Casimir Forces:
confronting different geometries

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KITP, UCSB, Santa Barbara, 11/18/2008

Outline

First talk (Tuesday)

Introduction and motivations

An overview of the second generation experiments

Geometries to study the Casimir force

Some surprises to be understood

Final remarks

Second talk (Thursday)

Introduction and motivations

Photon extraction from vacuum

Two possible experimental routes

QFT in strong fields

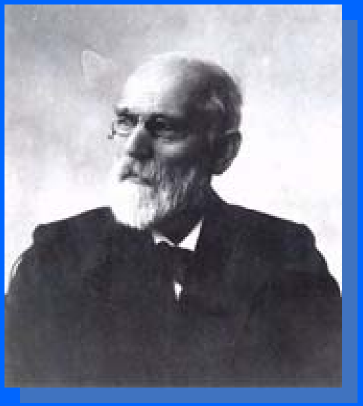
Overall conclusions, open issues, suggestions

Acknowledgments

[Woo-Joong Kim PhD thesis, defended on 22 August 2007, one copy here]

van der Waals forces

- Interactions between the molecules, and neutral atoms in colloids
- Crucial role in biological and physical-chemistry phenomena



London theory

- Description of the van der Waals forces in the framework of quantum mechanics
- Retardation effects are neglected

The experimental results

- At short distances the experiments confirm the London theory

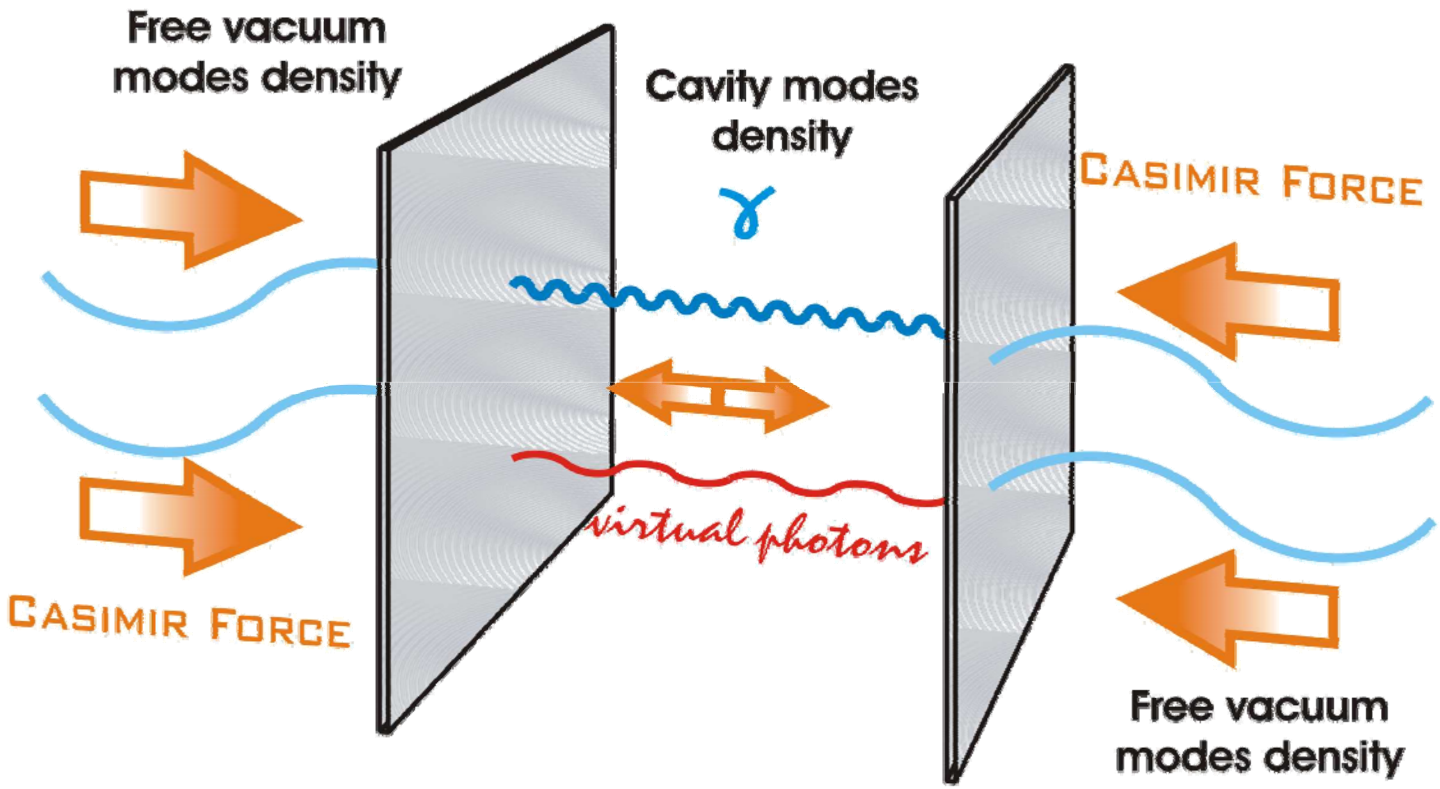
$$F \propto 1/r^7$$
$$E \propto 1/r^6$$

"… I visited Niels Bohr in Copenhagen.

We went for a walk and he asked me what I had been doing and I told him about the results of Polder and myself. That is nice he said, that is something new.

When I explained that I was still looking for a more satisfactory proof of the elegant asymptotic formulae he mumbled something about zero point energy. That was all, but it may well be that this almost forgotten remark put me on the right track."

Torricelli, von Guericke, Pascal, Boyle…



$$P_C = \frac{K_C}{d^4} \qquad K_C = \pi^2 \hbar c / 240 = 1.3 \times 10^{-27}\, Nm^2$$

$$(130\, nN / cm^2 \ @\ d = 1\,\mu m \rightarrow 10\,\mu Torr)$$

Remarks:

a) Casimir forces (or effects) are both quantum and relativistic, the Planck constant and the speed of light must appear in the relevant formulas: short distance effects as the one usually relevant to nanotechnology do not fall within the original Casimir realm;

b) The vacuum field approach is a convenient and elegant interpretation, but it is not essential, Lifshitz approach based on fluctuating sources is also viable (and more effective in taking into account “classical” effects);

c) The Casimir force is NOT small, nN is a large force on the microscale;

d) There are better ways to demonstrate quantum virtual vacuum, in particular Lamb shifts, g-2 of electron and muon, electroweak radiative corrections at LEP energy scale

One source of interest in Casimir forces arises from the need to discover or rule out new forces of gravitational origin in the micrometer range

ELSEVIER

13 March 1995

PHYSICS LETTERS A

Physics Letters A 198 (1995) 365–370

Detecting Casimir forces using a tunneling electromechanical transducer

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Communicated by P.R. Holland

Abstract

We propose the use of a tunneling electromechanical transducer to dynamically detect Casimir forces between two conducting surfaces. The maximum distance for which Casimir forces should be detectable with our method is around 1 μm, while the lower limit is given by the ability to approach the surfaces. This technique should permit one to study gravitational forces in the same range of distances, as well as vacuum friction provided that very low dissipation mechanical resonators are used.

This requires to perform experiments, rather than demonstrations

Experiments	Demonstrations
Interrogate nature in a novel regime of its parameters space	To show in the lab that a model works
Often there are no models, or alternatively at least two	There is THE model/theory
One learns a lot also from “failures”and even more from surprises	The goal is a successful implementation, failures are failures
Curiosity-driven, initially useless	Driven by society, technology enabling, useful
Often leads to controversies, requires reproducibility in other labs	Almost never controversial, if repeated is to implement the result to enable the new technology elsewhere

Examples: Michelson exp., Photoel. effect, Large Hadron Collider

Examples: Airplanes, Lasers, Quantum Computers

Modifications to the Newton's gravitational law

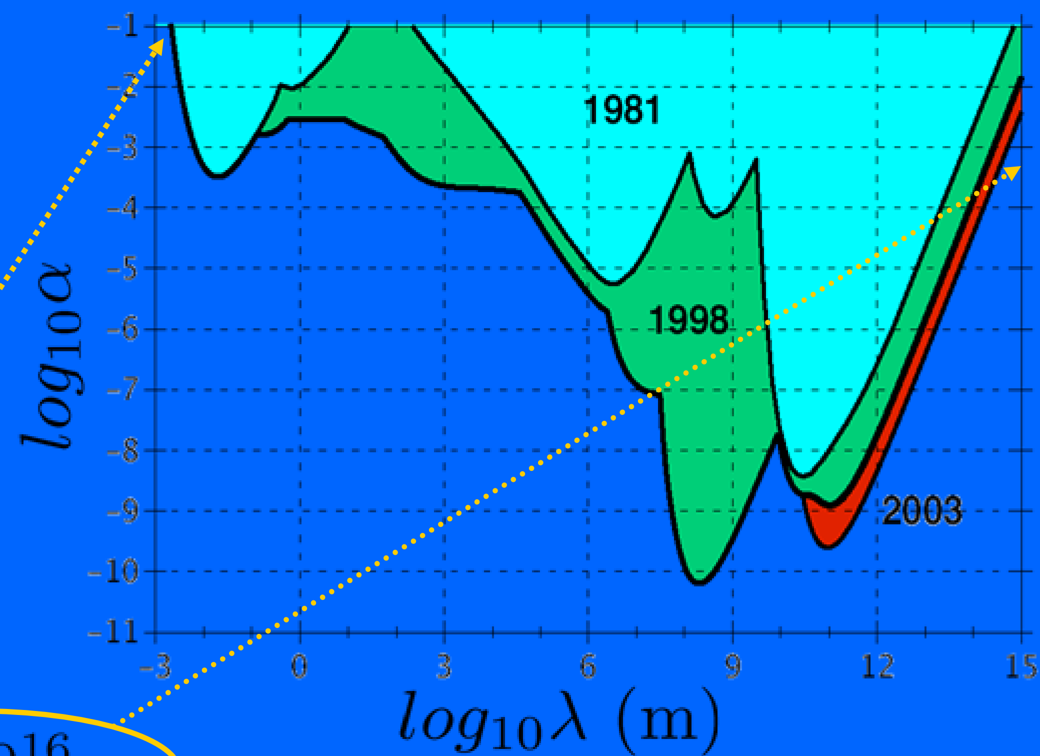
They seem required by any reasonable unification of gravity to the other forces

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

$$\frac{V_Y}{V_N} = \alpha e^{-\frac{r}{\lambda}}$$

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

…short distances

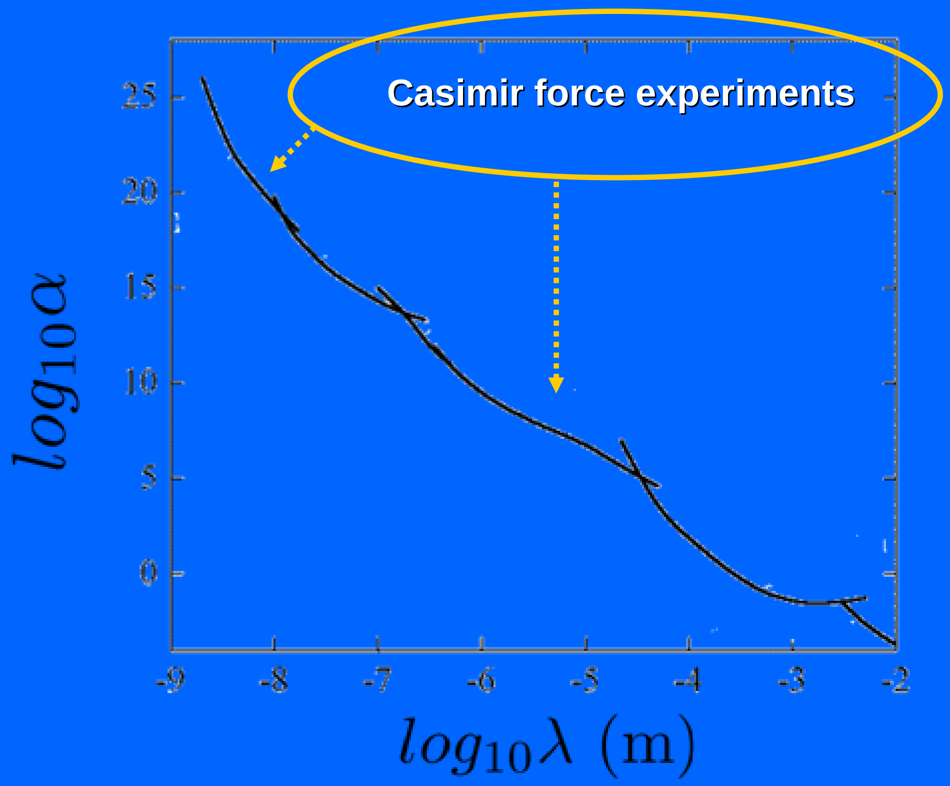


…long distances

$\lambda > 10^{16} m$

All this has started from a reanalysis of Eotvos experiments by Fischbach et al.

