El Efecto Casimir

¿Qué es?, experimentos, teoría y otros fenómenos relacionados

Fernando C. Lombardo

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Departamento de Física Juan José Giambiagi
Facultad de Ciencias Exactas y Naturales,
Universidad de Buenos Aires

Plan de la charla

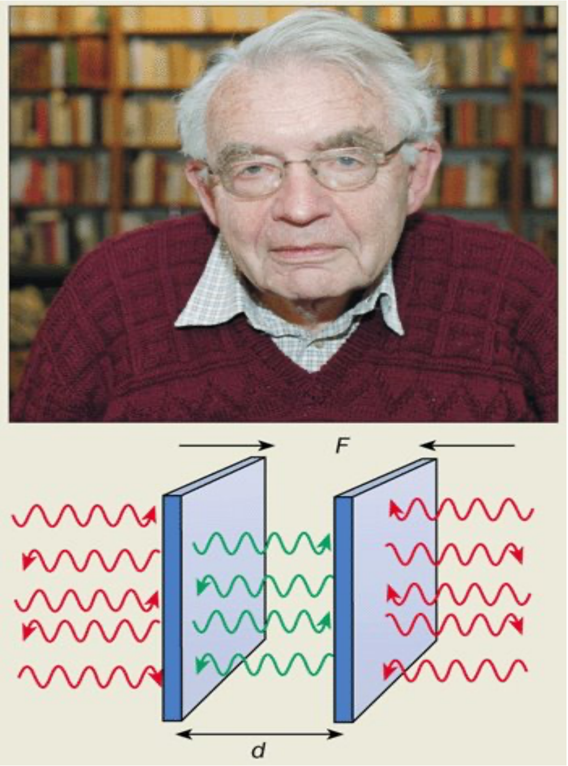
- Qué es el vacío?

  El principio de incertidumbre y el vacío cuántico

- Electrodinámica cuántica y la “fuerza del vacío”
  Efecto Casimir estático: teoría y experimentos

- Efecto Casimir dinámico

- El vacío cuántico y la gravitación
  La polarización del vacío alrededor de estrellas y agujeros negros
  La energía del vacío y la constante cosmológica



Real Academia Española

vacío, a. (Del lat. vacīvus).

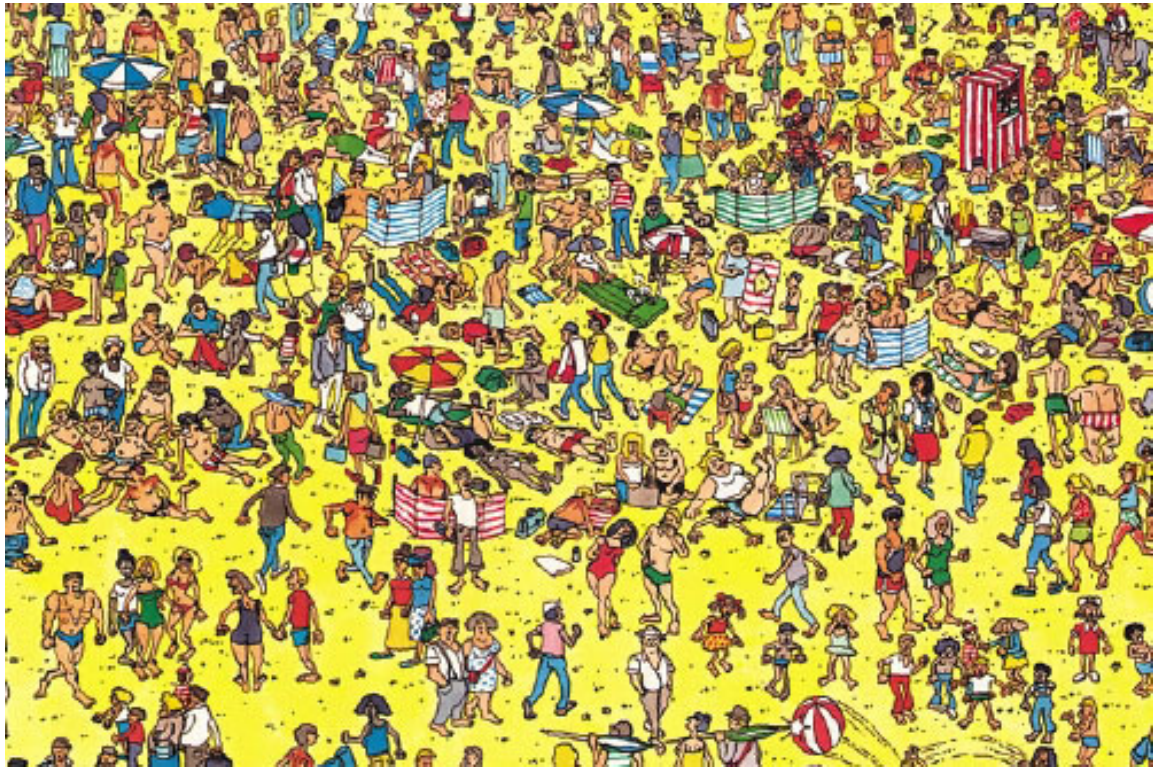
1. adj. Falto de contenido físico o mental.
2. adj. Dicho de una hembra: Que no puede tener cría.
3. adj. Dicho de un sitio: Que está con menos gente de la que puede concurrir a él.
4. adj. Hueco, o falto de la solidez correspondiente.
5. adj. vano (‖ arrogante, presuntuoso).

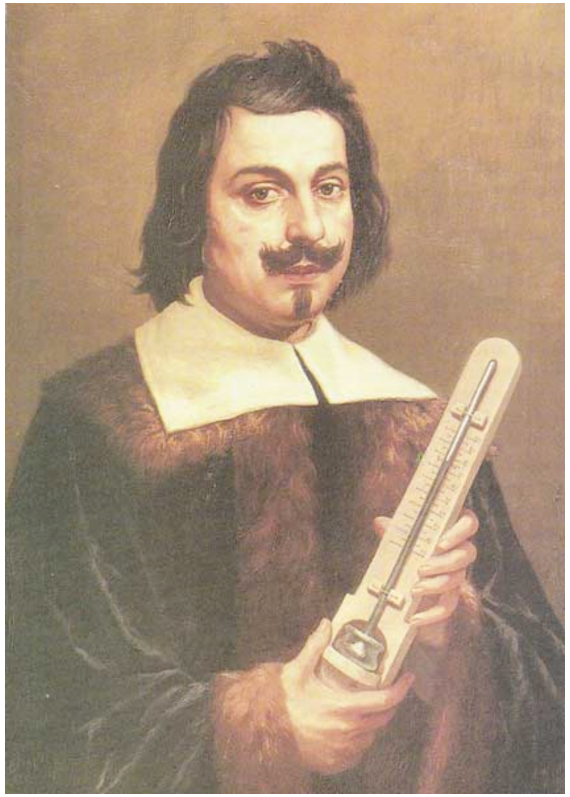
ARISTÓTELES LA NATURALEZA ABORRECE EL VACÍO

“Horror vacui”

Horror al vacío en el arte….

