Surface roughness & optical properties influence on the Casimir/vdW force

George Palasantzas

Materials innovation institute (M2i)

university of groningen

Acknowlwdgements

RUG: P. Van Zwol (my student!)

Collaborator→ Vitali Svetovoy (MESA+, NL)

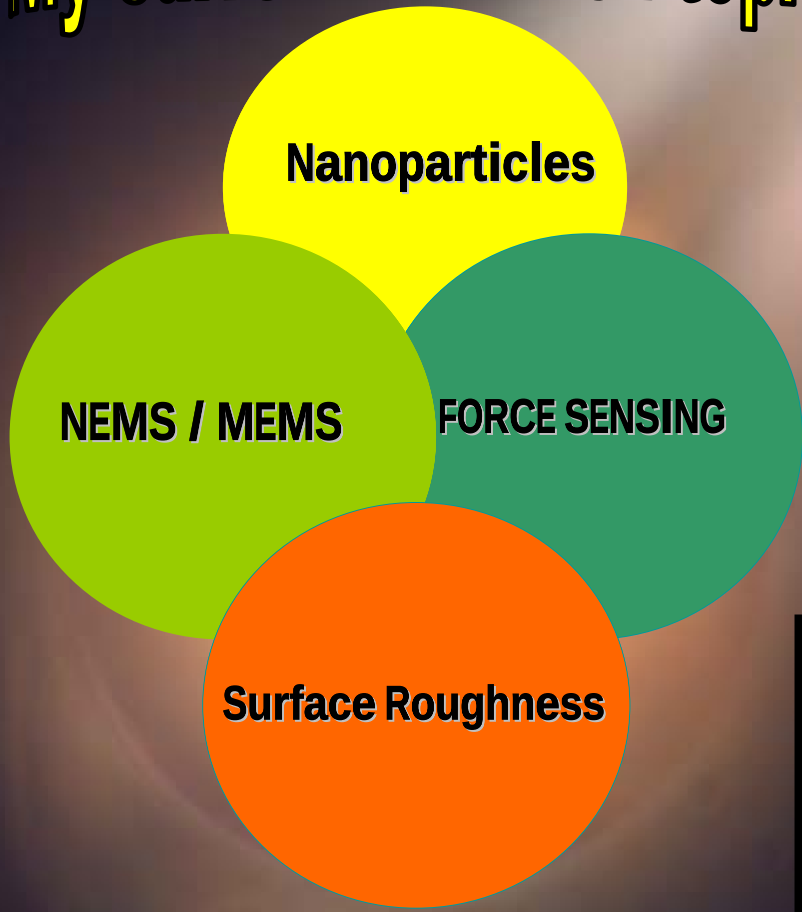
Steve Lamoreaux (Yale, USA)
Astrid Lambrect & Serge Reynaud (France)
R. Onofrio (USA)
Alex Maradudin (Irvine, USA)
D. Iannuzzi (NL)
J. Munday, F. Capasso (USA)

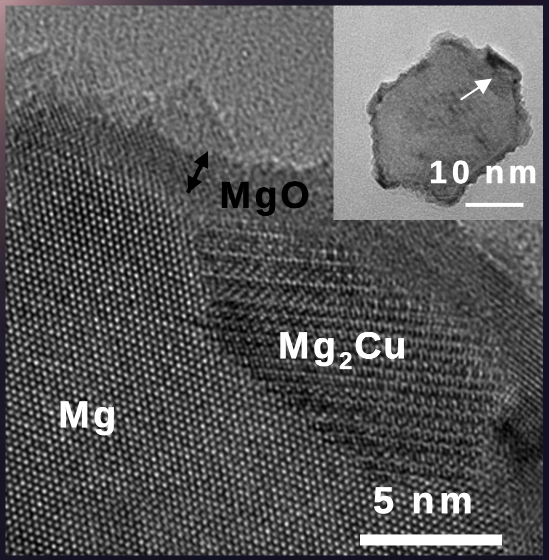
Funding agency→ M2i / TNO

M2i Materials innovation institute

TNO | Kennis voor zaken

My current research topics





PhD projects

- *Casimir effect & NEMS*
- *Hydrogen stogage-nanoparticles*
- *Piezoresponse Force Microscopy*
- *AFM optical data storage*
- *NEMS / MEMS (look for student!)*

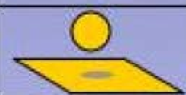
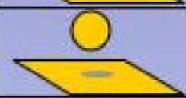
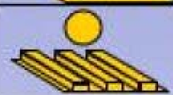
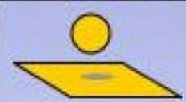
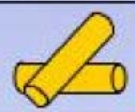
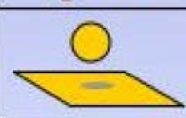
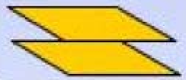
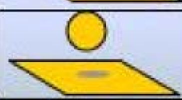
http://palasantzas.fmns.rug.nl

ESF network (2008-2013): *"New trends and applications of the Casimir effect (CASIMIR)"* **EU-Participants:** NETHERLANDS, FRANCE, GERMANY, NORWAY, SPAIN, SWEDEN, SWITZERLAND, UK.

The main lines of this research involve:

- **Casimir force in complex geometries and novel topologies such as patterend or corrugated surfaces, nanospheres or small spheroidal shaped bodies** (Barton, Binns, Bordag, Brevik-Hoye, Chevrier, Duplantier, Lambrecht-Reynaud)
- "**Vacuum torques" acting on irregular bodies** (Iannuzzi, Lambrecht- Reynaud, Svetovoy)
- **Studying the Casimir force using new materials such as superconductors, magnetic materials, meta-materials or Carbon nanotubes** (Binns, Bordag, Bimonte-Calloni, Lambrecht, Henkel)
- **Dispersion forces and NEMS Devices** (Andreucci, Iannuzzi, Palasantzas, Svetovoy)
- **Nanoscale surface/interface roughness influence on functional properties of MEMS, NEMS** (Andreucci, Emig, Lambrecht, Palasantzas)
- **Development of new instrumentation for surface force measurements in liquids, also at cryogenic temperatures** (Iannuzzi)
- **New forces**

Recent Measurements of Casimir Force

Investigators	Year	Geometry	Method	Distance Scale (nm)	Materials	Pressure (mbar)	Temp (K)	Accuracy (%)
S. K. Lamoreaux	1997		Torsion pendulum	600 - 6000	Au(500nm)	10^{-4}	300	5
U. Mohideen & A. Roy	1998		AFM	100 - 900	Al (300nm) + AuPd (20nm)	$5x10^{-2}$	300	
A. Roy and U. Mohideen	1999		AFM	100 - 900	Al (250nm)+ AuPd (8nm)	$5x10^{-2}$	300	
G. L. Klimthitskaya, A. Roy, U. Mohideen and V. M. Mostepanenko	1999		AFM	100 - 900	Al (300nm) + AuPd (20nm)	$5x10^{-2}$	300	
T. Ederth	2000		Piezo-tube manipulator	20 - 100	50μm Au wires coated in thiol SAM	1000	300	
H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop & F. Capasso	2001		MEMS torsion bar capacitance	90 - 1000	Au (200nm) + Cr underlayer	1000	300	1
G. Bressi, G. Carugno, R. Onofrio & G. Ruoso	2002		Interferometry	500 - 3000	Cr (50nm) on Si	10^{-3}	300	15
R. S. Decca, D. Lopez, E. Fischbach & D. E. Krause	2003		MEMS torsion bar capacitance	200 - 2000	Cu/Au	10^{-4}	300	
NANOCASE	2005-		AFM, MEMS	10 - 1000	Si, Au	10^{-11}	20 - 1000	

Today’s topics

- *Real materials*
- *Roughness, Optical properties*
- *Critics ……..Cosmology……*
- *Conclusions………………*

Real Materials→ Corrections to the Casimir / vdW force

Finite conductivity

$\omega < \omega_p \; (\lambda_p \sim 100\, nm)$

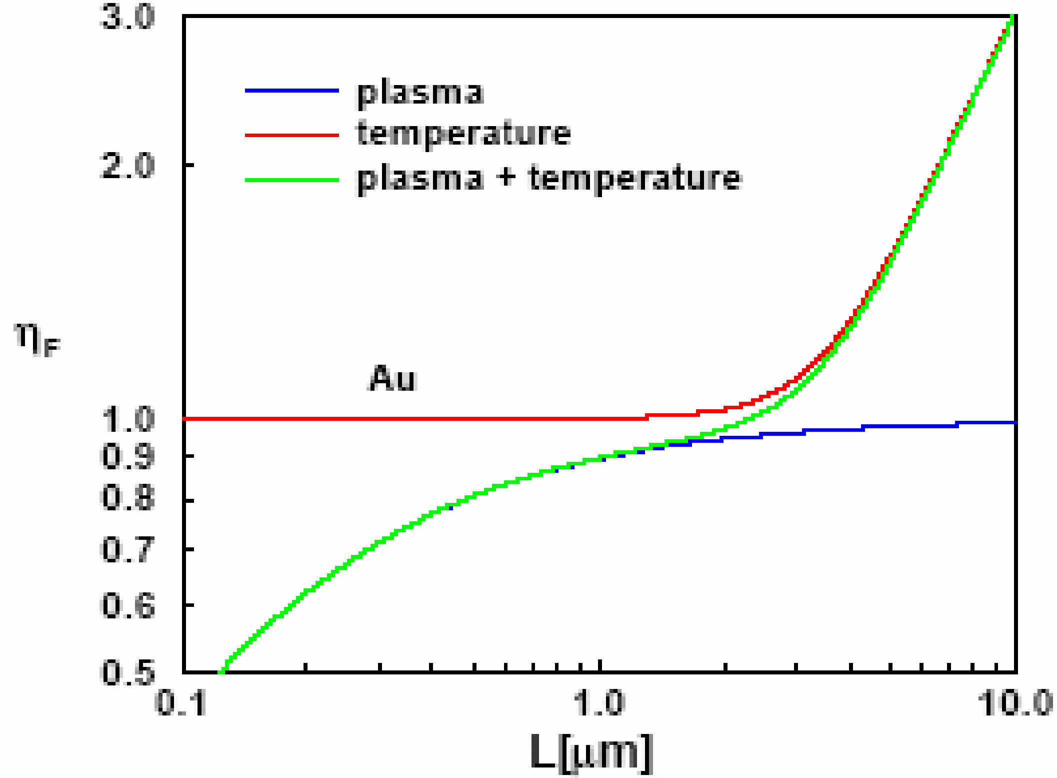
$\lambda_p = 2\pi c / \omega_p$

Temperature correction

$$\lambda_T = \frac{\hbar c}{k_B T} \cong 7\, \mu m \qquad (T = 300\, K)$$

Roughness correction

$$\eta_F = \frac{F_{Cas}^{Real}}{F_{Cas}^{Perf}}$$

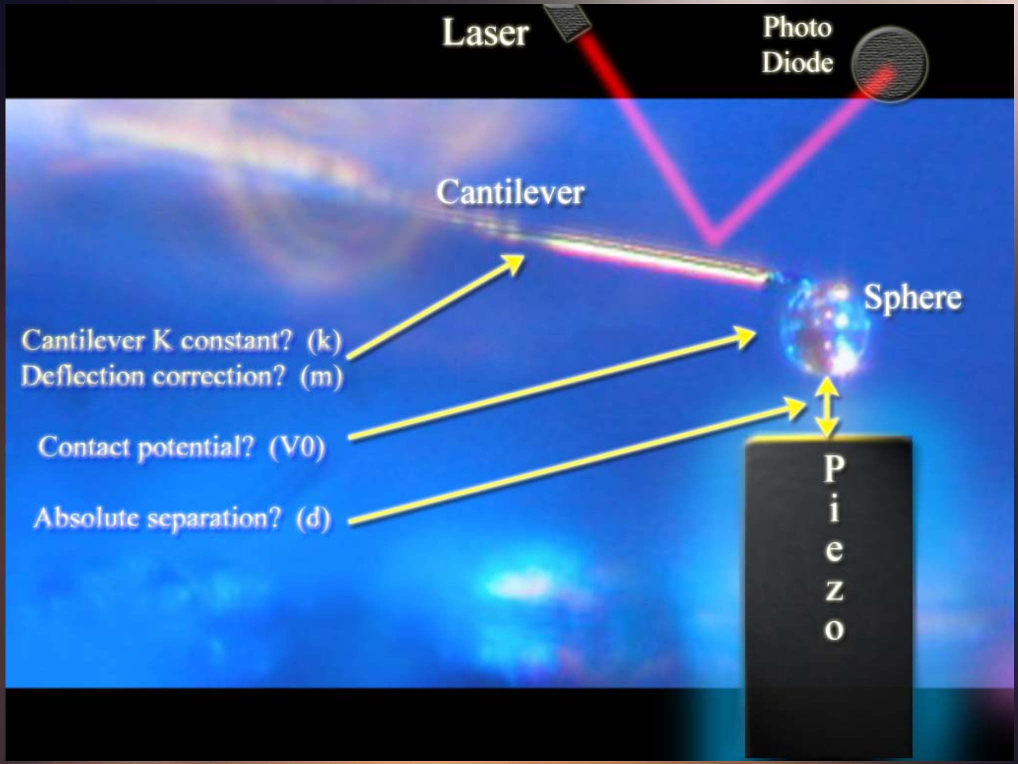


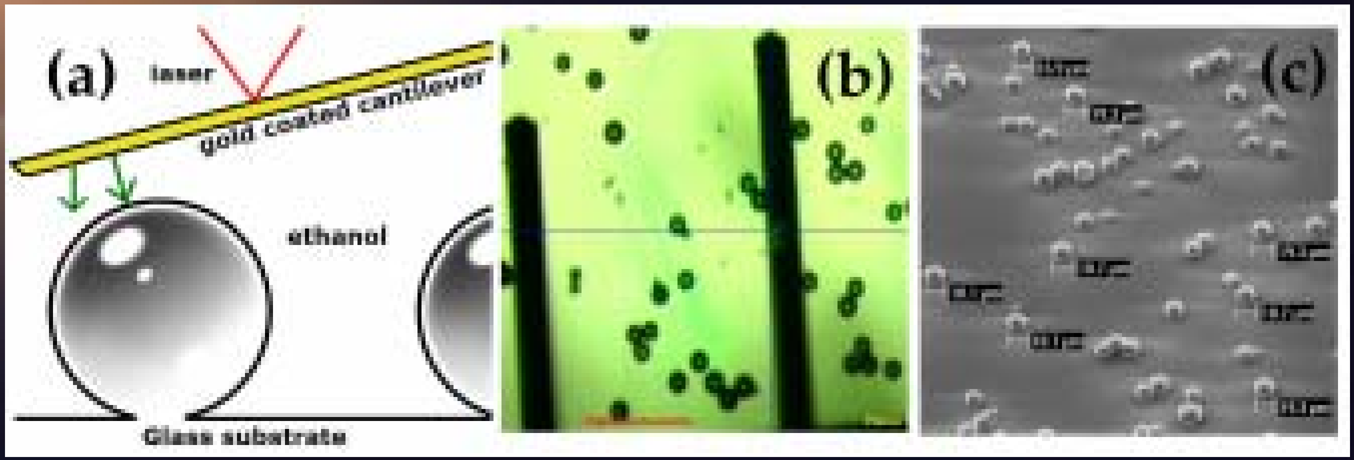
C. Genet, A. Lambrecht, and S. Reynaud, PRA (2000)

Temperature correction (accuracy > 1 %)

