Short-range tests of gravity and the Casimir effect

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UNIVERSITE
PIERRE & MARIE CURIE
LA SCIENCE A PARIS

Workshop on Advances in Precision Tests and
Experimental Gravitation in Space, Florence 2006

EU Framework 6 project

NEST (New Emerging Science & Technology)

Motivation : Tests of the Newtonian law

New hypothetical forces

(cf. G.Veneziano's and G. Tino's talk)

Generic representation :
Yukawa + Newtonian
potential

$$V(r) = V_N(r) + V_Y(r)$$

$$V_N(r) = -G_N \frac{M_1 M_2}{r}$$

$$V_Y(r) = V_N(r)\alpha \exp(-r/\lambda)$$

$$F(r) = F_N(r) + F_Y(r)$$

$$F_N(r) = -G_N \frac{M_1 M_2}{r^2}$$

$$F_Y(r) = F_N(r)\alpha\left(1 + \frac{r}{\lambda}\right)\exp(-r/\lambda)$$

Modification of
Newtonian law between
pointlike masses

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

How to test the Newtonian law ?

Measurement give constraints in the the plane(λ, α)

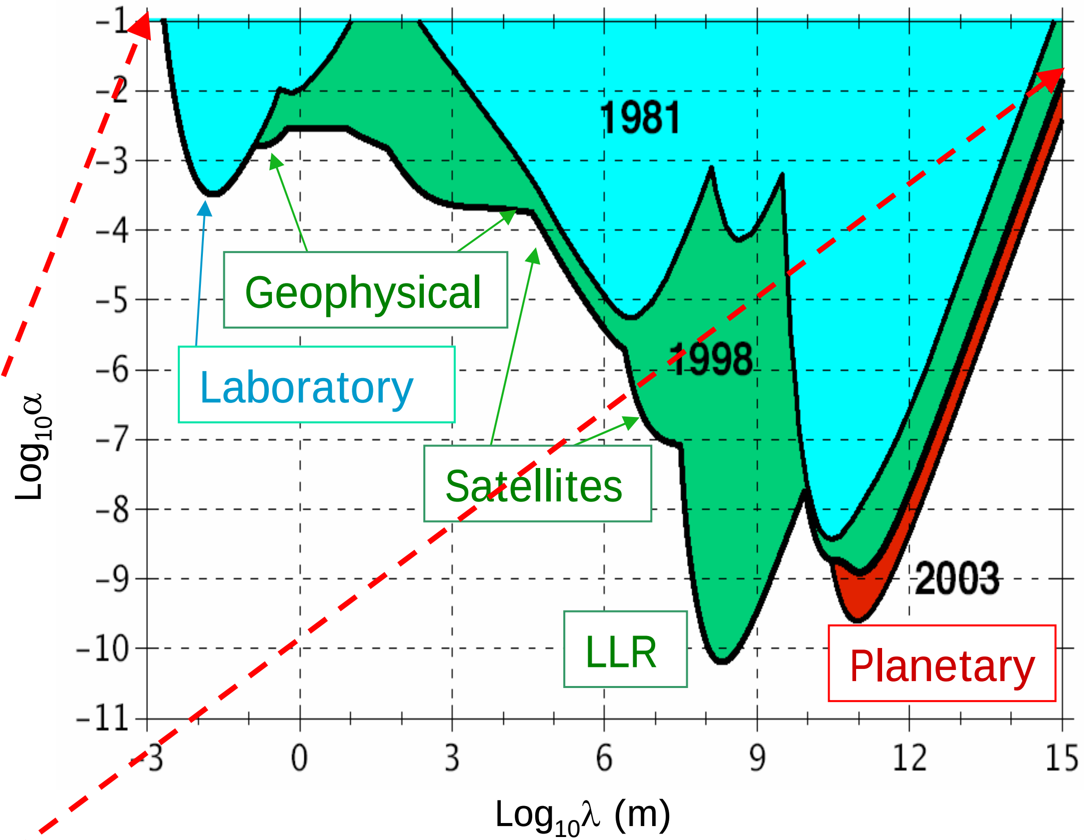
Open window
at short distances…

$\lambda < 10^{-3}\,\mathrm{m}$

and at long distances

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

(cf. Marc Jaekel's talk)



Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge, and E. M. Standish (2003)

