Simulation of GBAR experiment

(Gravitational Behavior of Antihydrogen at Rest)

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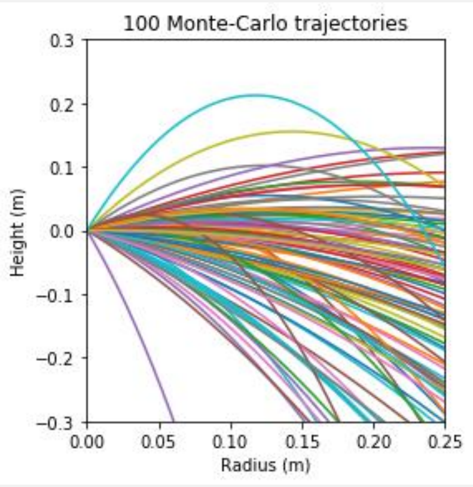
1. Presentation of GBAR experiment (CERN)

One of the main questions of fundamental physics is the action of gravity on antimatter.
Current experimental bound: $\boxed{-65 \leq \bar{g}/g \leq 110}$
(*Alpha Collaboration, 2013*).

GBAR collaboration: https://gbar.web.cern.ch/
Classical measurement: the $\overline{H}$ atom having velocity dispersion *Δv=0,44m/s* freely falls from a height *H=30 cm* on a detector.
Goal: measuring $\bar{g}$ with an accuracy of the order of 1%.

3. Monte-Carlo simulation and analysis

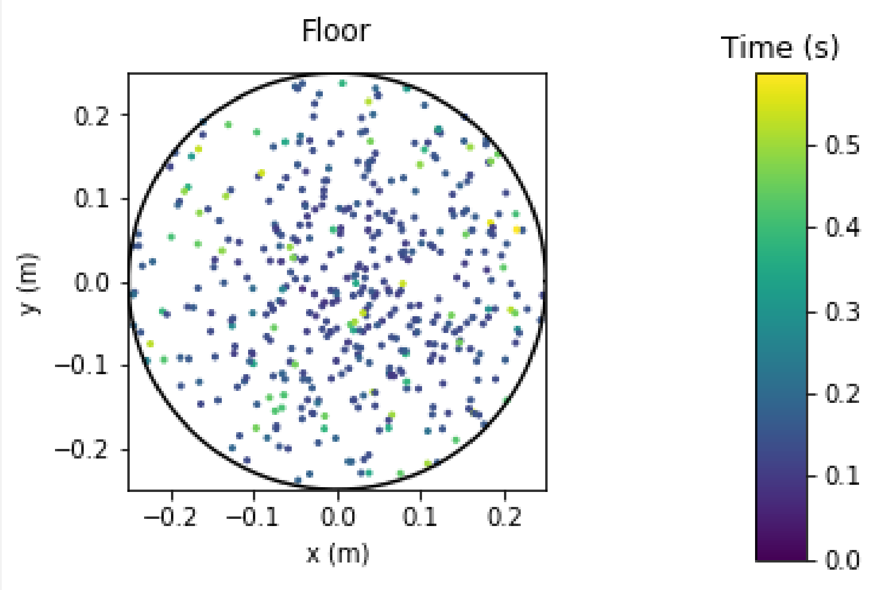
Use of Python as programming language
Monte-Carlo generation of trajectories.



$$(V_x, V_y, V_{z,0}) \longrightarrow (X, Y, Z, T)$$

Initial velocity — Impact

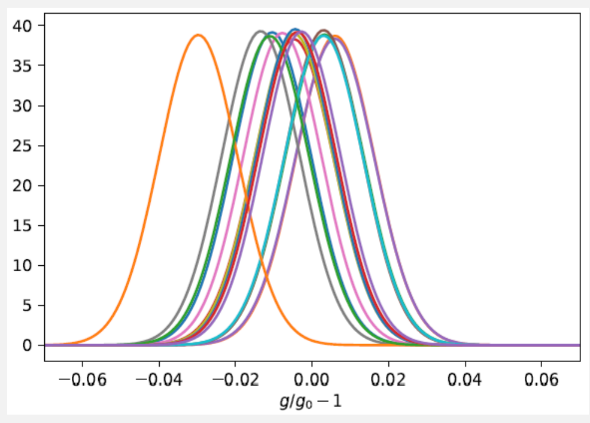
$$V_x = \frac{X}{T} \quad , \quad V_y = \frac{Y}{T} \quad , \quad V_{z,0} = \frac{Z}{T} + \frac{gT}{2}$$



Generation of *N=1000* events
(with g_0=9.81 m/s²)

