D1565
EGU2020-8392

# Quantum Absolute Sensors for Gravity measurements

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https://syrte.obspm.fr/spip/science/iaci/

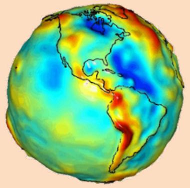
# Gravimetry & Sensors

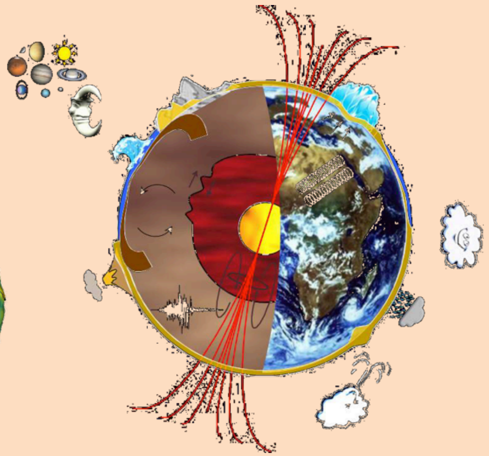
$$\vec{g} \qquad g = |\vec{g}| \qquad \text{grad } \vec{g}$$

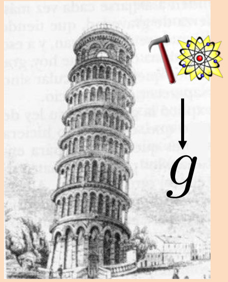
$$1\ \mu Gal = 10\ nm.s^{-2} \sim 10^{-9} g \qquad 1\ E = 10^{-9}\ s^{-2} = 0.1\ \mu Gal.m^{-1}$$

## Geophysical studies

*Crustal deformations, mass changes, geoid, …*







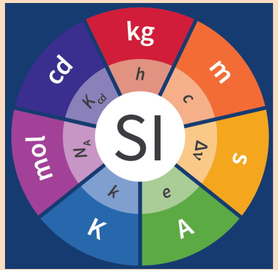

## Tests of Fundamental physics

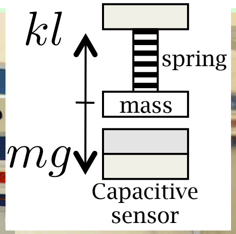
*G, equivalence principle*

## Metrology

*Redéfinition du kg,*

*Kibble balance*

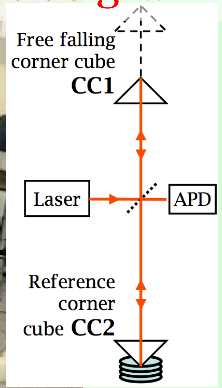



**Relative**
**« spring » gravimeter**

Continuous
Drift
To be calibrated

**Absolute**
Free Fall Corner Cube gravimeter




Not continuous (0.3 Hz) dead time, #FF limited (mechanical wear)

$U \sim 20 - 30\ nm.s^{-2}$

$\sim 10\ nm.s^{-2}$ in $90\ s$

Gradiometers: Combination of accelerometers, (gyro stabilized plateform), Electrostatic, superconducting

Differential measurements

$FTG: \ 20 - 2\ E.Hz^{-1/2}$

$SG: \ 0.5\ E.Hz^{-1/2}$

$GOCE: \ \sim 10\ mE.Hz^{-1/2}$

*FTG (Lockheed Martin)*

*EGG (ARkEX)*

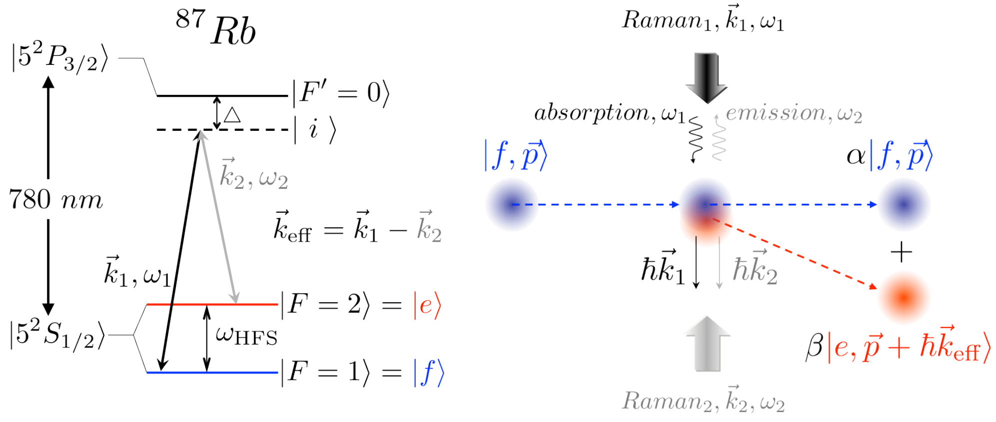

*GOCE (ESA)*


*VK1 (UWA)*

# Atom interferometer

## Stimulated Raman transitions

*3 level atom*



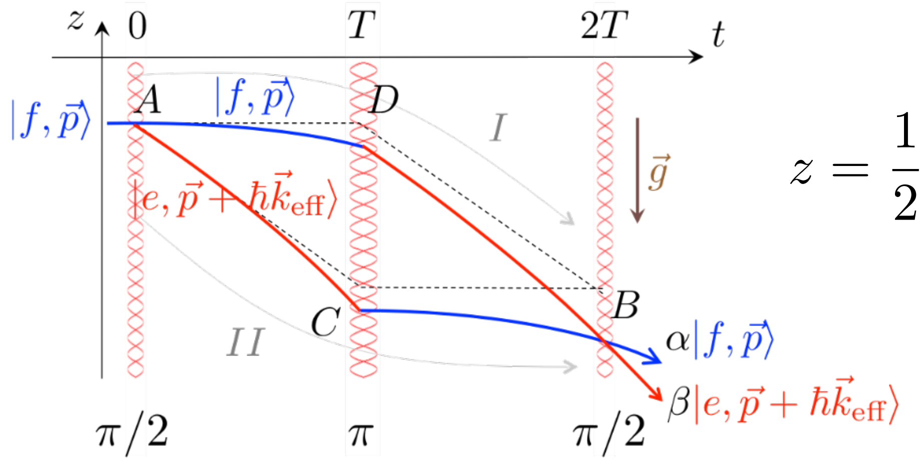

Two photon transition coupling $|f\rangle$ and $|e\rangle$

$$\phi(t) = \omega_{\text{eff}} t - \vec{k}_{\text{eff}} \vec{z}(t) + \varphi_{\text{eff}}(t)$$

**Interest of Raman transitions:**
Bijection internal – external state

**Consequence :** detection on internal state

*Sampling of the positions at the 3 pulses*




$$z = \frac{1}{2}gt^2$$

$$P_{|\vec{p}\rangle \to |\vec{p}+\hbar\vec{k}_{\text{eff}}\rangle} = \frac{1}{2}(1 - C\cos\Delta\Phi)$$

$$\begin{aligned} \triangle\Phi &= \Phi_{II} - \Phi_I \\ &= (\phi_A - \phi_C)\text{-}(\phi_D - \phi_B) \\ &= \phi(0) - 2\phi(T) + \phi(2T) \end{aligned}$$

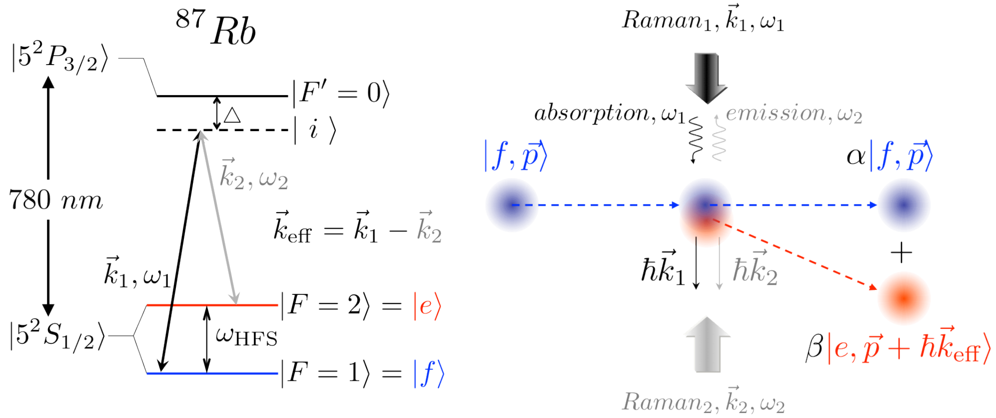
$$\Delta\Phi = -\vec{k}_{\text{eff}} \vec{g} T^2$$

