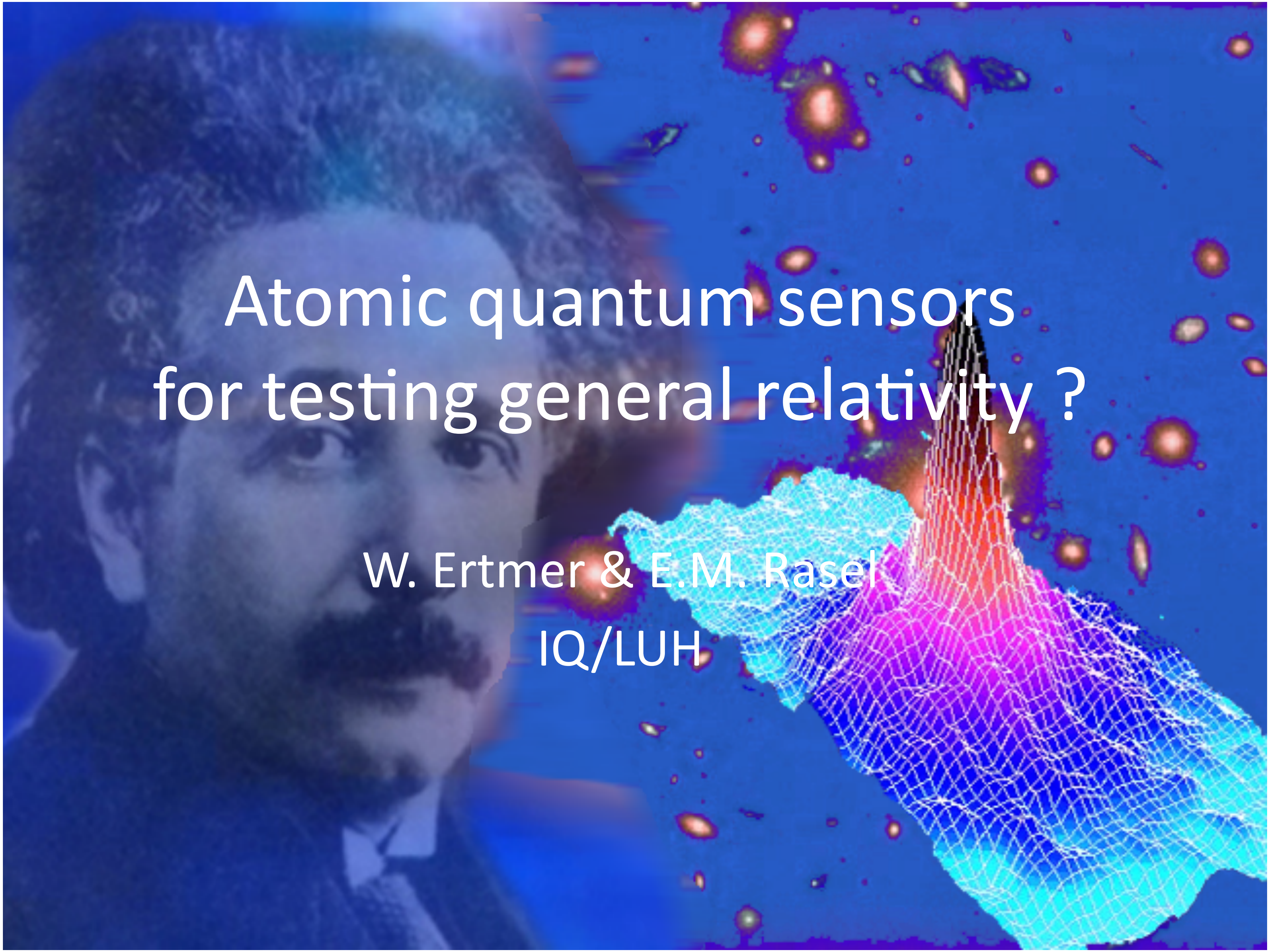

Atomic quantum sensors
for testing general relativity ?
W. Ertmer & E.M. Rasel
IQ/LUH

Topics

- detection and observation of gravitational waves,
- test of the Lense-Thirring effect,
- test of the Weak Equivalence Principle.

Atom interferometer configuration

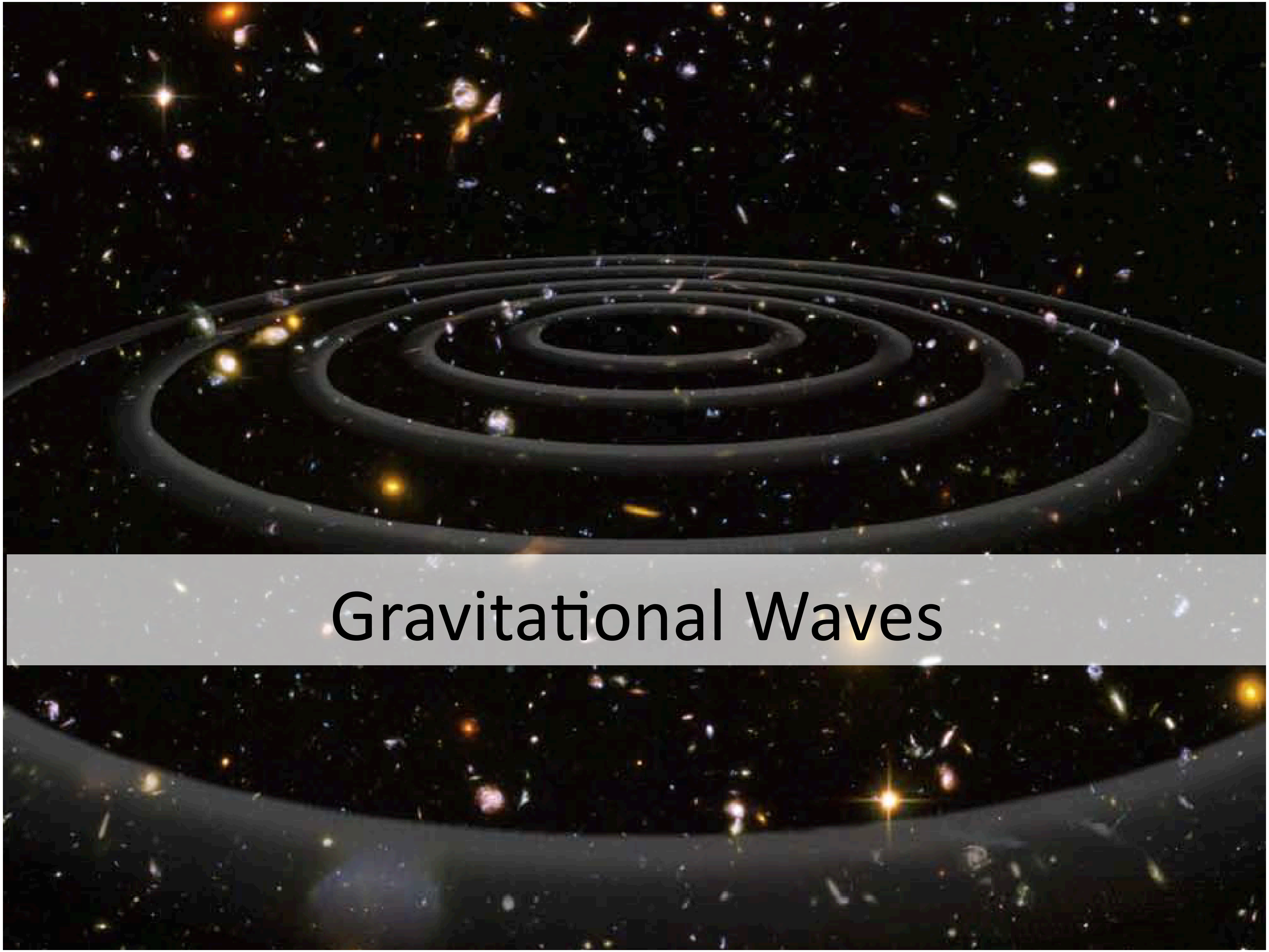
- detection and observation of gravitational waves:

  Phase meter, accelerometer
- test of the Lense-Thirring effect:

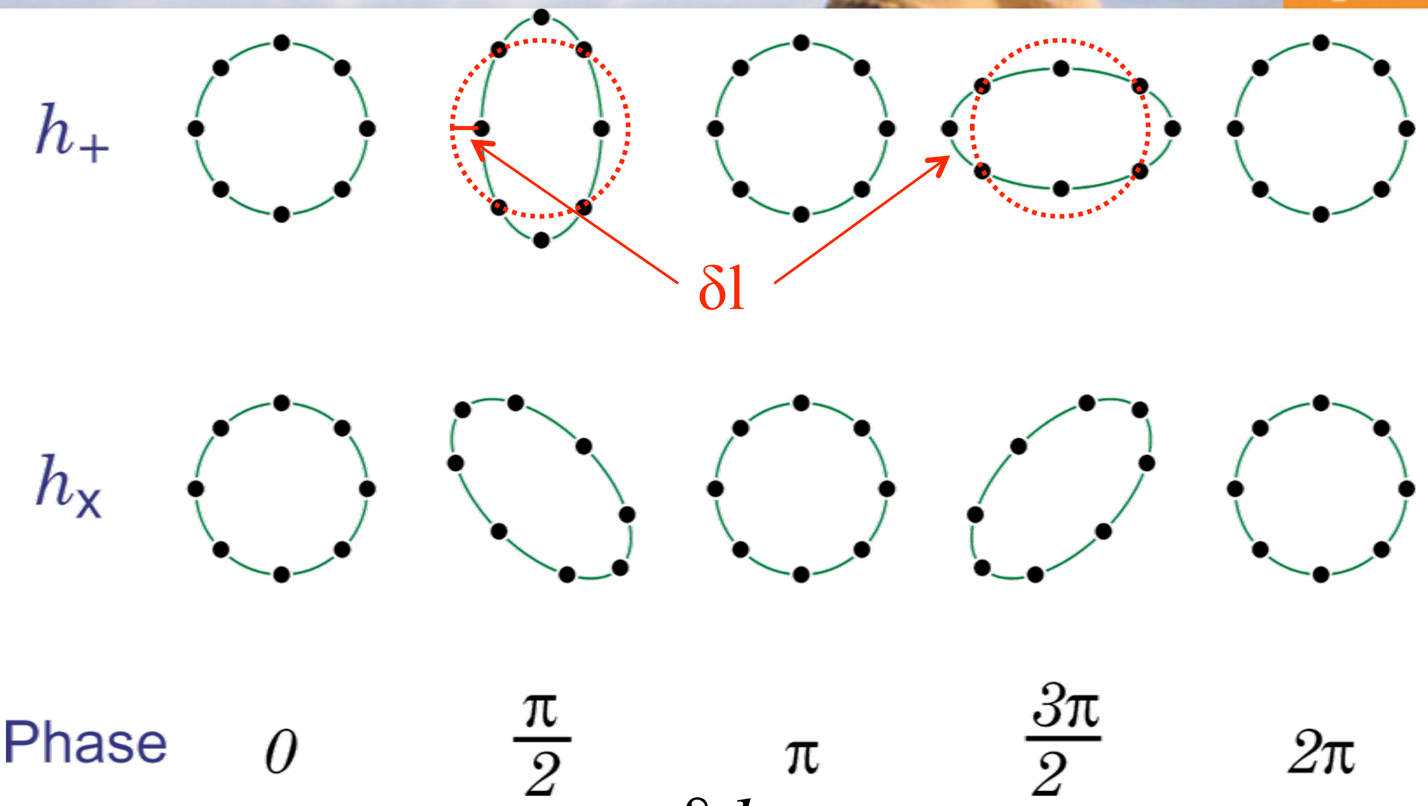
  Gyroscope
- test of the Weak Equivalence Principle:

