Near-field radiative heat transfer and Casimir Force Measurement

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Radiative heat transfer at the nanoscale

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Probing near-field thermal radiation

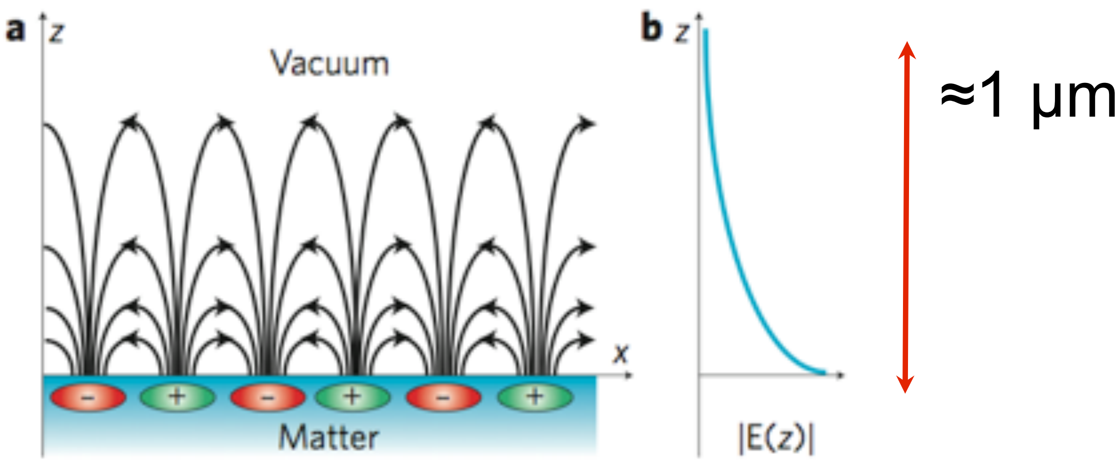
New insights into the behaviour of radiative heat transfer at the nanoscale have now been made, thanks to highly precise measurements made using scanning probe microscopy.

Achim Kittel

News and views Nature Photonics

In 1900, Max Planck used quantum theory to explain the puzzling nature of the spectral density of thermal far-field radiation.

However, Planck realized that the situation becomes more complex in the near-field regime, where the distance between two bodies is comparable to the characteristic wavelength of thermal radiation (that is, the sub-micrometre range).



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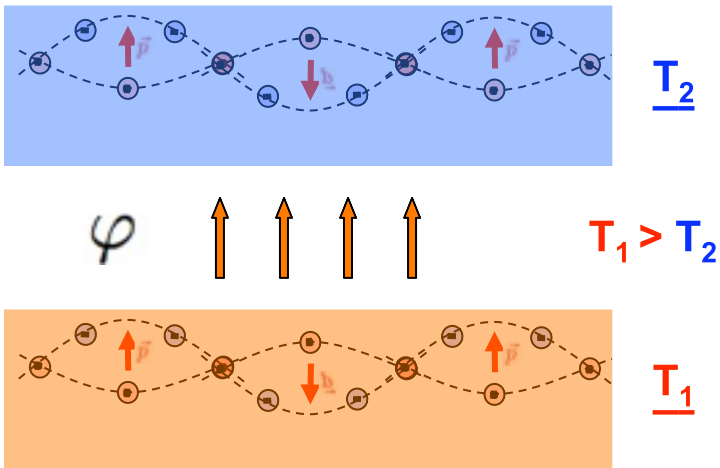
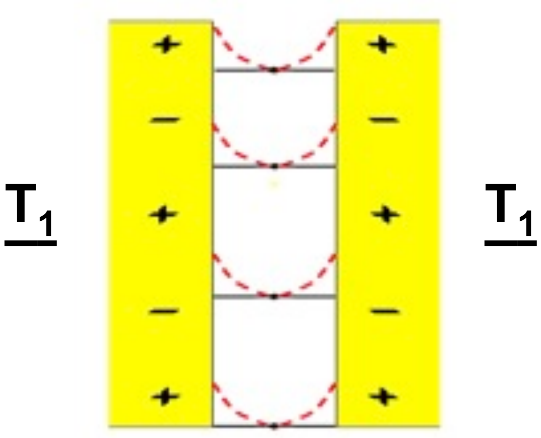

T2
φ
T1 > T2
T1

Casimir force and radiative heat transfer: two phenomena with the same origin

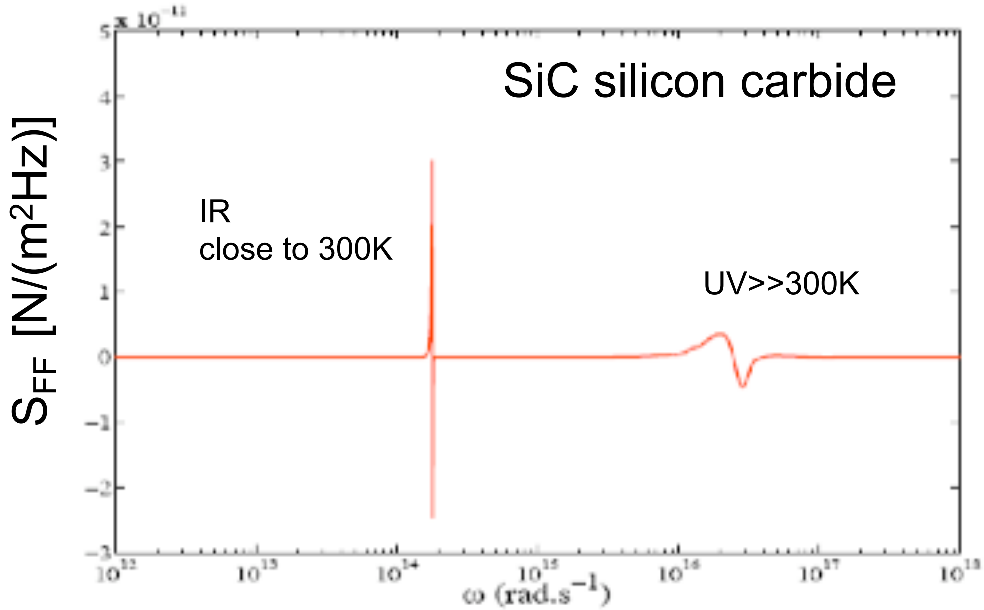
Casimir force at short distances:

10 nm SiC/SiC plane/plane geometry

C. Henkel et al 2004 PRA



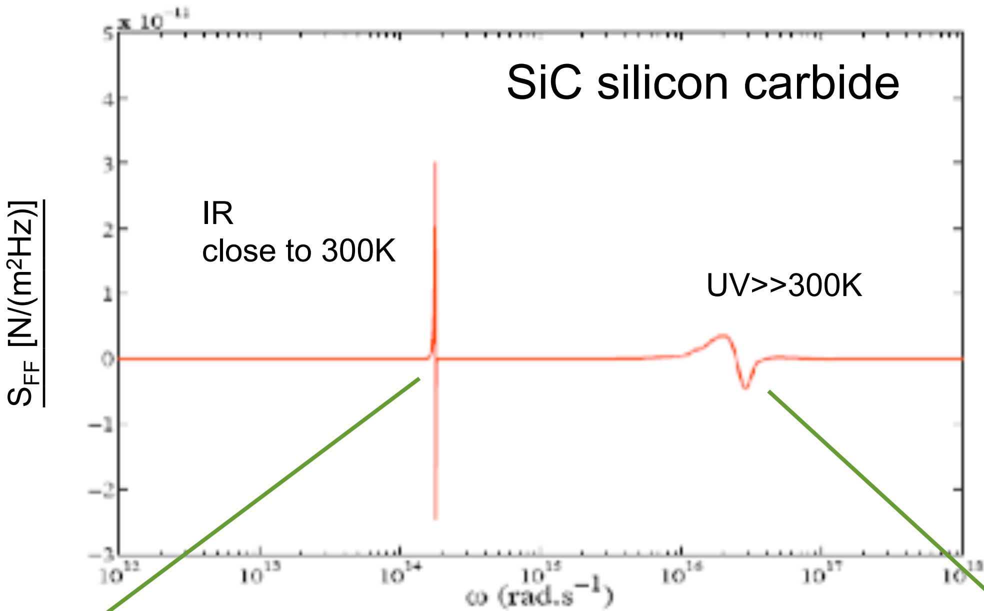
d=10nm



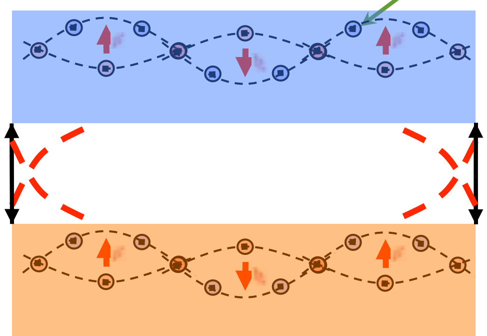
Casimir force power spectrum

FIG. 1: Contributions of s and p polarized, propagating and evanes cent modes to the force spectrum (Eq. (2)) integrated over th wavevector u). Distance $d = 10$ nm. Material: SiC, dielectric func tion taken from tabulated data [23]. The corresponding surface reso nances ($\mathrm{Re}\,\varepsilon(\omega) = -1$) are located at $1.78 \times 10^{14}\ \mathrm{s}^{-1}$ in the IR an $2.45 \times 10^{16}\ \mathrm{s}^{-1}$ in the UV

