

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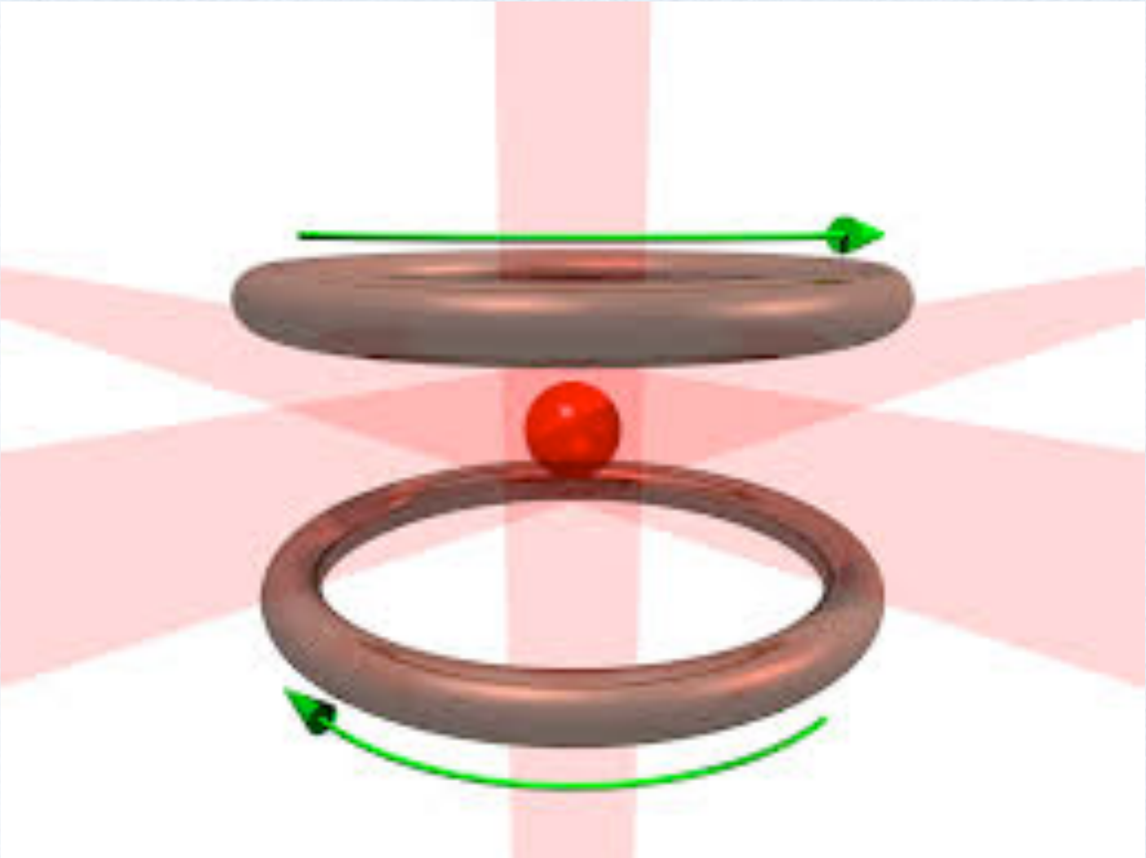
http://coldatoms.lens.unifi.it

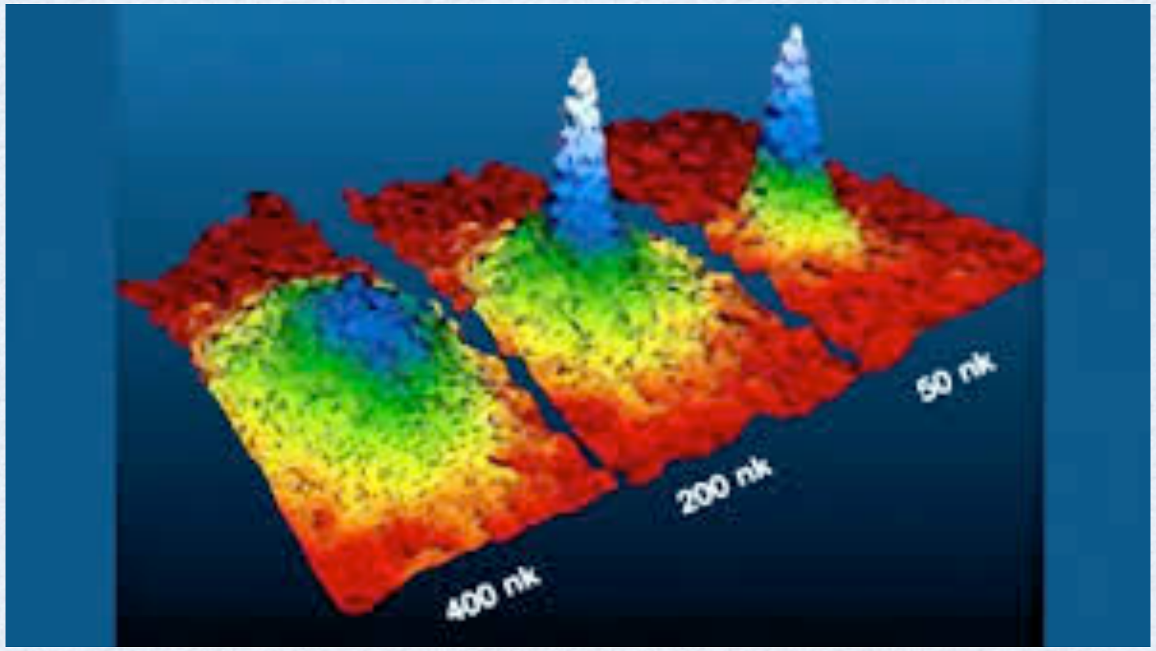
UNIVERSITÀ DEGLI STUDI FIRENZE

LENS European Laboratory for Non-Linear Spectroscopy

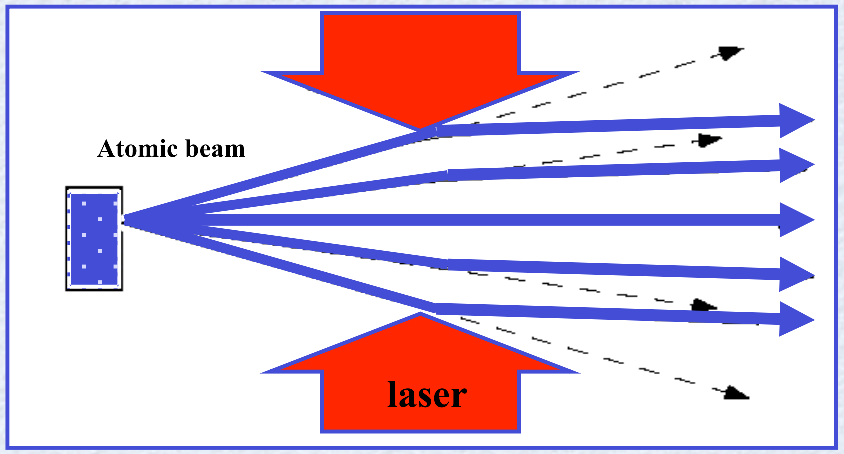
Outline

- Introduction to quantum sensors
  - atom optics and ultracold atoms
  - atom interferometers
- AI gravity sensors: state of the art
  - gravimeters
  - gradiometers
  - gyroscopes
  - illustrative example: *G* measurement
  - other applications
  - compact AI sensors: TRL
- Future prospects
  - advanced atom interferometers
  - ongoing space projects

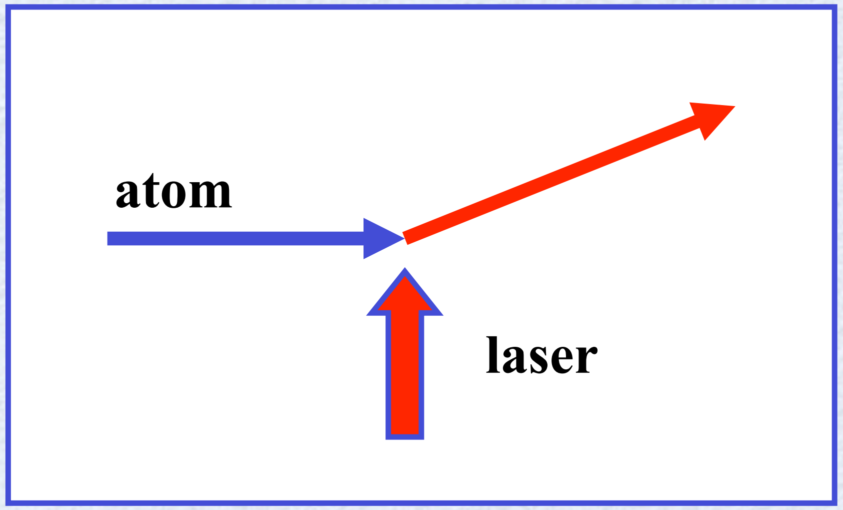




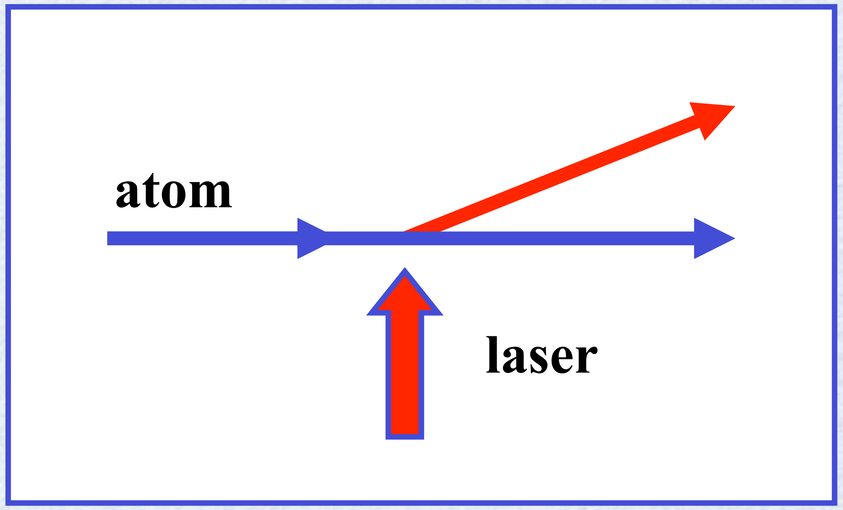
Lenses



Mirrors

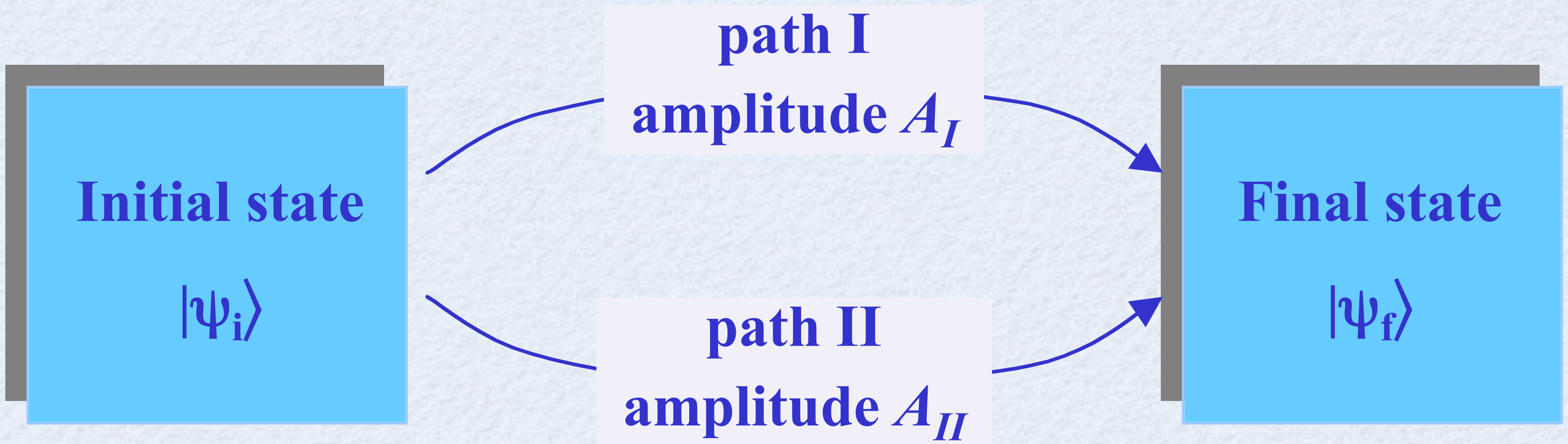


Beam splitters



Matter-wave interferometry

Quantum interference



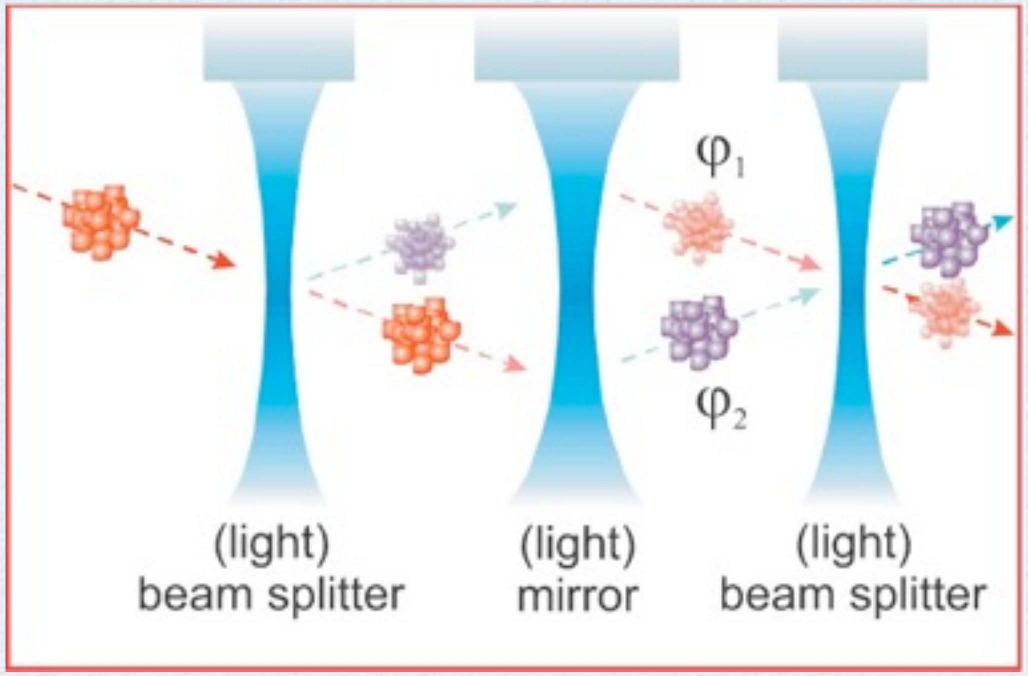
Interference of transition amplitudes

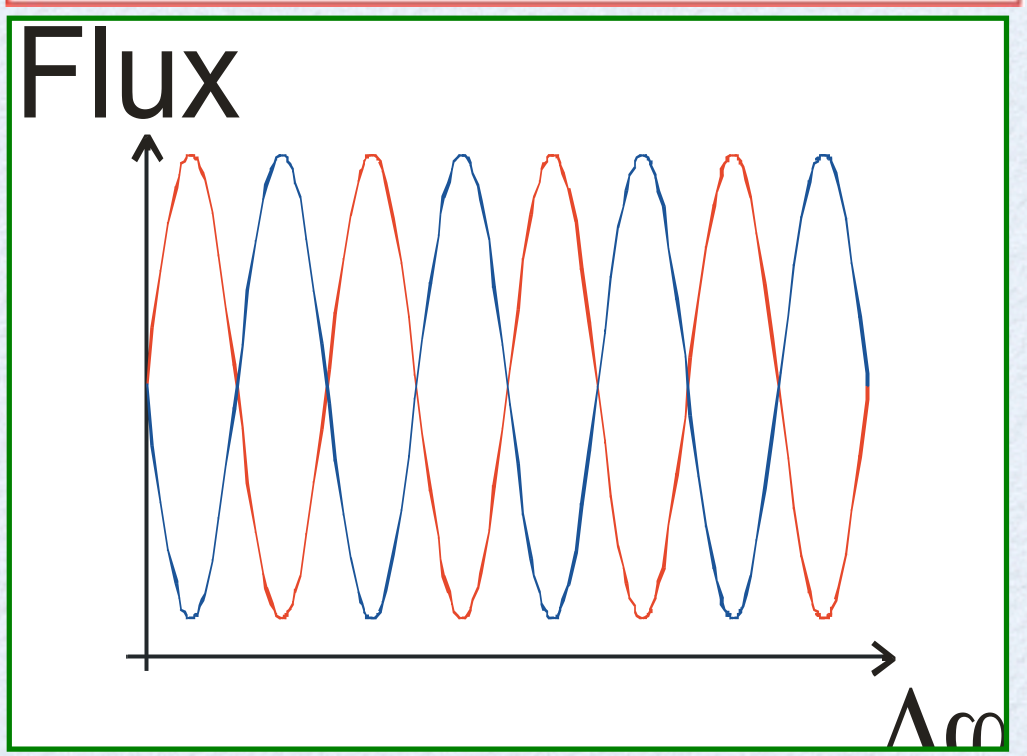
$$P(|\psi_i\rangle \to |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2Re(A_I A_{II}^*)$$

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**

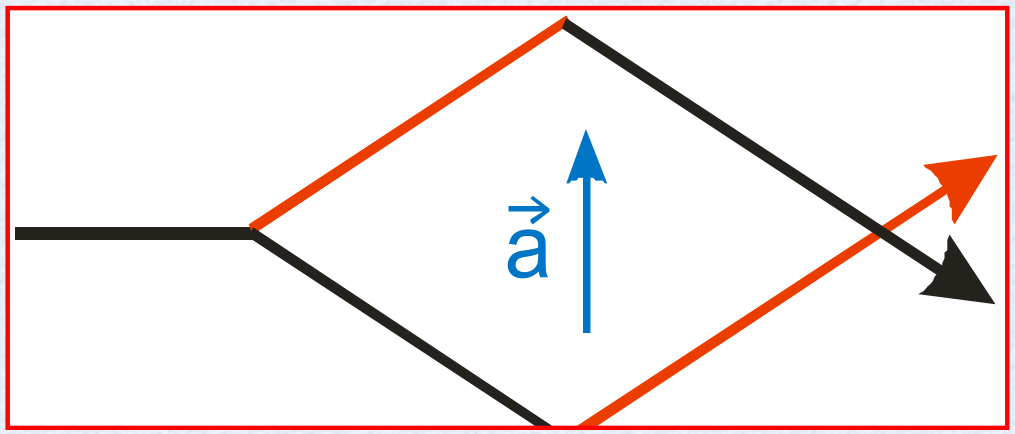
- atom optics
- different internal states/isotopes
- phase difference may depend on:
  - accelerations
  - rotations
  - photon recoil
  - laser phase
  - laser frequency detuning
  - electric/magnetic fields
  - interactions with atoms/molecules

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.)
  - quantum gravity (e.g. testing Newton's $1/r^2$ law at short distance)
  - GW detection
  - Test of fundamental symmetries (e.g. atom neutrality)
  - realization of mass unit (Watt balance)