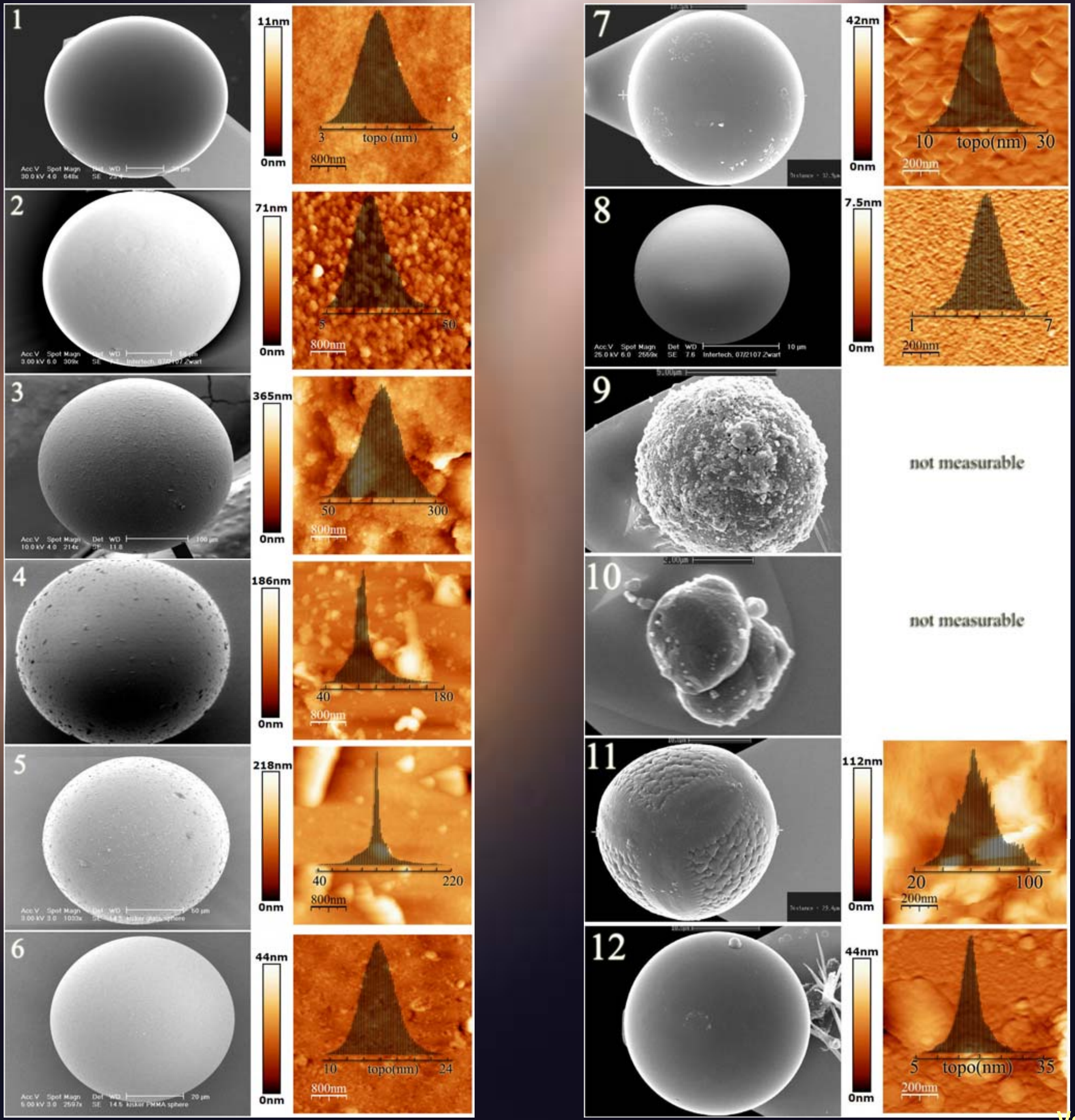
$$F^T(T,d) = \begin{cases} 1 + \dfrac{720}{\pi^2}\left\{\left(\dfrac{K_B T d}{\hbar c}\right)^3 \dfrac{\zeta(3)}{2\pi} - \dfrac{45}{\pi^2}\left(\dfrac{K_B T d}{\hbar c}\right)^4\right\} & \textbf{if } K_B T d/\hbar c < 1/2 \\ \left(\dfrac{K_B T d}{\hbar c}\right)\dfrac{\zeta(3)}{8\pi} - \dfrac{\pi^2}{720} & \textbf{if } K_B T d/\hbar c > 1/2 \end{cases}$$

Force measurement by AFM



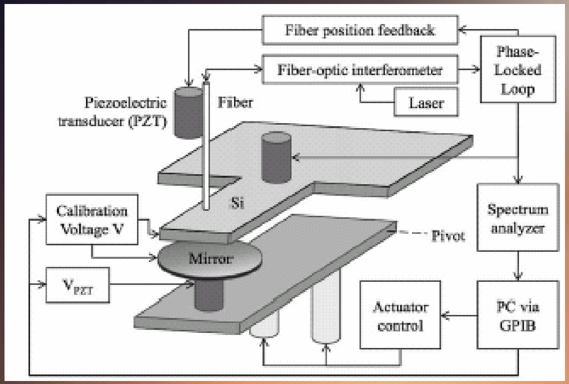


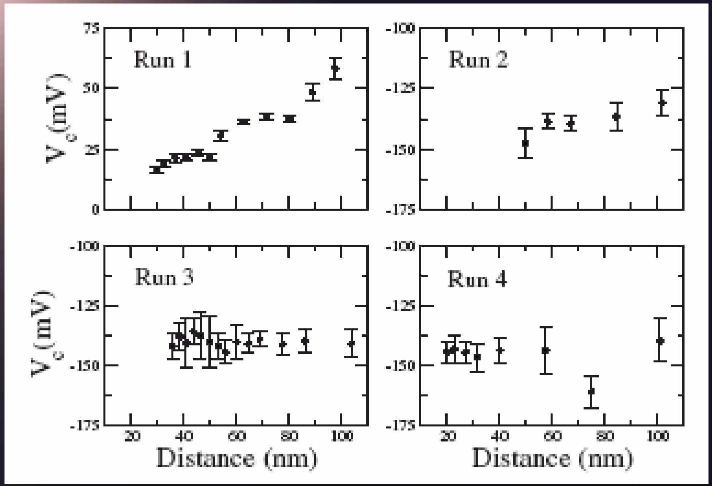
After R. Onofrio, PRA 2008



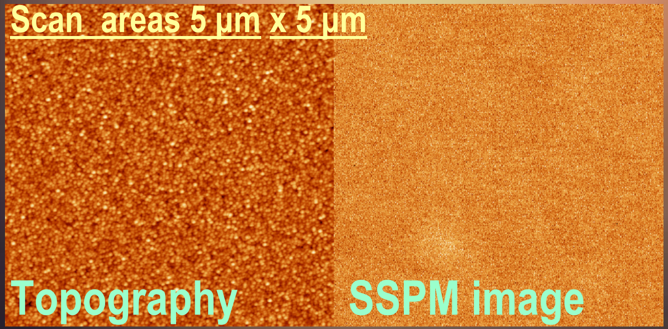
Van Zwol et al, Langmuir 2008

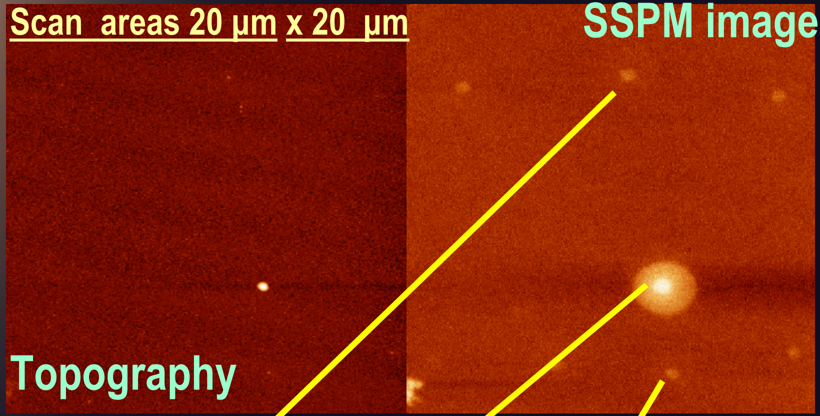
R. Onofrio et al., PHYSICAL REVIEW A 78, 020101(R) (2008)

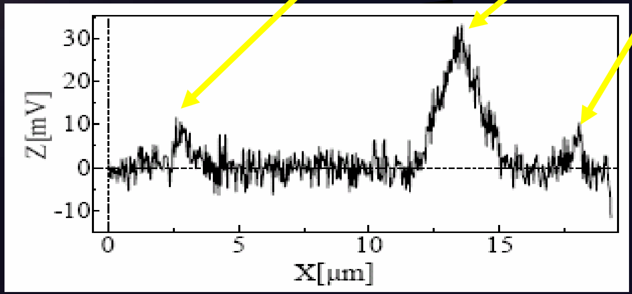




~~$F'_{el} = -\pi\epsilon_0 R V^2 / d^2$~~







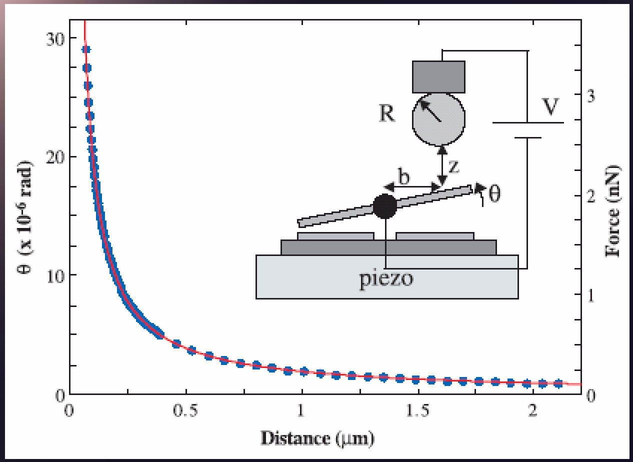
Iannuzzi et al, arxiv 2008

$$F'_{el} = -\pi\epsilon_0 R V^2 / d^2$$

Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force

H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, Federico Capasso*

SCIENCE VOL 291 9 MARCH 2001



values to better than 1%. As pointed out by Lamoreaux (*26*, *27*), a fundamental test of the theory would require a direct measurement of the optical properties of the metal under study.

26. S. L. Lamoreaux, *Phys. Rev. A* **59**, 3149 (1999).
27. ———, *Phys. Rev. Lett.* **83**, 3340 (1999).

Sample dependence of the Casimir force

I Pirozhenko[1], A Lambrecht[1] and V B Svetovoy[2,3] *New Journal of Physics* 8 (2006) 238

Table 1. The Drude parameters found by fitting the available infrared data for $\varepsilon'(\omega)$ and $\varepsilon''(\omega)$ with equation (10). The error is statistical.

N	ω_p (eV)	$\omega_\tau \cdot 10^2$ (eV)	$\mathcal{P}$	
1	7.50 ± 0.02	6.1 ± 0.07	−27.67 ± 5.79	Palik, 66 points, ·
2	8.41 ± 0.002	2.0 ± 0.005	7.15 ± 0.035	Weaver, 20 points, ■, □
3	8.84 ± 0.03	4.2 ± 0.06	12.94 ± 16.81	Motulevich, 11 points, ●, ○
4	6.85 ± 0.02	3.6 ± 0.05	−12.33 ± 9.13	Padalka 11 points, ▼, ▽

$$\eta_F = \frac{120L^4}{c\pi^4}\int_0^\infty d\kappa\,\kappa^2\int_0^\kappa d\zeta\sum_\mu \frac{r_\mu^2}{e^{2\kappa}-r_\mu^2},$$

ω_p, ω_τ(eV) \ L(μm)	0.1	0.3	0.5	1.0	3.0
1. $\omega_p = 7.50$, $\omega_\tau = 0.061$	0.43	0.66	0.75	0.85	0.93
2. $\omega_p = 8.41$, $\omega_\tau = 0.02$	0.45	0.69	0.79	0.88	0.95
3. $\omega_p = 8.84$, $\omega_\tau = 0.0422$	0.46	0.69	0.78	0.87	0.94
4. $\omega_p = 6.85$, $\omega_\tau = 0.0357$	0.42	0.65	0.75	0.84	0.93
5. $\omega_p = 9.00$, $\omega_\tau = 0.035$	0.47	0.71	0.79	0.88	0.95
6. $\omega_p = 7.50 \pm 15\%$	0.45	0.68	0.77	0.86	0.94
$\omega_\tau = 0.061$	0.41	0.63	0.73	0.83	0.92
7. $\omega_p = 7.50$	0.42	0.65	0.74	0.84	0.92
$\omega_\tau = 0.061 \pm 30\%$	0.44	0.67	0.76	0.86	0.93

Variation of optical data & associated Drude parameters → variation in the Casimir force : 5.5% at 100 nm → 1.5 % at 3μm

optical data for Au

Lifshitz -Theory

$$E_{ppflat} = -\hbar A \sum_{P} \int [d^2k/4\pi^2] \int_0^{\infty} [d\Phi/2\pi] \ln[1 - r^p(k,\Phi)^2 e^{-2\kappa d}]$$

$$r_s = -\frac{\sqrt{\mathbf{k}^2 + \varepsilon(\mathrm{i}\zeta)\frac{\zeta^2}{c^2}} - c\kappa}{\sqrt{\mathbf{k}^2 + \varepsilon(\mathrm{i}\zeta)\frac{\zeta^2}{c^2}} + c\kappa} \qquad r_p = \frac{\sqrt{\mathbf{k}^2 + \varepsilon(\mathrm{i}\zeta)\frac{\zeta^2}{c^2}} - c\kappa\varepsilon(\mathrm{i}\zeta)}{\sqrt{\mathbf{k}^2 + \varepsilon(\mathrm{i}\zeta)\frac{\zeta^2}{c^2}} + c\kappa\varepsilon(\mathrm{i}\zeta)}$$

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

Ellipsometry measurement of the dielectric function

Svetovoy et al, PRB (2008)

Ellipsometry: → *ratio of p-polarized and s-polarized complex Fresnel reflection coefficients is obtained*

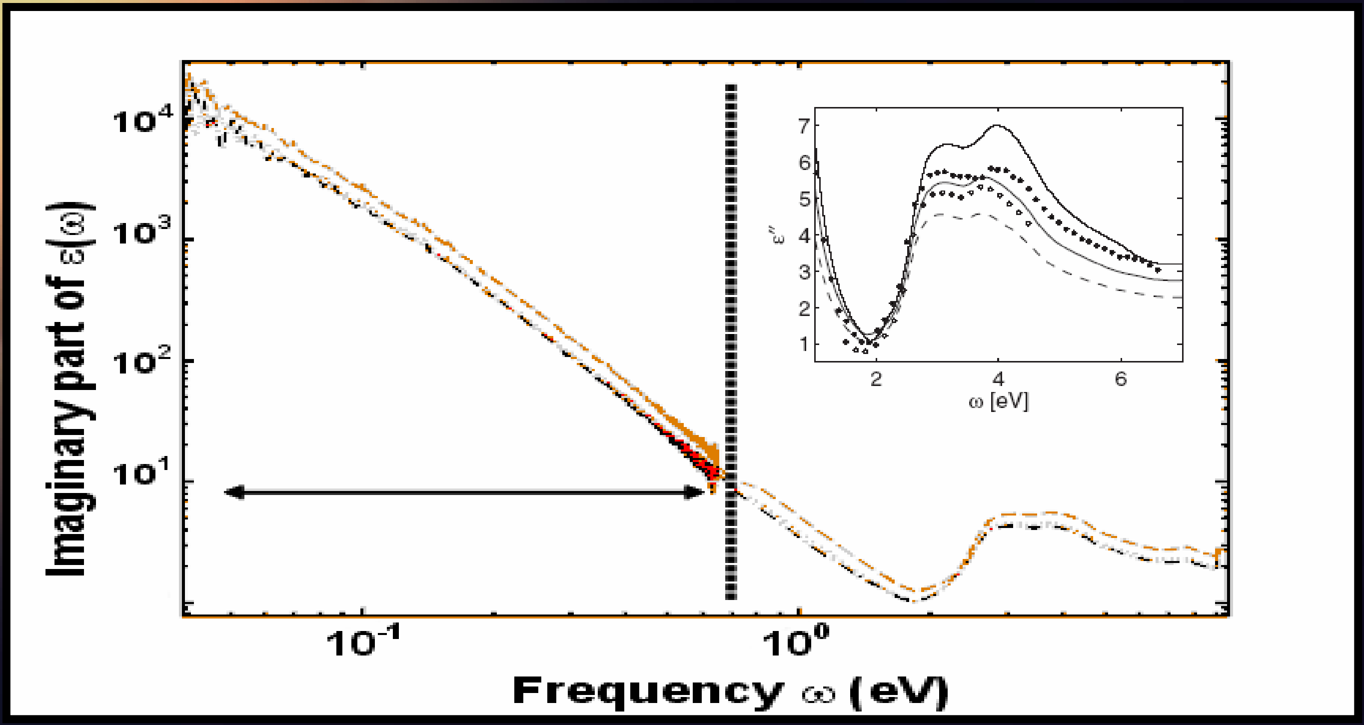
$$\rho = \frac{r_p}{r_s} = \tan \Psi e^{i\Delta}$$

$$r_p = \frac{\langle\varepsilon\rangle\cos\vartheta - \sqrt{\langle\varepsilon\rangle - \sin^2\vartheta}}{\langle\varepsilon\rangle\cos\vartheta + \sqrt{\langle\varepsilon\rangle - \sin^2\vartheta}}, \quad r_s = \frac{\cos\vartheta - \sqrt{\langle\varepsilon\rangle - \sin^2\vartheta}}{\cos\vartheta + \sqrt{\langle\varepsilon\rangle - \sin^2\vartheta}}$$

