Observation of the thermal Casimir force

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Collaborators

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Funding provided by:

Outline of this Talk

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- Torsional balance apparatus at Yale
- Electrostatic calibrations
- Measurements of short-range forces between Au plates
- Experiment-theory comparison
  - Electrostatic patches contribution
  - Casimir force contribution

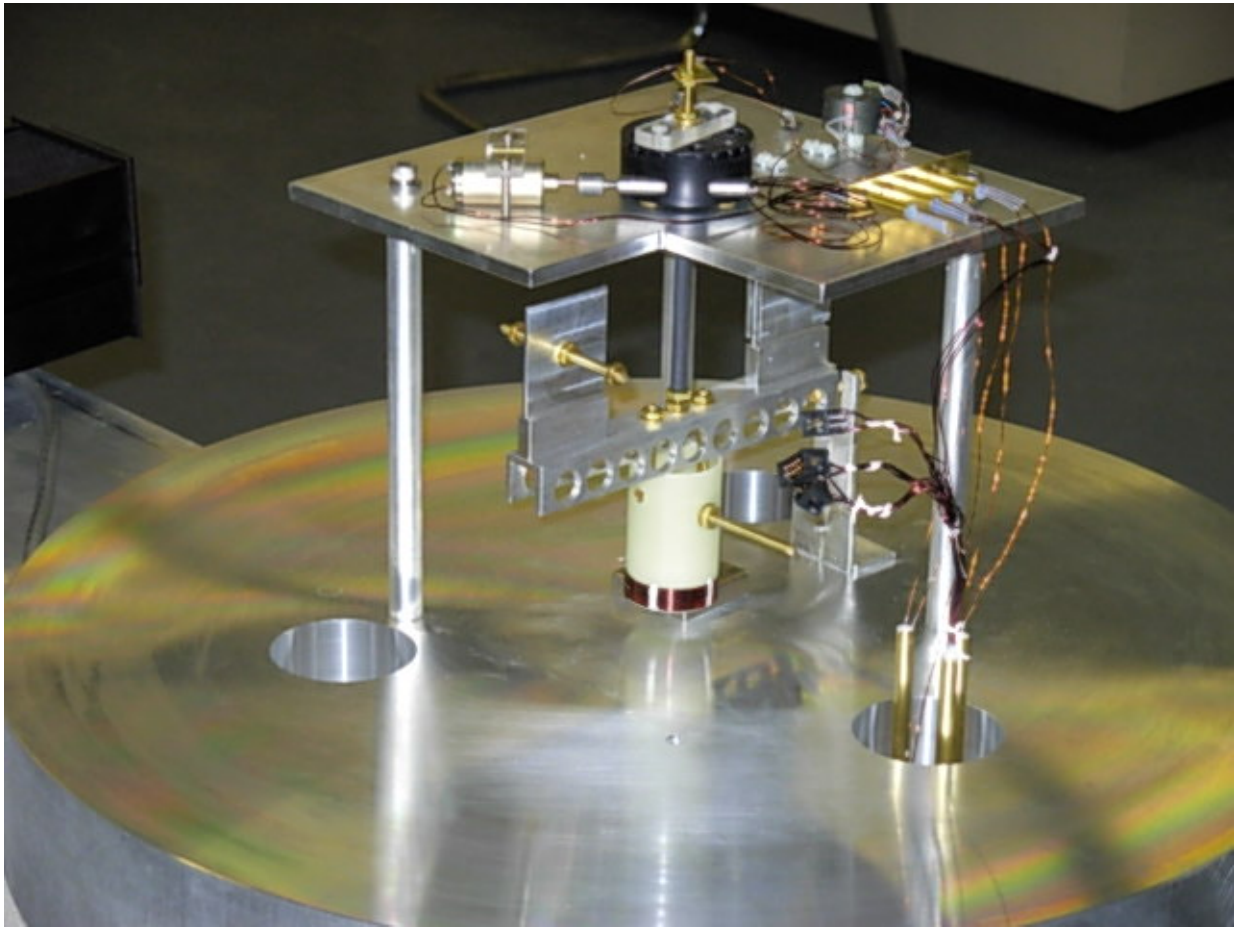
Nature Physics **7**, 230 (2011)

- Modeling patch effects in Casimir force measurements

arXiv:1108.1761

[see also talks by Ryan Behunin (Thusday) and Serge Reynaud (Friday)]

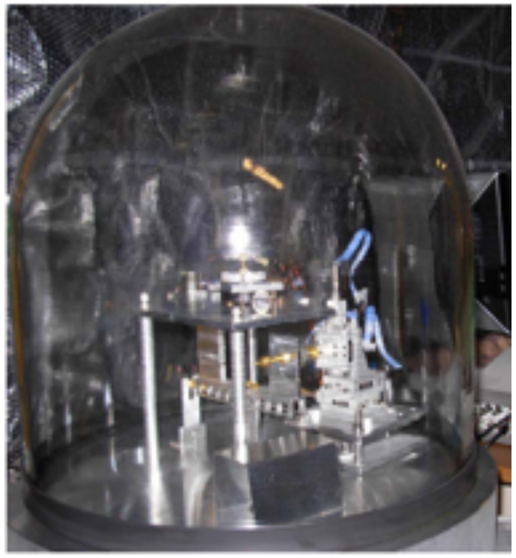
Torsion Pendulum at Yale



Torsional Pendulum Set-up

✱ Upgrade of Lamoreaux's 1997 experiment

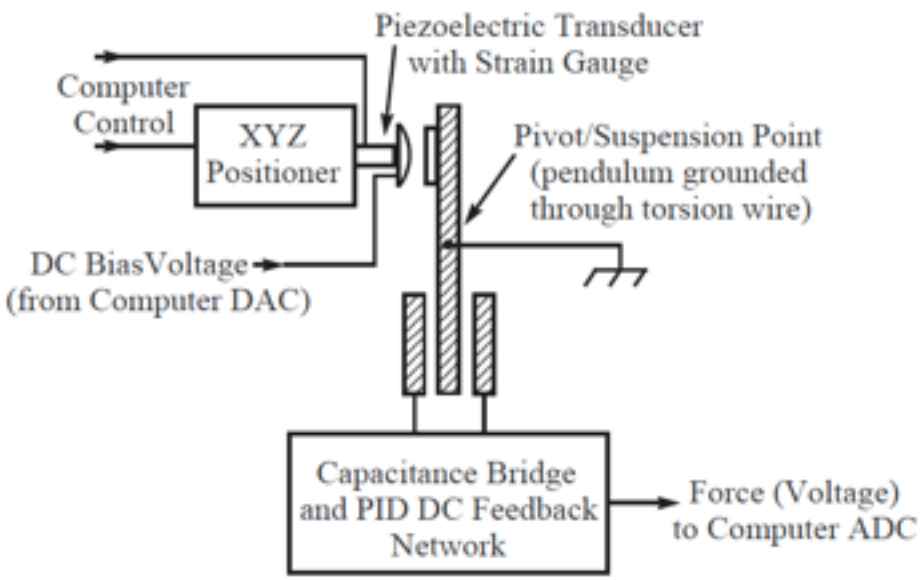
- Tungsten wire: length 2.5 cm, diameter 25 um. Pendulum tilt is reduced.
- Vacuum chamber at $P = 5 \times 10^{-7}$ torr
- NdFeB magnet at bottom of pendulum to damp swinging modes.
- Experiment is placed on a vibration-isolation slab.
- Temperature monitored, variations less than 1C.



