Гравитационные состояния ультрахолодных квантовых систем

Institut Laue-Langevin, Grenoble

LPSC, Grenoble

JINR, Dubna

CERN, Geneva

PNPI, Gatchina

University of Virginia

FIAN, Moscow

А.Ю. Воронин **ФИАН**

ПЛАН

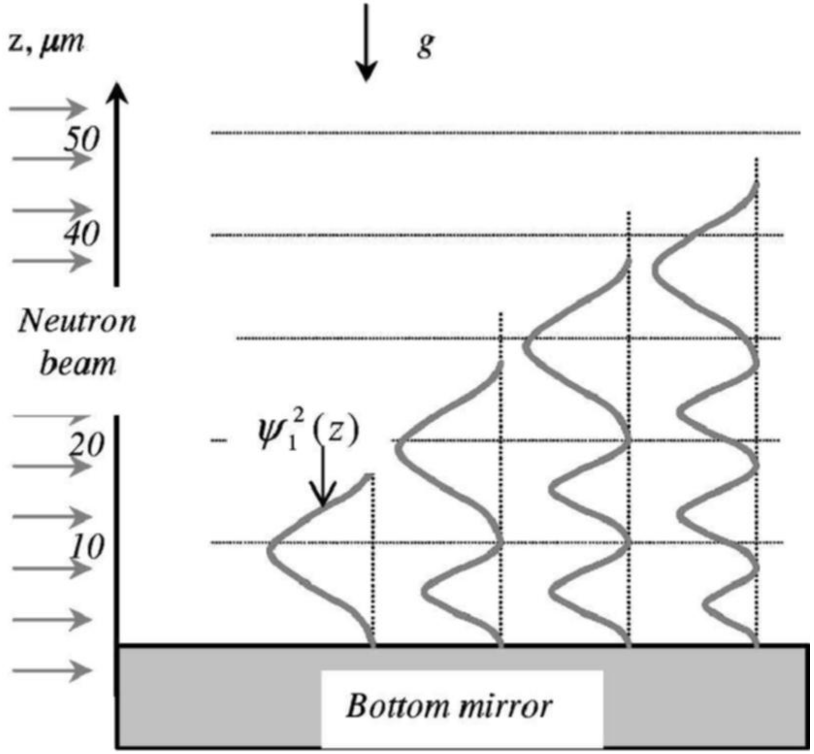
- Квантовые состояния ультрахолодных нейтронов в гравитационном поле Земли-спектрометр ГРАНИТ
- Поиск «нестандартной физики»: ограничения на характеристики аксионного поля из гравитационных экспериментов с УХН
- Гравитационные состояния Антиводорода и измерение гравитационной массы

Гравитационные состояния УХН

$$\begin{cases} \left[-\frac{\hbar^2}{2M}\frac{\partial^2}{\partial z^2} + Mgz - \varepsilon_n \right] \varphi_n(z) = 0 \\ \varphi_n(0) = 0 \end{cases}$$

$$\varphi_n(z) = C_n Ai(z / l_0 - \lambda_n)$$

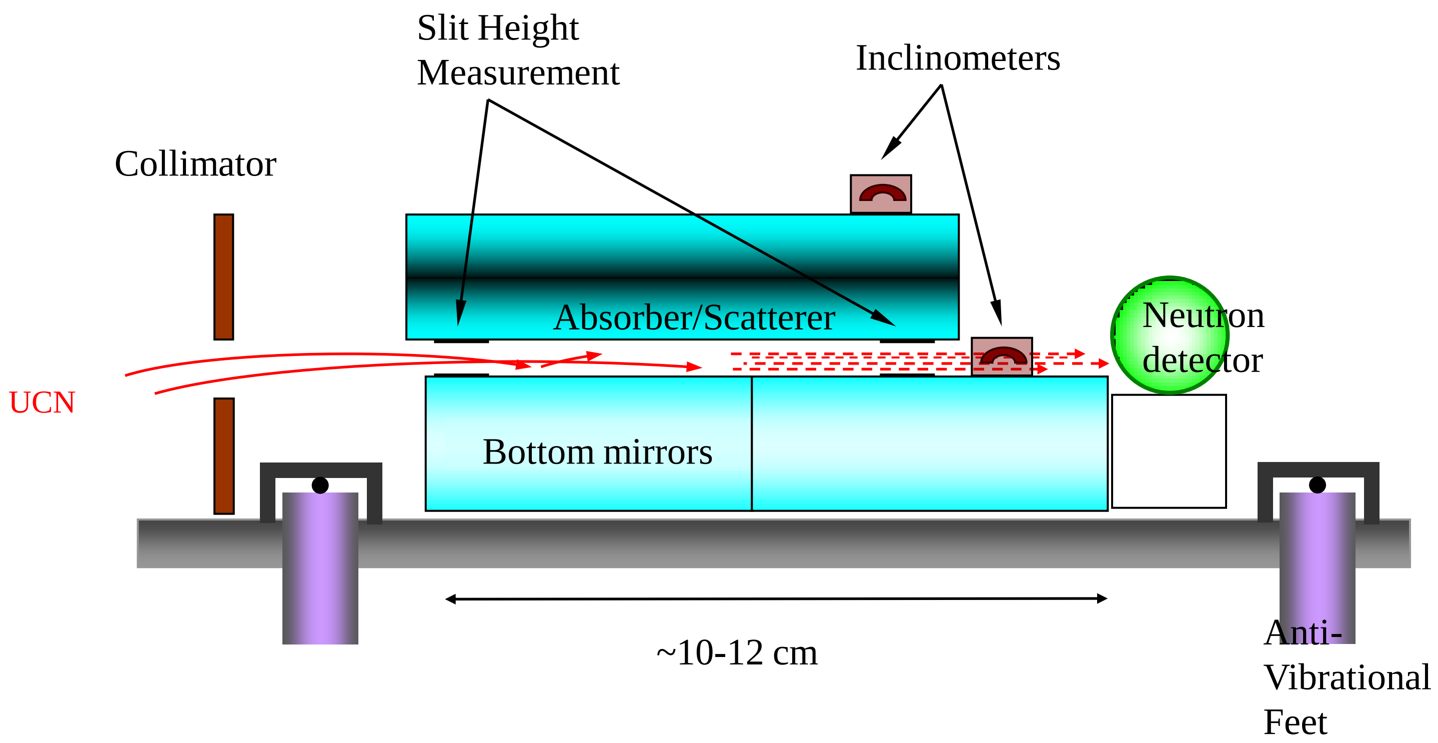
$$Ai(-\lambda_n) = 0$$



$$\varepsilon_n = \lambda_n \varepsilon \quad \varepsilon = \sqrt[3]{\frac{\hbar^2 M g^2}{2}} = 0.61\ 10^{-12}\text{eV} \quad l_0 = \sqrt[3]{\frac{\hbar^2}{2M^2 g}} = 5.87\ 10^{-6} m$$

Gravitational Bound states – The experiment

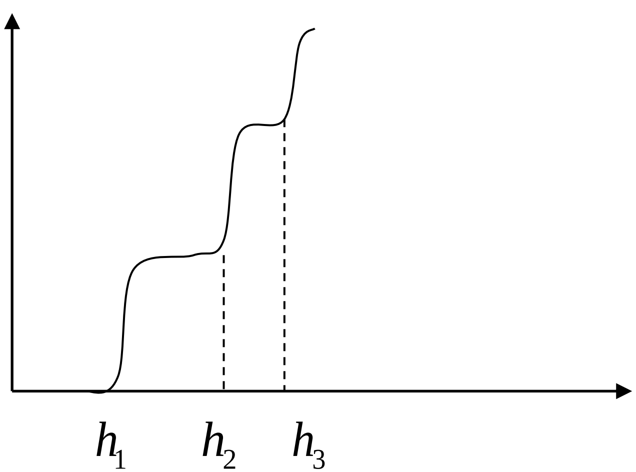
Nesvizhevsky V.V. et. al. Nature 415, 297 (2002)

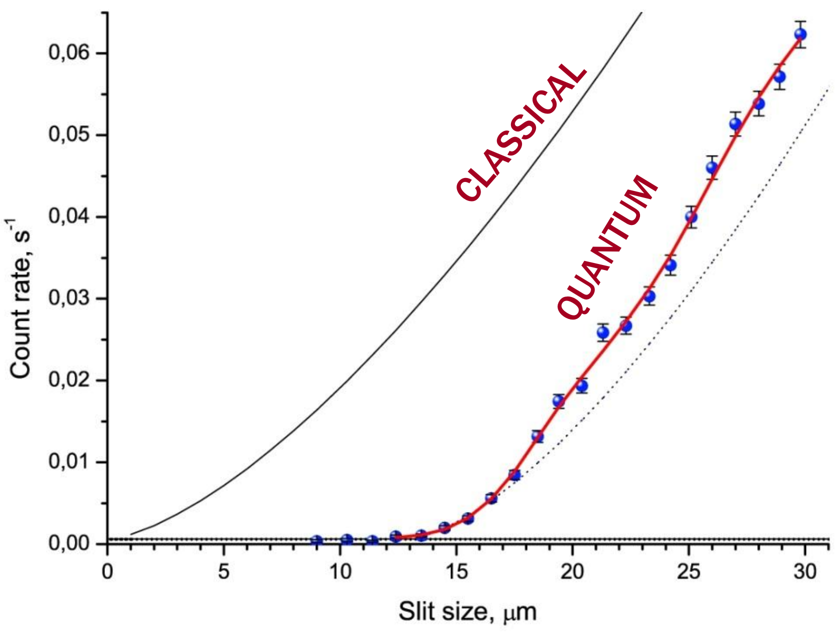


- Count rates at ILL turbine: ~1/s to 1/h
- Effective (vertical) temperature of neutrons is ~20 nK
- Background suppression is a factor of ~10^8-10^9
- Parallelism of the bottom mirror and the absorber/scatterer is ~10^{-6}

