Experimental Gravitation and Geophysics with Matter Wave Sensors

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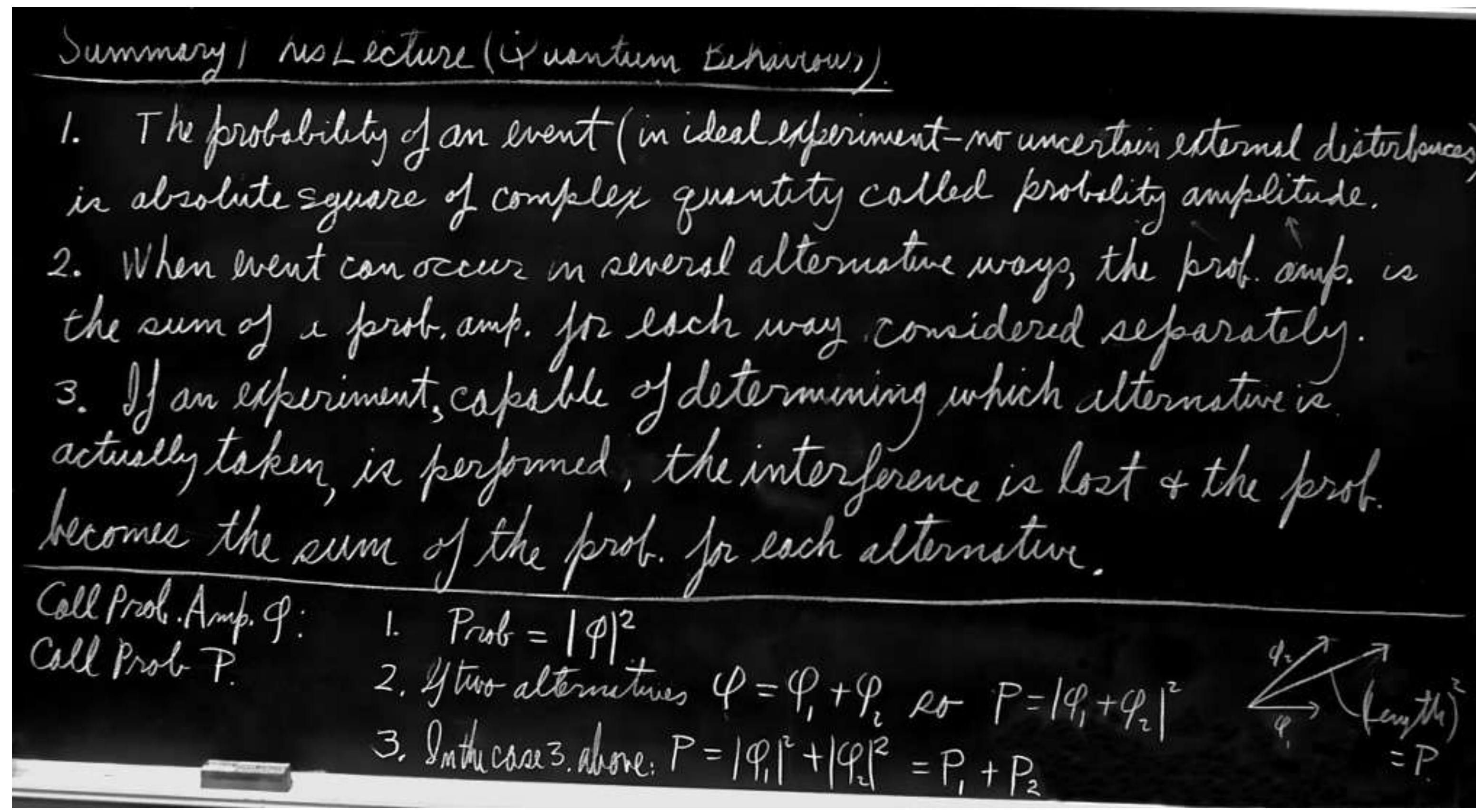
INSTITUT d'OPTIQUE GRADUATE SCHOOL

université de BORDEAUX

Introduction : aim of these lectures

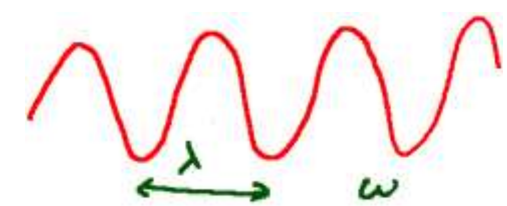
Wave - particle duality

"The only mystery" for R. Feynman (in his lectures on quantum mechanics), who later corrected his statement pointing Entanglement as the only mystery

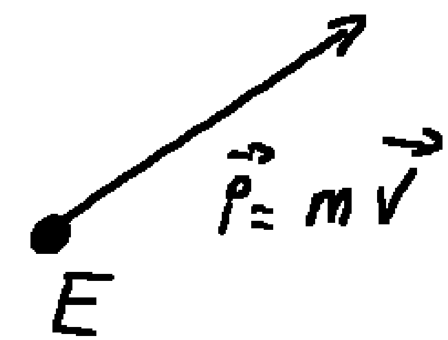


Matter waves

- **Matter waves is a direct consequence of quantum mechanics and in particular the duality between**
  - ⇨ **a wave described by *frequency* and *wavelength***



  - ⇨ **a particle described by *energy* and *momentum (mass.velocity)***



- **Formalized by Louis de Broglie who extended to any particle the concept of coexistence of waves and particles discovered by Albert Einstein in 1905 in the case of light and photons.**
  - ⇨ **introduced the *de Broglie wavelength*, matter analog of the photonic wavelength.**

$$\lambda_{opt} \Rightarrow \lambda_{dB} = \frac{h}{m\, v_{at}}$$

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$$\lambda_{opt} \Rightarrow \lambda_{dB} = \frac{h}{m\, v_{at}}$$

- ⇨ **The wavelength decreases with mass and momentum**
- ⇨ **Wave properties (diffraction, interferences) is more prominent with large wavelength**

	Mass (kg)	Speed (m/s)	Wavelength (m)
Human through door (1 m)	70	1	10^{-35}
Blood cells in capillary (100 µm)	10^{-16}	0,1	10^{-15}
Atoms through slits(100 nm)	10^{-27} - 10^{-25}	500	10^{-9} - 10^{-11}

- Atom Interferometry consists in physical phenomenas where the wave nature of atoms (and in particular the external degrees of freedom) is concerned.

  ⇨ **Analogous to light waves phenomenas, but for de broglie waves**

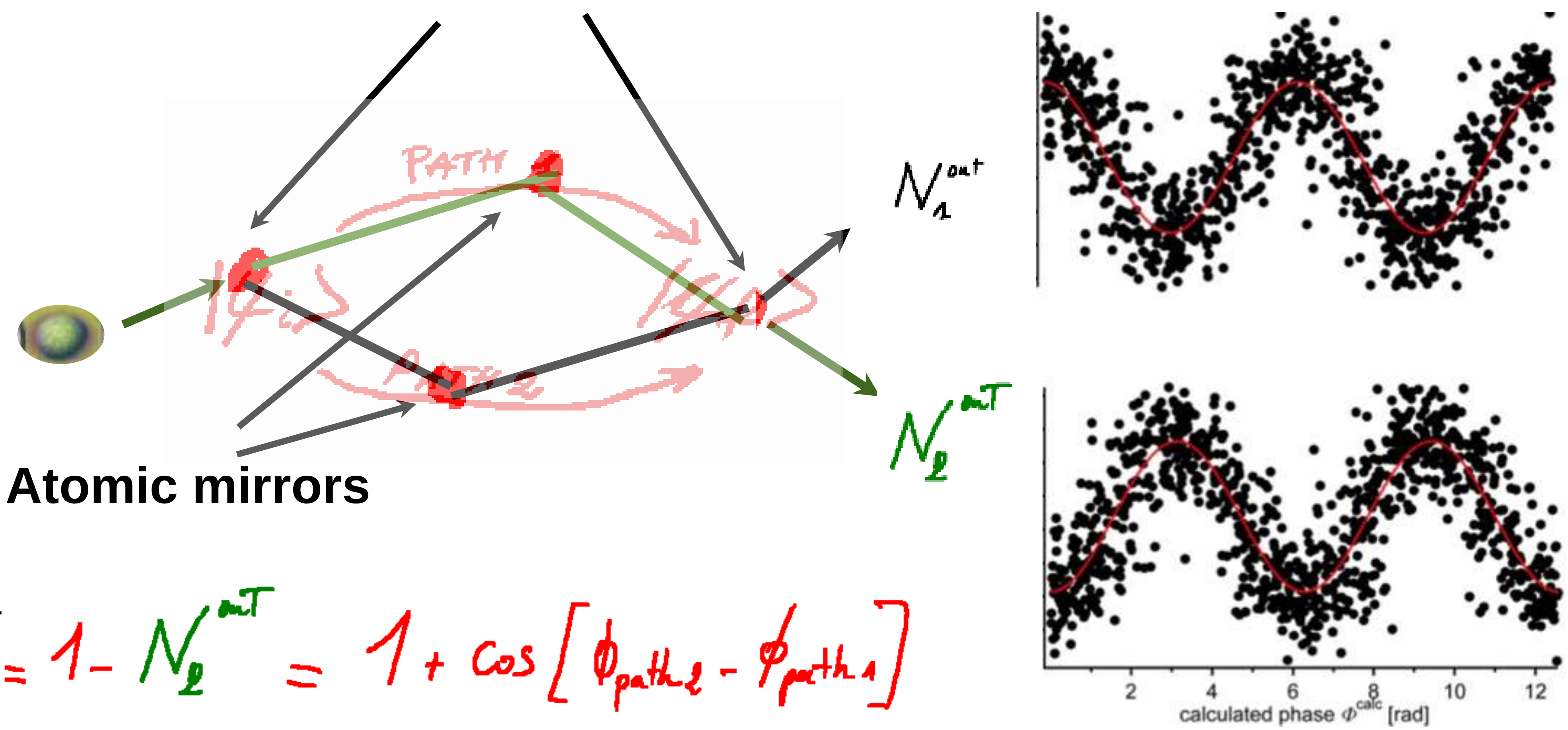
$$\lambda_{opt} \Rightarrow \lambda_{dB} = \frac{h}{m\, v_{at}}$$

$$T \sim 1\,\mu K \;\rightarrow\; V_{at} \sim 1\,mm/s \;\rightarrow\; \lambda_{dB} \sim 1\,\mu m$$

MATTER-WAVE INTERFEROMETERS

- De Broglie wave associated to atoms.
- Interference process with atoms similar with light waves.
- Use coherent splitting to create multiple paths that will interfere
- Phase dependent on perturbations on different paths

Atomic beam splitter (using light)



$$N_1^{out} = 1 - N_2^{out} = 1 + \cos\left[\phi_{path\,2} - \phi_{path\,1}\right]$$

Some key dates in Atom Interferometry

- ✓ 1979: First matter-wave gyroscope with neutron
  - → *S. A. Werner, J.–L. Staudenmann, R. Colella, Phys. Rev. Lett., 42, p 1103, (1979)*
- ✓ 1991: Demonstration of atomic interferometers
- ✓ 1994: Demonstration of first molecular interferometer
  - → *Ch.J. Bordé,et al. "Molecular interferometry experiments", Physics Letters A 188, 187 (1994)*
- ✓ 2001: Demonstration of interferometer with heavy molecules (C60)
  - → *M.Arnd,et al. "High contrast interference with C-60 and C-70", Compt. Rend. Acad. Sci. Serie IV 2(4), 581.*

Some key dates in Atom Interferometry

- 1991: Demonstration of atomic interferometers
  - Atom interferometer using double-slit diffraction:
    - *O. Carnal, J. Mlynek, "Young s double-slit experiment with atoms : A simple atom interferometer ", Phys. Rev. Lett., 66, 2689 (1991)*
  - Atom interferometer gyroscope with atomic beam and light wave diffraction
    - *F. Riehle, Th. Kister, A. Witte, J. Helmcke, Ch. Bordé, Phys. Rev. Lett., 67, p 177 (1991)*
  - Atom interferometer gyroscope with atomic beam and mechanical gratings diffraction
    - *D.W. Keith, C.R. Ekstrom, Q.A. Turchette, D.E. Pritchard, Phys. Rev. Lett., 67, p 2693 (1991)*
  - Cold atom interferometer : accelerometer with cold atoms and light beam splitter (Diffraction using raman transitions)
    - *M. Kasevich, S. Chu, Phys. Rev. Lett., 67, p 177 (1991)*

A brief history of atom interferometry

Mobile and Remote Inertial Sensing with Atom Interferometers
- arXiv:1311.7033
- Proceedings of the International School of Physics "Enrico Fermi" on Atom Interferometry

1924

de Broglie

$\lambda_{opt} \Rightarrow \lambda_{dB} = \frac{h}{m v_{at}}$

1930

Electron diffraction

1950

Electron interferometry

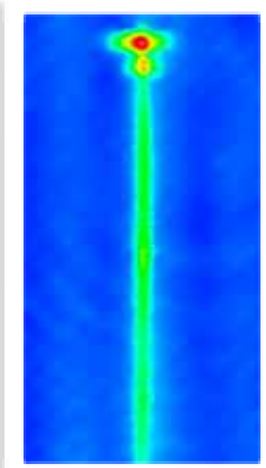
1960

Neutron interferometry

1990

2000

Inertial sensors (US, Germany, France)



Projets spatiaux

Embedded systems

Commercial products

2015

Compact inertial sensors

Transportable experiments

Large scale interferometers

High precision fundamental physics tests

BEC interferometers

Atom chips

…

(More than 30 groups in all world, at leat 5 large facilities, large consortiums, 2 compagnies …)

Matter-wave interferometry, although a rather old subject, is nowadays at the leading edge of many new developments in geophysics and fundamental physics thank to laser cooling

- ✓ Commercial development of transportable sensors
- ✓ Development of space interferometer and space missions
- ✓ Recent proposals of gravitational wave detectors using atom sensors.

The following lectures will aim to :

- ✓ Introduce the basics of atom inertial sensors.
- ✓ Introduce the recent developments in atom interferometry and inertial sensor.
- ✓ Give a general overview of the methods and the tools to be used with atom inertial sensors.
- ✓ Present some recent experimental achievements and recent project developments.

Organization of the lectures

Lecture 1 : Introduction to Atom Interferometry and inertial sensors

- ✓ History of experimental developments
- ✓ Theoretical tools for atom interferometry
- ✓ How to build an inertial sensor

Lecture 2 : Measuring acceleration and rotations - methods, precision, accuracy

- ✓ Atom gyroscopes, atom accelerometers, atom gravi/gradiometers
- ✓ How to reach high precision and accuracy
- ✓ Some examples

Lecture 3 : Application to geophysics and fundamental physics - from ground to space

- ✓ Equivalence principle tests with atom interferometry
- ✓ Gravity antenna and gravitational wave detections

Lecture 1 : Introduction to Atom Interferometry and inertial sensors

MATTER WAVE DIFFRACTION

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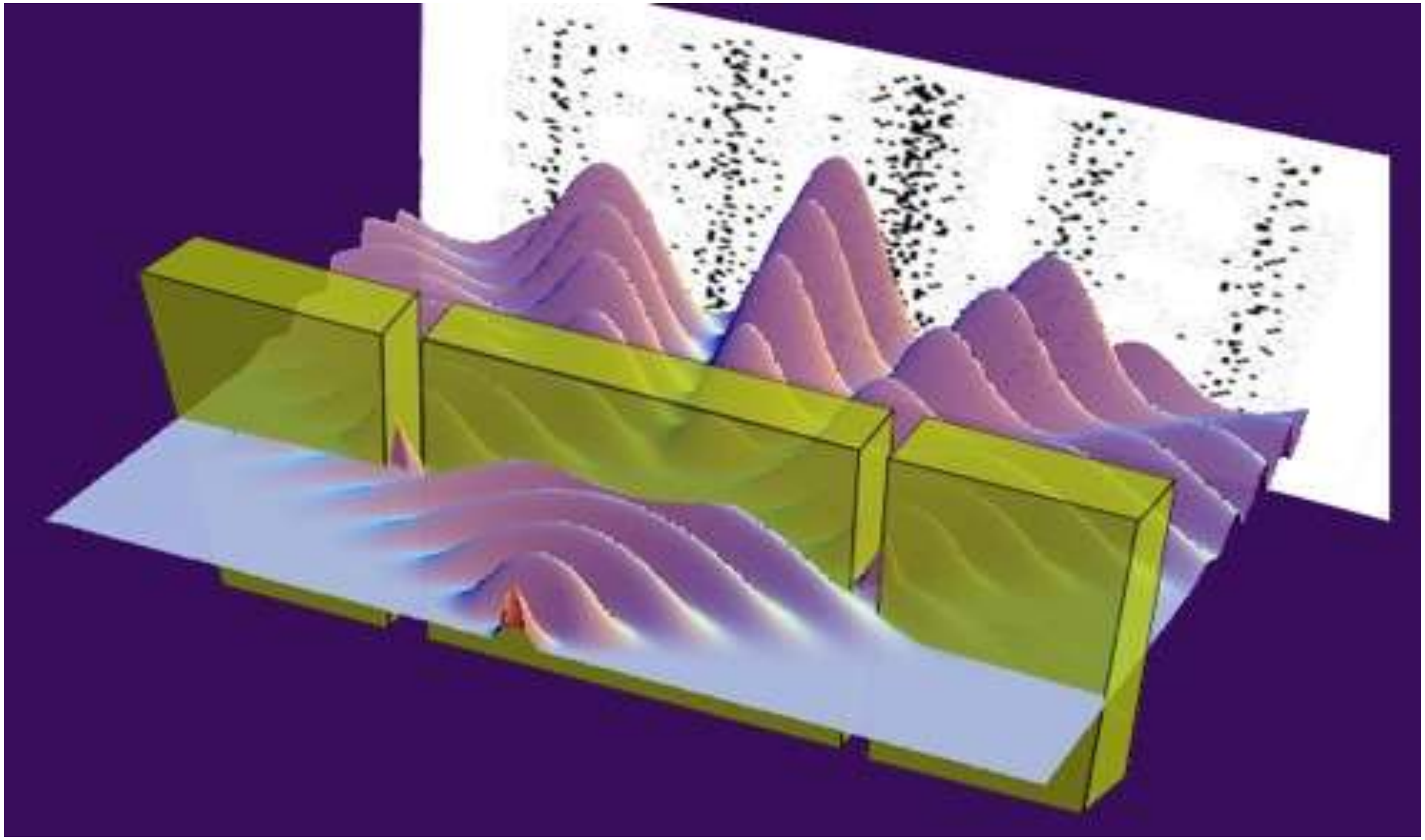
  - ⇨ **Analogous to light waves phenomenas, but for de broglie waves**



MATTER WAVE DIFFRACTION

A monikinetic beam of particle can be described by wave function $\psi(\vec{r},t)$

- The propagation is described by the Schrödinger equation

$$-\frac{\hbar^2}{2m}\Delta\psi(\vec{r},t) = E\psi(\vec{r},t) \Rightarrow \Delta\psi(\vec{r},t) + k^2\psi(\vec{r},t) = 0 \qquad k^2 = \frac{2mE}{\hbar^2}$$

- Analogy with electromagnetism : $\Delta E + k^2 E = 0,\ k = \frac{2\pi}{\lambda}$

- Analogy with optics :

$$\psi(x,y,z) = \psi_0 \exp\left[i\frac{m}{2\hbar T}(x^2+y^2)\right]$$

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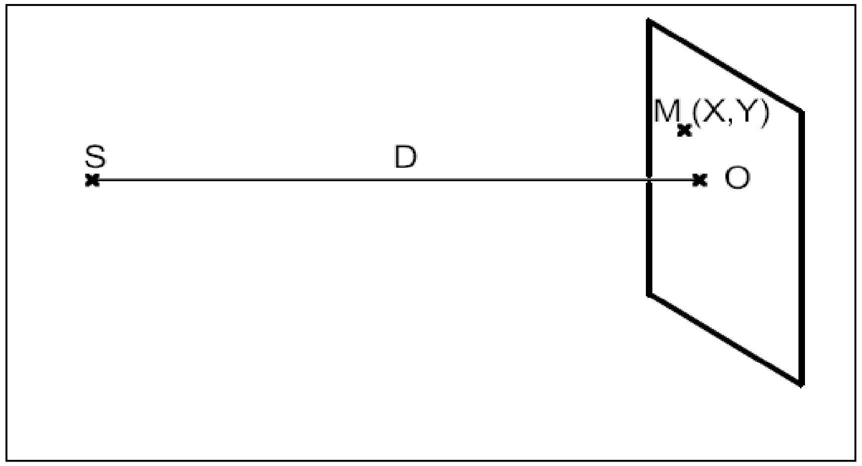
$$\psi(x,y,z) = \psi_0 \exp\left(\frac{ik(x^2+y^2)}{2D}\right)$$



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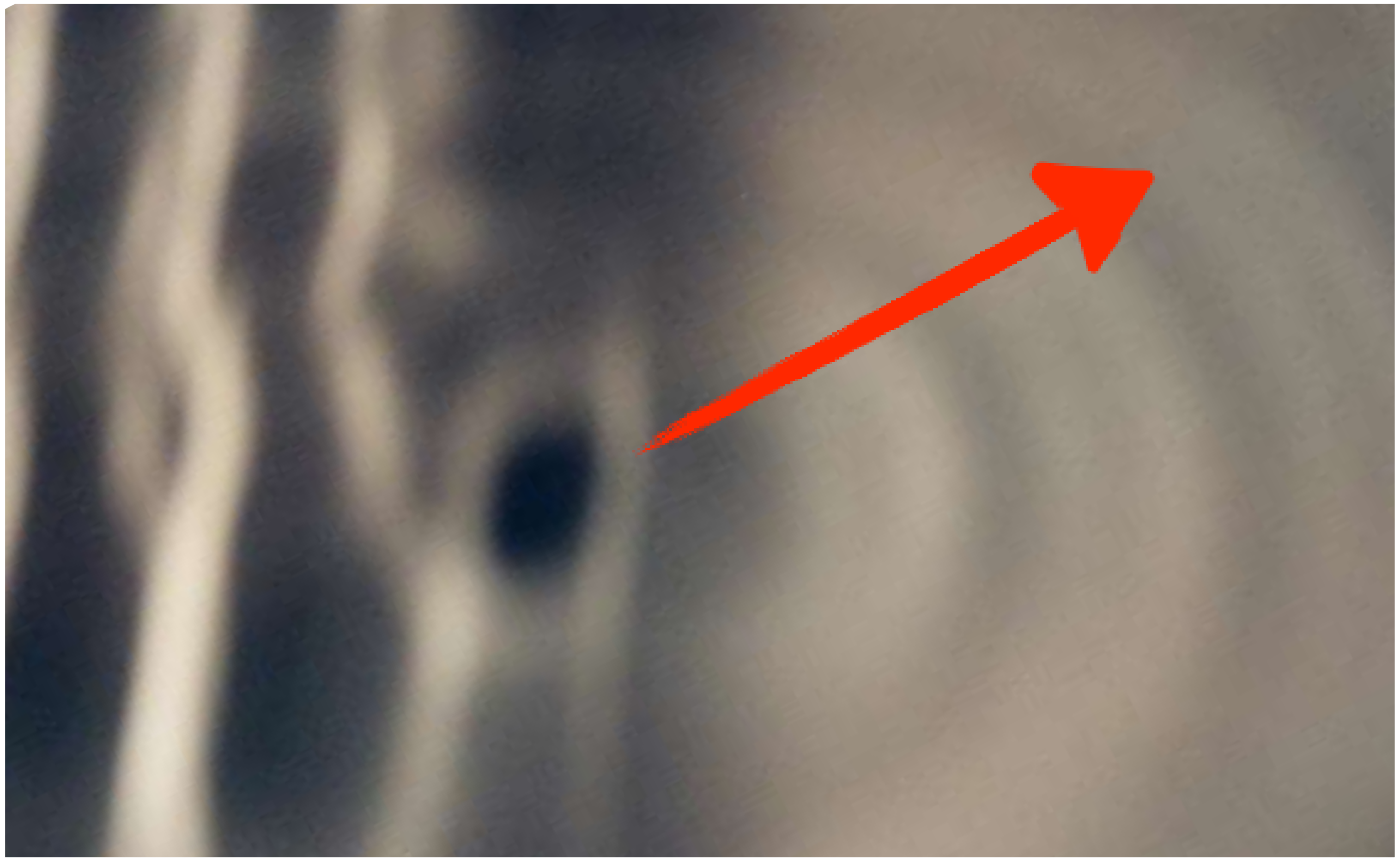

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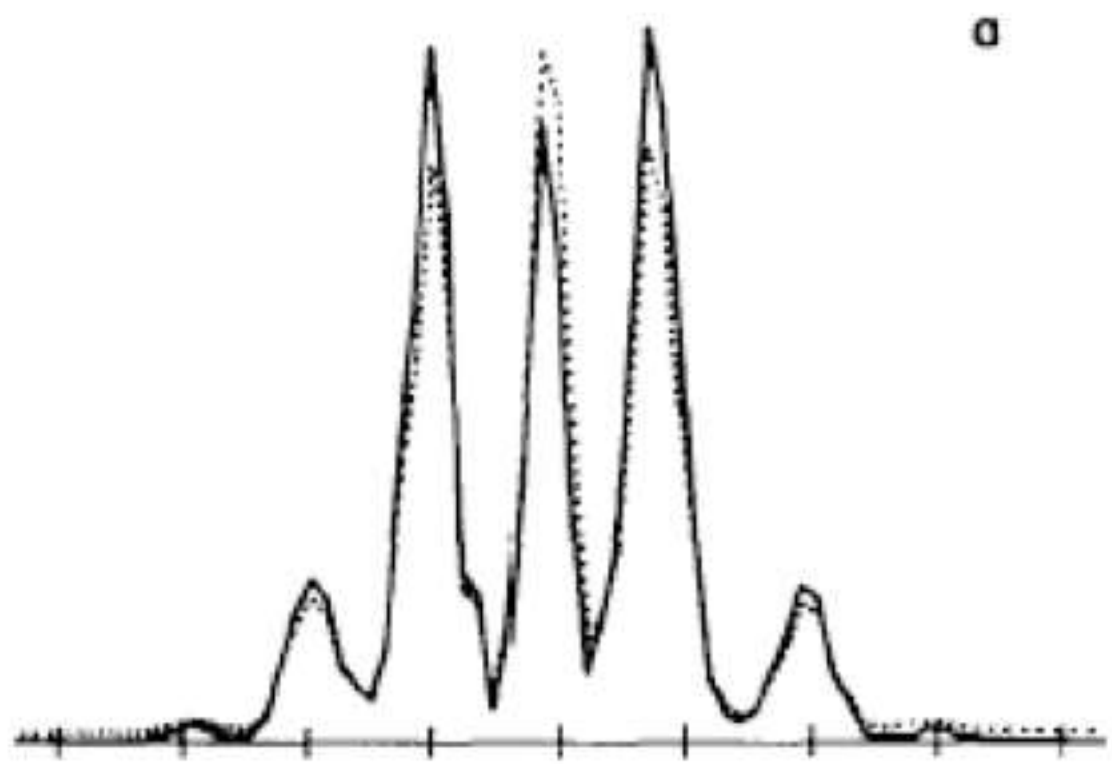
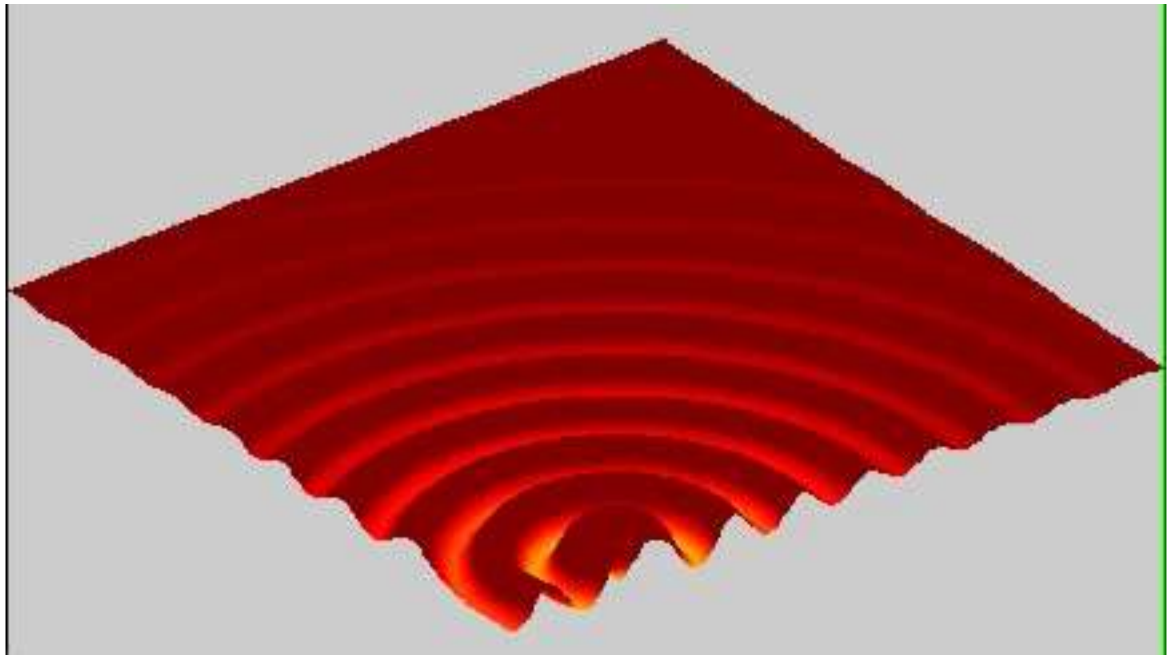
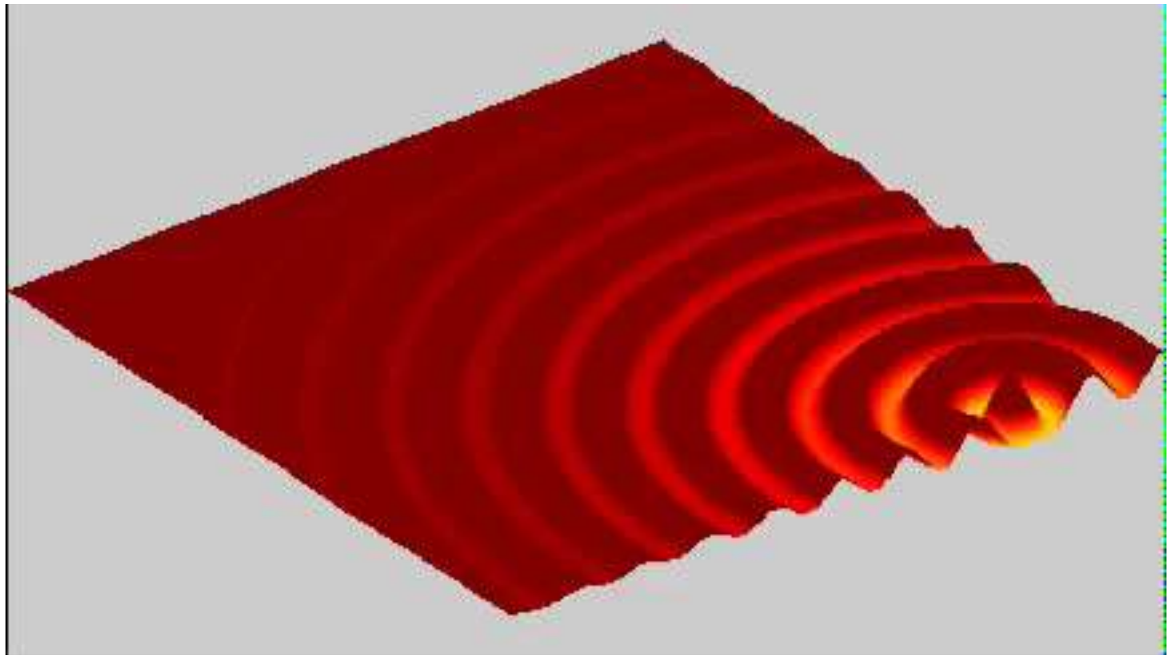


P. Gould et al. 1986

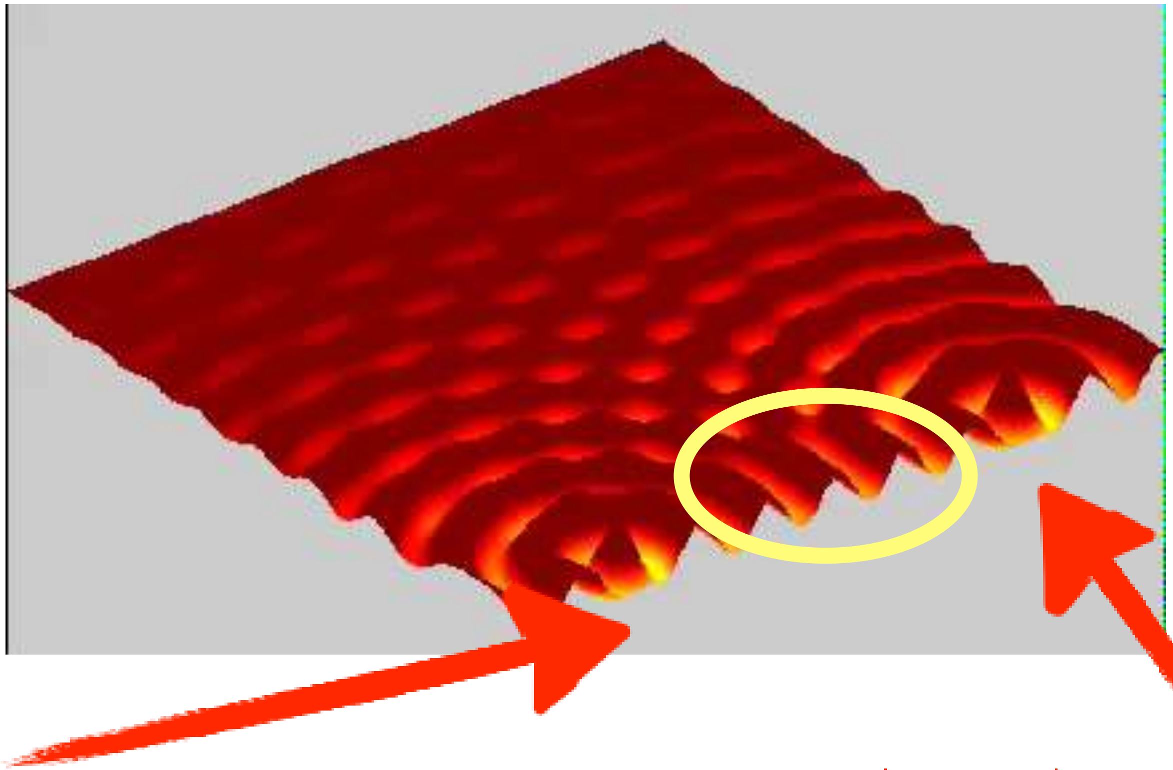




$$e^{-\frac{|\mathbf{r}+\mathbf{r}_0|}{l}} \cos(|\mathbf{r}+\mathbf{r}_0|+\omega t)$$

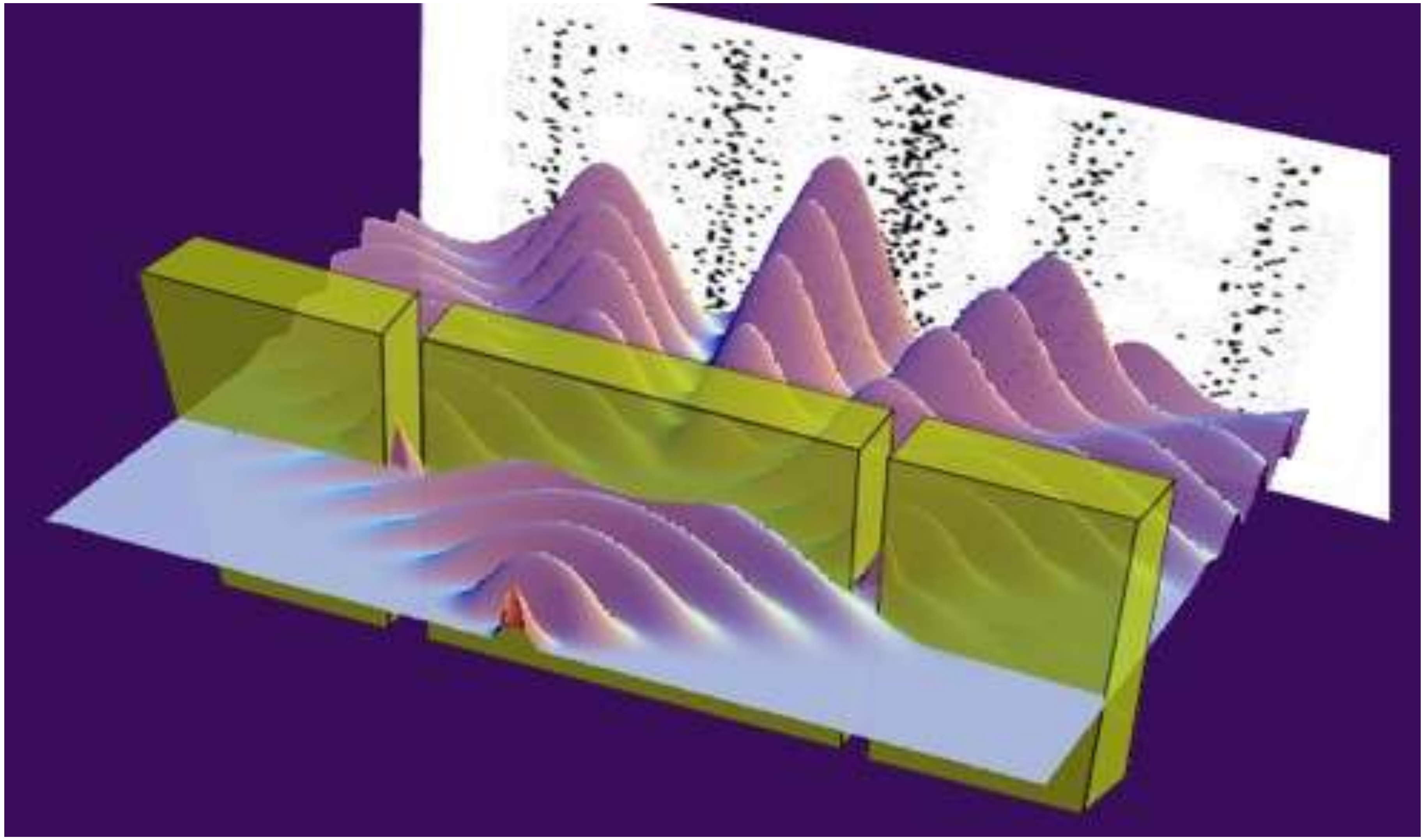
$$e^{-\frac{|\mathbf{r}-\mathbf{r}_0|}{l}} \cos(|\mathbf{r}-\mathbf{r}_0|+\omega t)$$

DIFFRACTION : KEY ELEMENT FOR ATOM INTERFEROMETRY



$$e^{-\frac{|\mathbf{r}+\mathbf{r}_0|}{l}}\cos(|\mathbf{r}+\mathbf{r}_0|+\omega t) \qquad e^{-\frac{|\mathbf{r}-\mathbf{r}_0|}{l}}\cos(|\mathbf{r}-\mathbf{r}_0|+\omega t)$$

YOUNG DOUBLE SLITS EXPERIMENT



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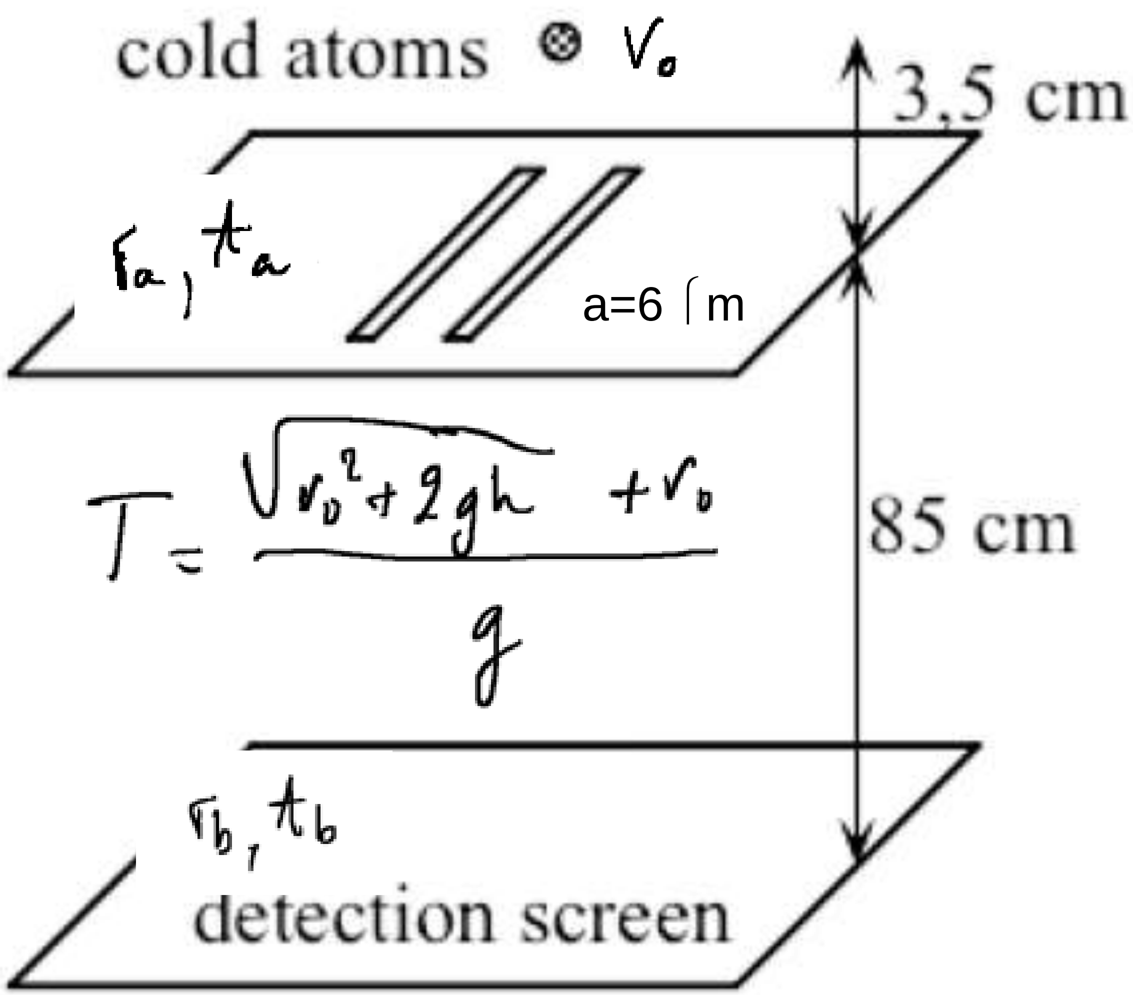
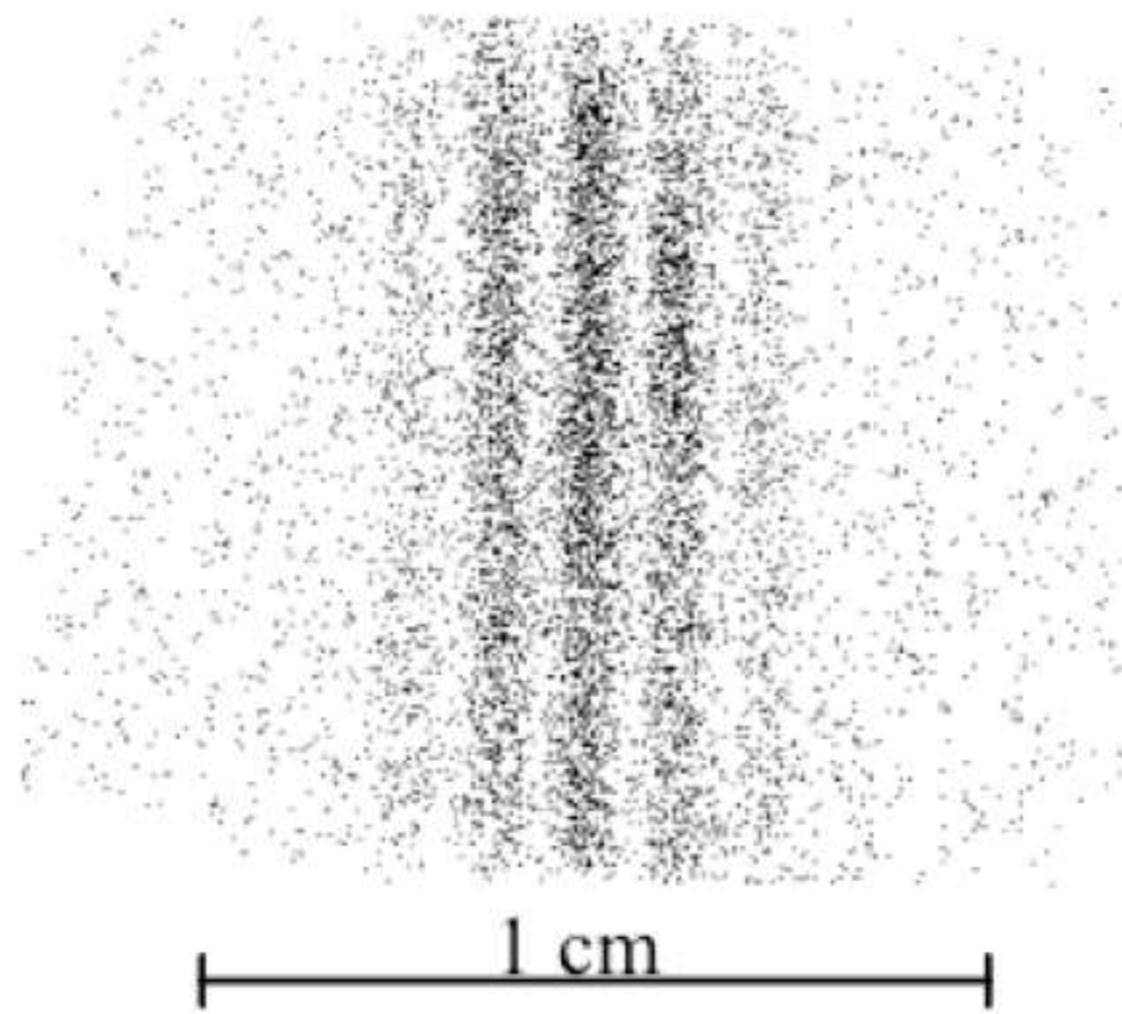
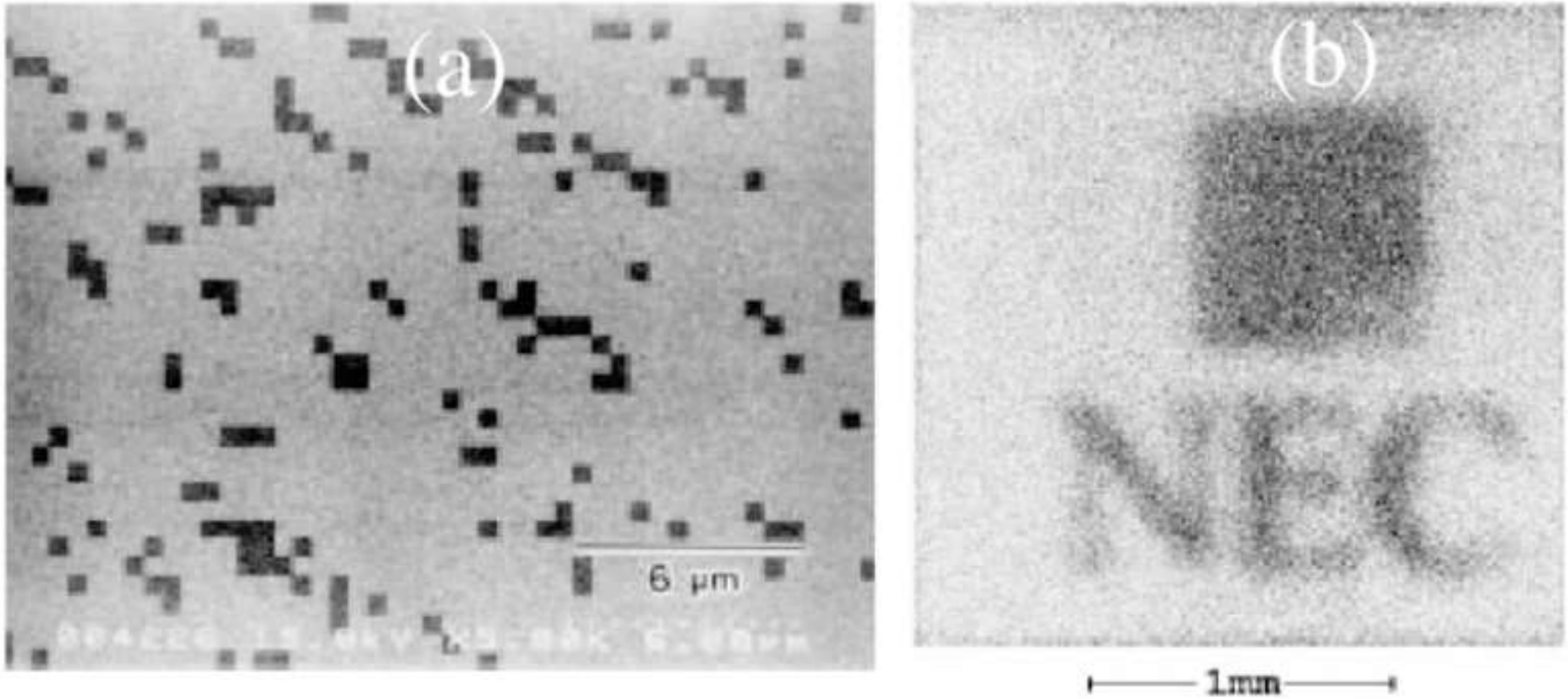




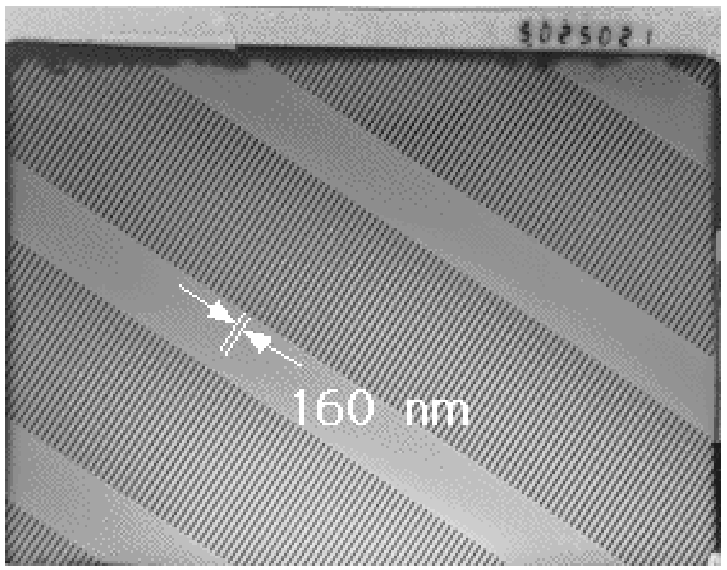
$$|\psi(r_b,t_b)|^2 \sim \cos^2\left(\frac{m x_b a}{2\hbar T}\right)$$

F. Shimizu et al., Phys. Rev A, 46 R17 (1992)

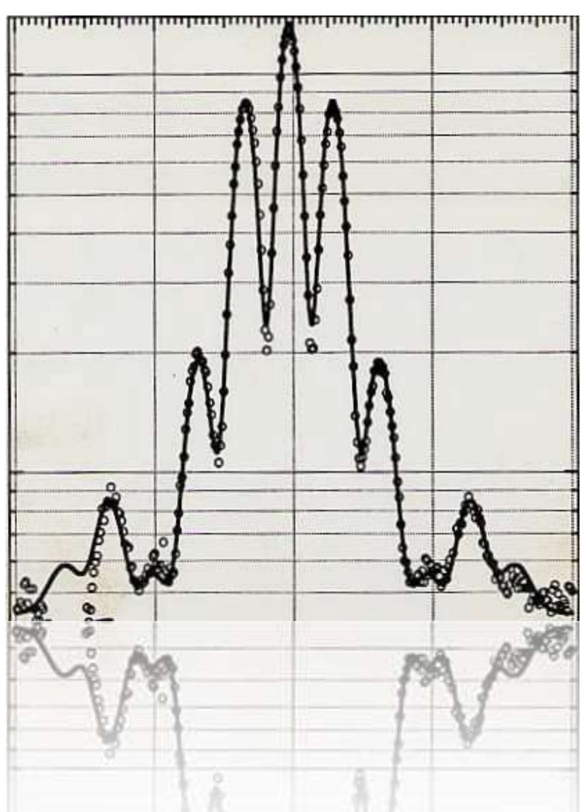
The extension to many holes gives atom holography, where an arbitrary pattern of matter is obtained ⇒ Fresnel lenses or even more complex... (Shimizu)

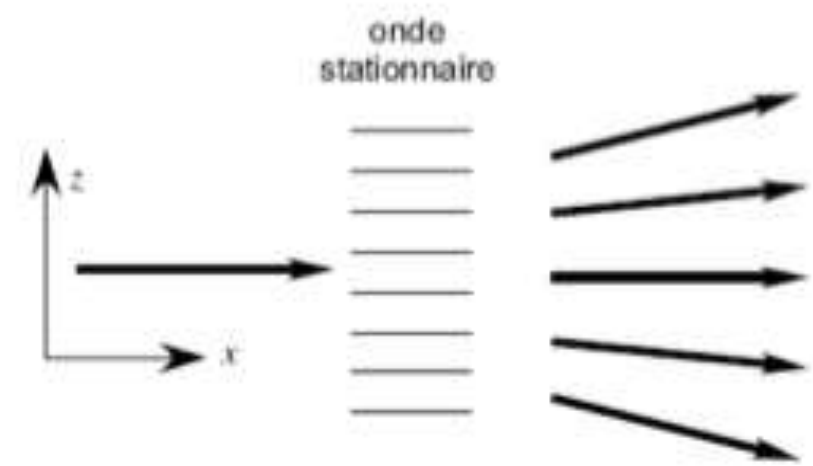


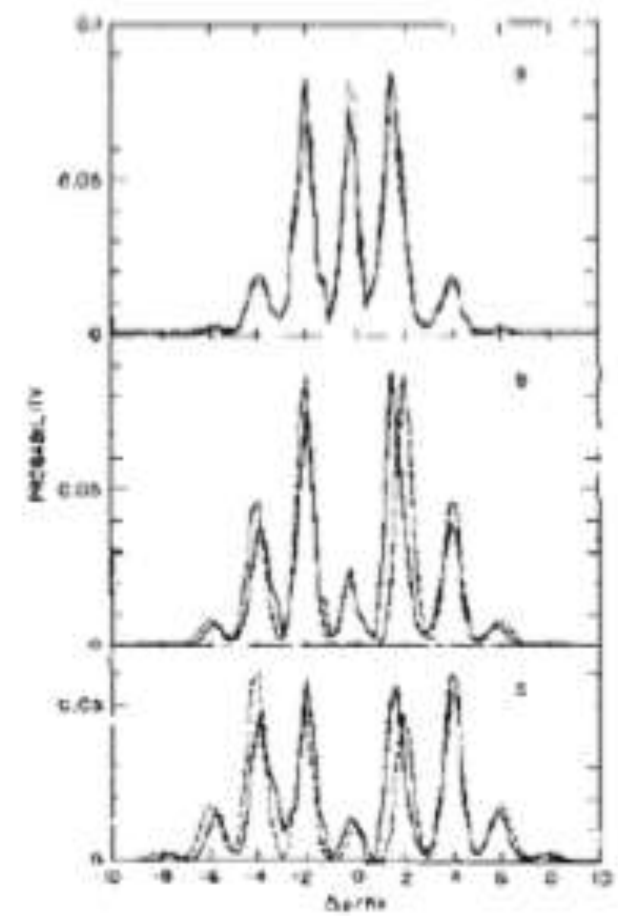
The atomic pattern (b) is the Fourier transform of the mask (a).



D. Keith et al (1988)







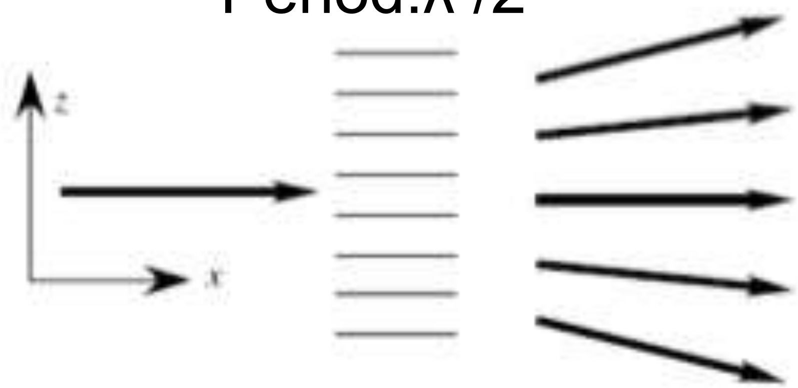
P. Gould et al. (1986)

- Material grating : amplitude modulation = loss
- Laser standing wave : phase modulation = 100 % transmission

DIFFRACTION BY STANDING LIGHT WAVE

- ✓ 1D along z, quasi monochromatic wave packet:
  - → mean momentum $p_{0,}$
  - $\Delta p_z \ll \hbar k$ →

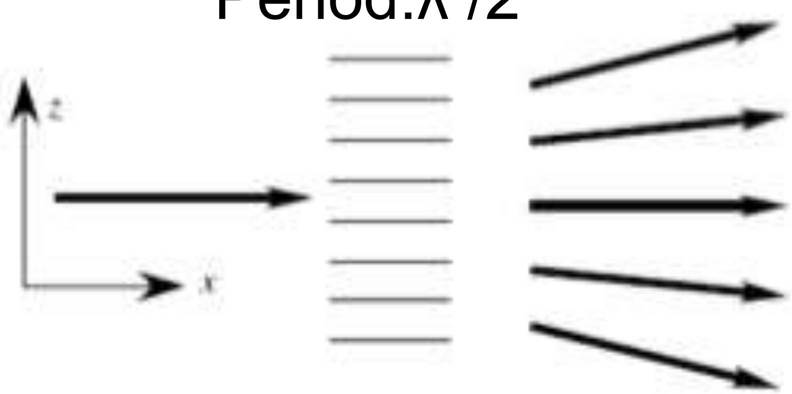
Standing wave
Period: λ /2



$$k = 2\pi / \lambda$$

DIFFRACTION BY STANDING LIGHT WAVE

Standing wave
Period: $\lambda/2$



$$k = 2\pi / \lambda$$

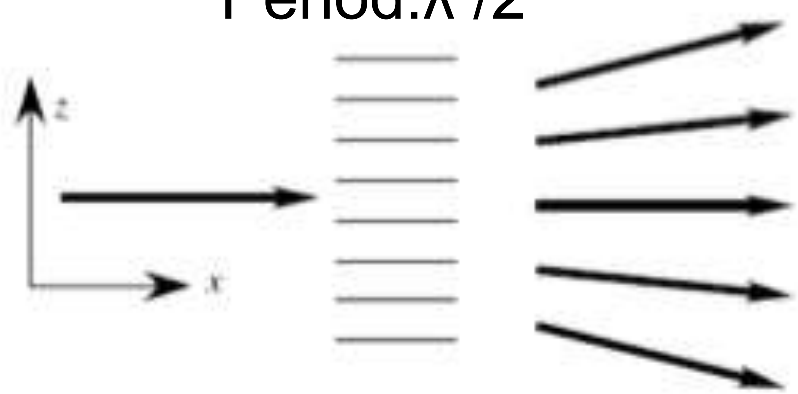
- 1D along z, quasi monochromatic wave packet:
  - mean momentum p_0,
    $\Delta p_z \ll \hbar k$
- Hamiltonian describing the grating :

$$H = \frac{p_z^2}{2m} + U_0 \sin^2 kz = \frac{p_z^2}{2m} + \frac{U_0}{2} - \frac{U_0}{2}\cos 2kz$$

$$= \frac{p_z^2}{2m} + \frac{U_0}{2} - \frac{U_0}{4}\left(e^{2ikz} + e^{-2ikz}\right)$$

DIFFRACTION BY STANDING LIGHT WAVE

Standing wave
Period:λ /2



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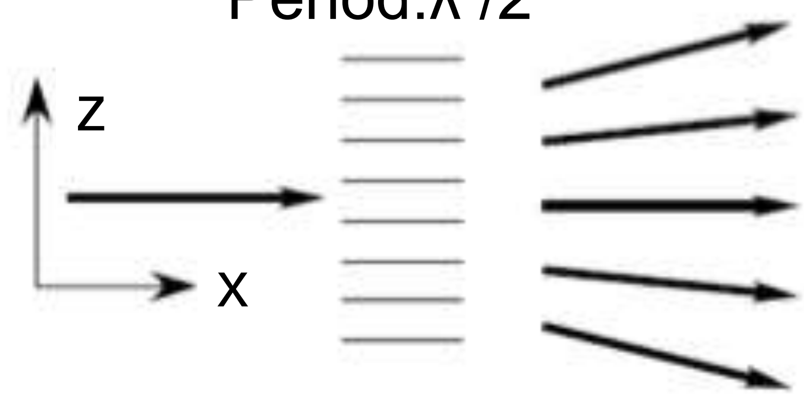
$$= \frac{p_z^2}{2m} + \frac{U_0}{2} - \frac{U_0}{4}\left(e^{2ikz} + e^{-2ikz}\right)$$

- Evolution of wavefunction :

$$\psi(T) = e^{-iHT/\hbar}\,|\psi(0)\rangle \; with \; |\psi(0)\rangle = |\,p_0\rangle$$

DIFFRACTION BY STANDING LIGHT WAVE

Standing wave
Period: $\lambda/2$



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$$= \frac{p_z^2}{2m} + \frac{U_0}{2} - \frac{U_0}{4}\left(e^{2ikz} + e^{-2ikz}\right)$$

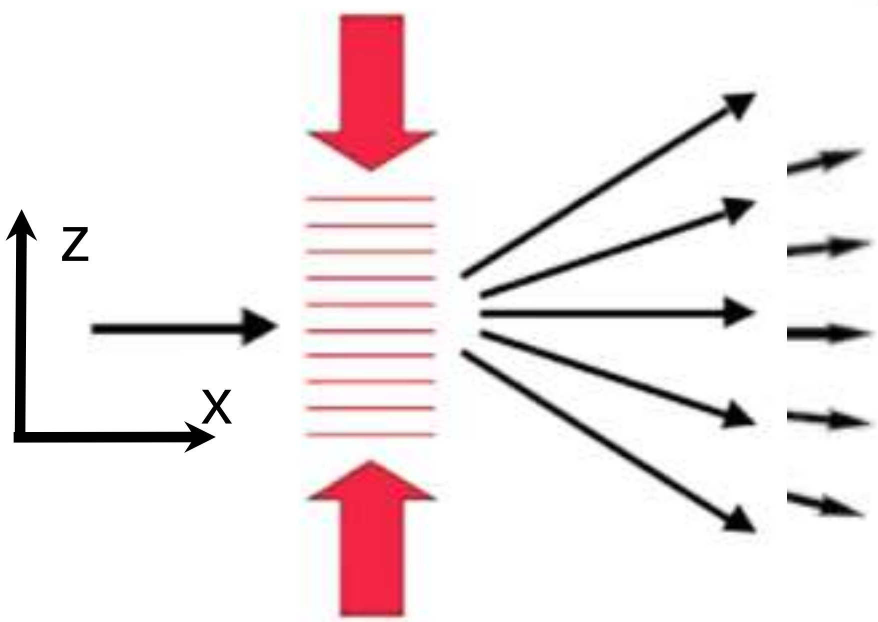
- First we neglect motion along z during T

Thin grating approximation

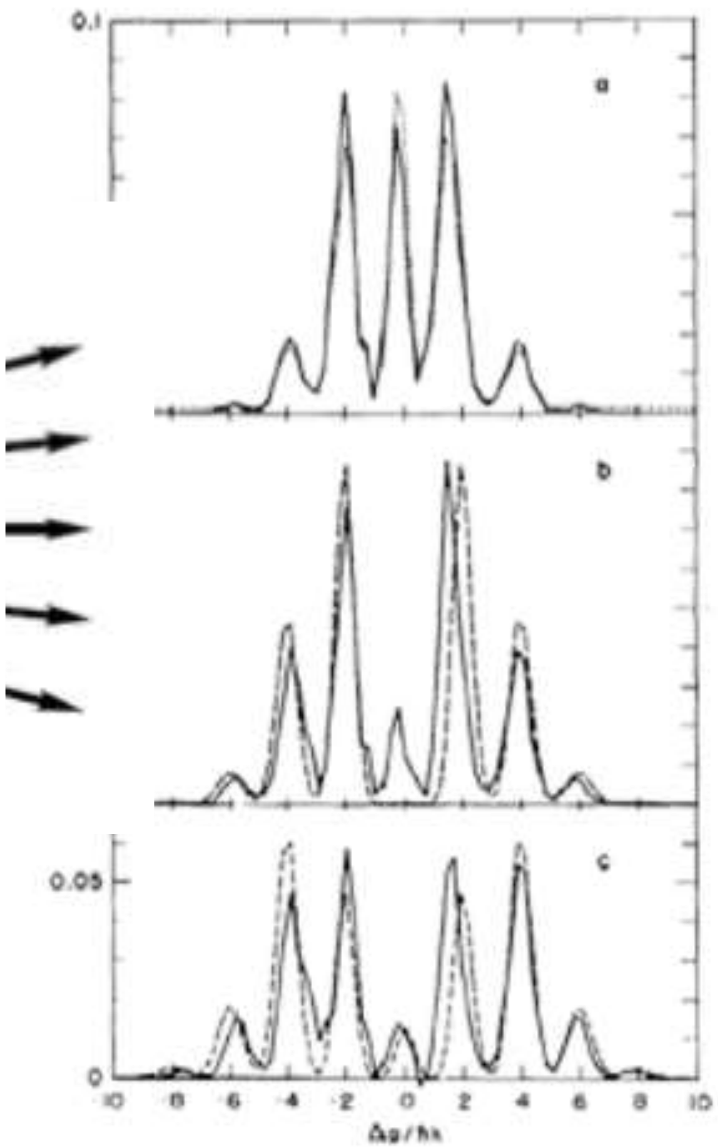
$$\psi(T) = e^{i(U_0T/2\hbar)\cos(2kz)}\,|\,p_0\rangle = \left(\sum_{n=-\infty}^{n=+\infty}(i)^n J_n\left(\frac{U_0T}{2\hbar}\right)e^{-2inkz}\right)|\,p_0\rangle$$

$$= \sum_{n=-\infty}^{n=+\infty}(i)^n J_n\left(\frac{U_0T}{2\hbar}\right)|\,p_0 - 2n\hbar k\rangle$$

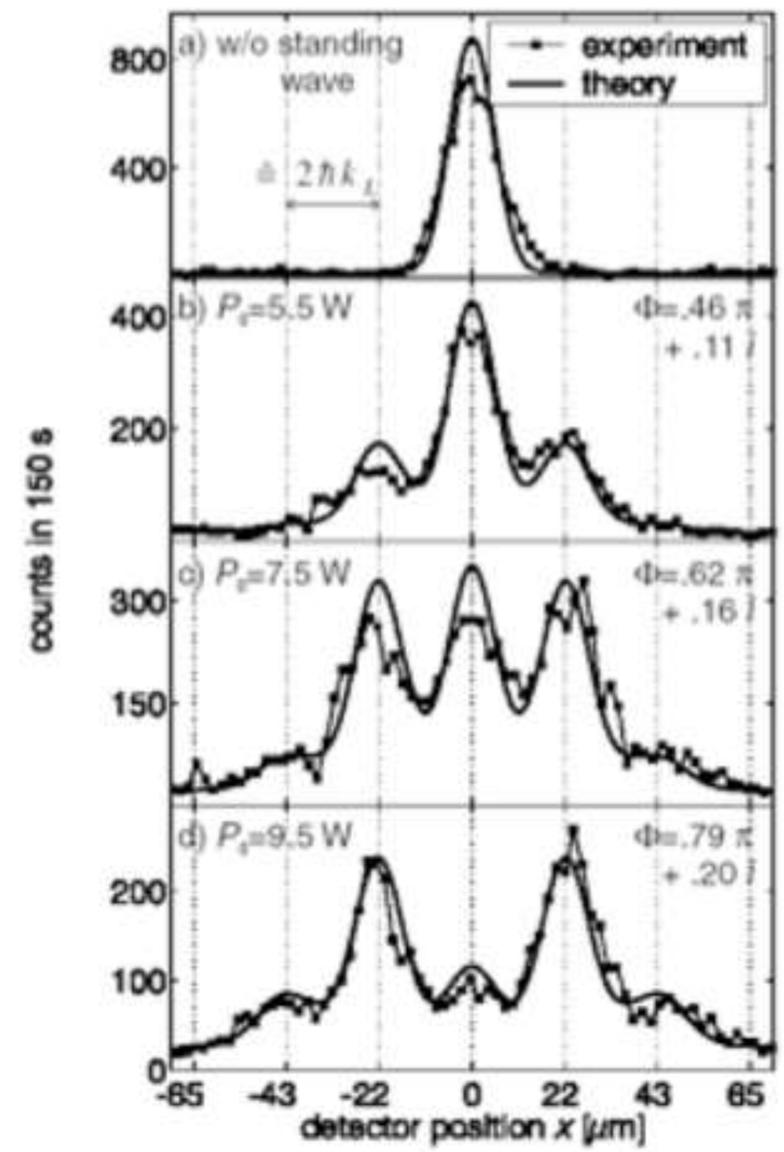
DIFFRACTION BY STANDING LIGHT WAVE



weight: $\left| J_n\left(\frac{U_0 T}{2\hbar}\right) \right|^2$



sodium atoms
Pritchard, 1985



C_{60} molecules
Zeilinger, 2001

DIFFRACTION BY STANDING LIGHT WAVE

Stationary problem: total energy is conserved

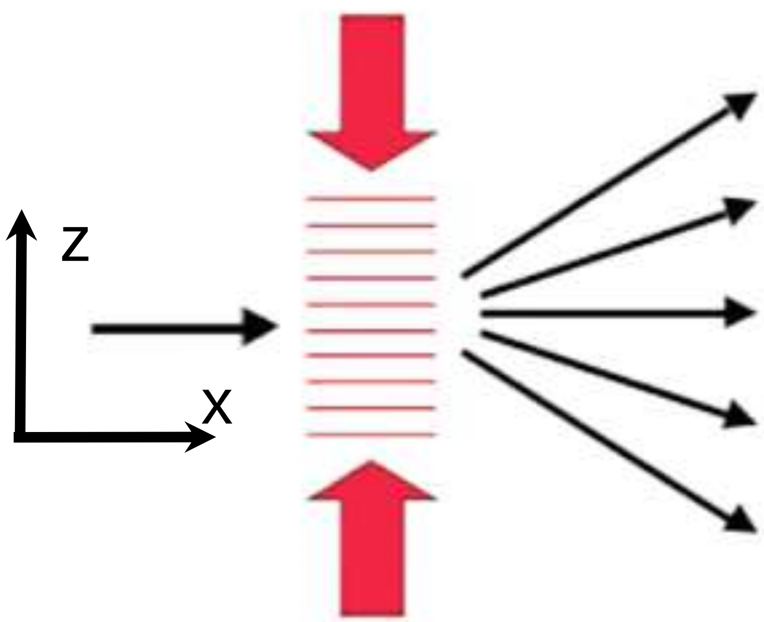
For small momenta along z, $p_0 \leq \hbar k$ and n~1

The kinetic energy along z changes by $\Delta E_z = \left| \frac{p_z^2}{2m} - \frac{(p_z \pm 2\hbar k)^2}{2m} \right| \sim E_R$

It must be compensated by a change along x : $\Delta E_z = -\Delta E_x$

Finite transit time enables momentum changes along x of $\sim h/w$

Change in kinetic energy $\Delta E_x = \frac{(p_x \pm h/w)^2}{2m} - \frac{p_x^2}{2m} \sim \frac{p_x h}{mw} = \frac{h}{T}$

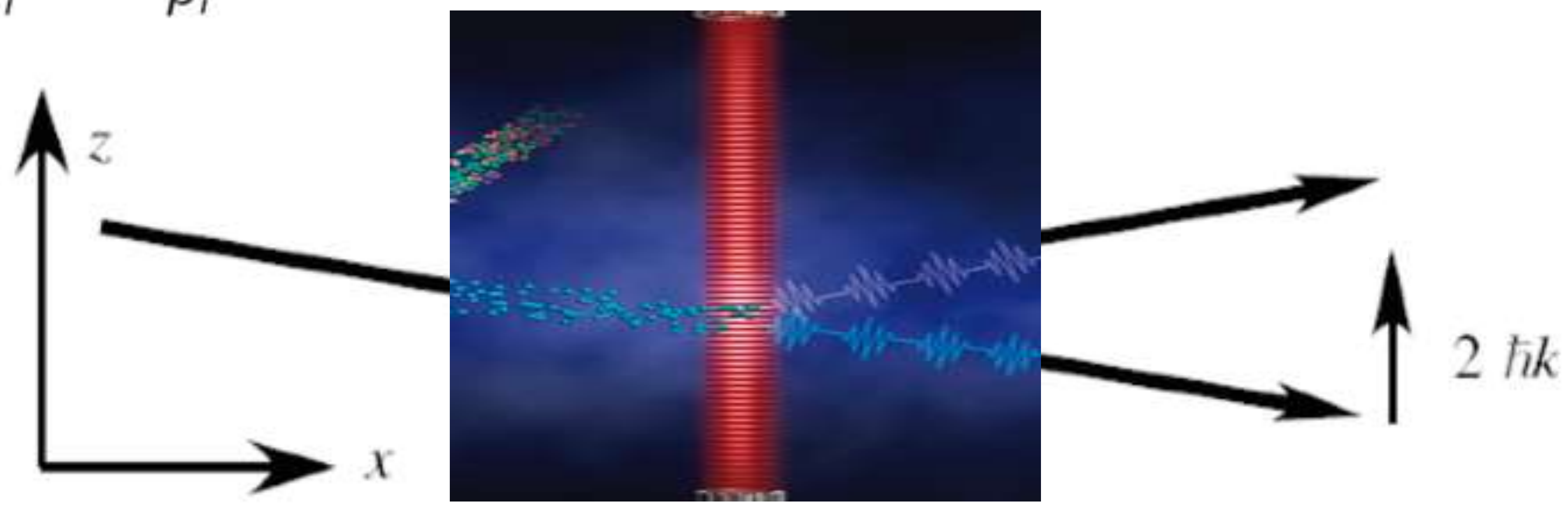


weight: $\left| J_n\left(\frac{U_0 T}{2\hbar}\right) \right|^2$

→ *As long as $\frac{h}{T} \geq E_R$, the total energy can be conserved and exchanged between x and z*

Thick grating : Bragg diffraction

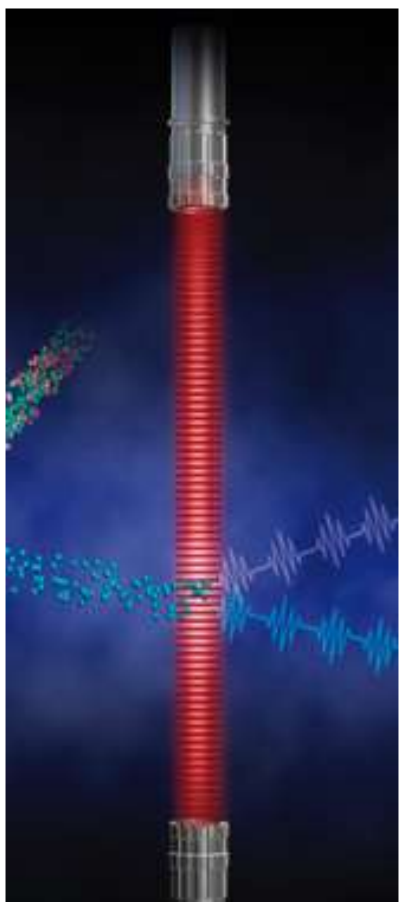
Energy and momentum are conserved for particular initial momenta $p_0 = (2n-1)\hbar k$ along z:
$\Rightarrow p_f = -p_i$

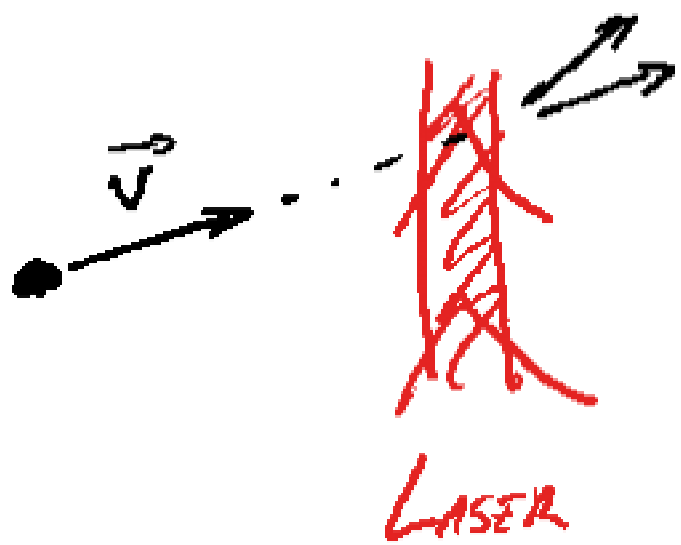


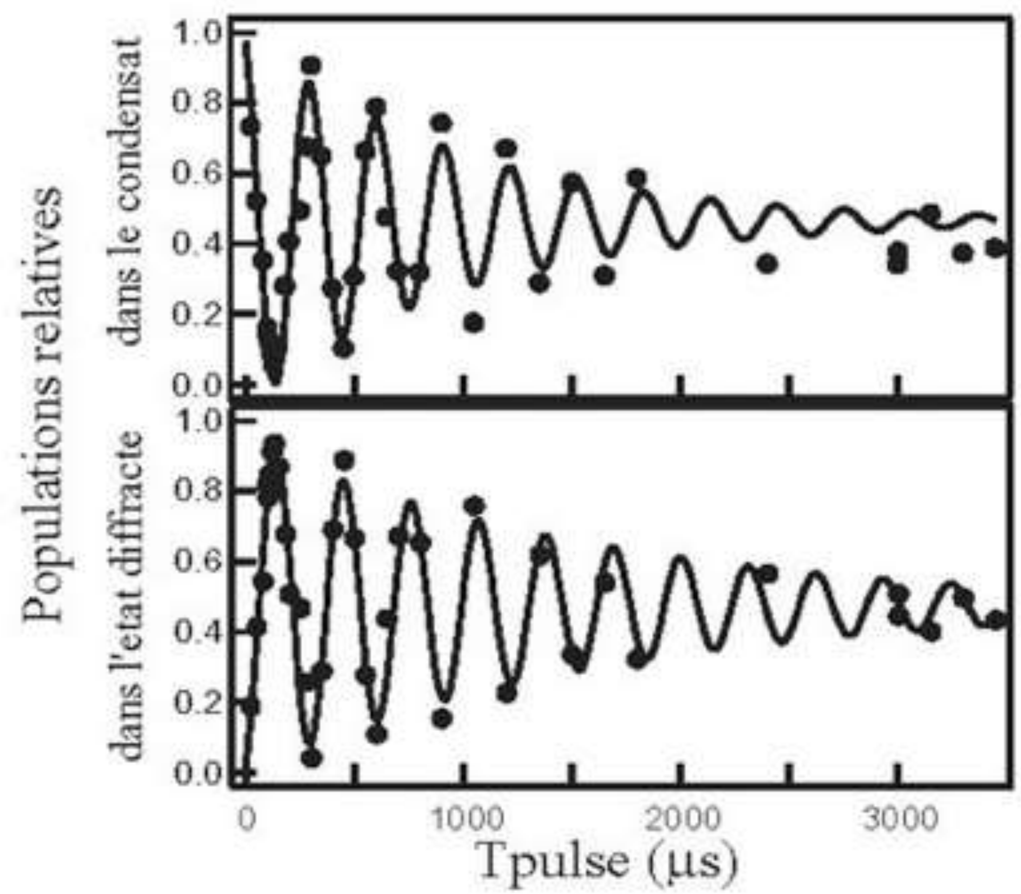
zeroth order: Rabi oscillations between $|p_z = -\hbar k\rangle$ and $|p_z = -\hbar k\rangle \Rightarrow$ beamsplitter with adjustable weights!

BRAGG DIFFRACTION

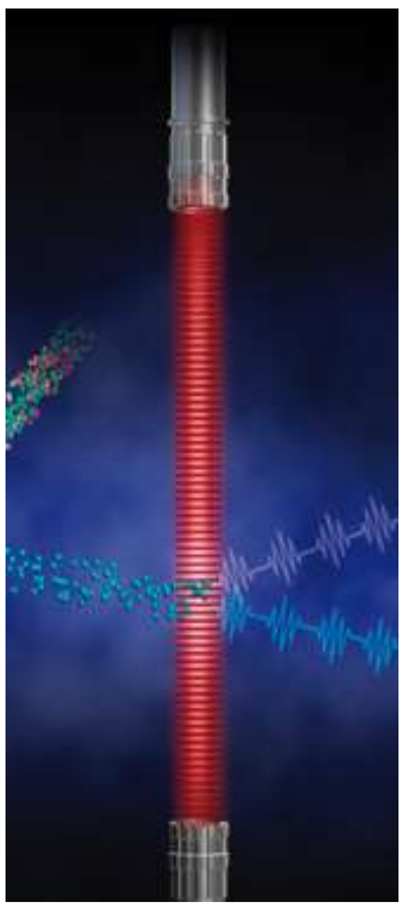
- Absorption of photon from on laser and stimulated emission to the retroreflected beam
  - ⇨ **Rabi oscillation between 2 (or more) state**
    - ⇨ **Different momenta since photons carry momentum**

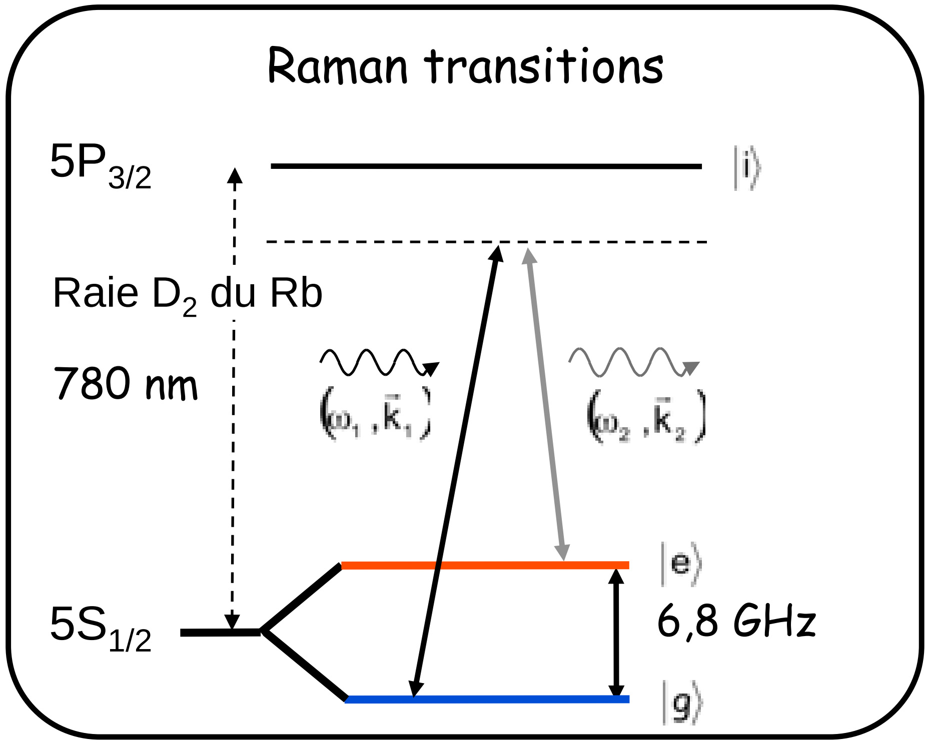


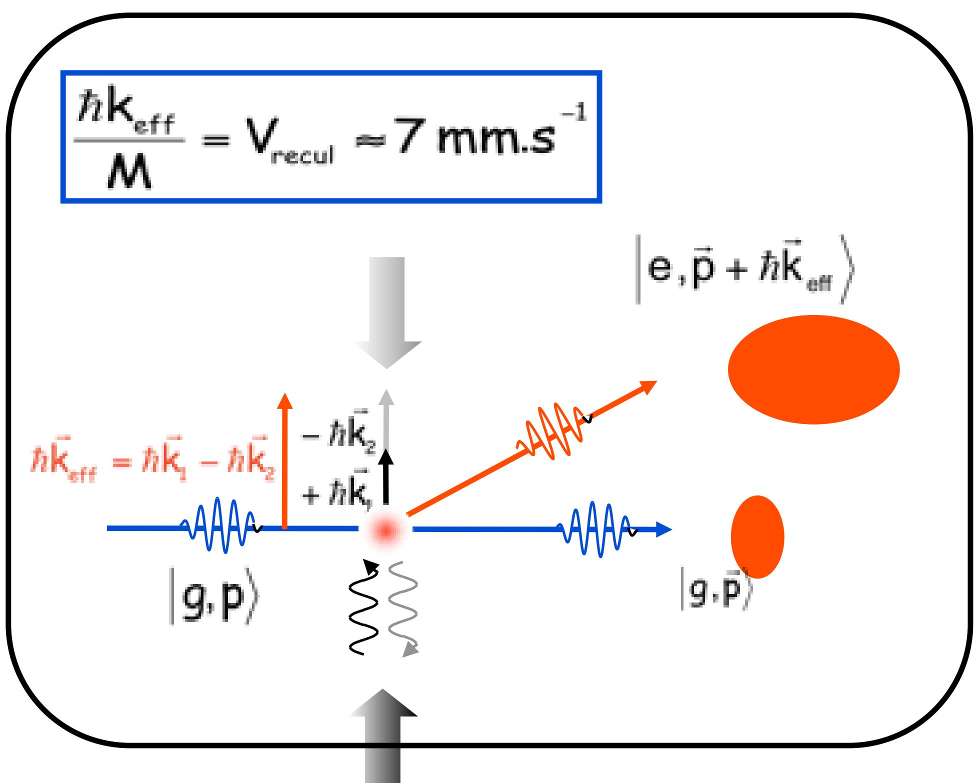




ATOMIC BEAM SPLITTER







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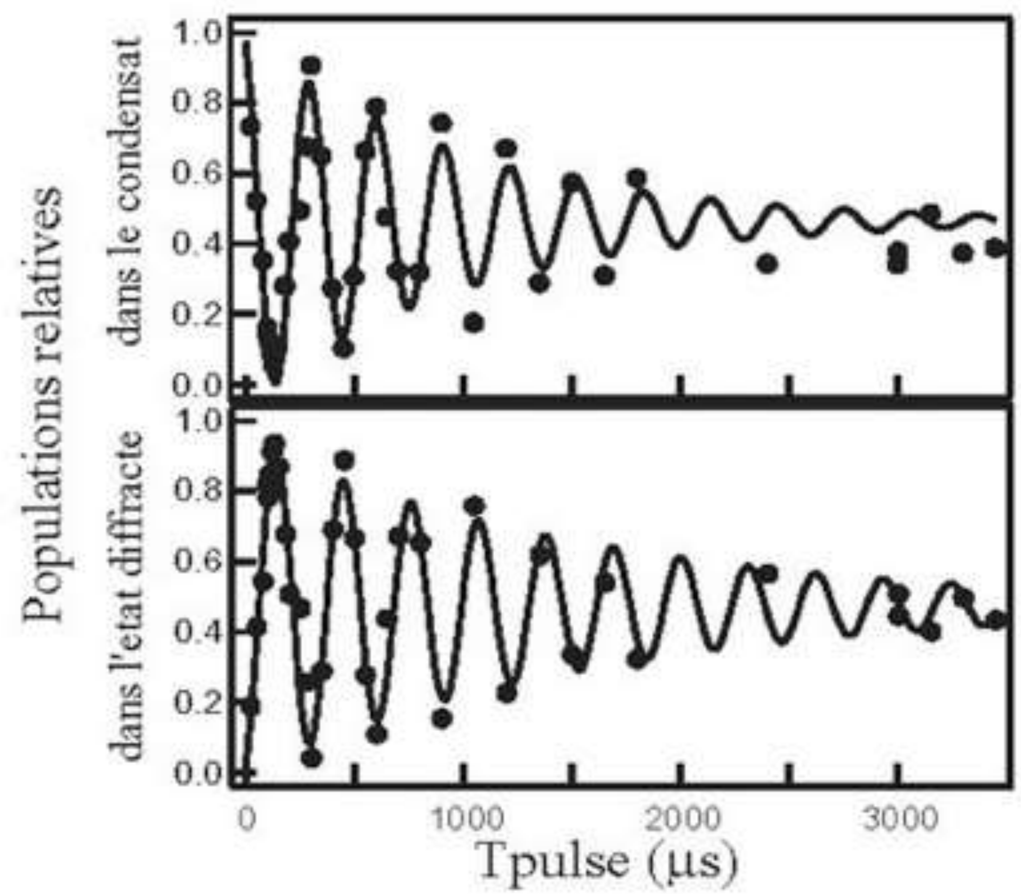
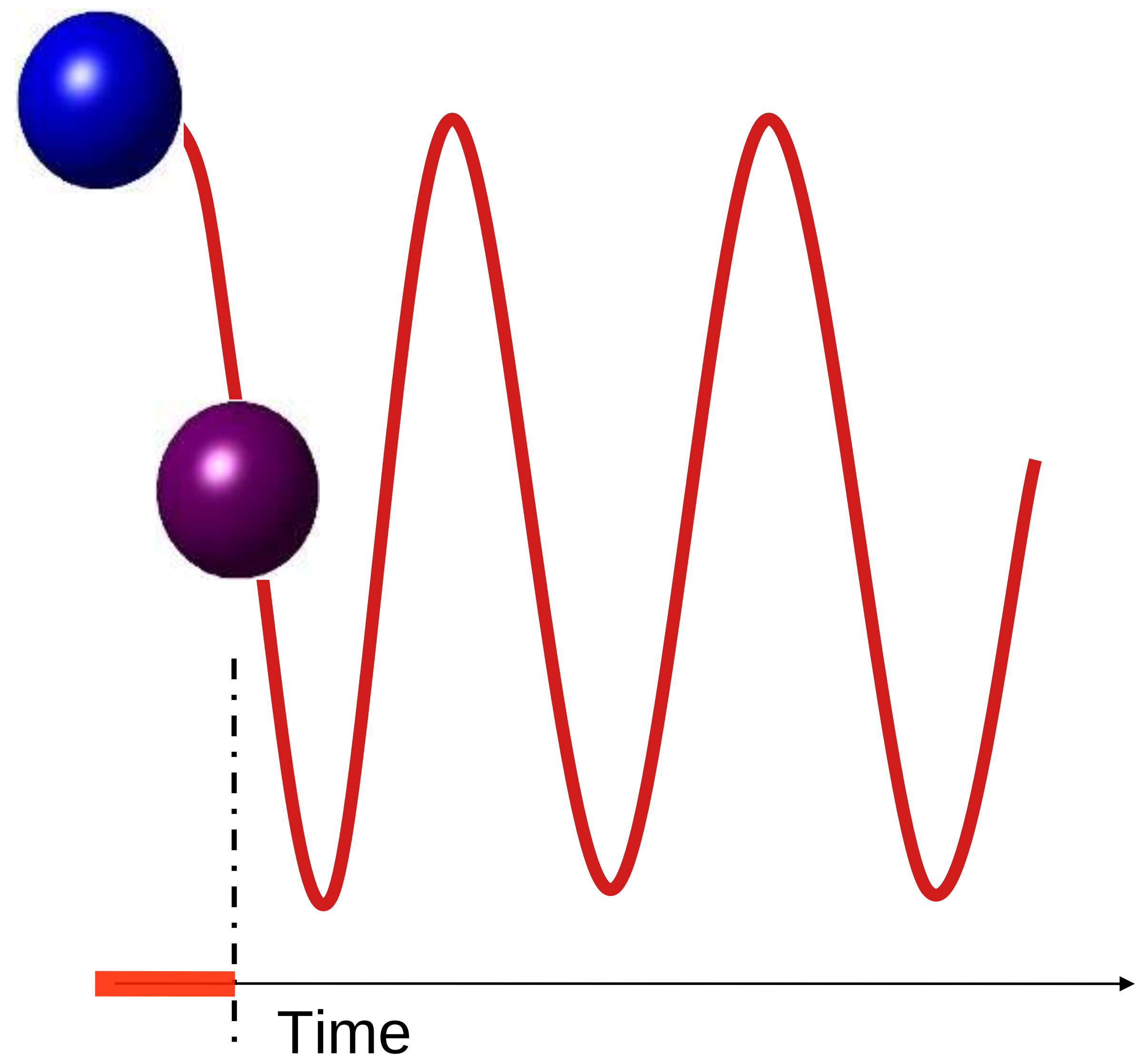
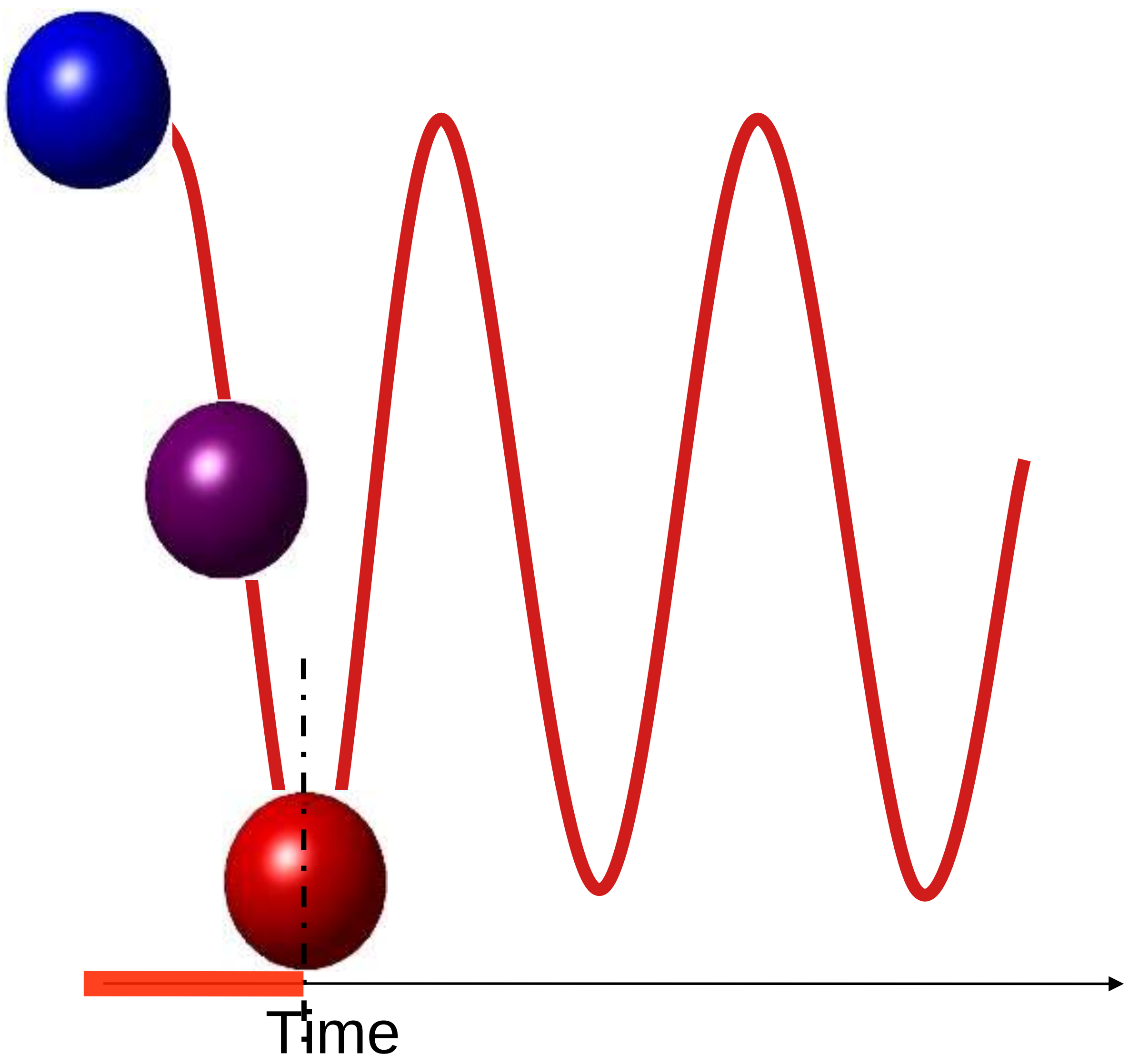


- Controlling the interfaction time controls the result of the oscillation
  - Half way between red and blue
    - ⊿/2 pulse



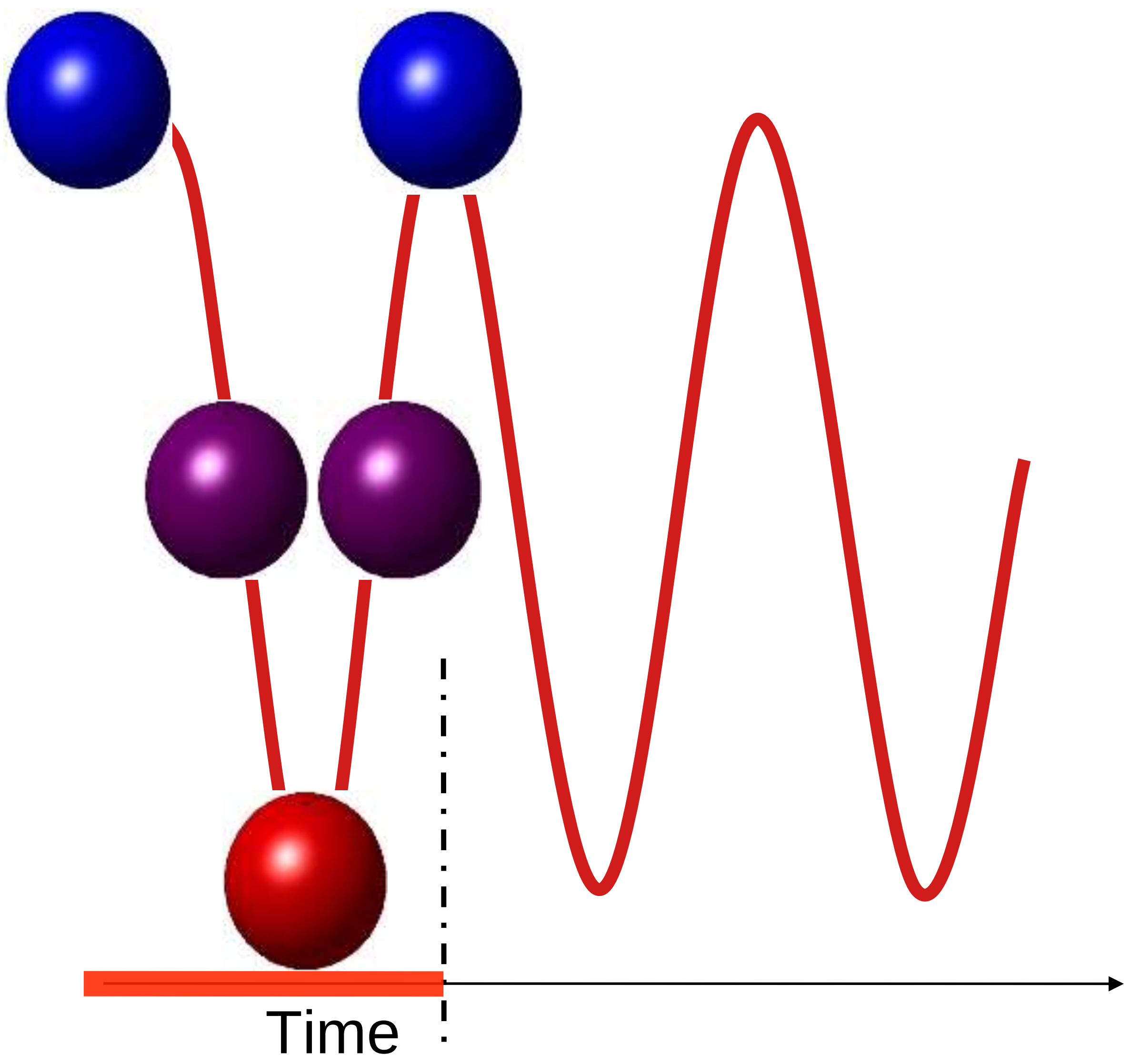
ADJUSTABLE BEAMSPLITTER

- Controlling the interfaction time controls the result of the oscillation
  - Half way between red and blue
    - ⊿/2 pulse
  - Another half : all the way from red to blue
    - ∠ pulse



ADJUSTABLE BEAMSPLITTER

- Controlling the interfaction time controls the result of the oscillation
  - Half way between red and blue
    - ⊿/2 pulse
  - Another half : all the way from red to blue
    - ∠ pulse
  - The other way : from blue to red
    - ∠ pulse



ADJUSTABLE BEAMSPLITTER

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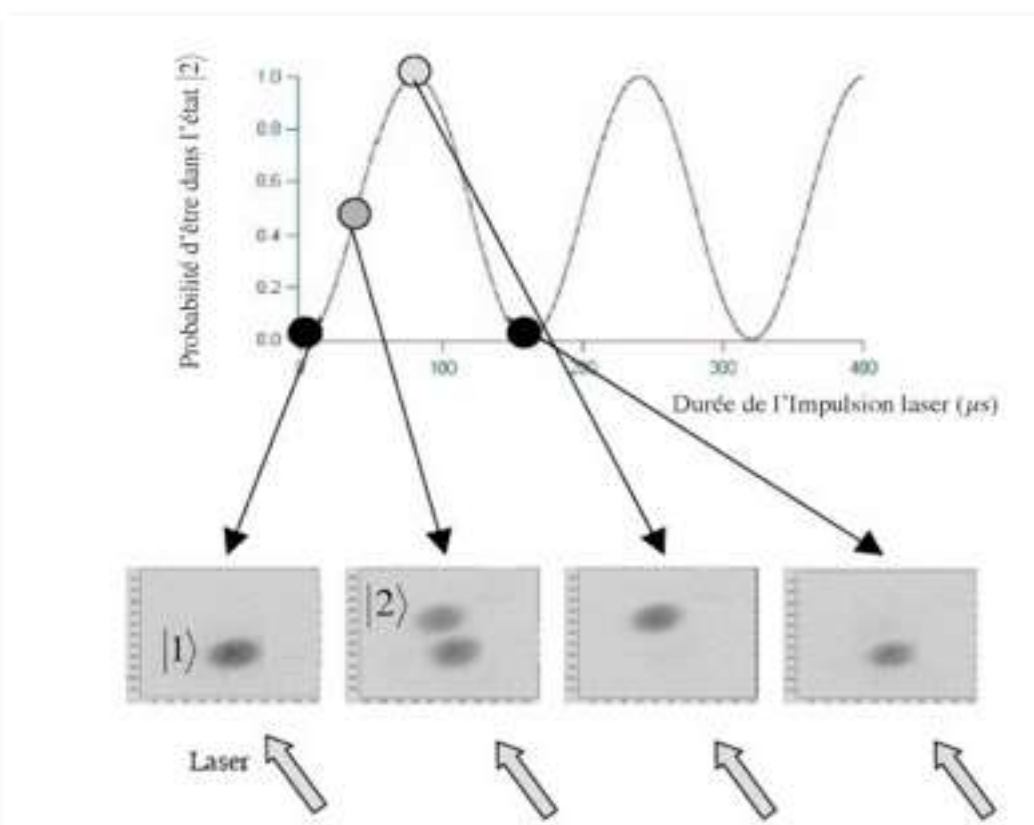
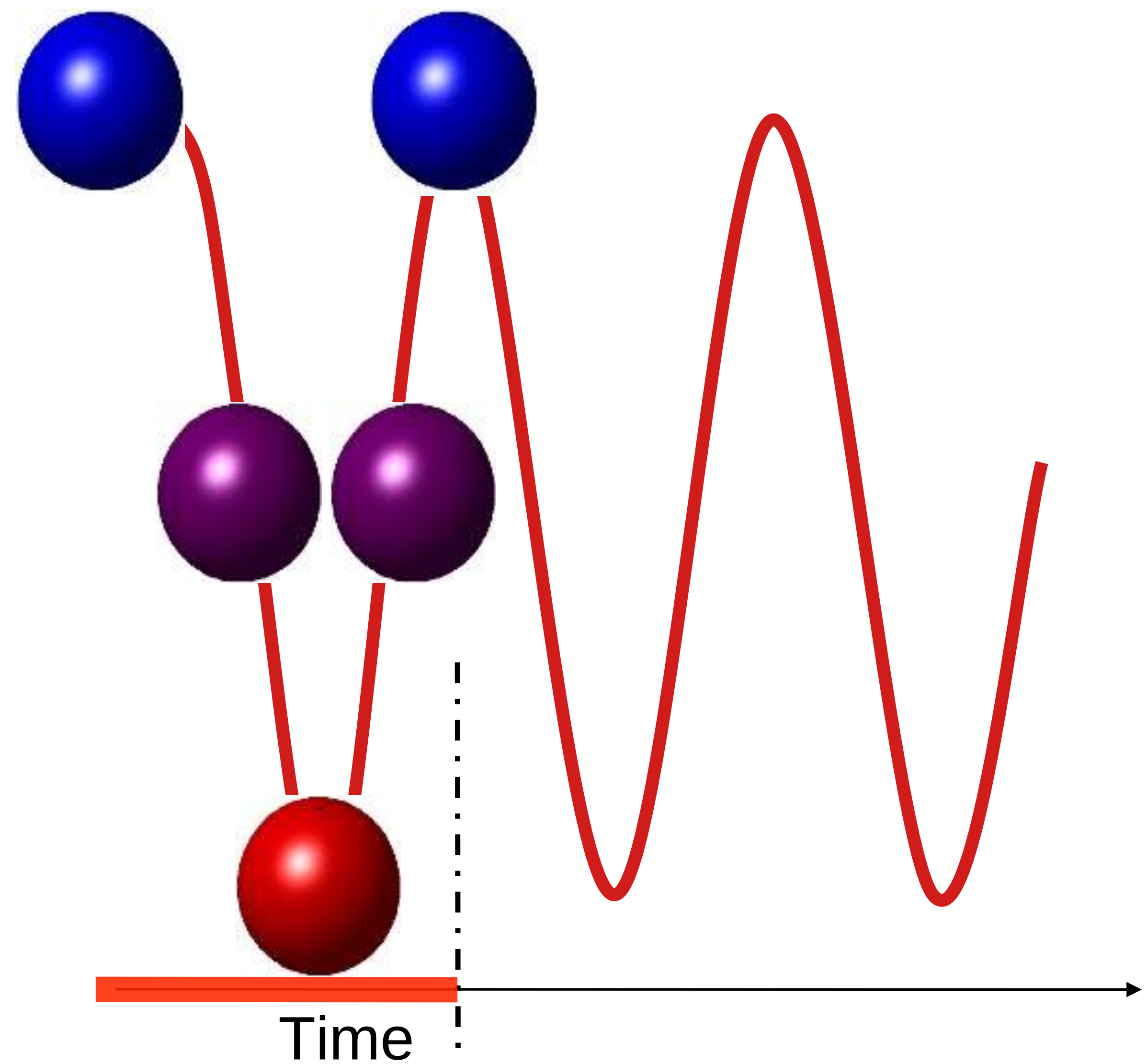




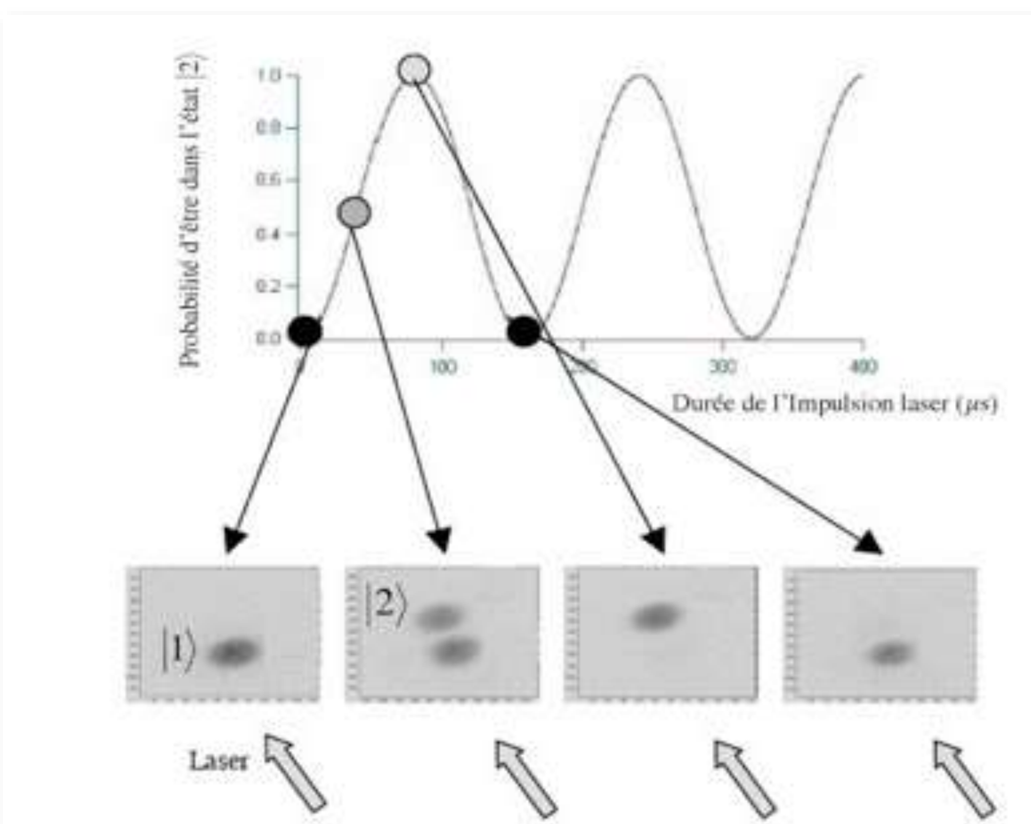
Raman beam splitter

$$V_{at-las} = \hbar \frac{\Omega}{2} \underbrace{|2\rangle\langle 1|}_{\text{Internal}} e^{\overbrace{ikz}^{\text{external}}} \ldots$$

$$V_{at\,las} |1,p\rangle = \hbar \frac{\Omega}{2} |2\rangle\langle 1|1\rangle \otimes e^{ikz}|p\rangle$$

$$\propto |2\rangle \otimes |p+\hbar k\rangle$$

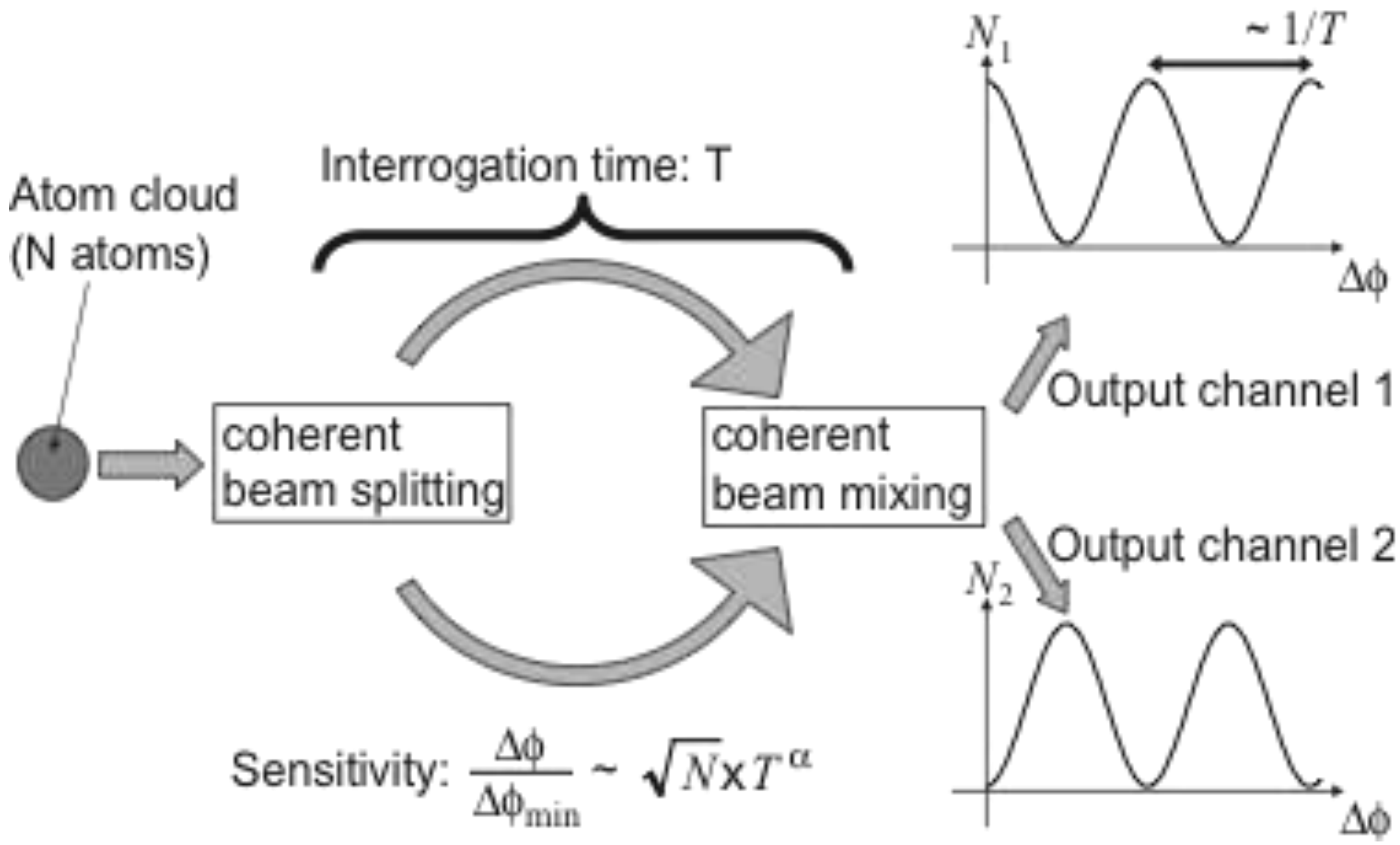
$$|2, p+\hbar k\rangle$$



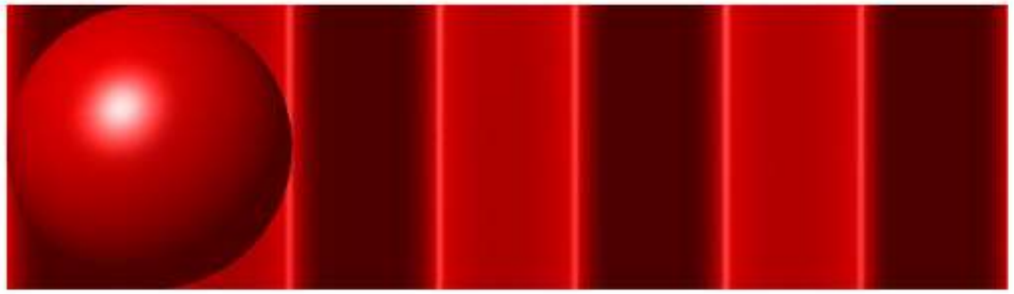
$$|\psi(t)\rangle = C_1(t)\,|1,p\rangle + C_2(t)\,|2,p+\hbar k\rangle$$

HOW TO BUILD AN ATOM INTERFEROMETER

- An atom interferometer will use a series (at least two) coherent splitting processes to “create” multiple paths that will interfere.