✱ Sphere-plane geometry

- Both plates are coated with a 700 A (optically thick) layer of gold, evaporated on top of a 100 A-thick layer of titanium
- Spherical lens has radius $R = 15.6\,\mathrm{cm}$. This was measured with an interferometric microscope, and found to vary less than 2% over the surface of the lens.

Force Measurements

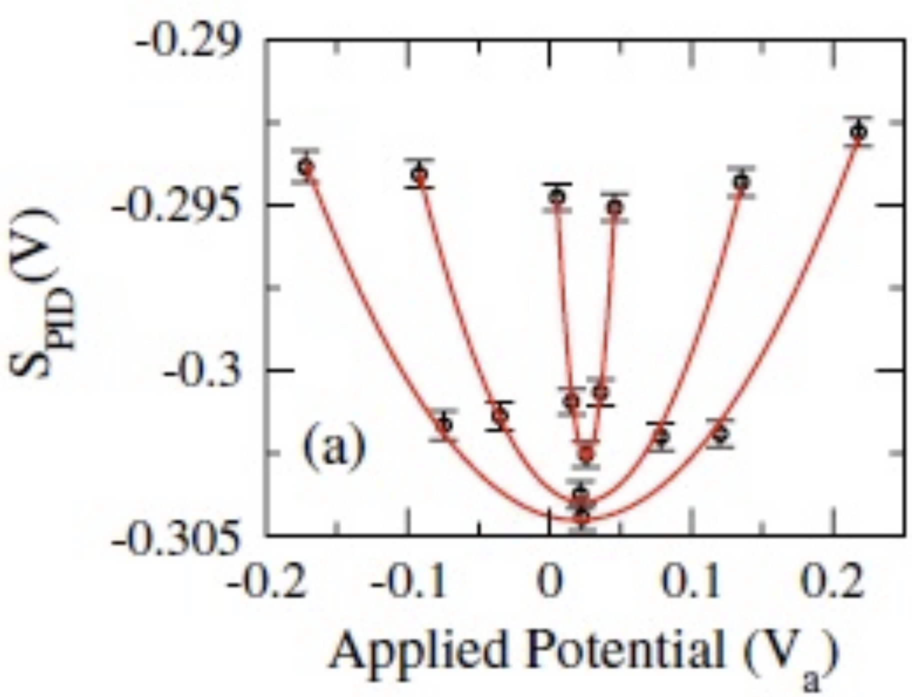


A proportional integro-differential (PID) controller provides a feedback correction voltage $S_{\mathrm{PID}}(d, V_a)$ to the compensator plates, restoring equilibrium.

$$F \propto (S_{\mathrm{PID}} + 9V)^2 \approx (9V)^2 + 2S_{\mathrm{PID}} \times 9V$$

The correction voltage is the physical observable, and it is proportional to the force between the Casimir plates

Electrostatic Calibrations



Typical Casimir Measurement

$$S_{\mathrm{PID}}(d,V_a) = S_{\mathrm{dc}}(d\to\infty) + S_a(d,V_a) + S_r(d)$$

force-free component of signal at large separations

electrostatic signal in response to an applied external voltage

residual signal due to distance-dependent forces, e.g. Casimir

The electrostatic signal between the spherical lens and the plate, in PFA $(d \ll R)$ is

$$S_a(d,V_a) = \pi\epsilon_0 R(V_a - V_m)^2/\beta d$$

β force-voltage conversion factor

This signal is minimized ($S_a = 0$) when $V_a = V_m$, and the electrostatic minimizing potential V_m is then defined to be the contact potential between the plates.

“Parabola” Measurements

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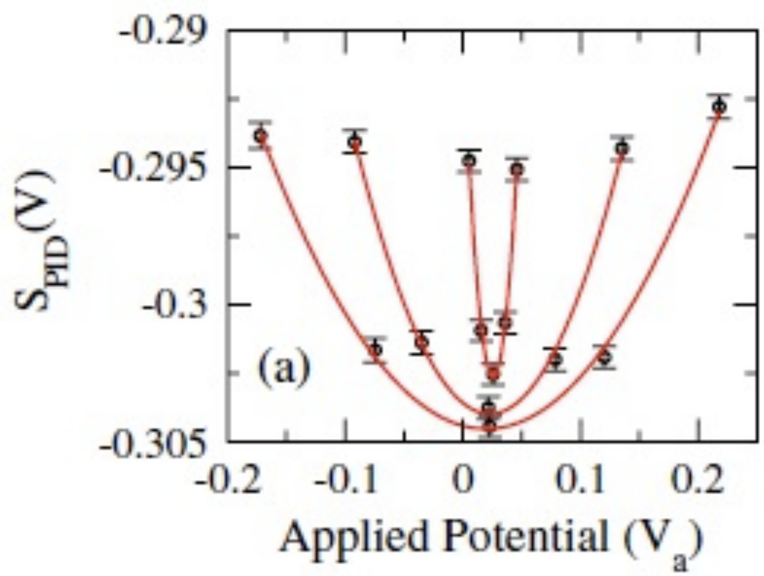
Calibration routine (Iannuzzi et al, PNAS 04)

A range of plate voltages V_a is applied, and at a given nominal absolute distance the response is fitted to a parabola

$$S_{\mathrm{PID}}(d, V_a) = S_0 + k(V_a - V_m)^2$$



Fitting parameters

$k = k(d)$ ⟶ voltage-force calibration factor + absolute distance

$V_m = V_m(d)$ ⟶ minimizing potential

$S_0 = S_0(d)$ ⟶ force residuals: electrostatic patches + Casimir + exotic gravity + ...

This procedure is repeated at decremental distances, from 7 um down to 0.7 um, completing a single experimental run.

Note: 0.7 um is the closest approach due to feedback instability at smaller plate separations caused by the large force gradient.

