Can Surface Plasmons tune the Casimir Forces between Metamaterials?

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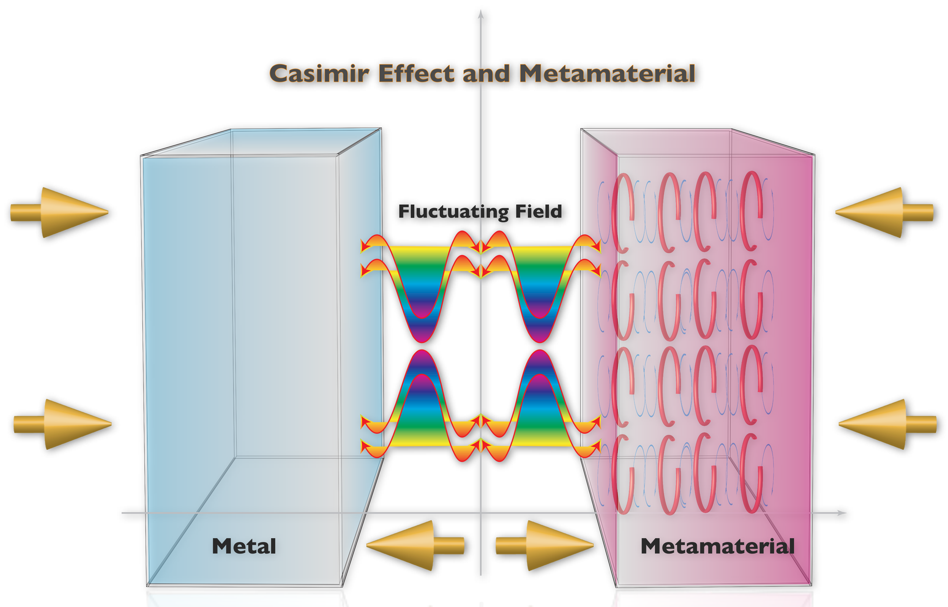
Summary. The Casimir force is significantly modified for mirrors made from metamaterials. It becomes much smaller in magnitude and may reverse its sign. This would certainly be important to prevent sticking phenomena of mobile elements in micro-electro-mechanical systems. We link this behavior to the surface plasmon-polariton modes which are showed to play a fundamental role in the system. This selects them as a possible candidate to further tune the strength and the sign of Casimir force.

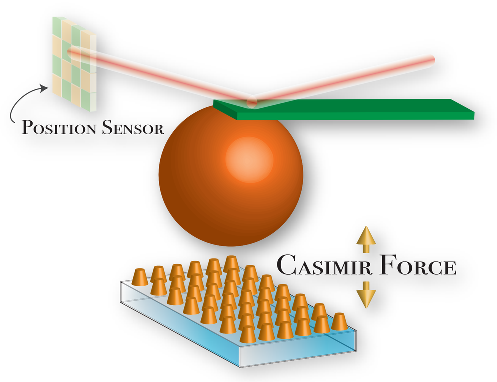
The Casimir effect and Metamaterials



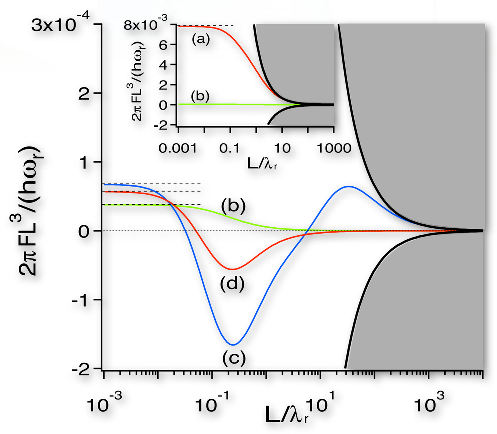
The Casimir effect is the archetype of macroscopic effects of vacuum fluctuations. It was discovered in 1948 by Hendrik Casimir. He calculated the force at zero temperature between two plane parallel mirrors placed at a distance L [1].

$$\frac{F}{A} = -\frac{\pi^2}{240}\frac{\hbar c}{L^4} = -\frac{0.13}{(L/\mu\mathrm{m})^4}\frac{\mu\mathrm{N}}{\mathrm{cm}^2}$$

Previous work has shown that this force can be significantly tuned and even made to reverse its sign, using bulk or layered metamaterials [2–9]: repulsion is achieved in a ***mixed configuration***, that is when only one of the plates is made by a metamaterial [3].



