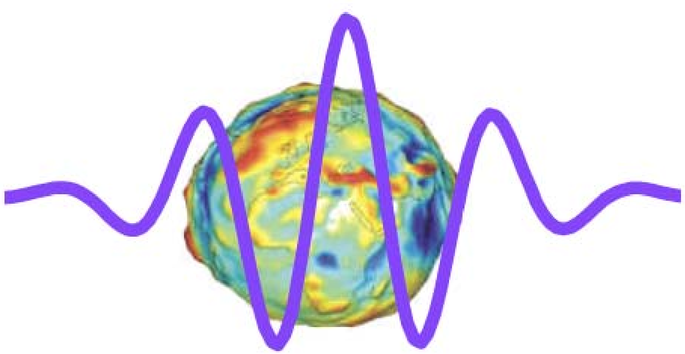
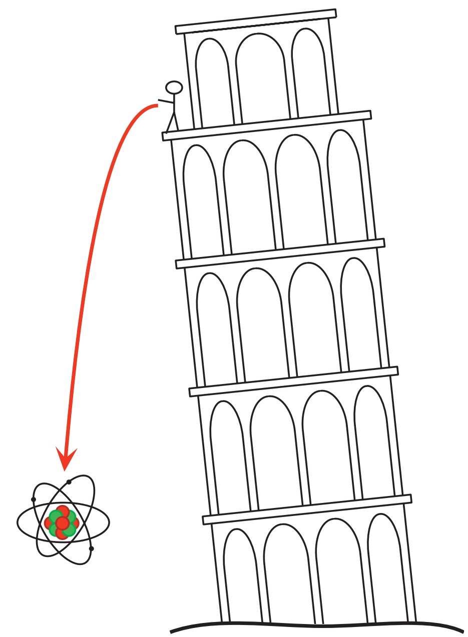
Prof. Achim Peters, Ph.D.

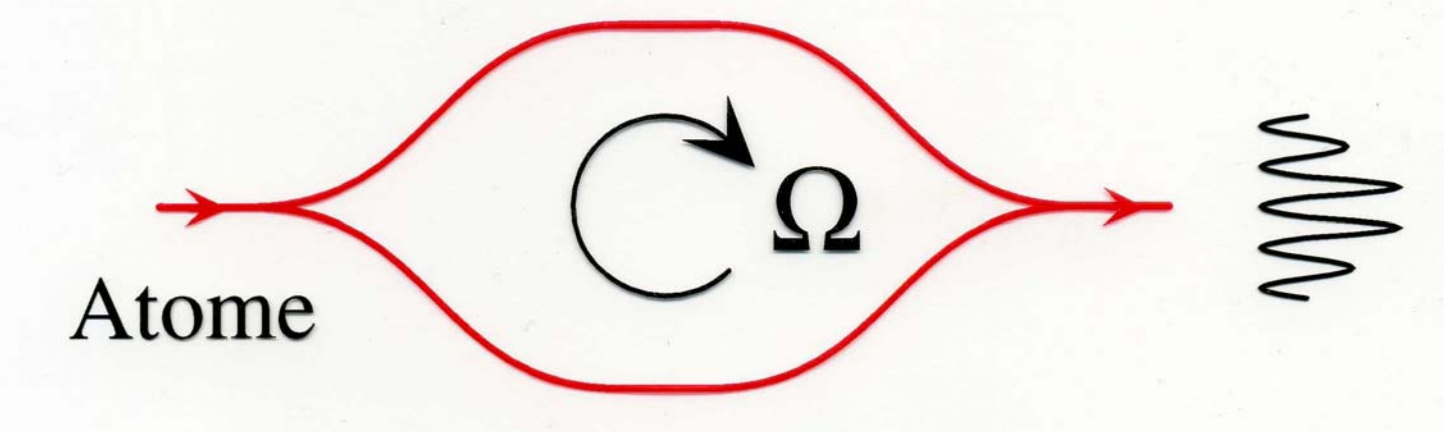
Atom interferometry – applications in gravimetry and some thoughts on current sensitivity limitations and concepts for future improvements

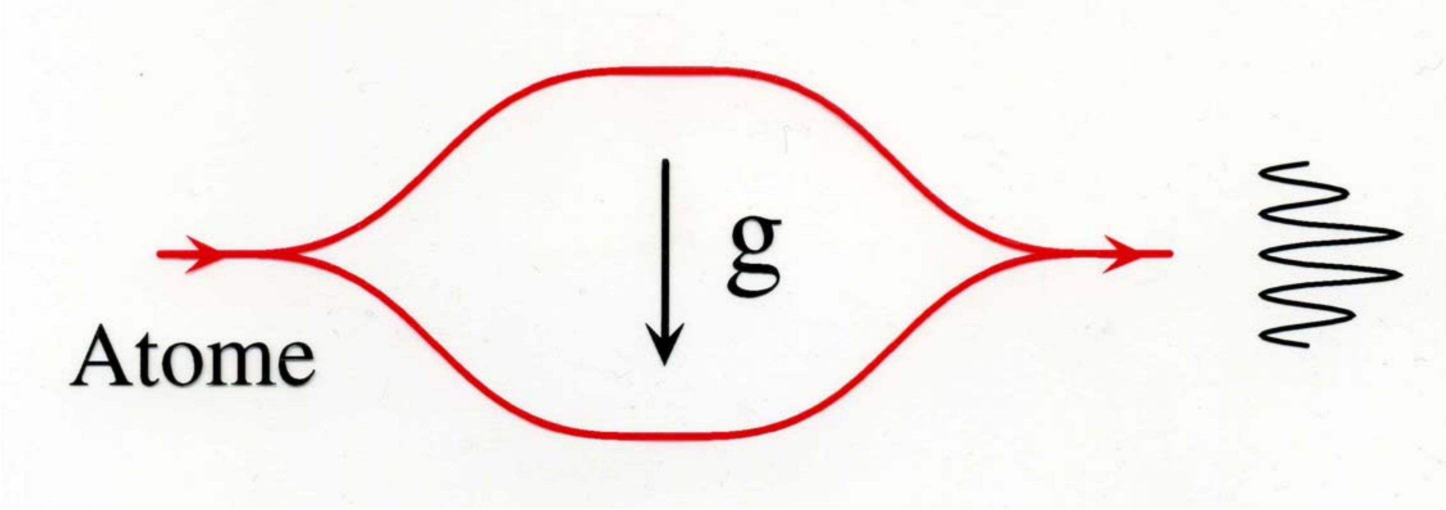




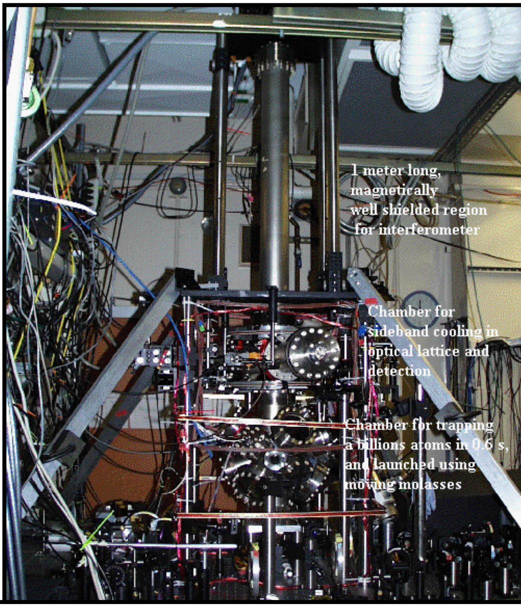
International Workshop on „Gravitational Waves Detection with Atom Interferometry“
February 23-24, 2009 / Galileo Galilei Institute for Theoretical Physics – Arcetri, Firenze

Inertial sensing using atom interferometers





State of Art: AI Gravimeters + Gradiometers

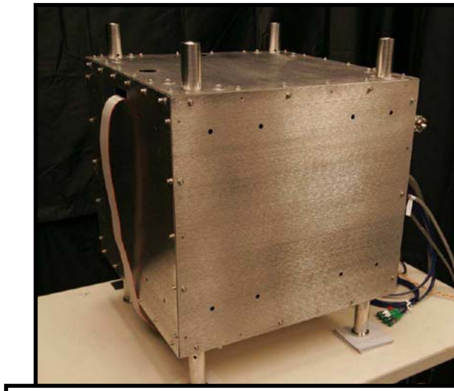


Stanford Gravimeter (non-mobile)

Achieved Accuracy: $4 \cdot 10^{-9}$ g (?)