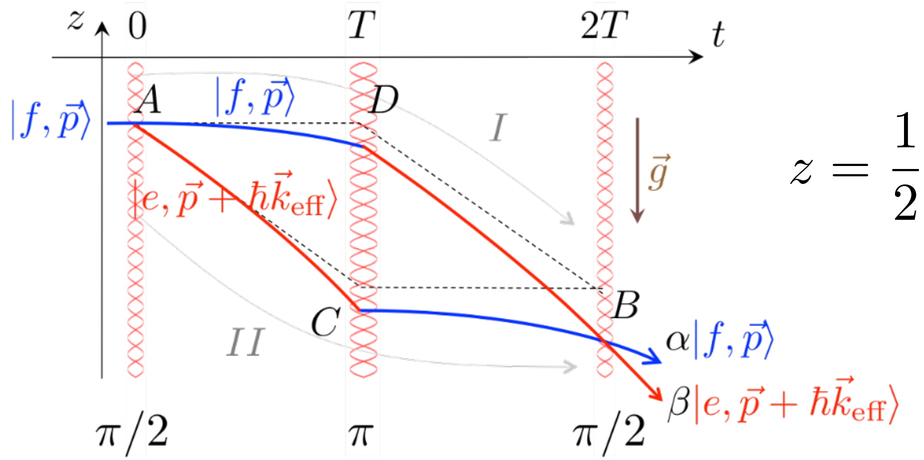
Scales as $T^2$, benefits of cold atoms

# Atom interferometer

Stimulated Raman transitions

*3 level atom*

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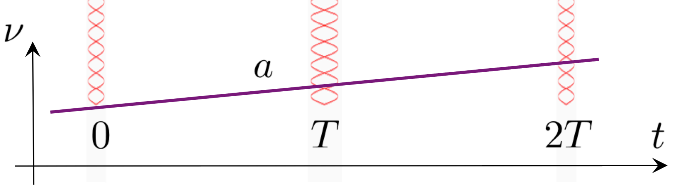



**Interest of Raman transitions:**
Bijection internal – external state

**Consequence :** detection on internal state

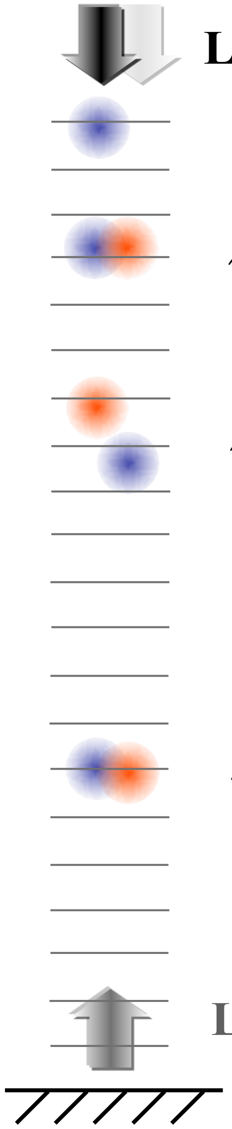
*Sampling of the positions at the 3 pulses*

$$\Delta\Phi = -\vec{k}_{\text{eff}}\vec{g}T^2 + aT^2$$

$$g = a/k_{\text{eff}}$$

Scales as $T^2$, benefits of cold atoms

# Cold Atom Gravimeter (CAG) sequence



**Laser 1**

Extinction PMO-3D

$Impulsion\ 1 : \pi/2$ $\quad z(0) = 0$

$Impulsion\ 2 : \pi$ $\quad z(T) = \frac{1}{2} g T^2$

$Impulsion\ 3 : \pi/2$ $\quad z(2T) = 2 g T^2$

Detection

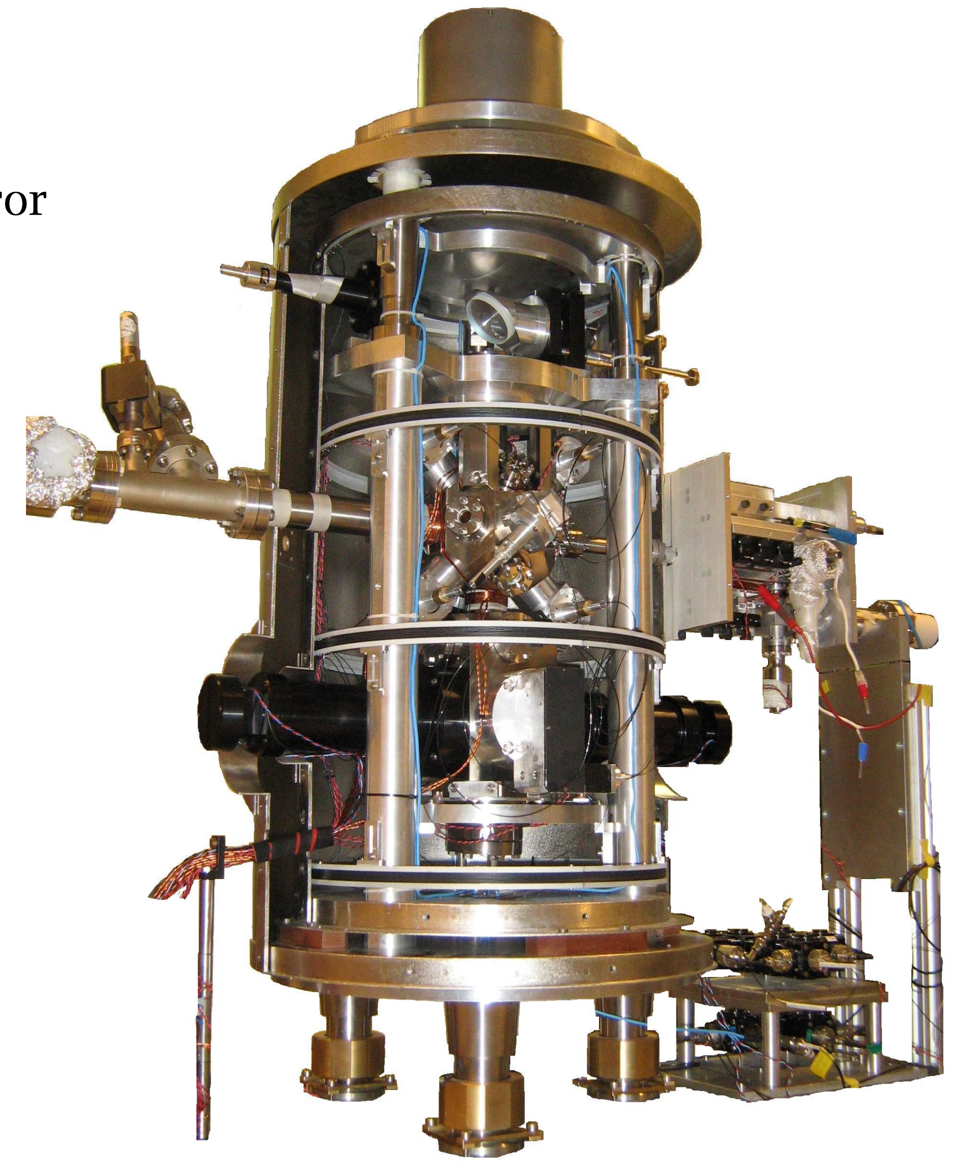
**Laser 2**

Mirror

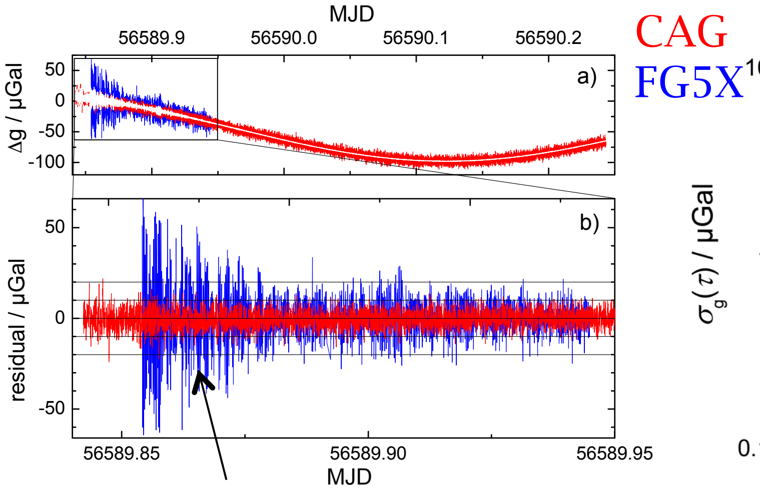
Bring two lasers in a co-propagating way and retroreflect them on a mirror