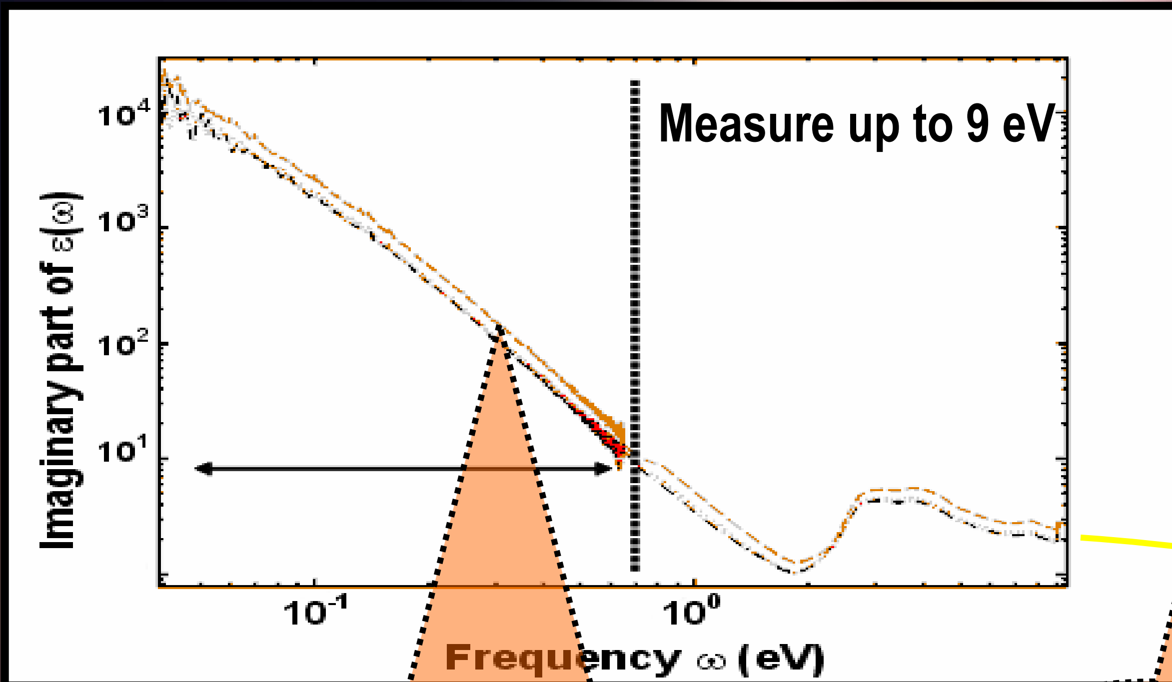
θ: is the angle of incidence

137 nm < λ < 32 μm

$\langle\varepsilon\rangle = \langle\varepsilon(\lambda)\rangle$ *"pseudodielectric" function*



Svetovoy et al, PRB (2008)



above 100 eV

$$\varepsilon(\omega) = 1 - \omega_p^2/\omega^2 + iA/\omega^3$$

$$\varepsilon'(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \omega_\tau^2}, \quad \varepsilon''(\omega) = \frac{\omega_p^2 \omega_\tau}{\omega(\omega^2 + \omega_\tau^2)}$$

$9 < \omega < 100$ eV
handbook data

Kramers-Kronig (KK) consistency

$0.01 < \omega < 100$ eV

$$\varepsilon'(\omega) - 1 = \frac{2}{\pi} P \int_0^\infty dx \frac{x \varepsilon''(x)}{x^2 - \omega^2}$$

$$\varepsilon(i\zeta) = 1 + \varepsilon_{cut}(i\zeta) + \varepsilon_{expt}(i\zeta)$$

ω_{cut}=0.038 eV

$$\varepsilon_{cut}(i\zeta) = \frac{2}{\pi}\int_0^{\omega_{cut}} d\omega \frac{\omega\varepsilon''(\omega)}{\zeta^2+\omega^2}, \quad \varepsilon_{expt}(i\zeta) = \frac{2}{\pi}\int_{\omega_{cut}}^{\infty} d\omega \frac{\omega\varepsilon''(\omega)}{\zeta^2+\omega^2}.$$

- **Our films → contribution from the extrapolated region, ω_{cut} dominates ζ<0.2 eV**
- **handbook data it dominates up to ζ =4 eV**
- **Result of reduced ω_{cut} (hanbook:0.125 eV) → calculations based on our data** ***are more reliable ⇔ smaller part of $\varepsilon(i\zeta)$ depends on the extrapolation.***

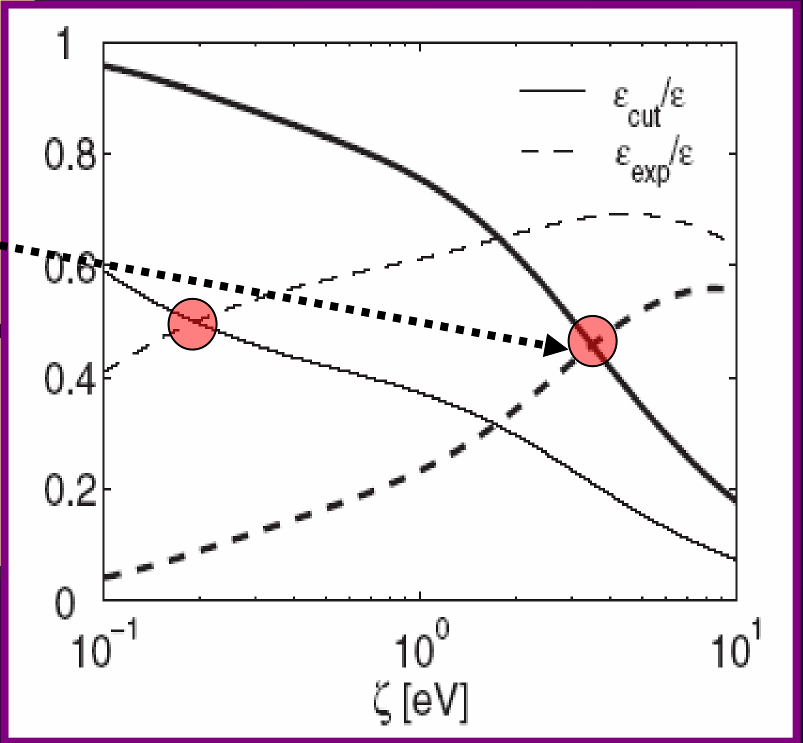


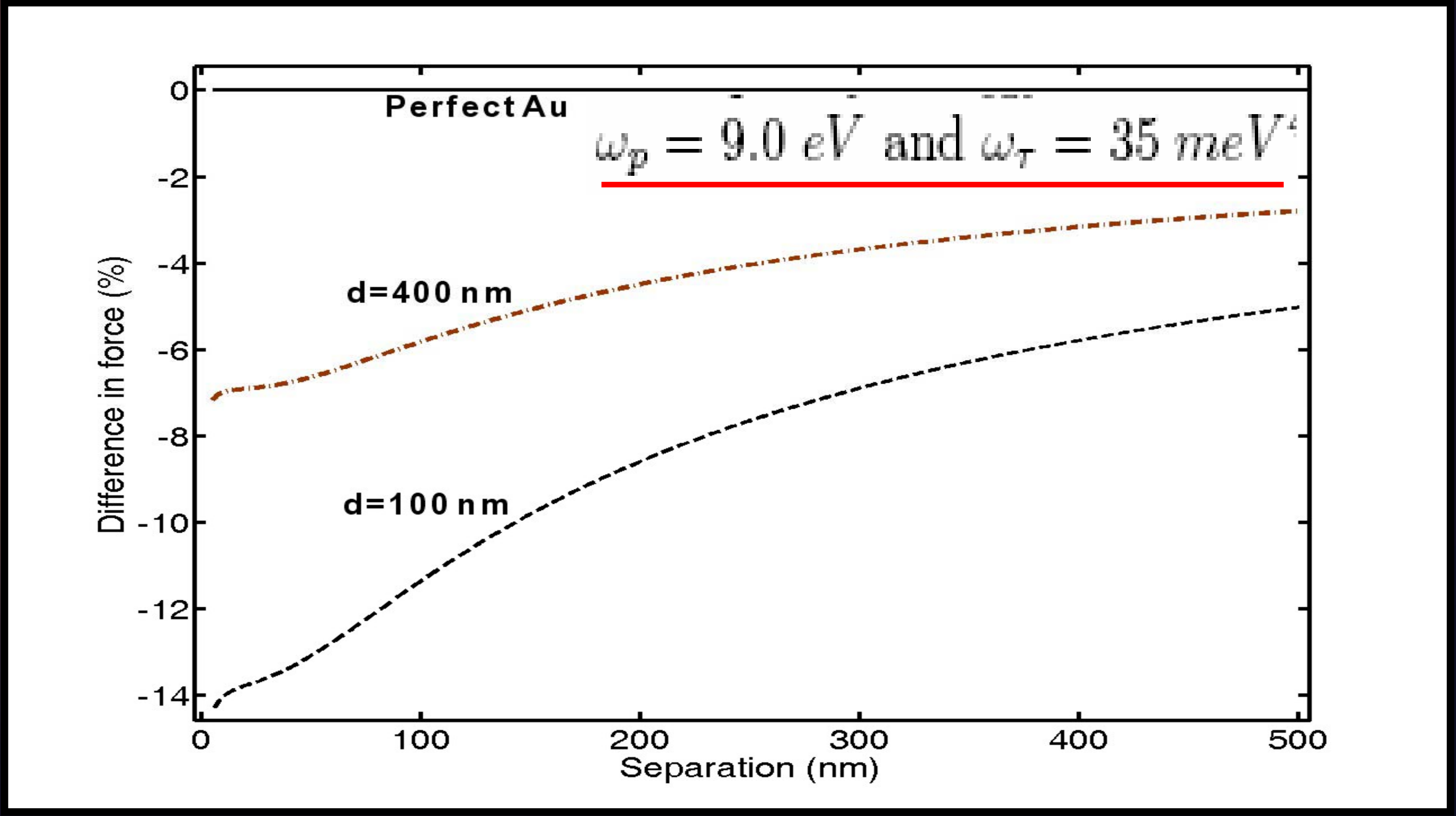
TABLE II. The Drude parameters determined by different methods described in the text. In all cases the statistical errors in the parameters are on the same level: 0.01–0.03 meV for ω_p and 0.2–0.5 meV for ω_τ. The last column shows the values of the parameters averaged on different methods and the corresponding rms errors.

Sample	Parameter	Joint ε', ε''	Joint n, k	KK ε'	KK n	Average
1	ω_p [eV]	6.70	6.87	6.88	6.83	6.82 ± 0.08
400 nm/Si	ω_τ [meV]	38.4	43.3	40.2	39.9	40.5 ± 2.1
2	ω_p	6.78	7.04	6.69	6.80	6.83 ± 0.15
200 nm/Si	ω_τ	40.7	45.3	36.1	36.0	39.5 ± 4.4
3	ω_p	7.79	7.94	7.80	7.84	7.84 ± 0.07
100 nm/Si	ω_τ	48.8	52.0	47.9	47.4	49.0 ± 2.1
4	ω_p	7.90	8.24	7.95	7.90	8.00 ± 0.16
120 nm/Si	ω_τ	37.1	41.4	35.2	29.2	35.7 ± 5.1
5	ω_p	8.37	8.41	8.27	8.46	8.38 ± 0.08
120 nm/mica	ω_τ	37.1	37.7	34.5	39.1	37.1 ± 1.9

Important contribution to Casimir force comes from imaginary frequencies around →

$$\zeta_{ch} = c / 2a$$

$$10 \text{ nm} \lesssim a \lesssim 1 \ \mu\text{m} \longleftrightarrow 0.1 \lesssim \zeta_{ch} \lesssim 10 \text{ eV}$$



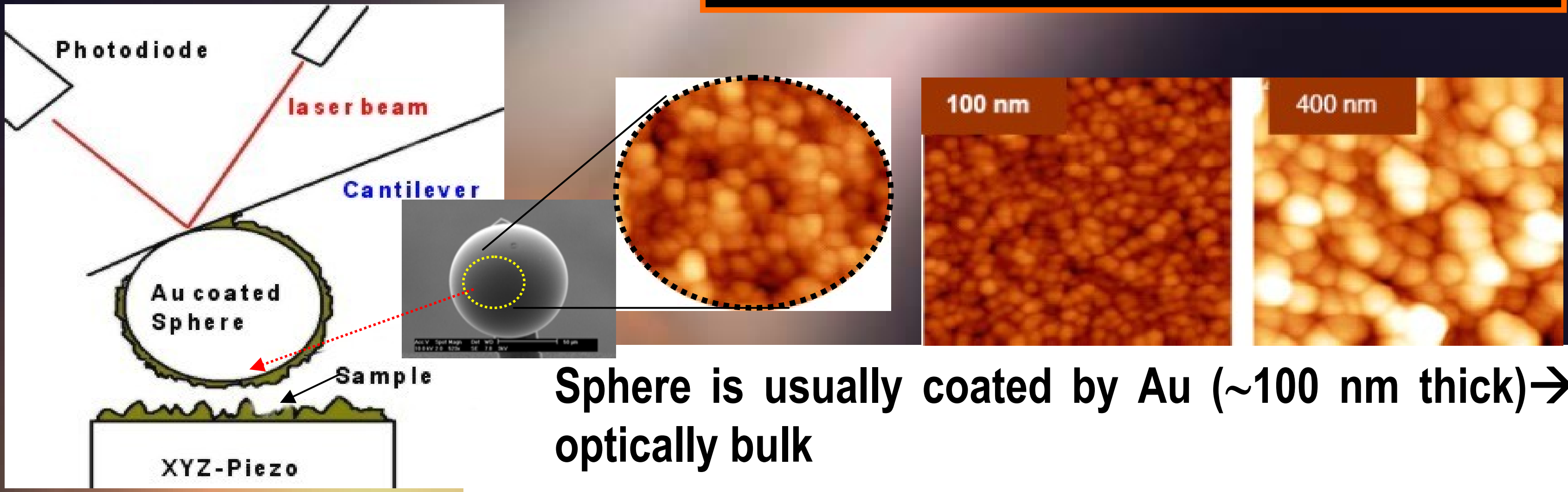
Noise in the optical data is responsible for the force variation within 1%

PHYSICAL REVIEW B 77, 035439 (2008)

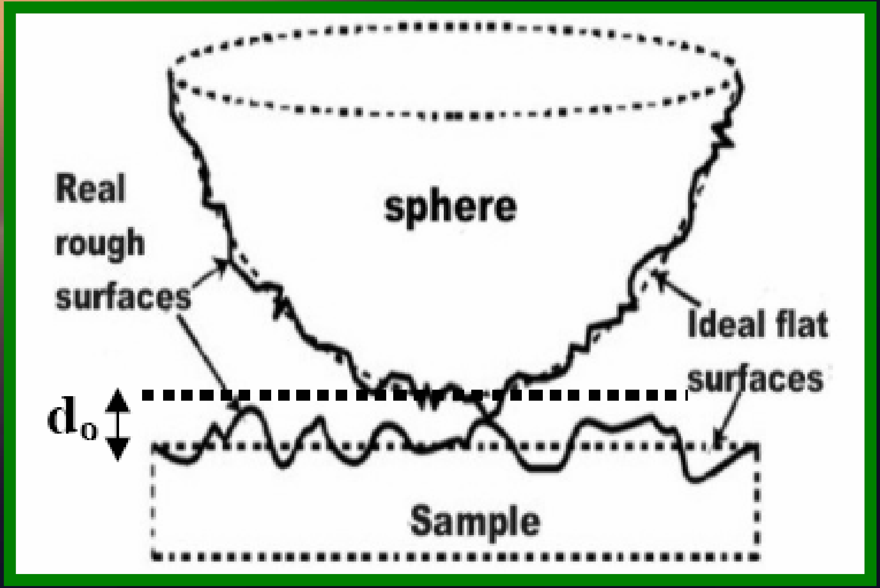
Optical properties of gold films and the Casimir force

Precise optical properties of metals are very important for accurate prediction of the Casimir force acting between two metallic plates. Therefore we measured ellipsometrically the optical responses of Au films in a wide range of wavelengths from 0.14 to 33 μm. The films at various thicknesses were deposited at different conditions on silicon or mica substrates. Considerable variation of the frequency dependent dielectric function from sample to sample was found. Detailed analysis of the dielectric functions was performed to check the Kramers-Kronig consistency, and extract the Drude parameters of the films. It was found that the plasma frequency varies in the range from 6.8 to 8.4 eV. It is suggested that this variation is related with the film density. X-ray reflectivity measurements support qualitatively this conclusion. The Casimir force is evaluated for the dielectric functions corresponding to our samples, and for that typically used in the precise prediction of the force. The force for our films was found to be 5%–14% smaller at a distance of 100 nm between the plates. Noise in the optical data is responsible for the force variation within 1%. It is concluded that prediction of the Casimir force between metals with a precision better than 10% must be based on the material optical response measured from visible to mid-infrared range.

Surface roughness influence



Sphere is usually coated by Au (~100 nm thick)→ optically bulk



Accuracy down to < 1 % …is it possible …yes but!….