Casimir force and radiative heat transfer: two phenomena with the same origin



Casimir force power spectrum

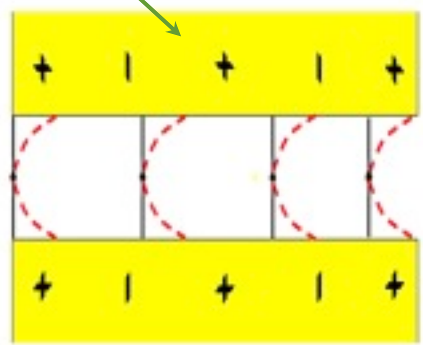


ion/ion resonance

hw ≅ kT

phonon polariton

m/M

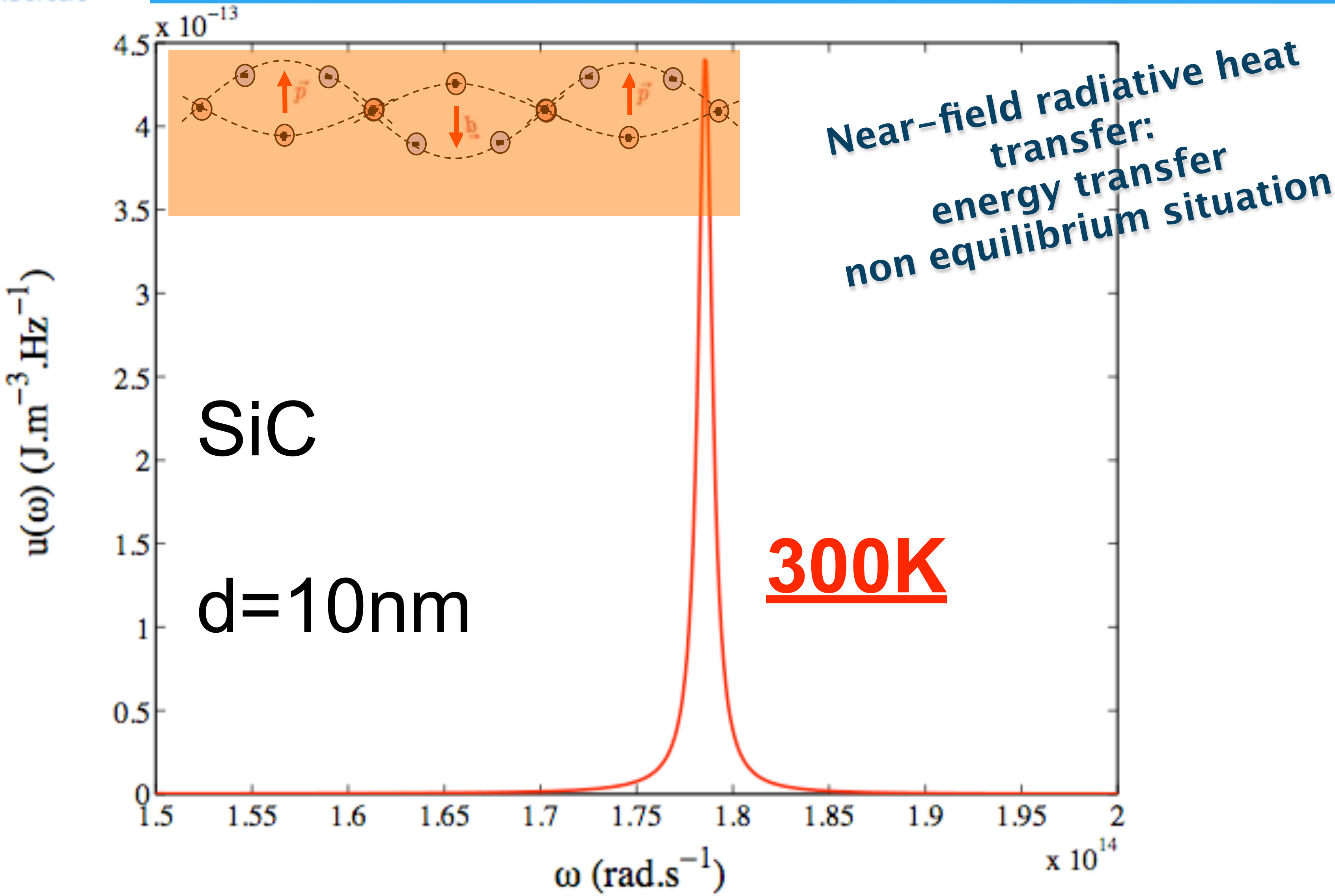


electron/ion resonance

hw >> kT

plasmon polariton

Casimir force and radiative heat transfer: two phenomena with the same origin



Thermal energy density in near field regime at 300K

Dielectric materials: surface Phonon-Polariton enchantement effect

Density of energy near a SiC-vacuum interface

Far field: the energy density well reproduces the Planck black body theory

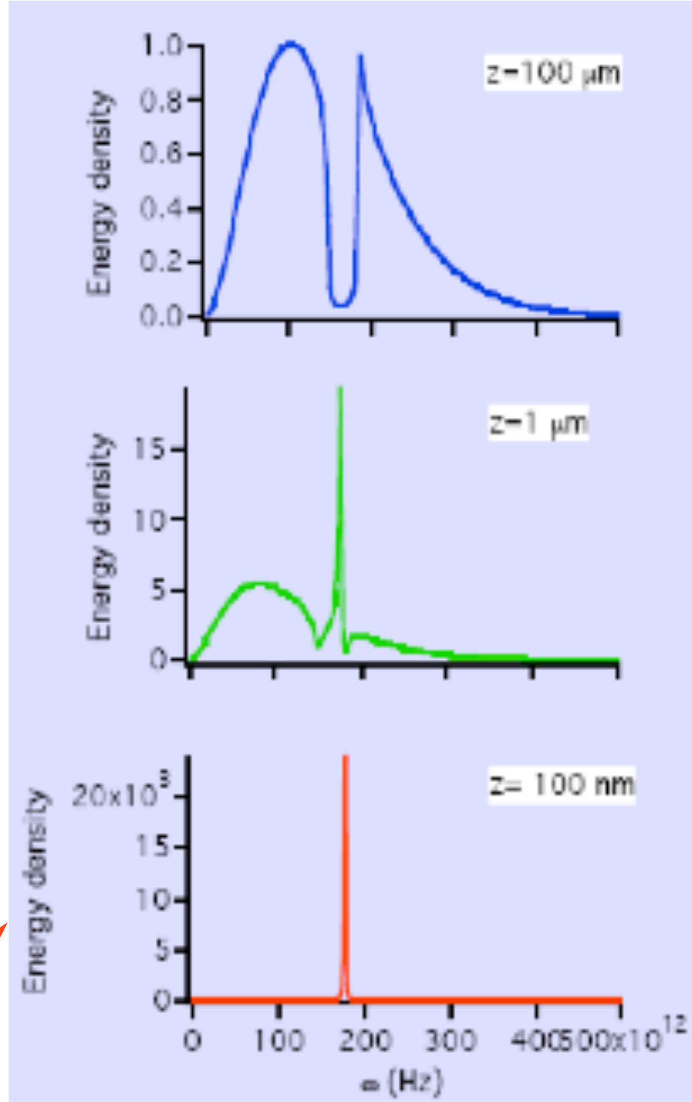
propagating waves

orders of magnitude

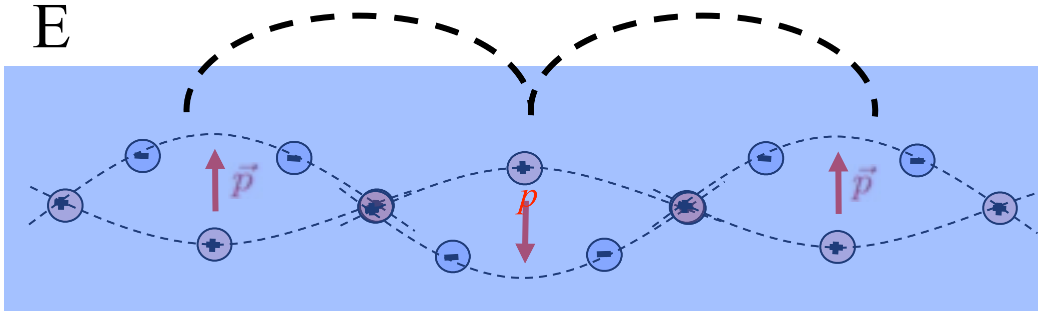
Near field: the energy density exceeds the Planck black body theory

evanescent waves

*PRL, **85** p 1548 (2000)*



Dielectric materials: surface Phonon-Polariton enhancement effect



Surface waves: described by dielectric constant $\varepsilon(\omega)$

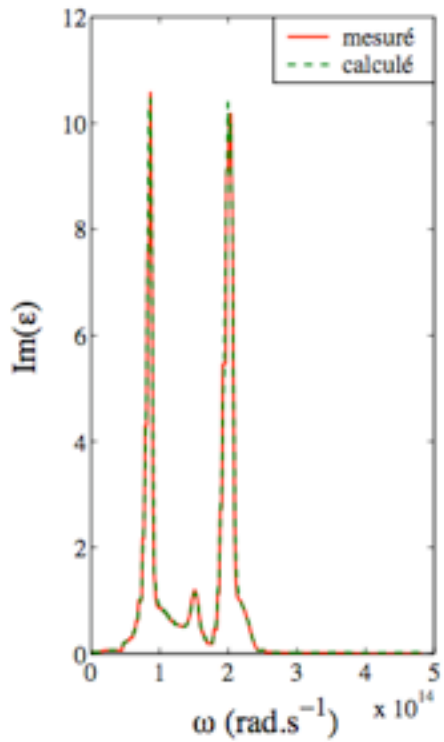
Infra-red resonance

(SiC, silica= glass)

Radiative thermal transfer

dominated by the resonance effect

Sheng Shen et al. Nano Letters July 2009



flat Glass

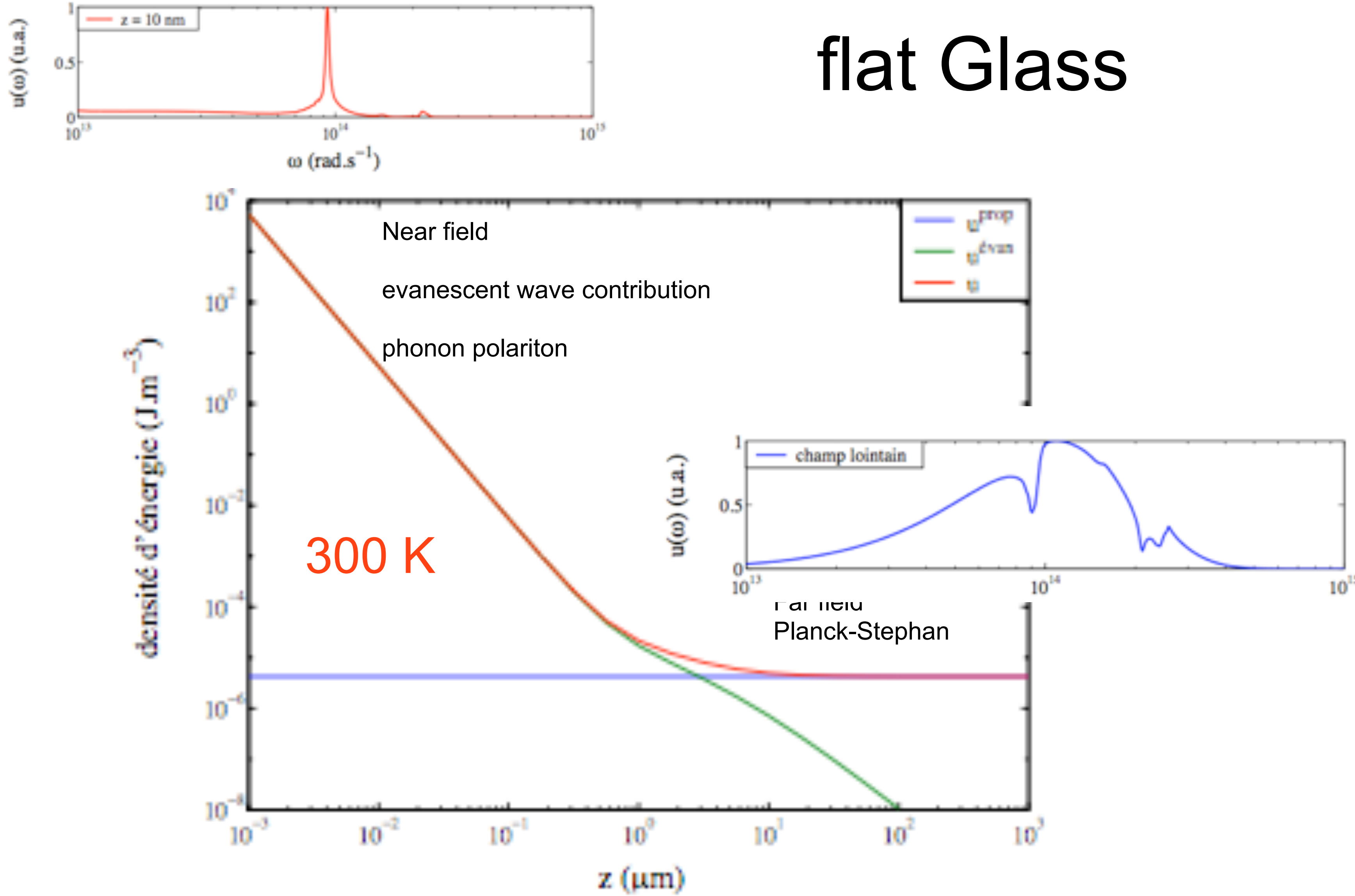


Fig. 2.16 – *Densité d'énergie électromagnétique au-dessus d'une interface plane de verre à la température de 300 K : contribution des ondes propagatives et évanescentes en fonction de la hauteur z d'observation.*

