# Atom interferometry sensors

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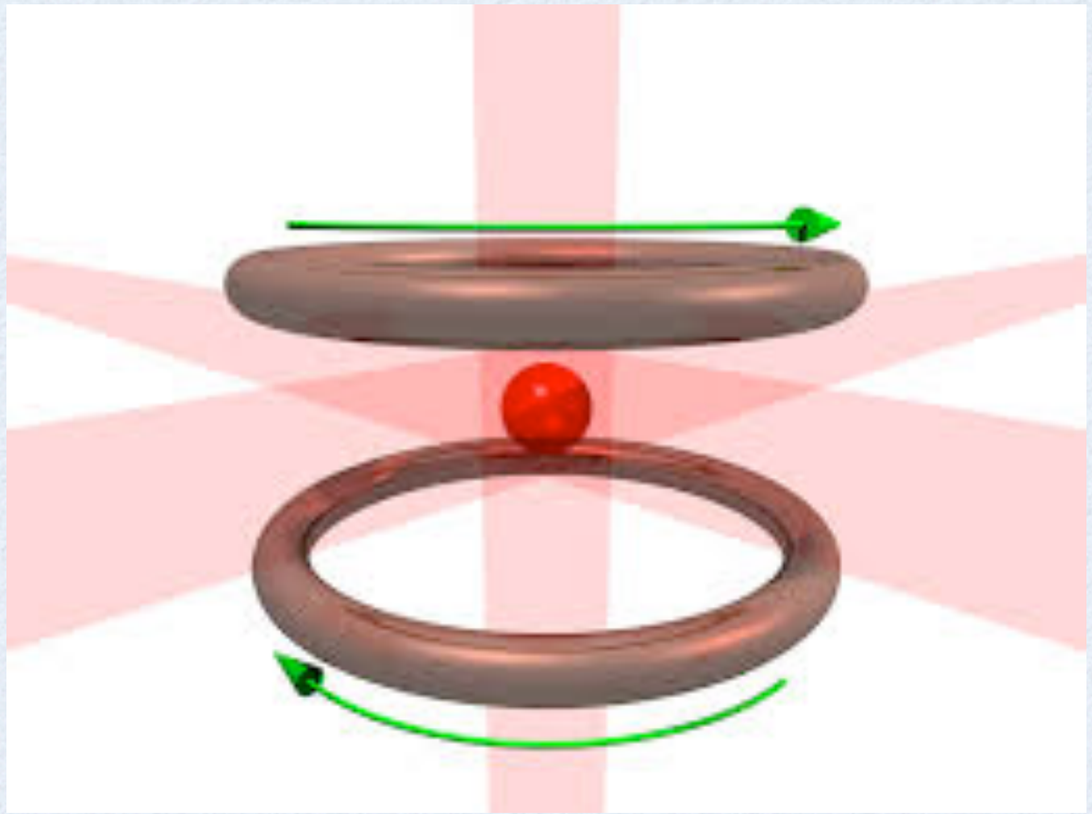
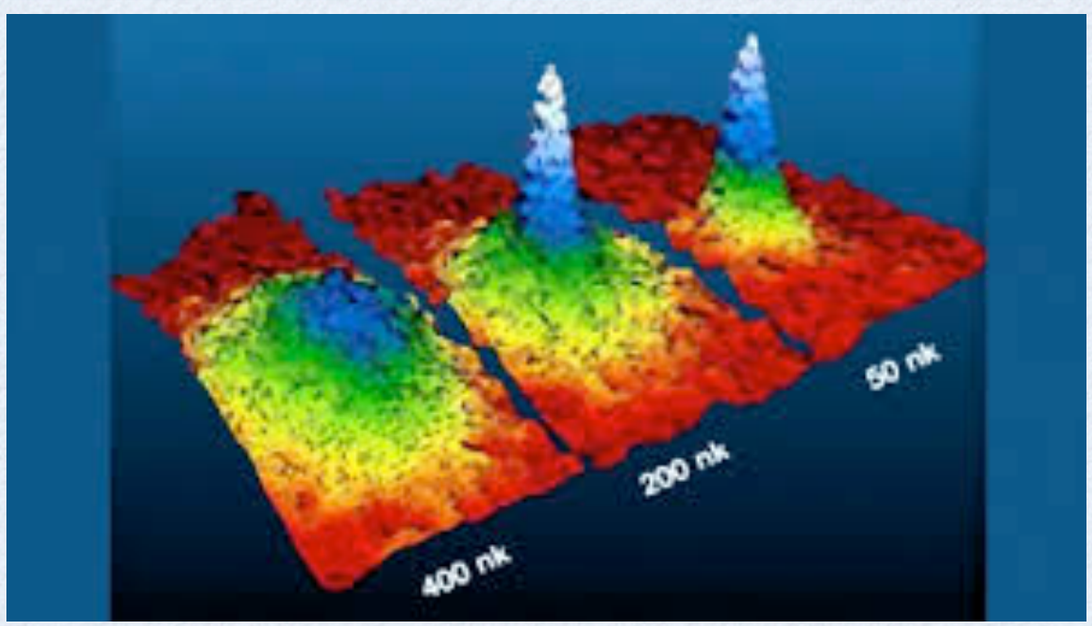
# Outline

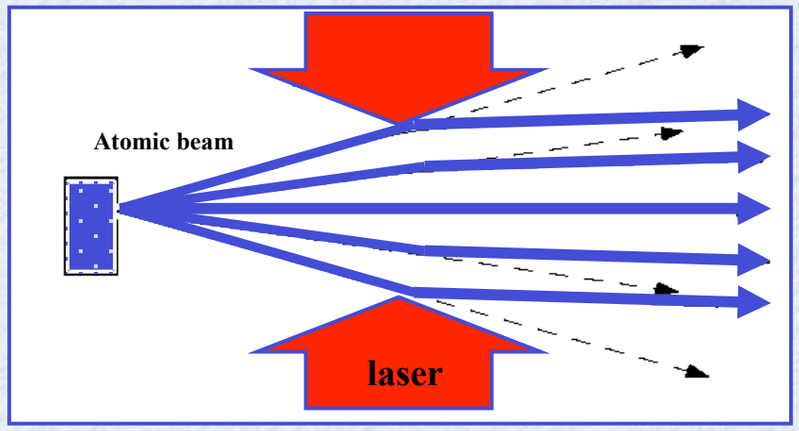
- Introduction to quantum sensors
  - atom optics and ultracold atoms
  - atom interferometers
- Precision measurements with quantum sensors
  - inertial sensing and geophysical applications
  - fundamental constants: $G$ and recoil measurements
  - tests of fundamental physics (GR, quantum gravity)
  - other applications
- Future prospects
  - advanced atom interferometers
  - future space experiments

# Ultracold atoms and atom optics

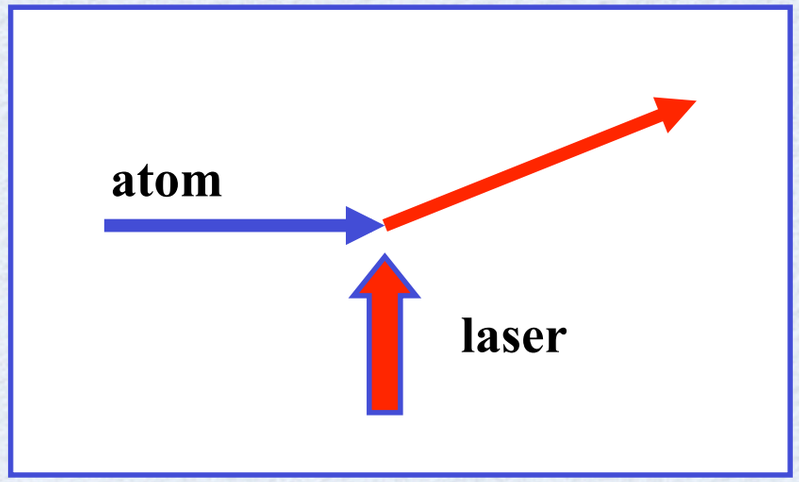




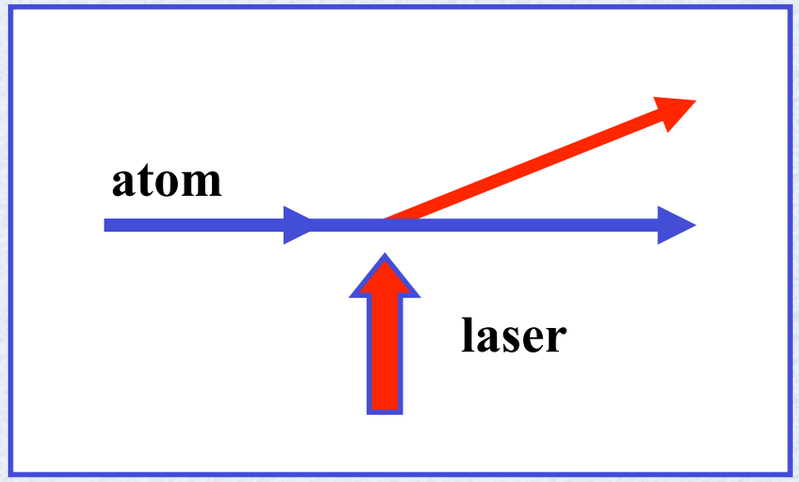

Lenses




Mirrors

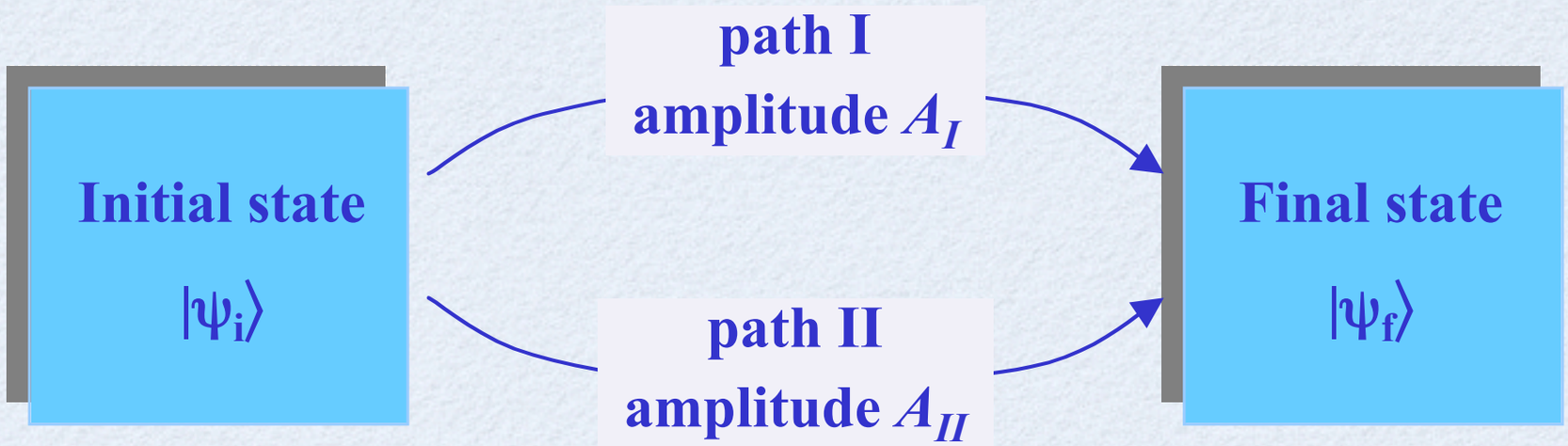



Beam splitters



# Matter-wave interferometry

*Quantum interference*



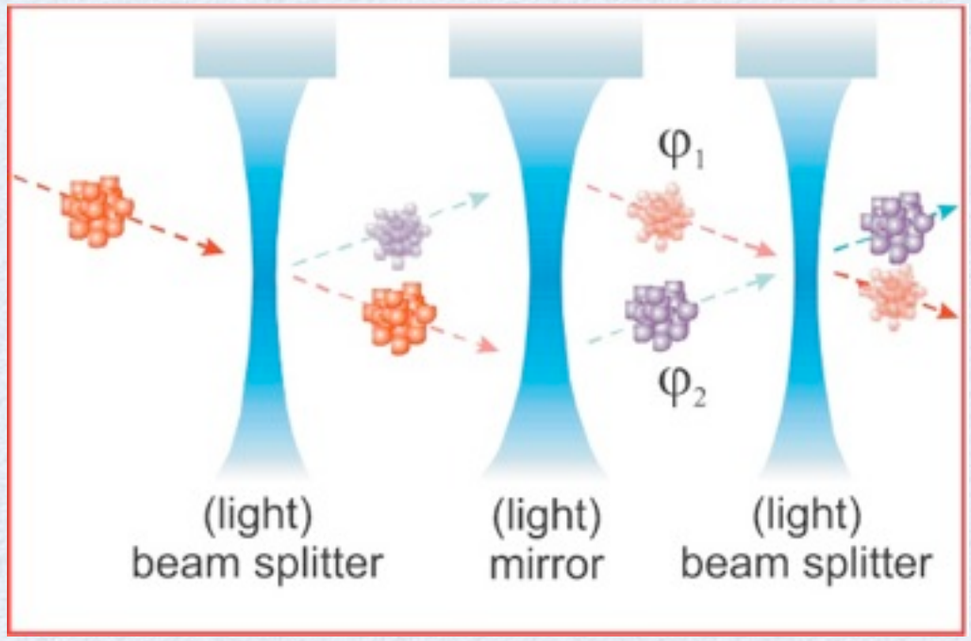

Interference of transition amplitudes

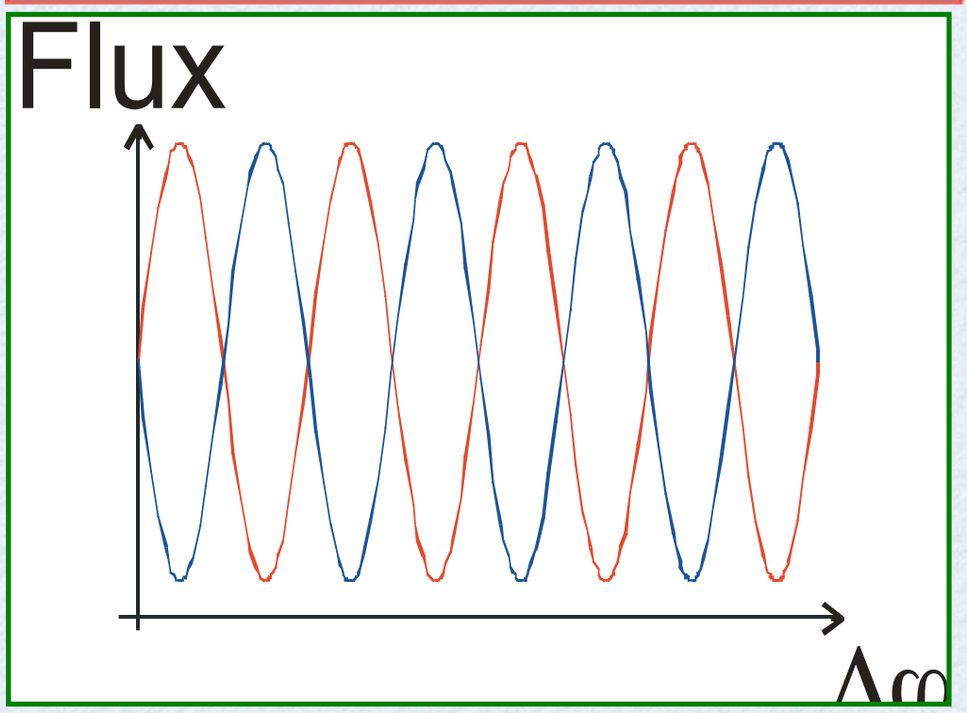
$$P(|\psi_i\rangle \rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2Re(A_I A_{II}^*)$$

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

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

# Atom interferometry




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

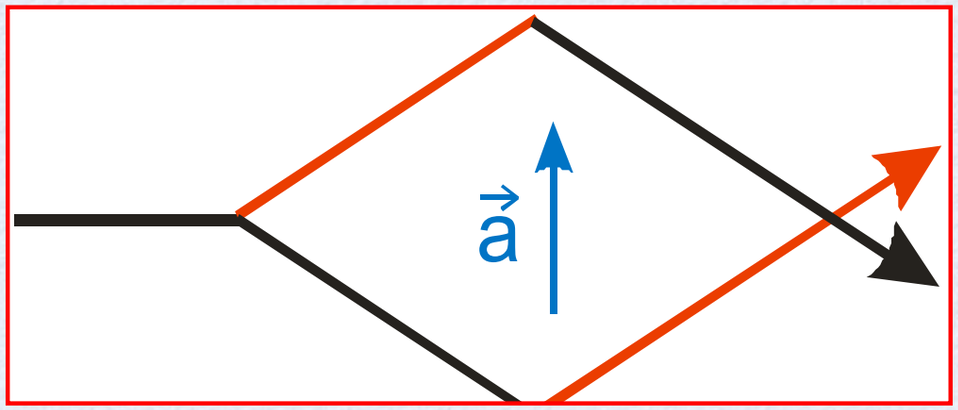
- atom optics
- different internal states / isotopes
- phase difference may depend on:
  - accelerations
  - rotations
  - photon recoil
  - laser phase
  - laser frequency detuning
  - electric / magnetic fields
  - interactions with atoms / molecules

# Possible applications of AI

- Already achieved:
  - inertial sensing (accelerations, gravity gradients, rotations)
  - measuring fundamental constants ($\alpha$, $G$)
- 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

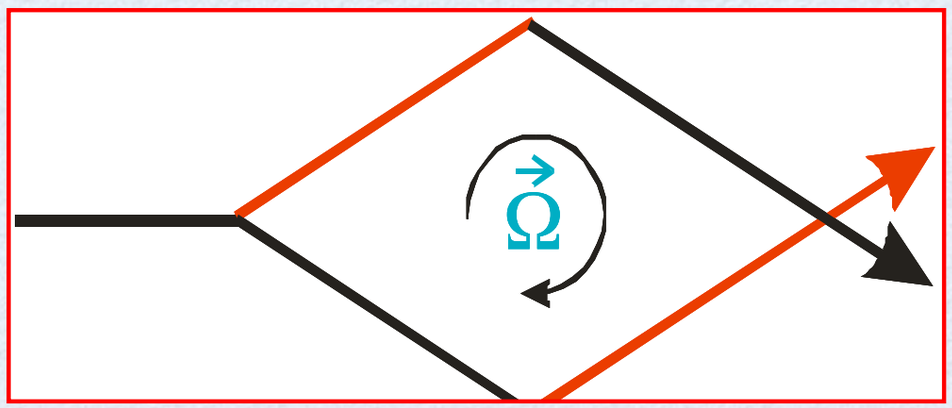
## Accelerations




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

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

## Rotations



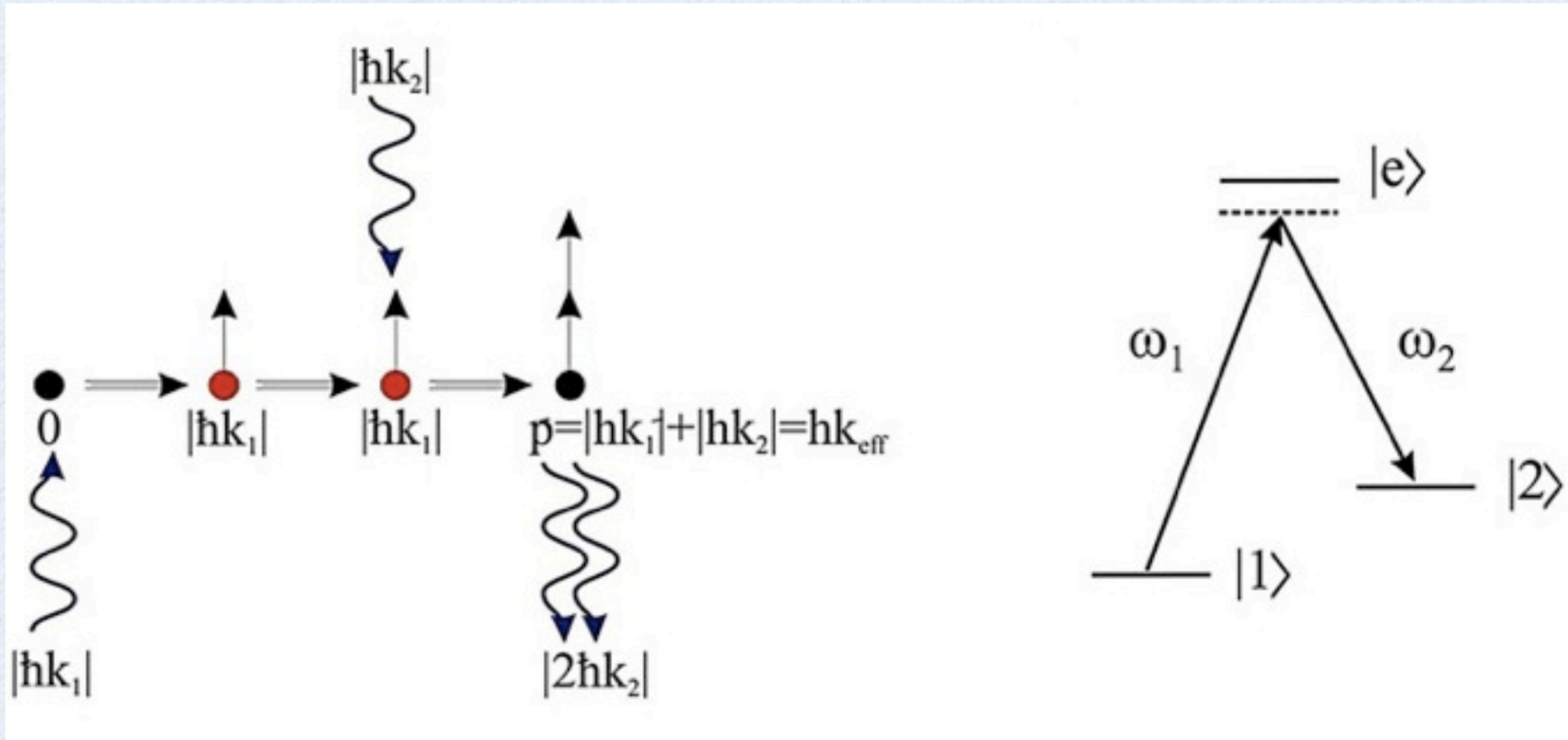

$$\Delta\Phi_{rot} = 2\pi \frac{2m_{at}}{h} A \cdot \Omega$$

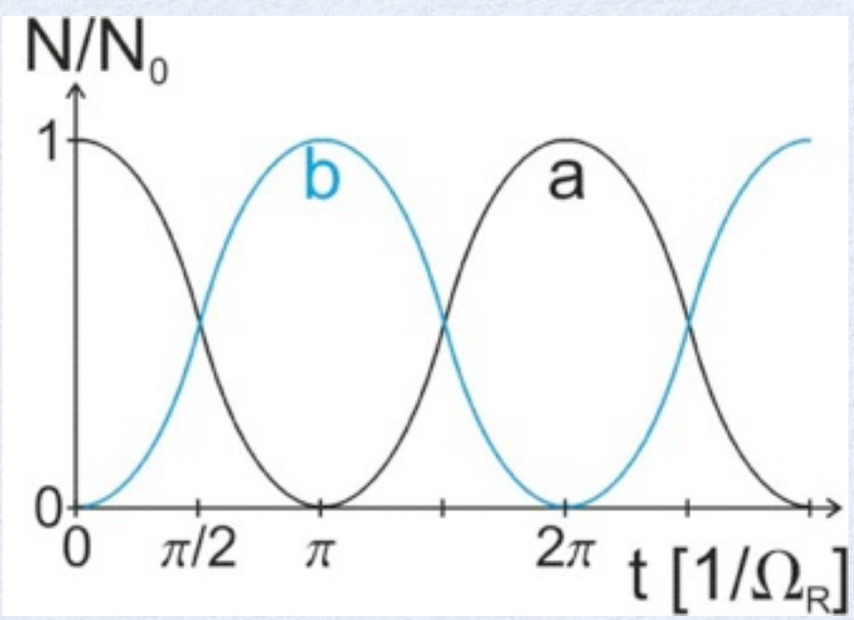
$$\frac{\Delta\phi_{mat}}{\Delta\phi_{ph}} \sim \frac{m_{at}\lambda c}{h} \approx 5 \cdot 10^{11}$$

