Influence of patch effects in Casimir force measurements

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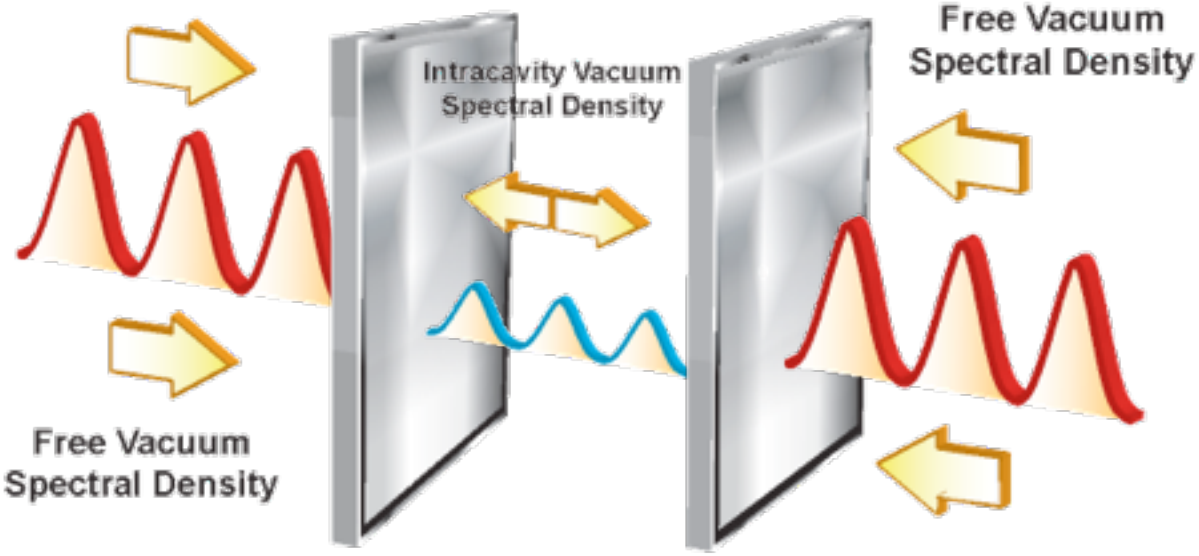
Outline of this talk

- **Brief intro to Casimir physics**
  - Basics, modern theory and experiments
- **Measuring Casimir forces**
  - Electrostatic calibrations
- **Electrostatic patch effects**
  - What they are, why they are relevant
  - Modeling patch effects
  - KPFM measurements
- **Conclusions**

Brief intro to Casimir phys.



The Casimir force

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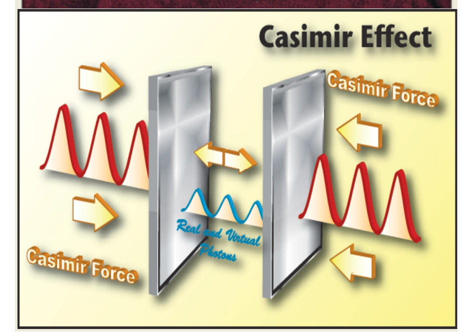
- **Universal effect from confinement of vacuum fluctuations**

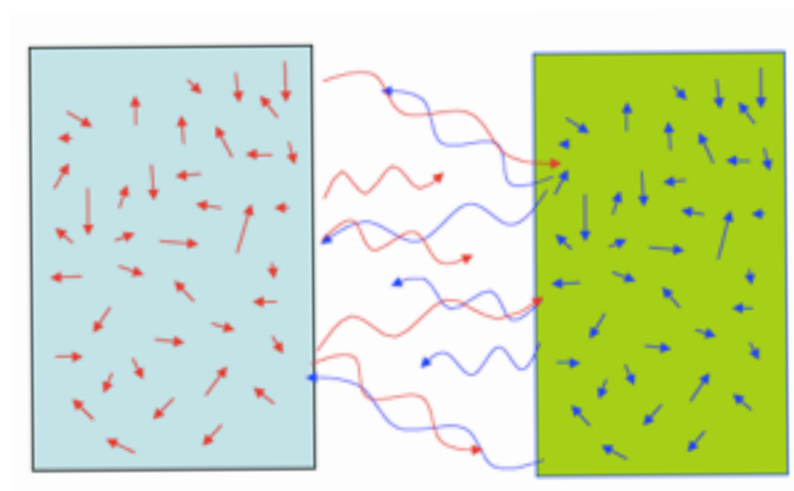
- Depends only on $\hbar, c$, and geometry

$$E = \frac{1}{2}\sum_{\mathbf{k}} \hbar\omega_{\mathbf{k}} \Rightarrow \boxed{\frac{F}{A} = \frac{\pi^2}{240}\frac{\hbar c}{d^4}}$$

$$(130\mathrm{nN/cm}^2 \text{ @ } d = 1\mu\mathrm{m})$$



- Alternative interpretation: **fluctuating charges and currents**



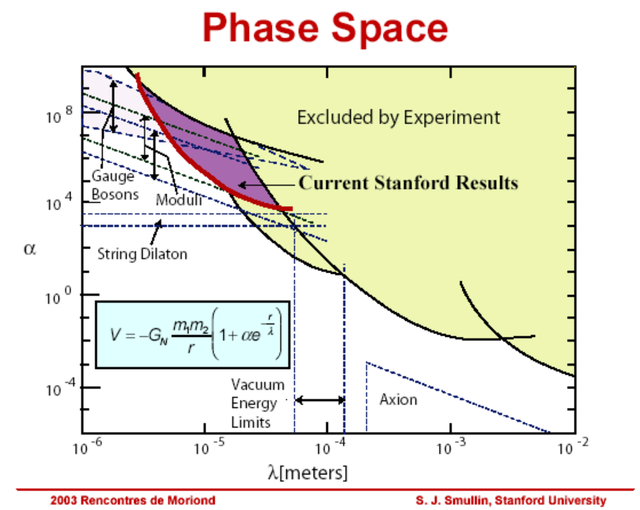
- The magnitude and sign of the force depends on geometry, materials, and temperature

Some relevant applications

Gravitation / Particle theory

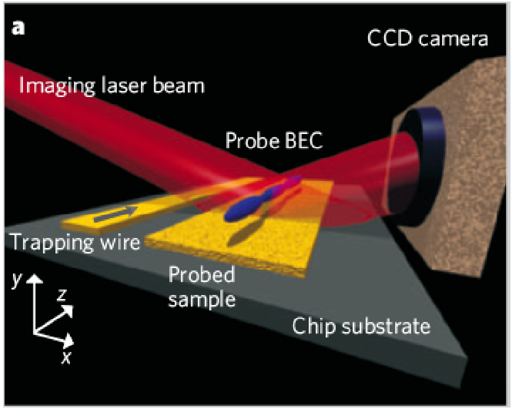
The Casimir force is the main background force to measure non-Newtonian corrections to gravity predicted by high energy physics

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



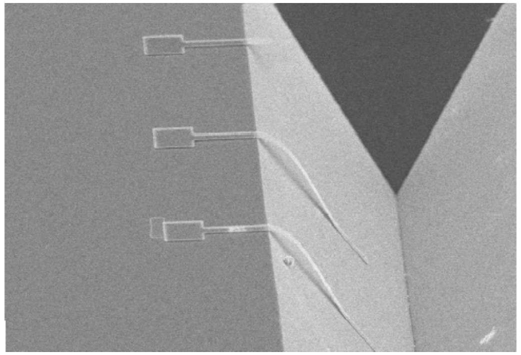
Quantum Science and Technology

Atom-surface interactions (e.g., ion traps, atom chips, BECs) and precision measurements



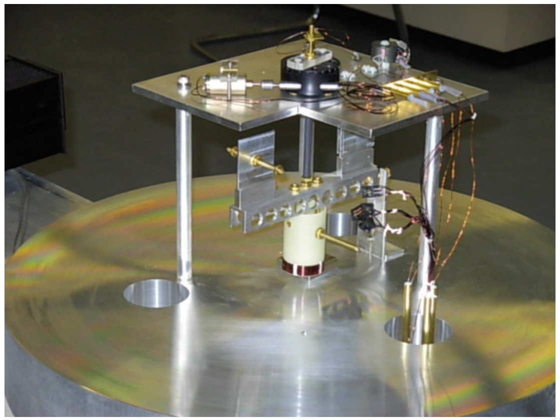
Nanotechnology

Casimir force is a challenge (stiction), but also an opportunity (contactless force transmission)