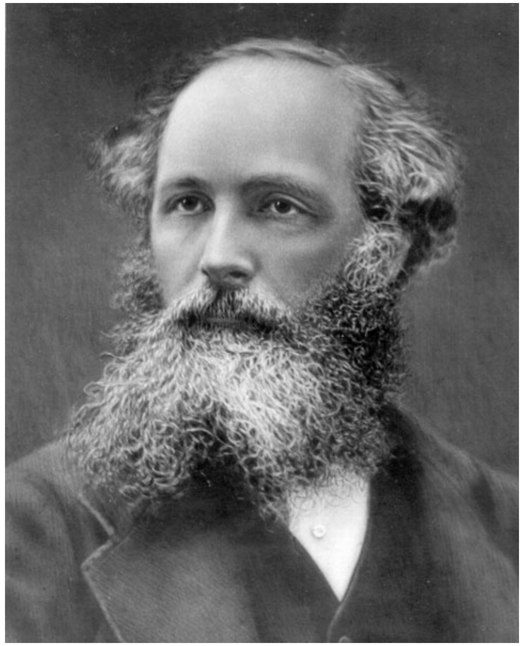
y en las historietas





E. Torricelli, 1642

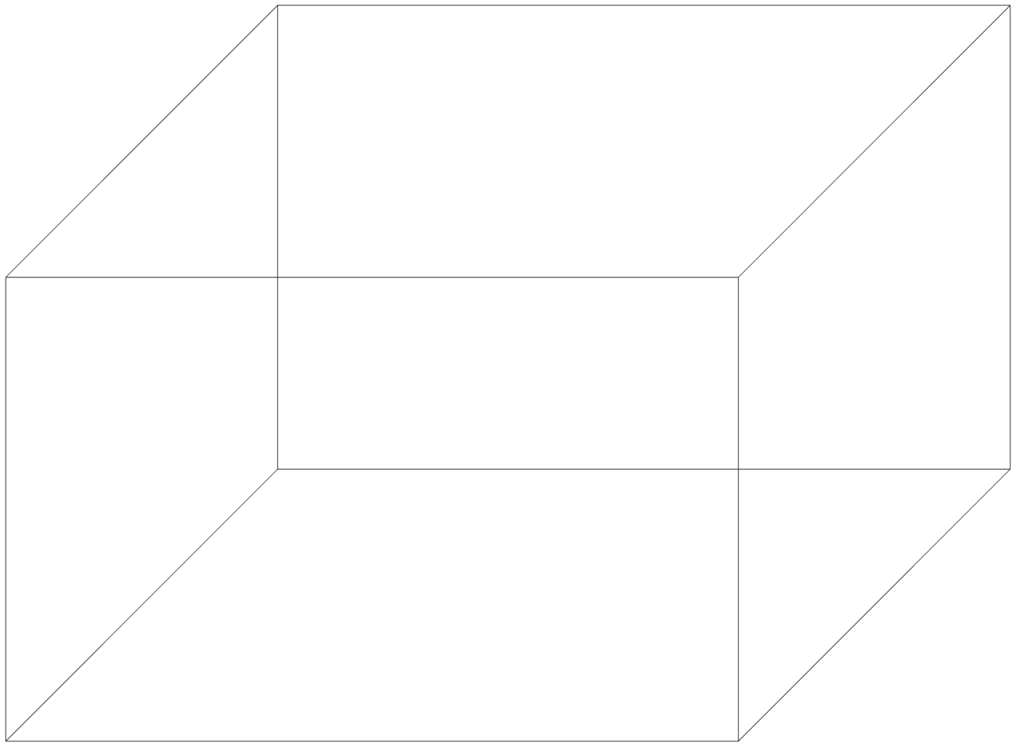
El vacío existe !!



J. C. Maxwell

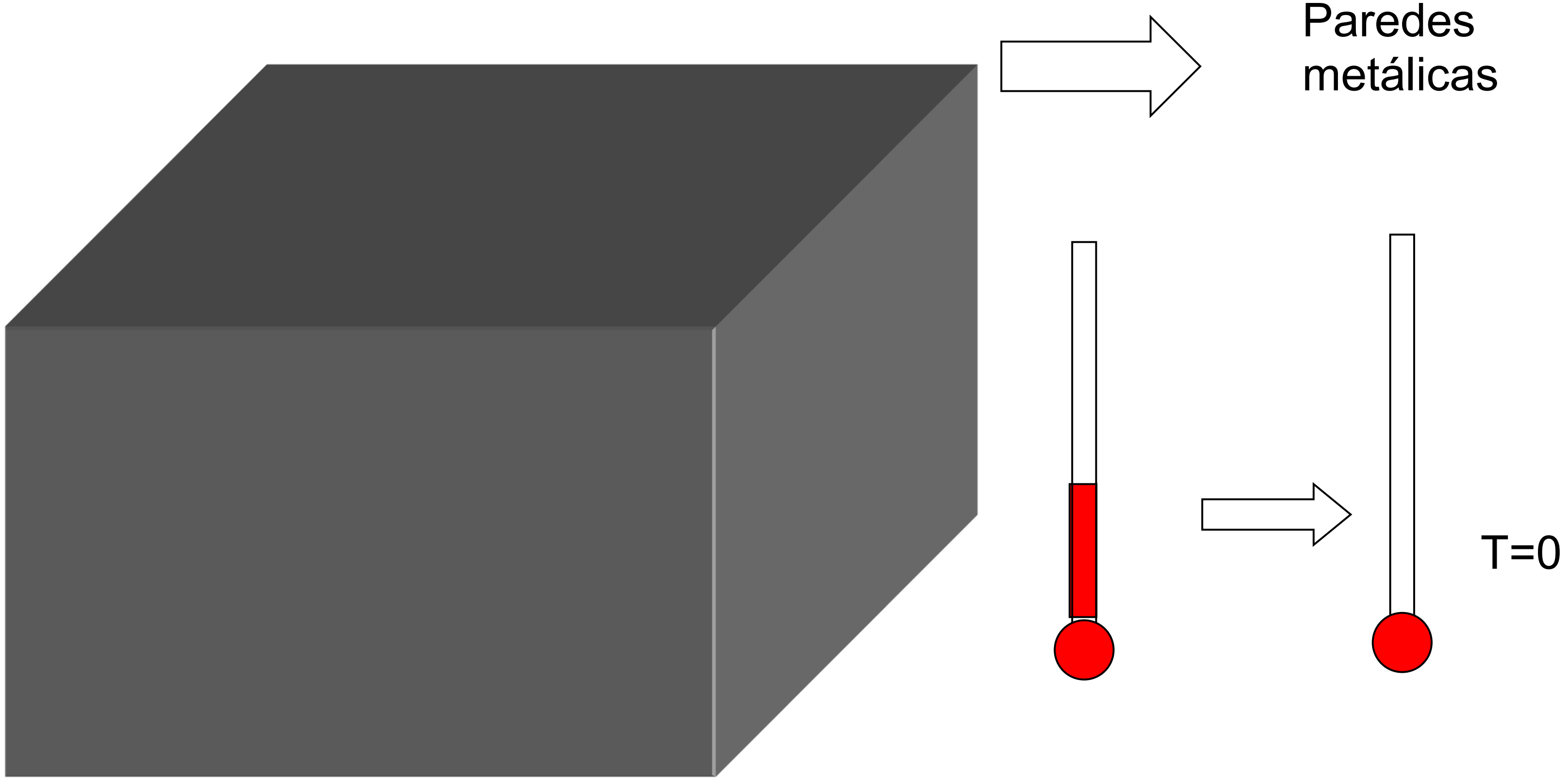
Vacío es lo que queda en un recipiente cuando se retira todo lo que se puede retirar de él…

Cómo hacemos vacío? Torricelli



Sacar objetos
Extraer el aire

Cómo hacemos vacío? Sigamos a Maxwell



Sacar objetos
Extraer el aire

Aislar de radiacion electromagnetica
Bajar la temperatura de las paredes
Aislar de rayos cósmicos,…

Éter ?

~~Éter~~ ?

El vacío clásico

acá no hay partículas…..

acá no hay partículas…..

pero en mecánica cuántica relativista (teoría de campos)
las partículas elementales se describen como excitaciones de campos

Fotón → campo electromagnético

Electrón → campo de Dirac

XX → campo asociado a XX

El principio de incertidumbre aplicado al electromagnetismo implica que los campos eléctrico y el magnético no pueden anularse simultáneamente.

POR LO TANTO, AÚN EN “VACÍO” LOS CAMPOS FLUCTÚAN Y TIENEN CIERTA ENERGÍA (ENERGÍA DE PUNTO CERO).

LA ENERGÍA ELECTROMAGNÉTICA CONTENIDA EN LA CAJA NO ES CERO, AUNQUE ESTÉ “VACÍA”

Hay una energía de punto cero asociada a cada campo cuántico, no sólo al campo electromagnético

Casimir Effect

Each mode of the (free) electromagnetic field

harmonic oscillator

$$E = \sum_{\mathbf{k},\alpha} \hbar\omega_{\mathbf{k},\alpha}\left(n_{\mathbf{k},\alpha} + \frac{1}{2}\right)$$

$n_{\mathbf{k},\alpha}$ photons with $\omega_{\mathbf{k},\alpha}$

$$E_0 = \frac{1}{2}\sum_{\mathbf{k},\alpha} \hbar\omega_{\mathbf{k},\alpha}$$

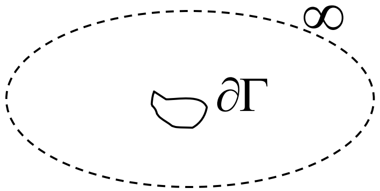
Vacuum energy

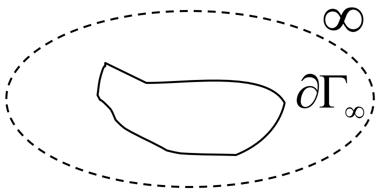
IRRELEVANT IN FLAT SPACE WITHOUT BOUNDARIES

Introduction

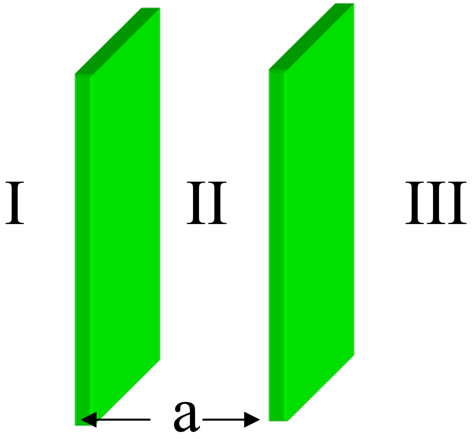
In the presence of boundaries

$$E_C(\partial\Gamma) = E_0(\partial\Gamma) - E_0(\partial\Gamma_\infty) = \frac{1}{2}\sum_{\mathbf{k},\alpha}\hbar\left(\omega_{\mathbf{k},\alpha} - \varpi_{\mathbf{k},\alpha}\right)$$