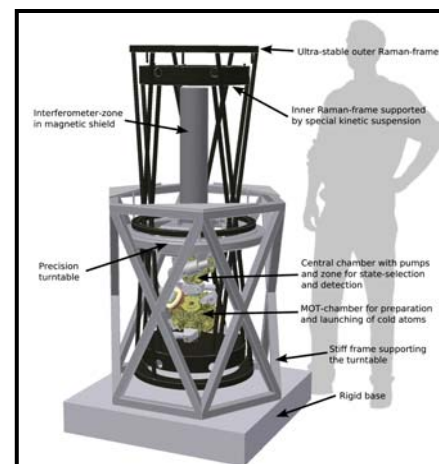
Paris Gravimeter („mobile“)

Achieved Accuracy: $1.4 \cdot 10^{-8}$ g



Kasevich Gravimeter (mobile)

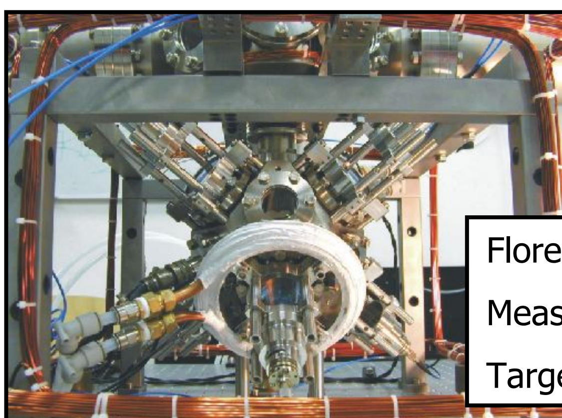
Bias Stability: $< 10^{-10}$ g



Berlin Gravimeter GAIN

(mobile, under construction)

Targeted Accuracy: $5 \cdot 10^{-10}$ g



Florenz INFN Gravity Gradiometer MAGIA

Measurement of the gravitational constant G

Targeted Accuracy: $\Delta G/G = 1 \cdot 10^{-4}$

Important gravitational effects

- spatial gravity variations

– gravity gradient $\sim 3 \cdot 10^{-7}$ g / m

– global scale $\sim 10^{-3}$ g

– regional scale $\sim 10^{-6}$ g

- navigation
- finding oil, water, minerals, archeological sites, ...

- temporal gravity variations

– tides $\sim 10^{-7}$ g

– man-made changes $\sim 10^{-9}$ g

– atmospheric pressure $\sim 10^{-10}$ g / mbar

– local water table $\sim 10^{-8}$ g

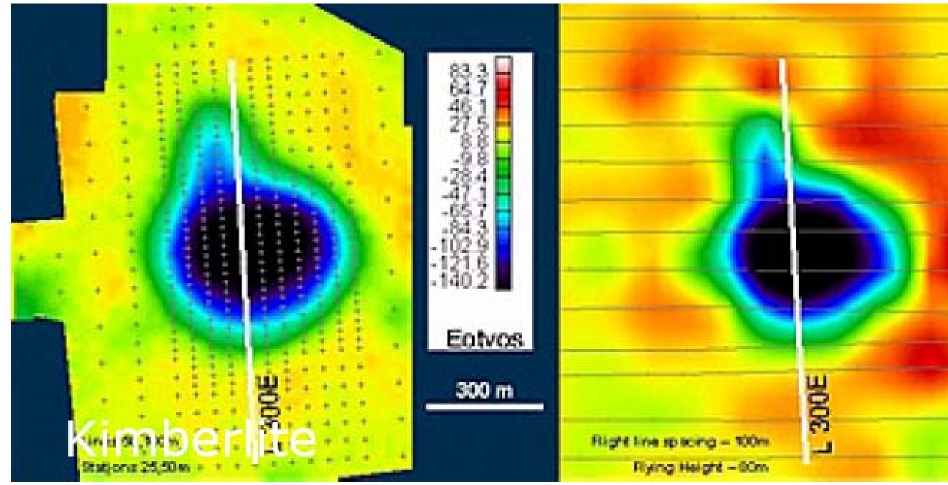
– ... $\sim 10^{-9}$ g

Airborne gravity gradiometery

Existing technology

Land: 3 wks.

Air: 3 min.



AI sensors potentially offer 10 x – 100 x improvement in detection sensitivity at reduced instrument costs.

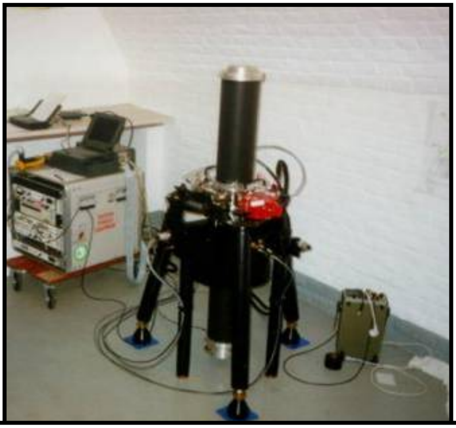
Gravitational effects of various objects

Object	mass (kg)	distance (m)	gravity (μGal)	gradient (μGal/m)	angle (deg)	gravity change (μGal)
Earth	6.0×10^{24}	6.4×10^{6}	9.8×10^{8}	308	0	9.8×10^{8}
Optical table	1000	1.5	3.0	4	0	3.0
Aluminum spacers	1	0.1	0.7	13	0	0.7
Experimental physicist	90	1.0	0.7	1.2	45	0.5
Theoretical physicist	120	3.0	0.1	0.06	0	0.1
Loaded truck	40000	10	2.7	0.5	45	2.0
Physics lecture hall (demolished)	2.0×10^{6}	50	5.0	0.2	90	0.0
Hole (excavated)	2.0×10^{7}	100	13.3	0.3	85	1.3

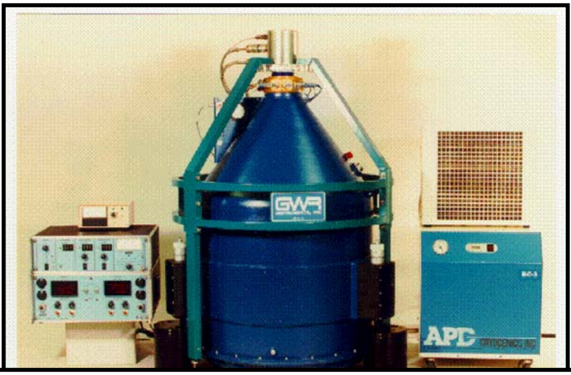
Different types of gravimeters

	Noise [g/Hz$^{1/2}$]	Drift [g/day]	Accuracy [g]
Spring/Mass Systems	$1 \cdot 10^{-10}$	$3 \cdot 10^{-8}$	N/A
Levitated Superconducting Spheres (Cyogenic)	$< 10^{-12}$	$< 2 \cdot 10^{-10}$	N/A
Falling Corner Cubes	$5 \cdot 10^{-8}$ *)	-	$2 \cdot 10^{-9}$
Atom Interferometer	$2 \cdot 10^{-8}$ *)	-	$7 \cdot 10^{-9}$

*) measured in the same laboratory; noise could be a factor 10 lower at a seismologically quiet site



FG-5 corner-cube gravimeter



GWR superconducting gravimeter

Burris Spring Gravity Meter

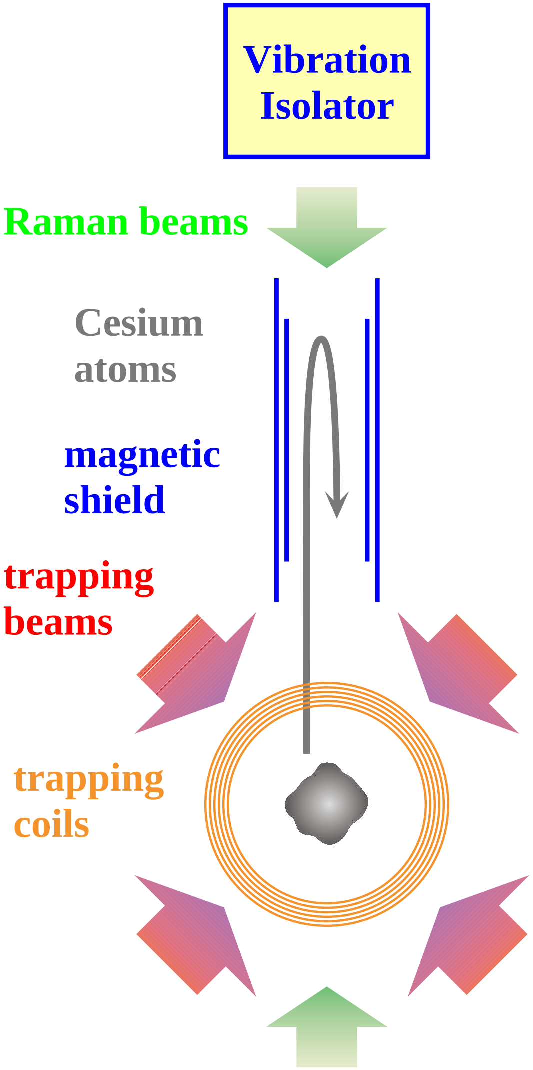
Main Purpose of absolute gravimeters

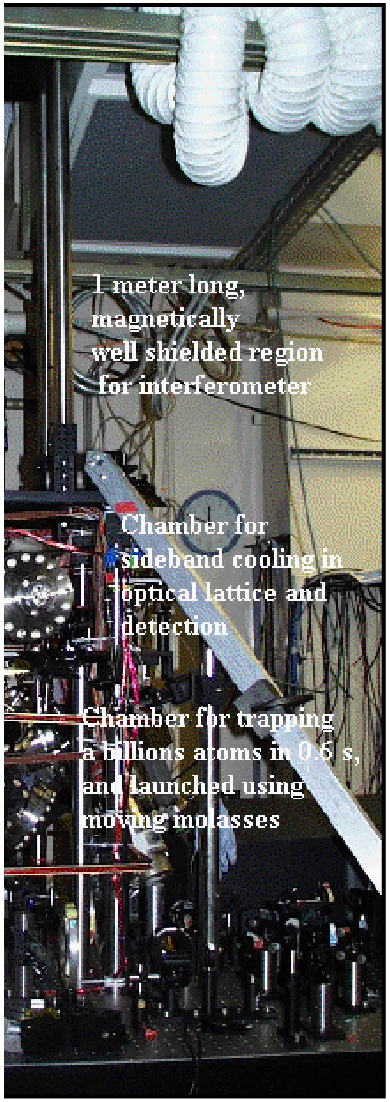
Compare readings taken at different locations and monitor changes for unlimited periods of time