K : **spring constant (~ 1-3 % : Electrostatic)**

V_c: **contact potential** (Au/Polysterene sphere: 5-20 mV)

Measure $\varepsilon(\omega)$: 100 nm $\leq \lambda \leq 30\ \mu$m (*Ellipsometry*)

$d = Z_{piezo} + d_o - Z_{defl}$ **(surface separation)**

Z_{piezo}: **piezo movement**, Z_{defl}: **catilever deflection correction**

d_o: **contact distance due to roughness** $\approx 3.7(w_{plate} + w_{sphere})$

$$Error: \Delta F \approx (m\Delta z / d)F \ (m \approx 2.5 - 3)$$

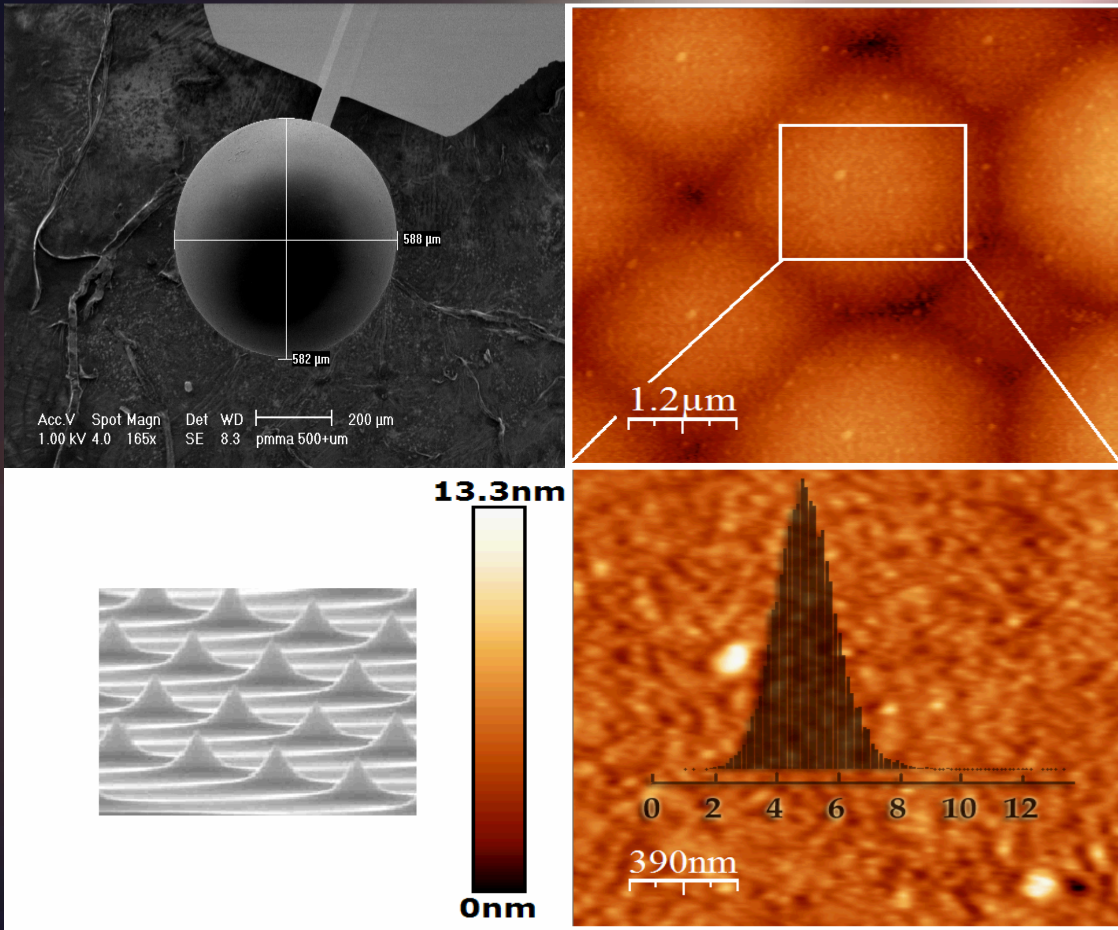
$\Delta z = 1\ nm \Leftrightarrow$ d_o **= 30 ± 1nm** $\rightarrow \Delta F / F \approx$ **10 %**

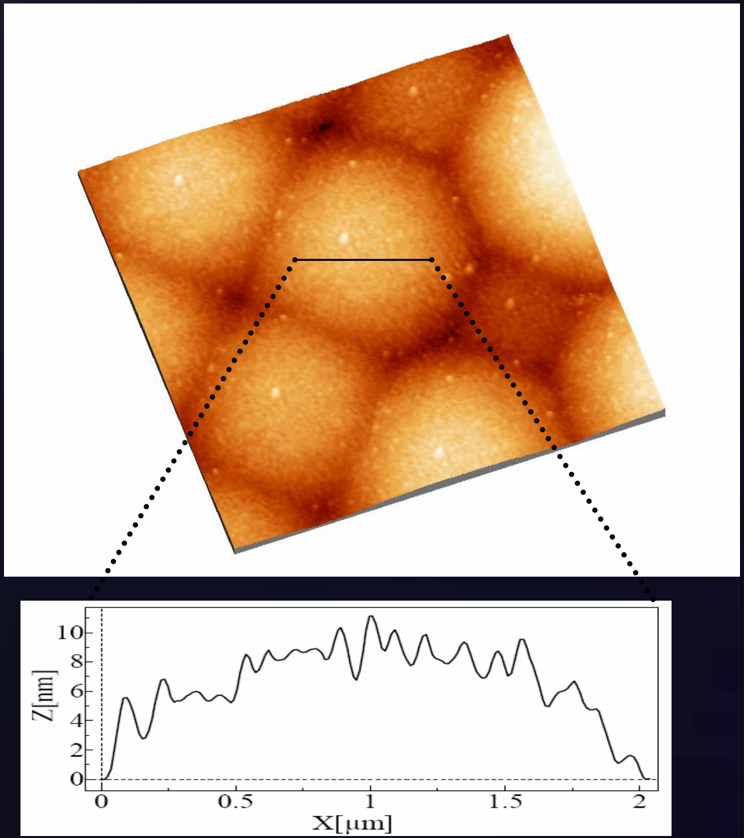
$\Delta z = 0.5\ nm \Leftrightarrow d_o$ **= 30 ± 0.5 nm** $\rightarrow \Delta F / F \approx$ **5 %**

?

Accuracy (%)
5
2
2
1
1
1
15
1
<1

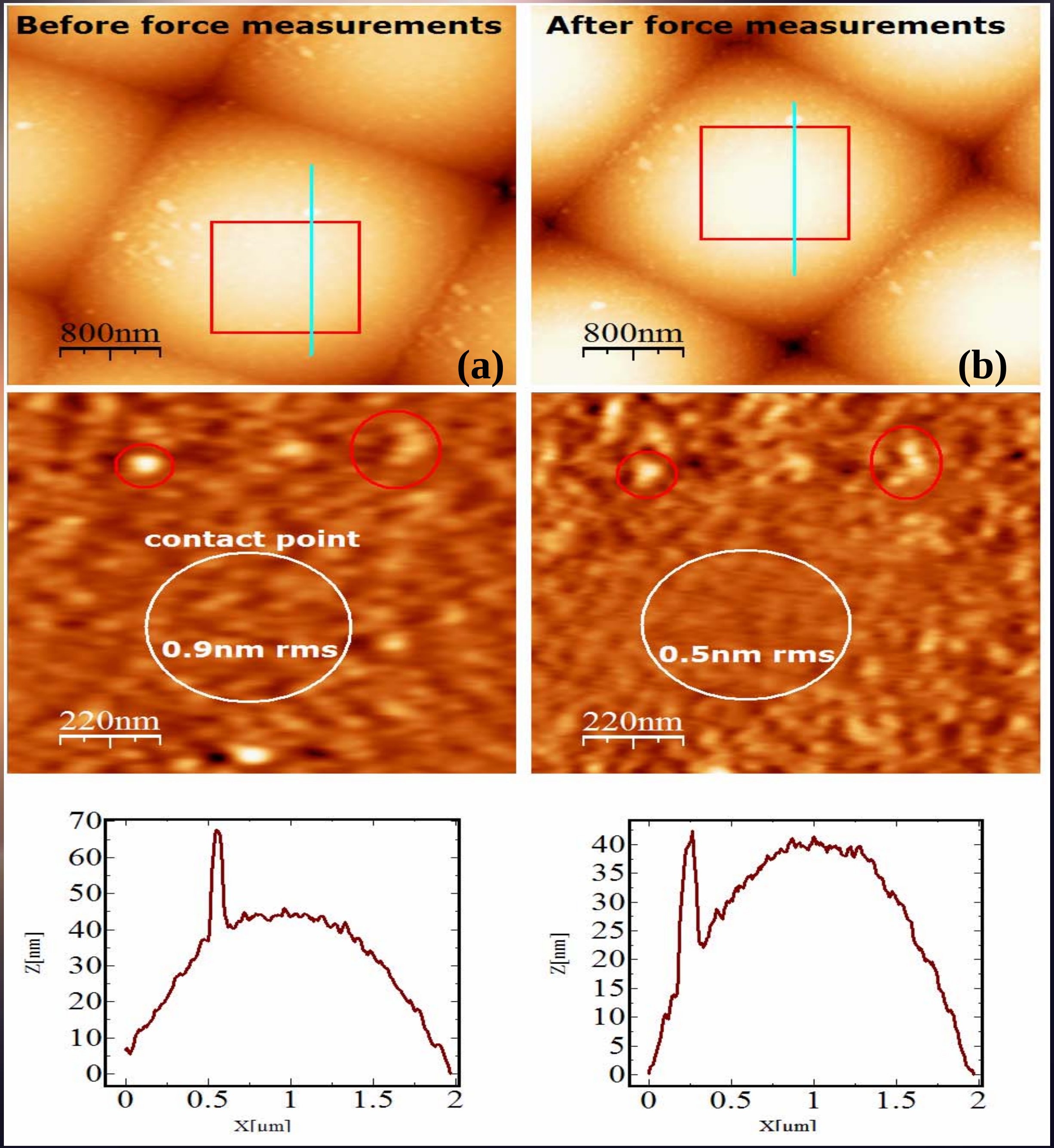
Reverse imaging, so we have knowledge of the roughness at the contact point of sphere and plate.





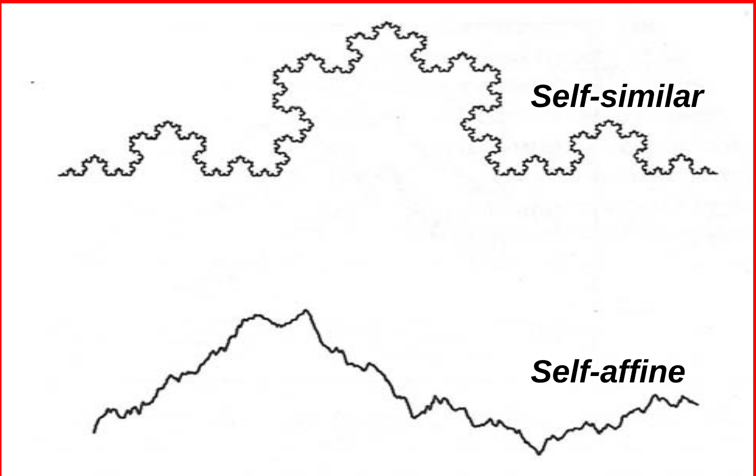
Van Zwol et al, Langmuir 2008

P.J. van Zwol, et al., APPL 2008

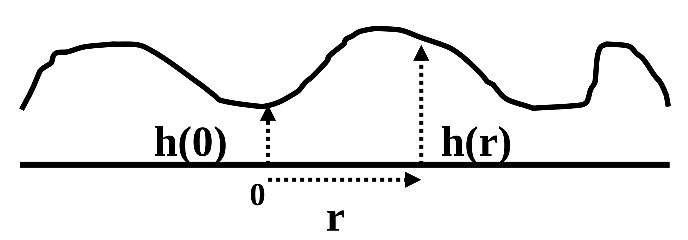


Van Zwol et al., PE 2008

Definition & characterization & growth of roughness

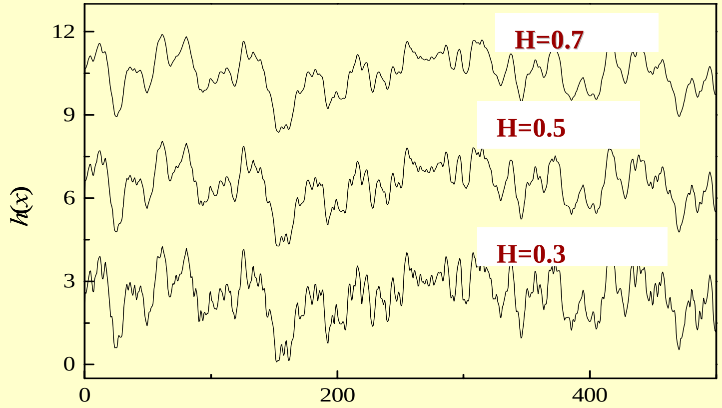


- Topography $\Rightarrow G(r)=<[h(r)-h(o)]^2>$



- For self-affine roughness:

$$G(r) \propto r^{2H} \text{ if } r<<\xi$$
$$G(r) = 2w^2 \text{ if } r>>\xi$$



w: Rms roughness amplitude
ξ: In-plane correlation length
H:Roughness exponent (0<H<1)

Normal self-affine growth

If $\beta=H/z$ (H<1)

$$w \propto t^{\beta} \quad \xi \propto t^{1/z}$$

Summary basic growth models

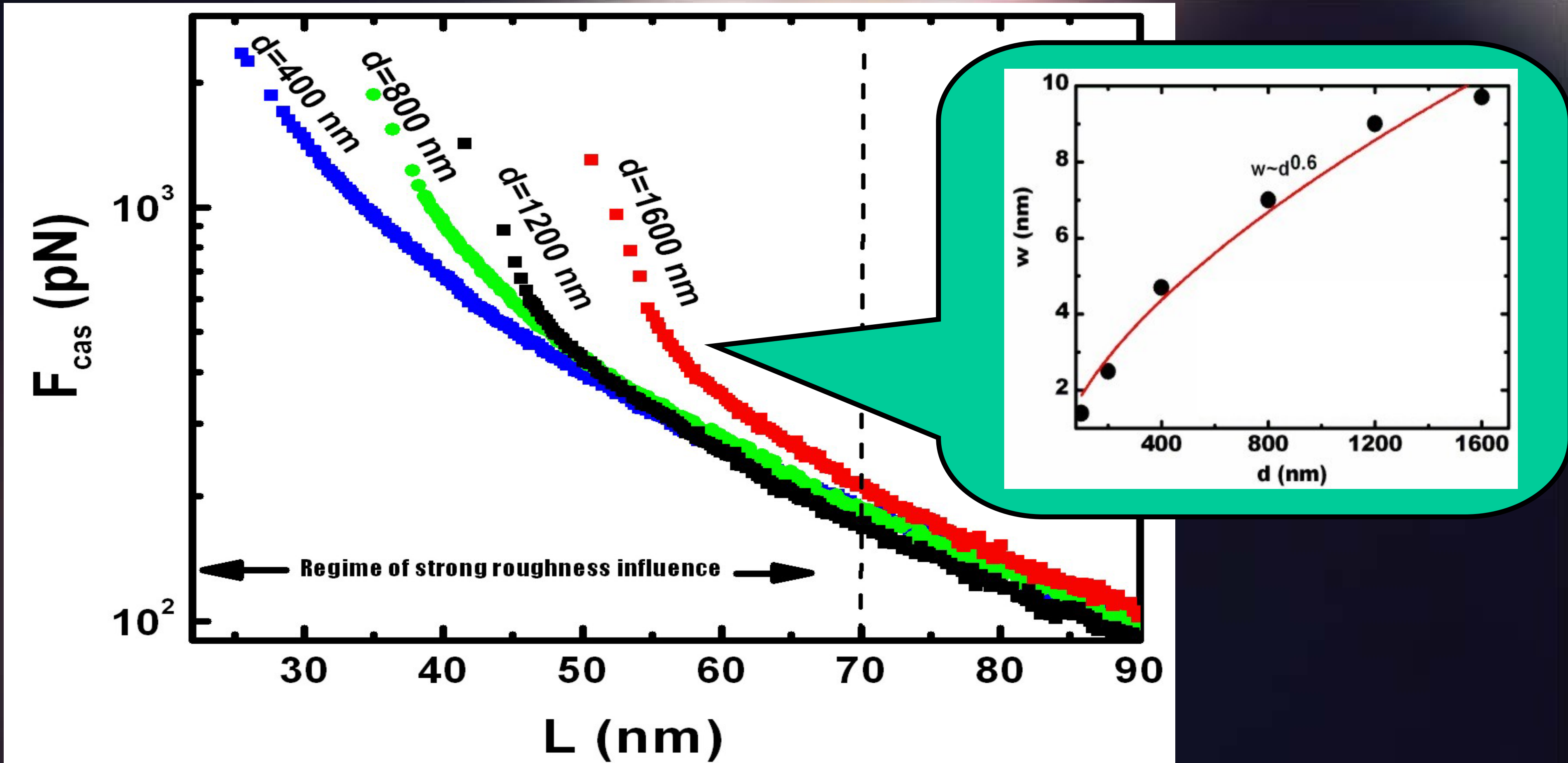
[Krim & Palasantzas, Int. J. Mod. Phys. B (1995)]

