HOW DOES ANTIMATTER FALL ?: FOCUS ON GBAR EXPERIMENT
RENCONTRES DE JEUNES PHYSICIEN.NE.S

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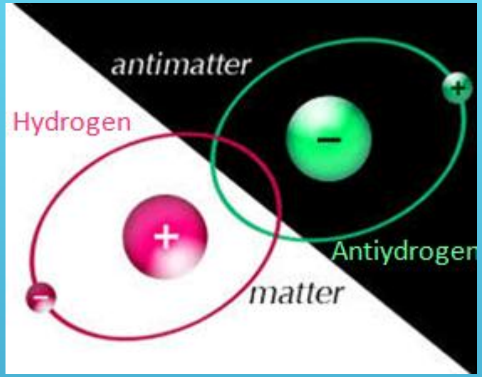
Antimatter

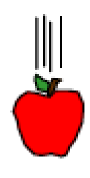
In 1928, Paul Dirac predicted the existence of antiparticles with the same mass as particles and an opposite charge .

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



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.

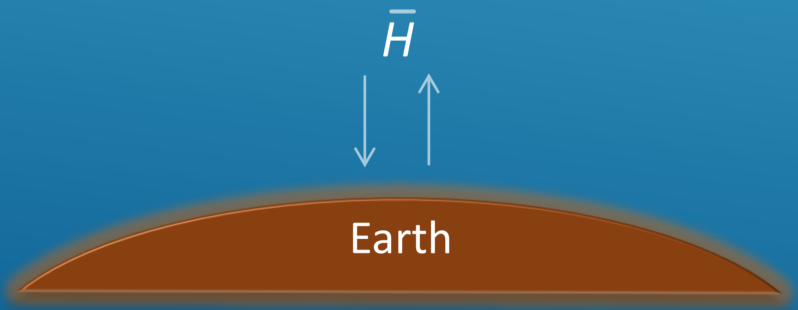
Sign of gravity acceleration not yet known experimentally, with bound: $-65 \leq \bar{g}/g \leq 110$

(*Alpha Collaboration, 2013*)

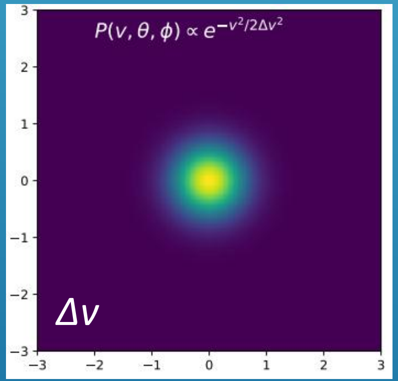
GBAR experiment: principle and motivations