Atom interferometric absolute gravimeter

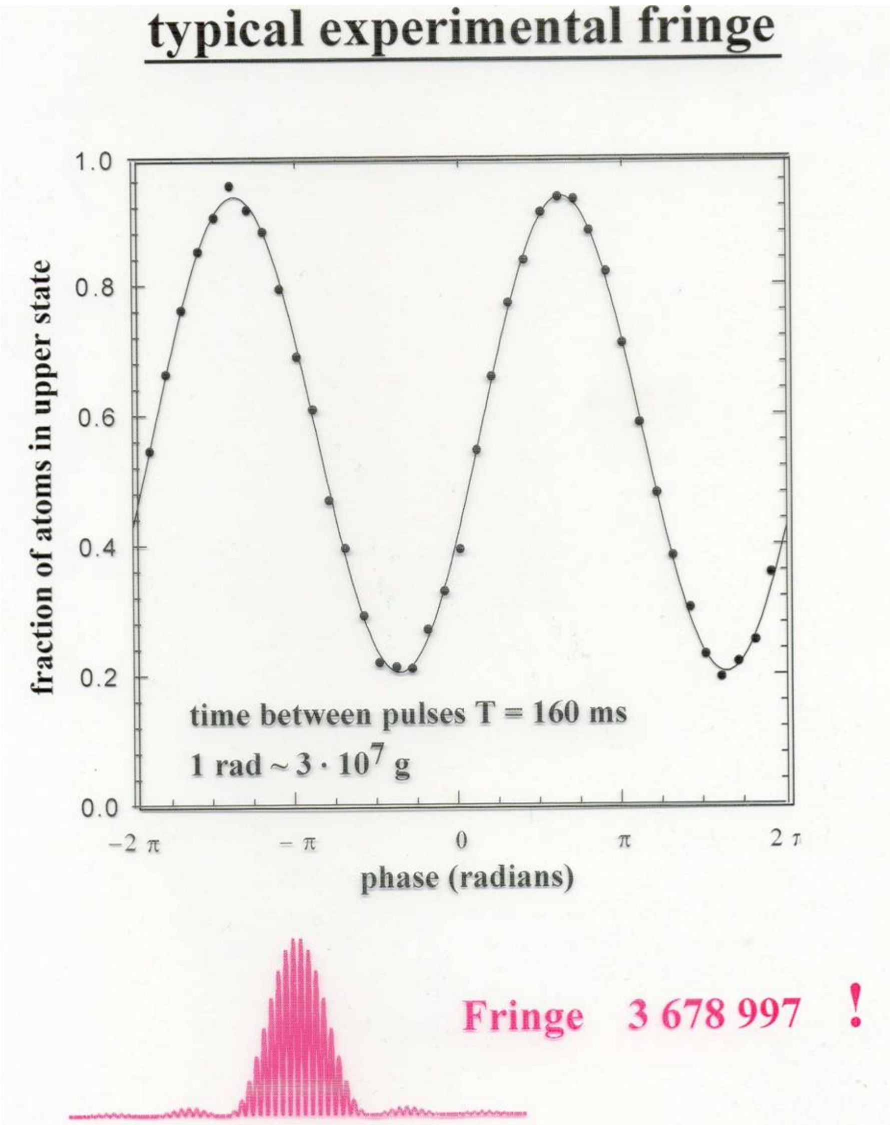
- Noise < 10^{-8} g / $Hz^{1/2}$
  (basically limited by tectonic noise)
- Accuracy better than 10^{-9}

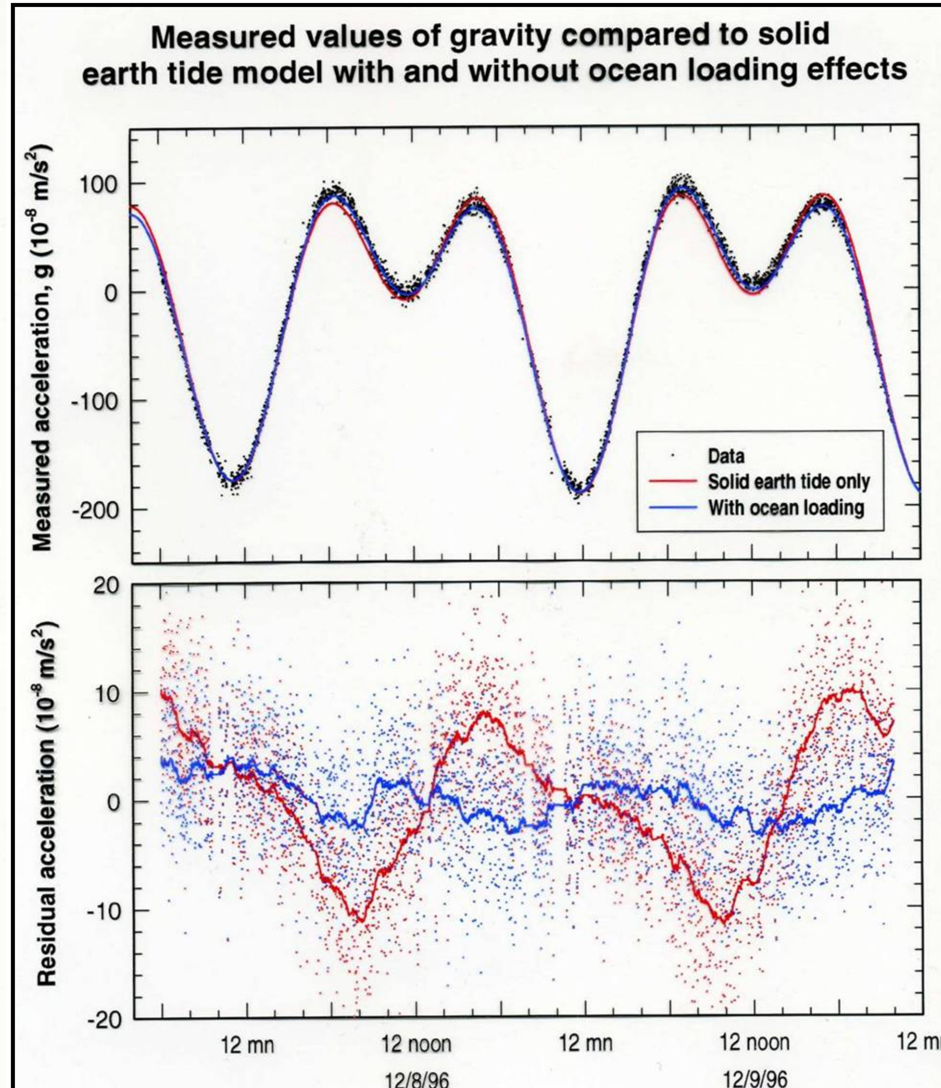
Stanford University atomic fountain gravimeter