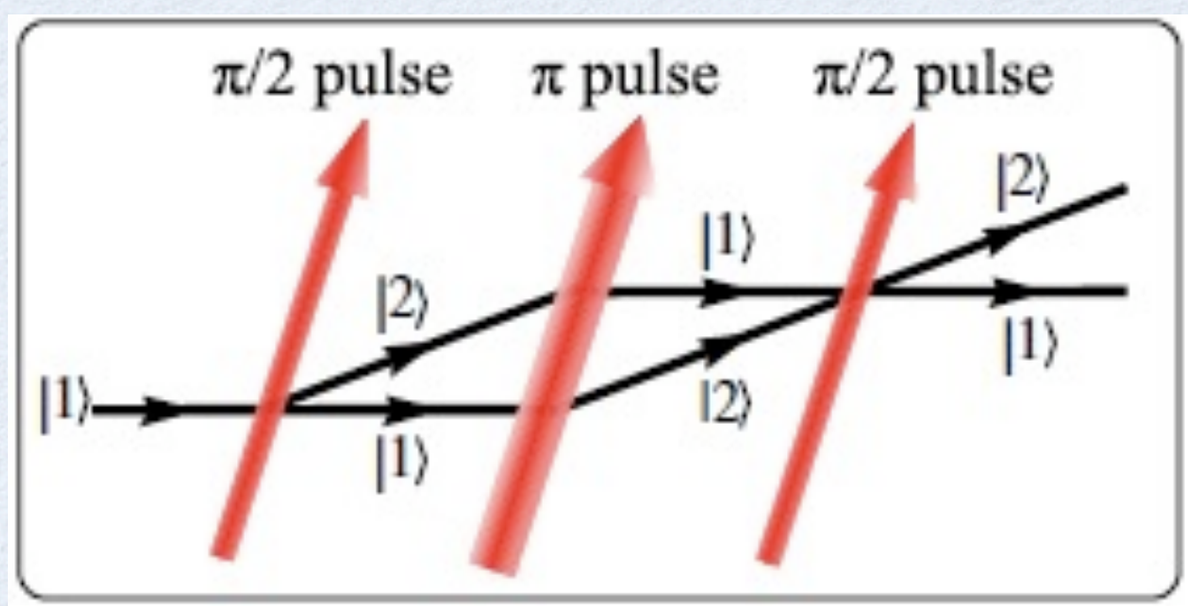
# Present limitations of AI

- 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, $\mu$-gravity, ultracold atoms

# Raman pulse atom interferometer



# Light-pulse AI inertial sensors

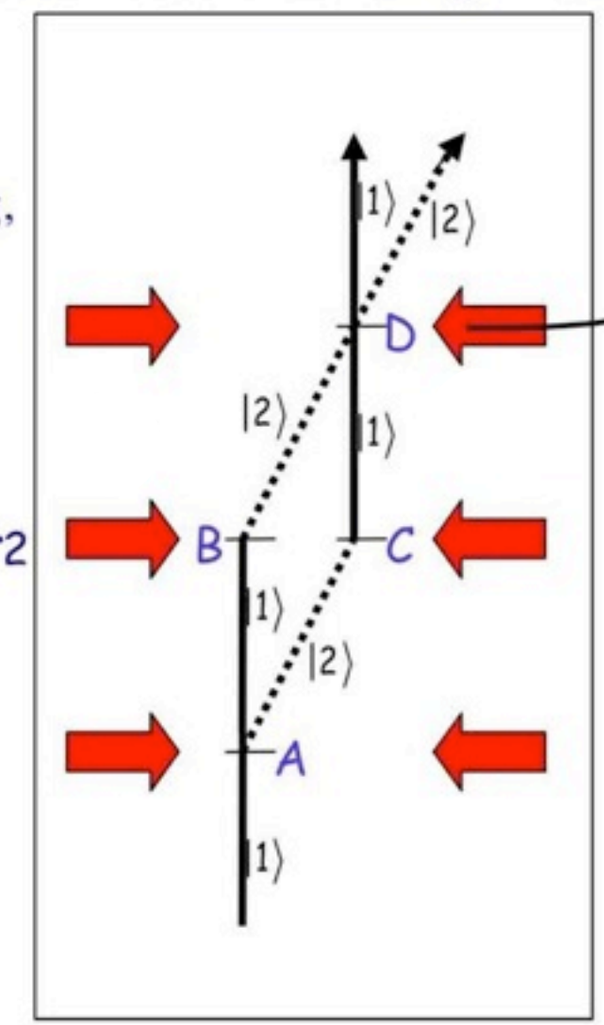
TRANSVERSAL PULSES
-the interferometer encloses an area
-used to measure rotations (GYROSCOPES)

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

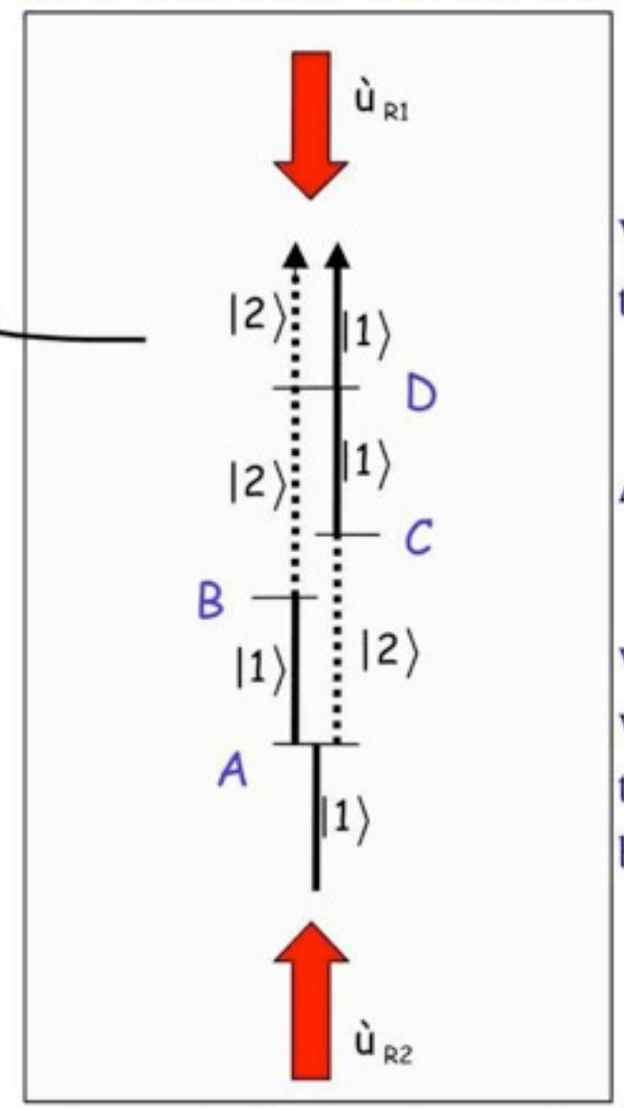
With an acceleration g, the phase difference

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

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




Fringes detected

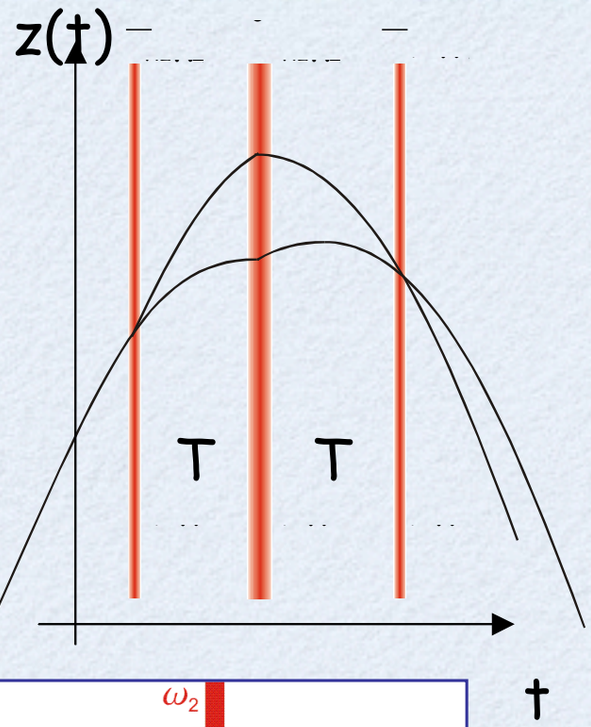



With an acceleration g, the phase difference

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

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

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



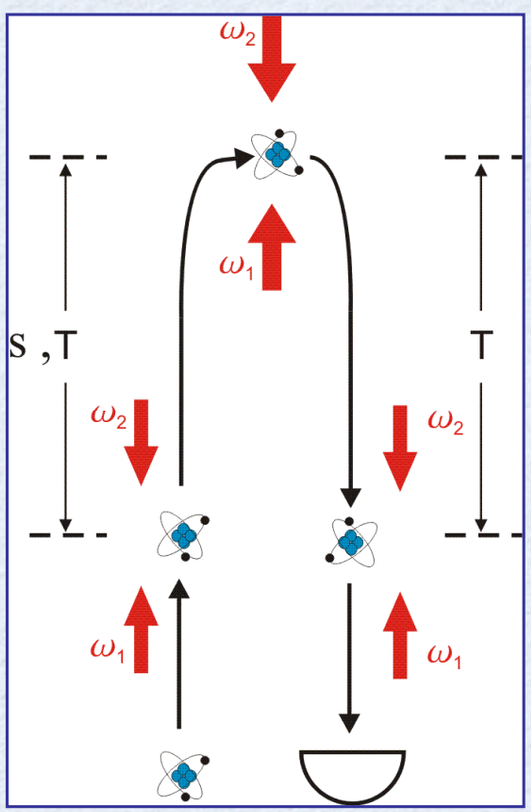

Phase difference between the paths:

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

$k_e = k_1 - k_2$

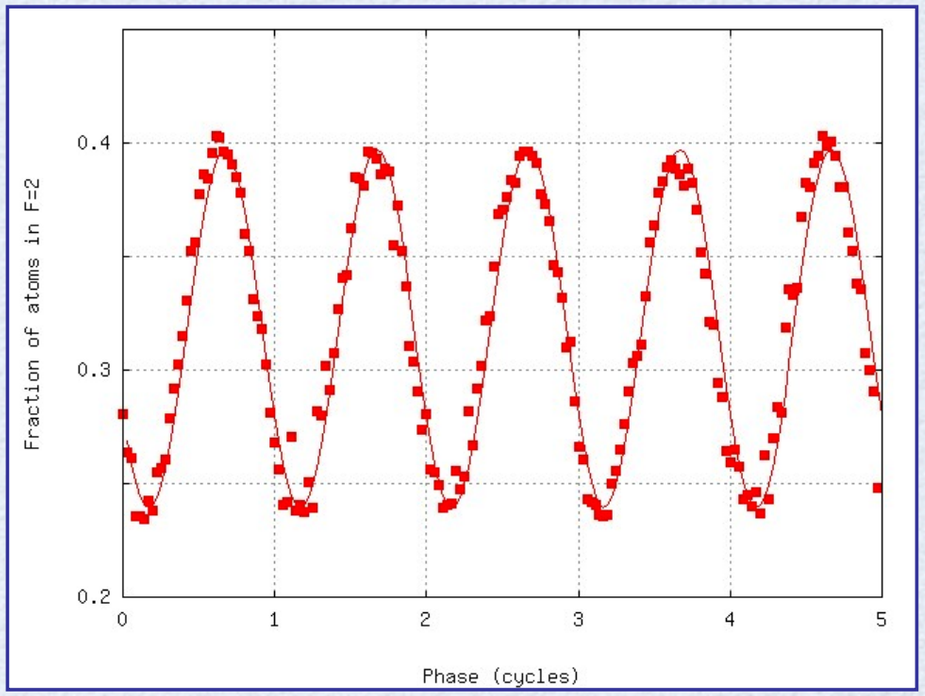
with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

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




Final population:

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

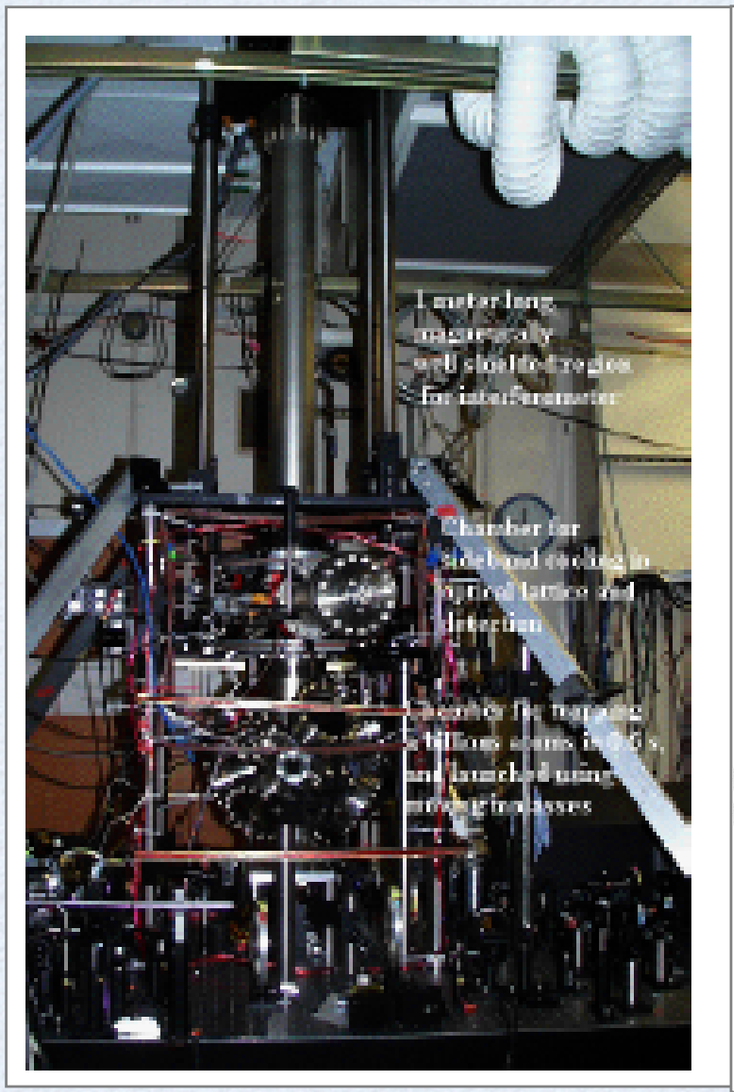


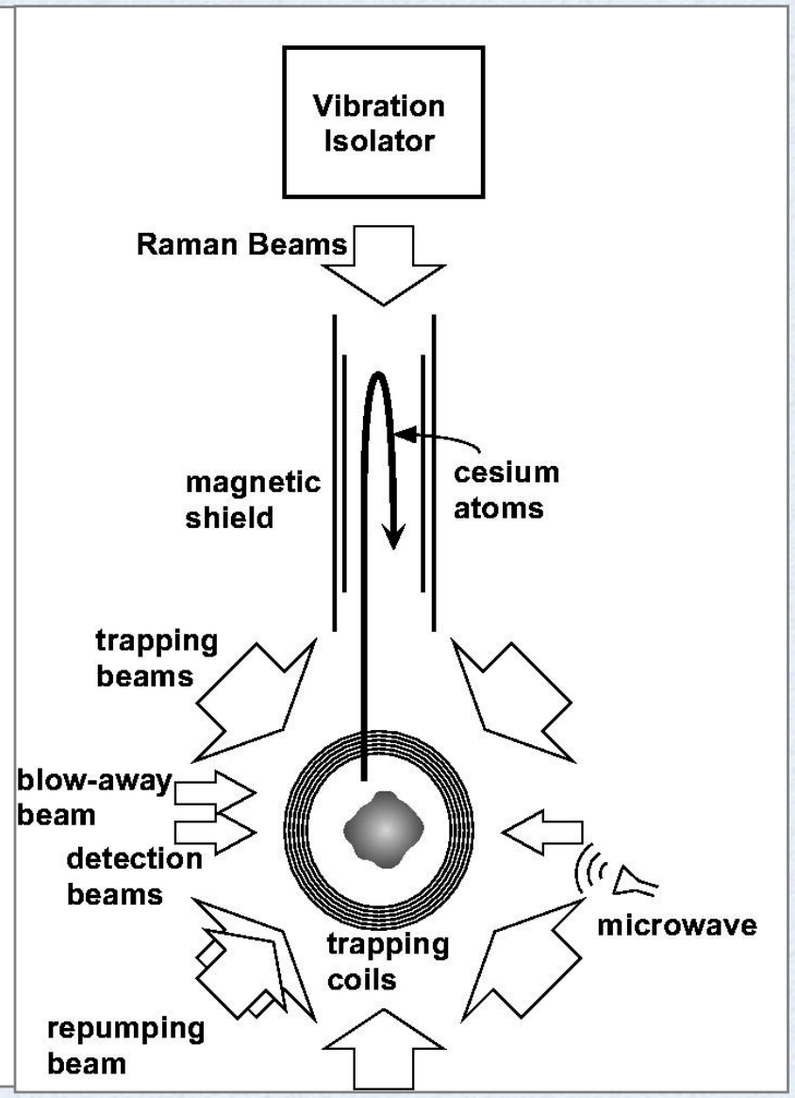

$T = 150$ ms $\rightarrow 2\pi = 10^{-6}$ g

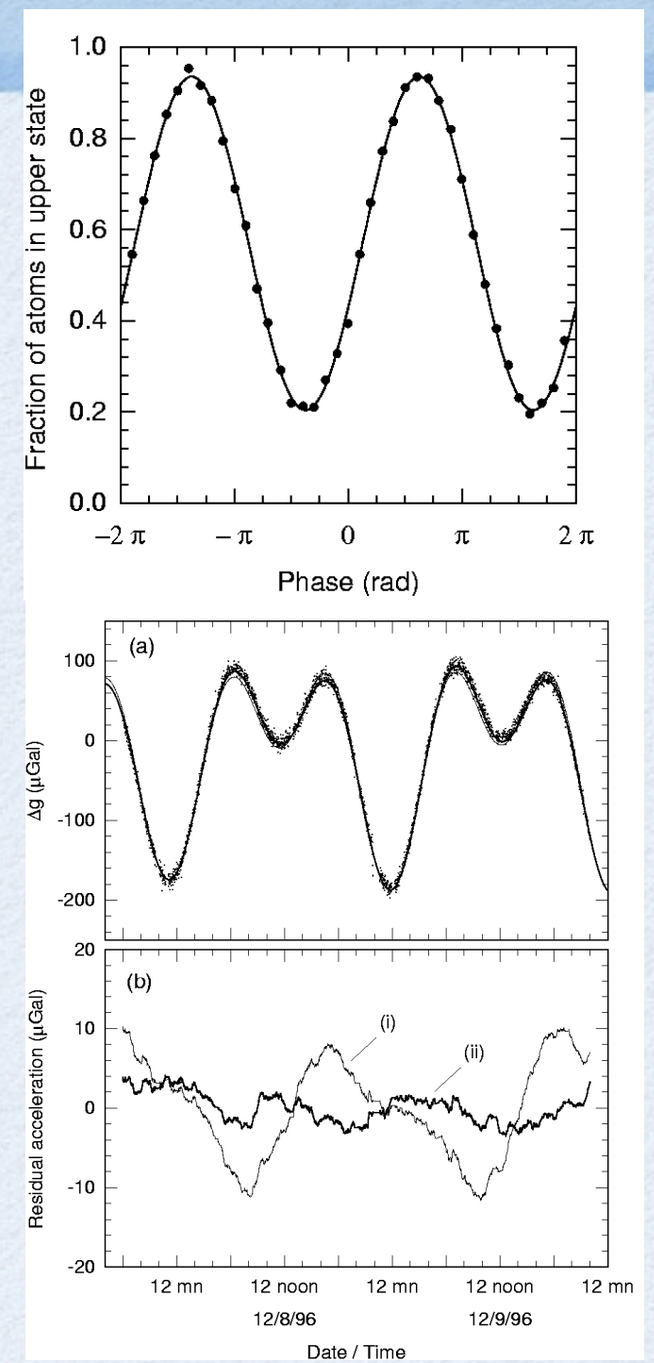
S/N=1000 $\rightarrow$ Sensitivity $10^{-9}$ g/shot

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

# Atom gravimeters (Stanford, Berlin, Paris)






resolution: $8\times10^{-9}$ g in 1 second (Stanford)

averaging down to $8\times10^{-10}$ g after 10 min (Berlin)

