The Casimir effect : theories and experiments

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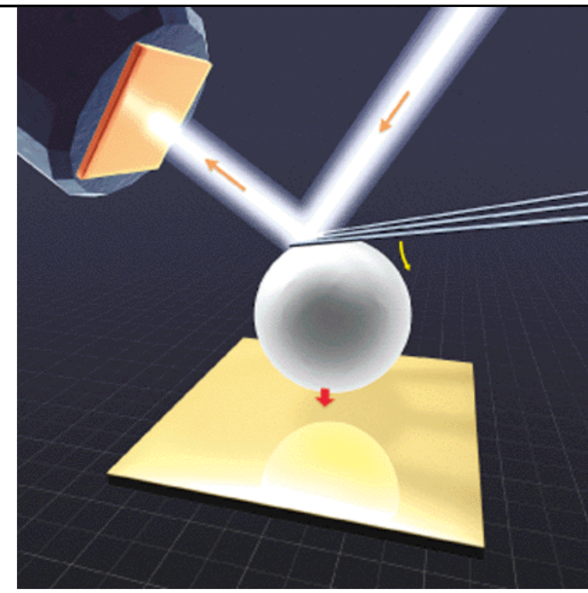
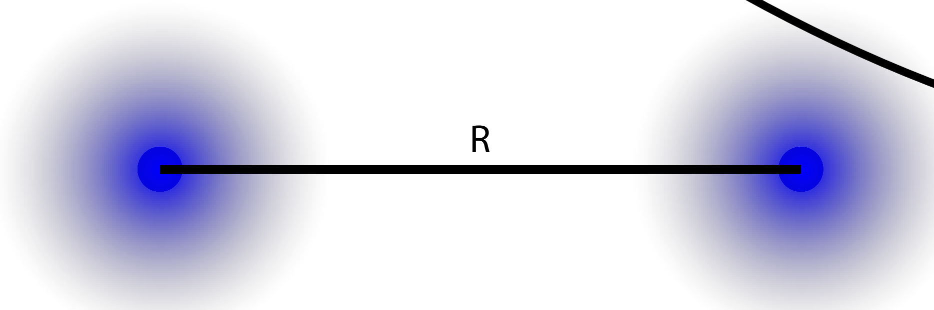
Outline

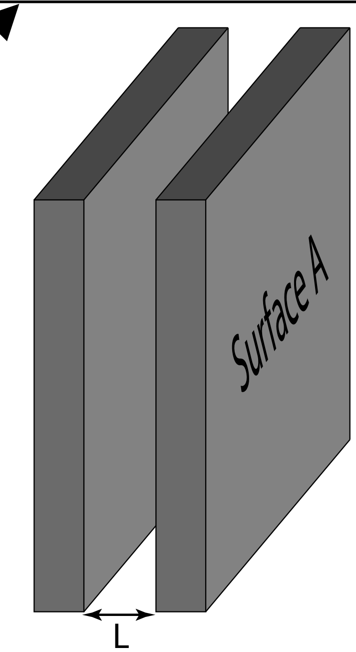
Typical experiment:
what is measured



Theory:
From vdW…
(microscopic, non–retarded)



Theory:
… to Casimir
(macroscopic, retarded)