Non-relativistic deviations from Newton's law at small distances



Casimir forces are leading for neutral and nonmagnetic objects in a distance range between nanometers and micrometers

At larger distances experiments with modulated torsional balances

Apart from ultracold neutrons, no alternative experiment seems competitive in the nanometer to micrometer range

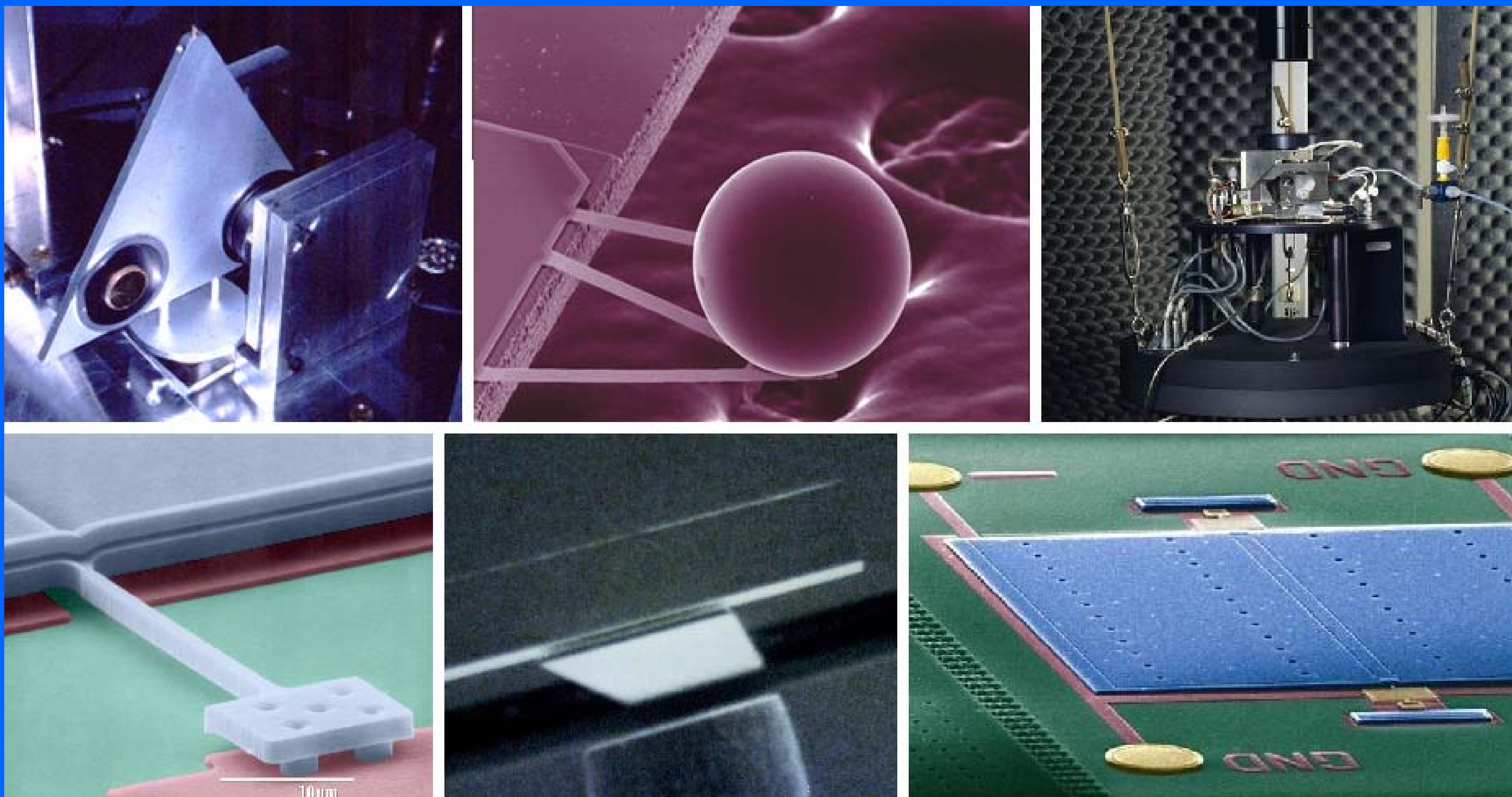
E. Adelberger et al Annu. Rev. Nucl. Part. Sci. (2003) [hep-ph/0307284]

Experimental configurations

Parallel plates	Sphere-plane
Original configuration proposed by Casimir, “textbook” geometry, clean theoretical predictions based on sum of modes	No sum of modes approach, theoretical interpretation relied on the proximity force approximation, under control at the <1 % level
Parallelism is difficult to achieve, dust is a problem	No parallelism issues, dust is not an issue
Large signal (nN)	Smaller signal (pN)

Status: a second generation of Casimir force experiments

(after the pioneers: Sparnaay, van Blokland, Oveerbeek, *et al*.)

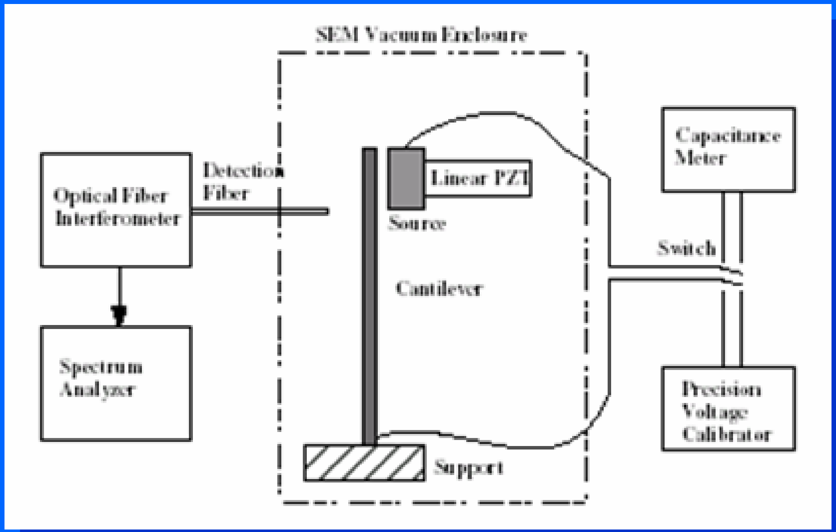


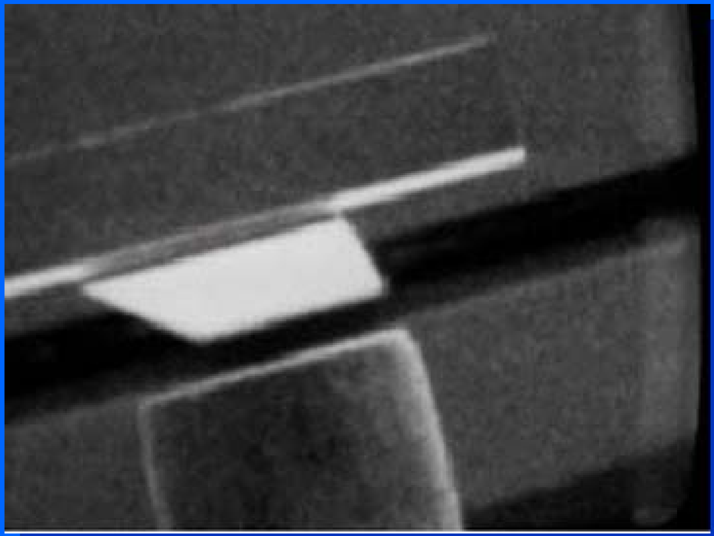
Now a third generation of experiments is ongoing

Parallel plane configuration

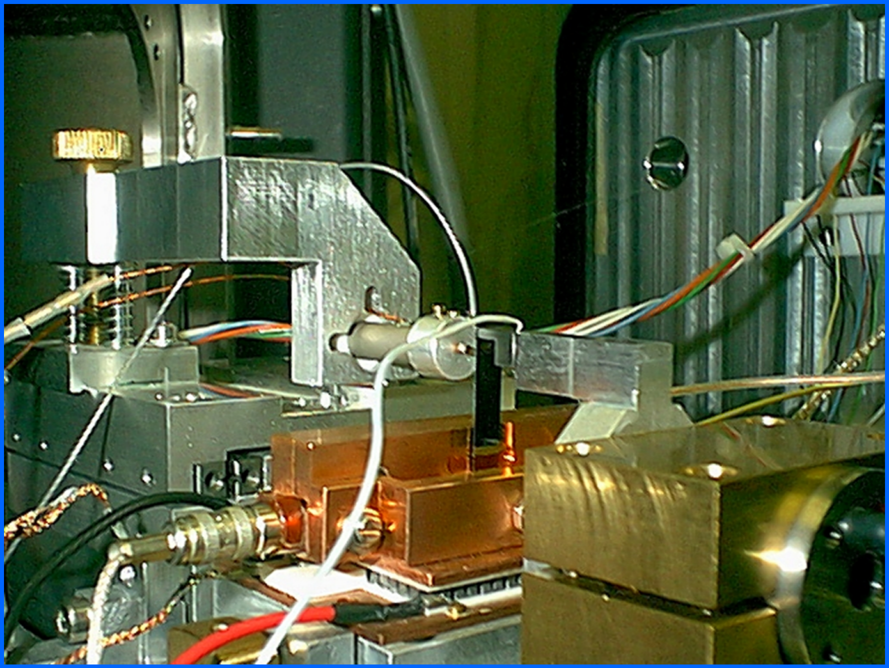
Early attempts by Sparnaay (1958) (about 100% accuracy and repulsive forces)

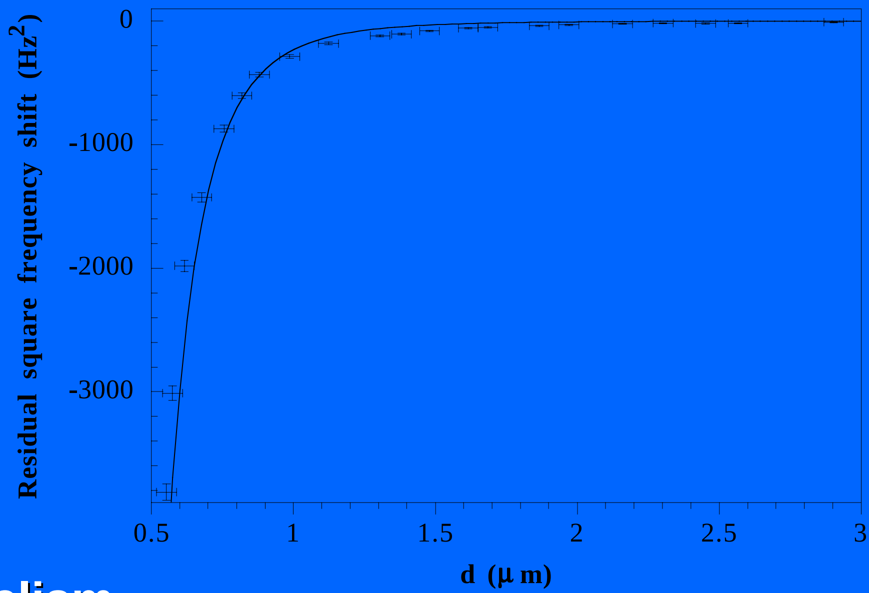
Measurement in Padova (June 2001), project started in 1994





- Surface of 1.2 x 1.2 mm
- Explored distances between 0.5 and 3 mm
- Fiber optic interferometer for readout





Complex system of actuators for parallelism

Use of Inchworm, PZT, in a SEM environment

Frequency-shift technique

$$K_C^{exp} = (1.22 \pm 0.18) \times 10^{-27}\ \mathrm{N\,m}^2$$

$$K_C^{th} = \pi hc / 480 = 1.3\ \times 10^{-27}\ \mathrm{N\,m}^2$$

[G. Bressi, G. Carugno, R. O., G. Ruoso, PRL 88, 041804 (2002)]

Cylinder-plane configuration

Control of thermal corrections critical for Casimir experiments at large (micrometers) distances

