Simultaneous Dual-Species Atom Interferometry

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SENSORS AND MICRO-TECHNOLOGY UNIT

ONERA

THE FRENCH AEROSPACE LAB

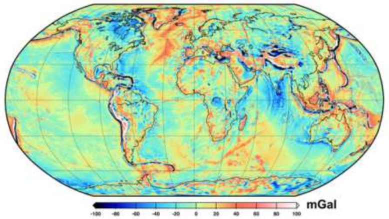
retour sur innovation

Applications of Cold Atom Interferometers

Development of cold atom inertial sensors: accelerometers, **gravimeters**, gradiometers, gyroscopes

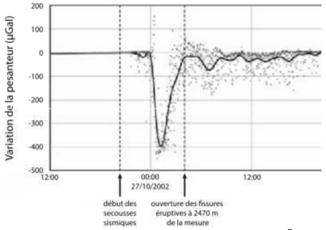
Sensitivity, accuracy, stability

- **Navigation** (inertial unit, gravity field mapping)

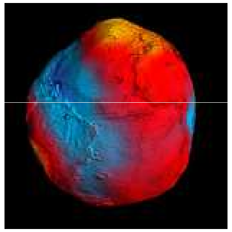


Gravity Anomaly (GRACE + LAGEOS)

- **Geophysics** (Earth internal structure and shape, seismology)

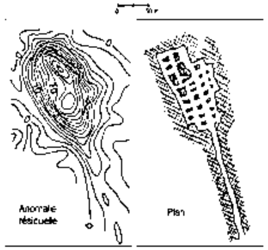


Gravity measurement 3km far from the erupting Etna



Geoid (GOCE)

- **Sub-surface detection** (Oil prospection, archeology)



Montreal old port mapped by gravity measurement

- **Fundamental Physics** (**Equivalence Principle**, Watt balance, short range forces, gravitation, G and α constants, gravitational wave detection)

Weak Equivalence Principle

The Weak Equivalence Principle or the Universality of Free Fall:

“The general theory of relativity owes its existence in the first place to the empirical fact of the numerical equality of the inertial and gravitational mass of bodies”

Albert Einstein, *Lecture at King's College, London, 1921*

Galileo thought experiment

Eötvös Parameter:

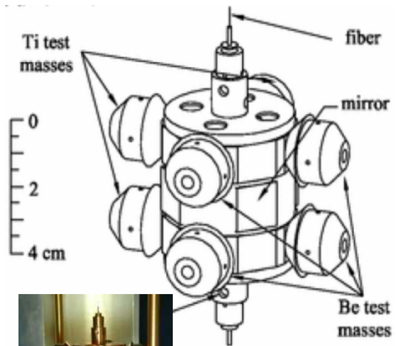
$$\eta(A,B) = 2\frac{\left(\frac{m_g}{m_i}\right)_A - \left(\frac{m_g}{m_i}\right)_B}{\left(\frac{m_g}{m_i}\right)_A + \left(\frac{m_g}{m_i}\right)_B}$$

$$\eta(A,B) = 2\frac{(a_A - a_B)}{(a_A + a_B)}$$

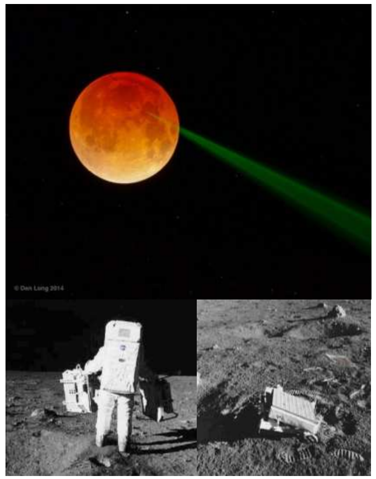
Today:

$$\eta \leq 1.8 \times 10^{-13}$$

Lunar Laser Ranging, Torsion Balance



Eöt-Wash experiment



Dual-species atom accelerometry & Weak Equivalence Principle

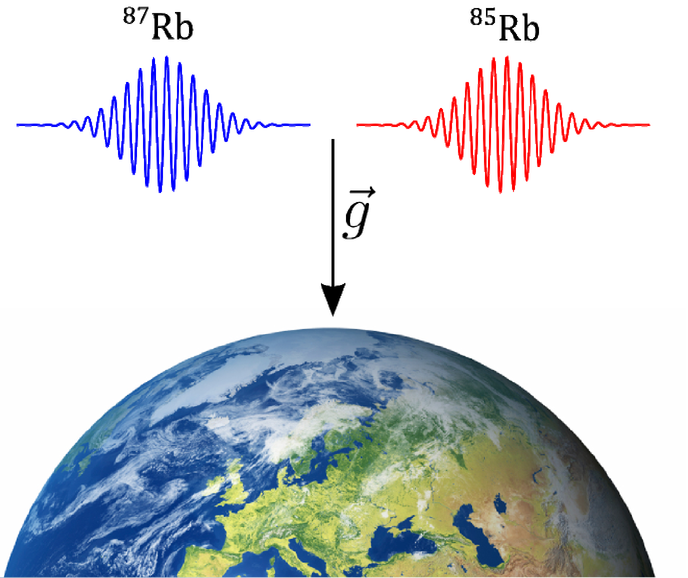
Tests with atoms (quantum objects):