$E_C(\partial\Gamma) =$ 

$-$ 

Parallel plates



$$E_C(a) = E_I + E_{II} + E_{III} - E_\infty$$

$$\frac{F_C}{A} = -\frac{1}{A}\frac{\partial E_C}{\partial a}$$

Dimensional analysis

$$\frac{F_C}{A} = g(a,c,\hbar) = const \times \frac{\hbar c}{a^4}$$

Explicit calculation (regularization is needed!!)

$$\sum_k \omega_k \longrightarrow \sum_k \omega_k f(\omega/\omega_{cutoff})$$

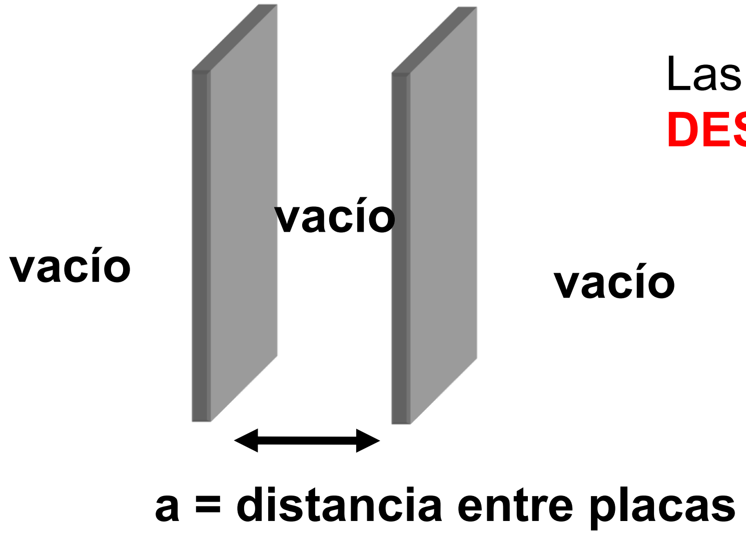
$$\omega_k{}^2 = k_{//}^2 + \frac{n^2\pi^2}{a^2} \qquad f(0)=1 \quad f(\infty)=0$$

Atractive force

Casimir 1948

$$\frac{F_C}{A} = \frac{\pi^2}{240} \times \frac{\hbar c}{a^4} = \frac{0.013}{a^4{}_{\mu m}} \frac{dyn}{cm^2}$$

Consecuencia macroscópica: La fuerza de Casimir



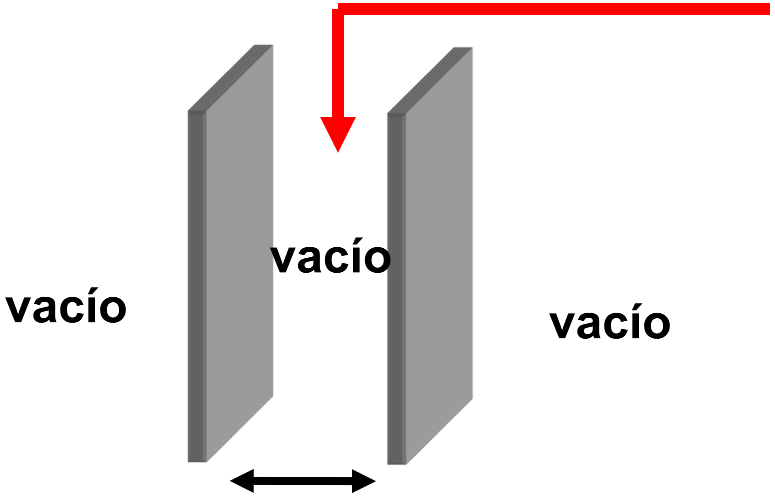
Las placas conductoras
DESCARGADAS se **ATRAEN**

Casimir (1948)

$$\frac{F_C}{A} = \frac{\pi^2}{240} \times \frac{\hbar c}{a^4} = \frac{0.013}{a^4{}_{\mu m}} \frac{dyn}{cm^2}$$

Consecuencia macroscópica: La fuerza de Casimir

La densidad de energía entre las placas es **NEGATIVA**



a = distancia entre placas

renormalización

Casimir (1948)

$$\frac{F_C}{A} = \frac{\pi^2}{240} \times \frac{\hbar c}{a^4} = \frac{0.013}{a^4{}_{\mu m}} \frac{dyn}{cm^2}$$

While the Casimir force is too weak to be measured on mirrors separated by a distance of one meter, can be measured if the plates are separated by a distance of a micron to each other.

For example, two mirrors with an area $1cm^2$, separated by a distance of 1 micron, have an attractive force of order of 10^{-7} N, comparable to the weight of a drop of water of 0.5 mm in diameter.

Although this force seems small, for distances less than the micrometer, becomes stronger than the forces between charged objects. For separations of 10 nm to hundreds of times the typical size of an atom, the Casimir effect produces pressures equivalent to 1 atm

Related effects:

- Van der Waals forces

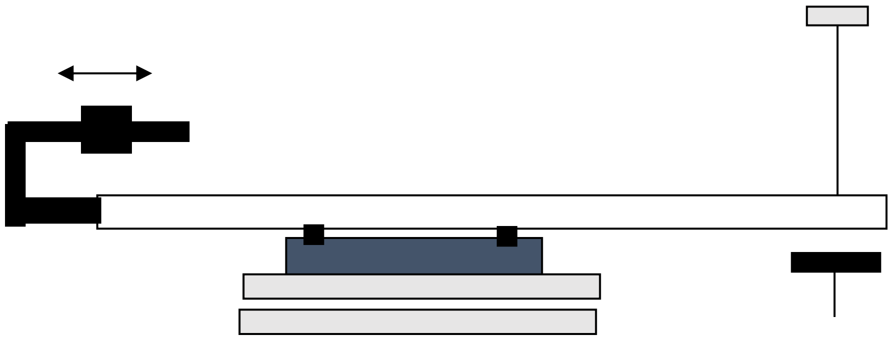
- Casimir – Polder force (atom close to a conducting wall)

- Gravitational effects?

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = -8\pi G (T_{\mu\nu} + < T_{\mu\nu} >)$$

Cosmological constant problem…

The first experiment (Sparnaay 1958)



“the experimental results do not contradict Casimir’s prediction”

error 100% , distance between plates aprox 1μm

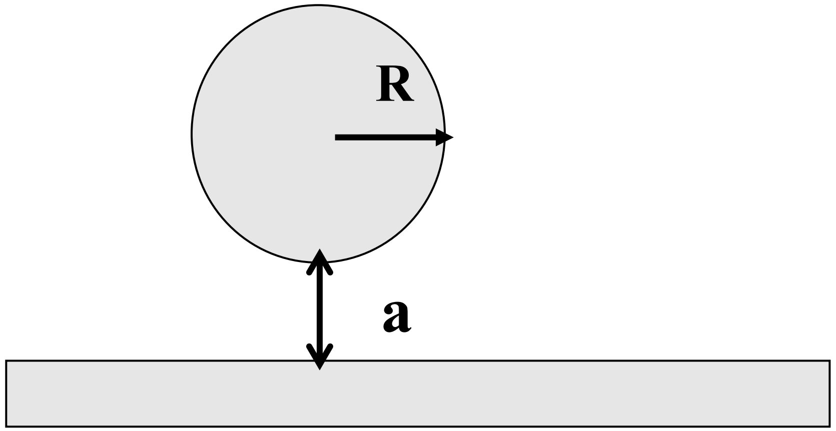
GEOMETRY-DEPENDENCE OF THE FORCE

Casimir force may be interpreted as due to the interplay between quantum fluctuations and geometry

"Quantum electrostatic"

Other Example

Force between a sphere and a plate: R>>a



Proximity approx.

$$F_C \cong \frac{\pi^3}{360}\hbar c \frac{R}{a^3}$$

2nd generation of experiments

(since 1997)

Resumen de experimentos

Year	Geometry	Range (μm)	Accuracy (%)	Reference
1958	Plane–plane	$0.3 \div 2.5$	100	Sparnaay [64]
1978	Plane–sphere	$0.13 \div 0.67$	25	van Blokland and Oveerbeek [65]
1997	Plane–sphere	$0.6 \div 12.3$	5	Lamoreaux [82]
1998	Plane–sphere	$0.1 \div 0.9$	1	Mohideen and Roy [89]
2000	Crossed cylinders	$0.02 \div 0.1$	1	Ederth [92]
2001	Plane–sphere	$0.08 \div 1.0$	1	Chan *et al* [93]
2002	Plane–plane	$0.5 \div 3.0$	15	Bressi *et al* [102]
2003	Plane–sphere	$0.2 \div 2.0$	1	Decca *et al* [110]