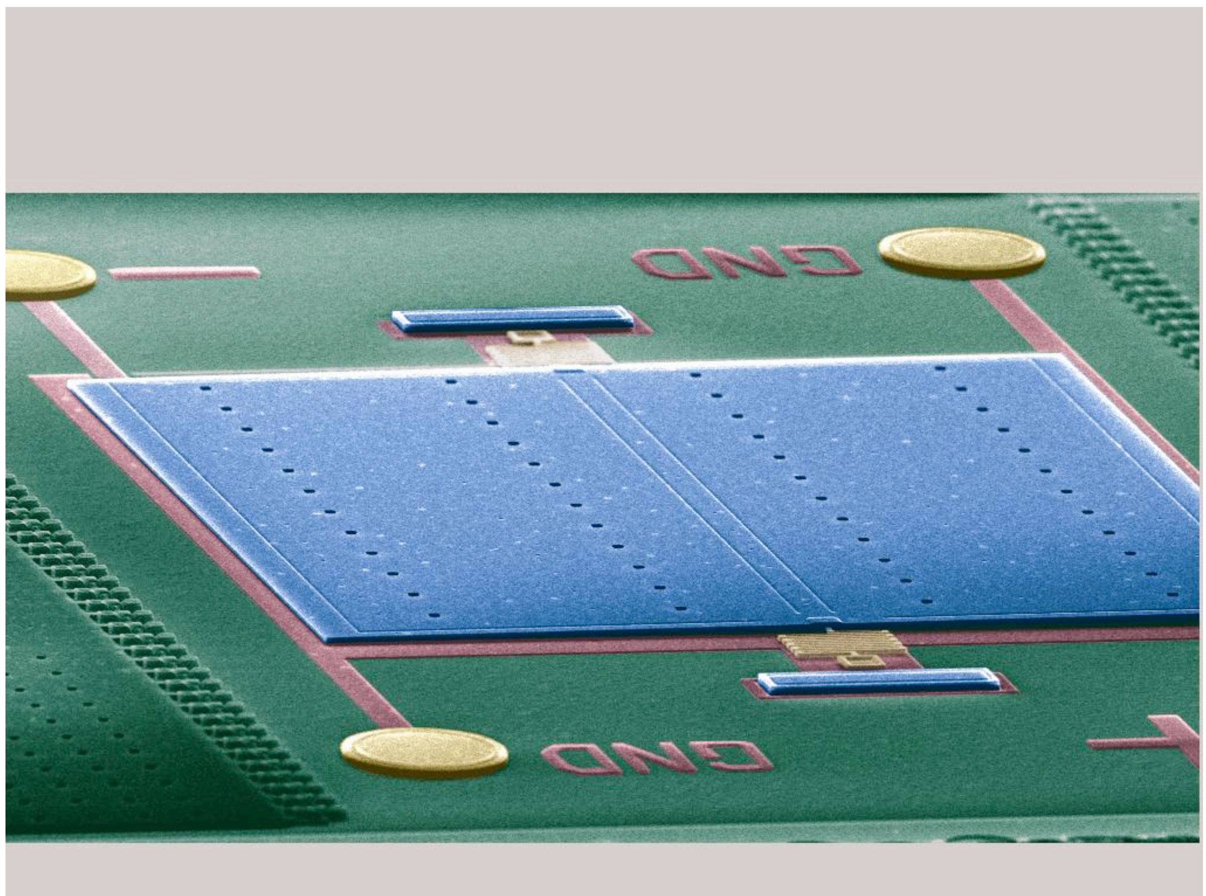


A typical experiment and what is measured

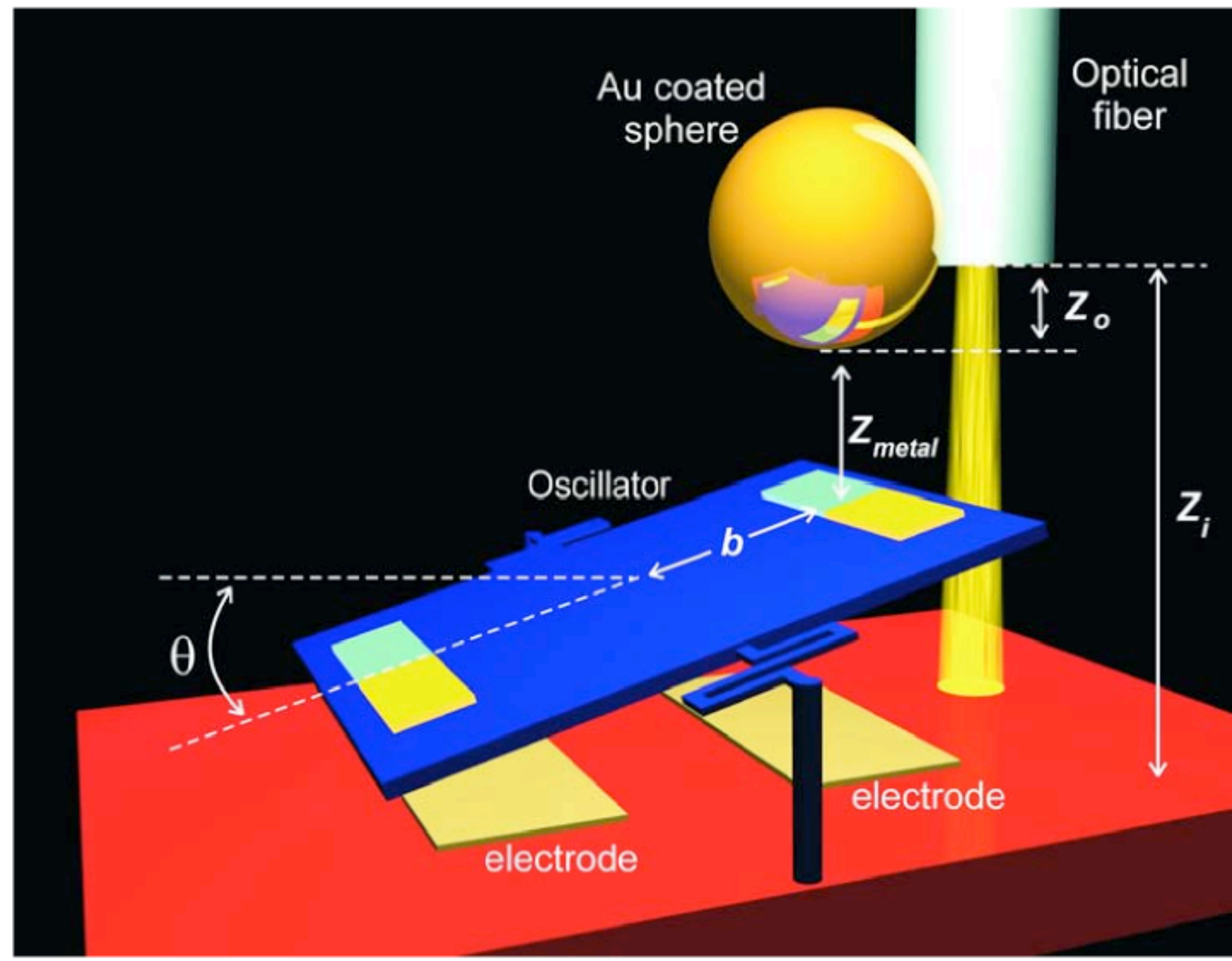
Casimir experiments

Most precise Casimir experiments:

dynamic measurements of the resonance frequency of a microelectromechanical torsional oscillator (MTO)



Courtesy R.S. Decca
(Indiana U – Purdue U Indianapolis)