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

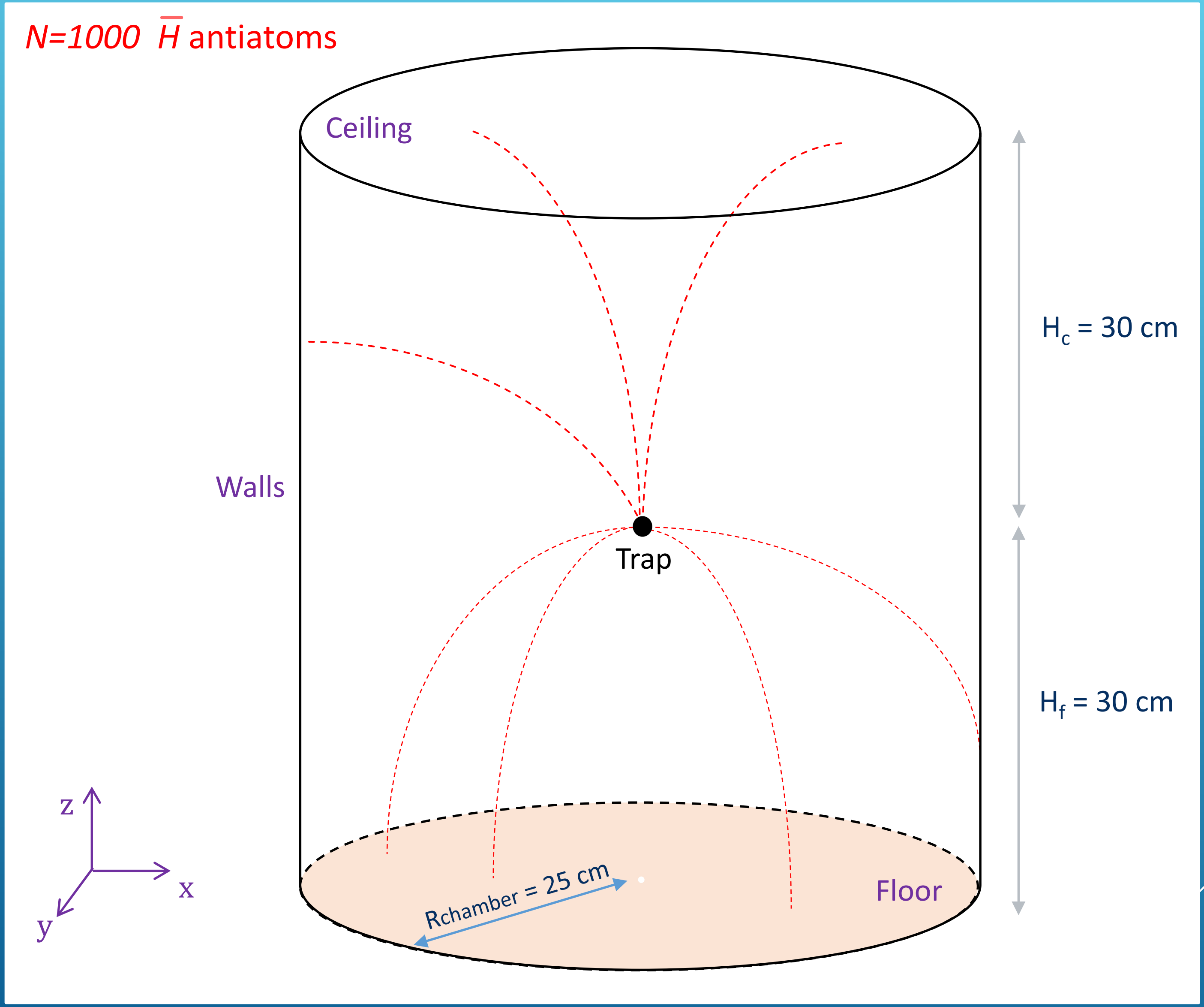
Gravitational Behaviour of Antihydrogen at Rest
Goal: measuring the acceleration $\bar{g}$ of ultracold antihydrogen atoms during a free fall in Earth's gravitational field, with 1% precision.

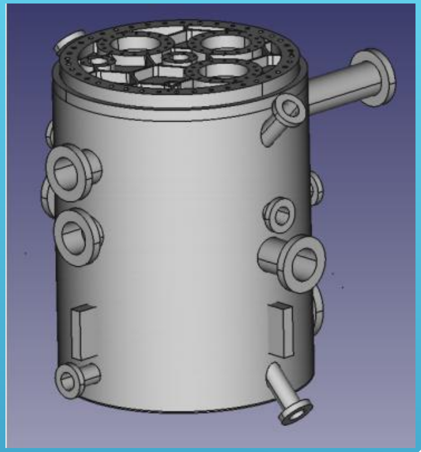


GBAR free fall chamber (initial geometry)



Ground state of the harmonic trap

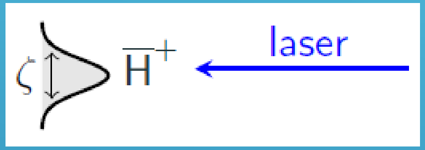




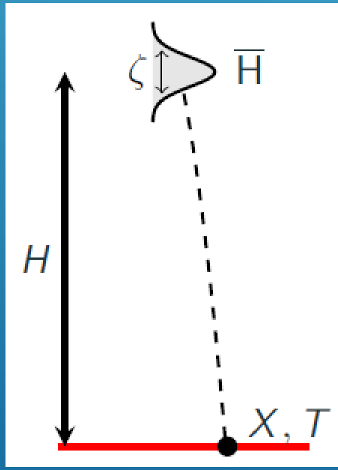
Free fall timing

Initially, ion $\bar{H}^{+}$ is trapped at very low temperature (*10 μK*)