In between a plane-plane and a sphere-plane: cylinder-plane geometry

The cylinder-plane case has intermediate advantages and drawbacks

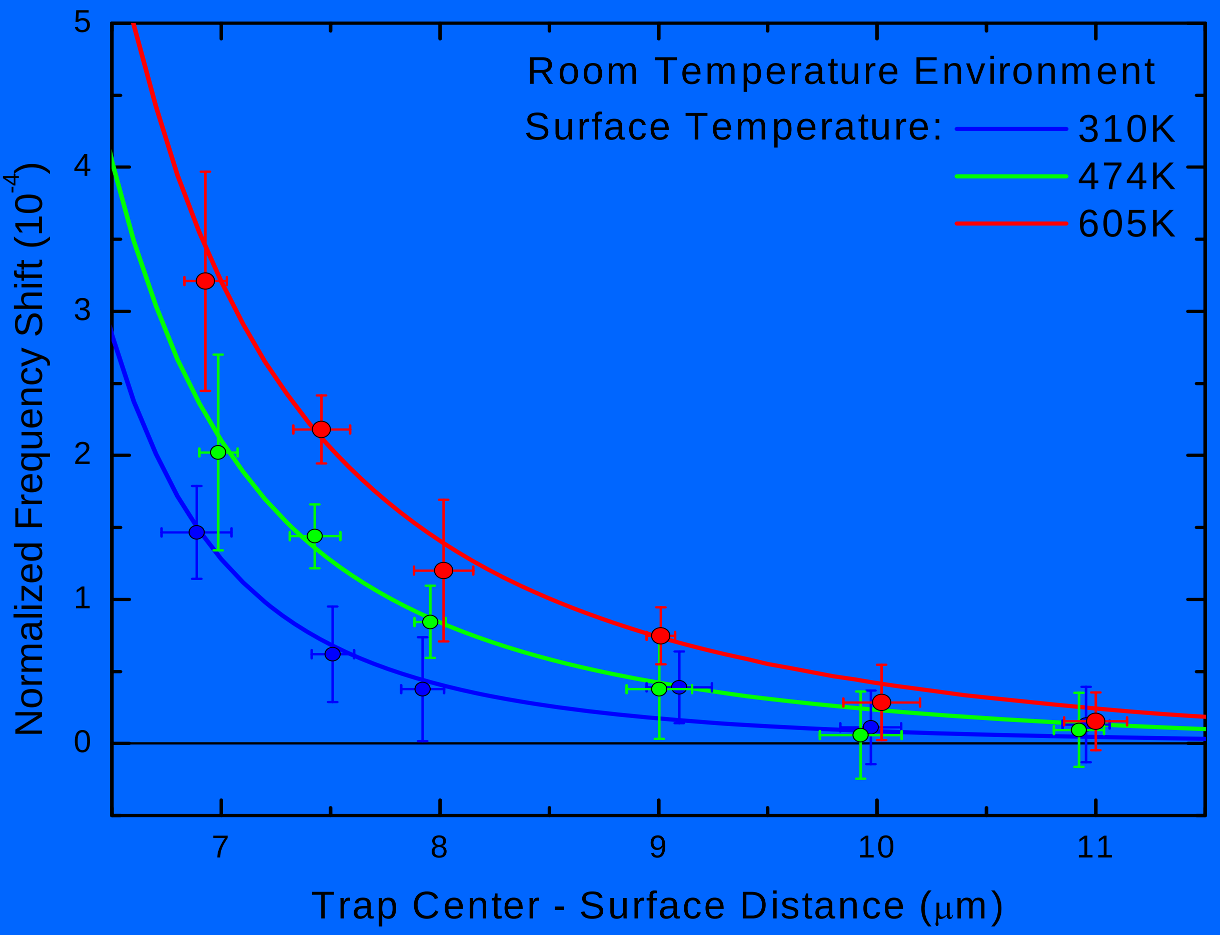
- With respect to the parallel plane configuration, it has less parallelism and dust issues, but less signal

- With respect to the sphere-plane configuration, it has an 1D issue of parallelism, but more signal, and it shares the proximity force approximation

[D. A. R. Dalvit *et al.*, Europhys. Lett. 67, 517 (2004)]

[M. Brown-Hayes *et al.*, Phys. Rev. A 72, 052102 (2005)]

Studies of thermal effects on Casimir-Polder force with BEC



J.M. Obrecht, R.J. Wild, M. Antezza, L.P. Pitaevskii, S. Stringari, and E.A. Cornell, PRL 98, 063901 (2007)

The expression for the Casimir force in a cylinder-plane configuration is

$$F_{cp} \approx \frac{\pi^3 \hbar c}{384\sqrt{2}} \frac{L a^{1/2}}{d^{7/2}}$$

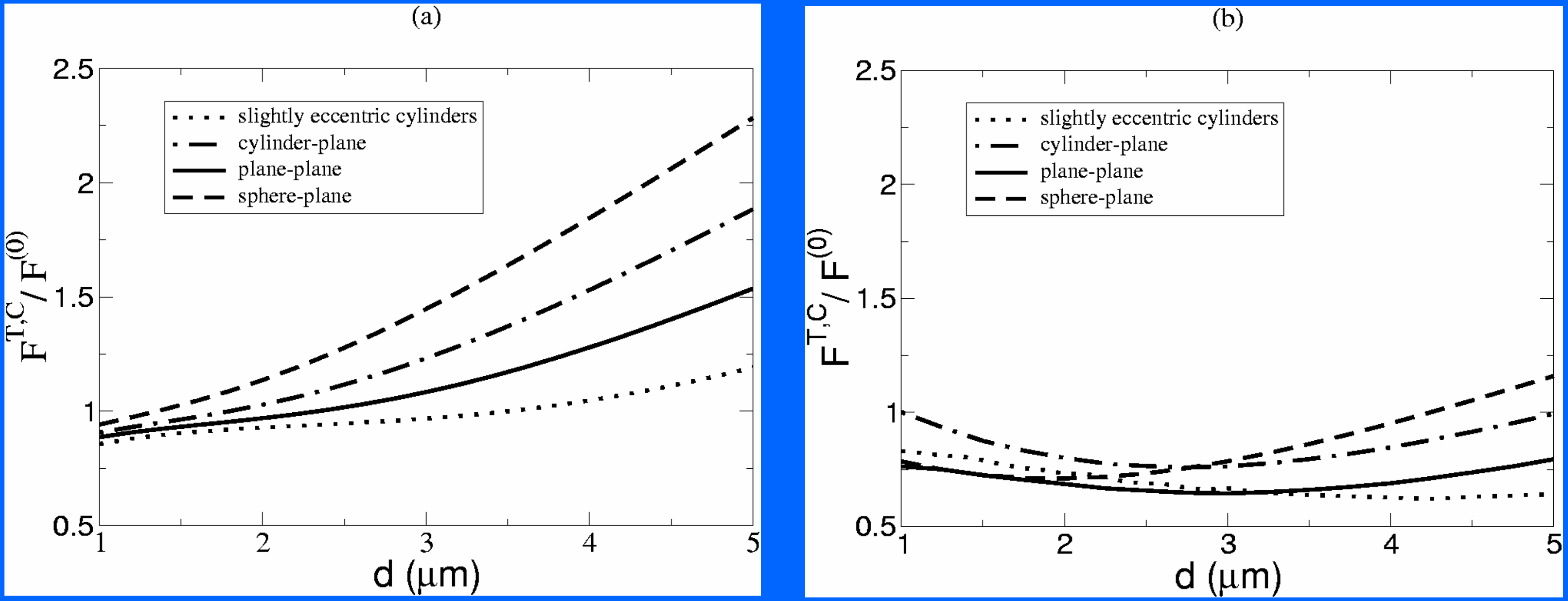
Signal linear in the cylinder length (if $L >> d, L >> a$)

Compare to the forces in sphere-plane and parallel plane

$$F_{sp} \approx \frac{\pi^3 \hbar c}{360} \frac{R}{d^3} \qquad F_{pp} = \frac{\pi^2 \hbar c}{240} \frac{A}{d^4}$$

Combined conductivity and thermal corrections

The combined conductivity-temperature corrections are larger than in the parallel-plane situation for at least two different models, the plasma model (a) and a model without the TE0 mode (b). The predictions of the two models differ by almost a factor 2 around 3-4 micrometers for all geometries.



Cylinder-plane is in between the two other configurations
Slightly eccentric cylinders has the softest dependence

Top micrometer (coarse) and PZT (fine) for optical fiber-resonator distance

Bottom 2-PZT actuators for distance control (common mode) and for 1D parallelization (differential mode)

20 mm diameter cylindrical lens (220 nm gold coating)

Rectangular-shaped silicon resonator (around 880 Hz)

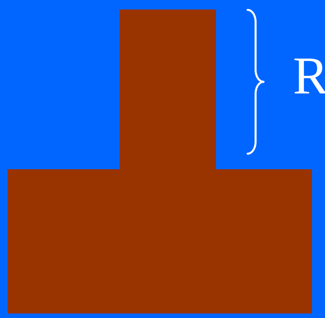
Optical microscope for assessment of cylinder-plane distance

Silicon Resonator

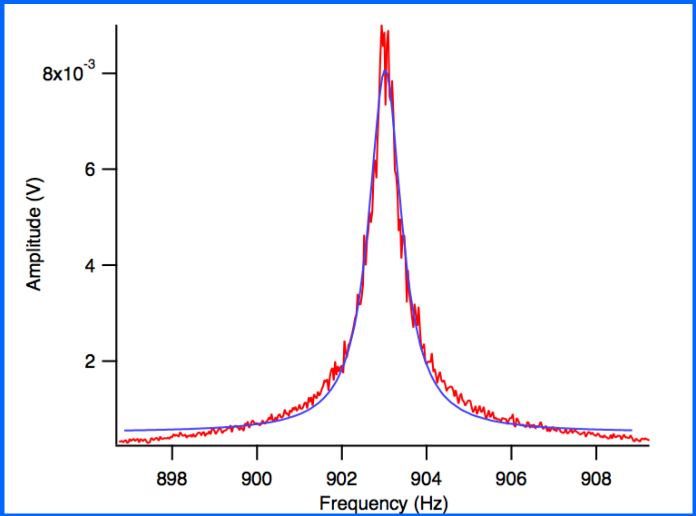
$$f_1 = (1.875)^2 \frac{t}{2\pi\ell^2}\sqrt{\frac{E(T)}{12\rho}} = 883 \pm 32\text{Hz}$$

$$t = 330 \pm 13\mu\text{m}$$

$$\ell = 2 \text{ cm}$$



- Measured Frequency = 884.370 ± 0.007 Hz
- Linewidth = 0.9 Hz
- Resonator mass= $(1.72\pm0.05)\times10^{-4}$ kg

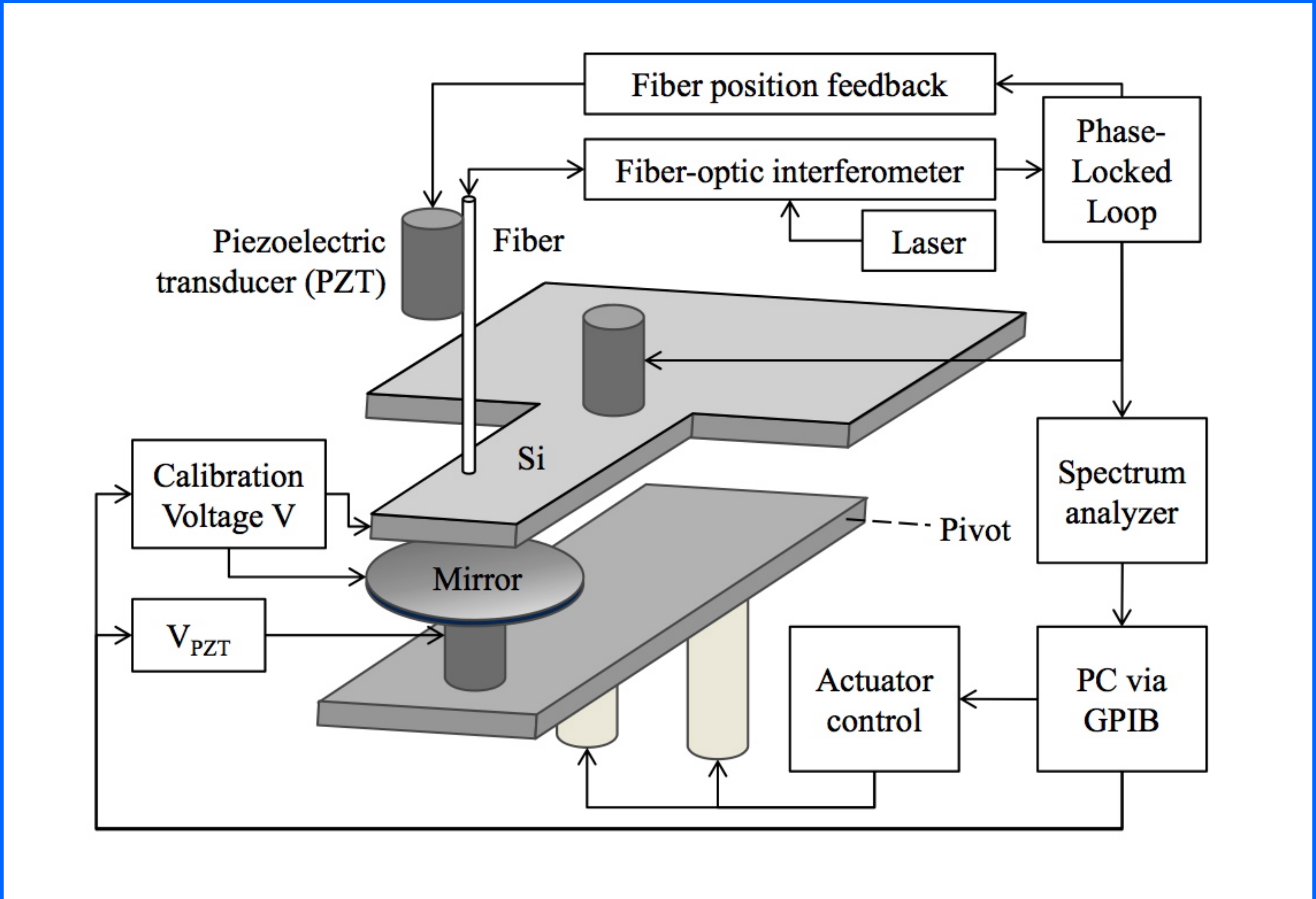


$$k_{eff} = f_1^{\,2} m = 1.04 E w t^3 / \ell^3 = 5421 \pm 342 \text{N/m}$$

Gold Coating by thermal evaporation: 200± 20 nm
Laser at 770 nm, 5-10 mW
Vacuum: 1.3×10^{-4} torr (Roughing/Turbo)

Open-loop scheme (fiber-optic signal directly to FFT SA)

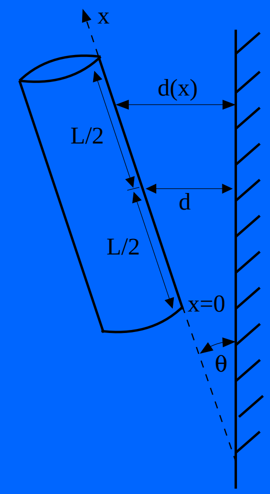
Close-loop scheme (using a phase-locked loop)



