Casimir force : theory and experiments

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Collaborations M.-T. Jaekel (ENS Paris), G.-L. Ingold (Augsburg), P.A. Maia Neto (Rio de Janeiro), D. Dalvit, R. Behunin, F. Intravaia (Los Alamos), C. Genet, T. Ebbesen (Strasbourg), H.B. Chan (Hong-Kong) …

Thanks to R. Decca, G. Palasantzas *et al*

ESF network "CASIMIR" http://www.casimir-network.com

The many facets of Casimir physics

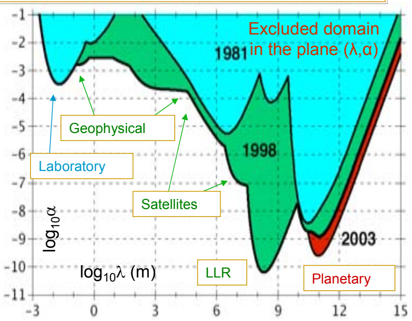
- Casimir effect and quantum vacuum
  - A crucial prediction of Quantum Field Theory !
- A fascinating interface with other fundamental physics questions
  - Gravity : "vacuum energy" problem
  - Geometry : non trivial effects beyond the "Proximity Force Approximation"
  - Relativity of motion : "Dynamical Casimir effect"
  - "New physics" expected to lie "beyond the standard model" : search for hypothetical new short-range forces
- A dominant force in the mesoscopic world, strong connections with
  - Atomic and molecular physics, quantum optics
  - Condensed matter physics, surface physics
  - Chemical physics and biological physics
  - Micro- and nano-physics & -technology …

Search for scale dependent modifications of the gravity force law

The exclusion plot for deviations with a generic 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 $\lambda > 10^{16}\,\mathrm{m}$

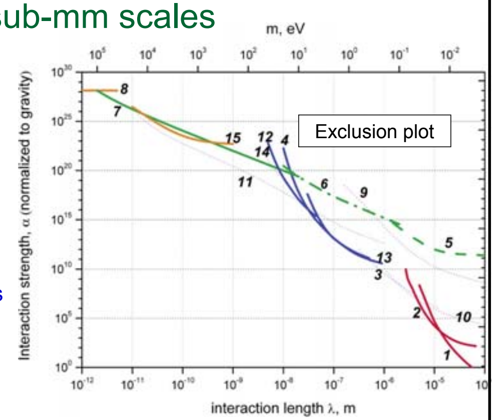


Courtesy : J. Coy, E. Fischbach, R. Hellings, C. Talmadge & E. M. Standish (2003) ; see M.T. Jaekel & S. Reynaud IJMP **A20** (2005)

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

Constraints at sub-mm scales

- Information coming from various domains
- From the mm down to the pm range
  - Short range gravity measurements
  - Casimir experiments
  - Neutron physics
  - Exotic atoms



Recent overview : I. Antoniadis, S. Baessler, M. Büchner, V. Fedorov, S. Hoedl, V. Nesvizhevsky, G. Pignol, K. Protasov, S. Reynaud, Yu. Sobolev, *Short-range fundamental forces* C. R. Phys. (2011) doi:10.1016/j.crhy.2011.05.004

information Jan 2011

The challenge of Casimir tests

In the µm range, the Casimir force is dominant (it is certainly much larger than the gravity force, and probably larger than the new force)

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

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

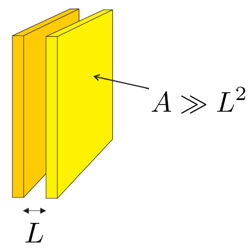
- The accuracy and reliability of theoretical and experimental values have to be assessed independently of each other
- The theory-experiment comparison should not be used for proving or disproving a specific experimental result or theoretical model
- If theory-experiment is used for such a purpose, then it is certainly not possible to use the difference to draw general constraints on hypothetical new forces

A. Lambrecht et al, in *"Casimir physics"* Lecture notes in physics (Springer 2011)

The Casimir force (ideal case)

