Measurement of the Casimir interaction between a Au sphere and Au gratings

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Sandia National Laboratories

Pan-American Advanced Studies Institute
In
Frontier in Casimir Physics

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Organizers:
R. S. Decca, D. Dalvit, R. Ezquivel-Sirvent,
Paulo Maia Neto, Diego Mazitelli, Hernán Pastoriza

Effects of geometry

Plate-plate measurements

-Most measurements done between a (large) sphere and a plate.

-Work between parallel plates and cylinder and a plate proved to be to difficult.

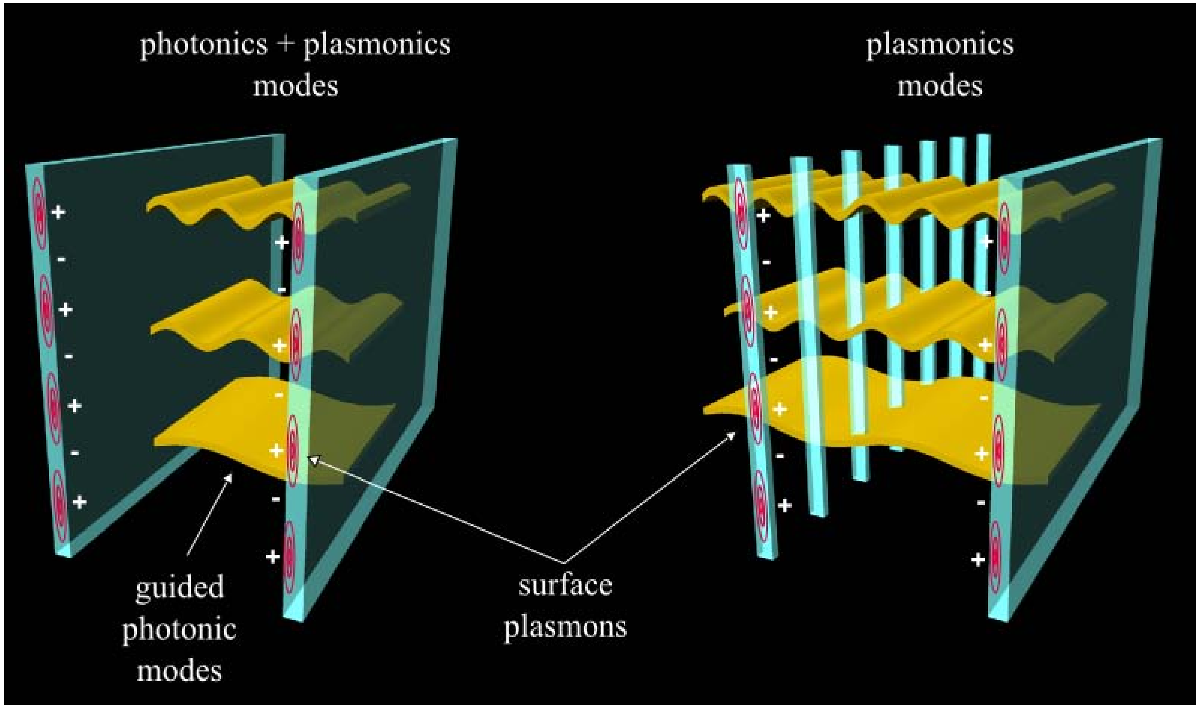
Replacing one of the plates

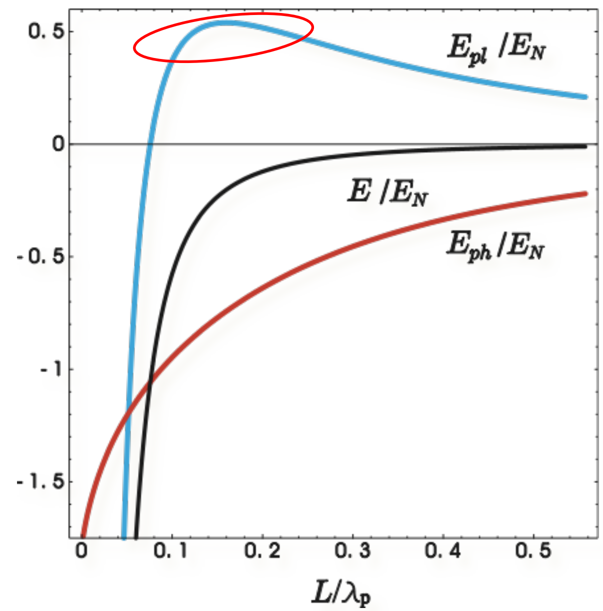
-Work by U. Mohideen and coworkers on corrugate surfaces

-Work by H-B. Chan and coworkers in Si gratings

Our approach

By modifying surface geometry at the scales of the order of plasma wavelength (~ 100nm) we will be able to alter the ratio of *plasmonic* vs. *photonic* contribution to the Casimir force, thus exerting control over its magnitude, including the possibility of nullifying and even reversing it.





$$E = \underbrace{\sum_{\mathbf{k}} \frac{\hbar}{2} \left[\omega_+ + \omega_-\right]_{L\to\infty}^{L}}_{\text{Plasmonic contribution } (E_{pl})} + \underbrace{\sum_{p,\mathbf{k}} \frac{\hbar}{2} \left[\sum_m \omega_m^p\right]_{L\to\infty}^{L}}_{\text{Photonic contribution } (E_{ph})}$$

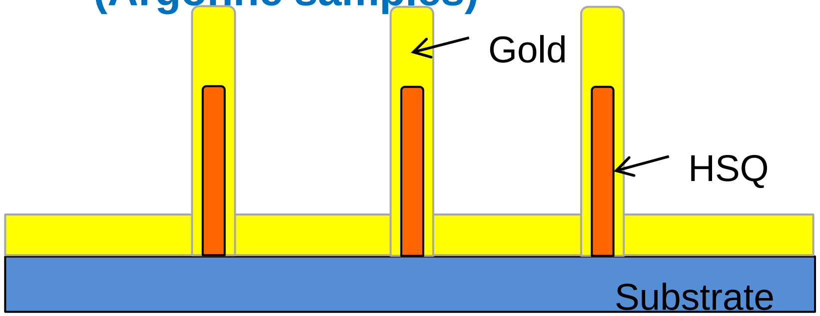
F. I. and A. Lambrecht, Phys. Rev. Lett. **94**, 110404 (2005).
F. I., C. Henkel and A. Lambrecht. Phys. Rev. *A* **76**, 033820 (2007).

Can we control the Casimir force by changing the balance of the two contributions?

Nanostructured surfaces

- Metallic surfaces
- High aspect ratio (5:1)
- Typical dimensions
  - width: 100nm
  - height: 500nm
- Roughness control
- Optical characterization

HSQ as a Structural Material (Argonne samples)

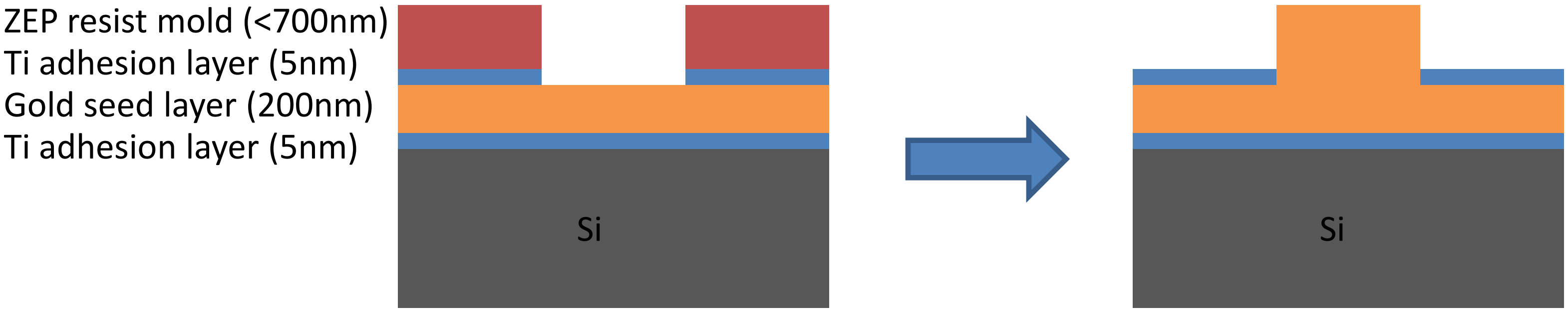


Inorganic negative tone e-beam resist

Minimum feature size: ~6nm

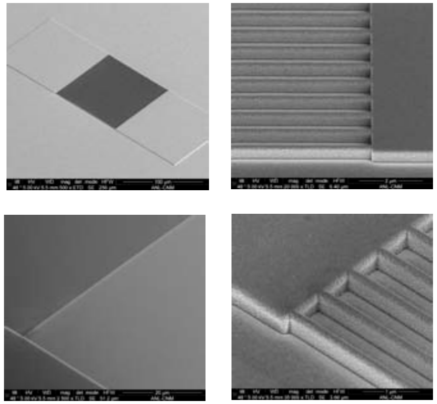
High aspect ratio lithography: ~10:1 (380nm tall, 40nm wide)