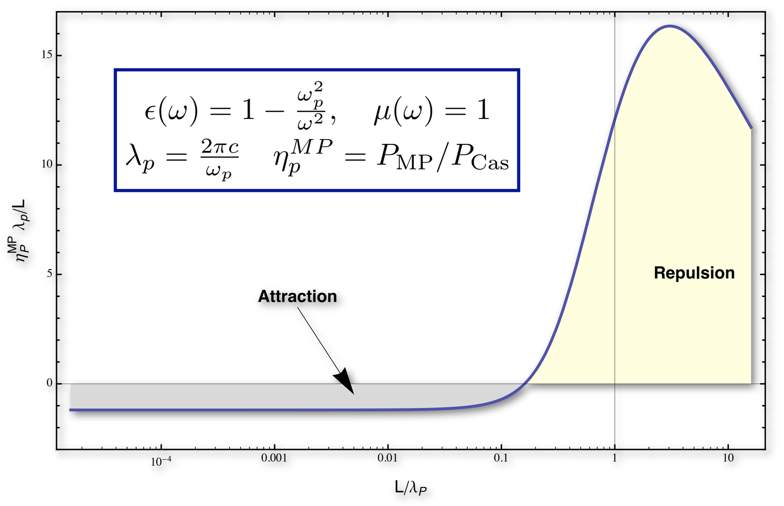
A schematic configuration in which a nanostructured surface could lead to a repulsive Casimir force (here measured with an atomic force microscope)



Casimir force between planar mirrors of different dispersive materials at zero temperature (from [2]).

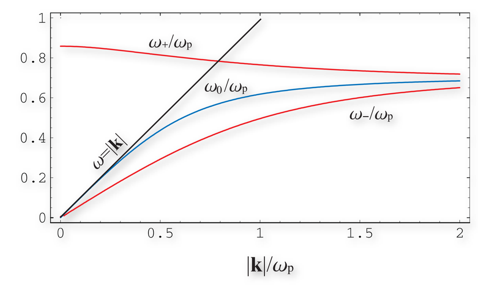
This prediction is currently an experimental challenge because metamaterials with high-frequency resonances are needed, i.e. with small-scale building blocks (size << L).

Casimir Effect and Metallic Plasmons

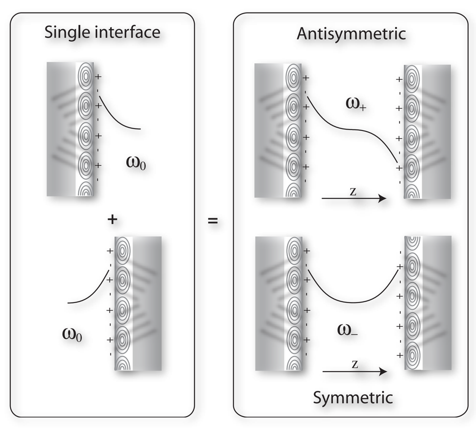


It has been shown that, for two parallel metallic mirrors, surface plasmons gives rise, to a ***repulsive*** contribution to the Casimir force [4,5].

The total force is always attractive but this result heavily relies on the planar symmetry and one might hope to affect the sign of the Casimir force by enhance the plasmonic repulsive contribution, e.g., by using nanostructured metallic surfaces.



Plasmonic mode dispersion relations for the two-metallic-mirror configuration [4,5].



Coupled plasmonic modes [4,5].

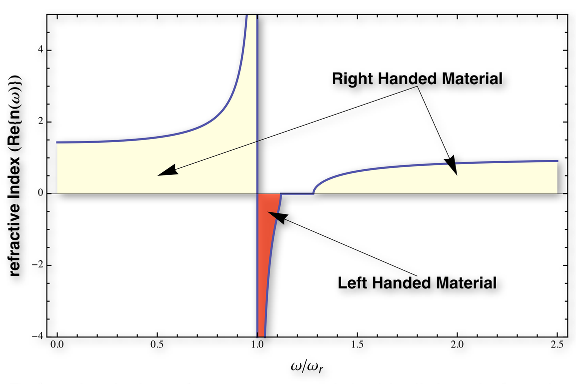
Effective medisum and mixed configuration

$$\epsilon(\omega) = 1 - \frac{\omega_\epsilon^2}{\omega^2 - \omega_r^2} \text{ and } \mu(\omega) = 1 - \frac{\omega_\mu^2}{\omega^2 - \omega_r^2}$$

Contrary to natural ones, metamaterials are made of micro- or mesoscopic metallic structures that confer them a strong magnetic response.