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

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



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

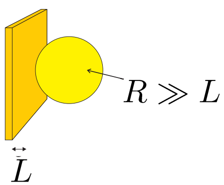
$$F_{\text{Cas}} = P_{\text{Cas}} A \,, \quad P_{\text{Cas}} = -\frac{\hbar c \pi^2}{240 L^4}$$

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

H.B.G. Casimir, Proc. K. Ned. Akad. Wet. (Phys.) **51** (1948) 79

The Casimir force (real case)

- Real mirrors not perfectly reflecting
  - Casimir force depends on non universal properties of the material plates used in the experiments
- Experiments performed at room temperature
  - Effect of thermal field fluctuations to be added to that of vacuum fluctuations
- Effects of geometry and surface physics
  - Plane-sphere geometry used in recent precise experiments
  - Surface state not ideal : patches, contamination, roughness …



A. Lambrecht et al, in *"Casimir physics"* Lecture notes in physics (Springer 2011)

Expression of the force (plane-plane)

- Electromagnetic fields in 3d space
- 2 plane parallel mirrors : specular reflection amplitudes depending on frequency ω, polarization *p*, incidence angle θ
- Lateral components (k_x, k_y) of the wavevector preserved

- General expression for the force and the free energy $\quad F = -\dfrac{\partial \mathcal{F}(L,T)}{\partial L}$

$$\mathcal{F} = k_{\text{B}} T \sum_{k_x,k_y} \sum_p \sum_m{}' \ln\left(1 - r^p e^{-2\kappa_m L/c}\right) \qquad r^p \equiv r_1^p r_2^p$$

- After the Wick rotation (at non null *T*), Matsubara sum

$$\kappa_m \equiv \sqrt{k_x^2 + k_y^2 + \frac{\xi_m^2}{c^2}} \qquad \xi_m = m\frac{2\pi k_{\text{B}} T}{\hbar c}$$

M. Jaekel, S. Reynaud, J. Physique **I-1** (1991) 1395 *quant-ph/0101067*

Models for the reflection amplitudes

- Lifshitz formula recovered for
  - bulk mirror described by a linear and local dielectric function
  - Fresnel laws for reflection

I.E. Dzyaloshinskii, E.M. Lifshitz, L.P. Pitaevskii, Sov. Phys. Usp. **4** (1961) 153

- Ideal Casimir formula recovered for
  - *$r \to 1$ and $T \to 0$*

J. Schwinger, L.L. de Raad, K.A. Milton, Ann. Physics 115 (1978) 1

- The scattering formula allow one to accommodate more general expressions for the reflection amplitudes
  - finite thickness
  - multilayer structure
  - non local dielectric response
  - non isotropic response
  - chiral materials …

L.P. Pitaevskii, PRL **101** (2008) 163202

V.B. Svetovoy, PRL **101** (2008) 163603

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

Models for the dielectric function

- Optical response of the metal described by a linear and local dielectric function written as a sum
  - Interband transitions
    - to be described by optical data (or modeled by Lorentz oscillators)
  - Conduction electrons
    - related to conductivity
    - relaxation to be accounted for (Drude model)
    - Drude parameters extrapolated from optical data at low frequencies and related to static conductivity

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

$$\sigma(i\xi) = \frac{\omega_P^2}{\xi + \gamma}$$

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

A. Lambrecht & S. Reynaud, EPJD **8** (2000) 309

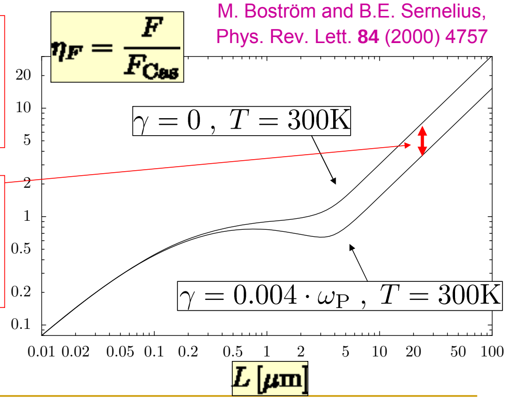
- A puzzle
  - Some experiments agree better with evaluations done with $\gamma=0$ than with the better motivated $\gamma\neq0$
  - But Gold certainly has a finite conductivity !

