SEMINAR

Gravitational behavior of antihydrogen at rest

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Plan of the talk

- Experiment GBAR: motivation, key idea, status
- Gravitational Quantum States of Antihydrogen
- Conclusions , future plans

GBAR

Irfu
RIKEN
Laboratoire Kastler Brossel
Physique quantique et applications
東京大学
THE UNIVERSITY OF TOKYO
Swansea University
School of Physical Sciences
IPCMS
CSNSM
東京理科大学
Tokyo University of Science
ETH ZÜRICH
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MOTIVATION

A direct test of the Equivalence Principle with antimatter

The acceleration imparted to a body by a gravitational field is independent of the nature of the body :

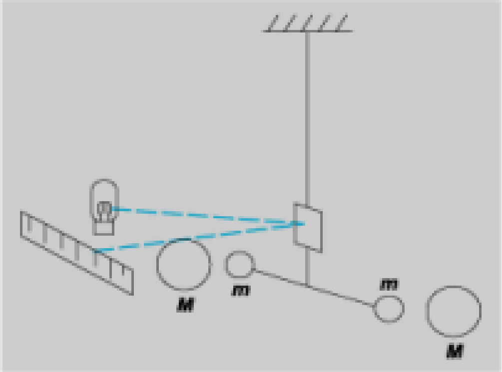
Inertial mass = gravitational mass

Tested to a very high precision with many materials

Weak Equivalence Principle (torsion pendulum)

$$(\Delta a / a)_{Be/Ti} = (0.3 \pm 1.8) \times 10^{-13}$$

S.Schlamminger et al, Phys Rev Lett 100 (2008) 041101



Strong Equivalence Principle (Lunar Laser Ranging)

$$(\Delta a / a)_{Earth/Moon} = (-1.0 \pm 1.4) \times 10^{-13}$$

J.G.Williams et al, Phys Rev Lett 93 (2004) 261101

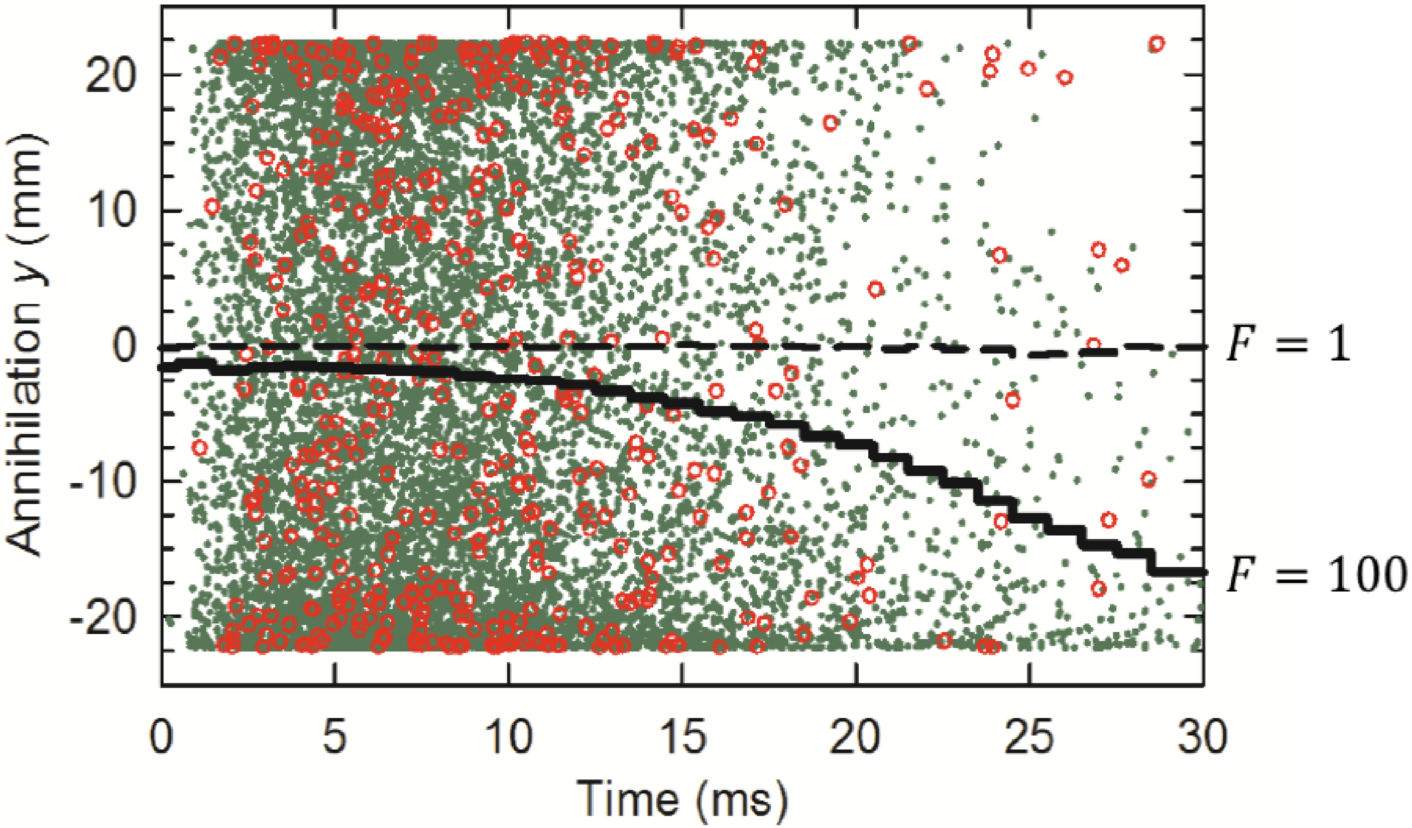
CPT symmetry assumed

(see talk by E. Adelberger at gbar2011 workshop http://indico.in2p3.fr//event/gbar2011.fr)

Antimatter Experiments: one result

Antihydrogen

$$F = M_G / M$$



Green dots---simulated annihilations

Red circles---434 Observed annihilations

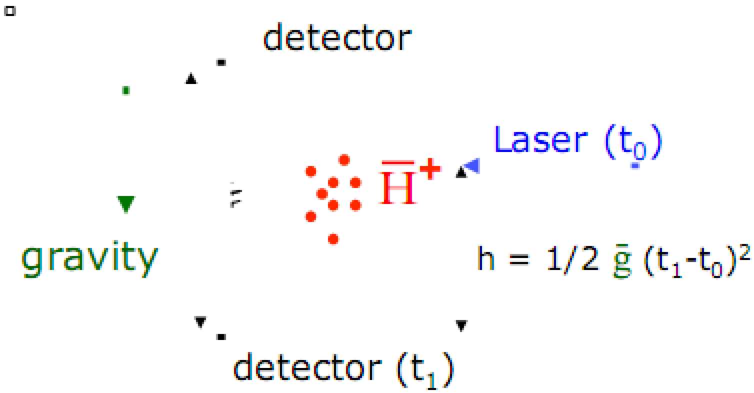
Vertical position of annihilation vertex during release of trapping field

KEY IDEA

Using $\bar{H}^+$ to get $\bar{H}$ atoms

- Produce ion $\bar{H}^+$
- Sympathetic cooling 10 μK
- Photodetachment of e^+
- Time of flight

Error dominated by temperature of $\bar{H}^+$



J.Walz & T. Hänsch,
General Relativity and Gravitation, **36** (2004) 561.

