Constraints on axion-nucleon coupling constants from measurements of the Casimir effect

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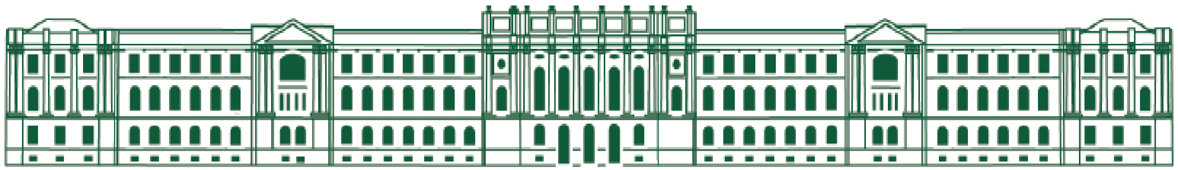


CONTENT

1. INTRODUCTION

A. AXION

Problems of QCD:

--- strong CP violation

--- large electric dipole moment of neutron

To solve them Peccei and Quinn postulated a new global U(1) symmetry.

Axion is a light pseudoscalar particle which is a consequence of spontaneous and dynamical breaking of this symmetry.

Axions interact with photons, electrons and nucleons.

Axions reasonably explain the nature of dark matter in astrophysics and cosmology.

Different kinds of axion-like particles were introduced in various models.

Experimental searches for axion-like particles are performed in many laboratories, but until now the region of axion masses from 0.01meV to 10meV is not investigated (the so-called axion window).

Exchange of a single pseudoscalar between two fermions

$$V(\vec{r};\vec{\sigma}_1,\vec{\sigma}_2) = \frac{g_{ak}^2}{16\pi m_k^2} e^{-m_a r}$$
$$\times \left\{ (\vec{\sigma}_1 \cdot \vec{r})(\vec{\sigma}_2 \cdot \vec{r}) \left[\frac{m_a^2}{r} + \frac{3 m_a}{r^2} + \frac{3}{r^3} \right] - (\vec{\sigma}_1 \cdot \vec{\sigma}_2) \left[\frac{m_a}{r^2} + \frac{1}{r^3} \right] \right\}$$

$$r = |\vec{r}| = |\vec{r}_1 - \vec{r}_2|$$

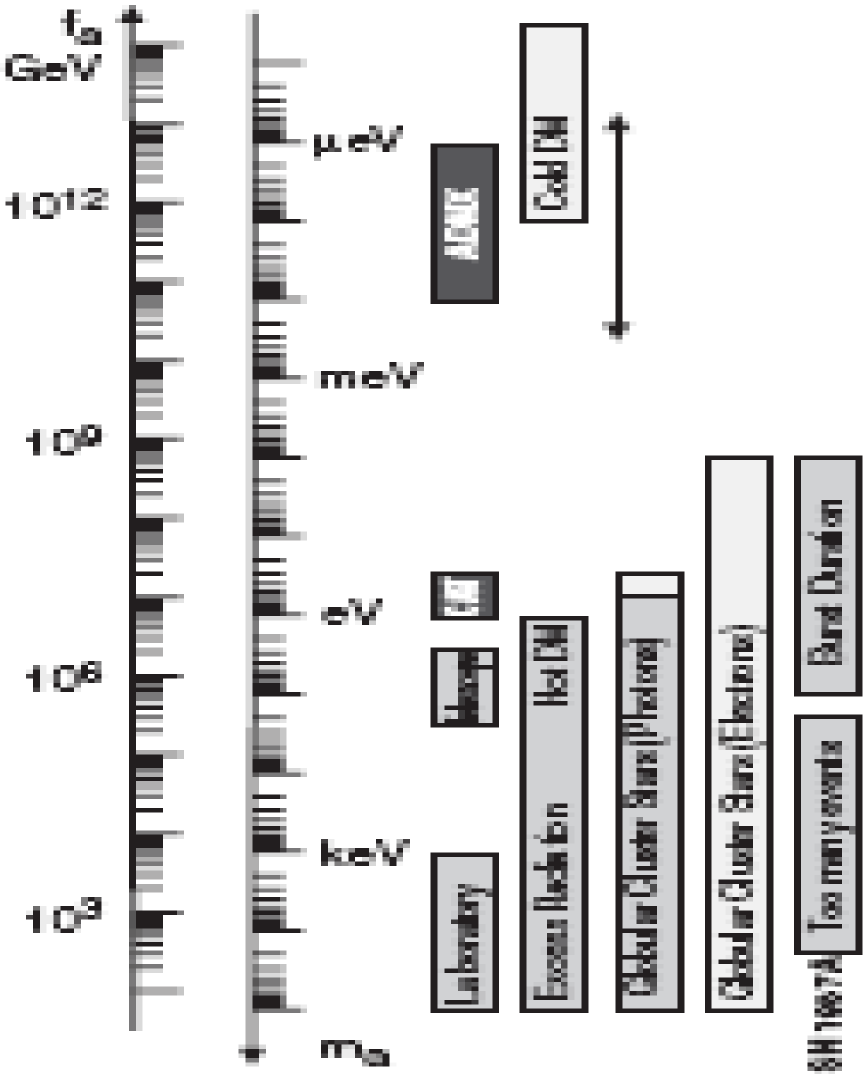
A. Bohr and P.G. Mottelson,
Nuclear Structure (N.Y., 1969)

The leading-order pseudoscalar interaction between unpolarized bodies arises from the simultaneous exchange of two pseudoscalars between two fermions:

$$V(\vec{r}) = -\frac{g_{ak}^2 g_{al}^2}{32\pi^3 m_k m_l}\frac{m_a}{r^2}K_1(2m_a r)$$

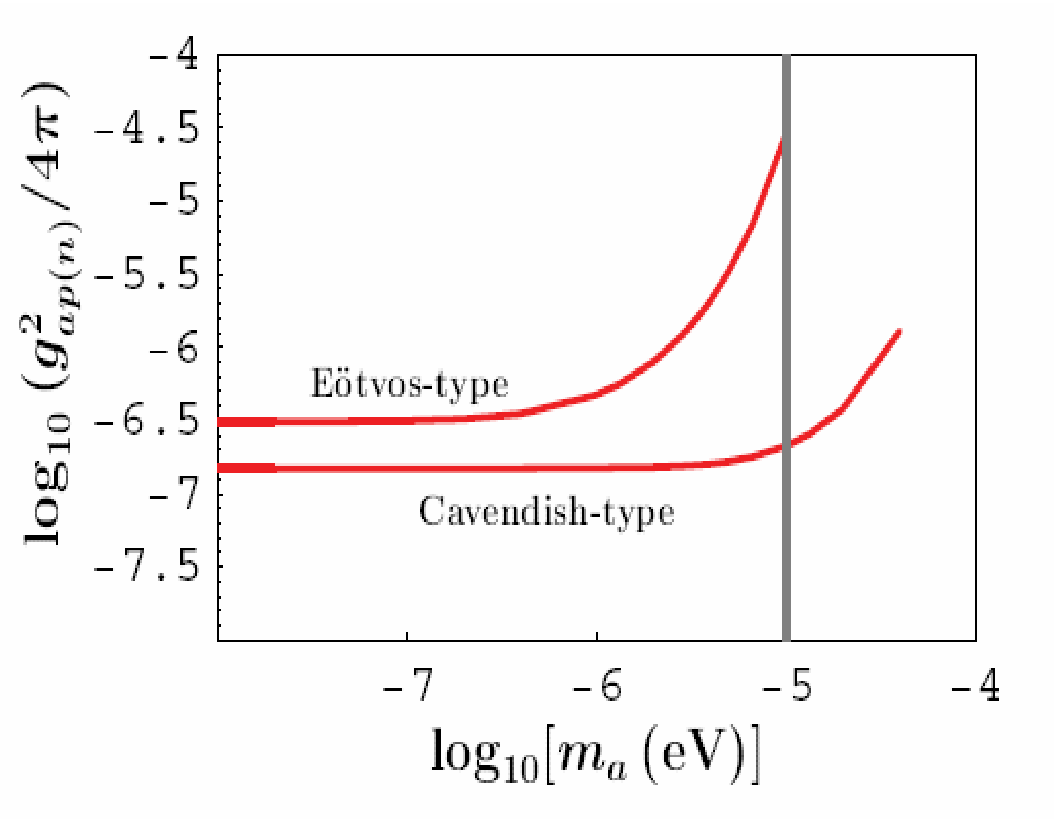
Drell, Huang, Phys. Rev. v.91, 1527 (1953);
Ferrer, Nowakowski, PRD, v.59, 075009 (1999).