The crucial role of dissipation

- Strong correlation between thermal and dissipation effects

M. Boström and B.E. Sernelius, Phys. Rev. Lett. **84** (2000) 4757

- Here we represent the ratio of real pressure to ideal Casimir pressure
- Large difference (factor 2) at large distances between γ=0 and $\gamma\neq$0

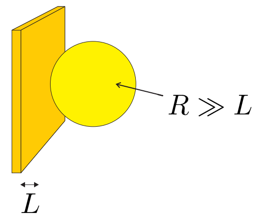


G. Ingold, A. Lambrecht, S. Reynaud, Phys. Rev. **E80** (2009) 041113

The plane-sphere case within PFA

- Force between a plane and a large sphere usually computed using the "Proximity Force Approximation" (PFA)
  - Integrating the (plane-plane) pressure over the distribution of local inter-plate distance

$$F_{PFA} = \int_L^\infty \mathrm{d}A\, P(L')$$



- For a plane and a large sphere

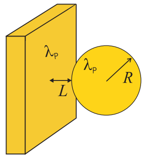
$$F_{PFA} = 2\pi R \int_L^\infty \mathrm{d}L'\, P(L')$$

$$G \equiv \frac{\partial F}{\partial L} = 2\pi R P(L)$$

- Casimir forces not additive !
  - PFA is not a theorem !
  - It is an approximation valid for large spheres
  - Accuracy to be assessed

➡ Talk A. Canaguier-Durand

The plane-sphere case beyond PFA



- General scattering formula

$$\mathcal{F} = k_B T \sum_m{}' \mathrm{Tr}\ln\left(1 - \mathcal{R}_P\, e^{-\kappa L}\, \mathcal{R}_S\, e^{-\kappa L}\right)_{i\xi_m}$$

- $\mathcal{R}_P$: reflection matrix on the plane mirror
  $\mathcal{R}_S$: reflection matrix on the sphere
  (Mie scattering of vacuum and thermal fluctuations)

- Corrections to PFA can be evaluated for the free energy, the force F, the gradient G $\quad \rho_G \equiv \frac{G_{PS}}{G_{PS}^{PFA}} \simeq 1 + \beta_G x + \ldots$
- For large spheres, they vary ~ linearly with the aspect ratio $x \equiv \frac{L}{R}$
- PFA recovered when $x \to 0$, accuracy assessed by the value of β

A. Canaguier-Durand et al, PRL 2009, PRL 2010, PRA 2010

Casimir expt/theory comparison ..

IUPUI and UCR experiments deviate from theoretical expectations when dissipation is taken into account

BRIEF REPORTS PHYSICAL REVIEW D 75, 077101 (2007)

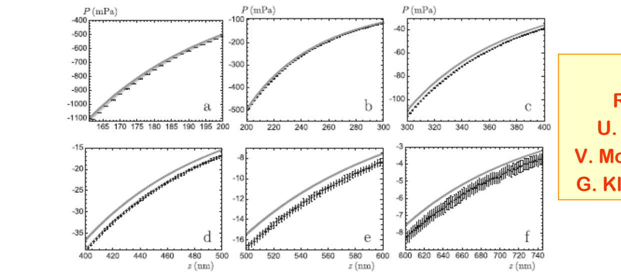


FIG. 1. Experimental data for the Casimir pressure as a function of separation z. Absolute errors are shown by black crosses in different separation regions (a–f). The light- and dark-gray bands represent the theoretical predictions of the impedance and Drude model approaches, respectively. The vertical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

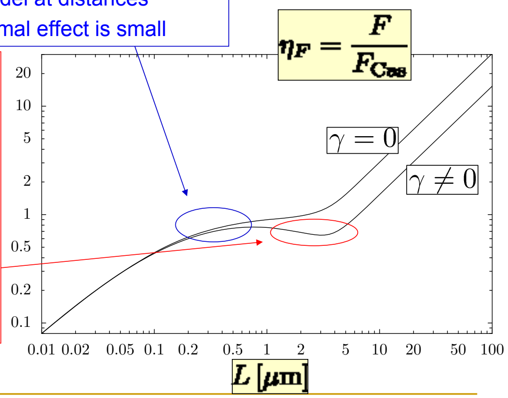
➧ Talks
R. Decca
U. Mohideen
V. Mostepanenko
G. Klimchitskaya