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

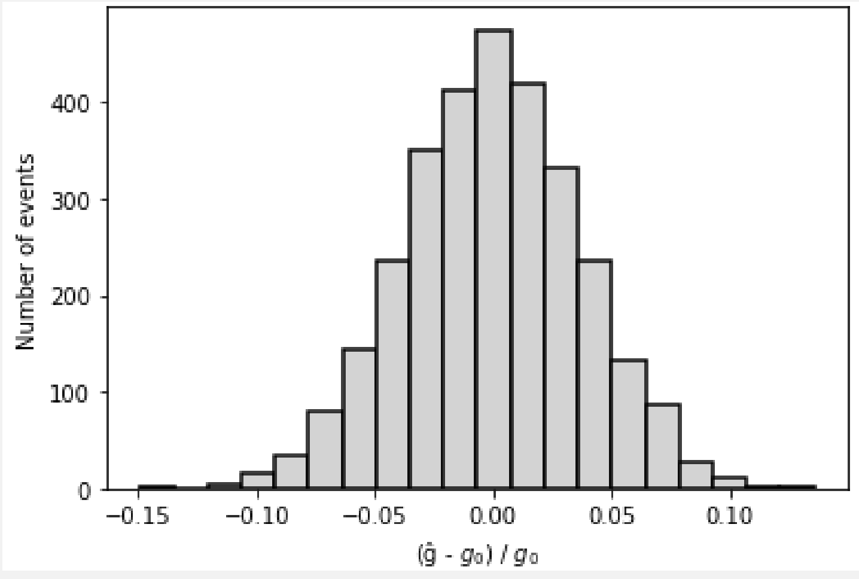
Likelihood



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

Mean likelihood estimator

Process repeated *M* times

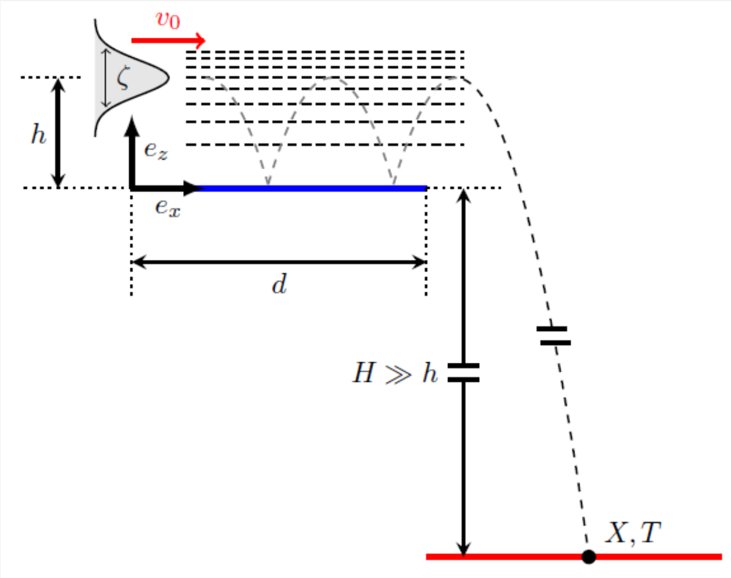


Histogram of the distribution of $\hat{g}$

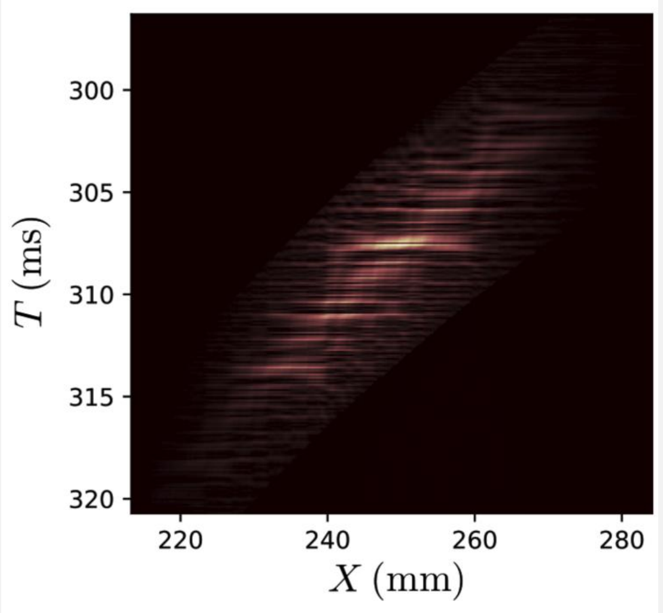
$\boxed{\text{Average: } \mu_g \approx g_0 \text{ (no bias)}}$ $\boxed{\text{Relative uncertainty: } \sigma_g/g_0}$

5. Prospect: quantum interference measurement

Implementation of a mirror some *µm* below the trap (*P.P. Crépin et al., 2019*). Atoms bounce several times above the mirror (quantum reflection on Casimir-Polder potential), and the quantum paths corresponding to different GQS (Gravitational Quantum States) interfere.