  Differential Accelerometer

Gravitational Waves



Strain in Space Curvature

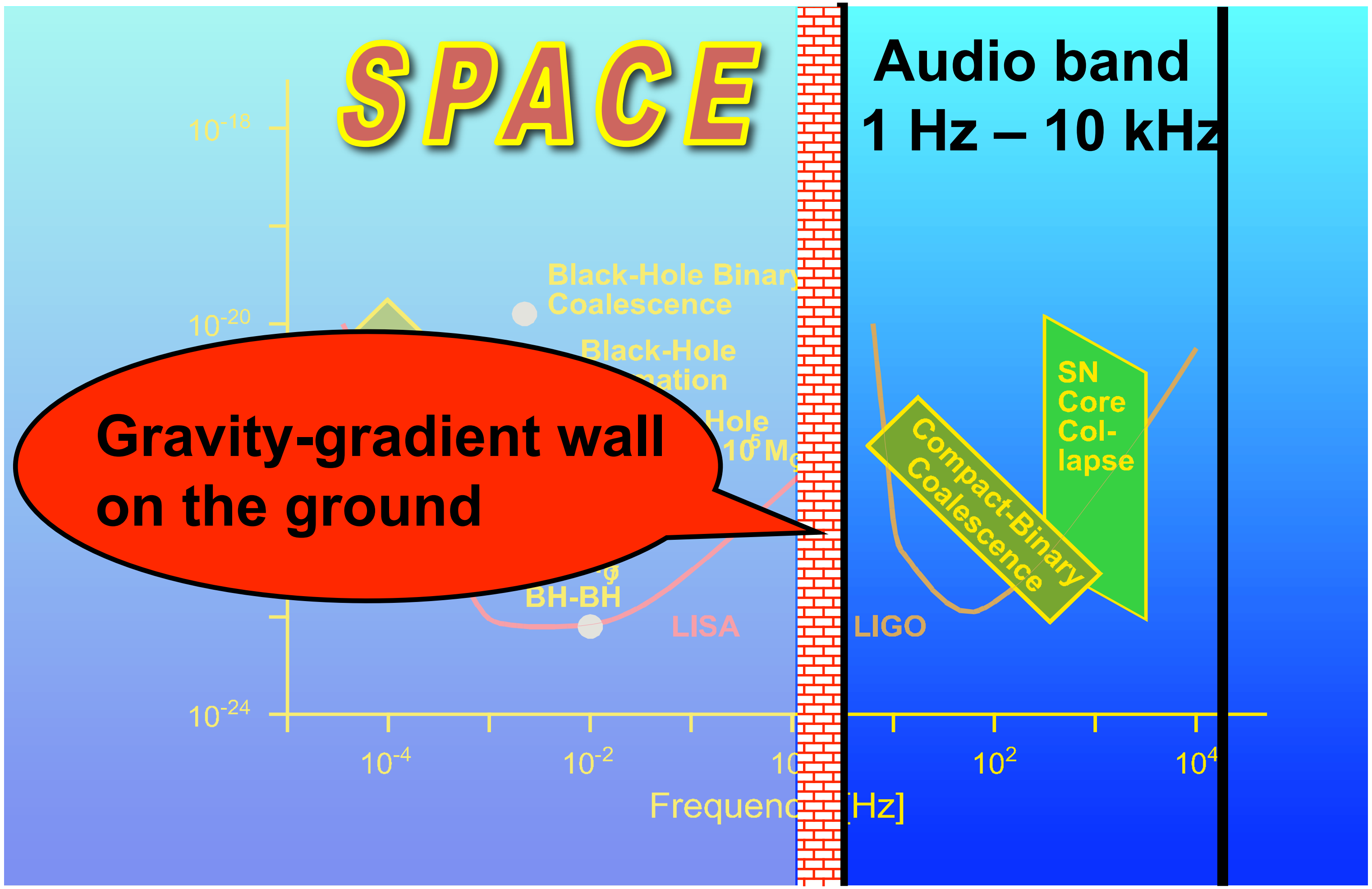


$$h = 2\frac{\delta l}{l} \leq 10^{-21}$$

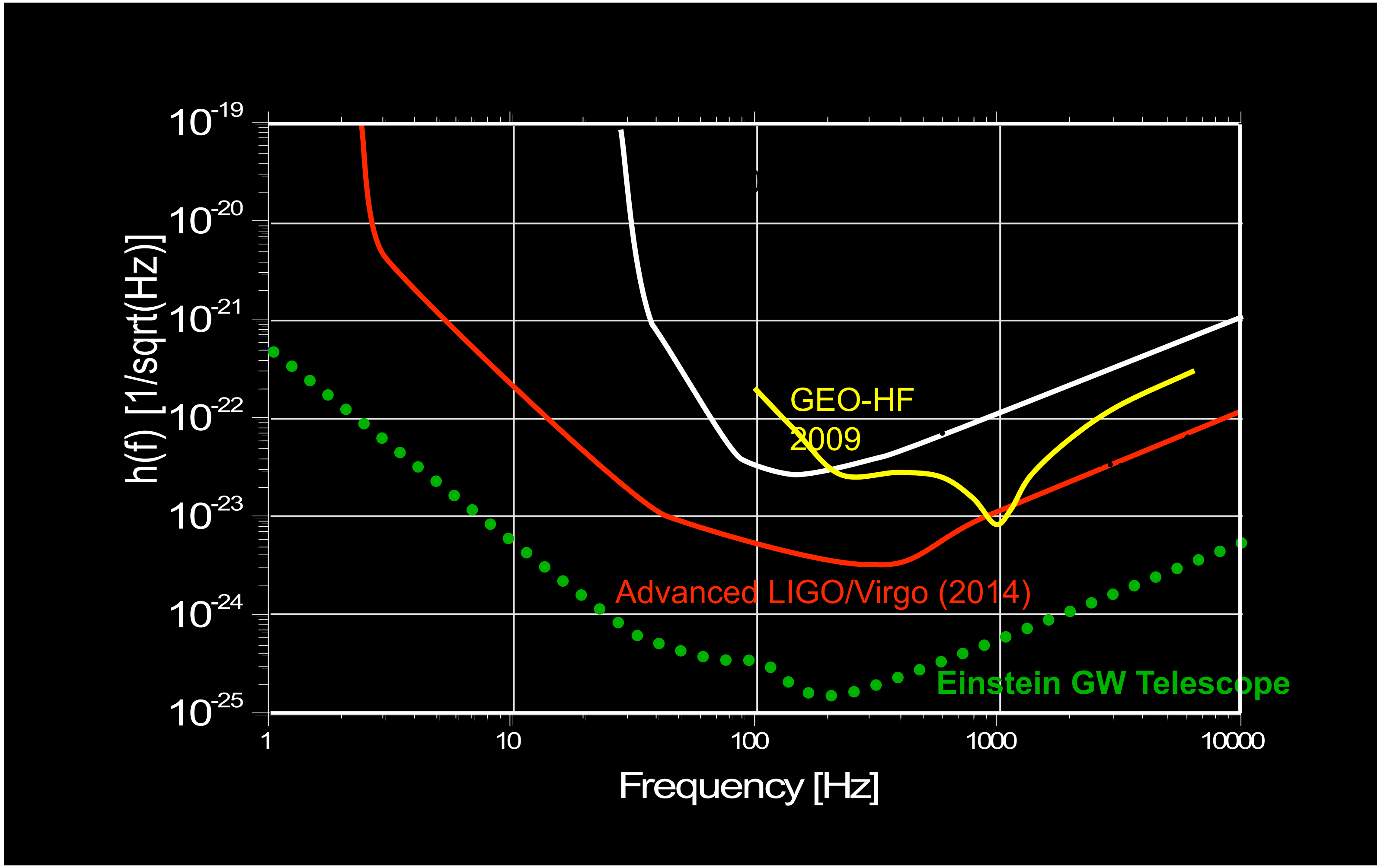
- Abs. length variation δl increases with distance!
- Free test bodies will change their relative distance
- Transversal waves

Gravitational Wave Sources

- Ground-based detectors observe in the audio band
- Space detectors observe low frequencies

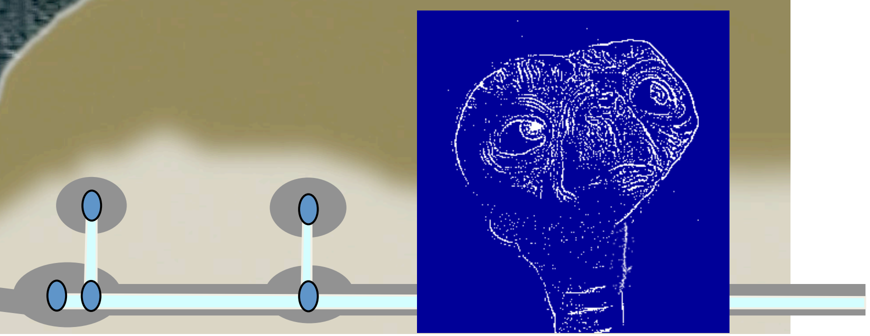


GWD today and in future



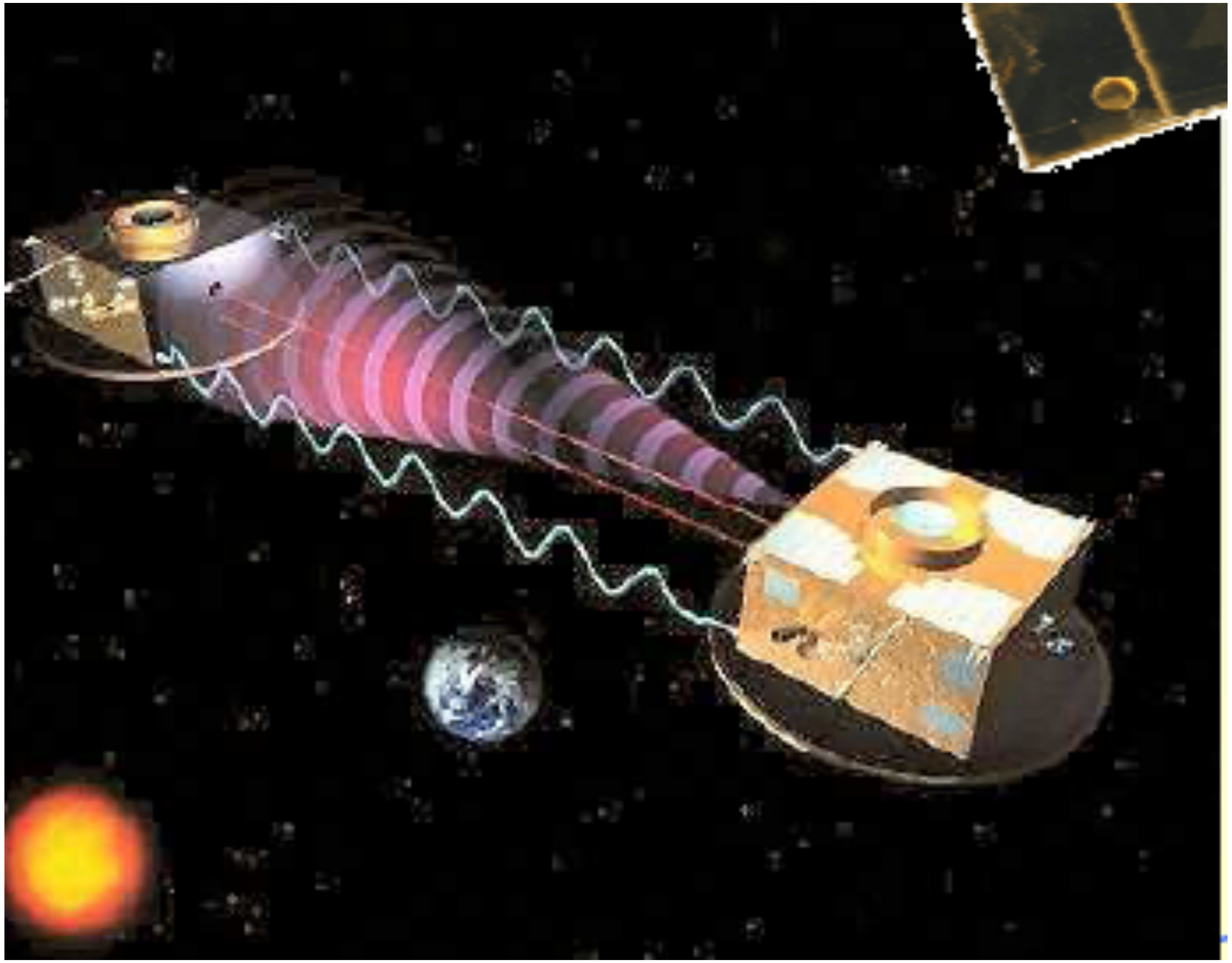
The Third Generation
The Einstein Gravitational Telescope
E.T.

