Kelvin probe force microscopy of metallic surfaces used in Casimir force measurements

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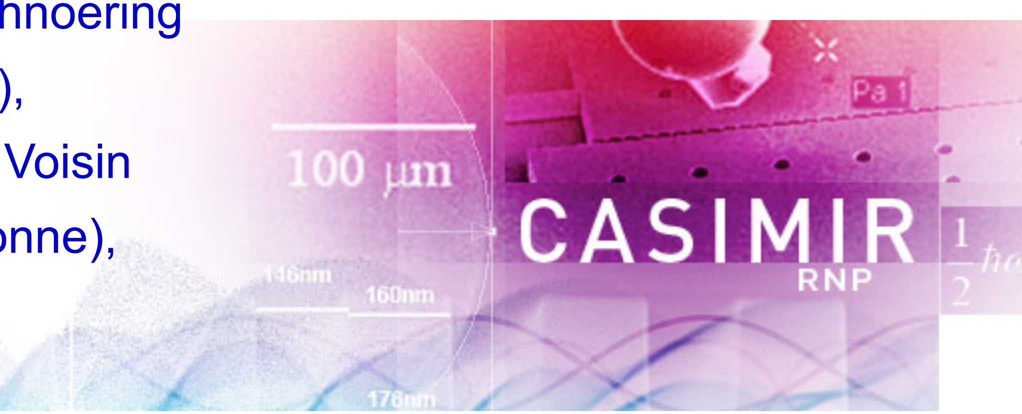
Thanks to D. Dalvit, Y. Zeng (Los Alamos), R. Behunin (Yale), F. Intravaia (Berlin), P.A. Maia Neto (Rio de Janeiro), C. Genet, T. Ebbesen, P. Samori, G. Schnoering (Strasbourg), A. Liscio (Bologna), R. Decca, E. Fischbach (Purdue), G. Voisin (Meudon), I.W. Jung, D. Lopez (Argonne), C. Speake (Birmingham), G. Palasantzas (Groningen) …