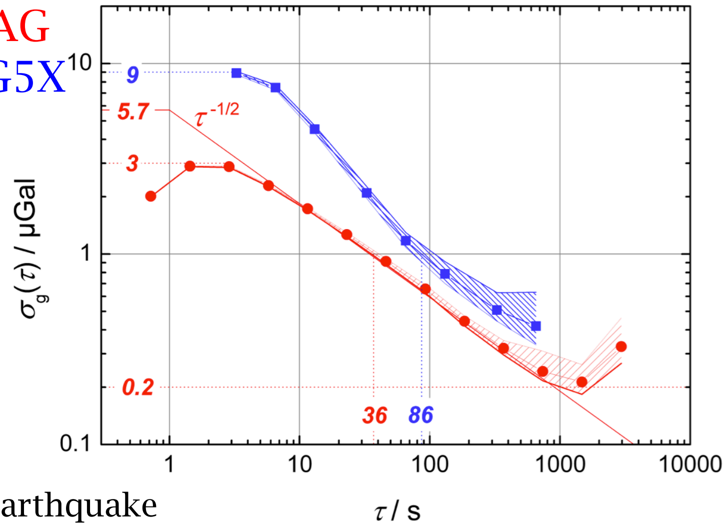
Position of the equiphases defined by the mirror position

atomic measurement
=
measure of the relative displacement atoms/mirror



# CAG performances & capabilities

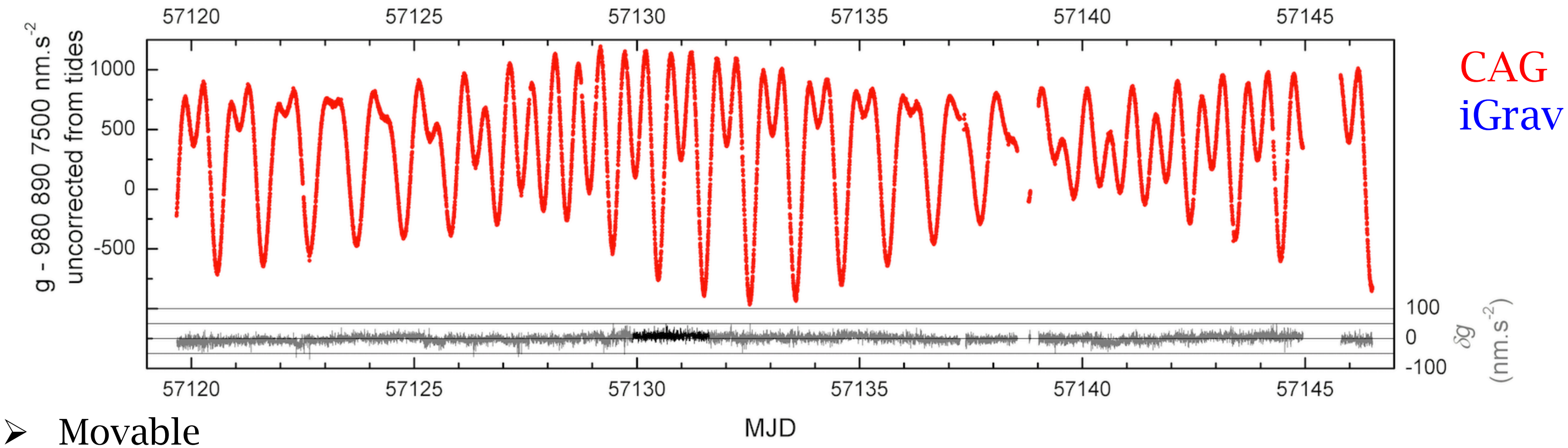


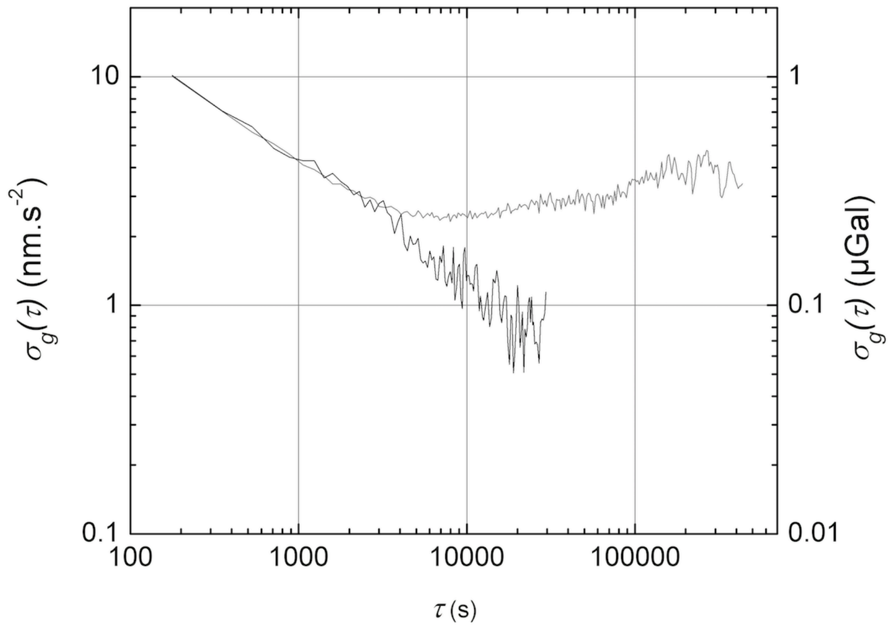




Excess noise due (end of an) earthquake

**Better immunity of the CAG**

*P. Gillot et al., Metrologia **51** (2014)*

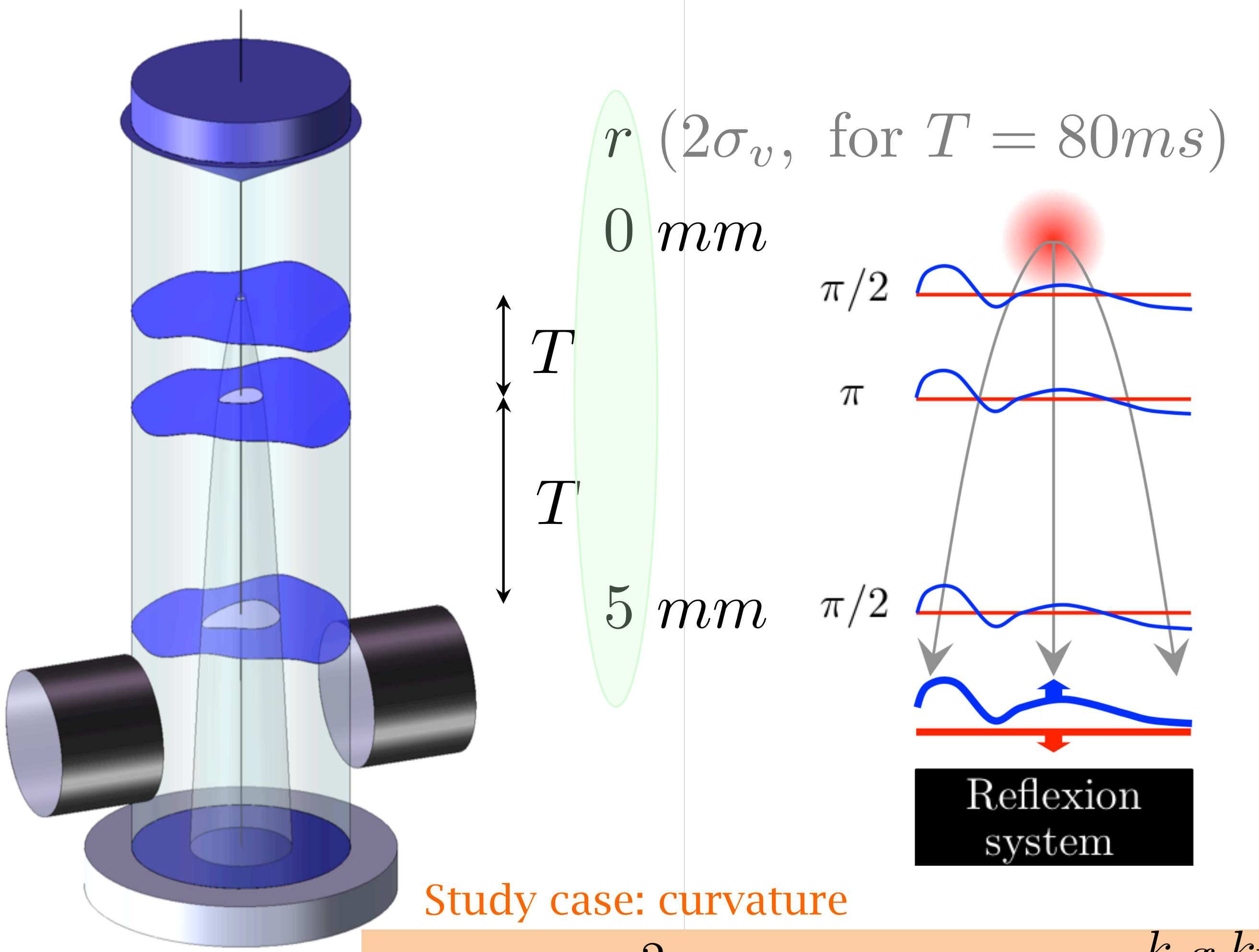



- Movable
- Comparison with other technologies
- Participation to international Key Comparisons
- Continuous accurate measurement
- Industrial transfer