Matter-wave vs optical inertial sensors

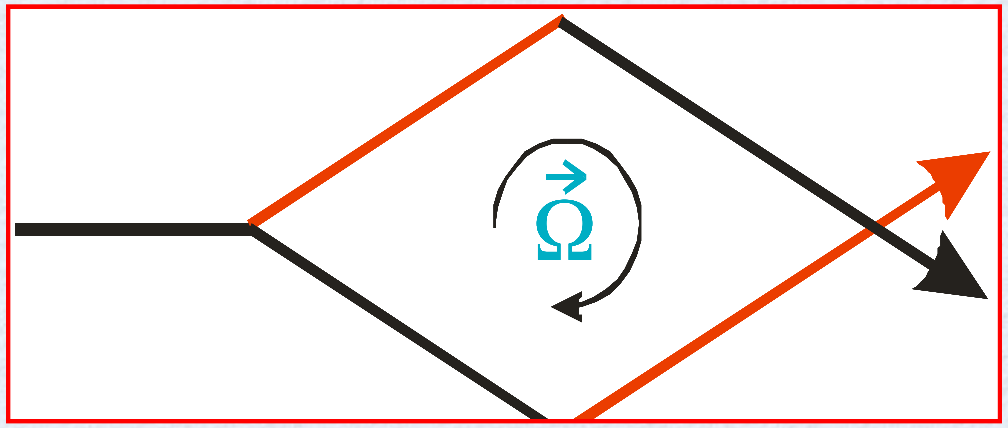
Accelerations



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

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

Rotations



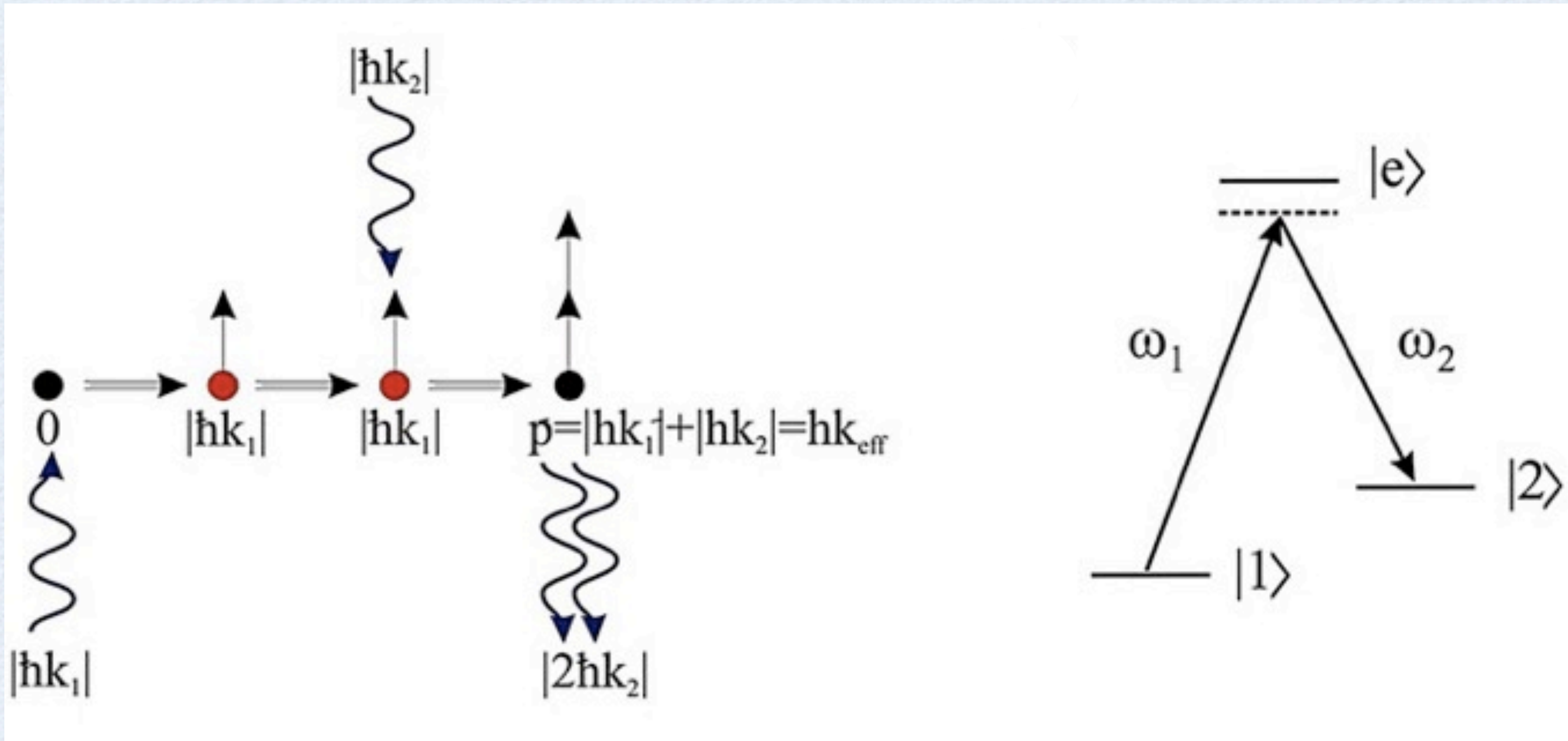
$$\Delta\Phi_{rot} = 2\pi\frac{2m_{at}}{h}A \cdot \Omega$$

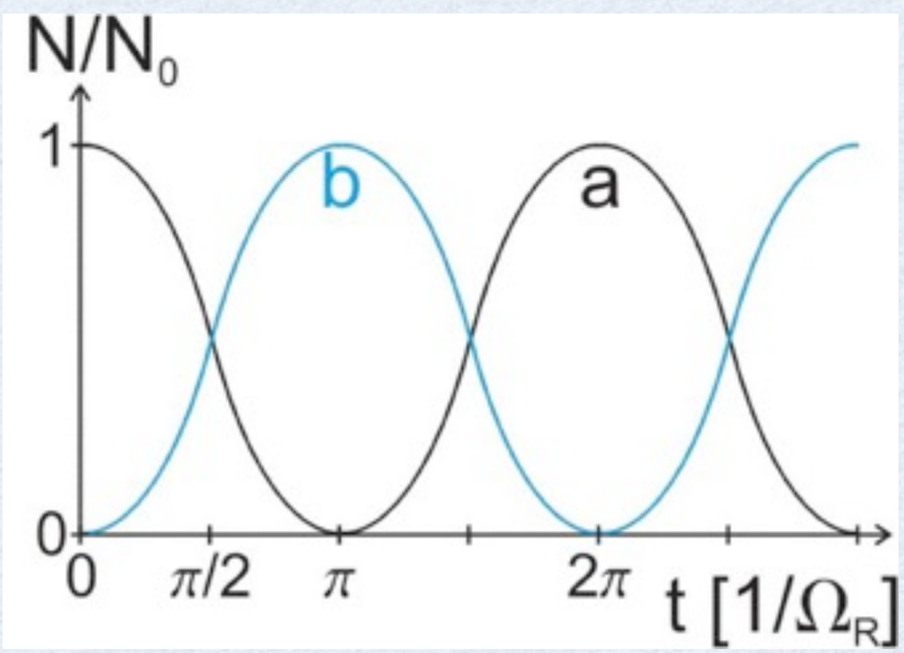
$$\frac{\Delta\phi_{mat}}{\Delta\phi_{ph}} \sim \frac{m_{at}\lambda c}{h} \approx 5 \cdot 10^{11}$$

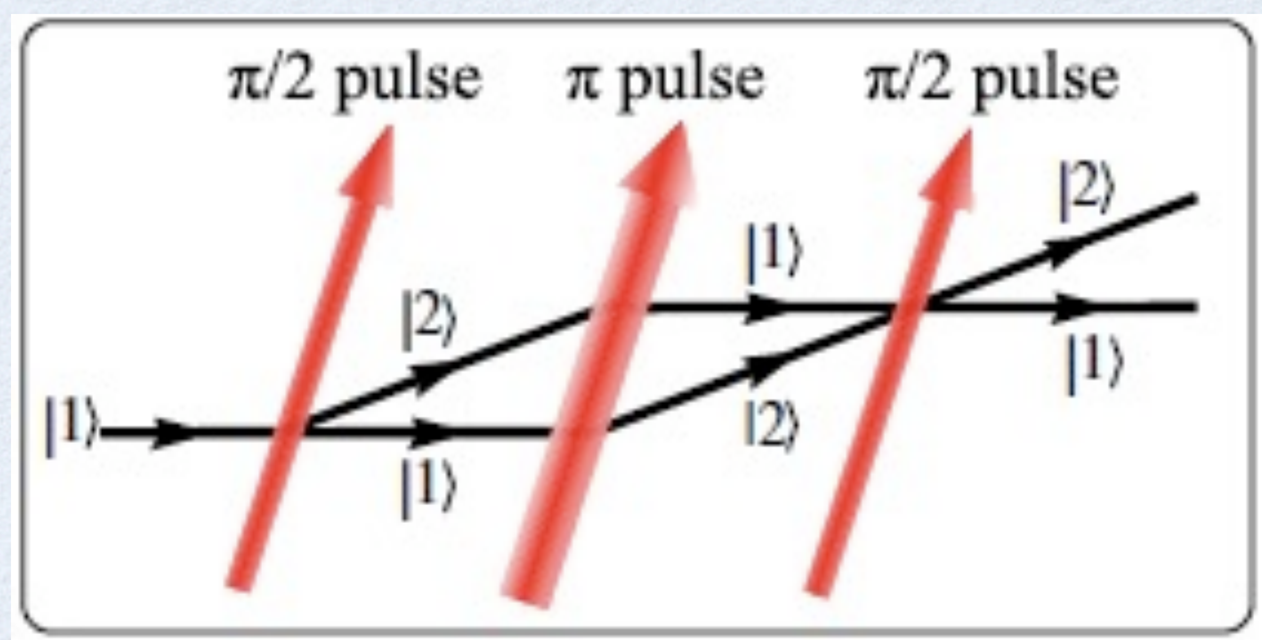
Present limitations of AI

- 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

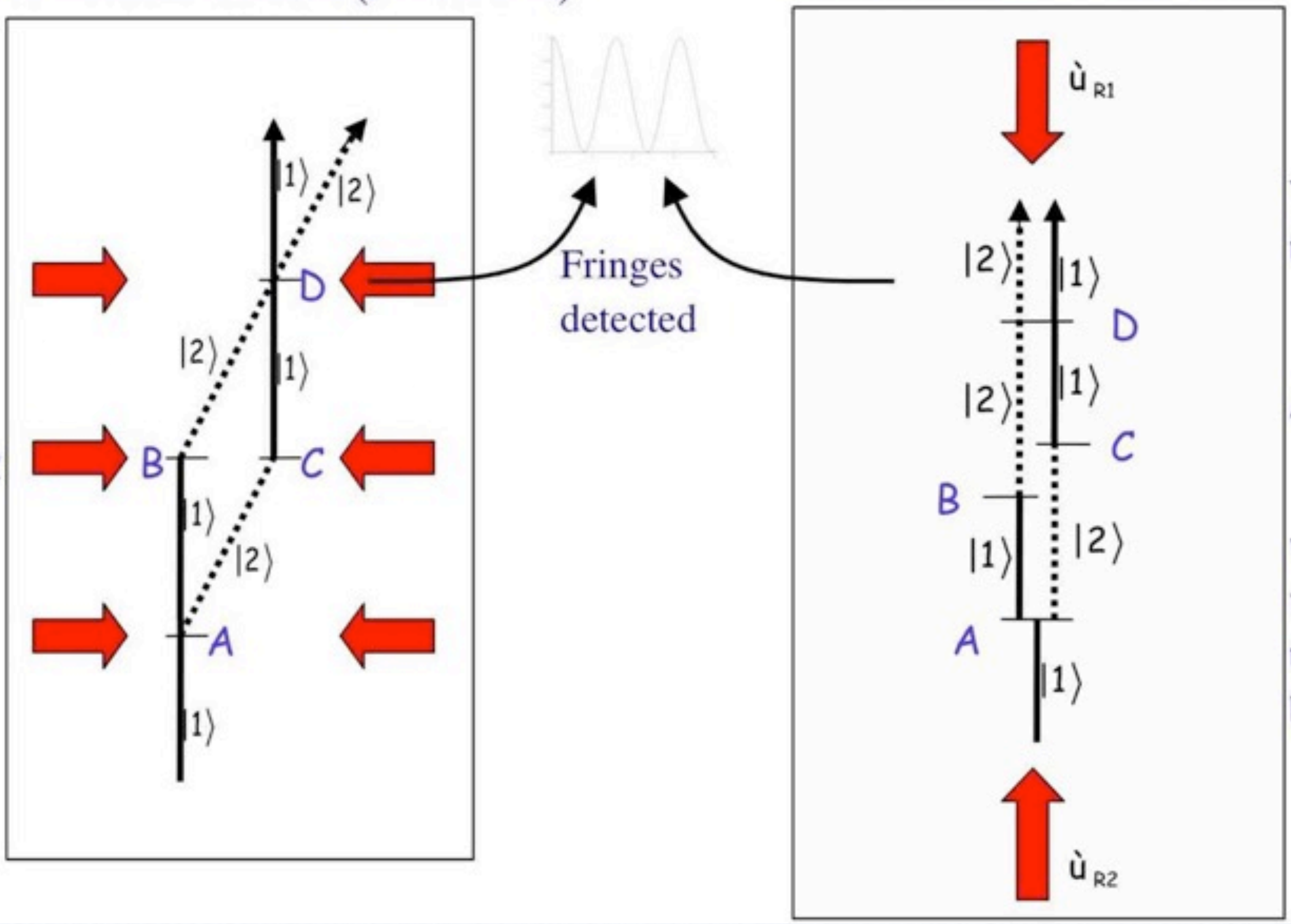
-no area enclosed

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

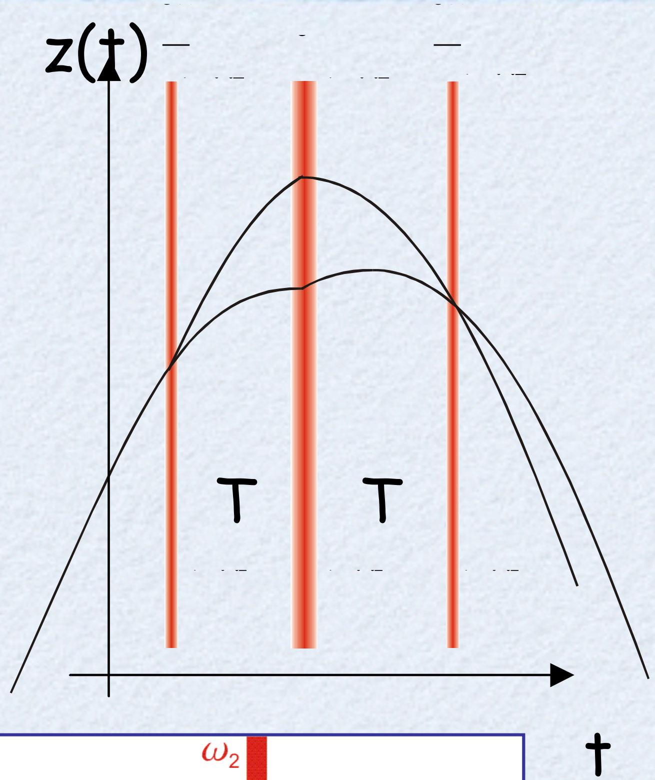


With an acceleration g, the phase difference

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

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

Raman interferometry in a ^{87}Rb atomic fountain: QPN limit



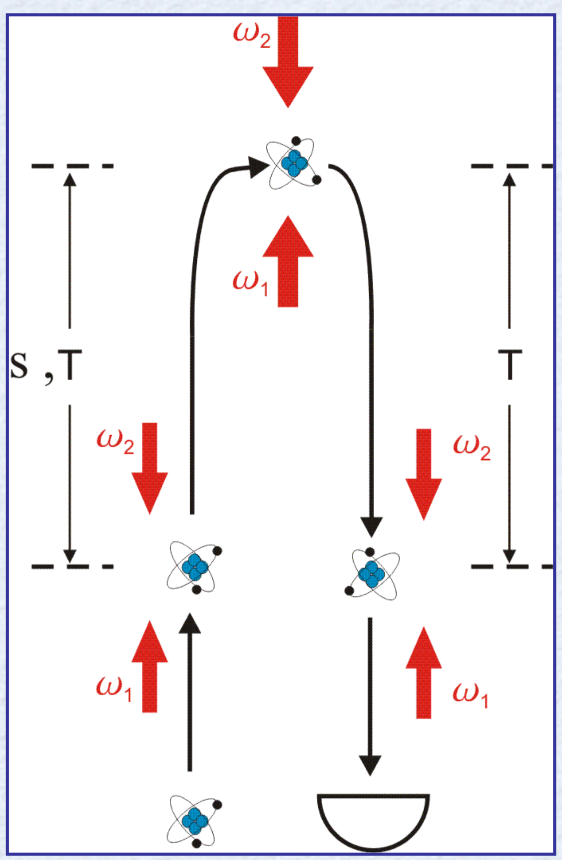
Phase difference between the paths:

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

$k_e = k_1 - k_2$

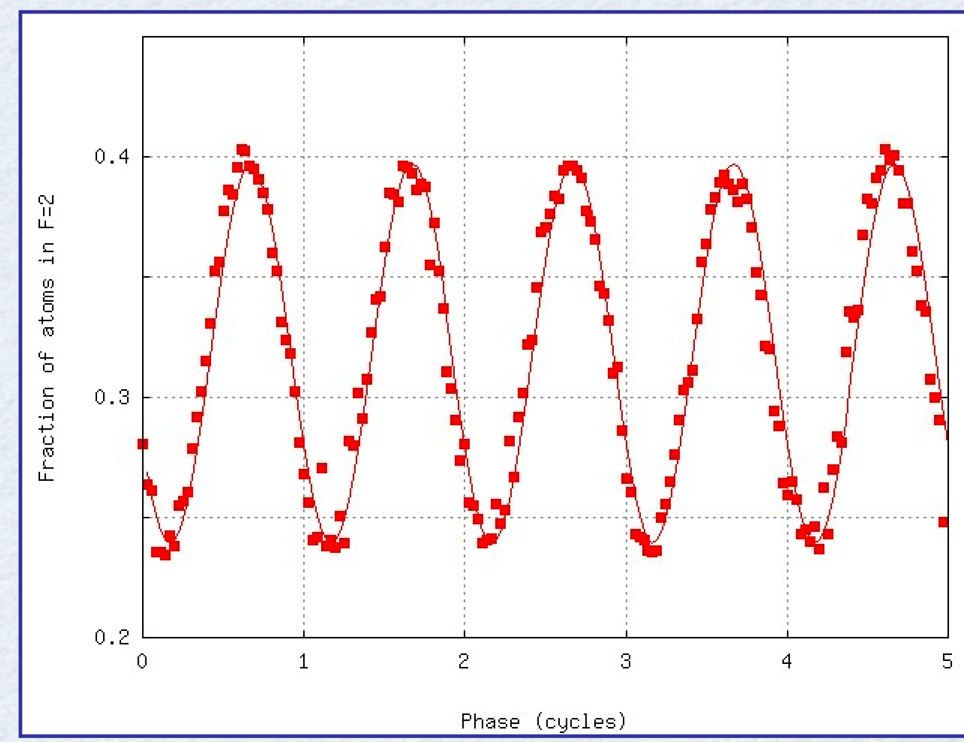
with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

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



Final population:

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

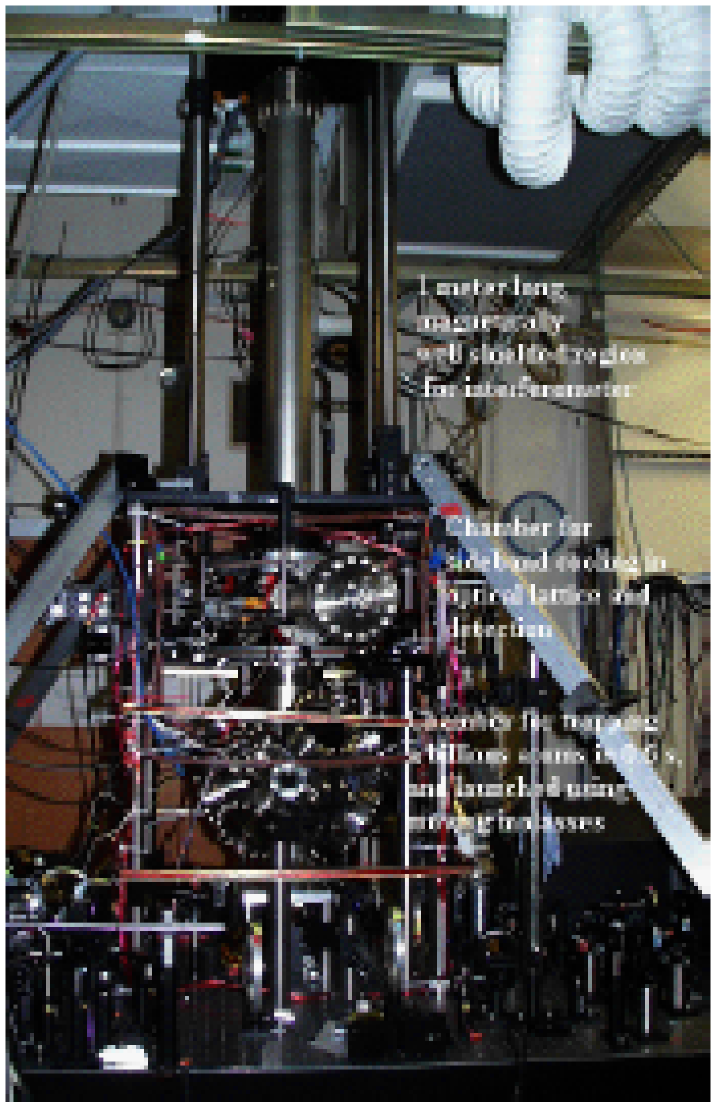


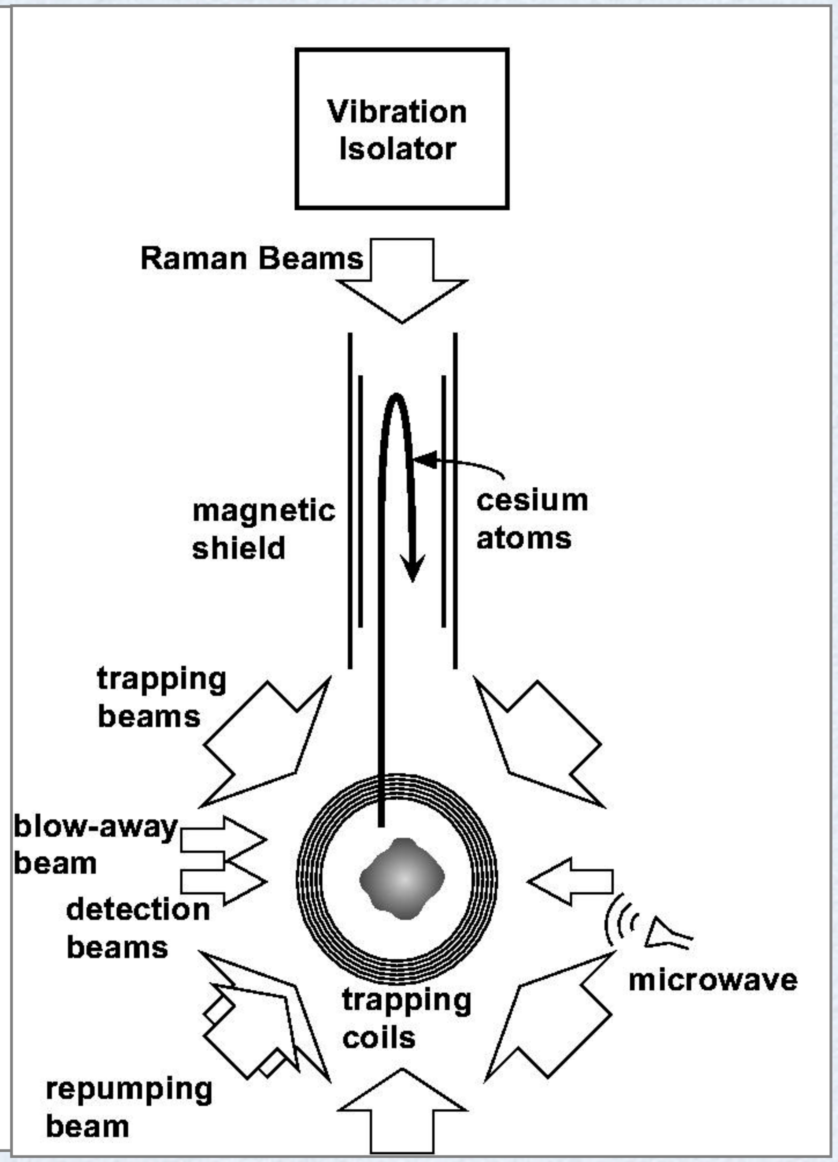
$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