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



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



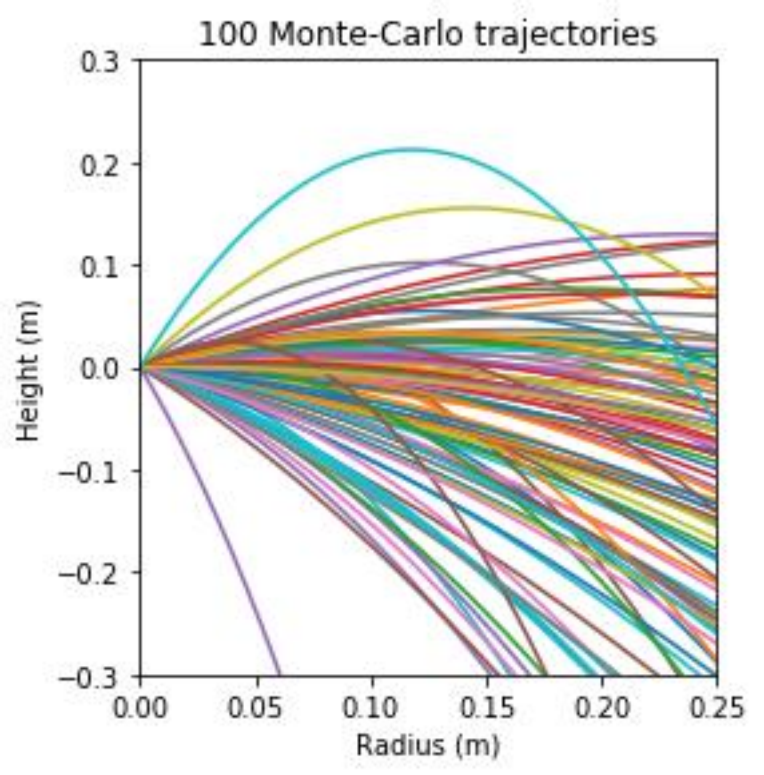
The free fall acceleration $\bar{g}$ is deduced from a statistical analysis of annihilated events.

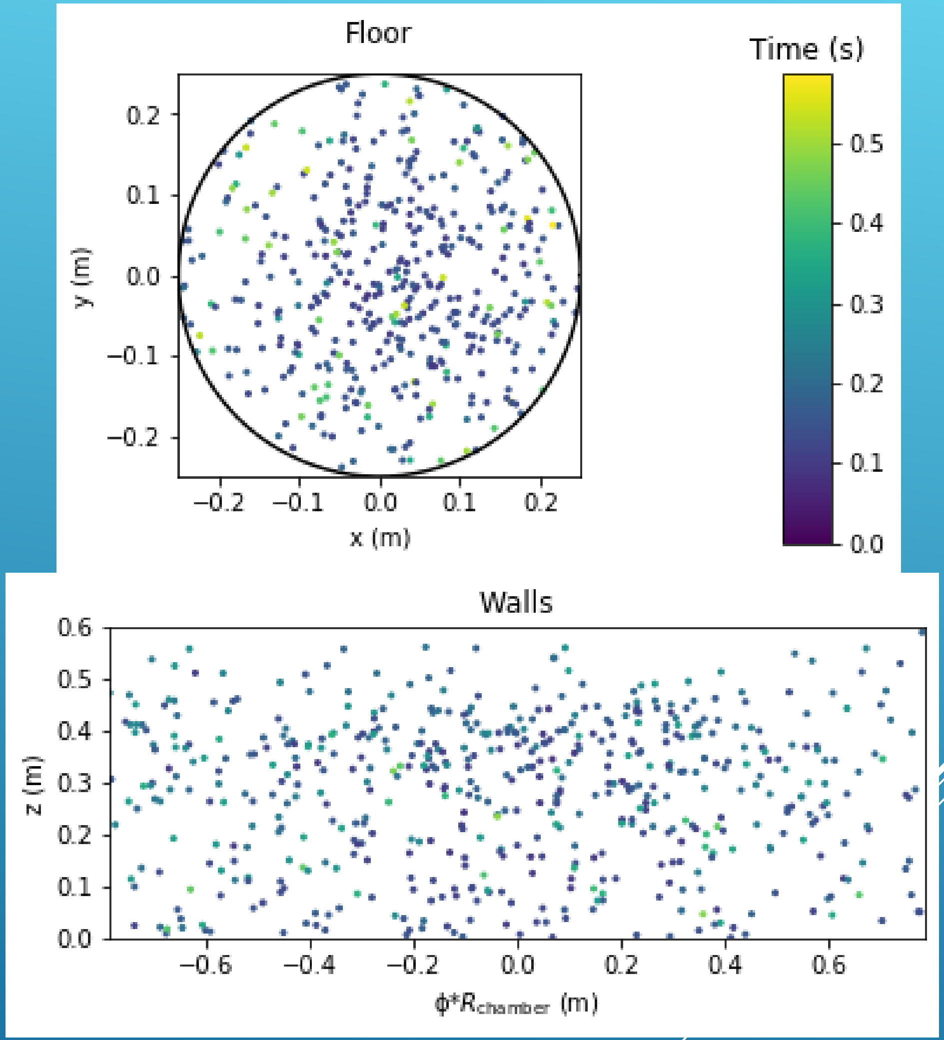
Monte-Carlo simulation: generation of events

