Nano Electro Mechanical Systems (NEMS)

and

interactions at nanoscale

Alessandro Siria:

Institut Néel-CNRS Grenoble
CEA-LETI/MINATEC Grenoble

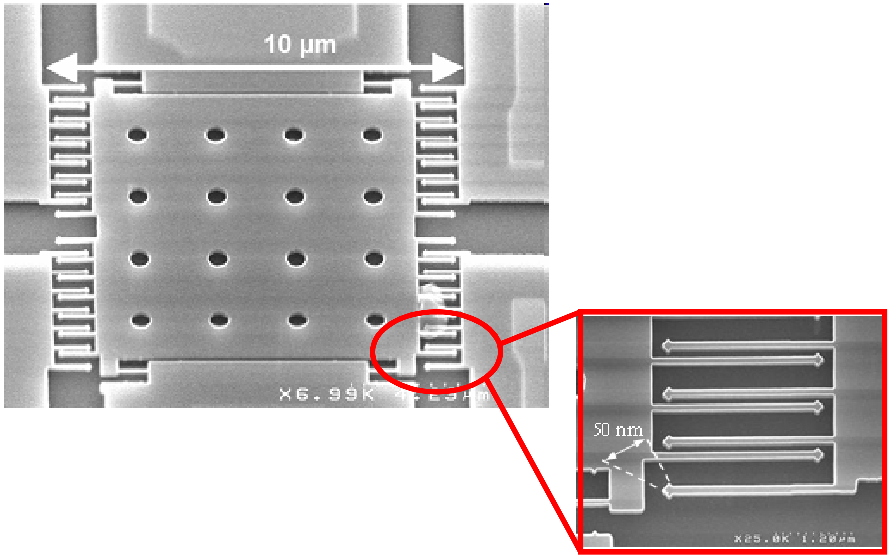
Advisors:

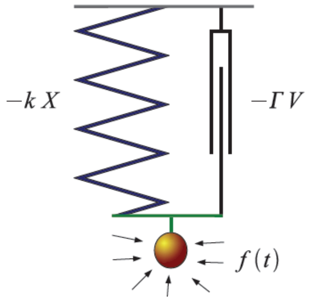
Joel Chevrier, UJF and CNRS Grenoble
Hubert Grange, CEA-LETI/MINATEC Grenoble

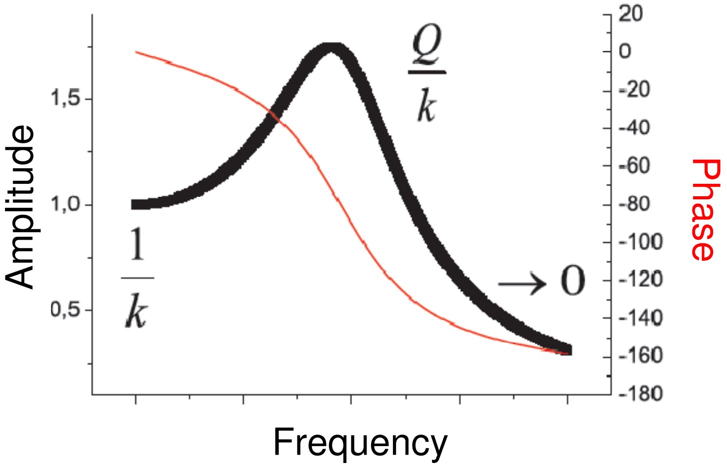
Nano Electro Mechanical Systems (NEMS)

NEMS are devices integrating electrical and mechanical functionalities at the nanoscale.

NEMS are among the best candidates for measurement of interactions at nanoscale



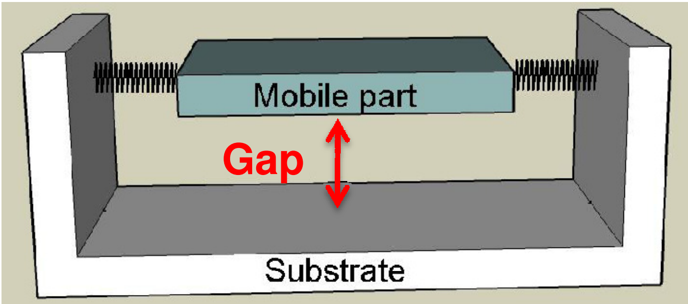




NEMS resonators can be assimilated to harmonic oscillators

$$\chi(\omega) = \frac{1}{m\left(\omega_0^2 - \omega^2\right) + i\gamma\omega}$$

Interactions at nanoscale



NEMS standard scheme:

- Mobile part suspended over a fixed substrate;
- Gap from tens nanometers to several microns;
- Plane-Plane geometry.

Interactions between mobile and fixed parts can dominate the NEMS dynamics

- Chemical forces;
- Van der Waals and Casimir forces
- Electrostatic (residual) forces;
- Optical forces;
- Hydrodynamic forces;
- Near field thermal radiation.

Outlines

- Detection set-up: fibre-based optical interferometry.

- Hydrodynamic forces at micron and submicron scale:
  1. Cavity damping of a microlever;
  2. Cavity freezing of a microlever.

- Radiative heat transfer at nanoscale:
  1. Electromagnetic treatment of thermal radiation;
  2. Radiative heat transfer between a sphere and a plane.

- Conclusions and perspectives.

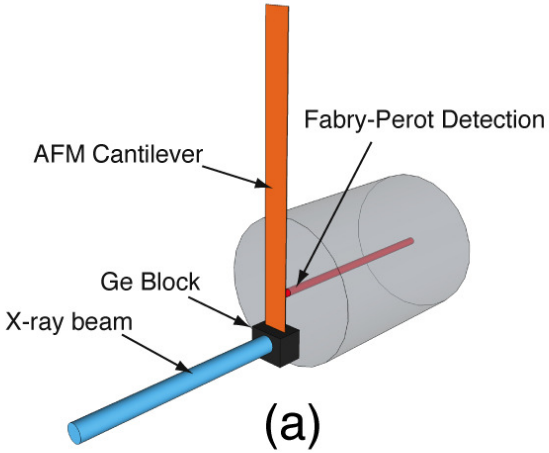
X-ray and Mechanical Systems

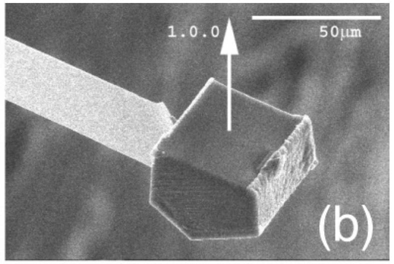
OPTICAL FORCES

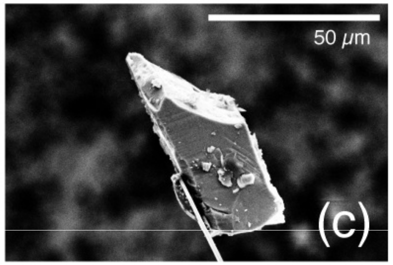
Interaction between X-ray and Mechanical systems:

1) Mechanical effect of X-ray beam;

2) MEMS based X-ray chopper.





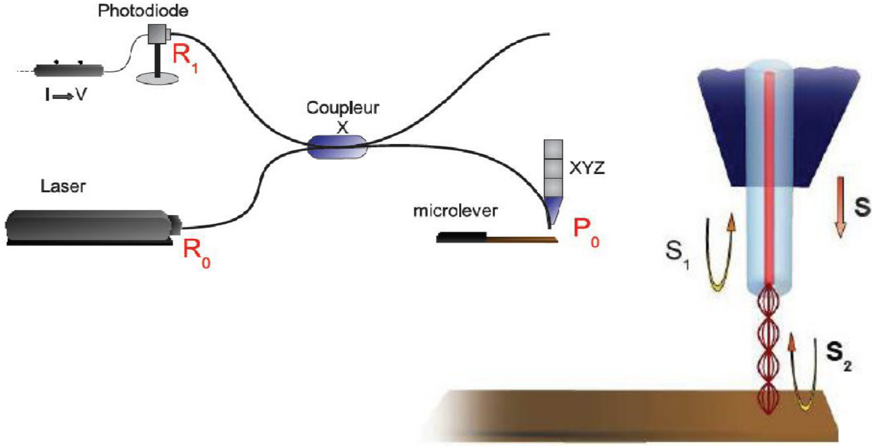


European Synchrotron Radiation Facility

@ Surface Science Laboratory (SSL)

In collaboration with
Fabio Comin

Detection set-up: optical interferometry

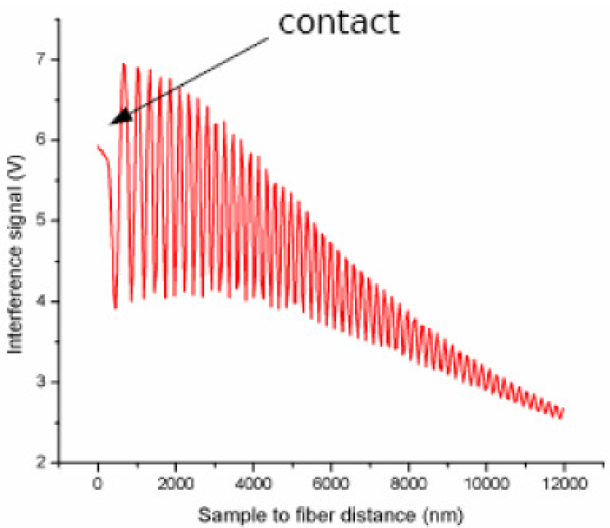


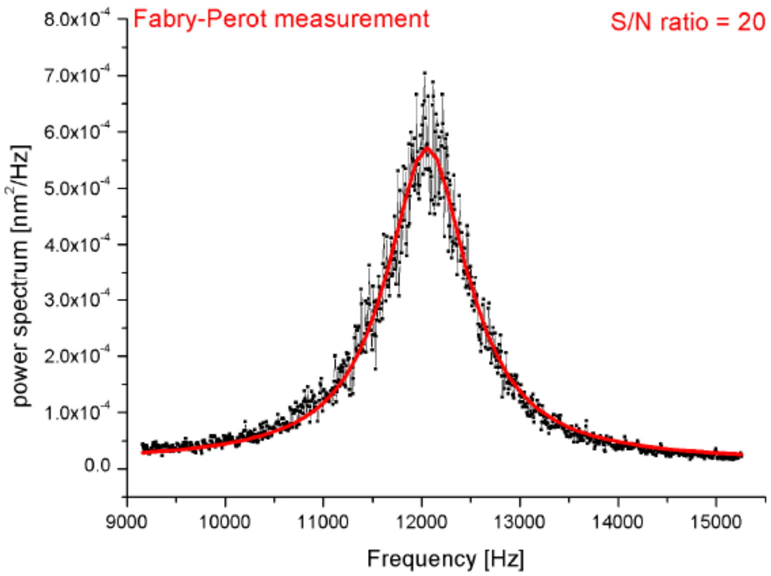
Fabry Perot cavity formed between the fibre end and the sample surface

Movement of the surface is translated in detectable light intensity modulation.

$$Sensibility < 10^{-12}\ m/\sqrt{Hz}$$

$$I_{ph}(d) = I_1 + I_2 + 2\sqrt{I_1 I_2}\,\sin\left(\frac{4\pi}{\lambda}d + \varphi\right)$$



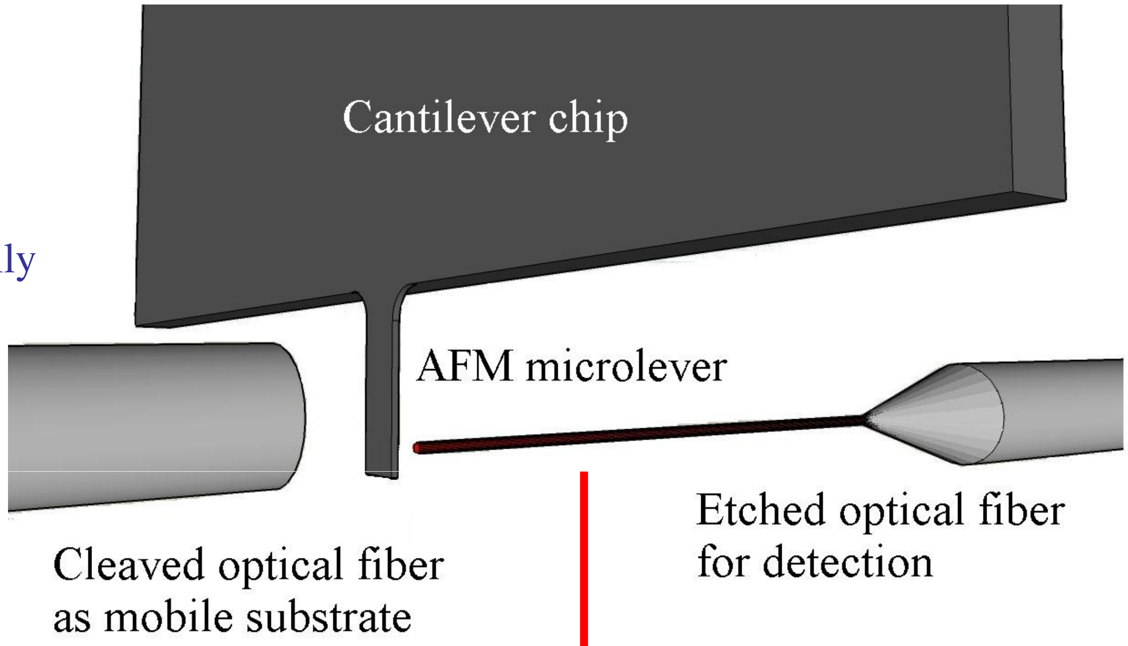


Microlever Brownian motion detection

Hydrodynamic forces at micron and sub-micron scale

Hydrodynamic forces at short distances

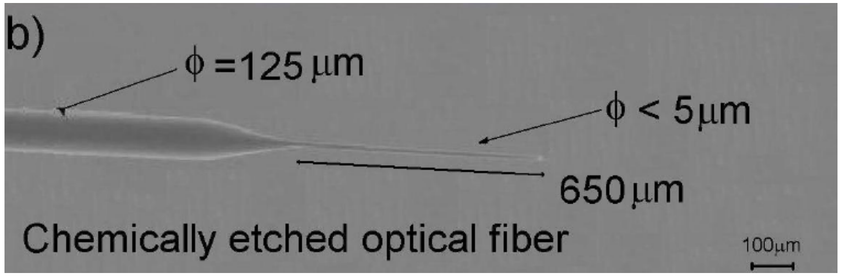
The oscillating behavior of a lever is studied when an “infinite” wall is gradually approached.