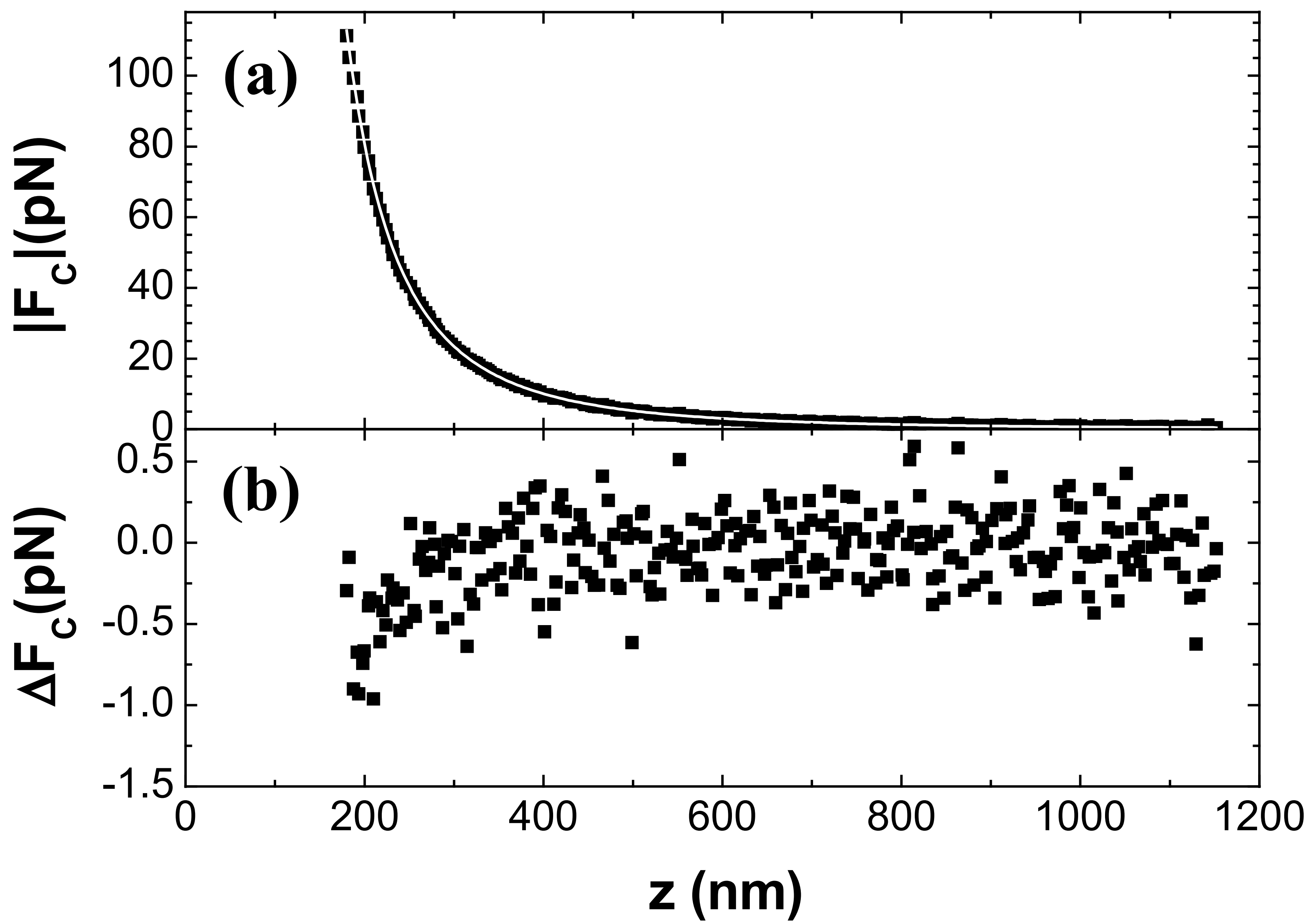


Silicon MTO : 3.5 µm thick, 500 x 500 µm^2

Gold coated sphere : 300 µm radius

Casimir experiments

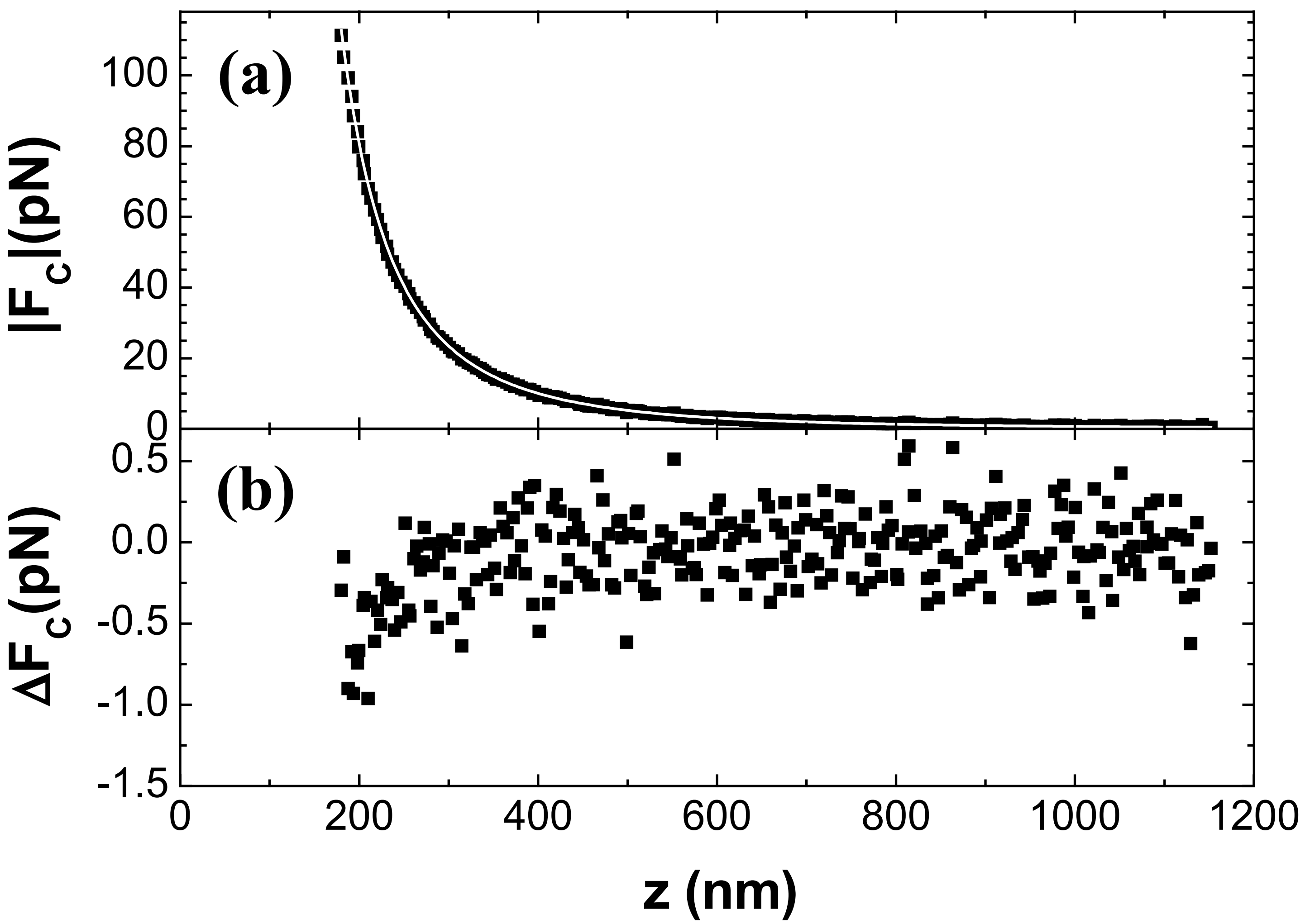
- MTO excited to its resonance frequency
- Measure of the change of this frequency as the gold sphere approach the MTO



- Ambient temperature
- 10^{-4} Torr

See: R. S. Decca *et al*, PRL **91**, 050402 (2003)

Casimir experiments



Undoubtedly, there IS a force between the silicon MTO and the gold sphere…

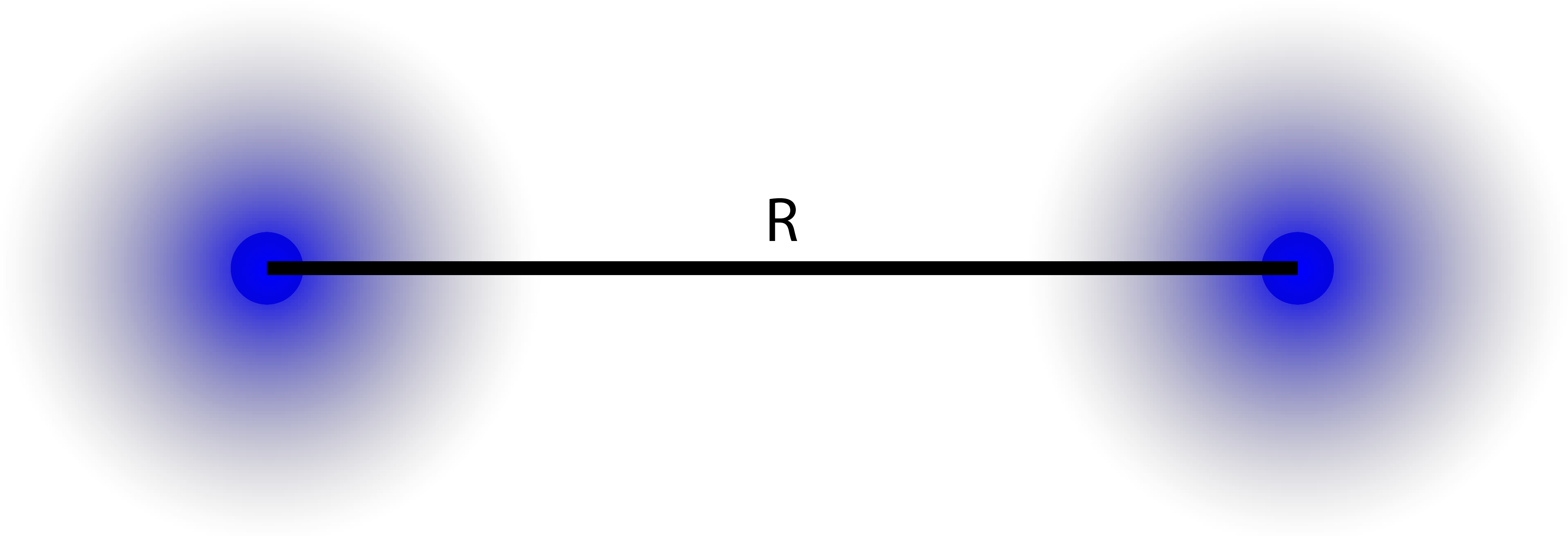
… even though, those two objects are separated by, well, nothing.

