Perspectives...

Inertial Sensors

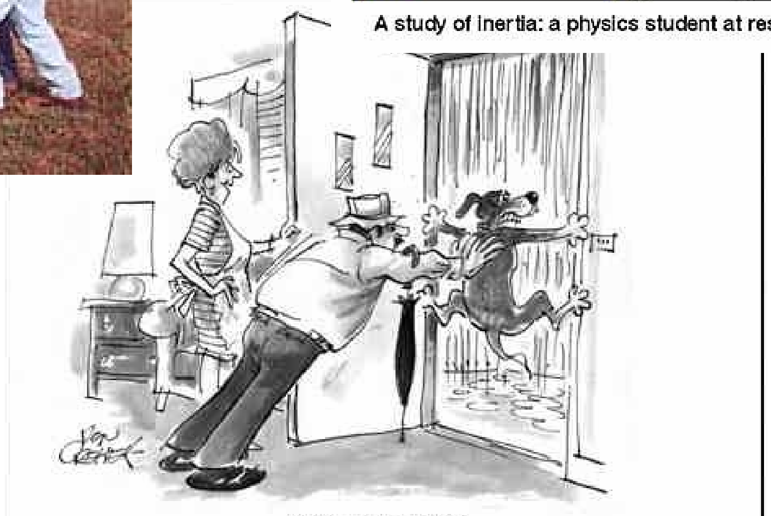
Based on Cold Atoms

Ernst Rasel and Wolfgang Ertmer

A Tutorial…

Many disadvantages of

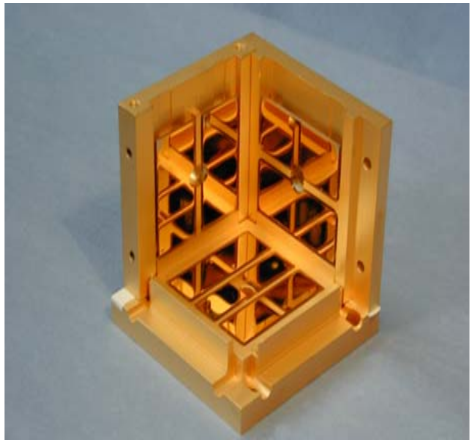
A study of inertia: a physics student at rest

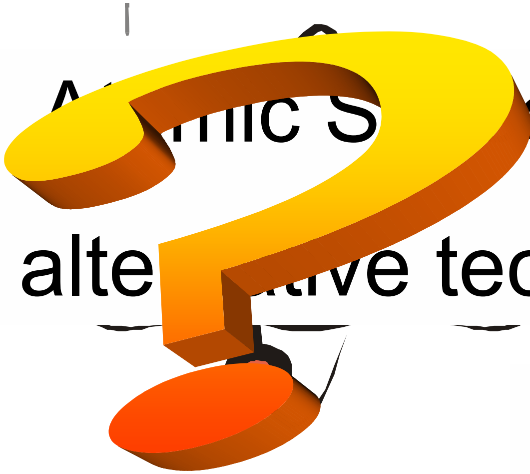


"He's such a baby!"

how to benefit from

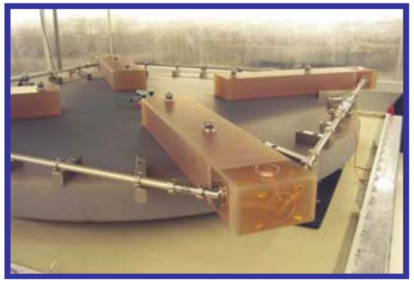
the inertia of atoms





A mic S ors

-an alte ative technique



Bell Geospace

Outline

- **Principle of Atom Interferometry**
- **Accelerometers and Gyroscopes**
- **Applications & Alternative Techniques**
- **Outlook**

5

Principle of Atom Interferometry

The atomic ruler

$$\left|\vec{k}_{at}\right| = \frac{2\pi}{\lambda_{dB}}$$

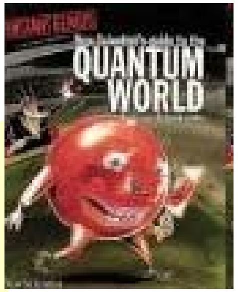
De-Broglie wavelength

Louis Victor de Broglie
Nobel prize 1929

Classical World

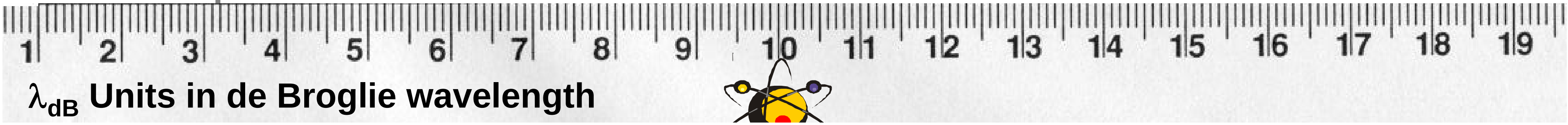
$$m_{at}\cdot\vec{v}_{at} = \vec{p}_{at} = \hbar\cdot\vec{k}_{at}$$

$$m_{at}v_{at} = \frac{h}{\lambda_{dB}}$$



Atomic momentum

Planck‘s constant

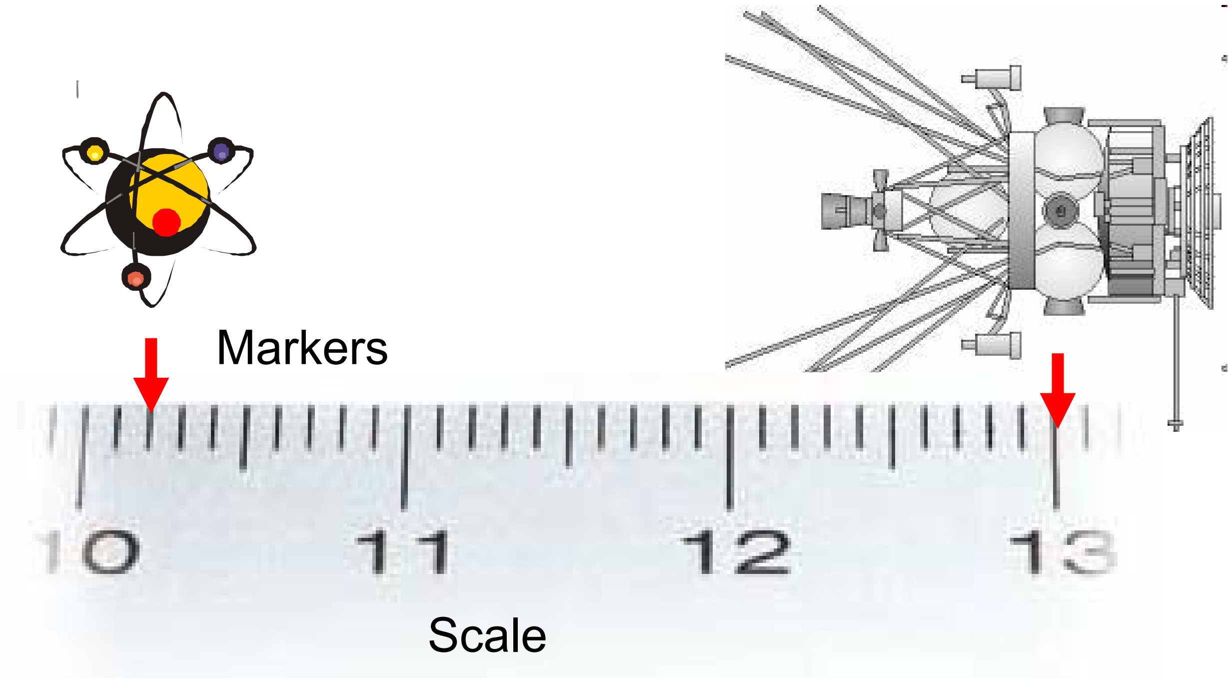


λ_{dB} Units in de Broglie wavelength

Atomic Sensors…

for the local measurement of tiny accelerations/forces and rotations with high resolution:

Measuring displacements with cold atoms

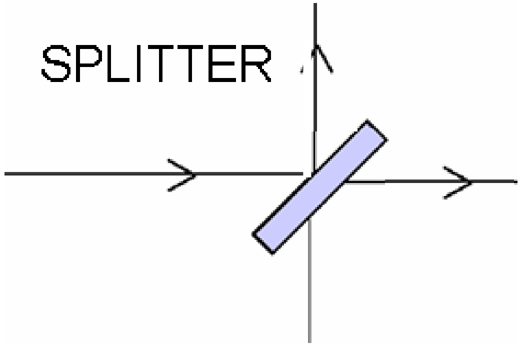


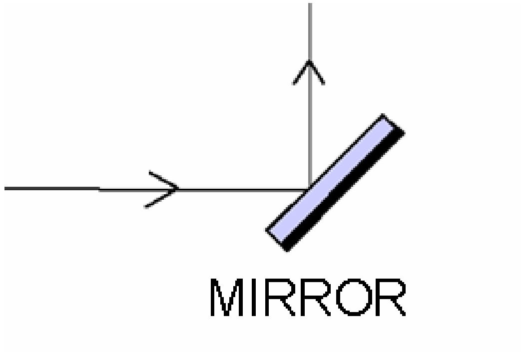
Comparing 2 rulers..

…with Atom Interferometers

using Light as coherent Beam Splitter:

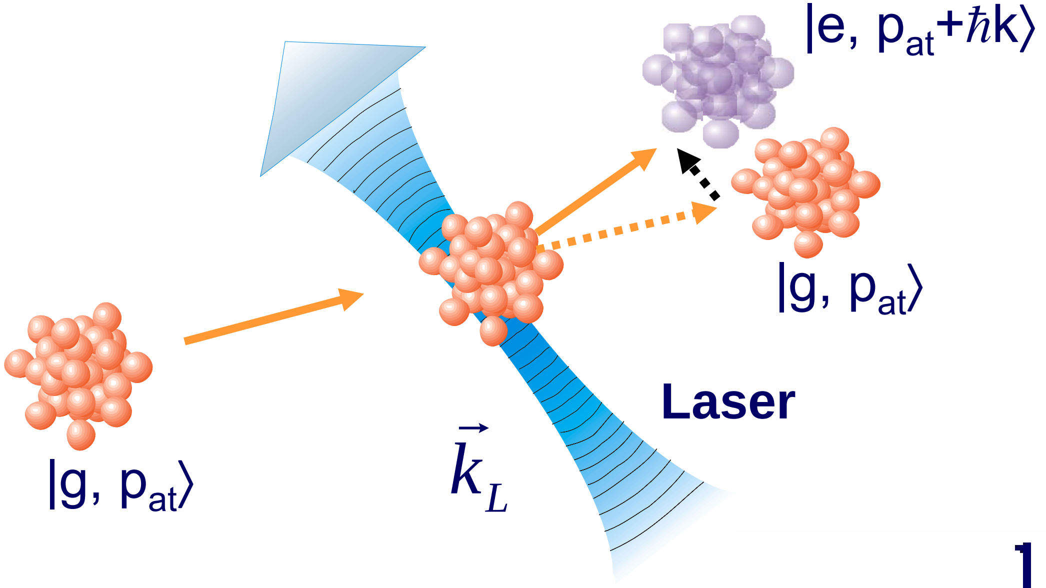
Generating spatial modes of matter waves