- New type of test masses (new species, spin, bosons – fermions, bigger λ_{DB} …)
- Extend the range of test parameters
- Complementary to tests with classical matter

Measurement principle & quantum test of the WEP :

- Free fall of two objects of different compositions with respect to the same frame: the Earth
- The objects : two matter waves, cold atoms (^{85}Rb & ^{87}Rb) falling in vacuum
- Acceleration measured by atom interferometry

→ highly sensitive and stable measurement



Test of the Weak Equivalence Principle with cold atoms:

the sensitivity scales as T^2, where 2T is the time of free fall.

Very Large atom interferometers

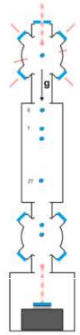
M. Kasevich group (Stanford ,USA)

10m tower (^{85}Rb & ^{87}Rb)

Chinese Academy of Sciences (Wuhan, China)

10m tower (Rb, Li, Cs)

E. Rasel group (Hanover, Germany)



10m tower (^{87}Rb & ^{170}YB)

Micro-gravity environments

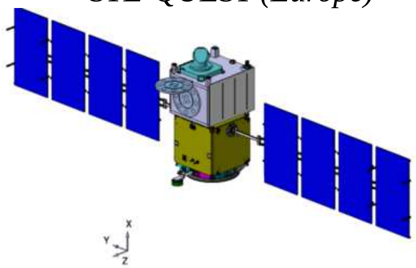
QUANTUS (Germany)

Bremen Drop Tower (^{40}K & ^{87}Rb)

ICE (France)

CNES project (LP2N, SYRTE, ONERA) (^{39}K & ^{87}Rb)

STE-QUEST (Europe)



ESA project (^{85}Rb & ^{87}Rb) or (^{41}K & ^{87}Rb)

Dual-species atom accelerometry & Weak Equivalence Principle

Test of the Weak Equivalence Principle with cold atoms:

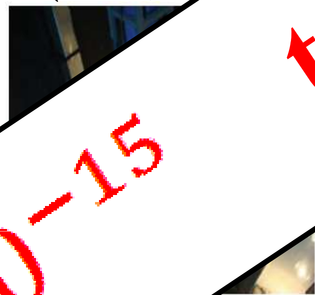
the sensitivity scales ... is the time of free fall

Very Large atom interferometers

M. Kasevich group (Stanford ,USA)

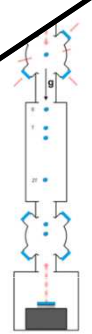
10m tower (^{85}Rb ...

Chinese Academy of Sci...
(Wuhan, Chi...



..., Li, Cs)

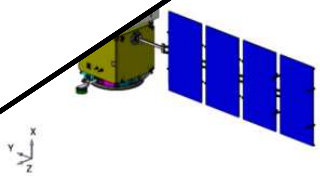
..., Germany)



10m tower (^{87}Rb & ^{41}K)

Micro-...

$10^{-12} \geq \eta \geq 10^{-15}$ **targeted**



ESA project (^{85}*Rb* & ^{87}*Rb*) or (^{41}*K* & ^{87}*Rb*)

ICE (France)

CNES project (LP2N, SYRTE, ONERA)
(^{39}*K* & ^{87}*Rb*)

QUANTUS (Germany)

Bremen Drop Tower
(^{40}*K* & ^{87}*Rb*)

Alexis BONNIN, DAMOP 2015, June 8-12 2015

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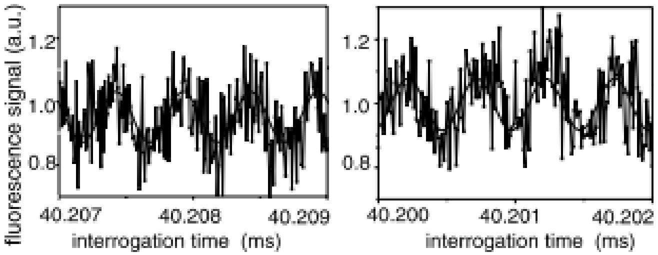
Dual-species atom accelerometry & Weak Equivalence Principle

State of the art laboratory experiments: $\eta \leq 10^{-7} - 10^{-8}$ demonstrated

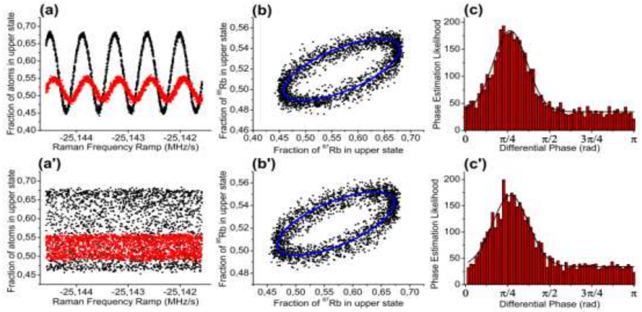
T. Hansch group (Germany)