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

Recent experiment at Yale

- IUPUI and UCR experiments favor the plasma model at distances where the thermal effect is small

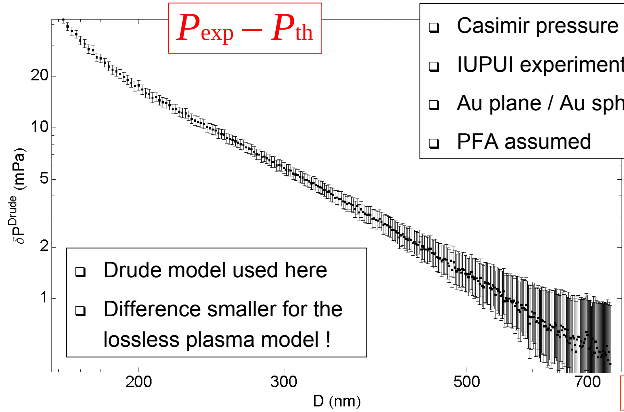
- Yale experiment at larger distances 0.7-7µm → larger thermal effect
- Results favor the Drude model after subtraction of a large contribution of the patch effect



➧ Talk D. Dalvit

A.O. Sushkov, W.J. Kim, D.A.R. Dalvit, S.K. Lamoreaux, Nature Phys. 6 Feb 2011

Another representation of the problem



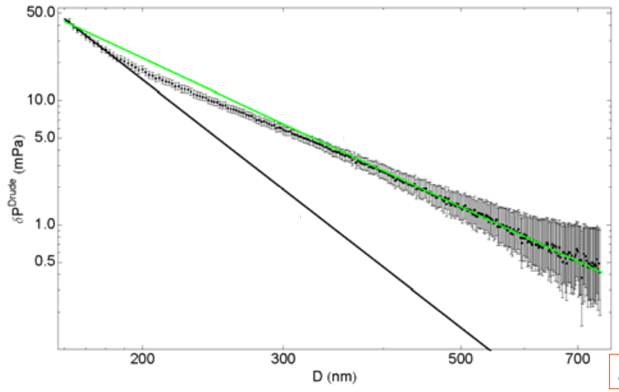
- Casimir pressure
- IUPUI experiment
- Au plane / Au sphere
- PFA assumed

- Drude model used here
- Difference smaller for the lossless plasma model !

D → L

Experimental data kindly provided by R. Decca (IUPUI)
Theoretical pressure calculated by R. Behunin, D. Dalvit, F. Intravaia (LANL)

New forces ????



D → *L*

The difference does not look like a Yukawa law …

But it looks like a combination of power laws !

What can this difference mean ?

- Some experiments agree better with evaluations done with $\gamma=0$ than with the better motivated $\gamma\neq 0$
  - This is an observation, not an explanation !
- New forces ????
- Artifact in the experiments ??
- Inaccuracy in the theoretical evaluations ?
  - A problem with Lifshitz formula ?
  - A problem with the Drude model ?
  - A problem with the PFA ?
- Systematic effects misrepresented in the analysis ?
  - The contribution of electrostatic patches ?
  - The contribution of plate roughness ?
  - Something else we are missing ??

The patch effect

- The effect of electrostatic patches is a known limitation for a large number of high precision measurements in many different domains

  Large number of references in arXiv:1108.1761
- It is a source of concern for Casimir experiments

  C.C. Speake and C. Trenkel, PRL **90** (2003) 160403
- Surfaces of metallic plates are not equipotentials
  - crystallite faces correspond to different work functions
  - this "voltage roughness" is something else than the "topographic roughness", though the two may be related for clean metallic surfaces
  - contamination of the surfaces is known to spread out the electrostatic patches, enlarge correlation lengths and reduce voltage dispersions

R.O. Behunin, F. Intravaia, D.A.R. Dalvit, P.A. Maia Neto, SR, arXiv:1108.1761

Modeling the patches ..

