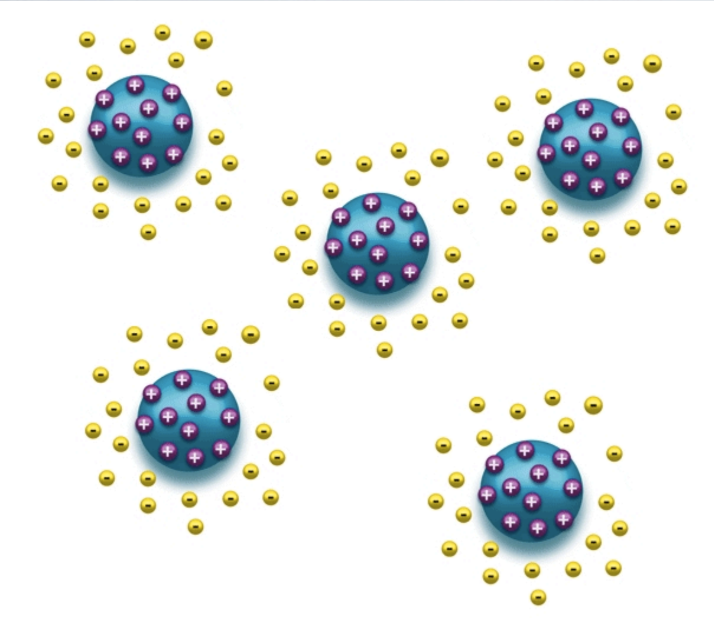
Martes Cuantico

Efecto Casimir

M. Asorey

Colloidal forces



- Van der Waals forces
- London theory (1930)

$$V(r) = -\frac{3}{4}\frac{\hbar\,\omega_0\,\alpha^2}{r^6}$$

- Verwey-Oberbeek (1947) Exp.

Casimir-Polder (1948)

$$V(r) = -\frac{23}{4\pi}\frac{\hbar\,c\,\alpha^2}{r^7}$$

Colloidal forces

London theory (1930)

$$V(r) = -\frac{3}{48}\frac{\hbar\,\omega_0\,\alpha}{r^3}$$

Casimir-Polder (1948)

$$V(r) = -\frac{3}{8\pi}\frac{\hbar\,c\,\alpha}{r^4}$$

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

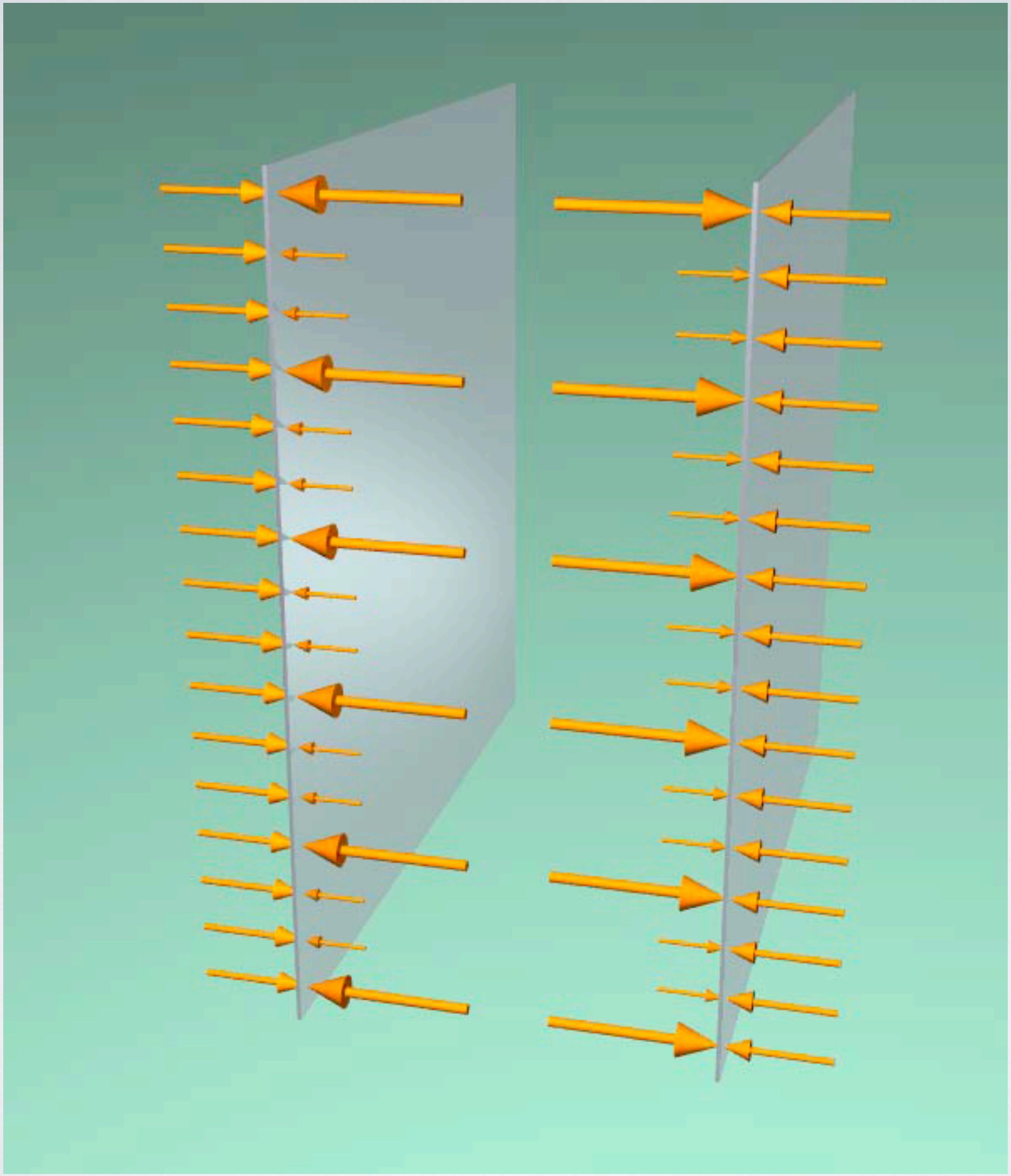
(Communicated at the meeting of May 29, 1948.)

In a recent paper by POLDER and CASIMIR [1]) it is shown that the interaction between a perfectly conducting plate and an atom or molecule with a static polarizibility α is in the limit of large distances R given by

$$\delta E = -\frac{3}{8\pi} \hbar c \frac{\alpha}{R^4}$$

and that the interaction between two particles with static polarizibilities α_1 and α_2 is given in that limit by

$$\delta E = -\frac{23}{4\pi} \hbar c \frac{\alpha_1 \alpha_2}{R^7}.$$



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

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The higher derivatives will contain powers of (π/ak_m). Thus we find

$$\delta E/L^2 = -\hbar c \frac{\pi^2}{24 \times 30} \cdot \frac{1}{a^3},$$

a formula which holds as long as $ak_m \gg 1$. For the force per cm^2 we find

$$F = \hbar c \frac{\pi^2}{240} \frac{1}{a^4} = 0{,}013 \frac{1}{a_\mu^4} \text{ dyne/cm}^2$$

where a_μ is the distance measured in microns.

We are thus led to the following conclusions. There exists an attractive force between two metal plates which is independent of the material of the plates as long as the distance is so large that for wave lengths comparable with that distance the penetration depth is small compared with the distance. This force may be interpreted as a zero point pressure of electromagnetic waves.

Although the effect is small, an experimental confirmation seems not unfeasable and might be of a certain interest.

Natuurkundig Laboratorium der N.V. Philips' Gloeilampenfabrieken, Eindhoven.)

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

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$$F = -\hbar c \frac{\pi^2}{240} \frac{1}{a^4} = -0{,}013 \frac{1}{a_\mu^4} \text{ dyne/cm}^2$$

- The formula only depends on h, c and a
- The minus sign means that F it is attractive
- The force is the dominant force between neutral objects a submicron distances
- At a=10nm the Casimir force equals the atmospheric pressure

Origin of Casimir force

- Modification of vacuum (zero-point) energy due to the presence of the plates

$$\frac{\Delta E}{A} = \sum_{\omega_c} \hbar\omega_c - \sum_{\omega_0} \hbar\omega_0$$