S. Fray et al, Phys. Rev. Let. ***93****, 2040404 (2004)*

Non-simultaneous, ^{85}Rb & ^{87}Rb (2004)

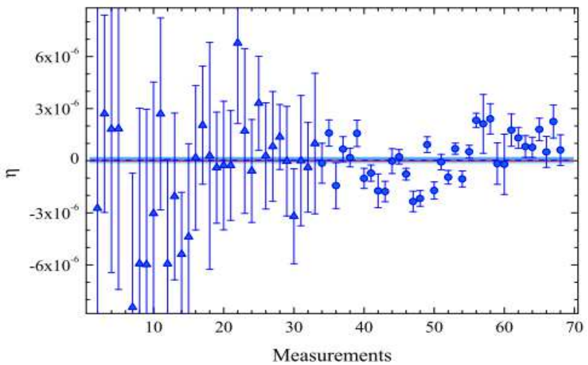
ONERA (France)



A. Bonnin et al, Phys. Rev. A ***88****, 043615 (2013)*

Simultaneous, ^{85}Rb & ^{87}Rb (2013)

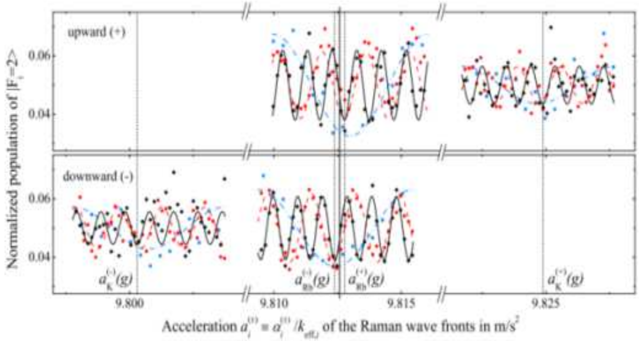
G. M. Tino group (Italy)



M. G. Tarallo et al, Phys. Rev. Let. ***113****, 023005 (2014)*

Non-simultaneous, ^{88}Sr & ^{87}Sr (2014)

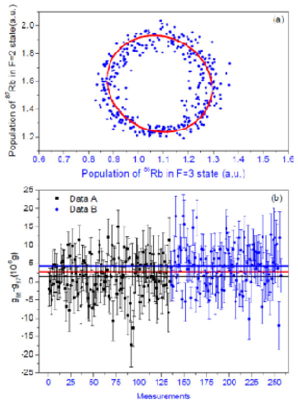
E. Rasel group (Germany)



D. Schlippert et al, Phys. Rev. Let. ***112****, 203002 (2014)*

Simultaneous, ^{39}K & ^{87}Rb (2014)

M. Zhan group (China)

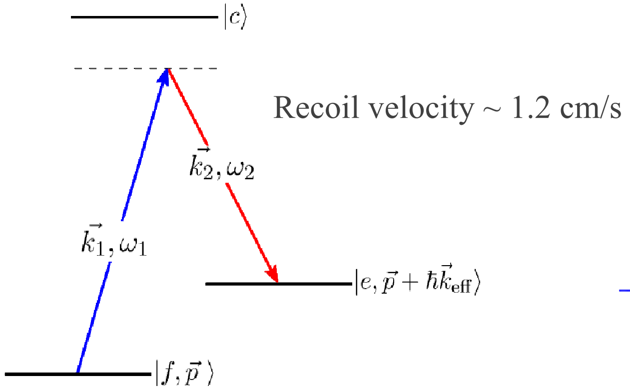


L. Zhou et al, arXiv 1503.00401 (2015)

Simultaneous, ^{85}Rb & ^{87}Rb (2015)

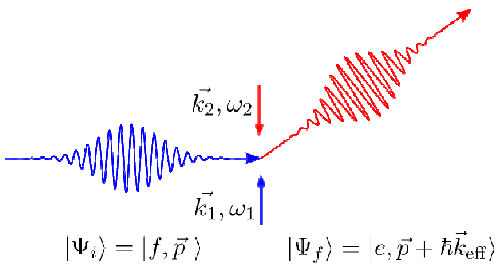
Atom interferometry

Handling of atomic wave functions: use of Raman transitions to split, reflect and recombine the atomic wave packets



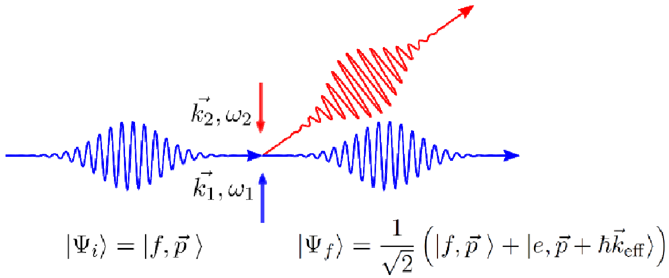
Atomic mirror

(**π pulse**, impulsion transfer)