# Wavefront distortion and cloud expansion

Cold Atoms
$T_{emp} \sim 2\mu K$
$\sigma_v \sim 14\ mm.s^{-1}$




*Following an atomic trajectory the total phase coming from wavefront imprinted at each pulse is non zero due to the ballistic expansion of the atomic cloud.*

Study case: curvature

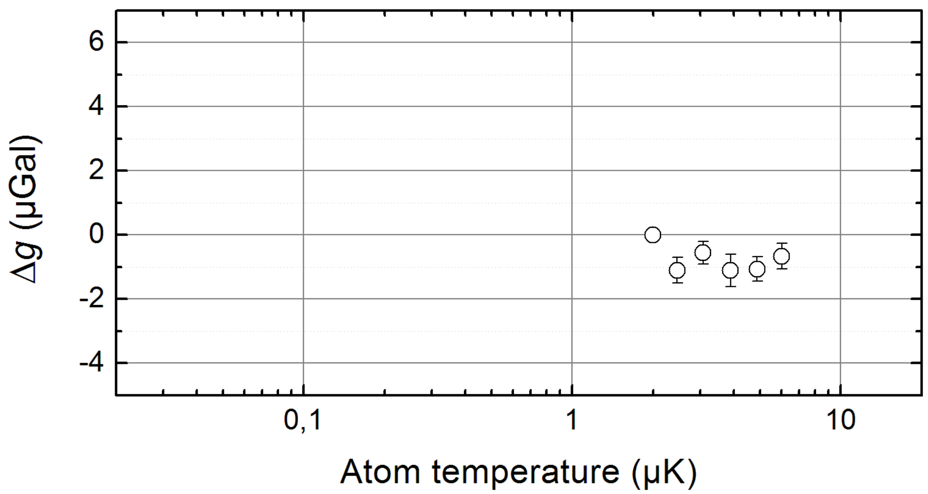
$$\phi \sim Kr^2 \qquad \Delta\Phi = 2K\sigma_v^2 T^2 = \frac{k_{\mathrm{eff}}}{R}\frac{k_B T_{emp}}{m_{\mathrm{Rb}}} T^2$$

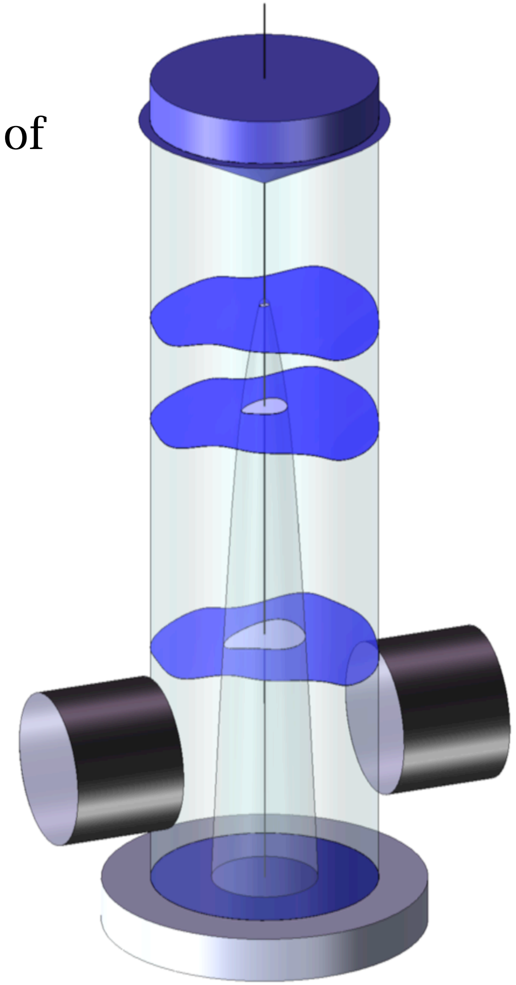
for $\Delta g = 10^{-9} g,\ R = 20km,\ \lambda/300\ PV\ (2r = 1cm)$

# Wavefront Bias determination

Previous determination:
Increase the temperature to modify the effect of **wavefront aberrations**

*A.Louchet-Chauvet et al New J. Phys.* ***13****, 065025 (2011)*

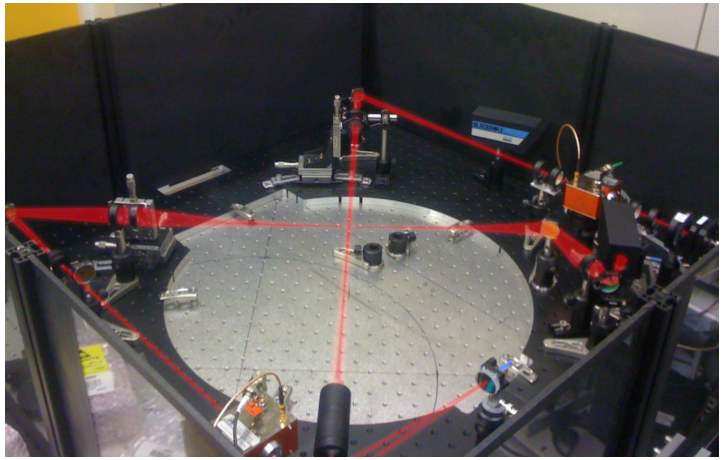


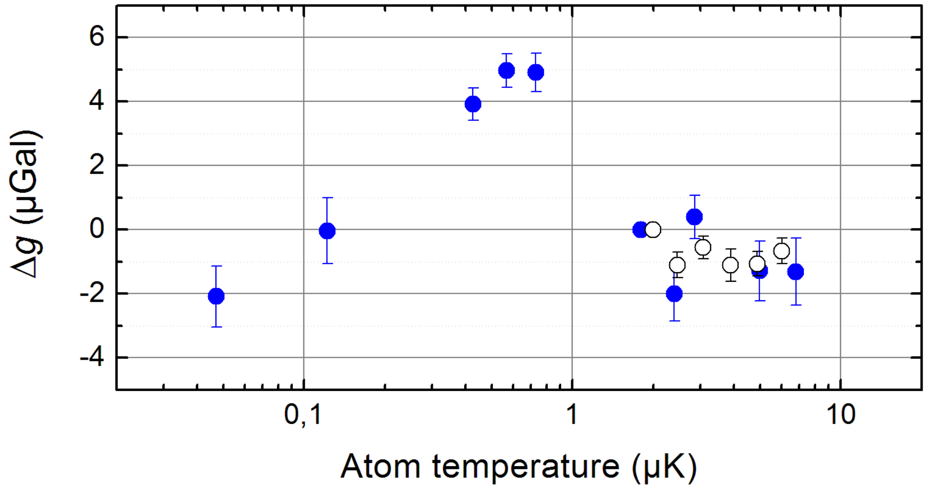



| Effect | Bias $\mu$Gal | u $\mu$Gal |
|---|---|---|
| Alignments | 0.3 | 0.5 |
| Frequency reference | 0.5 | <0.1 |
| RF phase shift | 0.0 | <0.1 |
| *vgg* | -13.4 | <0.1 |
| Self gravity effect | -2.1 | 0.1 |
| Coriolis | -5.3 | 0.8 |
| Wavefront aberrations | 0.0 | 4.0 |
| LS1 | 0.0 | <0.1 |
| Zeeman | 0.0 | <0.1 |
| LS2 | -3.6 | 0.8 |
| Detection offset | 0.0 | 0.5 |
| Optical power | 0.0 | 0.5 |
| Cloud indice | 0.4 | <0.1 |
| Cold collisions | <0.1 | <0.1 |
| CPT | 0.0 | <0.1 |
| Raman $\alpha$ LS | 0.3 | <0.1 |
| Finite Speed of Light | 0.0 | <0.1 |
| **TOTAL** | **-22.9** | **4.3** |