Modern experiments

- Torsion pendulum

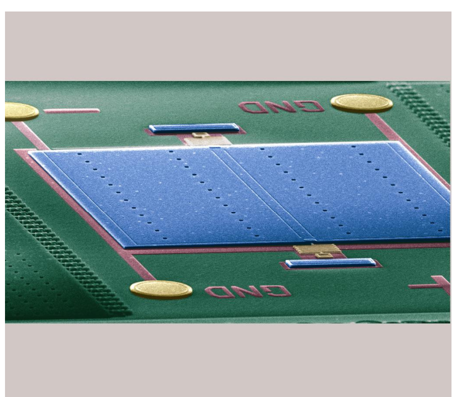


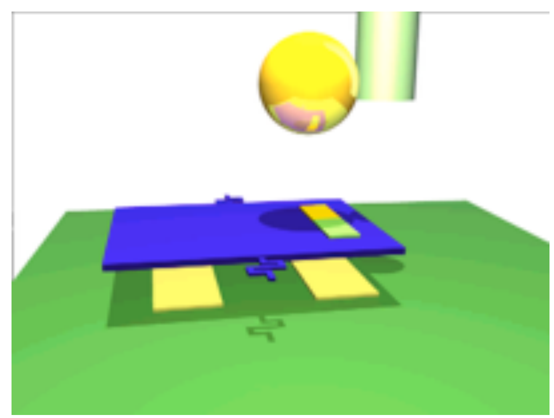
Lamoreaux (1997), 0.7-6.0 um

- Atomic force microscope

Mohideen (1998), 0.1-0.9 um

- MEMS and NEMS





Capasso (2001), Decca (2003), 0.2-1.0 um

The Lifshitz formula

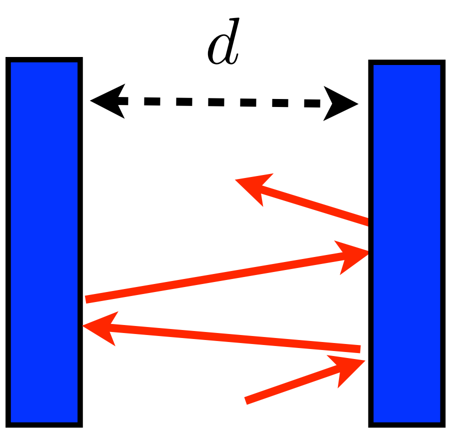
Casimir interaction energy between materials slabs (Lifshitz 1956)

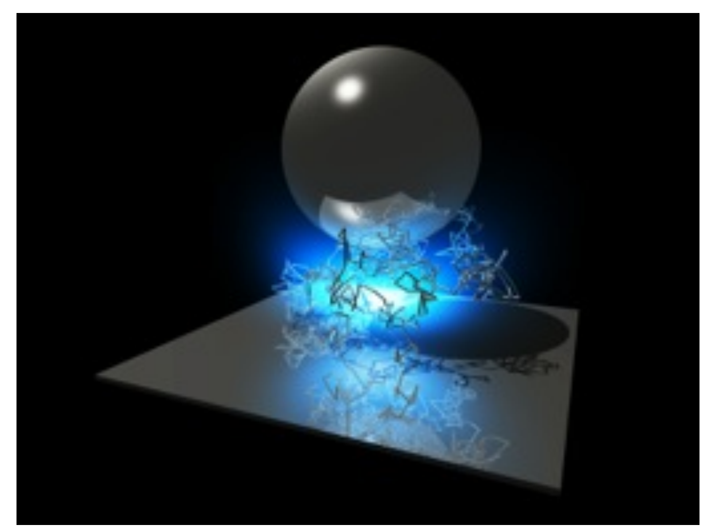
$$\boxed{\frac{E(d)}{A} = \hbar \sum_p \int_0^\infty \frac{d\omega}{2\pi} \int \frac{d^2\mathbf{k}}{(2\pi)^2} \coth\left(\frac{\hbar\omega}{2k_B T}\right) \mathrm{Im}\, \log[1 - R_{1,p}(\omega,k)\ R_{2,p}(\omega,k)\ e^{2id\sqrt{\omega^2/c^2 - k^2}}]}$$

Fresnel reflection coefficients $R_{\mathrm{TE}} = \frac{k_z - \sqrt{\epsilon(\omega)\omega^2/c^2 - k^2}}{k_z + \sqrt{\epsilon(\omega)\omega^2/c^2 - k^2}}$ $\quad R_{\mathrm{TM}} = \frac{\epsilon(\omega)k_z - \sqrt{\epsilon(\omega)\omega^2/c^2 - k^2}}{\epsilon(\omega)k_z + \sqrt{\epsilon(\omega)\omega^2/c^2 - k^2}}$

The log factor can be re-written as

$$\propto \sum_{n=1}^{\infty} \frac{1}{n} [R_{1,p}\ e^{idk_z}\ R_{2,p}\ e^{idk_z}]^n$$



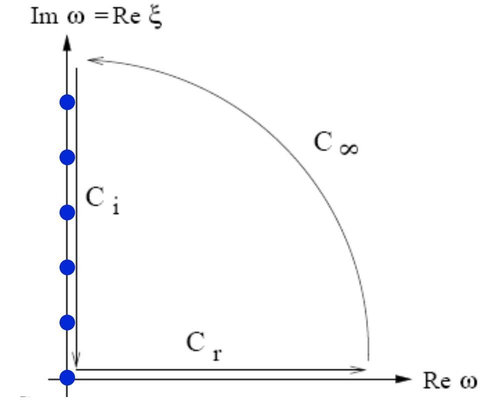


Scattering theory

Going to imaginary freq.

The function $\coth(\hbar\omega/2k_BT)$ has poles on the imaginary frequency axis at

$$\omega_m = i\xi_m \quad , \quad \xi_m = m\frac{2\pi k_B T}{\hbar}$$



After Wick rotation:

$$\boxed{\frac{F}{A} = -2k_BT\sum_p \sum_{m=0}^{\infty}{}' \int \frac{d^2\mathbf{k}}{(2\pi)^2}\sqrt{\xi_m^2/c^2+k^2}\;\frac{R_{1,p}(i\xi_m,k)R_{2,p}(i\xi_m,k)e^{-2d\sqrt{\xi_m/c^2+k^2}}}{1-R_{1,p}(i\xi_m,k)R_{2,p}(i\xi_m,k)e^{-2d\sqrt{\xi_m/c^2+k^2}}}}$$

$$\epsilon(i\xi) = 1 + \frac{2}{\pi}\int_0^\infty \frac{\omega\epsilon''(\omega)}{\omega^2+\xi^2}d\omega$$

Kramers-Kronig (causality)

Some limiting cases:

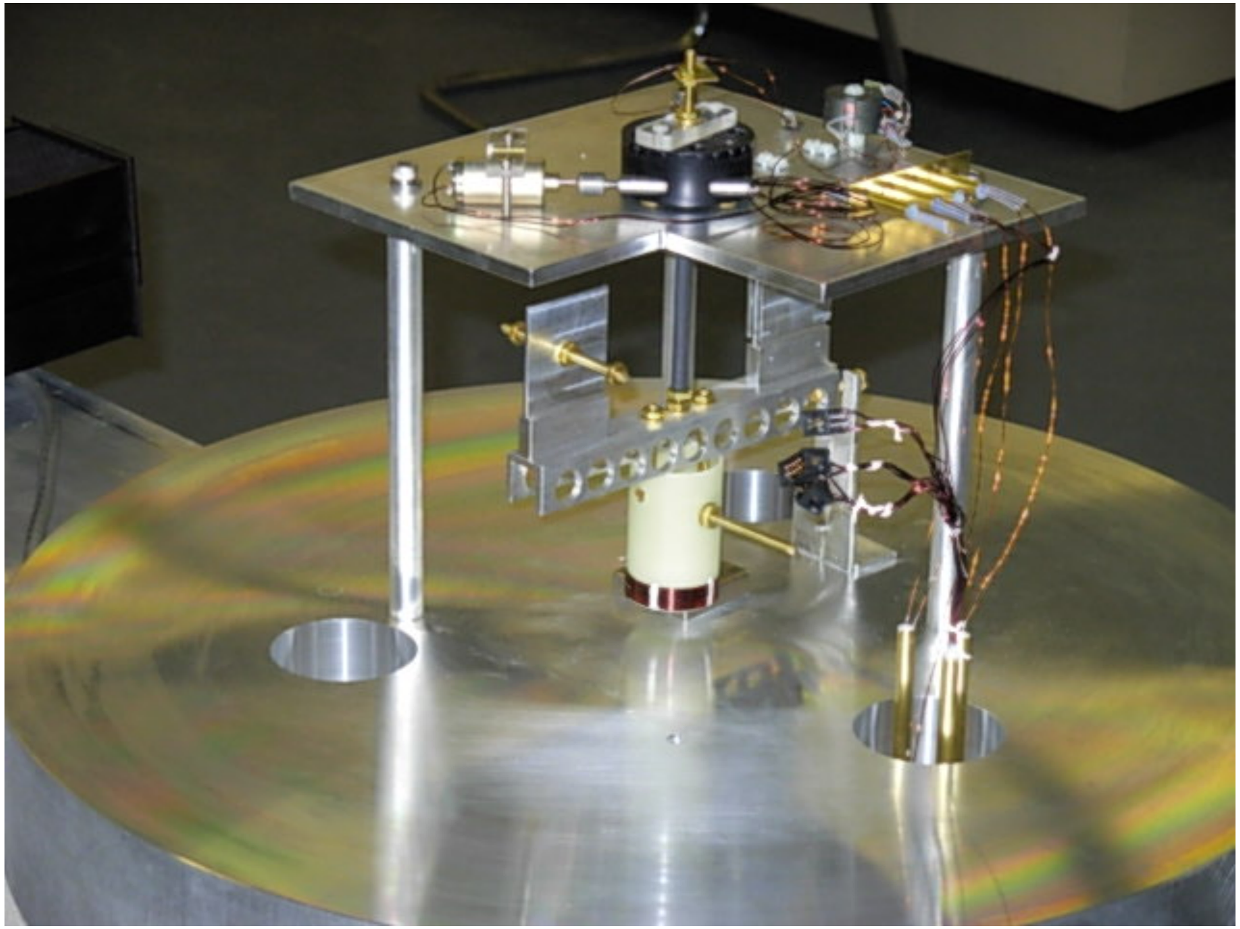
$F \propto d^{-3}$ (non-retarded limit, small distances)

