DOES ANTIMATTER FALL LIKE MATTER ?: FOCUS ON GBAR EXPERIMENT

BEYOND STANDARD MODEL: FROM THEORY TO EXPERIMENT (BSM- 2021)

29/03/2021

Olivier Rousselle

Laboratoire Kastler Brossel
Physique quantique et applications

SORBONNE UNIVERSITÉ

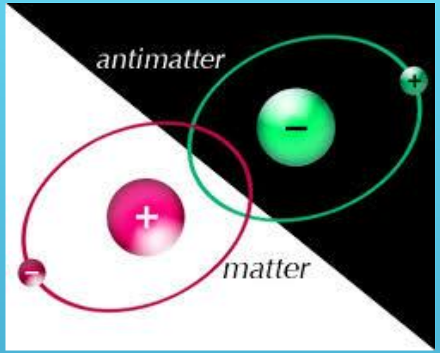
ENS

COLLÈGE DE FRANCE
1530

Antimatter

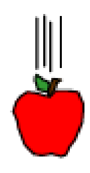
In 1928, Paul Dirac predicted the existence of antiparticles with the same mass as particles and an opposite charge .

$$i\hbar\gamma^{\mu}\partial_{\mu}\psi - mc\psi = 0$$



One of the main questions of fundamental physics is the asymmetry between matter and antimatter observed in the universe, and the action of gravity on antimatter.

« How does antimatter fall? »



Antigravity:
- is compatible with GR and would indicate that antimatter has a gravitational mass <0 ;
- could explain the asymmetry matter/antimatter in the universe (*G. Chardin*);
- can be a candidate for dark matter.

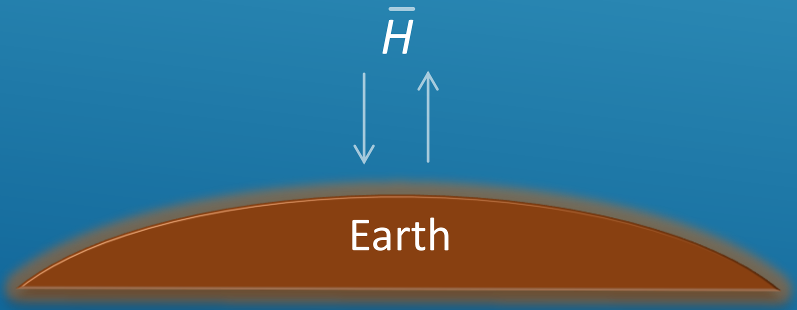
Sign of gravity acceleration not yet known experimentally, with bound: $-65 \leq \bar{g}/g \leq 110$

(*Alpha Collaboration, 2013*)

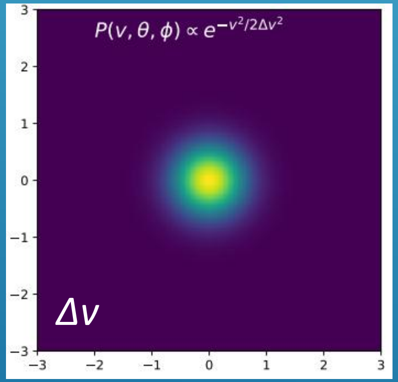
GBAR experiment: principle and motivations

GBAR collaboration (LKB, ETHZ, ILL Grenoble and other labs)
https://gbar.web.cern.ch/