Atomic beam splitter

(**π/2 pulse**, superposition of states)



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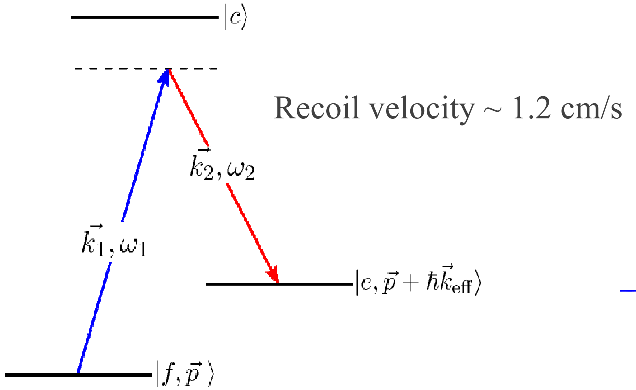

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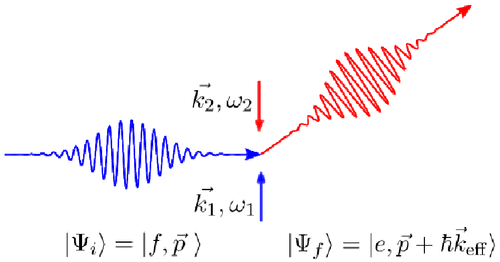

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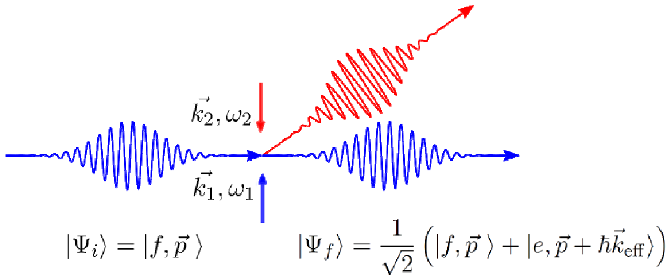
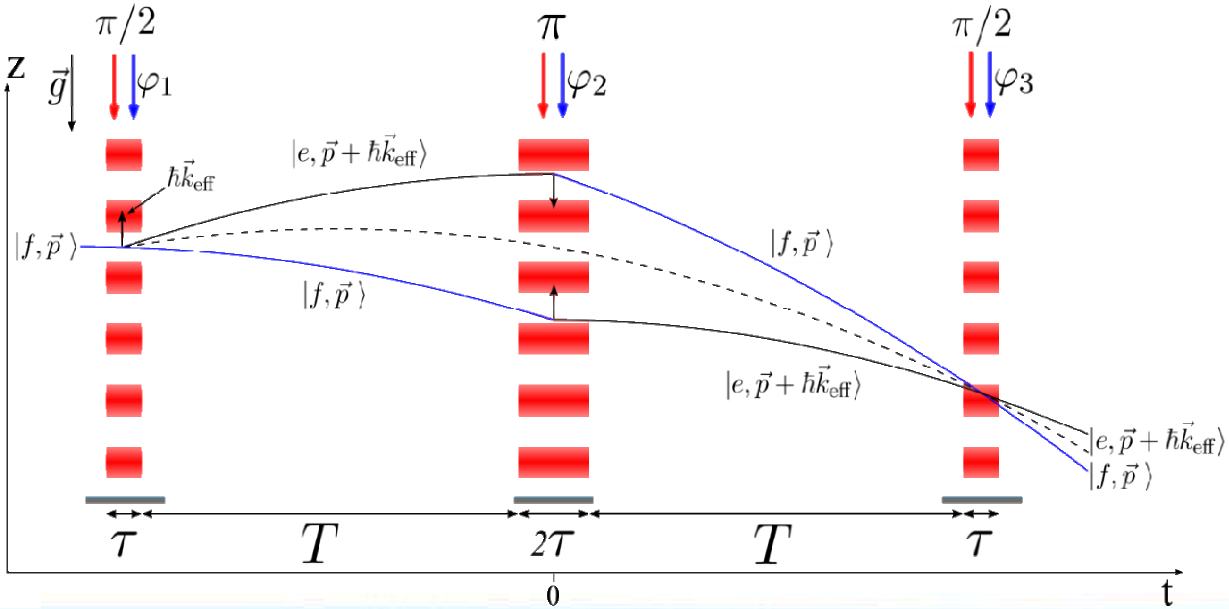


Realization of a Mach-Zehnder type atom interferometer:



Phase shift between both interferometer ports:

$$\Delta\Phi_i = \underbrace{k^i_{eff} T^2}_{\text{Scale factor}} g_i$$

Probability of being in a certain state:

$$P_e \propto \cos(\Delta\Phi_i)$$

Differential phase measurement:

Simultaneously for (^{85}Rb & ^{87}Rb)

$$\Delta\Phi_{87} - \Delta\Phi_{85}$$

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Full Sequence of Measurement

Source of Cold atoms

Simultaneous trapping and cooling

(MOT & Optical Molasse)

Zeeman selection

^{87}Rb & ^{85}Rb

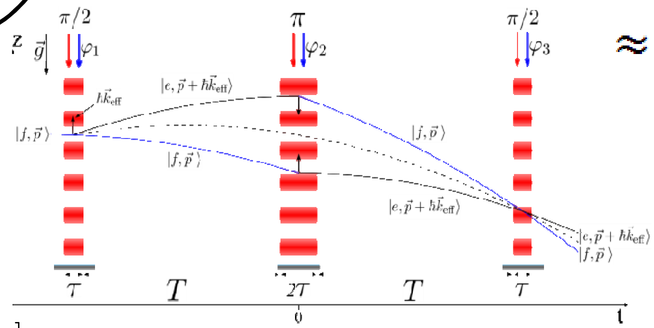
@ T=1µK

(~ 1cm/s)

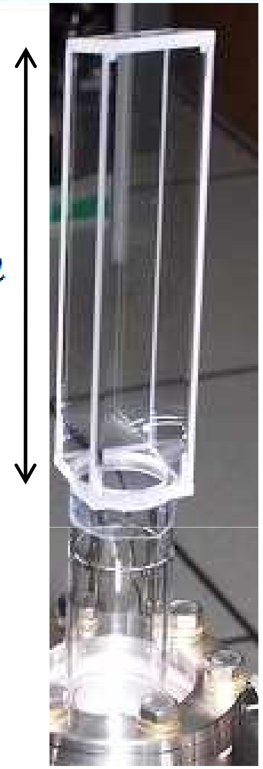
$m_F=0$

T = 40 to 47 ms

Repetition rate : 4 Hz



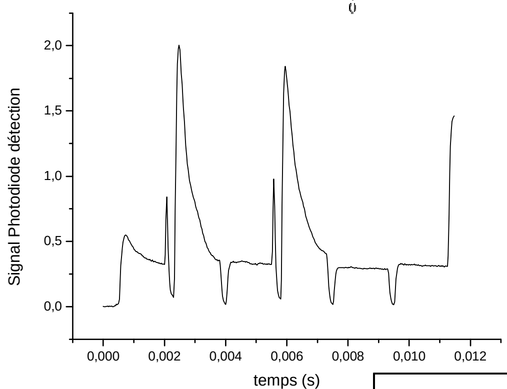
≈ 6cm



Simultaneous interferometric sequence during the free fall

Probability of being in a particular state:

$$P_e \propto \cos(\Delta\Phi_i)$$



Detection by fluorescence

Number of atoms in each state

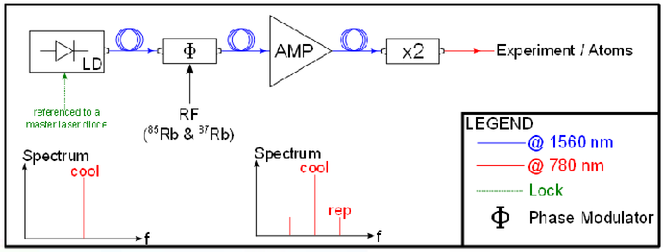
Successively for both isotopes

Experimental setup:

A single laser source for handling two species

Required laser lines generated by

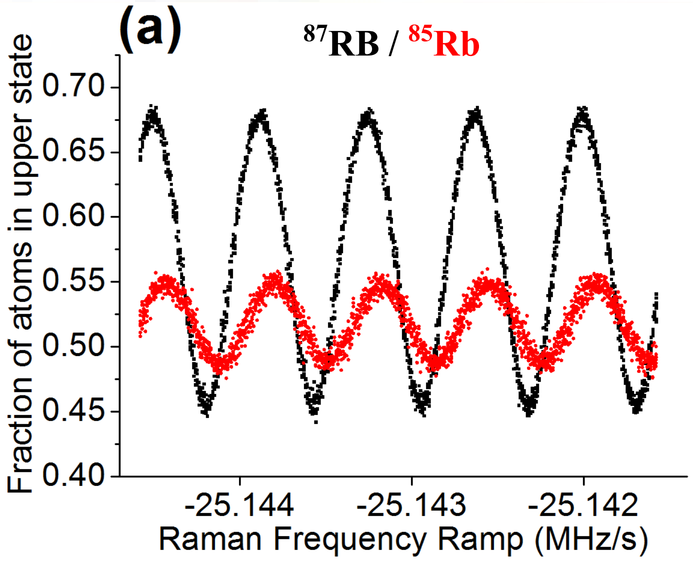
phase modulation



Test of the Weak Equivalence Principle

First simultaneous dual-species interferometric signal:

- **Simultaneous** interferometric fringes
- Non-zero differential phase:
  - ✓ Slightly different scale factors
  - ✓ Systematic effects



A. Bonnin et al, Phys. Rev. A ***88****, 043615 (2013)*

TABLE II. Main contributions affecting the differential acceleration measurement.