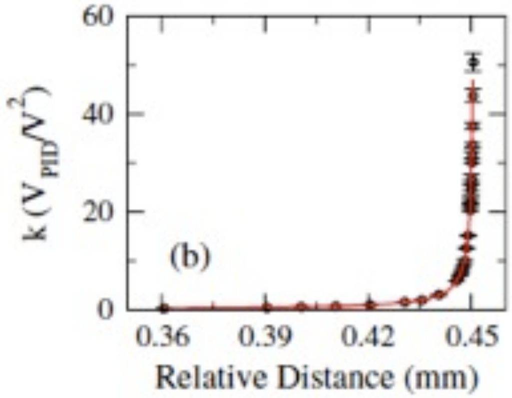
$k(d)$, $V_m(d)$, and $S_0(d)$

- From the parabola curvature one obtains the absolute distance

$$k(d) = \frac{\pi\epsilon_0 R/\beta}{d}$$

$$\beta = (1.27 \pm 0.04) \times 10^{-7}\ \mathrm{N/V}$$

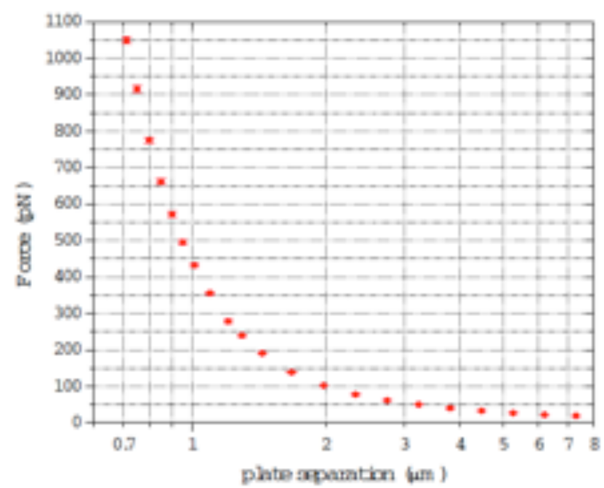
$$d = d_0 - d_{\mathrm{rel}}$$



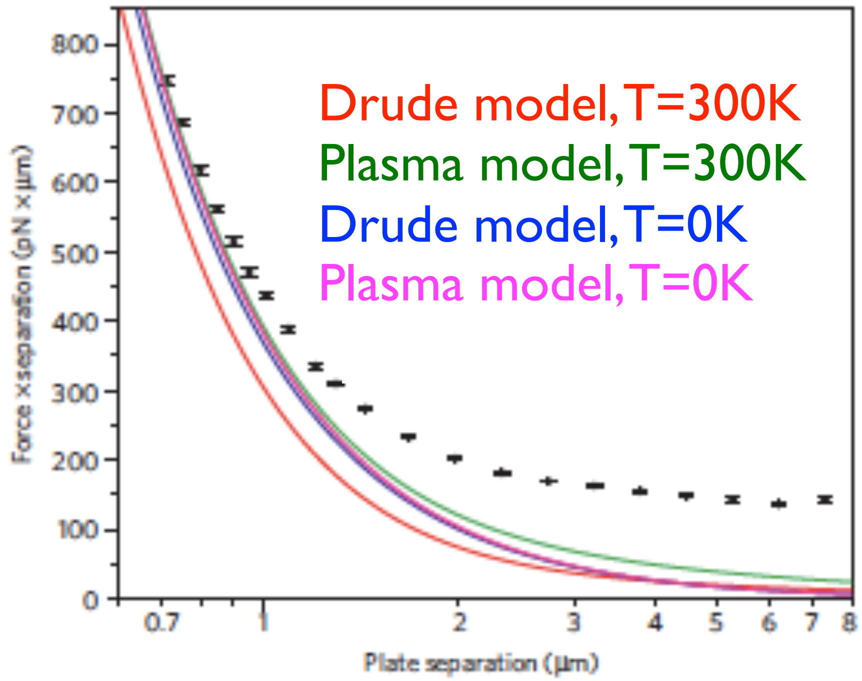
- From the parabola minimum one obtains the minimizing potential

Our Au data shows a *distance-independent* minimizing potential $V_m \approx 20\,\mathrm{mV}$, with variations of 0.2 mV in the 0.7-7.0 um range.

- From $S_0(d)$ one obtains the residual force $F_r(d)$



Force Residuals



Solid lines correspond to predictions from Lifshitz theory (with no roughness correction) and Drude-like permittivity with parameters

$$\omega_p = 7.54\,\mathrm{eV} \qquad \gamma = 0.051\,\mathrm{eV}$$ (best fit to Au optical data by Palik)

In our experiment, these force residuals are *too large* to be explained just by the Casimir-Lifshitz force between Au plates.

Experiment-Theory Comparison

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ARTICLES
PUBLISHED ONLINE: 6 FEBRUARY 2011 | DOI: 10.1038/NPHYS1909
nature physics

Observation of the thermal Casimir force

A. O. Sushkov[1]*, W. J. Kim[2], D. A. R. Dalvit[3] and S. K. Lamoreaux[1]

$$F_r(d) = \mathrm{Patches} + \mathrm{Casimir} + \ldots$$

Metals are NOT Equipotentials

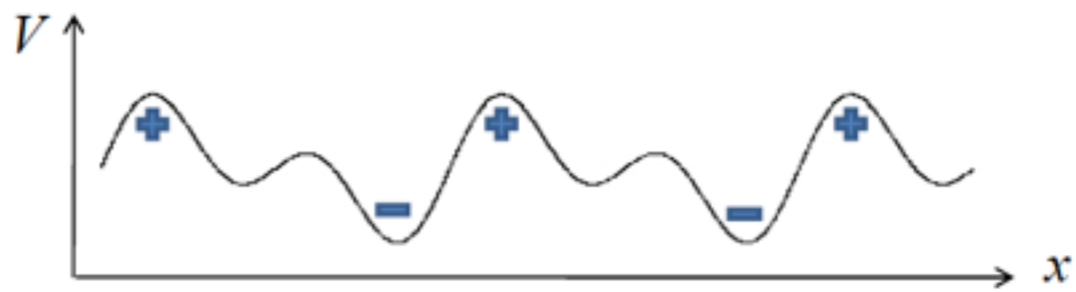
(despite what we've learned in freshman physics!)

- Different crystal faces have different work functions

Au crystal direction	Work function
⟨100⟩	5.47 eV
⟨110⟩	5.37 eV
⟨111⟩	5.31 eV

- Dirt: oxides, surface adsorbates strongly affect work function and surface potential by creating dipoles on the surface.

Resulting potential variation across a surface:



- Surface strains generate surface potentials through electrostriction

(French and Beams, PRB 1970).