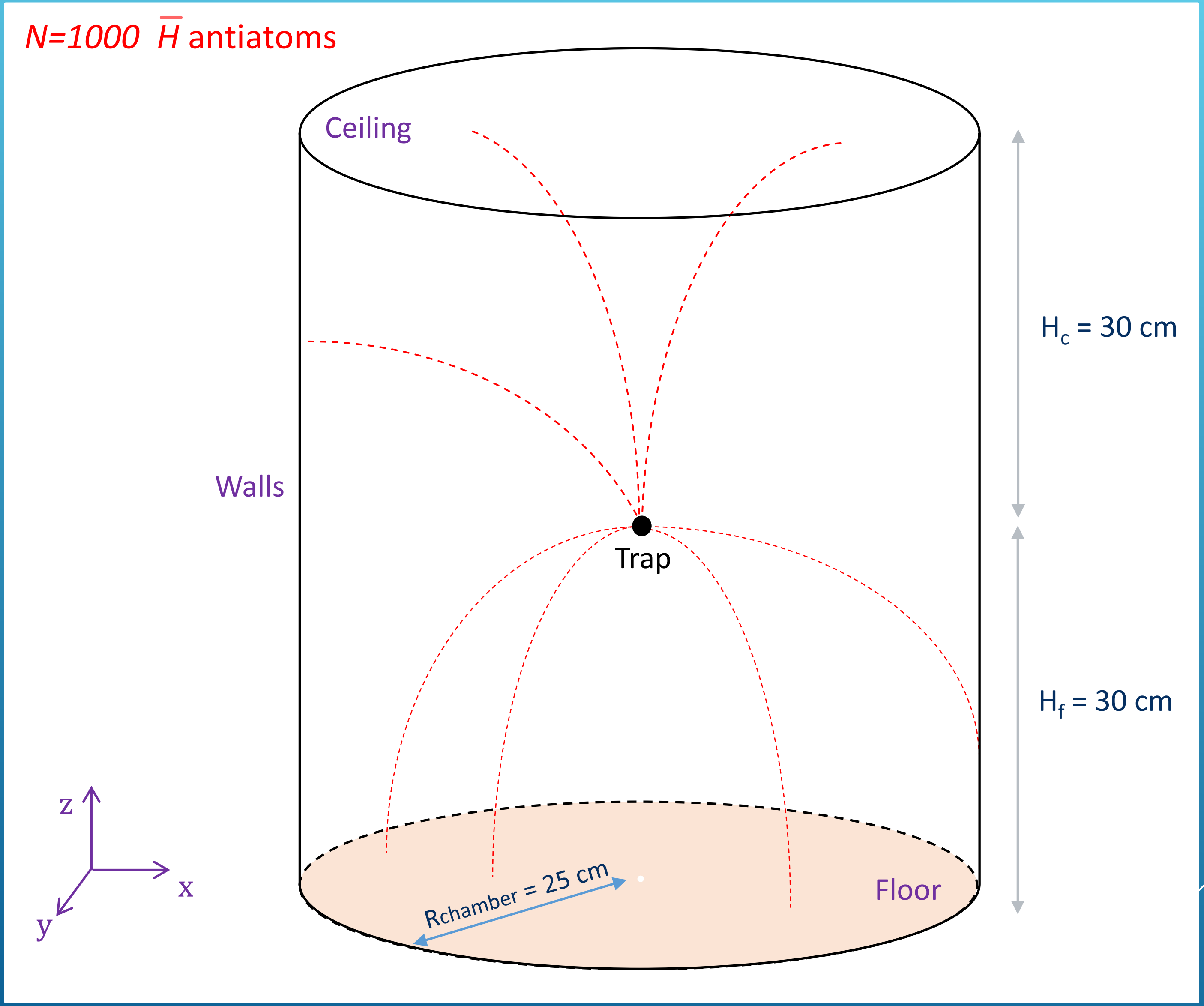
Gravitational Behaviour of Antihydrogen at Rest
Goal: measuring the acceleration $\bar{g}$ of ultracold antihydrogen atoms during a free fall in Earth's gravitational field, with 1% precision.

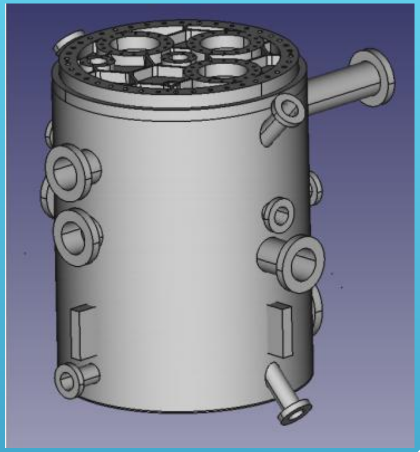


GBAR free fall chamber (initial geometry)