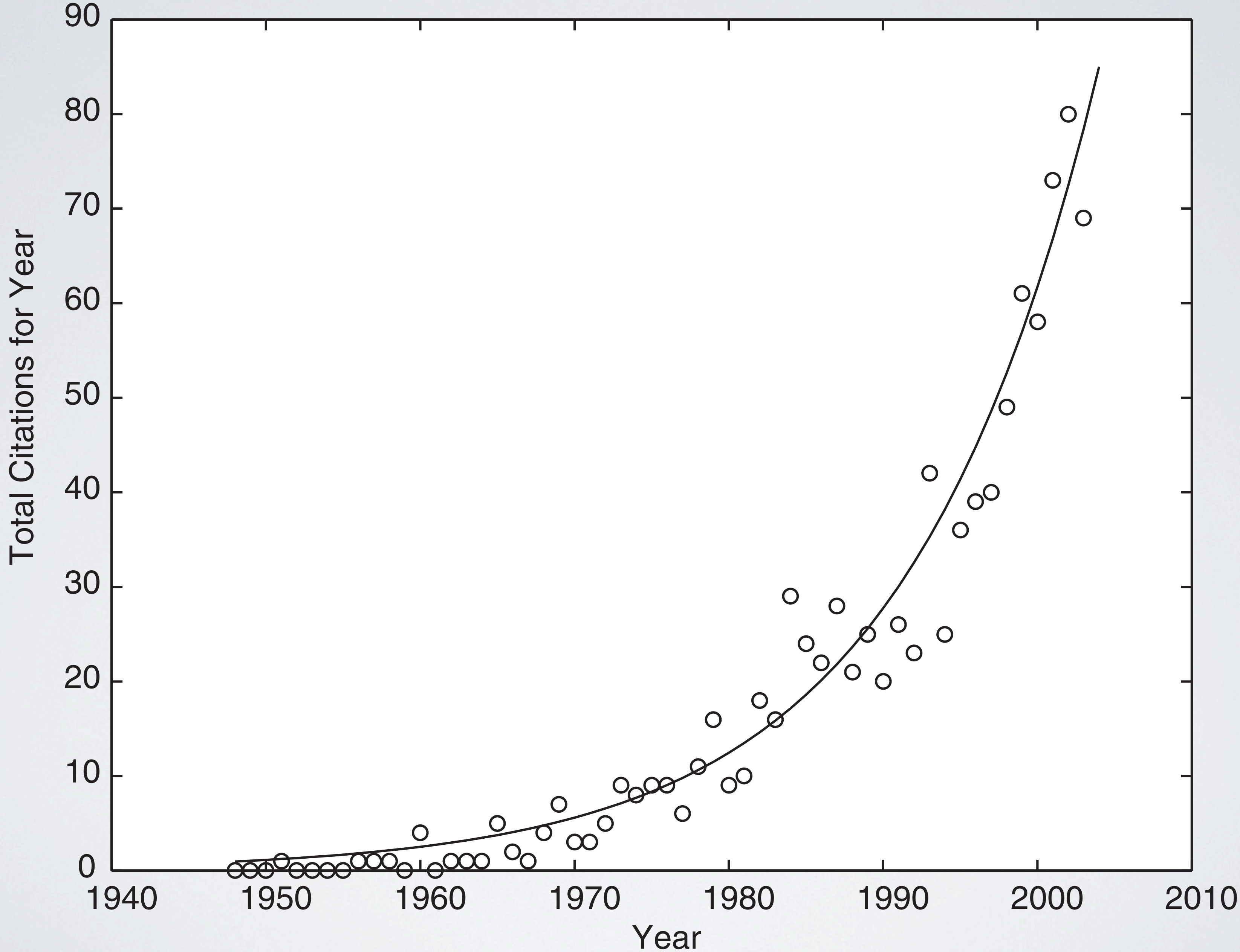
$$\frac{\Delta E}{A} = \sum_{\omega_c} \hbar\,\omega_c\, e^{-\frac{\omega_c}{\omega_\infty}} - \sum_{\omega_0} \hbar\,\omega_0\, e^{-\frac{\omega_0}{\omega_\infty}}$$

$$\omega_0 = \sqrt{k_x^2 + k_y^2 + k_z^2} \qquad \omega_c = \sqrt{k_x^2 + k_y^2 + \left(\frac{\pi n c}{d}\right)^2}$$

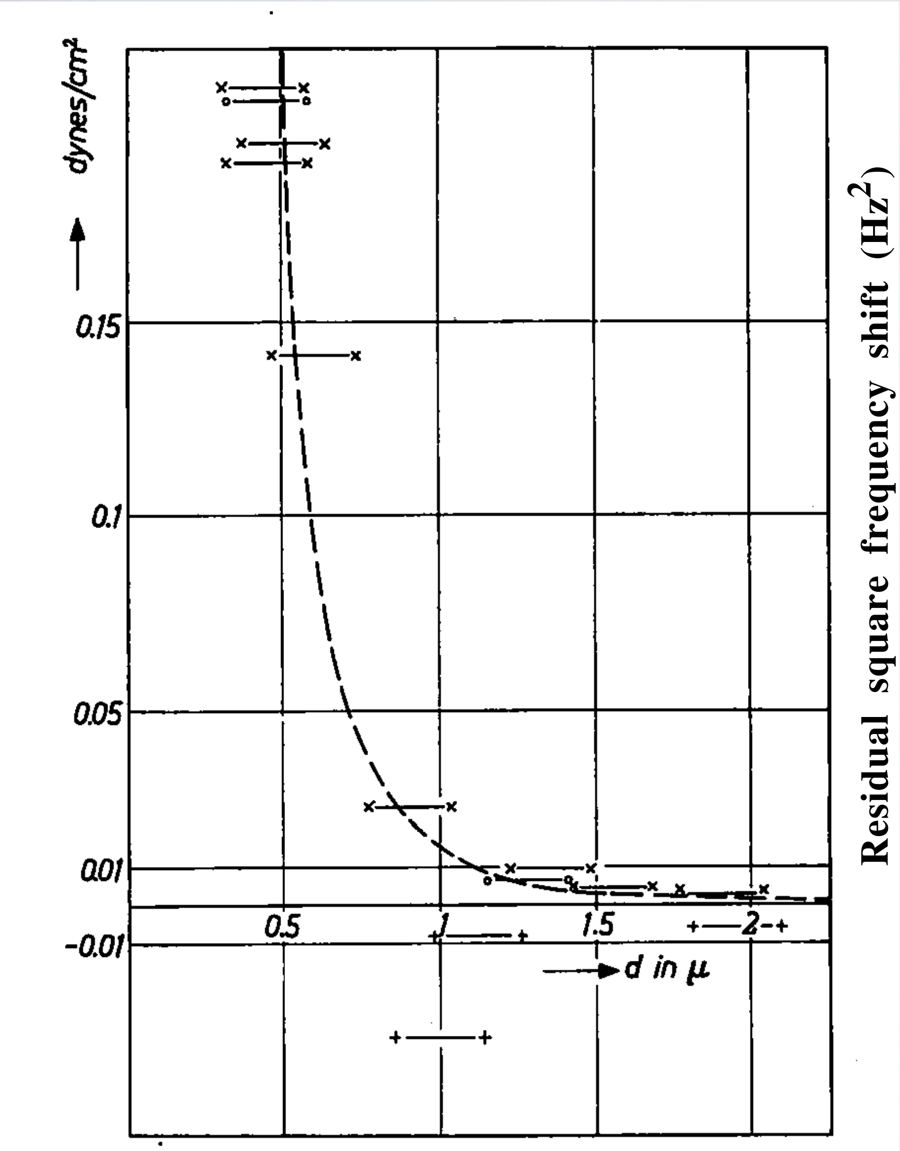
$$\frac{\Delta E_c}{A} = \frac{\hbar\, c\, \omega_\infty^4}{8\,\pi^2} a + f_s\, \hbar\, c\, \omega_\infty^2 - \frac{\hbar\, c\, \pi^2}{720\, a^3}$$