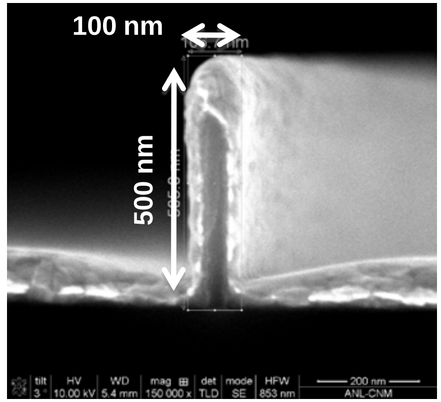
Electroplating process (NIST samples)



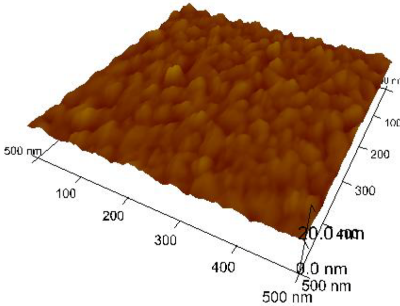
Nanostructured surfaces

HSQ as a Structural Material





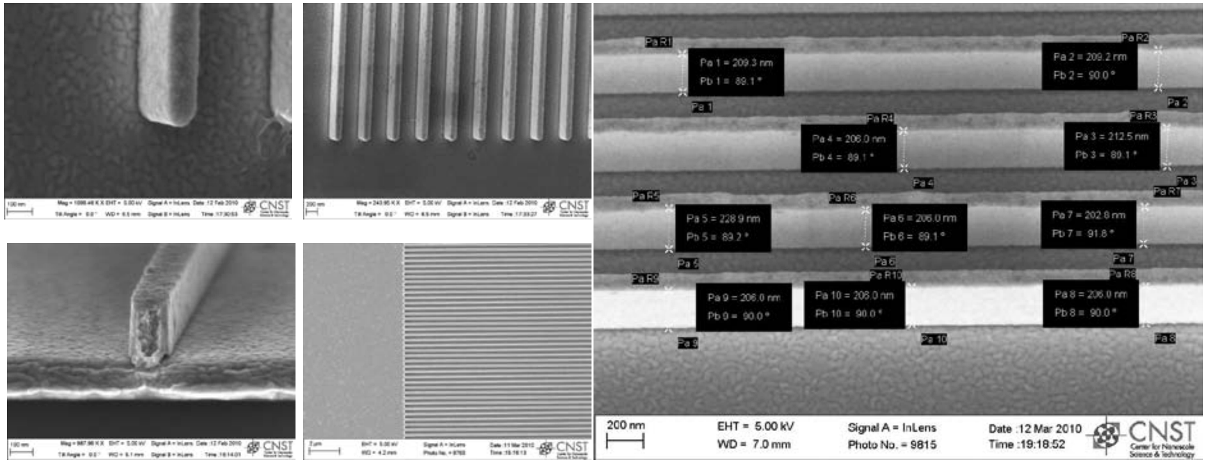
Surface roughness
R_q ~ 1.09 nm

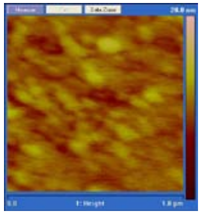


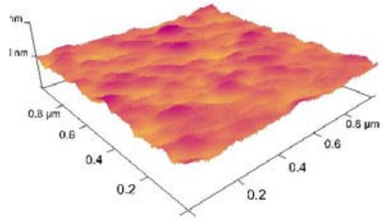
Sputtered gold deposition (Kurt Lesker PVD Sputter/E-beam)
120nm Au / 20nm Ti (~130nm actual thickness)

Gold deposition conformality: ~0.25
Surface thickness: ~130nm
Side coating thickness: ~30nm