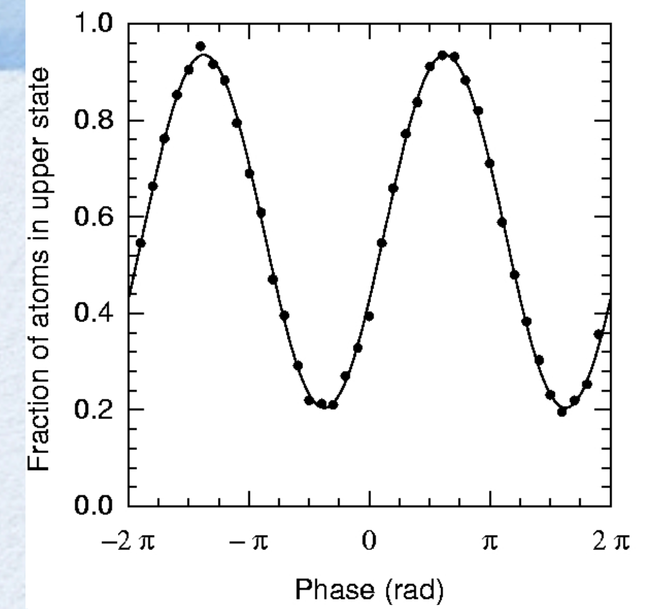
S/N=1000 $\rightarrow$ Sensitivity 10^{-9} g/shot

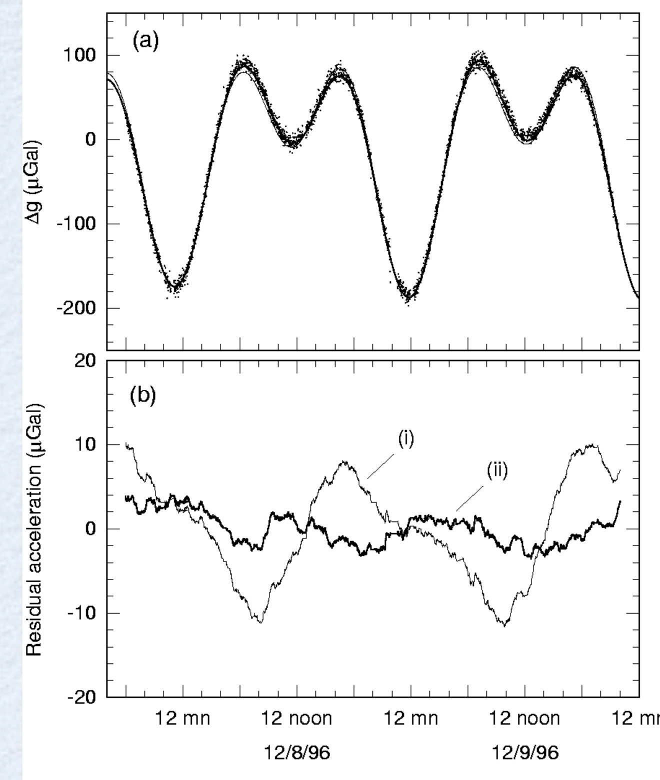
A. Peters et al., Nature **400**, 849 (1999)

Atom gravimeters (Stanford, Berlin, Paris)









resolution: $8\text{x}10^{-9}$ g in 1 second (Stanford)

averaging down to $8\text{x}10^{-10}$ g after 10 min (Berlin)

accuracy: ~ 10^{-9} g, limited by tidal models

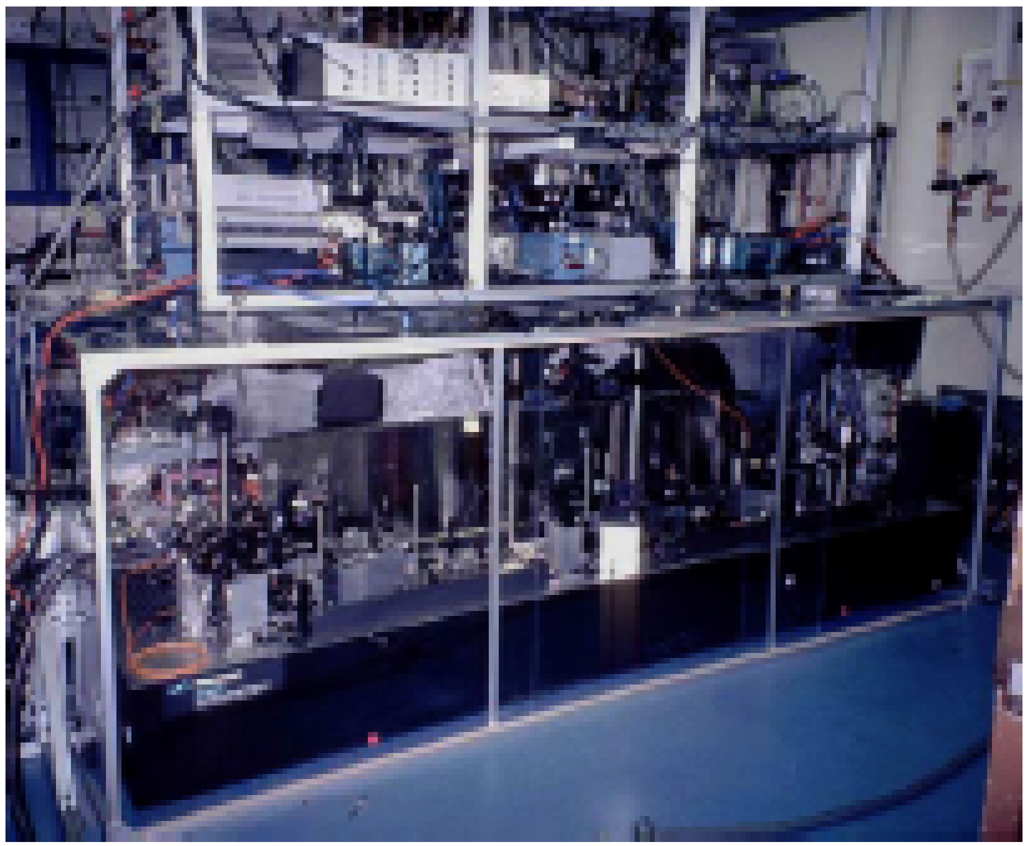
A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)

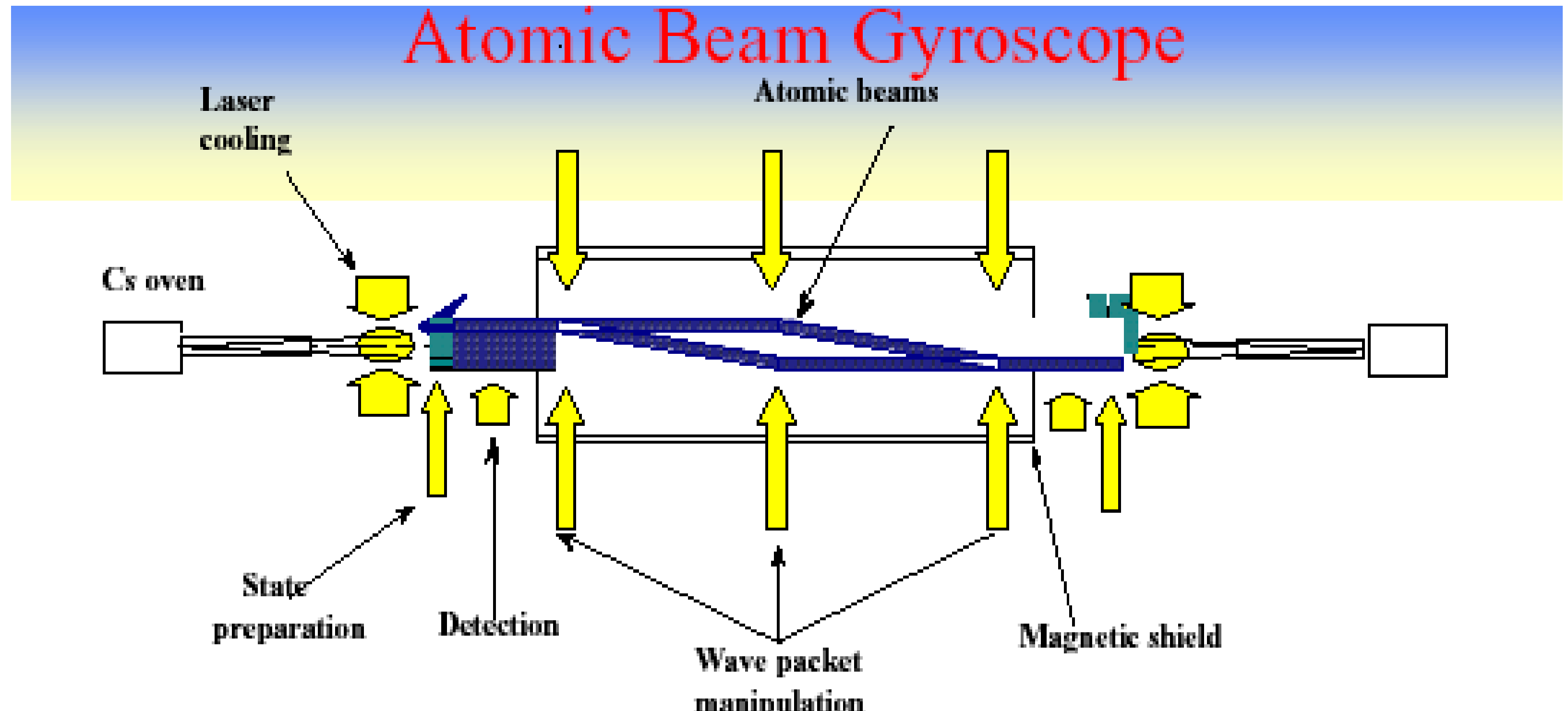
H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)

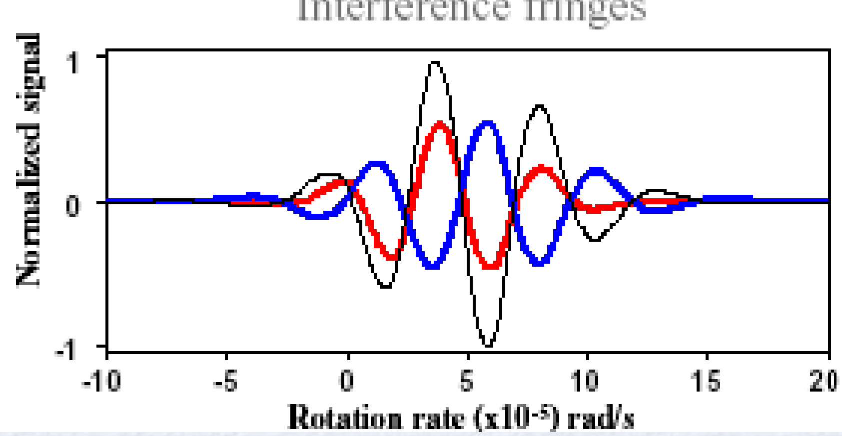
M. Hauth et el., Appl. Phys. B 113, 49 (2013)

P. Gillot et al., Metrologia 51, L15 (2014)

Gyroscopes (Stanford, Paris, Hannover)







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

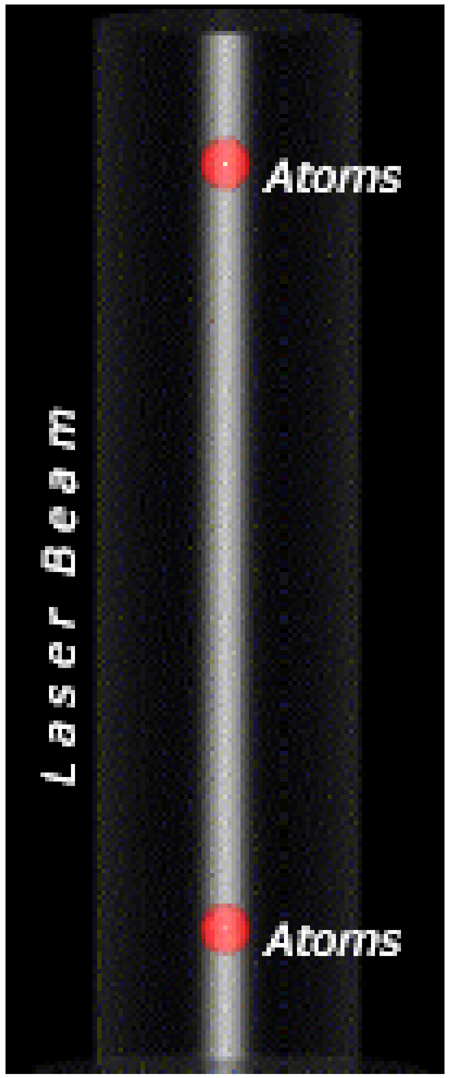
scale factor stability < 5 ppm

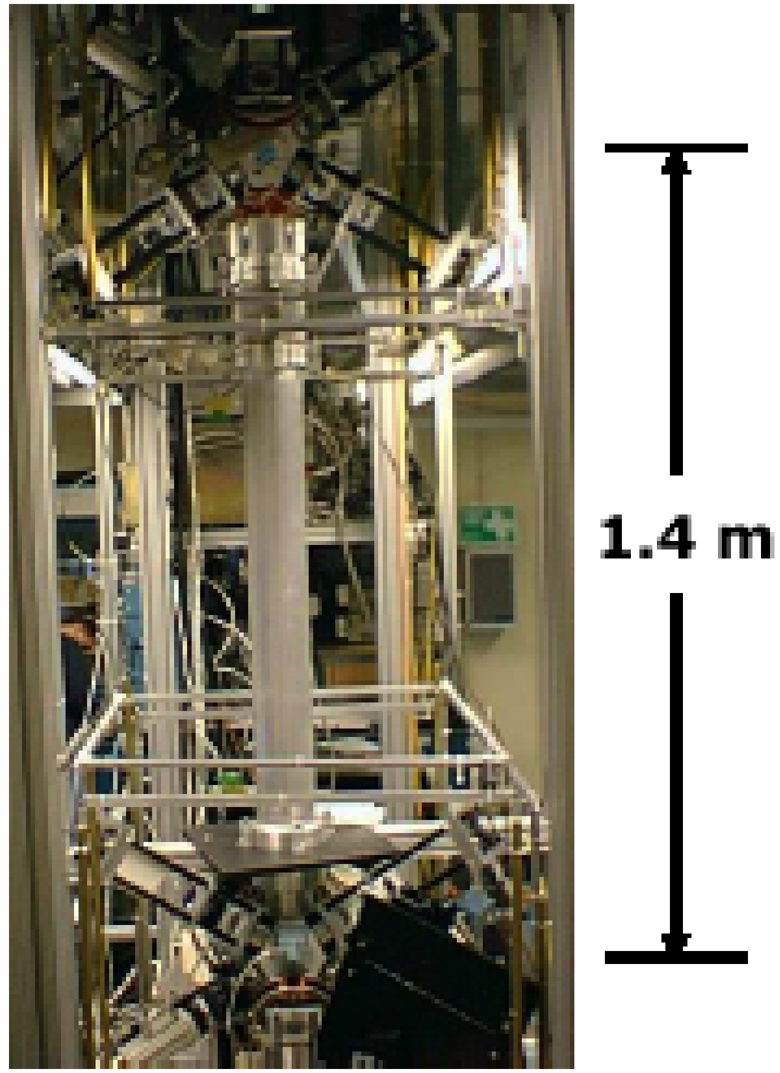
bias stability $< 70\,\mu$deg/h

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

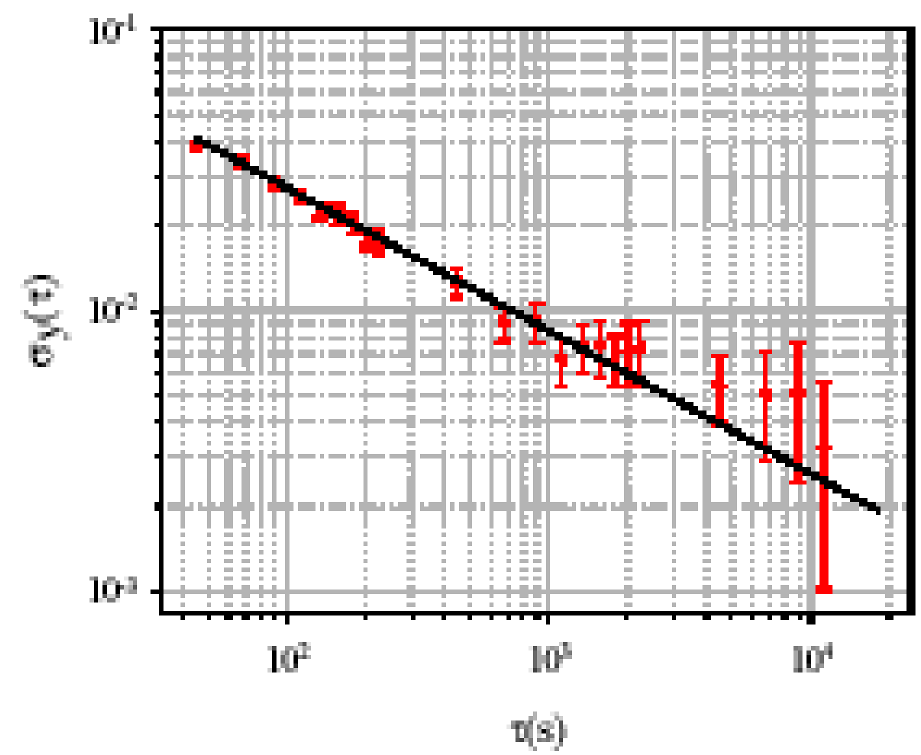
D. S. Durfee, Y. K. Shaham, M.A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006)

Gravity gradiometers (Stanford, Firenze)





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



Demonstrated diffential acceleration sensitivity:

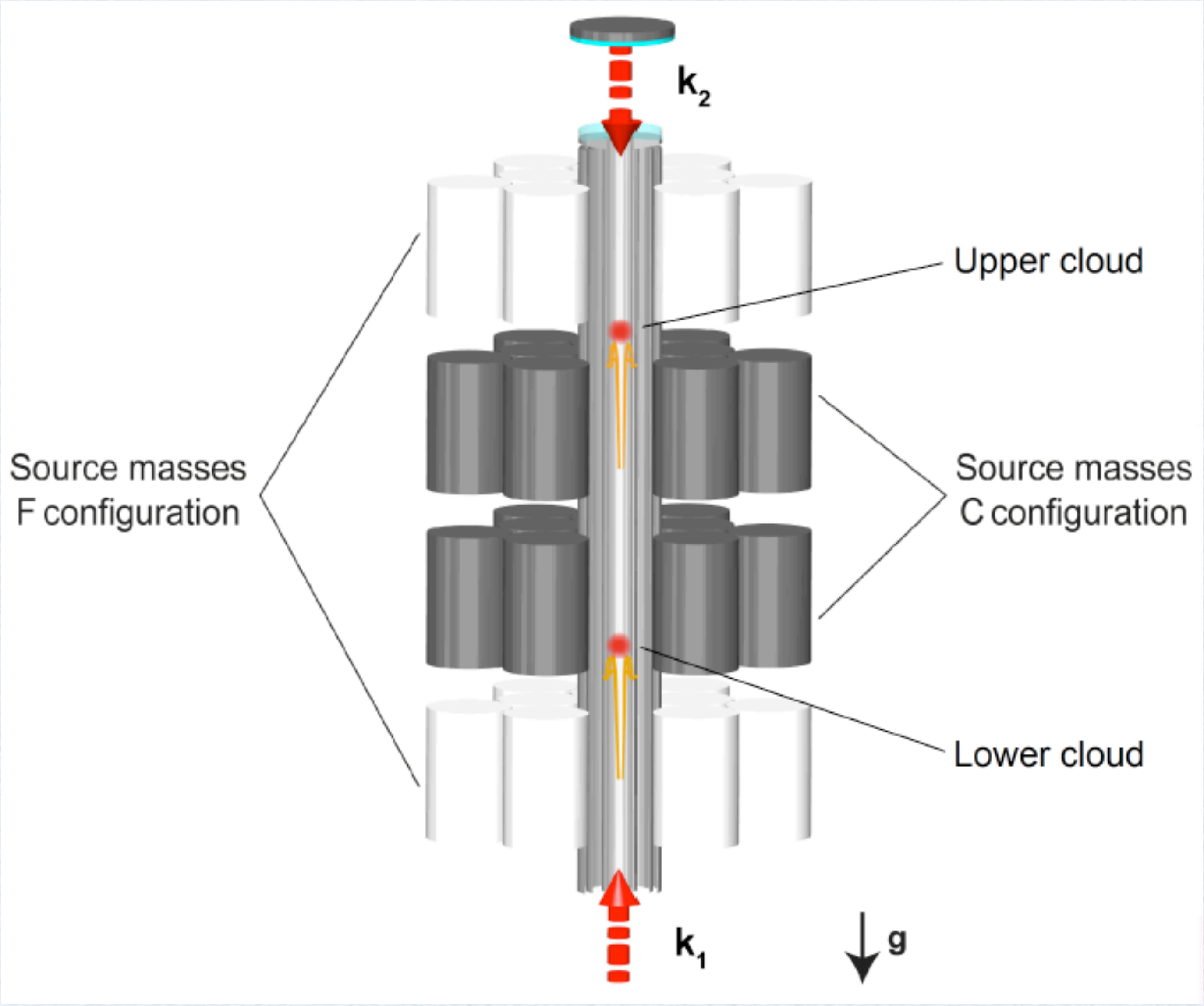
4×10^{-9} g/Hz$^{1/2}$

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

MAGIA

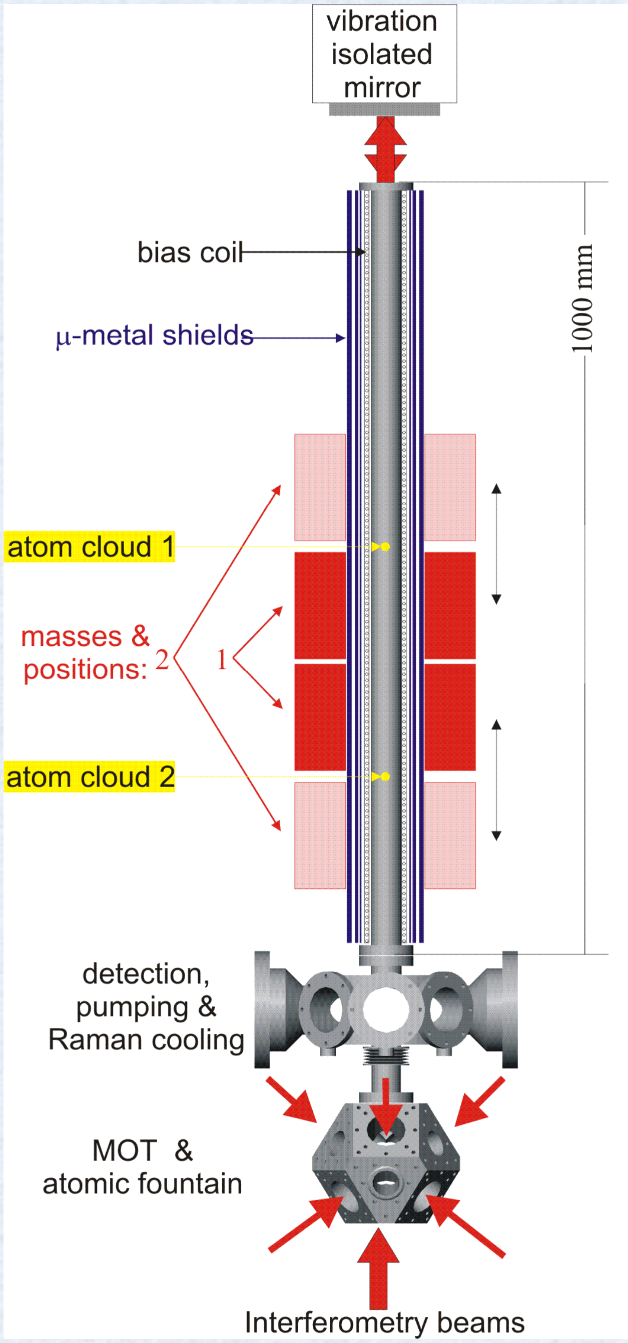
Misura Accurata di G mediante Interferometria Atomica

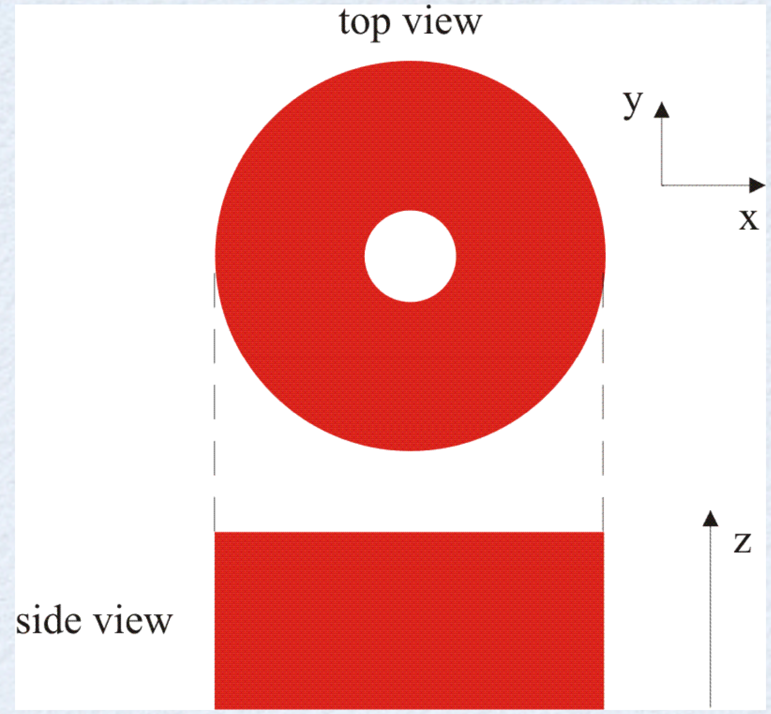
- Rb fountain gradiometer
- + set of source masses

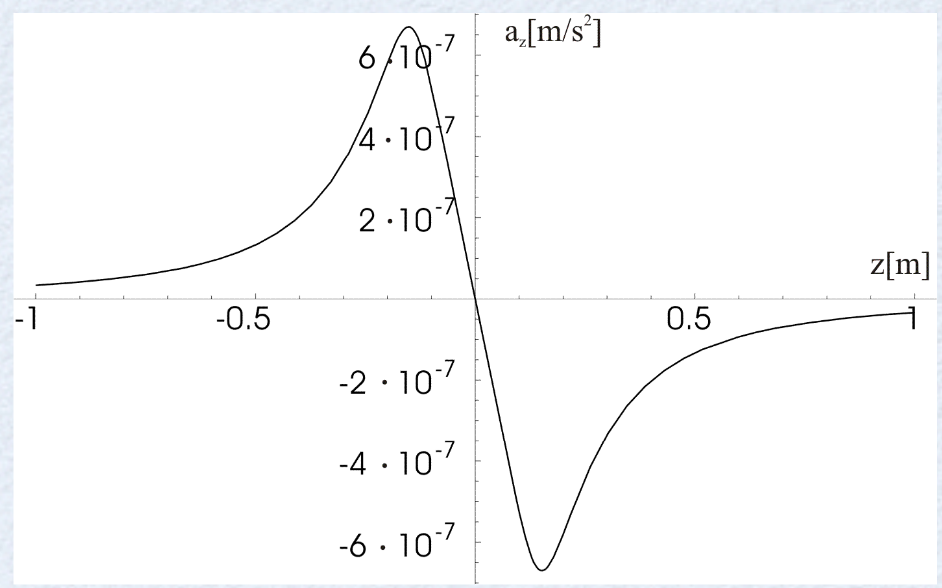


http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Atom gravimeter + source masses







Sensitivity 10^{-9} g/shot

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

500 Kg tungsten mass

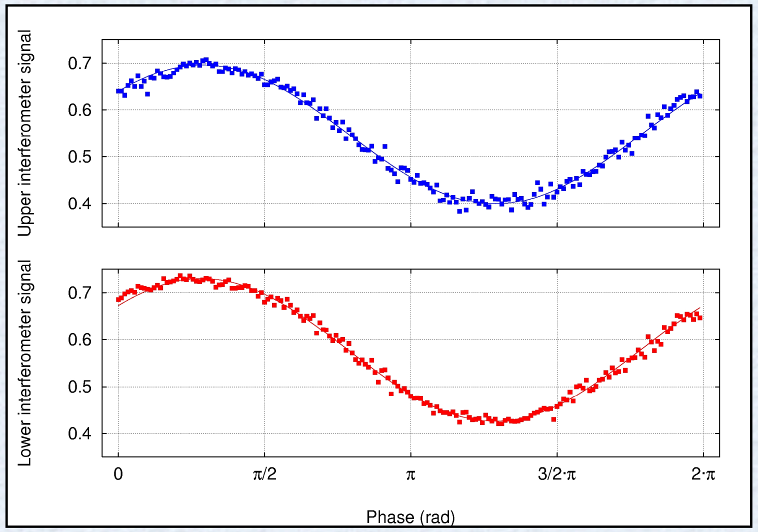
Peak mass acceleration $a_g \sim 10^{-7}$ g

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

Raman gravity gradiometer

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

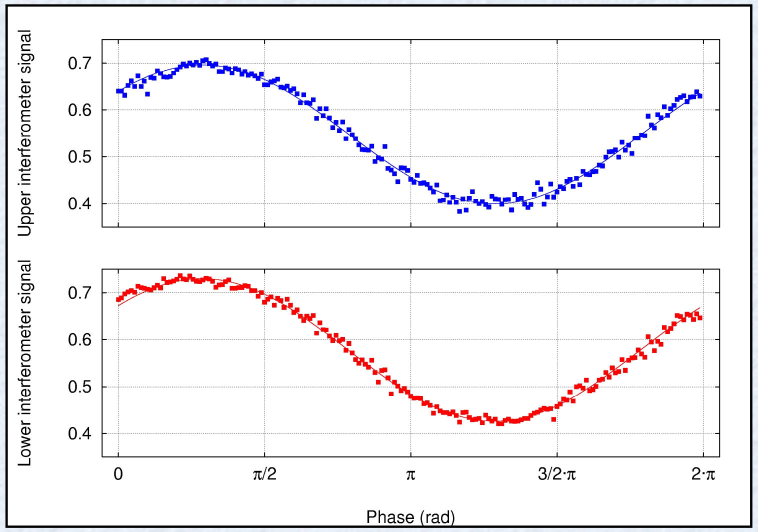
Raman gravity gradiometer



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

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

Raman gravity gradiometer



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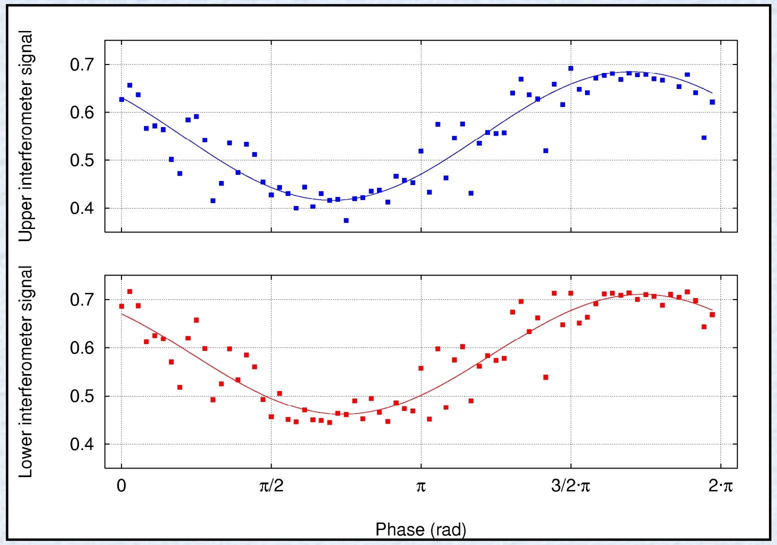
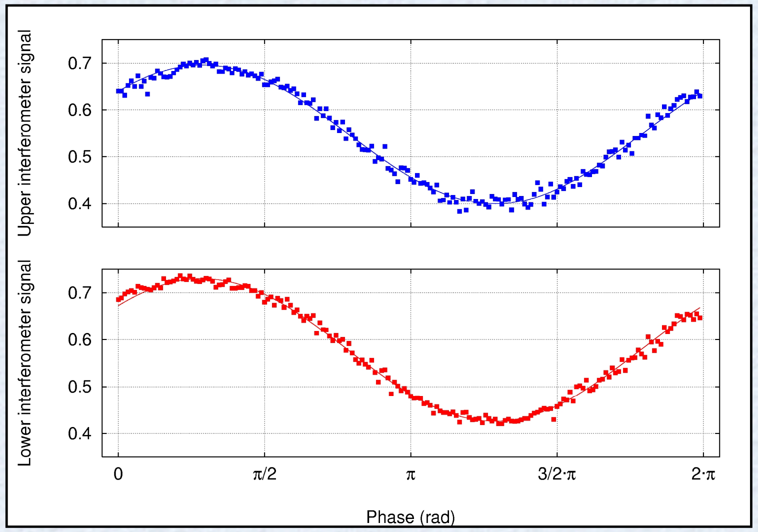


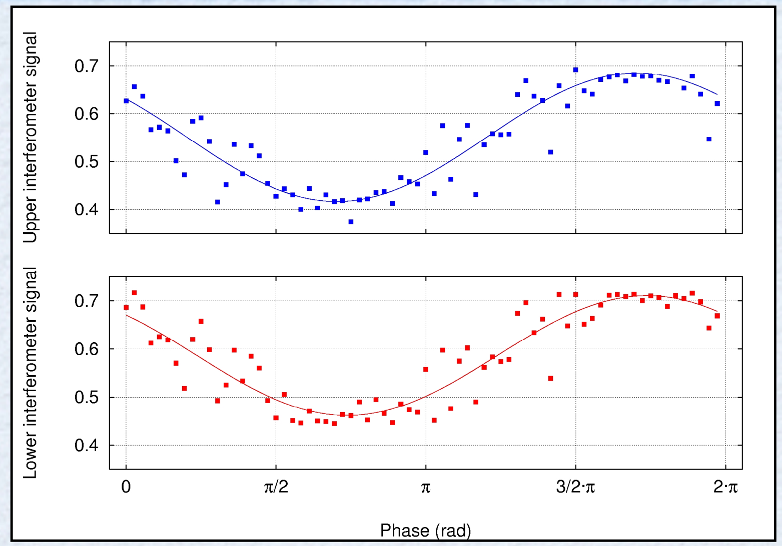
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot

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

Raman gravity gradiometer



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



$T=50$ ms
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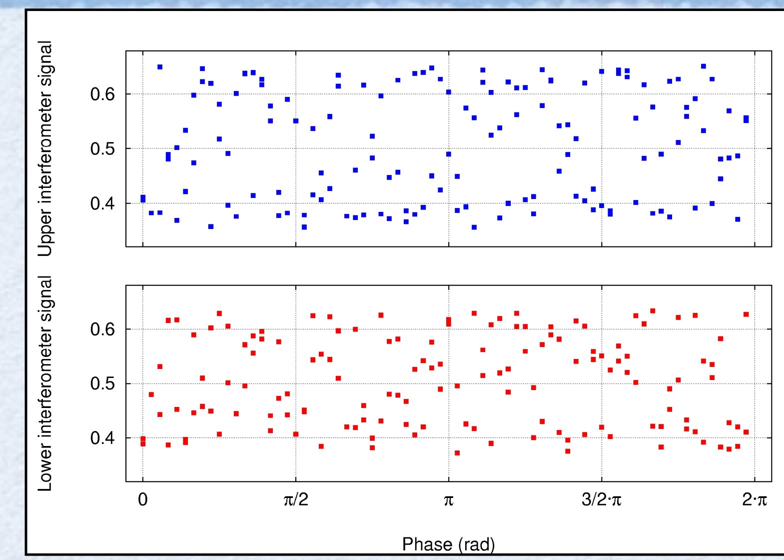
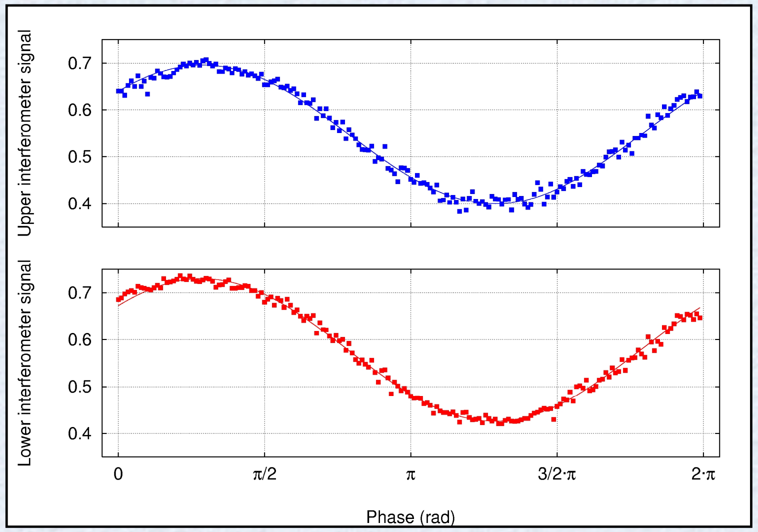


