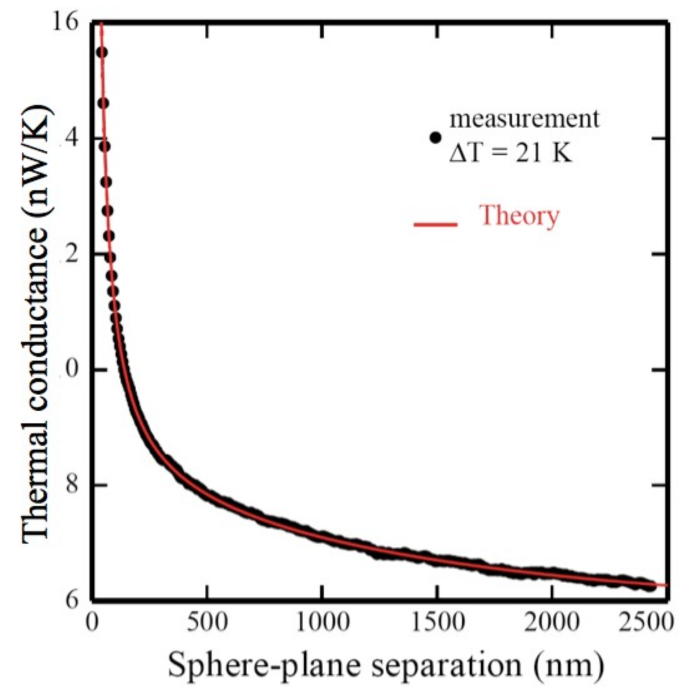
Some details about radiative heat transfer measurements at the nanoscale



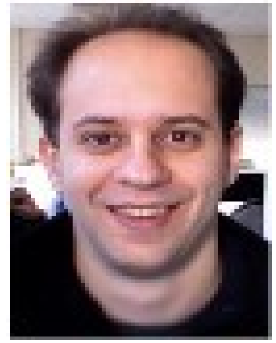
<u>E. Rousseau</u>

Now at
Laboratoire Charles Coulomb
CNRS- Université Montpellier 2

emmanuel.rousseau@univ-montp2.fr

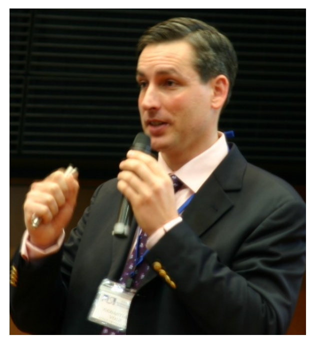
Main Protagonists

Pierre-Olivier Chapuis
Centre de Thermique de Lyon
Lyon



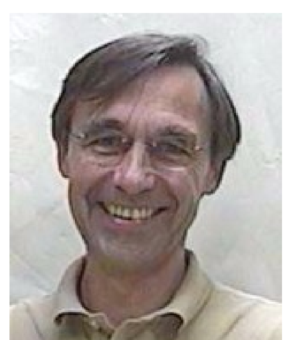
Alessandro Siria
Institut Lumière Matière
Lyon

Sebastian Volz
Laboratoire Energétique macroscopique et moléculaire, Combustion
Châtenay-Malabry



Joël Chevrier
Institut Néel
Grenoble

Jean-Jacques Greffet
Laboratoire Charles Fabry
Palaiseau



1- Two ingredients along this talk:

The heat transfer coefficient

The thermal conductance

2-Plane-Plane experiments:

Is there a good temperature to work at?

Measuring $1/d^2$ law

3- Sphere-Plane experiments

A sensitive flux-meter

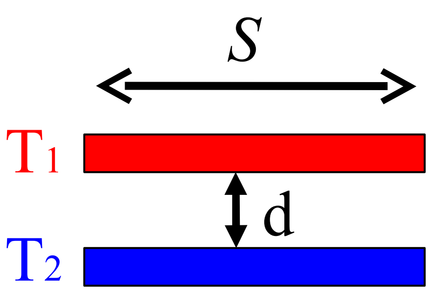
The experimental setup

Connecting the measurements to the theory

emmanuel.rousseau@univ-montp2.fr

Ingredients: *heat transfer coefficient*

Two infinite planes separated by d



$$\delta\varphi = \int d\omega K(\omega, \varepsilon_i, d, \ldots)(L(\omega, T_1) - L(\omega, T_2))\, S$$

$$\delta\varphi = \int d\omega K(\omega, \varepsilon_i, d, \ldots)\frac{\partial L(\omega, T)}{\partial T}\delta T\, S$$

$$\delta\varphi = \int d\omega h(\omega, \varepsilon_i, d, T)\delta T\, S$$

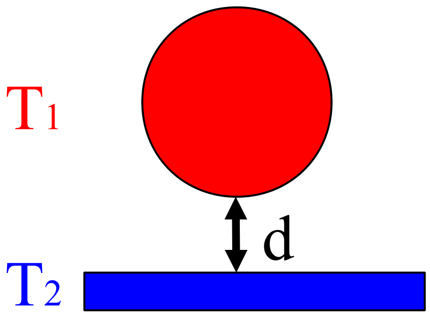
$$\delta\varphi = h(\varepsilon_i, d, T)\delta T\, S \quad W.m^{-2}.K^{-1}$$

From Joulain et al., Surface Sciences Reports **57**, 59 (2005)

emmanuel.rousseau@univ-montp2.fr

Ingredients: *thermal conductance*

Heat transfer between a sphere and a plane separated by d



$$\delta\varphi = G(\varepsilon_i, d, T)\,\delta T \qquad W.K^{-1}$$

In my talk: from the Derjaguin approximation

Now: from exact theory

1- Two main ingredients:

The heat transfer coefficient

The thermal conductance

2-Plane-Plane experiments:

Is there a good temperature to work at?

Measuring $1/d^2$ law

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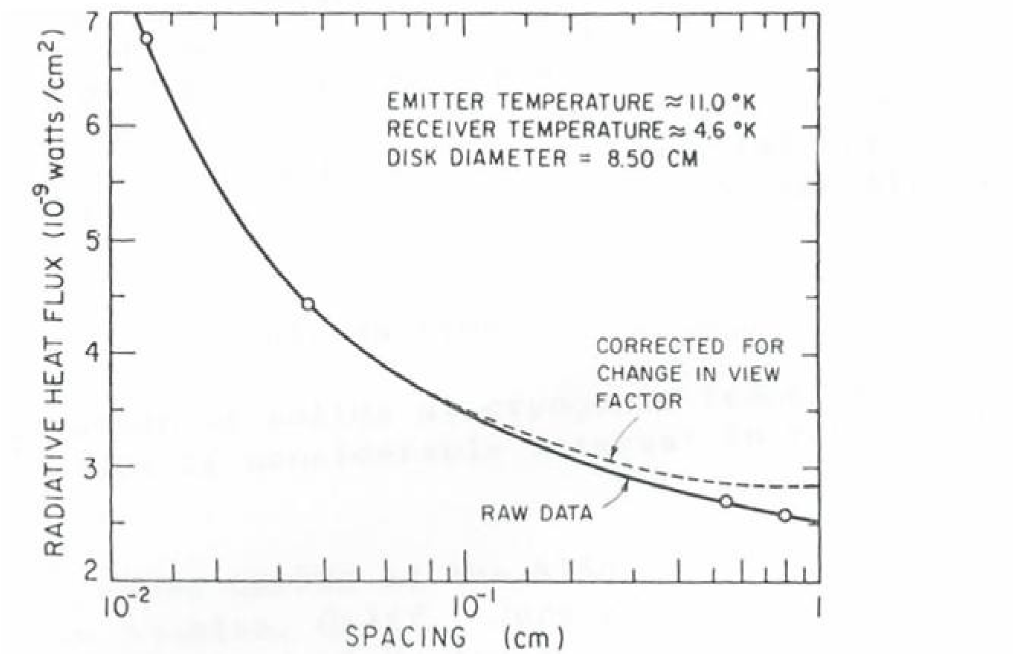
Emmanuel.rousseau@univ-montp2.fr

Measurements at low temperature ~10 K

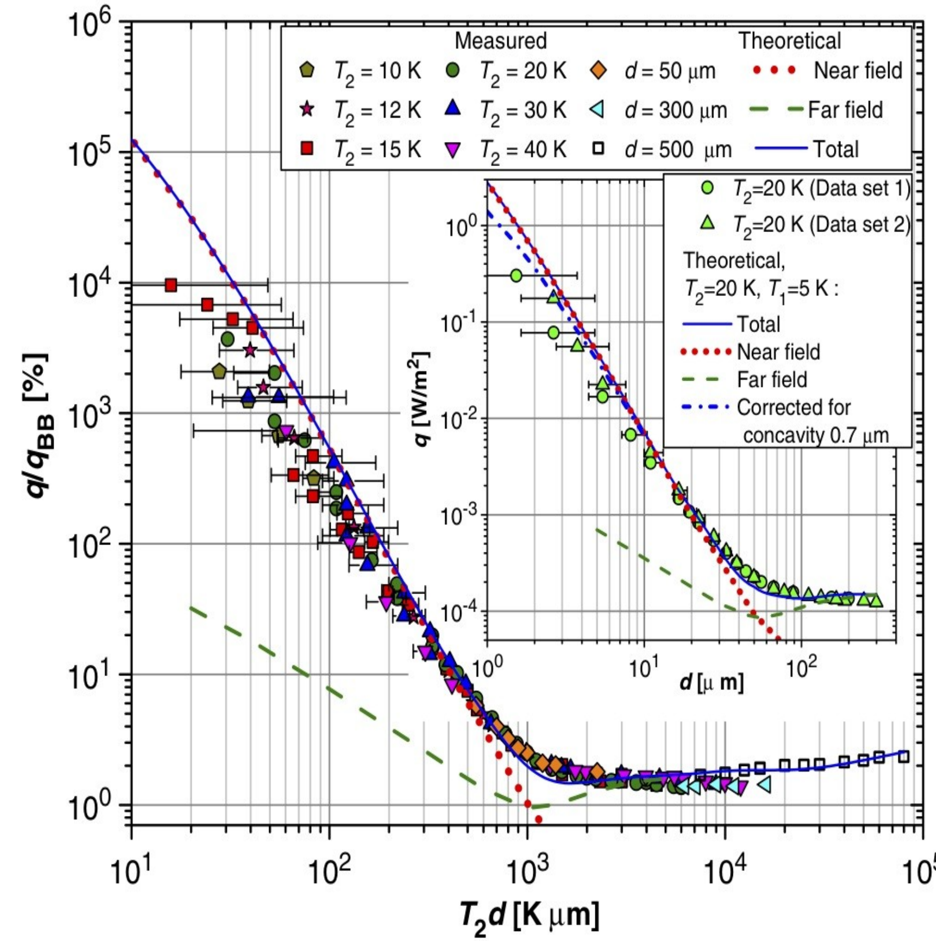
Between metals



Radiative heat flux vs spacing between parallel copper disks.

From E.G. Cravalho et al. , Progres in Aeronautics and Astronautics **22**, 531 (1968)

Between metals



From Kralik et al. PRL **109**, 224302 (2012)

Emmanuel.rousseau@univ-montp2.fr

Measurements at room temperature

Between metals

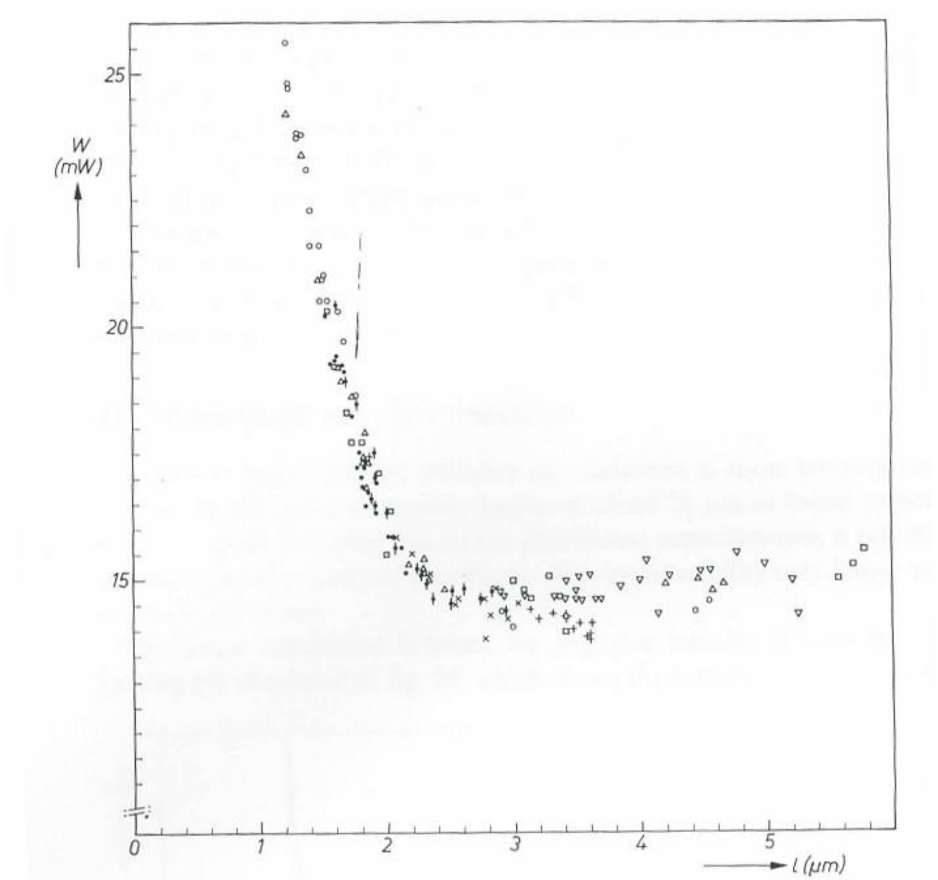
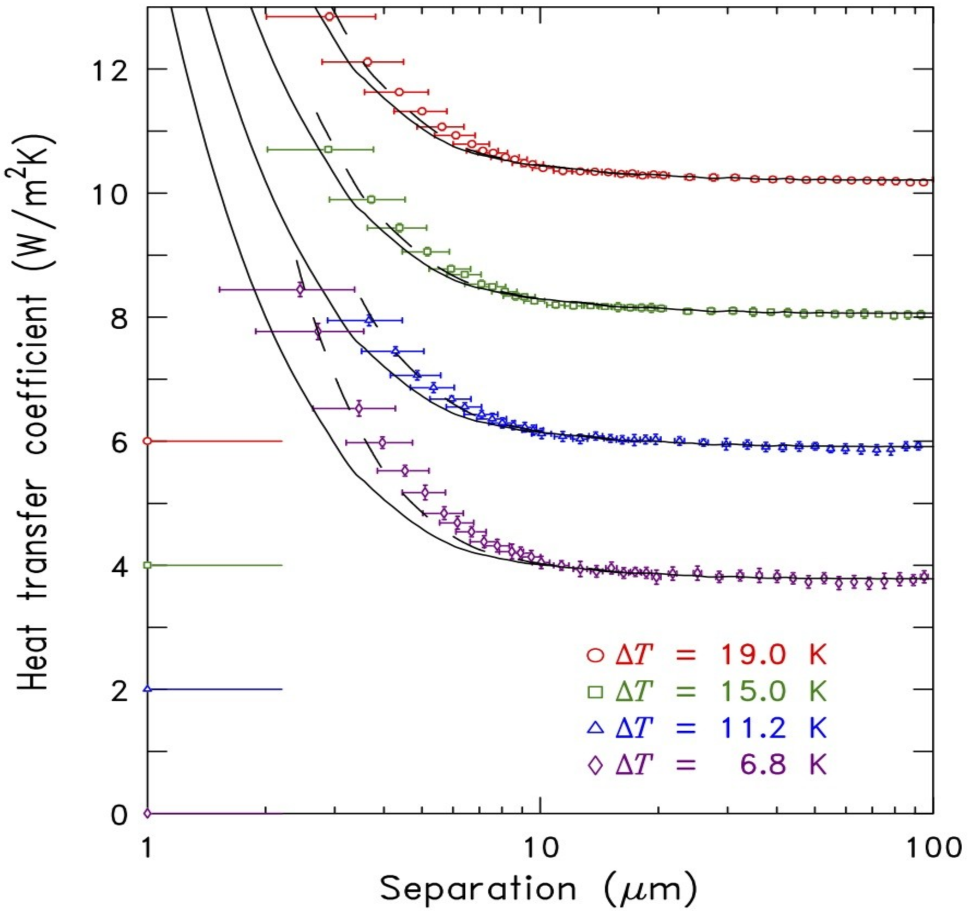


