Atom interferometry gravity sensors: state of the art and applications

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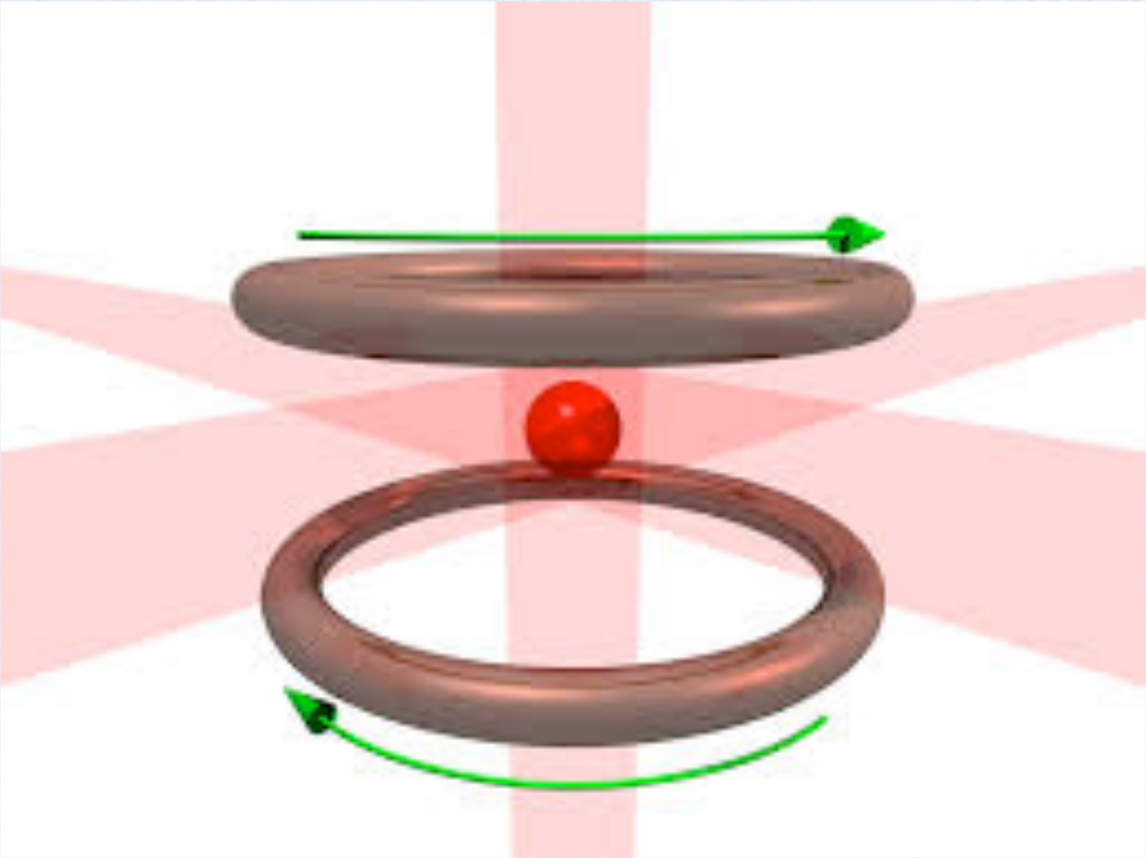
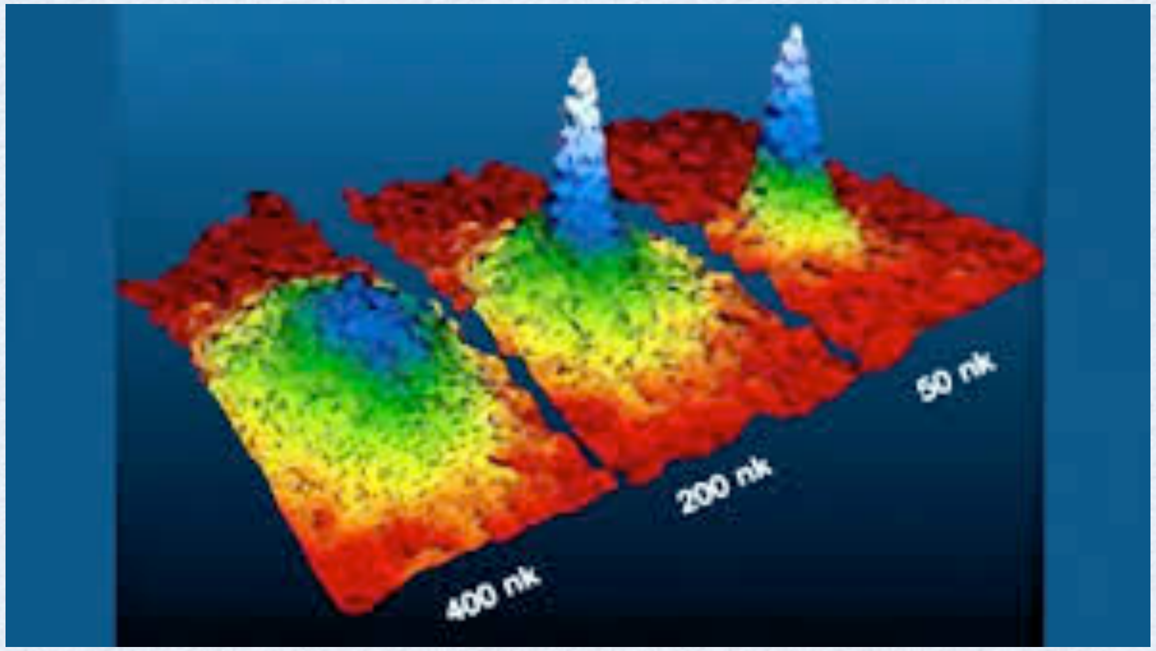
http://coldatoms.lens.unifi.it

Outline

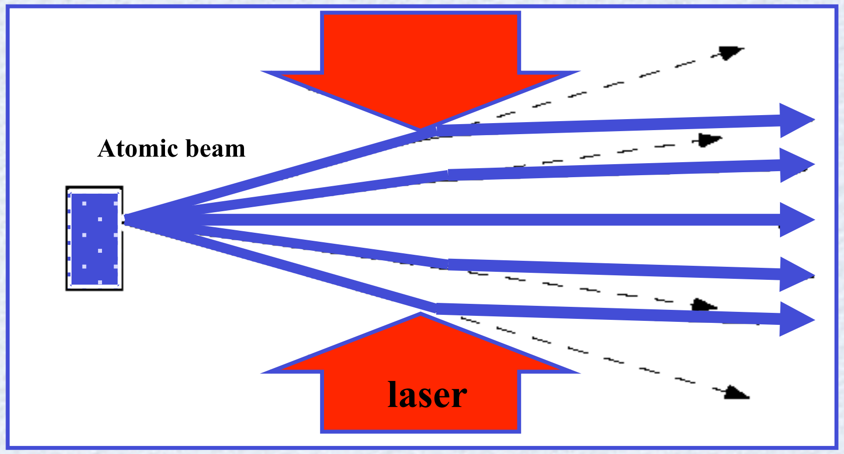
- Introduction to quantum sensors
  - atom optics and ultracold atoms
  - atom interferometers
- Precision measurements with quantum sensors
  - inertial sensing and geophysical applications
  - fundamental constants: *G* and recoil measurements
  - tests of fundamental physics (GR, quantum gravity)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

Ultracold atoms and atom optics

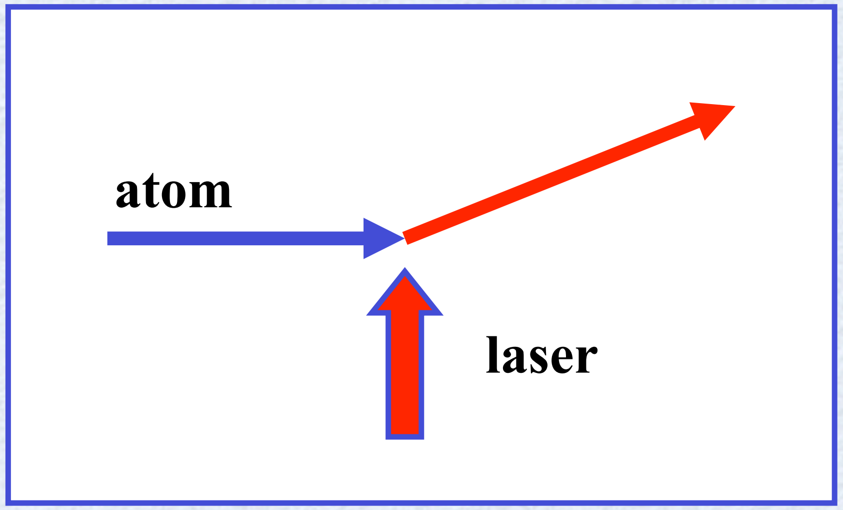




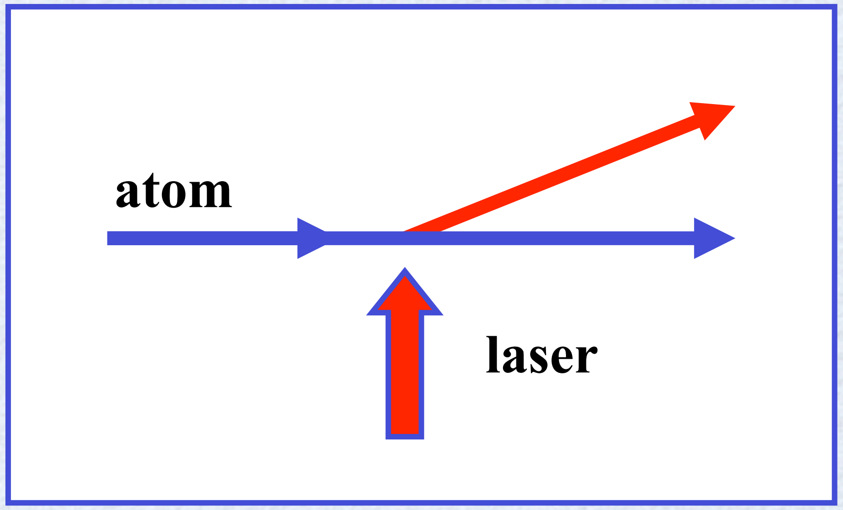
Lenses



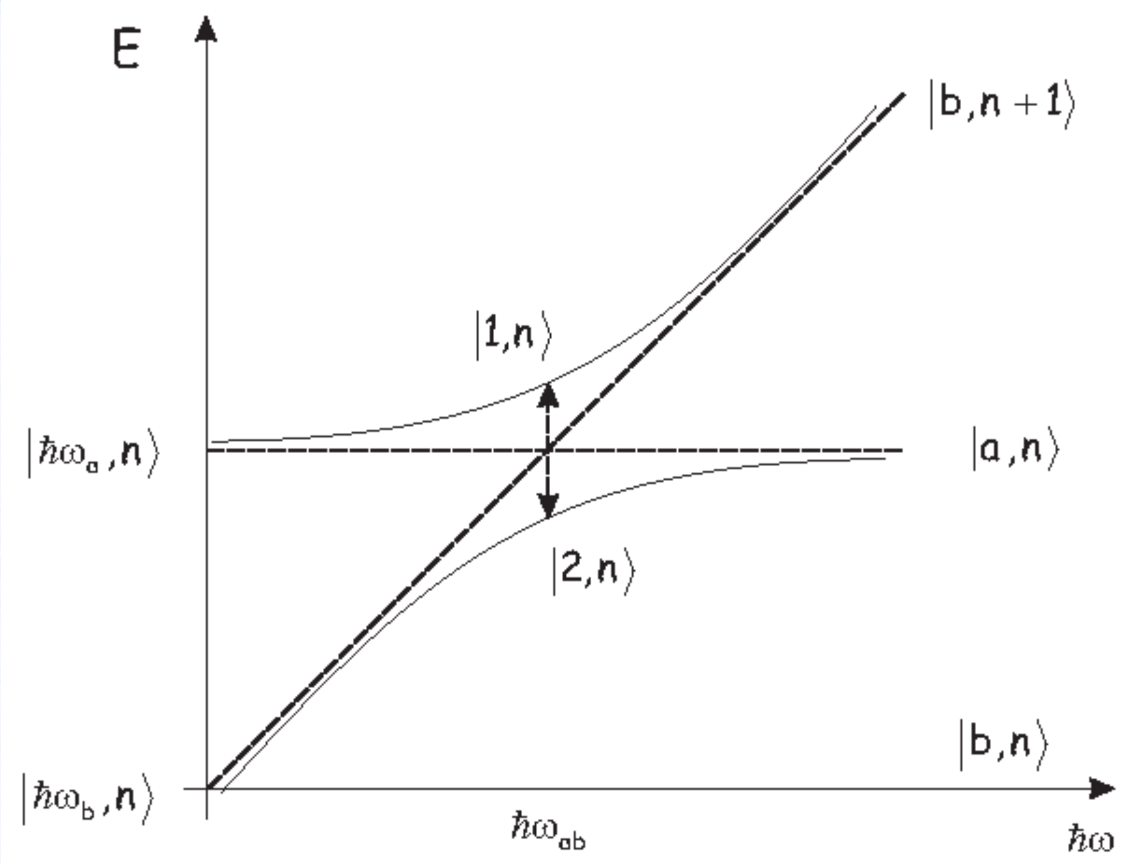
Mirrors

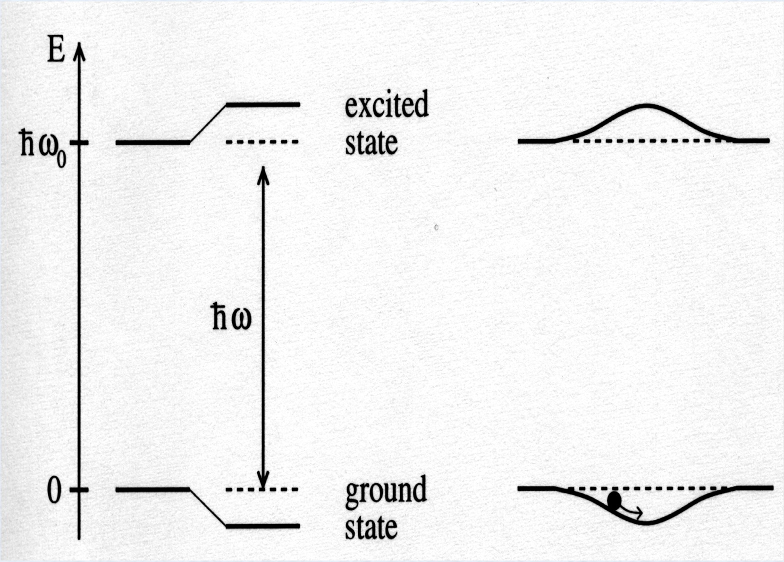


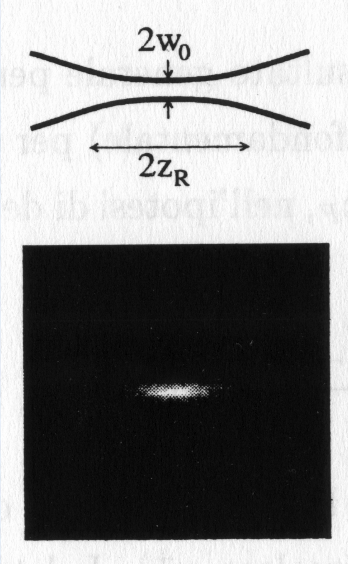
Beam splitters



Light shift & optical traps

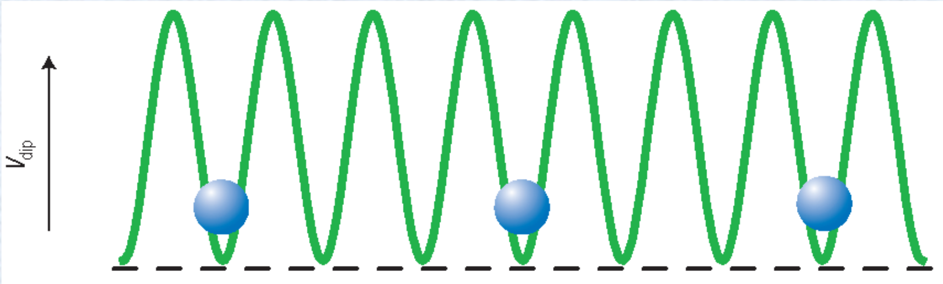




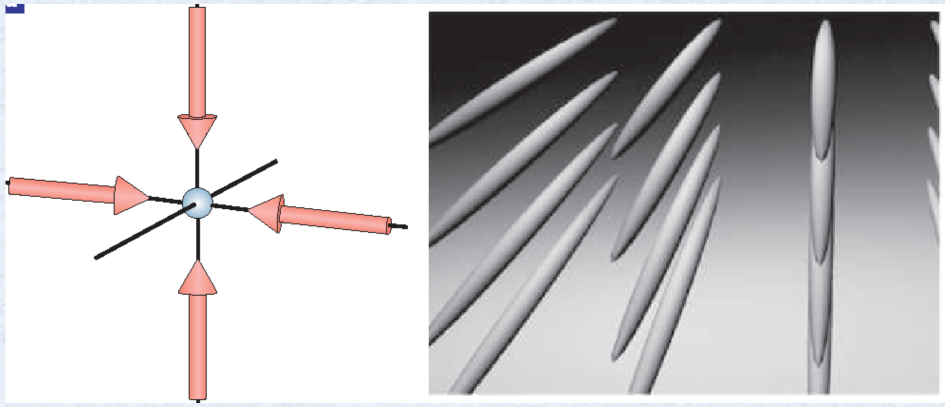


$$V_{\mathrm{dip}}(\mathbf{r}) = -\mathbf{d}\cdot\mathbf{E}(\mathbf{r}) \propto \alpha(\omega_L)\left|\mathbf{E}(\mathbf{r})\right|^2$$

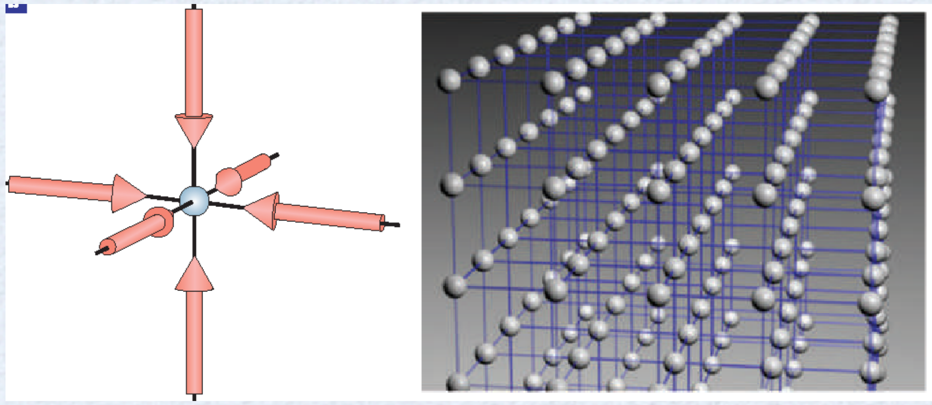
optical lattices



1D optical lattice array of 2D disk-like trapping potentials



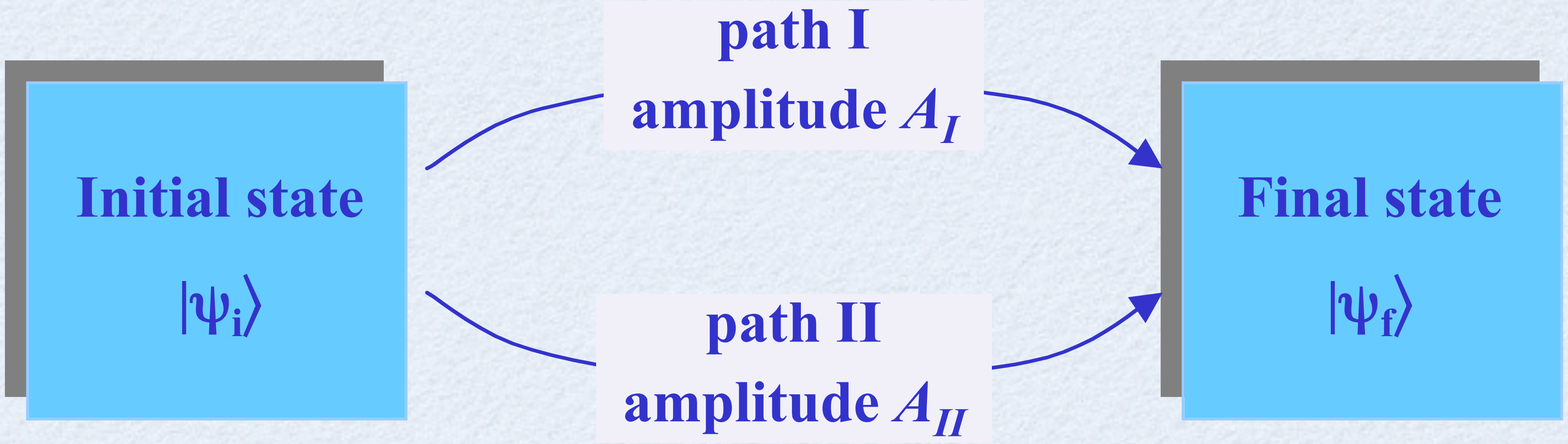
2 D optical lattice array of 1D potential tubes



3 D optical lattice 3D simple cubic array of h.o. potentials

Matter-wave interferometry

Quantum interference


Initial state

$|\psi_i\rangle$

path I

amplitude A_I

path II

amplitude A_{II}

Final state

$|\psi_f\rangle$

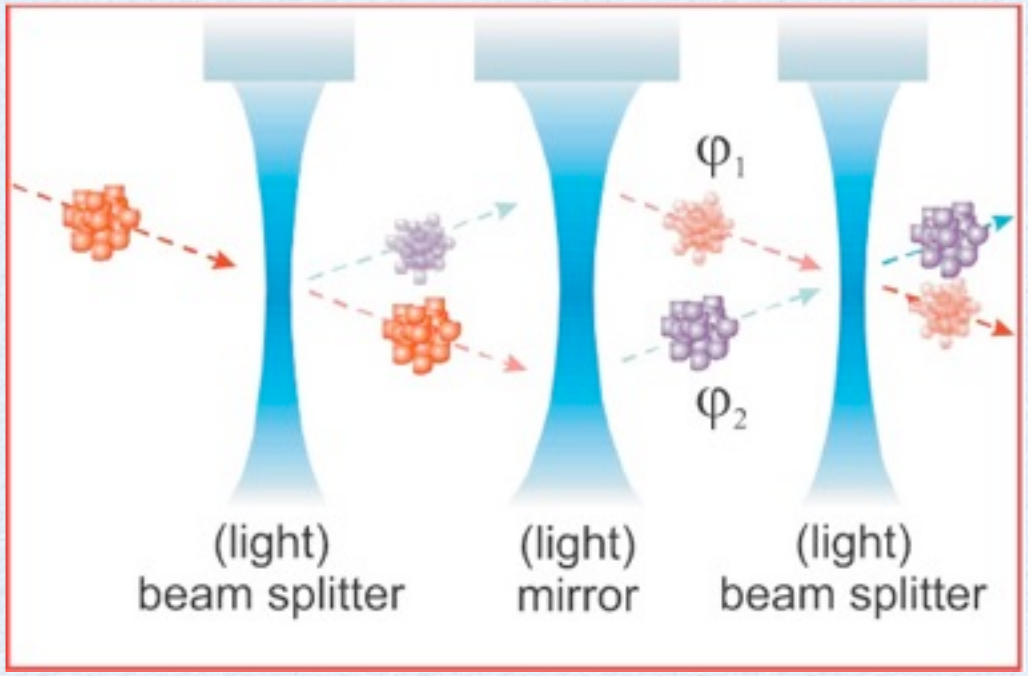
Interference of transition amplitudes

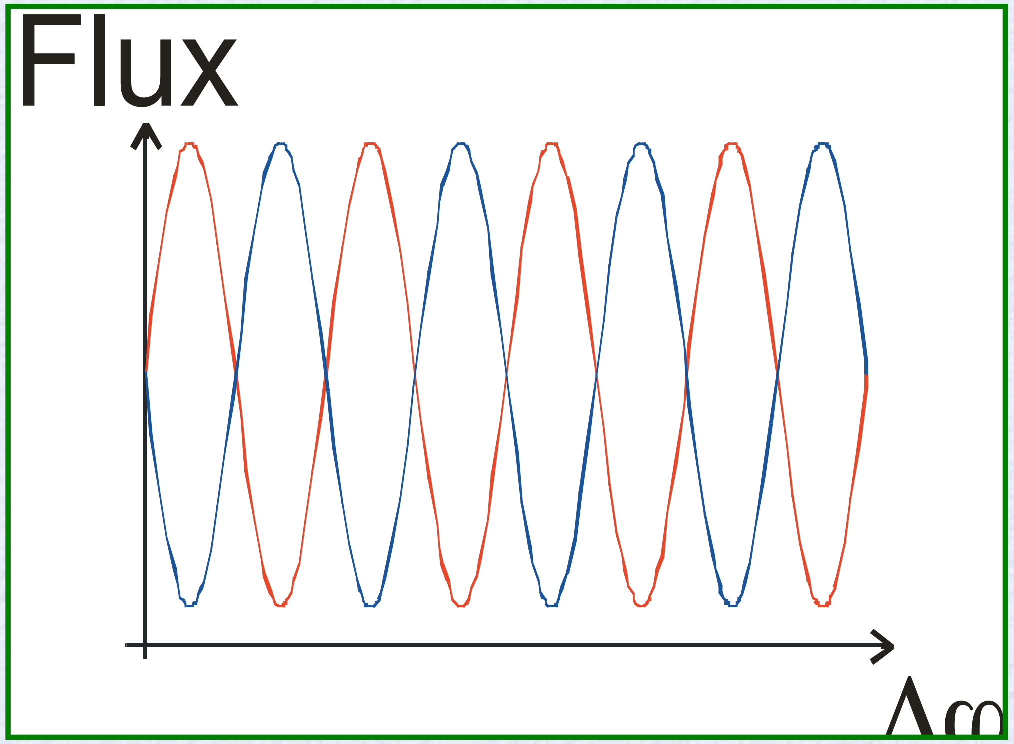
$$P(|\psi_i\rangle \rightarrow |\psi_f\rangle) = |A_I + A_{II}|^2 = |A_I|^2 + |A_{II}|^2 + 2Re(A_I A_{II}^*)$$

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

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

Atom interferometry





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

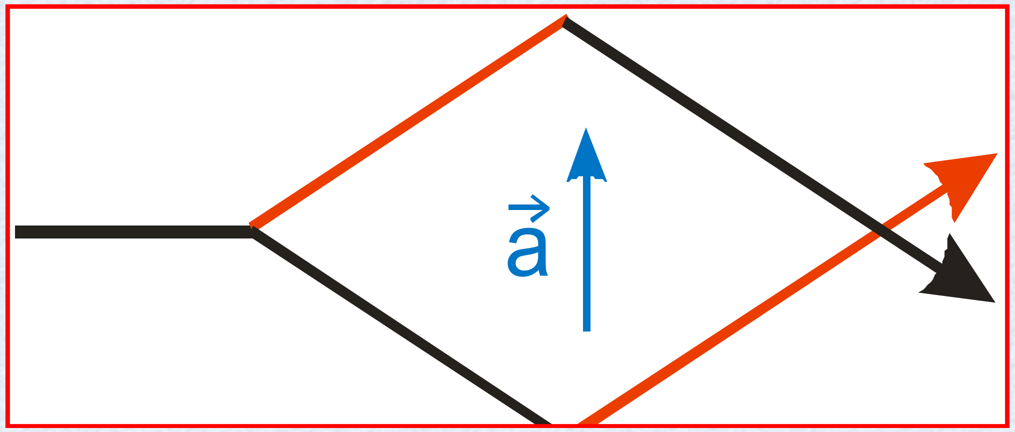
- atom optics
- different internal states/isotopes
- phase difference may depend on:
  - accelerations
  - rotations
  - photon recoil
  - laser phase
  - laser frequency detuning
  - electric/magnetic fields
  - interactions with atoms/molecules

Possible applications of AI

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

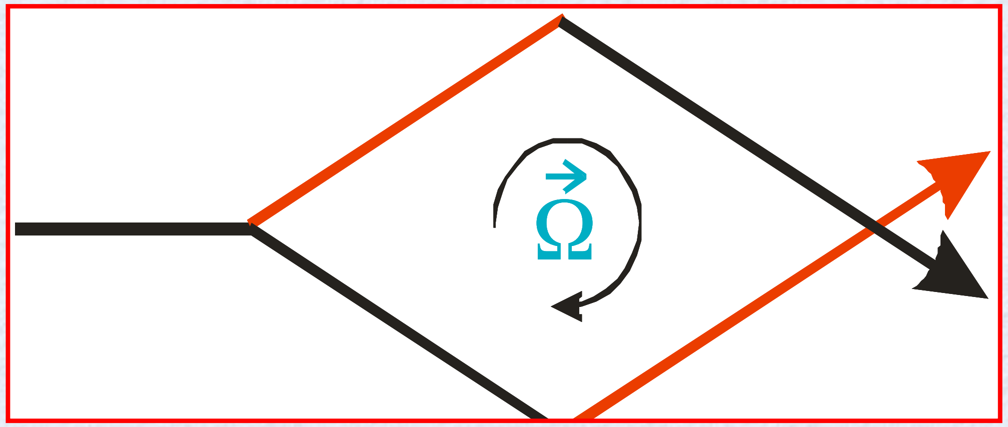
Accelerations



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

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

Rotations



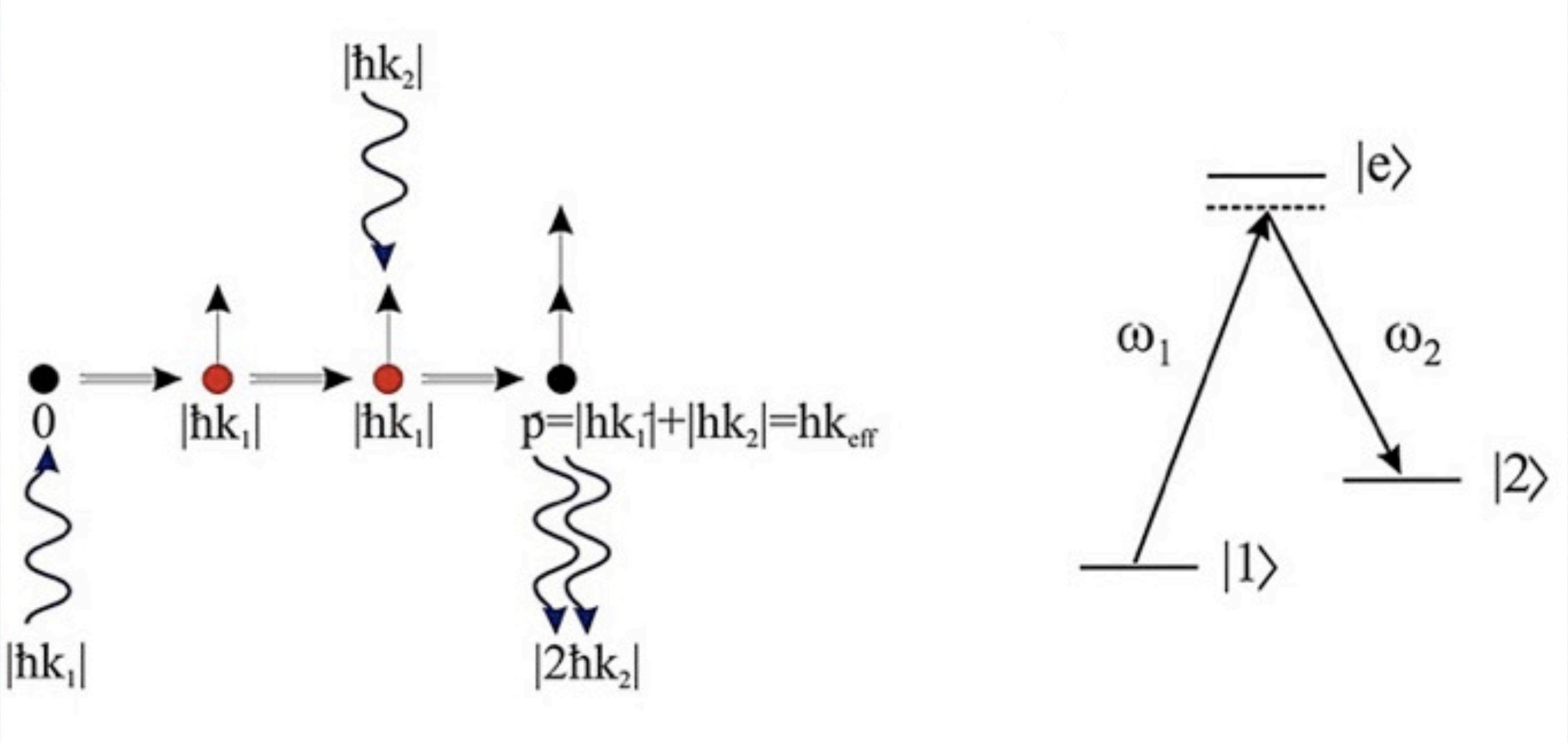
$$\Delta\Phi_{rot} = 2\pi\frac{2m_{at}}{h}A \cdot \Omega$$

