Gravitational tests using simultaneous atom interferometers

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Workshop Quantum Foundations: New frontiers in testing quantum mechanics from underground to the space

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Outline

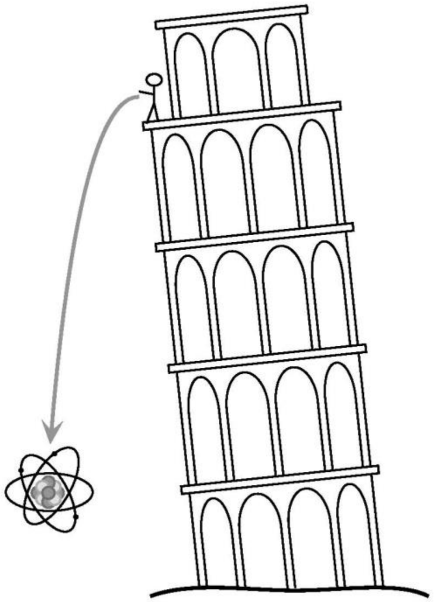
- Introduction to atom interferometry
- The history: MAGIA experiment (apparatus and G measurement)
- Test of the weak equivalence principle in its quantum formulation
- Geometry free determination of the gravity gradient

Atom Interferometry for gravity measurement

Atom Interferometry can measure accelerations

We use Cold Atoms as free falling microscopic masses

Quantum features of matter allow to improve the sensitivity
(not just a time-of-flight measurement in the "classical way")



Ingredients:

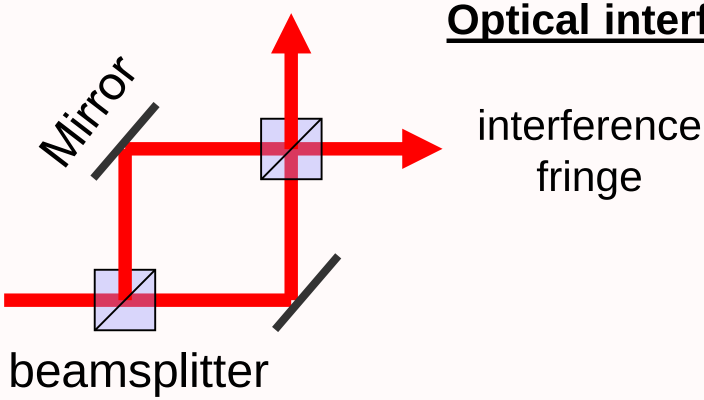
- A source of Cold Atoms (~ μ K or less)

  (the sample must be slowly expanding and weakly interacting)

- A laser system to cool the sample and to manipulate the wavepacket

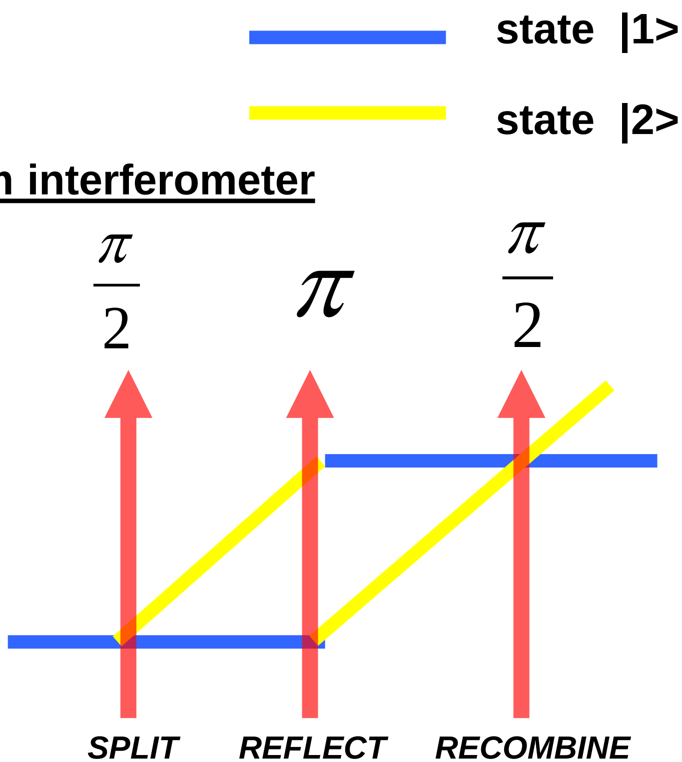
Atom / light Interferometry: the analogy

Optical interferometer

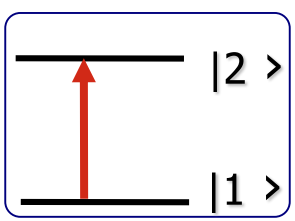


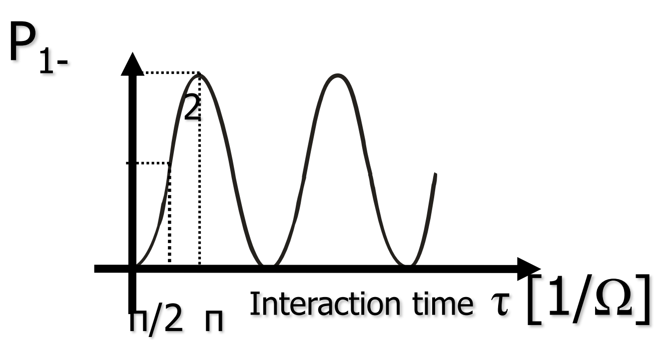
- **π /2 pulse** works like a **beamsplitter**
  momentum transfer
- **π pulse** works like **mirror**;
  momentum transfer

Atom interferometer

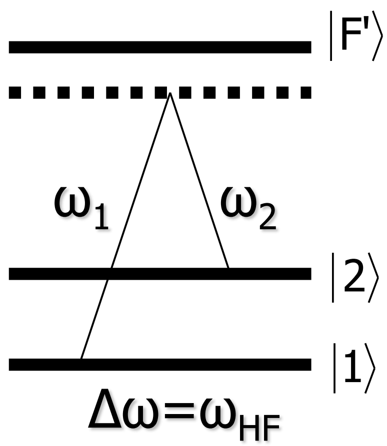


Once you have an **atomic two level system** you can make the analogy with light looking at the Rabi's population oscillations scheme