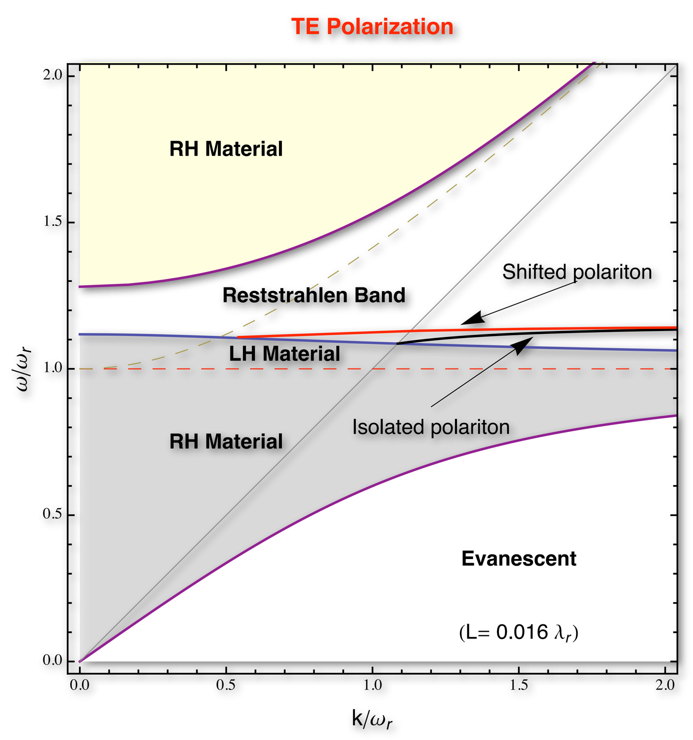
An **effective medium approach** is used**:** both the dielectric function and the magnetic permeability of the metamateral depend on the frequency. The **Drude-Lorentz** functional is taken, allowing therefore for resonance frequencies (here supposed overlapping for simplicity).

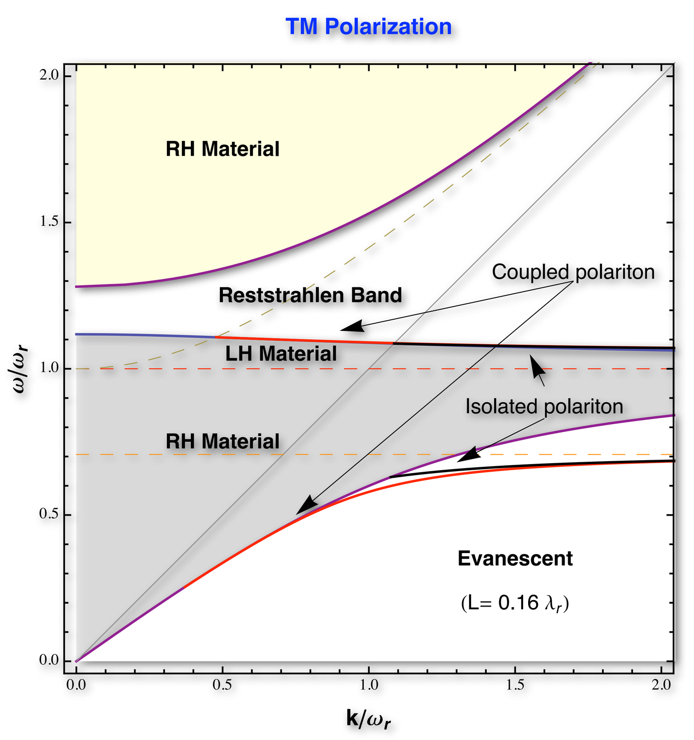
We investigate here the plasmon-polariton contribution to the zero temperature Casimir effect in a mixed configuration (metallic plate + metamaterial plate). This exotic configuration gives rise to a richer zoology of polaritonic modes, which has no equivalent in configuration involving metallic plates.



Refractive index of a metamateraial with dielectric function and magnetic permeability given by the Drude-Lorentz model.