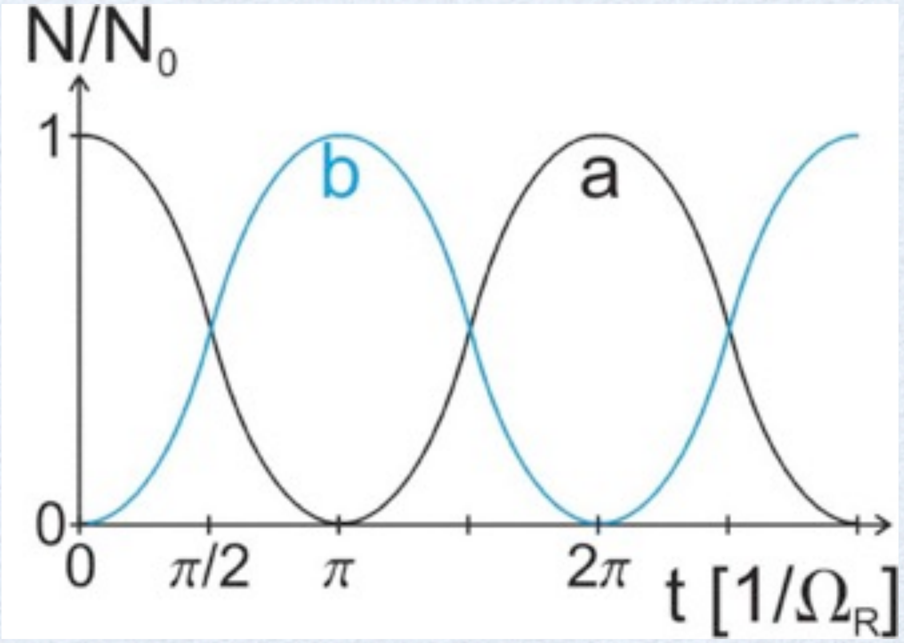
$$\frac{\Delta\phi_{mat}}{\Delta\phi_{ph}} \sim \frac{m_{at}\lambda c}{h} \approx 5 \cdot 10^{11}$$

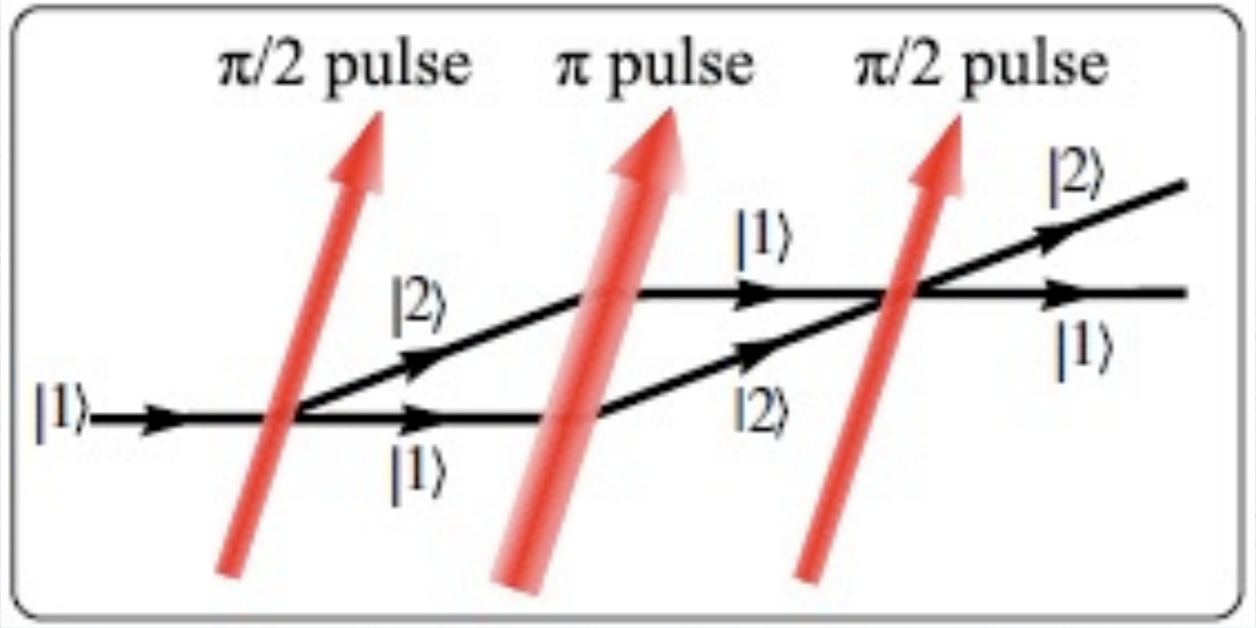
Present limitations of AI

- 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)

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

LONGITUDINAL PULSES

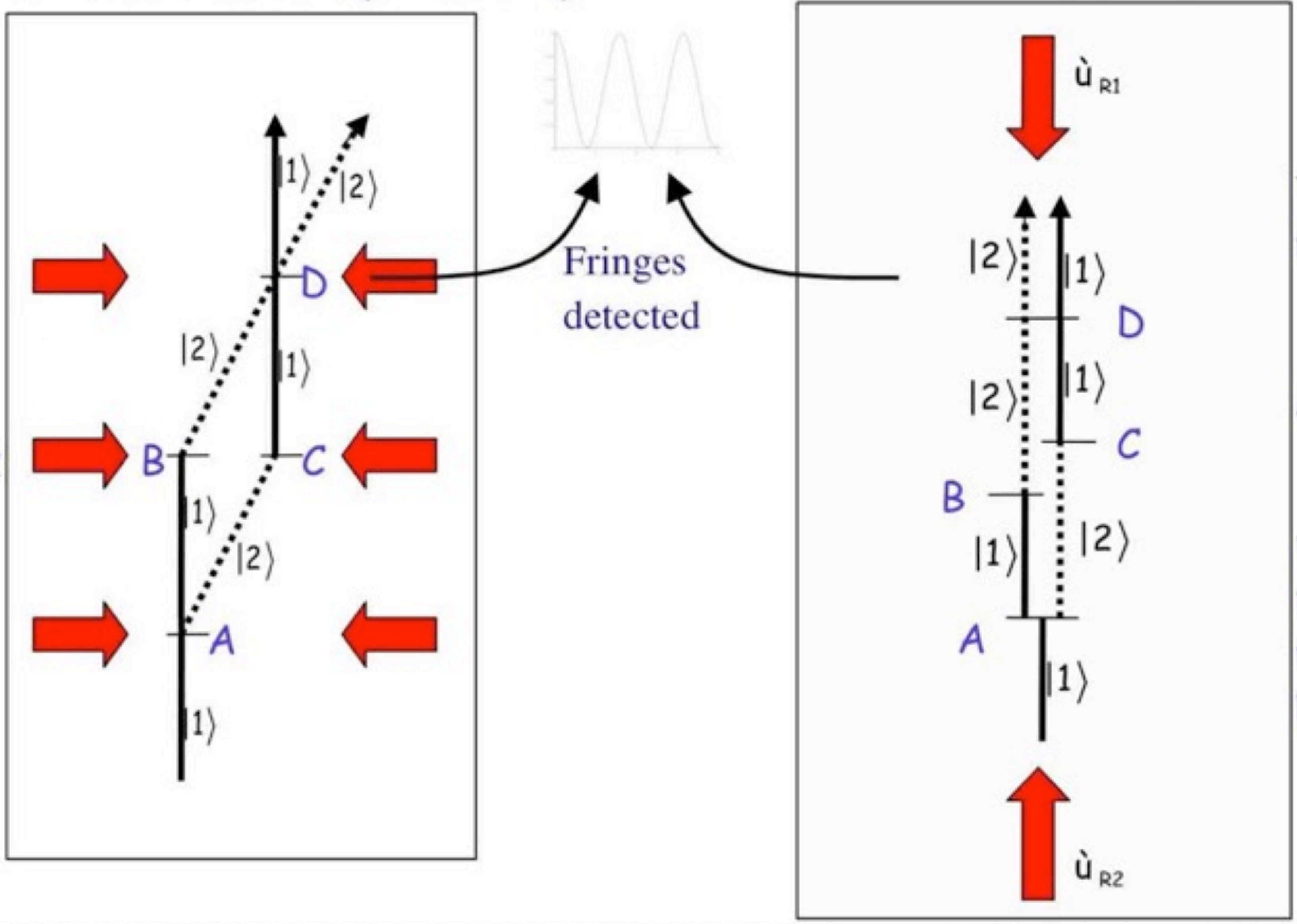
-no area enclosed

-used to measure accelerations (GRAVIMETERS)

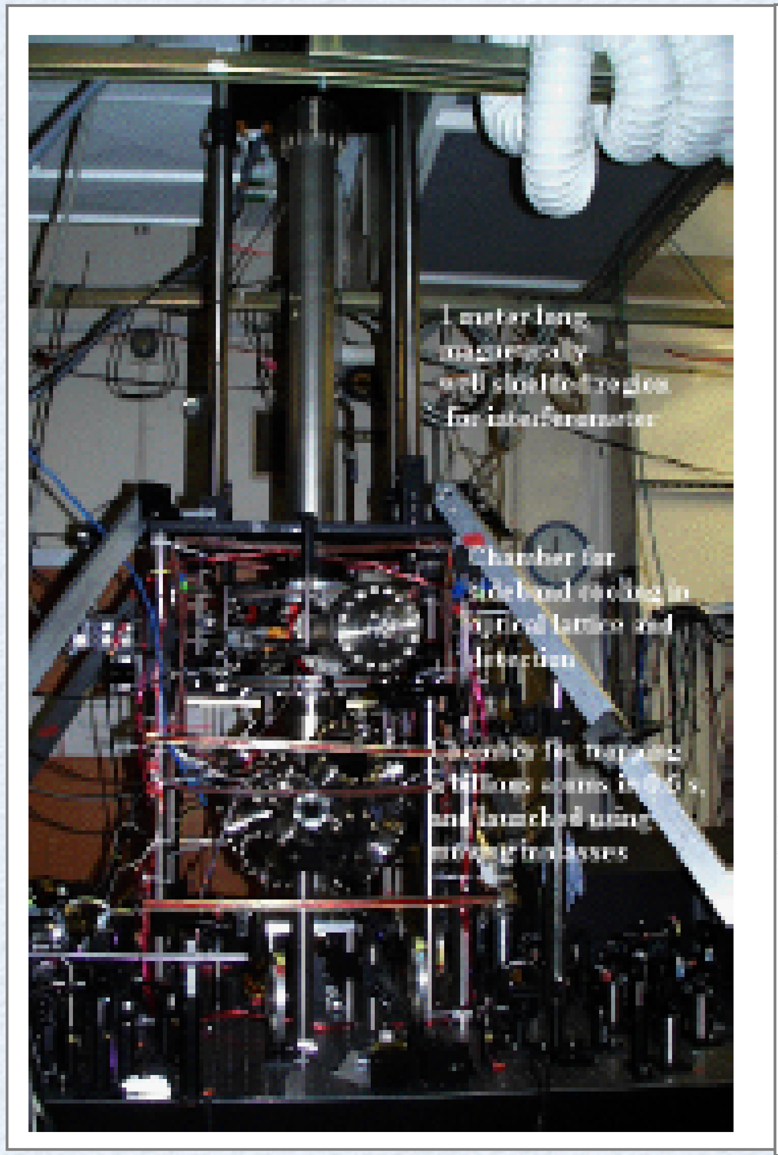
With an acceleration g, the phase difference

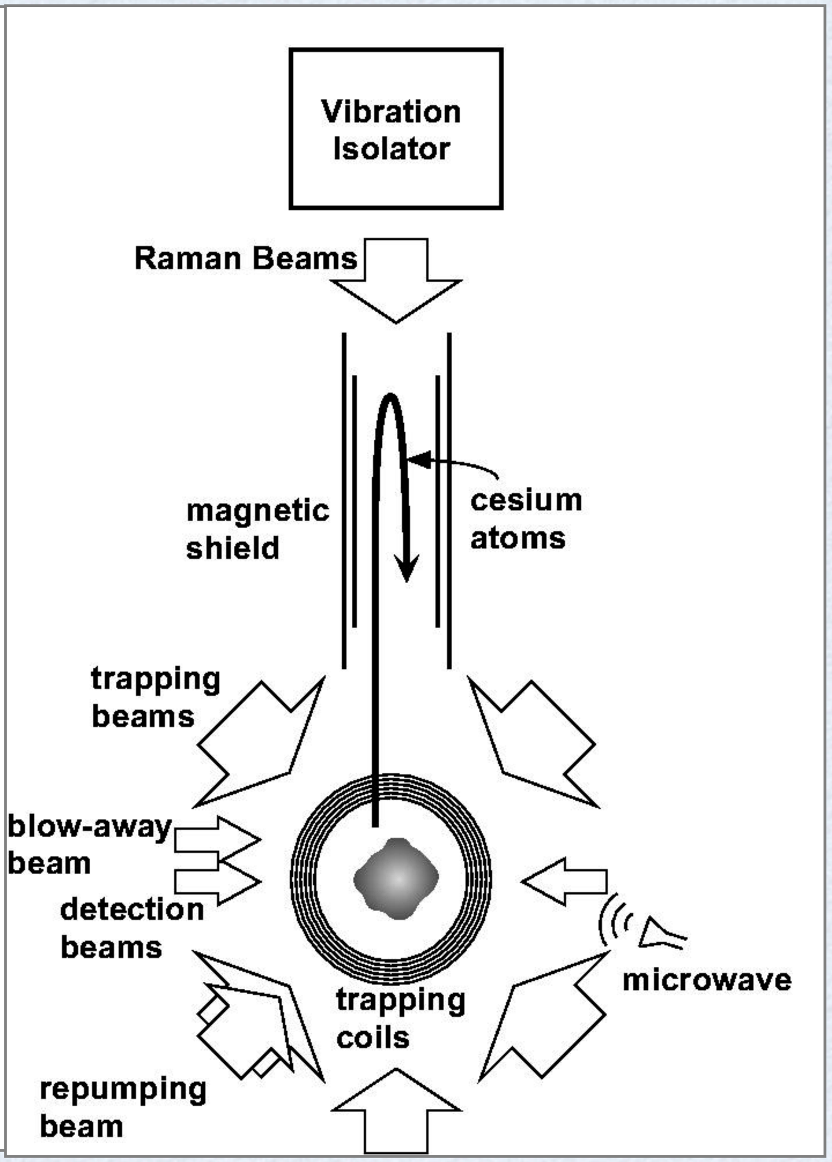
$$\Delta\phi=k_{eff}g\,T^2$$

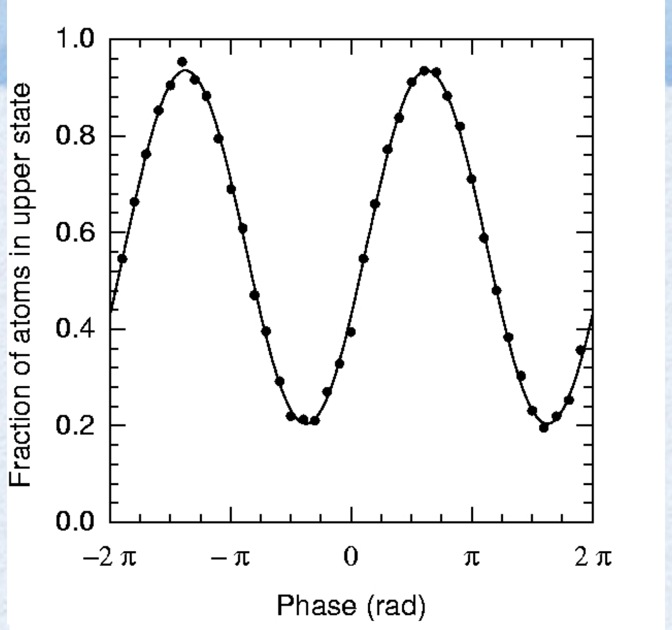
where ***k*** is the laser wavenumber and ***T*** the time interval between laser pulses

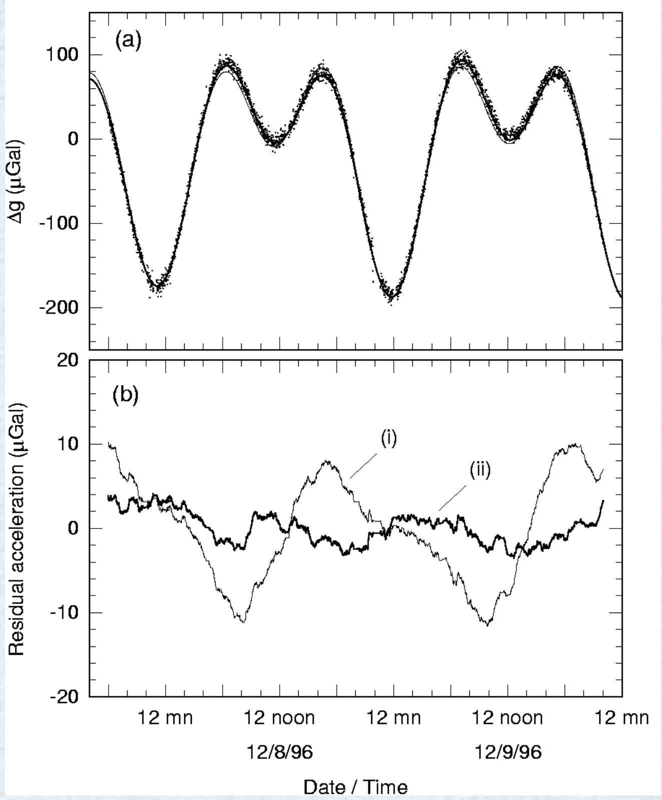


Atom gravimeters (Stanford, Berlin, Paris)





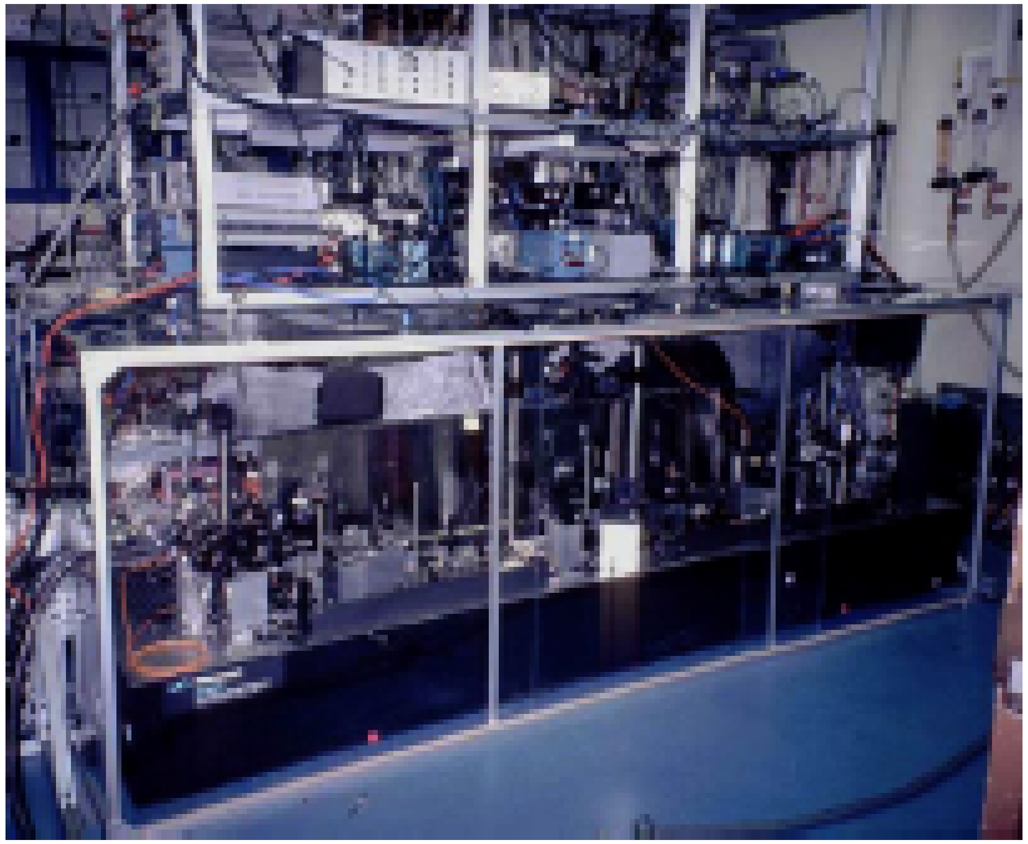




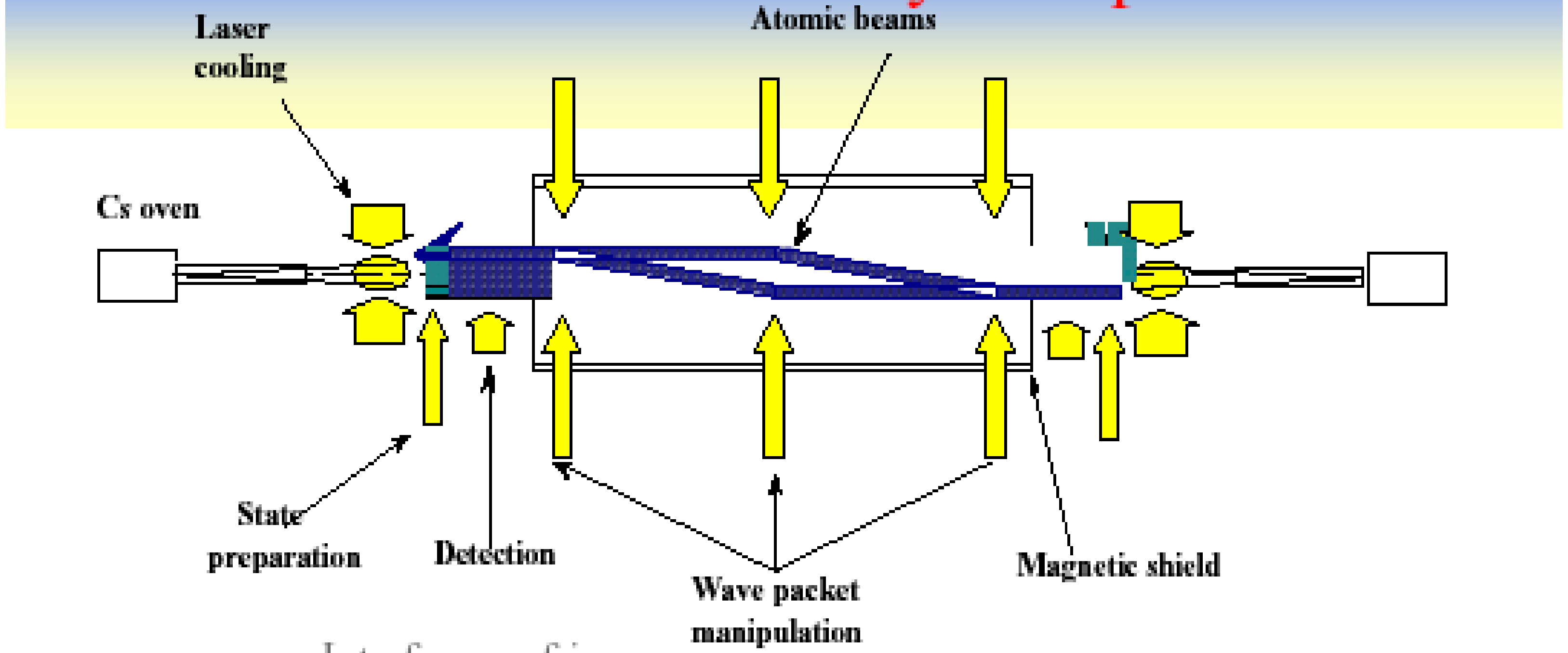
resolution: 3x10^{-9} g in 1 second (SYRTE)
averaging down to 2x10^{-10} g after 30 min (SYRTE)
accuracy: ~ 10^{-9} g, limited by tidal models

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)

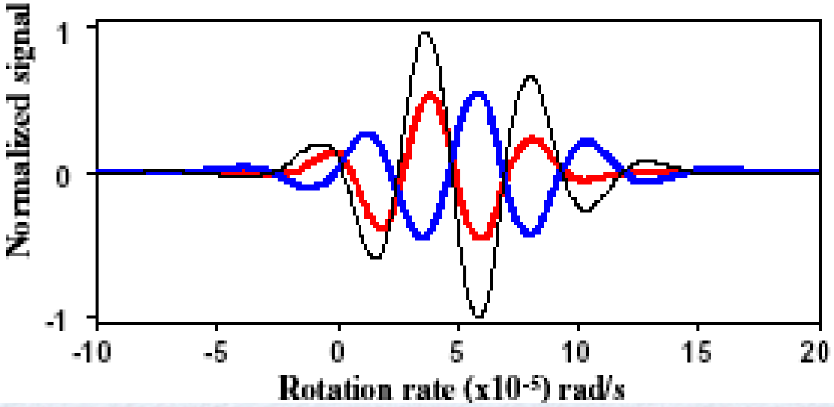
Gyroscopes (Stanford, Paris, Hannover)



Atomic Beam Gyroscope



Interference fringes



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

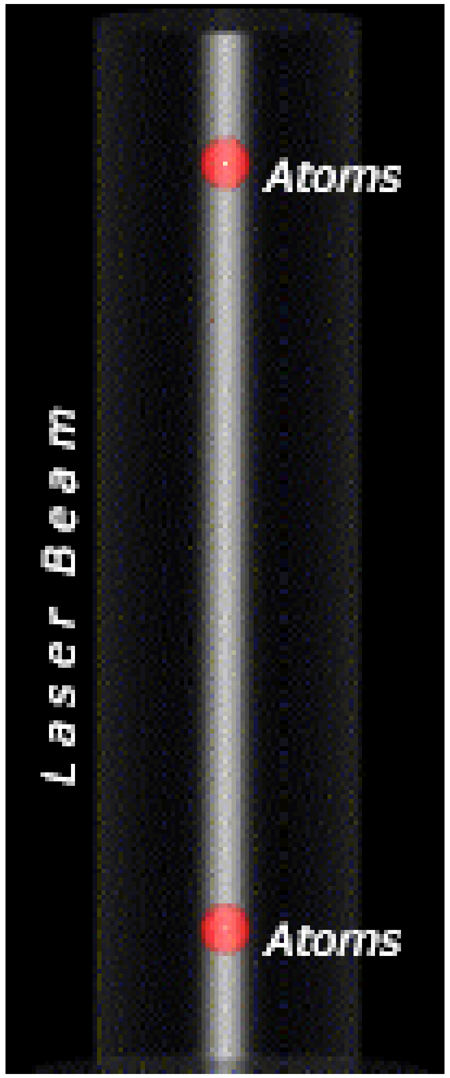
scale factor stability < 5 ppm

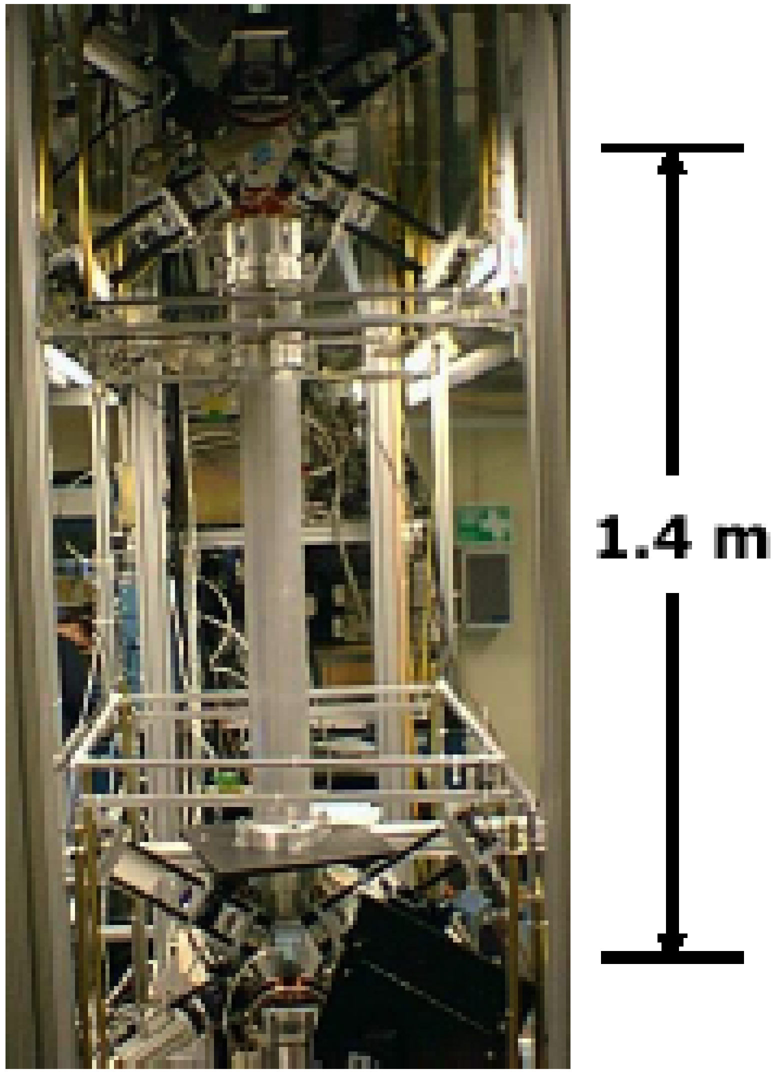
bias stability $< 70\,\mu$deg/h

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

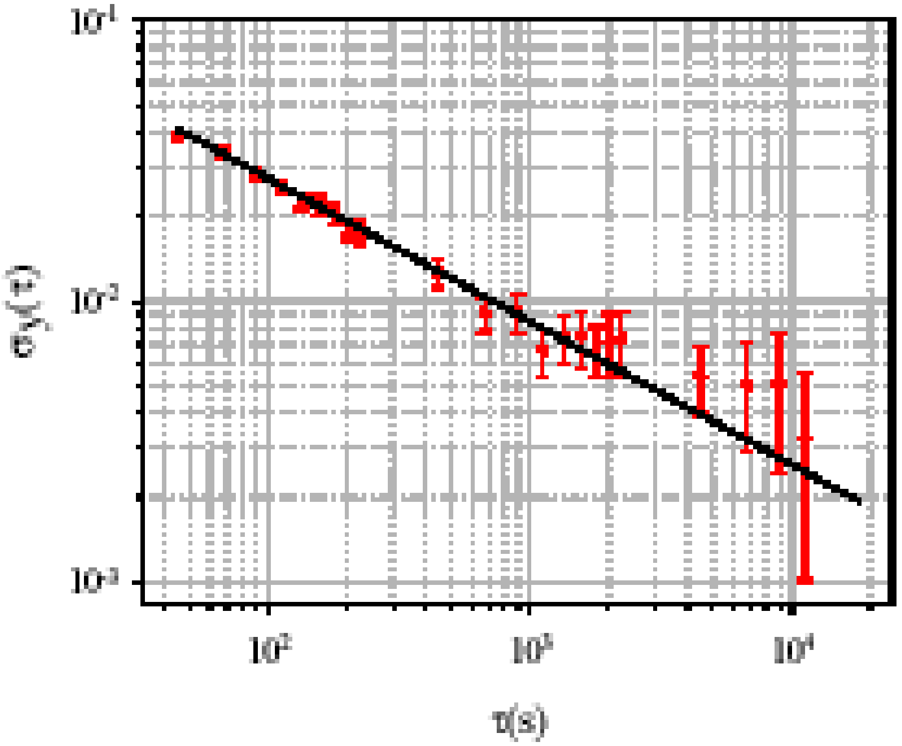
D. S. Durfee, Y. K. Shaham, M.A. Kasevich, Phys. Rev. Lett. 97, 240801 (2006)