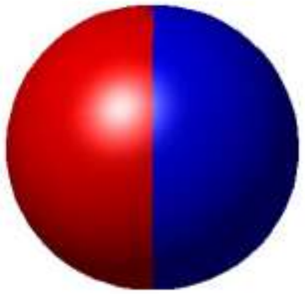


- ✓ The first π/2 pulse - beam splitter
  - ⇨ Creates the coherent superposition



ATOM INTERFEROMETER

- The first π/2 pulse - beam splitter
  - ⇨ Creates the coherent superposition
- The two parts of the atom separate
  - ⇨ Splitting between the two parts

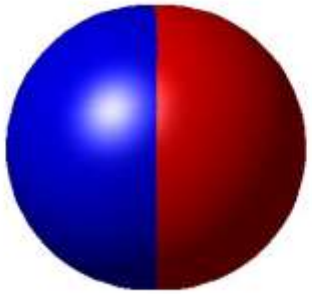


ATOM INTERFEROMETER

- ✓ The first π/2 pulse - beam splitter
  - ⇨ Creates the coherent superposition
- ✓ The two parts of the atom separate
  - ⇨ Splitting between the two parts
- ✓ Apply the π pulse - mirror
  - ⇨ Changes blue to red
    - ⇨ Velocity from 0 to recoil
  - ⇨ Changes red to blue
    - ⇨ Velocity from recoil to 0

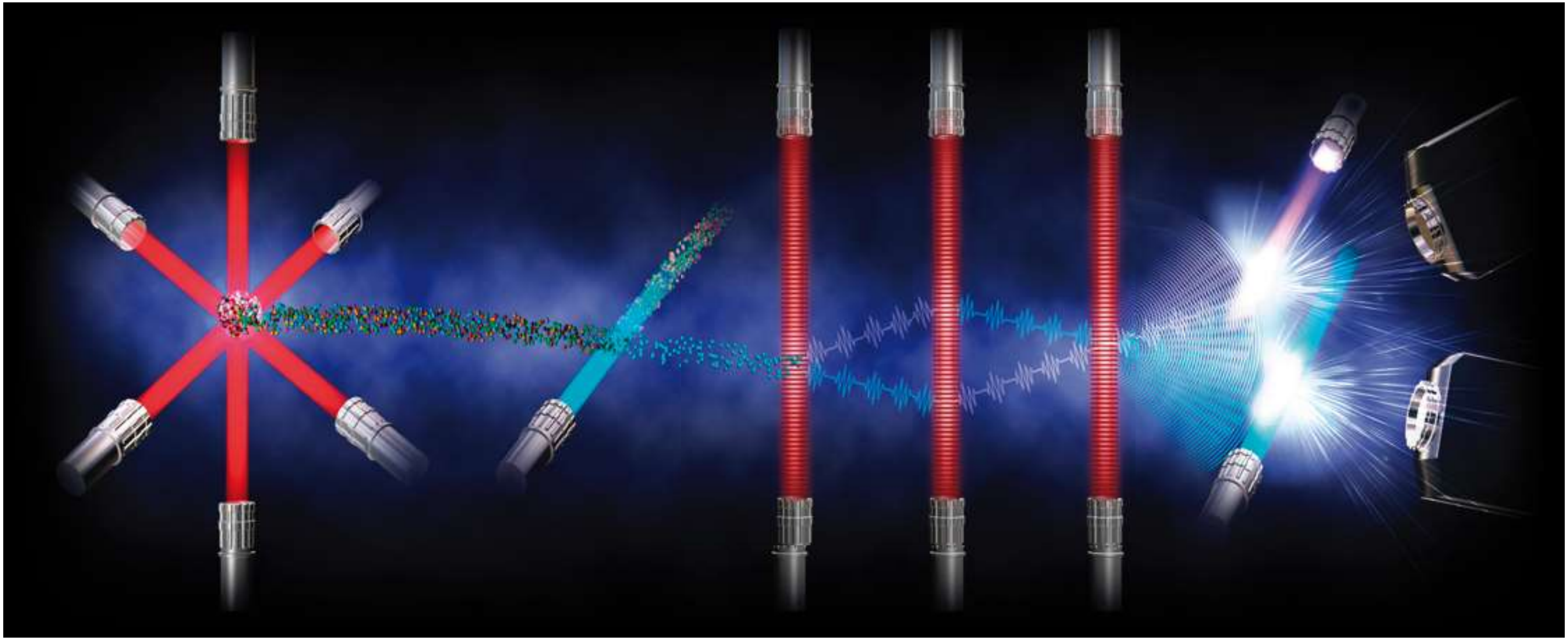
ATOM INTERFEROMETER

- ✓ The first π/2 pulse - beam splitter
  - ⇨ Creates the coherent superposition
- ✓ The two parts of the atom separate
  - ⇨ Splitting between the two parts
- ✓ Apply the π pulse - mirror
  - ⇨ Changes blue to red
    - ⇨ Velocity from 0 to recoil
  - ⇨ Changes red to blue
    - ⇨ Velocity from recoil to 0
- ✓ Apply last π/2 pulse when the two parts overlap again

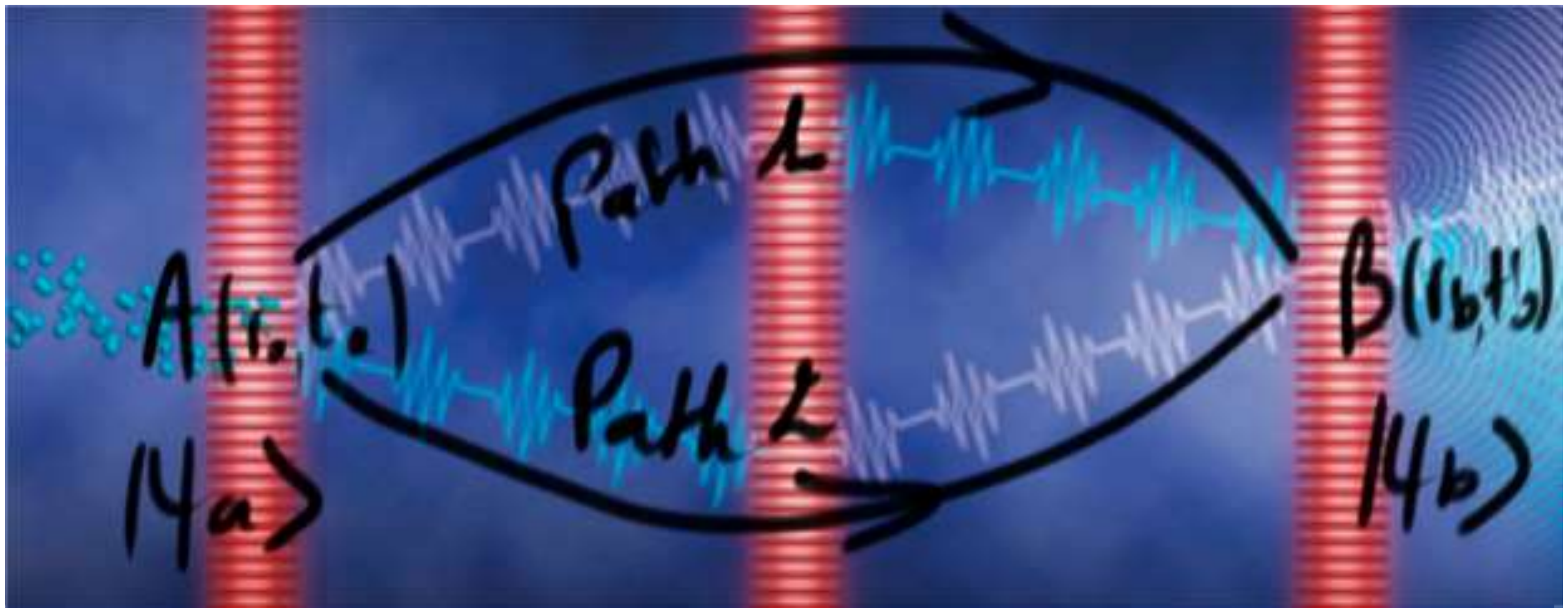


ATOM INTERFEROMETER

Cold atom source | State prep. | 3-pulse interferometer | Detection



How to calculate the phase shifts



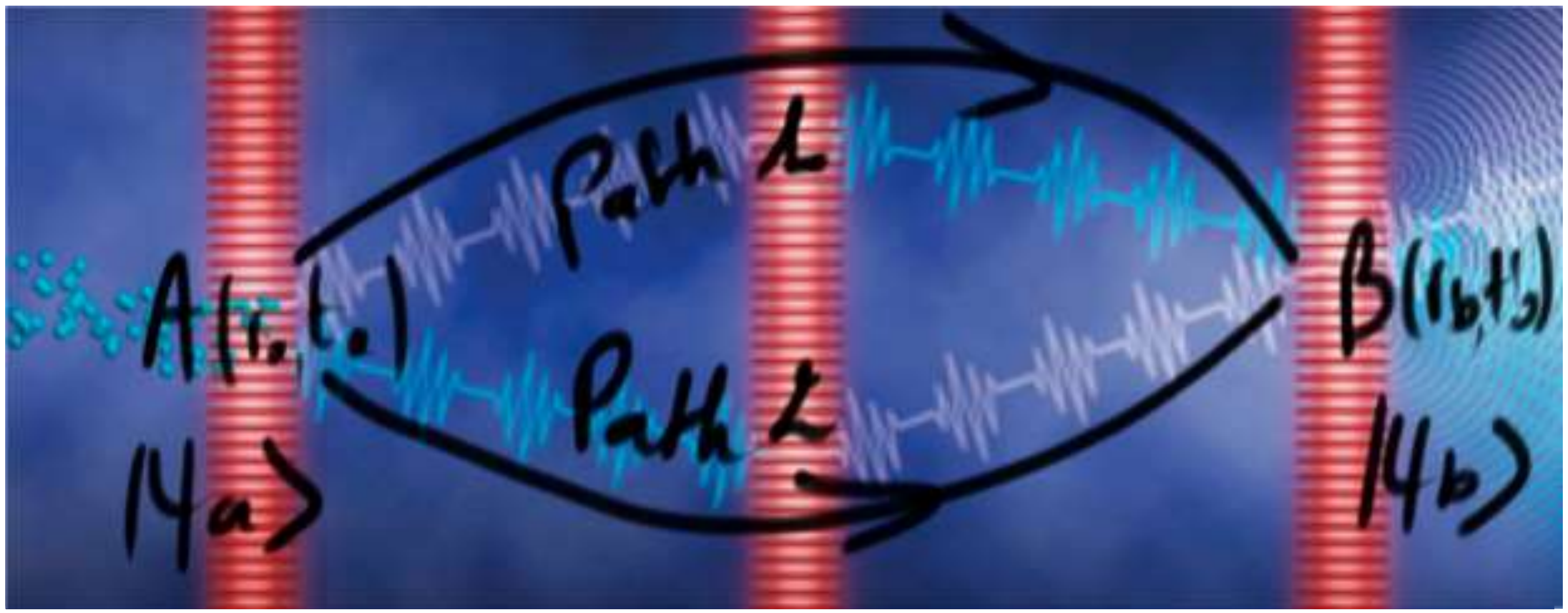
Path 1 : $|\mathcal{A}_I|^2 = |\langle \psi_f | \psi_i \rangle_I|^2$

Path 2 : $|\mathcal{A}_{II}|^2 = |\langle \psi_f | \psi_i \rangle_{II}|^2$

2 Paths : $|\mathcal{A}|^2 = |\mathcal{A}_I + \mathcal{A}_{II}|^2$

$= |\mathcal{A}_I|^2 + |\mathcal{A}_{II}|^2 + 2\,\mathrm{Re}\,\mathcal{A}_I \mathcal{A}_{II}^*$.

How to calculate the phase shifts



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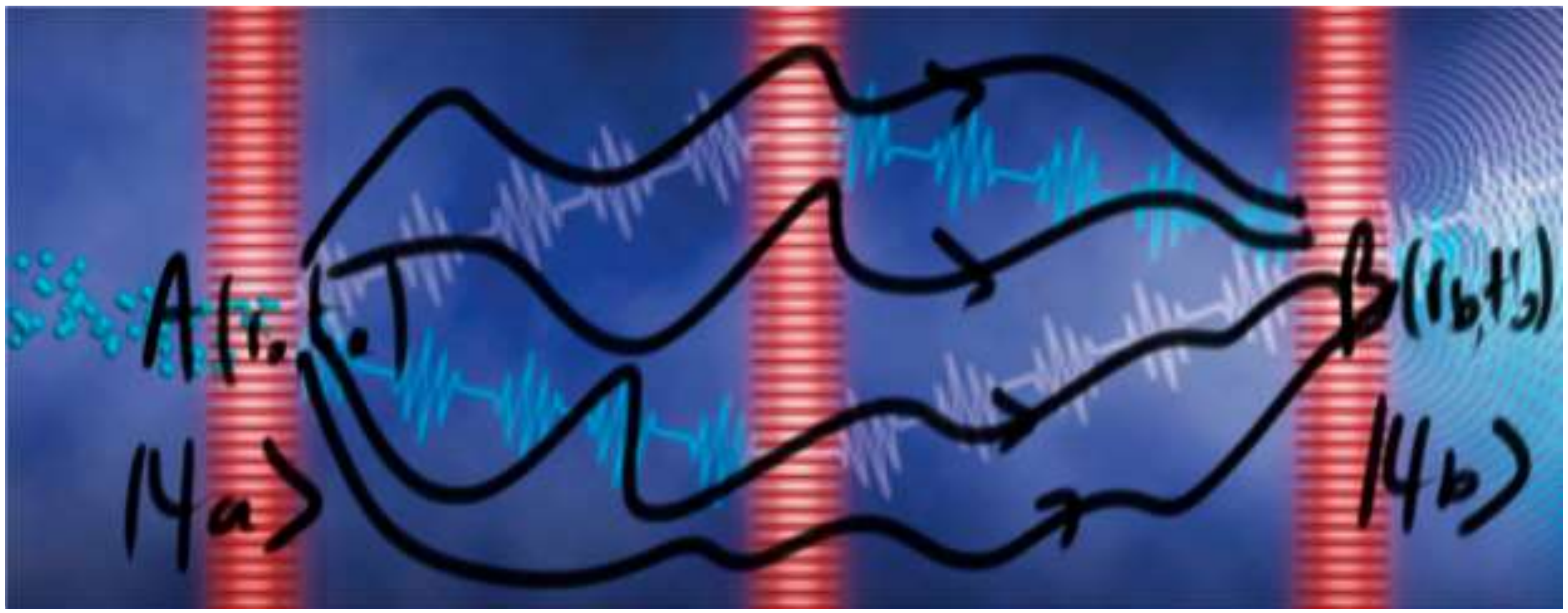
$= |\mathcal{A}_I|^2 + |\mathcal{A}_{II}|^2 + 2\,\mathrm{Re}\,\mathcal{A}_I \mathcal{A}_{II}^*$.

The probability amplitude for a particle to travel from $A(\mathbf{r}_a, t_a)$ to $B(\mathbf{r}_b, t_b)$ is the Feynmann propagator

$$K(\mathbf{r}_b, t_b; \mathbf{r}_a, t_a) = \sum_{\Gamma} e^{iS_\Gamma/\hbar}$$

HOW TO CALCULATE THE PHASE SHIFTS



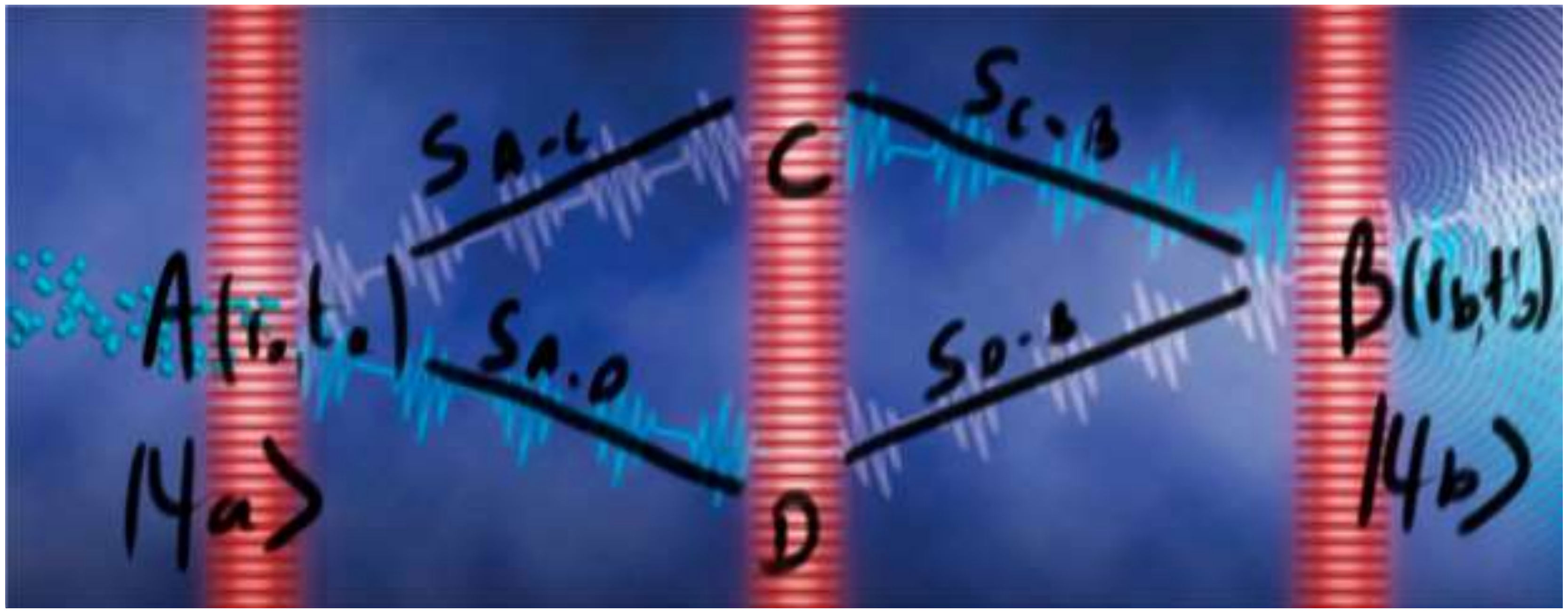
The sum is over all paths from A to B. The wave function at B is

$$\psi(\mathbf{r}_b, t_b) = \int K(\mathbf{r}_b, t_b; \mathbf{r}_a, t_a)\psi(\mathbf{r}_a, t_a)\, d\mathbf{r}_a$$

and the action S_Γ is deduced from the Lagrangian

$$S_\Gamma = \int_{t_a}^{t_b} \mathcal{L}\left(\mathbf{r}(t), \dot{\mathbf{r}}(t), t\right) dt$$

How to calculate the phase shifts



For a Lagrangian at most quadratic in $\mathbf{r}$ and $\dot{\mathbf{r}}$, K is deduced from the classical action: $K \propto e^{iS_{\mathrm{cl}}/\hbar}$

Why?

Summation over all paths $\sum_\Gamma e^{iS_\Gamma/\hbar}$: only stationary phase contributes significantly

$\Rightarrow$ keep paths Γ minimizing the action, *i.e.* classical trajectories

ATOM INTERFEROMETER

For a Lagrangian at most quadratic in $\mathbf{r}$ and $\dot{\mathbf{r}}$, K is deduced from the classical action: $K \propto e^{iS_{\rm cl}/\hbar}$

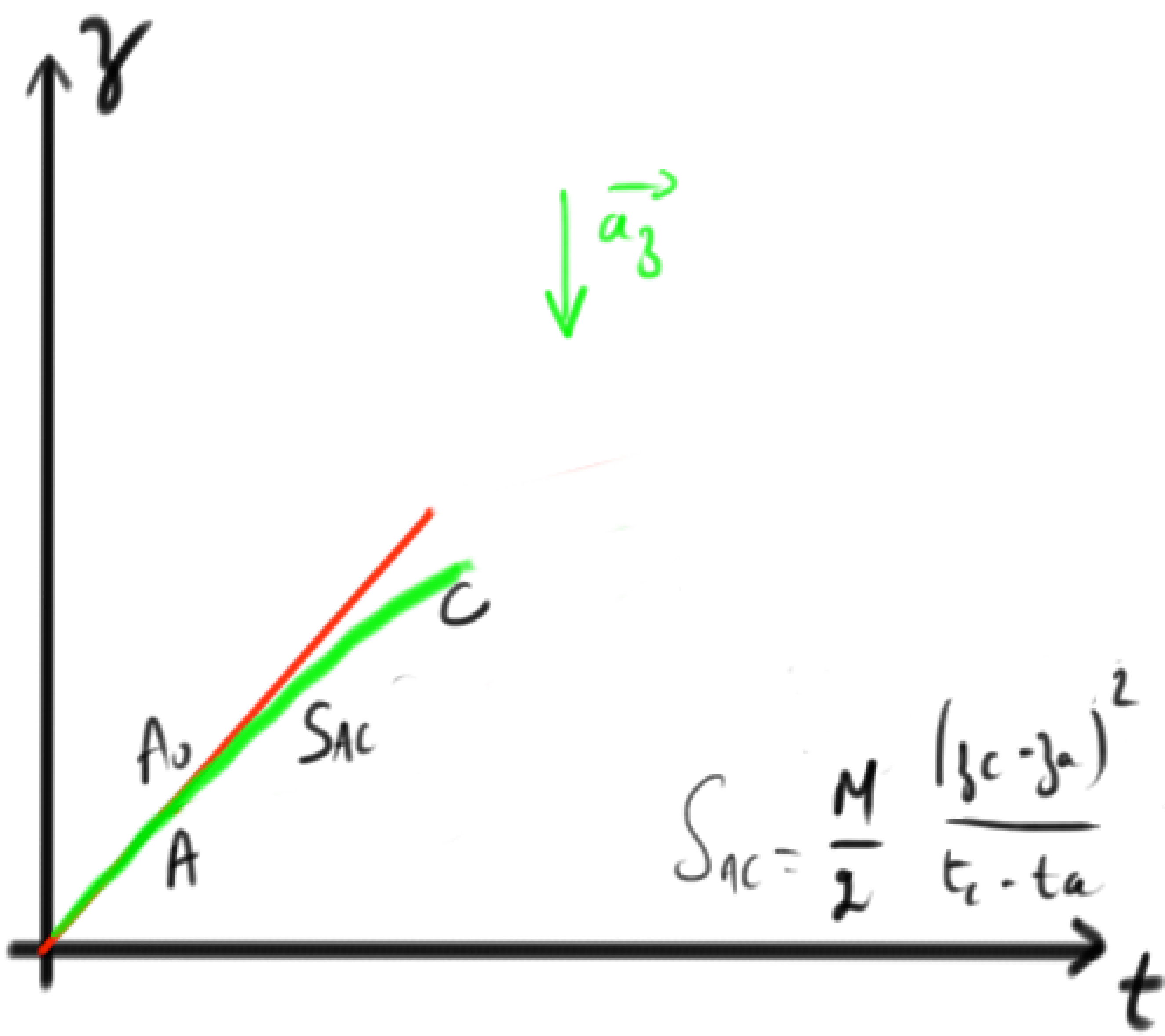
Why?

over all paths $\sum_\Gamma e^{iS_\Gamma/\hbar}$: only stationary phase contributes significantly

$\Rightarrow$ keep paths Γ minimizing the action, *i.e.* classical trajectories

- free particle: $\mathcal{L} = M\dot{r}^2/2$
- particle in gravitational field: $\mathcal{L} = M\dot{r}^2/2 - Mgz$
- particle in an harmonic trap: $\mathcal{L} = M\dot{r}^2/2 - M\omega_0^2 r^2/2$
- particle in a rotating frame:
  $\mathcal{L} = M\dot{r}^2/2 + M\dot{\mathbf{r}} \cdot (\mathbf{\Omega} \times \mathbf{r}) + M(\mathbf{\Omega} \times \mathbf{r})^2/2$

Phase shift from matter wave propagation



$$\mathcal{L}(z,\dot z) = \frac{1}{2} M \dot z^2 - M g z$$

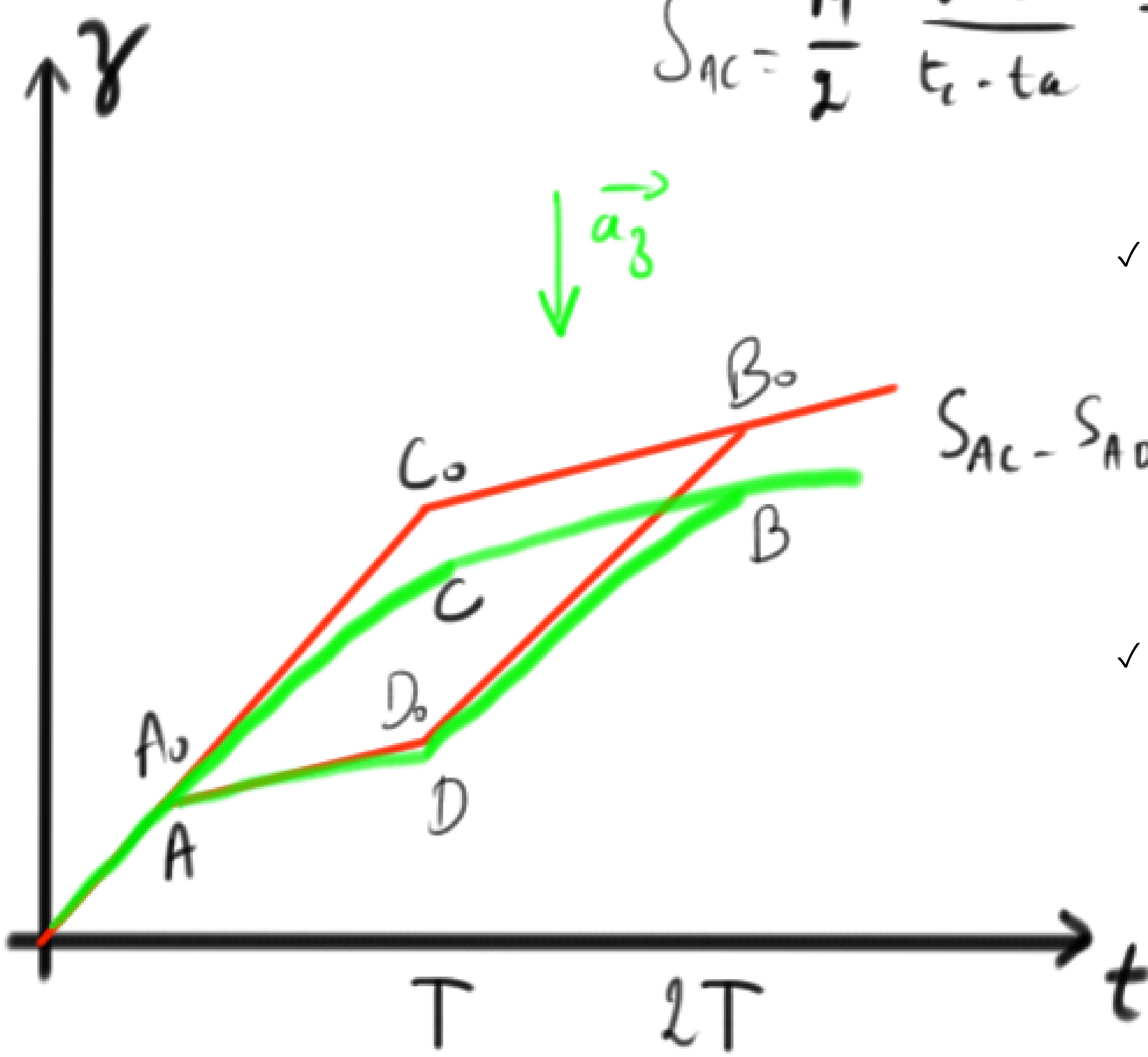
$$\begin{cases} z_C = z_A + v_A(t_c - t_a) - \frac{1}{2} a_z (t_c - t_a)^2 \\ v_C = v_A - a_z (t_c - t_a) \end{cases}$$

$$S_{A-C} = S_{cl}(z_c t_c, z_a t_a)$$

$$S_{AC} = \frac{M}{2} \frac{(z_c - z_a)^2}{t_c - t_a} - \frac{Mg}{2}(z_c + z_a)(t_c - t_a) - \frac{Mg^2}{24}(t_b - t_a)^3$$

Phase shift from matter wave propagation

$$S_{AC} = \frac{M}{2}\frac{(z_c - z_a)^2}{t_c - t_a} - \frac{Mg}{2}(z_c + z_a)(t_c - t_a) - \frac{Mg^2}{24}(t_b - t_a)^3$$

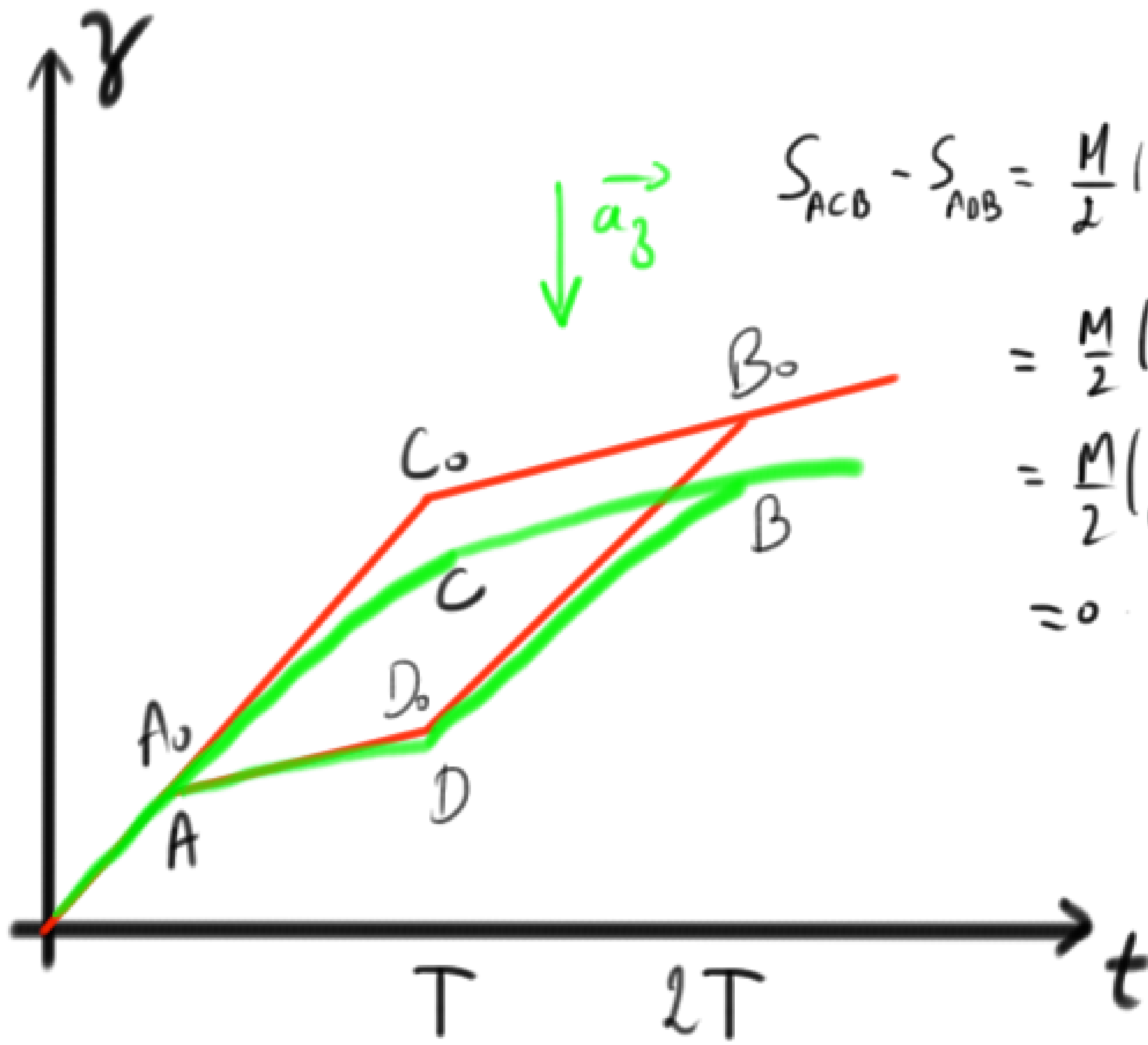


✓ Calculate S_{AC}-S_{AD} and S_{CB}-S_{DB}

$$S_{AC} - S_{AD} = \frac{M}{2T}(z_c - z_d)\left[z_c + z_d - 2z_A - gT^2\right]$$

✓ Sum S_{AC}-S_{AD} and S_{CB}-S_{DB}

- ✓ Sum S_{AC}-S_{AD} and S_{CB}-S_{DB}



$$S_{ACB} - S_{ADB} = \frac{M}{2}(z_C - z_D)\left[z_C + z_D - z_A - z_B - gT^2\right]$$

$$= \frac{M}{2}(z_C - z_D)\left[(z_{C_0} - \cancel{\tfrac{1}{2}gT^2}) + (z_{D_0} - \cancel{\tfrac{1}{2}gT^2}) - z_{A_0} - (z_{B_0} - \cancel{2gT^2}) - \cancel{gT^2}\right]$$

$$= \frac{M}{2}(z_C - z_D)\left[(z_{C_0} + z_{D_0}) - (z_{A_0} + z_{B_0})\right]$$

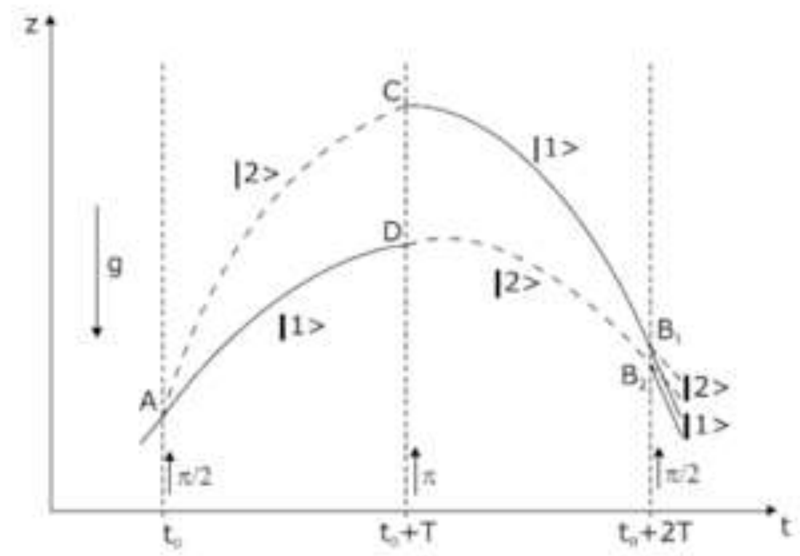
$$= 0$$

No phase shift from matter wave propagation

TOTAL PHASE SHIFT ON ATOM INTERFEROMETER

Three contributions to interferometer phase shift:

$$\Delta\phi_{\text{total}} = \Delta\phi_{\text{prop}} + \Delta\phi_{\text{laser}} + \Delta\phi_{\text{sep}}$$



Propagation shift: $\frac{S_{\text{cl,B}} - S_{\text{cl,A}}}{\hbar}$

Laser fields (Raman interaction): $k(z_c - z_b + z_d - z_a) + \phi_I - 2\phi_{II} + \phi_{III}$

Wavepacket separation at detection: $\vec{p} \cdot \Delta\vec{r}/\hbar$

See Bongs, et al., quant-ph/0204102 (April 2002) also App. Phys. B, 2006.

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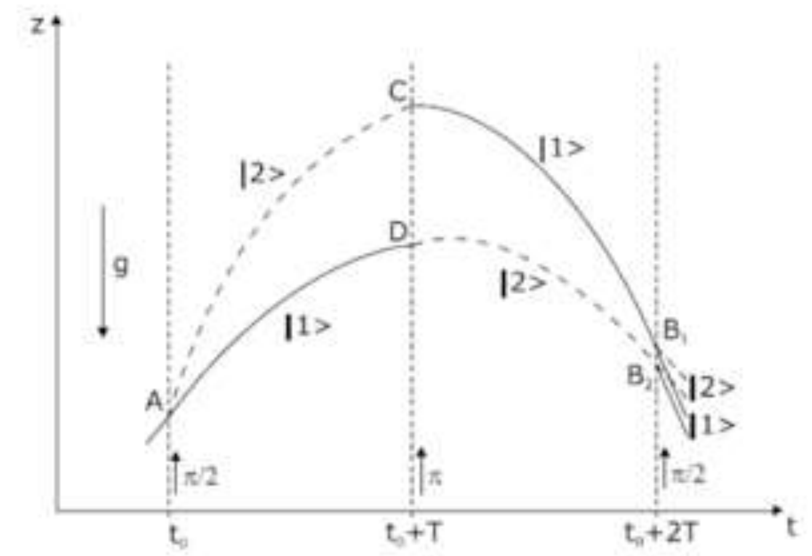

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PHASE SHIFT FROM LASER INTERACTION

- Each time the atom changes state, the laser imprints its phase on the atom

$$|\psi(t)\rangle = c_1(t)|1,p\rangle + c_2(t)|2,p+\hbar k\rangle$$

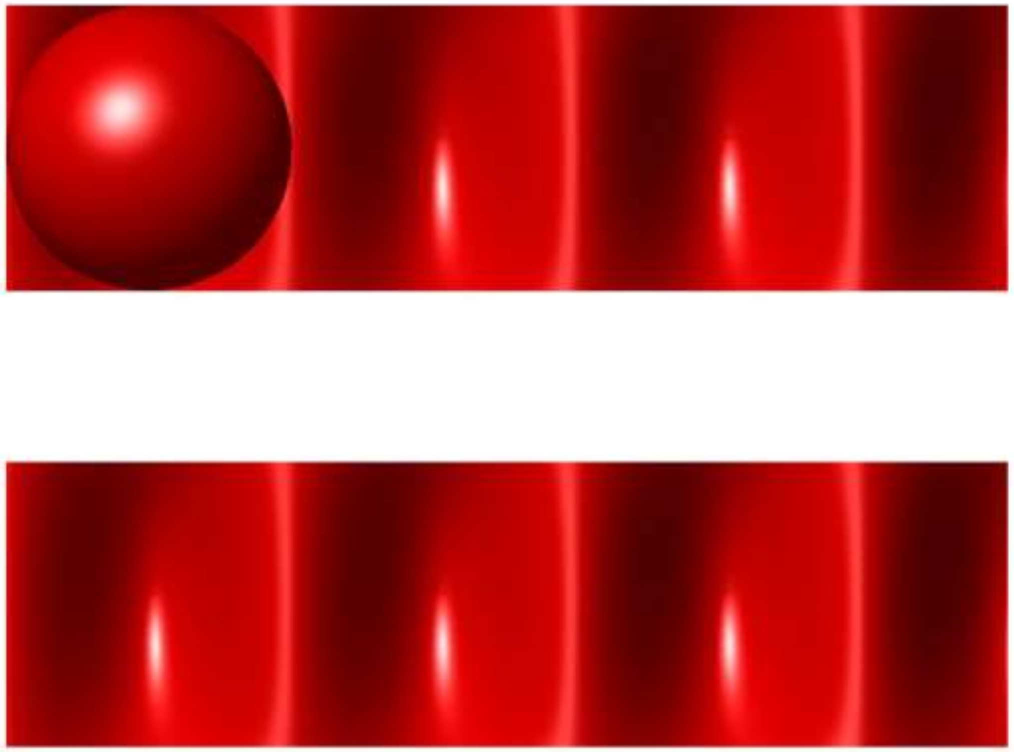
before pulse

$$c_1(t_-) \quad \& \quad c_2(t_-)$$

after pulse

$$c_1(t_+) = \cos\frac{\Omega\tau}{2}\, c_1(t_-) - i\sin\frac{\Omega\tau}{2}\, e^{i(\Delta t+\varphi)}\, c_2(t_-)$$

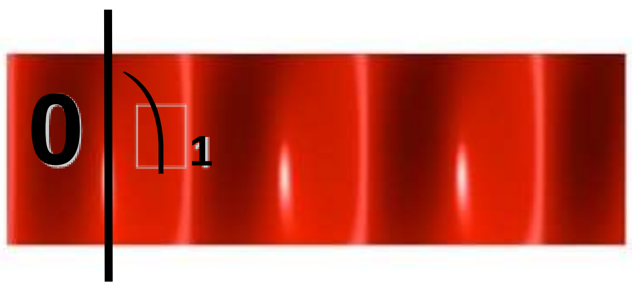
...



«Stationary» Laser Phase e^{ikx}

PHASE SHIFT FROM LASER INTERACTION

- ✓ **Each time the atom changes state, the laser imprints its phase on the atom**



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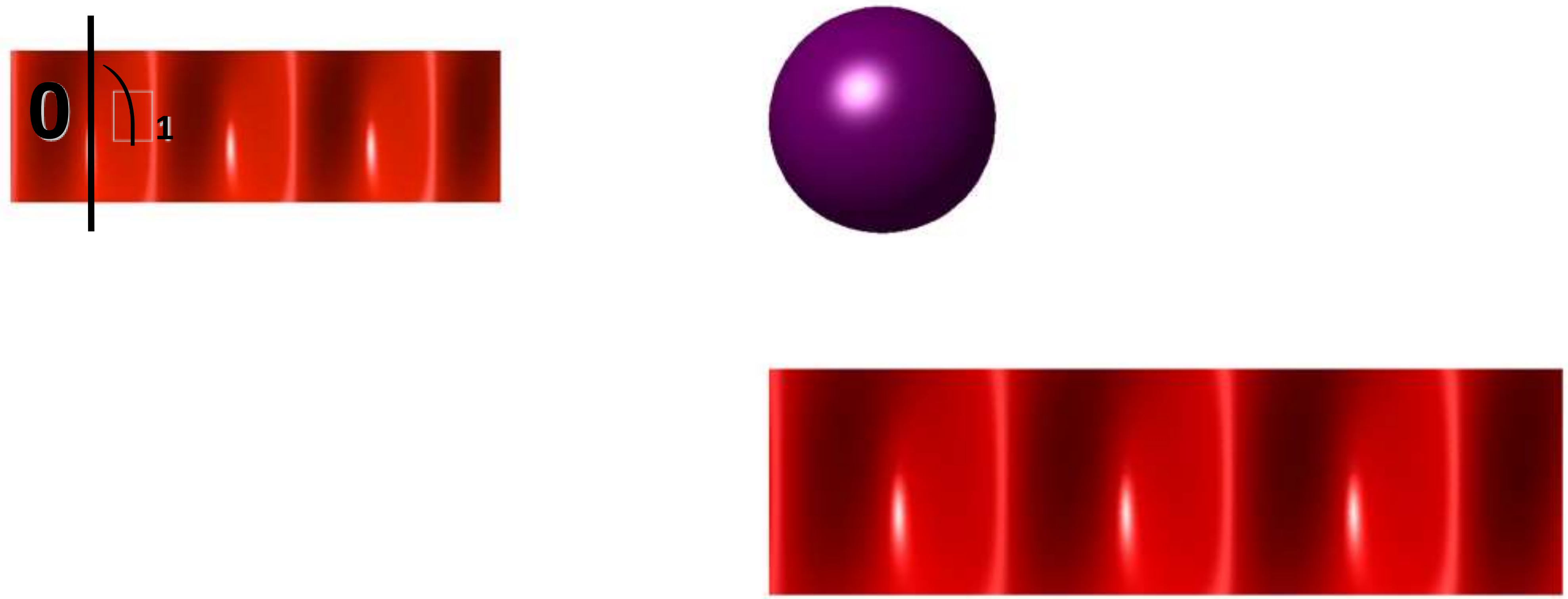

PHASE SHIFT FROM LASER INTERACTION

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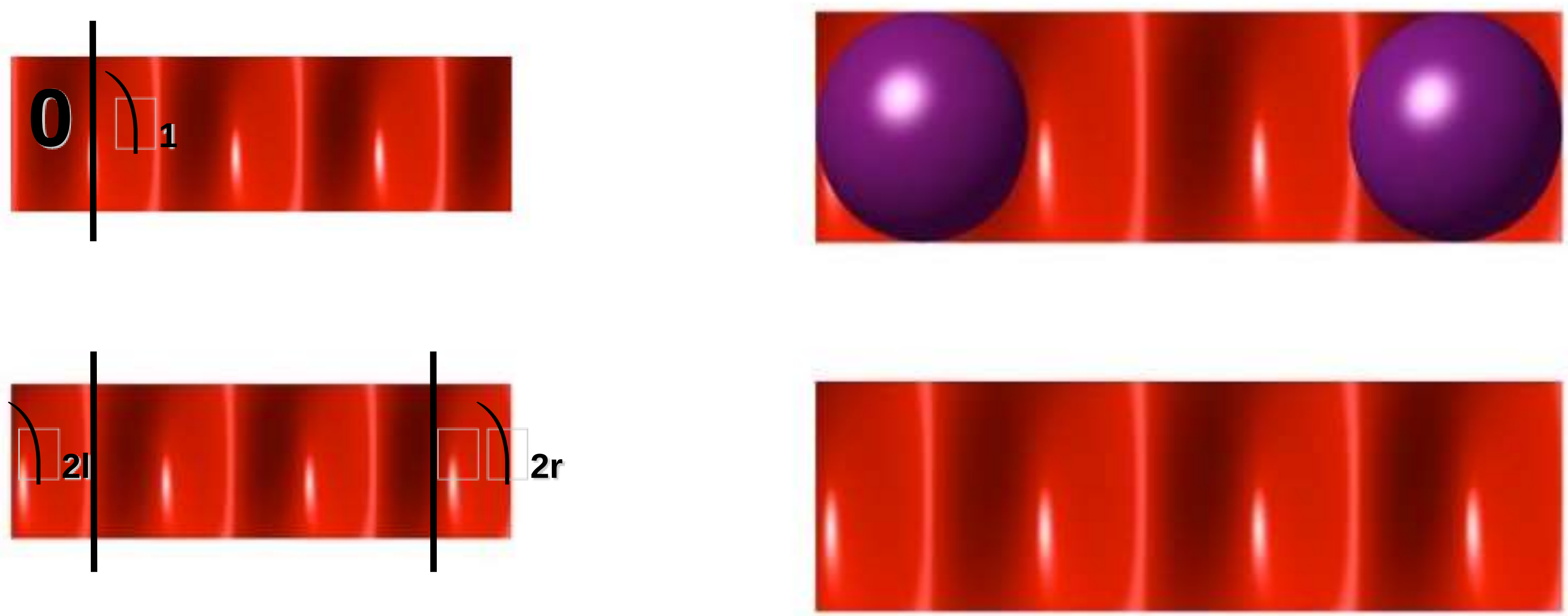

PHASE SHIFT FROM LASER INTERACTION

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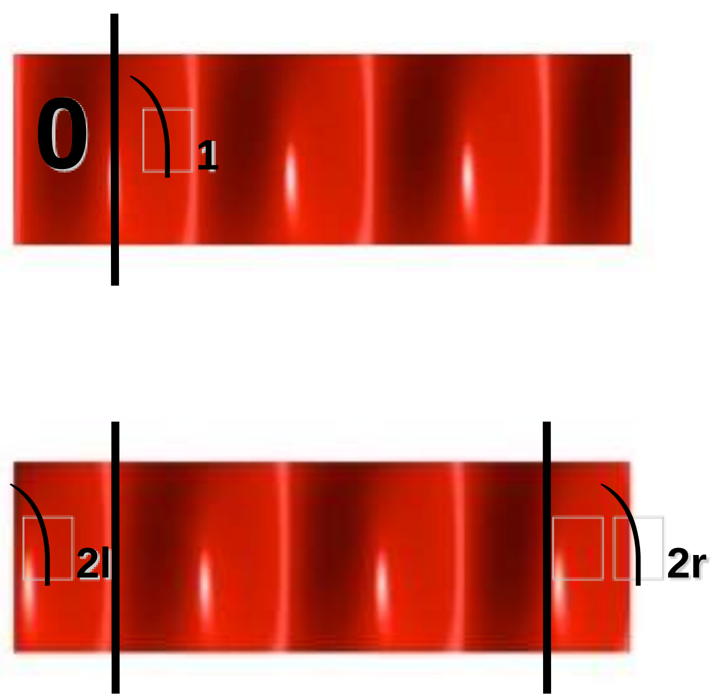

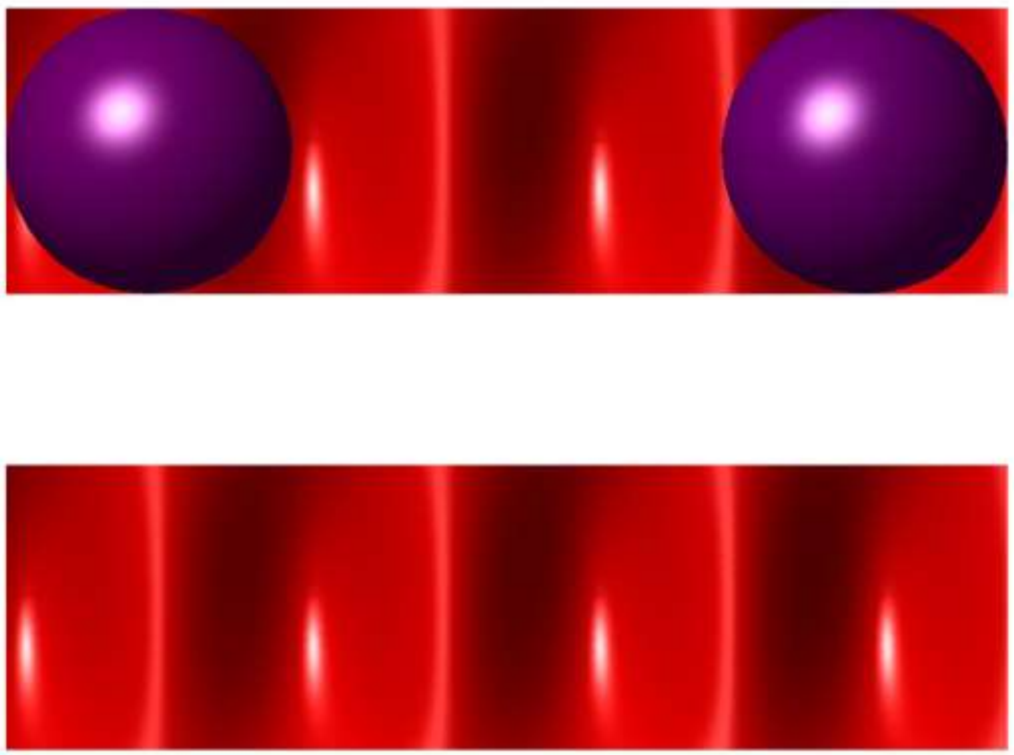

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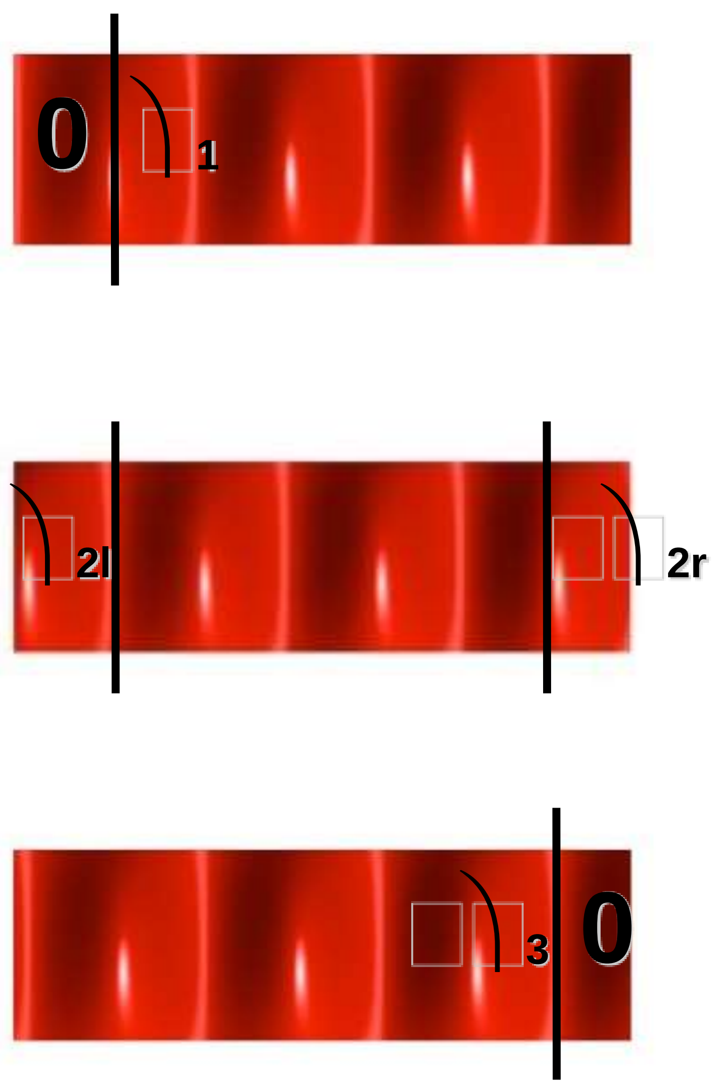
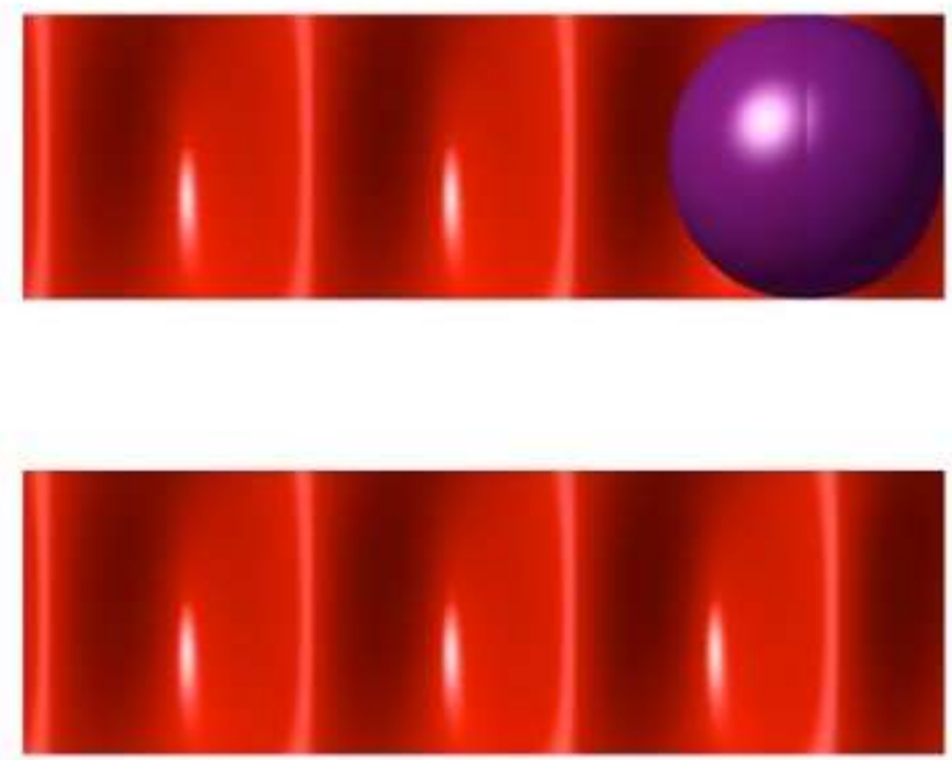
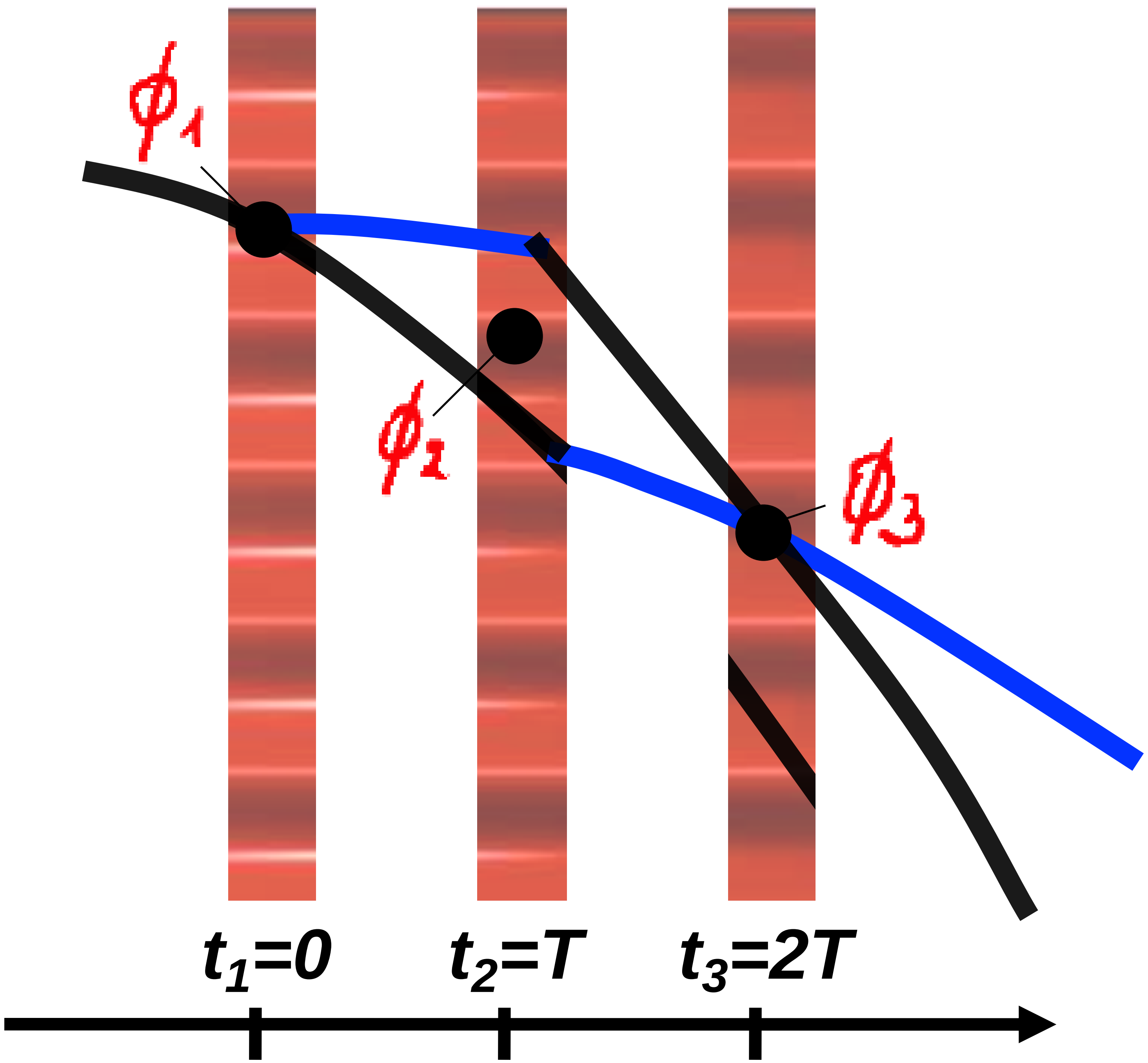




Final phase difference

$$(\varphi_1 - \varphi_{2r}) - (\varphi_{2l} - \varphi_3)$$

TOTAL PHASE SHIFT ON ATOM INTERFEROMETER



- The fact that each splitting process "imprints" the laser phase makes the laser act as a "ruler"
  - We read the atom position with the laser

- The phase depends on the center of mass position of the atomic WP :

$$\Phi(t_i) = kx(t_i) + \Phi_0$$

$$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$$

Accelerometer

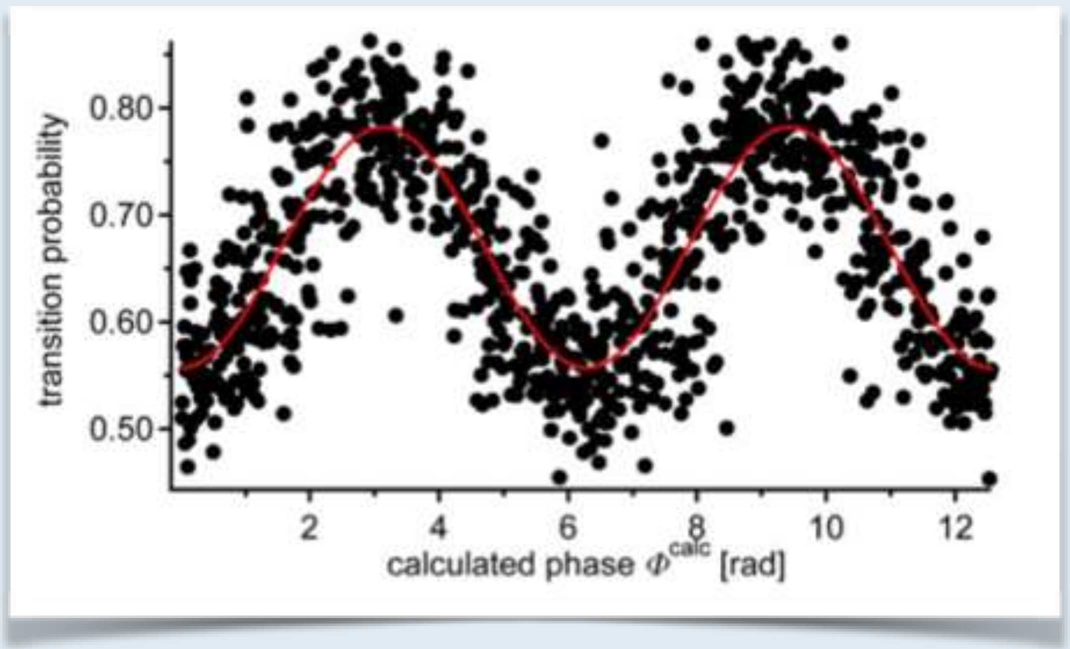
$$\Delta a_{min} = \frac{a/\Delta\phi \cdot 1\,\mathrm{rad}}{\sqrt{N}} = \frac{1}{k T^2 \sqrt{N}}$$

- The atoms "reads" its position and we get it with atom interferometry
  - ⇰ velocity measurement proportional to T
  - ⇰ Acceleration measurement proportional to T^2

ATOM ACCELEROMETER

- Interference fringes : $N_{at} \sim \cos(2\pi a T^2/\lambda + \Phi)$

$\cos(k x + \Phi_0)$



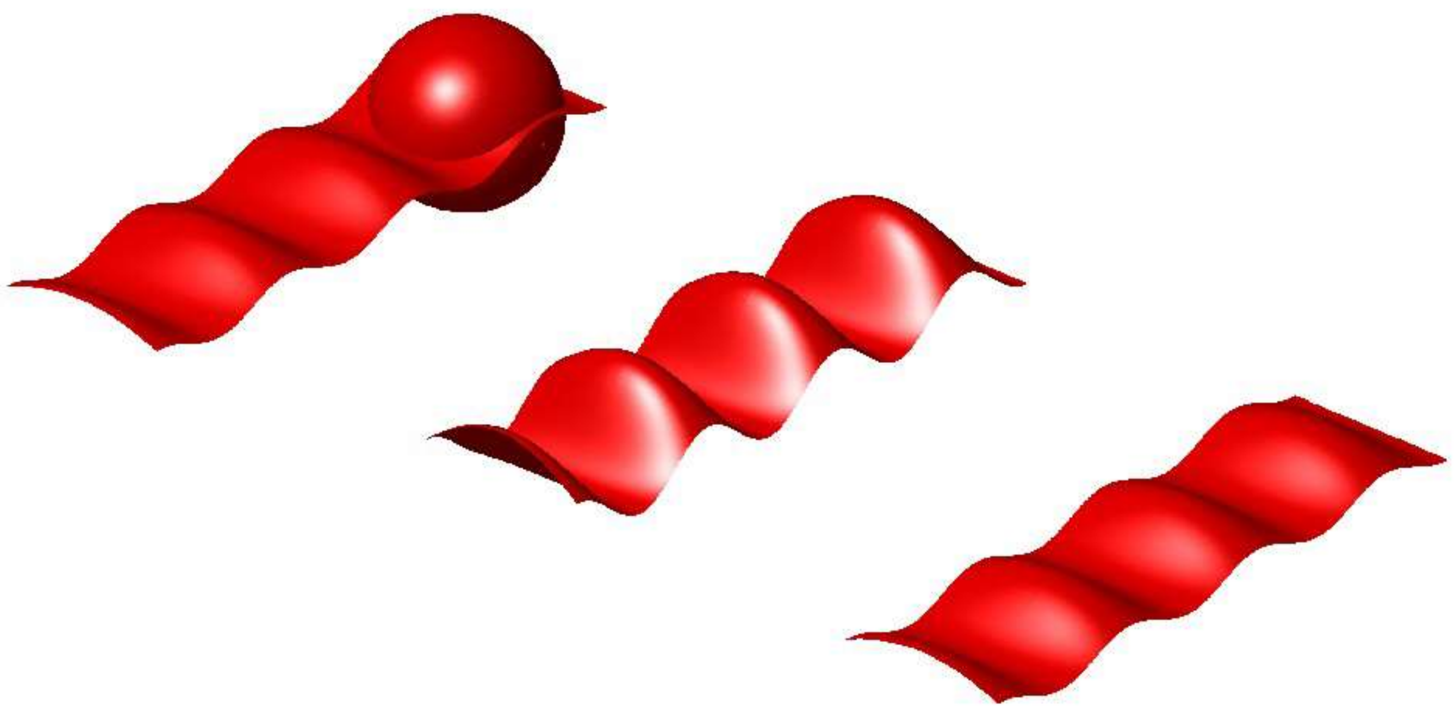
$$\Delta\phi \sim \frac{2\pi}{\lambda_{laser}} g T^2$$

⇨ **If we have a S/N ration of 1000, the sensitivity of the accelerometer is (T = 1s) :**

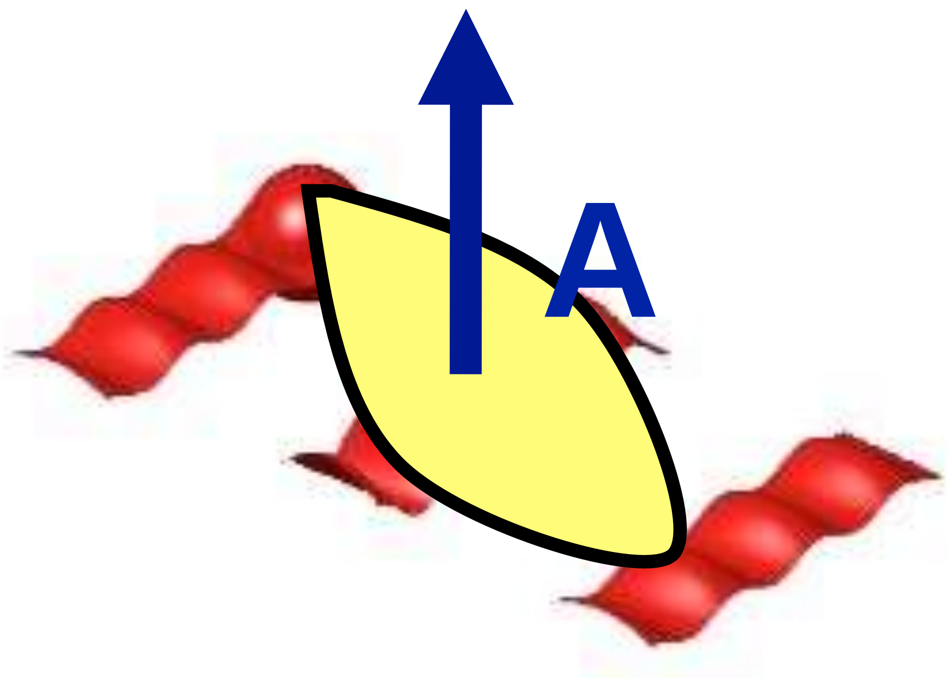
$$\Delta g_{min} \sim \frac{\lambda_{laser}}{6000} \frac{1}{T^2} \sim \frac{6\ 10^{-7}}{6\ 10^{3}} \sim 10^{-10}\ m.s^{-2}$$

GYROMETER

- ✓ **3 separated diffraction zones**
- ✓ **Corriolis acceleration comes from rotating lase**



GYROMETER

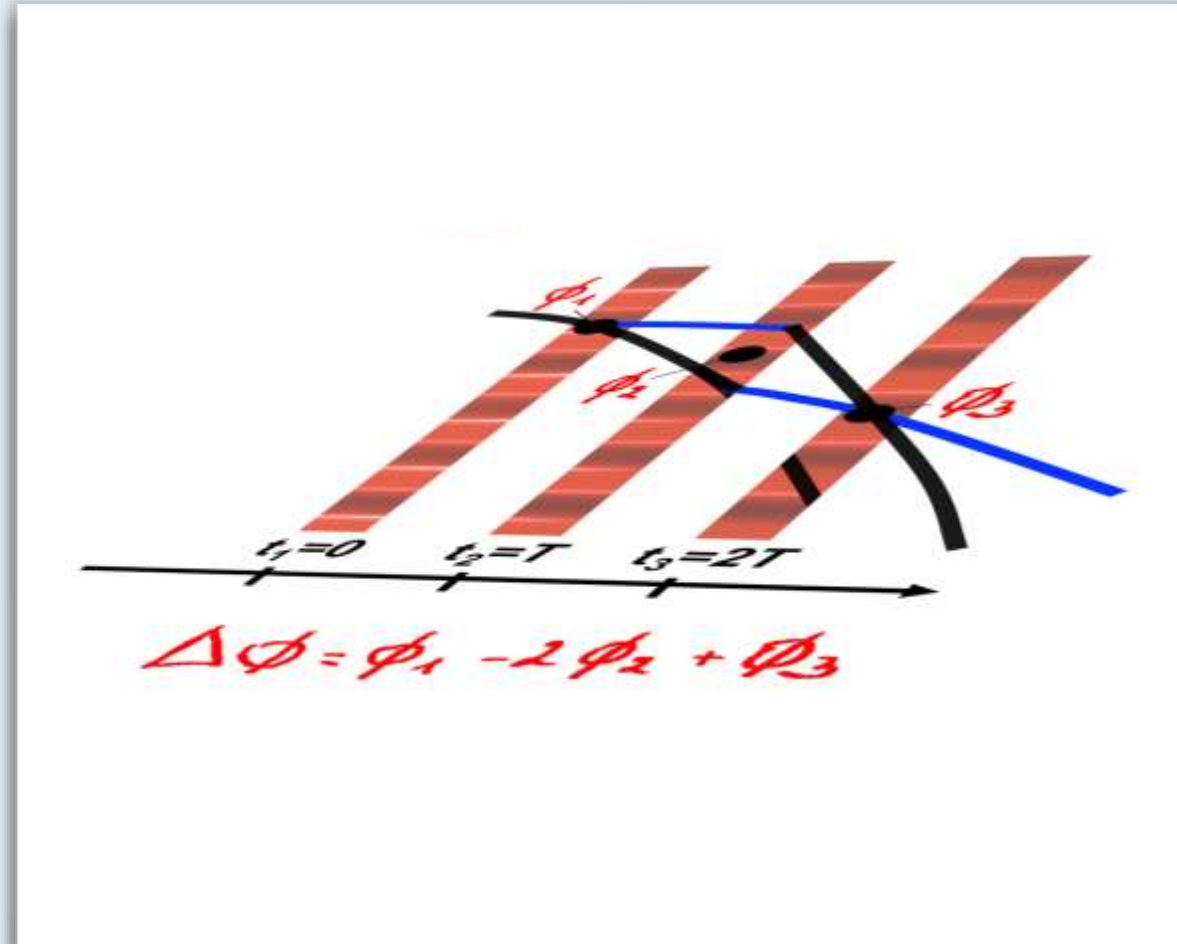


1 GeV/nucléon

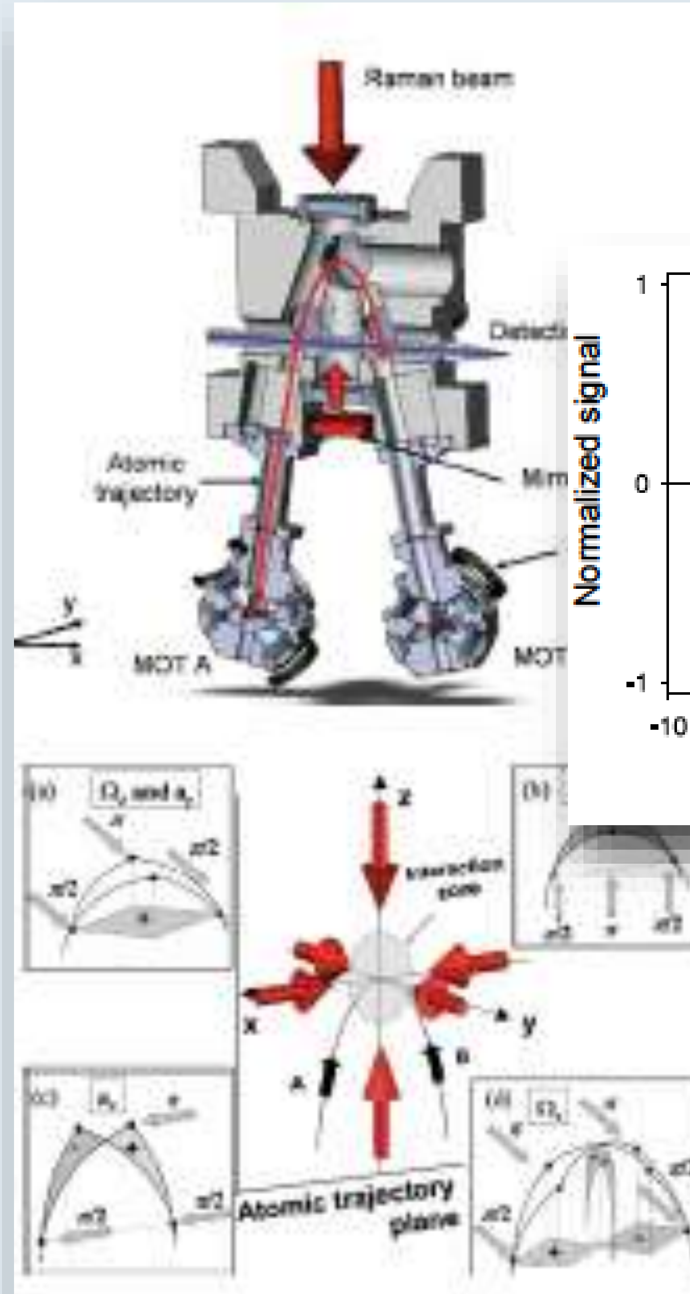
$$\Delta R = \frac{d\phi_{dB}}{d\phi_{ph}} = \frac{c\,\lambda_{ph}}{v\,\lambda_{dB}} \simeq \frac{Mc^2}{\hbar\,\omega_0} \simeq 10^{11}$$

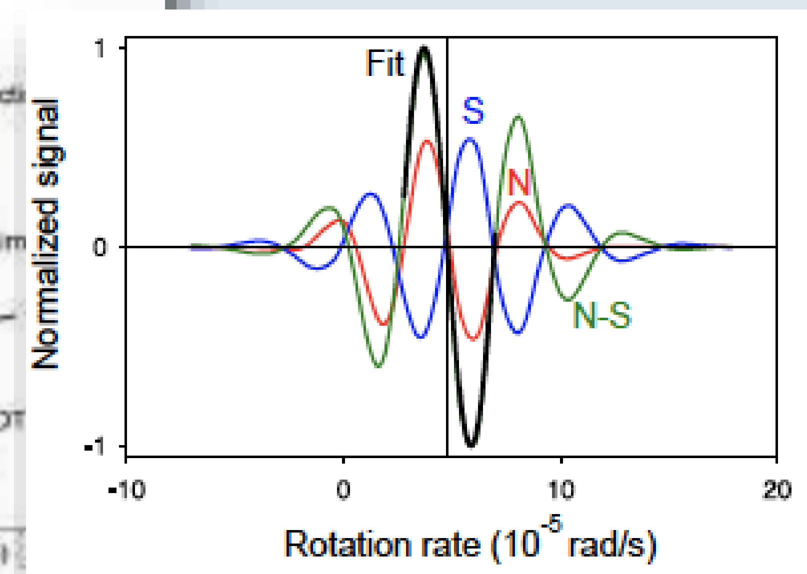
1 eV

ATOM GYROSCOPE



$$\Delta\Phi_{rot} = 2\pi \frac{2\, m_{at}}{h} A \times \Omega = L^2 \frac{v_t}{v_L} \Omega$$





AI gyroscope, demonstrated laboratory performance:

2×10^{-6} deg/hr$^{1/2}$ ARW; $< 10^{-4}$ deg/hr bias stability

Lecture 2 : Measuring acceleration and rotations - method, precision, accuracy

✓First pulse is the 1st beam splitter

⇨ Coherent superposition

⇨ Different speed

⇨ The two components split

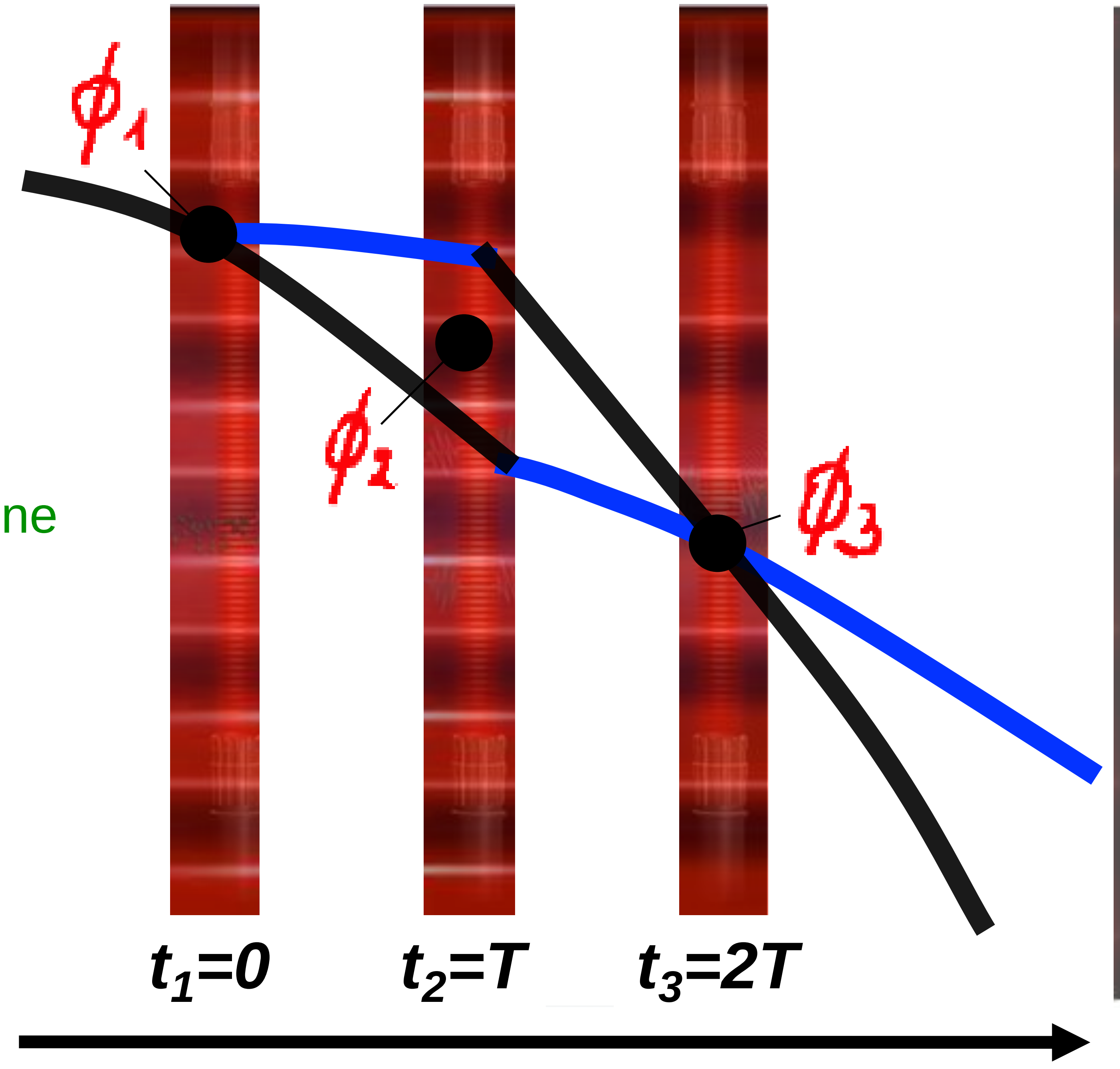
✓second pulse : mirror

⇨ redirect wavepackets

✓Last π/2 pulse when wavepackets recombine

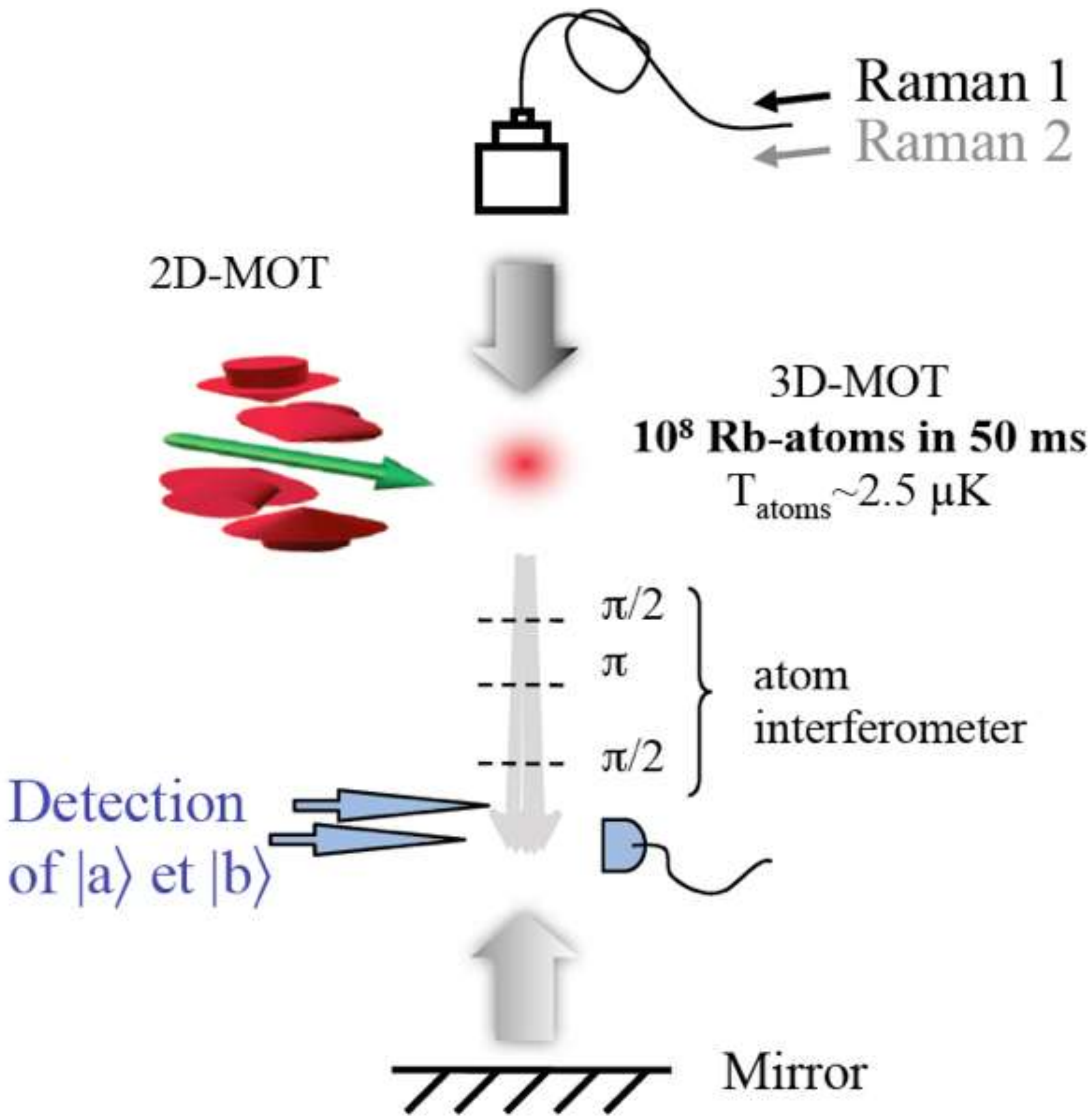
⇨ output depends on phase difference

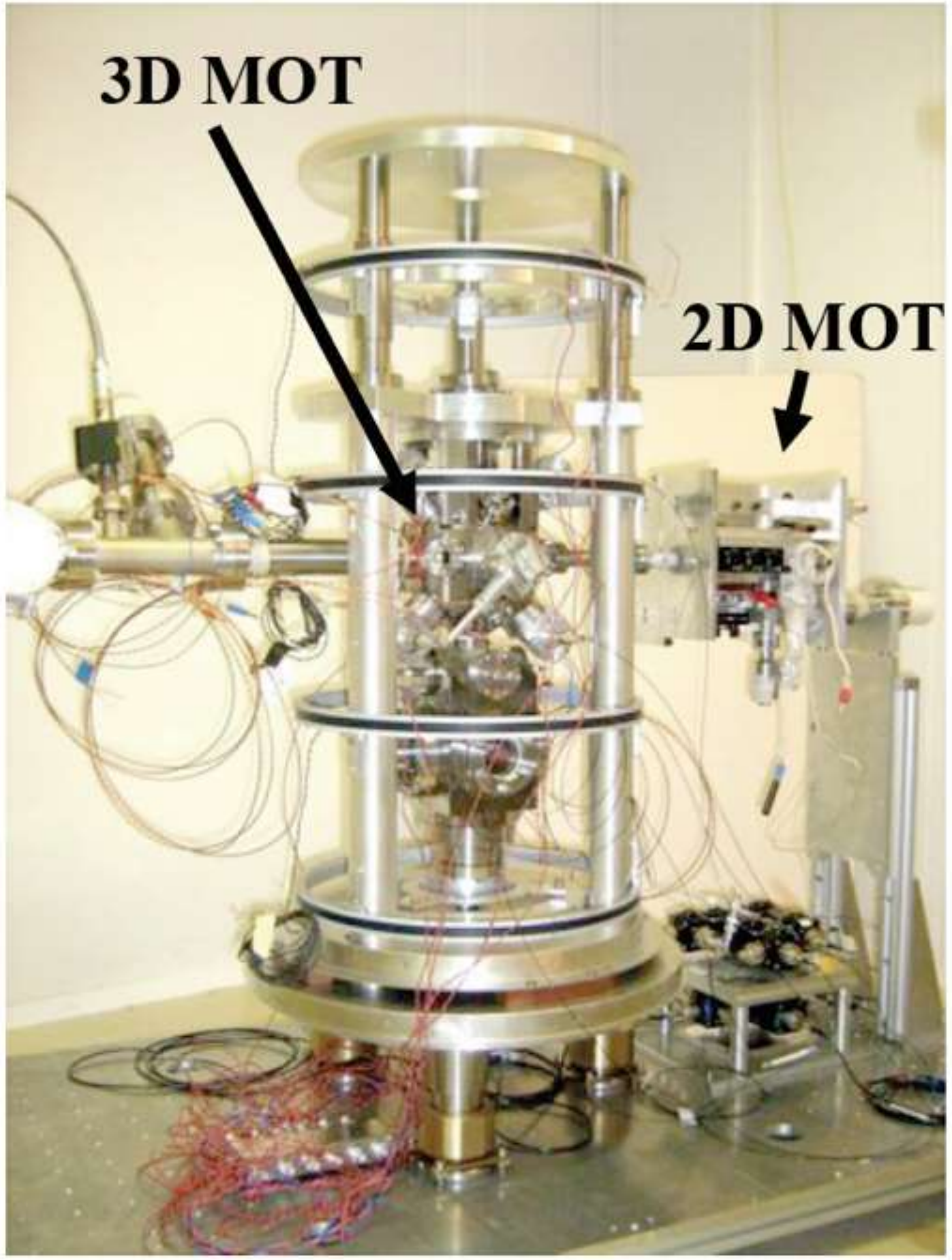
❑ The phase depends on the center of mass position of the atomic WP : $\Phi(t_i) = kx(t_i) + \Phi_0$



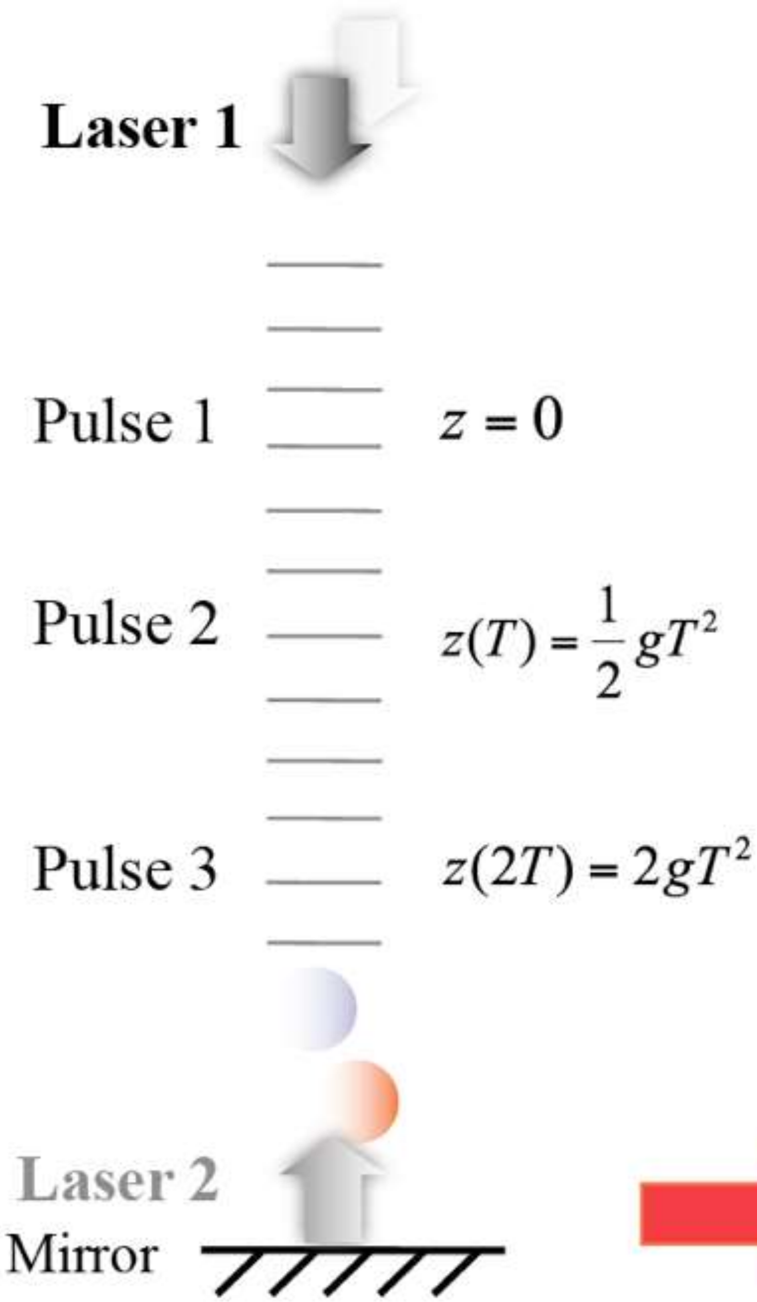
$\Delta\phi = \phi_1 - 2\phi_2 + \phi_3$

ATOM GRAVIMETER





ATOM GRAVIMETER



Vertical interferometer

⇒ Free fall along the equiphase planes

Sensitivity to gravity acceleration :

$$\Delta\Phi_{\text{int}} = -\vec{k}_{eff}\,\vec{g}\,T^2 + \delta\Phi_{noise} + \delta\Phi_{sys}$$

Two overlapped Raman beams retroreflected

⇒ Equiphases defined by the mirror position

$\alpha\ (z_1 - 2\, z_2 + z_3)$

measure of the relative displacement atoms/mirror with a very precise ruler

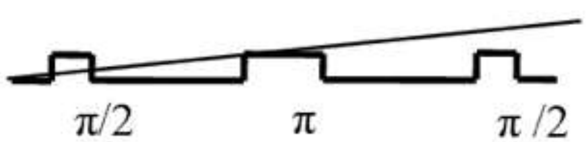
ATOM GRAVIMETER

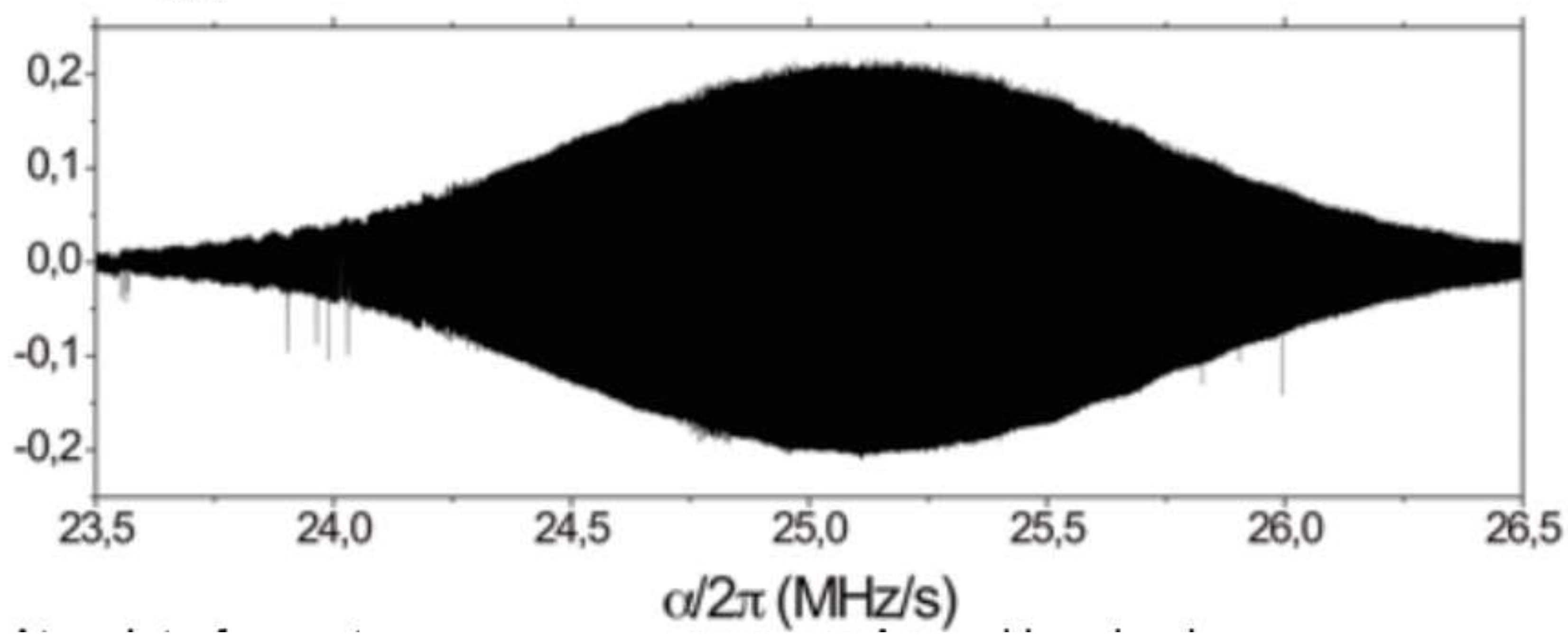
- Free fall → Doppler shift of the resonance condition of the Raman transition

$$\omega_1 - \omega_2 = \omega_e - \omega_f + \vec{k}_{eff}\,\vec{v}(t) + \frac{hk_{eff}^2}{2m}$$

- Ramping of the frequency difference to stay on resonance : $\omega = \omega_0 + \alpha\, t$

$$\boxed{\Delta\Phi = \overrightarrow{k_{eff}}\,\vec{\mathbf{g}}\,T^2 - \alpha\, T^2}$$





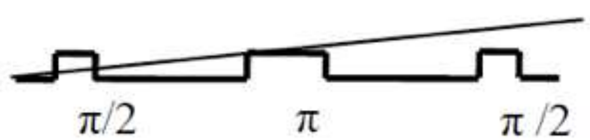
Atom gravimeter

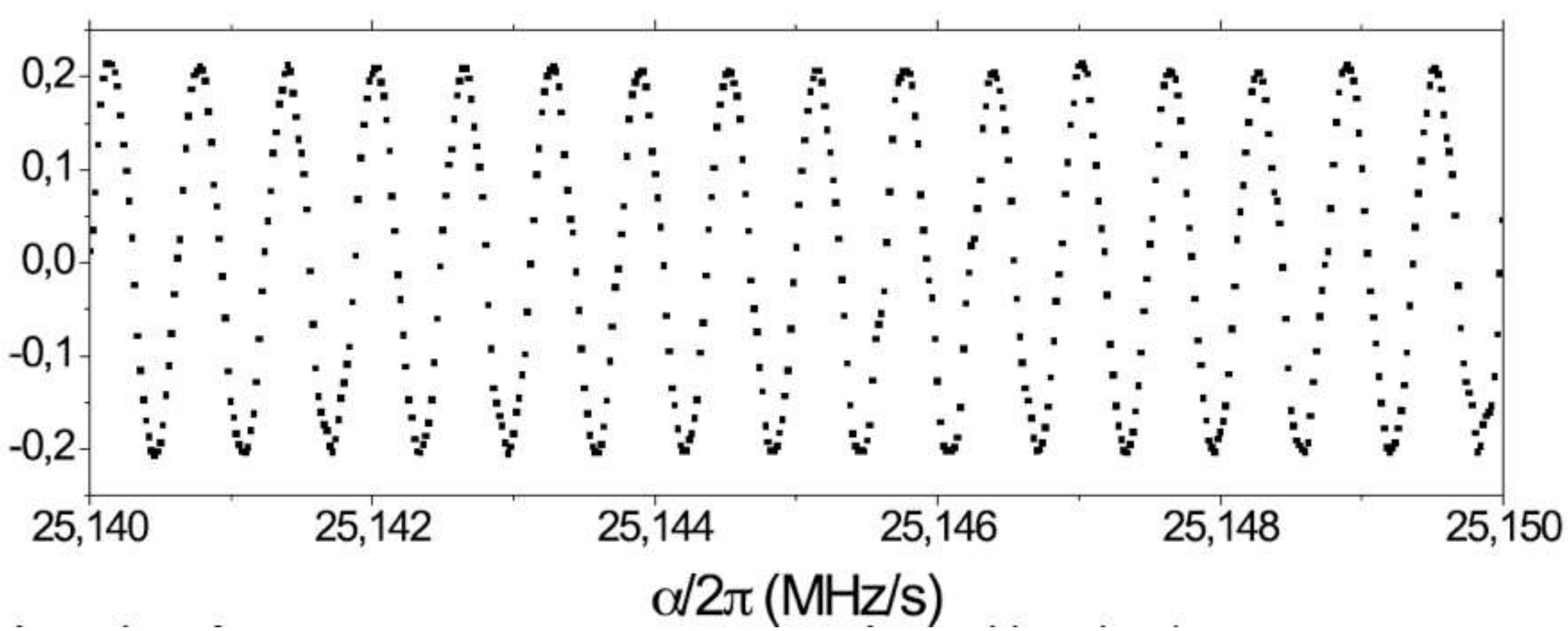
- Free fall → Doppler shift of the resonance condition of the Raman transition

$$\omega_1 - \omega_2 = \omega_e - \omega_f + \vec{k}_{eff}\,\vec{v}(t) + \frac{hk_{eff}^2}{2m}$$

- Ramping of the frequency difference to stay on resonance : $\omega = \omega_0 + \alpha\, t$

$$\boxed{\Delta\Phi = \overrightarrow{k_{eff}}\,\vec{\boldsymbol{g}}\,T^2 - \alpha\, T^2}$$





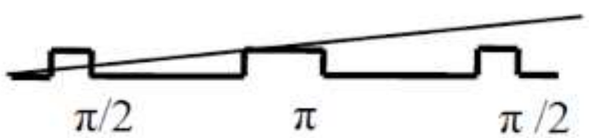
ATOM GRAVIMETER

- Free fall → Doppler shift of the resonance condition of the Raman transition

$$\omega_1 - \omega_2 = \omega_e - \omega_f + \vec{k}_{eff}\,\vec{v}(t) + \frac{hk_{eff}^2}{2m}$$

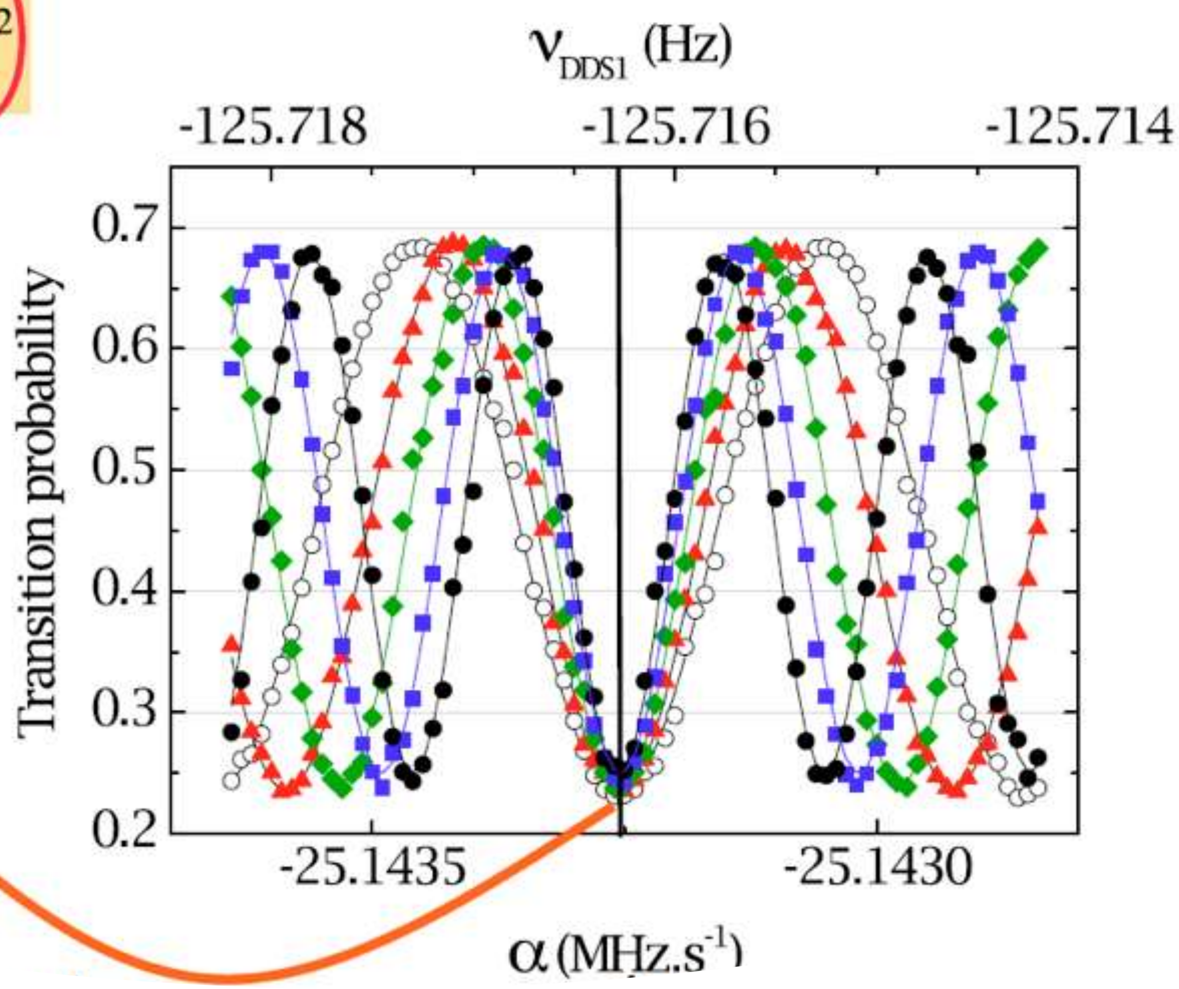
- Ramping of the frequency difference to stay on resonance : $\omega = \omega_0 + \alpha\ t$

$$\Delta\Phi = \overrightarrow{k_{eff}}\ \vec{\boldsymbol{g}}\,T^2 - \alpha\ T^2$$

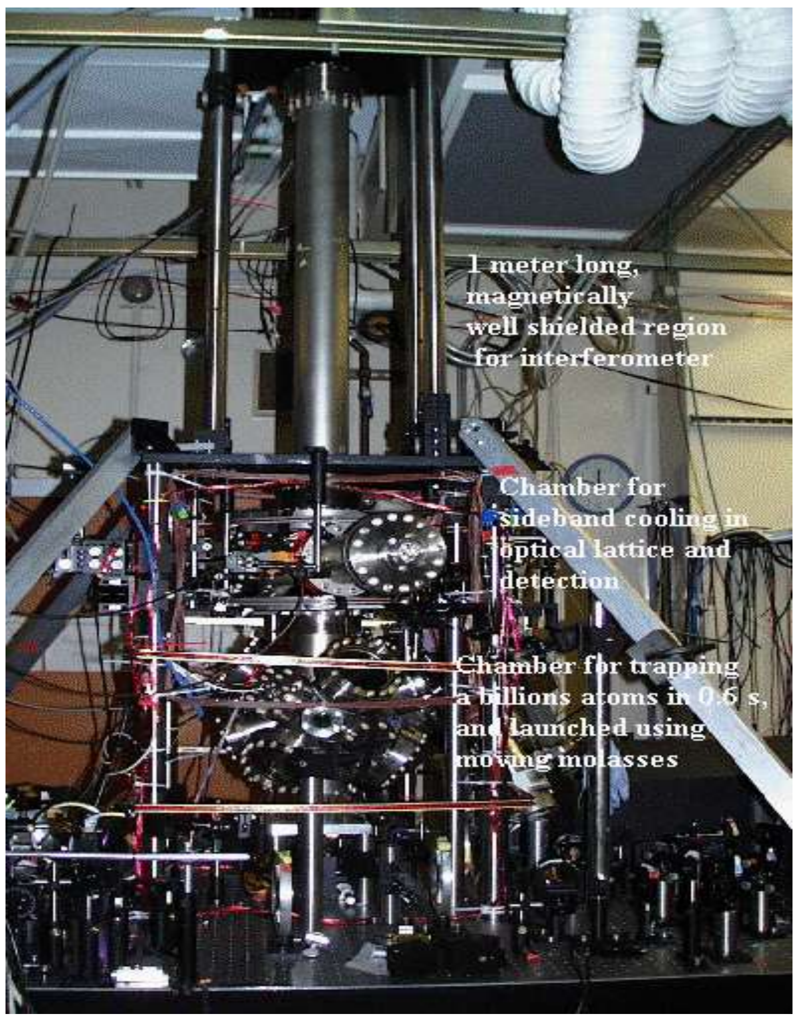


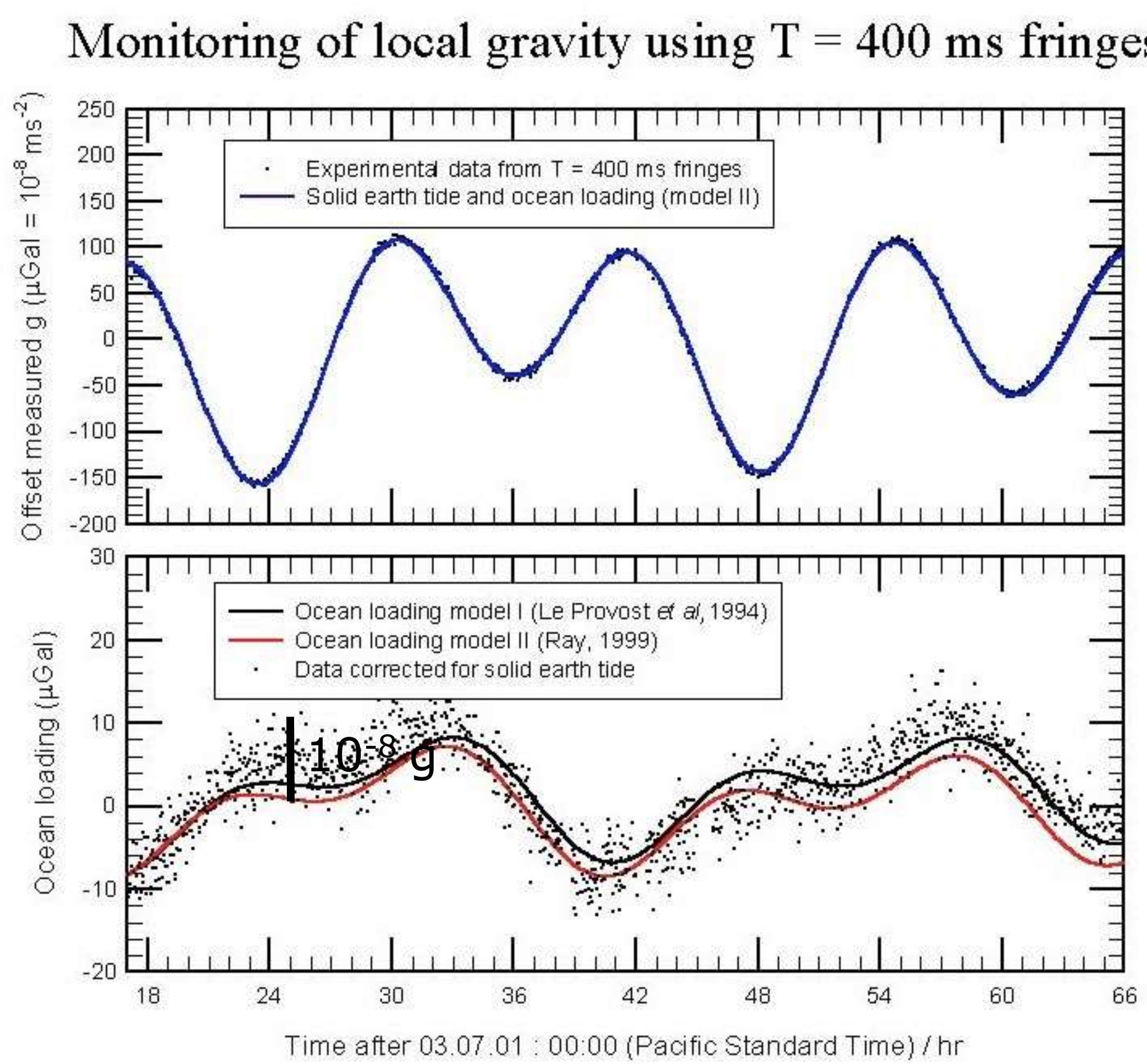
- Dark fringe : independent of T

$$\boldsymbol{g} = \frac{\alpha_0}{k_{eff}}$$

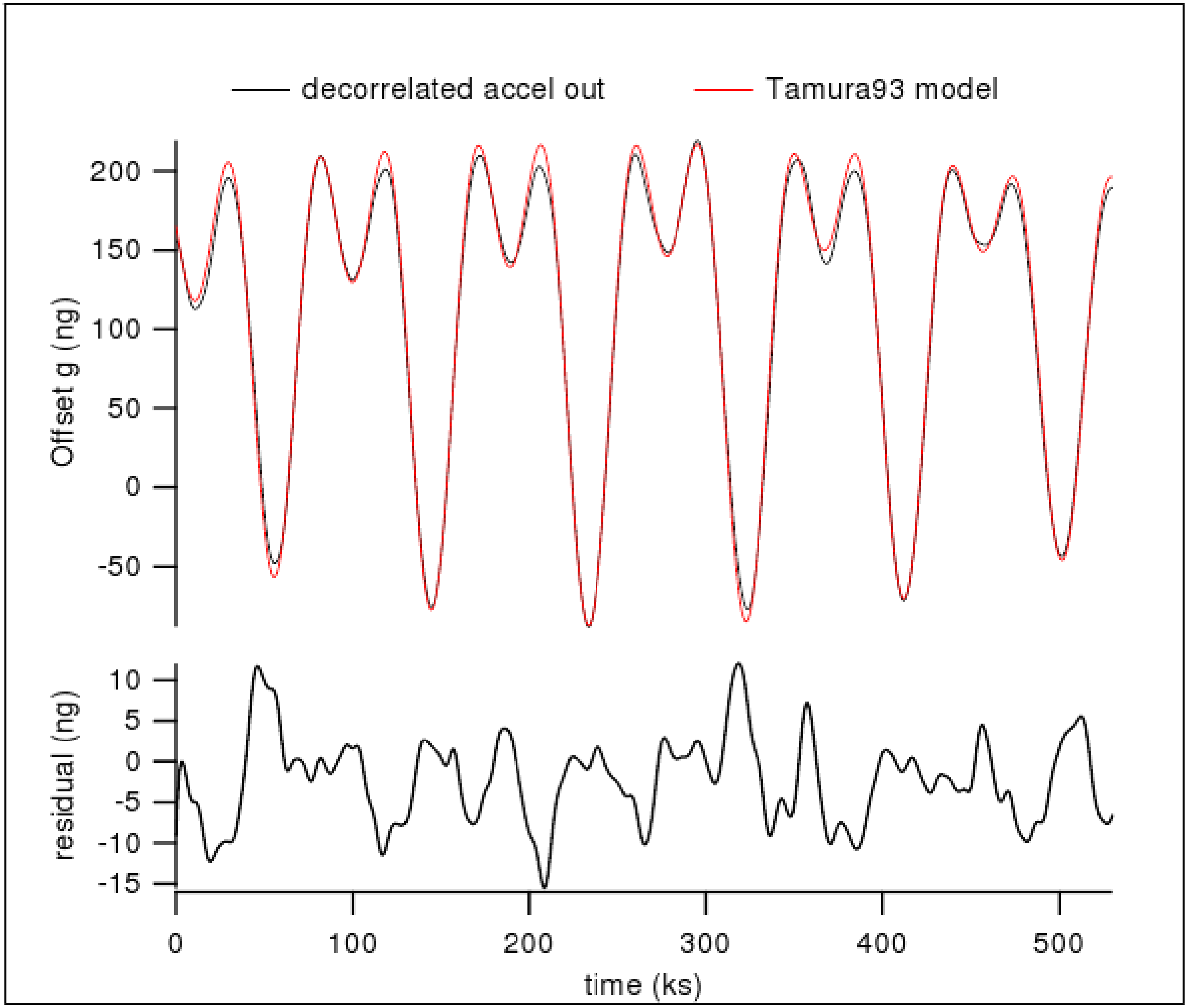


FIRST GRAVIMETER AT STANFORD UNIV.

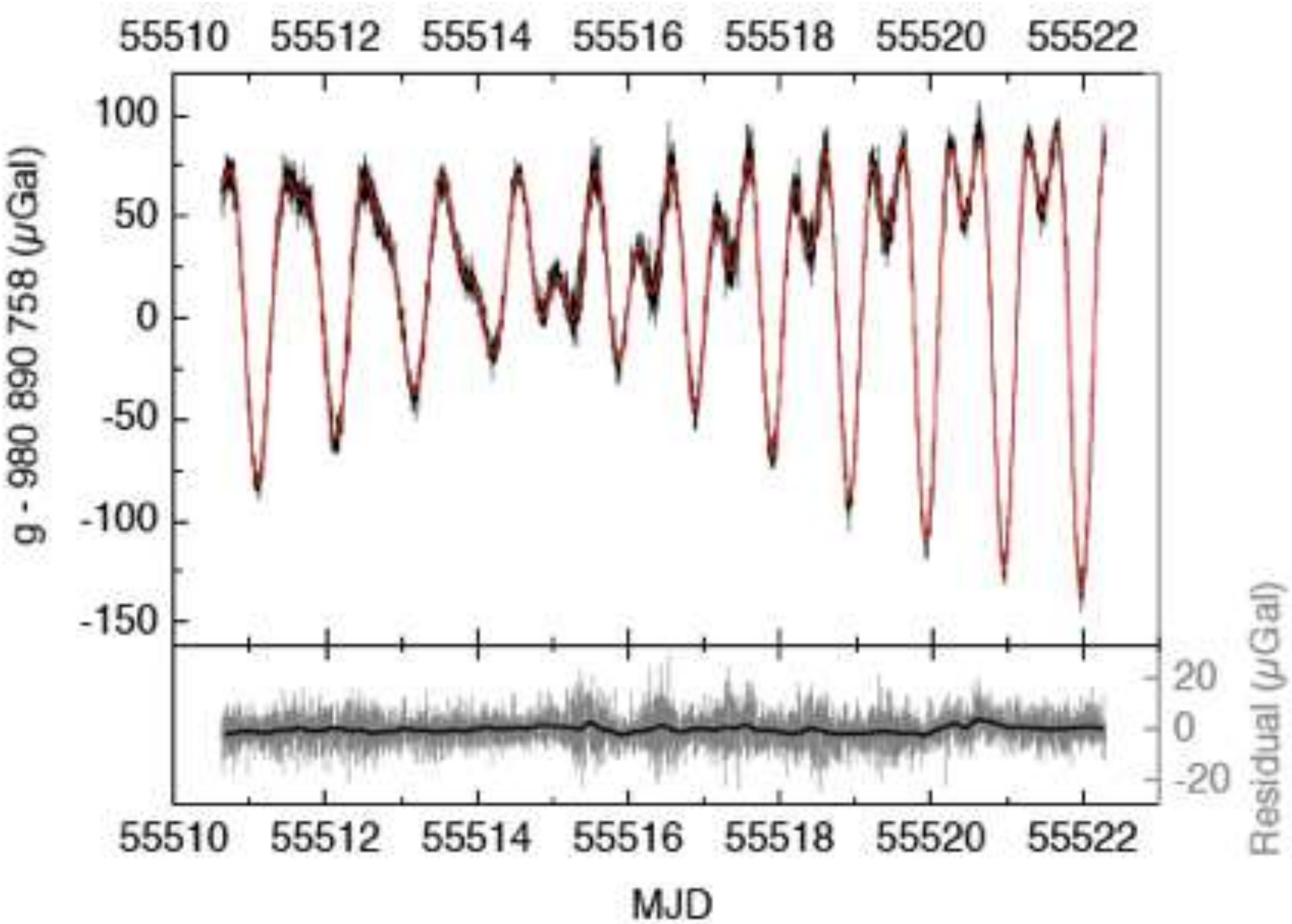


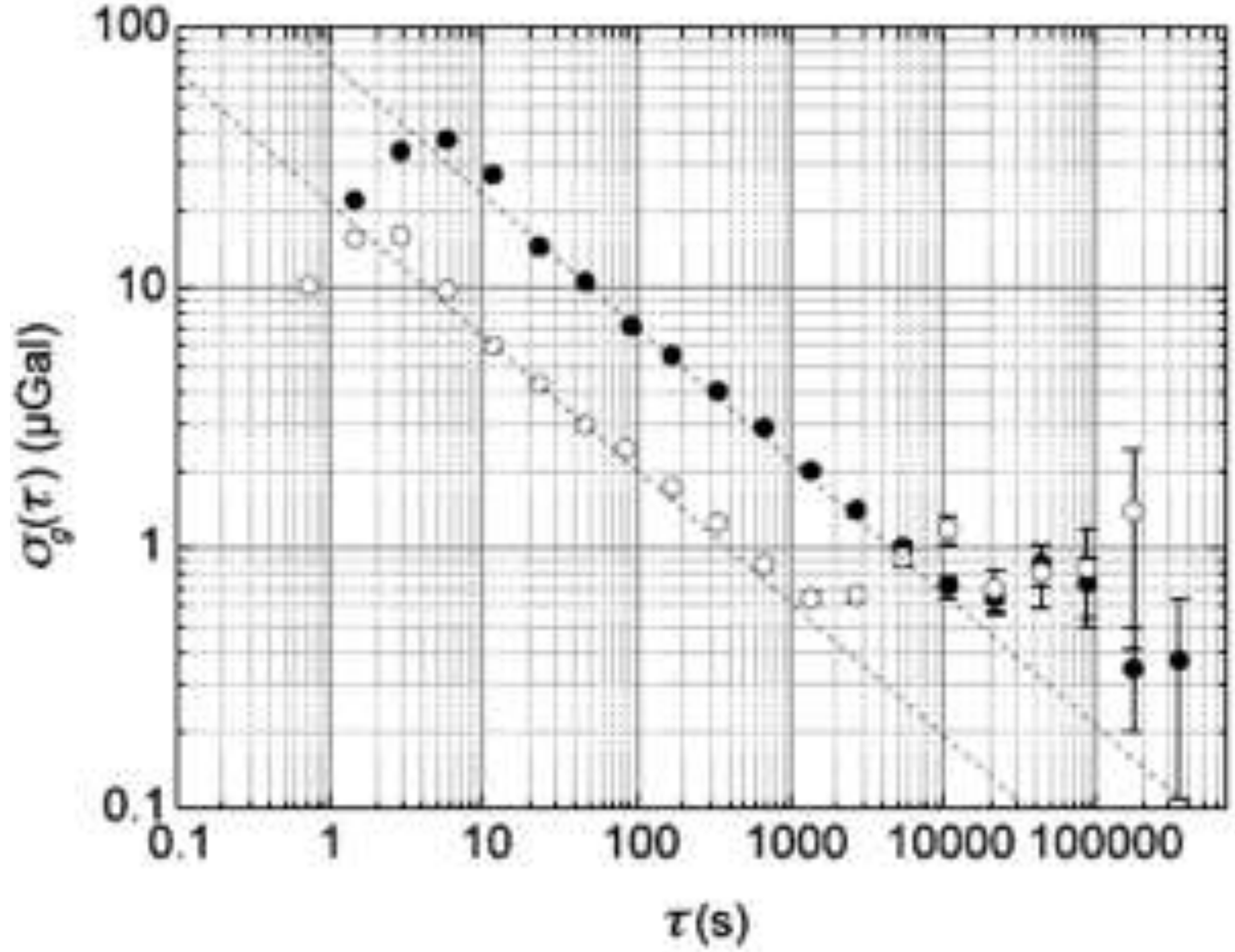


AOSENSE INC. "COMMERCIAL" GRAVIMETER



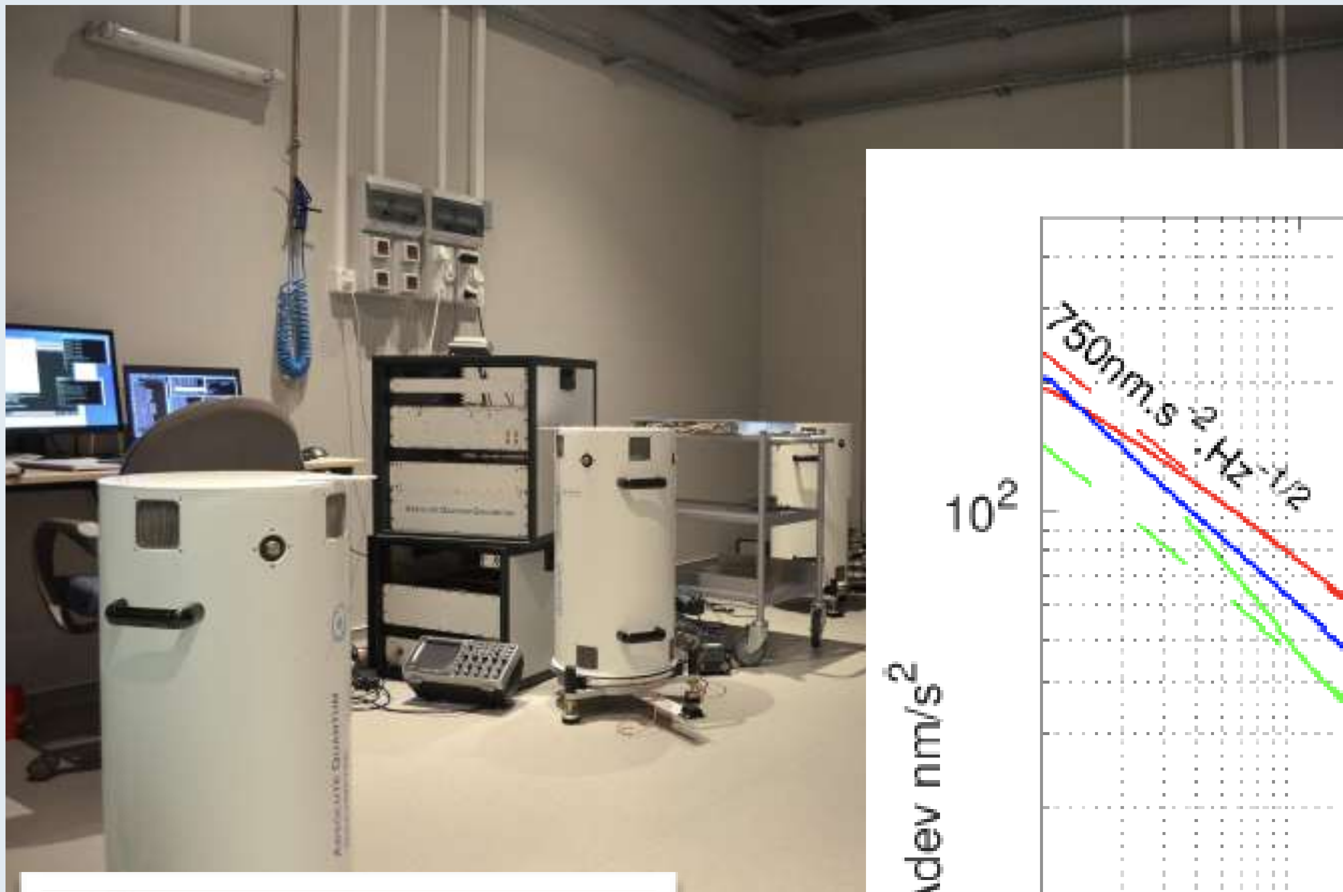
SYRTE GRAVIMETER

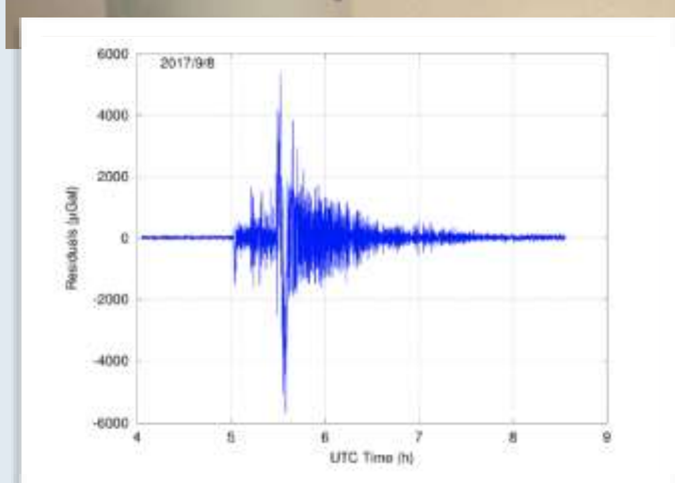


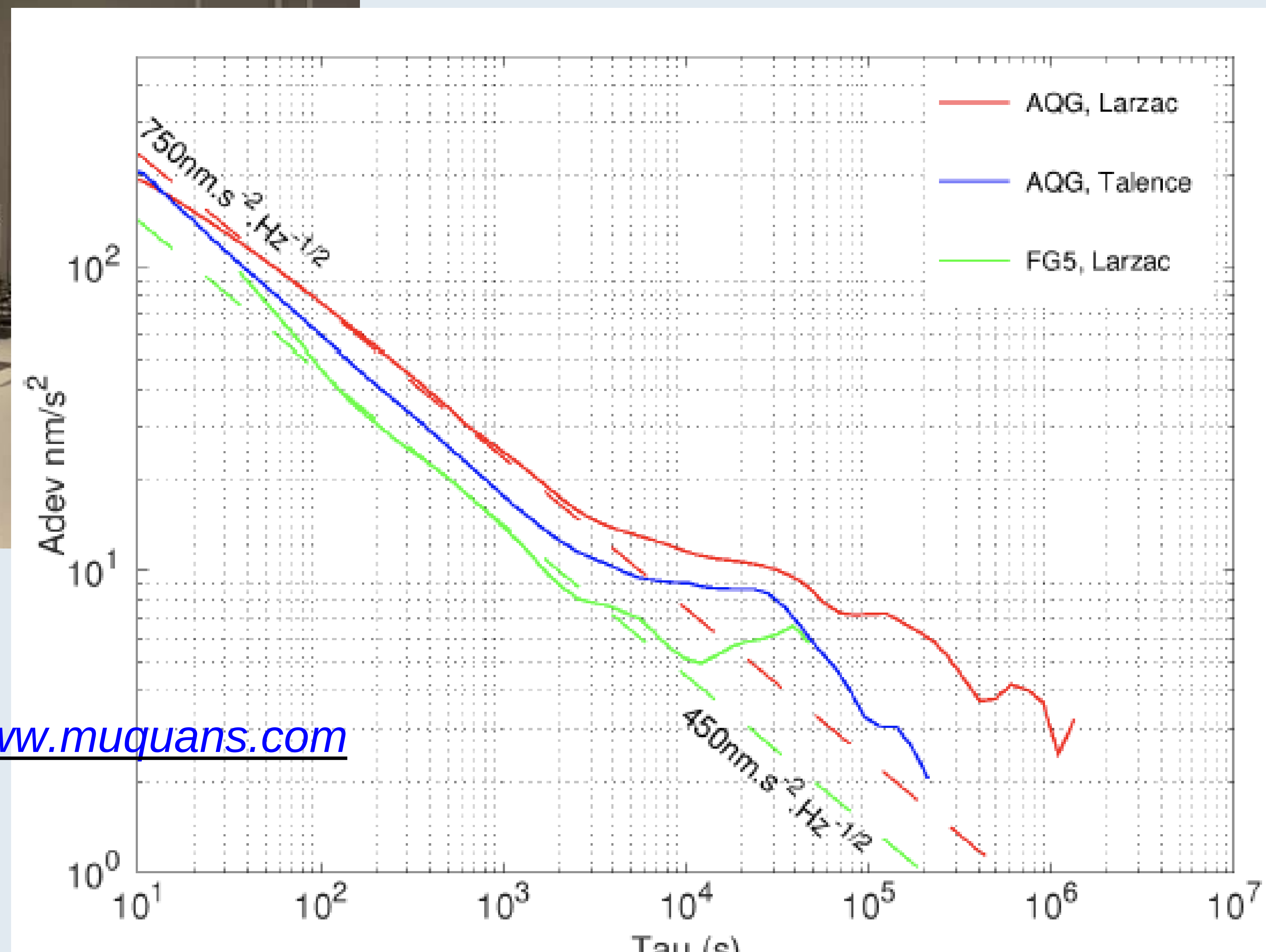


- Excellent agreement measurement/tide model
  - Tides : ± 10-7 g
  - (1 **µ**Gal = 10-8 m.s-2, ou ~10-9 g)
  - Accuracy at 5.10-9 level
- Long term stability : < 7 10-10g
  - International gravity comparison in BIPM 2009 : S. Merlet, et al., Metrologia 47, L9-L11 (2010); A. Louchet-Chauvet et al, IEEE (2011), arXiv:1008.2884.