Relative Precision on $\bar{g}$:

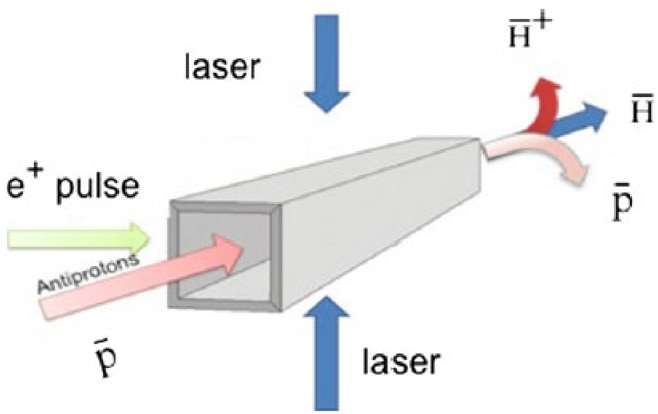
$\bar{H}$ detected free falls	Δg/g
1.5 10^5	0.001
1500	0.01

h = 20 cm → Δt = 202 ms

h = 15 cm → Δt = 175 ms

First stage

$\bar{H}^+$ Production



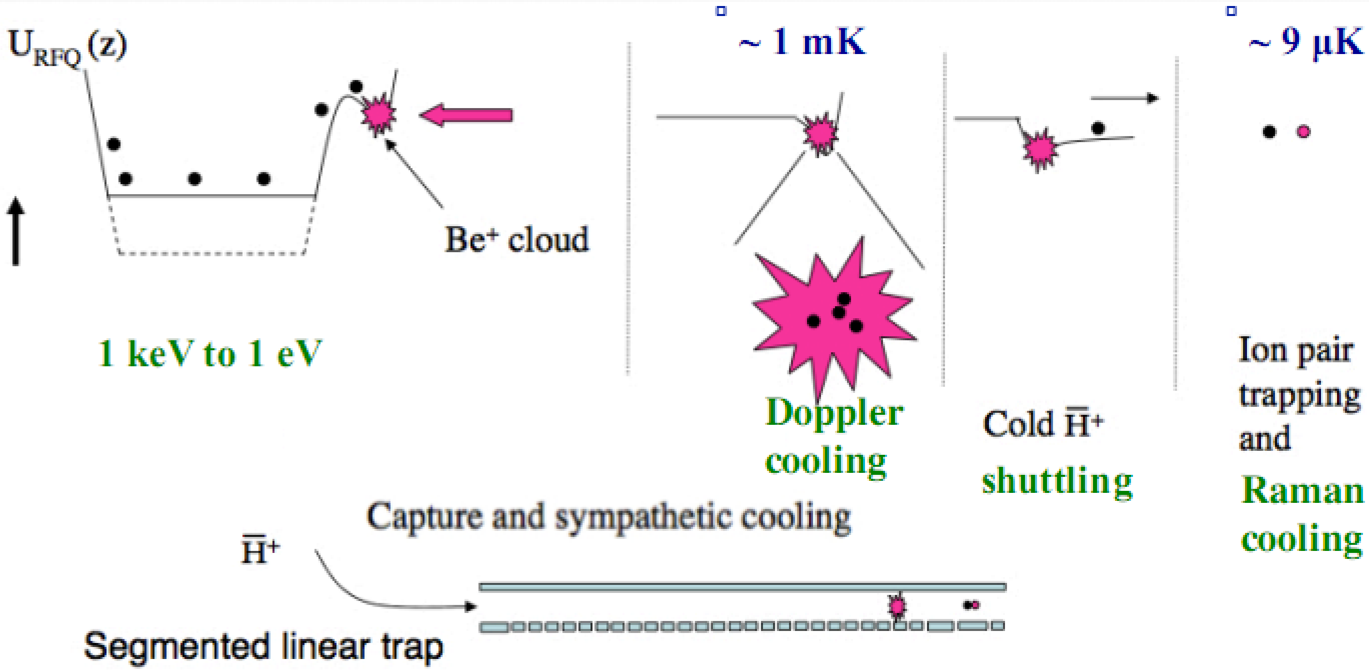
$$\bar{p} + Ps \rightarrow \bar{H} + e^-$$

$$\bar{H} + Ps \rightarrow \bar{H}^+ + e^-$$

Ortho-positronium

Ion cooling

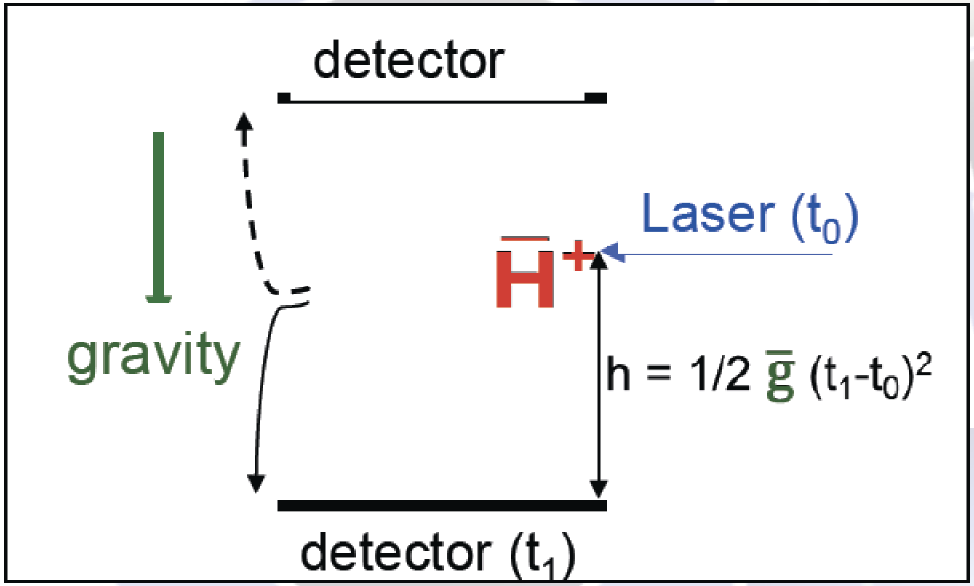
$\bar{H}^+$ cooling challenge



NIST group
M. D. Barrett, ..., D. Wineland, PRA ***68****, 042302 (2003)*
Sympathetic cooling of $^9Be^+$ and $^{24}Mg^+$ for quantum logic

Gbar
Falling antihydrogen

principle



J.Walz & T. Hänsch
General Relativity and Gravitation, 36 (2004) 561

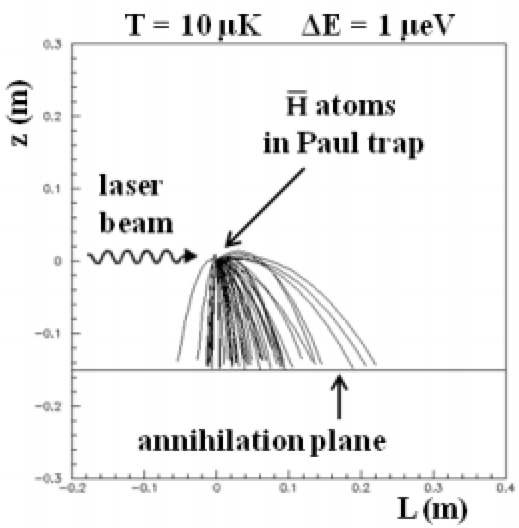
$$z = z_0 + v_{z0}t + \frac{1}{2}\overline{g}t^2$$