Fig. 22. Provisional measurements [79]) of the radiative transfer W between parallel metal surfaces as a function of the spacing l. Mean temperature $T = 315$ K, $\Delta T \approx 17$ K.

From Hargreaves et al. Phys. Lett. A **30A** 491 (1969)

Between dielectrics



From Ottens et al. PRL **107**, 014301 (2011)

Interest for plane-plane experiments

Plane –plane experiments are:

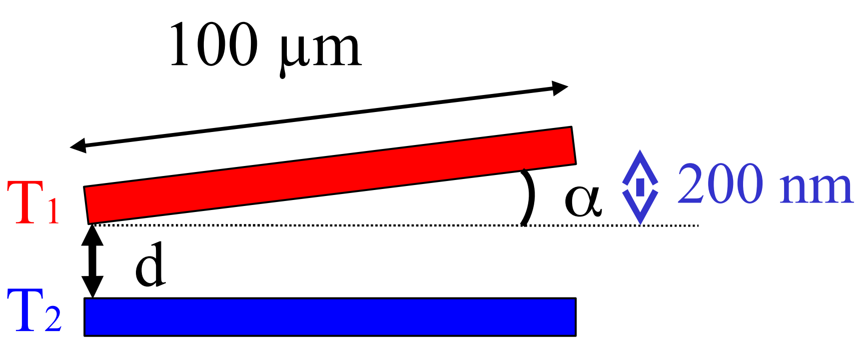
- important: easily compared to the theory

- interesting from an experimental point of view:
large area = large flux even if surfase fluxes are not so high

- difficult: because parallelism is a difficult task

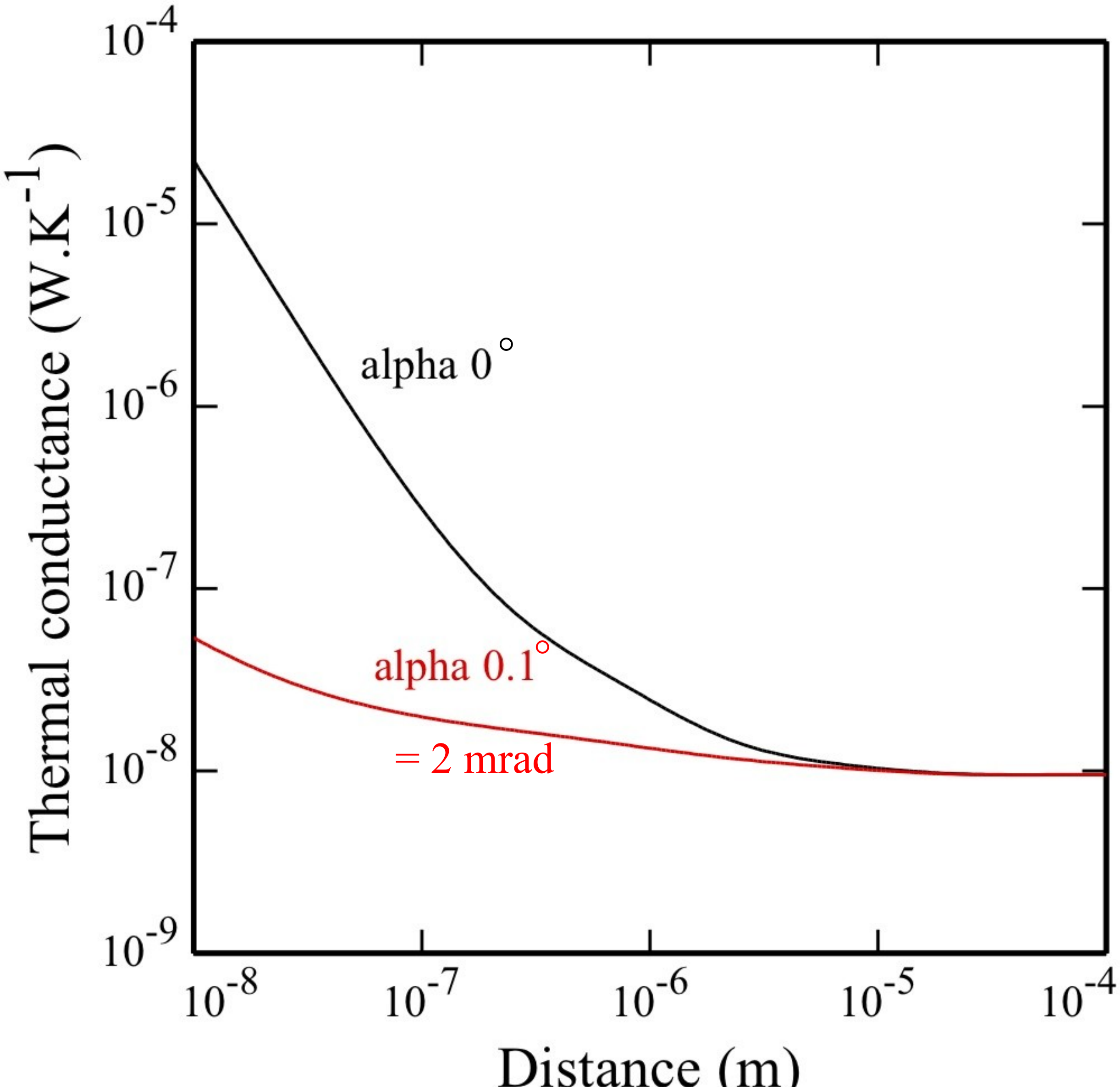
Emmanuel.rousseau@univ-montp2.fr

Misalignement consequences…

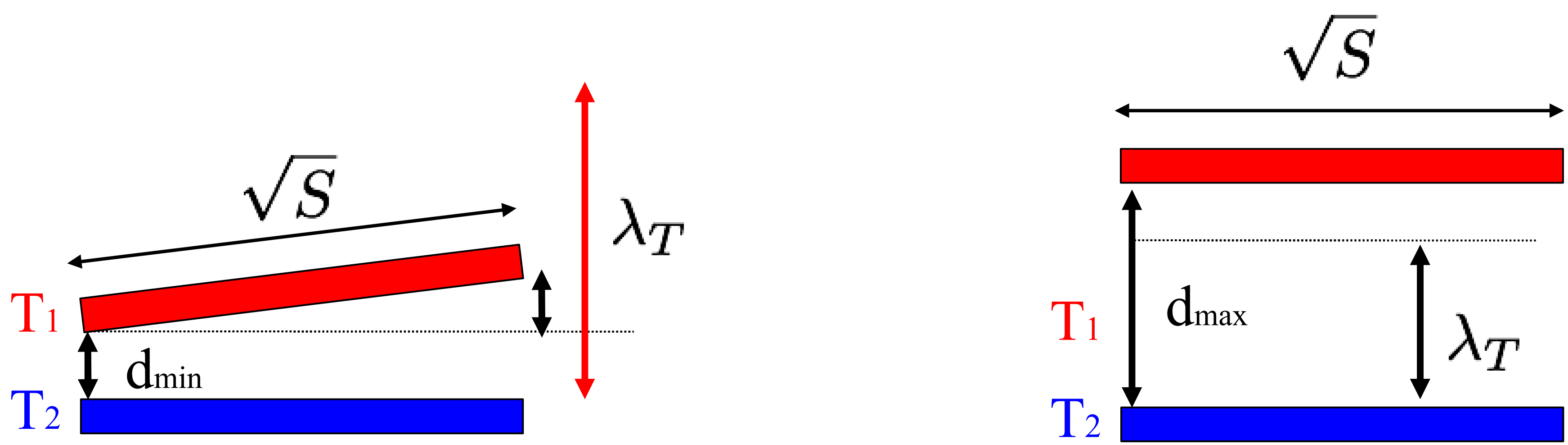


Surface modes gap-dependence ($1/d^2$) cannot be measured if angle are not extremely well control

Crude estimation with Proximity Approximation



At which temperature should I work?



$\sqrt{S}$ Characteristic lateral scale

d_{max} Maximum achived gap ~ **10 µm**

d_{min} Minimum achived gap ~ **100-10 nm**

Maybe what I would like to measure will fix the temperature?

Emmanuel.rousseau@univ-montp2.fr

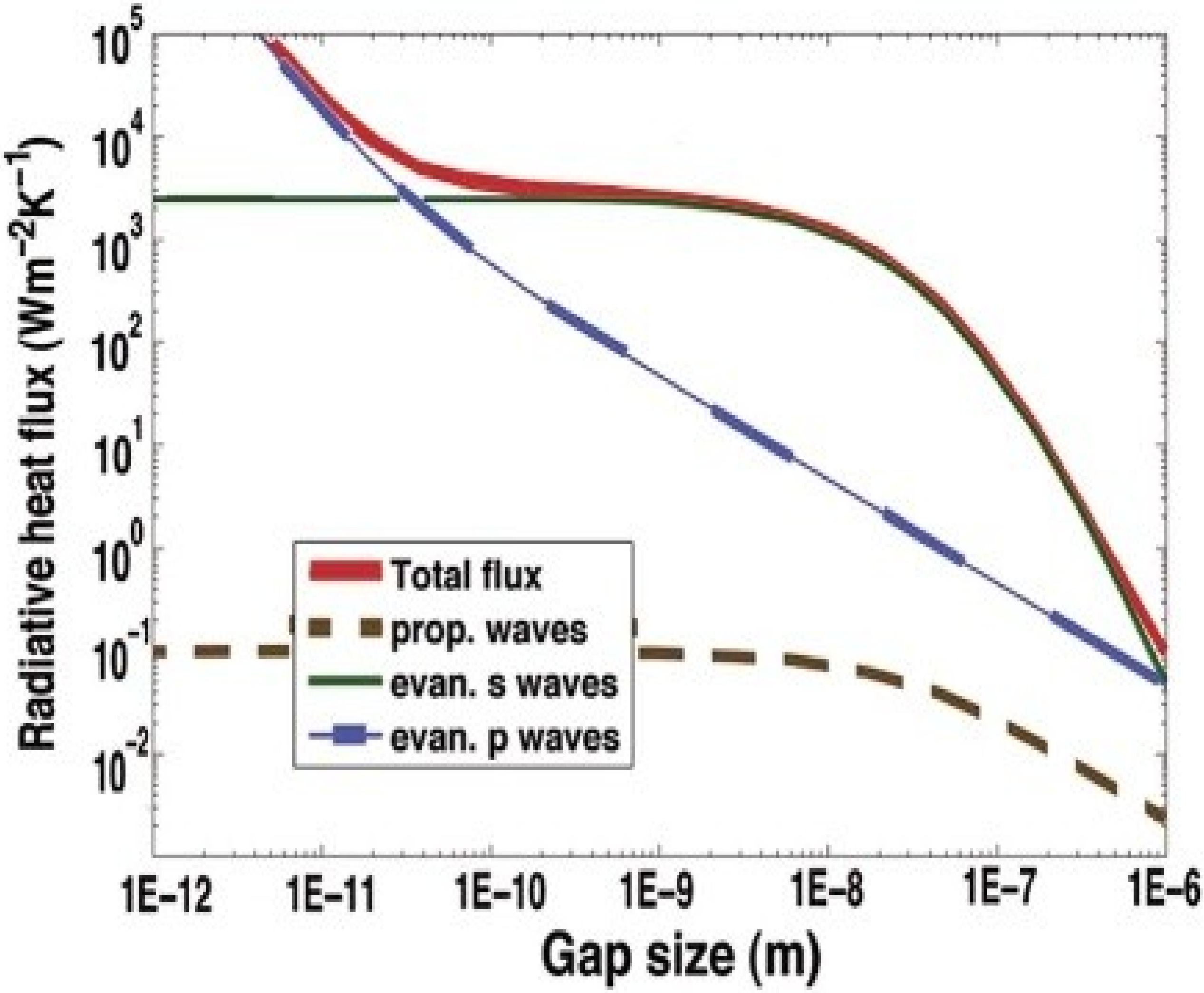
What have not been shown yet?