2D Schematic representation of the quantum experimental setup; Mirror in blue and detector in red.



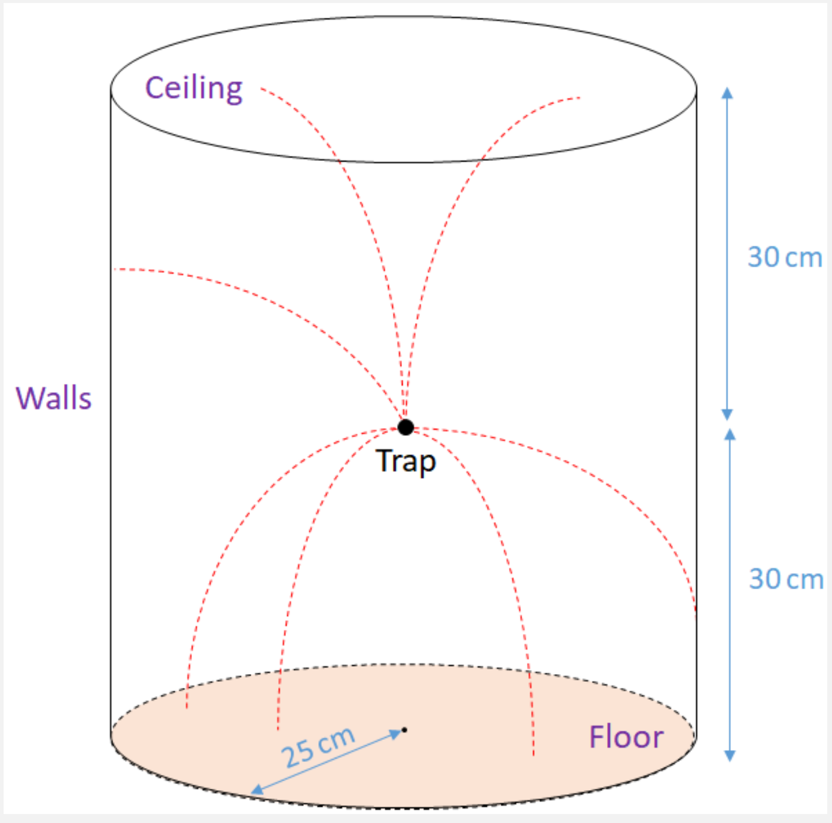
Probability current density *|J(X,T)|* on the detection plate, with interference pattern

After free fall, the quantum interference pattern on the detector reveals much more information than the classical one -> better uncertainty (*10*$^{-6}$).
Future work: how does the photodetachement affect interference fringes?

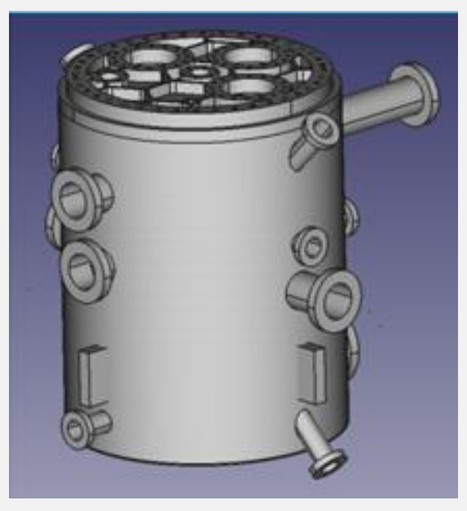
2. Outlook

We present in this poster the simulation of the last part of the experiment GBAR, i.e. the measurement of the free fall acceleration $\bar{g}$ of cold antihydrogen atoms in the gravitational field of Earth.