Physical origin of the Casimir force

Physical origin of the Casimir force

One of the interpretation : van der Waals interactions

Long–range interactions between two neutral atoms

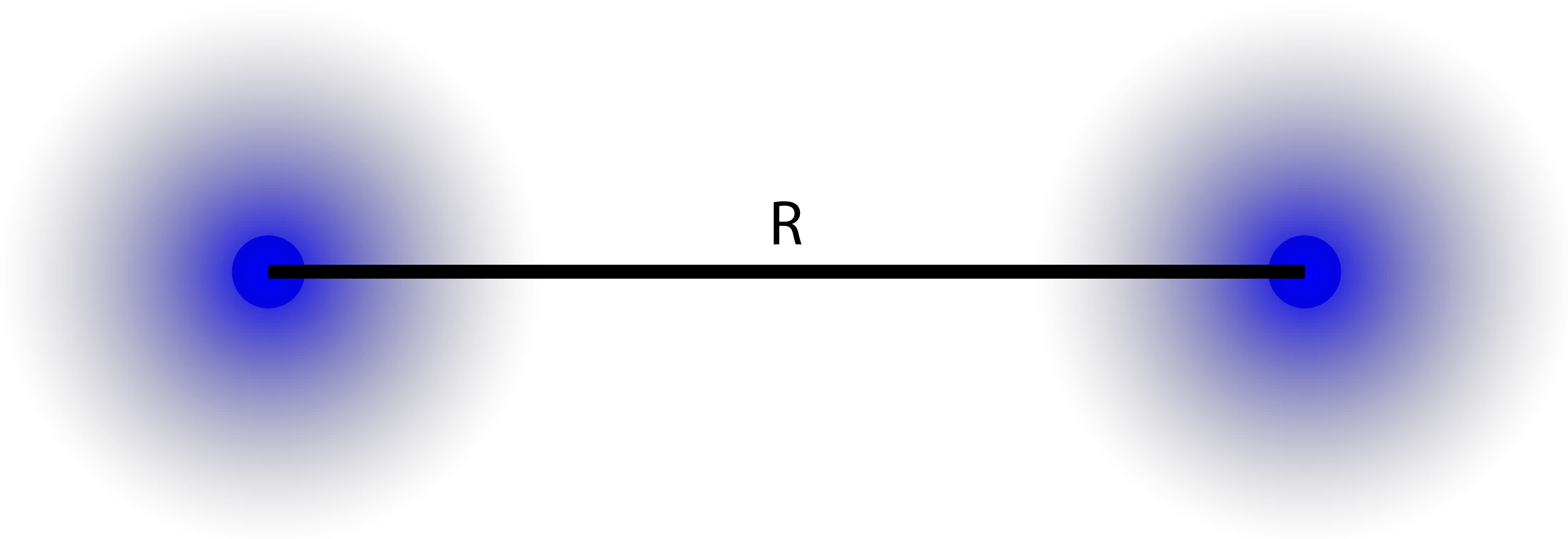


van der Waals interactions

Distance between the atoms: well beyond the “chemical” range (≈ 1nm)

Each atom has a fluctuating dipole moment

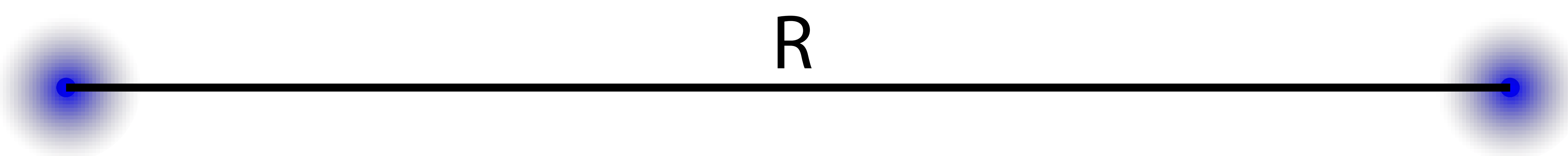
Results in an attractive force in $-1/R^7$



Retarded van der Waals interactions

Distance between the atoms: well beyond a “typical” wavelength for each atom (≈ 200 nm)

Retardation effects result in an attractive force in $-1/R^8$

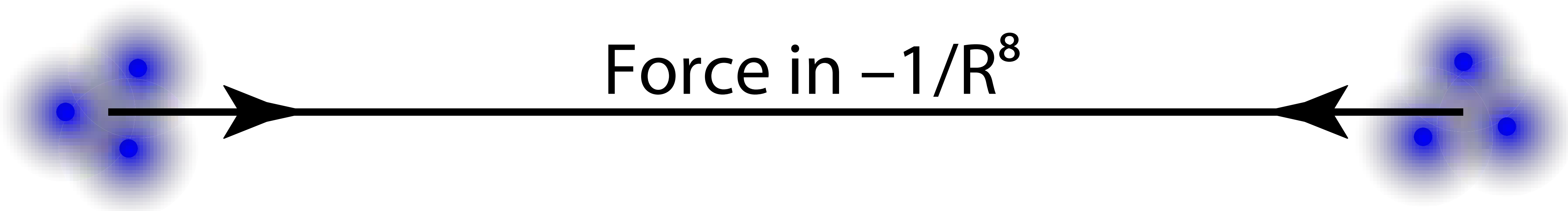


van der Waals interactions

Two neutral atoms attract each other in vacuum!

What about two molecules?

van der Waals interactions



Two neutral molecules attract each other in vacuum!

Leap of faith : What about two macroscopic objects?

From microscopic to macroscopic…

SOVIET PHYSICS

USPEKHI

A Translation of Uspekhi Fizicheskikh Nauk

SOVIET PHYSICS USPEKHI (Russian Vol. 73, Nos. 3-4 SEPTEMBER-OCTOBER 1961

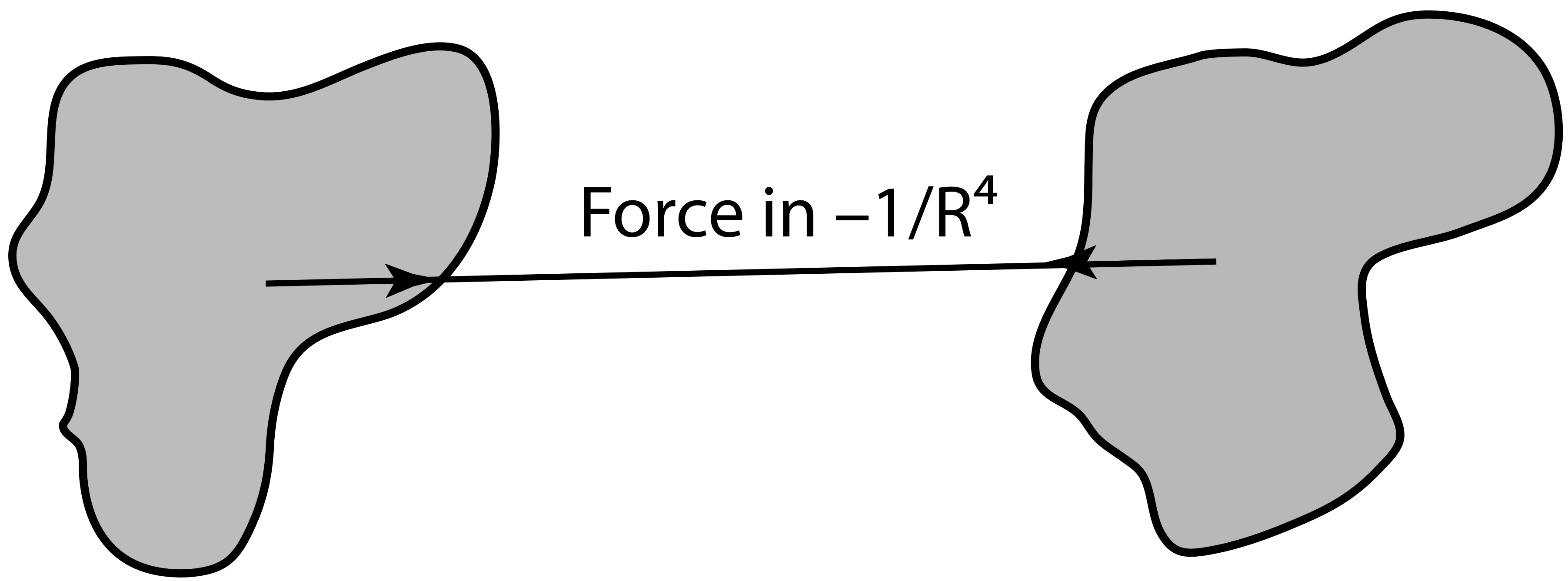
GENERAL THEORY OF VAN DER WAALS' FORCES

I. E. DZYALOSHINSKII, E. M. LIFSHITZ, and L. P. PITAEVSKII

Usp. Fiz. Nauk **73**, 381-422 (March, 1961)