$F \propto d^{-4}$ (retarded limit, larger distances)

$F \propto Td^{-3}$ (classical limit, very large distances)

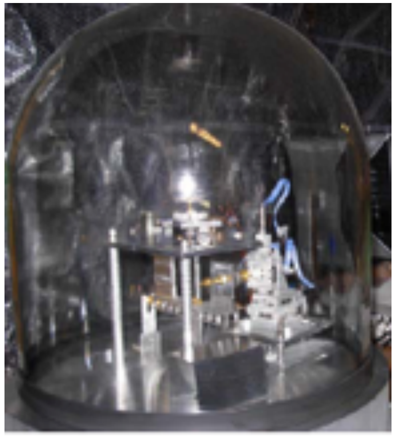
- **Casimir physics is a <u>broad-band</u> frequency phenomenon**

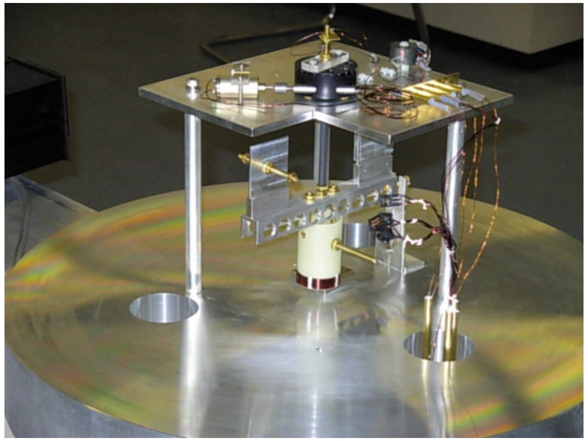
Measuring Casimir forces

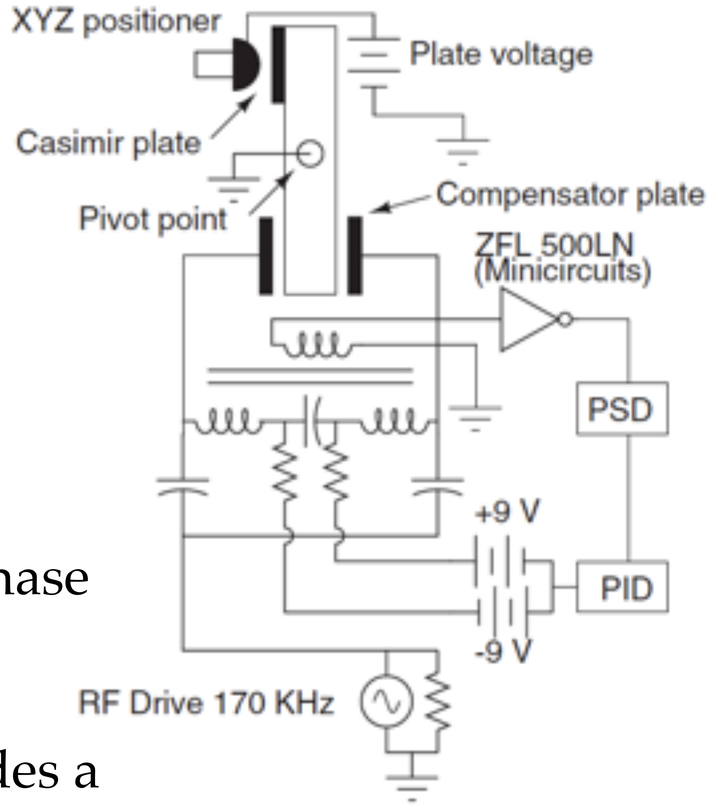


Torsional pendulum set-up

* Yale experiment: upgrade of Lamoreaux's 1997 experiment







An imbalance in capacitance is amplified and sent to a phase sensitive detector (PSD), which generates error signals.

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

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.

Naive picture (often used in the past):

Counterbias $V_a = V_m$ fixed at large separations, and *assumed to be distance-independent*

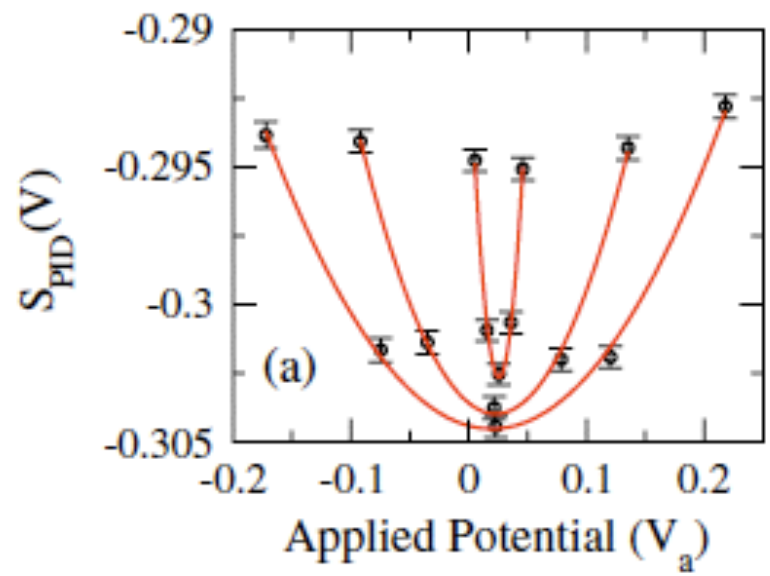
electrostatic force is supposedly *nullified*

“Parabola” measurements

Calibration routine (Iannuzzi *et al*, PNAS 2004)

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

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

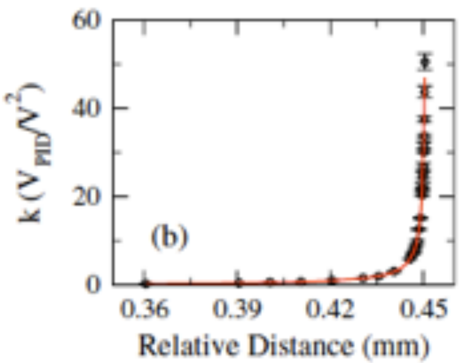


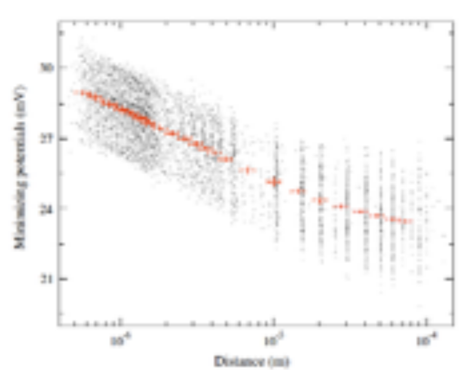
Fitting parameters:

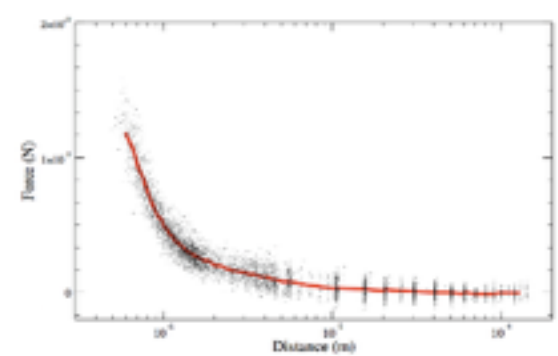
$k = k(d)$ ⟶ voltage-force calibration factor + absolute distance

$V_m = V_m(d)$ ⟶ distance-dependent minimizing potential

$S_0 = S_0(d)$ ⟶ force residuals: Casimir + non-Newtonian gravity + ...