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

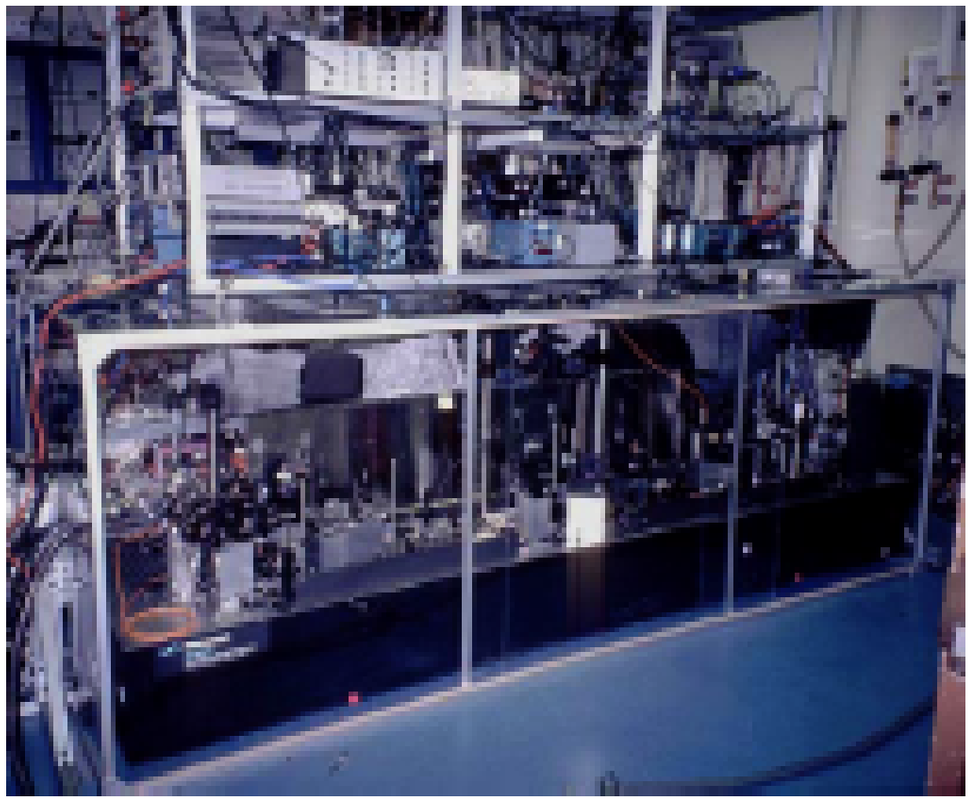

A. Peters, K.Y. Chung and S. Chu, Nature 400, 849 (1999)

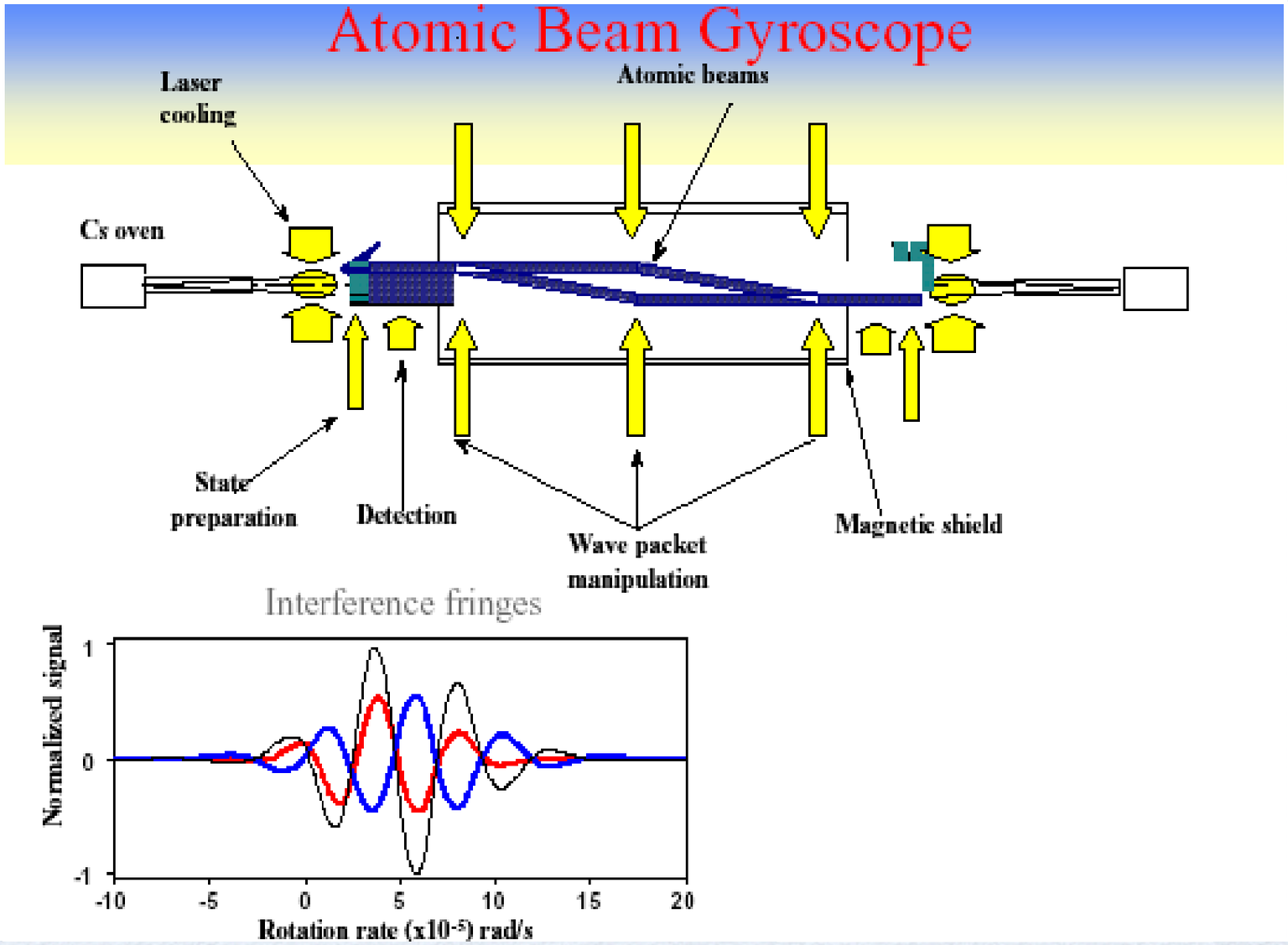
H. Müller et al., Phys. Rev. Lett 100, 031101 (2008)

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

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

# Gyroscopes (Stanford, Paris, Hannover)






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

scale factor stability $< 5$ ppm

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

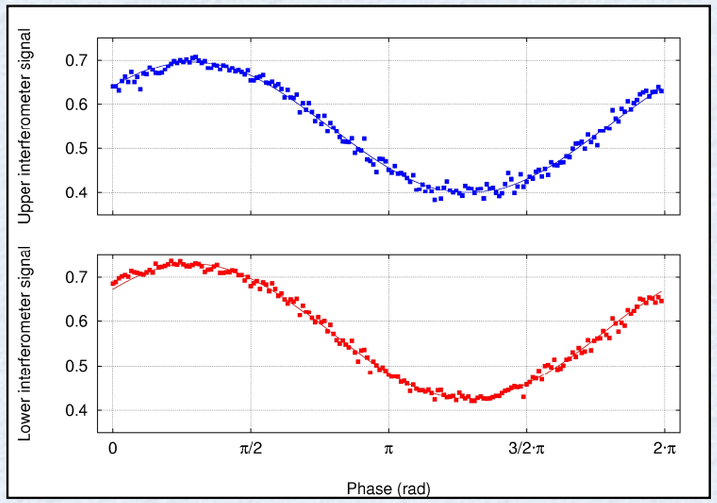
T.L. Gustavson, A. Landragin and M.A. Kasevich, Class. Quantum Grav. 17, 2385 (2000)

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

# Raman gravity gradiometer

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

# Raman gravity gradiometer

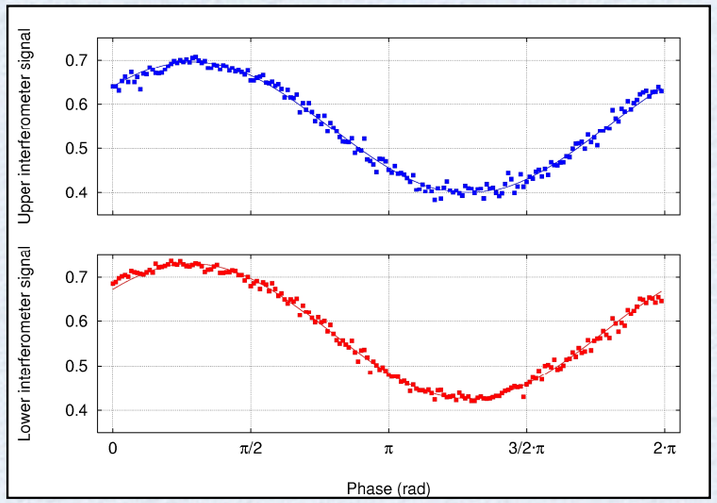


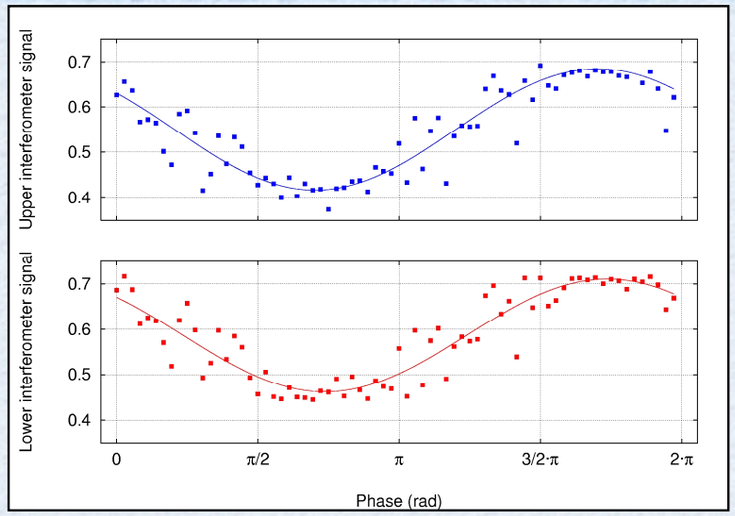

T=5 ms

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

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

# Raman gravity gradiometer



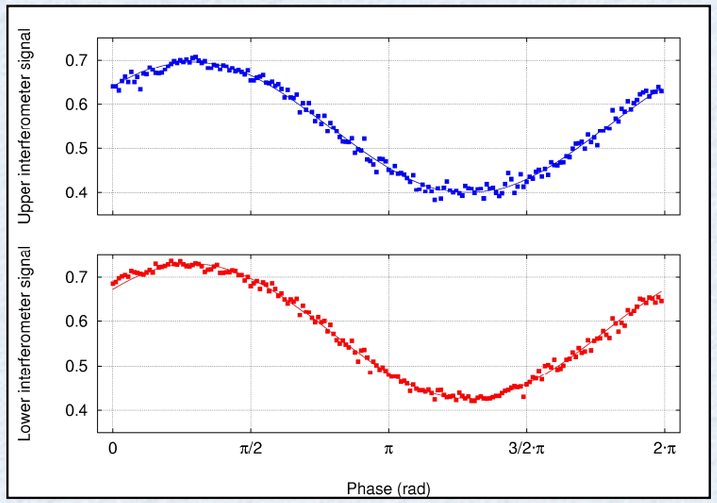




T=5 ms
resol. $= 2.3 \times 10^{-5}$g/shot

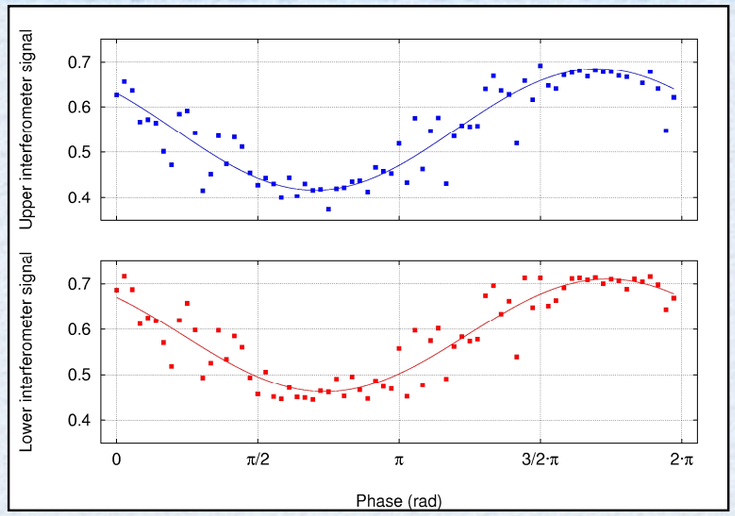
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot

