Casimir Effect and Short-Range Forces

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Discussions with a number of other people, in particular within the ESF network "CASIMIR"
http://www.casimir-network.com

The "vacuum energy catastrophe"

- The mean energy density per unit volume
  of electromagnetical field at thermal equilibrium

$$\rho = \sum_{\text{modes}} \bar{n}\hbar\omega + \sum_{\text{modes}}^{\omega_{max}} \frac{\hbar\omega}{2} = \frac{\pi^2 (k_B T)^4}{15\,(\hbar c)^3} + \frac{(\hbar\omega_{max})^4}{8\pi\,(\hbar c)^3}$$

- is finite for the first Planck law (1900) $\quad \bar{n} = \frac{1}{e^{\hbar\omega/k_B T} - 1}$
- is infinite when accounting for zero-point fluctuations (Planck 1912)
- is much too large to be compatible with gravity observations for any reasonable cutoff frequency ω_{max} (Nernst 1916)

A major problem for fundamental physics
known since 1916, still unsolved today …

S. Weinberg, Rev. Mod. Phys. **61** 1 (1989)

A common "solution" : the denial of vacuum energy

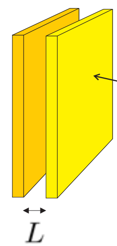
Quotation : Pauli 1933

« For fields [in contrast to the material oscillator], it is more consistent not to introduce the zero-point energy …
For, on the one hand, the latter would give rise to an infinitely large energy per unit volume due to the infinite number of degrees of freedom ...
and, as is evident from experience, it does not produce any gravitational field ...
And, on the other hand, it would be unobservable since it cannot be emitted, absorbed or scattered, and hence, cannot be contained within walls. »

W. Pauli, Die Allgemeinen Prinzipien der Wellenmechanik (Springer, 1933)

Confining the vacuum in a cavity : the Casimir effect

$$F_{Cas} = -\frac{dE_{Cas}}{dL}\ , \quad E_{Cas} = -\frac{\hbar c \pi^2 A}{720 L^3}$$



- Here written for an ideal case
  - Parallel plane mirrors
  - Perfect reflection
  - Null temperature
- Attractive force (negative pressure)

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

$|P_{Cas}| \sim 1\text{mPa}$ at $L = 1\mu\text{m}$

A universal effect from confinement of vacuum fluctuations :
it depends only on ħ, *c, and geometry*

Hendrik Casimir 1948

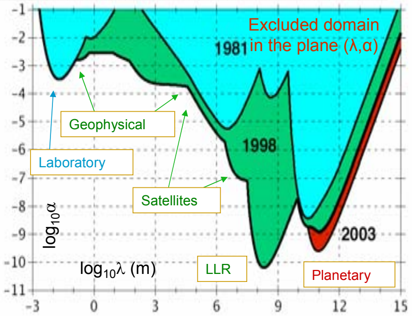
Search for scale dependent modifications of the gravity force law ("fifth-force experiments")

The exclusion plot for deviations with a Yukawa form

$$V(r) = -\frac{GMm}{r}\left(1 + \alpha e^{-\frac{r}{\lambda}}\right)$$

Windows remain open for deviations at short ranges $\lambda < 1\,\mathrm{mm}$

or long ranges $\lambda > 10^{16}\,\mathrm{m}$



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge & E. M. Standish (2003) ; see M.T. Jaekel & S. Reynaud IJMP **A20** (2005)

The Search for Non-Newtonian Gravity, E. Fischbach & C. Talmadge (1998)

Constraints at sub-mm scales

- Best result to date : Eöt-wash group (U. Washington, Seattle)
- Cavendish-type experiments with torsion pendulum
- At 95% confidence, a Yukawa interaction with gravitational strength $\alpha > 1$ must have a range $\lambda < 56\mu m$

- D.J. Kapner *et al* PRL **98** (2007) 021101
- E.G. Adelberger et al PRL **98** (2007) 131104

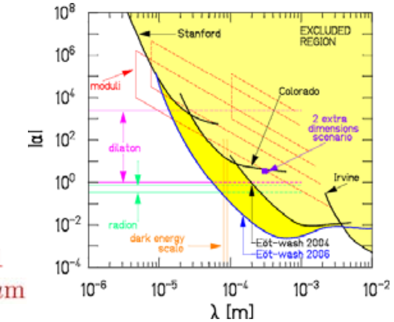


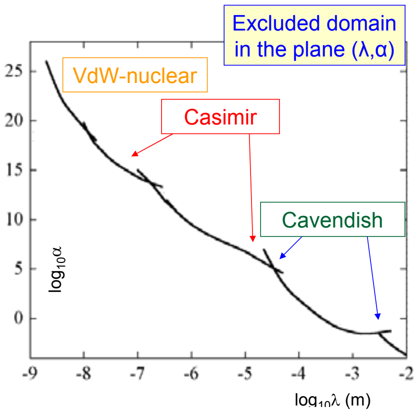
FIG. 6: Constraints on Yukawa violations of the gravitational 1/r² law. The shaded region is excluded at the 95% confidence level. Heavy lines labeled Eöt-Wash 2006, Eöt-Wash 2004, Irvine, Colorado and Stanford show experimental constraints from this work, Refs. [11], [14], [15] and [16, 17], respectively. Lighter lines show various theoretical expectations summarized in Ref. [9].