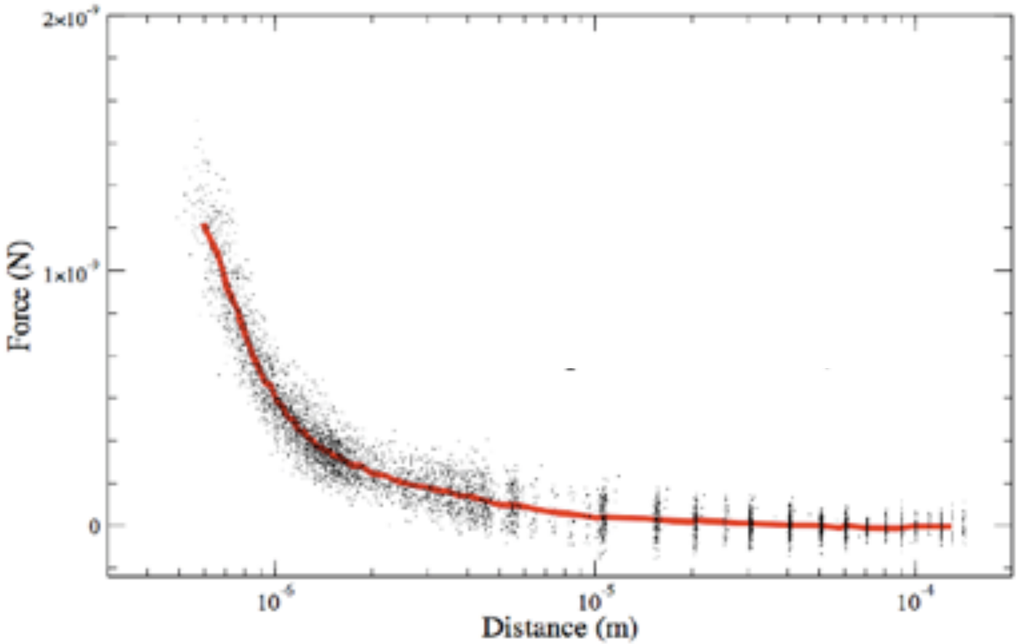




Force residuals for Ge plates

Residuals from Coulomb force obtained from the value of the PID signal at the minima of each parabola,

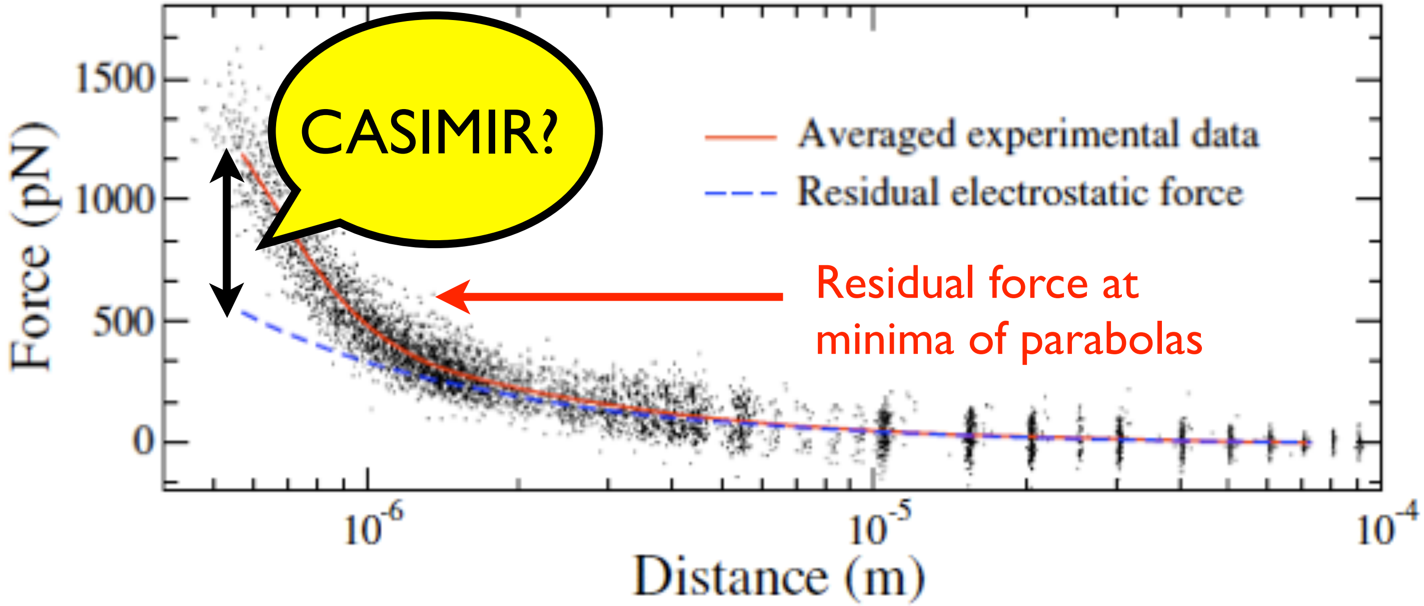
$$S_0(d) \rightarrow F_r(d)$$



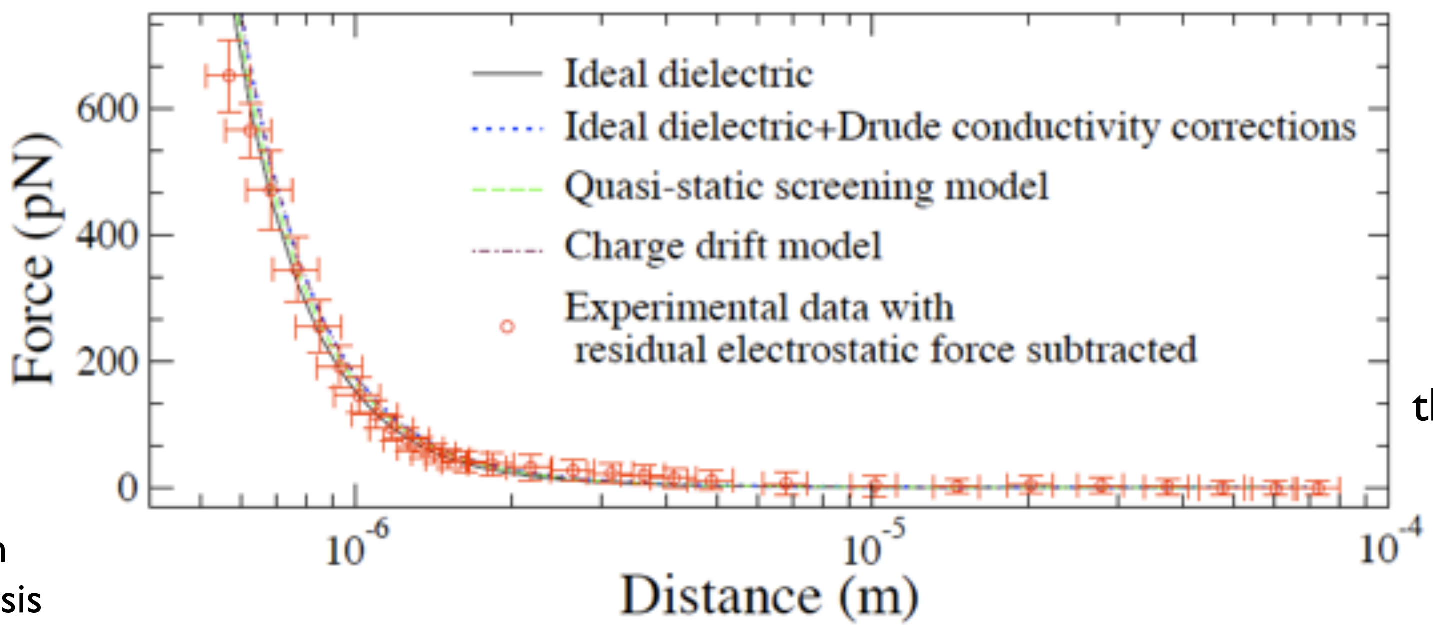
In the experiment, these force residuals are *too large* to be explained just by the Casimir-Lifshitz force between the Ge plates.

In fact, the experimental data shows a $1/d$ force residual at distances $d > 5\mu\mathrm{m}$, where the Casimir force should be negligible.

Subtracting 1/d in Yale Ge exp.



After subtraction of the electrostatic force residual $F_r^{\mathrm{el}}(d) = F_0 + \pi\epsilon_0 R \, \frac{[V_m(d) + V_1]^2 + V_{\mathrm{rms}}^2}{d}$



<u>Error bars:</u>

3% statistical uncertainties

10% fitting uncertainties from electrostatic analysis

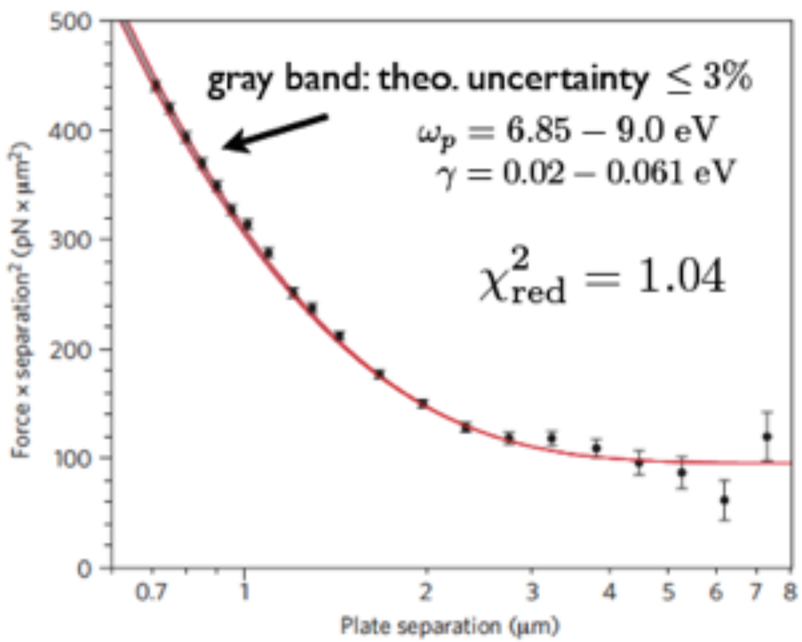
For $d < 5\mu\mathrm{m}$

$\chi_0^2 \approx 1$

for all the theoretical models

Subtracting 1/d in Yale Au exp.