COMMERCIAL GRAVIMETER @ MUQUANS

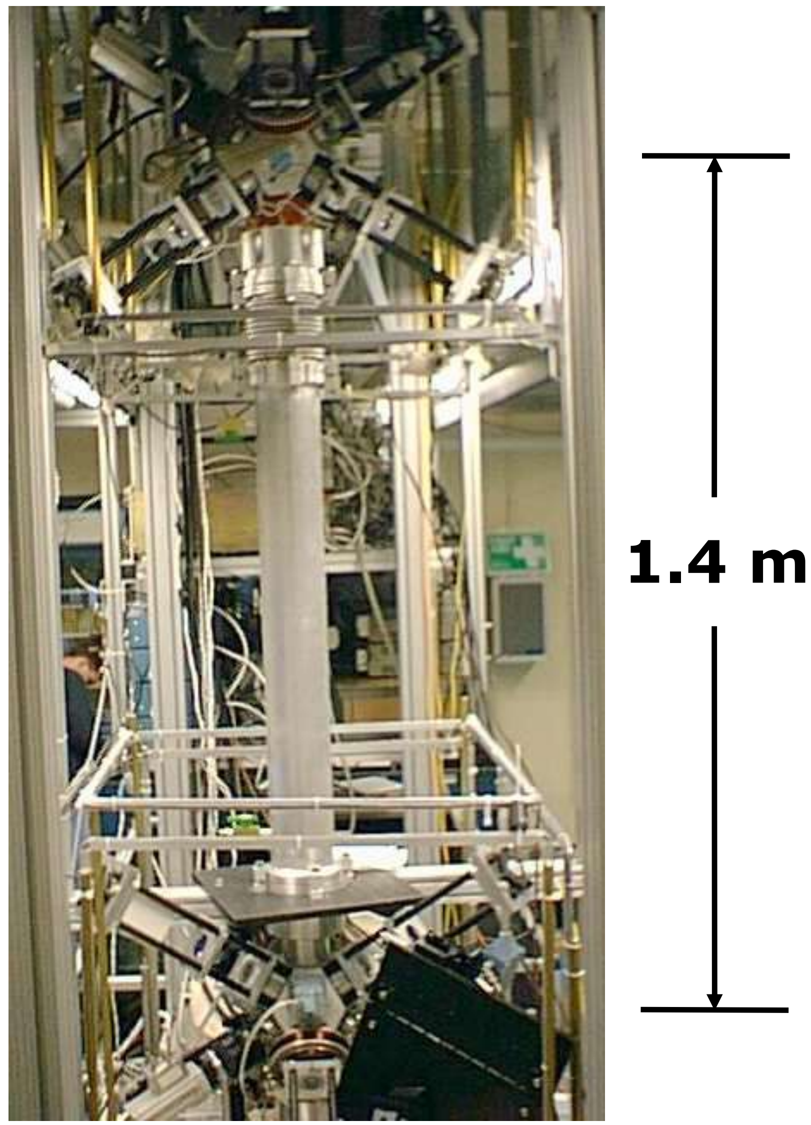


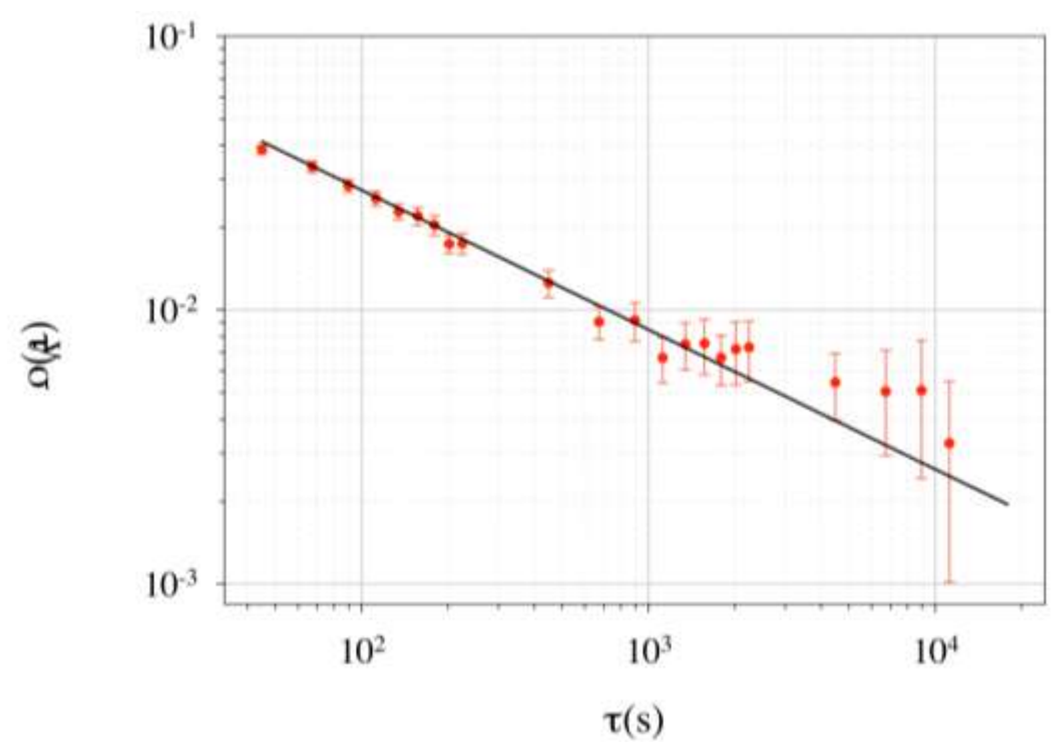




www.muquans.com

GRAVITY GRADIOMETER





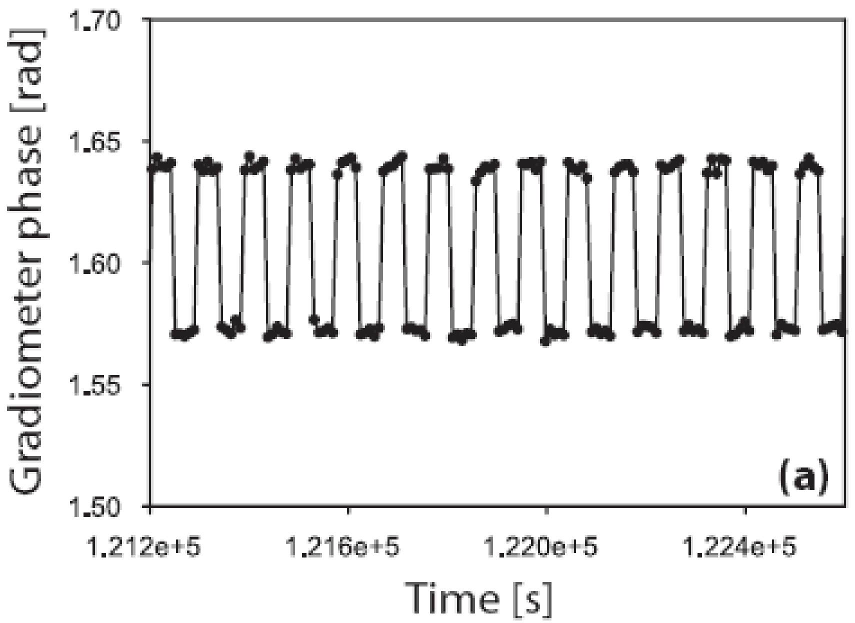
Distinguish gravity induced accelerations from those due to platform motion with differential acceleration measurements.

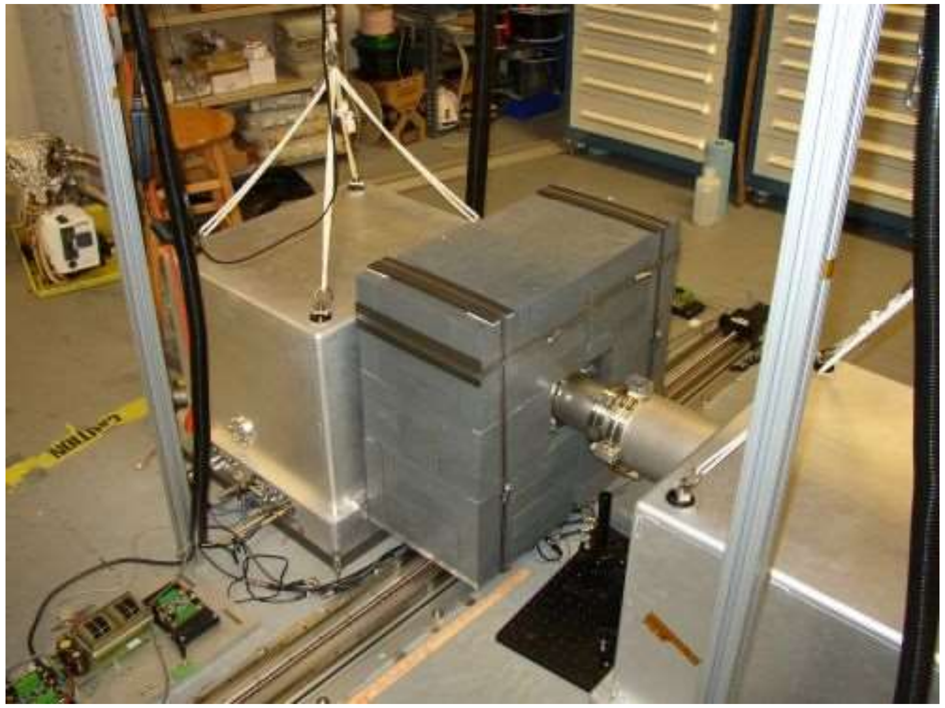
Demonstrated diffential acceleration sensitivity:

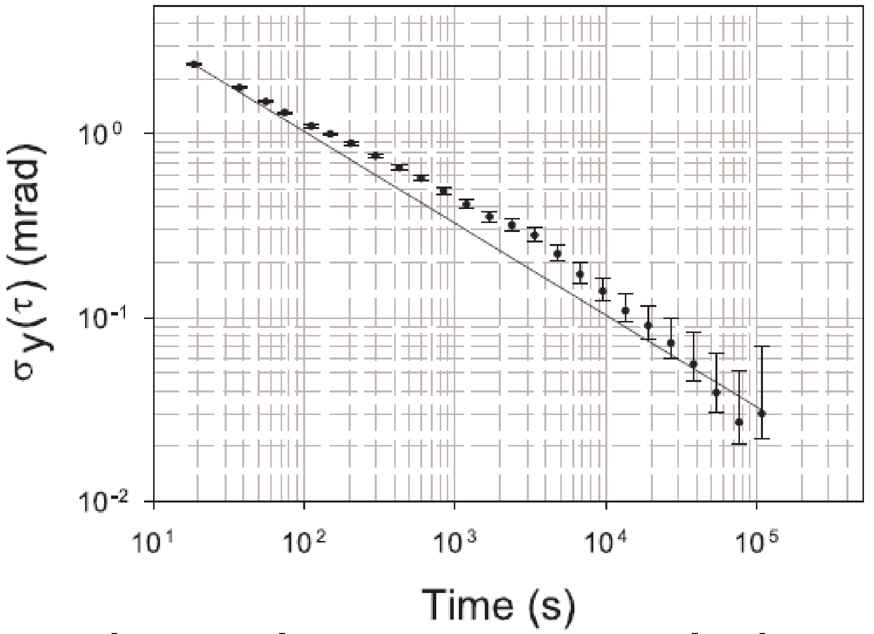
$4x10^{-9}$ g/Hz$^{1/2}$

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

IMPROVED COMPACT GRADIOMETER (STANFORD)







Demonstrated accelerometer resolution: ~10^{-11} g.

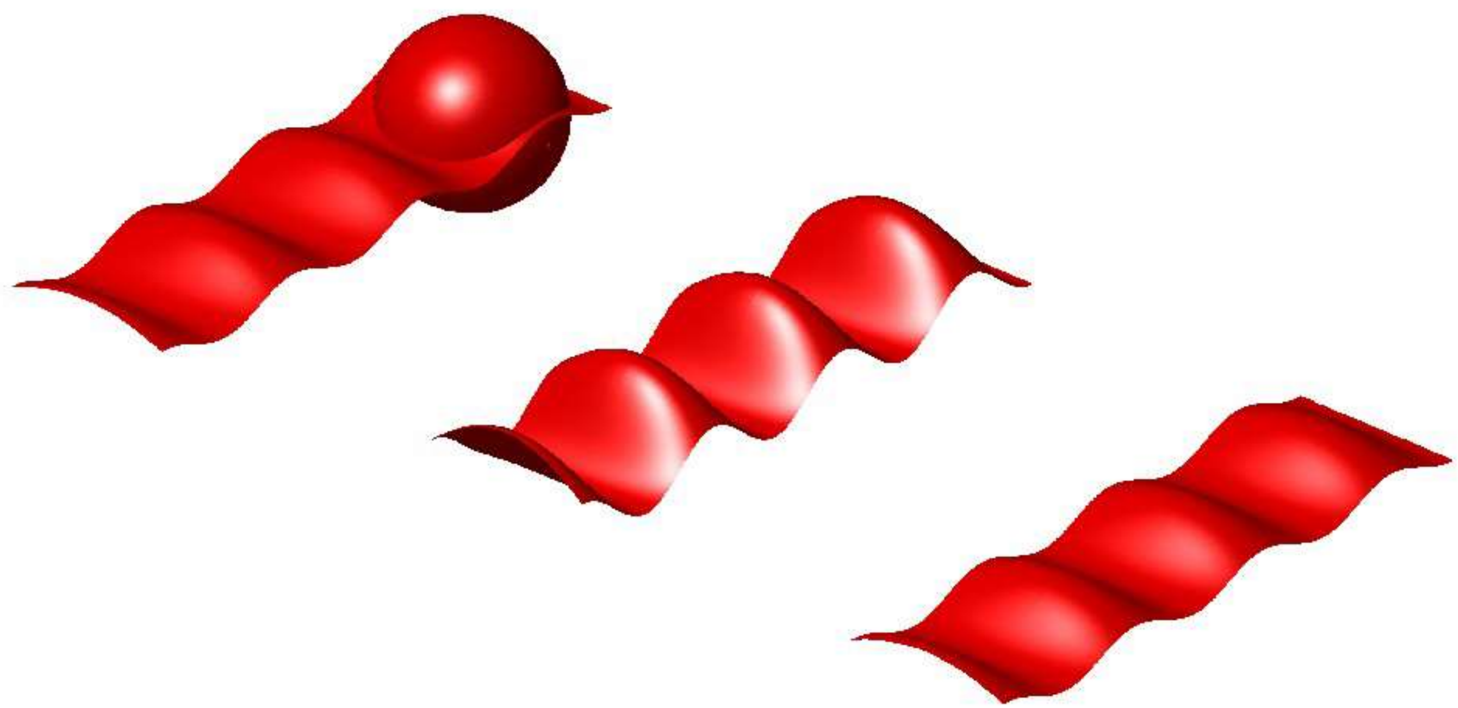
GYROMETER

- 3 separated diffraction zones
- Corriolis acceleration comes from rotating laser

$$\Delta\Phi_{rot} = 2\pi \frac{2\, m_{at}}{h} A \times \Omega = L^2 \frac{v_t}{v_L} \Omega$$

- How can we discriminate between acceleration and rotation ?

- Use two atom interferometers in opposite directions



COUPLING TWO INTERFEROMETERS

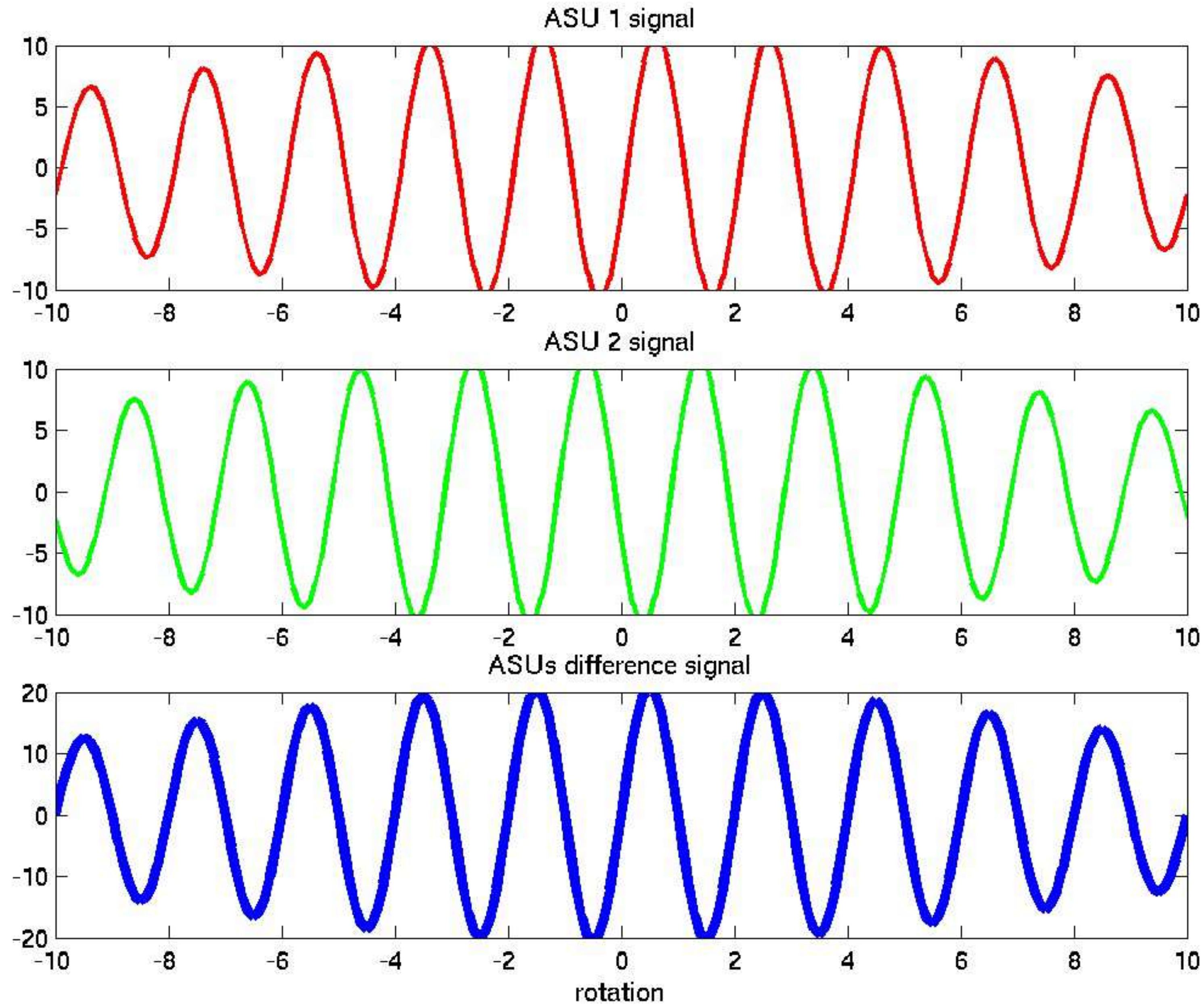
- **3 separated diffraction zones**
- **Corriolis acceleration comes from rotating laser**

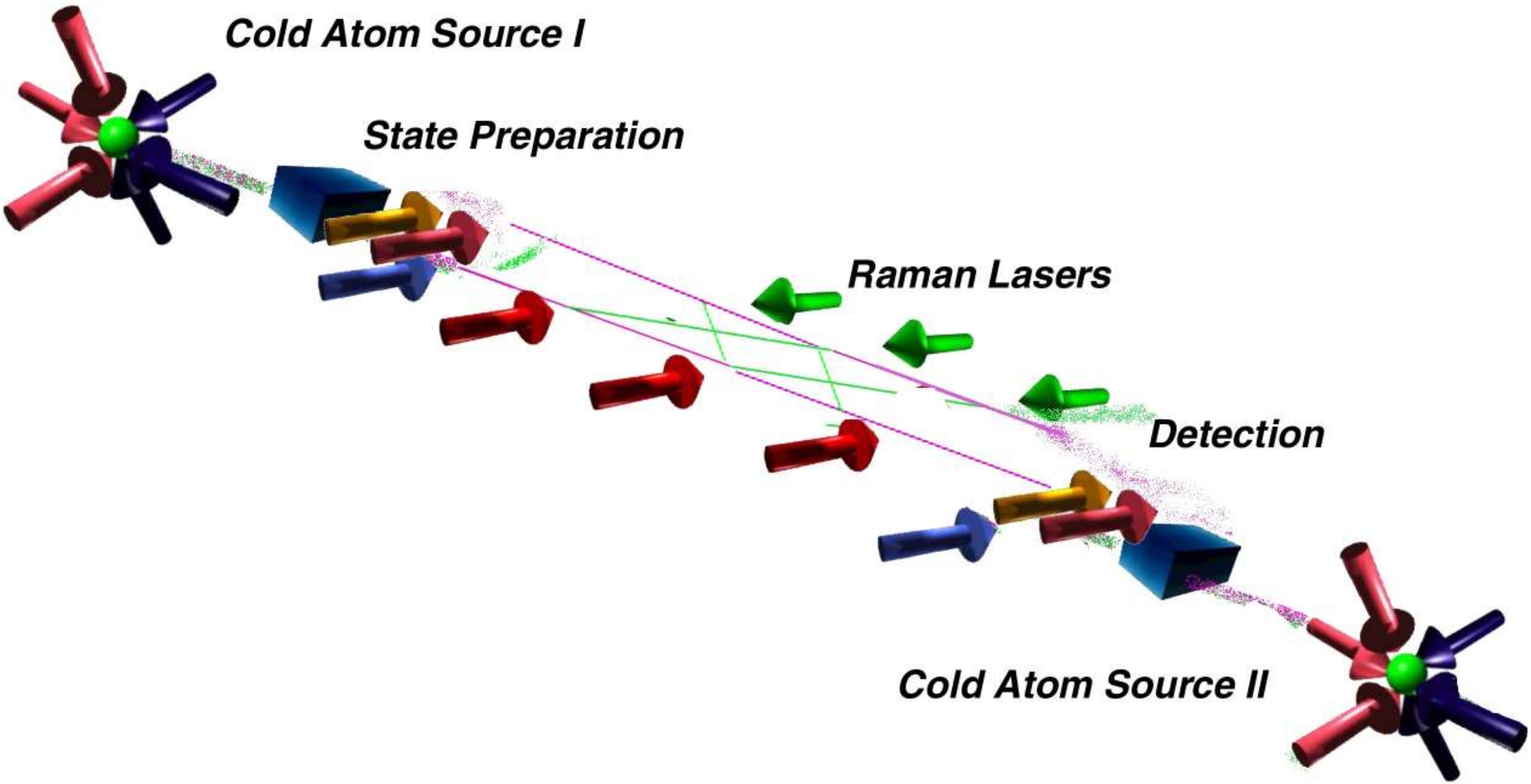
$$\Delta\Phi_{rot} = 2\pi \frac{2\,m_{at}}{h} A \times \Omega = L^2 \frac{v_t}{v_L} \Omega$$

- **How can we discriminate between acceleration and rotation ?**

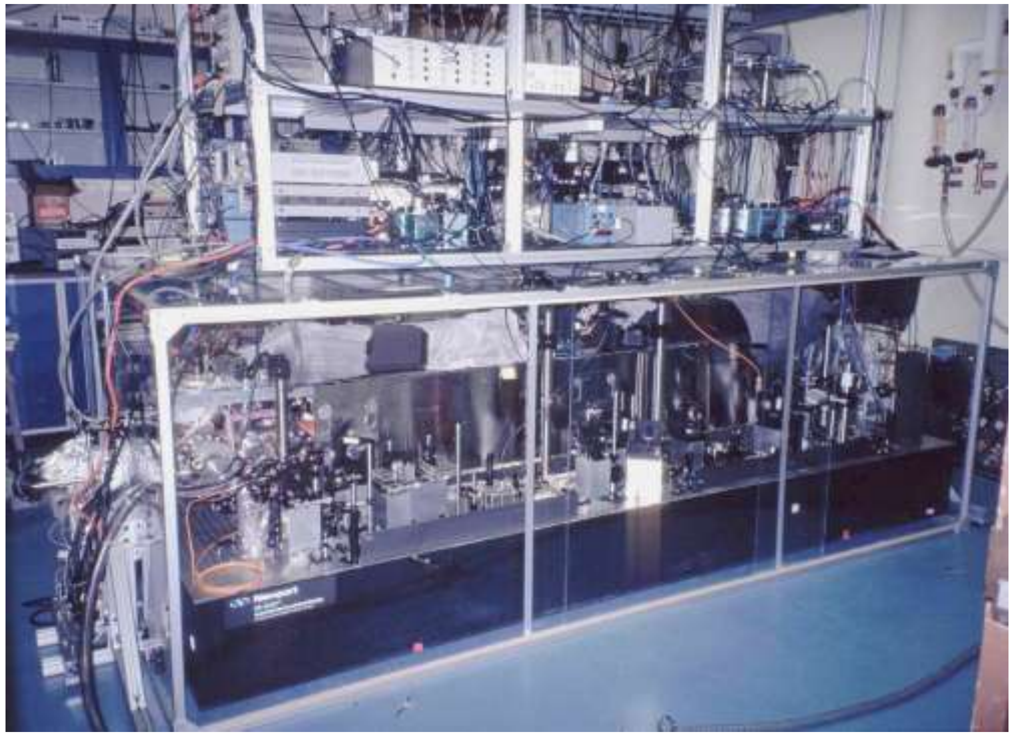
$$\Delta\Phi_{acc} = k\,T_{drift}^2 \; a = \frac{L^2}{v_L^2} \; a$$

- **Use two atom interferometers in opposite directions**




Cold Atom Source I
State Preparation
Raman Lasers
Detection
Cold Atom Source II

FIRST ATOMIC GYROSCOPE



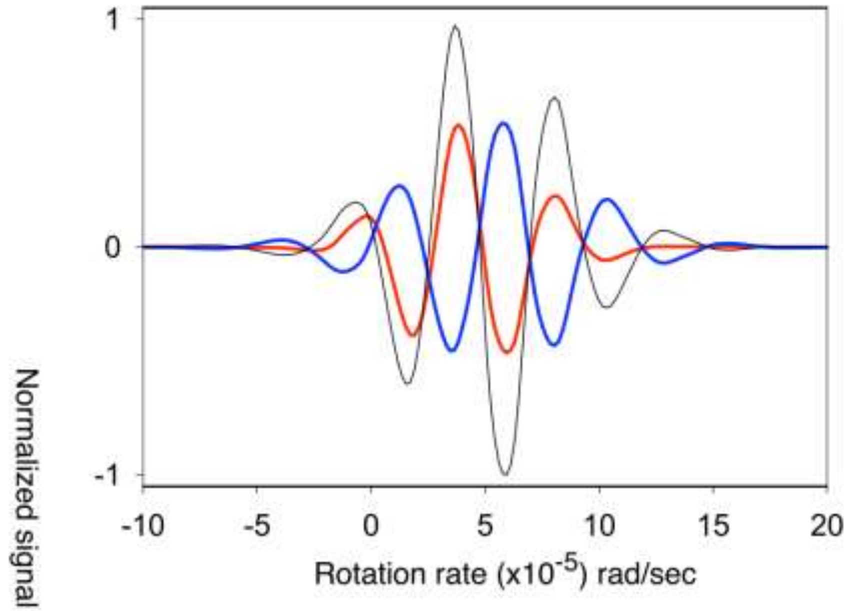
AI gyroscope, demonstrated laboratory performance:

2×10^{-6} deg/hr$^{1/2}$ ARW

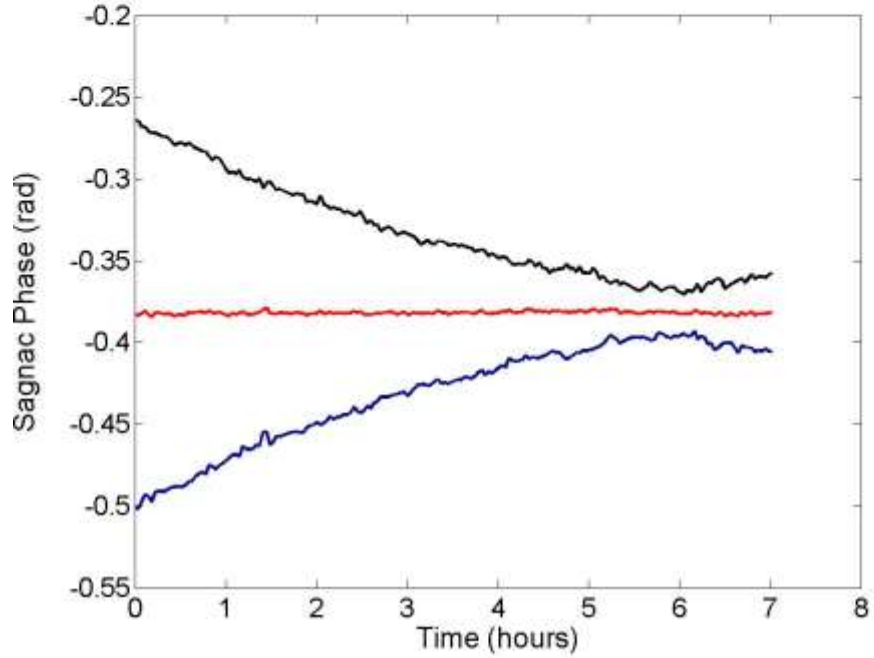
< 10^{-4} deg/hr bias stability

Compact, fieldable (navigation) and dedicated very high-sensitivity (Earth rotation dynamics, tests of GR) geometries possible.

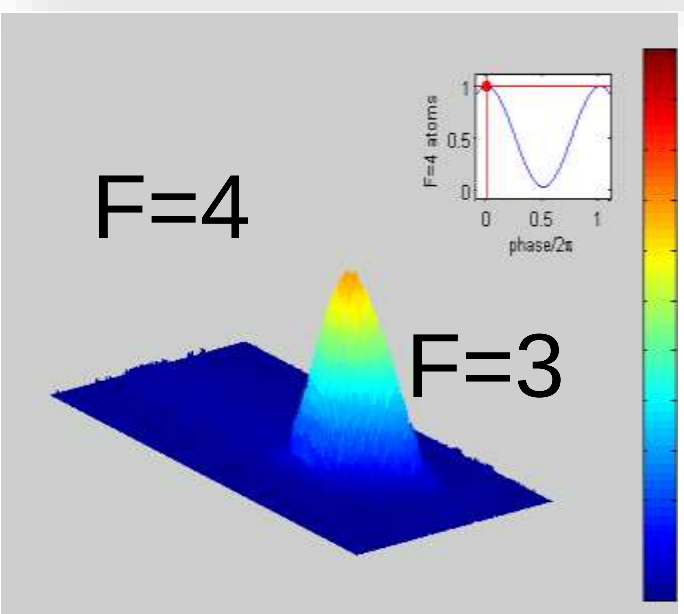
Rotation signal

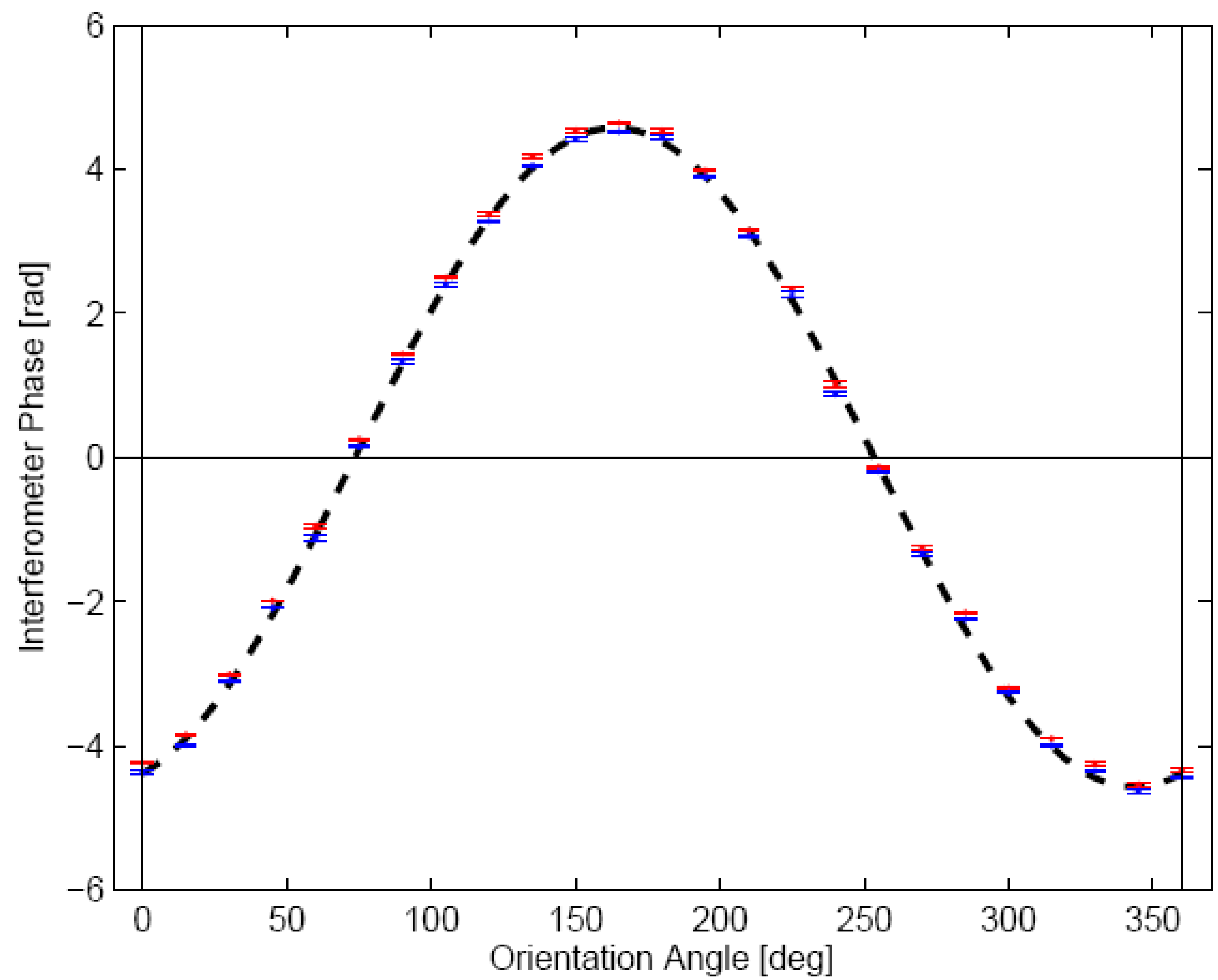


Bias stability



AOSENSE INC. "COMMERCIAL" GYROSCOPE

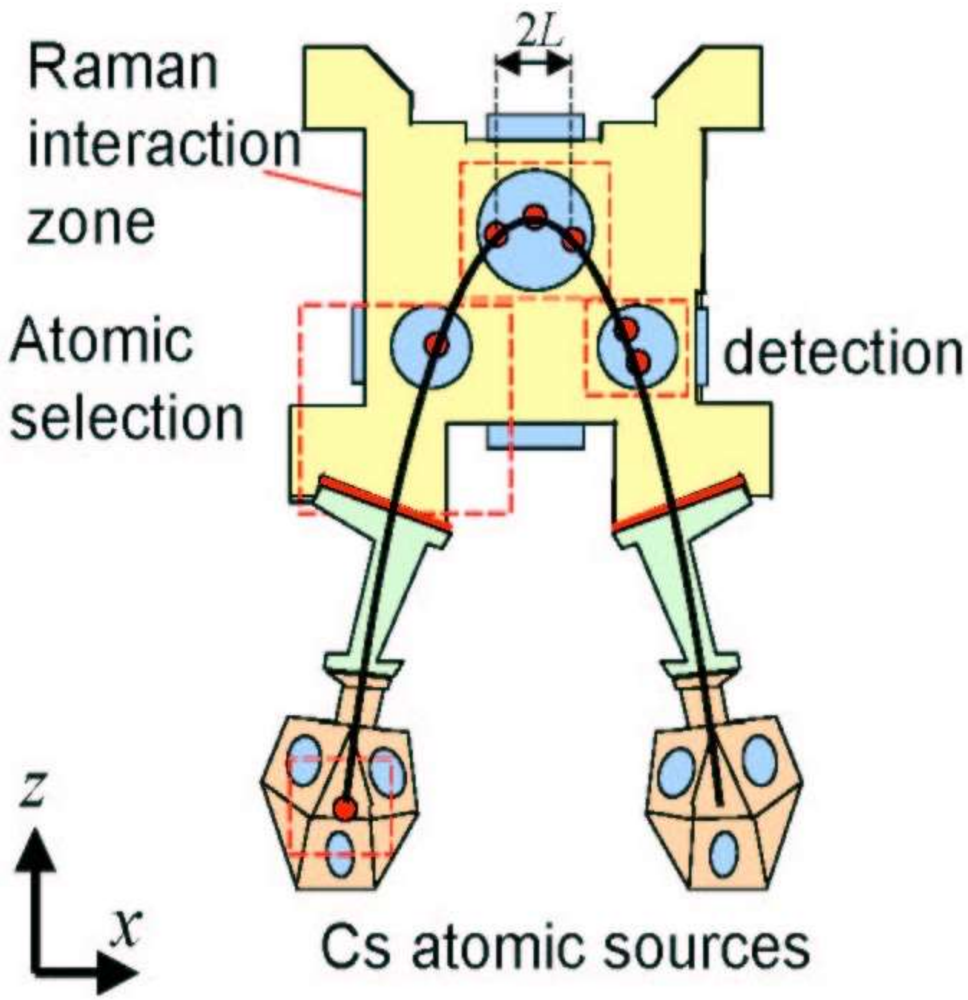


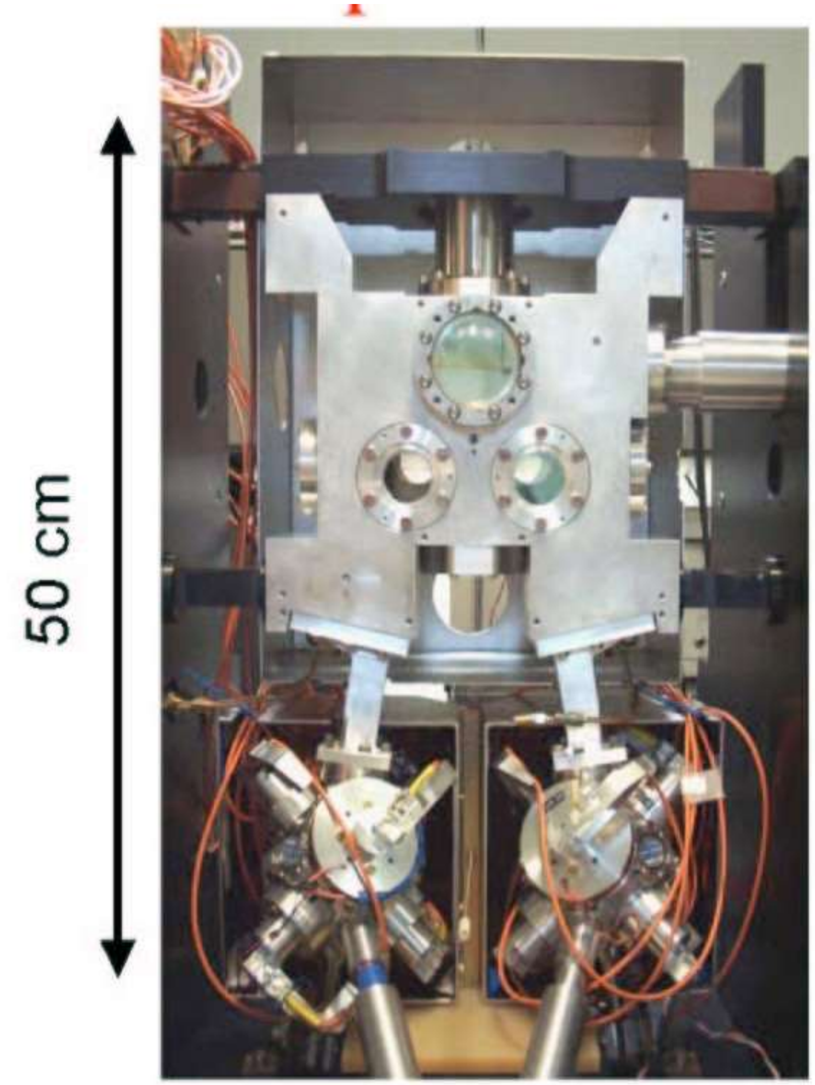


Gyroscope output vs.orientation.

200 µdeg/hr$^{1/2}$

PARIS AI INERTIAL BASE



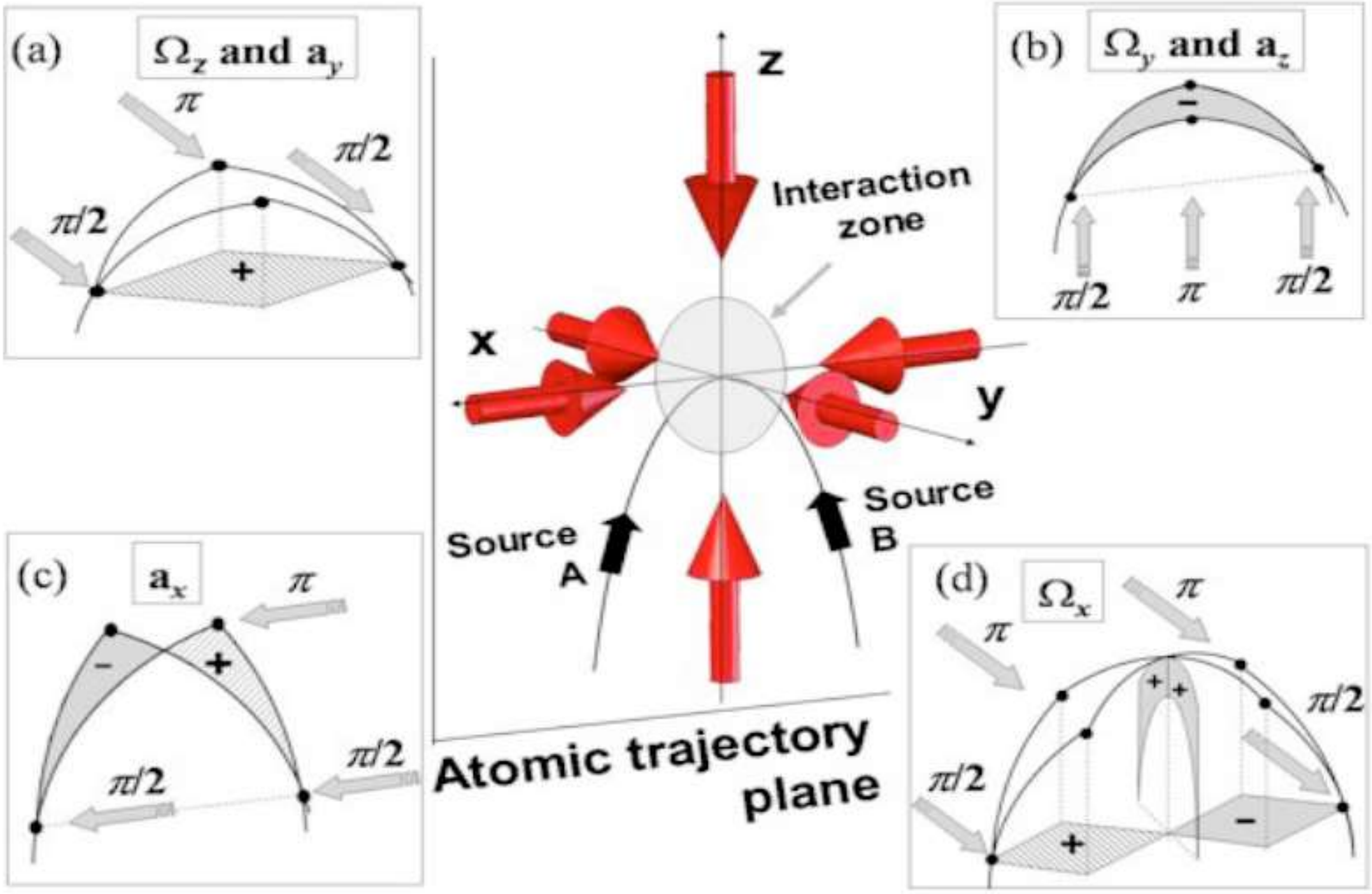


Launching velocity :
V = 2,6 m.s^{-1}
θ = 8°

Interrogation zone :
$2L$ = 30 mm
$2T$ = 100 ms
V_x = 30 cm.s^{-1}
area = 6 mm^2

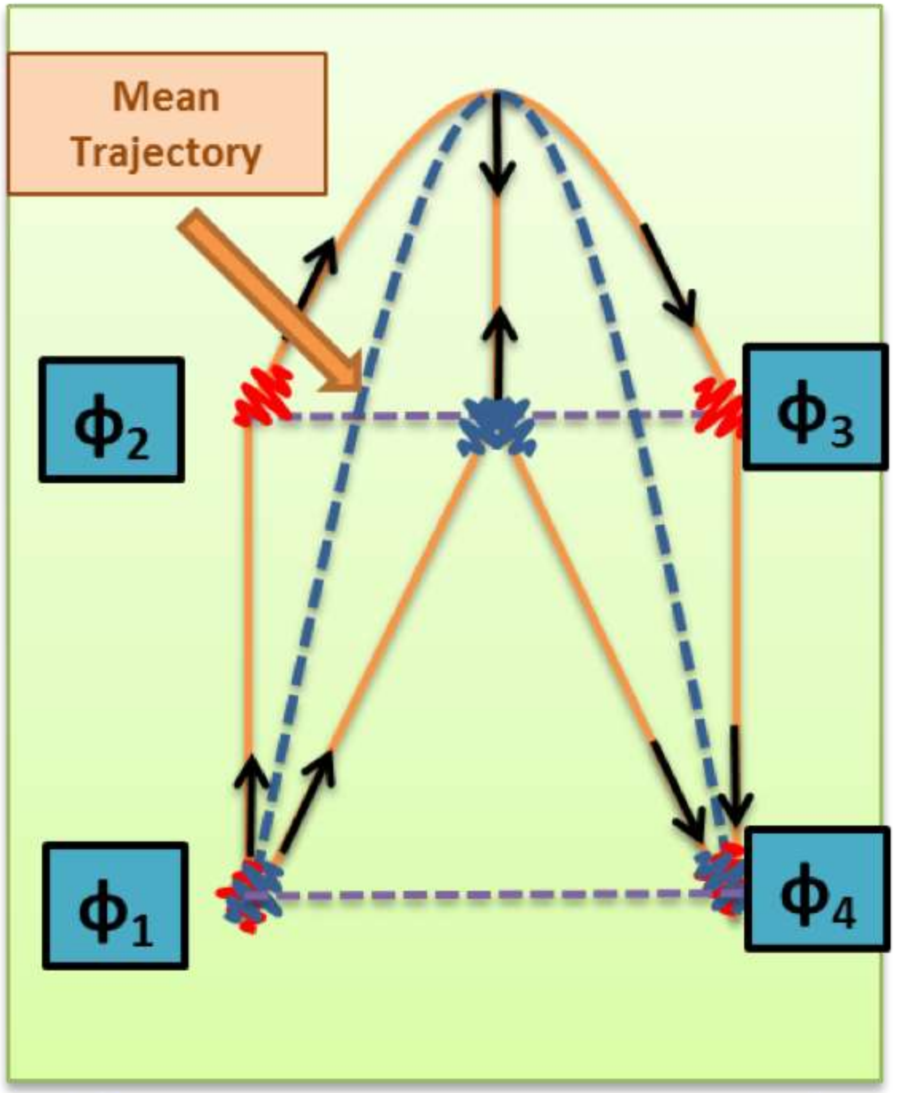
Expected sensitivity of 30 nrad.s^{-1}.Hz$^{-1/2}$

PARIS AI INERTIAL BASE



- Ability to measure the six axes of inertial in the same apparatus (rotations and accelerations) : B. Canuel et al., PRL 97, 010402 (2006)
- Rotation measurement sensitivity limited by standard QPN competitive with best gyro technologies : A. Gauguet, et al., Phys. Rev A 80 (2009), 063604

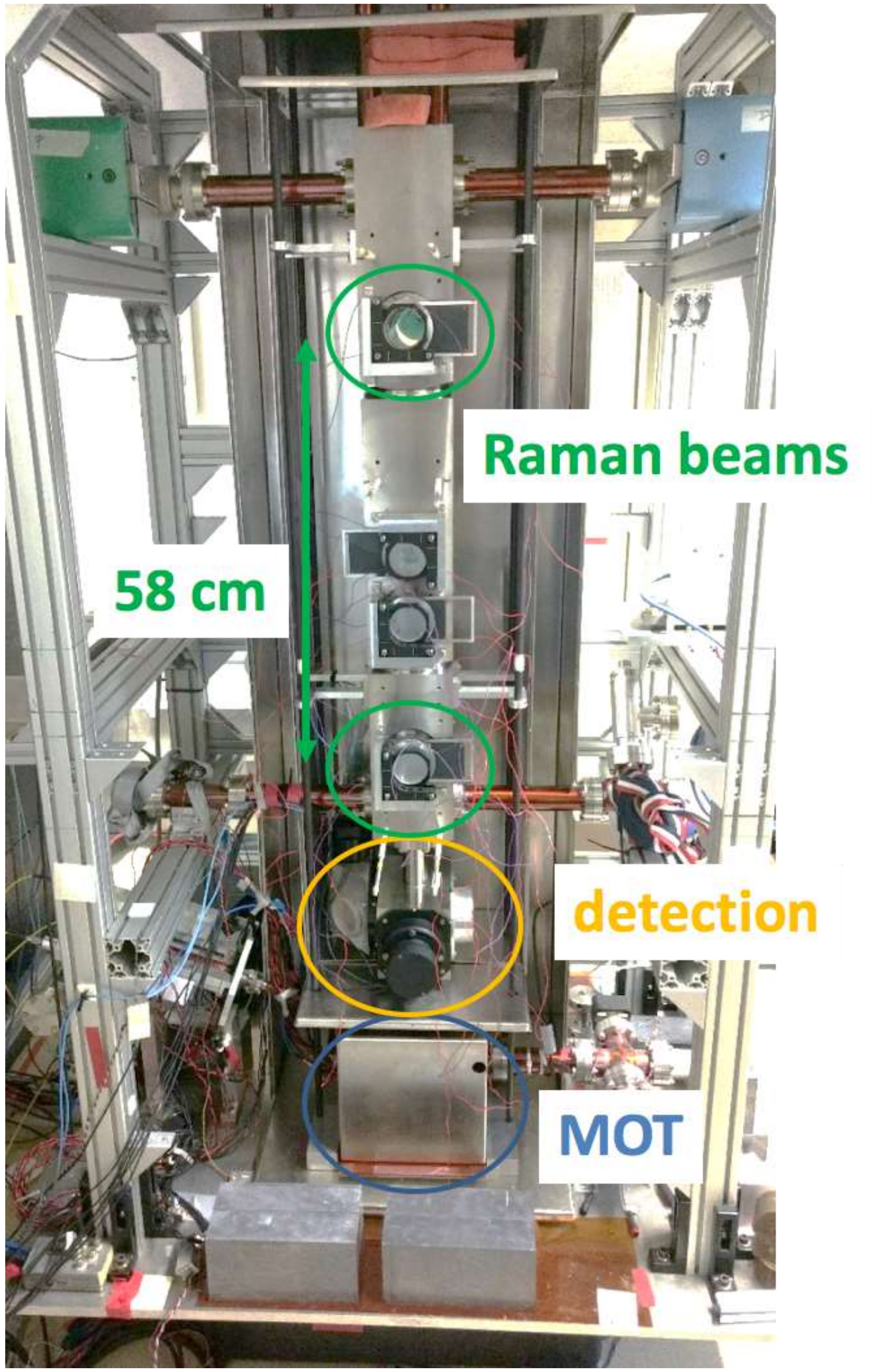
4-PULSE ATOM GYROMETER



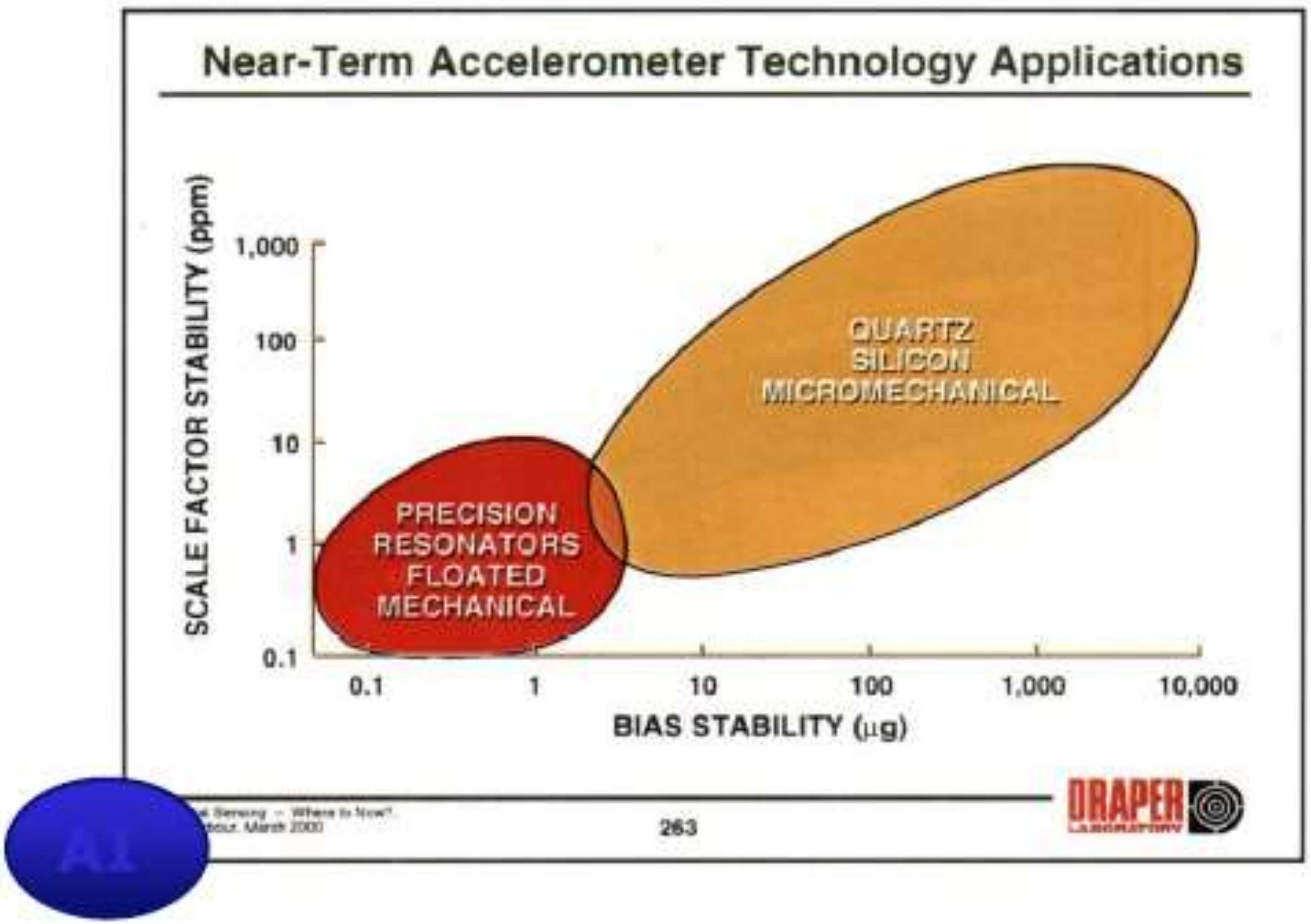
« Butterfly » configuration

$$\Phi_\Omega = \frac{1}{2}\vec{k}_{\mathrm{eff}} \cdot \left(\vec{g} \times \vec{\Omega}\right) T^3$$

- $4\mathrm{x}10^7$ Cesium atoms @ 1.2 µK launched vertically at 5 m/s
- Relative alignement of the beams < 2 µrad
- passive isolation platform (> 0.4 Hz)



ATOM ACCELEROMETERS PERFORMANCES



ATOM GYROMETER PERFORMANCES

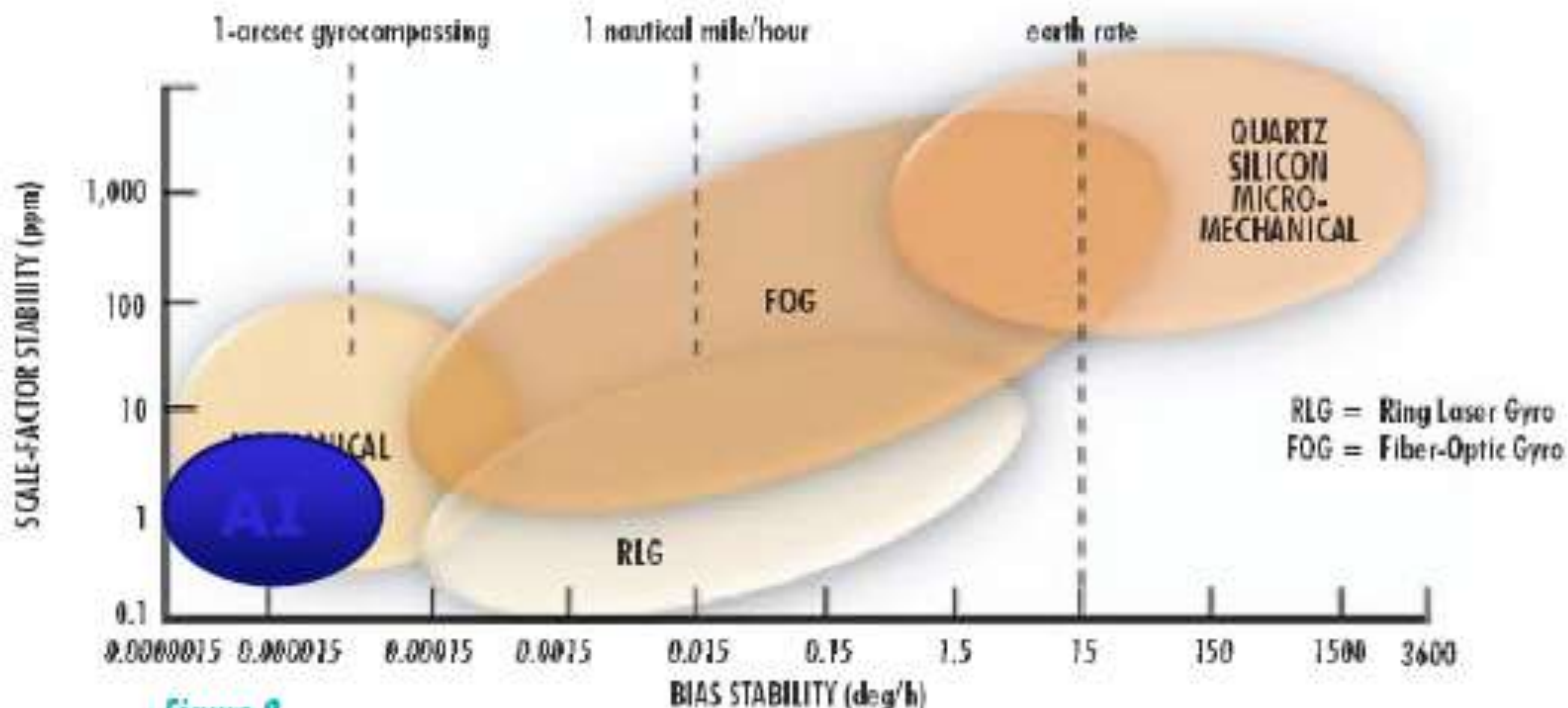
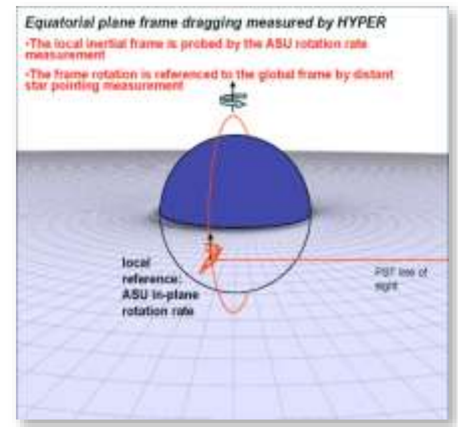


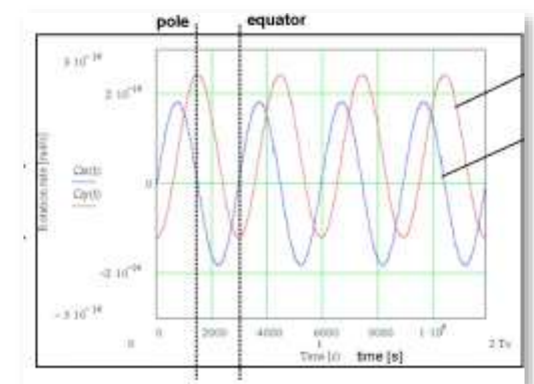
Figure 8

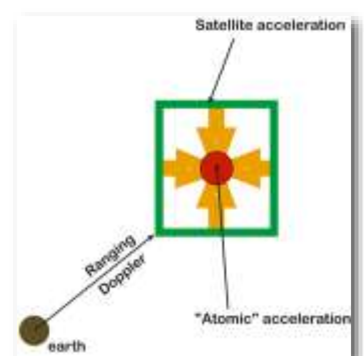
Source: Proc. IEEE/Workshop on Autonomous Underwater Vehicles

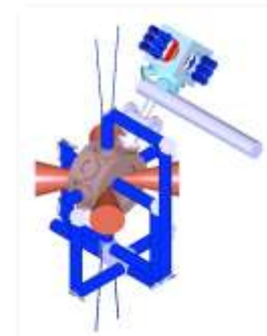
APPLICATIONS

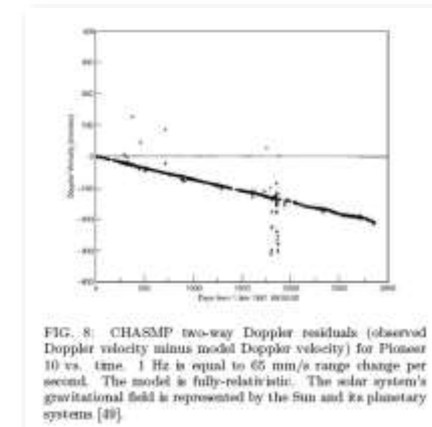
- Gravimetry
  - Geodesy/Earthquake prediction
  - Oil/mineral/resource management
  - Gravity anomaly detection
- Low cost, compact, navigation grade IMU
  - Autonomous vehicle navigation
  - Gravity compensated IMU (grav grad/gyro)
  - GPS-free high accuracy navigation
- Gravitational physics
  - Equivalence Principle
  - Gravity-wave detection
  - Post-Newtonian gravity, tests of GR
  - Tests of the inverse square law
  - Dark matter/energy signatures?
- Beyond Standard model
  - Charge neutrality
  - h/m, tests of QED

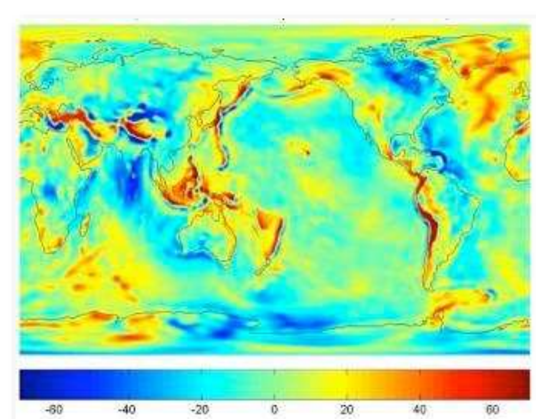


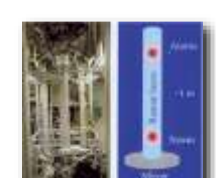


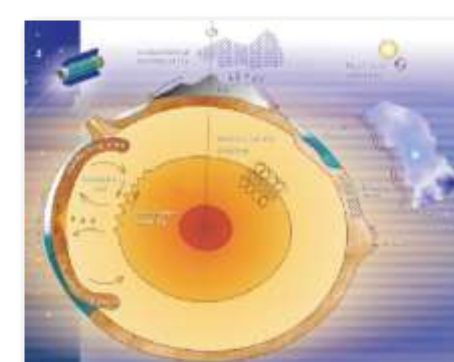












ATOM ACCELEROMETER SENSITIVITY FUNCTION

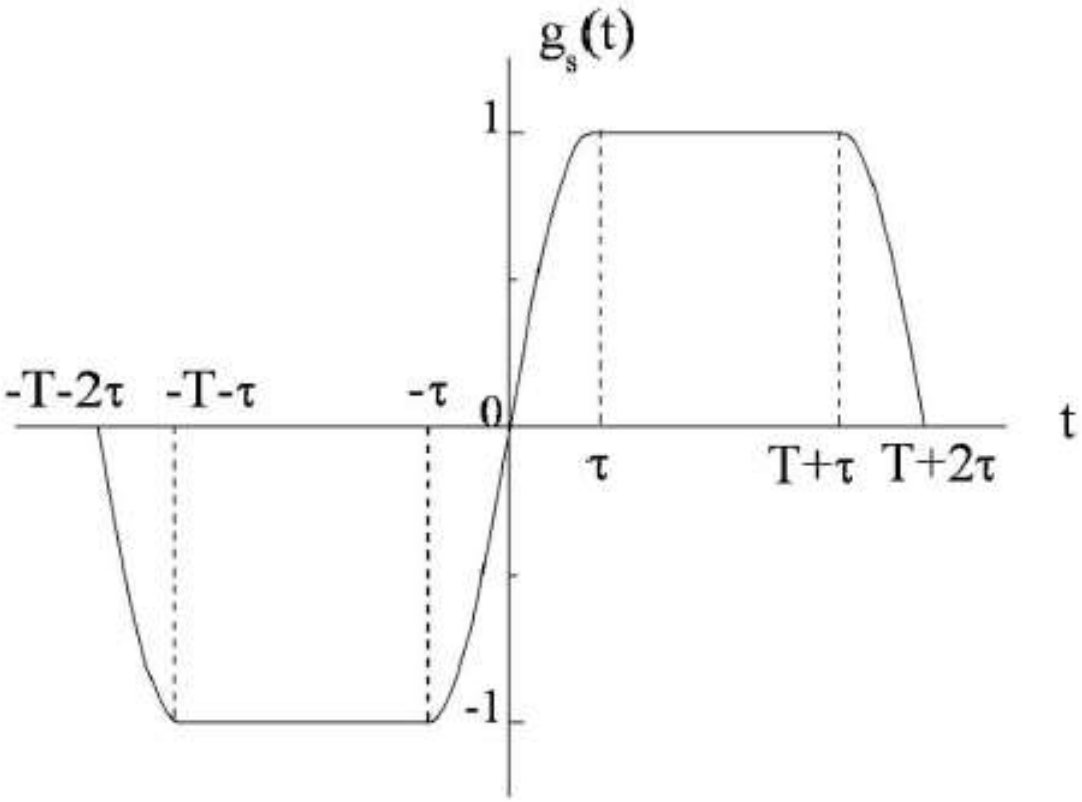
The sensitivity function is a natural tool to characterize the influence of the noise of the environment on the the interferometric phase.

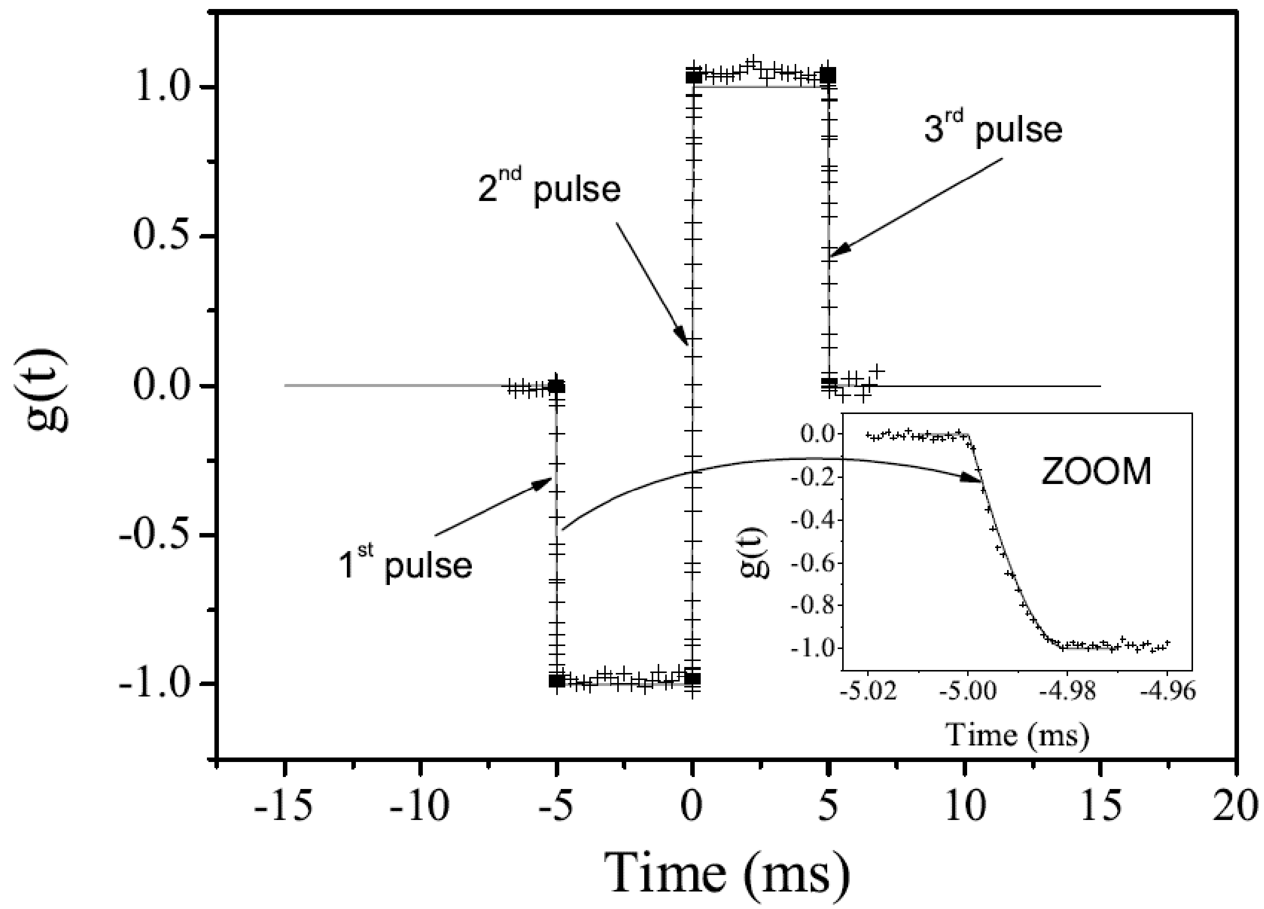
Let's assume a phase jump $\delta\phi$ occurs on the laser phase at time t during the interferometer sequence.

- → change in the transition probability $\delta P(\delta\phi, t)$
- → Sensitivity function $g(t) = 2 \lim_{\delta\phi \to 0} \frac{\delta P(\delta\phi, t)}{\delta\phi}$

$$g(t) = \begin{cases} \sin(\Omega_R t) & 0 < t < \tau_R \\ 1 & \tau_R < t < T + \tau_R \\ -\sin(\Omega_R (T - t)) & T + \tau_R < t < T + 2\tau_R \end{cases}$$

THE SENSITIVITY FUNCTION





$$g(t) = \begin{cases} \sin(\Omega_R t) & 0 < t < \tau_R \\ 1 & \tau_R < t < T + \tau_R \\ -\sin(\Omega_R (T - t)) & T + \tau_R < t < T + 2\tau_R \end{cases}$$

How to recover the interferometric sensitivity

- Integrate the sensitivity function

$$\delta\Phi = \int_{-\infty}^{+\infty} g_s(t)\,d\phi(t) = \int_{-\infty}^{+\infty} g_s(t)\frac{d\phi(t)}{dt}dt$$

- Compute the phase evolution during atomic free fall in the presence of gravity (for a gravimeter) :

$$\phi(t) = k\left(\frac{gt^2}{2} + \cancel{v_0 t}\right) + \phi^0(\cancel{t})$$

=
$g_s(t) = g_s(-t)$
≡
0

≡
0 (supposed fixed)

How to recover the interferometric sensitivity

- Integrate the sensitivity function

$$\delta\Phi = \int_{-\infty}^{+\infty} g_s(t)\,d\phi(t) = \int_{-\infty}^{+\infty} g_s(t)\frac{d\phi(t)}{dt}dt$$

- Compute the phase evolution during atomic free fall in the presence of gravity (for a gravimeter) :

$$\phi(t) = k\left(\frac{gt^2}{2} + \cancel{v_0} t\right) + \phi^0(\cancel{t})$$

||

$g_s(t) = g_s(-t)$

|||

0

|||

0 (supposed fixed)

$$\delta\Phi = \int_{-\infty}^{+\infty} g_s(t)\,k\,g\,t\,dt$$

$$\delta\Phi = kg(T+2\tau)(T+\frac{4\tau}{\pi})$$

Sensitivity to laser phase noise

- Model of the phase noise

$$\phi(t) = A_0 \cos(\omega_0 t + \psi) \qquad \frac{d\phi(t)}{dt} = -A_0\omega_0 \sin(\omega_0 t + \psi)$$

- Go to Fourrier space

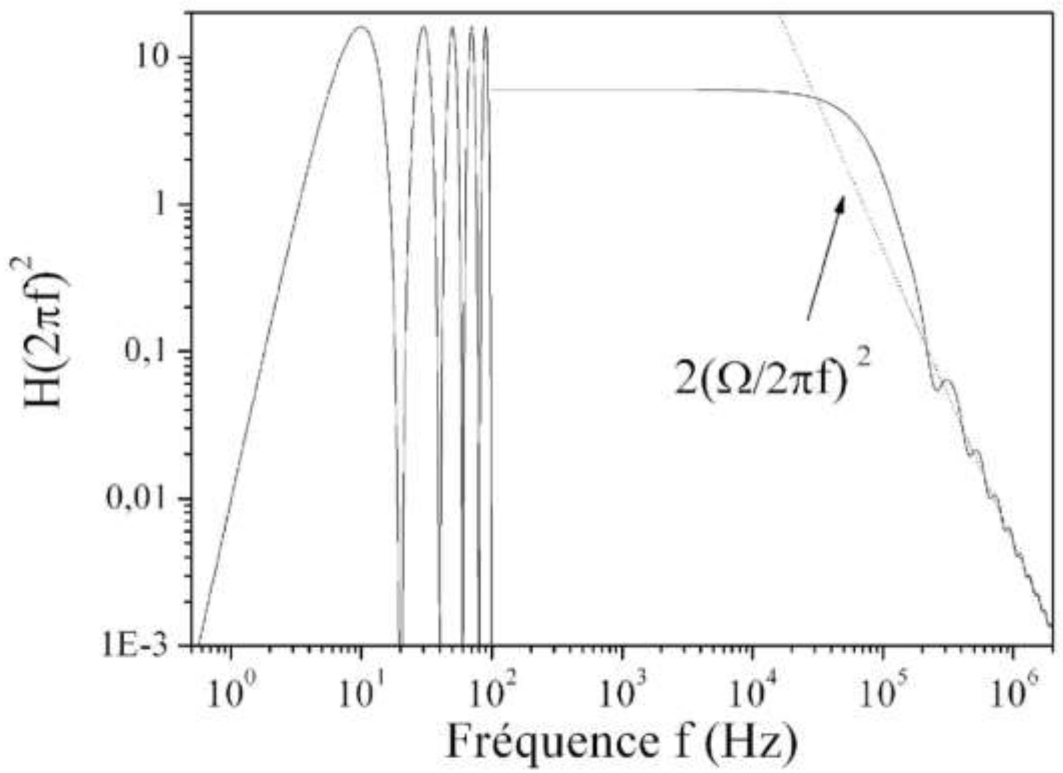
$$G(\omega) = \int_{-\infty}^{+\infty} e^{-i\omega t} g_s(t)dt = \int_{-\infty}^{+\infty} -i \sin(\omega t) g_s(t)dt$$

- Get the phase sensitivity for a phase fluctuation at frequency ω_0

$$\boxed{\begin{aligned} &\delta\Phi = -iA_0\omega_0 G(\omega_0)\cos(\psi) = -A_0\omega_0\cos(\psi)|G(\omega_0)| \\ &G(\omega) = \frac{4i\Omega_R}{\omega^2 - \Omega_R^2}\sin\left(\frac{\omega(T+2\tau)}{2}\right)\left(\cos\left(\frac{\omega(T+2\tau)}{2}\right) + \frac{\Omega_R}{\omega}\sin\left(\frac{\omega T}{2}\right)\right)\end{aligned}}$$

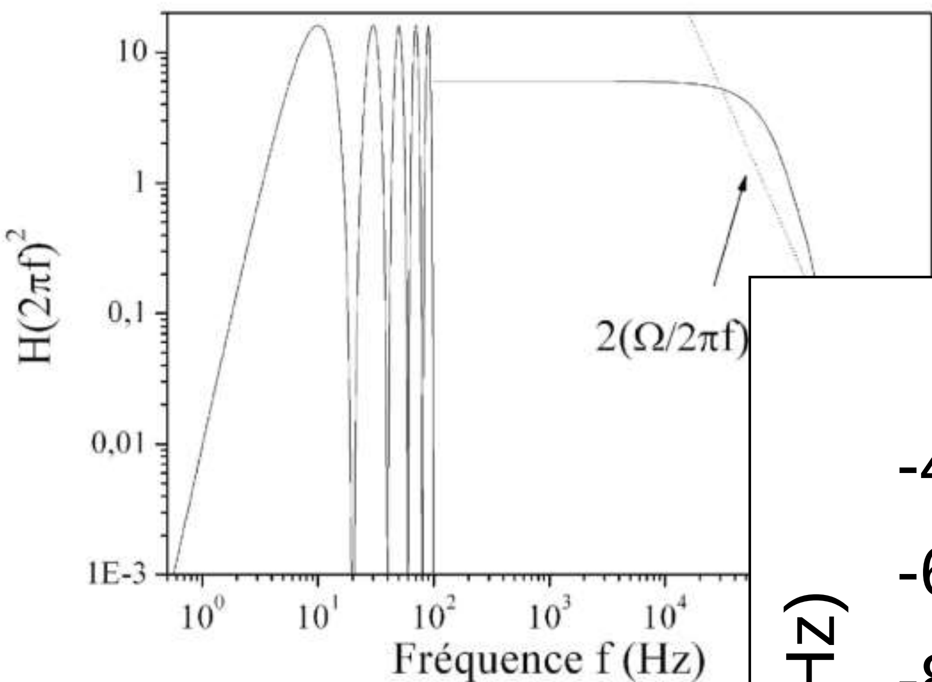
Interferometer transfer function (acts as a filter)

- Introduce the transfer function $H(\omega) = |\omega G(\omega)|$



- Error induced by phase noise $$\sigma_\Phi^2 = \int_0^{+\infty} |\omega G(\omega)|^2 S_\phi(\omega) \frac{d\omega}{2\pi}$$

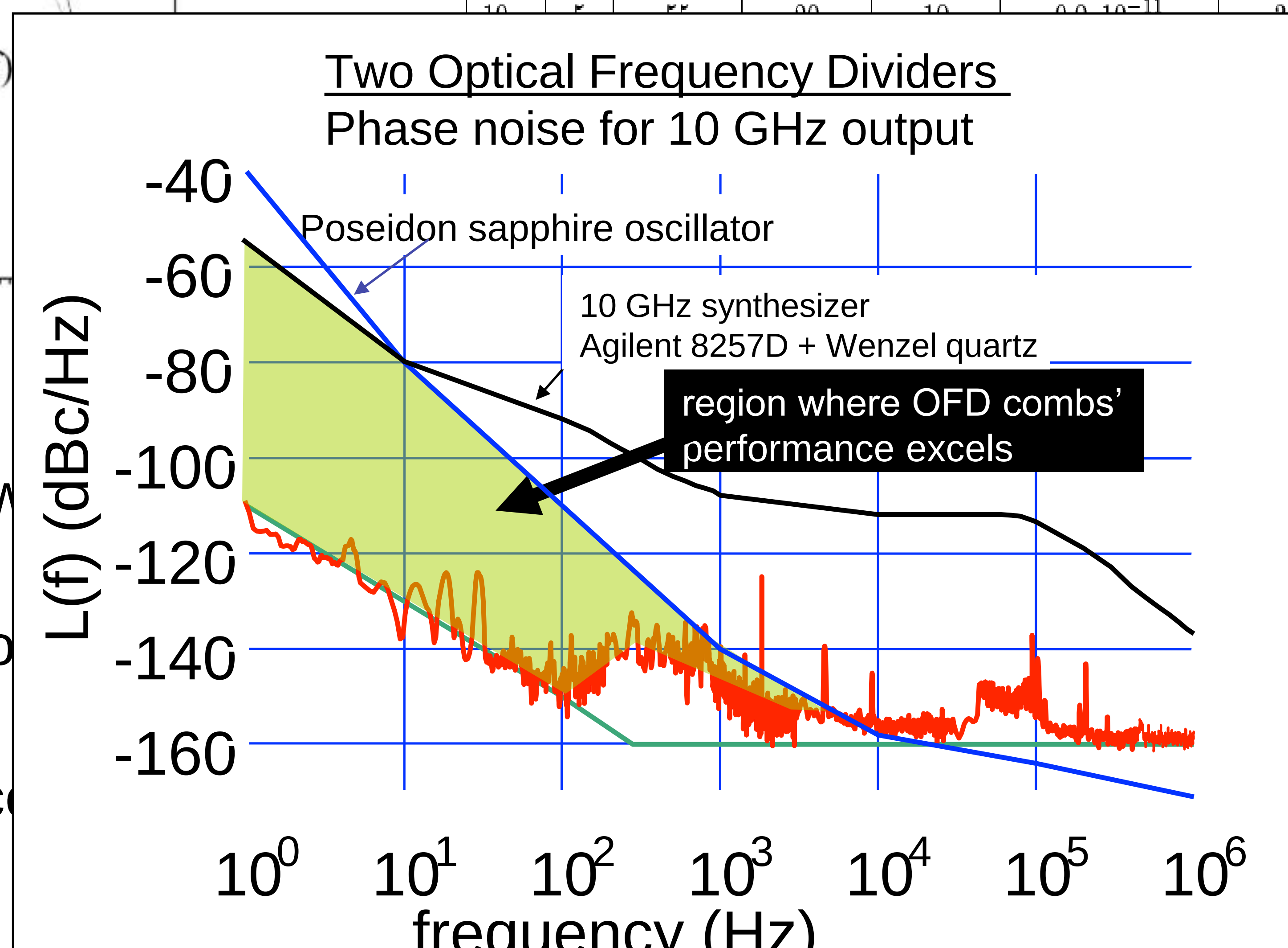
LASER PHASE NOISE



T_c (s)	$2T$ (s)	Source 1 $\sigma_\Phi(T_c)$ (mrad)	Source 2 $\sigma_\Phi(T_c)$ (mrad)	Source 3 σ_Φ (mrad)	Best Source $\sigma_a(T_c)$ ($m.s^{-2}$) / shot	Best Source $\sigma_a(1s)$ ($m.s^{-2}.Hz^{-1/2}$)
0.25	0.1	1.2	3.5	2.2	$3x10^{-8}$	$1.5x10^{-8}$
10	2	22	8.8	4.6	$1.1x10^{-9}$	$3.6x10^{-9}$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$x10^{-10}$
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$x10^{-10}$

ons (σ_Φ) and to the acceleration
three different sources assuming
ion time. (Source 1: Premium;

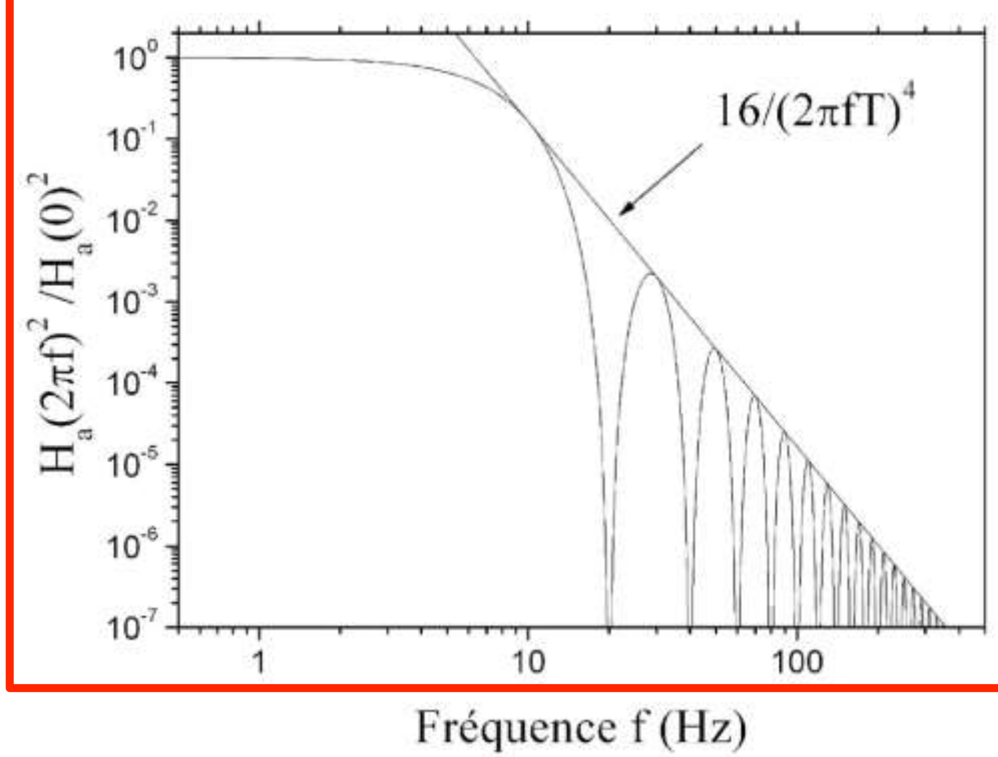
- Raman phase noise w
- Best known µwave so
- Expected performanc



It is now possible to calculate the signal for a "noisy" acceleration spectrum

→ Introduce the sensitivity function for acceleration

$$g_a(t) = 2 \lim_{\delta_a \to 0} \frac{\delta P_a(\delta_a, t)}{\delta_a} \qquad g_s(t) = \frac{1}{k_{eff}} \frac{d^2 g_a(t)}{dt^2}$$

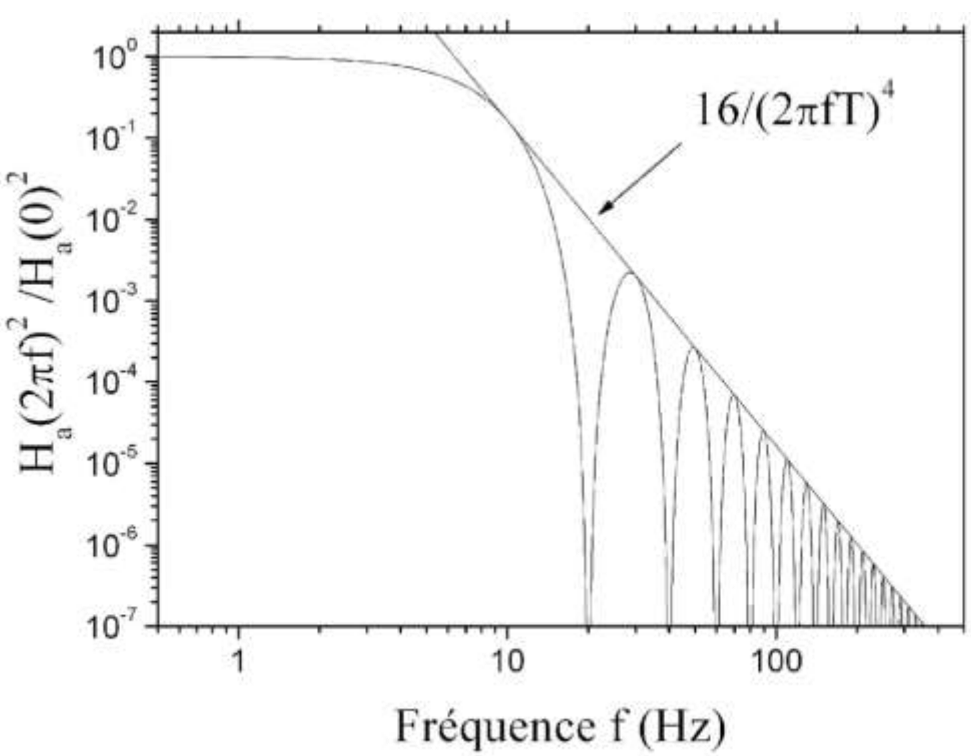


$$|H_a(\omega)|^2 = \frac{k_{eff}^2}{\omega^4} |H(\omega)|^2$$

$$\sigma_\Phi^2(\tau_m) = \frac{k_{eff}^2}{\tau_m} \sum_{n=1}^{\infty} \frac{|H(2\pi n f_c)|^2}{(2\pi n f_c)^4} S_a(2\pi n f_c)$$

PROBLEM OF THE « SEQUENTIAL » MEASUREMENT

Integration time

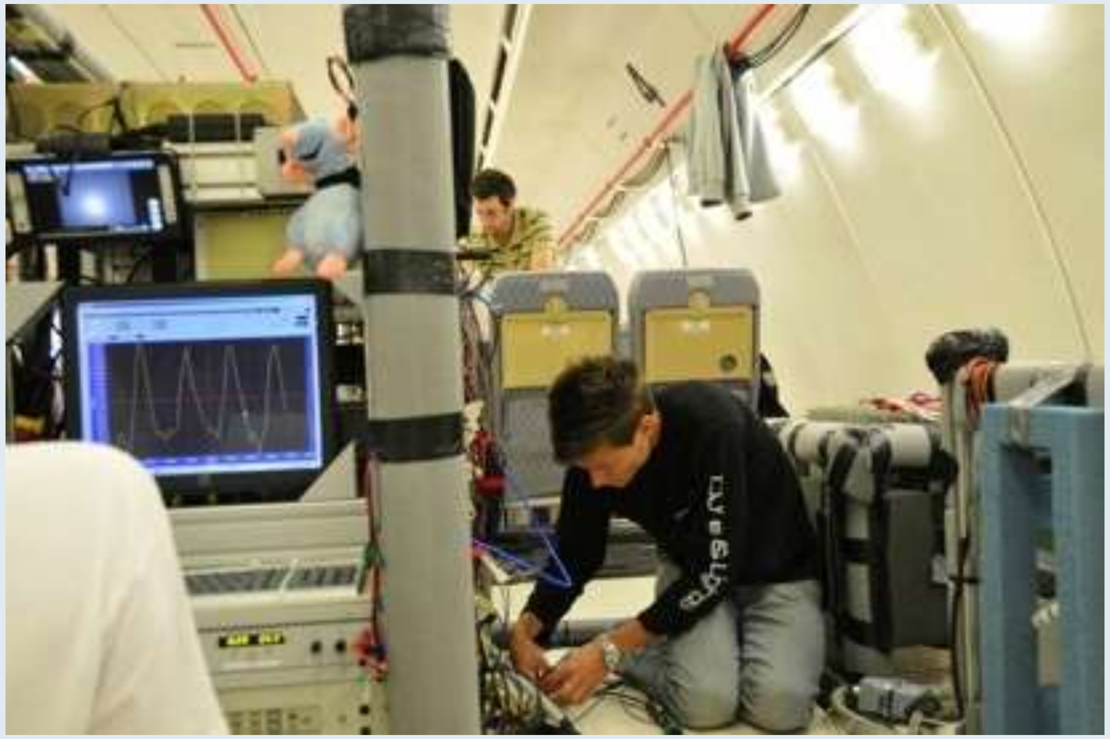


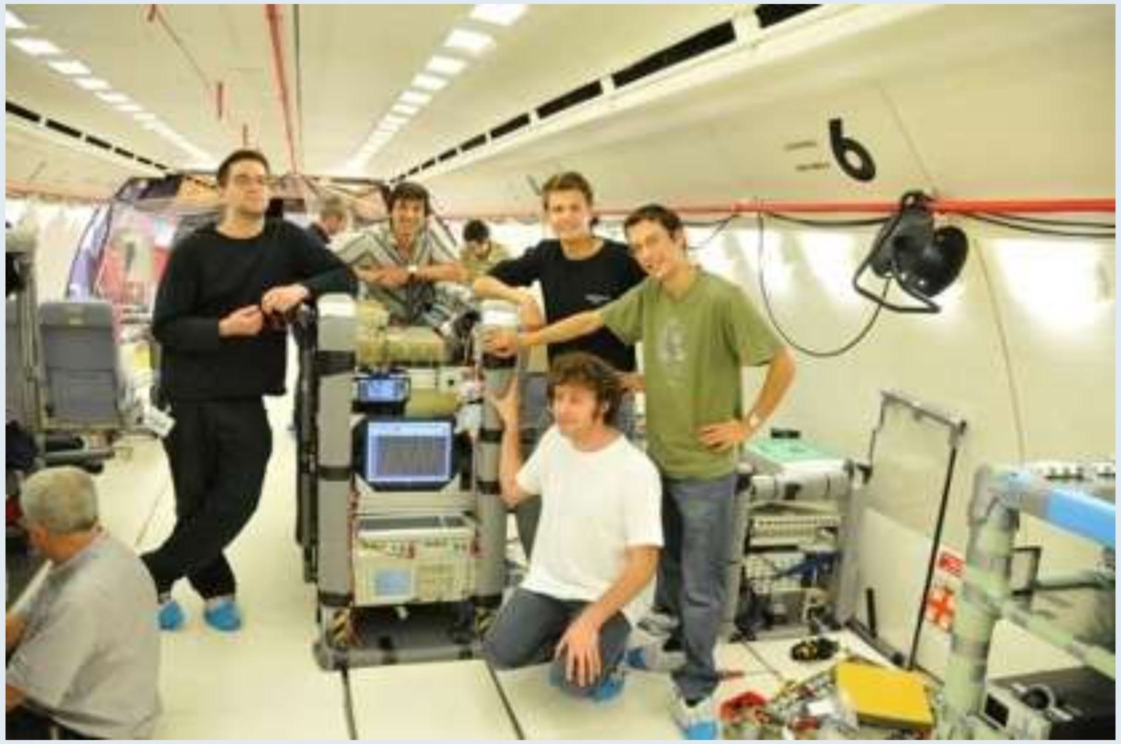
$$|H_a(\omega)|^2 = \frac{k_{eff}^2}{\omega^4}|H(\omega)|^2$$

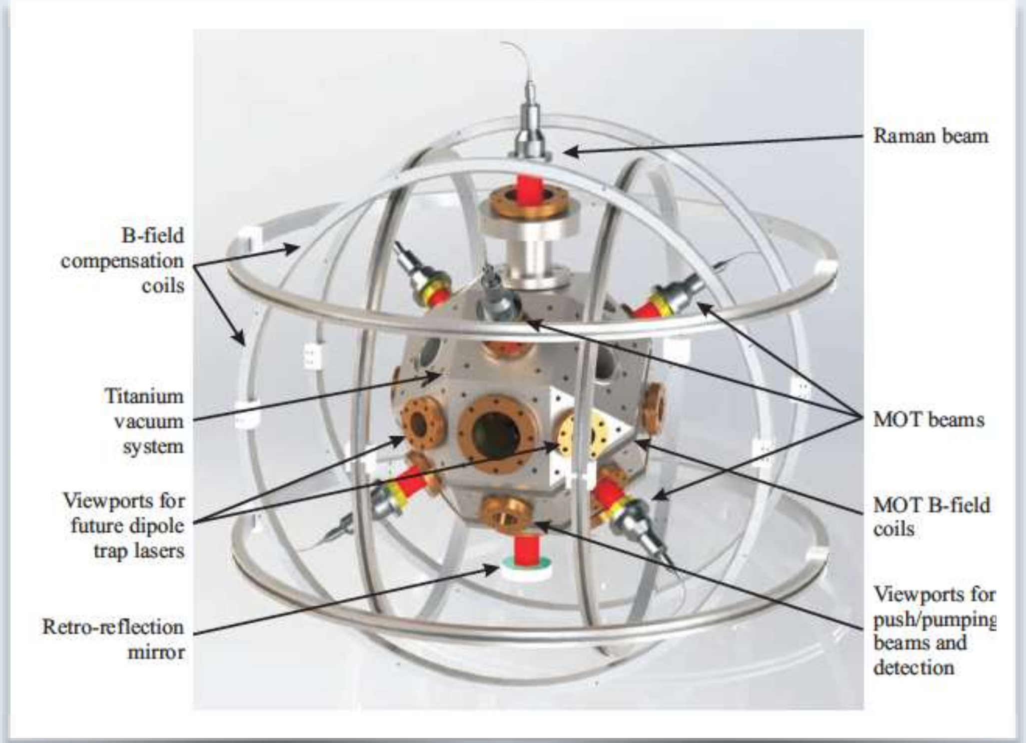
$$\sigma_\Phi^2(\tau_m) = \frac{k_{eff}^2}{\tau_m}\sum_{n=1}^{\infty}\frac{|H(2\pi n f_c)|^2}{(2\pi n f_c)^4}S_a(2\pi n f_c)$$

P. Cheinet, et al., *"Measurement of the sensitivity function in time-domain atomic interferometer",* IEEE Trans. on Instrum. Meas. 57, 1141, (2008)

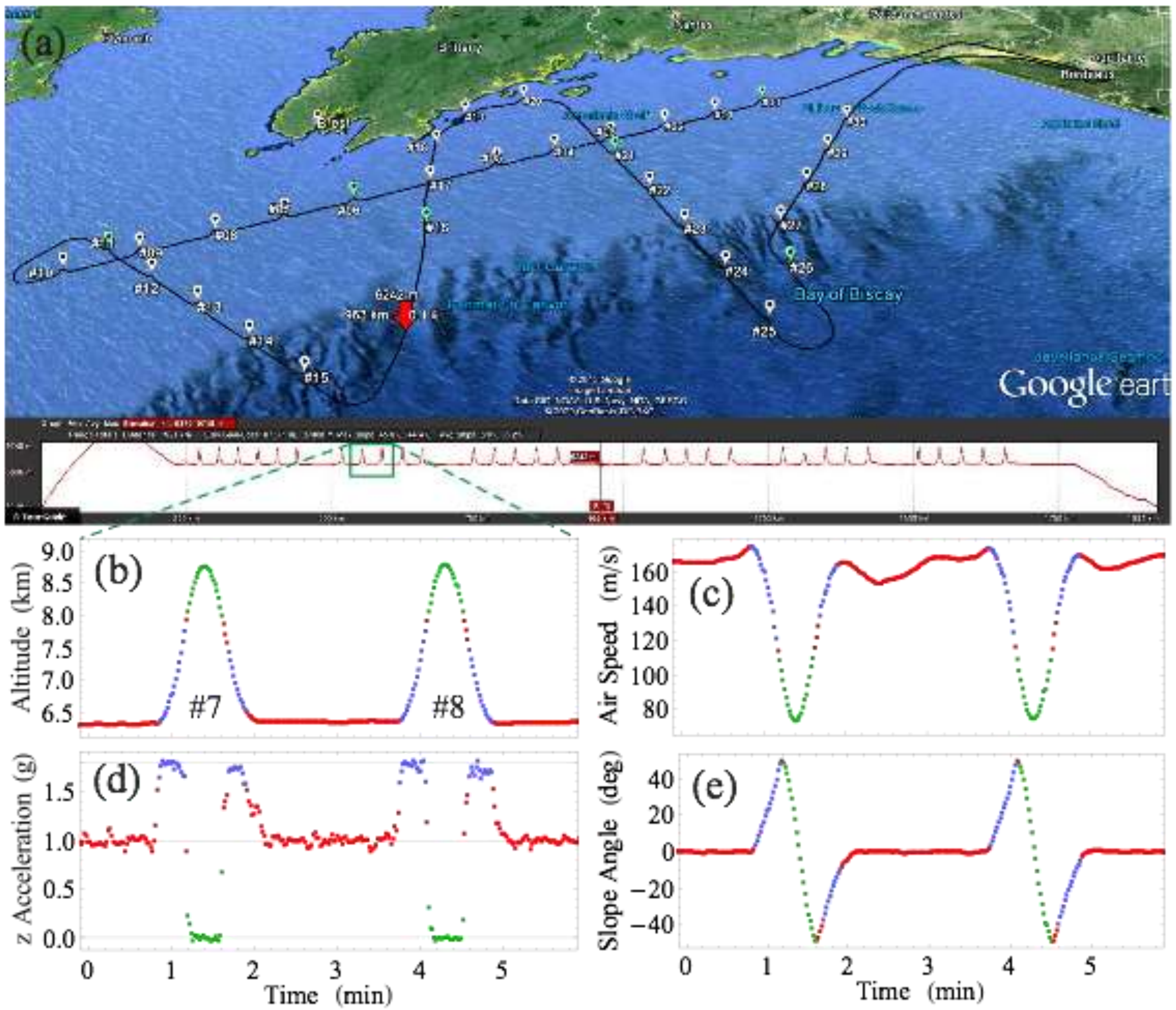
Airborne Atom sensor

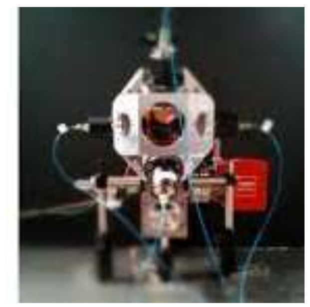






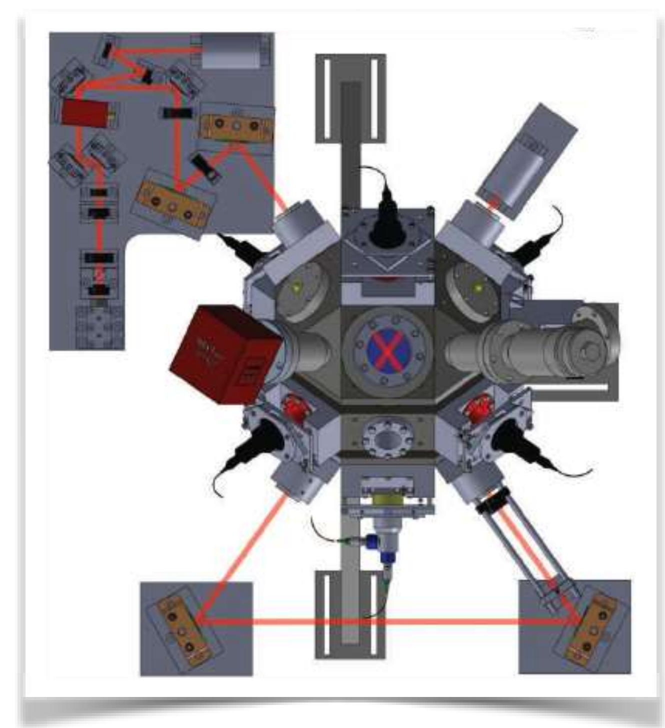
APPLICATIONS TO NAVIGATION





IXBLUE

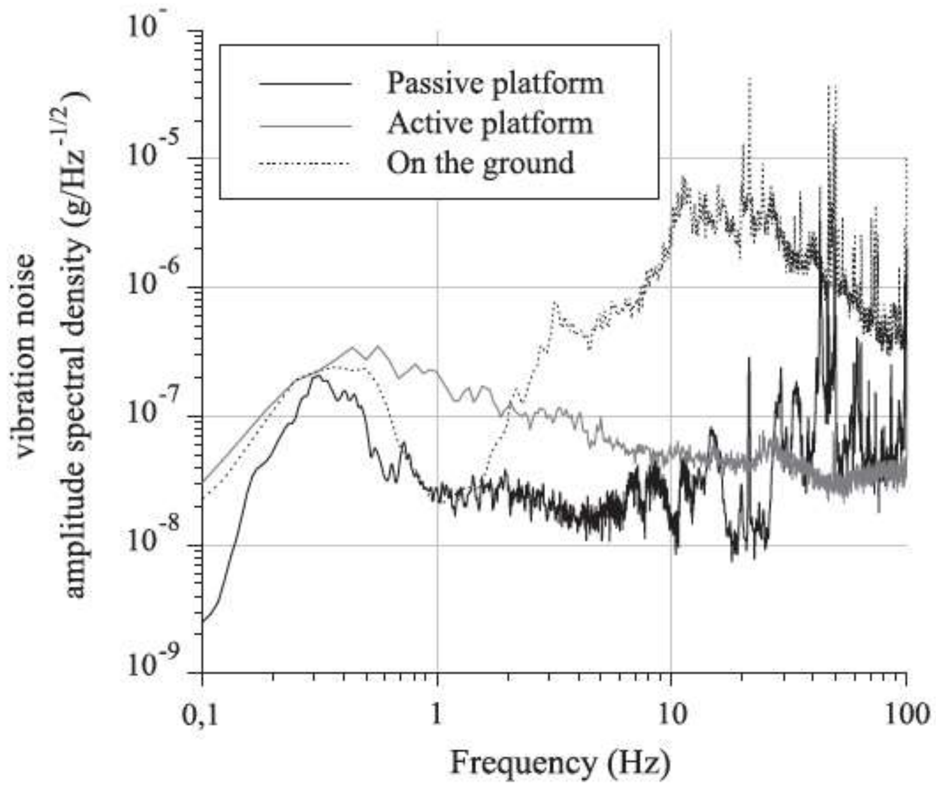
INSTITUT d'OPTIQUE GRADUATE SCHOOL ParisTech



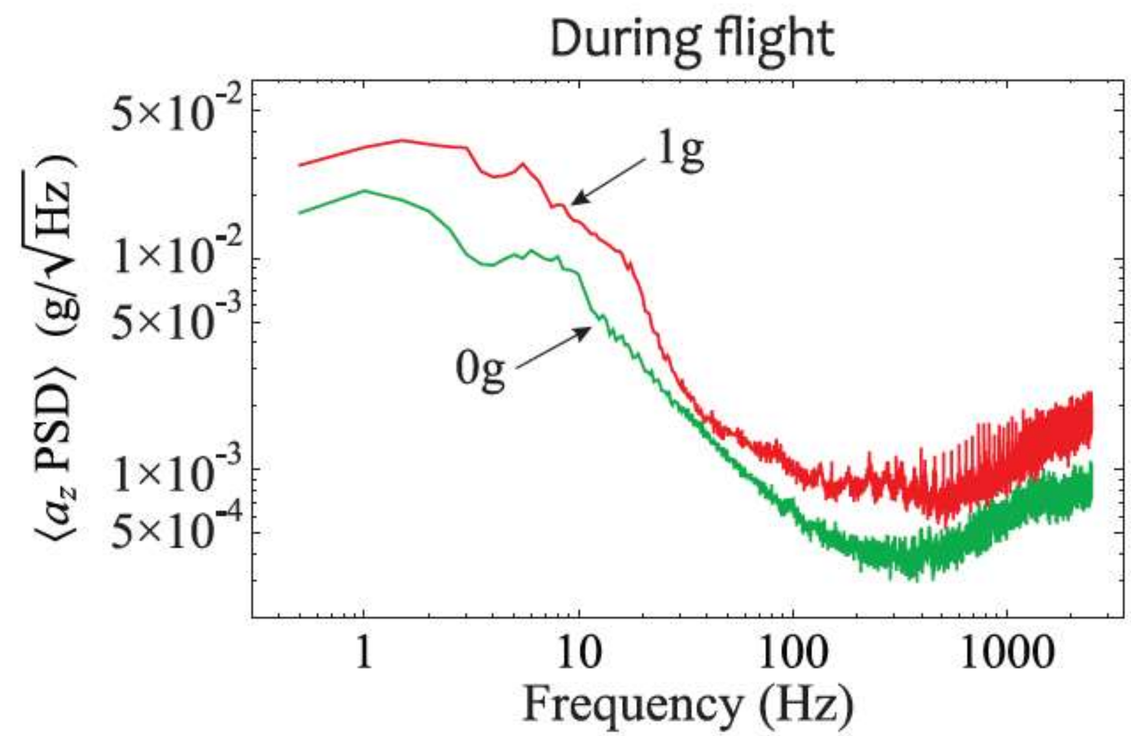
iXAtom

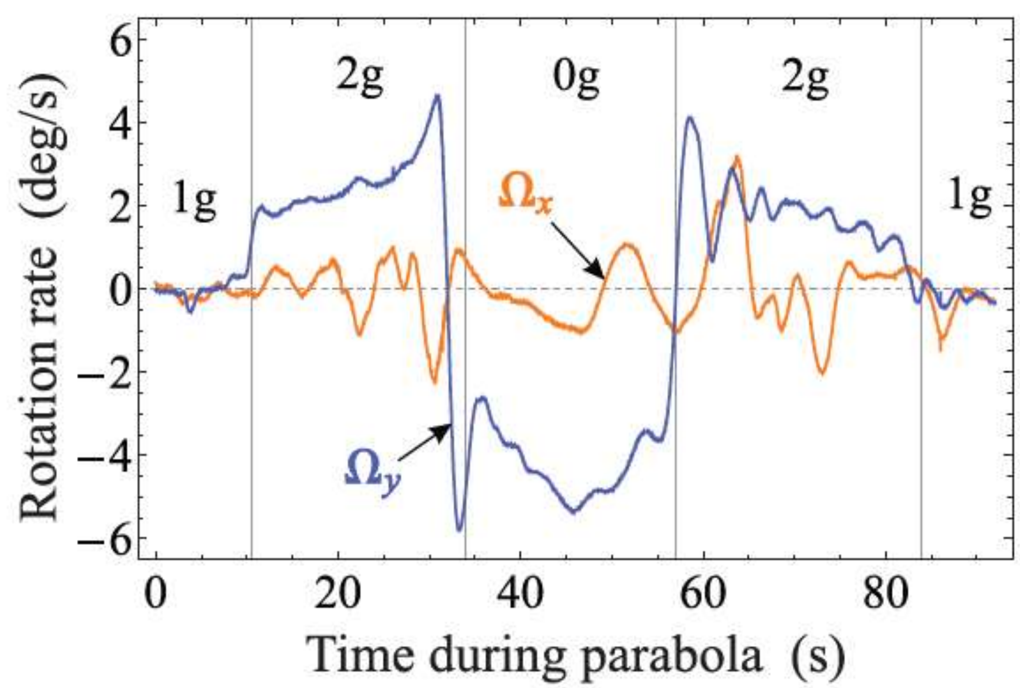
How to measure precisely in a noisy environment

- Strong vibrations (10^5 times larger than on ground)



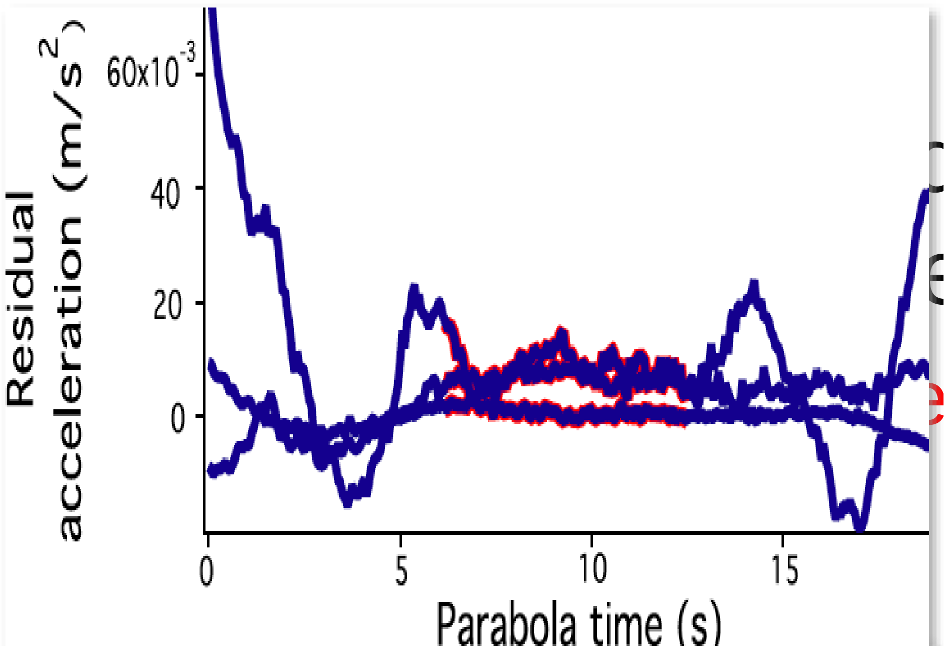
J. Le Gouét *et al*, Appl. Phys. B **92**, 133 (2008)

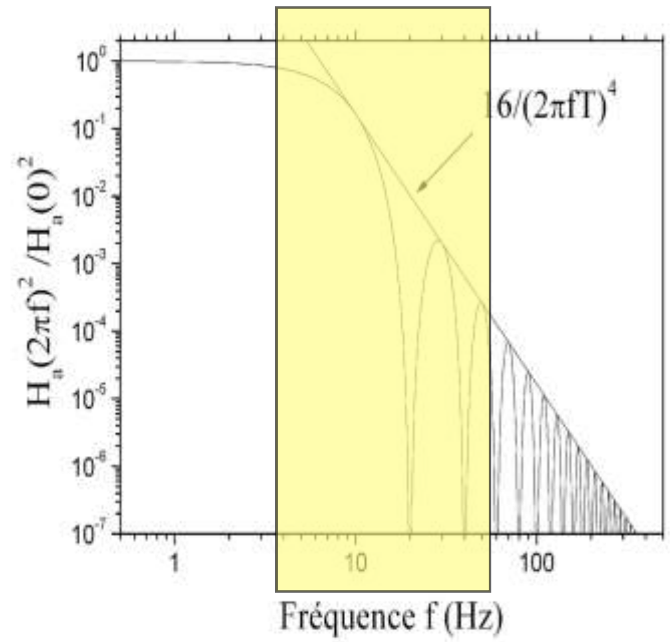


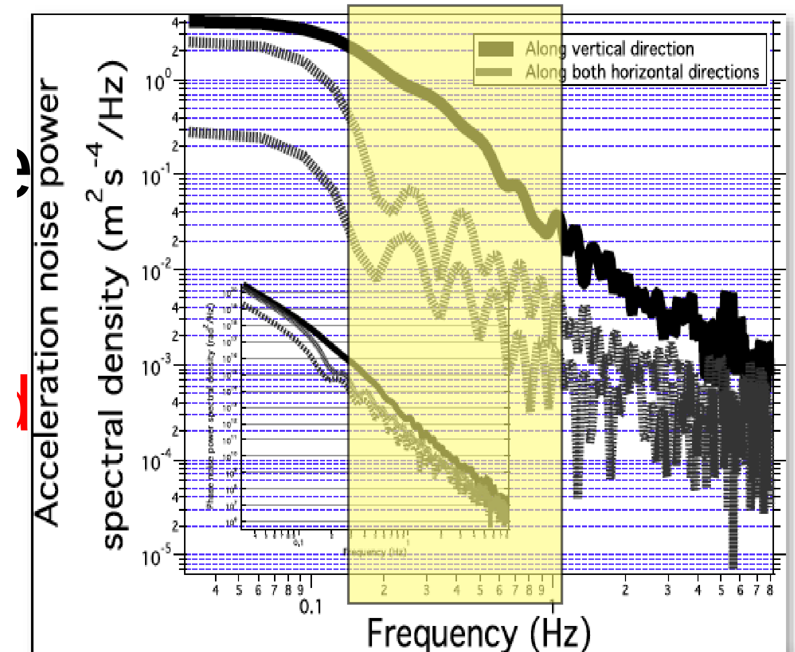


- High rotation rates (10^3 times larger than on ground)
- Large temperature fluctuations (20 C)
- Requires robust and automated systems
- Time constraints (only 3 or 6 flights per year)

VIBRATIONS AS INTERFEROMETRIC PHASE NOISE

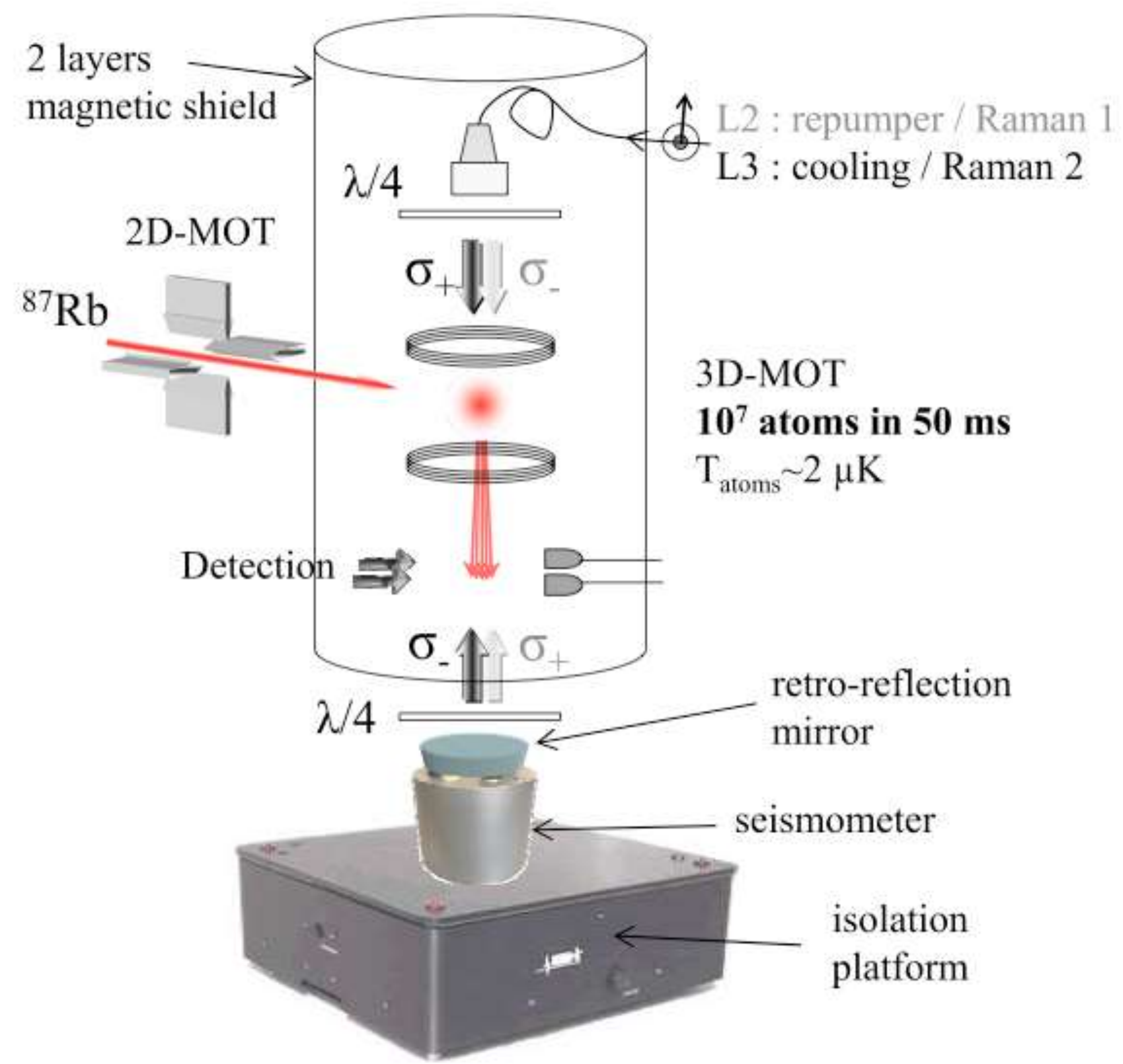


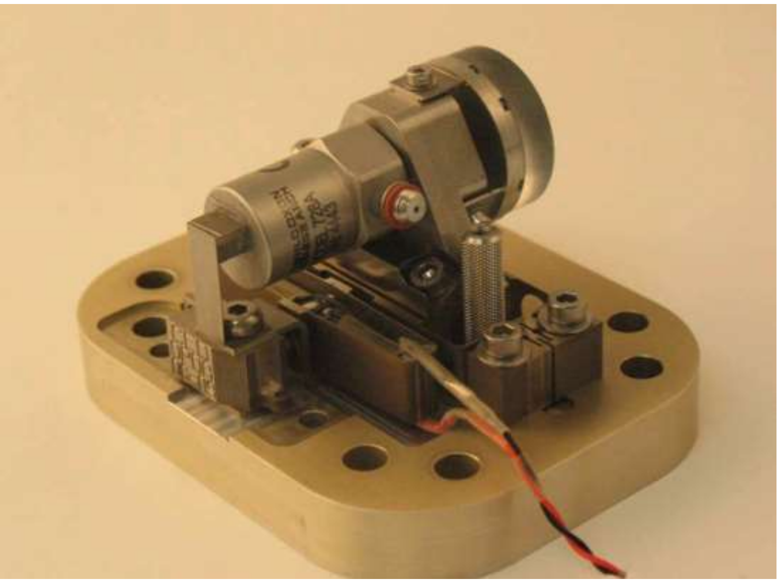




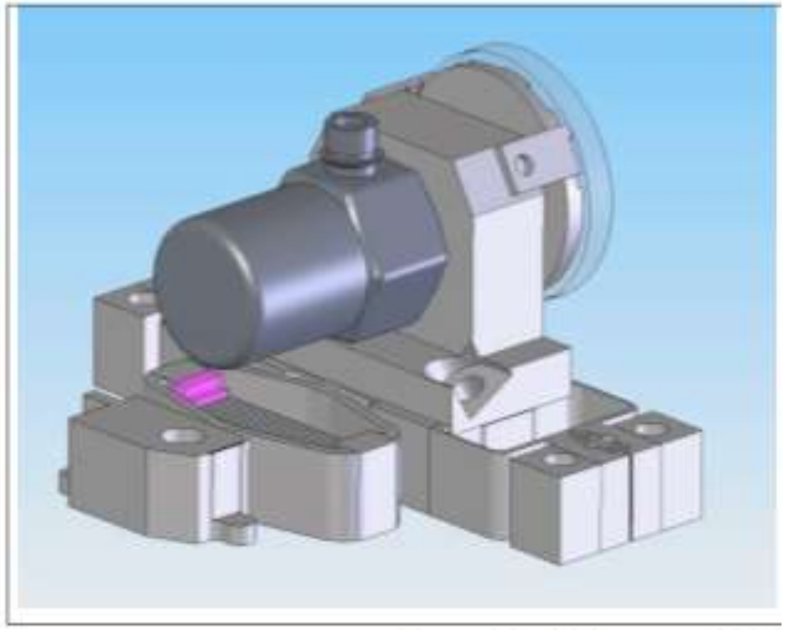
- One frequency range needs to be cancelled (directly averaged in interference signal)

RECORD RETROREFLECTING MIRROR NOISE

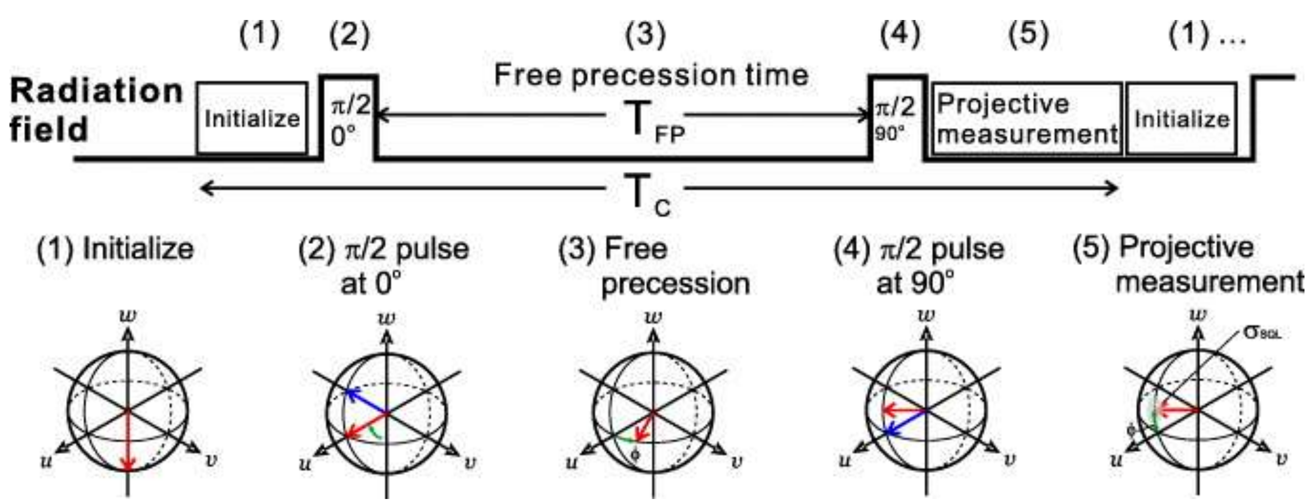


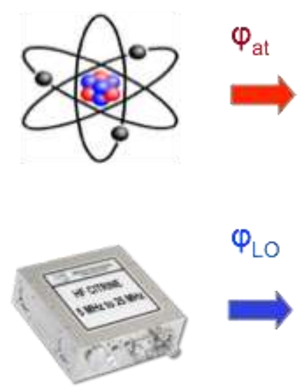


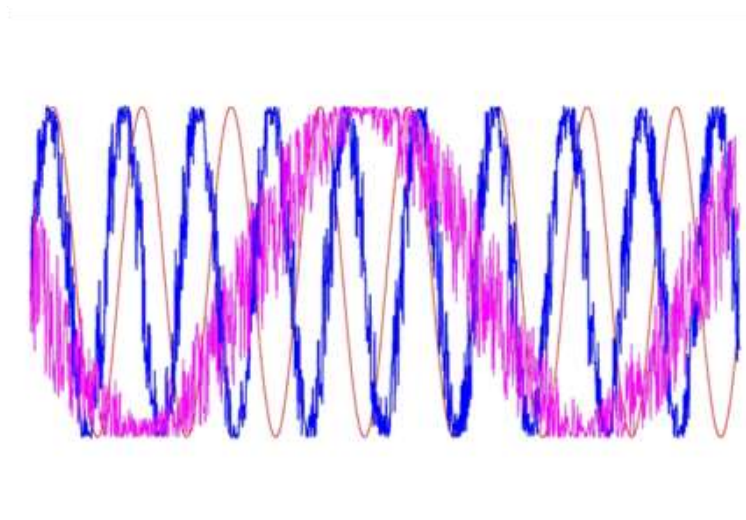
Accelerometer wilcoxon 728 A



Clocks and sensors act as "integrators" for the noise in a certain band.