…based on

the mechanical effect of light

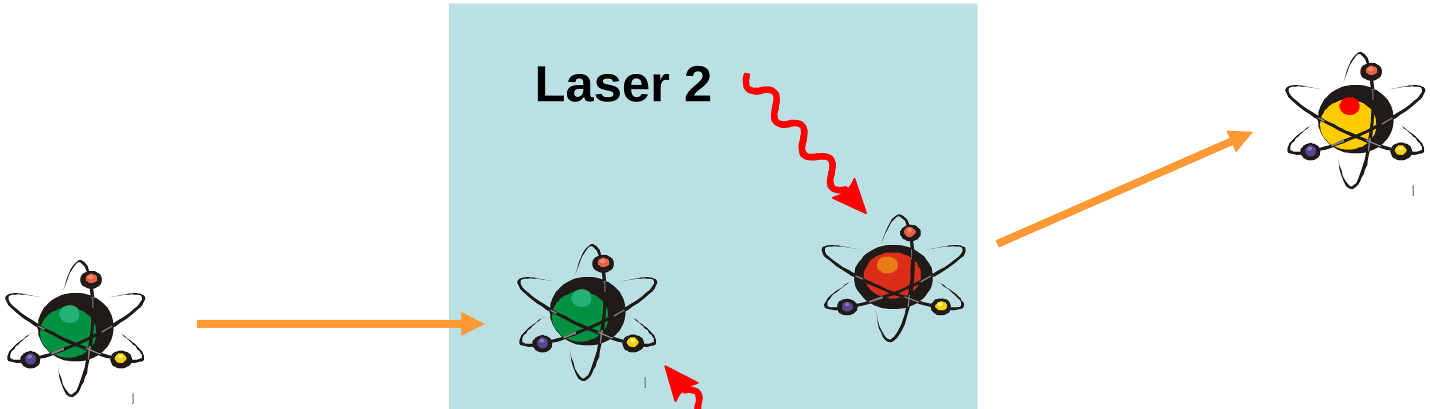


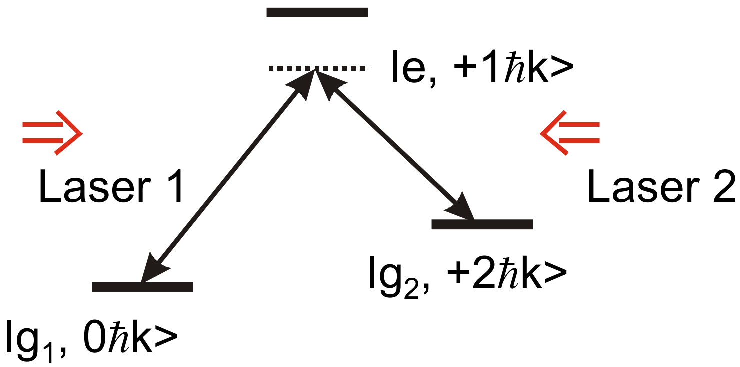
$$\vec{\mathbf{v}}_{rec} = \frac{1}{m_{atom}} \hbar \vec{k}_L$$

2-Photon Transition

…transfer of two recoils by absorption & stimulated emission:

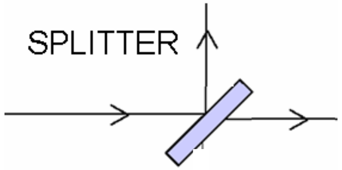
Bragg or Raman type beam splitter

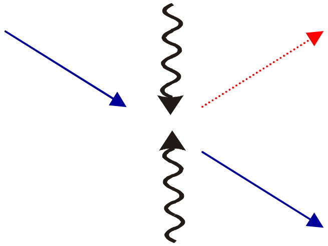




Optics Componets

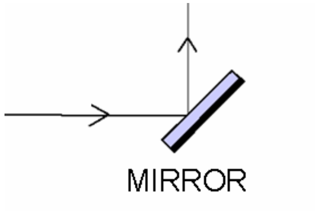
… made out of Light

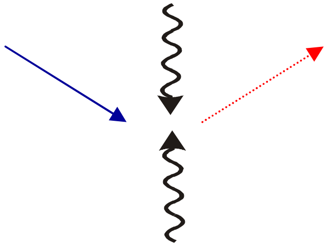




$\pi/2-\text{pulse}$

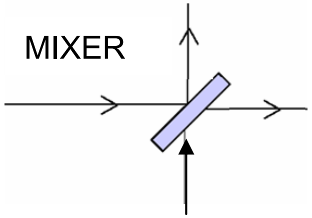
$$|g_1, p+0\,\hbar\vec{k}\rangle \to \frac{1}{\sqrt{2}}\left[|g_1, p+0\,\hbar\vec{k}\rangle + e^{i\Phi}|g_2, p+2\,\hbar\vec{k}\rangle\right]$$

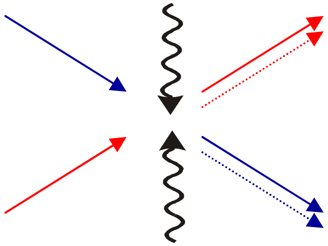




$\pi-\text{pulse}$

$$|g_1, p+0\,\hbar\vec{k}\rangle \to e^{i\Phi}|g_2, p+2\,\hbar\vec{k}\rangle$$

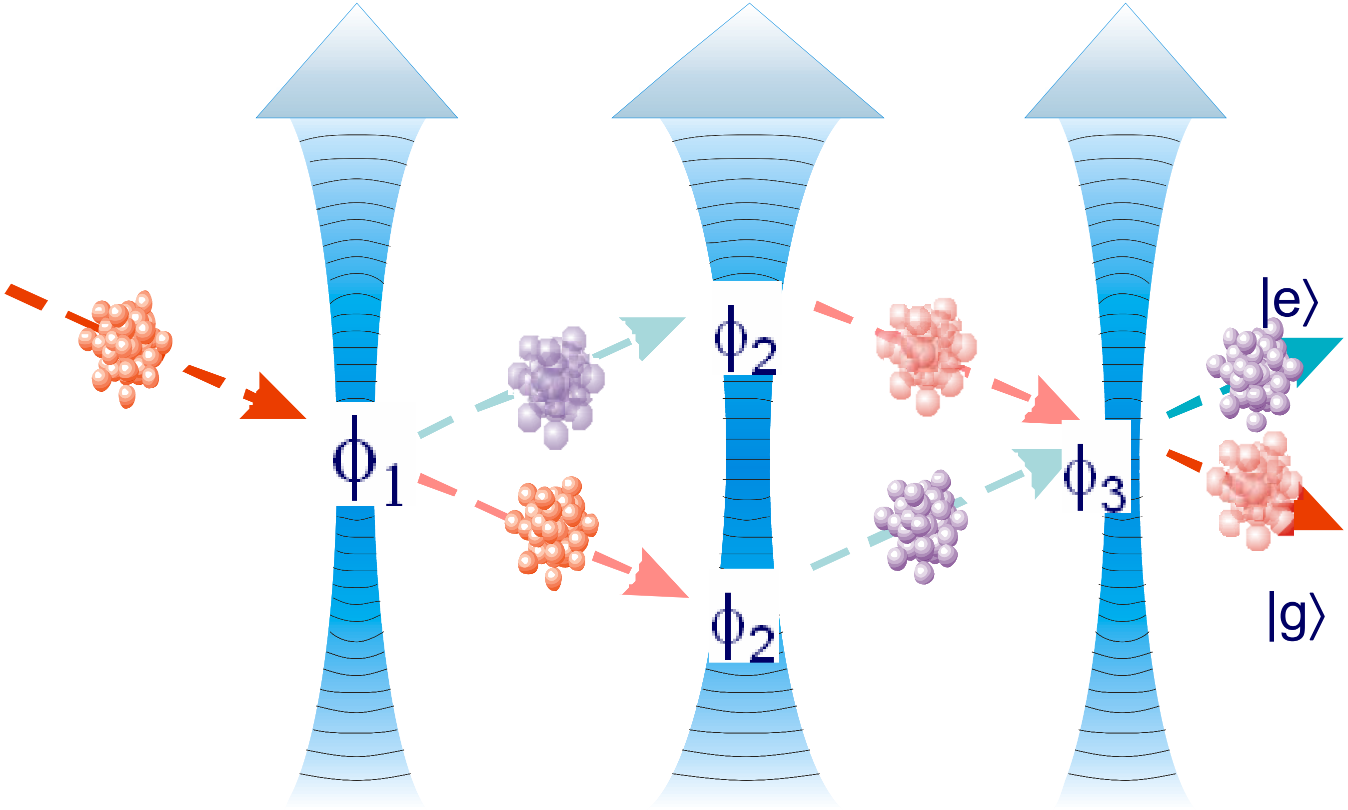




$\pi/2-\text{pulse}$

$$|g_1, p+0\,\hbar\vec{k}\rangle + e^{i\Phi}|g_2, p+2\,\hbar\vec{k}\rangle \to \frac{1}{\sqrt{2}}\begin{bmatrix} |g_1, p+0\,\hbar\vec{k}\rangle + e^{i\Phi}|g_1, p+0\,\hbar\vec{k}\rangle \\ +|g_2, p+2\,\hbar\vec{k}\rangle + e^{-i\Phi}|g_2, p+2\,\hbar\vec{k}\rangle \end{bmatrix}$$

Atomic Mach-Zehnder Interferometer



$$S \sim \cos[(\phi_3 - \phi_2)-(\phi_2 - \phi_1)]$$

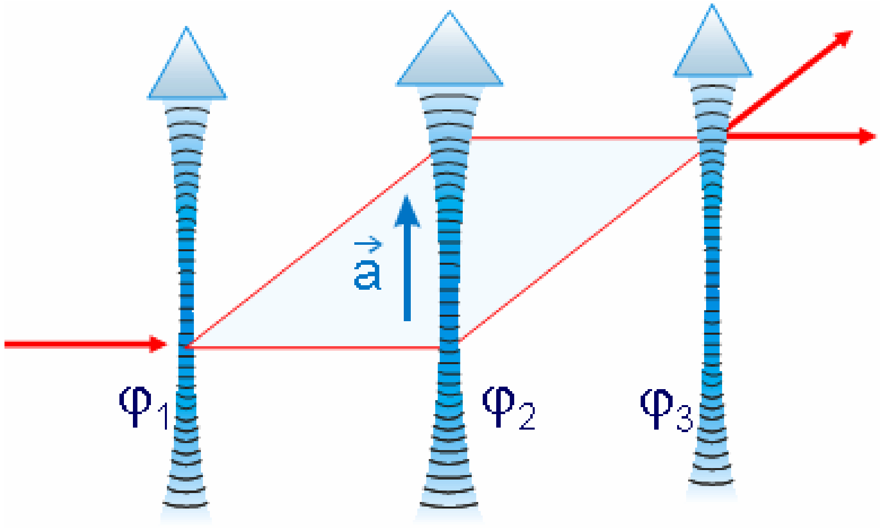
$$\sim \cos(\phi_1 - 2\phi_2 + \phi_3)$$