TABLE OF CONTENTS

…from vdW to Casimir



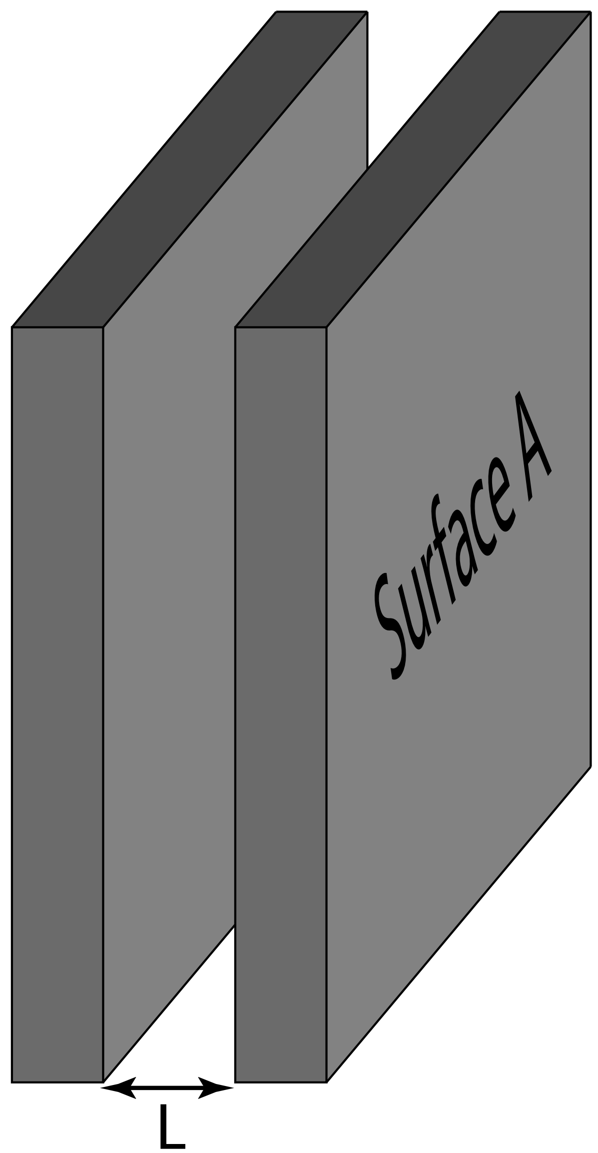
The Casimir force depends in the optical properties of the materials:

Microscopic		Macroscopic
Dynamic polarizability	→	Dielectric function

Casimir force: plate–plate geometry

In general, no analytical closed form (depends on ε(ω))

Historically, Casimir focused on two infinite, perfectly reflecting plates



$$\frac{F_{Cas}}{A} = \frac{\hbar c \pi^2}{240 L^4}$$

Casimir force: plate–plate geometry

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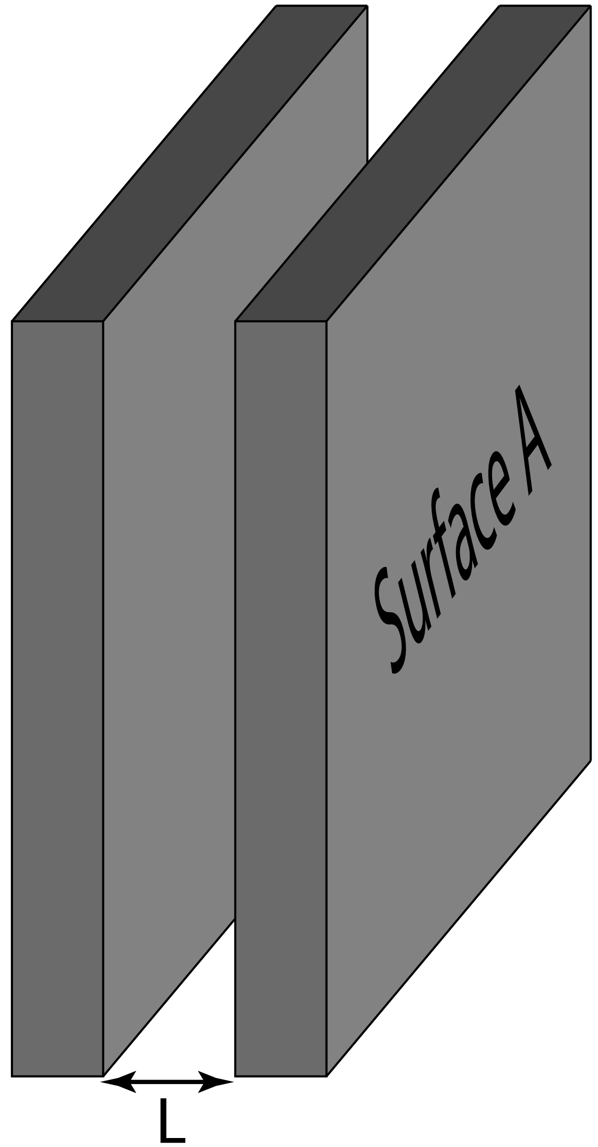


Quantum effect

Retardation effect

$$\frac{F_{Cas}}{A} = \frac{\hbar c \pi^2}{240 L^4}$$

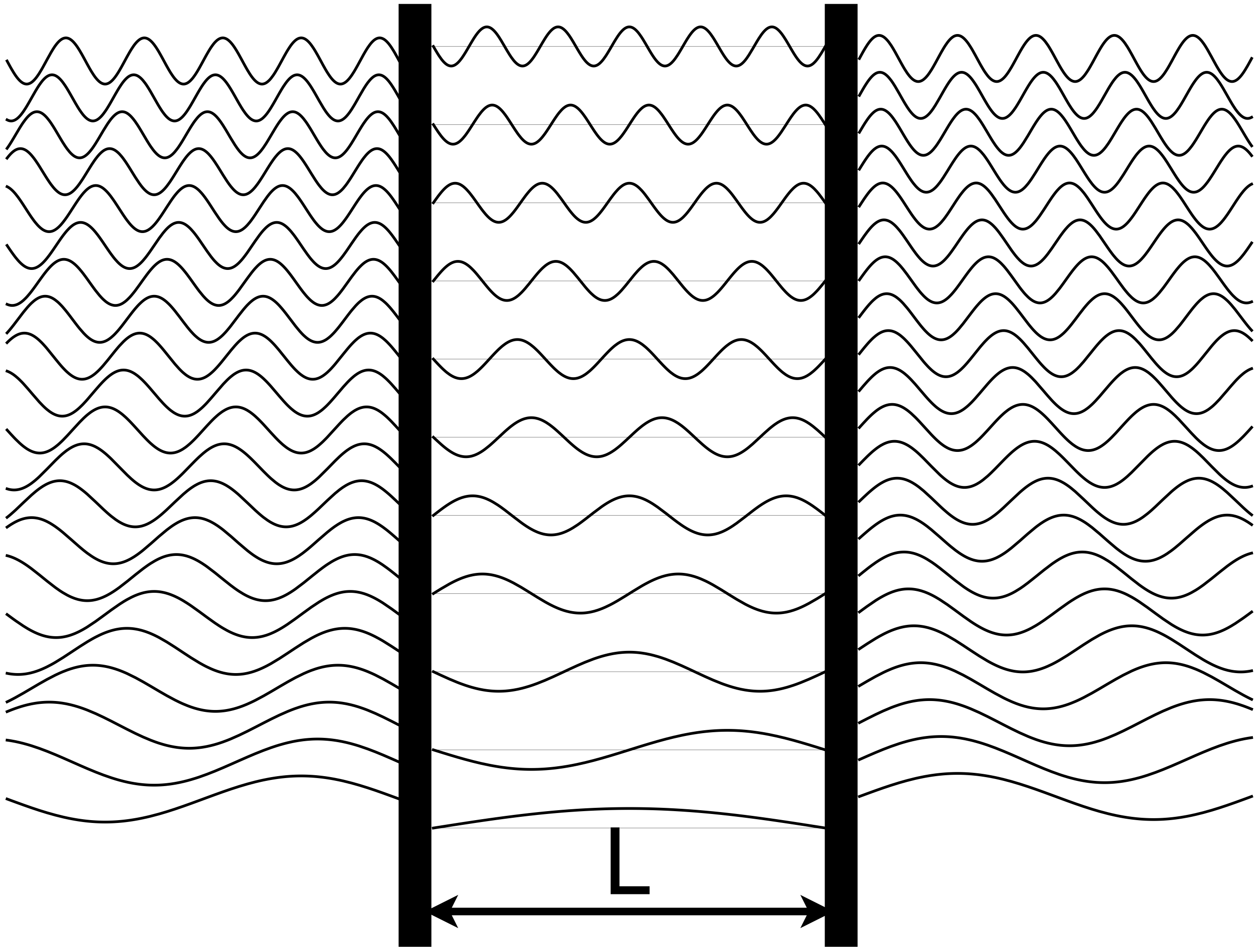
The many faces of the Casimir effect

Casimir's formulation

Mathematics. — *On the attraction between two perfectly conducting plates.* By H. B. G. CASIMIR.