Electroplating process

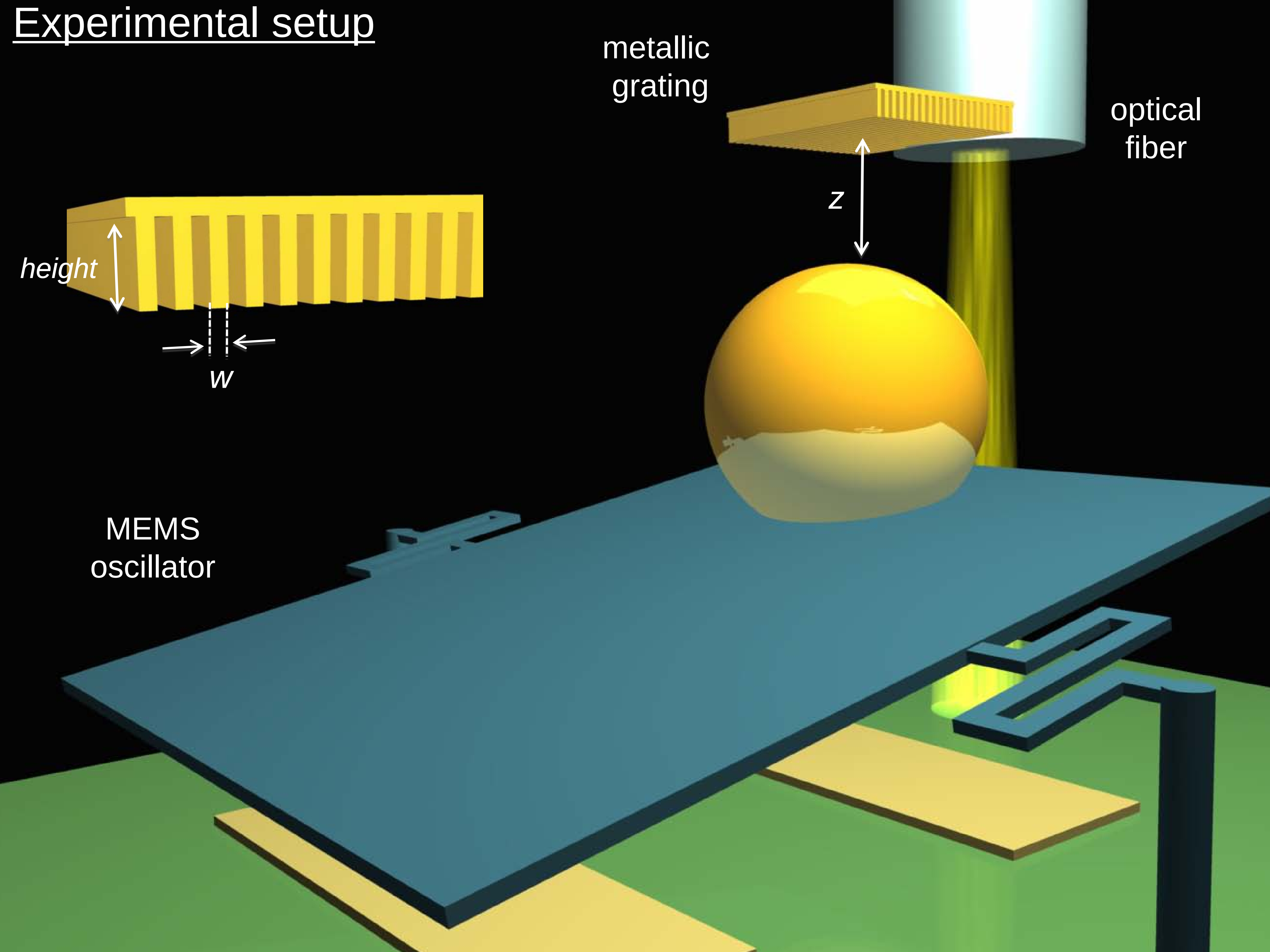






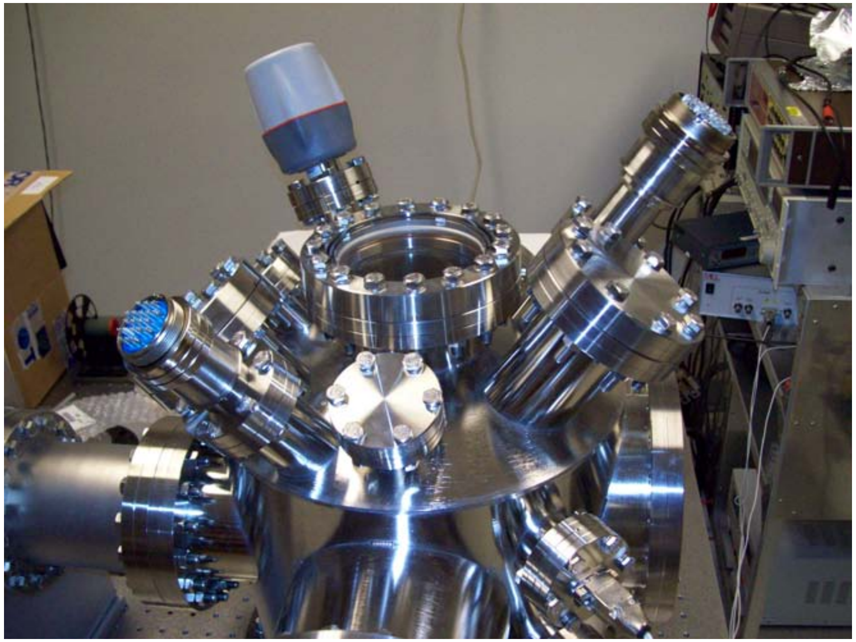
Surface roughness
R_q ~ 1.2 nm

Experimental setup



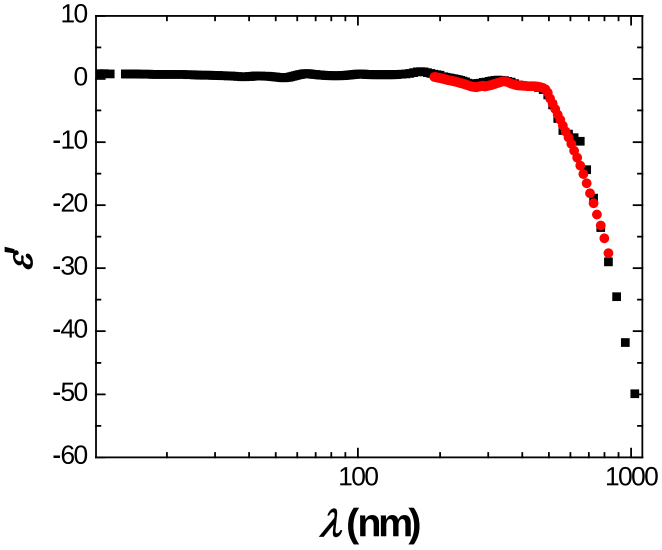
Experimental setup

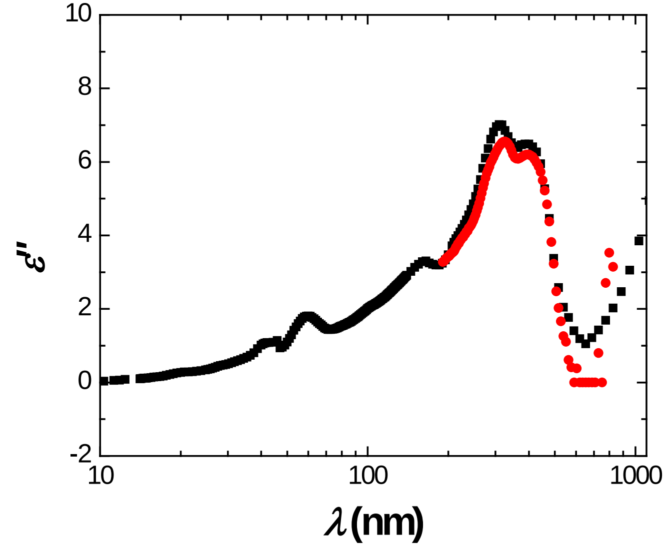
- 5 axis (*xyz*, rock and tilt) stepper motor drive
- 3 axis (*xyz*) closed loop 70 micron range piezo stage
- Two color interferometer integrated into the system for continuous absolute position measurement
- Total position stability control better than 0.2 nm



- New experimental system.
- Base pressure: ~ $1x10^{-7}$ Torr
- Mounted in an active damping control air table
- Passive magnetic damping on floating system

Optical data

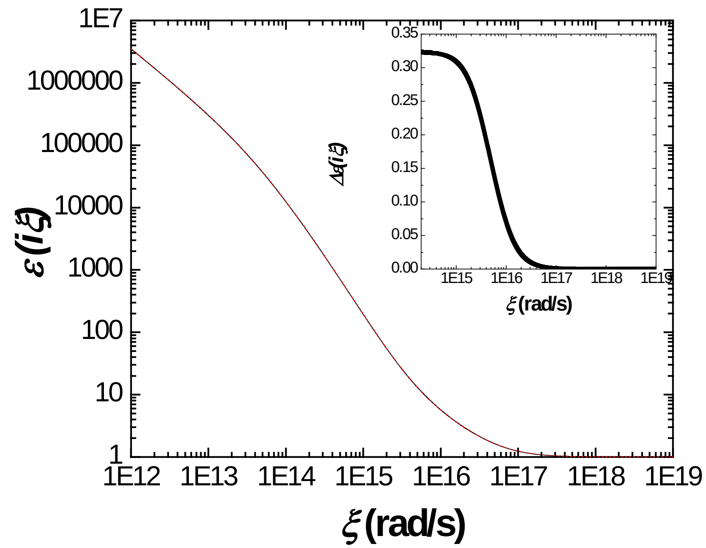




-Measured real and imaginary parts of the dielectric functions (red circles) are similar to published values (Palik, black squares)

-It was checked that either can be used to calculate the Casimir interaction *via* Lifshitz expression. Palik values are used on the rest of this presentation.

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



Electrostatic calibration

- Used to provide a calibration for the elastic constant of the MEMS
- Also used to obtain the separation between the sphere and the sample at one position (δz ~ 2 nm)

Sphere-plane configuration

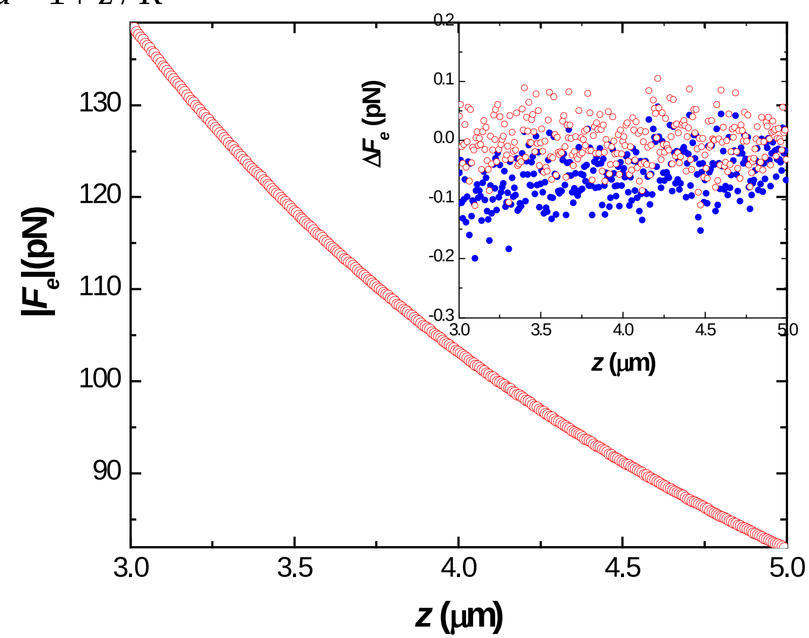
- Analytical expression for the force (and its derivative) between a sphere and an infinite plate

$$F_e(z,V) = -2\pi\varepsilon_o (V_b - V_o)^2 \sum_{n=1}^{\infty} \frac{\coth(u) - n\coth(nu)}{\sinh(nu)}$$