Accelerometers & Gyroscopes

Accelerometer

$$\Delta\varphi = [\varphi_3(2T+t_0) - \varphi_2(T+t_0)] - [\varphi_2(T+t_0) - \varphi_1(t_0)]$$

constant accelerations:



$$\Delta\varphi_{acc} = T^2 \vec{k} \cdot \vec{a}$$

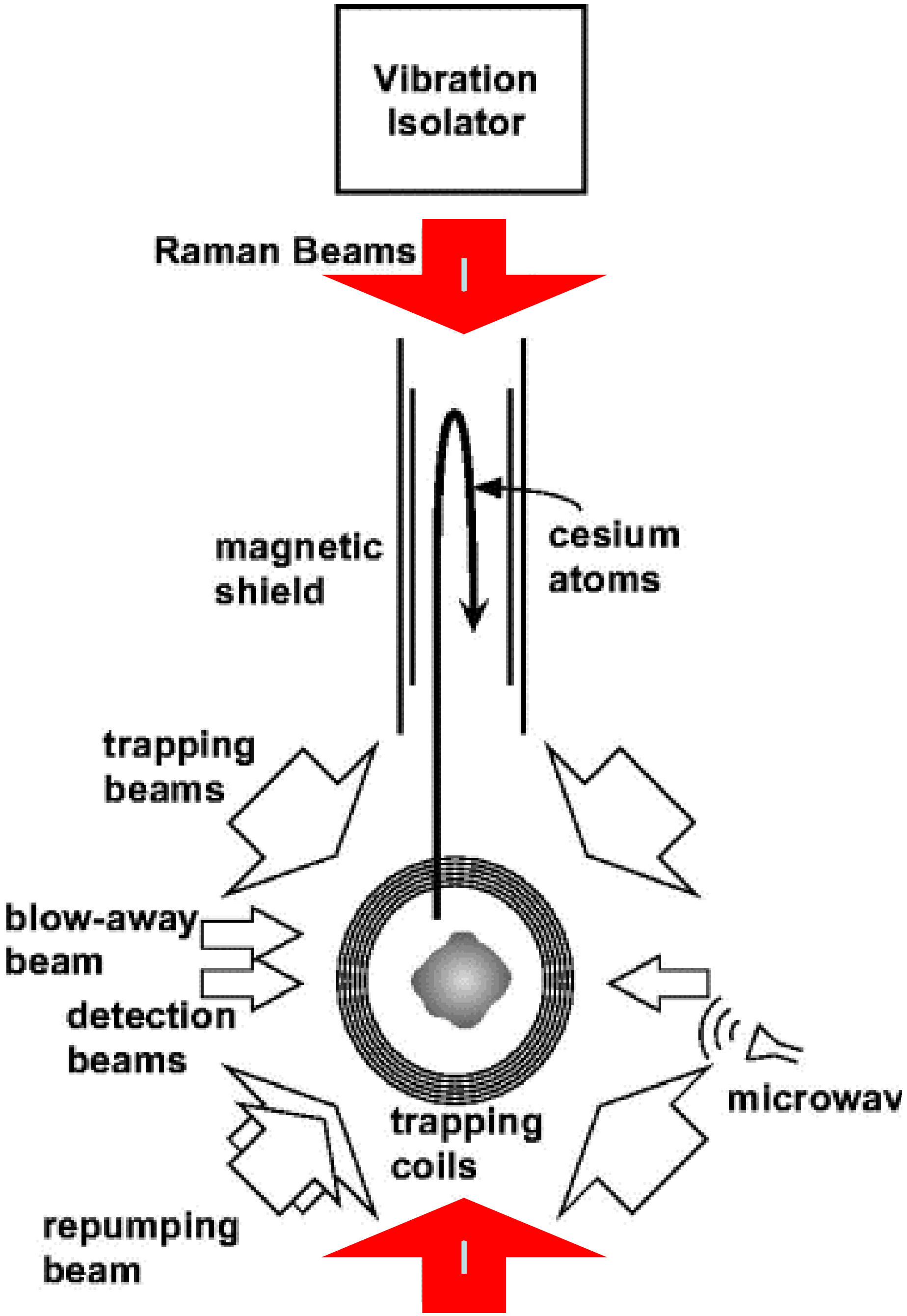
to be used as…

Gravimeter

Accuracy of Δ g resp. g:

1part in 10^9

1 Gal=10^{-2} m/s^2

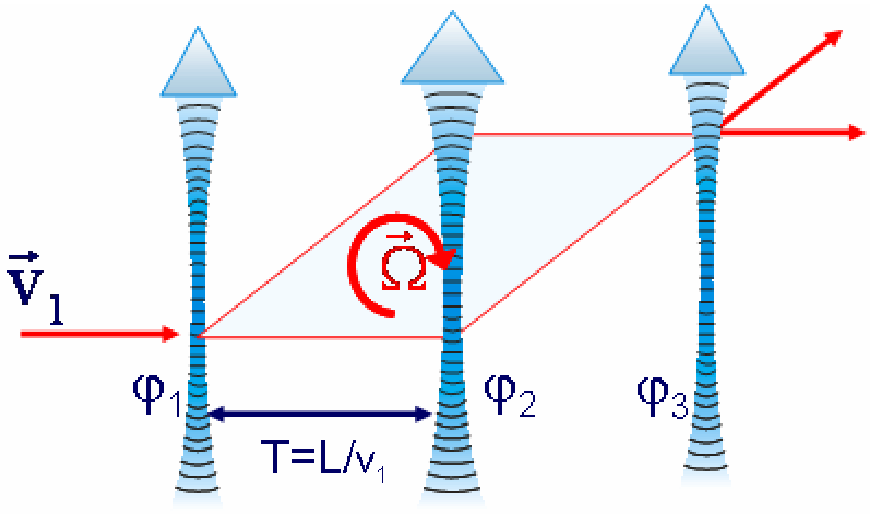


A. Peters et al., Metrologia **38**, 25 (2001)

Gyroscope

$$\Delta\varphi = [\varphi_3(2T+t_0) - \varphi_2(T+t_0)] - [\varphi_2(T+t_0) - \varphi_1(t_0)]$$

constant rotations:

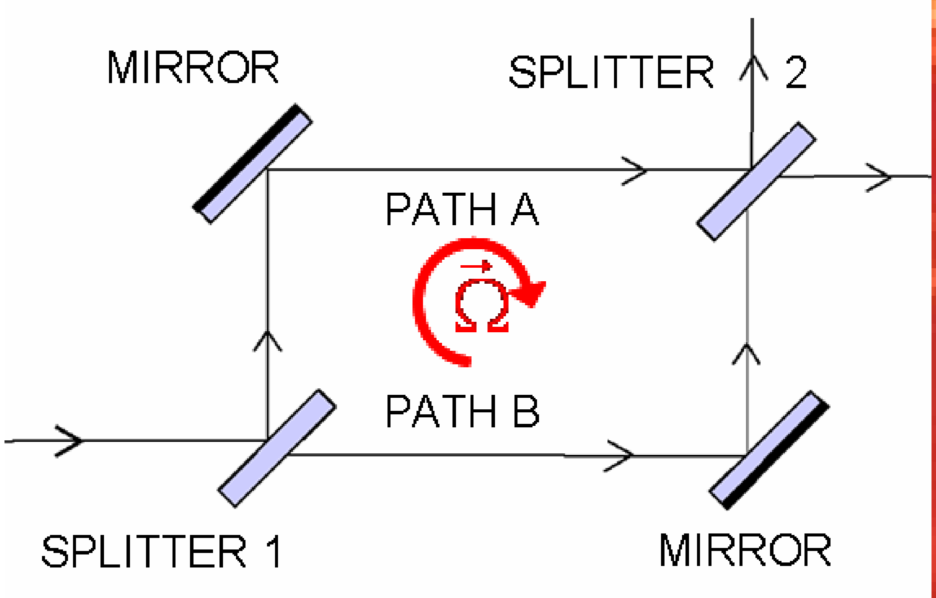


$$\Delta\varphi_{rot} = \frac{2\, m_{Atom}}{\hbar}\, \vec{A}\cdot\vec{\Omega}$$

T: drift time

v_1: atomic forward drift

Sagnac-Effect



Rotational induced Phase shift:

for Light :

$$\Delta\varphi_{rot} = \frac{4\pi}{\lambda c}\vec{A}\cdot\vec{\Omega}$$

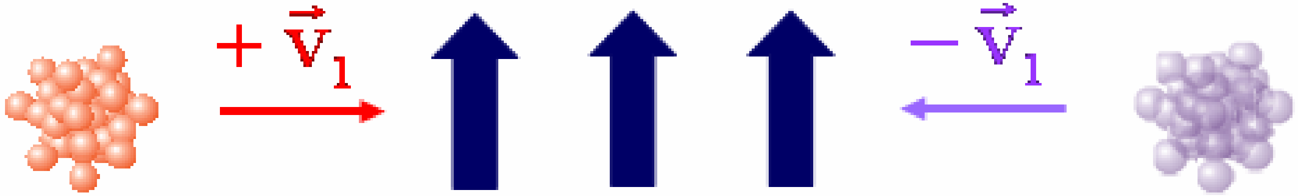
for Atoms :

$$\Delta\varphi_{rot} = \frac{4\pi}{h} m_{at}\vec{A}\cdot\vec{\Omega}$$

→ Gain by de Broglie-Waves : ~ 10^{11}

Differential Interferometry

Definition of the Area



$$S_1 \sim \cos(\varphi_{rot} + \varphi_{acc})$$

$$S_2 \sim \cos(-\varphi_{rot} + \varphi_{acc})$$

$$\Downarrow$$

Substraction $\longrightarrow$ φ_{rot}

Addition $\longrightarrow$ φ_{acc}

Distinction betwenn rotations and accelerations

Gyroscope

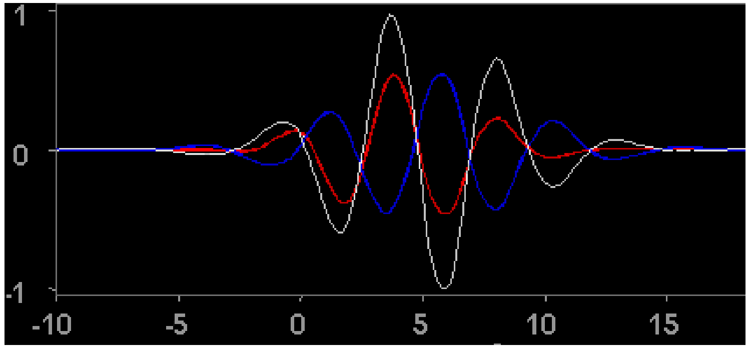
- 2 atom sources
- thermal Cs-beams
- transverse laser cooling
- Sensitivity:

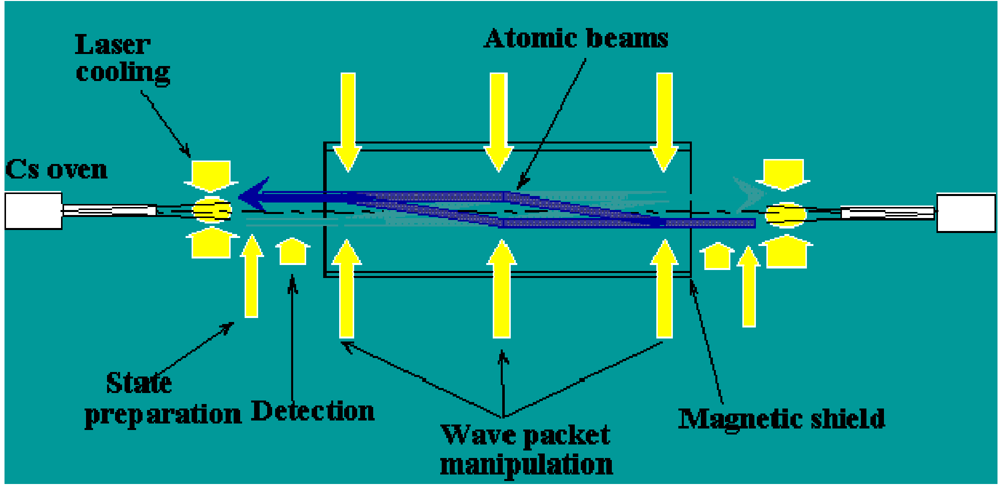
close to shot noise

$5*10^{-10}$ rad/s

4.8 µrad = 1 arcsec

Earth‘s rotation: 72 µrad/s



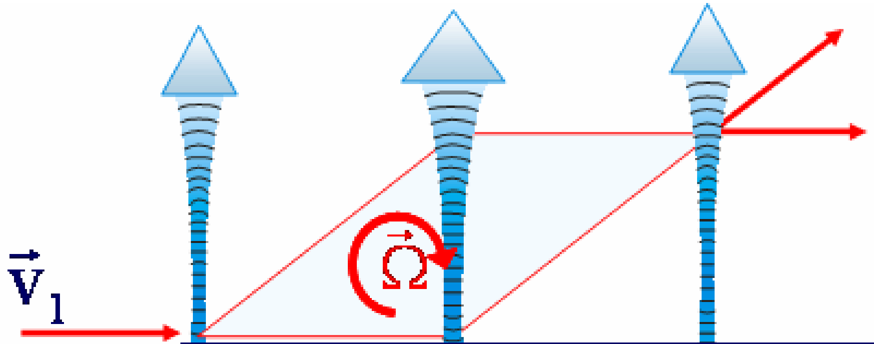


T. L. Gustavson, et al., Classical and Quantum Gravity, **17**, 2385 (2000)

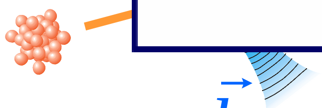
Definition of the Area

constant rotations:

$$\vec{A} = \vec{v}_{rec}\frac{L}{\vec{v}_1}\times\vec{v}_1\frac{L}{\vec{v}_1}$$



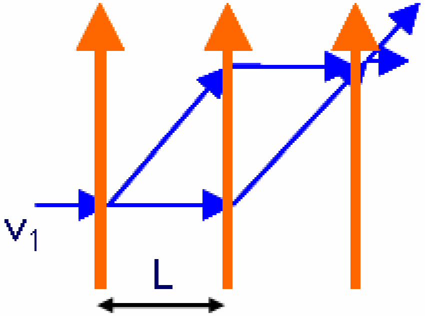
$$\Delta\varphi_{rot} = \frac{2\,m_{Atom}}{\hbar}\underbrace{\vec{A}\cdot\vec{\Omega}}$$



$$v_{rec} = \frac{\hbar k_L}{m_{atom}}$$

$$2\cos(\vartheta)$$

$$v_1$$



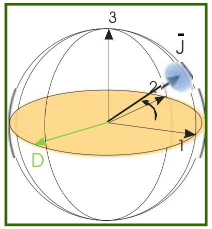
Area enclosed by interfereometer:

$$A = L^2\cdot\boxed{\frac{v_T}{v_1}}\quad <<1$$

Noise Sources

$$(\Delta\varphi)^2_{ges} = \boxed{\frac{1}{N_J}} + \frac{1}{N_J n_{Ph}} + \frac{2\sigma^2_{\delta N}}{N_J^2} + \gamma + \dots$$