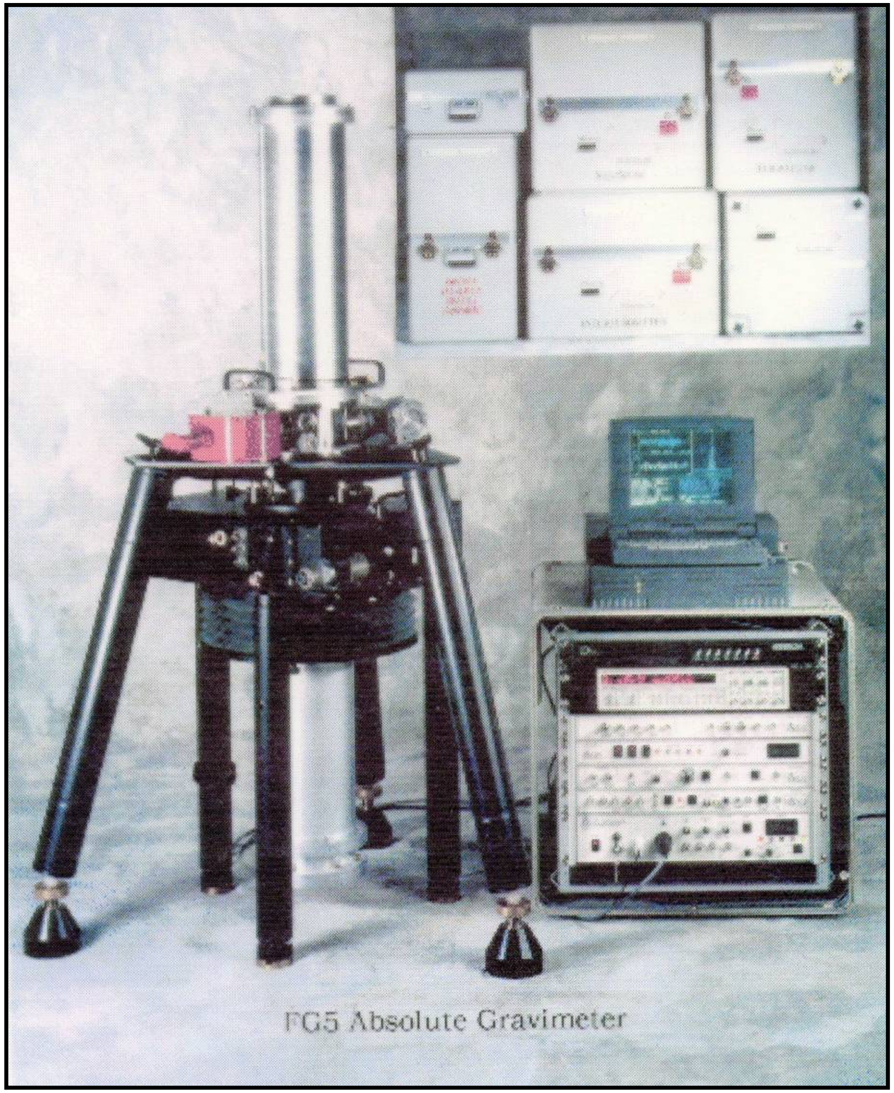


Stanford University atomic fountain gravimeter

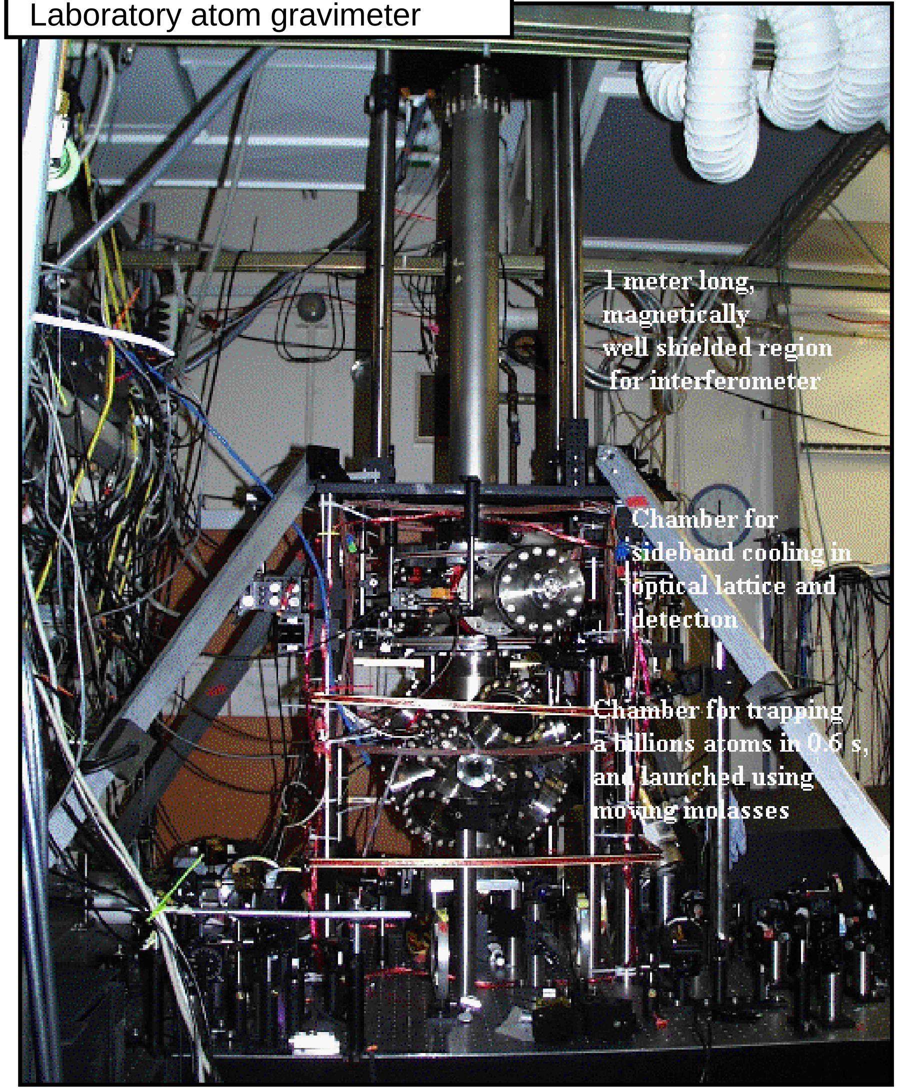




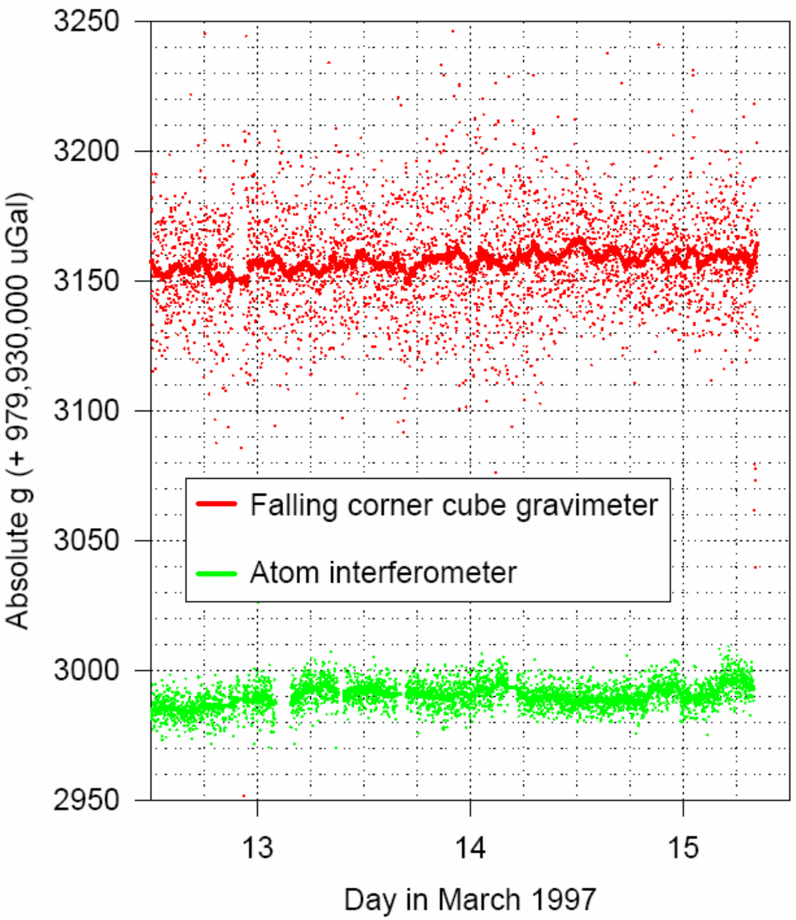
Stanford gravimeter comparison



Laboratory atom gravimeter



Stanford gravimeter comparison



	Value (μGal)	Uncertainty
Measured g value (tide corrected)	$979,933,179$	± 1
Polar motion	-4.8	± 0
Atmospheric pressure	$+0.7$	± 0.1
RF phase shift	-6	± 2
Cesium lock offset	-3	± 1
AC Stark shift	0	± 2
Coriolis effect due to Earth's rotation	0	± 2
Tilt and retro-reflection	0	± 1
Finite speed of light	$+0.3$	± 0.1
Transfer to top of fountain	-6.0	± 0.2
Atom interferometer gravity value	$979,933,160$	± 4

Table 7.1: Calculation of atom interferometer gravity value.

	Value (μGal)	Uncertainty
Measured g value (tide corrected)	$979,933,304$	± 2
Polar motion	-5.9	± 0
Atmospheric pressure	$+1.7$	± 0.1
Falling corner–cube gravity value	$979,933,300$	± 2

Table 7.2: Calculation of falling corner–cube gravity value.