$$\cong \Xi(z)(V_b - V_o)^2;$$

$$\Xi(z_{metal}) = -2\pi\varepsilon_o \sum_{m=0}^{7} B_m t^{m-1}$$

$$u = 1 + z/R$$

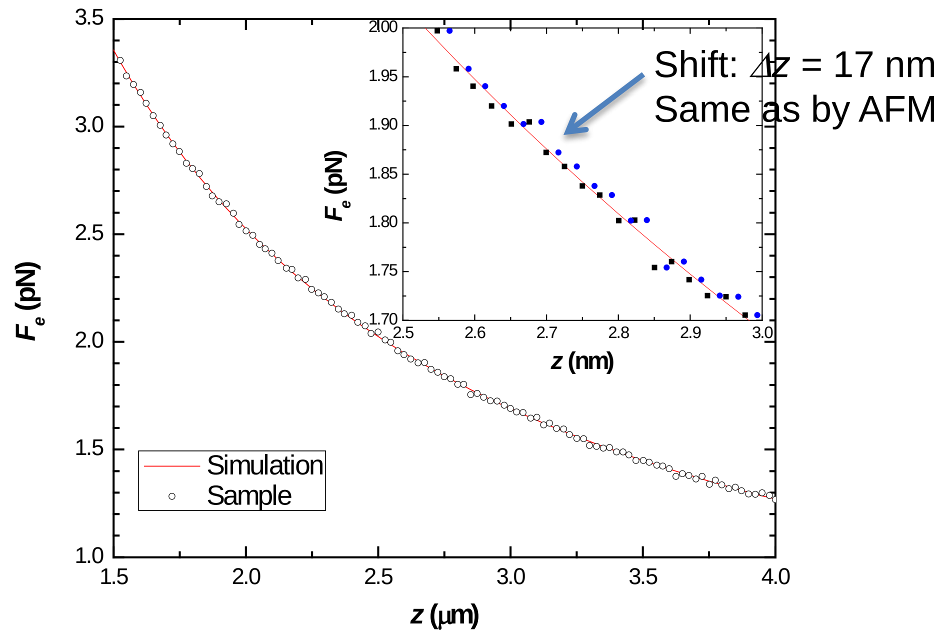


Sphere-grating configuration

- Finite elements simulation to obtain the capacitance between an infinite plane and a 1D periodic grating

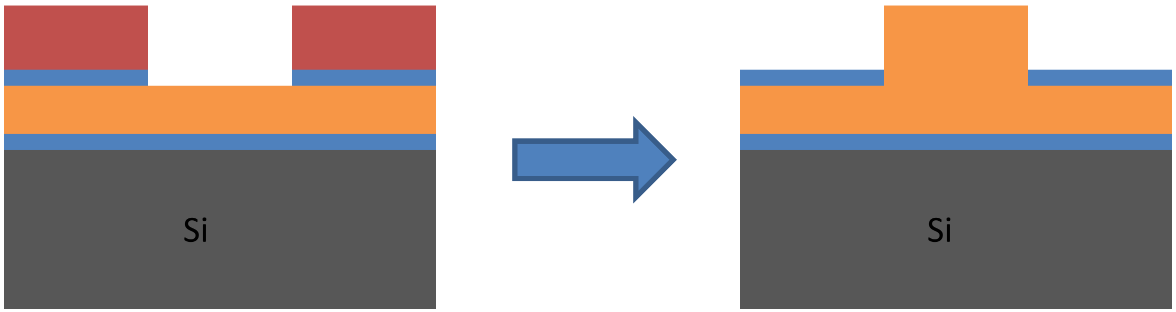
- PFA yields the electrostatic force between the Au-coated sphere and the Au-grating:

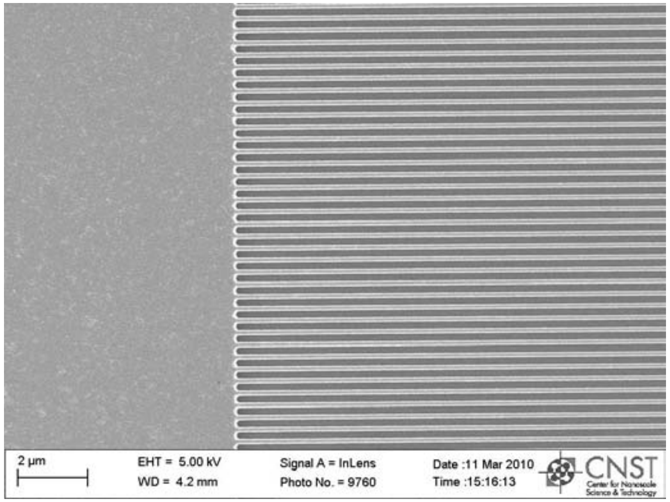
$$F_{SG} = -\frac{1}{2\pi R} E_{PG} = -\frac{1}{4\pi R} C_{PG} (V_b - V_o)^2$$

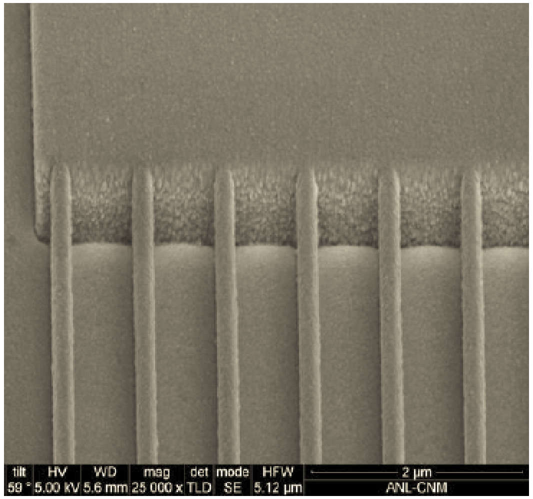


Electrostatic calibration

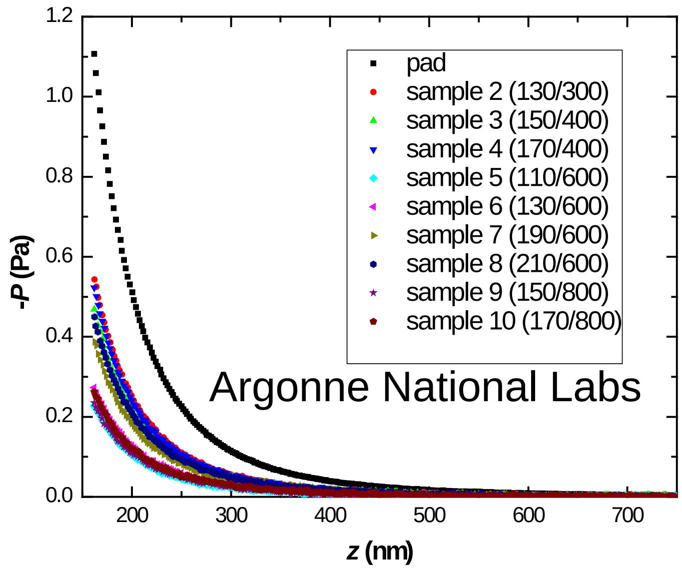
Electroplating process (NIST samples)