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

Initial velocity — Impact

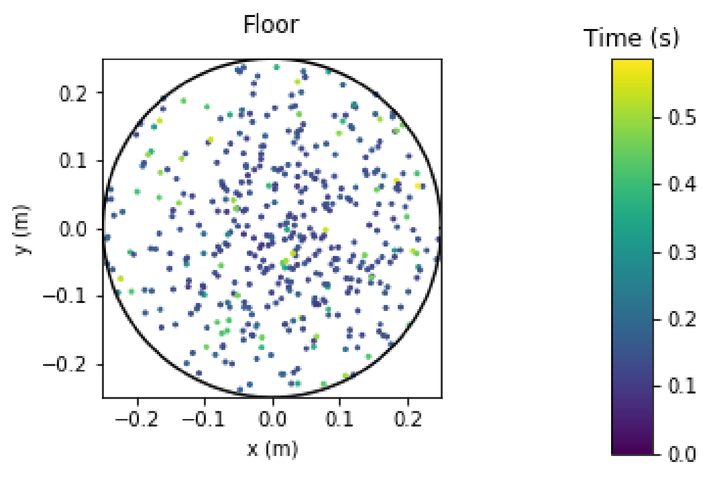
$$V_x = \frac{X}{T} \quad , \quad V_y = \frac{Y}{T} \quad , \quad V_{z,0} = \frac{Z}{T} + \frac{gT}{2}$$





Simulations performed with Python 3

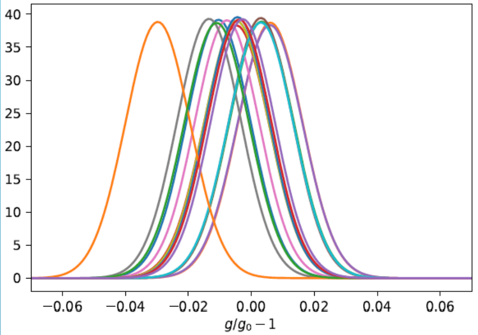
Monte-Carlo analysis (same scheme as an experimentalist)



Generation of *N* events (with g_0=*9.81 m/s²*)

Likelihood

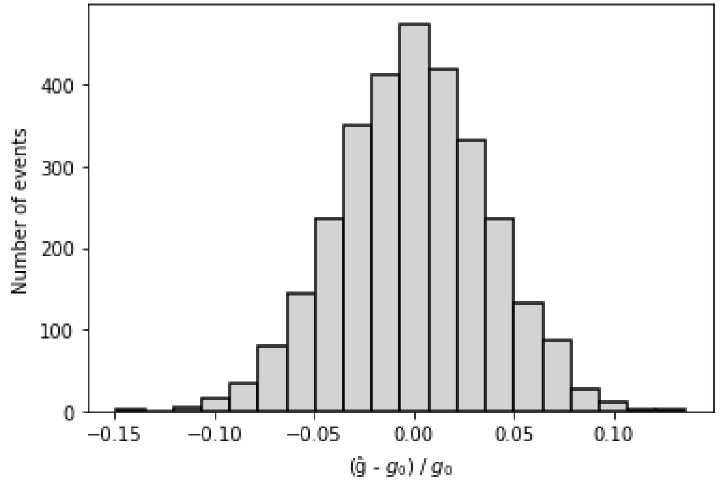
$$\mathcal{L}(g) = \prod_{i=1}^{N} J_g(x_i, y_i, z_i, t_i).$$