2. CONSTRAINTS ON AN AXION FROM ASTROPHYSICS AND GRAVITATION



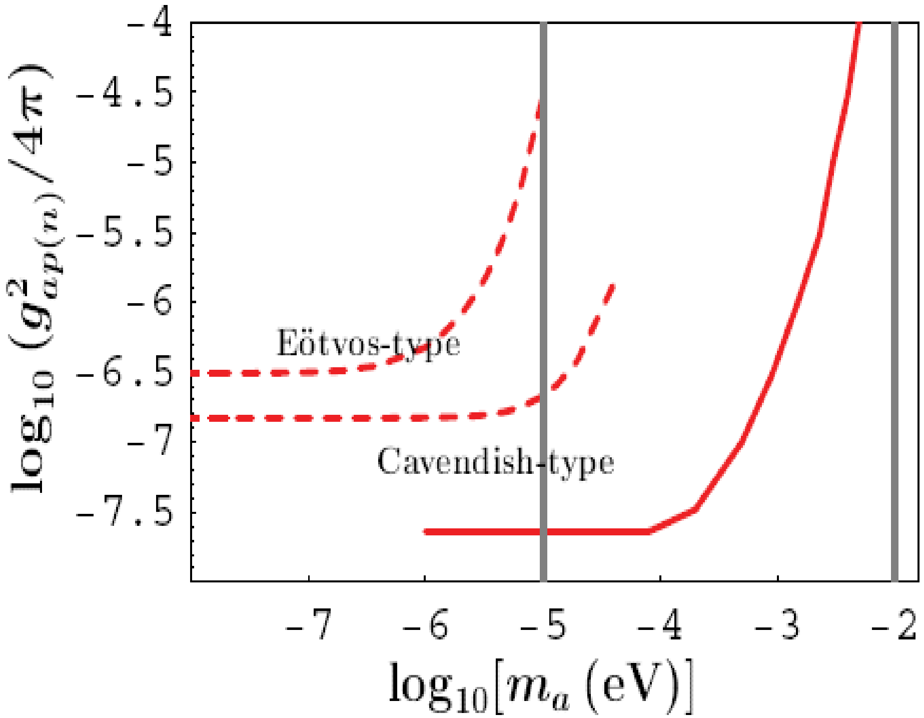
Raffelt, JPA (2007)

Constraints on coupling constants of axion-nucleon interactions from gravitational experiments



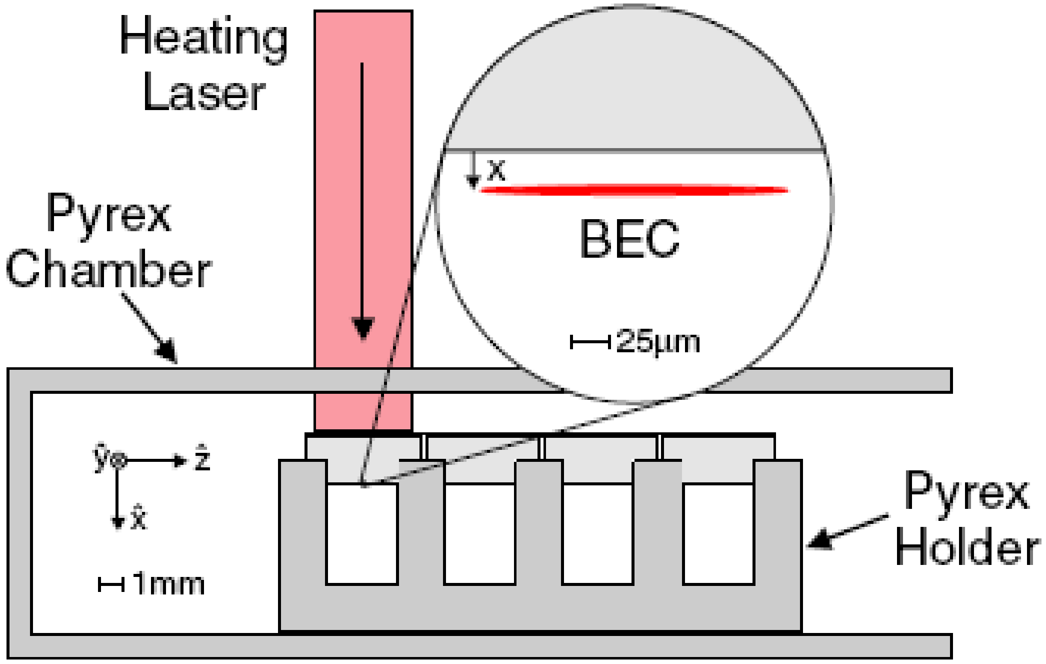
Adelberger, Fischbach, Krause, Newman,
Phys. Rev. D, v.68, 062002 (2003).

Constraints on coupling constants of axion-nucleon interactions from recent Cavendish-type experiment



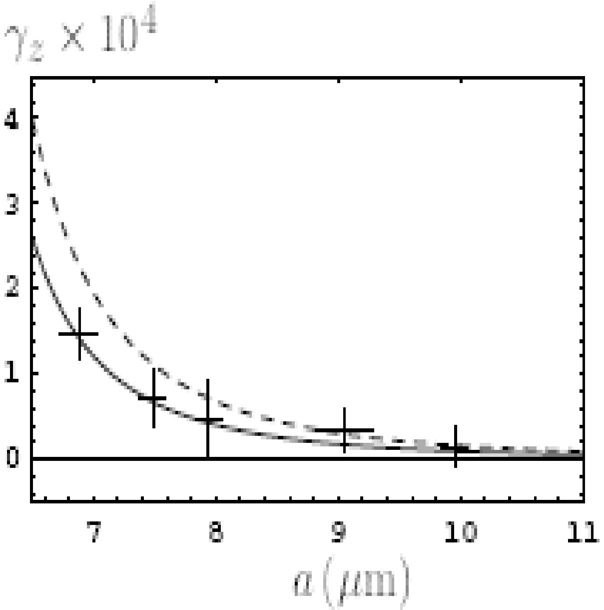
Kapner, Cook, Adelberger, Gundlach, Heckel, Hoyle, Swanson, Phys. Rev. Lett., v.97, 021101 (2007).
Adelberger, Heckel, Hoedl, Hoyle, Kapner, Upadhye, Phys. Rev. Lett., v.98, 131104 (2007).

3. CONSTRAINTS FROM MEASUREMENTS OF THE THERMAL CASIMIR-POLDER FORCE

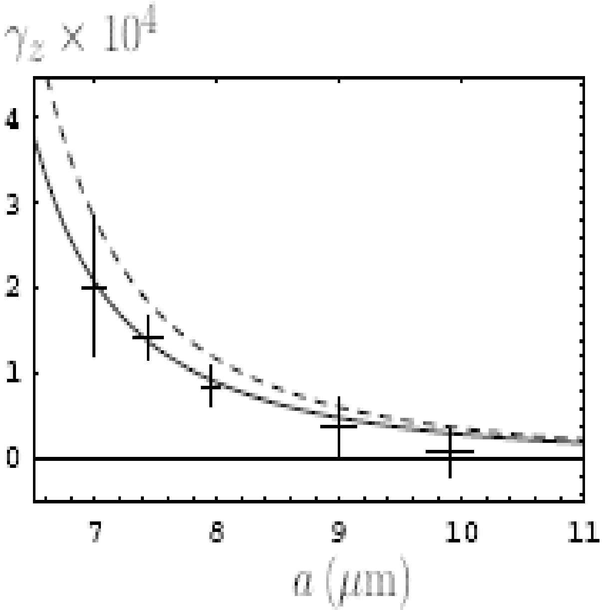


Obrecht, Wild, Antezza, Pitaevskii, Stringari, Cornell, PRL (2007);

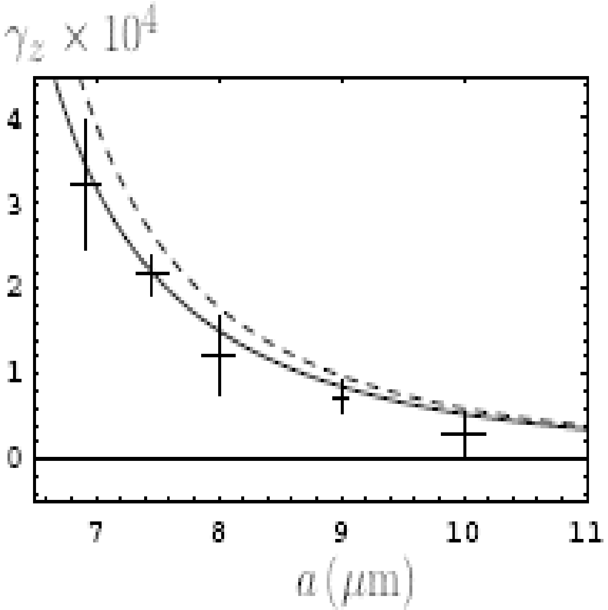
Relative frequency shift: comparison with theory



$T_p = T_e = 310\,\mathrm{K}$



$T_p = 479\,\mathrm{K}$



$T_p = 605\,\mathrm{K}$

Obrecht, Wild, Antezza, Pitaevskii, Stringari, Cornell, PRL (2007);
Klimchitskaya, Mostepanenko, JPA (2008).