Parallelism procedure

Deviations from parallelism can be detected by studying the dependence of the force and/or capacitance upon the "degree of parallelism"

$$\alpha = \frac{L \sin\theta}{2d}$$

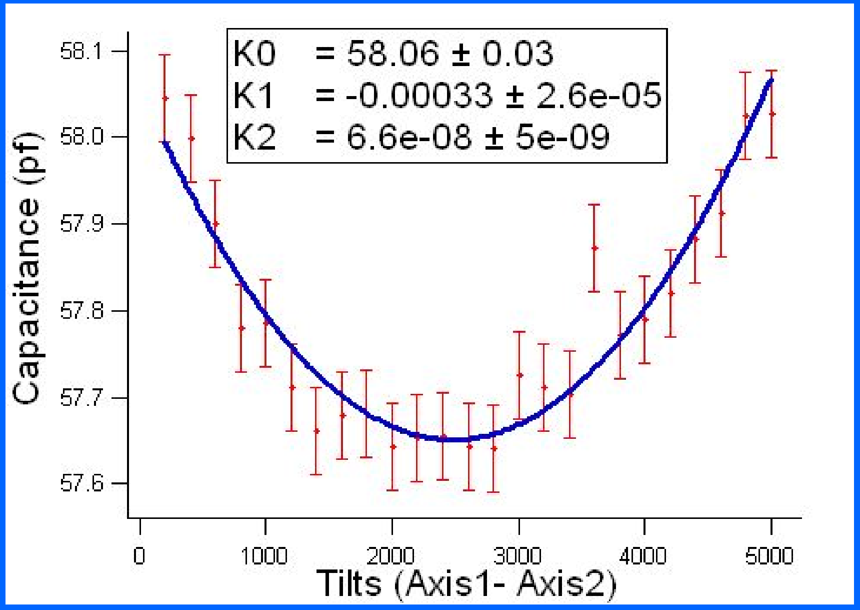


$$F_{np} \cong F_p \left[1 + \frac{5}{8}\alpha^2 + O(\alpha^4) \right]$$

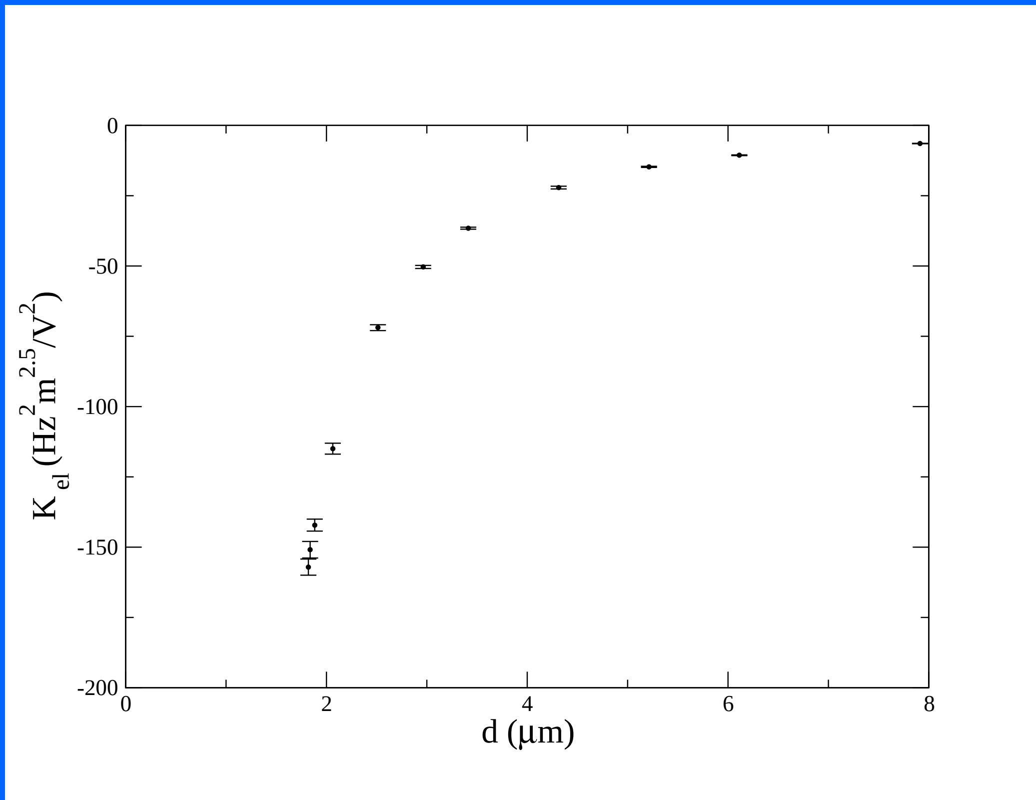
Coulomb

$$F_{np} \cong F_p \left[1 + \frac{21}{8}\alpha^2 + O(\alpha^4) \right]$$

Casimir



Minimization of the force for a constant distance allows to find the parallel configuration



$$\Delta v^2(V) = a + b \times \frac{(V - V_0)^2}{(d_0 - d_{pzt})^{2.5}}$$

$$b = -\frac{3\varepsilon_0 \sqrt{RL}}{16\sqrt{2}\pi m_{eff}}$$

Closest approach:

d_{min}=1.8 μm

Possible limitations

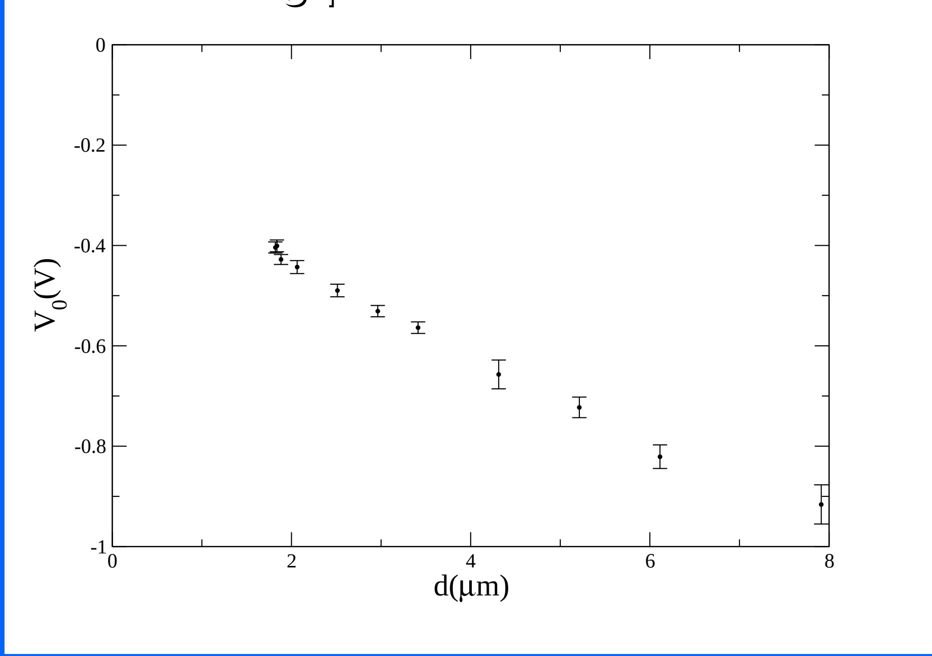
(1) Limited precision in parallelism

(2) Micron sized dust particles

(3) Resonance drifts due to thermal and mechanical instability

We will use soon cylindrical lenses with 3 mm lateral width

Moreover, the minimizing potential is found to be dependent on distance



To clarify some issues campaign of measurements in the

March-June 2007 period on the sphere-plane geometry

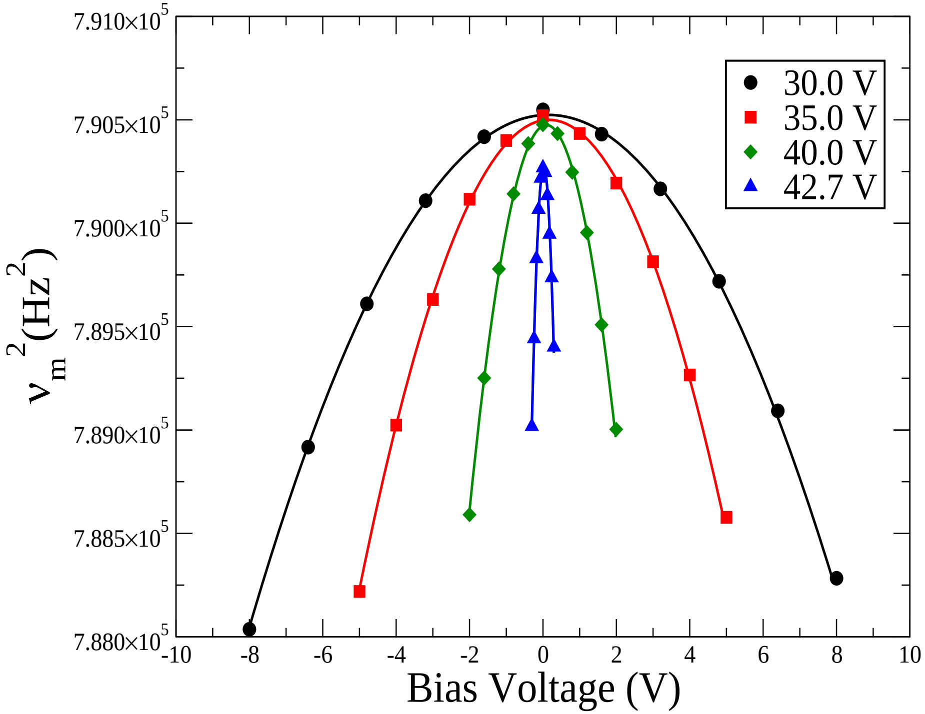
Spherical lens with radius of curvature

R=(30.9 +- 0.15) mm, diameter a=(8.00 +- 0.25) mm

Comparable to Lamoreaux's case, but we can reach smaller gaps

Electrostatic calibrations in the sphere-plane

$$\nu_m^2 = \nu_p^2 - \Delta\nu_r^2(d) - K_{el}(V - V_0)^2$$



Proper frequency of the resonator

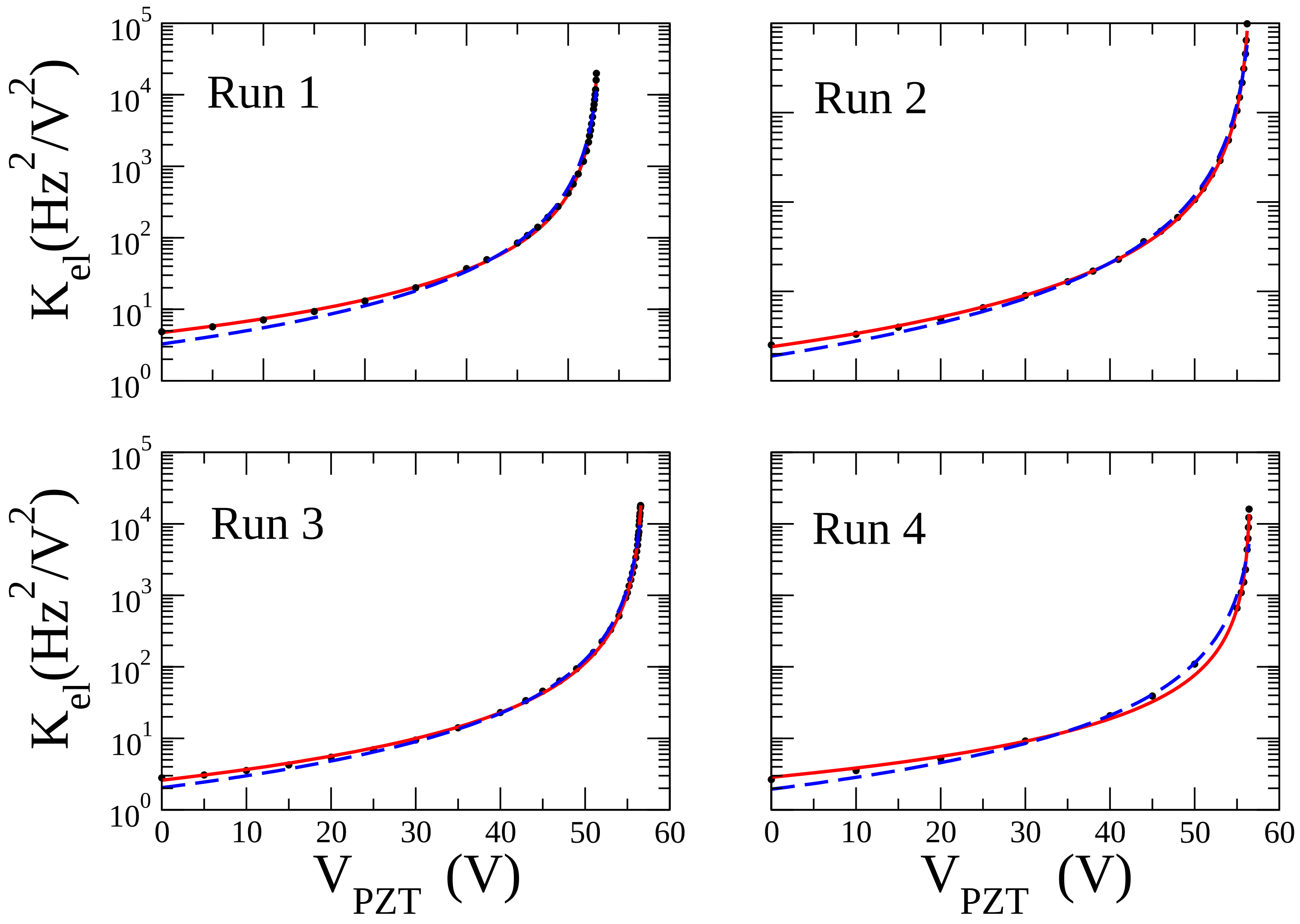
Electrostatic contribution

"Residuals" (Frequency drifts + Casimir physics + any other possible known or unknown physics contribution)