Kelvin Probe Measurements

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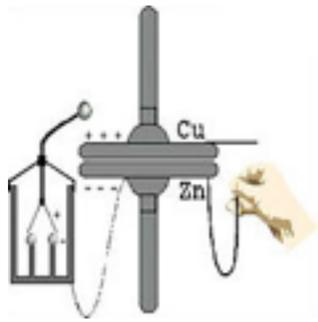
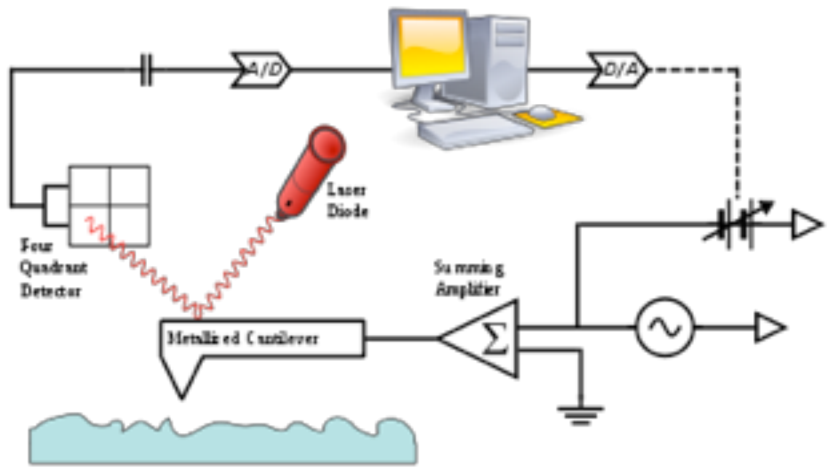
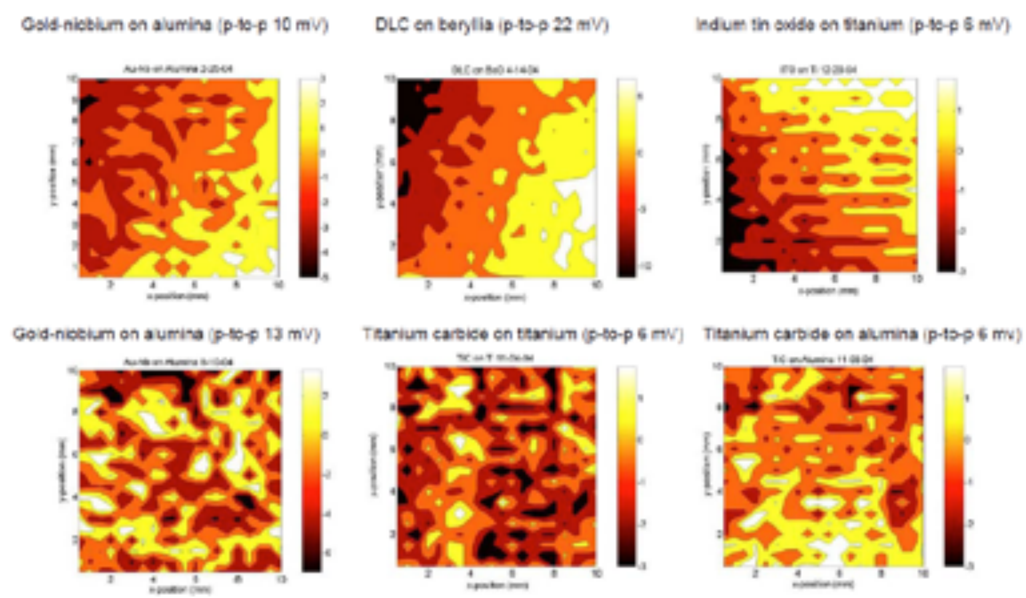


Kelvin's original apparatus



$$E = \frac{C}{2}[V_{\mathrm{DC}} + V_{\mathrm{AC}} \sin(\omega_0 t)]^2 = \frac{C}{2}\left[V_{\mathrm{DC}}^2 + \frac{1}{2}V_{\mathrm{AC}}^2 + 2V_{\mathrm{DC}}V_{\mathrm{AC}}\sin(\omega_0 t) - \frac{1}{2}V_{\mathrm{AC}}^2 \cos(2\omega_0 t)\right]$$

Kelvin probe measurements done by LIGO collaboration detected order 10 mV patches on UHV-evaporated coatings, without air exposure.



Norna A Robertson*
LIGO-Caltech and University of Glasgow

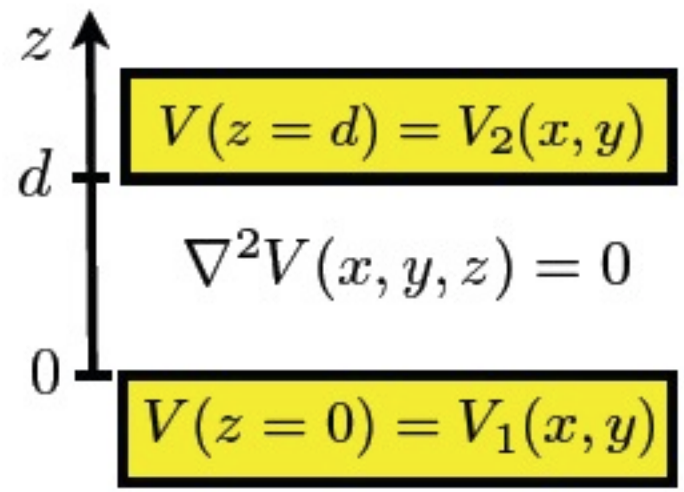
LSC/Virgo Meeting – Charging Workshop
MIT, July 26th 2007

LIGO - G070481-00-R

Modeling Electrostatic Patches. I

The patch effect is a possible systematic limitation to Casimir force measurements (Speake and Trenkel, PRL 03).

Plane-plane geometry:



$$\langle V_i(\mathbf{r})\rangle = 0$$

$$C_{ij}(\mathbf{r}) = \langle V_i(\mathbf{r}) V_j(\mathbf{0})\rangle = \int \frac{d^2\mathbf{k}}{4\pi^2} e^{i\mathbf{k}\cdot\mathbf{r}} C_{ij}[\mathbf{k}]$$

$$\boxed{\begin{aligned} P_{pp}^{\mathrm{patch}}(d) &= \frac{\epsilon_0}{4\pi}\int_0^\infty \frac{dk k^3}{\sinh^2(kd)} \\ &\times\{C_{11}[k] + C_{22}[k] - 2C_{12}[k]\cosh(kd)\}\end{aligned}}$$

(Kim, Sushkov, DD, Lamoreaux, PRA 10).