	$\Delta g/g$ $(\times 10^{-7})$	Uncertainty $(\times 10^{-7})$
Expt. results	−27.6	0.25
Term 2 $(\delta k/k_{\mathrm{eff}})$	49.4	0
Term 6 correction:		
Additional lines	−23.3	1.1
Frequency shifts	0.3	2.9
Coriolis effect	0	0.6
Wavefront aberrations	0	0.1
Total	1.2	3.2

A. Bonnin et al, Phys. Rev. A ***88****, 043615 (2013)*

Weak Equivalence Principle test:

- After systematic effects correction:

$$\eta = (1{,}2 \pm 3{,}2).10^{-7}$$

State of the art test of the Weak equivalence Principle with atom interferometry

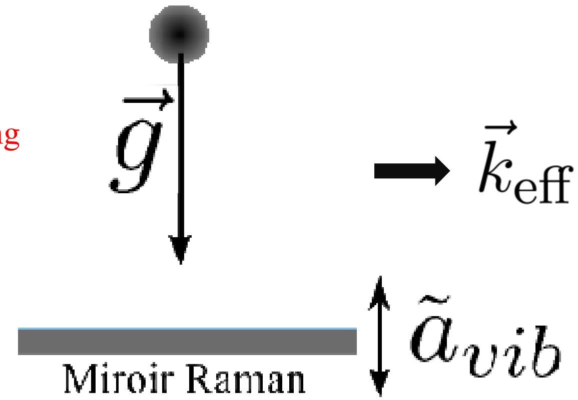
(limited by systematic effects uncertainties)

Simultaneous measurement & Common-mode noise rejection

Rejection of vibration noise:

Acceleration of atoms is measured compare to a frame: the retro-reflecting mirror of the laser beam

Vibrations limit the sensitivity of the acceleration measurement



$$\rightarrow \vec{k}_{\text{eff}} \cdot (\vec{g} + \tilde{a}_{vib}) T^2$$

Simultaneous measurement :

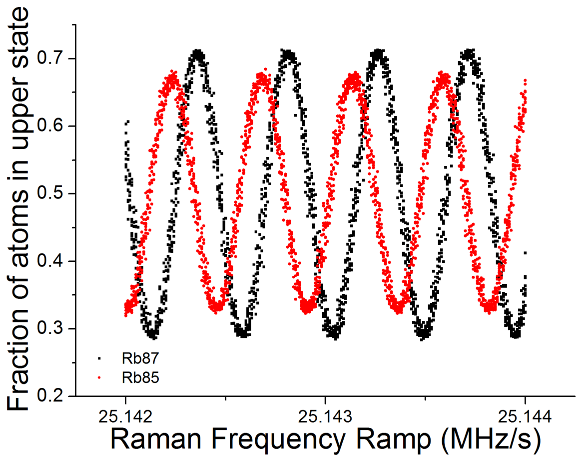
$$\Delta\Phi_{87} = S_{87}(g_{87} + \tilde{a}_{vib}) \qquad \Delta\Phi_{85} = (S_{87} + \Delta S)(g_{85} + \tilde{a}_{vib})$$

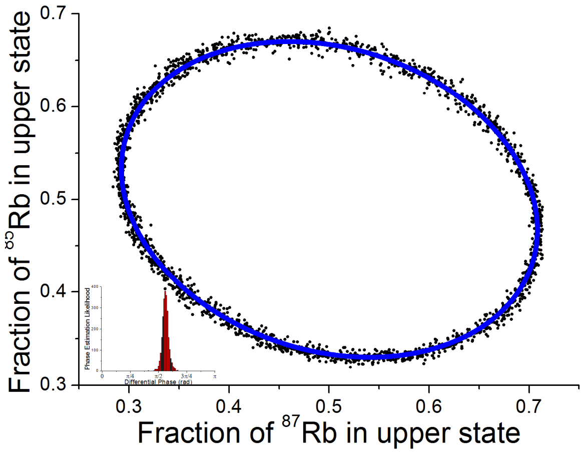
$$\phi_d = S_{87}(g_{85} - g_{87}) + \Delta S g_{85} + \Delta S \tilde{a}_{vib}$$