Velocity fluctuation	100 m/s	3 m/s	0.1 m/s
Temperature equivalent	1 K	1 mK	1 µK

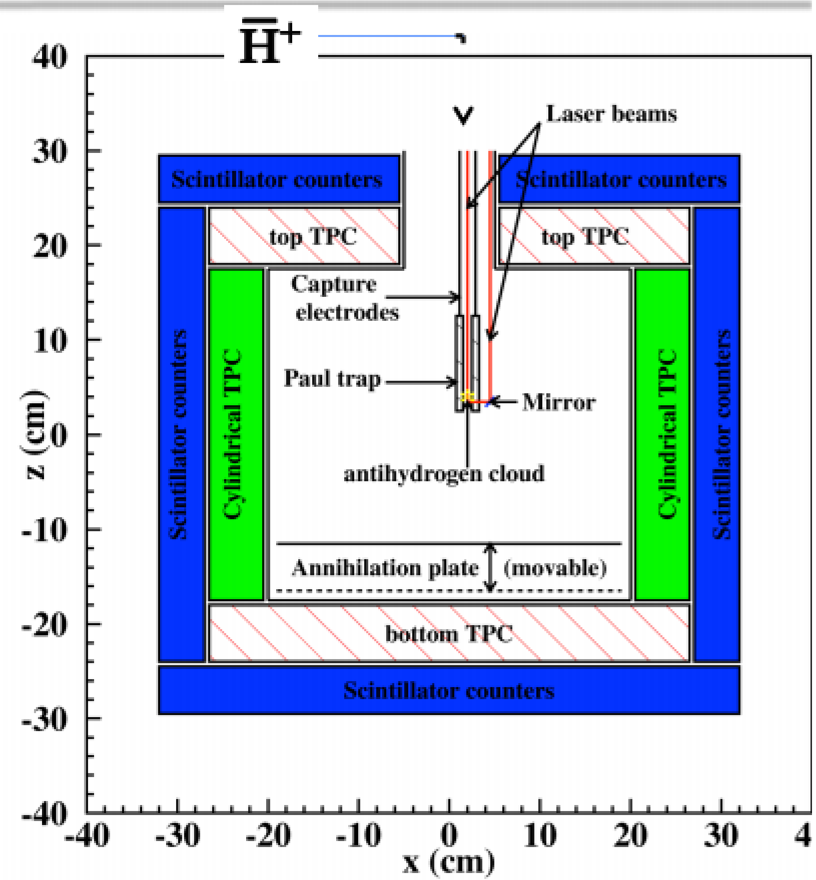
Desired range

FREE FALL

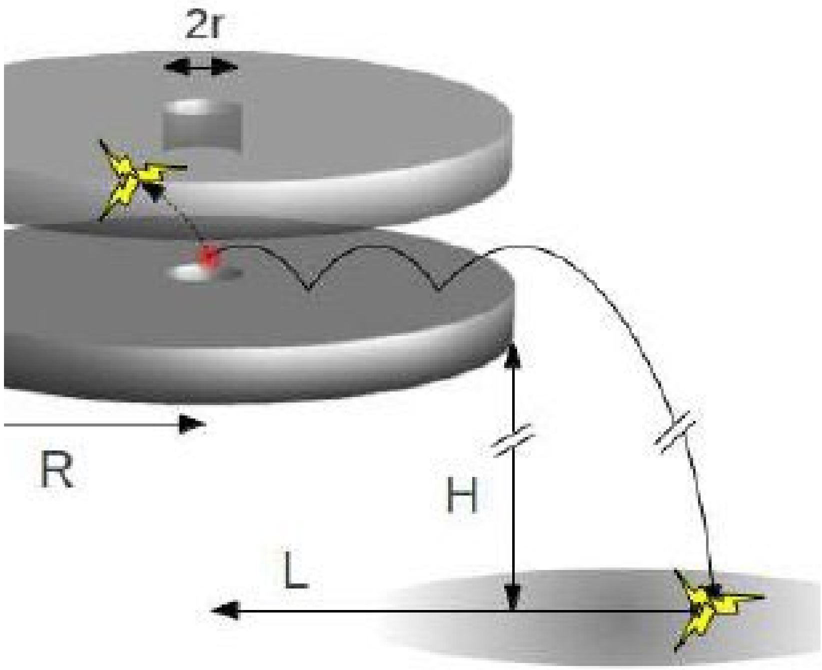
$\bar{H}$ free fall detection



Detection	Requirement
TOF precision	150 µs
Annihil. vertex precision	2 mm
Background rejection	event topology



Antihydrogen bouncing on the table



PHYSICAL REVIEW A **83**, 032903 (2011)

Gravitational quantum states of Antihydrogen

A. Yu. Voronin, P. Froelich, and V. V. Nesvizhevsky

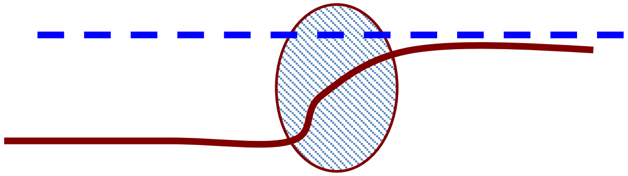
Bouncing Antihydrogen?!

Quantum reflection

- Over-barrier Reflection from the fast changing attractive potential

$$\frac{d\lambda_B(z)}{dz} \geq 1; \;\; \lambda_B(z) = \frac{2\pi\hbar}{\sqrt{2M(E-V(z))}}$$

$$z \geq \sqrt{2MC_4}$$



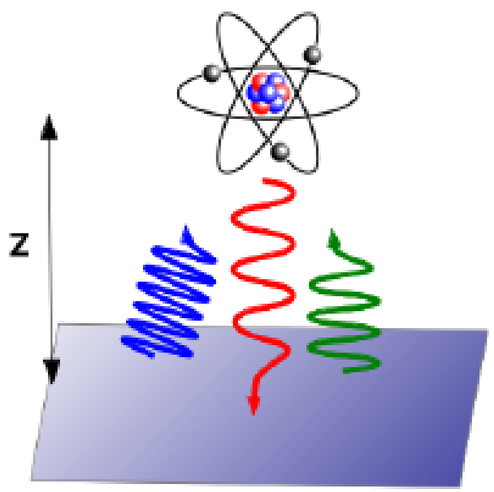
$$\Psi(z \to -\infty) = Te^{-ikz}$$

$$\Psi(z \to +\infty) = e^{-ikz} - Se^{ikz} \;\; ; S = 1 - 2ika \;\; ; a = \mathrm{Re}\, a - i\left|\mathrm{Im}\, a\right|$$

$$R = \left|S\right|^2 = 1 - 4k\left|\mathrm{Im}\, a\right| \to 1; \, P = 4k\left|\mathrm{Im}\, a\right| \to 0$$

The Casimir-Polder force

Electromagnetic (EM) modes are modified when the atom comes close to the detector:
$\Rightarrow$ the EM ground state (vacuum) energy changes
$\Rightarrow$ attractive Casimir-Polder force between atom and detector