Atom interferometer gravity value	$979,933,160$	$\pm$	4
Falling corner-cube gravity value	$979,933,300$	$\pm$	2
Measurement height correction	147	$\pm$	5
Difference	7	$\pm$	7

Stanford gravimeter comparison

the environment at the time of measurement …

The FINAQS Project

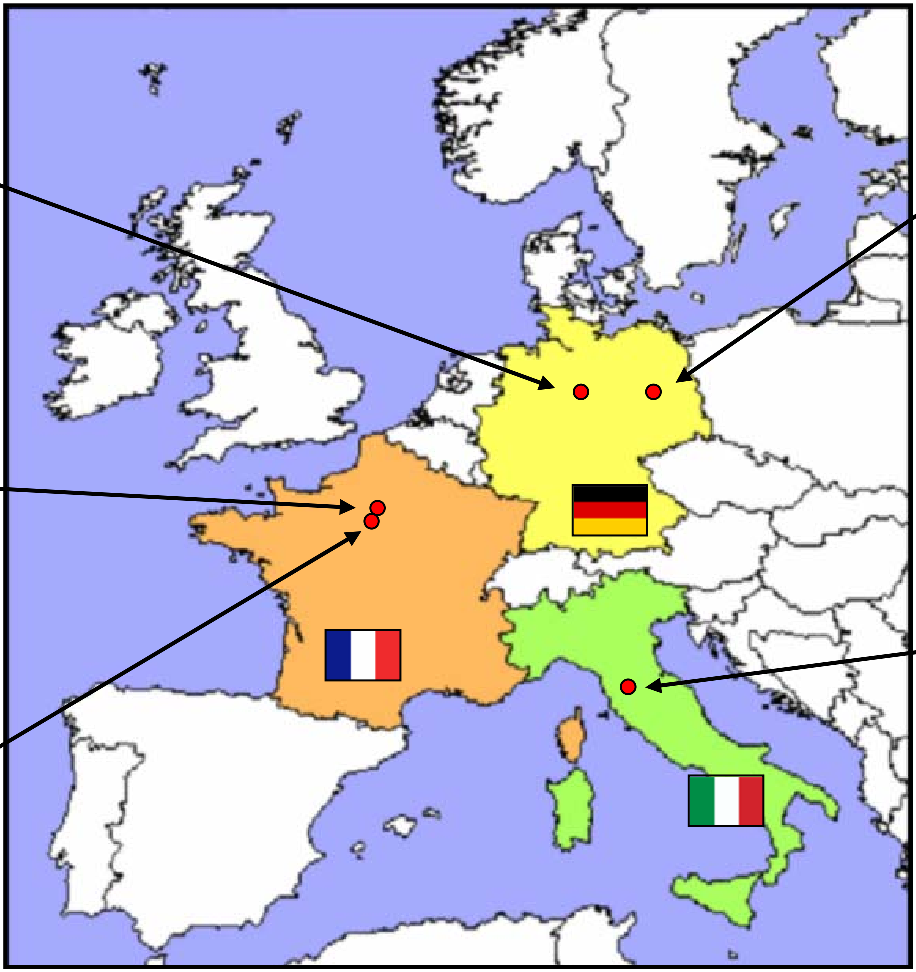
(Future Inertial Atomic Quantum Sensors)

Collaboration of Five European research groups

IQO, Hannover
Ernst Rasel

BNM-SYRTE, Paris
Arnaud Landragin

Institut d'Optique, Orsay
Philippe Bouyer

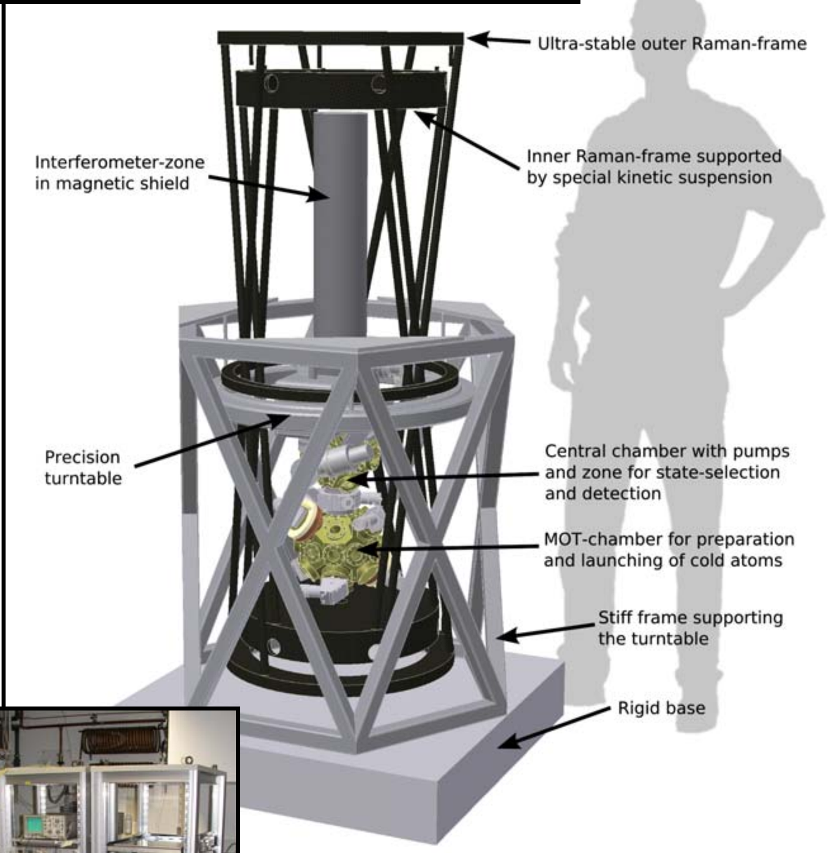


Humboldt Universität, Berlin
Achim Peters

LENS, Florence
Guglielmo Tino

Portable atomic quantum gravimeter GAIN

GAIN interferometer assembly



- Compact: three ~ 1 m^3 Modules (interferometers assembly + two 19“ racks for laser system and electronics)
- Robust: critical components based on technology developed for the high g-loads in drop tower experiments
- Mobile: designed to be „truckable“ and for use at a variety of interesting locations

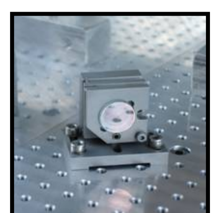
Targeted sensitivity:

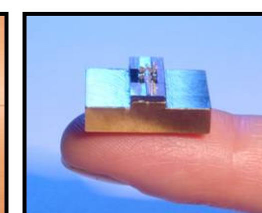
$1 \cdot 10^{-9}$ g / sqrt(Hz) at a SNR of 300:1 (intrinsic noise only)

$1 \cdot 10^{-8}$ g / sqrt(Hz) at a SNR of 30:1 (under realistic vibration conditions)

Targeted absolute accuracy: $5 \cdot 10^{-10}$ g

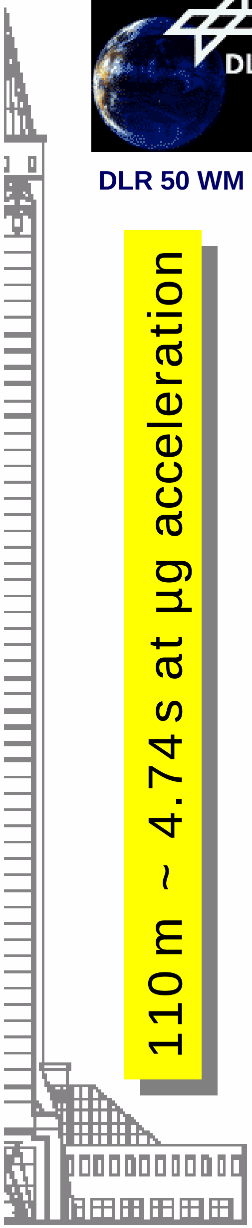




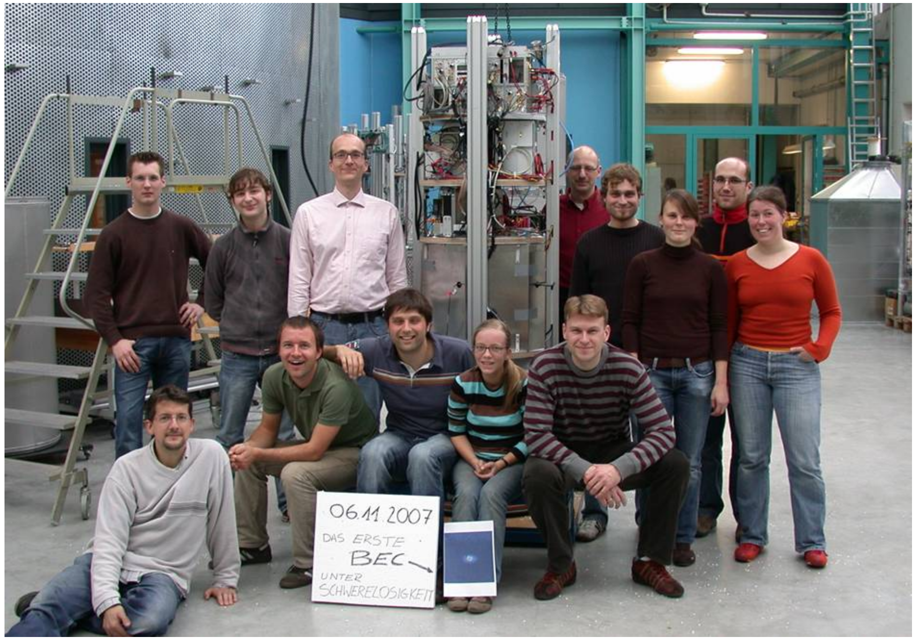



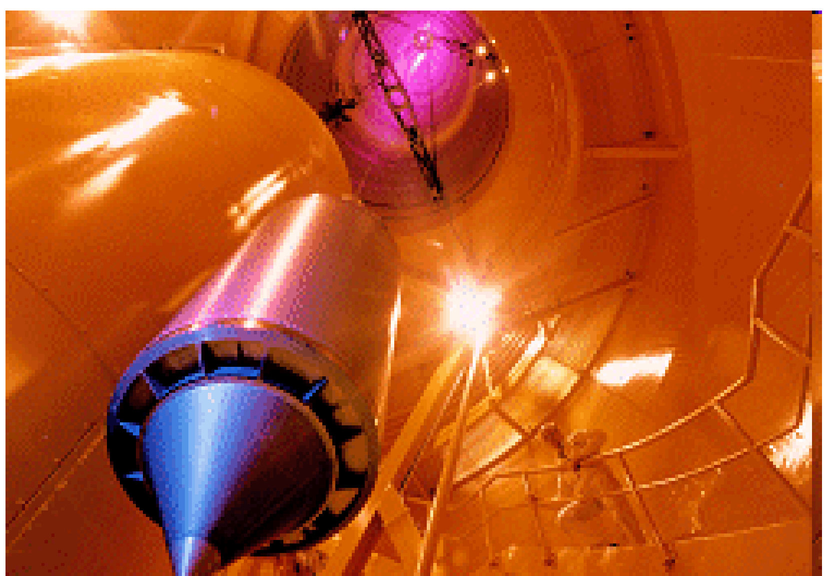
QUANTUS - Quantum Gases under Microgravity