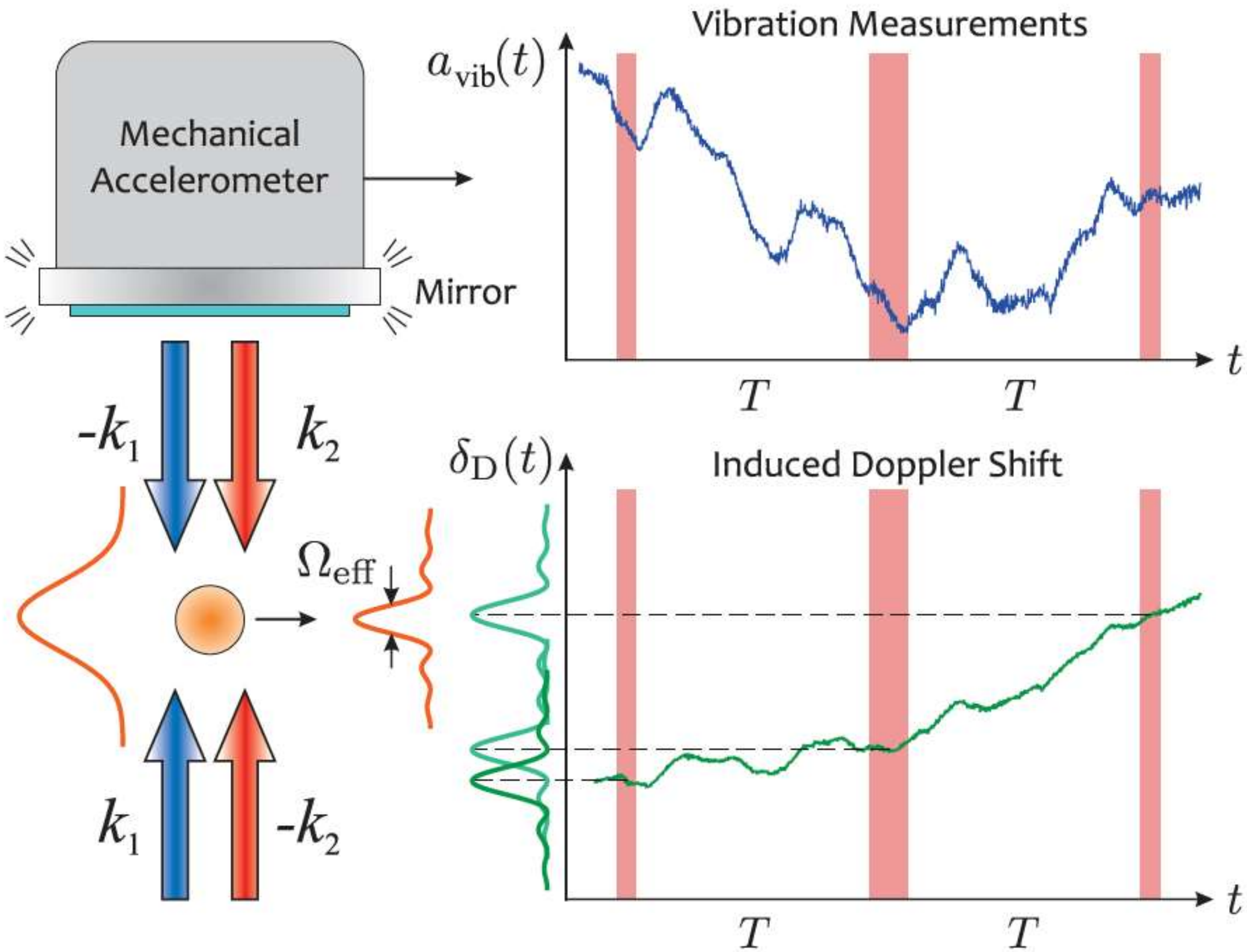
⇨In clocks, we basically "track" the difference between the LO and the atomic natural frequency

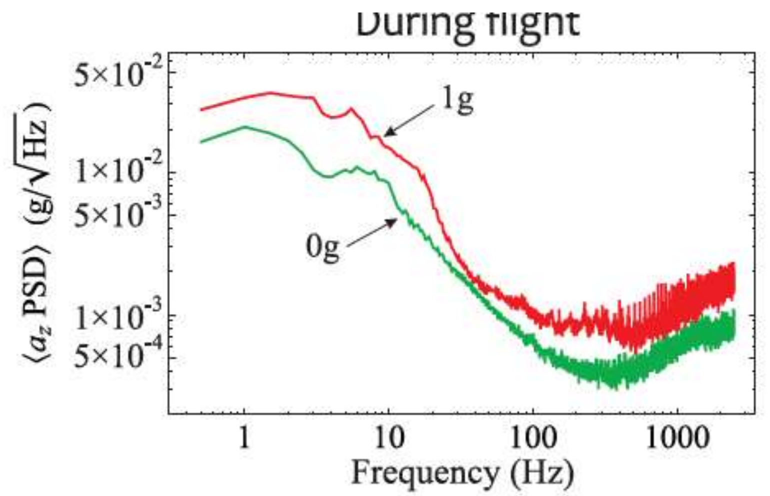
⇨Drift and/or noise should not lead to ambiguity ($\Delta\varnothing>\pi/2$).

Limits in sensitivity

- Vibration level 10^5 times at a quiet ground location
- Doppler shift follows random walk between Raman pulses

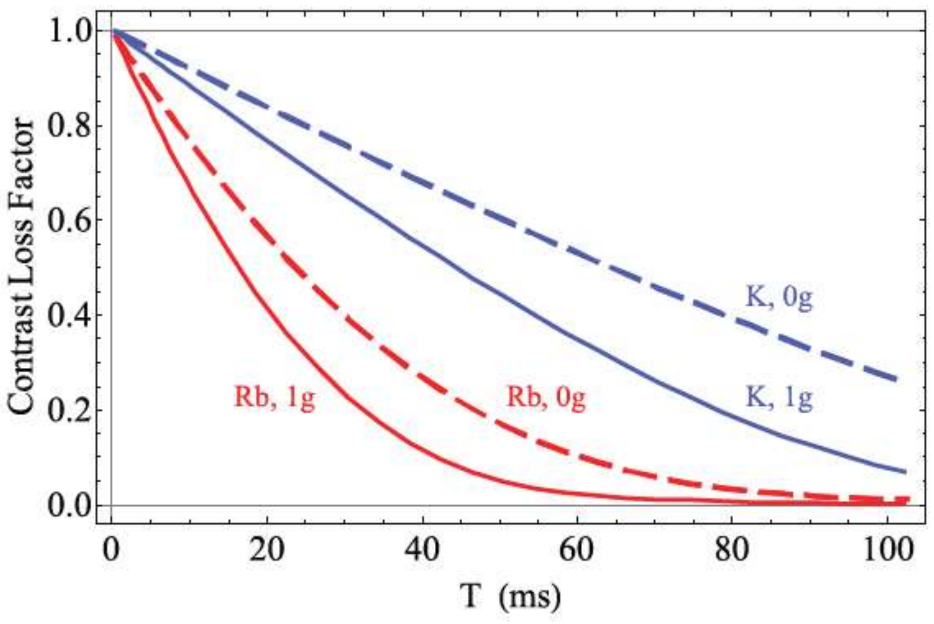
$$\delta_{\mathrm{D}}(t) = \boldsymbol{k}_{\mathrm{eff}} \cdot \int \boldsymbol{a}_{\mathrm{vib}}(t)\mathrm{d}t$$





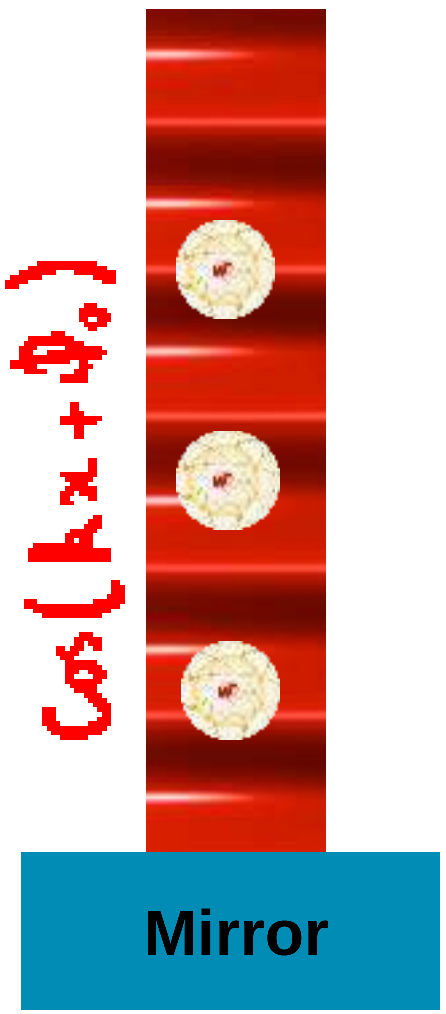
$$|\delta_{\mathrm{D}}(t_p) - \delta_{\mathrm{D}}(t_p - T)| \ll \Omega_{\mathrm{eff}}$$

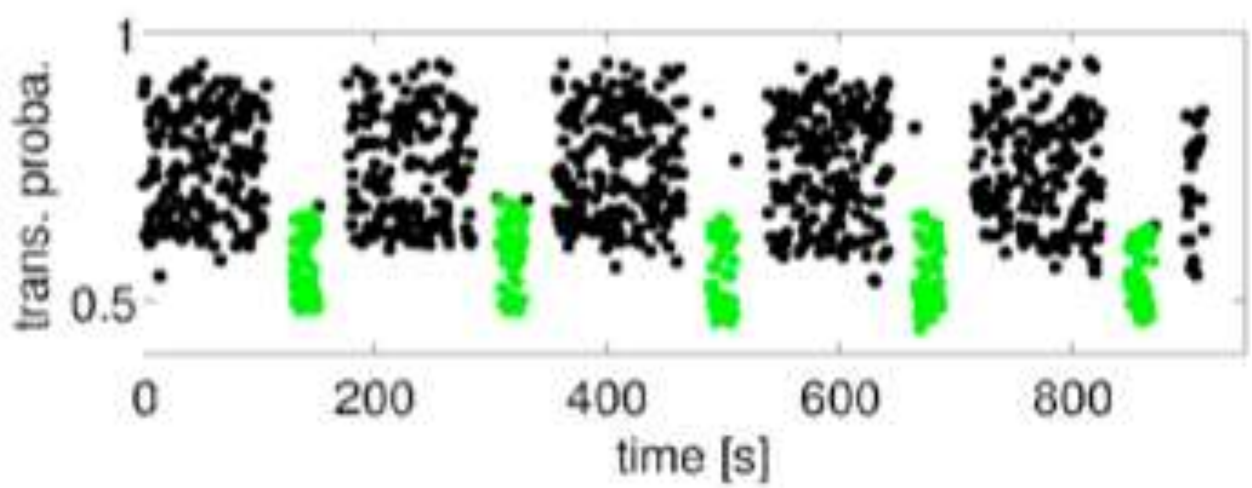
$$\Rightarrow \sigma_{\mathrm{vib}} \ll \Omega_{\mathrm{eff}}/k_{\mathrm{eff}}T$$



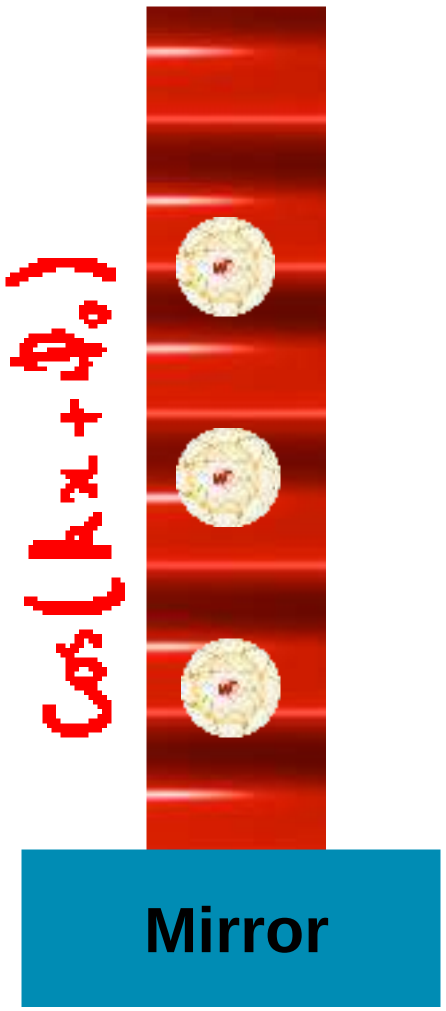
CORRELATED MEASUREMENTS

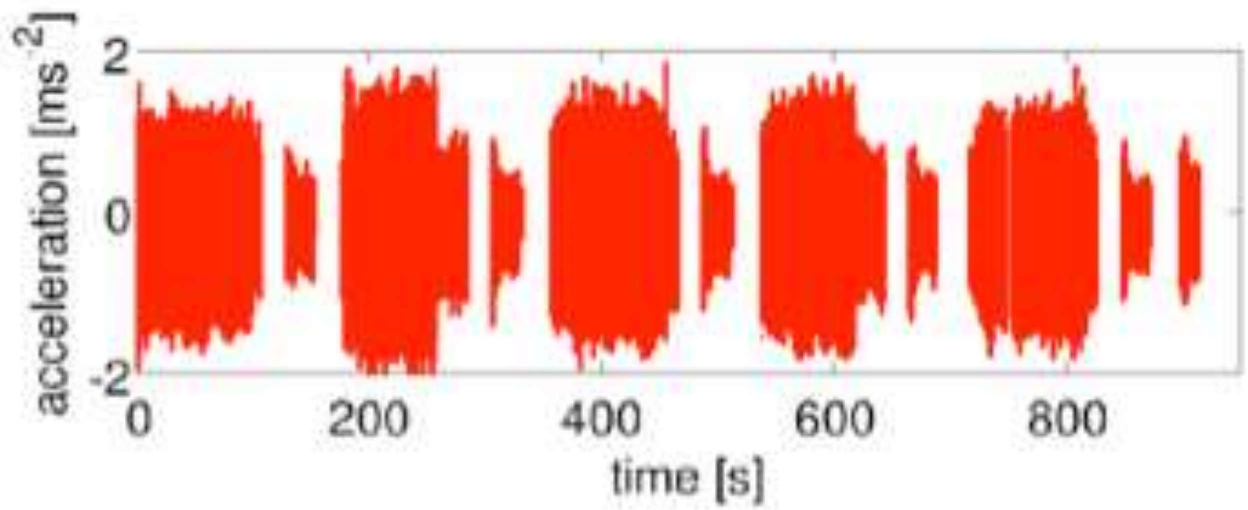
$\cos(kx+\varphi_0)$



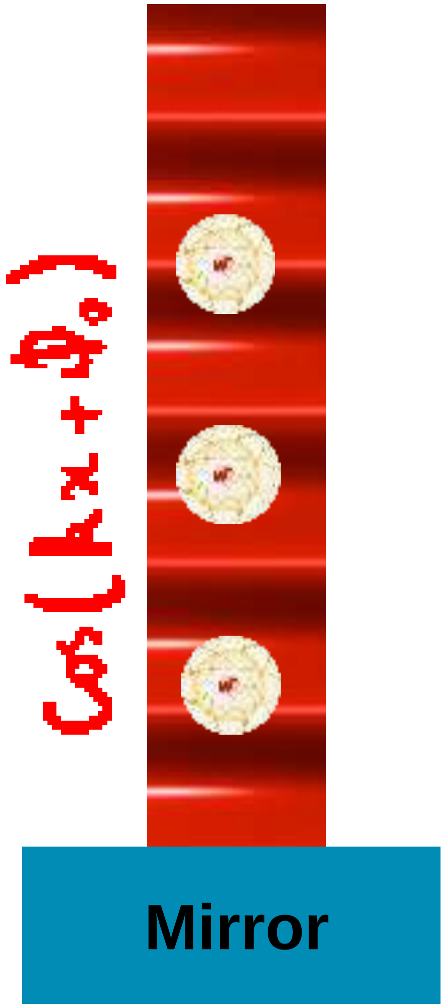


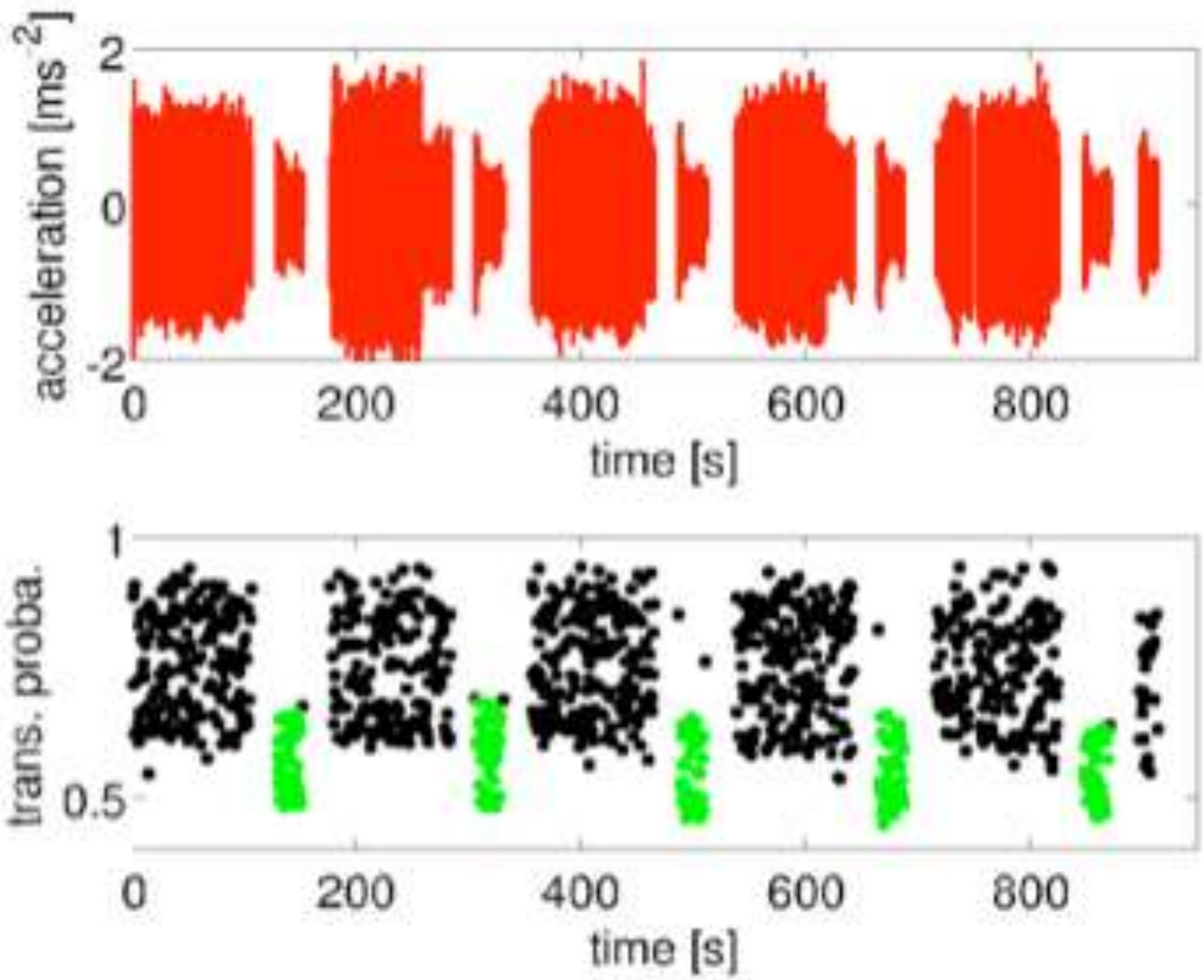
CORRELATED MEASUREMENTS



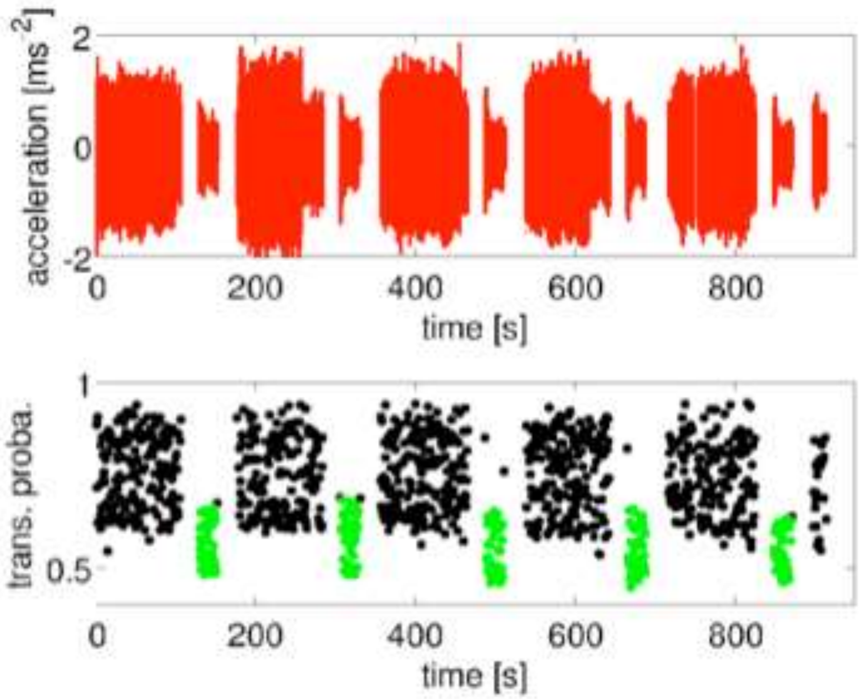


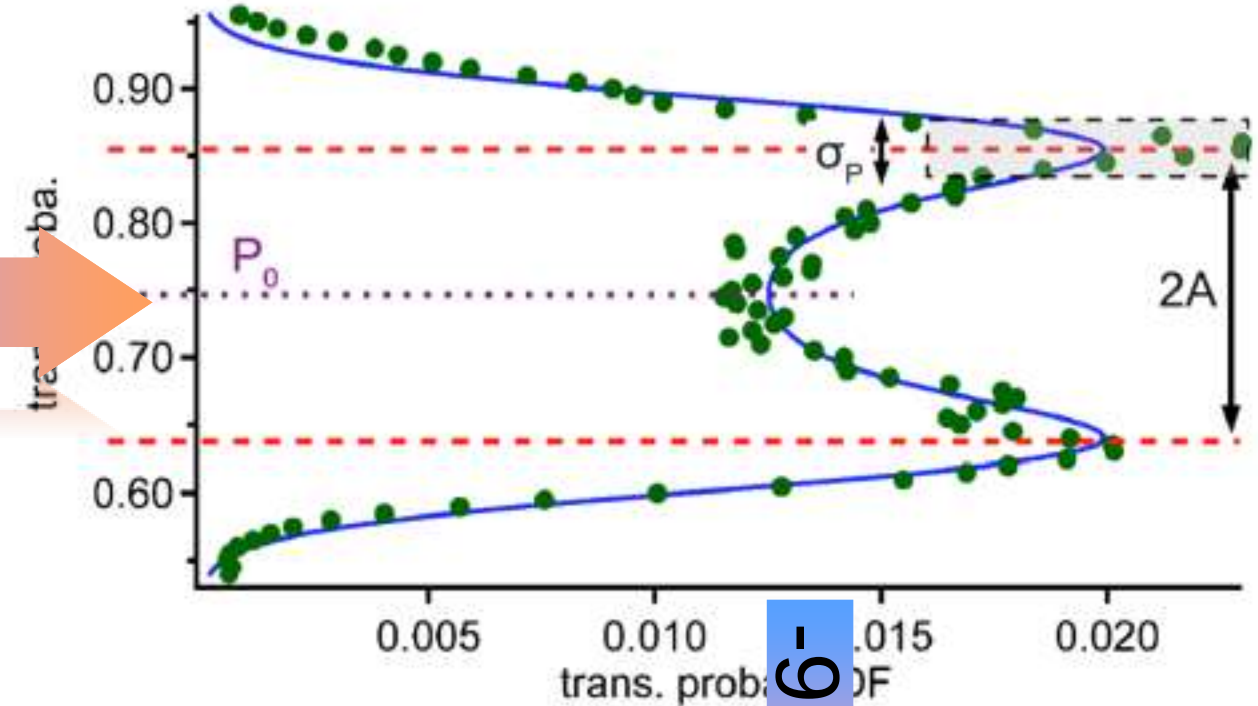
CORRELATED MEASUREMENTS





Correlated measurements



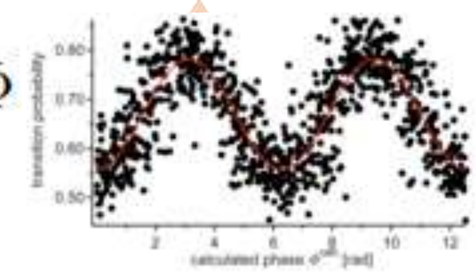


-90

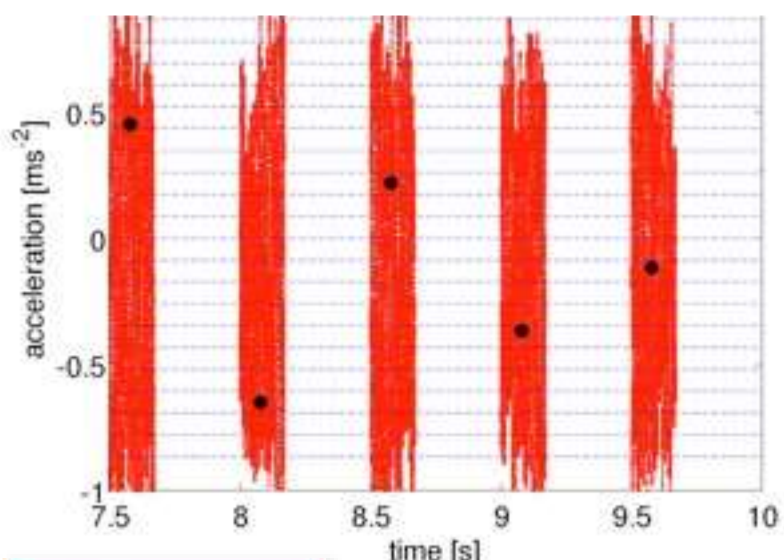
$$\Phi = a_{\mathrm{m}} \times kT^2$$

$$P^{\mathrm{AI}}(\Phi) = P_0 - A\cos\Phi$$

$$\mathrm{SNR} = A/\sigma_P$$



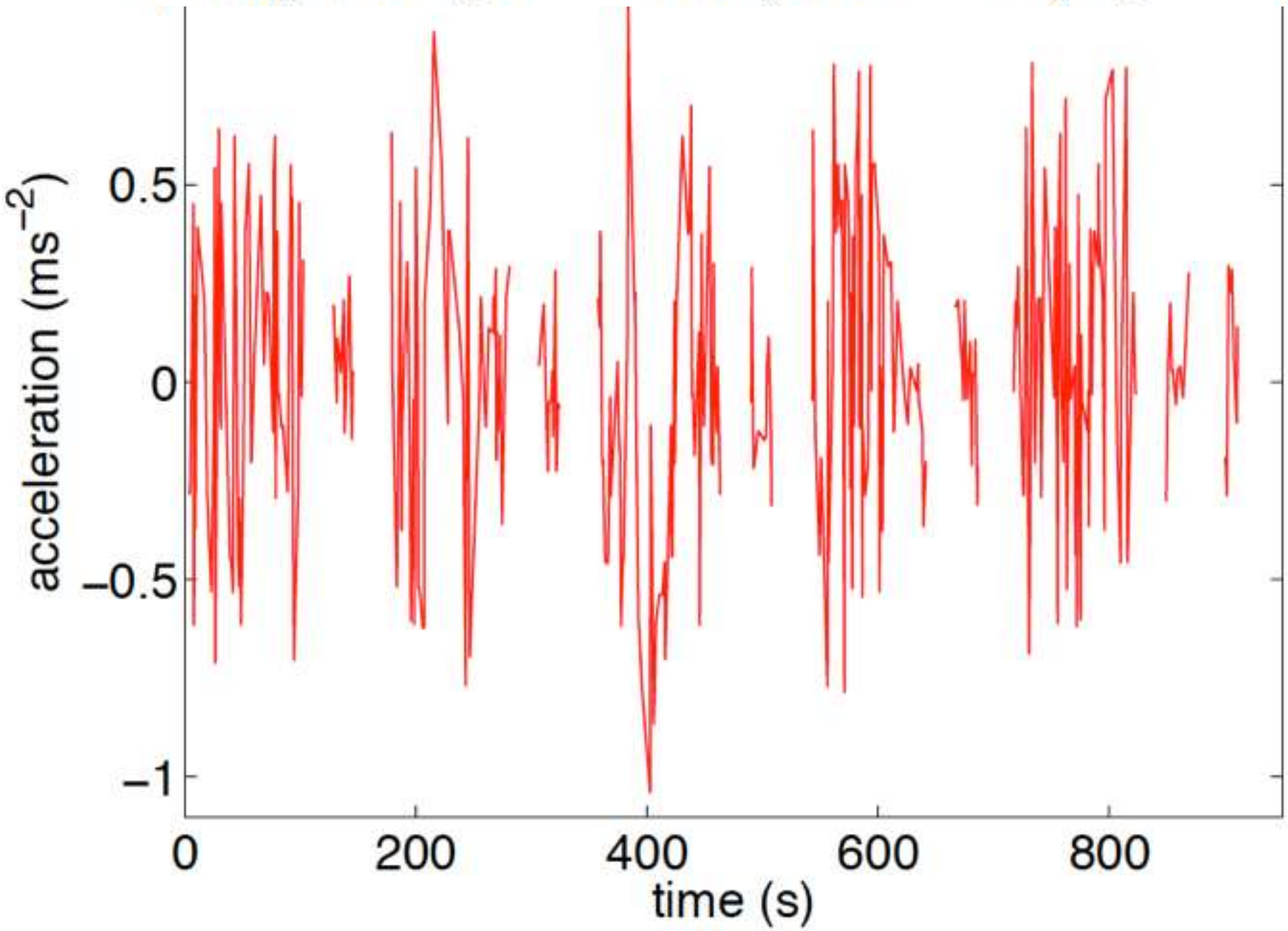
$$P_0 = 0.747\,,\, 2A = 0.261 \text{ and SNR} = 4.7$$



Geiger et al., I.C.E. project, Nature Communication

FIRST ACCELERATION RECORDING WITH AI

$$0.35\ \mathrm{mg}/\sqrt{\mathrm{Hz}}\ (2T = 3\ \mathrm{ms},\ \mathrm{SNR} = 4.7,\ T_c = 350\ \mathrm{ms})$$

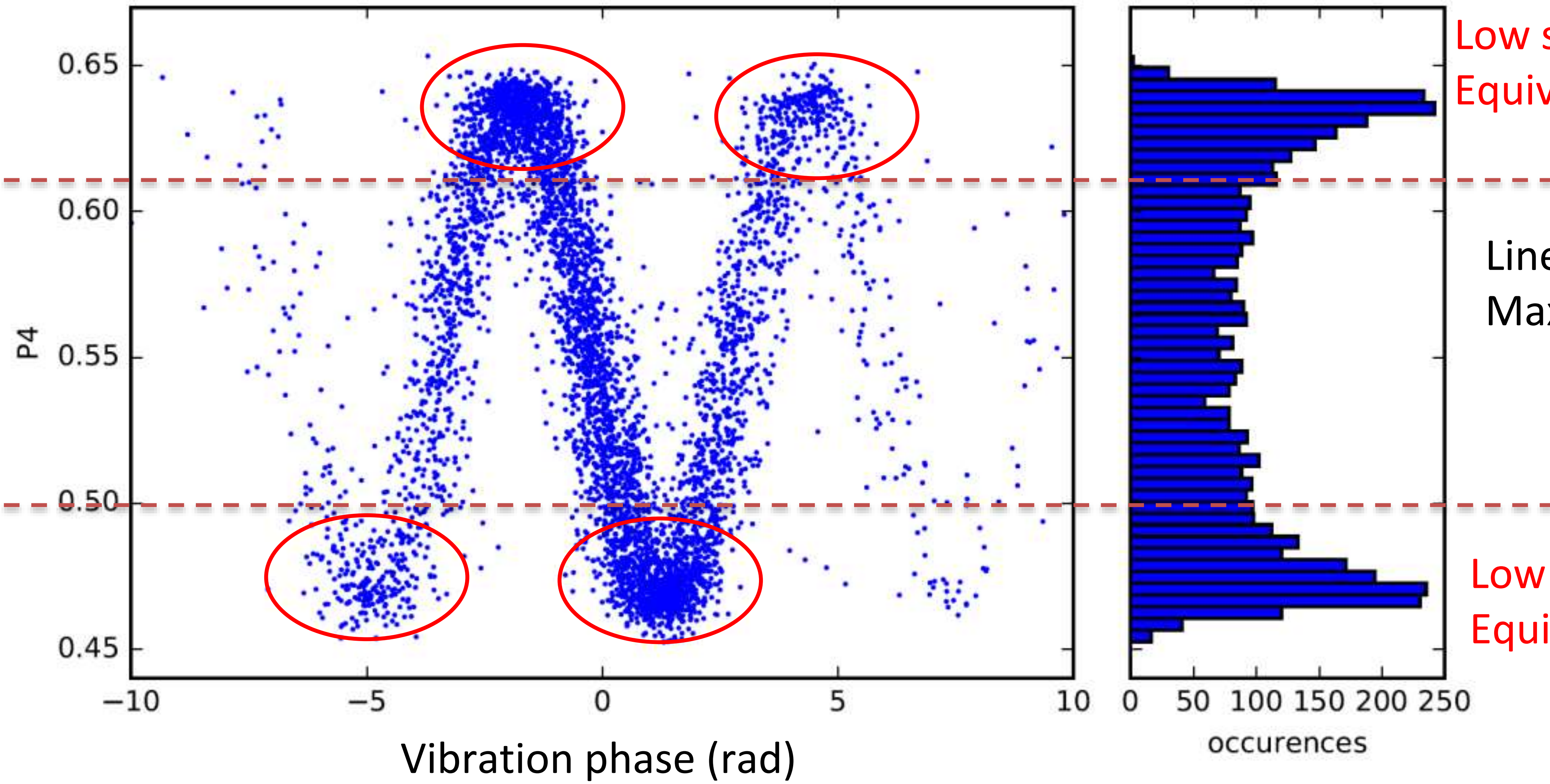


0-g time

- Sensitivity (max interrogation time) limited by the linearity of the standard accelerometer (Sensorex SX46020 and IMI 626A03)

Geiger et al., Nature Comm. DOI: 10.1038/ncomms1479

Operation in the linear regime

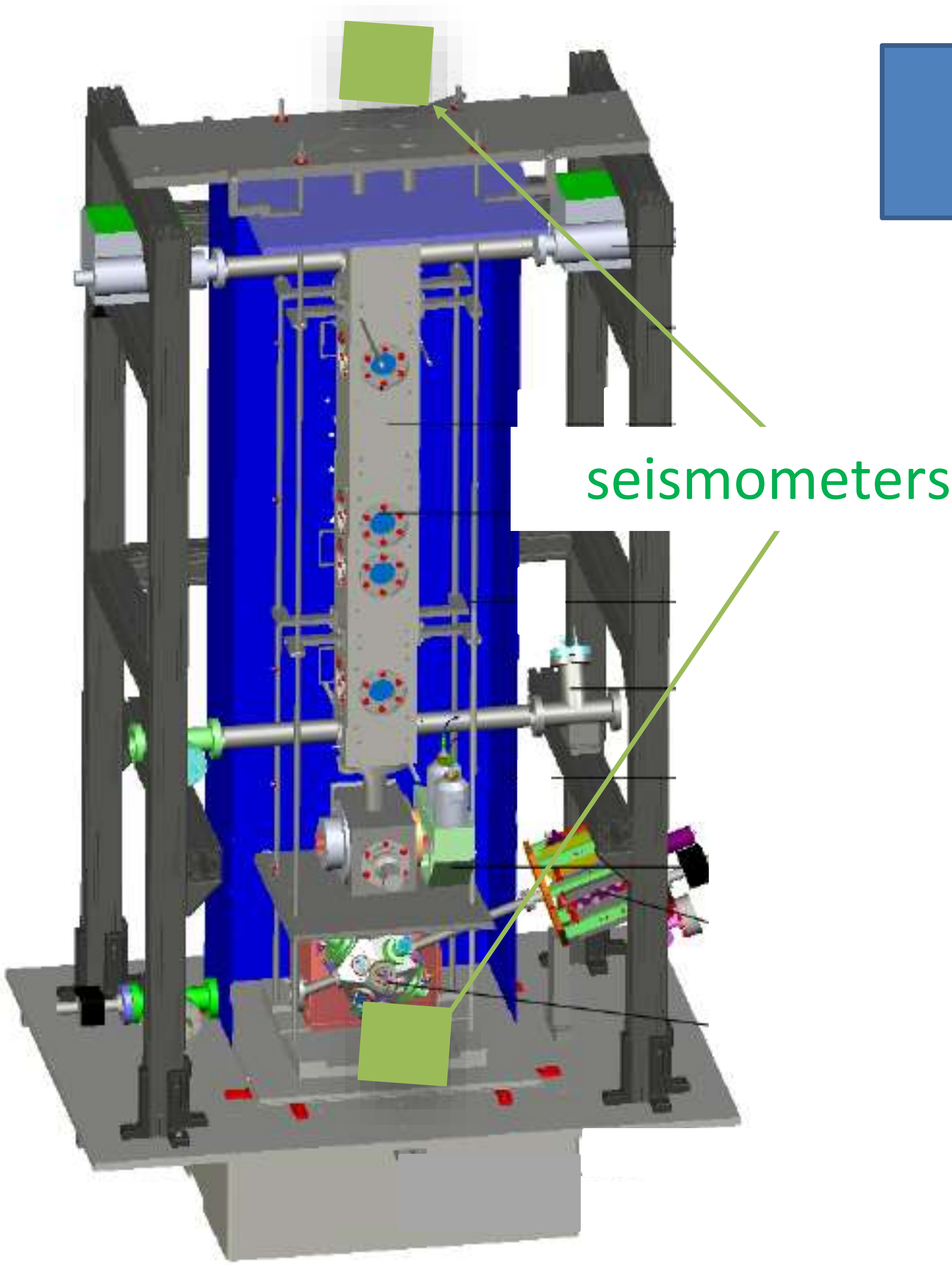


Low sensitivity
Equivalent dead time

Linear range
Max. sensitivity

Low sensitivity
Equivalent dead time

Vibration noise rejection

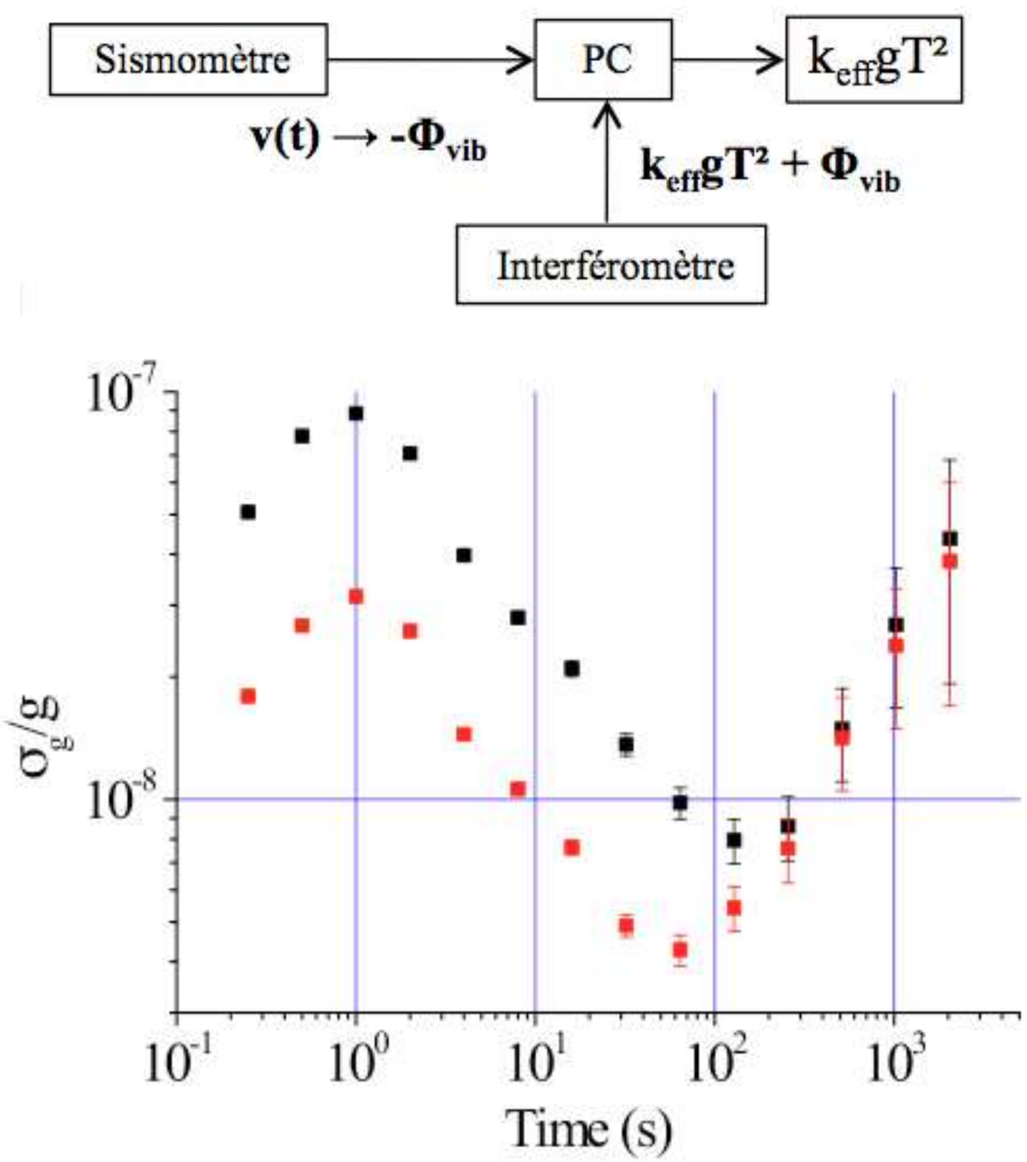


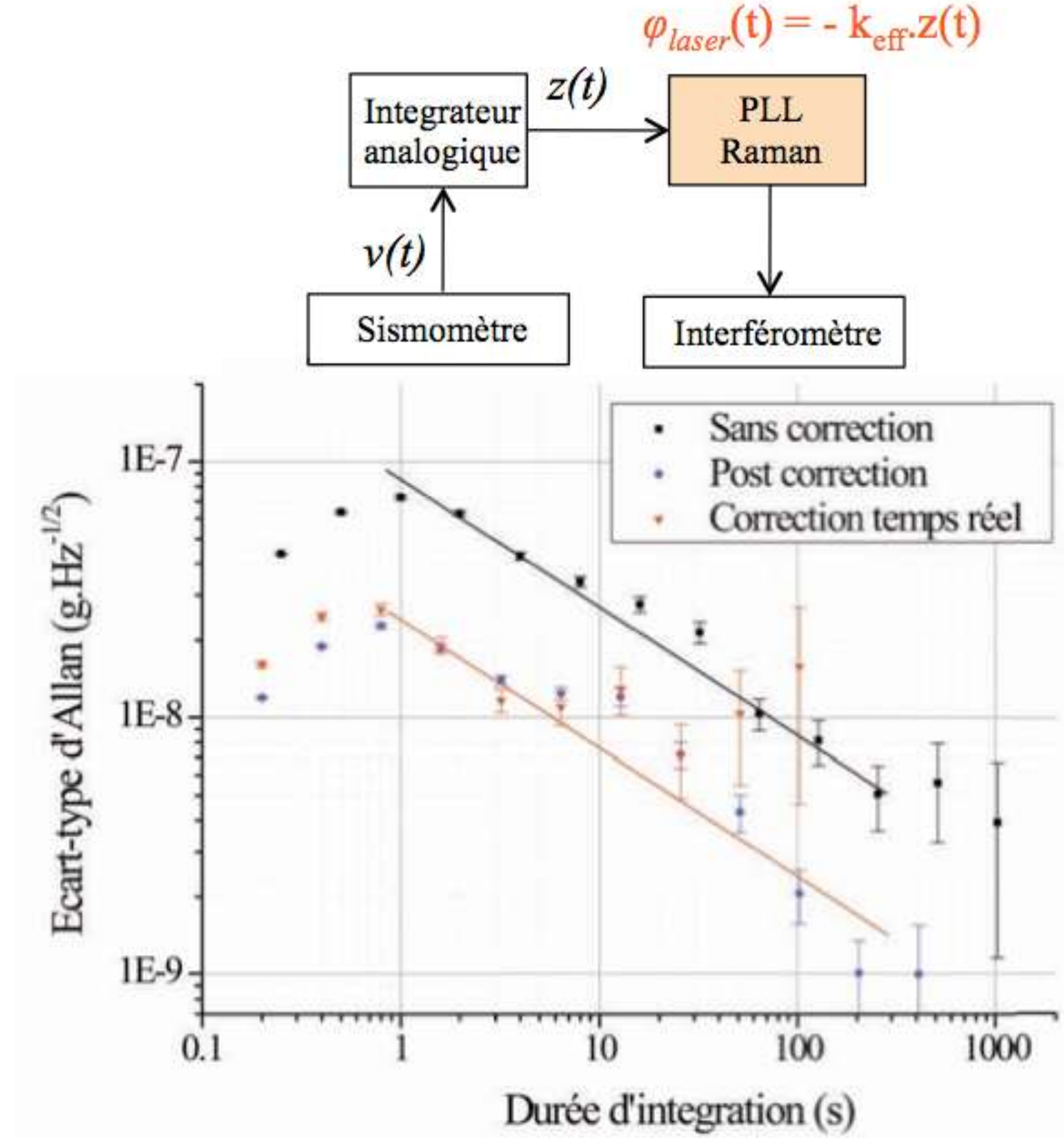
Measured vibrations → AI transfer function → Calculated phase → Feed-forward → AI phase

J. Lautier et al, App. Phys. Letters **105** 144102 (2014)

VIBRATIONS AS INTERFEROMETRIC PHASE NOISE

Passive/Active

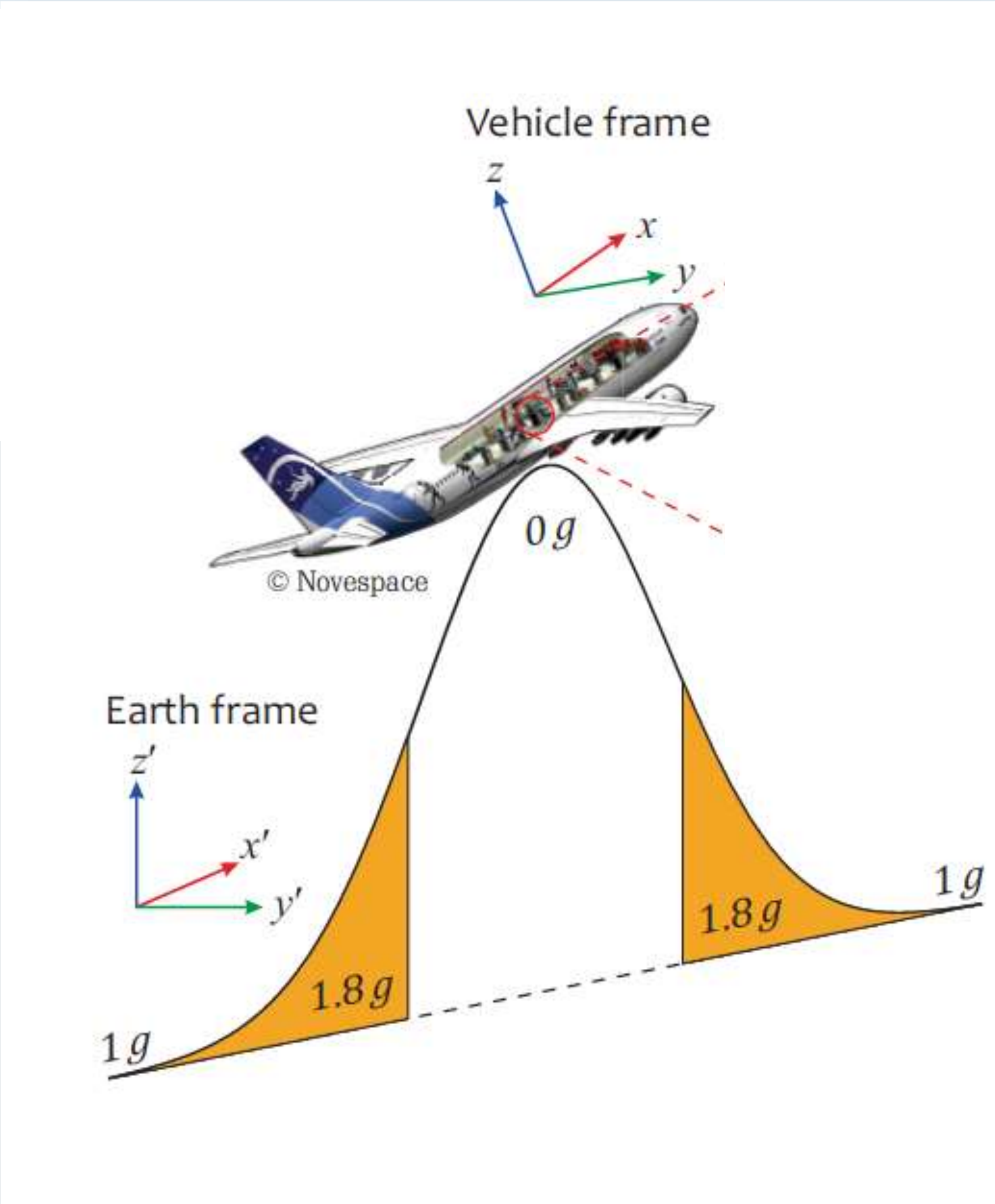


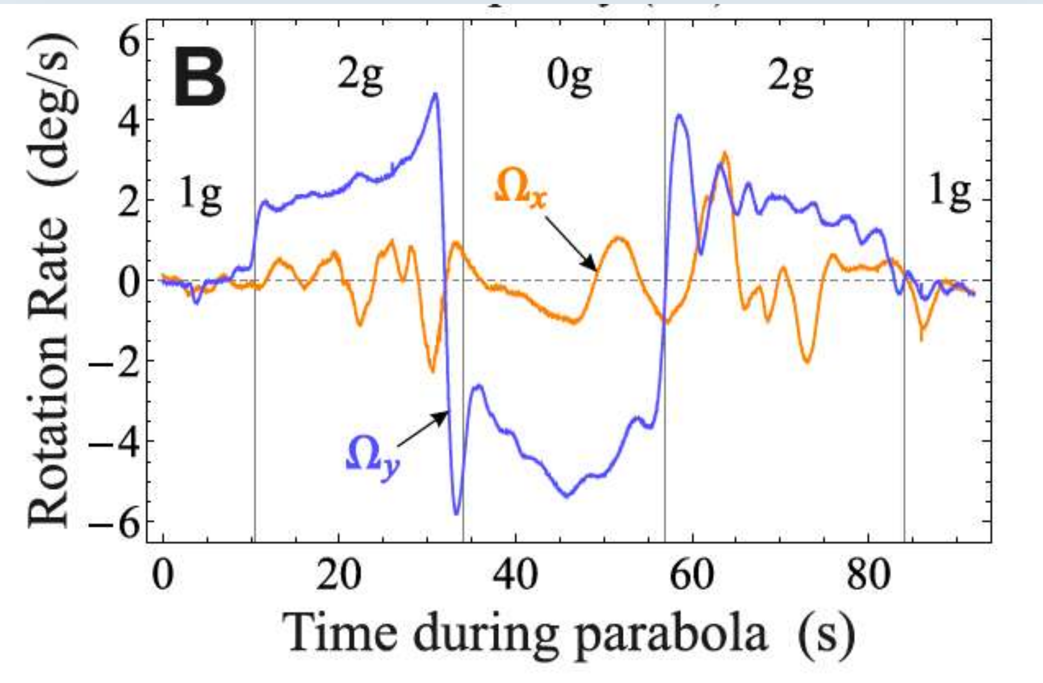


Sensitivity improved from 80 to 30 ng/√Hz

Sensitivity improved from 80 to 20 ng/√Hz

EFFECT OF TRAJECTORY





Coriolis acceleration

- **Additional phase shift**
- **Changes the interferometer**

Limits in sensitivity

- Lagrangian for a body undergoing rotations and linear accelerations

$$L(\boldsymbol{r},\boldsymbol{v}) = \frac{1}{2}M(\boldsymbol{v}+\boldsymbol{\Omega}\times\boldsymbol{r})^2 + M\boldsymbol{a}\cdot\boldsymbol{r}$$

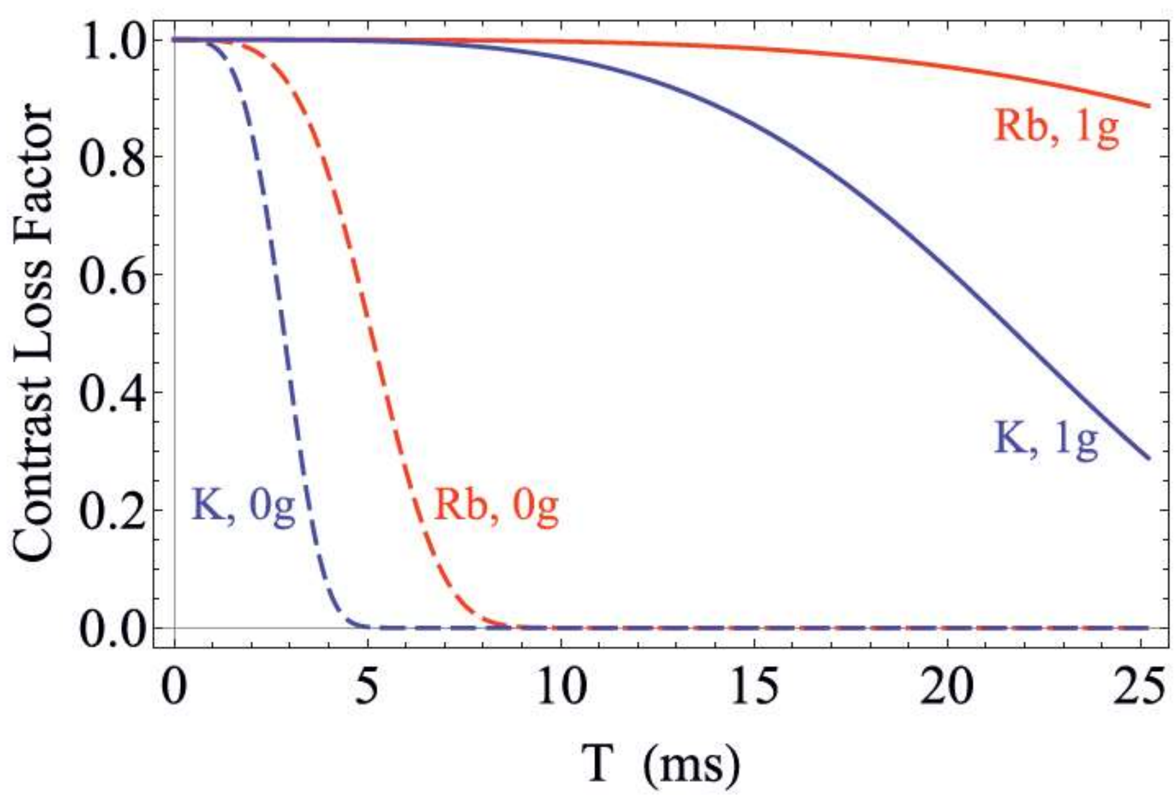
- Evaluate interferometer trajectories and insert into Roura model: New J. Phys. 16, 123012 (2014)

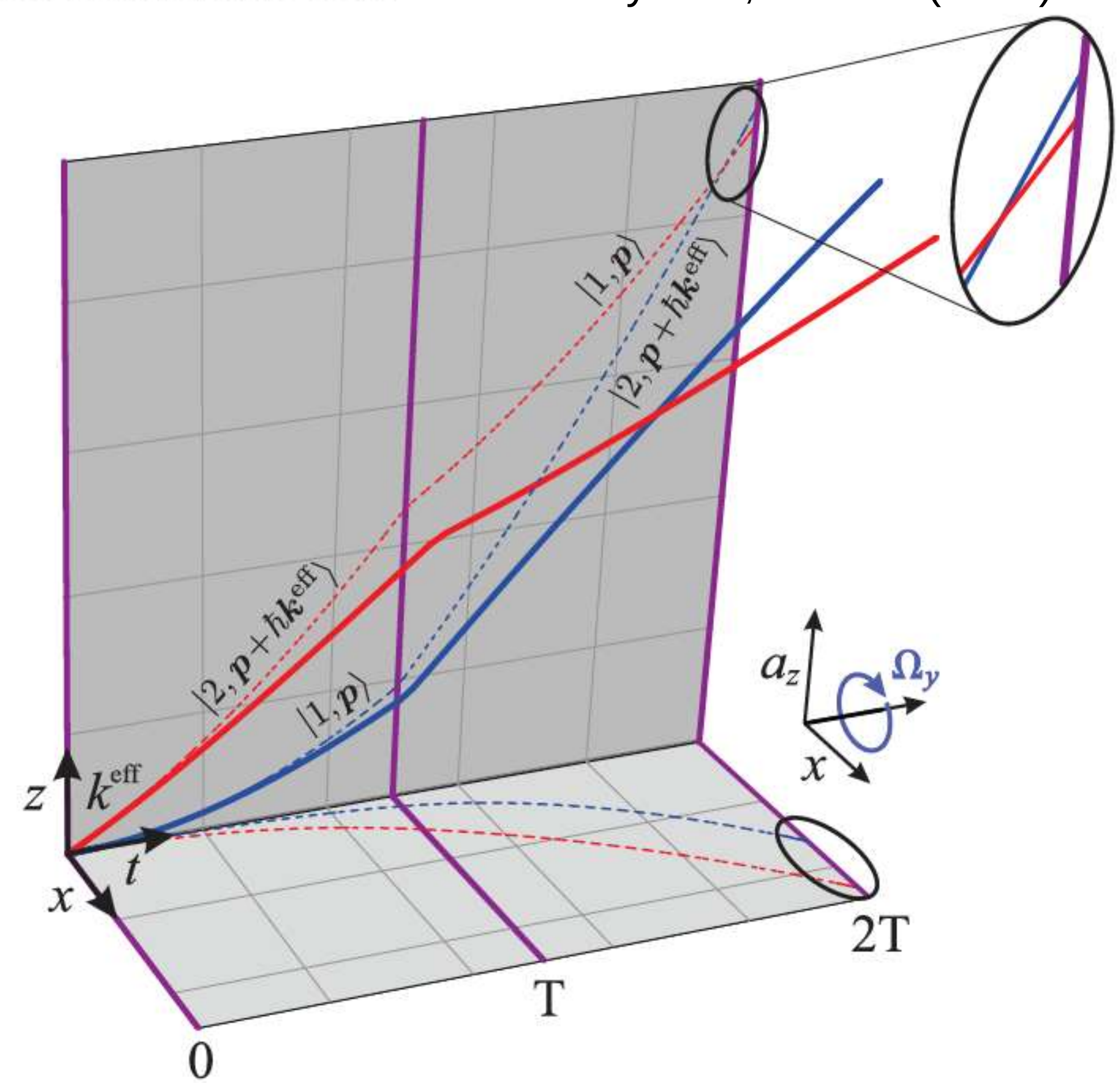
$$C \sim \exp\left[-(k_{\mathrm{eff}}\sigma_v T)^2\,(|\boldsymbol{\Omega}_{\mathrm{T}}|T)^2\right]$$

Velocity spread

Interrogation time

Rotation rate transverse to $\mathbf{k}_{\mathrm{eff}}$





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CORIOLIS INDUCED REDUCTION OF CONTRATS

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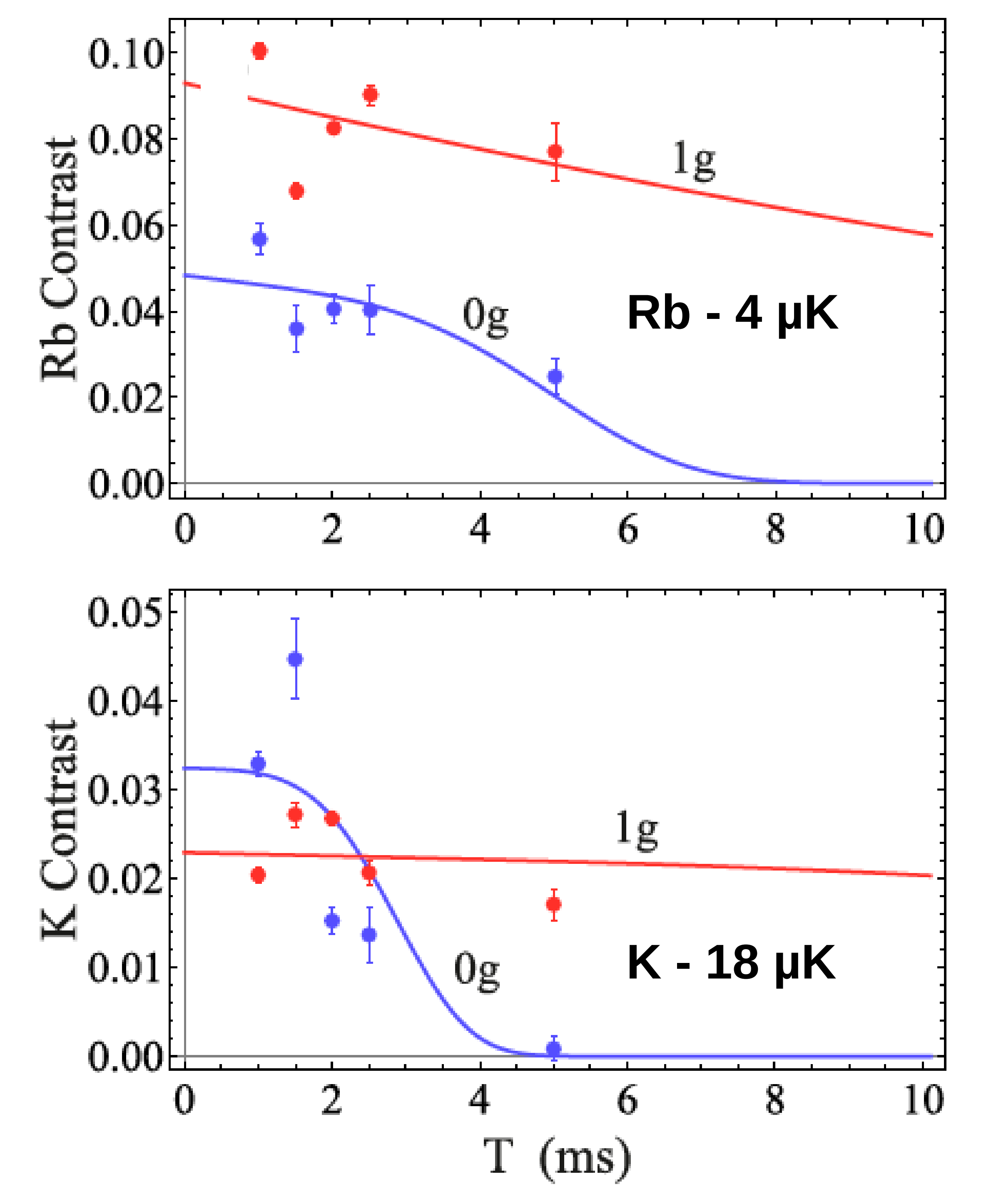

Rotation in the plane Ωy ≈ 5 deg/s

- **100 % contrast loss in ≈ 10 ms**
  - **Limiting for navigation systems**
  - **Limiting for space mission in LEO**
- **For 5 second interrogation time, rotation needs to be ≈ 6 10^{-5} deg/s (50 times than earth rotation)**
  - **Rotation compensation of retroretlecting mirror**

S. M. Dickerson, et al., Phys. Rev. Lett. 111, 083001 (2013).

For navigation

- **Large rotation rates**
- **Large acceleration (+/- 2 g)**
  - **Limits T to 10 ms**
  - **Find locking methods to enhance measurement (T^2)**

INSTITUT d'OPTIQUE GRADUATE SCHOOL

PROBLEM OF THE REPETITION RATE

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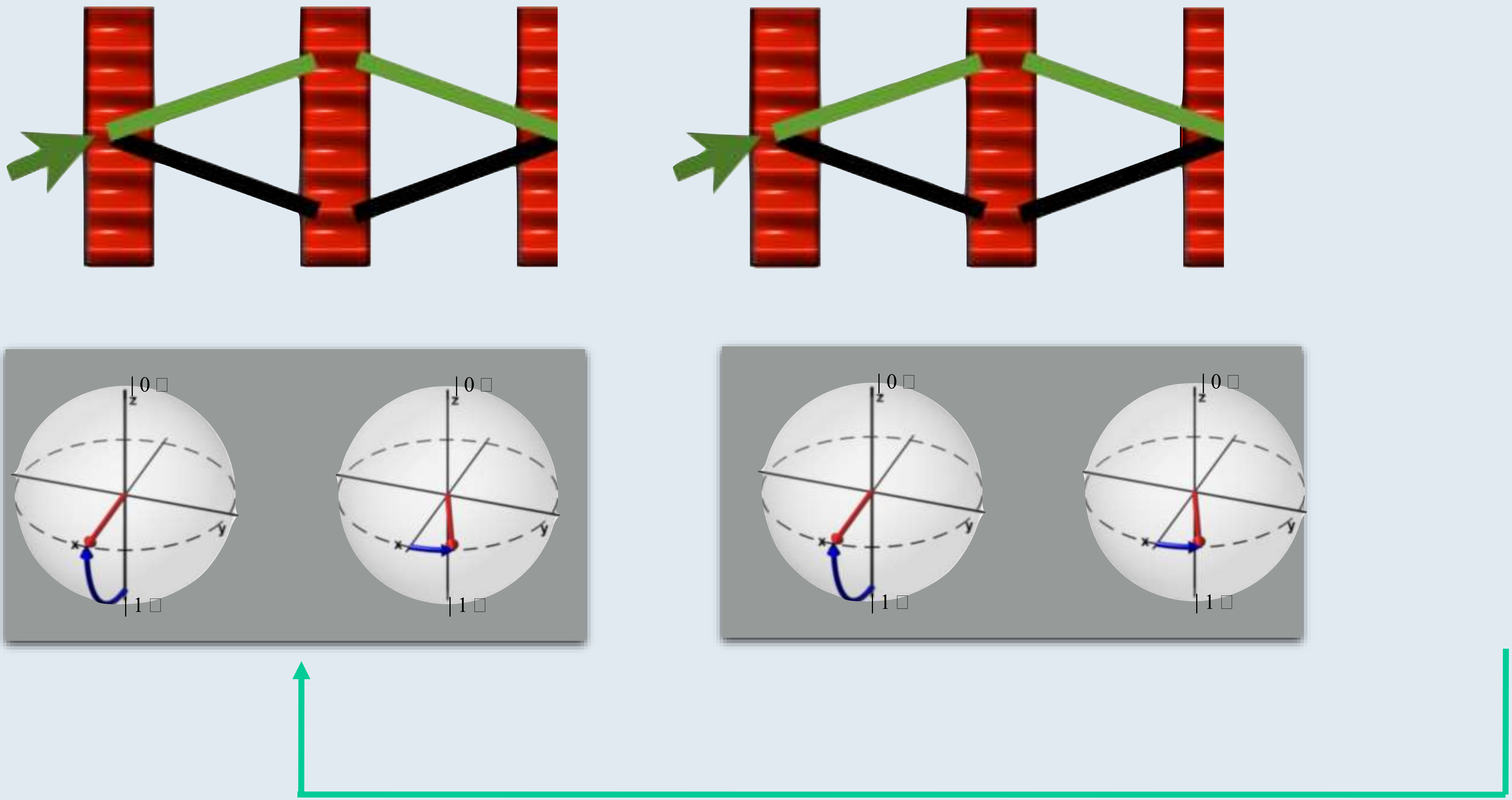
INSTITUT d'OPTIQUE GRADUATE SCHOOL

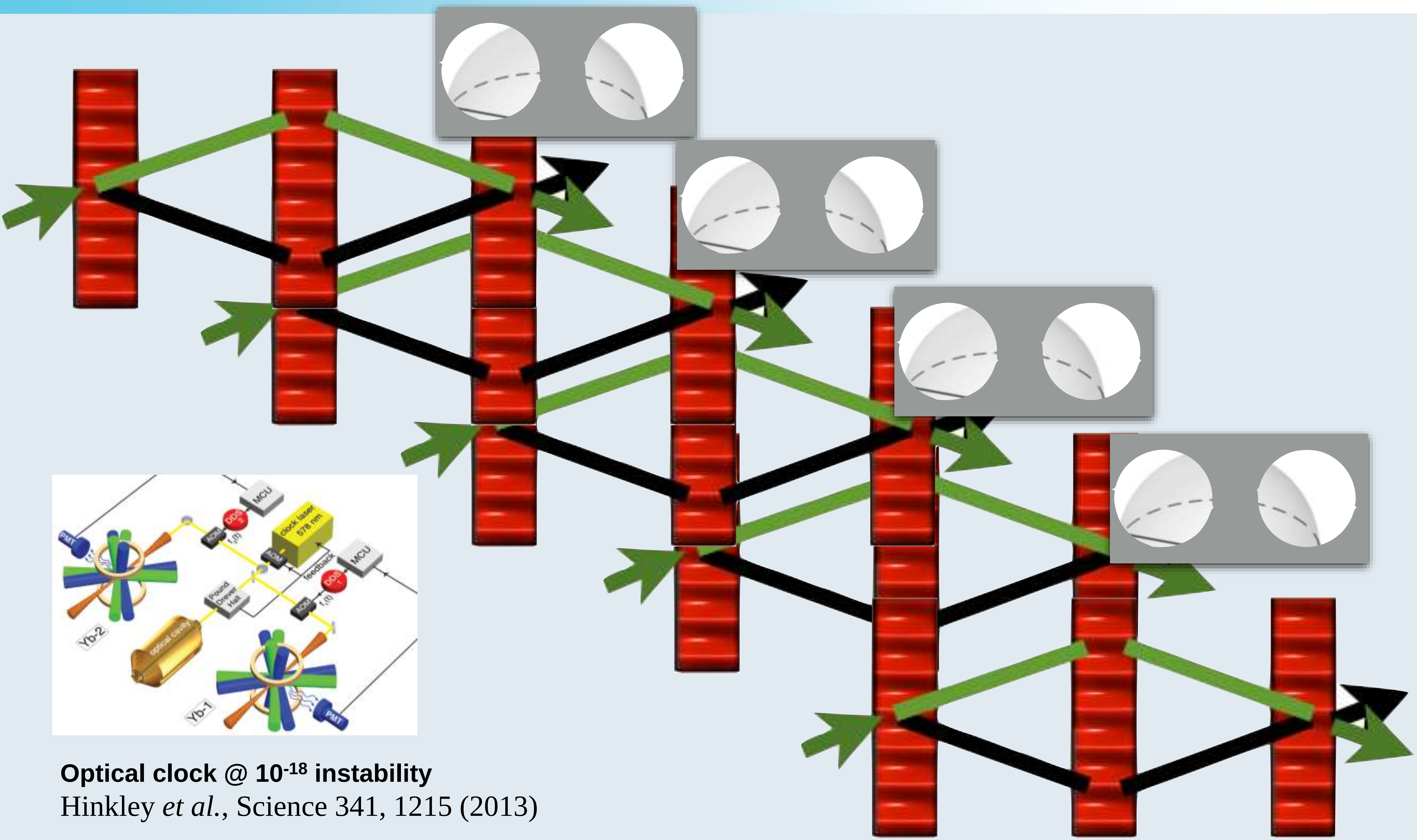
INTERLEAVING TWO CLOCKS MEASUREMENTS



repeat

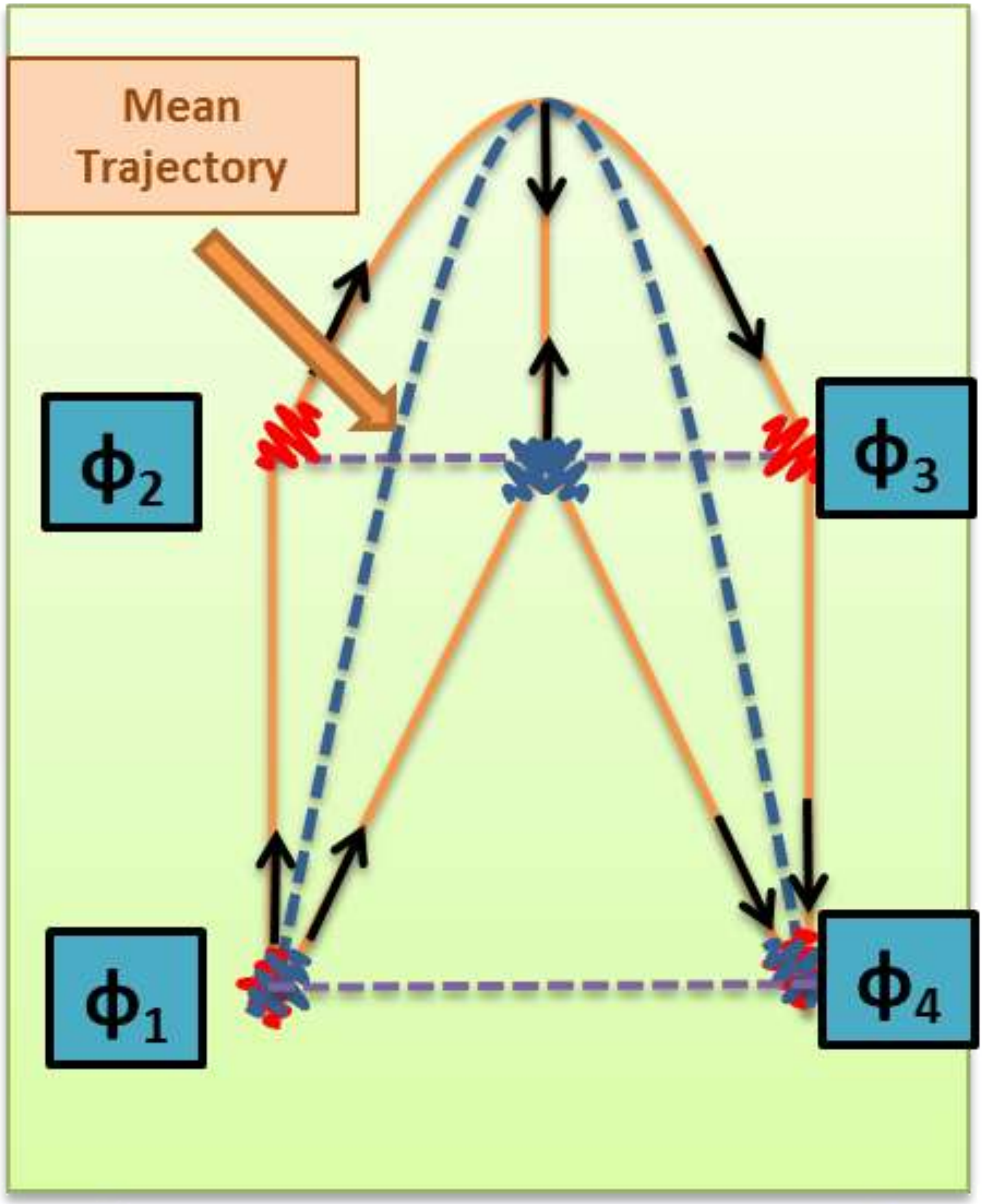
INSTITUT d'OPTIQUE GRADUATE SCHOOL

Problem of the repetition rate

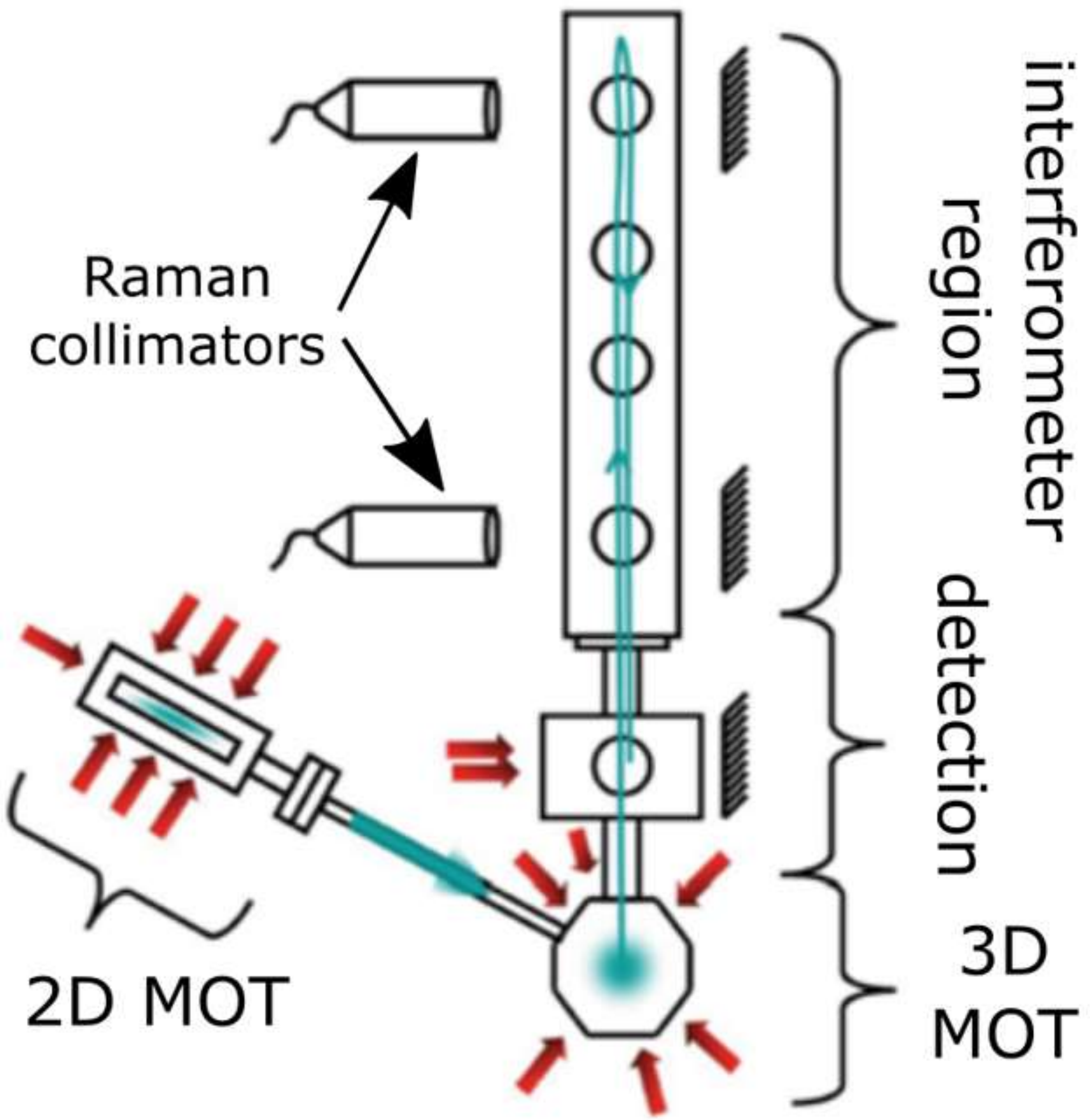


Optical clock @ 10^{-18} instability
Hinkley *et al.*, Science 341, 1215 (2013)

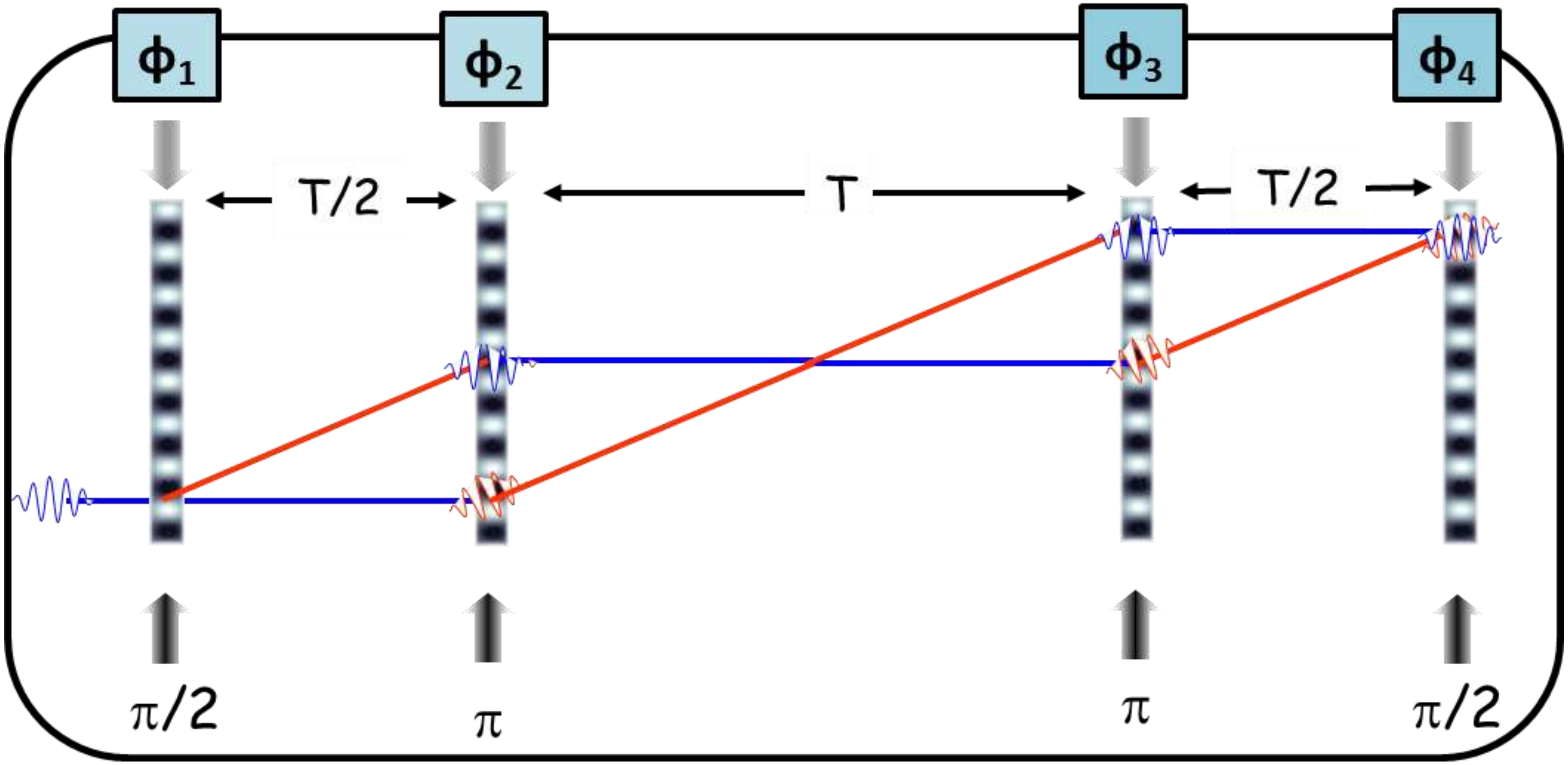
4-light pulse gyroscope



« Butterfly » configuration



4-LIGHT PULSE GYROSCOPE

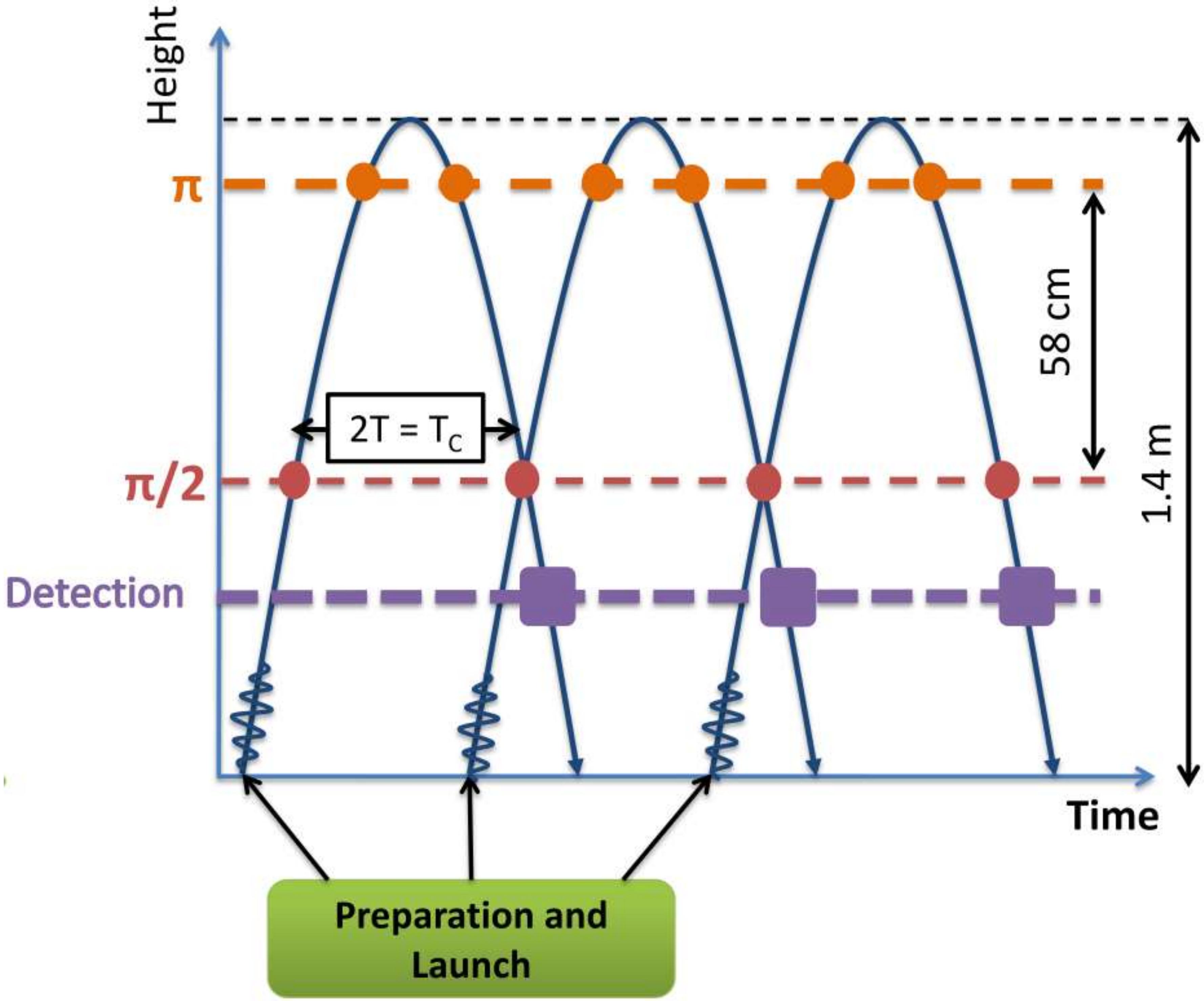


$$\boxed{\Delta\phi = \phi_1 - 2\phi_2 + 2\phi_3 - \phi_4}$$

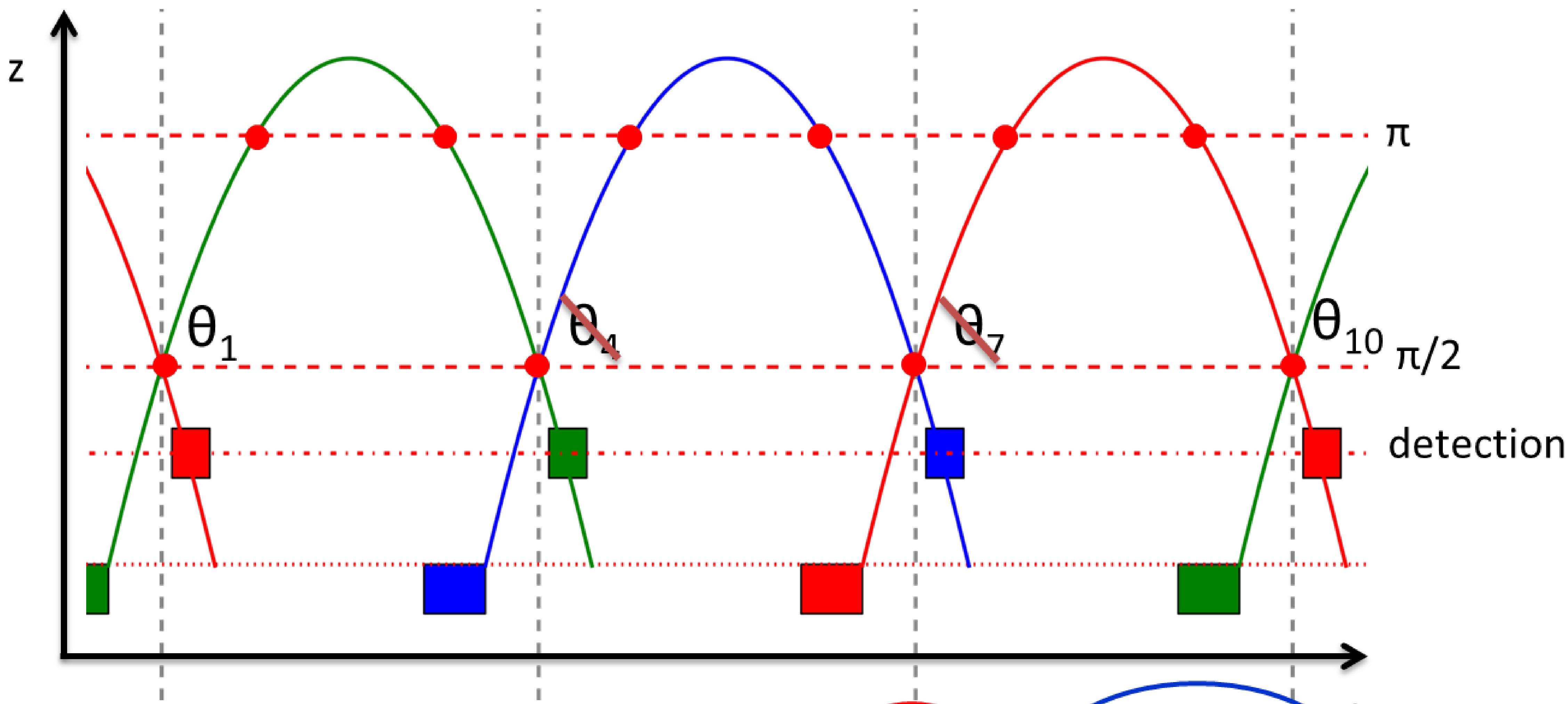
B. Canuel et al., PRL 97, 010402 (2006)

INTERLEAVED INTERFEROMETER WITH SINGLE AI

Prepare the cold atoms and operate the AI in parallel



1. Rotation noise is canceled from shot to shot by the joint measurements

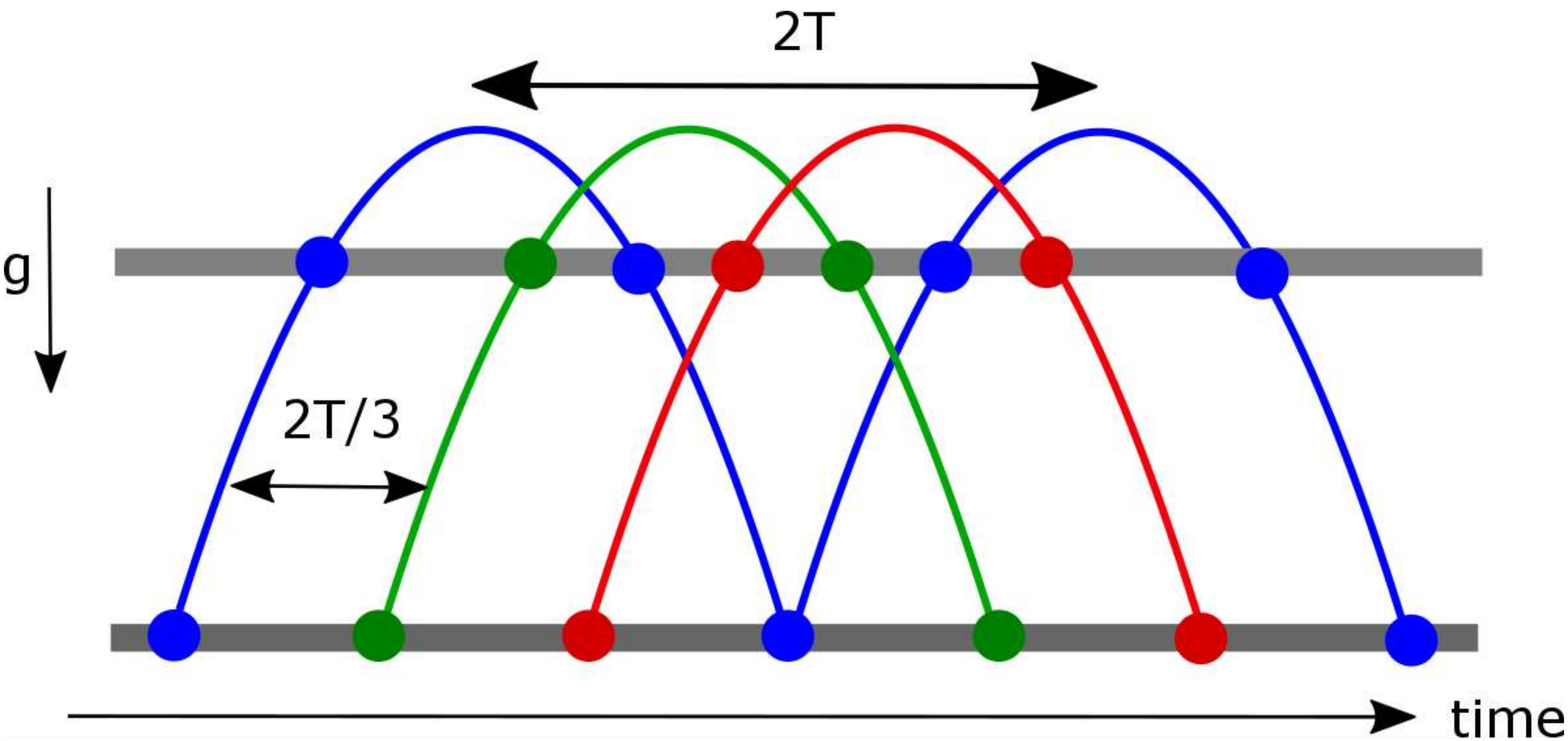


$$\Omega = \frac{1}{2NT}\sum_{i=1}^{N}\left(\boxed{\theta_{3i+3}-\theta_{3i}}+\boxed{\delta\theta_i^{NC}}\right) = \frac{\theta_{3N}-\theta_1}{2NT} + \frac{1}{2NT}\sum_{i=1}^{N}\delta\theta_i^{NC}$$

➔ Integration as $\frac{1}{N}$

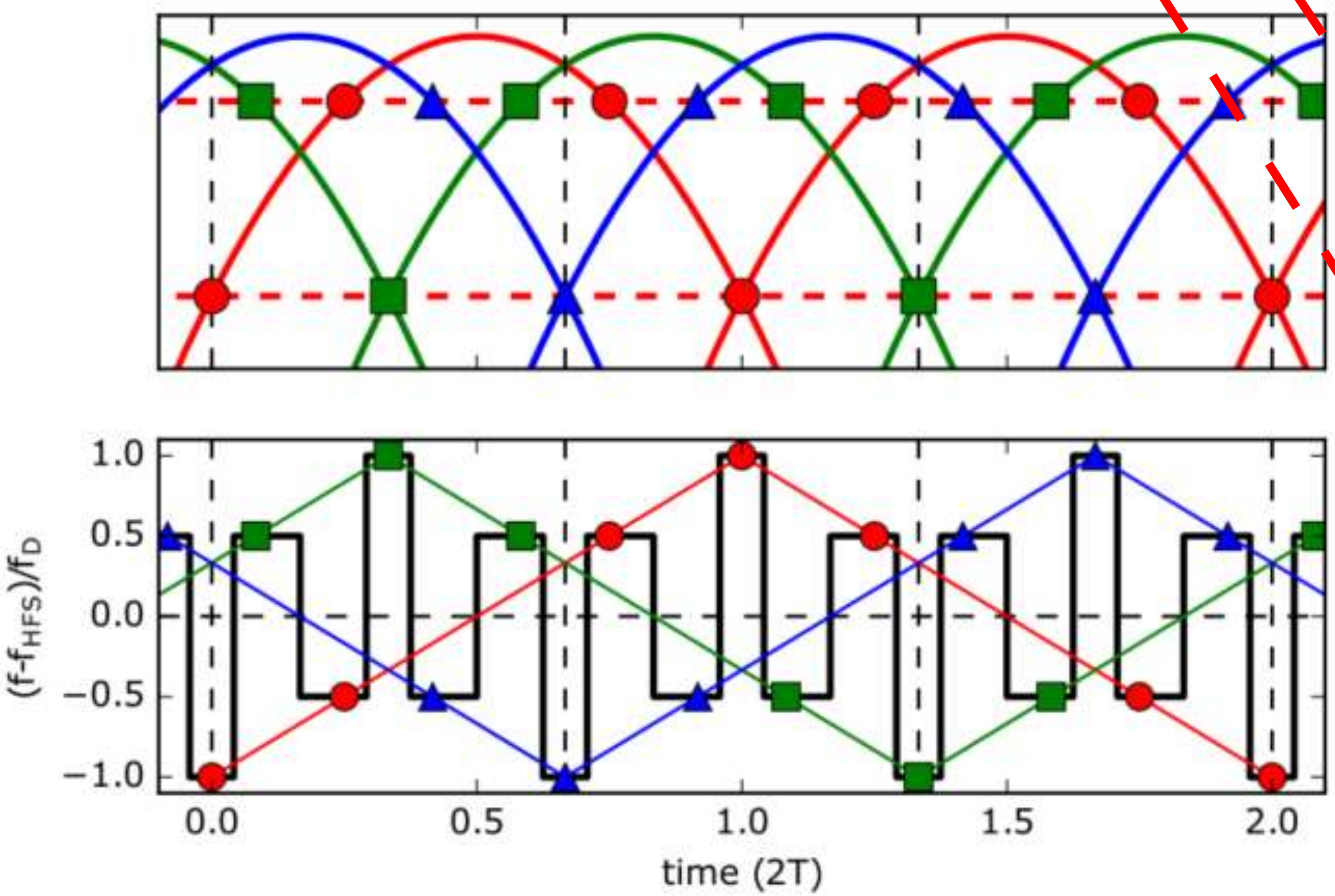
➔ Integration as $\frac{1}{\sqrt{N}}$

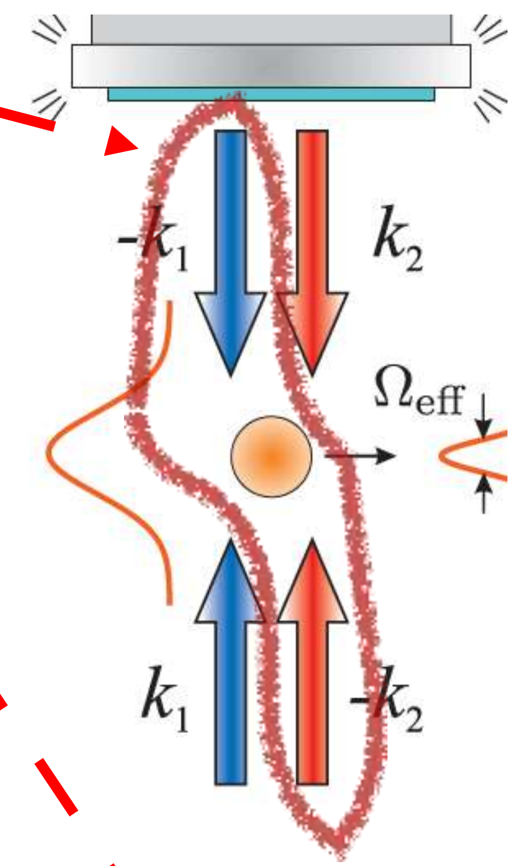
INCREASE CYCLING RATE TOWARD CW MEASUREMENT

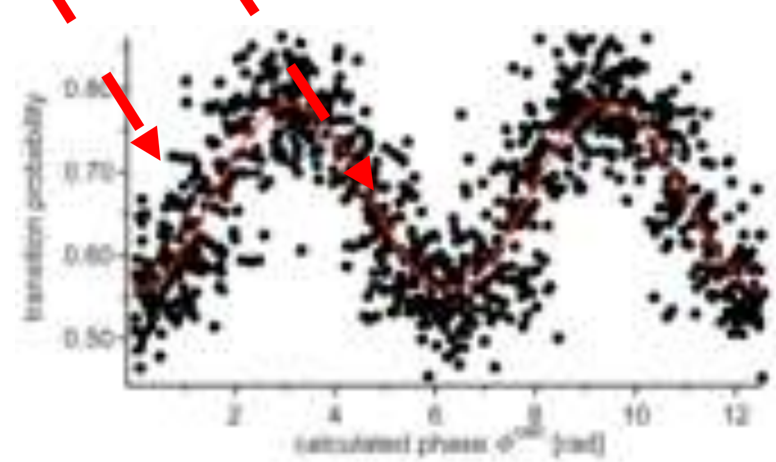


MEASUREMENT SEQUENCE

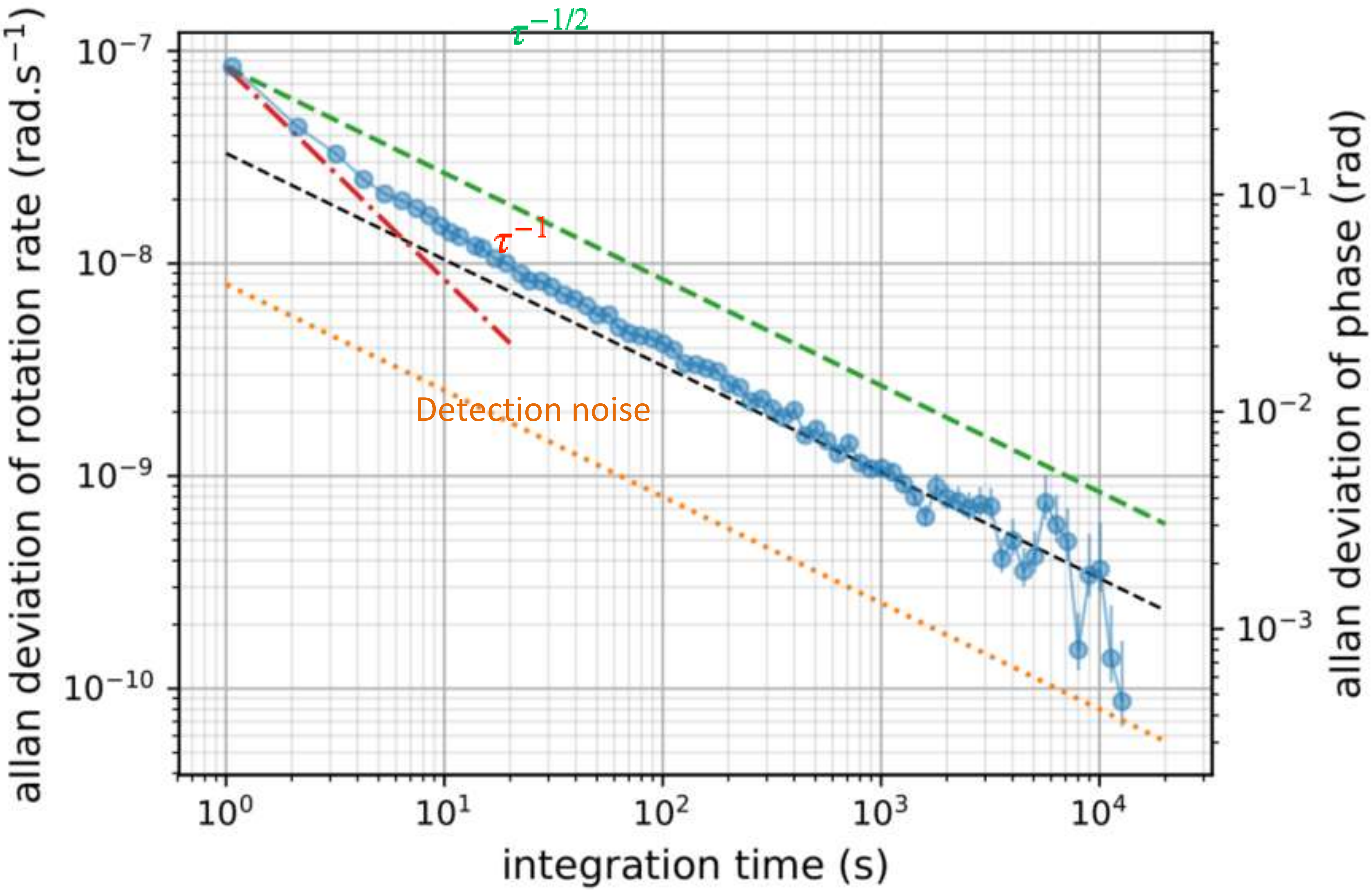
keff	+	-	+	-	+	-	+	-	+
fringe side	+	+	-	-	+	+	-	-	+



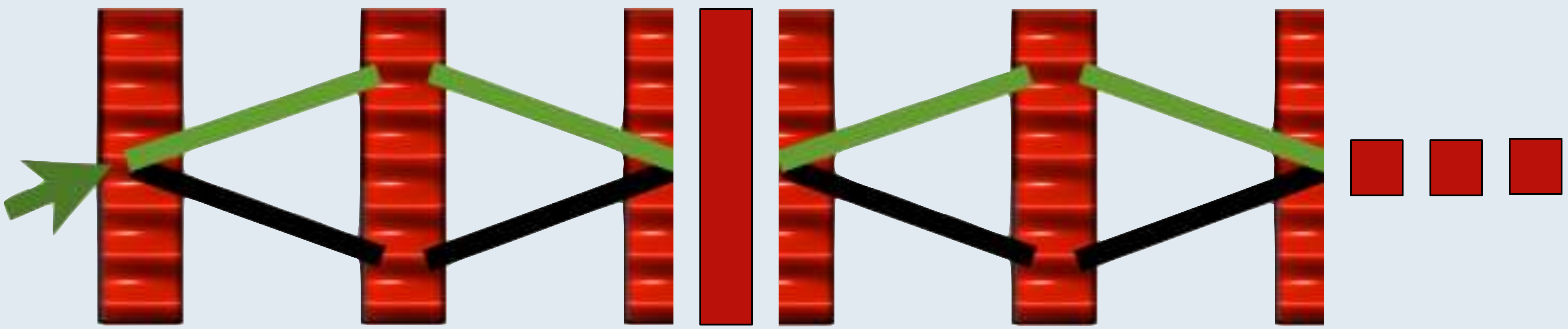




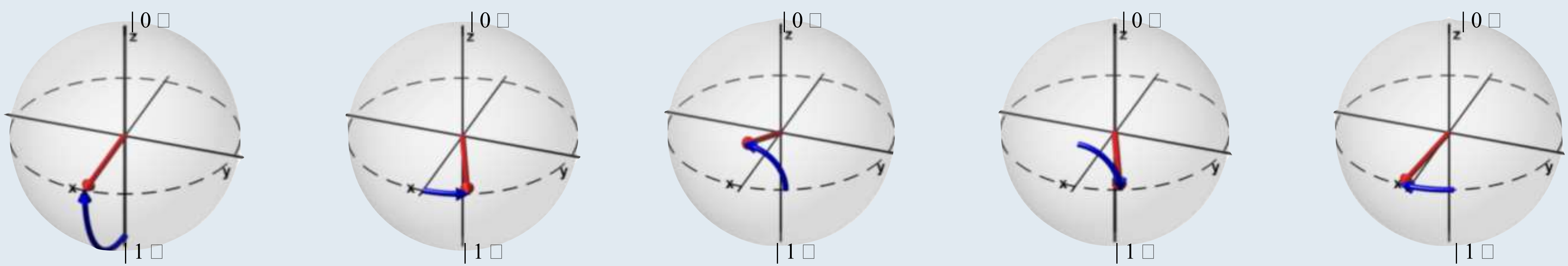
AVERAGING AND INTEGRATION



PHASED LOCKED REPETITION OF INTERFEROMETERS



QND/weak measurement



prepare CSS

free precession

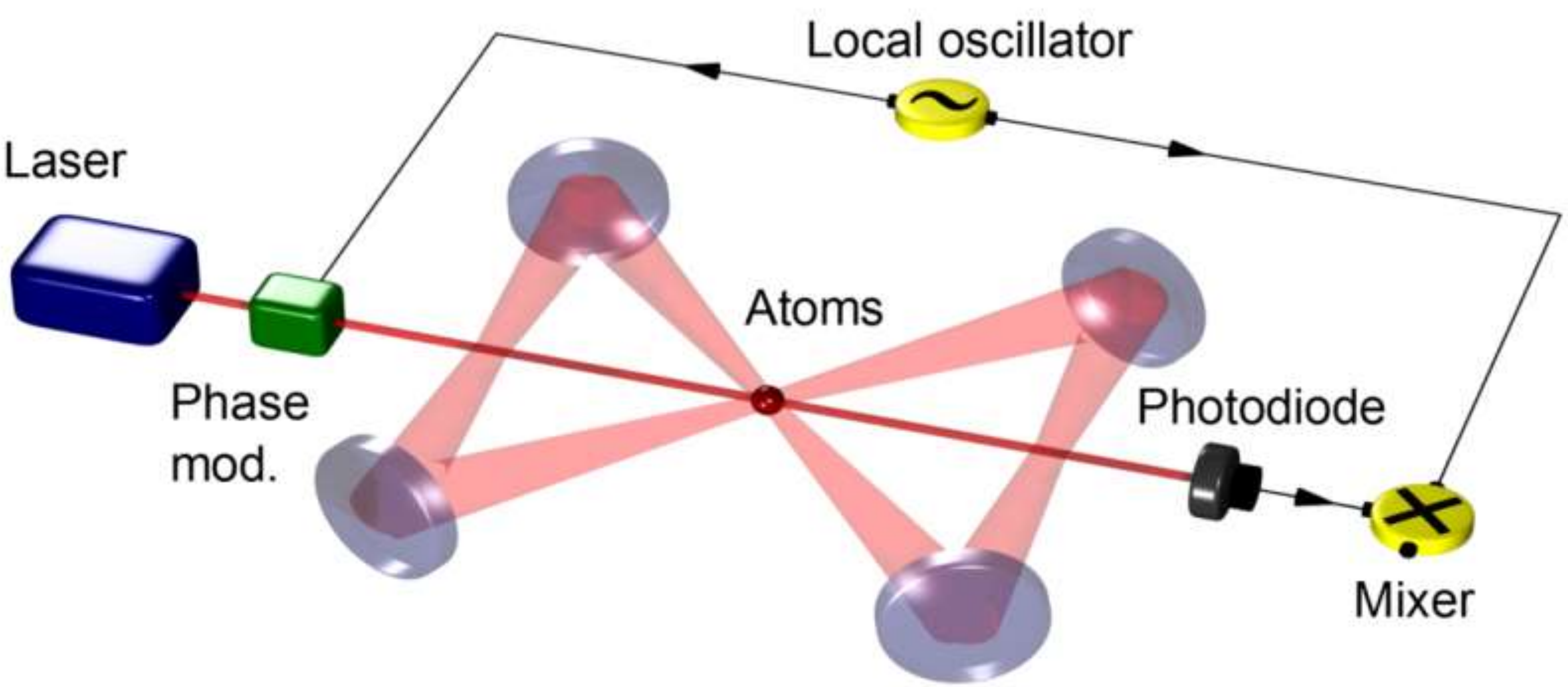
Coherence preserving measurement

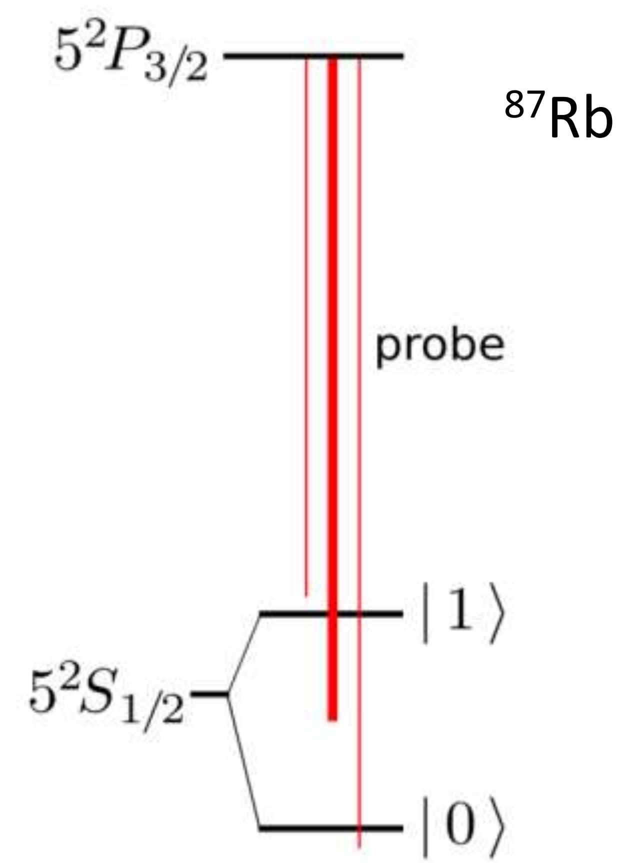
reinsert

Feedback on the LO phase

repeat

PHASE LOCKING A LOCAL OSCILLATOR TO THE ATOMIC PHASE



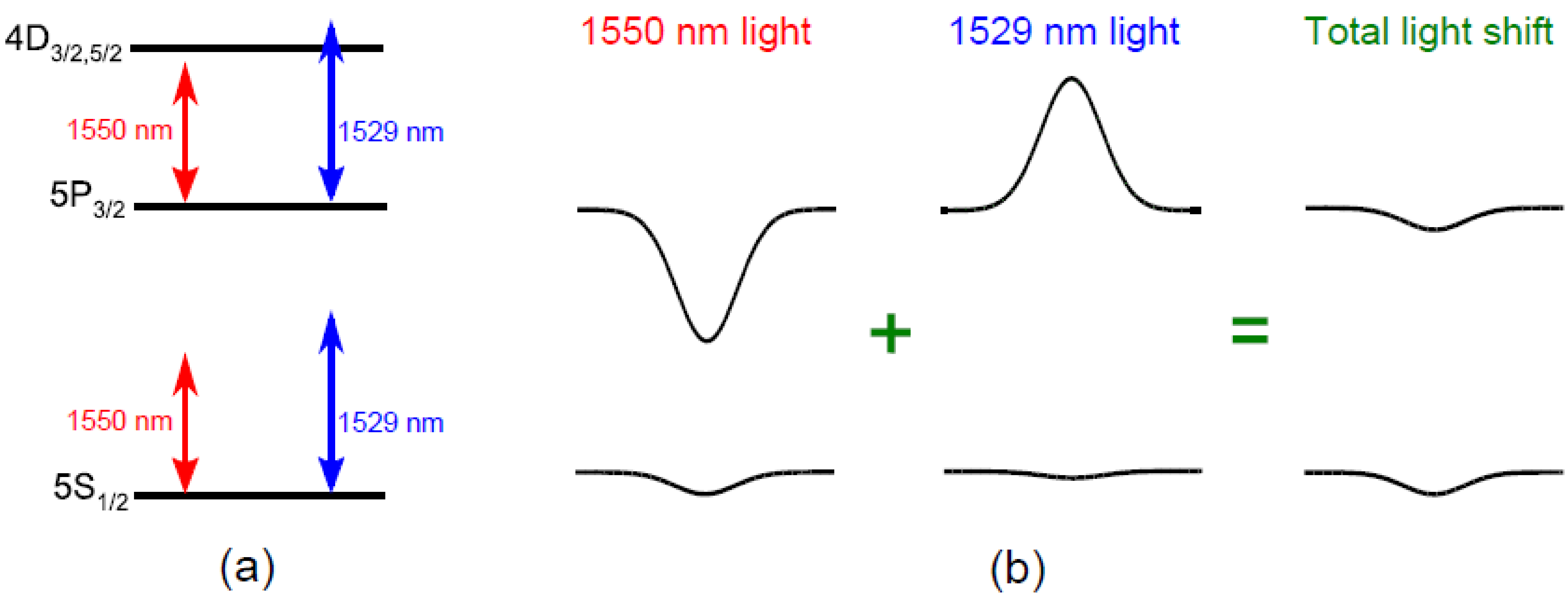


5×10^5 atoms @ 10 μK in the cavity enhanced dipole trap

Frequency modulation spectroscopy to measure non-destructively N_1-N_0

to which is mapped the atom-LO phase

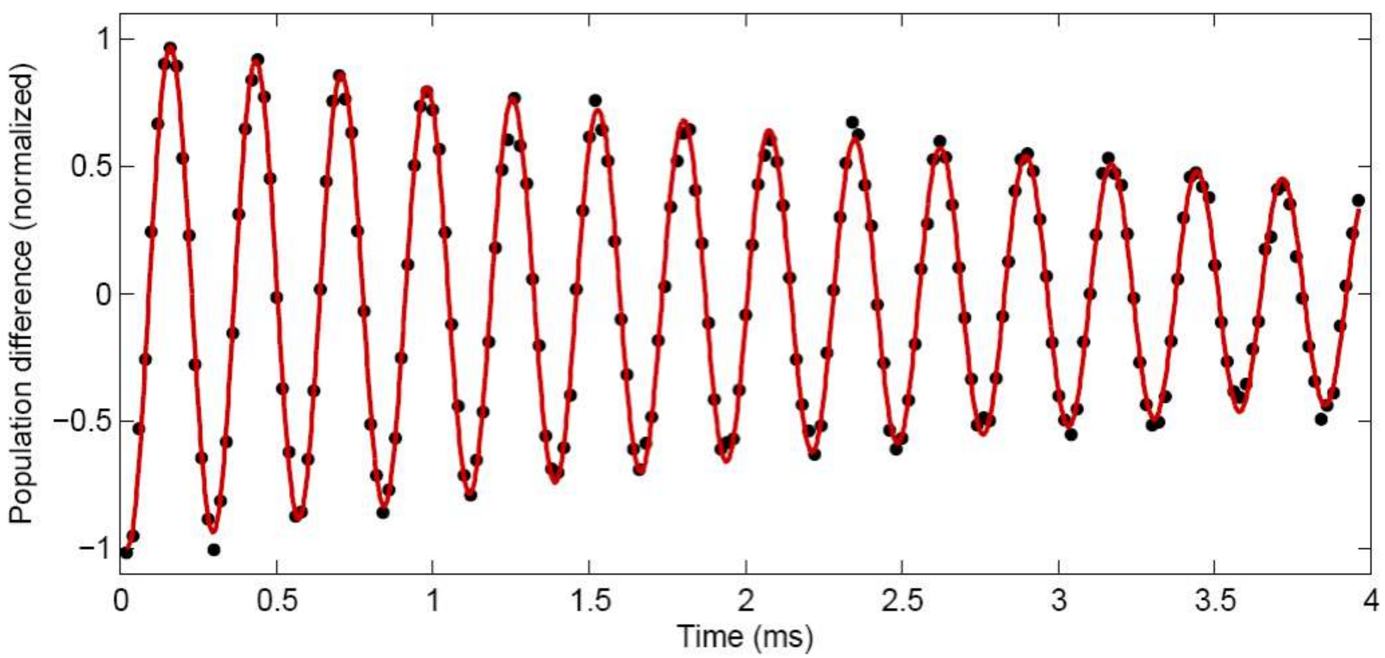
TRAPPED CLOCK WITH COMPENSATED LIGHT SHIFTS

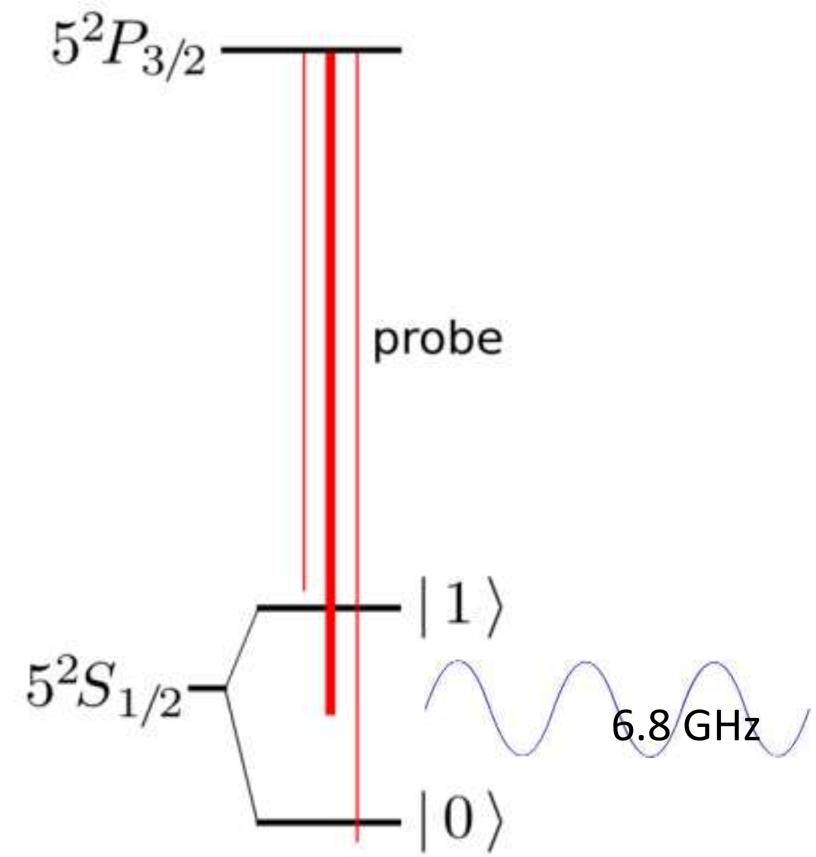


New laser stabilization scheme for cavity locking of 1529 nm laser

Kohlhaas et al., Opt. Lett. 37, 1005 (2012)

NON DESTRUCTIVE MEASUREMENT OF A RABI OSCILLATION



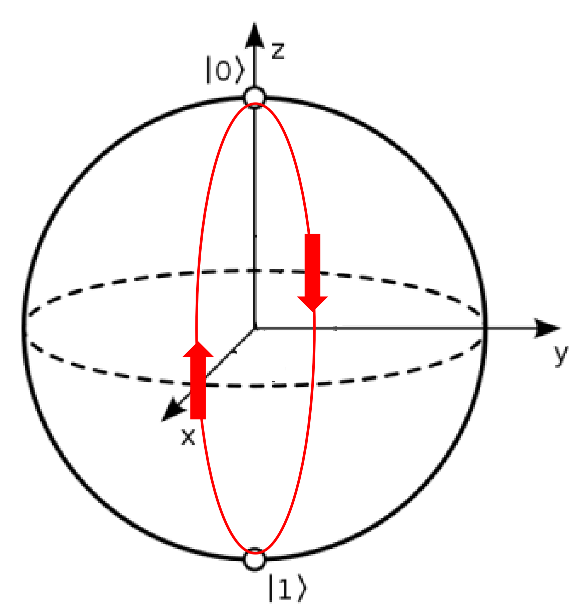


Probe pulse every 20 ⌠s

45% residual coherence after 200 measurements

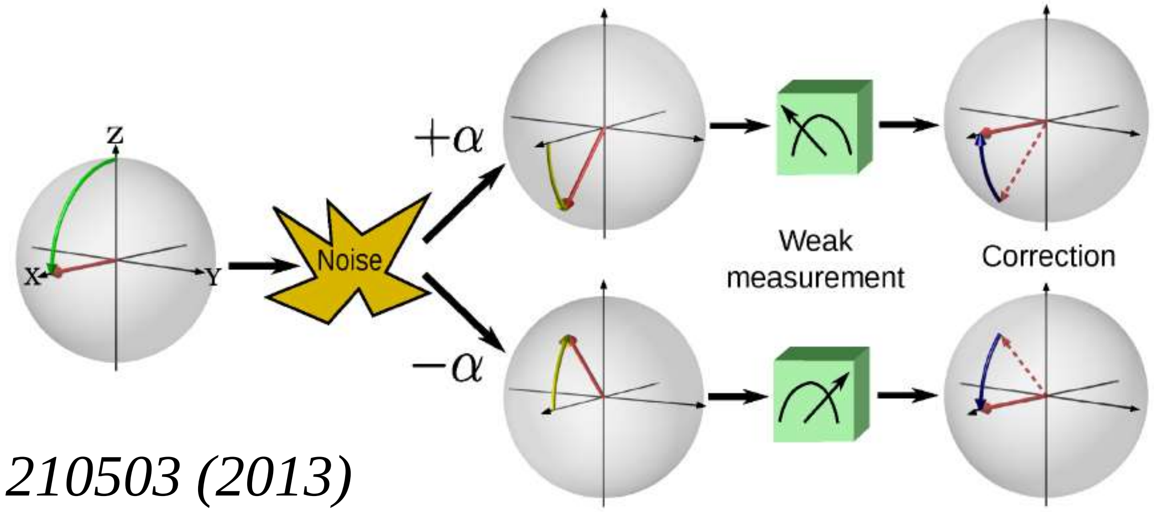
Decay dominated by spontaneous emission

→measurement preserves coherence!