Torsion pendulum

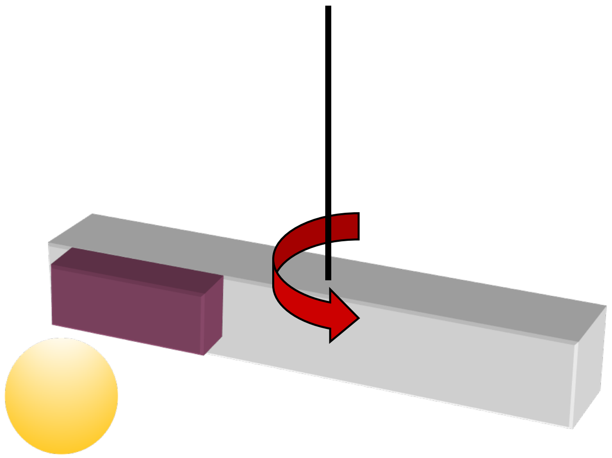
Atomic Force Microscope

Microscopic seesaw

microresonators

From R. Onofrio, New J. Phys. 2006

Torsion pendulum (Lamoreaux 1997)



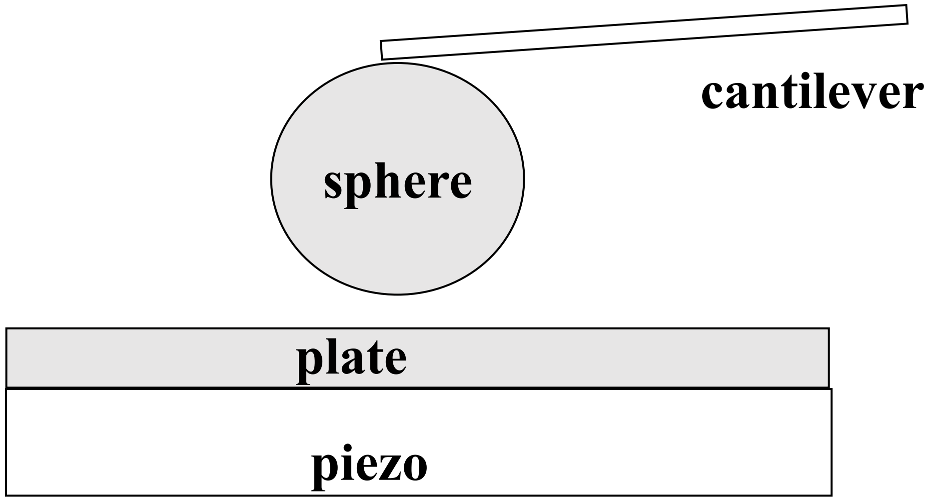
$R \sim 1\text{cm} \quad a \sim 1\ \mu\text{m}$

error $< 5\%$

Atomic force microscope (Mohideen et al 1998)

R ~ 200μm
a < 1 μm

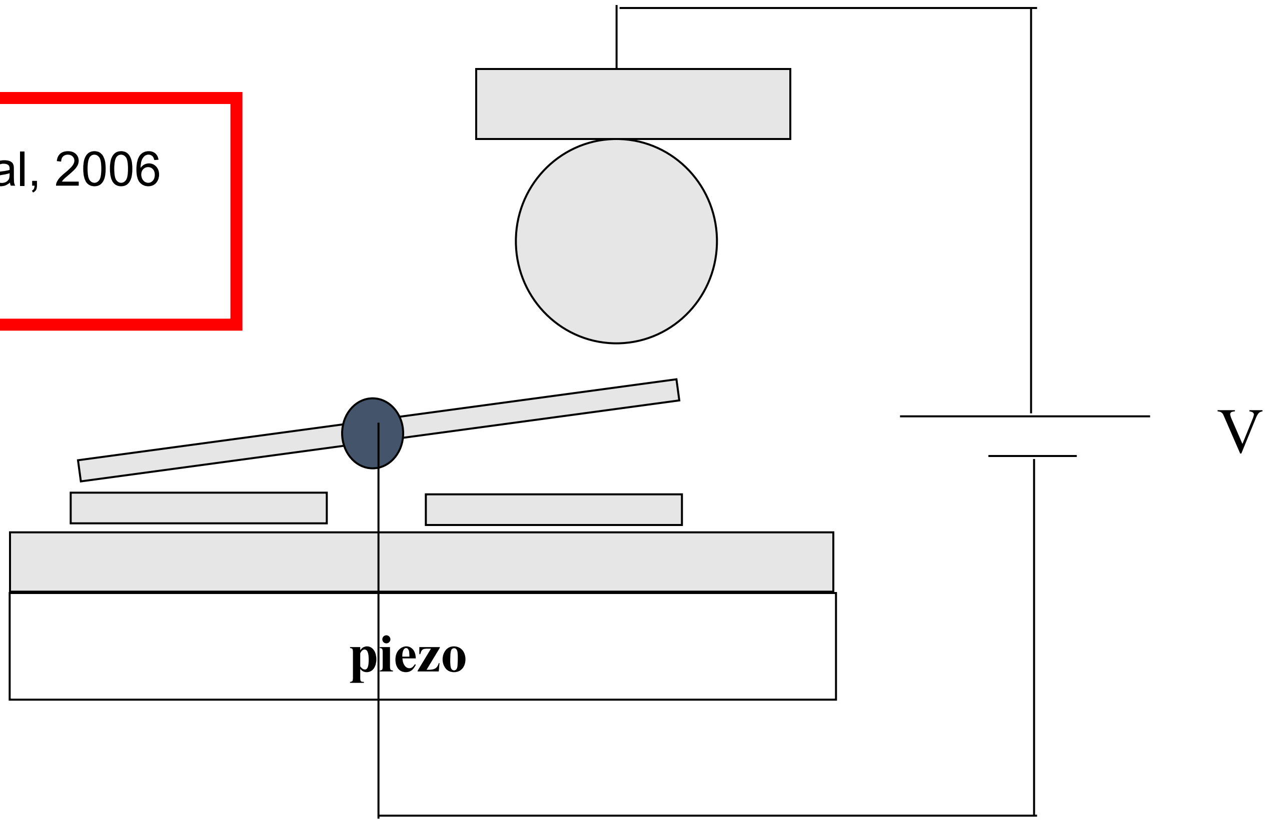
error 1%



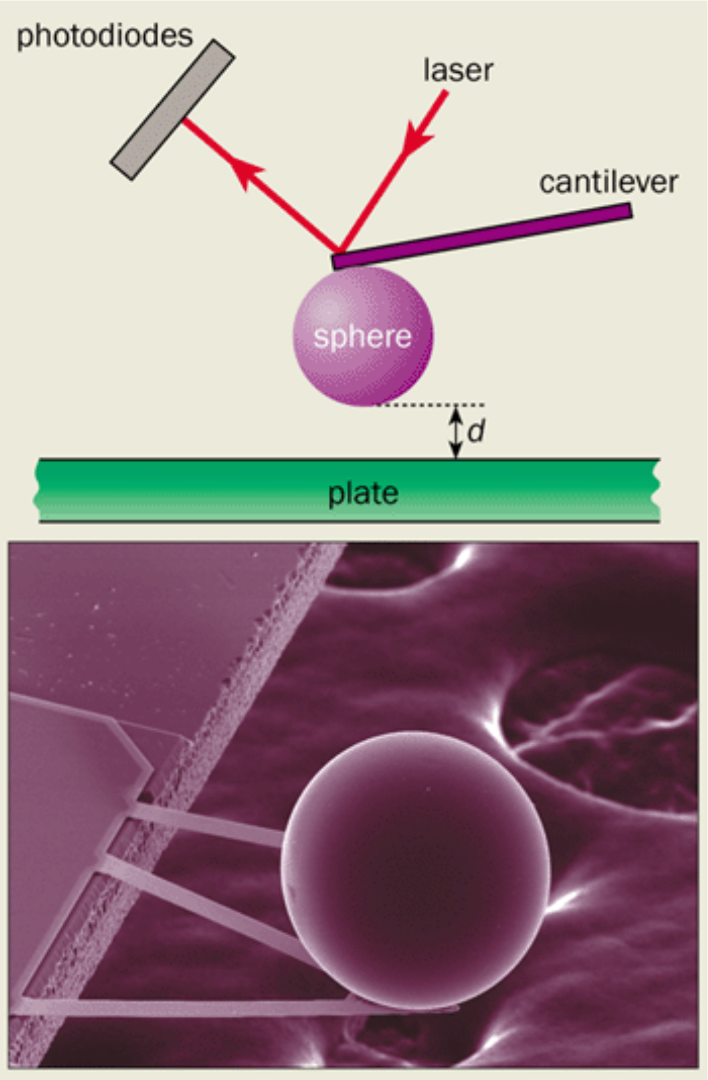
Microscopic seesaw (Bell Labs 2001)

error 1%

R. Decca et al, 2006
error 0.1%



Experimentos usando AFM (Mohideen et al, 1998…..)