Between two Gold plates at 300 K

Metallic materials:
Induction zone

Surface modes coupling:
Unavailable at reasonable temperature

Saturation:
after skin depth
Not shown yet



From Chapuis et al. PRB 77 035431 (2008)

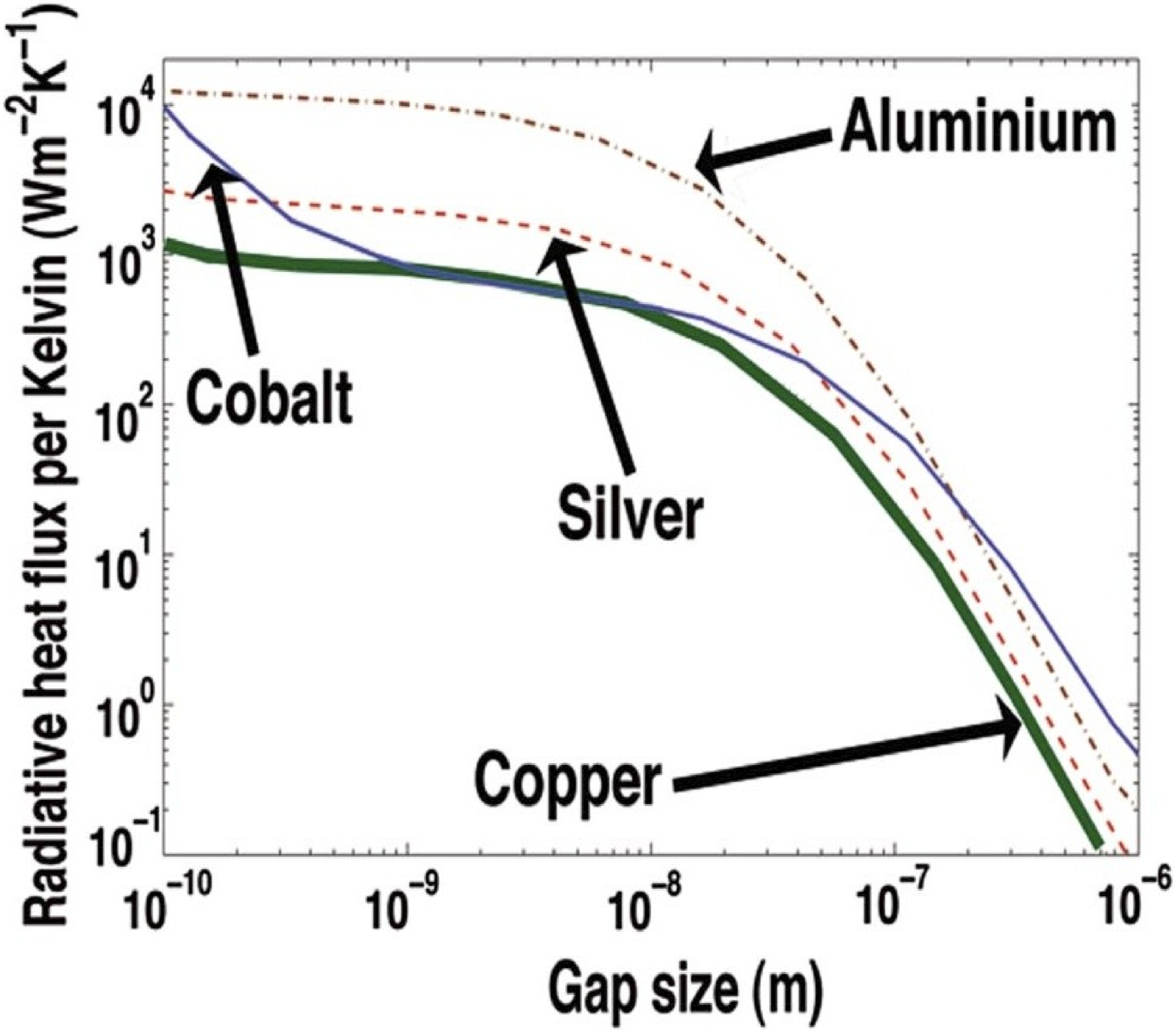
What have not been shown yet? *For metals*

Distance of saturation:

Material dependent

But

Temperature independent



From Chapuis et al. PRB 77 035431 (2008)

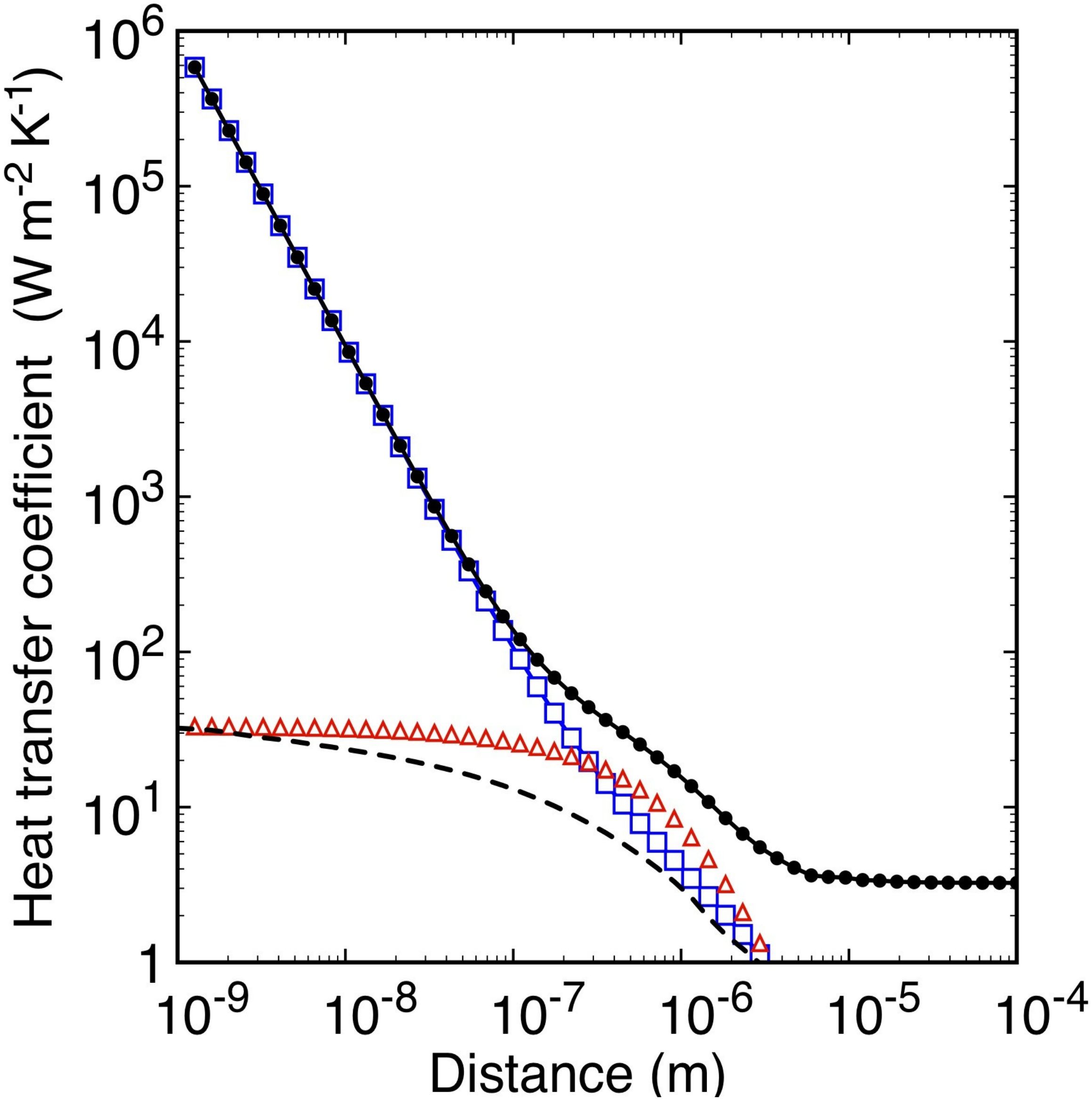
What have not been shown yet?

For materials supporting surface modes in the IR:
(Dielectric polar materials or doped silicon)

Intermediate regime: contribution of frustrated reflexions

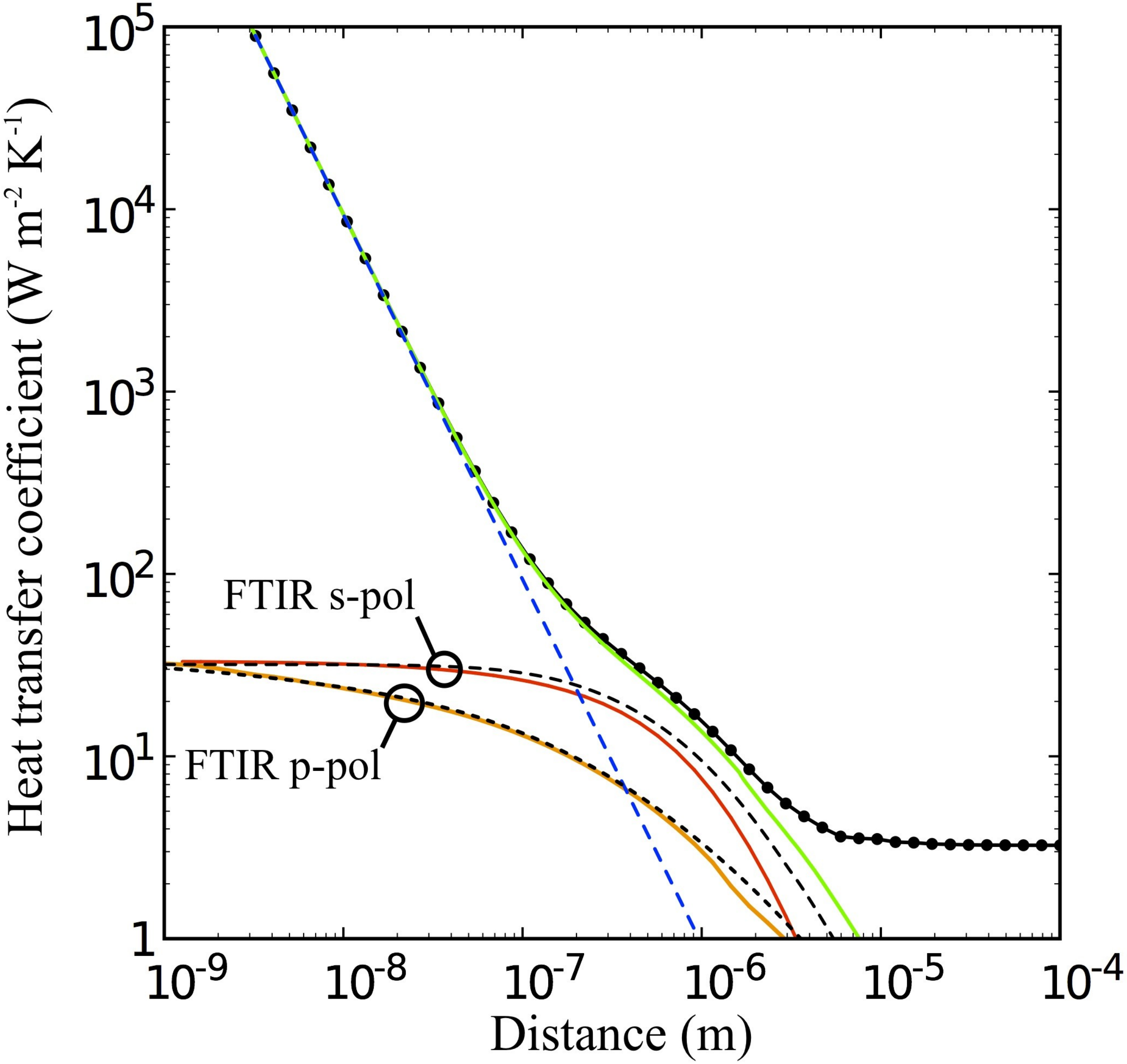
Surface modes contribution: electrostatic approximation $1/d^2$
Not shown yet

What is the best temperature to work at?



Some asymptotic results

It is possible to measure the $1/d^2$ law
when SPP contribution dominates



From Rousseau et al. JAP 111 014311 (2012)

Some analytical results

$$h_{spp}(d,T) = \frac{\delta G(T)}{d^2}$$

Starting from stochastic electrodynamics

TM polarisation evanescent contribution:

$$h^{p}_{evan}(u,d,T) = \frac{3}{2\pi^3}\frac{g_0}{\lambda_T^2}h^0(u) \times$$

$$\int_0^\infty \tilde{\gamma} d\tilde{\gamma} \frac{4Im(r_{31})Im(r_{32})e^{-2k_T\tilde{\gamma}ud}}{|1 - r_{31}r_{32}e^{-2k_T\tilde{\gamma}ud}|^2}$$

$$u = \frac{\hbar\omega}{k_B T}$$

Emmanuel.rousseau@univ-montp2.fr

Some analytical results

$$h^p_{evan}(u,d,T) = \frac{3}{2\pi^3}\frac{g_0}{\lambda_T^2}h^0(u) \times$$

$$\int_0^\infty \tilde{\gamma} d\tilde{\gamma} \frac{4Im(r_{31})Im(r_{32})e^{-2k_T\tilde{\gamma}ud}}{|1 - r_{31}r_{32}e^{-2k_T\tilde{\gamma}ud}|^2}$$