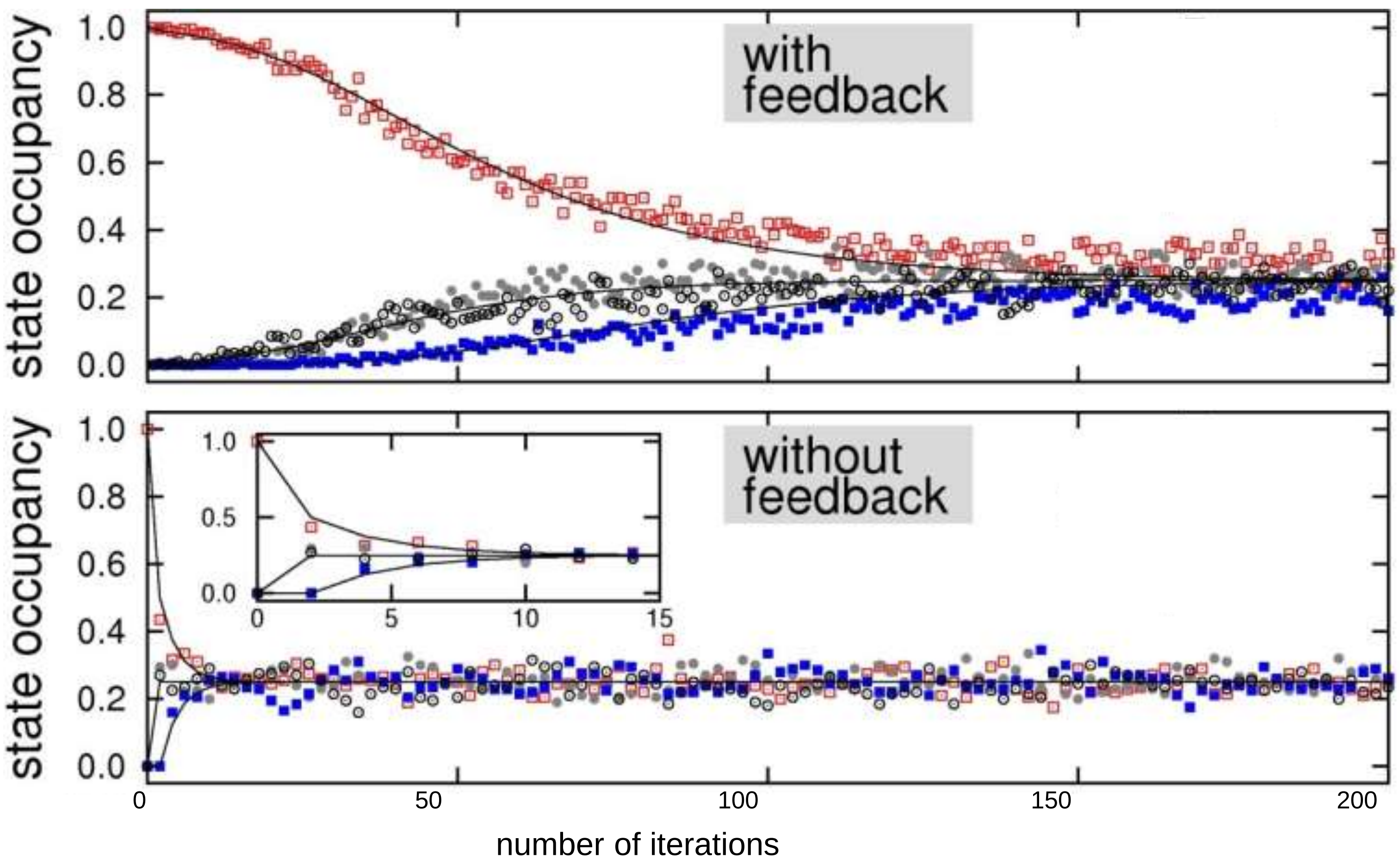


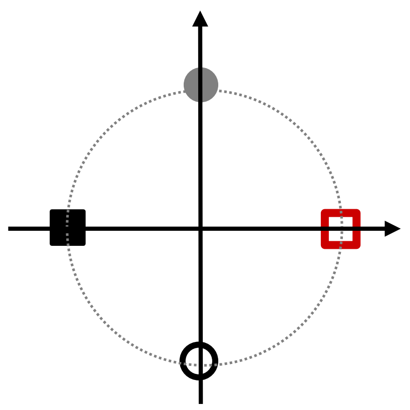
Bernon S. et al., NJP 13 (2011)

PROTECTING A COHERENT SPIN STATE AGAINST DECOHERENCE

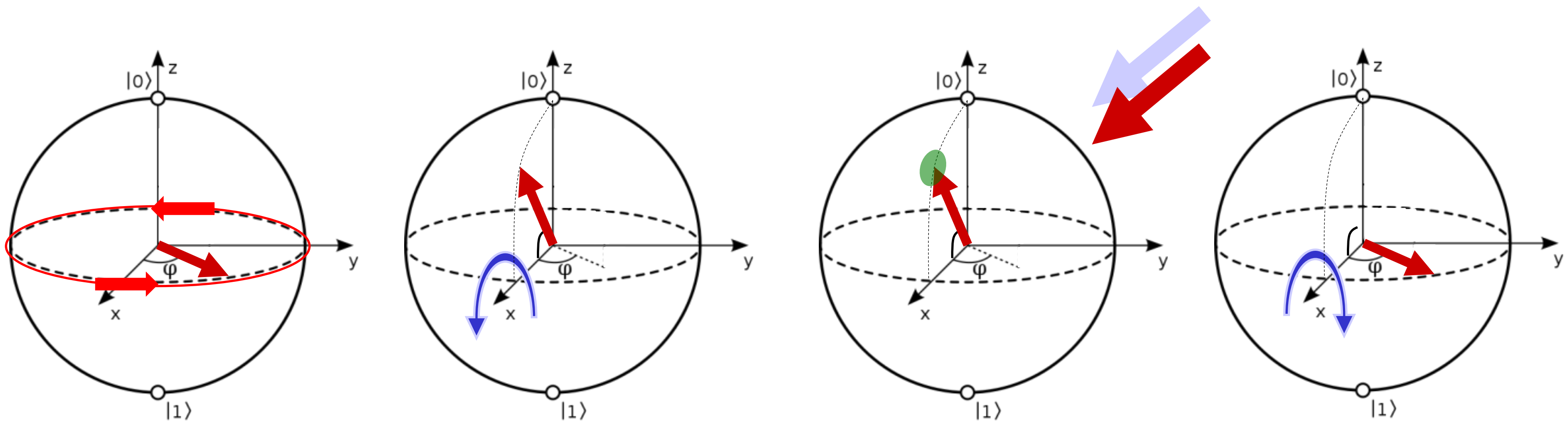


Vanderbruggen, T. et al., PRL 210503 (2013)



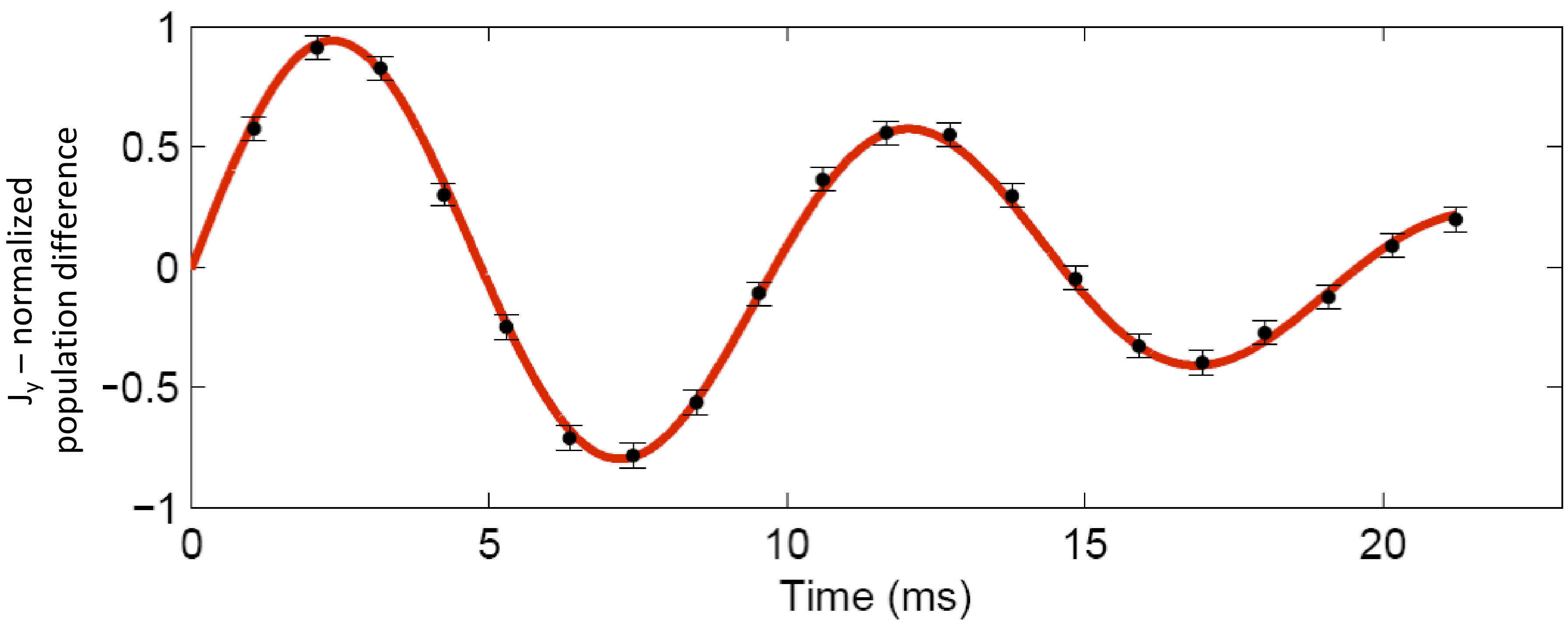


Following the phase difference evolution



1. 100 Hz Frequency offset on LO

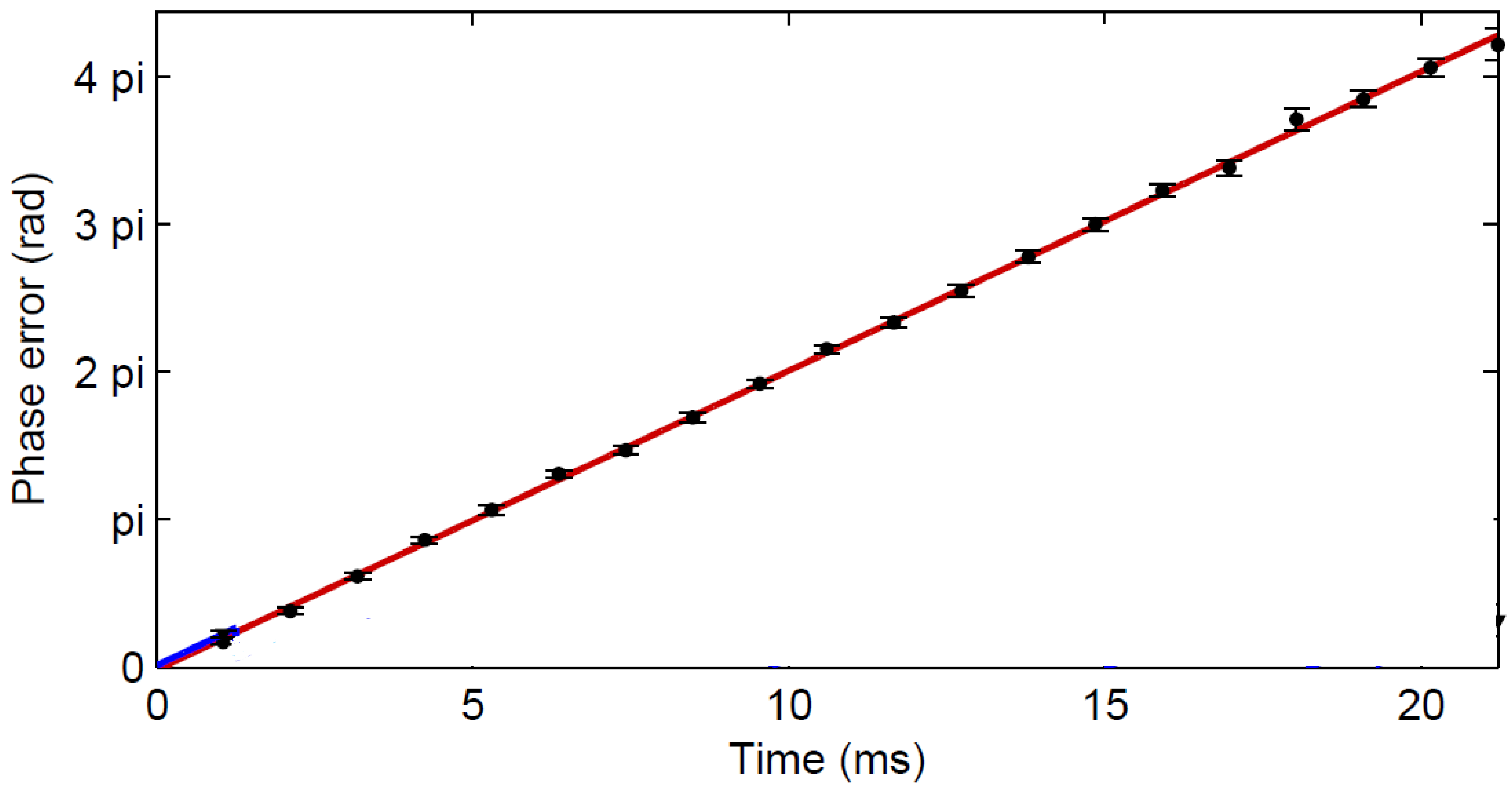
2. repeat weak measurement of the relative phase



Measure in real time phase in atomic interferometer

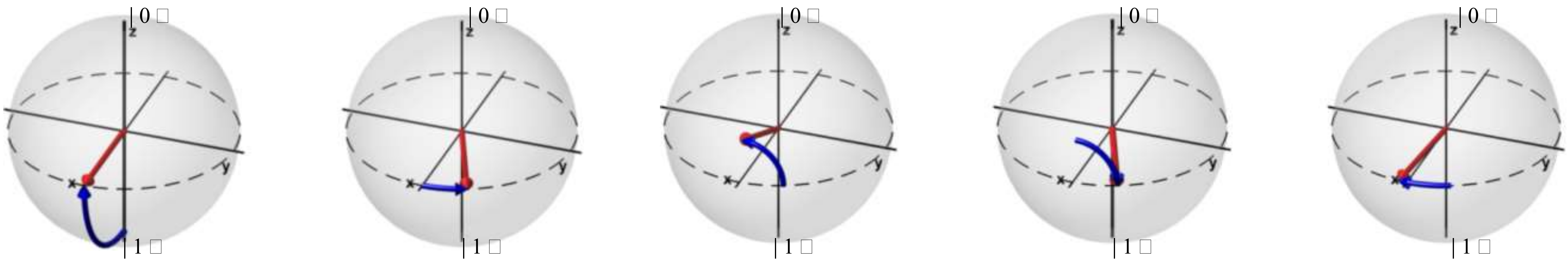
Decay by inhomogeneous lightshift in trap

RECONSTRUCTION OF THE PHASE EVOLUTION



Well beyond the [-π/2; π/2] inversion region

How to keep the phase drift small



prepare CSS

free precession

Coherence preserving measurement

reinsert

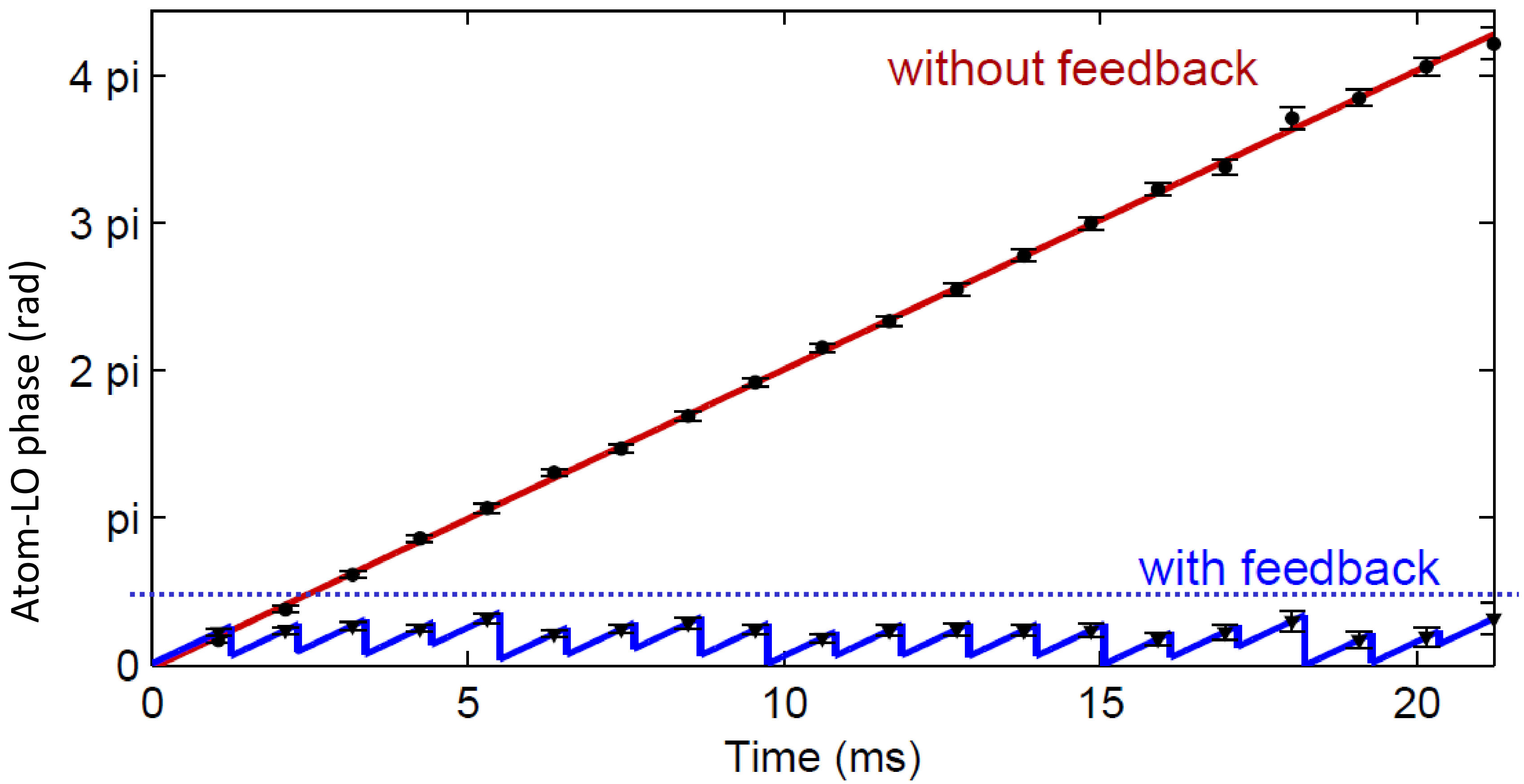
Feedback on the LO phase

repeat

Phase corrections saved for final evaluation

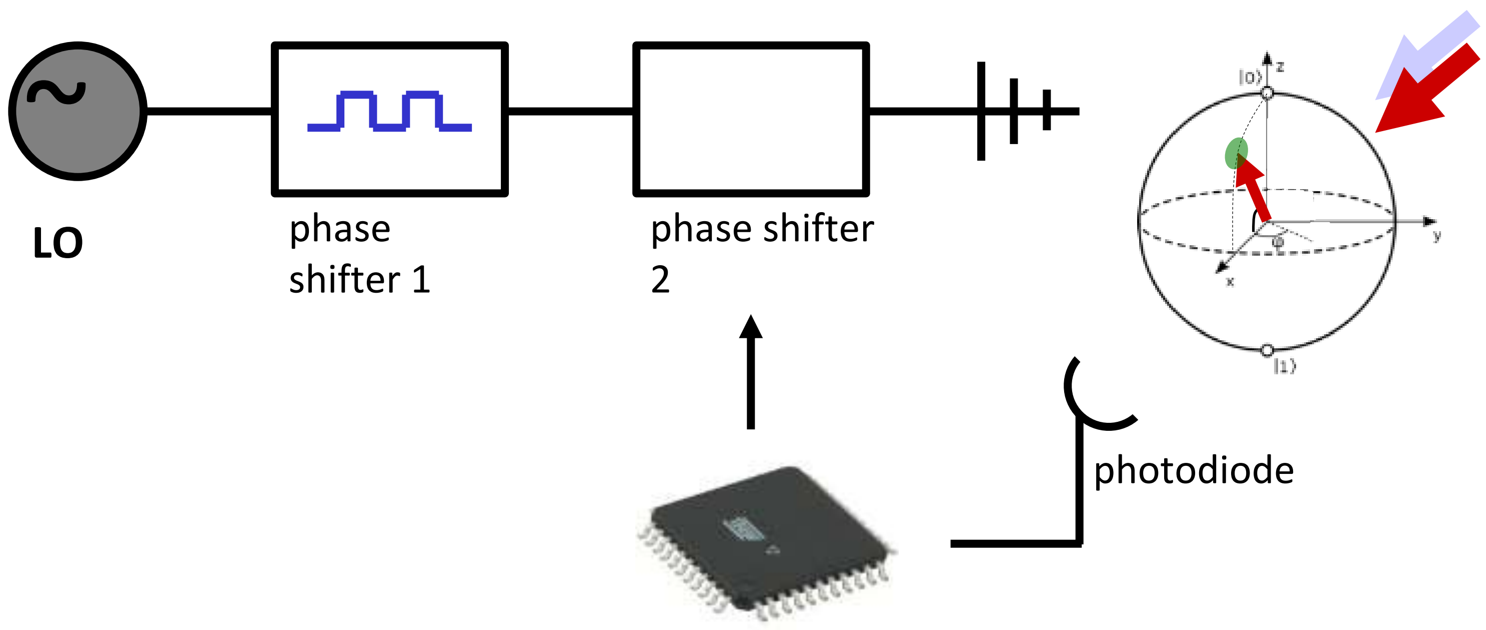
Classical oscillator is stabilized on superposition state

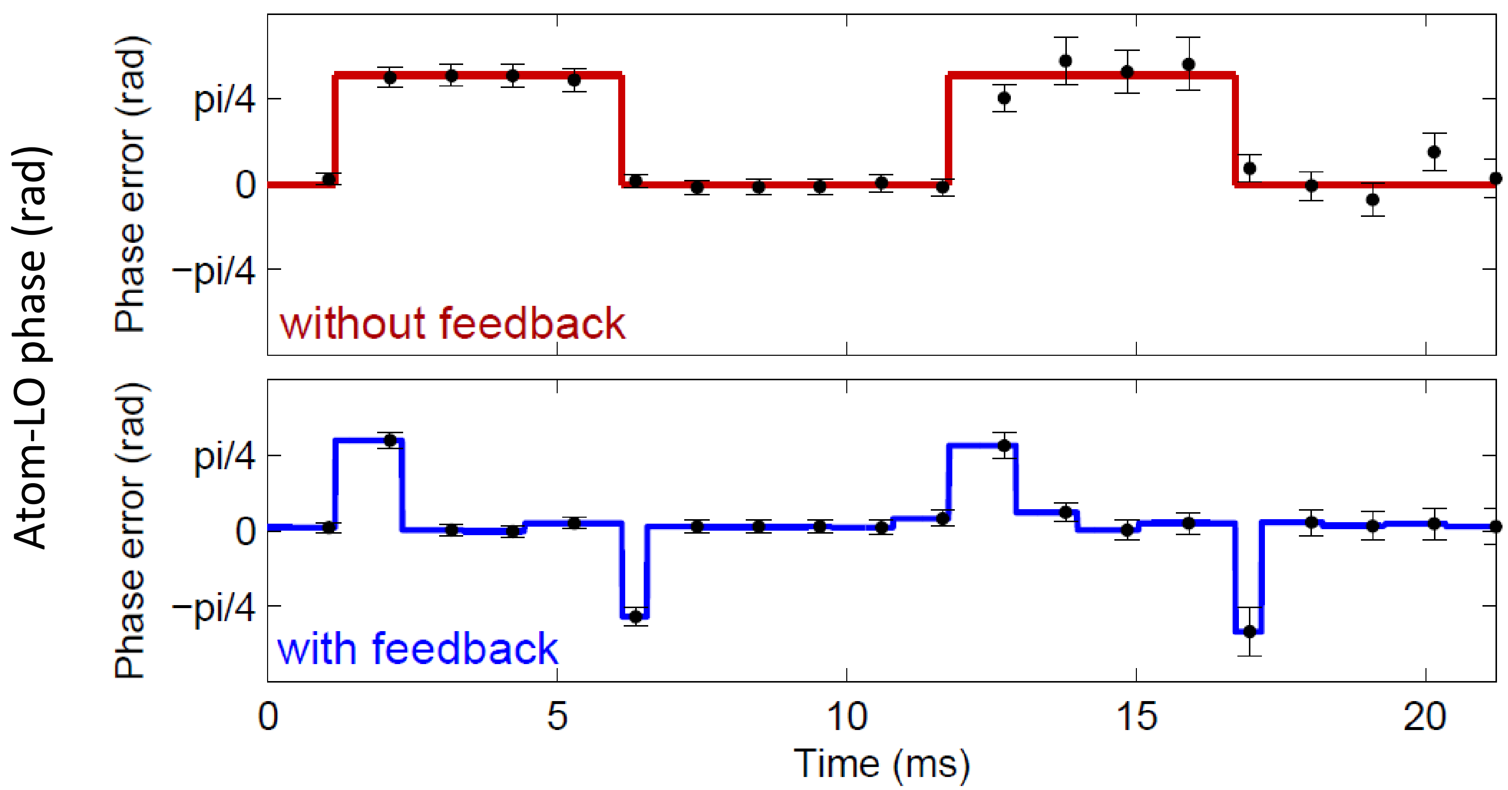
RECONSTRUCTION OF THE PHASE EVOLUTION



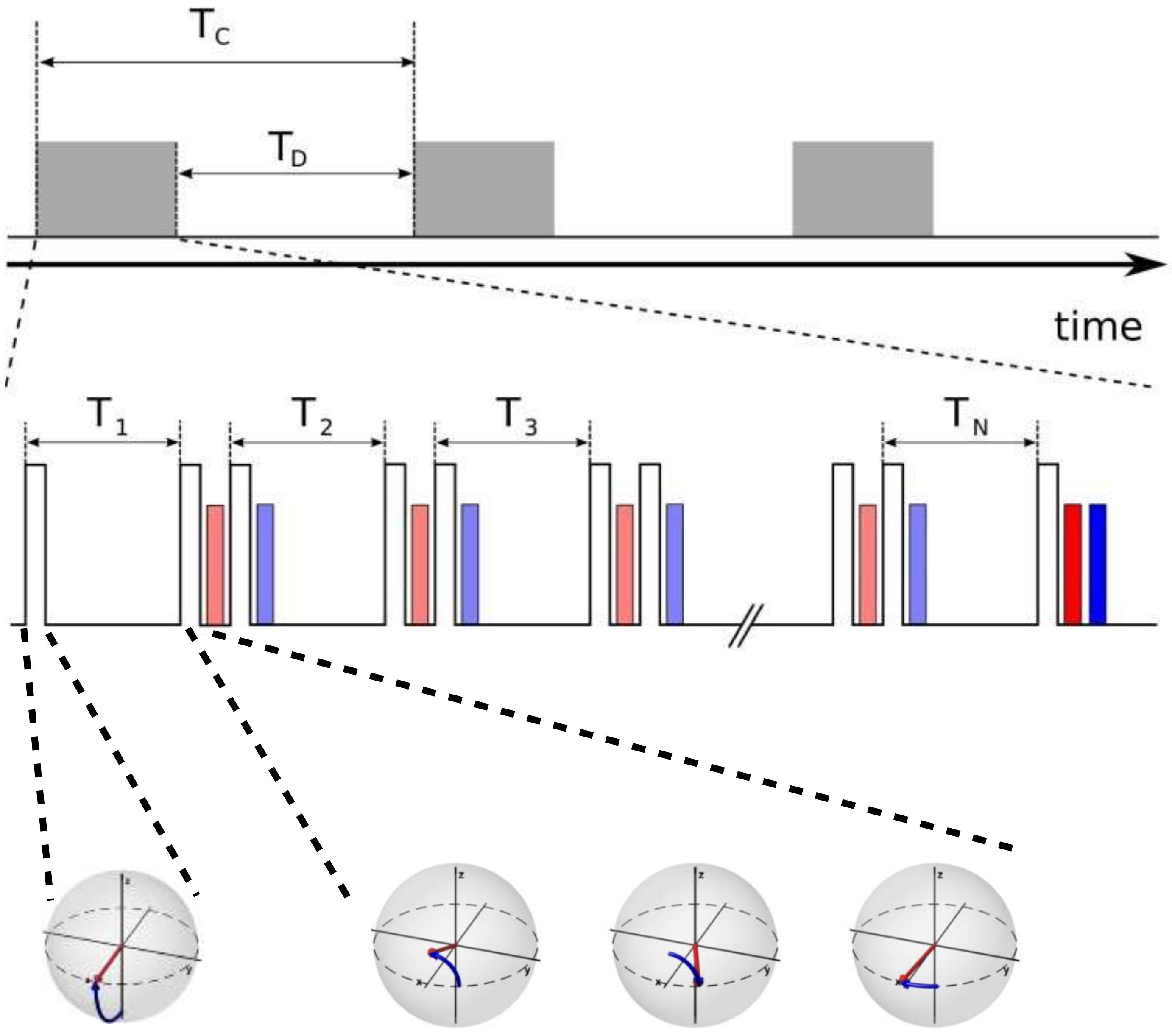
Feedback maintains phase in inversion region

RECONSTRUCTION OF THE PHASE EVOLUTION WITH ARBITRARY NOISE





EXTENDING THE CLOCK INTERROGATION TIME

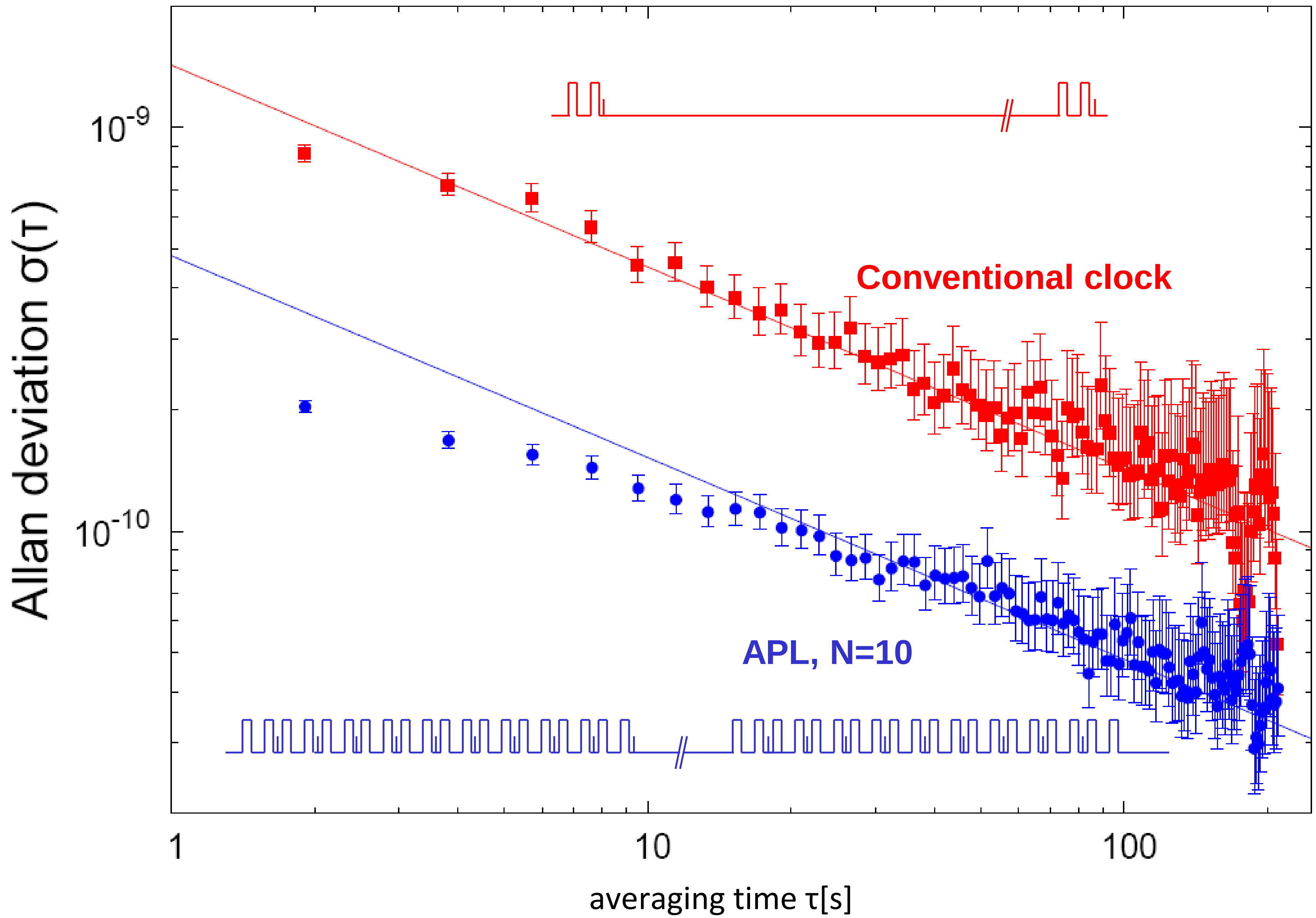


1. atomic state preparation

2. N-cycles of **coherence preserving measurement of J_z** and **phase correction on the LO** to stay in the inversion region for the differential phase

3. final destructive measurement, calculation of the total differential phase cumulated on the extended interrogation time, frequency correction on the LO

EXTENDING THE CLOCK INTERROGATION TIME



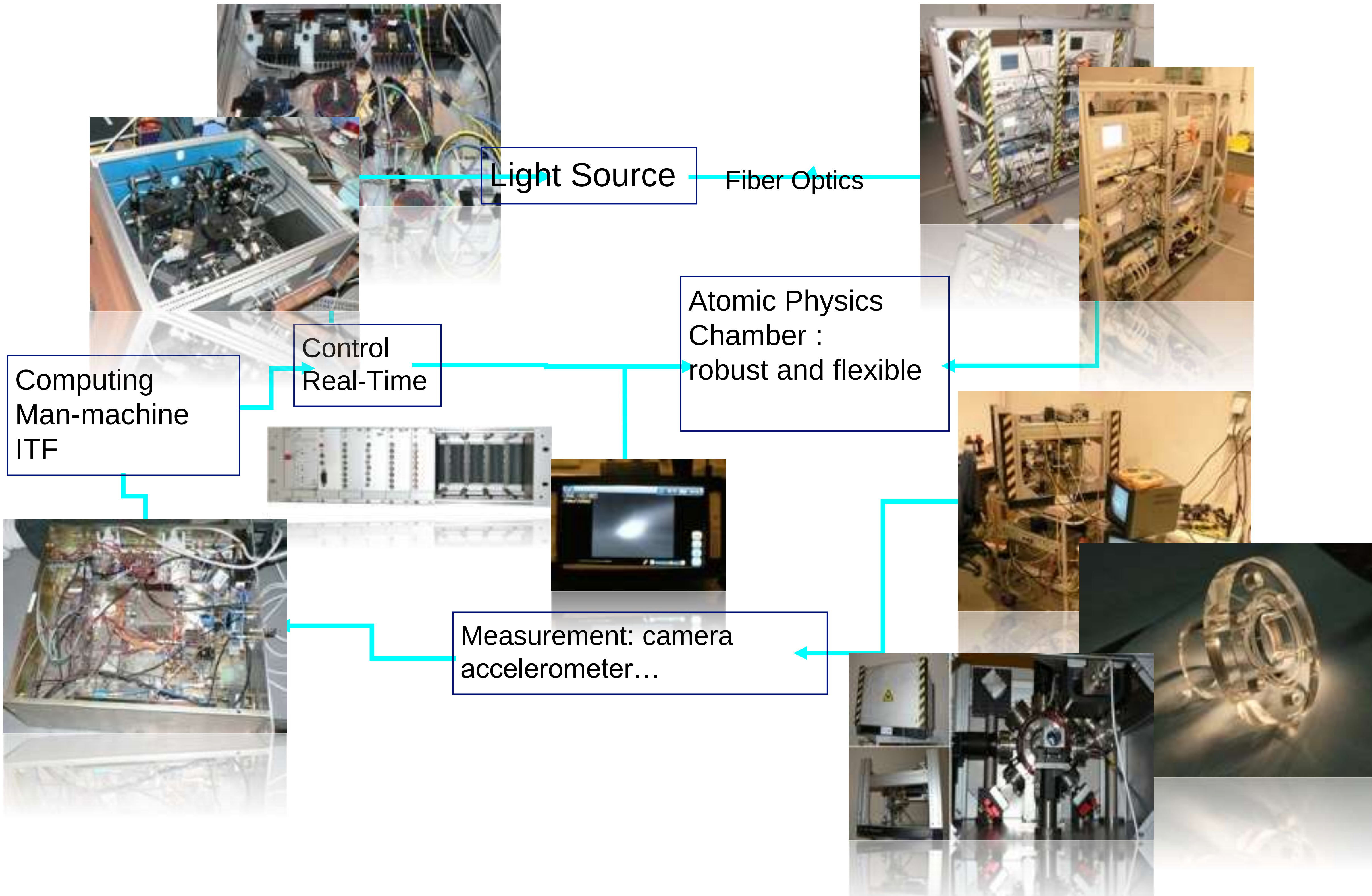
- white frequency noise on the LO, φ_{rms}=430 mrad @ 10 ms
- 10 measurements / phase corrections, T=1 ms (blue)
- comparison with "standard" clock with T=1 ms (red)
- better Allan deviation by 5 dB

BUT: T is not limited to 1 ms by the noise on the LO...

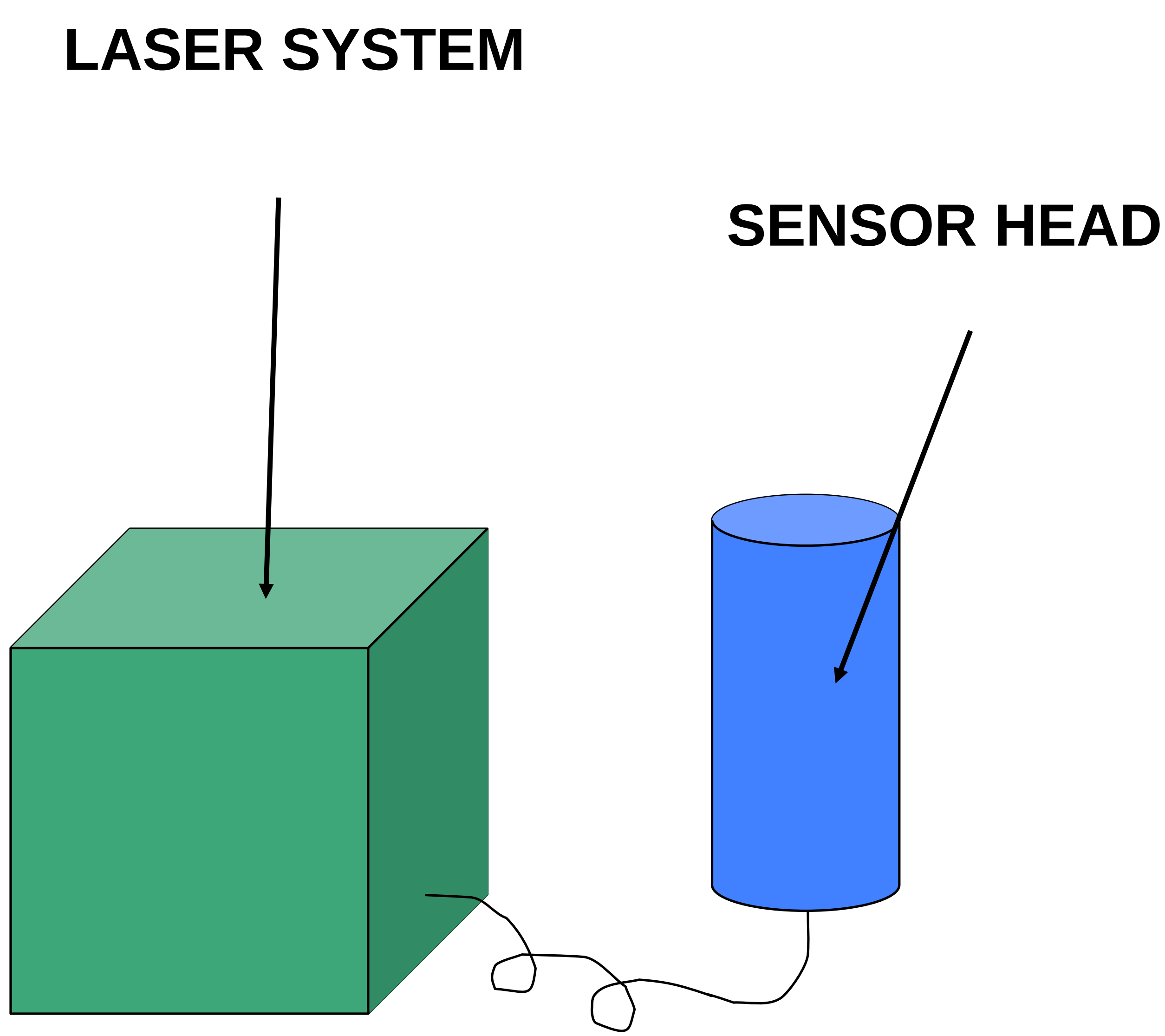
Kohlhaas, R., et al. Physical Review X 5 (2015)

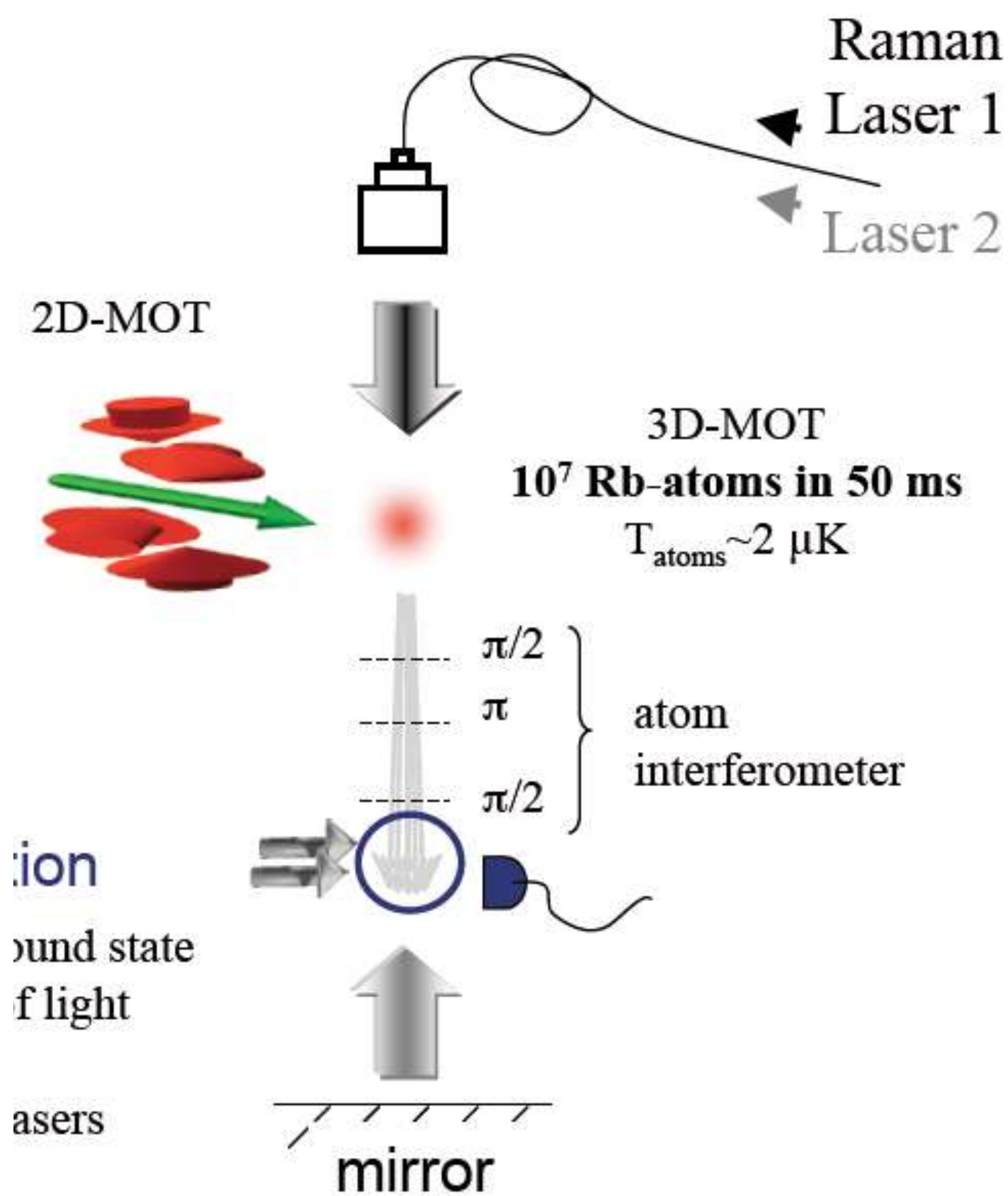
Lecture 3 : Application to geophyscis, navigation, fundamental physics

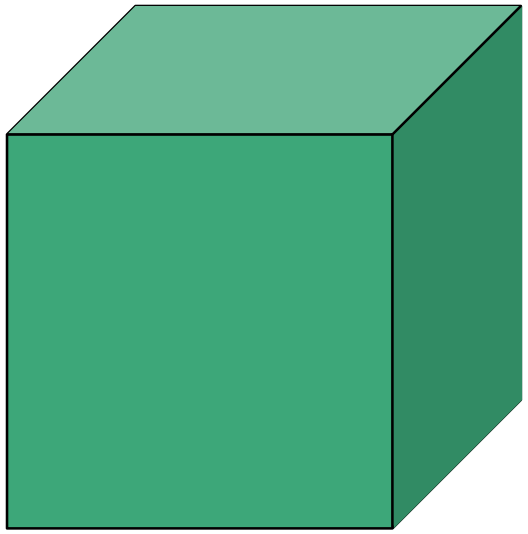
ATOM INTERFEROMETER KEY COMPONENTS



KEY ELEMENTS OF AN ATOM GRAVIMETER







Laser manipulation is key for the atom interferometer

- many frequencies required for laser cooling (780 nm for Rb, 767 nmfor K, 850 nm for Cs ...)
- Need precise control of frequency and intensity

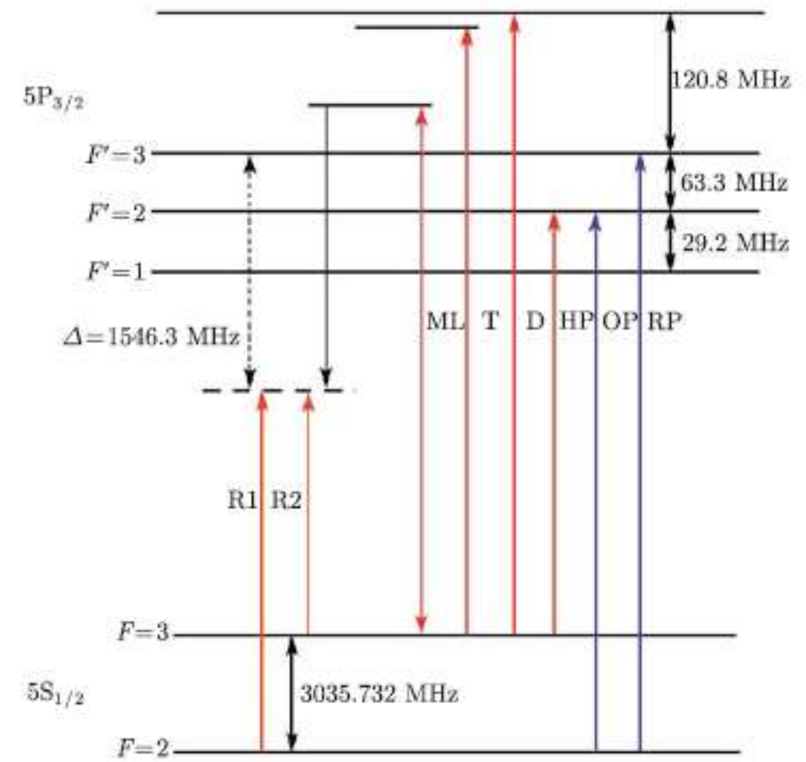
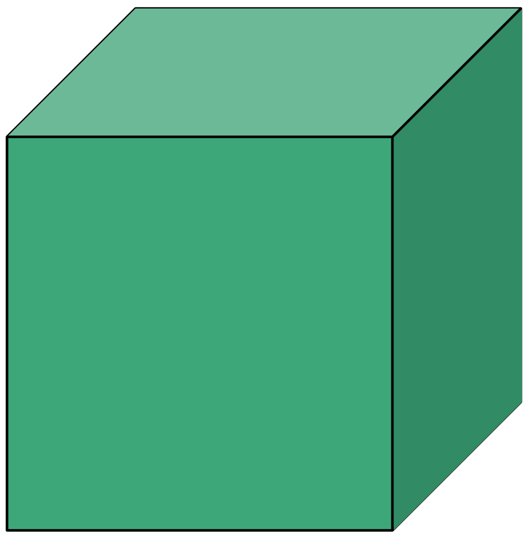


Fig. 4 Laser frequency assignment and energy levelsof [85]Rb. R1, R2: Raman laser beams, ML: Main Laser; T: Trapping laser, D: Detection laser; OP: Optical pump laser; HP: Hyperfine pump laser, RP: Repumping laser.



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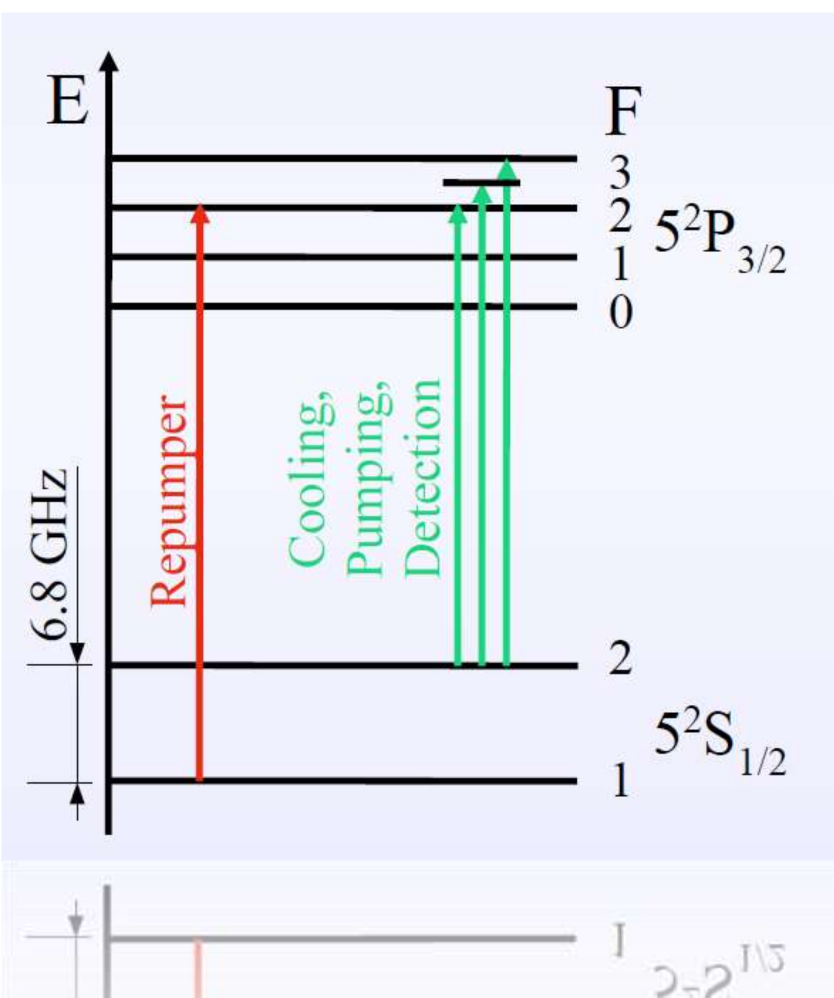
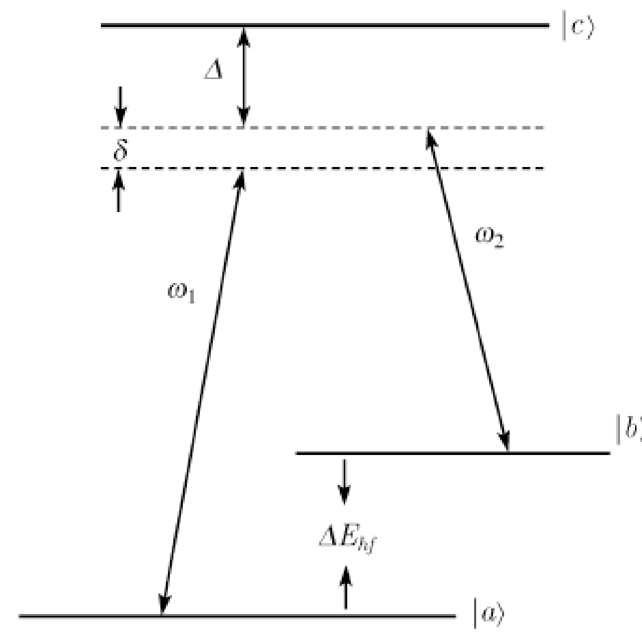
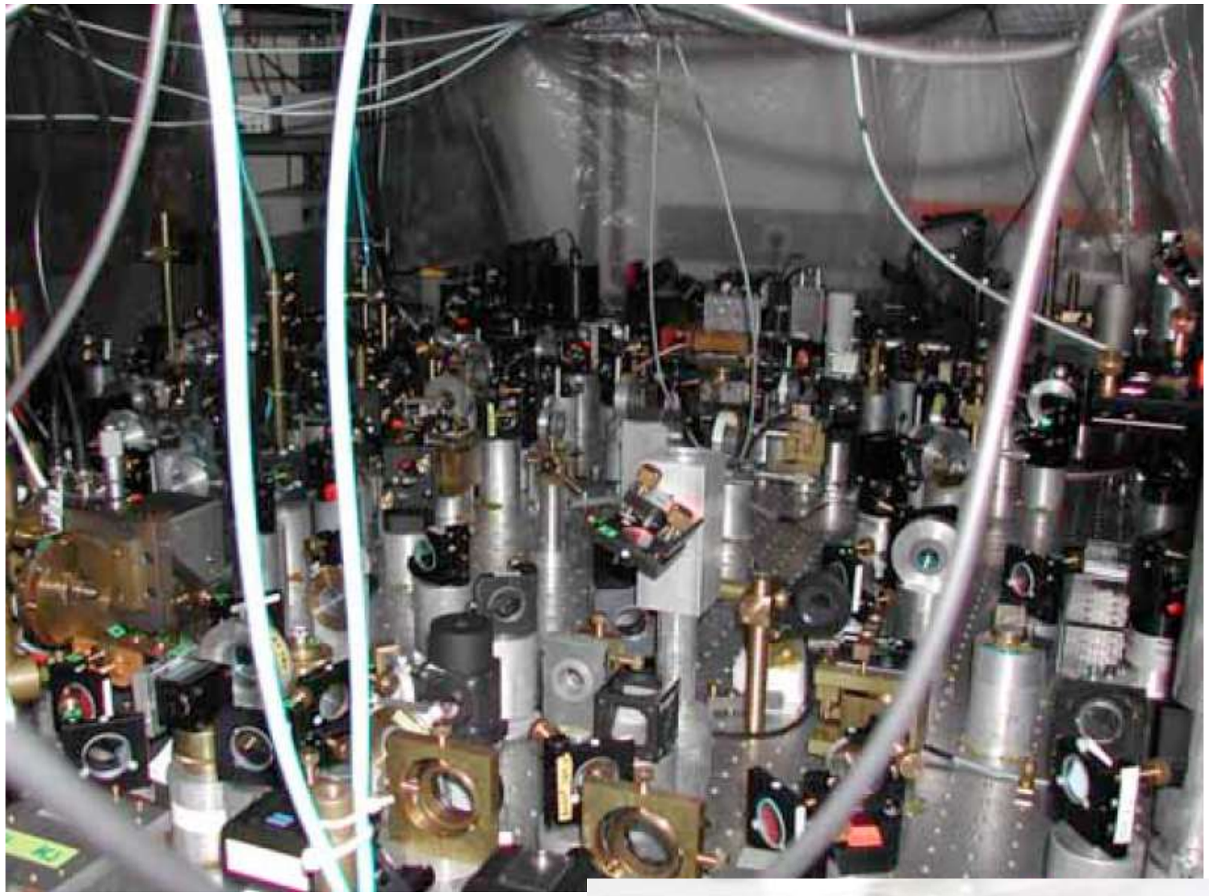


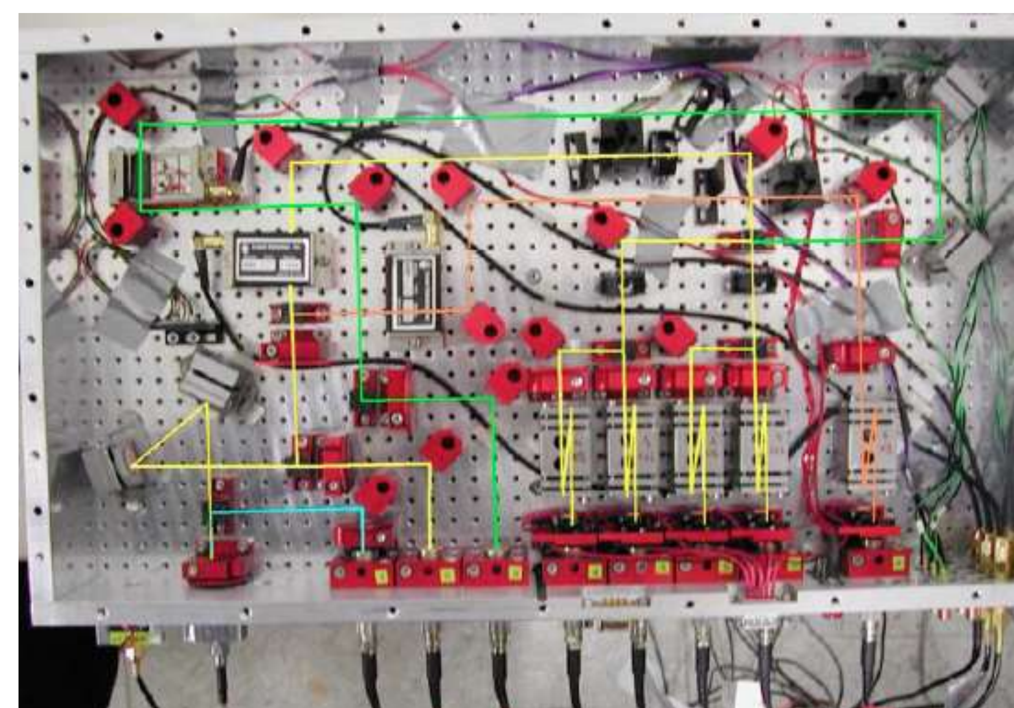


- For Raman diffraction, phase noise between lasers is a key

COMPLEX OPTICAL BENCHES

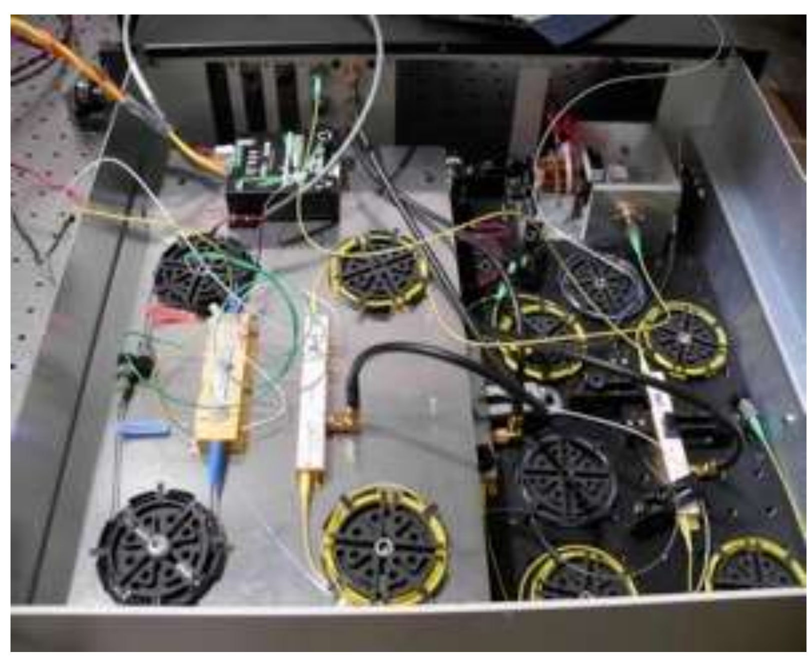


- Need many optical elements (AOs, mirrors, photodiodes ...)
- Before : large optical tables
- Now (Quantus project, AOsense) : compact optical benches



INTEGRATED OPTICS AS NEW GENERATION

- ✓ One single telecom laser diode, frequency doubled
- ✓ Low noise highly compact HF generation
- ✓ Off-the-shelf fiber coupled telecom & micro-wave components
- ✓ Drastic reduction of volume (overall packaging ~ 70 cm^3)



INSTITUT d'OPTIQUE GRADUATE SCHOOL

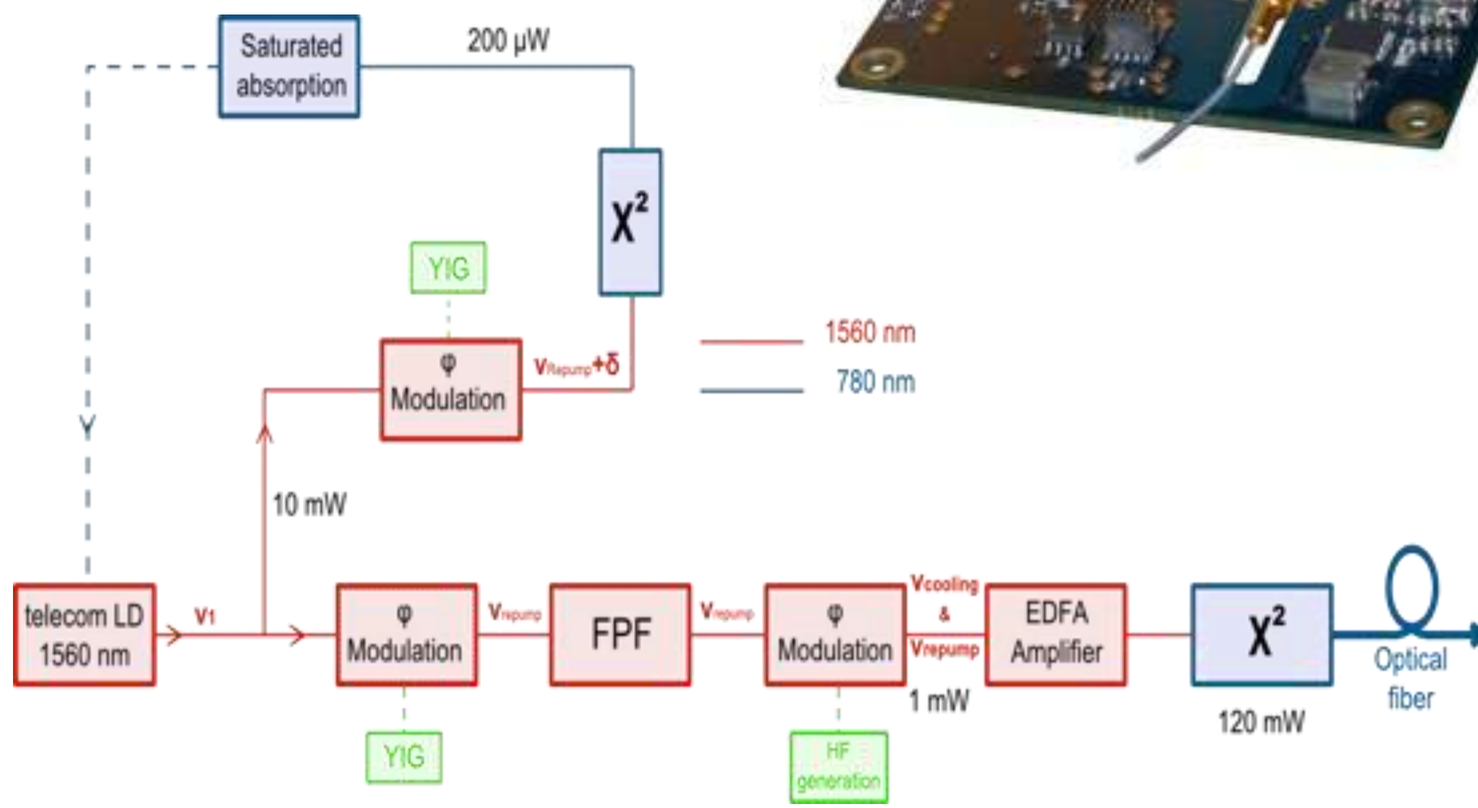
FIBER OPTICS OPTICAL BENCH

cnrs
université de BORDEAUX

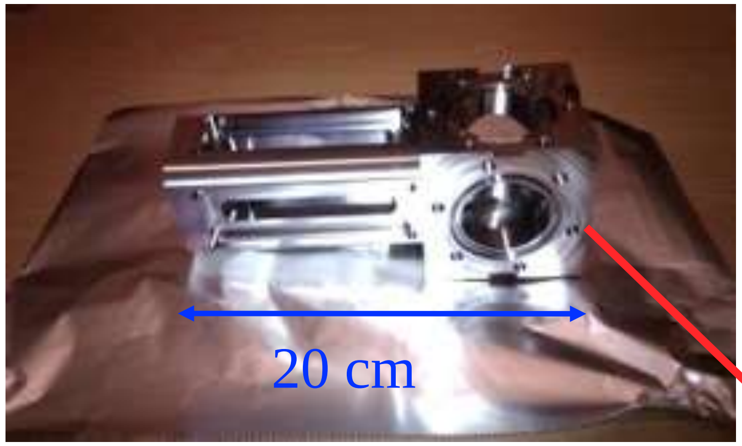
Rack 12U, 19"x19",78 kgs

G. Stern et al.,Eur. Phys. J. D 53, 353–357, 2009

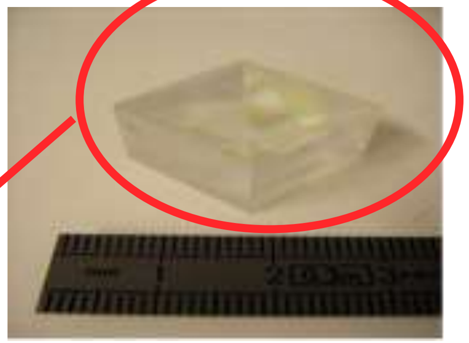
- Up to 150 mW out of fiber
- Power consumption 170 W
- Compact electronics

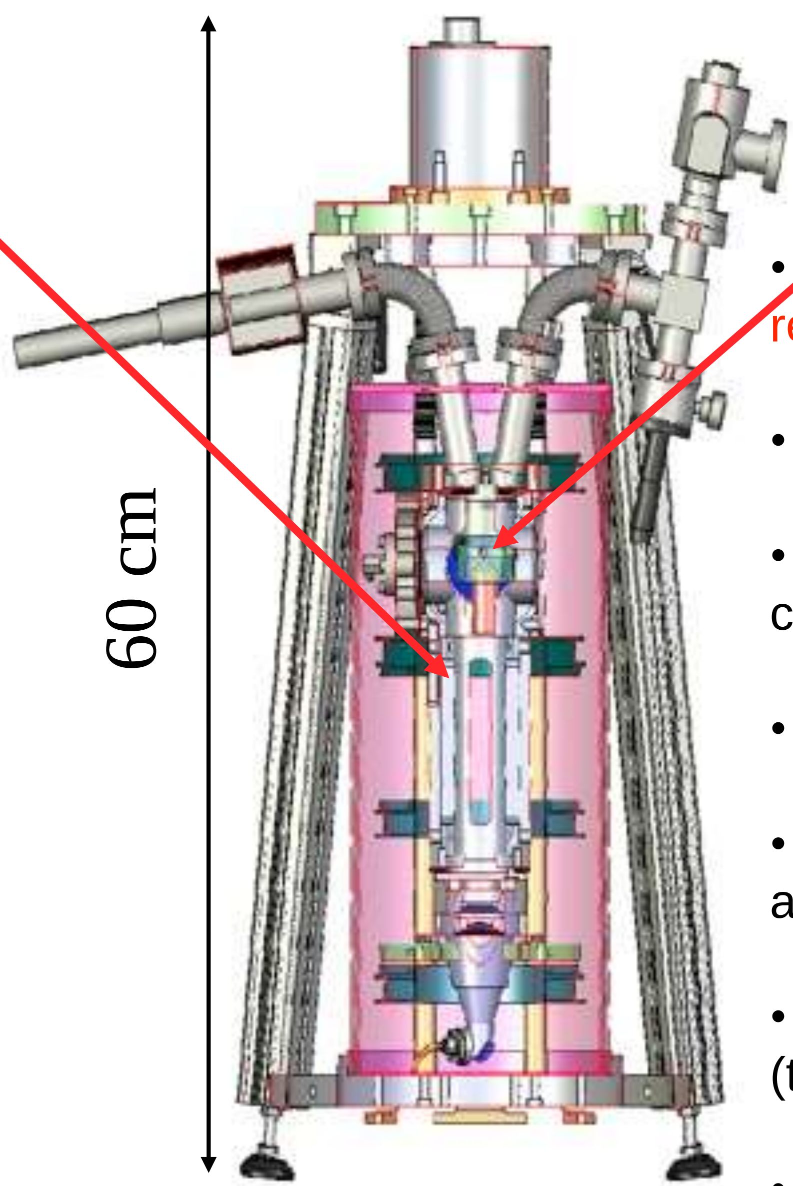


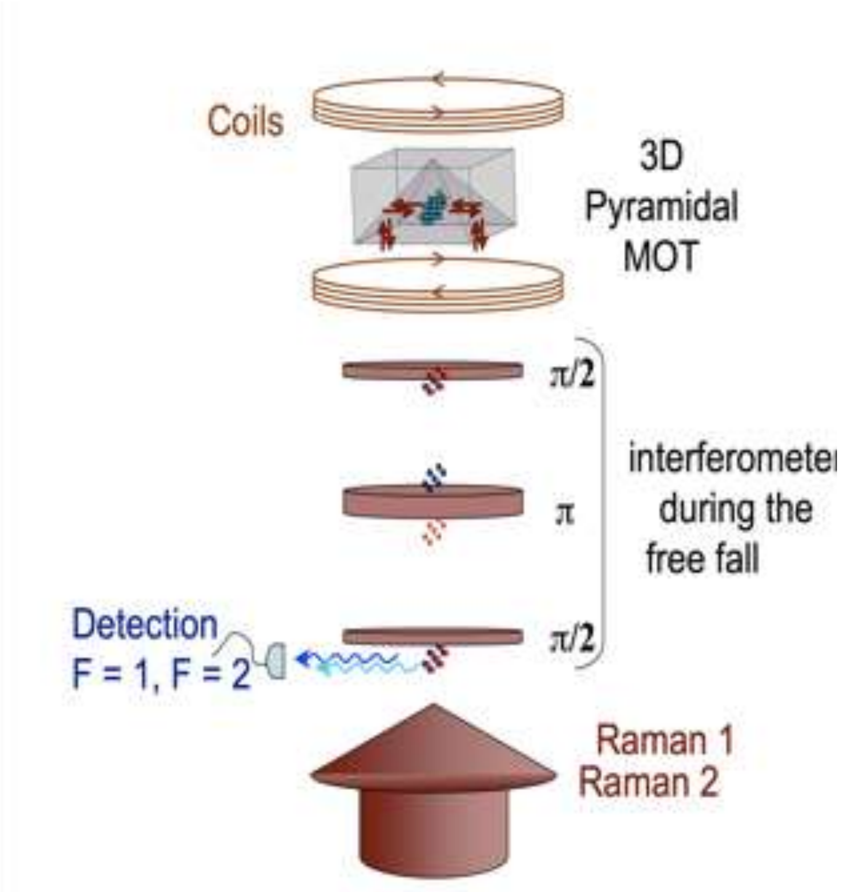
Compact Sensor Head



Patent filled (WO 2009/118488 A2)





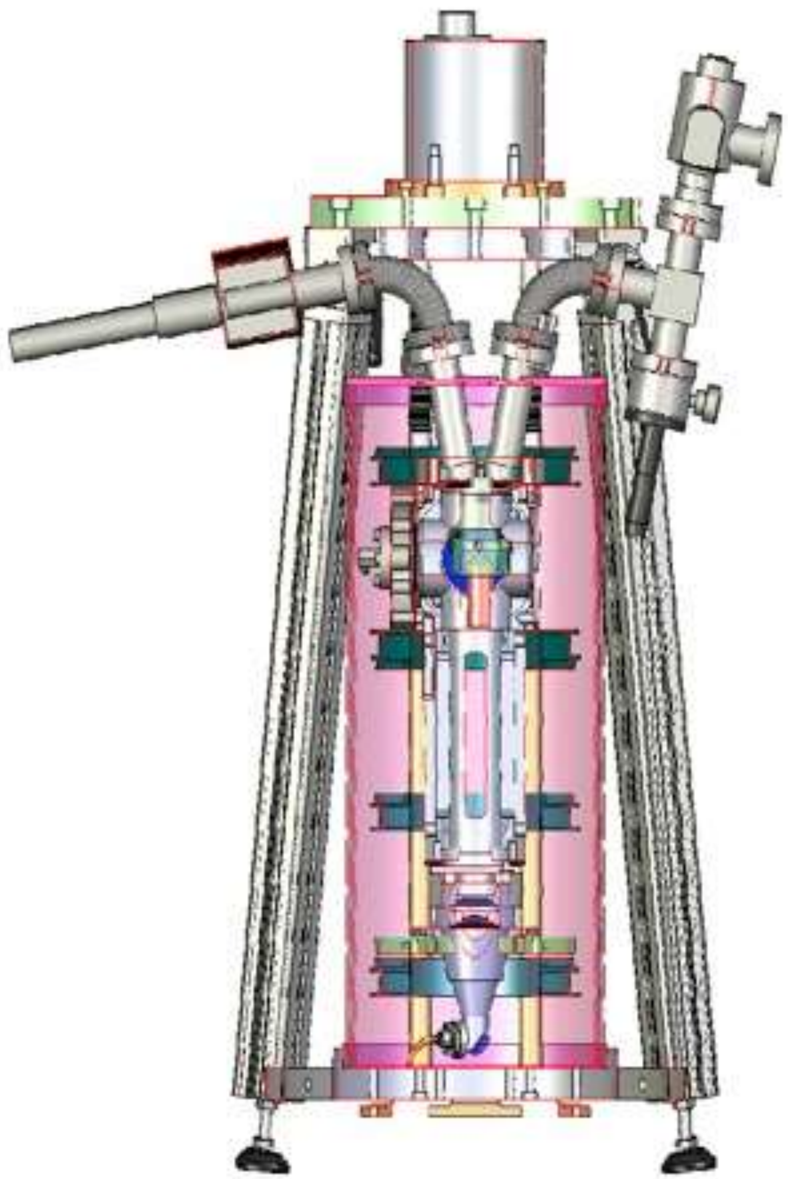


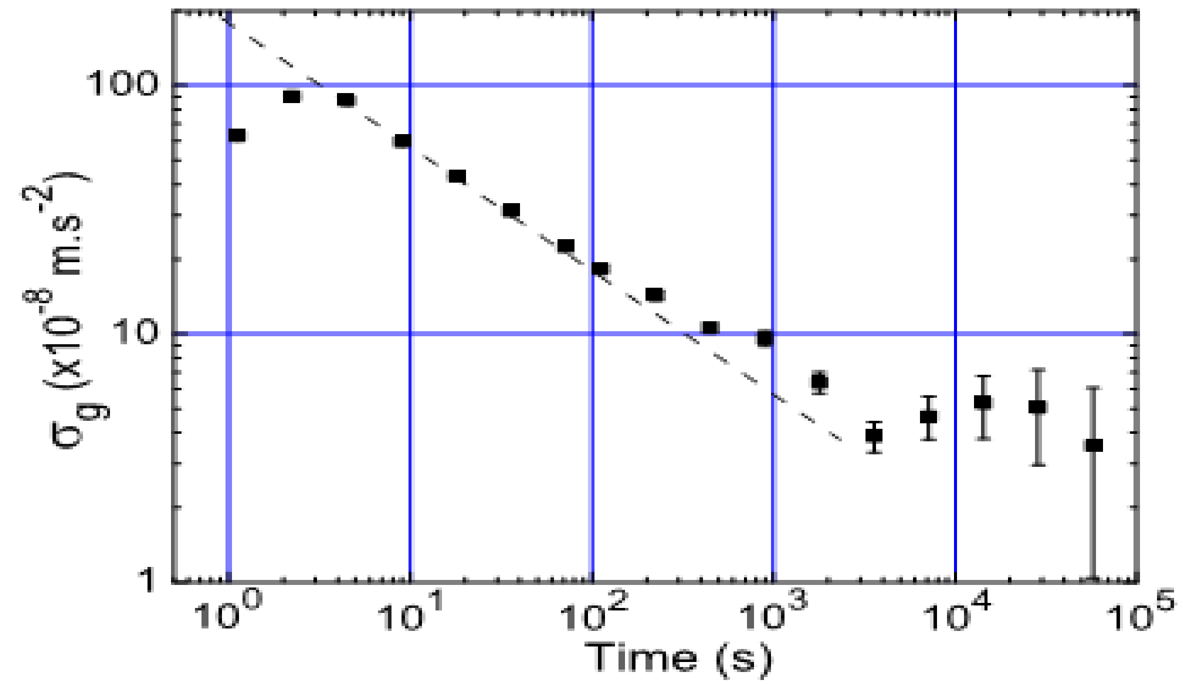
- Innovative hollow pyramidal retro-reflector
- Single beam trap & interferometer
- 2 L Ti magnetically shielded vacuum chamber (Indium sealed)
- Trapping from a vapor (P~ 10^{-8} hPa)
- Continuous monitoring by a tilt-meter and a seismometer
- Polarization controlled optical injection (through a PMF)
- Development of home-made electrical and HF feedthroughs

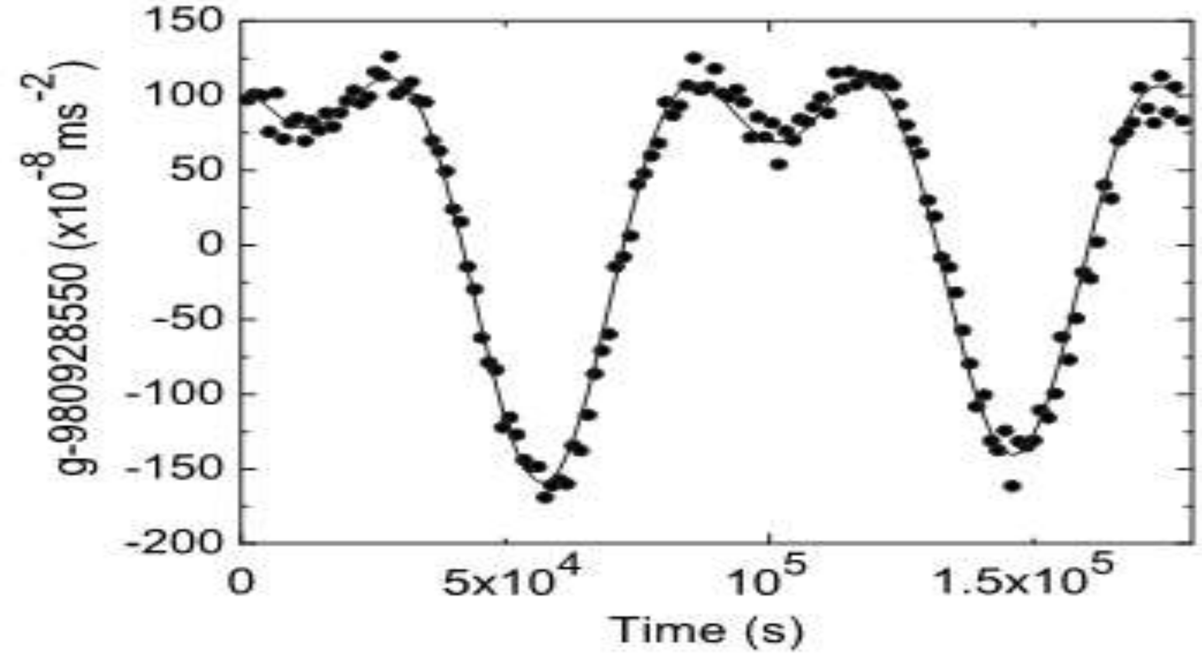
Demonstration of the compact interferometer with a hollow pyramid:
[Bodard et al., Applied Physics Letters 96, 134101, 2010]

COMPACT SENSOR HEAD

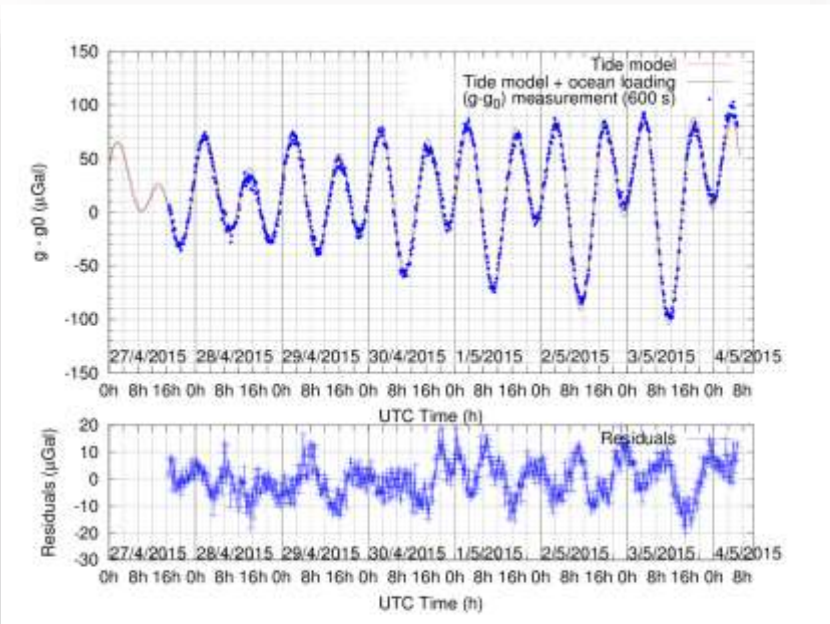
Patent filled (WO 2009/118488 A2)





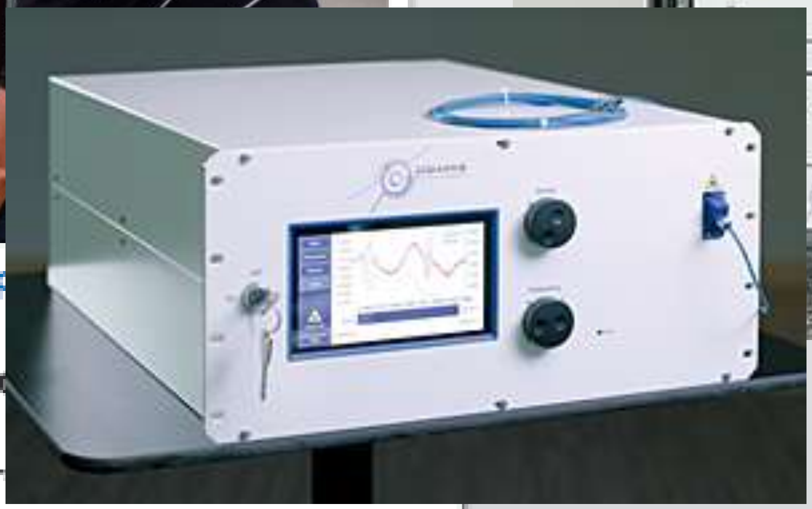


Demonstration of the compact interferometer with a hollow pyramid*:*
[Bodard et al., Applied Physics Letters 96, 134101, 2010]



μQUANS

PRECISION QUANTUM SENSORS



▸ **Gravimetric p**

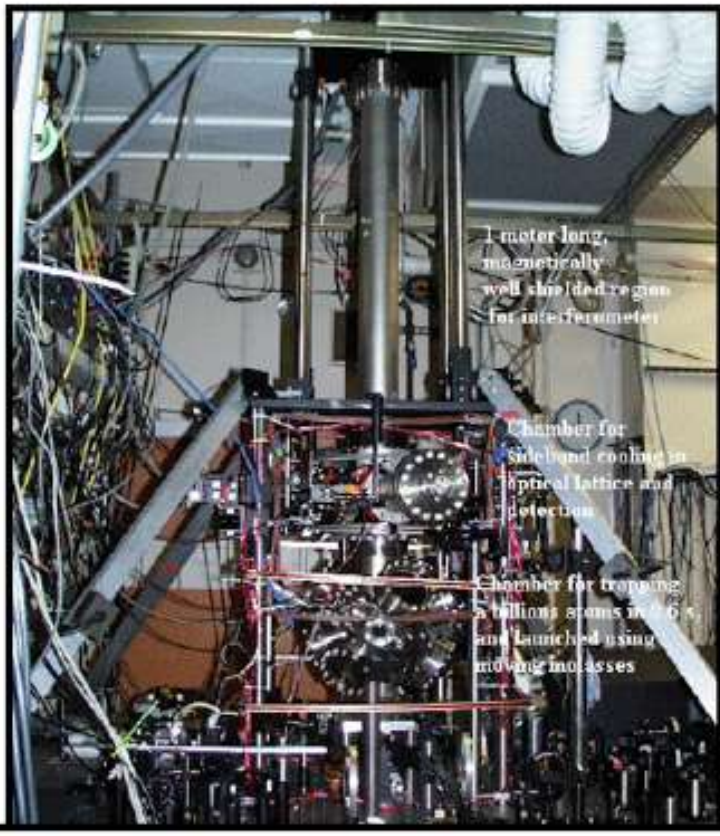
Sensitivity	
Ultimate stabili	
Accuracy	
Measurement fr	

▸ **Power**

Operating power	300 W
Peak power (warm-up)	400 W

▸ **Frequency stability**

1 s	≤ $3.0\ 10^{-13}$
10 s	≤ $9.5\ 10^{-14}$
100 s	≤ $3.0\ 10^{-14}$
1000 s	≤ $9.5\ 10^{-15}$
10000 s	≤ $3.0\ 10^{-15}$
1 day	≤ $2.0\ 10^{-15}$
Flicker floor	≤ $2.0\ 10^{-15}$ (@ 10 days)

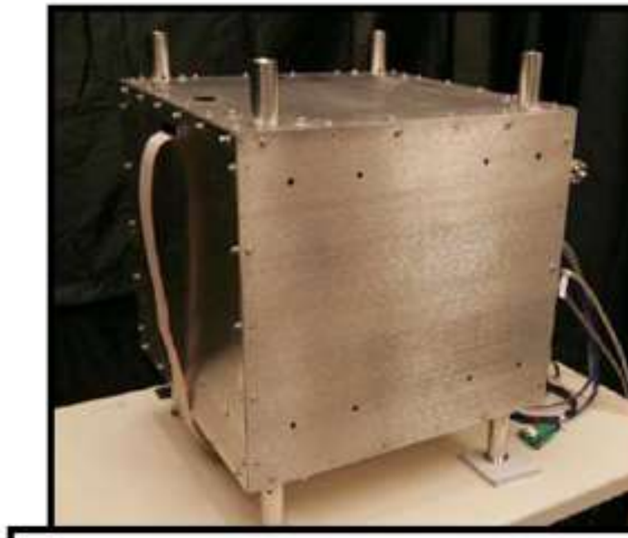


Stanford Gravimeter (non-mobile)

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

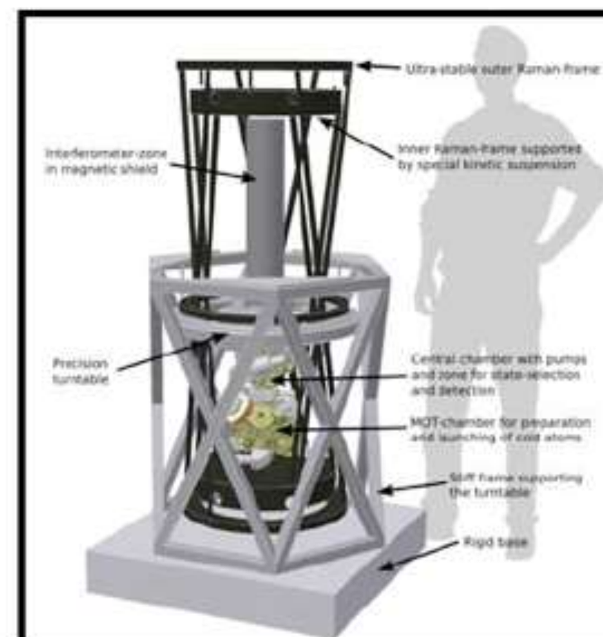
Paris Gravimeter („mobile")

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



Kasevich Gravimeter (mobile)

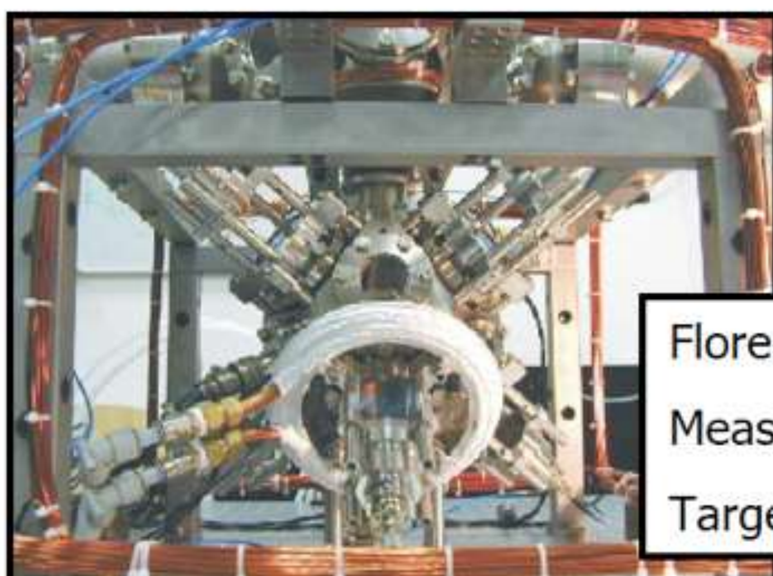
Bias Stability: < 10^{-10} g



Berlin Gravimeter GAIN

(mobile, under construction)

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

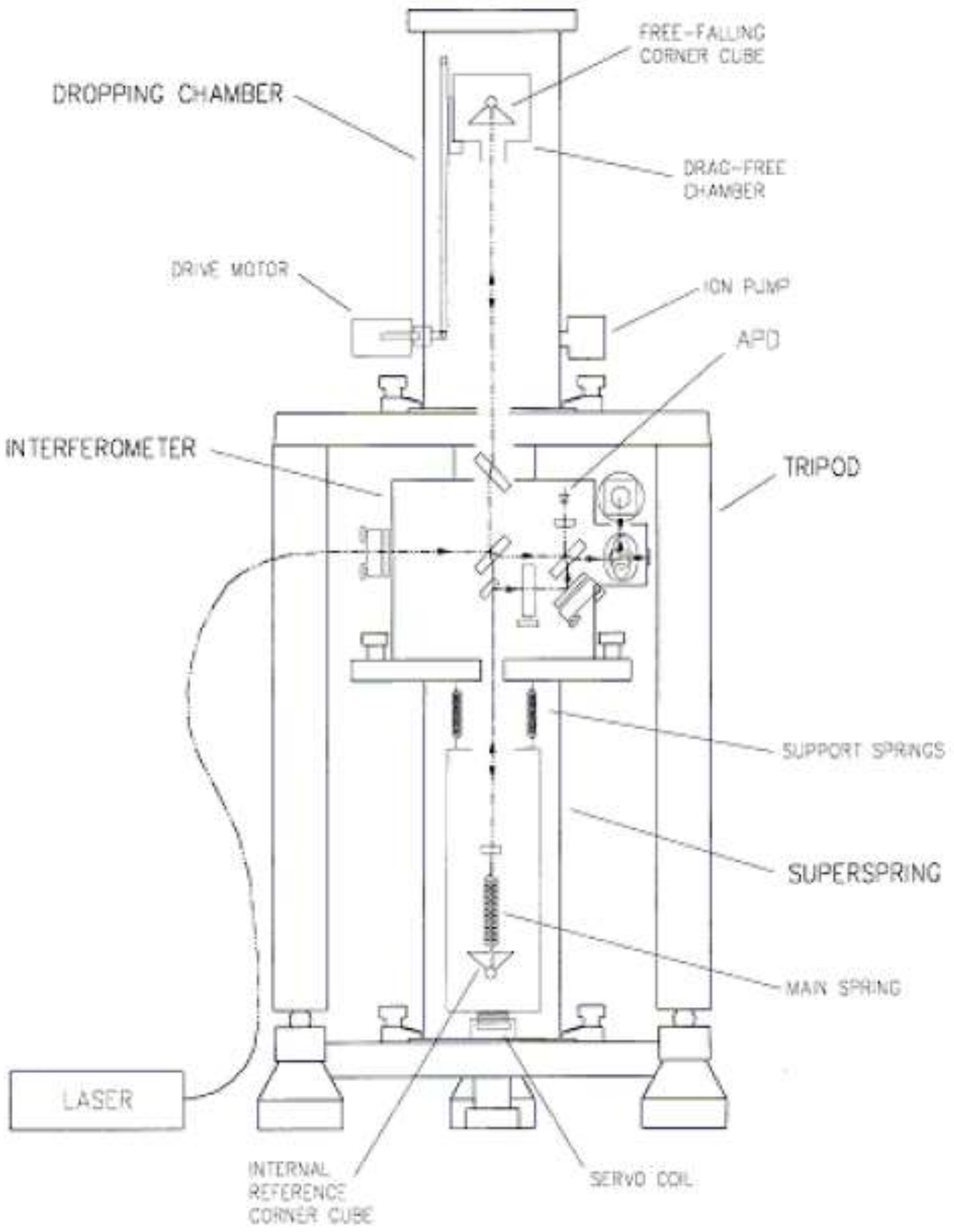


Florenz INFN Gravity Gradiometer MAGIA

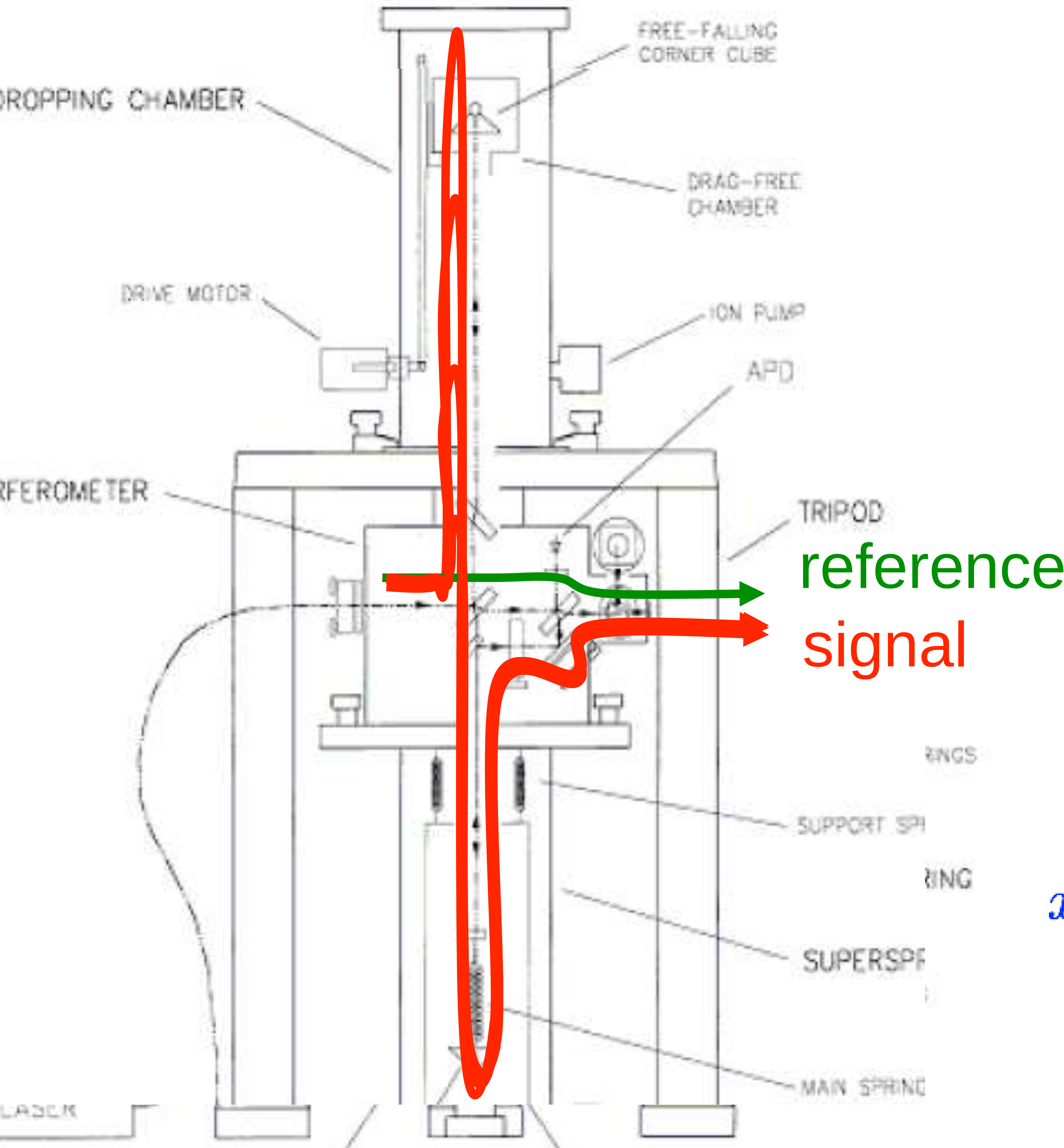
Measurement of the gravitational constant G

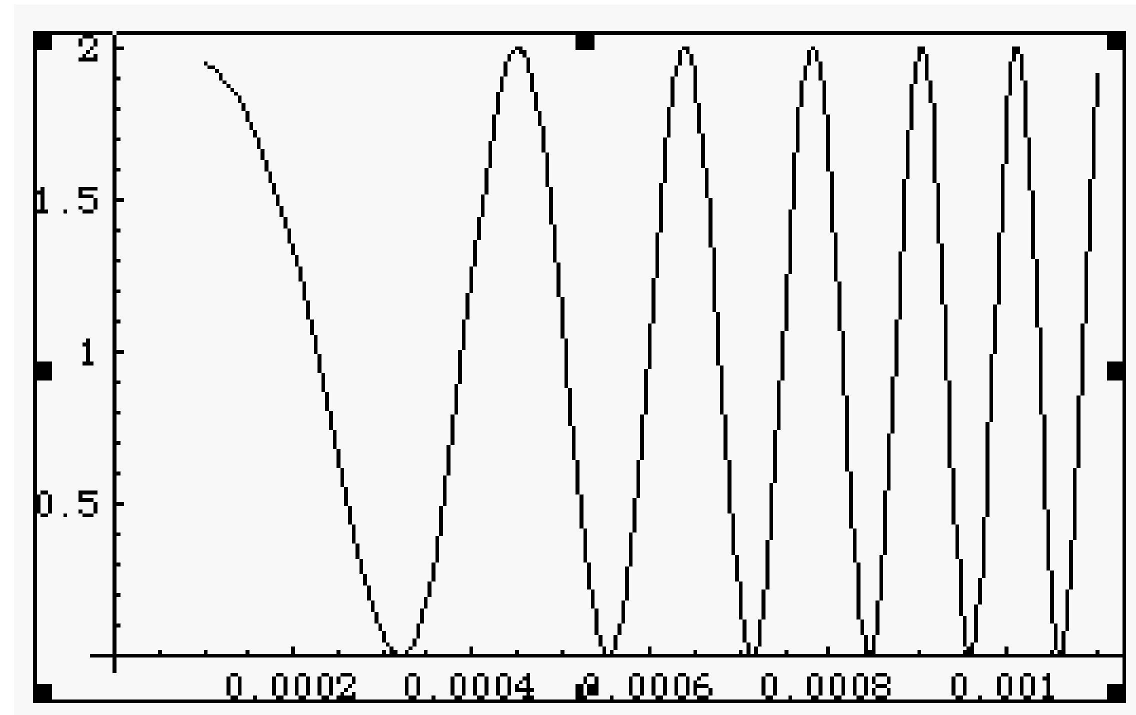
Targeted Accuracy: $\Delta G/G = 1 \cdot 10^{-4}$

FALLING CORNER CUBE GRAVIMETER



FALLLING CORNER CUBE GRAVIMETER





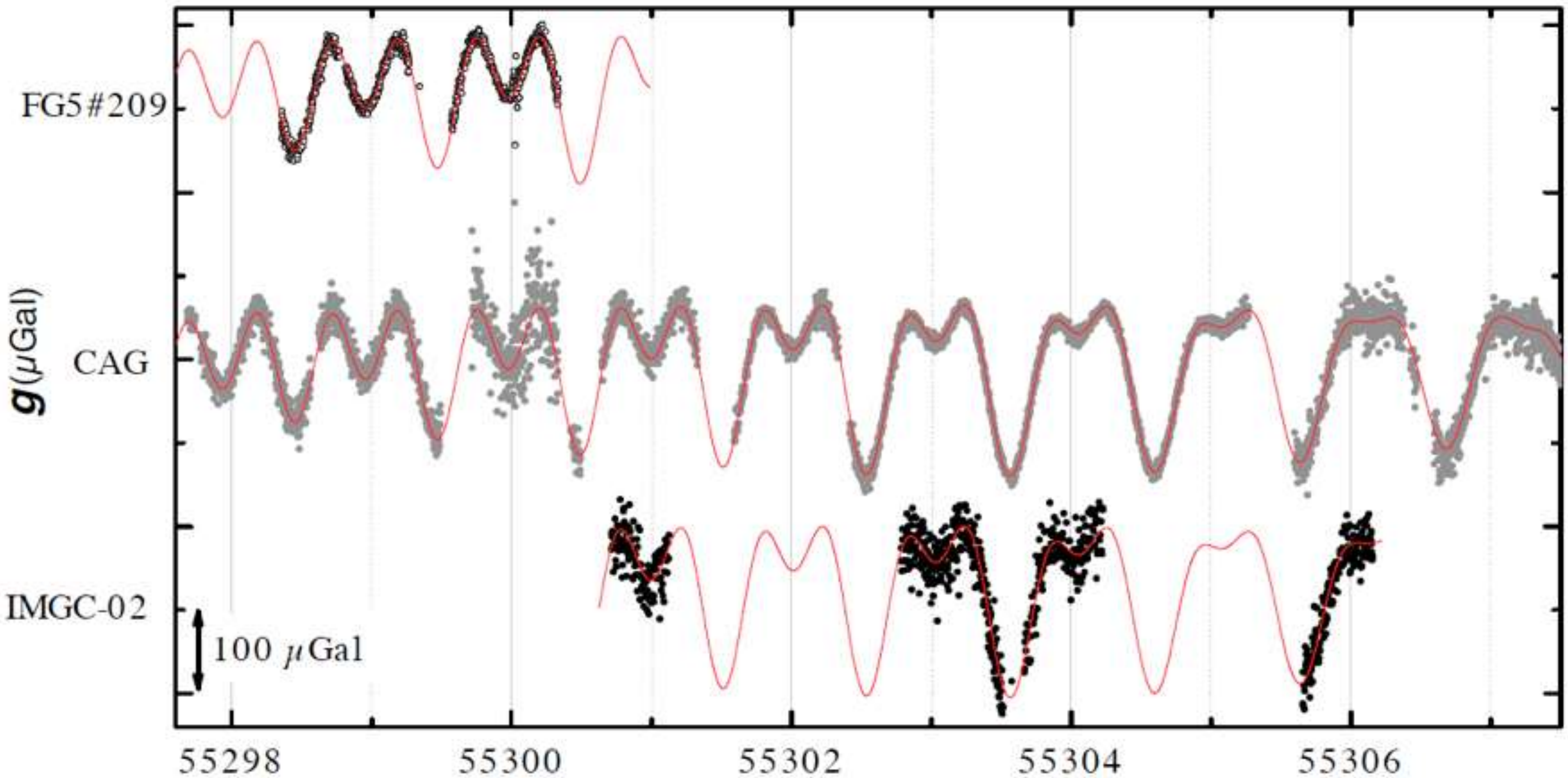
recording of fringe vs time

$$x_i = x_0 + v_0\tilde{t_i} + \frac{g_0}{2}\left(\tilde{t_i}^2 + \frac{\gamma\tilde{t_i}^4}{12}\right)$$

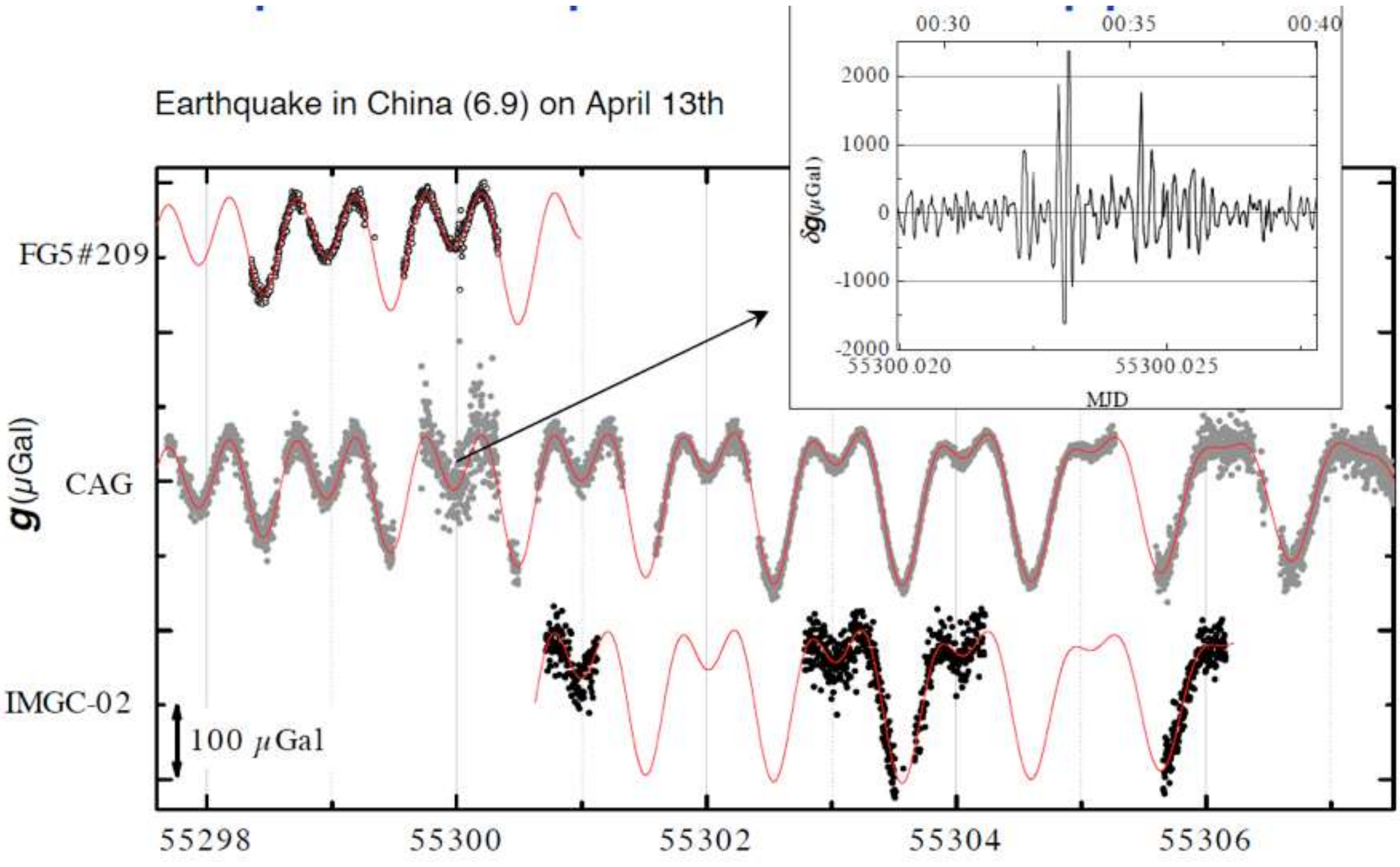
$$\tilde{t_i} = t_i - \frac{x_i - x_0}{c}$$