$$\gamma_z^{\mathrm{add}}(a_i) \leq \Delta_i \gamma_z$$

$$\gamma_z^{\mathrm{add}}(a) = \frac{15 A(g_{ap,p}, g_{an,p})}{2\pi A_z m_{\mathrm{Rb}} \omega_{0z}^2} \int_1^\infty du \frac{\sqrt{u^2-1}}{u}$$

$$\times\, e^{-2m_a a u} \left(1 - e^{-2m_a D u}\right) I_1(2m_a A_z u) \Theta(2m_a R_z u)$$

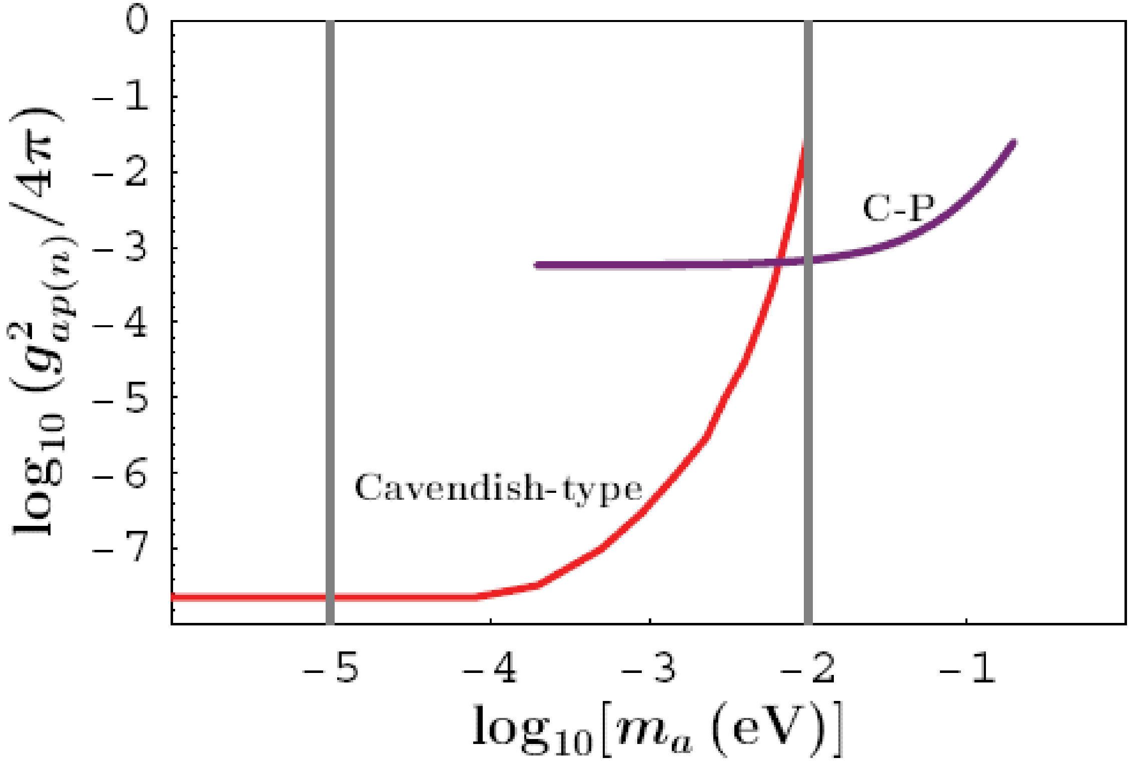
$$\Theta(t) \equiv \frac{1}{t^3}(t^2 \sinh t - 3t \cosh t + 3 \sinh t)$$

$$A(g_{ap,p}g_{an,p}) = \frac{\rho_{\mathrm{SiO_2}} m_a}{16\pi^2 m^2 m_{\mathrm{H}}} (37 g_{ap,p}^2 + 50 g_{an,p}^2)$$

$$\times \left(\frac{Z_{\mathrm{SiO_2}}}{\mu_{\mathrm{SiO_2}}} g_{ap,p}^2 + \frac{N_{\mathrm{SiO_2}}}{\mu_{\mathrm{SiO_2}}} g_{an,p}^2 \right)$$

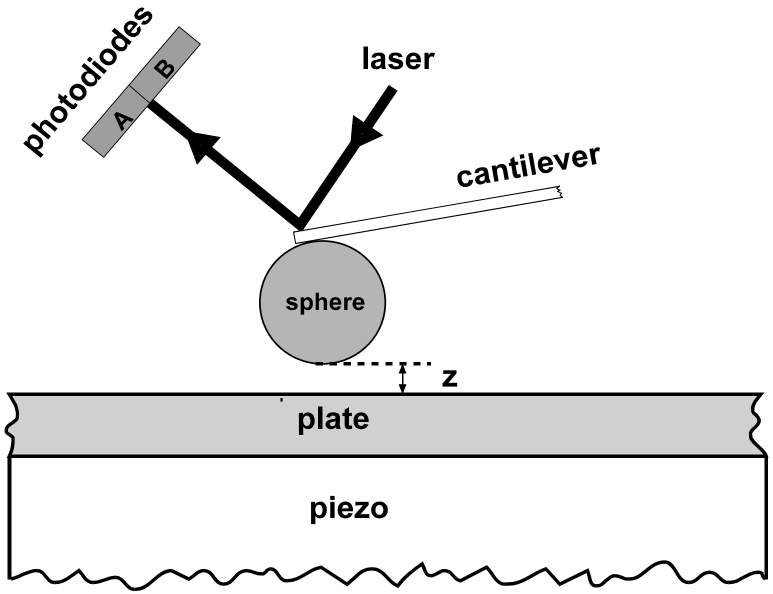
Fischbach, Talmadge,
The Search for Non-Newtonian Gravity
(AIP, NY, 1999)

Constraints on coupling constants of axion-nucleon interactions from measurements of the Casimir-Polder force



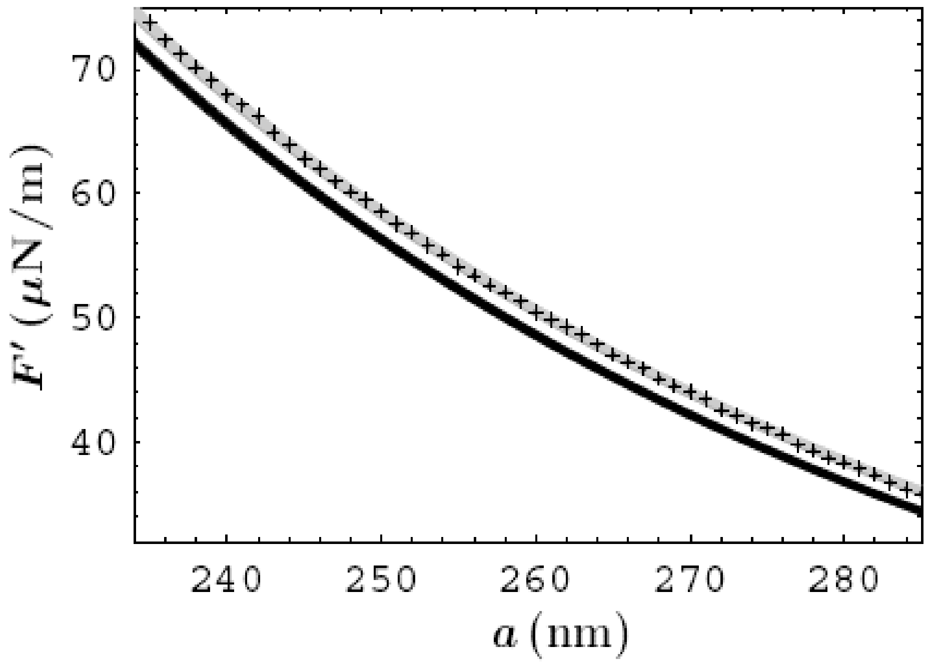
Bezerra, Klimchitskaya, Mostepanenko, Romero, Phys. Rev. D, v.89, 035010 (2014).