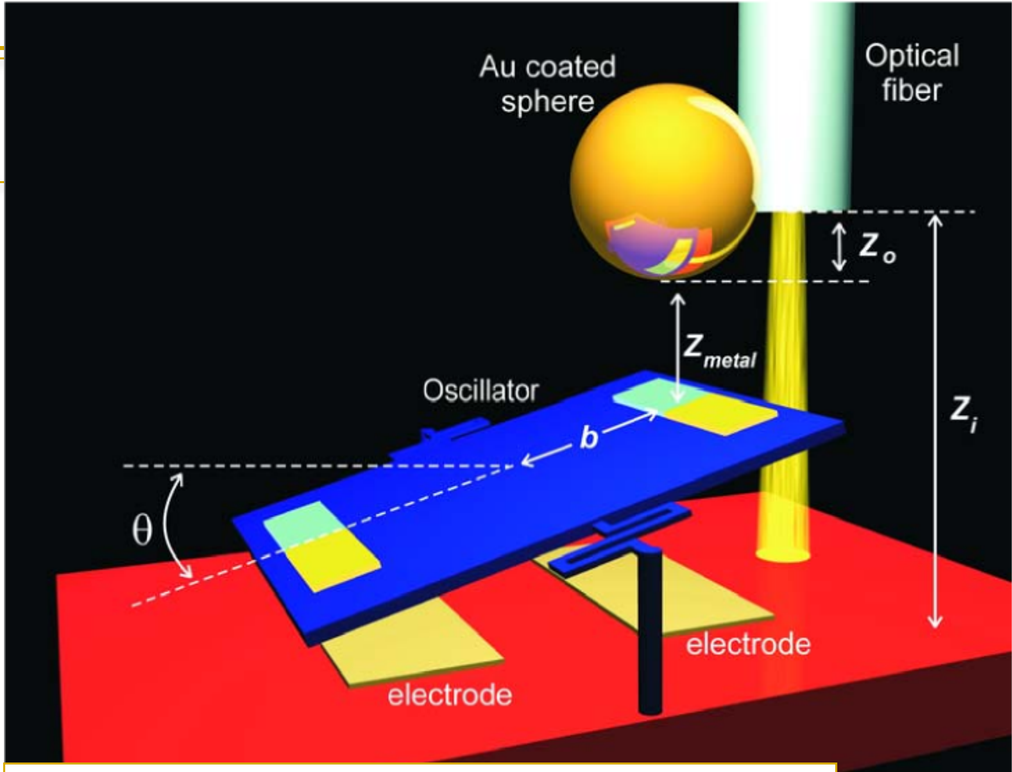


casimir-network.org

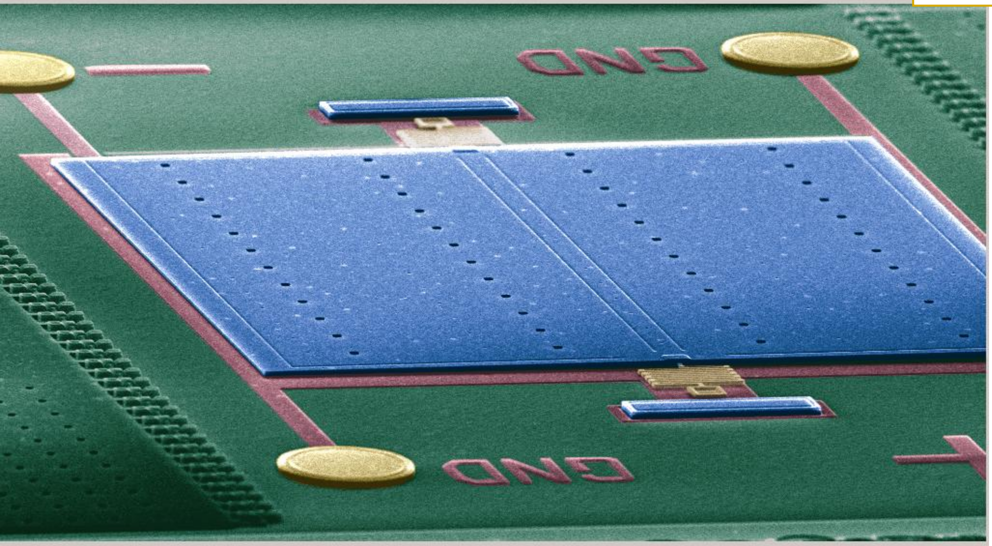
Casimir experiments

- Dynamic measurements of the resonance frequency of a microresonator
- Shift of the resonance gives the gradient of the force measured between a plane and a sphere

➡ More details in the talk at Microscope Colloquium - Jan 2013



Courtesy R.S. Decca (IUPUI : Indiana U – Purdue U Indianapolis)



Sphere Radius: R = 150 μm

Distances: L = 0.16 - 0.75 μm

As $R>>L$, the measured gradient is given by the pressure P between two plane mirrors at distance L

$$G = -2\pi R \, P(L)$$

Casimir experiments and theory …

Measurements at IUPUI favor the lossless plasma model
and deviate from theory with dissipation accounted for