- The pressure due to electrostatic patches can be computed exactly by solving the Poisson equation

$$P = \frac{\varepsilon_0}{4\pi}\int_0^\infty \frac{dk\; k^3}{\sinh^2 kD}\{C_{11}[k] + C_{22}[k] - 2C_{12}[k]\cosh kD\}$$

D → *L*

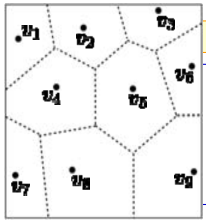
- The estimation depends on the patch spectrum, in particular on the small-*k* tail of the spectrum (*i.e.* on the large size patches)
- The spectrum has not been measured in any Casimir experiment up to now
- In a simple (often used) model, the small-*k* tail is cut off at some k_{min}

Speake and Trenkel (2003)

R.S. Decca *et al* (2005-…)

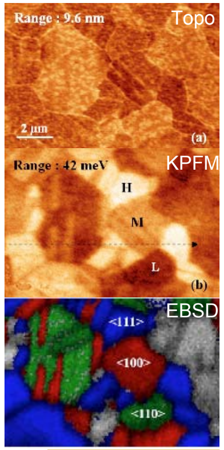
.. Modeling the patches

- This simple “sharp-cutoff” model does not represent well the patches as they are characterized by surface physics specialists



➡ Talk R.O. Behunin

tessellation of sample surface and random assignment of the voltage on each patch

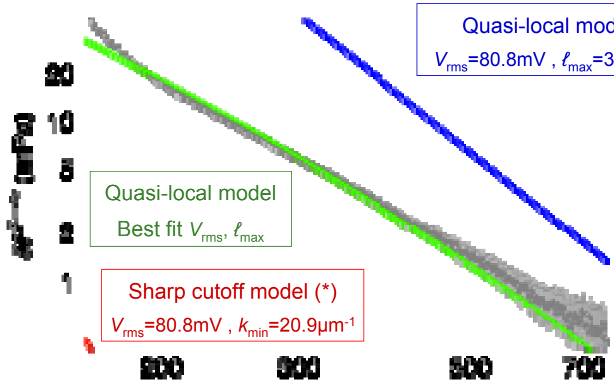


- We have proposed a “quasi-local” model which we think to be a better representation of the patches on real surfaces

N. Gaillard *et al*, Appl. Phys. Lett. **89** (2006) 154101

Similar ideas : R. Dubessy *et al*, PRA **80** (2009) 031402

The output of the calculations ..

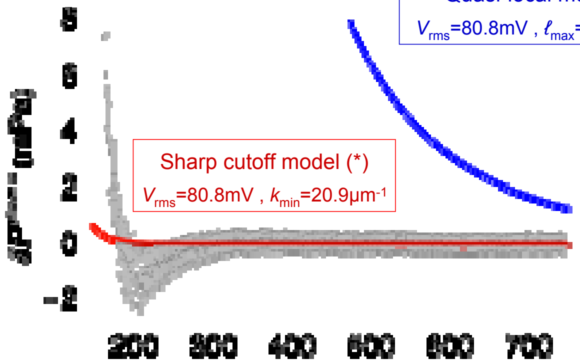


(*) same as in R. Decca *et al* (2005-…)

D (nm)

R.O. Behunin *et al*, arXiv:1108.1761

.. The output of the calculations



(*) same as in R. Decca *et al* (2005-…)

D (nm)

R.O. Behunin *et al*, arXiv:1108.1761

Provisional conclusions on the patch effect

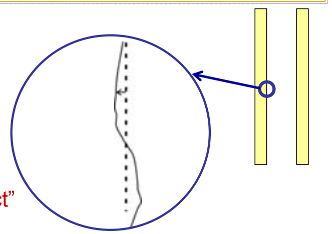
- The difference between IUPUI data and Drude model predictions can be fitted by the quasi-local model for electrostatic patches
  - This is nothing more than a fit; the fit was done on purpose on a simplified model; conclusions are robust against small changes (except for the values of the best fit parameters !)
  - We do not make any statistical claim
  - The values obtained for the best fit are not compatible with the identification of patches as crystallites