4. CONSTRAINTS FROM MEASUREMENTS THE GRADIENT OF THE CASIMIR FORCE USING A DYNAMIC AFM



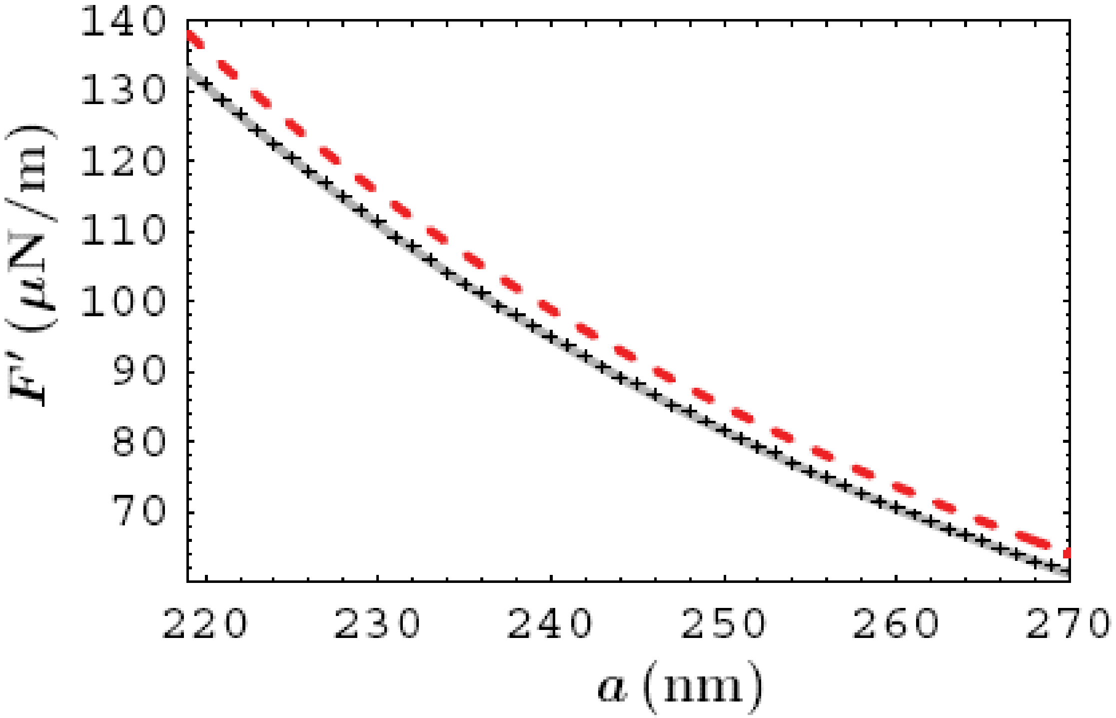
$$\Delta\omega(a) = -\frac{\omega_0}{2k} F'_{\text{tot}}(a, T)$$

Comparison between theory and experiment Au-Au test bodies:



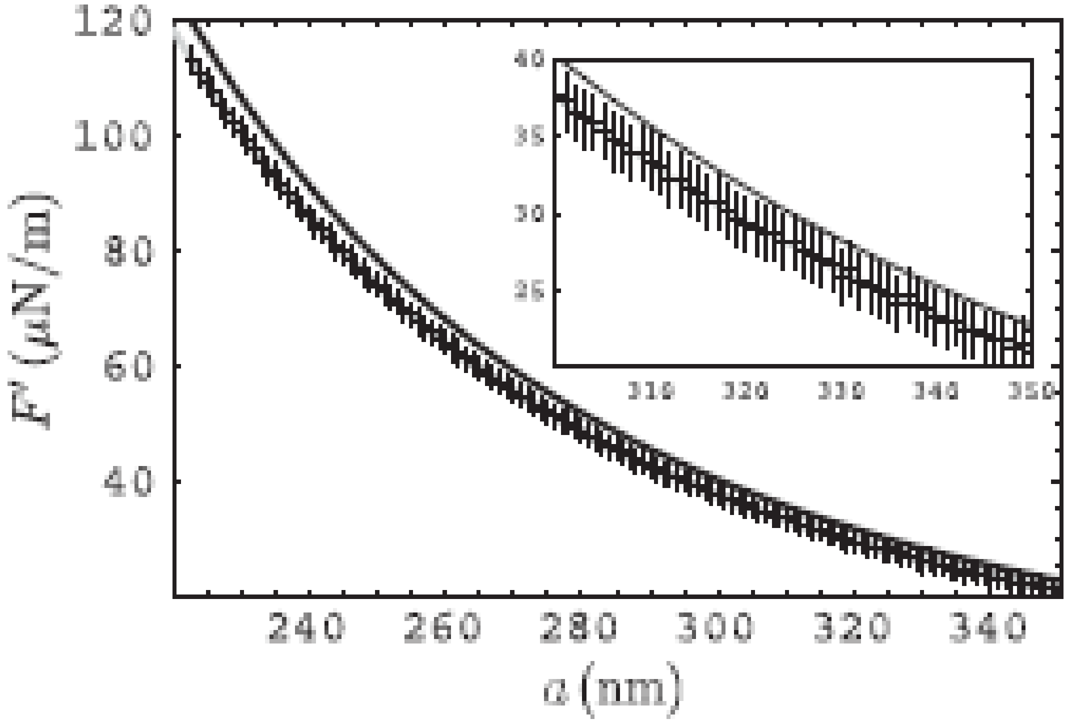
Chang, Banishev, Castillo-Garza,
Klimchitskaya, Mostepanenko, Mohideen,
Phys. Rev. B, v.85, 165443 (2012).

Comparison between theory and experiment Au-Ni test bodies:



Banishev, Chang, Klimchitskaya, Mostepanenko, Mohideen, Phys. Rev. B, v.85, 195422 (2012).

Comparison between theory and experiment Ni-Ni test bodies:



Banishev, Klimchitskaya,
Mostepanenko, Mohideen,
Phys. Rev. Lett., v.110, 137401 (2013);
Phys. Rev. B, v. 88, 155410 (2013).

$$\frac{\partial F_{\mathrm{add}}(a)}{\partial a} \leq \Delta F_C'(a)$$

$$\frac{\partial F_{\mathrm{add}}(a)}{\partial a} = \frac{\pi}{m^2 m_H^2} C_d C_s \int_1^\infty du \frac{\sqrt{u^2-1}}{u^2} \left(1 - e^{-2m_a u D}\right)$$

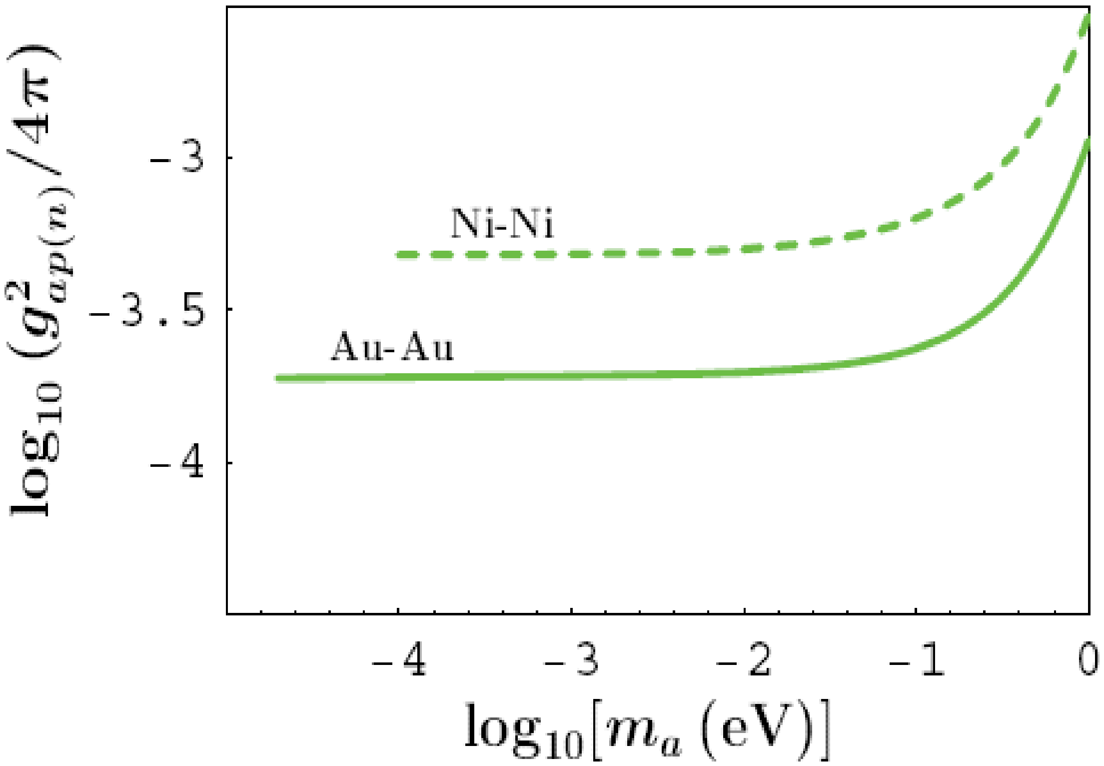
$$\times\, e^{-2m_a a u} \left[\Phi(R, m_a u) - e^{-2m_a u \Delta_s} \Phi(R - \Delta_s, m_a u)\right]$$