Impact of Casimir paper

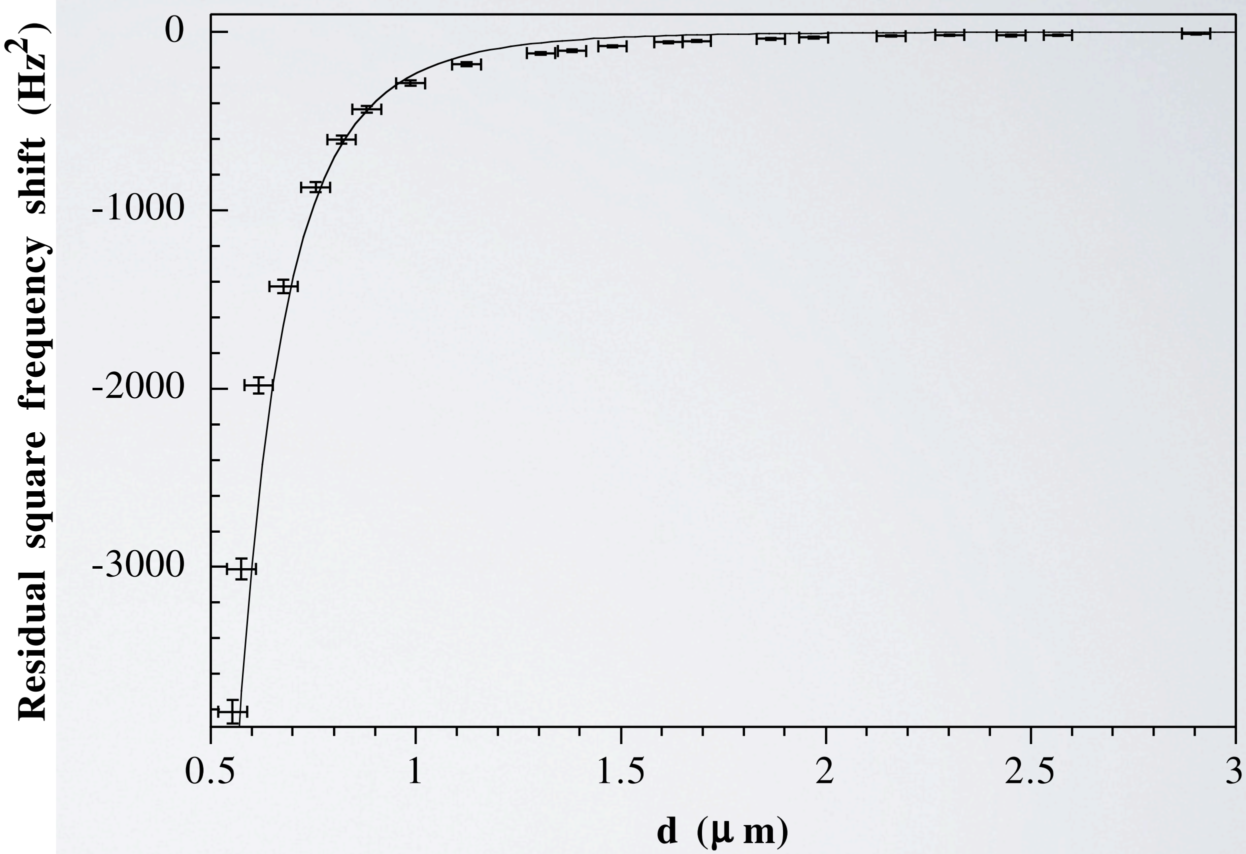
Proc. K. Ned. Akad. Wet. 51, 793 (1948)



Casimir effect experiments

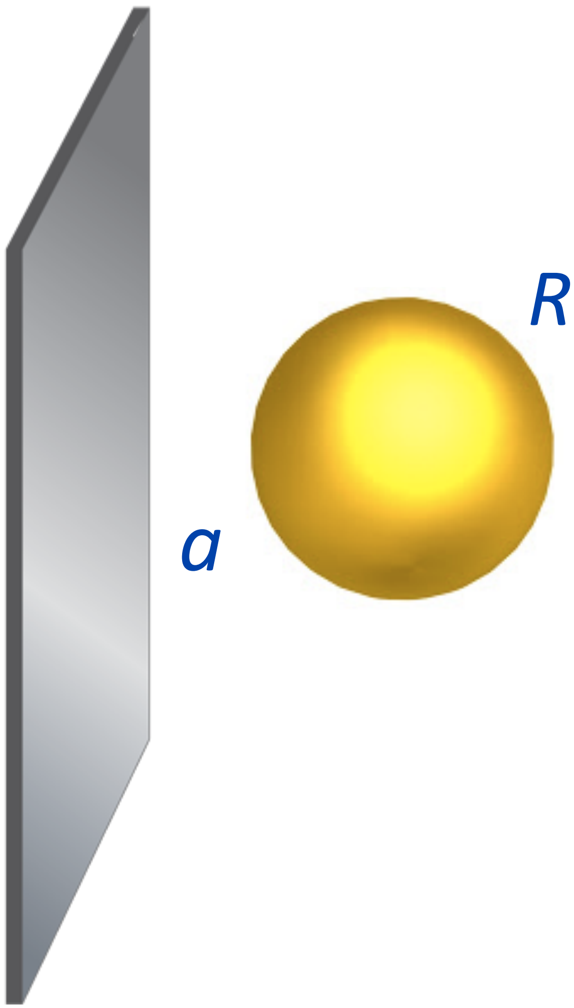


Sparnaay 1958



Onofrio 2003

Casimir effect plane-sphere



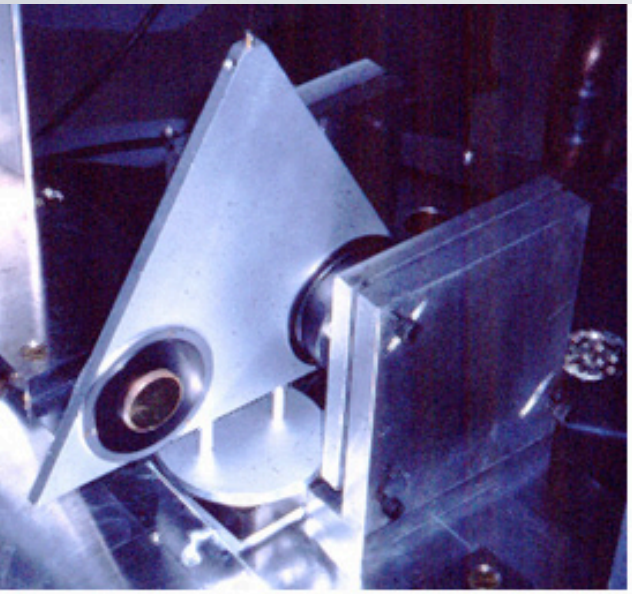
$$\Delta E = -\frac{\hbar\, c\, R\, \pi^2}{360\, a^2}$$

Casimir effect experiments

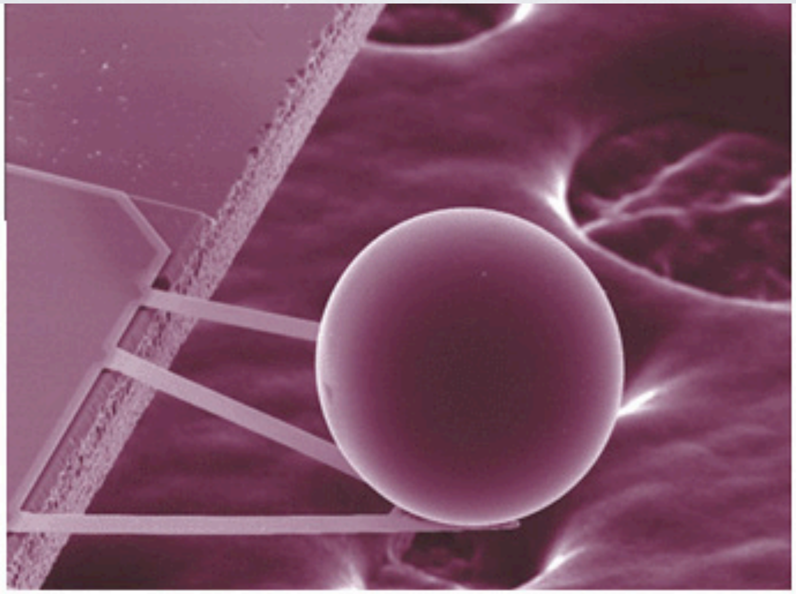
Year	Geometry	Range (μm)	Accuracy (%)	Reference
1958	Plane–plane	$0.3 \div 2.5$	100	Sparnaay 1958
1978	Plane–sphere	$0.13 \div 0.67$	25	van Blokland and Oveerbeek 1978
1997	Plane–sphere	$0.6 \div 12.3$	5	Lamoreaux 1997
1998	Plane–sphere	$0.1 \div 0.9$	1	Mohideen and Roy 1998
2000	Crossed cylinders	$0.02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