$$\Delta g = (0 \pm 4)\ \mu Gal$$

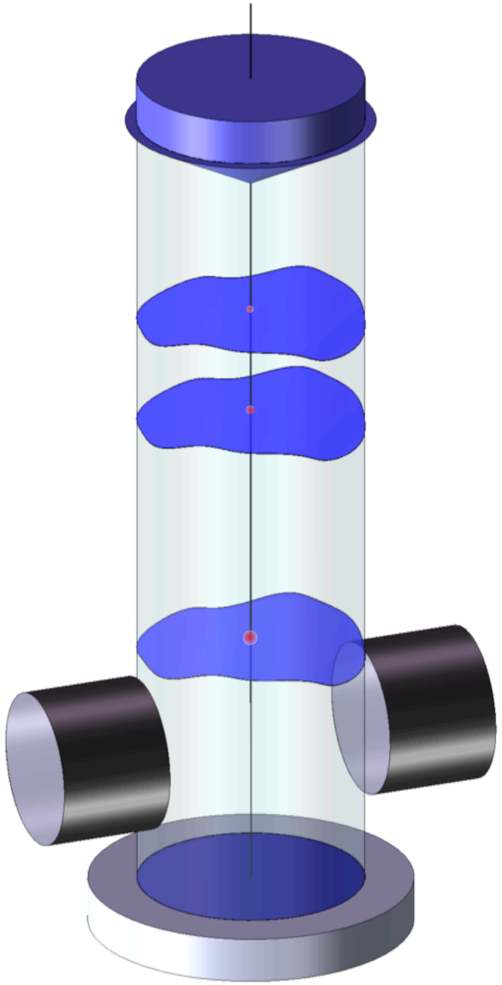
# Implement Ultracold Source on CAG






**Differential gravity measurements** as a function of the atomic temperature from 50nK to 7μK

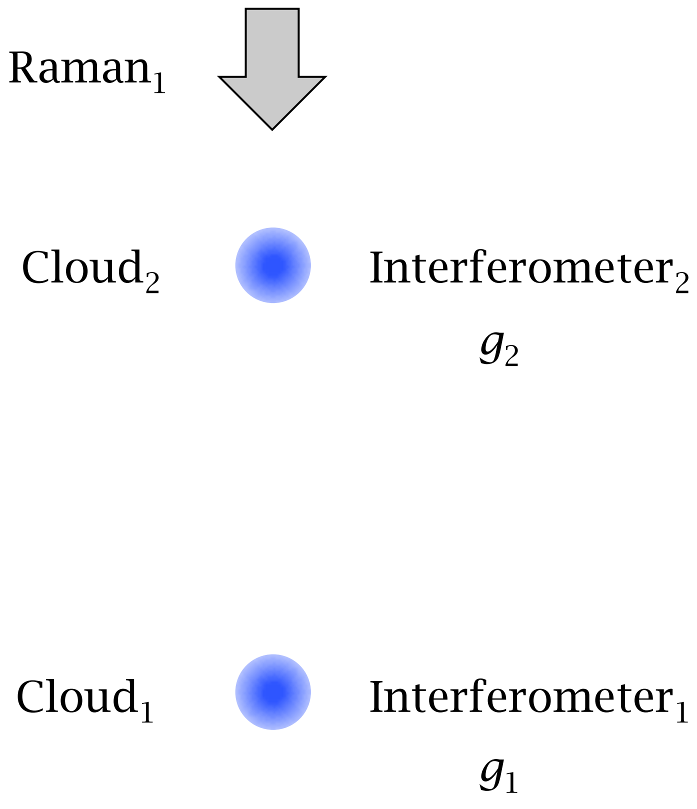
*R. Karcher et al., New J. Phys.* ***20*** *(2018) 113041*



$$\Delta g = (-5.3 \pm 1.3)\ \mu Gal$$

| Effect | Bias $\mu$Gal | u $\mu$Gal |
|---|---|---|
| Alignments | 0.3 | 0.5 |
| Frequency reference | 0.5 | <0.1 |
| RF phase shift | 0.0 | <0.1 |
| *vgg* | -13.4 | <0.1 |
| Self gravity effect | -2.1 | 0.1 |
| Coriolis | -5.3 | 0.8 |
| Wavefront aberrations | -5.6 | 1.3 |
| LS1 | 0.0 | <0.1 |
| Zeeman | 0.0 | <0.1 |
| LS2 | -3.6 | 0.8 |
| Detection offset | 0.0 | 0.5 |
| Optical power | 0.0 | 0.5 |
| Cloud indice | 0.4 | <0.1 |
| Cold collisions | <0.1 | <0.1 |
| CPT | 0.0 | <0.1 |
| Raman $\alpha$ LS | 0.3 | <0.1 |
| Finite Speed of Light | 0.0 | <0.1 |
| **TOTAL** | **-28.5** | **2.0** |

# Quantum dual gravi-gradio meter




$g_1, \; g_2, \; g_1 - g_2$

- Simultaneous interferometers on two cold atom clouds with common Raman lasers
- Differential measurement allows for extracting the acceleration difference (and thus the Earth gravity gradient)
- **Suppression of common mode noise**, and in particular of the vibration noise
- Adapted for onboard measurements
- $g$ and $\Delta g$: resolve ambiguities in determination of mass and position

How to increase the sensitivity ?