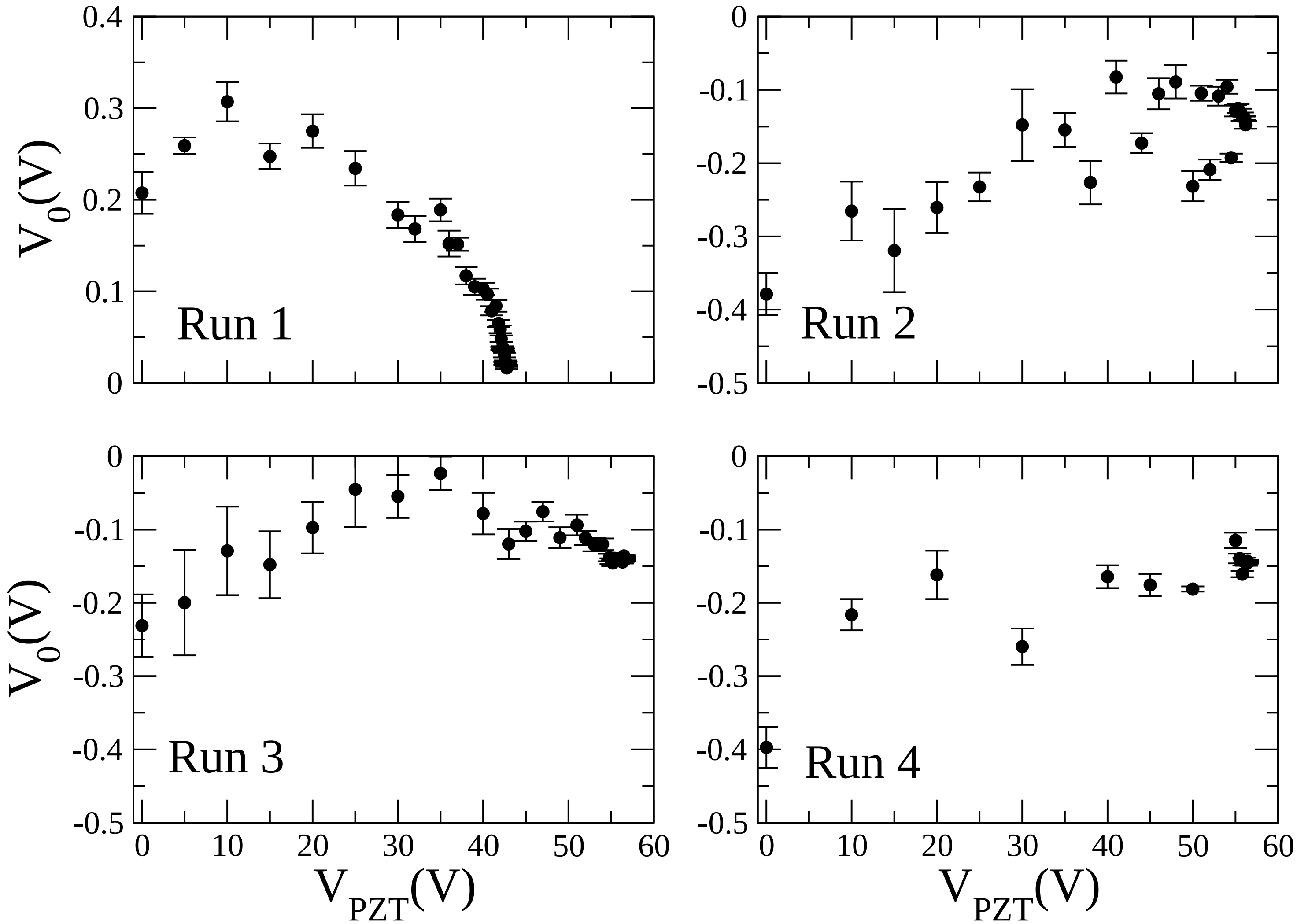
[Iannuzzi *et al.*,PNAS 101, 4019 (2004)]

$$K_{el} = \frac{\varepsilon_0 R}{4\pi m_{eff}} \frac{1}{d^2} = \frac{\alpha}{\left(V_{PZT}^0 - V_{PZT}\right)^2}$$

We have found that leaving the distance scaling exponent free (instead of holding it at -2) results in fits better by a factor about 10 in the reduced Chi^2



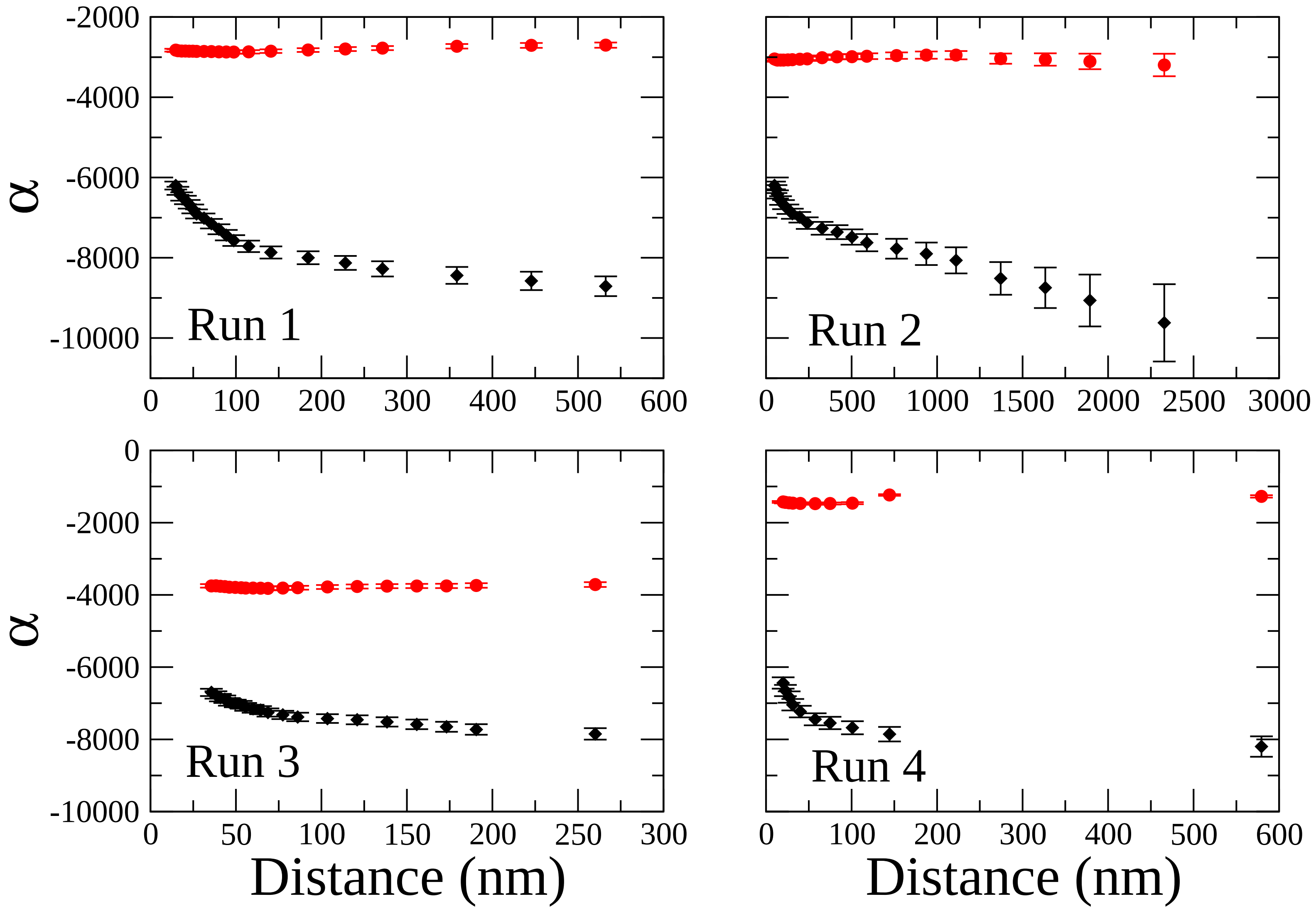
Also, we found that the minimizing potential may depend on distance

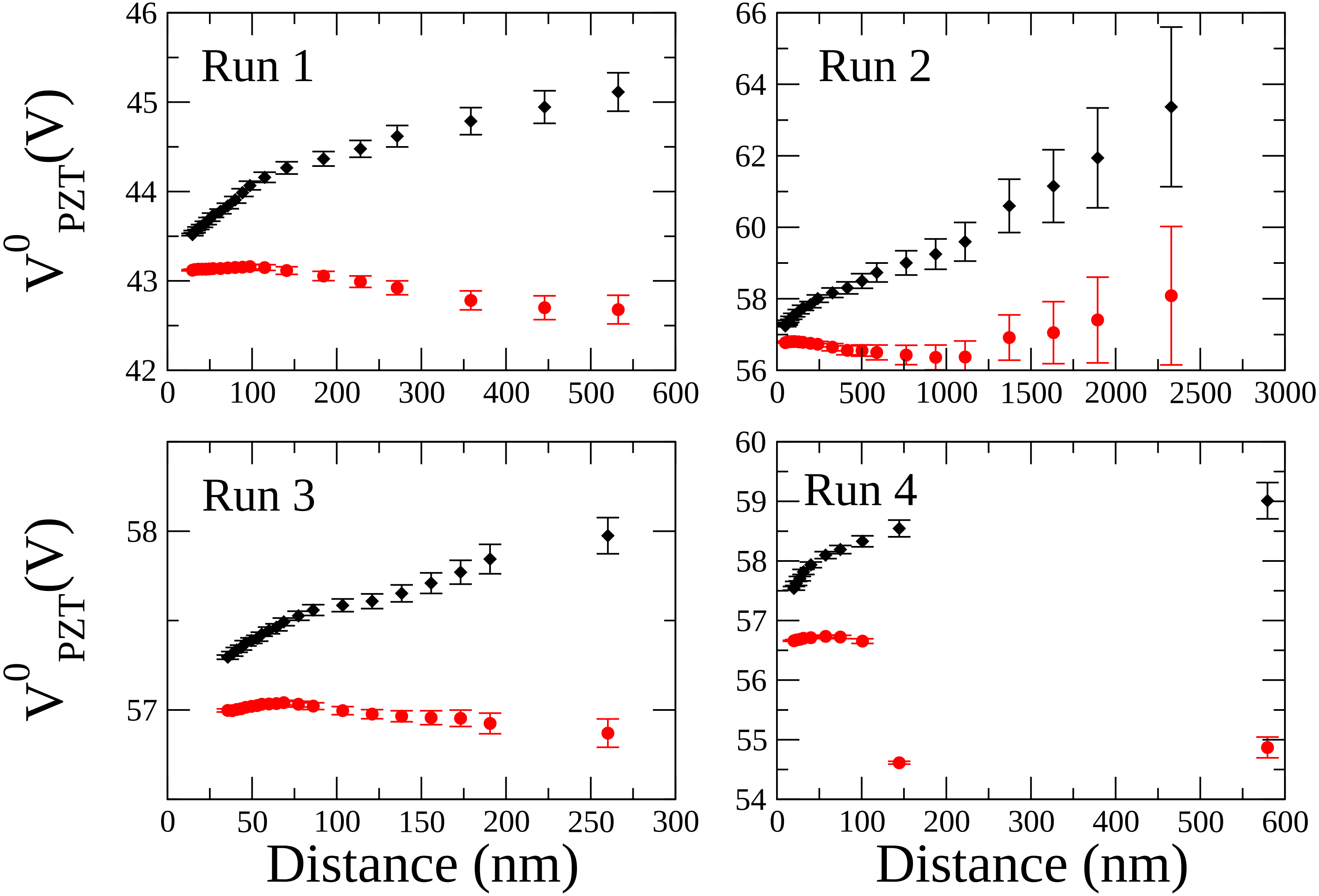


In the two runs above, the minimizing potential is distance-dependent

(this has been confirmed in many other measurements)

Stability of the fit in the case of a -2 exponent and the optimized exponent




Run 1
Run 2
Run 3
Run 4
V^0_{PZT}(V)
V^0_{PZT}(V)
Distance (nm)
Distance (nm)
46
45
44
43
42
0
100
200
300
400
500
600
66
64
62
60
58
56
0
500
1000
1500
2000
2500
3000
58
57
0
50
100
150
200
250
300
60
59
58
57
56
55
54
0
100
200
300
400
500
600

a) Static deflection of the cantilever → very stiff (less than 0.02 nm)

b) Thermal drift (the apparatus is more bulky than typical AFM setups): (possible but one needs an *ad hoc* history for each run to take into account the effect, with a monotonic nonlinear drift)

c) Nonlinearity of PZT: calibrated several times in the entire range of measurements with fiber optic interferometer.