$T=150$ ms
$\text{resol.} = 3.2 \times 10^{-8}\text{g/shot}$

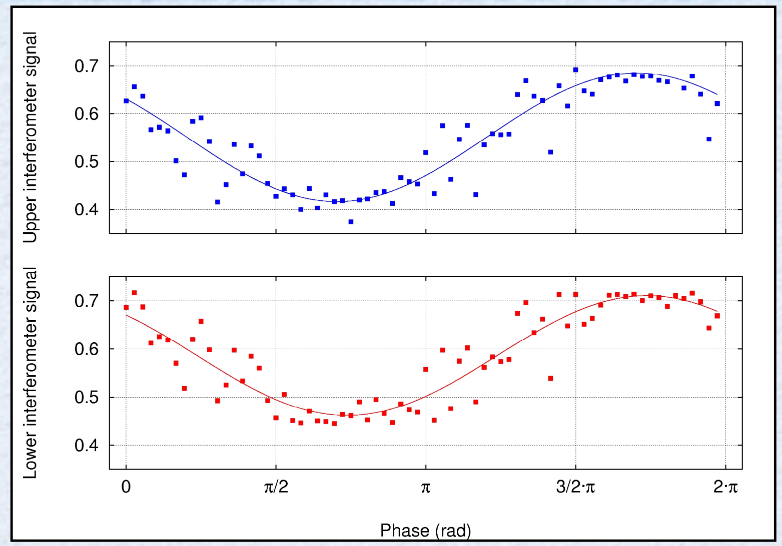
$$\Delta\Phi = k_e g T^2$$

Raman gravity gradiometer



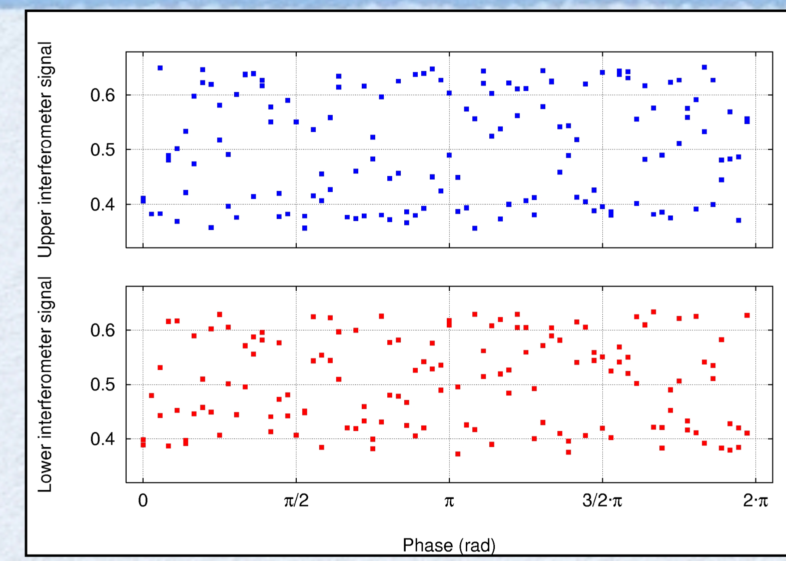
T=5 ms

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



T=50 ms

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



T=150 ms

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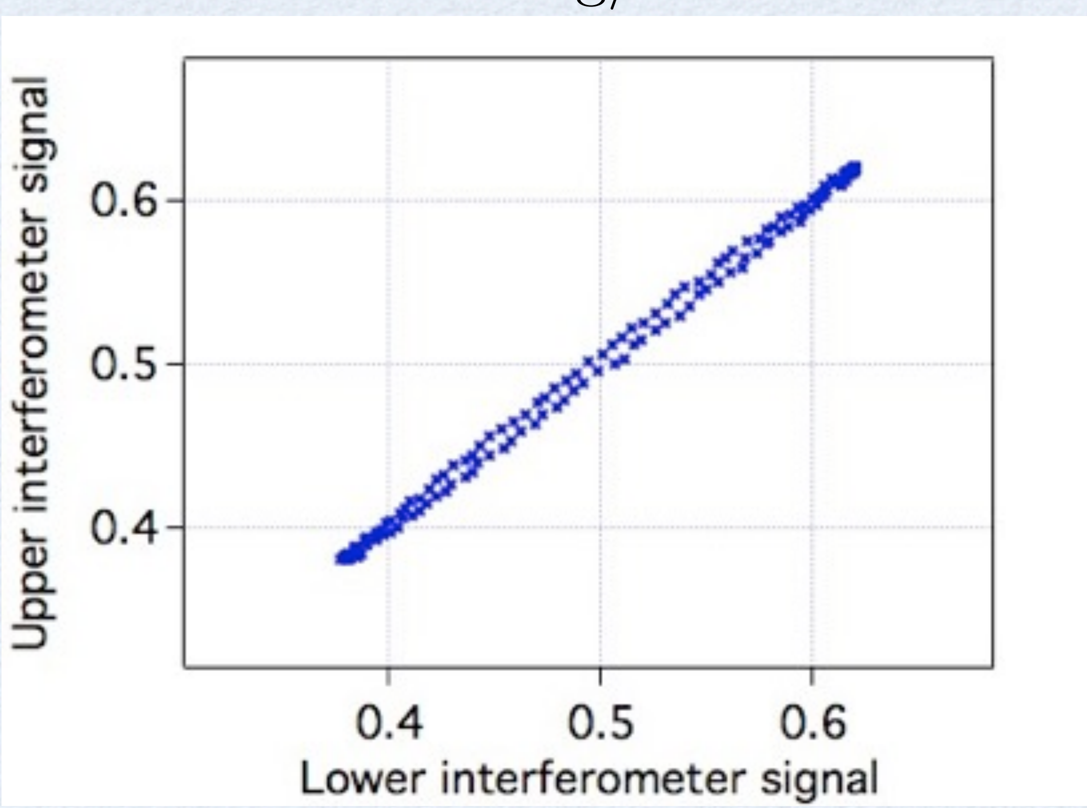
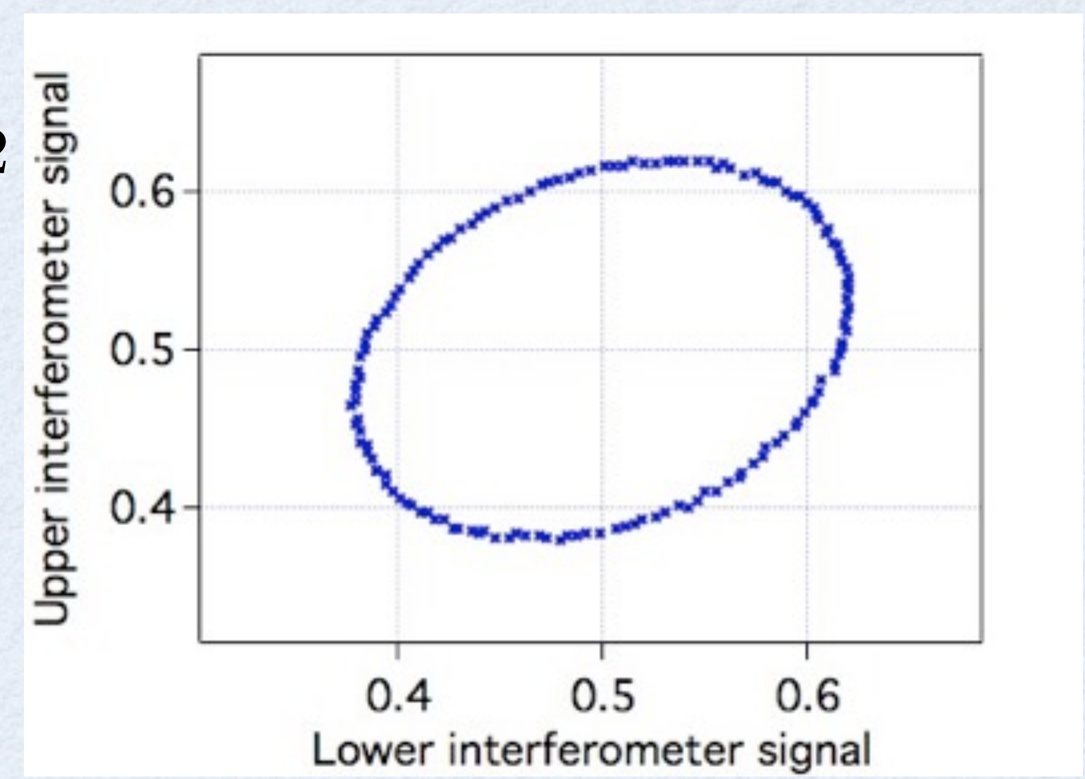
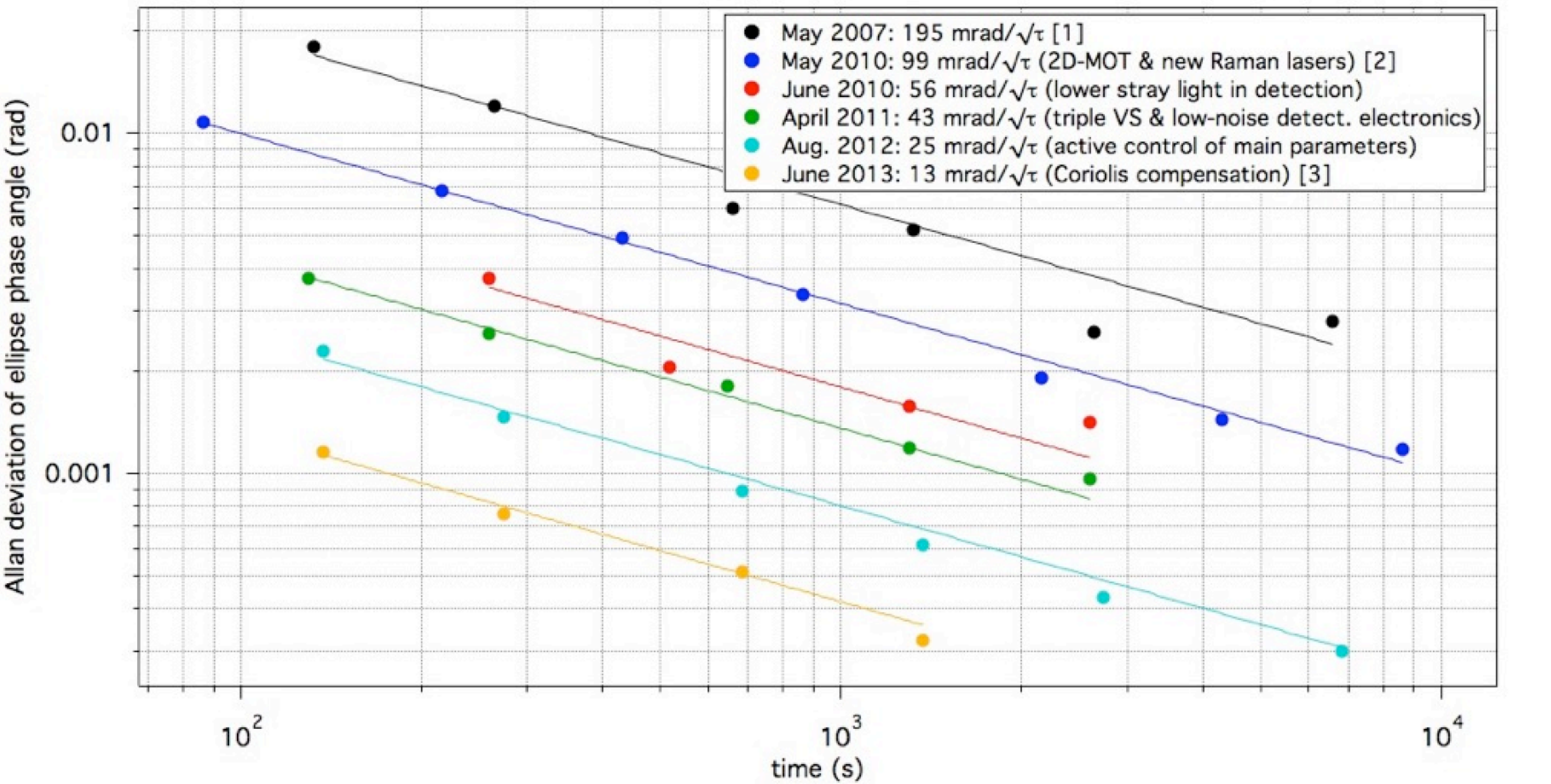


$$\Delta\Phi = k_e g T^2$$



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

Short-term sensitivity



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

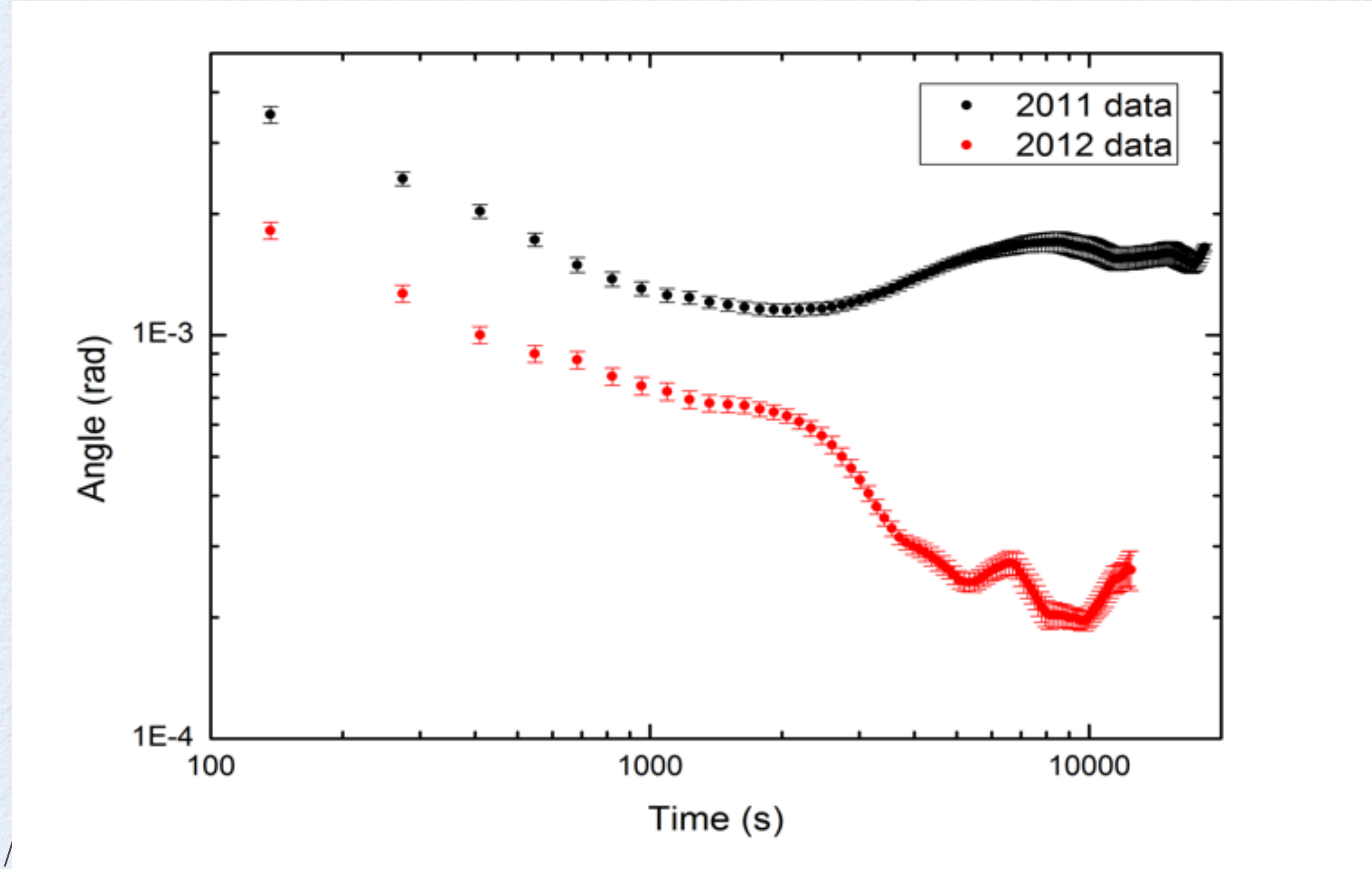
[1] G. Lamporesi et al., Phys. Rev. Lett 100, 050801 (2008)

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

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

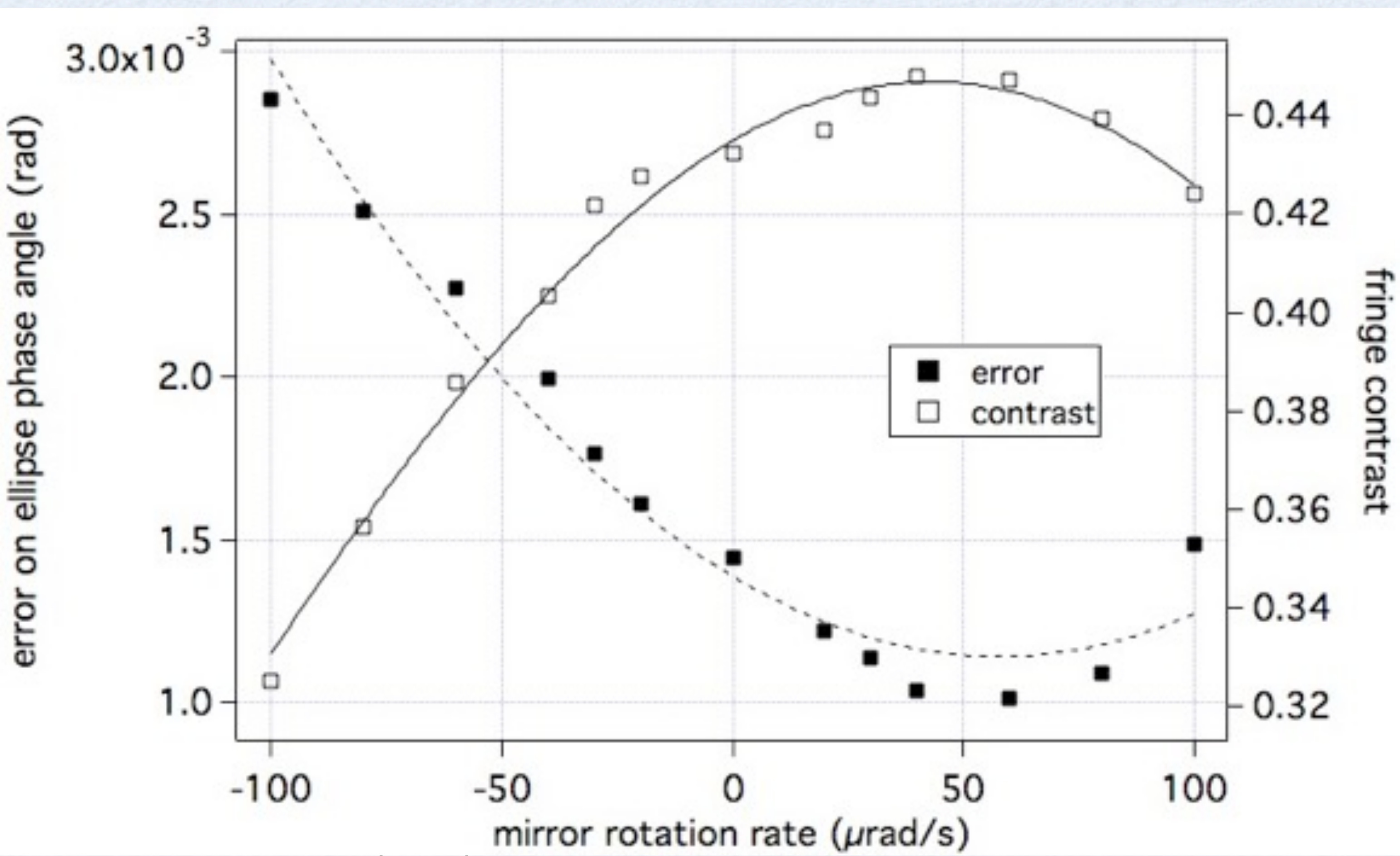
Long term sensitivity

- 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 $5x10^{-11}$ g (5x improvement from 2011)

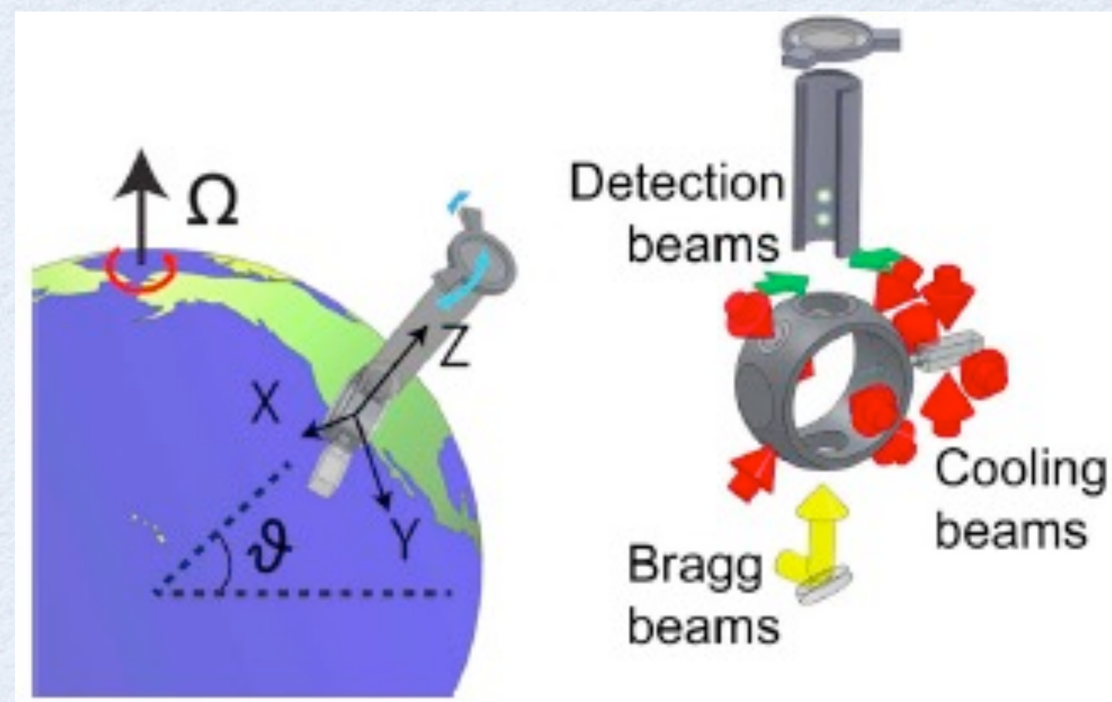


Coriolis compensation

- Tip-tilt mirror steering the retro-reflected Raman beam to compensate for the Earth rotation
- Already shown to improve contrast in AI with LMT beam splitters
- In MAGIA, contrast drop due to Coriolis is minimal, but still detectable thanks to the large SNR
- Besides ellipse contrast, Coriolis acceleration affects AI noise as well because of dispersion of atomic transverse velocities