Constraints at shorter scales

- At (~) μm scales, comparison with theory of Casimir measurements
- Also worth with Van der Waals * and nuclear # forces at shorter scales

- The hypothetical new force would be seen as a difference between experiment and theory

$$F_{\mathrm{new}} \equiv F_{\mathrm{exp}} - F_{\mathrm{th}}$$

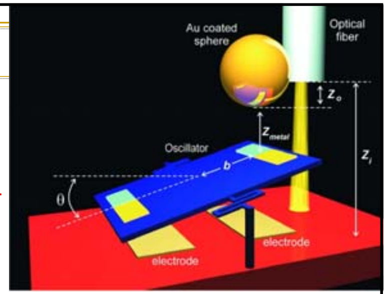


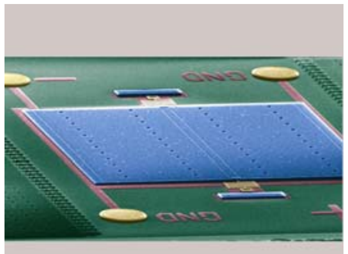
* S. Lepoutre *et al,* EPL **88** (2009) 20002

\# V. Nesvizhevsky *et al,* Phys. Rev. **D77** (2008) 034020

Casimir experiments

- Recent precise experiments : dynamic measurements of the resonance frequency of a microelectromechanical resonator





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

- Shift of the resonance determined by the gradient *G* of the Casimir force
- Plane-sphere Casimir effect calculated within the proximity force approximation (see below)

R.S. Decca, Talk at Sante Fe Workshop (09/2009) @ http://cnls.lanl.gov/casimir/

Comparison with theory

Recent experimental results deviate from theoretical expectations

BRIEF REPORTS PHYSICAL REVIEW D 75, 077101 (2007)

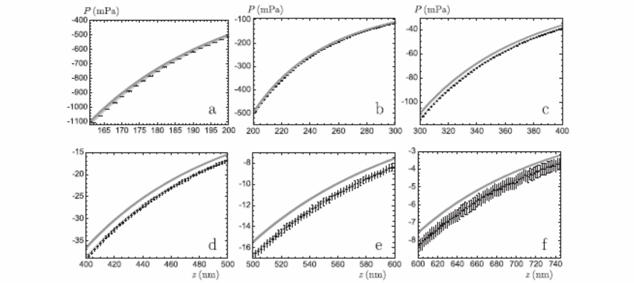


FIG. 1. Experimental data for the Casimir pressure as a function of separation z. Absolute errors are shown by black crosses in different separation regions (a–f). The light- and dark-gray bands represent the theoretical predictions of the impedance and Drude model approaches, respectively. The vertical width of the bands is equal to the theoretical error, and all crosses are shown in true scale.

The difference does not have a Yukawa form !

R.S. Decca, D. Lopez, E. Fischbach *et al*, Phys. Rev. **D75** (2007) 077101

The description of metals ?

- A problem with the description of metallic mirrors ?
  - Lifshitz formulation of the Casimir force
    - interaction between two plane mirrors
  - Dielectric functions modelled
    - conduction electrons in the metals with relaxation accounted for (Drude model)
  - Gold has a finite conductivity
    - $\gamma \neq 0$ is certainly a better description than $\gamma=0$

$$\varepsilon(\omega) = \bar{\varepsilon}(\omega) + \frac{\sigma(\omega)}{-i\omega}$$

$$\sigma(\omega) = \frac{\omega_P^2}{\gamma - i\omega}$$

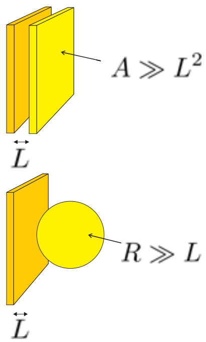
$$\sigma(0) = \frac{\omega_P^2}{\gamma}$$

- Experiments agree better with $\gamma=0$ than with the expected $\gamma\neq 0$!
  - Artifact in the experiments ?
  - Problem in the theoretical evaluations ?
  - Difference between the situation studied in theory and the experiments ?