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

Mean likelihood estimator

Repeated *M* times



Distribution of $\hat{g}$

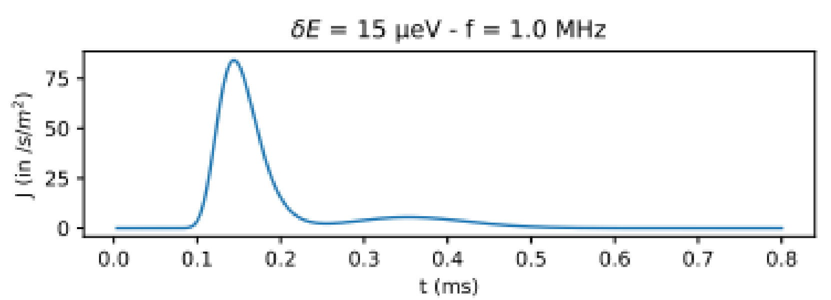
Average: μ_g

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

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

Relative uncertainty

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

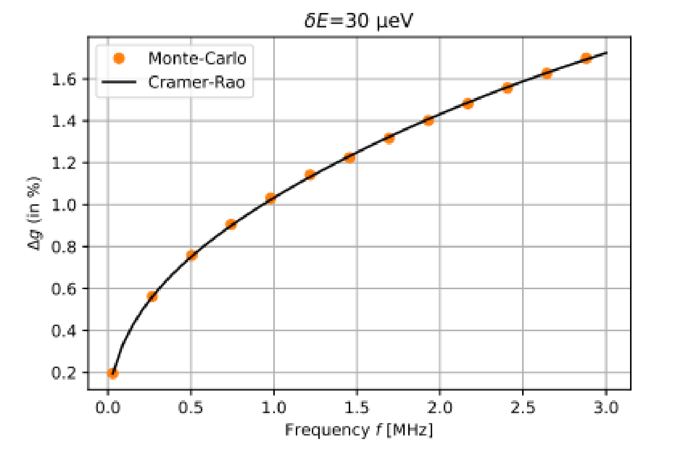
Statistical efficiency

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

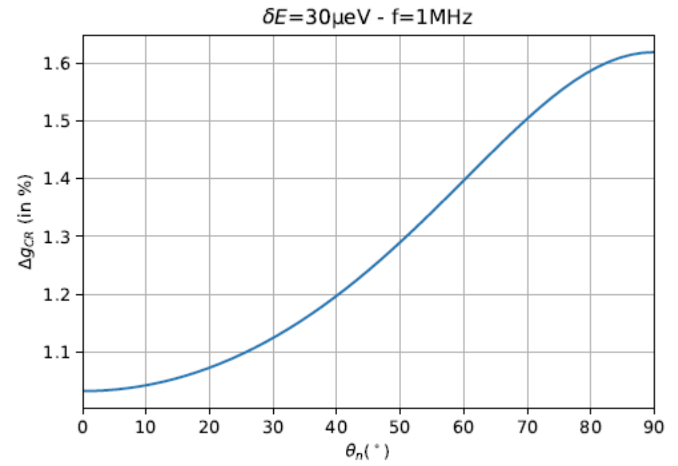
Effects of design parameters

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

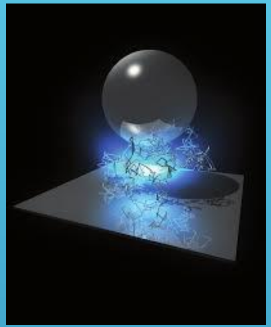


Horizontal polarization
$\Delta v=0{,}44 m/s$, $v_e=1{,}77 m/s$:
$\sigma_g / g \approx 0{,}91\%$
→ confirmation of the goal of uncertainty < 1%.