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

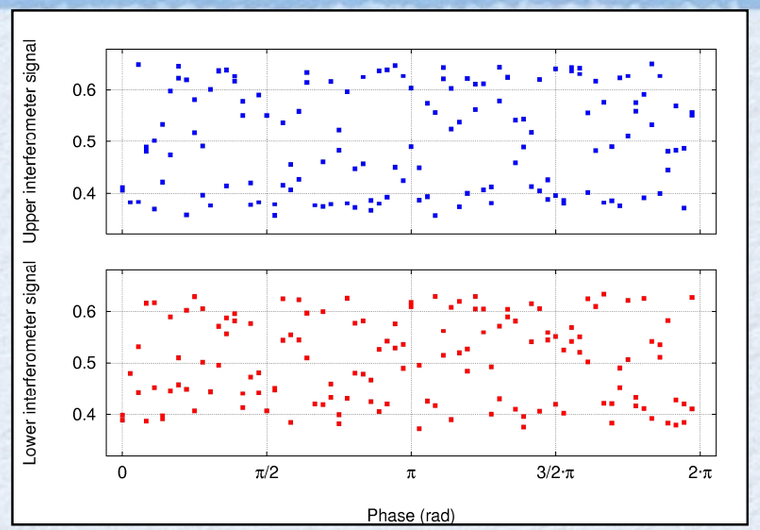
# Raman gravity gradiometer




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



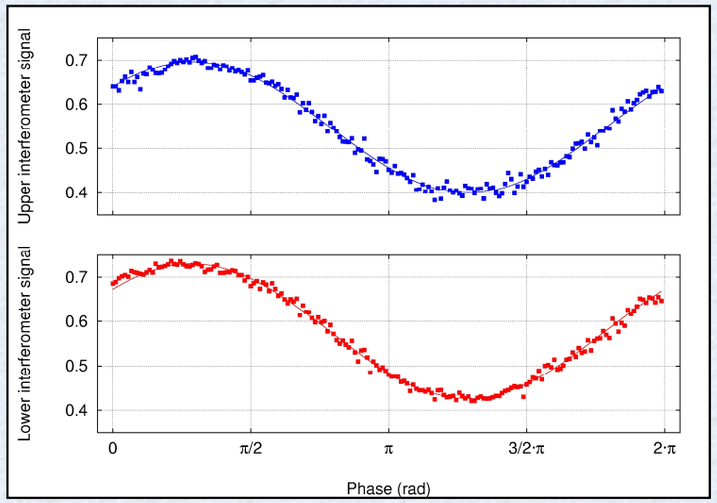

T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot




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

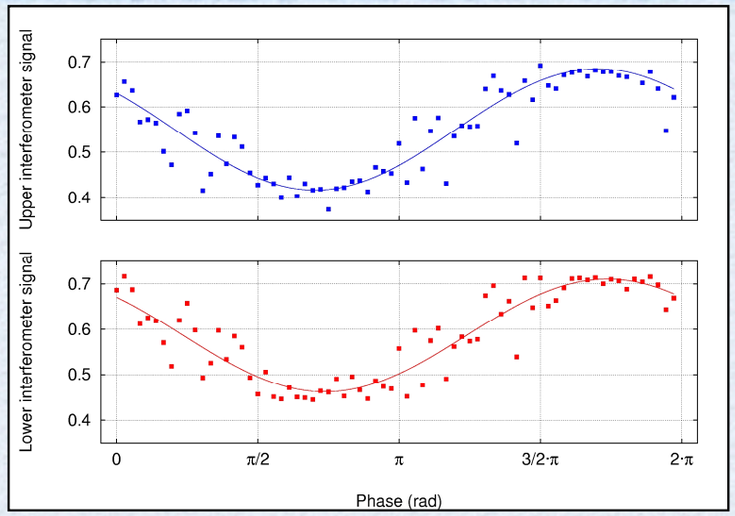
$$\Delta\Phi = k_e g T^2$$

# Raman gravity gradiometer



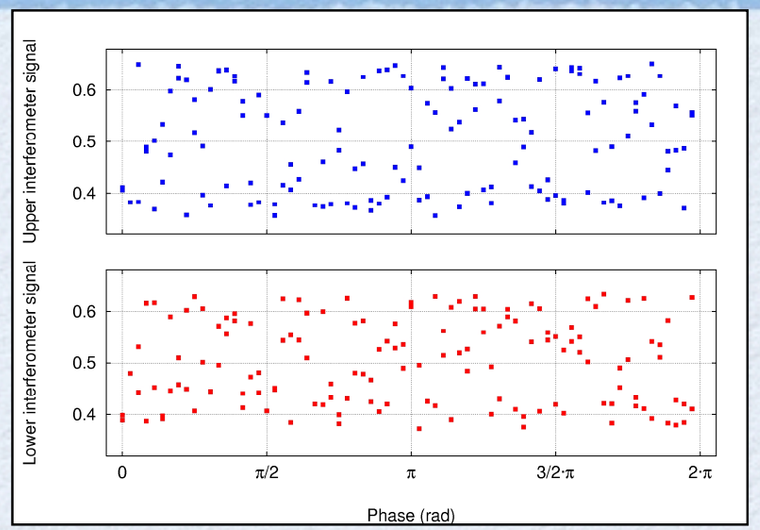

T=5 ms

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



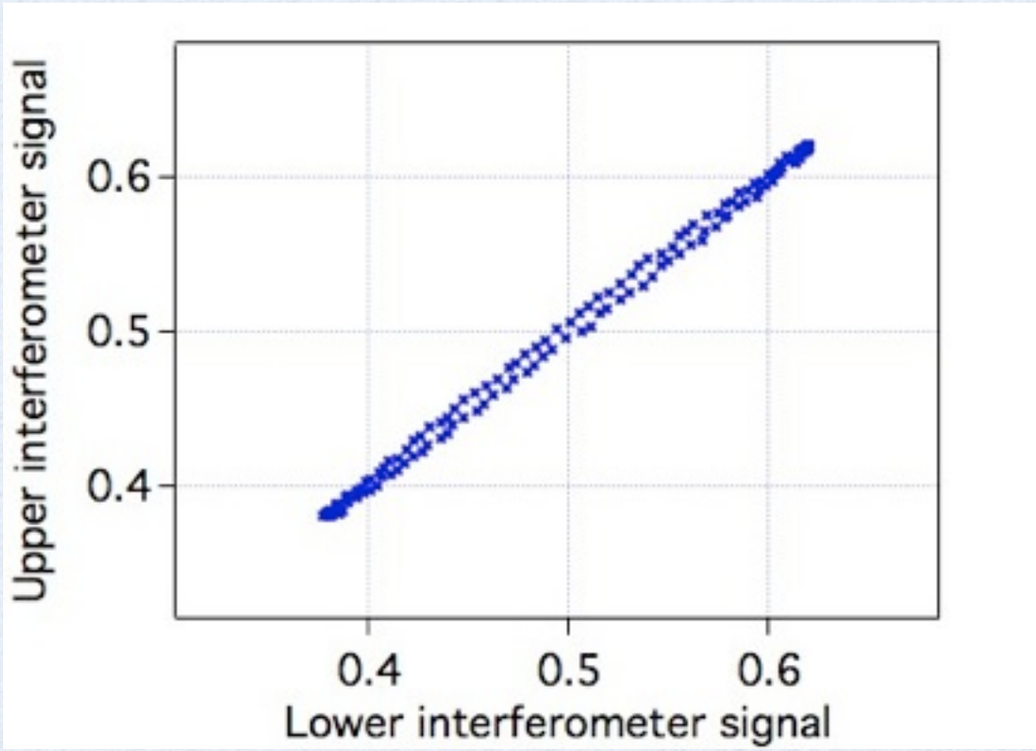

T=50 ms

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

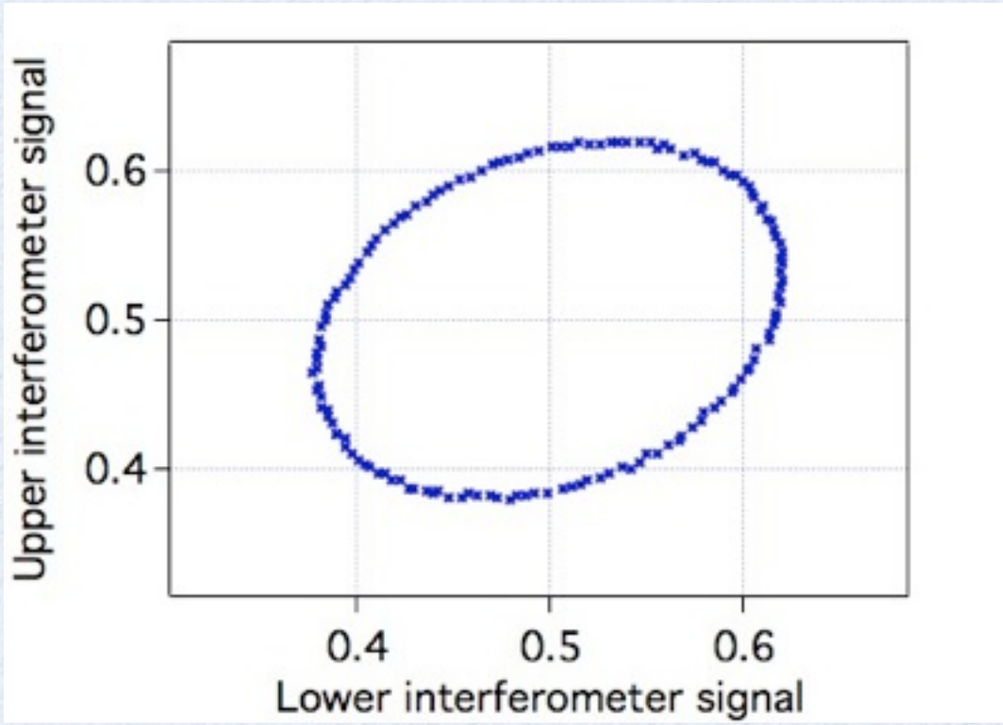



T=150 ms

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

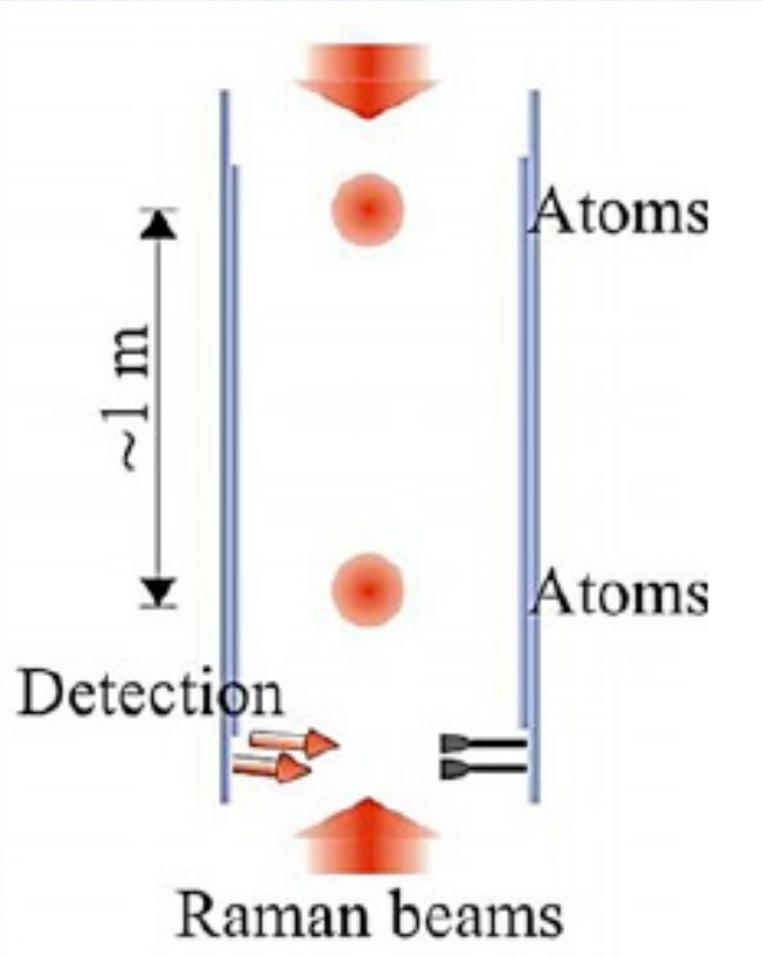


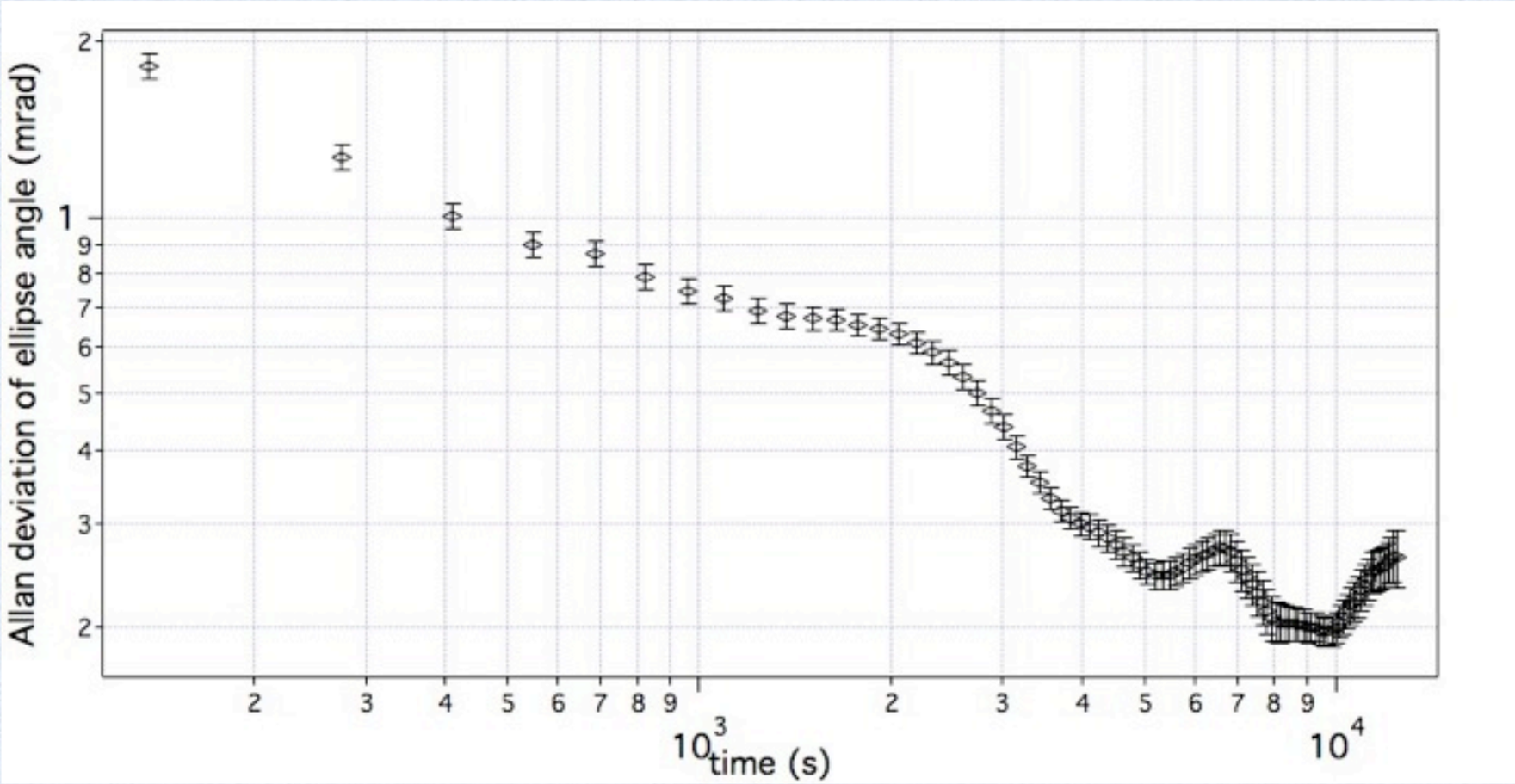

$$\Delta\Phi = k_e g T^2$$




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

# Gravity gradient measurement at QPN



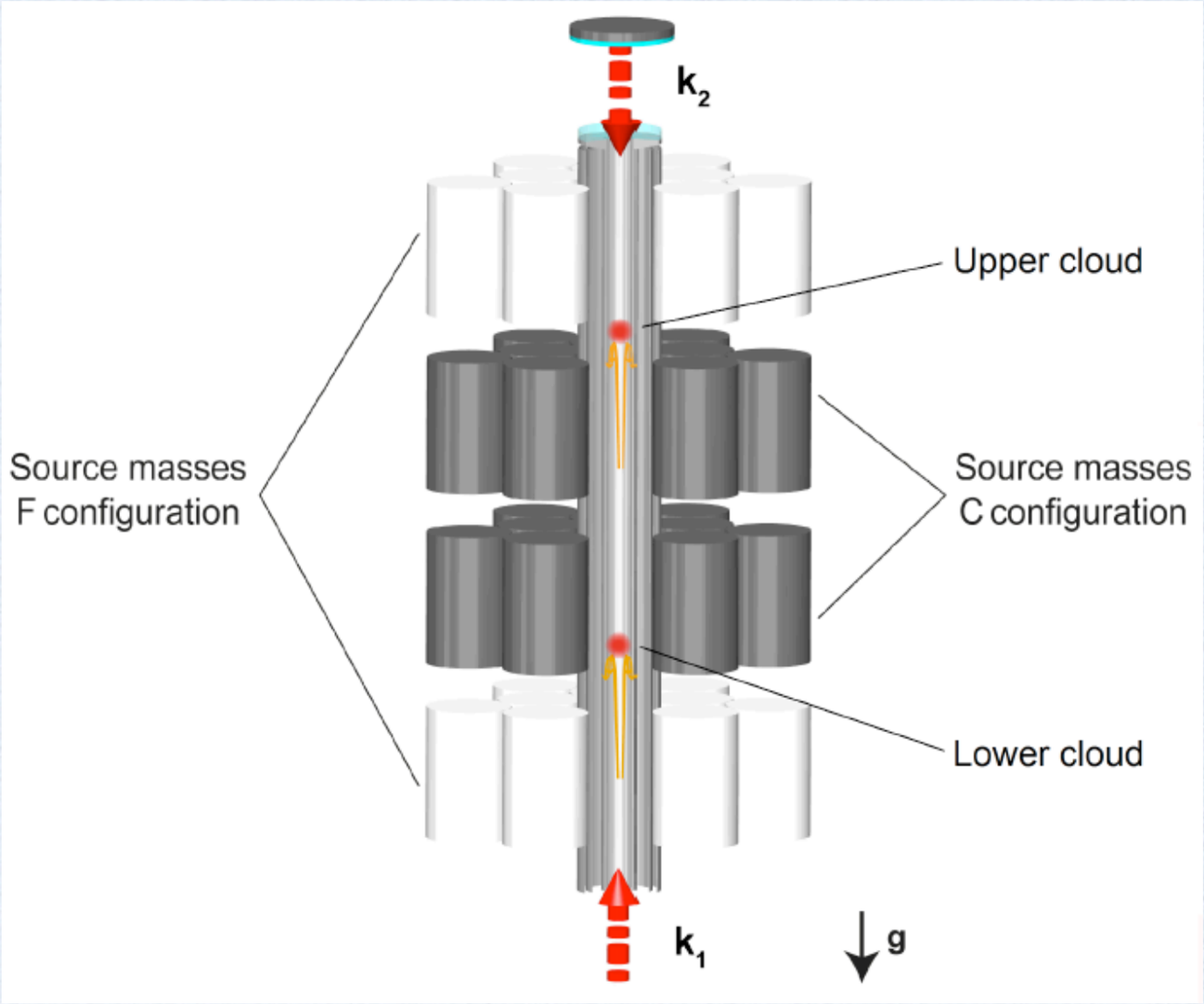

Short-term sensitivity to differential acceleration: $3\times10^{-9}$ g @ 1s (=QPN for $4\times10^{5}$ atoms)
Allan variance ~0.2 mrad @ 10000 s, corresponding to $5\times10^{-11}$ g

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

# MAGIA

*Misura Accurata di G mediante Interferometria Atomica*

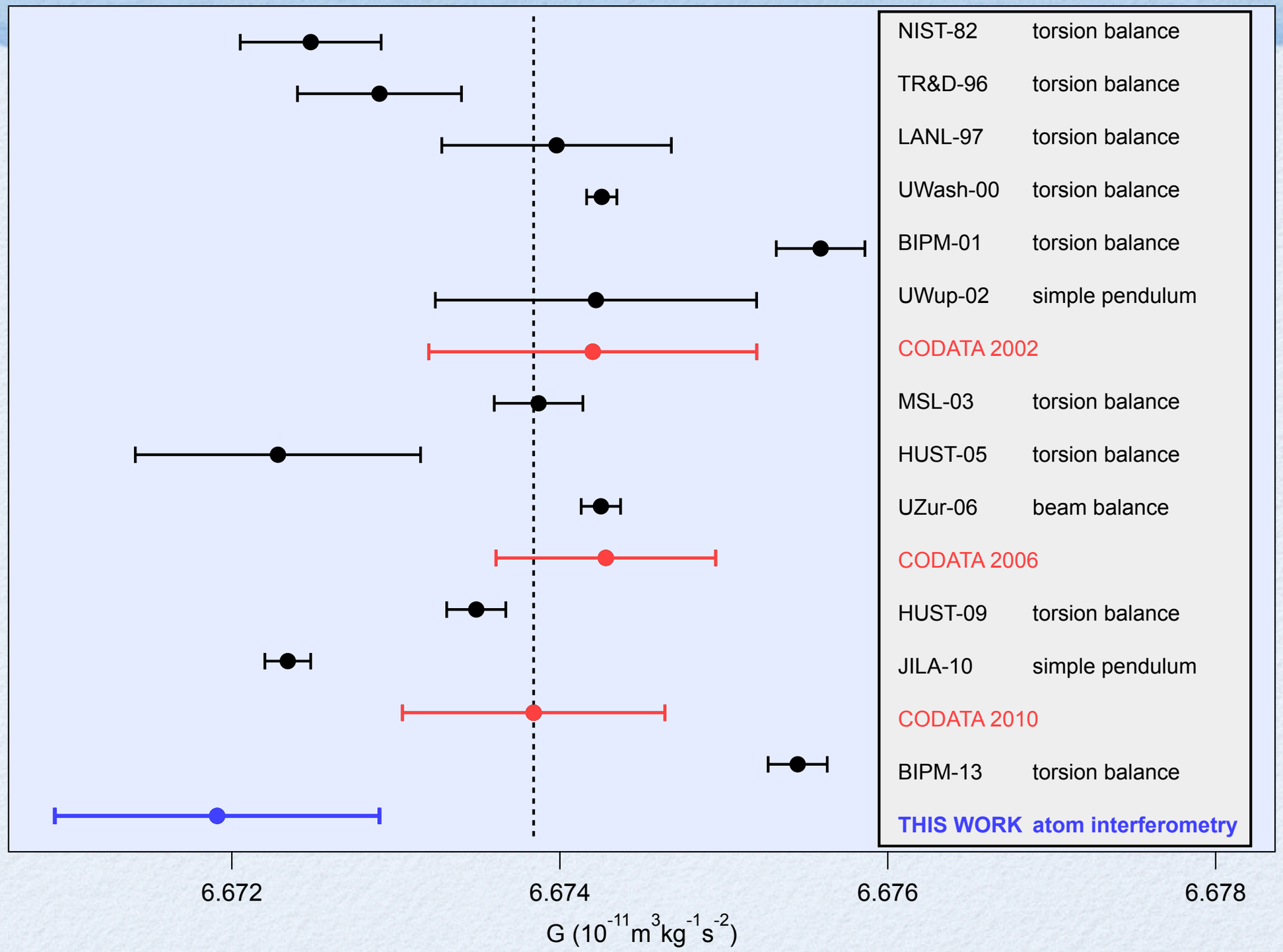
- Rb fountain gradiometer
- + set of source masses




***See talk by G. Rosi on Wed. 24 (sez. II)***

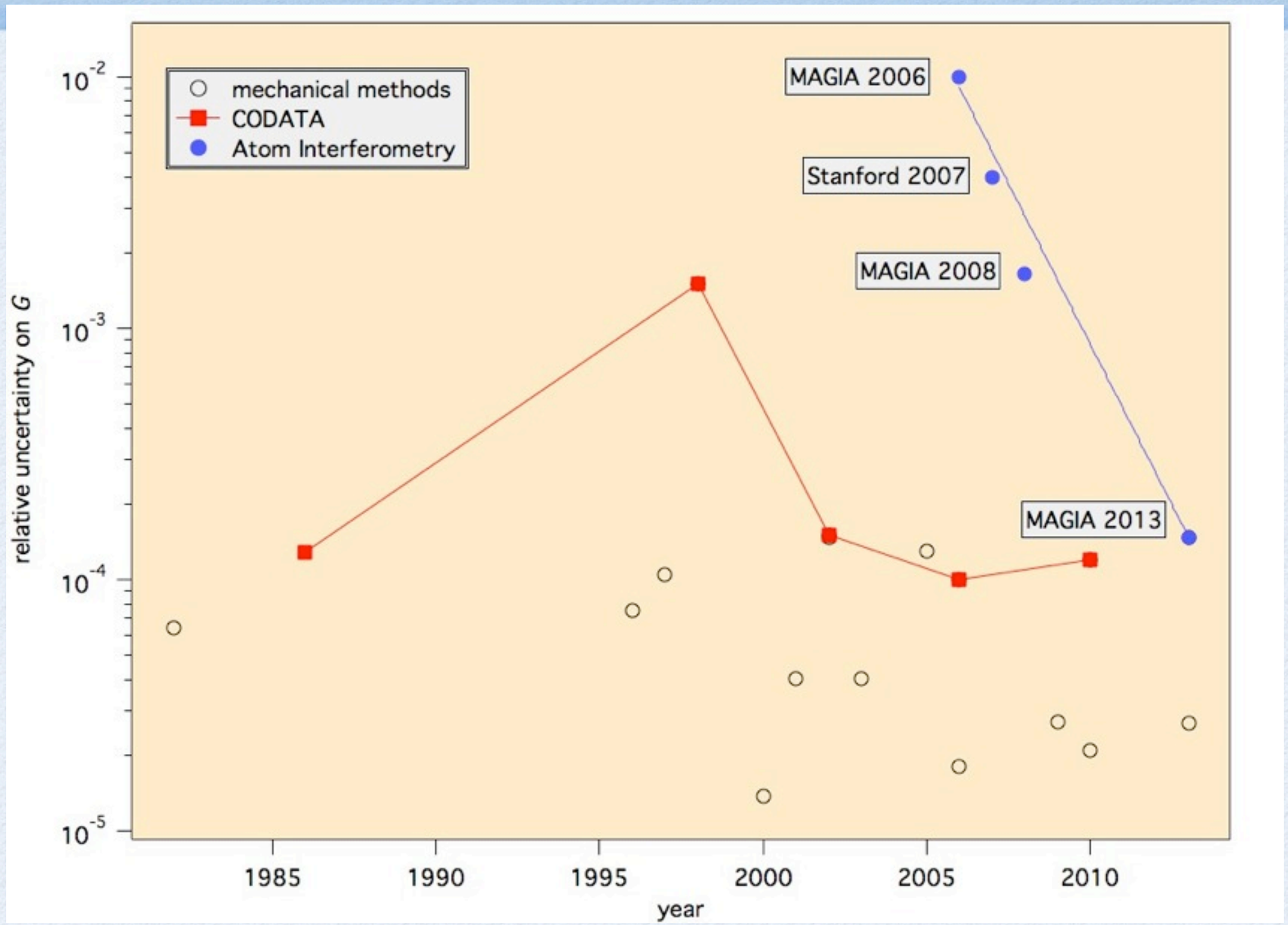
**http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html**

# 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



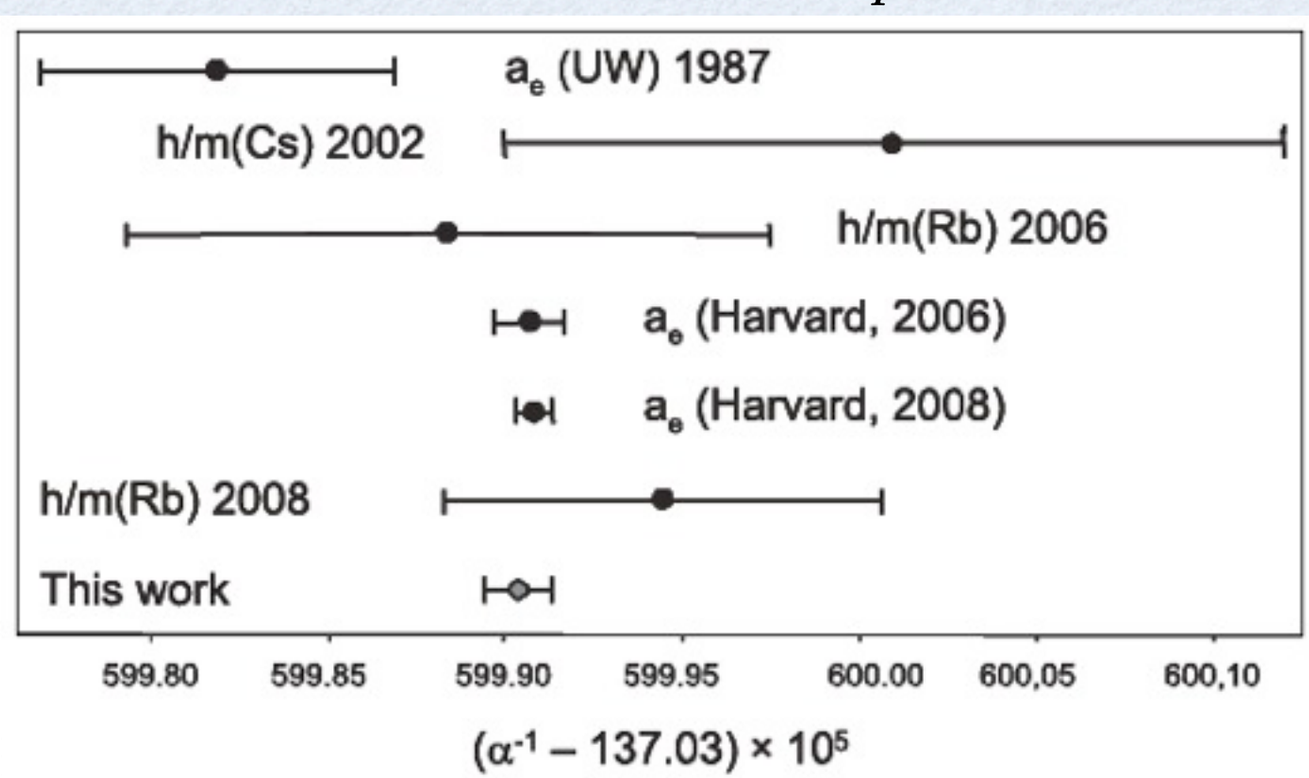
# $h/m$ and fine-structure constant

**fine-structure constant**

$$\alpha = e^2/4\pi\epsilon_0\hbar c$$

| | |
|---|---|
| Value | $7.297\ 352\ 568 \times 10^{-3}$ |
| Standard uncertainty | $0.000\ 000\ 024 \times 10^{-3}$ |
| Relative standard uncertainty | $3.3 \times 10^{-9}$ |
| Concise form | $7.297\ 352\ 568(24) \times 10^{-3}$ |

$$\alpha^2 = \frac{2R_\infty}{c}\frac{m_p}{m_e}\frac{m_{Cs}}{m_p}\frac{h}{m_{Cs}}$$