Ground state of the harmonic trap

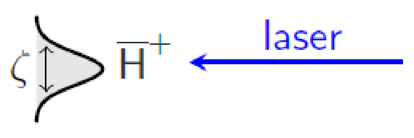




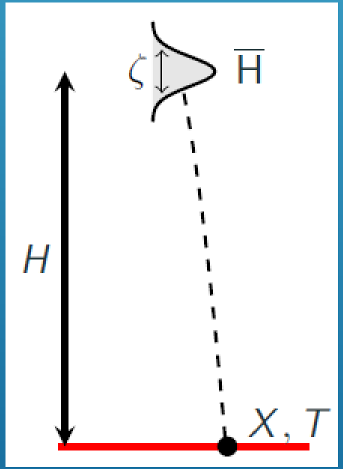
Free fall timing

Initially, ion $\overline{H}^+$ is trapped at very low temperature ($10\ \mu K$)

Start t_0 : The extra e^+ of $\overline{H}^+$ is photodetached -> neutral H anti-atom released



Stop T : annihilation of $\overline{H}$ on the surface of the detector after free fall



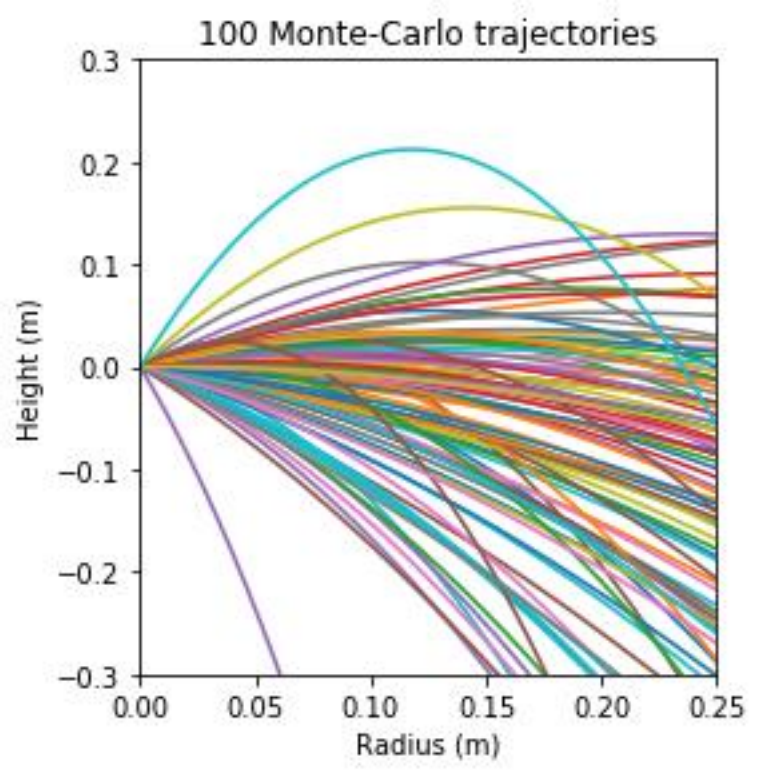
The free fall acceleration $\overline{g}$ is deduced from a statistical analysis of annihilated events.