Dielectric materials: surface Phonon–Polariton enhancement effect

Theoretical estimation

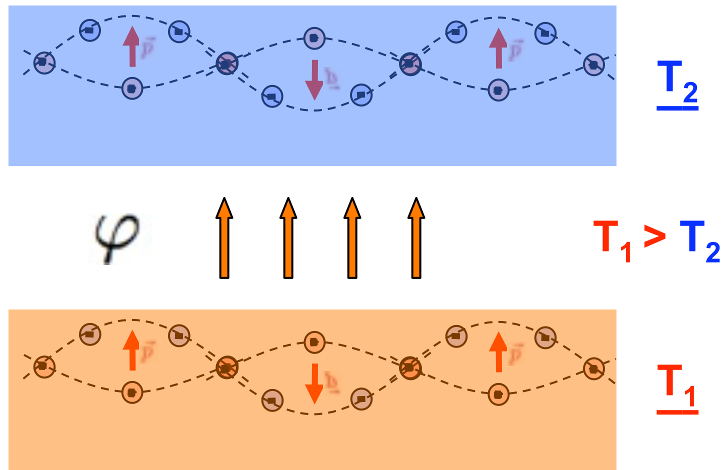
Plane-Plane geometry

see method and results in:

J. Ph. Mulet PhD thesis

and
papers from

JJ Greffet group

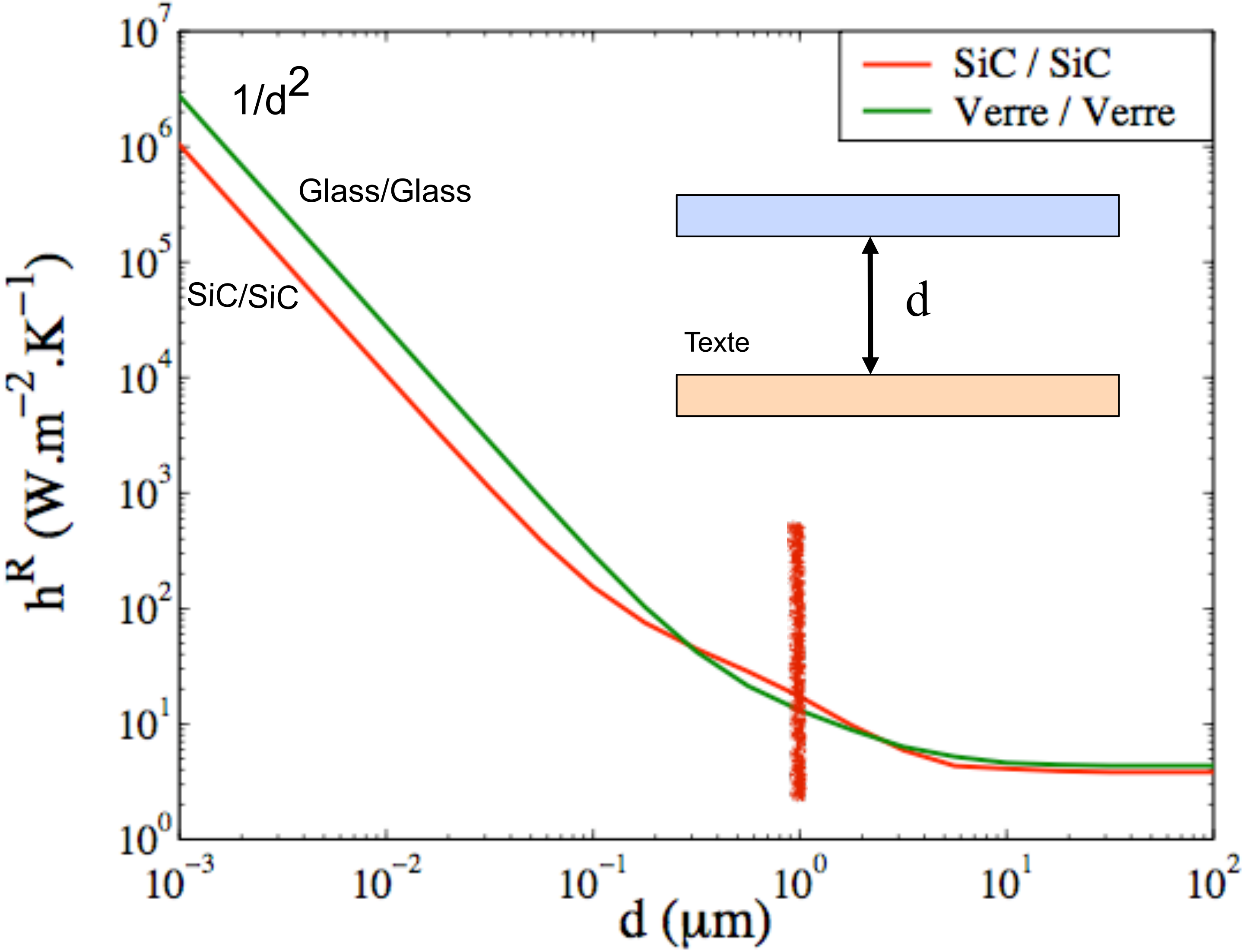


$$P(d,\omega,T_1,T_2) = \langle \Pi_z(d^+,\omega)\rangle - \langle \Pi_z(0^-,\omega)\rangle$$

$$h^R_\omega(d,T_1) = \lim_{T_2\to T_1} \frac{P(d,\omega,T_1,T_2)}{T_1 - T_2} \quad (\mathrm{W.m^{-2}.K^{-1}.Hz^{-1}})$$

$$h^R(d,T) = \int_0^\infty \mathrm{d}\omega\, h^R_\omega(d,T)$$

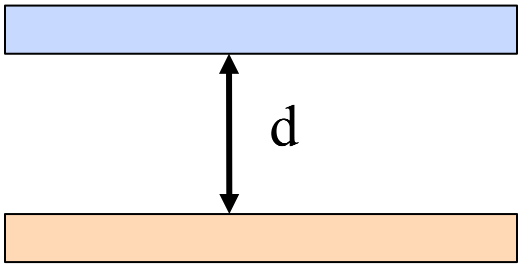
evanescent and propagative waves included

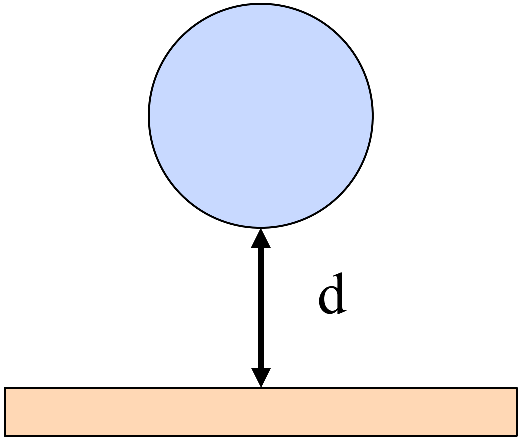


see method and results in J. Ph. Mulet PhD thesis
from JJ Greffet group

Plane-plane geometry:

experimental issue





Plane-Plane

Theory developed

BUT

Parallel planes: very hard

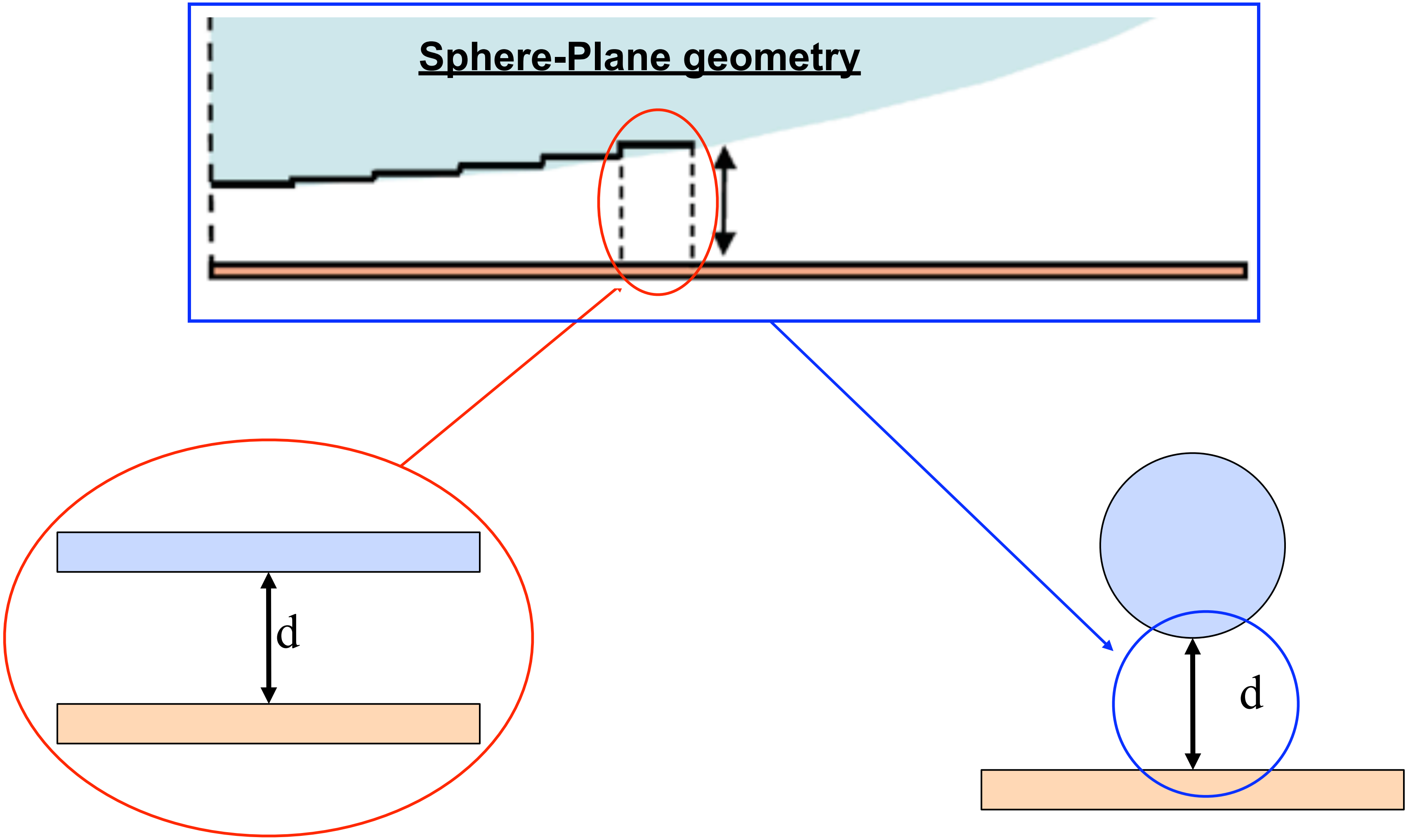
Plane-sphere

Experimentally possible

BUT

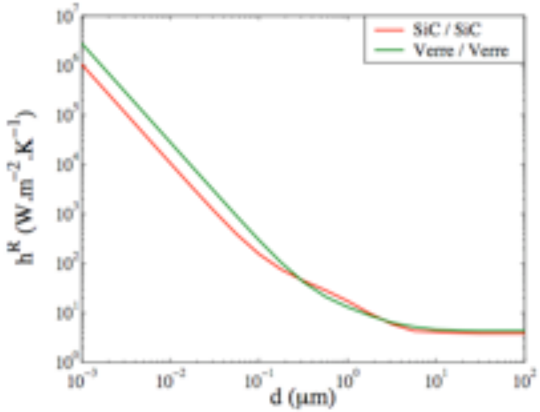
Theory not yet developed

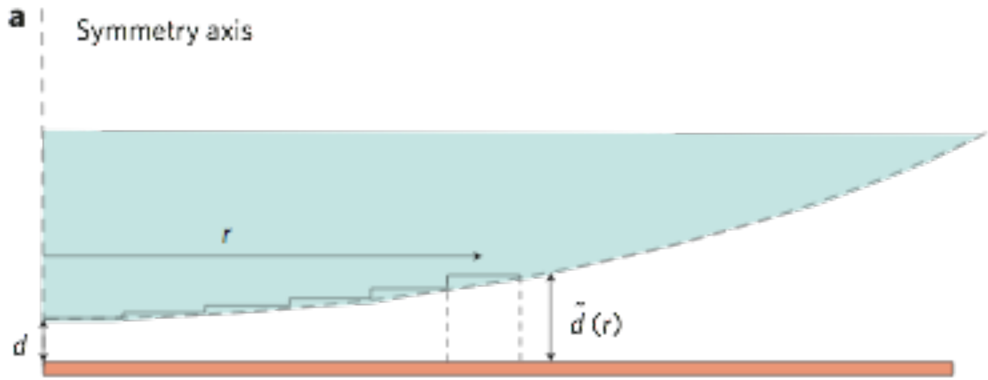
Sphere-Plane geometry: theory



Proximity force approximation

Sphere-Plane geometry: theory

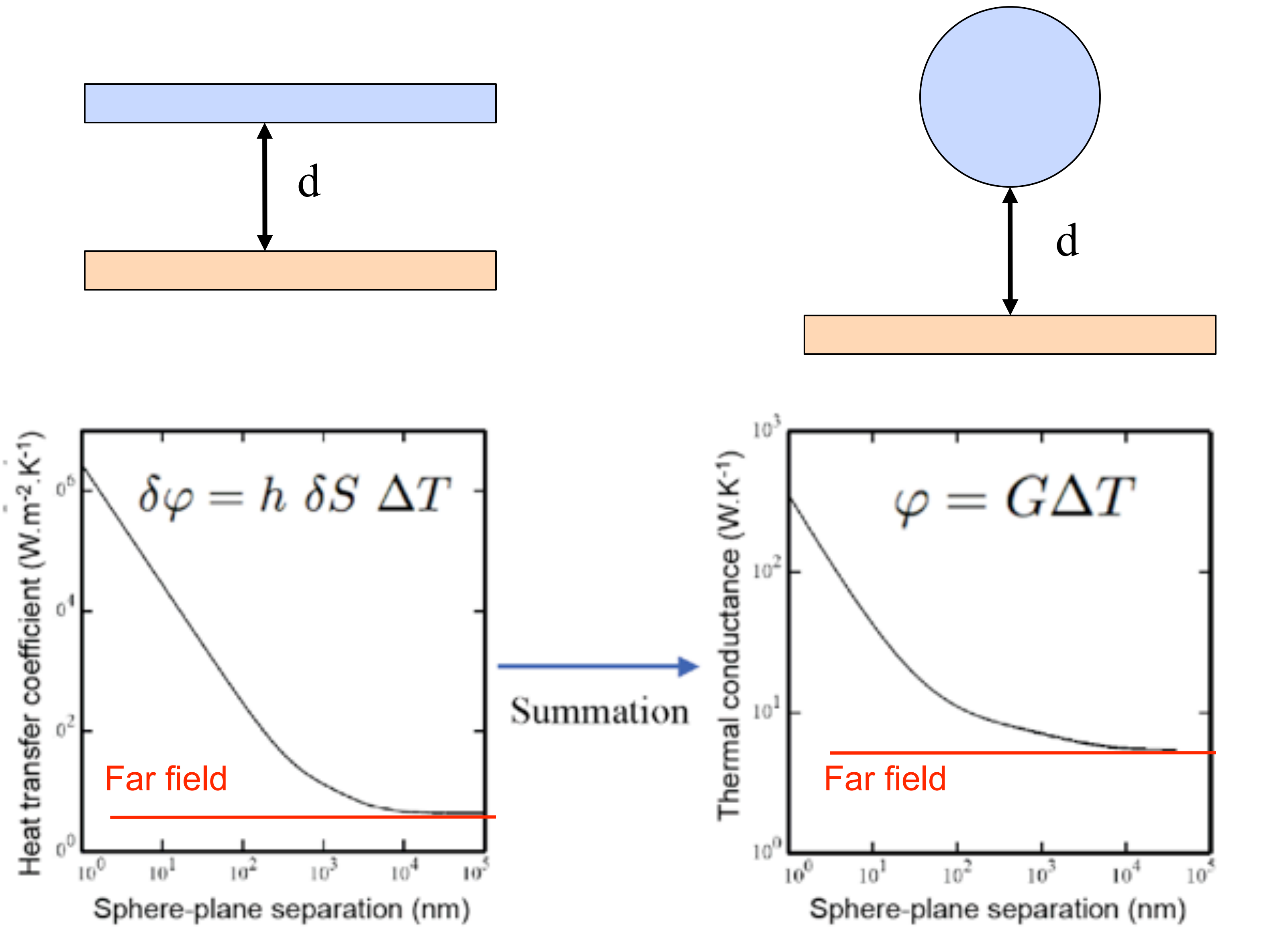




$$G_{\text{theo}}(d,T) = \int_0^R h[\tilde{d}(r),T]\,2\pi r\,\mathrm{d}r$$

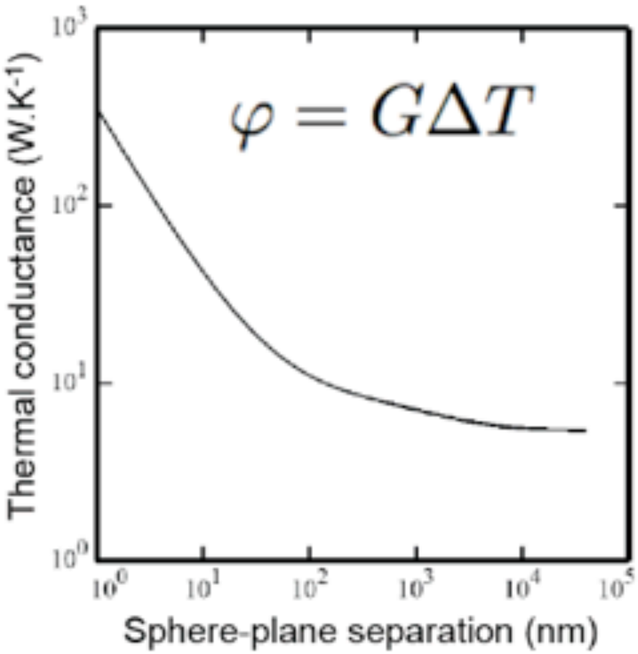
Vacuum thermal conductance at all distances in PFA (local)