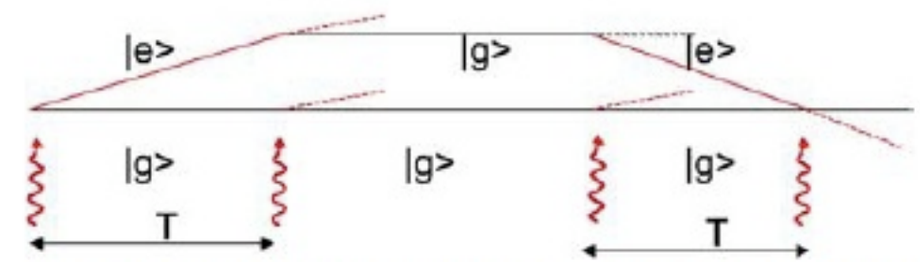




**FIGURE 2** Basic (Ramsey–Borde) atom interferometer with four $\pi/2$ laser pulses as beam splitter

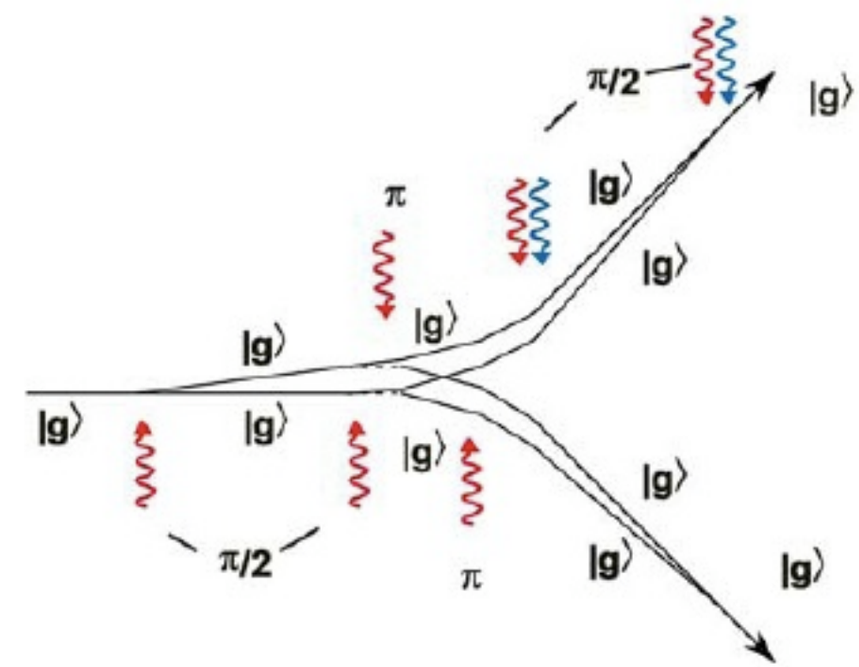
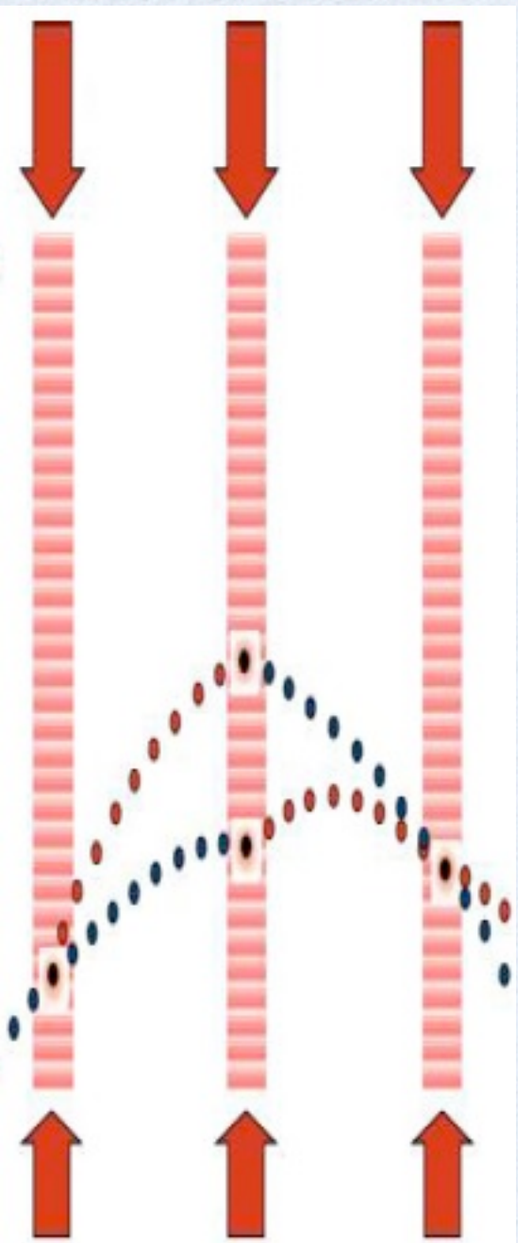


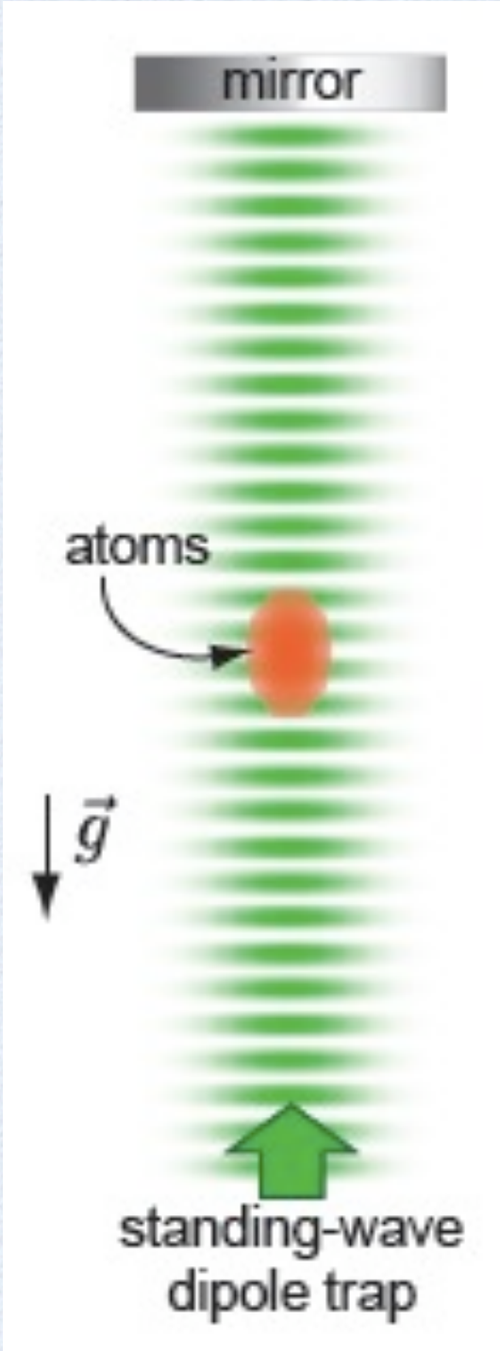

**FIGURE 3** SCIs used in this experiment. The last two $\pi/2$ pulses contain four frequencies in two pairs, to simultaneously address both conjugate interferometers

S.-W. Chiow et al., PRL **103**, 050402 (2009)
R. Bouchendira et al., PRL **106**, 080801 (2011)

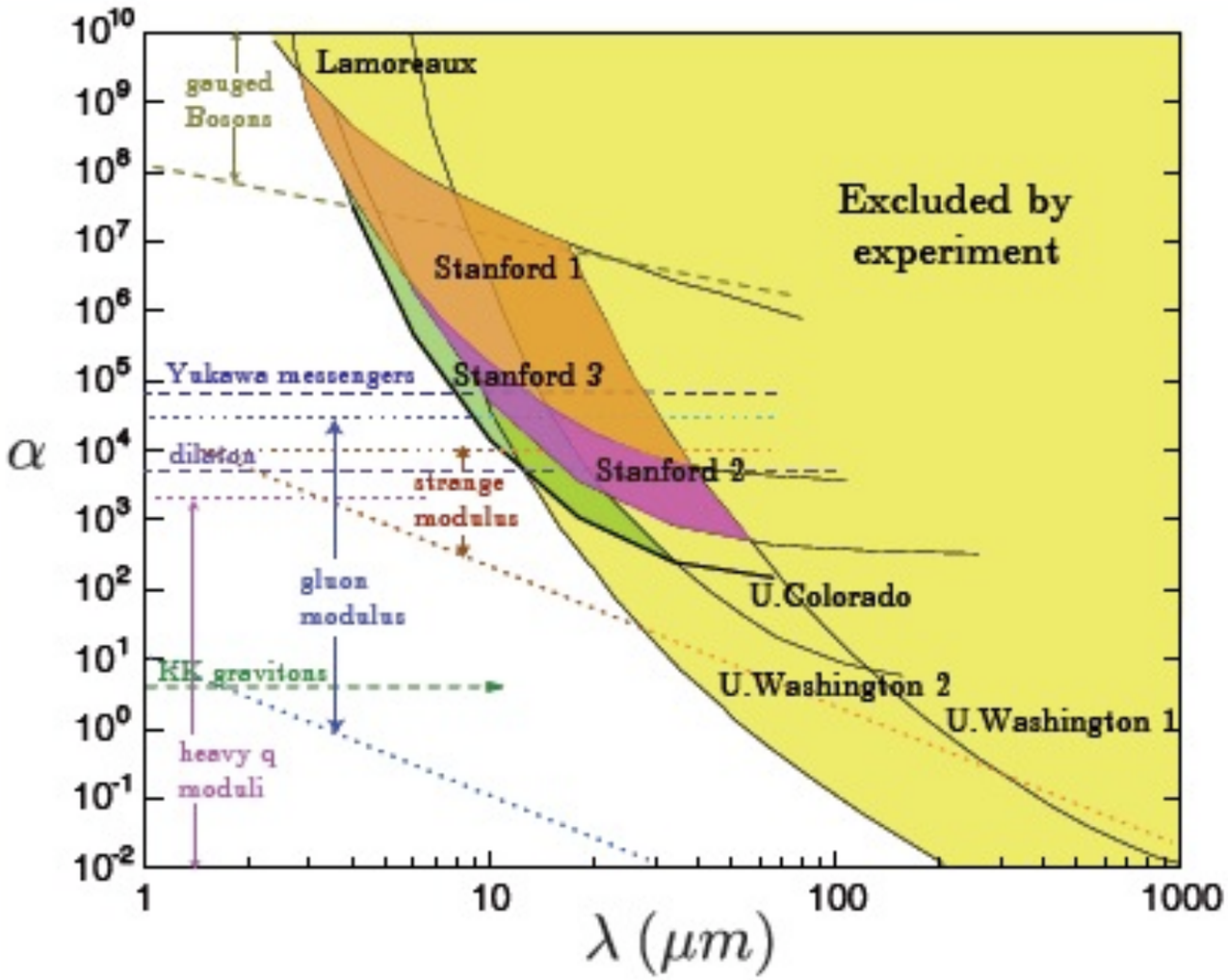
# Freely falling vs trapped atoms



- 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



# Short-range force measurements

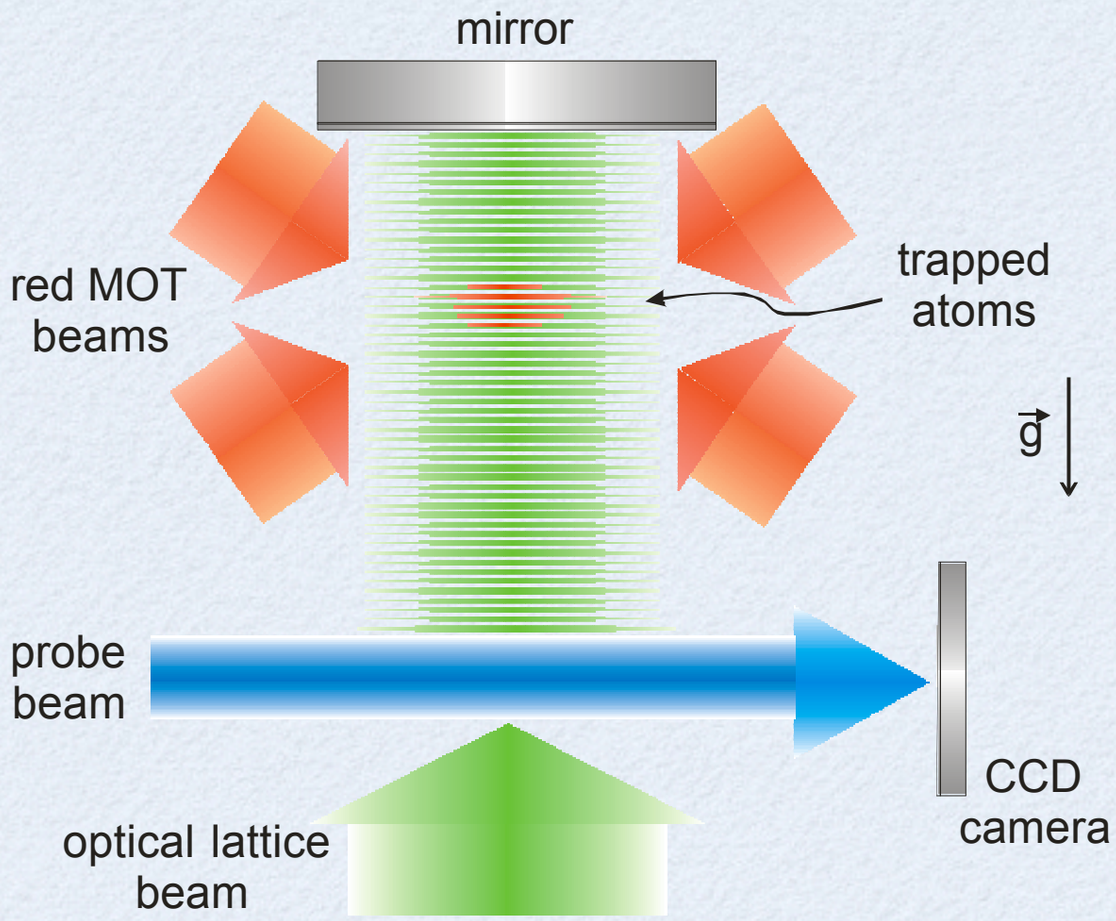


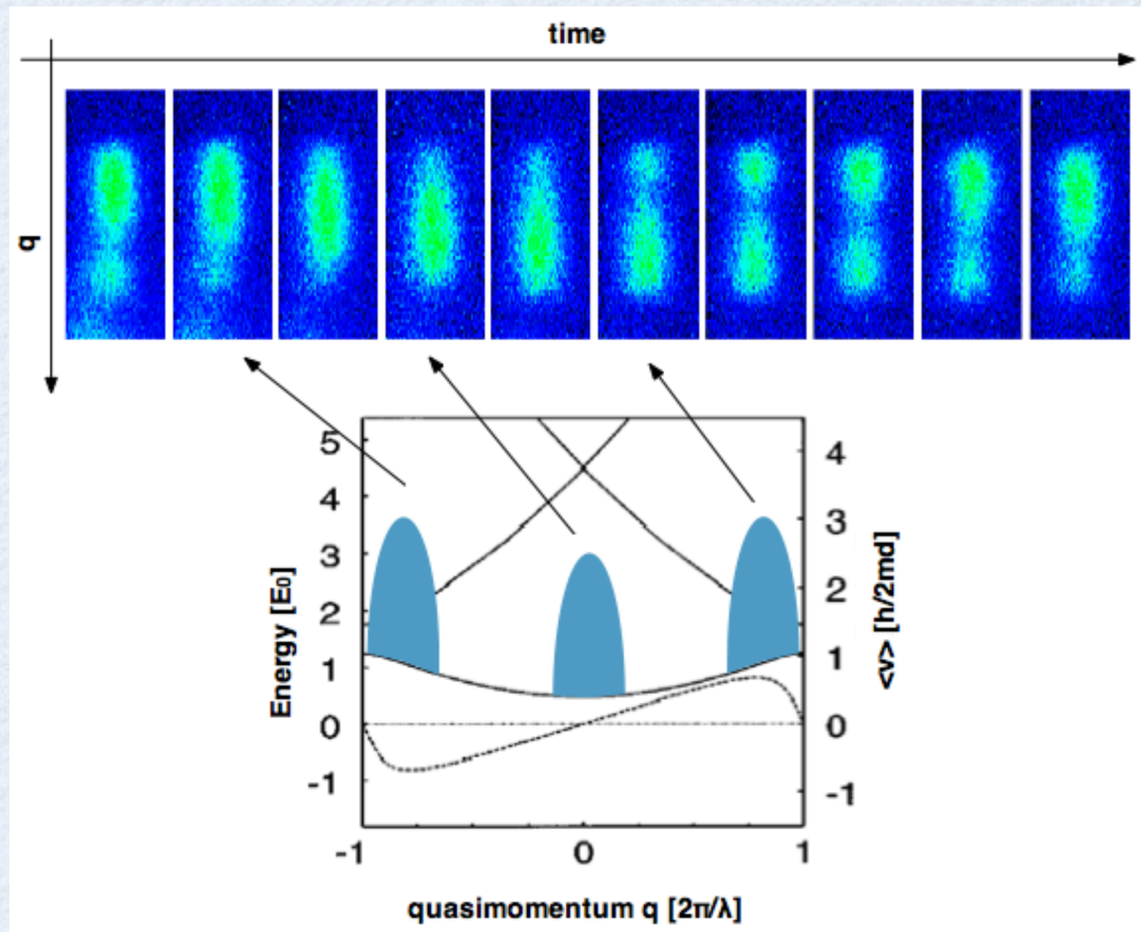

Geraci et al. Phys. Rev. D **78** 22002 (2008)

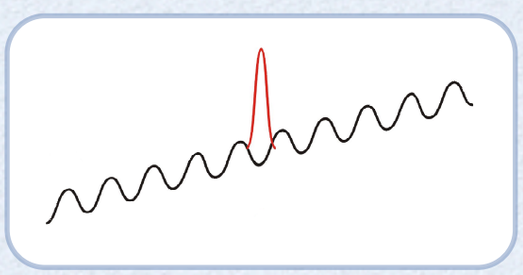
- Characterization of the Casimir-Polder effect
- Exotic theories predict violations of Newton's law on some length scale
- Effect parametrized through Yukawa potential
- experiment set limits in parameters space $(\alpha - \lambda)$

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

# Bloch oscillations in optical lattice

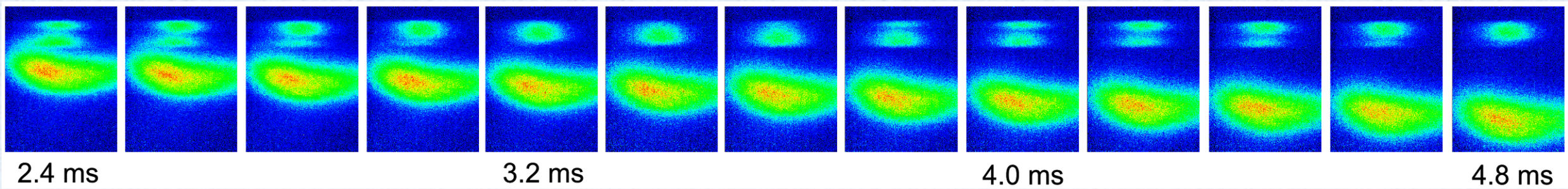


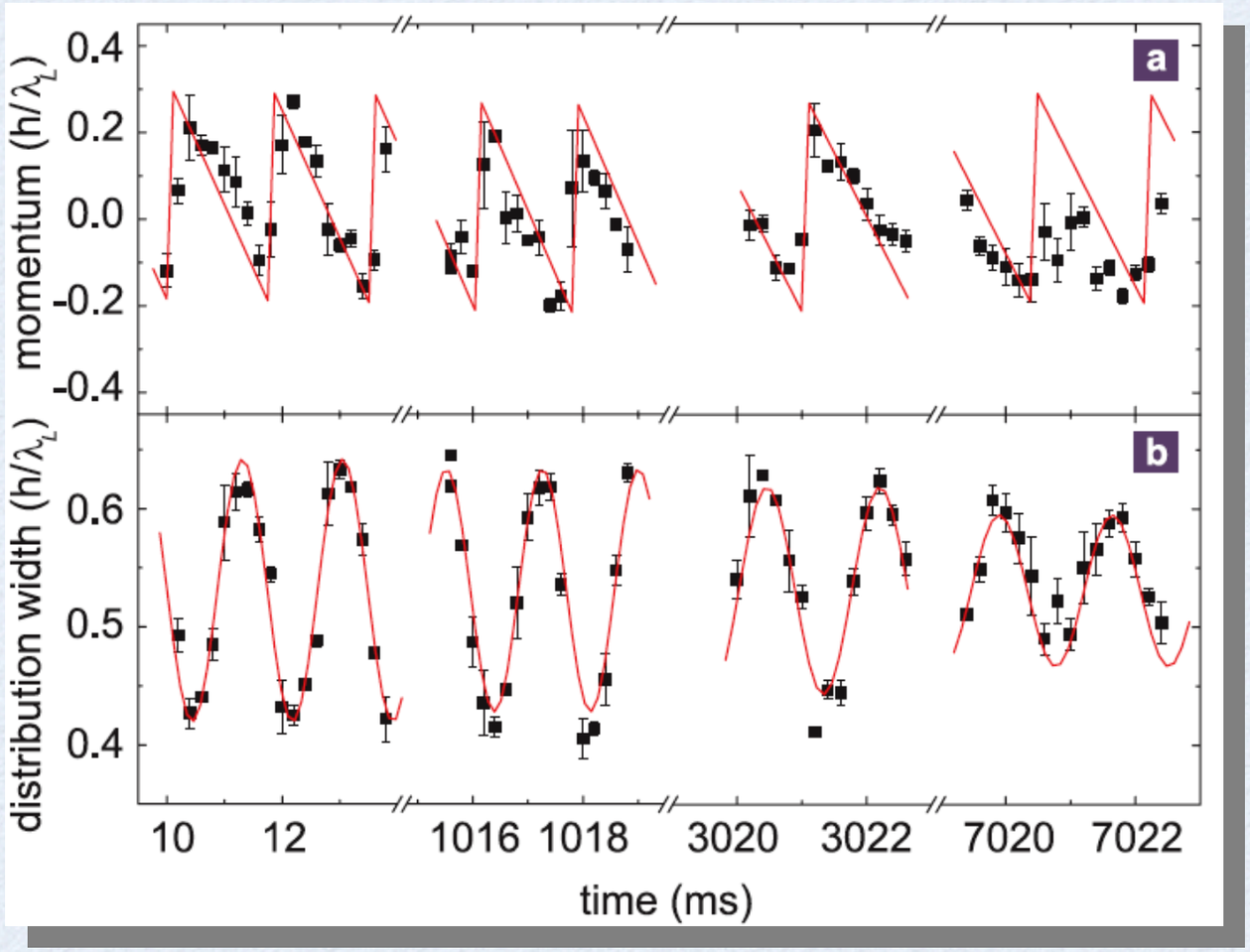



$$q(t) = q_0 + Ft/\hbar \quad \Rightarrow \quad \nu_B = \frac{F\lambda}{2h} = \frac{mg\lambda}{2h}$$