Electrostatic approximation: integration over wavevectors

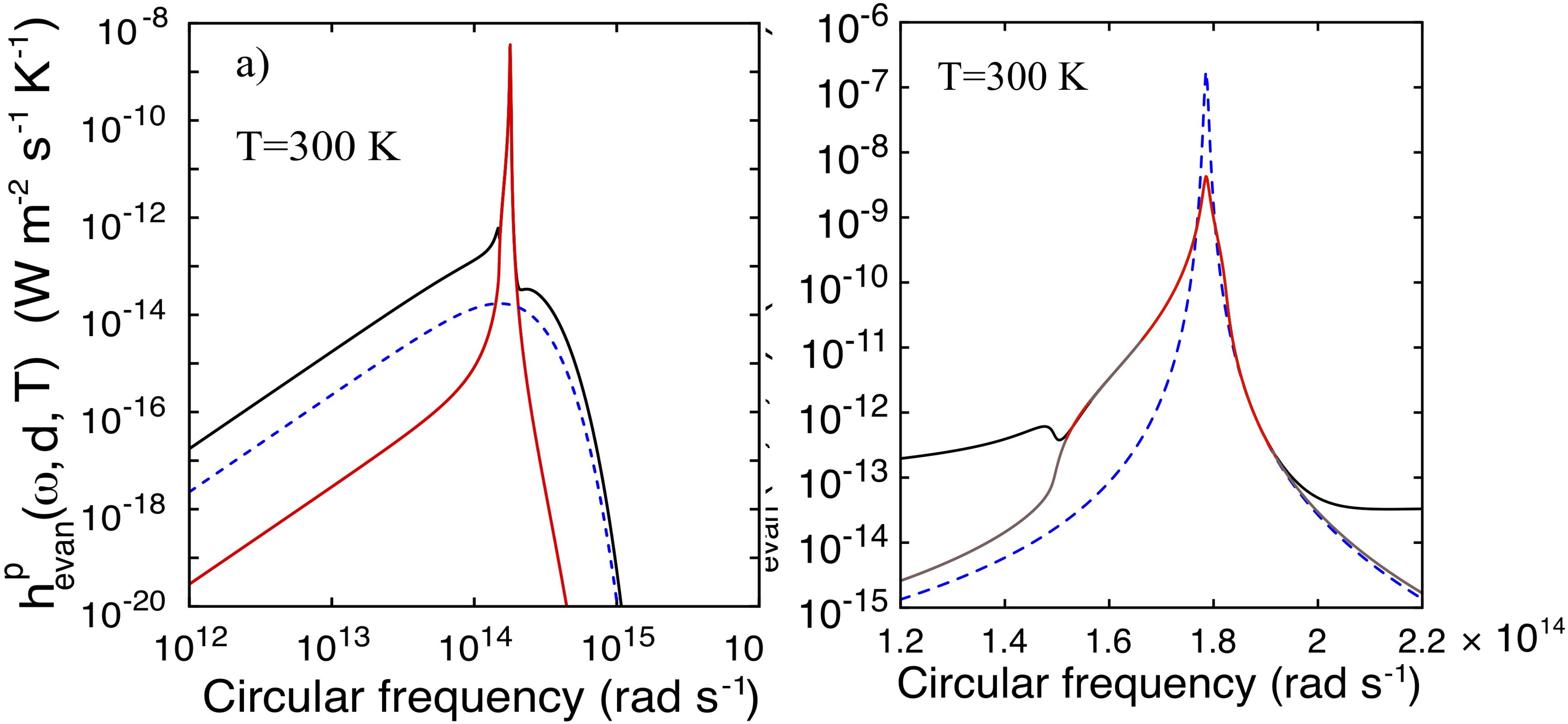
$$h_{spp}(u,d,T) = \frac{3}{2\pi^3}\frac{g_0}{d^2}\frac{h^0(u)}{u^2} \times$$

$$\frac{Im(\tilde{r}_{31})Im(\tilde{r}_{32})}{Im(\tilde{r}_{31}\tilde{r}_{32})} Im[Li_2(\tilde{r}_{31}\tilde{r}_{32})]$$

Emmanuel.rousseau@univ-montp2.fr

Some analytical results

Two SiC slab separated by 10 nm



This asymptotic expression capture the dispersion relation of the two-plates geometry

Emmanuel.rousseau@univ-montp2.fr

Some analytical results

$$h_{spp}(u,d,T) = \frac{3}{2\pi^3}\,\frac{g_0}{d^2}\,\frac{h^0(u)}{u^2} \times \frac{Im(\tilde{r}_{31})Im(\tilde{r}_{32})}{Im(\tilde{r}_{31}\tilde{r}_{32})} Im[Li_2(\tilde{r}_{31}\tilde{r}_{32})]$$

In the complex plane:

From Rousseau et al. JAP 111 014311 (2012)

Some analytical results

$$h_{spp}(u,d,T) = \frac{3}{2\pi^3}\ \frac{g_0}{d^2}\frac{h^0(u)}{u^2} \times$$

$$\frac{1}{f(u)} = \frac{Im(\tilde{r}_{31})Im(\tilde{r}_{32})}{Im(\tilde{r}_{31}\tilde{r}_{32})} Im[Li_2(\tilde{r}_{31}\tilde{r}_{32})]$$

In the complex plane:

$$h_{spp}(d,T) = \frac{\delta G(T)}{d^2}$$

$$\delta G(T) = \frac{3}{2\pi^2} g_0 \times$$

$$\sum_{u_i} \frac{1}{f'(u_i)} u_i^2 \frac{e^{u_i}}{(e^{u_i}-1)^2} Re[Li_2(\tilde{r_1}(u_i)\tilde{r_2}(u_i))]$$

Emmanuel.rousseau@univ-montp2.fr

Some analytical results

$$h_{spp}(d,T) = \frac{\delta G(T)}{d^2} \qquad u = \frac{\hbar\omega}{k_B T}$$

$$\delta G(T) = \frac{3}{2\pi^2} g_0 \times$$

$$\sum_{u_i} \frac{1}{f'(u_i)} u_i^2 \frac{e^{u_i}}{(e^{u_i}-1)^2} Re[Li_2(\tilde{r_1}(u_i)\tilde{r_2}(u_i))]$$

u_i are zeros of

$$f(u) = \frac{Im(\tilde{r}_{31}) Im(\tilde{r}_{32})}{Im(\tilde{r}_{31}\tilde{r}_{32})}$$

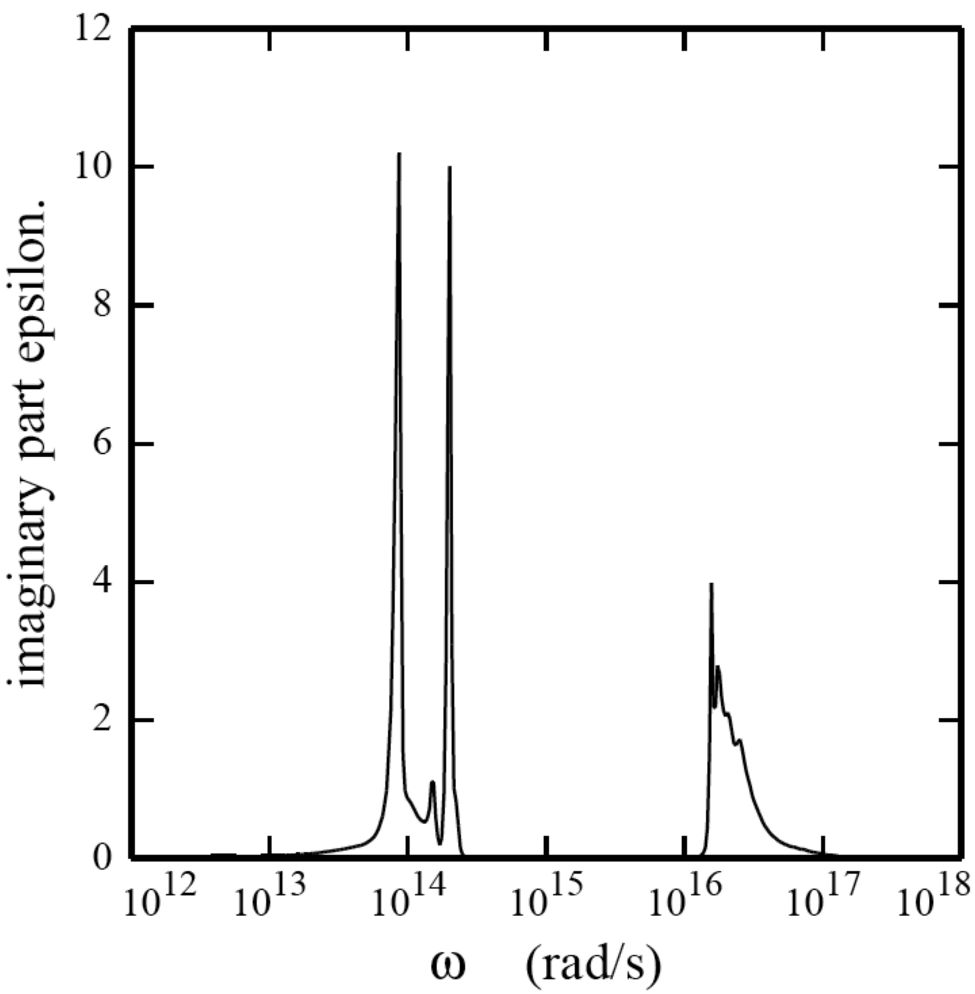
with $f'(u) < 0$

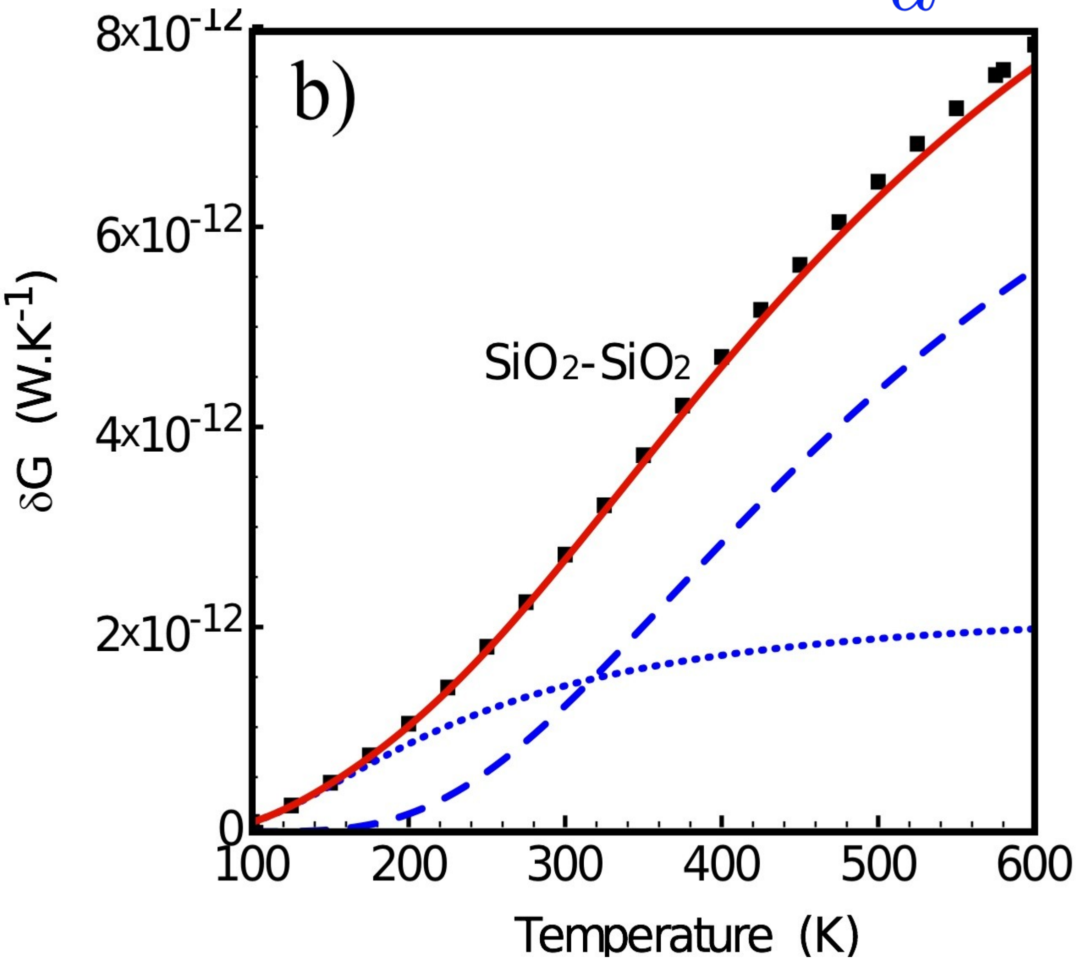
Can be found directly from experimental data

Some analytical results

Two surface modes for silica

$$h_{spp}(d,T) = \frac{\delta G(T)}{d^2}$$





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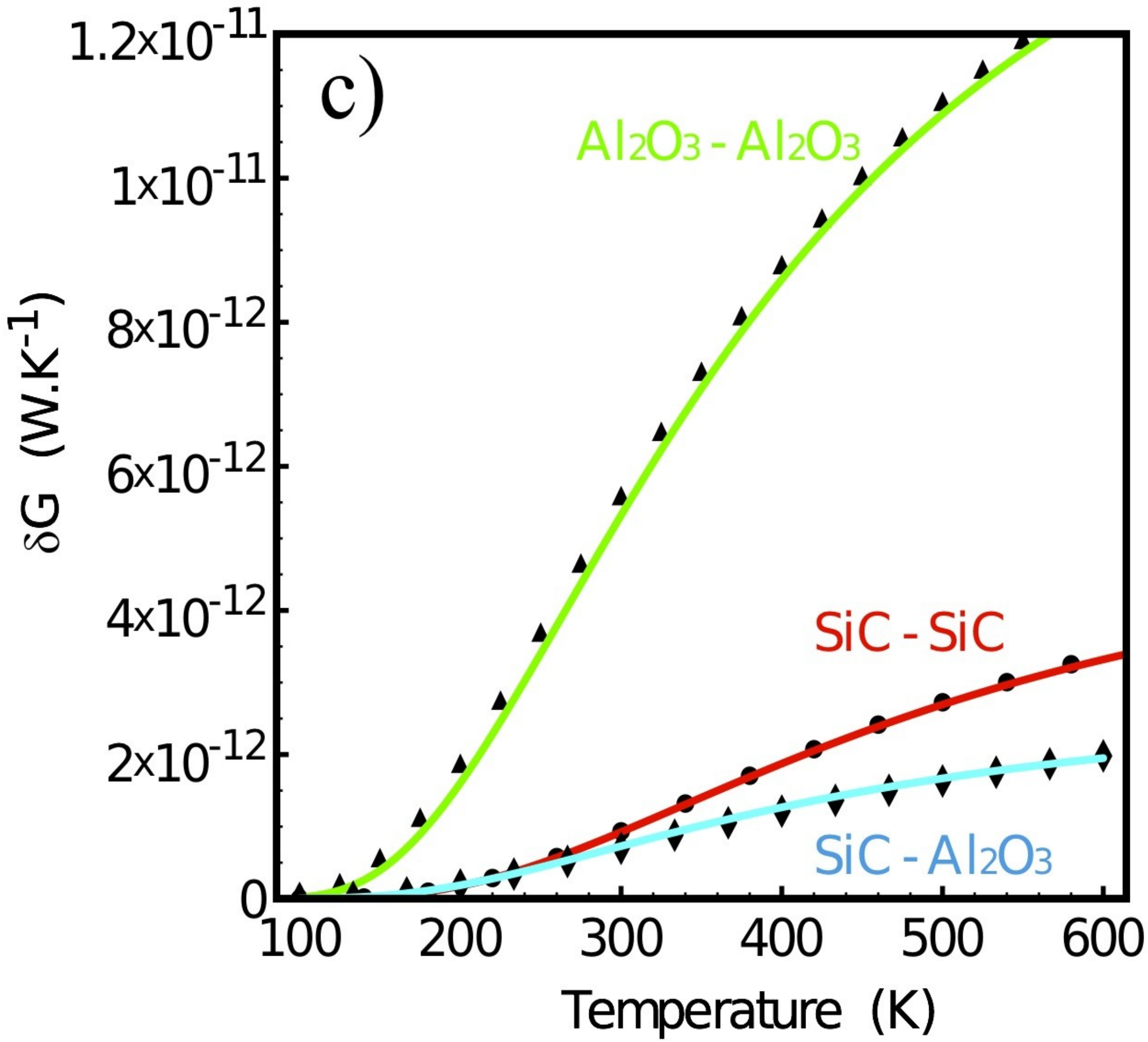
Some analytical results