$$\triangle\Phi = \vec{k}_{\text{eff}}\vec{g}T^2$$

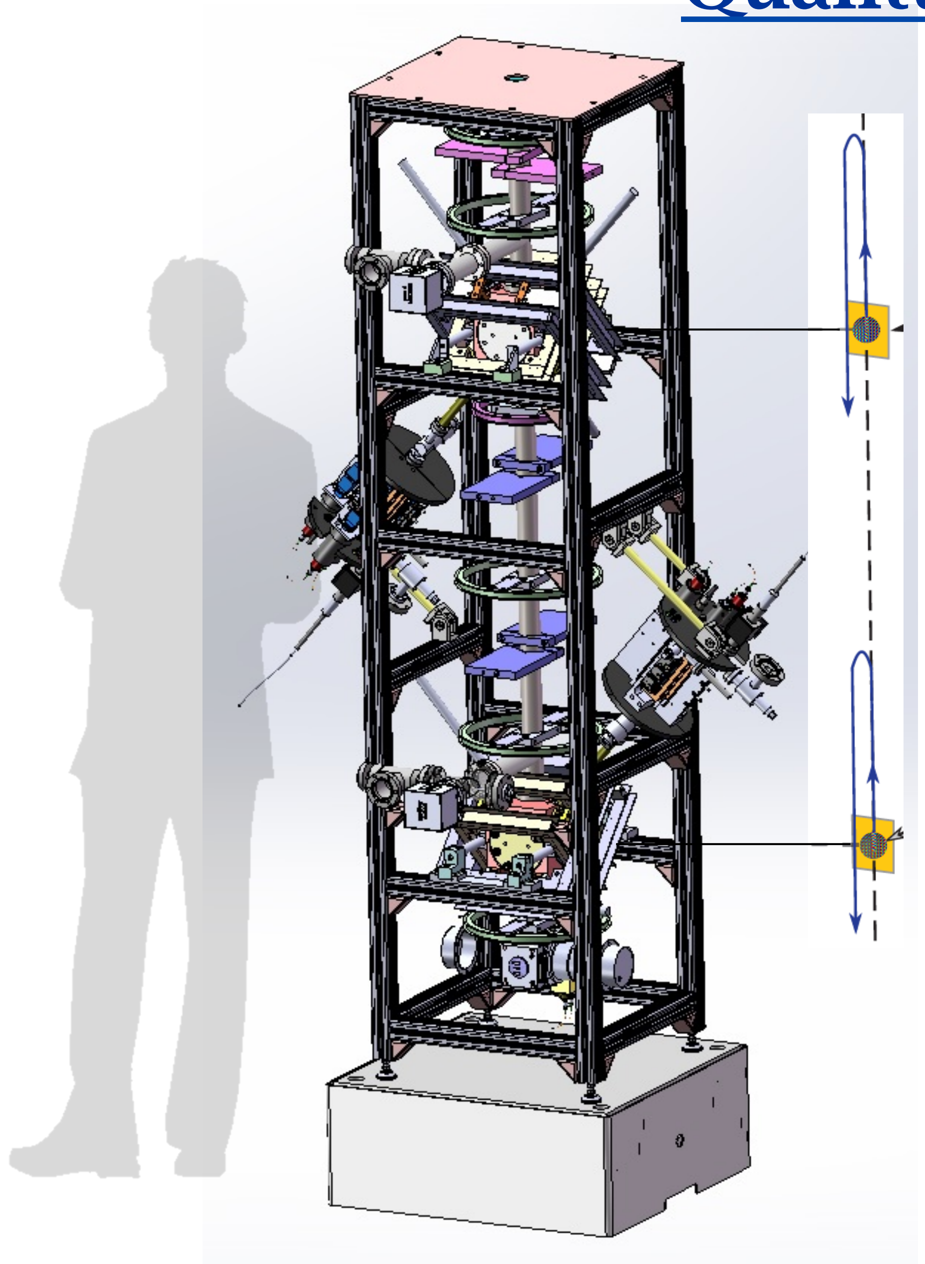
Increase the scale factor

New tools

- High order Bragg diffraction LMBS with up to N photons
- Ultracold atoms

Fast generation on atom chip

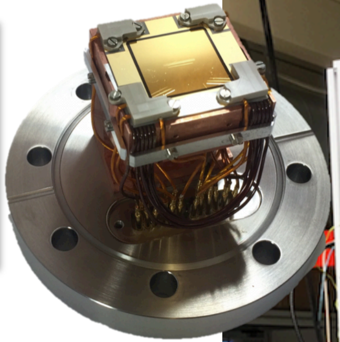
# Quantum dual gravi-gradio meter

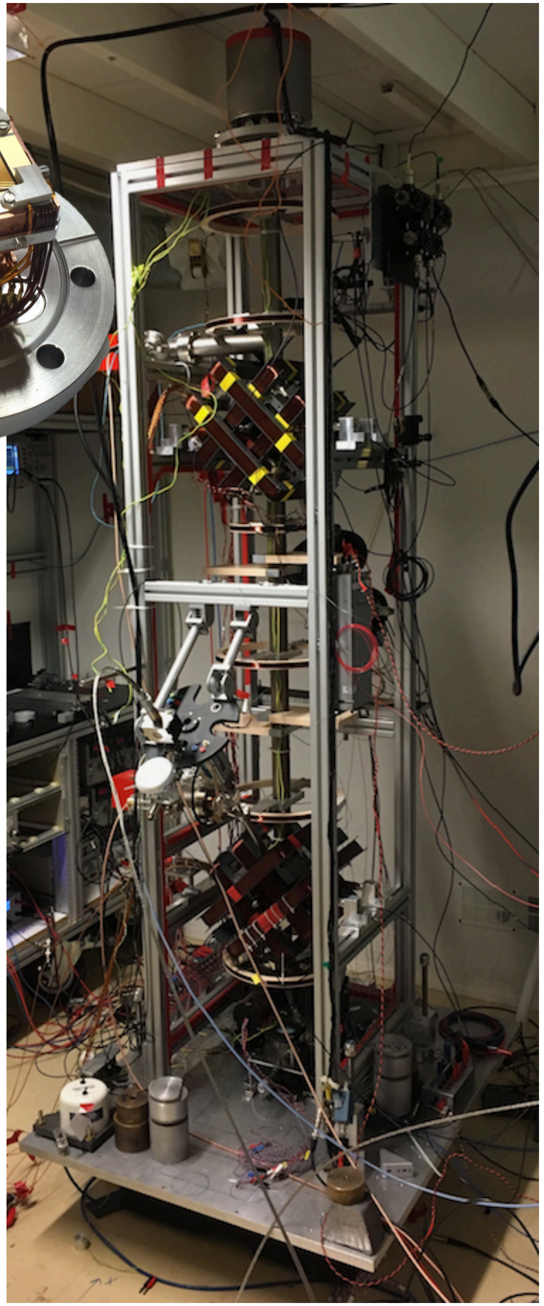


→ 2 ultracold Rb clouds obtained on 2 chips

→ 2 clouds launched with elevator

→ 2 Interferometers drived by LMTB





Targeted parameters

$$T_c = 2s \quad N_{\mathrm{atoms}} = 5.10^5$$
$$T_{emp} = 10 - 100nK$$
$$p = 100\hbar k \quad 2T = 0.5s$$

$$\sigma_{\mathrm{g}}^1 = 9 \times 10^{-11} m.s^{-2}.Hz^{-1/2}$$

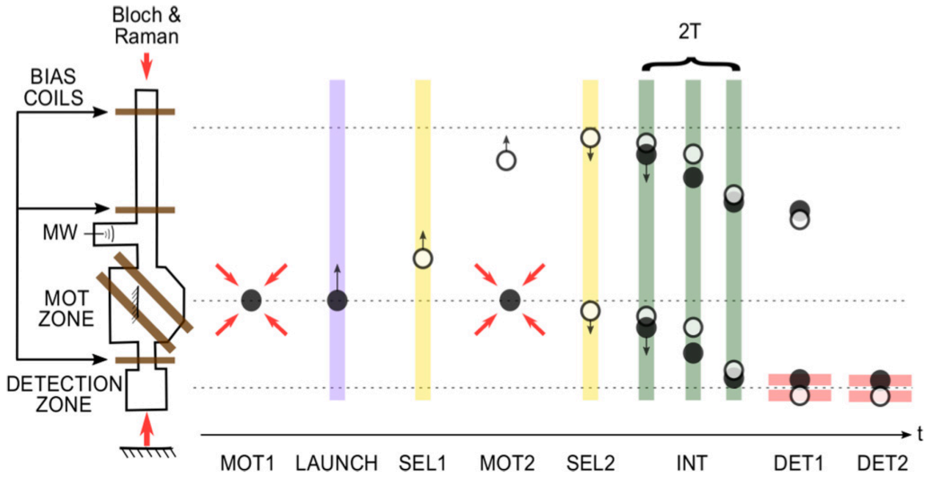
*If limitated by QNP*

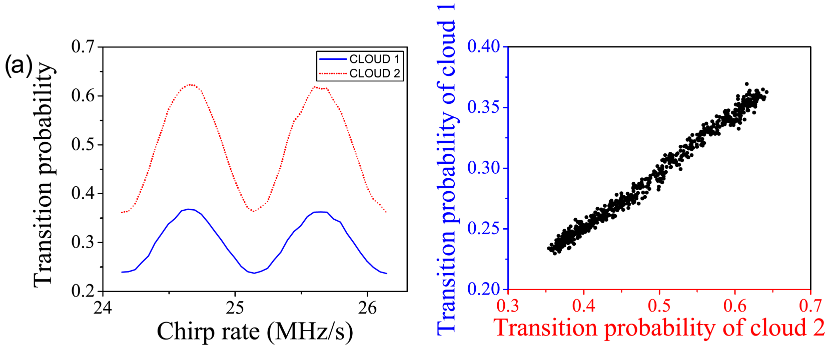
$$\Delta z = 1m$$

$$\sigma_{\mathrm{gradg}} = 126\ mE\ @1s$$

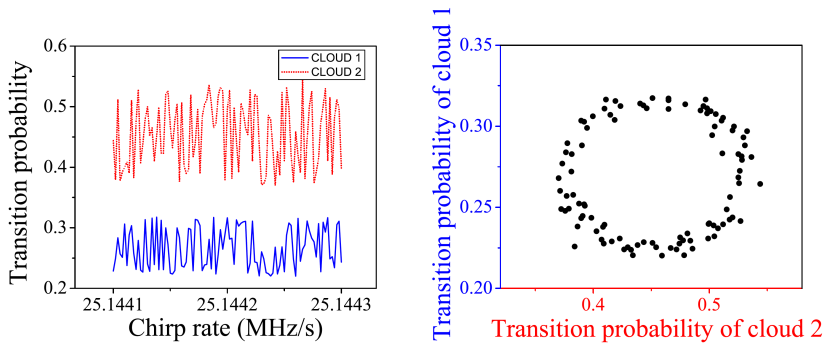
More than one order of magnitude better than state of the art