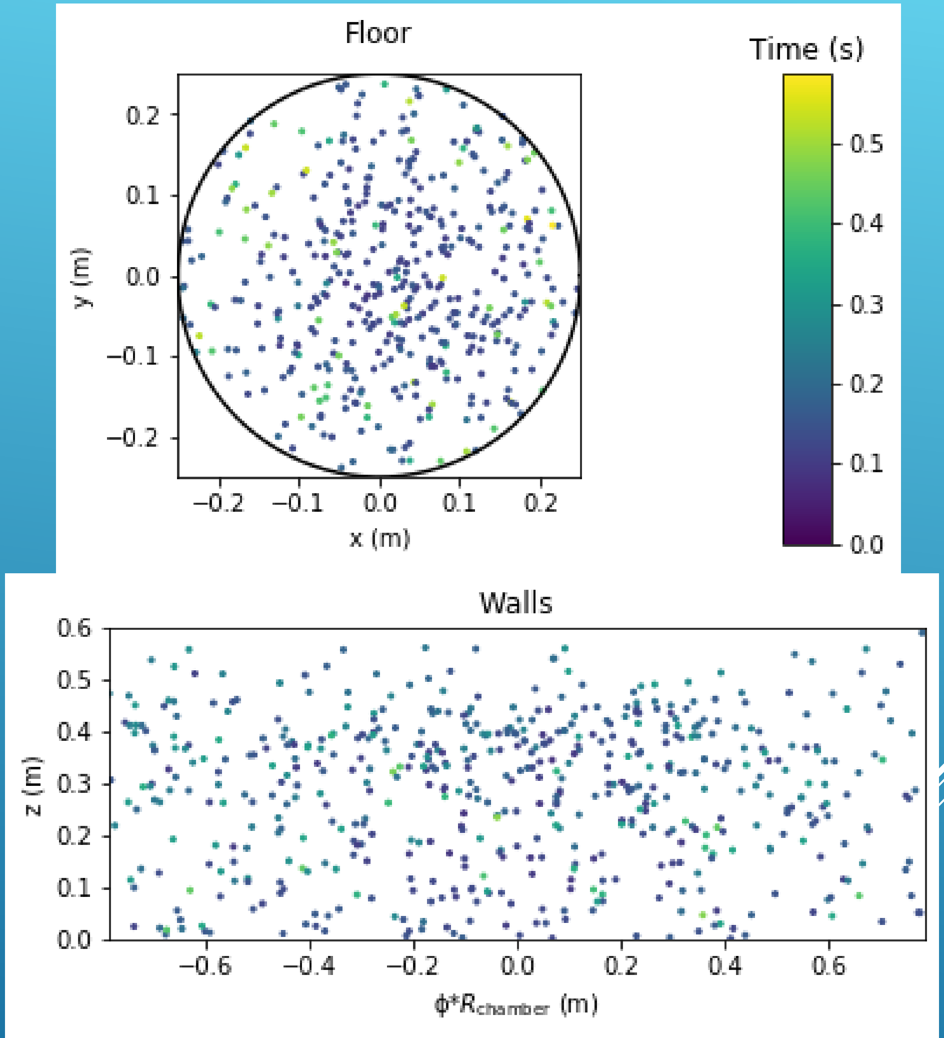
Monte-Carlo simulation: generation of events

$(Vx_0, Vy_0, Vz_0) \longrightarrow (X, Y, Z, T)$

Initial velocity Impact

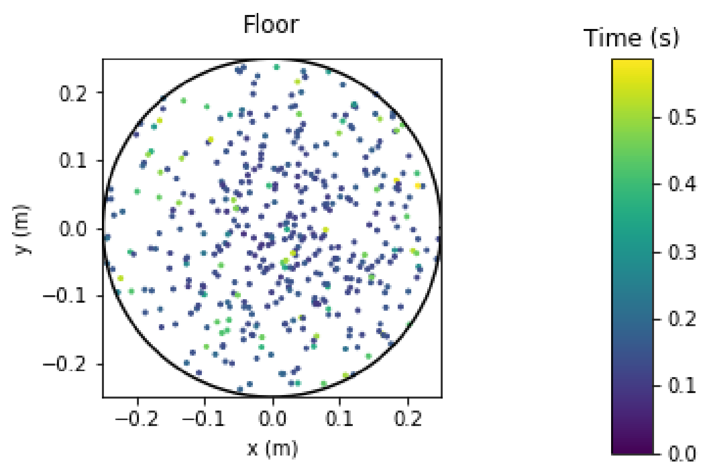
$$V_x = \frac{X}{T} \quad , \quad V_y = \frac{Y}{T} \quad , \quad V_{z,0} = \frac{Z}{T} + \frac{gT}{2}$$