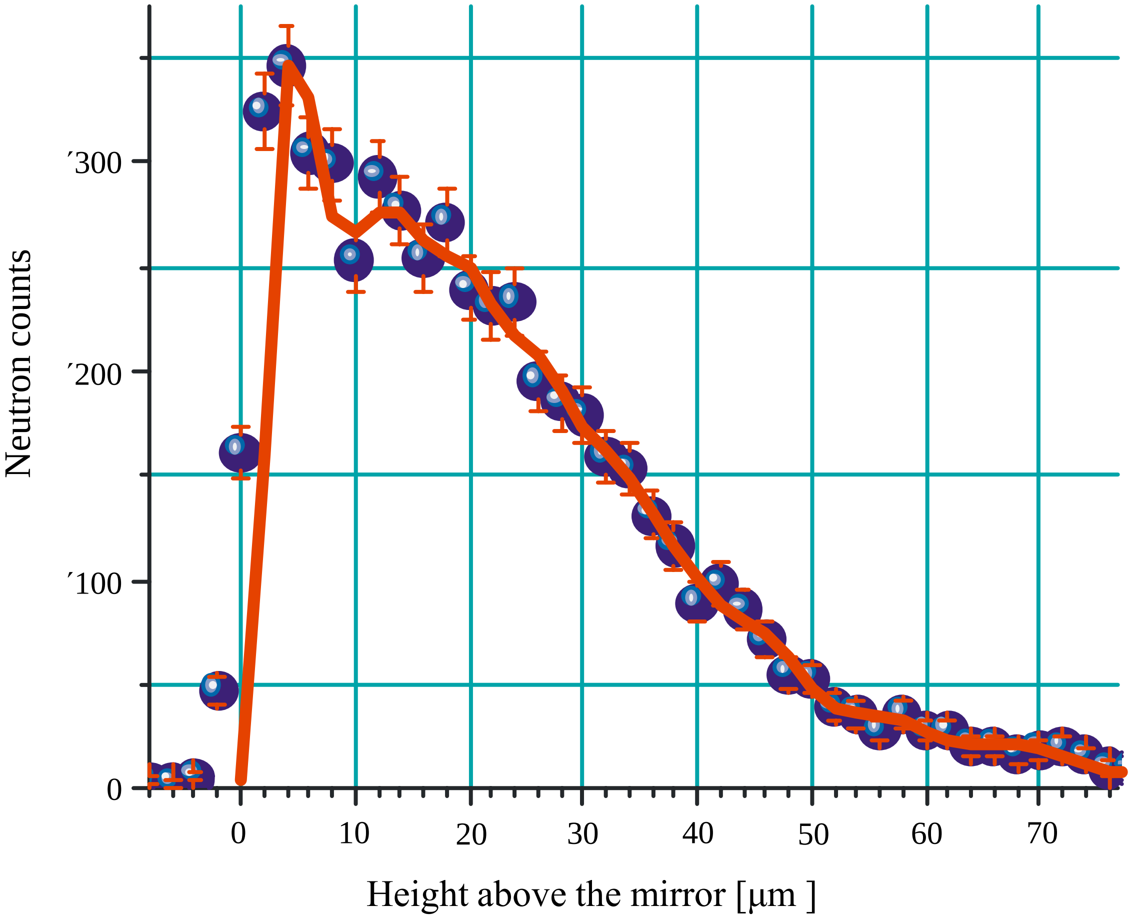
$$
\begin{aligned}
z_1^{\mathrm{exp}} &= 12.2 \pm 1.8_{\mathrm{sys}} \pm 0.7_{\mathrm{stat}}\ \mu\mathrm{m} \\
z_1^{\mathrm{q.c.}} &= \frac{3}{2}\langle 1|z|1\rangle = 13.7\ \mu\mathrm{m} \\
z_2^{\mathrm{exp}} &= 21.6 \pm 2.2_{\mathrm{sys}} \pm 0.7_{\mathrm{stat}}\ \mu\mathrm{m} \\
z_2^{\mathrm{q.c.}} &= \frac{3}{2}\langle 2|z|2\rangle = 24\ \mu\mathrm{m}
\end{aligned}
$$

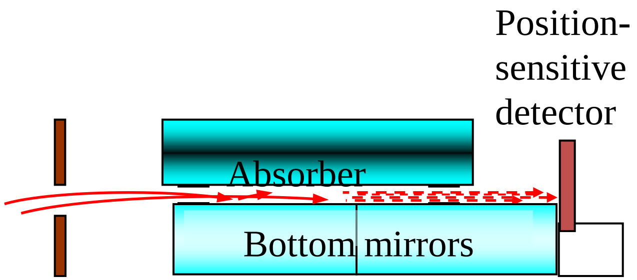
DREAM





Results with the Position-Sensitive Detector





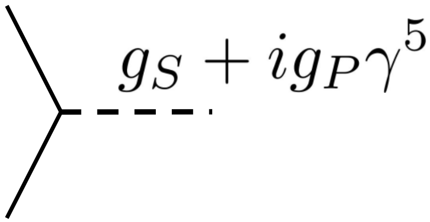
AXION and UCN gravitational states

- Strong CP-problem- explanation of extremely small electric dipole moment of neutron
- Pseudo-scalar neutral light bozon

$$10^{-6} < M_a < 10^{-3} eV\,;\, 1.3\ 10^{-4} < \lambda < 1.3\ 10^{-1}\mathrm{m}$$

- Axion coupling with electron, photons and **nucleon**

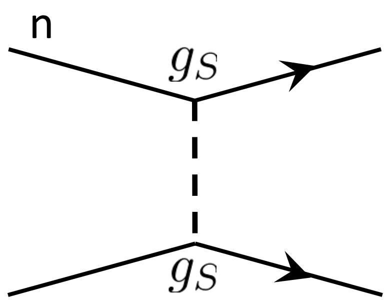
Short-range spin-dependent forces



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

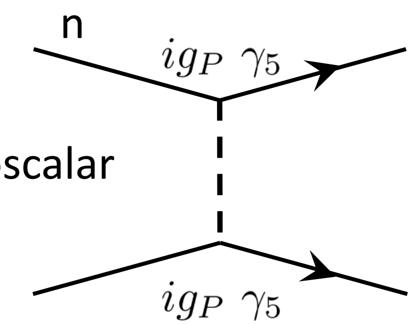
$$\lambda = \frac{\hbar}{Mc}$$

Scalar-scalar



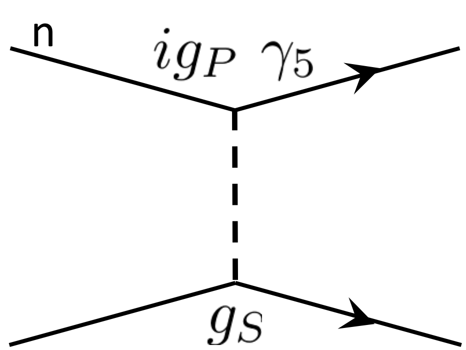
$+$

PseudoScalar-Pseudoscalar



Dipole
(probe)

$+$



Monopole
(source)

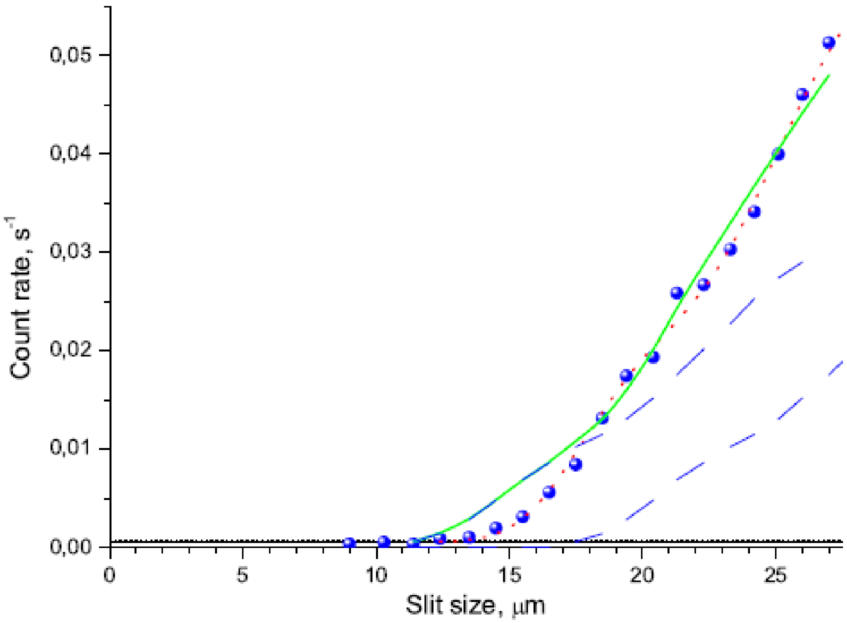
~~P~~ ~~CP~~ Scalar–Pseudoscalar (Axion–like)