(Communicated at the meeting of May 29, 1948.)

Modification of the zero point energy of the vacuum by the mere presence of the perfectly plates



The two mirrors form a cavity

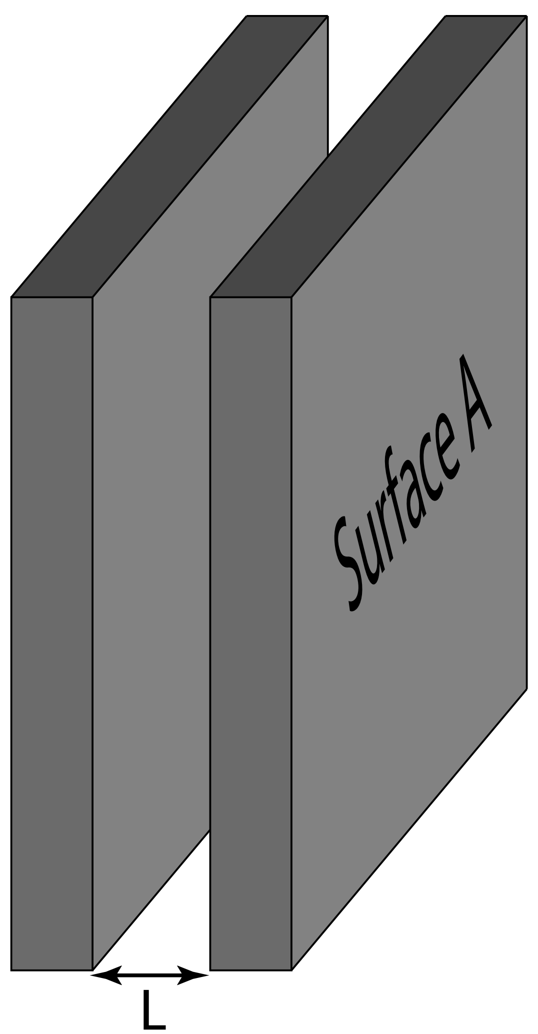
Outside: all EM modes are allowed

Inside: only certain EM modes are allowed

The many faces of the Casimir effect

Our formulation: scattering approach (S. Reynaud, A. Lambrecht,…)

The Casimir force caused by the radiation pressure of the virtual photons from the vacuum fluctuations



$$F_{Cas}(L) = \frac{\hbar A}{8\pi^3} \iint \mathrm{d}^2\boldsymbol{k}_\perp \int \mathrm{d}\xi \ \mathrm{Tr}[(\mathbf{1} - \boldsymbol{\mathcal{M}})^{-1}\partial_L \boldsymbol{\mathcal{M}}]$$

$$\boldsymbol{\mathcal{M}} = \mathbf{R_1}(\imath\xi)e^{-\boldsymbol{\kappa}L}\mathbf{R_2}(\imath\xi)e^{-\boldsymbol{\kappa}L}$$

Matrix M contains the reflexion operators of the two plates

What the theory can calculate

“real” materials: optical properties of the materials included in the dielectric function $\varepsilon(\omega)$ (from exp. data or modeled).

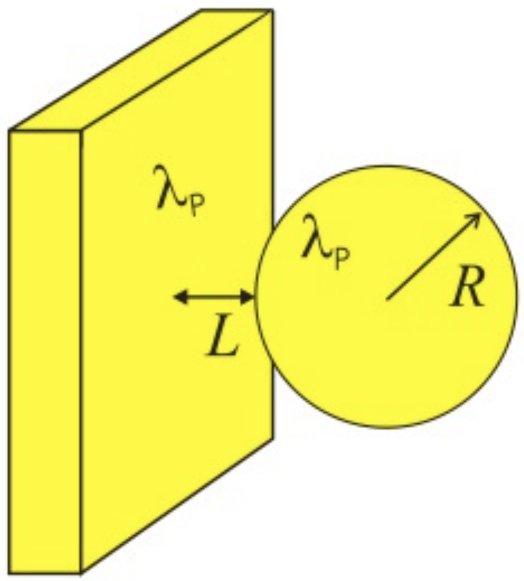
Temperature: ambient temperature in general enhance the Casimir force. Real thermal photons in addition of virtual ones.

Surface roughness: surfaces can have roughness with a rms of several nanometers. Can be taken into account for precise theory/exp. comparisons.

What the theory can calculate

Other geometries than plate–plate

Plane–sphere

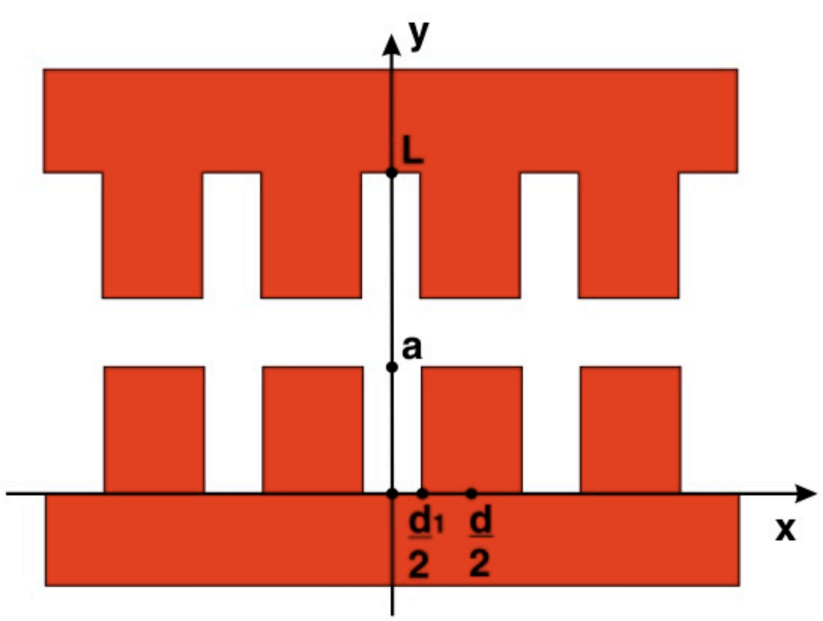


The geometry mostly used in experiments (no parallelism to control).

Can be calculated exactly.

See: A. Canaguier–Durand *et al*, PRL **104**, 040403 (2010)

Nanostructured surfaces (gratings)



Effect of the diffraction on the Casimir effect.

Can be calculated exactly.