Atomic projections noise



Shot noise of photon detection

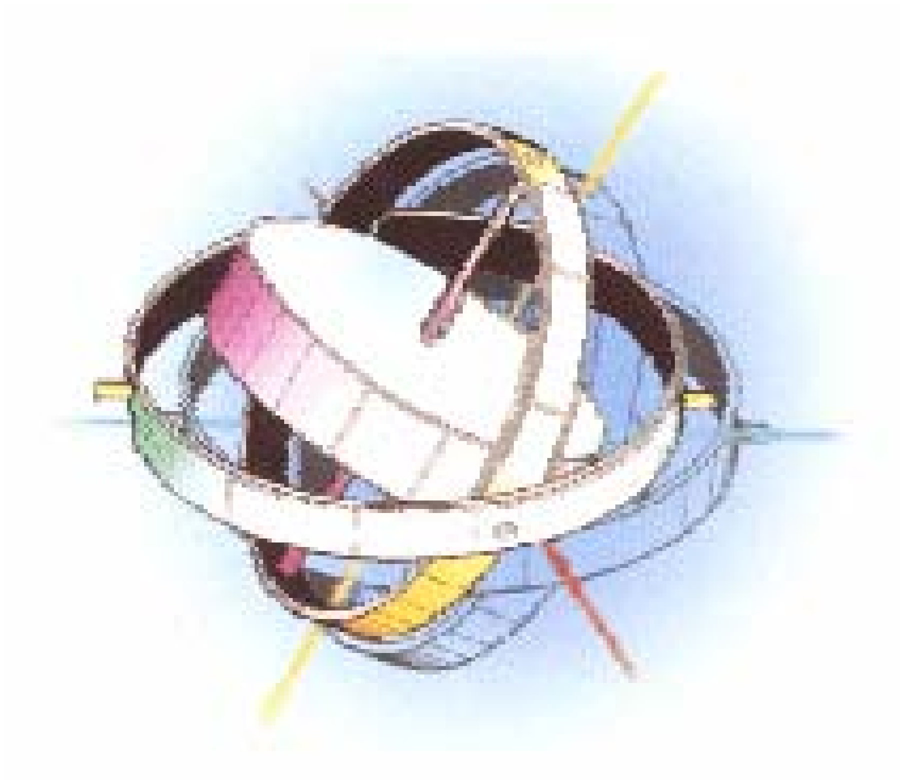
Noise of electronics for detection

Raman-Laser

„quantum limit “, all contributions negligible compared to 1/N_J

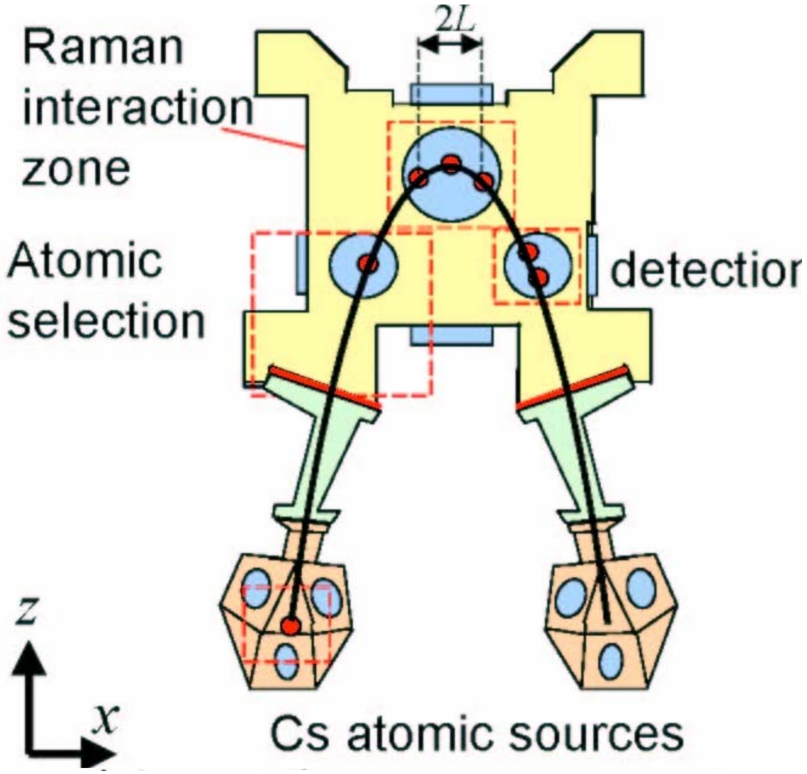
Concepts…

for
(ultra-)cold atomic inertial sensors

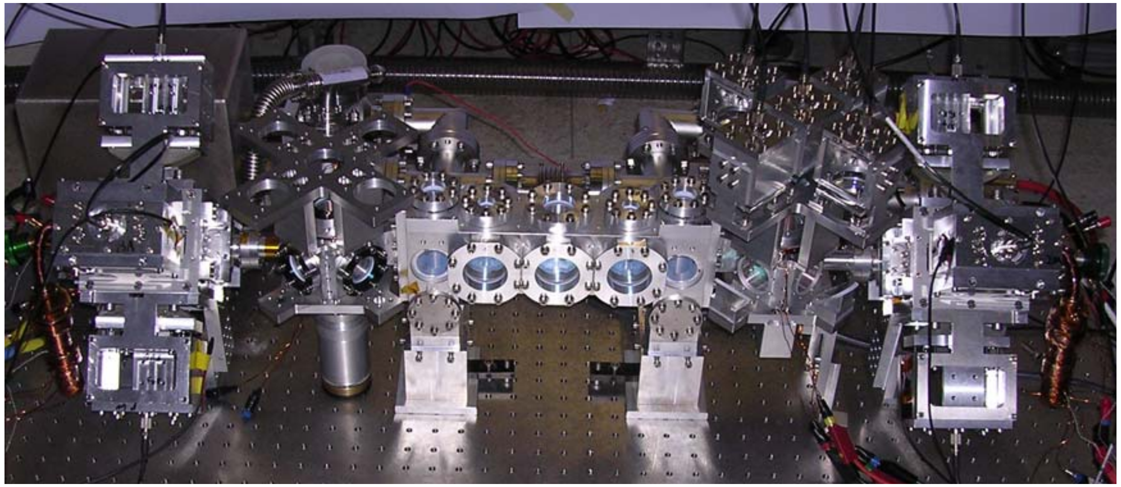


Cold Atom Gyros

Gyromètre
d‘ ondes matières
(A. Landragin, SYRTE Paris)

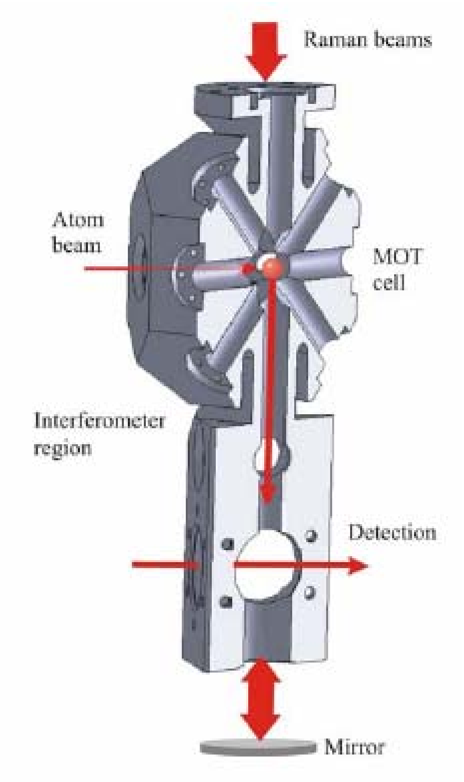


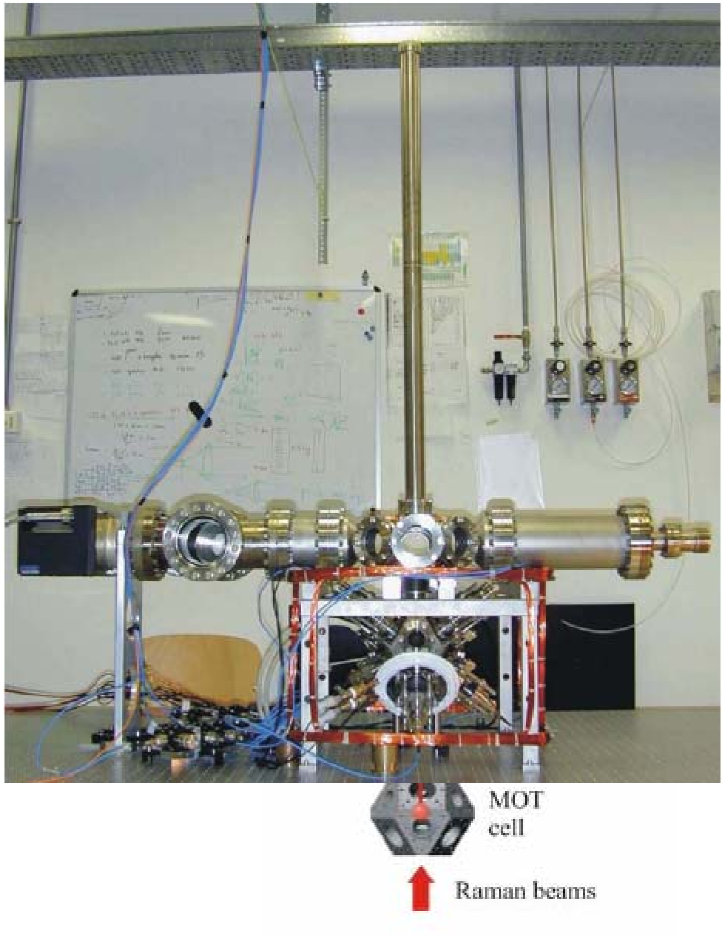
Cold Atom Sagnac Interferometer
(W.E., IQ Hanover)