Gravity gradiometers (Stanford, Firenze)





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



Demonstrated diffential acceleration sensitivity:

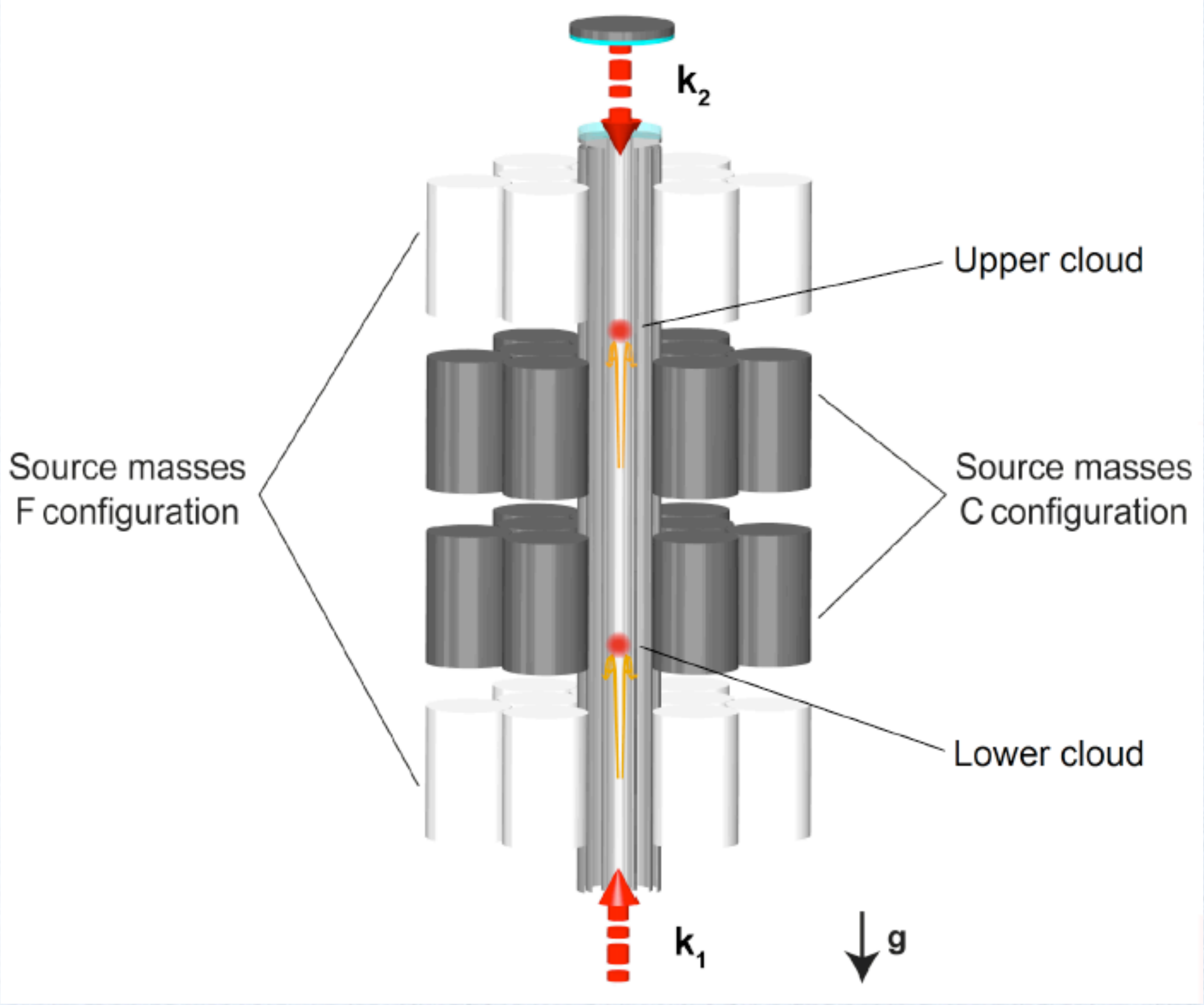
4x10^{-9} g/$Hz^{1/2}$

(2.8x10^{-9} g/$Hz^{1/2}$ per accelerometer)

MAGIA

Misura Accurata di G mediante Interferometria Atomica

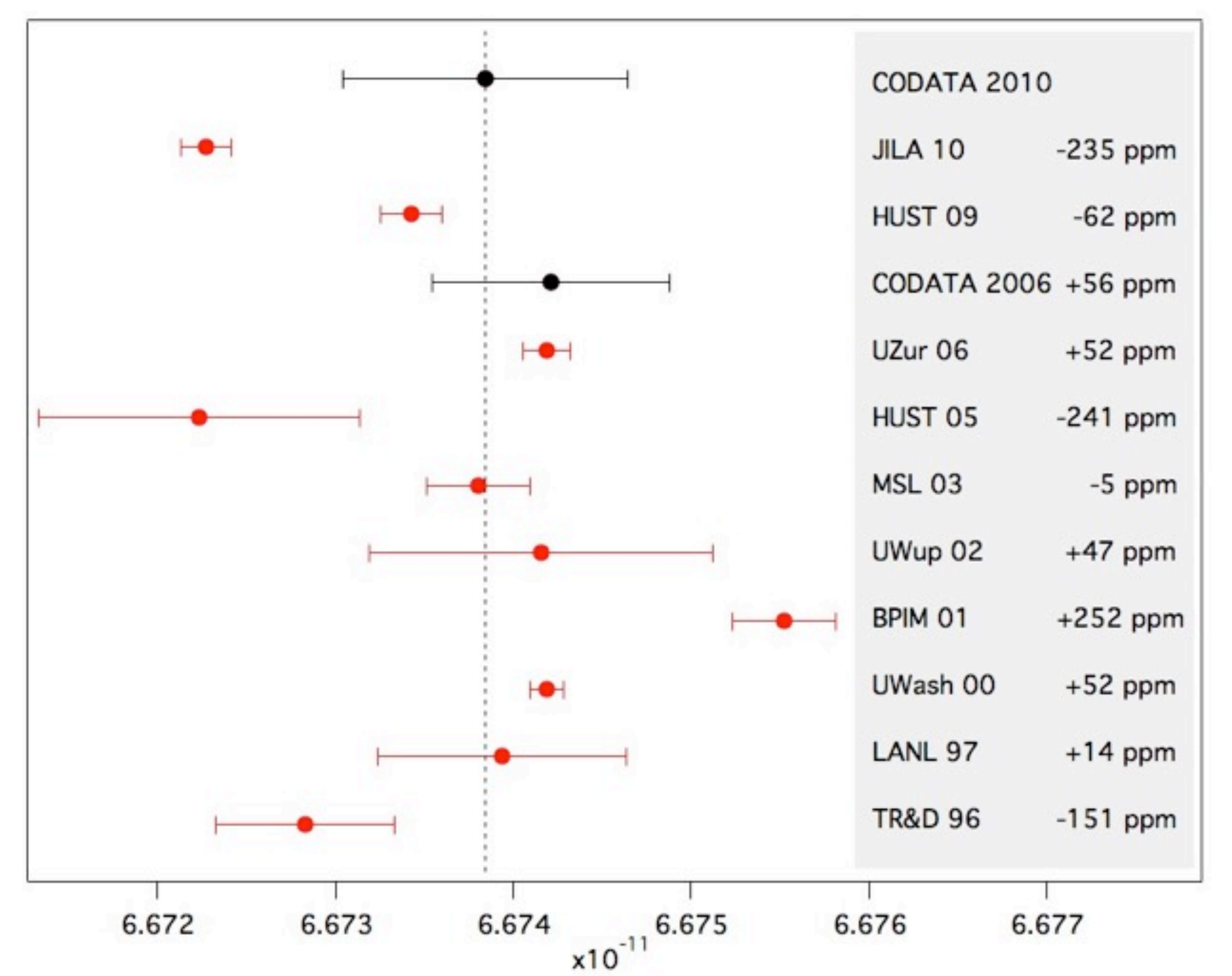
- Rb fountain gradiometer
- + set of source masses

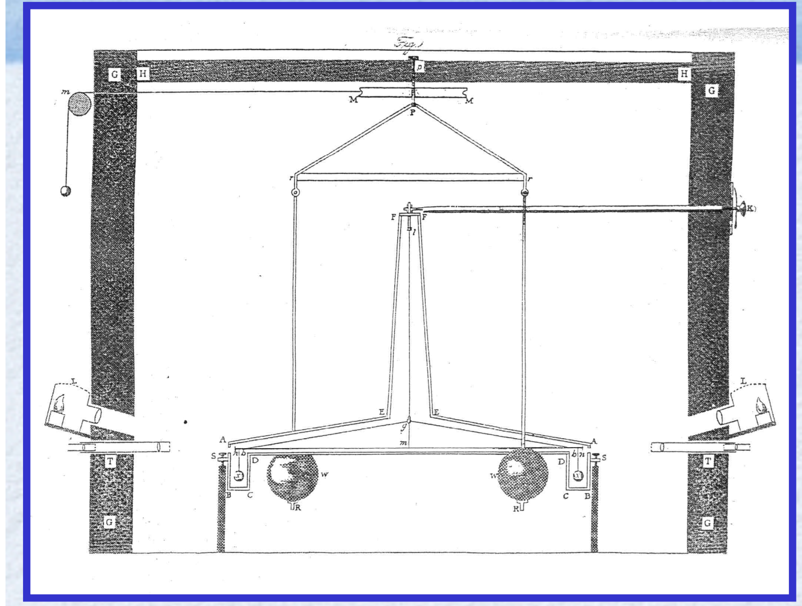


See talk by G. Rosi on Wed. 24 (sez. II)

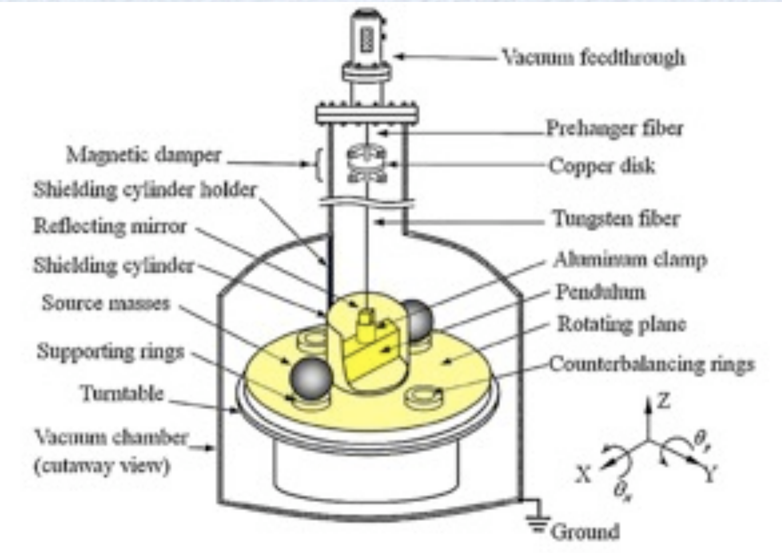
http://www.fi.infn.it/sezione/esperimenti/MAGIA/home.html

Motivation





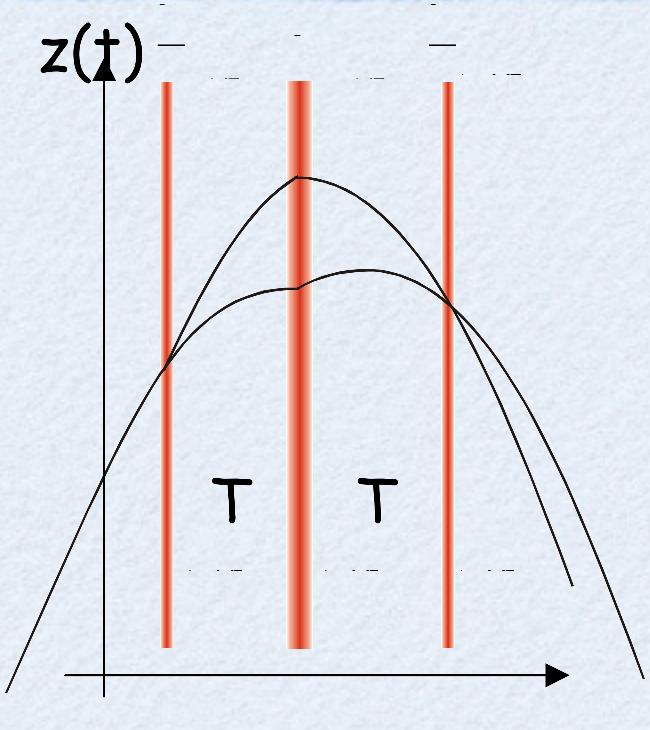
Cavendish 1798



Zang 2009

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

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



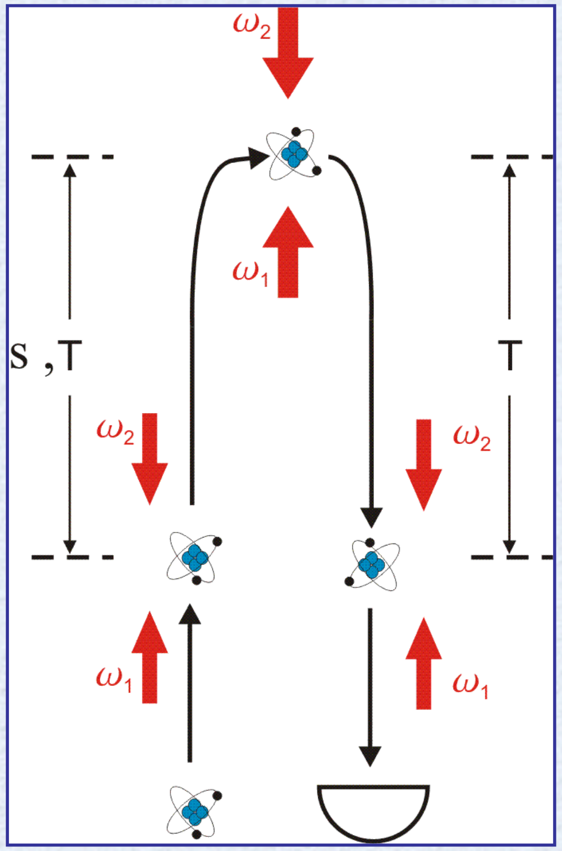
Phase difference between the paths:

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

$$k_e = k_1 - k_2$$

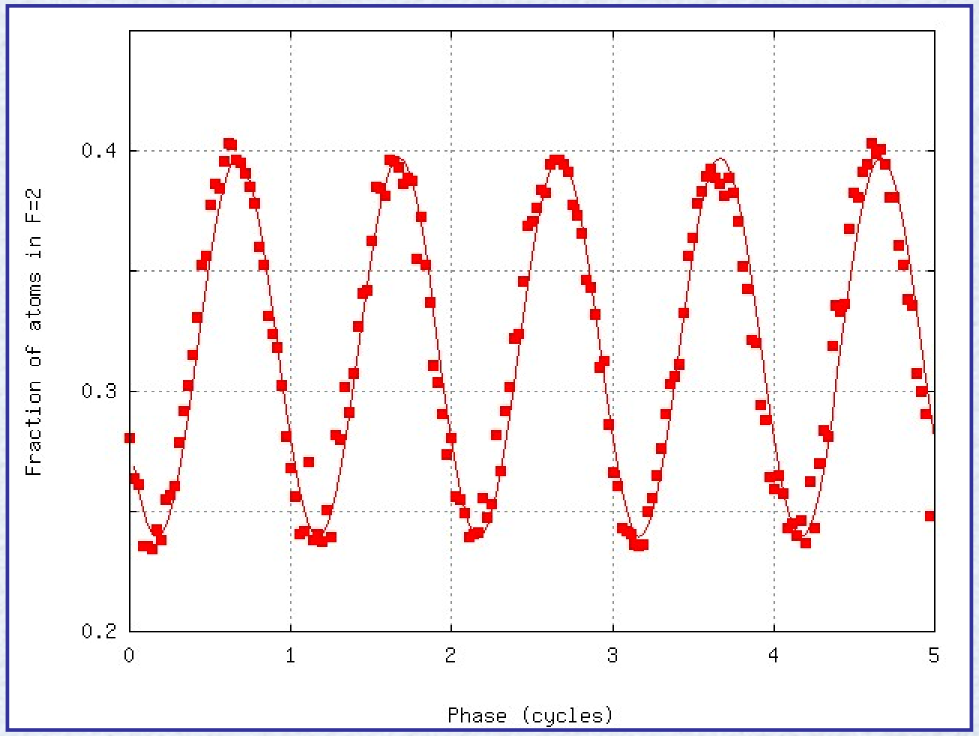
with $z(t) = -gt^2/2 + v_0 t + z_0$ & $\Phi_e = 0$

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



Final population:

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

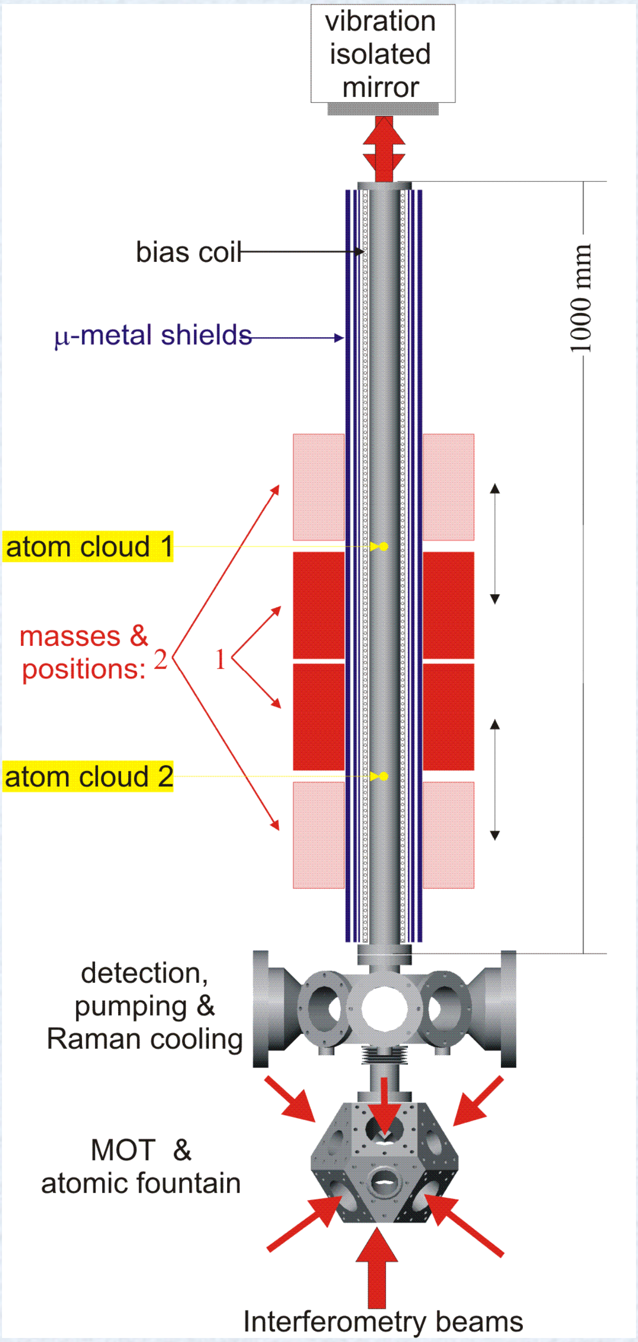


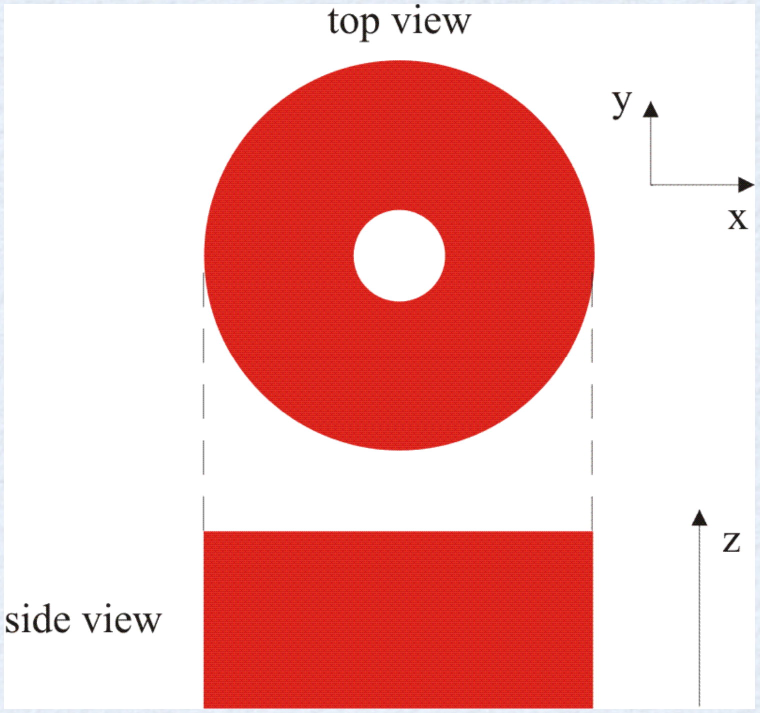
$T = 150$ ms → $2\pi = 10^{-6}$ g

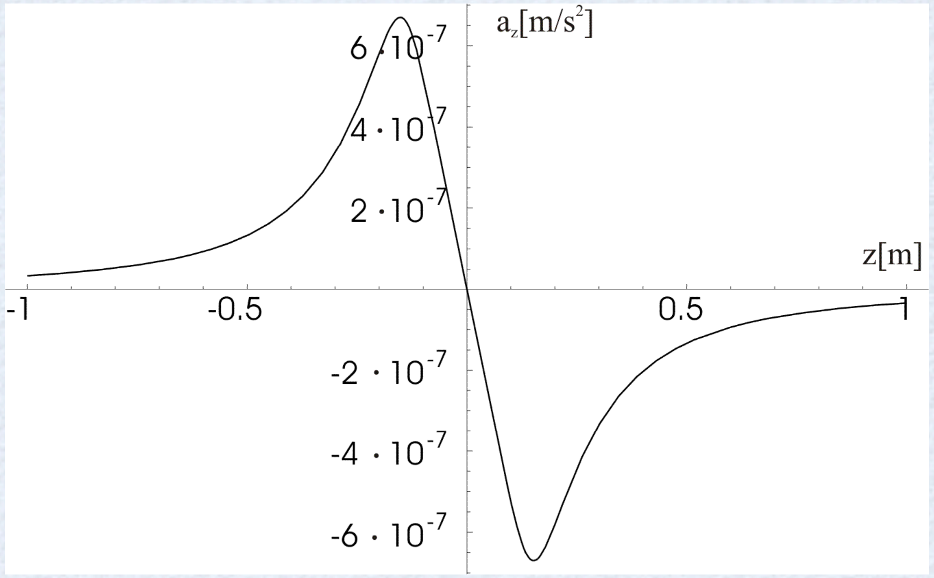
S/N=1000 → Sensitivity 10^{-9} g/shot

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

Atom gravimeter + source masses







Sensitivity 10^{-9} g/shot

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

500 Kg tungsten mass

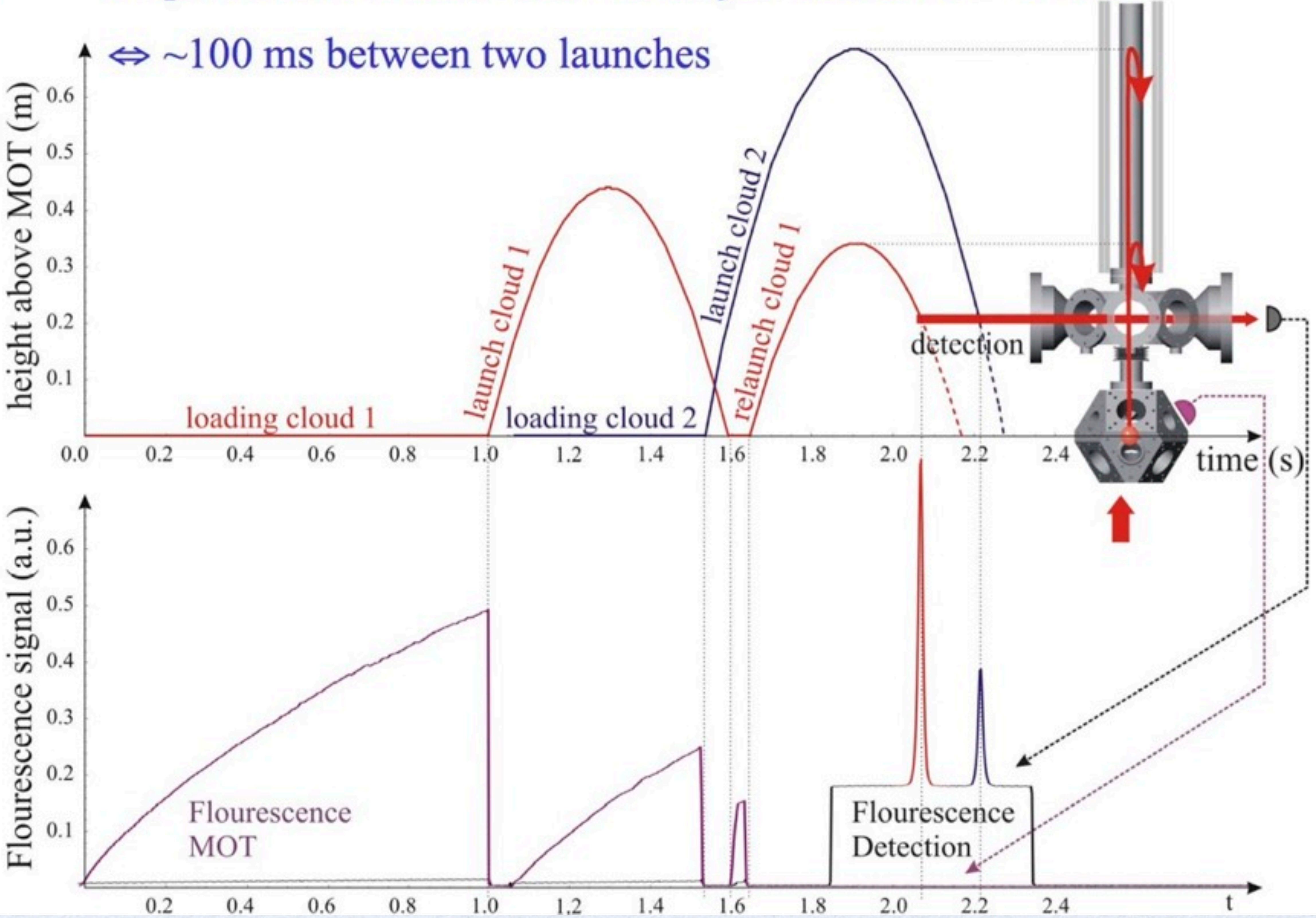
Peak mass acceleration $a_g \sim 10^{-7}$ g