$$h_{spp}(d,T) = \frac{\delta G(T)}{d^2}$$

Different materials

Similar or not

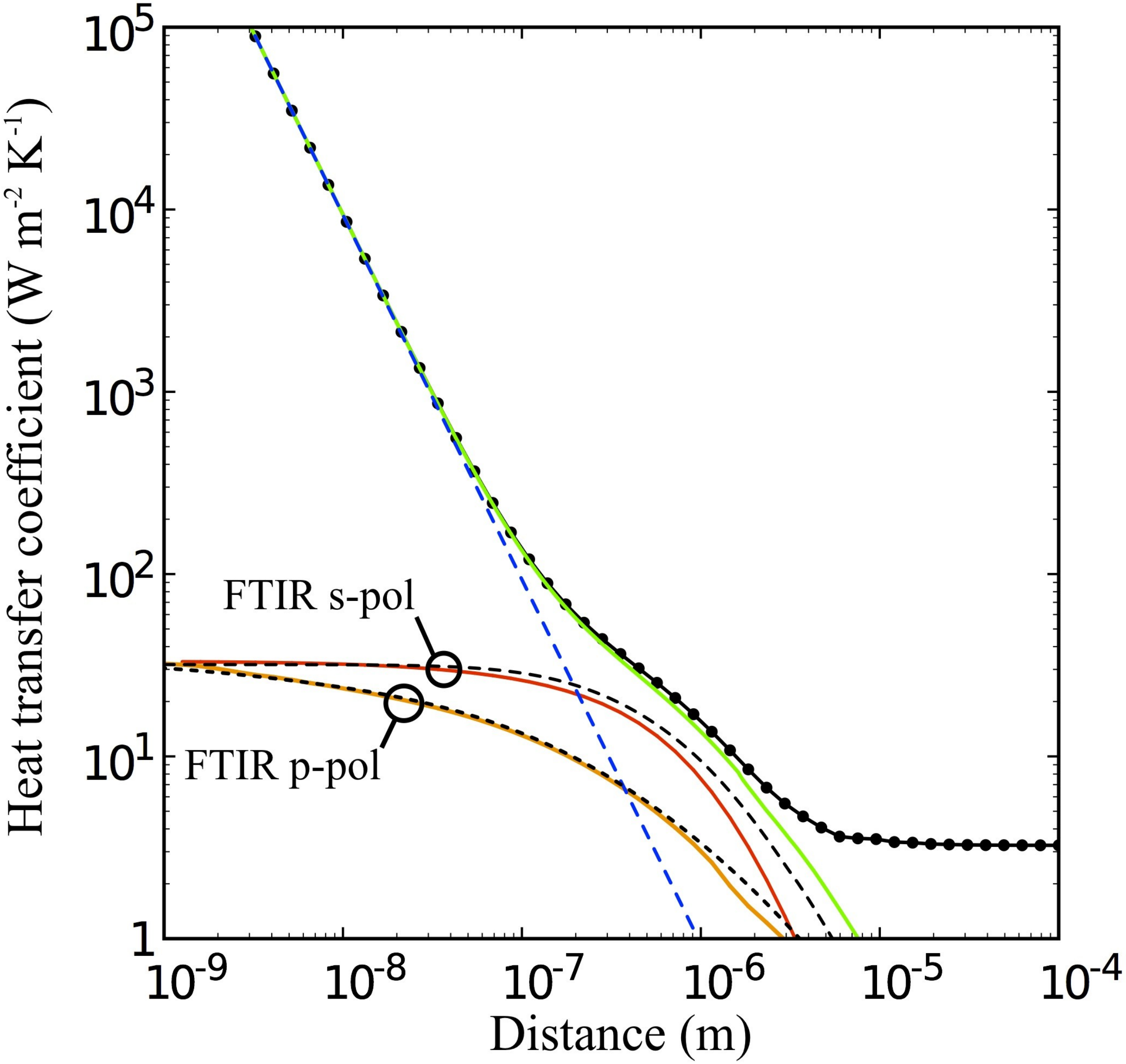
Emmanuel.rousseau@univ-montp2.fr

SPP contribution

Surface modes coupling
Contribution OK

Frustrated Total Internal
Reflections

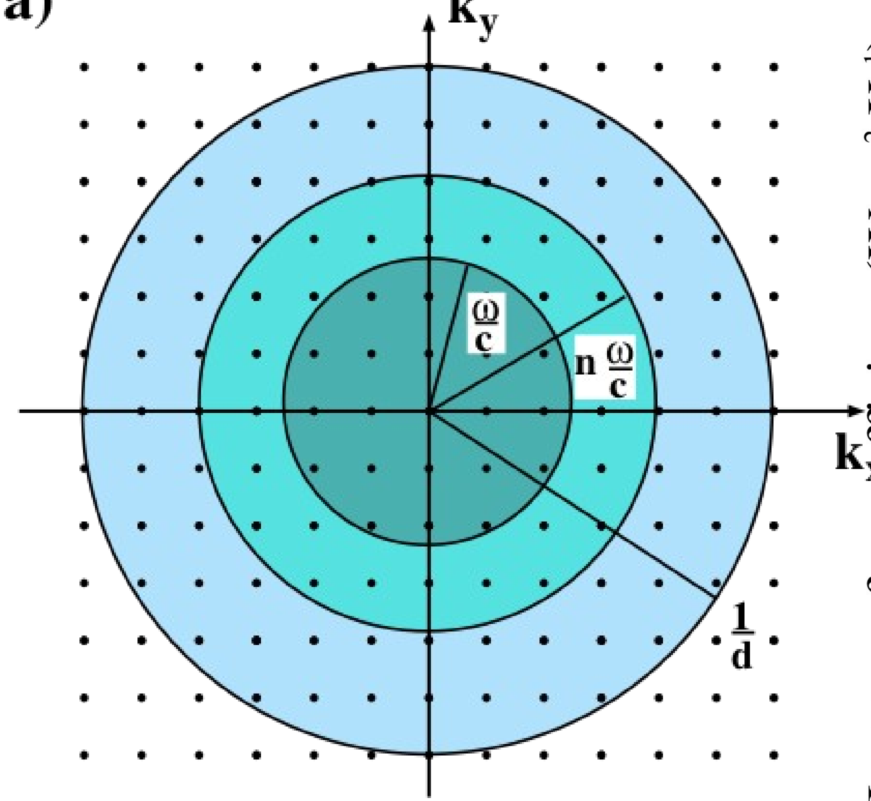
In a Landauer point of view

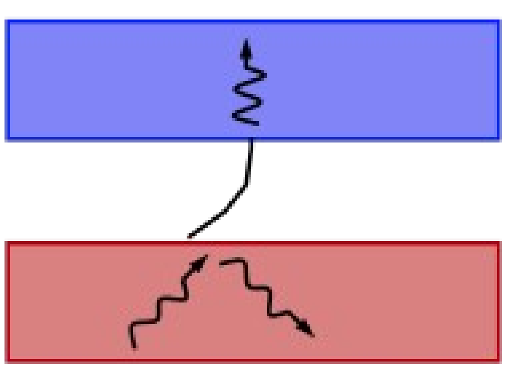


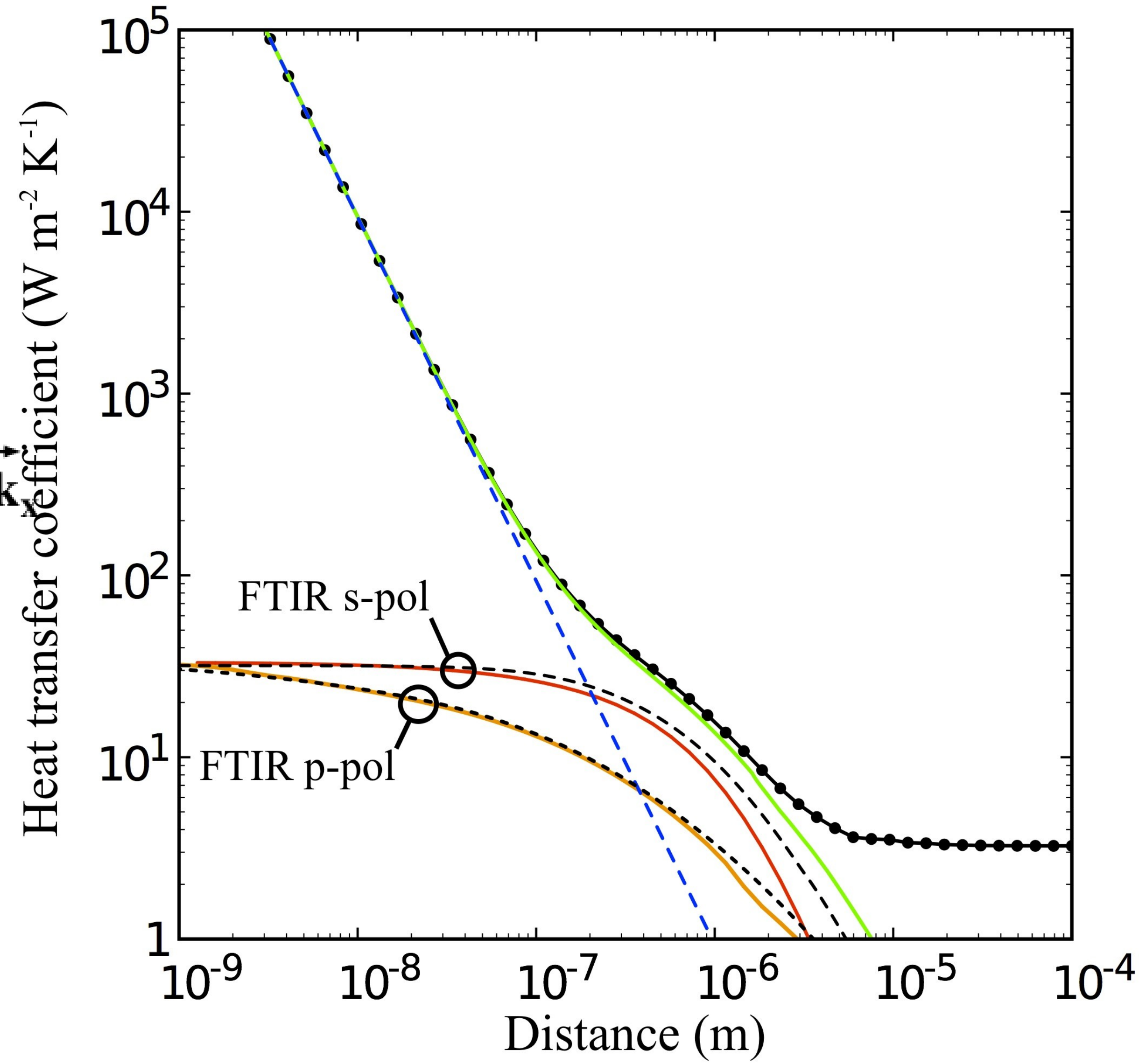
From Rousseau et al. JAP 111 014311 (2012)

FTIR contribution

a)