This system mimics a MEMS oscillating closed to a substrate

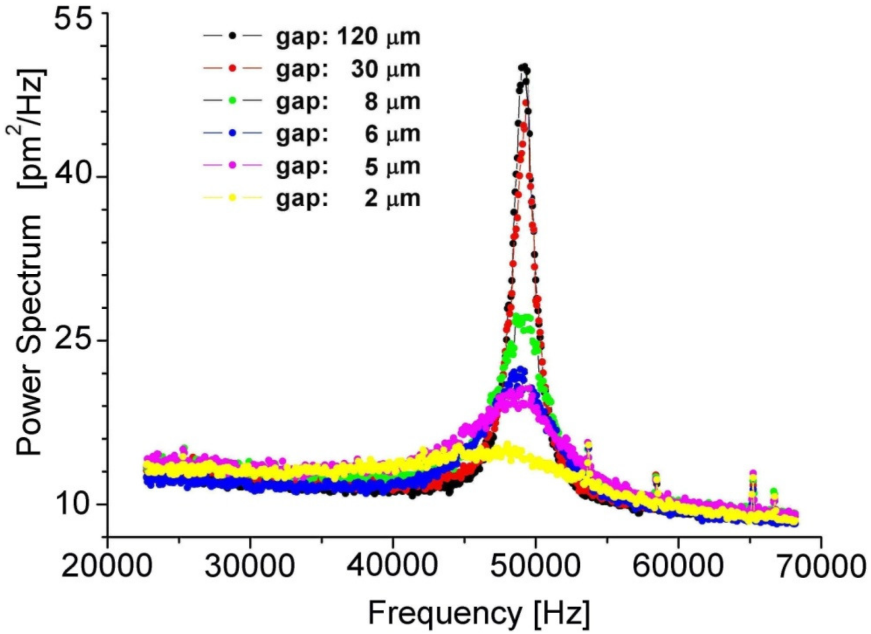
Si cantilever:
$L = 107\ \mu m$
$w = 30\ \mu m$
$t = 0.18\ \mu m$
$\omega_0/2\pi \approx 50$ kHz

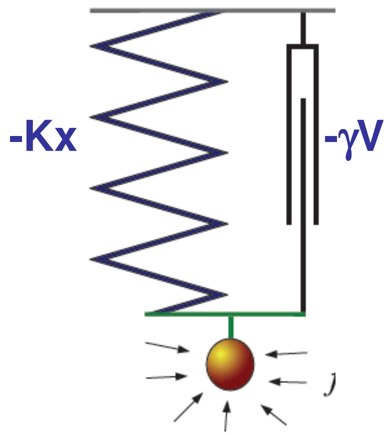
No additional damping



Hydrodynamic forces at short distances

The lever is thermally actuated.
With decreasing gap in micrometer range we observe a broadening and softening of fundamental resonance.





Driven and damped 1D oscillator

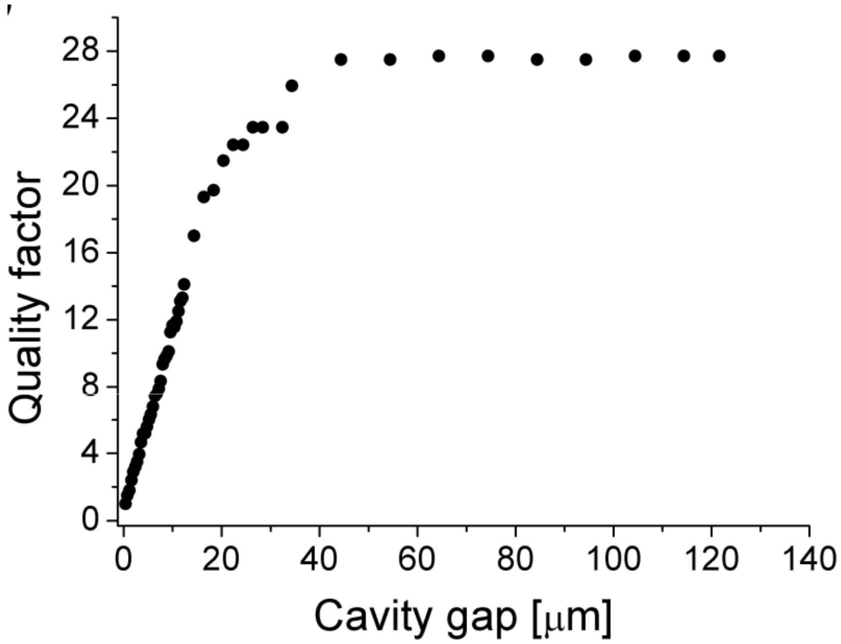
$$\chi(\omega) = \frac{1}{m\left(\omega_0^2 - \omega^2\right) + i\gamma\omega}$$

Damping of lever studied recording resonance quality factor

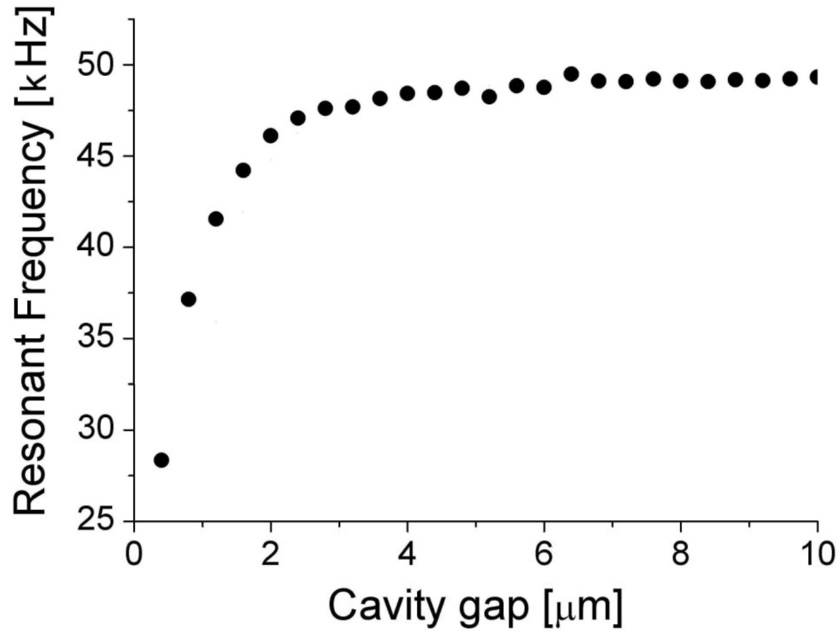
$$Q = \frac{\Delta\omega}{\omega_{res}} = \frac{k}{\omega_0 \gamma}$$

Experimental results

Broadening:



Softening:



Micrometric lenght scale:

$$d_L \approx 20\mu m$$

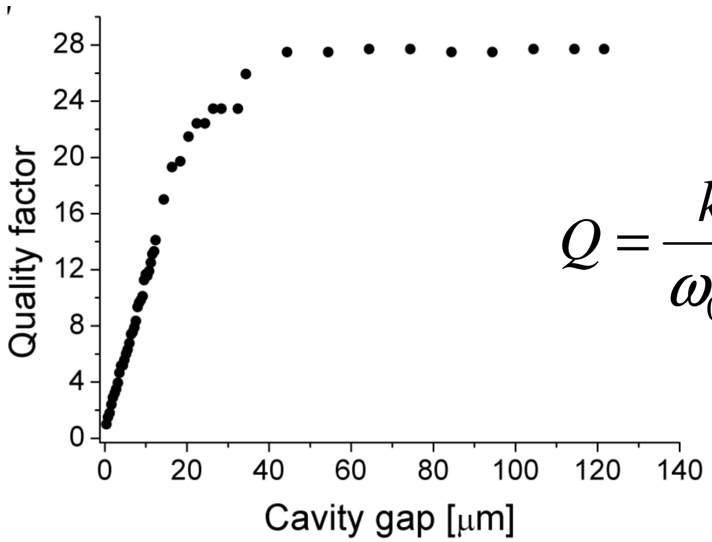
Confinement effect

Nanometric lenght scale:

$$d_C \approx 400nm$$

Freeezing of resonance

Cavity damping of the oscillator



$$Q = \frac{k}{\omega_0 \gamma}$$

Large gap: damping independent on distance

Small gap : damping depending on inverse of distance

Theoretical description based on Navier-Stokes equation

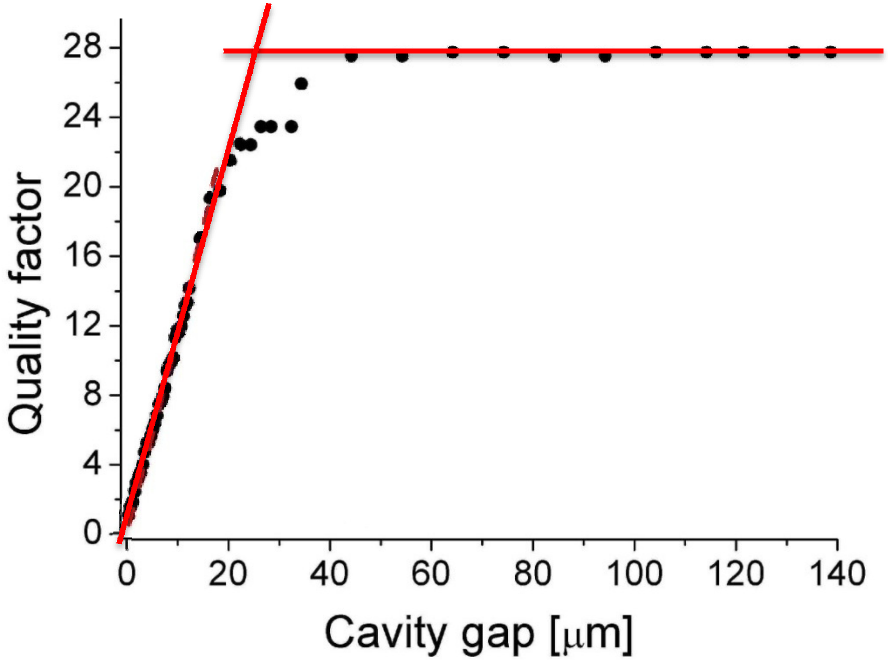
$$\rho\left[\frac{\partial \vec{v}}{\partial t}\right] = \eta \nabla^2 \vec{v} - \nabla p$$

Reynold's number: $\mathrm{Re} = \dfrac{v \cdot d \cdot \rho}{\eta} \approx 10^{-6} \div 10^{-4}$ LAMINAR REGIME

Which boundary conditions??

<u>Boundary conditions control the agreement theory - experiments</u>

Confinement characteristic length



Boundary layer definition: $d_L = \sqrt{\dfrac{2\eta}{\rho\omega}}$

At lever resonance: $d_L \approx 20\mu m$

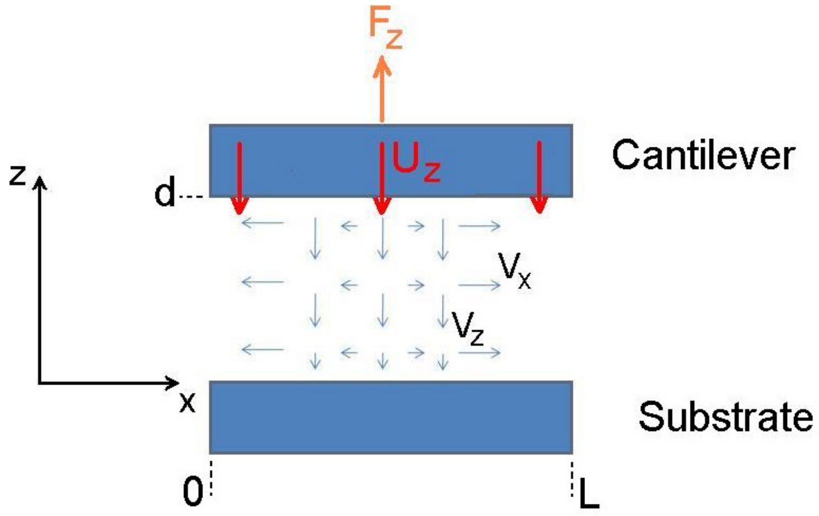
Spatial region surrounding the lever where viscosity dominates the fluid behavior

$$\frac{\rho\left[\dfrac{\partial \vec{v}}{\partial t}\right]}{\eta \nabla^2 \vec{v}} \approx \frac{\rho\omega d^2}{\eta} \approx \frac{d^2}{d_L^2}$$

$$d << d_L \Rightarrow$$ Inertial << Viscosity

$$\eta \nabla^2 \vec{v} = \nabla p$$

Perfect slip boundary conditions



$$v_z = g(z)$$
$$v_x = f(x)$$

Perfect slip at fluid-solid interface:

Navier-Stokes equation

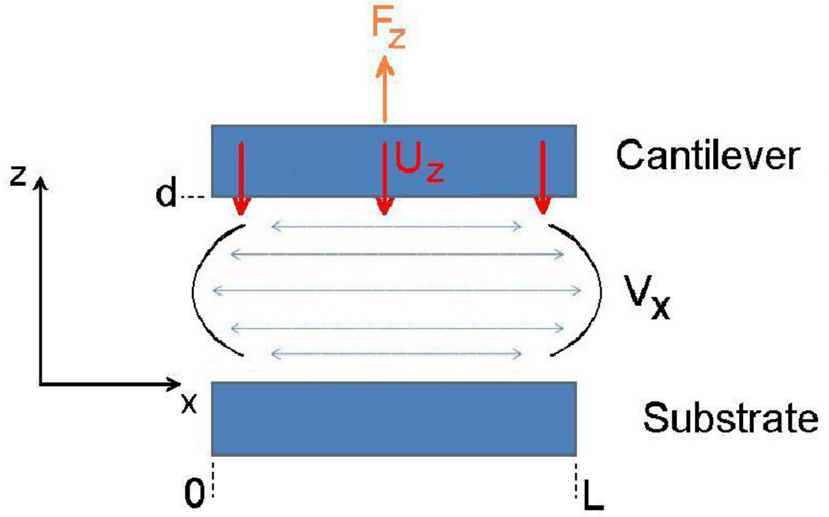
$$\frac{\partial p}{\partial x} = \eta \frac{\partial^2 v_x}{\partial x^2}$$
$$\frac{\partial p}{\partial z} = \eta \frac{\partial^2 v_z}{\partial z^2}$$

$$\Longrightarrow \quad F_z = -\frac{2\eta A}{d} U_z \quad \Longrightarrow \quad \boxed{\gamma = \frac{2\eta A}{d}}$$

$$Q = \frac{k}{2\eta A \omega_0} d$$

Linear dependency of the quality factor with the gap size.
Consistent with experimental evidence

No slip boundary conditions (Couette)



No slip at fluid-solid interface:

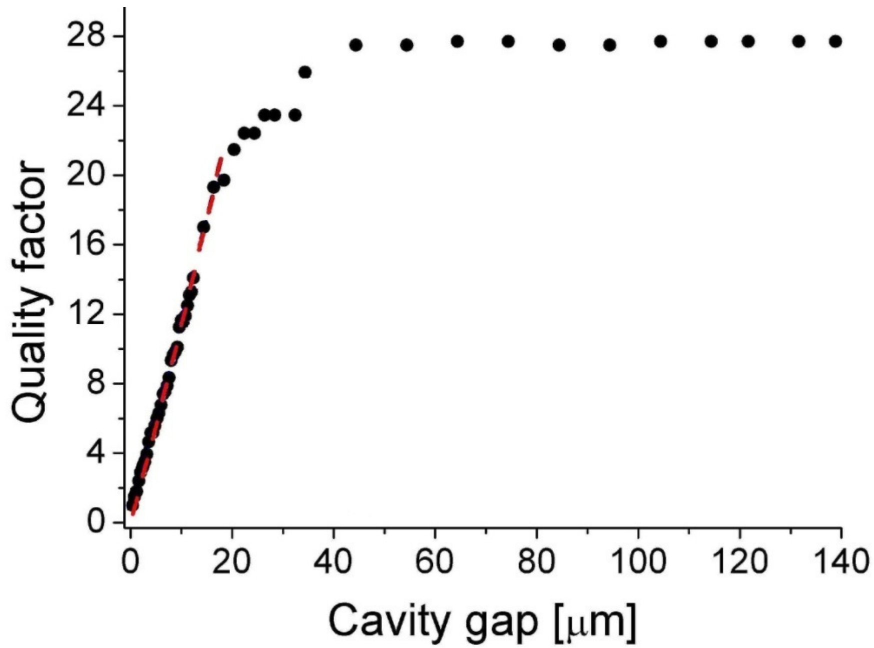
$$v_x(z=0)=0$$
$$v_x(z=d)=0$$

Navier-Stokes equation $\dfrac{\partial p}{\partial x}=\eta\dfrac{\partial^2 v_x}{\partial z^2} \Longrightarrow F_z=-\dfrac{\eta L^3 w}{d^3}U_z \Longrightarrow \boxed{\gamma=\dfrac{\eta L^3 w}{d^3}}$

$$Q=\frac{k}{\eta L^3 w \omega_0}\boxed{d^3}$$

NOT Consistent with experiments

Comparison Experiments-Theory

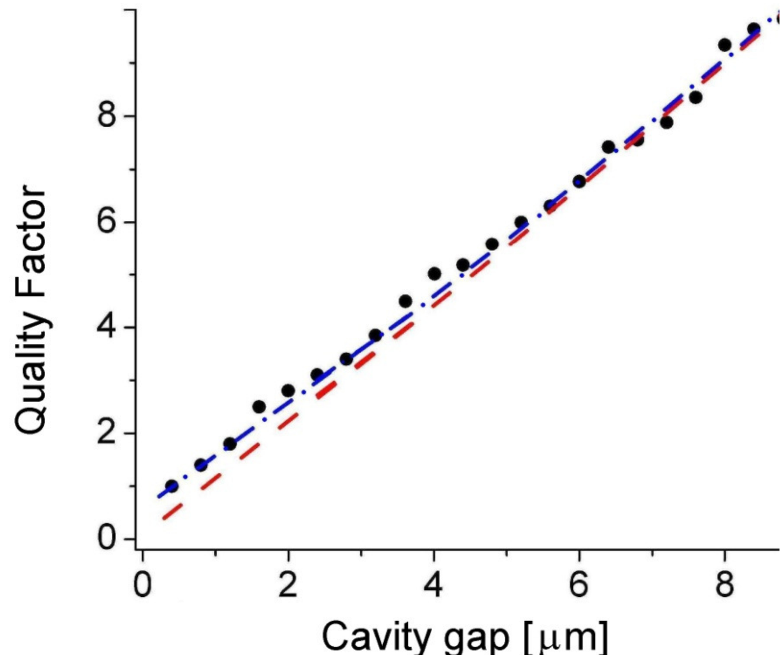


• Experimental data

- Theoretical model (perfect slip)

$$Q = \frac{k}{2\eta A\omega_0} d$$

<u>No adjustable parameter</u>

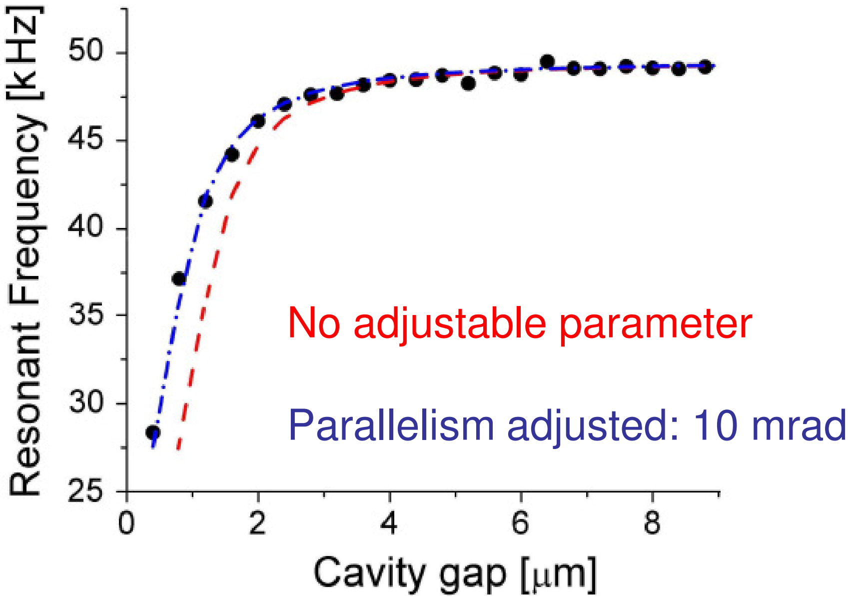


No adjustable parameter: 80% error at 400 nm

Parallelism adjusted: 5% error at 400 nm

Residual misalignement : 10 mrad

Cavity freezing of the oscillator

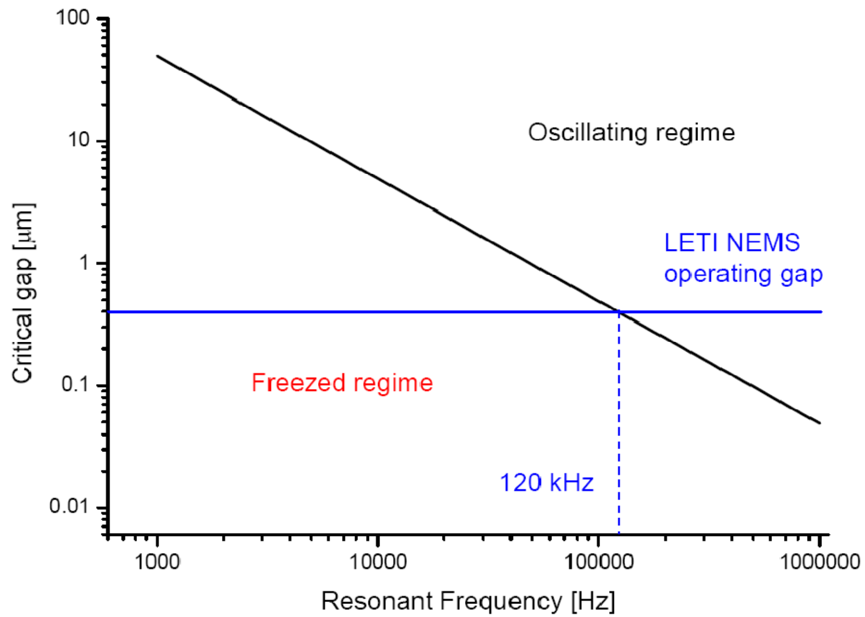


In the limit of large damping the oscillator has a down-shift of the resonance

$$\omega' = \sqrt{\omega_0^2 - \frac{1}{2}\left(\frac{\gamma}{m}\right)^2}$$

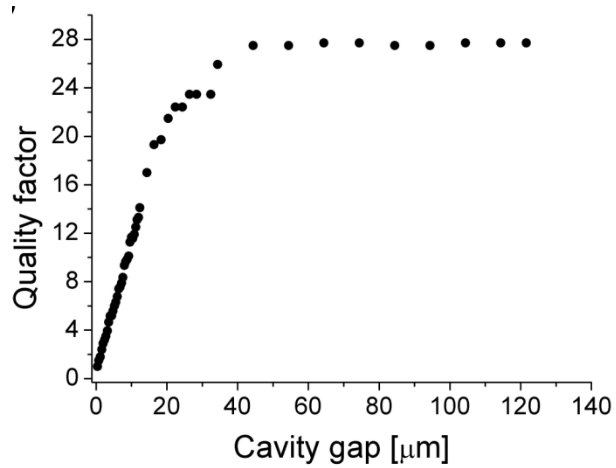
If the gap is small enough air confinement can eventually freeze the mechanical oscillator

$$Gap_{crit} = \frac{\sqrt{2}\eta}{m}\frac{A}{\omega_0} \Leftrightarrow \omega' = 0$$

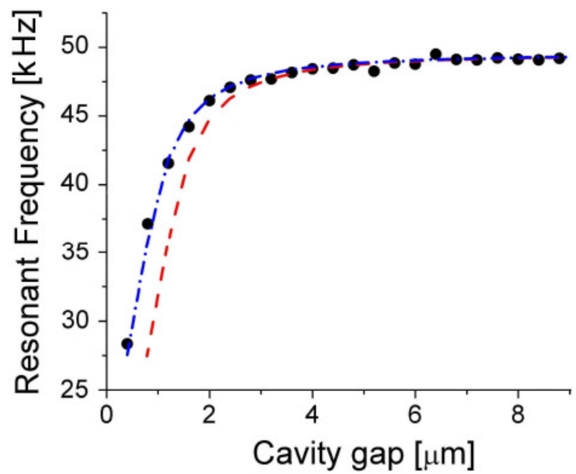


Hydrodynamic forces: summary

Cantilever dynamics modified by fluid confinement according to Navier-Stokes equation;



Perfect slip at fluid-solid interface induces a long range hydrodynamic force: $F \rightarrow 1/d$

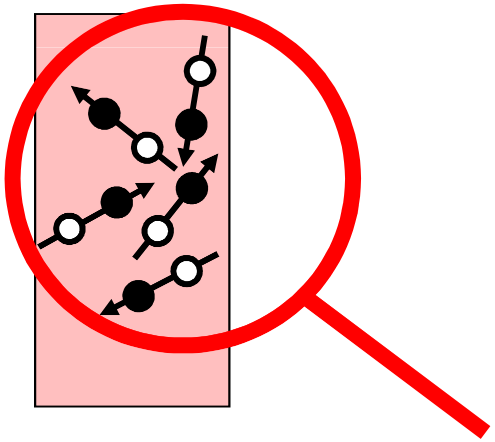


For nanometre size cavity the lever oscillation can be freezed because of the fluid confinement.

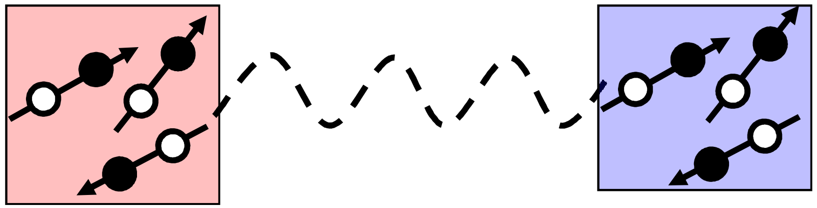
Near – Field radiative heat transfer

Electromagnetic treatment.

Fluctuating dipole
induced by thermal effect

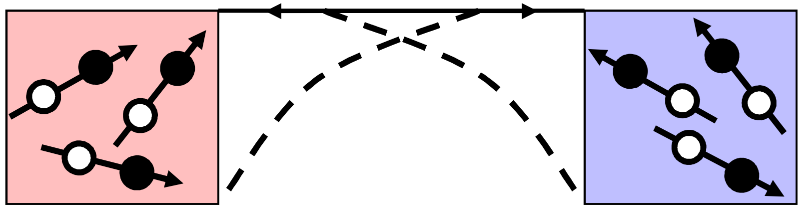


- **FAR-FIELD: propagative waves**



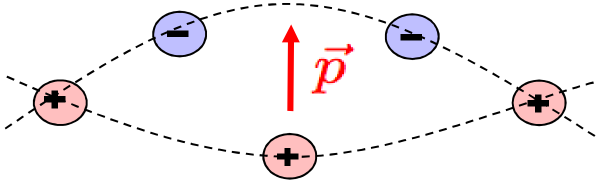
Independent by distance

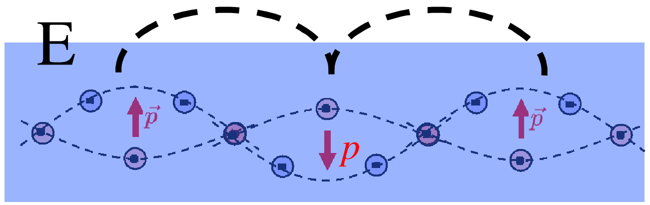
- **NEAR-FIELD: evanescent waves**



Strongly dependent by distance

Dielectric materials: surface Phonon-Polariton enhancement effect





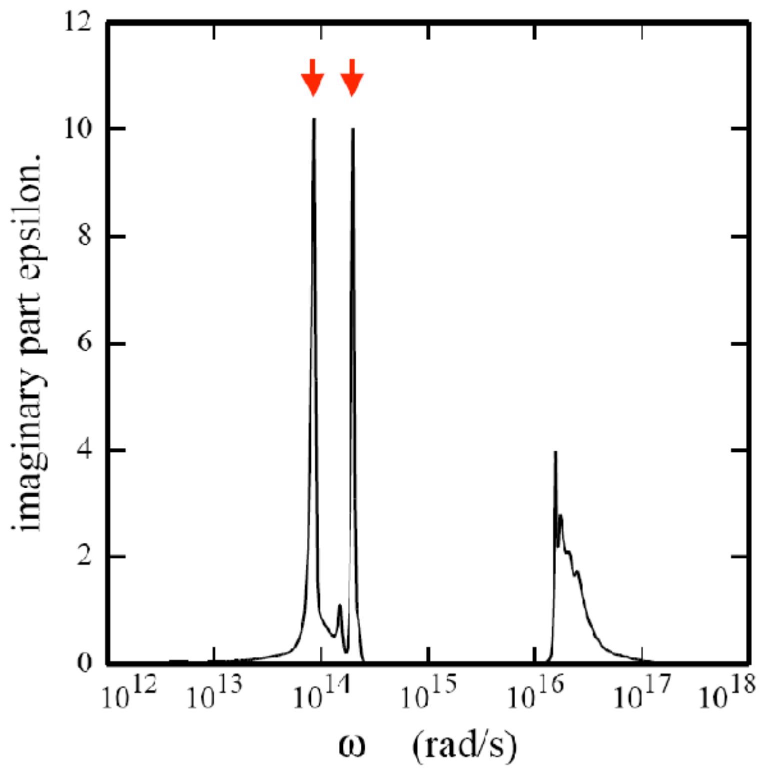
Surface waves: described by dielectric constant $\varepsilon(\omega)$

Infra-red resonance

(SiC, quartz, alumine, silica, Si doped)

Radiative thermal transfer

increased by the resonance effect



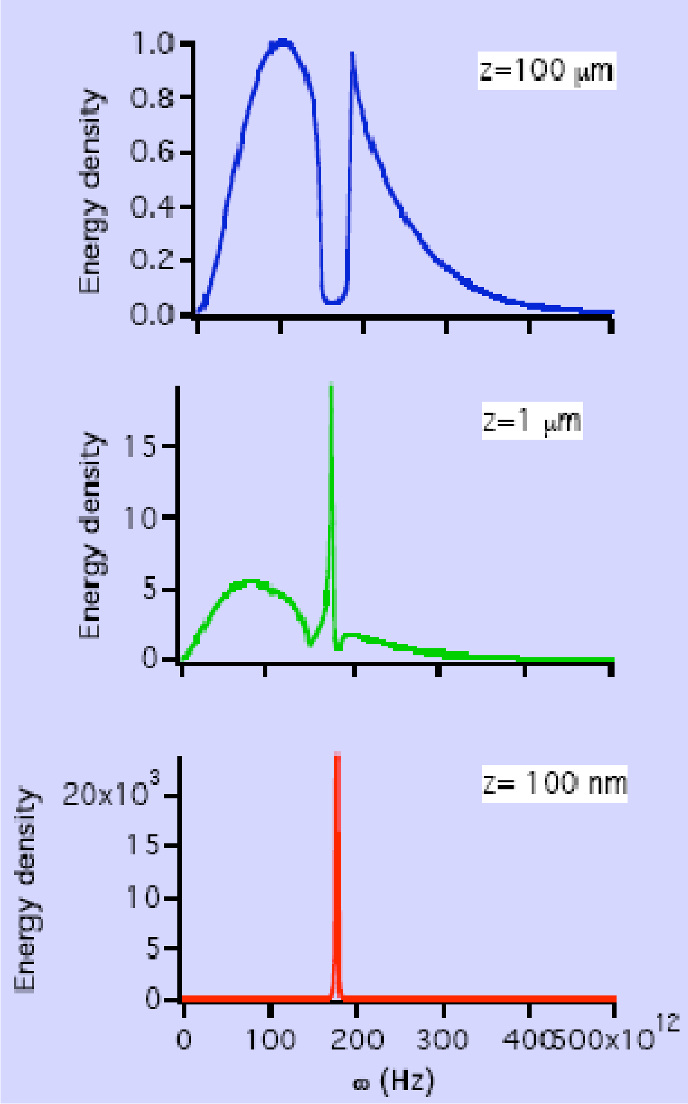
Dielectric materials: surface Phonon-Polariton enhancement effect