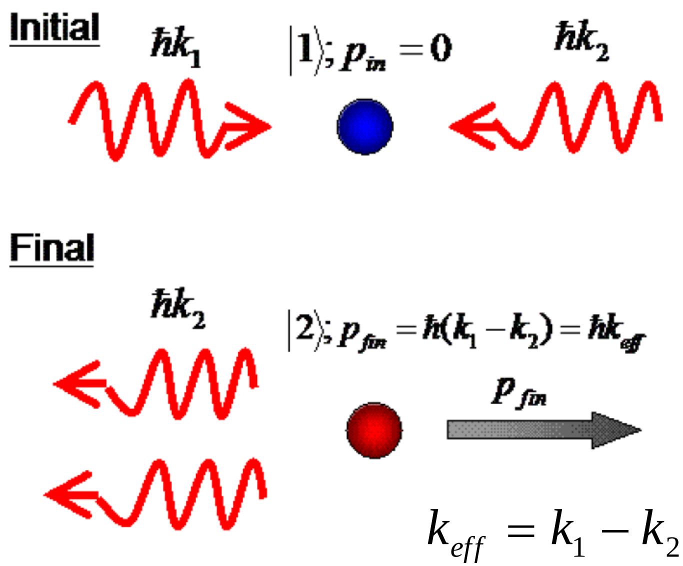
Atom Interferometry: theory

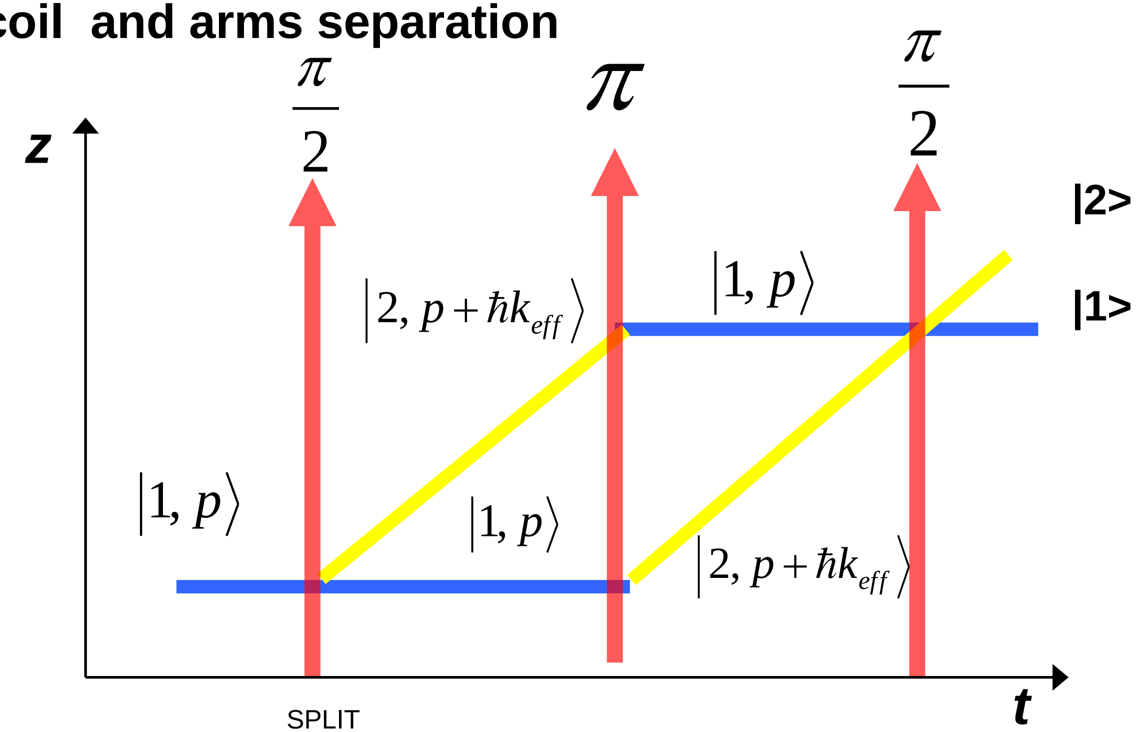


Two **hyperfine states** are coupled by **two photon RAMAN Transition** using two **couterpropagating beams**
frequency difference must be equal to hyperfine states separation

- We need to couple two long-lived states
- Why RAMAN: we need large momentum recoil (arms separation)

Momentum recoil and arms separation





Atom Interferometry: theory

Wave function PHASE evolution

GRAVITY BREAKS THE SIMMETRY

totally symmetric evolution

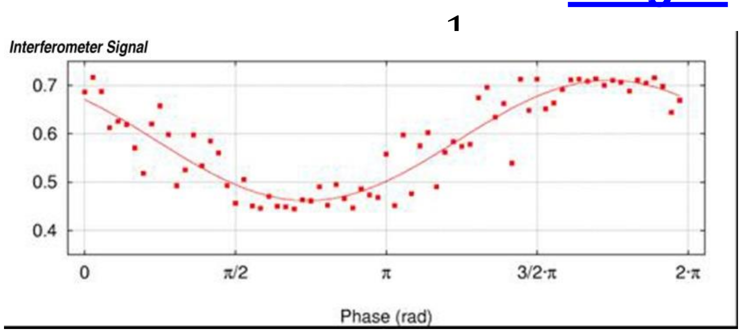
If $g = 0 \;\Longrightarrow\; \Delta\Phi_{tot} = 0$