$$\Phi(r, z) = r - \frac{1}{2z} + e^{-2rz} \left(r + \frac{1}{2z}\right)$$

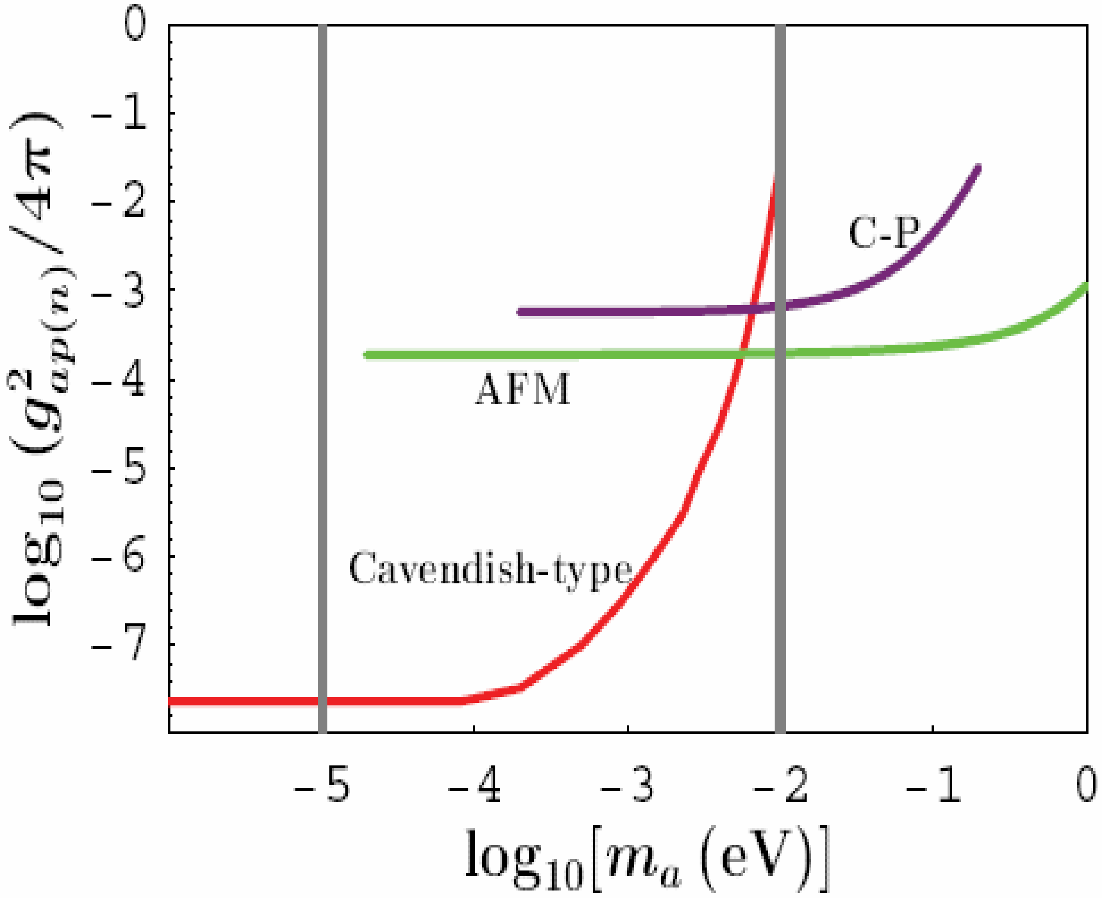
$$C_d = \rho_d \left(\frac{g_{ap}^2}{4\pi} \frac{Z_d}{\mu_d} + \frac{g_{an}^2}{4\pi} \frac{N_d}{\mu_d} \right)$$

$$C_s = \rho_s \left(\frac{g_{ap}^2}{4\pi} \frac{Z_s}{\mu_s} + \frac{g_{an}^2}{4\pi} \frac{N_s}{\mu_s} \right)$$

Constraints on coupling constants of axion-nucleon interactions from dynamic AFM measurements

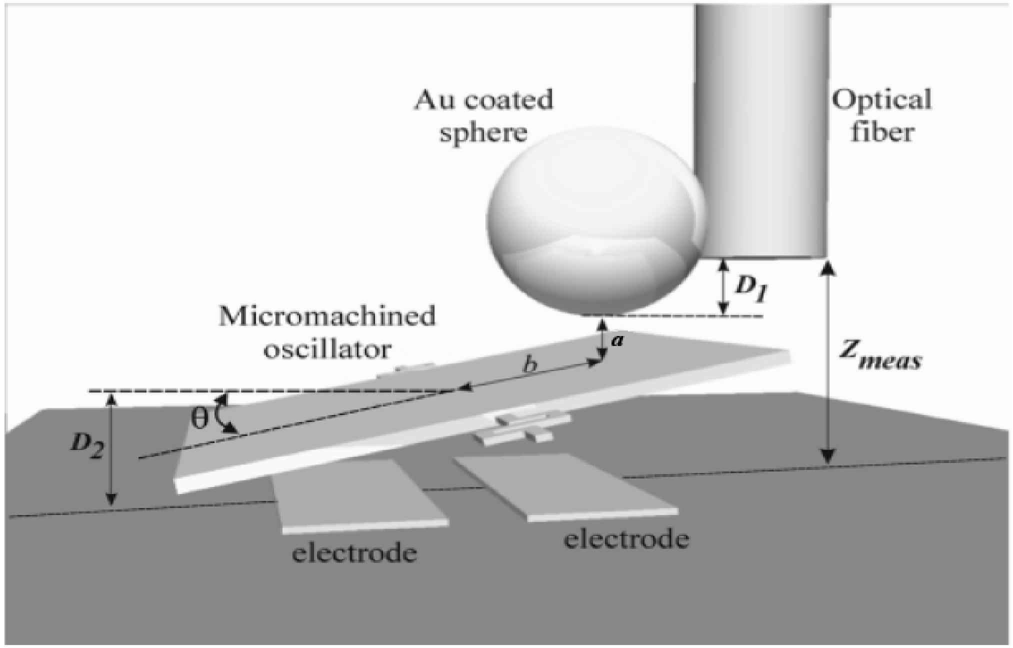


Bezerra, Klimchitskaya, Mostepanenko, Romero, PRD, v.89, 075002 (2014).

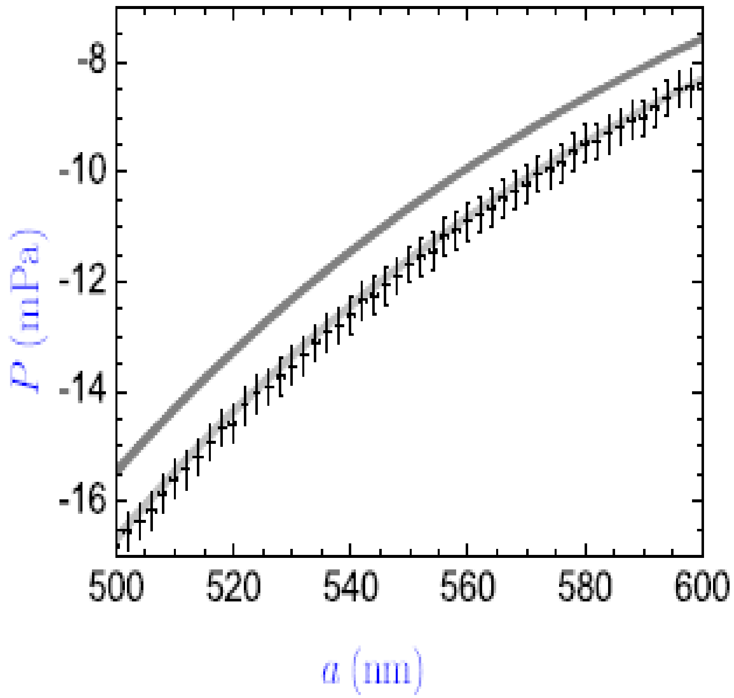


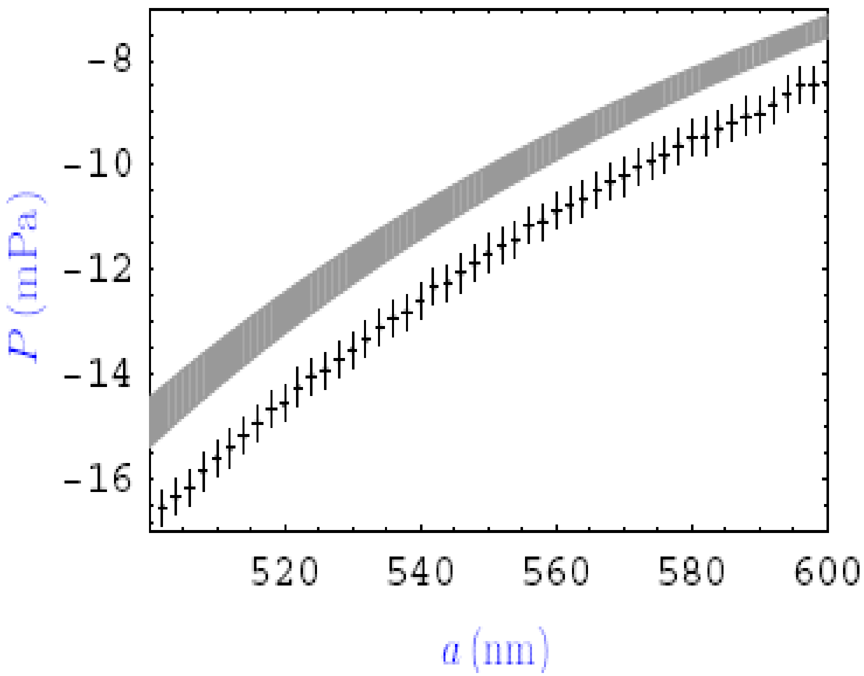
0
-1
-2
-3
-4
-5
-6
-7
$\log_{10}(g^2_{ap(n)}/4\pi)$
C-P
AFM
Cavendish-type
-5
-4
-3
-2
-1
0
$\log_{10}[m_a\,(\mathrm{eV})]$

