Measurement of the Casimir force on nanoscale corrugated surfaces

Ho Bun Chan

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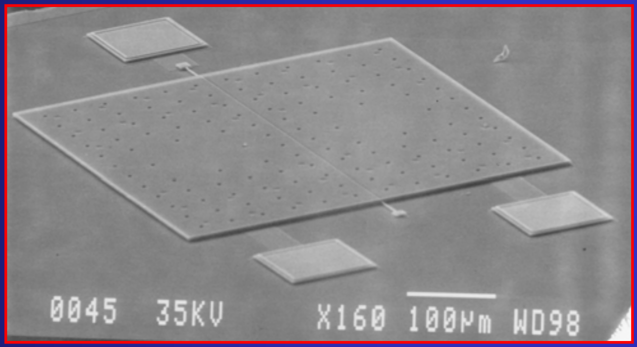
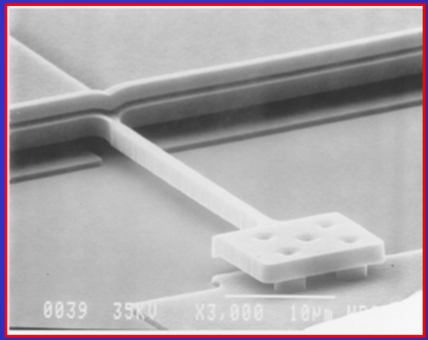
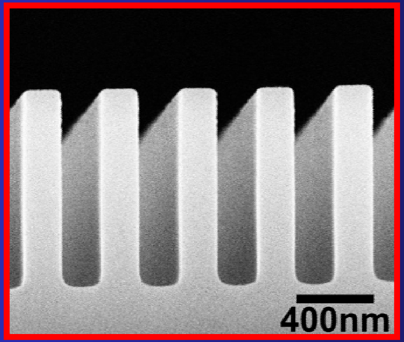






October 1st, 2008. KITP

Outline

• Micromechanical torsional oscillator for measuring the Casimir force.

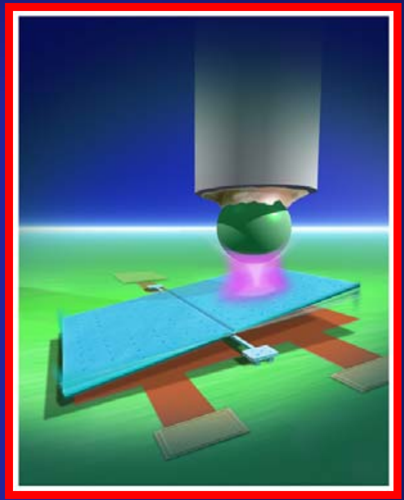
• nonlinear Casimir micromechanical oscillator.

• Geometry dependence of the Casimir force:

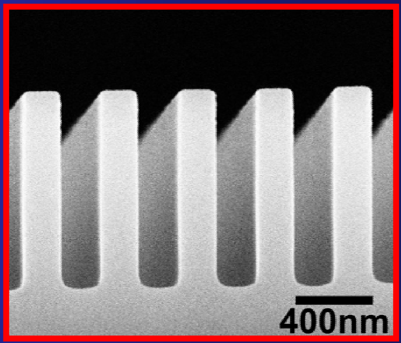
• Experiment on strongly deformed surface: array of nanoscale trenches

Up to 30% deviation from pairwise additive approximation

A factor of 2 smaller than theory on perfect metals



Collaborators



University of Florida

Yiliang Bao

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Andreas Hanke

Bell Labs

Federico Capasso

Vladimir Aksyuk

Raffi Kleiman

David Bishop

Ray Cirelli

Fred Klemens

Bill Mansfield

C.S. Pai

Casimir force

Hendrik B. G. Casimir 1948

- attractive force between two electrically neutral conducting surfaces

- arise from zero point fluctuations of the electromagnetic field

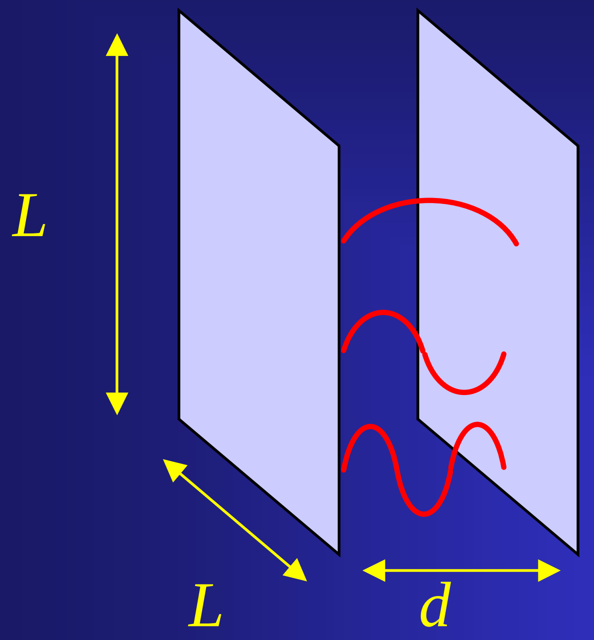
Energy for each electromagnetic mode with frequency ω:

$$E_{n,\omega} = (n + 1/2)\hbar\omega$$

Uncertainty Principle: electric and magnetic fields fluctuate, even at ground state ($n = 0$)

Total zero point energy:

$$E_{total} = \sum_{\omega} \frac{1}{2}\hbar\omega$$



Derivation of Casimir force

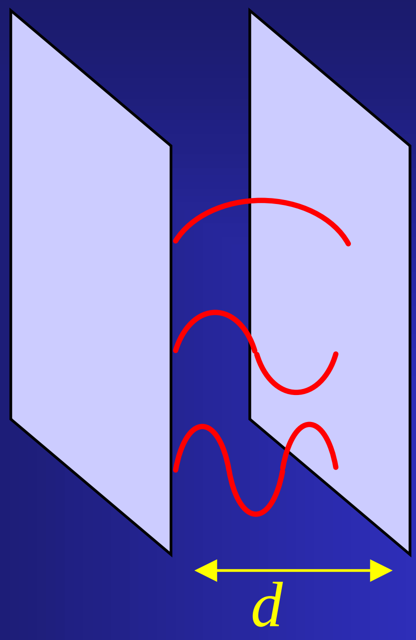
$$\omega_{k_x k_y n} = c\left(k_x^{\,2} + k_y^{\,2} + \frac{\pi^2}{d^2} n^2\right)^{1/2}$$

Total zero point energy: $$E = \sum_{k_x k_y n} \frac{1}{2} \hbar \omega_{k_x k_y n}$$

$$E(d) = \frac{\hbar c L^2}{\pi^2} \sum_n \int_0^\infty \mathrm{d}k_x \int_0^\infty \mathrm{d}k_y \left(k_x^{\,2} + k_y^{\,2} + \frac{\pi^2}{d^2} n^2\right)^{1/2}$$

Potential energy of the plates: $$U(d) = E(d) - E(\infty) = -\frac{\pi^2 \hbar c}{720 d^3} L^2$$

Casimir force $$F = {-U'(d)}\big/{L^2} = -\frac{\pi^2 \hbar c}{240 d^4}$$



Casimir force between conducting surfaces:

$$F_{Casimir} = -\frac{\pi^2}{240 d^4} \frac{\hbar c}{} \quad \text{per unit area}$$

Quantum effect due zero-point fluctuations on a macroscopic system

Between 2 μm thick silicon plates.

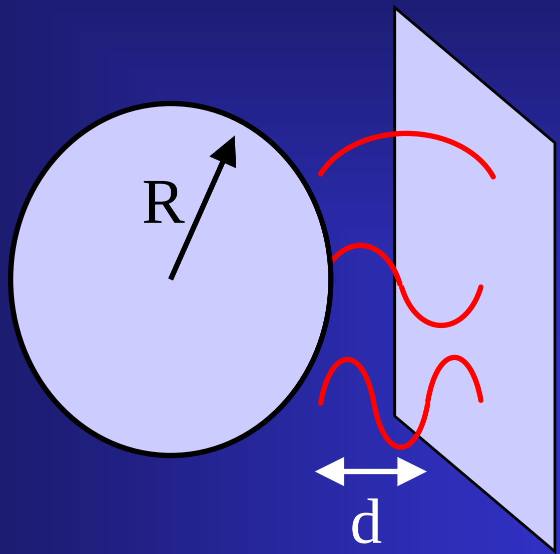
At d = 1 μm, $F_{Casimir}$ ~ gravitational attraction

At d = 10 nm, 10^8 times larger,

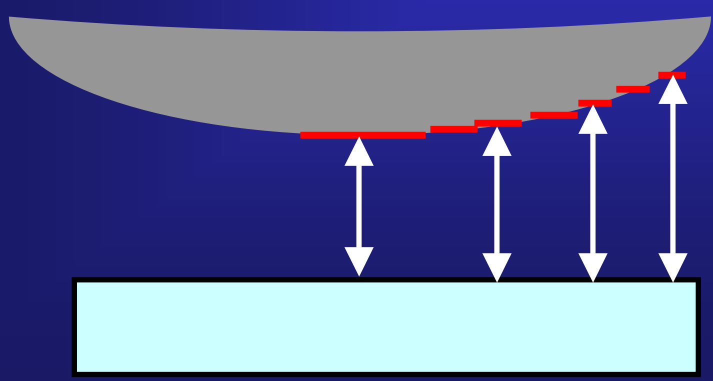
$F_{Casimir}$ ~ 1 atmosphere of pressure.

Non-ideal surfaces: finite conductivity, roughness, finite temperature, geometry effects

Experiments measuring Casimir force:



$$F_{Casimir} = -\frac{\pi^3 R}{360} \frac{\hbar c}{d^3}$$



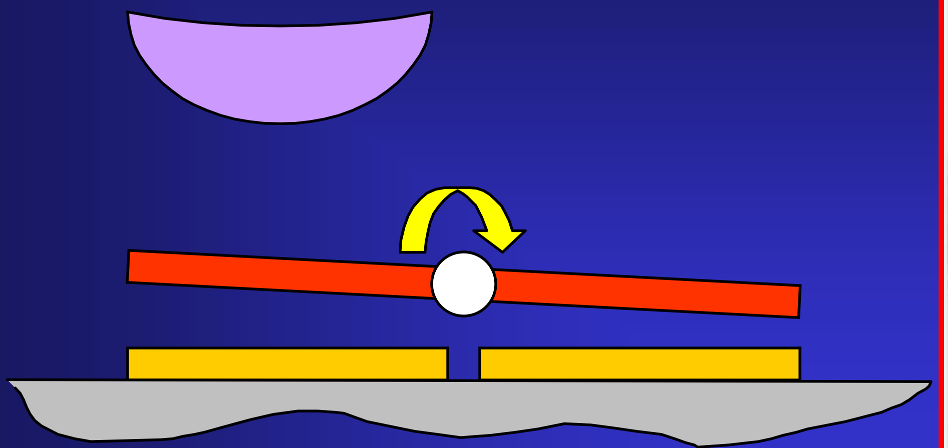
- Lamoreaux '1997
  - Torsional Pendulum
  - 5% agreement with theory
- Mohideen & Roy '1998
  - AFM, 1 % agreement with theory
- Ederth '2000
  - cylindrial geometry
- Chan, Aksyuk, Kleiman, Bishop & Capasso '2001
  - Actuation of micromechanical devices using the Casimir force
- Bressi, Carugno, Onofrio & Ruoso '2002
  - parallel plates
- Decca, Lopez, Fischbach & Krause '2003
  - dissimilar metals, 'Casimir-less' experiments

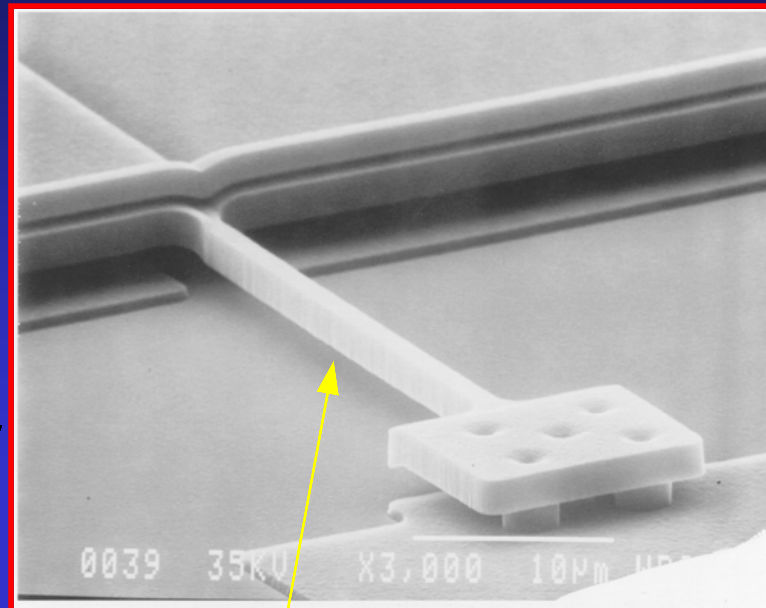
Proximity force approximation (Derjaguin approx)