Capacitance measurements versus gap distance accurate.

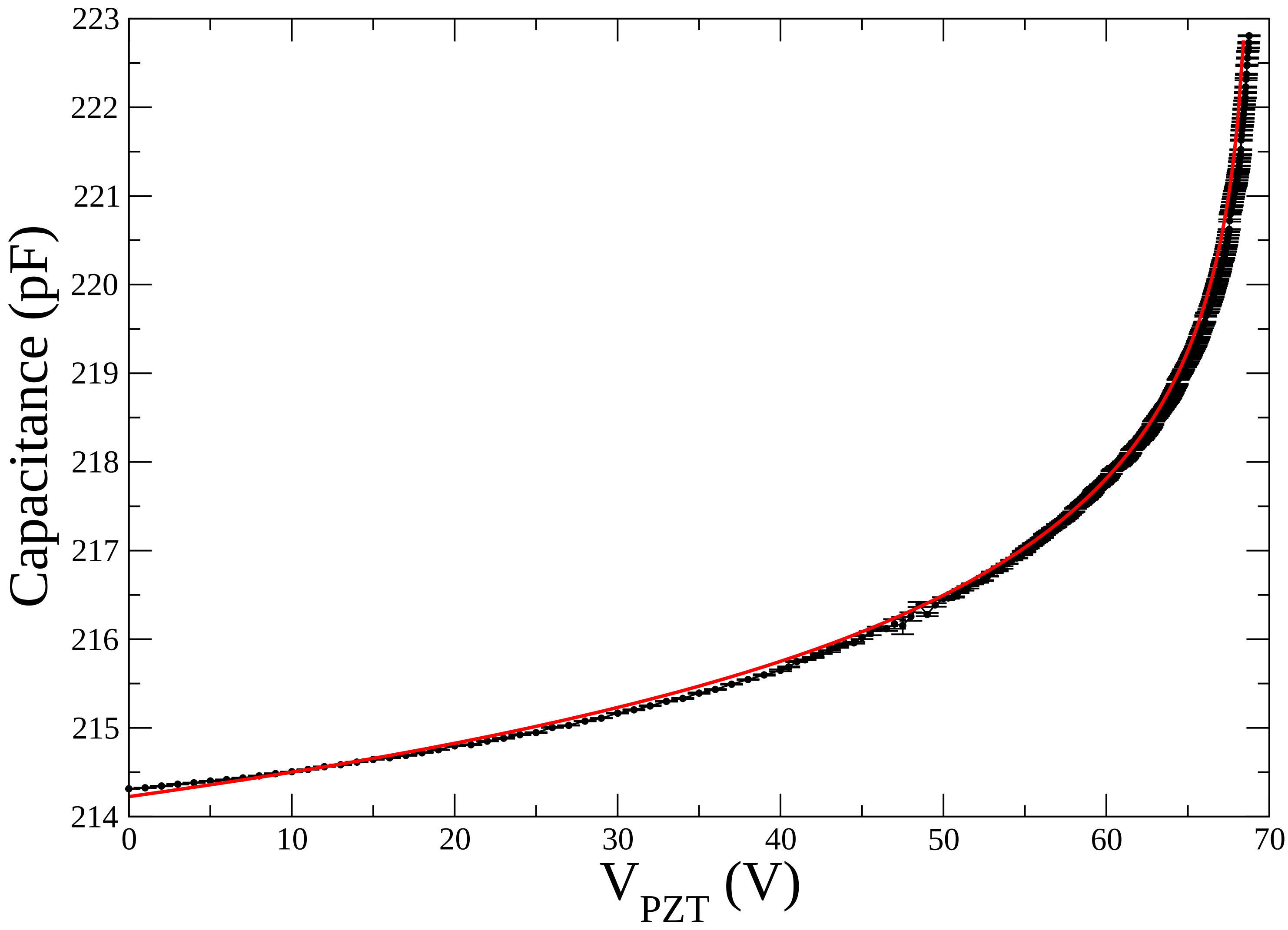
Measurements performed with different starting positions of the PZT

d) Nonlinear oscillations: higher harmonics at the FFT, not observed

e) Convolution of different radii of curvatures: does not affect scaling

f) Surface roughness: corrections negligible even at smaller gaps

Capacitance measurements with an AC bridge



Agreement with PFA formula within 2.1 %

We believe that the anomalous exponent is some artifact of using spheres with large radius of curvature, more susceptible to geometrical defects and/or a more complex electrostatics (patch effects may give a relatively larger contribution than in the case of small spheres)

Noticing that no mention of this issue appears in previously reported electrostatic calibrations, we have suggested to check existing data re-fitting them with a free exponent ("reanalysis")

[W.J.Kim *et al.*, PRA 78, 020101(R) (2008)]

DISCLAIMER (thanks to e-mail exchange with R. Decca and U. Mohideen): we do not argue anywhere in our paper that previous experiments were "wrong" (no experiment can be wrong), we just suggest to reanalyze existing data or perform new experiments having our findings in mind (i.e. just simply fitting with a free exponent in alternative to the expected Coulombian one, and compare the two fits, and see consequencies)

Second anomaly: it is less harmful and it turns out to be more general than the first

If one keep the optimal exponent the analysis of the residuals is ambiguous, as one cannot identify a known force and get parameters like the effective mass (in other words, one cannot calibrate the apparatus)

If the minimizing potential is distance-dependent, one can design a consistent strategy to measure the residuals, provided that it has an asymptotic or quasi-asymptotic behavior at large distances

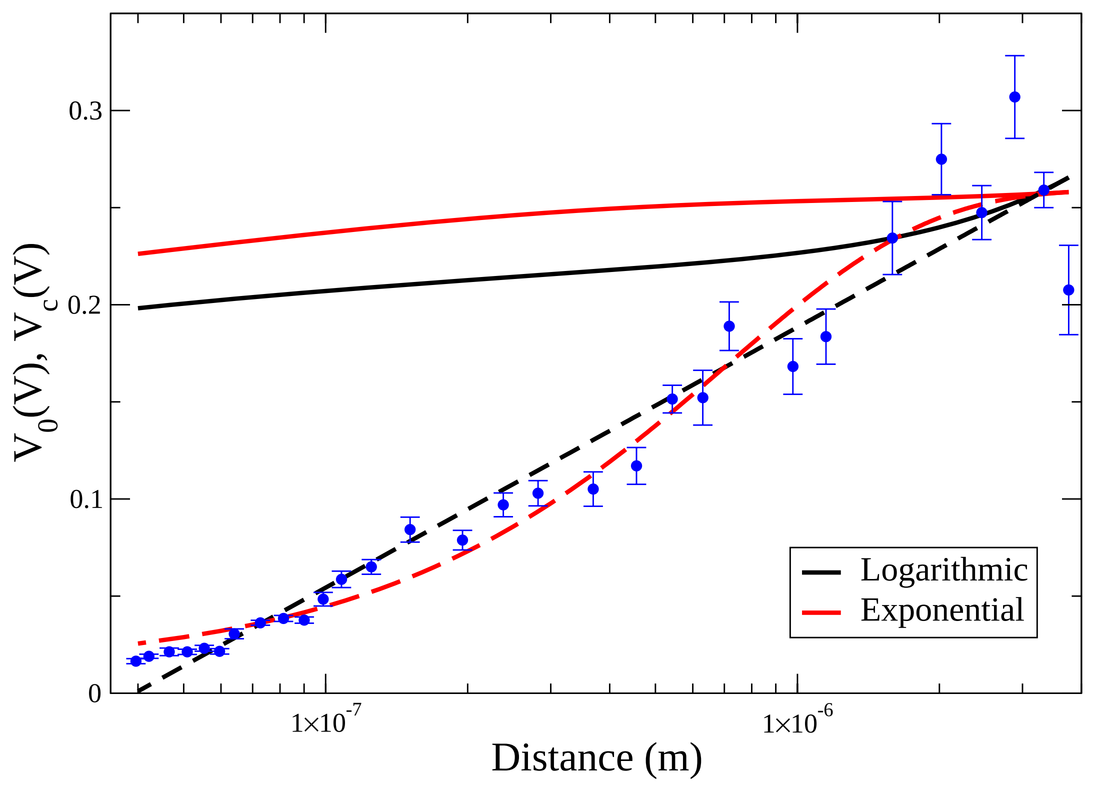
Starting point: S.K. Lamoreaux, arXiv:0808.0885 on 6 Aug 2008

$$E(x) = \frac{1}{2} C(x) \left[V - V_0(x) \right]^2$$

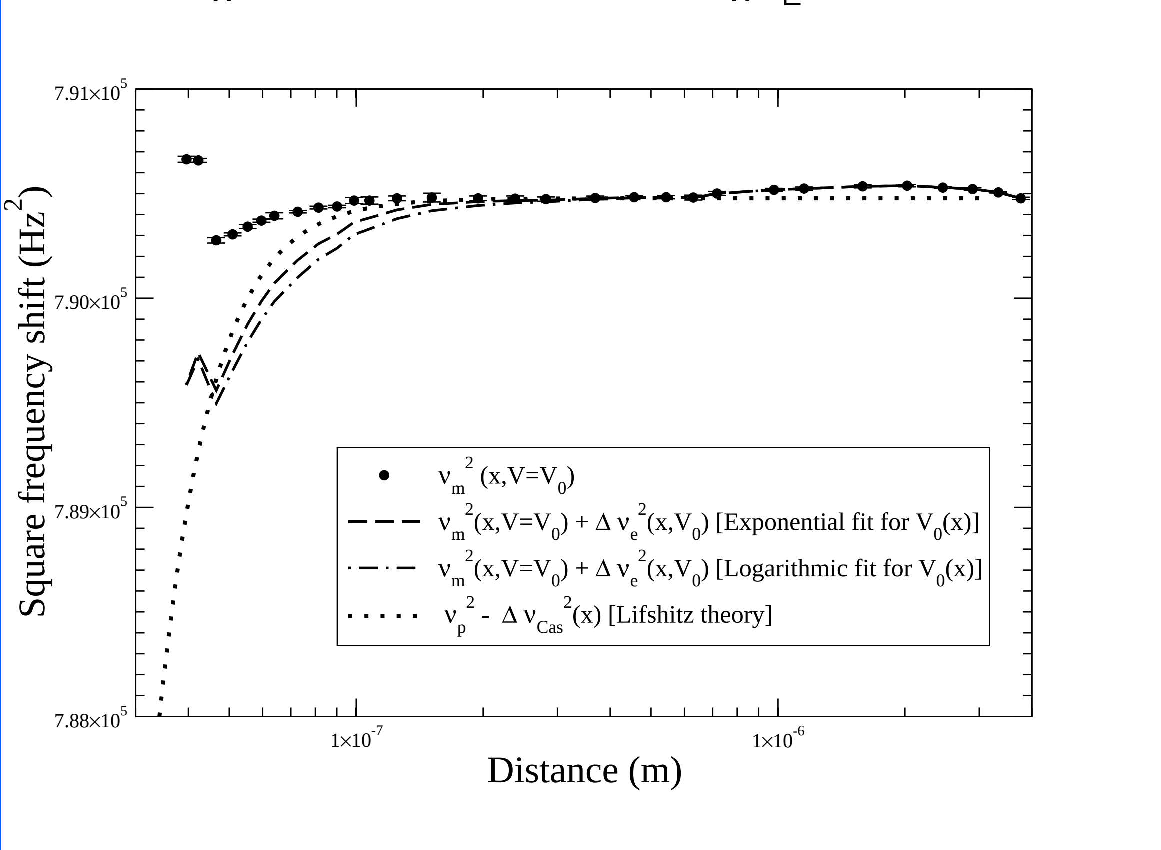
$$V_0(x) = V_C(x) + \frac{(2C'V_c' + CV_c'')^2}{2C''}$$

Relationship between the minimizing potential and the contact potential for frequency-shift measurements

Parametrization of the minimizing potential vs. distance, solving the differential equation for the contact potential