Density of energy near a SiC-vacuum interface

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

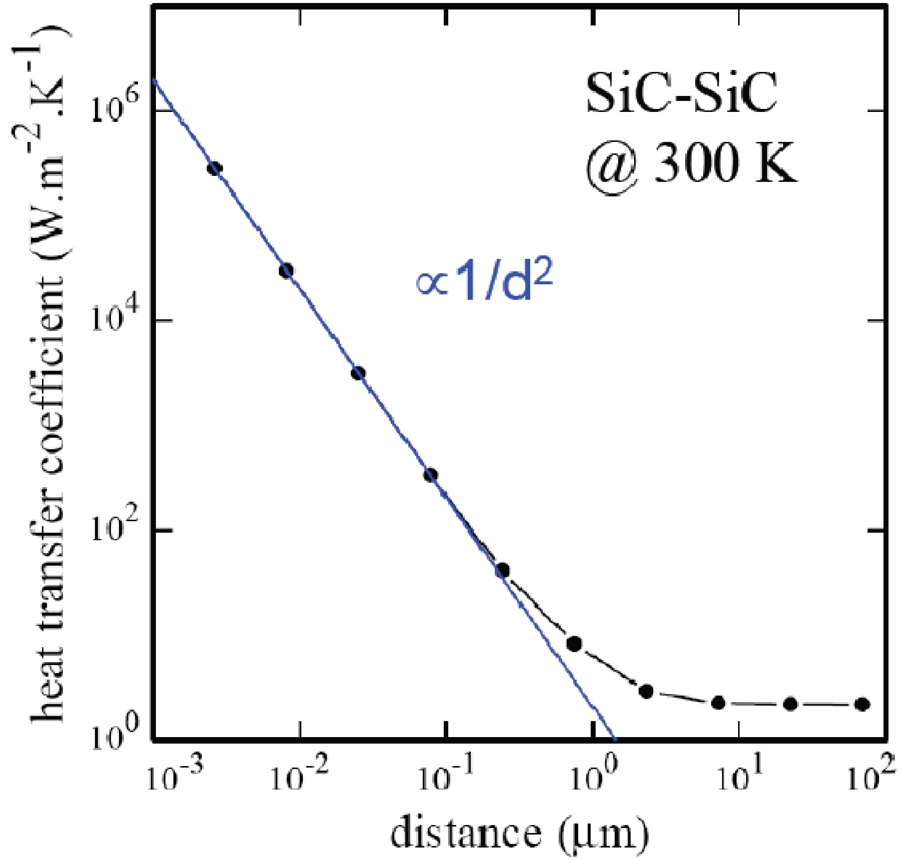
Near field: the energy density exceeds the Plank black body theory:

Monochromatic thermal emission and exponential decay with the distance

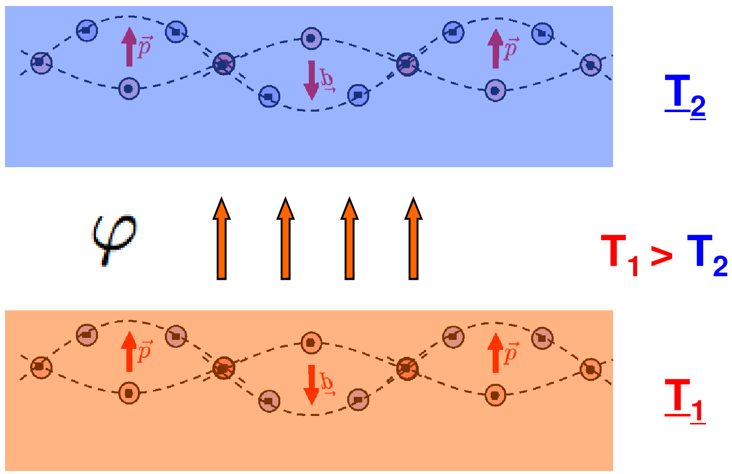


Dielectric materials: surface Phonon-Polariton enhancement effect

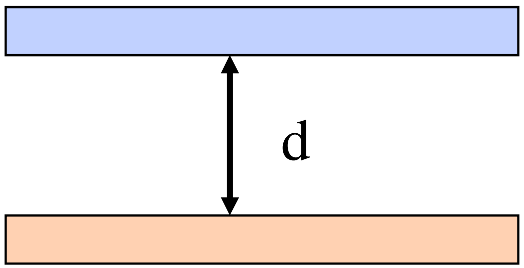
Theoretical model

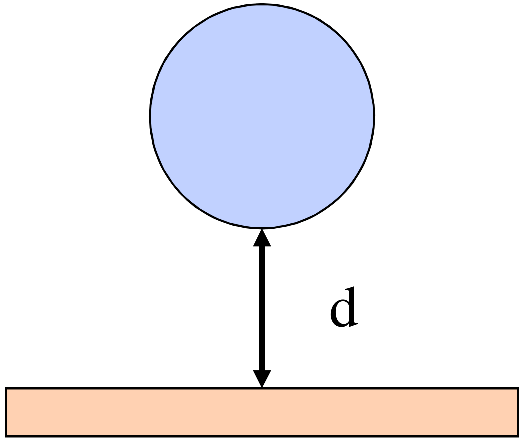


Plane-Plane geometry



Plane-plane geometry: experimental issue

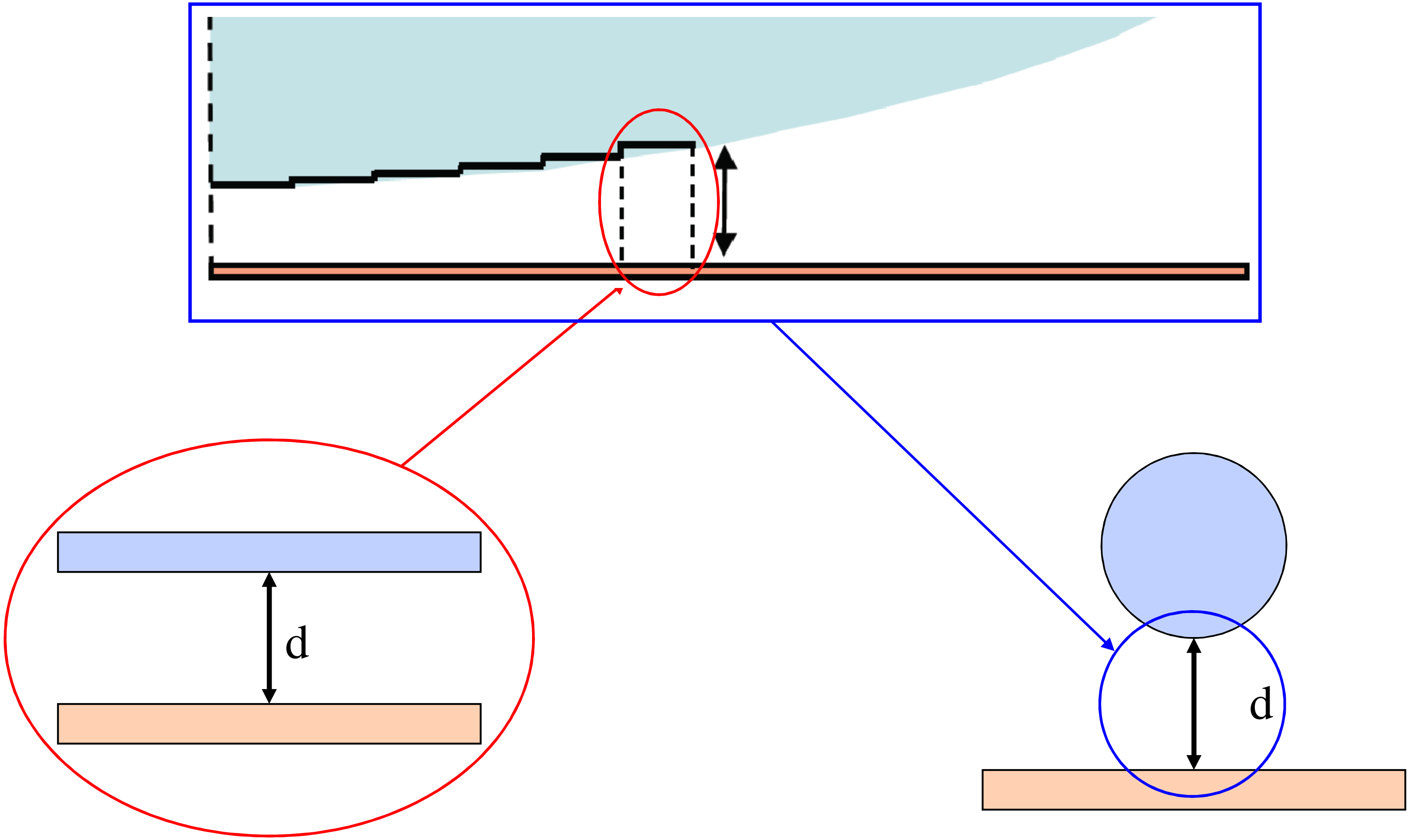




Plane-Plane	Plane-sphere
Theory developed	Experimentally possible
BUT	BUT
Experiments very difficult	Theory not yet developed