✱ Yale experiment: agreement between experiment and (preferred) Casimir model for Au plates, after subtracting 1/d contribution via fitting



Thermal Casimir force

$$F^{(T)}_{\rm Drude} = \frac{\zeta(3) R k_{\rm B} T}{8 d^2} = 97\,{\rm pN}\,\mu{\rm m}^2$$

ARTICLES
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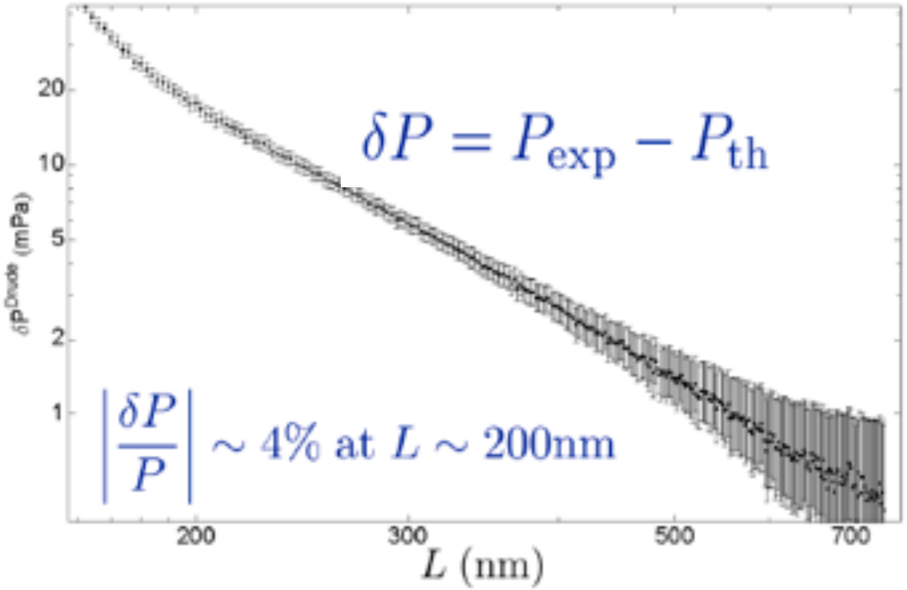
nature physics

Observation of the thermal Casimir force

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

Other Au experiments

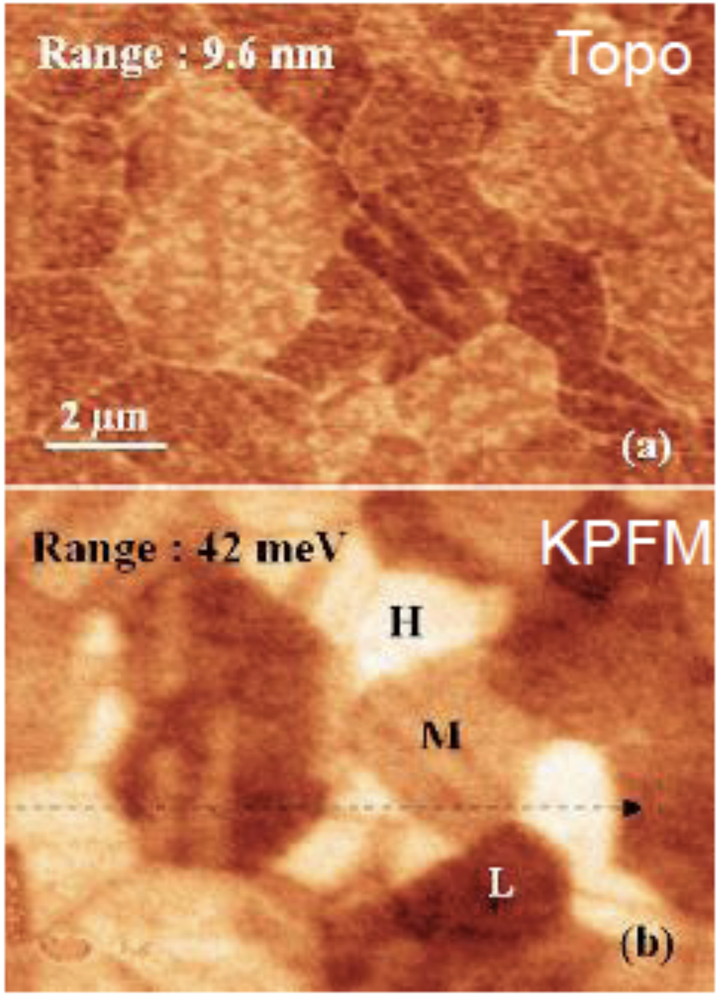
✱ Indiana/Riverside experiments: no agreement between experiment and (preferred) Casimir model for Au plates, 1/d does not work here!



What is the origin of the additional force residual?

- Experimental artifacts?
- Theoretical inaccuracies?
- Misrepresented systematic effects? $\longrightarrow$ electrostatic patches
- New forces?

Electrostatic patches



The patch effect

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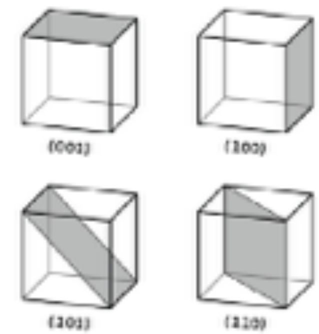
The surface of a conductor is an equipotential <u>only</u> for a perfectly clean surface of a homogeneous system cut along one of its crystalline planes.



Real metallic surfaces are not equipotentials

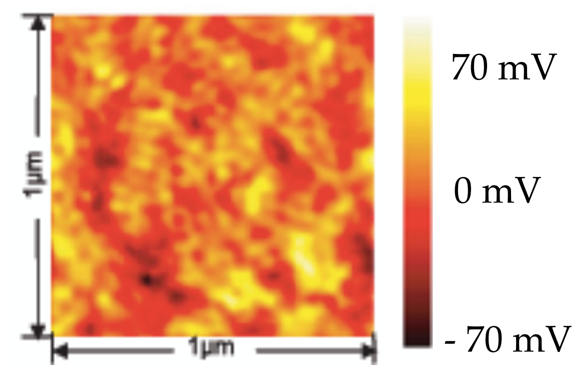
- Energy to extract an electron from a crystal depends on crystallographic orientation of the surface $\longrightarrow$ different work functions

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

- Real surfaces are composed of crystallites

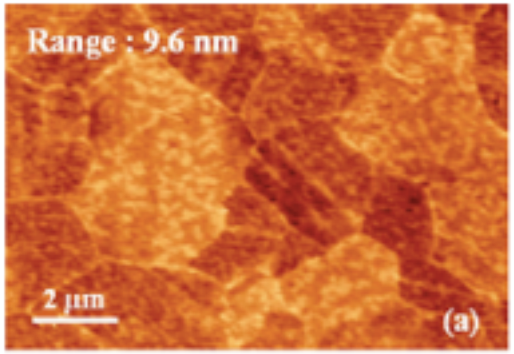
- Even a single crystal can produce patch effects due to the presence of contaminants

Au (111) face

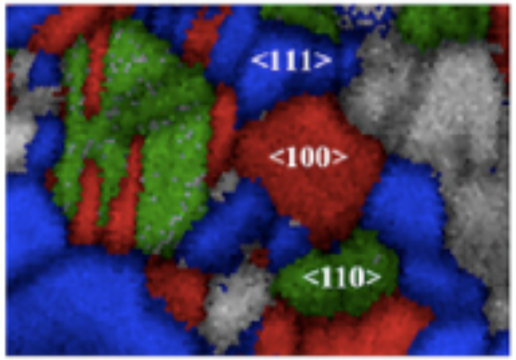


Topography and patches

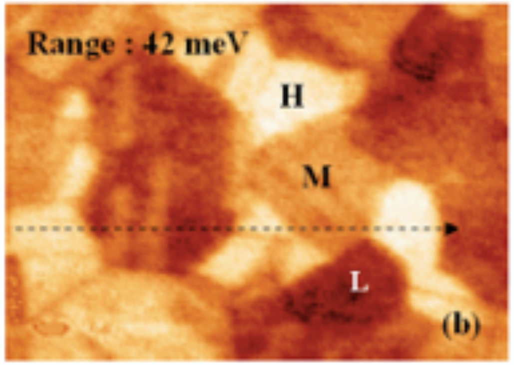
Atomic force microscopy
topography



Electron backscattered diffraction
crystallographic orientation



Kelvin probe force microscopy
surface potential



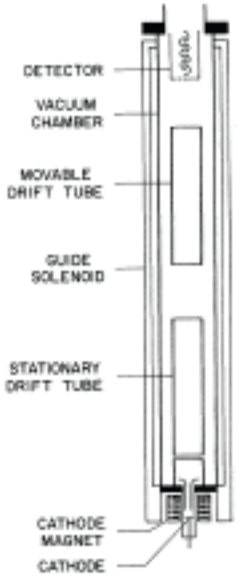
Each crystallographic plane has an associated work function which determines the local potential