Valid for d << R

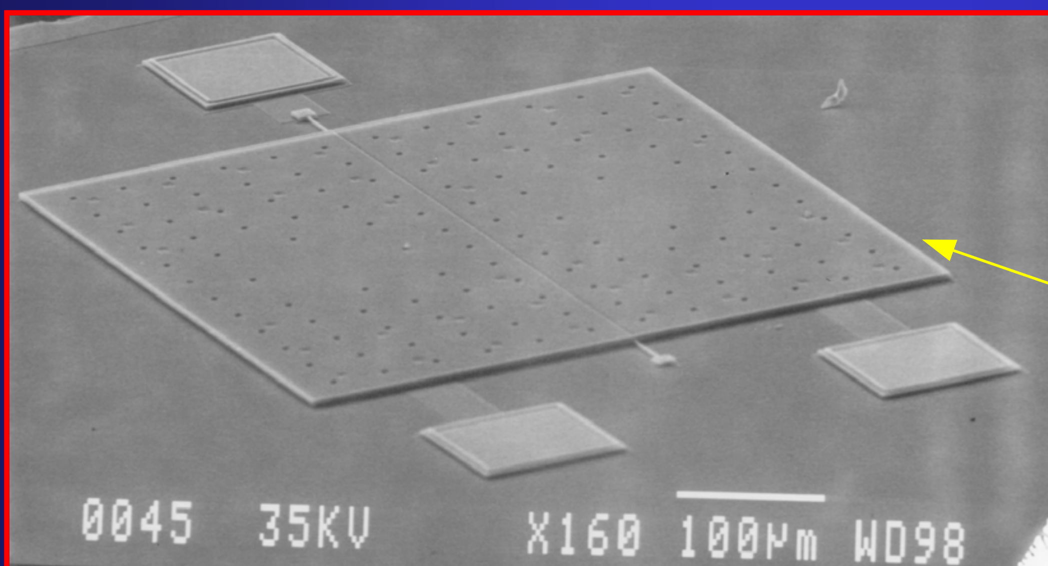
(typical d ~ 100 to 400 nm, R ~ 50 to 100 um)

Micromechanical torsional device



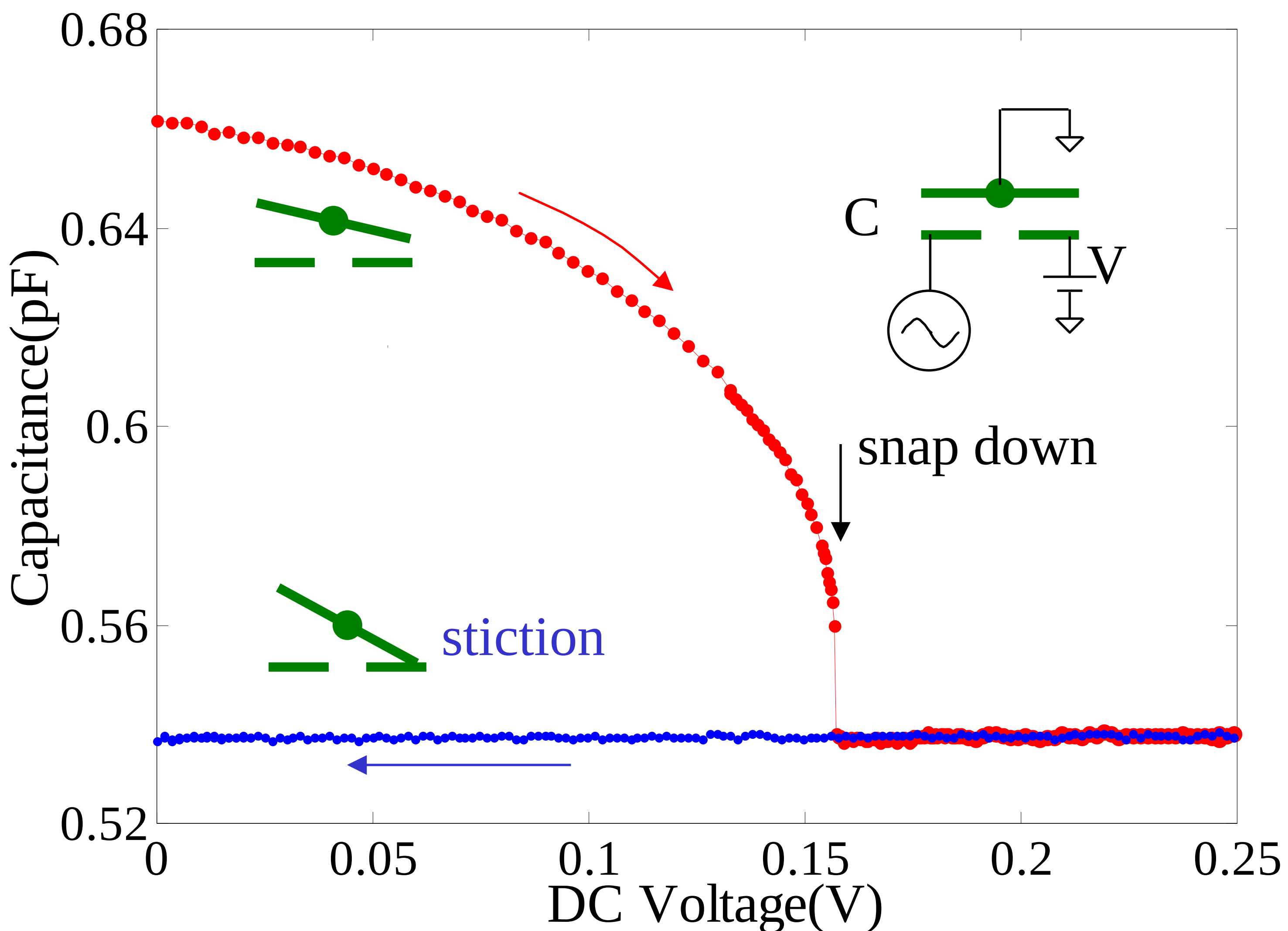


Torsional rod
cross section: 1.5 x 2 μm^2

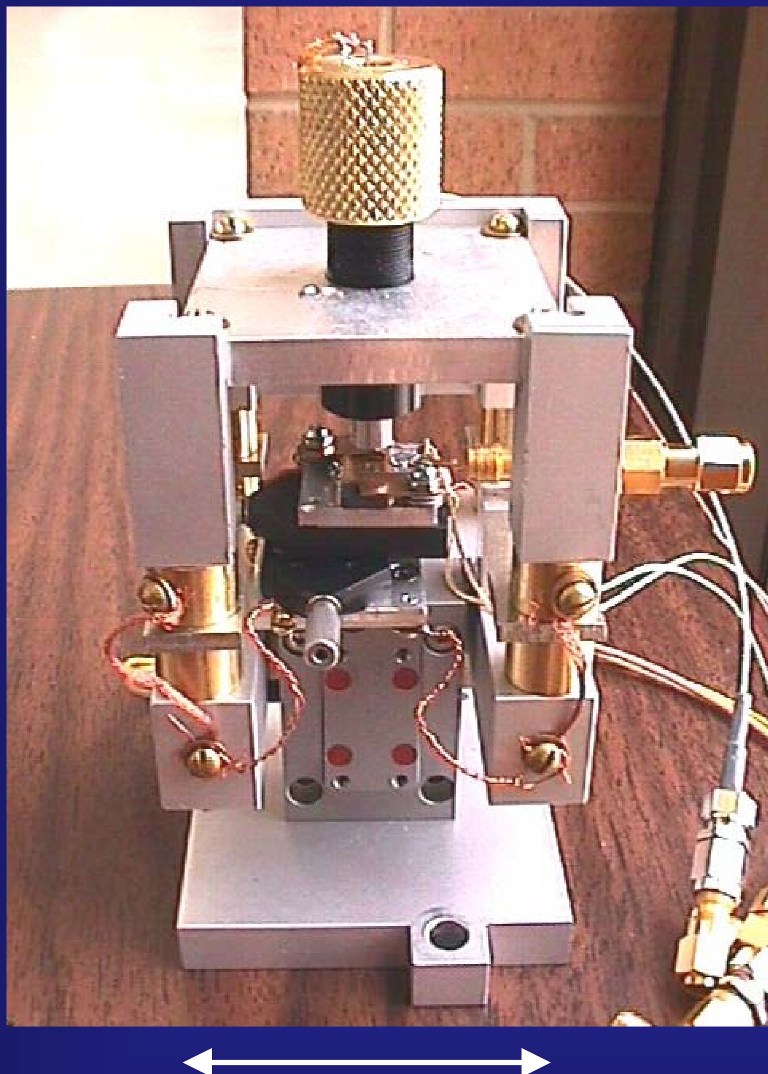


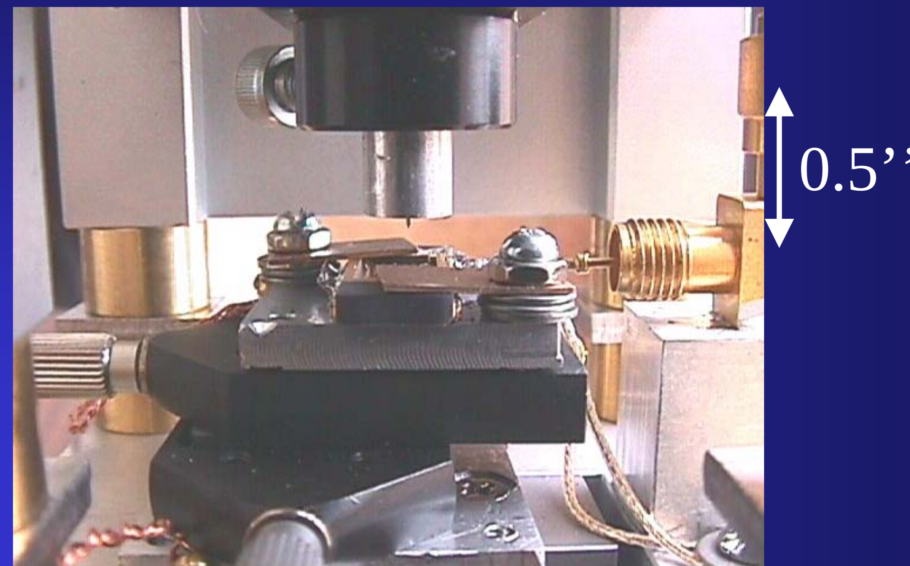
poly-Si plate:
500 µm x 500 µm x 3.5 µm

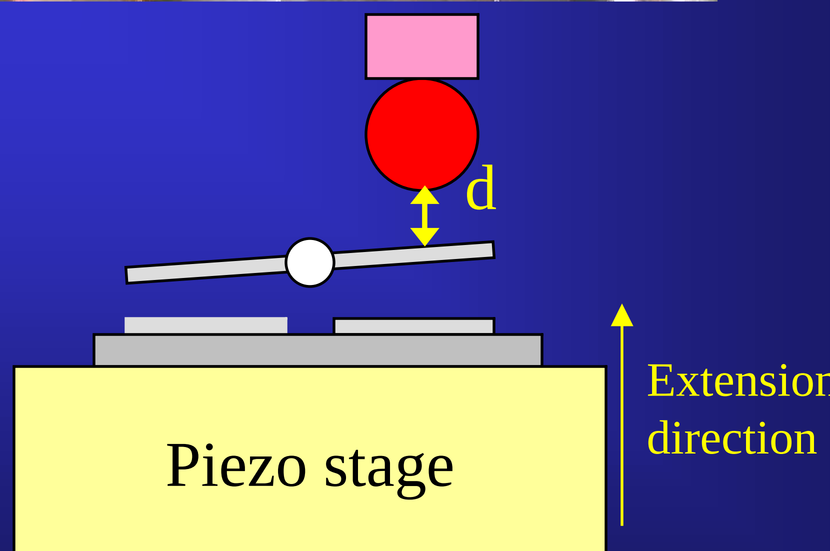
Tilting the top plate by applying DC bias to electrode