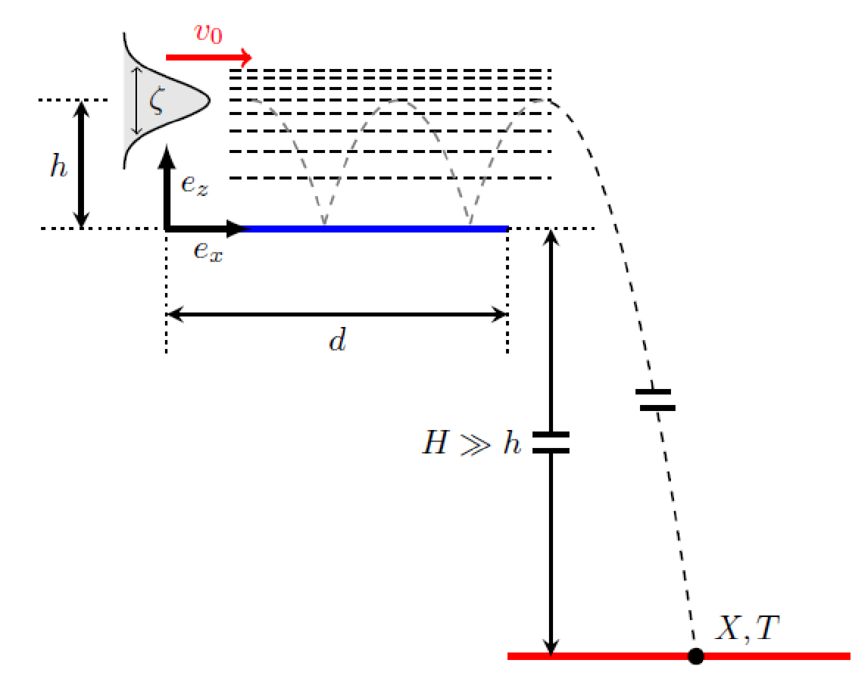
Quantum interference measurement

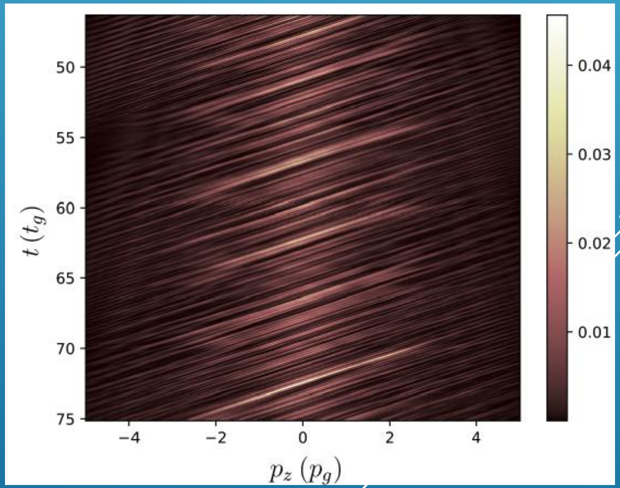
Goal: use quantum reflection to produce an interference pattern on the detector. The information extracted from the interference figure will lead to an improved uncertainty.

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.