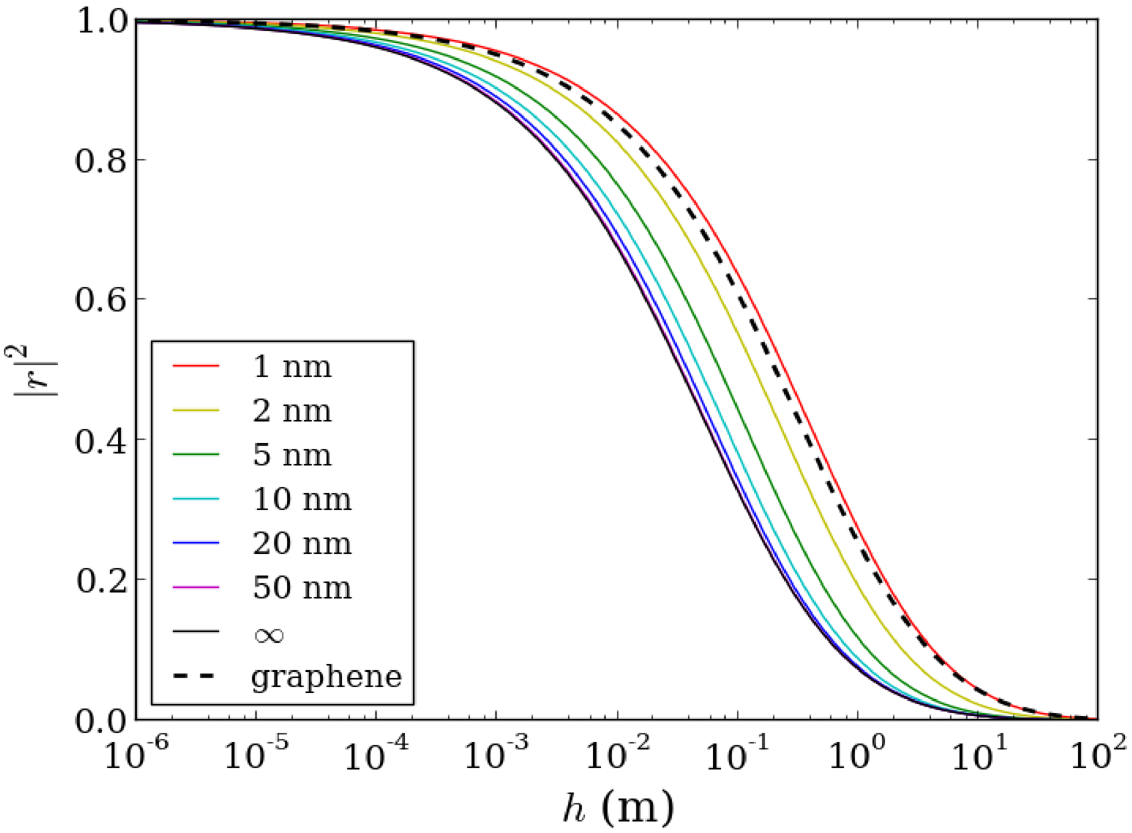


Casimir 1948 : long-range interaction energy between an atom and a perfectly conducting mirror:

$$V^*(z) = -\frac{3\hbar c}{8\pi z^4}\frac{\alpha(0)}{4\pi\epsilon_0} = -\frac{C_4^{perfect}}{z^4}$$

For H and $\overline{\mathrm{H}}$, $C_4^{perfect} \approx 73.6\ E_h a_0^4$
$V(35\text{ nm}) \approx$ - $mg \times 10$ cm

Reflection coefficient



PHYSICAL REVIEW A 87, 022506 (2013)

Quantum reflection of antihydrogen from nanoporous media

G. Dufour,[1] R. Guérout,[1] A. Lambrecht,[1] V. V. Nesvizhevsky,[2] S. Reynaud,[1] and A. Yu. Voronin[3]

Quantum reflection of antihydrogen from a liquid helium film
P.-P. Crépin[1] et al
Europhysics Letters, Volume 119, Number 3

Gravitational quantum states?

$$\varepsilon_g = \sqrt[3]{\frac{\hbar^2 M g^2}{2}} = 0.61\ 10^{-12}\text{eV};$$

$$l_g = \sqrt[3]{\frac{\hbar^2}{2M^2 g}} = 5.87\ 10^{-6} m.$$

$$\left[-\frac{d^2}{dx^2} + x - \lambda\right]\mathrm{F}(x) = 0,\ F(0) = 0$$

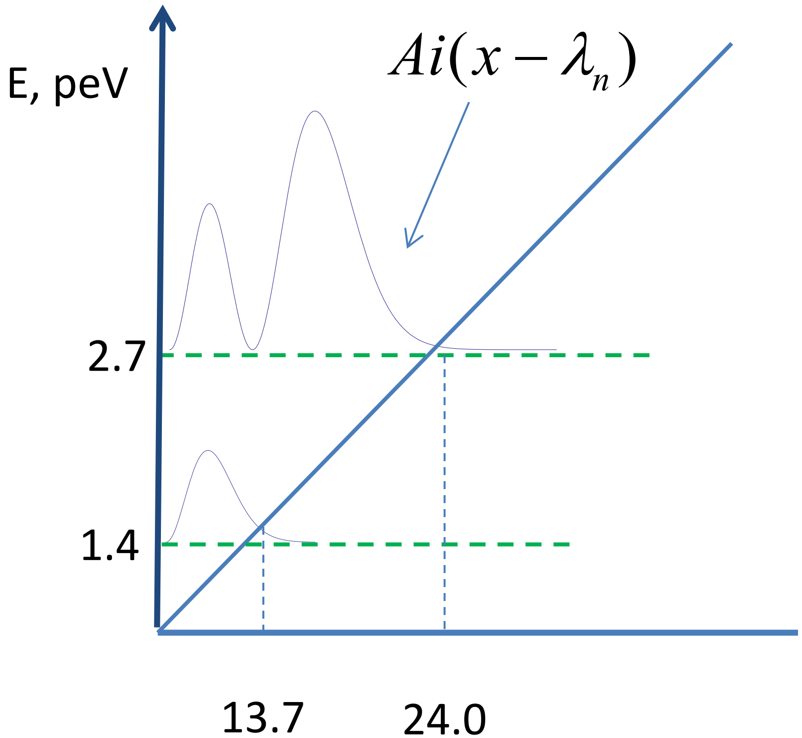
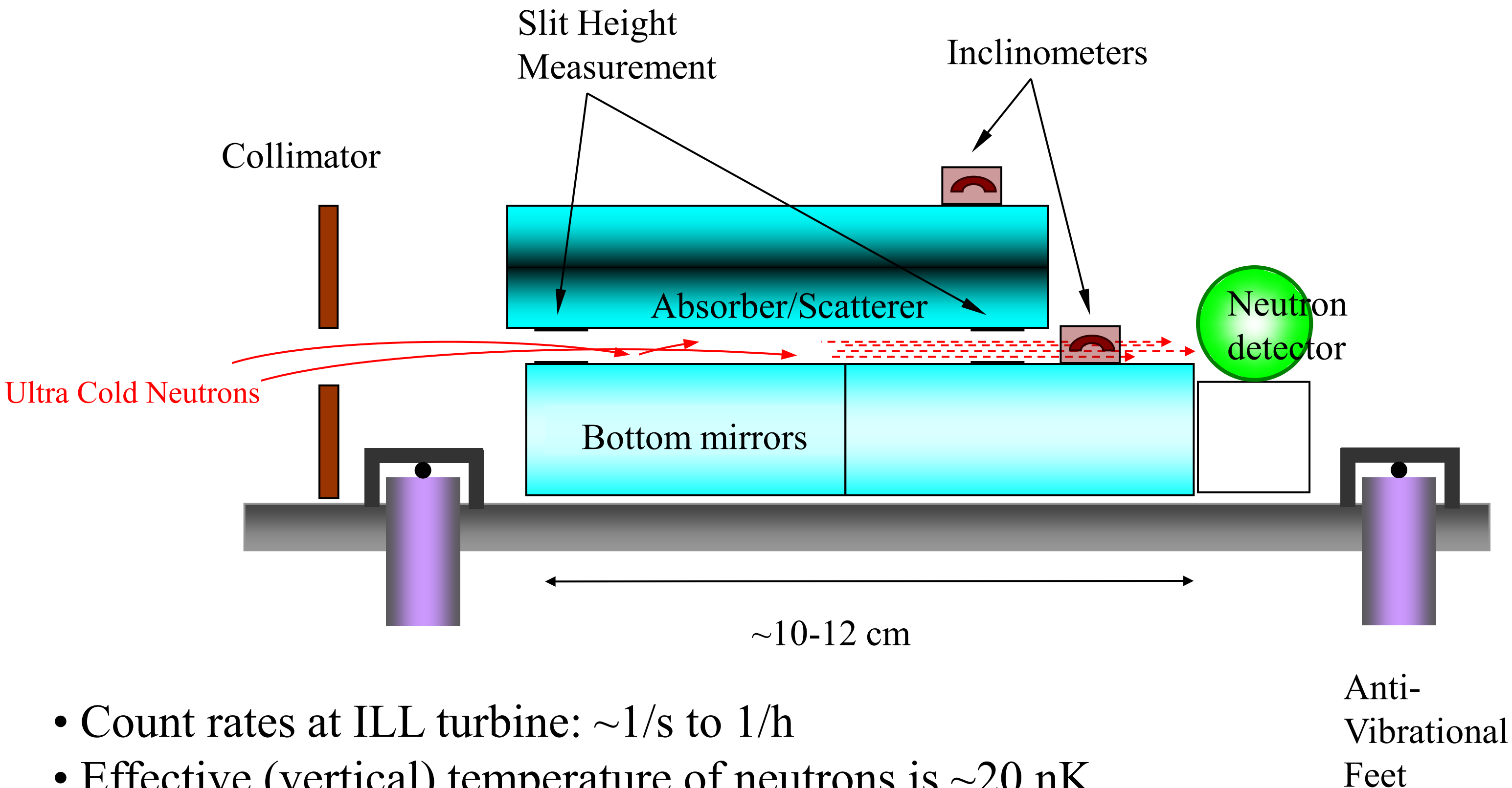