Suface Polariton dispersion relations



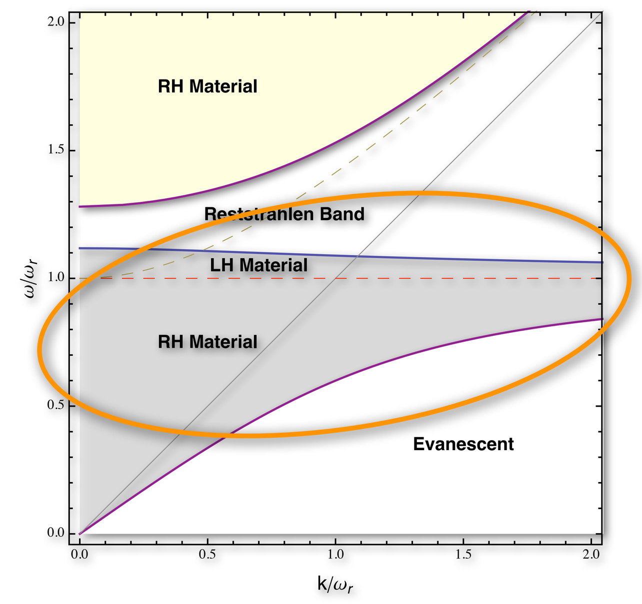


The TE polarization shows a mode in the evanescent region. This modes has analogies with the the antibinding mode in the two-metallic-mirror configuration. It crosses the light cone to take values in the propagating region.

Both the coupled and the corresponding isolated plasmon-polariton modes stop at the frontier of the ***metamaterial continuum***.

With full analogy with the two-metallic-mirror configuration the TM polarization shows two plasmon-polariton modes, one living in the evanescent region, the other crossing the light cone to take values in the propagating region. The limit for the existence of these modes are set by the ***metamaterial continuum***.

Metamaterial Continuum



This is a characteristic structure of this configuration. It corresponds to a mode continuum bounded from the dispersion relations obtained solving the equation:

$$\frac{\omega^2}{c^2}\epsilon(\omega)\mu(\omega) - k^2 = 0$$

The modes in this continuum propagate in the metamaterial (behaving like a left or right handed material) but the can be either evanescent or propagating in the vacuum between the two mirrors.

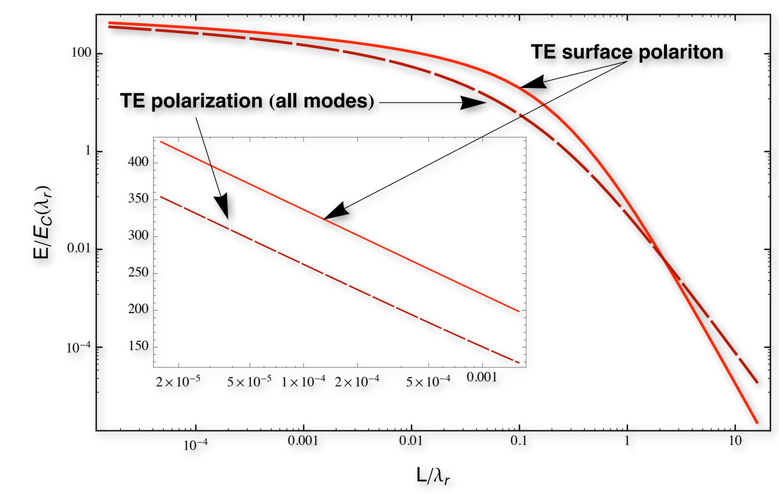
Mode "Anatomy" of the Casimir Effect

The Casimir energy for the configuration including a metamaterial mirror can be decomposed in different contributions. Here we present them normalized with respect to :

$$E_{\mathrm{Cas}}(\lambda_r) = \frac{\hbar c \pi^2}{720}\frac{A}{\lambda_r^3}, \qquad \lambda_r = \frac{2\pi\omega_r}{c} \quad \text{(resonance wavelength)}$$