Best fit parameters
V_{rms}=12.9mV , ℓ_{max}=1074nm

- These values may be compatible with a contamination of the metallic surfaces, which is known to enlarge the patch sizes (with respect to crystallite sizes) and spread out the patch voltages (with respect to a clean surface of bare crystallites)

F. Rossi and G.I. Opat, *J. Appl. Phys.* **25** (1992) 1349

The effect of roughness (or corrugations)



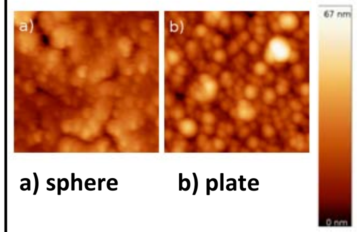
- For a static non flat surface, frequency is preserved but lateral wavevector is changed (non specular scattering)
- PFA disregards this “diffraction effect”
  - it is valid for smooth variations but does not remain accurate for rapid ones
  - using the scattering approach with linearization of the roughness, a spectral sensitivity function valid “beyond PFA” has been calculated for perfect and metallic mirrors

P. Maia Neto, A. Lambrecht, S. Reynaud, EPL **69** (2005) 924; PRA **72** (2005) 012115

  - similar results available for corrugations

R.B. Rodrigues, P.A. Maia Neto, A. Lambrecht, S. Reynaud PRL **96** (2006) 100402

Roughness correction to the Casimir force: Surface statistics from AFM images



a) sphere b) plate

Broer, Palasantzas et al, EPL 95 (2011) 30001 ; PRA in preparation (2011)

Count # features < z:

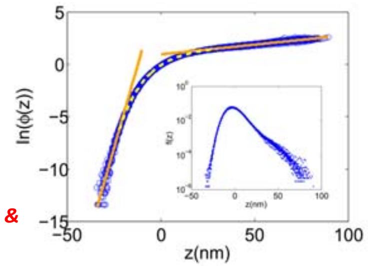
$P(z)$ **Cumulative probability**

$f(z) = P'(z)$ **Prob. density**

$\phi(z) \equiv -\ln(1-P(z))$ **“Phase”**

Cumulative probability→ *force calculation & determination of distance upon contact d_0*

Linear asymptotic fit: Gumbel distribution



Roughness correction to the Casimir force: results

$F_{Cas}(d) = F_{PT}(d) + F_{PFA}(d)$ ← **Peaks: rare events, with PFA**

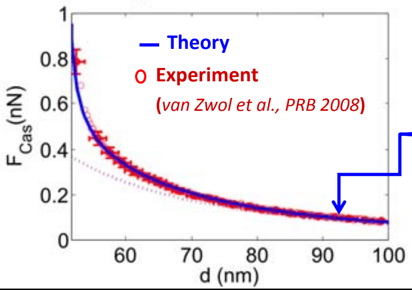
Near average height: perturbation theory (*Maia Neto et al, EPL & PRA 2005*)

Contact distance due to roughness:

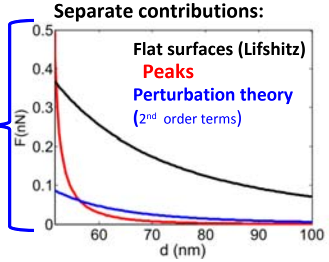
$d > d_0$ **Singularity at d=d₀ !**

Thanks to W. Broer & G. Palasantzas for these two slides

d_0 = 50.8 nm Δd=1.3 nm



Separate contributions:



Some conclusions

- Casimir effect is verified (not at the % level)
- There is ample room available for improvement of Casimir tests of short range gravity

- A puzzle
  - some experiments favor the lossless plasma model rather than the better motivated dissipative Drude model
  - a solution would lead a better understanding !

- May this be due to the contribution of electrostatic patches ?
  - only one solution to be sure : measure the patch voltages with KPFM (Kelvin Probe Force Microscopy)
  - other options : compare Casimir data with the results accumulated in surface physics, ion traps, cold atom physics …

Thanks for your attention