# 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

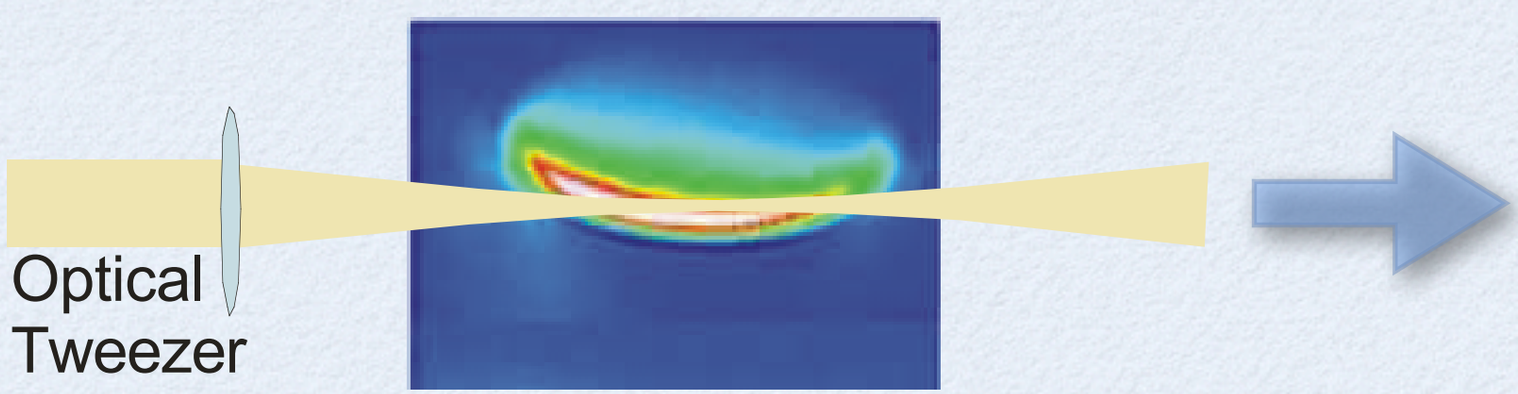
*M. Tarallo et al., PRA* ***86****, 033615 (2012)*

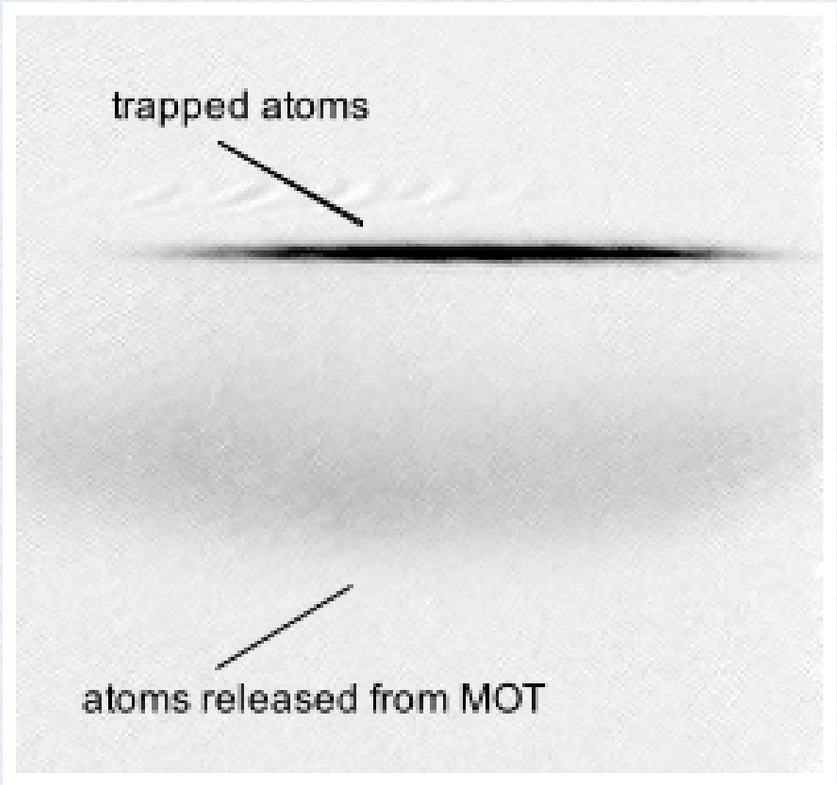
- Direct acceleration sensitivity limited by the small splitting (~1 $\mu$m)
- However, acceleration via BO already employed for LMT splitters in free-fall interferometers

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

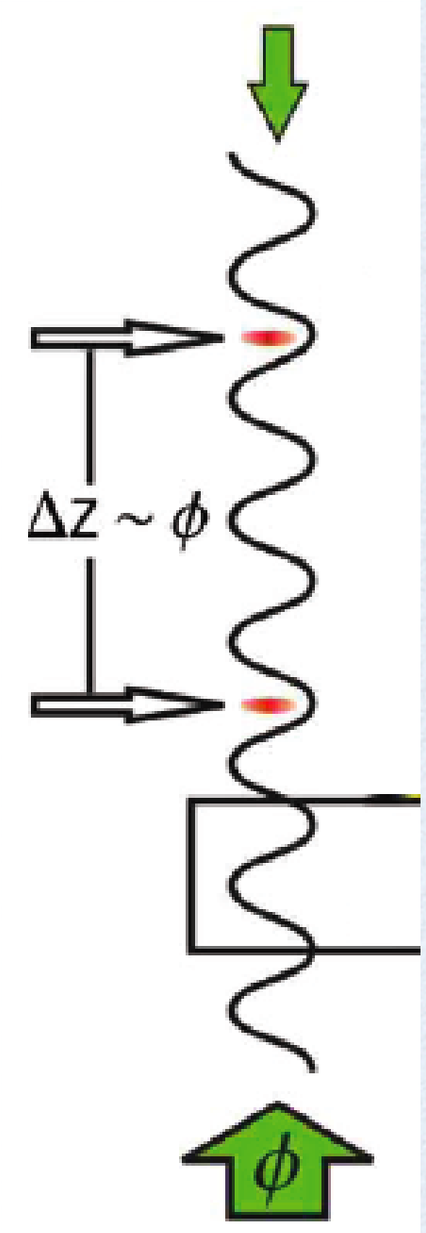
# Sample compression

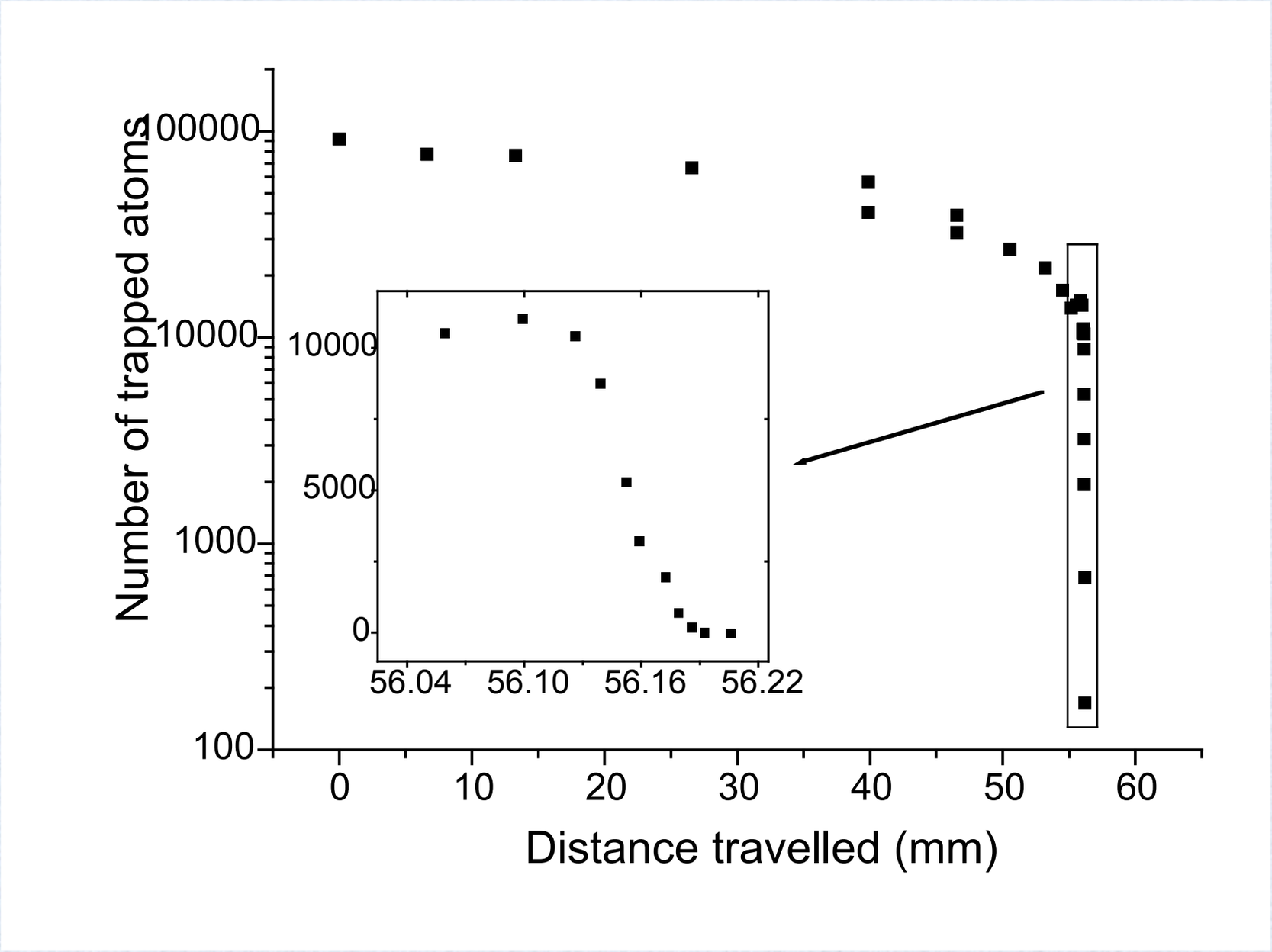
- Vertical size in final MOT ≈ 12 $\mu$m rms
- We reduce it to 4 $\mu$m with an optical tweezer



# Optical elevator

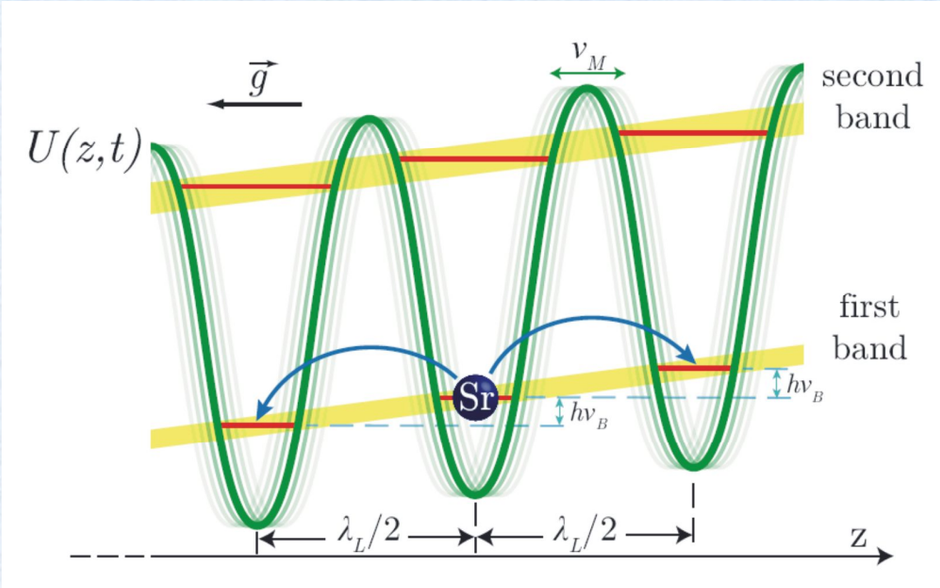


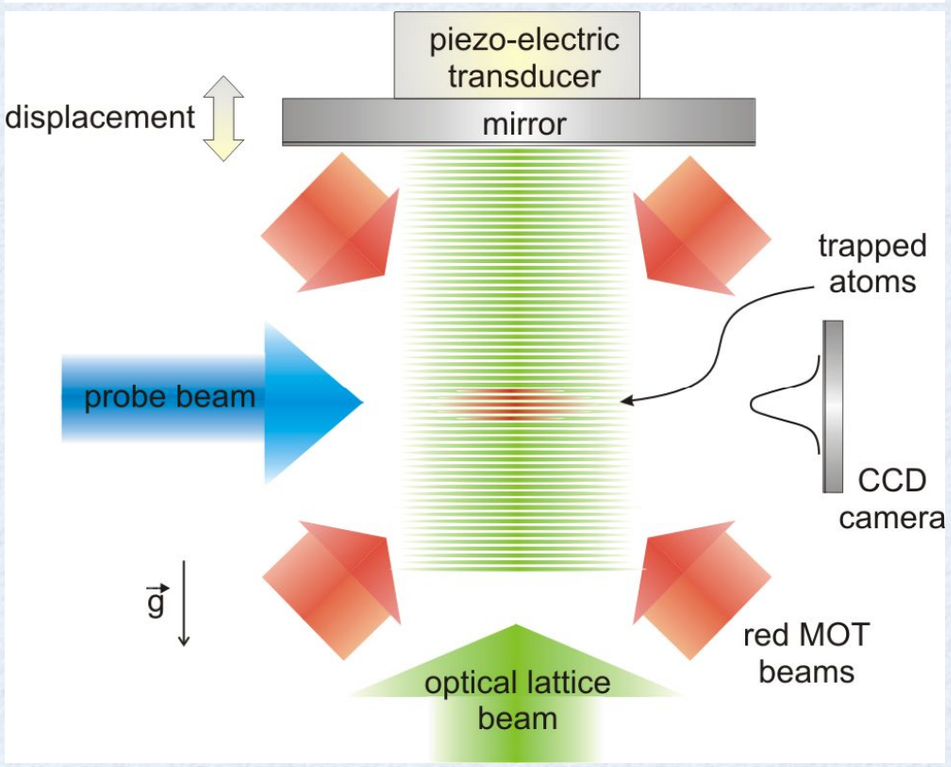



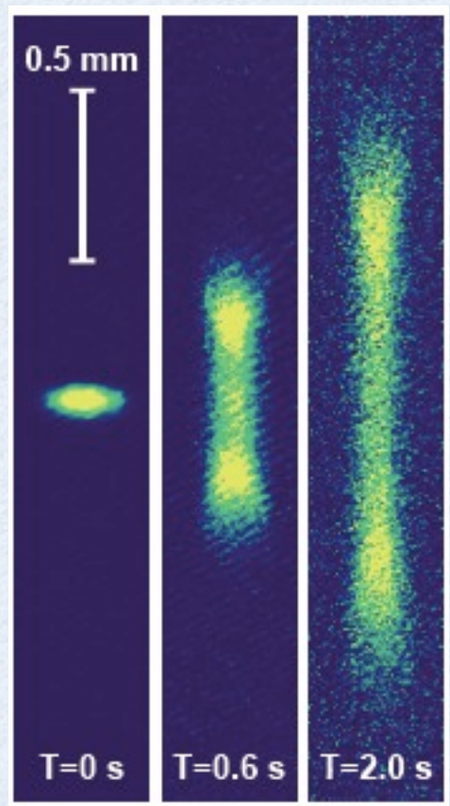

Atom-surface position jitter < 1 $\mu$m

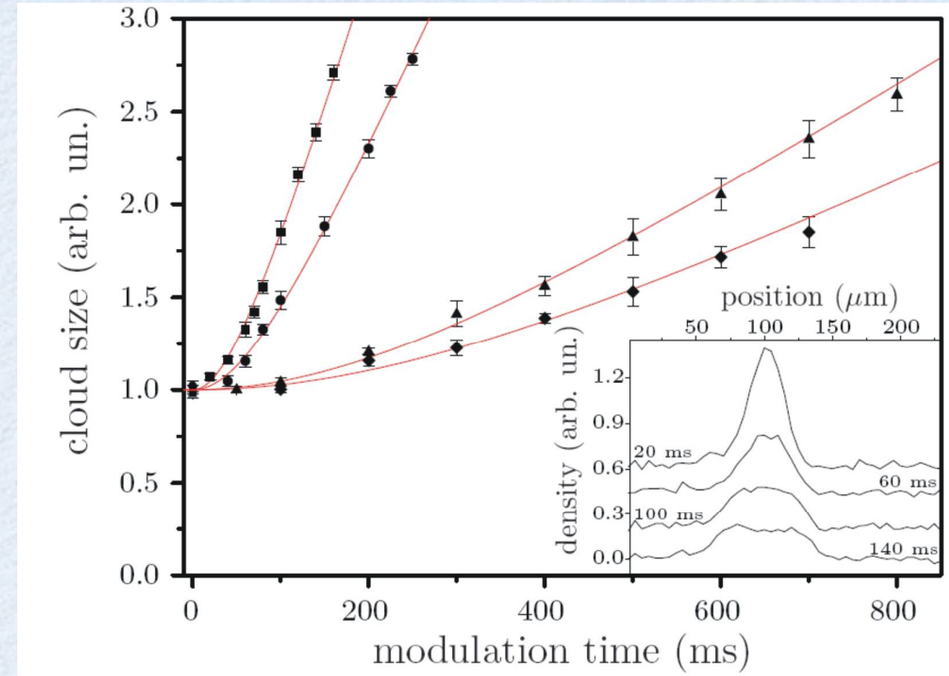
F. Sorrentino et al., Phys. Rev. A **79**, 013409 (2009)