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

MAGIA: experimental sequence

Goal: Prepare 2 clouds with same velocity at distance of ≈ 35 cm

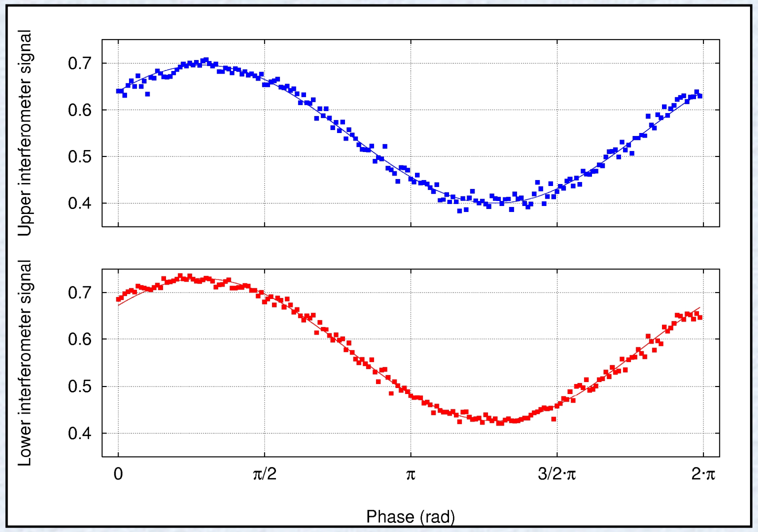
⇔ ~100 ms between two launches



Raman gravity gradiometer

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

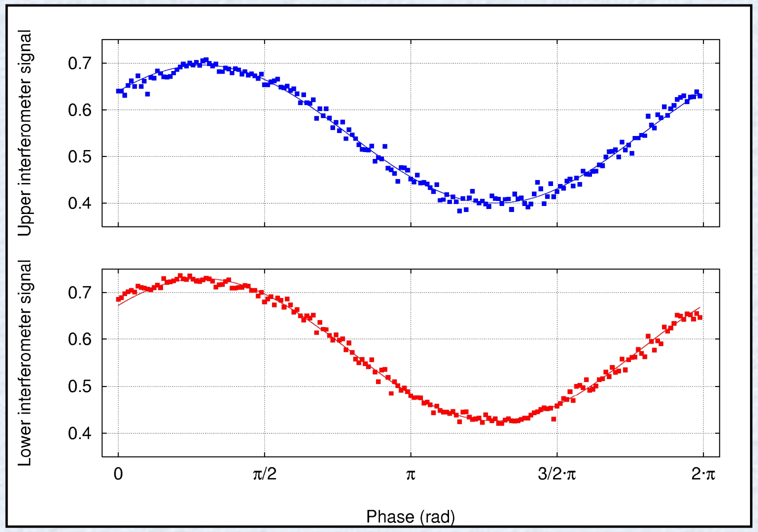
Raman gravity gradiometer



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

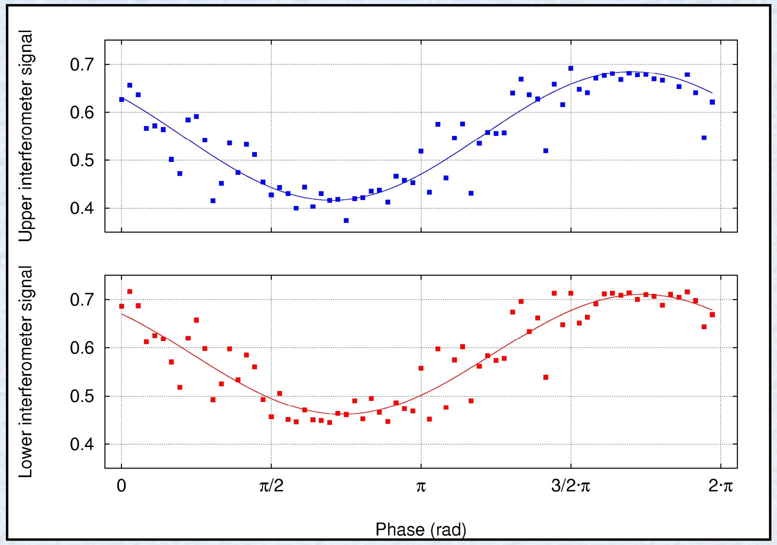
$$\Delta\Phi = k_e g T^2$$

Raman gravity gradiometer



T=5 ms

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

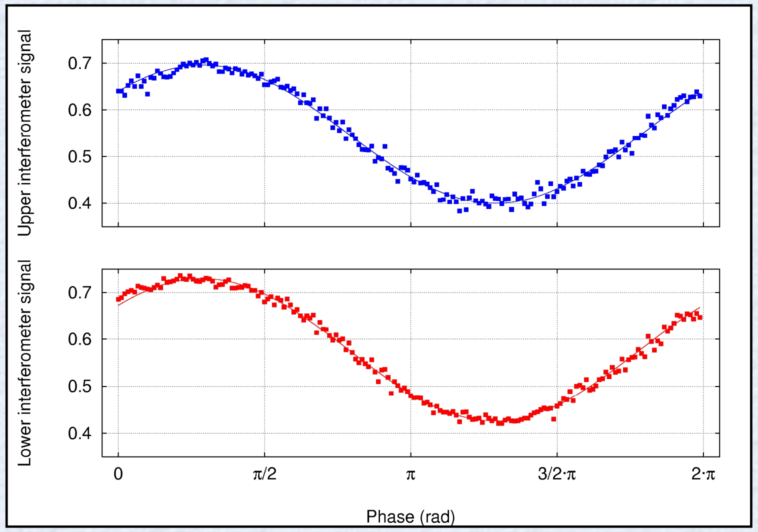


T=50 ms

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

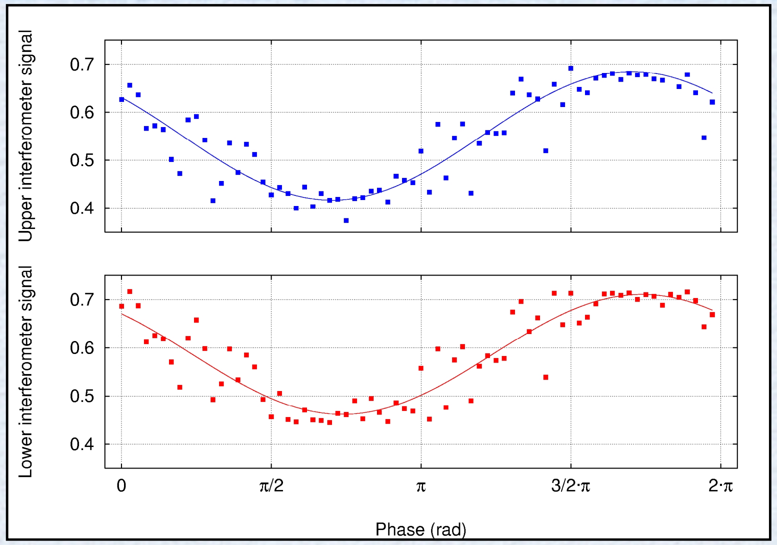
$$\Delta\Phi = k_e g T^2$$

Raman gravity gradiometer



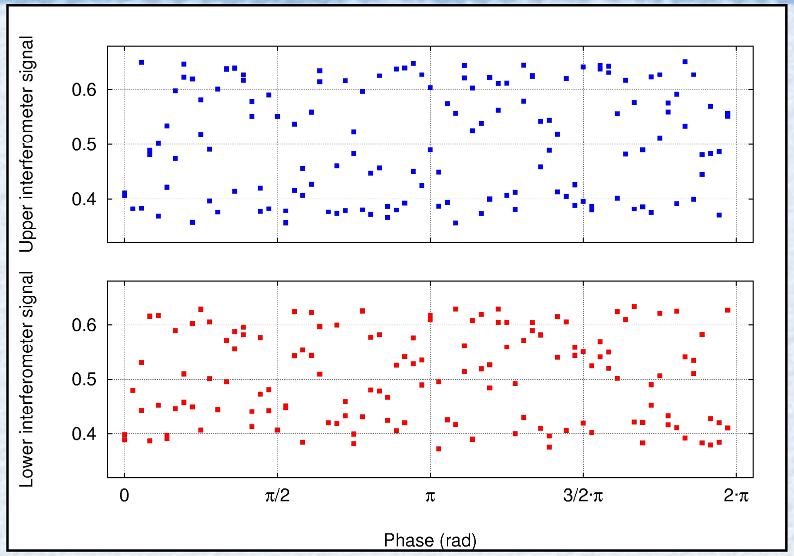
T=5 ms

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



T=50 ms

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

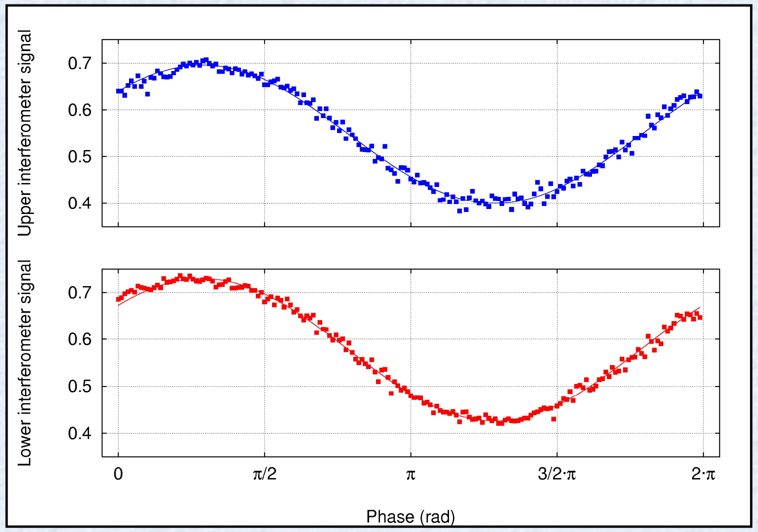


T=150 ms

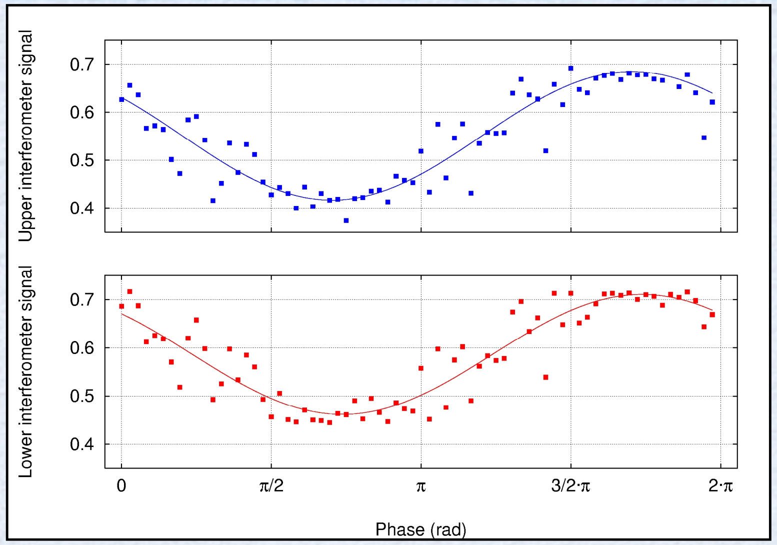
$\text{resol.} = 3.2 \times 10^{-8} \text{g/shot}$

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

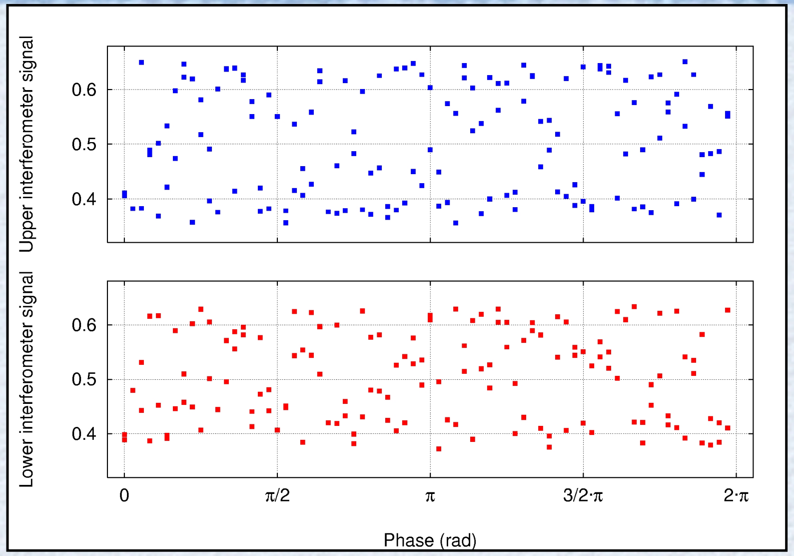
Raman gravity gradiometer



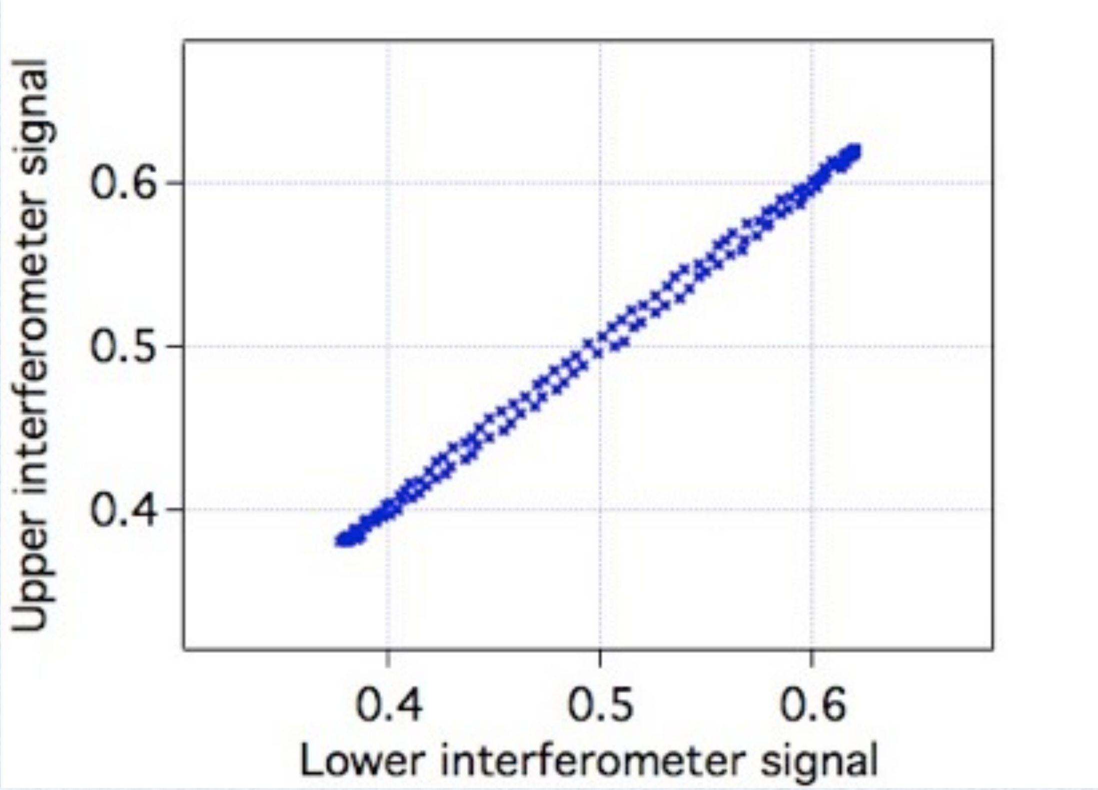
T=5 ms
resol. $= 2.3 \times 10^{-5}$g/shot



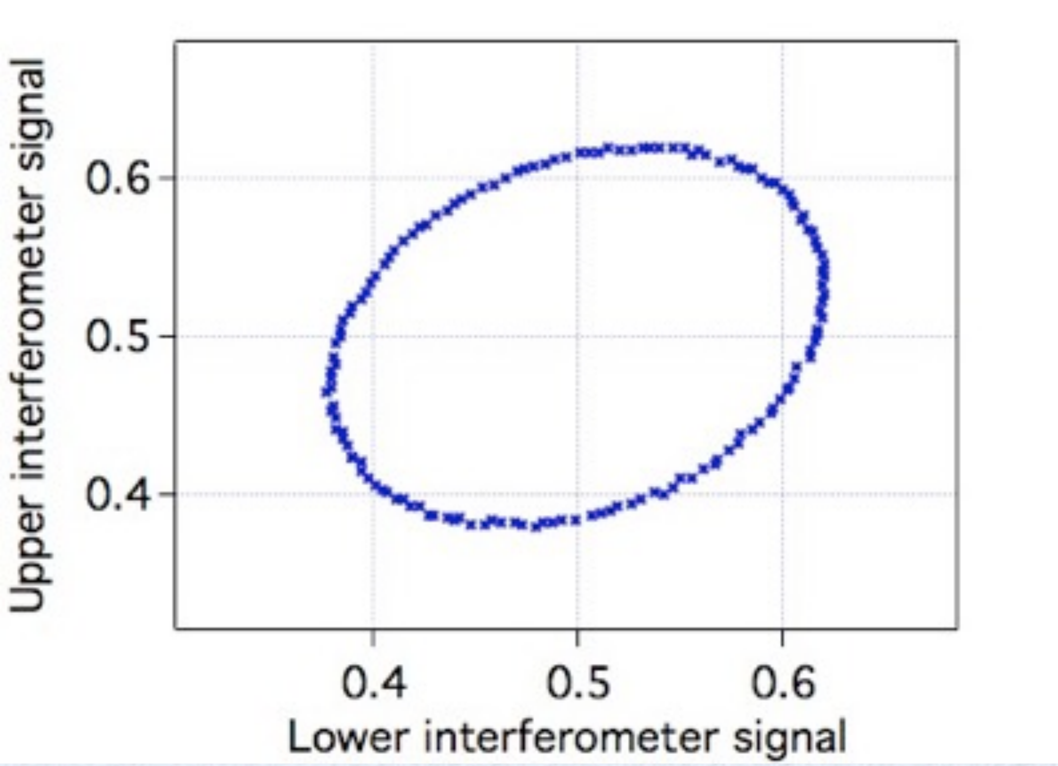
T=50 ms
resol. $= 1.0 \times 10^{-6}$g/shot



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



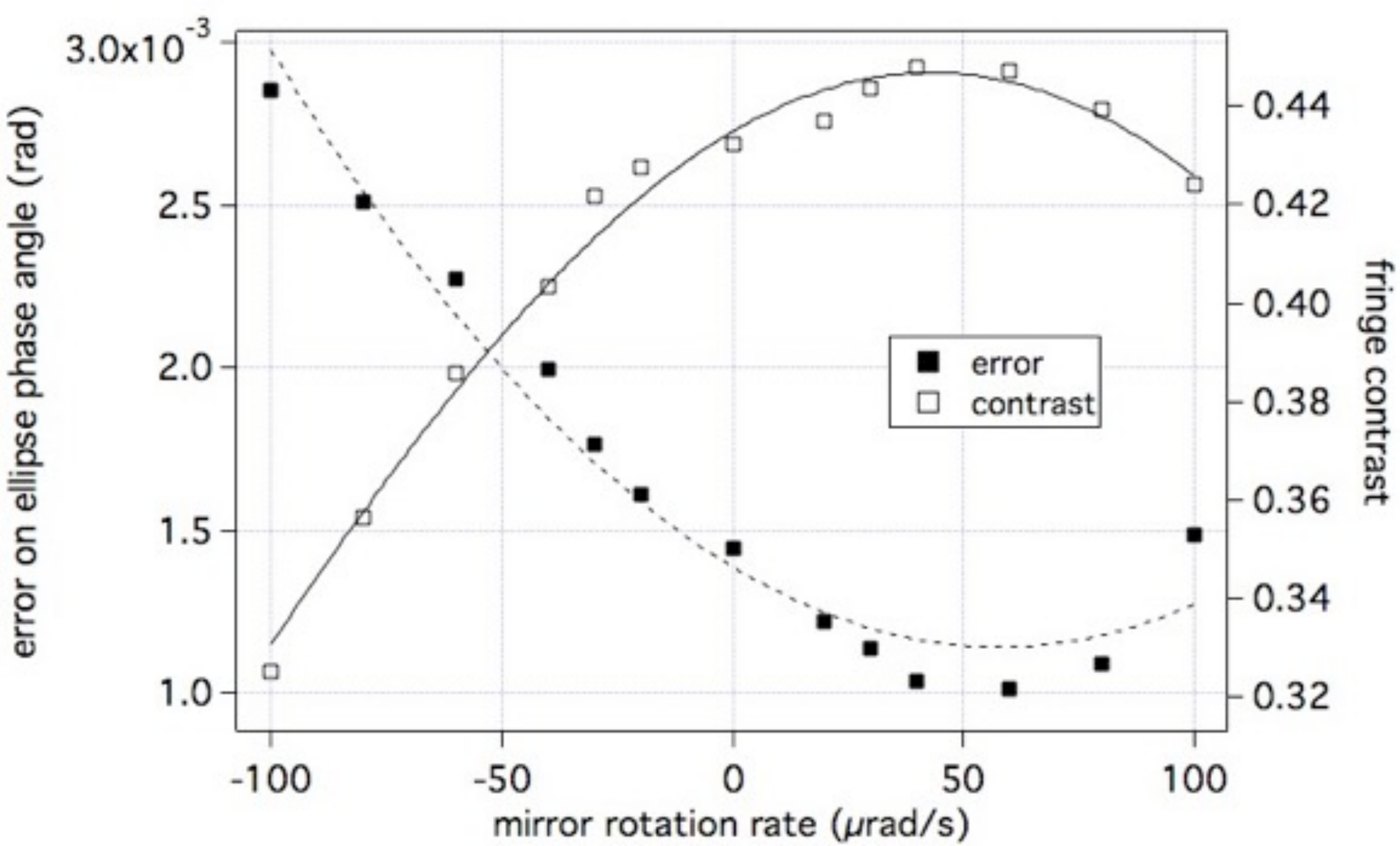
$$\Delta\Phi = k_e g T^2$$



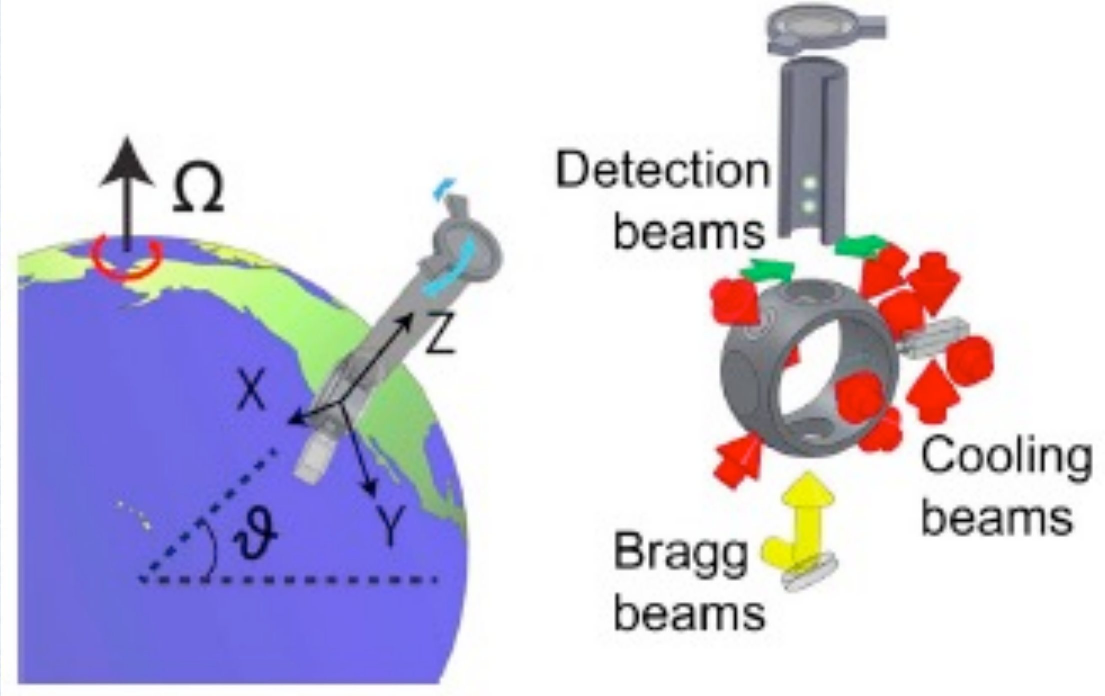
G. T. Foster et al., Opt. Lett **27**, 951 (2002)

Coriolis compensation

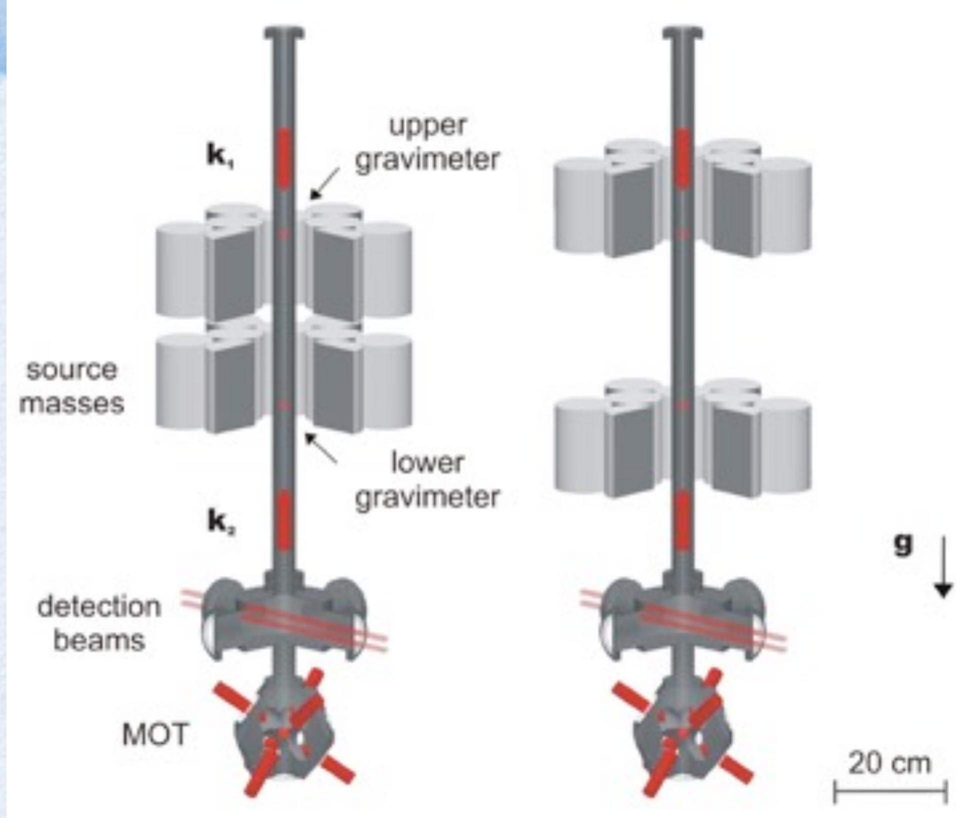
- Tip-tilt mirror steering the retro-reflected Raman beam to compensate for the Earth rotation
- Already shown to improve contrast in AI with LMT beam splitters
- In MAGIA, contrast drop due to Coriolis is minimal, but still detectable thanks to the large SNR
- Besides ellipse contrast, Coriolis acceleration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

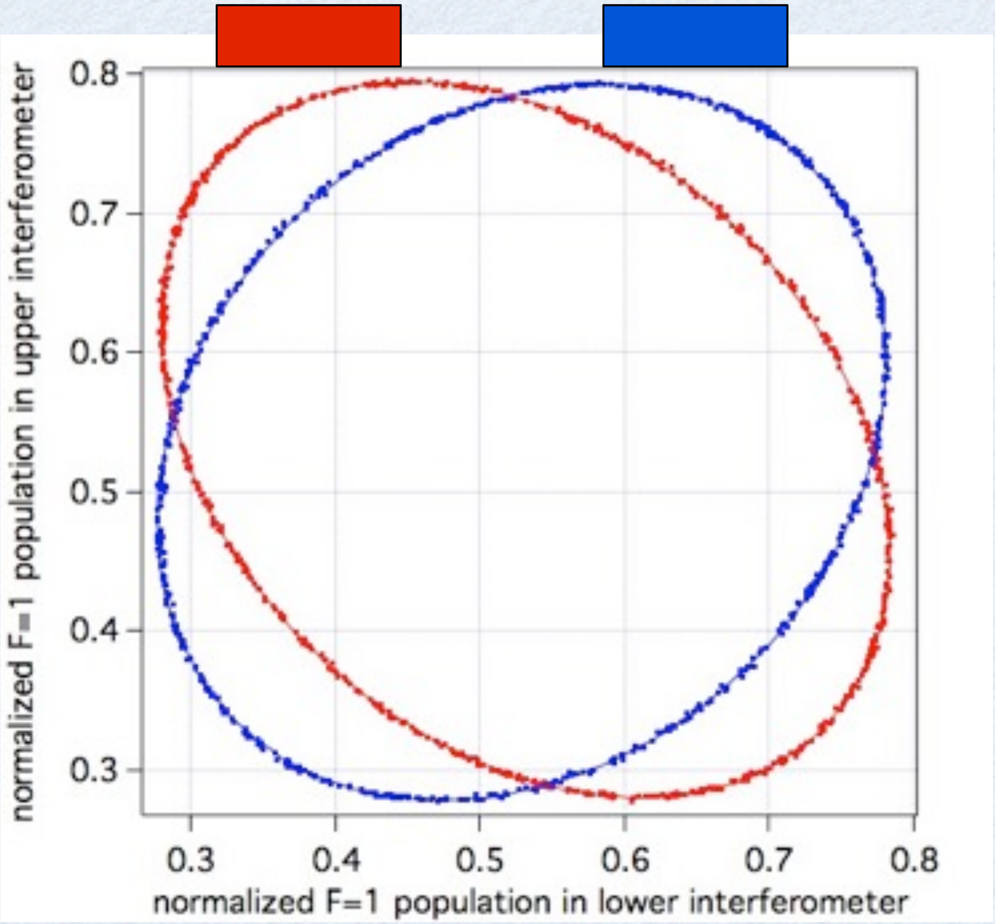


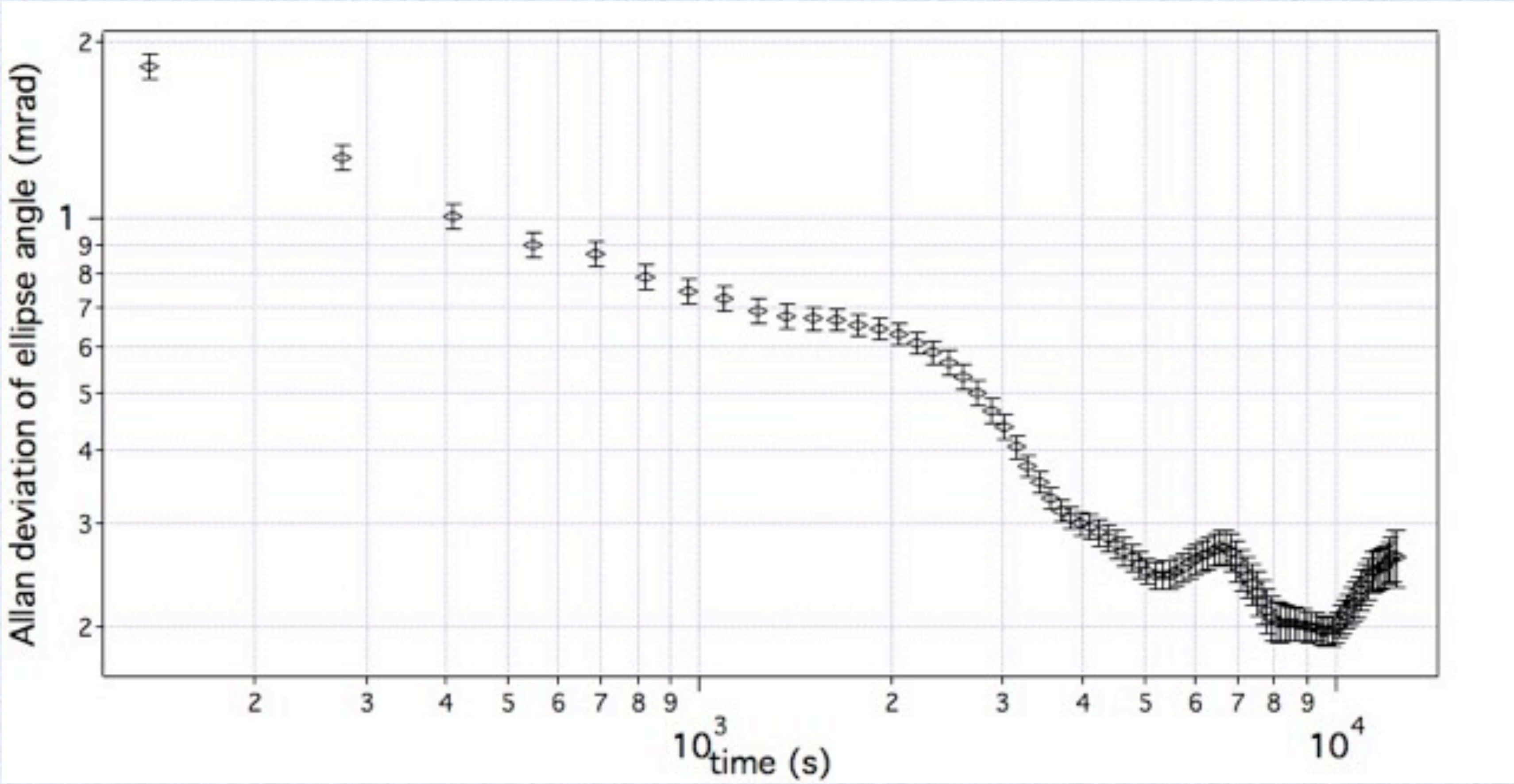
J. M. Hogan et al., Proc. intern. school of physics Enrico Fermi CLXVIII, 411 (2007)
S.-Y. Lan et al., PRL **108**, 090402 (2012)



MAGIA gradiometer performance







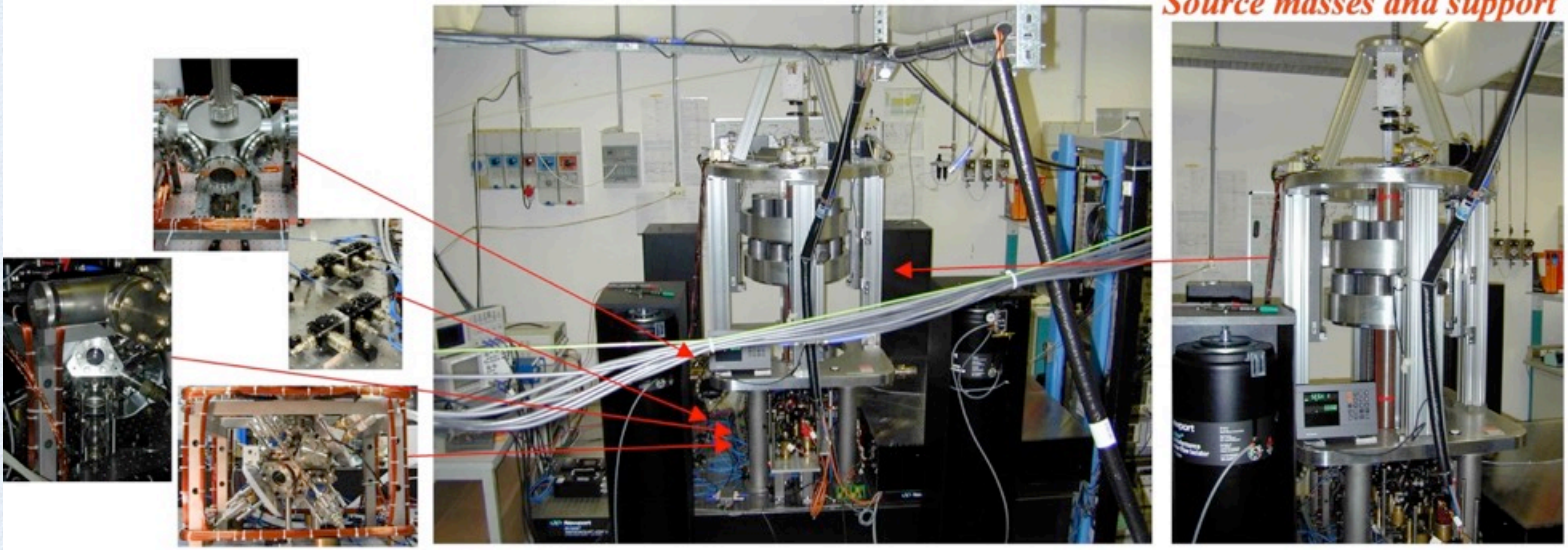
Short-term sensitivity to differential acceleration: $3\text{x}10^{-9}$ g @ 1s (=QPN for $4\text{x}10^{5}$ atoms)