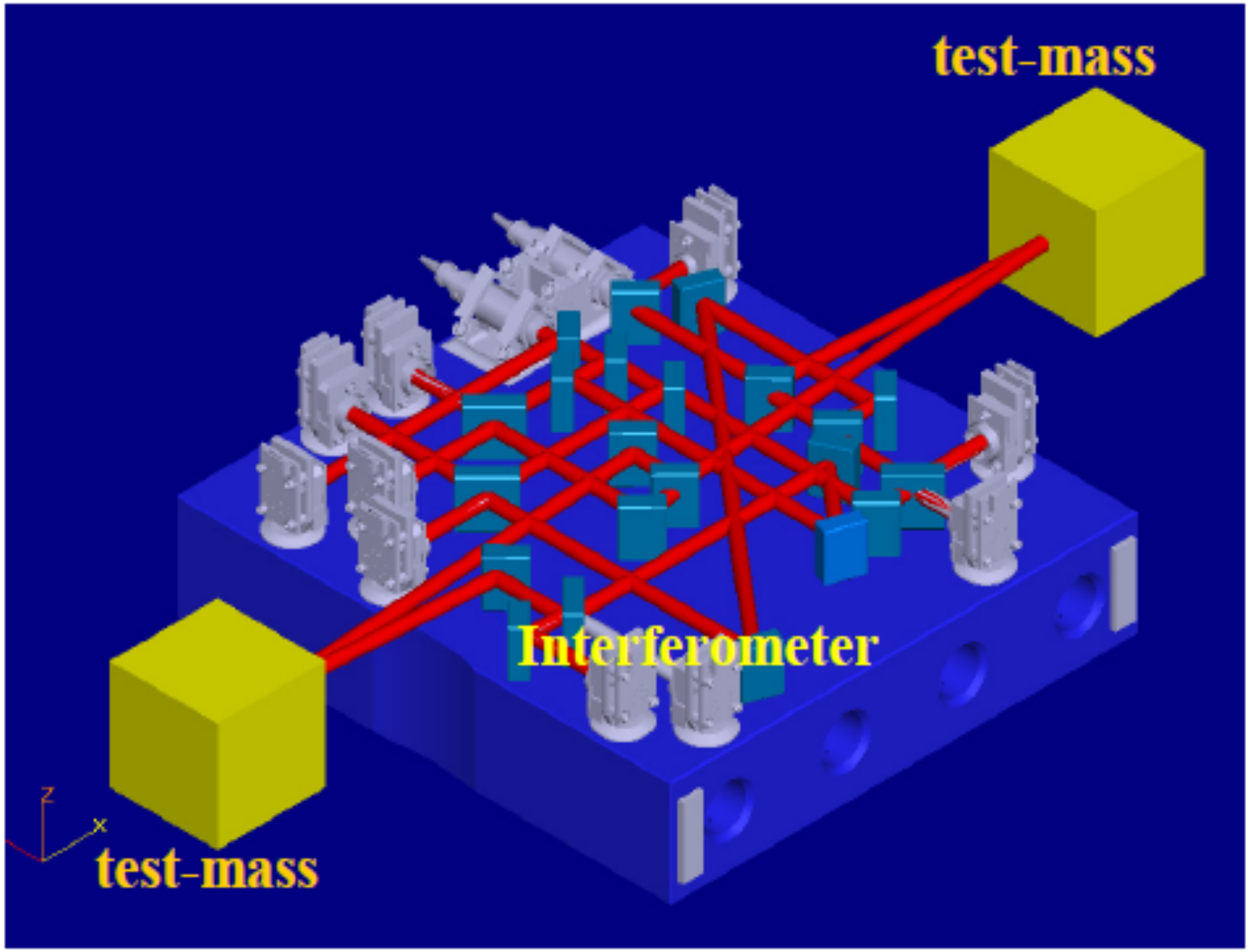
- Overall beam tube length ~ 30km
- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic
- Squeezing
- QND Readout

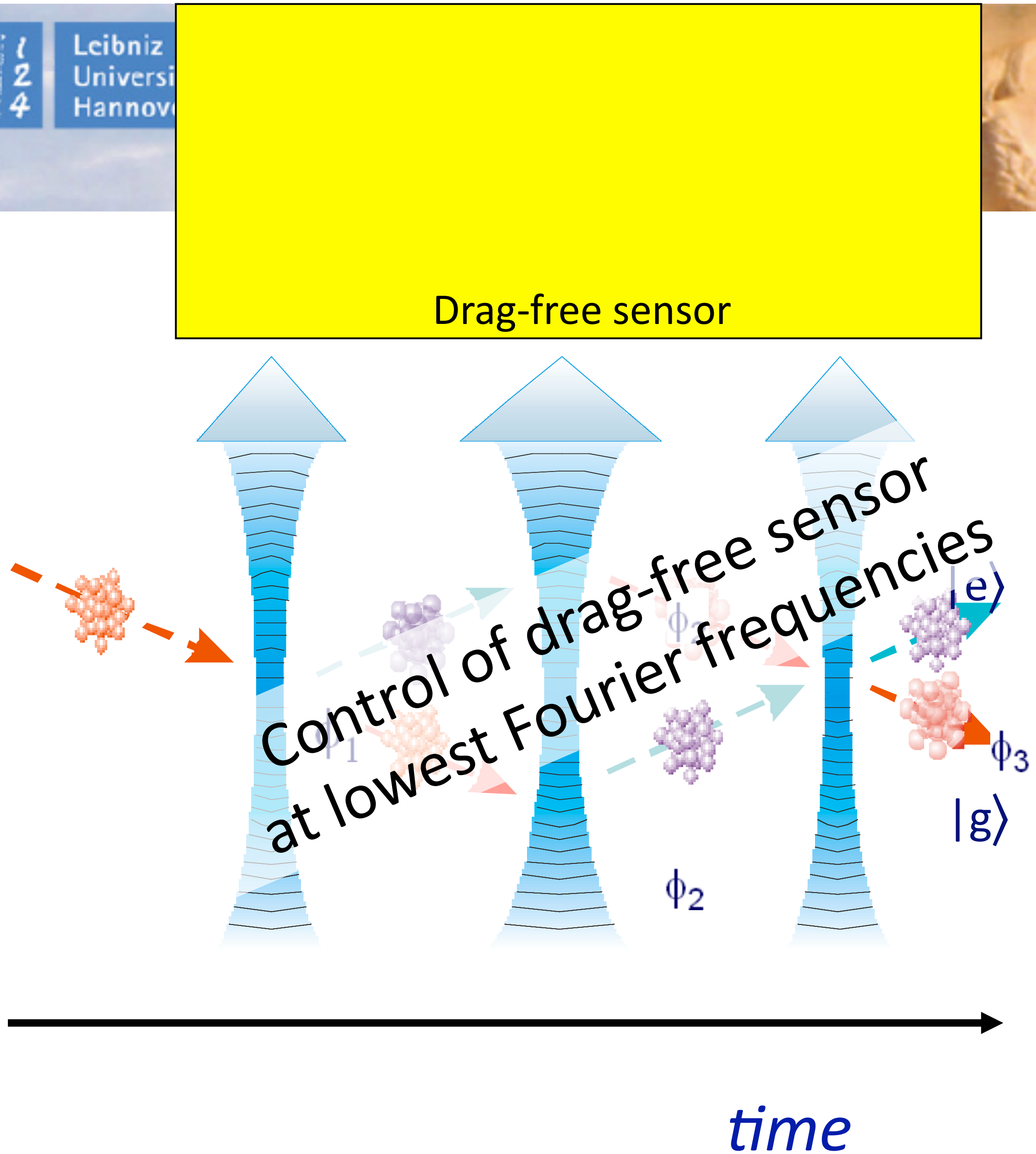


Can atomic sensors contribute ?

Combining microscopic and macroscopic test masses



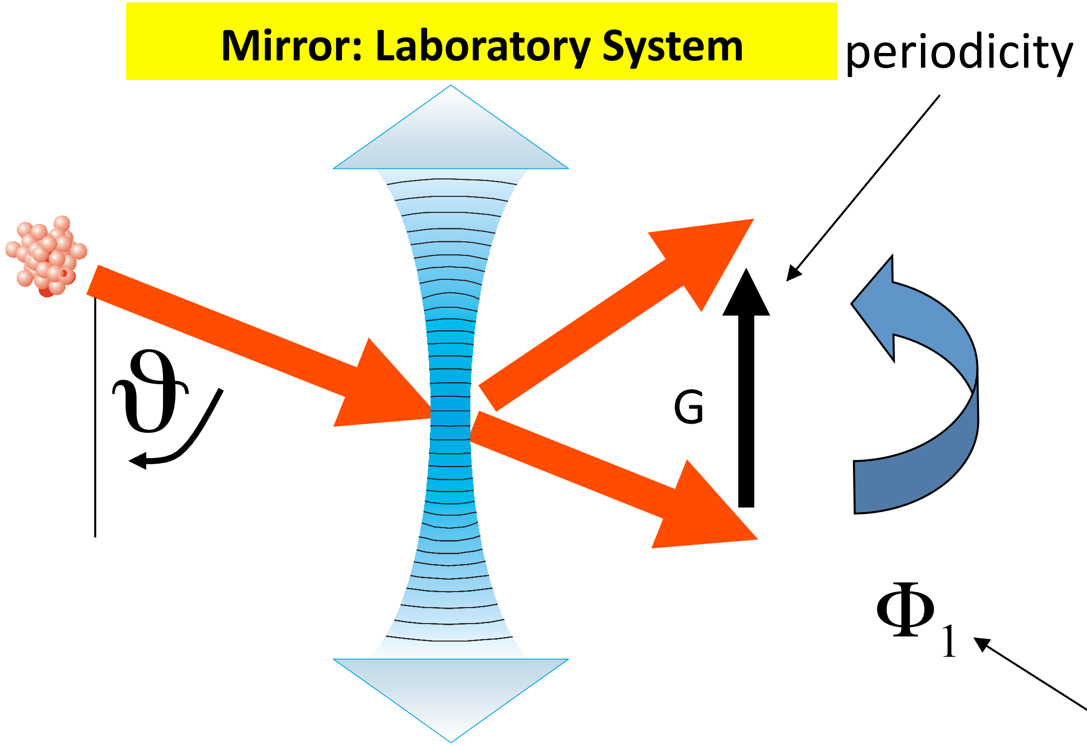

test-mass
Interferometer
test-mass



Signal at the output ports

$$S \sim \cos[(\phi_3 - \phi_2)-(\phi_2 - \phi_1)] \qquad \Delta\Phi \approx 2k_{eff} hL \sin(\omega_{GW} T)$$

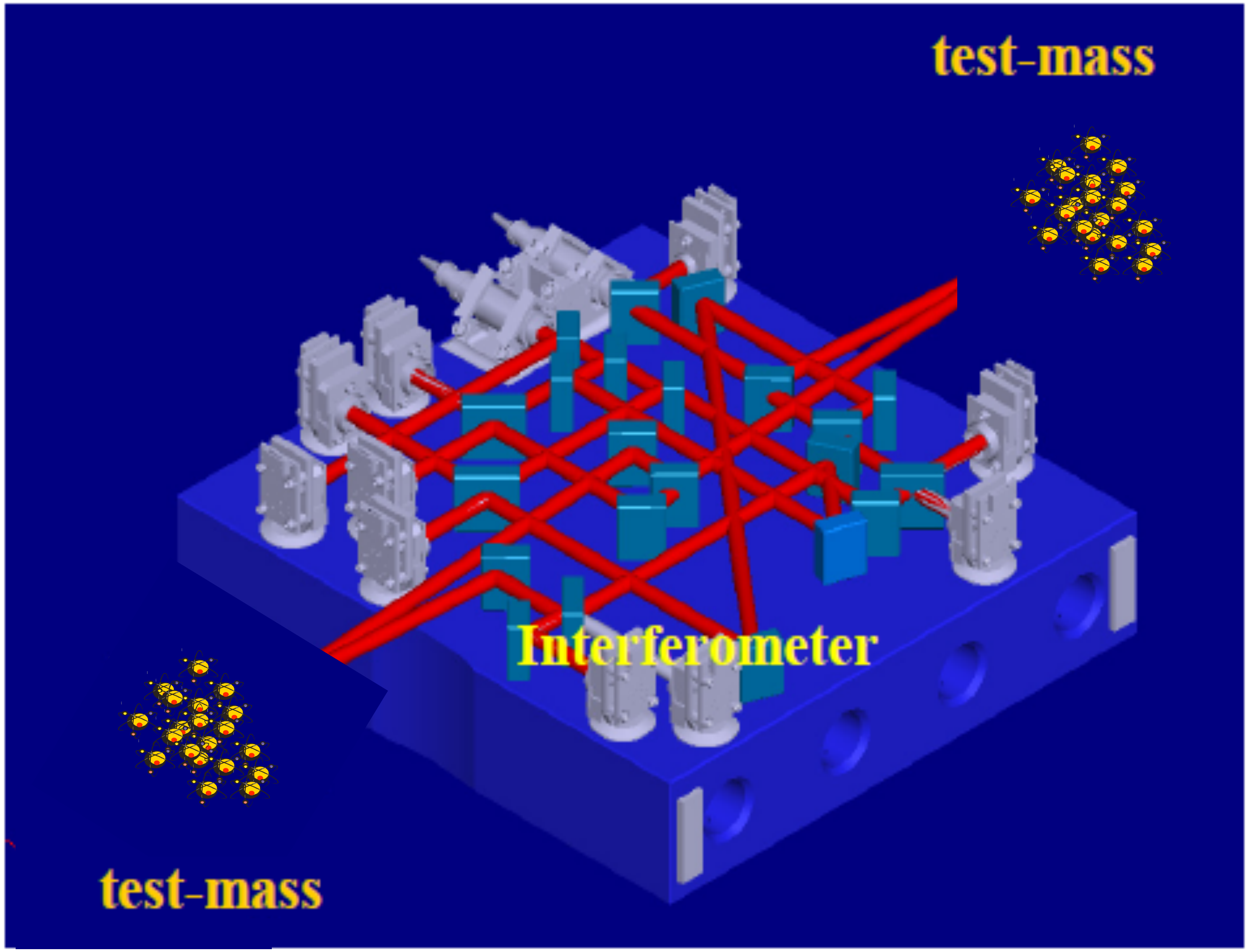
Coherent Atomic Beam Splitter
Position Sensitivity