5. CONSTRAINTS FROM MEASUREMENTS THE EFFECTIVE CASIMIR PRESSURE BY MEANS OF A MICROMACHINED OSCILLATOR



Comparison between experiment and theory



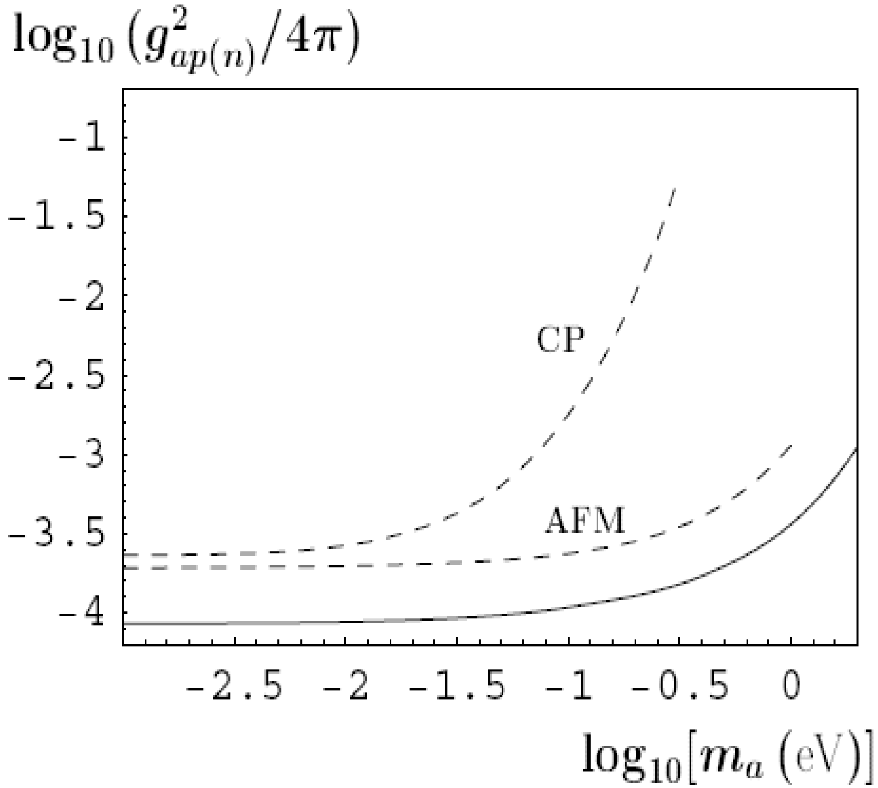


The relative experimental error (at a 95% confidence level) varies from 0.19% at 162 nm to 0.9% at 400 nm and 9% at 746 nm.

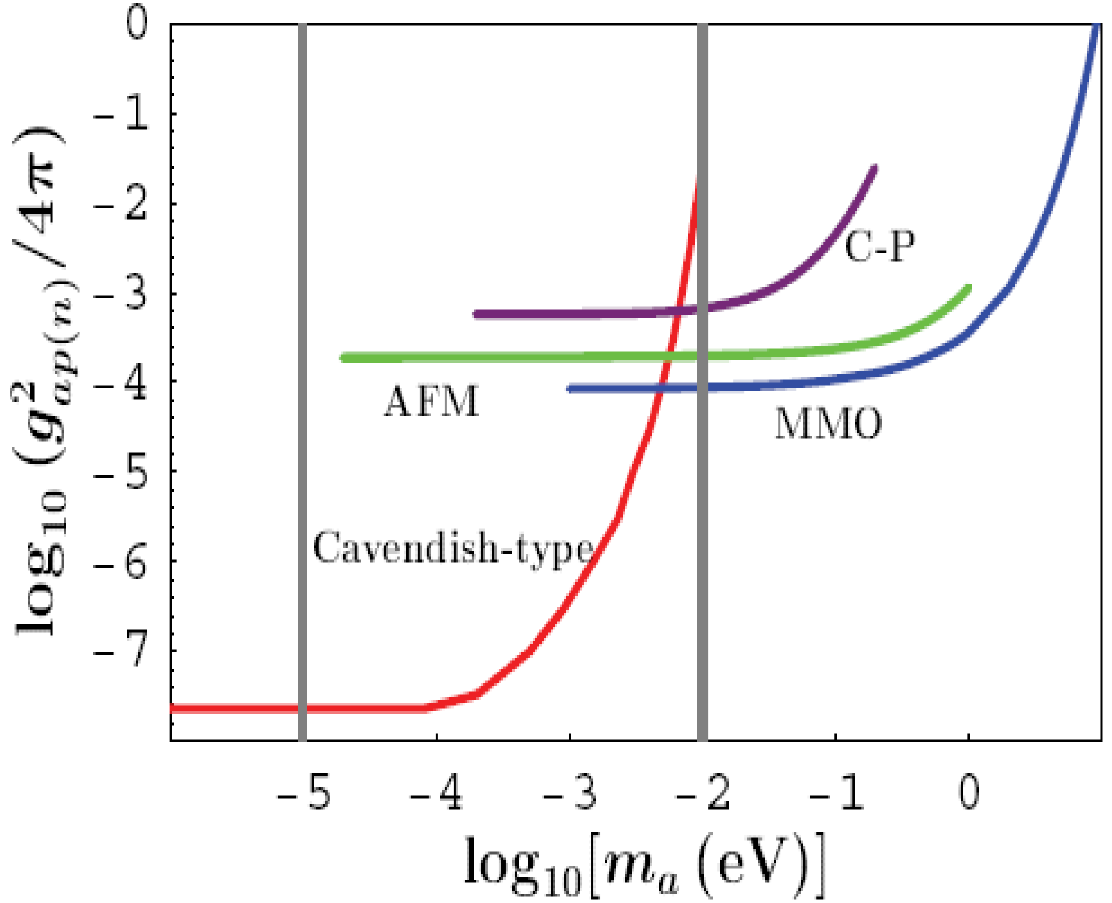
$$|P_{\rm add}(a)| \leq \Delta P(a)$$

$$P_{\rm add}(a) = -\frac{1}{2m^2 m_H^2} C_p C_s \int_1^\infty du \frac{\sqrt{u^2-1}}{u^2} e^{-2m_a a u}$$
$$\times \left(1 - e^{-2m_a u D_p}\right) \left(1 - e^{-2m_a u D_s}\right)$$

Constraints on coupling constants of axion-nucleon interactions from measurements of effective Casimir pressure using a micromachined oscillator

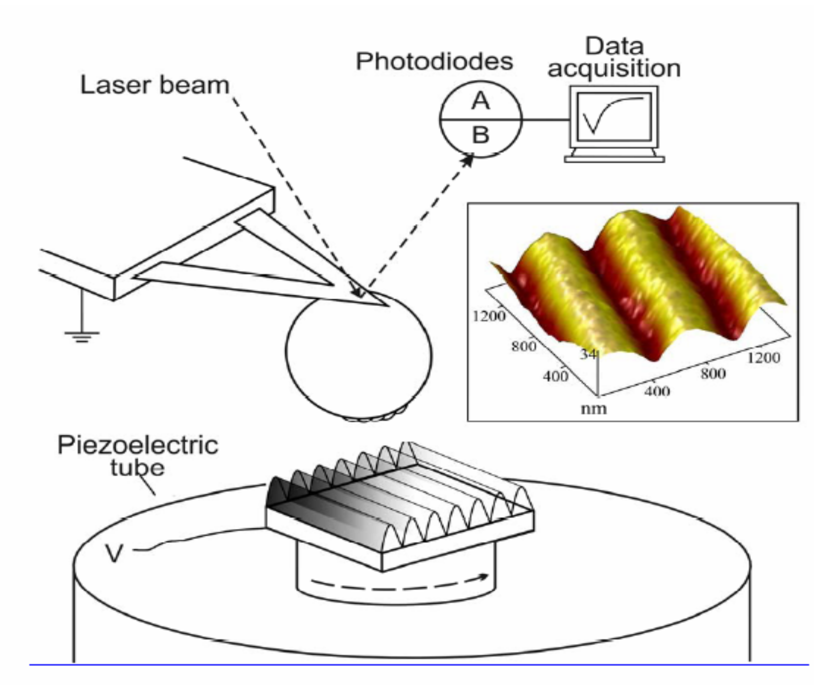


Bezerra, Klimchitskaya, Mostepanenko, Romero,
Eur. Phys. J. C, v.74, 2859 (2014)