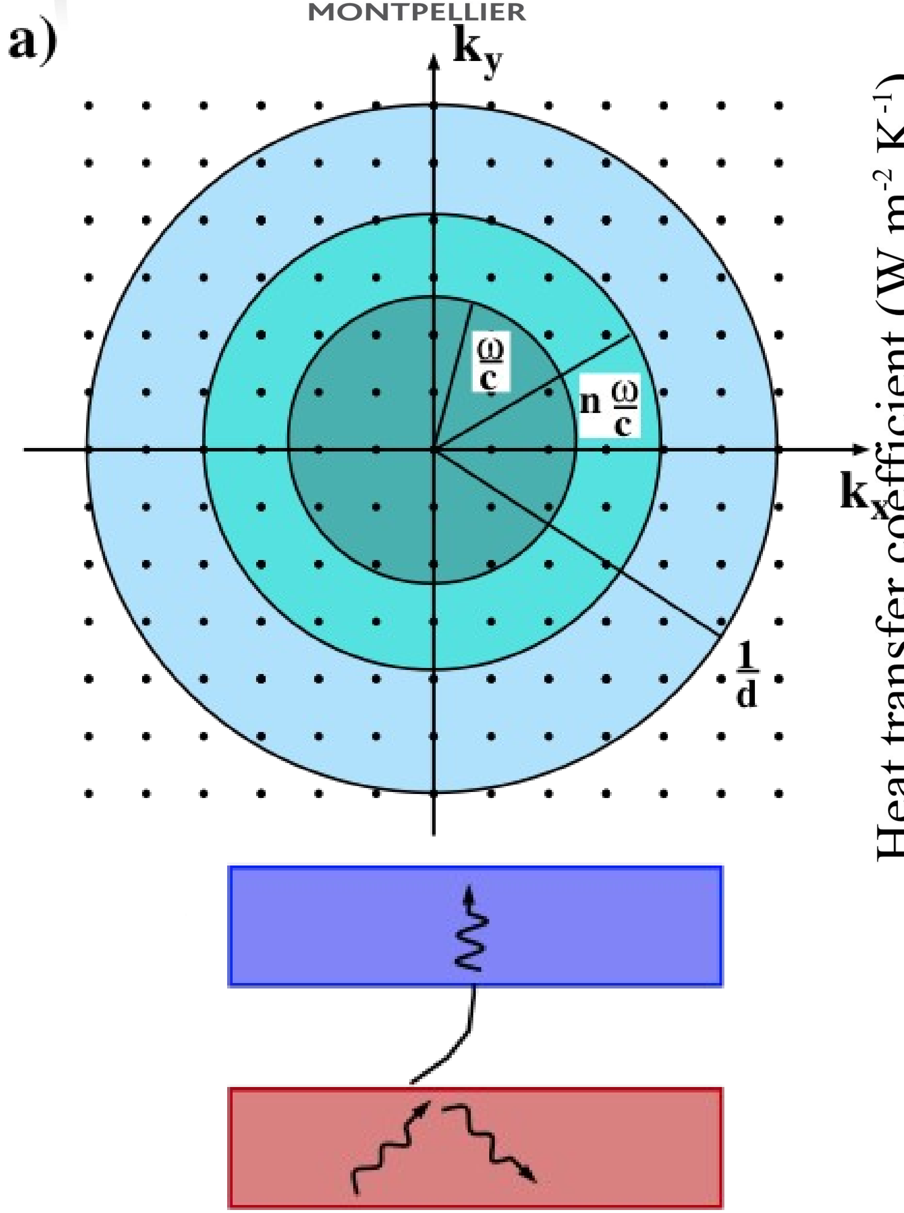


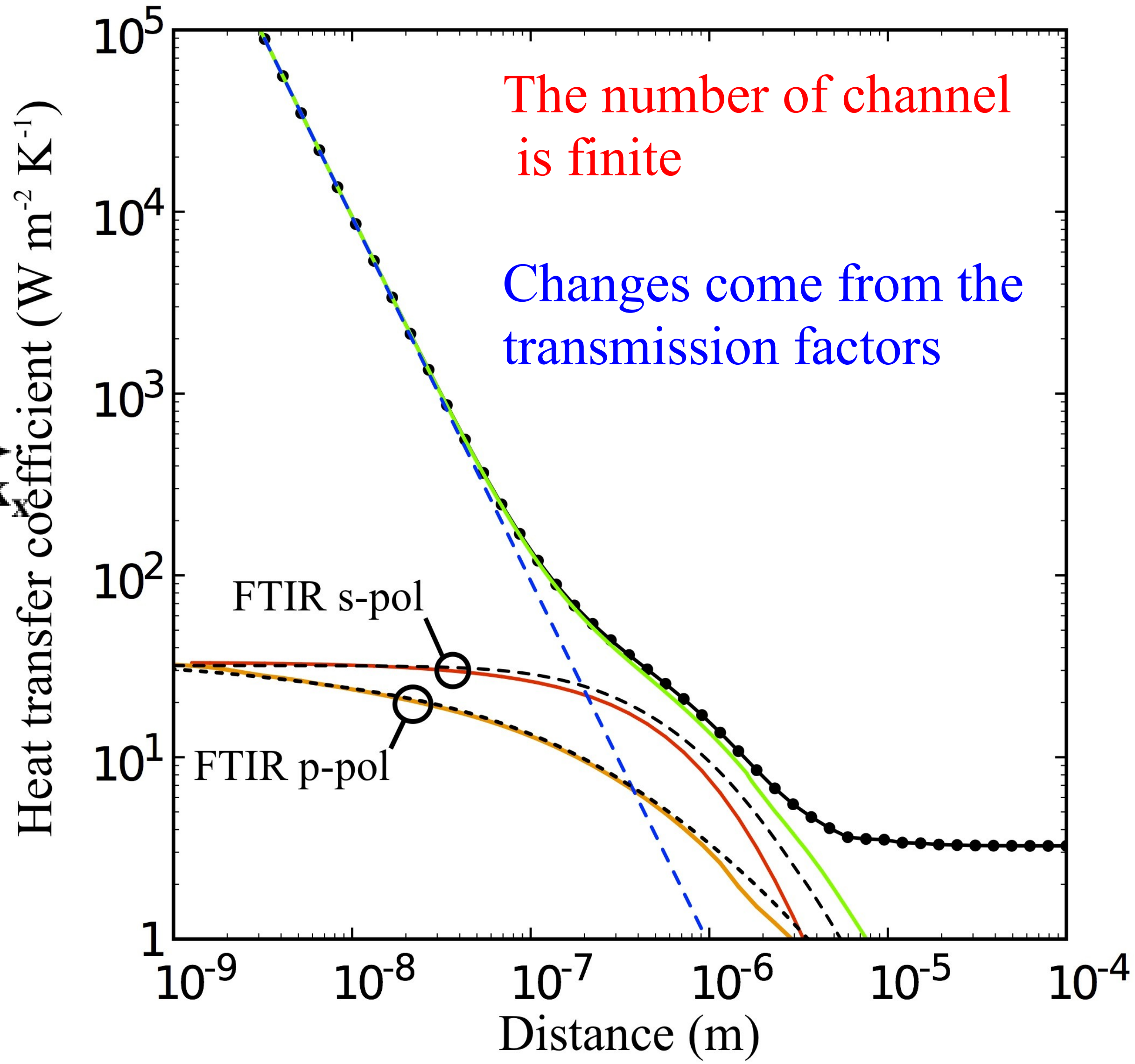


FTIR contribution

Emmanuel.rousseau@univ-montp2.fr

FTIR contribution





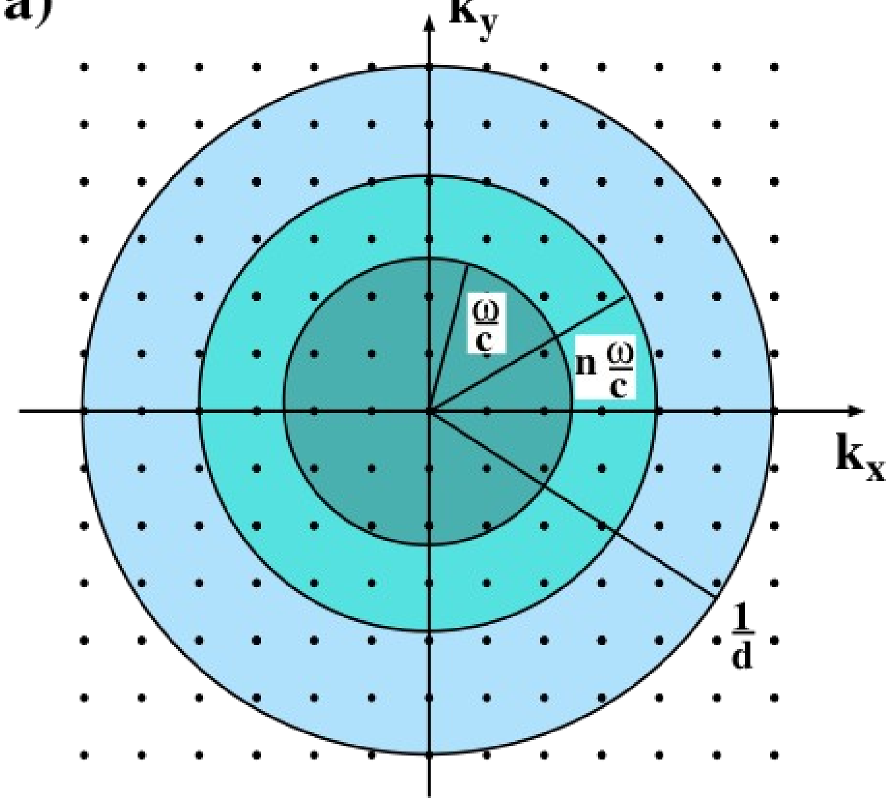
The number of channel is finite

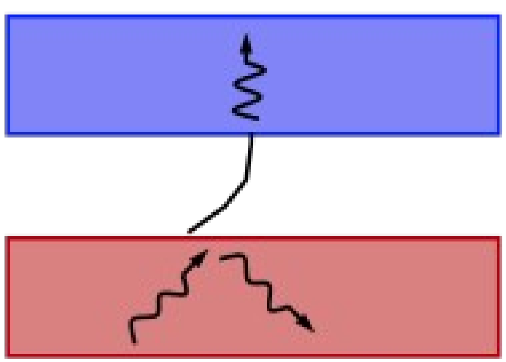
Changes come from the transmission factors

From Rousseau et al. JAP 111 014311 (2012)

FTIR contribution

a)





$$h^p_{evan}(u,d,T) = \frac{3}{2\pi^3}\frac{g_0}{\lambda_T^2}h^0(u) \times$$

$$\int_0^{\gamma_{max}} \tilde{\gamma} d\tilde{\gamma} \frac{4Im(r_{31})Im(r_{32})e^{-2k_T\tilde{\gamma}ul}}{|1 - r_{31}r_{32}e^{-2k_T\tilde{\gamma}ul}d|^2}$$

$$T = \frac{4Im(r_s)^2 e^{-2\gamma'' d}}{|1 - r_s^2 e^{-2\gamma'' d}|^2} \leq 1$$

Emmanuel.rousseau@univ-montp2.fr

FTIR contribution

$$T = \frac{4Im(r_s)^2 e^{-2\gamma'' d}}{|1 - r_s^2 e^{-2\gamma'' d}|^2} \leq 1$$

The trick $\quad T = 1 - \varepsilon(d)$

Rousseau et al. JAP 111 014311 (2012)

$$h_f^s(\omega, d, T) \simeq h^0(\omega) \frac{n_r^2 - 1}{2} \times$$

$$\left\{1 + (\frac{k_0 d}{2})^2 (\varepsilon_r - 1) ln[(\frac{k_0 d}{2})^2 (\varepsilon_r - 1)]\right\}$$

FTIR contribution

$$h_f^s(\omega, d, T) \simeq \boxed{h^0(\omega)\frac{n_r^2-1}{2}} = 4\sigma T^3(n_r^2-1)$$

$$\left\{1 + (\frac{k_0 d}{2})^2(\varepsilon_r - 1)ln[(\frac{k_0 d}{2})^2(\varepsilon_r - 1)]\right\}$$

See also

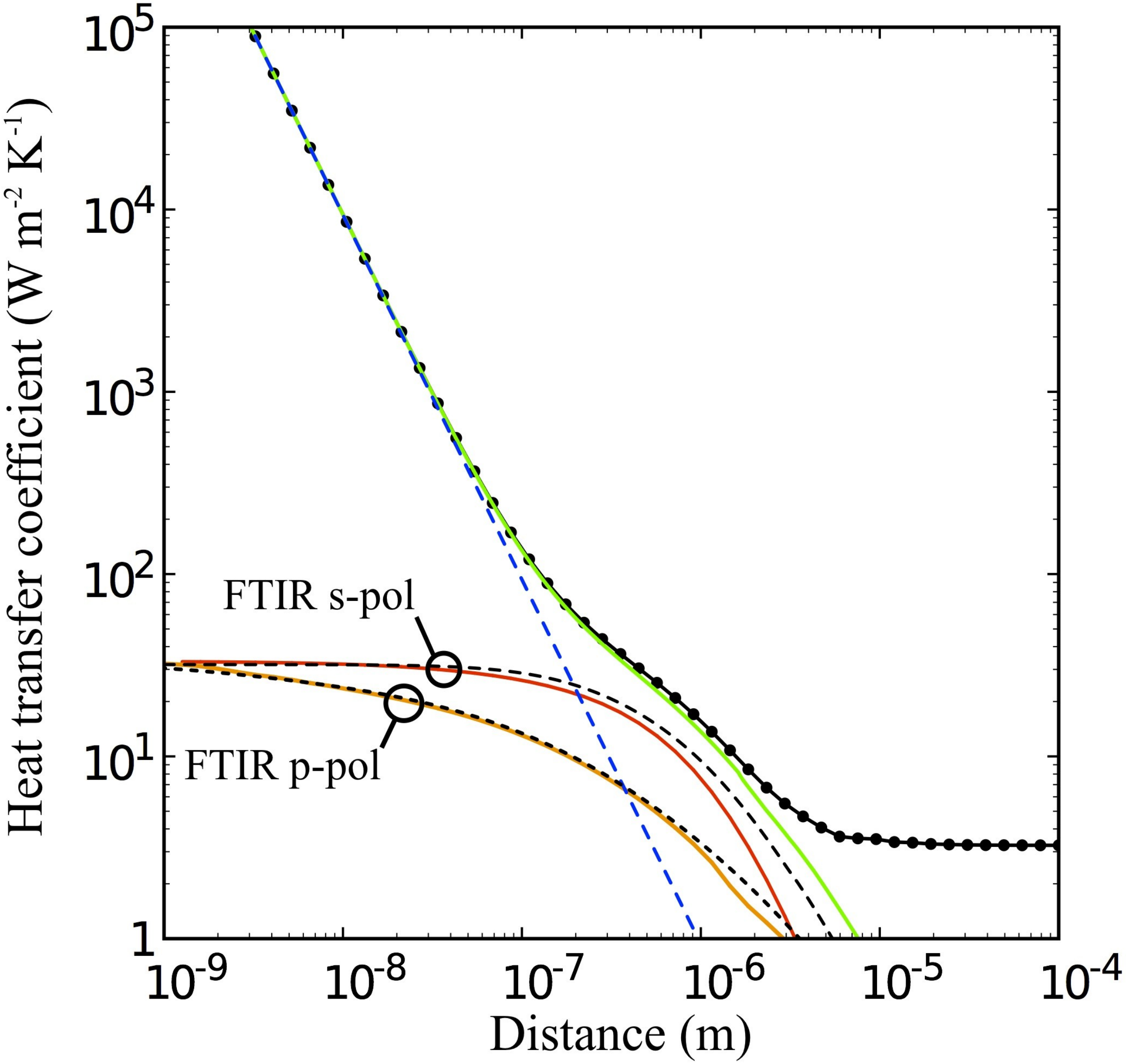
Rousseau et al. APL **95** 231913 (2009)
Rousseau et al. Journal of Quantitative Spectroscopy and Radiative heat transfer **111** 1005 (2010)