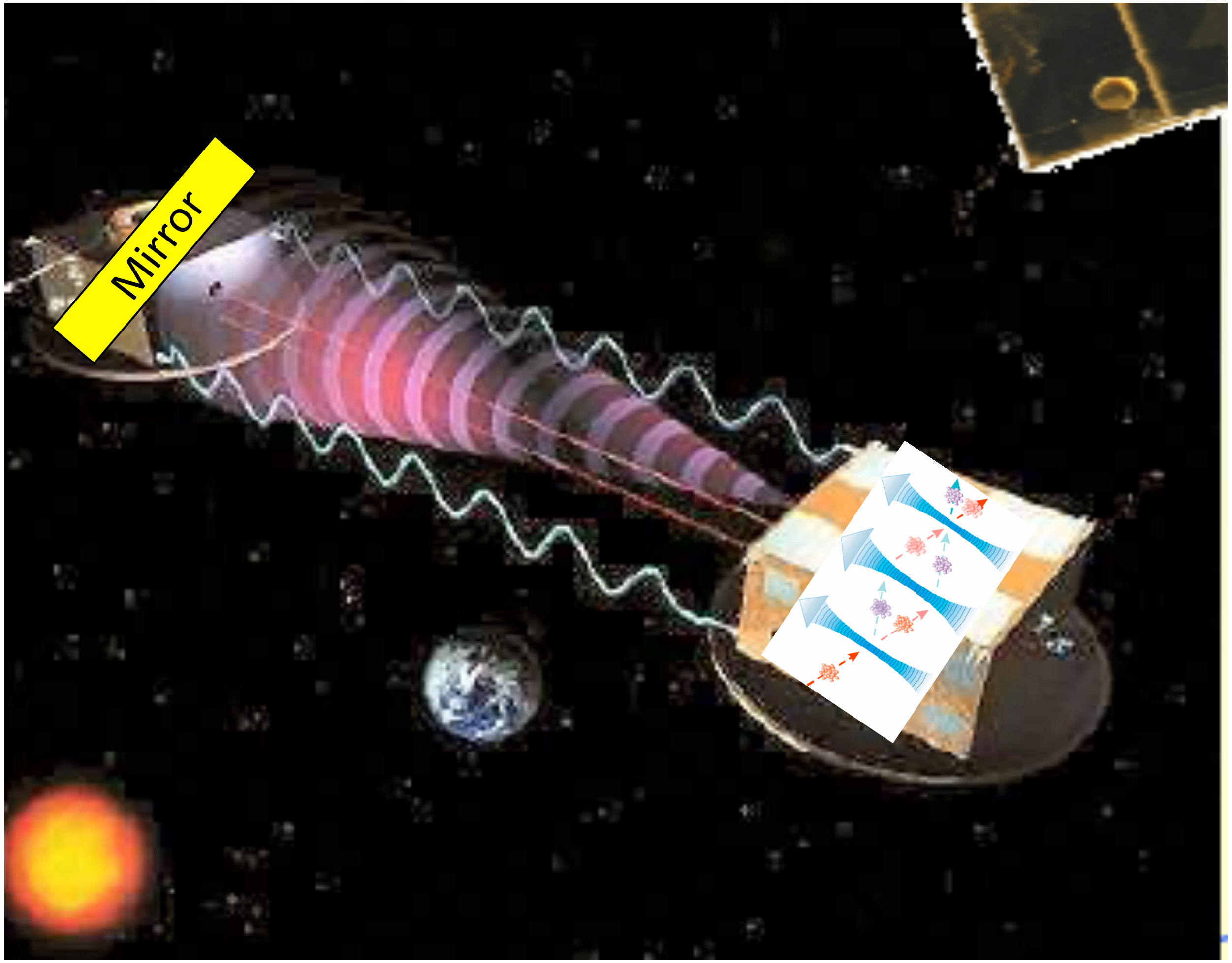
$$\Phi_1$$

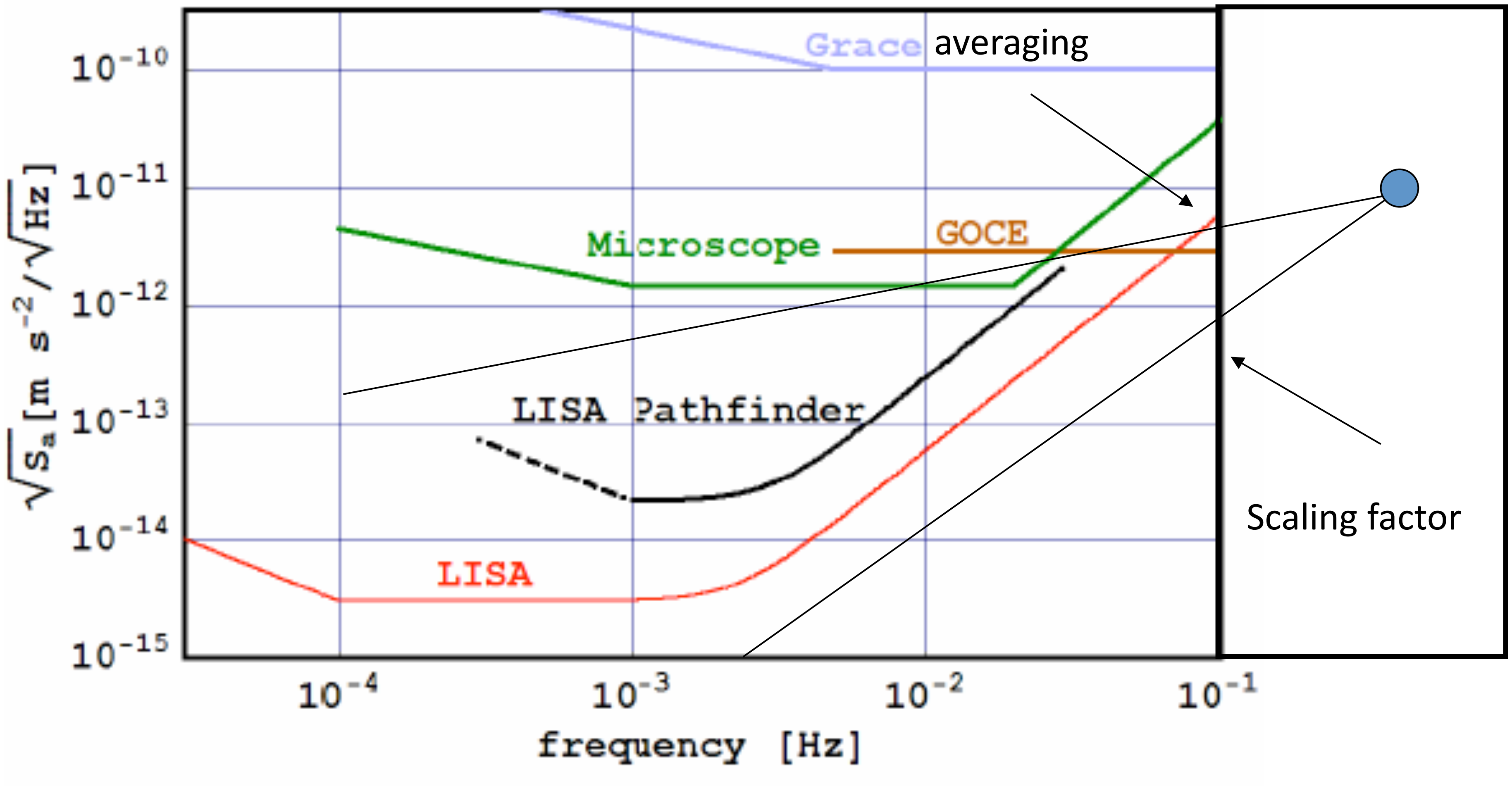
$$n \cdot \lambda = 2d \cos \vartheta$$

Fringe position


test-mass
Interferometer
test-mass

Replacement of drag-free sensor at lowest Fourier frequencies



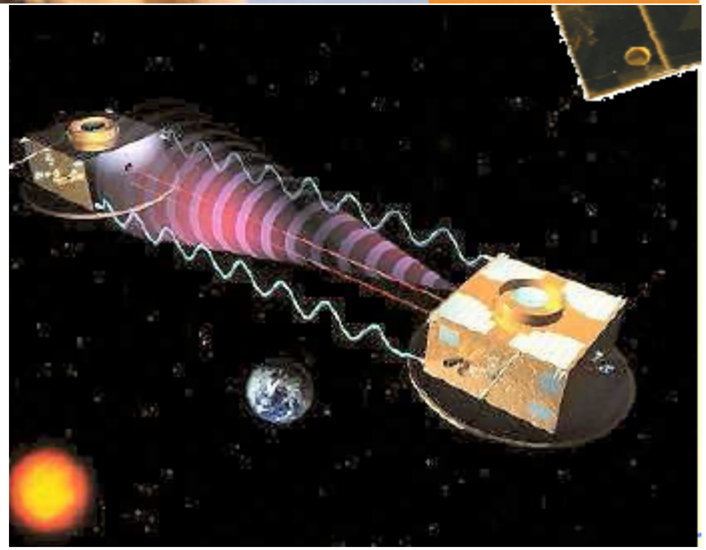


Averaging √T/τ

Atomic Temperature an issue and beam splitter velocity : T^2

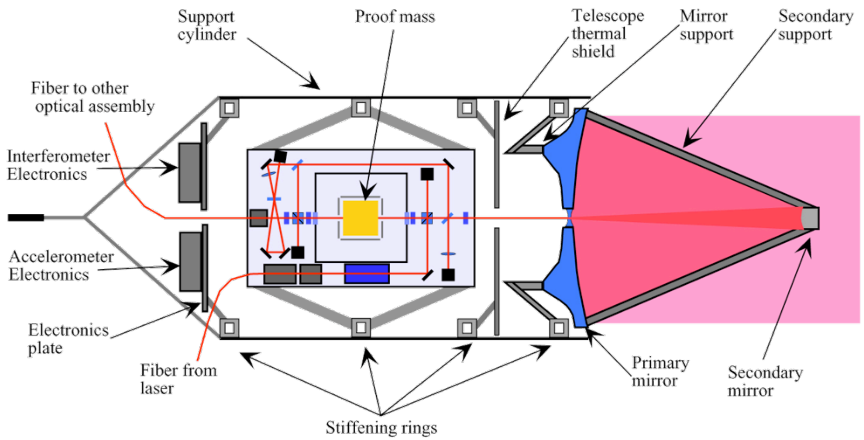
GW-Sensors

Performance

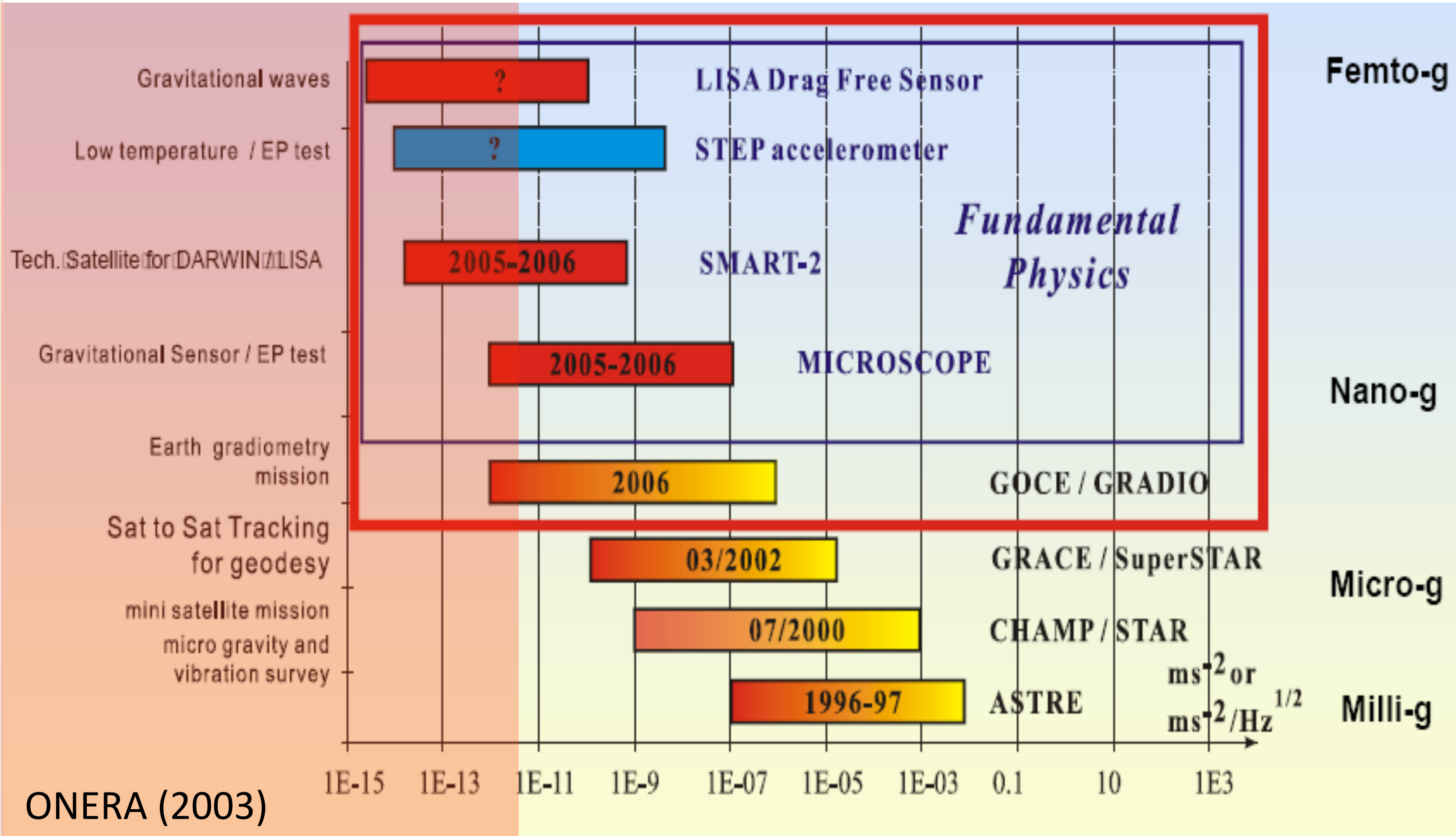


Noise limited sensitivity

$$\sigma \approx 10^{-16} \frac{\mathrm{g}}{\sqrt{\mathrm{Hz}}} @ 10^{-3} - 10^{-4}\,\mathrm{Hz}$$