Simulations performed with Python 3

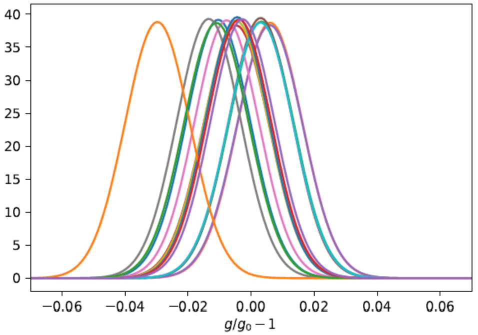
Monte-Carlo analysis (same scheme as an experimentalist)



Generation of *N* events (with $g_0=9.81\ m/s^2$)

Likelihood

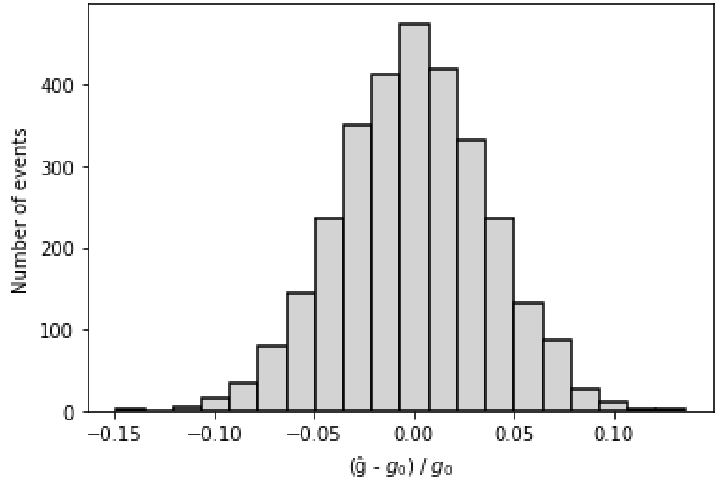
$$\mathcal{L}(g) = \prod_{i=1}^{N} J_g(x_i, y_i, z_i, t_i).$$



$$\hat{g} = \frac{\int g\mathcal{L}(g)dg}{\int \mathcal{L}(g)dg}.$$

Mean likelihood estimator

Repeated *M* times



Distribution of $\hat{g}$

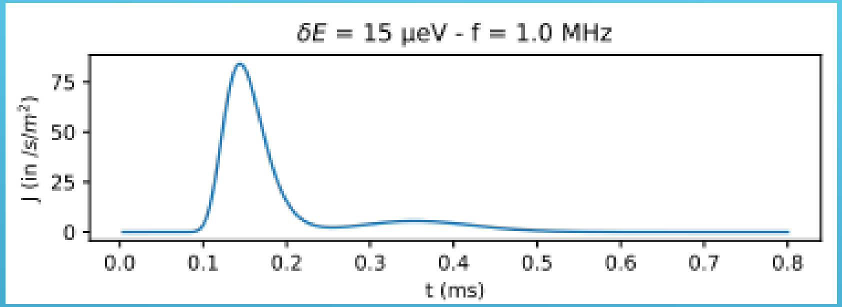
Average: μ_g

Relative uncertainty: σ_g/g_0

Not biased: $\mu_g - g_0 < \sigma_g$

Validation of the measurement uncertainty of *g*: analytical Cramer-Rao method

Analytical expression of the annihilation probability current *J* for each point of the detector



Ex. of current obtained for a point on the floor

Calculation of Fisher information

$$\mathcal{I}_g = \mathbb{E}\left[\left(\frac{\partial}{\partial g} \ln J_g\right)^2\right] = \int \mathrm{d}^2 R_\parallel \, \mathrm{d}T \, \frac{(\partial_g J_g)^2}{J_g}$$