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

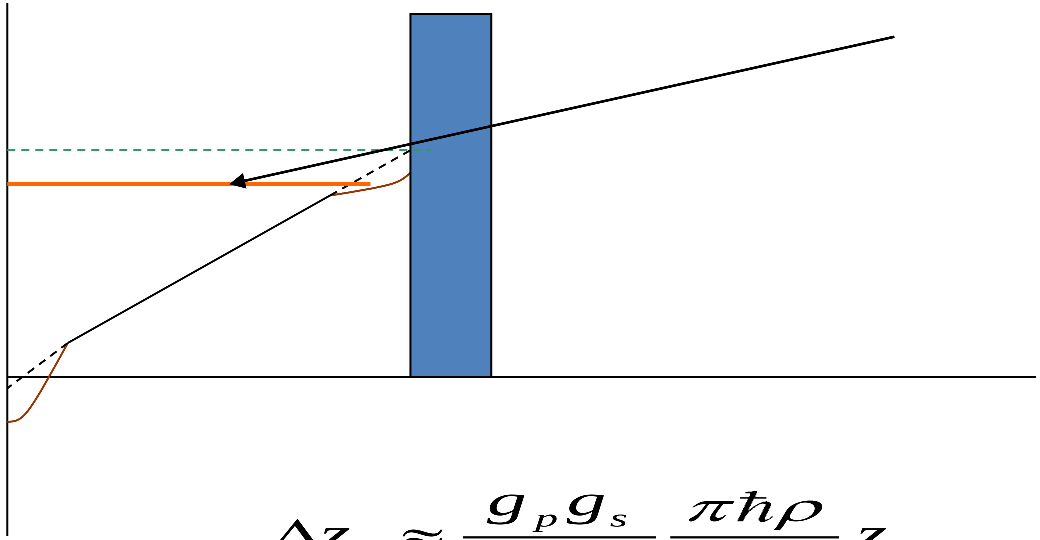
Axion-nucleon interaction:

$$V(\vec{r}) = \frac{\hbar g_p g_s}{8\pi mc}(\vec{\sigma}\vec{n})\left[\frac{1}{\lambda r} + \frac{1}{r^2}\right]\exp(-r/\lambda)$$

$$V_A(z) = \int_{mirror} V(x, y, z+z')dz' = \frac{g_p g_s}{4\pi}\frac{\pi\hbar\rho\lambda}{2m^2c}\exp(-z/\lambda)$$



Level and turning point shift

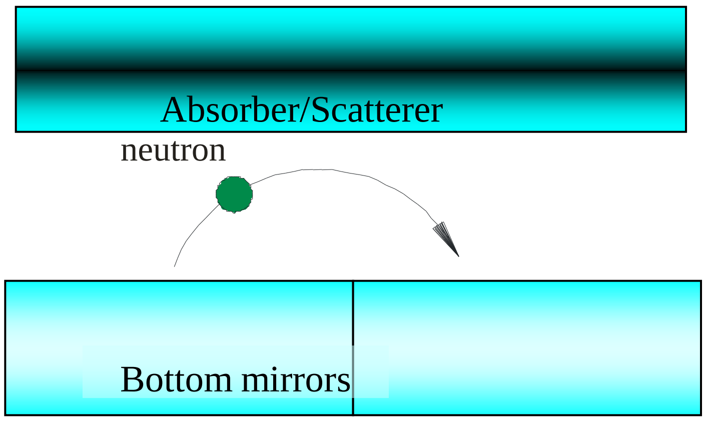


$$\Delta z_n \approx \frac{g_p g_s}{3\pi mg}\frac{\pi\hbar\rho}{2m^2c} z_n$$

Effect on Gravitationally Bound States

Integration of 2nd potential over mirror:

$$V(z) = -g_S{}^N g_P{}^n \frac{\hbar \rho_{\mathrm{m}} \lambda}{8 m_{\mathrm{n}}{}^2 c} \exp(-z/\lambda) \underbrace{(\sigma_n \cdot \hat{z})}_{\pm 1}$$



Inclusion of absorber:

$$W(z) = \pm g_S{}^N g_P{}^n \frac{\hbar \rho_{\mathrm{m}} \lambda}{8 m_{\mathrm{n}}{}^2 c} \underbrace{\left[\exp(-z/\lambda) - \exp(-(\Delta h - z)/\lambda)\right]}_{\frac{2z}{\lambda} + \text{const.}}$$

After dropping the invisible constant piece,

$W(z)$ is linear in z

$$g \rightarrow g_{\mathrm{eff}} = g \pm g_S{}^N g_P{}^n \frac{2\hbar \rho_{\mathrm{m}}}{8 m_{\mathrm{n}}{}^3 c}$$

$$z_1 = 2.34 \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 13.7\ \mu\mathrm{m}$$

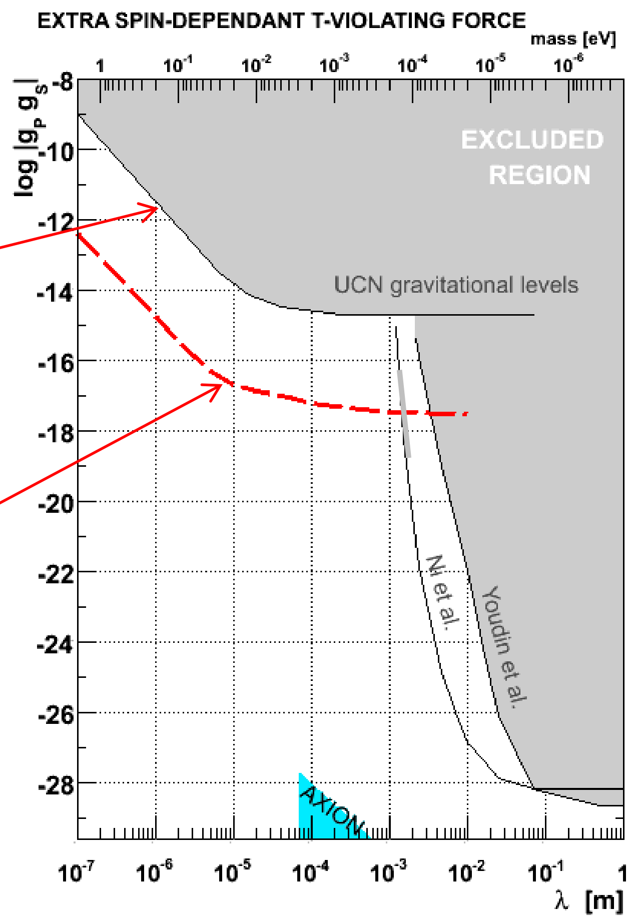
$$z_2 = 4.09 \sqrt[3]{\frac{\hbar^2}{2m^2 g}} = 24.0\ \mu\mathrm{m}$$

Our limits are calculated from a shift of the turning point by 3 μm.