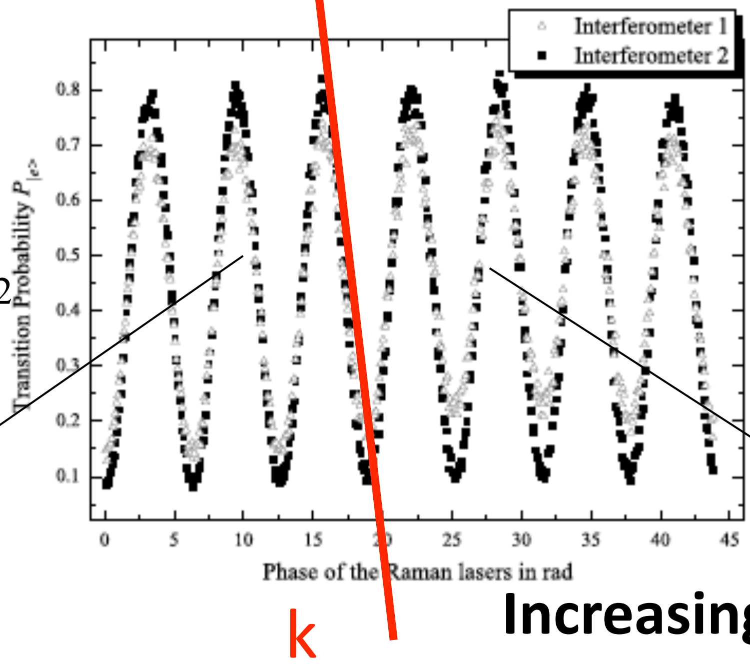


Need for Femto-g



With cold atoms ?

$$(\Delta\Omega)^2 = (\Delta\varphi)^2 / \left(\frac{\partial\varphi}{\partial\Omega}\right)^2$$



Increasing sensitivity

- large area

Holger Müller (Berkeley):
Large area atom interferometry

Minimising phase noise

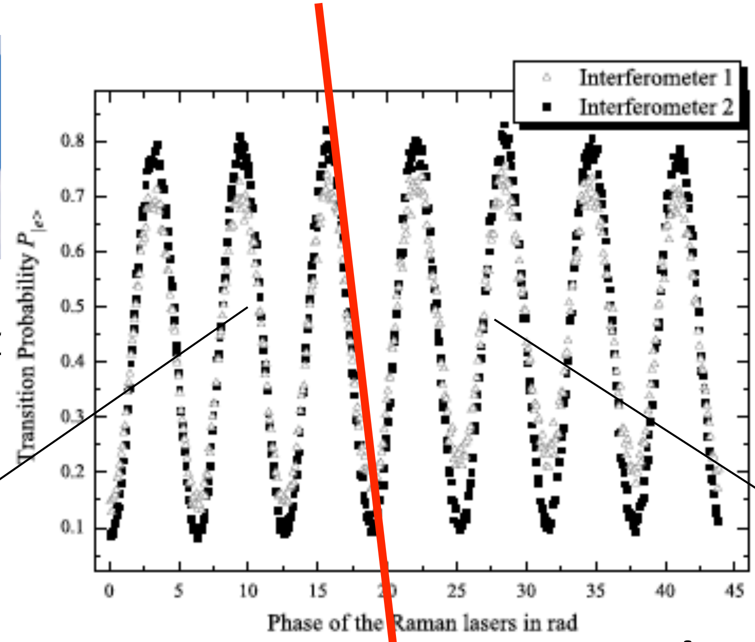
- Increasing number of atoms
- Beating the shot noise
- Environmental control → Space
- Ultrastable lasers (frequency, intensity)

Raman Laser

Leibniz Universität Hannover

quest

$$(\Delta\Omega)^2 = (\Delta\varphi)^2 / (\frac{\partial\varphi}{\partial\Omega})^2$$



k

Increasing sensitivity

- large area
- low frequency signal

long interaction times

→ large atomic mass

→ Space

- ultra cold atoms
- Coherence

Minimising phase noise

- Increasing number of atoms
- Beating the shot noise
- Environmental control → Space
- Ultrastable lasers (frequency, intensity)

Systematics

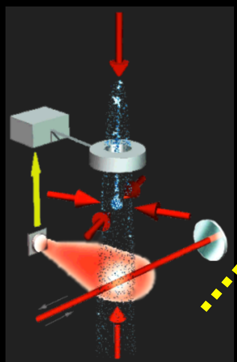
Raman Laser

Quantum Matter in Microgravity

From Fountains to Large Facilities

- Prototype experiments
- 10m fountain or drop
- Atom drop tower

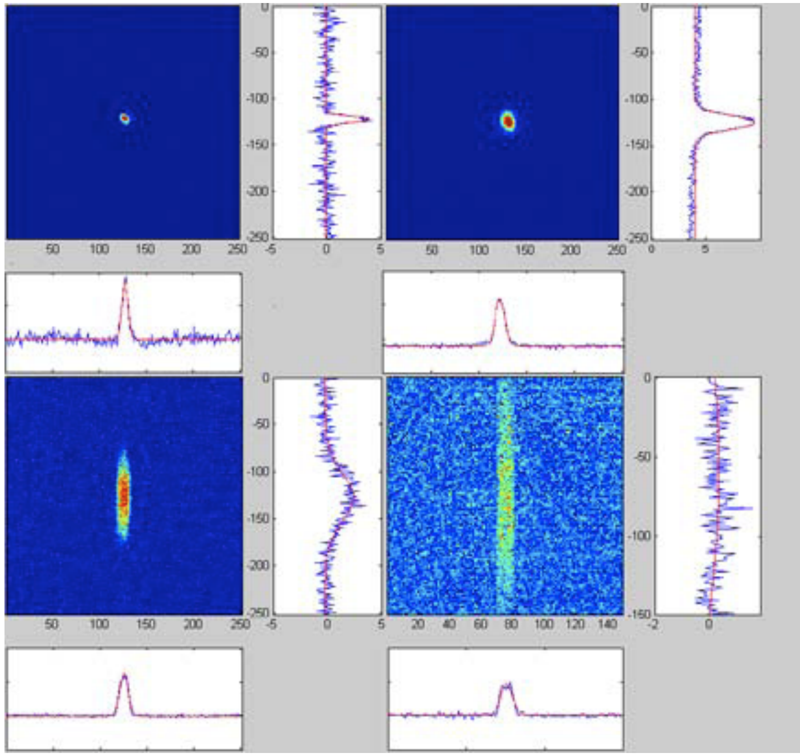
1 m

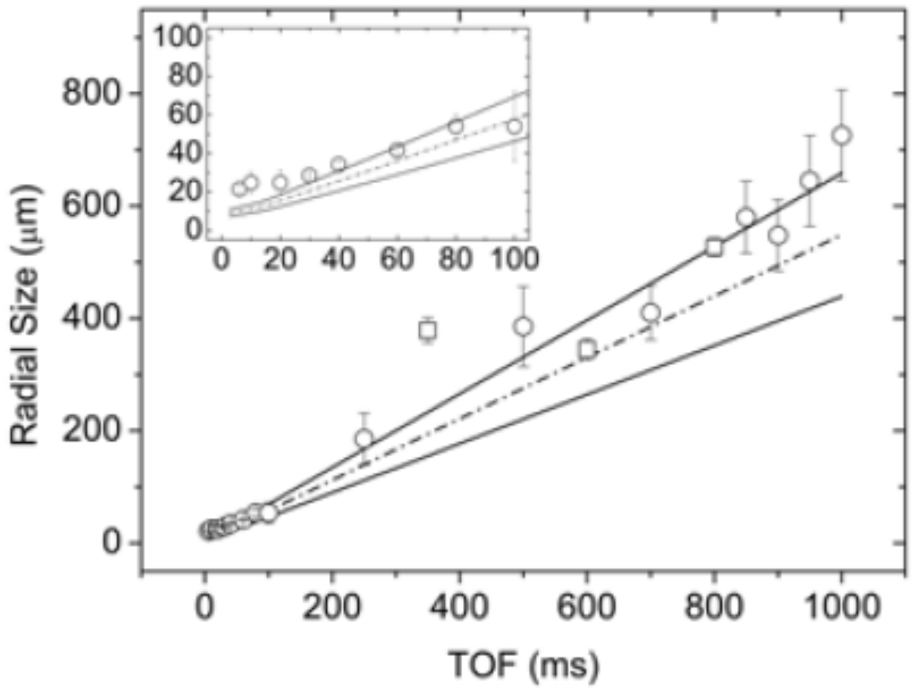


10 m

Recent results: Evolution of the wave function

Time-of-flight: 50, 100, 500 and 1000 ms





Recent results: Evolution of the wave function

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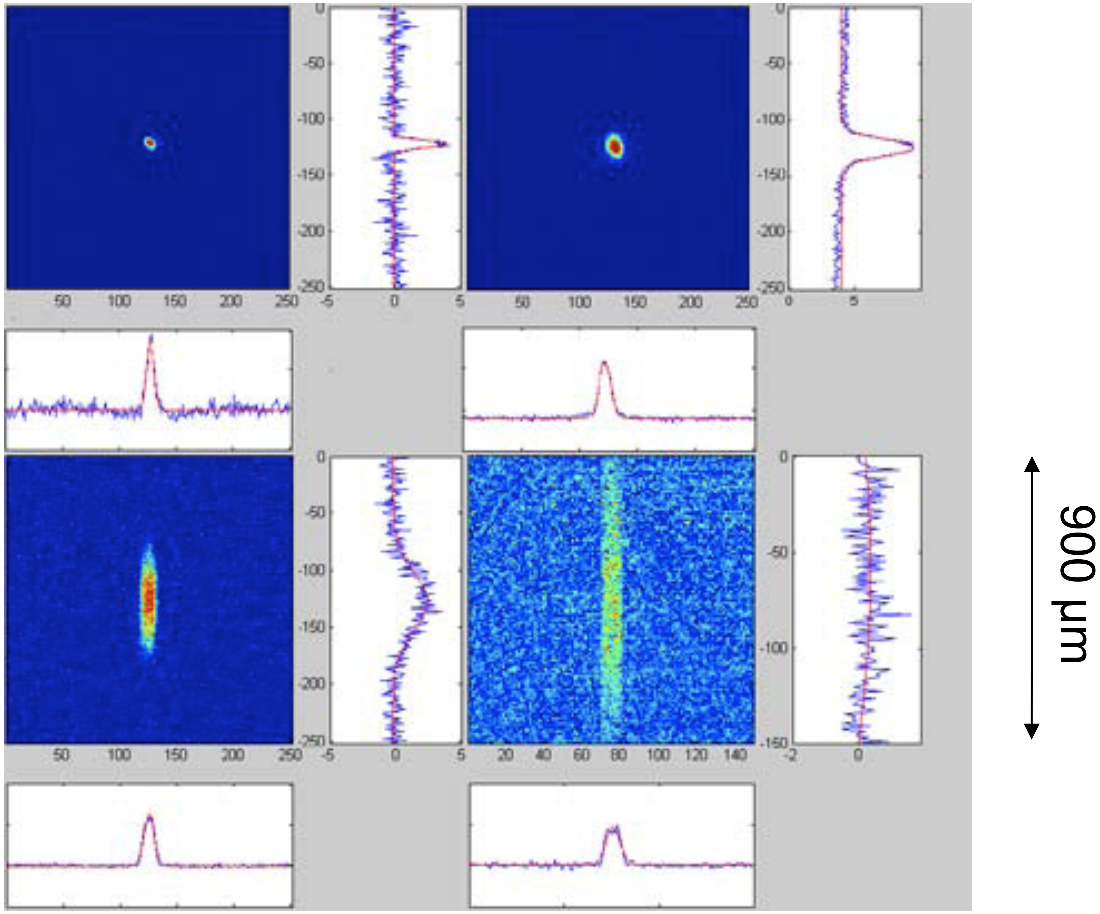


$$\omega_x / 2\pi \cong 4\,\text{Hz},$$
$$\omega_y / 2\pi \cong 13\,\text{Hz},$$
$$\omega_Z / 2\pi \cong 22\,\text{Hz}$$