Summary of Experiments

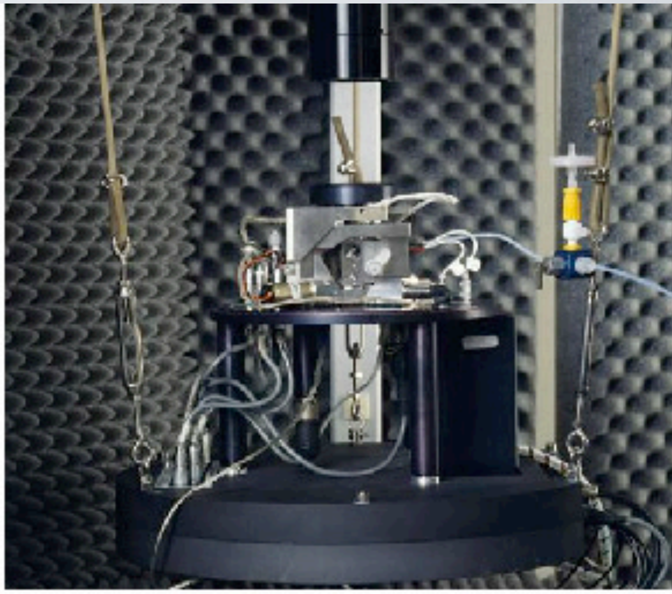
Seattle

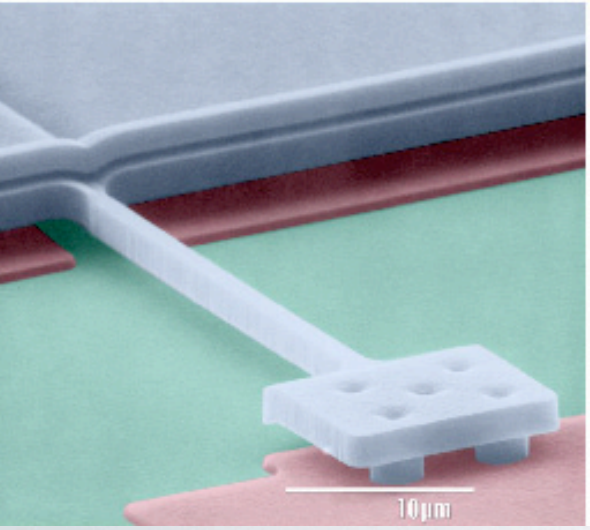


Riverside

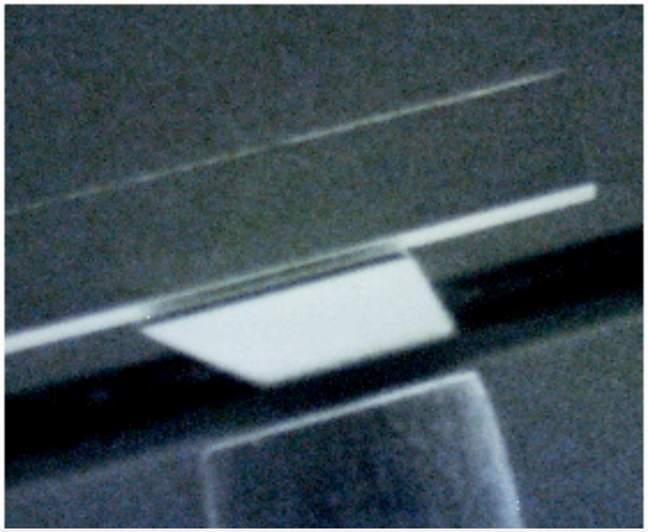


Stockholm

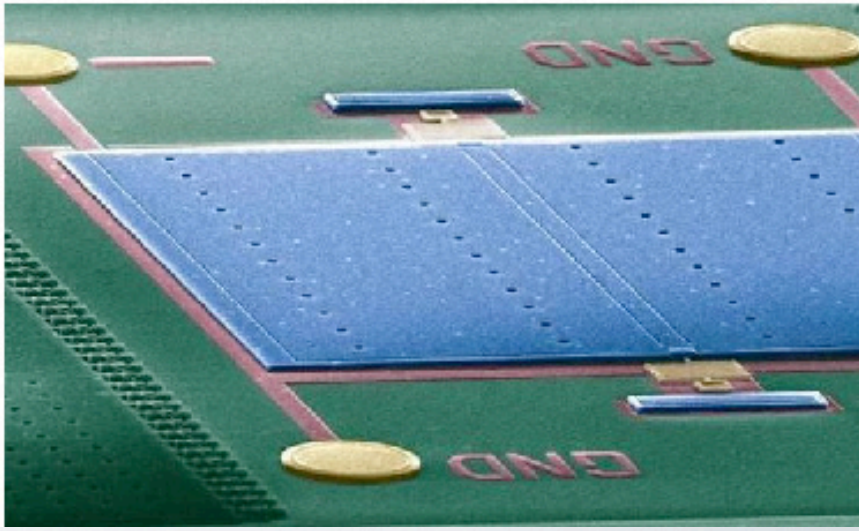




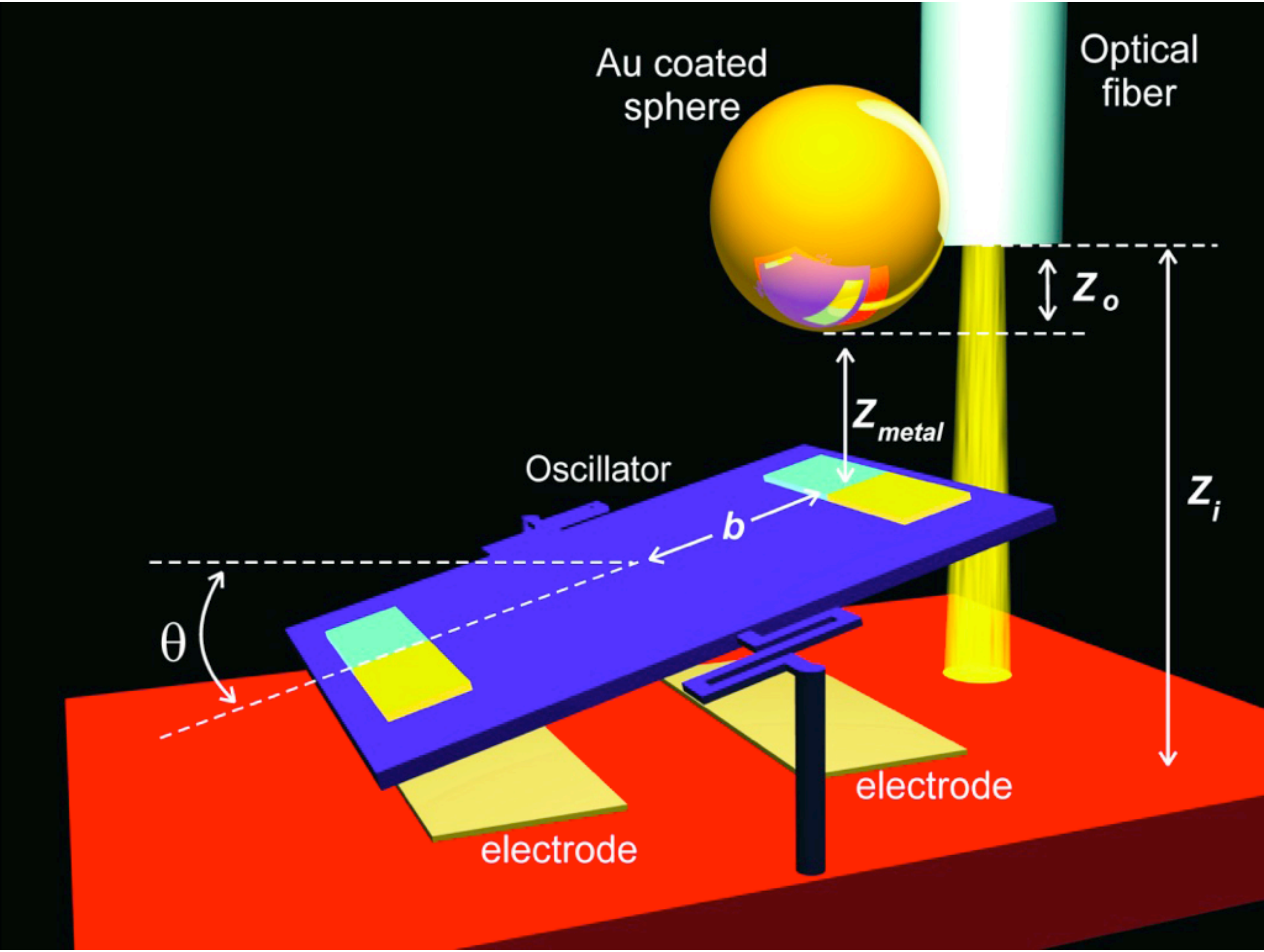
Murray-Hill (Bell Labs)