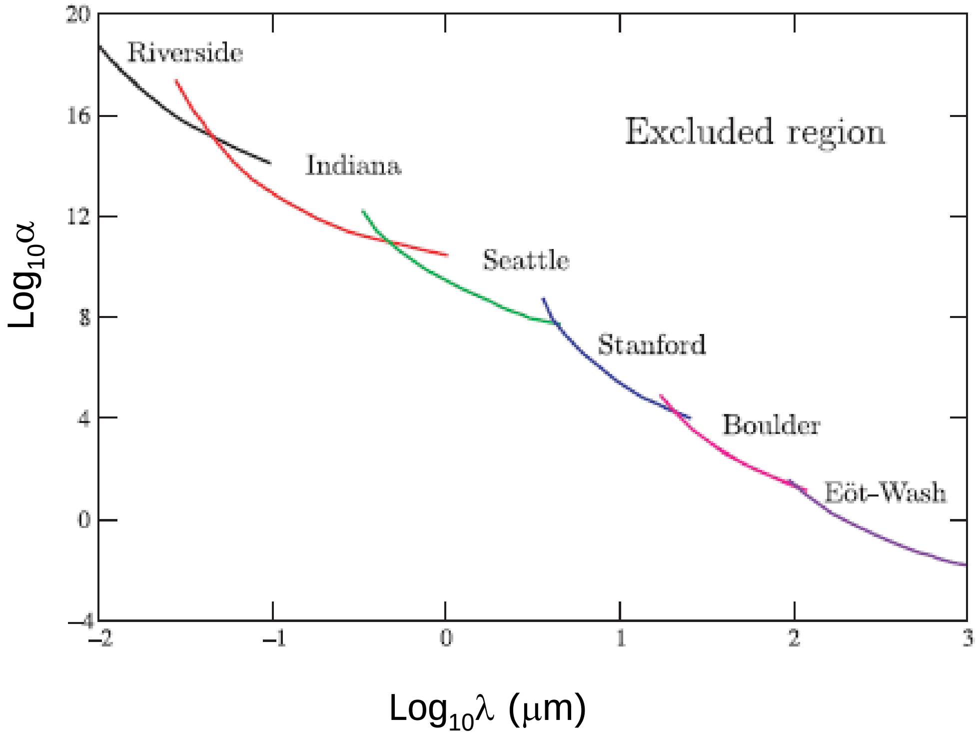
***The Search for Non-Newtonian Gravity*, E. Fischbach & C. Talmadge (1998)**

Test at short distances

- Gravity measurements at millimetric distances

$$\frac{GM_1M_2}{r}\left(1+\alpha e(-r/\lambda)\right)$$

- λ ≤30µm : comparison between experimental results and theoretical predictions of the Casimir force

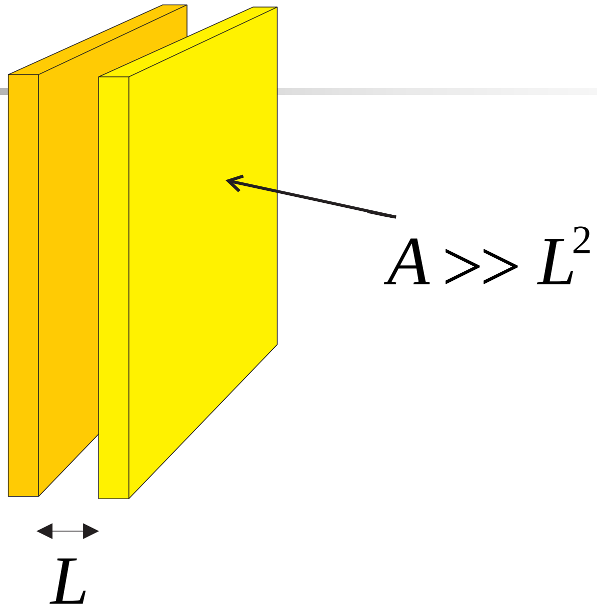


E. Adelberger *et al* Ann. Rev. Nucl. Part. Sci. (2003) *hep-ph/0307284*

Casimir 1948

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

$$E_{\mathrm{Cas}} = -\frac{\hbar c \pi^2}{720\, L^3} A$$



- Assumptions
  - plane parallel mirrors
  - perfect reflection
  - zero temperature
  - perfectly flat surfaces

- Order of magnitude of the Casimir pressure

$$L = 1\mu\mathrm{m} \rightarrow \frac{F_{Cas}}{A} \approx 10^{-3}\,\mathrm{Pa}$$

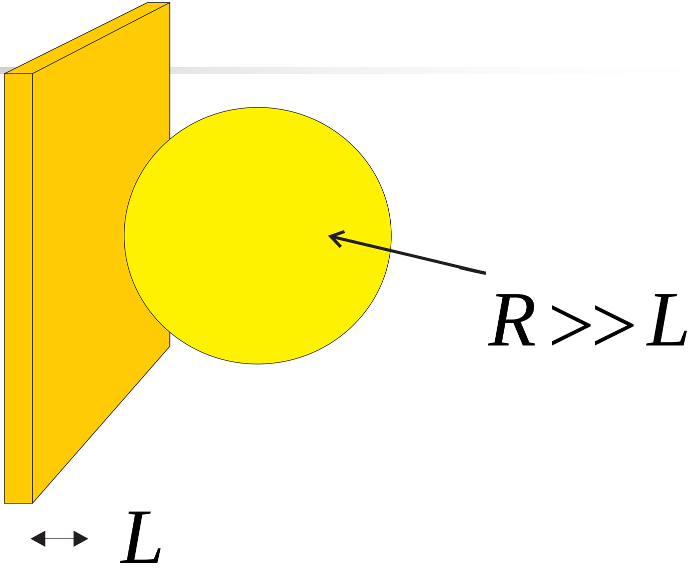
Plane-sphere geometry

- Proximity force approximation (PFA)