TABLE I. The eigenvalues, gravitational energies, and classical turning points of a quantum bouncer with the mass of (anti)hydrogen in the Earth's gravitational field.

n	λ_n^0	E_n^0 (peV)	z_n^0 (μm)
1	2.338	1.407	13.726
2	4.088	2.461	24.001
3	5.521	3.324	32.414
4	6.787	4.086	39.846
5	7.944	4.782	46.639
6	9.023	5.431	52.974
7	10.040	6.044	58.945

Z, μm

First Observation: Gravitational States of Neutrons
Nesvizhevsky et al. Nature 415, 297 (2002)



- Count rates at ILL turbine: ~1/s to 1/h
- Effective (vertical) temperature of neutrons is ~20 nK
- Background suppression is a factor of $\sim 10^8$-10^9
- Parallelism of the bottom mirror and the absorber/scatterer is $\sim 10^{-6}$

Spectroscopy- to induce transitions between gravitational states

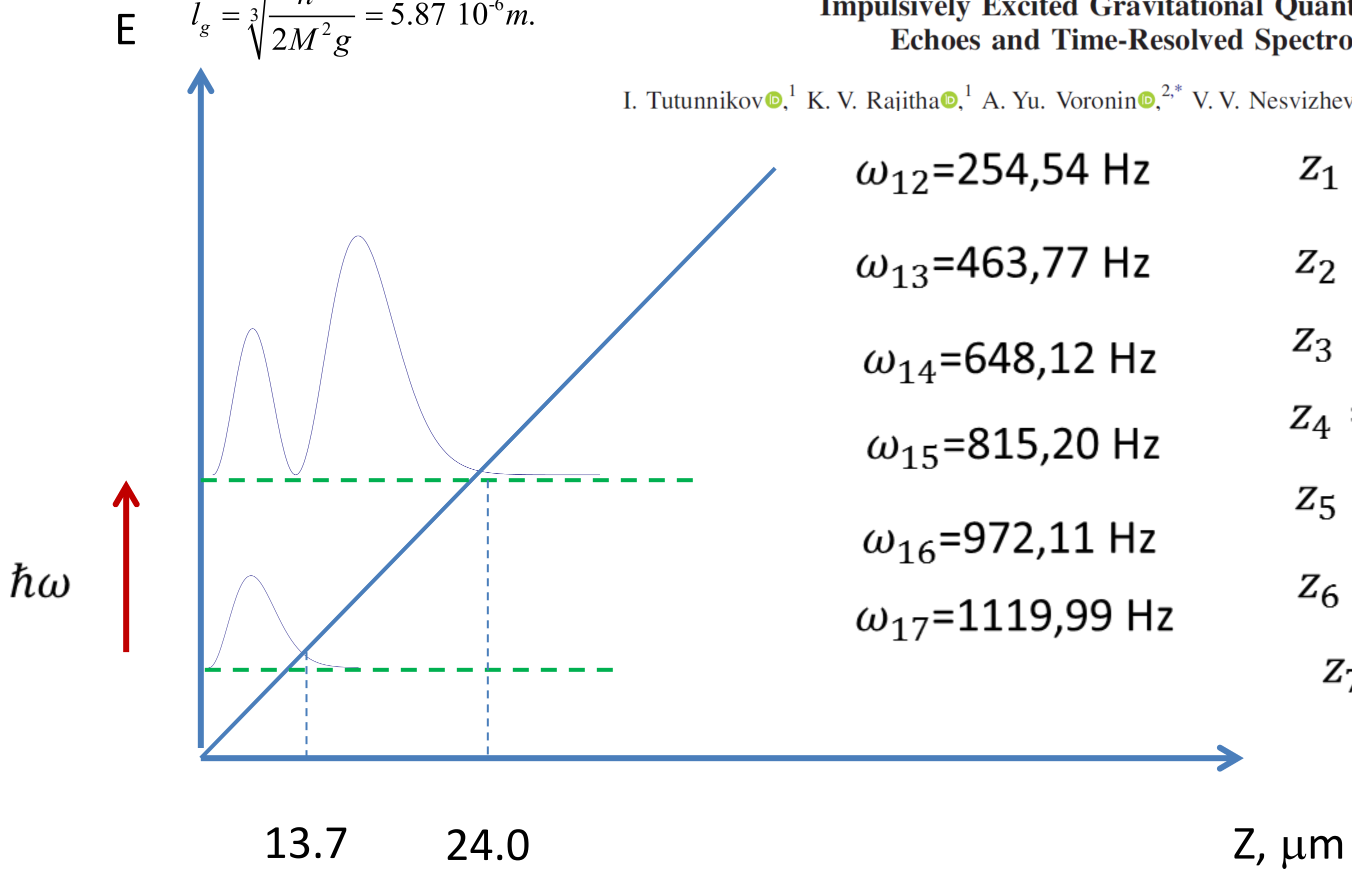
$$\varepsilon_g = \sqrt[3]{\frac{\hbar^2 M g^2}{2}} = 0.61\ 10^{-12} \text{eV};$$

$$l_g = \sqrt[3]{\frac{\hbar^2}{2M^2 g}} = 5.87\ 10^{-6} m.$$

PHYSICAL REVIEW LETTERS **126,** 170403 (2021)

Impulsively Excited Gravitational Quantum States: Echoes and Time-Resolved Spectroscopy