$g \neq 0 \;\Longrightarrow\; \Delta\Phi_{tot} = k_{eff}\, g T^2 + \Delta\Phi'$

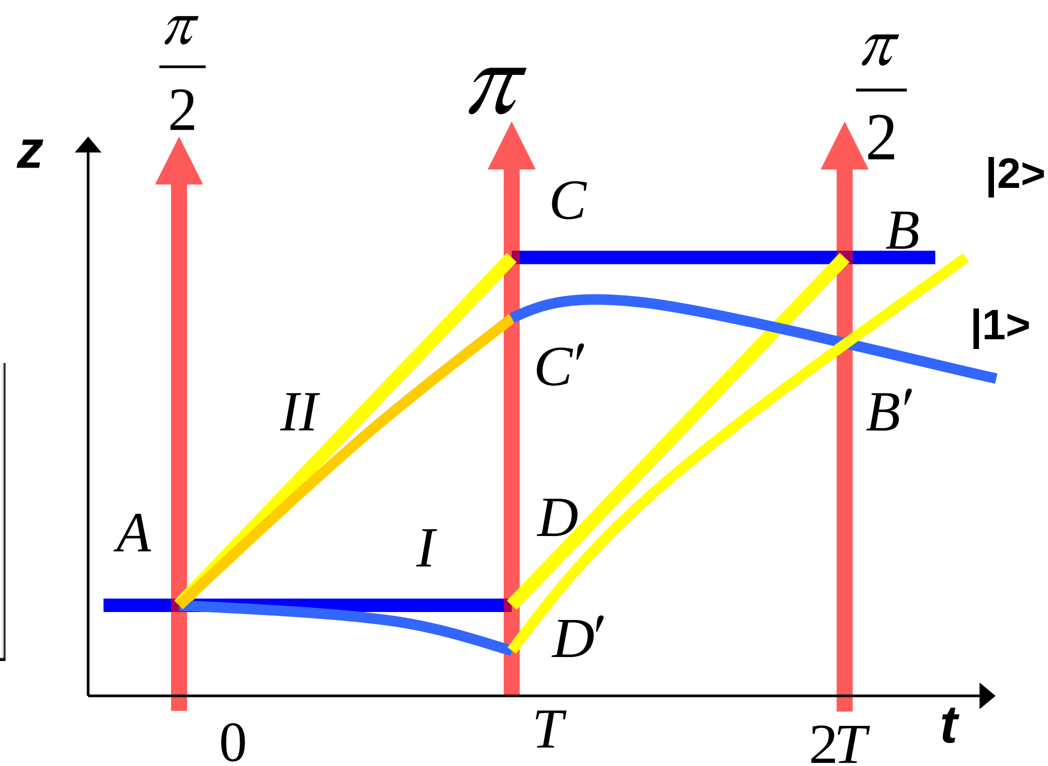
Population on final State depends
On the interferometer phase

$$P_1 = \frac{1}{2}(1 + \cos\Delta\Phi_{tot}) \qquad P_2 = \frac{1}{2}(1 - \cos\Delta\Phi_{tot})$$