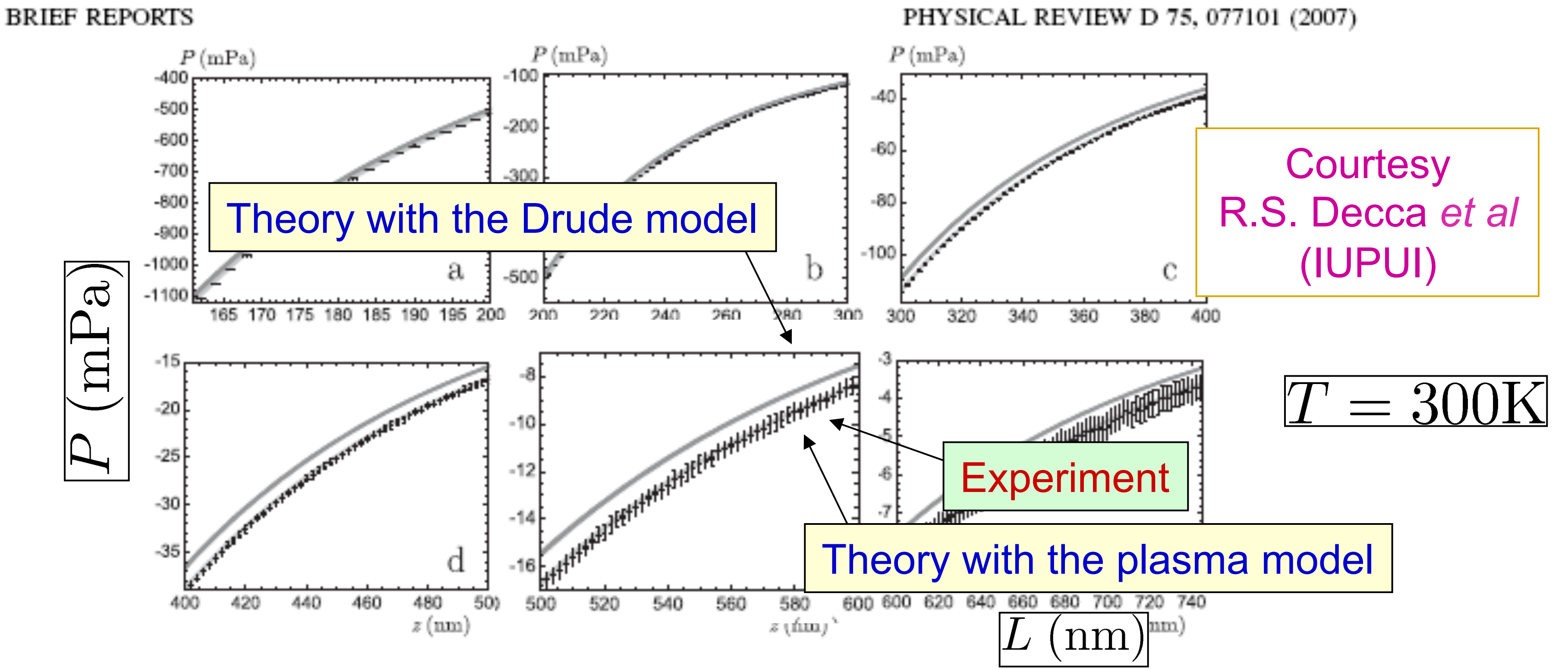
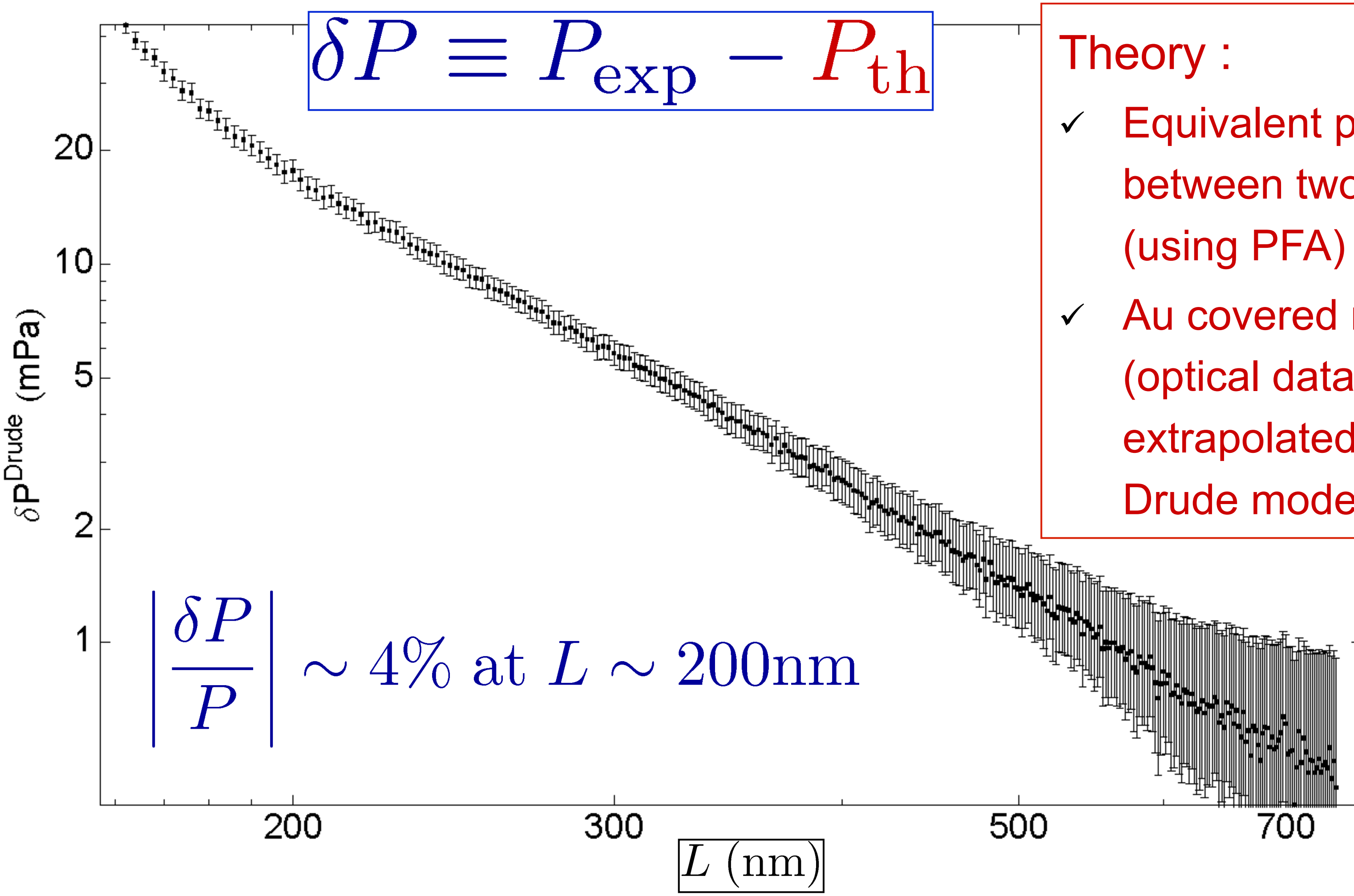


FIG. 1. Experimental data for the Casimir pressure as a function of separation z. Absolute errors are shown by black crosses in different separation regions (a–f). The light- and dark-gray bands represent the theoretical predictions of the impedance and Drude model approaches, respectively. The vertical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

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

Casimir experiments and theory …

$$\delta P \equiv P_{\mathrm{exp}} - P_{\mathrm{th}}$$



$$\left|\frac{\delta P}{P}\right| \sim 4\% \text{ at } L \sim 200\mathrm{nm}$$

Theory :