DLR 50 WM 0346

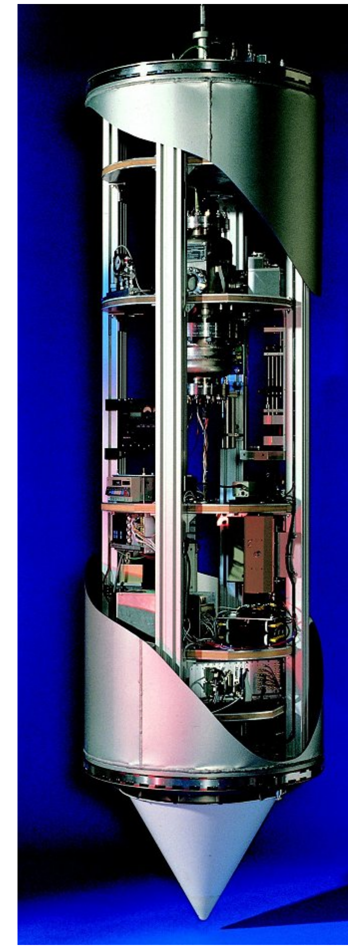


110 m ~ 4.74 s at µg acceleration





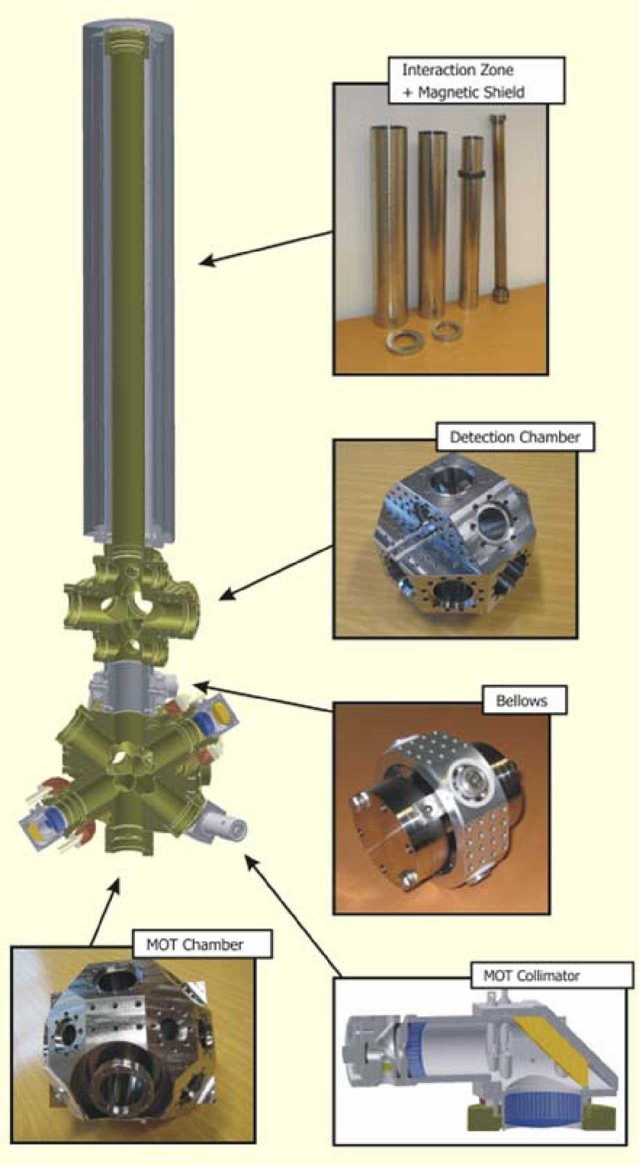
Drop Capsule

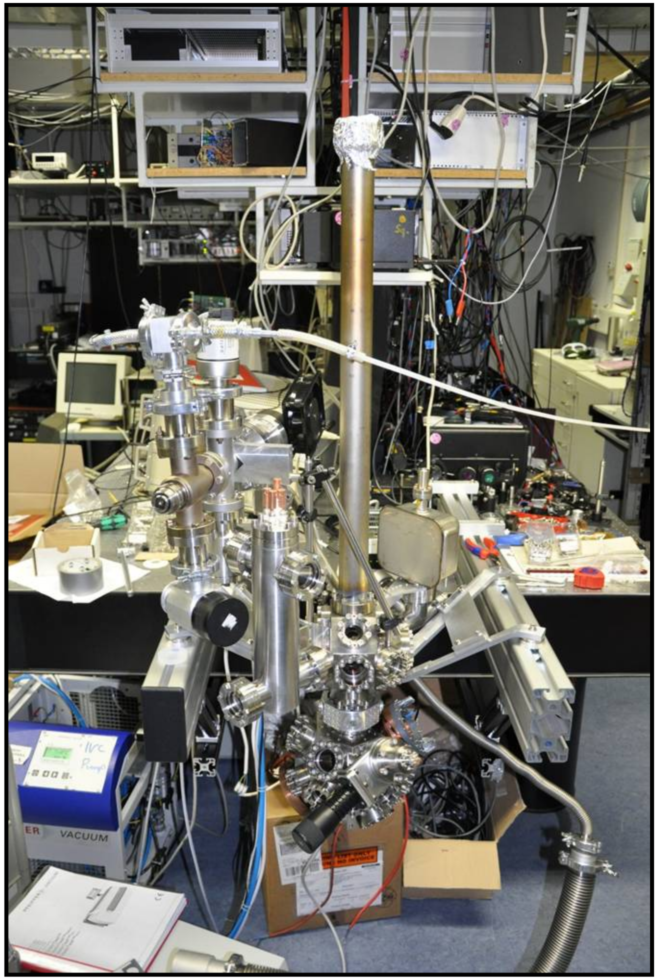


H = 2.40m
Ø = 0.8 m
Mass < 280 kg

GAIN – current status

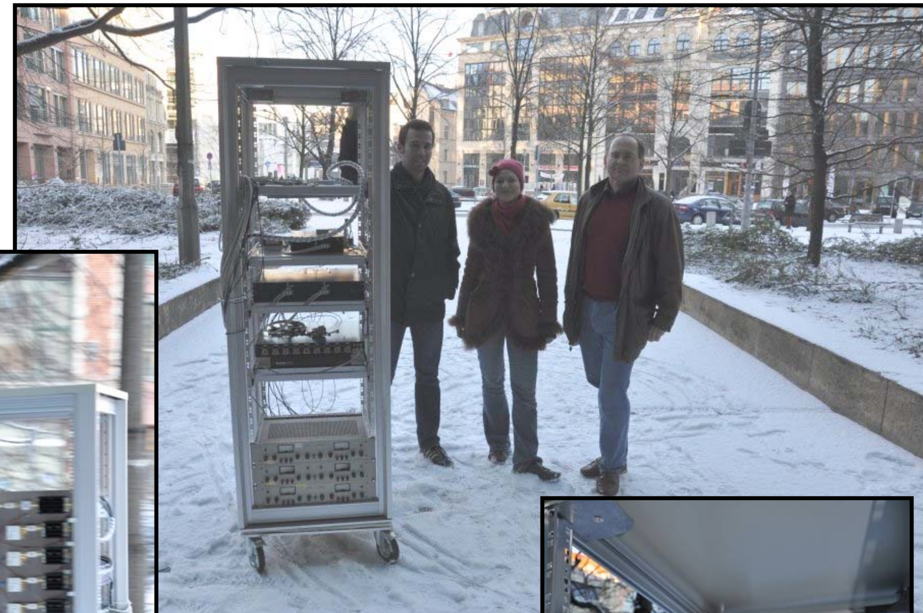
Laser System assembled and in Operation

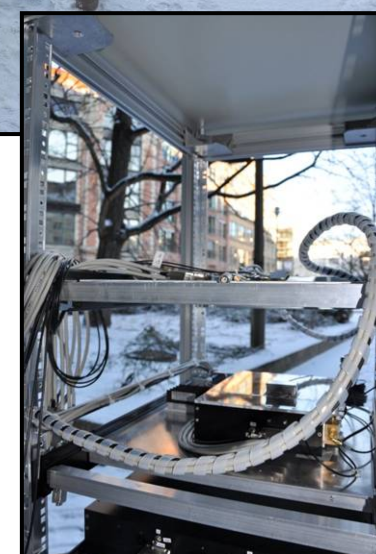




Vacuum chamber assembled, currently baking out

GAIN – first environmental testing

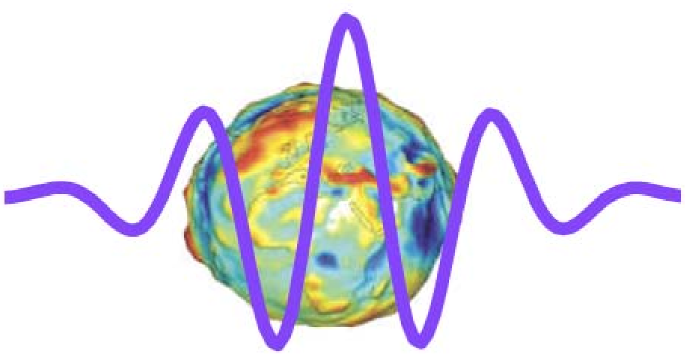


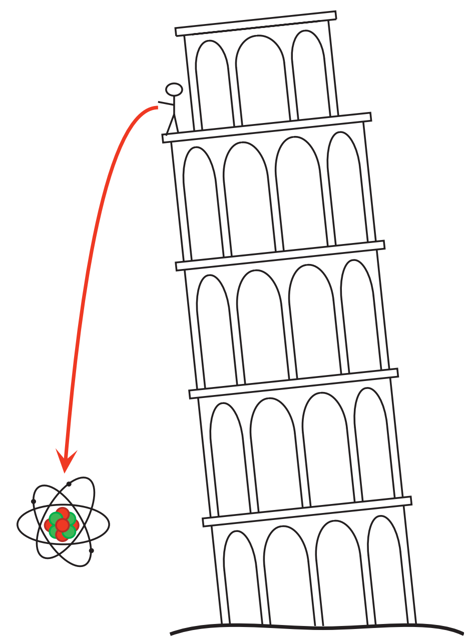


Result: Laser back in lock within an hour of returning to the lab

Prof. Achim Peters, Ph.D.

Atom interferometry – applications in gravimetry
and some thoughts on current sensitivity and concepts for future improvements





International Workshop on „Gravitational Waves Detection with Atom Interferometry“
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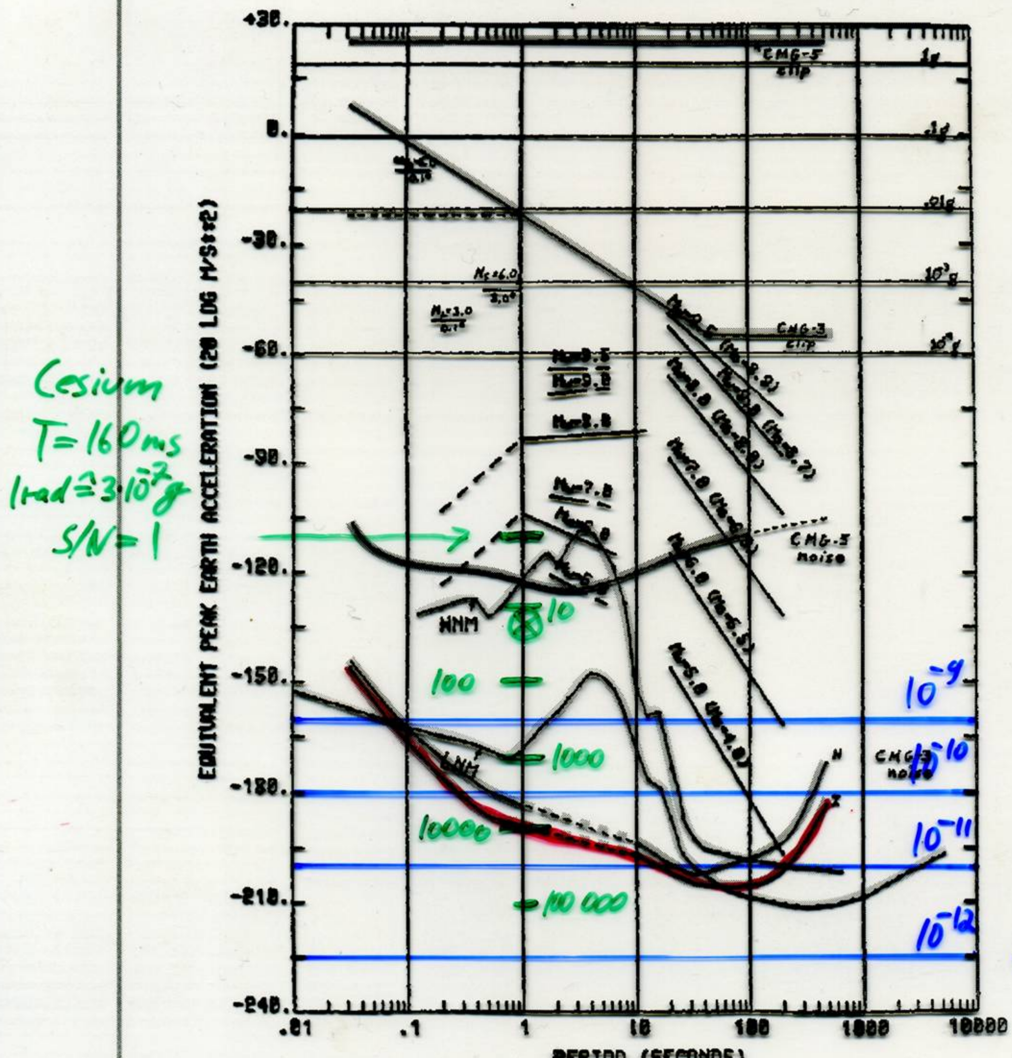
Atom interferometer vs. high performance Seismometer

This figure describes the estimated system noise and clip level for CMG-5T broadband accelerometers and CMG-3T weak-motion sensors in terms of non-coherent power. Noise levels for the CMG-3T are shown separately for the vertical and horizontal sensors.



g/√Hz

For reference, this graph also shows the Peterson NLNM (New Low Noise Model) and NHNM, as well as signal levels for seismic events of various magnitudes.

(Taken from *USGS Technical Summary*, US Geological Survey, 25 January 1990.)