WEP violation signal — **DC acceleration** — **Rejection limit (100 dB)**

Simultaneous measurement & Common-mode noise rejection

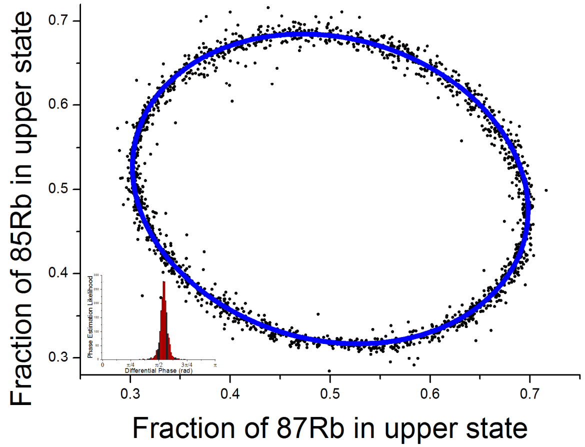
Vibration of 10^{-7}g





Vibration of **3.3×10^{-3}g**

Blurred Fringes



➡ Vibration

➡ blurred fringes

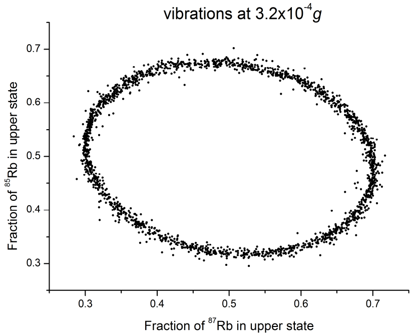
➡ differential phase

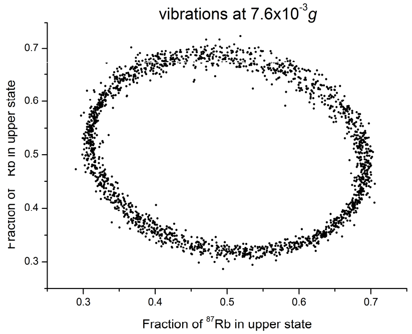
derived from the ellipse

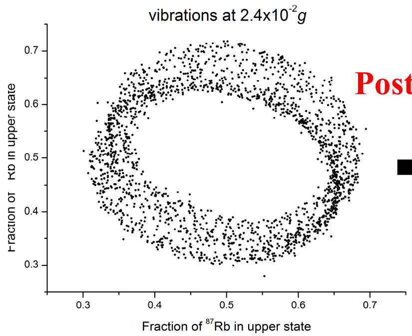
Simultaneous measurement & Common-mode noise rejection

Rejection of vibration noise:

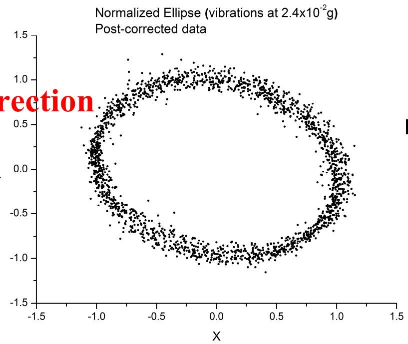
Excitation of the sensor at a well-defined frequency (2.08Hz)