Experimental setup

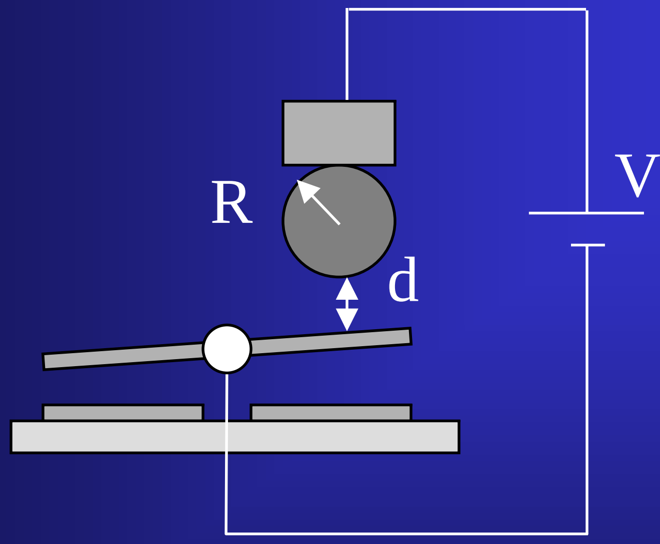


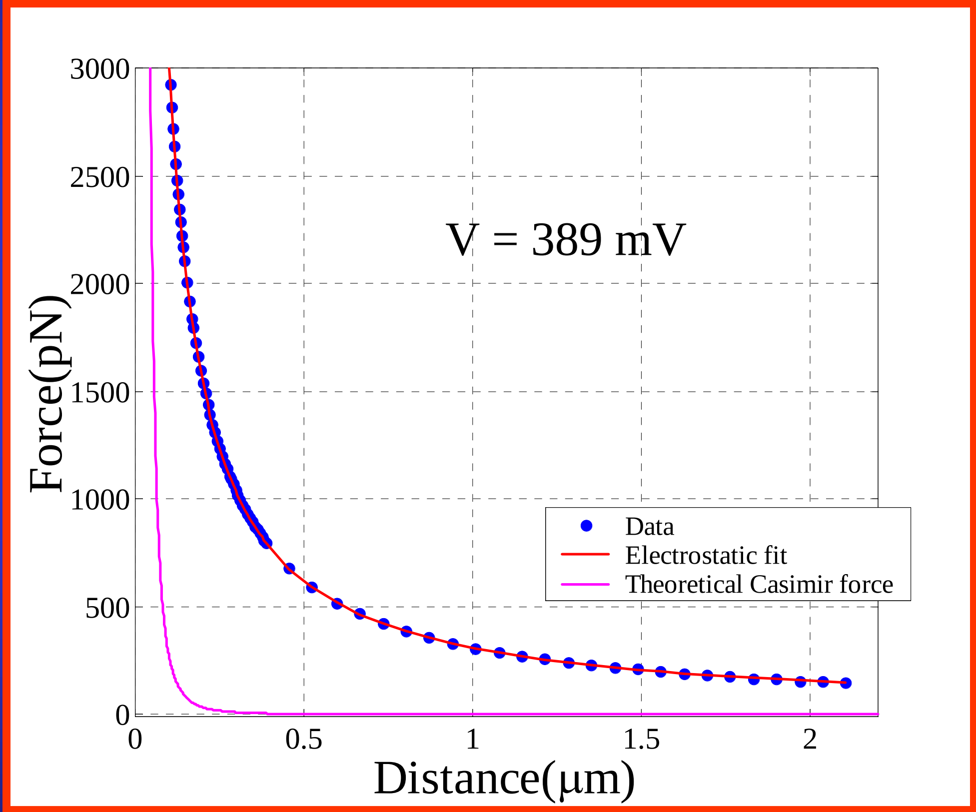




Calibration by electrostatic force

$$F = \varepsilon_o \pi R \frac{(V - V_o)^2}{d}$$

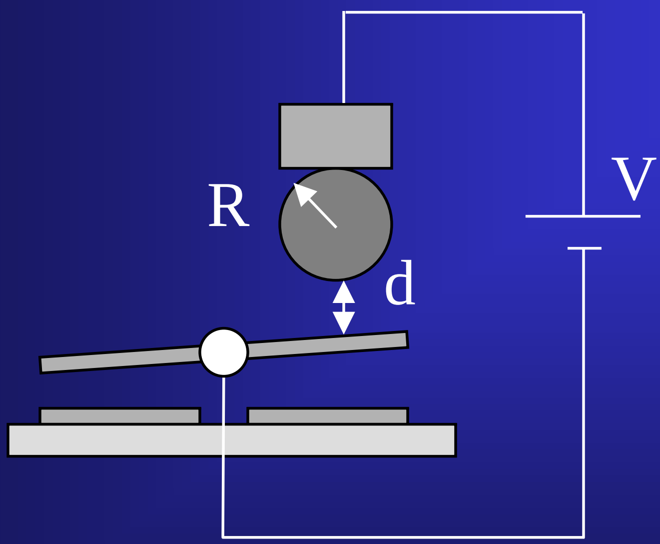


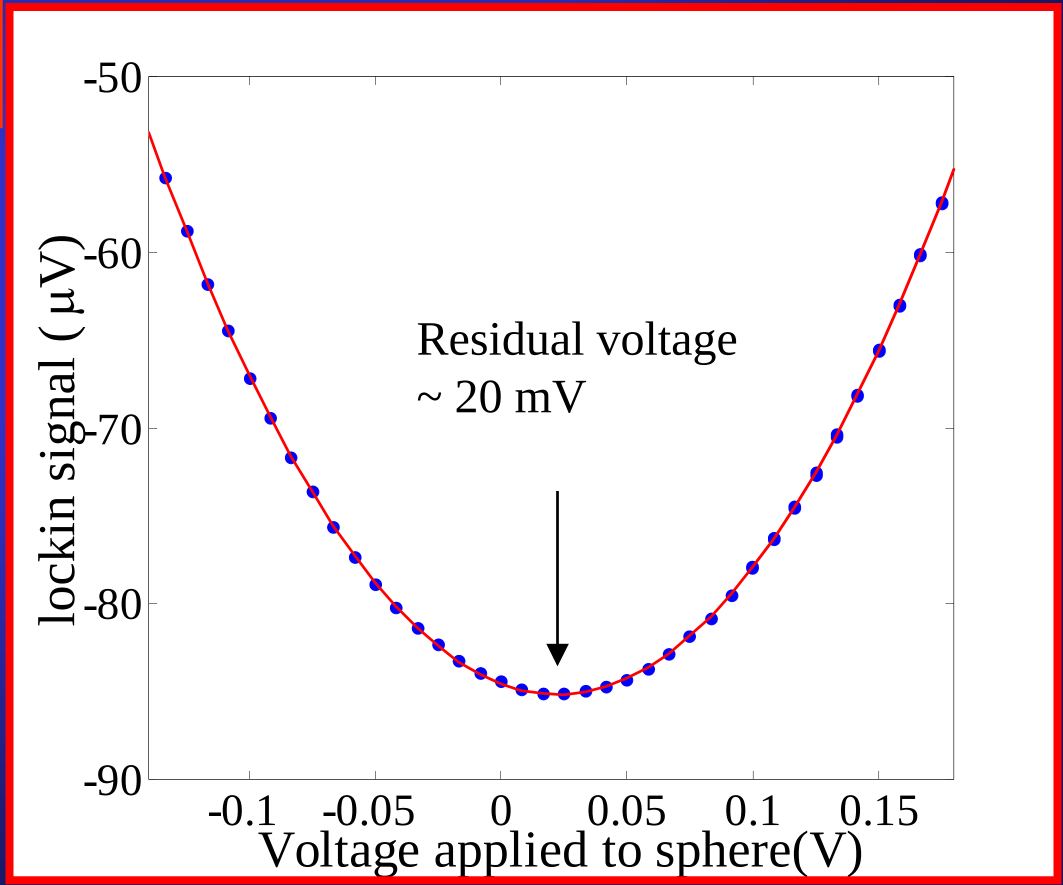


Residual voltage

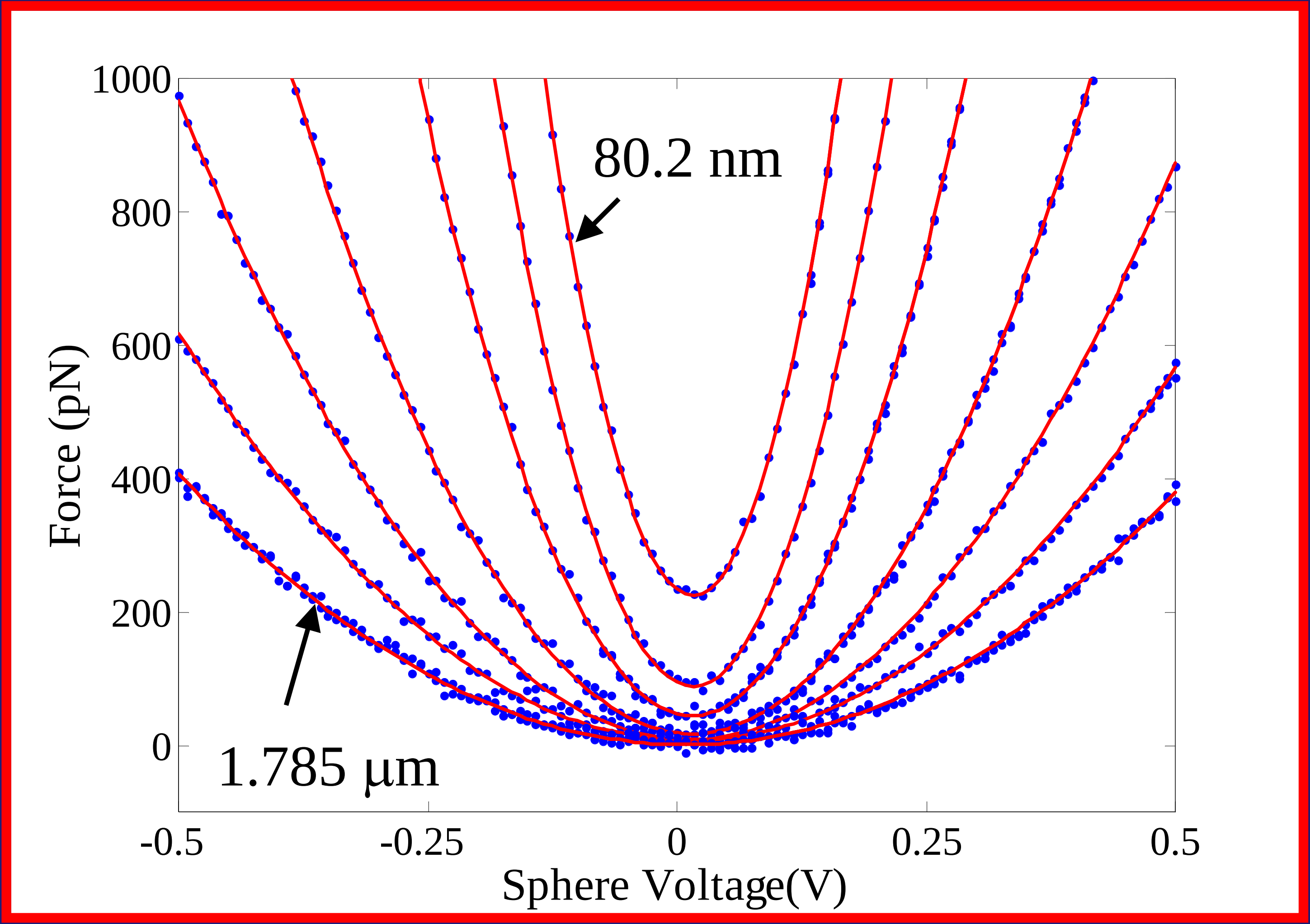
Differences in work functions of metal films

$$F = \varepsilon_o \pi R \frac{(V - V_o)^2}{d}$$

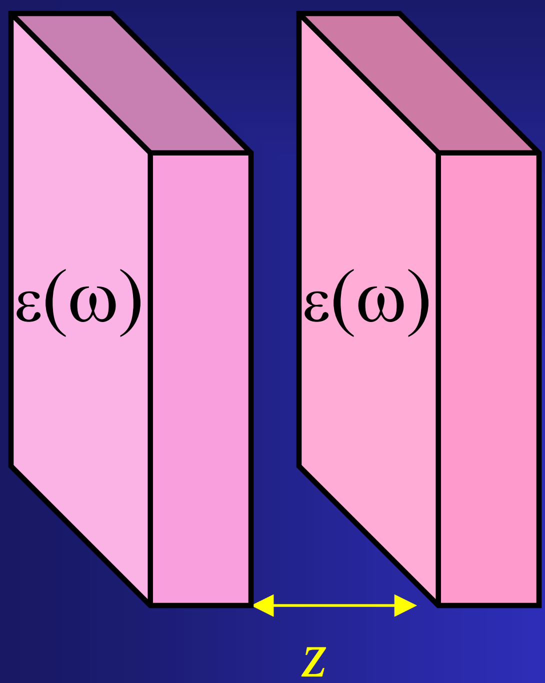




Residual voltage dependence on distance



$$F_{total} = V^2 F_{electrostatic}(d) + F_{Casimir}(d)$$



Finite conductivity corrections

Lifshitz `1956

in material body:
fluctuating electromagnetic field
⇔ Charge and current fluctuations