# Quantum dual gravi-gradio meter, first results



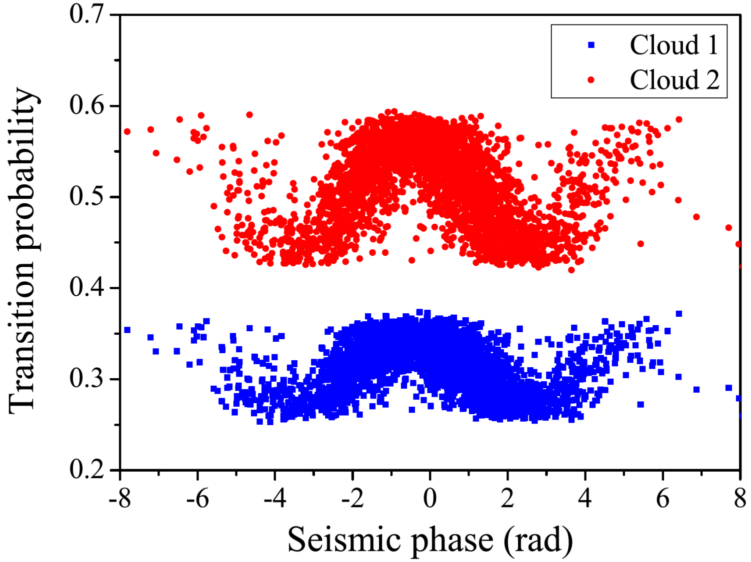



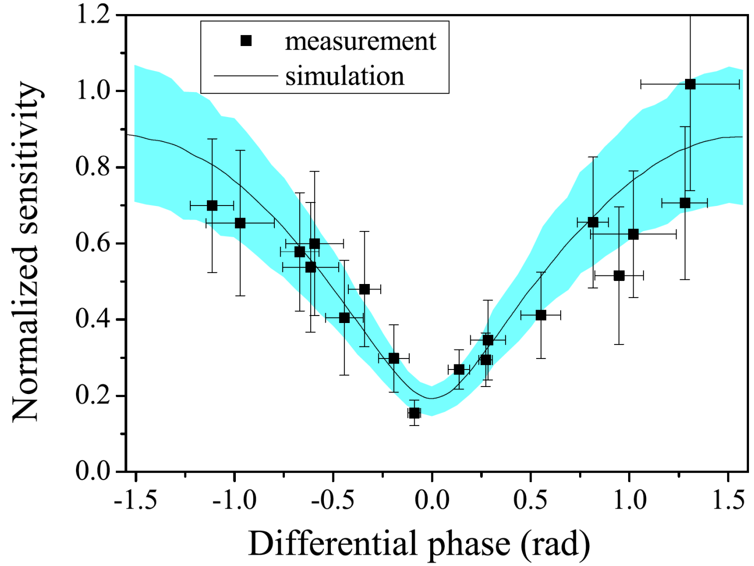

T=1ms




T=35ms

T=60ms



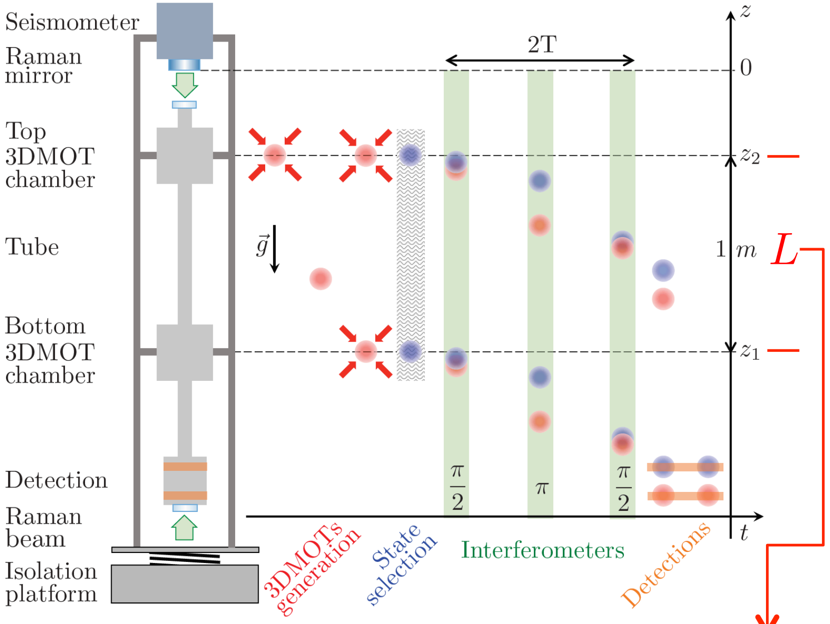




Use of a seismometer

$$P_i = A_i + \frac{C_i}{2}\cos(D_i \Phi_{\mathrm{vib},s} + \Phi_i)$$

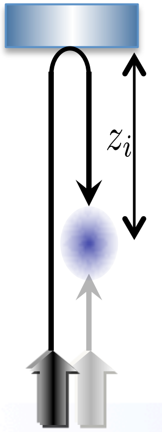
*M. Langlois et al., Phys. Rev. A **96** 053624 (2017)*

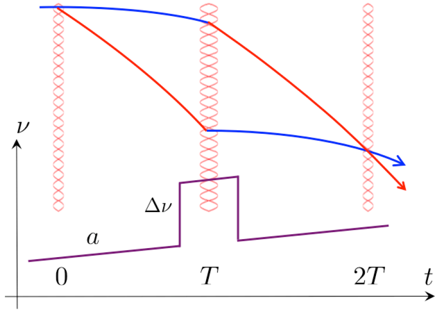
# Quantum dual gravi-gradio meter, first results




$$\Delta\Phi = \Phi_2 - \Phi_1 = k g_2 T^2 - k g_1 T^2 = k\gamma L T^2$$

$$\Phi_i = k g_i T^2 + a T^2 + K_i \Delta\nu \begin{cases} \Delta\Phi_i^{\mathrm{FC}} = aT^2 \\ \Delta\Phi_i^{\mathrm{FJ}} = K_i \Delta\nu \end{cases}$$

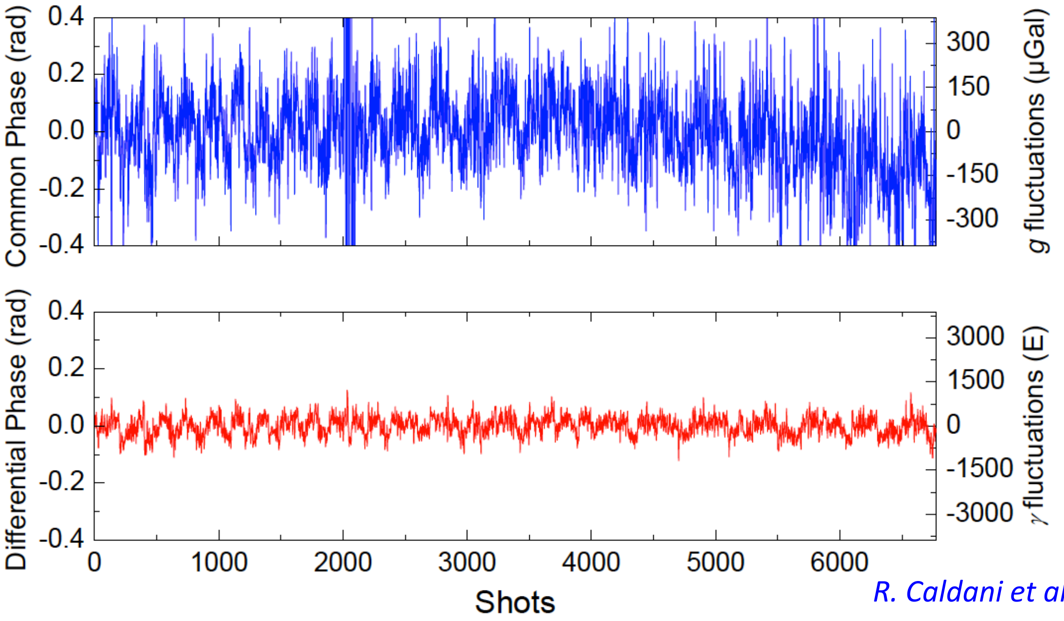



$$\begin{cases} \Delta\Phi = 0 \rightarrow \Delta\nu_0 = \dfrac{k(g_1 - g_2)T^2}{K_2 - K_1} \\ \Phi_1 = \Phi_2 = 0 \rightarrow 2\pi a_s = -k\left(\dfrac{K_2 g_1 - K_1 g_2}{K_2 - K_1}\right) = -k g_s \end{cases}$$

$$K_i = 8\pi z_i / c, \quad g_i = g_0 + \gamma z_i \quad \rightarrow \quad \begin{cases} \Delta\nu_0 = -\gamma \dfrac{kT^2 c}{8\pi} \\ a_s = -k g_0 \end{cases}$$

Accurate determinations of **both** the gravity acceleration (at the mirror position) and the gravity gradient, **INDEPENDANT OF THE BASELINE *L***




$$\sigma_g \begin{cases} 190\ mrad/\sqrt{Hz} \\ 180\ \mu Gal/\sqrt{Hz} \end{cases}$$

$$\sigma_\gamma \begin{cases} 91\ mrad/\sqrt{Hz} \\ 890\ E/\sqrt{Hz} \end{cases}$$

*R. Caldani et al., Phys. Rev. A **99**, 033601 (2019)*

Collaboration with Muquans, see D1741 EGU2020-9185 7th of may G.4.2

# Conclusions and Prospects

**Quantum gravimeter** demonstrated **accurate** and **continous** *g* measurements in **a single instrument**.

*g in $h_{LNE-2017}$, taken into account by CODATA for $h_{2018}$ for new kg definition*

*Measurement included in French geoïde.*

International and National comparisons done to guarantee users and stakeholders .