fringes



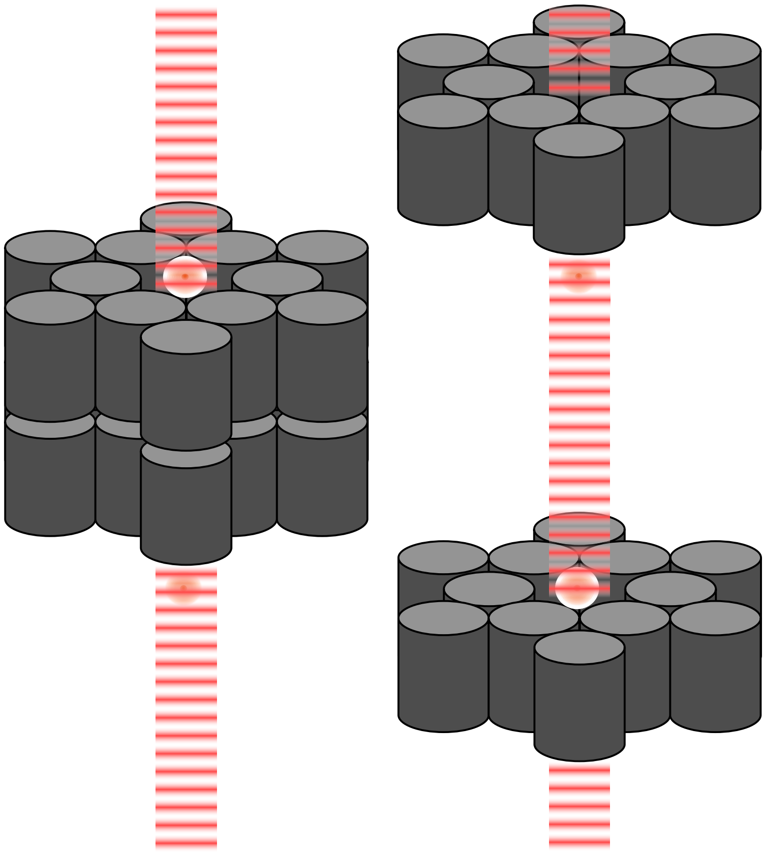
varying RAMAN laser's phase



MAGIA

Misura Accurata di G mediante Interferometria Atomica

MAGIA - the procedure



SOURCE MASSES
Well-characterized tungsten cylinders

PROBE MASSES
Cold, freely falling ^{87}Rb atoms

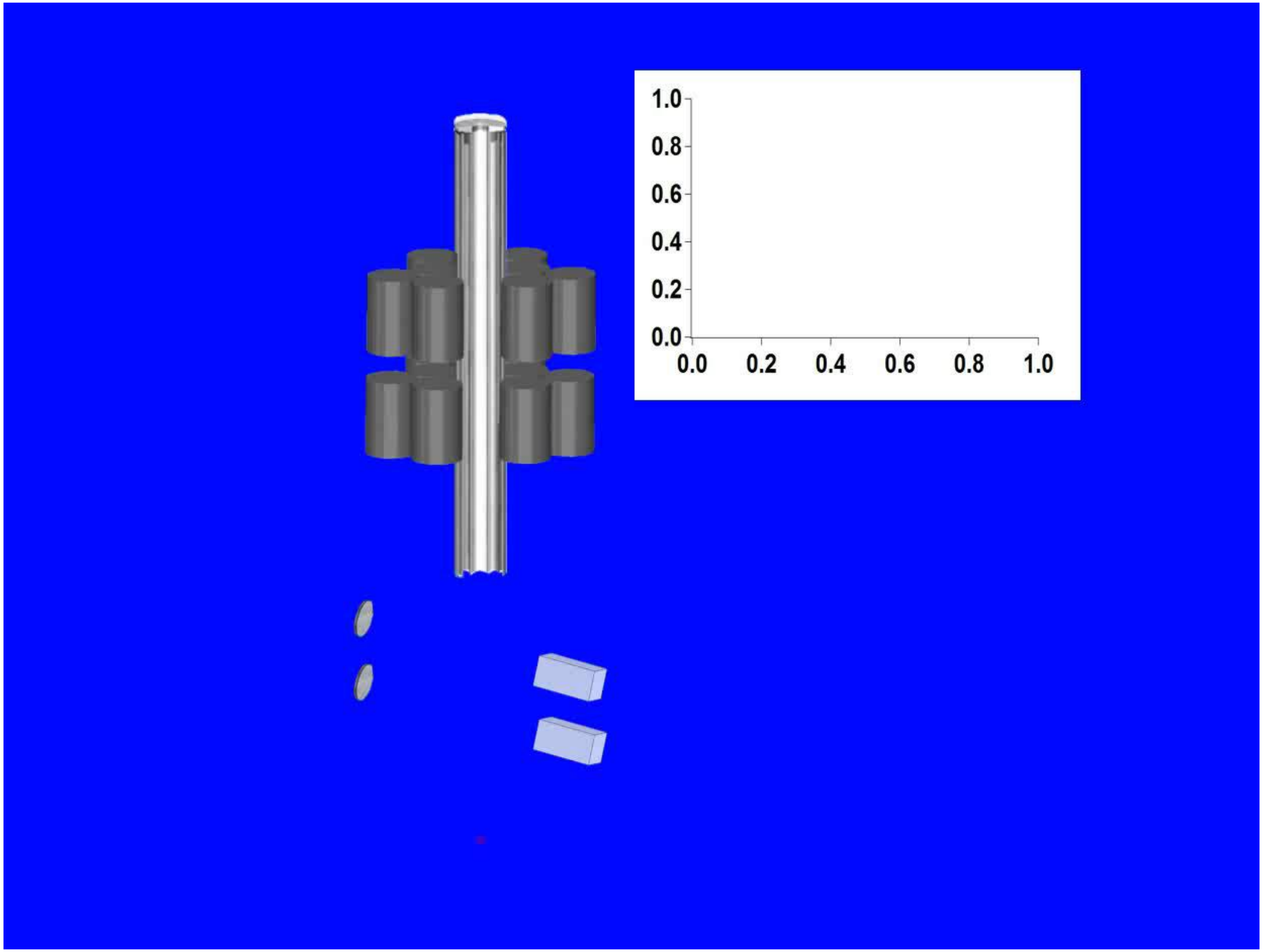
MEASUREMENT METHOD
Raman atom interferometry (local acc.)
Spatial & temporal differential scheme

CALCULATION of gravitational attraction

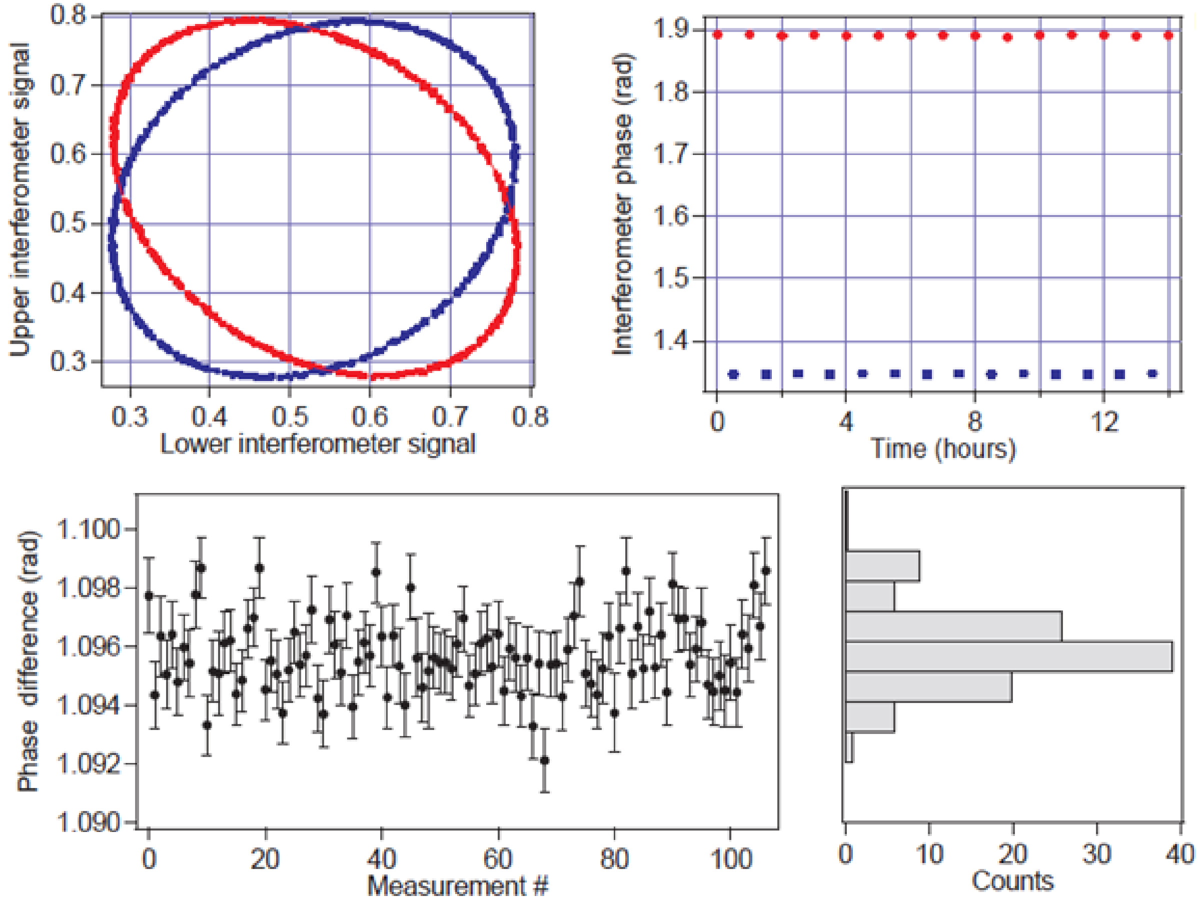
⬇

G

MAGIA - the experimental sequence



The G measurement



Features:

- Source masses modulation time: 30 mins
- Integration time:
  more than 100 hours over 2 weeks (July 2013)
- Sensitivity: 3×10^{-9} g/Hz$^{1/2}$
- Final sensitivity: ~ 10^{-11} g

$$G = 6.67191(77)_{stat}(62)_{sys} \times 10^{-11}\ m^3\,Kg^{-1}\,s^{-2}$$

MAGIA ADV

- Quantum test of the Weak Equivalence Principle
- Cancelling gravity gradients for future precision G measurements

Quantum formulation of the EEP

The Einstein Equivalence Principle plays a crucial role in our understanding of gravity. It can be organized into three conditions:

- Equivalence between the system's inertia and weight (WEP)
- Independence of local non-gravitational experiments from the velocity of the free falling reference frame (LLI)
- Independence of local non-gravitational experiments of their location (LPI)

How to implement EEP in a non-relativistic quantum theory?*

$$\hat{H}_{nr} = m_r c^2 + \frac{\hat{P}^2}{2m_i} + m_g \phi(\hat{Q})$$

← Non-relativistic Hamiltonian with classical potential

$$\hat{M}_\alpha := m_\alpha \hat{I}_{int} + \frac{\hat{H}_{int,\alpha}}{c^2} \quad \alpha = r, i, g,$$

Developing to the first order:

$$\hat{H}^Q_{test} = m_r c^2 + \hat{H}_{int,r} + \frac{\hat{P}^2}{2m_i} + m_g \phi(\hat{Q}) - \hat{H}_{int,i} \frac{\hat{P}^2}{2m_i^2 c^2} + \hat{H}_{int,g} \frac{\phi(\hat{Q})}{c^2}$$

Relativistic time dilation term: $\hat{H}_{int,i} \frac{\hat{P}^2}{2m_i^2 c^2}$

Gravitational time dilation term: $\hat{H}_{int,g} \frac{\phi(\hat{Q})}{c^2}$

*Zych et al. "Quantum formulation of the Einstein Equivalence Principle", arXiv:1502.00971 (2015)

Quantum formulation of the WEP

		EEP			
		WEP	**LLI**	**LPI**	**# param.**
Newtonian	classical & quantum	$m_i = m_g$	–	–	1
Newtonian + mass-energy equiv.	classical	$m_i c^2 + E_i = m_g c^2 + E_g$	$E_r = E_i$	$E_r = E_g$	$2n - 1$
	quantum	$m_i c^2 \hat{I} + \hat{H}_i = m_g c^2 \hat{I} + \hat{H}_g$	$\hat{H}_r = \hat{H}_i$	$\hat{H}_r = \hat{H}_g$	$2n^2 - 1$

The acceleration operator in the Heisenberg picture is:

$$\hat{a}_{\hat{H}^Q_{test}} := d^2\hat{Q}/dt^2 = -\frac{1}{\hbar^2}[[\hat{Q}, \hat{H}^Q_{test}], \hat{H}^Q_{test}] = -\hat{M}_g \hat{M}_i^{-1} \nabla\phi(\hat{Q}) + \frac{i}{\hbar}[\hat{H}_{int,i}, \hat{H}_{int,r}] \frac{\hat{P}}{m_i c^2} + \mathcal{O}(1/c^4)$$

where

$$\hat{M}_g \hat{M}_i^{-1} = \hat{I}_{int} - \hat{\eta} \quad \text{and} \quad \hat{\eta} \approx m_g/m_i(\hat{I} + \hat{H}_{int,g}/m_g c^2 - \hat{H}_{int,i}/m_i c^2)$$

If $[\hat{H}_{int,i}, \hat{H}_{int,g}] \neq 0$ internal and external degrees of freedom can be entangled!

*Zych et al. “Quantum formulation of the Einstein Equivalence Principle”, arXiv:1502.00971 (2015)

A quantum WEP test

Quantum formulation of WEP requires $\widehat{M_g} = \widehat{M_i}$

In QM a state of internal energy can involve superpositions of states → for the validity of the quantum WEP we need equivalence between the off-diagonal elements of the operators.

- Let us consider a two level systems (in our case F=1 and F=2 hyperfine ground state of ^{87}Rb:

$$\hat{M}_g \hat{M}_i^{-1} \approx \begin{pmatrix} r_1 & r \\ r^* & r_2 \end{pmatrix}$$

r_1 and r_2 are real numbers
r is a complex number $r=|r|e^{i\varphi}$

Classical WEP is valid if $r_1 = r_2 = 1$

Quantum WEP holds if $r = 0$

A quantum WEP test

Instrument is sensitive to*:

$$a_1 = g\,\langle 1 \mid \widehat{M_g}\widehat{M_i^{-1}} \mid 1\rangle = g r_1$$

$$a_2 = g\,\langle 2 \mid \widehat{M_g}\widehat{M_i^{-1}} \mid 2\rangle = g r_2$$

$$a_s = g\,\langle s \mid \widehat{M_g}\widehat{M_i^{-1}} \mid s\rangle = g\big((r_1 + r_2)/2 + \mid r \mid \cos(\varphi + \gamma)\big)$$