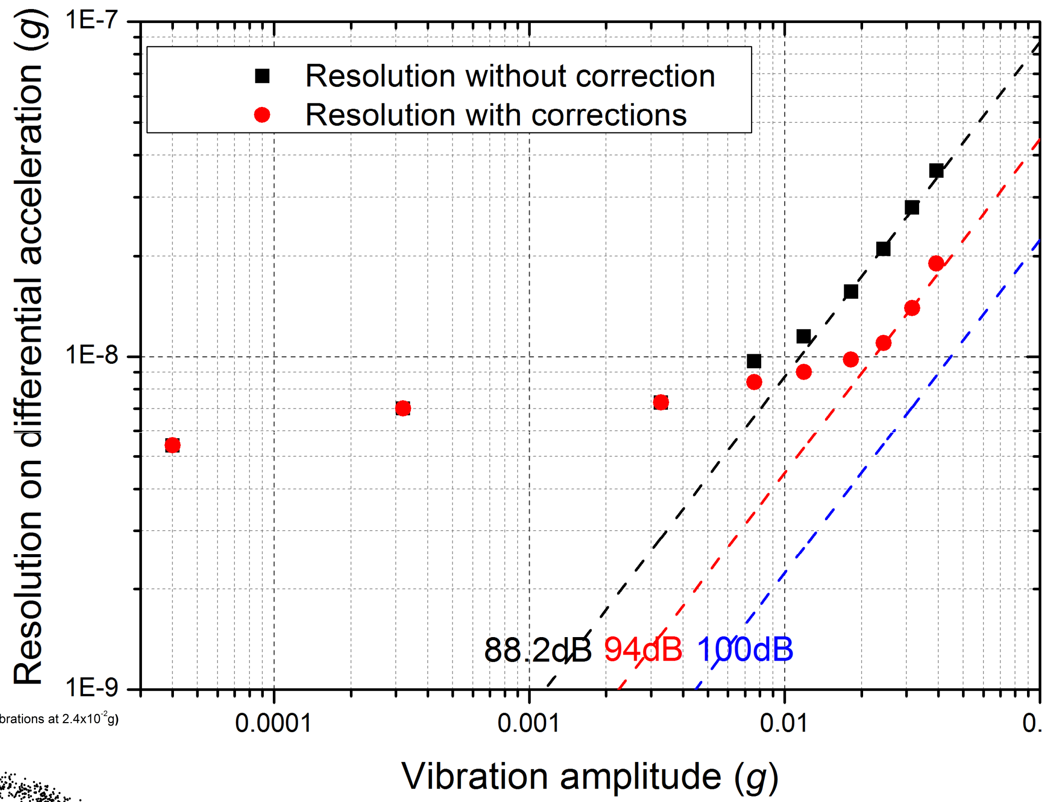






Post-correction





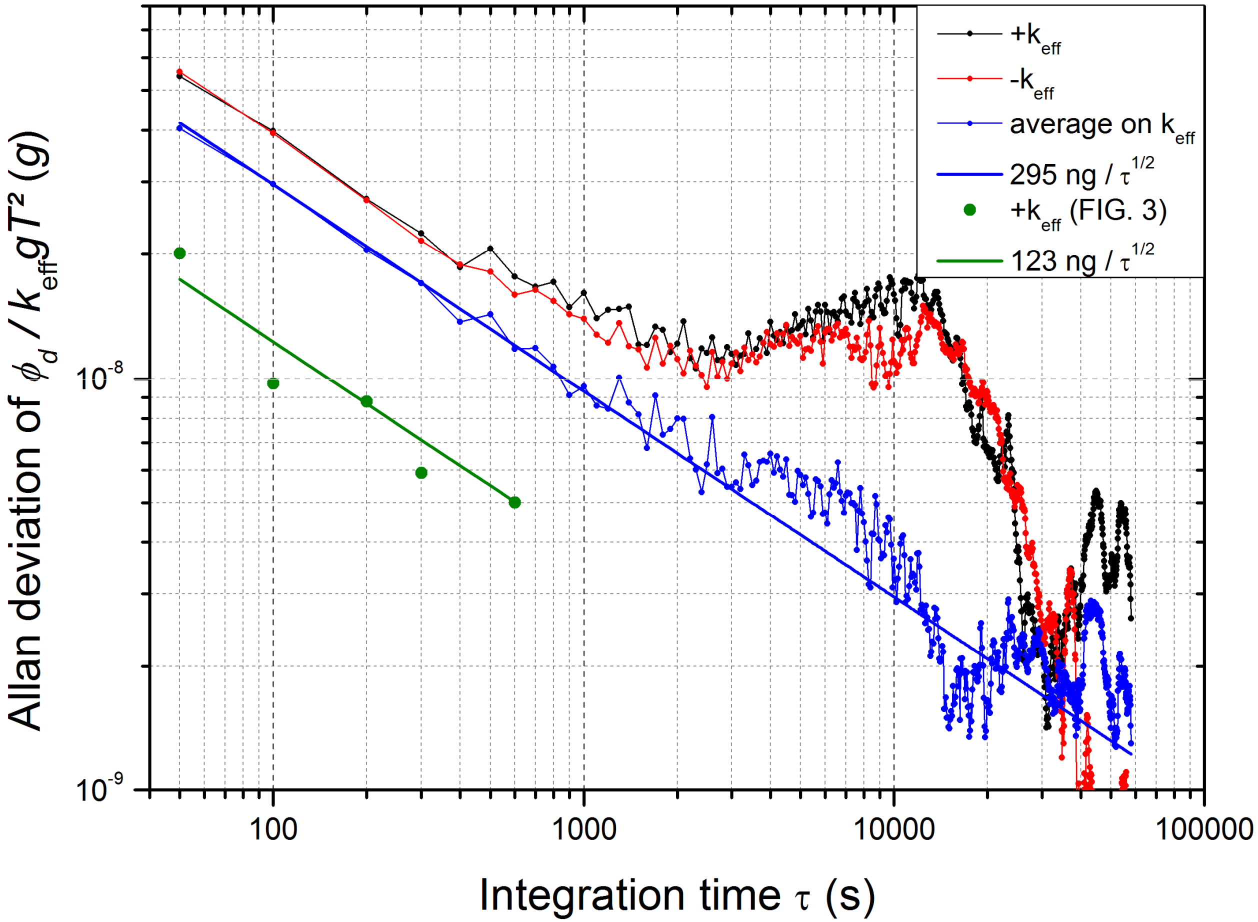
Rejection factor of 50 000 (94dB)

For large vibrations : drop of contrast (Doppler shift because of vertical accelerations, spurious rotations)

Post-correction of these contributions

Sensitivity & Resolution on differential acceleration

Allan deviation of the differential acceleration: the acceleration is derived from ellipses



Best sensitivity:

$$1.2 \times 10^{-7} g/\sqrt{Hz}$$

Resolution:

$$\frac{\sigma_g}{g} = 2.10^{-9}$$

No significant drift for integration times of ≈ 1 day

Prove the ability of a quantum test of the WEP by atom interferometry at a level of 10^{-9} with a small and compact sensor

Thank you for your attention

Atom Inertial Sensors Team at ONERA