(Gaillard *et al*, APL 2006)

Relevance of patches

- Measurements of gravity on elementary charged particles

  (Witteborn and Fairbank, PRL 1967)



- Large systematics in tests of general relativity

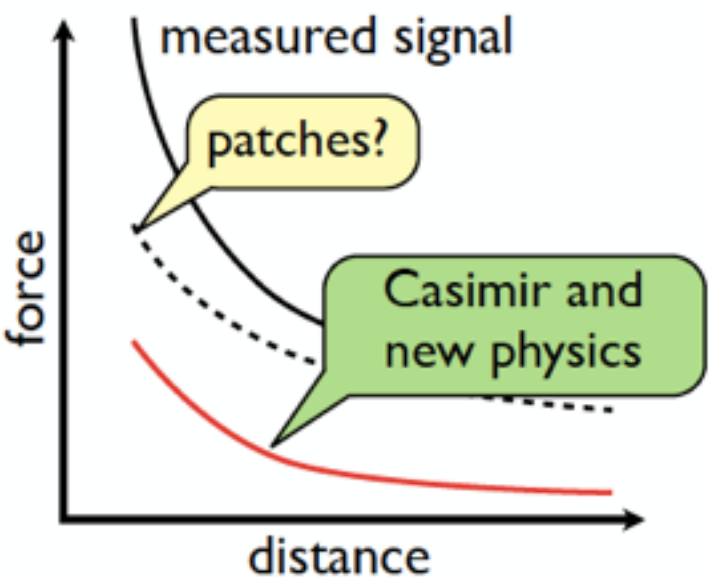
  (Everitt *et al*, PRL 2011)

- Produce heating loss in ion traps and Rydberg atoms

  (Monroe *et al*, PRL 2006)

- Force sensing, eg. Casimir interactions

  (Speake and Trenkel, PRL 2003)



Estimating patch effects

- Solve the Laplace equation for given geometry

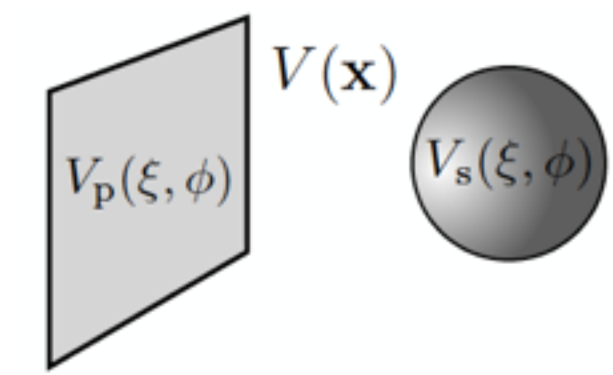
$$\nabla^2 V(\mathbf{x}, z) = 0$$

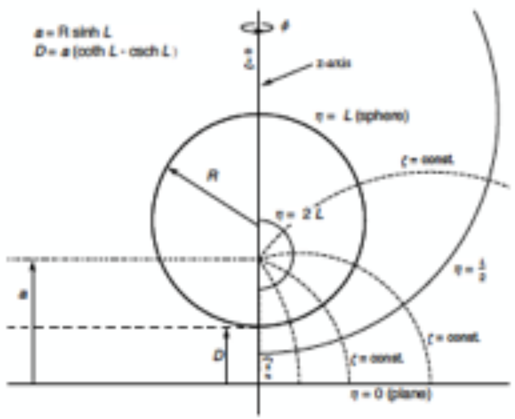
boundary conditions
on each surface

$$V(\mathbf{x}, z)|_{\mathbf{x},z\in \mathbf{S}_2} = V_2(\mathbf{S}_2)$$
$$V(\mathbf{x}, z)|_{\mathbf{x},z\in \mathbf{S}_1} = V_1(\mathbf{x})$$

Sphere-plane: use bi-spherical coordinates

$$\mathrm{E_{sp}} = \sum_{\mathrm{a,b=s,p}} \int d\Omega_{\mathrm{a}} \int d\Omega_{\mathrm{b}} V_{\mathrm{a}}(\Omega_{\mathrm{a}}) \mathcal{E}_{\mathrm{ab}}(\Omega_{\mathrm{a}}, \Omega_{\mathrm{b}}; D) V_{\mathrm{b}}(\Omega_{\mathrm{b}})$$





(Behunin, DD *et al*, PRA 2012)

- Input surface potential information (surface physics)

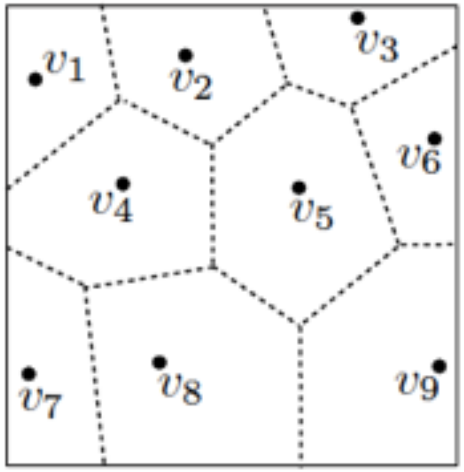
  - modeling
  - KPFM measurements

Modeling patch effects

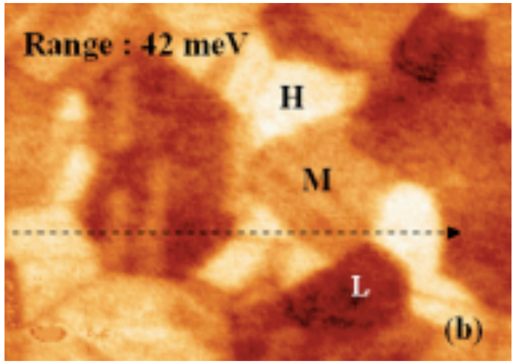
Assuming one does not know the patch voltage distribution, one follows an statistical approach:

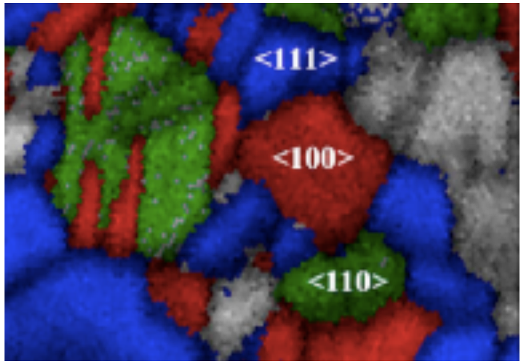
- patch layout is an stochastic process
- tesselate the surface
- assign potential to each patch

  - polygons: patch domains
  - potential = crystallographic orientation



Inspiration: voltage is constant over a given patch domain, as is observed in experiments (KPFM+ electron diffraction)





Voltage correlations

If many patches are contained within the effective area of interaction

$$V_a(\mathbf{x}_a)V_b(\mathbf{x}_b) \to \langle V_a(\mathbf{x}_a)V_b(\mathbf{x}_b)\rangle \equiv C_{ab}(\mathbf{x}_a, \mathbf{x}_b)$$ two-point correlator

Quasi-local model

1. tesselate surface and assign random voltages

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

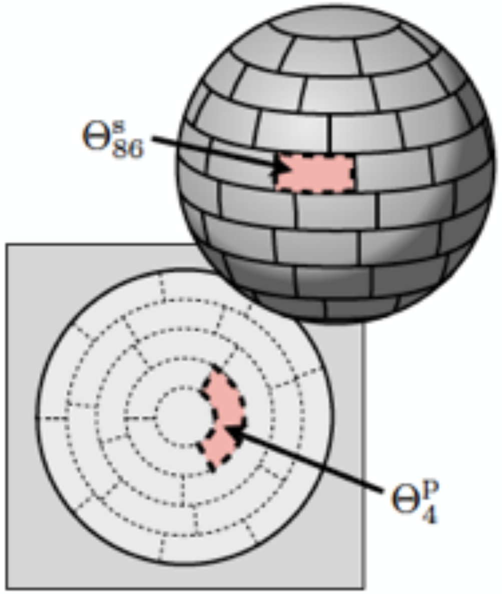
random voltage on patch a

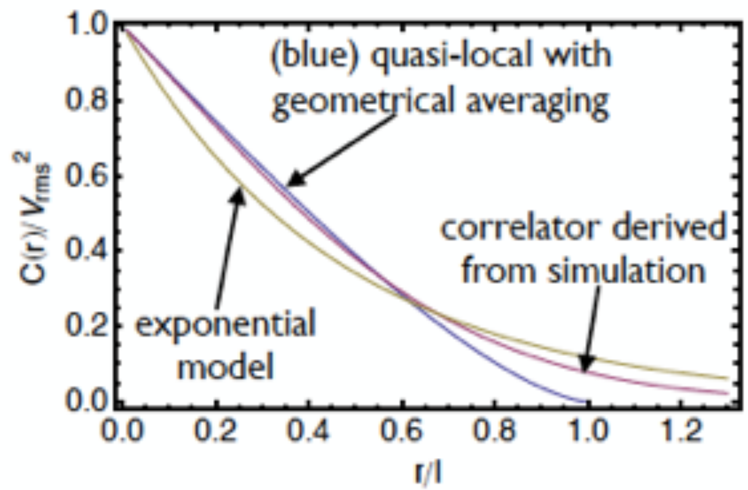
2. perform ensemble average with fixed geometry
statistical independence implies $\langle v_a v_b \rangle_v = v_{\rm rms}^2 \delta_{ab}$
giving the correlation function below for fixed patch geometry