See: A. Lambrecht *et al*, PRL **101**, 160403 (2008)

Casimir theory: overview

Casimir effect is

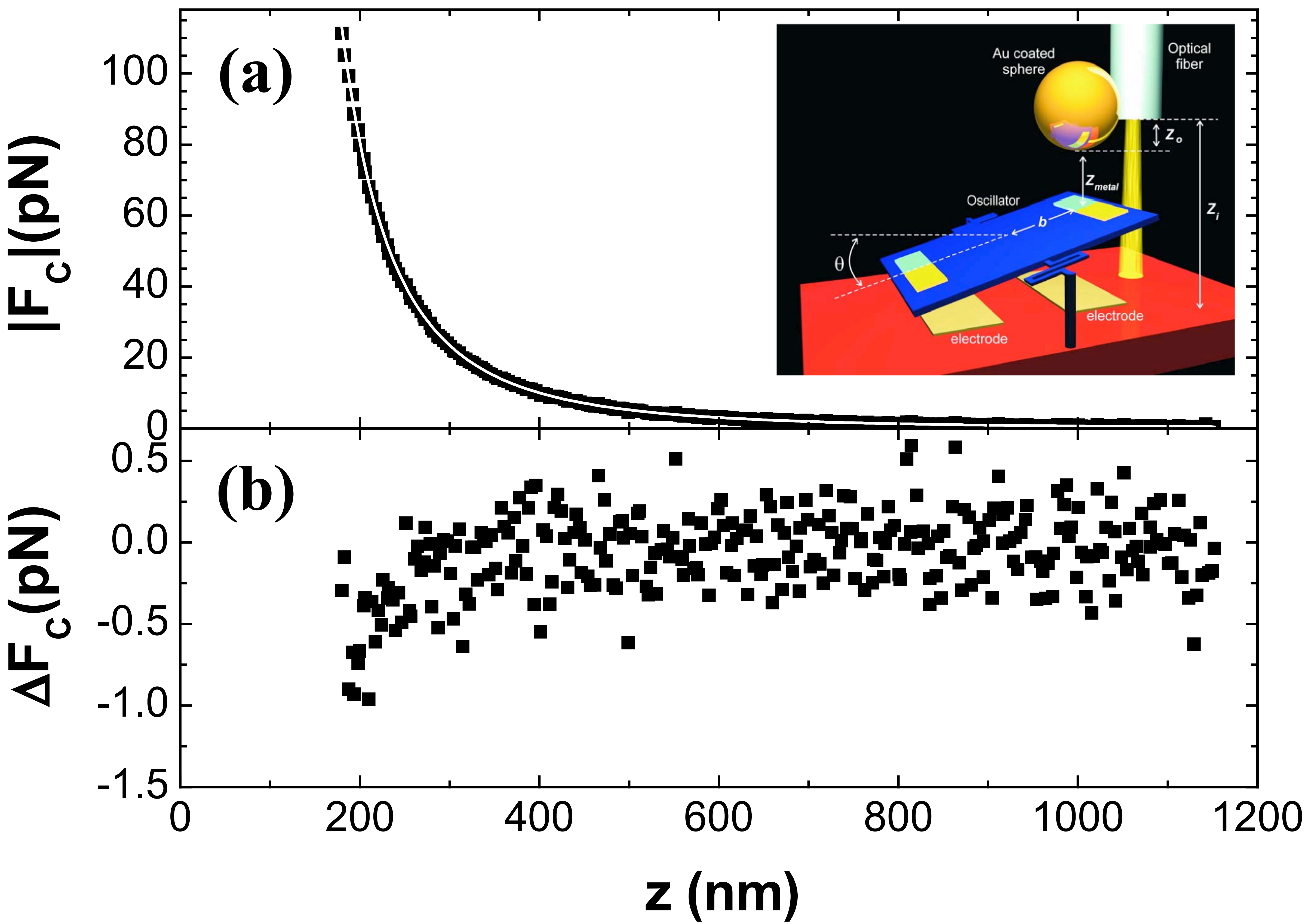
- "macroscopic" vdW interactions
- change in ZPE of EM vacuum
- radiation pressure from vacuum's virtual photons

The Casimir force can be calculated taking into account realistic conditions:

- Optical properties of the materials
- Temperature
- Surface roughness
- …

So, does it works ?!

Comparisons theory/experiments



Comparisons theory/experiments

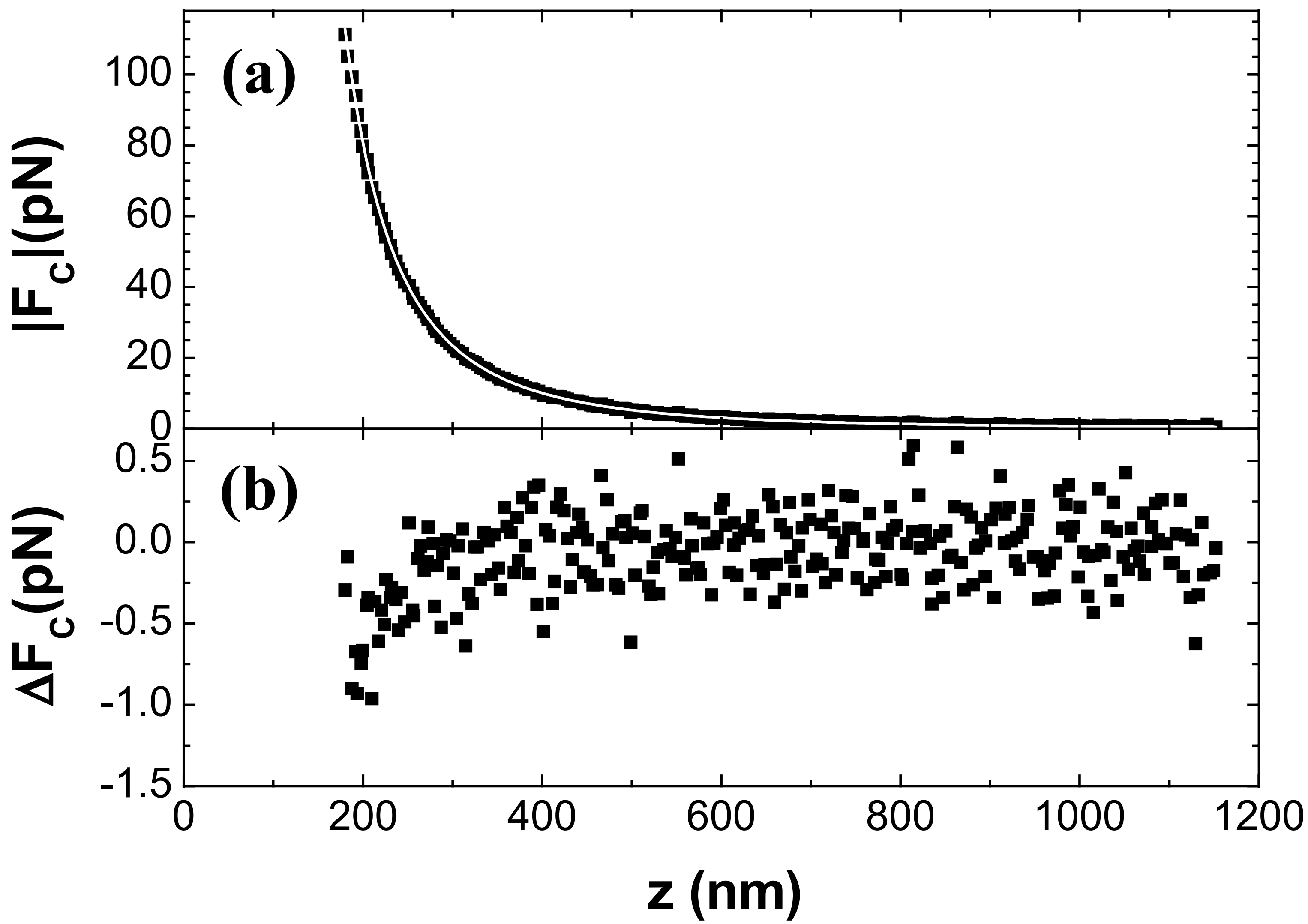


FIG. 3. Casimir force as a function of separation. The separation between the metallic layers has been adjusted to account for the roughness: $z = z_{\text{metal}} + 2\delta_o$. (a) Direct measurement of the force. The solid line is a fit using Eq. (4b). (b) Experimental data subtracted from the theoretical model.