Evaporation over 1s

8000 - 10 000 atoms

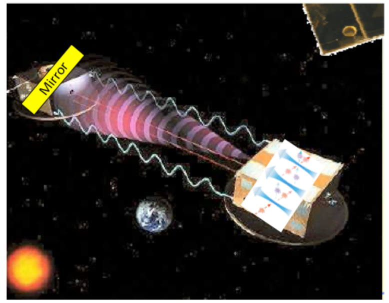
T < 10nK

delocalised after 1s

over 900 µm

Back-of-enevelope estimates for atomic phase meter

$$\Delta\Phi \approx 2k_{eff}hL\,\sin(\omega_{GW}T)$$



- S/N limited resolution: 1 to 10^{-2} mrad/√Hz

  → Newtonian Noise

- Scale factor for displacements: 1.6 10^{-6}
- Photon recoil, Multiplication factor: 10-100

  → to be combined with high S/N

- Displacement sensitivity: 10^{-9} -10^{-13} m
- Length, Multiplication Factor: 100-1000 m
- T≅ 1-10 s

Strain sensitivity 10^{-13}-10^{-16}

detection and observation of gravitational waves on ground

- Suspension „free“ gravitational wave detector
- Sensitivity identical to light interferometer: „Phase meter“
- Newtonian Noise is fundamental barrier
- Combining sensors at different Fourier frequencies (light and matter interferometer)
- You need a pair of detectors for signal correlation

Many „Firsts“ to be demonstrated

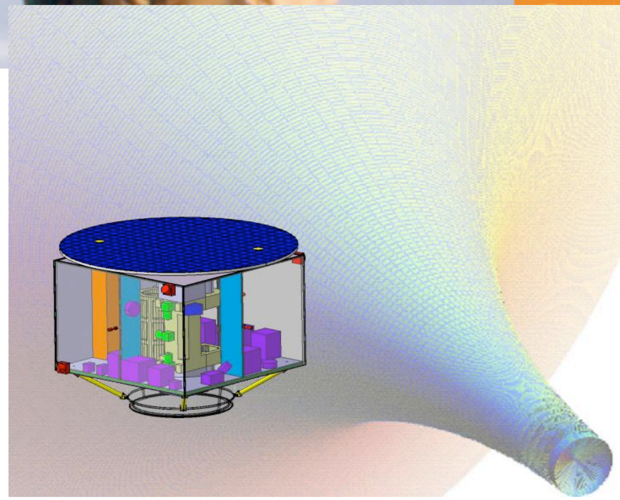
- High-frequency source for ultracold (BEC) atoms (10Hz rate)
- Combining high-recoil beam splitters with high phase resolution
- Sub-mrad resolution per shot
- Novel microwave sources & ultra stable lasers
- Control of systematic errors
- ...

- Control of drag-free sensor at lowest Fourier frequencies

- Replacement of the drag-free sensor for measurements at lowest Fourier frequencies.

Towards the limits

...with cold atoms



Accelerational Sensitivity with 10^{8} ats:

Microgravity 10^{-12} g/√Hz @ Expansion Time 3 s

Rotational Sensitivity with 10^{8} ats:

Microgravity: $8{\cdot}10^{-12}$ rad/√Hz @ Expansion Time 3 s

Extended Time of Evolution

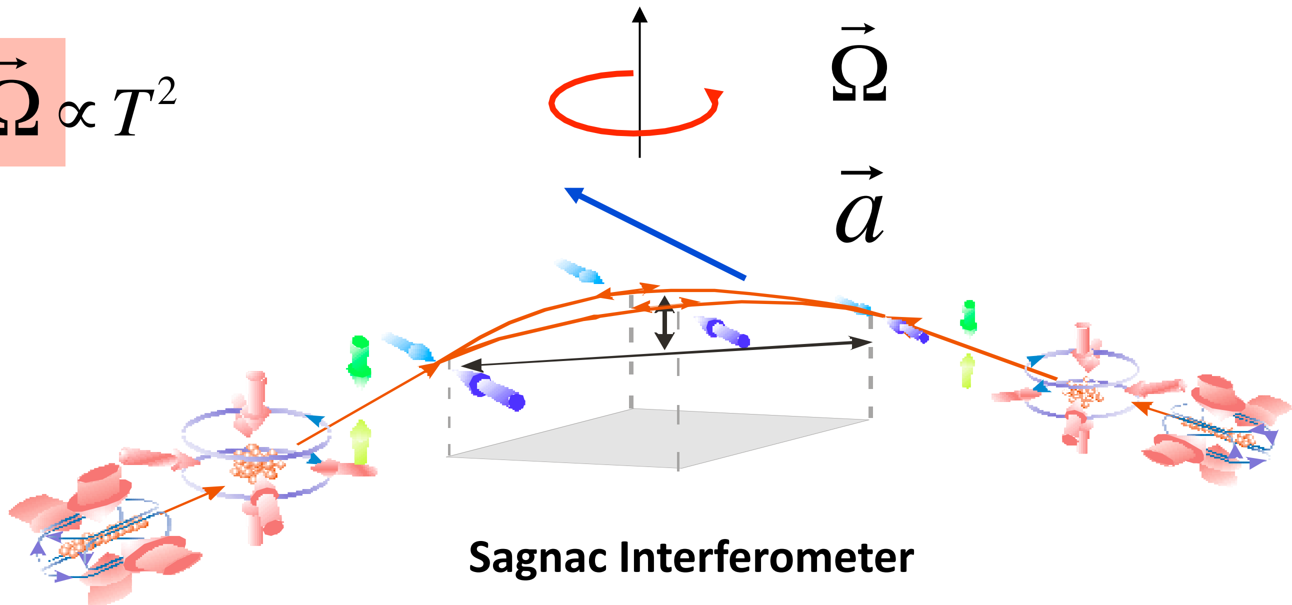
Inertial Quantum Sensors

Rotational Phase shift

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

Accellerational Phase shift

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



Sagnac Interferometer

Extended Time of Evolution

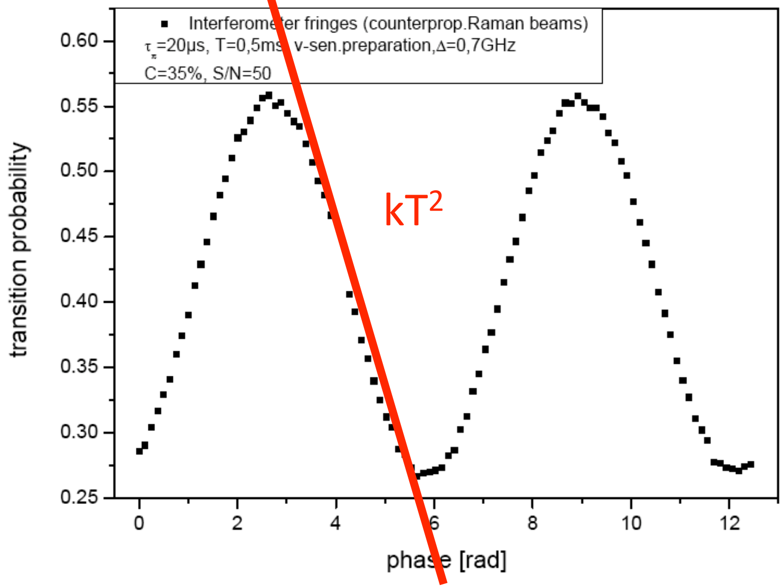
Increase in sensitivity

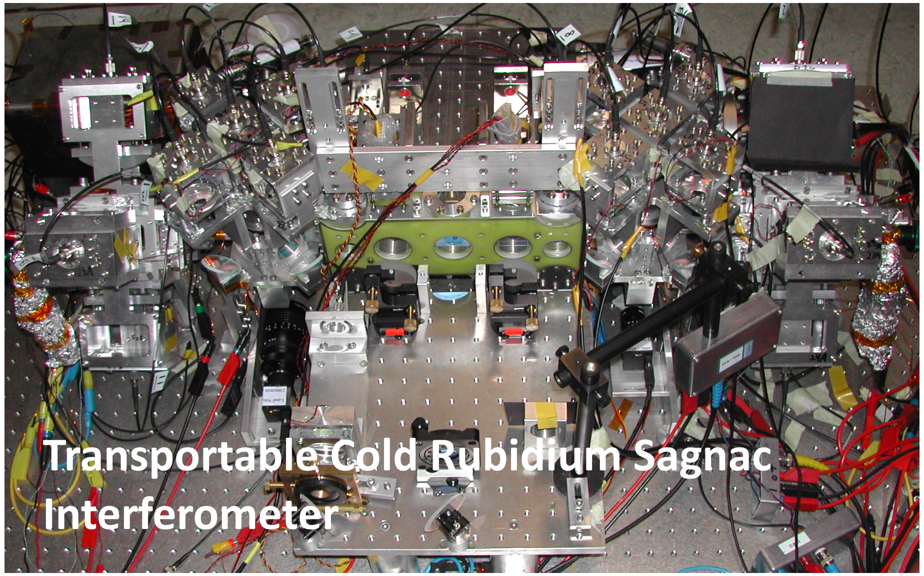
Rotational Phase shift

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

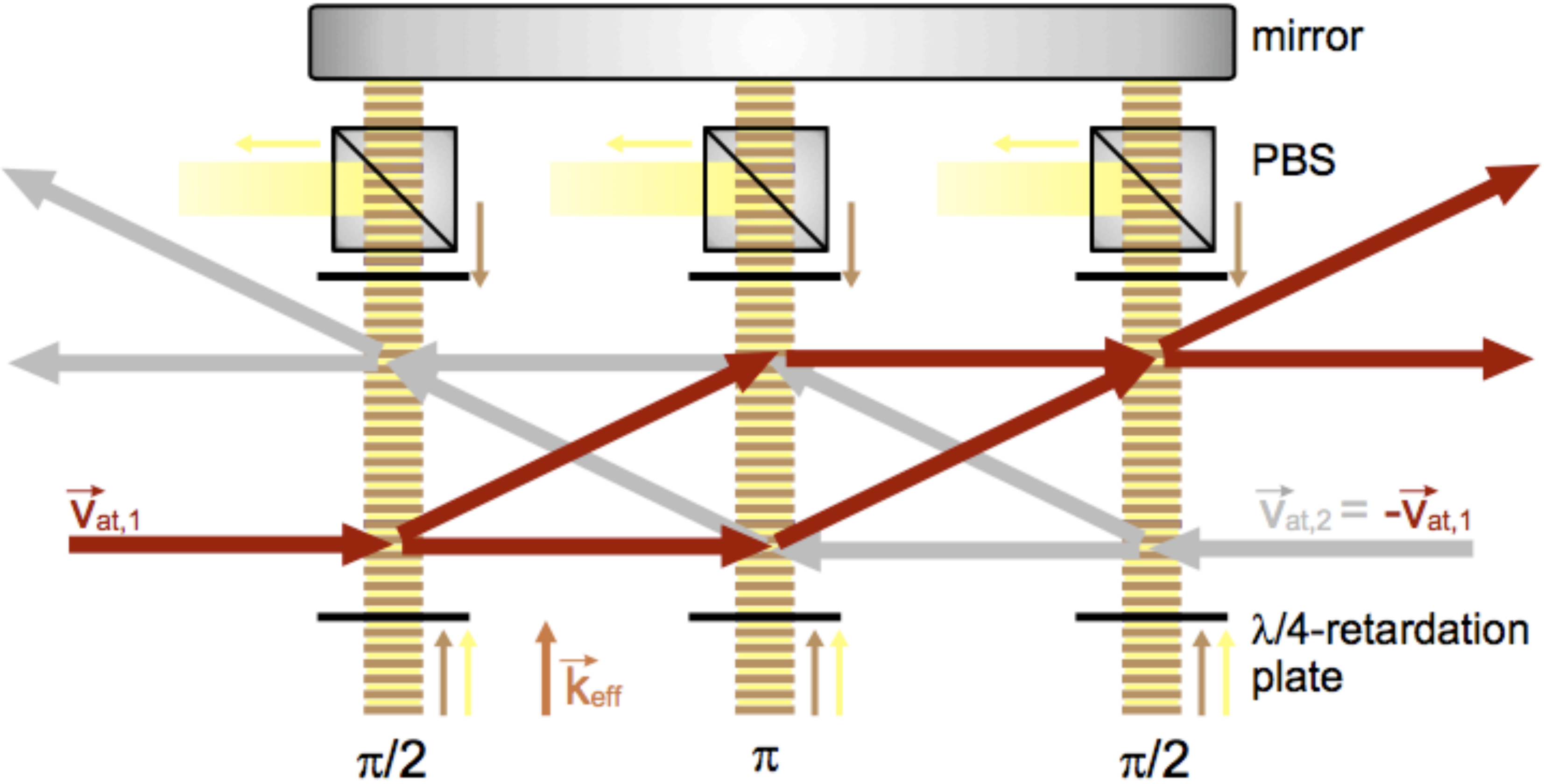
Accellerational Phase shift

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



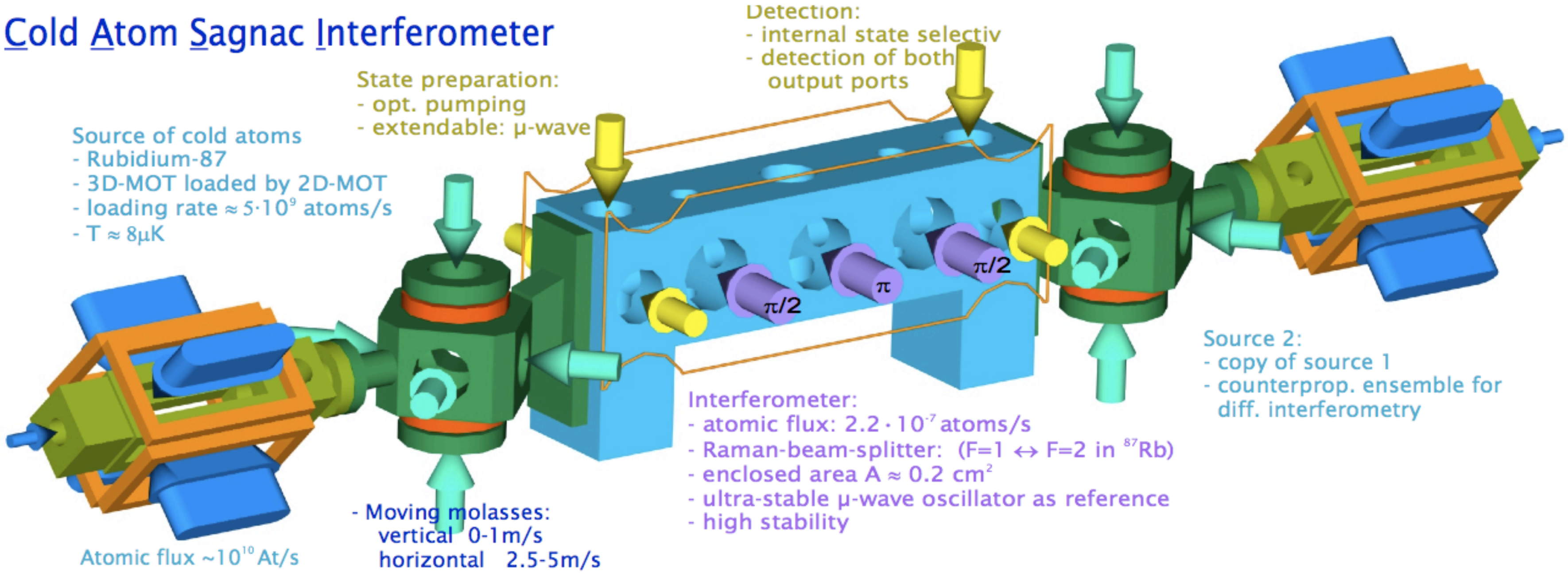


CASI


mirror
PBS
$\vec{v}_{at,1}$
$\vec{v}_{at,2} = -\vec{v}_{at,1}$
λ/4-retardation plate
$\vec{k}_{eff}$
π/2
π
π/2

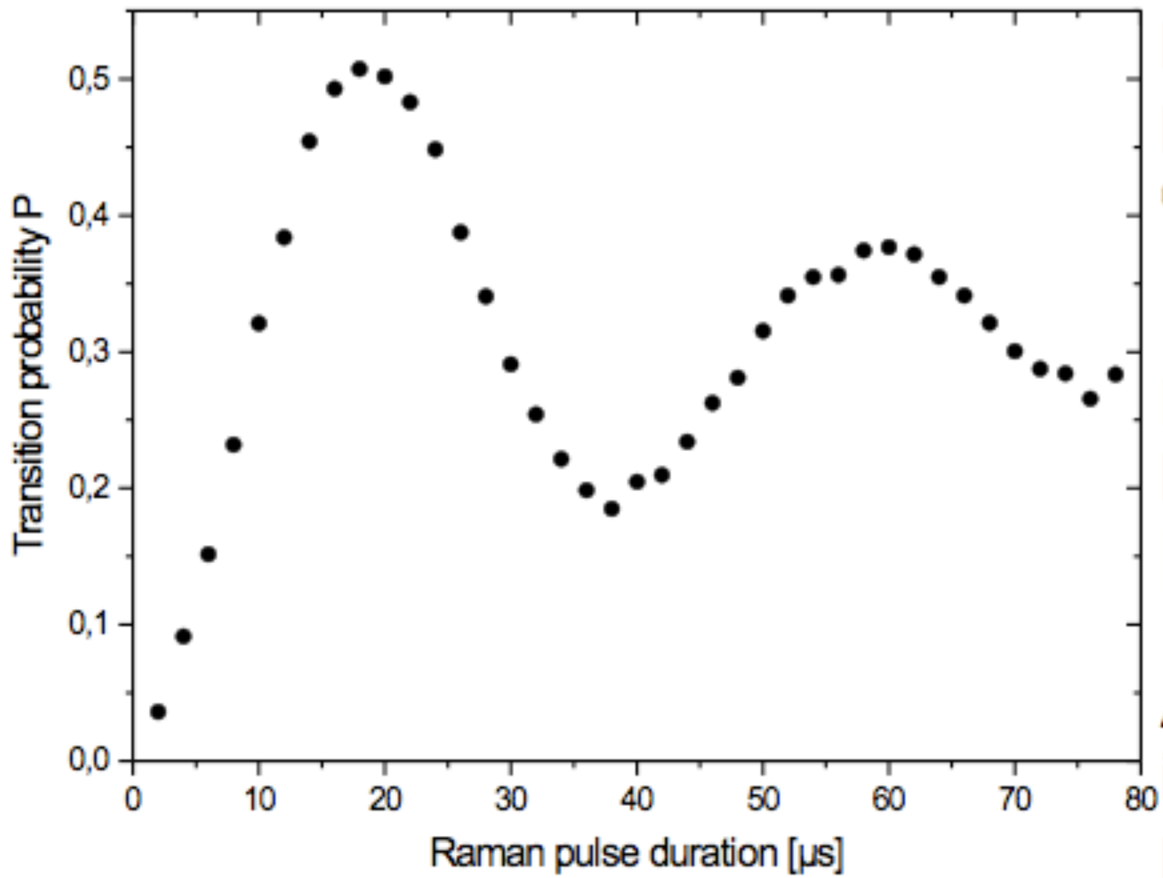
CASI

CASI: Cold Atom Sagnac Interferometer



Coherent beam splitting

Rabi oscillation measured after velocity selective preparation pulse

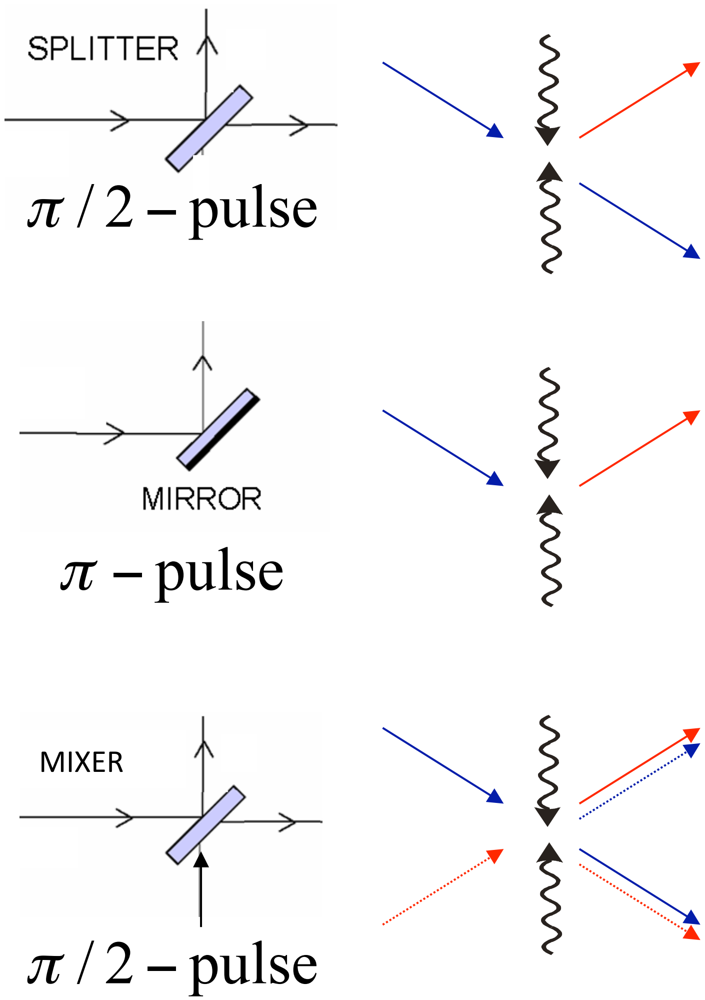


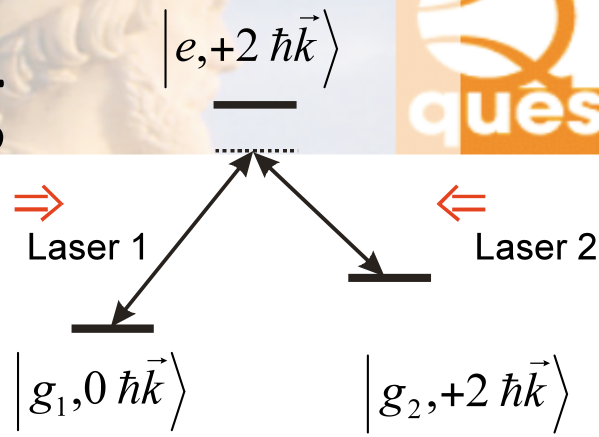
Measured transition probability P as function of the pulse duration.
⟶ P_π ~ 50%

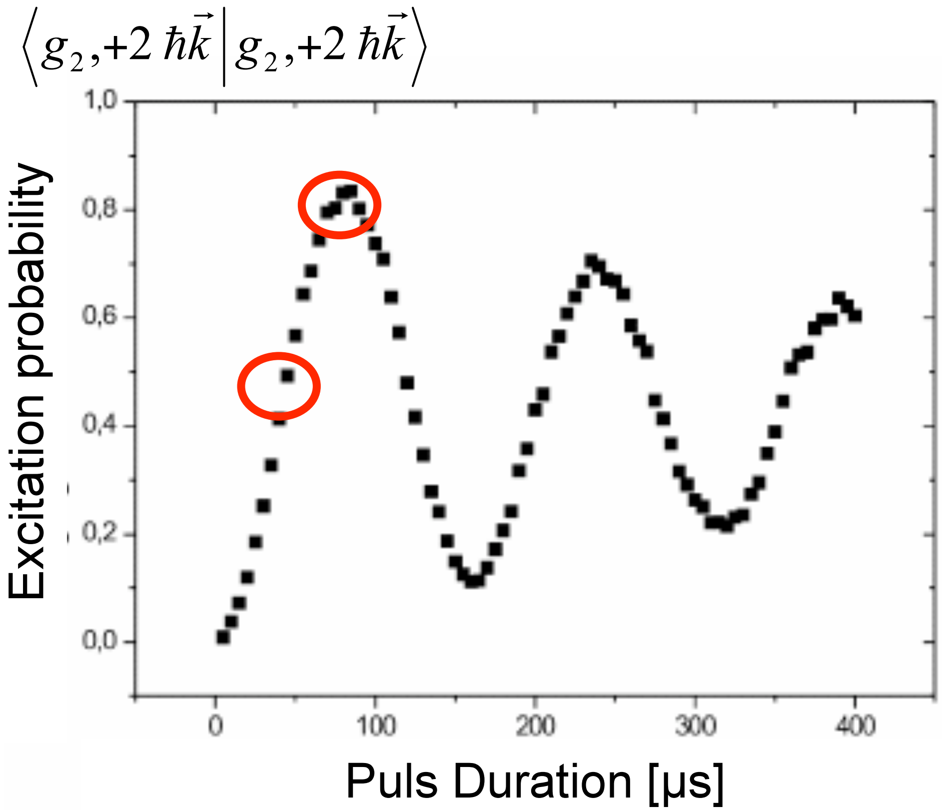
Reduction of $P\pi$ due to background of atoms in $|F=1,2,m_F \neq 0>$