$(|s\rangle = (|1\rangle + e^{i\gamma}\,|2\rangle)/\sqrt{2})$

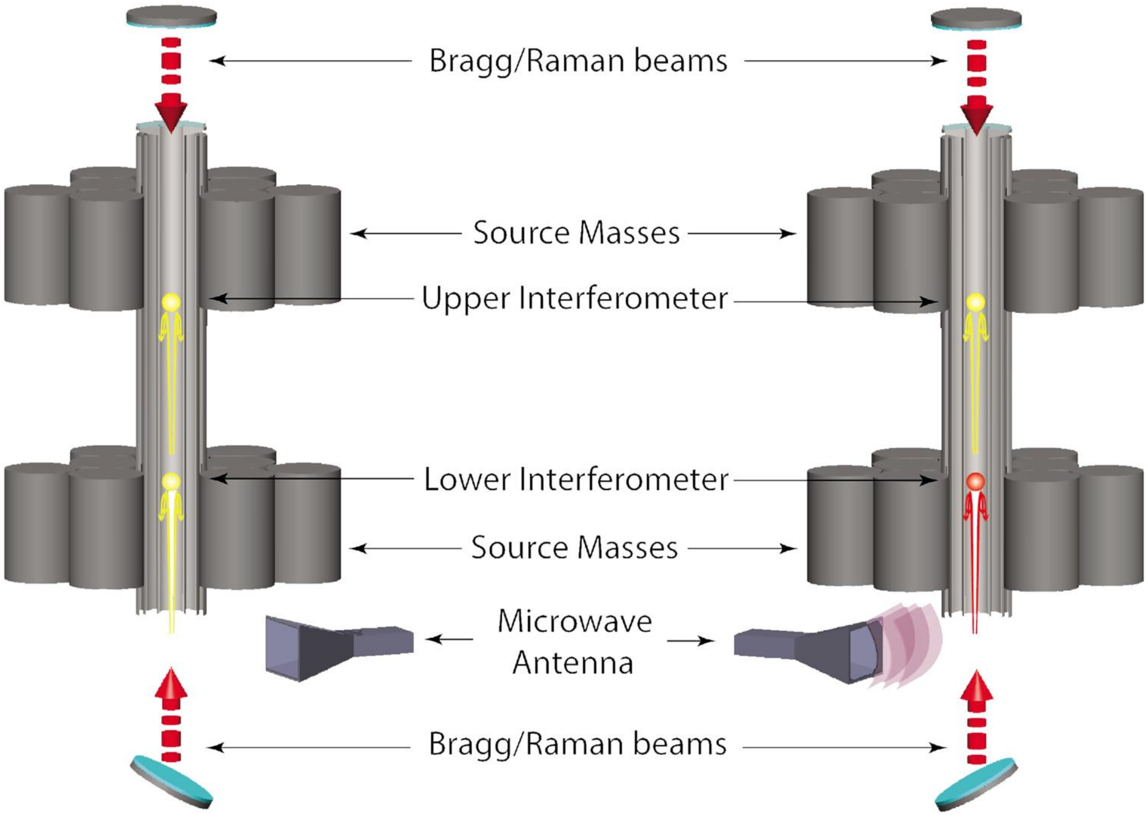
A classical WEP violation (introduced by diagonal elements $r_{1,2}$) emerges as a differential acceleration proportional to $r_1 - r_2$.

A quantum WEP violation would produce an excess phase noise on the acceleration measurements due to γ (random phase >> 2π).

*G. Rosi et al. Nature Communications 8, 15529 (2017)

A quantum WEP test

With the Bragg gradiometer we compare the free fall accelerations for atoms prepared in pure hyperfine states (F = 1, F = 2) and atoms prepared in a coherent superposition of two different hyperfine states.



Superposition state is prepared with RF pulse

$s = (|1\rangle + |2\rangle e^{i\gamma})/\sqrt{2}$

γ: random phase introduced with RF pulse

*G. Rosi et al. Nature Communications 8, 15529 (2017)

A quantum WEP test

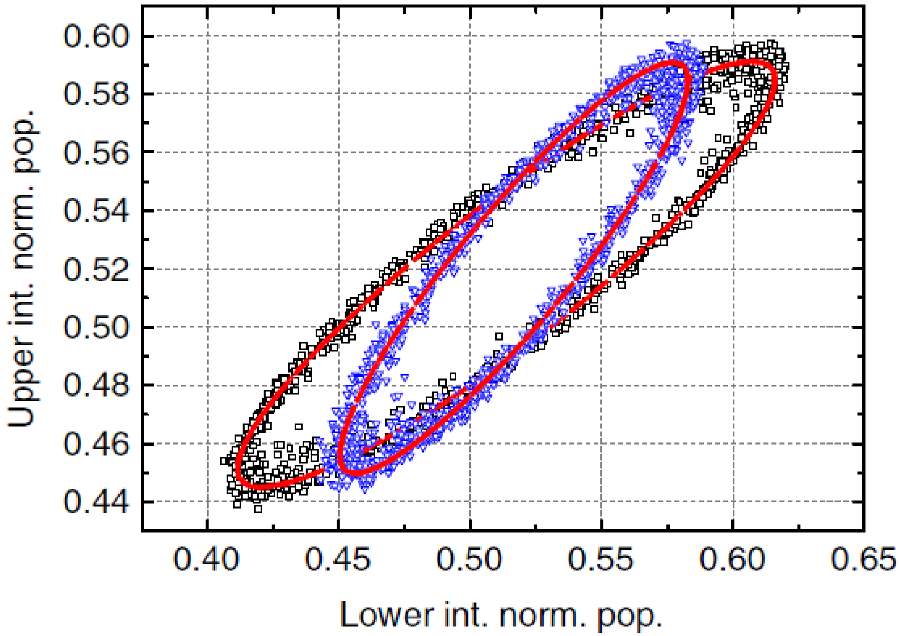
We realize three possible gradiometric configurations → $\Phi_{1\text{-}1}$, $\Phi_{1\text{-}2}$, $\Phi_{1\text{-}s}$

Classical WEP test → $\delta g_{1\text{-}2} \sim (\Phi_{1\text{-}1} - \Phi_{1\text{-}2})$ → $\eta_{1\text{-}2} = (1{,}4 \pm 2{,}8) \times 10^{-9}$

Quantum WEP test → Attributing all observed phase noise on 1-s ellipse to a WEP violation we estimate an upper limit for $|r|$ → $r \leq 5 \cdot 10^{-8}$.