Padova

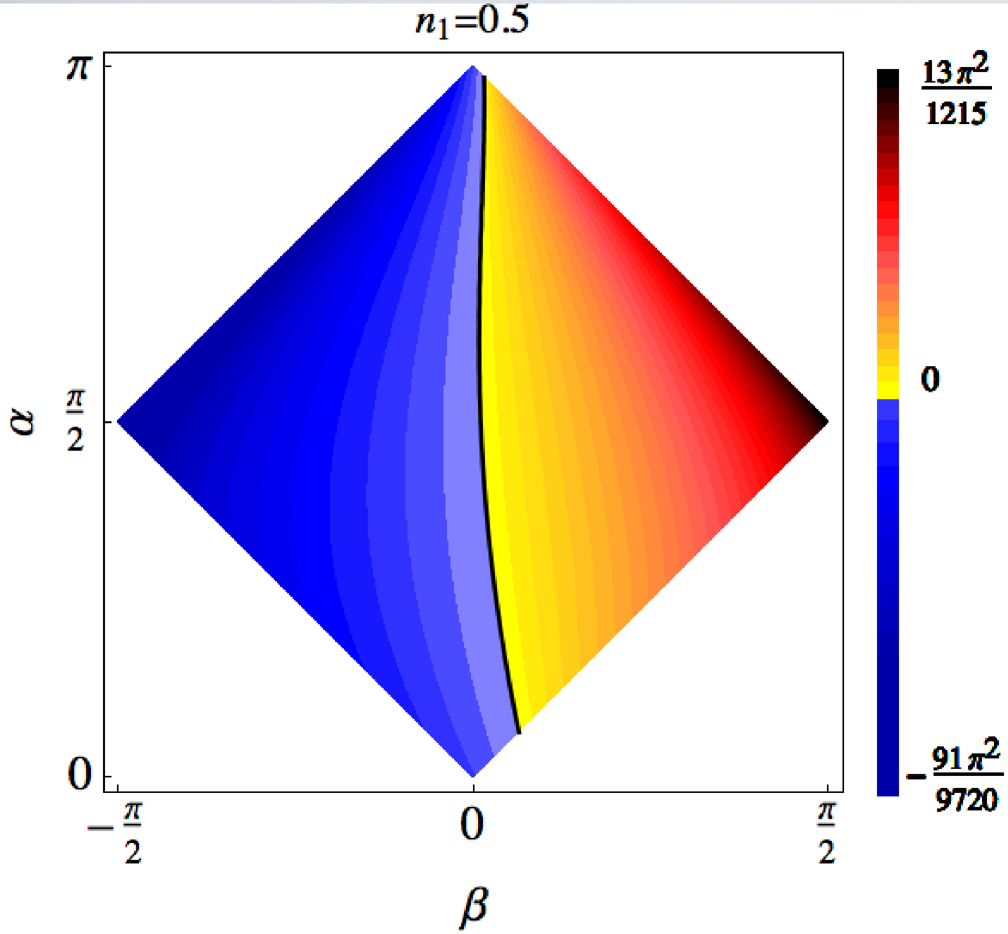


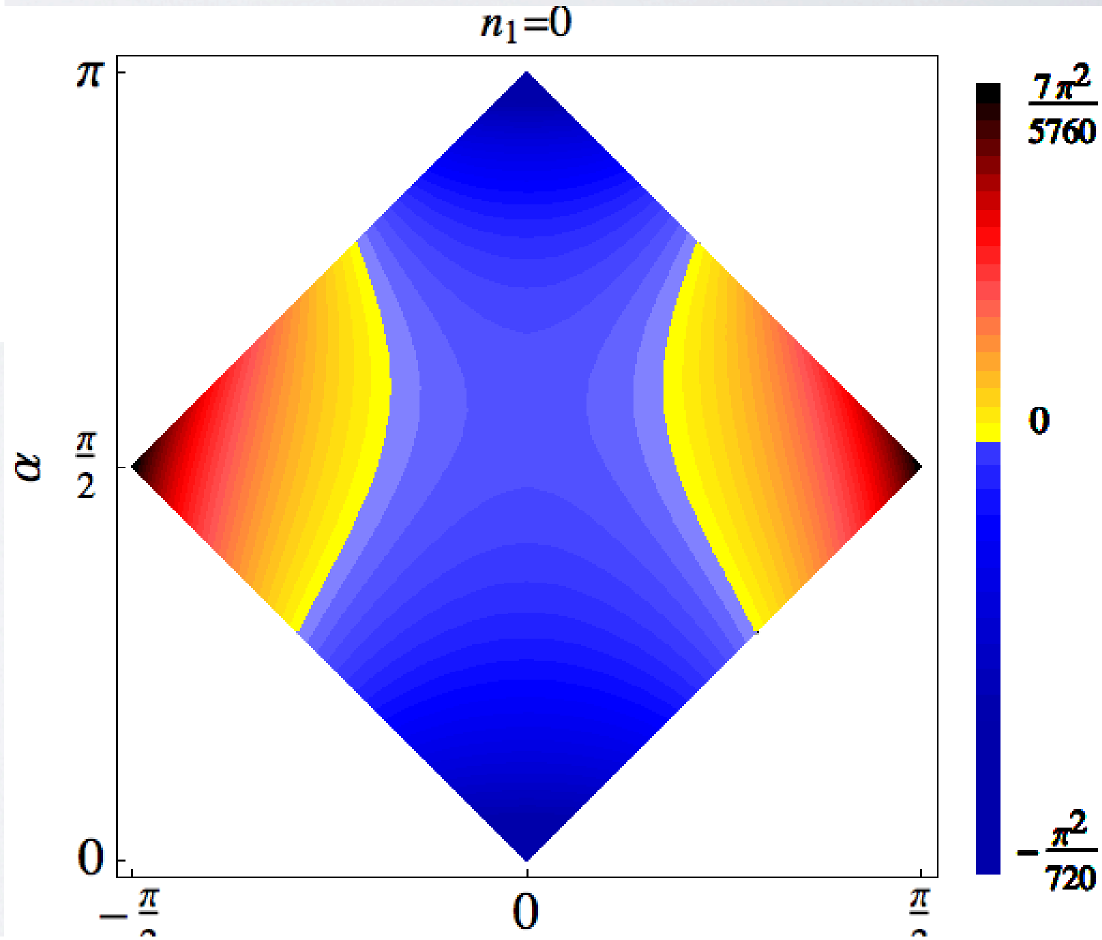
Indiana



Au coated sphere
Optical fiber
z_o
z_{metal}
z_i
Oscillator
b
θ
electrode
electrode

Capasso (2009)

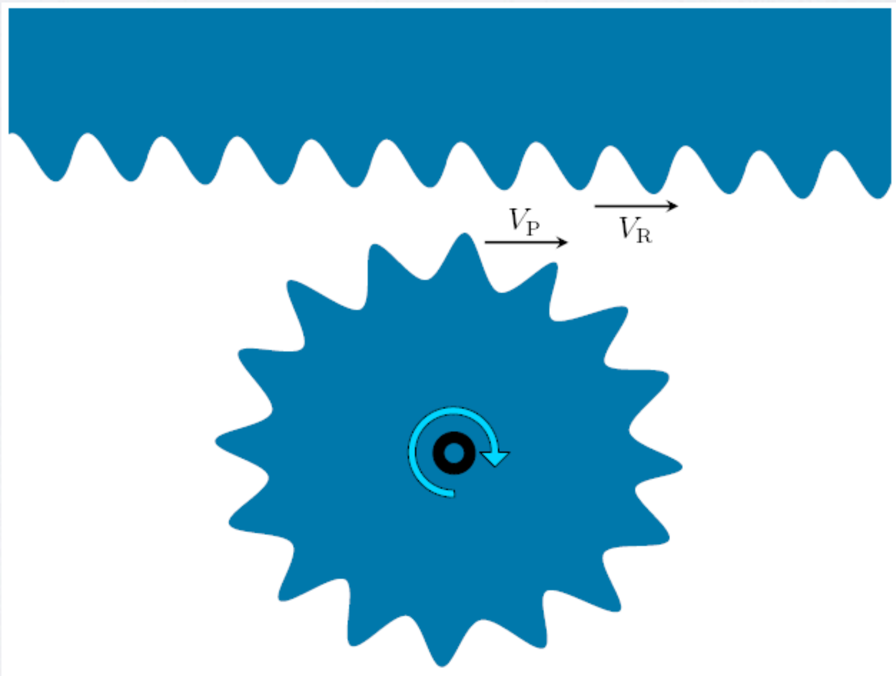




Asorey-Muñoz Castaneda (2013)