Detailed calibration information is provided with every instrument, including amplitude and phase response curves, transducer outputs, the transfer function in poles/zeros notation, and (if applicable) the digitizer sensitivity in counts per μV.

Precision in determination of g in a single measurement

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

use appropiate bias, limit ourselves to changes $\Delta\varphi$, Δg

$$\sigma_g := \sqrt{\langle \Delta g^2 \rangle} \quad , \quad \sigma_\varphi := \sqrt{\langle \Delta \varphi^2 \rangle}$$

$$\boxed{\sigma_g = \frac{1}{k_{eff} T^2} \sigma_\varphi}$$

$\propto \frac{1}{\sqrt{N}}$ number of atoms for standard techniques...

How to achieve higher precision / lower noise ?

- increase $k_{eff} T^2$
- increase number of atoms
- do better than $\frac{1}{\sqrt{N}}$ $\Longleftarrow$ use of entanglement

Increase of T:

limited by atomic fountain hight

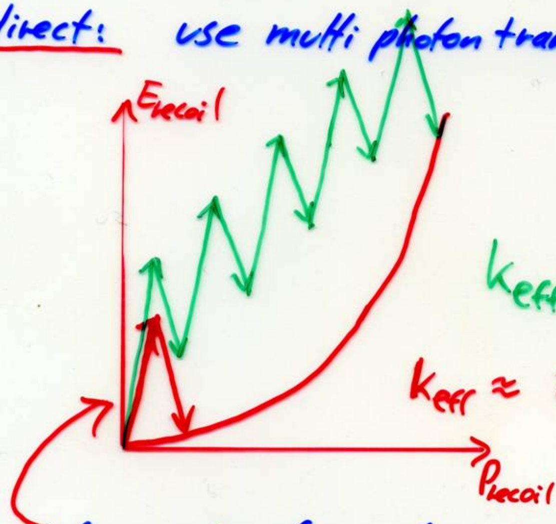
$\rightarrow T \lesssim 0.5\,s$ for terrestrial applications

different in space !

Increase of k_{eff}:

direct: limited by laser technology

indirect: use multi photon transitions / high order Bragg-diffraction !



$k_{eff} \approx 2n\left(\frac{2\pi}{\lambda}\right)$

$k_{eff} \approx 2\left(\frac{2\pi}{\lambda}\right)$

frequencies of counterpropagating beams are not equal for atoms initially at rest...

$\Leftrightarrow$ requires small velocity spread $\ll v_{recoil}$

but very promising !

What about using heavier atoms?