QAI are now suitable for applications previously limited to superconducting gravimeters and/or free fall corner cube gravimeters.

AI technology transfered to industrie, commercial instruments already exist.

see D1574 EGU2020-8969 G.4.4

see D1566 EGU2020-9076 G.4.4

Performances will be improved with UC atoms, opening the « sea of problems » and new applications.

**→ sub-µGal objective**

Dual **Gravi-Gradio** sensor under development. *The measurement of both quantities, which depend differently on the masses and their positions, will allow to resolve ambiguities between masses and positions of gravity anomaly sources.*

see D1741 EGU2020-9185 7th of may G.4.2

Onboard gravity mapping will soon be possible with UC atoms gradiometers based on LMBS.

- Why not going to space ?
- Atoms are free falling but satelites also, (increase of T up to 10s?), 2T=5s, **2mE@1s**

https://syrte.obspm.fr/spip/science/iaci/

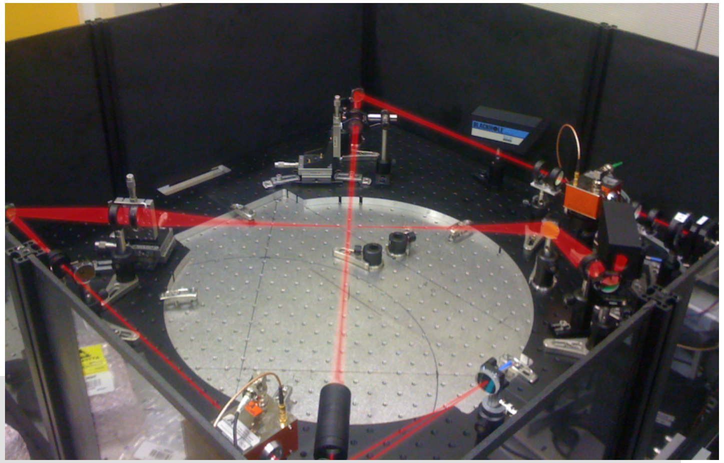
https://syrte.obspm.fr/spip/science/iaci/publications/

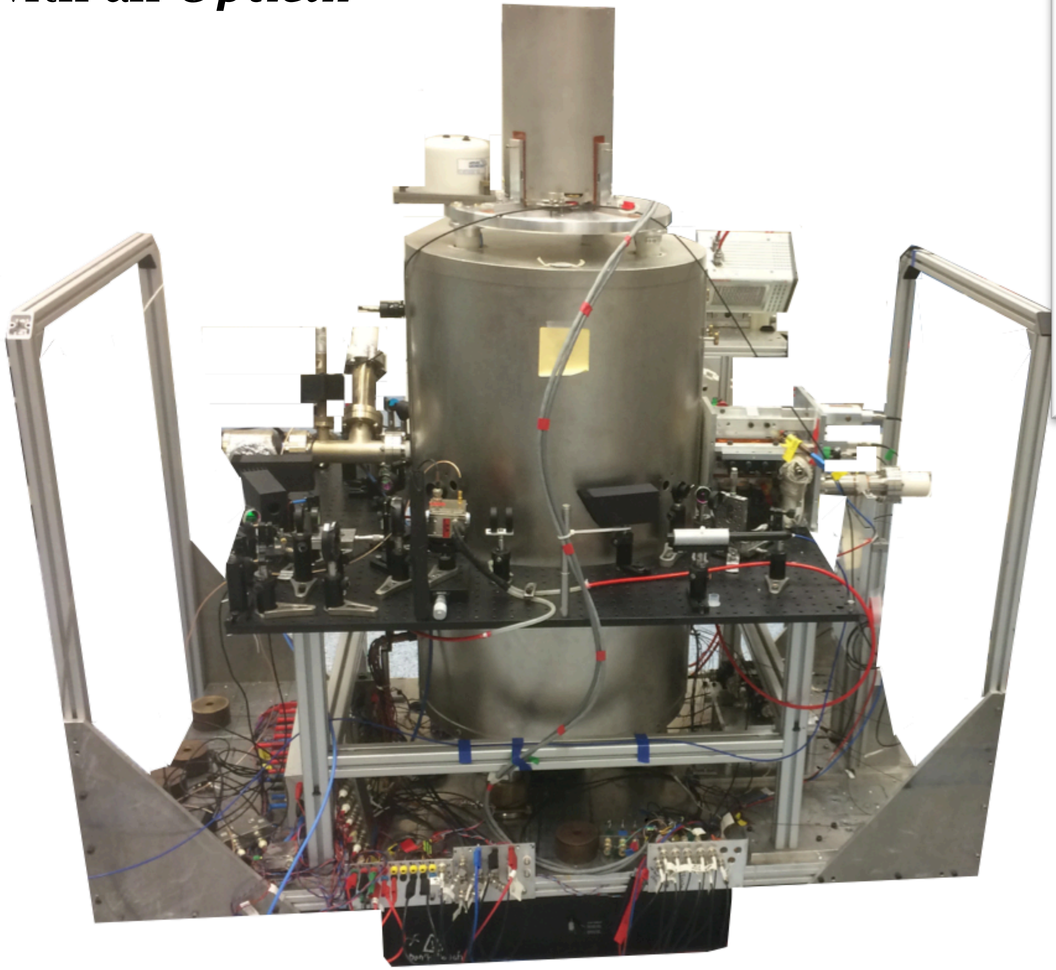
# Thank you

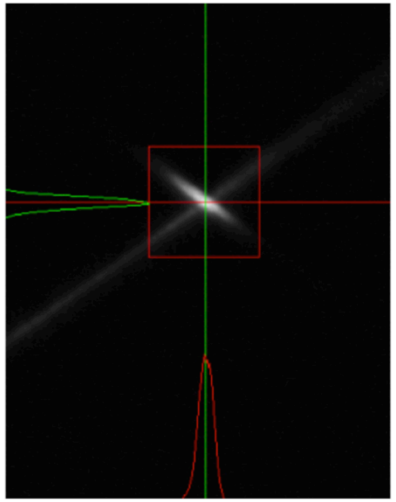
https://syrte.obspm.fr/spip/science/iaci/
https://syrte.obspm.fr/spip/science/iaci/publications/

# Implement Ultracold Source on CAG

***Evaporative cooling*** and ***trapping*** techniques with an ***Optical Dipole Trap***







**Parameters :**

- **A crossed dipole trap ,** total depth : 680 μK
- **Laser Kheopsys** 1550 nm, 30 W
- **First arm for large volume** P = 14.8 W, waist = 170 μm
- **Second arm for tight confinement** P = 8 W, waist = 27 μm

Access to a wide range of temperature from ***50nK to 10μK***

# Comparison with other gravimeters

| Type | Techno | Institut / Company | Name | $\nu_c$ Hz | u $\mu$Gal | $u_{wfab}$ $\mu$Gal | $\sigma_g$ $\mu$Gal | $\tau$ s | Rq |
|---|---|---|---|---|---|---|---|---|---|
| Abs | FFCC | Micro-g | FG5X | 0.3 | 2.0 | . | $\sim$ 1.0 | $\sim$ 100 | dead time, |
| | | Lacoste | | 0.1 | . | . | 1.0 | $\sim$ 700 | wearing |
| Rel | Supra | GWR | iGrav | 1.0 | . | . | 0.01 | 600 | drift |
| Abs | Atom | SYRTE | CAG | 2.8 | 2.0 | 1.3 | 5.7 | 1 | T=80ms |
| | | | | | . | . | 1.0 | 36 | dropped atoms |
| | | | | | . | . | 0.06 | 20 000 | |
| Abs | Atom | HUB | GAIN | 0.7 | 3.2 | 2.2 | 9.6 | 1 | T=260ms |
| | | | | | . | . | 1.0 | 100 | launched atoms |
| | | | | | . | . | 0.05 | 100 000 | |
| Abs | Atom | HUST | | 0.5 | 5.0 | . | 4.2 | 1 | T=300ms |
| | | | | | . | . | 1.0 | 18 | launched atoms |
| | | | | | . | . | 0.3 | 200 | |
| Abs | Atom | muquans | AQG | | . | . | 59.4 | 1 | |
| | | | | | . | . | 1.0 | 4000 | dropped atoms |
| | | | | | . | . | 0.3 | 200 000 | |
| Abs | Atom | AOSense | | | . | . | . | | |
| Abs | Atom | M Squared | | | . | . | . | | |