S. Reynaud *et al*, Proceedings of QFEXT'09, arXiv:1001.3375 (2010)

The role of geometry ?

- The geometry of the precise experiments is not the geometry of the precise calculations !



- Calculations in the plane-sphere geometry usually performed by using the proximity force approximation (PFA) which amounts to a mere averaging of the plane-plane result over the distances
- PFA expected to be accurate at the limit *R*>>*L*

- But what is the accuracy for given values of *R* and *L* ?
- How does this accuracy depend on the properties of the mirror, on the distance, on the temperature ?

S. Reynaud *et al*, Proceedings of QFEXT'09, arXiv:1001.3375 (2010)

Detailed theory of Casimir forces

- Casimir physics : mechanical effects of the coupling between mirrors and vacuum fluctuations
  - Mirrors described by their scattering properties, which are determined by optics and condensed matter physics
  - Confining vacuum fluctuations in a cavity affects the radiation pressure and produces the Casimir effect
- The "scattering approach"
  - Used for years for evaluating the Casimir force between "real" mirrors (non perfect mirrors)
  - Today the best solution for calculating the Casimir force in non trivial geometries

M.-T. Jaekel, S. Reynaud, J. Physique **I-1** (1991) 1395 *arXiv:quant-ph/0101067*
A. Lambrecht, S. Reynaud EPJD **8** (2000) 309 *arXiv:quant-ph/9907105*

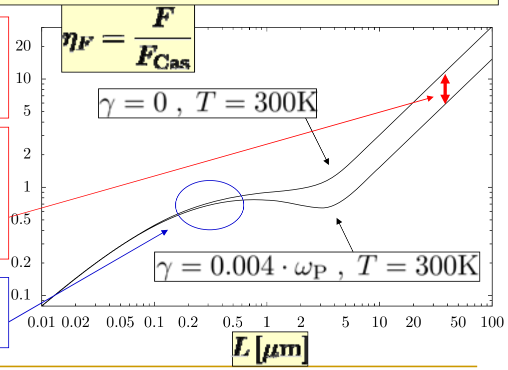
A. Lambrecht, P. Maia Neto & S. Reynaud, New J. Physics **8** (2006) 243

Temperature and dissipation for plane mirrors

Casimir force calculated between plane mirrors

Expressed as a ratio to ideal Casimir formula

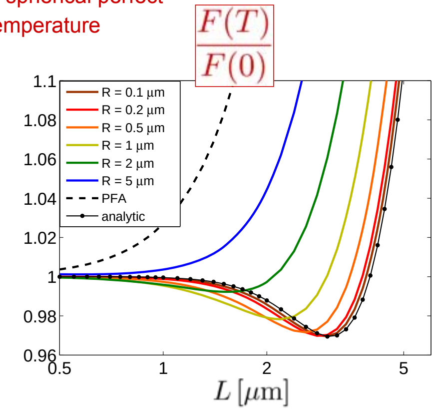
- Strong correlation between dissipation and thermal effects
- Variation by a factor 2 at the high temperature limit (large distances)
- Current precise experiments



G. Ingold, A. Lambrecht, S. Reynaud, Phys. Rev. **E80** (2009) 041113

Temperature in the plane-sphere geometry

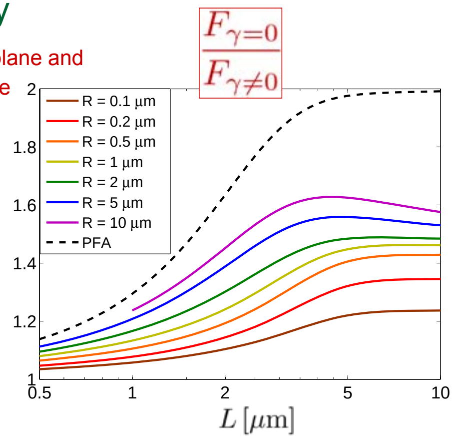
- Force between plane and spherical perfect reflectors at room or zero temperature
- Drawn as the ratio of force at *T≠0* to force at *T=0*
  - Contribution of thermal photons repulsive at some distances !
  - Casimir entropy also found negative at some distances
  - Features never seen for perfect plane mirrors



A. Canaguier-Durand, P.A. Maia Neto, A. Lambrecht, S. Reynaud
PRL **104** (2010) 040403

Temperature and dissipation in the plane-sphere geometry

- Force between metallic plane and sphere at room temperature
- Drawn as the ratio of force at $\gamma = 0$ (plasma) to force at $\gamma \neq 0$ (Drude)
  - Plasma and Drude always closer than expected from PFA
  - Ratio at large *L* never approaches the factor 2 given by PFA



A. Canaguier-Durand, P.A. Maia Neto, A. Lambrecht, S. Reynaud
PRL **104** (2010) 040403