Comparison between different gravimeters

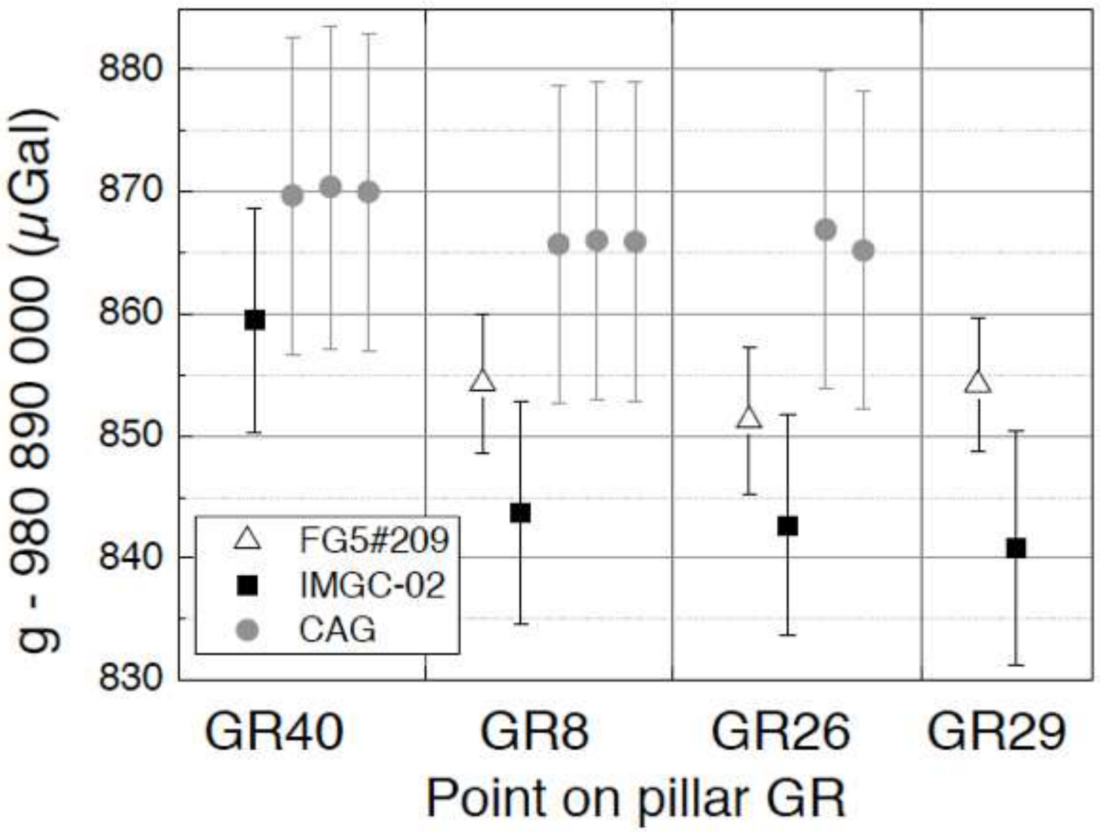
Done in Trappe, near Paris, with the gravimeter developed at Observatoire de Paris



COMPARISON BETWEEN DIFFERENT GRAVIMETERS



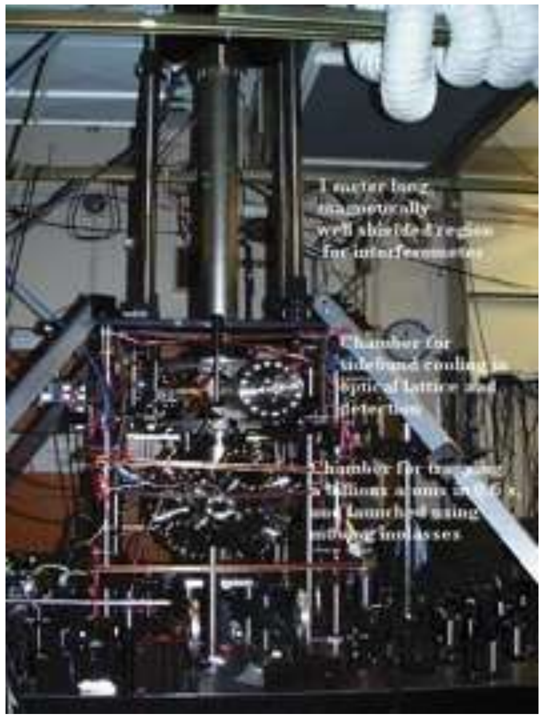
Comparison between different gravimeters

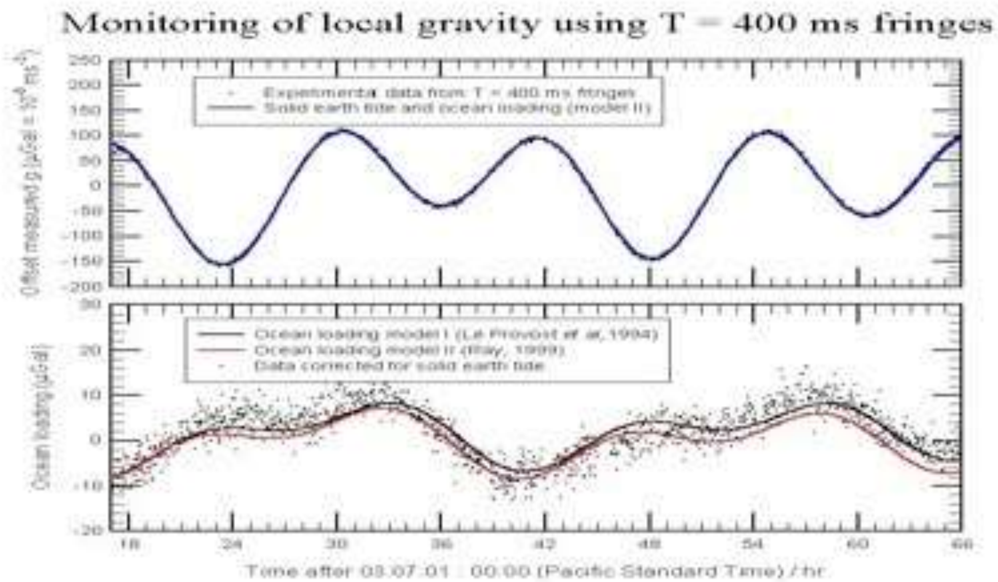


- Reproducible differences
- Limit of agreement
- Some systematics not well controlled

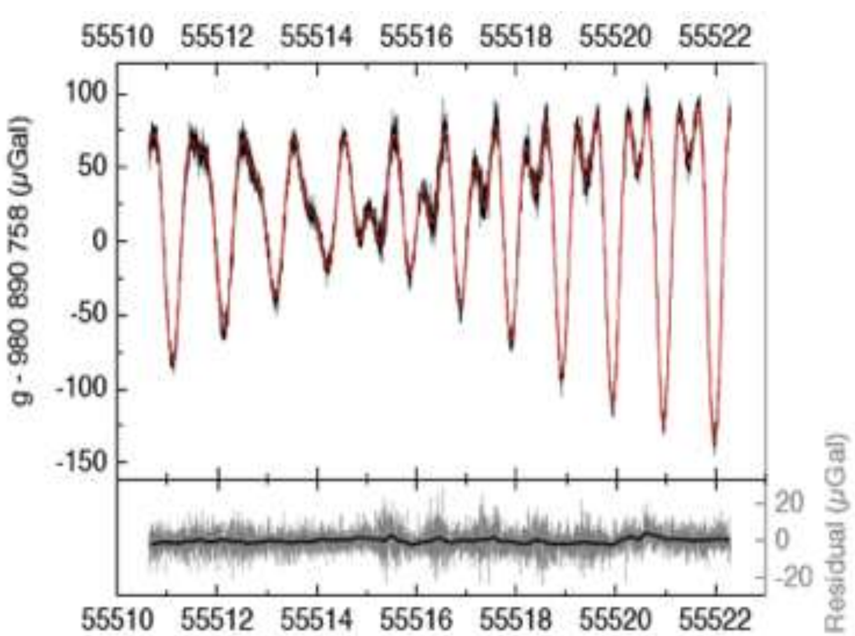
	Accuracy (μGal)	s_{gm} (μGal)	U (k=2) (μGal)
FG5#209	2.0	1.1 – 1.7	5.4 – 5.9
IMGC-02	4.1	1.2 – 2.0	9.0 – 9.5
CAG	6.5	0.2 – 1.2	13.0 – 13.2

«CLASSICAL» INTERFEROMETERS : INERTIAL SENSORS

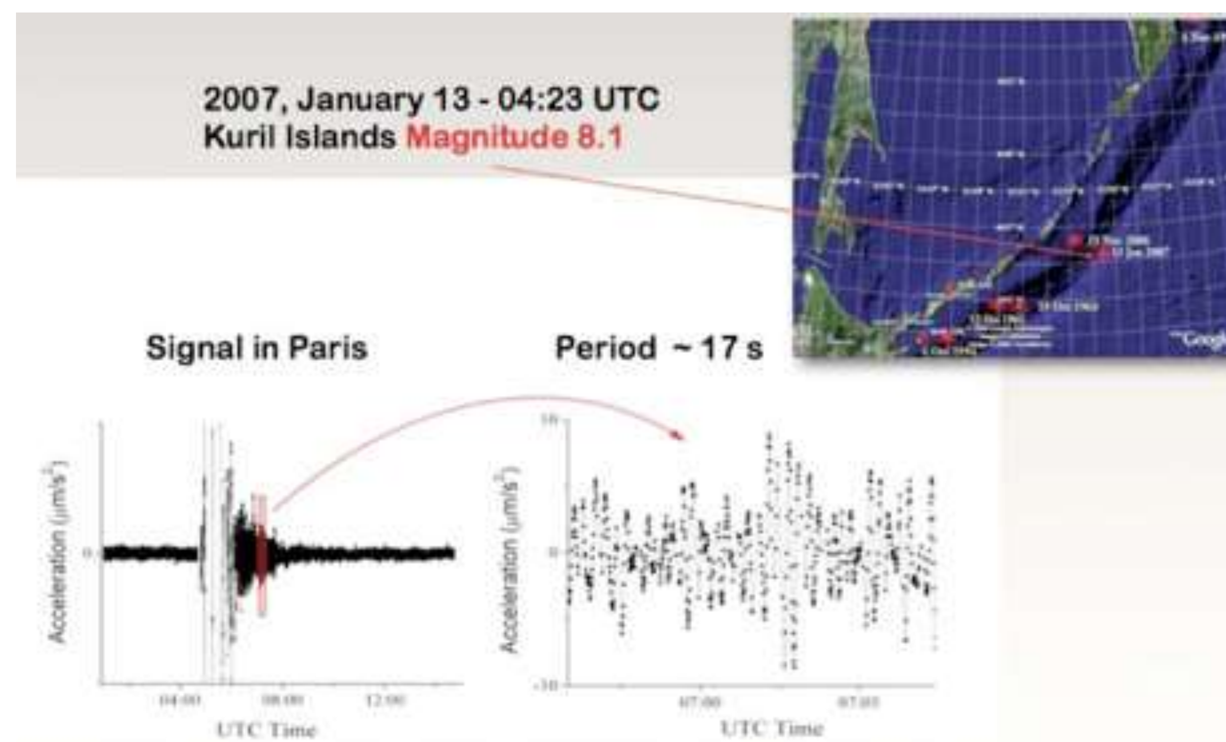




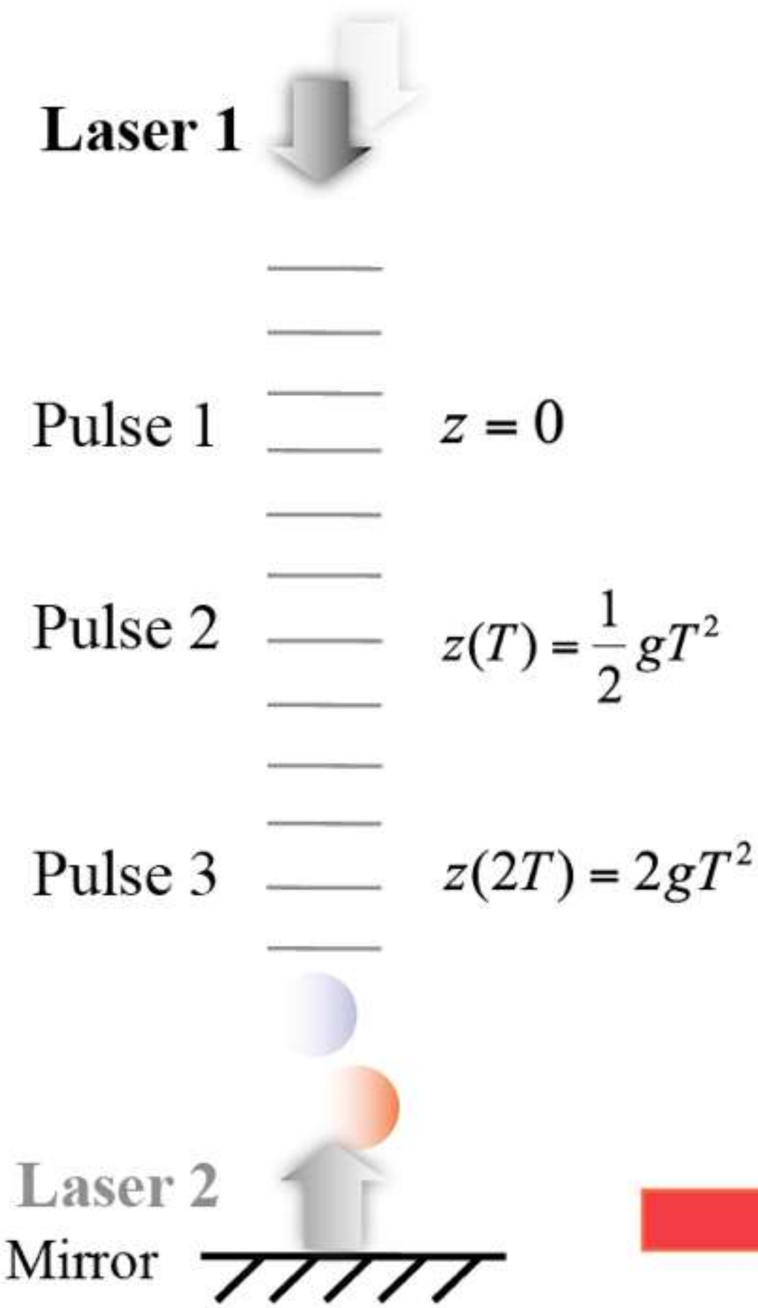
- ✓In laboratories, atom gravimeters beat the best commercial gravimeters
  - ⇨ Seismic wave detections
  - ⇨ Gravity monitoring
  - ⇨Watt ballance : quantum definition of the kilogram



Very robust experiment



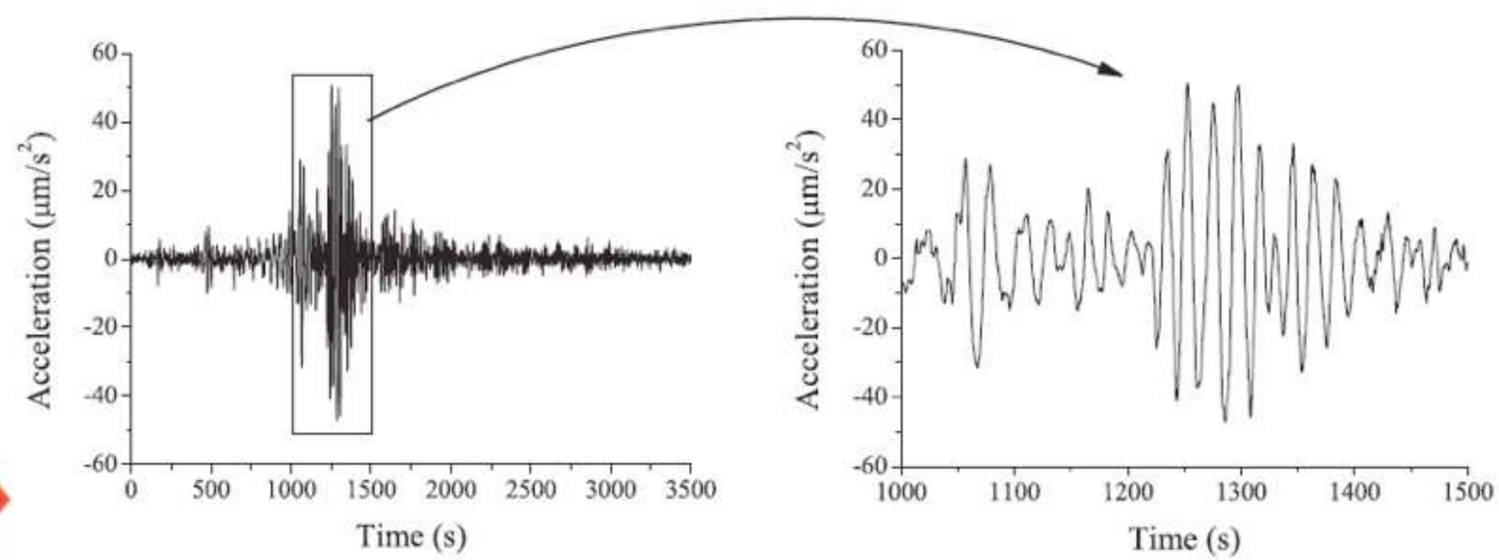
APPLICATIONS : GRAVIMETER AS SEISMOMETER



Vertical interferometer
⇒ Free fall along the equiphase planes

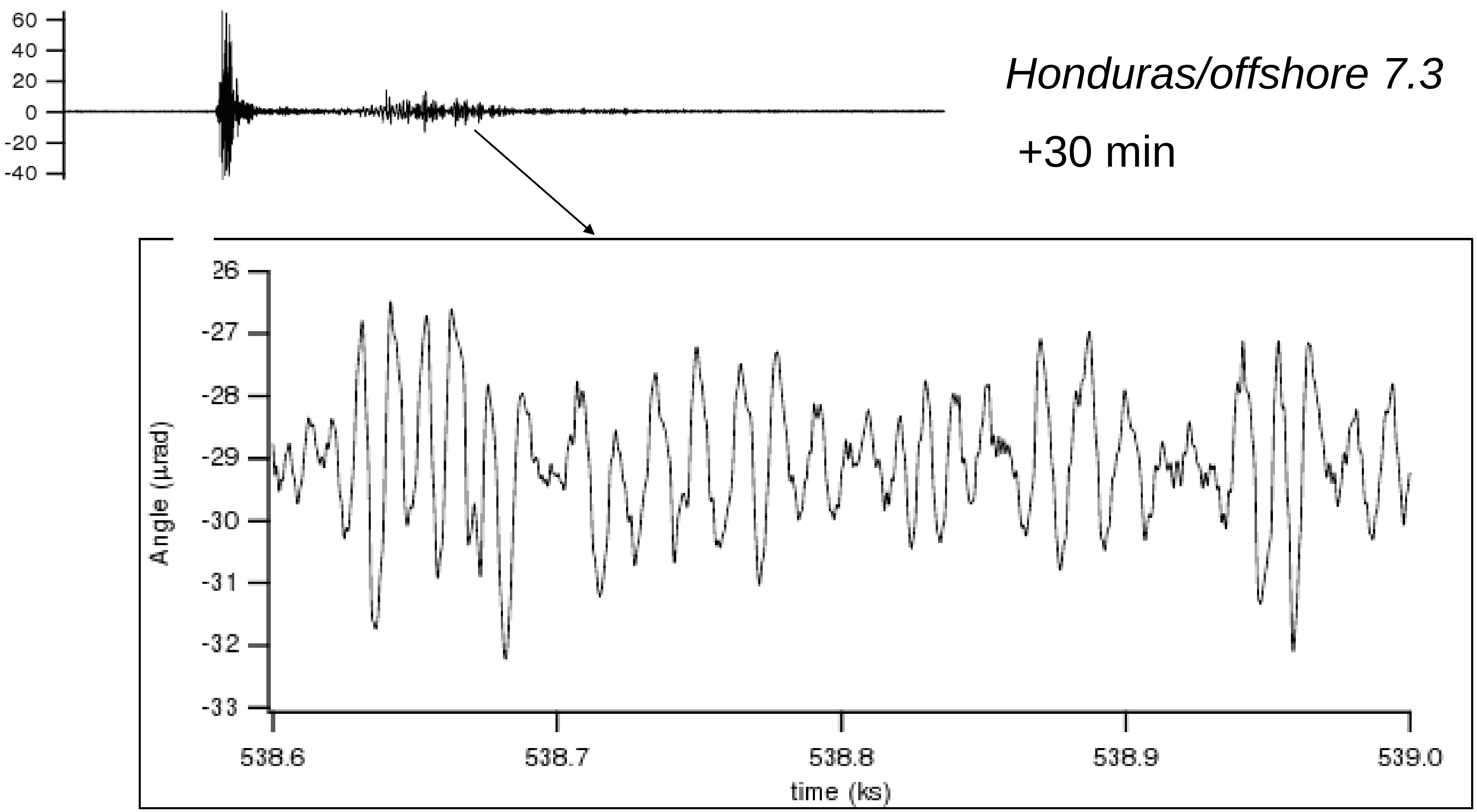
Sensitivity to gravity acceleration :

$$\Delta\Phi_{\text{int}} = -\vec{k}_{eff}\,\vec{g}\,T^2 + \delta\Phi_{noise} + \delta\Phi_{sys}$$



Earthquake in China 2 Mars 20th 2008

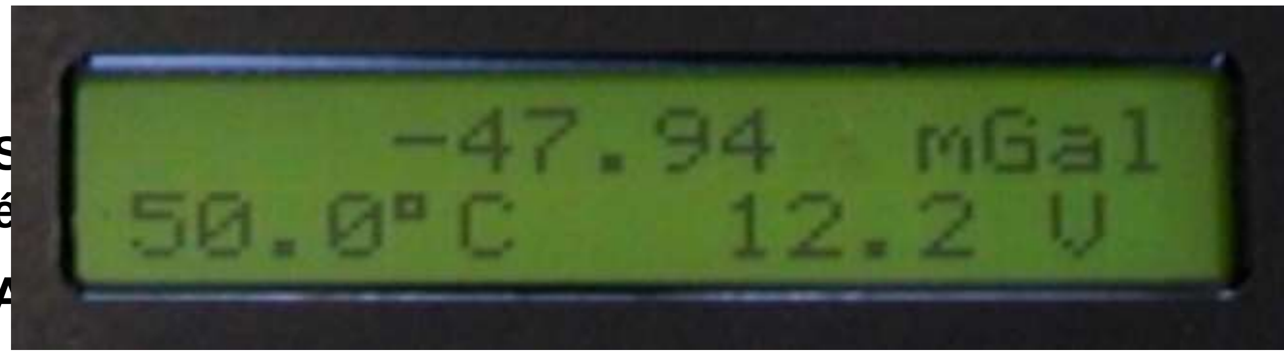
APPLICATION : SEISMIC STUDIES WITH GYROSCOPE

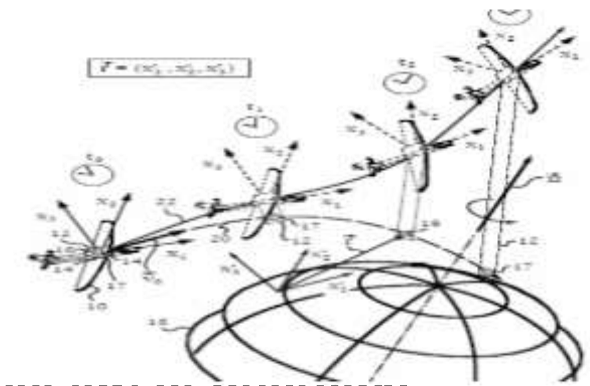


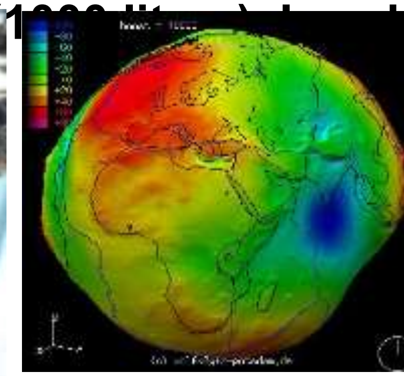
Gyroscope output necessary to disambiguate tilt from horizontal motion (navigation problem).

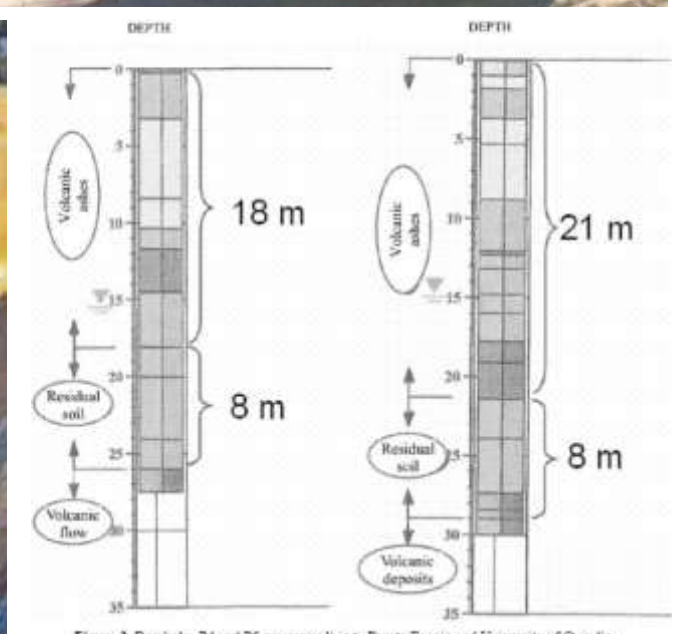
Geophysics

TRANSPORTABLE GRAVITY SENSORS

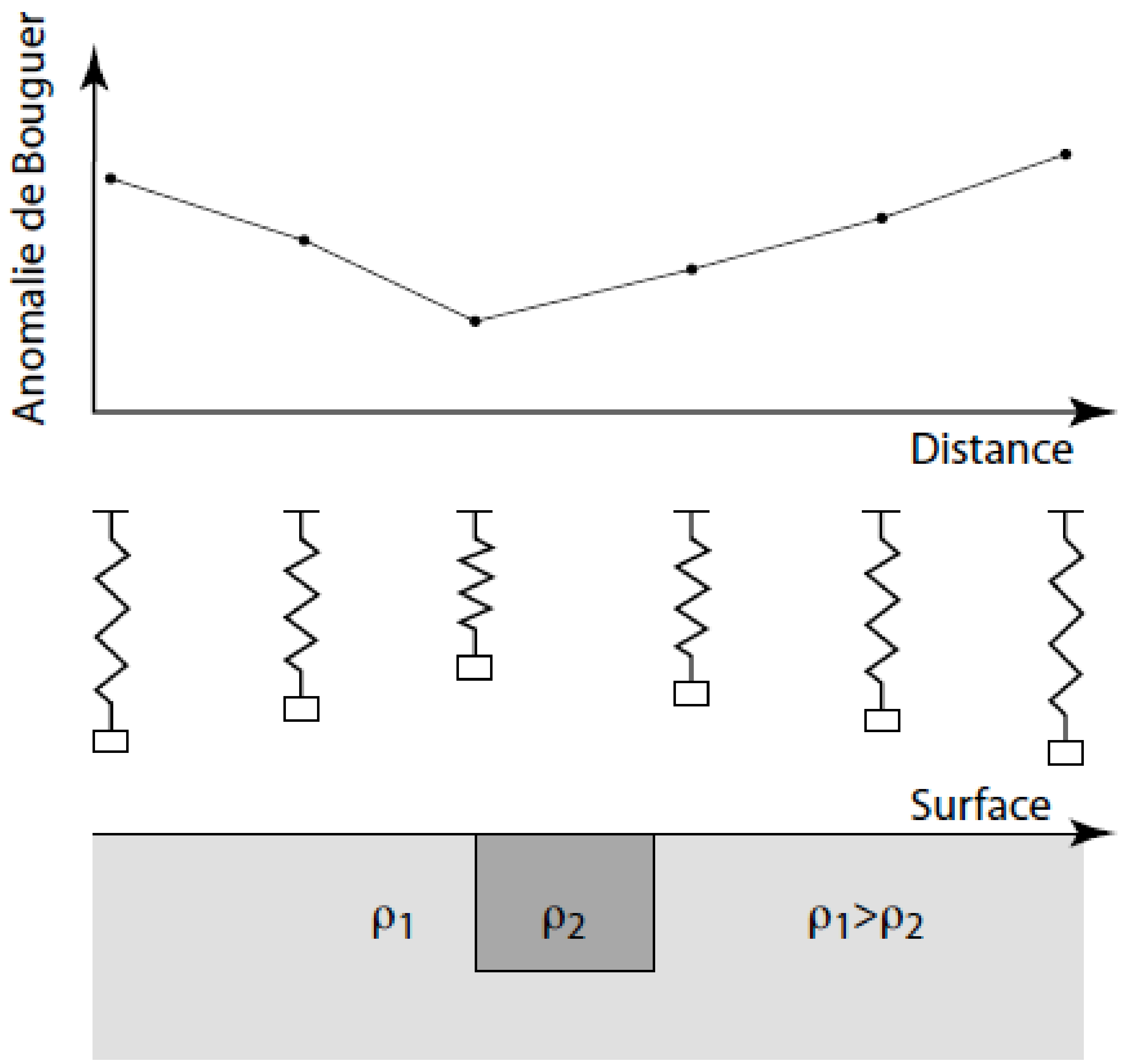




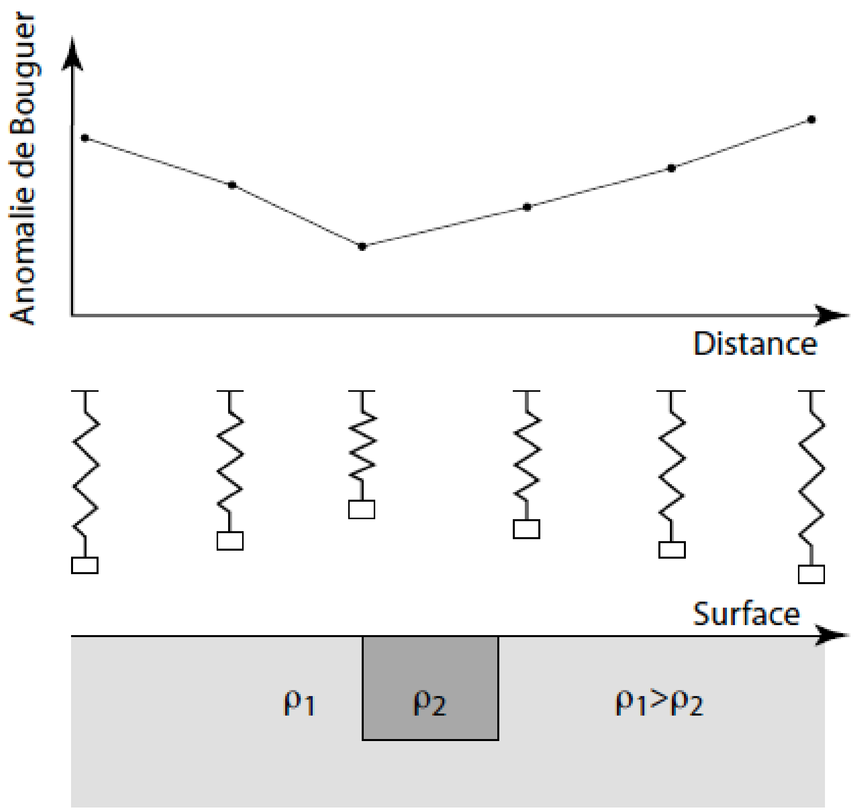




✓ Deduce from the variations of gravity locally the density variations the ground



Micro and nano - gravimetry



- Small variations
  - nanogravi : 10^{-9} g with g ~9.87 m/s^2 = 987 Gal
  - microgravi : 10^{-6} g, 1 µGal = 10^{-6} Gal
- Looking for small changes 10 - 100 µGal
- Variation of g with height : 3 µGal/cm

Table 1: Field of application, accuracy target, type of instruments and their availability.

Application	Accuracy target	Instruments/availability
Isostasy	10^{-5}	Relative gravimeters (pendulum)/1817
Prospection for oil and gas	10^{-6}—10^{-7}	Relative gravimeters/1950
Structural geology	10^{-6}	Relative gravimeters/1950
Microgravity prospection	10^{-8}	Relative gravimeters/1980
Metrology (forces)	10^{-6}—10^{-7}	Absolute gravimeters/1980
Metrology (kilogram)	10^{-8}—10^{-9}	Absolute gravimeters/1990
Geodetic metrology	10^{-8}	Absolute gravimeters/1980
Geodesy	10^{-7}—10^{-8}	Rel + Abs gravimeters/1980
Earth tide and earth dynamic	10^{-10}—10^{-11}	Superconducting gravimeters/1970

Table 2: Progress in measuring g(partially compiled after Torge 1989, page 14, figure 1.1 [1]

Type of instrument	Time span	Uncertainty range	Rate
Reversible pendulum	1817 to1945	4×10^{-5} to 2×10^{-6}	One order of magnitude/130 years
Spring type gravimeters	1935 to 2010	4×10^{-7} to 3×10^{-9}	Two orders of magnitude/75 years
Superconducting gravimeters	1965 to 2010	5×10^{-10} to 5×10^{-12}	Two orders of magnitude/45 years
Absolute gravimeters	1970 to 2010	8×10^{-7} to 2×10^{-9}	Two orders of magnitude/40 years

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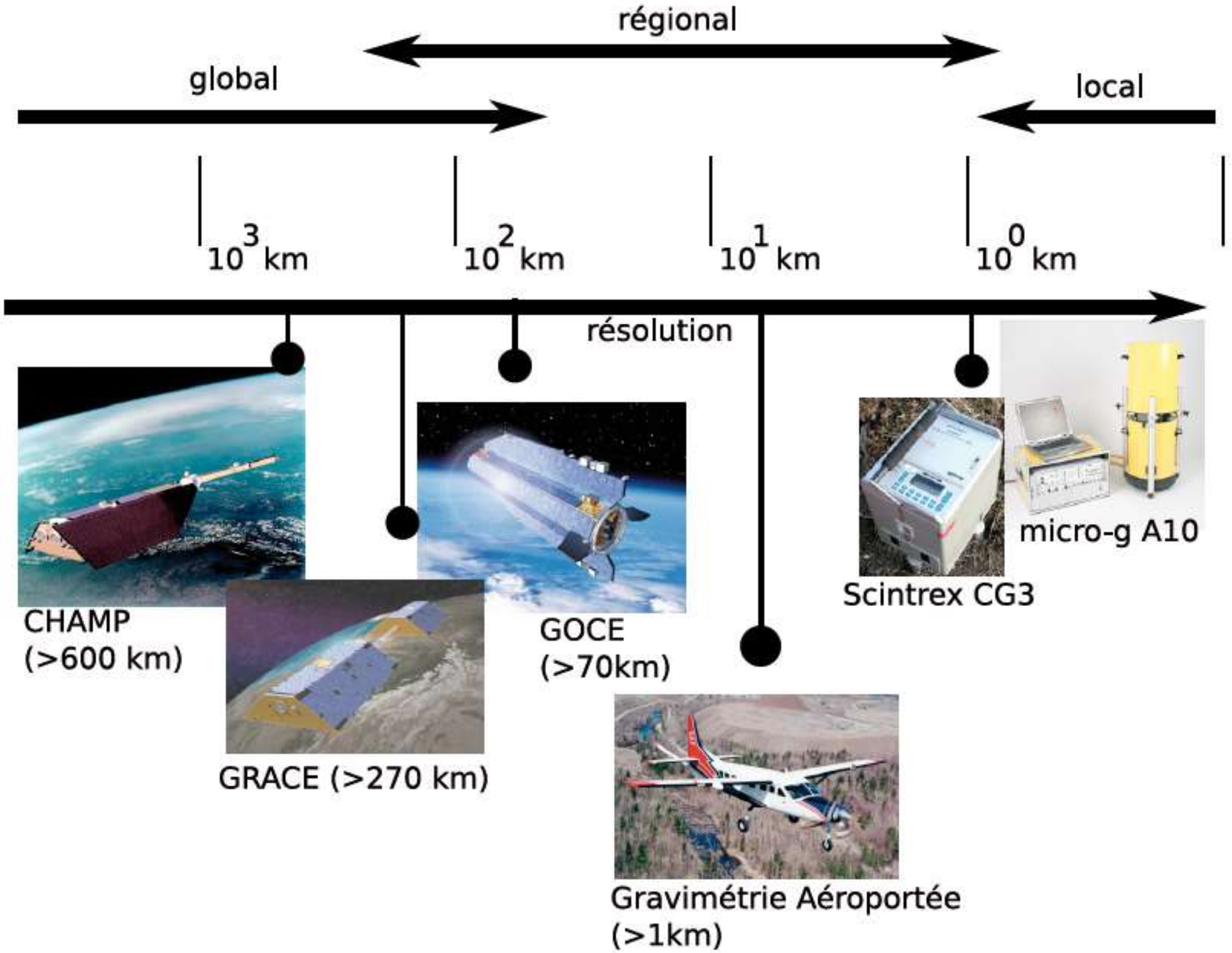
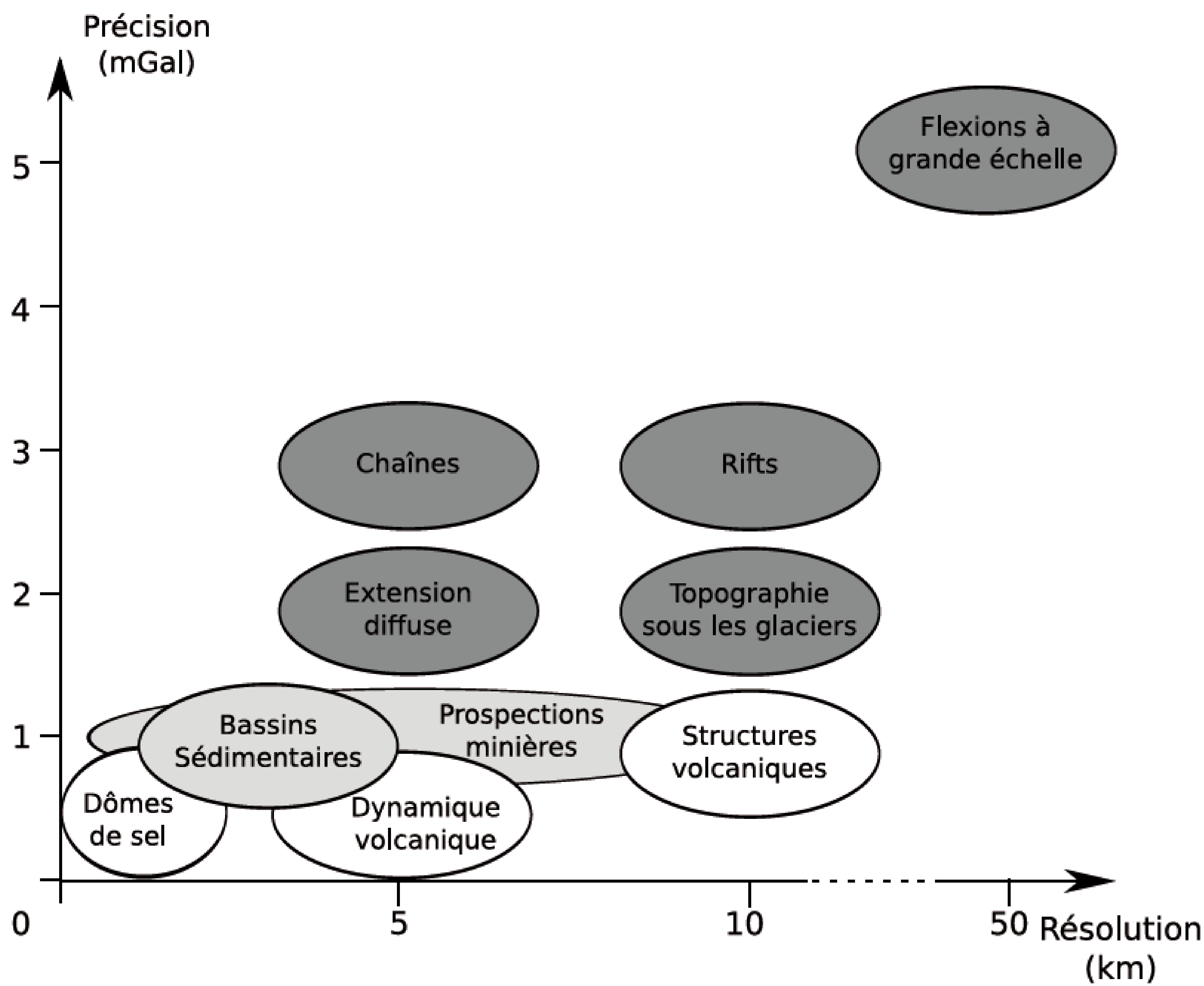
doi:10.1155/2012/687813

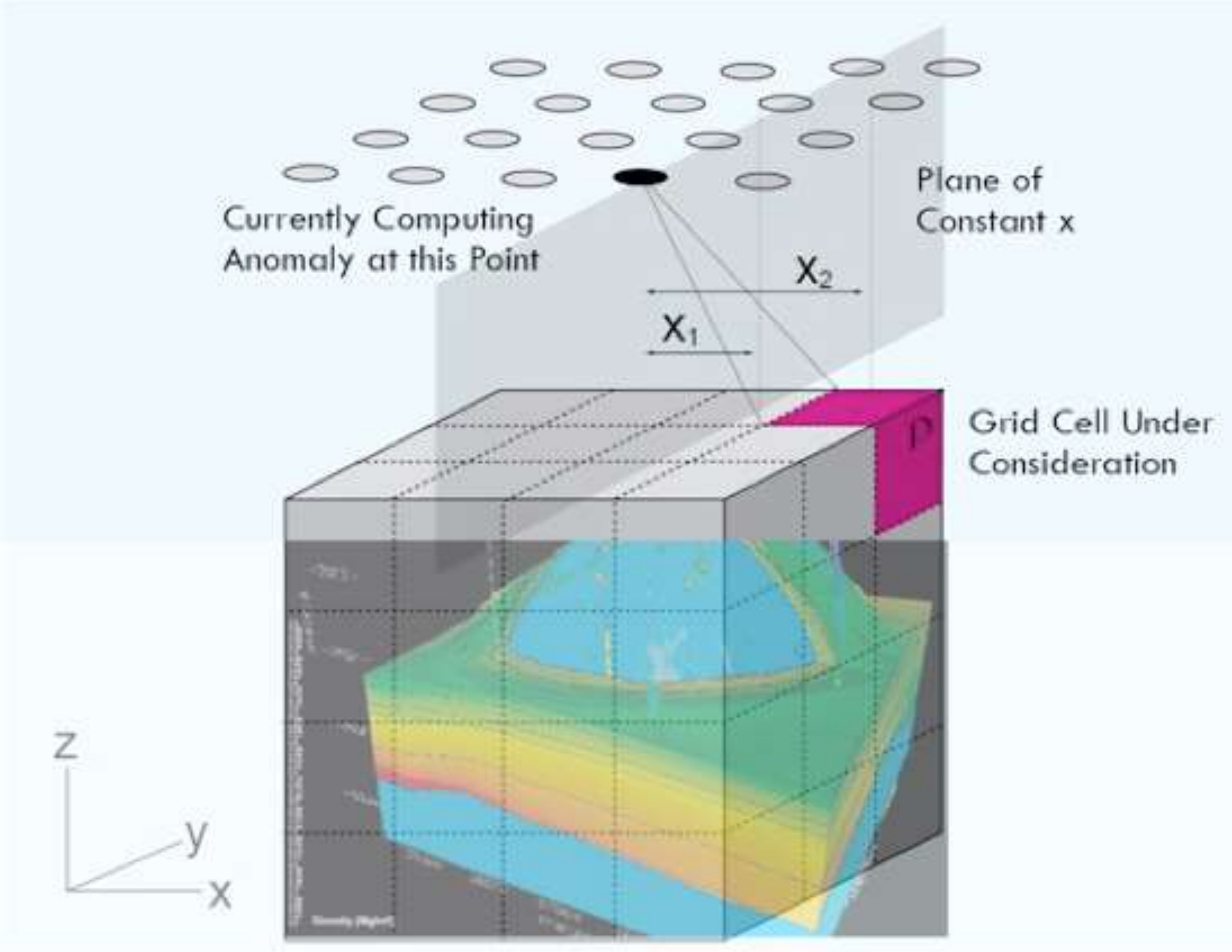
RESOLUTION VS HEIGHT OF MEASUREMENT

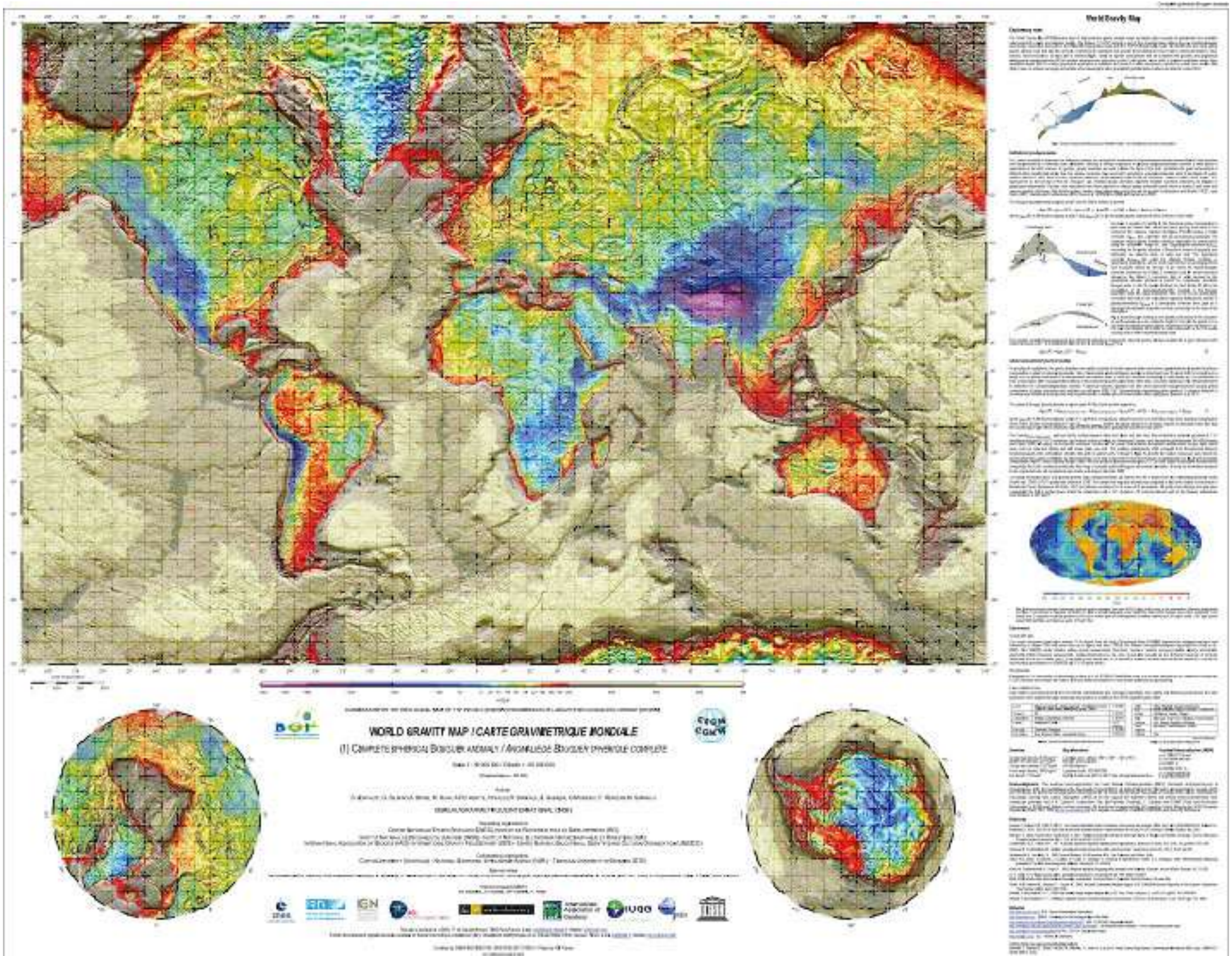


RESOLUTION VS PRECISION OF MEASUREMENT



GRAVITY MAPPING

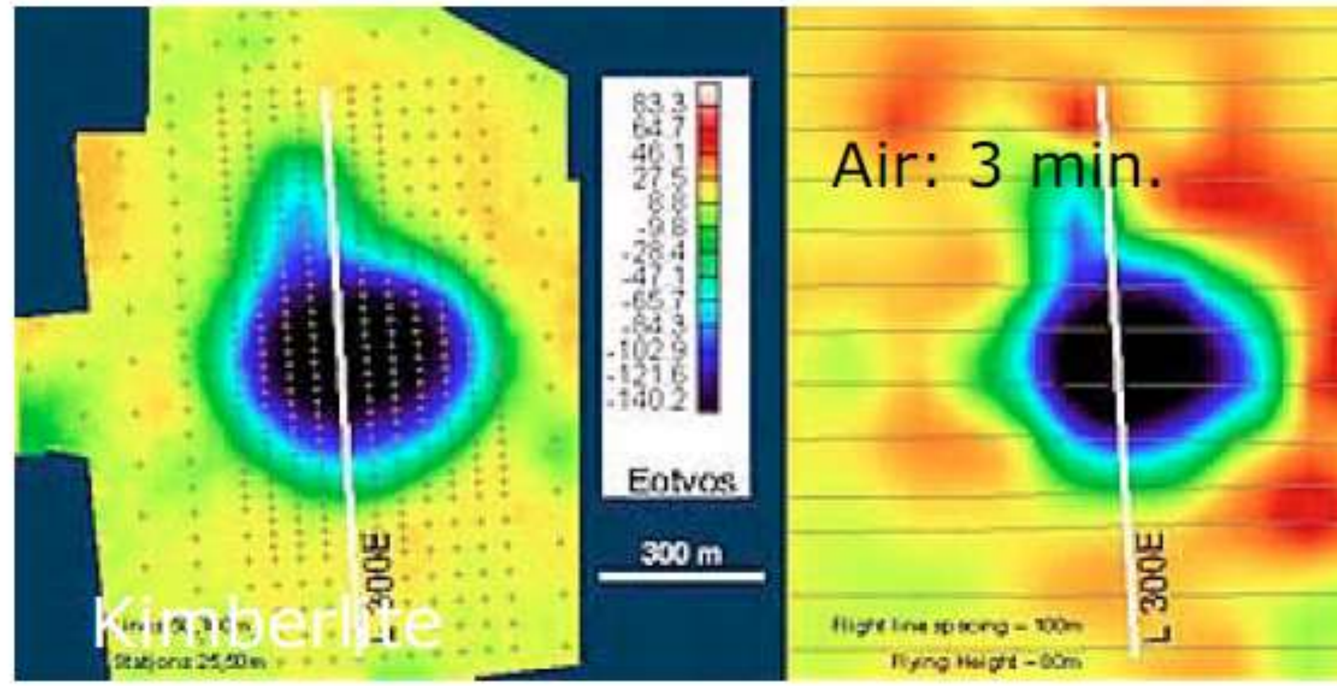




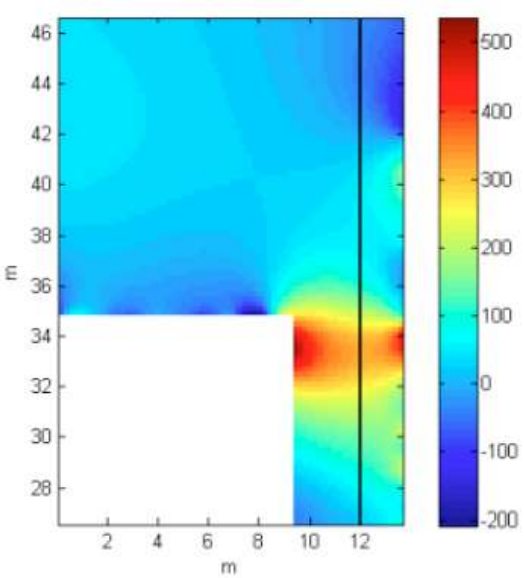
World Gravity Map
WORLD GRAVITY MAP / CARTE GRAVIMETRIQUE MONDIALE

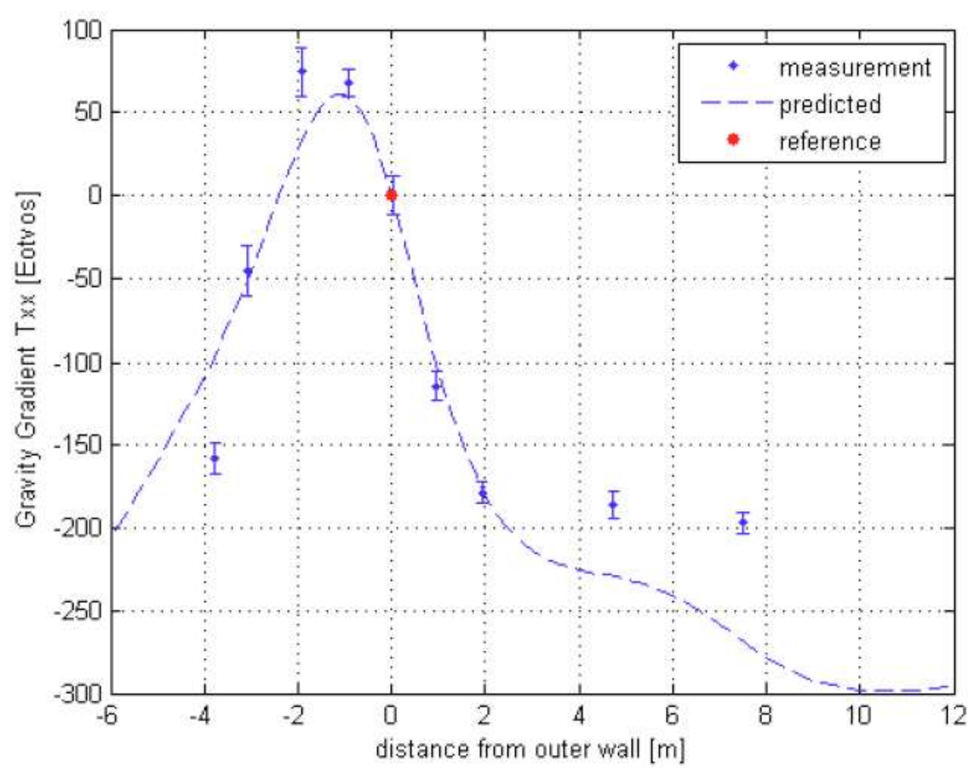
Existing technology

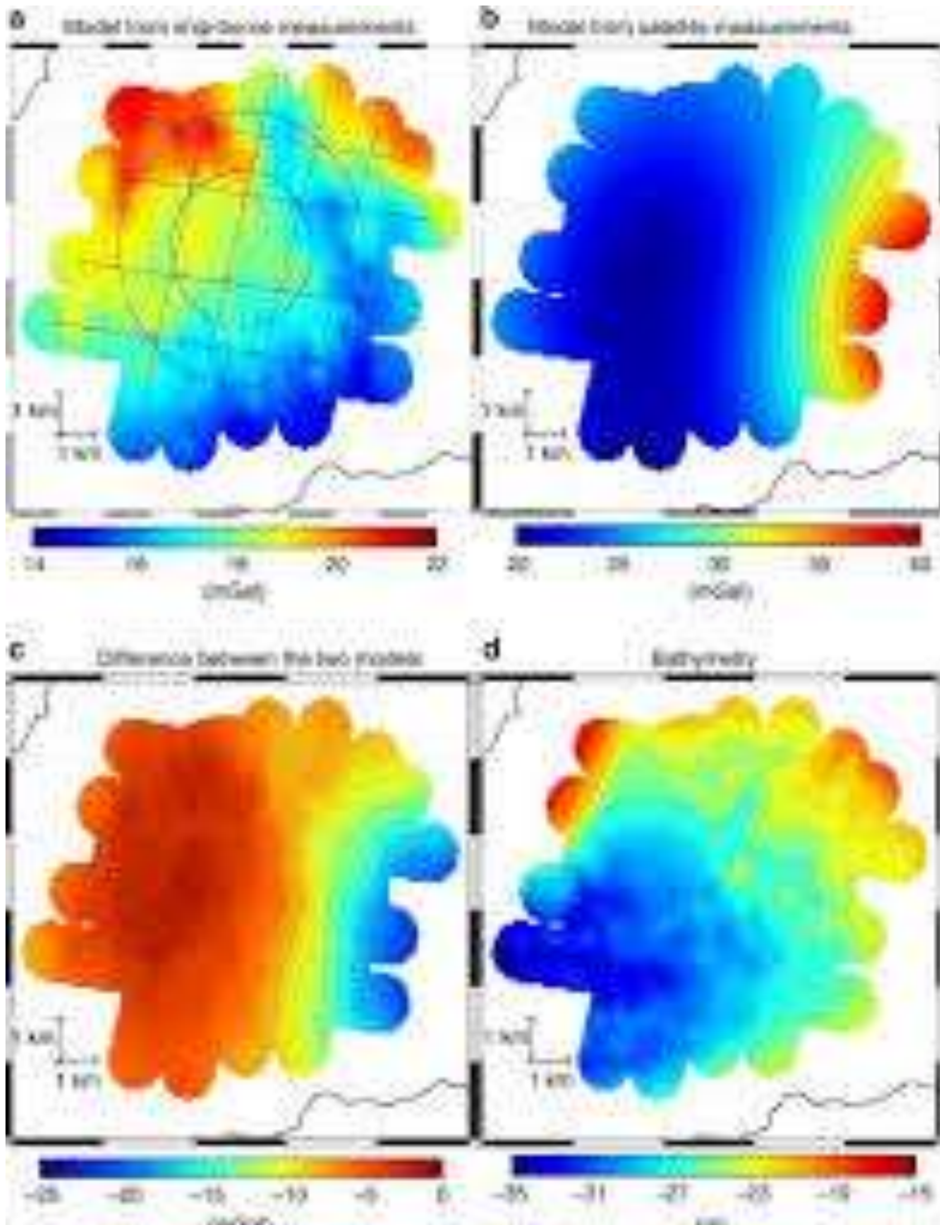
Land: 3 wks.



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

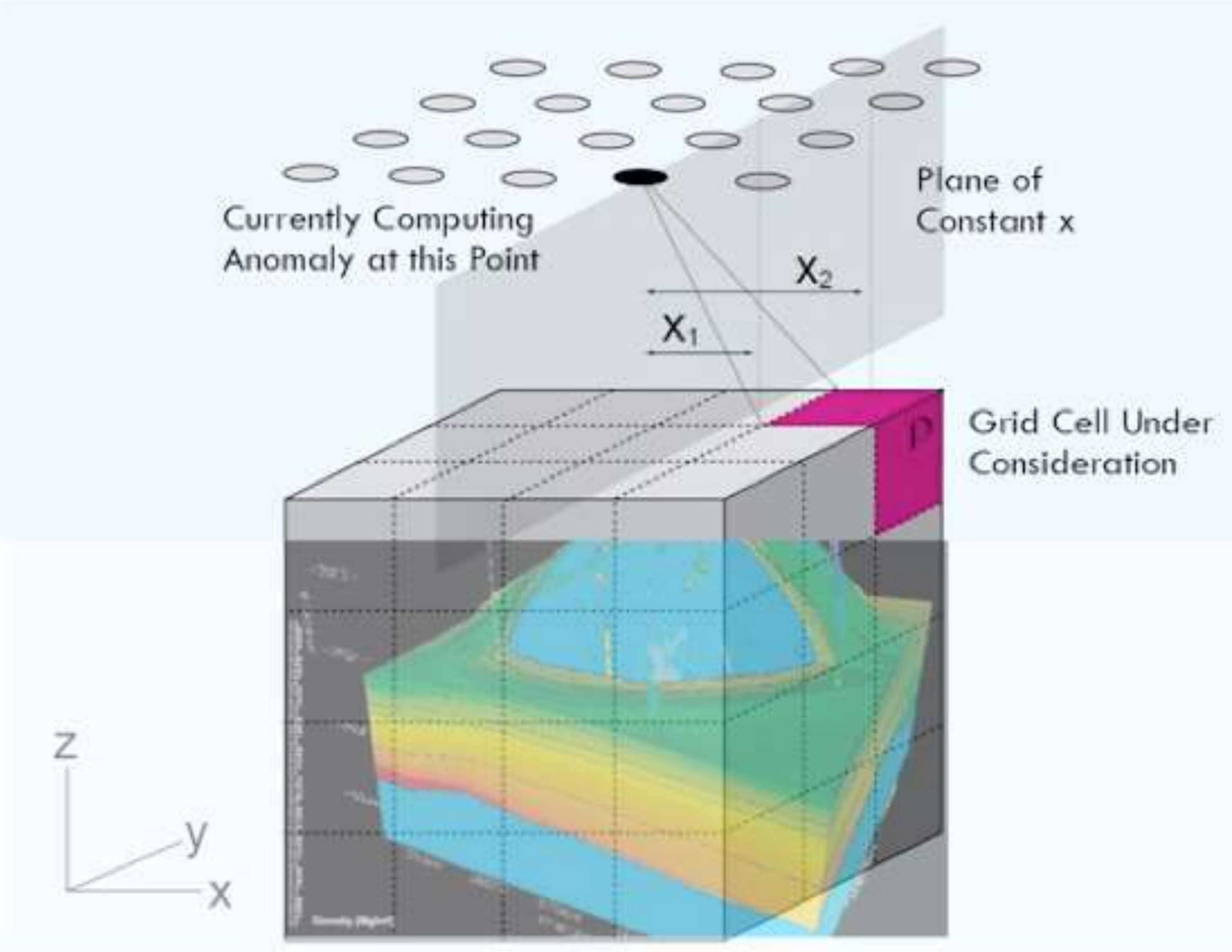

46
44
42
40
38
36
34
32
30
28
m
2
4
6
8
10
12
m
500
400
300
200
100
0
-100
-200


measurement
predicted
reference
Gravity Gradient Txx [Eotvos]
100
50
0
-50
-100
-150
-200
-250
-300
-6
-4
-2
0
2
4
6
8
10
12
distance from outer wall [m]

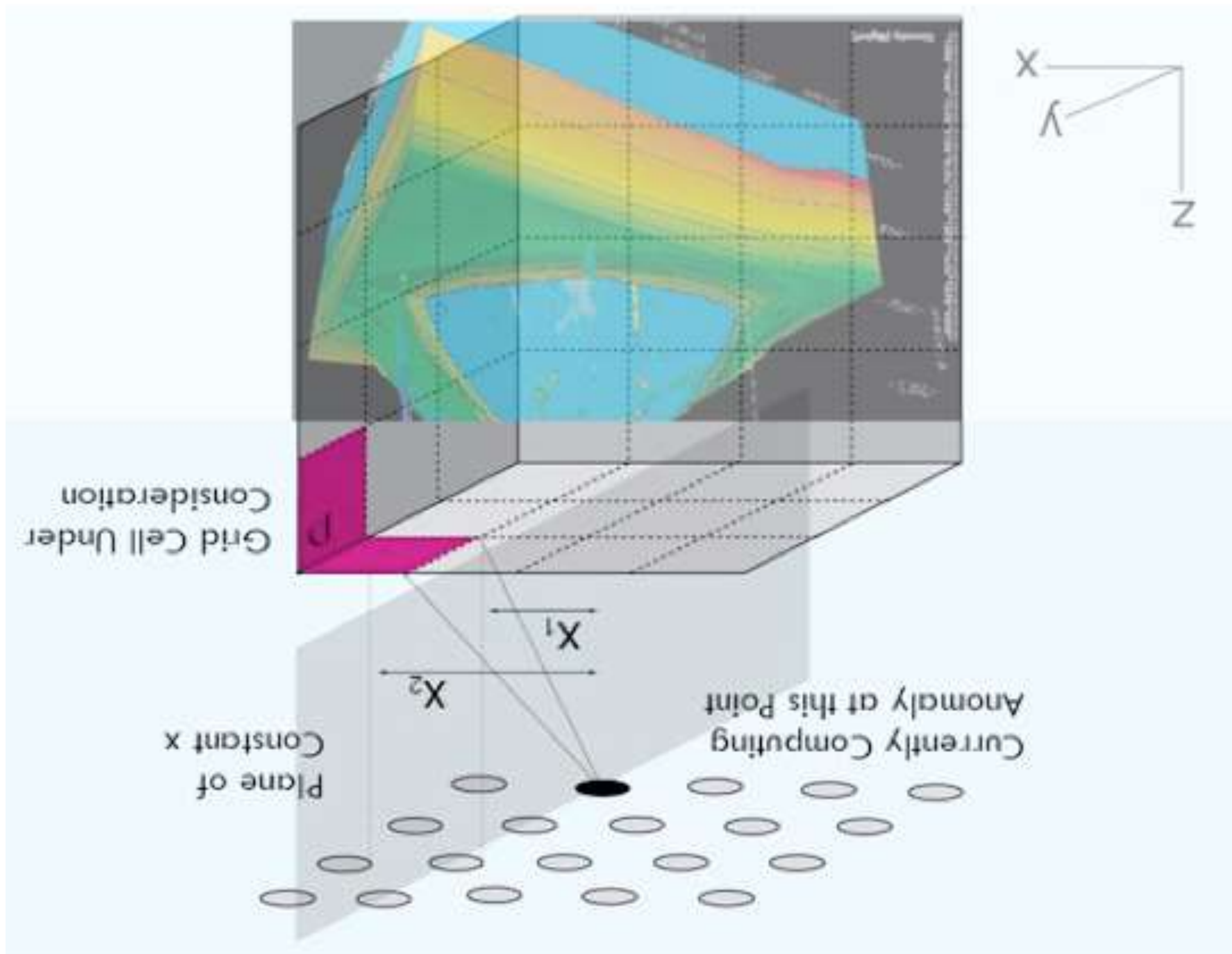


ONERA
THE FRENCH AEROSPACE LAB

GOING UNDERGROUND



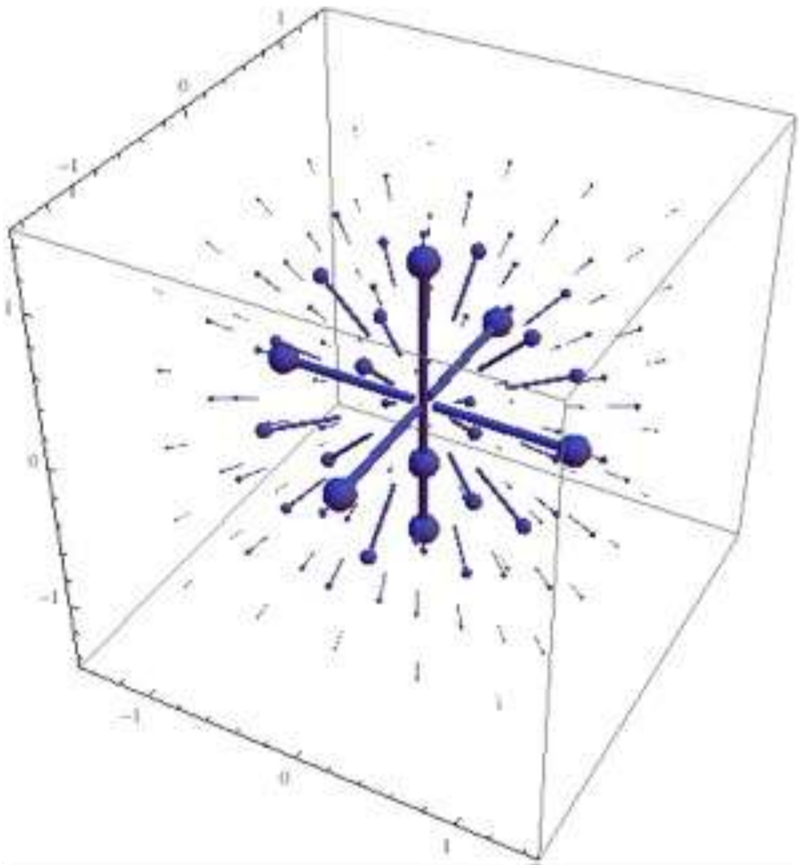
UNDERGROUND ARRAY OF DETECTORS



- Underground gravity monitoring can provide informations about seisms, water transfer in rocks, gradient noise ...

  - Underground laboratories are very quiet : improved performance limits on AI sensors.

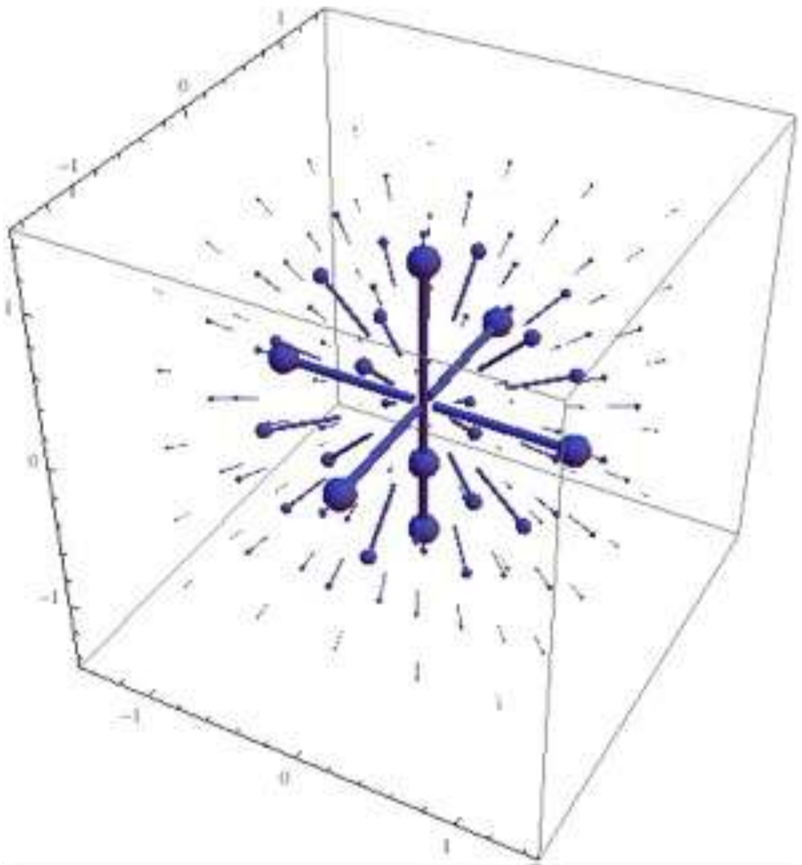
point source of gravity

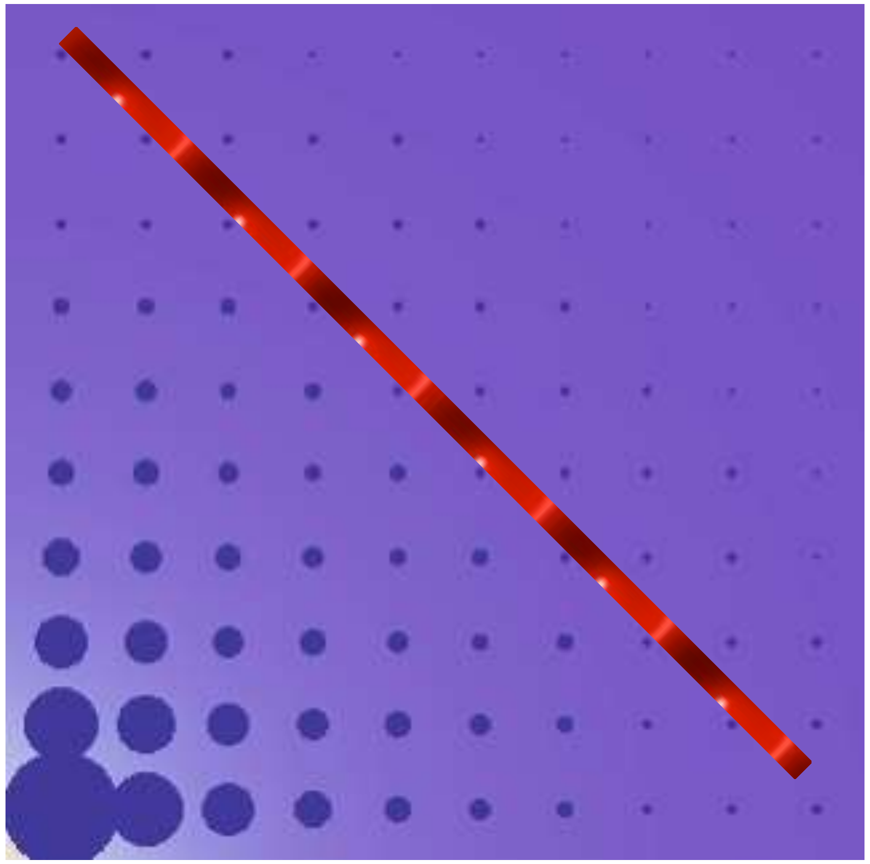


$$\boxed{\mathbf{g}(\mathbf{r}) = -G\frac{m_1}{|\mathbf{r}|^2}\hat{\mathbf{r}}}$$

WHAT CAN WE SEE ...

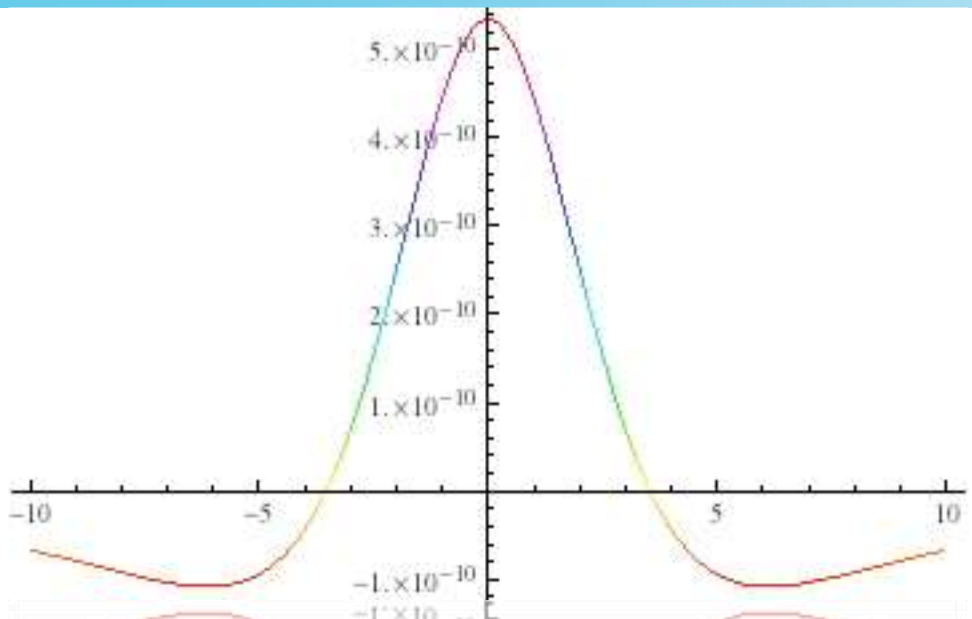
point source of gravity



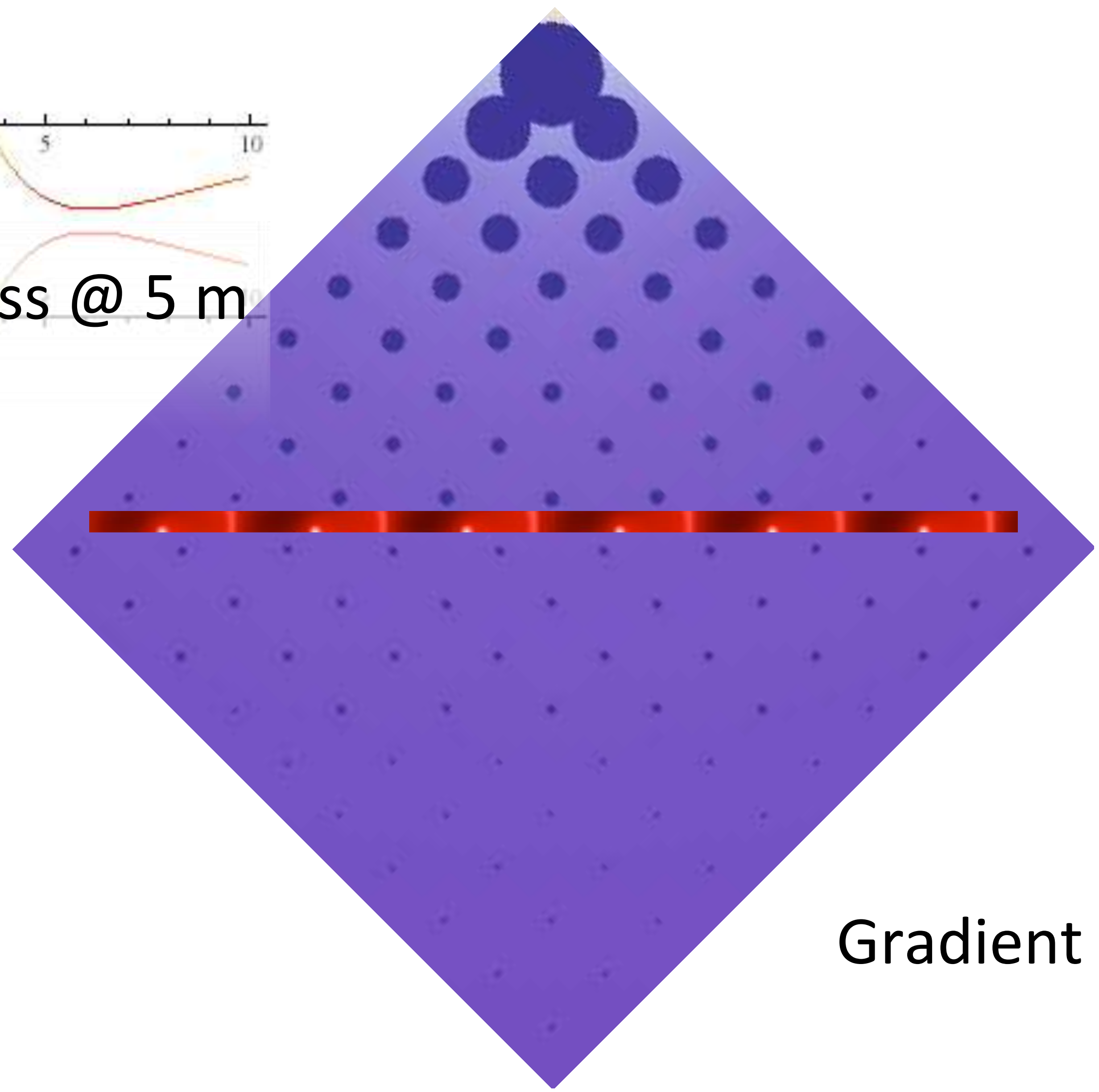


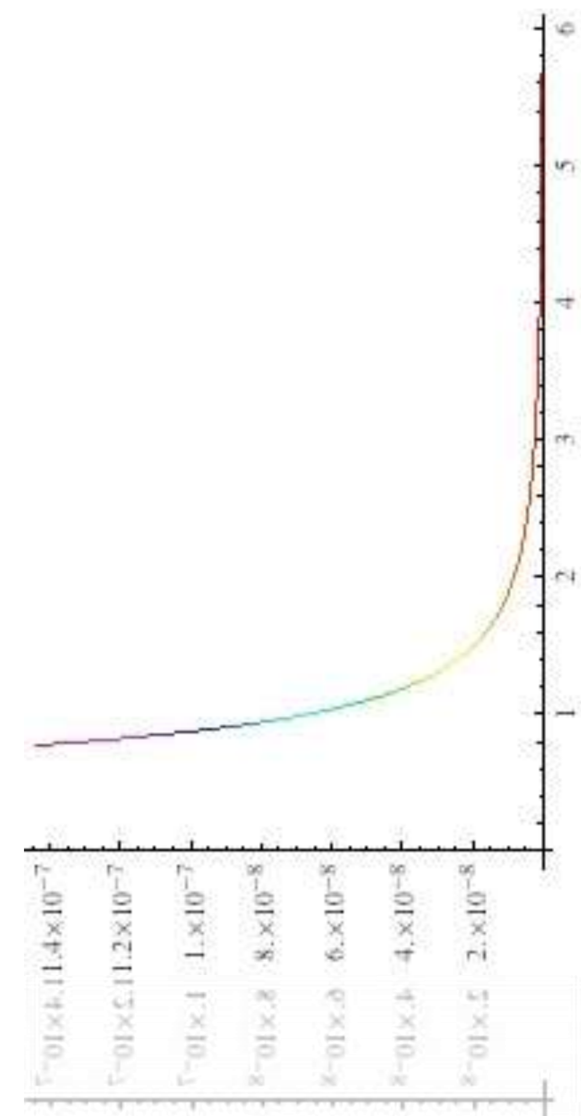
$$\mathbf{g}(\mathbf{r}) = -G\frac{m_1}{|\mathbf{r}|^2}\hat{\mathbf{r}}$$

What can we see ...



Gradient for a 1t mass @ 5 m





Gradient for a 1t mass

SURVEYING THE WATER TRANSIT IN MOUNTAIN

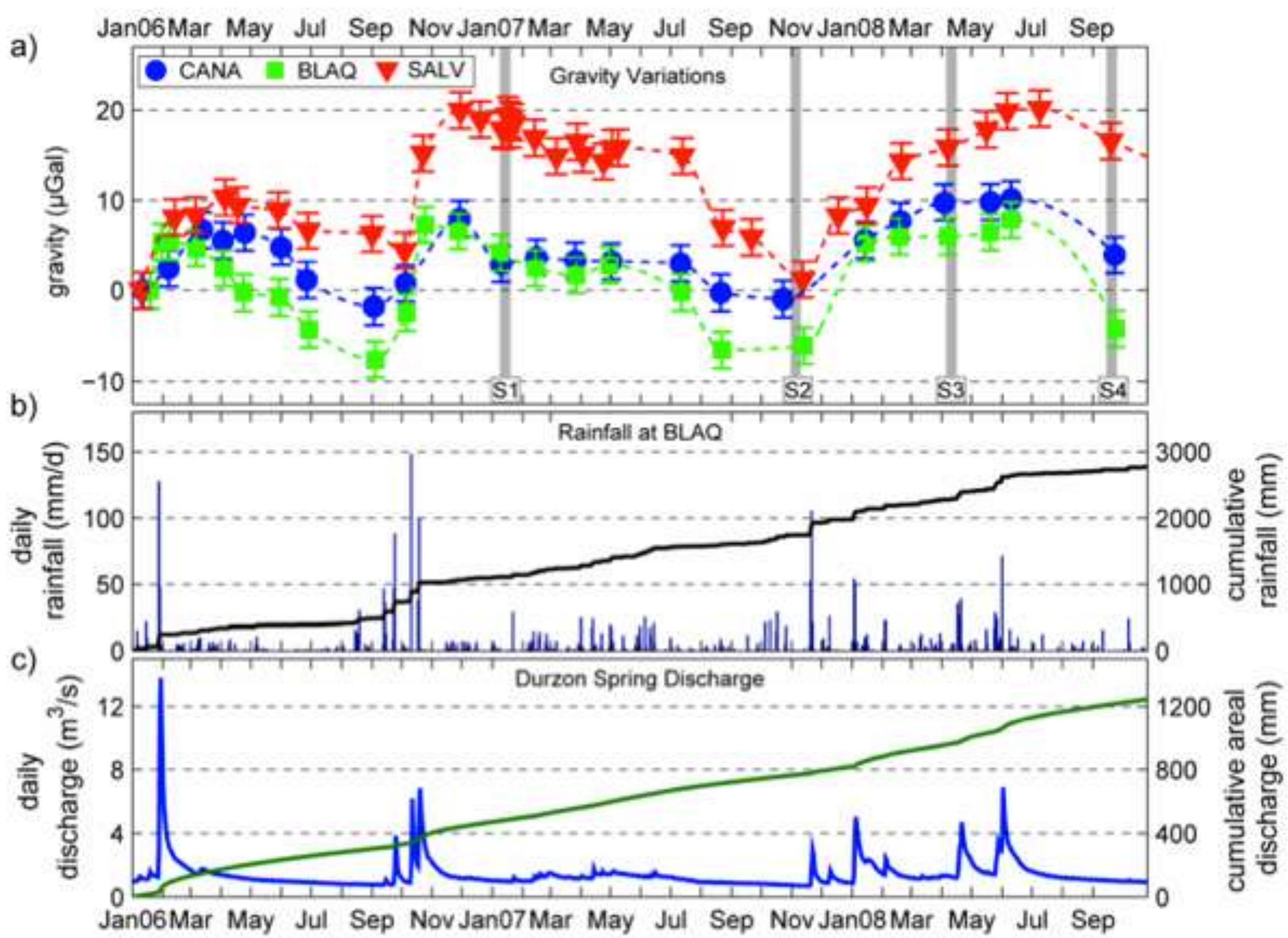
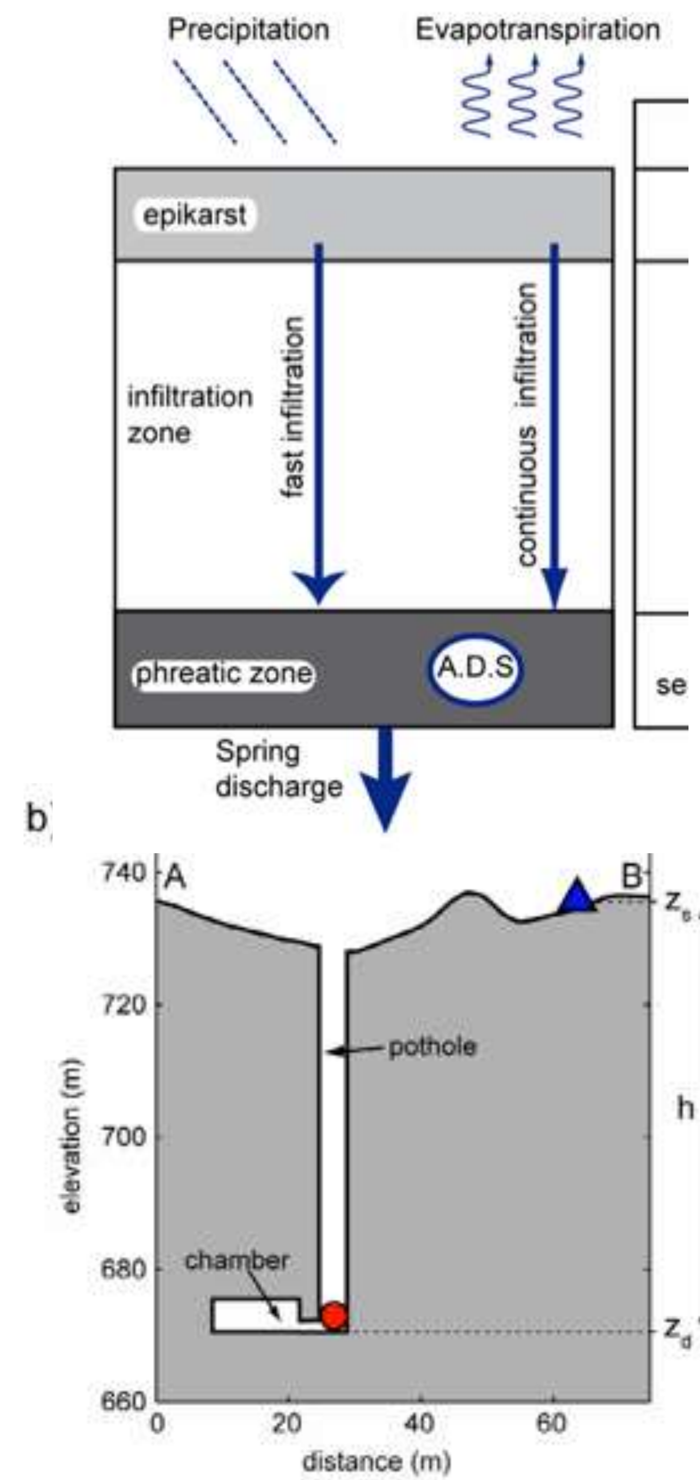
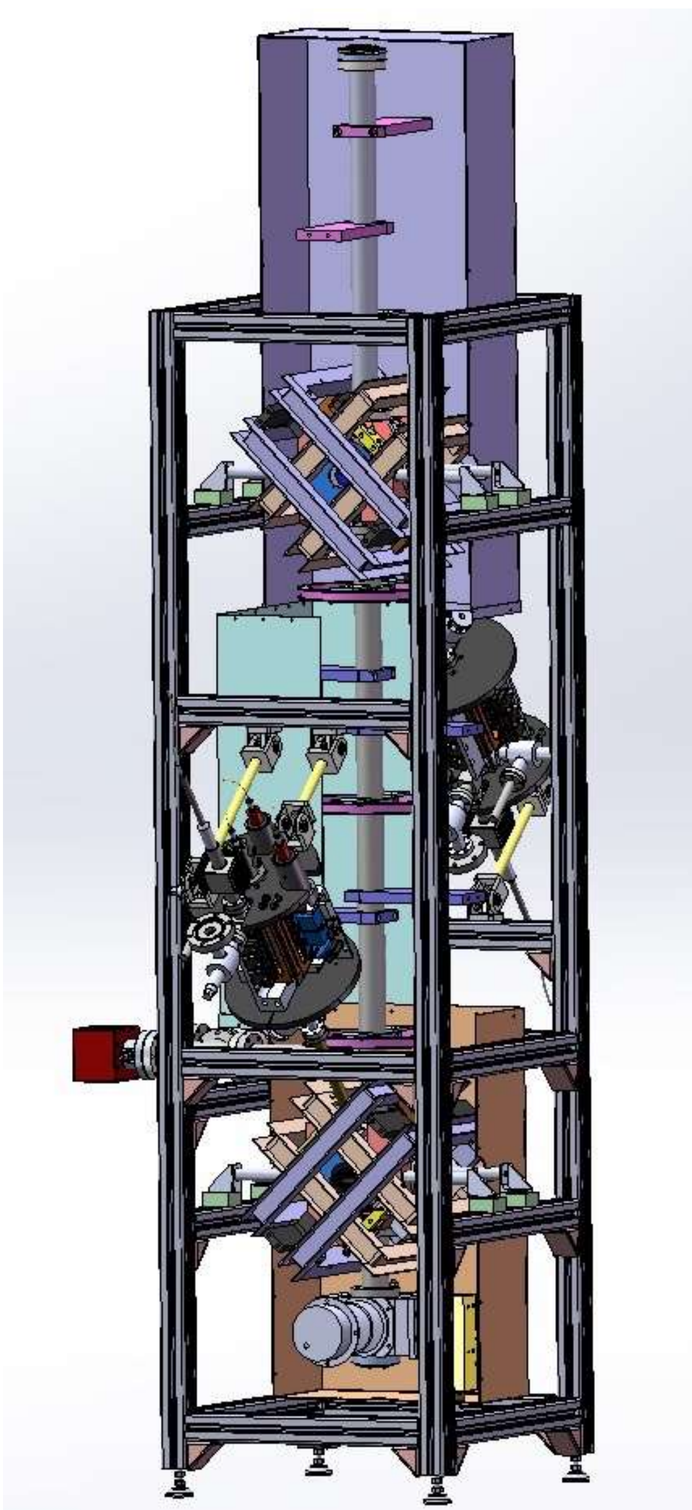
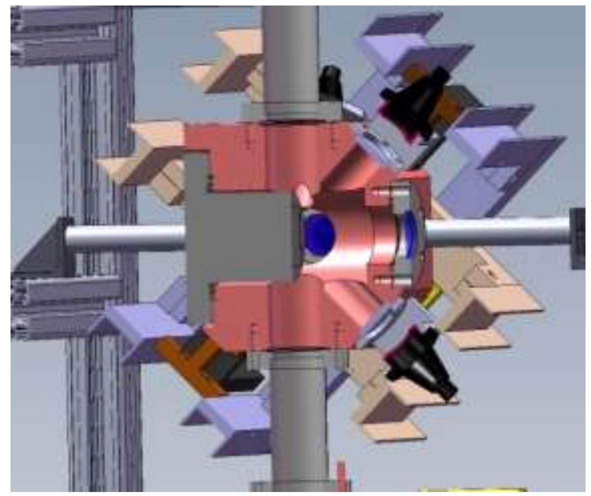


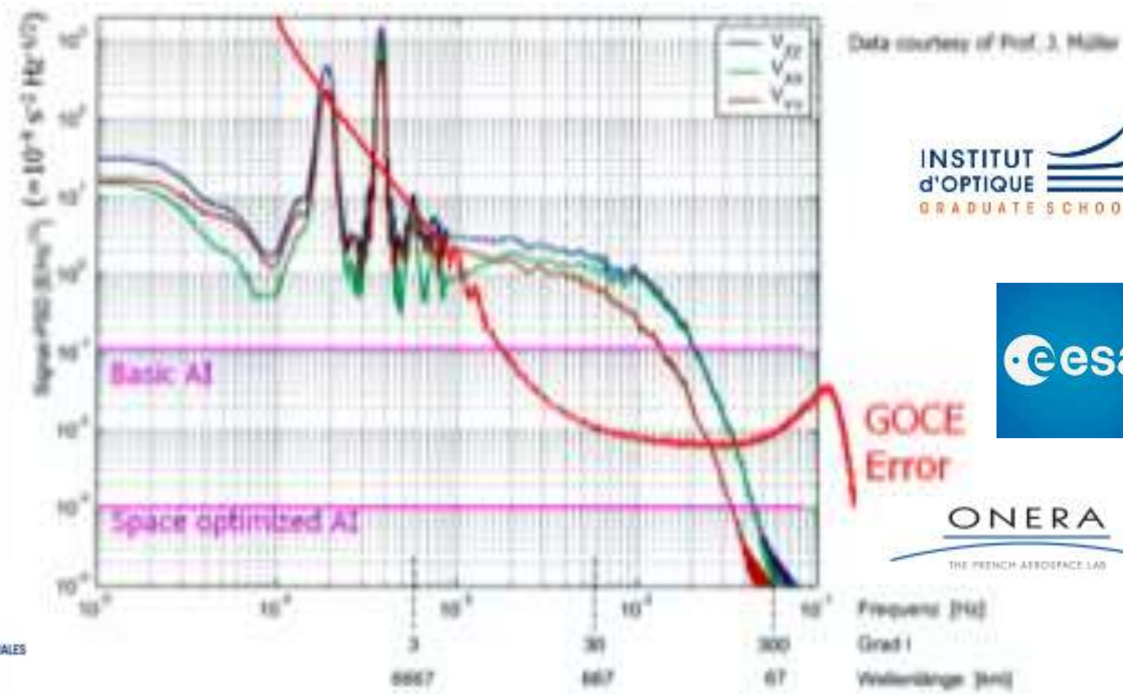
Figure 7.2 : a) Absolute gravity variations at site CANA, BLAQ and SALV, corrected for regional hydrology (see text for explanations). Survey periods S1 to S4 are indicated by vertical grey bars. b) Daily and cumulative rainfall measured at BLAQ, c) Daily Durzon spring discharge (blue line) and cumulative areal discharge (green line).



APPLICATIONS TO GEODESY

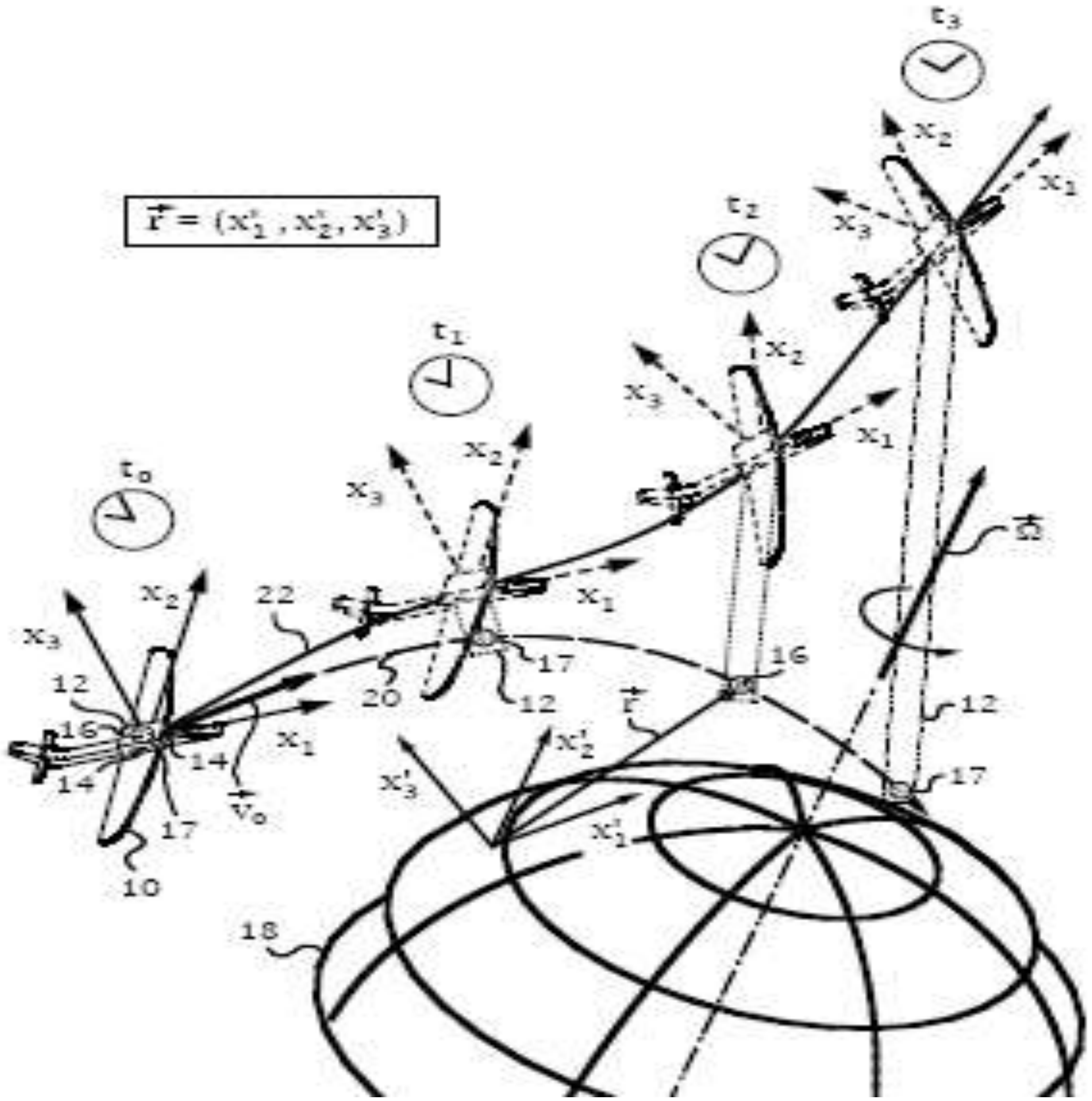






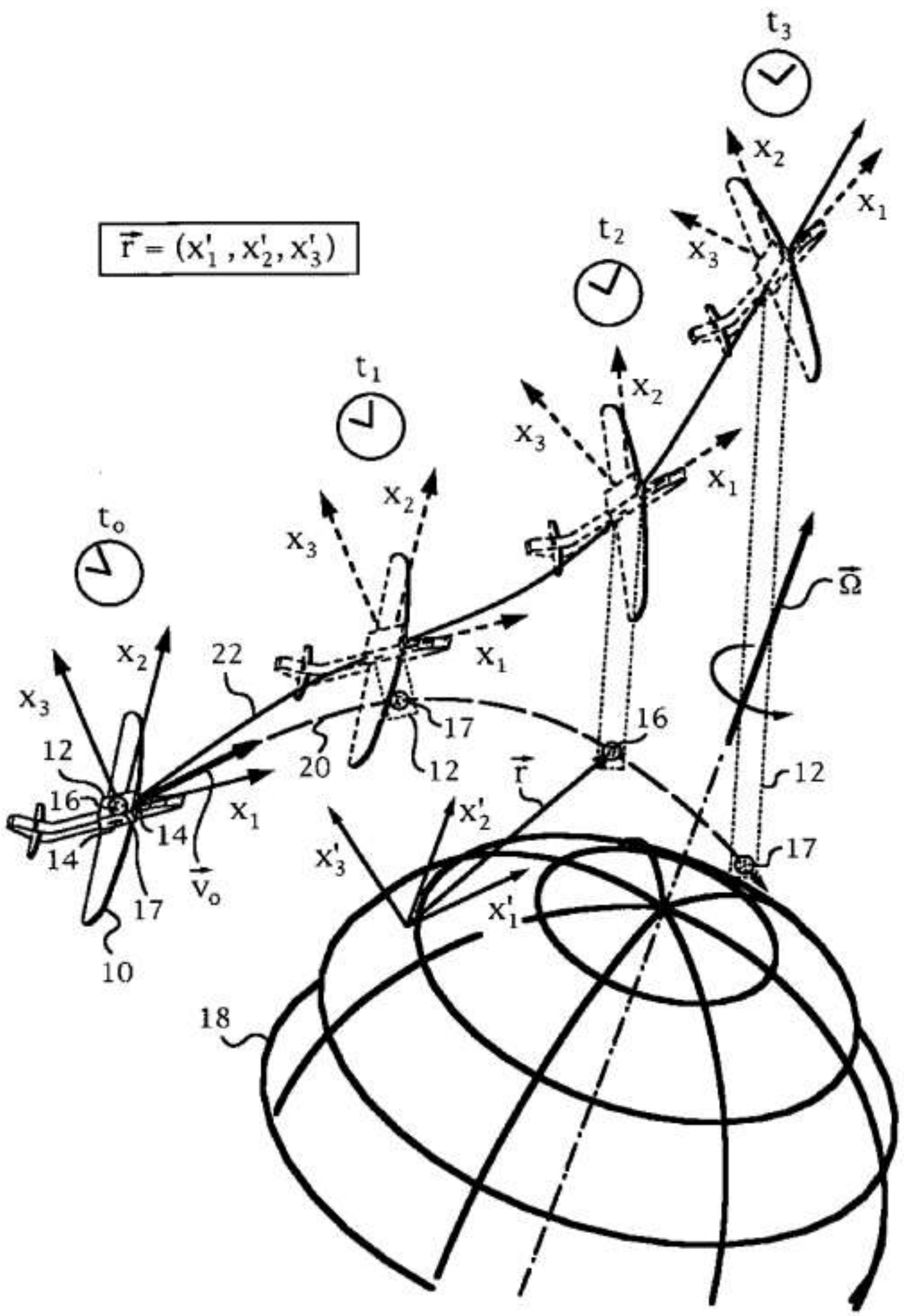
Concept 1	Concept 2
Single satellite (GOCE-like) using Mach-Zehnder interferometry, 3-axis	Multiple ultra-compact satellites, size of approximately one soda bottle each
• Conceivable sensitivity: 10^{-12} ms^{-2} @ T=10 s, SNR=1000:1 (improved sensitivity possible...)	• Conceivable sensitivity: 10^{-12} ms^{-2} @ T=10 s, SNR=1000:1 (improved sensitivity possible...)
100 to 1 mE Hz$^{-1/2}$ level @ baseline=1m	1 µE Hz$^{-1/2}$ level @ baseline=1km probably limited by mission complexity
Technology already demonstrated outside of lab environment, possible to measure complete gravity gradient tensor plus absolute value	Possible to measure complete gravity gradient tensor plus absolute value at very high sensitivity
• No calibration problems, no drag free needed	• No calibration problems, dragg free or high sensitivity standard accelerometers

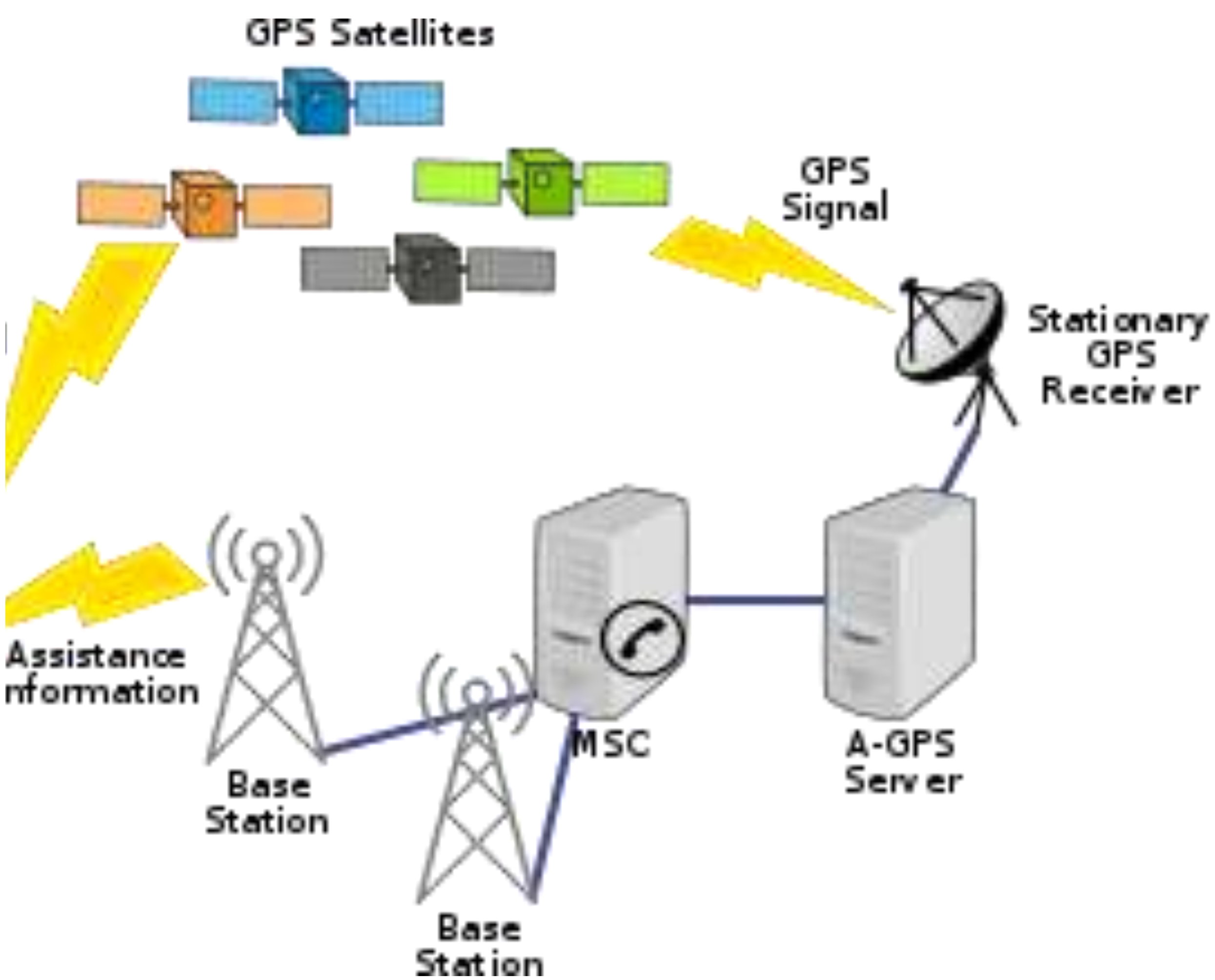
Navigation

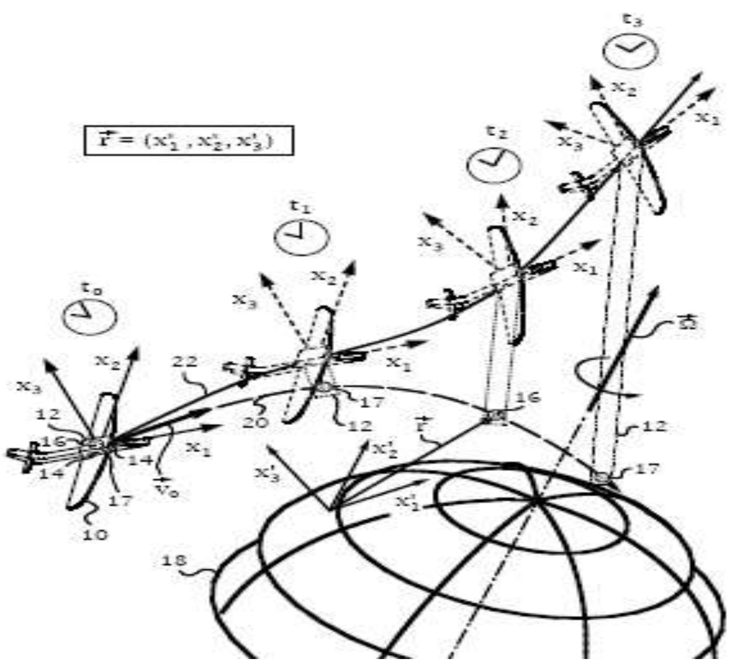


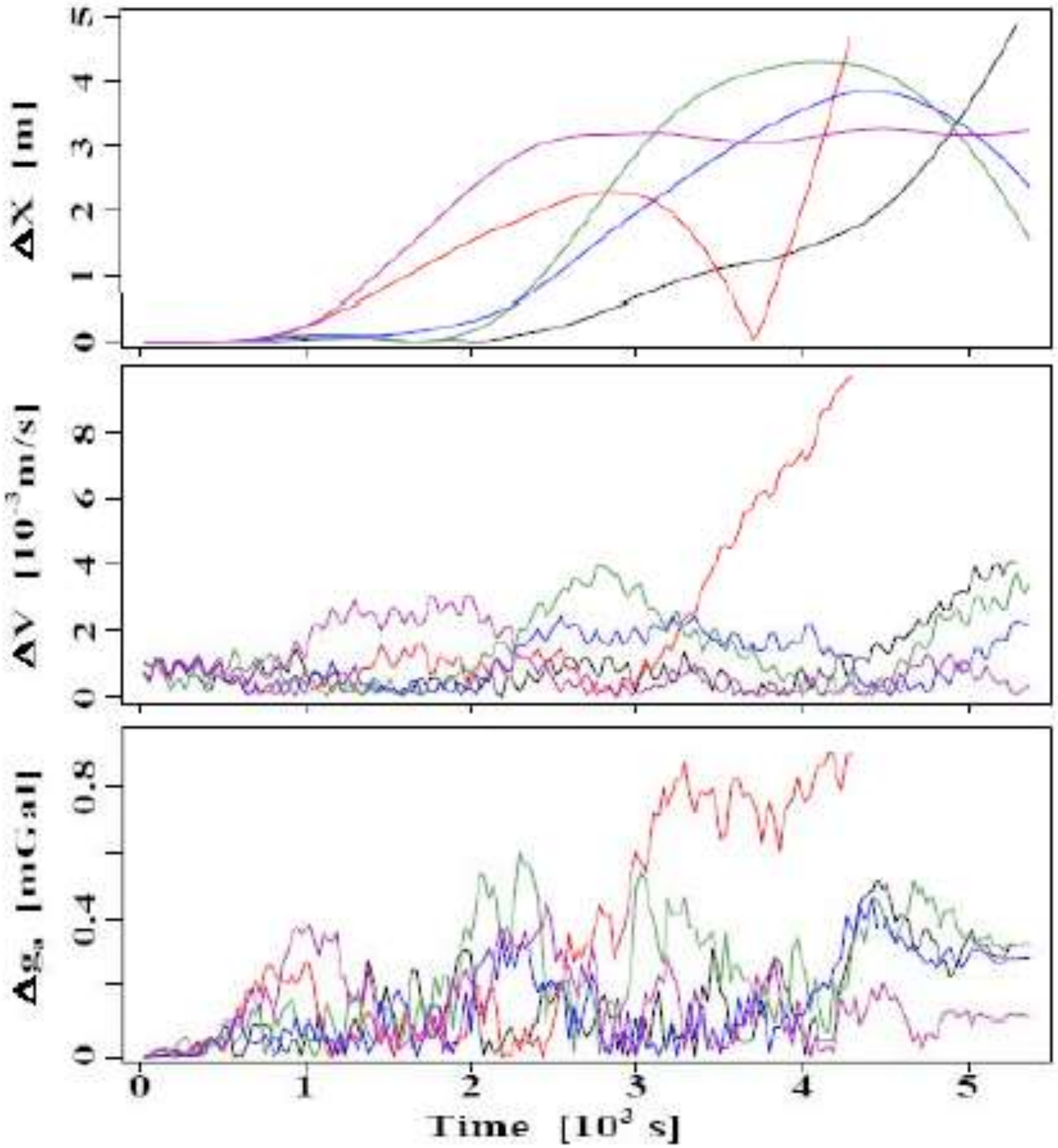
Navigation system

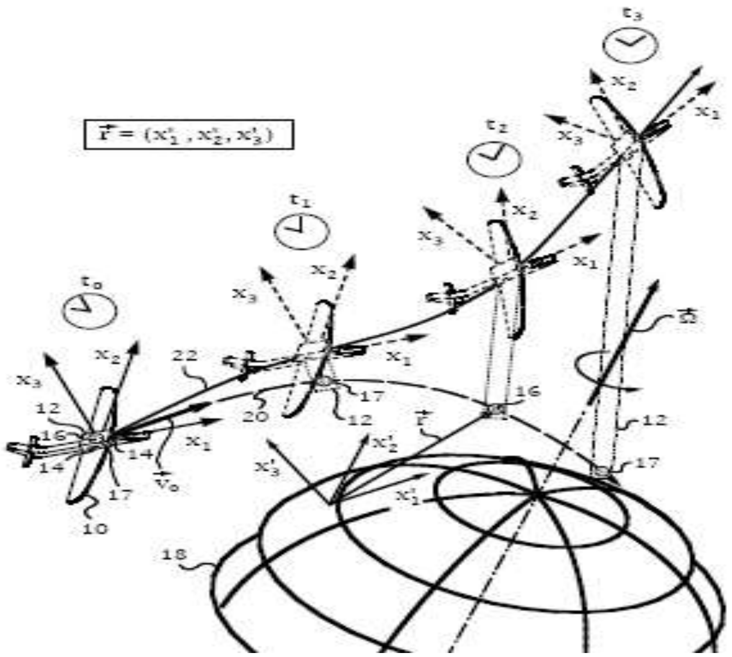
- Radionavigation
- On sight radio beacons (GPS, VOR, …)

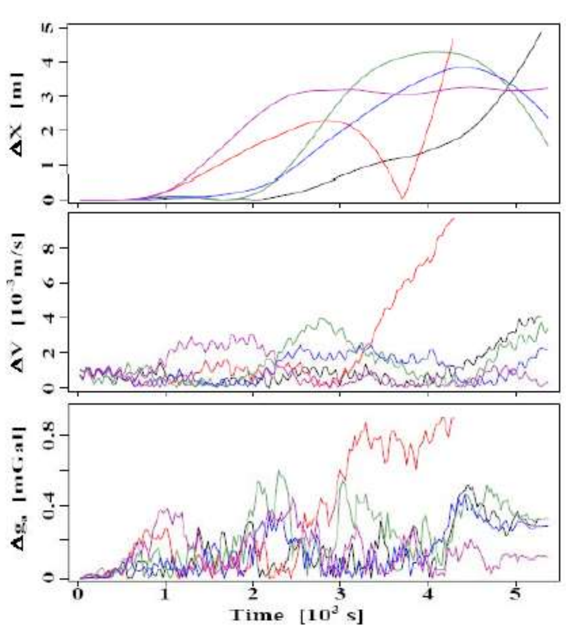




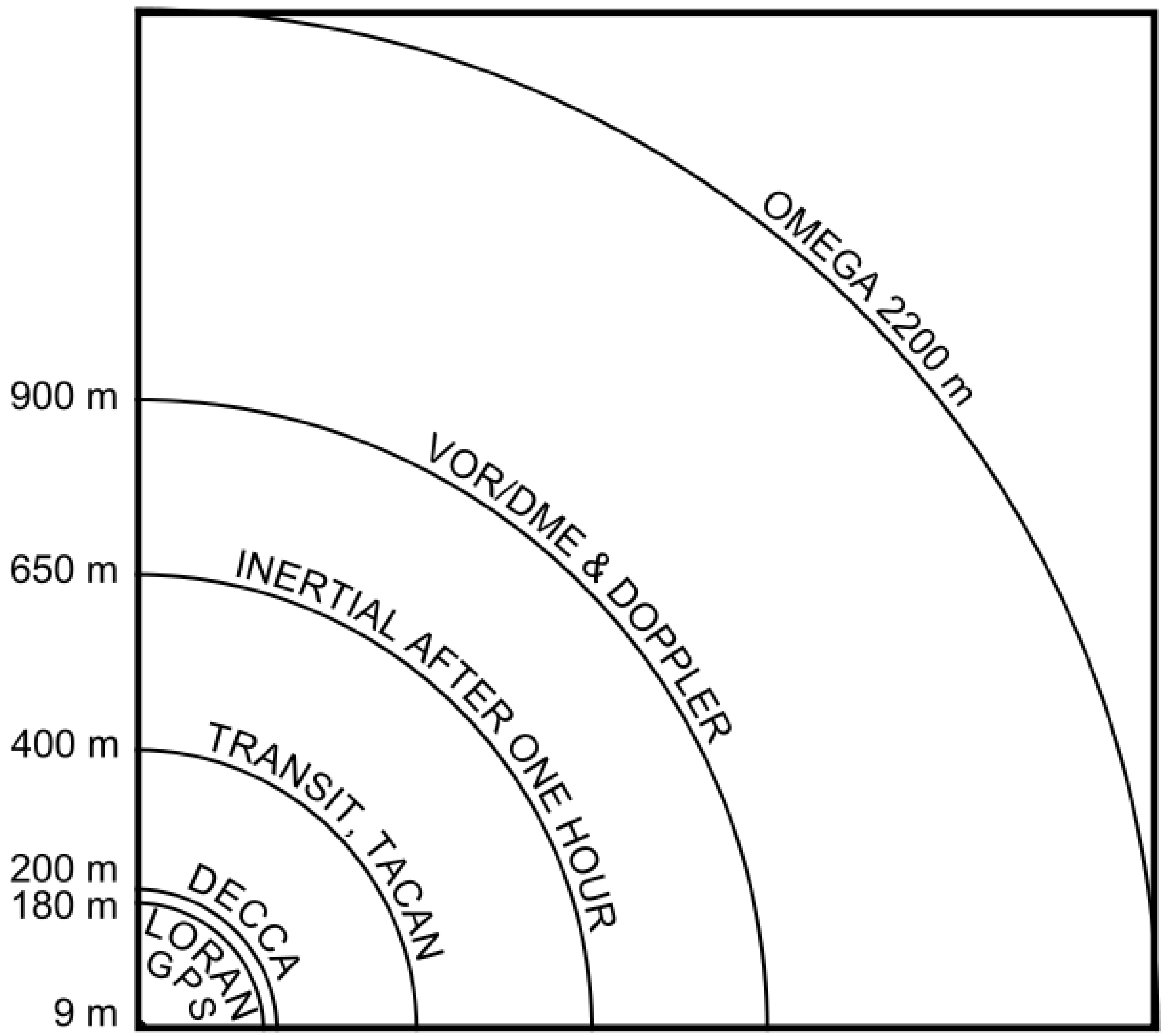

r' = (x'1, x'2, x'3)
t0
t1
t2
t3


ΔX [m]
ΔV [10⁻³ m/s]
Δg_a [mGal]
Time [10³ s]