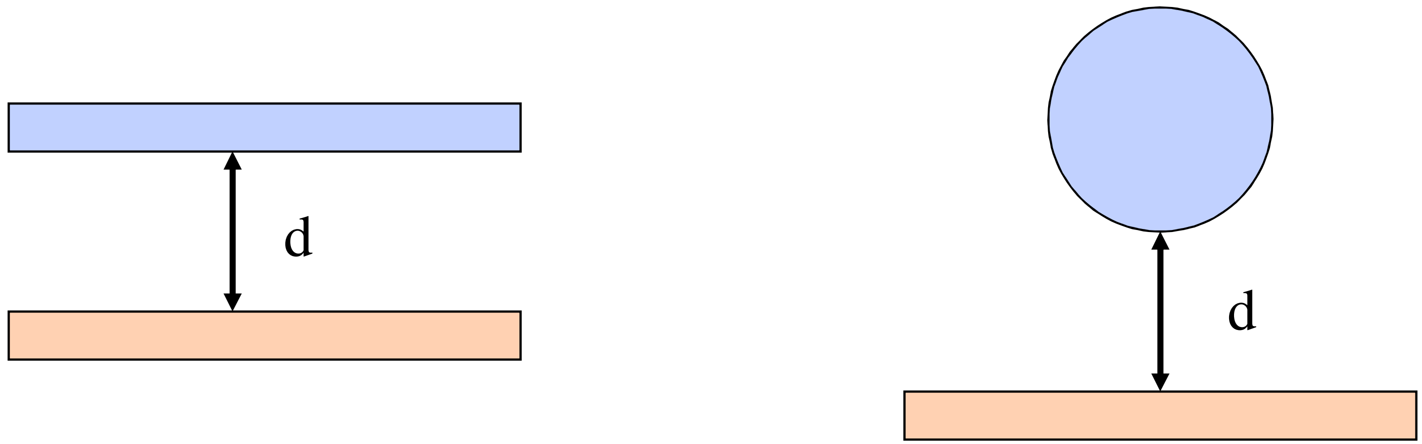
Sphere-Plane geometry: theory

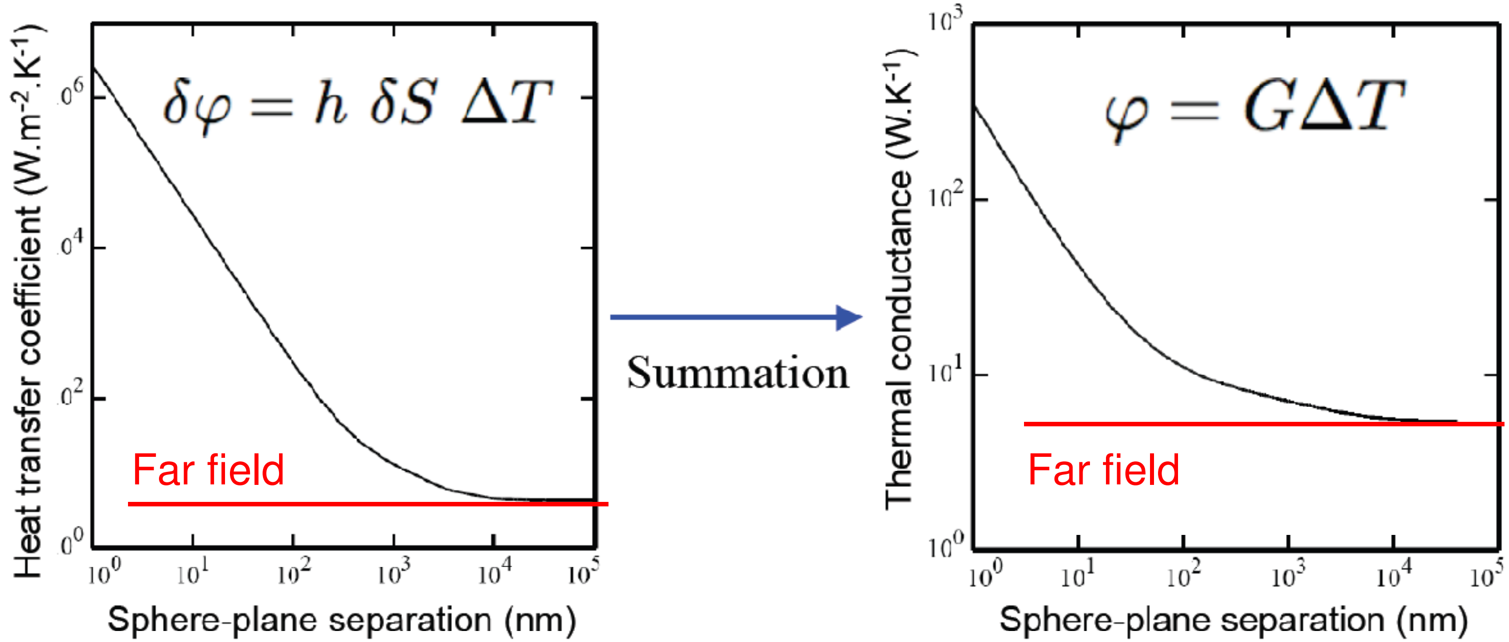
Sphere-Plane geometry



Proximity force approximation

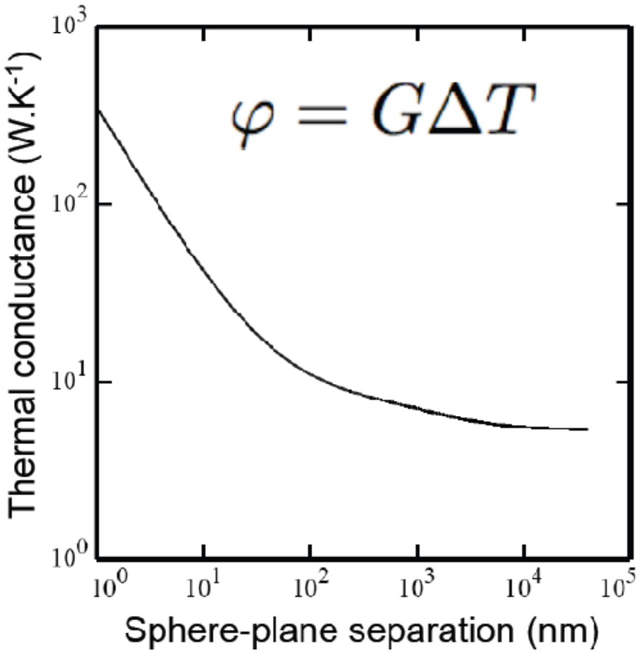
Sphere-Plane geometry: theory





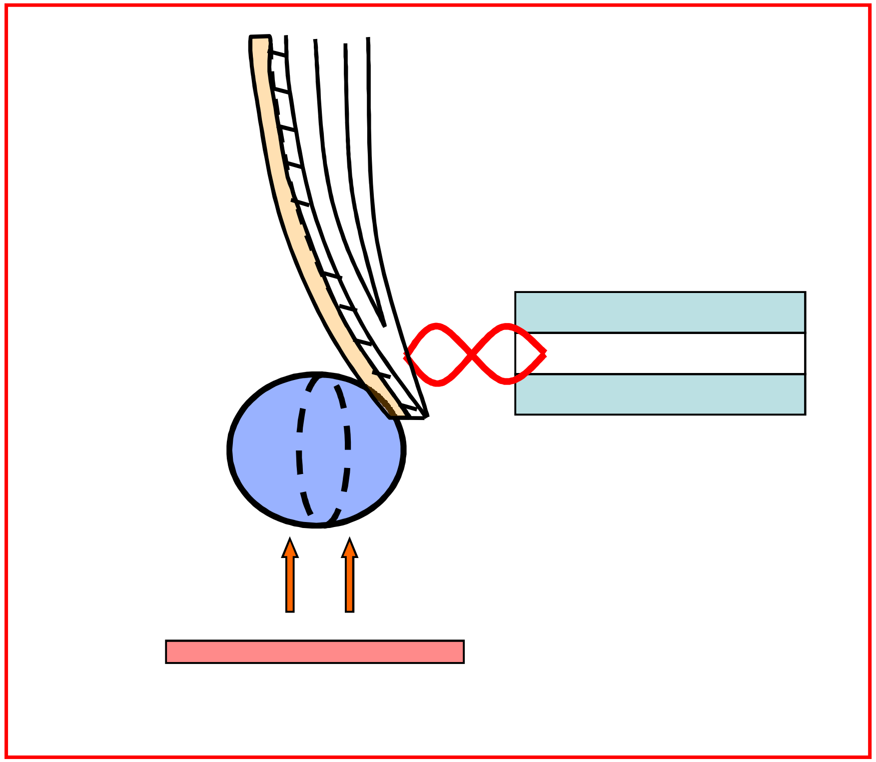
Proximity force approximation

Switch to radiative heat transfer measurement…

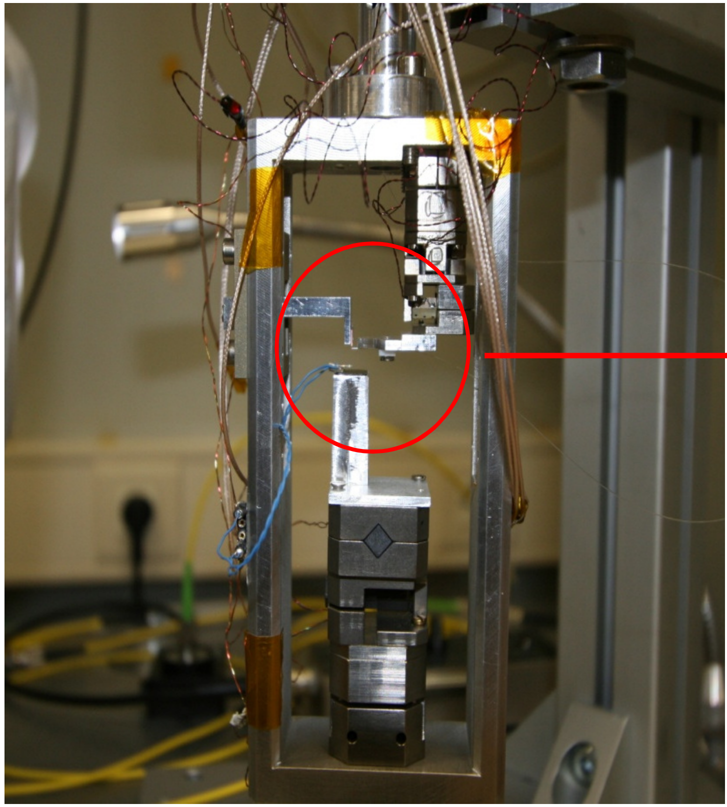


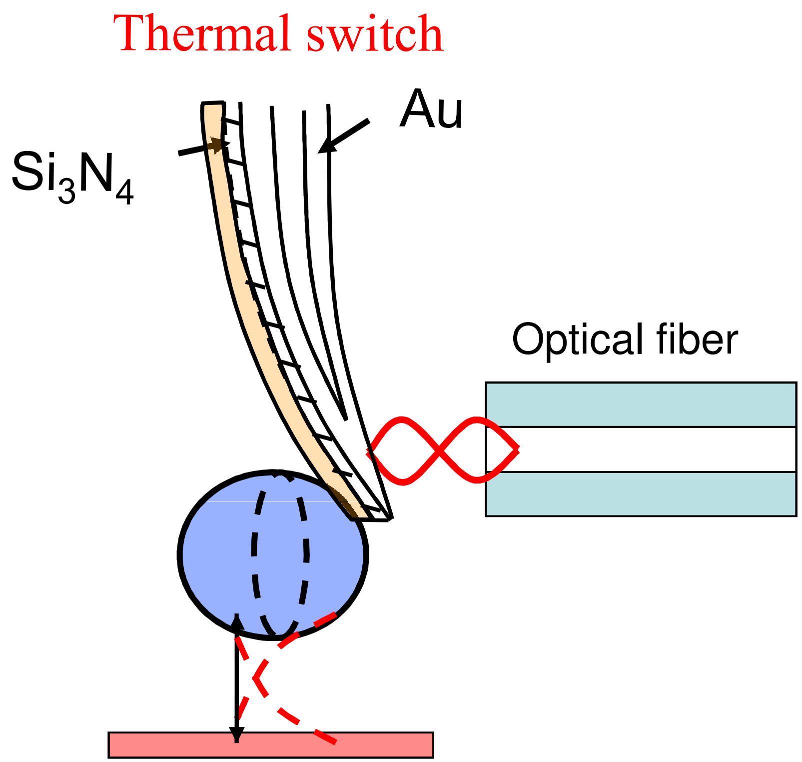
What we want to measure

How we want to measure



Experimental set-up

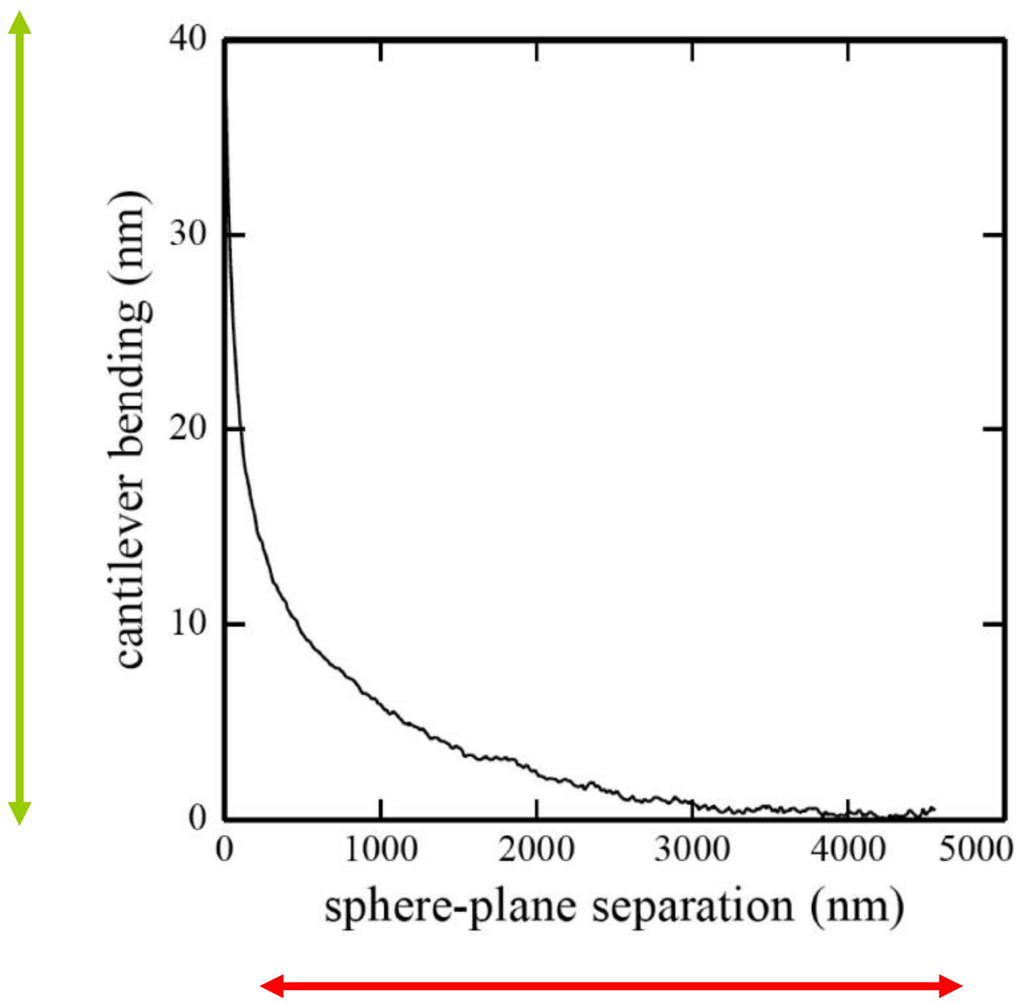


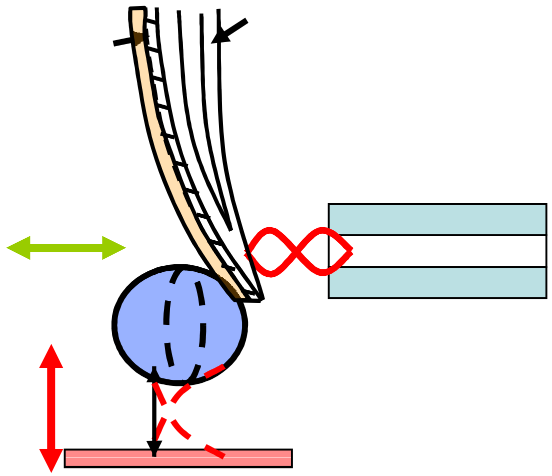


- Power exchanged = lever deflection : thermal switch effect on the lever
- High vacuum P~10^{-6} mbar : conduction negligible
- ΔT = 10-20 K.

Experimental raw data

Calibration ???

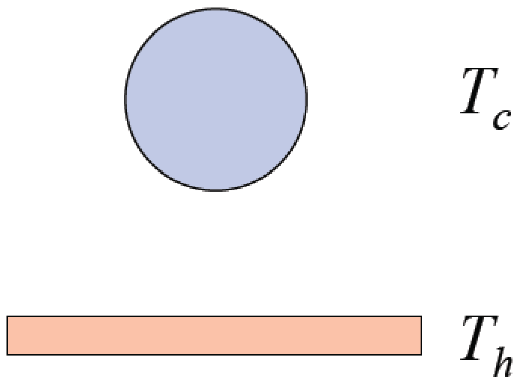




Contact definition ???

Fluxmeter calibration

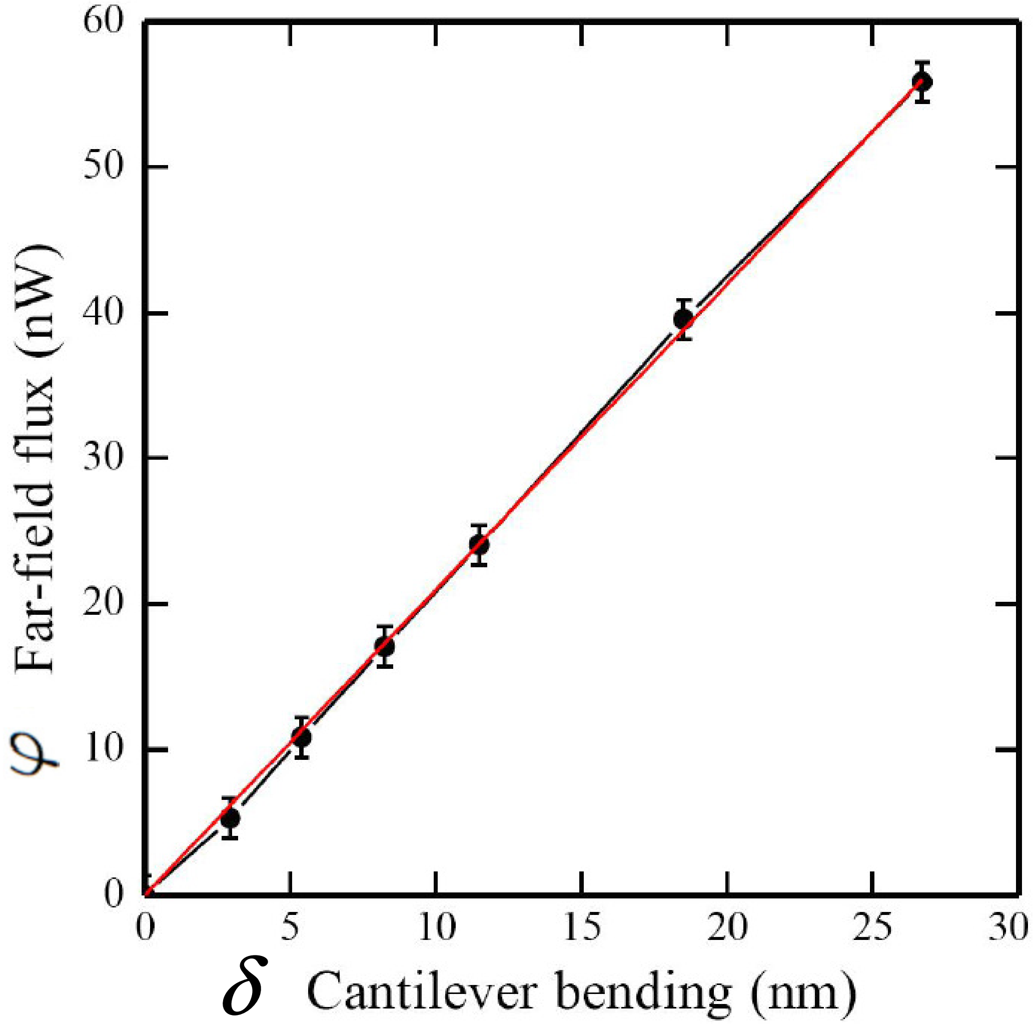
Far-field



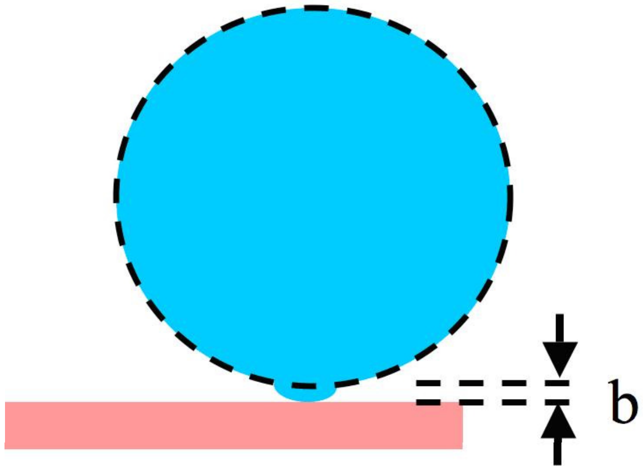
$$\varphi = 2\pi R^2 4\varepsilon\sigma T^3 \Delta T$$