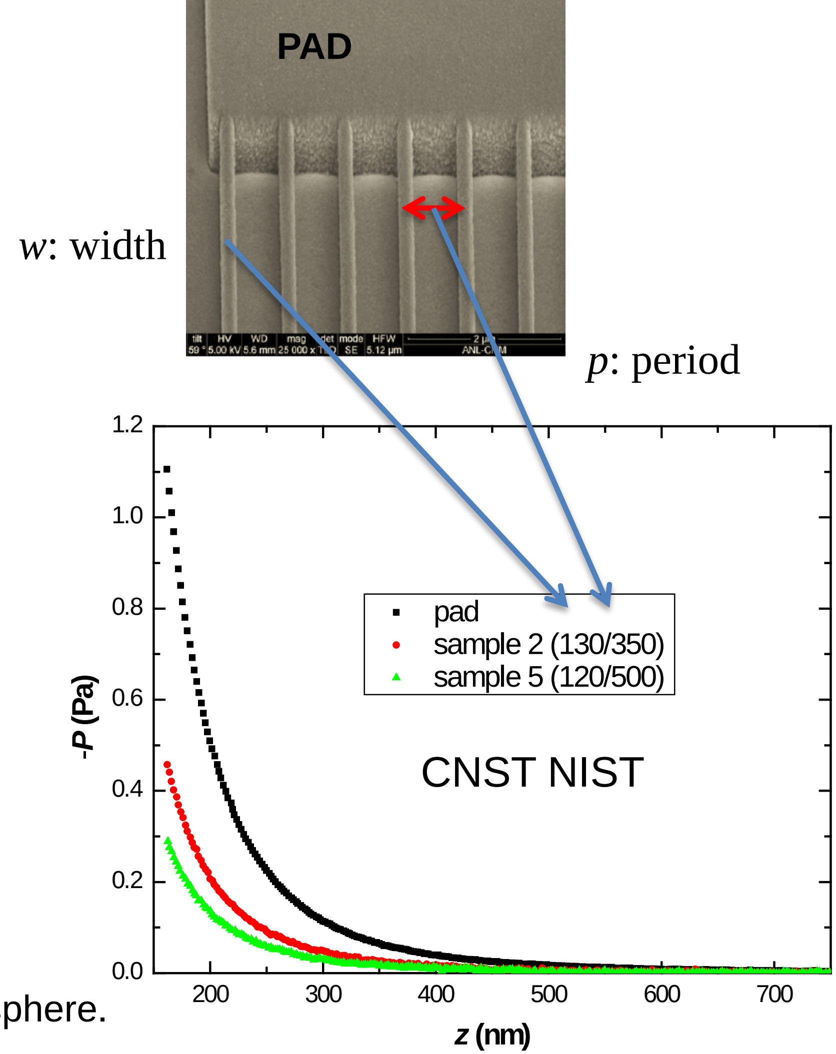






Casimir interaction





All ANL samples have h =480 nm.
All NIST samples have h = 380 nm

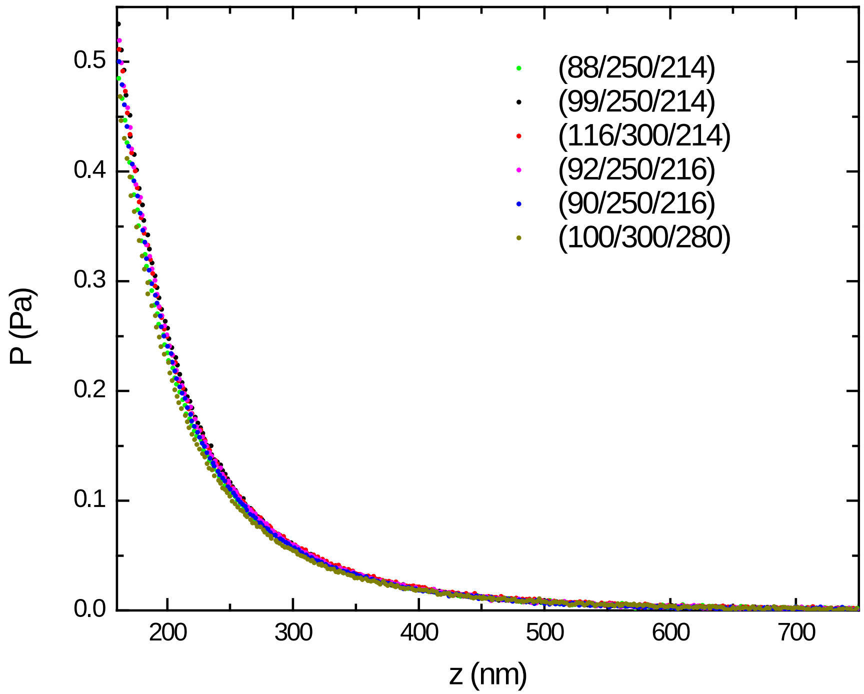
- All samples were measured using the same *R* = 151.7 µm sphere.

- -*P* (attractive) is obtained as $P = -\frac{1}{2\pi R}\frac{\partial F_C}{\partial z}$. δP = 10 mPa/(Hz)$^{0.5}$

- Samples have a range of *w*, *p* and *f* = *w*/*p*

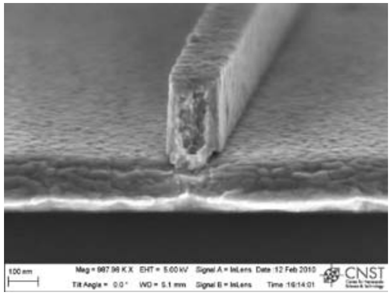
- Clear decrease in the measured interaction as filling factor *f* decreases

Casimir interaction

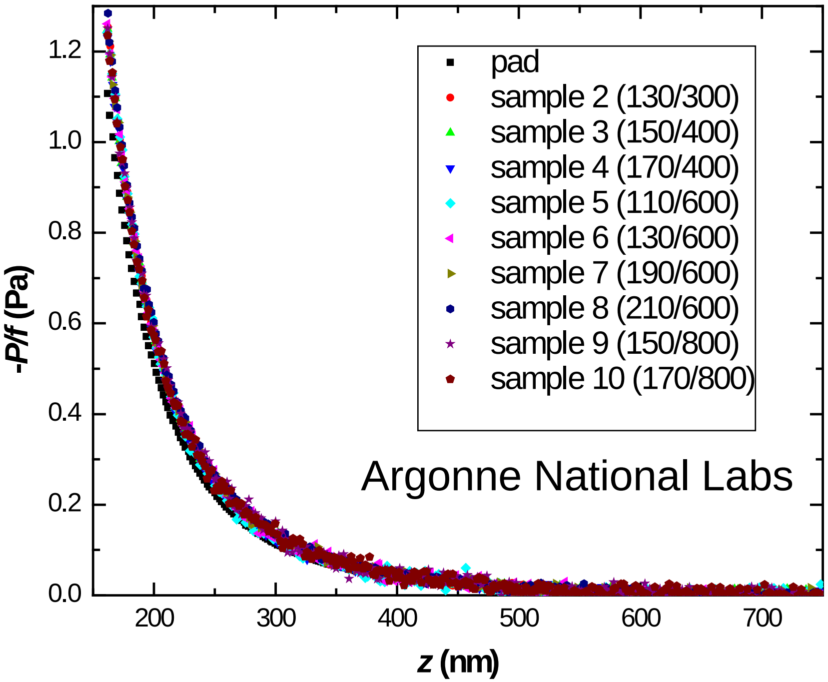


CNST NIST samples

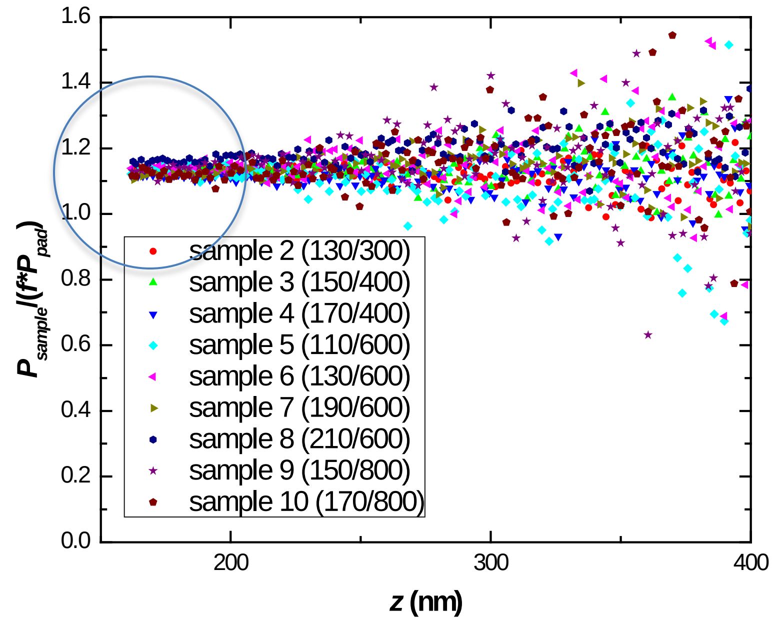
All samples here have $f = w/p \sim 0.38$



Casimir interaction



Most of the observed quantitative effect in the reduction of the Casimir interaction is geometric in origin.

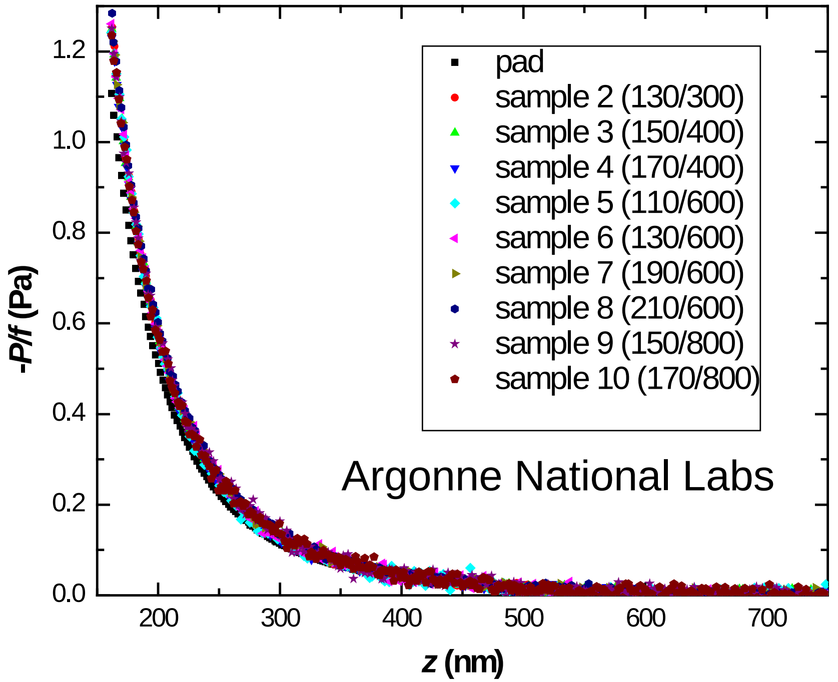


- There is a remarkable agreement among all measurements done on the sphere-plane configuration over a wide range of *f*. (*f* has been changed from 0.18 to 0.43)