+ boundary conditions

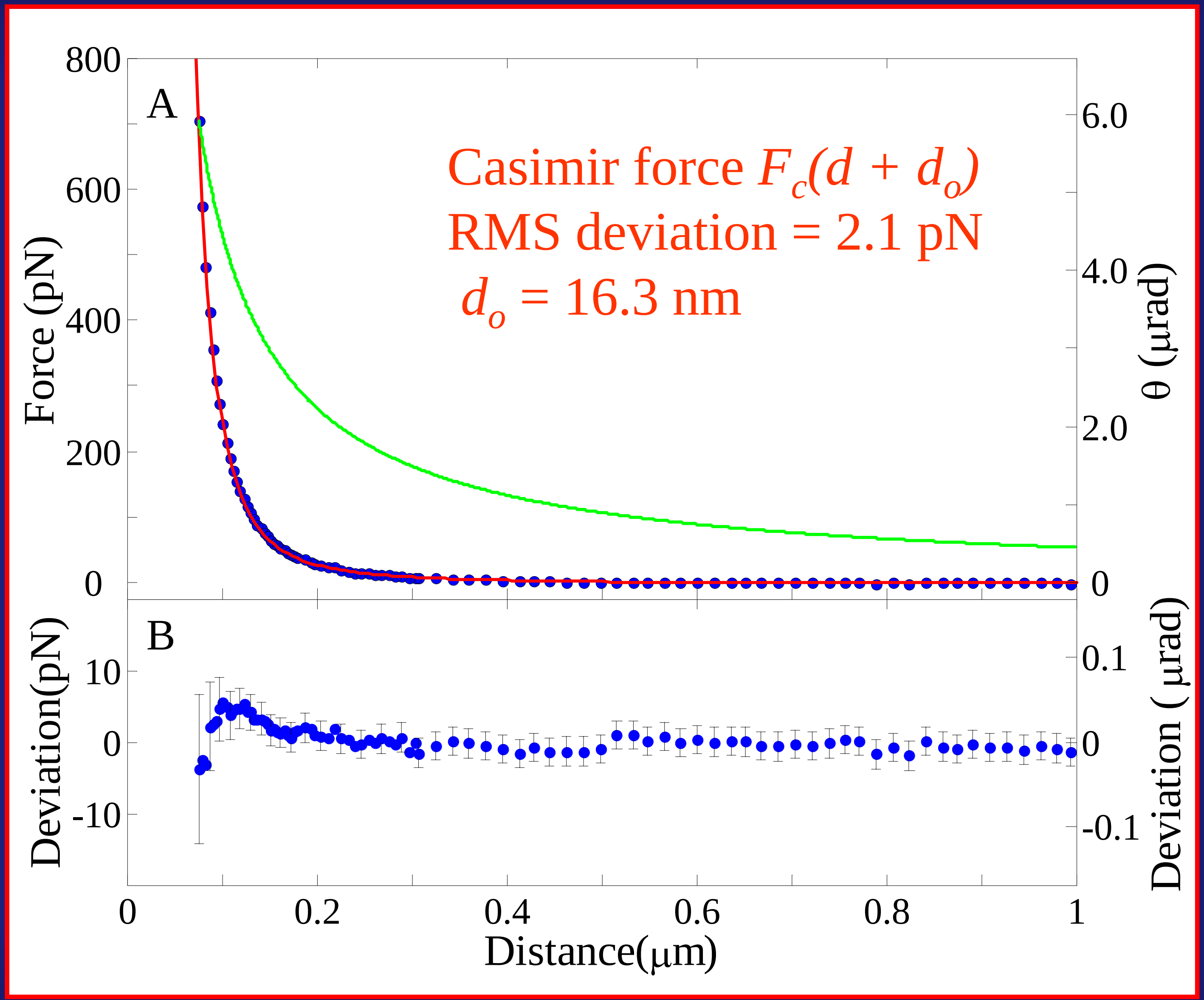
$$F_{Lifshitz}(z) = \frac{\hbar}{2\pi c^2} R \int_0^\infty \int_1^\infty p\xi^2 \left\{ \ln\left[1 - \frac{(s-p)^2}{(s+p)^2} e^{-2pz\xi/c}\right] + \ln\left[1 - \frac{(s-p\varepsilon)^2}{(s+p\varepsilon)^2} e^{-2pz\xi/c}\right] \right\} dp\, d\xi$$

$$s = \sqrt{\varepsilon(i\xi) - 1 + p^2} \qquad \varepsilon(i\xi) = \frac{2}{\pi}\int_0^\infty \frac{x\varepsilon''(x)}{x^2 + \xi^2} dx + 1$$

Kramers-Kronig

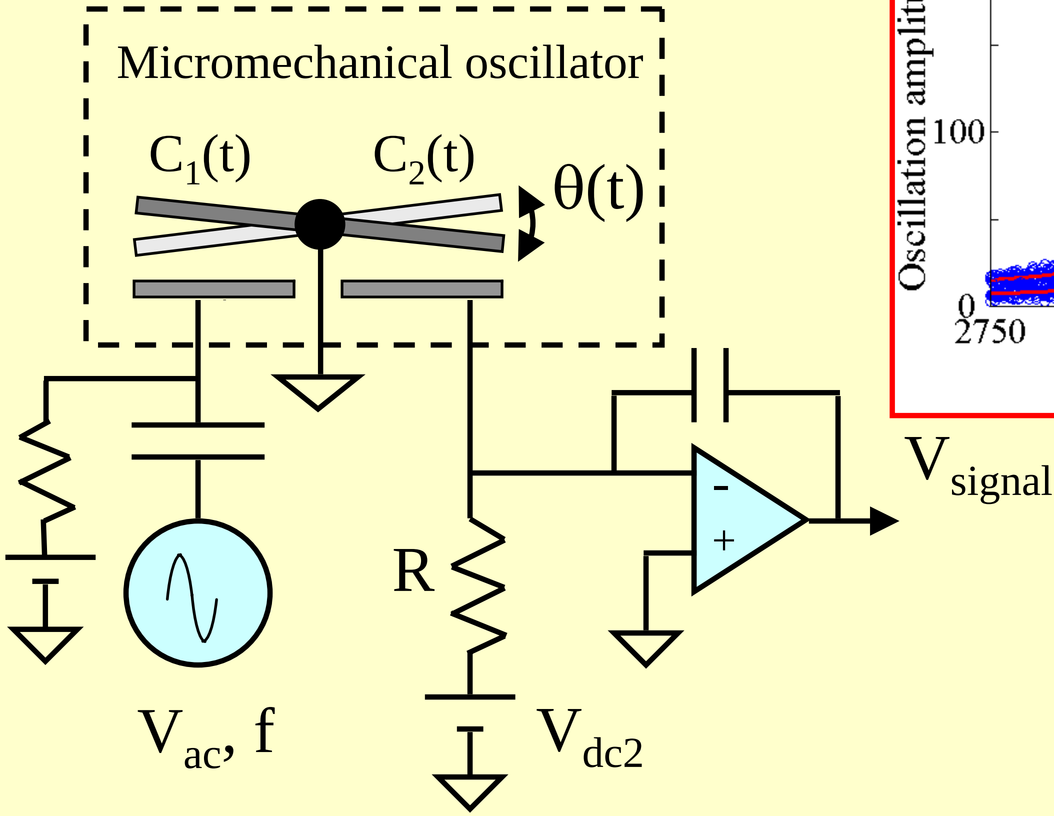
Need: z, ε’’(ω) ← tabulated in data books

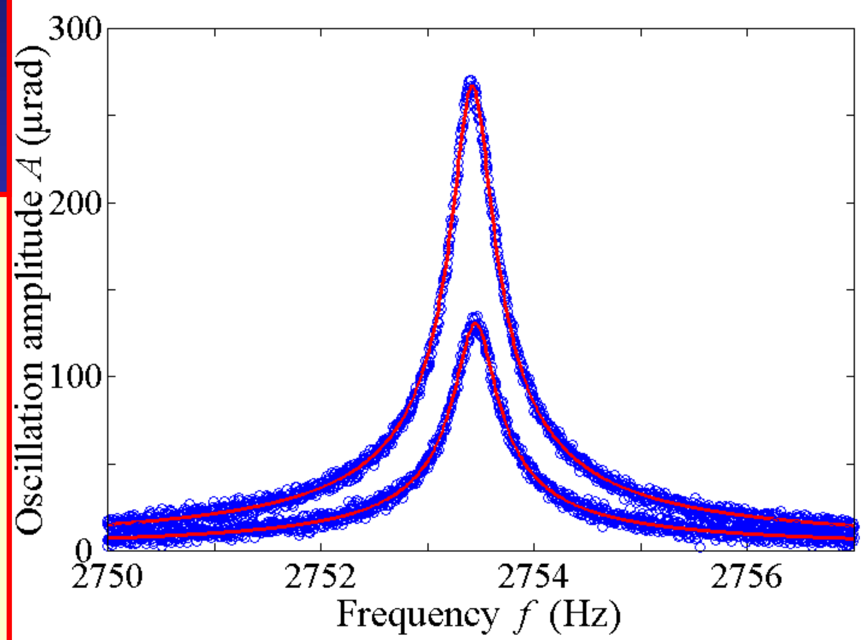
Casimir force with roughness and finite conductivity corrections



Chan *et al*., Science **291**, 1941 (2001).

Simple Harmonic Oscillations

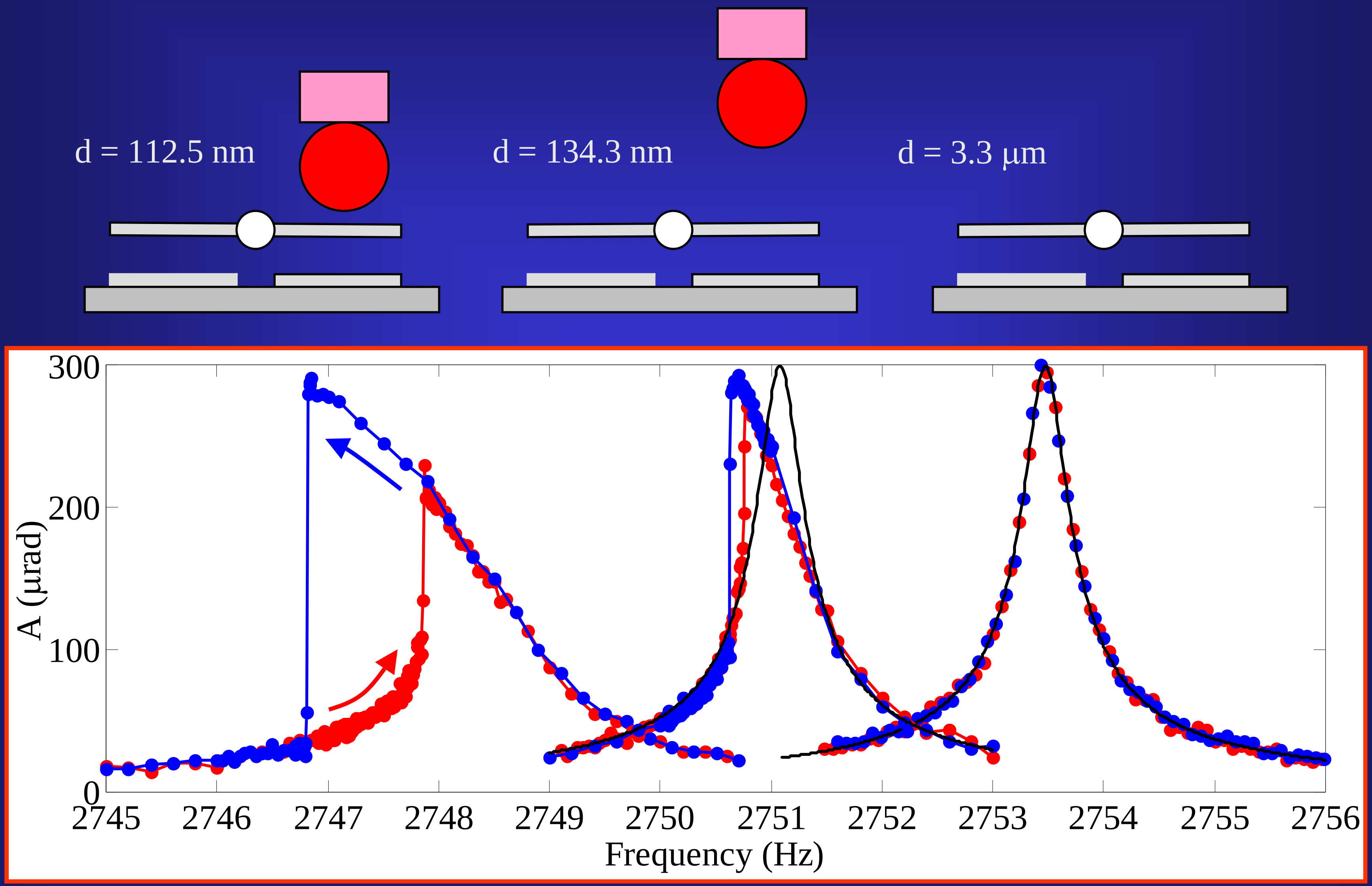




At small excitation, response depends linearly on excitation voltage

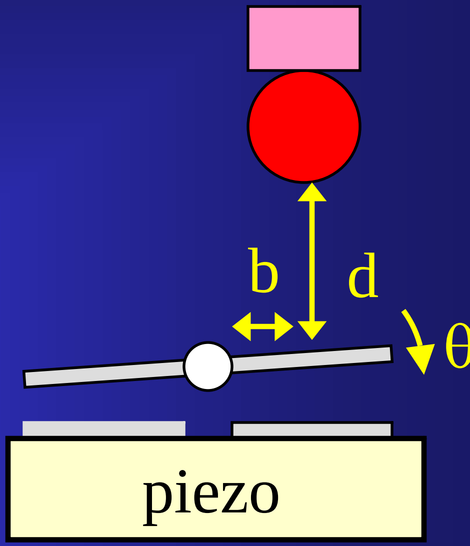
Q = 7150

Nonlinear behavior induced by the Casimir force



Anharmonic Oscillator: Equation of motion

$$I\ddot{\theta} + \lambda\dot{\theta} + k\theta = \tau \cos \omega t + bF\left(d + b\theta\right)$$



Taylor series:

$$F\left(d + b\theta\right) = F\left(d\right) + F'\left(d\right)\left(b\theta\right) + \tfrac{1}{2} F''\left(d\right)\left(b\theta\right)^2 + \tfrac{1}{6} F'''\left(d\right)\left(b\theta\right)^3$$

$$\ddot{\theta} + 2\gamma\dot{\theta} + \left[\omega_o{}^2 - \left(b^2/I\right)F'\left(d\right)\right]\theta = \left(\tau/I\right)\cos \omega t + bF\left(d\right)/I - \alpha\theta^2 - \beta\theta^3$$

Frequency shift:

$$\Delta\omega = -\frac{b^2}{2I\omega_o} F'\left(d\right)$$

Nonlinear terms:

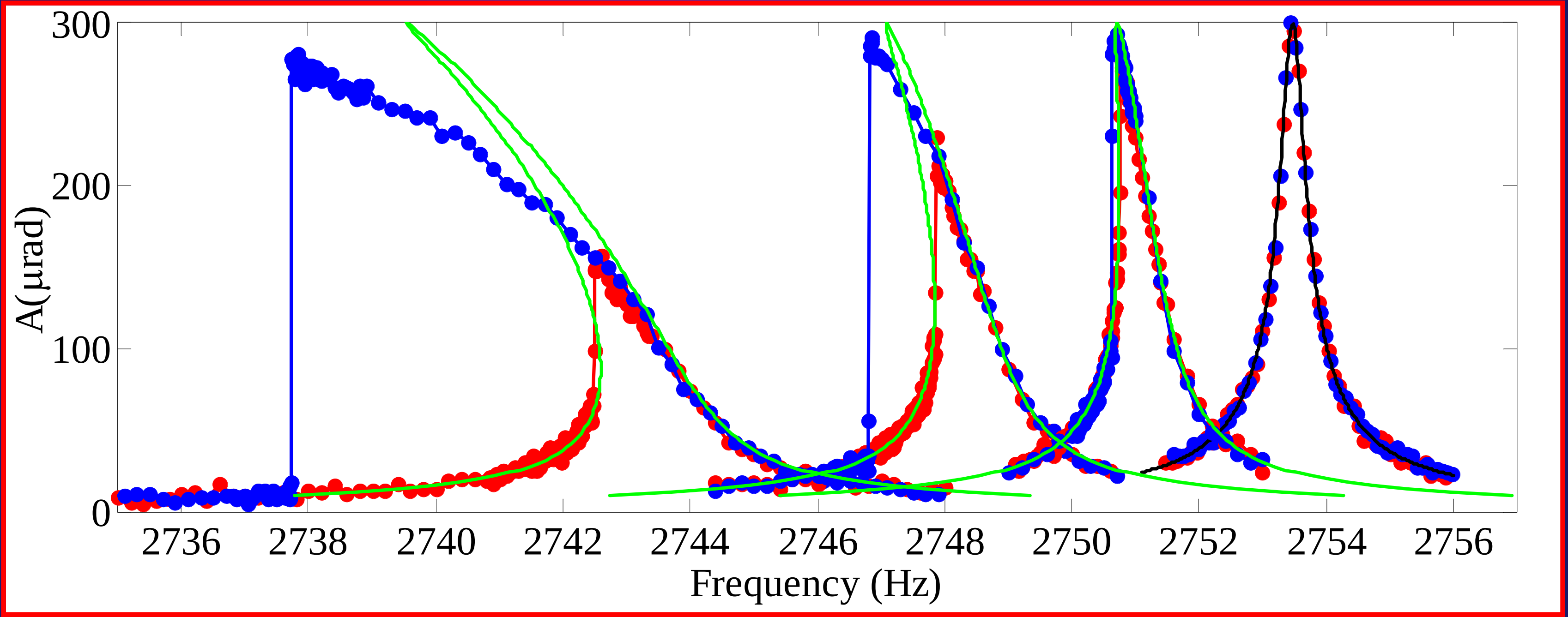
$$\alpha = -b^3 F''\left(d\right)/2I \qquad \beta = -b^4 F'''\left(d\right)/6I$$

Nonlinear Casimir oscillator

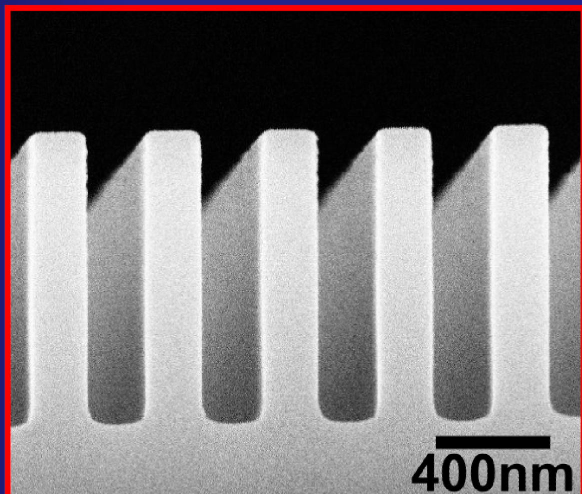
$$I\ddot{\theta} + \lambda\dot{\theta} + k\theta = \tau\cos\omega t - \alpha\theta^2 - \beta\theta^3$$

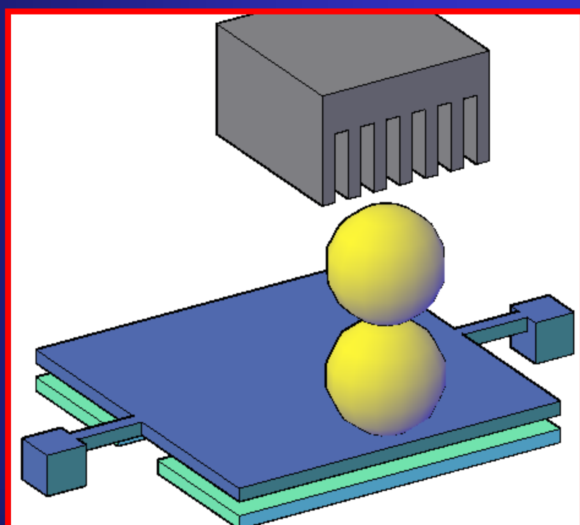
Strongly nonlinear oscillator

bistability and hysteresis



Geometry dependence of the Casimir force: Nanoscale trench arrays





Chan et al., PRL 101, 030401 (2008).

Ho Bun Chan (U Florida)

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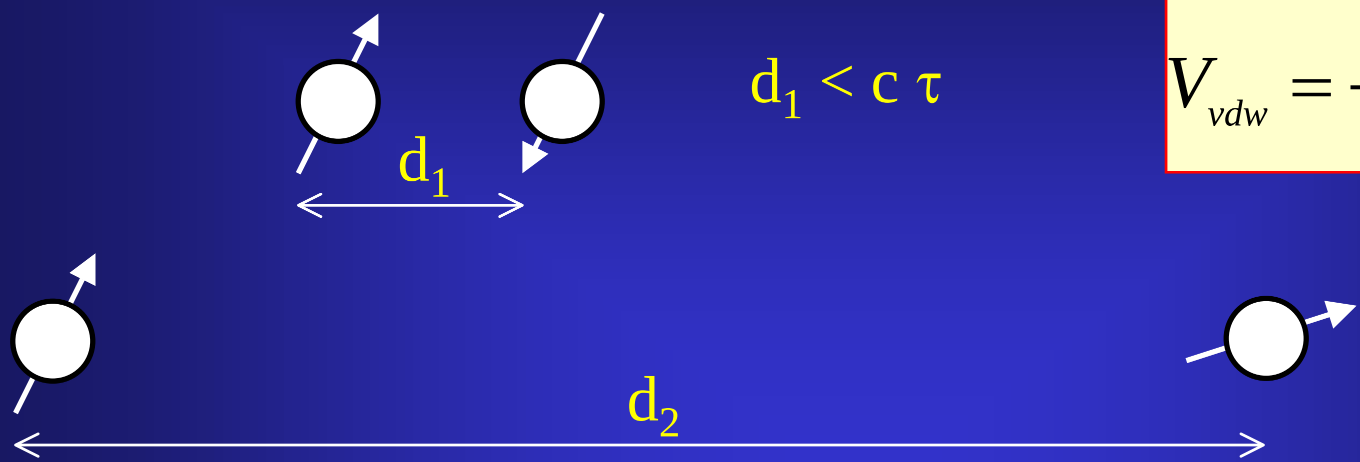
Quantum fluctuations: Casimir force vs van der Waals' force



$d_1 < c\,\tau$

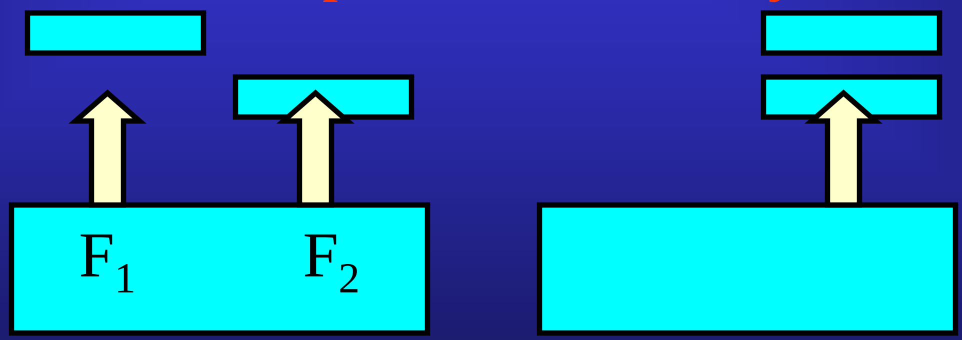
$$V_{vdw} = -\frac{B}{r^6}$$

$d_2 > c\,\tau$

$$V_{retarded\,vdw} = -\frac{B'}{r^7}$$

retardation effects: finite propagation speed of light

Non-pairwise additivity



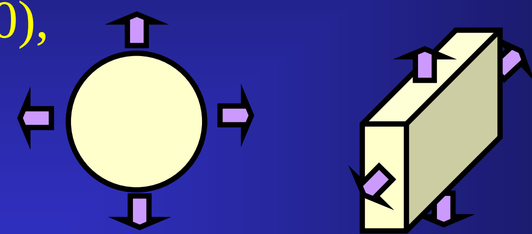
$F_{total} \sim F_1 + F_2$ $\qquad$ $F_{total} \neq F_1 + F_2$

Repulsive Casimir force and micromechanics

If experimentally feasible, repulsive Casimir force can potentially reduce stiction.

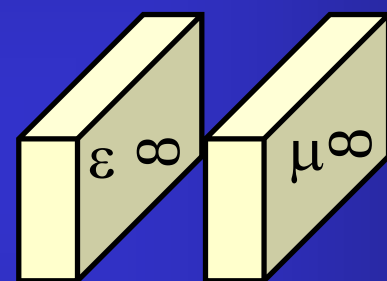
1. Closed geometries: Boyer (1968), Maclay (2000),

   cannot cut sphere or box in half

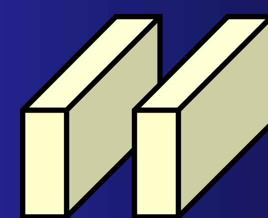


2. Make one surface infinitely permeable

   (Hushwater 96)



3. Introduce liquid into the gap (current experiments by Capasso)



$\varepsilon_1 < \varepsilon_2 < \varepsilon_3$

4. Possible use of meta material (Leonhardt and Philbin 2007)

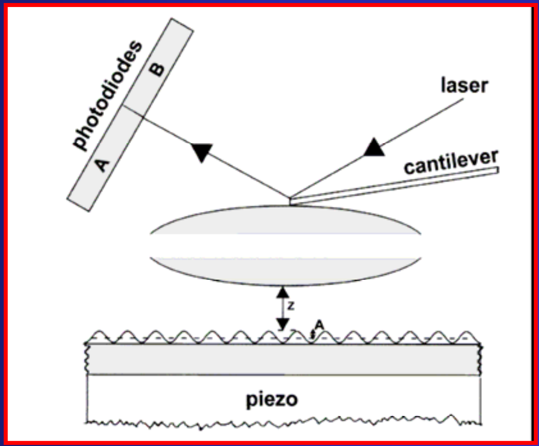
   need negative index over a wide spectral range

   introduce gain (Lifshitz formula no longer applies)

It remains a major challenge to generate repulsive Casimir force with a vacuum gap.

Experimental attempts to demonstrate the non-trivial boundary dependence of the Casimir force

- Experiment: Roy & Mohideen, PRL **82**, 4380 (1999).



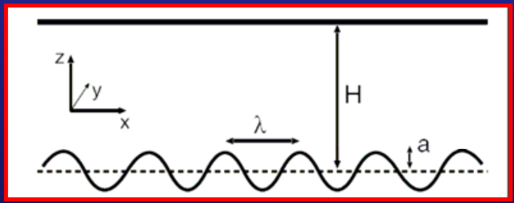
A large sphere and a plate with periodic sinusoidal corrugation

$a = 59.4$nm, $\lambda = 1.1\,\mu$m, $H/\lambda \approx 0.1$-0.8

Measured force exceeds pairwise additive interaction

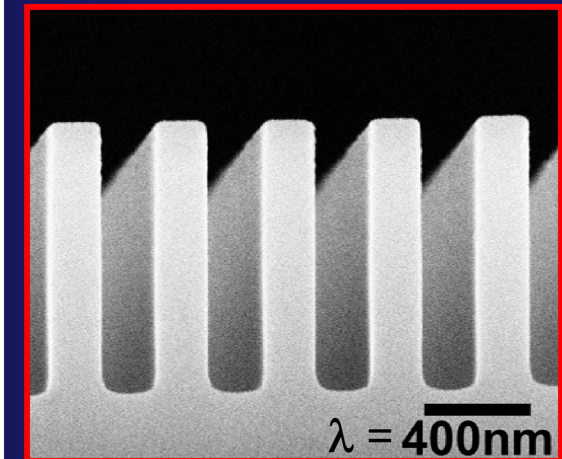
Klimchitskaya *et al.* PRA 63, 014101 (2001):
possibility of of lateral force

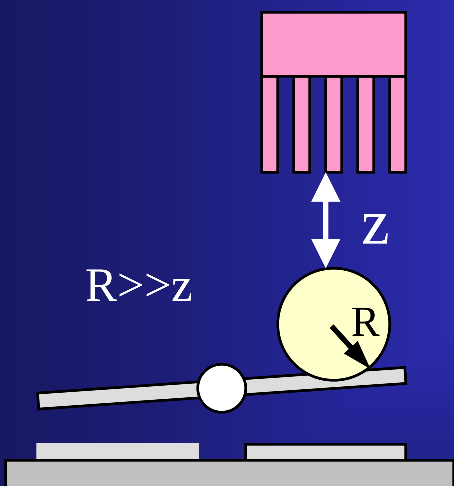
- Theory: Emig, Hanke, Golestanian & Kardar, PRL **87**, 260402 (2001):
  a path integral quantization of the electromagnetic field



Correction is strong with large H/λ

Non-trivial boundary dependence of the Casimir force



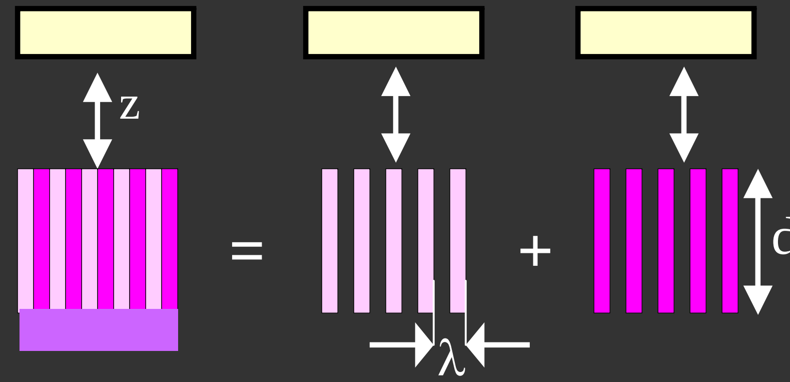


Chan et al., PRL 101, 030401 (2008).