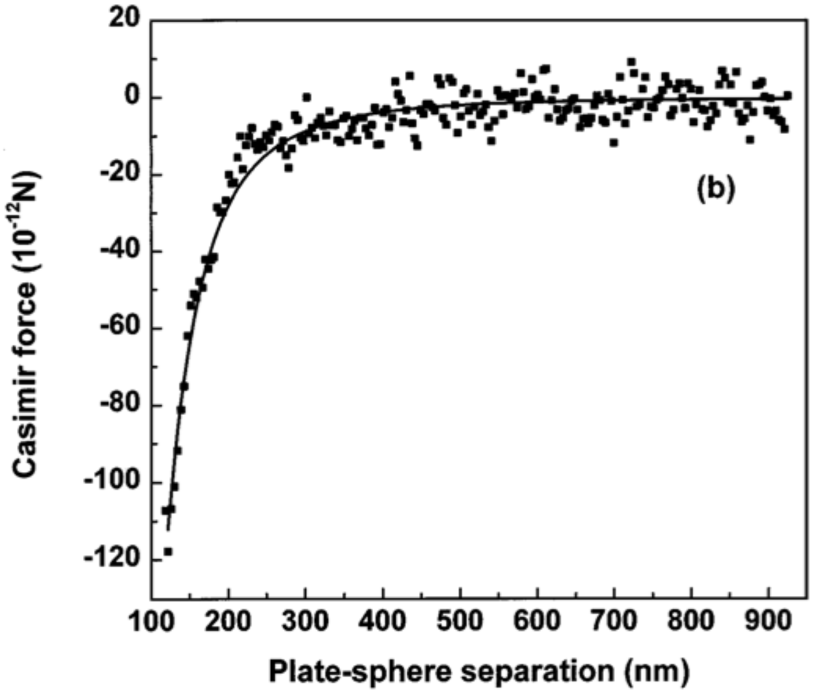
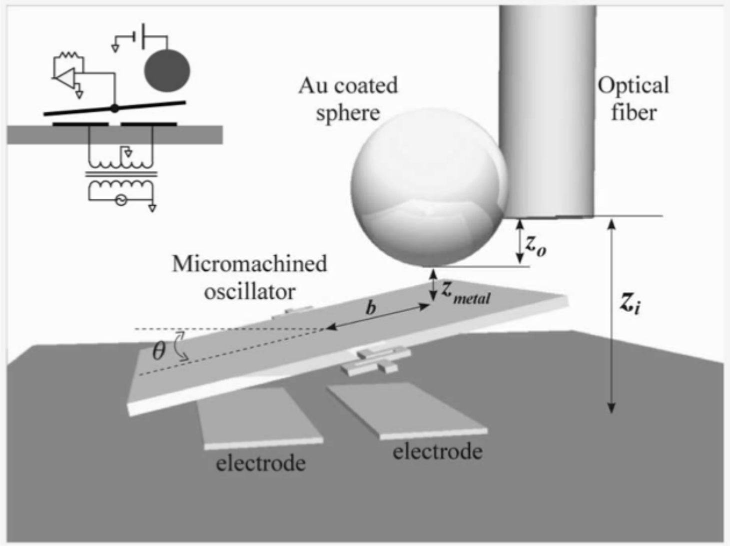


FIG. 3. (a) A typical force curve as a function of the distance moved by the plate; (b) the measured Casimir force corresponding to (a) as a function of sphere-plate surface separation. The solid line is the theoretical Casimir force from Eq. (4).

Experimentos usando microresonadores (Decca et al 2003….)

Medición estática o dinámica



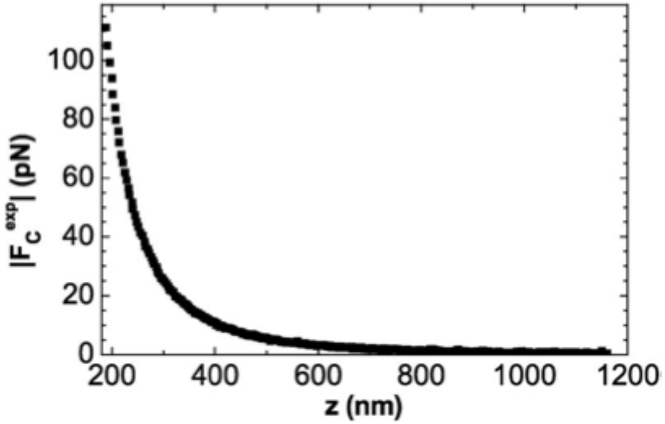


FIG. 8. Absolute value of the measured Casimir force as a function of separation obtained using the static mode. The value of the separation between the two metals is determined as discussed in the text.

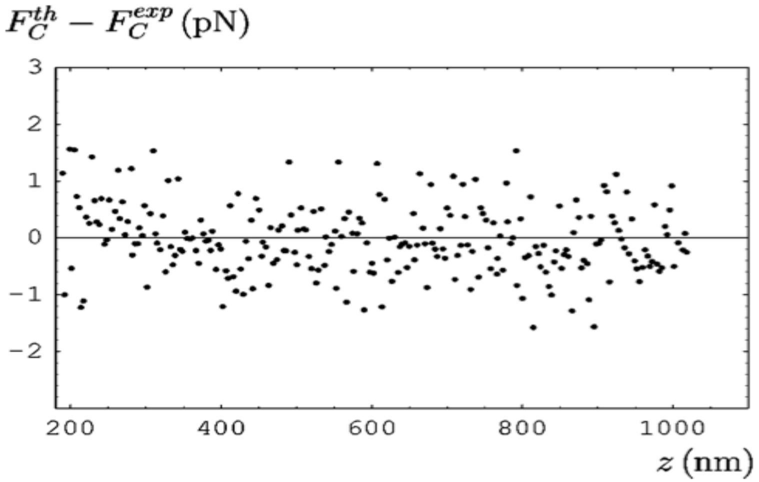


FIG. 10. Difference of the theoretical and experimental Casimir forces between the sphere and plate versus separation obtained from the static measurement.

Corrections to Newtonian potential at short distances

Thanks to the Casimir's experiments we now have a deeper knowledge of the gravitational field in the region from a few millimetres to planetary distances

The hypotetical forces superimposed on Newtonian gravity are typically parametrized by a Yukawa range λ and a coupling strength α with respect to gravity

$$V(r) = -\frac{G m_1 m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

Experiments

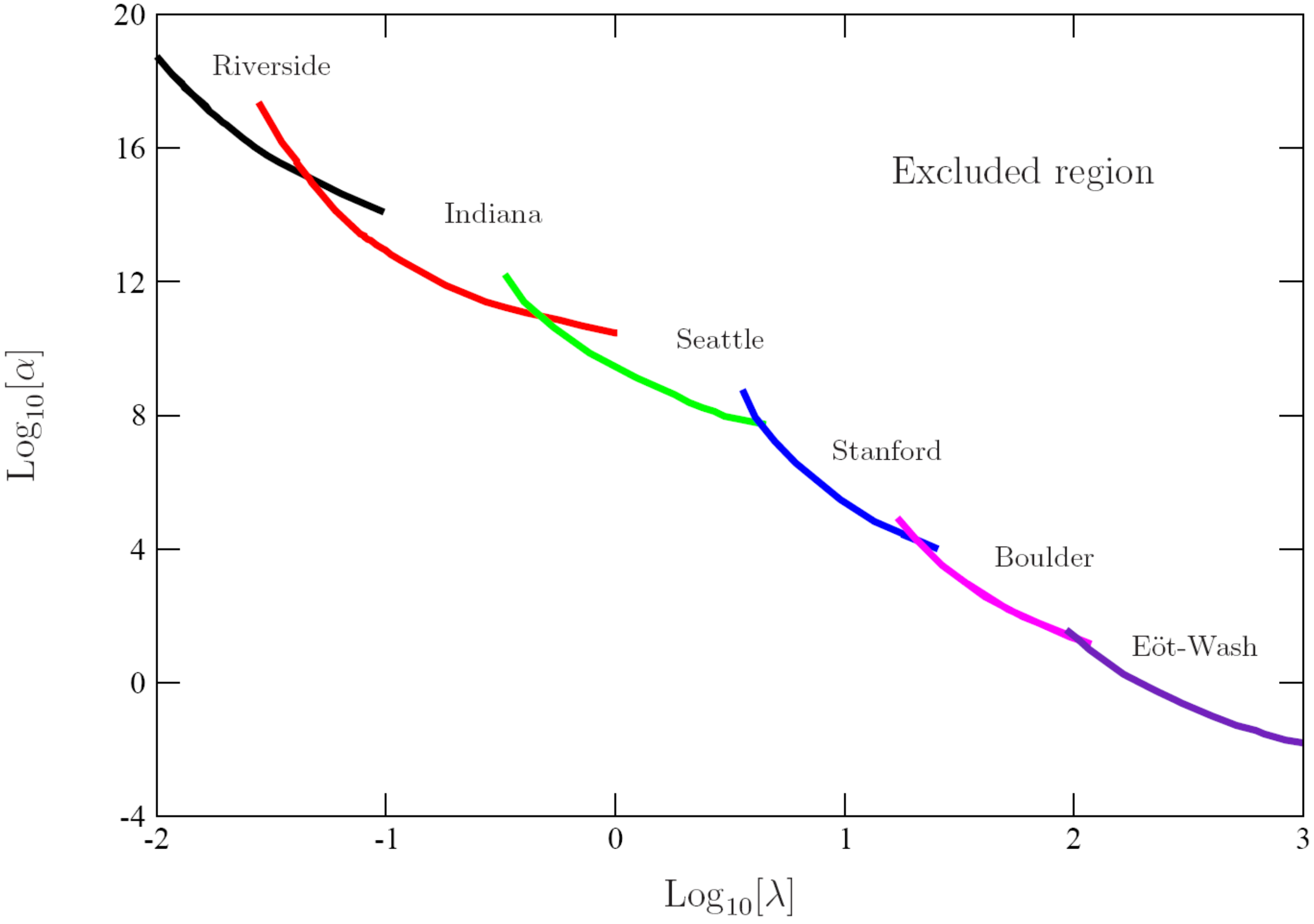
• The strongest expected background in the micrometre range for forces between electrically neutral bodies is due to the Casimir force