$$\varphi = H \cdot \delta$$

$$H = 2.03\, nW / nm$$



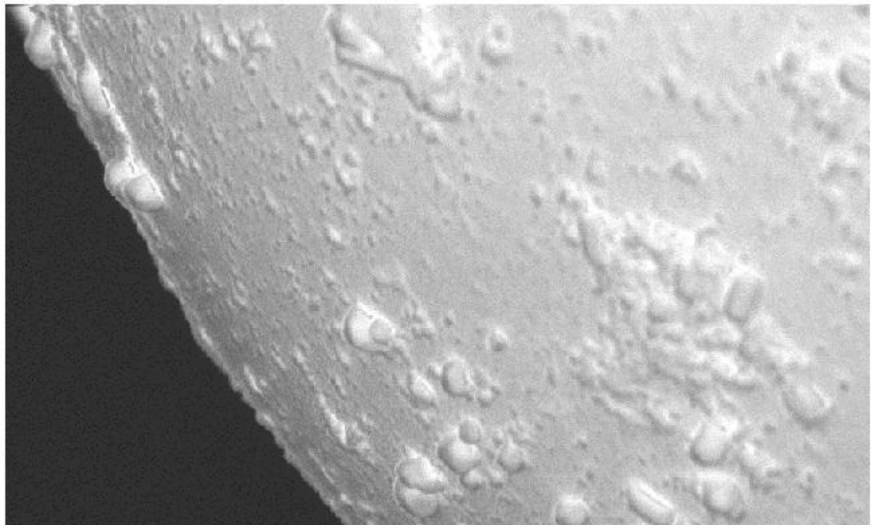
Surface roughness



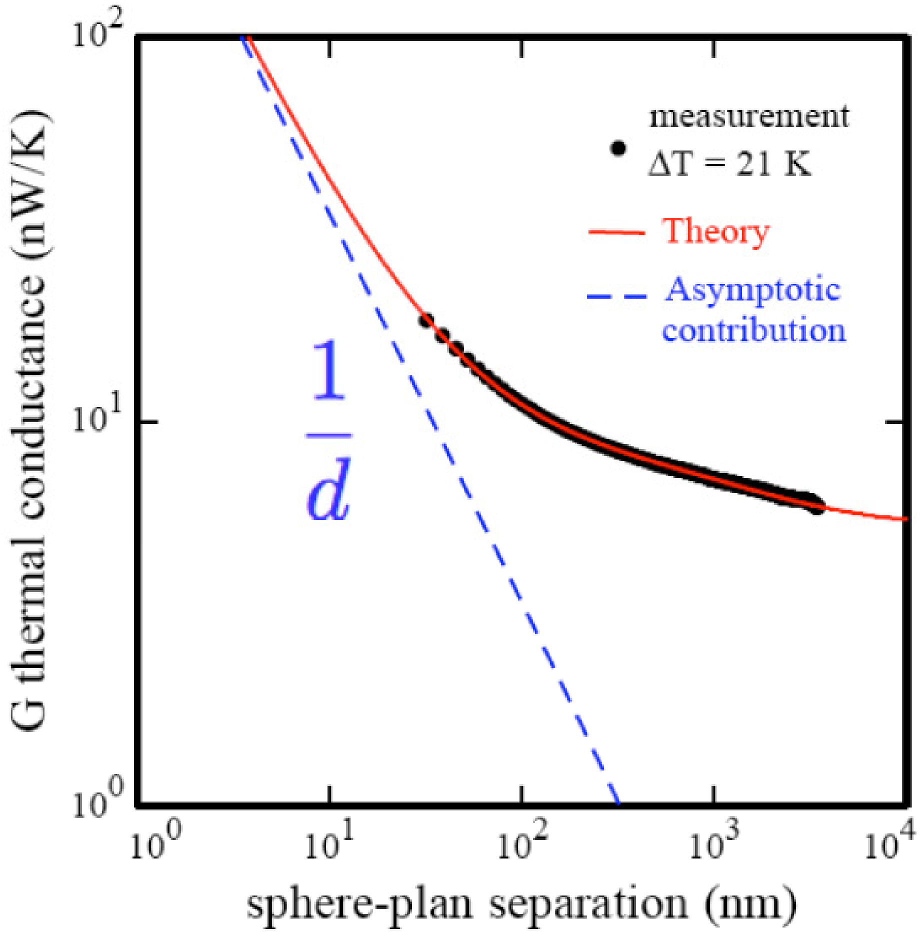
Contact between plate and sphere asperity

Average surface contact shifted repect hard contact

From SEM image sphere roughness:
50 nm rms



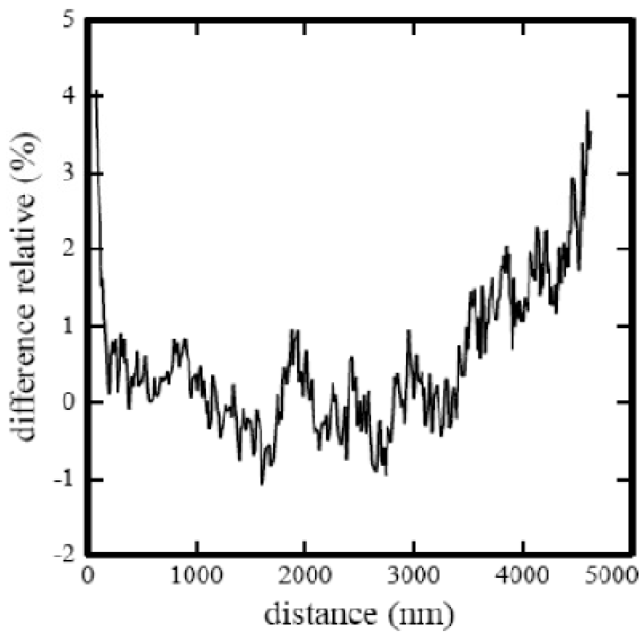
Comparison Experiments-theory



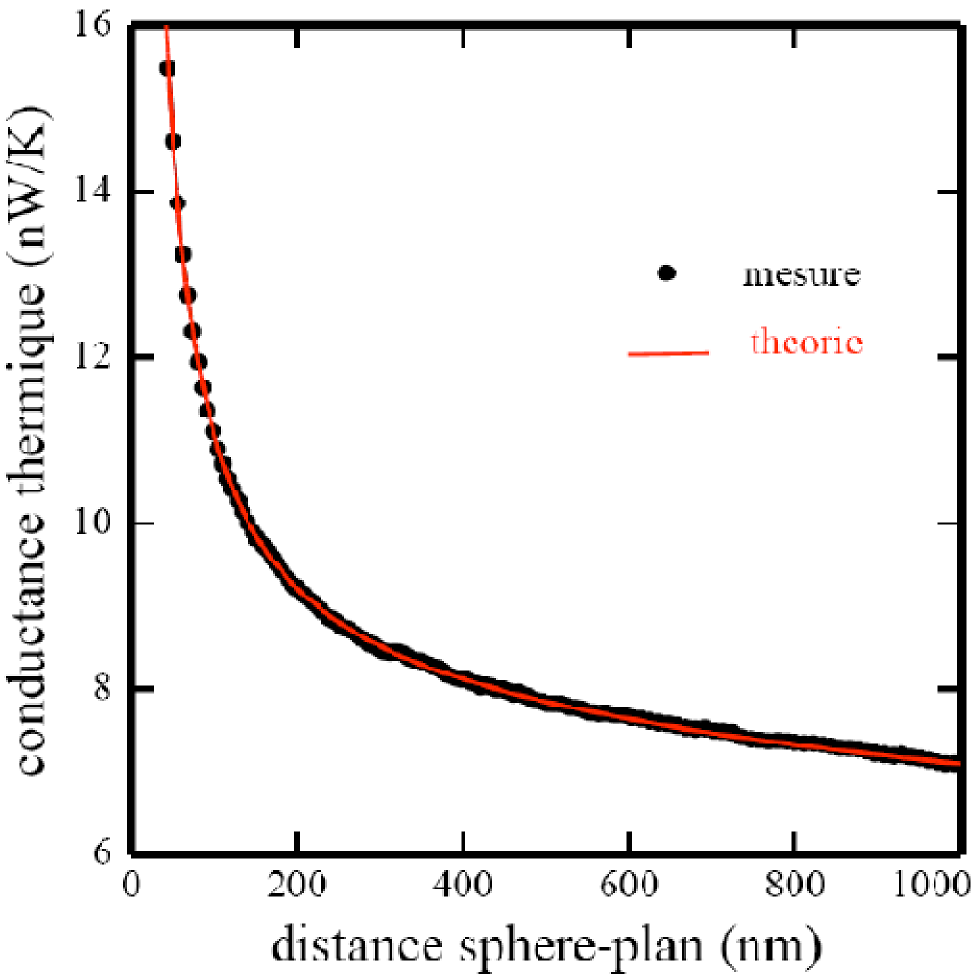
H and b adjusted:
H = 2,162 nm/nW
b = 31,8 nm

<u>Glass sphere – glass plane</u>

<u>Sphere diameter 40 μm</u>



Comparison Experiments-theory



Glass sphere – glass plane

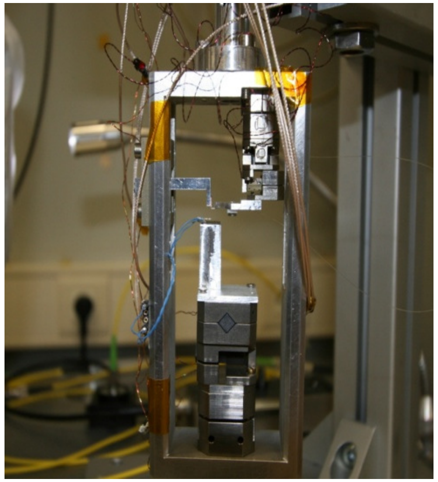
Sphere diameter 40 µm

ZOOM ON NEAR-FIELD REGIME

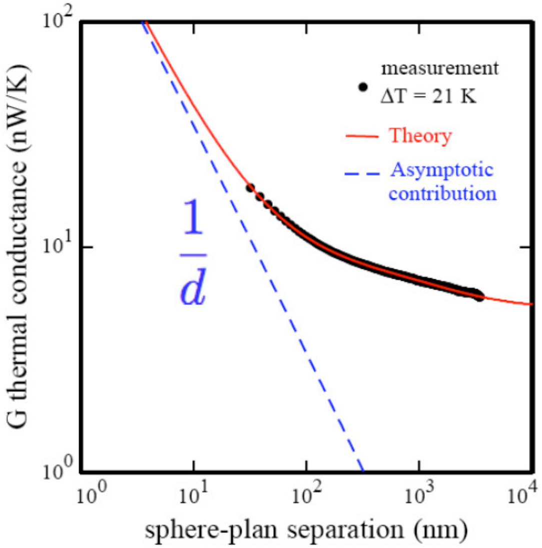
H and b adjusted:
H = 2,162 nm/nW
b = 31,8 nm

Conclusions

Development of experimental set-up for the radiative thermal transfer



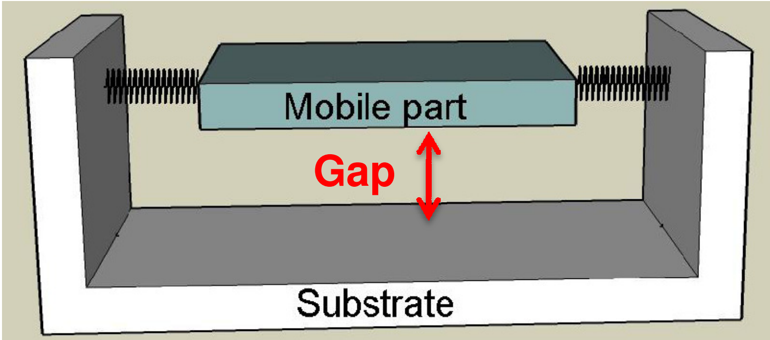
Precise measurement heat transfer in 50nm-5um range



Relative comparison theory-experience with 4% indetermination

Perspectives

Interaction forces in plane-plane geometry:



Dependency on distance of the major interaction forces

Hydrodynamic force (perfect slip):
$F \longrightarrow 1/d$

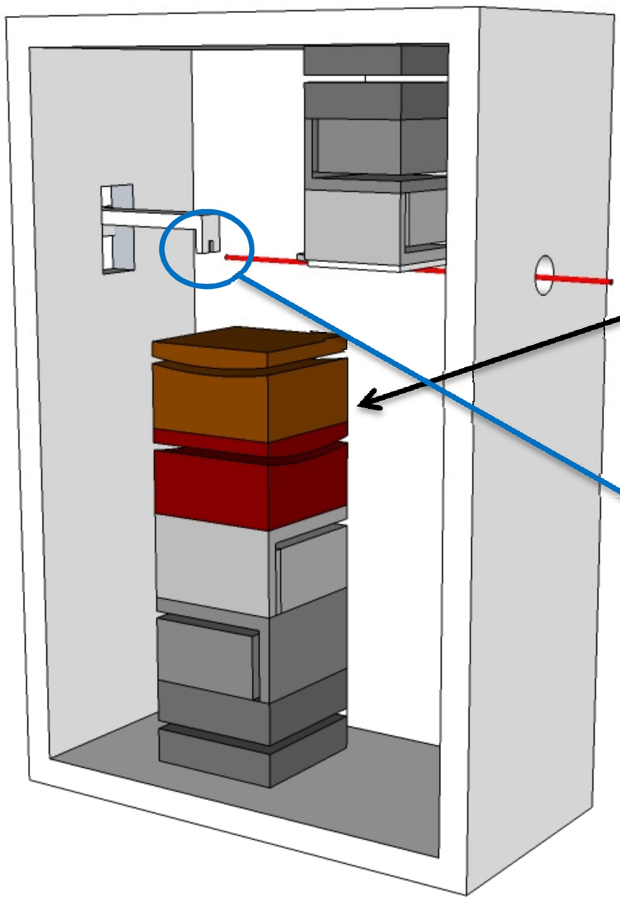
Electrostatic force:
$F \longrightarrow 1/d^2$