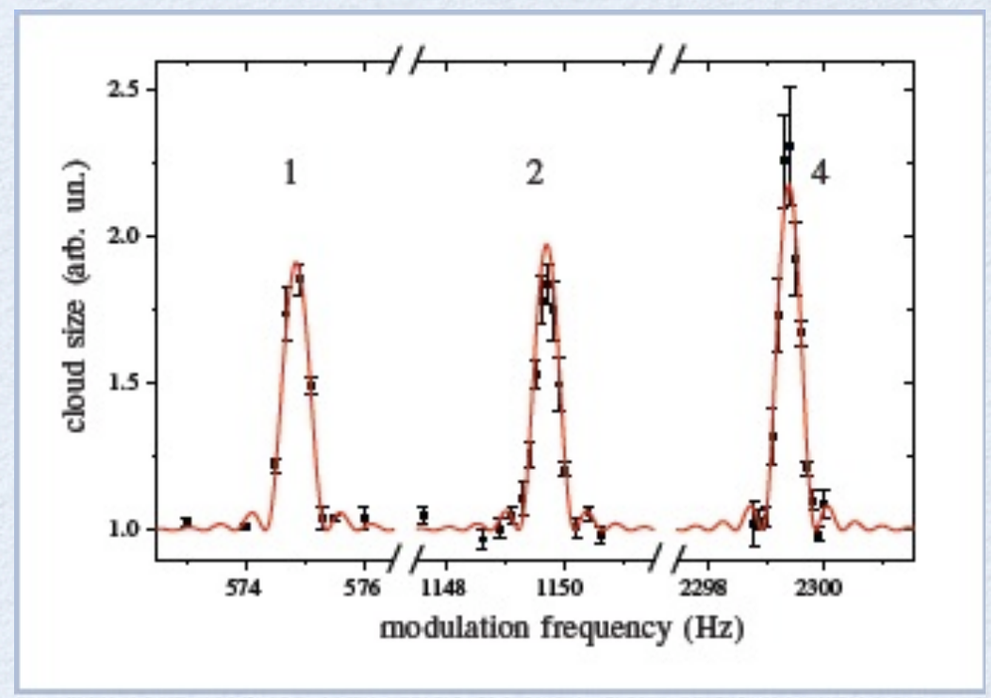
# Resonant tunneling



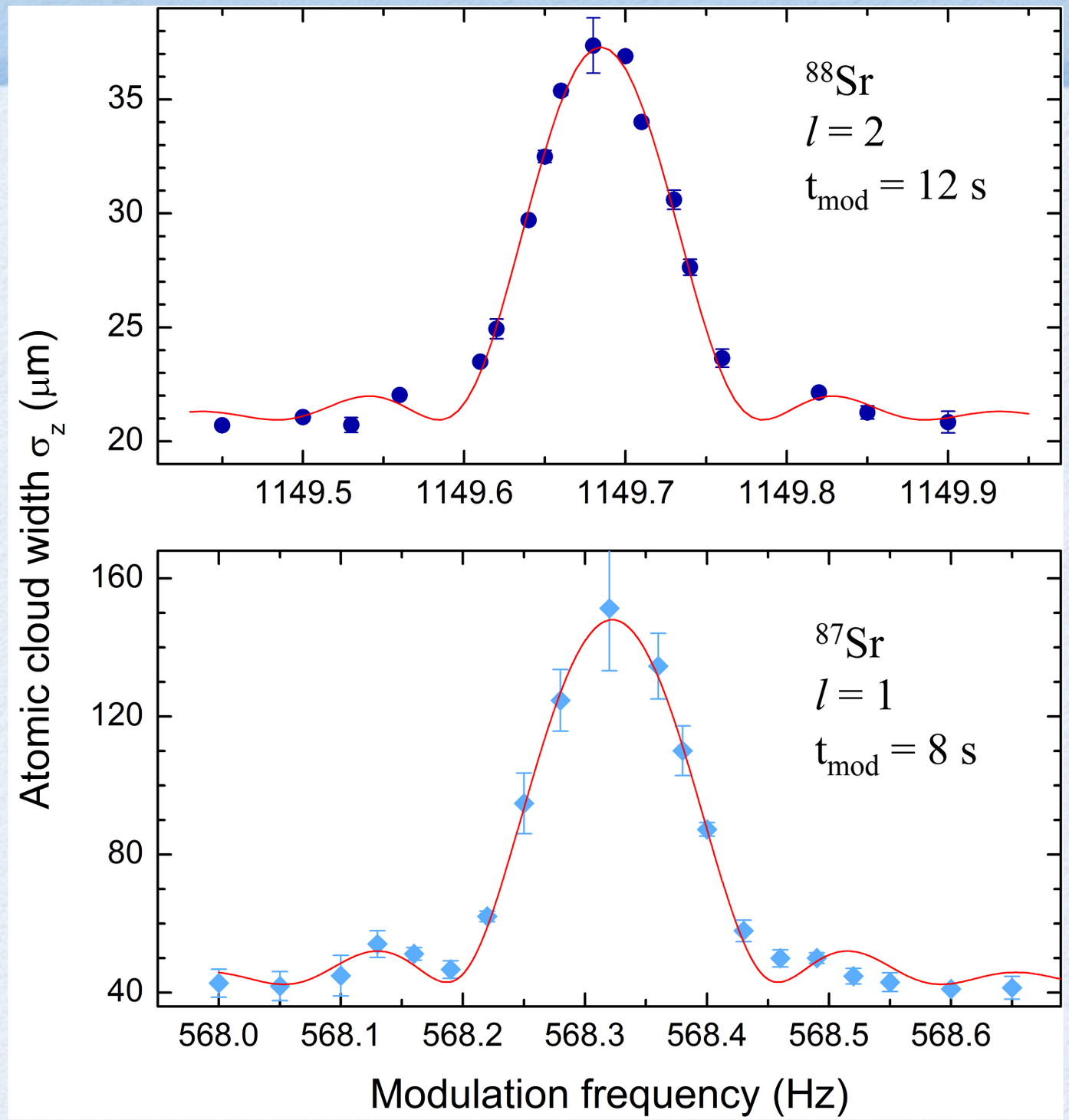




V. V. Ivanov et al., PRL **100**, 043602 (2008)

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

# Test of EP with bosons & fermions

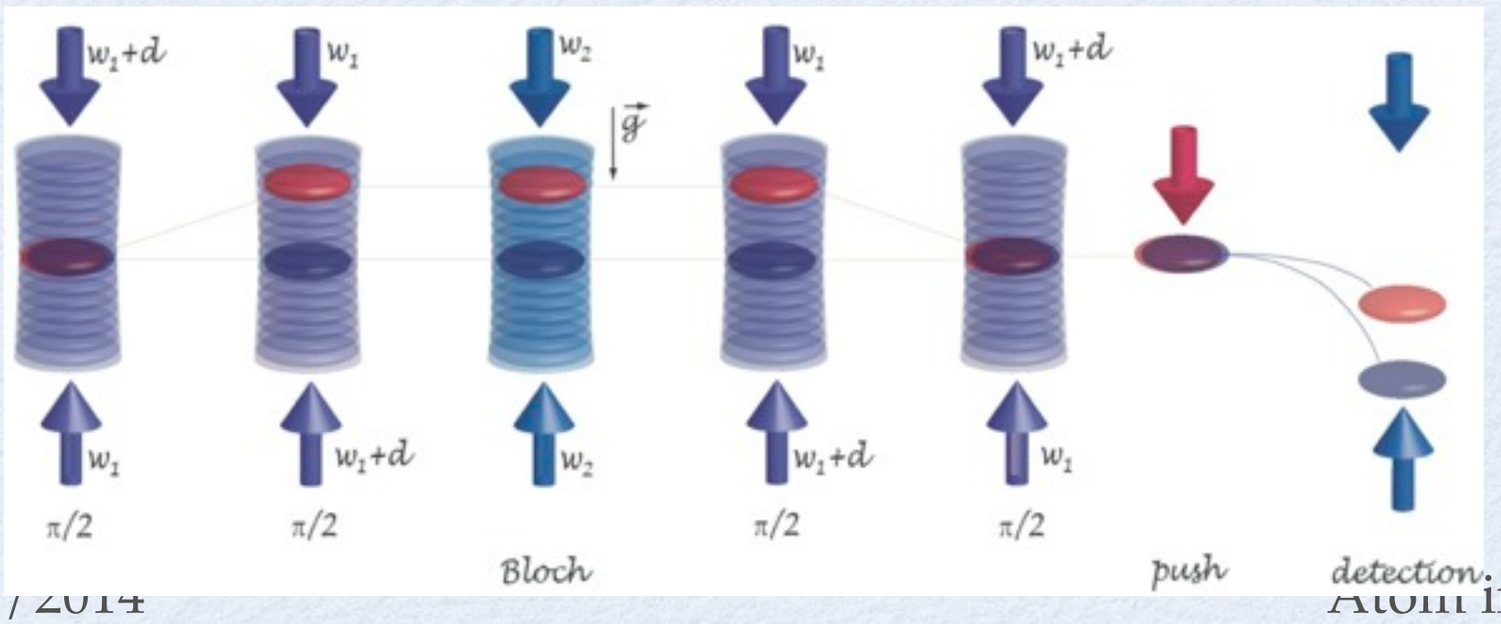



measurement of the Eötvös ratio at the $10^{-7}$ level

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

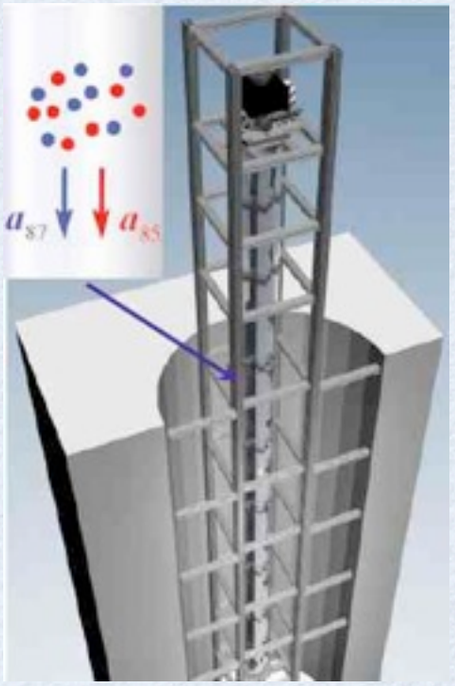
# Possible scheme for MAGIA Advanced

- 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. ~$3\times10^{-10}$ g/shot
  - **MAGIA ADV 2**: t=10 ms, T=10 s, N=20, sens. ~$10^{-11}$ g/shot



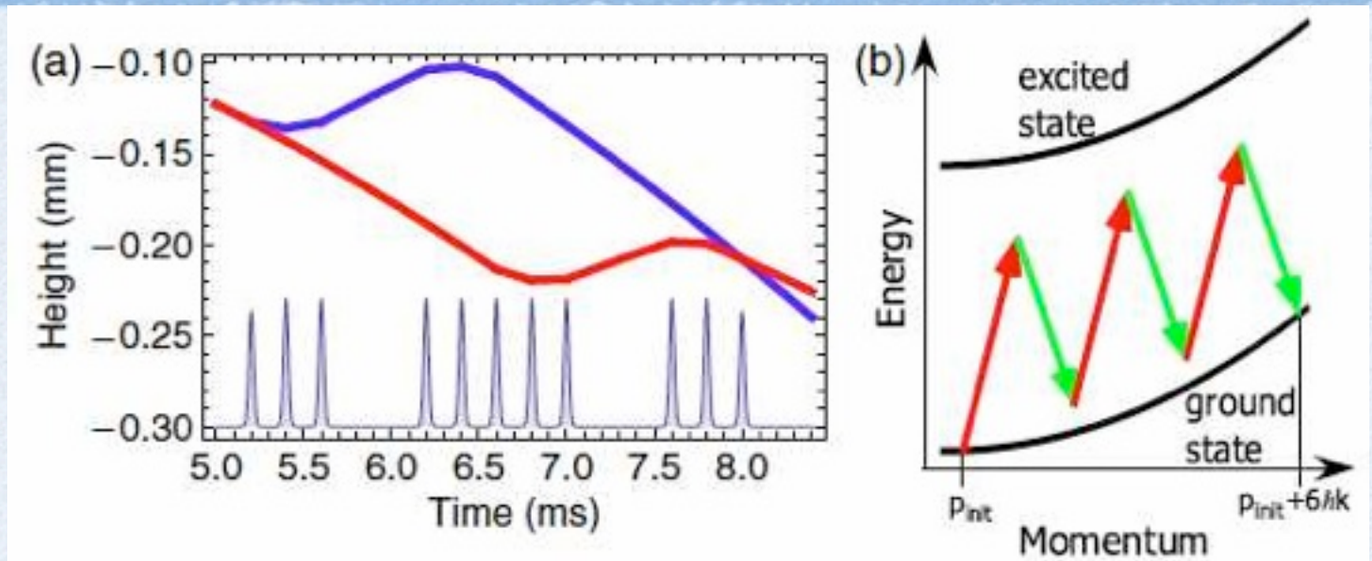
# Future of AI inertial sensors

- 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 (up to 100 hk demonstrated)
  - coherent / squeezed atomic states to surpass QPN detection
  - large size AI (some 10 m towers already developed)

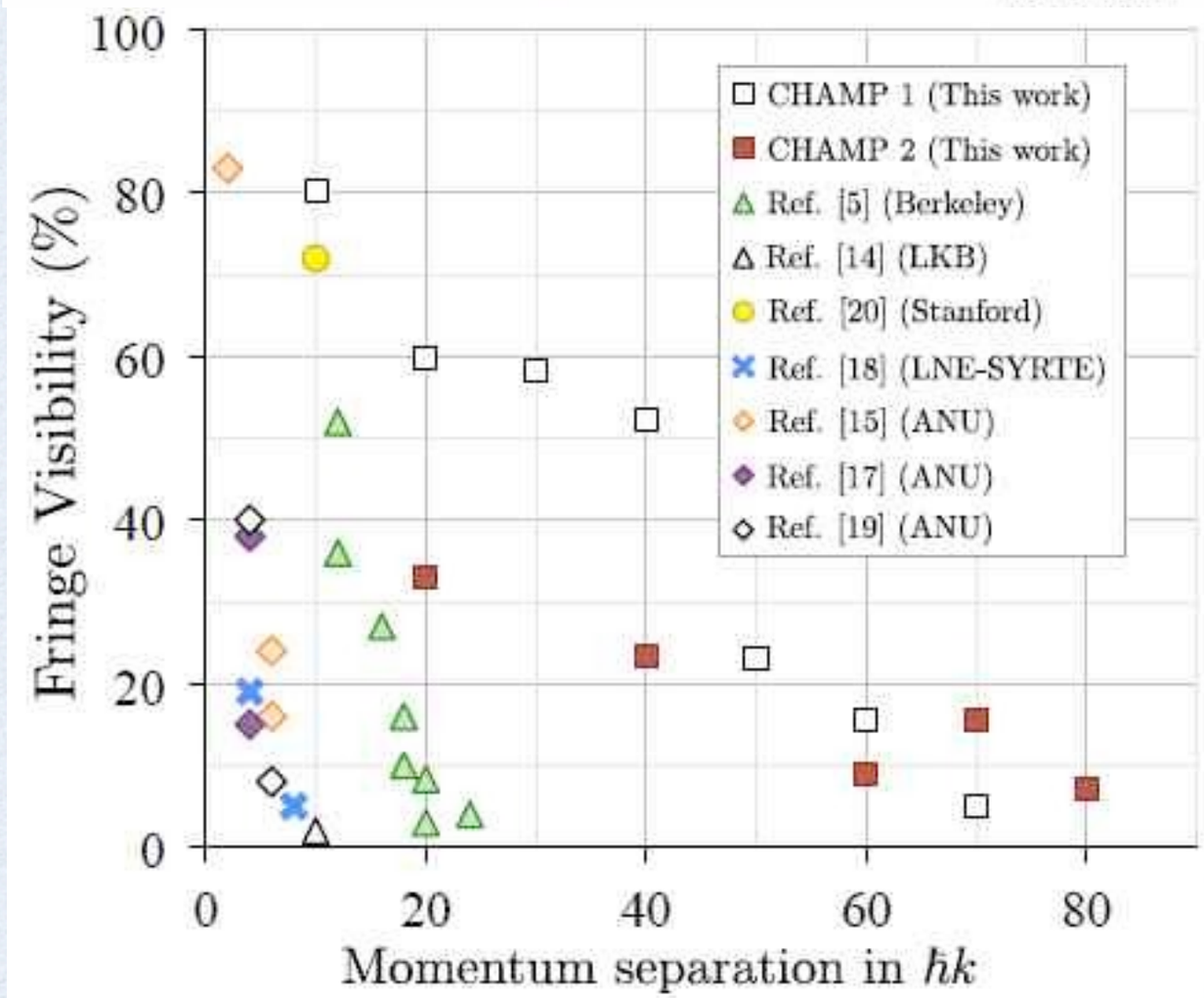


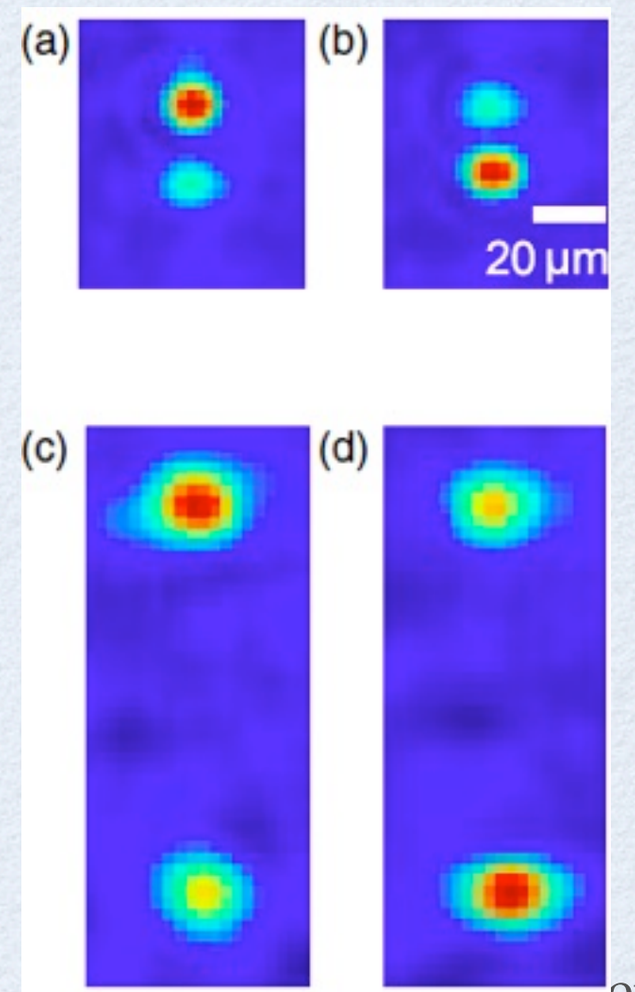

- New applications
  - GW, quantum gravity, etc.

# 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)

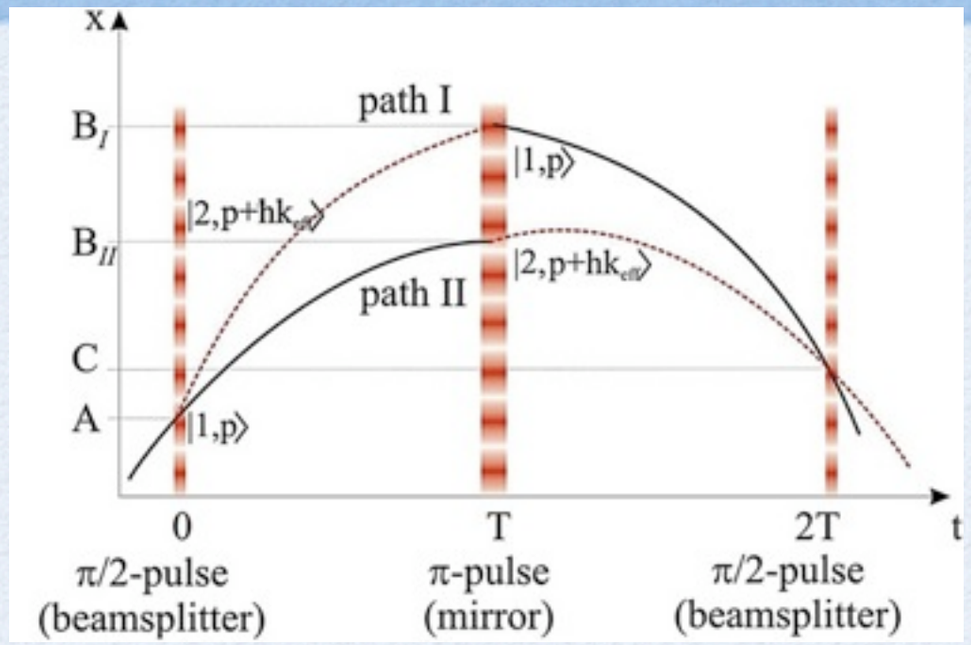


# Other possible applications of AI

- Fundamental physics
  - test of equivalence principle
  - measurement of gravitational red shift
  - test of atom neutrality
  - GW detection
  - quantum gravity
  - force measurements at micrometer scale
  - gravity for antimatter
- 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)

# AI measurements in space



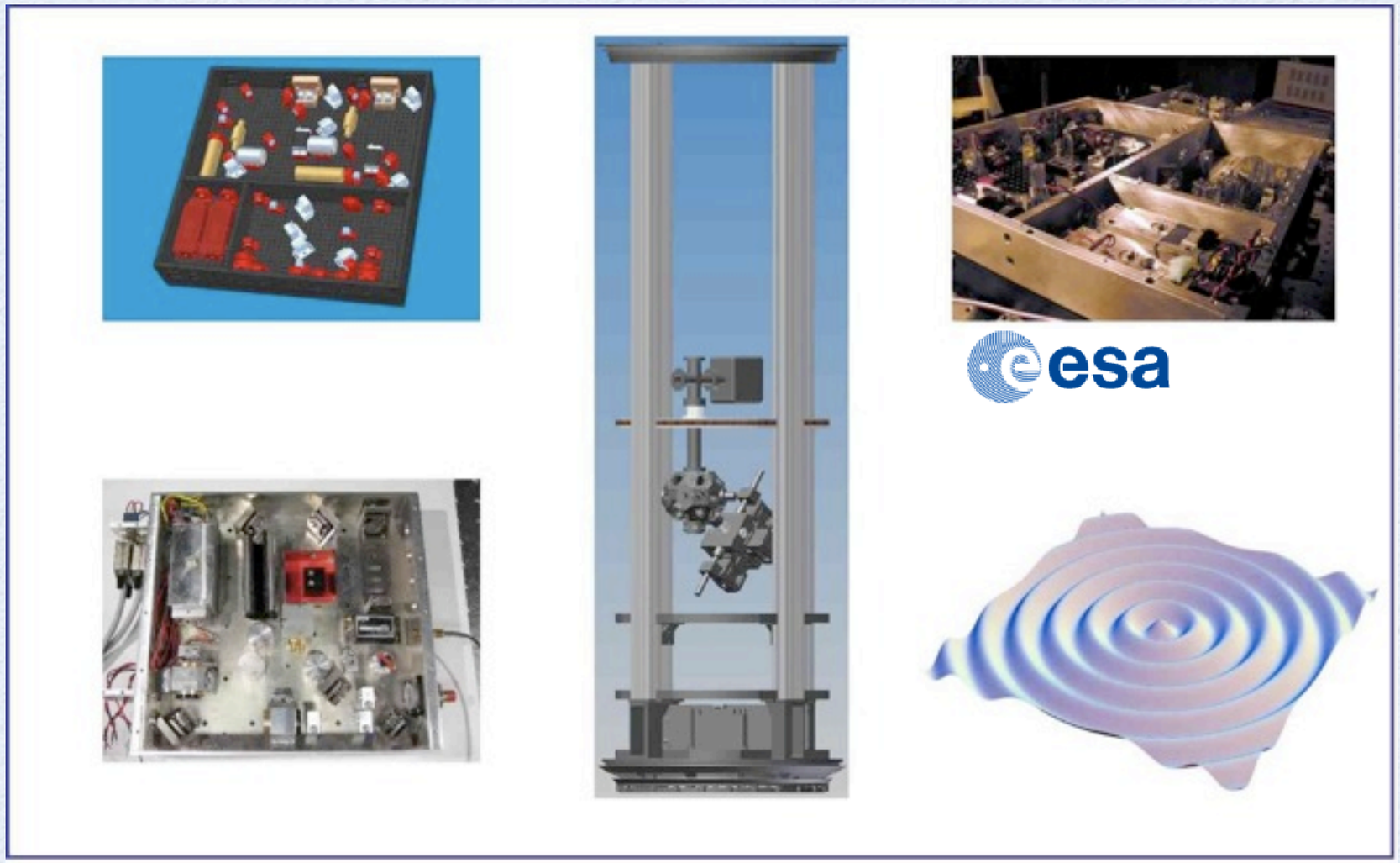

$$\Delta\phi = kgT^2$$

- 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)

# Space Atom Interferometers

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

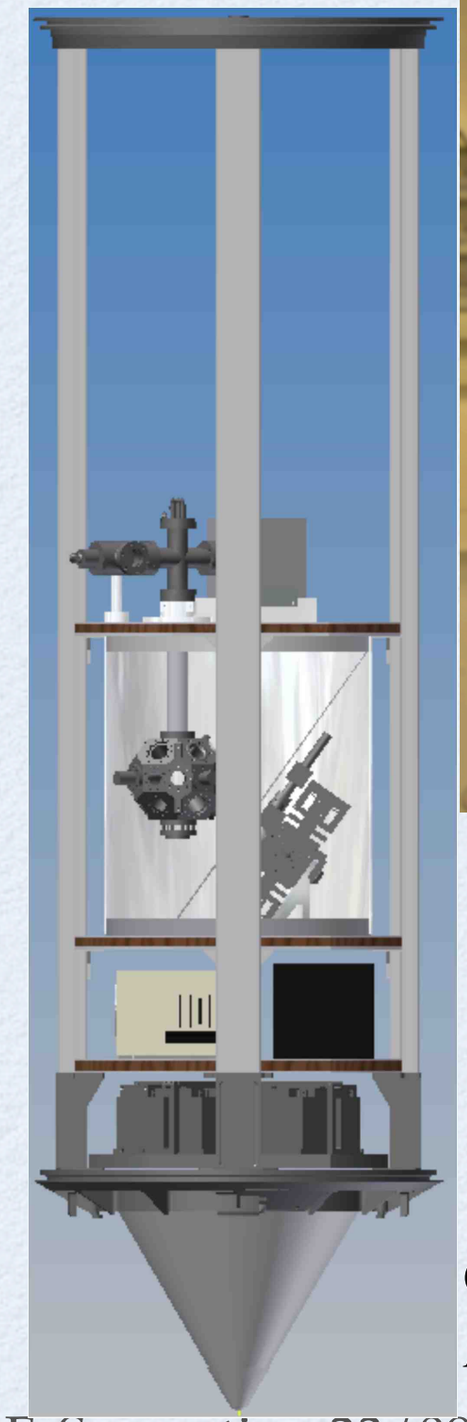
Project coordinator: Prof. G. M. Tino
Dipartimento di Fisica and LENS
Università di Firenze, Italy