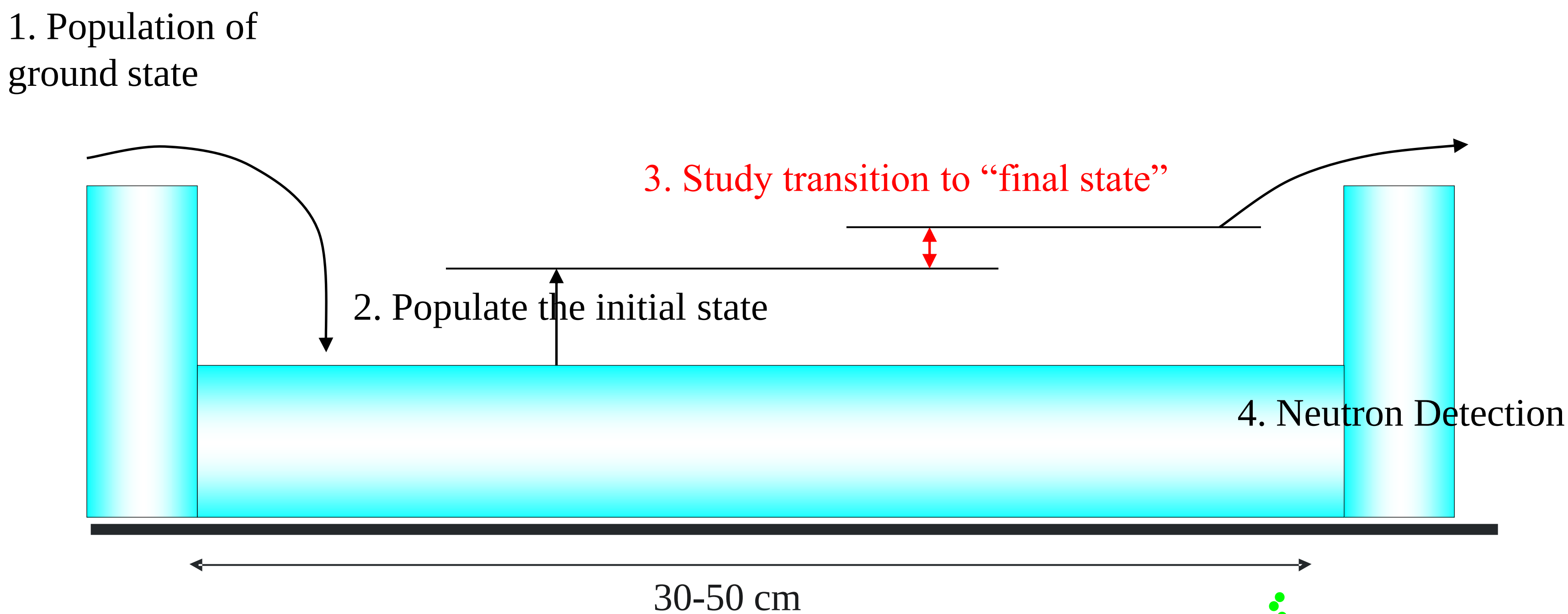
Exclusion plot

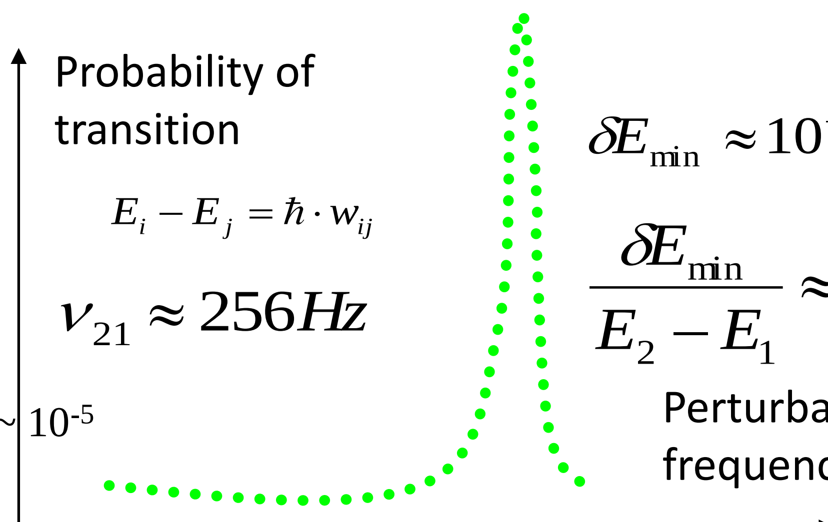
Flow-Through Mode

Trap Mode



GRANIT spectrometer





$$\delta E_{\min} \approx 10^{-18} eV$$

$$\frac{\delta E_{\min}}{E_2 - E_1} \approx 10^{-6}$$

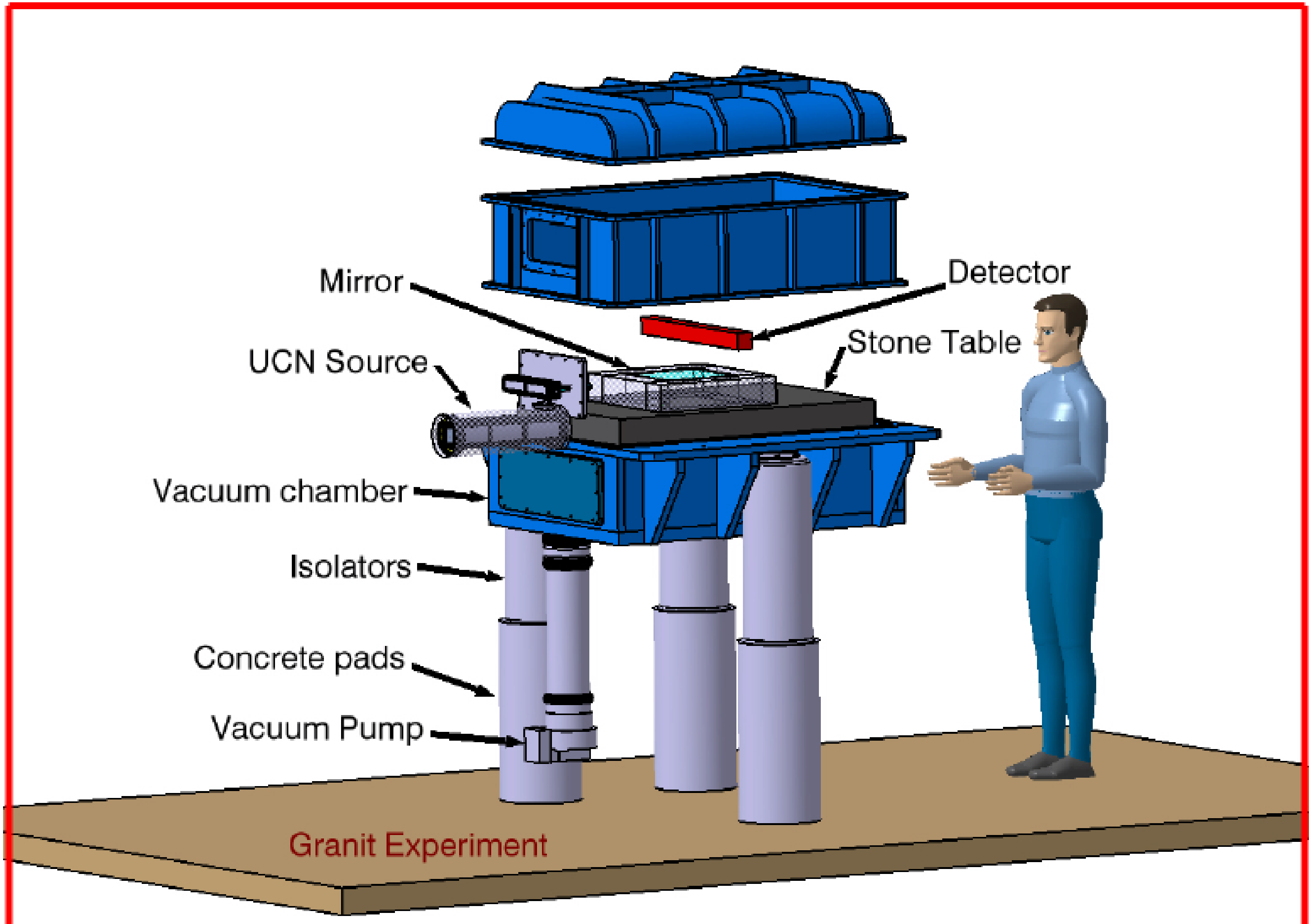
If lifetime is $\tau_n \sim 500$ s, $\frac{\Delta E}{E} \sim \frac{\hbar}{\tau_n E} = 2 \cdot 10^{-6}$