contributions of surface elements are added up independently

$$F_{PS} = \int d^2x \frac{F_{PP}(x)}{A}$$

$$F_{PS} = 2\pi R E_{PP}$$



- BUT
- Casimir forces are not additive
- Approximation is valid for

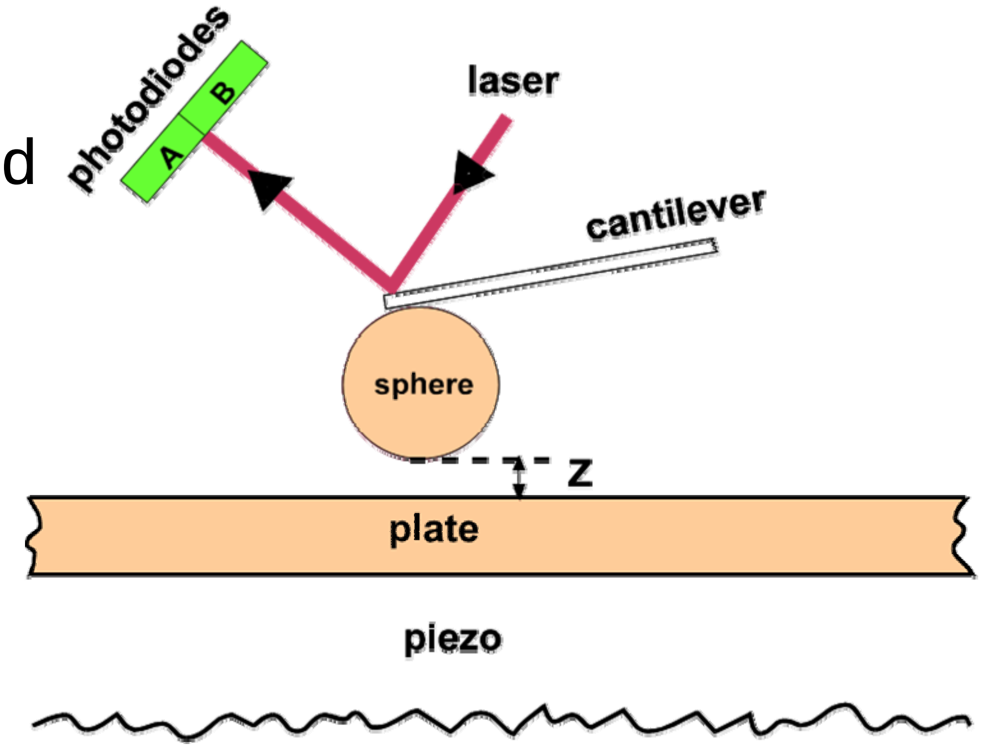
$$R >> L$$

Mohideen et al. (Riverside)

Atomic force microscope (AFM)

Courtesy U. Mohideen

- Plane-sphere geometry
- Sphere and plane covered with Au
- Distances 60-900nm
- Optical readout
- Experimental accuracy ~1% @ short distances

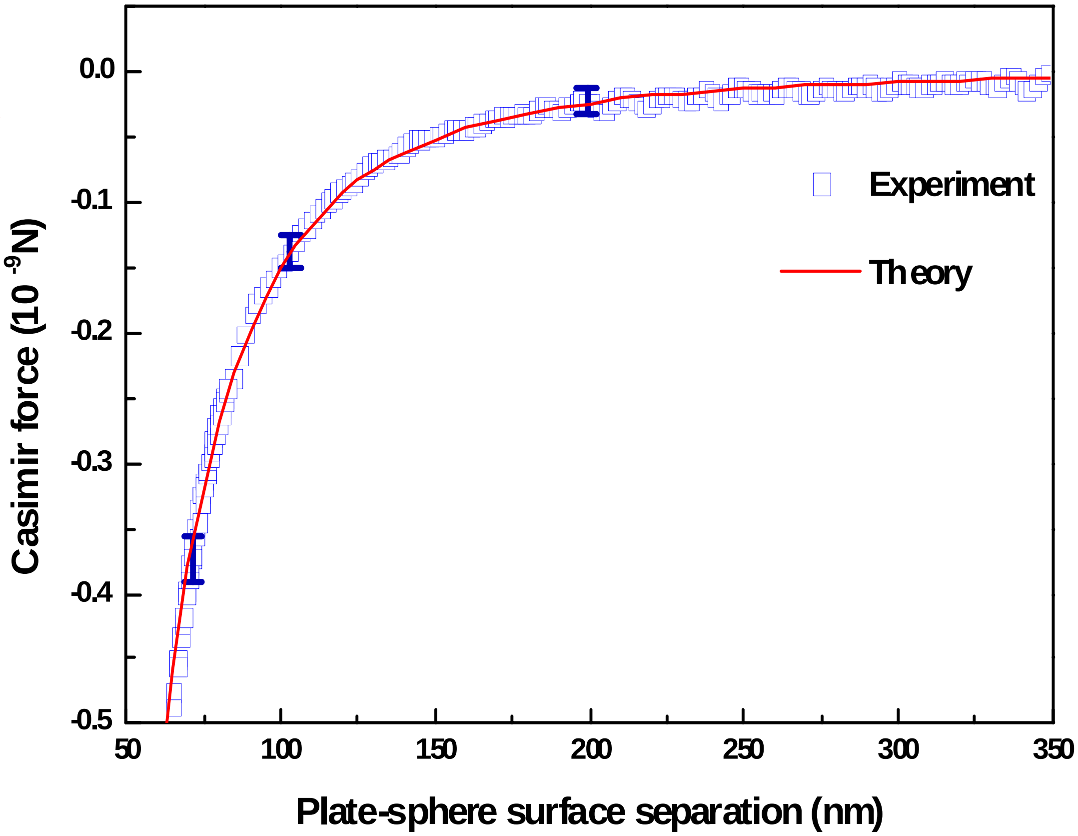


PRL 81, 4549 (1998)
PRA 62 052109 (2000)