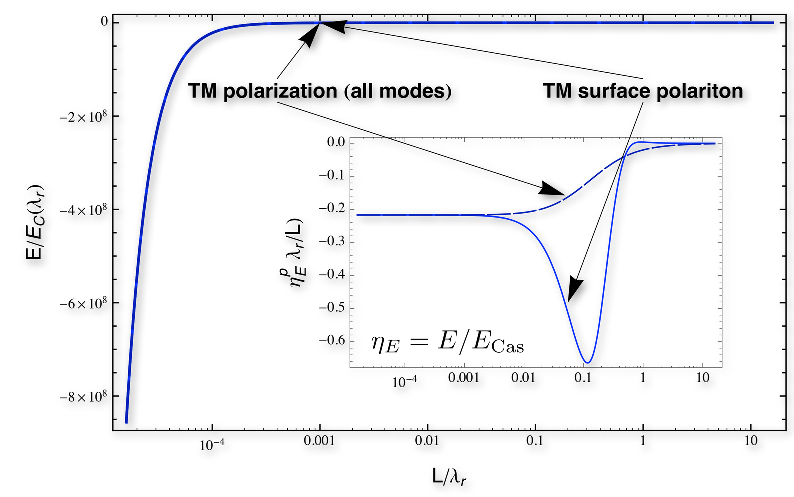
The ***TE surface polariton mode*** is antibinding and leads to a repulsive force. At short distance it is responsible of the main contribution to the TE part of the total energy although the contribution of the other modes (bulk, propagating) cannot be neglected.

$$E \propto -\log[L/\lambda_r], \text{ for } L/\lambda_r \ll 1$$

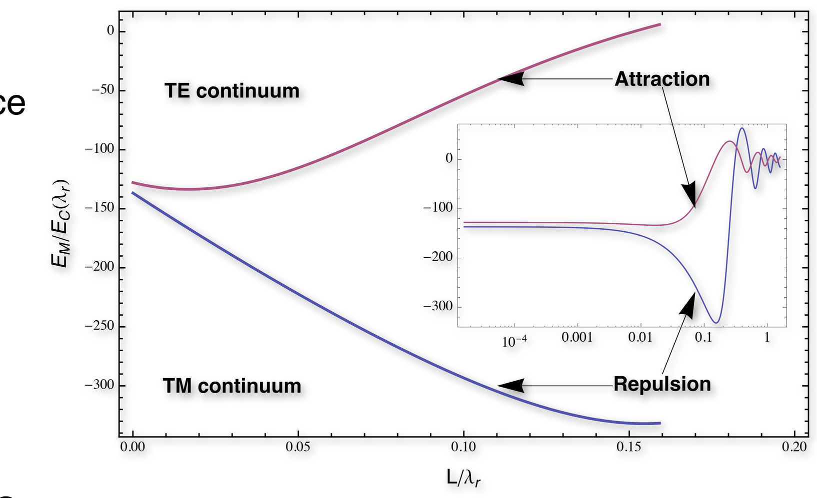


The ***TM surface polaritons*** dominate all other TM polarized modes. A small repulsion occurs for distance of the order of the resonance wavelength. At short distance they give rise to an attractive force.