Relative uncertainty

$$\frac{\Delta g_{\mathrm{CR}}}{g} = \frac{1}{g\sqrt{N\mathcal{I}_g}}$$

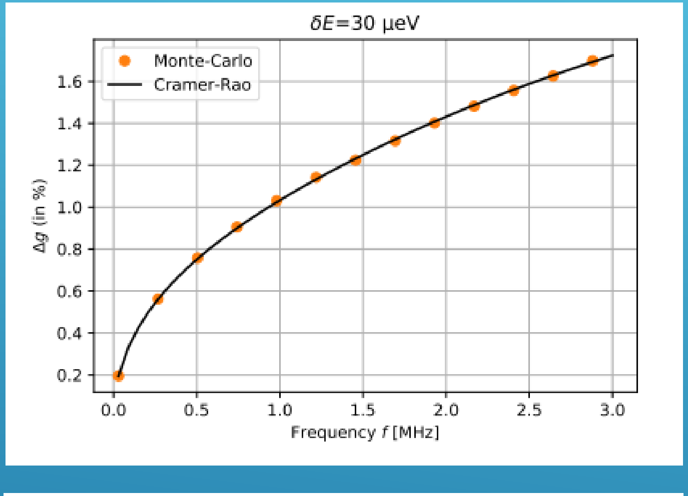
Statistical efficiency

$$e(\hat{g}) = \left(\frac{\Delta g_{\mathrm{CR}}}{\Delta \hat{g}}\right)^2 \leq 1$$

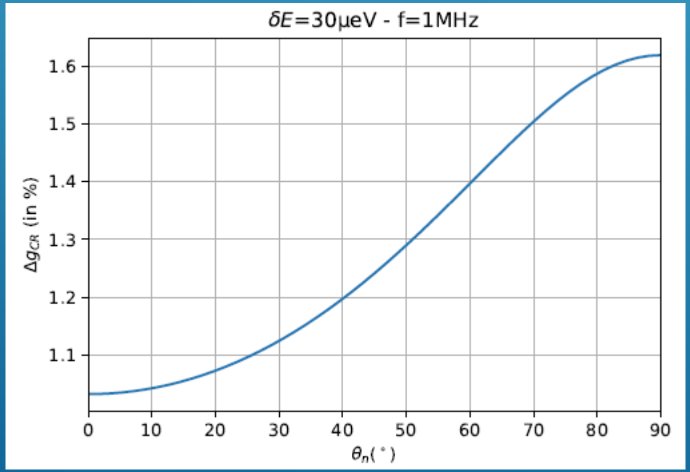
Effects of design parameters

Which parameters affect the accuracy of the measurement?

- Geometry of the free-fall chamber
- Number of atoms *N*
- Photodetachement atom recoil v_e
- Wavepacket velocity dispersion Δv



- Polarisation of the laser ϑ_n

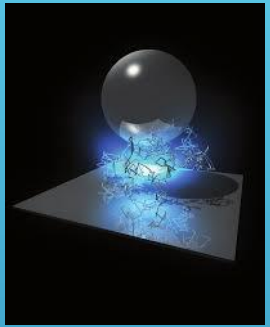


Horizontal polarization
$\Delta v = 0{,}44 m/s$, $v_e = 1{,}77 m/s$:
$\sigma_g / g \approx 0{,}91\%$
→ confirmation of the goal of uncertainty < 1%.