Characteristic distance

Surface modes coupling Contribution OK

Frustrated Total Internal Reflections OK

Now I can estimate when SPP dominates the heat transfer



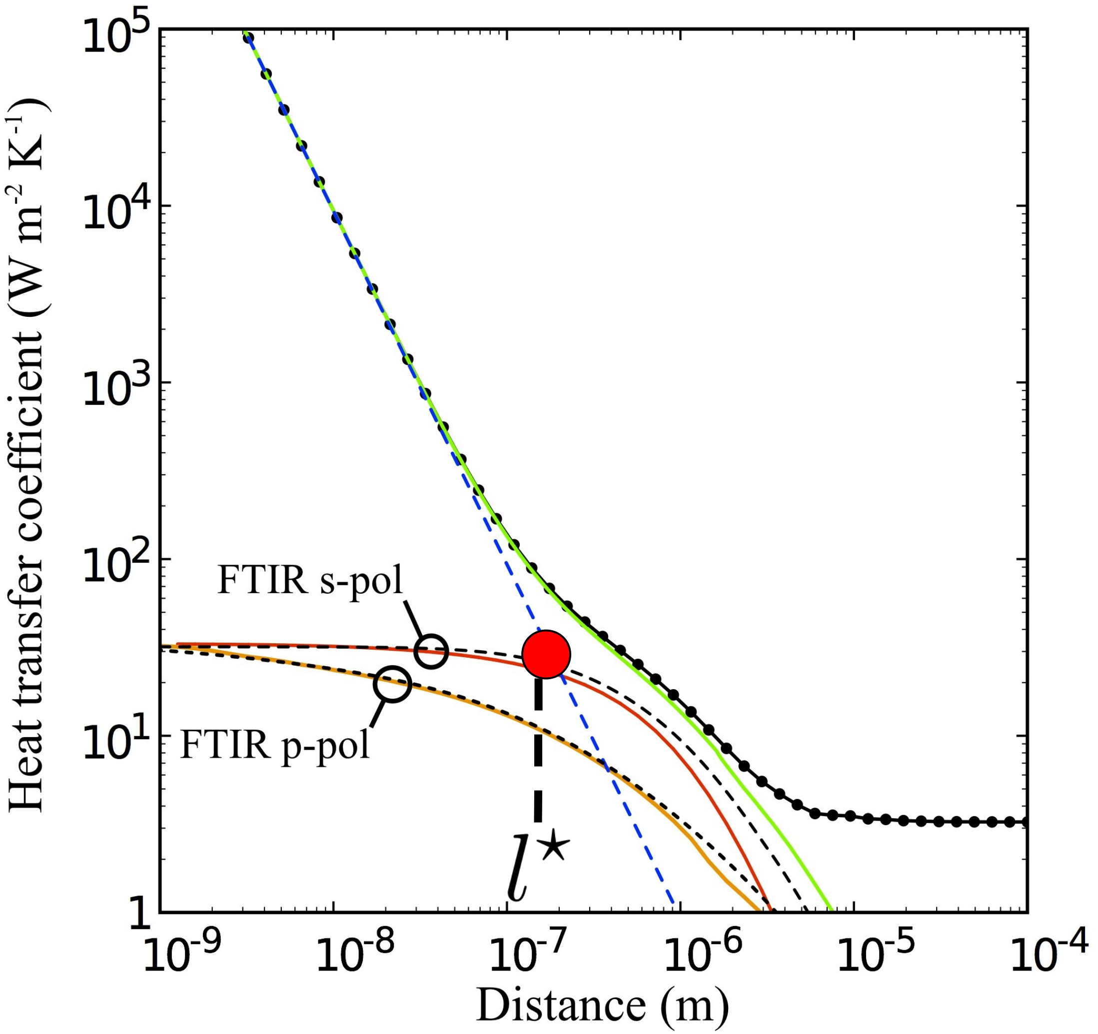
From Rousseau et al. JAP 111 014311 (2012)

Characteristic distance

$$l^\star = \sqrt{\frac{\delta G(T)}{4\sigma T^3(n_r^2 - 1)}}$$

T	λ_T	$l^\star$
100 K	29 µm	19 nm
300 K	10 µm	170 nm
500 K	6 µm	110 nm

For SiC-SiC



Better for Al_2O_3 $\quad l^\star \sim 400nm$ @ 300 K

Emmanuel.rousseau@univ-montp2.fr

Summary about plane-plane comments

Choosing temperature:
Total displacement *vs* angle requirement

Not really temperature requirements for metals

To measure the $1/d^2$ law:

Room temperature is more suitable for materials supporting resonance near 10 µm

But in any cases nanometer gaps have to be reached

1- Two main ingredients:

The heat transfer coefficient

The thermal conductance

2-Plane-Plane experiments:

Is there a good temperature to work at?

Measuring $1/d^2$ law

3- Sphere-Plane experiments

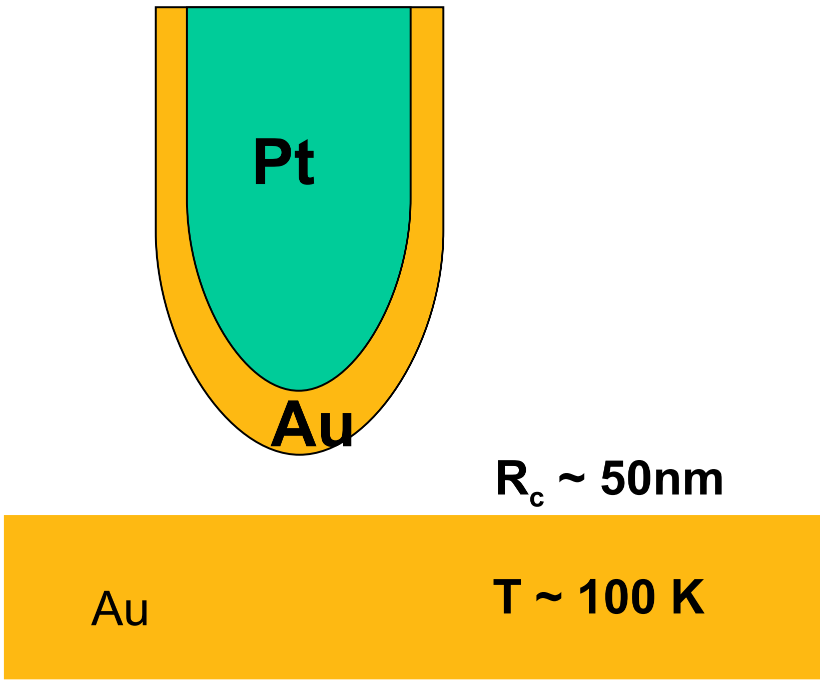
A sensitive flux-meter

The experimental setup

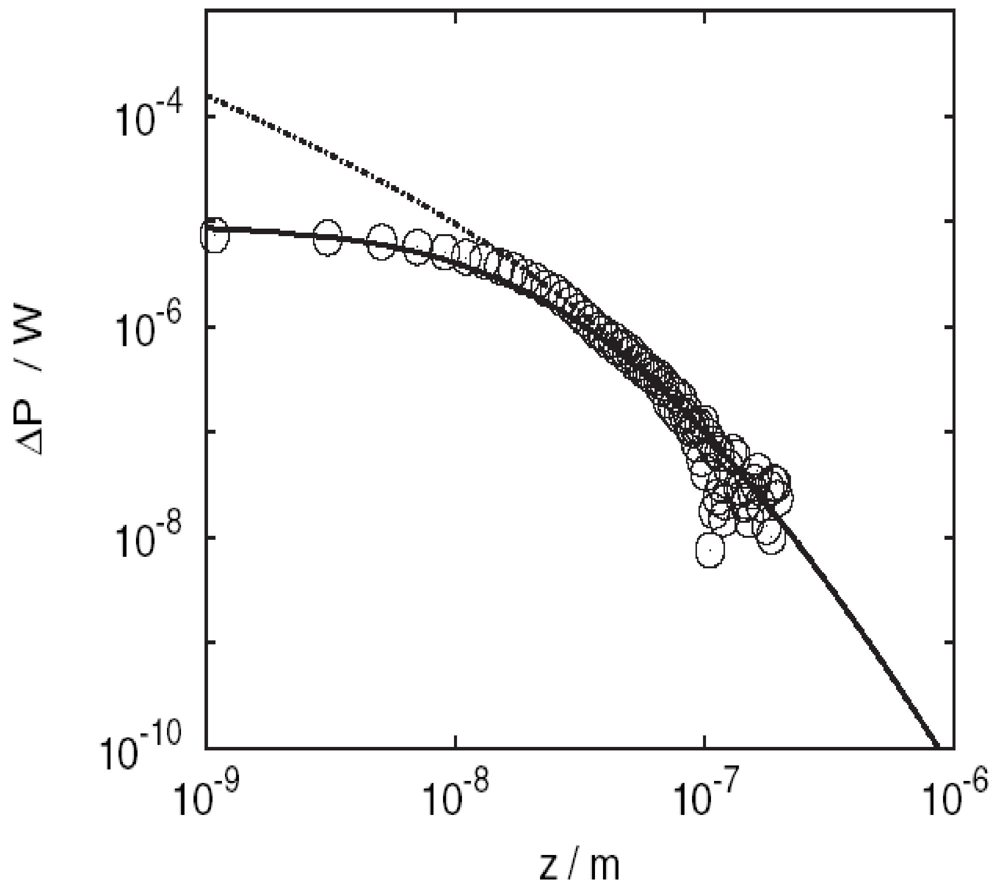
Connecting the measurements to the theory

Previous non plane-plane geometries explored

SEM
Thermocouple



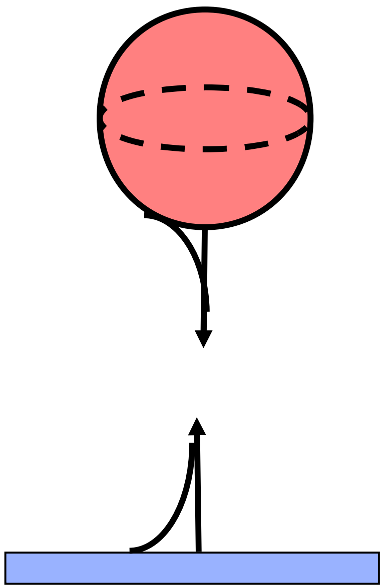
Radiatif transfer vs distance



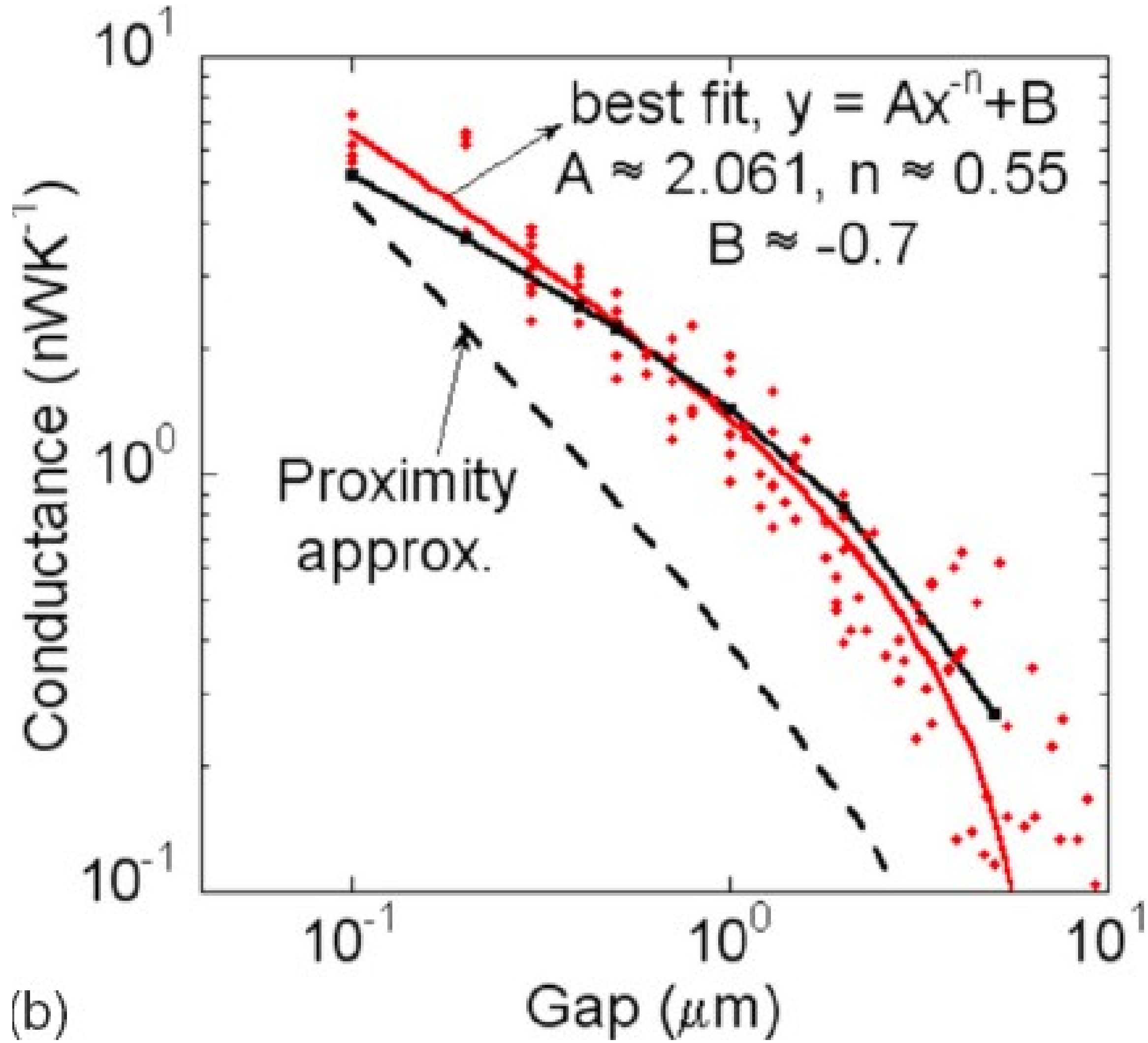
Kittel et al. , PRL 95 p 224301 (2005)