Sphere–Plane geometry: theory



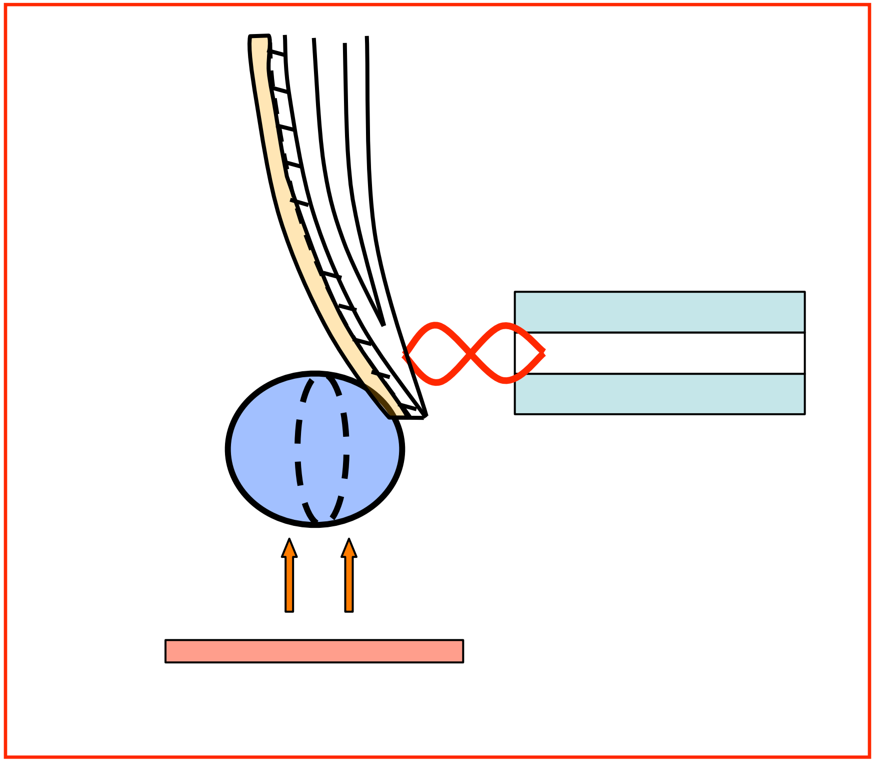
<u>Proximity force approximation</u>

Switch to radiative heat transfer measurement…

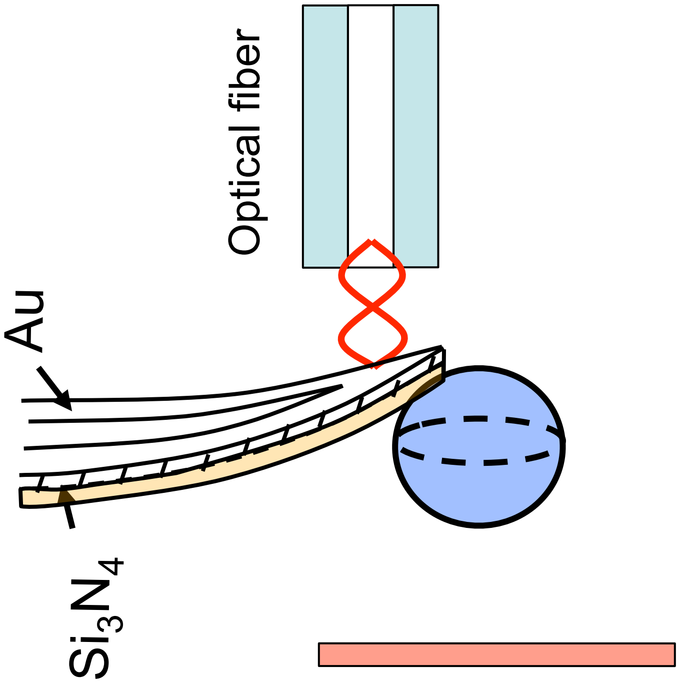


What we want to measure

How we want to measure



Experimental set-up

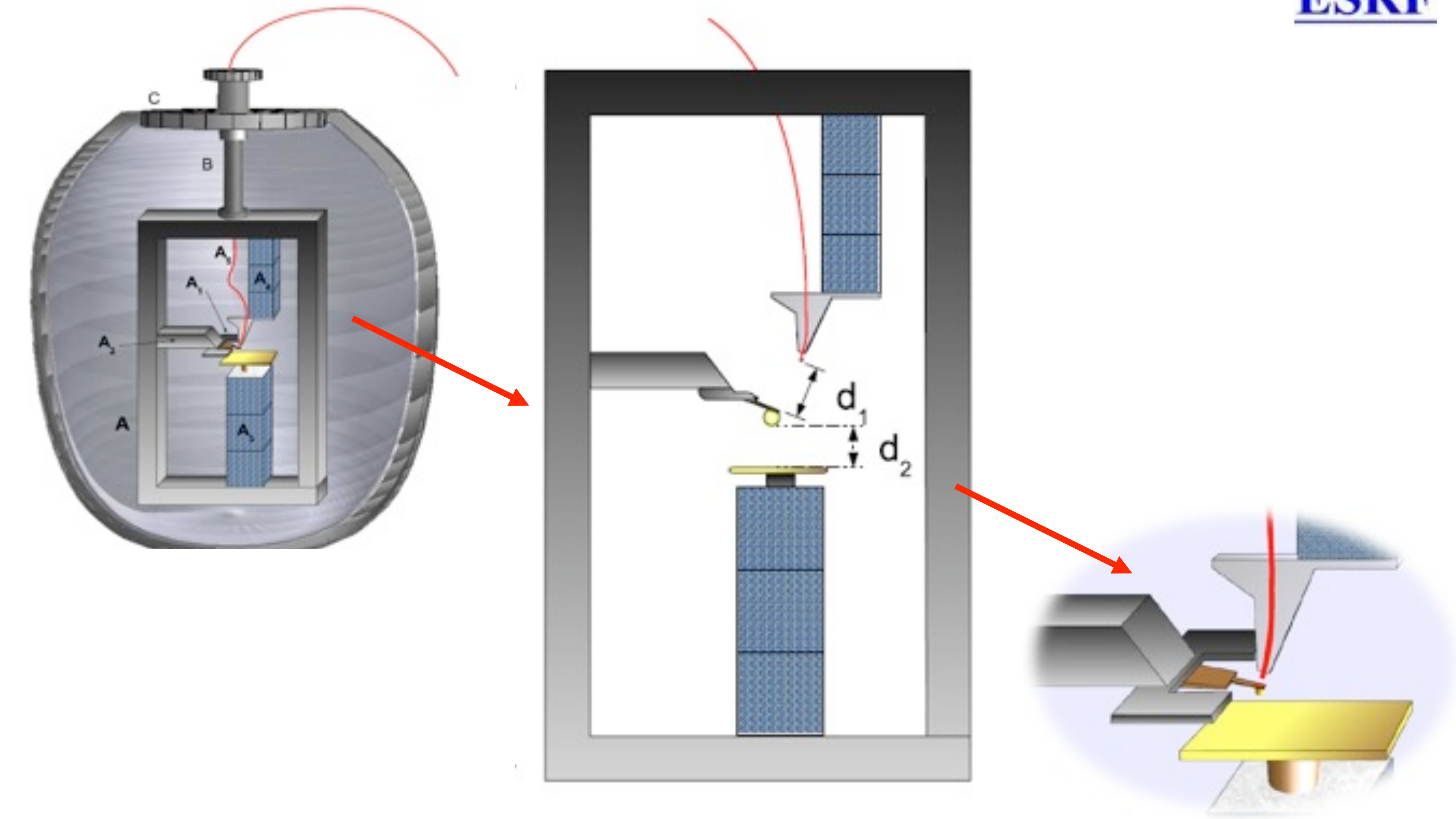


starting with our Casimir set up

from Guillaume Jourdan thesis

EPL **85** No 3 (February 2009) 31001
Phys. Rev. Lett. **101**, 133904 (2008)
Nanotechnology **19** No 44 (5 November 2008)
Nanotechnology **18** No 47 (28 November 2007)

Room temperature Casimir Machine



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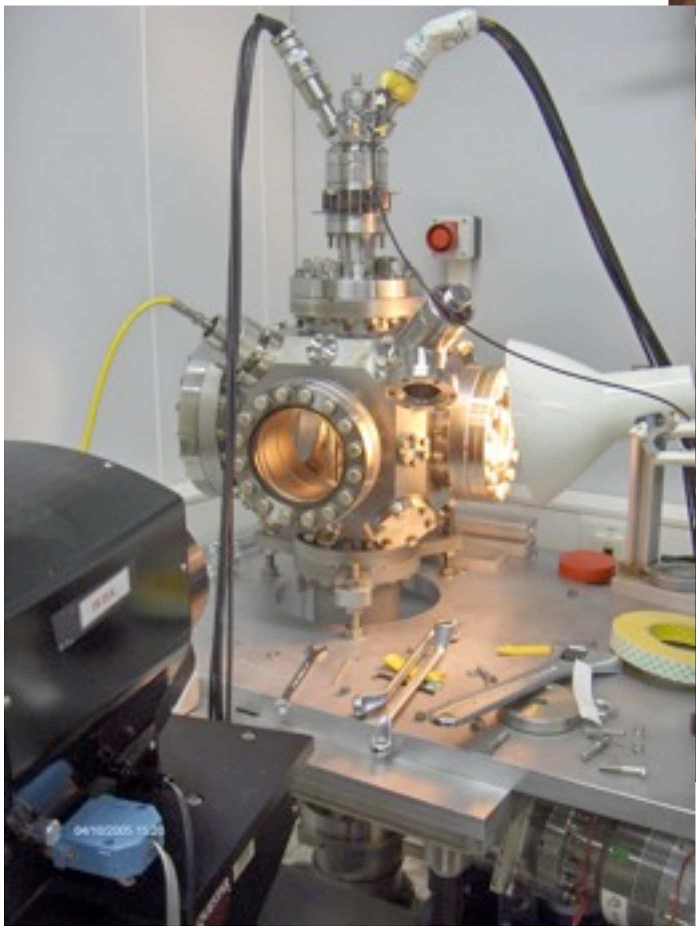
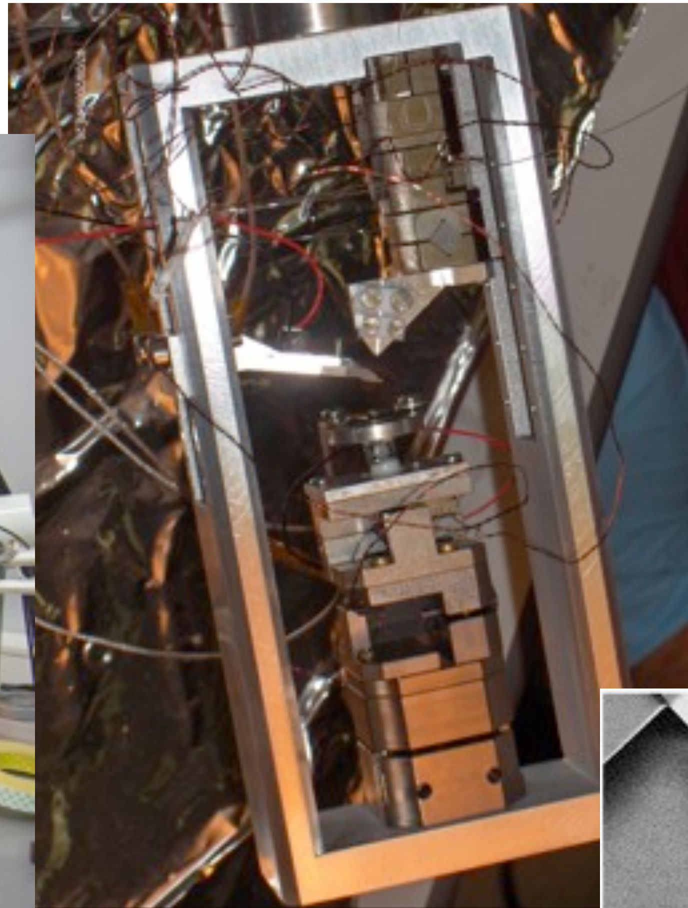
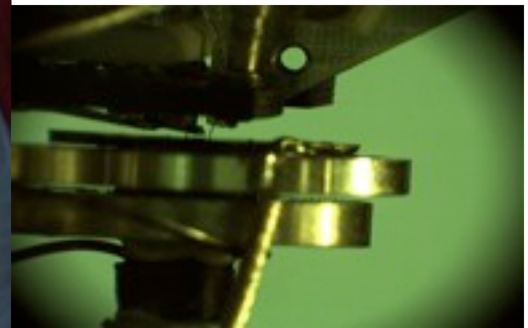
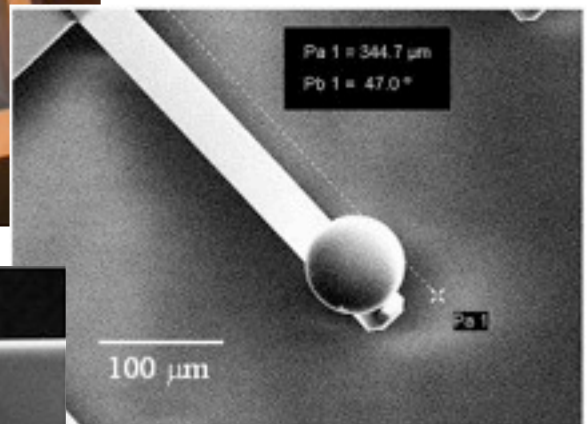
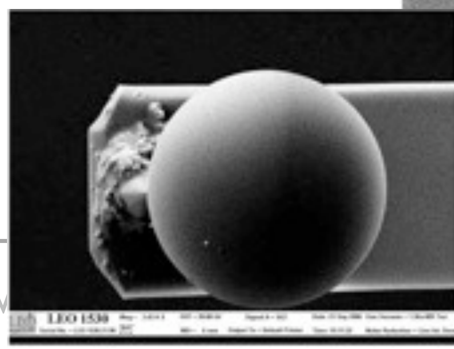










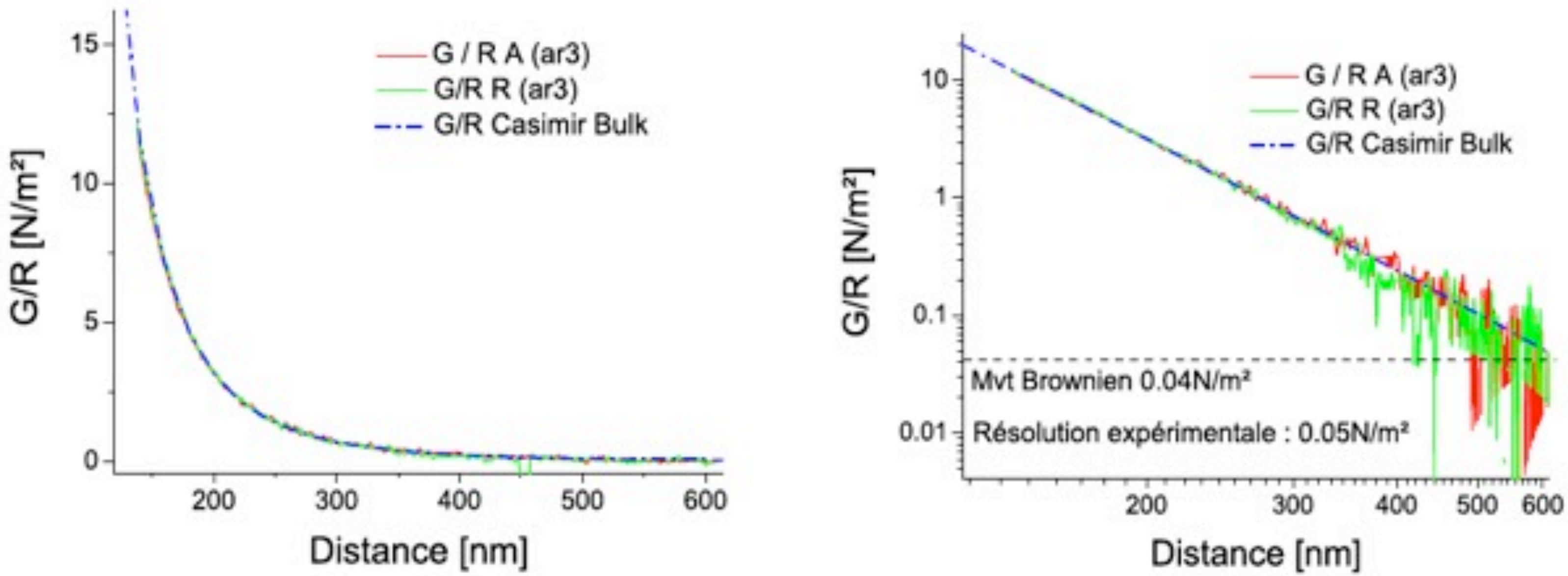
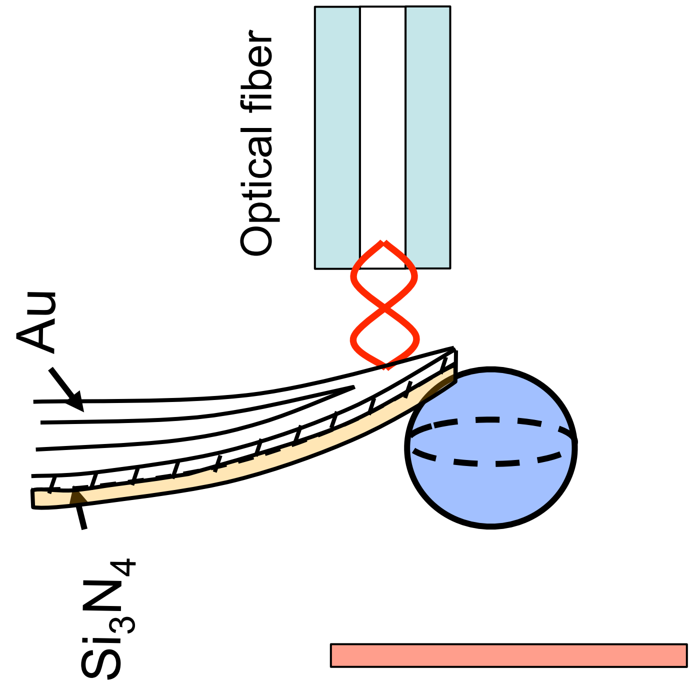