Modeling Electrostatic Patches. II

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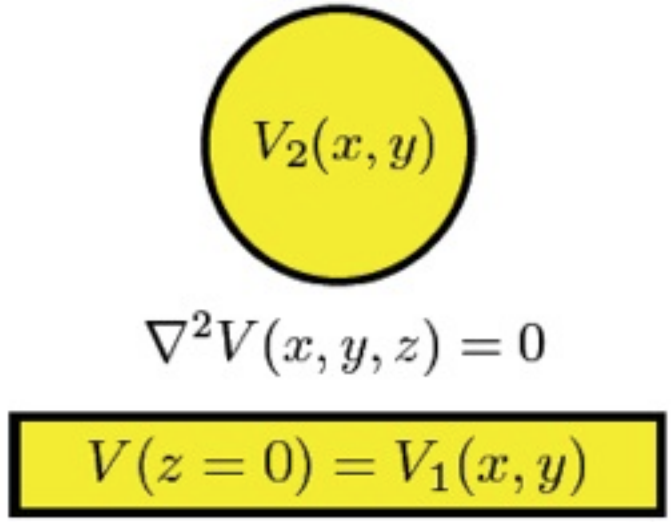
Sphere-plane geometry:



To compute the patch effect in the sphere-plane configuration we use PFA for the curvature effect $(d \ll R)$ but leave kd arbitrary

$$F_{sp}^{\text{patch}}(d) = 2\pi R\, U_{pp}^{\text{patch}}(d)$$
$$= \frac{\epsilon_0 R}{16} \int_0^\infty \frac{dk k^2 e^{-kd}}{\sinh(kd)} \{C_{11}[k] + C_{22}[k] - 2C_{12}[k]\cosh(kd)\}$$

Different models to describe surface potential fluctuations (more later). However, in the limit of large patches $d \ll l_{\text{patch}}$ all models lead to a universal behavior:

$$\boxed{F_{sp}^{\text{patch}}(d) = \pi\epsilon_0 R \frac{V_{\text{rms}}^2}{d}}$$

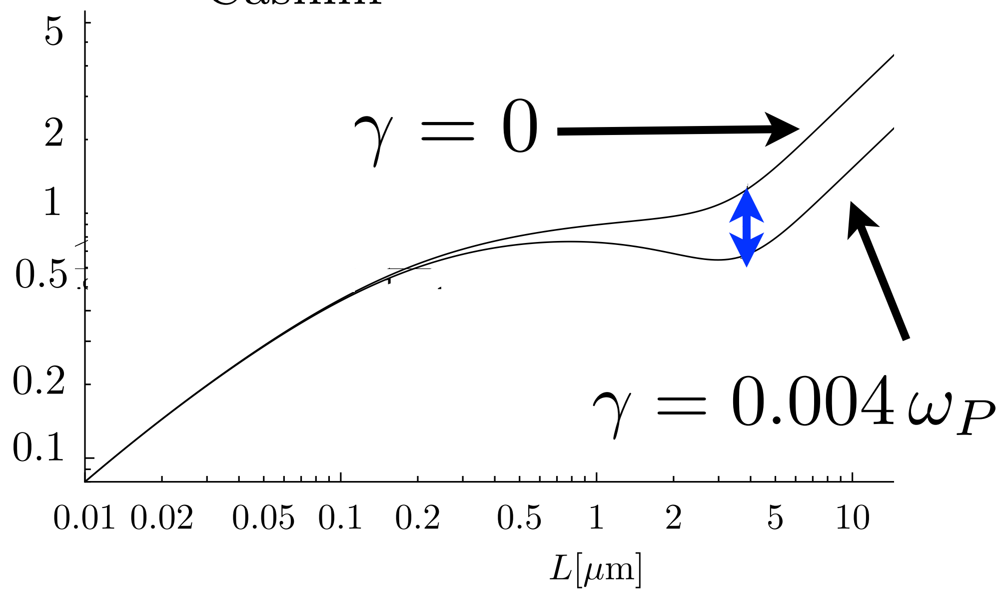
Calculation of the Casimir force

$$F_{\text{Casimir}} = -\frac{\partial}{\partial L} k_{\text{B}} T \sum_{l=0}^{\infty'} \text{Tr}\log\left(1 - \mathcal{R}_1\, e^{-L\mathcal{K}}\, \mathcal{R}_2\, e^{-L\mathcal{K}}\right)$$

Casimir force between two plane metallic mirrors calculated at room temperature T=300K and expressed as a ratio to the ideal Casimir formula

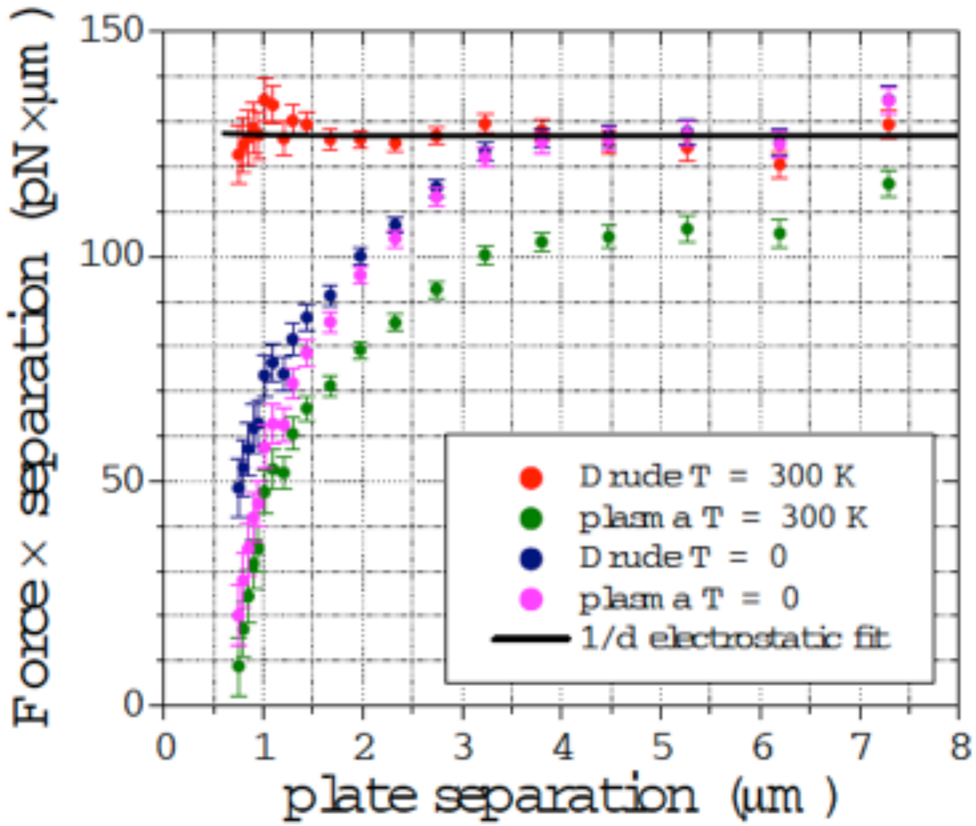
- Increase due to thermal fields at large distances
- Large difference (factor 2) at large distances between plasma and Drude predictions
- Reduction due to imperfect reflection at short distances

$$\eta_F = \frac{F_{\text{Casimir}}}{F^{\text{ideal}}_{\text{Casimir}}} \qquad \lambda_p = \frac{2\pi c}{\omega_P} = 136\,\text{nm}$$