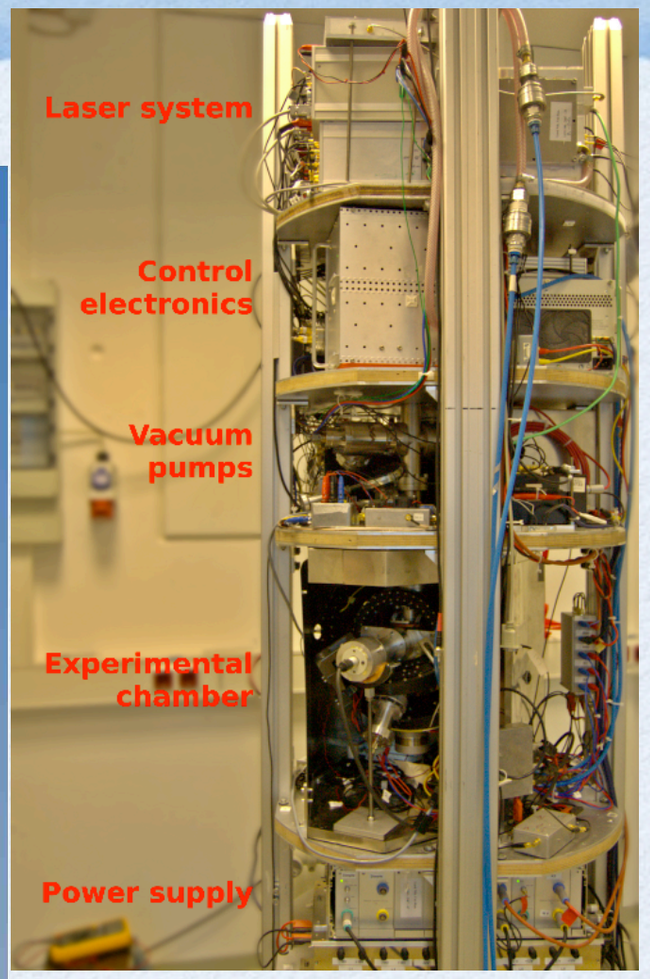


F. Sorrentino et al., *A compact atom interferometer for future space missions*, Microgravity Sci. Technol. **22**, 551 (2010)

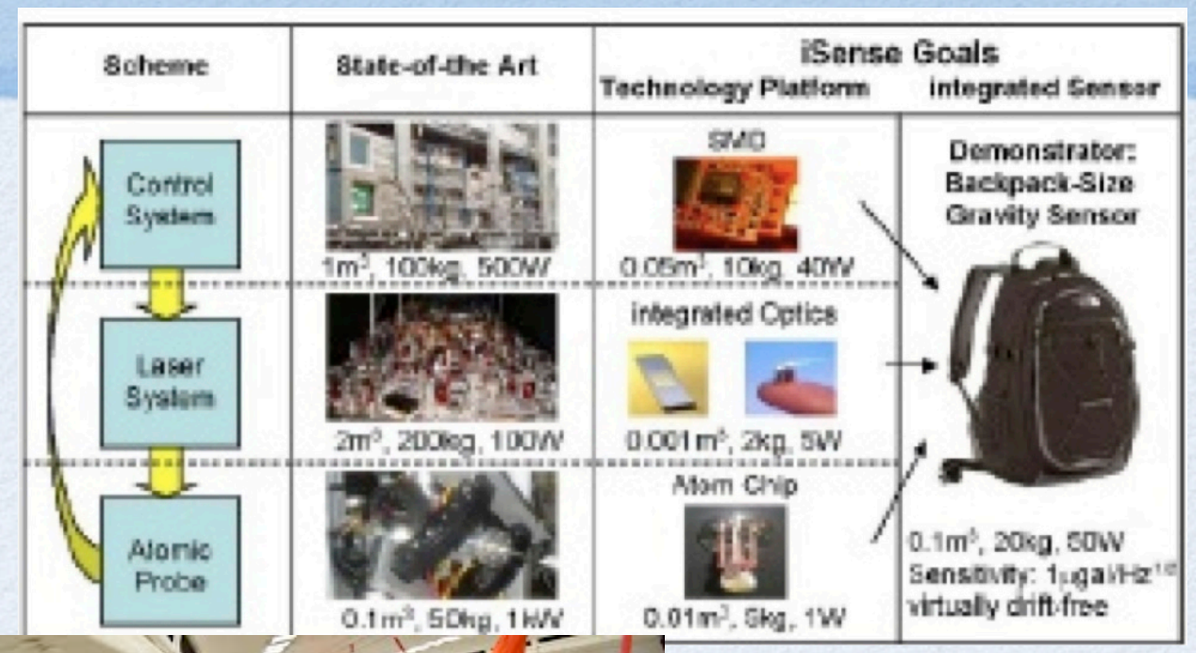
# TRL of AI

SAI



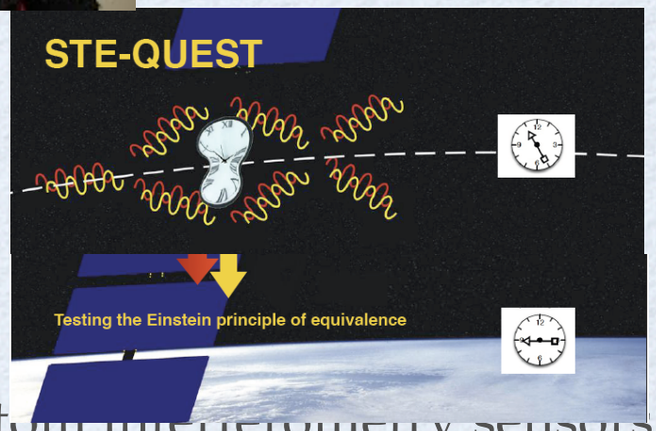



QUANTUS



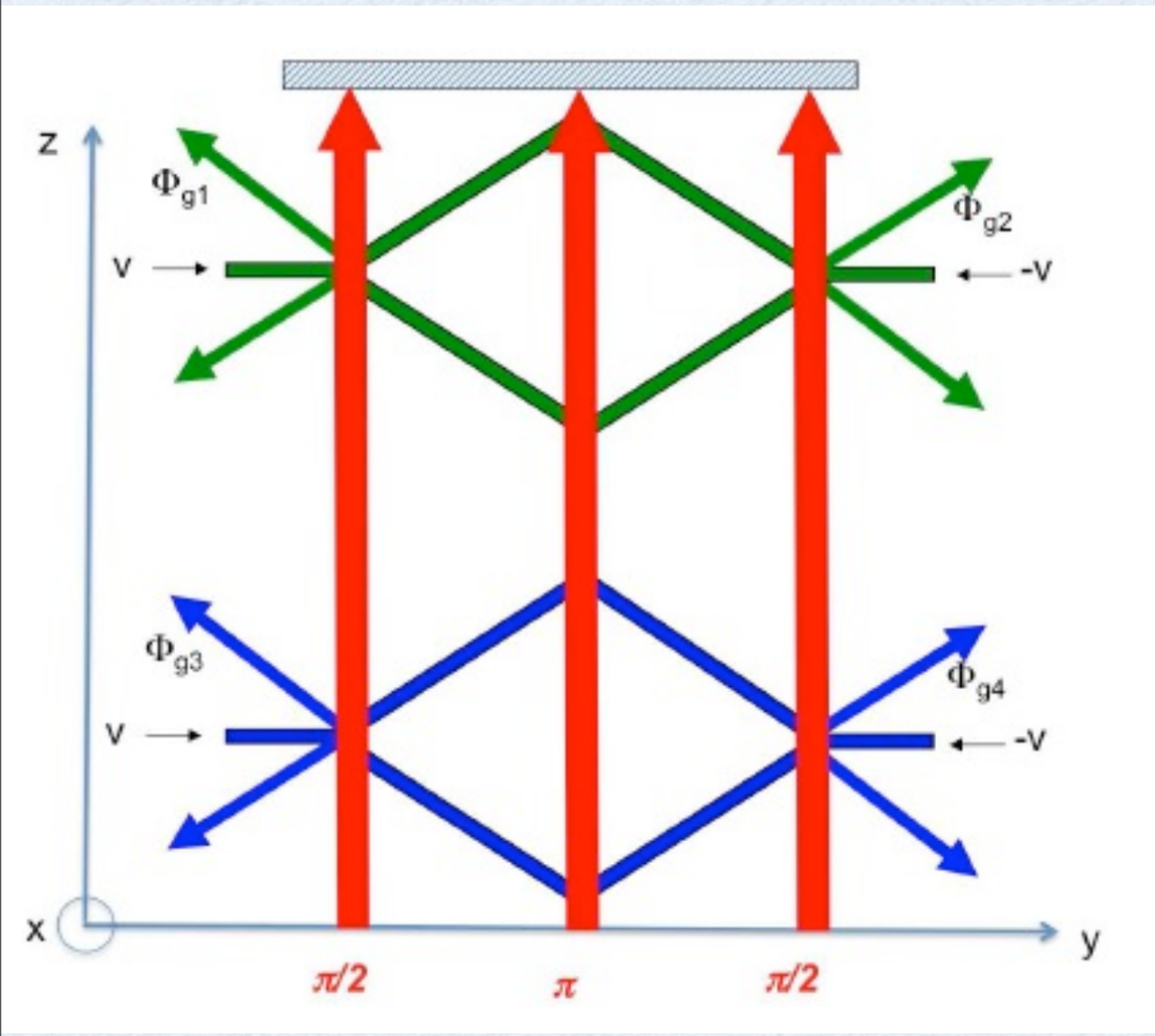


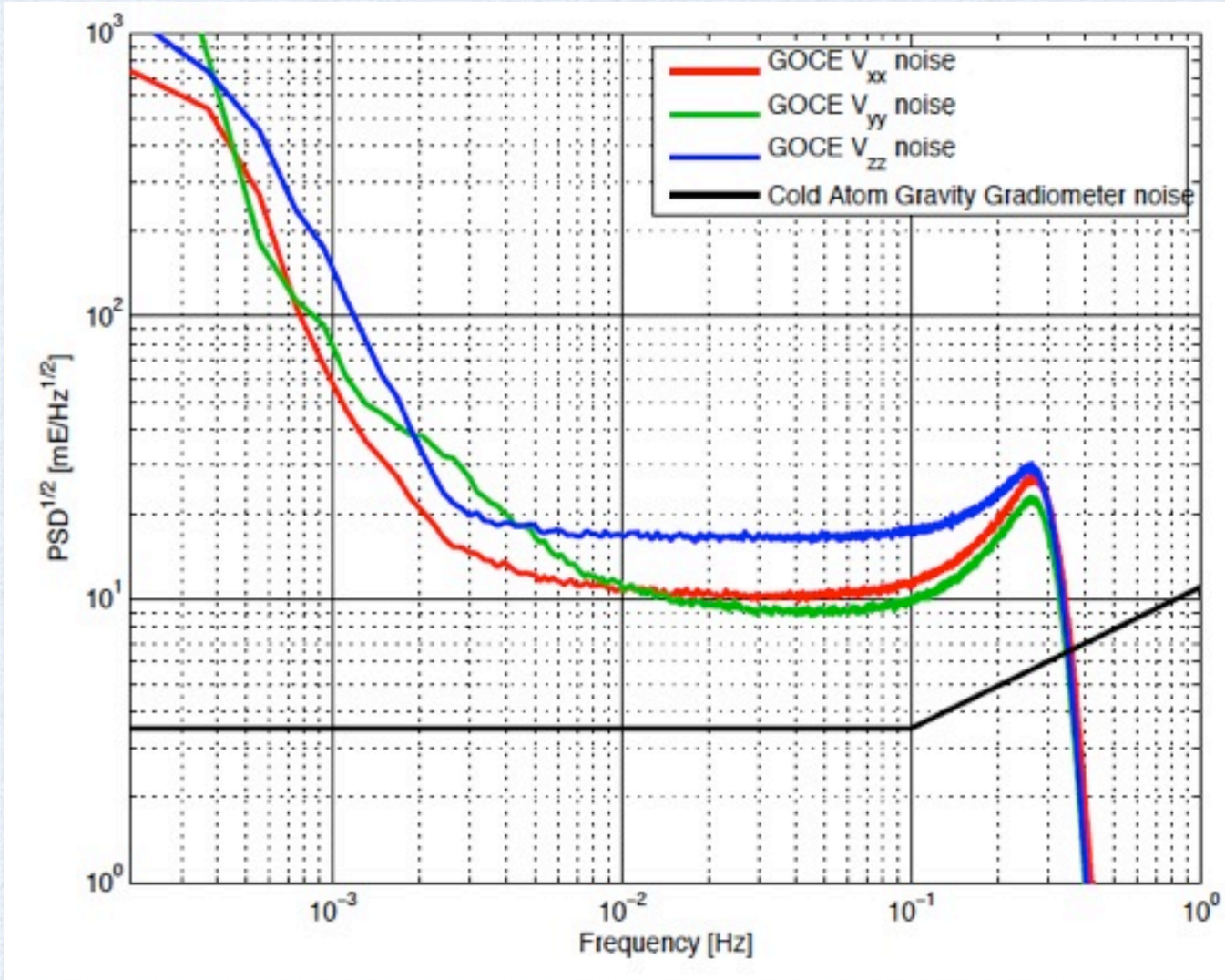
iSENSE


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

# AI for space gradiometry

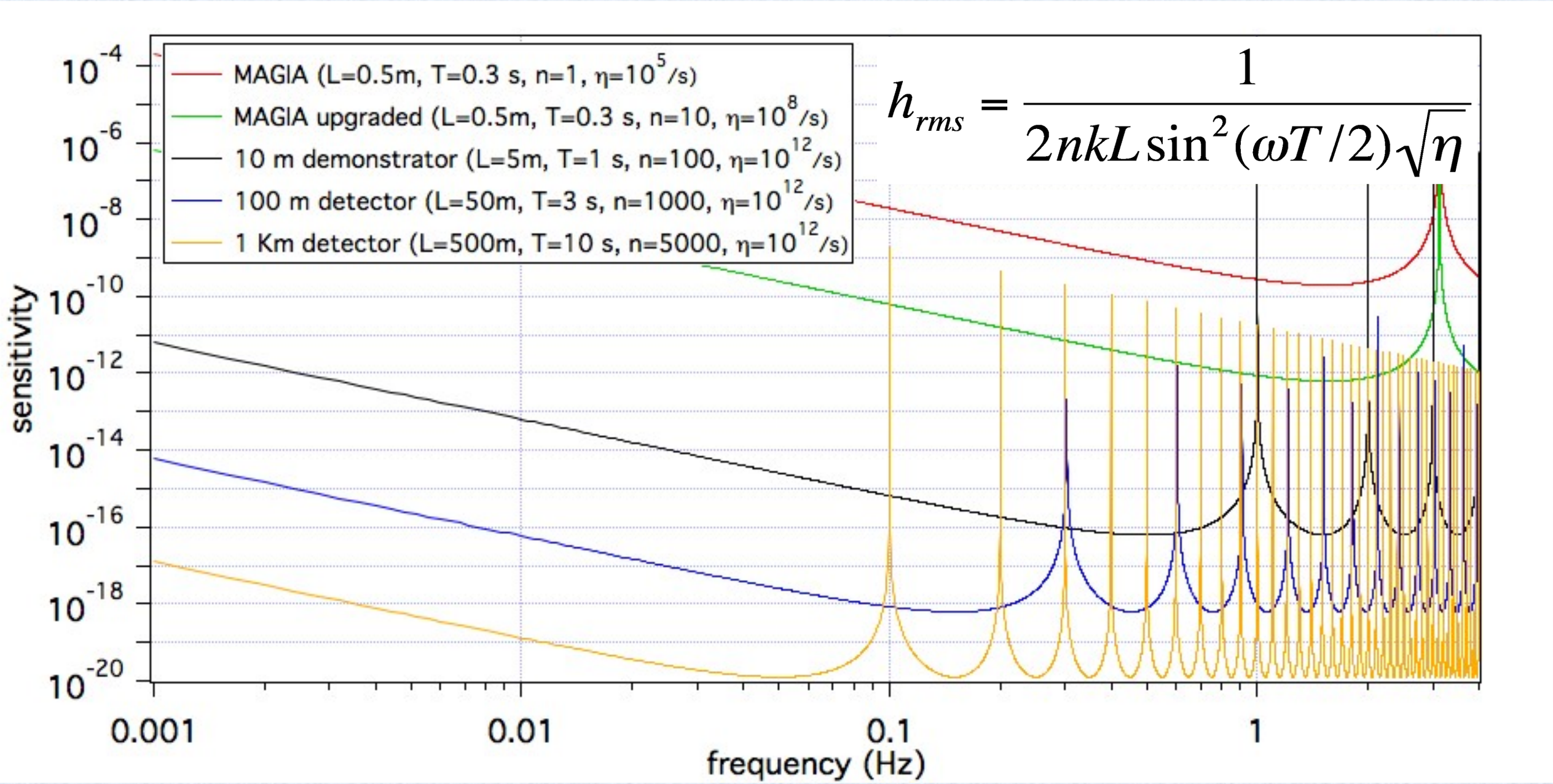



O. Carraz et al., arXiv:1406.0765 (2014)

# AI & GW detection

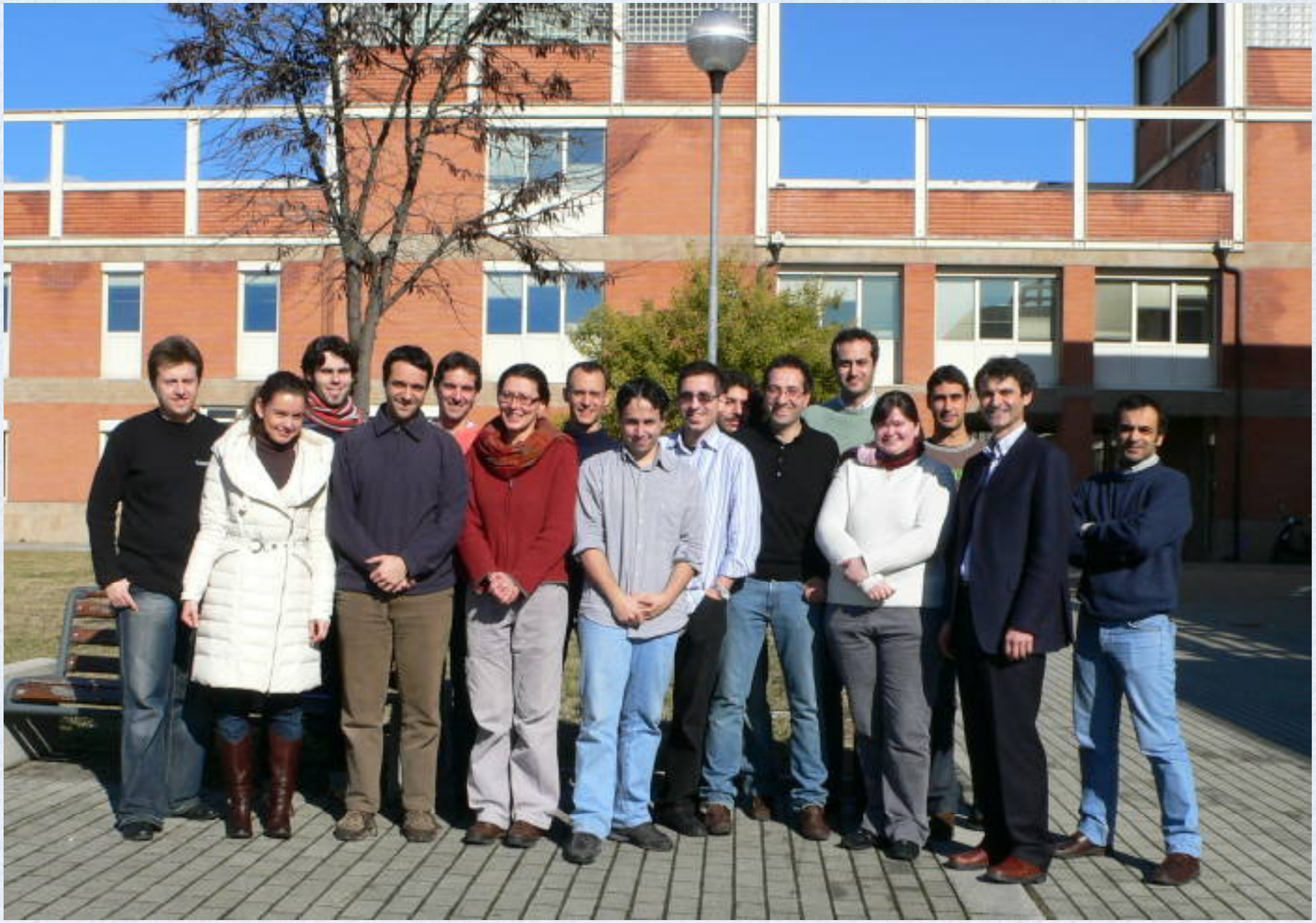
G. M. Tino, F. Vetrano and C. Lämmerzahl Eds., Special Issue on Gravitational waves detection with atom interferometry, Gen. Relativ. Gravit. **43**, 1901 (2011)



# Conclusions

- New atomic quantum devices have been developed with unprecedented sensitivity using ultracold atoms and atom optics
- Applications: fundamental physics, Earth science, space research
- MAGIA: statistical & systematic errors at the 100 ppm level
  - QPN limited gravity gradient measurement down to several hours
  - more in G. Rosi's talk tomorrow
- Atom interferometry with ultracold $^{88}$Sr
  - Fast and efficient cooling down to nK temperature
  - Long coherence time up to 500 s
  - Optical atomic clock and gravity sensor in the same device
- Future prospects: advanced atom interferometers for gravitational physics
  - gravity sensor with free fall + BO in optical lattice
  - large interaction time within small size
  - LMT splitters + high flux atomic source
  - foreseen G measurements down to the ppm level and WEP test @ $10^{-13}$
  - demonstrators for GW detection
- Well developed laboratory prototypes, first transportable devices, work in progress for space-compatible systems
- Expected large improvements in next future

# The team



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