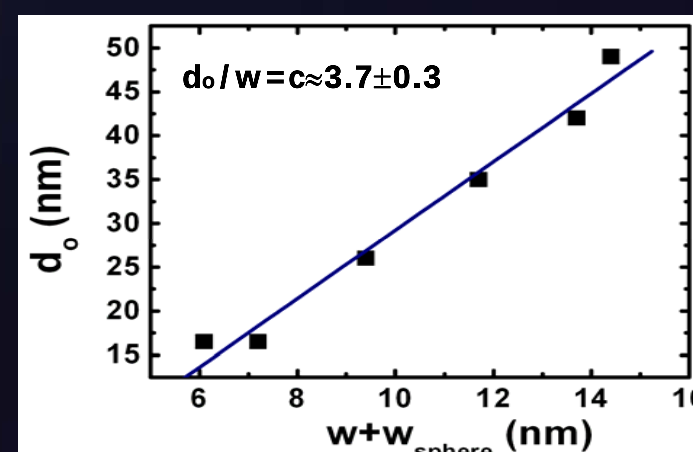
	H	β	[HD]
$\partial h / \partial t = \eta(r,t)$	-	0.5	Gaussian
$\partial h / \partial t = \nu \nabla^2 h + \eta(r,t)$	0	0	Gaussian
$\partial h / \partial t = -\kappa \nabla^4 h + \eta(r,t)$	1	0.25	Gaussian
$\partial h / \partial t = \nu \nabla^2 h + \lambda (\nabla h)^2 / 2 + \eta(r,t)$	0.38	0.24	Non-Gaussian
$\partial h / \partial t = -k \nabla^4 h + \nu \nabla^2 (\nabla h)^2 + \eta(r,t)$	2/3	0.20	Non-Gaussian

$$\begin{cases} < \eta(r,t) > = 0 \\ < \eta(r,t) \eta(r',t') > = 2D \delta(r - r') \delta(t - t'). \end{cases}$$

white-noise

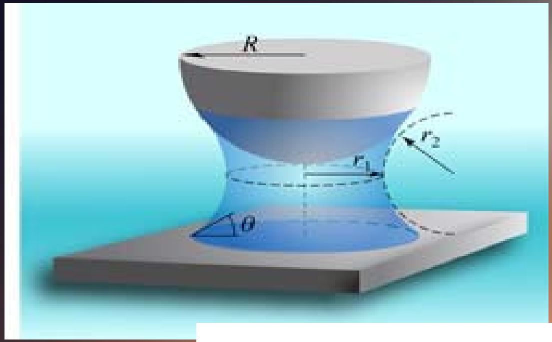
Gaussian: h ↔ -h symmetry



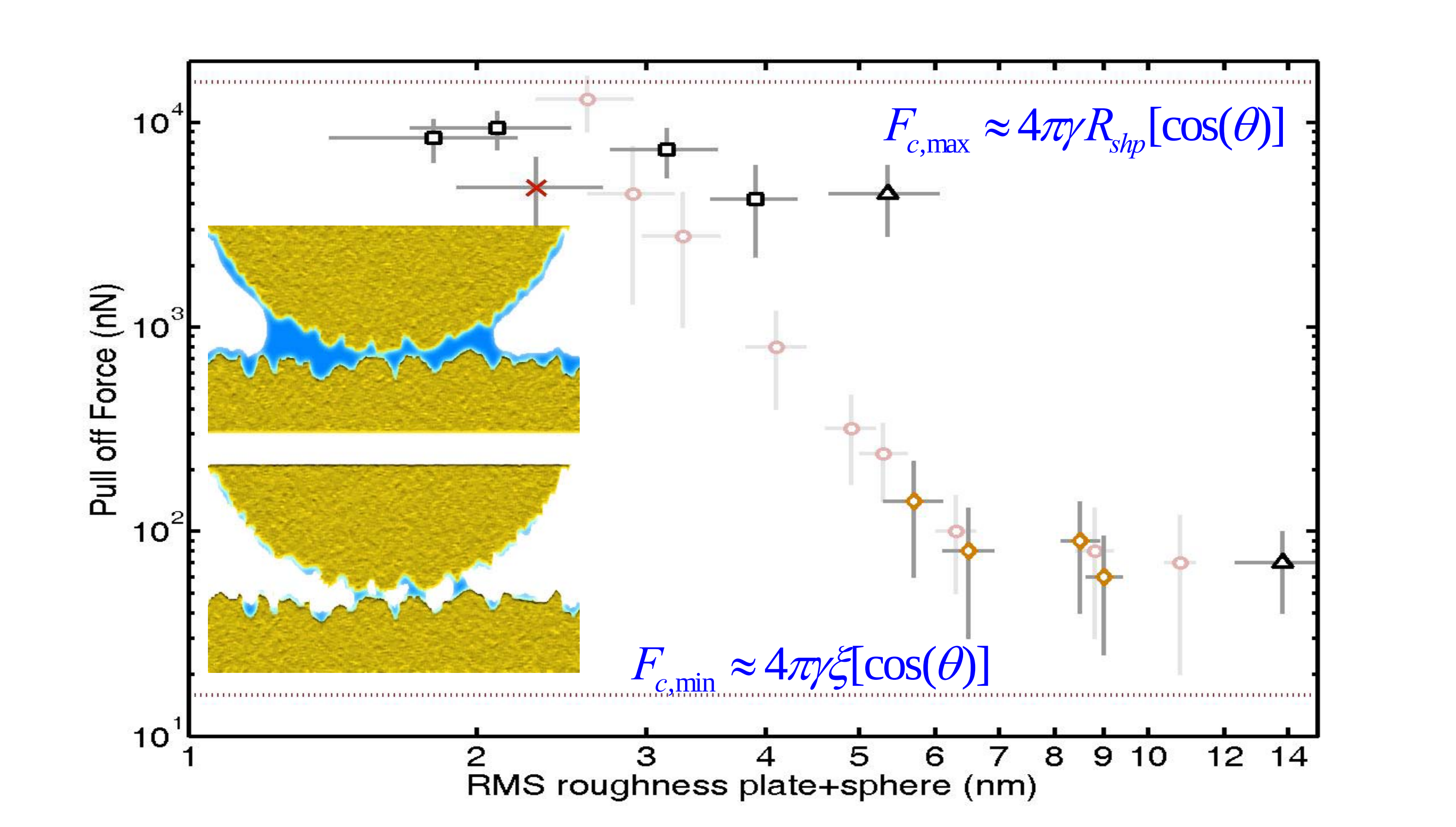


Zwol et al, PRB (2008)

Operate in air so upon contact we have capillary codensation



$$F_{ad} = \pi\gamma R_{sph}\{-\sin\varphi + [\cos(\theta_1+\varphi)+\cos(\theta_2)]\sin^2\varphi(1-\cos\varphi + D/R_{sph})^{-1}\} + 2\pi\gamma R_{sph}\sin\varphi\sin(\theta_1+\varphi)$$



Van Zwol, et al., APL 2007, PRE 2008

$$F_{theory}=(2\pi R/A)E_{pp,rough}$$

$$E_{pp,rough} = E_{ppflat} + \delta E_{pp,rough}$$

$$E_{ppflat} = \hbar A \sum_{P} \int [d^2k/4\pi^2] \int_0^\infty [d\Phi/2\pi] \ln[1 - r^p(k,\Phi)^2 e^{-2\kappa d}]$$

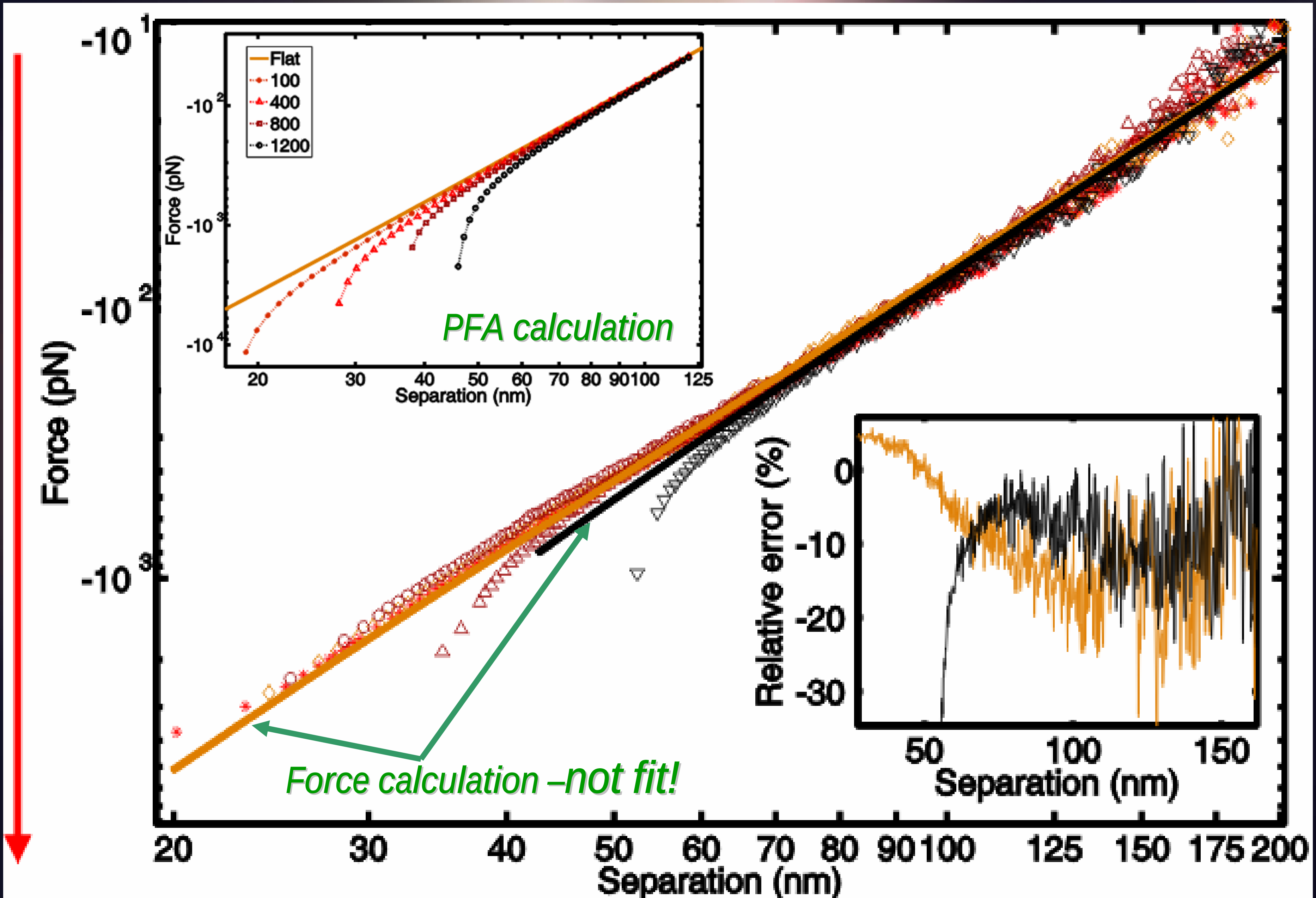
$$\delta E_{pp,rough} = \int [d^2k/4\pi^2] G(k)\sigma(k)$$

Neto, Lambrecht, Reynaud, PRA 2005

$$\sigma(k) = (AHw^2\xi^2)/(1+k^2\xi^2)^{1+H}$$

Palasantzas, PRB 1993

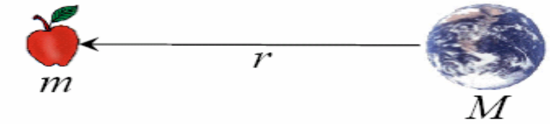
Roughness influence: Experiment & Perturbation theory



A Short-Range Test of Newton's Gravitational Inverse-Square Law

Isaac Newton's Gravitational Inverse-Square Law (ISL)

$$F = \frac{GMm}{r^2}$$



Gravity is an *attractive* force that acts between all mass/energy in the Universe.

Expect the expansion of the Universe to slow.

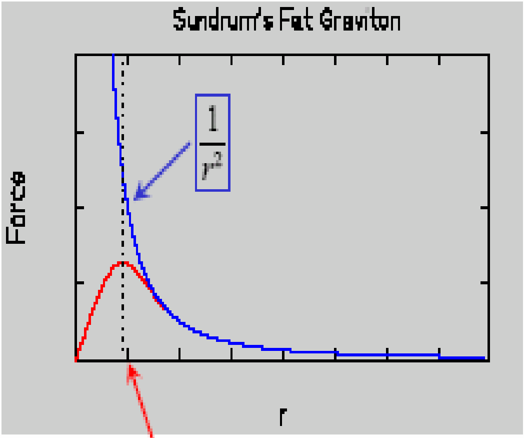
The expansion is accelerating, which implies a dark energy density :

$$\rho_d = 3.8\ \mathrm{keV/cm^3}$$

- And a natural length scale :

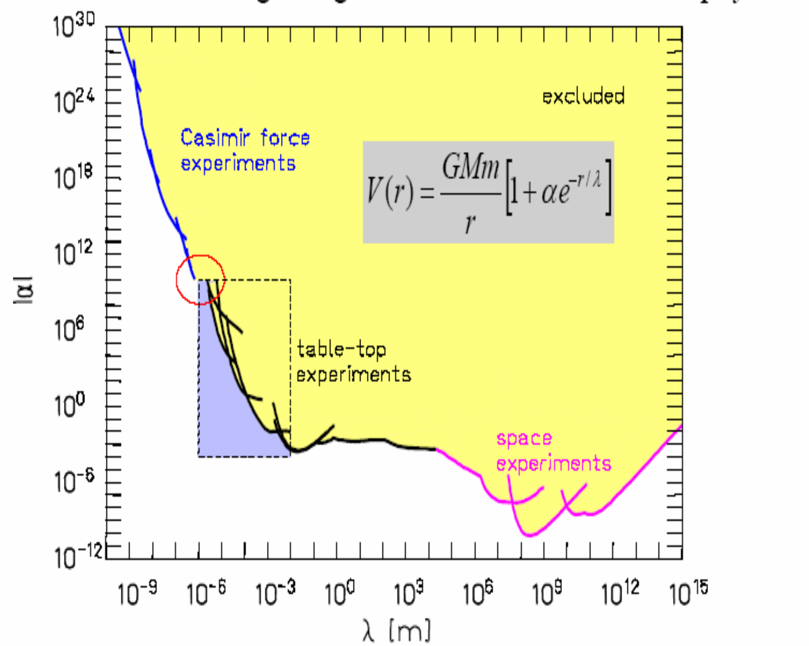
$$\lambda_d = \sqrt[4]{\hbar c/\rho_d} \approx 85\mu\mathrm{m}$$

A modified ISL could potentially link the dark energy density with vacuum fluctuations, a much higher energy density. Gravity might be blind to small-scale (high-energy) physics.



This length scale is unknown, but should be > 20μm.

Measured over a huge range of scales in search of new physics :



•Fifth force & Higher dimensions → short range force with coupling of order of gravity

$$V_{tot} = V_N + V_Y$$

$$V_N(r) = -G\frac{M}{r}$$

$$V_Y(r) = -\alpha G\frac{M}{r}e^{-r/\lambda}$$

$N = 4 + n$ *dimensions*

$\lambda \sim R_n$ $\quad R_n$ is the size of the compact dimensions.