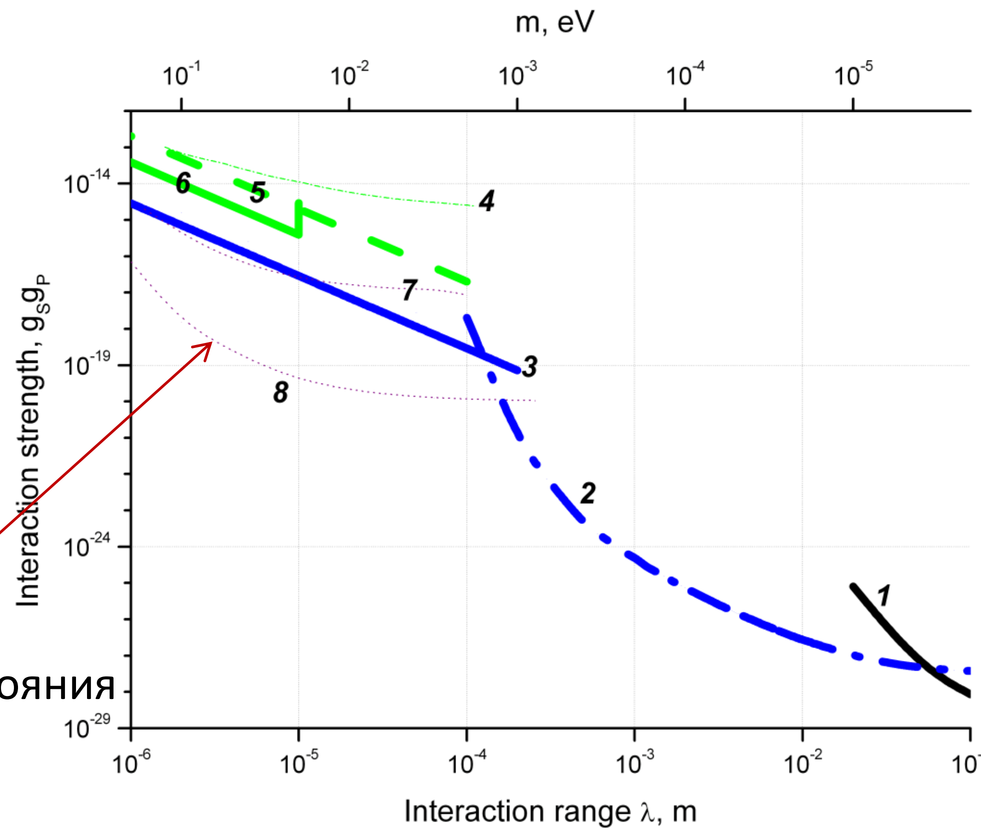
Flatness of bottom mirror: < 100 nm

Accuracy of setting the side walls perpendicular: ~ 10^{-5}

Vibrations, Count Rate, Holes, …

GRANIT spectrometer

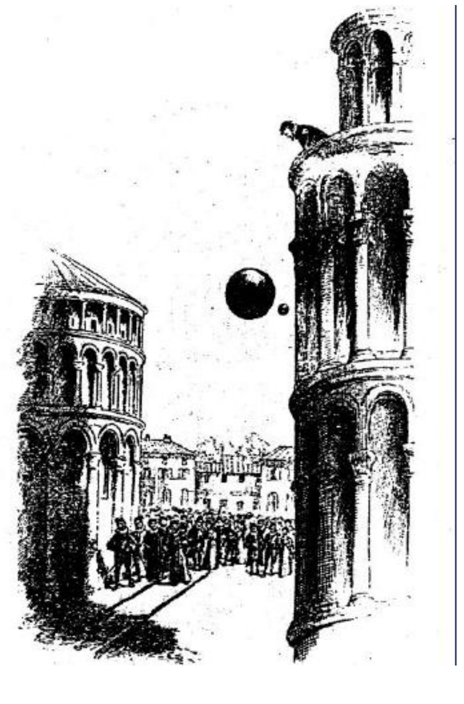




Гравитационные состояния

Гравитационные состояния Антиводорода

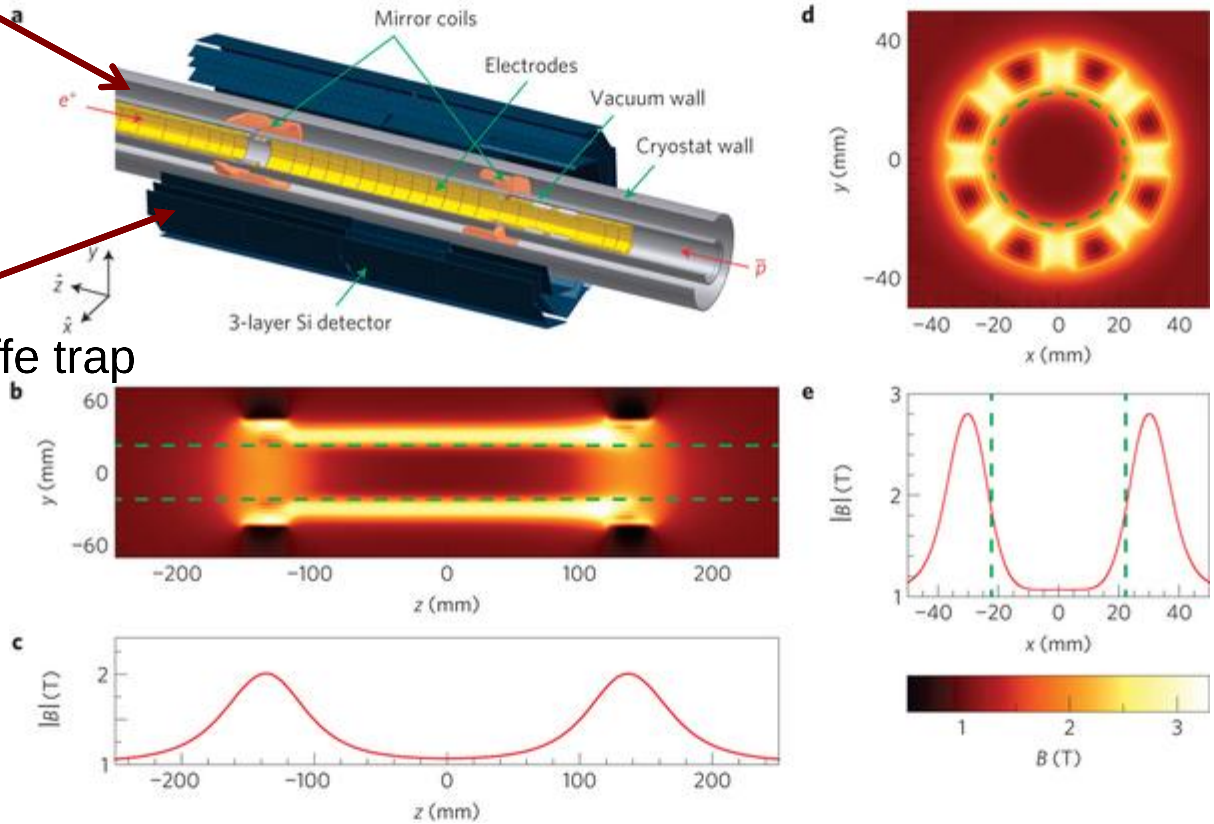
$$m = M?$$



ALPHA collaboration Nature Physics (April, 2011)

309 атомов антиводорода удержаны в течении 1000 с

Penning trap



Atom Ioffe trap

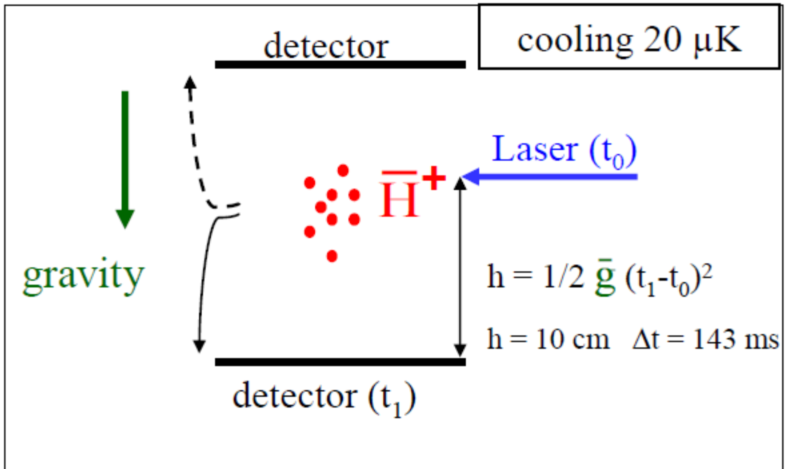
Глубина ямы для атомов 0.54 К

Gbar : $\bar{g}$ experiment using $\bar{H}^+$ to get $\bar{H}$ atoms

irfu cea saclay

- Produce ion $\bar{H}^+$
- Capture ion $\bar{H}^+$
- Sympathetic cooling 20 μK
- Photodetachment of e^+
- Time of flight

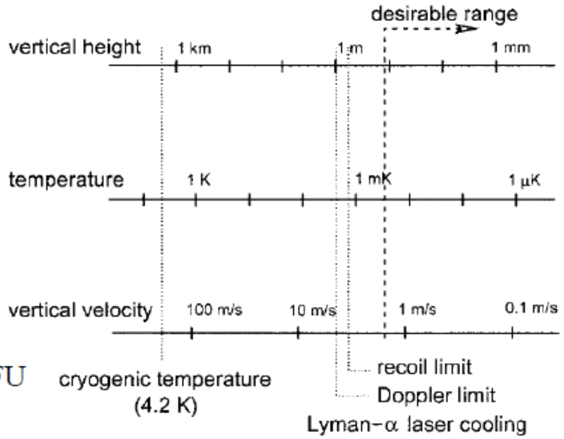
Error dominated by temperature of $\bar{H}^+$



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

Relative Precision on $\bar{g}$:

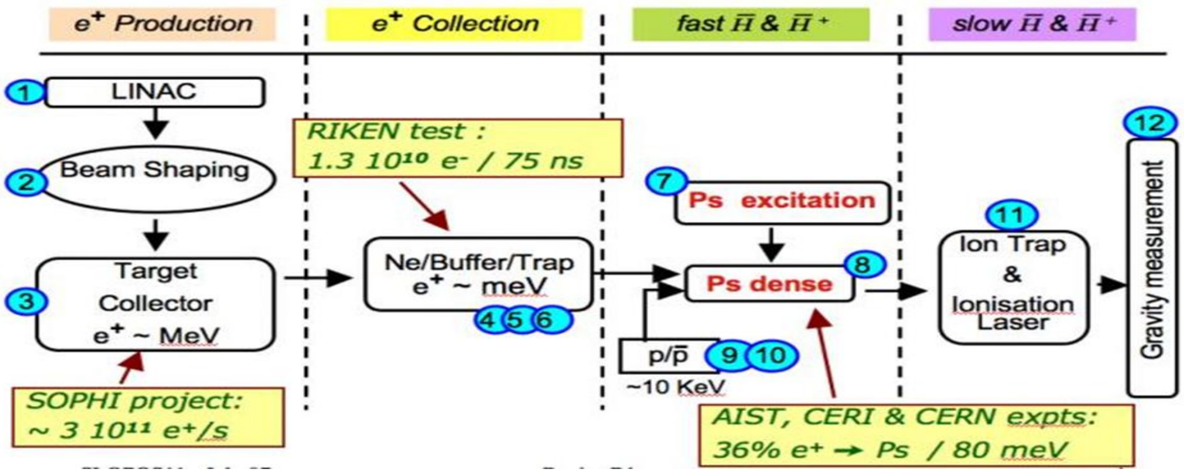
$\bar{H}^+$ in ion trap	$\Delta g/g$
$5\ 10^5$	0.001
10^4	0.006
10^3	0.02



GBar Project CERN approved may2012

гравитационные свойства антиводорода

Прямой тест Принципа Эквивалентности с антивеществом при T~1 nK



2013

2015

ФИАН

Квантовое отражение ультрахолодных антиатомов

Спектроскопия долгоживущих гравитационных состояний

$\bar{H}$ + WALL

$\neq$

ANNIHILATION ?

A. Yu. Voronin, P. Froelich, and B. Zygelman, Phys. Rev. A **72**, 062903 (2005).

J. E. Lennard-Jones, Trans. Faraday Soc. **28**, 333 1932.

Quantum reflection=

Reflection from the fast changing attractive potential

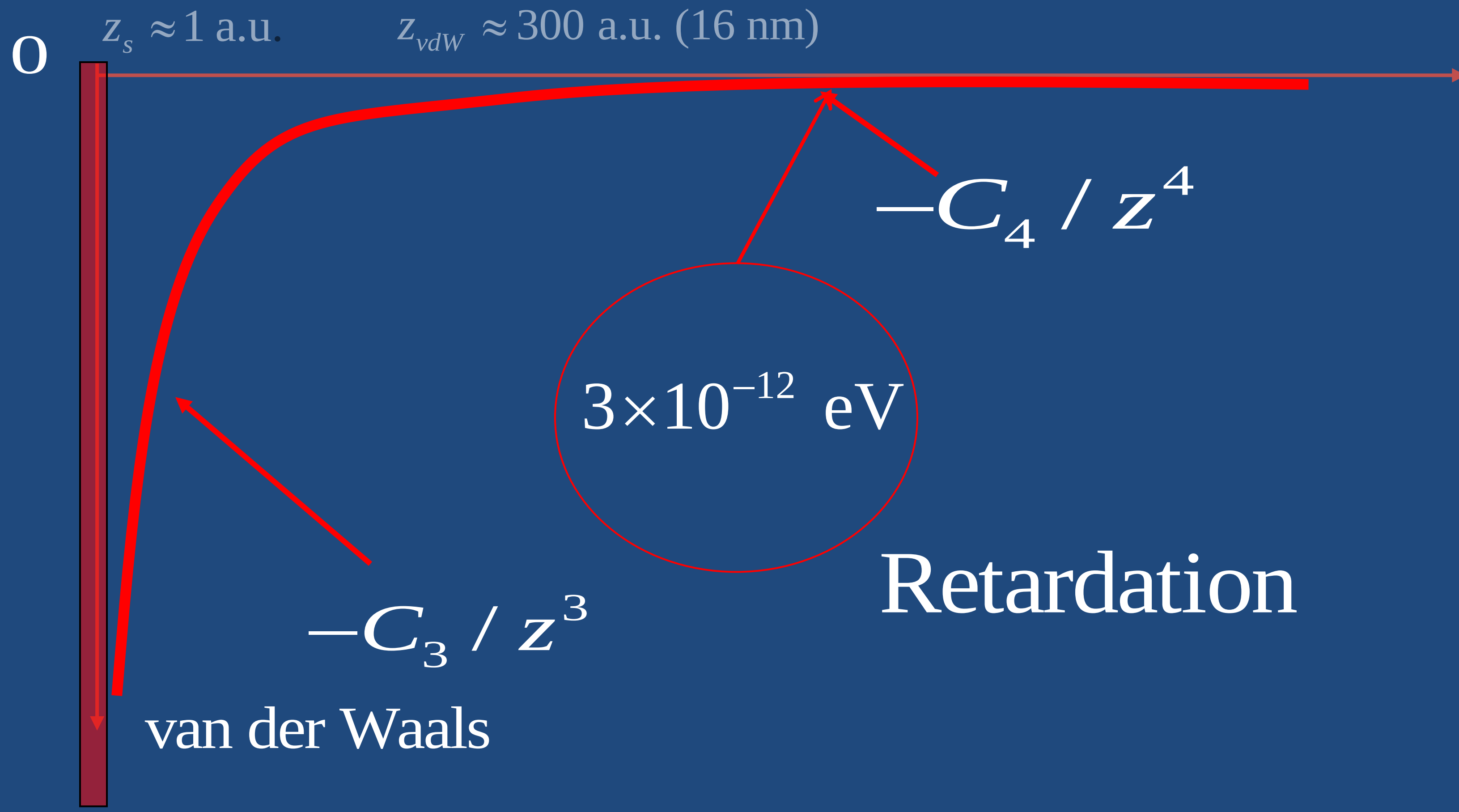
$$\frac{d\lambda_B(z)}{dz} \geq 1;\ \lambda_B(z) = \frac{2\pi h}{\sqrt{2m(E - V(z))}}$$

$$\frac{d\lambda_B(z)}{dz} = \frac{m\lambda_B^3}{\hbar^2}\frac{dV(z)}{dz}$$

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

$$\lim_{k\to 0} S = 1 - 2ika \qquad a = \mathrm{Re}\, a - i\left|\mathrm{Im}\, a\right|$$

$$\lim_{k\to 0} R_{\mathrm{qr}} \equiv \left|S\right|^2 = 1 - 4k\left|\mathrm{Im}\, a\right| \to 1;\ P_{\mathrm{ann}} = 4k\left|\mathrm{Im}\, a\right| \to 0$$