Theory - experiment comparison

Agreement at ~% level after having accounted for

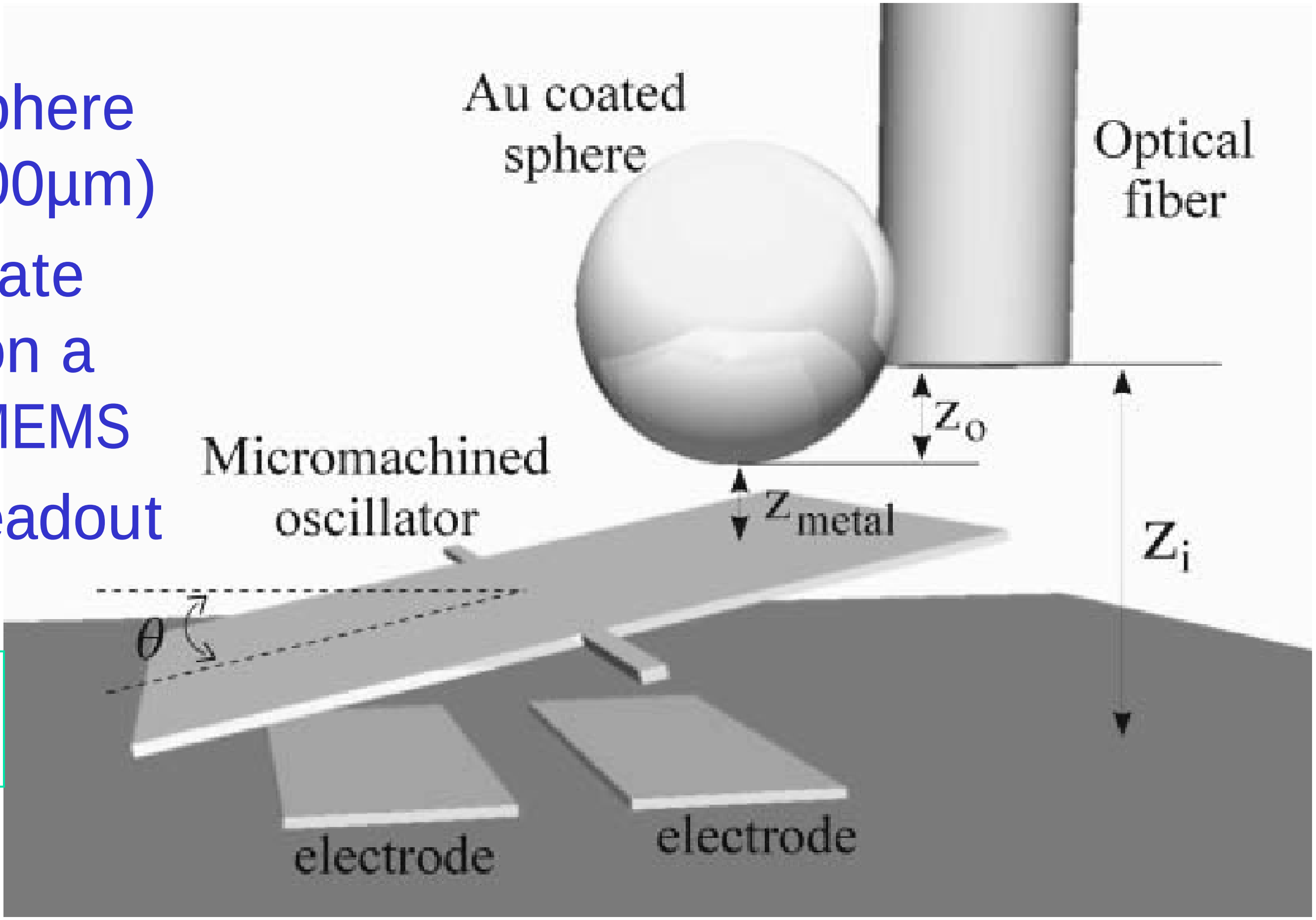
- Plane-sphere geometry
- Imperfect reflection
- Room temperature (correction < 1%)
- Surface roughness



Courtesy U. Mohideen

Fischbach et al. (Purdue University)

- Au-coated sphere (R=100-600µm)
- Cu-coated plate mounted on a torsional MEMS
- Capacitive readout