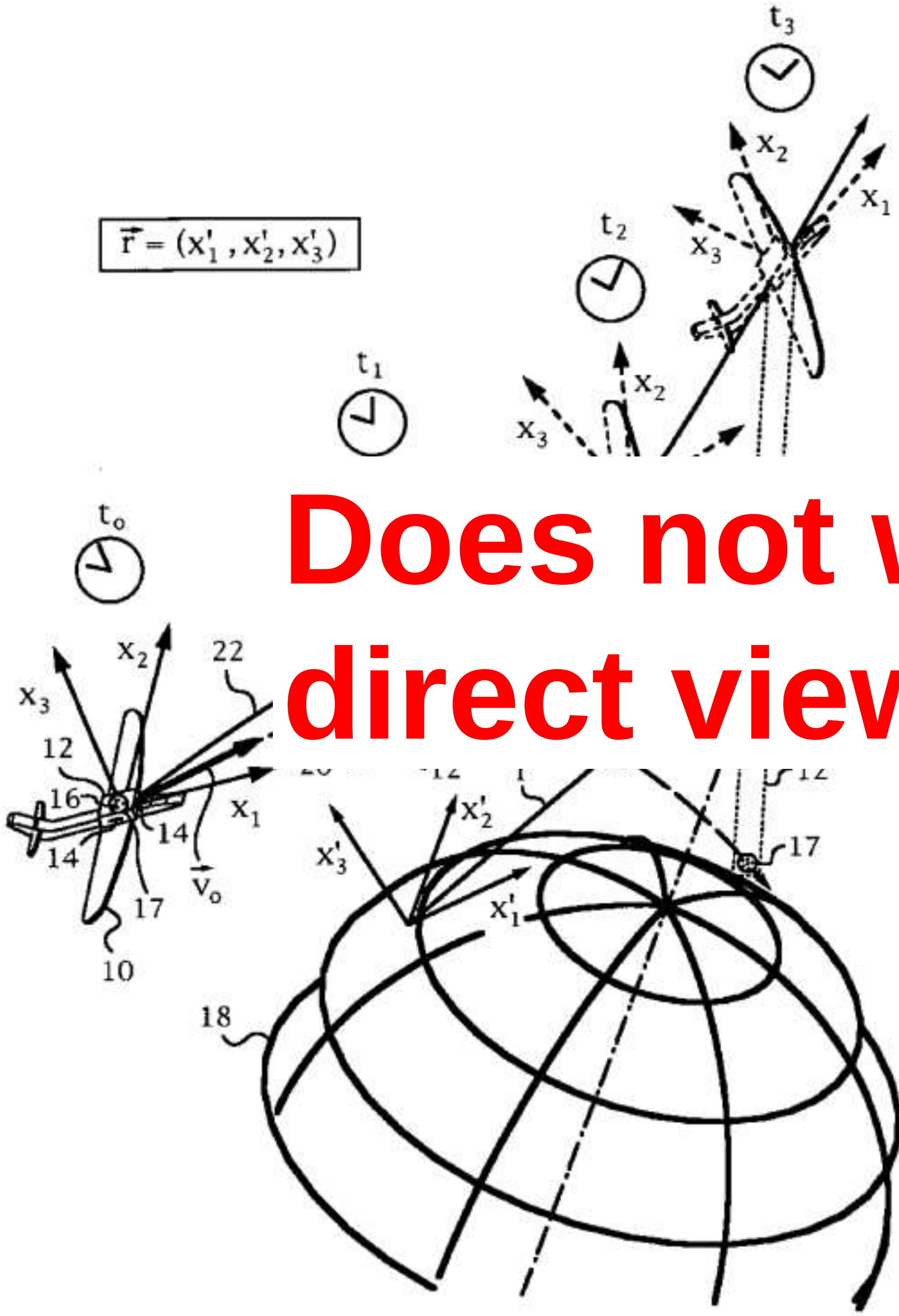


ACCURACY OF NAVIGATION SYSTEMS
(2-dimensional)

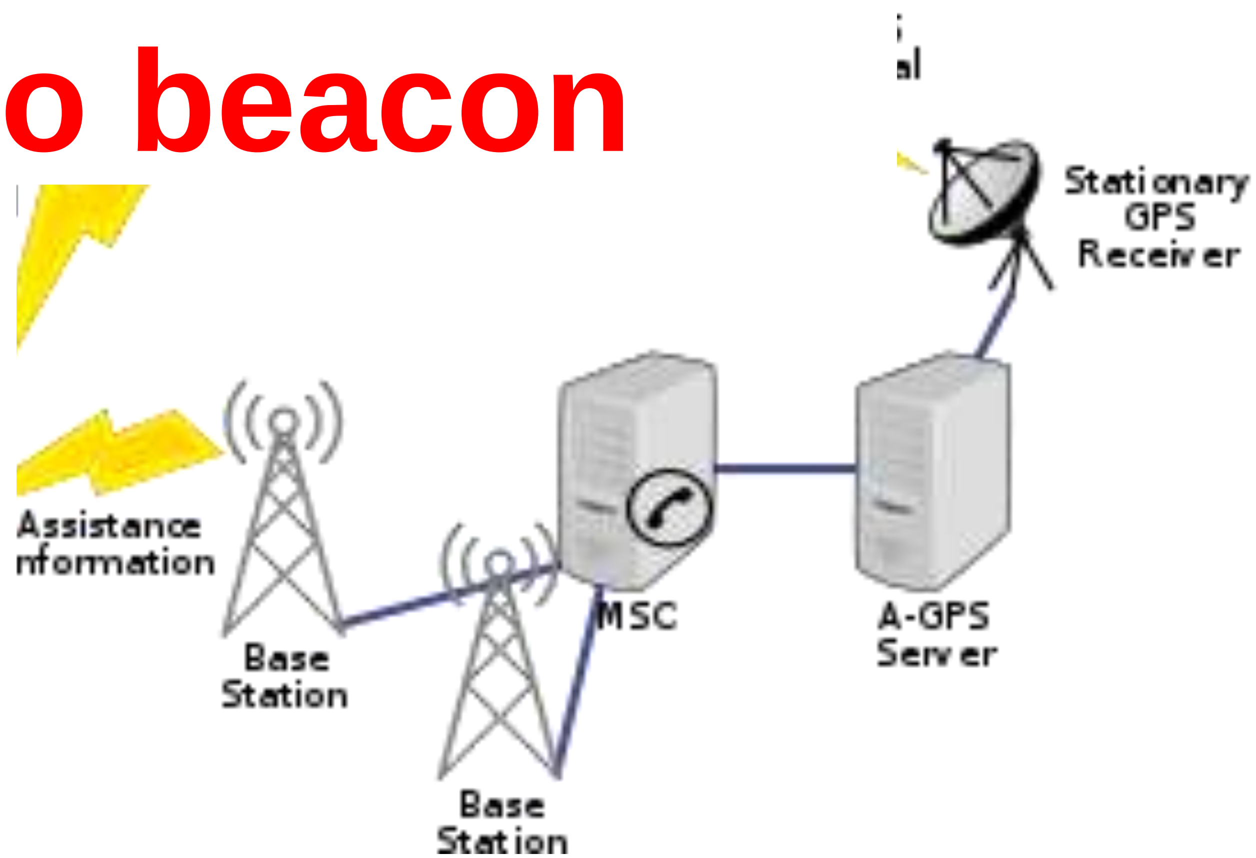


Navigation system

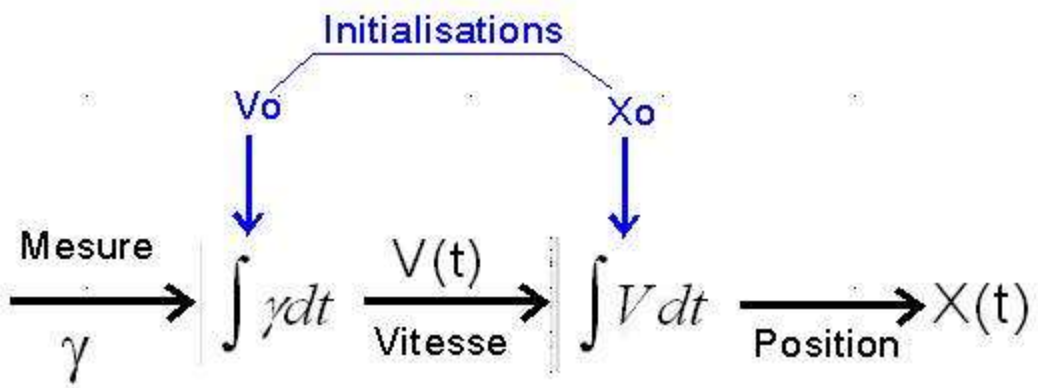
- Radionavigation
- On sight radio beacons (GPS, VOR, …)

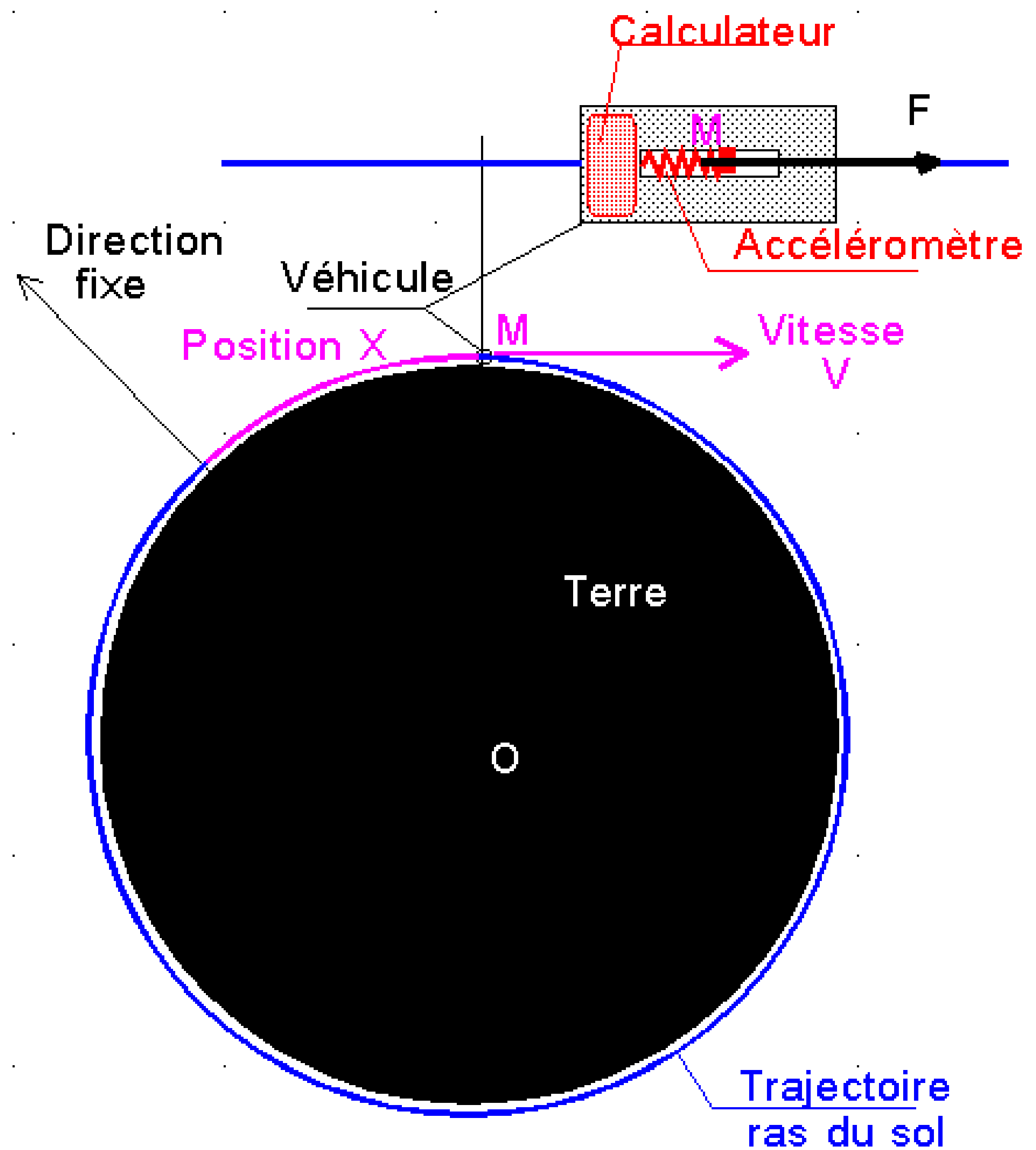


Does not work without direct view to beacon



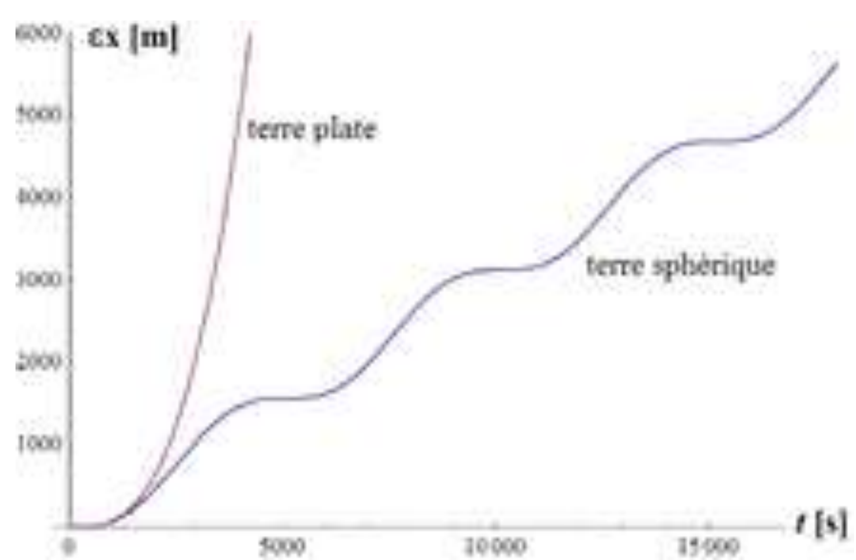
- Uses the onboard measurement of the specific force as well as the instantaneous rotation vector.
- Measurement of acceleration (other than gravity)
- Embedded calculation integration
- Knowledge of initial conditions
- Error handling and resetting



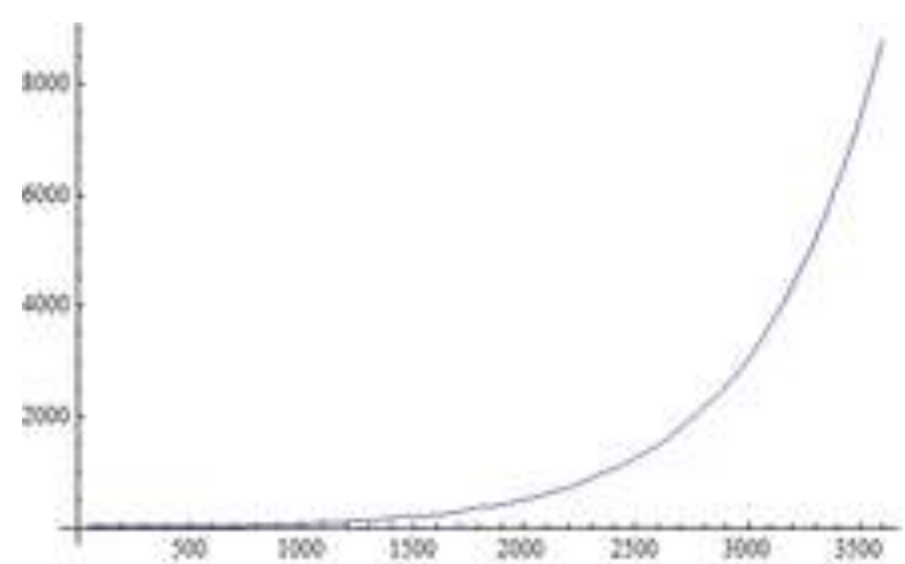


BIAS COMPENSATION

- The bias of the standard inertial sensors is non-zero and varies over time
- After integration, it leads to a position error that exponentially believes
- For a few NM/h of precision
- Knowledge of rotation bias at a few °/h (degrees per hour = µradian/s)
- Knowledge of acceleration bias of a few tens of µG



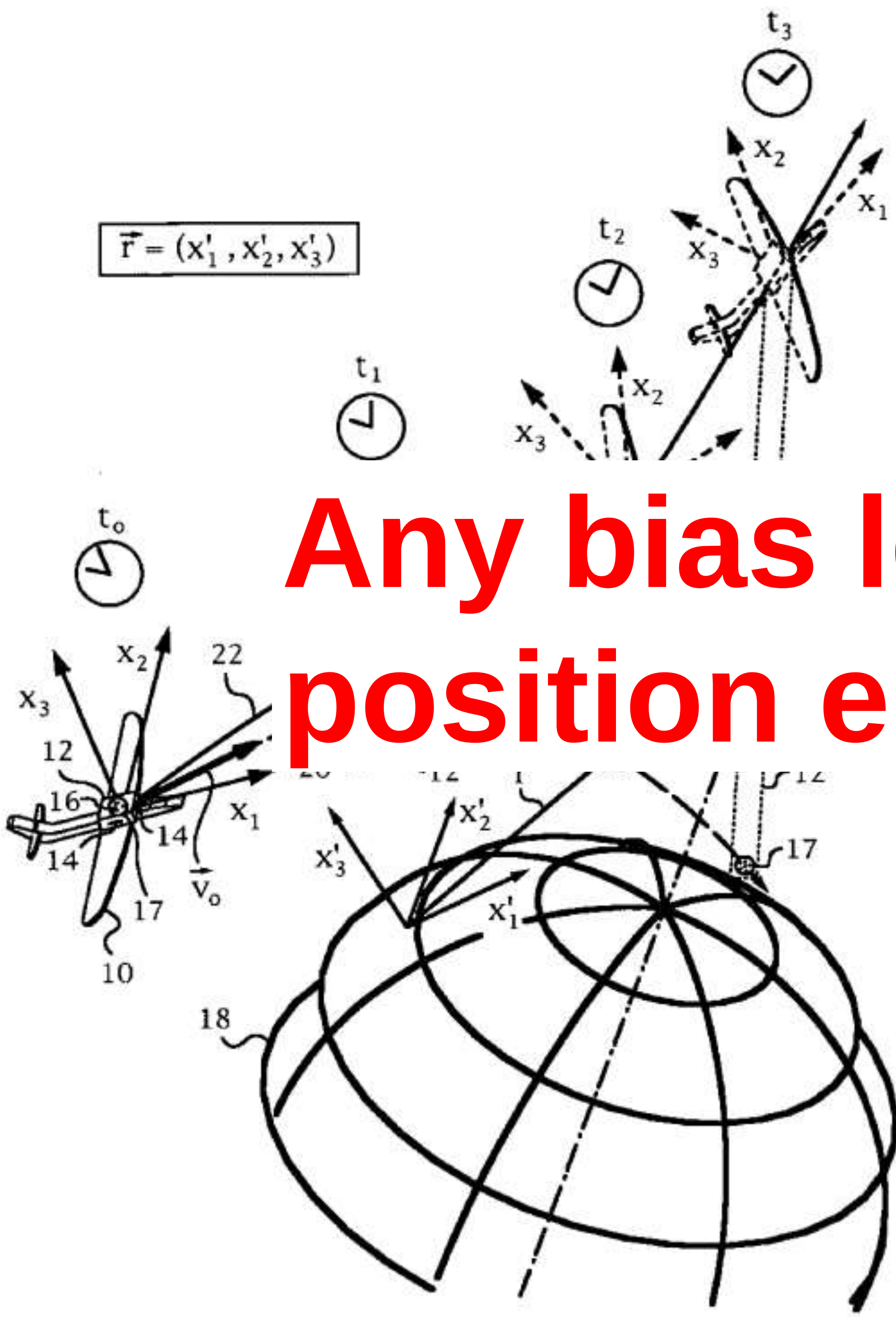
Gyromètre affecté d'un biais de 0,01 °/h



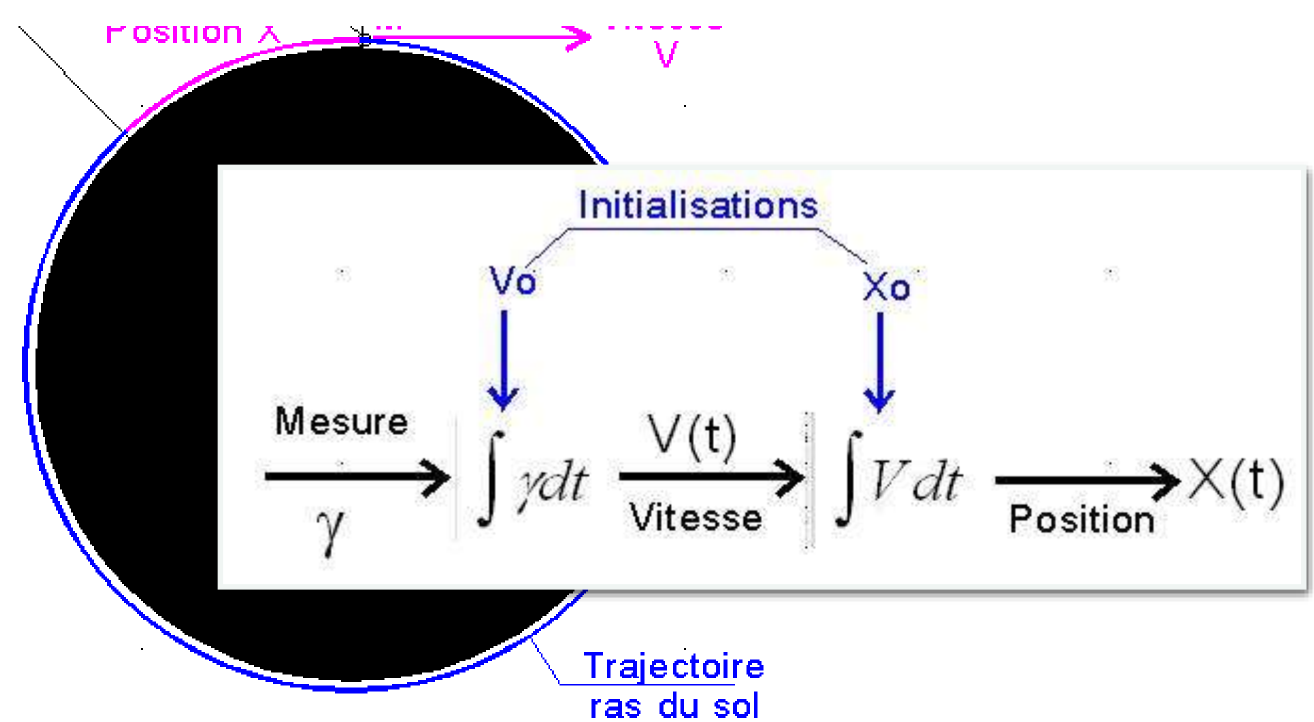
Accéléromètre affecté d'un biais de 10 µg

Navigation system

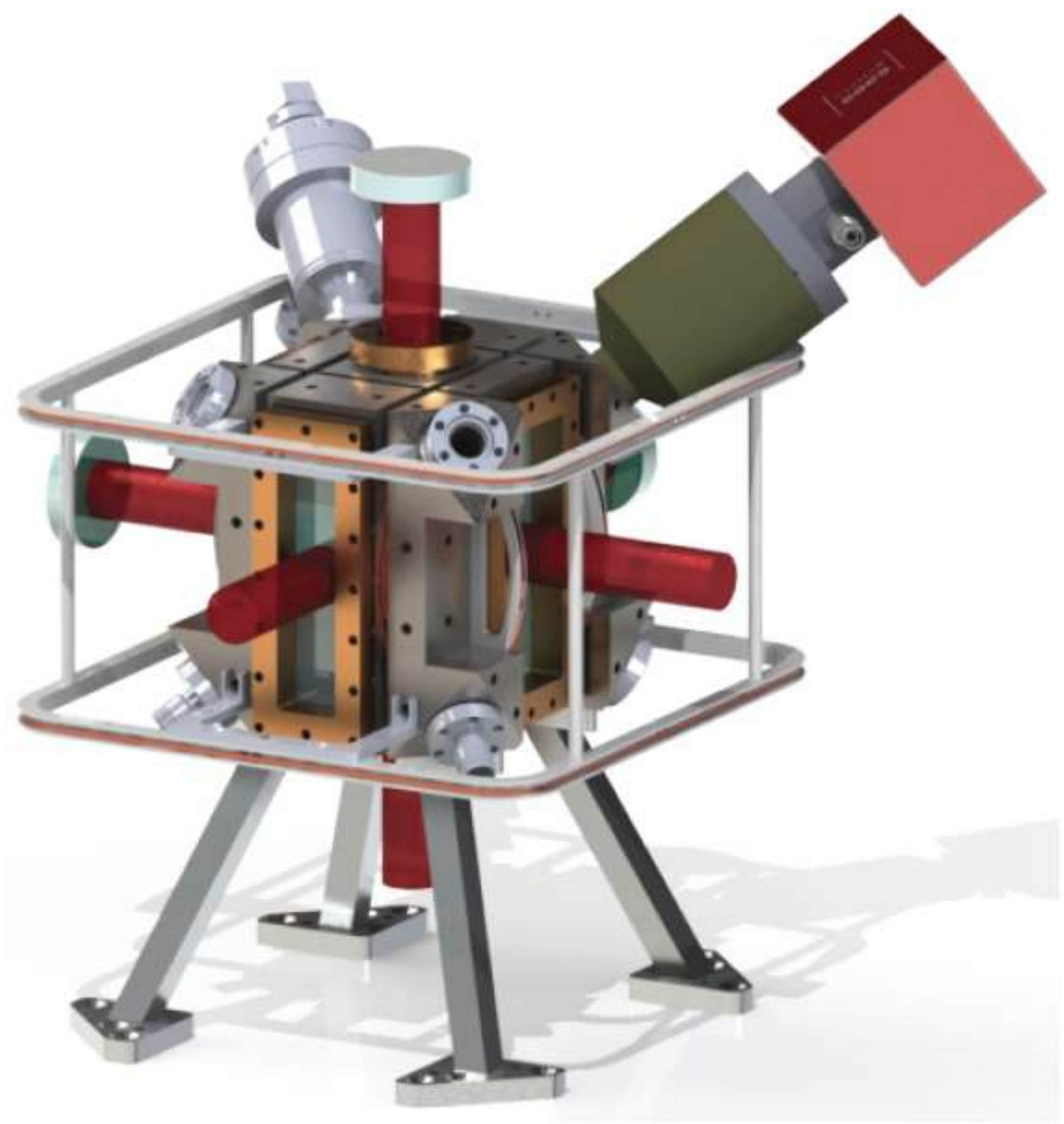
- Inertial
- Integrate acceleration and angle measurement

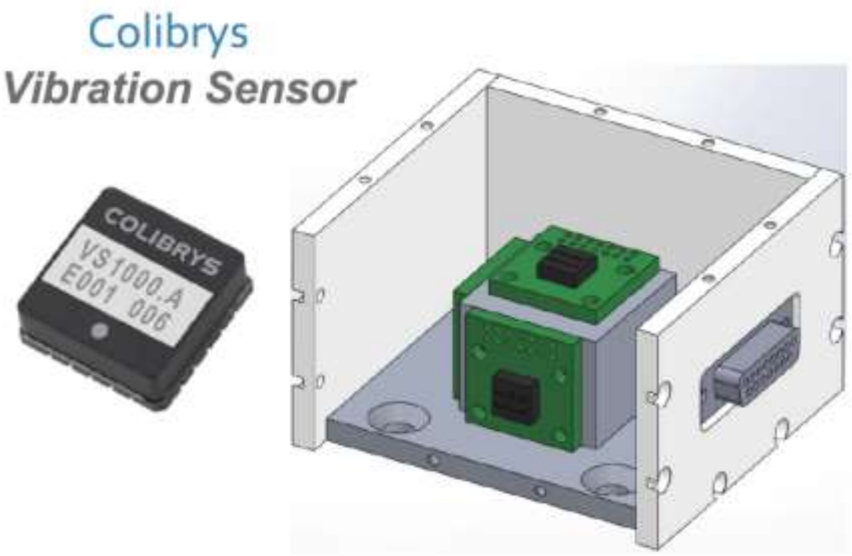


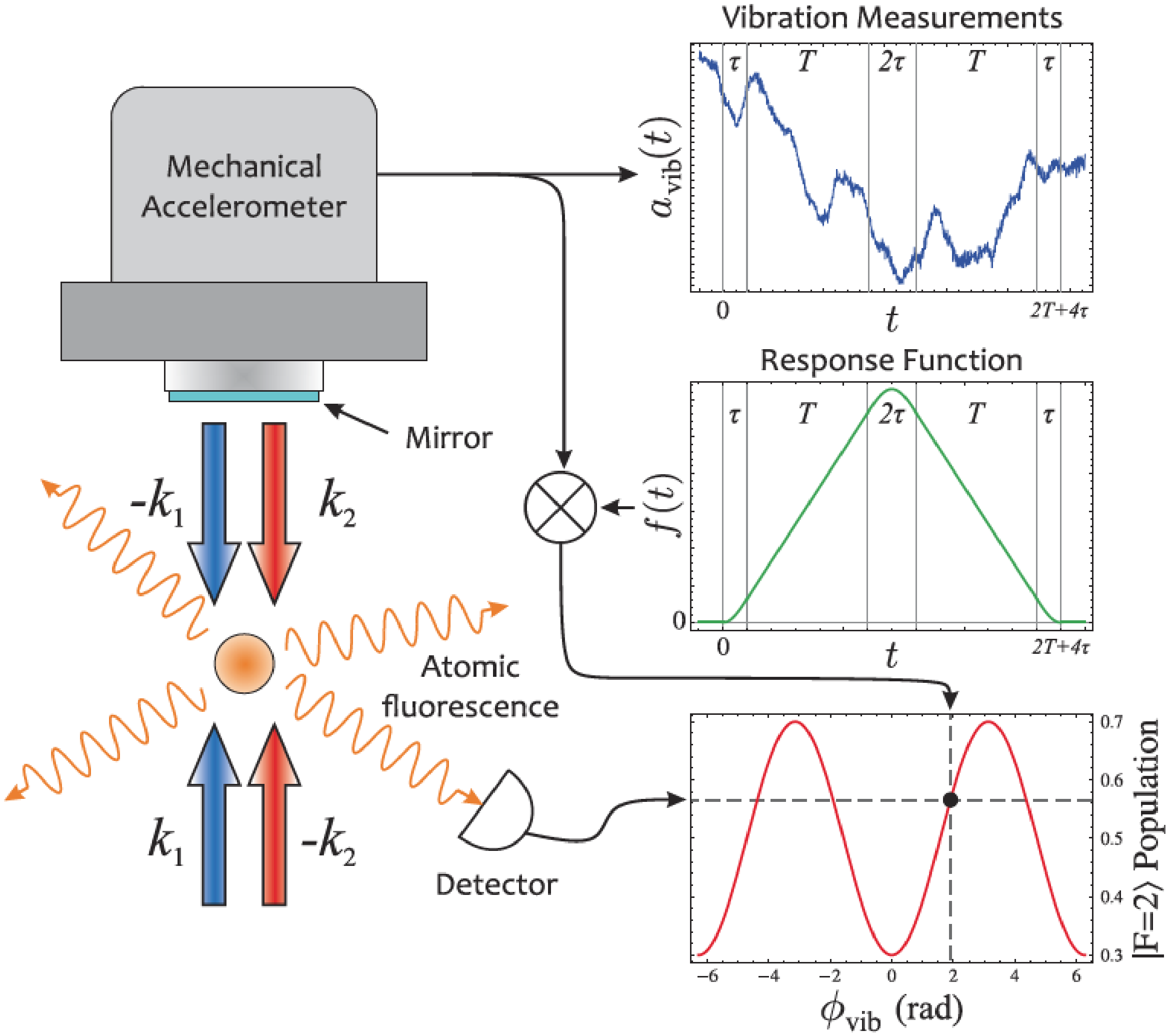
Any bias leads to large position error



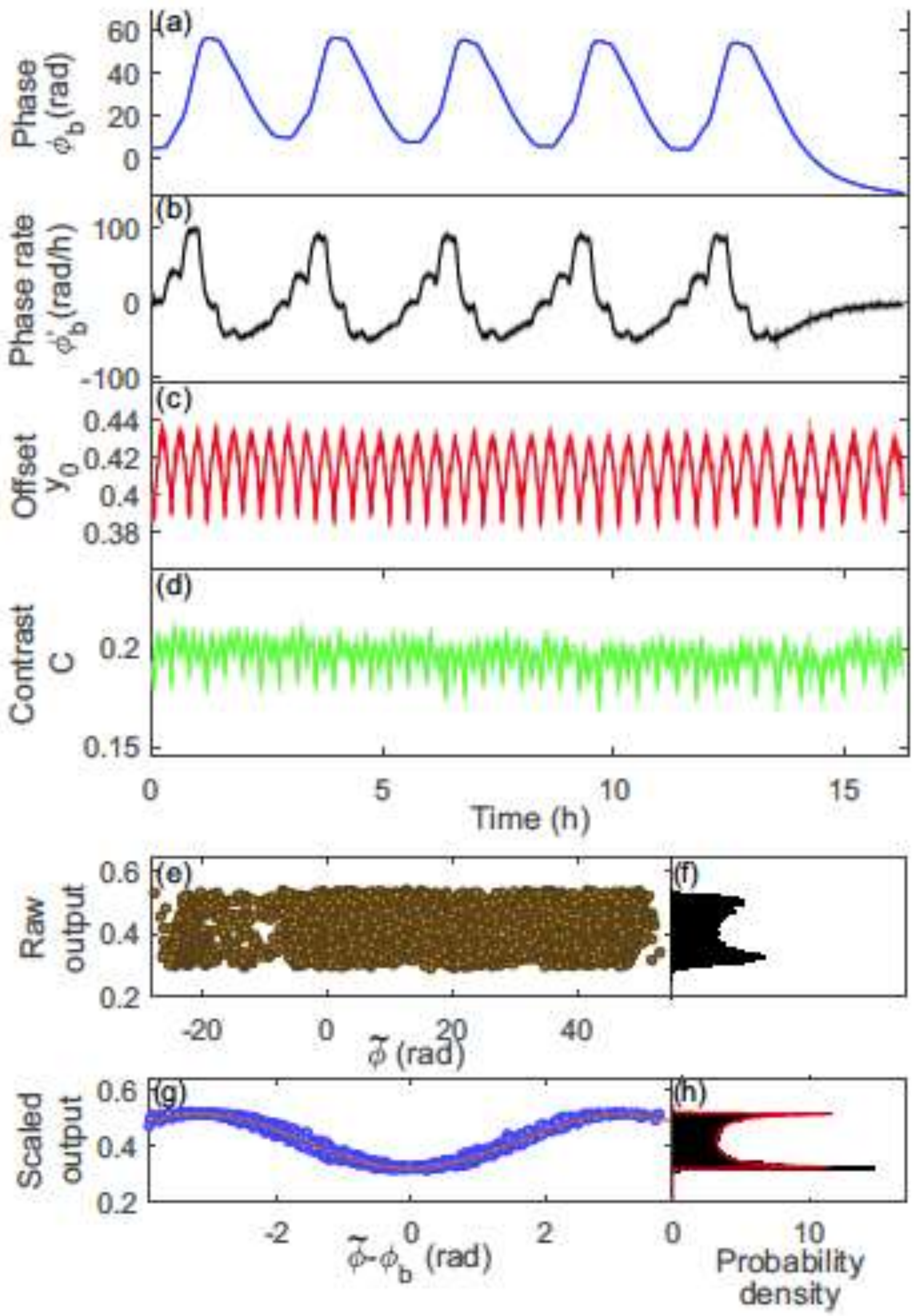
HYBRID QUANTUM SENSOR



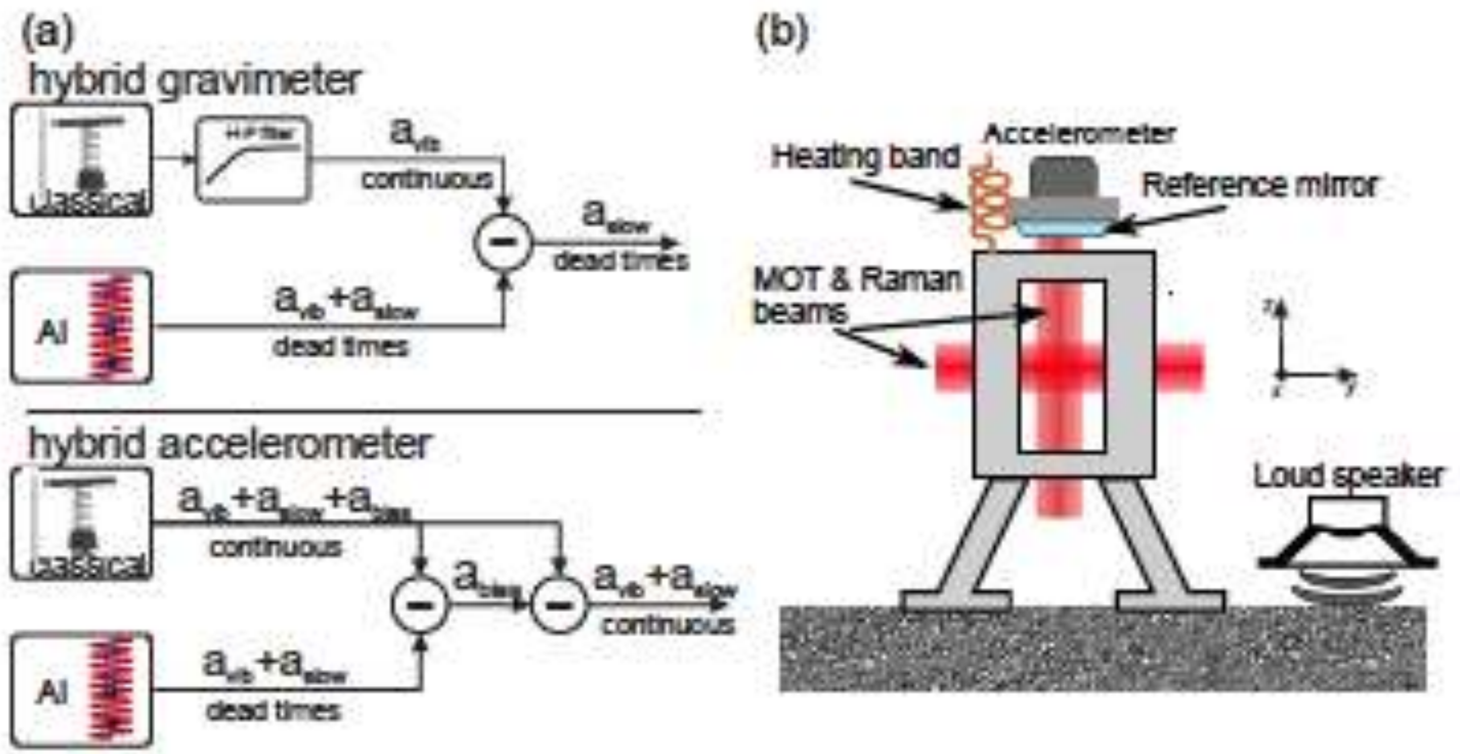




HYBRID QUANTUM SENSOR



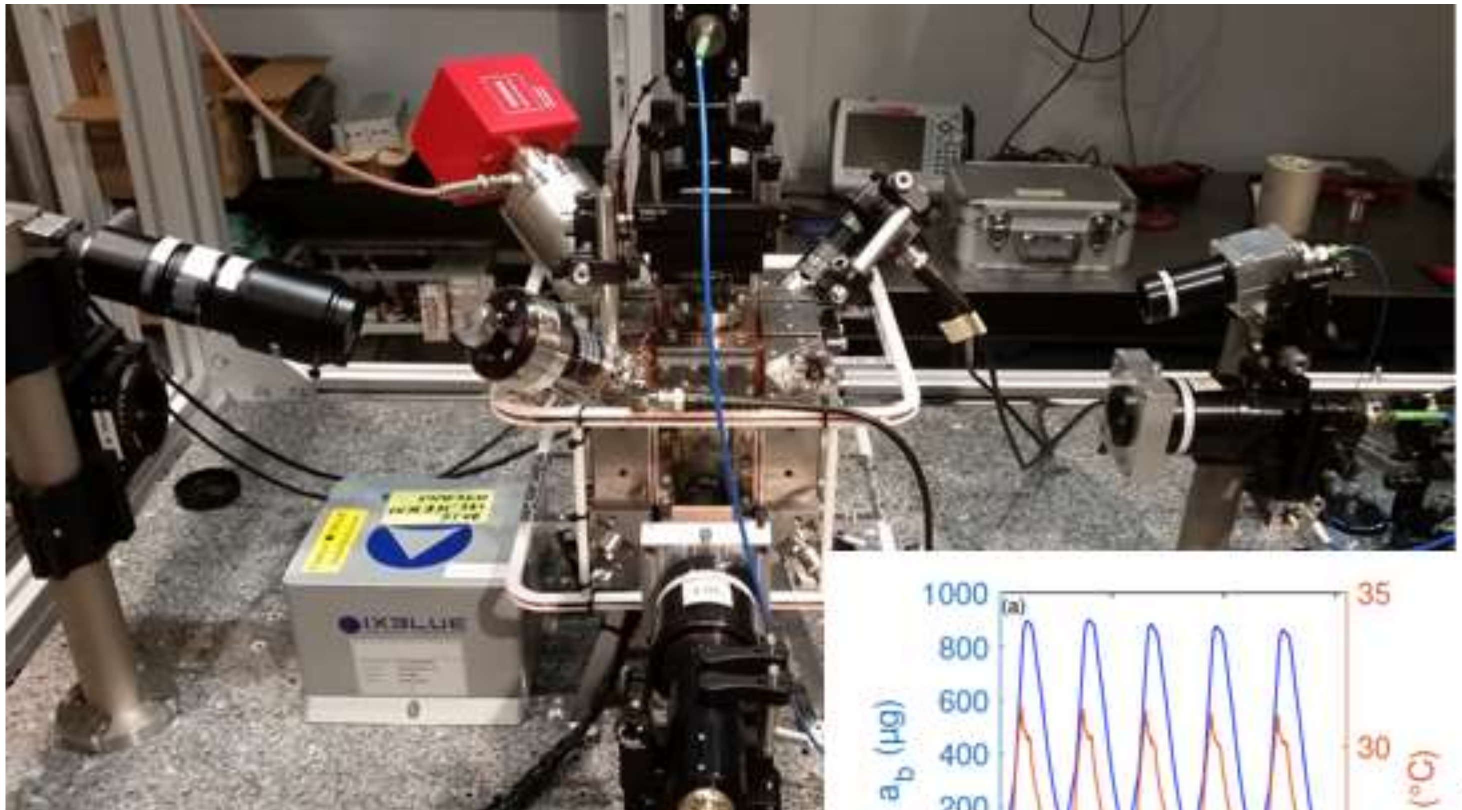
- **Test du couplage quantique-hybride dans des conditions “réalistes”**

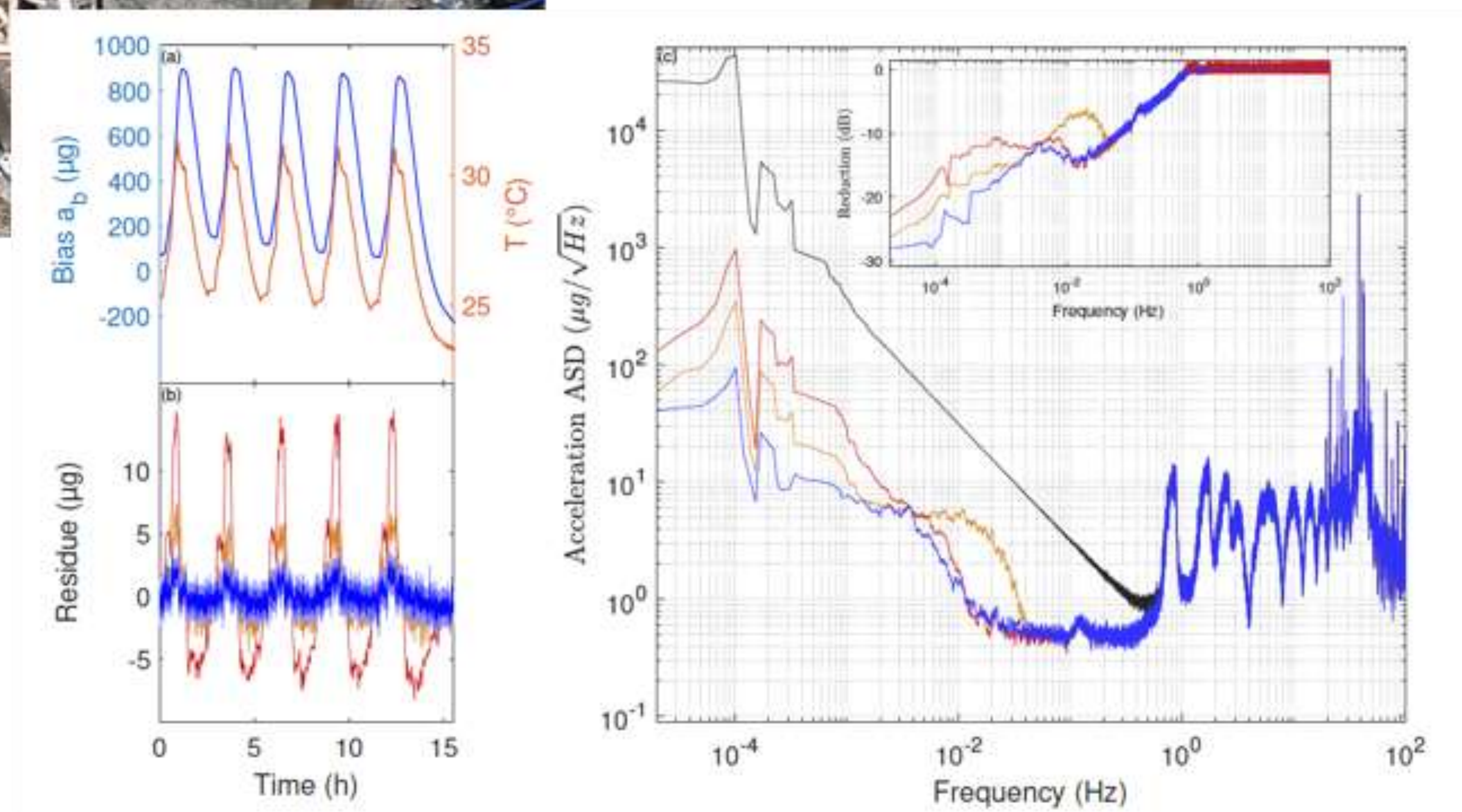


- **Détermination et intégration du biais de mesure pour permettre l’intégration des équations du mouvement.**

HYBRID QUANTUM SENSOR

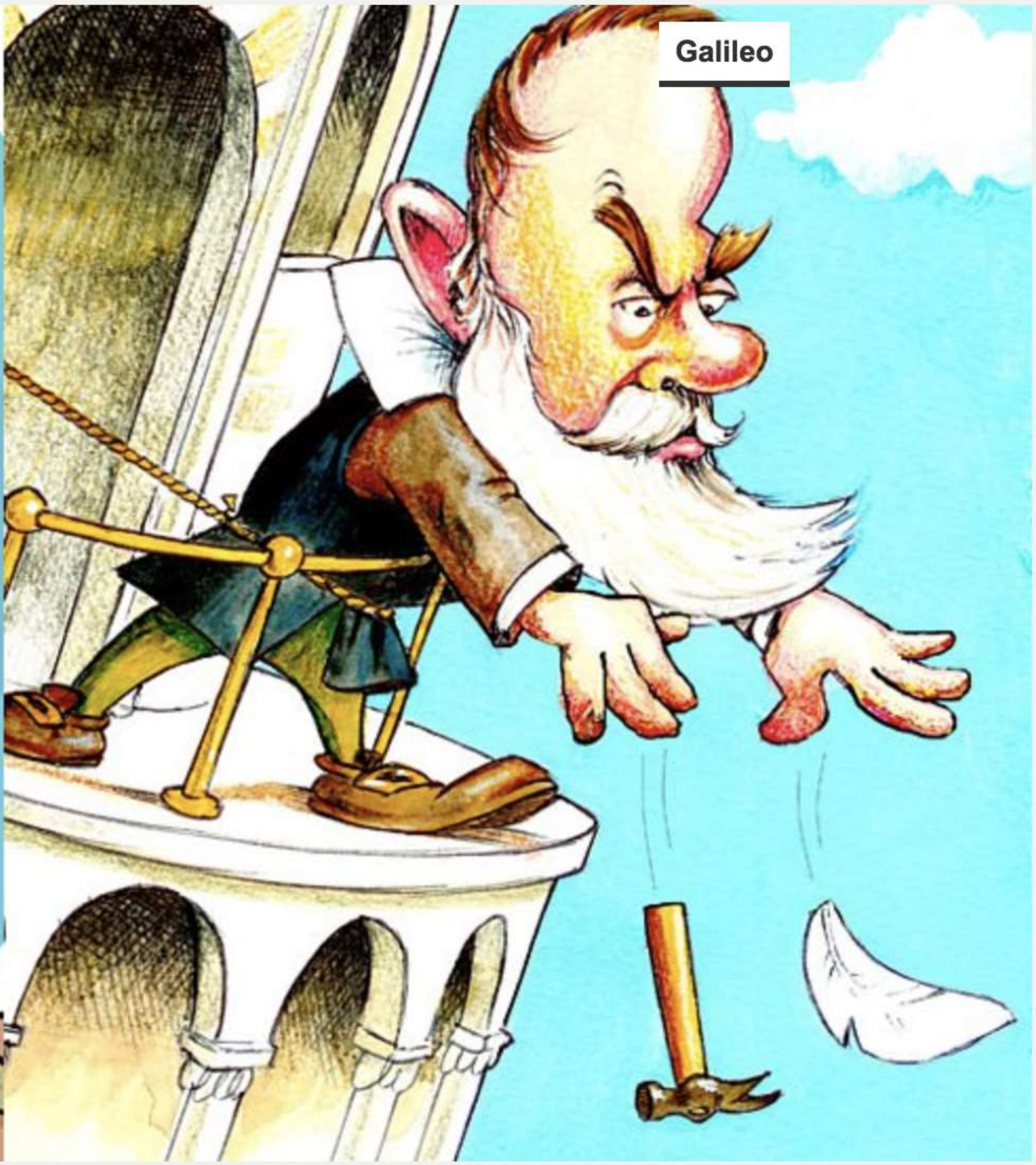
- **Compensating the bias of classical accelerometers by coupling with a "perfect" accelerometer**





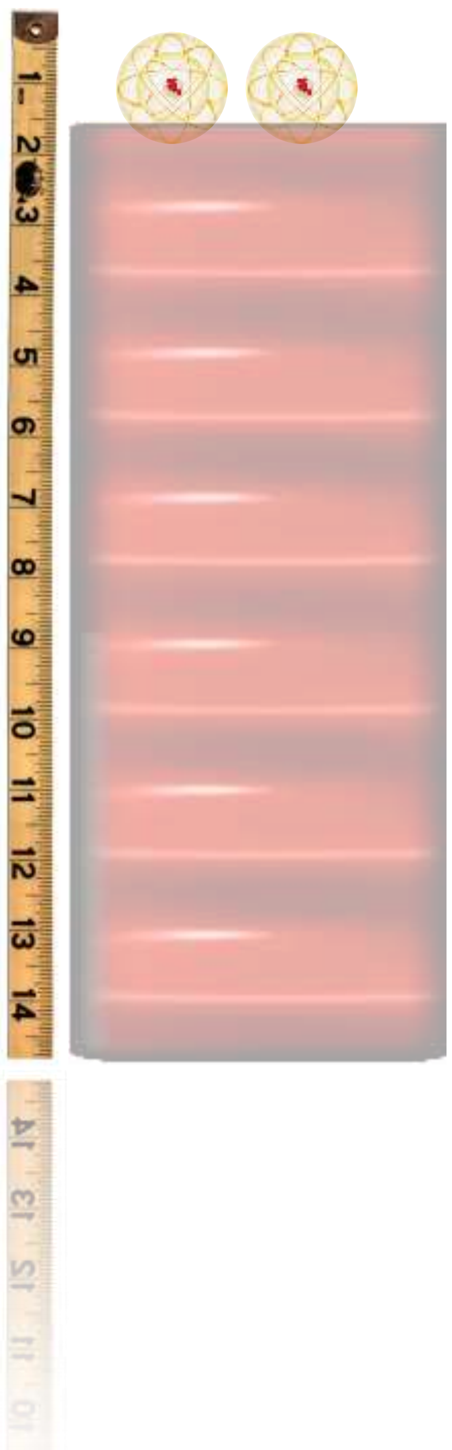
- **Use of Kalman filtering techniques for recalibration**

What falls faster ?

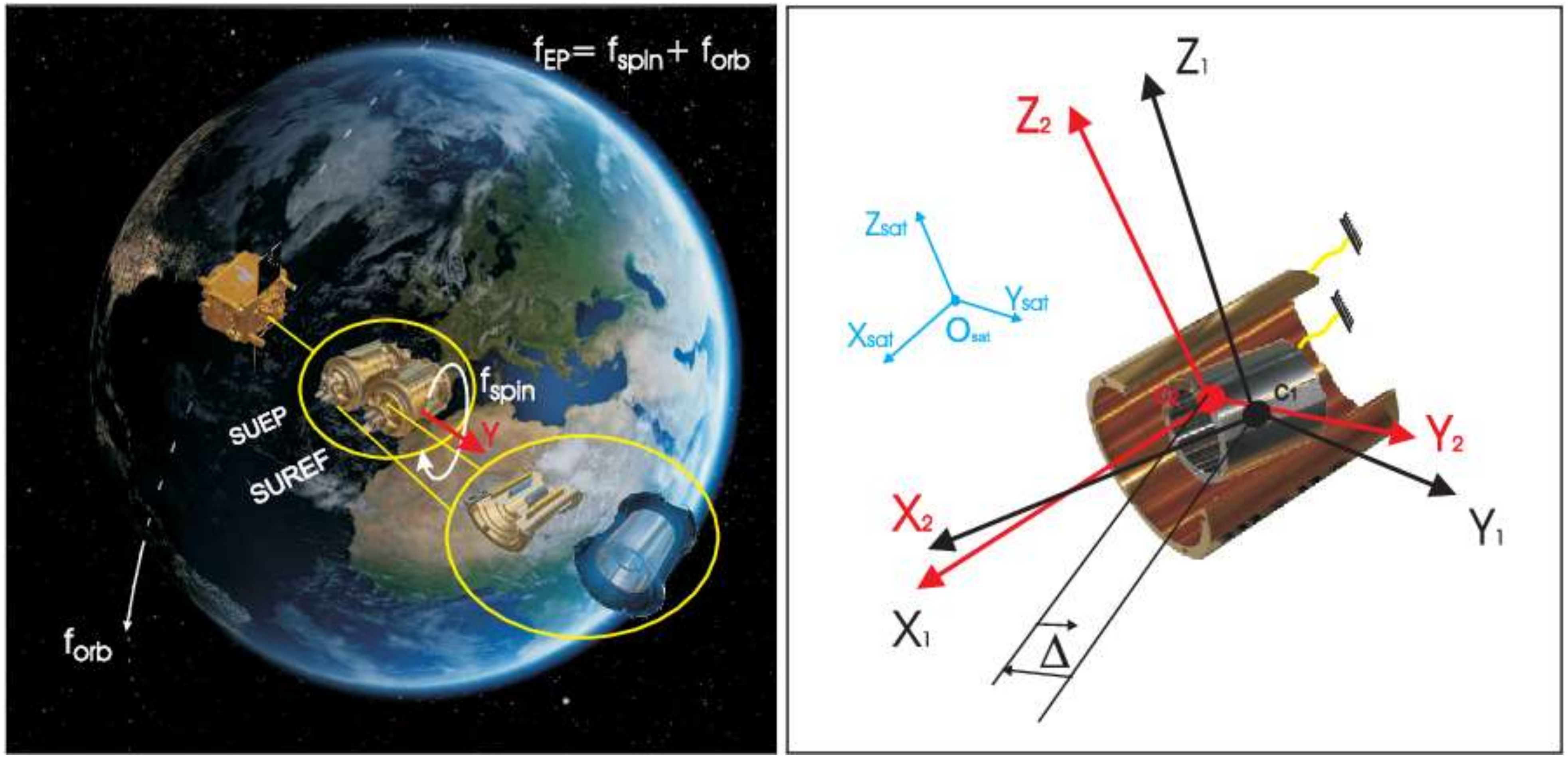


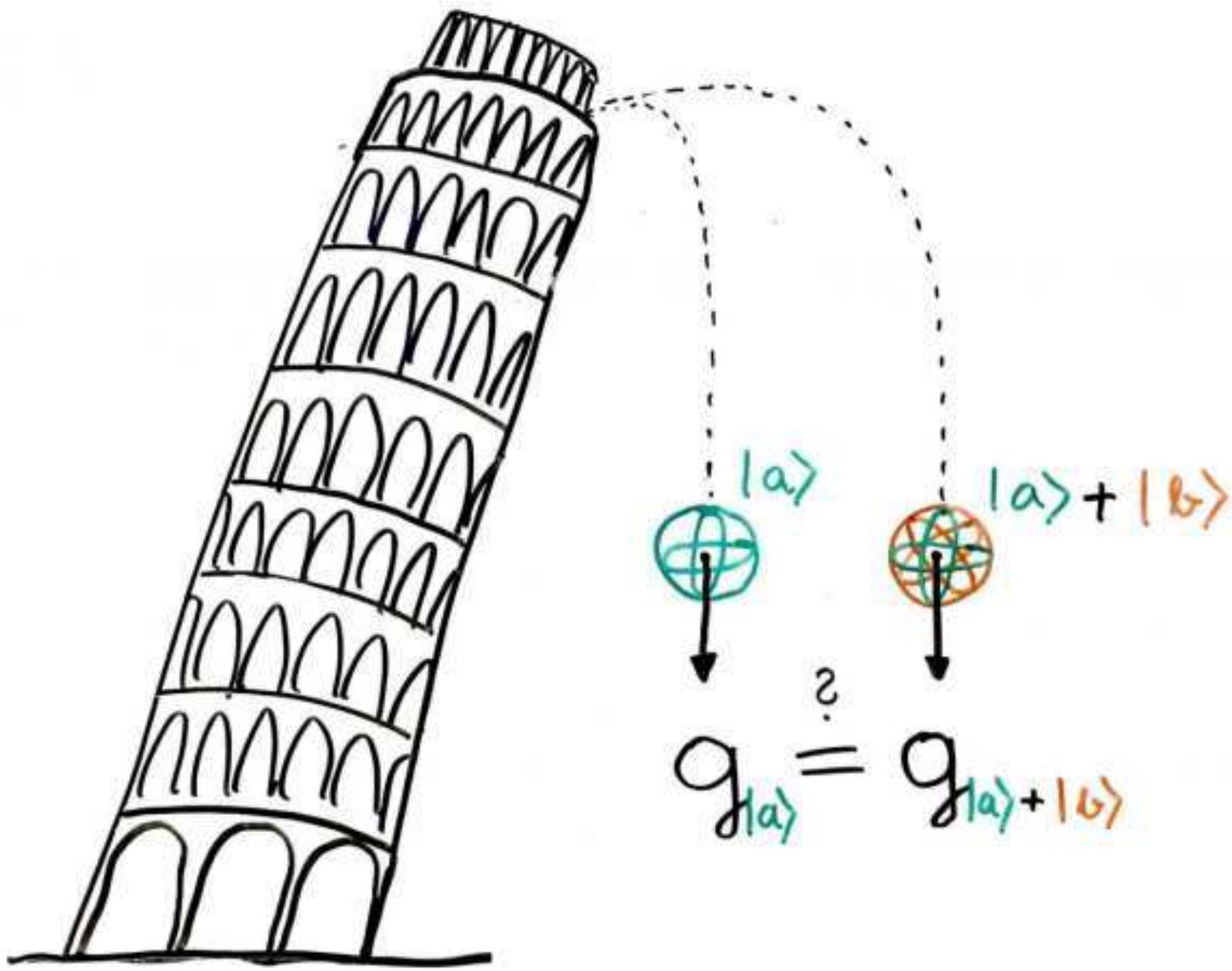
APPLICATIONS TO FUNDAMENTAL PHYSICS

- **How to test and verify general relativity**
  - **Is gravity the same for two different atoms (or in other words is inertial mass equal to the gravitational mass) ?**
    - **Testing the Einstein Equivalence principle, a cornerstone of Relativity.**

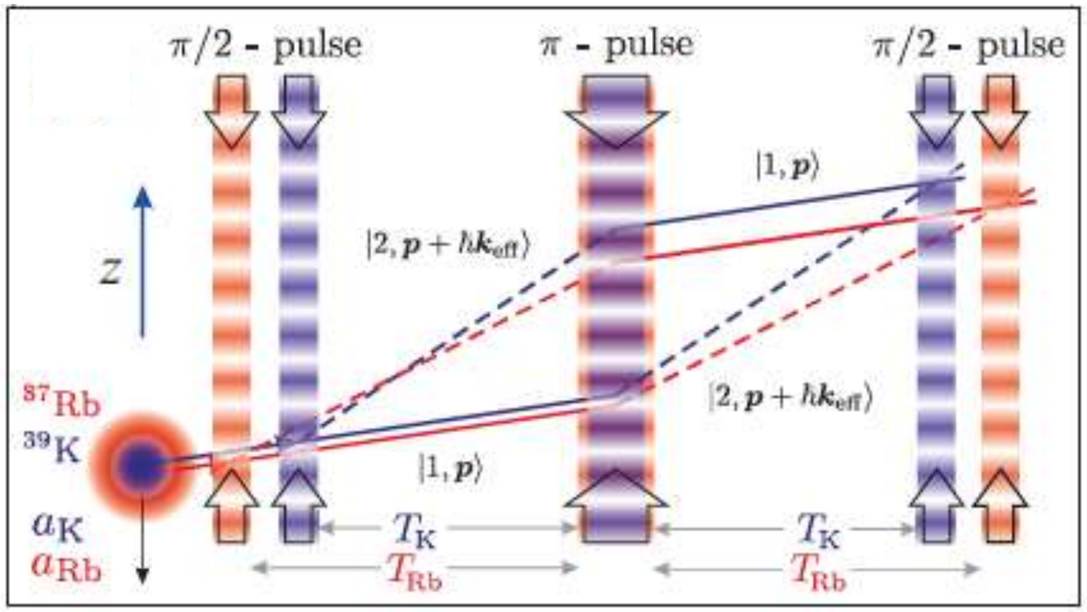


THE WEAK EQUIVALENCE PRINCIPLE





- Do the same with atoms
  - ⇨ Perfect inertial masses
  - ⇨ Atoms can follow the exact same geodetic
  - ⇨ Change of mass, composition, internal state …

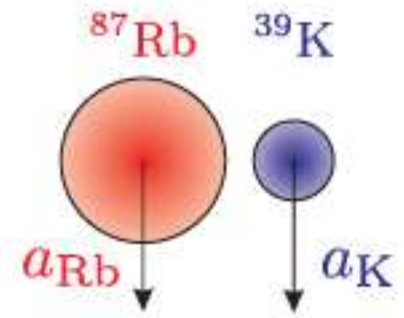


$$\phi_{\mathrm{Rb}} = k_{\mathrm{Rb}} a T^2$$

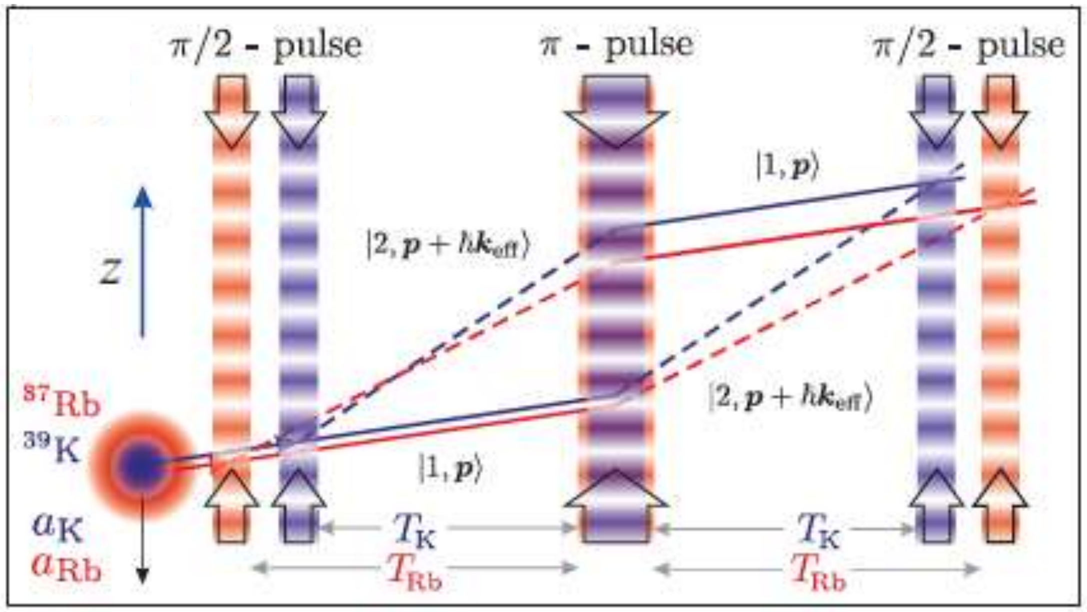
$$\phi_{\mathrm{K}} = k_{\mathrm{K}} a T^2 + \Delta\phi_{\mathrm{d}}$$

Use of Potassium (767 nm) and Rubidium (780 nm)

- High mass and composition difference (39 vs 85 amu, atomic number 19 vs 37)
- Similar wavelength allow rejection and simple laser



$$\eta = \frac{a_{\mathrm{K}} - a_{\mathrm{Rb}}}{g}$$



$$\phi_{\mathrm{Rb}} = k_{\mathrm{Rb}} a T^2$$

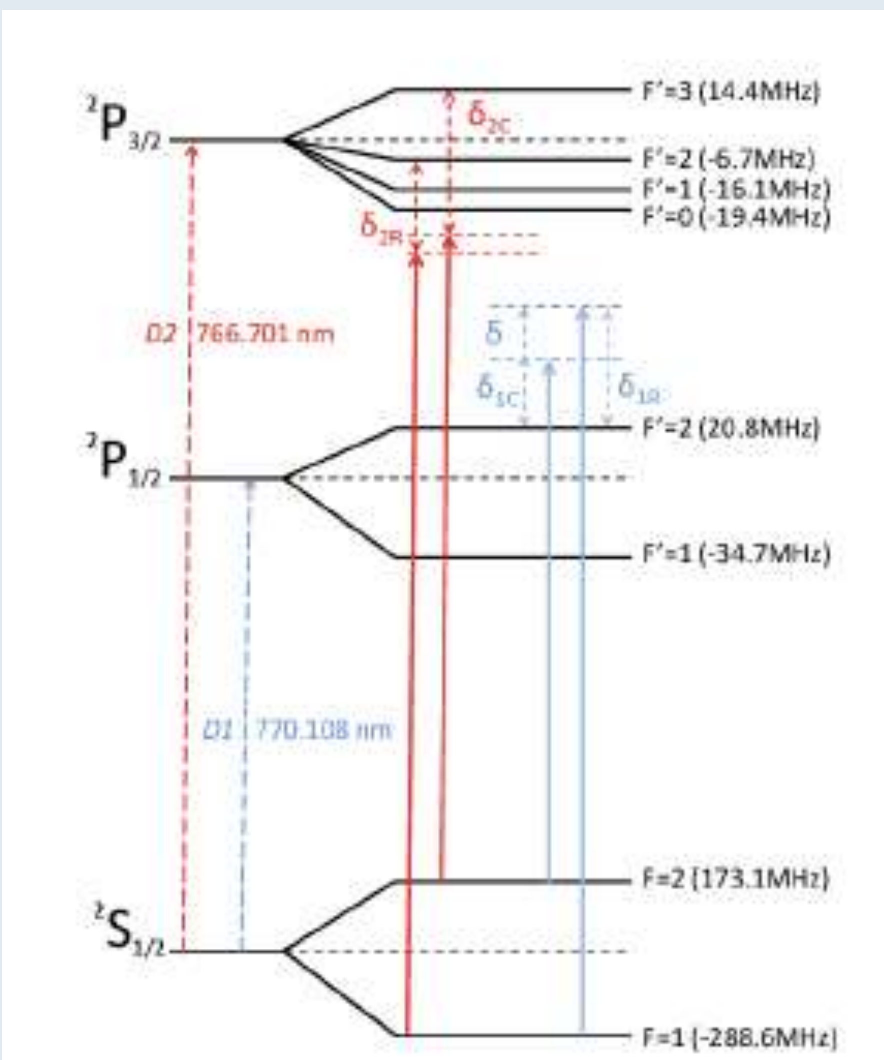
$$\phi_{\mathrm{K}} = k_{\mathrm{K}} a T^2 + \Delta\phi_{\mathrm{d}}$$

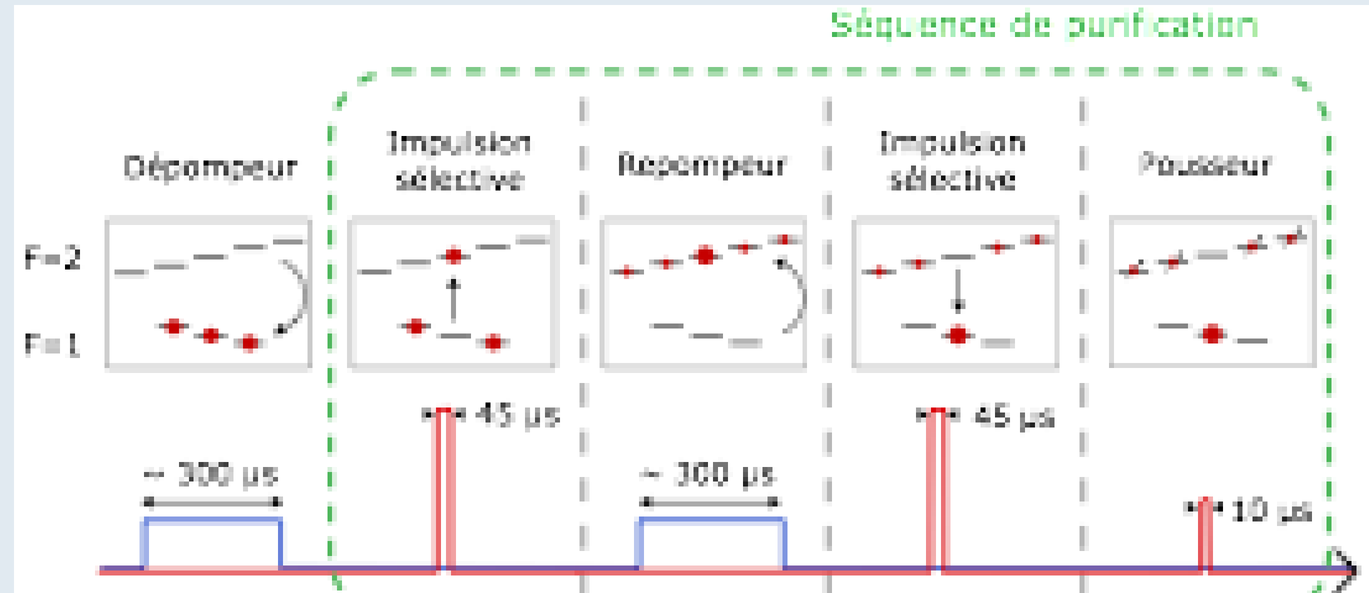
Cooling and preparing potassium

Potassium (^{39}K) is cooled via blue molasses

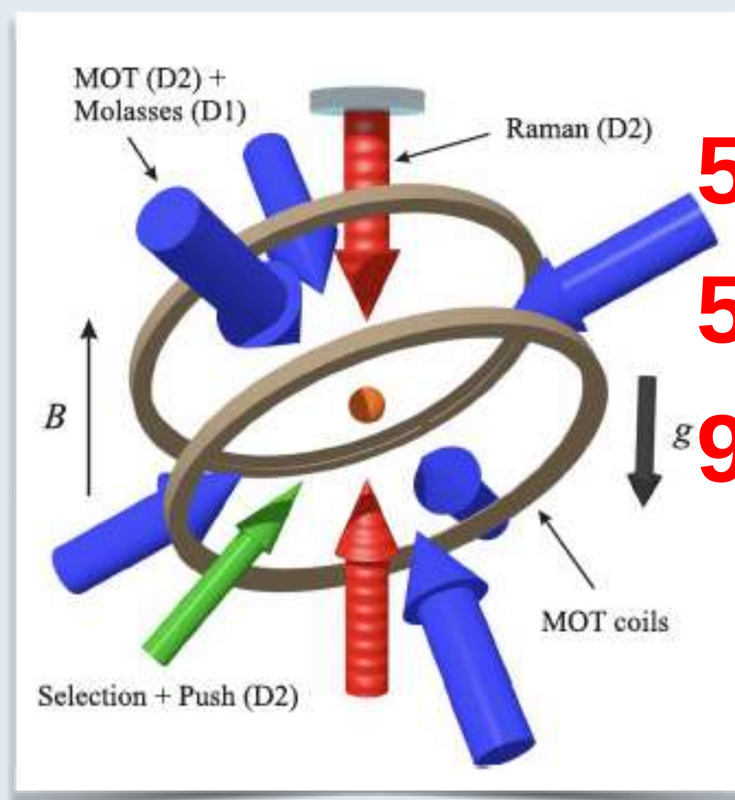
Salomon et al., EPL 104, 63002 (2014).

^{39}K contrast increased by state purification





hal-00870074



5×10^7 atoms

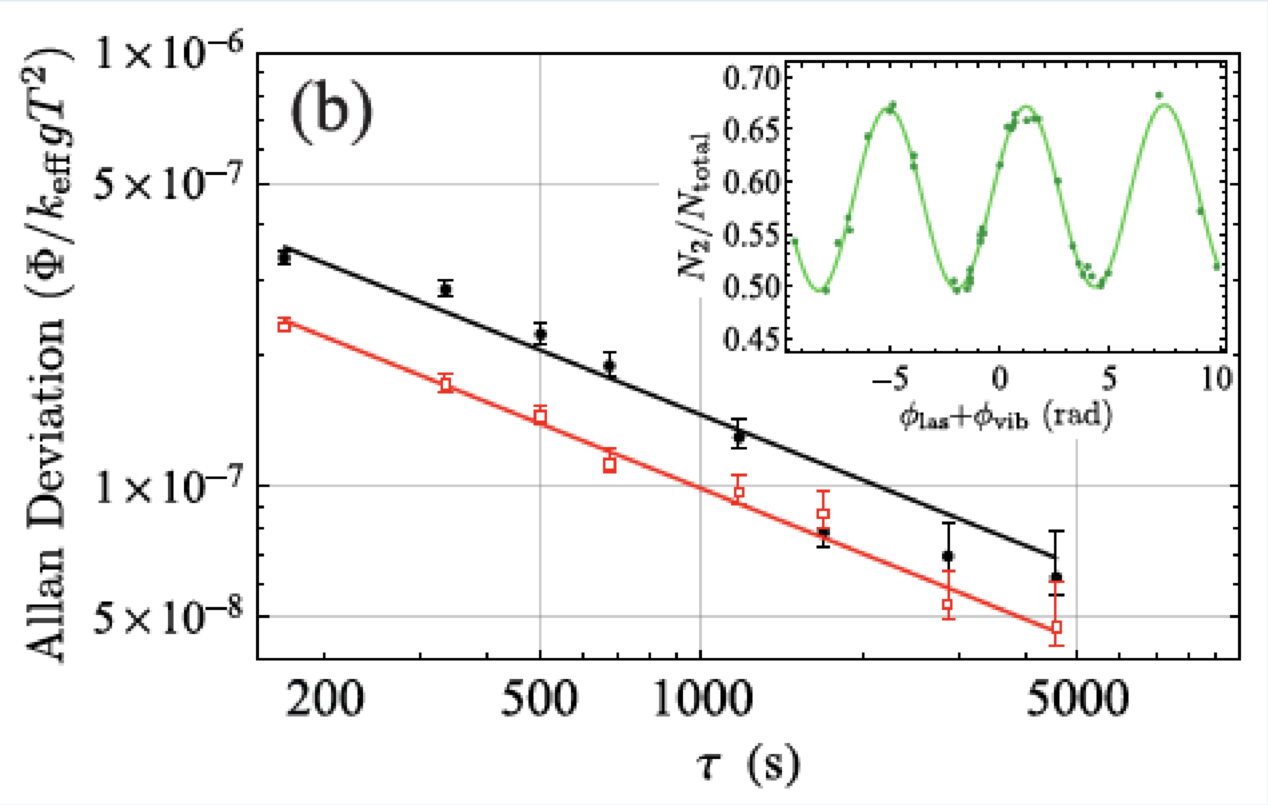
5 µK

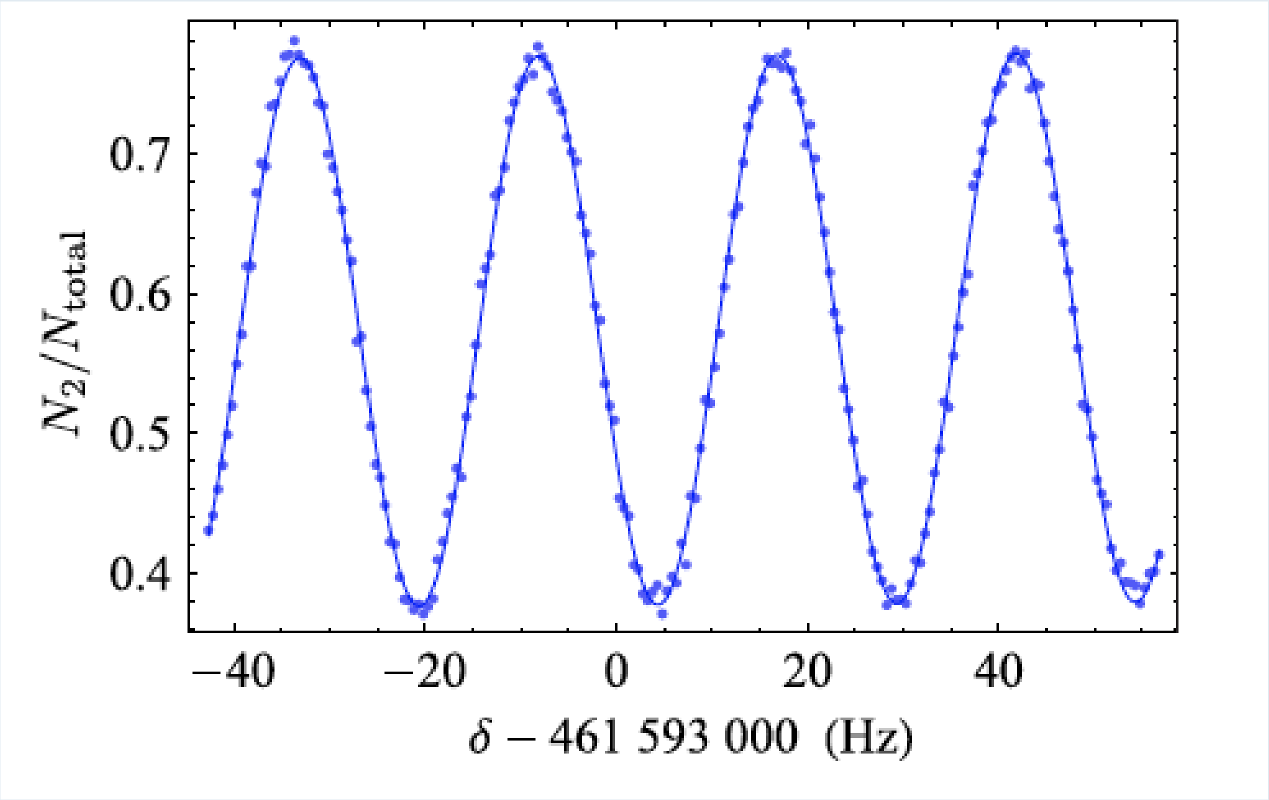
95% purity $m_F=0$

INSTITUT d'OPTIQUE GRADUATE SCHOOL

METROLOGY WITH POTASSIUM

cnrs université de BORDEAUX

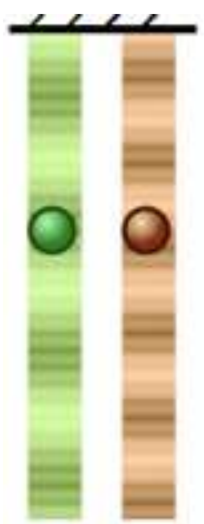




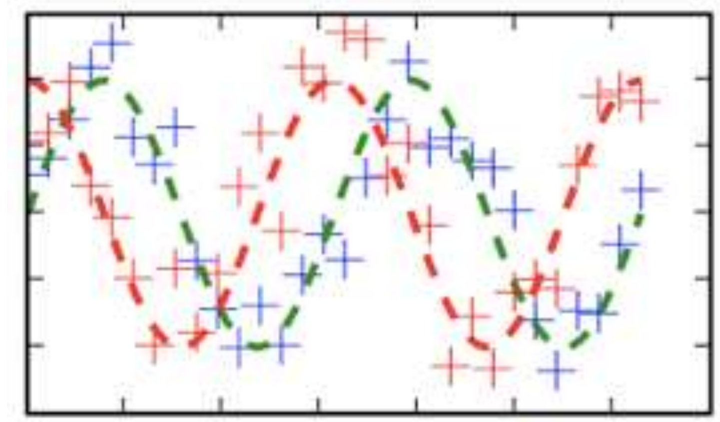
- **Gravity "measurement"**
  - **Short term 2 mg/√Hz**
  - **Long term 60 µGal after 1 hr**

- **Hyperfine spectroscopy**
  - **Statistical *Δf/f* at 4x10^{-11}**
  - **Current systematic at 10^{-9}**

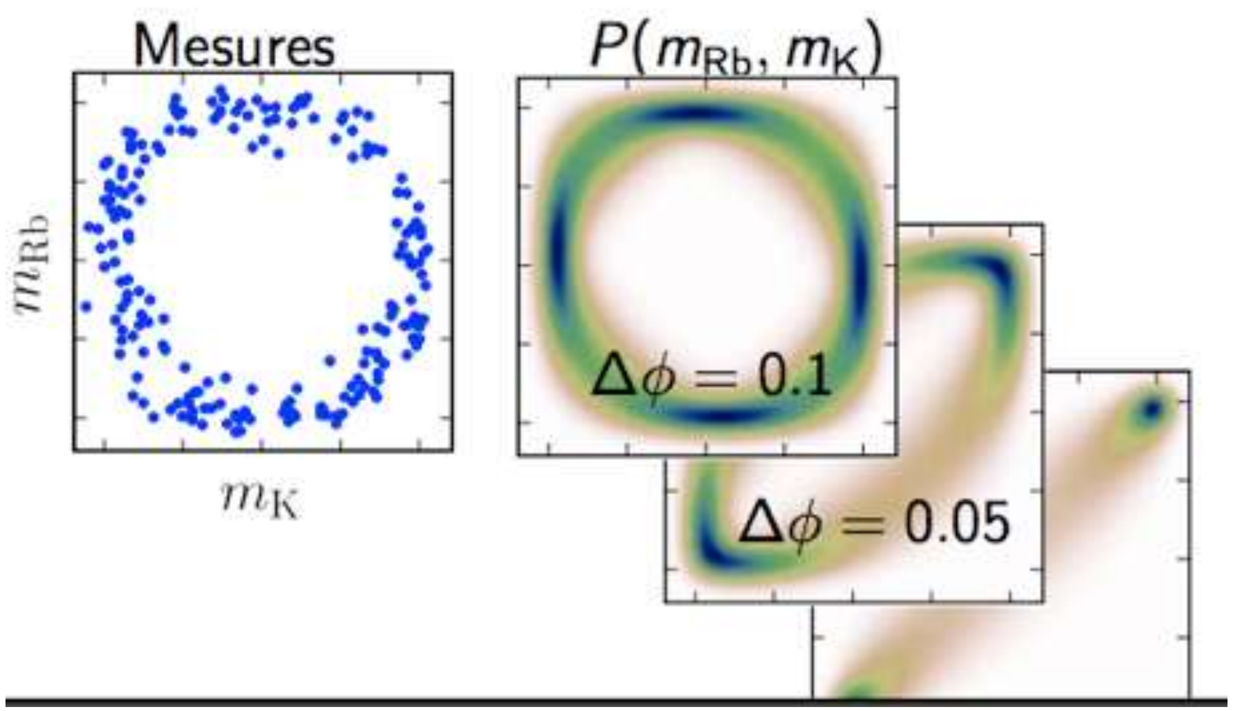
COMMON MODE REJECTION



$$\begin{cases} \phi_{K} &= k_{K}\left(a_{K} T^2 + X_{\mathrm{mirroir}}\right) \\ \phi_{Rb} &= k_{Rb}\left(a_{Rb} T^2 + X_{\mathrm{mirroir}}\right) \end{cases}$$

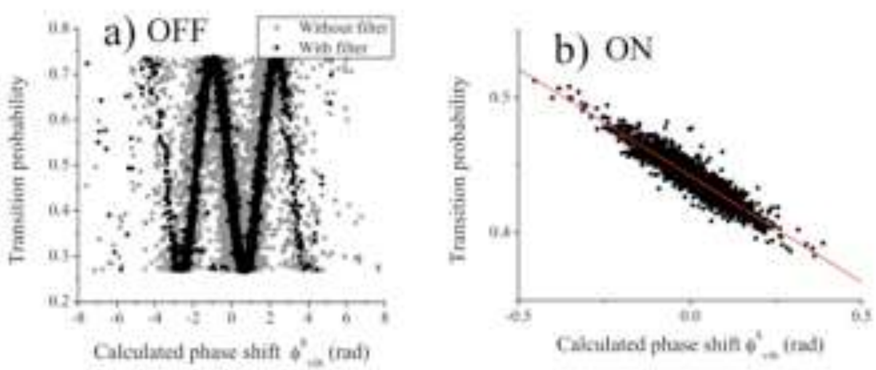


$$\begin{cases} m_{K} &= A + B\cos\left(k_{K}\left(a_{K} T^2 + X_{\mathrm{mirroir}}\right)\right) \\ m_{Rb} &= C + D\cos\left(k_{Rb}\left(a_{Rb} T^2 + X_{\mathrm{mirroir}}\right)\right) \end{cases}$$

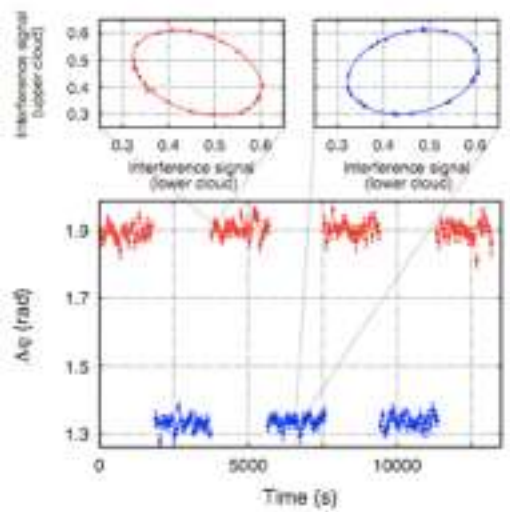


Comparison of two accelerometer signals to measure $\Delta\Phi \propto a_{Rb}T^2_{Rb}/\Lambda_{Rb} - a_K T^2_K/\Lambda_K$

COMMON MODE REJECTION



S. Merlet, *et al.* arXiv:0806.0164v1

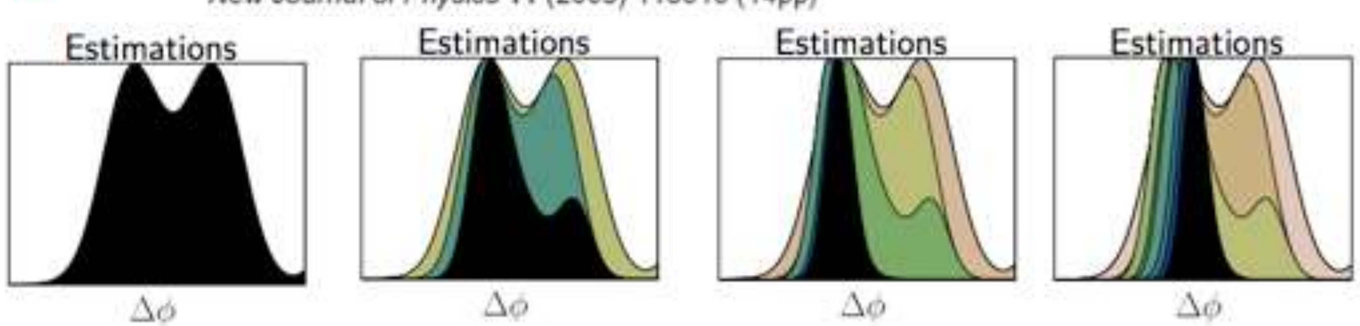


G. Lamporesi, *et al.* Phys. Rev. Lett. 100, 050801 (2008)

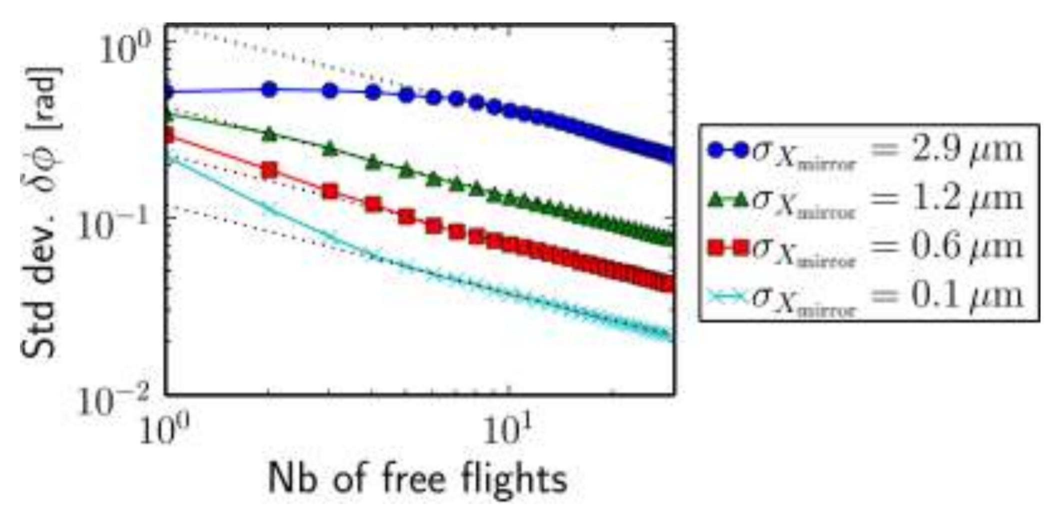
How to estimate the differential acceleration in a two-species atom interferometer to test the equivalence principle

G Varoquaux[1,3], R A Nyman[1,4], R Geiger[1], P Cheinet[1], A Landragin[2] and P Bouyer[1]
[1] Laboratoire Charles Fabry de l'Institut d'Optique, Campus Polytechnique, RD 128, 91127 Palaiseau, France
[2] LNE-SYRTE, UMR8630, UPMC, Observatoire de Paris, 61 avenue de l'Observatoire, 75014 Paris, France
E-mail: philippe.bouyer@institutoptique.fr

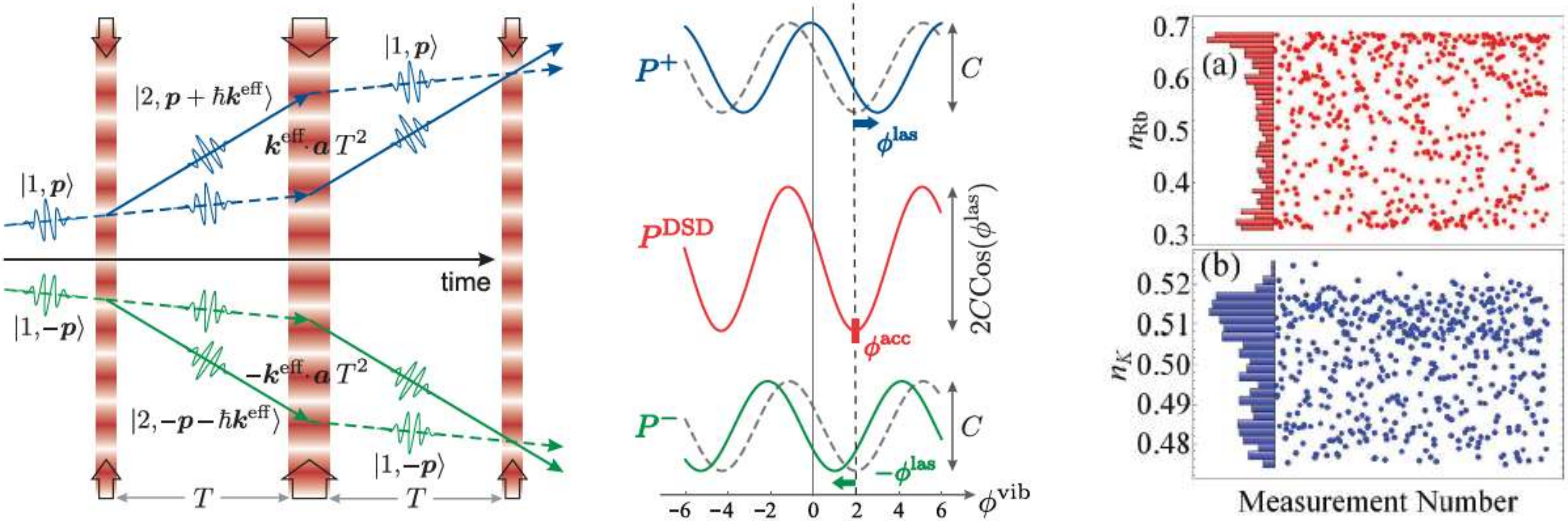
New Journal of Physics **11** (2009) 113010 (14pp)



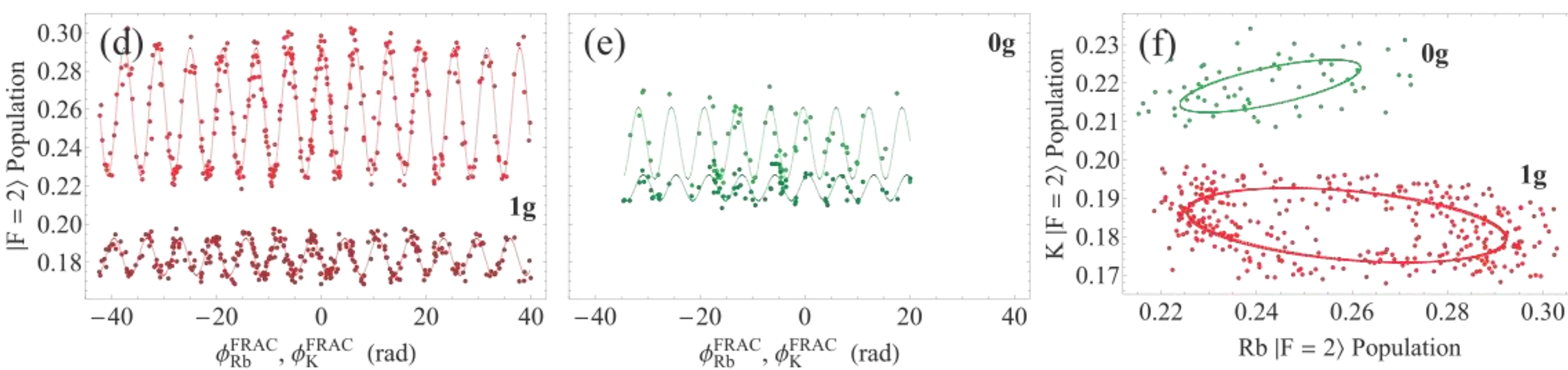
- Differential mesurements
- Use of statistical estimators (Stokton et al. Phys. Rev. A 76, 033613 (2007)
- Fast convergence (<10 meas.)



TESTING THE EQUIVALENCE PRINCIPLE IN AN EINSTEIN ELEVATOR



Fringe reconstruction by accelerometer correlation



AIRBORNE TEST OF THE EQUIVALENCE PRINCIPLE

GAIN in 0-g

LOSS in 0-g

Atoms stay still

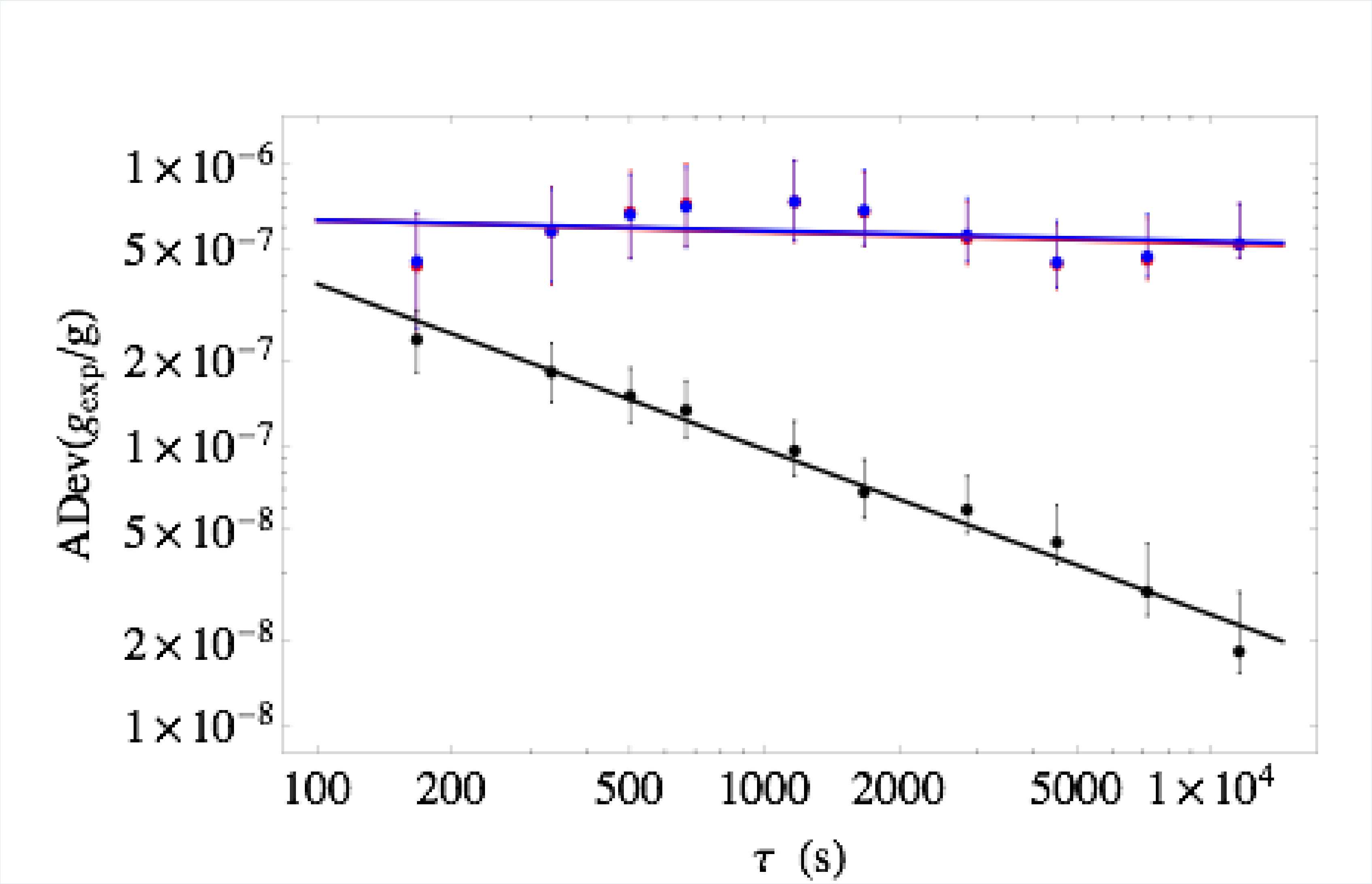
Large rotation

	$+k^{\text{eff}}$ Interferometers in $1g$		$\pm k^{\text{eff}}$ Interferometers in $0g$				
Systematic effect	$\phi^{\text{sys}}_{\text{Rb}}$	$\phi^{\text{sys}}_{\text{K}}$	$\phi^{\text{dep}}_{\text{Rb}}$	$\phi^{\text{ind}}_{\text{Rb}}$	$\phi^{\text{dep}}_{\text{K}}$	$\phi^{\text{ind}}_{\text{K}}$	Unit
Quadratic Zeeman	2.351(51)	33.78(73)	—	2.355(36)	—	33.83(52)	rad
Magnetic gradient	0.0302(90)	0.91(24)	0.0196(44)	1.90(43)E-5	0.75(0.13)	0.00126(23)	rad
Coriolis effect	-1.06(58)	-1.8(1.0)	13.2(1.5)	-0.600(69)	17.9(2.3)	-1.64(21)	mrad
One-photon light shift	-2.1(3.6)	-51(81)	—	-2.1(3.6)	—	-51(81)	mrad
…ght shift	1.3(2.8)	16(68)	1.3(2.0)	—	16(48)	—	
Extra laser lines	-0.18(10)	—	0.030(26)	0.19(16)	—	—	
FRAC method	0.0(4.1)	0.0(4.2)	0.0(4.1)	—	0.0(4.2)	—	mrad
Gravity gradient	0.022(20)	0.061(20)	5.4(5.2)E-6	0.015(14)	1.60(59)E-5	0.039(14)	μrad
Total	2.379(52)	34.65(78)	0.0341(65)	2.352(36)	0.78(14)	33.78(52)	rad

EP sensitivity : 10^{-5}, EP accuracy 10^{-4}

	$+k^{\text{eff}}$ Interferometers in $1g$			$\pm k^{\text{eff}}$ Interferometers in $0g$			
	Rb	K	Difference	Rb	K	Difference	Unit
ϕ_j^{FRAC}	3.291(18)	1.345(32)	1.192(37)	2.854(75)	3.71(10)	0.85(13)	rad
$\phi_j^{\text{acc}} + \phi_j^{\text{las}}$	0.778	1.255	0.476	0.4667	0.4672	3.33E-5	rad
ϕ_j^{sys}	2.379(52)	34.65(78)	0.85(78)	0.0341(65)	0.78(14)	0.74(14)	rad
ϕ_j^{DSD}	—	—	—	-0.0480(34)	-0.0469(49)	1.15(59)E-3	rad
Φ_j	0.134(55)	-34.56(78)	-0.13(78)	2.401(76)	2.50(18)	0.10(20)	rad
η	—	—	-0.2(1.2)E-3	—	—	1.5(3.1)E-4	

GROUND BASED TEST OF THE EQUIVALENCE PRINCIPLE

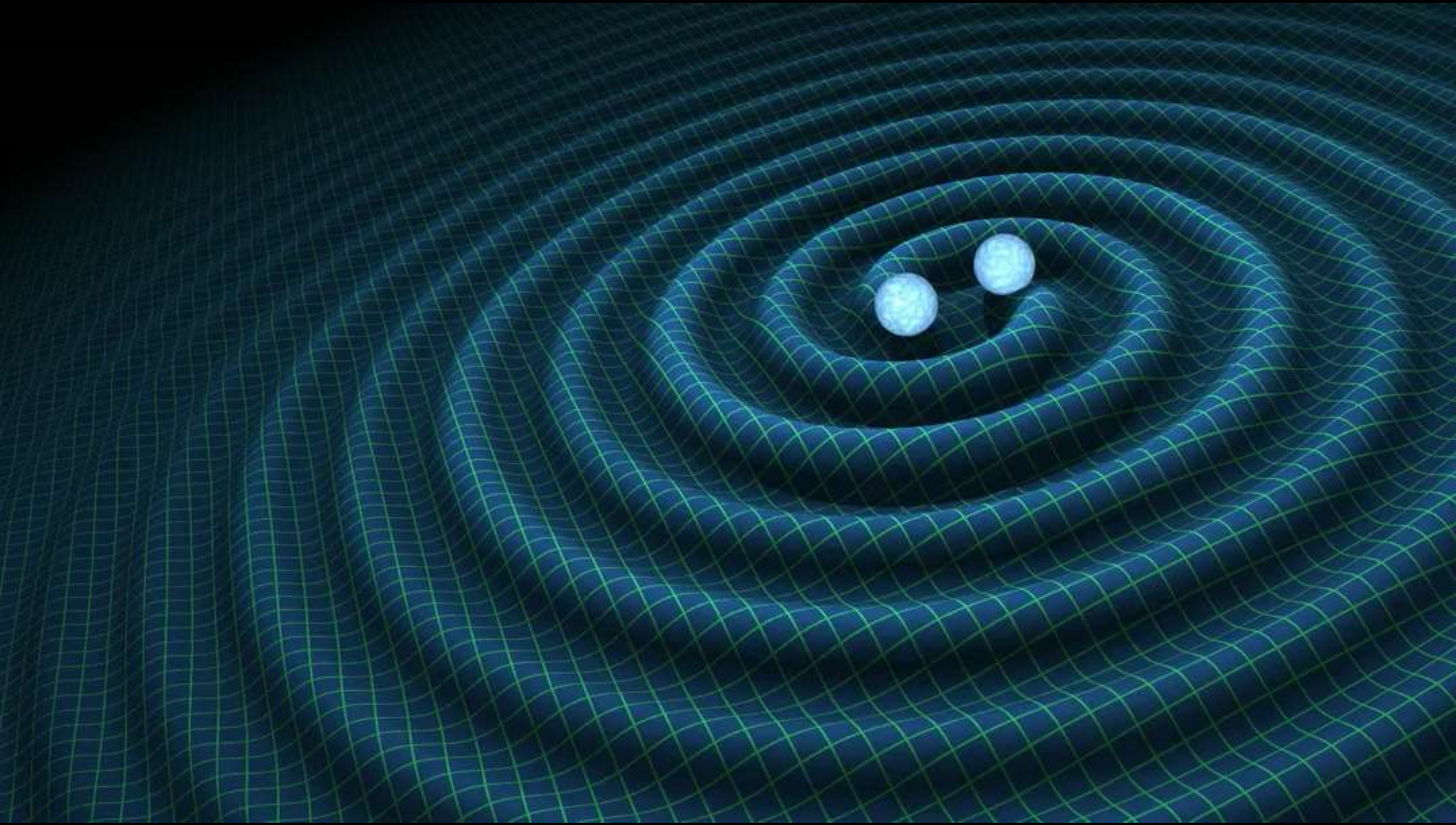


UFF test on ground (20 ms) : statistical error at 1.5×10^{-8}

Still some systematic effects to track

Systematic effect of $\Delta\eta=10^{-6}$

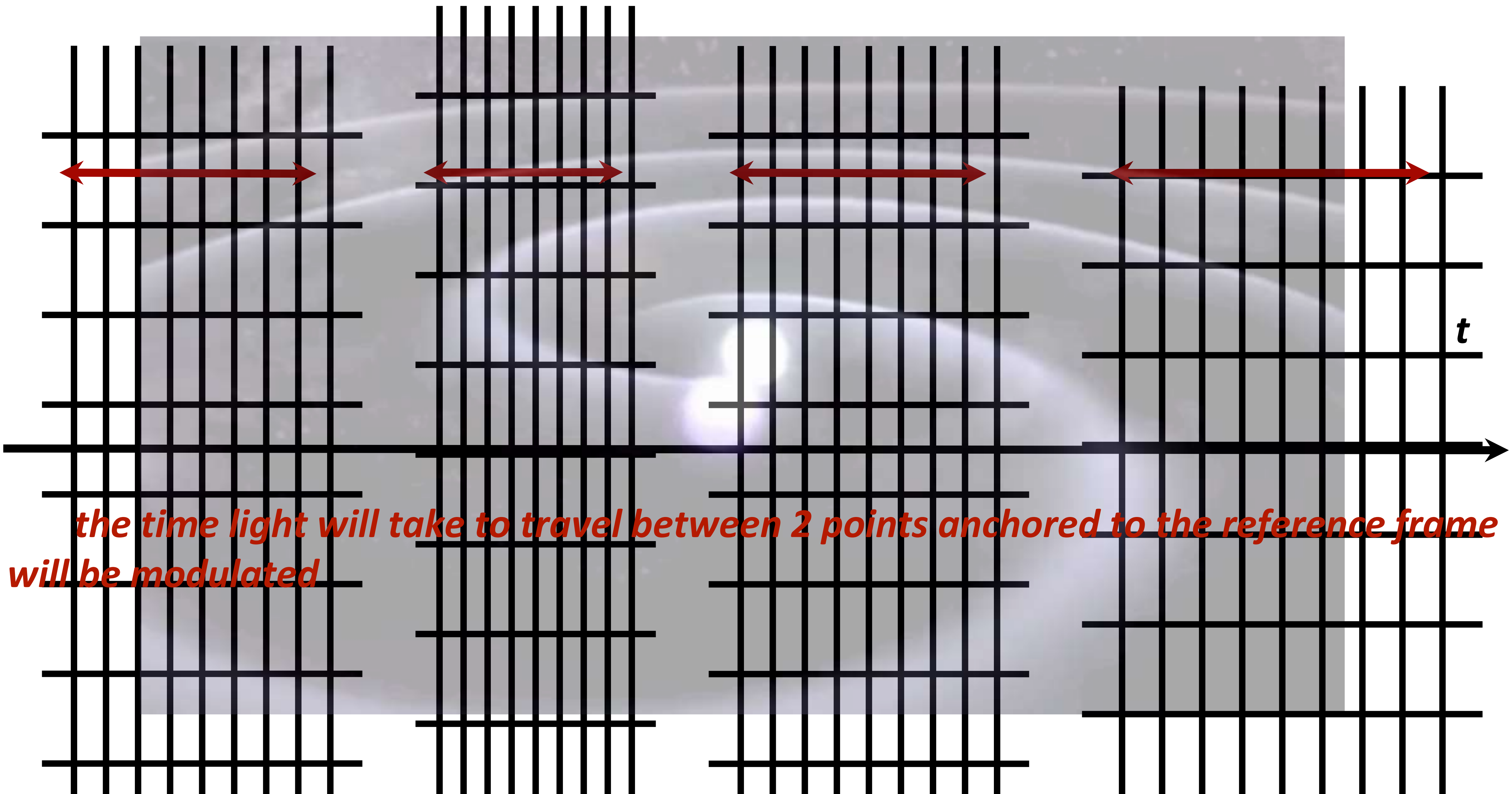
Calibrated at 10% for Quadratic Zeeman effect and 2-photon light shift



Gravitational waves

Gravity waves will distort space time

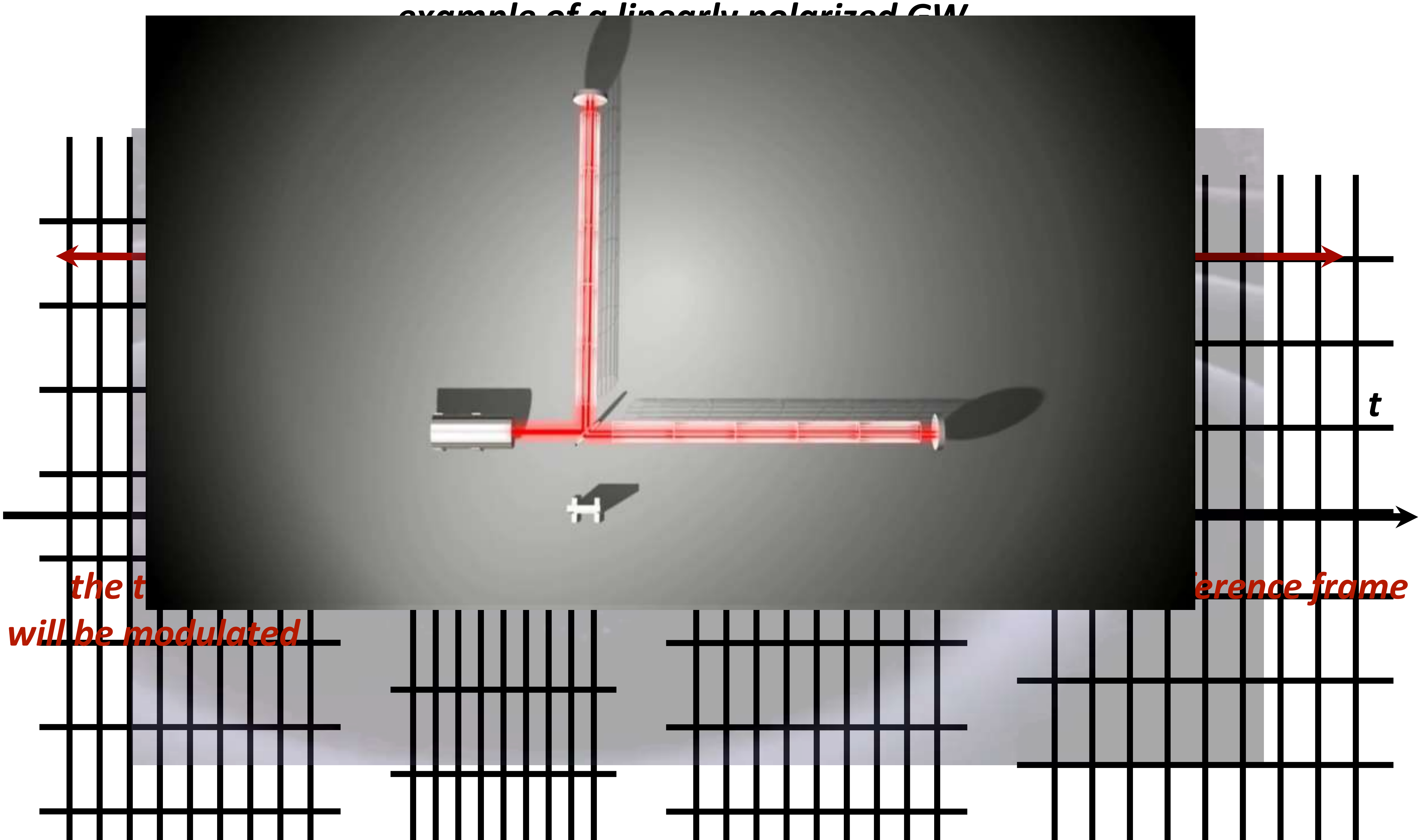
example of a linearly polarized GW



the time light will take to travel between 2 points anchored to the reference frame will be modulated

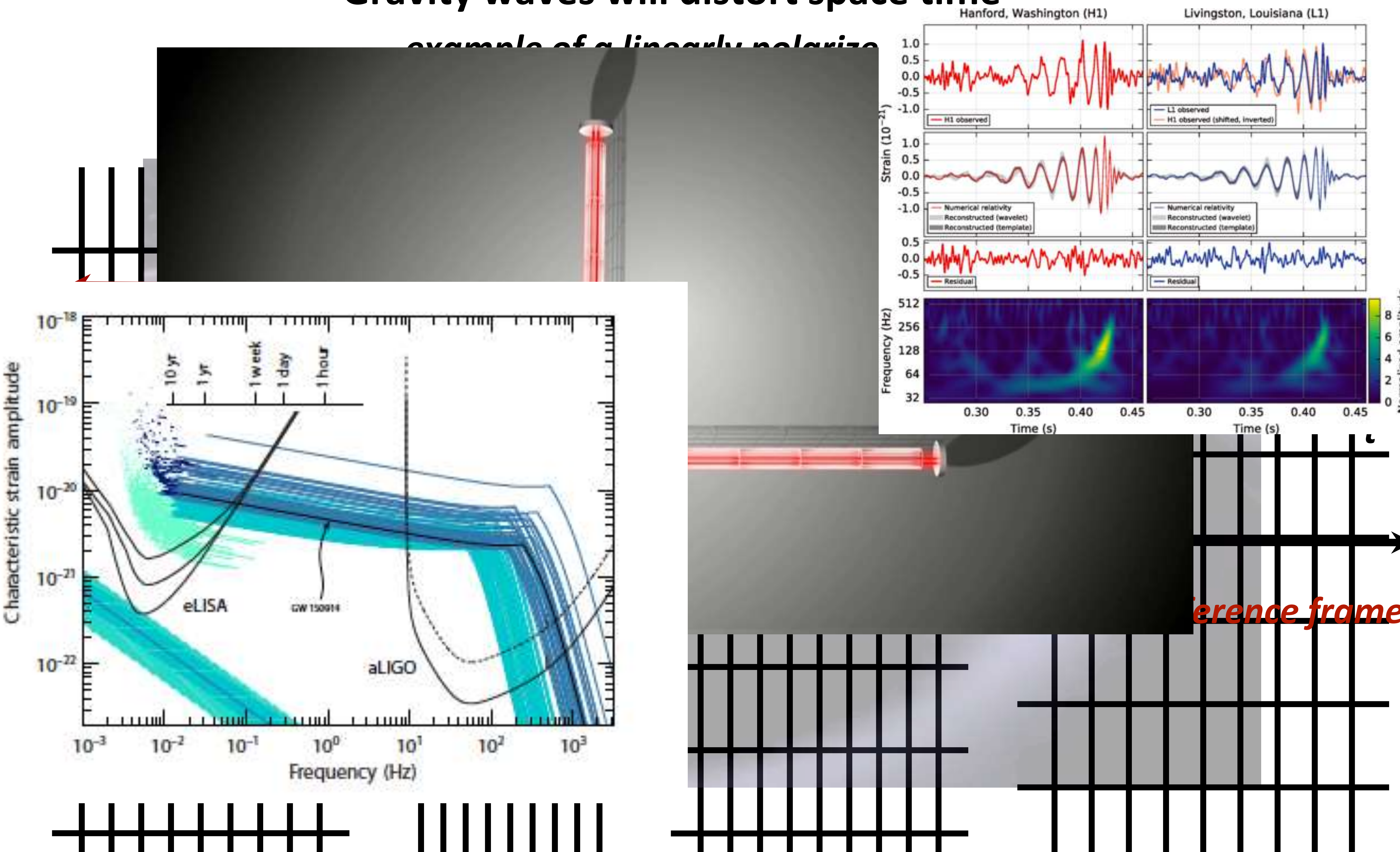
Gravity waves will distort space time

example of a linearly polarized GW



Gravity waves will distort space time

example of a linearly polarize



erence frame

EQUIPEX 2011 : a new initiative to prepare the next generation of gravitation antenna

Underground infrastructure for geophysics and gravitational wave detection

15 institutes - 3 compagnies

Laboratoire(s)/ Laboratory
Laboratoire Photonique, Numérique et Nanosciences – LP2N
Laboratoire Souterrain Bas Bruit - LSBB
Systèmes de Référence Temps - Espace - SYRTE
Astrophysique Relativiste Théories Expériences Métrologie Instrumentation Signaux - ARTEMIS
Centre Lasers Intenses et Applications - CELIA
Laboratoire Kastler-Brossel – LKB
Astroparticule et Cosmologie – APC
GEOAZUR
Géologie des Systèmes et des Réservoirs Carbonatés - GSRC
Environnement Méditerranéen et Modélisation des Agro-Hydrosystèmes - EMMAH
Institut Pluridisciplinaire de Recherche Appliquée dans le domaine du génie pétrolier - IPRA
IDES
Laboratoire d'Electronique Antennes et Télécommunication - LEAT
Geosciences Montpellier
Institut de Physique du Glode de Strasbourg - IPGS
Entreprise(s) / company
ALPHANOV
MUQUANS
SOLETANCHE BACHY TUNNELS

Geoscience

Gravity sensitivity of 10^{-10} g/Sqrt(Hz) @ 2Hz

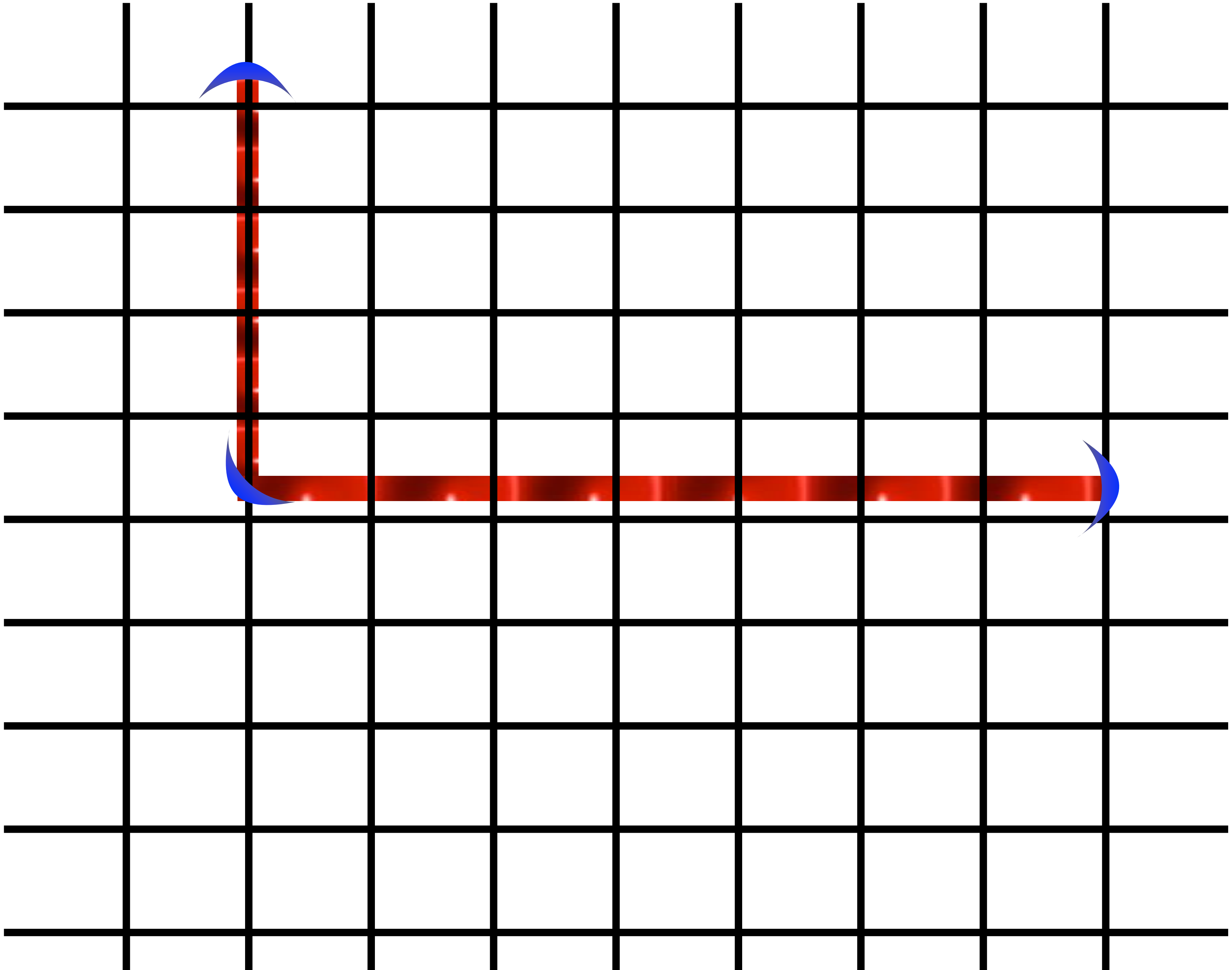
Gradient sensitivity of 10^{-13} s^2/Sqrt(Hz) @ 2Hz (resolves motion of $1m^3$ of water at of 100m).Applications in geology, hydrogeology…

Gravitational wave physics

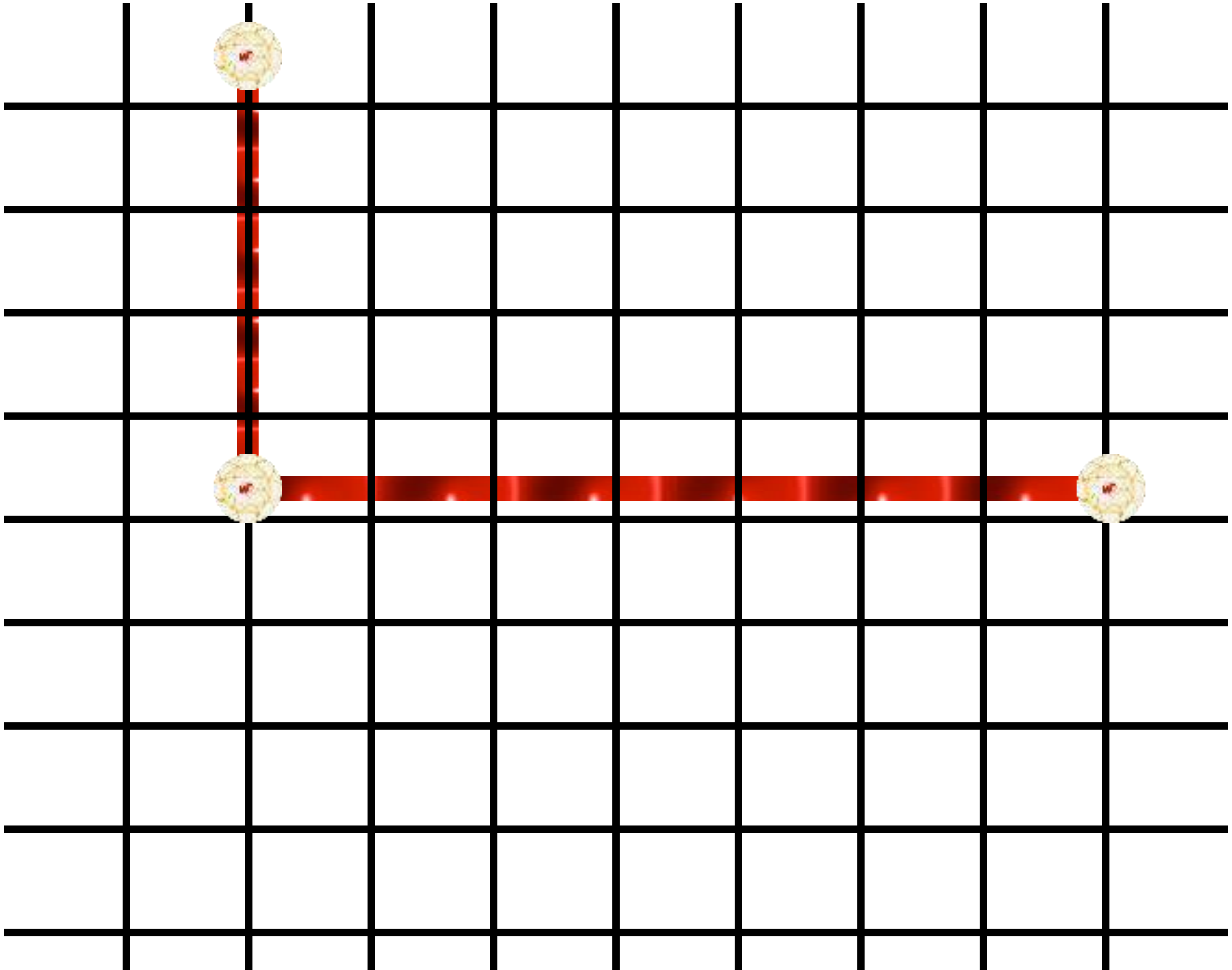
Different limitations with respect to optical detectors.