FIG. 1.27 – Mesure de Gradient de force de Casimir : mesure 2

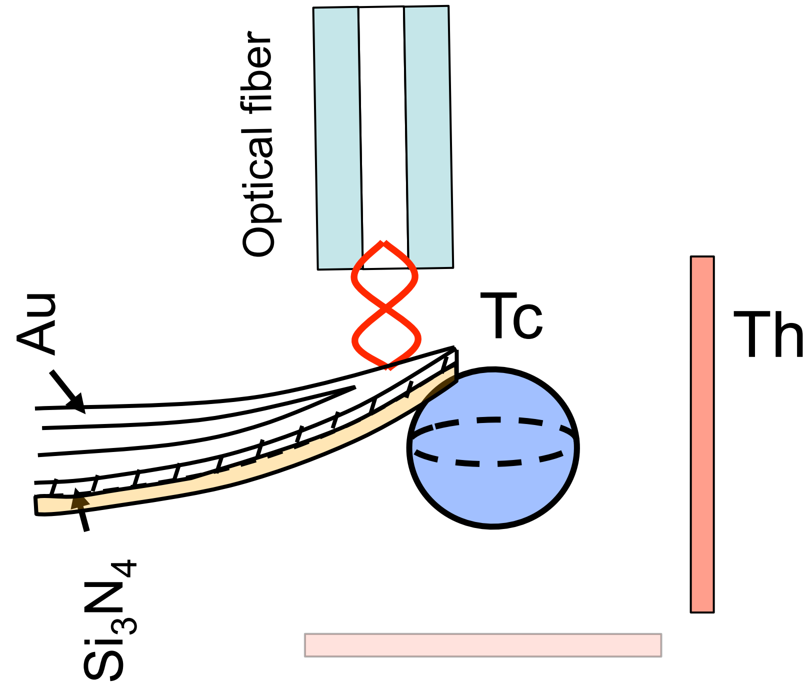
Les deux graphes ci dessus présentent une mesure de gradient de force réalisée avec un temps de filtrage de 500ms. *La vitesse de balayage étant de* 1.9nm/s, *le gradient de force expérimental est dans ces conditions lissé sur* 1nm *environ : La figure se compose d'une courbe d'approche* (G/R_s *A*), *d'une courbe de retrait* (G/R_s *R*) *et du modèle théorique* (G/R_s *Casimir Bulk*).

Experimental set-up



Gold sphere
Gold plane

Casimir set up

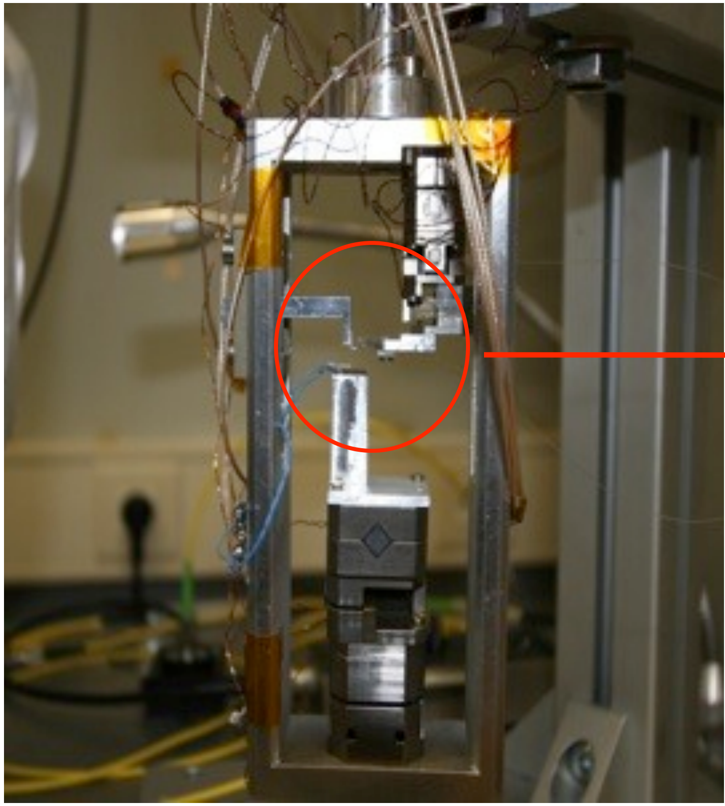


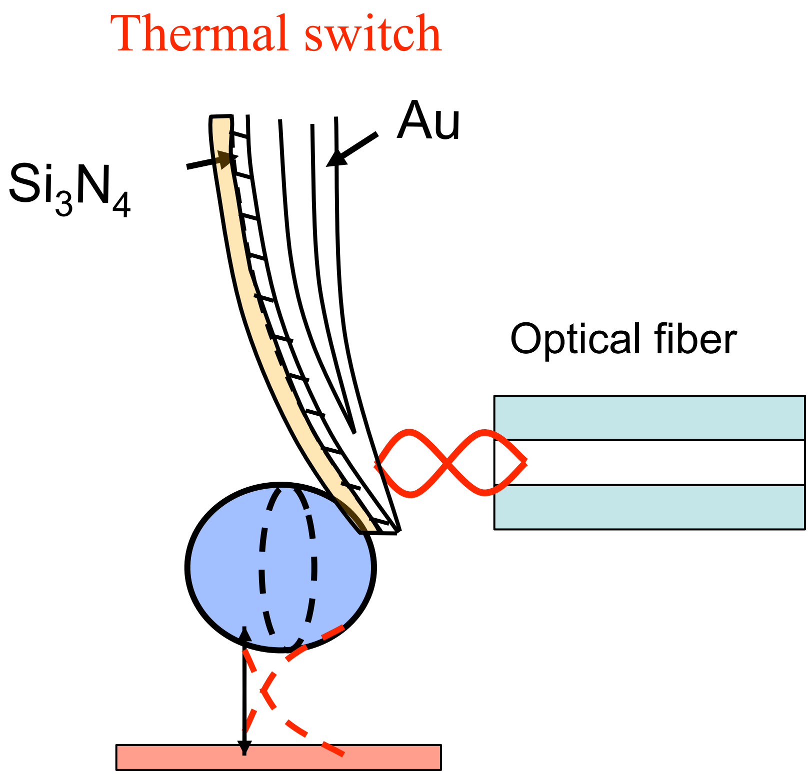
Glass sphere
Glass plane

Static measurement

Thermal transfer set up

Experimental set-up



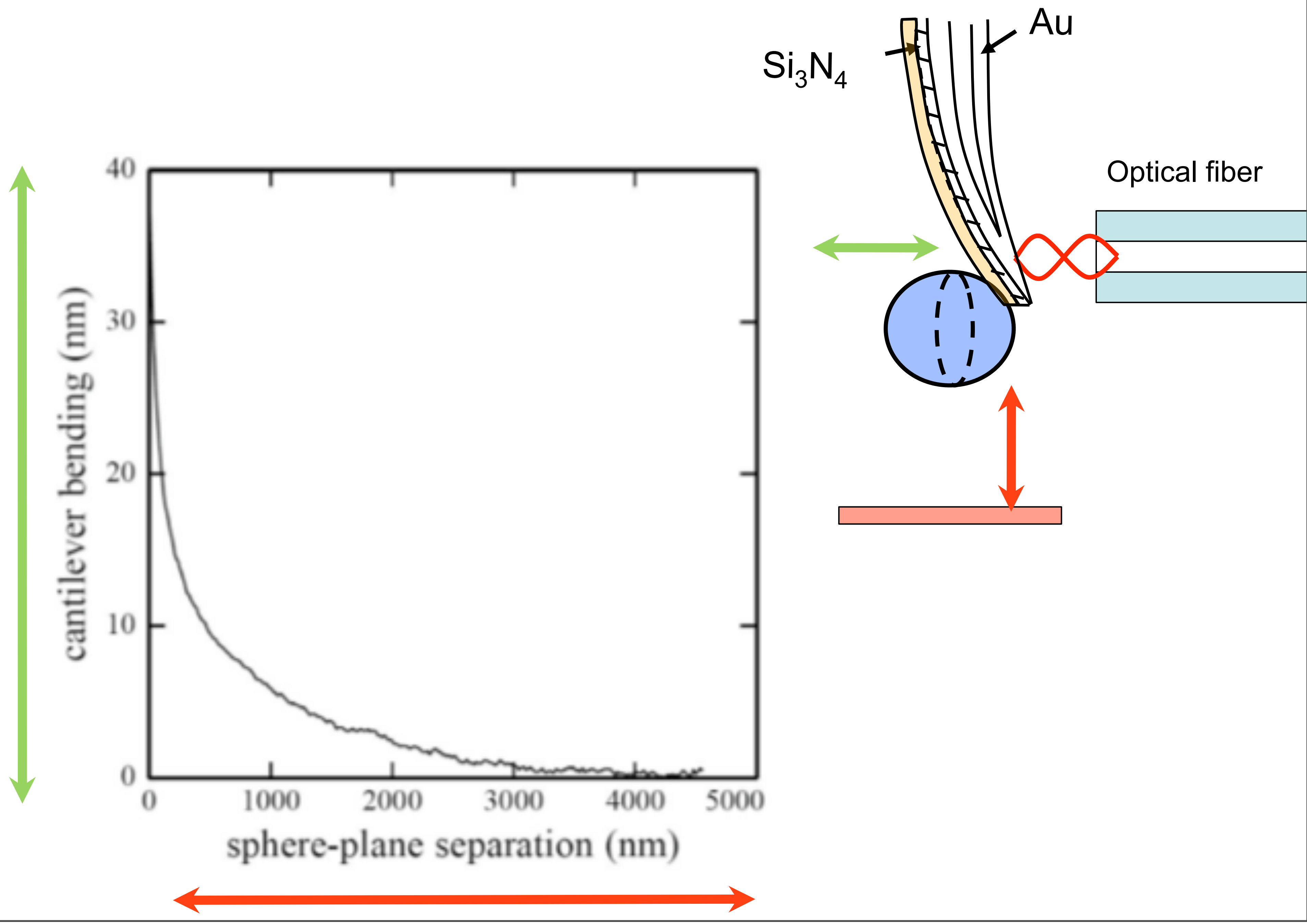


- Power exchanged = lever deflection : thermal switch effect on the lever

-- High vacuum P~10^{-6} mbar : conduction neglegible

- ΔT = 10-20 K.