Some non-trivial effects…

-The main effect of the grating is also very similar between the samples made by both groups

Casimir interaction



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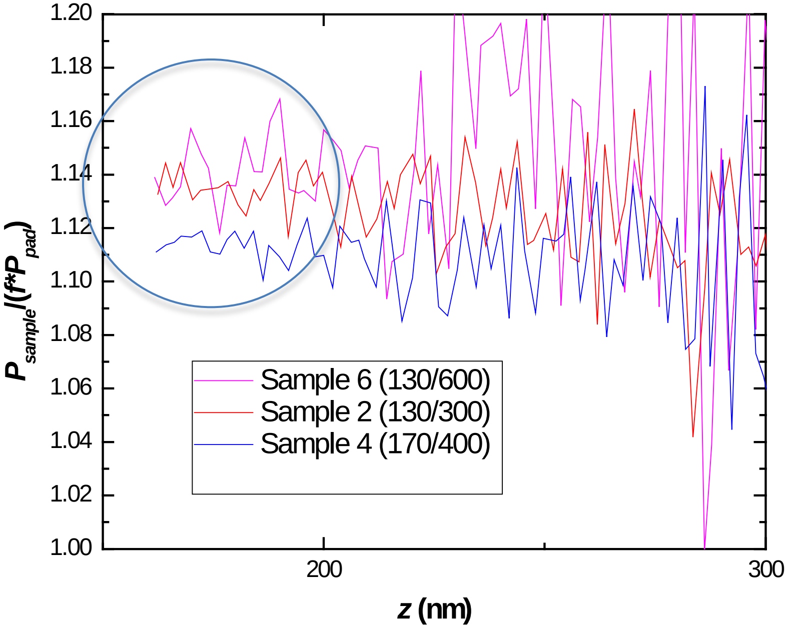

<u>Short separations</u>

Interaction per unit area between the gratings and the sphere is *more attractive* than the corresponding one between a sphere and an uniform pad.

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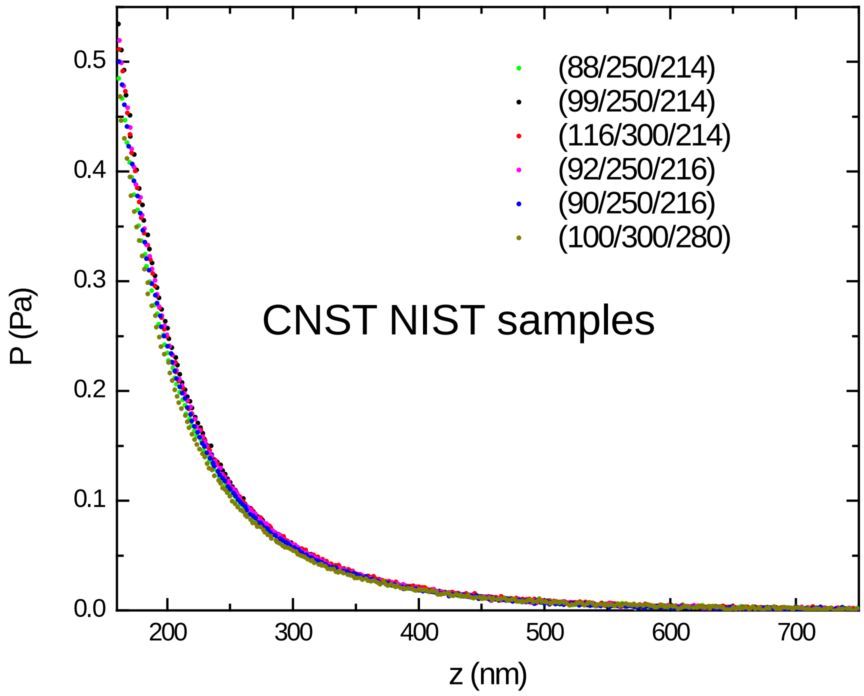
Casimir interaction



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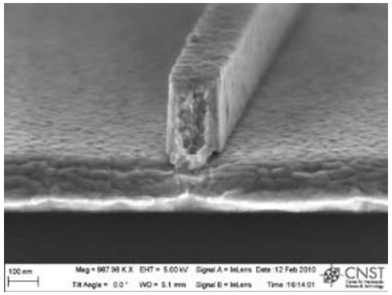
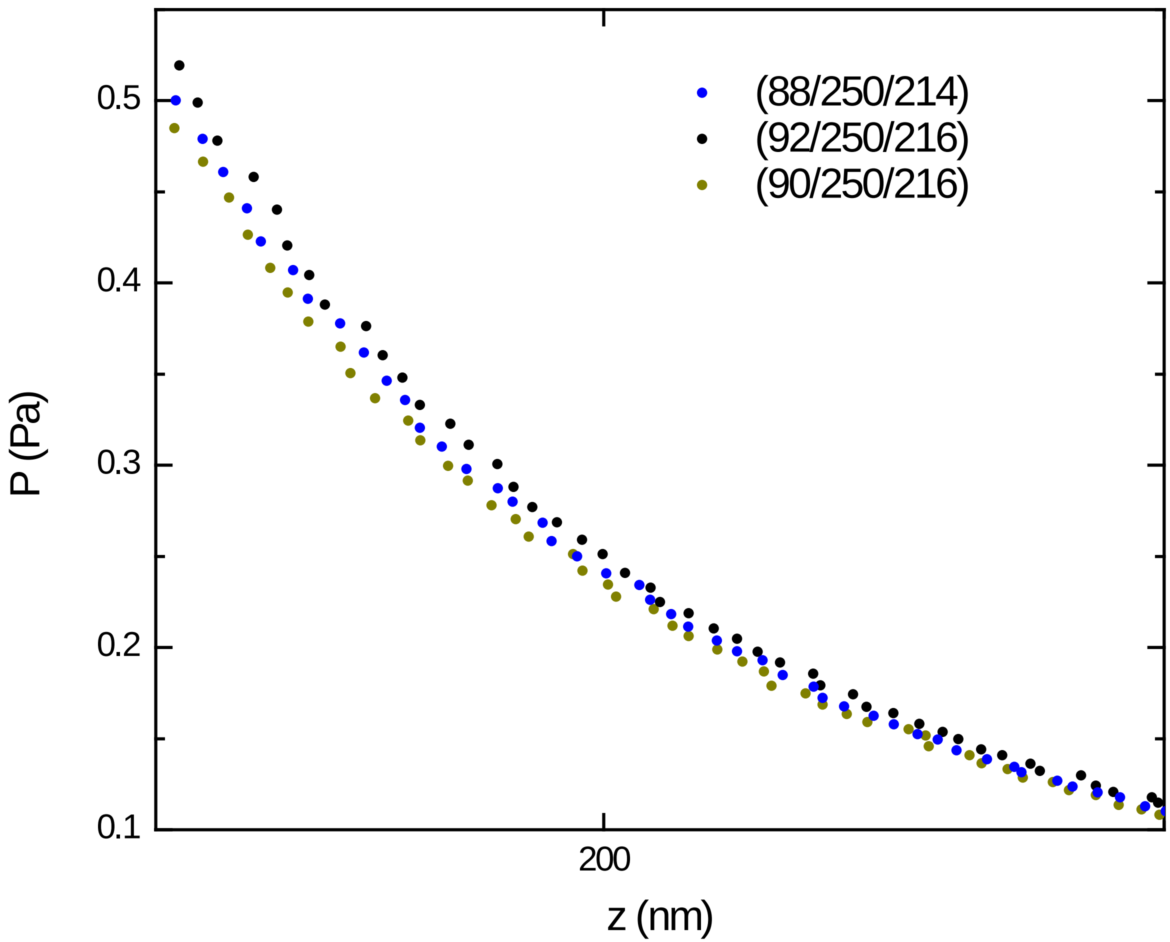
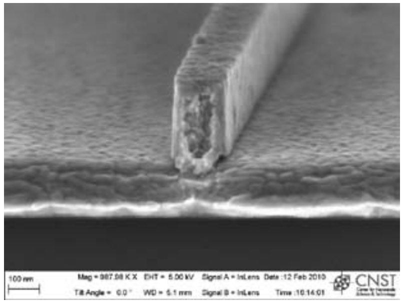