Advanced Gravimeter

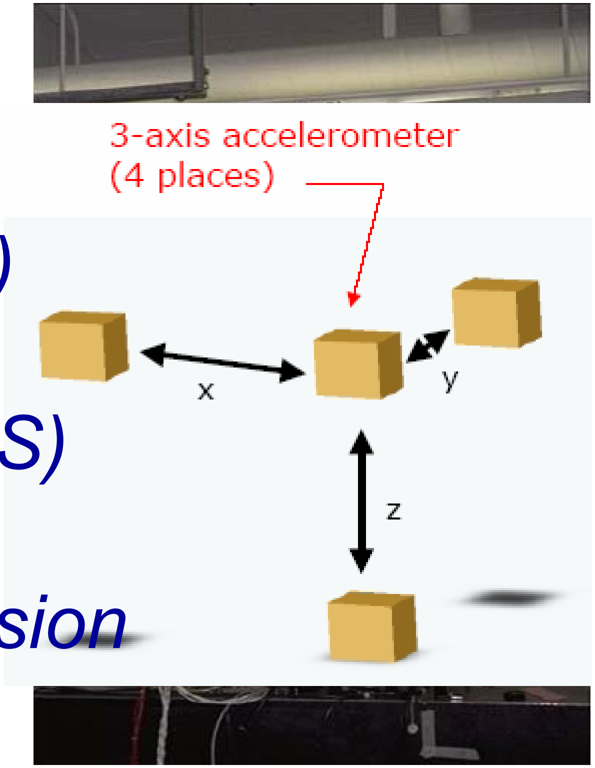
MAGGIA
(G. Tino, Univ. Florence)

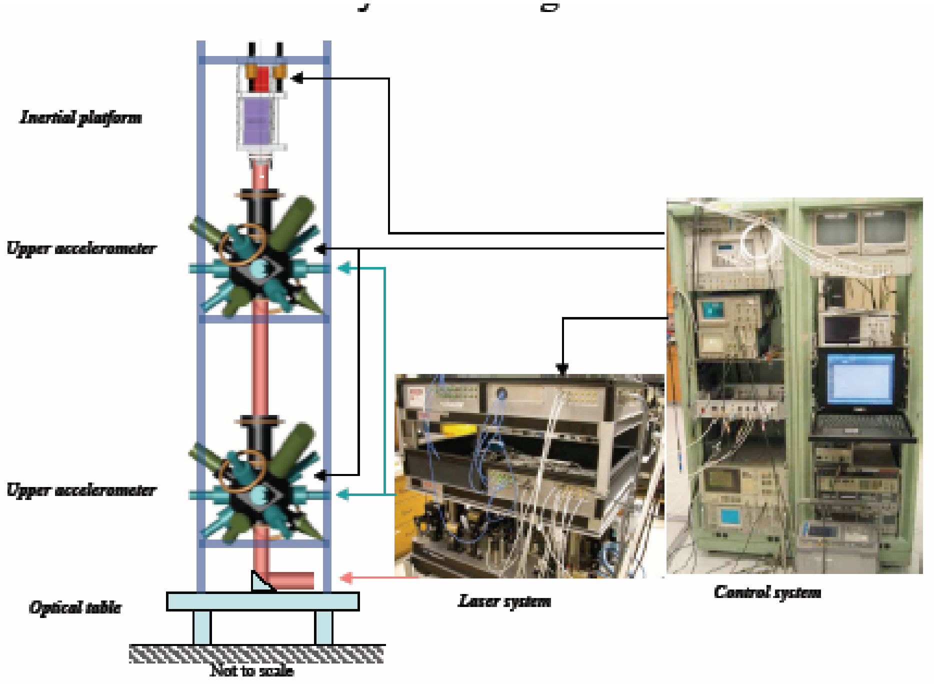




Paris Gravimeter
(F.Pereira d. Santos,
SYRTE, Paris)

Mobile Atomic Gravity Gradiometer Prototype Instrument (MAGGPI)
Accelerometer Arrays
(M. Kasevich, Stanford Univ., US)
Airborne System,
140 dB common mode suppression

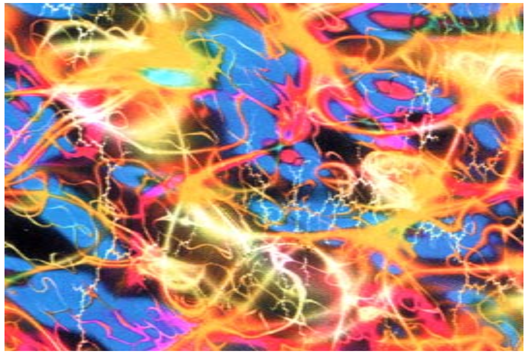




Space Gravigradiometer
(L. Maleki, JPL, US)

Applications of *inertial* sensors based on *cold atoms*

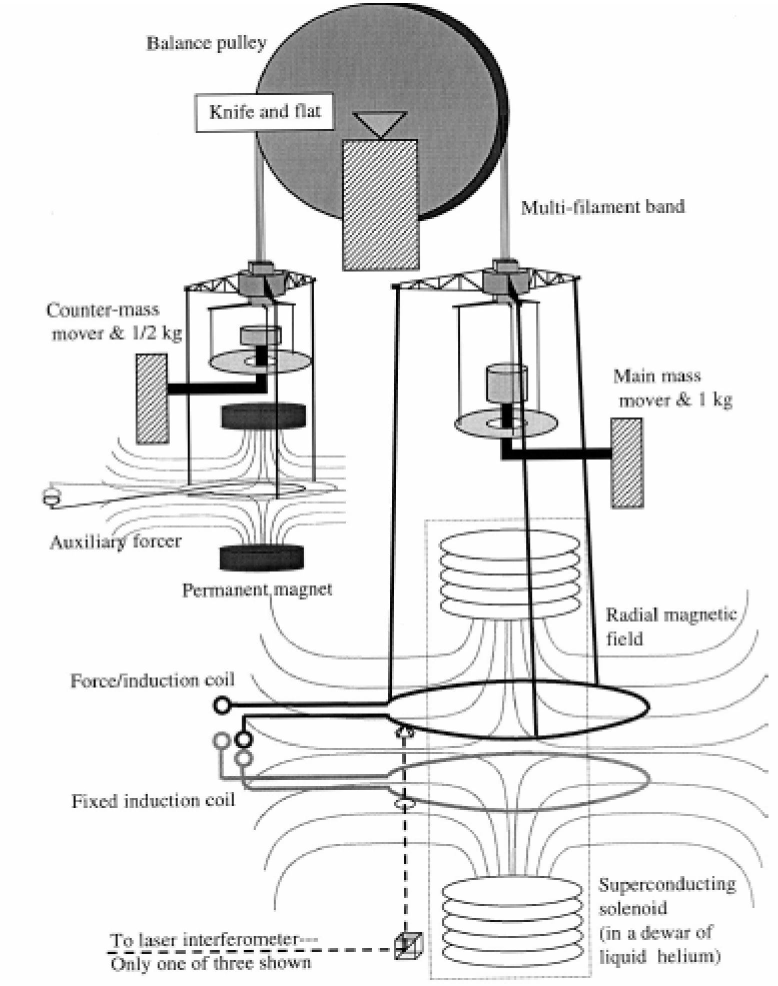
- Fundamental Physics



- Applied Physics and connected fields

Watt Balance:

Replacement of the kg artifa

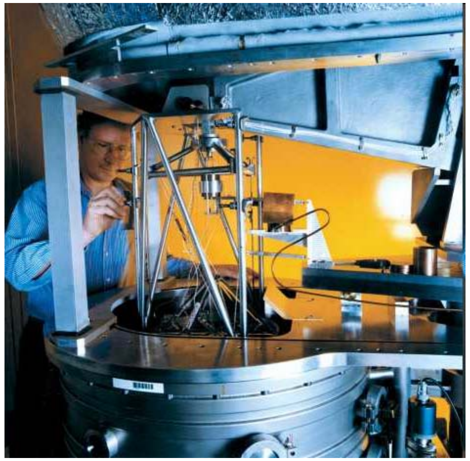


2 Steps:

1) Weighing by balancing with the magnetic force

$$F_g=m\,g = I\nabla\Phi$$

2) Measuring the flux gradient



AQS serves for measuring local gravity with a relative accuracy of 1 part in 10^9

… the determination of the Gravitational constant „G“

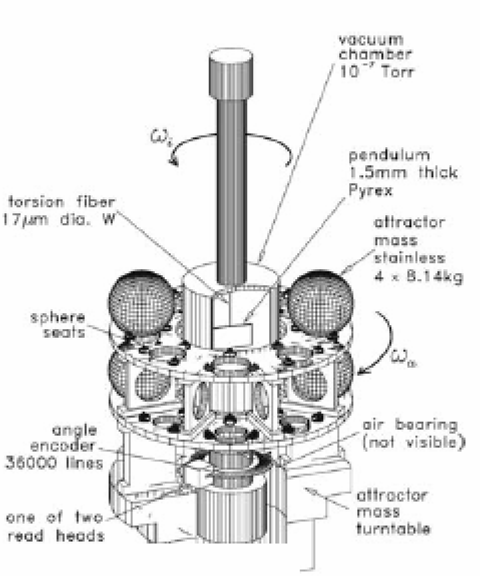
G- the worst known constant

complementary method

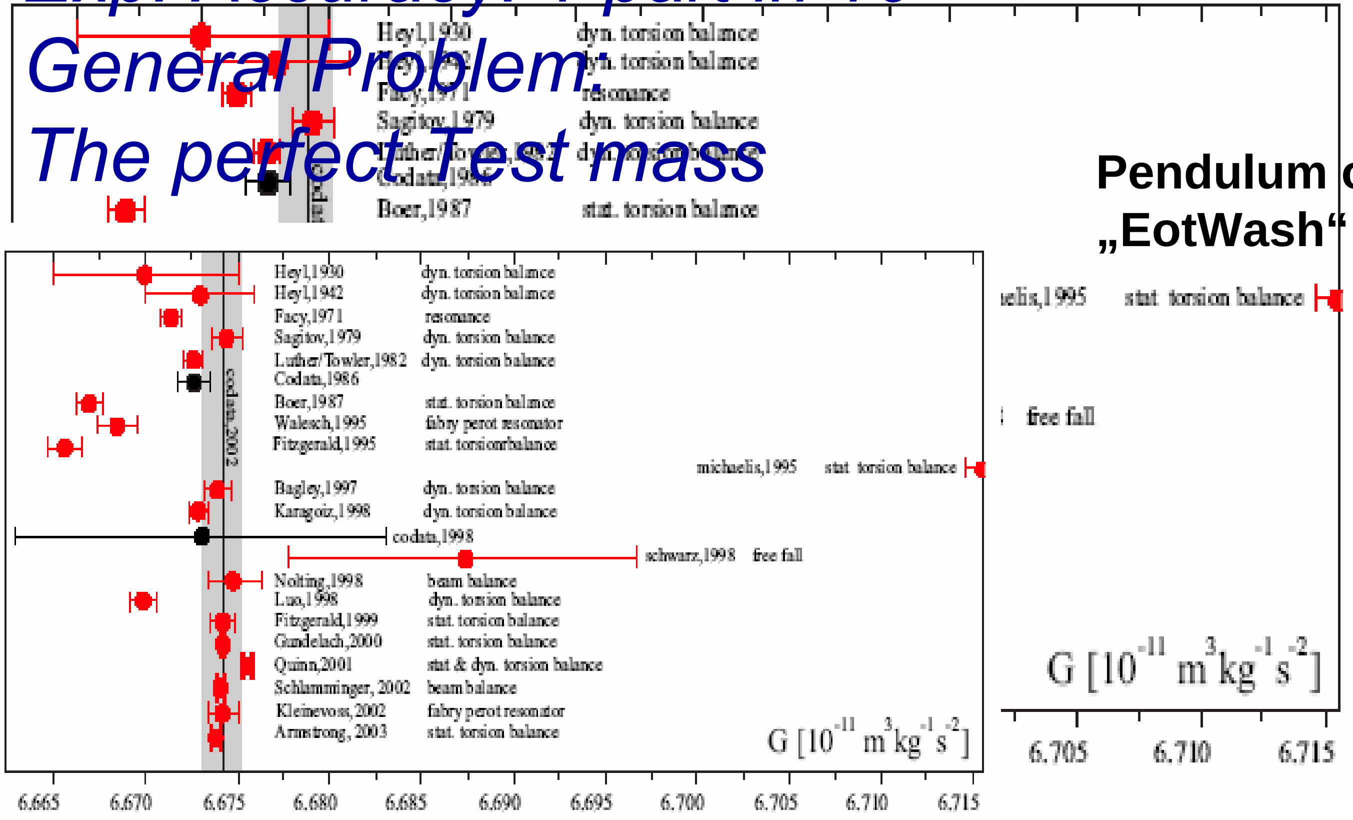
Exp. Accuracy: 1 part in 10^4

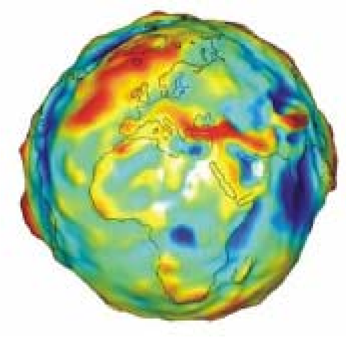
General Problem:

The perfect Test mass



Pendulum of the „EotWash“ group

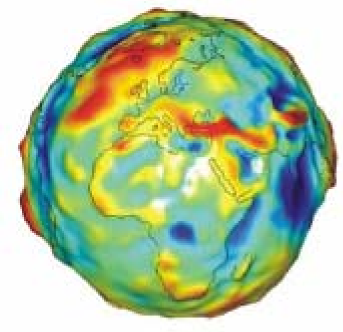




Earth Observation: The Geoid

Earth Observation…

global and high-resolution models of the static and the time variable components of the Earth's gravity :



- *global mass distribution*
- *ocean heat flux,*
- *long term sea level change,*
- *upper oceanic heat content*
- *large scale evapo-transpiration and soil moisture changes,*
- *glaciology (Greenland ice sheet changes)*
- *Space Exploration (Mars!)*

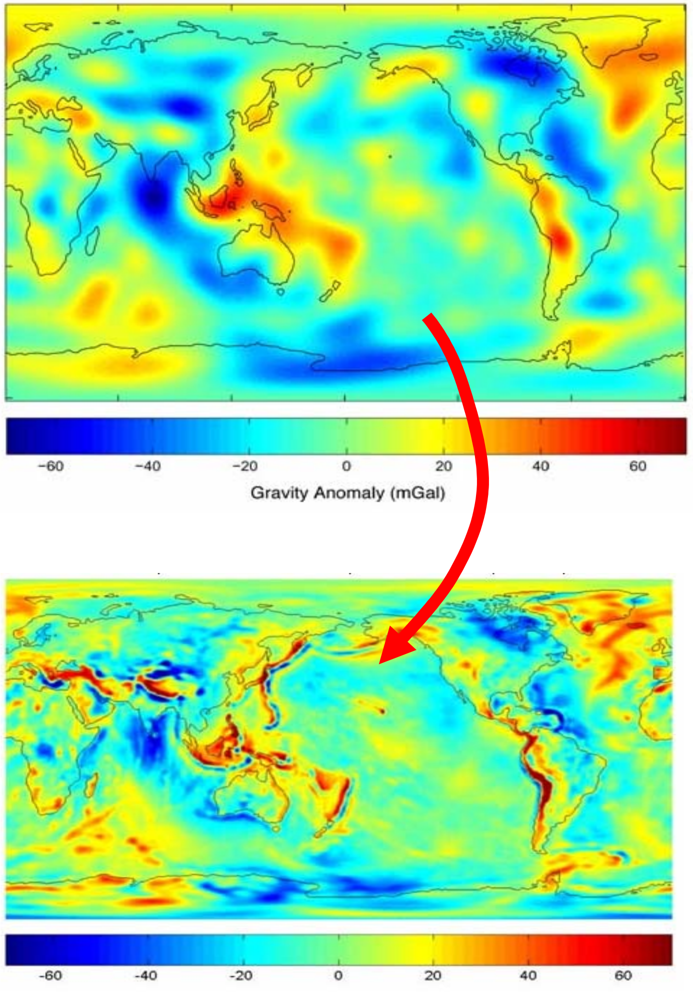
3-D simulation of compressible mantle convection

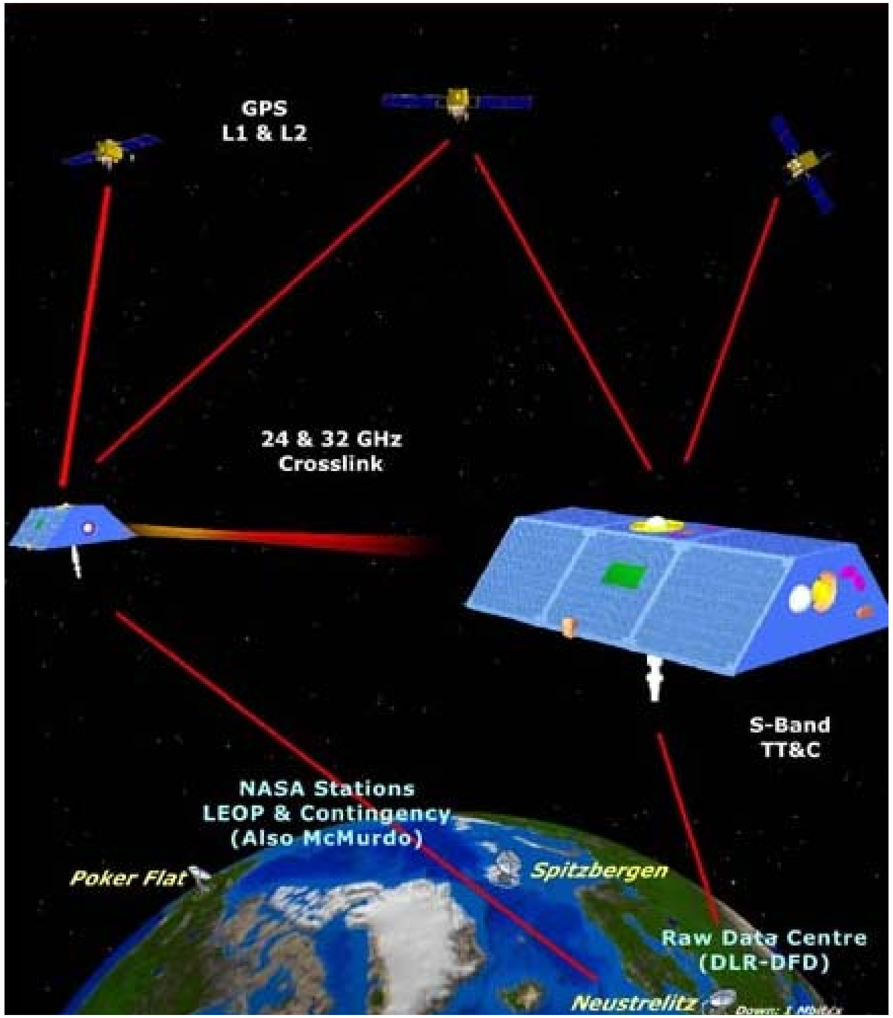
Mars gravity field mapping. Supporting Mars exploration.

Earth and Planetary Observation

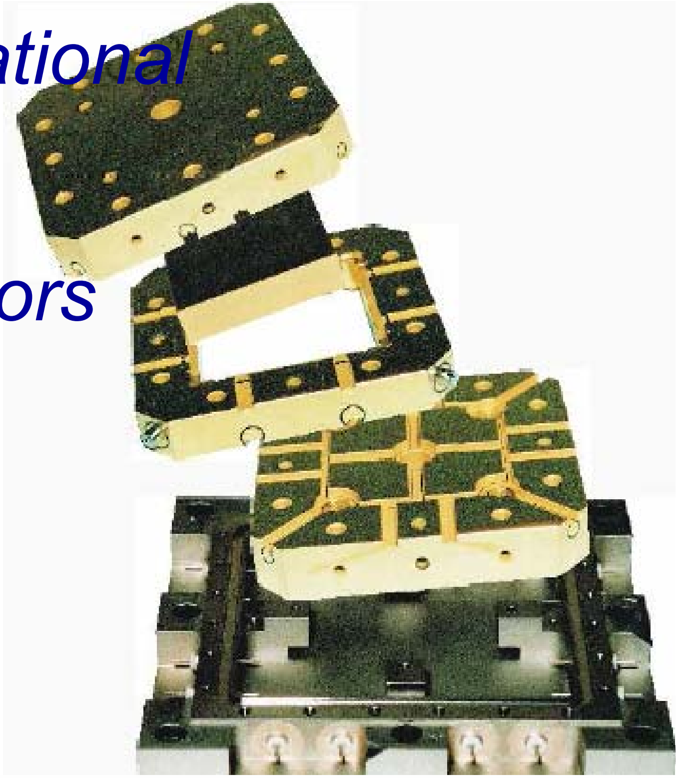
The Geoid

$$U_s(r,\varphi,\lambda;t)=\frac{GM_e}{r}+\frac{GM_e}{r}\sum_{l=2}^{N_{\max}}\left(\frac{a_e}{r}\right)^l\sum_{m=0}^{l}\overline{P}_{lm}(\sin\varphi)\left[\overline{C}_{lm}(t)\cos m\lambda+\overline{S}_{lm}(t)\sin m\lambda\right]$$





Correction of the non-gravitational accelerations

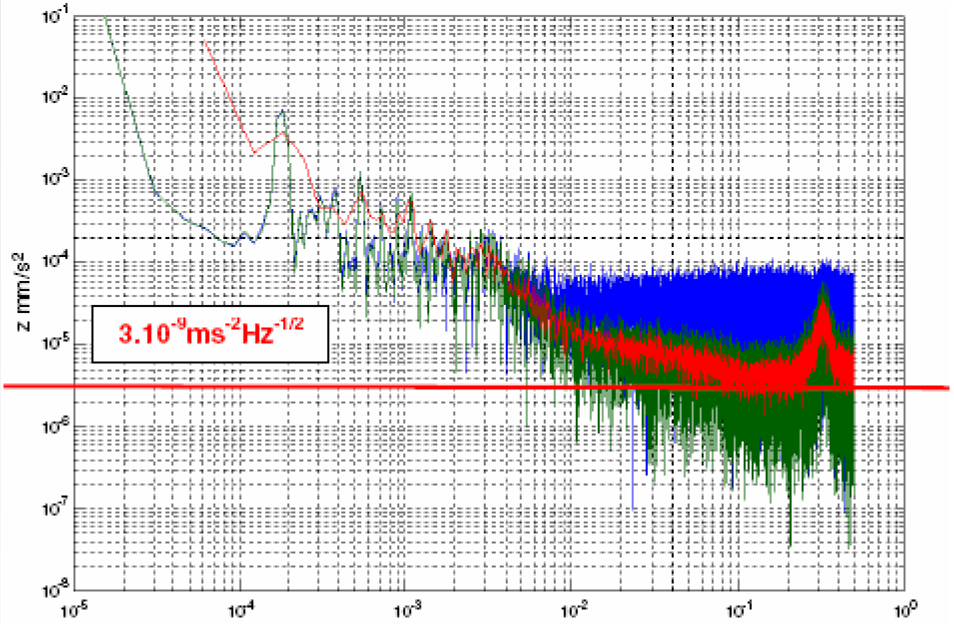


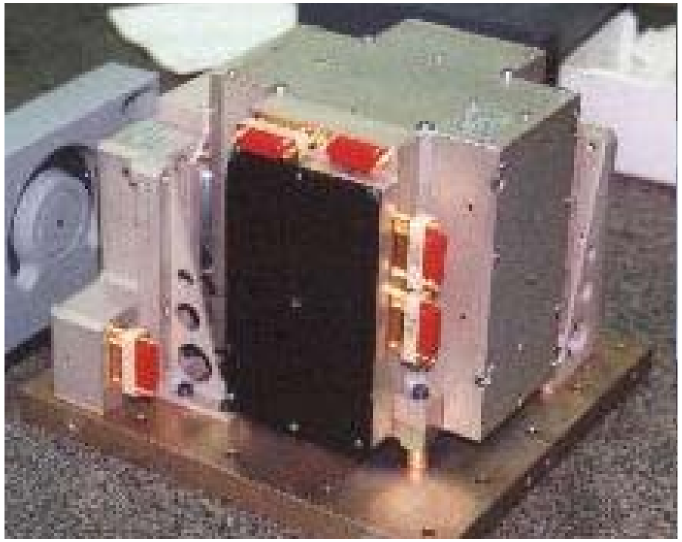
STAR & SUPERSTAR Sensors

P.Touboul, ONERA Paris

$$3 \cdot 10^{-10} \frac{g}{\sqrt{Hz}} @ 10^{-2} / 10^{-1} Hz$$

$$3 \cdot 10^{-11} \frac{g}{\sqrt{Hz}} @ 10^{-4} - 10^{-1} Hz$$





EARTH'S ROTATION IS SLOWING DOWN

. . . and will come to a halt in 3 years, warn scientists

By MIKE FOSTER / *Weekly World News*

ANCHORAGE, Alaska — Worried scientists say they have detected a significant slowing of our planet's rotation — and predict the Earth will stop spinning altogether in as little as three years!