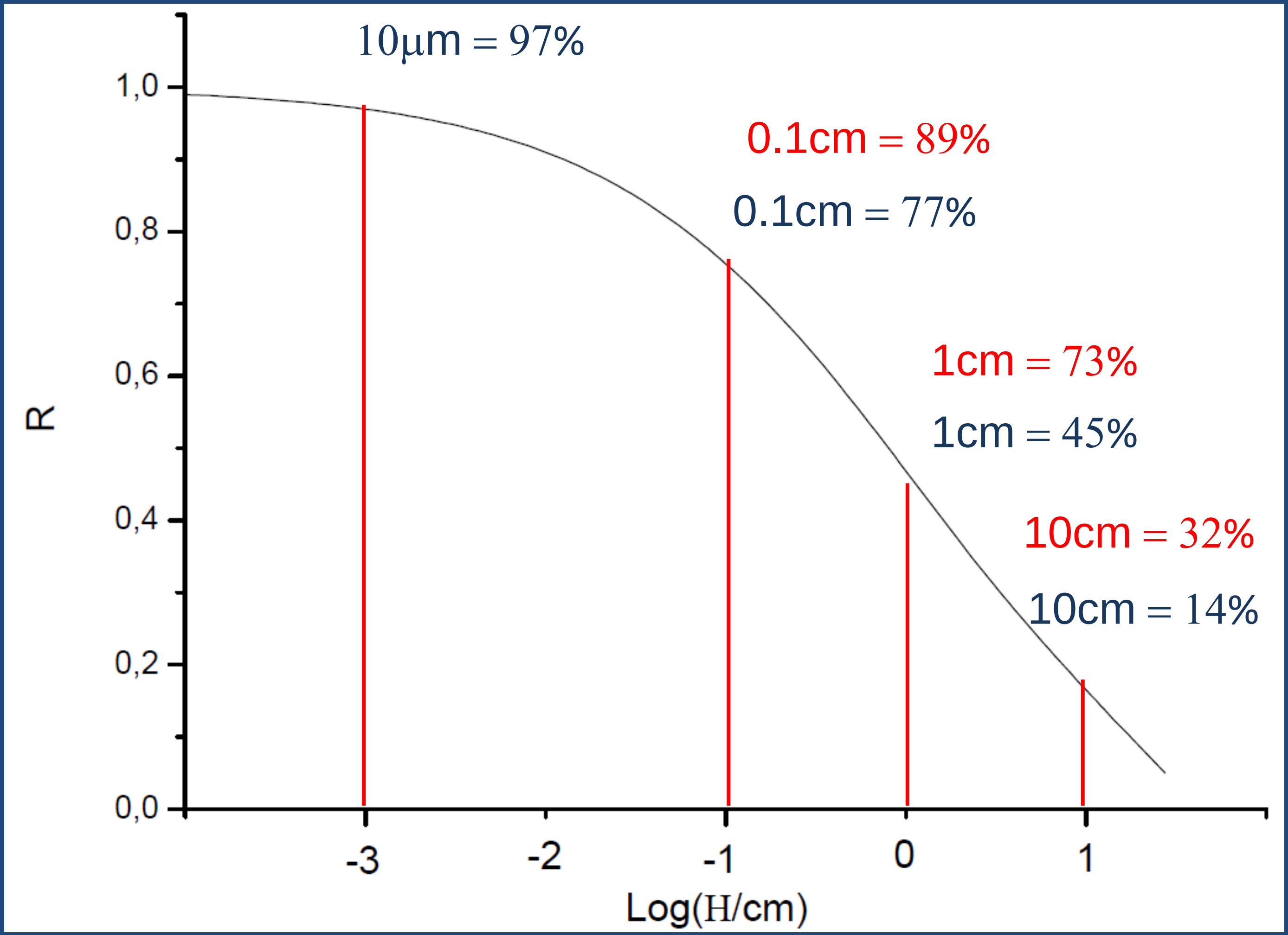


$$a = -0{,}0028 - i0{,}027\mu m$$

CASIMIR-POLDER POTENTIAL

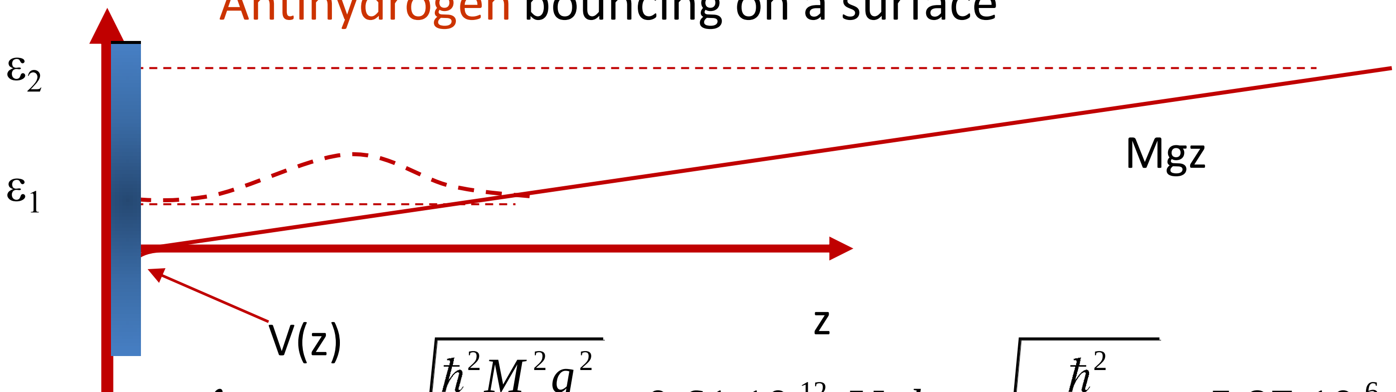
$$P_{\text{ann}} = 4k\left|\operatorname{Im} a\right| \rightarrow 0$$

From which height can we drop antihydrogen?



Gravitational states

Antihydrogen bouncing on a surface



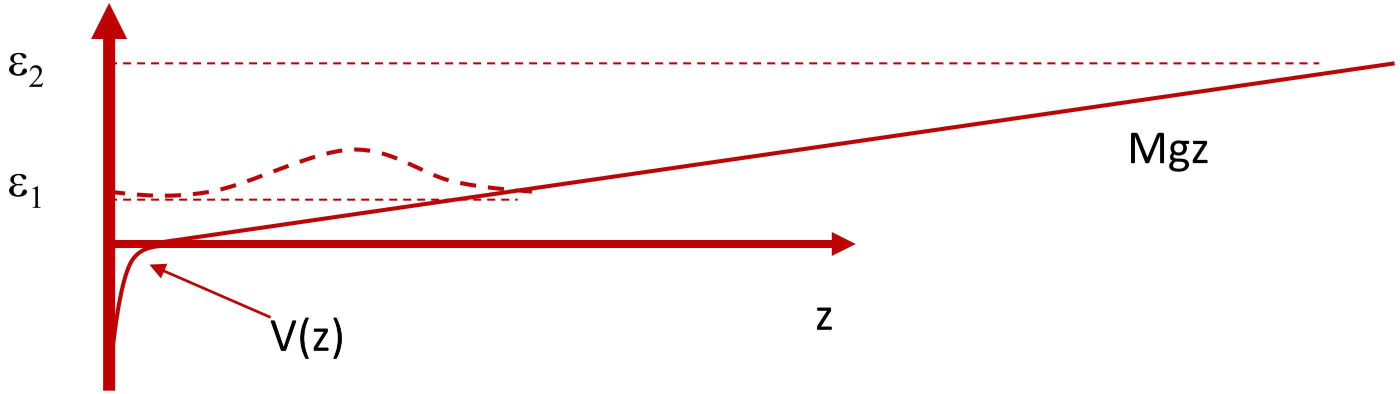
$$\varepsilon_n = \lambda_n \varepsilon_0 \qquad \varepsilon_0 = \sqrt[3]{\frac{\hbar^2 M^2 g^2}{2m}} = 0.61\ 10^{-12}\,\mathrm{eV} \quad l_0 = \sqrt[3]{\frac{\hbar^2}{2Mmg}} = 5.87\ 10^{-6} m$$

$$\varepsilon_0 / l_0 = Mg \quad \mathrm{Ai}(-\lambda_n) = 0$$

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

Correction by Casimir-Polder potential + annihilation



$$|a| \approx \sqrt{2mC_4}/\hbar\ ; l_0 = \sqrt[3]{\hbar^2/(2Mmg)};$$

$$|a|/l_0 \approx 0.005$$

Correction by Casimir-Polder V(z): $\varepsilon_n = \varepsilon\tilde{\lambda}_n$

$$\tilde{\lambda}_n = \lambda_n + a/l_0$$

$$\varepsilon_n = \varepsilon_0(\lambda_n + \mathrm{Re}\, a/l_0) \quad \Gamma = 2\varepsilon_0 |\mathrm{Im}\, a|/l_0$$

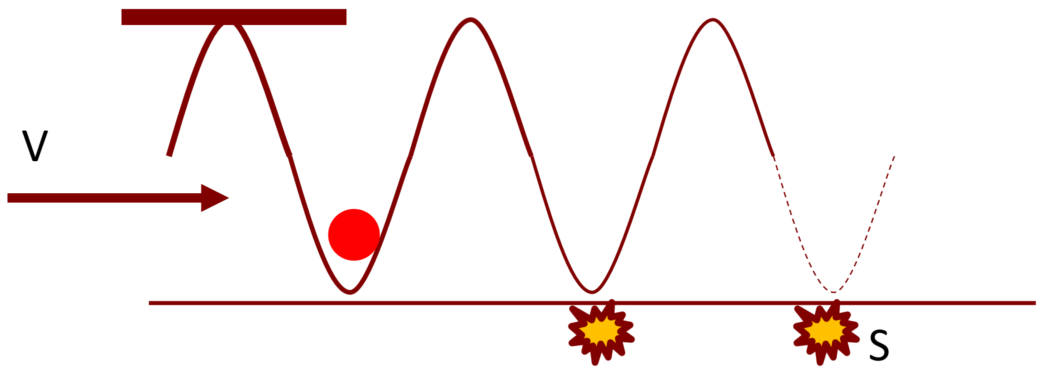
$$\tau = \frac{l_0}{\varepsilon_0}\frac{\hbar}{2|\mathrm{Im}\, a|} = \frac{\hbar}{2Mg|\mathrm{Im}\, a|} \approx 0.1s$$

Lifetime is determined by gravitational force Mg and $|\mathrm{Im}\, a|$.