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

3. use correlator obtained from an ensemble average of patch voltage assignments and geometry

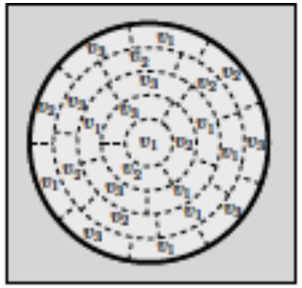
$$\langle V(\mathbf{x})V(\mathbf{x}')\rangle = C(|\mathbf{x}-\mathbf{x}'|)$$

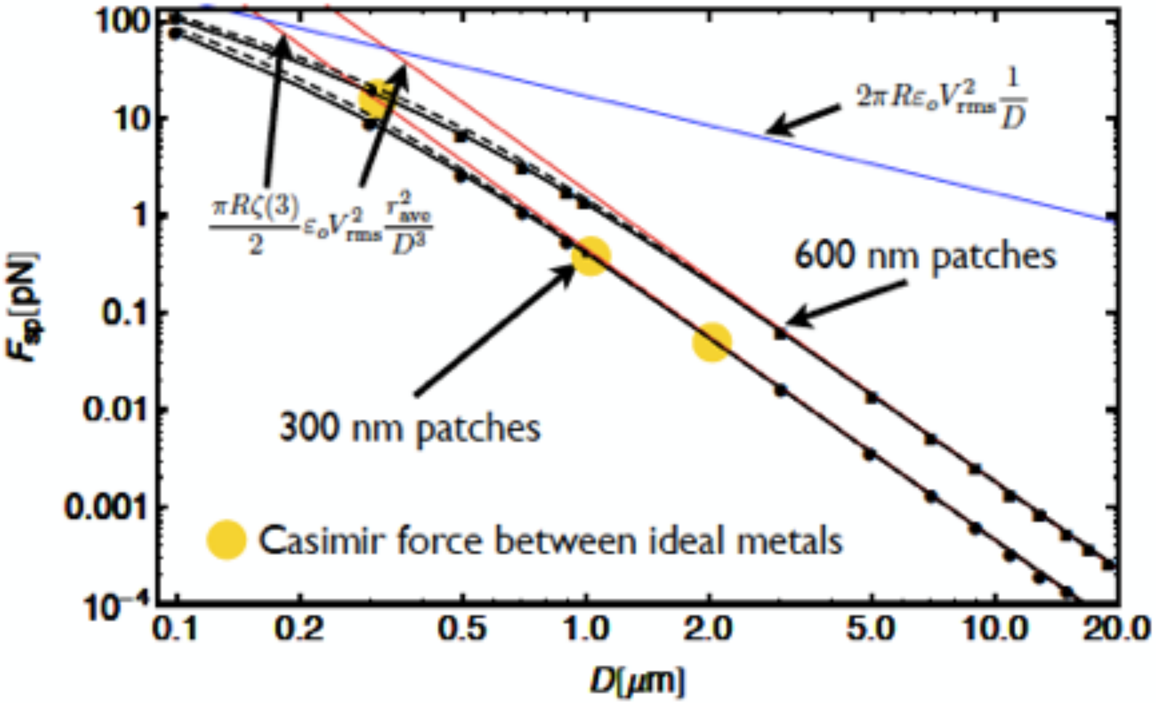




Results for sphere-plane

Using the quasi-local model with correlations computed for a fixed tesselation, $\langle V(\mathbf{x})V(\mathbf{x}')\rangle_v = v_{\rm rms}^2 \sum_a \Theta_a(\mathbf{x})\Theta_a(\mathbf{x}')$, we compute $F_{\rm sp}$





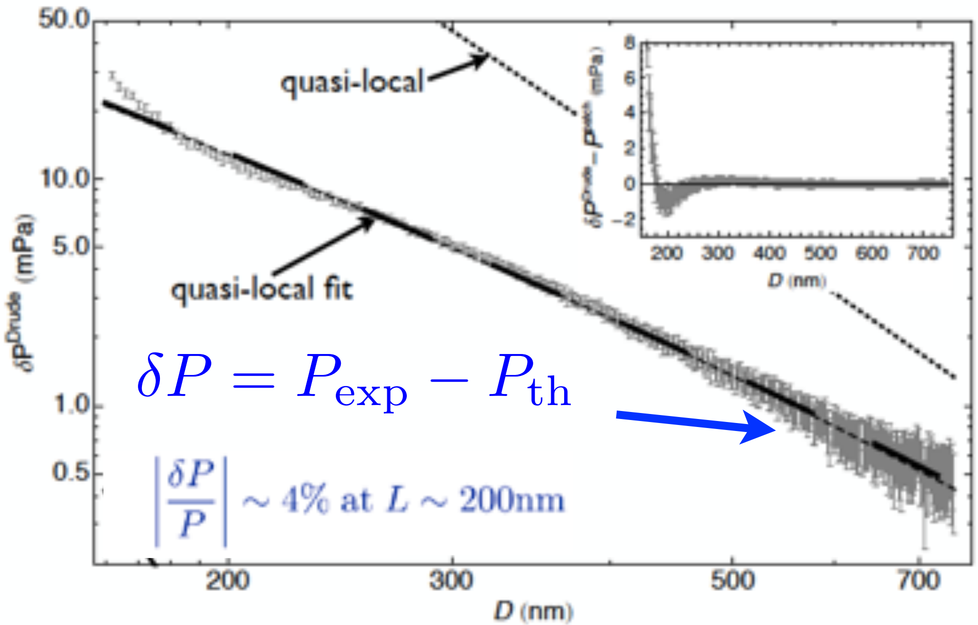
Asymptotic values for small and large patches:

$$L_{\rm patch} \ll D \rightarrow F_{sp} \propto D^{-3} \qquad L_{\rm patch} \gg D \rightarrow F_{sp} \propto D^{-1}$$

Comparing to Casimir residual

We compare the computed patch pressure to the difference between Casimir experiment and theory:

- Experimental pressure residual P_{exp} from Decca *et al* (2010-2014)
- Casimir pressure P_{th} via Lifshitz theory
  - finite temperature, roughness, Au optical data (with Drude extrapolation to low ω)
- Patch pressure P_{patches} from quasi-local model



- too large pressure for clean Au

- good fit for dirty Au

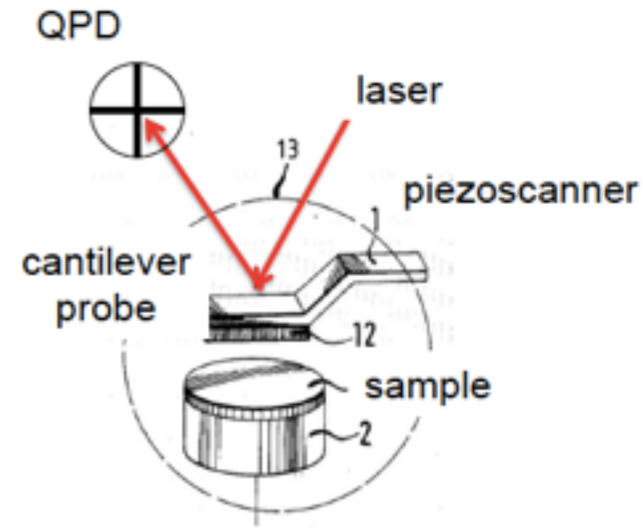
- patches are larger than crystallites (l_{ave} ~ 500 nm)
- rms voltage smaller than clean sample V_{rms} = 9 mV

(Behunin, Intravaia, DD *et al*, PRA 2012)

Measuring patches with KPFM

Kelvin probe force microscopy: a special kind of AFM

- tip at free end of a flexible cantilever
- cantilever raster-scanned over the sample
- deflection measures tip-sample interaction



$$U(D) = \frac{1}{2} C \Delta V^2 \qquad F(D) = \partial_D U$$

In order to quantify ΔV, two extra potentials are applied:

- A DC bias V_0 to minimize the tip-sample electrostatic interaction
- An AC potential $V_1 \sin(\omega t)$

$\boxed{F_\omega = -\partial_D C[(\Delta V - V_0) V_1 \sin(\omega t)]}$ is measured with a lock-in

At $F_\omega = 0$ the local patch potential is given by $\Delta V(x,y) = V_0$

Surface potential maps

- AM-KPFM measurements performed at ambient pressure and temperature on the same samples used for Casimir experiments

- Parameters:

  - Tip: 20 nm radius of curvature

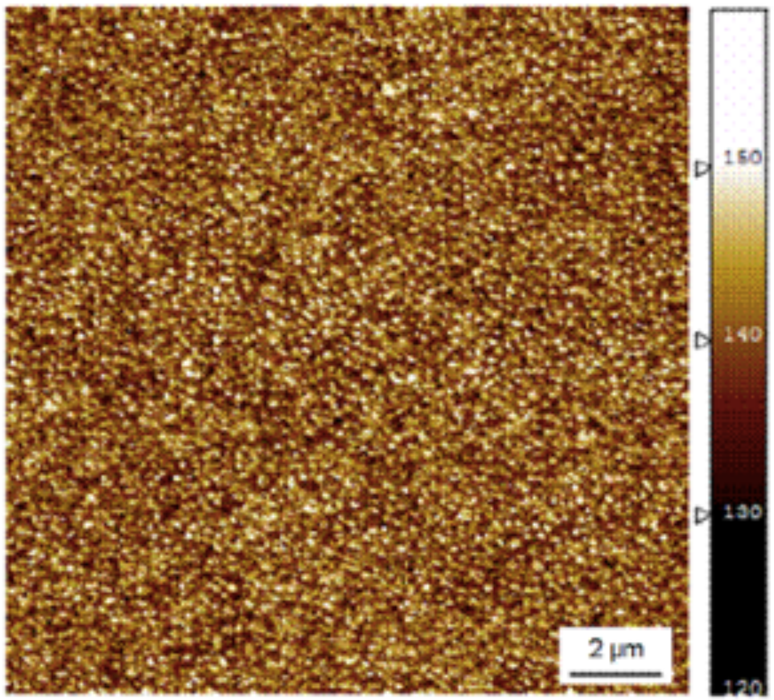
  - Cantilever: oscillation freq: $\omega \approx 75$ kHz
    stiffness: $k \approx 2.8$ N m^{-1}

  - tip-sample distance fixed at $D = 30$ nm
    (no cross-talk topo/electrical signals)

  - Scanning parameters 1 Hz per line
    $V_1 = 2.5V$
    scan range is 20 mV

  - Map area: $15.4 \times 15.4\ \mu\text{m}^2$
    (512 x 512 pixels)

Electrostatic potential map $V_s(\mathbf{r})$



Measurements performed by A. Liscio, ISOF Bologna

Theo-exper. comparison

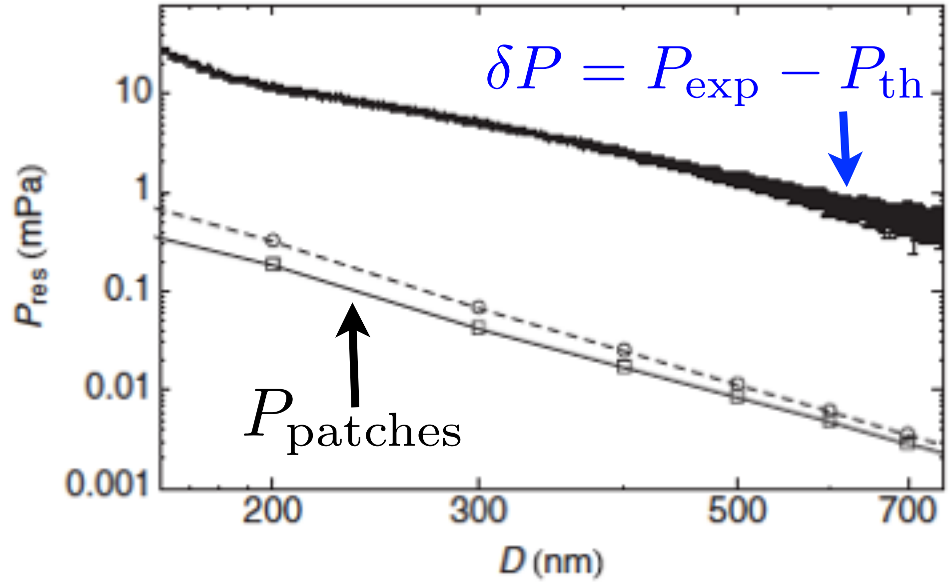
Sphere-plane patch force: $$F_{\rm sp} = \sum_{a,b} \int\int d\Omega_a d\Omega_b V_a(\Omega_a)\mathcal{F}_{a,b}(\Omega_a;\Omega_b)V_b(\Omega_b)$$

$$\mathcal{F}_{a,b} = \partial_D \mathcal{E}_{a,b}$$

- Patches measured only on the planar surface
- Assumption: patches on sphere w/ similar stat. prop. as on plane

$$F_{\rm sp} \approx 2\int\int d\Omega_{\rm p} d\Omega'_{\rm p} V_{\rm p}(\Omega_{\rm p})\mathcal{F}_{\rm p,p}(\Omega_{\rm p};\Omega'_{\rm p})V_{\rm p}(\Omega'_{\rm p}) \qquad (R \gg D)$$

- Equivalent sphere-plane patch pressure $P = (2\pi R)^{-1}\partial_D F_{sp}$



Patch force too small to explain the difference between the measured Casimir pressure and the theoretical expectations from Lifshitz theory!

(Behunin, DD *et al*, PRA 2014)

Some observations

Further work is needed to cure the limitations of the previous analysis:

- Measure patch distribution on sphere, and verify if there are no cross-correlations between sphere and plane

- Measure patch distribution at the same pressures ($P \approx 10^{-7}$ torr) at which Casimir measurements are performed. Contamination, and hence patch distribution, vary with pressure.

- Perform Casimir and KPFM measurements in situ, if possible

With the present information, we conclude that patches do not explain the Casimir theory-experiment of Casimir measurements using Au plates.

Another recent preprint

However, in a recent preprint from Munday's group (arXiv:1409.5012):

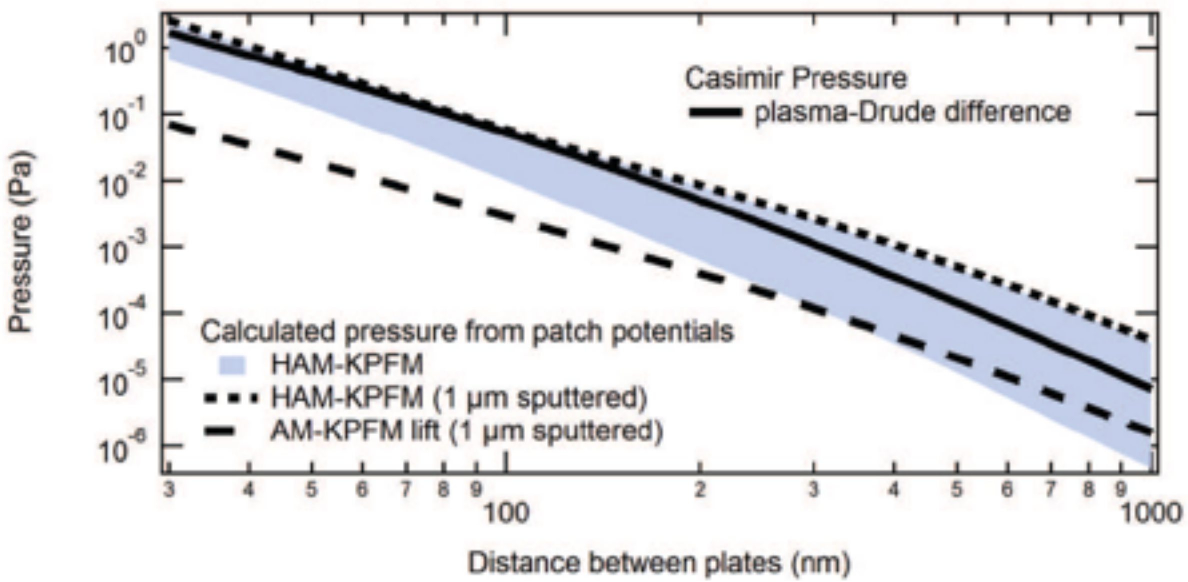
- Performed heterodyne AM-KPFM measurements on Au samples

$$D(t) = D + \delta D \sin(\omega_1 t)$$

$$F_{\omega_2} = -(\delta D/2)\, \partial_D^2 C[(\Delta V - V_0) V_1 \sin(\omega_2 t)]$$

higher spatial resolution

- Obtained a much higher patch pressure, (potentially) in agreement with the Casimir experiment-theory discrepancy.



Conclusions

- **Patches do contribute to the Casimir pressure as a systematic effect**

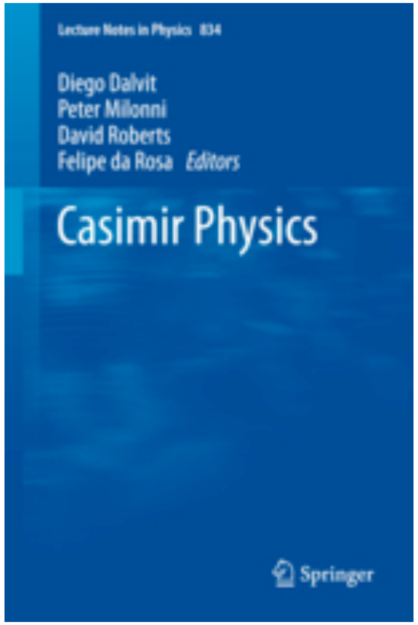
- **Patches on Casimir plates have been measured for the first time**

  however, at normal conditions of pressure and temperature

- **They do not seem to fill the gap of the theory/experiment discrepancy**

- **More work to be done:**
  - in situ measurements
  - KPFM on larger planar areas
  - KPFM on sphere
  - AM- vs HAM-KPFM measurements

Thank you!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