Allan variance ~0.2 mrad @ 10000 s, corresponding to $5\text{x}10^{-11}$ g

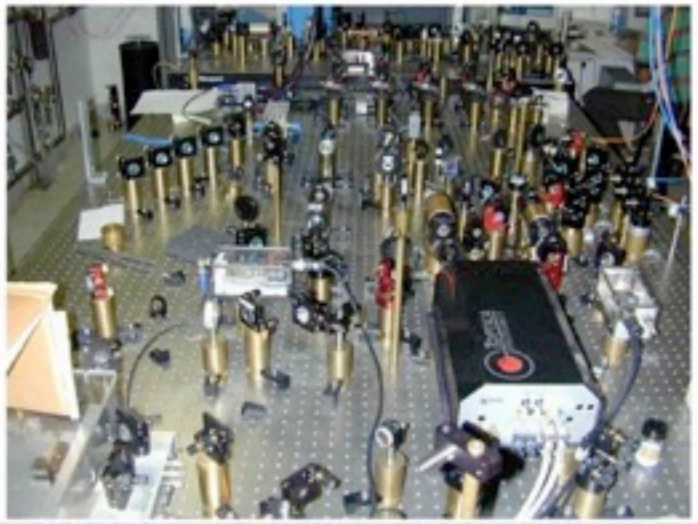
F. Sorrentino et al., Phys. Rev. A **89**, 023607 (2014)

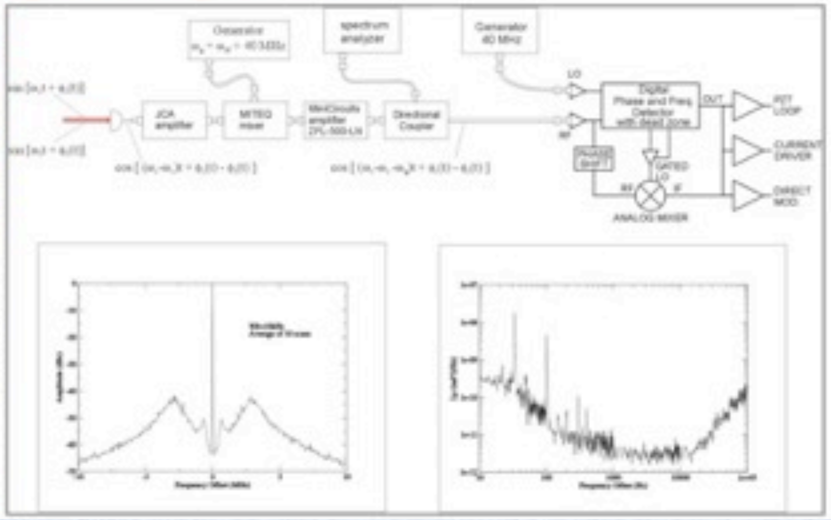
The MAGIA apparatus

Source masses and support



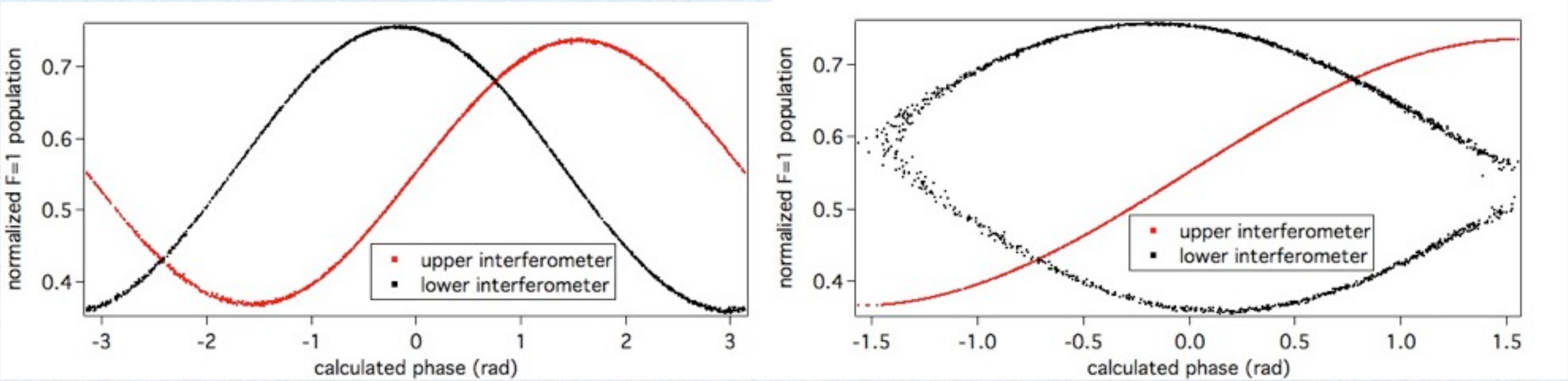
Laser and optical system





g measurement with two clouds

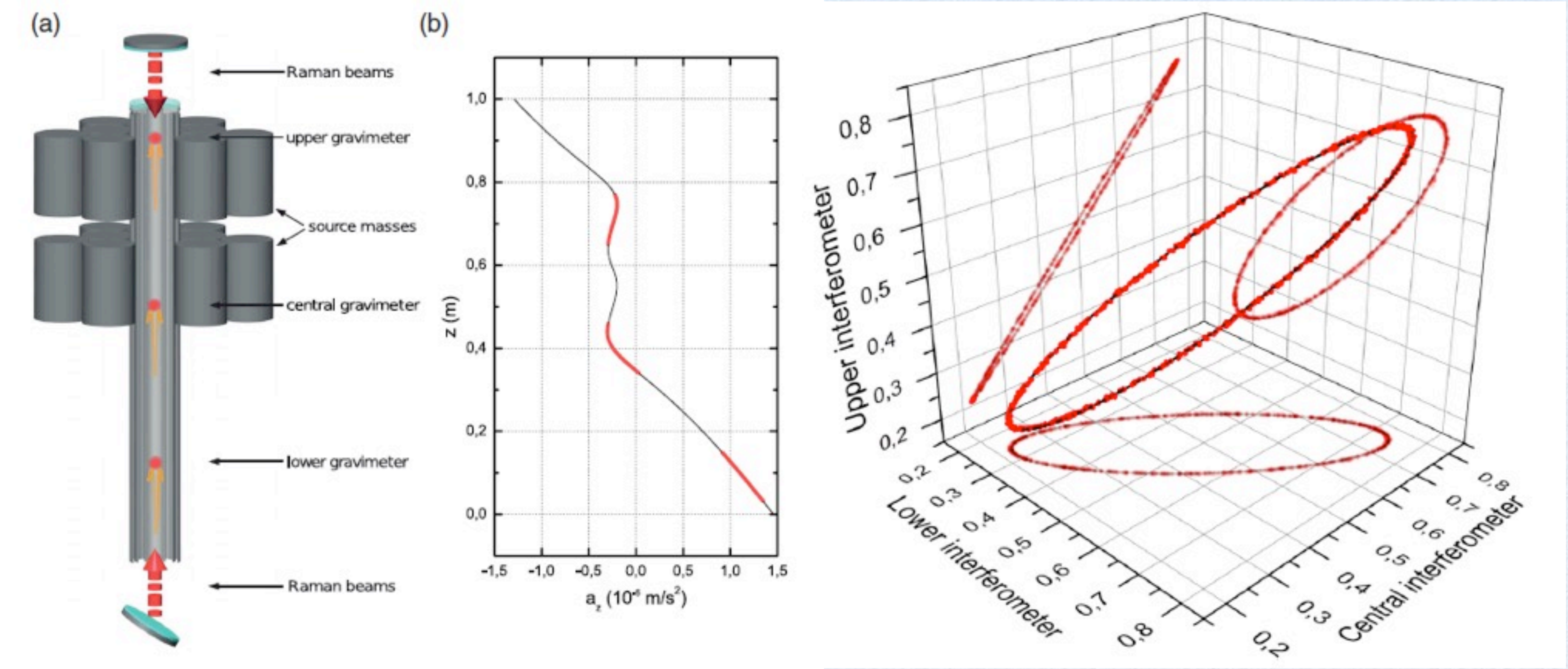
- Using a dual-cloud Raman interferometer for g measurements
- Simultaneous interferometers allow g measurements in the presence of larger phase noise because of
  - twice larger range for phase retrieval
  - suppressed conversion of amplitude noise into phase noise at the edges of the fringe



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)

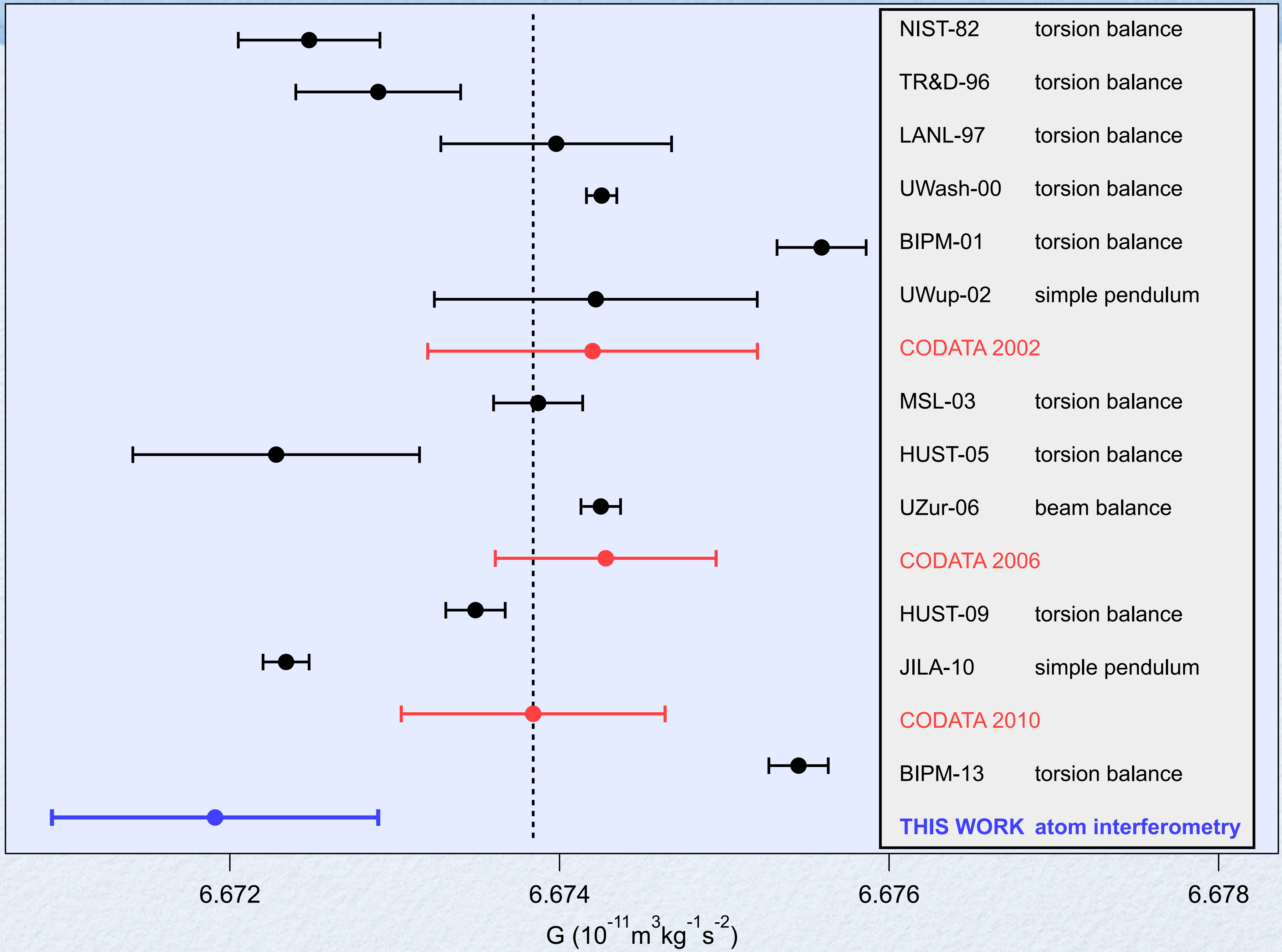
Higher order gravity spatial derivatives



- Use three atomic clouds to measure the vertical derivative of vertical gravity gradient
- Sensitivity ~3x10^{-8} s^{-2} m^{-1} after 1 hr integration time

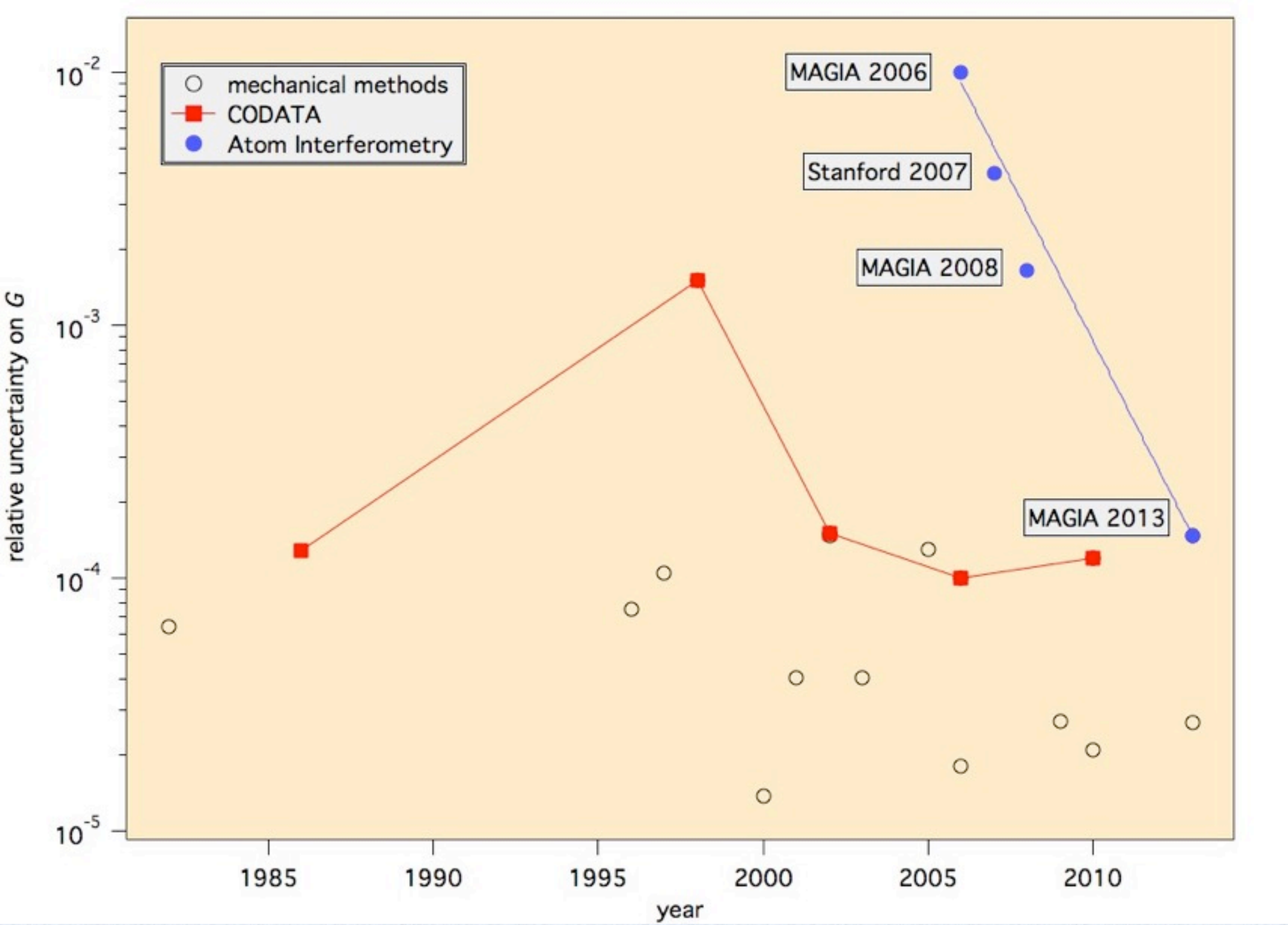
G. Rosi et al., Phys. Rev. Lett. 114, 013001 (2015)

G measurements: current status

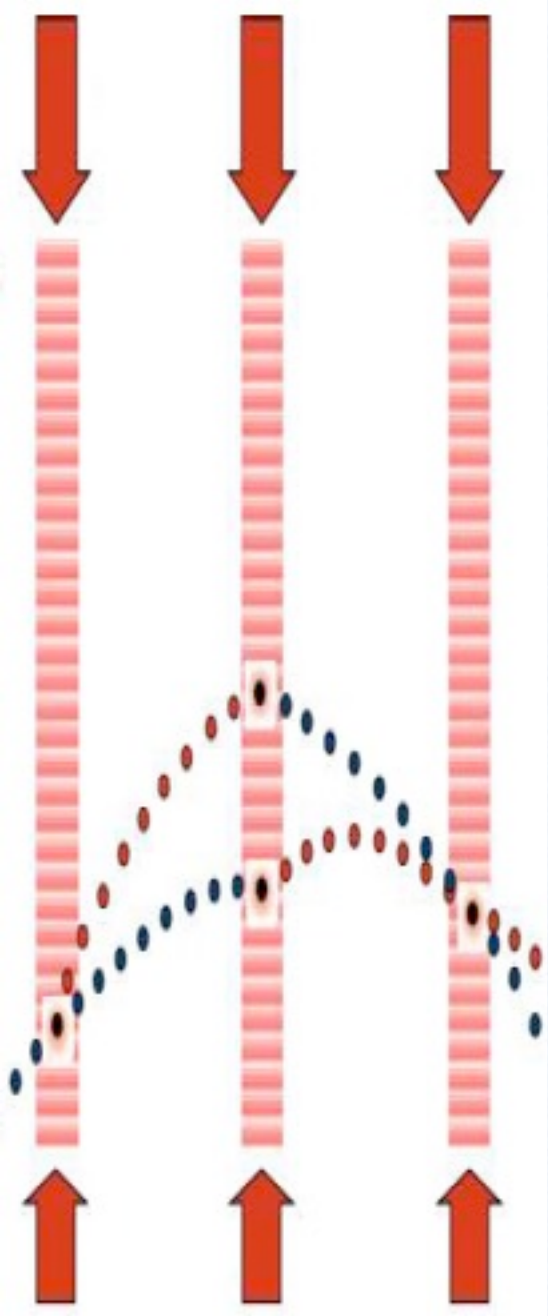


G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli and G. M. Tino, Nature **510**, 518 (2014)

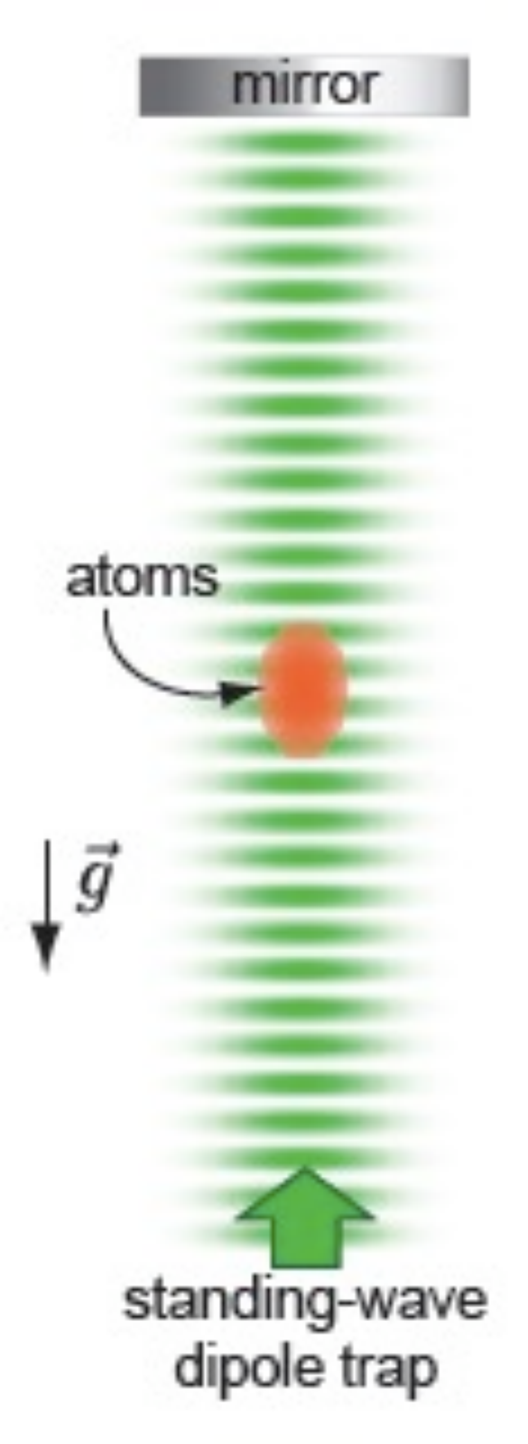
From proof of principle to G measure



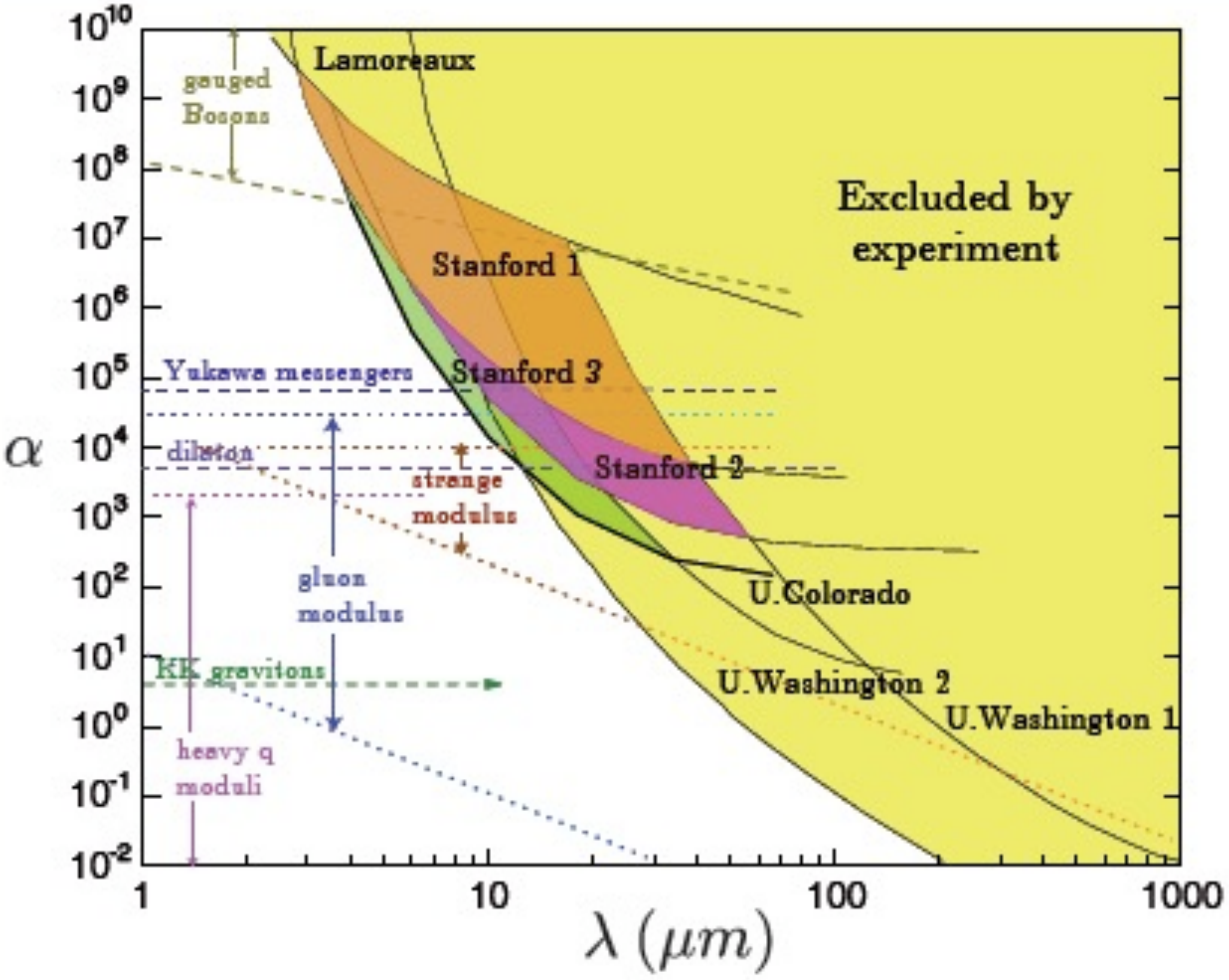
Freely falling vs trapped atoms



- 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



Short-range force measurements



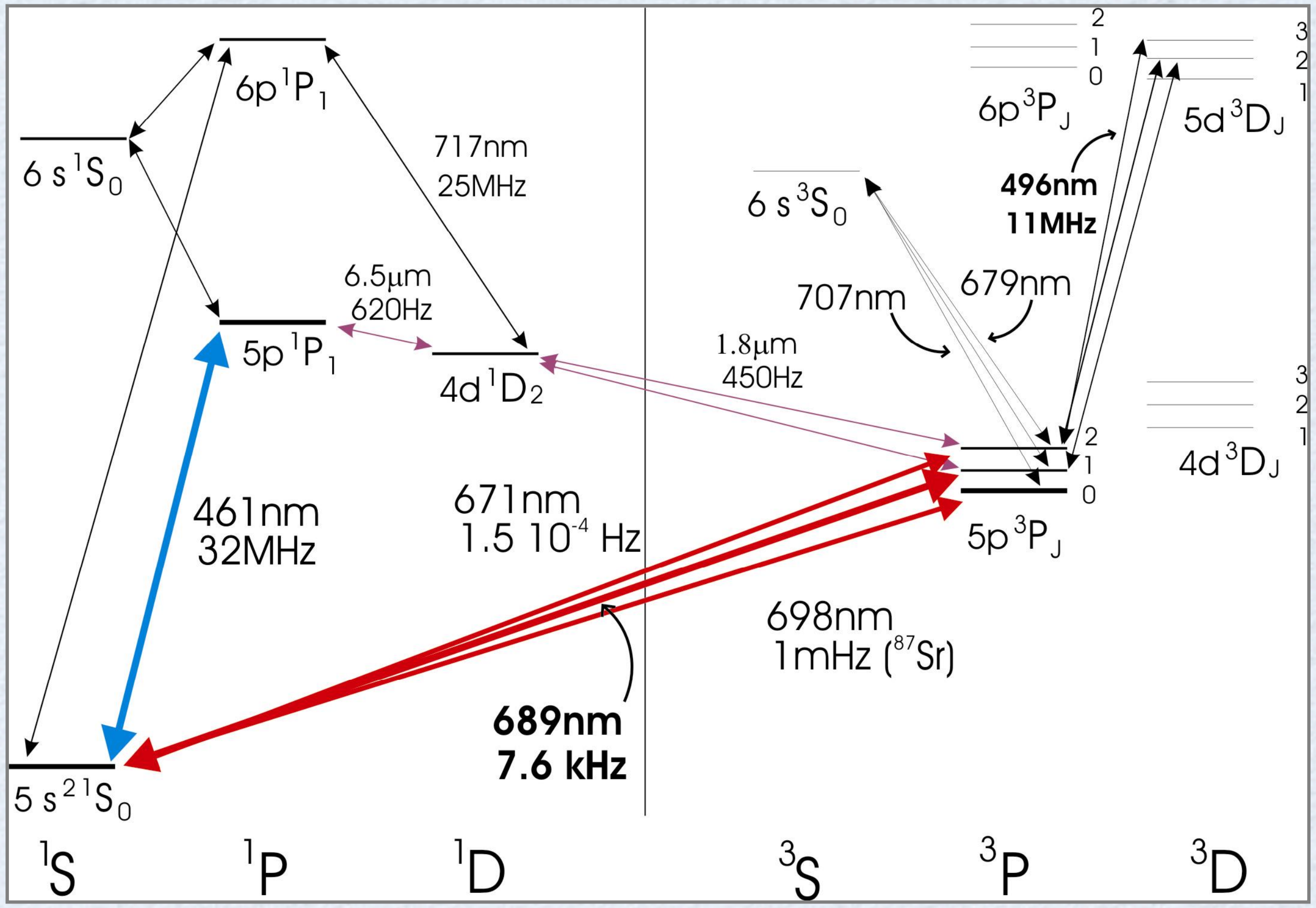
Geraci et al. Phys. Rev. D **78** 22002 (2008)

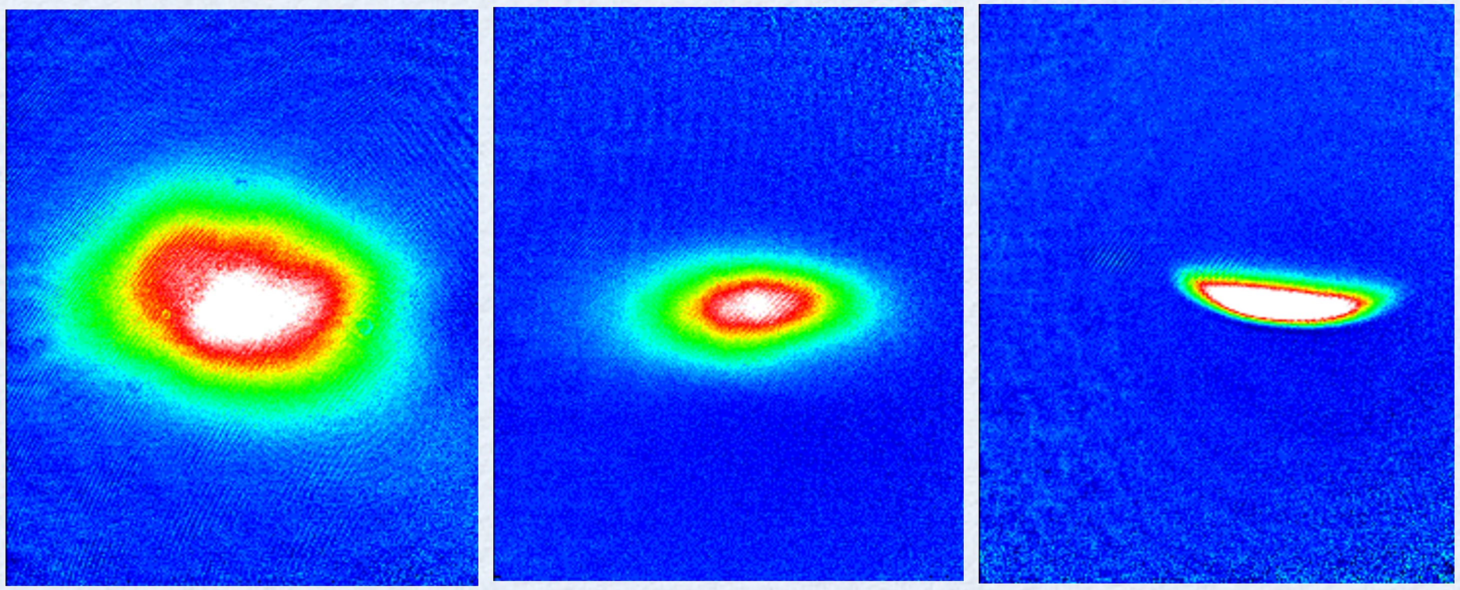
- Characterization of the Casimir-Polder effect
- Exotic theories predict violations of Newton's law on some length scale
- Effect parametrized through Yukawa potential
- experiment set limits in parameters space $(\alpha - \lambda)$

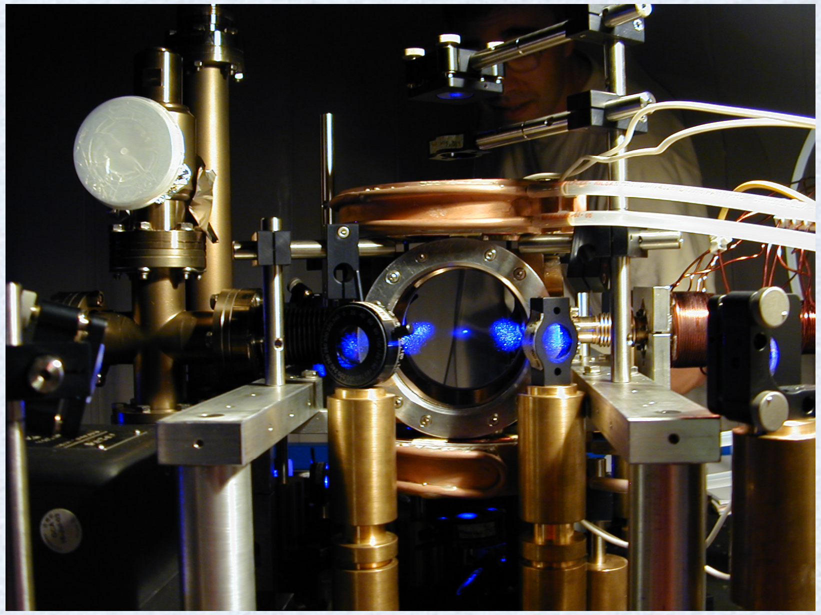
$$V(r) = -G\frac{m_1 m_2}{r}[1 - \alpha e^{-(r/\lambda)}]$$