The slowdown will lead to steadily longer days and nights and could cause everything from disastrous floods and earthquakes to mass starvation.

"This is by far the most serious and immediate problem now facing mankind," declared geophysicist Dr. Joseph R. Kopeski, who first observed the phenomenon.

Scientists have long believed the Earth's rotation is slowing. It's estimated that three billion years ago, a day zipped by in about 13 hours, while now one full rotation of the Earth on its axis takes 23 hours, 56 minutes and 4.091 seconds.

Old theories held that the effect was gradual, with the length of an Earth day increasing just .002 seconds per century.

But now new sophisticated measurements show that changes in the Earth's rotation have become more dramatic than ever before.

"By summer of 2001, a day will lengthen to 38.6 hours," revealed Dr. Kopeski.

And according to his chilling calculations, the Earth's rotation will wind down to a dead stop by January 16 of the year 2003.

Incredibly, this will result in permanent day on one side of the globe and permanent night on the other!

"Those individuals unlucky enough to end up on the dark side of the Earth will find themselves in a grim, cold world of eternal blackness," said the expert.

"Virtually all plant life — which depends on photosynthesis — will die within a few short weeks, leading to a halt in farming and the worst famines the human race has ever experienced."

But life will be no picnic for survivors on the bright side of the globe, the noted scientist added.

"Imagine a spinning top slowly running out of momentum — before it stops it begins to wobble.

"The same thing will happen to our planet, causing the continental plates to slosh about wildly.

"The result will be massive tidal waves and earthquakes in which billions will die."

What's more, year-round daylight will throw the lifecyles of insects and birds out of whack.

"The effect will snowball, disrupting the entire ecosystem," said the professor. "This could lead to mass extinctions all the way up the food chain."

Several other scientists have cautioned against panic, calling for calm until the phenomenon can be "studied thoroughly."

But Dr. Kopeski warned: "Governments around the world must begin planning for this inevitable catastrophe right now!"

'By the summer of 2001, a day will lengthen to 38.6 hours'

AS THE WORLD TURNS slower and slower, billions will die as longer days disrupt the Earth's ecosystem.

Dr. Kopeski

Earth Observation: The Spin

High resolution rotation sensors

Rotation sensing

The Earth‘s rotation:
$\Omega_E \approx 7{,}2 \cdot 10^{-5}$ rad/s

Applications:

- Investigation of the Earth‘s rotation
- Geology
- Star motion
- Satellite navigation
- Relativistic effects
- ...

Ω_E Effects:

10^{-4}
10^{-5} - seismology
10^{-6}
10^{-7} - Tidal forces
10^{-8} - Variation of the Earth‘s rotation
10^{-9}
10^{-10} - Relativistic Effects

Resolution:

$10^{-8} - 10^{-9}$ rad in 24 h

VLBI

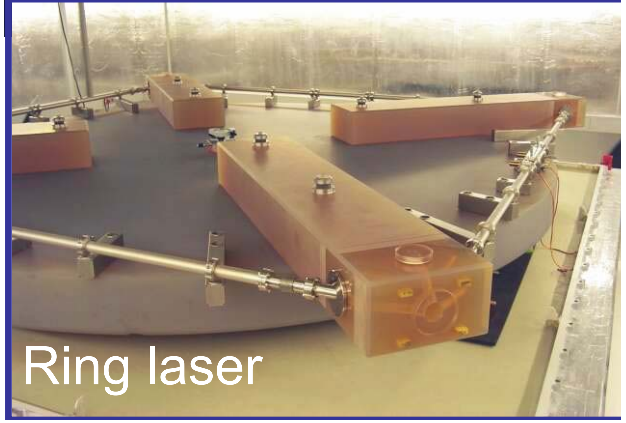
Resolution:

10^{-9} rad in 1 year

Gravity Probe B

Resolution:

$10^{-10} - 10^{-11}$ rad/s $\sqrt{\text{Hz}}^{-1}$



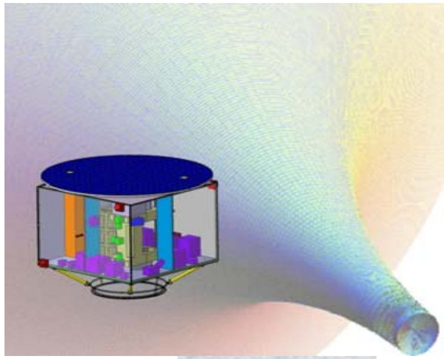
Ring laser

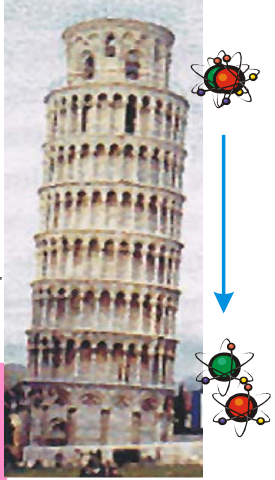
Outlook

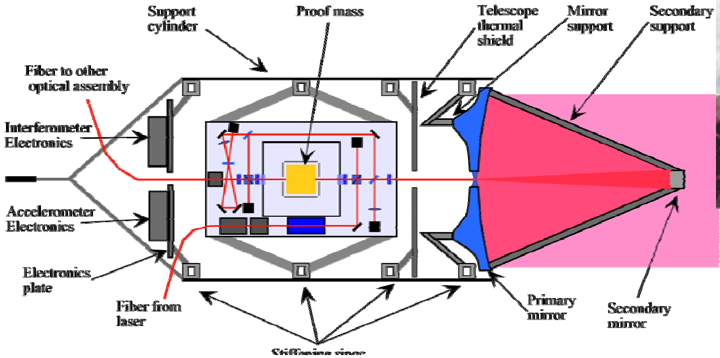
Atomic Quantum Sensors

are a promising alternative and complimentary technique for experiments in fundamental physics, like

- Absolute inertial references
- The measurement of relativistic effects
- Testing the Equivalence Principle
- Drag-free sensors
  perhaps in gravitational wave detectors ?

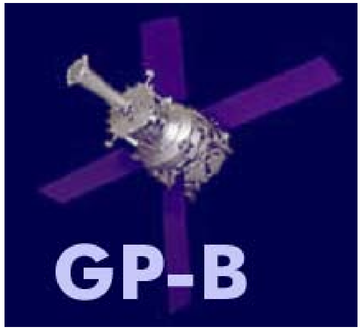






Observing the Lense-Thirring effect <1%

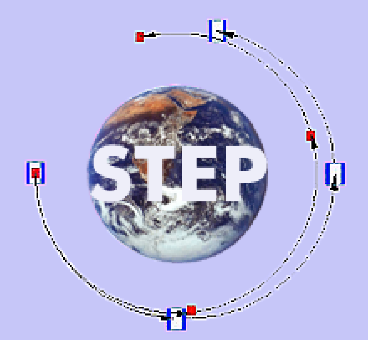
(Results end of the year!)