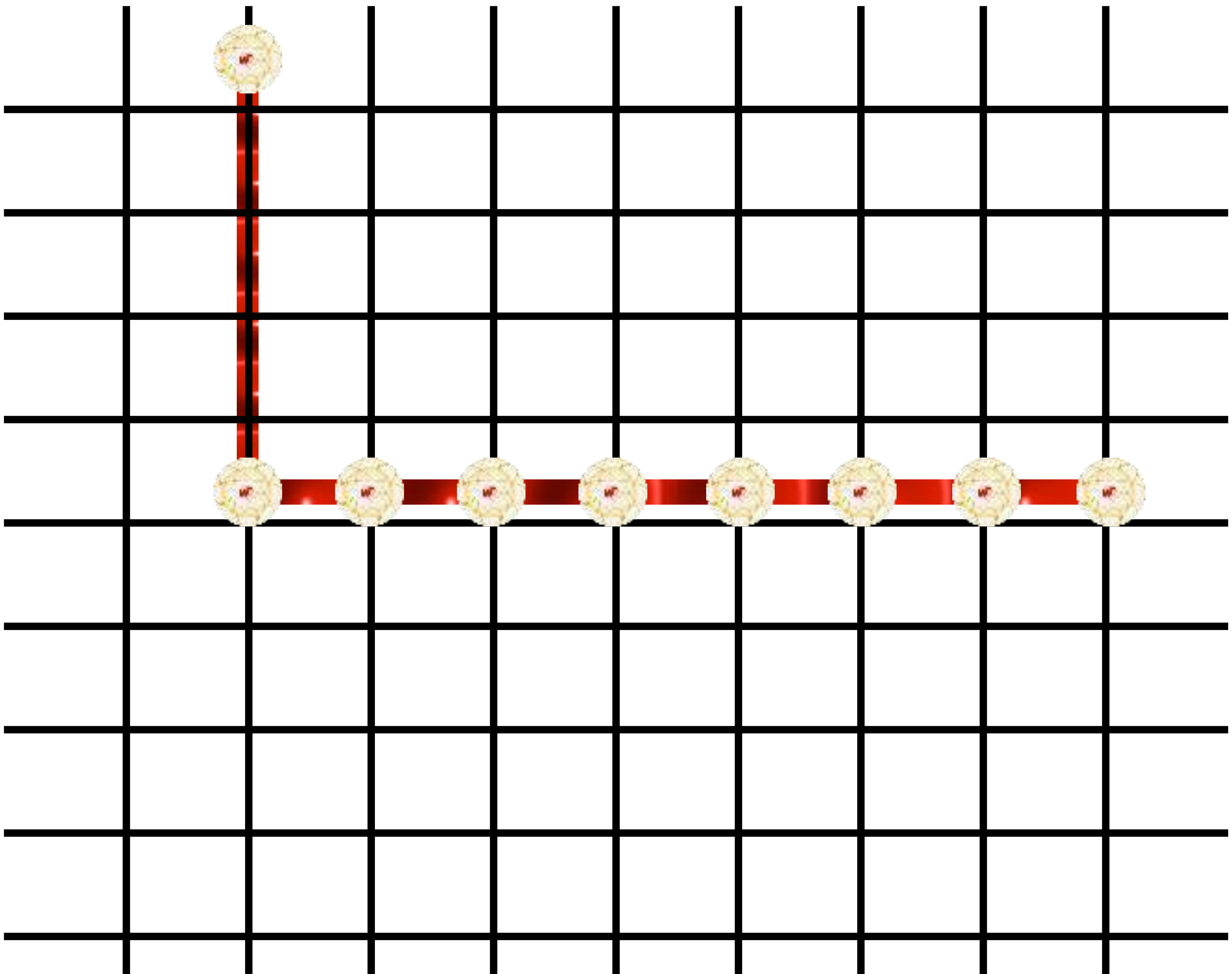
Interesting astrophysics sources in the subHz region.

www.matterwave-antenna.org

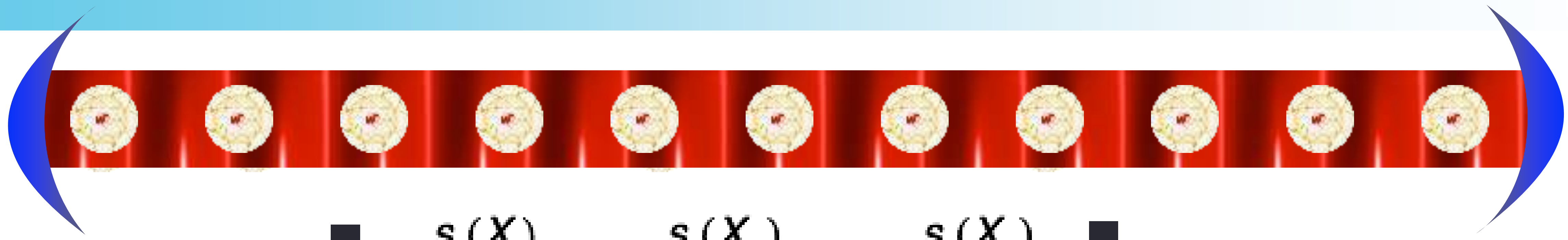


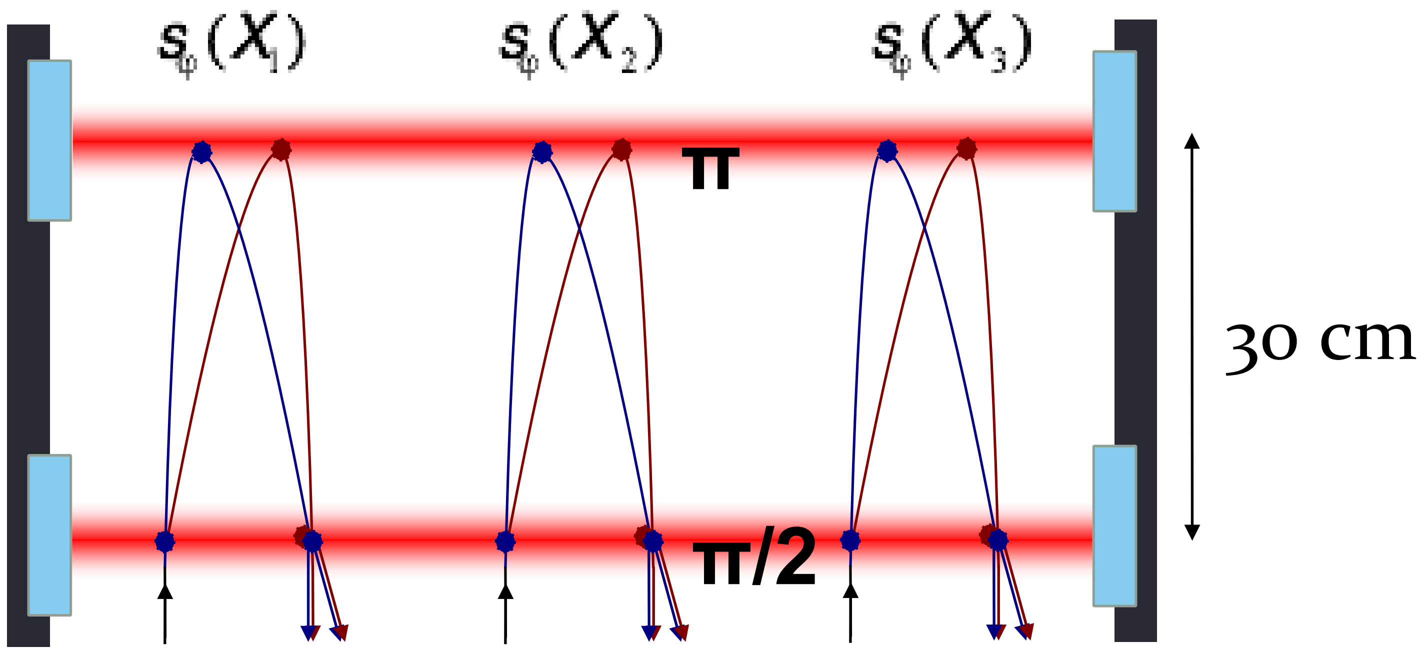
GRAVITATIONAL WAVE DETECTION WITH MATTER WAVE

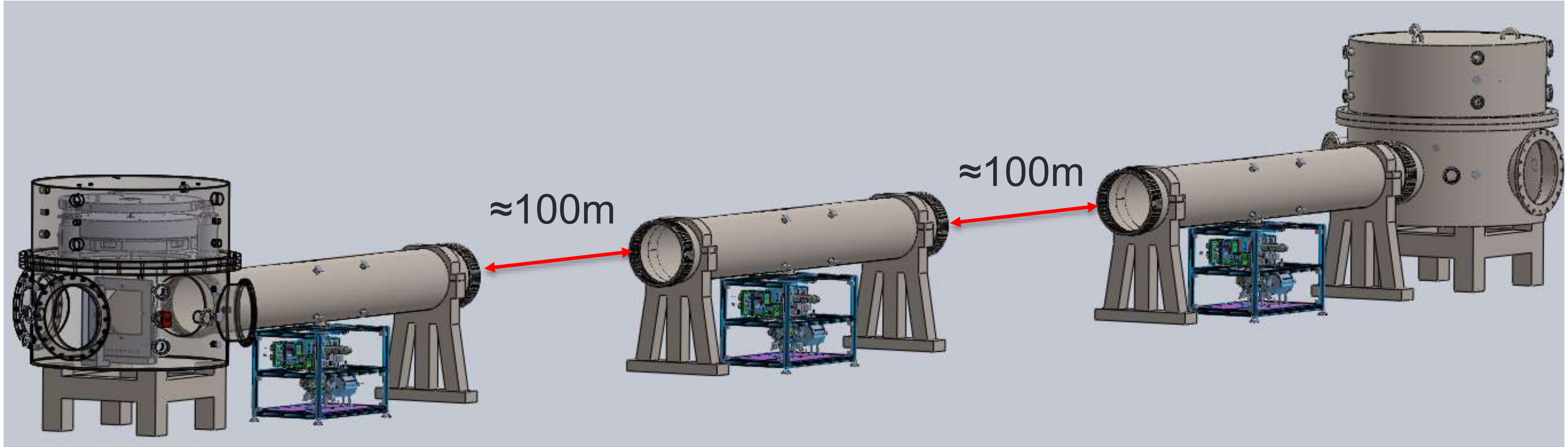


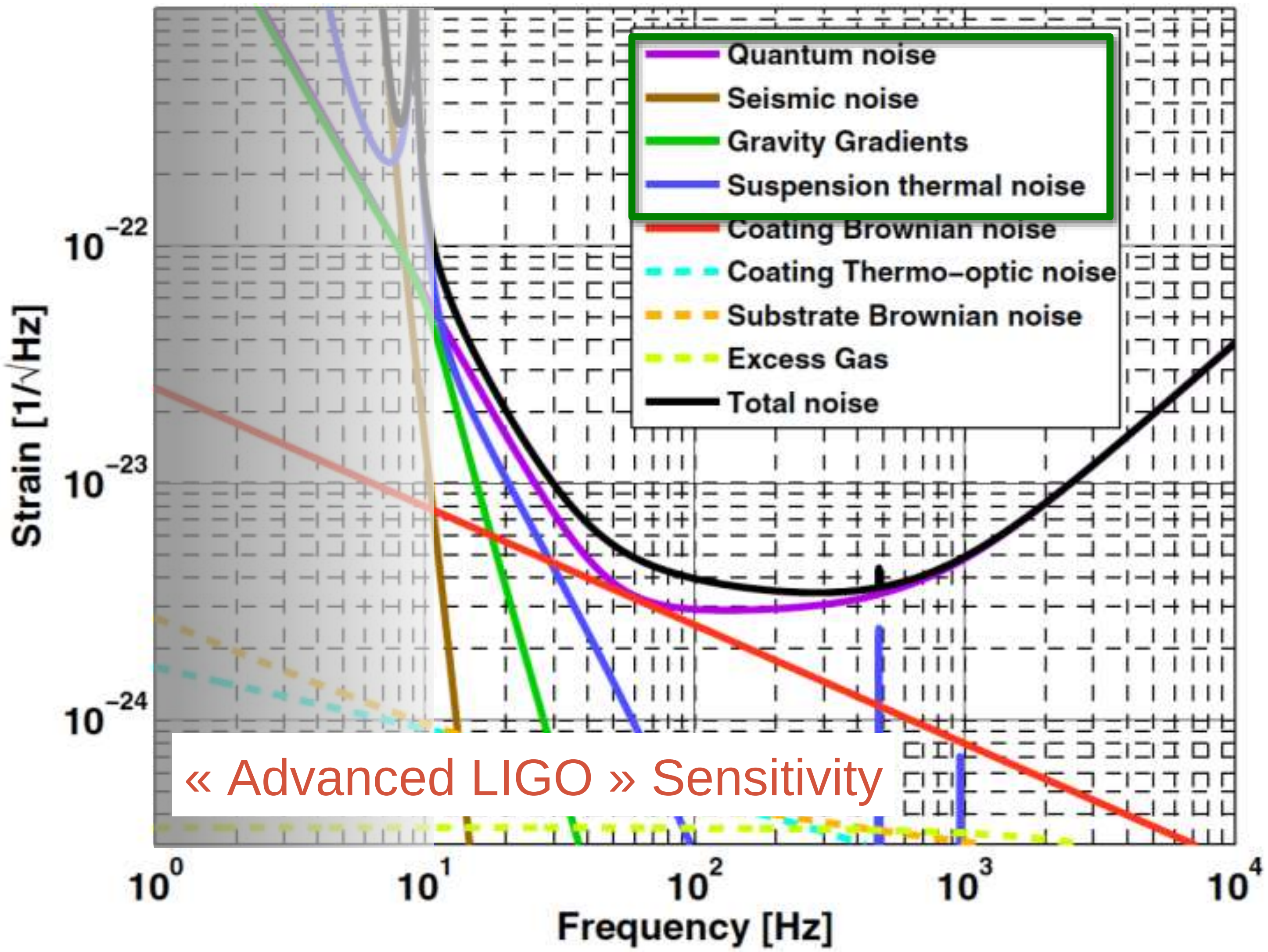


THE MIGA PROJECT







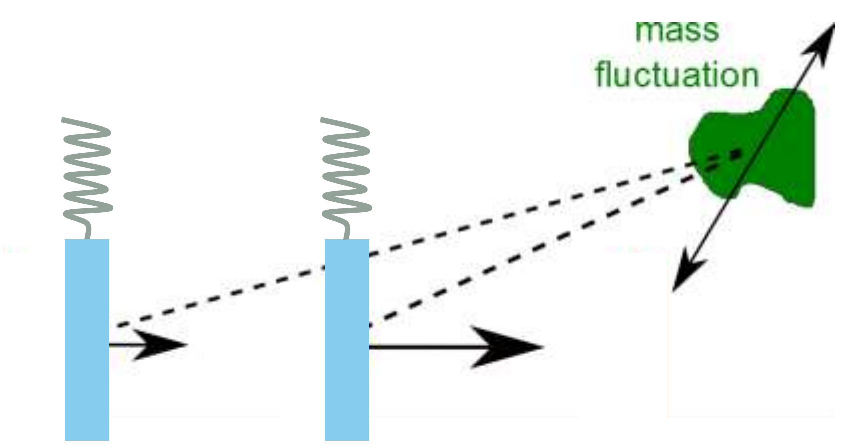


Limitations for f<10 Hz:

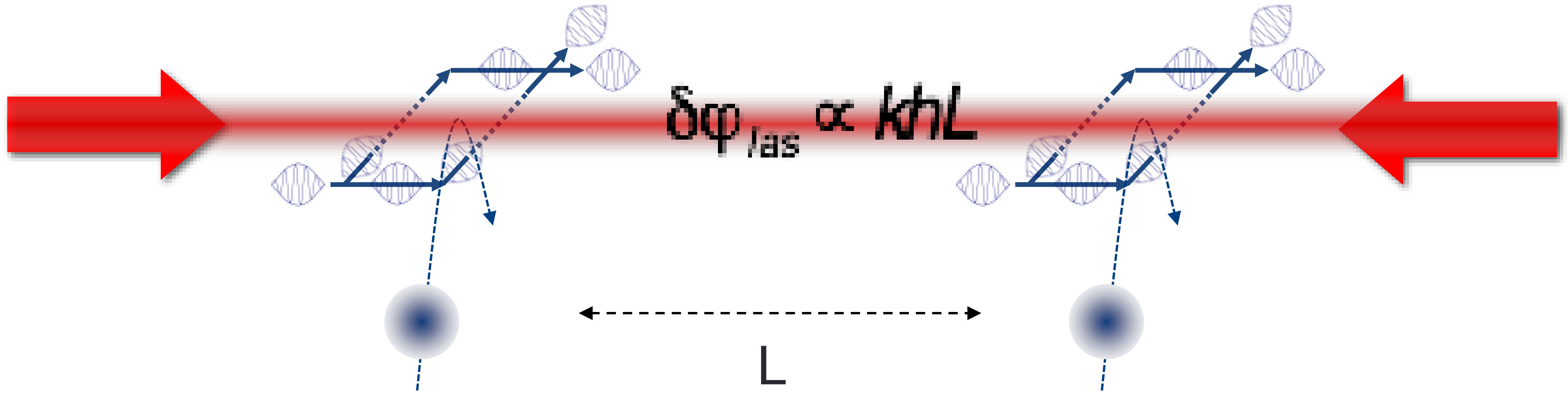
- Radiation pressure noise
- Imperfections of Mirror suspensions
- **« Gravity gradient » noise**

« Gravity Gradient » noise

Fluctuations of the Earth gravity field



Let's use free falling atoms as “test masses” instead of mirrors



PHYSICAL REVIEW D **78**, 122002 (2008)

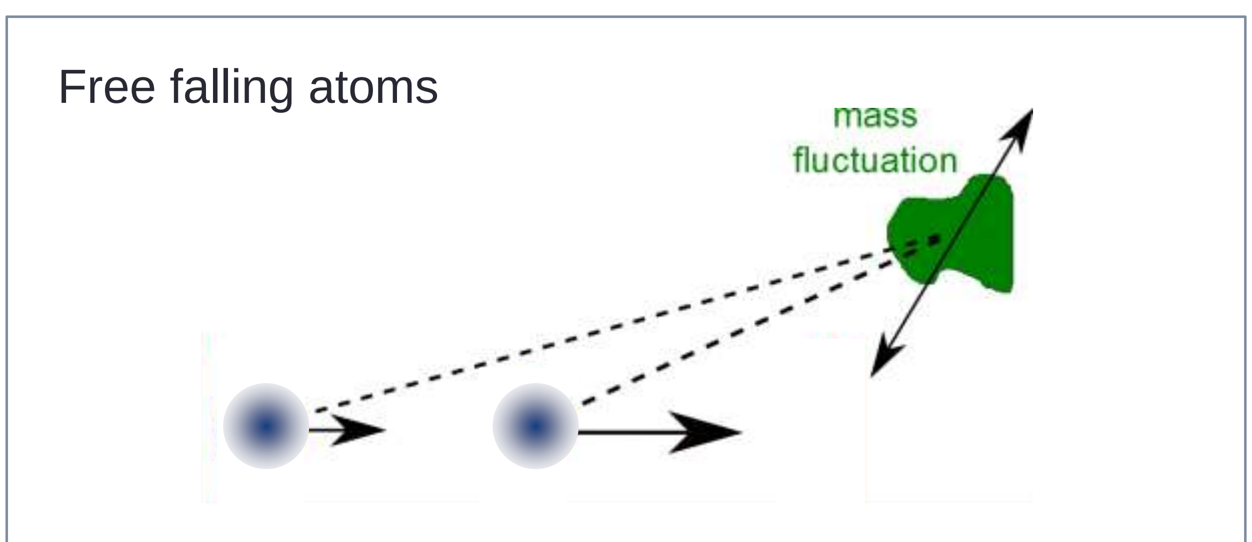
Atomic gravitational wave interferometric sensor

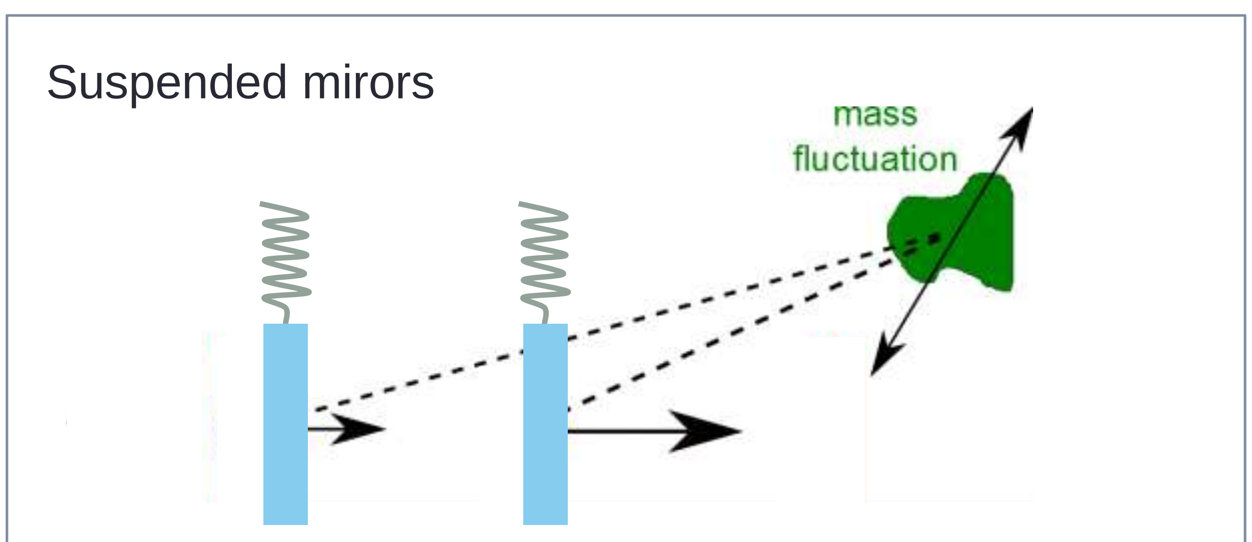
Savas Dimopoulos,[1,*] Peter W. Graham,[2,†] Jason M. Hogan,[1,‡] Mark A. Kasevich,[1,§] and Surjeet Rajendran[1,2,∥]
[1]*Department of Physics, Stanford University, Stanford, California 94305, USA*
[2]*SLAC, Stanford University, Menlo Park, California 94025, USA*
(Received 28 August 2008; published 19 December 2008)

Enable to overcome:

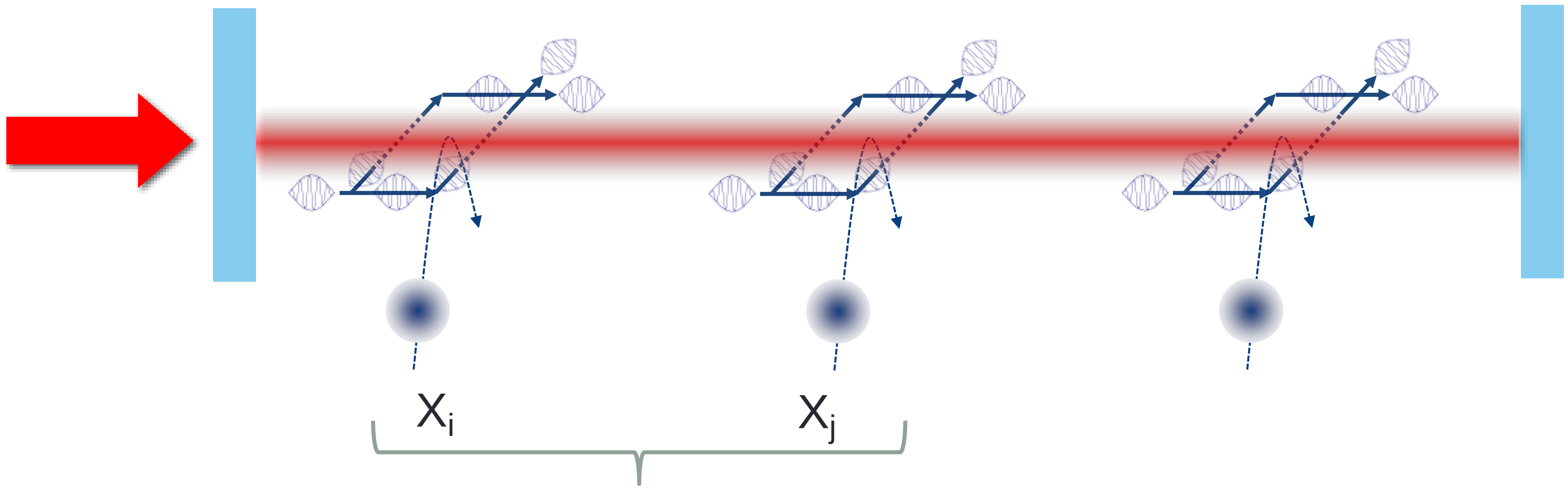
- Limitations related to suspension systems.
- Radiation pressure noise.

Sensitivity to Gravity Gradient Noise is the same !





Example of the MIGA Geometry



$\otimes\rangle_{at}^{i}-\otimes\rangle_{at}^{j}$

- Effet GW $\propto kh(X_i - X_j)$
- Gravity gradient $\propto 2kT^2\left[a(X_i) - a(X_j)\right]$

Discrimination between GW effects and gravity gradients using the spatial resolution of the antenna

PHYSICAL REVIEW D 93, 021101(R) (2016)

Low frequency gravitational wave detection with ground-based atom interferometer arrays

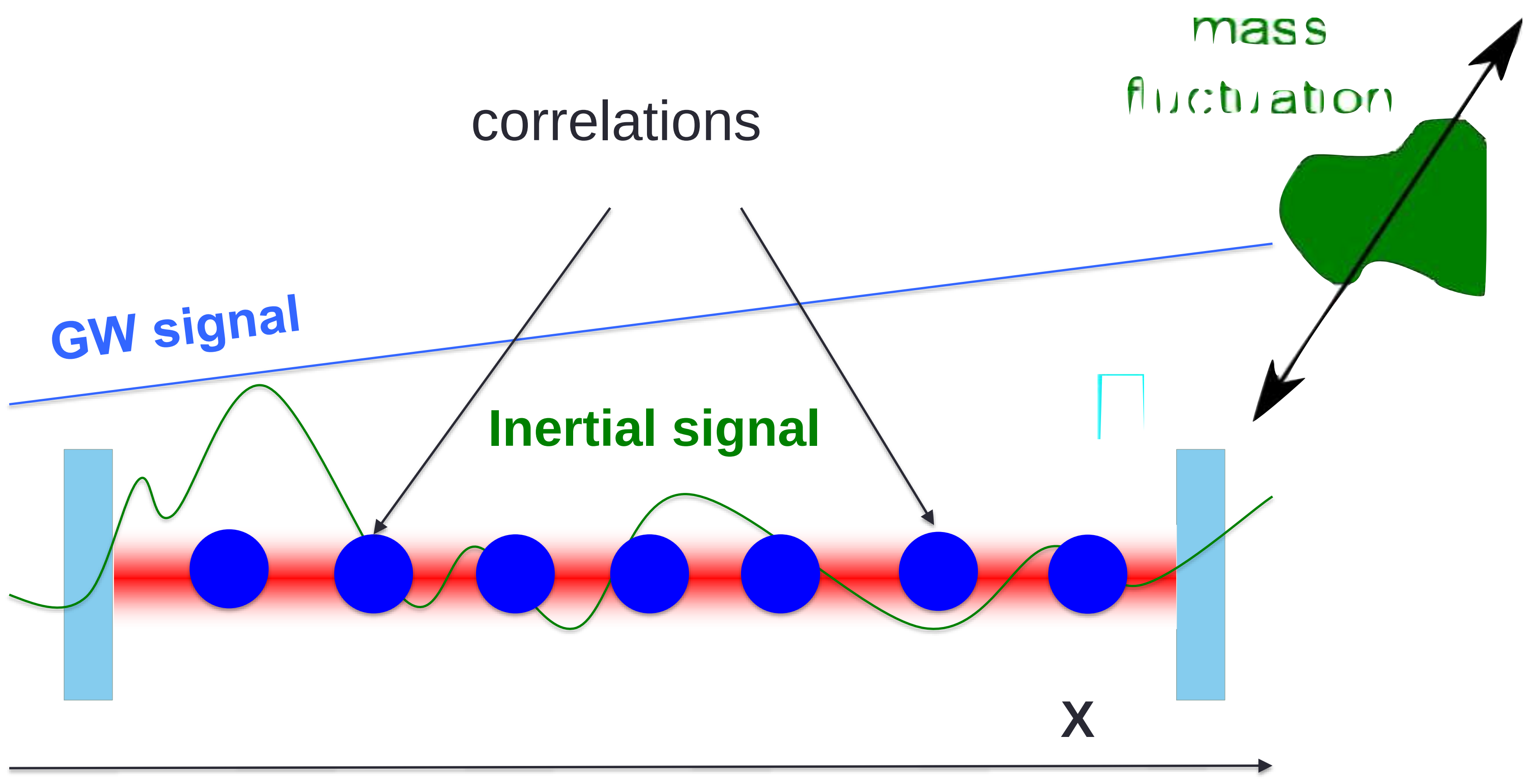
W. Chaibi,[1,*] R. Geiger,[2,†] B. Canuel,[3] A. Bertoldi,[3] A. Landragin,[2] and P. Bouyer[3]
[1]*ARTEMIS, Université Côte d'Azur, CNRS and Observatoire de la Côte d'Azur, F-06304 Nice, France*
[2]*LNE-SYRTE, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Universités, UPMC Univ. Paris 06, 61 avenue de l'Observatoire, 75014 Paris, France*
[3]*LP2N, Laboratoire Photonique, Numérique et Nanosciences Université Bordeaux-IOGS-CNRS:UMR 5298, rue Mitterrand, F-33400 Talence, France*
(Received 23 June 2015; published 15 January 2016)

- **Low frequency (10^{-2}-10 Hz) GW detection limited by detection noise**
- **Measures of the local gravity field = Geoscience**

Use of AI offers possibility to spatially resolve gravity

→GW have long wavelength while GG have short characteristic length of variation (1 m – few km)

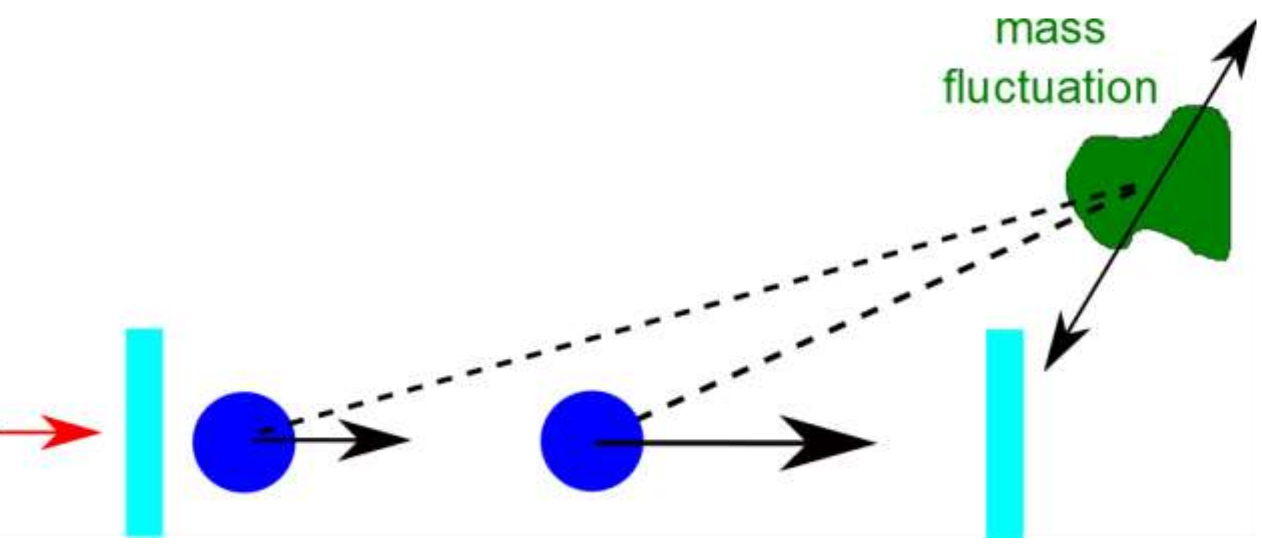
→**Correlations between distant sensors provide information on the GG noise and allows to discriminate it from the GW signal**

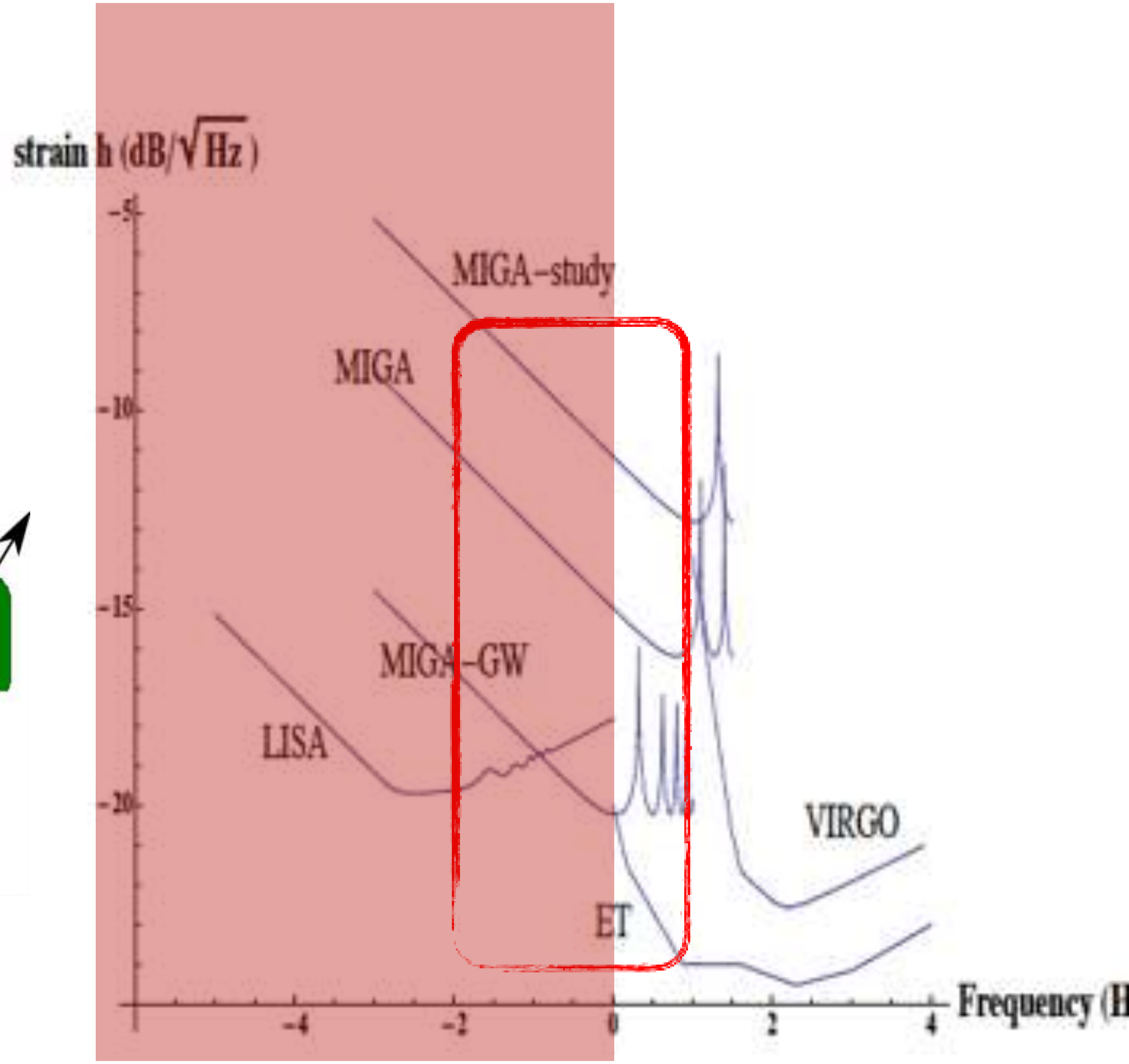


CAN WE BEAT THE NEWTONIAN NOISE LIMIT

GGN is a fundamental limit for ground based GW detectors

- Noise due to nearby mass fluctuation
- Limiting factor under 1-10Hz





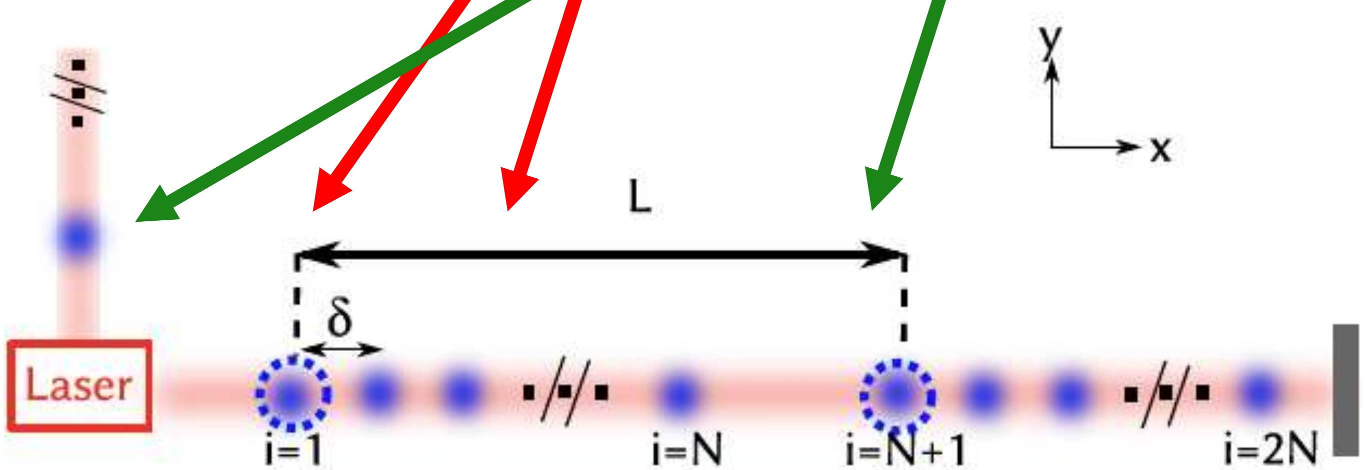
Strain sensitivity

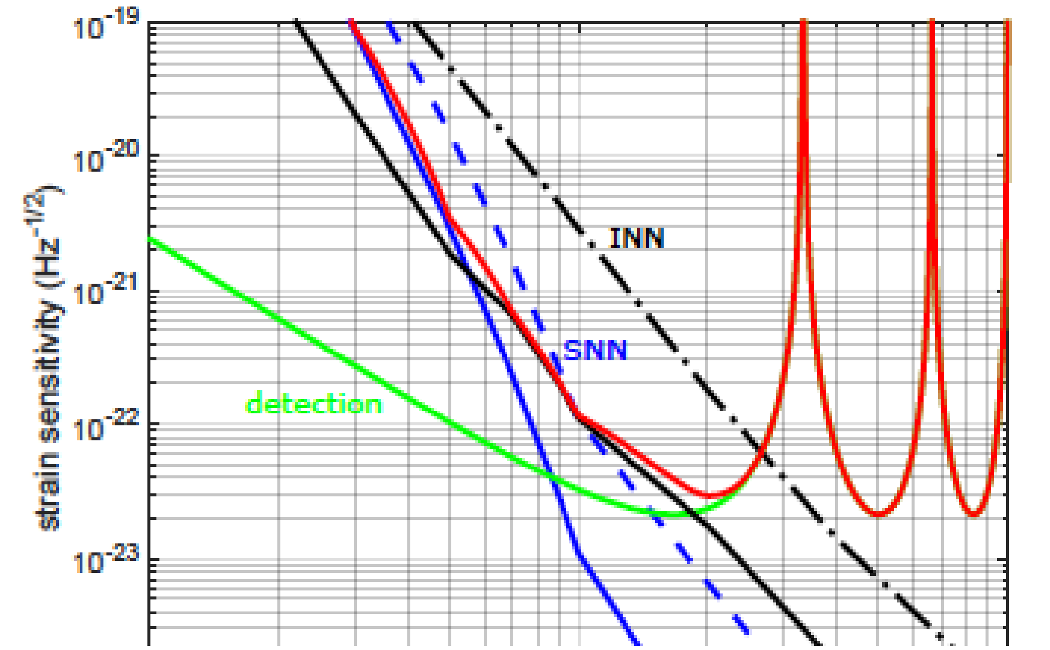
$$S_h(\omega) = \frac{S_a(\omega)}{\omega^4 L^2} + \frac{4S_\epsilon(\omega)}{16NL^2(2nk)^2\sin^4(\omega T/2)}.$$

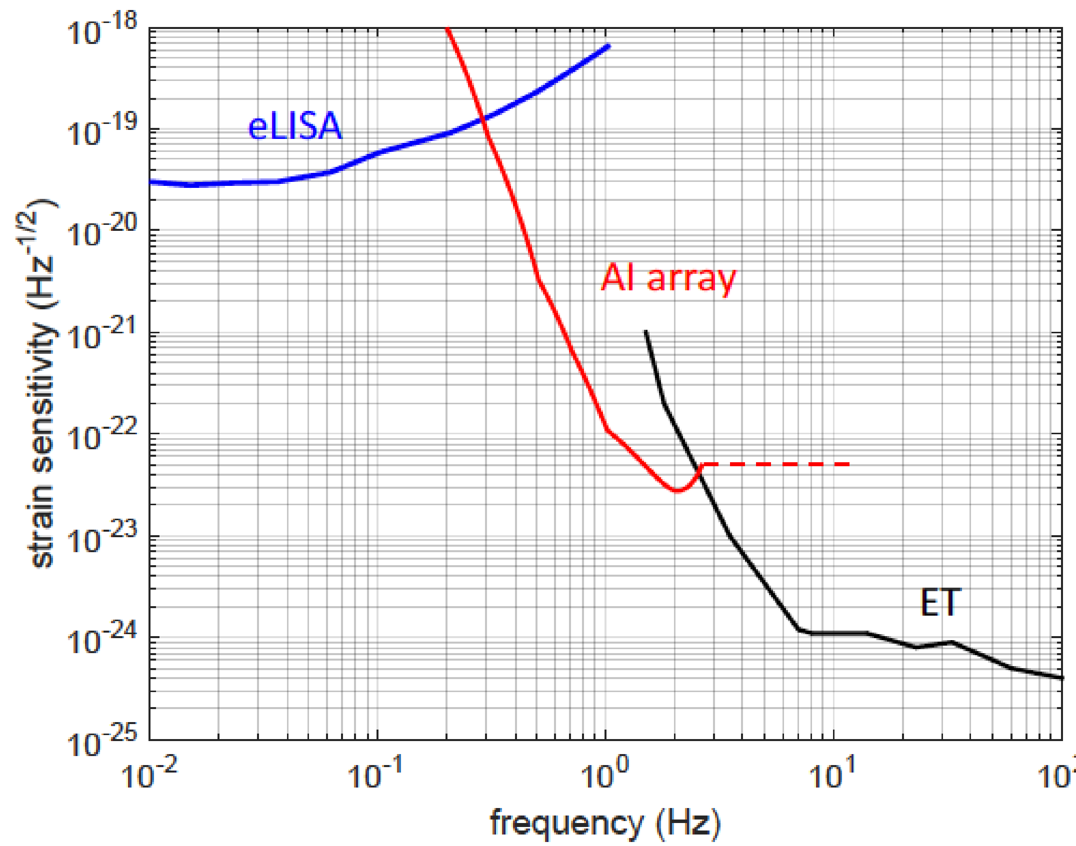
Shot noise

Seismic noise

$$S_a(\omega) = \frac{1}{N^2}\sum_{i,j=1}^{2N}\left(\mathcal{C}_\parallel(X_i, X_j, \omega) + \mathcal{C}_\perp(X_i, Y_j, \omega)\right)$$

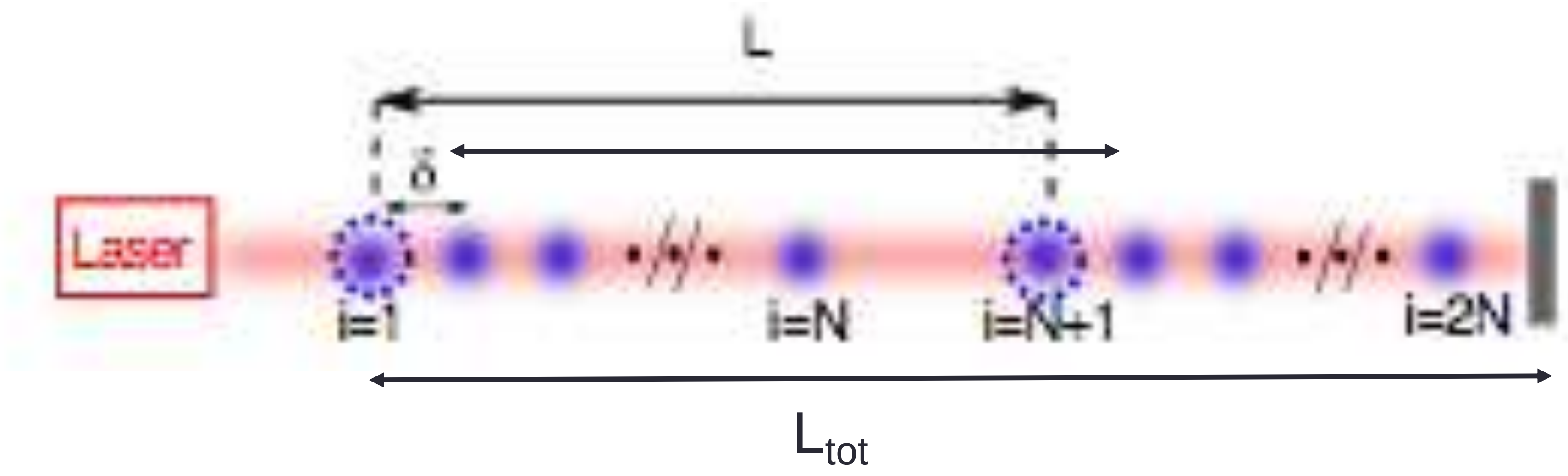






W. Chaibi, et al. Phys. Rev. D 93, 021101(R), 2016

Dense arrays of Atom Interferometers could be used as future GW dete

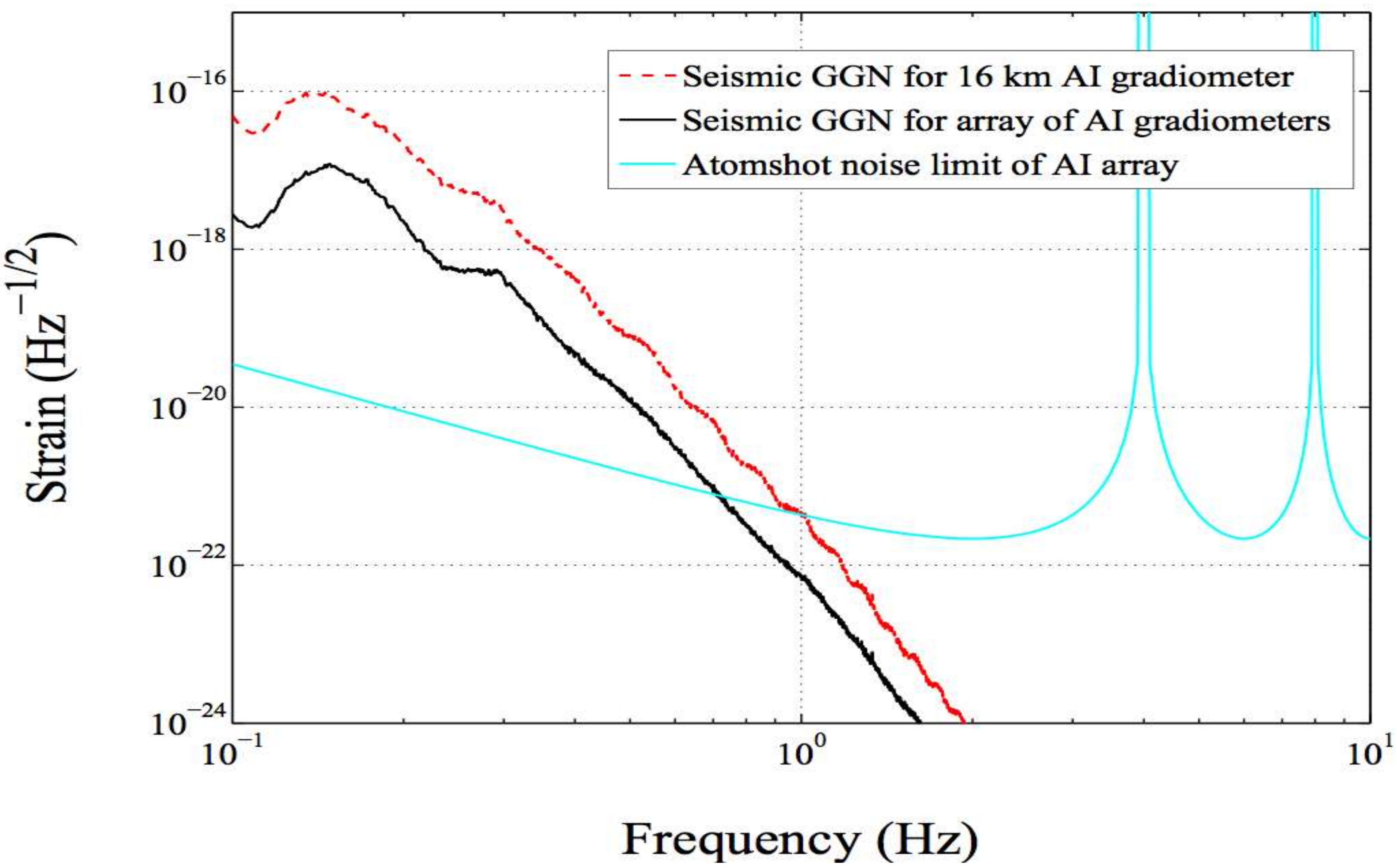


- L_{tot}=32 km
- N=80 gradiometers
- baseline L = 16 km

- Gravitational Wave signal can be extracted using a spatial averaging method
- N Correlated gradiometers enable to average the GGN over several realizations

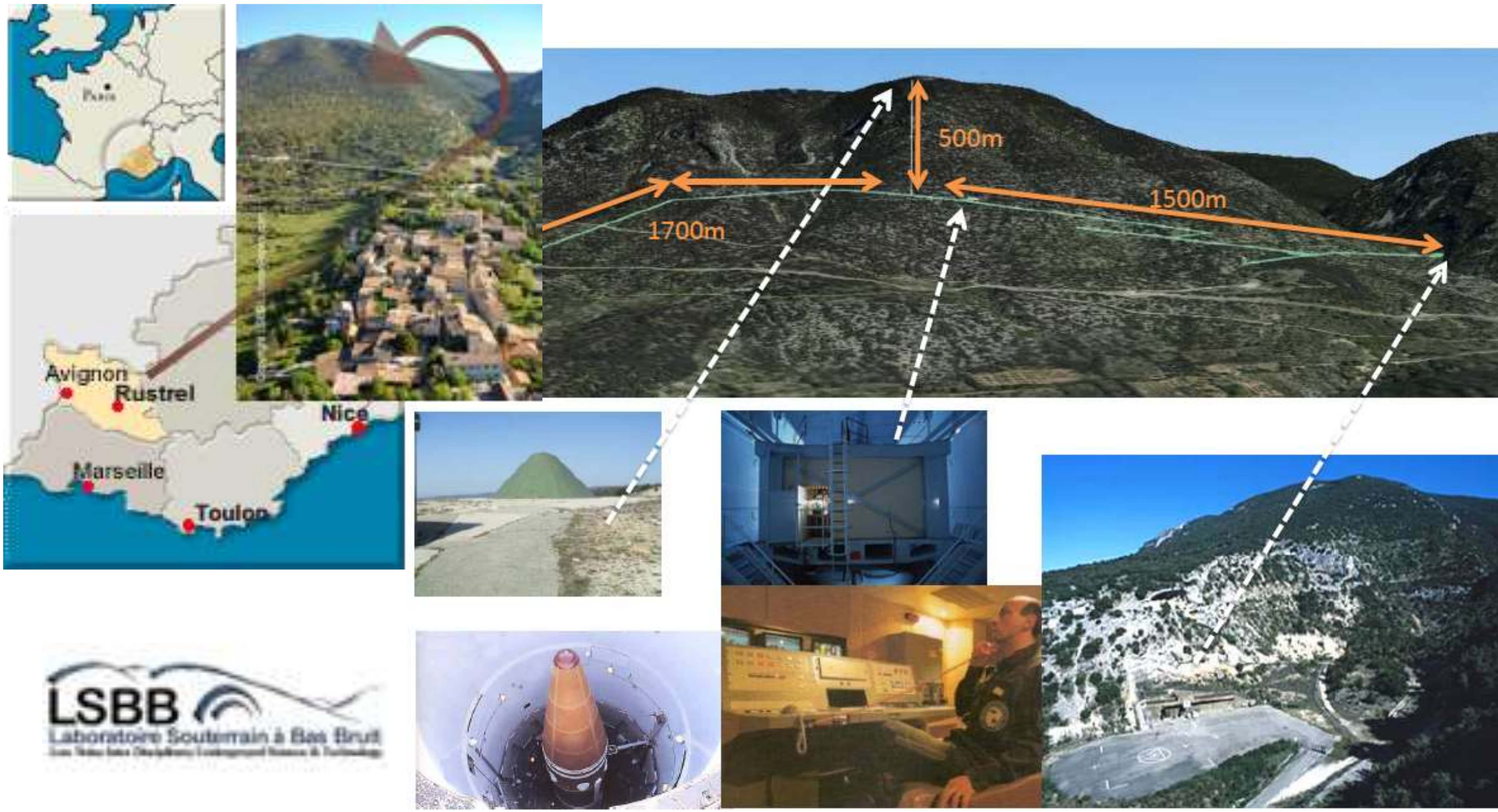
$$H_N(t) = \frac{1}{N}\sum_{i=1}^{N}\psi_i(t)$$

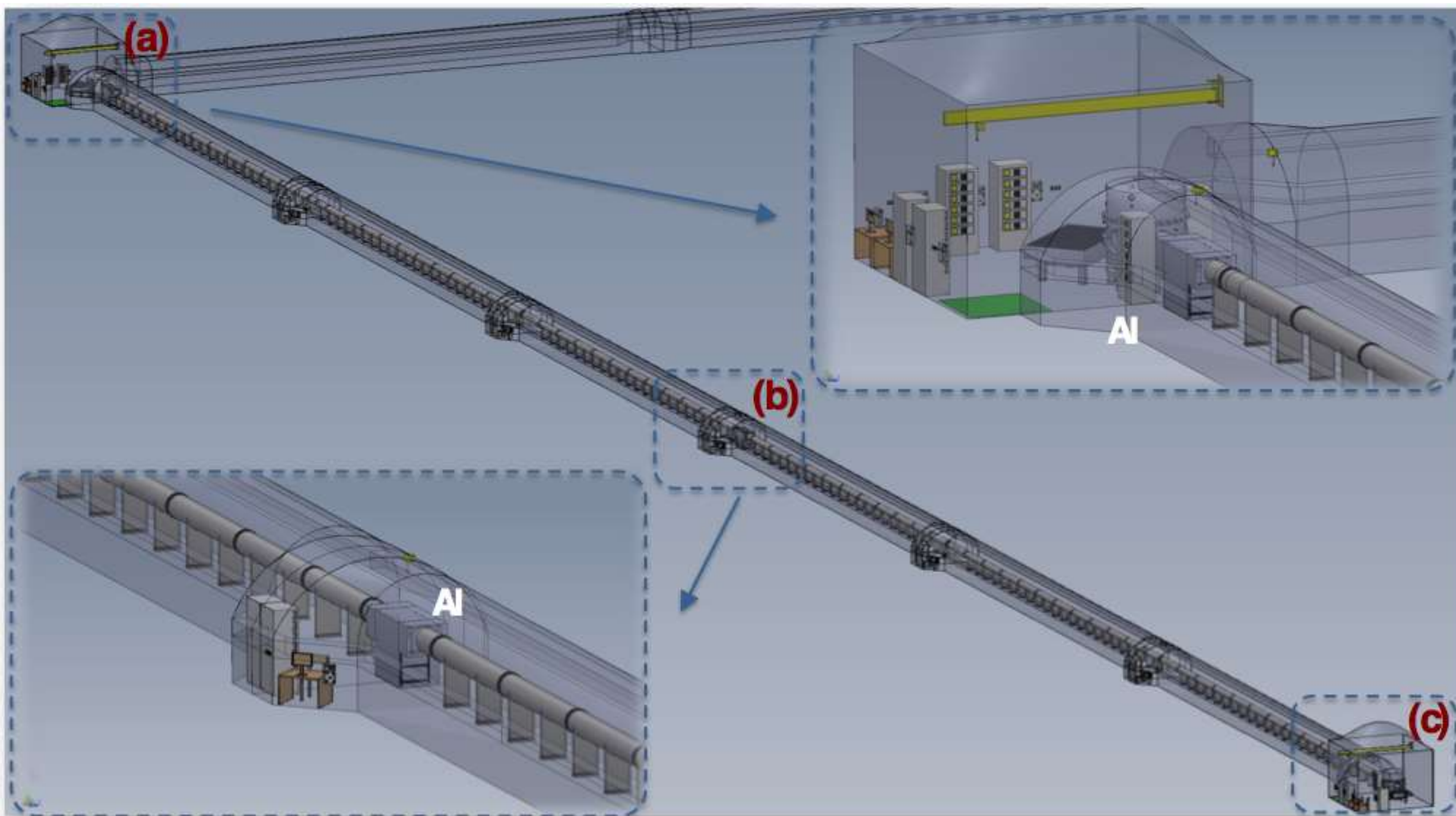
- The geometry of the detector (™,L) is chosen with respect to the spatial correlation properties of the GGN.

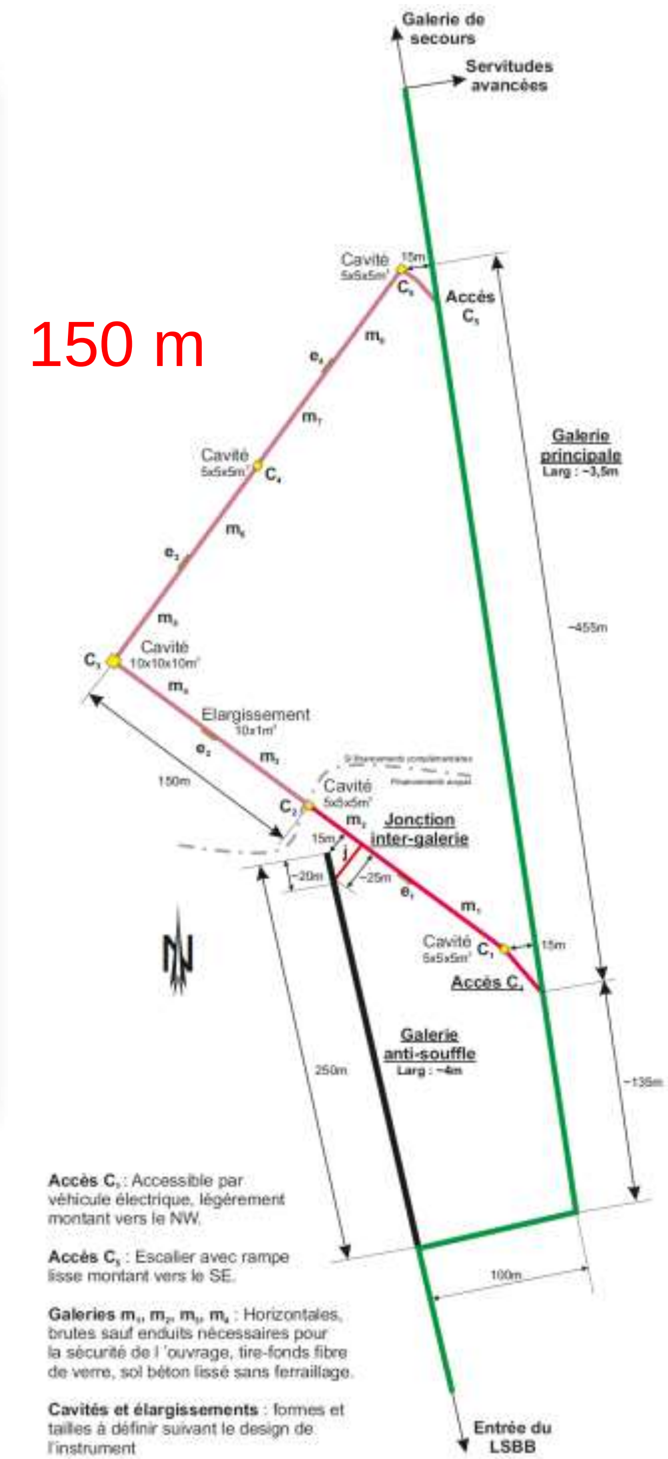


- Gain of about factor 10 in the 100 mHz 1 Hz band
- Space for improvement using all spatial information of the network (use different baseline L in the numerical treatment)

RESEARCH INFRASTRUCTURE AT LSBB







<u>Construction of different subsytems in on the way</u>

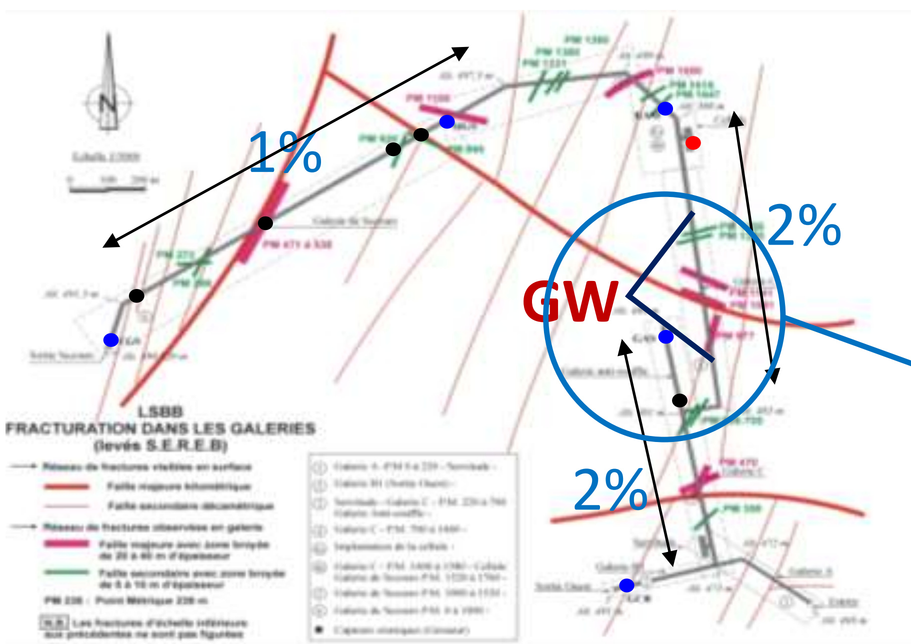
A prototype AI and a full suspension is available at LP2N

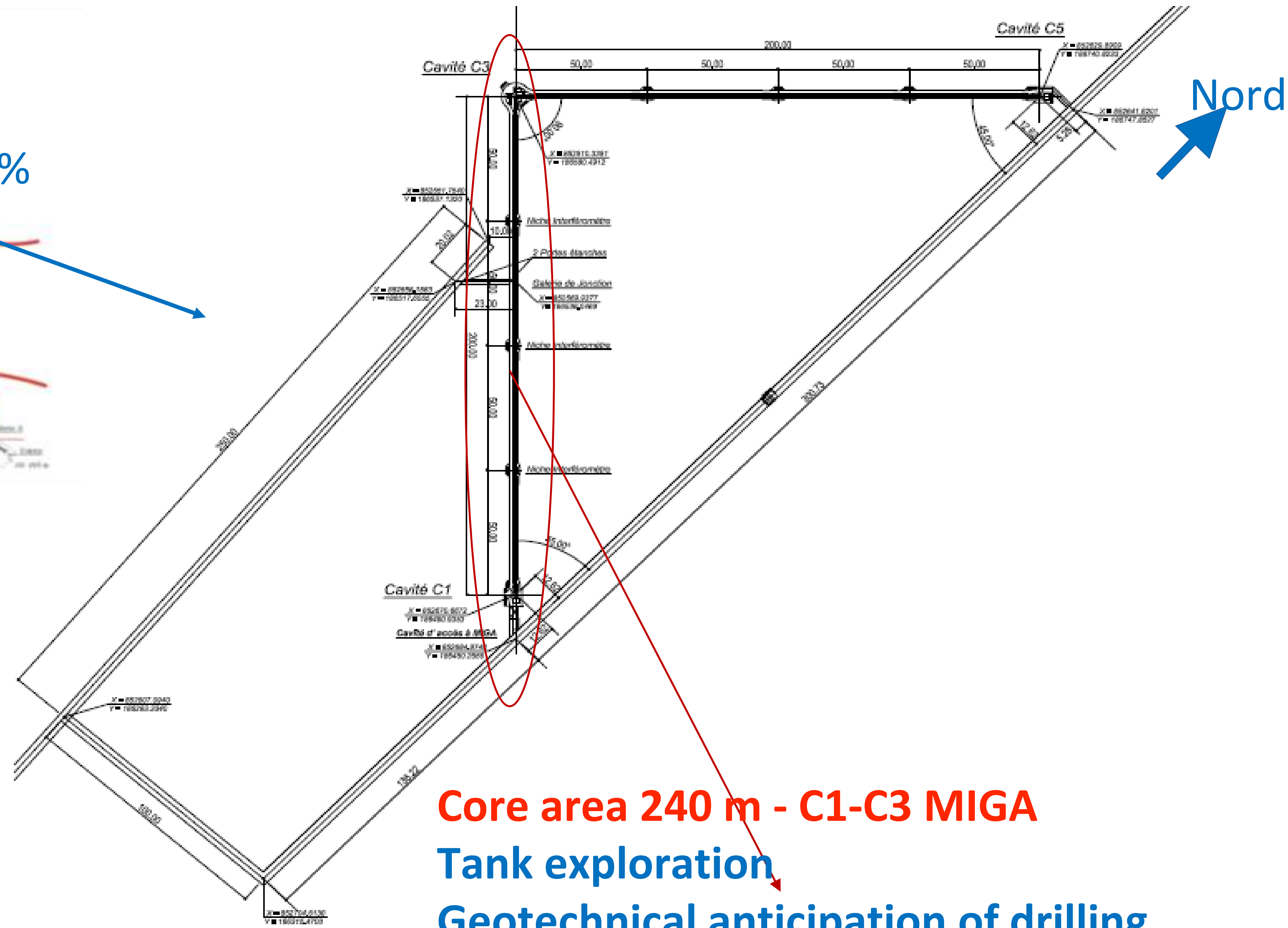
Start commissioning of the 10 m prototype in 2018

Start Gallery preparation mid 2018

MIGA installation mid 2019

First operation 2020





Core analysis and wall imaging

Geological modeling

Carbonated reservoir prediction

Environment

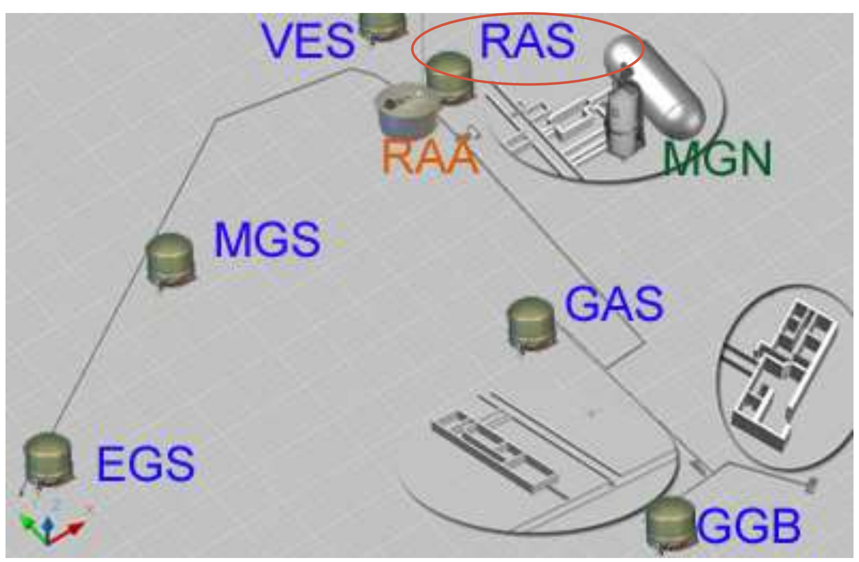
hydro-geological analysis around

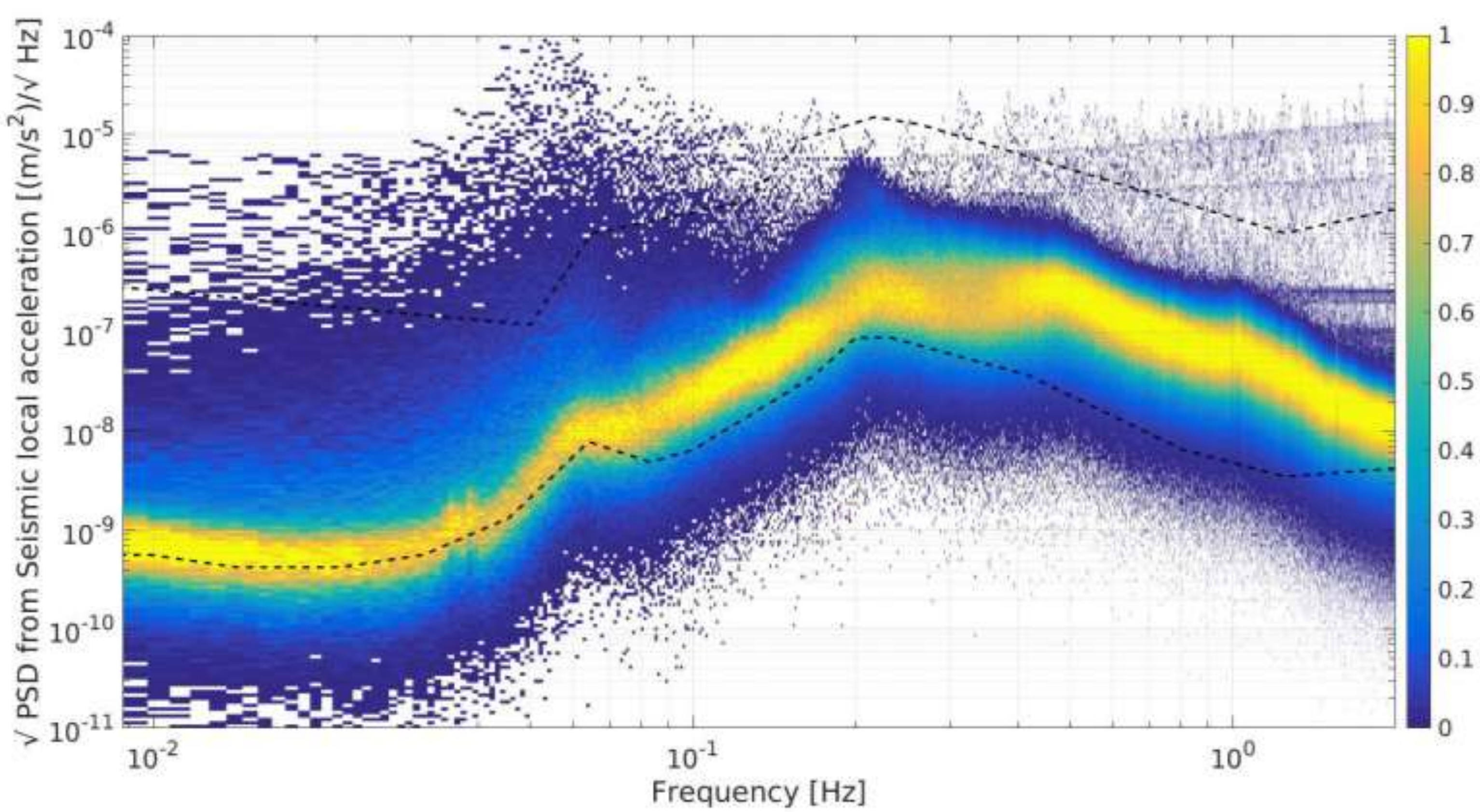
Sources Gravity Gradient noise on detector site (10^{-2}-10 Hz)

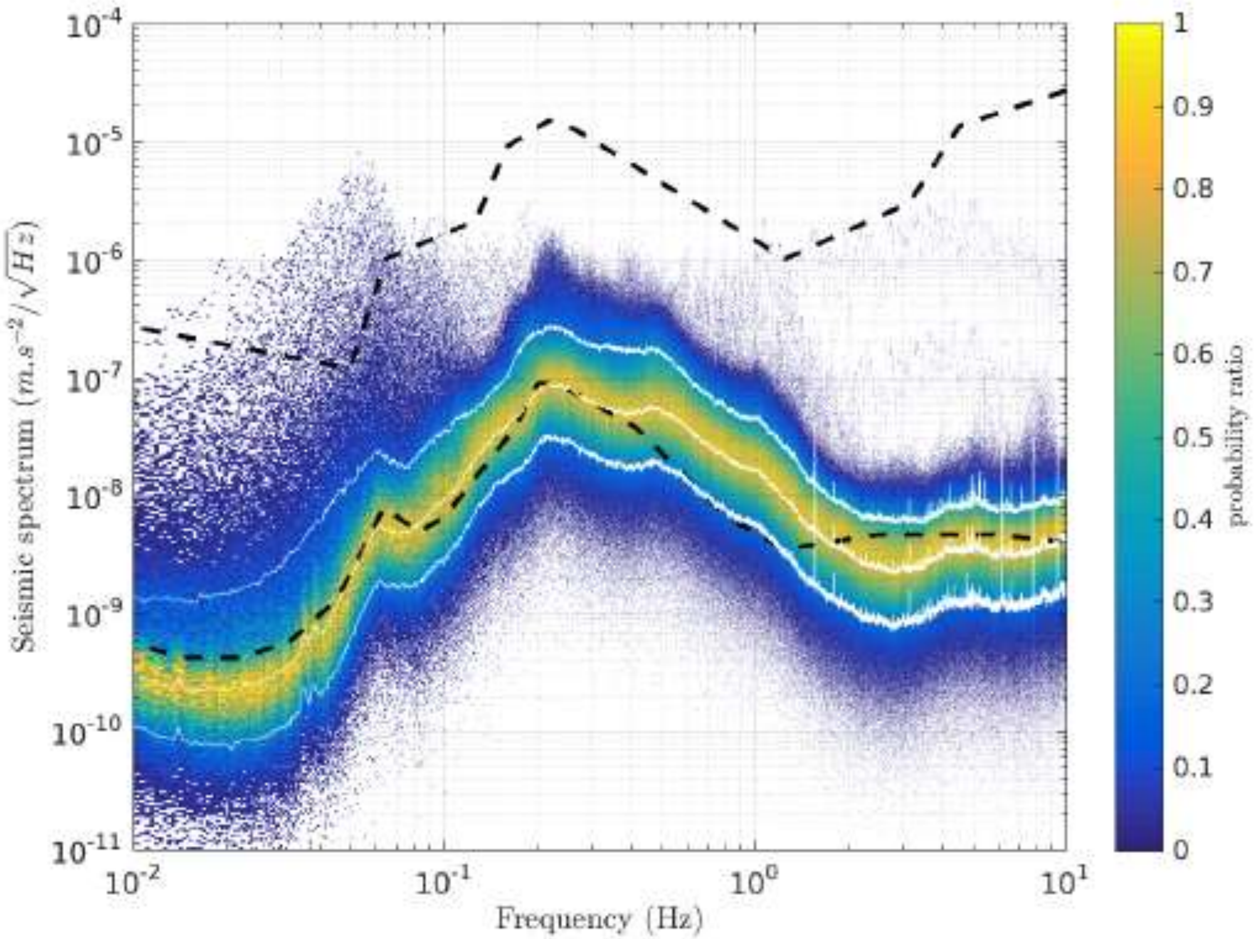
- Seismic GGN
- Atmospheric GGN
- Other : geophysical properties (hydrology), linked to human activity

Seismic GGN for MIGA at LSBB

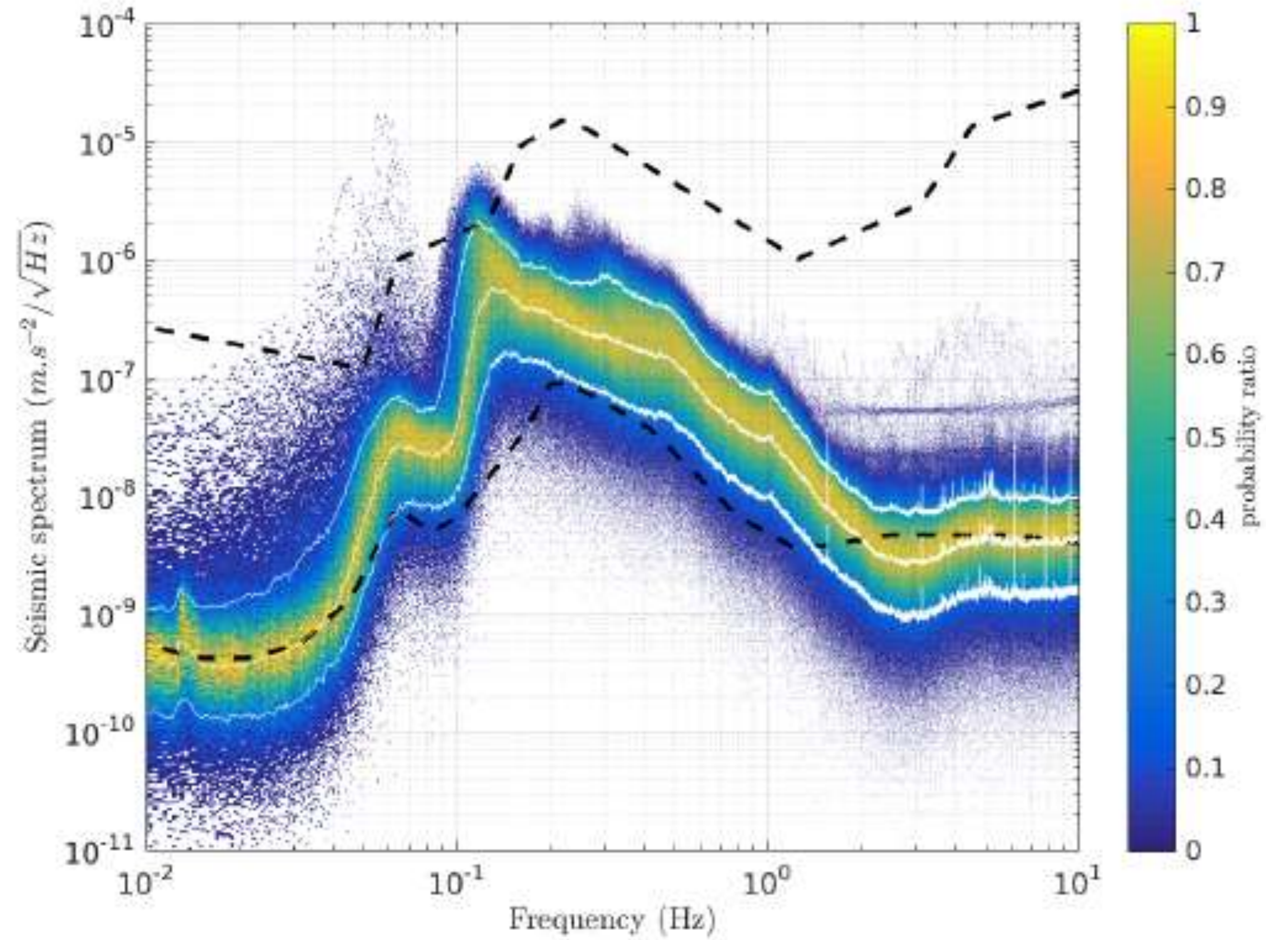
- STS-2 sensor





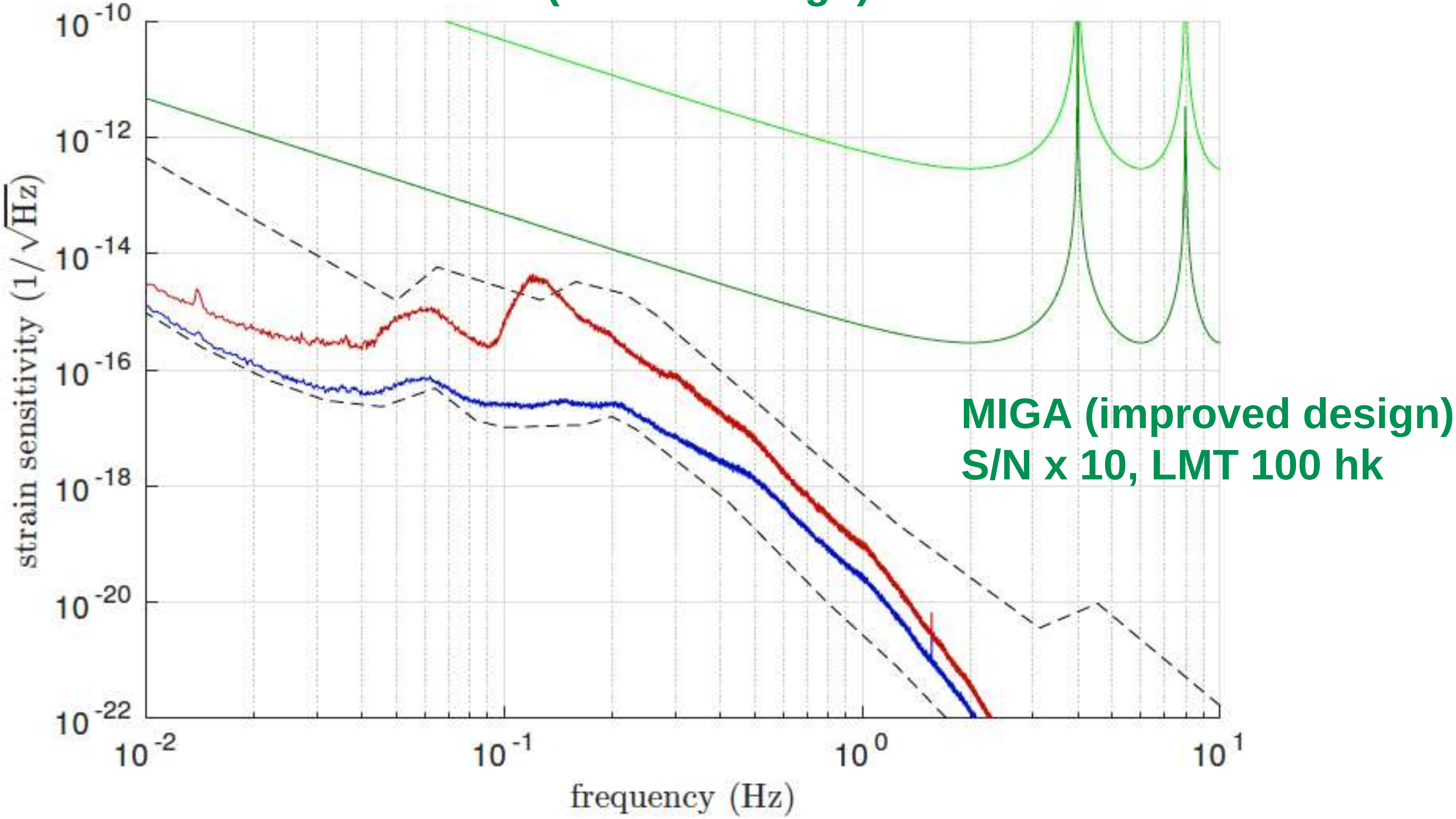


(a) on a "quiet" month (august)

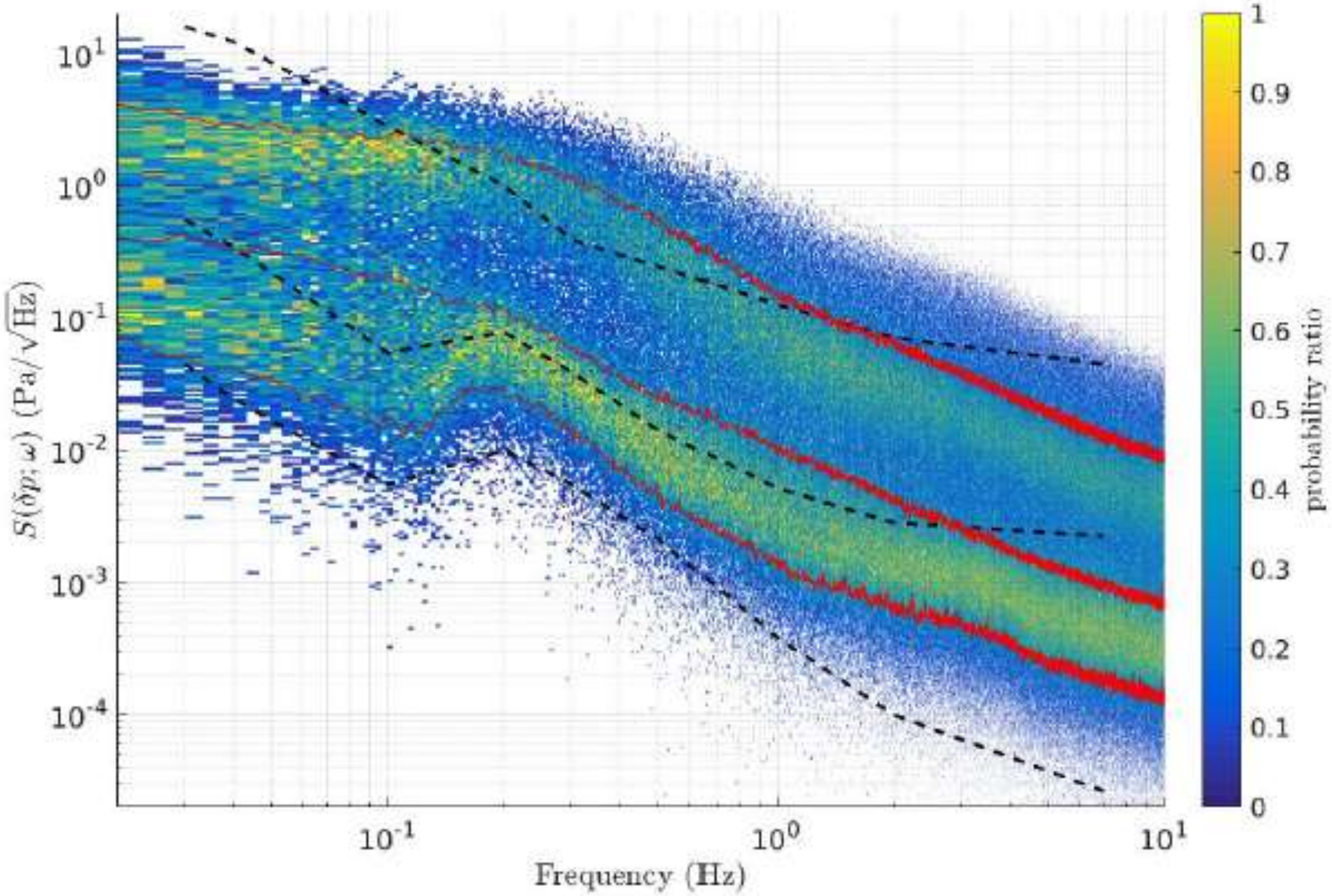


(b) on a "noisy" month (February)

MIGA (current design)

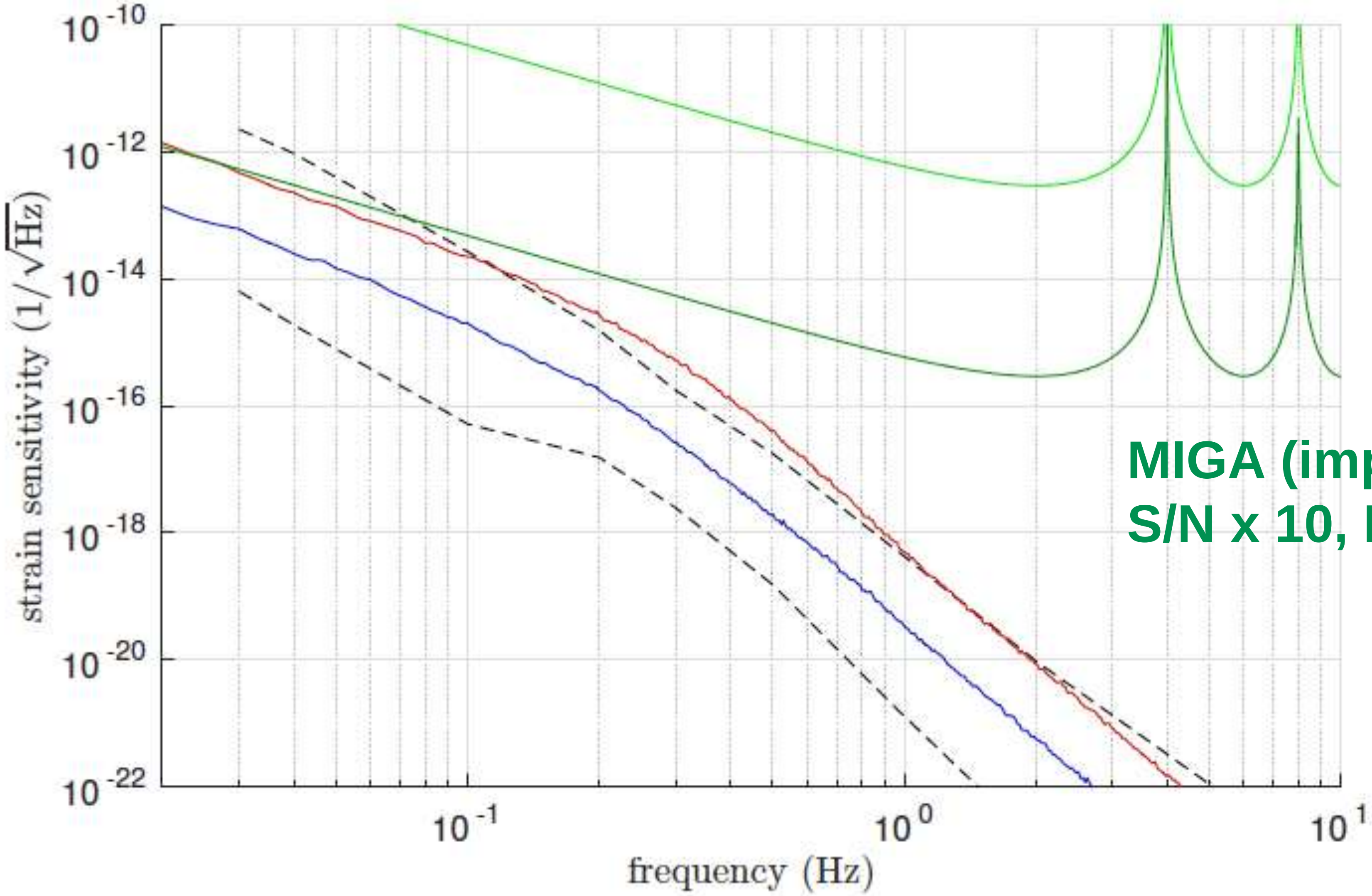


MIGA strain sensitivity. In blue (resp. red) seismic GGN projection from Lsbb 50th percentile of a quiet week (resp. 90th percentile of a noisy week), in dashed black from Peterson model data, in green detection noise for MIGA in its initial configuration (light green) and for an improved version (dark green).



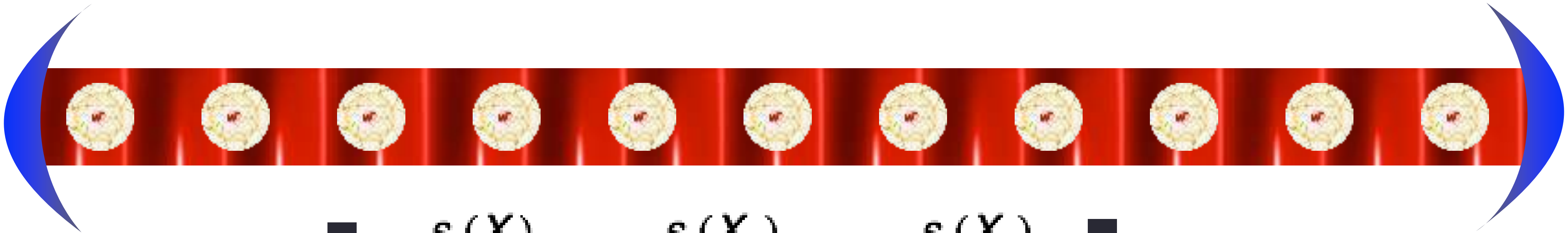
Histogram of the outside pressure variations 500 m above the future MIGA gallery with 10th, 50th and 90th percentile in red and Bowman low, mid and high model in dashed black.

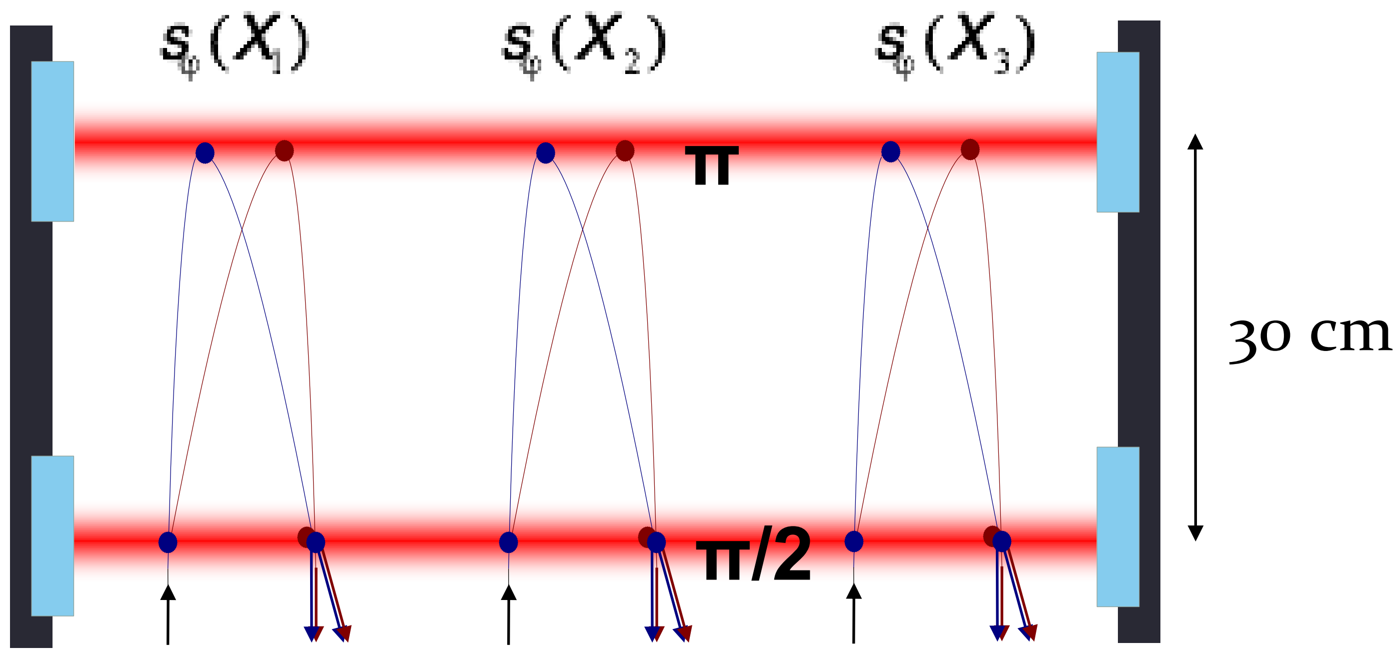
MIGA (current design)

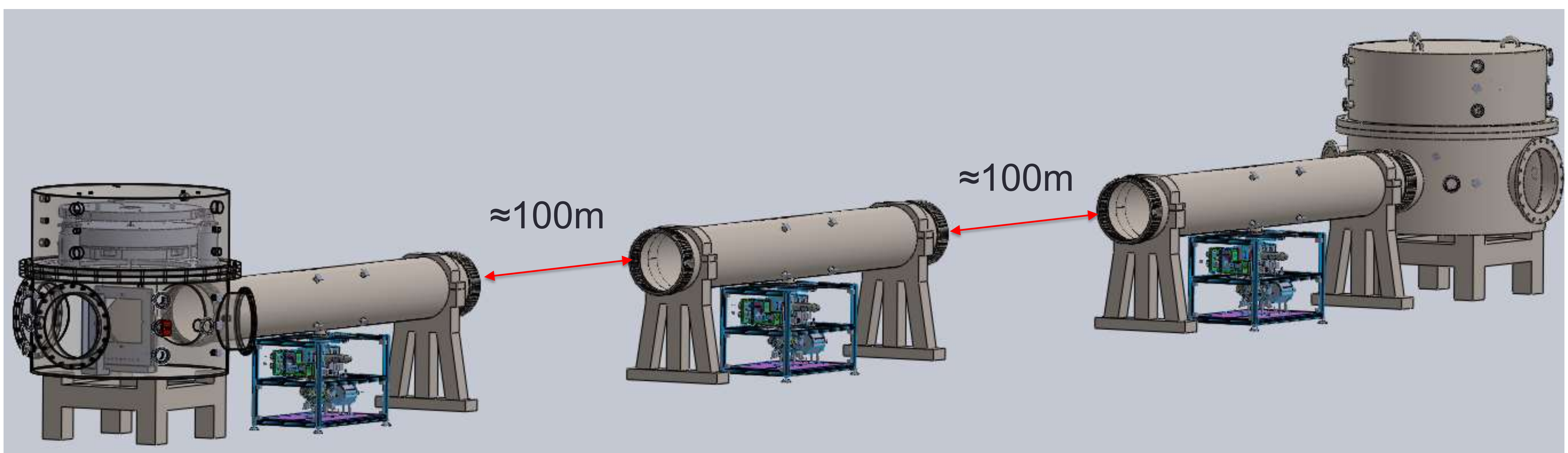


MIGA (improved design)
S/N x 10, LMT 100 hk

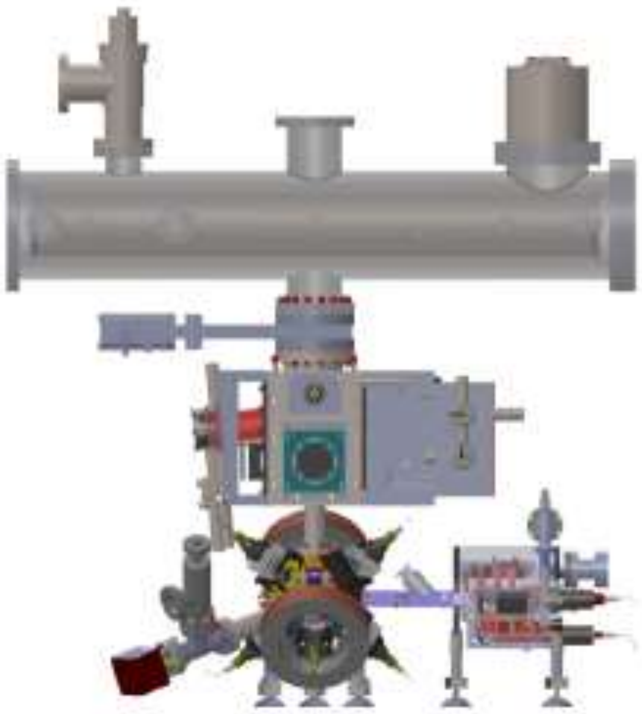
MIGA strain sensitivity for the infrasound GGN, with data from Bowman model (dashed black) and from data gathered on site at the Lsbb (50th percentile in blue and 90th percentile in red).




$s_\phi(X_1)$
$s_\phi(X_2)$
$s_\phi(X_3)$
π
π/2
30 cm


≈100m
≈100m

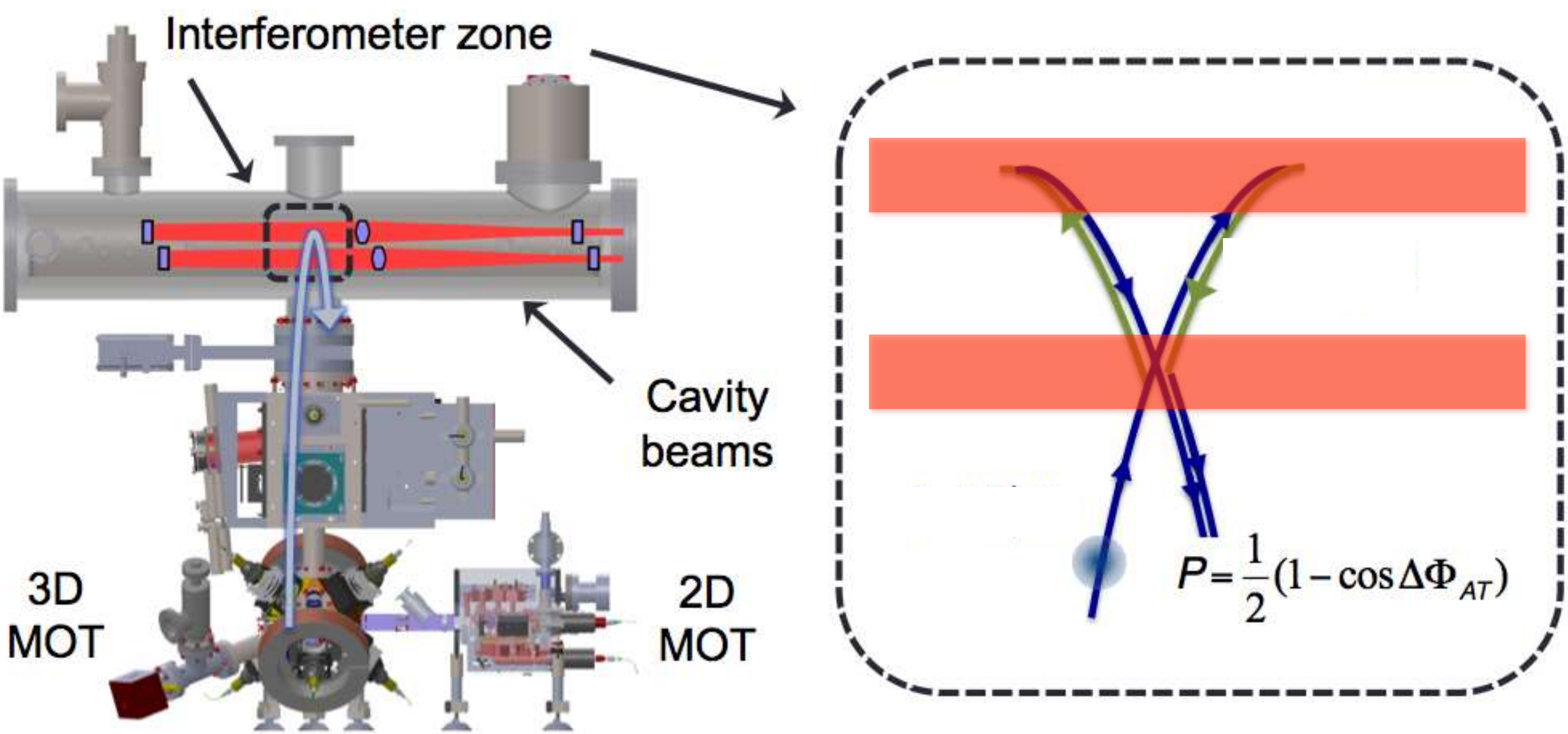
Accelerometer

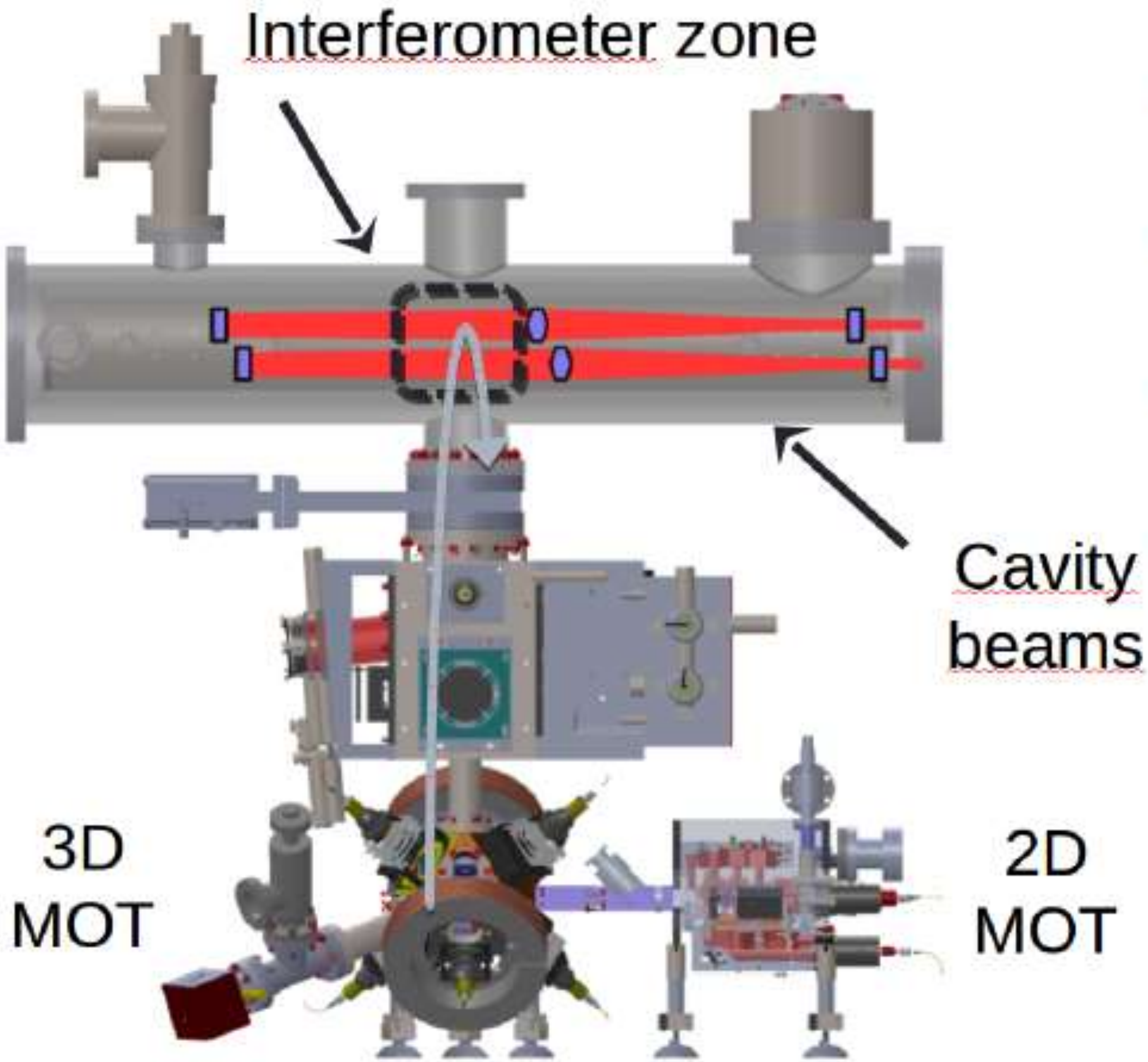


- One cold atom source
- two parallel 80 cm long cavities
- Study cavity enhanced Bragg pulses

Gradiometer

- Two cold atoms sources
- Two parallel 5.7 m long cavities
- Study of differential measurements (gradiometer)
- Testing the equipment

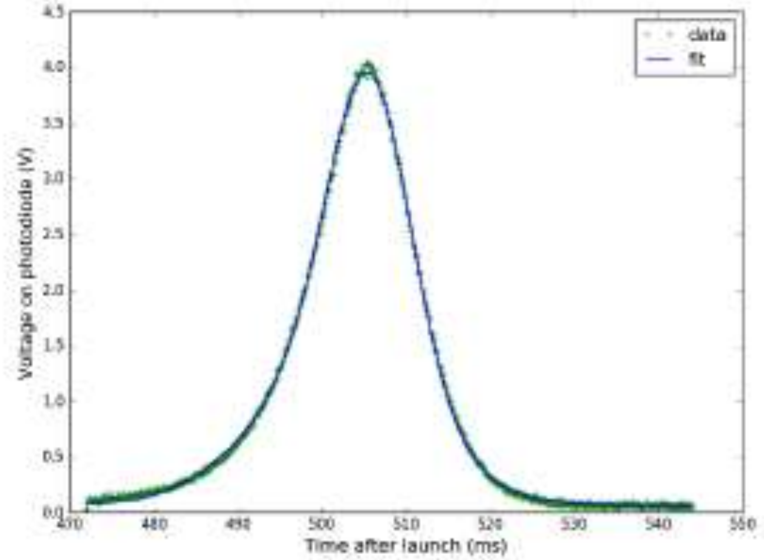

Interferometer zone
Cavity beams
3D MOT
2D MOT
$P = \frac{1}{2}(1 - \cos \Delta\Phi_{AT})$



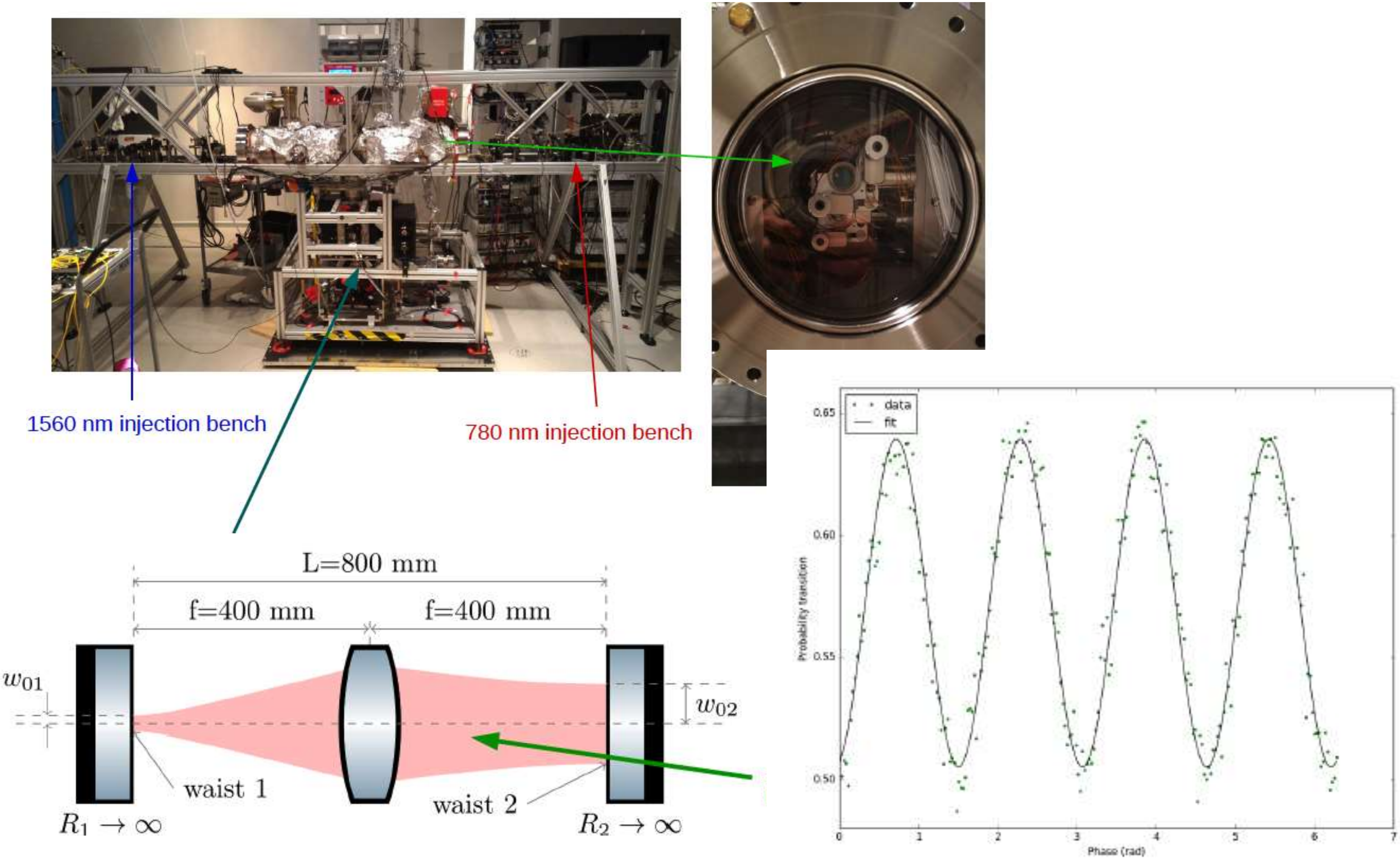
^{87}Rb $\sim 10^{-10}$ mbar

Fountain configuration

- Loading a 3D Magneto-optical trap (MOT) with a 2D MOT
- Preparation : velocity an magnetic selection with Raman beams
- Interferometry with intracavity Bragg pulses
- Detection by fluorescence with sheet of lights



T ~ 4 μK


1560 nm injection bench
780 nm injection bench
L=800 mm
f=400 mm
f=400 mm
w_{01}
w_{02}
waist 1
waist 2
$R_1 \to \infty$
$R_2 \to \infty$
data
fit
Probability transition
Phase (rad)
0.50
0.55
0.60
0.65
0
1
2
3
4
5
6
7

2012

2013

2014

2015

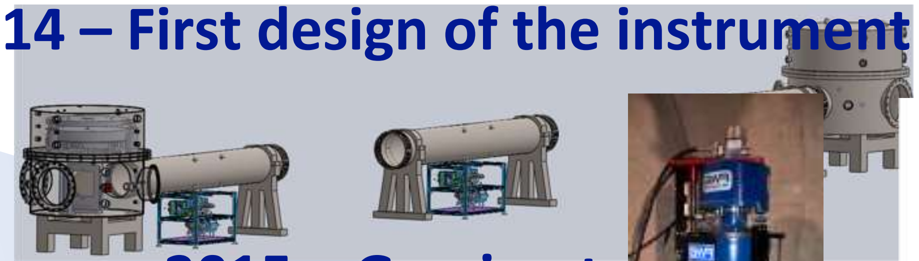
2016

2017

2018

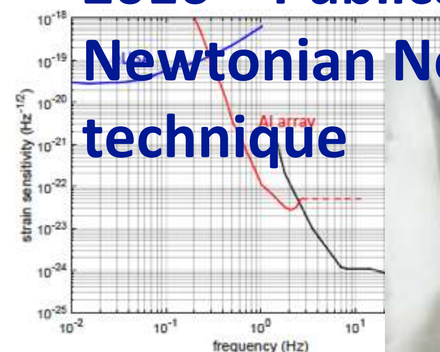
2019

2014 – First design of the instrument



2015 – Gravimeter

2016 – Publication (PRD) of the Newtonian Noise suppression technique



2013 - Project manager hired from VIRGO

2017 – Gallery preparations

2017 – 3 sensors ready

2015 – First suspension and sensc prototype

2016 – GW discovery

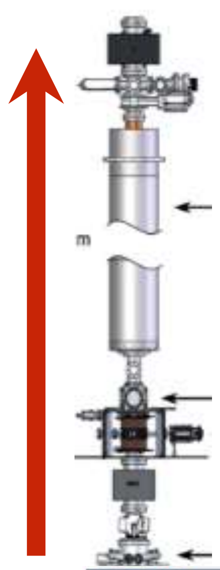
2018 - prototype

2019 Instrument online

European Laboratory for Gravitation and Atom-interferometric Research (ELGAR)

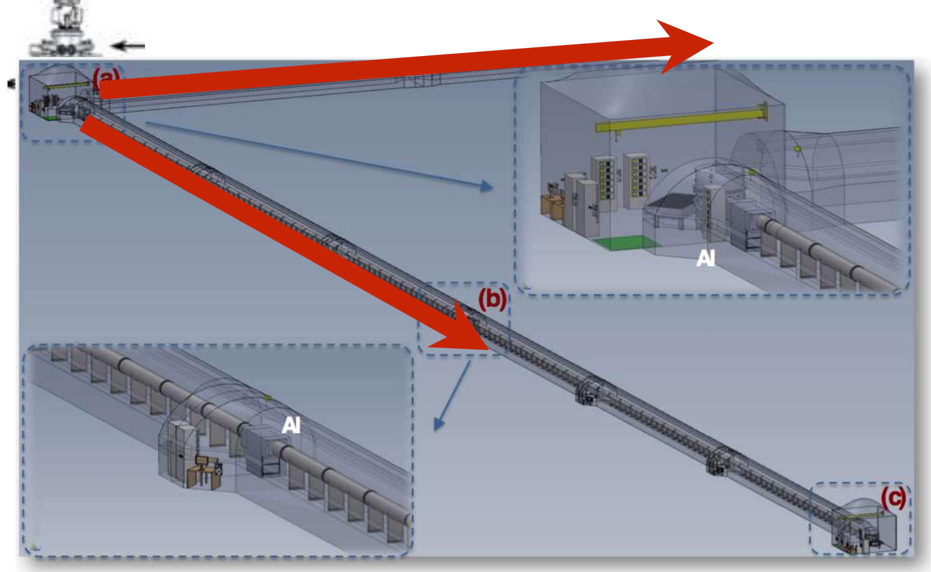
Sync with other GW observation instruments

3D antenna configuration



Arm Length (1 - 10 km)
Number of AI nodes (10 - 100)

Strain :10^{-20}
Frequency 0.1 - 10 Hz



"full band analysis", gravitational noise analysis improvement, joint data management and analysis