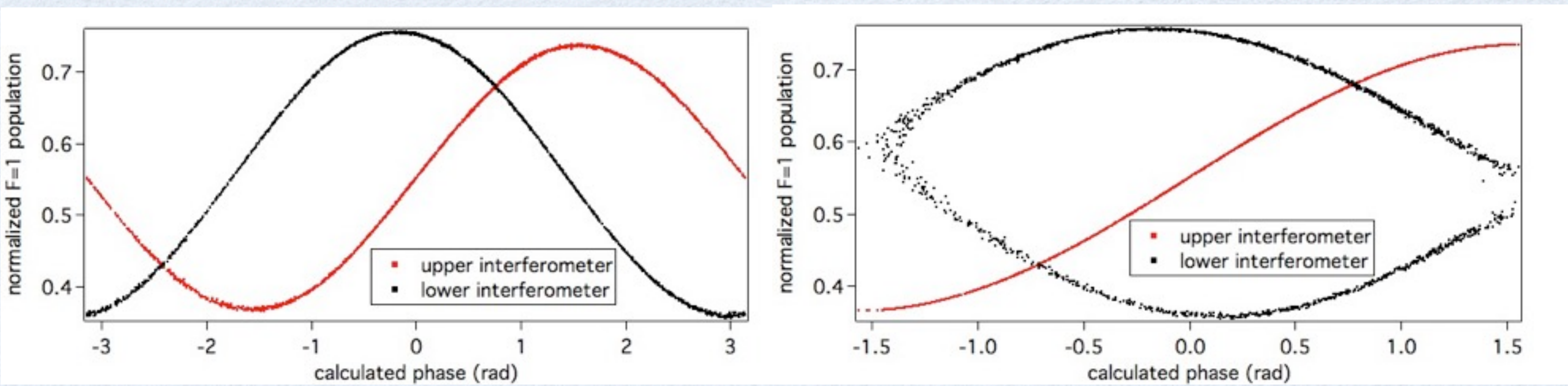


J. M. Hogan et al., Proc. intern. school of physics Enrico Fermi CLXVIII, 411 (2007)
S.-Y. Lan et al., PRL **108**, 090402 (2012)



g measurement with two clouds

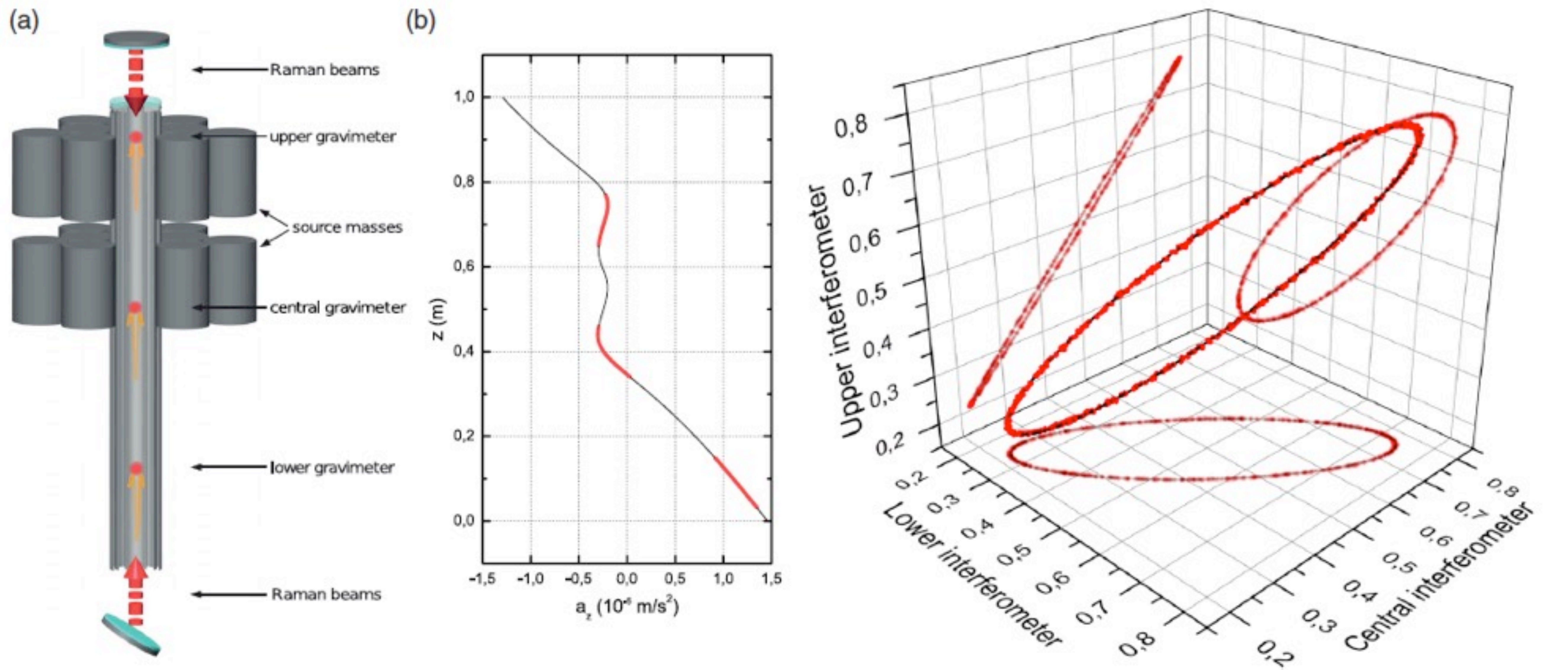
- Using a dual-cloud Raman interferometer for g measurements
- Simultaneous interferometers allow g measurements in the presence of larger phase noise because of
  - twice larger range for phase retrieval
  - suppressed conversion of amplitude noise into phase noise at the edges of the fringe



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

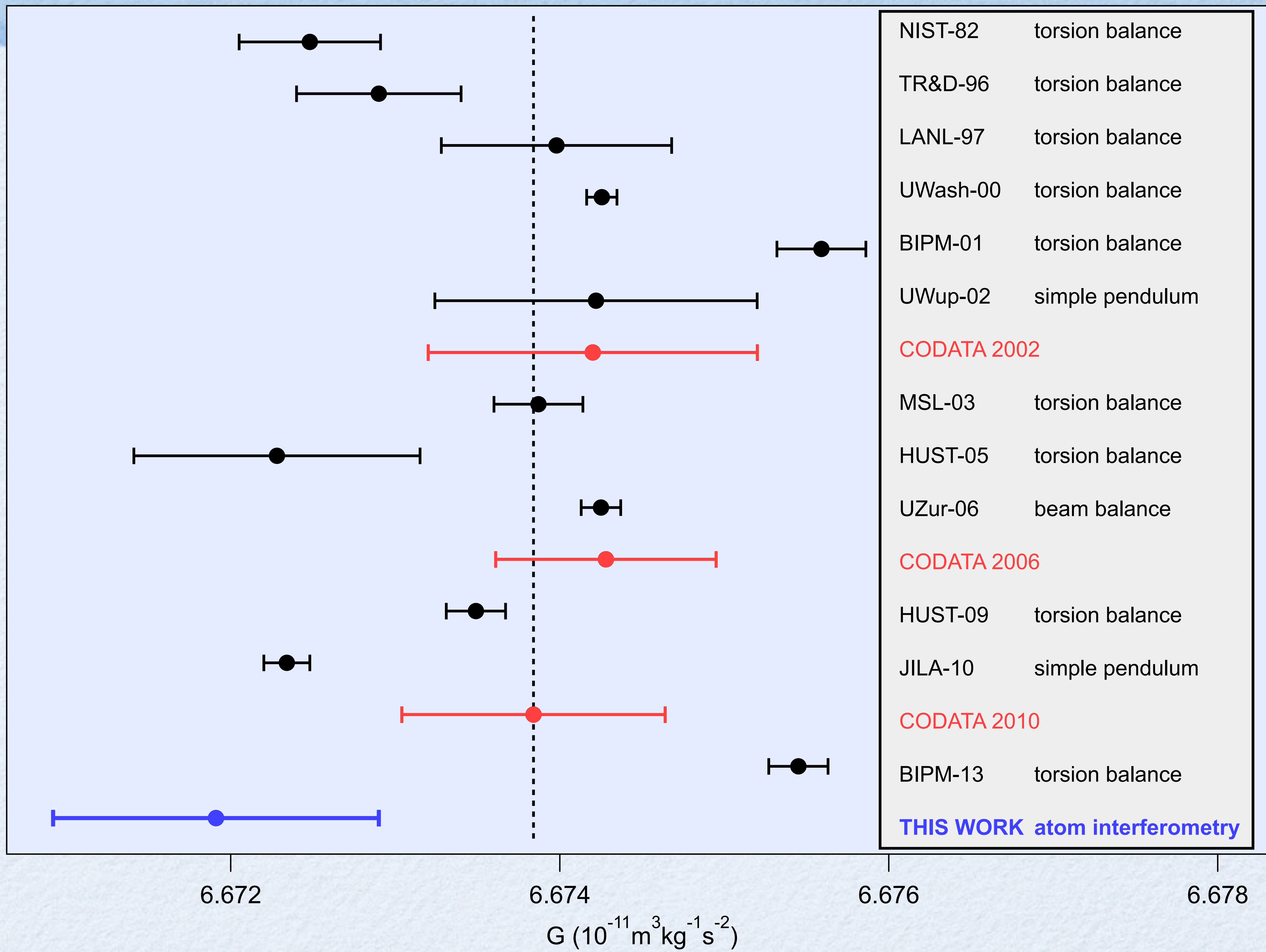
Somewhat similar to using a mechanical accelerometer to correct the phase shift from seismic noise, see J. Le Gouët et al., Appl. Phys B **92**, 133 (2008)

Higher order gravity spatial derivatives



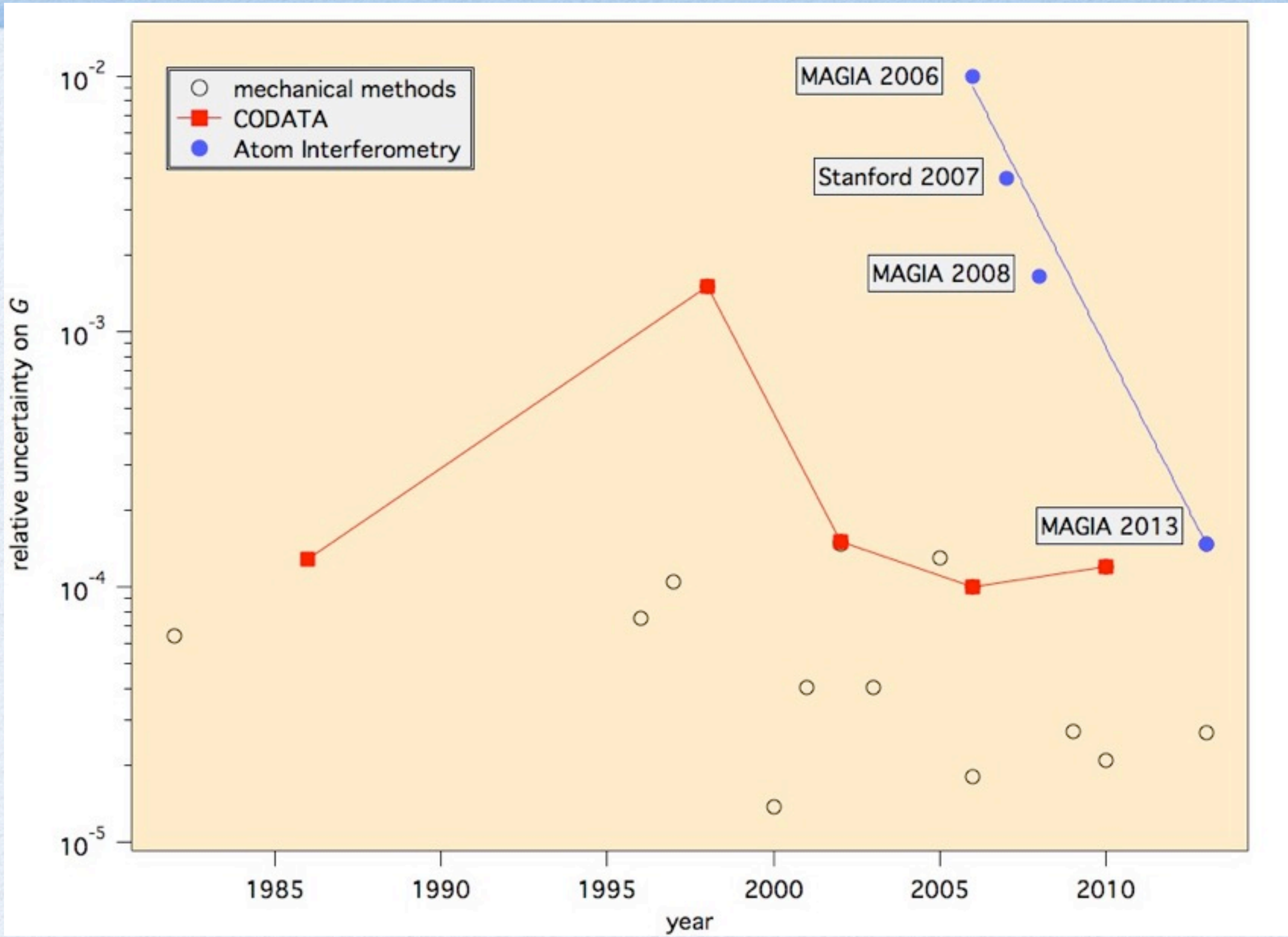
- Use three atomic clouds to measure the vertical derivative of vertical gravity gradient
- Sensitivity ~3×10^{-8} s^{-2} m^{-1} after 1 hr integration time
- G. Rosi et al., PRL **114**, 013001 (2015)

G measurements: current status

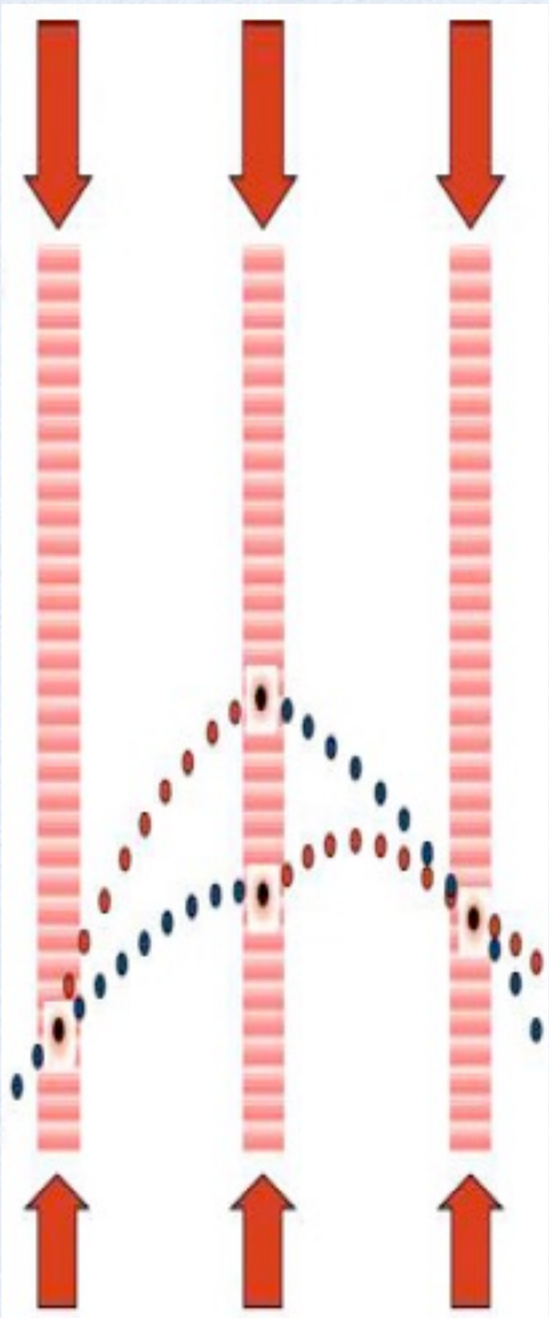


G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli and G. M. Tino, Nature **510**, 518 (2014)

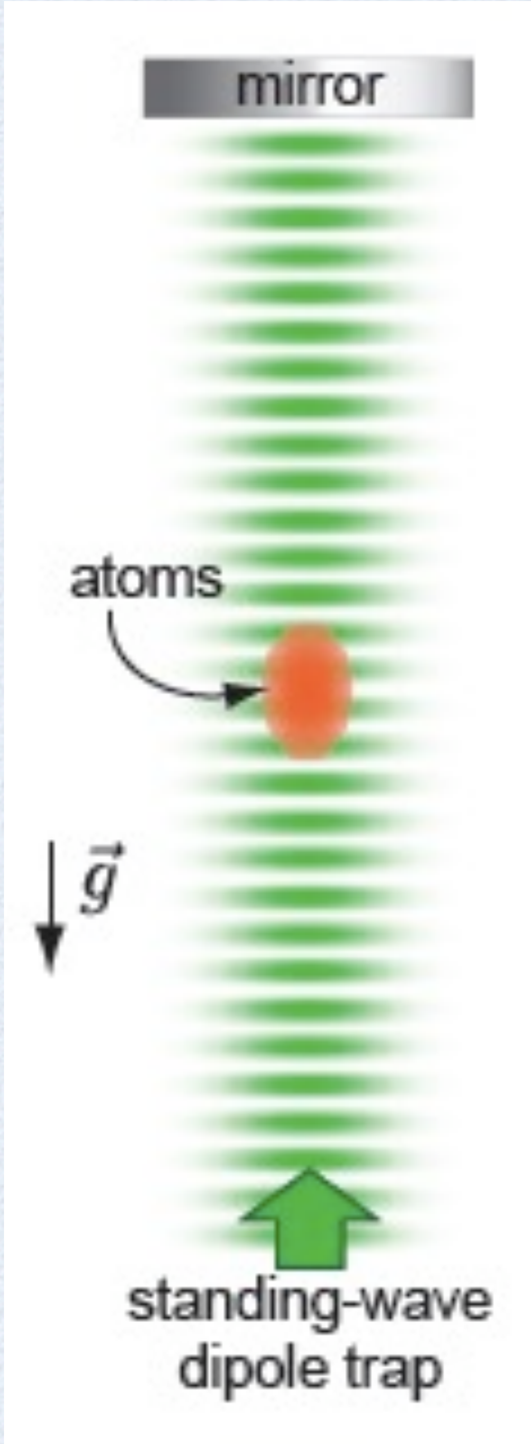
From proof of principle to G measure



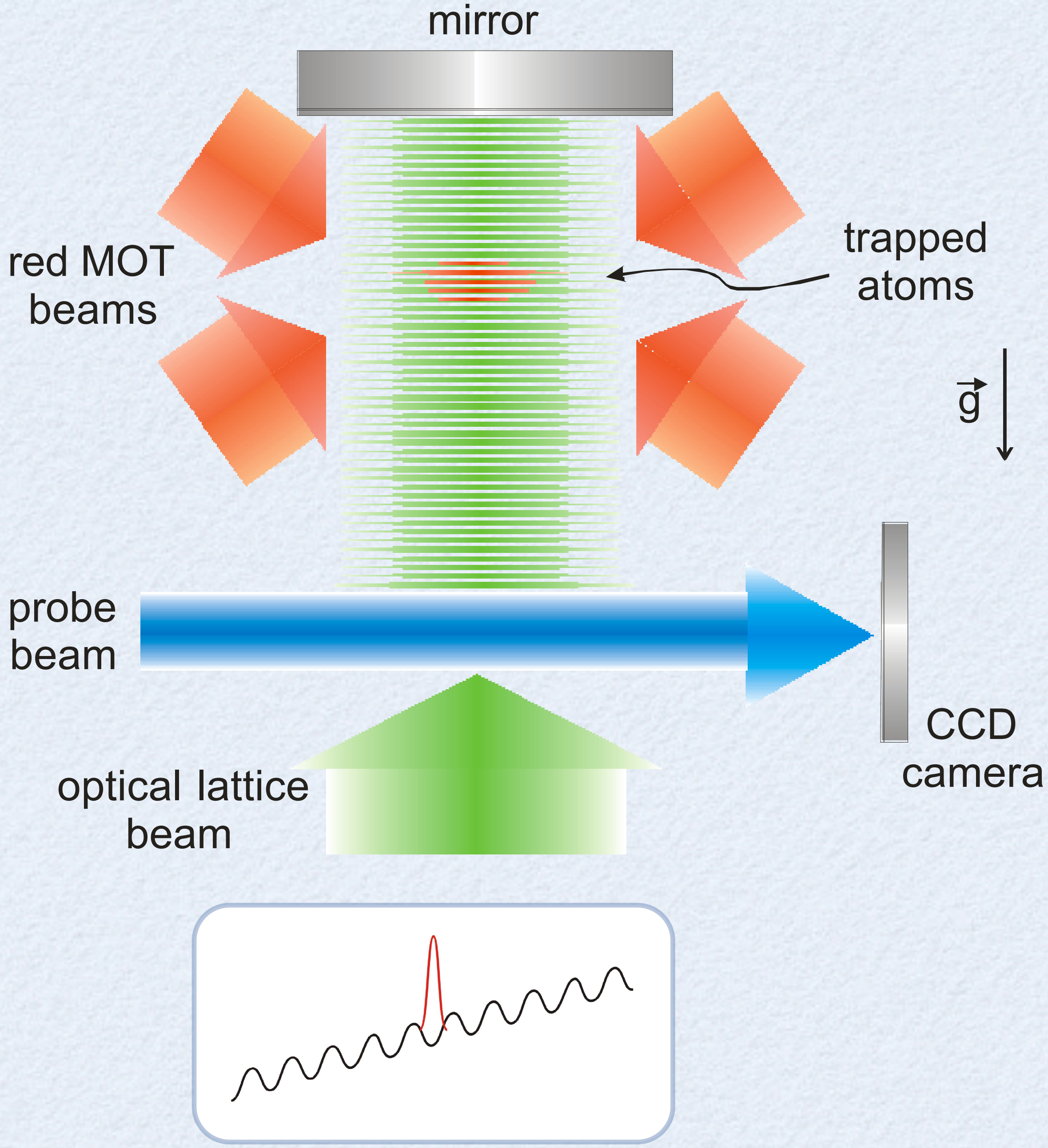
Freely falling vs trapped atoms

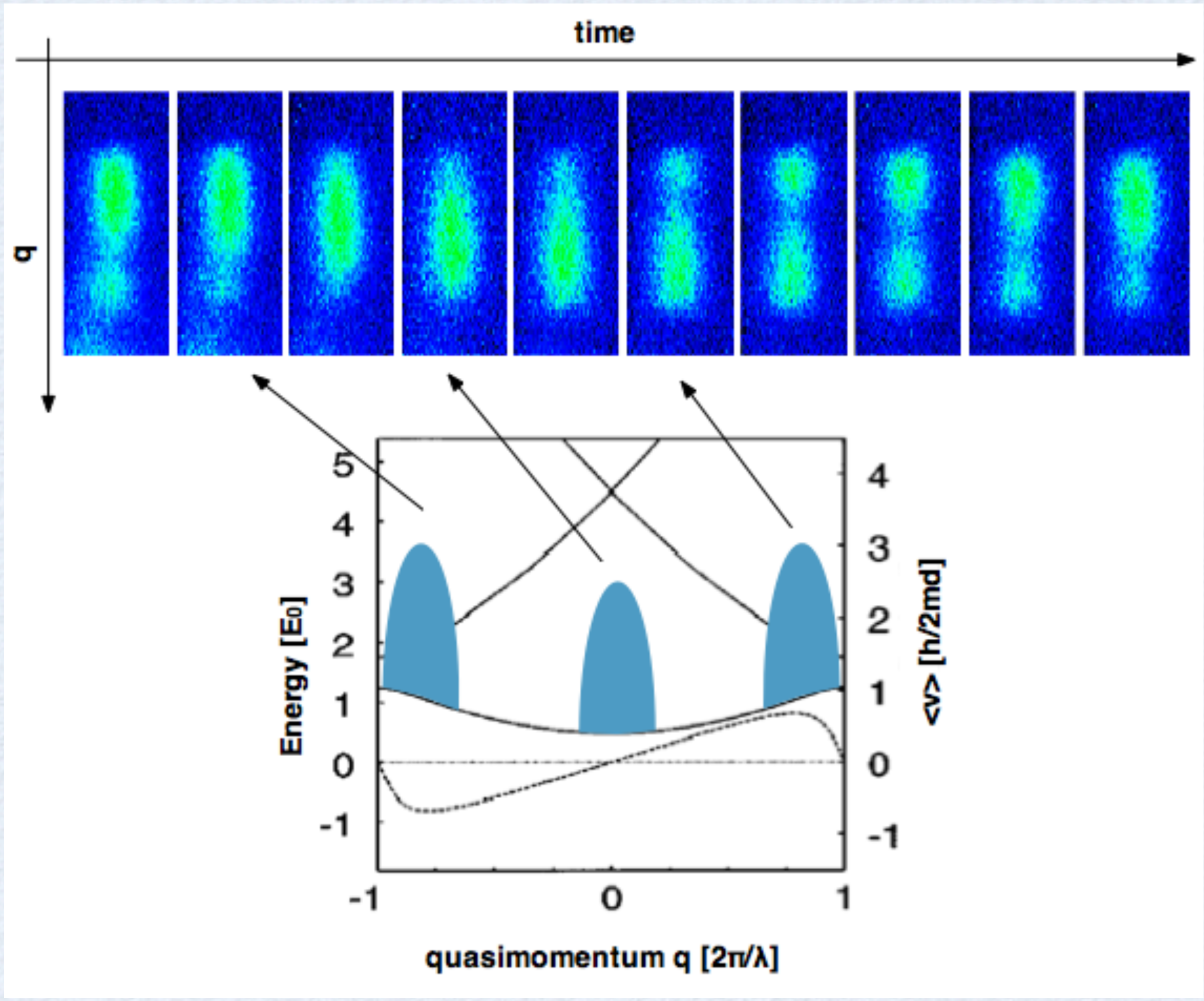


- Light-pulse (Raman or Bragg) atom interferometry
  - highest precision and highest accuracy so far demonstrated
  - atomic wave-function evolves in the absence of external fields
- AI in optical lattices
  - No free fall or free expansion
  - Small intrinsic size of the sensor
  - but... perturbation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