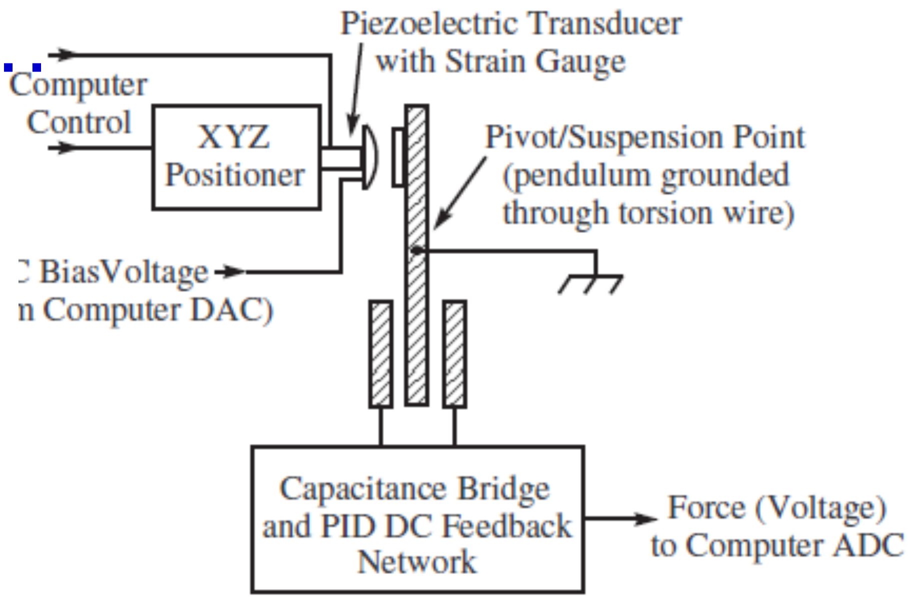
- ✓ Equivalent pressure between two planes (using PFA)
- ✓ Au covered mirrors (optical data for gold extrapolated to a Drude model)

Experimental data kindly provided by R. Decca (IUPUI)

Theoretical pressure calculated by R. Behunin *et al* PRA **85** (2012) 012504

Deviation looking like a superposition of power laws !

Casimir experiments …



- Lamoreaux group @ Yale
  - torsion-pendulum experiment
  - larger radius: R = 156 mm
  - larger distances: L = 0.7 - 7 μm

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

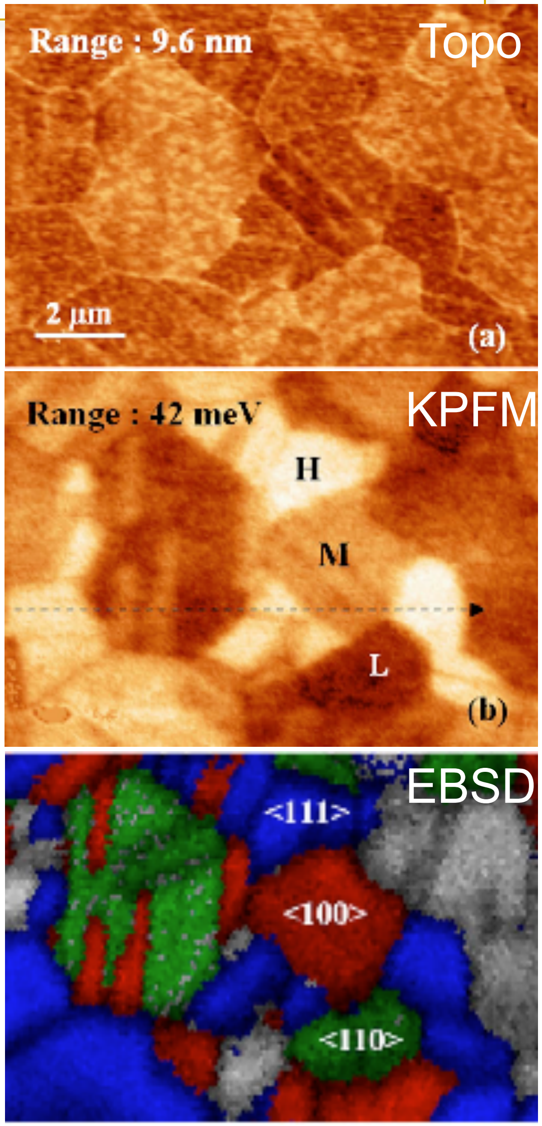
- Thermal contribution seen at large distances (where it is large)
- Results favoring the Drude model after subtraction of a large contribution of the electrostatic patch effect (more discussions below)

- Results of different experiments point to different models
- Some experiments disagree with the best theoretical model
- Patches are not measured in any of the existing experiments

The patch effect

N. Gaillard *et al*, APL **89** (2006) 154101

- Surfaces of metallic plates are not equipotentials
  - Real surfaces are made of crystallites
  - Crystallites correspond to ≠ crystallographic orientations and ≠ work functions
- For ultraclean surfaces ▶
  (ultra-high vacuum, ultra-low temperature)
  - Patch pattern is related to topography
  - AFM, KPFM, EBSD maps are directly related
- Otherwise, contamination affects the patches
  - enlarges patch sizes and smoothes voltages
- Patch effect has been known for decades to be a limitation for precision measurements
  - Free fall of antiparticles, gravity tests, experiments with cold atoms or ion traps...