Let's take a look into a couple of facts…

Casimir interaction

First, the casimir interaction appears to be very sensitive to the width of the teeth of the structured surfaces





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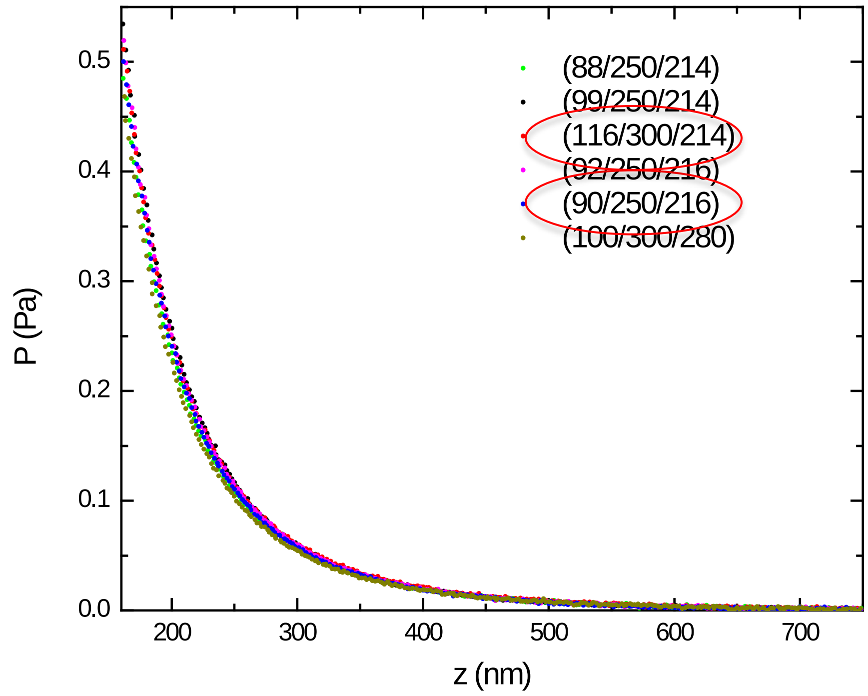
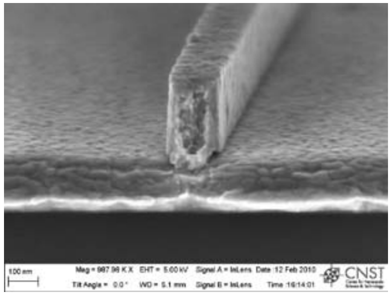
Casimir interaction