Static or dynamic measurements

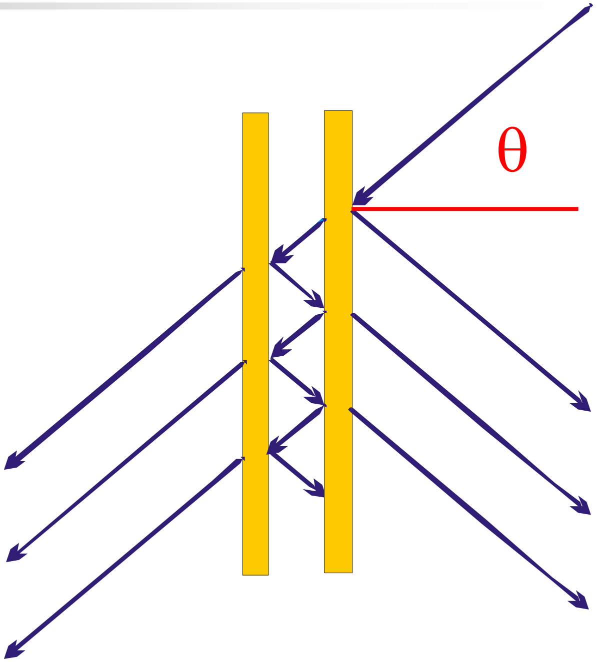
L=260-1200nm

Courtesy E. Fischbach

R. Decca *et al* Phys. Rev. D68, 116003 (2003)

Origin of the Casimir Force

Vacuum radiation pressure



- outside the cavity : $\frac{\hbar\omega}{2}\cos^2\theta$
- inside the cavity : $\frac{\hbar\omega}{2}\cos^2\theta\times g(\omega)$

Spectral mode density :

$$g_k^p(\omega)=\frac{1-\left|r_1^p(\omega)r_2^p(\omega)e^{2ik_zL}\right|^2}{\left|1-r_1^p(\omega)r_2^p(\omega)e^{2ik_zL}\right|^2}$$

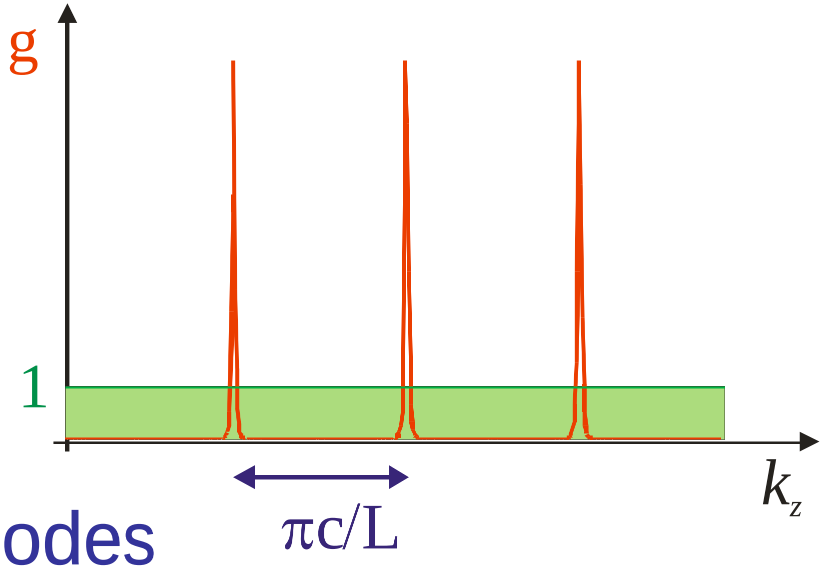
$$k_z=\frac{\omega}{c}\cos\theta$$

longitudinal wave vector

Mode density and Casimir force

- Cavity resonances

- Casimir force = integral over all field modes



$$F = A\sum_{p}\int\frac{\mathrm{d}^2k}{4\pi^2}\int_0^\infty\frac{\mathrm{d}k_z}{2\pi}\hbar\omega\cos^2\Theta\left(1\text{-}g_k^p(\omega)\right);\quad p = \mathrm{TE},\mathrm{TM}$$

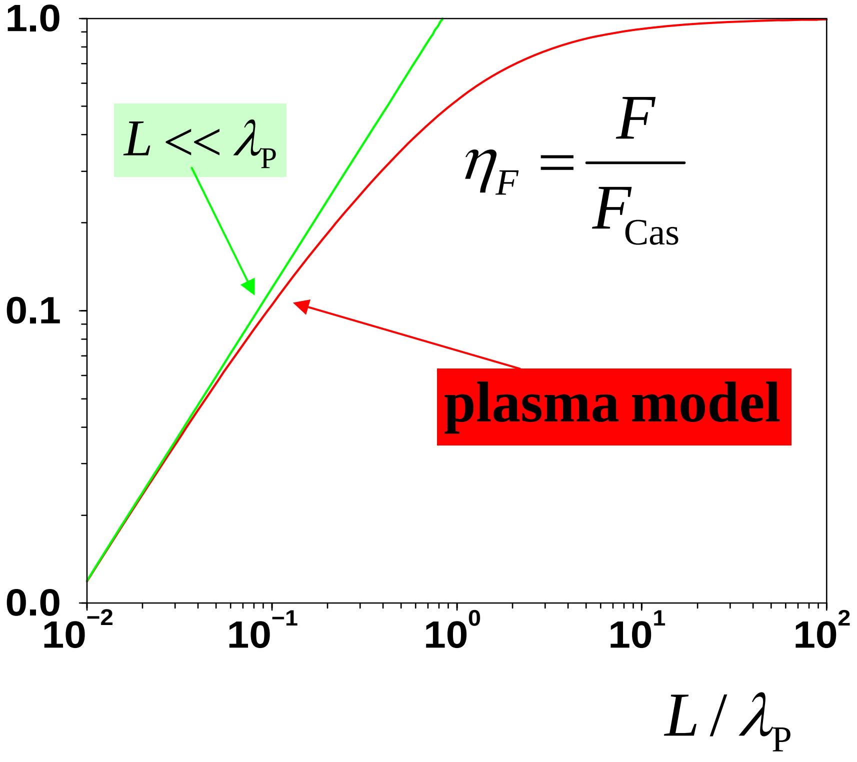
C. Genet, A. Lambrecht & S. Reynaud, Phys. Rev. A67 043811 (2003)