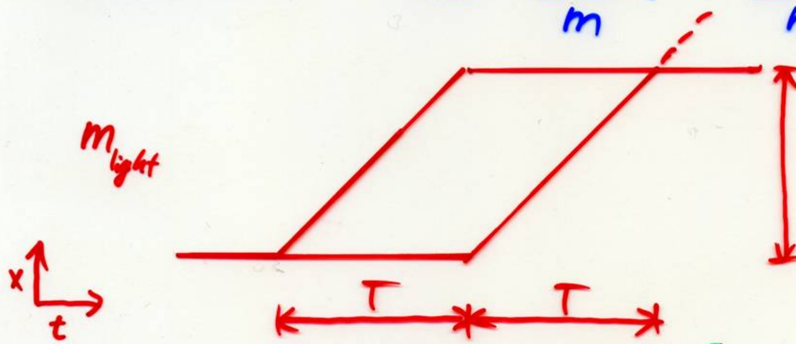
case a): T fixed

$$\boxed{\sigma_g = \frac{1}{k_{eff} T^2}\,\sigma_\varphi}$$

where actually *is* m ?
where is $\hbar$?

substitute: $\quad v_{rec} = \dfrac{p_{rec}}{m} = \dfrac{\hbar k_{eff}}{m}$ $\quad$ voila...

m_{light}



$$d_l = v_{rec} \cdot T = \frac{\hbar k_{eff}}{m_{light}}\, T$$

m_{heavy}

$$d_h = \frac{\hbar k_{eff}}{m_{heavy}}\, T < d_l$$

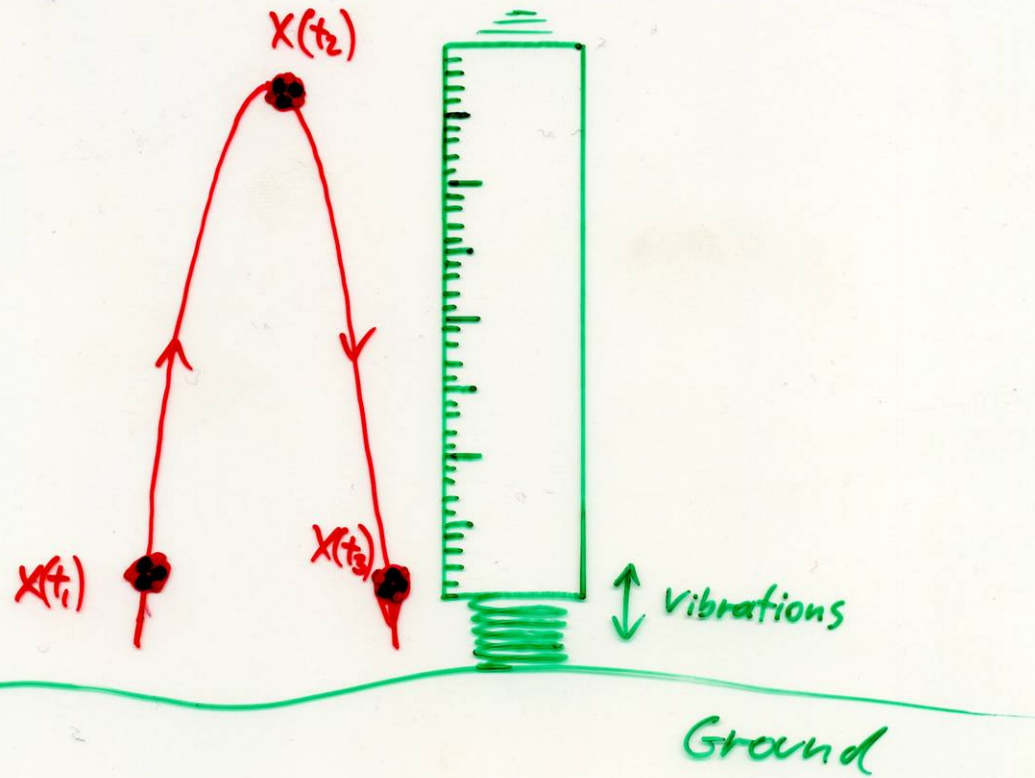
but: same phaseshift, same σ_φ, same σ_g !

extreme case: macroscopic limit $m \to \infty$

$\Rightarrow \quad d \to 0$

$\Rightarrow$ classical parabolic trajectory, no splitting

Another way to look at atomic gravimeters:



$$g = \frac{(X_2 - X_1) - (X_3 - X_2)}{T^2}$$

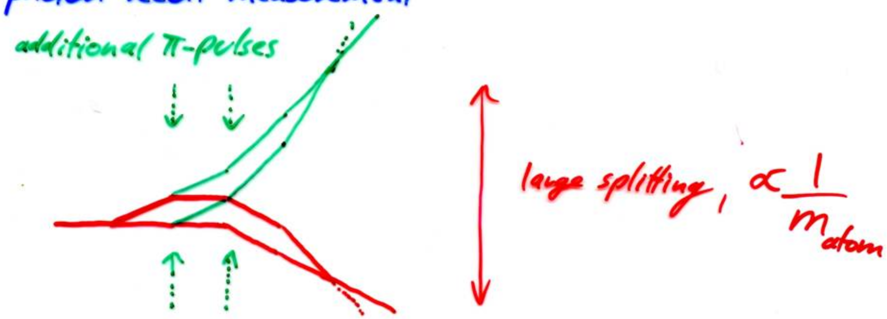
case b): sizescale constrained

$\Longrightarrow$ large atomic mass is beneficial

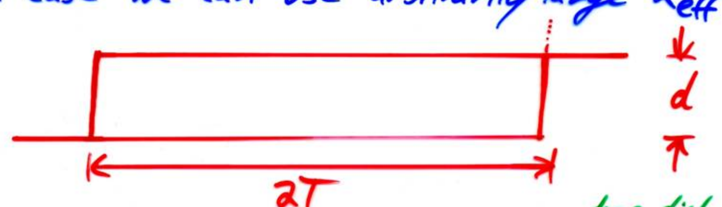
examples:

- measurement of small, gravitational strength forces at a given distance scale "d"

- photon recoil measurement



- in case we can use arbitrarily large k_{eff}



drop distance $h = gT$

want $d \approx h$

$\Longrightarrow$ $\boxed{\text{in each case sensitivity } \propto m_{atom}}$

Use of entanglement:

a) If other sensitivity improvements are not enough ...

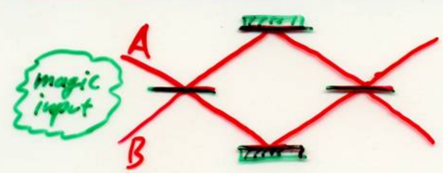
- in space
- in differential measurements
  ($\hbar/m$, small forces, equivalence principle, gradients, ...)

$\Rightarrow$ try to achieve Heisenberg limited ($\propto \frac{1}{N}$) sensitivity

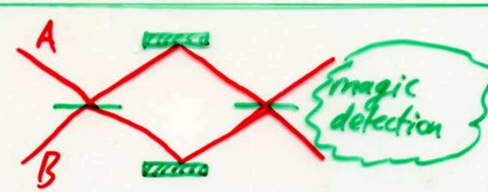
Methods, classified à la
"A quantum Rosetta Stone for Interferometry"; H. Lee, P. Kok, J. Dowling, arXiv: quant-ph/0202133 9 Apr. 2002

in general: use both inputs with appropiat states ...

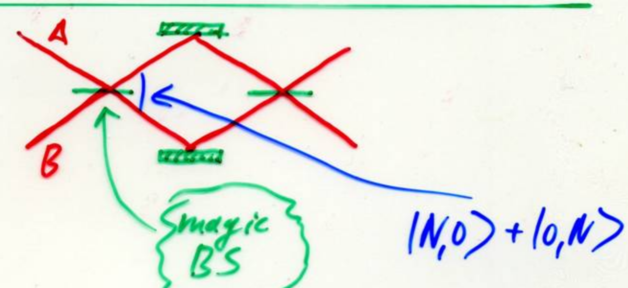
$$|\varphi_{in}\rangle = \frac{1}{\sqrt{2}}\left[\left|\frac{N+1}{2},\frac{N-1}{2}\right\rangle_{AB} + \left|\frac{N-1}{2},\frac{N+1}{2}\right\rangle_{AB}\right]$$



$$|\varphi_{in}\rangle = |N,N\rangle_{AB}$$



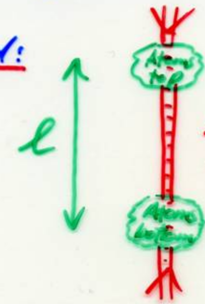
$$|\varphi_{in}\rangle = |N,0\rangle_{AB}$$



Use of entanglement:

b) make phaseshift directly proportional to gradient
(or even higher spatial derivatives)

standard method:



same beams for splitters and mirrors

$$g_{top} = \frac{\varphi_{up}}{kT^2}$$

$$g_{bot} = \frac{\varphi_{bot}}{kT^2}$$

$$\gamma := \frac{g_{top} - g_{bot}}{\ell} = \frac{\varphi_{top} - \varphi_{bot}}{\ell\,(kT^2)}$$

$\Longrightarrow$ two independent measurements, then take classical difference

with entanglement:

$\rightarrow$ one pair of atoms (top, bottom) at a time ....
... somehow prepared in state

$$\frac{1}{\sqrt{2}}\left(|g,0\rangle_{top} |e,\hbar k\rangle_{bot} - |e,\hbar k\rangle_{top} |g,0\rangle_{bot} \right)$$

$\rightarrow$ perform appropiate (non-local) measurement after remainder of interferometer sequence (π, $\frac{\pi}{2}$ pulses)

$$\Longrightarrow \boxed{\Phi = \gamma \ell\, k_{eff} T^2}$$