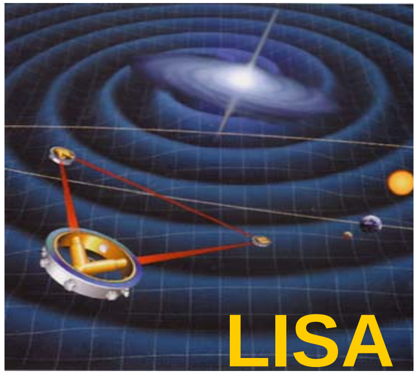


Testing the Equivalence Principle

1 part in $10^{15}/10^{18}$

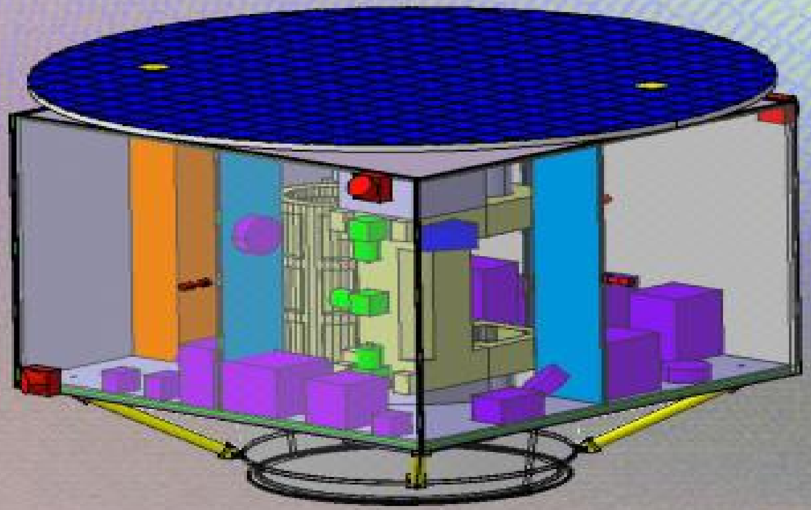
Detecting Gravitational Waves



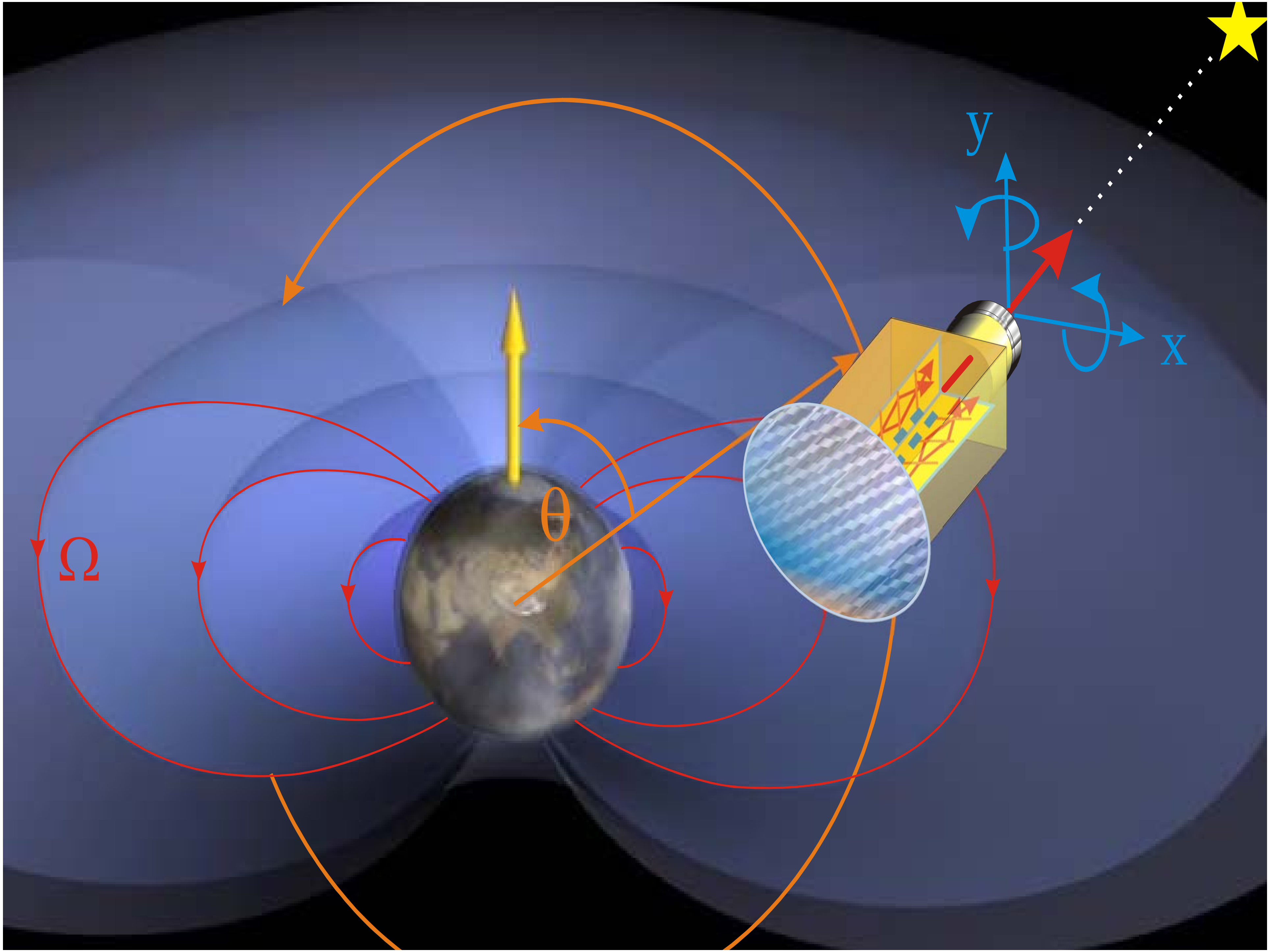


HYPER: Precision Atom Interferometry in Space

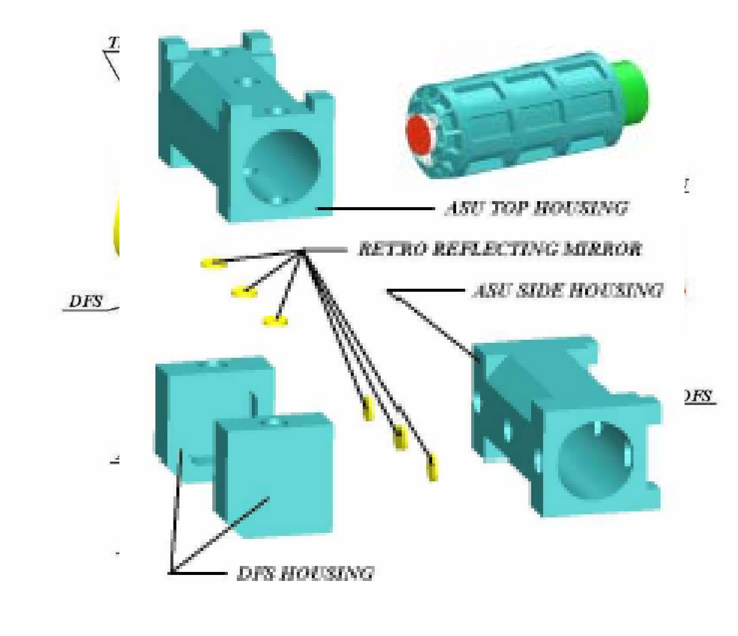
Aim: Spatial resolution of the Lense-Thirring-Effect: Schiff effect



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


y
x
θ
Ω

…performance



2 atomic MOTs

Launch of 10^8 at @ 1μK

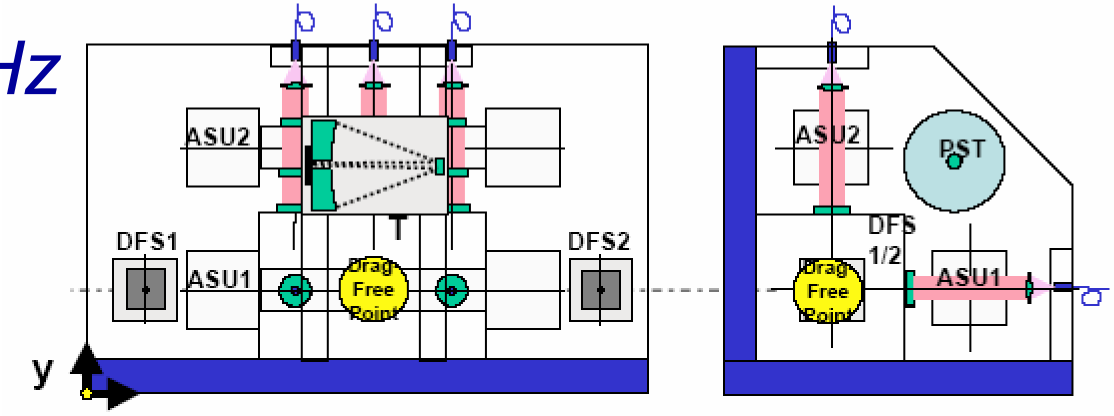
with 20 cm/s, $2T_{Drift} = 3$ s

Length: 60 cm

$\Omega_{SNL}=2\cdot10^{-12}$ rad/s/√Hz

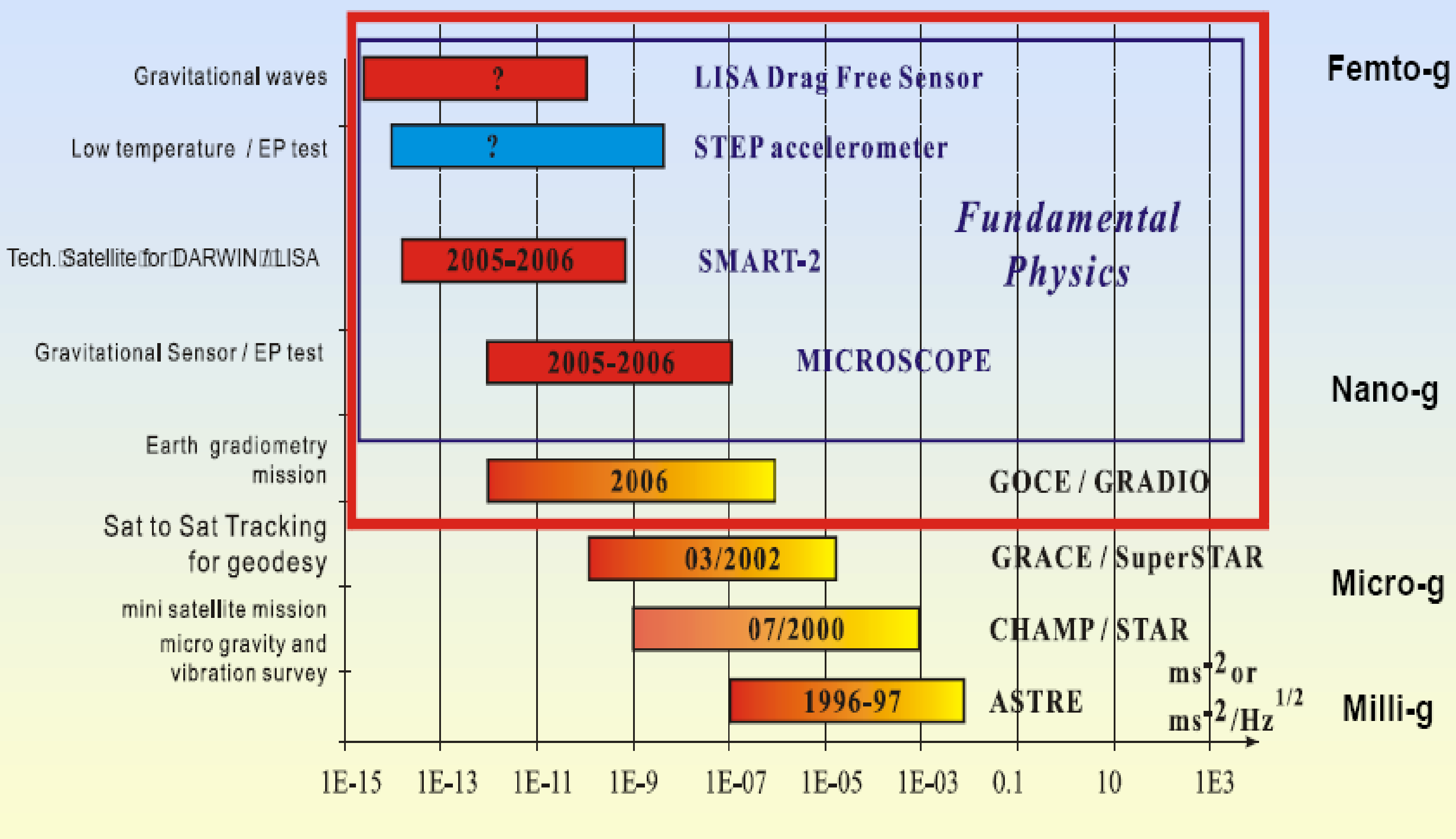
$A_{SNL}=4\cdot10^{-14}$ g/√Hz

per shot, 0.3 Hz



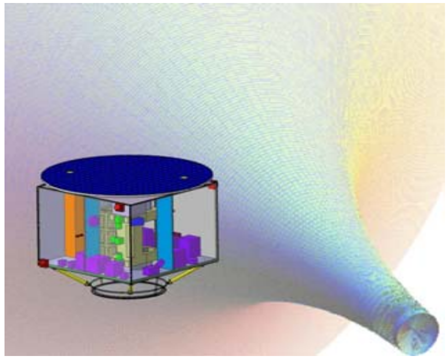
Optical Bench Structure

Need for Femto-g



With cold atoms ?

Need for Femto-g



$\Omega_{SNL}=2\cdot 10^{-12}$ rad/s/√Hz
$A_{SNL}=4\cdot 10^{-14}$ g/√Hz
per shot, 0.3 Hz

Time: 3s → ? + Resolution: $\sim T_{Drift}^{2}$
- $T_{at} < 1\mu K$
- Dynamic Range

Atoms: $10^{8}\rightarrow$? + Resolution: $\sim\sqrt{N}$
- T_{at} ?
- USO-Phase noise ?

Beam splitter: Multiphoton?- New Beam splitters?

„All-atomic“ Gravitational Wave detector?
Thermal Atoms: + High Flux
small de Broglie wavelength
Large Distances in short time
Beam splitter ?

CASI-Team

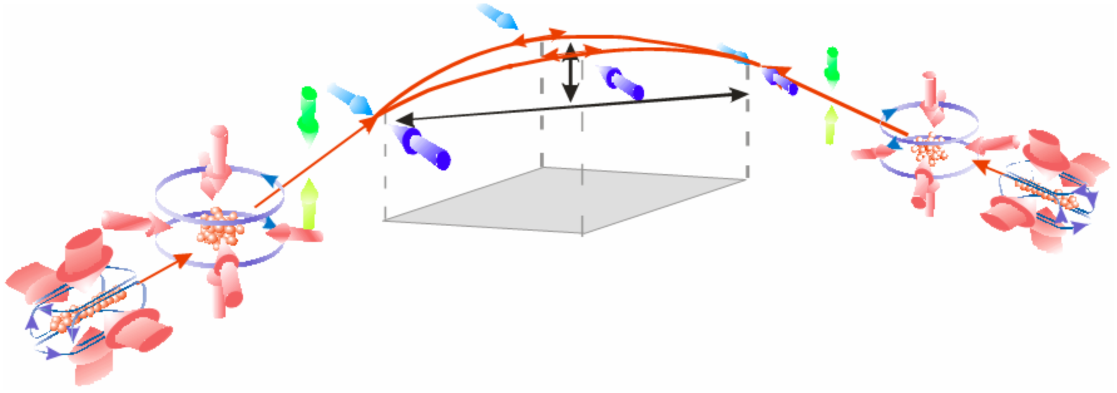
Cold Atom Sagnac Interferometer

Michael Gilovski

Thijs Wendrich
Tobias Müller

Christian Jentsch
(now at SYRTE)

Ernst M. Rasel
W.E.



THANK YOU