-Closed feedback loop and thermal drift



cantilever bending (nm)
sphere-plane separation (nm)
0
10
20
30
40
1000
2000
3000
4000
5000
Au
Si_3N_4
Optical fiber

$$G_{\mathrm{theo}}(d + b, T) = G_{\mathrm{ff}} + H\delta(d)/\Delta T$$

lever bending versus heat flux:

H nW/nm

calibration required

absolute distance between sphere/plane:

b: due to surface roughness

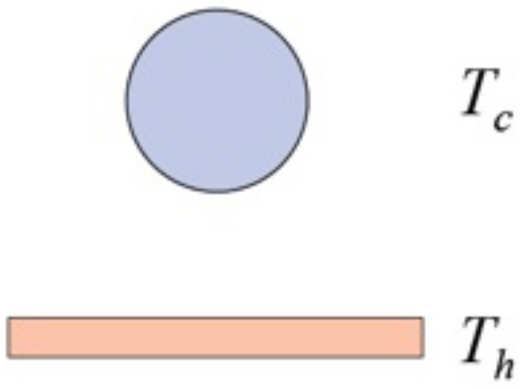
measured in direct contact for each measurement

always close to 50nm

consistent with SEM images of the glass sphere lever bending versus heat flux:

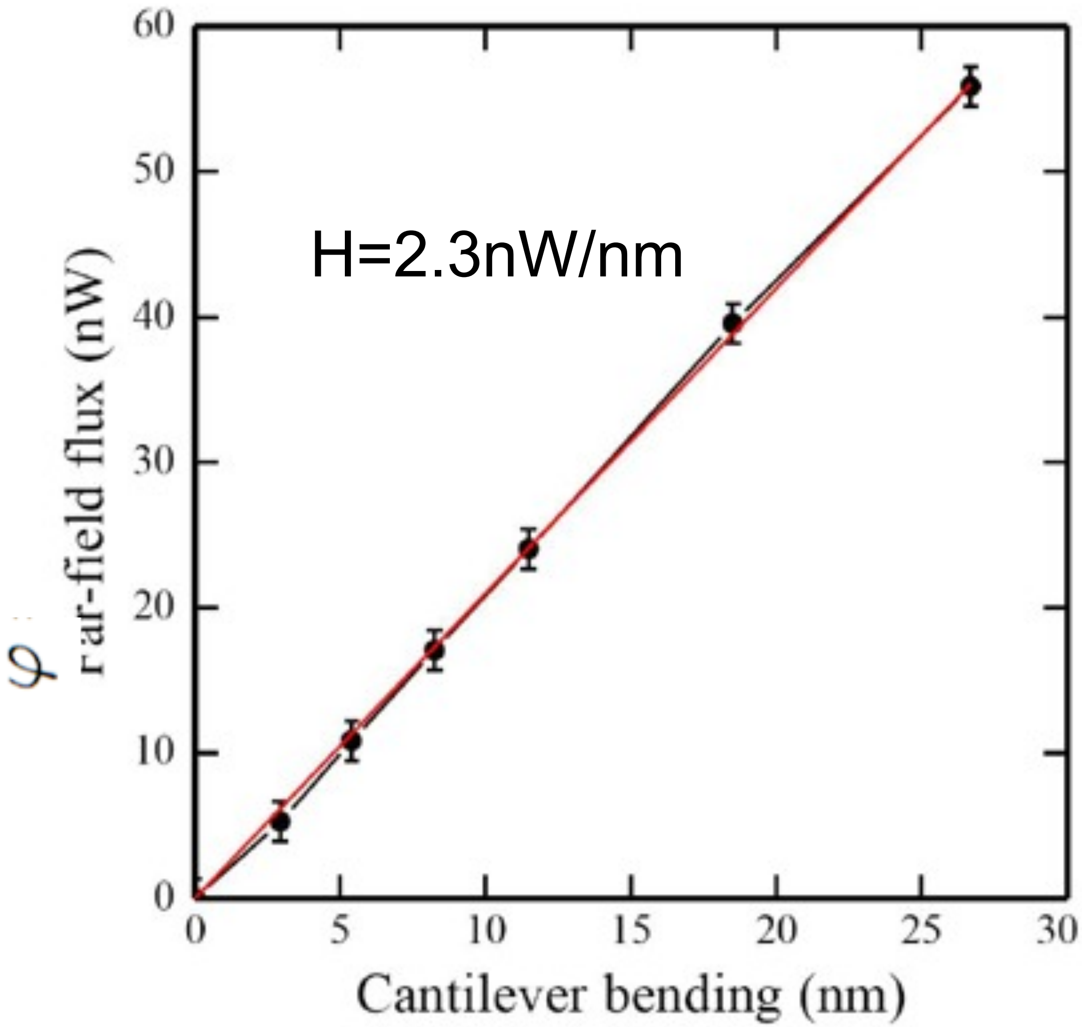
H nW/nm

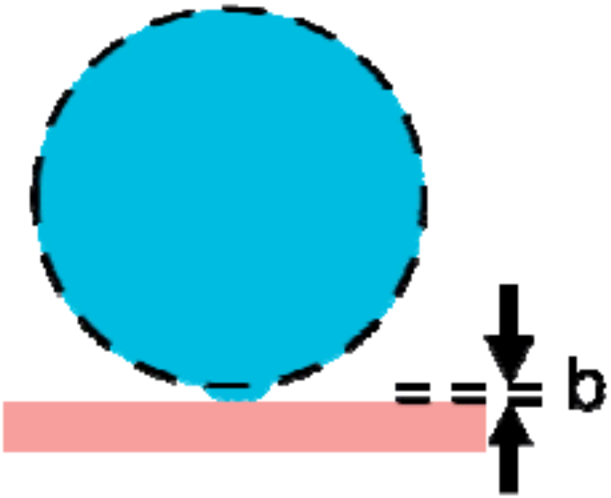
Far-field

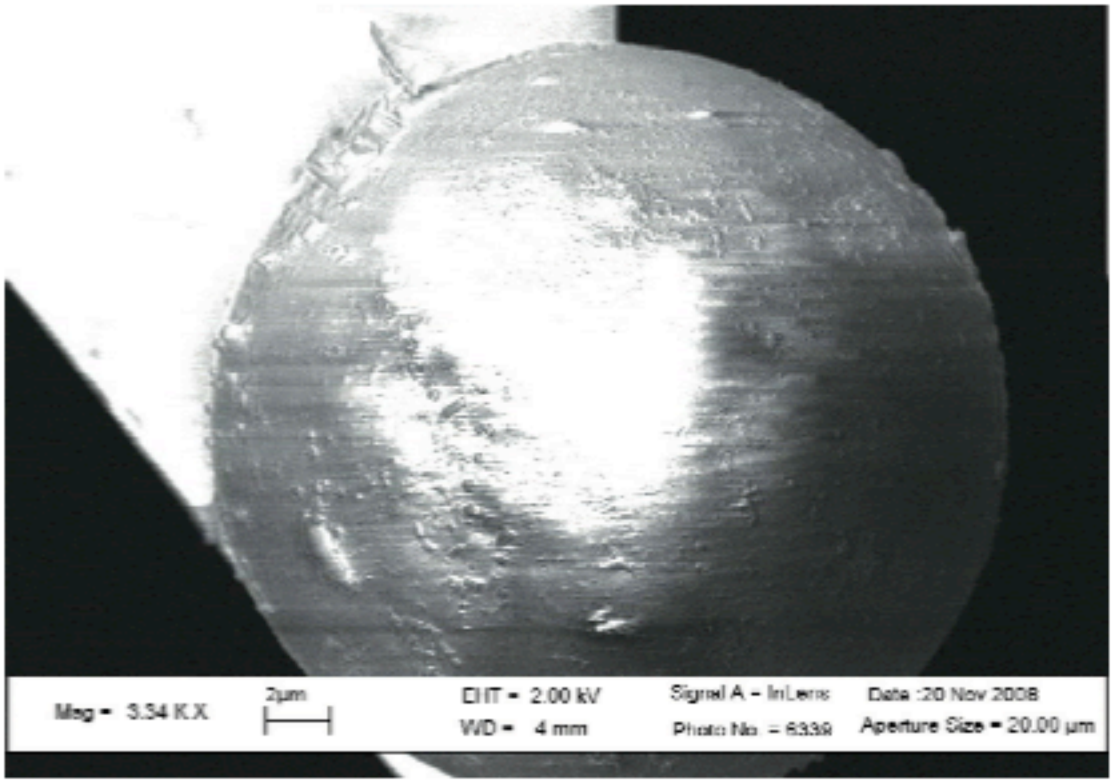


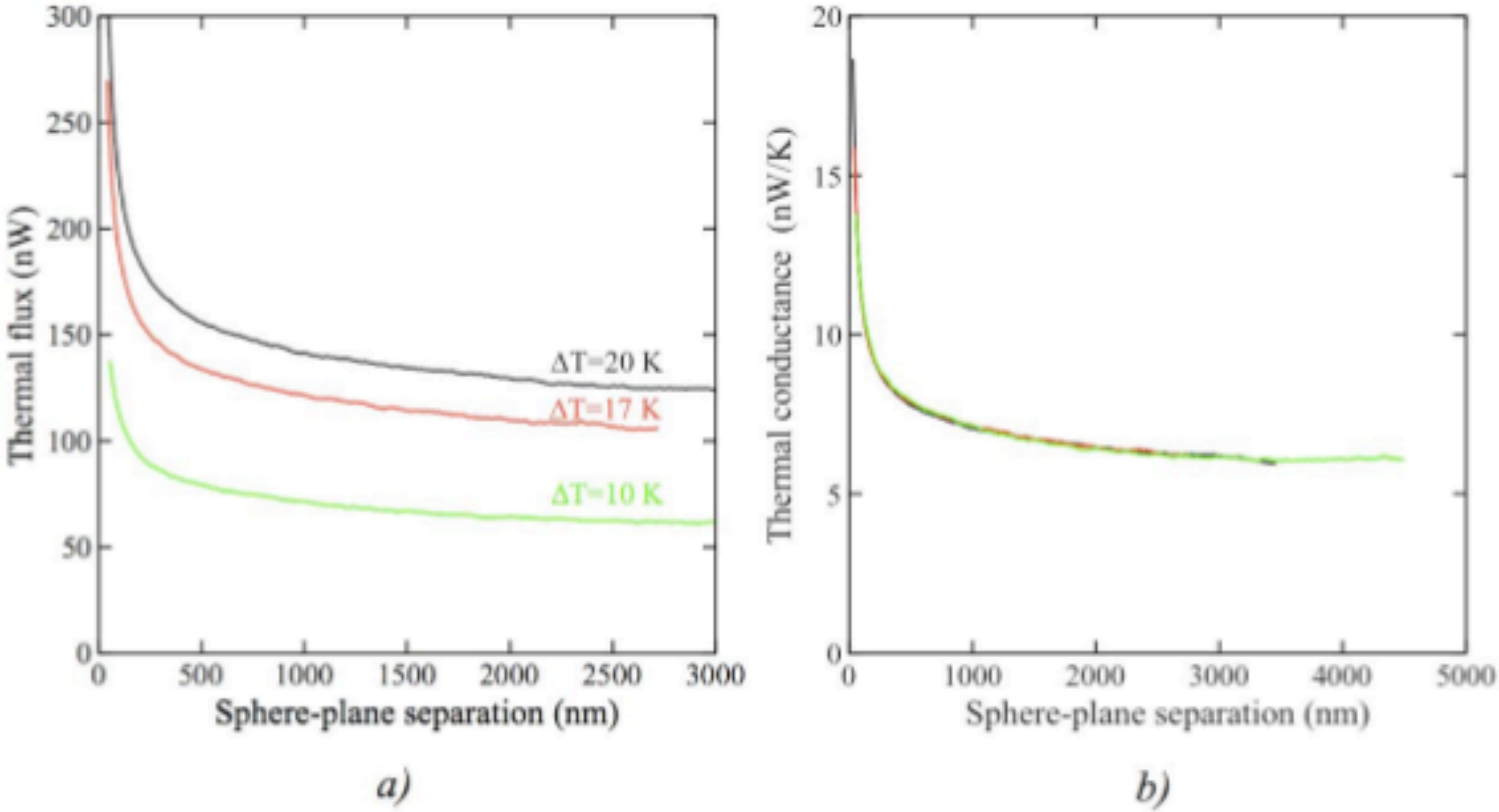
$$\varphi = 2\pi R^2 4\varepsilon\sigma T^3 \Delta T$$