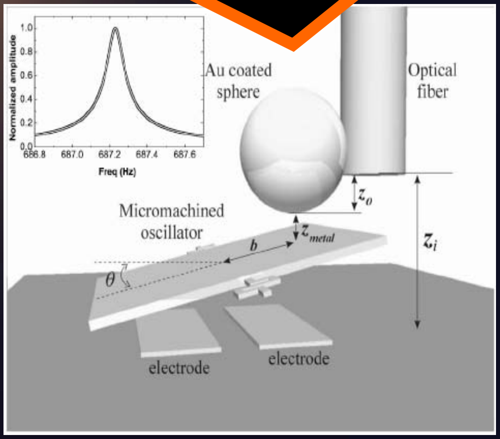
$$r \gg R_n \sim \frac{1}{M_{Pl}^{(N)}}\left(\frac{M_{Pl}}{M_{Pl}^{(N)}}\right)^{2/n} \sim 10^{32/n-17} \text{ cm.}$$

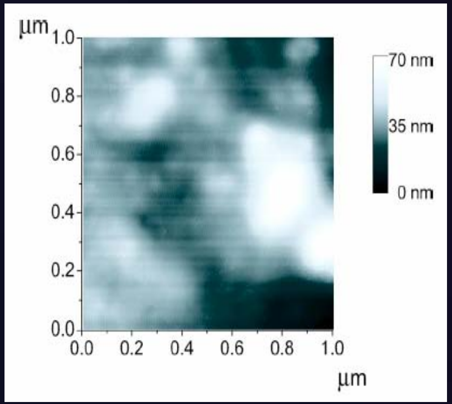
~~$R_1 \sim 10^{15}$ cm~~

$R_2 \sim 1$ mm or $R_3 \sim 5$ nm

Casimir force:
background force to be removed → seach for hypothetical forces

MEMS set-up for hypo-forces





Decca et al, PRD 2003

•Fifth force & Higher dimensions → short range force with coupling of order of gravity

Novel constraints on light elementary particles and extra-dimensional physics from the Casimir effect

R.S. Decca[1], D. López[2], E. Fischbach[3], G.L. Klimchitskaya[4,a], D.E. Krause[5,3], V.M. Mostepanenko[4,b,c]

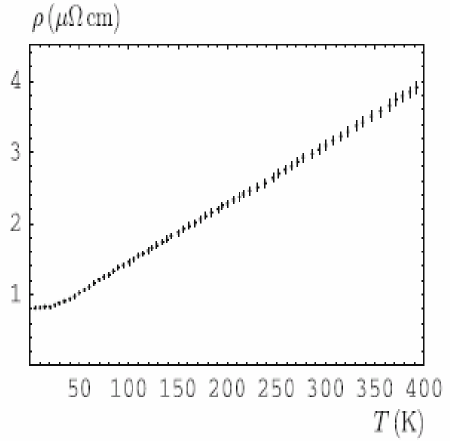


Fig. 2. Resistivity of the Au films (measured with an error of about 2%) as a function of temperature

$$\rho(T) = \frac{4\pi}{\omega_p^2 \tau(T)} = \frac{4\pi v_F}{\omega_p^2 l(T)} = \frac{CT}{\omega_p^{3/2}}. \quad (9)$$

Here $\tau(T) = l(T)/v_F$ is the relaxation time, $l(T) \sim T$ is the mean free path of an electron, $v_F \sim \omega_p^{1/2}$ is the Fermi velocity, and $C =$ const. The fit results in $C/\omega_p^{3/2} = (8.14 \pm 0.16)\,\mathrm{n}\Omega\,\mathrm{cm}\,\mathrm{K}^{-1}$. On the other hand, using the resistivity data for pure Au as a function of temperature [67] and the previously used value of the plasma frequency $\tilde{\omega}_p = 9.0$ eV [49, 68] we obtain $C/\tilde{\omega}_p^{3/2} = 8.00$. As a result we find for the Au film used in our experiment $\omega_p = (8.9 \pm 0.1)$ eV. Here, the absolute error of 0.1 eV arises from

quire knowledge of the relaxation parameter. The smooth Drude extrapolation of the imaginary part of the Au dielectric permittivity, given by the tabulated optical data [49], yields the relaxation parameter at room temperature $\gamma = 0.0357$ eV (which compares with $\tilde{\gamma} = 0.035$ eV used in previous work [43, 44, 68]).

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

$$\begin{aligned} P^{\text{hyp}}(z) &= -2\pi G \alpha \lambda^2 e^{-z/\lambda} \qquad (24) \\ &\times \left[\rho_g - (\rho_g - \rho_c) e^{-\Delta_g^{(s)}/\lambda} - (\rho_c - \rho_s) e^{-(\Delta_g^{(s)} + \Delta_c)/\lambda}\right] \\ &\times \left[\rho_g - (\rho_g - \rho_c) e^{-\Delta_g^{(p)}/\lambda} - (\rho_c - \rho_{Si}) e^{-(\Delta_g^{(p)} + \Delta_c)/\lambda}\right] . \end{aligned}$$

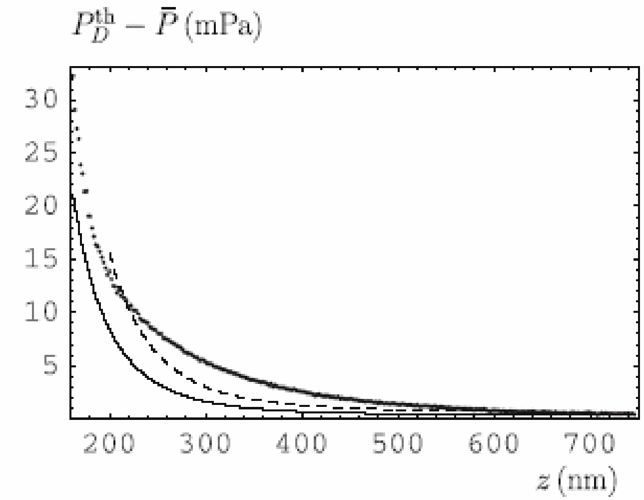
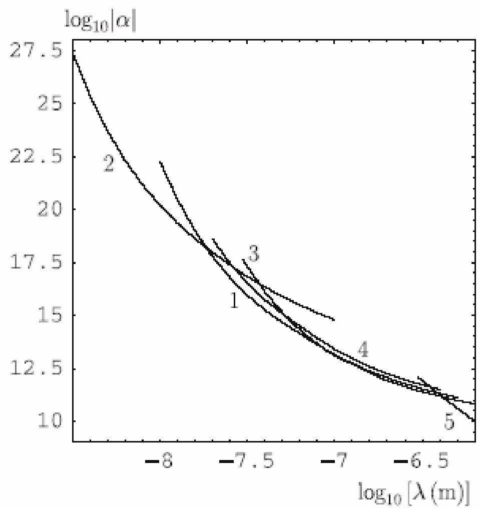
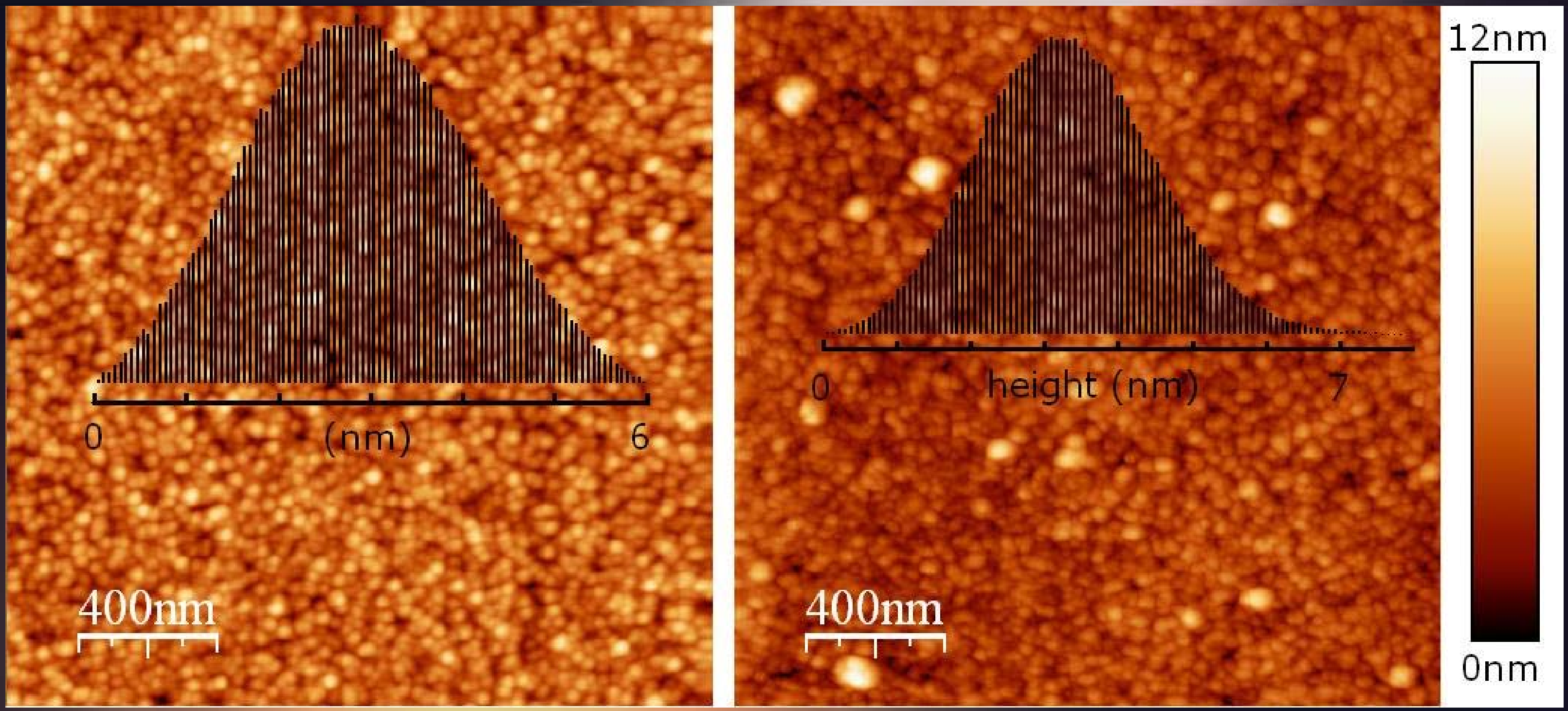


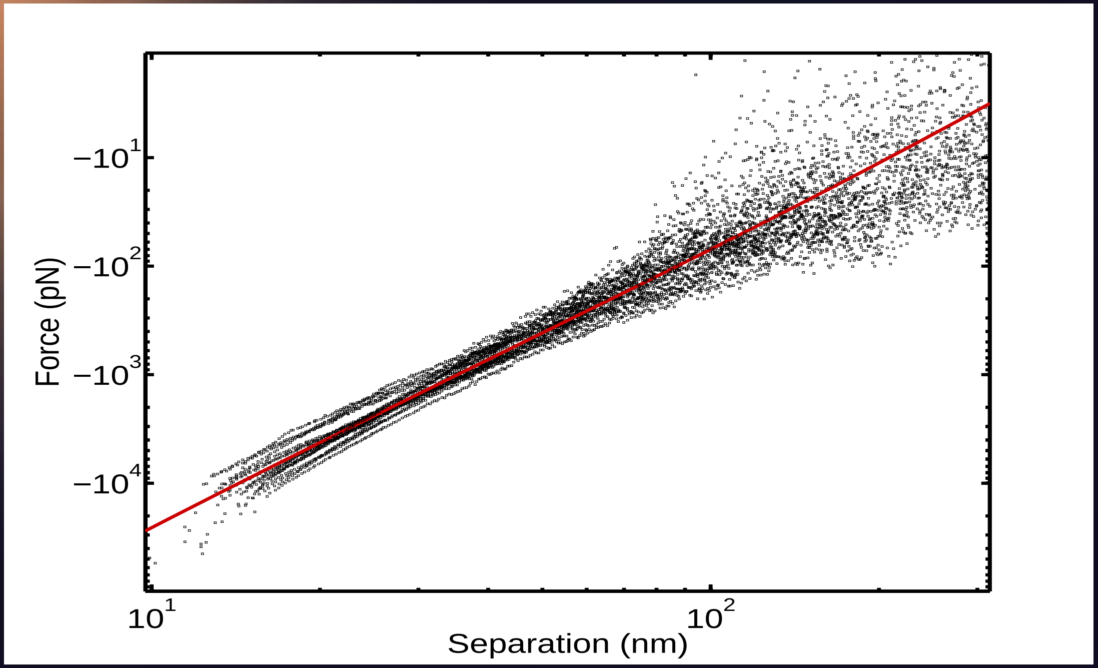
Fig. 5. Differences between theoretical Casimir pressures computed using the Drude model approach and mean experimental Casimir pressures (*dots*) versus separation. The *solid line* indicates the limits of the 95% confidence intervals, while the *dashed line* indicates the limits of the 99.9% confidence intervals

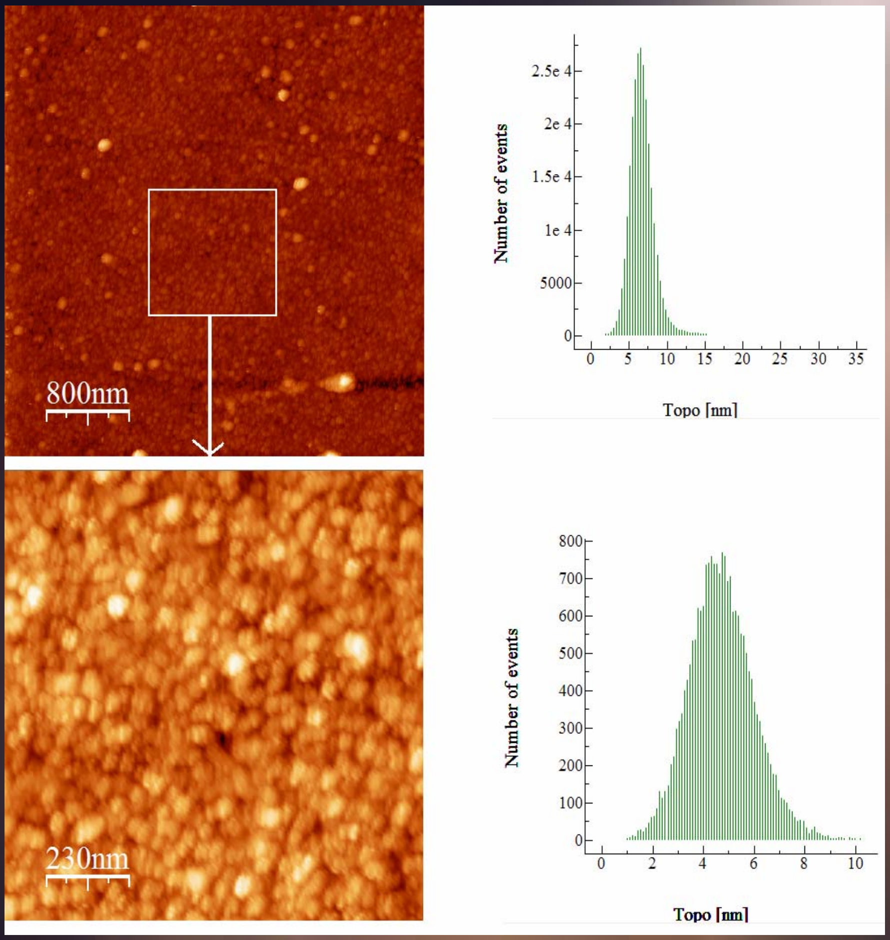


relevant theory. The strongest constraints within the interaction region $10\,\text{nm} \leq \lambda \leq 56\,\text{nm}$ are obtained from the comparison of measurements with theory at a separation $z = 180\,\text{nm}$. With the increase of λ, the strongest con-



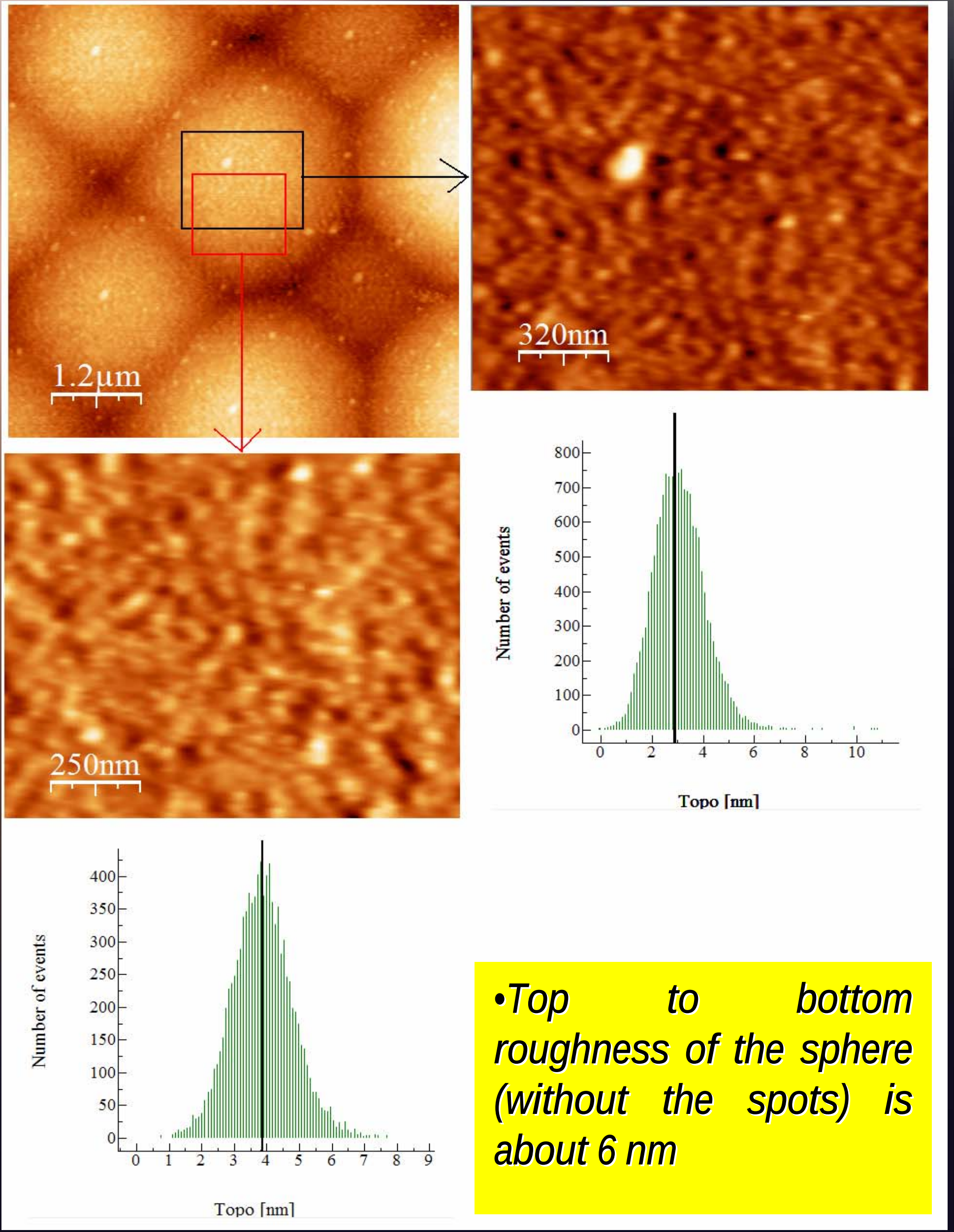
- •Stiff-cantilever→ K=4 N/m
- •Reduce jump-to-contact