Detailed studies for GPB : C. W. F. Everitt *et al.*, PRL (2011); S. Buchman *et al.*, RSI (2011)

Modeling the patches

- The pressure between two planes due to electrostatic patches can be computed by solving the Poisson equation

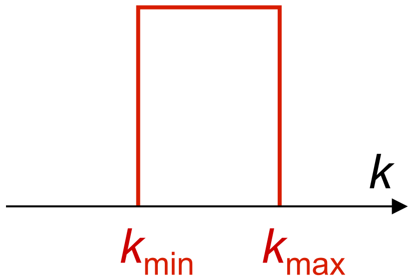
$$P = \frac{\varepsilon_o}{4\pi} \int_0^\infty \frac{\mathrm{d}k \ k^3}{\sinh^2(kL)} \{C_{11}[k] + C_{22}[k] - 2C_{12}[k] \cosh(kL)\}$$

- It depends on the spectra describing the correlations of the patch voltages
- The spectra had not been measured up to recently

$$C_{ij}[\mathbf{k}] = \int \mathrm{d}^2\mathbf{r} \, e^{-i\mathbf{k}\cdot\mathbf{r}} C_{ij}(\mathbf{r})$$

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

- In the commonly used model, the spectrum was supposed to have sharp cutoffs at low and high-*k*
- This is a very poor representation of the patches

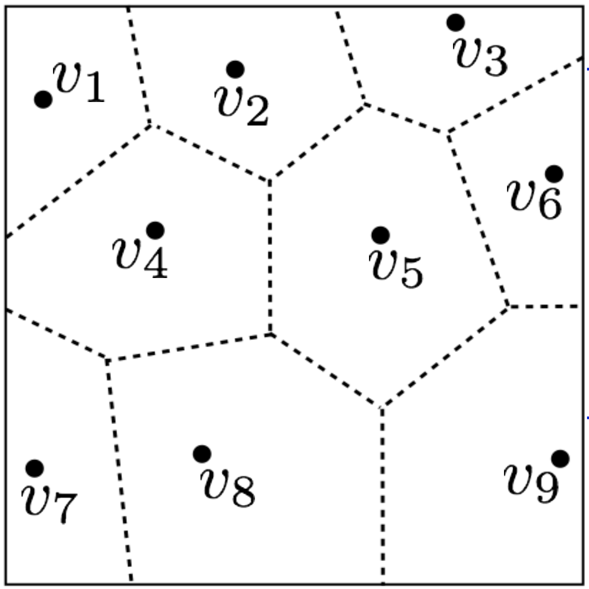


C.C. Speake & C. Trenkel PRL (2003) ; R.S. Decca *et al* (2005)

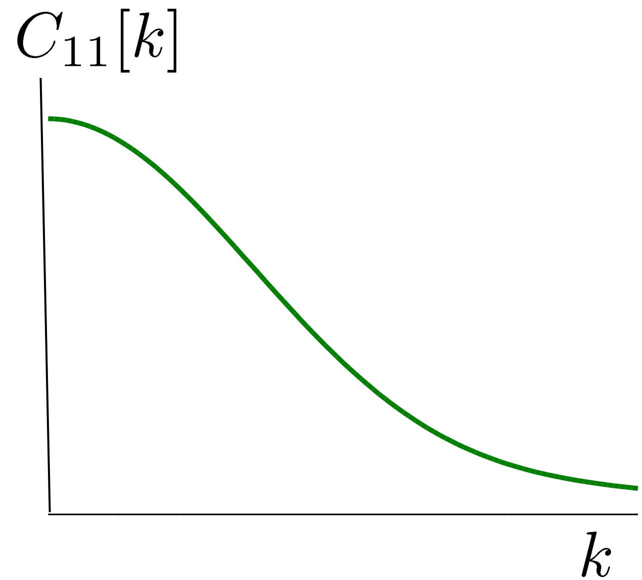
Modeling the patches …

- A "quasi-local" representation of patches

R.O. Behunin, F. Intravaia, D.A.R. Dalvit, P.A. Maia Neto, S. Reynaud, PRA **85** (2012) 012504