φ = H . cantilever bending




b

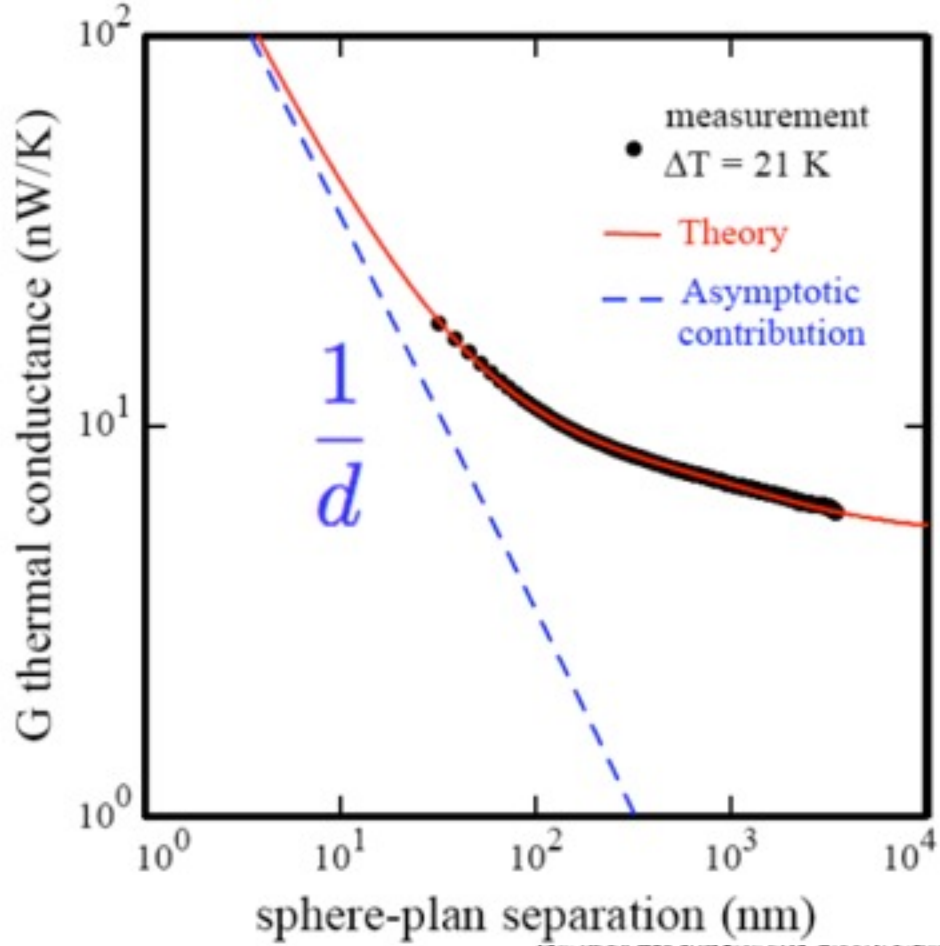

Mag = 3.34 K X
2µm
EHT = 2.00 kV
WD = 4 mm
Signal A = InLens
Photo No. = 6339
Date :20 Nov 2008
Aperture Size = 20.00 µm



ΔT=10, 17, 21 K,

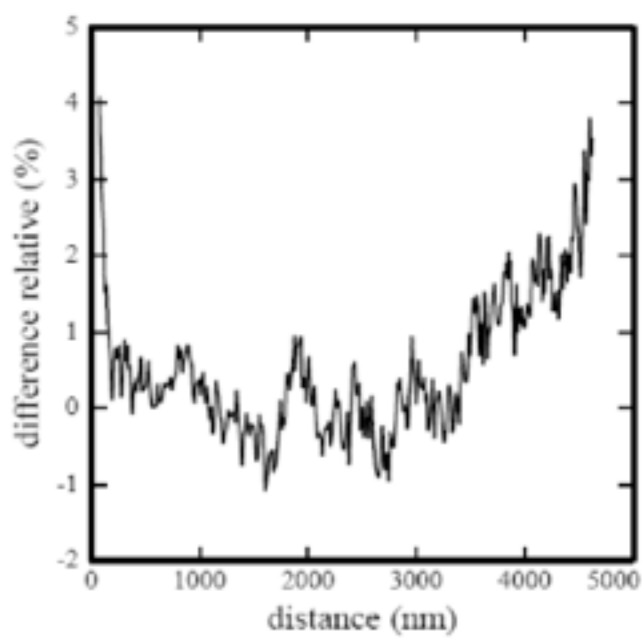
H=2.17, 2.16, 2.14
(same H)

Comparison Experience-theory



Glass sphere – glass plane

Sphere diameter 40 μm

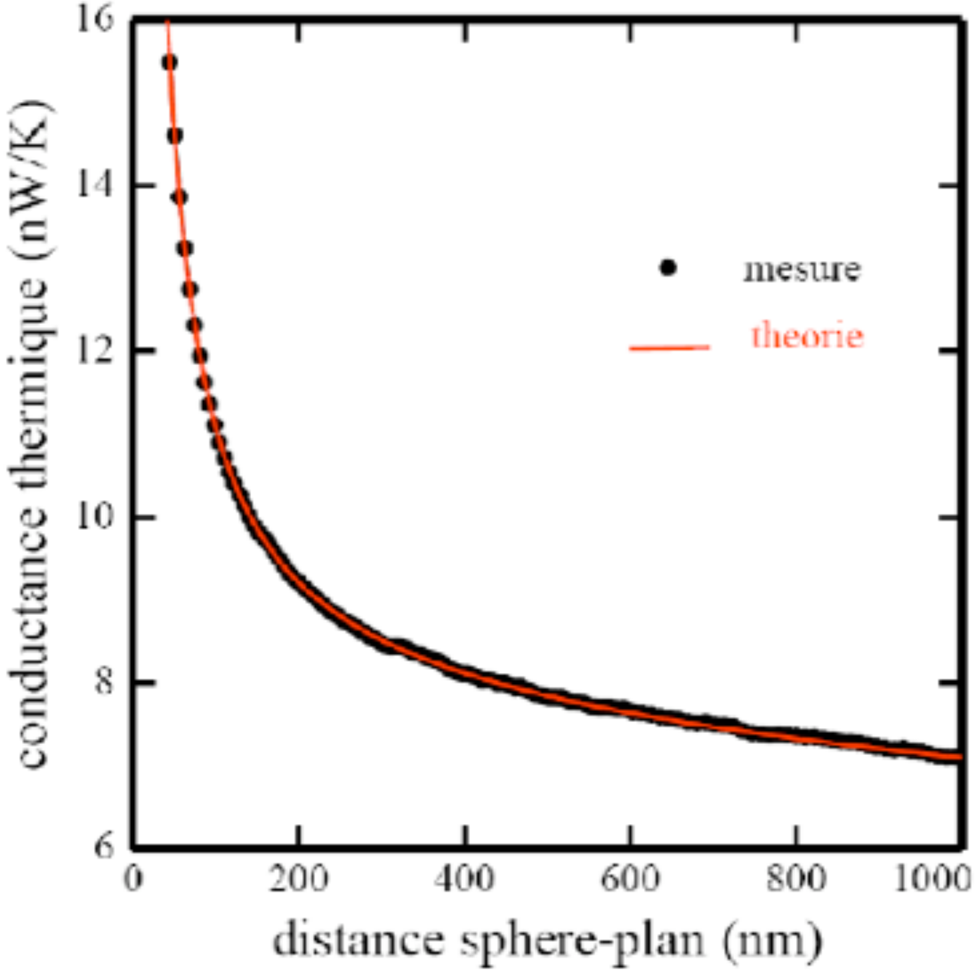


H and β adjusted

H = 2.162 nW/nm (2.2)

β = 31.8 νμ

Comparison Experience-theory



Glass sphere – glass plane

Sphere diameter 40 μm

ZOOM ON NEAR-FIELD REGIME

H and β adjusted

H = 2.162 nW/nm (2.2)

β = 31.8 νμ

Comparison Experience-theory

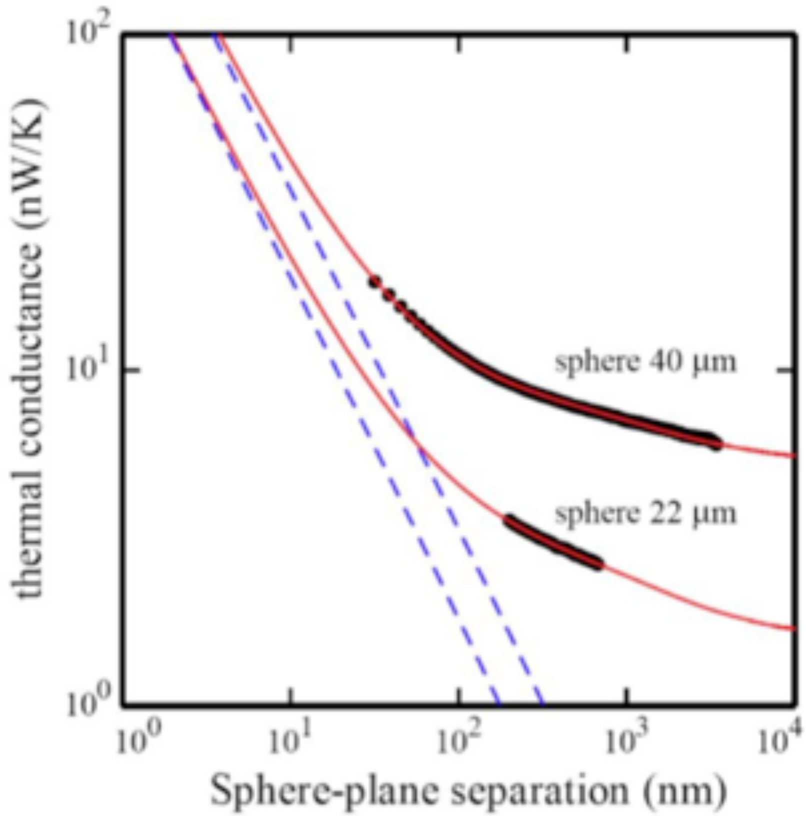


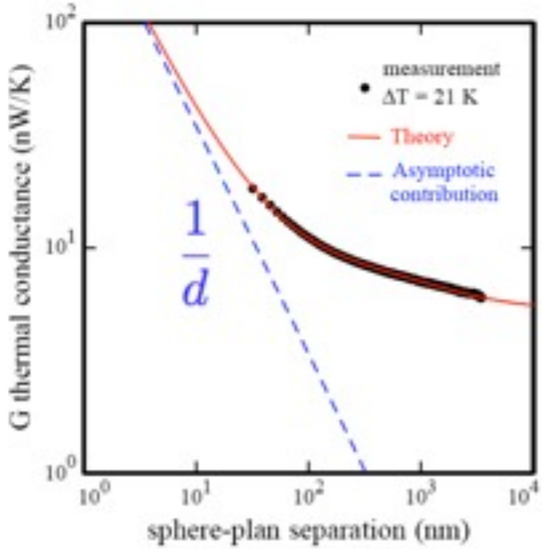
Figure 4.16: Thermal conductance between the sphere and the plate as a function of the gap for two sphere diameters (40 and 22 μm). Black dots are experimental data and red line is the theoretical model. The dashed blue line is the asymptotic contribution varying as $1/d$. This contribution is dominant for gaps smaller than 10 nm. For the 22 μm sphere the smallest separation is 150 nm due to roughness.

Conclusions and perspectives

Conclusions:

Development of experimental set-up for the radiative thermal transfer

Precise measurement of thermal flux in 50nm-5μm



Radiative thermal tranfer for
sphere-plane geometry based on PFA

Low temperature microscope