Pairwise additive approximation (PAA)

If d>>z, for all λ,

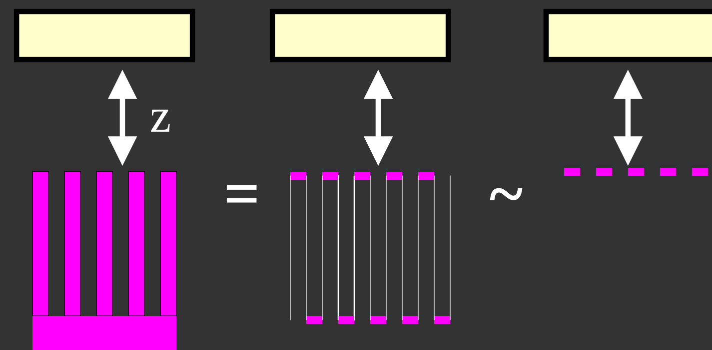
$F_{corrugated}(z) = ½ F_{flat}(z)$



Proximity force approximation (PFA)

If d>>z, for all λ,

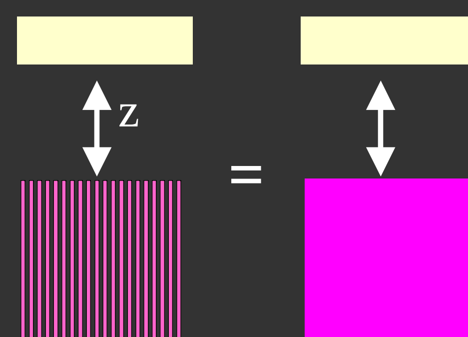
$F_{corrugated}(z) = ½ F_{flat}(z)$



Casimir force for perfect metal

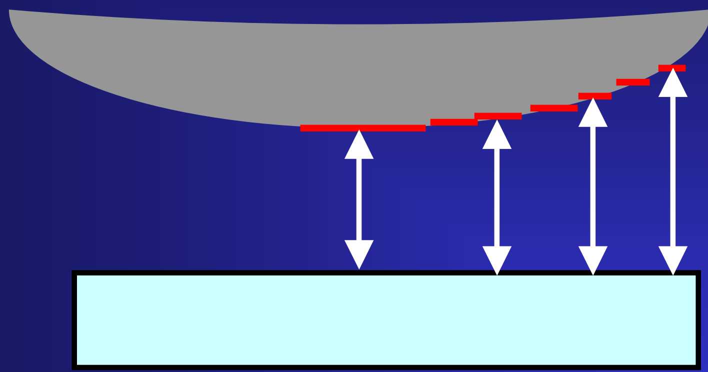
for λ << z,

$F_{corrugated}(z) = F_{flat}(z)$



Buscher & Emig, PRA **69**, 062101 (2004).

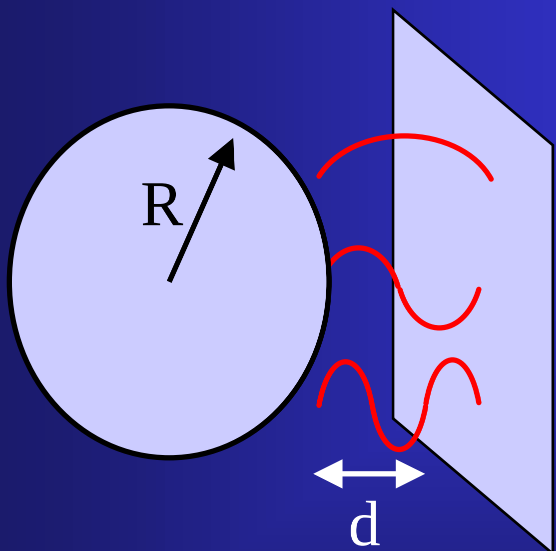
Experiments measuring Casimir force:



Proximity force approximation

Valid for d << R

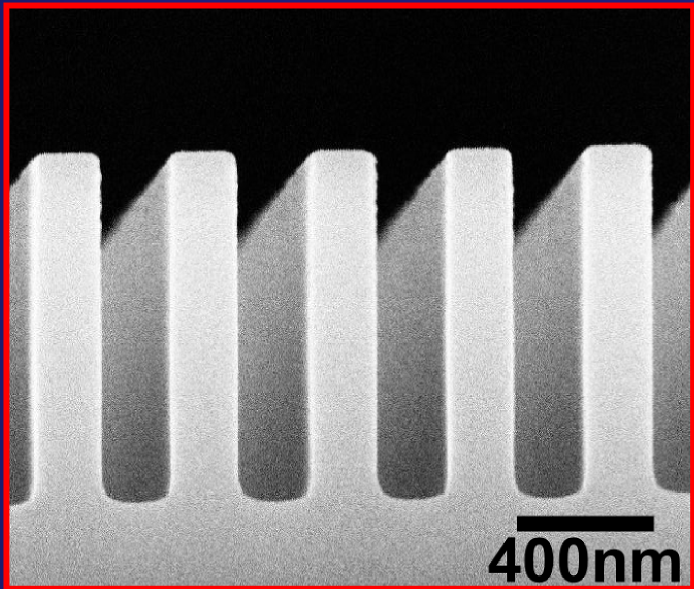
(typical d ~ 100 to 400 nm, R ~ 50 to 100 um)

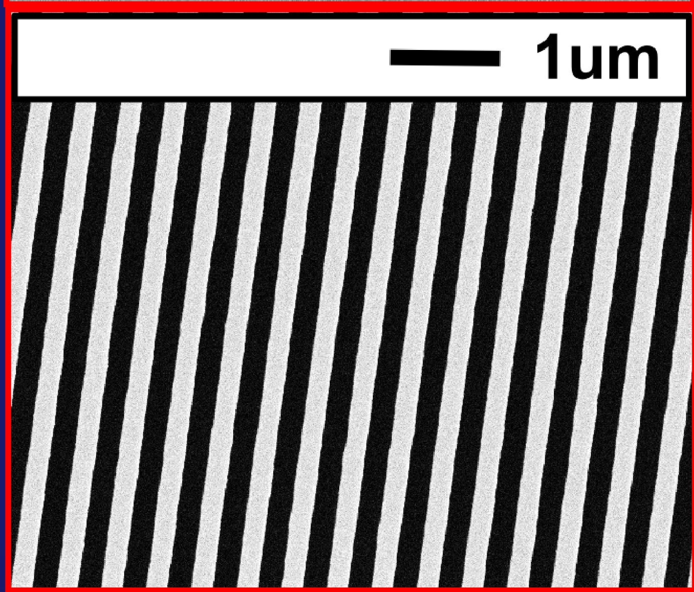


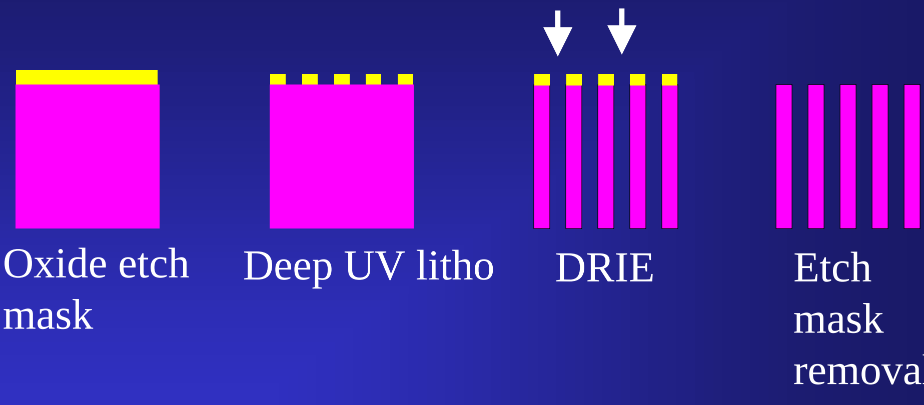
$$F_{Casimir} = -\frac{\pi^3 R}{360} \frac{\hbar c}{d^3}$$

- Lamoreaux ’1997
  Torsional Pendulum
  5% agreement with theory
- Mohideen & Roy ’1998
  AFM, 1 % agreement with theory
- Ederth ’2000
  cylindrial geometry
- Chan, Aksyuk, Kleiman, Bishop & Capasso ’2001
  Actuation of micromechanical devices using the Casimir force
- Bressi, Carugno, Onofrio & Ruoso ’2002
  parallel plates
- Decca, Lopez, Fischbach & Krause ’2003
  dissimilar metals, ‘Casimir-less’ experiments

Sample fabrication and characterization





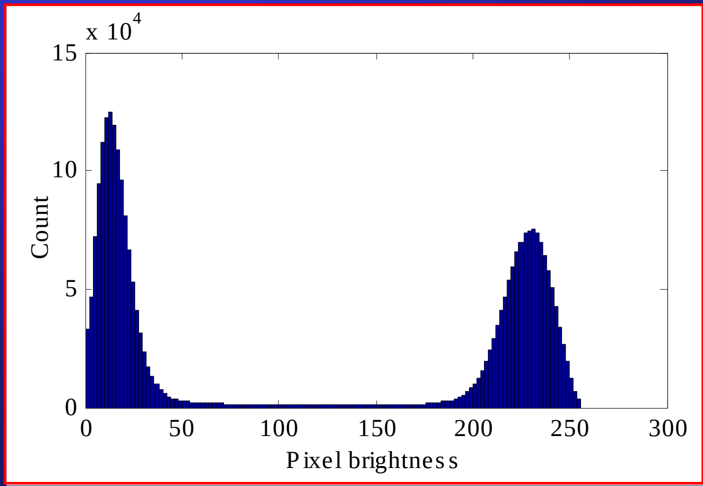


Solid fraction p = 0.51+ 0.001

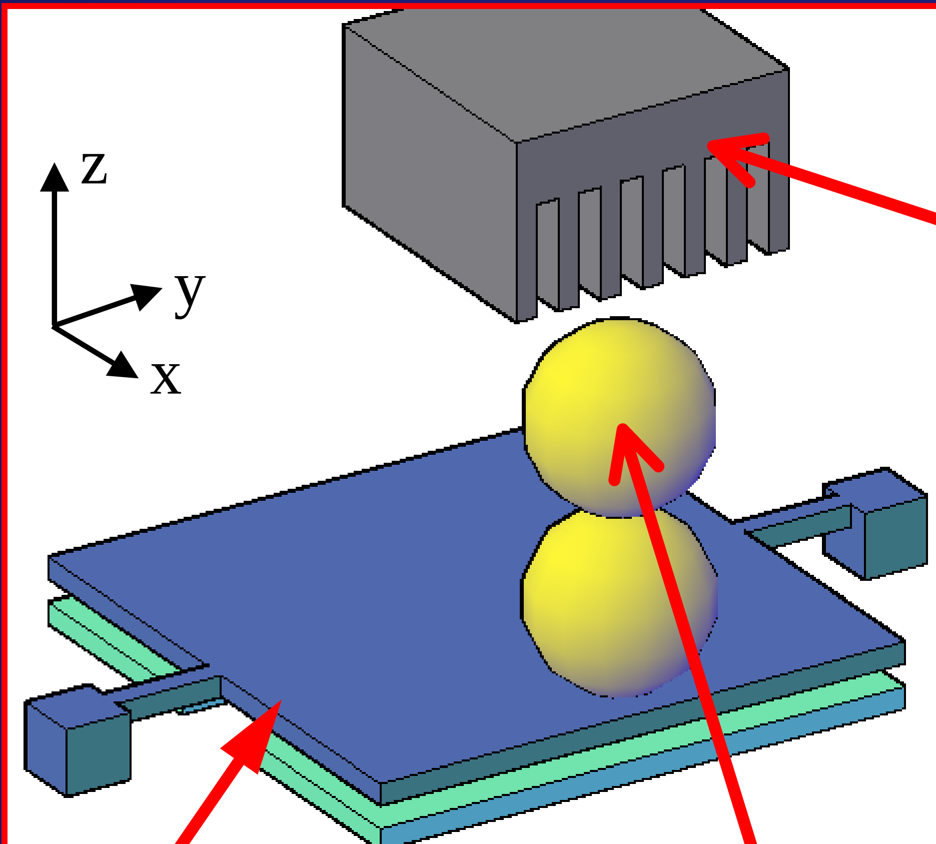
histogram of pixel brightness in top view

average from 10 pictures

Depth = 1.07 um



Experiment setup



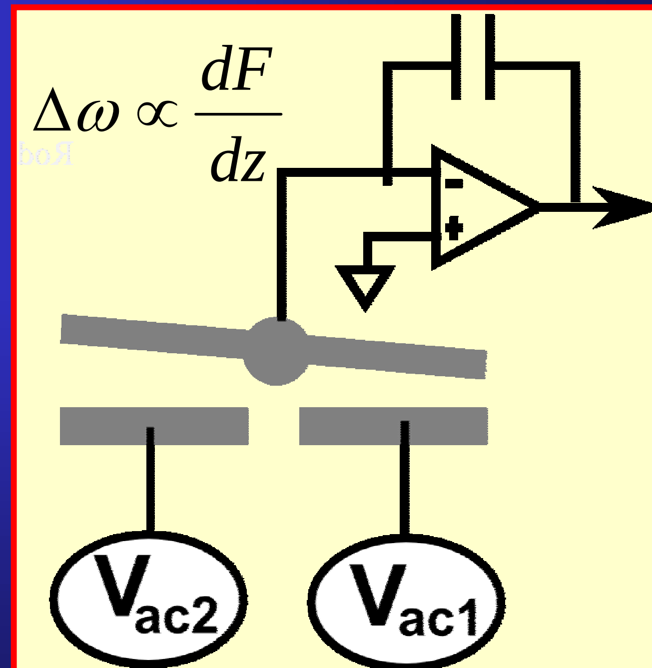
Sample orientation eliminate lateral motion.