• Any accurate measurement of Casimir forces gives limits on gravitational-like forces

• Precision studies of Casimir forces in the 200 nm – 2 μm range have allowed us to grasp a better understanding of the background in which novel macroscopic forces of gravitational origin could be inmersed. Forces in the micrometre range:

Casimir forces are expected to be the leading background

Experiments



Otros experimentos:

Fuerza de Casimir - Polder :

- Sukenik et al 1992, transición entre $1/d^3$ y $1/d^4$
- Cornell et al 2006, oscilaciones de BEC cerca de superficies conductoras

Fuerza de Casimir lateral

- Mohiddeen et al, 2002 (superficies corrugadas)

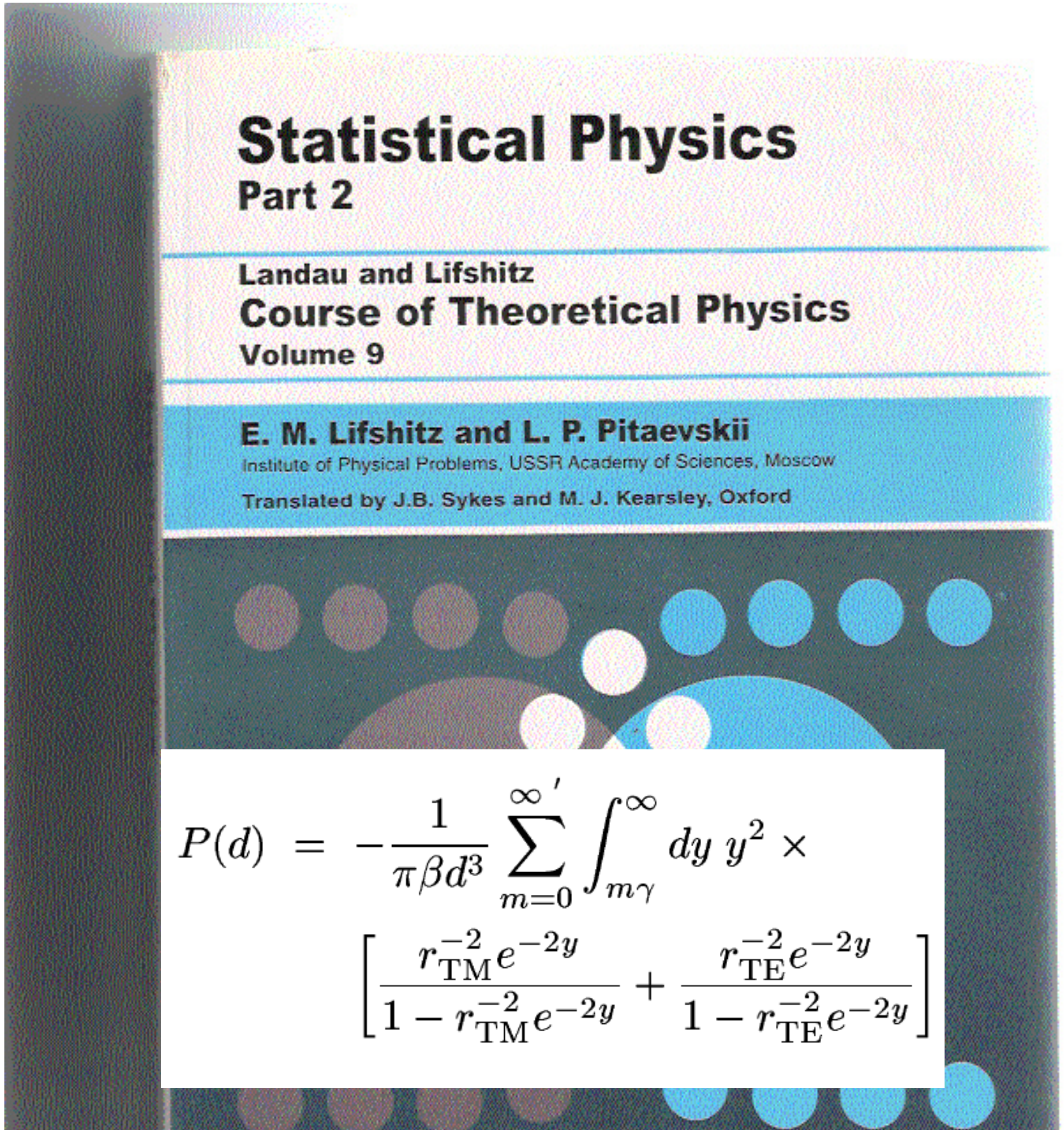
Modulación óptica de la fuerza de Casimir

Mohiddeen et al, 2006

Fuerzas repulsivas y levitación

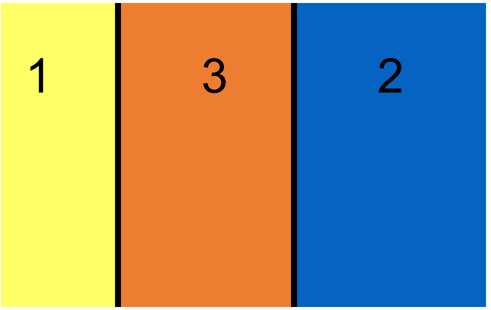
Munday et al, Nature 2009

Fuerzas de Casimir repulsivas. Fórmula de Lifshitz



$$P(d) = -\frac{1}{\pi\beta d^3} \sum_{m=0}^{\infty}{}' \int_{m\gamma}^{\infty} dy\, y^2 \times \left[\frac{r_{\mathrm{TM}}^{-2} e^{-2y}}{1 - r_{\mathrm{TM}}^{-2} e^{-2y}} + \frac{r_{\mathrm{TE}}^{-2} e^{-2y}}{1 - r_{\mathrm{TE}}^{-2} e^{-2y}} \right]$$

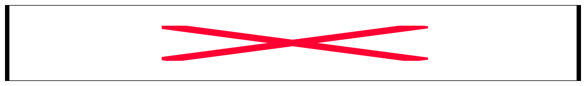
Semiespacios)