Numbers: $\varepsilon_1 = 1.43\ peV;\ \varepsilon 2 = 2.49\ peV; \tau \approx 0.1s$

Antihydrogen “clock”

temporal-energy properties of gravitational states



$$\Phi(z,t) = \varphi_1(z)\exp(-i\varepsilon_1 t - \Gamma t/2) + \varphi_2(z)\exp(-i\varepsilon_2 t - \Gamma t/2)$$

$$\varphi_k(z) \sim Ai(z - \lambda_k - a/l_0) \quad \varepsilon_k = \varepsilon_0\lambda_k \;\; \Gamma = 2\varepsilon_0 \left|\mathrm{Im}\, a\right| / l_0$$

$$\langle \varphi_k | \varphi_n \rangle = 2i\frac{\mathrm{Im}\, a}{l_0}\frac{1}{\lambda_k - \lambda_n + 2i\,\mathrm{Im}\, a/l_0} \neq \delta_{kn}$$

$$N_{ann}(t) = -\frac{\partial}{\partial t}\int_0^\infty \left|\Phi(z,t)\right|^2 dz = 2\Gamma\exp(-\Gamma t)\left[1 + \cos\left(\left(\varepsilon_2 - \varepsilon_1\right)t/\hbar\right)\right]$$

A. YU. VORONIN, P. FROELICH, AND V. V. NESVIZHEVSKY   PHYSICAL REVIEW A **83**, 032903 (2011)

Bouncing Antihydrogen 2 states

ω_{12}= $(\lambda_2$-$\lambda_1)$ ε_0=254.54 Hz

$$M = \sqrt{\frac{2m_{\mathrm{H}}\hbar\omega_{12}^{3}}{g^{2}\left(\lambda_{2}^{0}-\lambda_{1}^{0}\right)^{3}}}.$$

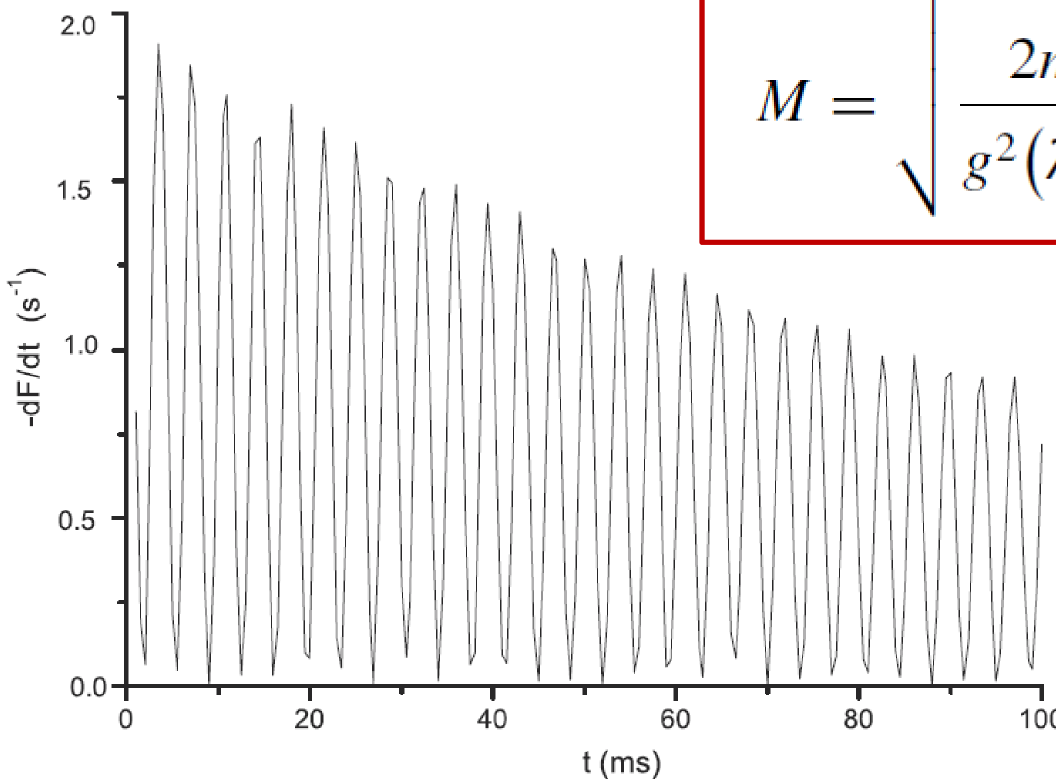


FIG. 2. Evolution of the annihilation rate of $\bar{\mathrm{H}}$ atoms in a superposition of the first and second gravitational states.

RESONANCE SPECTROSCOPY of Gravitational States

Studied by V.Nesvizhevsky et. al in connection with neutrons

E. Kupriyanova MEPHI- magnetic field induced transitions in antihydrogen

Induced resonance transitions :

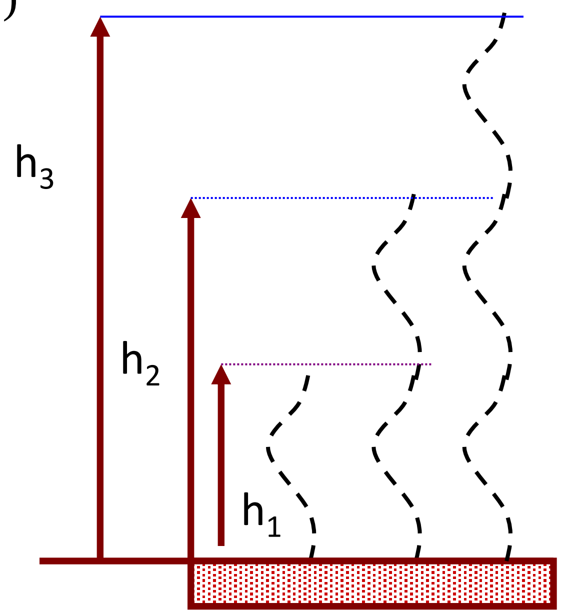
- Gradient magnetic field $\frac{\partial B}{\partial z} = B_0 \cos(\omega t)$
- Oscillating bottom mirror $\frac{\partial h}{\partial t} = a \cos(\omega t)$

$$\omega_{21} = 254.54 \text{ Hz} \quad h_1 = 13.7 \mu m$$

$$\omega_{31} = 462.83 \text{ Hz} \quad h_2 = 24.0 \mu m$$

$$\Gamma_{an} \approx 1.6 \text{ Hz} \qquad h_3 = 32.4 \mu m$$

$$\boxed{M = \sqrt{\frac{2 m_H \hbar \omega_{12}^3}{g^2 (\lambda_2^0 - \lambda_1^0)^3}}.}$$



Quantum ballistic experiment

spatial properties of gravitational states

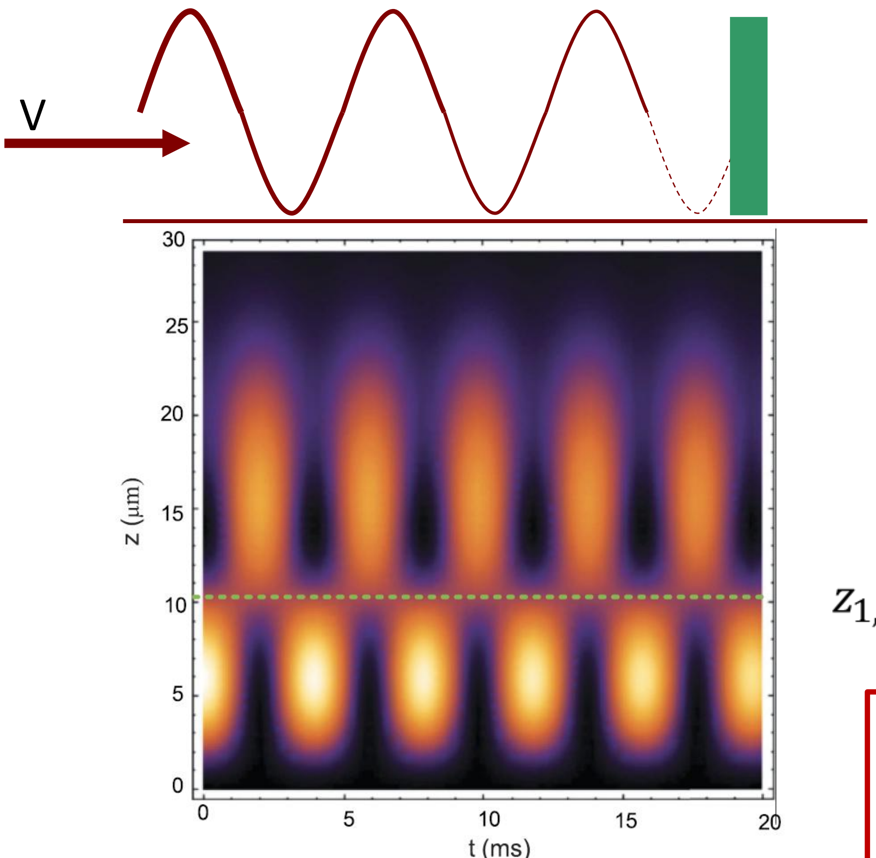


FIG. 4. (Color) The probability density of $\bar{H}$ in a superposition of the first and second gravitational states, as a function of the height z above the mirror (vertical axis) and the time t (horizontal axis). Dark shade, low probability density; light shade, high probability density. The dashed line indicates the position of the node in the wave function of the second state.

$z_{1,2} = (\lambda_2 - \lambda_1)\, l_0 = 10.27\ \mu\text{m}$

$$\boxed{M = \frac{\hbar^2 (\lambda_2 - \lambda_1)^3}{2 g m_H z_{1,2}^3}}$$

ВЫВОДЫ

- УХН в гравитационном поле- инструмент прецизионных исследований фундаментальных взаимодействий
- Спектроскопия и интерференция гравитационных состояний антиводорода- квантовые измерения гравитационной массы антиводорода