Atoms in the two interferometer states after preparation: ~ 55%

Coherent beam splitting

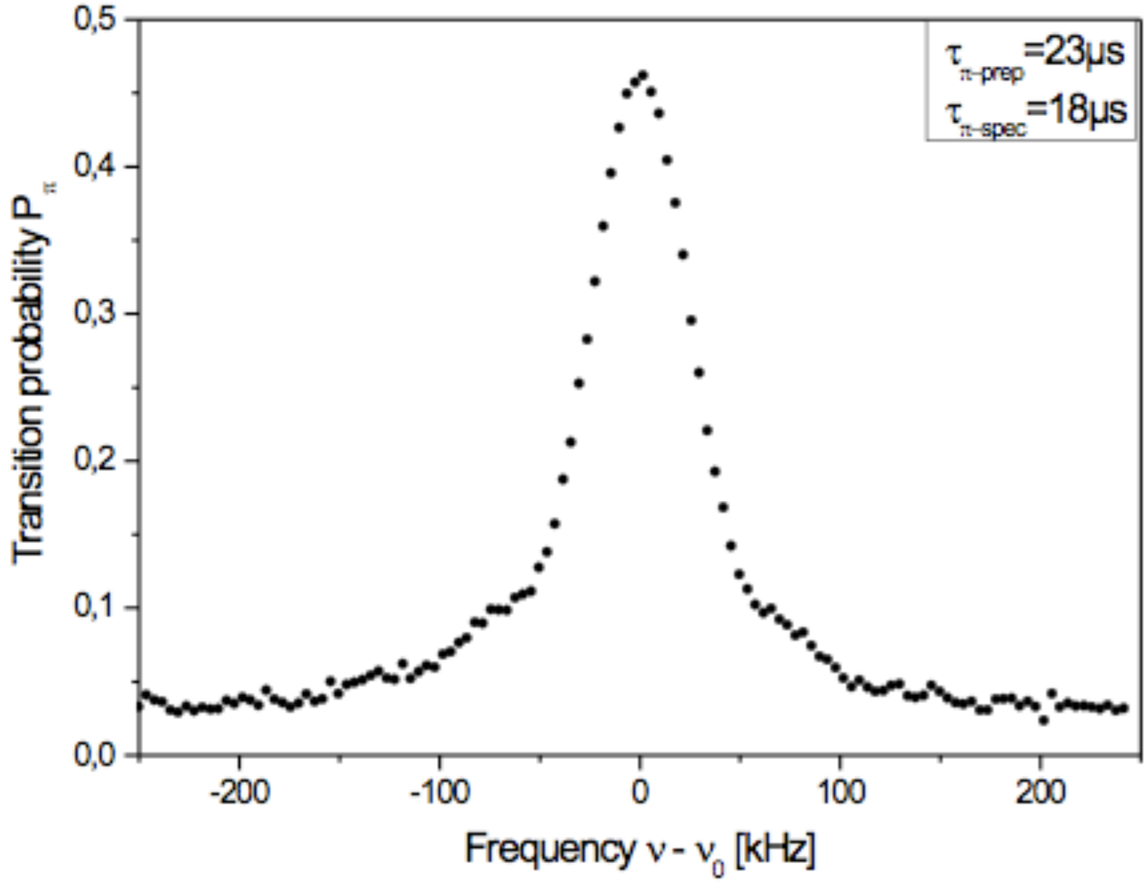






Velocity selection

Raman spectroscopy after velocity selection



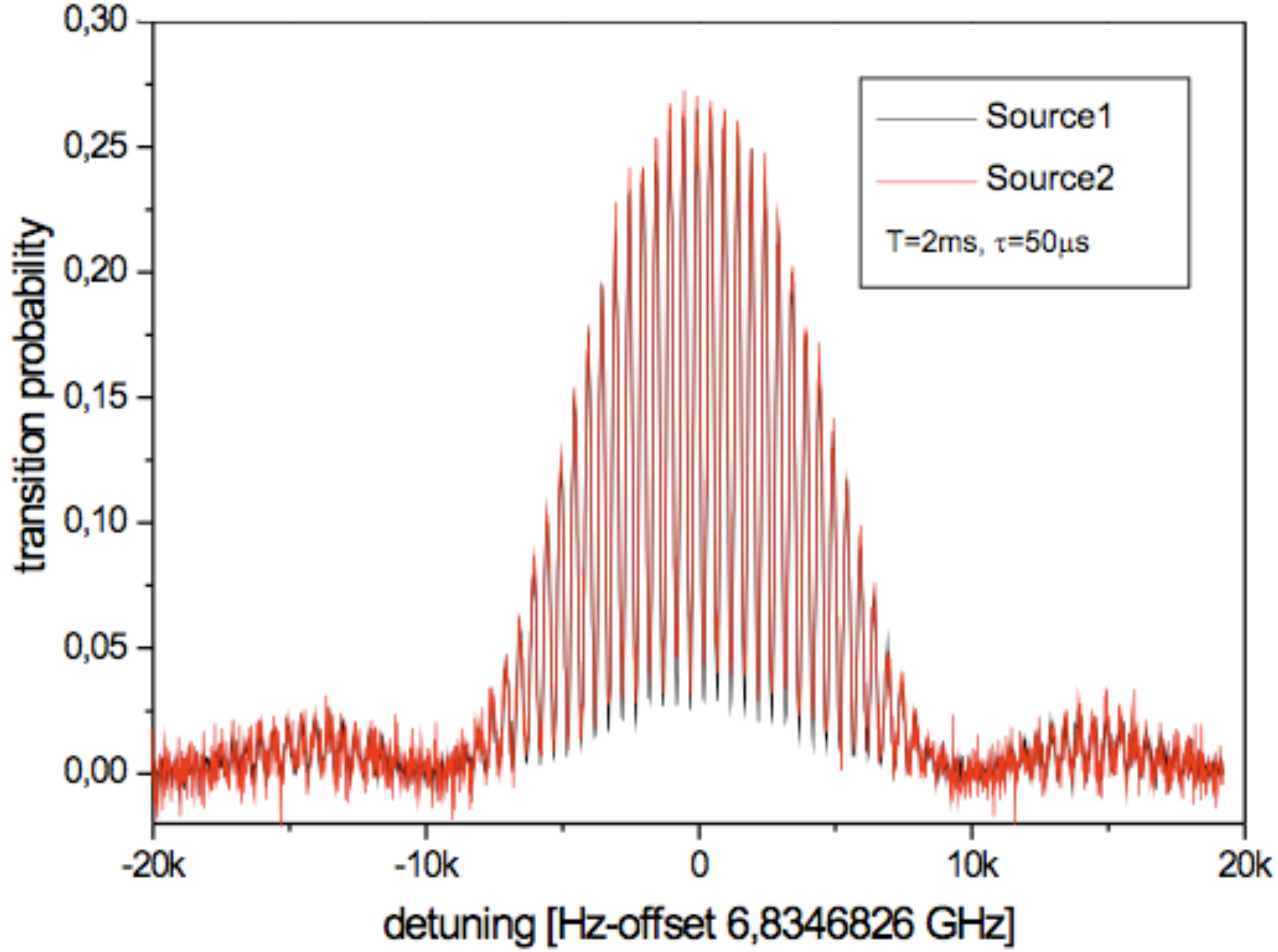
Measured transition probability P_π as a function of the transition frequency.

→ $\sigma_{e^{-1/2}}[f] \sim 26kHz$

→ $\sigma_{e^{-1/2}}[v] \sim 0{,}01m/s$

→ $T \sim 1\mu K$

Rb Clock



0,30
0,25
0,20
0,15
0,10
0,05
0,00
transition probability
Source1
Source2
T=2ms, τ=50μs
-20k
-10k
0
10k
20k
detuning [Hz-offset 6,8346826 GHz]

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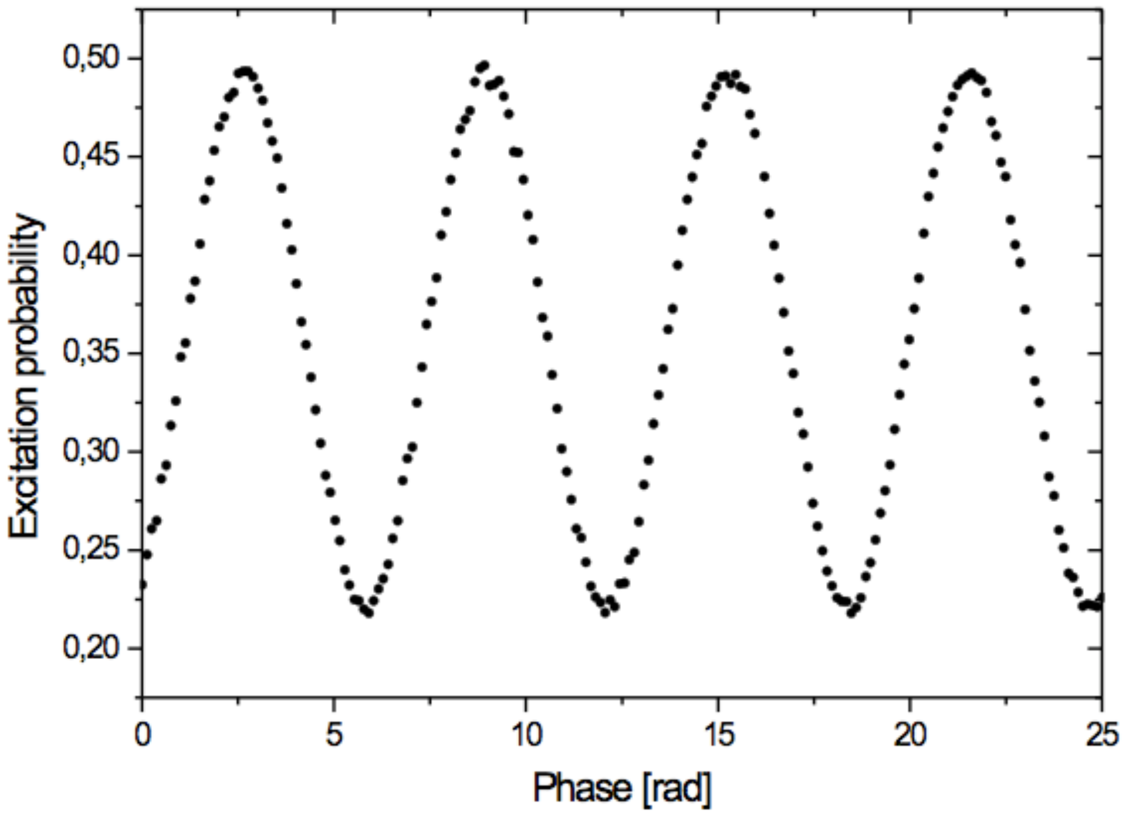
Rotation sensor



10^{-8} rad/s√Hz

- Interferometer sequence pulsed in time (one laser beam)
- π-pulse duration 10μs
- Time T between two pulses 0,5ms

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IQ

Rotation sensing

A

- I
  C
  Ea

10-

- Geo

10^{-5}

- Star r

10^{-6}

10^{-7}

- Satellit

10^{-8} -

- Relativist

10^{-9} E

-

10^{-10} - Rel

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 ...onds per century. ... new sophisti... show

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

... 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 2002.

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, eternal blackness, ... life — ... theorie... — 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 life-cycles 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!"

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

Dr. Kopeski

Rotation sensing

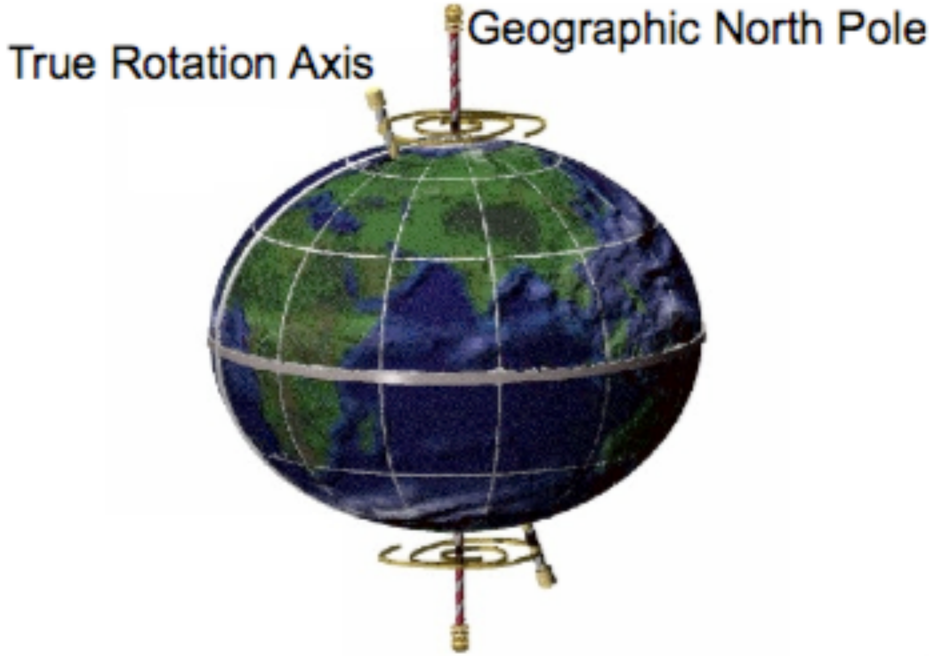
The Earth‘s rotation:
$\Omega_E \approx 7{,}2 \cdot 10^{-5}$ rad/s

Resolution:

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

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



Perspectives

Quantum sensors

- New atom interferometric techniques are emerging
- Fundamental limits ?

GWD:

- Bringing free fall to earth
- Atom-light interferometer is the most realistic scenario

Joint Actions needed
in order to proceed further
for

GAQS
Gravitational Wave Atomic Quantum Sensor


ENOUGH SPACE FOR EXCITING
EXPERIMENTS