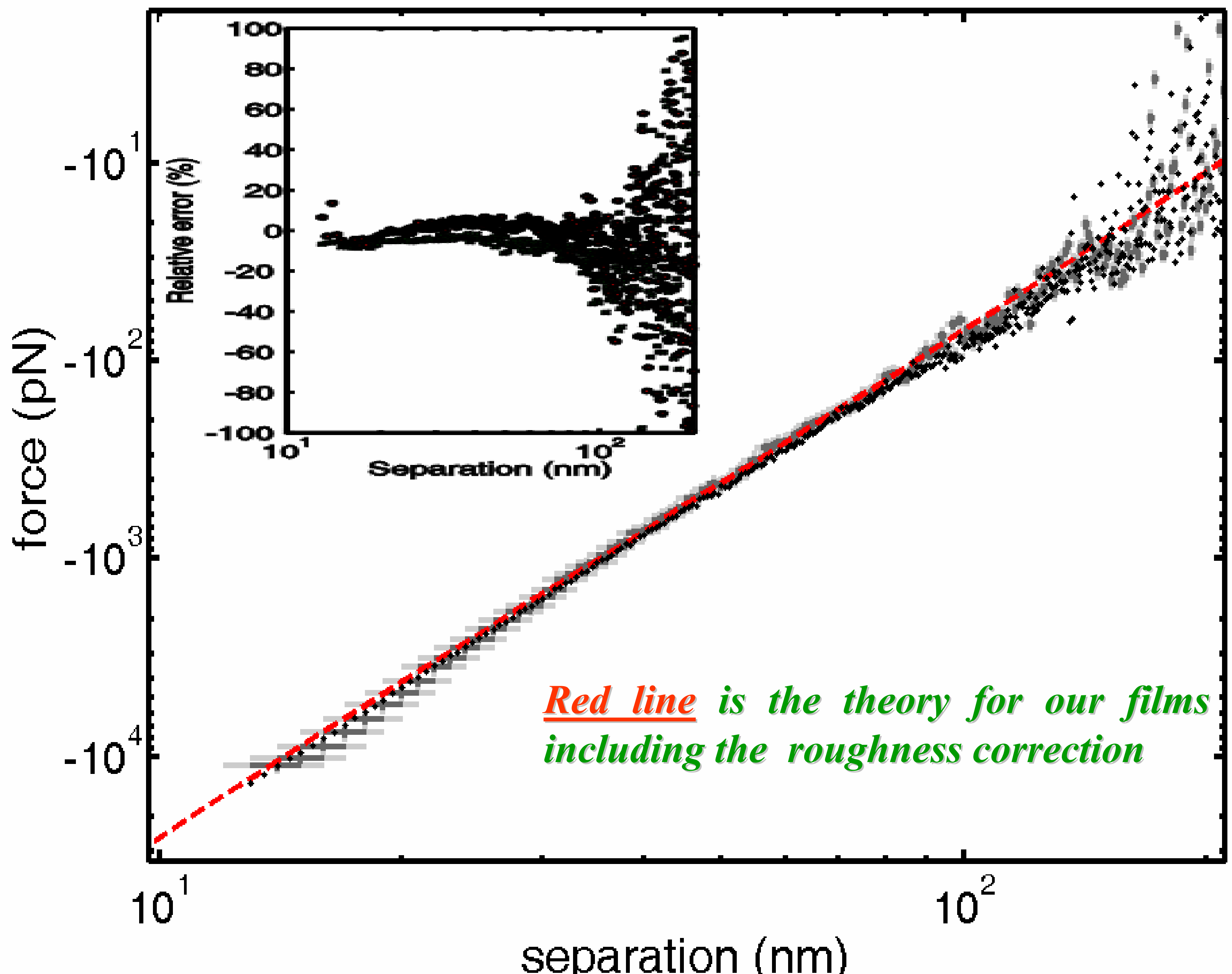


Rms roughness of 2.2 nm without spots → decreases to 1.3 nm.

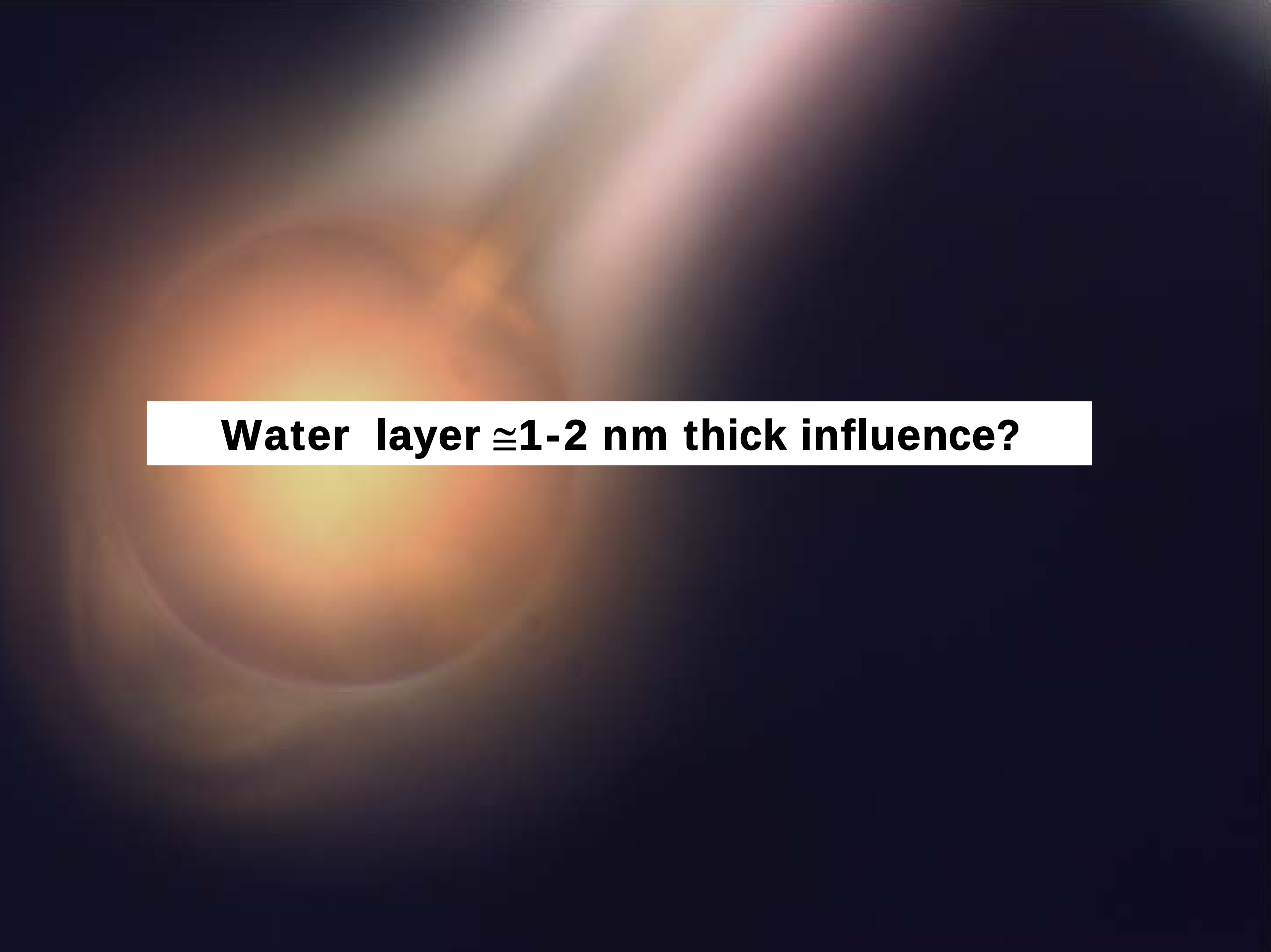
•*<u>we get d_0 = 7.5 nm±1 nm</u>*



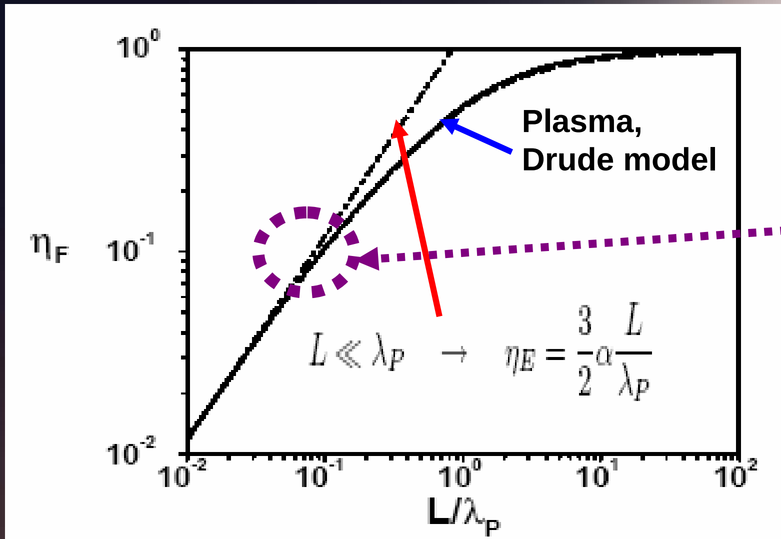
•*Top to bottom roughness of the sphere (without the spots) is about 6 nm*



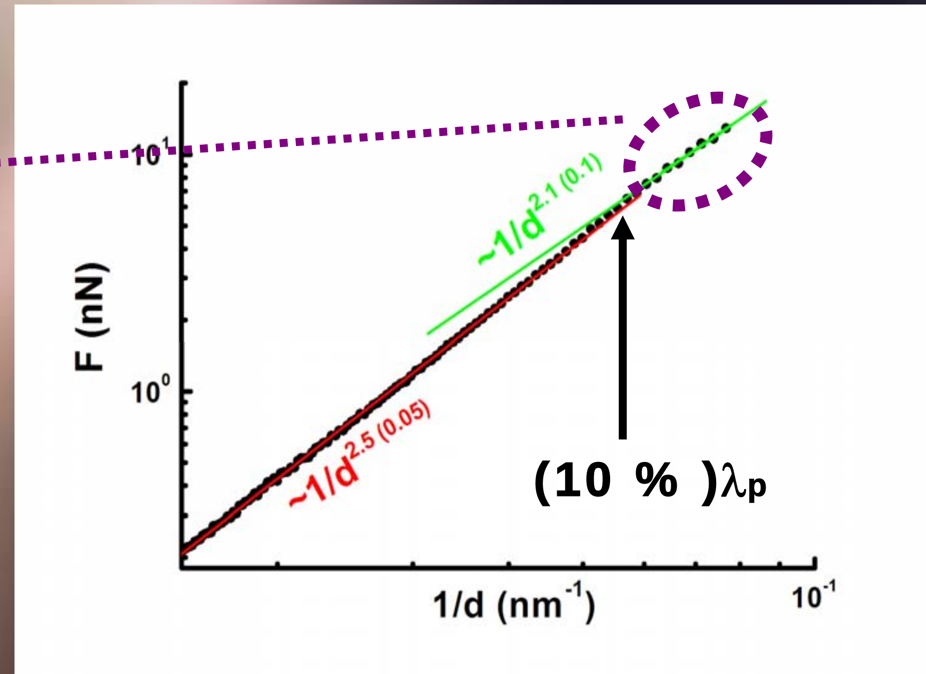
force (pN)
-10^1
-10^2
-10^3
-10^4
10^1
10^2
separation (nm)
Relative error (%)
100
80
60
40
20
0
-20
-40
-60
-80
-100
Separation (nm)
Red line is the theory for our films including the roughness correction



Water layer ≅1-2 nm thick influence?



Lambrecht, Reynaund, E. J. Phs. D (2000)



Palasantzas et al., APL 2008

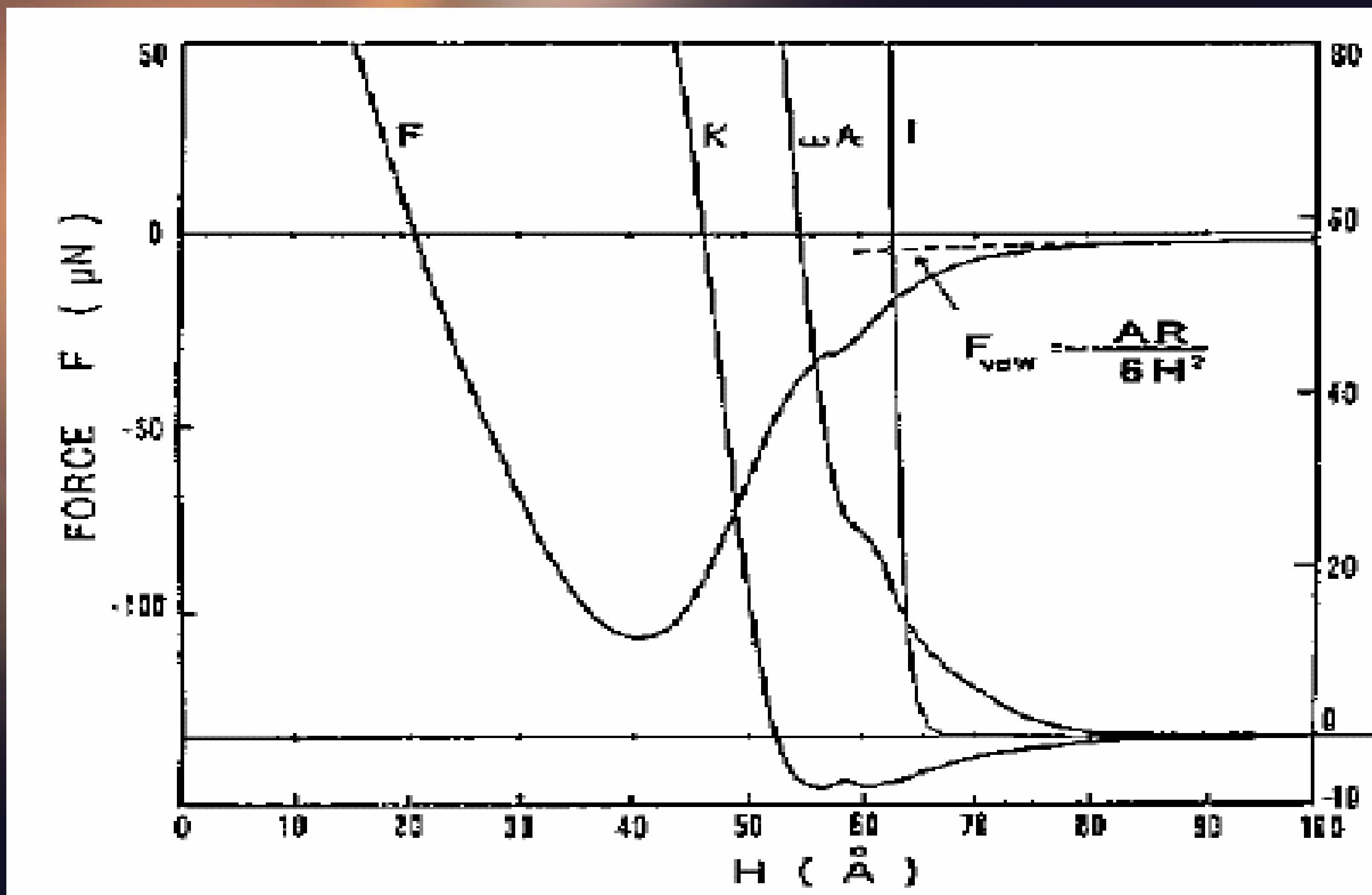
$$F_{vdW} \cong -\frac{A_H R}{6d^2} \rightarrow A_H \approx 29 \times 10^{-20}\ \mathrm{J}$$

surface force apparatus (SFA) → $A_H \approx 28 \times 10^{-20}$ J

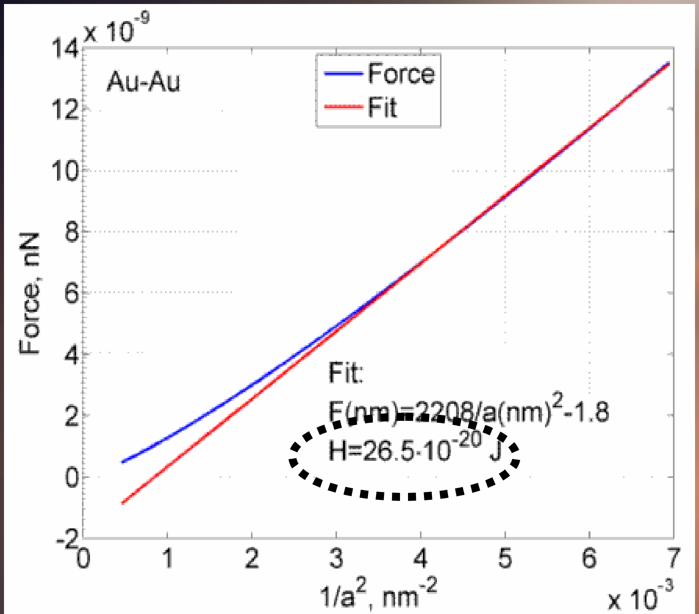
For d> 8.5 nm for Au - roughness of 5–6 nm peak to peak *(Tonckt et al., j. Phys. Con. Mat 1991)* surface force apparatus (SFA) → $A_H \approx 28 \times 10^{-20}$ J