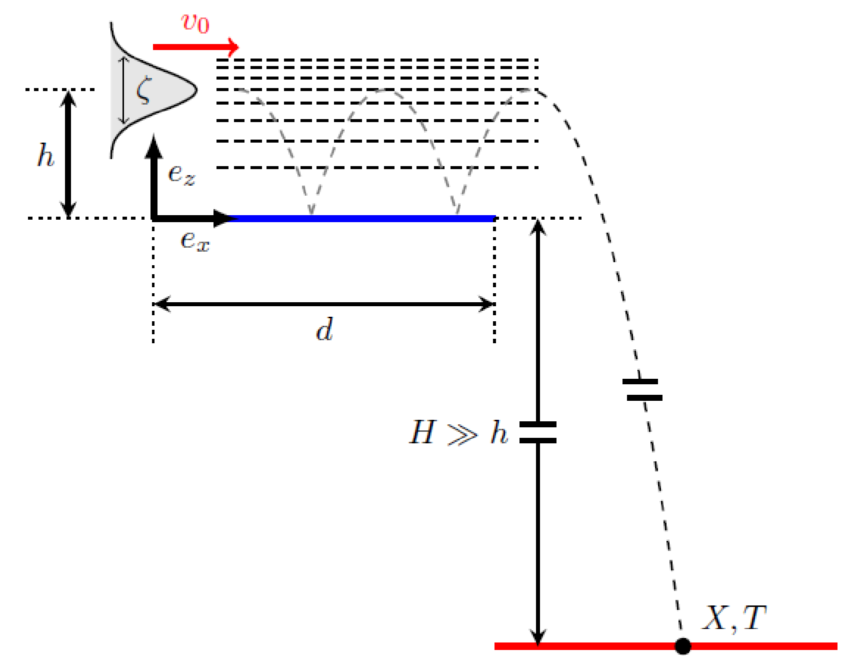
Quantum interference measurement

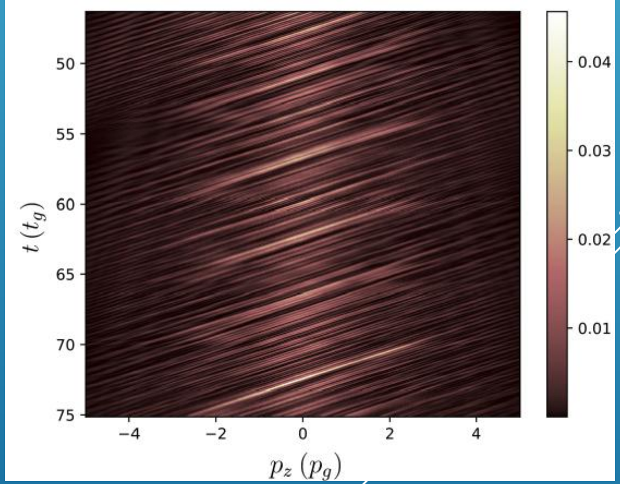
Goal: use quantum reflection to produce an interference pattern on the detector. The information extracted from the interference figure will lead to an improved uncertainty.

Implementation of a mirror some *μm* below the trap.
Atoms bounce several times above the mirror (quantum reflection on Casimir-Polder potential). Quantum paths corresponding to different GQS (Gravitational Quantum States) interfere. After free fall, the quantum interference pattern on the detector.