I. Tutunnikov,[1] K. V. Rajitha,[1] A. Yu. Voronin,[2,*] V. V. Nesvizhevsky,[3,†] and I. Sh. Averbukh[1,‡]



ω_{12}=254,54 Hz

ω_{13}=463,77 Hz

ω_{14}=648,12 Hz

ω_{15}=815,20 Hz

ω_{16}=972,11 Hz

ω_{17}=1119,99 Hz

$z_1 = 13.7\ \mu m$

$z_2 = 24.0\ \mu m$

$z_3 = 32.4 \mu m$

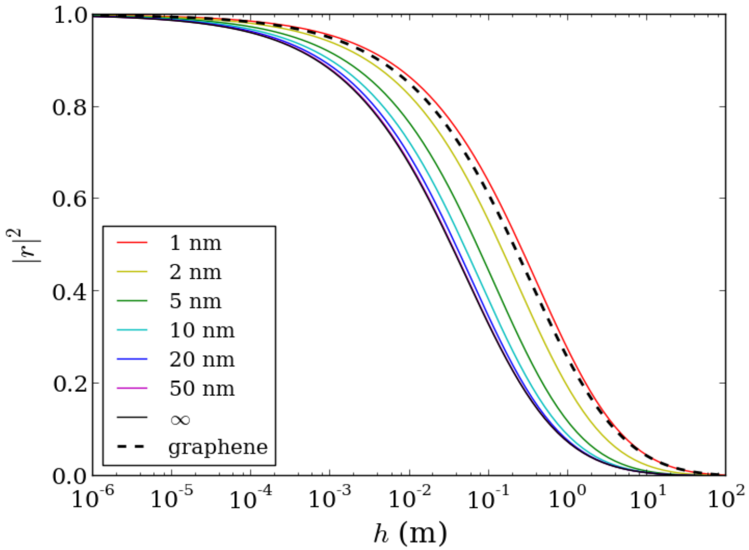
$z_4 = 39.8\ \mu m$

$z_5 = 46.6\ \mu m$

$z_6 = 52.9\ \mu m$

$z_7 = 58.9\ \mu m$

Antihydrogen GQS due to Quantum reflection



PHYSICAL REVIEW A **83**, 032903 (2011)

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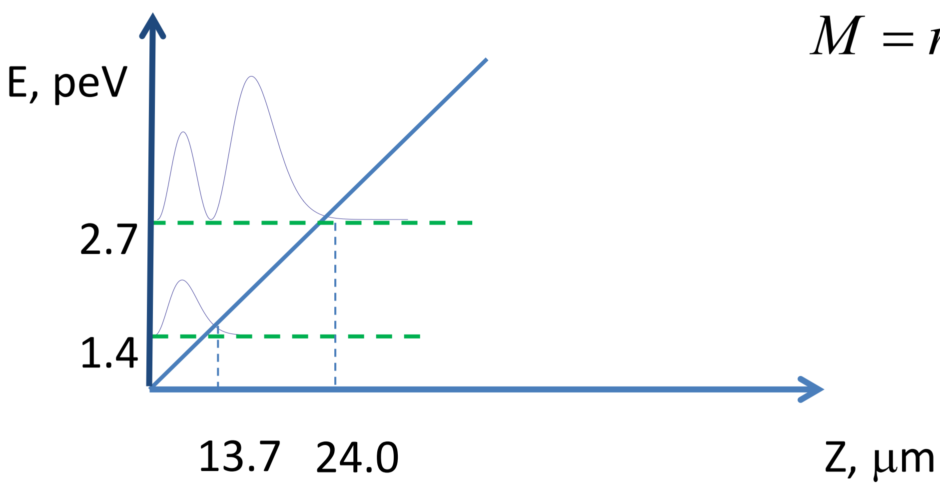
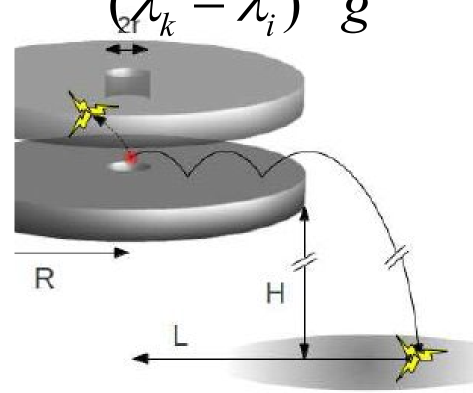
GBAR quantum fall

$$M = m \Rightarrow M = \frac{2\omega_{ik}^3}{(\lambda_k - \lambda_i)^3}\frac{\hbar}{g^2}$$





Gravitational states and Gravitational mass

Classical: $\not{m}\ddot{z} = \not{M}g \rightarrow \ddot{z} = g \rightarrow T = \sqrt{2H/g}$

$$\text{Quantum: } \left[-\frac{\hbar^2}{2m}\frac{d^2}{dz^2} + Mgz - E\right]\Psi(z) = 0 \Rightarrow \left[-\frac{d^2}{dx^2} + x - \lambda_n\right]\mathrm{F}(x) = 0$$

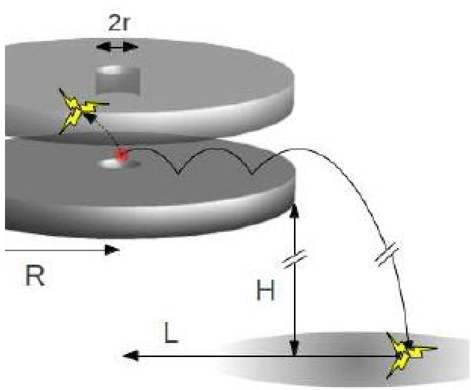
$$\varepsilon_g = \sqrt[3]{\frac{\hbar^2 M^2 g^2}{2m}} = 0.61\ 10^{-12}\,\text{eV};\quad l_g = \sqrt[3]{\frac{\hbar^2}{2Mmg}} = 5.87\ 10^{-6} m$$

$$m = \frac{\hbar^2}{2\varepsilon_g l_g^2};\quad M = \frac{\varepsilon_g}{g l_g}$$

$$M = m \Rightarrow \frac{\hbar}{\varepsilon_g} = \sqrt{\frac{2l_g}{g}} \text{ or } \mathrm{T} = \sqrt{\frac{2H}{g}}$$

EP test by measuring time and spatial scales of GQS

Interference of gravitational states



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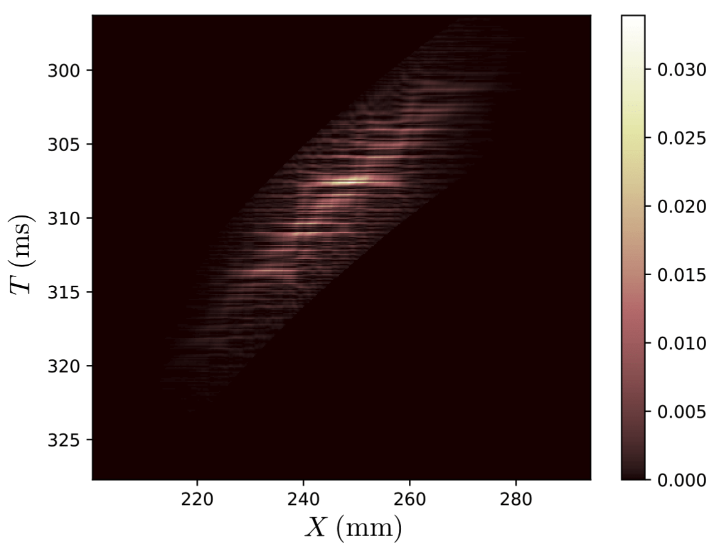


GBAR quantum fall

Quantum interference test of the equivalence principle on antihydrogen

P.-P. Crépin, C. Christen, R. Guérout, V. V. Nesvizhevsky, A.Yu. Voronin, and S. Reynaud