For d> 8.5 nm for Au - roughness of 5–6 nm peak to peak *(Tonckt et al., j. Phys. Con. Mat 1991)*

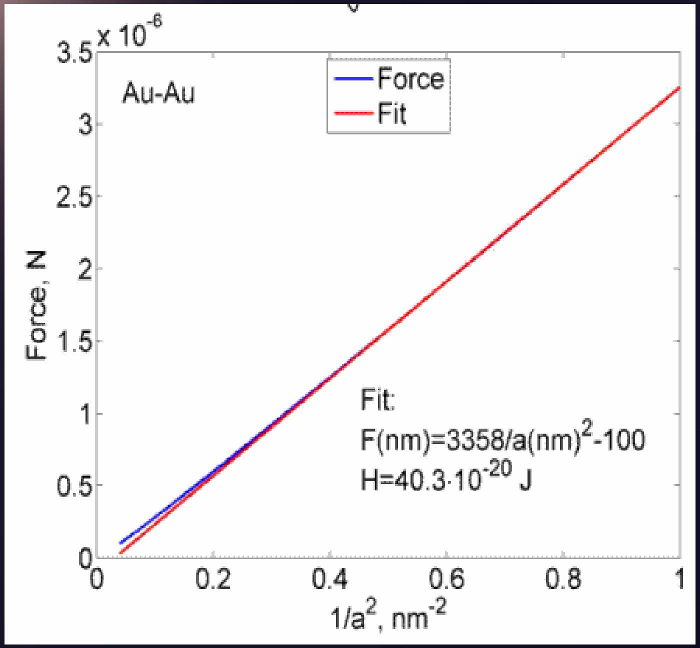
600 Å gold terminal coating. A STM examination of such surfaces shows irregular connected clusters producing a gently bumpy corrugation similar to the 'blackberry' roughness already observed on comparable Au films [12], with peak-to-valley heights of 50–60 Å and a mean distance between adjacent bumps of about 500 Å [13]. After

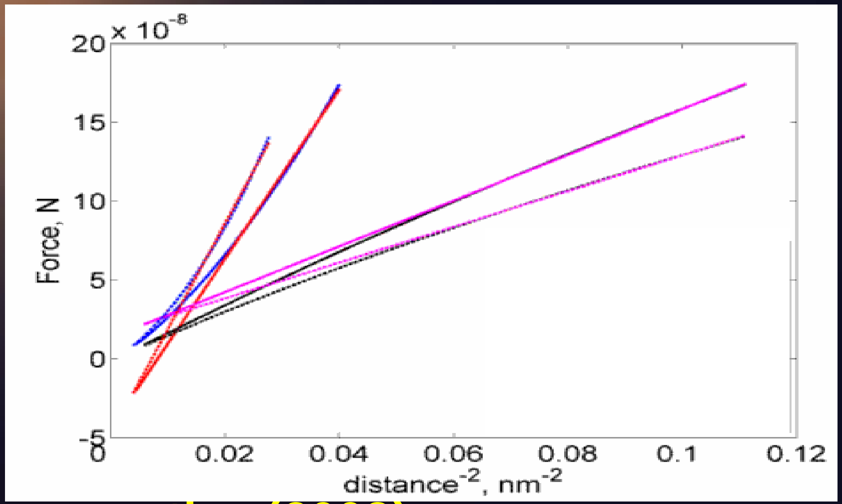


Water layer ≅ 1-2 nm thick influence?



No water





Svetovoy, Palasantzas et al, in preparation (2008)

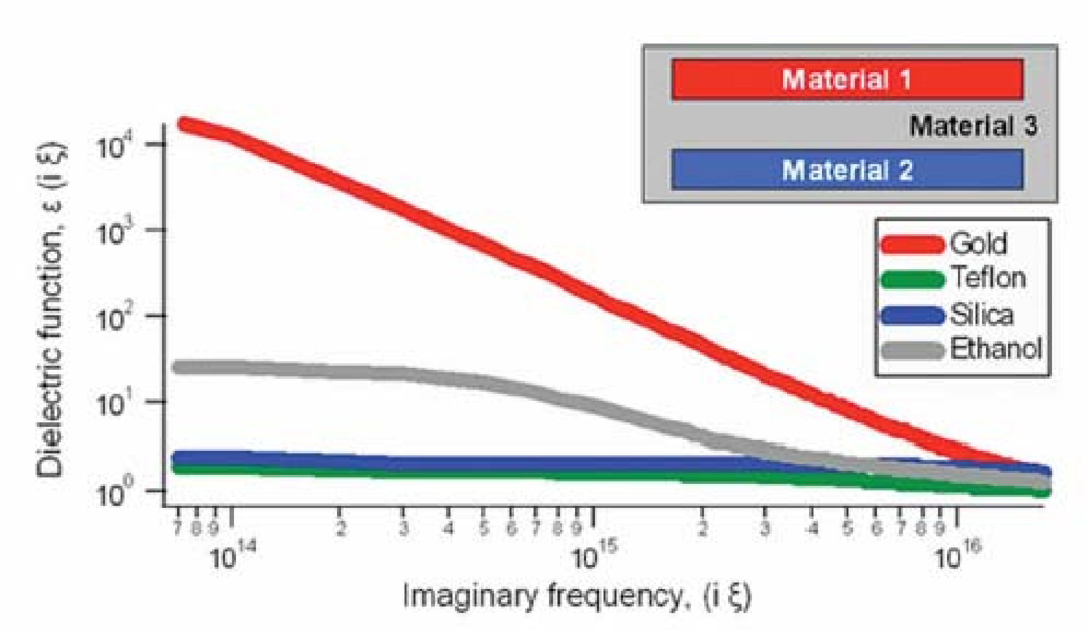
Measurement in liquids-Repulsive – attractive forces

•The Casimir–Lifshitz force is always attractive between two identical materials

•The force can become repulsive when two different materials are submerged in a third medium if→

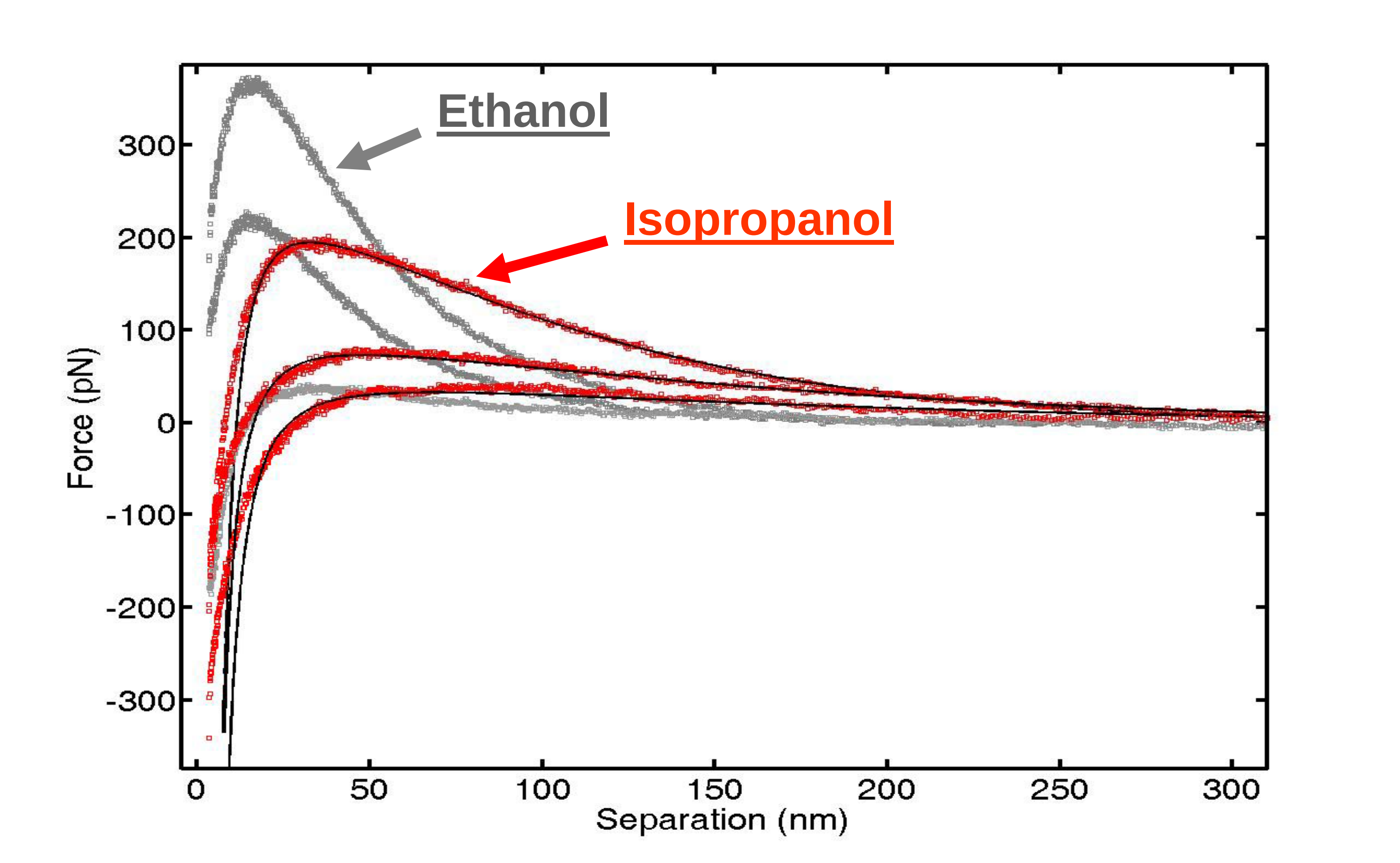
$$\varepsilon_1(i\xi) < \varepsilon_3(i\xi) < \varepsilon_2(i\xi)$$

$$\varepsilon_2(i\xi) < \varepsilon_3(i\xi) < \varepsilon_1(i\xi)$$



F. Capasso et al., IEEE (2007)

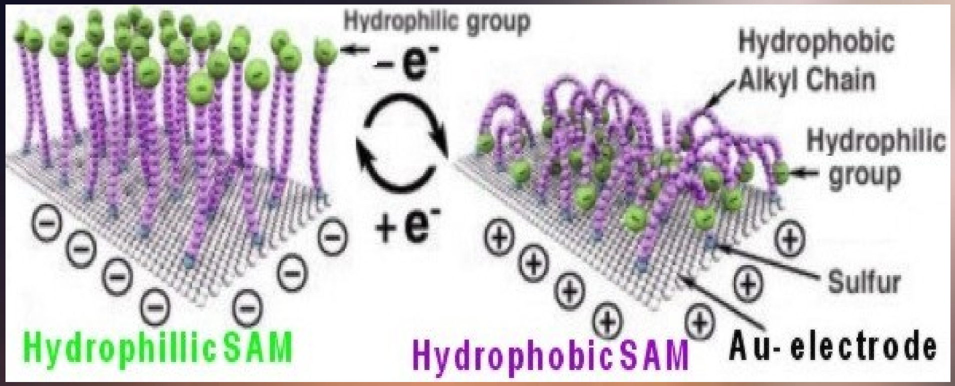
Measurement in liquids

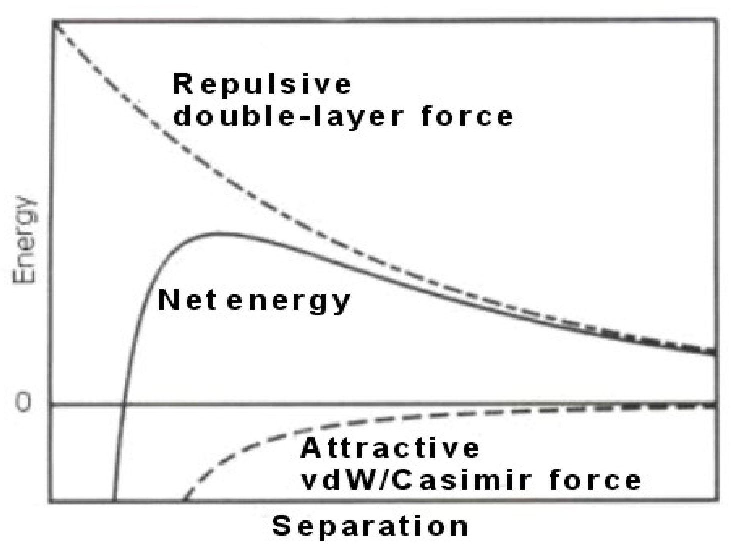


Van Zwol et al., in preparation 2008

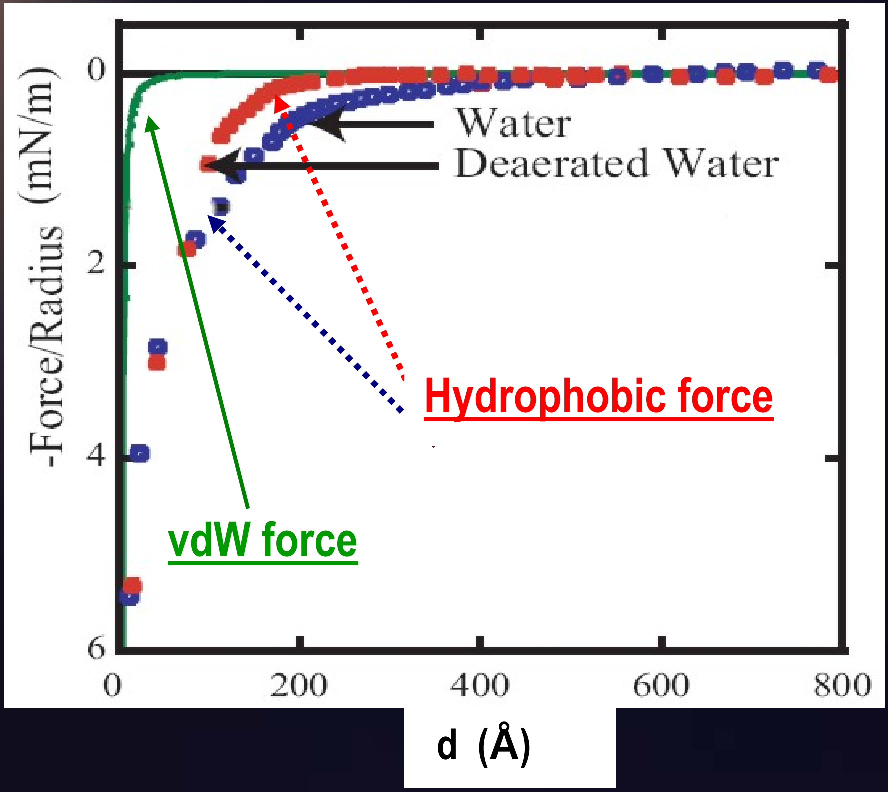
•Control surface chemistry

- Electrostatic forces & double layers
- Hydrophobic interactions





double-layer + vdW interaction energy



CONCLUSIONS

- → Surface roughness & optical properties affect forces
- → Short range forces → do better estimation – Inverse AFM
- → Change optical properties → modulate forces
- → Understanding water layer influence & force measurement below 10 nm
- → Mesurements in liquids …..separations < 10 nm
- →For the future ……stll a lot to be understood for vacuum engines, dark energy etc… !!!