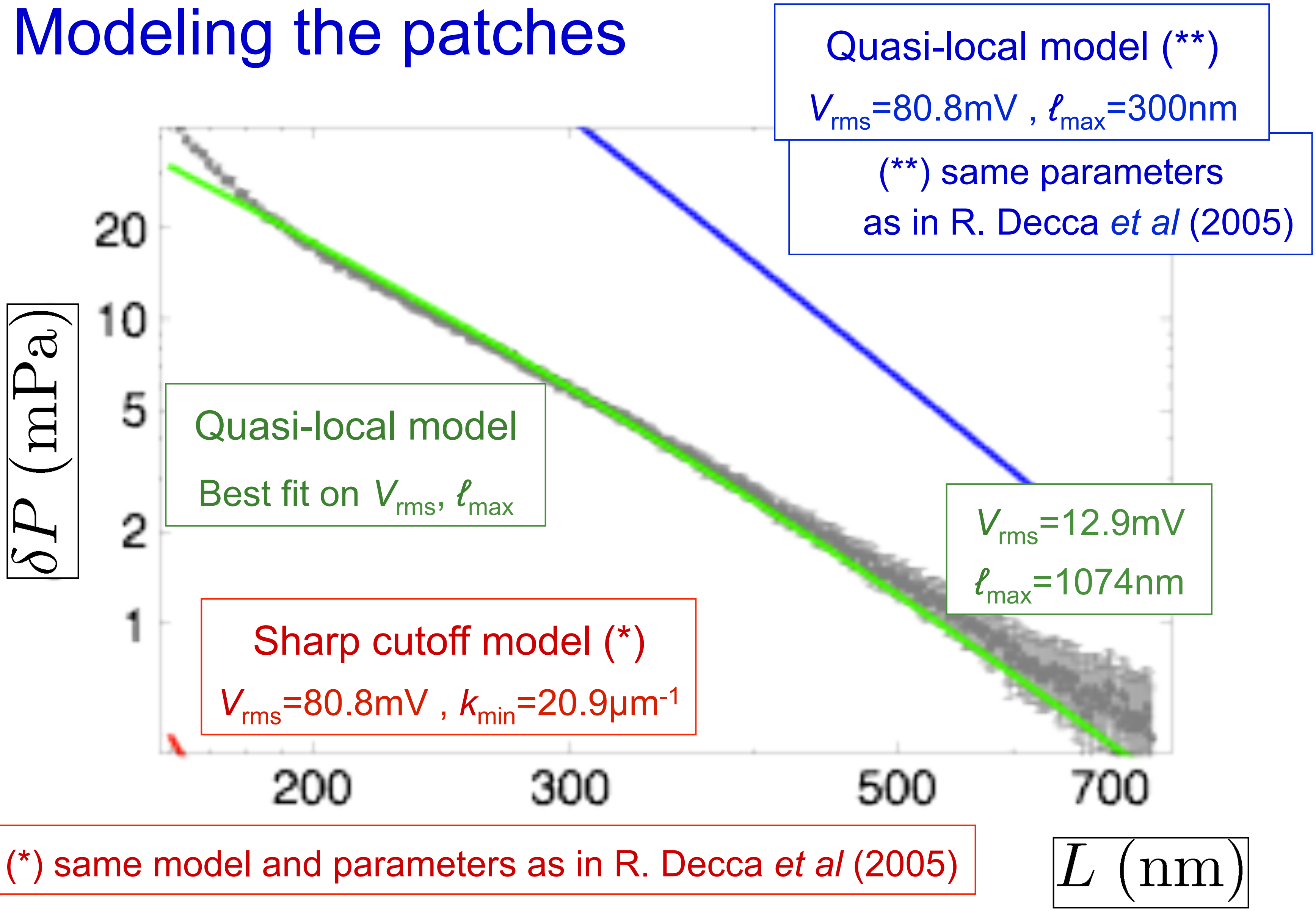
tessellation of sample surface and random assignment of the voltage on each patch



- This produces a smooth spectrum (no cutoff)

- Similar models used to study the effect of patches in ion traps
  - R. Dubessy, T. Coudreau, L. Guidoni, PRA **80** (2009) 031402
  - D.A. Hite, Y. Colombe, A.C. Wilson et al, PRL **109** (2012) 103001

Modeling the patches



(*) same model and parameters as in R. Decca *et al* (2005)

R.O. Behunin, F. Intravaia, D.A.R. Dalvit, P.A. Maia Neto & SR, PRA 85 (2012) 012504

Conclusions at this point (January 2013)

- Deviation of most precise Casimir force measurements from best theory might be due to a systematic effect of electrostatic patches
  - differences between IUPUI data and theoretical were fitted by a quasi-local model for electrostatic patches
    - this was only a fit
    - best fit parameters not compatible with patches being crystallites
    - compatible with a contamination of the metallic surfaces : patch sizes (~1000nm) larger than grain sizes (~300nm) ; rms voltages (~12mV) smaller than those on a clean surface (~80mV)

- Next steps (at this point)
  - measure real patch voltages with Kelvin Probe Force Microscopy
    - now done : ISIS Strasbourg / ISOF Bologna and IUPUI
  - deduce the force in the plane-sphere geometry
    - now done : LANL Los Alamos / LKB

Measuring the patches with KPFM

- Kelvin Probe + Atomic Force Microscope setup
- Kelvin Probe Force Microscopes measure local variations of work-function differences :
  - Electrostatic force dominant
  - Local measurement with a tip fixed at the end of a cantilever
  - Cantilever scanned over sample
  - Deflection monitored – or – Force monitored in an active system with deflection fixed