0
-1
-2
-3
-4
-5
-6
-7
$\log_{10}(g^2_{ap(n)}/4\pi)$
C-P
AFM
MMO
Cavendish-type
-5
-4
-3
-2
-1
0
$\log_{10}[m_a\,(\mathrm{eV})]$

6. CONSTRAINTS FROM MEASUREMENTS OF THE NORMAL CASIMIR FORCE BETWEEN SINUSOIDALLY CORRUGATED SURFACES



$$\Lambda = 570.5\,\mu\text{m}$$

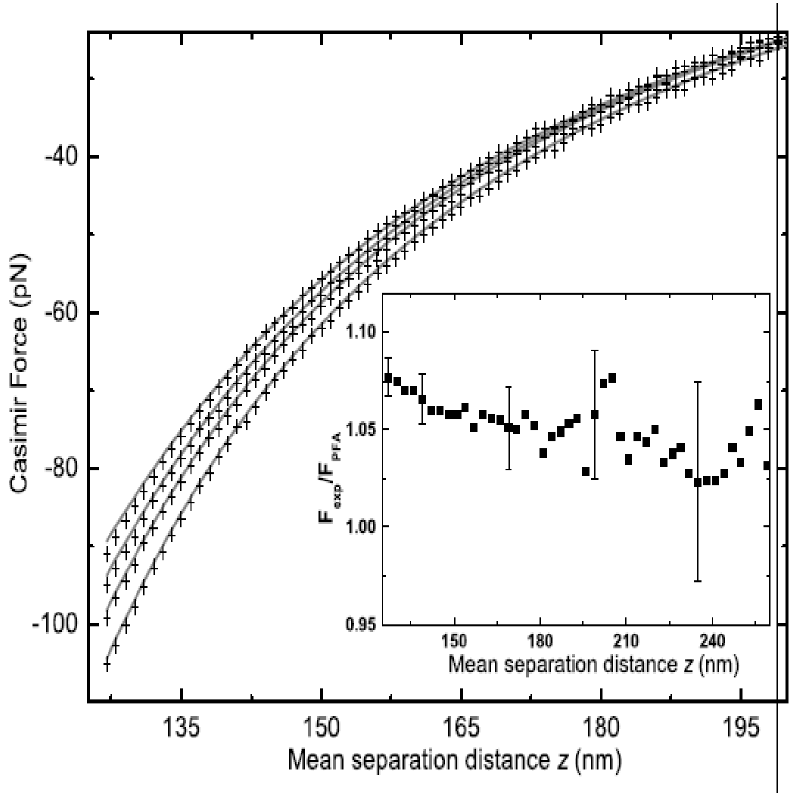
$$A_1 = 40.2\,\text{nm}$$

$$A_2 = 14.6\,\text{nm}$$

$$R = 99.6\,\mu\text{m}$$

Banishev, Wagner, Emig, Zandi, Mohideen, PRL (2013), PRB (2014).

Comparison with exact scattering theory:



$$
F_{\rm corr}^{(s,p)}(a) = -\frac{\pi R C_{\rm Au}}{2m_a m^2 m_{\rm H}^2} \int_1^\infty du \frac{\sqrt{u^2-1}}{u^3} e^{-2m_a u a}
$$

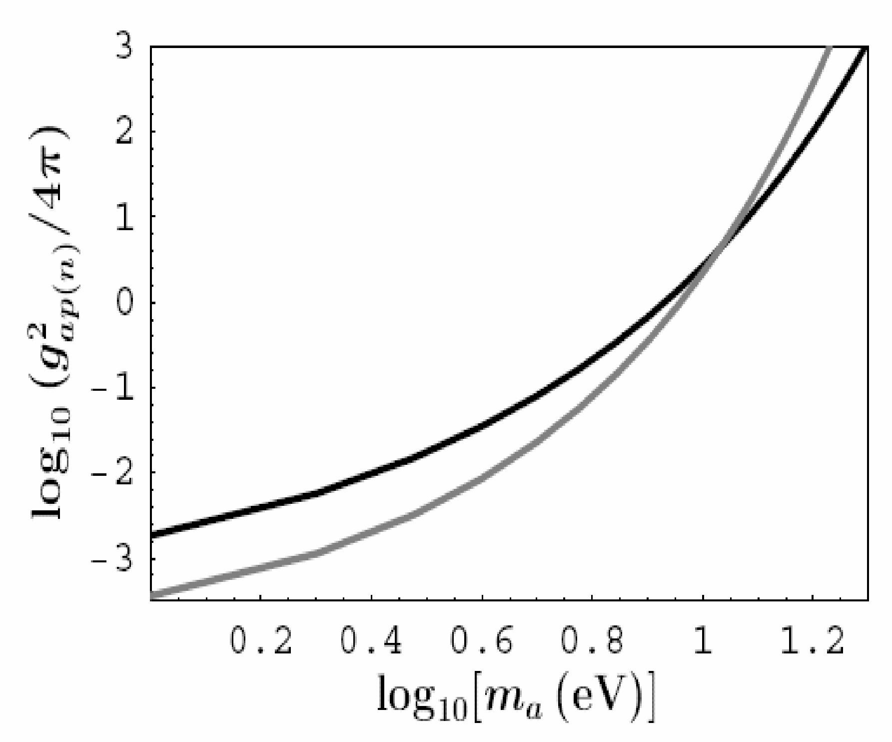
$$
\times I_0\left(2m_a u(A_1 - A_2)\right)\left(1 - e^{-2m_a u \Delta_{\rm Au}^{(1)}}\right)
$$

$$
\times \left[C_{\rm Au} + (C_{\rm Al} - C_{\rm Au}) e^{-2m_a u \Delta_{\rm Au}^{(2)}}\right.
$$

$$
+ (C_{\rm Cr} - C_{\rm Al}) e^{-2m_a u (\Delta_{\rm Au}^{(2)} + \Delta_{\rm Al}^{(2)})}
$$

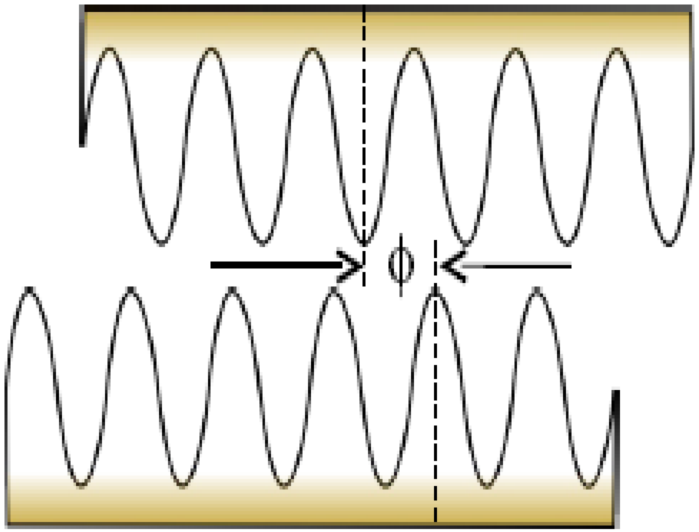
$$
\left. - C_{\rm Cr} e^{-2m_a u (\Delta_{\rm Au}^{(2)} + \Delta_{\rm Al}^{(2)} + \Delta_{\rm Cr}^{(2)})}\right]
$$

Constraints on coupling constants of axion-nucleon interactions from measurements of the normal Casimir force between corrugated Au-coated surfaces of a sphere and a plate



Bezerra, Klimchitskaya, Mostepanenko, Romero, Phys. Rev. D (2014).