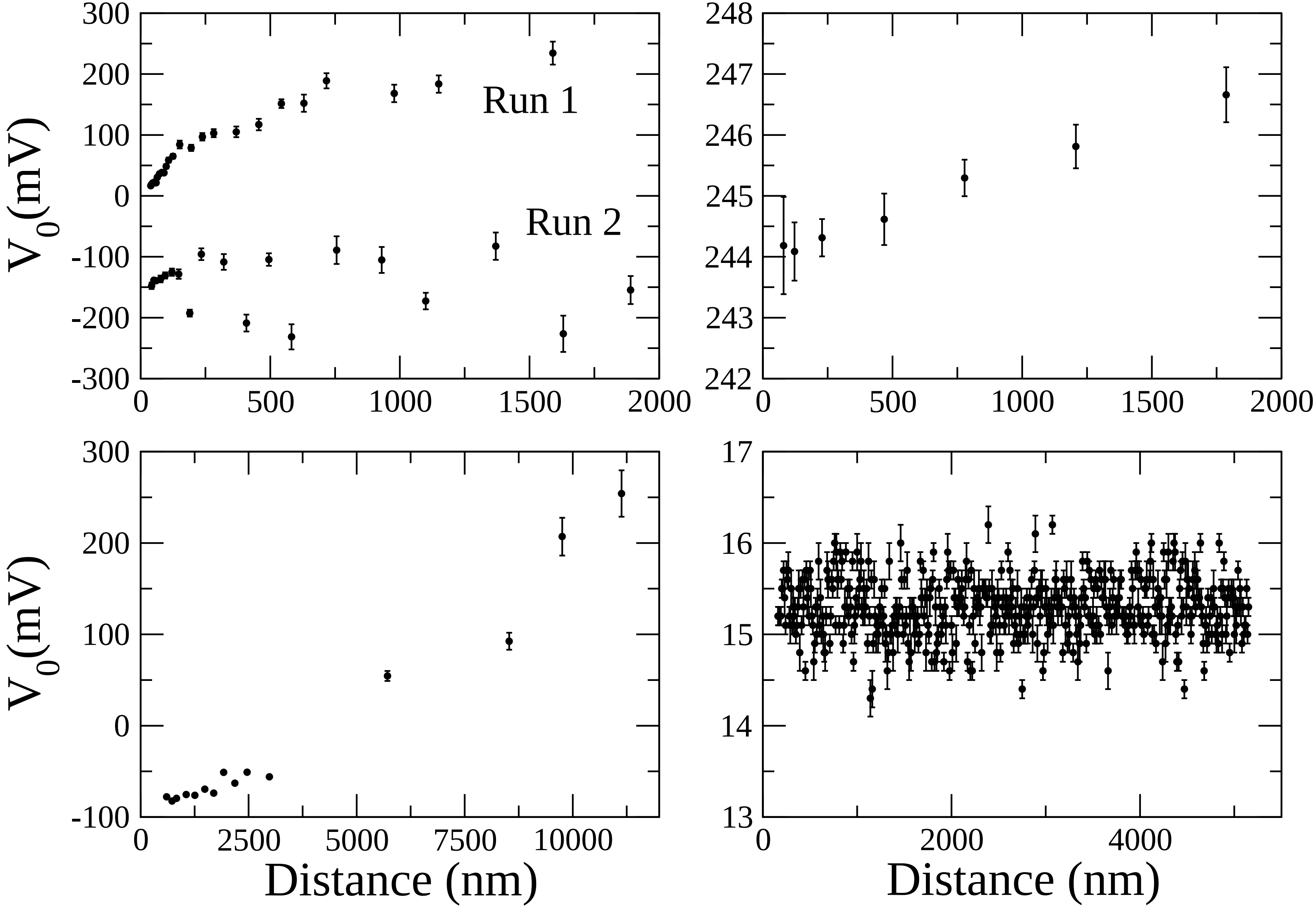
$$\nu_m^2 = \nu_p^2 - \Delta\nu_r^2(x) - \frac{C''}{8\pi^2 m_{eff}}\left[V - V_0(x)\right]^2 - \frac{1}{4\pi^2 m_{eff}}\left[-C V_c'^2 + \frac{(2C'V_c' + CV_c'')^2}{2C''}\right]$$



This has been possible only in one out of the four runs

I consider this rather accidental, but methodology at least consistent

“Us”, Lucent, Grenoble, and IU-Purdue University Indianapolis



Thanks to H.B.Chan, F. Capasso, J. Chevrier, G. Jourdan, R. Decca

J. Phys. A: Math. Theor. **41** (2008) 164022 H-C Chiu *et al*

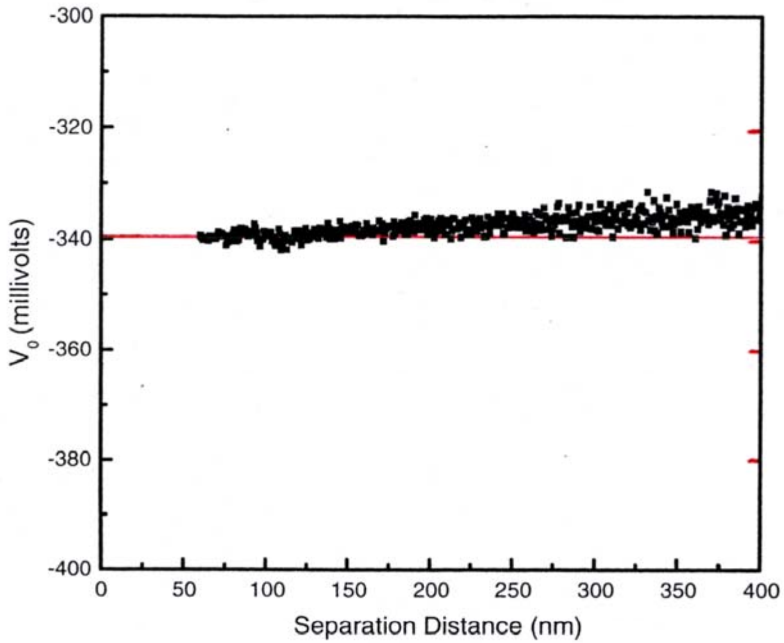


Figure 4. The residual sphere–plate potential difference shown as a function of the separation distance. The values correspond to the case of the high conductivity Si plate shown in figure 3(*b*) [22].

<u>Horizontal red line and red ticks have been added by myself as a eyeguide</u> (few mV similarly to Lucent lab data, but in a smaller range)

In the text, it is claimed that "the minimizing potential is constant within the resolution error"

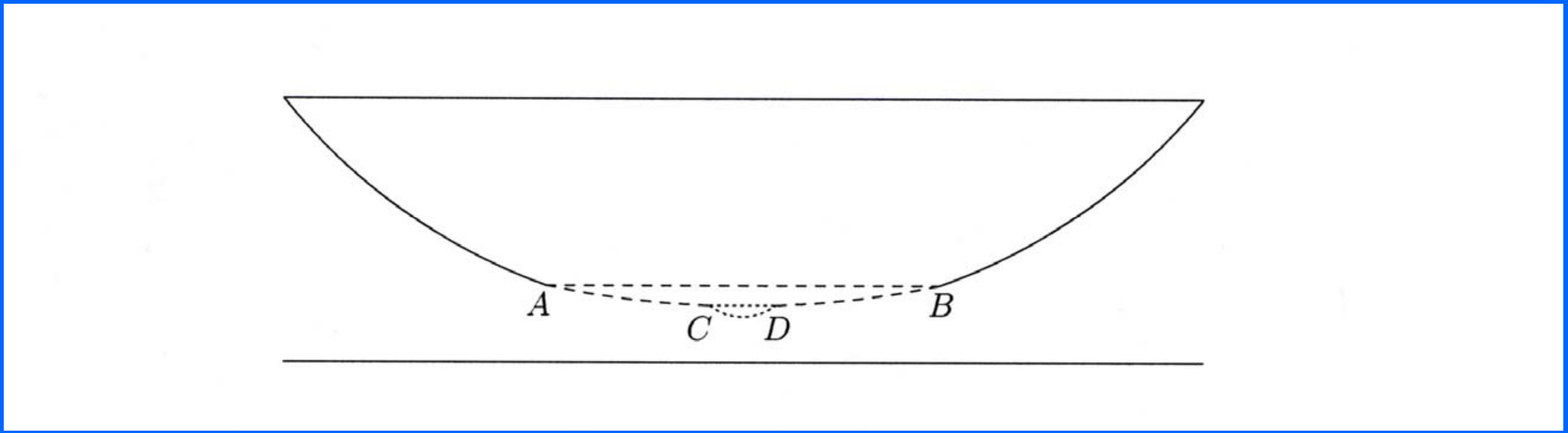
value at the maximum in the parabola, V_0 and $X(z)$. The values obtained for the particular set of data in figure 3 are shown. The numbers on the data points indicate the time sequence of the applied voltages to the plate. The parabola is repeated at every z and V_0 is measured as a function of z. The average value of V_0 so determined is the residual potential difference. Note that at this point in the analysis, the exact value of z is uncertain as the average separation on contact z_0 has not yet been determined. A plot of V_0 as a function of the separation distance z is shown in figure 4 for the case of the semiconductor plate of conductivity $3.2 \times 10^{20}\ \mathrm{cm}^{-3}$ and a gold-coated sphere, both used in one of our recent measurements [22]. The larger random error with increasing separation is due to the decrease in the signal-to-noise ratio. In this experiment, the average V_0 was determined to be -0.337 ± 0.002 V. An important feature to be noticed in figure 4 is the relative constant average value of V_0 as a function of the separation. The value changes only within the resolution error. This is a basic and necessary condition for every Casimir force measurement. If V_0 is not independent of separation, it indicates the presence of electrostatic surface impurities, space charge effects [45] and/or electrostatic inhomogeneities on the sphere or plate surface.

Such inhomogeneities can result from contamination which would lead to patches with different workfunctions. This requirement is particularly important as electrostatic forces

7

In Section 8, "Casimir force is measured as a function of the separation distance, after compensating the electrostatic force by applying a voltage V_0 to the plate while the sphere remains grounded".

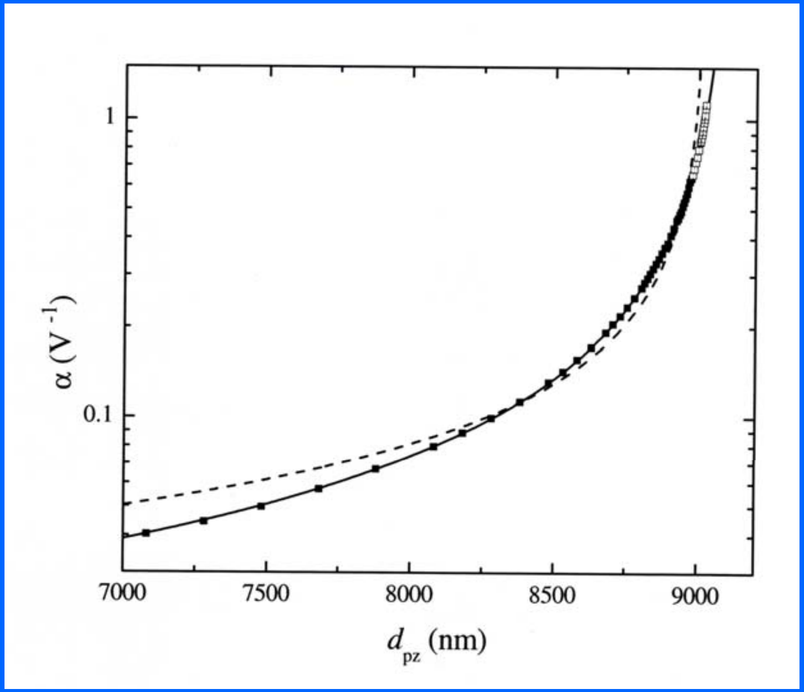
Ingenious possible explanation of our anomaly reported in arXiv:0809.3576

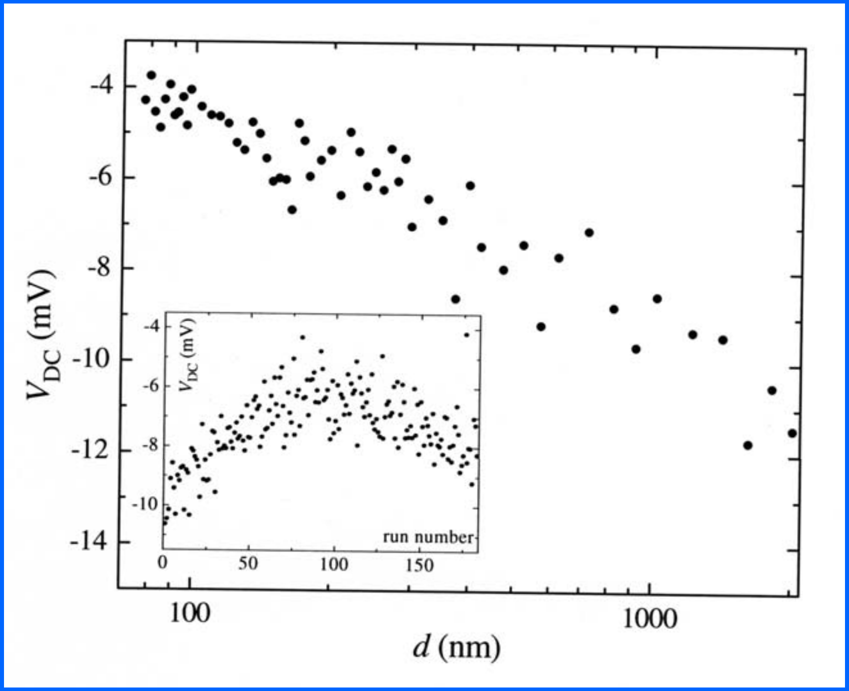


Strongly constrained by the measurements of capacitance vs. distance and the absence of structuring observed at the AFM

Discussion is constrained by the rigorous PRA procedure for a Comment & Reply, please check soon (hopefully) PRA and/or the Archive for a full account of the debate. You are all welcome to contribute.