Using ultracold strontium

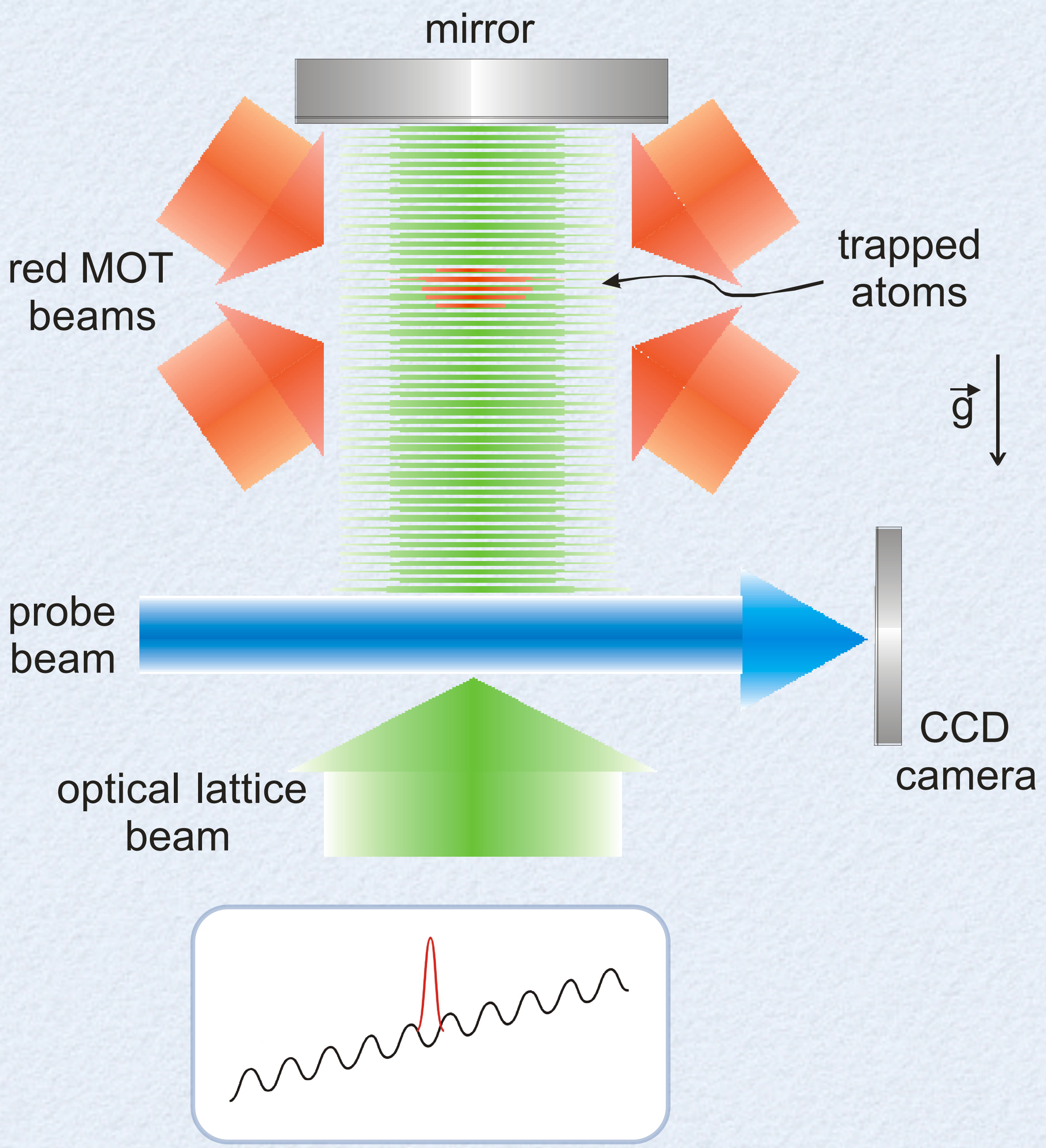
- Extremely fast multi-stage cooling
- Sub-recoil temperatures with narrow line cooling
- Very small size of ultracold atomic sample (few μm)
- Insensitive to stray fields
- Fermionic and bosonic isotopes
- Unique collisional properties
- Among best candidates for optical atomic clocks

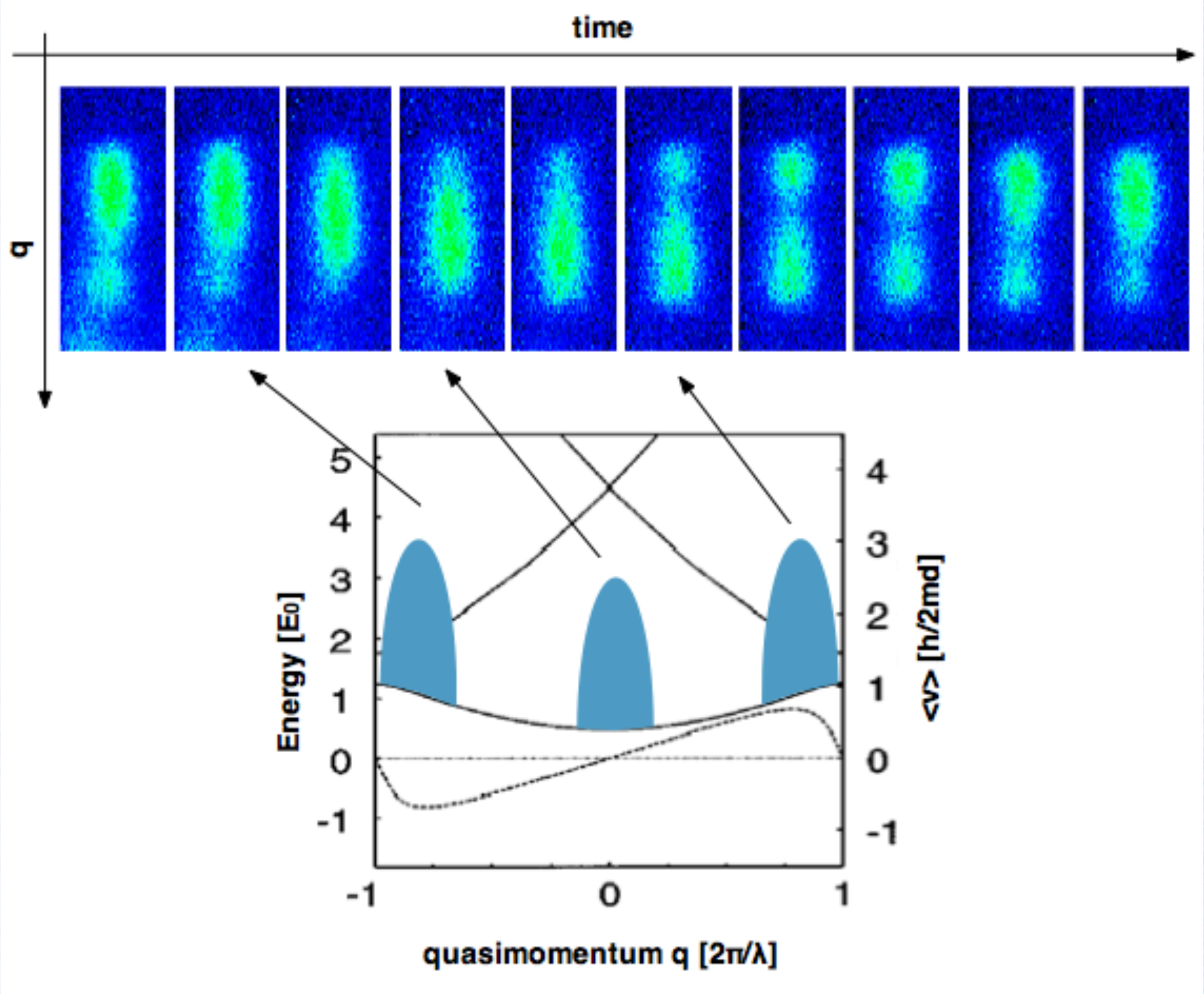






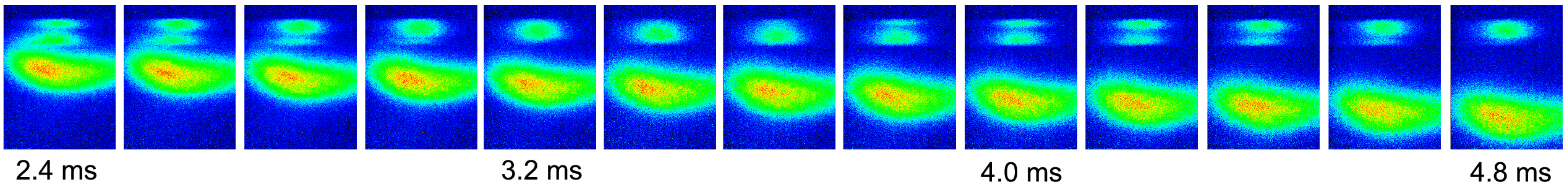
Bloch oscillations in optical lattice

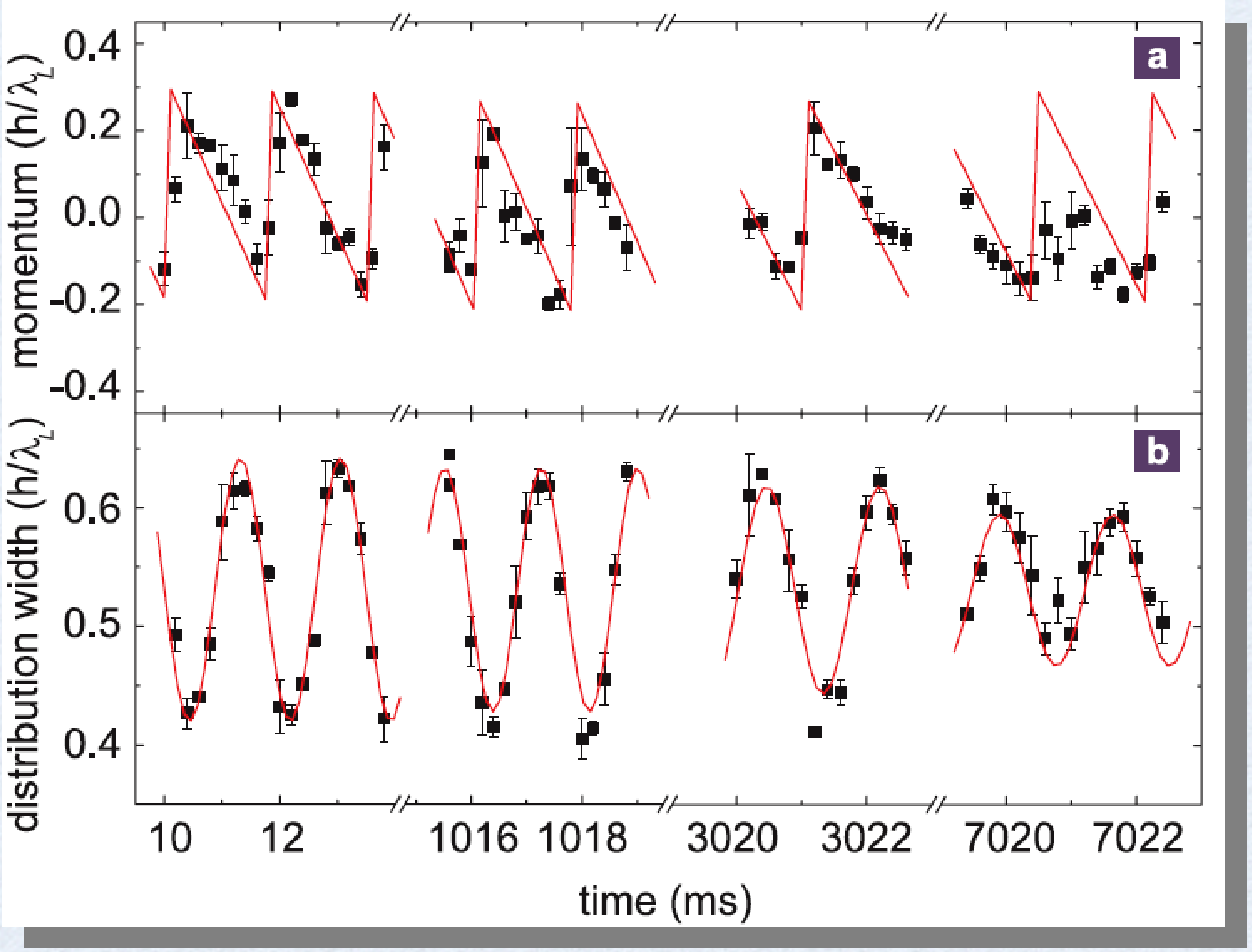




$$q(t) = q_0 + Ft/\hbar \quad \Longrightarrow \quad \nu_B = \frac{F\lambda}{2h} = \frac{mg\lambda}{2h}$$

Bloch oscillations of ^{88}Sr





Bloch frequency 574.568(3) Hz

8000 photon recoils in 7 s

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

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

Decoherence time > 500 s

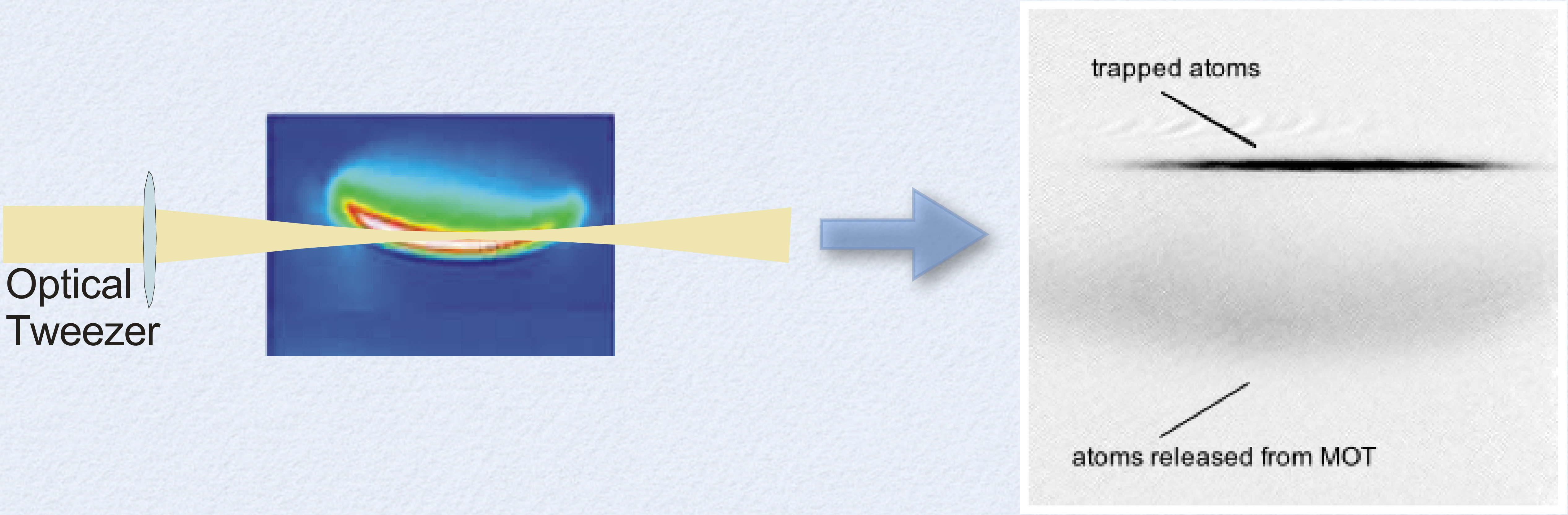
M. Tarallo et al., PRA ***86****, 033615 (2012)*

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

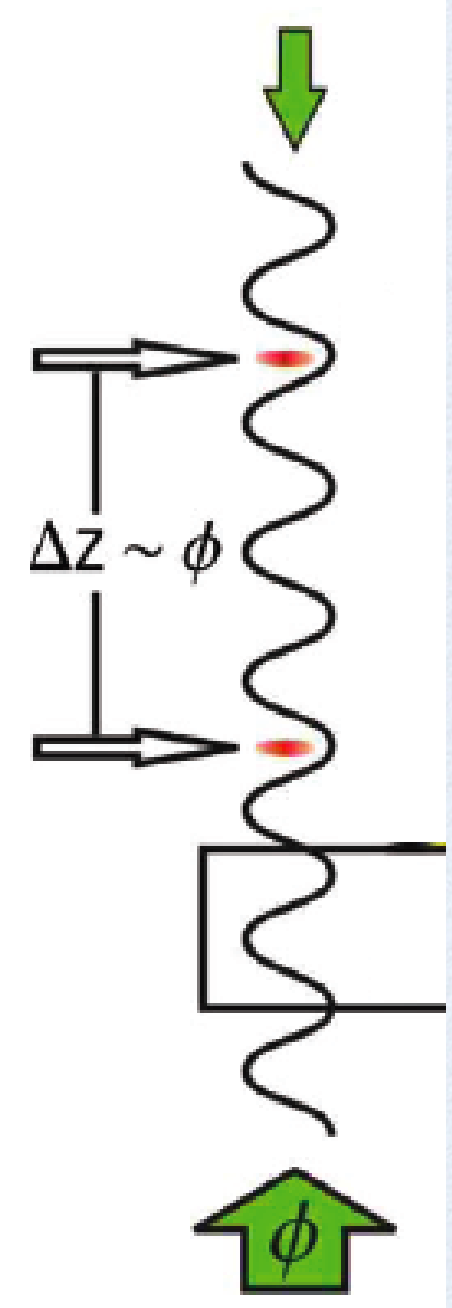
H. Mueller et al., PRL ***102****, 240403 (2009)*

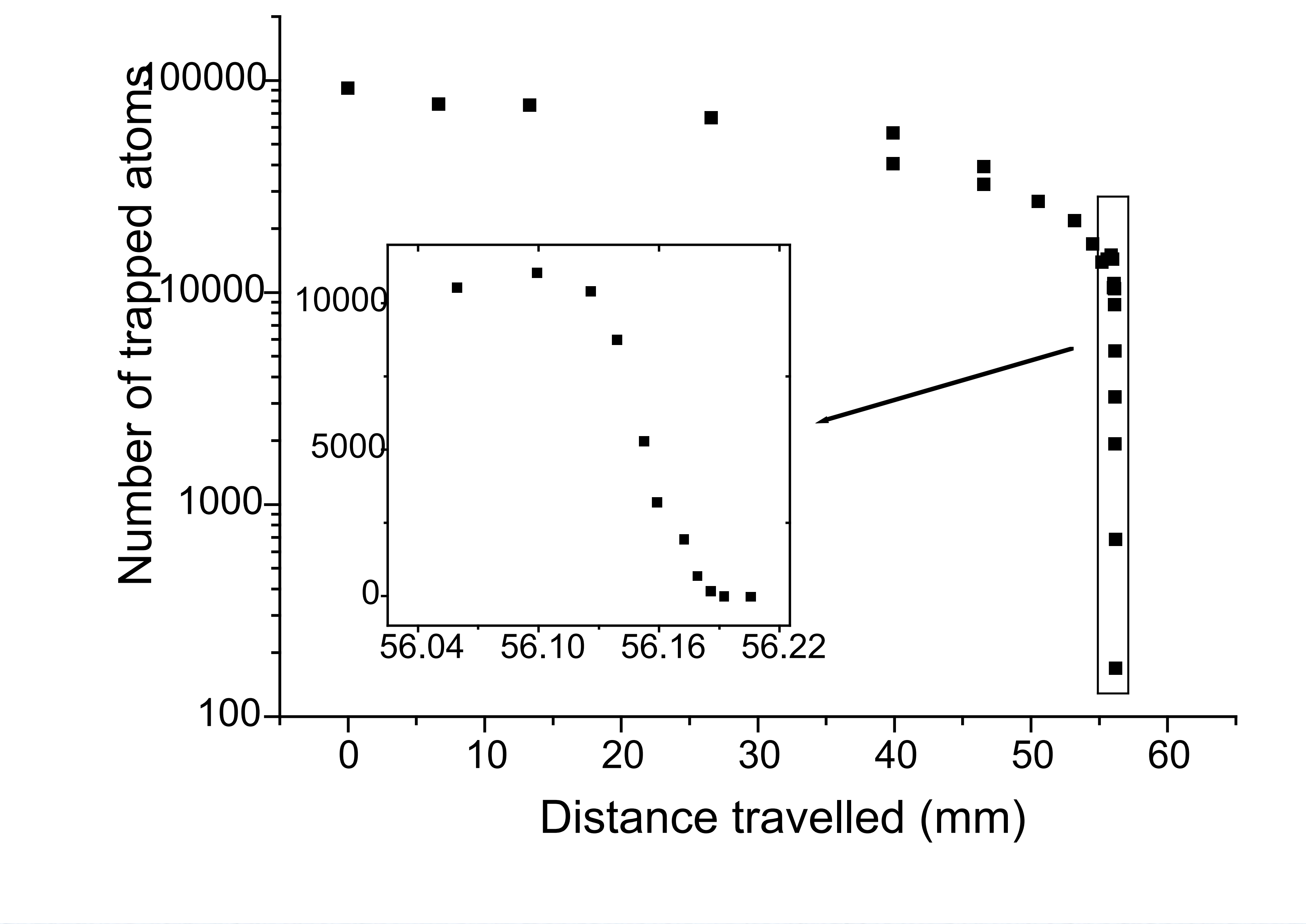
Sample compression

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



Optical elevator

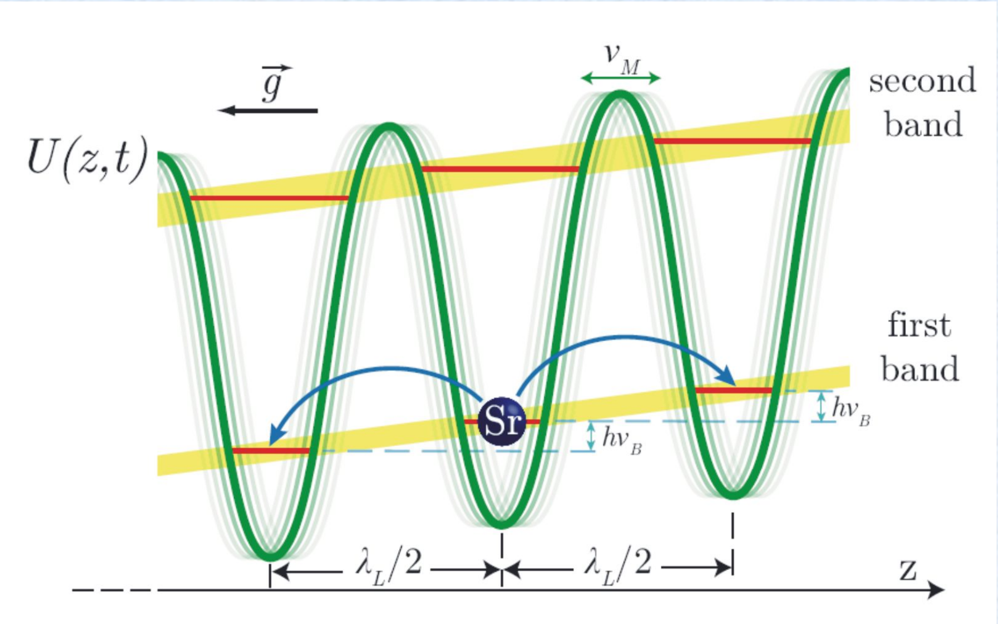


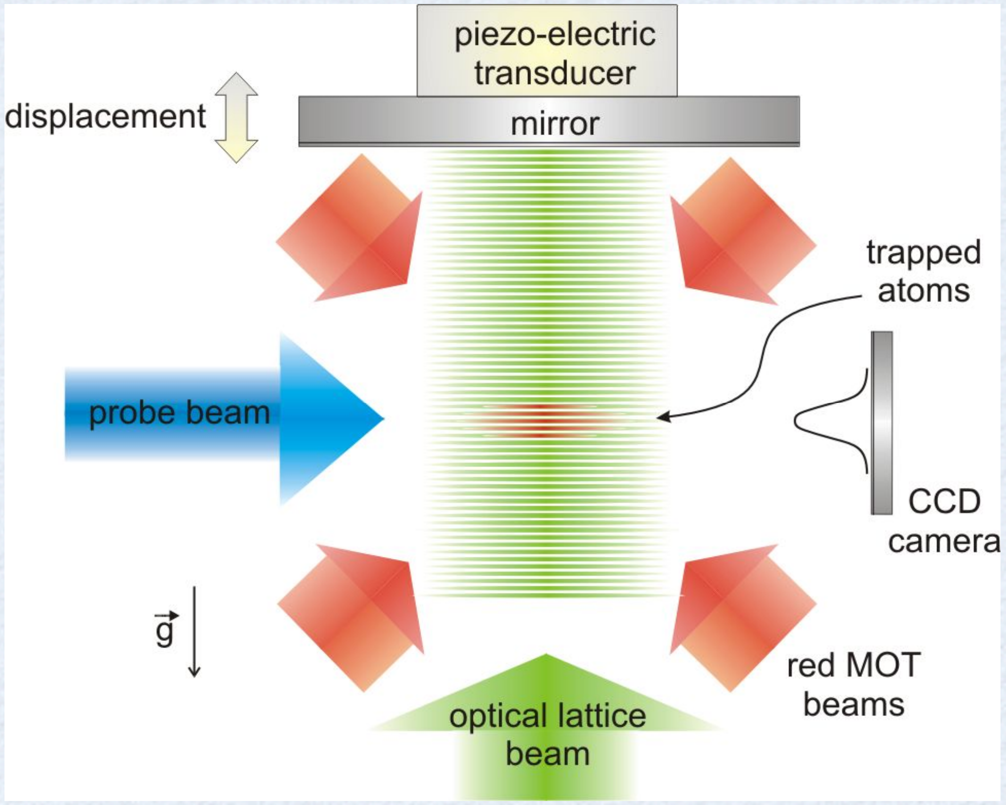


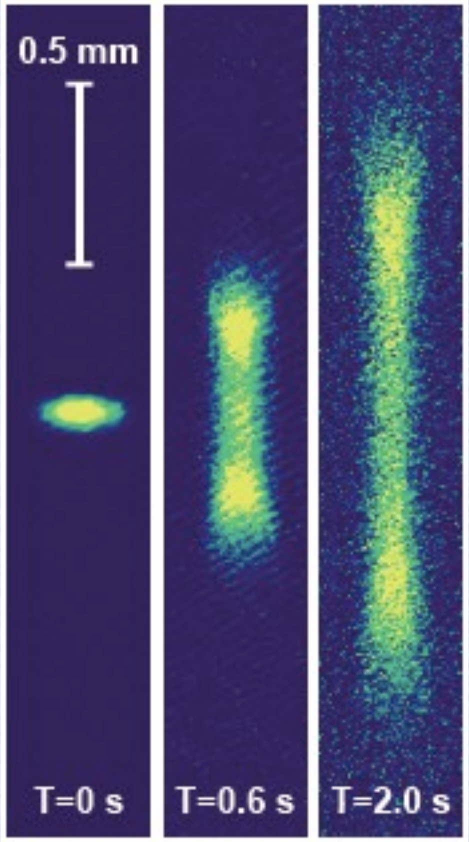
Atom-surface position jitter < 1 μm

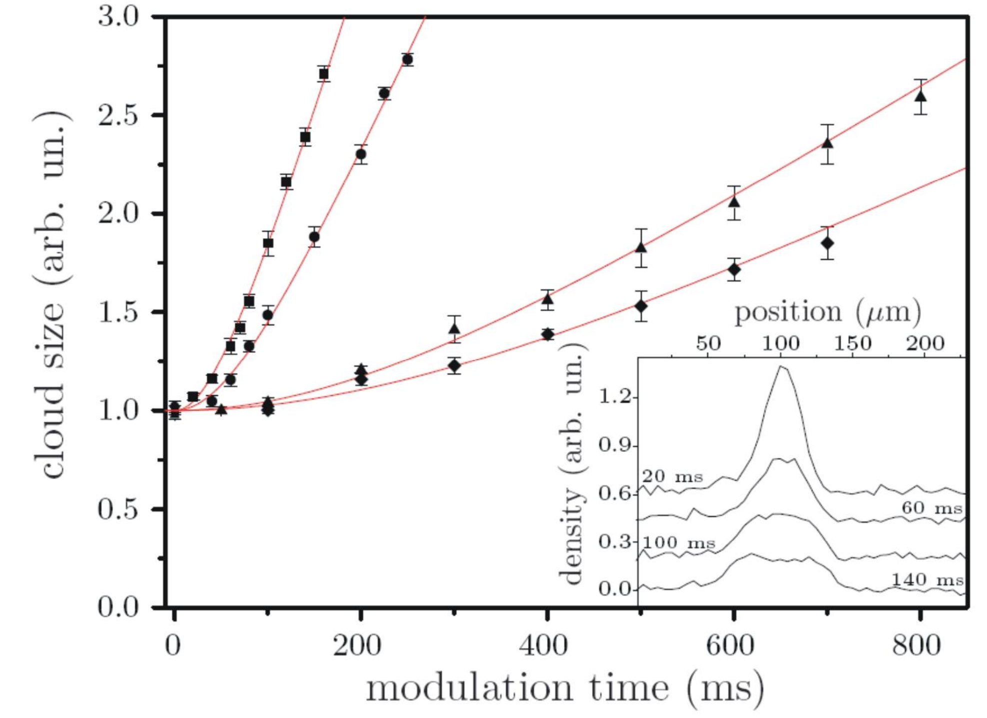
F. Sorrentino et al., Phys. Rev. A **79**, 013409 (2009)