Extracting the Patch Force

$$F_r - F_{\text{Casimir}} = \pi\epsilon_0 R V_{\text{rms}}^2/d$$



Drude T=300K

$$V_{\text{rms}} = (5.4 \pm 0.1)\text{mV}$$

$$\chi^2_{\text{red}} = 1.04$$

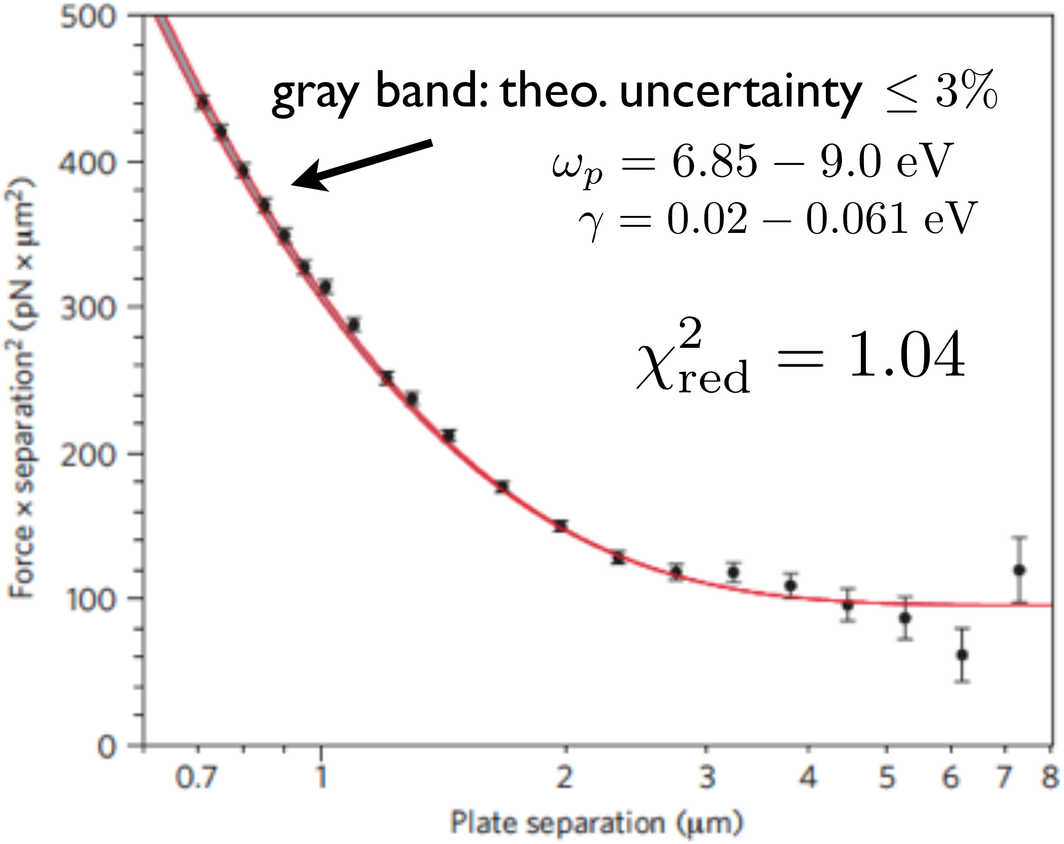
The other three models do not fit this description

Plasma T=300K: $\chi^2_{\text{red}} = 32$

Drude T=0K: $\chi^2_{\text{red}} = 23$

Plasma T=0K: $\chi^2_{\text{red}} = 43$

Final Result for Casimir Force

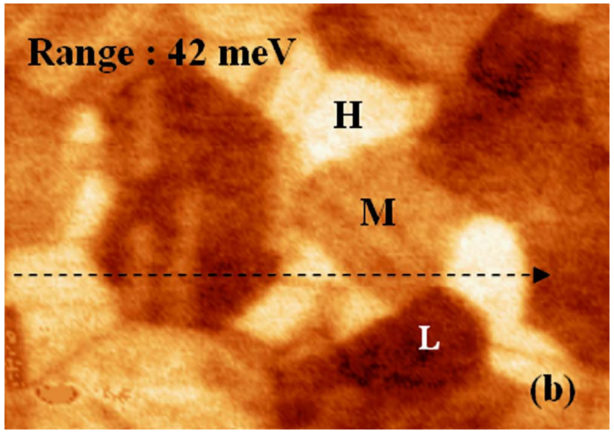


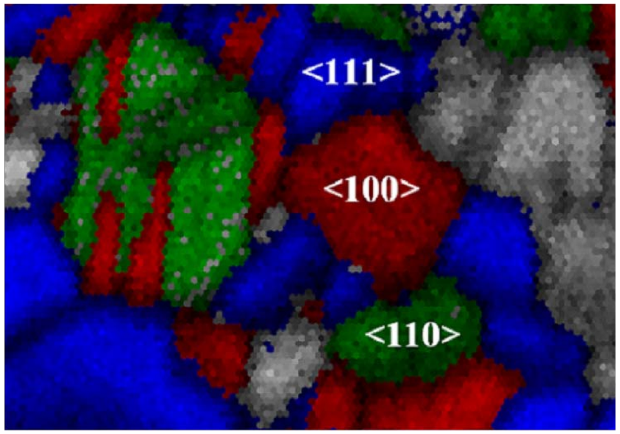
Thermal Casimir force

$$F^{(T)}_{\text{Drude}} = \frac{\xi(3) R k_B T}{8d^2} = 97\,\text{pN}\,\mu\text{m}^2$$

- Demonstrated thermal Casimir force
- Confirmed Drude model for ϵ as $\omega \to 0$

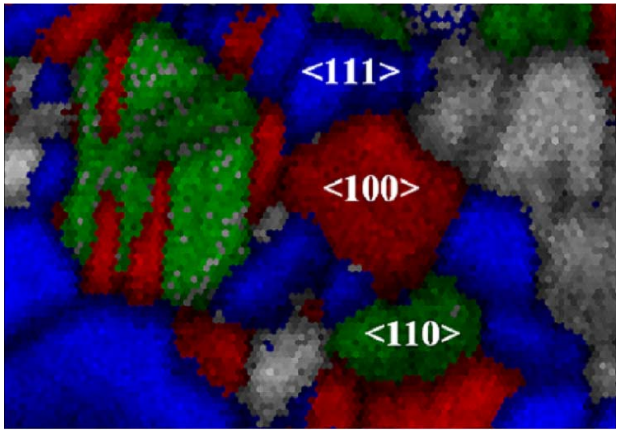
Improving Patch Modeling

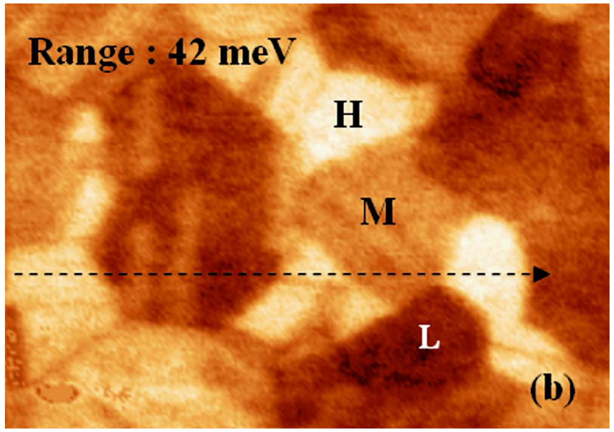




Behunin, Intravaia, DD, Maia Neto, Reynaud, arXiv:1108.1761

“Quasi-local” Patch Model. I





Voltages are constant in a given patch domain as observed in Kelvin probe experiments.