High statistics/low drifts work by the Amsterdam group (arXiv:0809.3858v2)



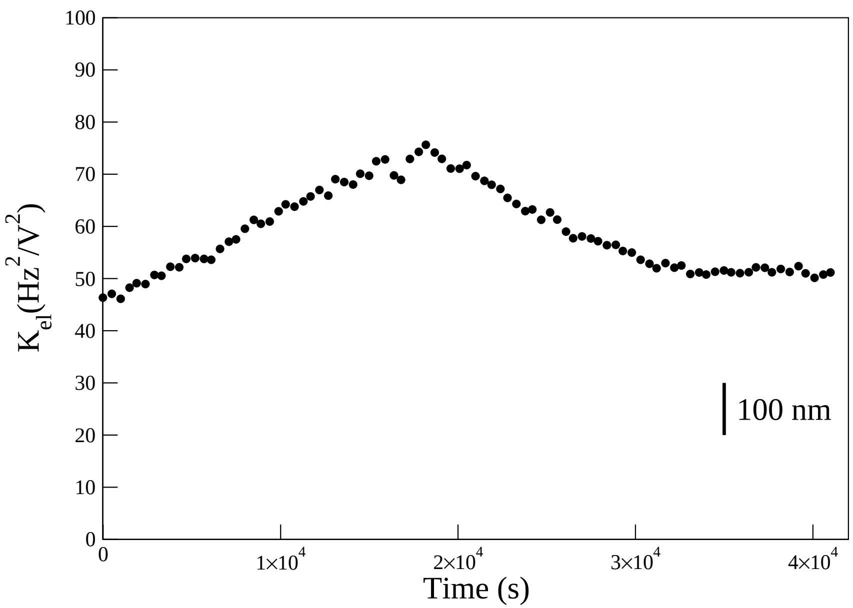


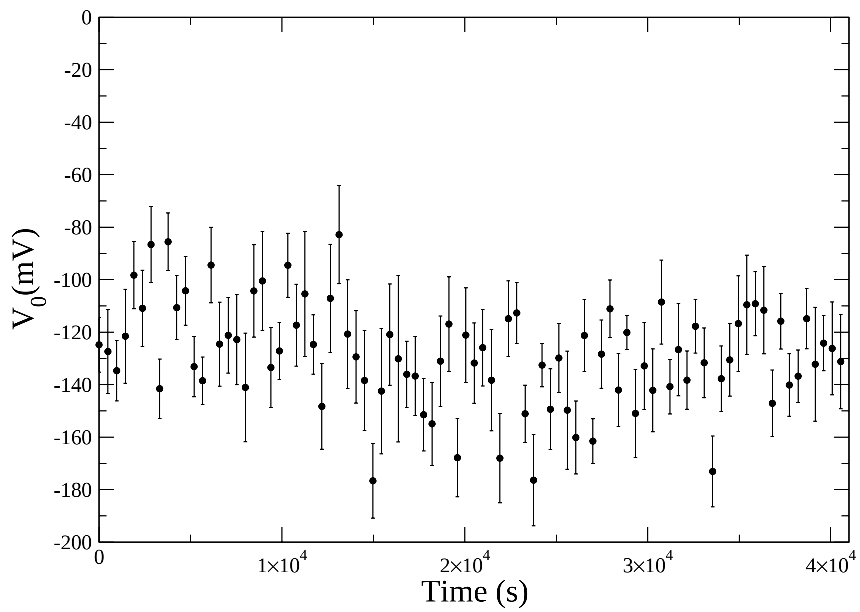
Usual electrostatic scaling checked, so our finding may be limited to large spheres

Also finds a strong dependence of the minimizing potential on distance and/or run number

Related work also going on *at least* in New Haven and Groningen

Time drift: dedicated run of 12 hours





The minimizing potential drifts (also observed in Amsterdam and Yale)

The minimizing potential is a function of x,y,z and time

More careful in-situ/on-time characterization of surfaces needed

Roughness should be studied already at the electrostatic calibration level

(for instance Palasantzas's work, Langmuir 24, 7528 (2008)]

This has been also evidenced in macroscopic torsional setups for the LISA project [Pollack *et al*., PRL 101, 070101 (2008)]

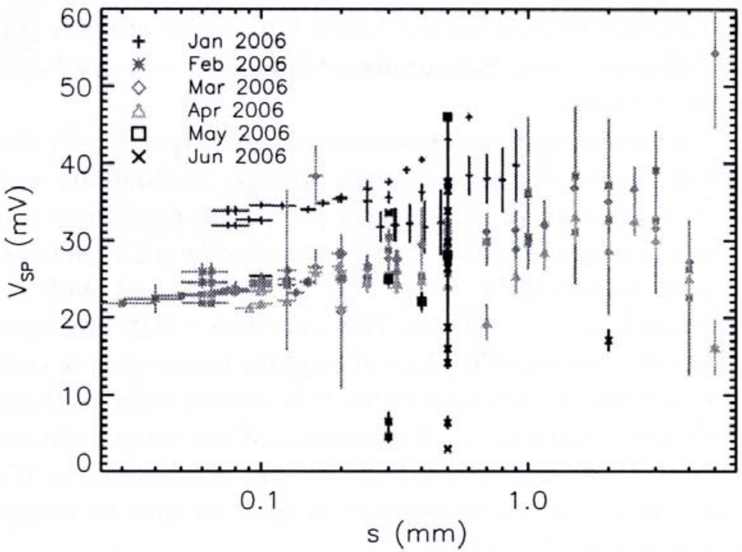


FIG. 3 (color online). Measurements of the surface potential between the pendulum and the right half of the Cu plate as a function of the plate-pendulum separation. Both halves of the Cu plate have similar separation and temporal characteristics. Variation with separation may be explained by spatial variations in the surface potential.

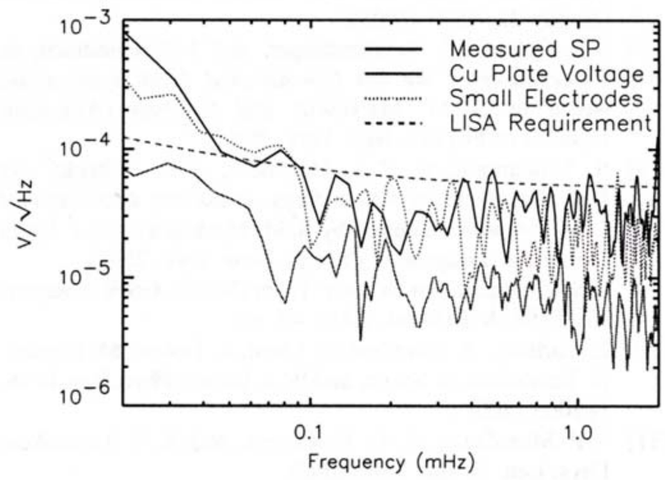


FIG. 4 (color online). Measured surface potential fluctuations (dark solid) using the method described in the text have a level of 30 $\mu V/\sqrt{Hz}$ rising as $1/f$ below 0.1 mHz. The LISA voltage fluctuation requirement (dashed) is 50 $\mu V/\sqrt{Hz}$ rising as $1/\sqrt{f}$ below 0.1 mHz [4]. The red (light solid) trace is the voltage noise on the split Cu plate measured electronically. Using the small control electrodes (blue or dotted) for control does not significantly reduce the measured noise level even though the contribution due to output voltage noise has been reduced by a factor ~3.

In the same paper, they performed a test of the sensitivity to the buffer gas and the pressure level

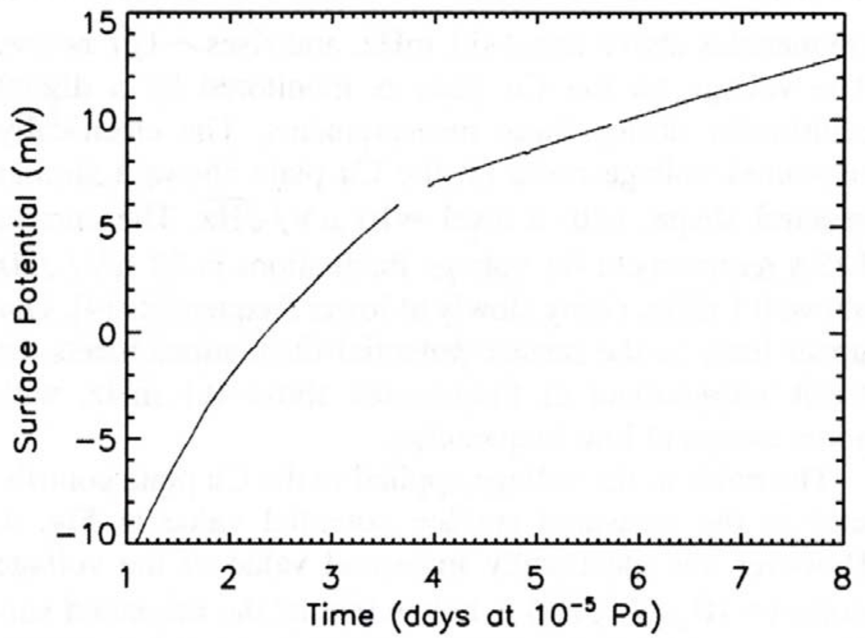


FIG. 5. Surface potential measurements after venting to nitrogen, atmosphere, and pumping back to ≈10^{-5} Pa, with a mild bakeout at 50°. An exponential fit to this data gives a time constant of about 2.5 days. The drift rate after 30 days at this pressure was measured to be ≈0.30 mV/day and after 50 days it was ≈0.15 mV/day. This slow drift of the surface potential is likely due to contamination located on our Au coated surfaces.

May be that contaminants play a role in the “first” anomaly too

Next steps

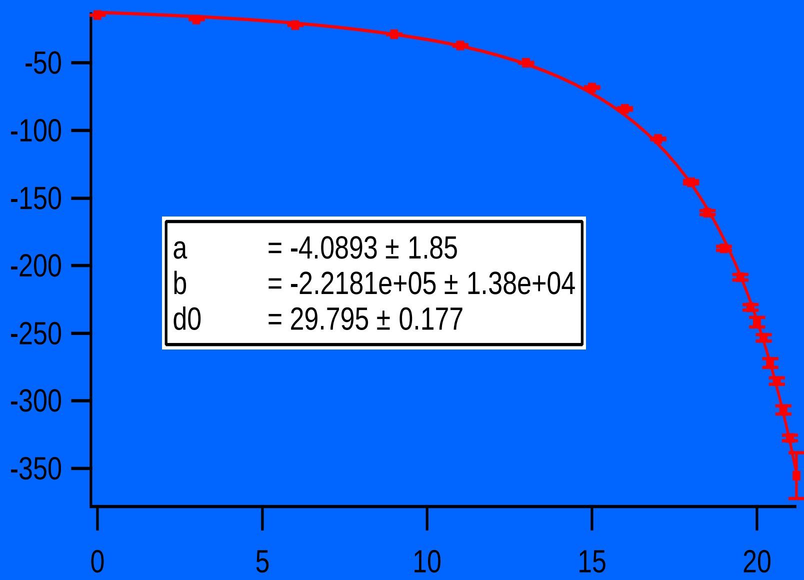
a) Measurements of the minimizing potential in three geometries

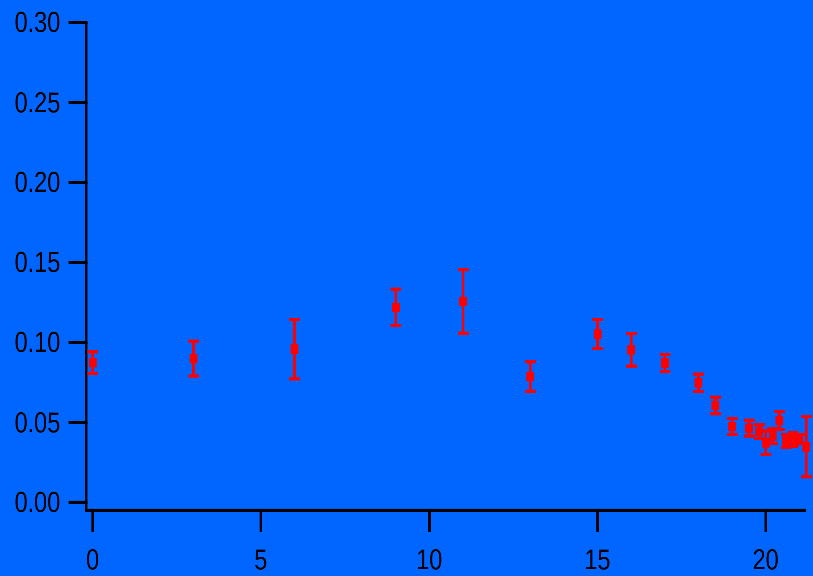
b) Attempt to measure the Casimir force in the cylinder-plane geometry taking into account the space-dependent minimizing potential

c) Systematic and careful reanalysis of ALL the experimental and demonstrational papers on Casimir forces, especially in regard to limits to Yukawian forces in the micrometer range.
First (incomplete) attempt in NJP 2006, but due to the strict timeframe for the review quantitative analysis has been limited

More on this, and some suggestions for research directions, tomorrow

The **case of parallel plates**





At small gaps it seems to be less distance dependent (see however Pollack case)

This could fit into the discussion of Stipe *et al.* [PRL 87, 096801 (2001)]

on the presence of inhomogeneous tip-sample electric fields

Curved geometries are more susceptible to inhomogeneities (?)

Conclusions

- I have highlighted issues of each geometry used for demonstrations and experiments on Casimir forces
- Cylinder-Plane geometry seems promising to look for the thermal contribution to the Casimir force
- Observation of space-dependent minimizing potentials
- Analysis of previous results and/or new experiments triggered by this finding confirm that in most of the collected data there is a dependence on distance, location, and time
- The spherical configuration has various issues only made explicit during 2008
- It would be nice to have more experiments on parallel plates
- Seminar on Thursday: dynamical Casimir effects +

  follow-up from present discussions