Phys. Rev. A **99**, 042119

Interference of gravitational states

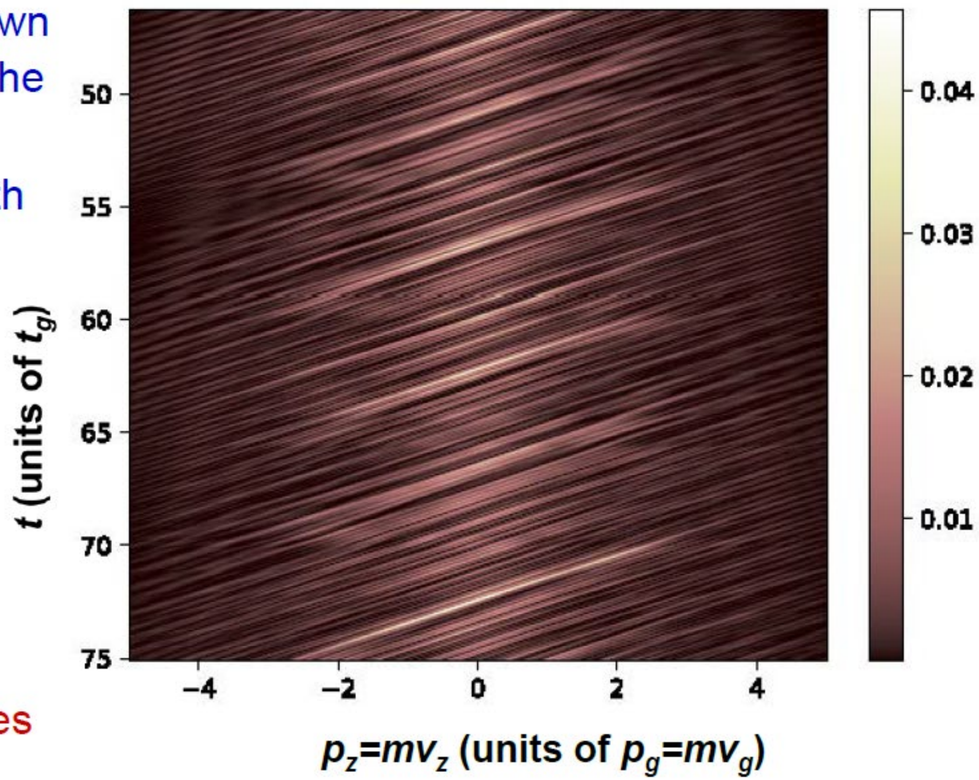
Quantum interference measurement (GBAR)

Interference pattern shown in momentum space at the end of the QR zone

Phase varies linearly with the interaction time *t*

Interaction time *t* on the vertical axis

Momentum p_z on the horizontal axis



Natural units for gravitational quantum states

$$\ell_g = \sqrt[3]{\frac{\hbar^2}{2m^2 g}} \approx 6\,\mu\mathrm{m}\,, \quad t_g \simeq 1\ \mathrm{ms}\,, \quad v_g = \frac{\hbar}{m\ell_g} \simeq 1\,\mathrm{cm/s}$$

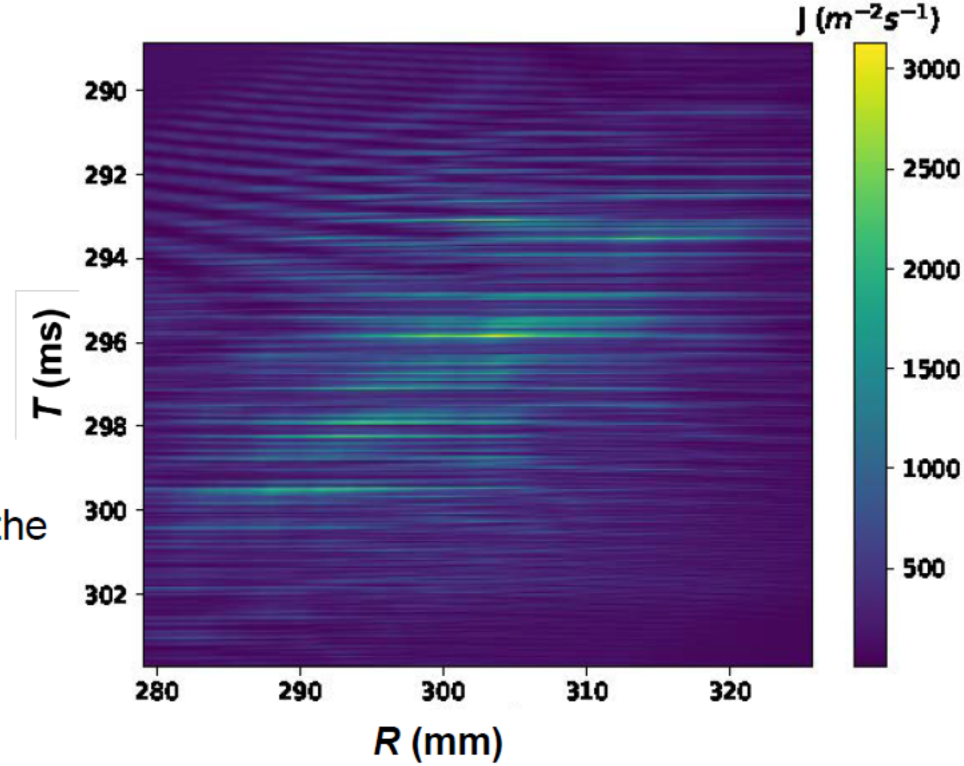
Interference of gravitational states

Quantum free fall measurement for GBAR

Density plot of the annihilation current *J* (number of events per unit of surface and unit of time)

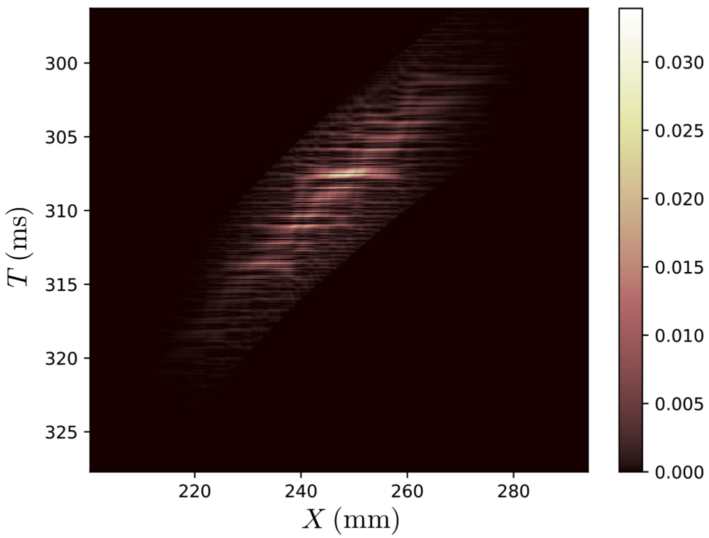
Time of flight *T* on the vertical axis

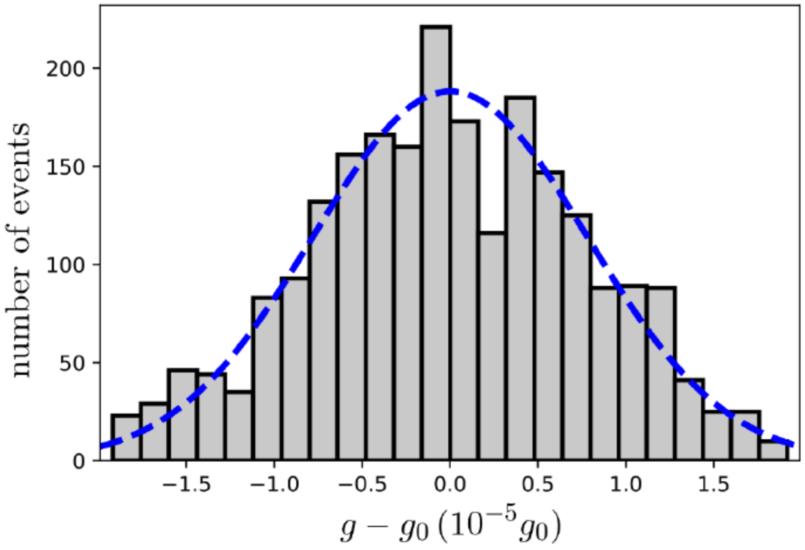
Radial distance *R* from the center of the horizontal annihilation plate