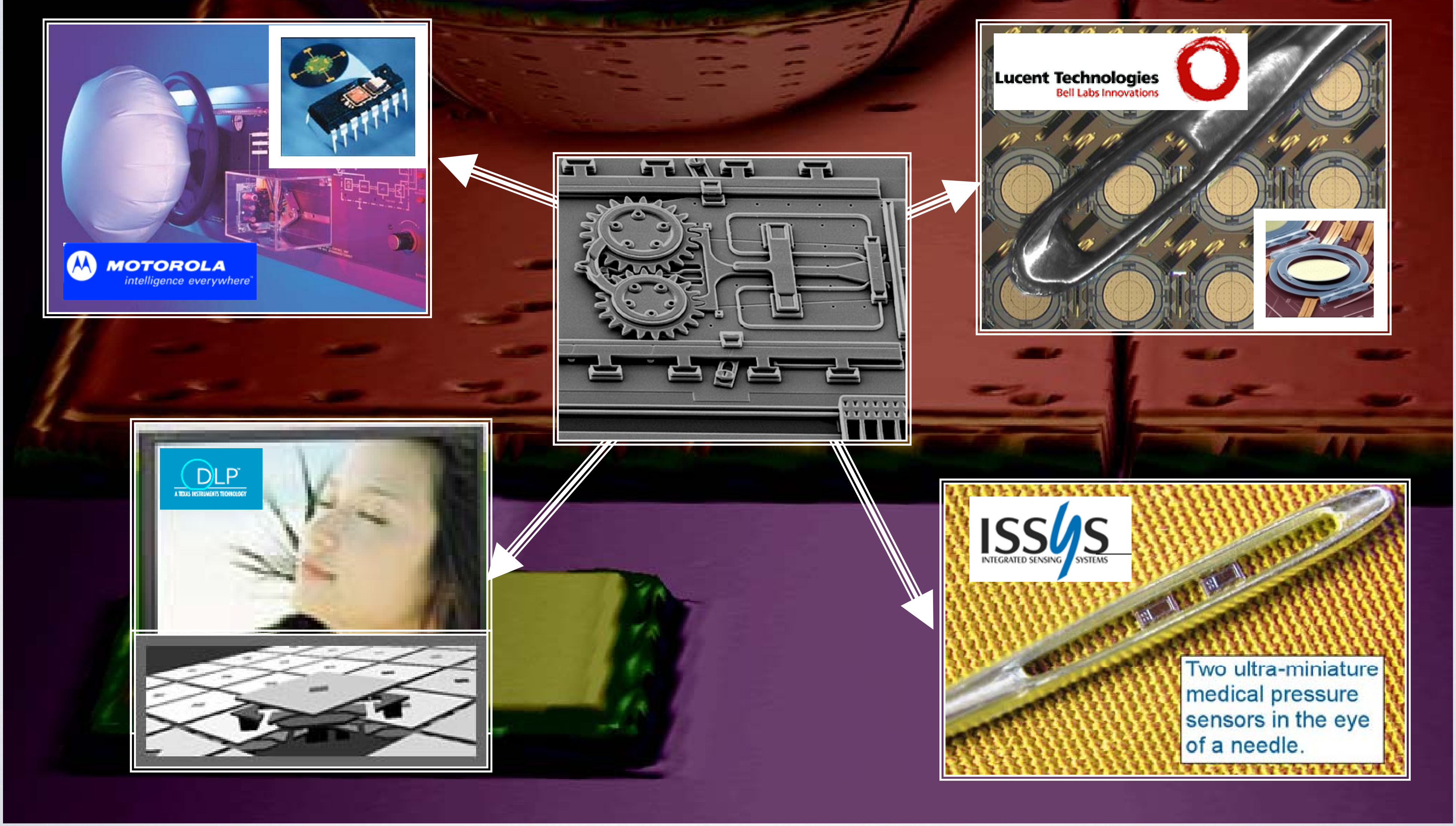
Real Casimir force

- Finite temperature effect (300 K)
- Real conductors and dielectrics (Lifshitz theory)
- Corrugated surfaces (lateral Casimir forces)



MEMS: a mature technology

Integrated circuits with mobile parts



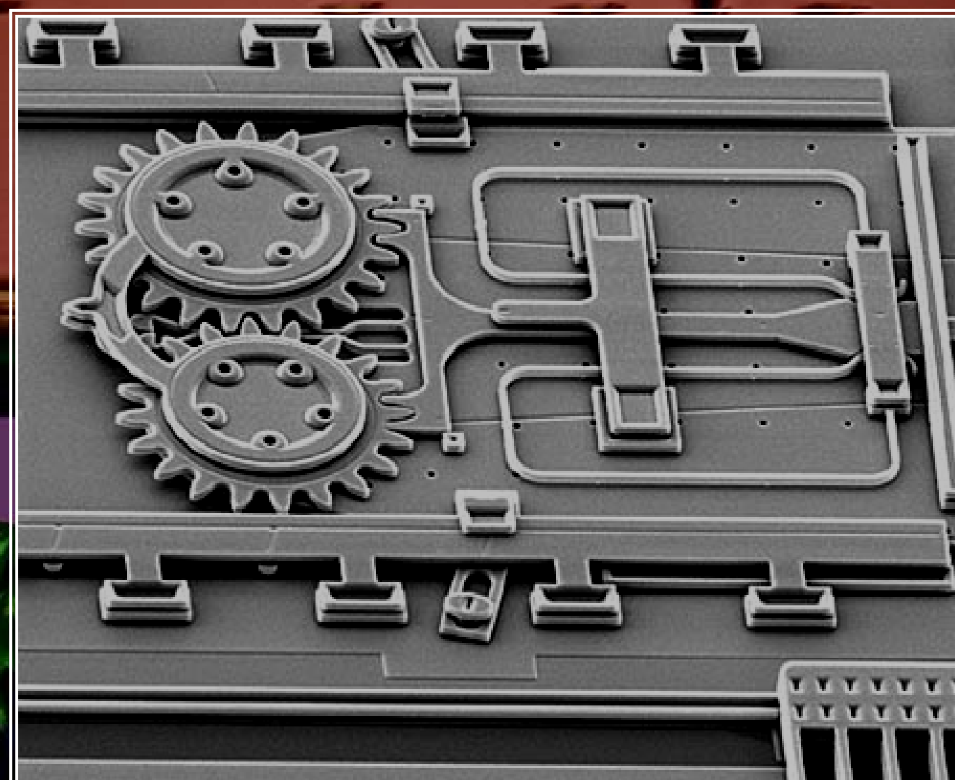
Casimir force at different scales

$$P = \frac{F}{L^2} = -\frac{\pi^2 \hbar c}{240\, d^4}$$

MEMS (1980-today):
Devices with components moving at ~μm distances based on IC technology + chemical release of the mechanical parts

At 1 μm

$$P = 1.3\ \mathrm{mN}/\mathrm{m}^2$$



Casimir force at different scals
e

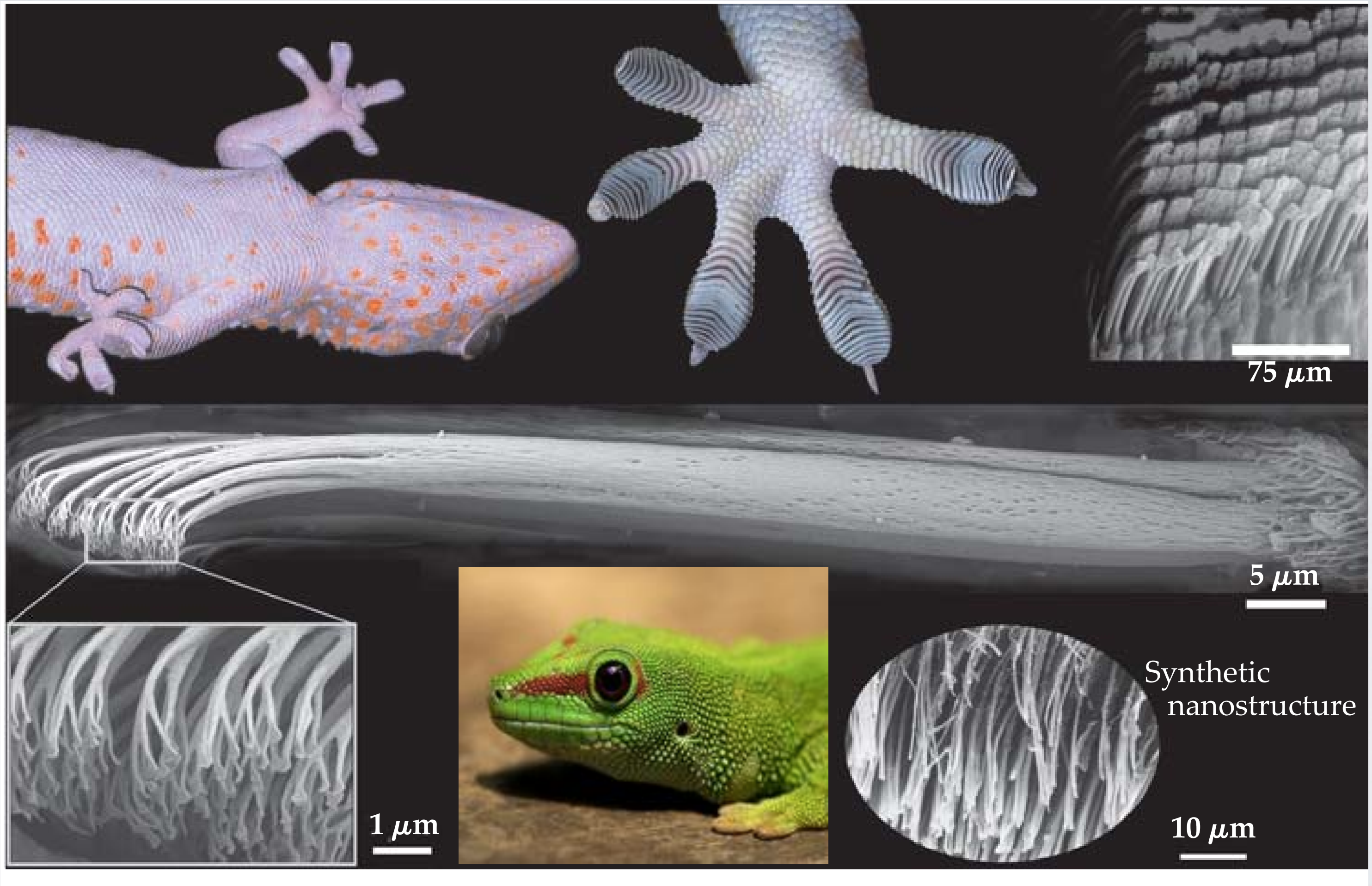
$$P = \frac{F}{L^2} = -\frac{\pi^2 \hbar c}{240\, d^4}$$

Feynaman's Challenge (1959):
"I offer 1000 $ to the first guy who makes an electric motor which is 1/64th of an inch cube"