(Gaillard et al, APL 2006)

- “Quasi-local” patch model:

1) Tesselate the surface, and assign a potential to each patch

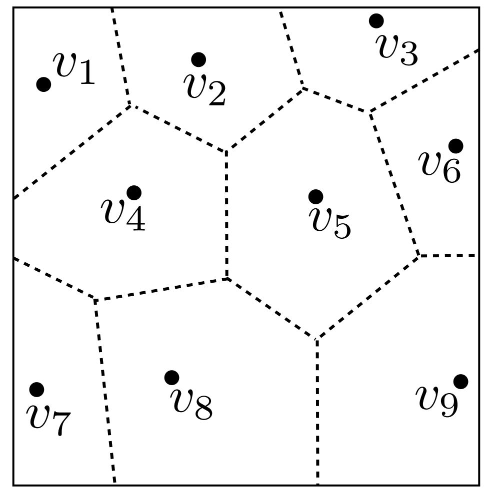
$$V(\mathbf{x}) = \sum_a v_a \theta_a(\mathbf{x})$$

2) Random crystallographic orientation at deposition

$$\langle v_a v_b \rangle_v = \delta_{ab} V_{\rm rms}^2$$

Therefore, the correlation function for a single layout micro-realization is:

$$\langle V(\mathbf{x}) V(\mathbf{x}') \rangle_v = V_{\rm rms}^2 \sum_a \theta_a(\mathbf{x}) \theta_a(\mathbf{x}')$$



poligons = patch domains
potential = crystallographic orientation

“Quasi-local” Patch Model. II

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3) Assume homogeneity and isotropy of average correlator

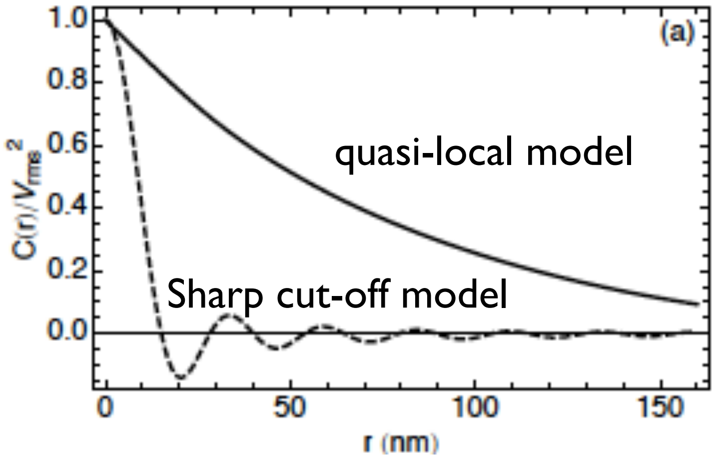
$$\langle V(\mathbf{x})V(\mathbf{x}')\rangle = C(|\mathbf{x}-\mathbf{x}'|) = C(r)$$

4) Perform average over layout micro-realizations

$$\boxed{C(r) = \frac{2V_{\rm rms}^2}{\pi}\int_r^\infty dl\,\Pi(l)\left[\cos^{-1}\left(\frac{r}{l}\right) - \frac{r}{l}\sqrt{1-\left(\frac{r}{l}\right)^2}\right]}$$

probability distribution of sizes of patches, e.g.

$$\Pi(l) = \frac{\theta(l_{\rm patch}^{\rm max} - l)\theta(l - l_{\rm patch}^{\rm min})}{l_{\rm patch}^{\rm max} - l_{\rm patch}^{\rm min}}$$



<u>Note</u>: similar “quasi-local” patch models have been recently used in the literature to study patch-assisted heating in ion-traps, etc.

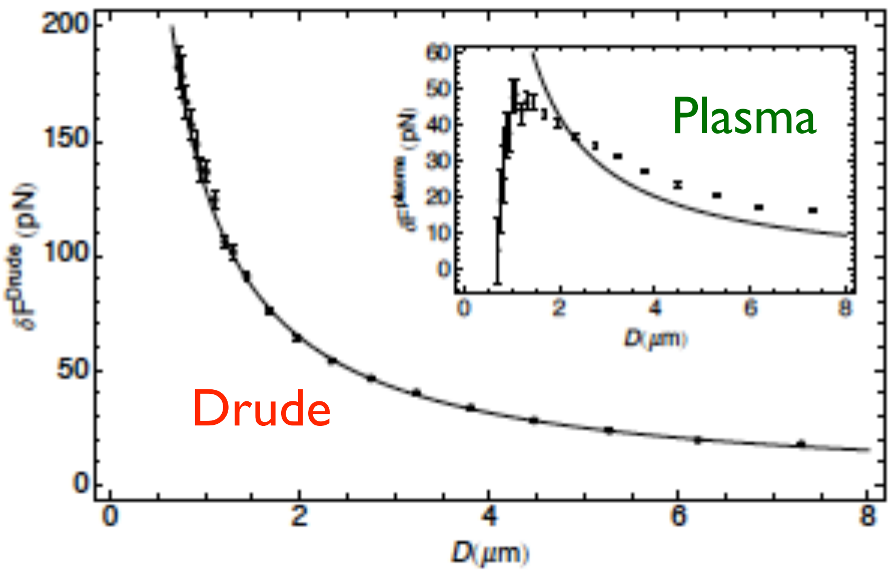
Quasi-local Patches + Casimir

Extracting the patch contribution described by the "quasi-local" model

$$F_r - F_{\text{Casimir}} = F_{\text{Patches}}$$

$$F_{\text{Patches}}(d) = \frac{\epsilon_0 R}{8} \int_0^\infty \frac{dk\, k^2 e^{-kd}}{\sinh(kd)} \times C[k]$$

Fitting model parameters $V_{\text{rms}}\,,\; l_{\text{patch}}^{\text{max}}\,,\; l_{\text{patch}}^{\text{min}}$



- Very good fit with Drude model, confirming the 1/d patch behavior.
- Bad fit with plasma model.
- V_{rms} smaller than for clean samples.
- Large patches.