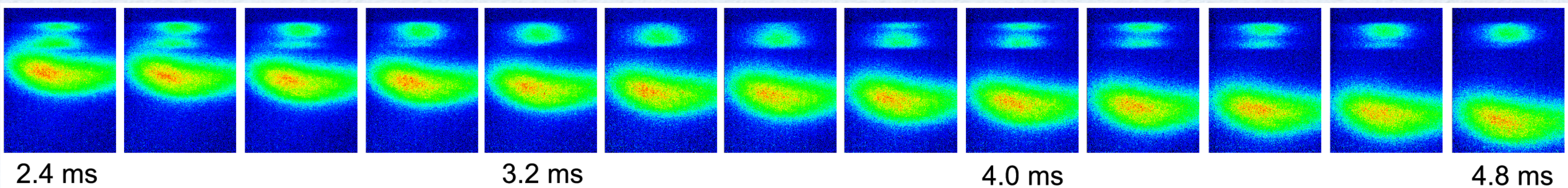
Bloch oscillations in optical lattice

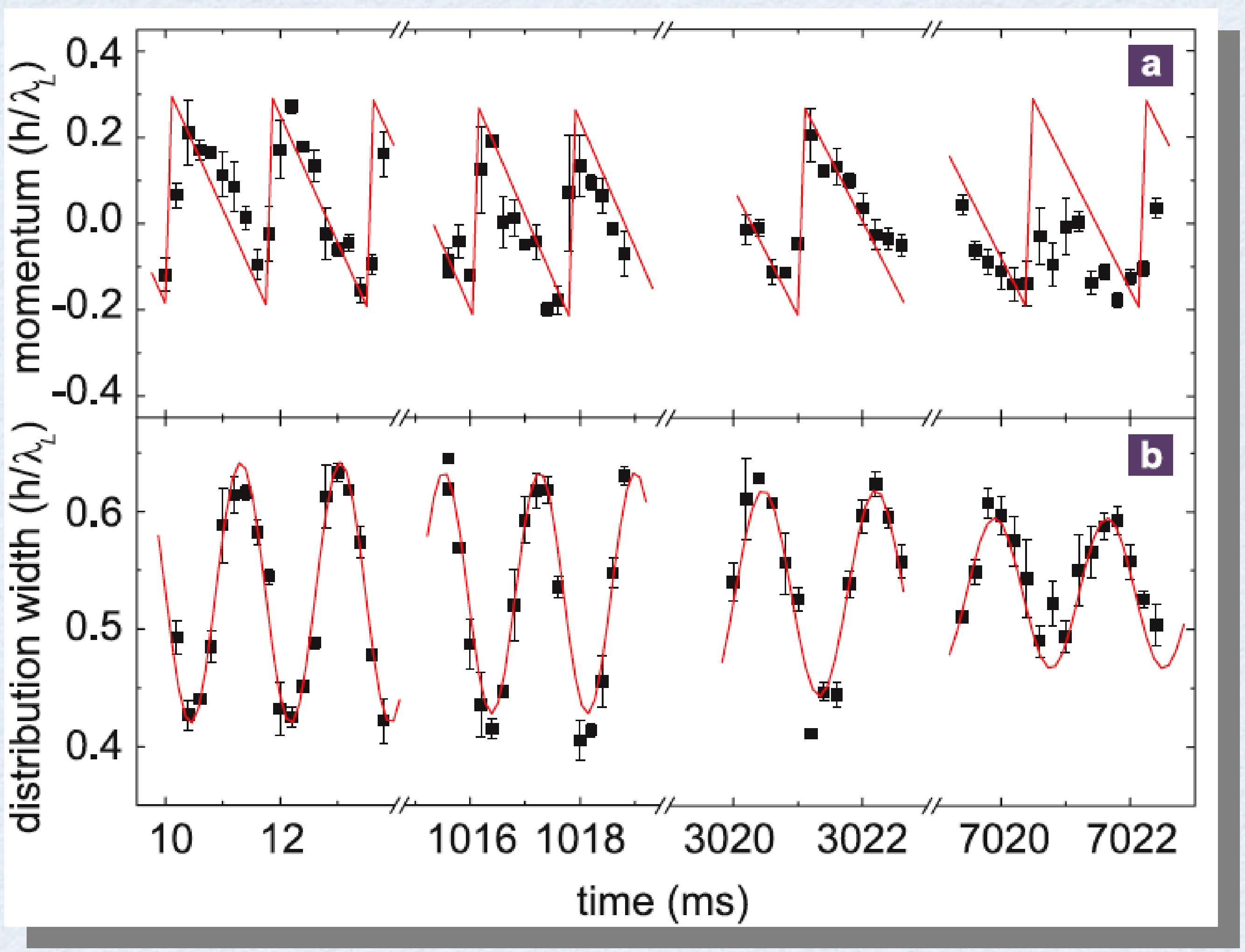




$$q(t) = q_0 + Ft/\hbar \quad \Rightarrow \quad \nu_B = \frac{F\lambda}{2h} = \frac{mg\lambda}{2h}$$

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

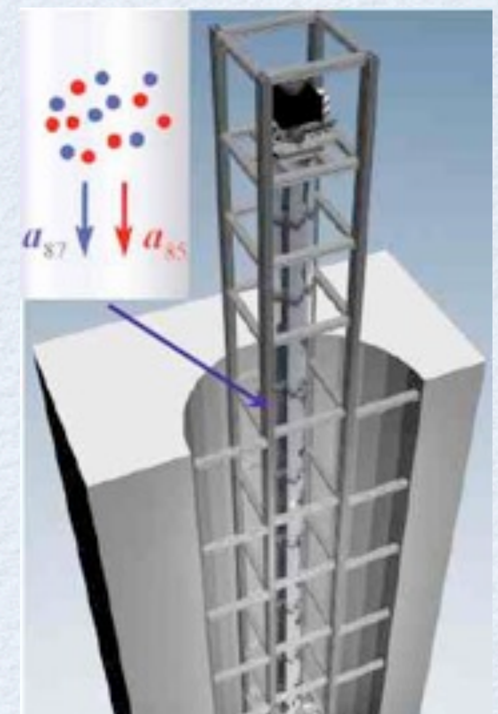
*M. Tarallo et al., PRA **86**, 033615 (2012)*

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

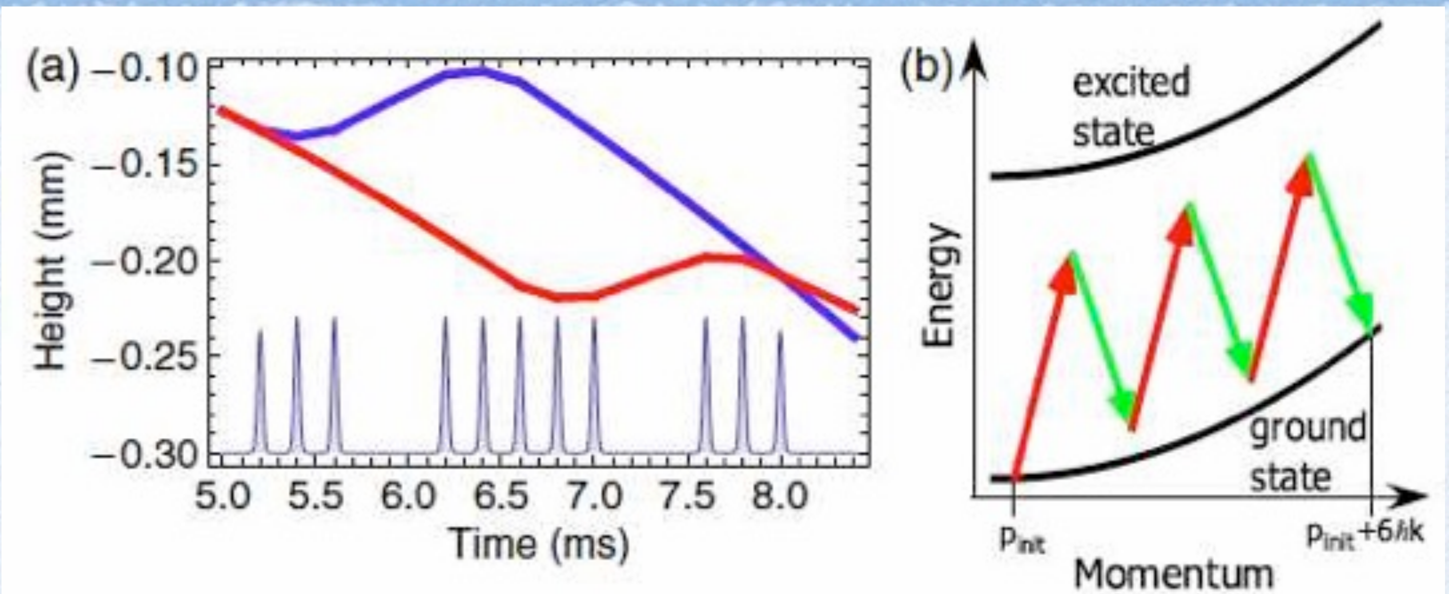
*H. Mueller et al., PRL **102**, 240403 (2009)*

Future of AI inertial sensors

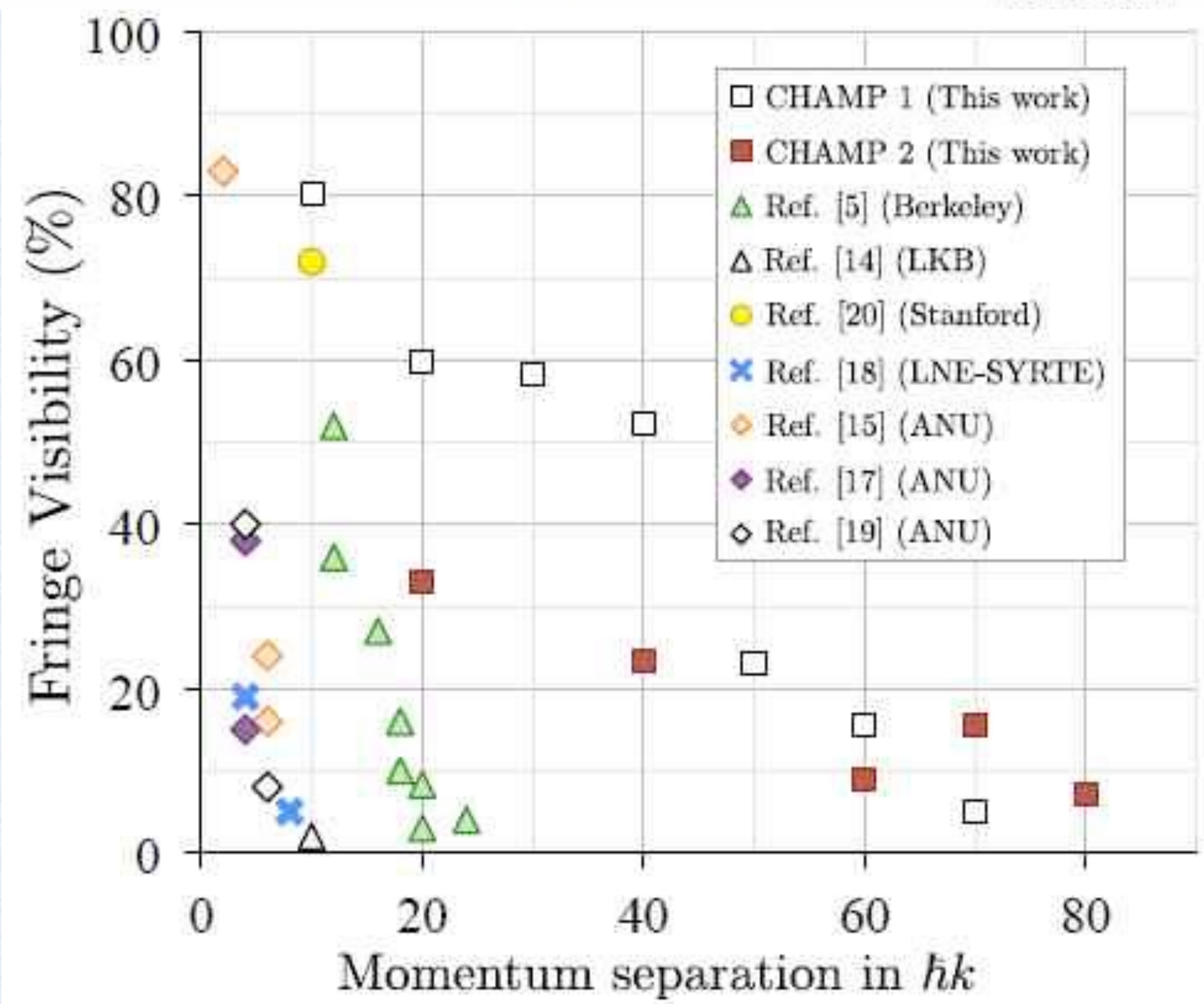
- Compact and transportable system without performance degradation
  - ground applications (geophysics)
  - space applications (satellite geodesy, inertial navigation, tests of fundamental physics)
- Novel schemes to improve sensitivity/accuracy
  - large-momentum-transfer (LMT) beam spitters
    - up to 100 hk demonstrated)
  - coherent/squeezed atomic states to surpass QPN detection
  - large size AI (some 10 m towers already developed)
- New applications
  - GW, quantum gravity, etc.



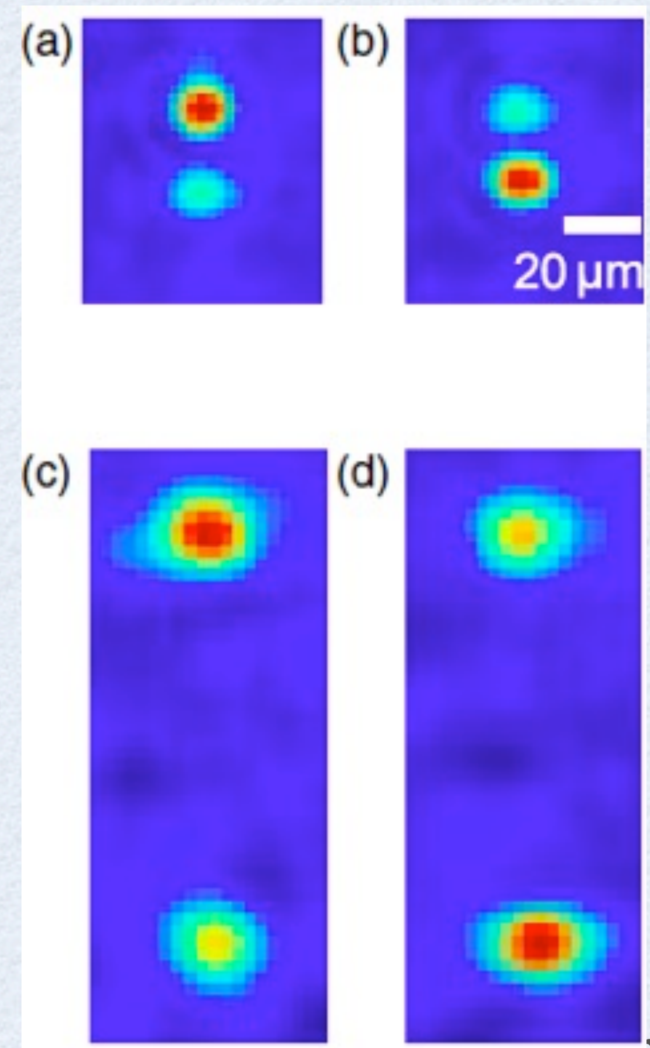
LMT beam splitters



- 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)

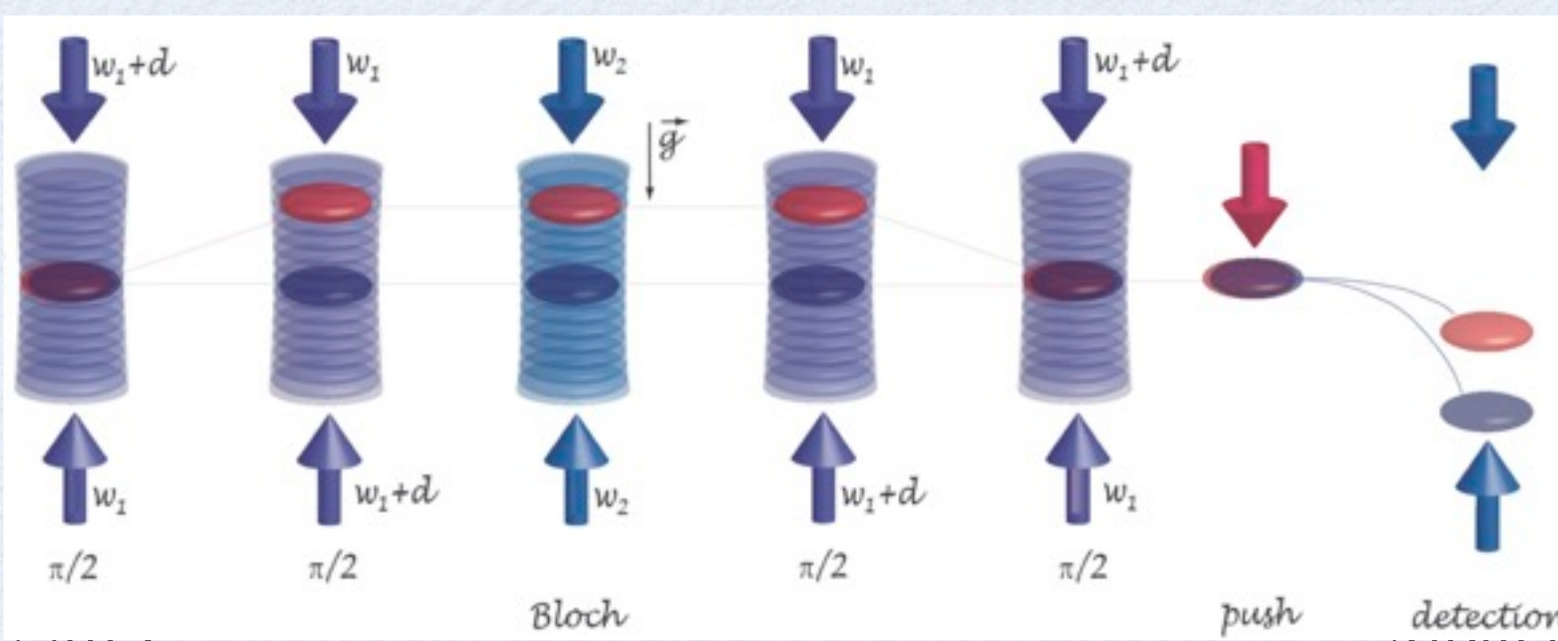


$$\Delta\phi = kgT^2$$

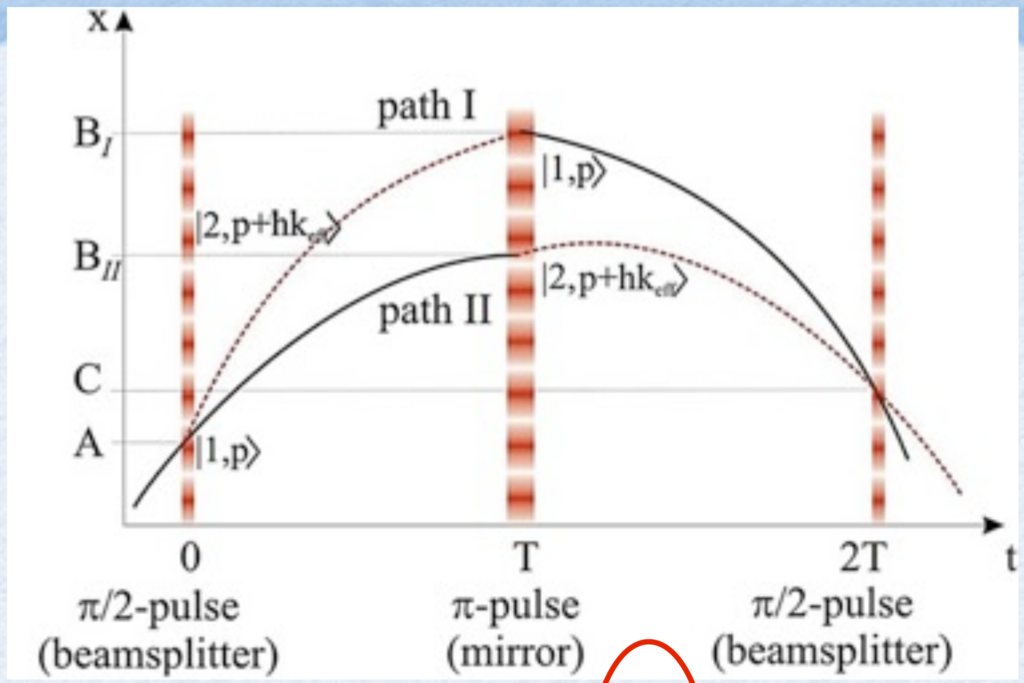


Possible scheme for MAGIA Advanced

- Combining the advantages of the two methods
  - free fall: large splitting -> large sensitivity
  - BO in optical lattice: small spatial scale & long coherent evolution
- Experimental sequence with
  - LMT splitter with *N* photon recoils and free fall for a time *t*
  - trapping in optical lattice and BO for time T
  - free fall for time *t* and recombination pulse with *N* photon recoils
  - already shown with Rb: R. Charrière et al., PRA **85**, 013639 (2012).
- Two configurations with increasing sensitivity
  - **MAGIA ADV 1**: t=0.2 s, T=0, N=20, sens. ~3×10^{-10} g/shot
  - **MAGIA ADV 2**: t=10 ms, T=10 s, N=20, sens. ~10^{-11} g/shot