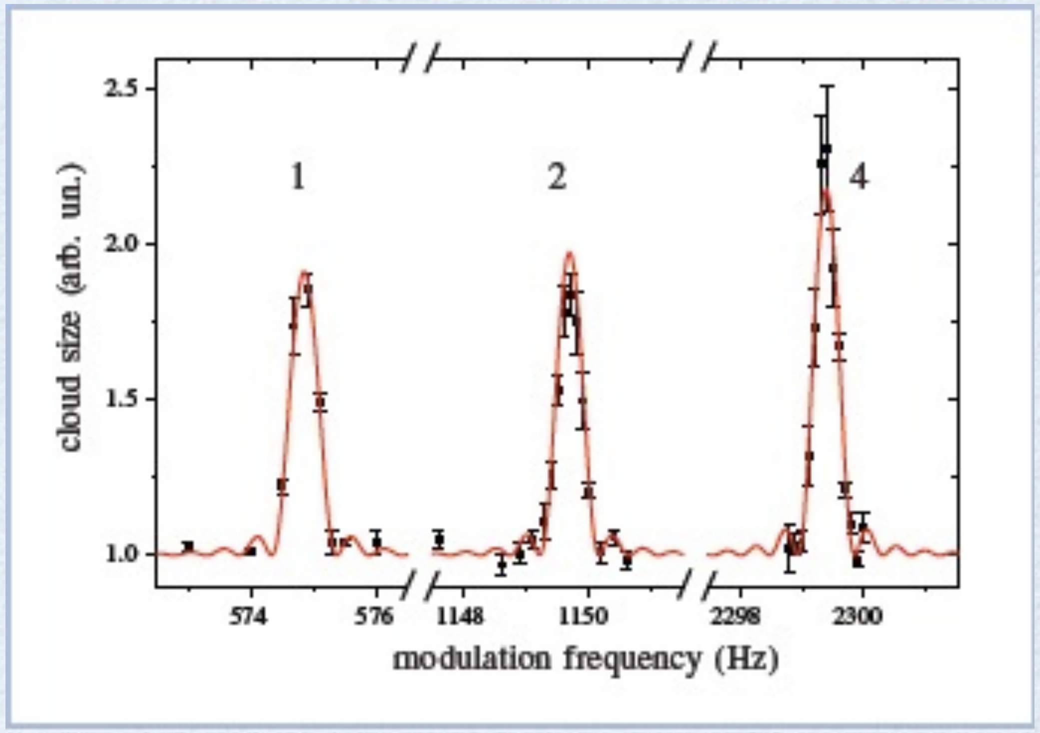
Resonant tunneling







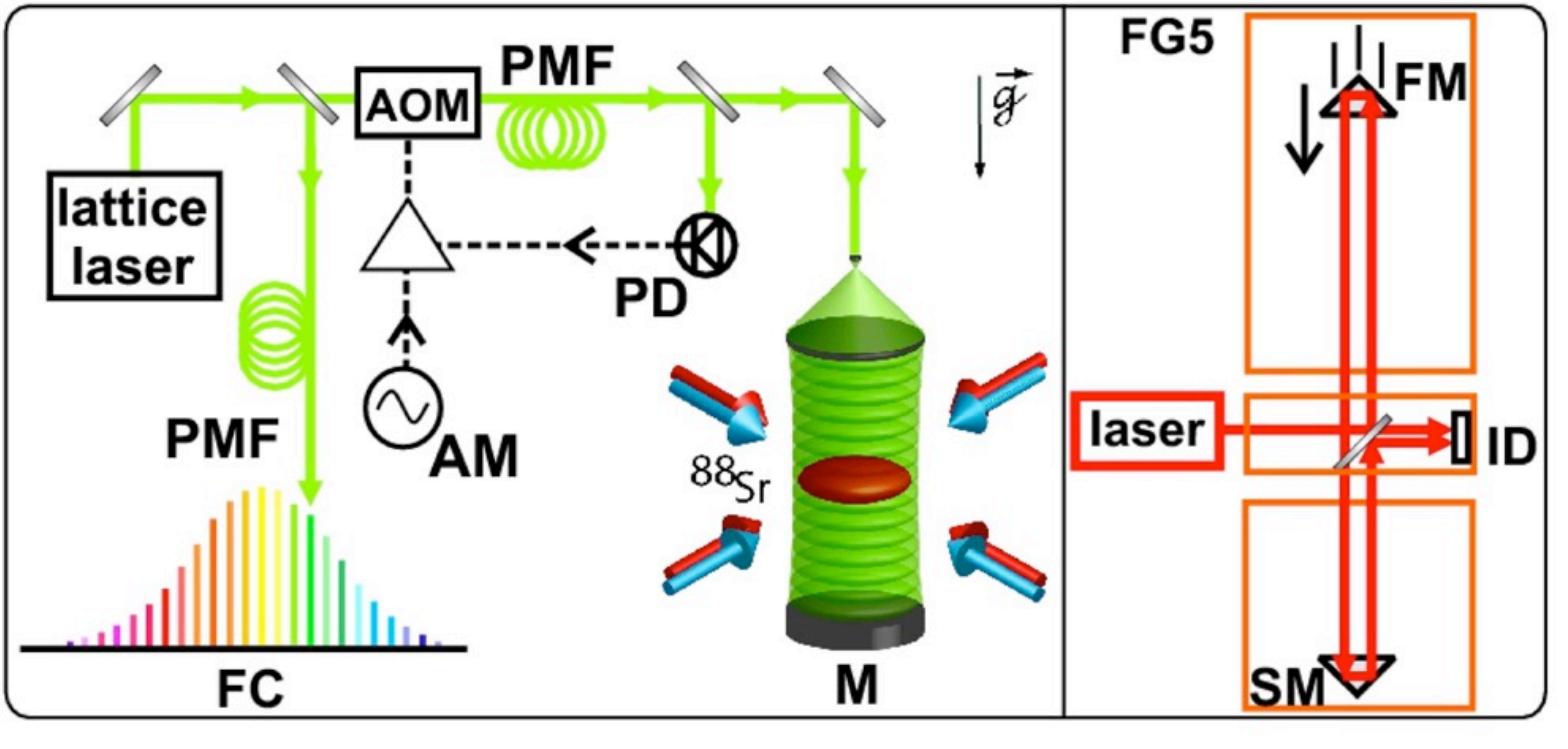




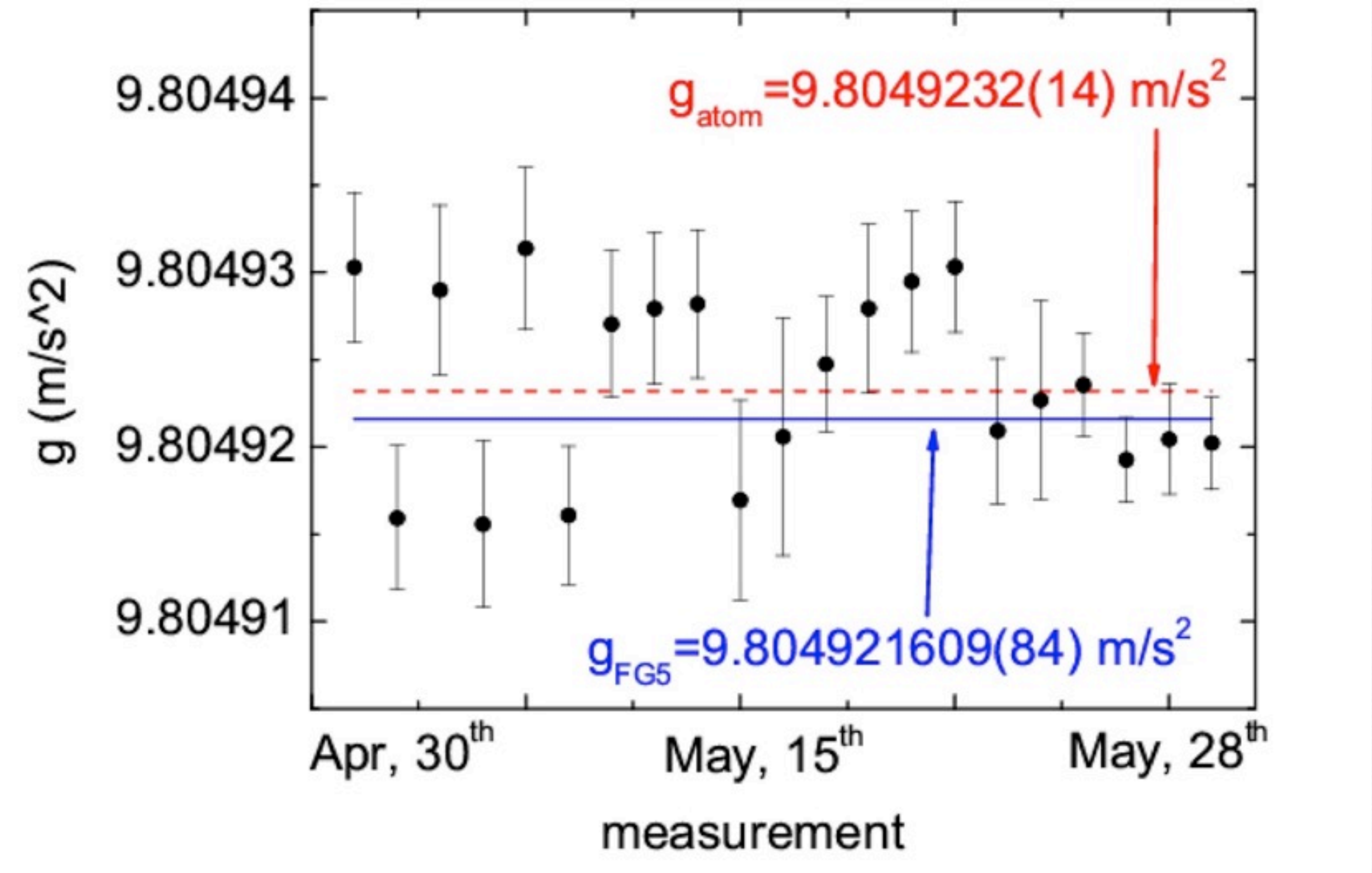
V. V. Ivanov et al., PRL **100**, 043602 (2008)

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

Absolute measurement of g with Sr

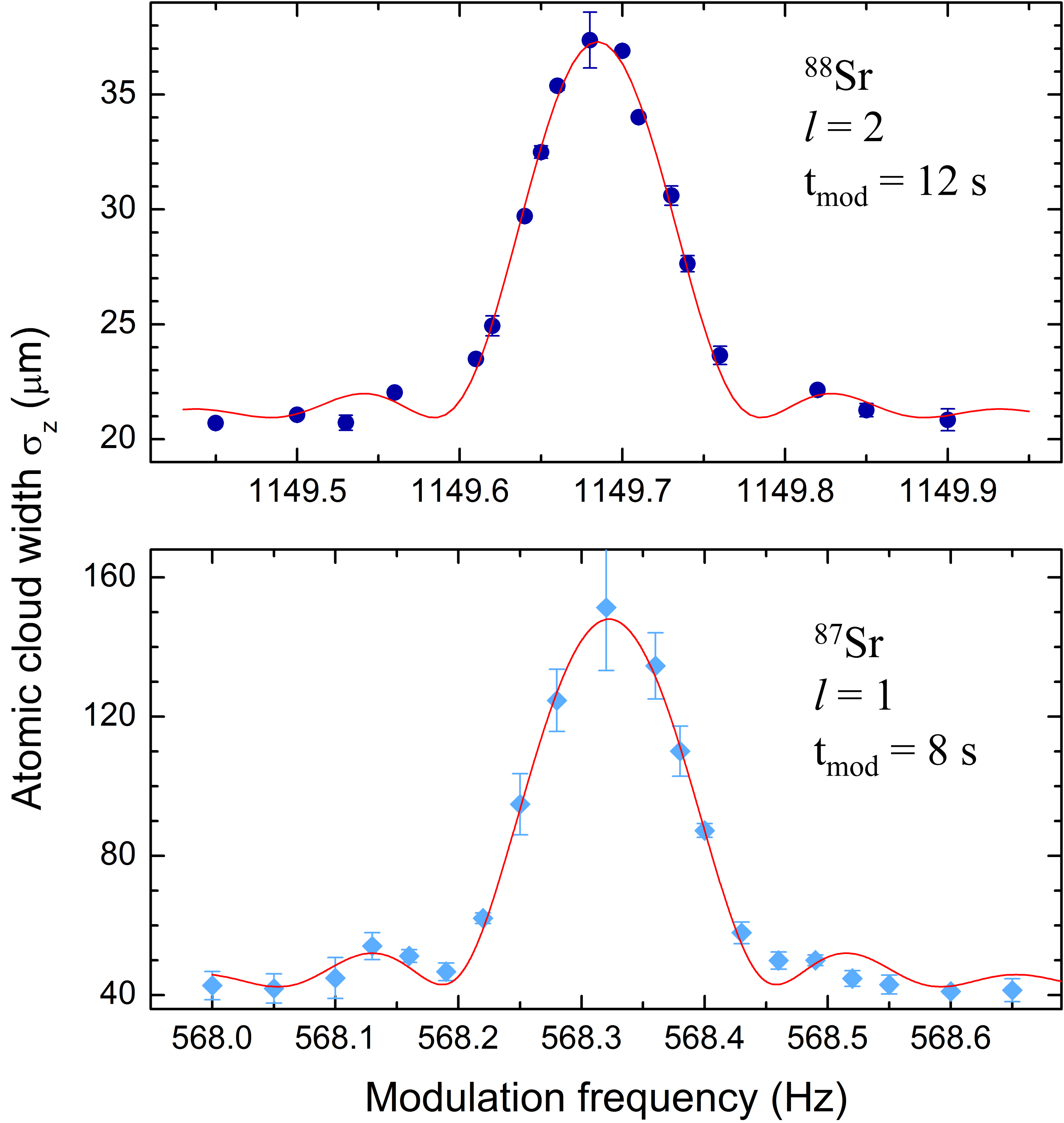


Comparison with a classical gravimeter



N. Poli, F.Y. Wang, M.G. Tarallo, A. Alberti, M. Prevedelli, G.M. Tino, PRL **106**, 038501 (2011)

Test of EP with bosons & fermions

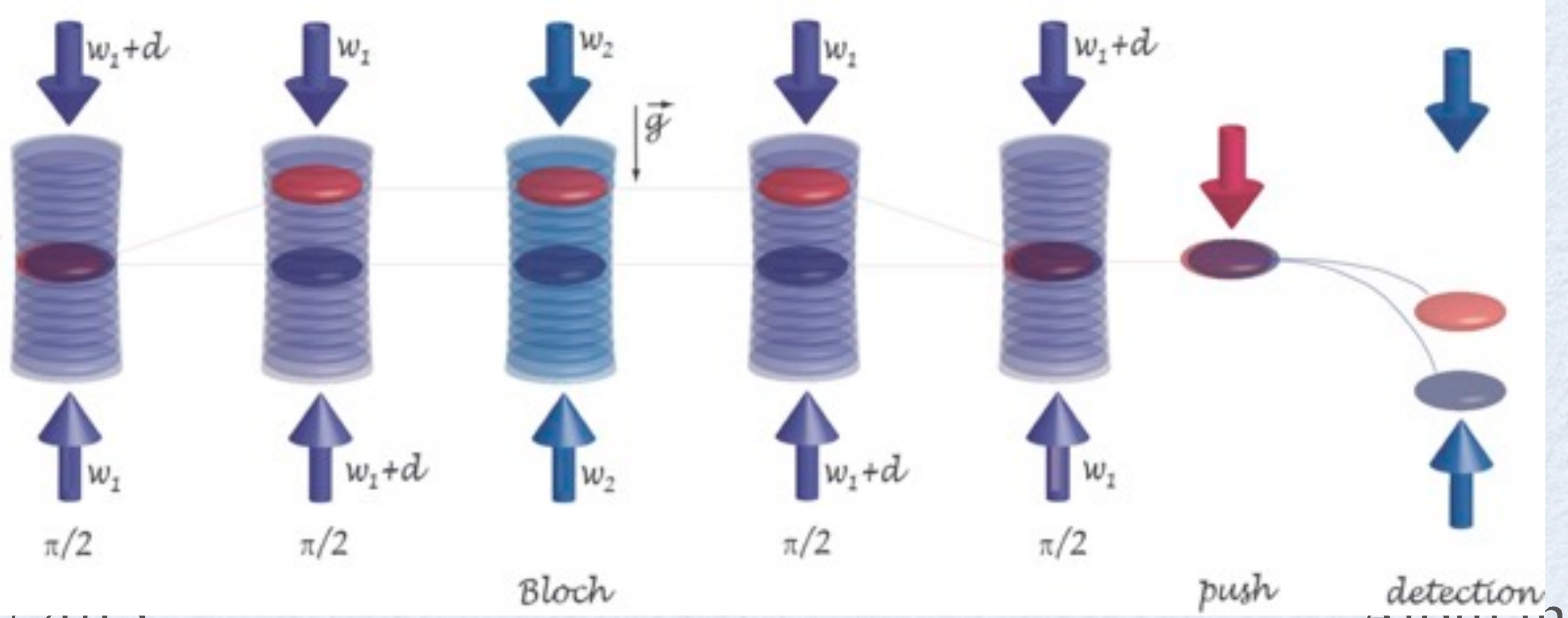


measurement of the Eötvös ratio at the 10^{-7} level

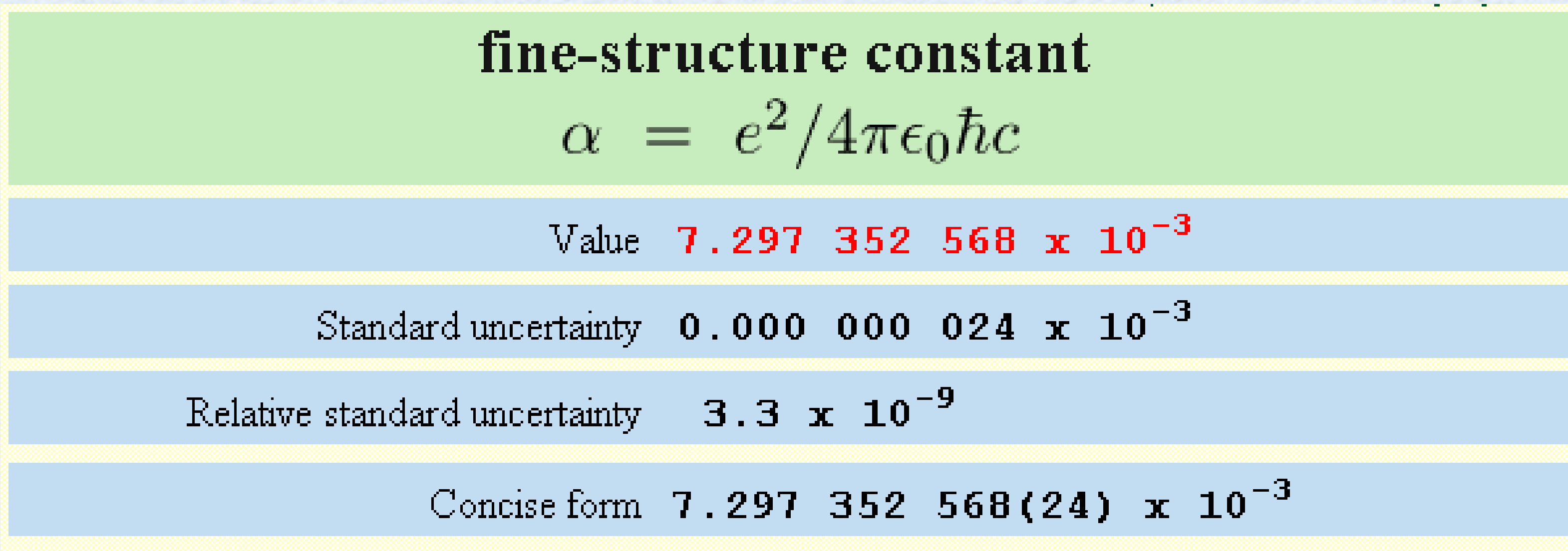
M. Tarallo et al., PRL **113**, 023005-1 (2014)

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. ~3x10^{-10} g/shot
  - **MAGIA ADV 2**: t=10 ms, T=10 s, N=20, sens. ~10^{-11} g/shot

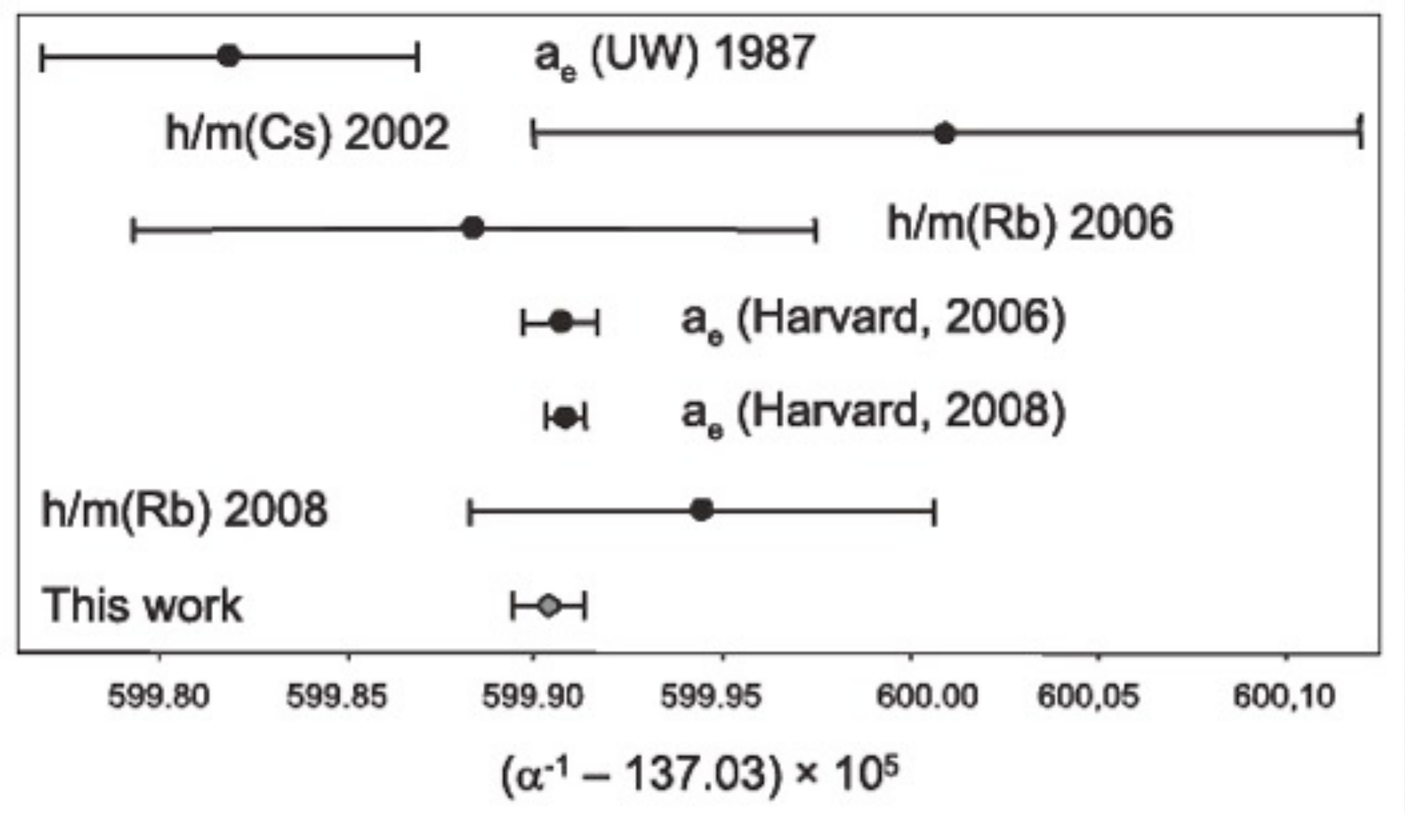


h/m and fine-structure constant



fine-structure constant $\alpha = e^2/4\pi\epsilon_0\hbar c$	
Value	7.297 352 568 x 10^{-3}
Standard uncertainty	0.000 000 024 x 10^{-3}
Relative standard uncertainty	3.3 x 10^{-9}
Concise form	7.297 352 568(24) x 10^{-3}

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



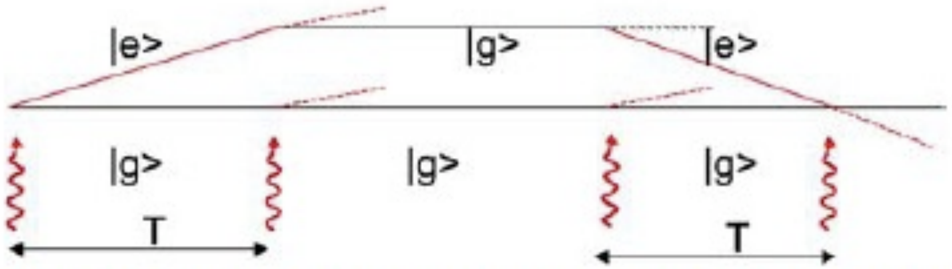


FIGURE 2 Basic (Ramsey–Borde) atom interferometer with four $\pi/2$ laser pulses as beam splitter

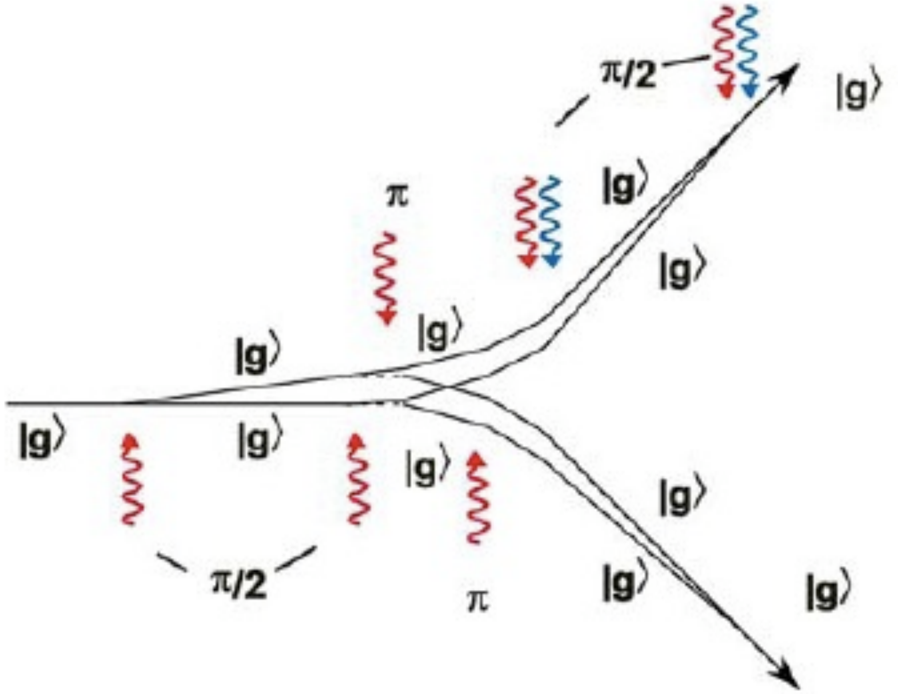
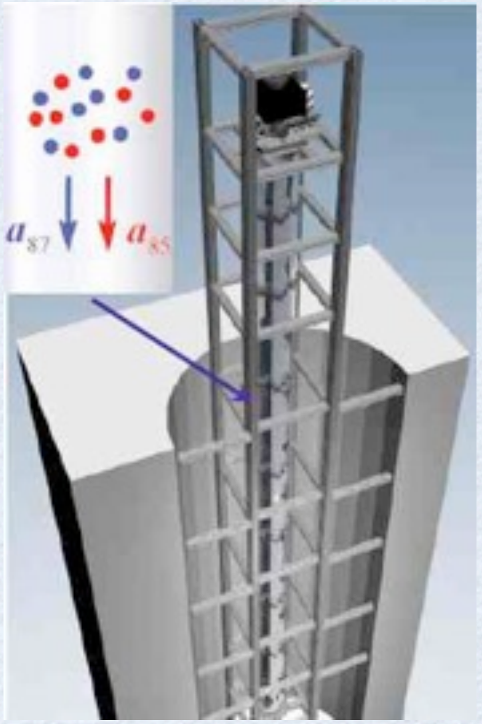


FIGURE 3 SCIs used in this experiment. The last two $\pi/2$ pulses contain four frequencies in two pairs, to simultaneously address both conjugate interferometers

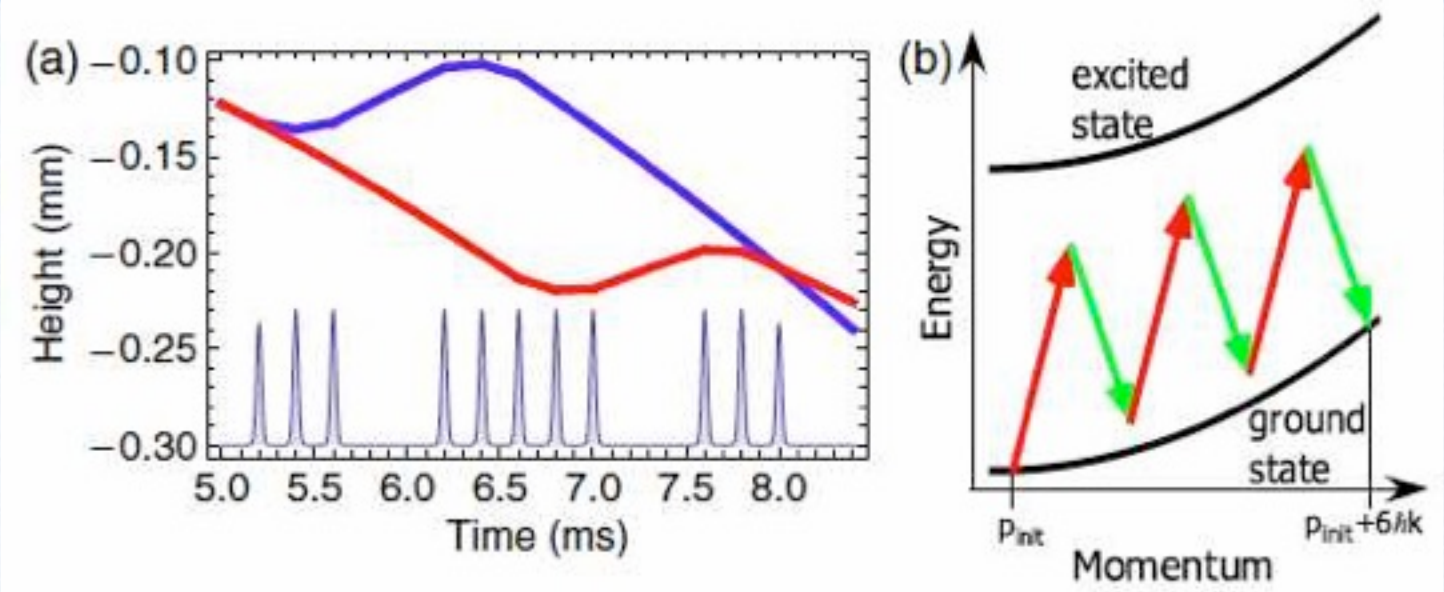
S.-W. Chiow et al., PRL **103**, 050402 (2009)
R. Bouchendira et al., PRL **106**, 080801 (2011)

Future of AI inertial sensors

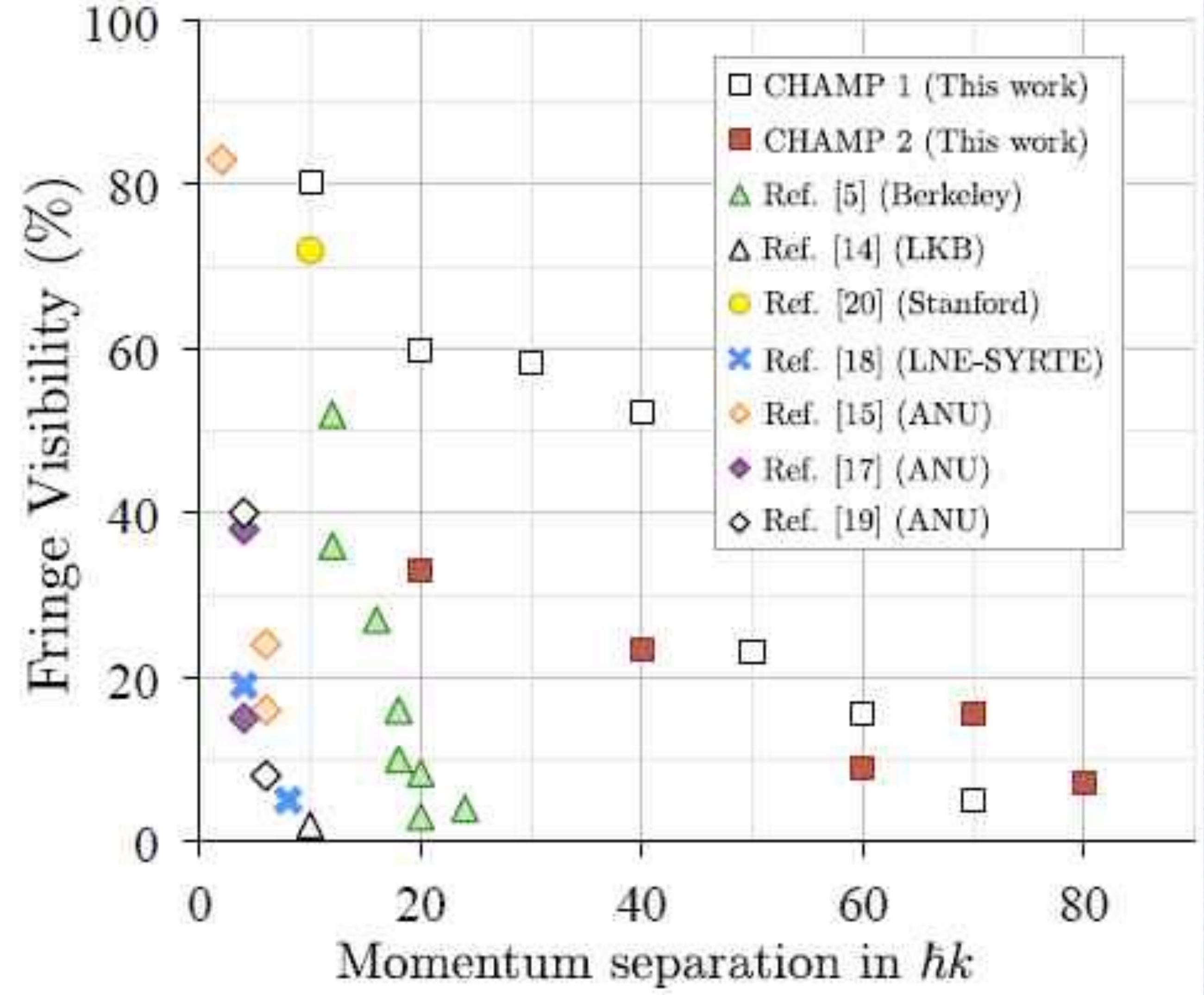
- Compact and transportable system without performance degradation
    - ground applications (geophysics)
    - space applications (satellite geodesy, inertial navigation, tests of fundamental physics): $\Delta\phi = kgT^2$
- Novel schemes to improve sensitivity/accuracy
    - high-momentum beam spitters (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.