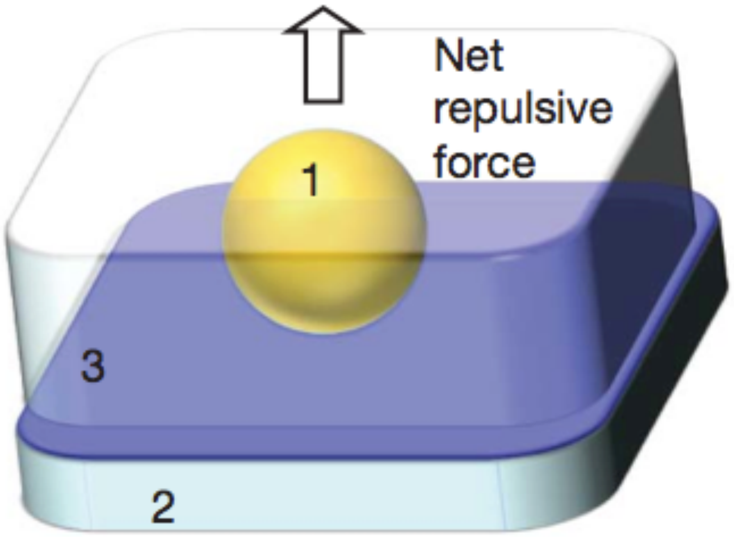


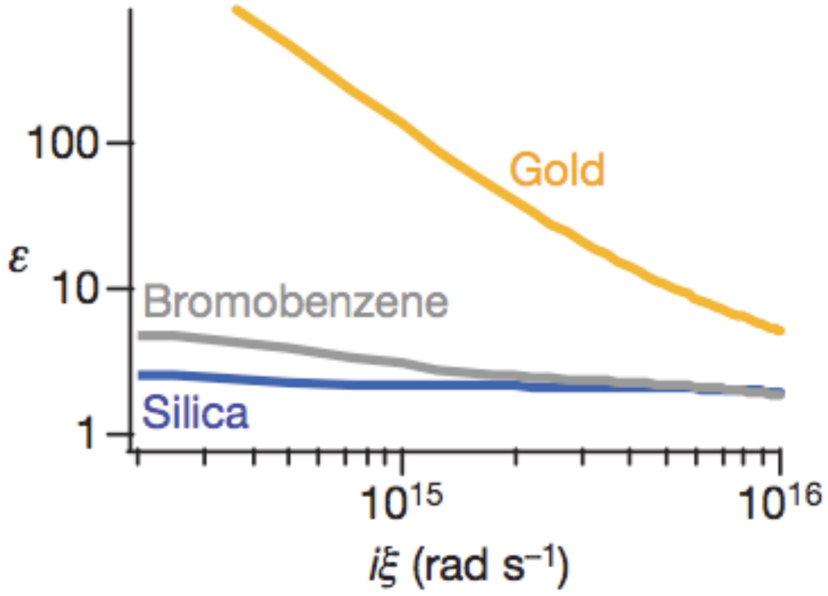
Repulsión

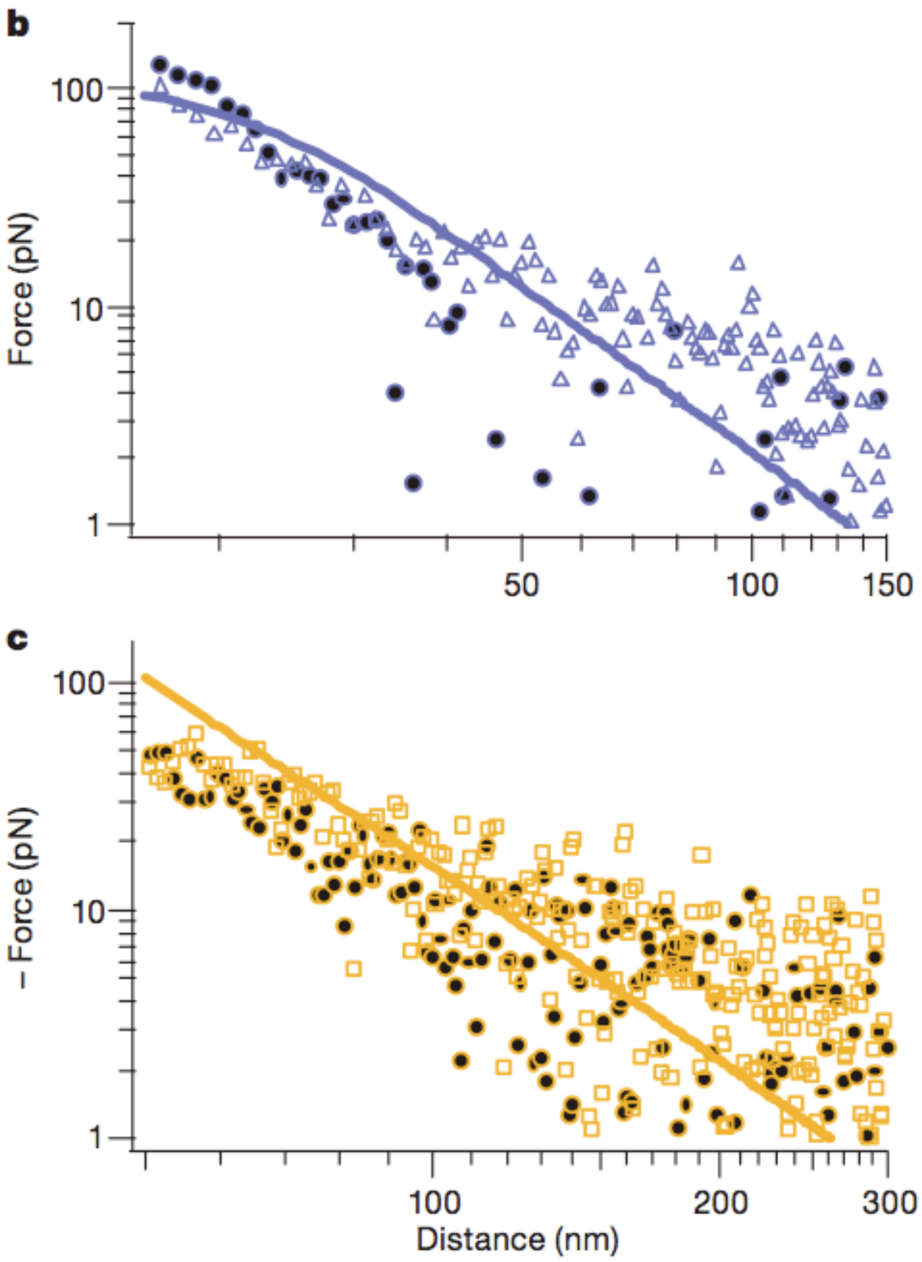
Primera medición de fuerzas de Casimir repulsivas: Munday, Capasso & Parsegian, Nature 2009

Lifshitz + PFA → repulsión









Oro - Bromo - SiO_2
(repulsiva)

Oro - Bromo - Oro
(atractiva)

Geometry dependance

For almost 50 years since Casimir's result, there was neither a precise determination of the Casimir force nor exact theoretical calculations of the interaction between two bodies, beyond the parallel-plates geometry and the PFA

There were some calculations of self-energies for spherical and cylindrical shells in d dimensions, and also some (*dubious) results* for rectangular boxes

Methods

Theoretical methods to compute the Casimir energy for more general geometries

Main problems:

- No explicit expressions for the eigenfrequencies

- A direct numerical evaluation of the sum over modes
  is almost impossible

Resultados exactos para distintas geometrías y materiales (desde 2006!!)

• Cilindro – Plano

• Cilindros eccéntricos

• Esfera – Plano

• Esfera – Esfera

• Superficies corrugadas

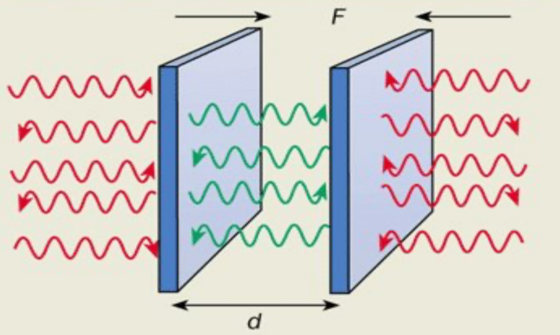
• Fuerzas entre pistones de forma arbitraria

• Fuerzas producidas por la interacción con los grados de libertad internos del material

• Cálculos completamente numéricos para objetos de forma y propiedades arbitrarias en 2D y 3D

Casimir effect and quantum open systems

Due to the presicion achieved in the measurement of the Casimir force, is inevitable to use realistic models for the description of the medium that constitutes the mirrors or plates



The calculations for mirrors with general electromagnetic properties, including absorption, have not been done successfully

Dissipative effects imply the possibility of exchanges of energy between different parts of the overall system: mirrors, field and environment

The theory of open quantum systems is the natural framework to explain the role of dissipation in the physics of the Casimir effect

DISSIPATION

FLUCTUATION

Dielectric media: non-linear, non-homogeneous and dissipative

Makes dificcult the quantization of the EM field when all these aspects are taken into account simultaneously

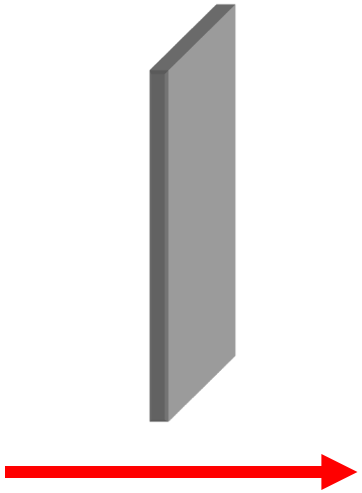
Different approaches

- Phenomenological description based on macroscopic properties of materials

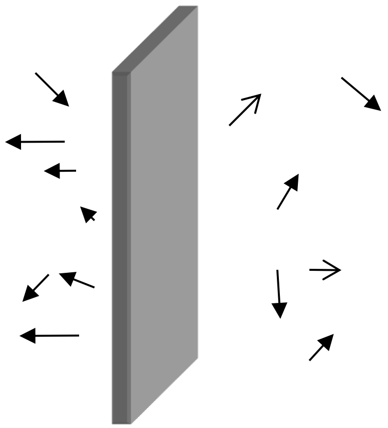
- Macroscopic Maxwell equations, including noise terms to account for absorption → can not perform a canonical quantization unless the EM field is coupled to an external environment, following the usual mechanism to incorporate dissipation in a quantum system

EL EFECTO CASIMIR DINÁMICO

El efecto Casimir dinámico



Espejo acelerado

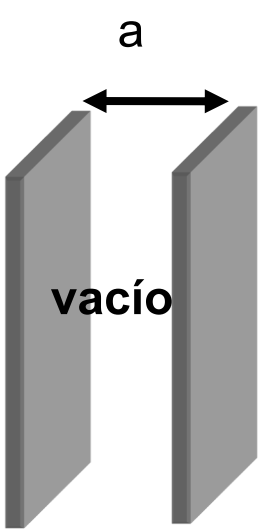


“radiación inducida por el movimiento”

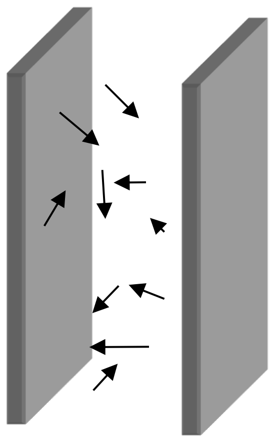
Fuerza disipativa sobre el espejo

$$f(t) = -\frac{\hbar A q^{(5)}(t)}{30\pi^2 c^4}$$

El efecto Casimir dinámico se amplifica en cavidades resonantes



Espejo oscilante



Creación de fotones del vacío!