The force between metallic mirrors

- Plasma model

$$\varepsilon(\omega) = 1 - \frac{\omega_P^2}{\omega^2} \qquad \omega_P = \frac{2\pi c}{\lambda_P}$$

Au: λ_p~137nm



- Reduction of the force

$$L \leq \lambda_P$$

$$F = \frac{\alpha L}{\lambda_P} F_{Cas} \propto \frac{1}{\lambda_P L^3}$$

A. Lambrecht & S. Reynaud, Eur. Phys. J. D8 309 (2000)

Temperature correction

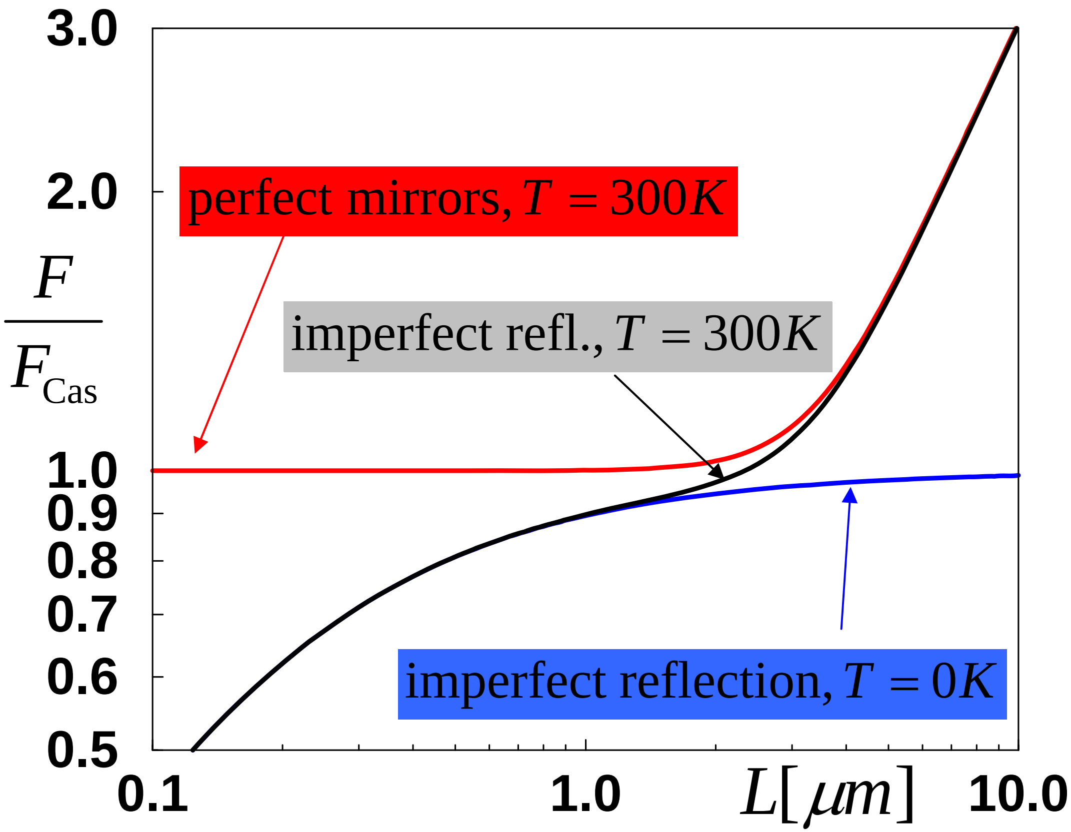
- Vacuum and thermal fluctuations in TD equilibrium