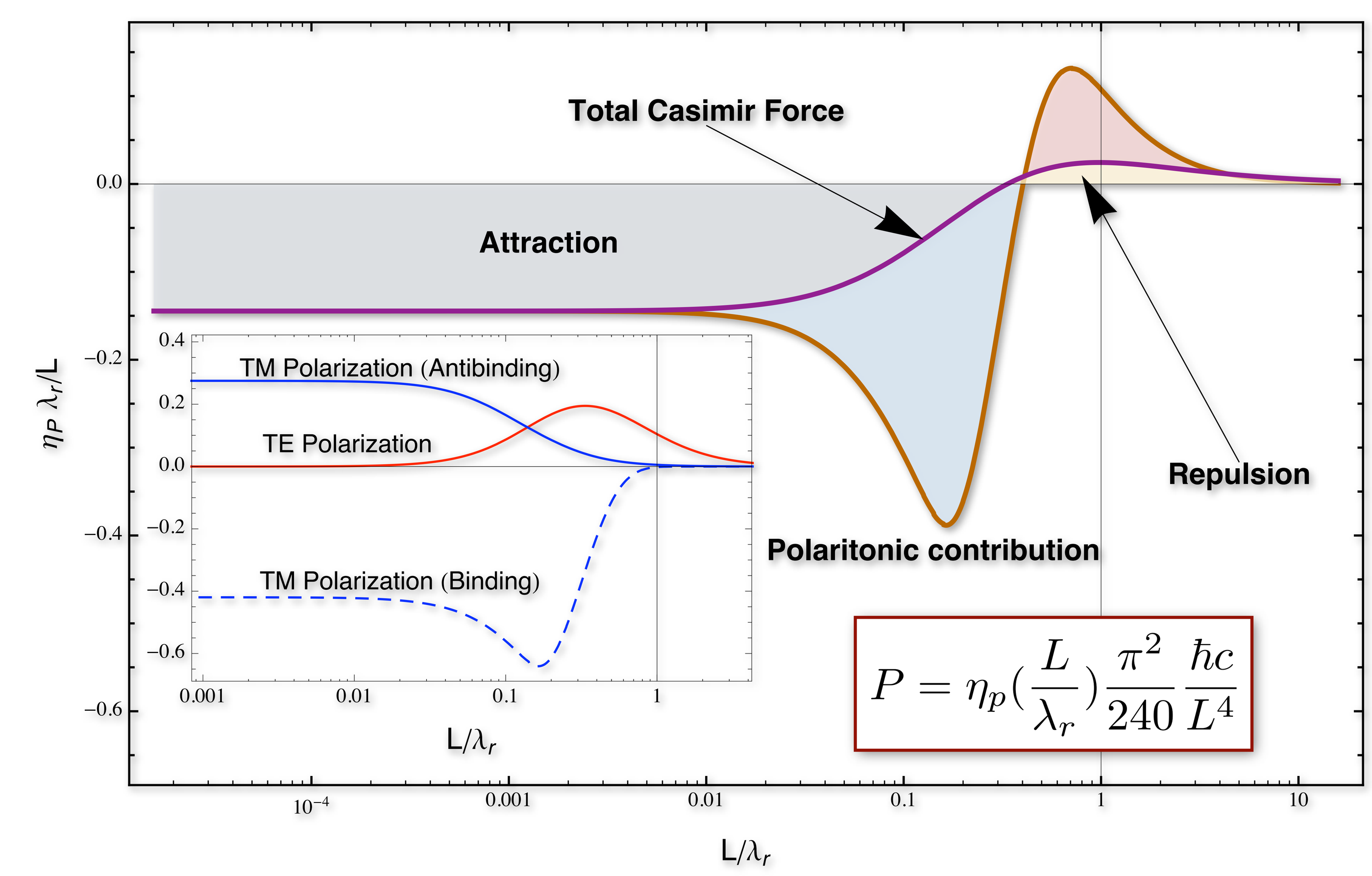
$$E \propto -\hbar\omega_r/L^2, \text{ for } L/\lambda_r \ll 1$$



The ***metamaterial continuum*** gives rise at short distance to an attractive or repulsive force depending on the polarization. It oscillates for distance of the order of the resonance wavelength (standing waves).



The Polaritonic contribution



Our calculations show that the polaritonic contribution is responsible for the change in sign of the Casimir force between a metallic and a metamaterial mirror.
For L ≳ λ_r/5 the binding TM polariton, which dominates at short distance, is overwhelmed by the joint repulsion due to the antibinding TM and TE polaritons.

This shows that, also for a mixed configuration, surface plasmons are crucial in determining not only the strength and the sign of the Casimir interaction. An ***"engineered" polaritonic contribution*** could further tune the strength and the sign of Casimir force (corrugation/supercell).

References

[1] H. Casimir, Proc. kon. Ned. Ak. Wet (1948) 51
[2] T. H. Boyer, Phys. Rev. A **9** (1974) 2078; O. Kenneth, I. Klich, A. Mann, and M. Revzen, Phys. Rev. Lett. **89** (2002) 033001
[3] C. Henkel and K. Joulain, Europhys. Lett. **72** (2005) 929
[4] F. Intravaia, C. Henkel and A. Lambrecht, Phys. Rev. A **76** (2007) 033820
[5] C. Henkel, K. Joulain, J.-P. Mulet, and J.-J. Greffet, Phys. Rev. A **69** (2004) 023808
[6] F. Intravaia and A. Lambrecht, Phys. Rev. Lett. **94** (2005) 110404
[7] U. Leonhardt and T. G. Philbin, New J. Phys. **9** (2007) 254
[8] A. Lambrecht and I. G. Pirozhenko, Phys. Rev. A **78** (2008) 062102
[9] F. S. S. Rosa, D. A. R. Dalvit and P. W. Milonni, Phys. Rev. Lett. **100** (2008) 183602
[10] V. M. Mostepanenko et al, J. Phys. A **39** (2006) 6589-66009

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