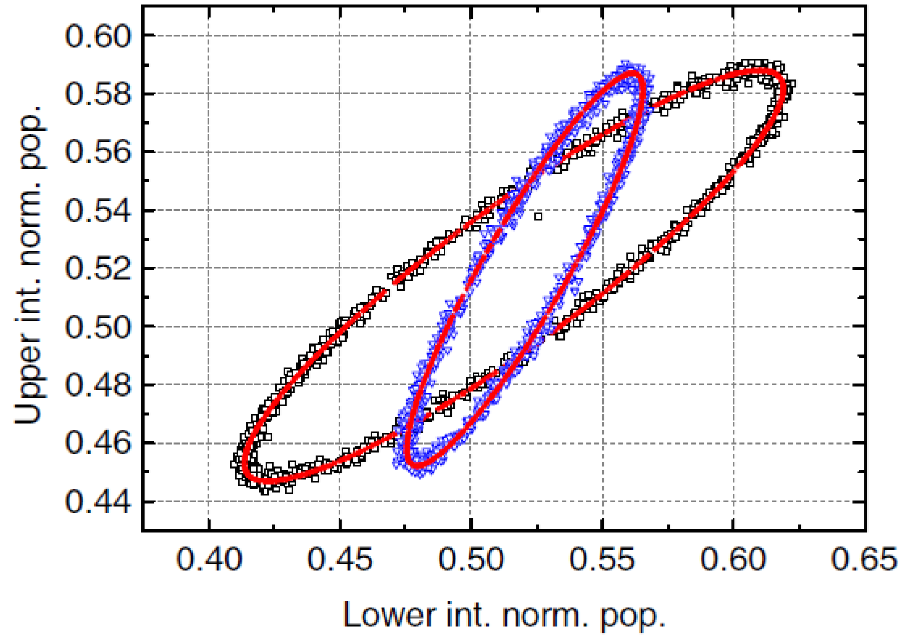
Black ellipse: 1 – 1 gradiometer

Blue ellipse: 1 – s gradiometer



Black ellipse: 1 – 1 gradiometer

Blue ellipse: 1 – 2 gradiometer



A quantum WEP test: prospects

- Energy difference between hyperfine state very tiny! (28 µeV)
- Likely, the commutator $[\hat{H}_{int,i}, \hat{H}_{int,g}]$ is proportional to the typical magnitude of H and therefore large ΔE yields to larger effects!
- Next step: Sr interferometer on clock transition!* ΔE= 1.8 eV!
- Next next step: entangled states between different isotopes?

*L.Hu et al., Accepted in PRL (2017)

MAGIA ADV

- Quantum test of the Weak Equivalence Principle
- Cancelling gravity gradients for future precision G measurements

Cancelling gravity gradients

- The tidal forces on the atoms in a uniform gravity field and gradient modify the wavepacket trajectories. The gravimetric phase shift is

$$\varphi = k_{eff} g T^2 + k_{eff} \Gamma_{zz} (z_0 + v_0 T) T^2$$

z_0, v_0 initial atomic position and velocity.

- The error on z_0 and v_0 is one of the major sources of noise and systematics:
  - For WEP tests at 10^{-15} level is required a control on z_0 and v_0 of 1 nm and 0,3 nm/s.
  - In the AI determination of G[1] one of the major sources of systematic error arises from the limited control on the thermal cloud degrees of freedom.

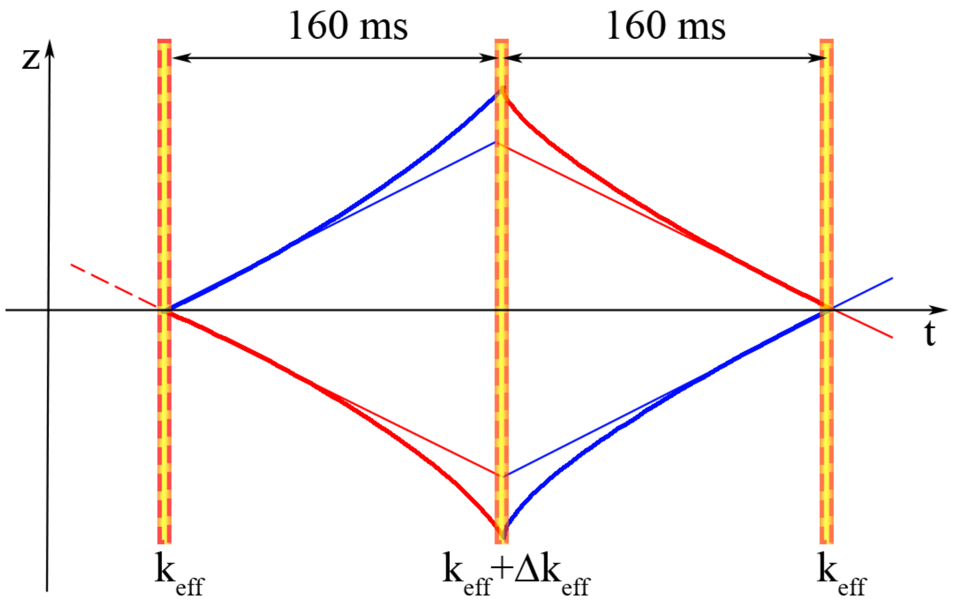
[1] G. Rosi, F. Sorrentino, L. Cacciapuoti, M. Prevedelli & G. M. Tino, *"Precision measurement of the Newtonian gravitational constant using cold atoms"*, Nature **510**, 518-521 (2014).

Cancelling gravity gradients

Readapting the effective wave vector k_{eff} of the π pulse it is possible to compensate the effect of Γ_{zz}[1]

$$\Delta k_{eff} = (\Gamma_{zz} T^2/2) k_{eff}$$

φ no longer depends on z_0 and v_0.