Contact Electricity of Metals :
L. Kelvin, Philos. Mag. **46** (1898) 82

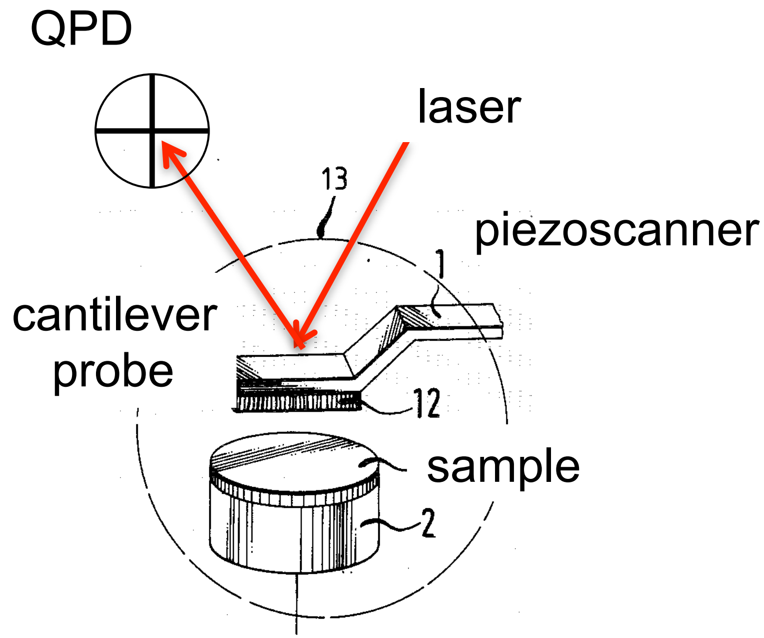


FIG. 1A

M. Nonnenmacher, M.P. Oboyle, and H.K. Wickramasinghe, APL **58** (1991) 2921

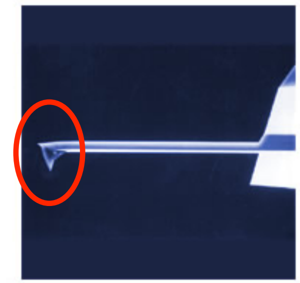
A. Liscio, V. Palermo, P. Samori, Accounts Chem. Res. **43** (2010) 541

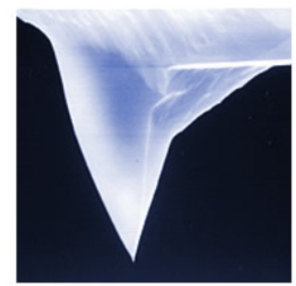
Measuring the patches with KPFM ..

- The finite size tip implies a distributed capacitance between the sample and the tip
- The measured potential is a convolution product of the true surface potential by the PSF (Point Spread Function)
- There are also noises which make it difficult to revert to the true potential

- Estimated PSF width ~ 100nm
- Sufficient for large patches (~ 1000nm) which could explain the difference ΔP

□ Pt/Ir coated Si tip





$60 < \omega < 90$ kHz

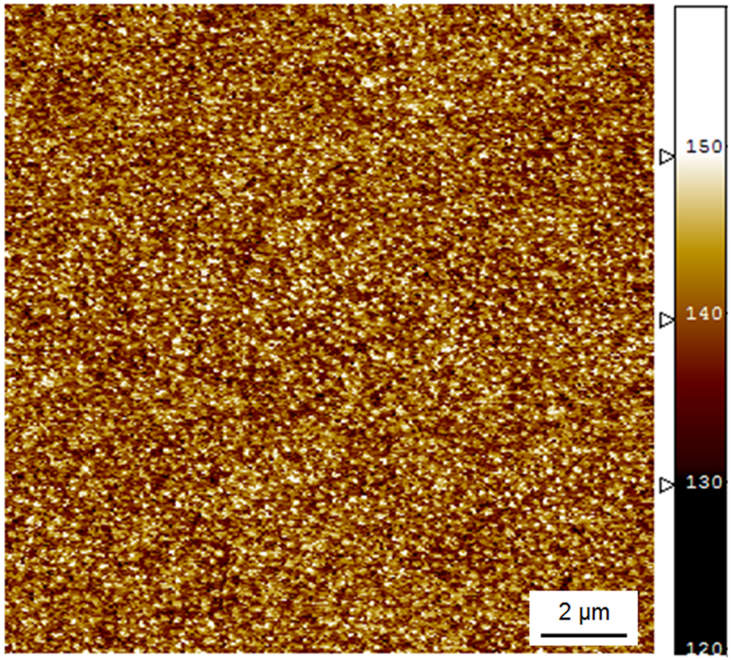
$k \sim 2.8$ N.m^{-1}

$Q \sim 200$ in air

A. Liscio, V. Palermo, P. Samori, Accounts Chem. Res. **43** (2010) 541

Measuring the patches with KPFM ..

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



Measurements performed by A. Liscio, ISOF Bologna

- Tip-to-sample distance
  fixed at *d*=30 nm
  no cross-talks topo./elec. signals

- Scanning parameters

  1 Hz per line
  V_{AC} ~ 1 V V_{DC} ~ 140 mV

  Map area : 15.4 x 15.4 mm^2
  Pixel array : 512 x 512
  Pixel size : Dx = Dy = 30 nm $< w$