Immediately before pump down
HF remove native oxide layer, hydrogen termination of the surface

poly-Si plate:
500 µm x 500 µm x 3.5 µm

Glass sphere: d~100µm

Sputtering: 400nm gold



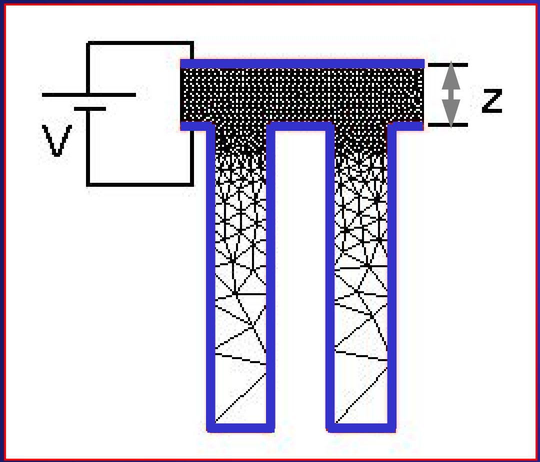
Calibration by electrostatic force

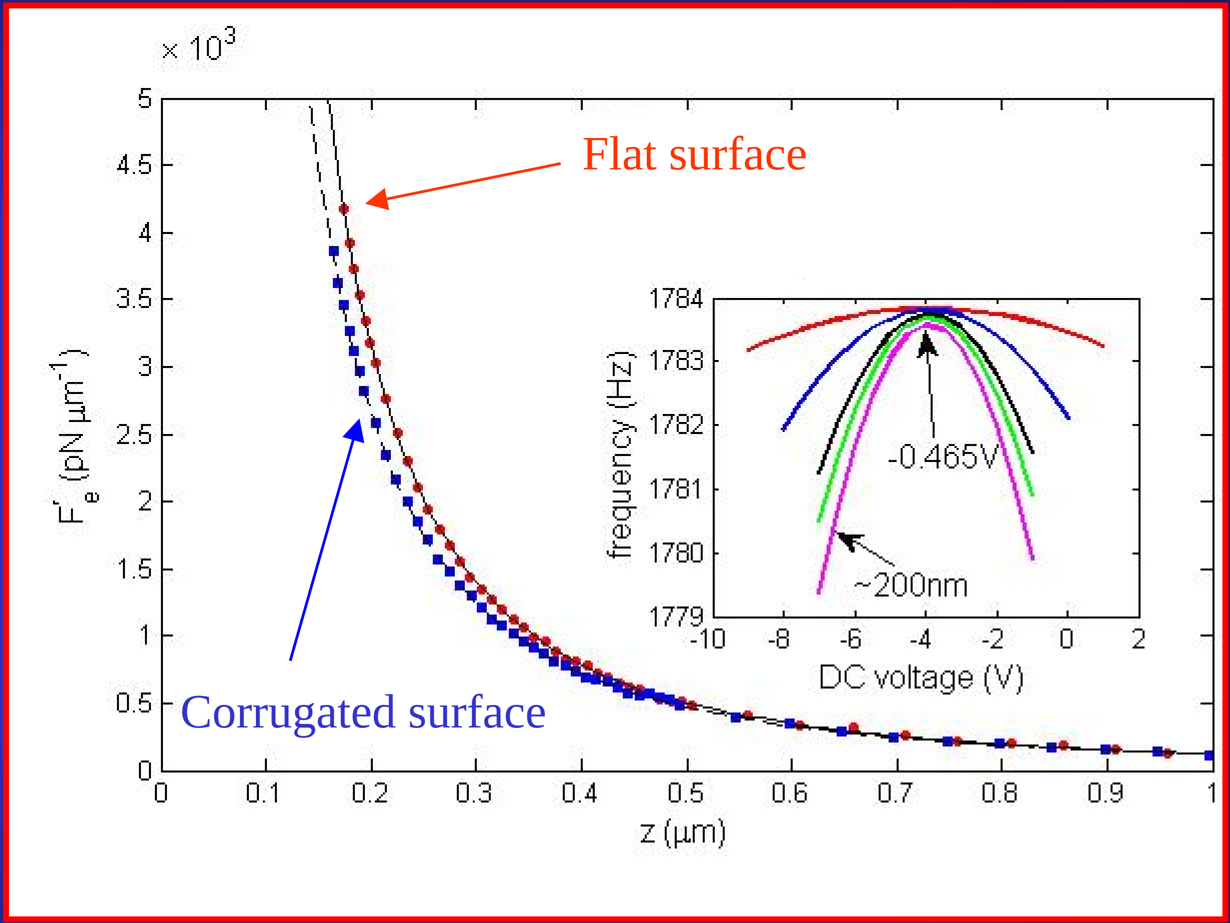
Flat surface

$$F_e' = \varepsilon_0 \pi R \frac{(V - V_0)^2}{(z + z_0)^2}$$

V_0: residual voltage
z_0: closest approach distance

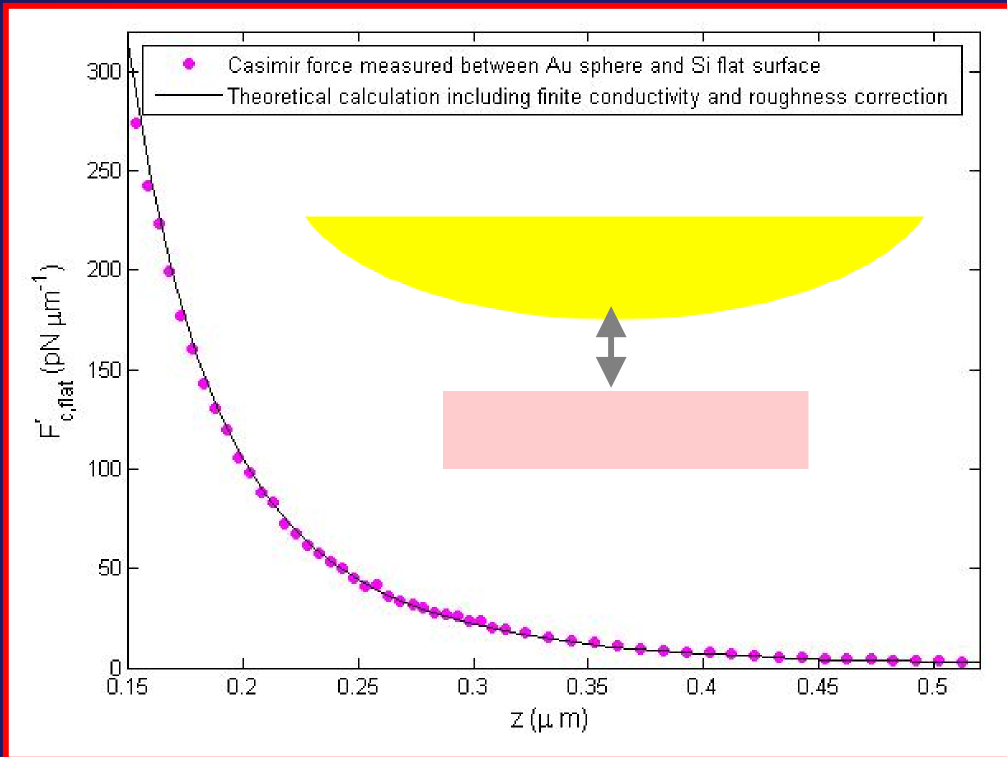
Corrugated surface



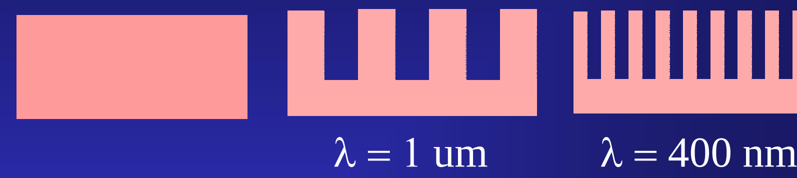


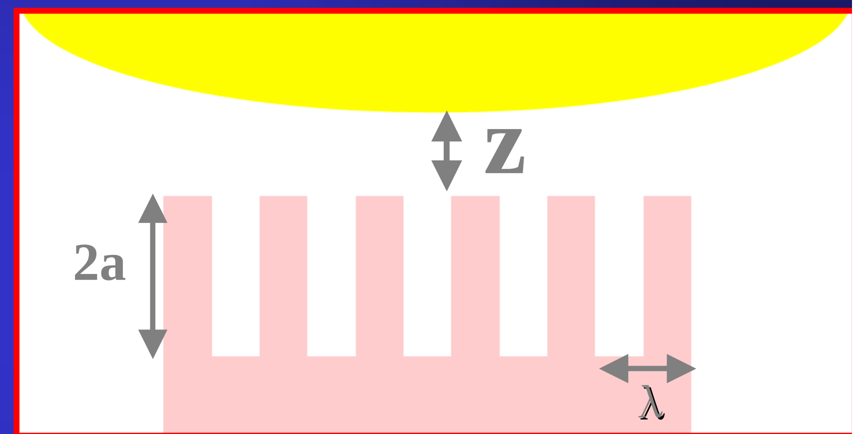
- Finite element analysis to solve 2D Poisson equation: N >10 000 triangles
- Proximity force approximation: $F_{sphere\text{-}conrrugate} = 2\pi R E_{flat\text{-}corrugate}$
- Check convergence: double N changes force by 0.1%

Casimir force measurements



3 samples made from the same silicon wafer





Pairwise additivity: $F_{c,trench} = \frac{1}{2} F_{c,\,flat}$

For all λ

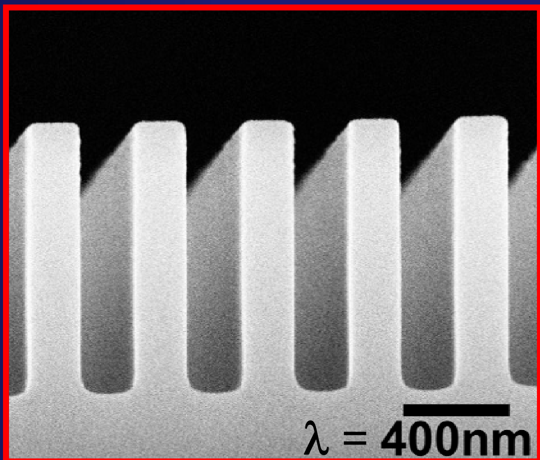
For solid fraction p: $F_{c,trench} = pF_{c,\,flat}$