AI measurements in space

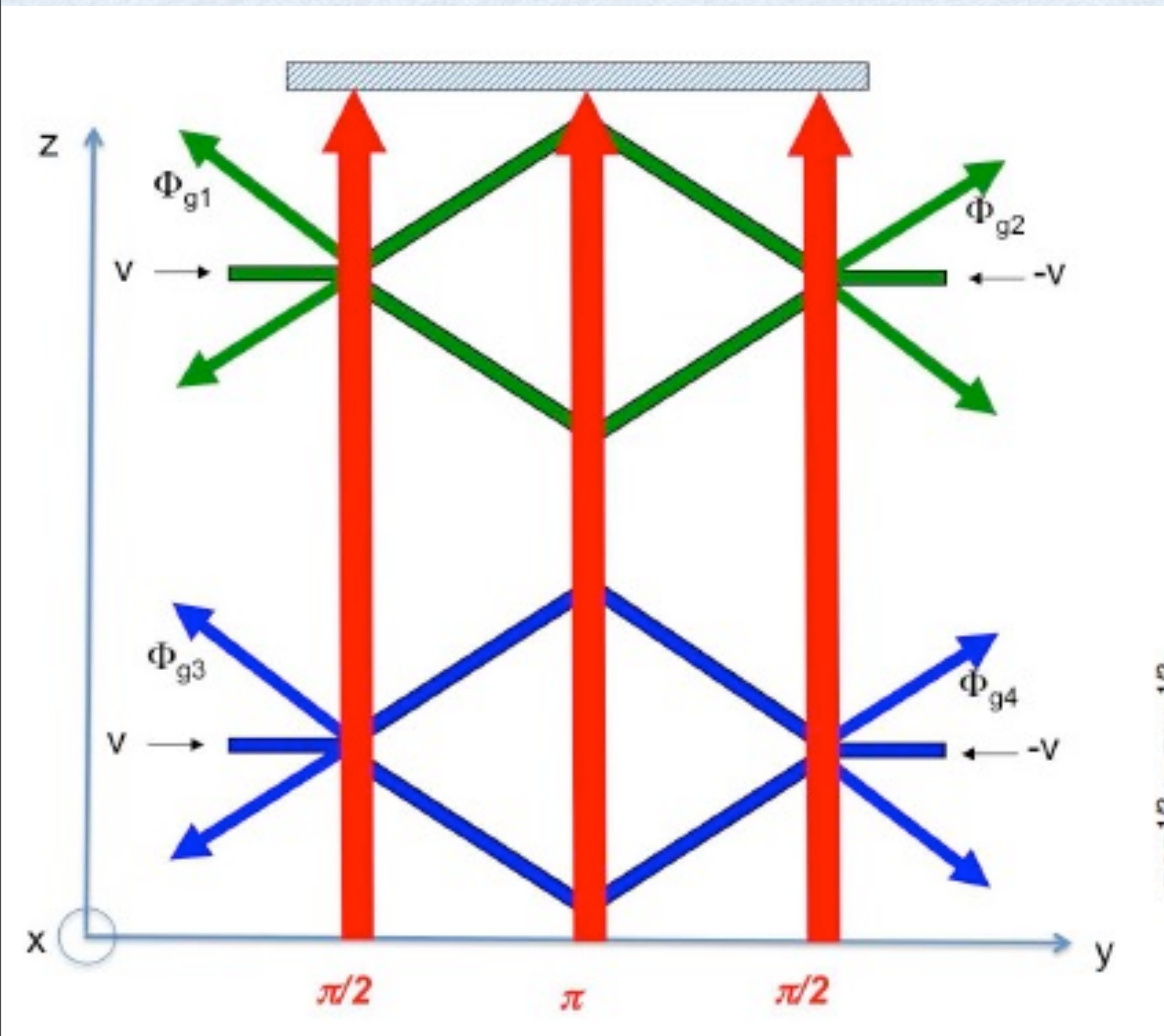


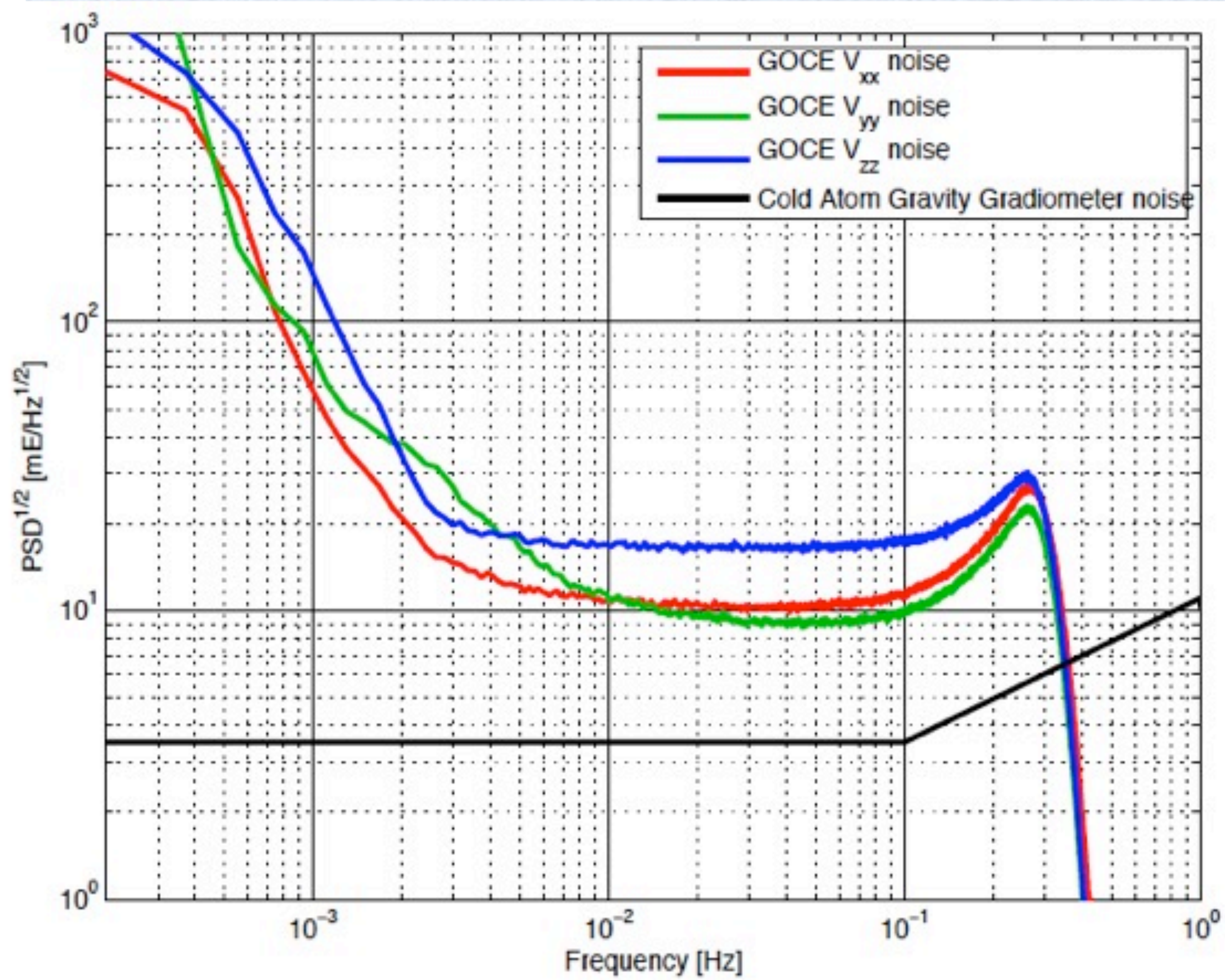
$$\Delta\phi = kgT^2$$

- 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)

AI for space gradiometry

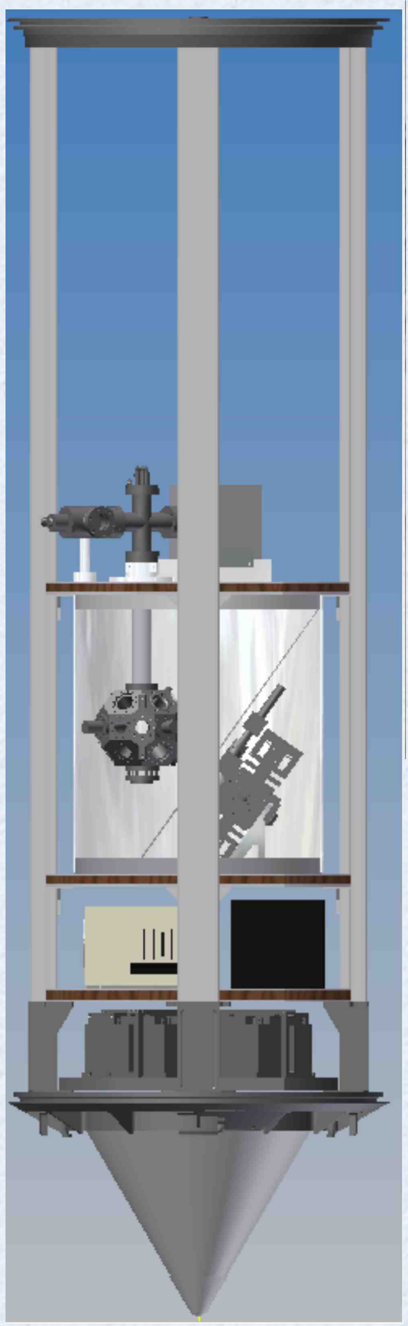


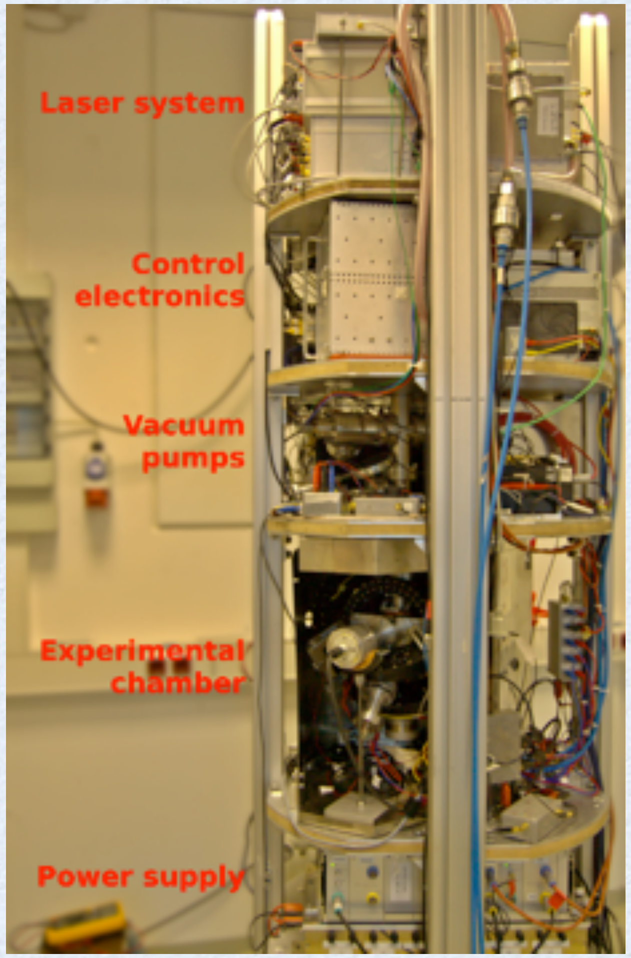


O. Carraz et al., arXiv:1406.0765 (2014)

TRL of AI: space research

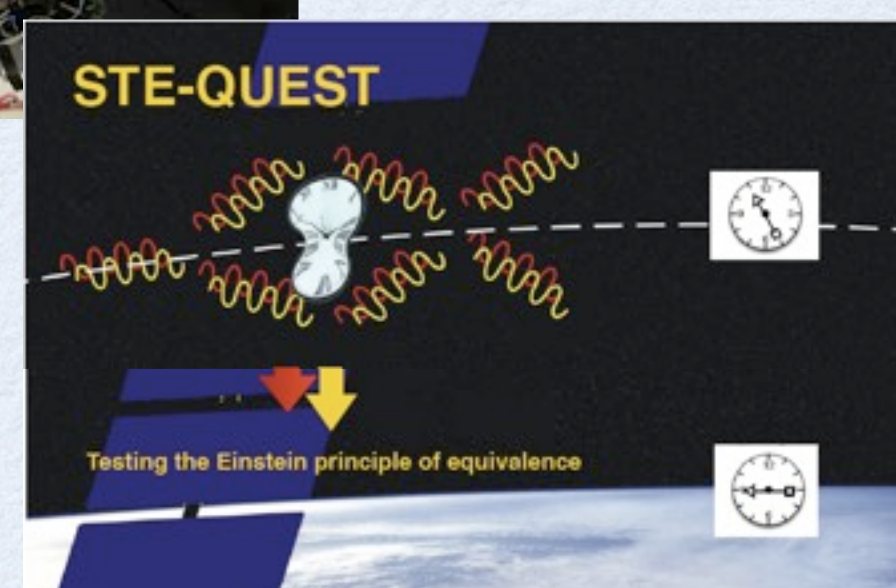
SAI





QUANTUS

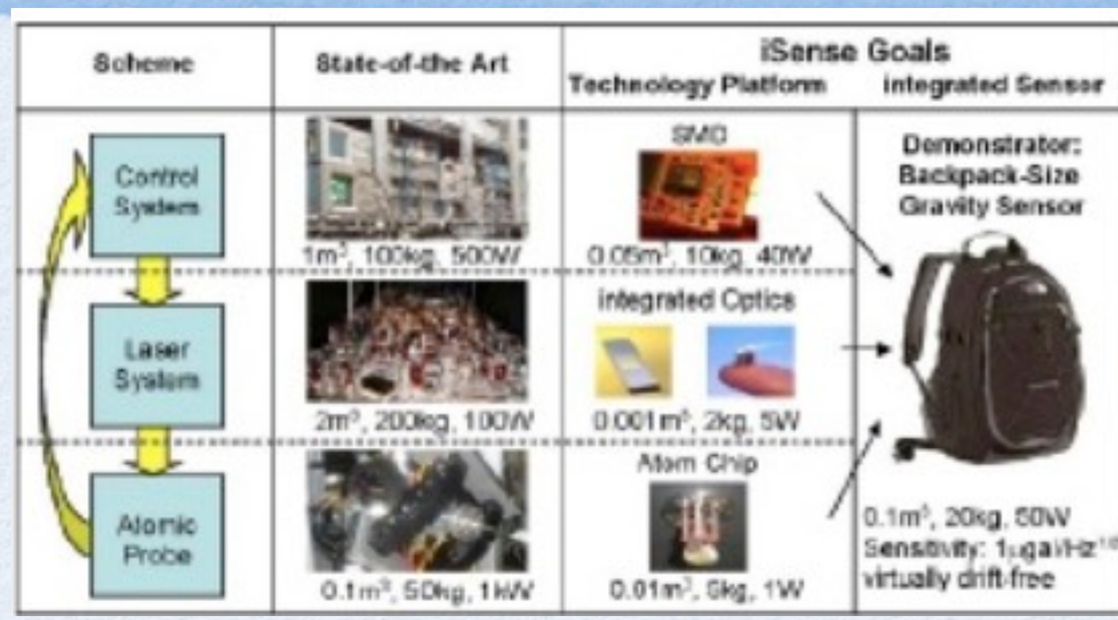
- ACES (atomic clock on the ISS)
- HYPER (test of Lense-Thirring effect)
- Q-WEP (testing WEP on ISS with AI using ^{87}Rb-^{85}Rb)
- STE-QUEST (atomic clock to measure red shift + AI to test WEP on dedicated satellite)
- QUANTUS (drop tower, DLR)
- I.C.E. (parabolic flights, CNES)



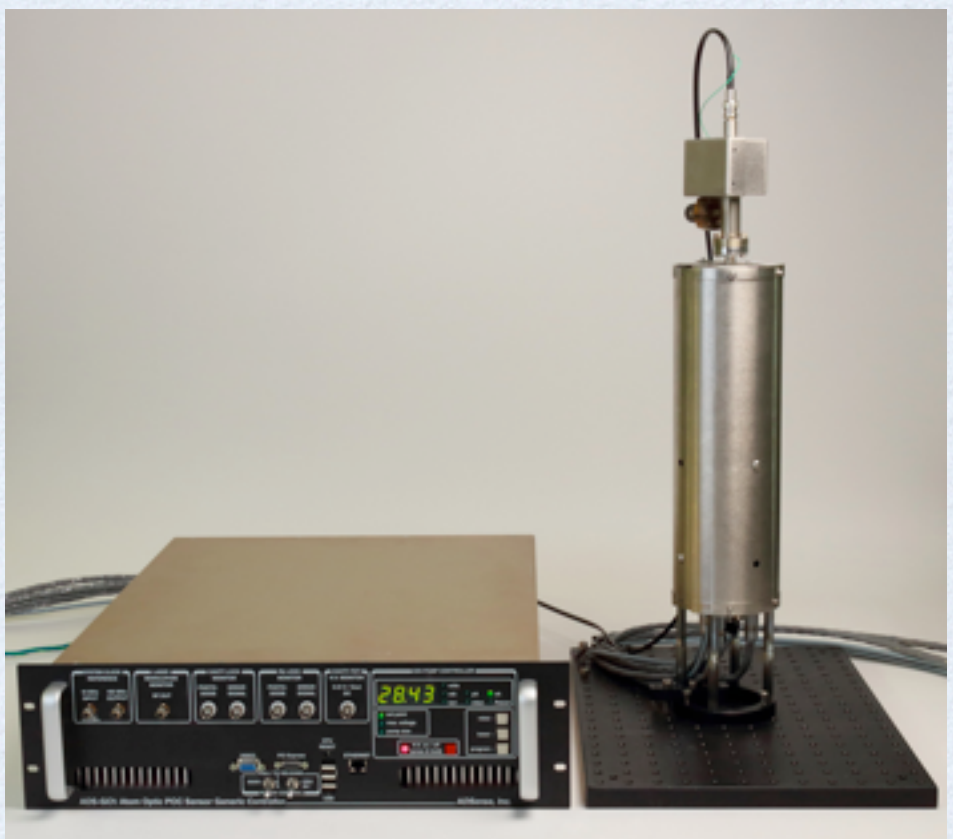
G. Tino et al., *Precision Gravity Tests with Atom Interferometry in Space*, Nuclear Physics B **243**, 203 (2013)

TRL: towards commercial AI instruments

iSENSE



μ-QUANS (SYRTE-CNRS)



AOSense (STANFORD)

AtomSensors (FIRENZE)

Conclusions

- AI gravity sensors: a young but promising science
  - excellent long-term performance
  - short term sensitivities in the μgal/√Hz and E/√Hz range
- Successfully applied to several fields
  - fundamental constants
  - inertial measurements
  - metrology (Watt balance)
  - WEP test
- More proposed and forthcoming applications
  - fundamental physics (short-range forces, atom neutrality, GW, etc.)
  - technology (inertial navigation, gravitational imaging)
  - geophysics
- Well developed laboratory prototypes, first transportable devices, work in progress for space-compatible systems
- Large room for improvements, expected in next future
  - improved TRL for mobile (ground and space) applications
  - advanced atom optics (LMT splitters, large-scale, cavity QED, etc.)