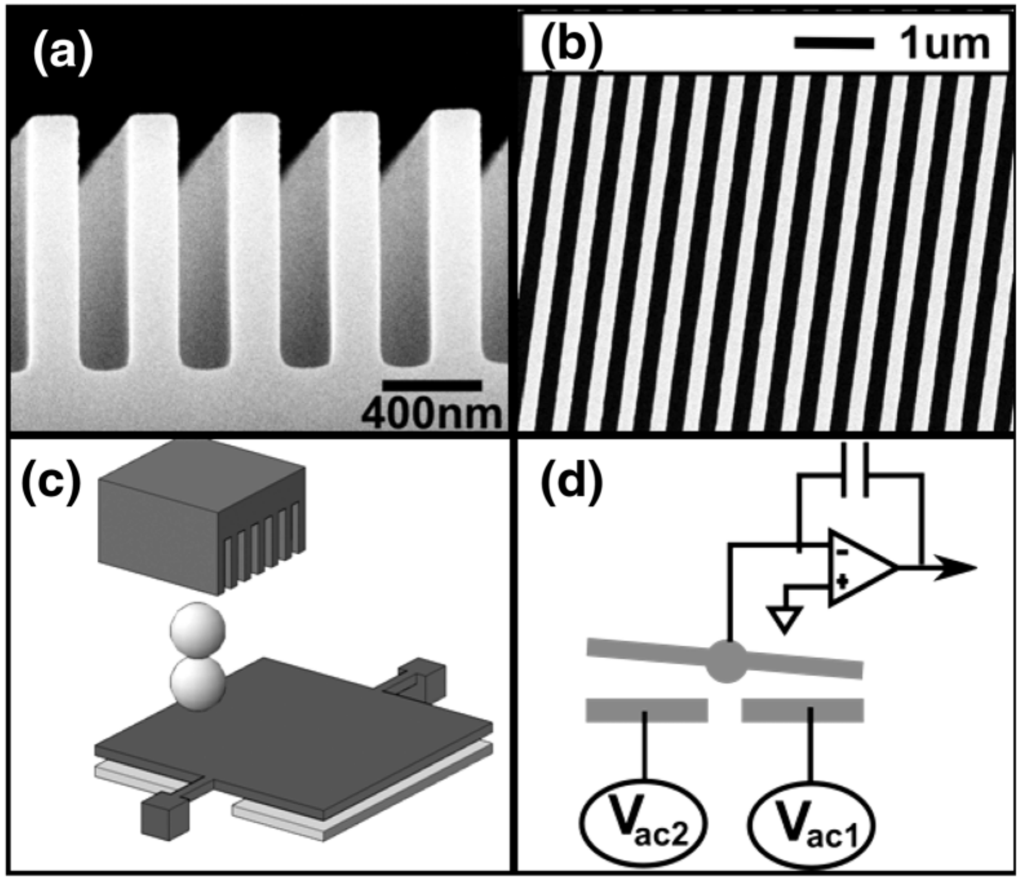
Probable cause for the discrepancies :

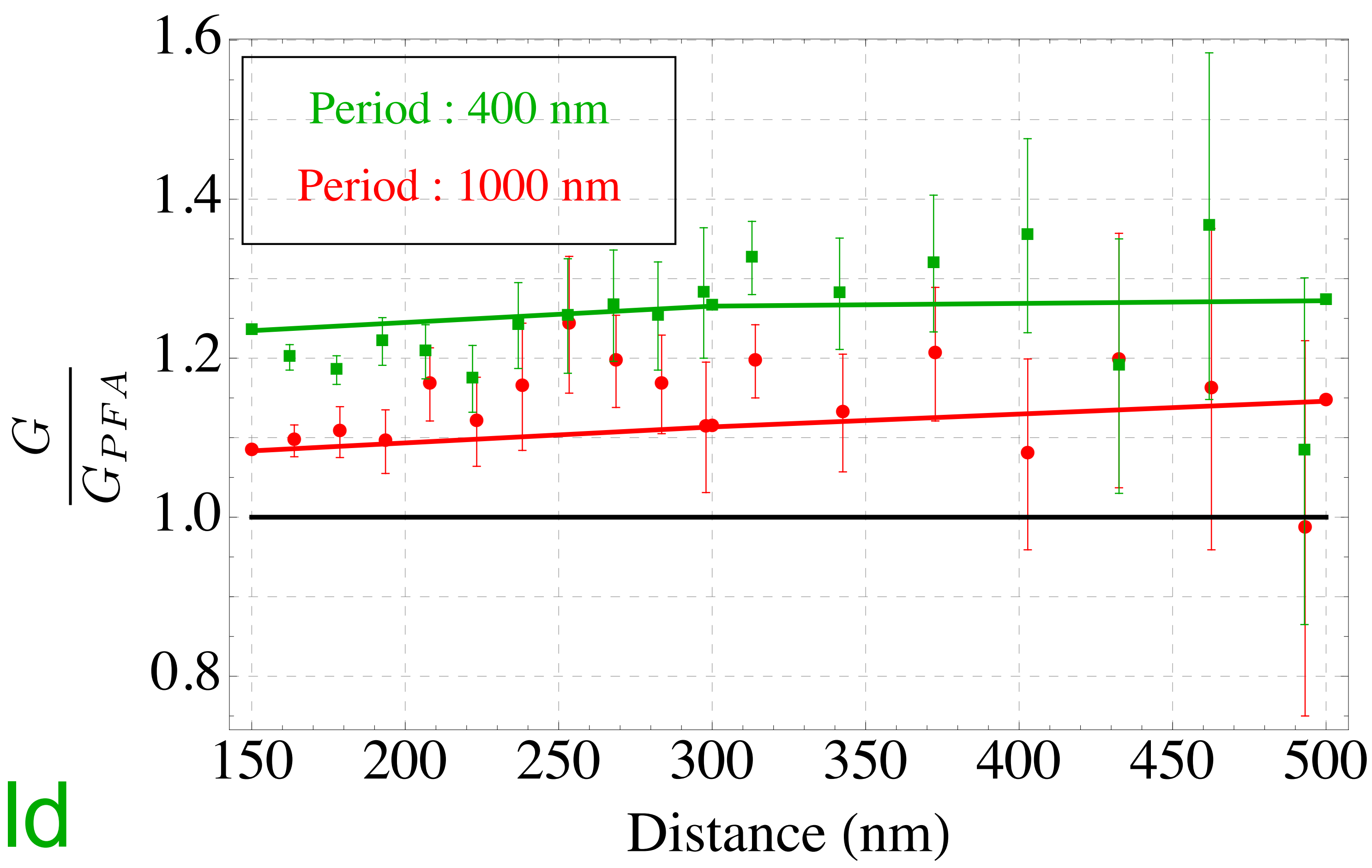
- ε(ω)
- Temperature
- model of surface roughness

Comparisons theory/experiments

Difficulties in the experiments:

- small force to measure
- distance between the two objects must be measured very accurately as well





Casimir force between gold sphere and silicon grating

See: H. B. Chan *et al*, PRL **101**, 030401 (2008)

Afterthoughts…

- Casimir force predicted theoretically more than 50 years ago.

- “Recent” experimental technics have renewed the interest in this effect thank to accurate theory/exp. comparisons.

- Promising applications in the field of nanotechnologies and photonics : towards ways to “control” the Casimir effect.

Thank you for your attention