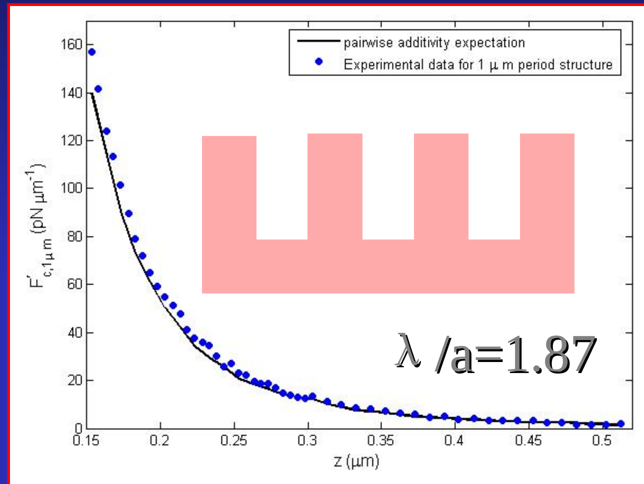
For all material

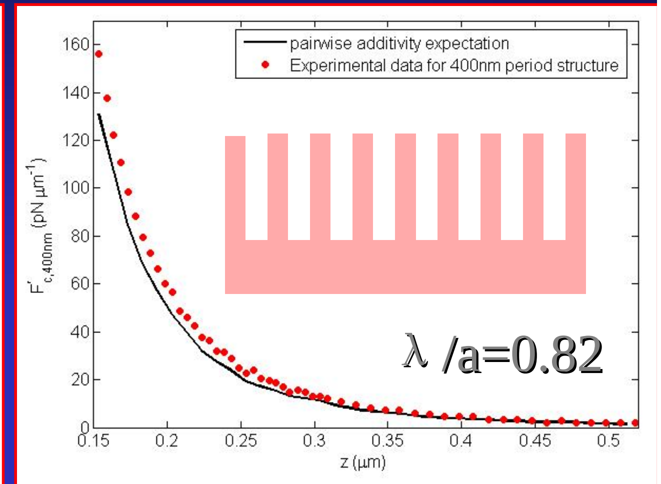
Any deviation of measured force on corrugation from $pF_{c,\ flat}$

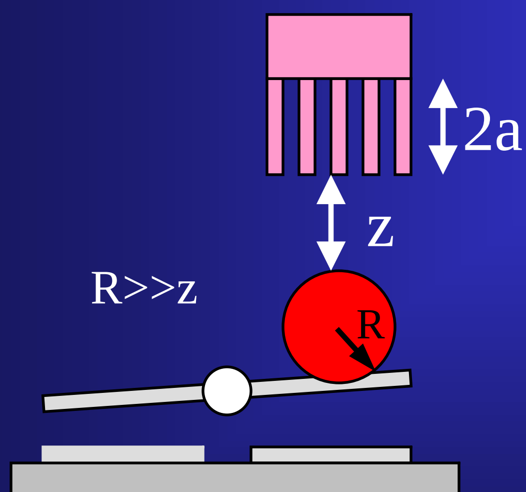
➔ deviation from pairwise additivity (dependence of Casimir force on geometry)

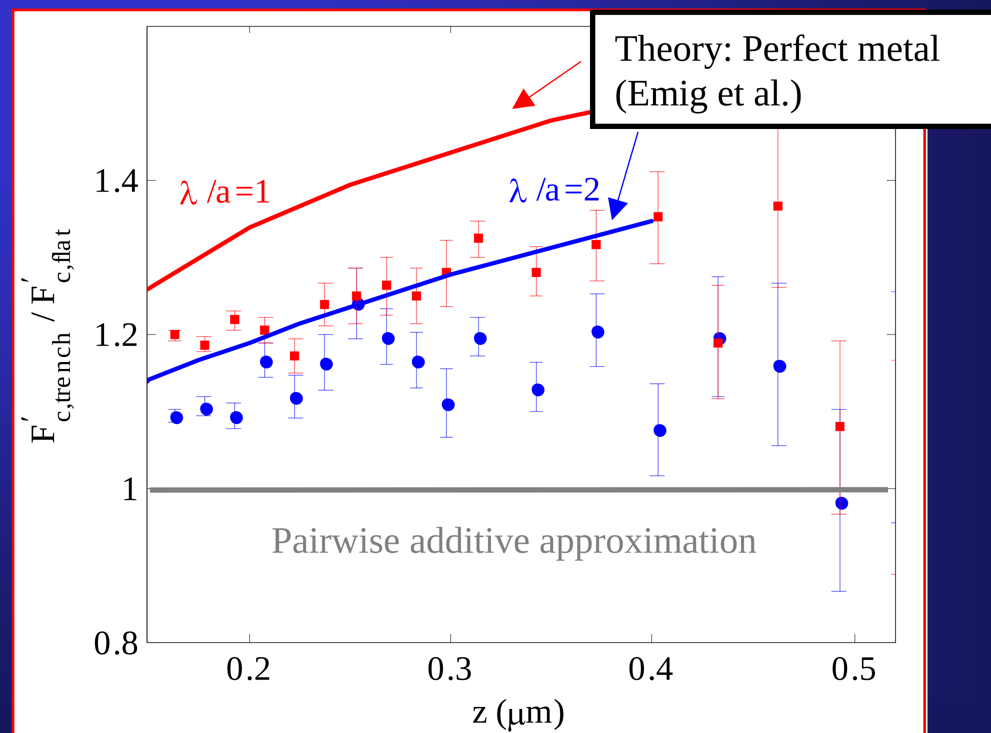
Non-trivial boundary dependence of the Casimir force





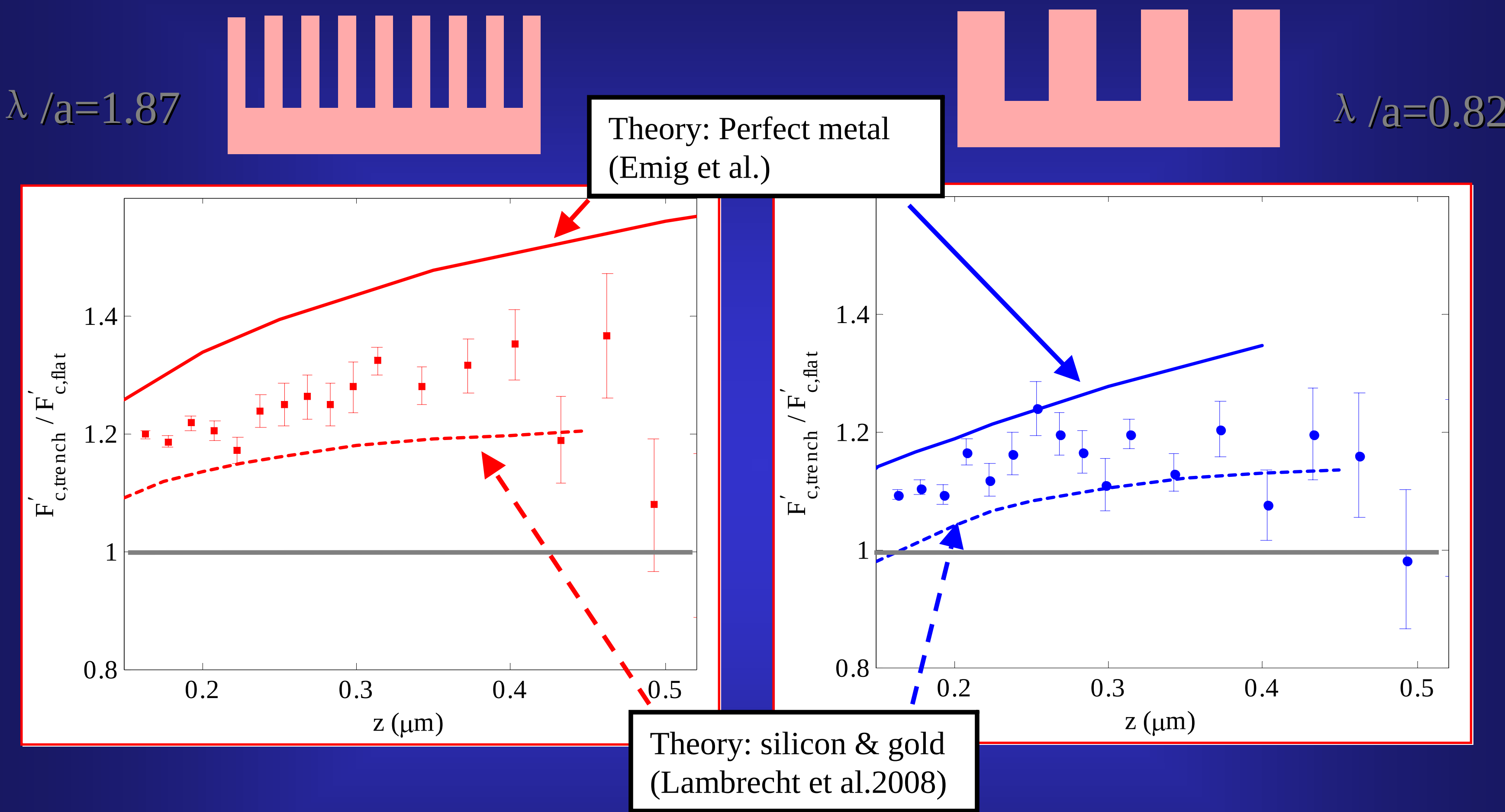






Chan et al., PRL 101, 030401 (2008).

Interplay of finite conductivity and geometry effects



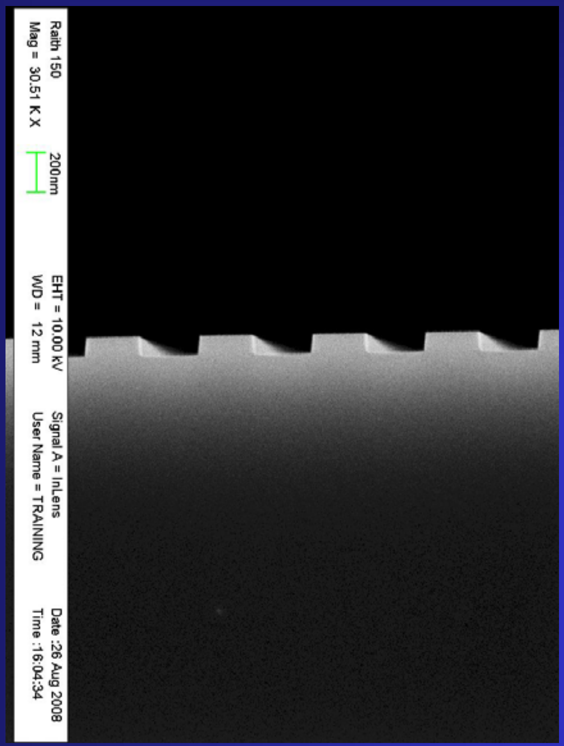
Lambrecht & Marachevsky 2008: includes both finite conductivity and geometry effects.

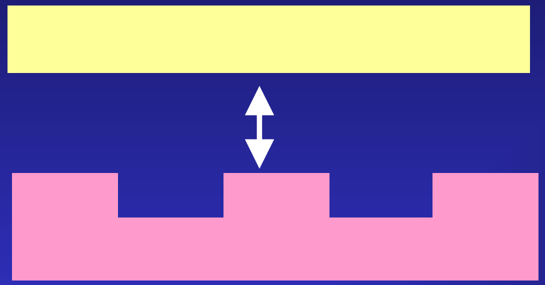
Using reflection coefficients and argument principle

Possible reason for discrepancy:

uncertainties in the optical properties of gold and silicon

In progress: shallow trench arrays

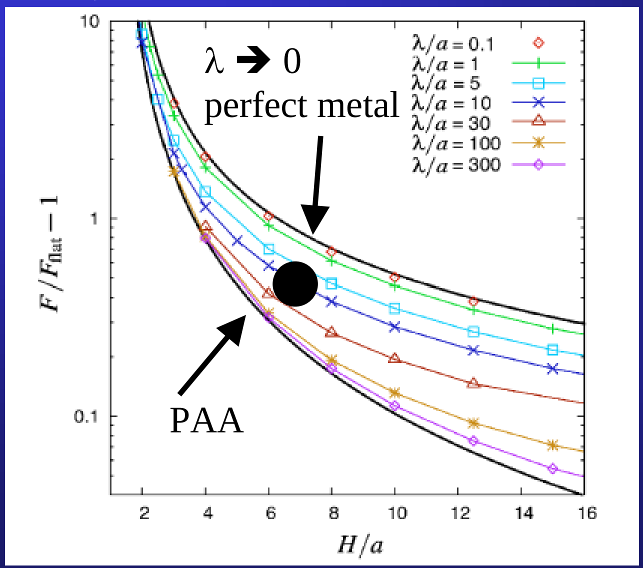




Contribution of bottom surface not negligible

Easier for comparison to theory (perturbative approaches)

Deep trench experiment (λ /a = 0.8 , H/a ~ 1)



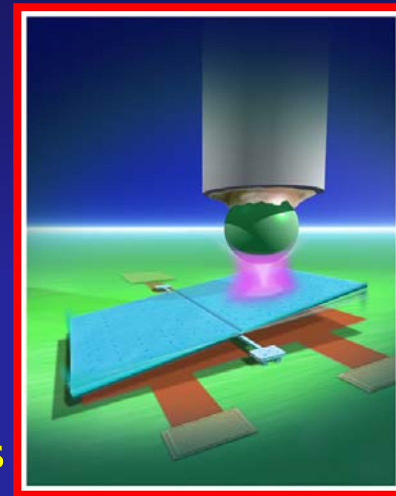
Buscher & Emig, PRA **69**, 062101 (2004).

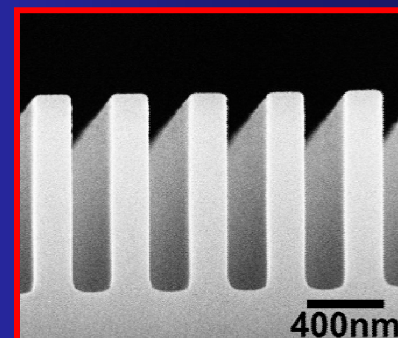
Summary

- Micromechanical torsional oscillator for measuring the Casimir force.
- nonlinear Casimir micromechanical oscillator.
- Geometry dependence of the Casimir force:
- Experiment on strongly deformed surface: array of nanoscale trenches

  Up to 30% deviation from pairwise additive approximation

  A factor of 2 smaller than theory on perfect metals





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