At 400 μm

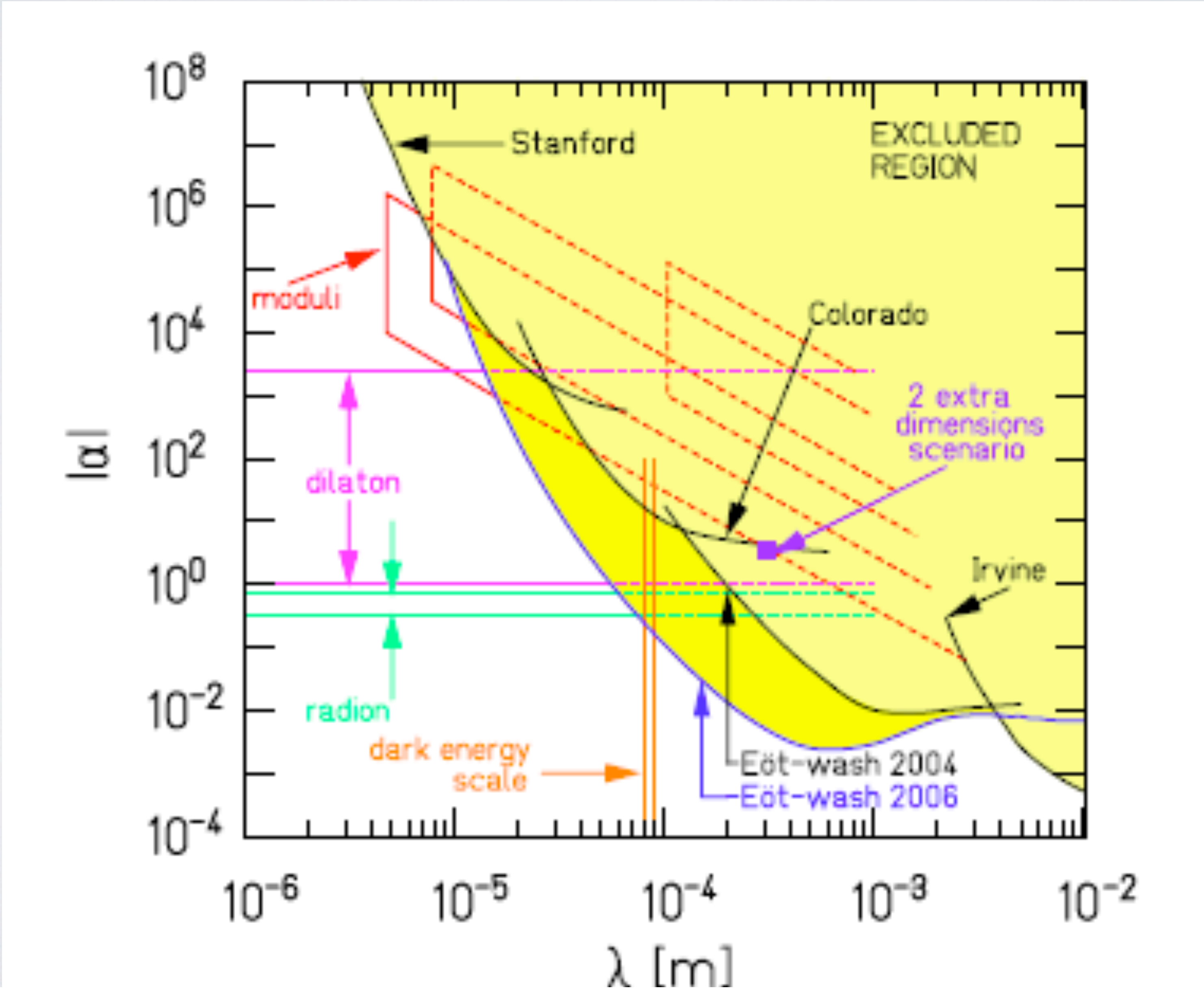
$$P = 5 \cdot 10^{-14}\ \mathrm{N/m^2}$$