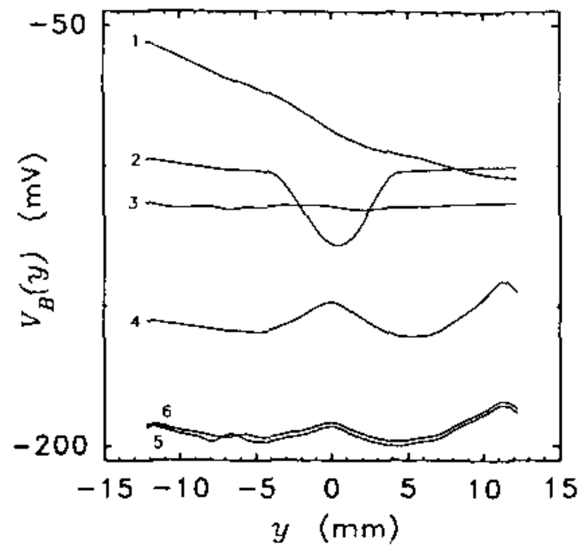
Effect of Adsorbates

adsorbates lead to:

- smeared surface potential variations

  - smaller voltages

  - patches larger than grain structure



(Rossi and Opat, JPD 1992)

(Darling et al, RMP 1992)

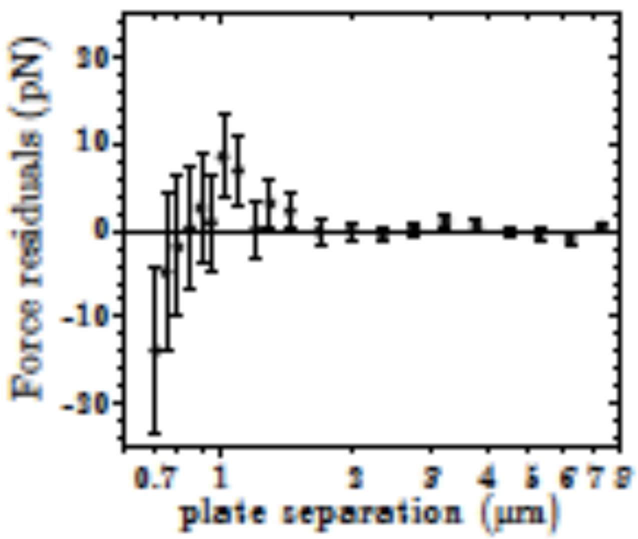
- transient patch effects (timescale of hours or less)

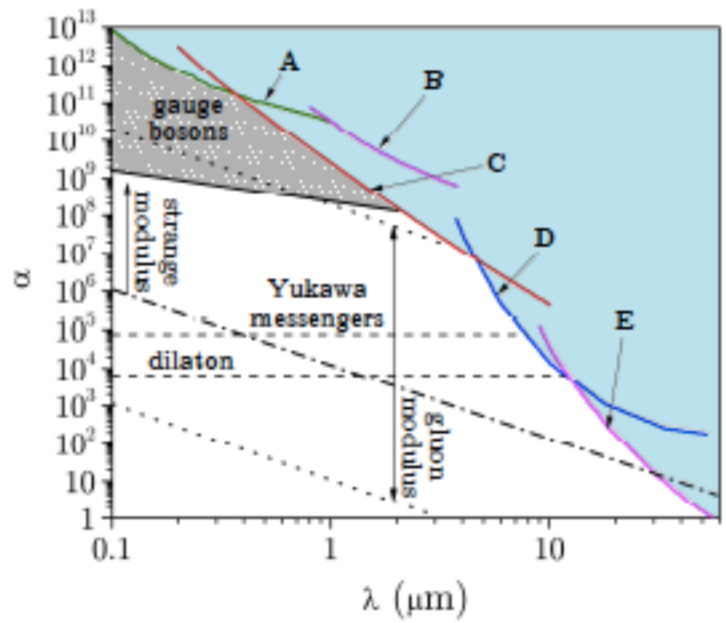
Without knowledge of the actual patch structure, the above justifies a fitting procedure for contaminated surfaces.

Constraining Exotic Gravity

Final force residuals $F_{\text{Exp}} - F_{\text{Patches}} - F_{\text{Casimir}}$ can be used to set constraints on non-Newtonian forces in the micrometer-range

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





Sushkov, Kim, DD, Lamoreaux, arXiv:1108.2547 (to appear in PRL)

Final Remarks

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- Observation of the thermal Casimir force.

  - modeled patch contribution

  - modeled Casimir contribution

- Our measurement and analysis indicate that the Drude model to describe Casimir interactions in metallic plates is correct.

- Independent measurements of patches would be extremely valuable.

  - Kelvin probe microscopy to measure patch distribution and voltage correlations.

  - Influence of sample fab processes, contamination, temperature, dynamics, ...

THE CASIMIR FORCE

Feeling the heat

A thermal Casimir force — an attraction between two metal surfaces caused by thermal, rather than quantum, fluctuations in the electromagnetic field — is now identified experimentally, with implications for our understanding of electrodynamics.

Kimball Milton

Evidently, this single experiment will not end the controversy about the thermal correction to the Casimir effect. Other experiments are in process that should offer independent evidence for or against the effect seen here. But if this experiment stands the test of time, it will help us understand better the electromagnetic and thermodynamic properties of real materials, and also of the quantum vacuum that pervades the universe.

CASIMIR Network Workshop/School in March 2012

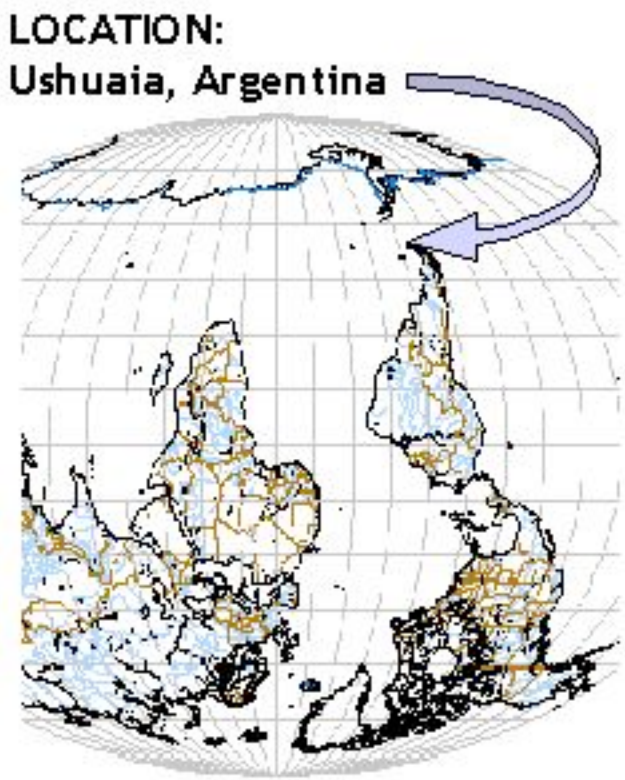
Lorentz center

Leiden, The Netherlands

Organizers: G. Palazantas, V. Svetovoy, S. Reynaud, and DD

NSF Pan American Advanced Study Institute (PASI)
School/Workshop in October 2012 on

Frontiers in Casimir Physics



Organizers: R. Decca, DD, R. Esquivel-Sirvent, P. Maia Neto, D. Mazzitelli, and H. Pastoriza