The incoherent sum on the direction of the recoil velocity does not affect significantly the interference fringes which are mainly encoded on the time of flight

Interference of gravitational states





An accuracy of 10^{-5} is obtained, approximately 3000 times better than that for the classical timing wit

New Physics Horizonts
Axion

$$L_{\theta} = \theta_{eff} \frac{\alpha}{8\pi} F^{ijk} \overline{F}_{ij}^{k}$$

CP violating terms

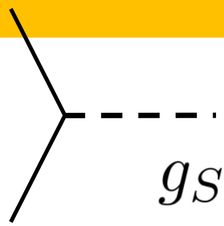
$$\theta_{eff} < 10^{-10} \longrightarrow \theta_{eff} = 0$$

New Pseudo Scalar Field (axion) , which has a vacuum minimum

WEAK interaction with matter Dark Matter Candidate

R. D. Peccei and H. R. Quinn, CP Conservation in the Presence of Pseudoparticles, Phys. Rev. Lett. 38, 1440 (1977).
[7] S.Weinberg, A New Light Boson?, Phys. Rev. Lett. 40, 223 (1978).

Short-range spin-dependent forces

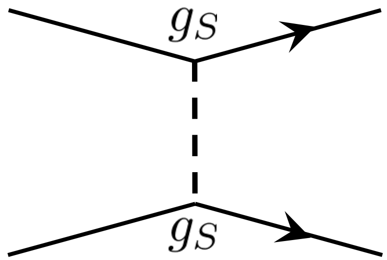


$g_S + i g_P \gamma^5$

interactions of range λ
mediated by new light boson of mass M

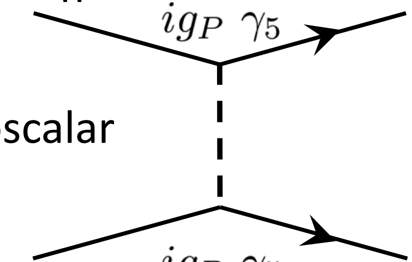
$$\lambda = \frac{\hbar}{Mc}$$

Scalar-scalar



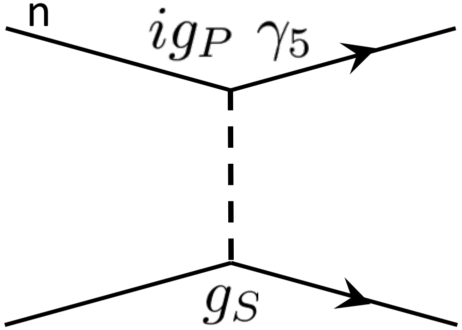
$+$

PseudoScalar-Pseudoscalar



$$1\,\mu eV < M < 1\,eV$$

Dipole
(probe)



$+$

Monopole
(source)

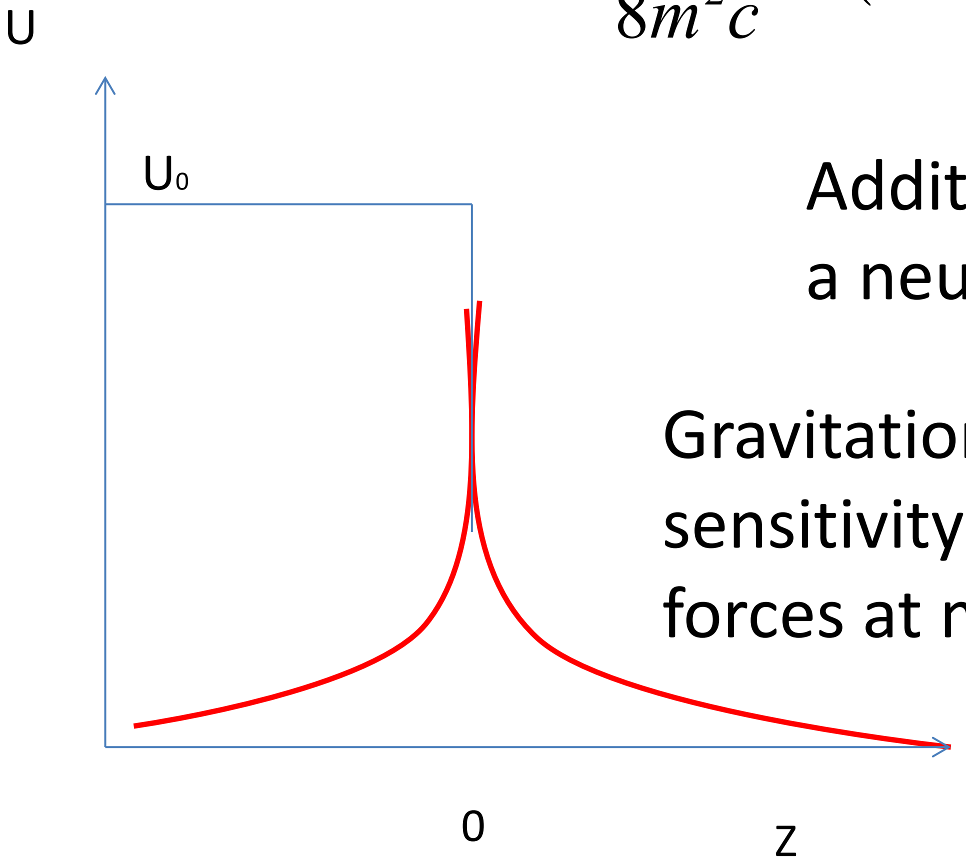
~~P~~ ~~CP~~ Scalar–Pseudoscalar (Axion–like)

$$V_{SP}(\mathbf{r}) = \frac{g_S g_P}{8\pi} \frac{\hbar}{m} \sigma \cdot \mathbf{r} \left(\frac{1}{\lambda} + \frac{1}{r} \right) \frac{e^{-r/\lambda}}{r^2}$$

Pavel Fadeev, et al PHYSICAL REVIEW A 99, 022113 (2019)

Macroscopic spin-dependent potential due to 5-th force

$$V_s(z) = \frac{g_p g_s \hbar \rho_m \lambda}{8m^2 c}\left(\vec{\sigma}\,\vec{\mathrm{n}}\right)\exp(-z/\lambda)$$



Additional interaction between a neutron and a material wall

Gravitational quantum states= extra sensitivity to 5th
forces at micrometer range

Conclusions

- GBAR project- crossroad of multiple intriguing physical problems
- Gravitational quantum states of Antihydrogen: simplest bound quantum system, determined by gravity. Perfect laboratory for EP, 5^{th} forces, non-newtonian gravity
- Provide accuracy 3000 better than classical approach with same parameters