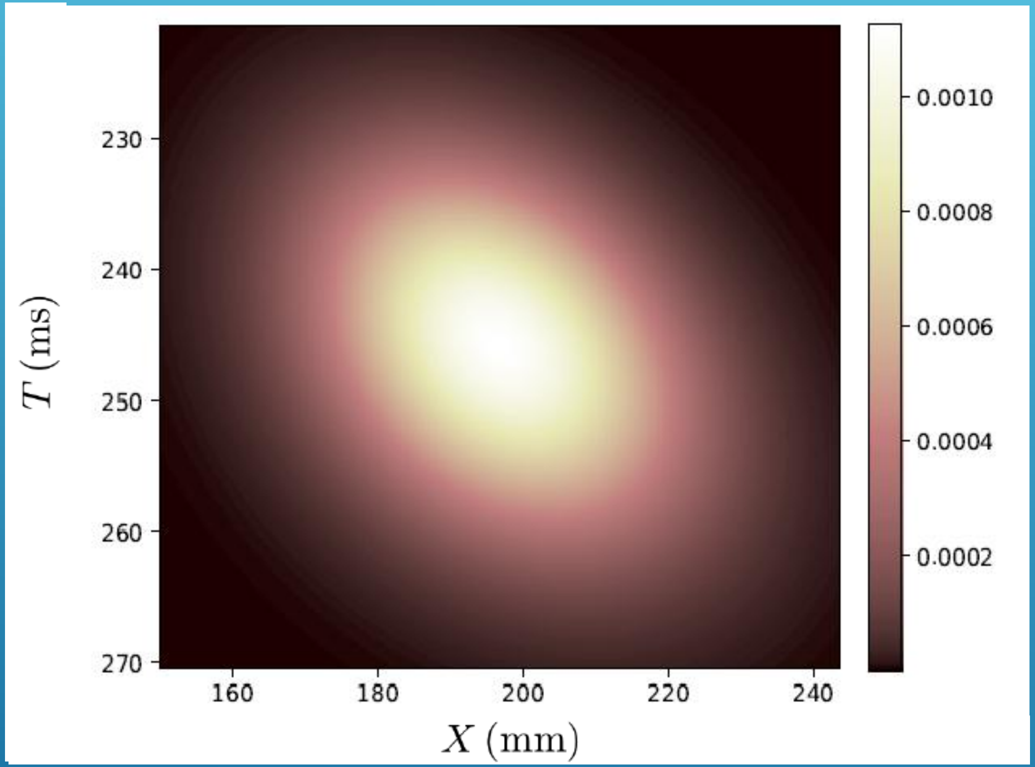


ζ=0.5 µm, h=10µm, d=5 cm, H=30cm

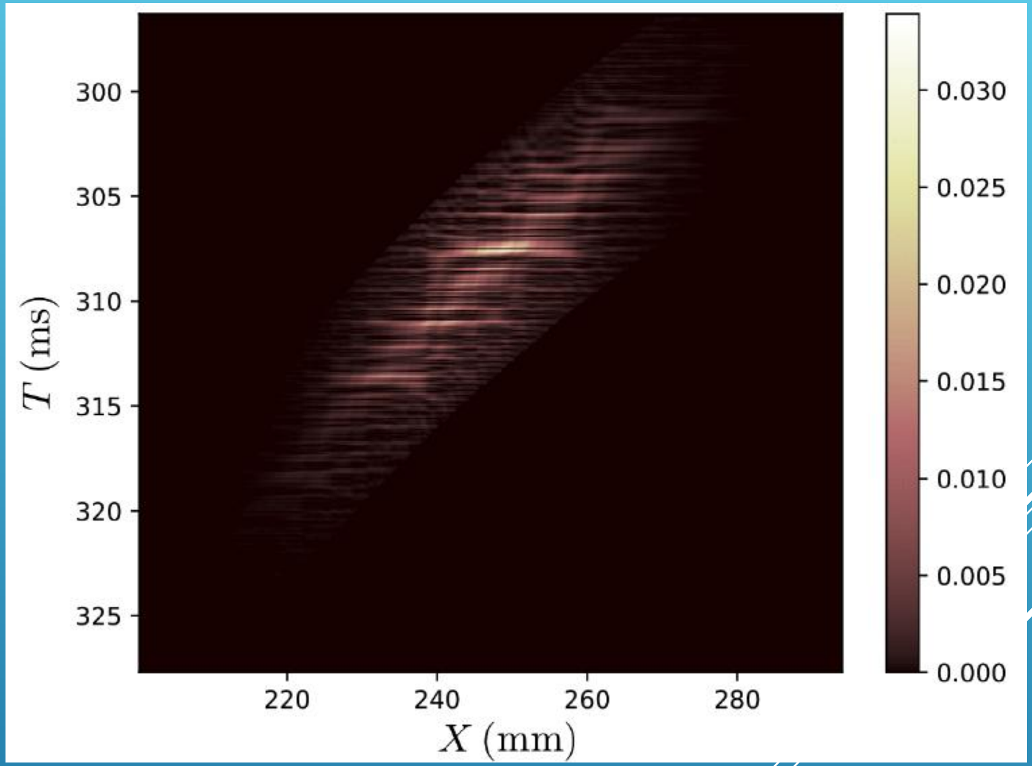




Final detection pattern: comparison classical / quantum cases



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



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

Thank you for your attention !

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