Thermal radiation:
$\Phi \longrightarrow 1/d^2$

Hydrodynamic force (no slip):
$F \longrightarrow 1/d^3$

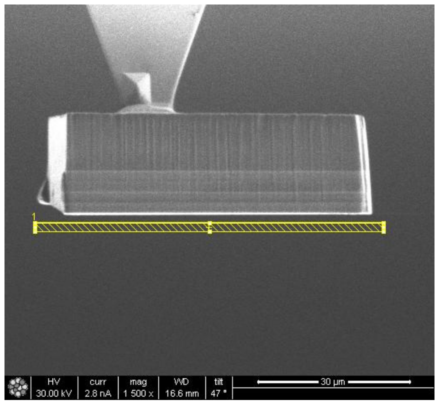
Casimir force:
$F \longrightarrow 1/d^4$

Set-up

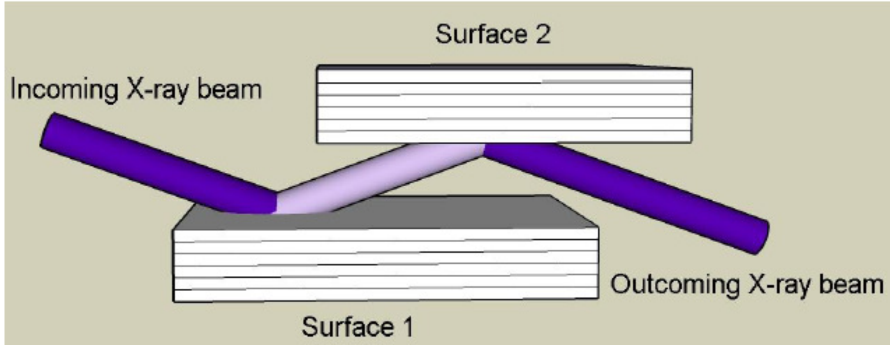


Misalignment correction
Attocube inertial motor goniometer:
10^{-4} deg

Focused Ion Beam sample realization



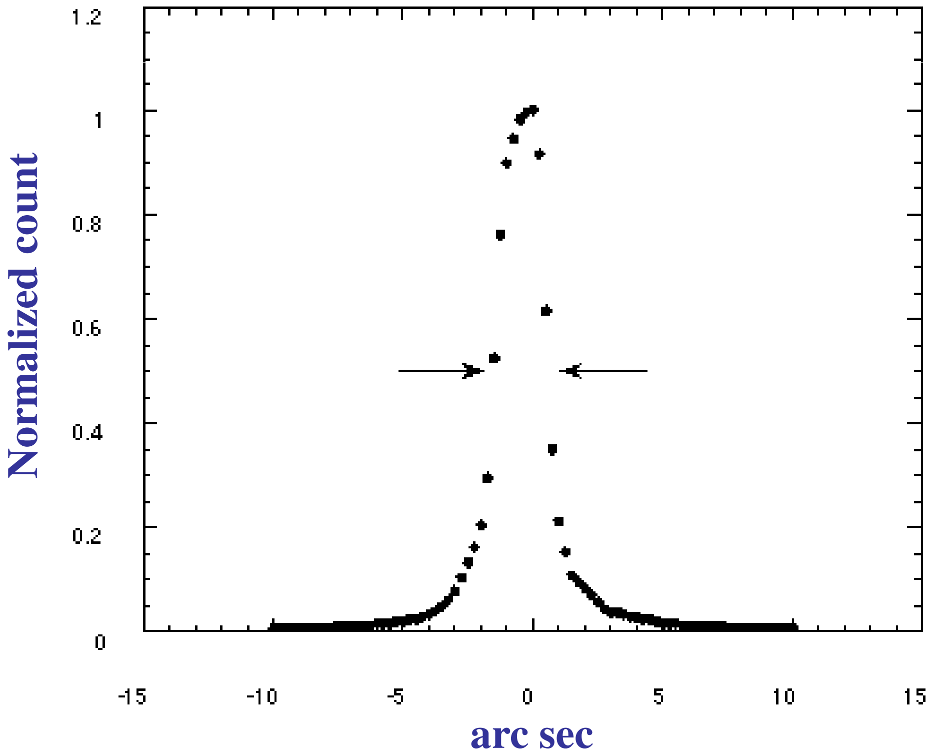
Alignment



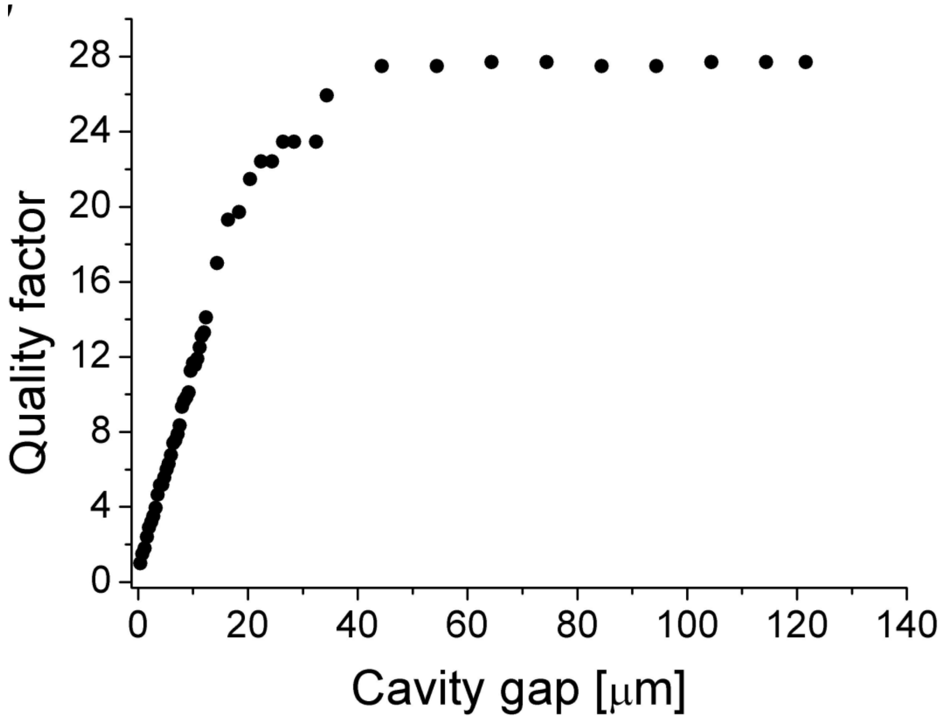
Alignment can controlled using X-ray diffraction

The precision in angle given by the Bragg peak .

For Silicon Bragg width $\sim 10^{-4}$ deg



What happens at large gap?



Damping of the lever is not depending on distance:

WHY?

Coming back to NS equation:

$$\rho\left[\frac{\partial \vec{v}}{\partial t}\right] = \eta \nabla^2 \vec{v} - \nabla p$$

Boundary layer definition: $d_L = \sqrt{\dfrac{2\eta}{\rho\omega}}$

$$d >> d_L \Rightarrow \rho\left[\frac{\partial \vec{v}}{\partial t}\right] >> \eta \nabla^2 \vec{v}$$

Damping should saturate

Theory: electromagnetic treatment.

Fluctuation-dissipation theorem:

$$\left\langle j_m^f(\vec{r},\omega) j_n^f(\vec{r}',\omega')^* \right\rangle = 2\frac{\omega\varepsilon_0}{\pi}\varepsilon''(\omega)\Theta(\omega,T)\delta_{m,n}\delta(\vec{r}-\vec{r}')\delta(\omega-\omega')$$

Green Tensor formalism:

$$\vec{E}(\vec{r},\omega) = (i\omega\mu_0)\overleftrightarrow{G}^E(\vec{r},\vec{r}',\omega)\cdot\vec{j}^f(\vec{r}',\omega)$$

$$\vec{H}(\vec{r},\omega) = \overleftrightarrow{G}^H(\vec{r},\vec{r}',\omega)\cdot\vec{j}^f(\vec{r}',\omega)$$

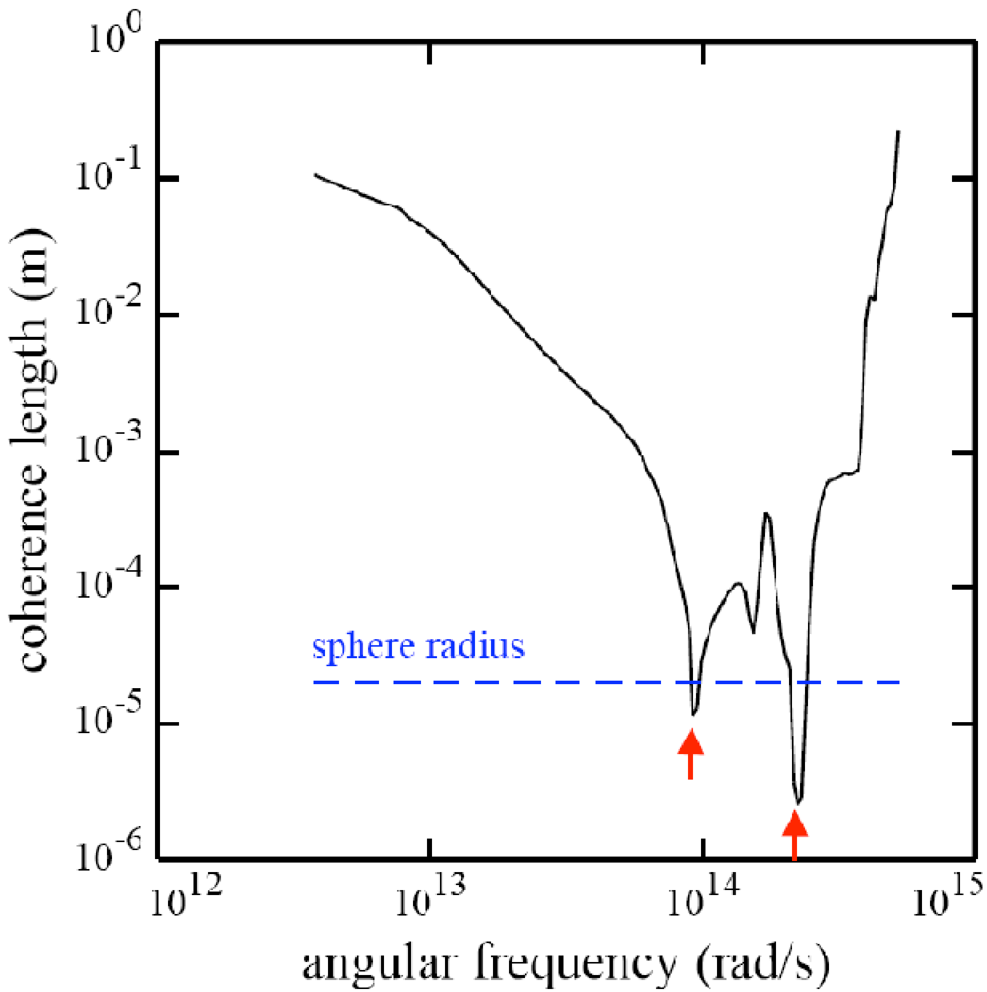
Electromagnetic energy density:

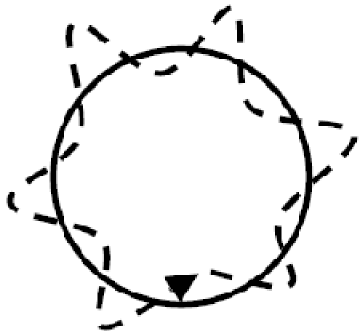
$$u(\vec{r},\omega,t) = \frac{\varepsilon_0}{2}\left\langle \vec{E}(\vec{r},\omega)\cdot\vec{E}(\vec{r},\omega)^* \right\rangle + \frac{\mu_0}{2}\left\langle \vec{H}(\vec{r},\omega)\cdot\vec{H}(\vec{r},\omega)^* \right\rangle$$

$$u(z,\omega,t) = \frac{1}{4}\frac{\omega^2\Theta(\omega,T)}{\pi^2c^2}\int_0^{k_0}\frac{KdK}{k_0|\gamma_0|}\frac{1}{2}\left[\left(1-|r_s|^2\right)+\left(1-|r_p|^2\right)\right]+$$

$$+\frac{\omega^2\Theta(\omega,T)}{\pi^2c^2}\int_{k_0}^{\infty}\frac{K^3dK}{k_0^{\,3}|\gamma_0|}\frac{1}{2}\left[\mathrm{Im}(r_s)+\mathrm{Im}(r_p)\right]e^{-2\gamma_0''z}$$