Inside view of the chamber

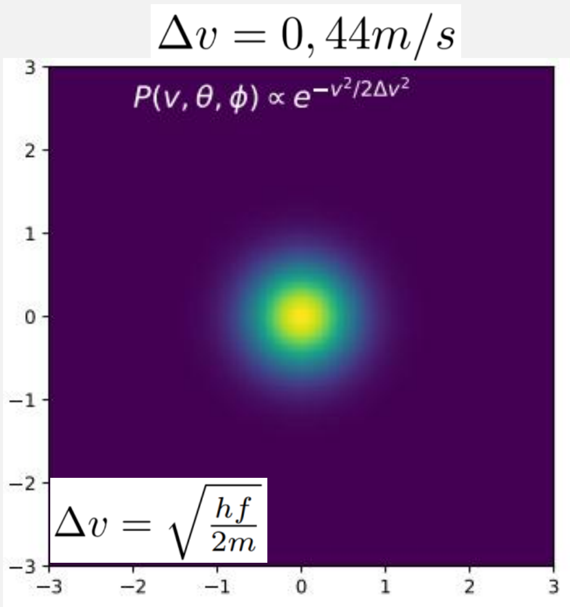


Outside view



Photodetachement process:
The extra e^+ of $\overline{H}^+$ is photodetached with a laser, to produce neutral antihydrogen atom -> initial time t_0.

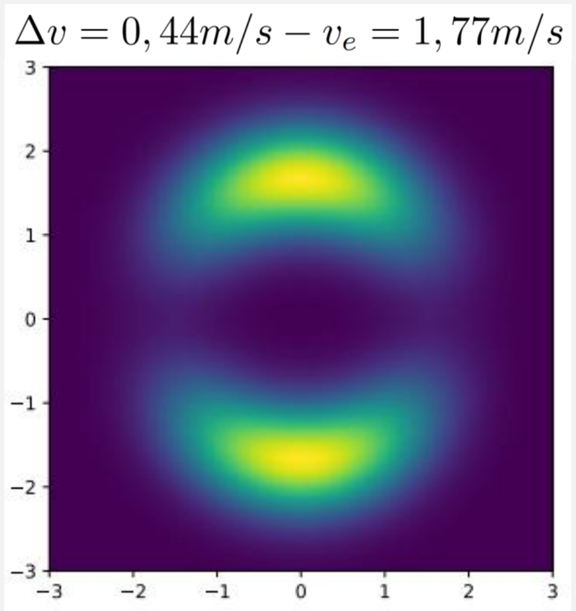
Fundamental state of harmonic oscillator



Atom recoil $v_e = \frac{\sqrt{2m_e \delta E}}{m}$

Velocity distribution

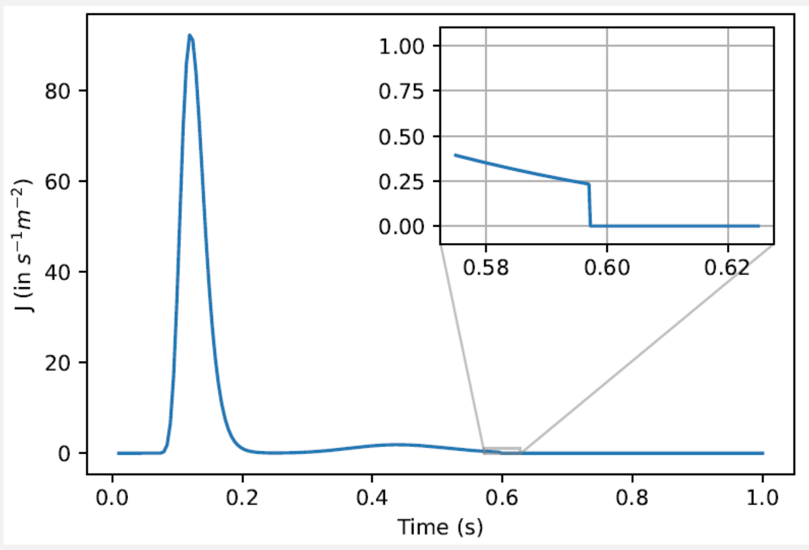
With photodetachement



4. Effects of design parameters

Which parameters affect the accuracy of the measurement ?

- Geometry of the free-fall chamber;
- Number of atoms *N (N=1000* below*);*
- Wavepacket velocity dispersion *Δv (Δv=0,44m/s* below*);*
- Polarization of the laser *ϑ*$_n$ (horizontal polarization below);
- Photodetachement atom recoil v_e (*v_e=1,77m/s* below*);*
- Cuts in the probability current density *J (*on the plot, cut due to a ceiling at 30cm above the trap*);*



- Spatial resolution *Δz (Δz=0,63mm* below)
  -> detection on spot, instead of point.
  ETH group: reconstruction of the pion tracks produced by annihilation of antihydrogen atoms on the surface, with particle physics techniques.

For the current geometry of the design*:*

$\sigma_g/g_0 \approx 0{,}86\%$

—> confirmation of the goal of uncertainty < 1%.
(*O. Rousselle et al., to be published*)

References

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