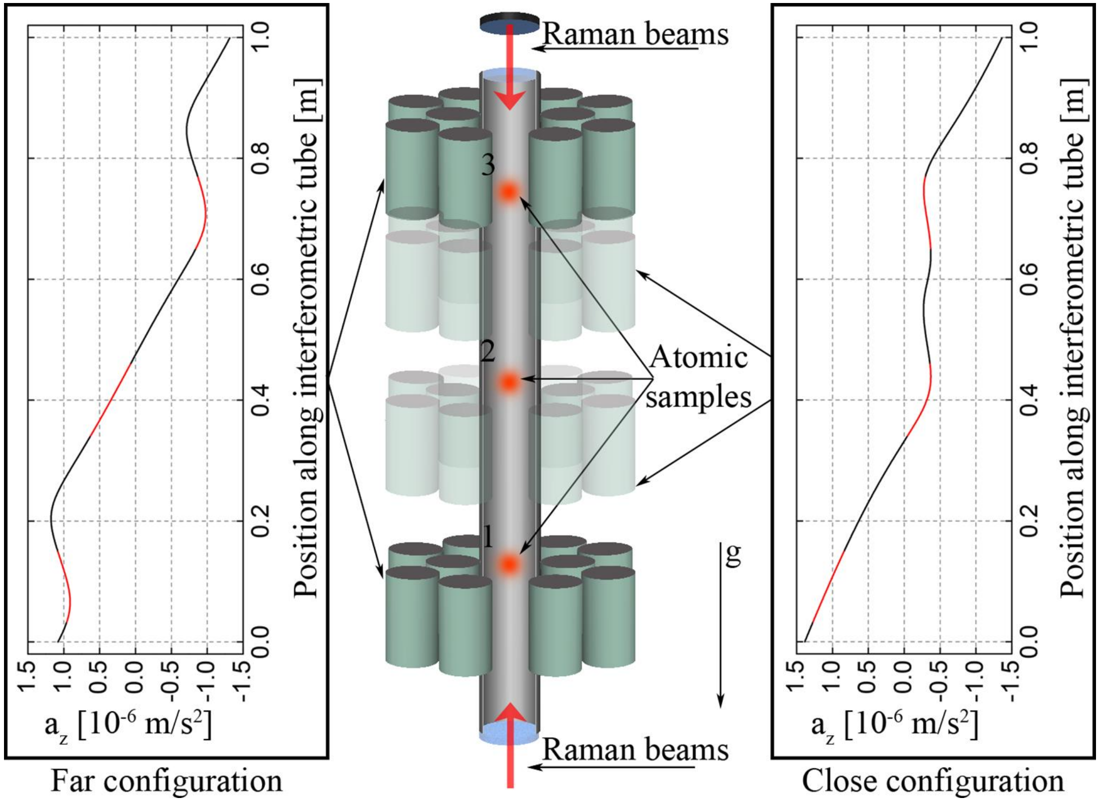


This procedure simulates the effect of a gravity gradient on the atomic trajectories.
We implement it to measure gravity gradients, gravity curvature

[1] A. Roura, Phys. Rev. Lett. **118**, 160401 (2017).

Cancelling gravity gradients

We simultaneously interrogate three clouds with the Raman interferometer for two source masses configurations. During the π pulse the frequency of the Raman lasers is changed by Δv*.



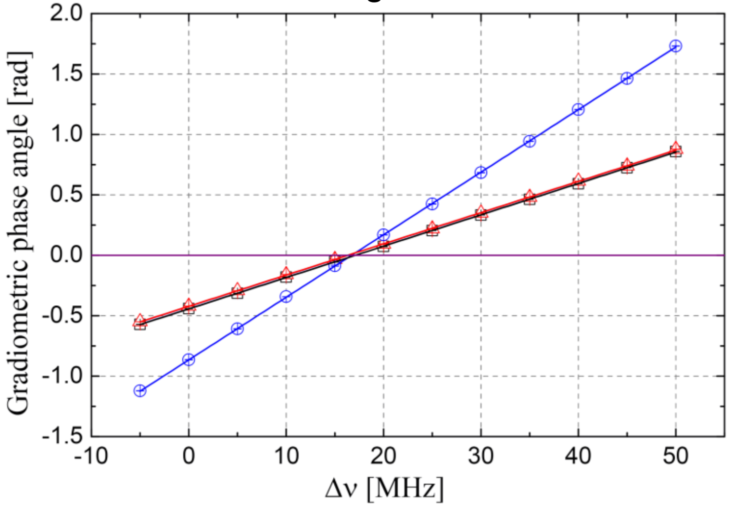
For the three gravity gradiometers (1-2, 2-3, 1-3) we measure the linear dependence Φ(Δv) vs Δv (Φ gradiometric phase)

Gravity gradient is traslated into a frequency!*

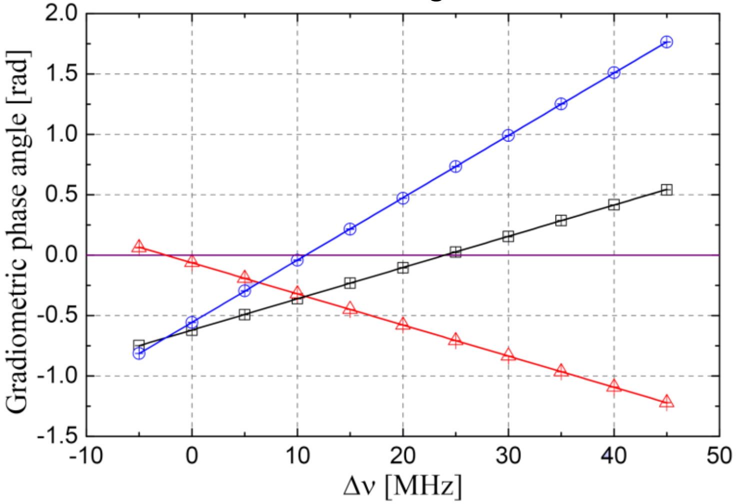
Cancelling gravity gradients

- Final results*:

Far configuration



Close configuration



	Γ_{23} [10^{-6} s^{-2}]	Γ_{12} [10^{-6} s^{-2}]	Γ_{13} [10^{-6} s^{-2}]
Far	-3,32 ± 0,02	-3,48 ± 0,01	-3,40 ± 0,01
Close	0,497 ± 0,006	-4,87 ± 0,01	-2,193 ± 0,006

- Measurements also provide gravity gradient sign.
- As expected $\Gamma_{13} = (\Gamma_{12} + \Gamma_{23})/2$.
- Measured cloud distances and gravity curvature in close configuration:

$$d_{23} = (307{,}2 \pm 0{,}3)\text{mm} \qquad d_{12} = (308{,}6 \pm 0{,}4)\text{mm}$$

$$\xi_{close} = (\Gamma_{23} - \Gamma_{12})/d = (1{,}743 \pm 0{,}004) \times 10^{-5}\ m^{-1}s^{-2}$$

*D'amico et al. Accepted in PRL

Conclusions and prospects

- In presence of a linear gravity gradient the zero crossing frequency is independent by clouds positions and velocities

- The main systematic effect in G determination with cold atoms arises from the required knowledge of atomic distribution

- Can we fabricate a source mass in order to produce an almost linear acceleration profile? Yes

➡ Determination of G at 10 ppm possible with thermal clouds!*

Recipe: double differential zero-crossing frequency determination

*G. Rosi, Metrologia (in press)

Thank you for the attention!

http://www.coldatoms.lens.unifi.it