Gecko Effect



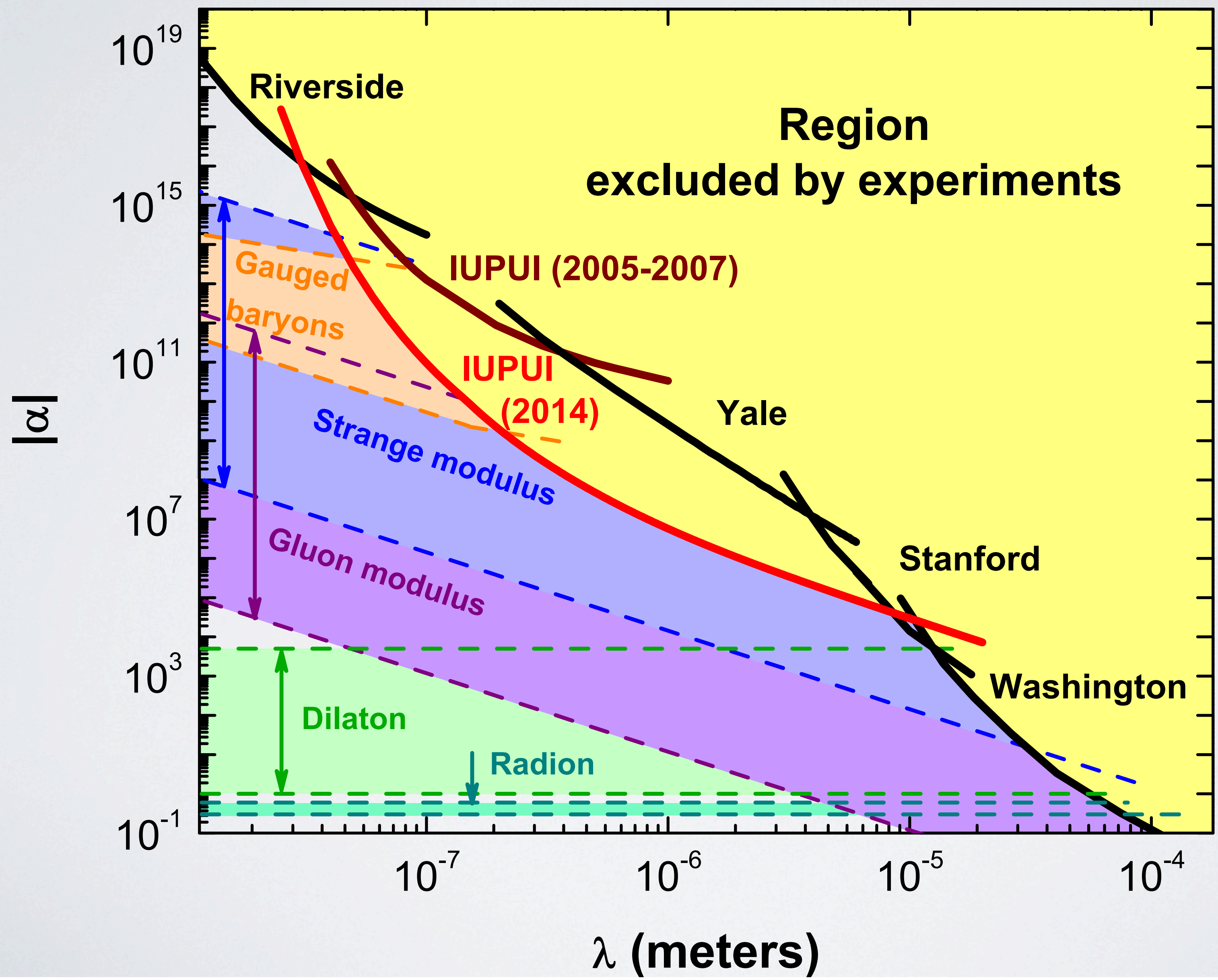
Gravity at short distances

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



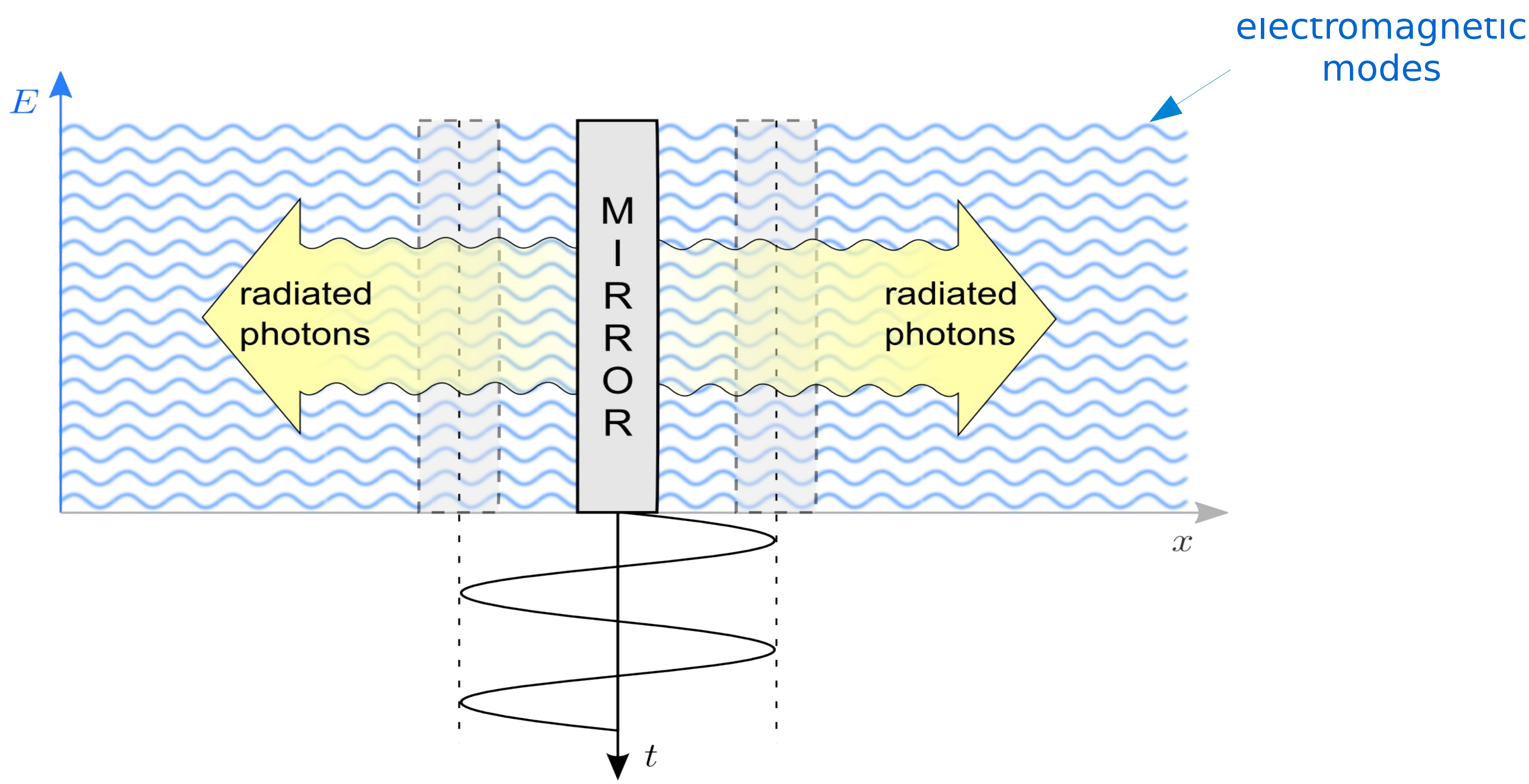
Experimental bounds

2 orders of magnitude improvement (2014)



Dynamical Casimir

Theory: Moore, G., J. Math. Phys. 11, 2679–2691 (1970).



Total photon production rates

Case	Frequency (Hz) Ω	Amplitude (m) a	Maximum velocity (m/s) v	Photon production rate (# photons / s)
moving a mirror by hand	1	1	1	e^{-18}
nano-mechanical oscillator	e^{9}	e^{-9}	1	e^{-9}
SQUID in coplanar waveguide	$18e^{9}$	e^{-4}	$2e^{6}$	e^{5}

Photon production rate:

$$\frac{N}{\tau} = \frac{\Omega}{6\pi}\left(\frac{v}{c}\right)^2$$

$\Omega, a =$ oscillation frequency, amplitude

$v = \Omega a =$ peak velocity of the mirror

$c =$ speed of light

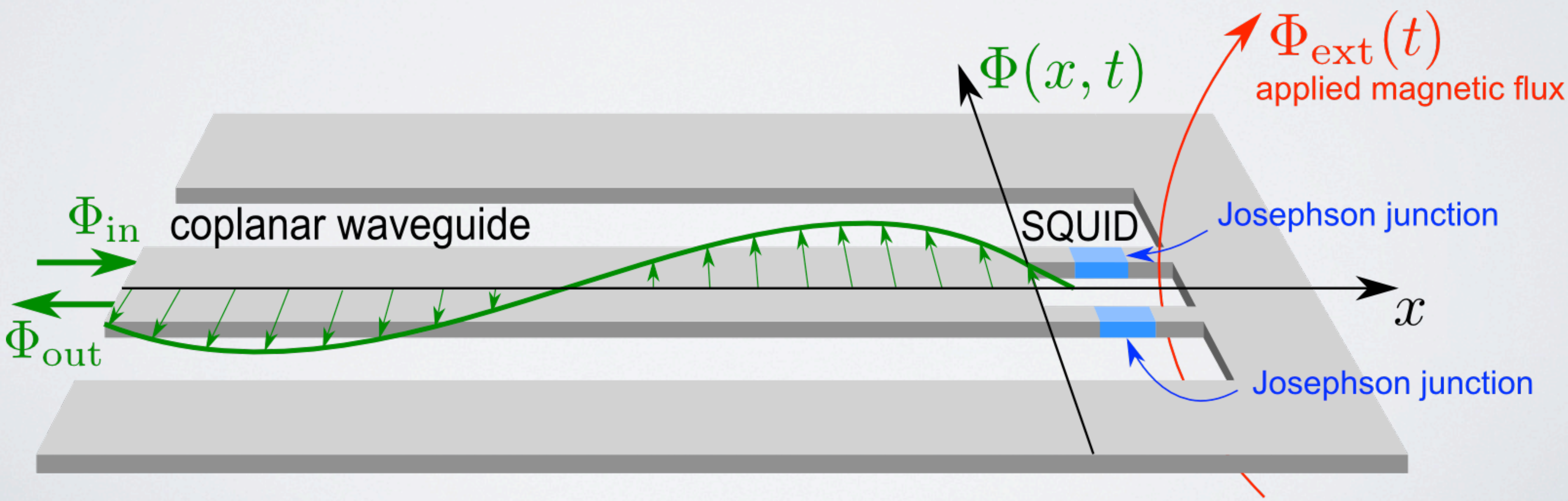
Dynamical Casimir

LETTER

doi:10.1038/nature10561

Observation of the dynamical Casimir effect in a superconducting circuit

C. M. Wilson[1], G. Johansson[1], A. Pourkabirian[1], M. Simoen[1], J. R. Johansson[2], T. Duty[3], F. Nori[2,4] & P. Delsing[1]



Vacuum Energy vs Dark Energy

- Cosmological constant (w=-1)

$$S = \frac{1}{16\,\pi\,G}\int d^4x\sqrt{-g}(R - 2\Lambda_0)$$

$$\frac{E_0}{V} = \frac{1}{8\,\pi\,G}\Lambda_0 = -\frac{P_0}{V}$$

- Cosmological constant is much smaller than any QFT vacuum energy

$$\frac{E_0}{V}^{\rm obs} \sim (10^{-12}\,{\rm GeV})^4$$

$$\frac{E_0}{V}^{\rm (EW)} \sim (100\,{\rm GeV})^4 \qquad \frac{E_0}{V}^{\rm (PL)} \sim (10^{18}\,{\rm GeV})^4$$

Vacuum Energy vs Dark Energy

- Minkowski spacetime

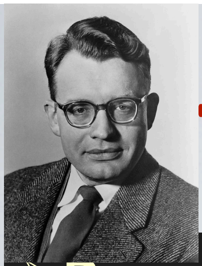
$$\frac{E_0}{V} = \frac{\hbar\, c}{8\,\pi^2}\omega_\infty^4$$

$$\frac{P_0}{V} = \frac{\hbar\, c}{24\,\pi^2}\omega_\infty^4 \qquad w = \frac{1}{3}$$

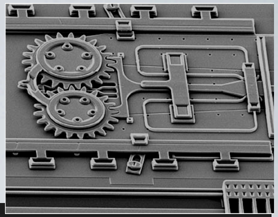
- Cosmological background FLRW

$$\frac{E_0}{V} = \frac{\hbar\, c}{8\,\pi^2}\omega_\infty^4 + \frac{H^2(t)}{8\,\pi^2}\omega_\infty^2 + \mathcal{O}(H^4 \log \omega_\infty)$$

$$\frac{P_0}{V} = \frac{\hbar\, c}{24\,\pi^2}\omega_\infty^4 - \frac{H^2(t)}{24\,\pi^2}\omega_\infty^2 + \mathcal{O}(H^4 \log \omega_\infty)$$



The Future of Casimir effect



- Popularity of QED fluctuations (both experiment and theory)
- Connect Casimir effect with world (Nanotechnology & fundamental physics)
- Casimir-Polder effect
- Drude – Plasma model discrepancy in relation to existing/new force data
- Casimir repulsive forces
- Biology and dispersion forces (biomolecule recognition by selective van der Waals/Casimir dispersion forces)
- Calculations and applications of Casimir dispersive forces
- Electrostatics – patch effects on contact potentials
- Nanoparticles & size effects on dispersion forces
- van der Waals/Gecko superadhesion for various types of rough surfaces and applications to robots, superadhesive tapes etc…
- Investigation of vacuum energy in quantum field theory with applications to QCD and cosmology
- ***Relation of Casimir effect to industry*** (develop further present industrial contacts) and impact on economy