El número de fotones aumenta exponencialmente

$$\langle \mathcal{N}_{\mathbf{m}} \rangle = \sinh^2 \left[\frac{1}{\Omega} \left(\frac{m_z \pi}{L_z} \right)^2 \varepsilon t_f \right]$$

Caso más sencillo, sin acoplamiento entre modos (Crocce, Dalvit, Lombardo, Mazzitelli 2005)

Observation of the Dynamical Casimir Effect in a Superconducting Circuit

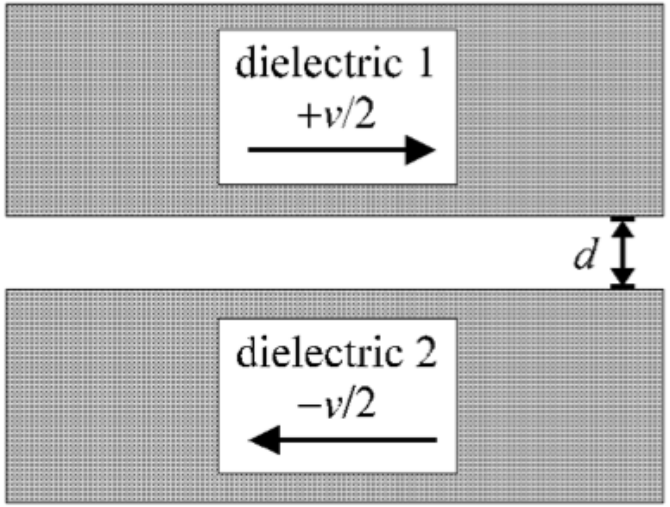
C.M. Wilson, G. Johansson, A. Pourkabirian, J.R. Johansson, T. Duty, F. Nori, P. Delsing

(Submitted on 24 May 2011) **NATURE**

One of the most surprising predictions of modern quantum theory is that the vacuum of space is not empty. In fact, quantum theory predicts that it teems with virtual particles flitting in and out of existence. While initially a curiosity, it was quickly realized that these vacuum fluctuations had measurable consequences, for instance producing the Lamb shift of atomic spectra and modifying the magnetic moment for the electron. This type of renormalization due to vacuum fluctuations is now central to our understanding of nature. However, these effects provide indirect evidence for the existence of vacuum fluctuations. From early on, it was discussed if it might instead be possible to more directly observe the virtual particles that compose the quantum vacuum. 40 years ago, Moore suggested that a mirror undergoing relativistic motion could convert virtual photons into directly observable real photons. This effect was later named the dynamical Casimir effect (DCE). Using a superconducting circuit, we have observed the DCE for the first time. The circuit consists of a coplanar transmission line with an electrical length that can be changed at a few percent of the speed of light. The length is changed by modulating the inductance of a superconducting quantum interference device (SQUID) at high frequencies (~11 GHz). In addition to observing the creation of real photons, we observe two-mode squeezing of the emitted radiation, which is a signature of the quantum character of the

FRICCION CUANTICA

Fricción entre espejos móviles imperfectos (Pendry 1997)



Caso más sencillo:

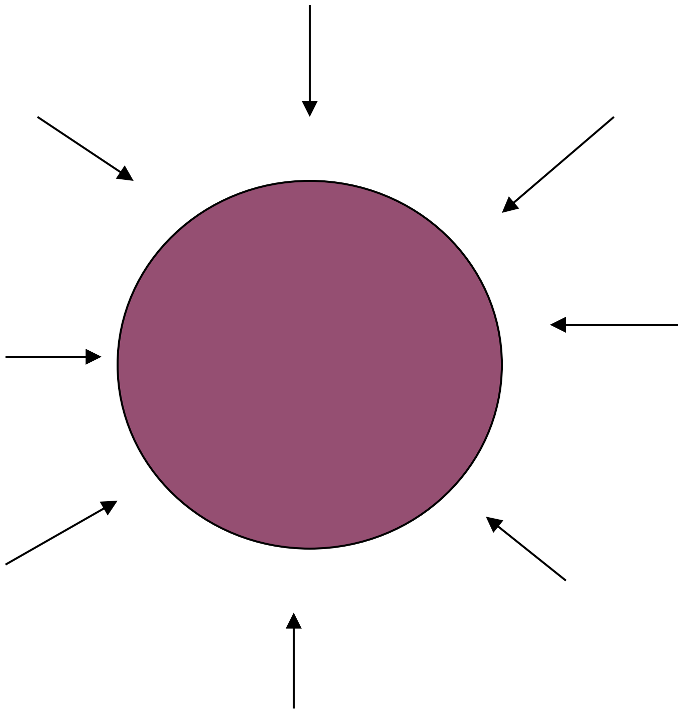
$$F = \left[\Im \frac{\varepsilon - 1}{\varepsilon + 1}\right]^2 \frac{3\hbar v}{2^6 \pi^2 d^4}$$

Fuerzas disipativas por excitación de grados de libertad internos

Efectos gravitacionales de las fluctuaciones del vacío

Qué pasa si la estrella colapsa?

Clásicamente nada!! (teorema de Birkhoff…o de Gauss!)

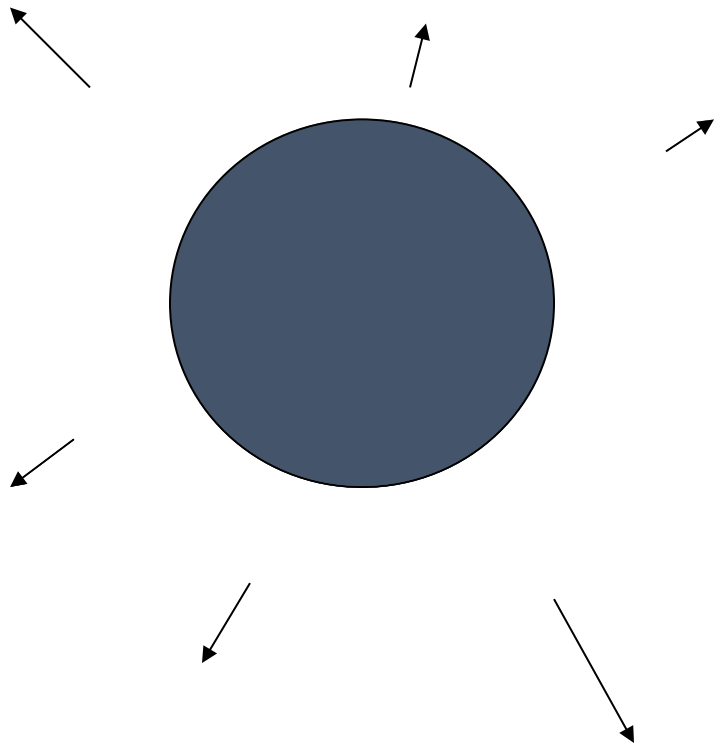


Pero las fluctuaciones del vacío se ven afectadas y por lo
tanto puede haber transferencia de energía del campo gravitacional a los campos de materia: **se crean partículas como en el efecto Casimir dinámico**

……………

Un efecto relacionado:

los agujeros negros no son negros! (radiación de Hawking 1975)



Conclusiones

- La noción de vacío en mecánica cuántica es más complicada que en la física clásica
- No es posible anular las fluctuaciones de los campos. El vacío cuántico es el estado de mínima energía compatible con el principio de incertidumbre y las condiciones externas.
- Estas fluctuaciones producen efectos observables, aún a escalas macroscópicas (fuerzas de Casimir) que fueron medidas con mucha precisión en los últimos años
- Las fluctuaciones del vacío son relevantes en varias ramas de la física, en particular en fenómenos gravitacionales
- La energía del vacío ha dado lugar a innumerables especulaciones (científicas y pseudo-científicas)