$$\frac{\hbar\omega}{2} + \frac{\hbar\omega}{e^{\hbar\omega/k_B T} - 1}$$

- T=300K

$$\lambda_T = \frac{\hbar c}{kT} \approx 7\,\mu m$$

- Important at long distances

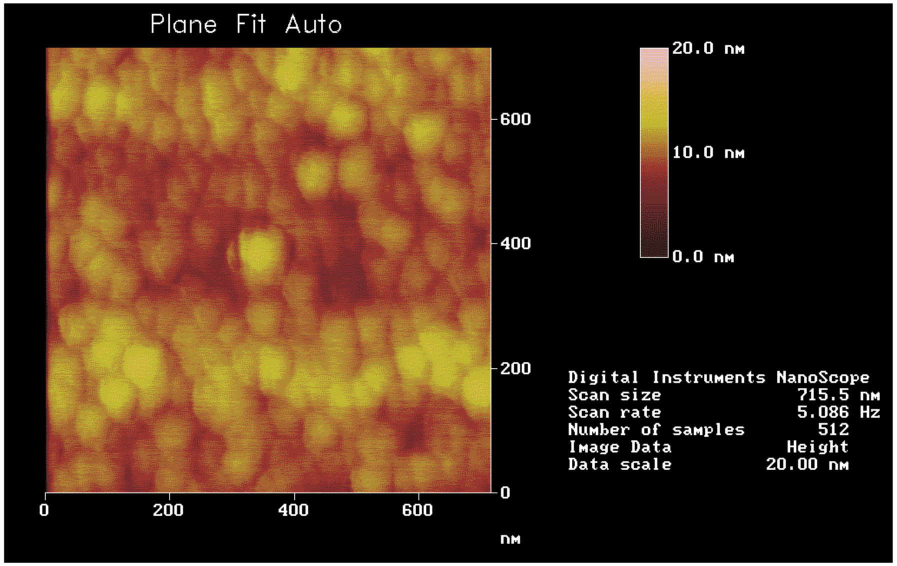


C. Genet, A. Lambrecht & S. Reynaud, Phys. Rev. A 62, 012110 (2000)

Surface state

- Surface roughness:
  PFA and specular reflection
- Characteristic lengthscale $\lambda_C \cancel{\gg} L$

Courtesy U. Mohideen

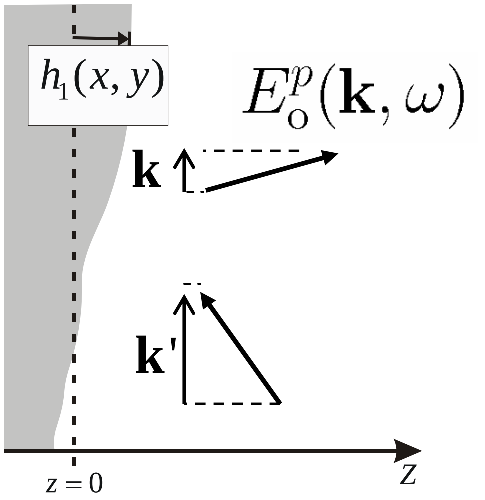


P. Maia Neto, A. Lambrecht & S. Reynaud, EPL (2003) & (2005)

Surface state

- Non specular reflection: mixes wavevectors and polarizations
- Surface roughness correction:

  important at short distances and intertwined with finite reflectivity correction



- Violation of PFA measurable in lateral Casimir force

P. Maia Neto, A. Lambrecht & S. Reynaud, PRA 72, 012115 (2005)
R. Rodrigues, P. Maia Neto, A.Lambrecht & S. Reynaud, PRL. 96, 100402 (2006)

State of the art

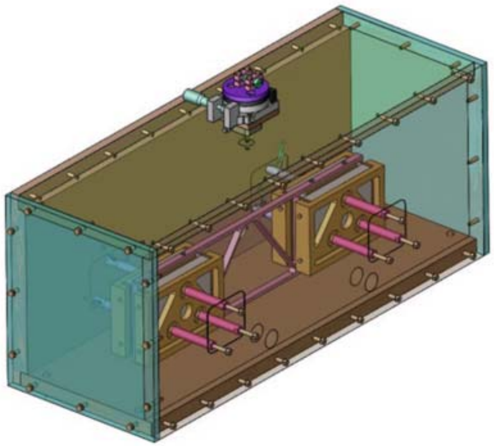
- The Casimir force is now measured with an experimental accuracy ~ %
- Theory and experiment agree at the same level in the distance range $100\,\mathrm{nm} < L < 500\,\mathrm{nm}$
- Going beyond the % level

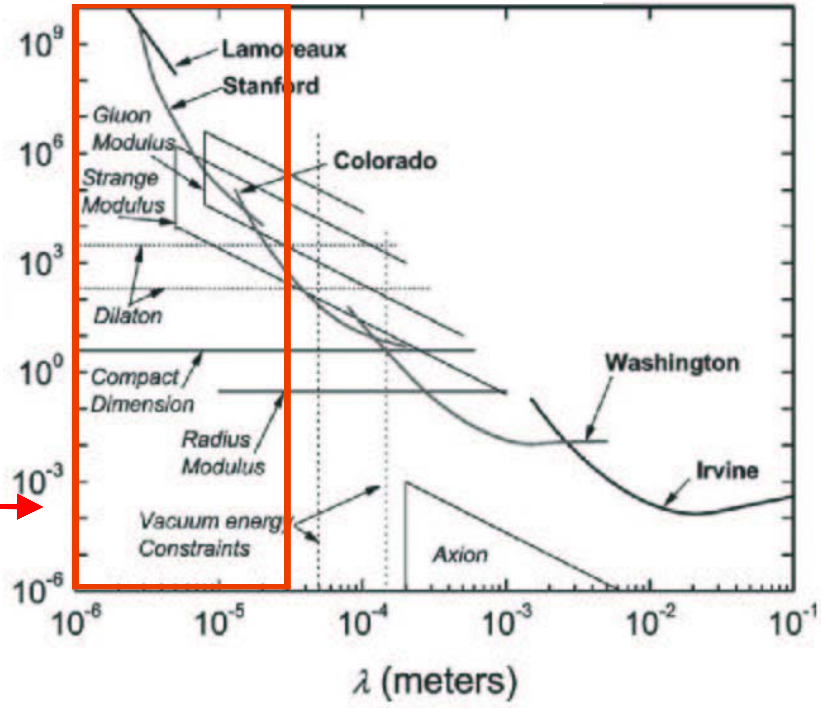
- Discussions are still going on for non zero T
- No experiments at distances > μm
- New trends : NEMS, repulsive Casimir forces
  beyond PFA : lateral Casimir force
  Casimir-Polder forces (BEC),
  non-thermal-equilibrium effects
  (cf. Mauro Antezza's talk),...