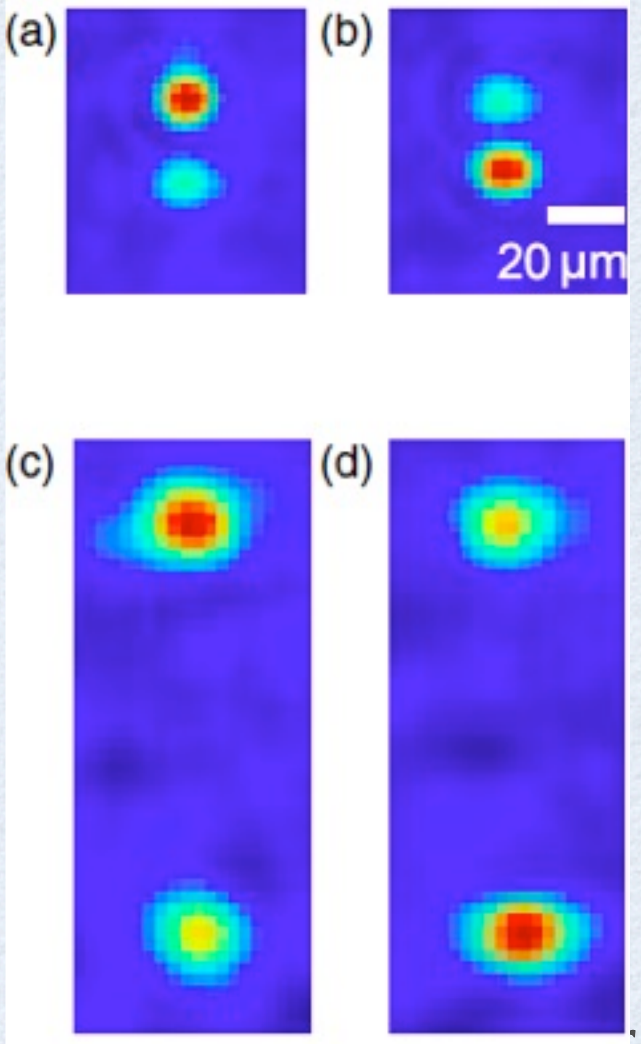


LMT beam splitters

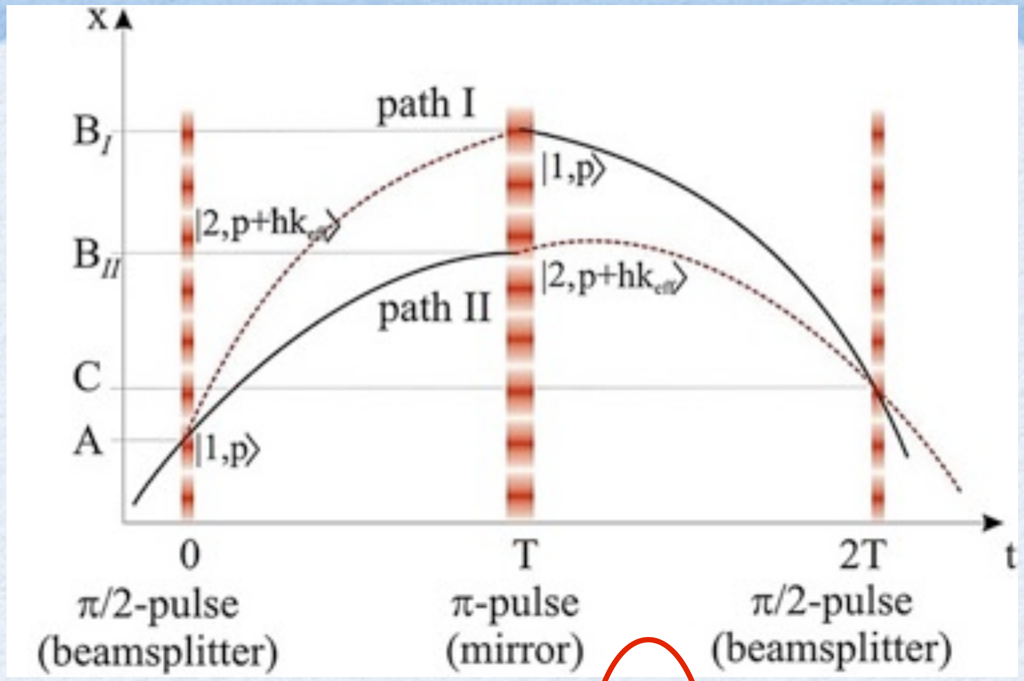


- H. Müller et al., PRL **102**, 240403 (2009)
- S.-W. Chiow et al., PRL **107**, 130403 (2011)
- G. D. McDonald et al., PRA **88**, 053620 (2013)





AI measurements in space

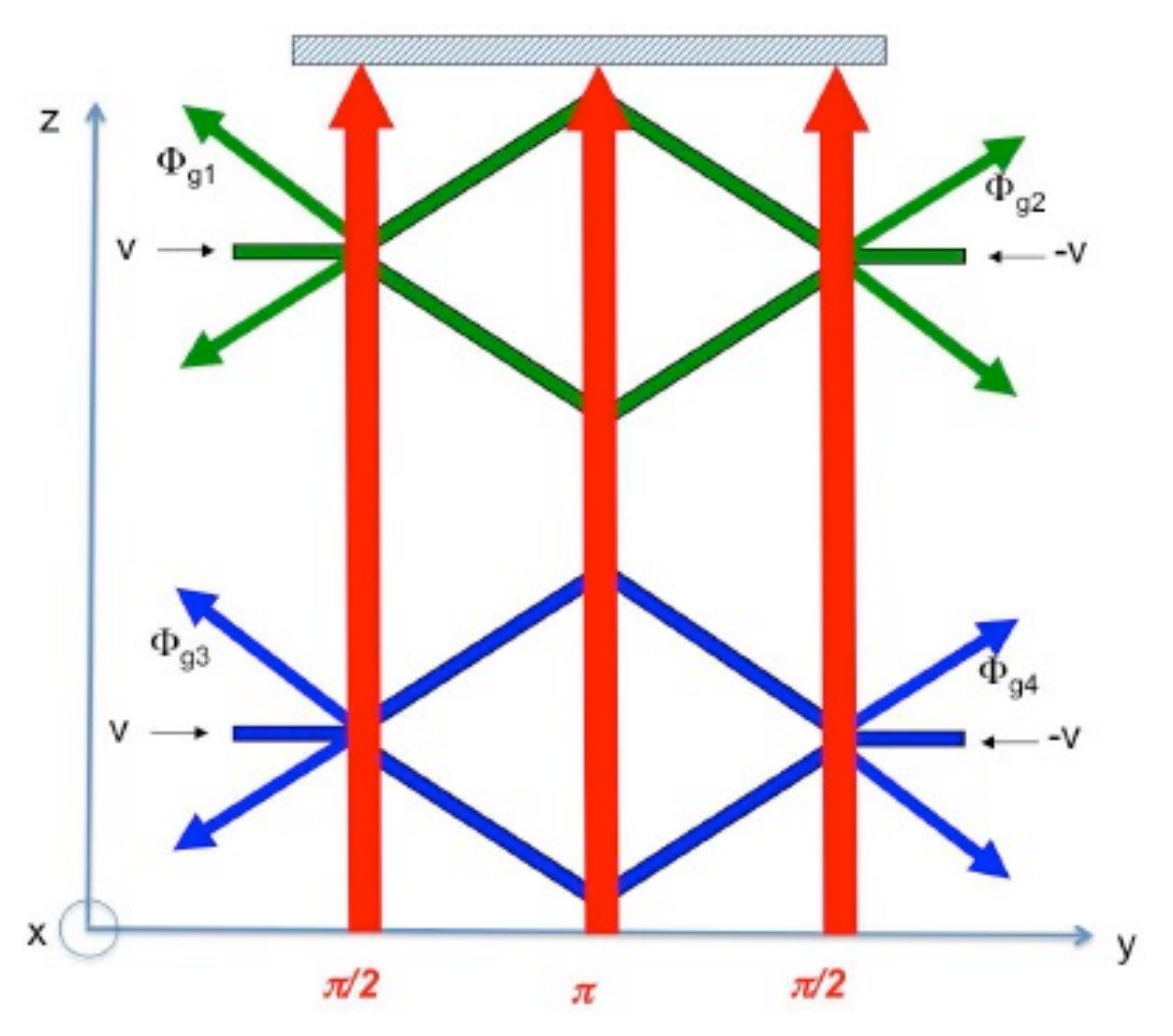


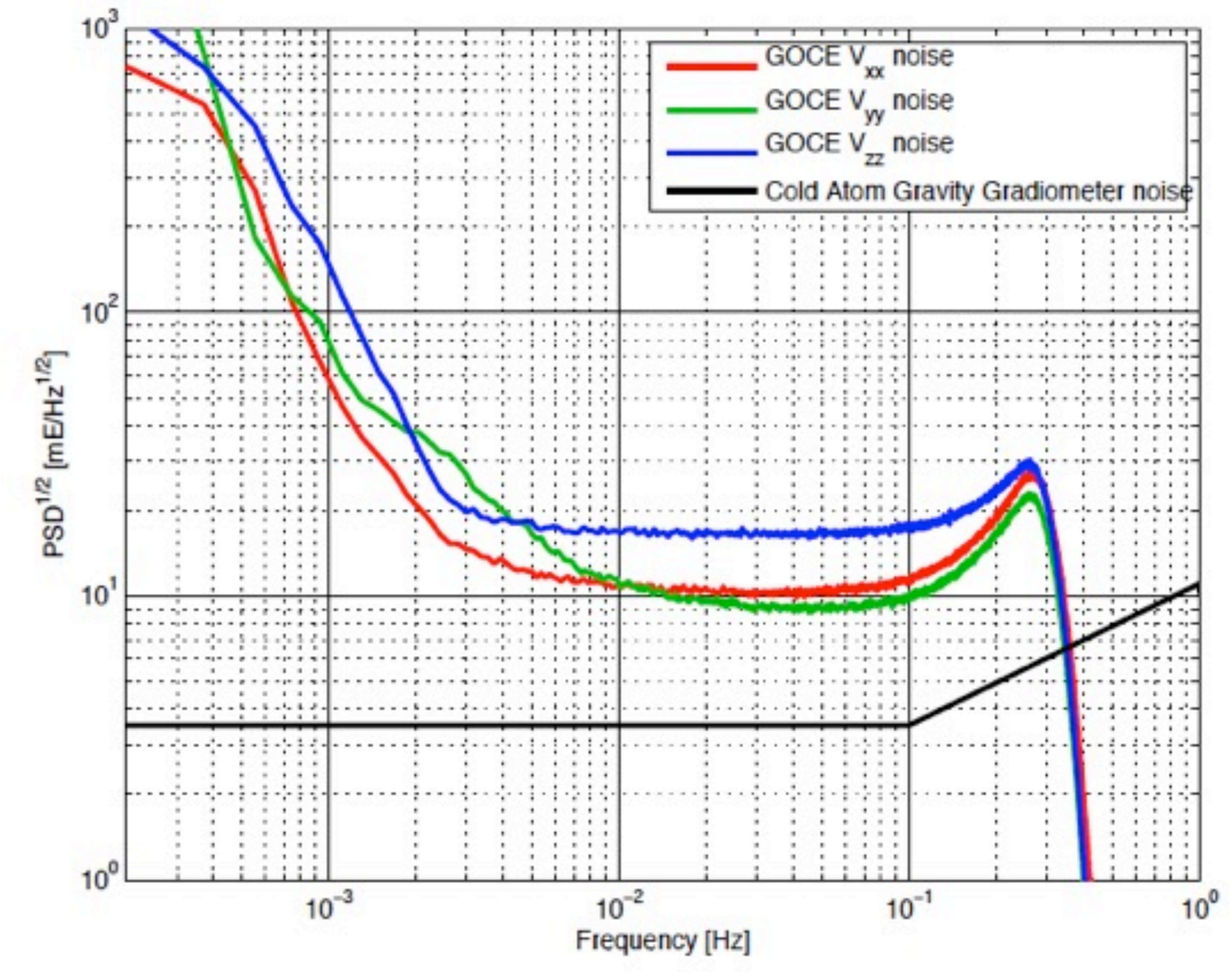
$$\Delta\phi = kgT^2$$

- 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)

AI towards GW detection

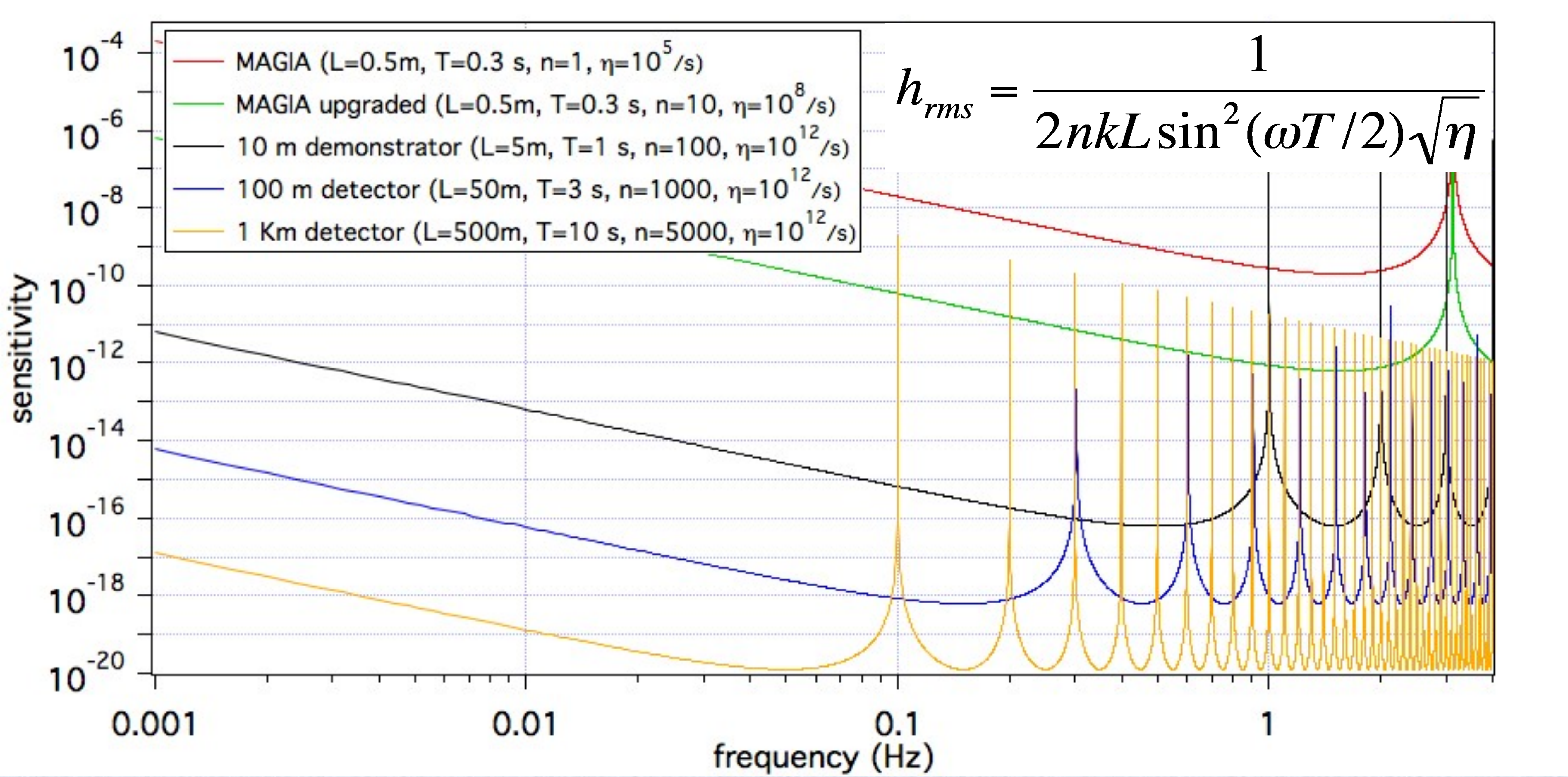
- Increasing the wave-packet separation with LMT splitters
  - interferometers with ~100 photon recoils already demonstrated
- Improving the QPN limit with large flux atomic sources
  - current achievements: ~10^8 at/s below 1 μK with alkali
- Increasing the size and separation between simultaneous interferometers
- Beating the QPN limit
  - QND measurement of atomic populations
  - use of entangled and/or coherent states
- Sensor modeling
  - understanding noise sources other than QPN (laser wavefront, Newtonian noise, atomic motion etc.)
  - design of optimal configurations
- Possible advantages:
  - excellent CMRR for vibration noise in differential configurations
  - no thermal noise
  - several “knobs” to tune sensitivity function and isolate noise sources
  - room for improvements (experimental configurations, technical limits)

Recent literature

- G. M. Tino, F. Vetrano and C. Lämmerzahl Eds., Special Issue on *Gravitational waves detection with atom interferometry*, Gen. Relativ. Gravit. **43**, 1901 (2011)
- F. Vetrano, G. M. Guidi, A. Vicerè, Q. Bodart, Y. Lien, M. Prevedelli, G. Rosi, F. Sorrentino and G. M. Tino *Principles of gravitational waves detection through atom interferometry*, International Journal of Modern Physics: Conference Series **23**, 135-143 (2013)
- G. M. Tino and M. Kasevich Eds., *Atom Interferometry*, Proc. intern. school of physics Enrico Fermi CLXXXVIII (2013)
- MIGA project (CNRS)

AI & GW detection

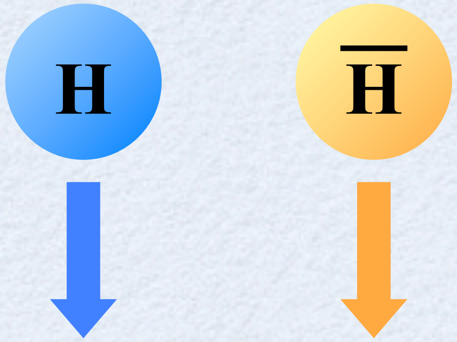
G. M. Tino, F. Vetrano and C. Lämmerzahl Eds., Special Issue on Gravitational waves detection with atom interferometry, Gen. Relativ. Gravit. **43**, 1901 (2011)

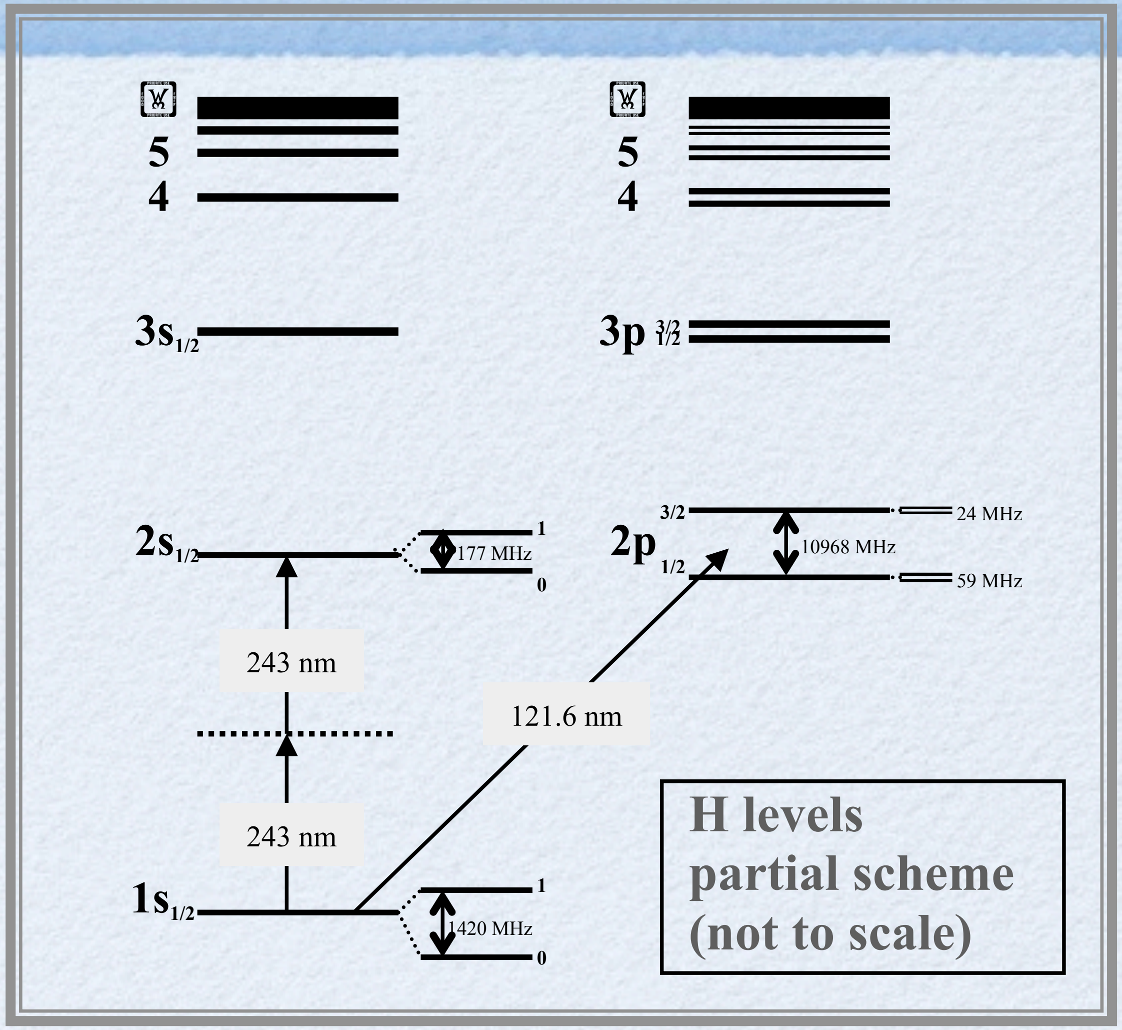


$$h_{rms} = \frac{1}{2nkL\sin^2(\omega T/2)\sqrt{\eta}}$$

Test of EP with antimatter (AEGIS)

- **Compare g**





H levels partial scheme (not to scale)

- **Steps:**

→ anti-H production (ATHENA, ATRAP)

→ anti-H selective state population

→ anti-H cooling

→ anti-H trapping

→ g measurement:

- Time of flight

$\Delta g/g \rightarrow 10^{-3}$?

- Atom interferometry

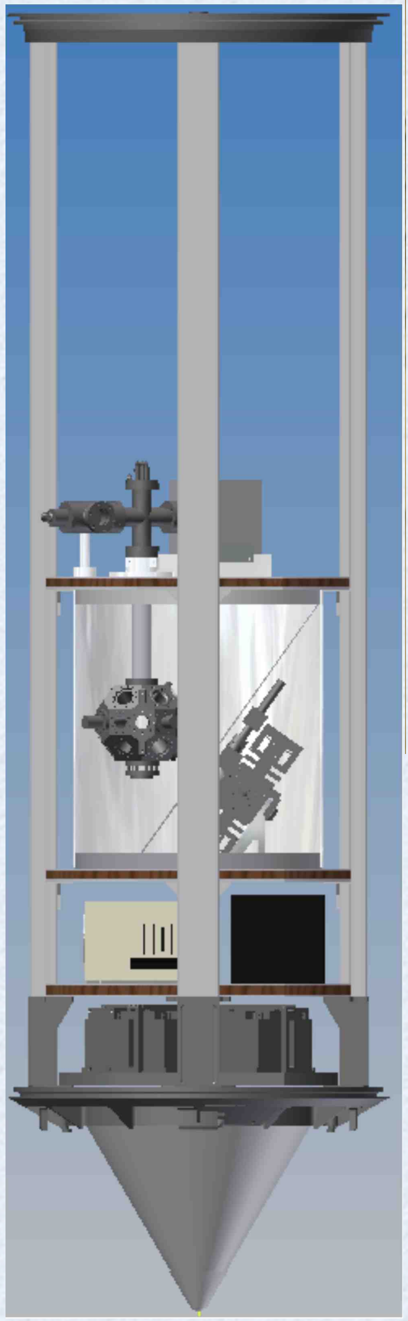
- **Raman transitions between 2S HFS sublevels**
- **2S→high-P levels transitions**
  (T. Heupel *et al.*, Europhys. Lett. 57, 158 (2002))

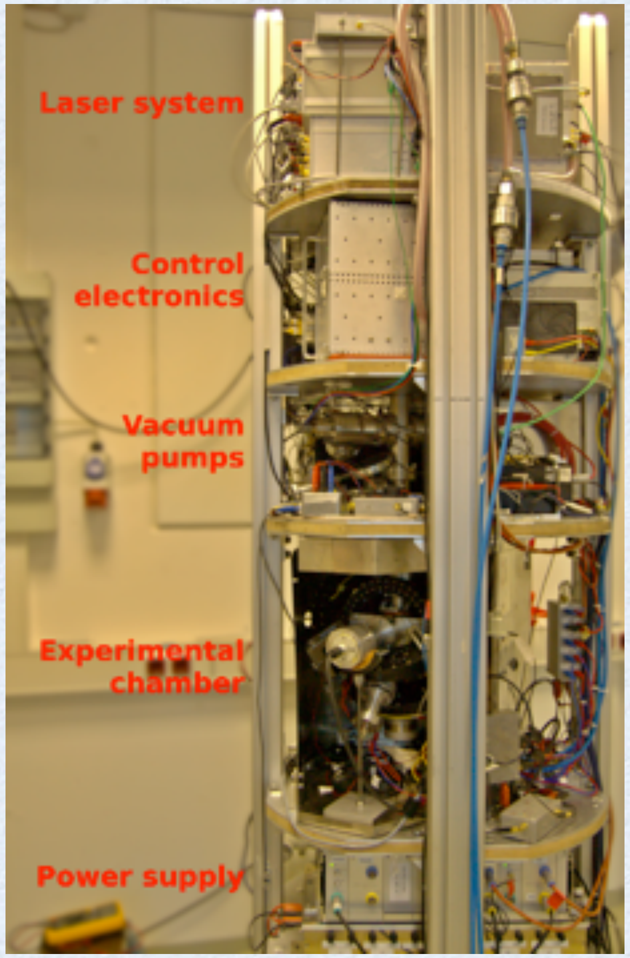
$\Delta g/g \rightarrow 10^{-9}$?

TRL of AI: space research

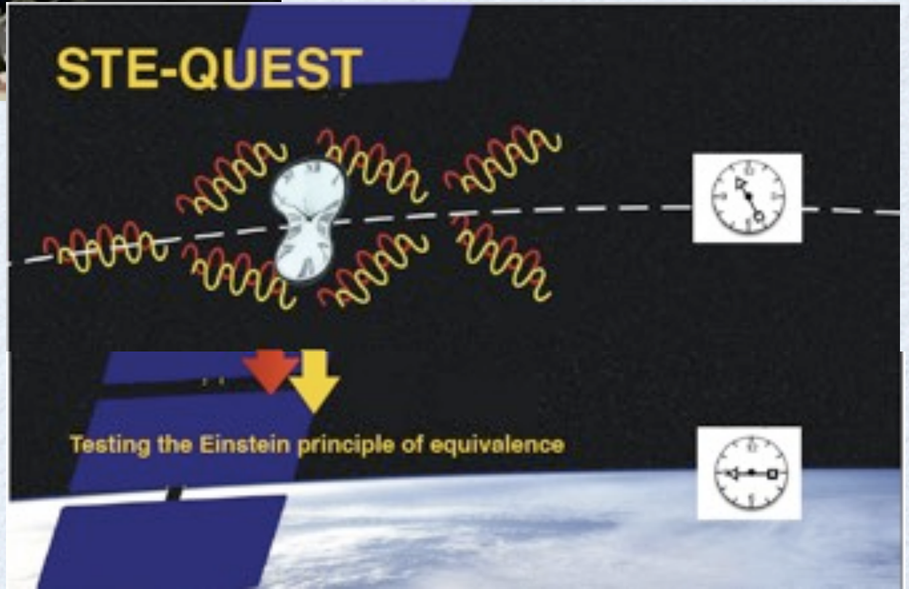
- ACES (atomic clock on the ISS)
- HYPER (test of Lense-Thirring effect)
- Q-WEP (testing WEP on ISS with AI using ^{87}Rb-^{85}Rb)
- STE-QUEST (atomic clock to measure red shift + AI to test WEP on dedicated satellite)
- QUANTUS (drop tower, DLR)
- I.C.E. (parabolic flights, CNES)

SAI





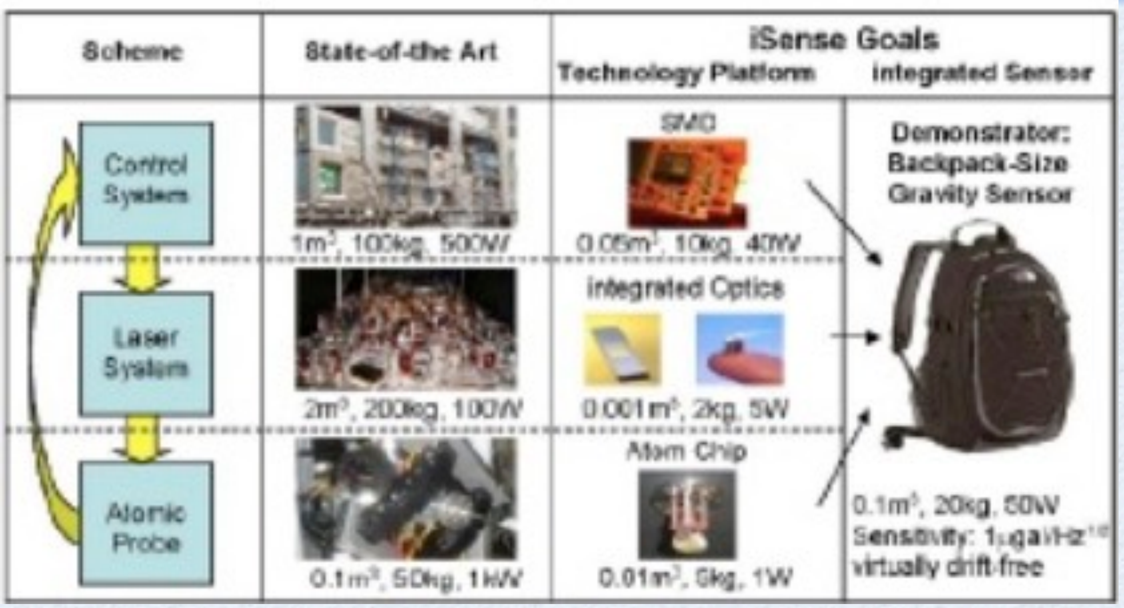
QUANTUS



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

TRL: towards commercial AI instruments

iSENSE



Scheme	State-of-the Art	iSense Goals Technology Platform	 Integrated Sensor
Control System	1m³, 100kg, 500W	SMD 0.05m³, 10kg, 40W	Demonstrator: Backpack-Size Gravity Sensor 0.1m³, 20kg, 50W Sensitivity: 1 μgal/Hz$^{1/2}$ virtually drift-free
Laser System	2m³, 200kg, 100W	Integrated Optics 0.001m³, 2kg, 5W	
Atomic Probe	0.1m³, 50kg, 1kW	Atom Chip 0.01m³, 5kg, 1W	

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 (G, alpha)
  - 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.)