7. CONSTRAINTS FROM MEASUREMENTS OF THE LATERAL CASIMIR FORCE BETWEEN CORRUGATED SURFACES

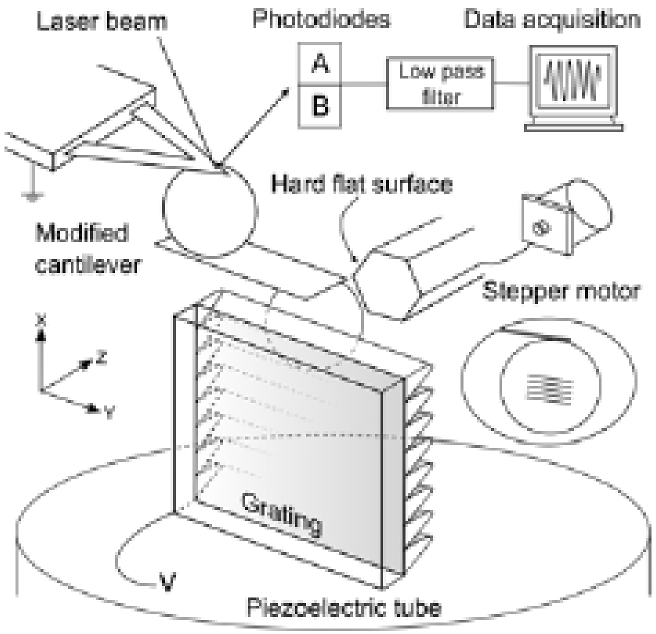


$$F_{\rm lat}(a,T,\Phi) = -\frac{\partial \mathcal{F}(a,T,\Phi)}{\partial \Phi}$$

Golestanian, Kardar, PRL (1997);
Chen, Mohideen, Klimchitskaya, Mostepanenko, PRL (2002), PRA (2002);

Chiu, Klimchitskaya, Marachevsky, Mostepanenko, Mohideen,
PRB (2009), PRB (2010).

Experimental setup with sinusoidally corrugated Au-coated surfaces of a sphere and a plate :



$$\Lambda = 574.4\,\mu\text{m}$$

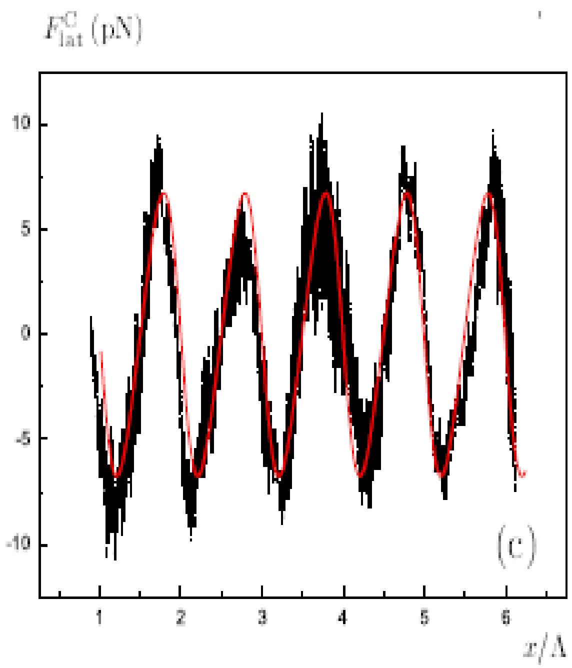
$$A_1 = 85.4\,\text{nm}$$

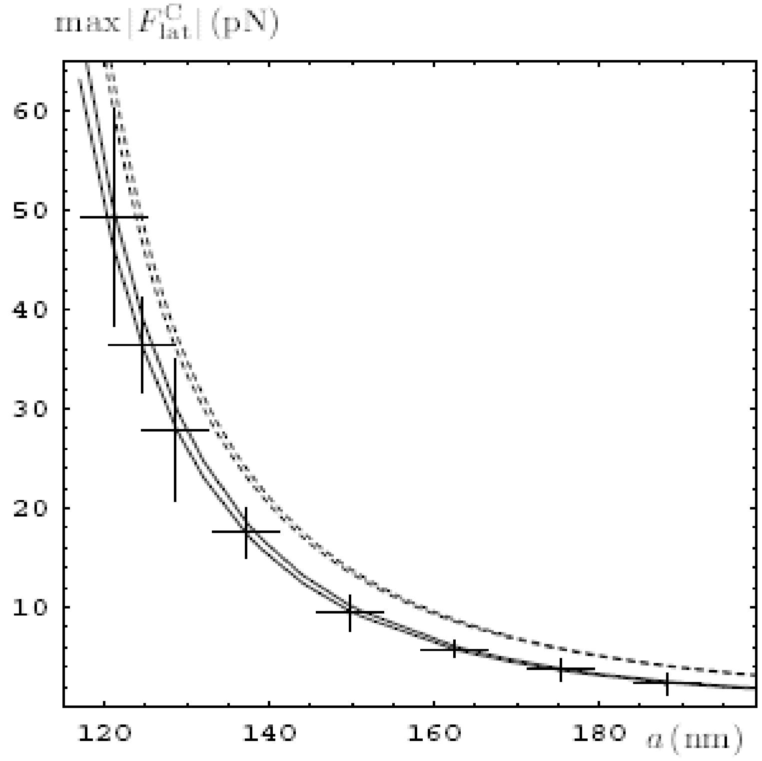
$$A_2 = 13.7\,\text{nm}$$

$$R = 97.0\,\mu\text{m}$$

Chiu, Klimchitskaya, Marachevsky, Mostepanenko, Mohideen, PRB 2009, PRB 2010.

Comparison between theory and experiment:





Chiu, Klimchitskaya, Marachevsky, Mostepanenko, Mohideen, PRB (2009), PRB (2010).

Lateral force in the experimental configuration

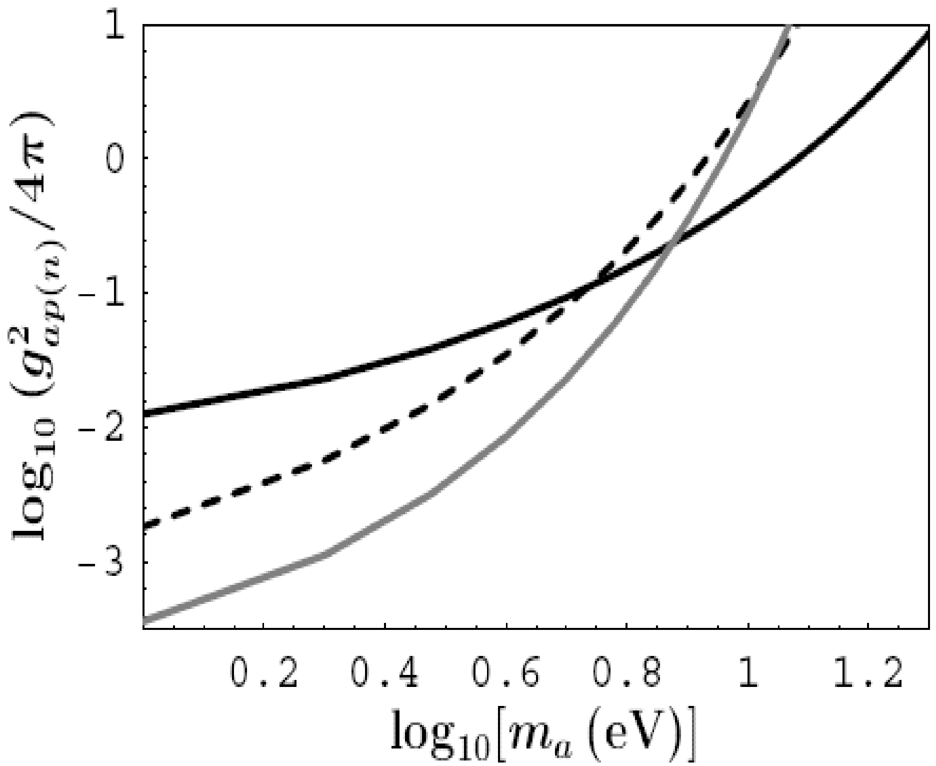
$$\max|F^{(s,p)}_{\text{corr, lat}}(a)| == \frac{\pi^2 R C_{\text{Au}}}{m_a m^2 m_{\text{H}}^2} \frac{A_1 A_2}{\Lambda\sqrt{A_1^2 + A_2^2}}$$

$$\times \int_1^\infty du \frac{\sqrt{u^2-1}}{u^3} e^{-2m_a ua} I_1\left(2m_a u\sqrt{A_1^2+A_2^2}\right)$$

$$\times\left(1 - e^{-2m_a u\Delta_{\text{Au}}^{(1)}}\right)\left[C_{\text{Au}} + (C_{\text{Cr}} - C_{\text{Au}})\right.$$

$$\left.\times e^{-2m_a u\Delta_{\text{Au}}^{(2)}} - C_{\text{Cr}} e^{-2m_a u(\Delta_{\text{Au}}^{(2)}+\Delta_{\text{Cr}}^{(2)})}\right]$$

Constraints on coupling constants of axion-nucleon interactions from measurements of the lateral Casimir force:



Bezerra, Klimchitskaya, Mostepanenko, Romero, PRD (2014).

7. CONCLUSIONS

1. Experiments on measuring the Casimir-Polder and Casimir interactions allow obtaining the model-independent constraints on the coupling constants of axions to nucleons.

2. The most strong constraints of this kind follow from measurements of the Casimir pressure by means of micromachined oscillator.

3. The obtained constraints cover the region of axion masses from 0.04meV to 15eV which partially overlaps with an axion window extending from 0.01meV to 10meV.

4. Further constraining of an axion from measurements of the Casimir interaction is expected in near future.