New Casimir force measurement

- Experiment with Valery Nesvizhevsky (ILL, Grenoble)
  - High precision torsion balance
  - Very high quality mirrors
  - Very good control of parallelism

- Advantage in window around 10μm where a variety of models can be ruled out or confirmed





A. Lambrecht, V. Nesvizhevsky, R. Onofrio, and S. Reynaud, Class. Quant. Grav. (2005)

New Casimir force measurement

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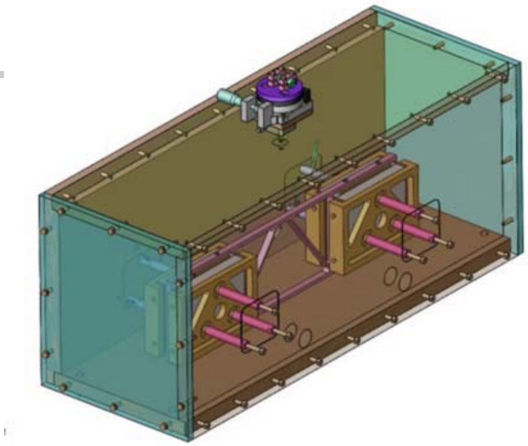
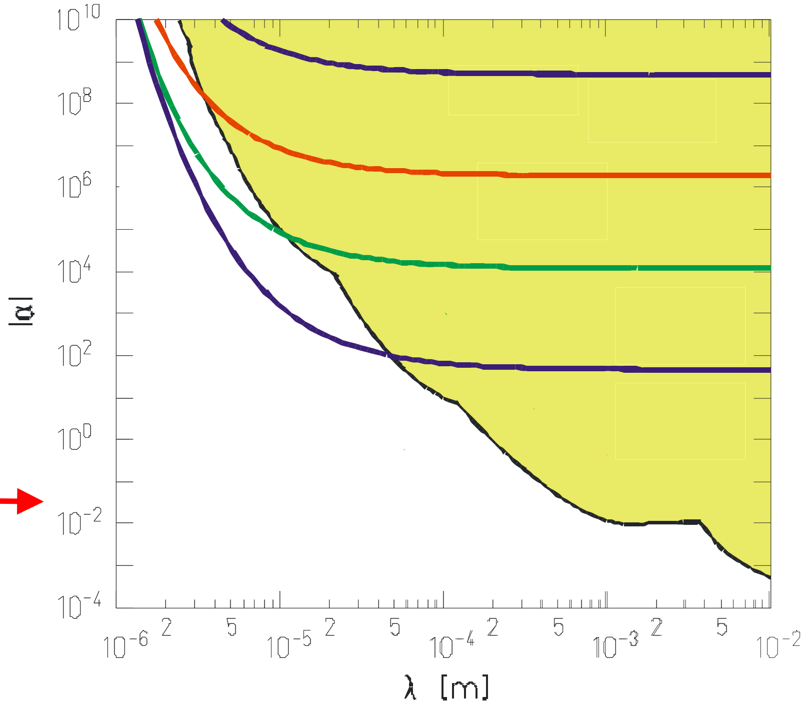
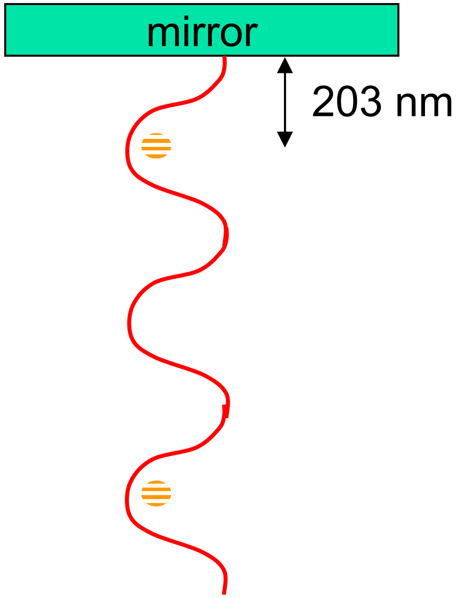


- Expected new constraints for
  - 0.1 μm
  - 1 μm
  - 3 μm
  - 10 μm thickness of Au layer



A. Lambrecht, V. Nesvizhevsky, R. Onofrio, and S. Reynaud, Class. Quant. Grav. (2005)

Casimir Polder Force Using Cold Atoms in an Optical Lattice



- Atomic interferometer: coherent superposition between atomic states at different lattice sites

- Measuring the atom-surface interaction potential :
  - Casimir Polder interaction
  - Search for new interactions : improvement by 2 to 4 orders of magintude

P. Wolf, P. Lemonde, A. Lambrecht, S. Bize, A. Landragin, A. Clairon, Proc. IEEE Freq. Controle Symposium (2006); ArXiv:physics/0608021

Casimir Team

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- Joël Chevrier (LEPES, Grenoble)
- Valery Nezvishevsky (ILL, Grenoble)
- NANOCASE (FP6-NEST contract)

Theory collaborations:
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- Marc-Thierry Jaekel (LPT-ENS Paris)
- Paulo Maia-Neto (Univ. Rio de Janeiro – CAPES COFECUB contract)