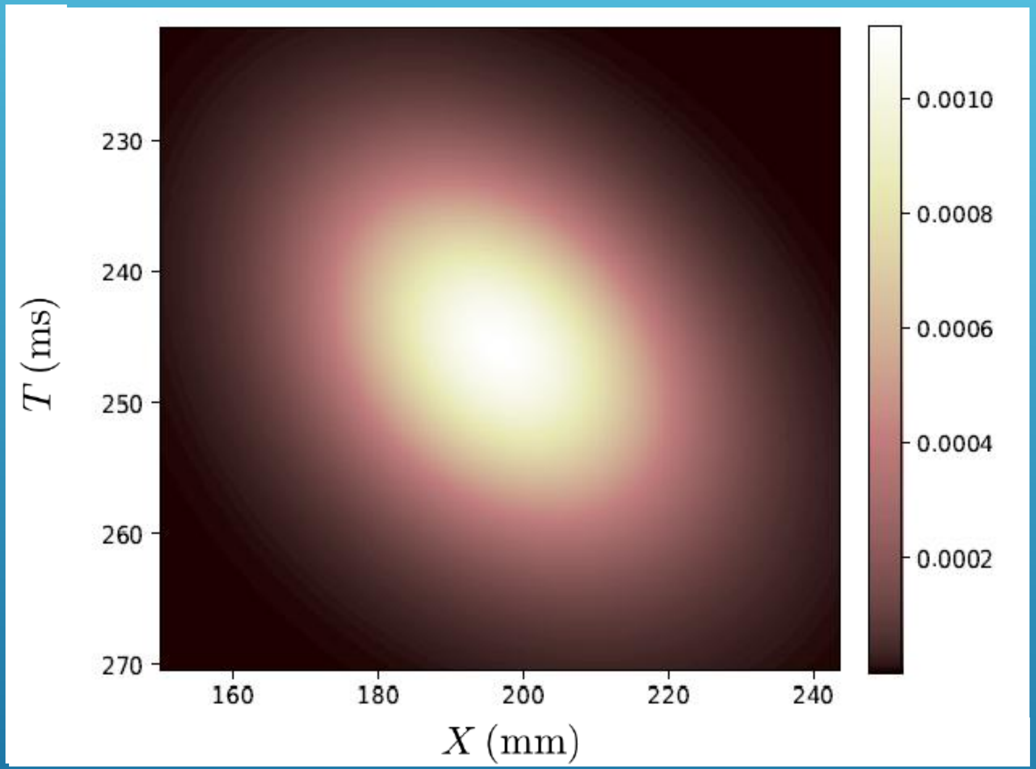


$\zeta=0.5\ \mu m$, $h=10 \mu m$,
$d=5\ cm$, $H=30 cm$

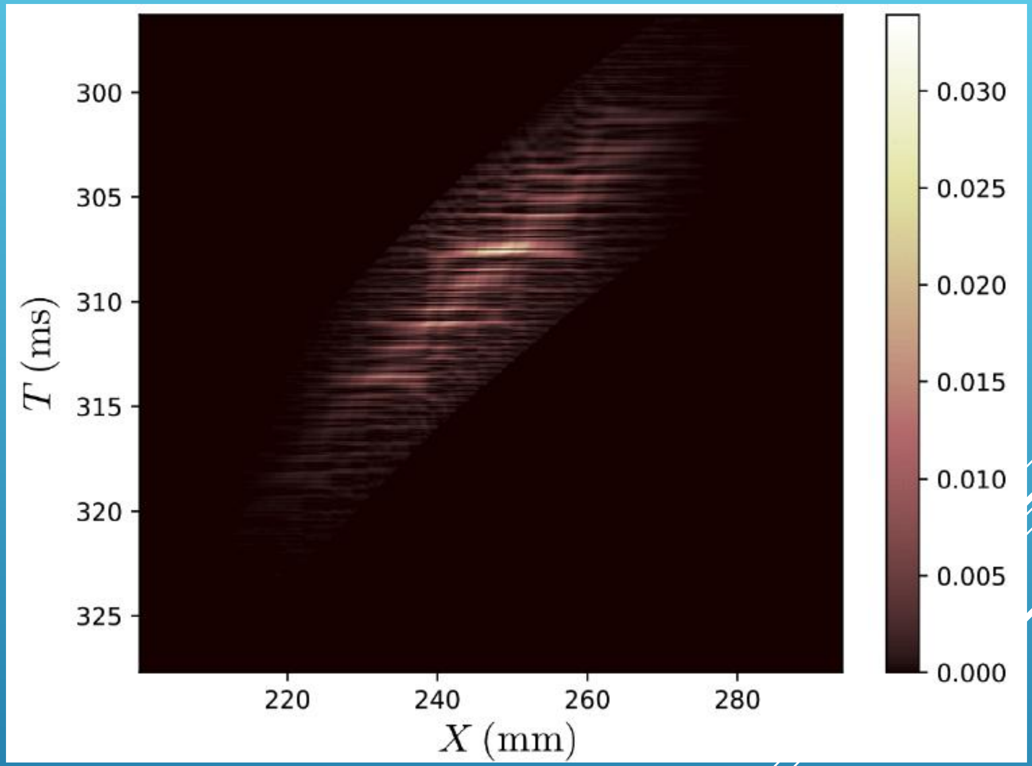




Final detection pattern: comparison classical / quantum cases



$\sigma_g/g \approx 10^{-2}$



$\sigma_g/g \approx 10^{-6}$

Thank you for your attention !

References:

Alpha Collaboration, *Description and first application of a new technique to measure the gravitational mass of antihydrogen*, Nature Communications volume 4, 2013

G. Chardin and G. Manfredi, *Gravity, antimatter and the Dirac-Milne universe*, Hyperfine Interactions, 239:45, 2018

GBAR Collaboration, *The GBAR project, or how does antimatter fall?*, Hyperfine Interactions 228, 2014

P.-P. Crépin et al., *Quantum interference test of the equivalence principle on antihydrogen*, Phys. Rev. A 99, 2019

P.-P. Crépin, *Quantum reflection of a cold antihydrogen wave packet*, thesis Sorbonne Université, 2019