More about Derjaguin approximation



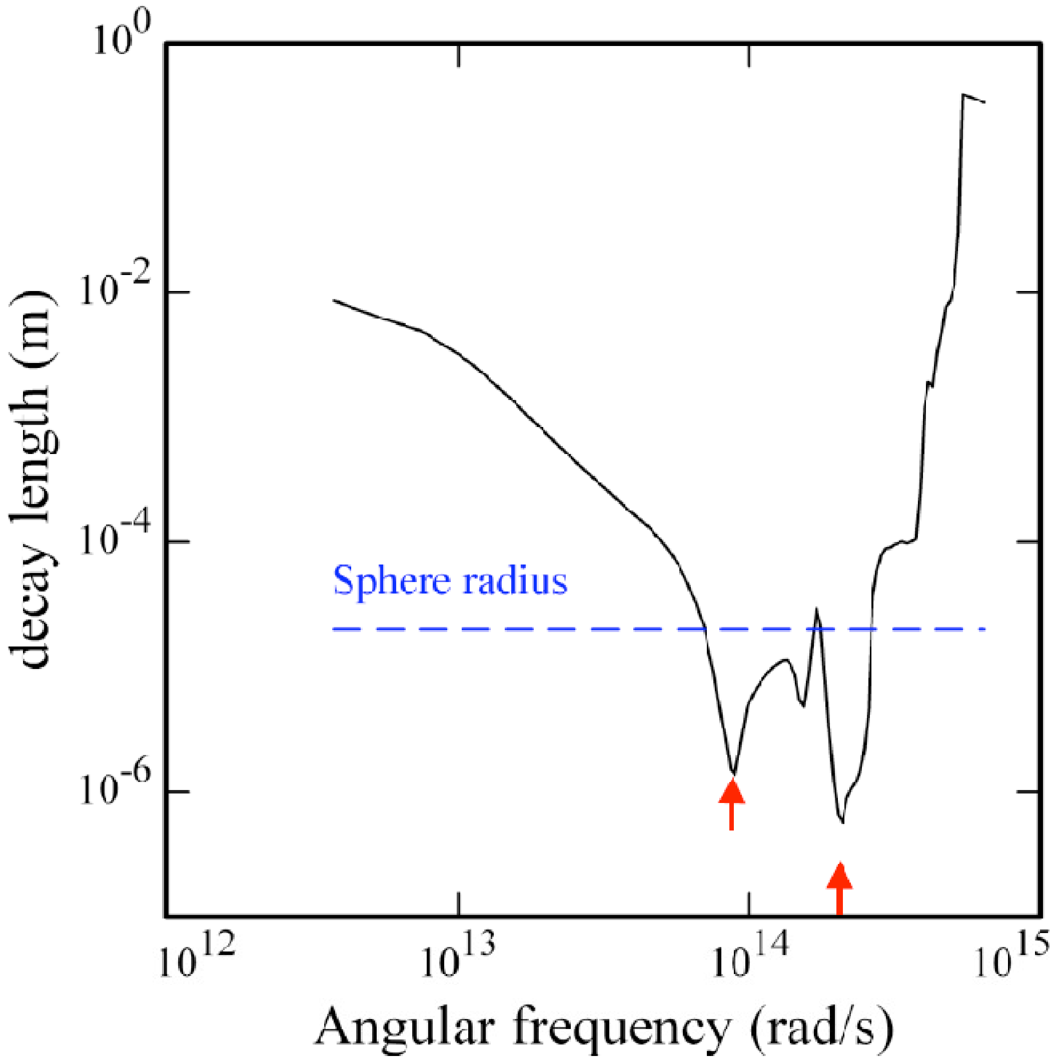


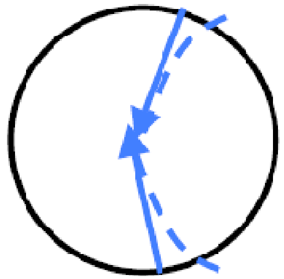
No Mie scattering

No interferences

2 points of the sphere: may be considered as independent

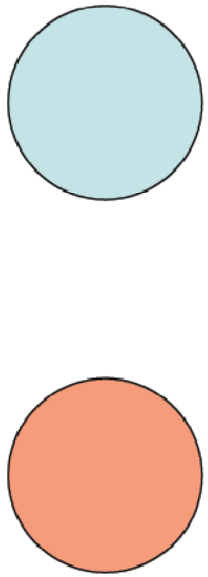
More about Derjaguin approximation

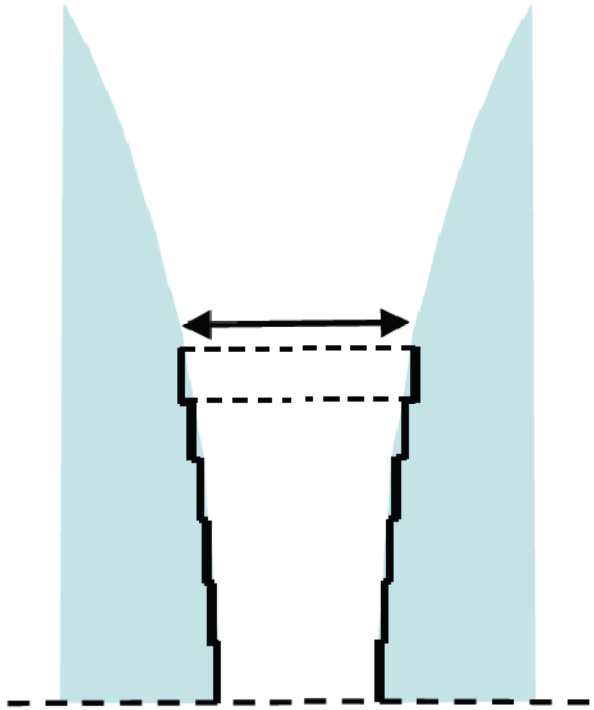




More about Derjaguin approximation

Radiative heat transfer between two spheres.

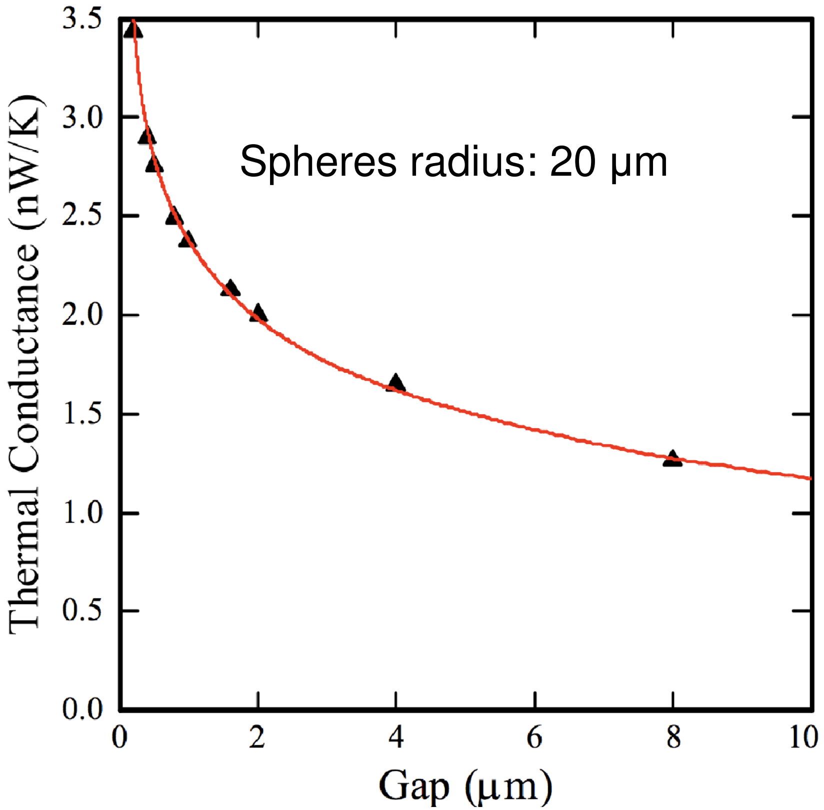




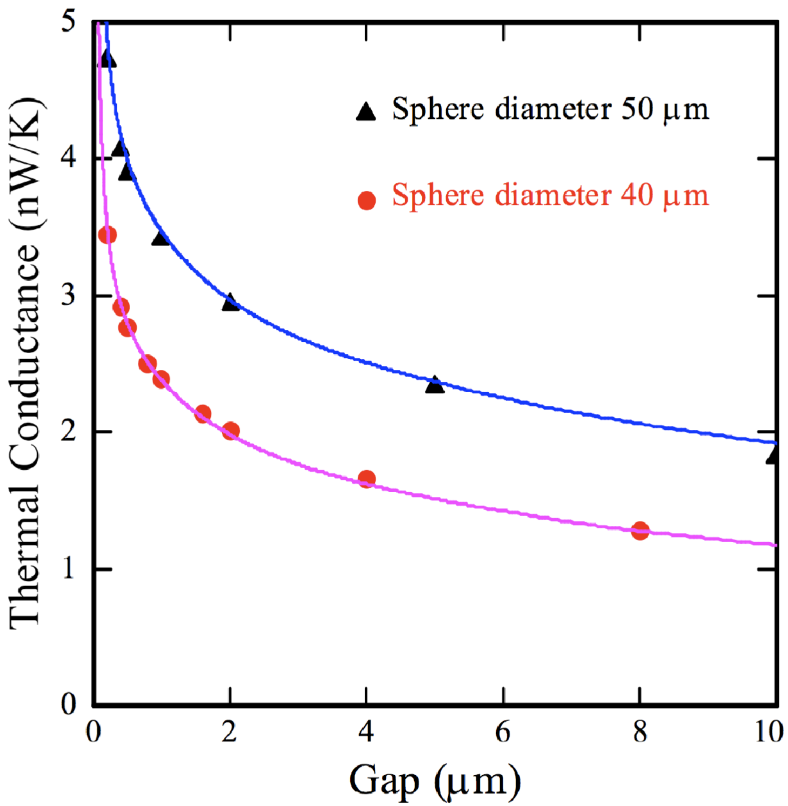
Can be computed exactly

PRB **77**, *075125*

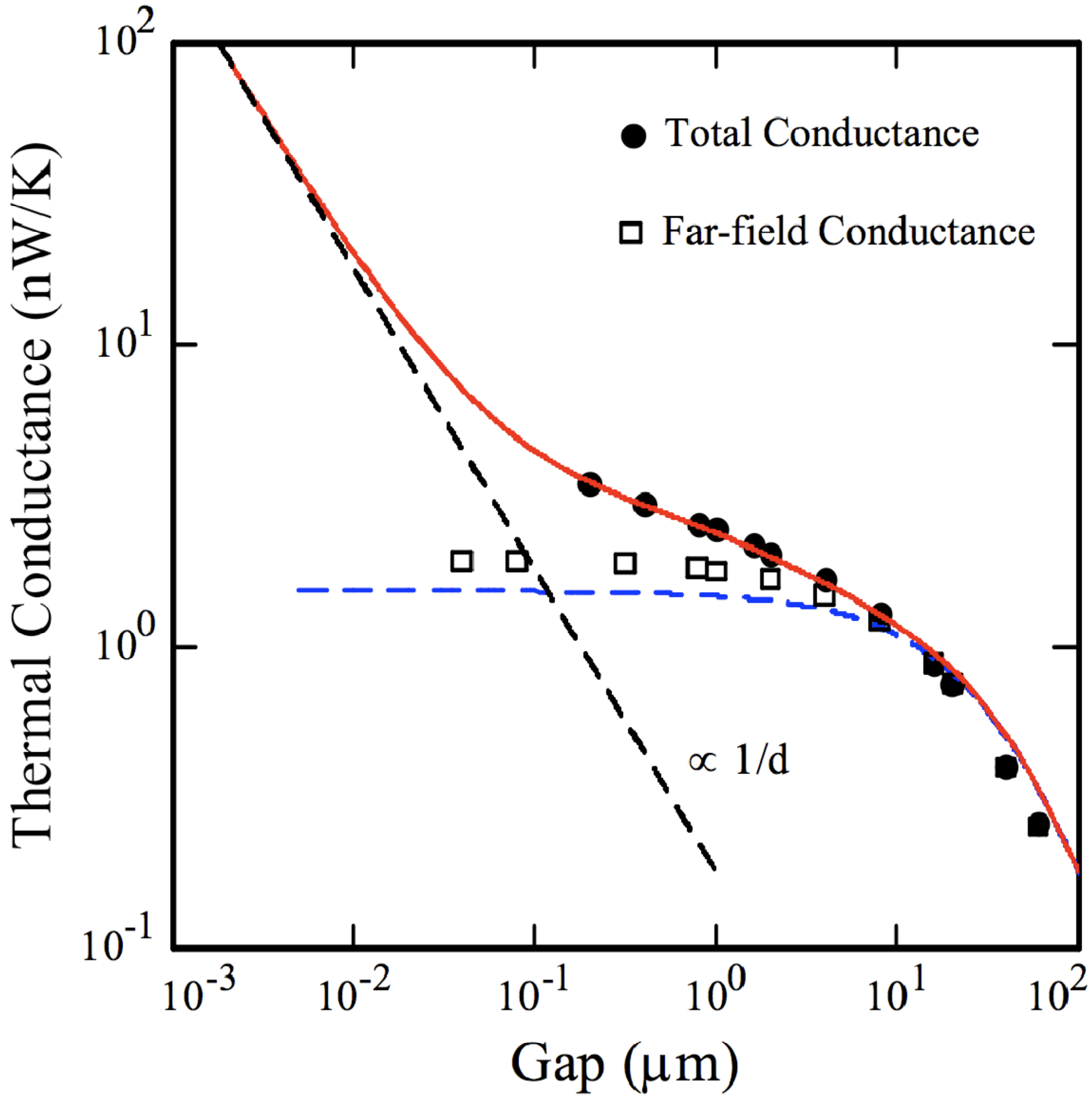
Far-field: view factor
Near-field: Derjaguin approximation



Spheres radius: 20 µm
Thermal Conductance (nW/K)
Gap (µm)

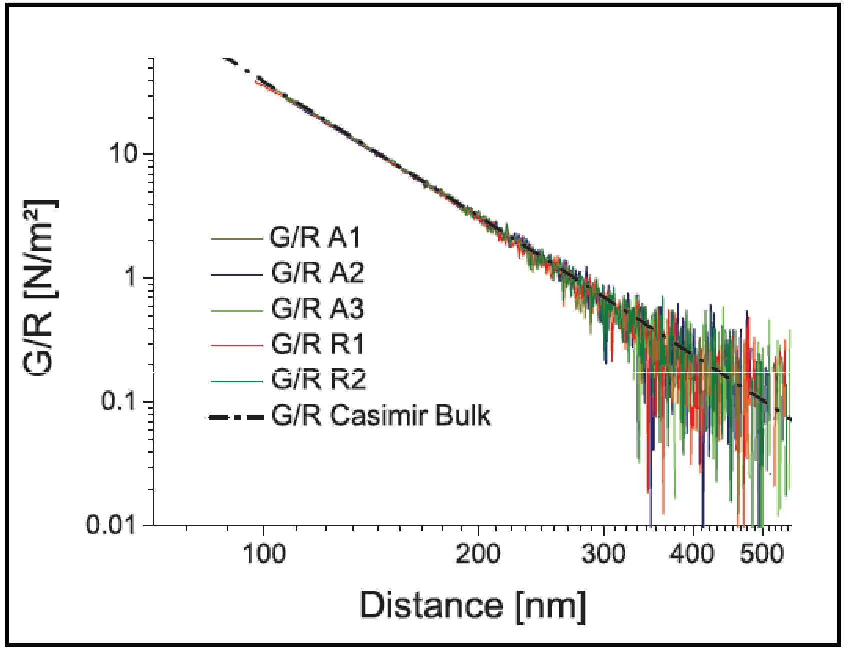


Sphere diameter 50 µm
Sphere diameter 40 µm
Thermal Conductance (nW/K)
Gap (µm)

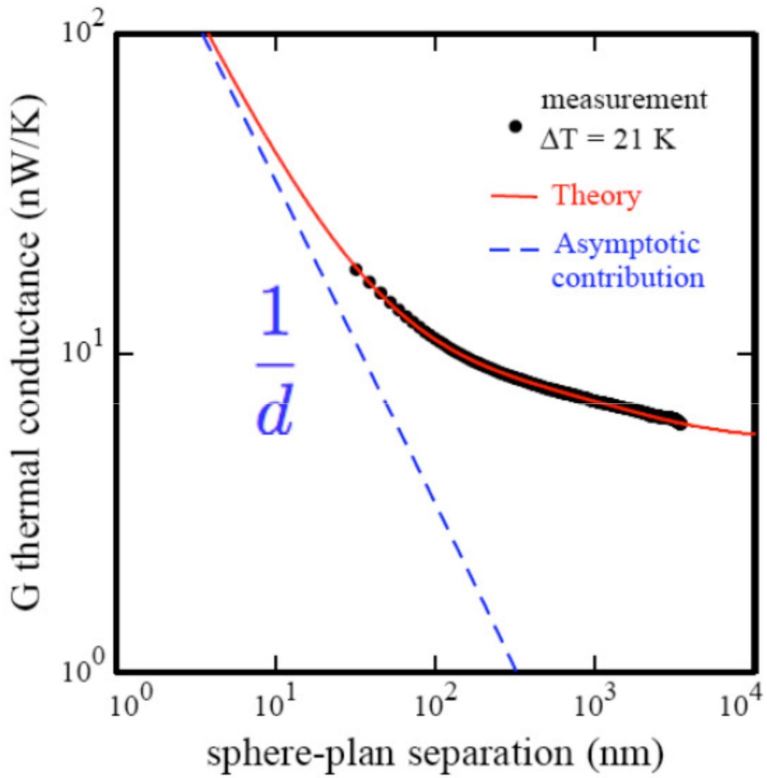


Total Conductance
Far-field Conductance
∝ 1/d
Thermal Conductance (nW/K)
Gap (μm)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}

Casimir force and radiative heat transfer: same origin, same experimental set-up



Jourdan *et al*, 2007



Siria *et al*, 2009