- Estimated resolution
  (Rayleigh criterion)

$$w/0.6 \simeq 160\text{nm}$$

Samples provided by R.S. Decca, similar to those used in Casimir experiments

Comparable results obtained in measurements by R.S. Decca at IUPUI

Calculating the effect of patches

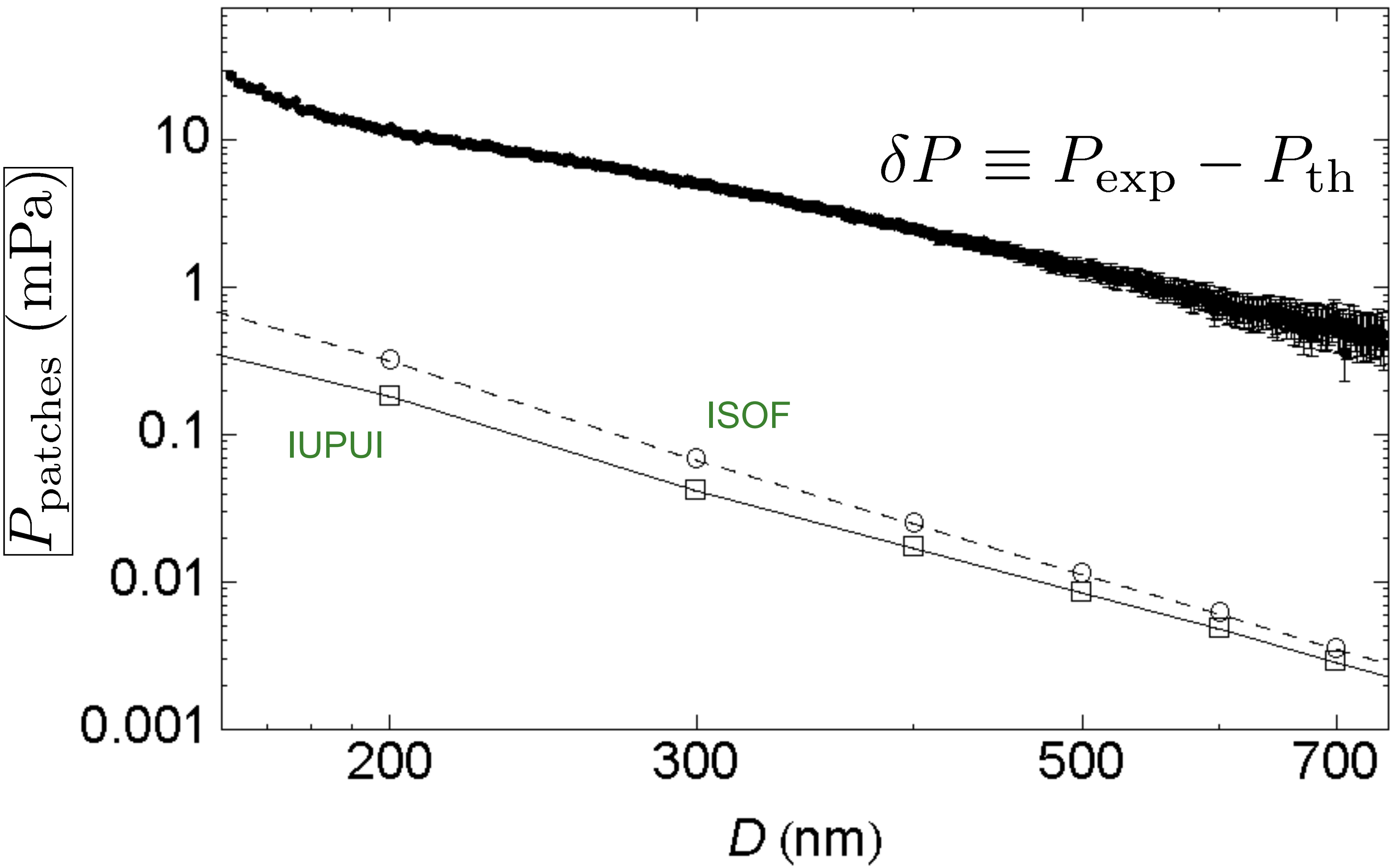
R.O. Behunin et al, PRA 86 (2012) 052509

- Force evaluated in the plane-sphere geometry
  - Poisson equation separated by using bispherical coordinates
  - The mean potential difference between the two plates is compensated in the Casimir measurements
  - What has to be evaluated is the effect of the dispersion of the potential difference over the zone of electrostatic influence

- To be kept in mind :
  - Patch measurements done on plane plates similar to those used in Casimir force measurements ; Similar statistical properties assumed on the spherical plates (radius much larger than grain sizes or patch sizes)
  - Patch measurements done under normal pressure ; Comparisons done with Casimir measurements done under primary vacuum pressure

R.O. Behunin, D.A.R. Dalvit, R.S. Decca, C. Genet, I.W. Jung, A. Lambrecht, A. Liscio, D. Lopez, S. Reynaud, G. Schnoering, G. Voisin, and Y. Zeng, arXiv: 1407.3741 (Oct 2014)

Calculating the effect of patches …



Conclusions at this point (November 2014)

- There is a contribution of electrostatic patches
  - it is much larger than was thought in first studies
  - but it is smaller than the gap between Casimir experiments and theory

- Patches on real samples now measured
  - they do not have the same properties *(magnitude and spectrum)* as the patches fitted to explain the difference ΔP
  - the observed gap between precise Casimir force measurements and best theory remains to be explained …

- Further work needed :
  - to confirm the measurements of patches, with better resolution, larger scan sizes, and also on spherical plates
  - to measure patches at the pressure of Casimir experiments
  - to compare with knowledge from other studies

Thanks for your attention