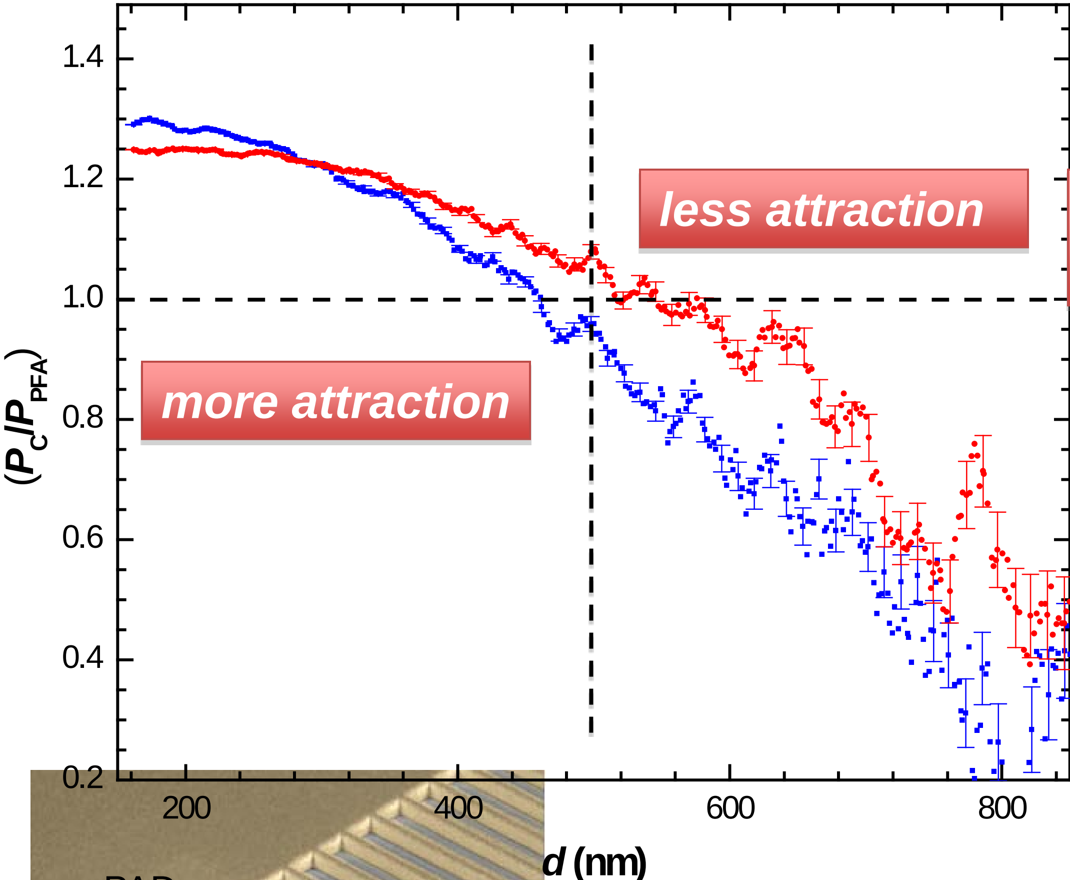
CNST NIST samples

All samples have $f = w/p = 0.38$

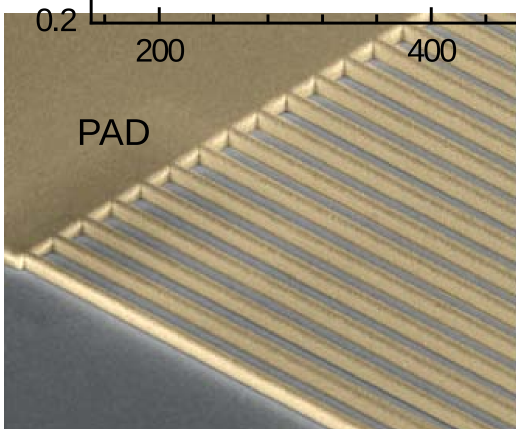


Second, we will concentrate in two samples

Casimir interaction



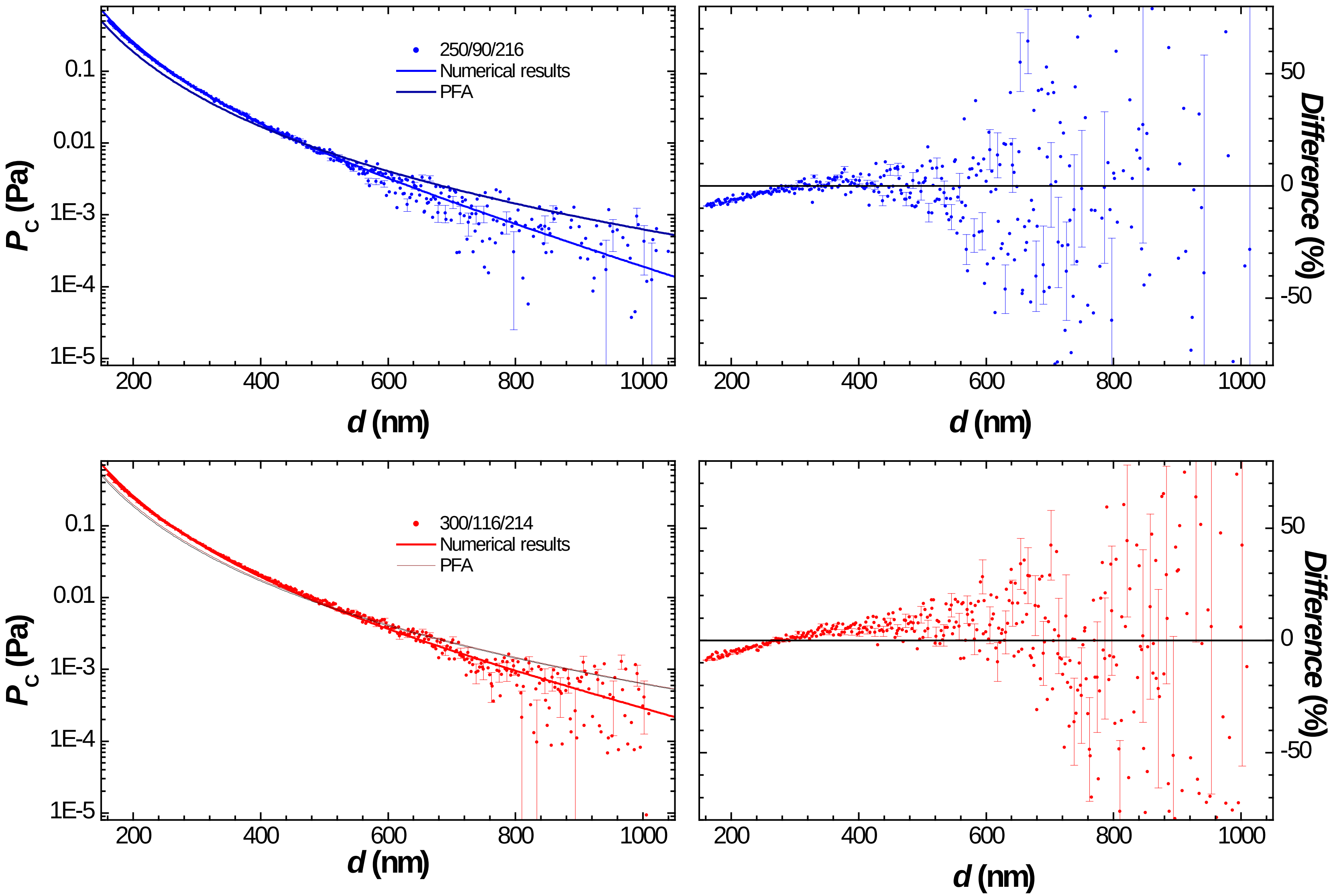
Decay faster than z^{-4}



These results have been obser

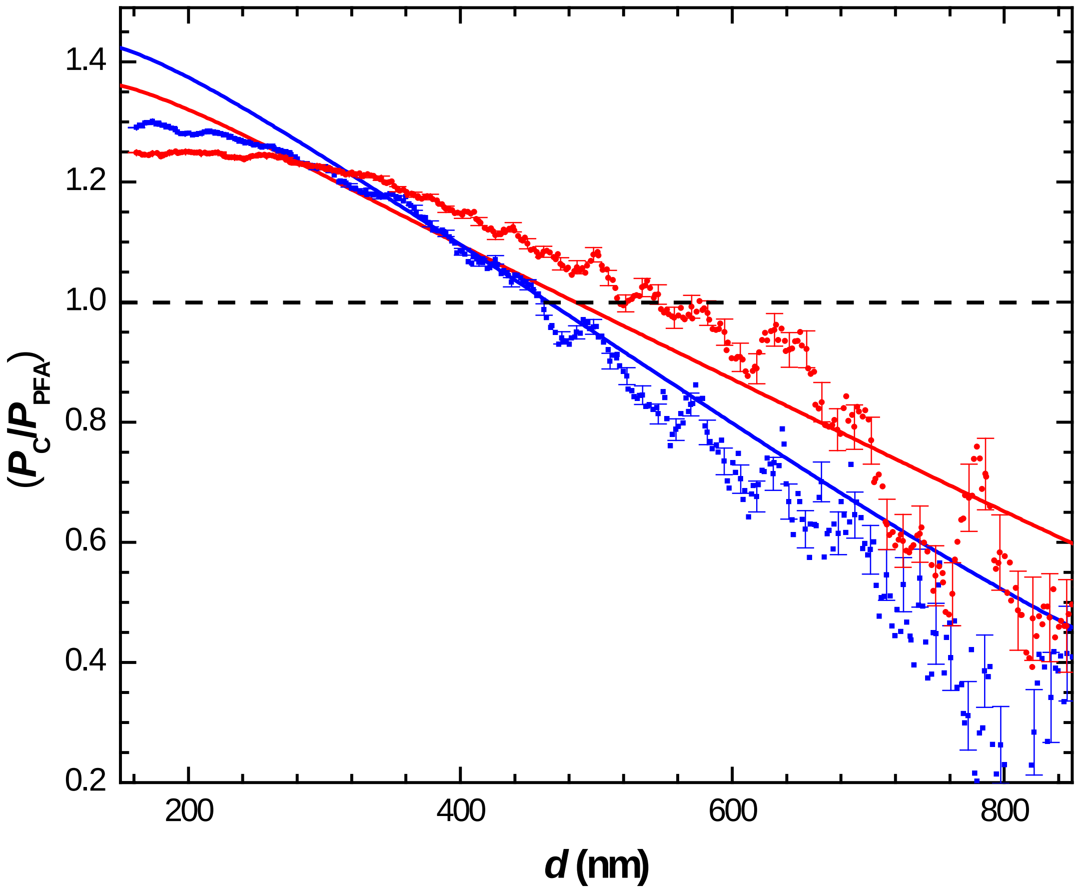
$$P_{PFA}(z) = f \times P_{Pad}(z) + (1 - f) \times P_{Pad}(z + 380\text{nm})$$

Casimir interaction



$$Difference\% = 100 \times \left(P_{\exp} - P_{calc} / P_{calc}\right)$$

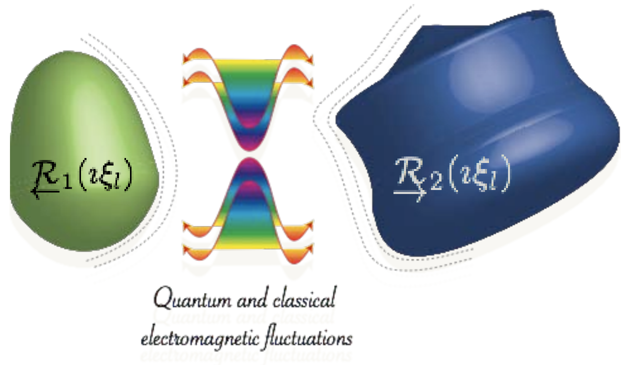
Casimir interaction



Theoretical results predict an exponential decay at large separations (up to a few microns)

(Calculations done using Drude model for Au)

Casimir Free Energy and Scattering formula



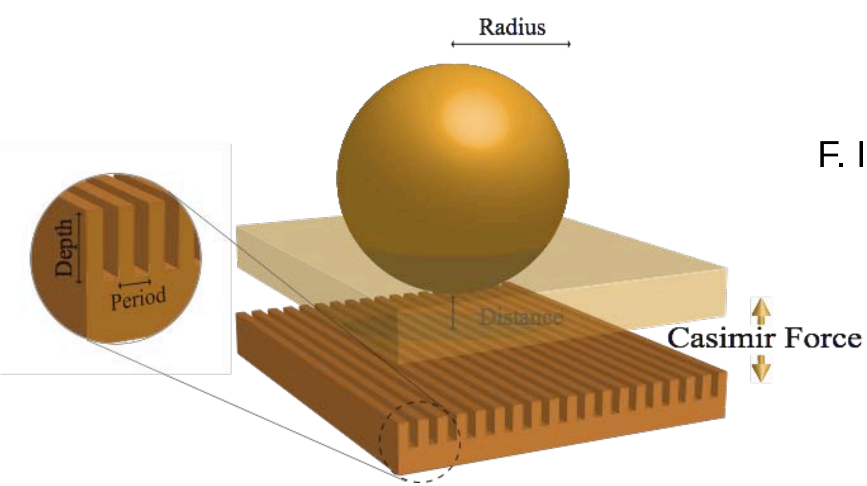
The scattering formula allows to calculate the free energy between two bodies (the Casimir energy) if we know the reflection operator of each isolated object.

$$\mathcal{F}(a) = \frac{1}{\beta}\sum_{l=0}^{\infty}{}' \log\det\left[1 - \mathcal{R}_1(i\xi_l)\cdot \mathcal{X}(a,i\xi_l)\cdot \mathcal{R}_2(i\xi_l)\cdot \mathcal{X}(a,i\xi_l)\right]$$

Reflection operators — Translation operators

The translation operators carry no information about the objects but their position in space

Rahi et al, PRD 2009
Lambrecht et al, NJP 2006



F. Intravaia will discuss the details of the calculations on Friday

Summary and future work

1- Experimental demonstration of a novel mechanism to reduce the *attractive* Casimir interaction:

- nano structuring surfaces on length scales comparable to the plasma wavelength of the materials (~ 100nm)
- significant and non-trivial near-field interaction (dominated by a single surface grating mode?)

2- Not discussed in the presentation:

- measurements done at larger separations for unstructured surfaces coincide with our previous results: Plasma model appears to provide a better explanation for the experimental data
- data from gratings at small separations could be used to obtain new limits on Yukawa like corrections to the Newtonian gravitational potential