The first sphere-plane experiments

Silica sphere



Silica plate

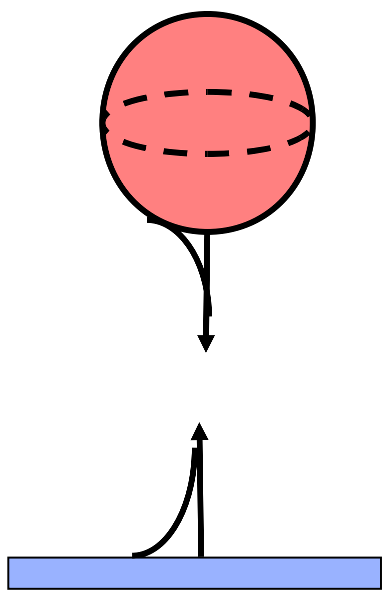


From Narayanaswamy A, G. Chen PRB **78**, *115303* (2008)

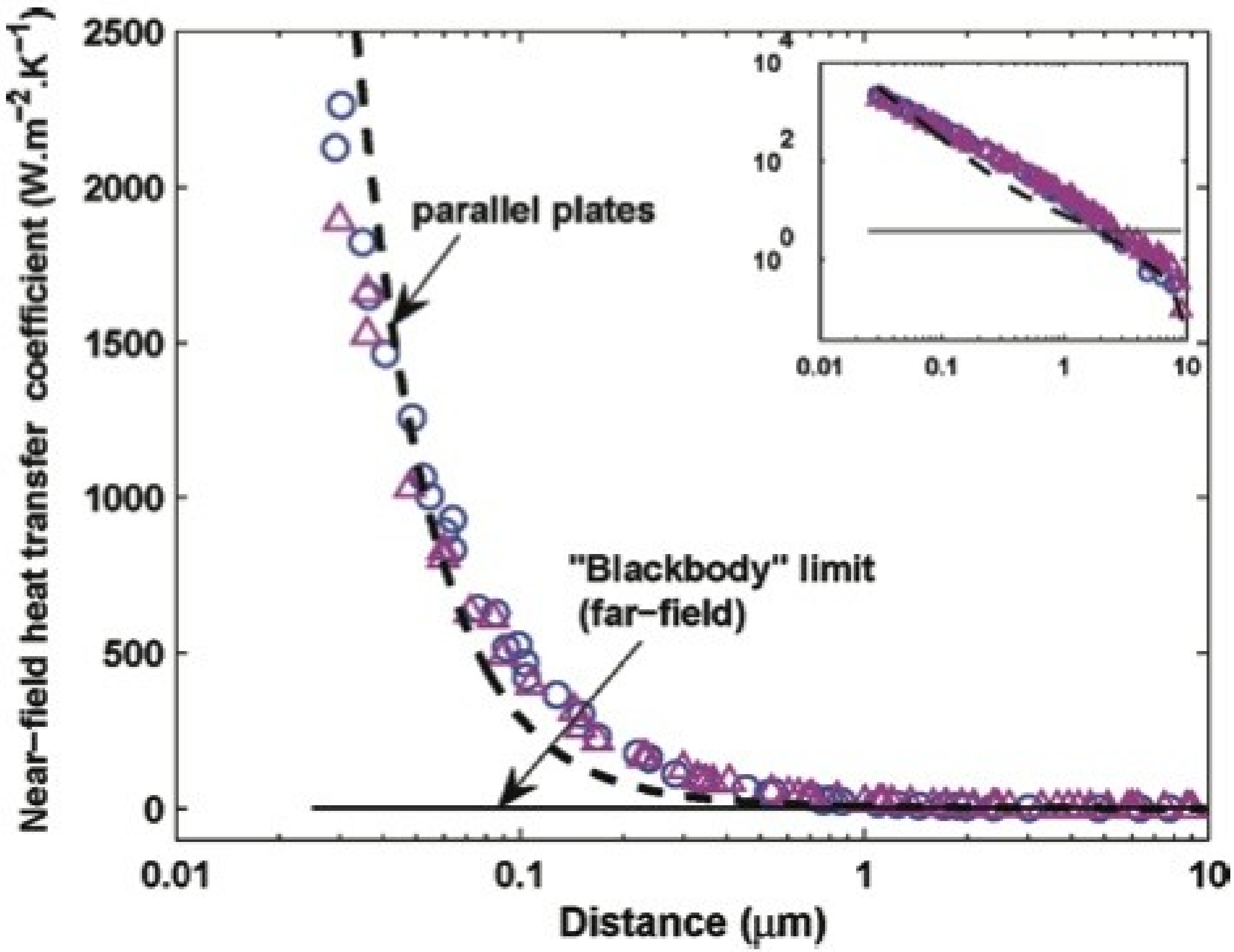
Emmanuel.rousseau@univ-montp2.fr

The first sphere-plane experiments

Silica sphere



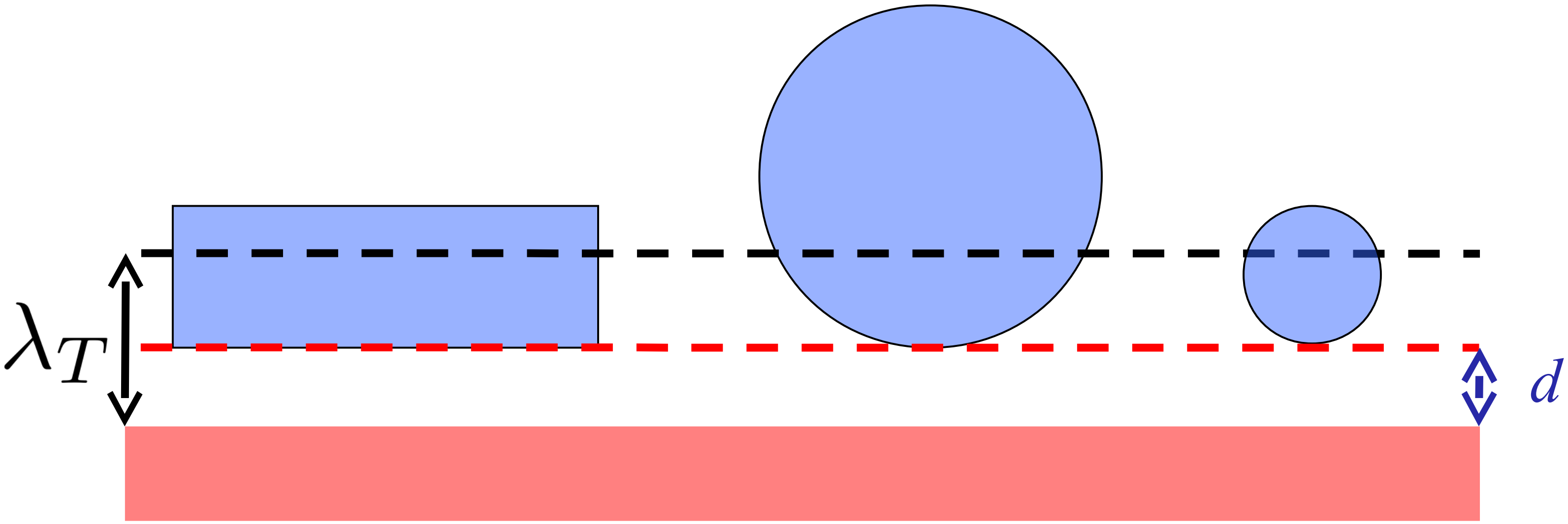
Silica plate



From S. Shen et al. NanoLetters **9**, 2909 (2009)

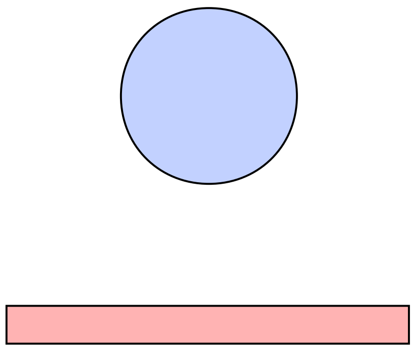
The problem of the sphere-plane geometry

Sphere radius should not be too large



Flux estimate

Far-field



$$\varphi = 4\pi R^2 F_{s-p} \varepsilon \sigma (T_h^4 - T_c^4)$$

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

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

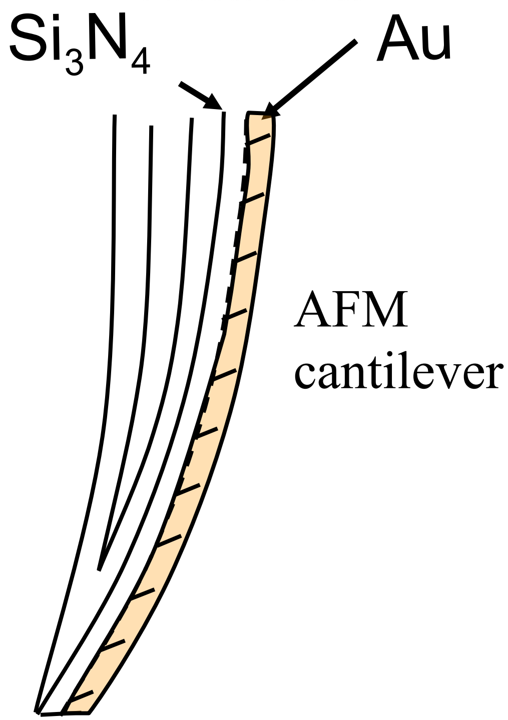
Flux in the order of ~100 nW

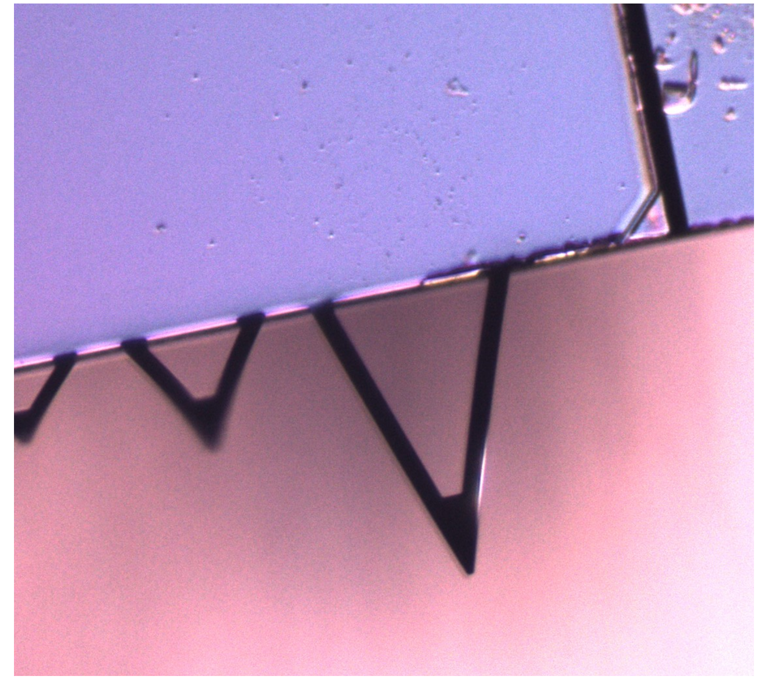
$R \sim 20\ \mu m$

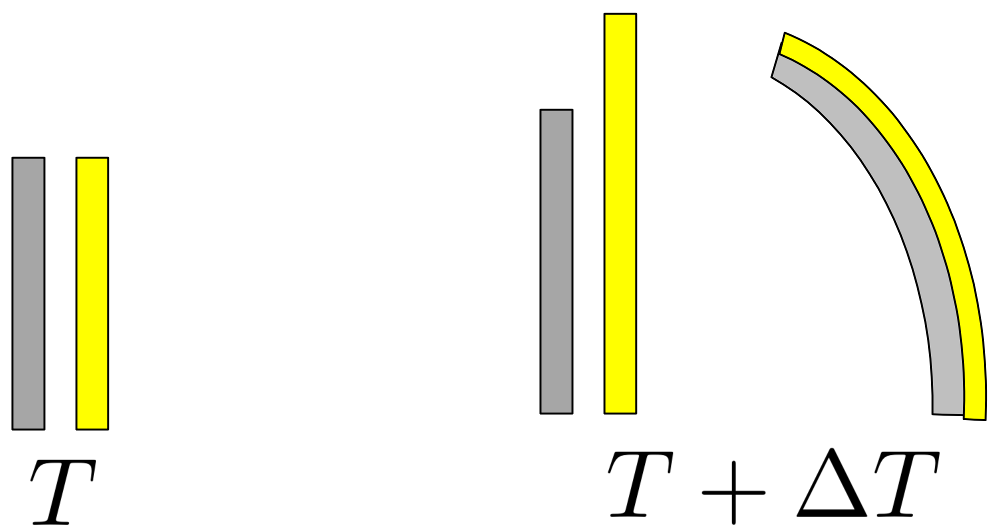
Not a too small sphere
Materials supporting surface modes (glass ~ silica)
A very sensitive fluxmeter

Emmanuel.rousseau@univ-montp2.fr

A very sensitive fluxmeter: a bimorph based on an AFM cantilever

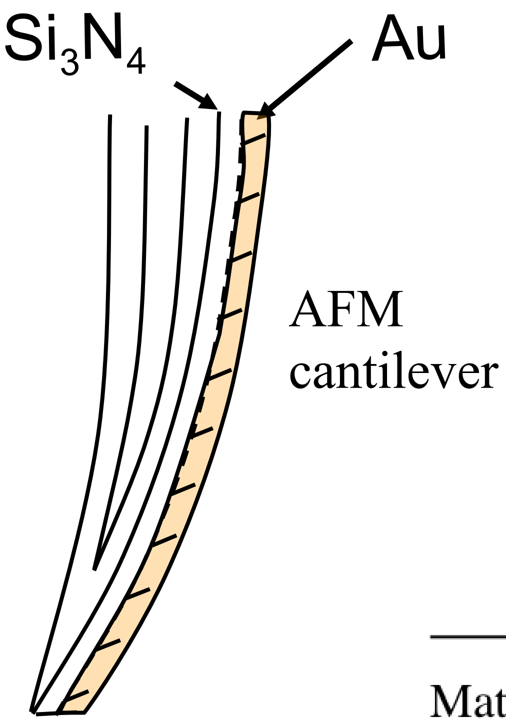


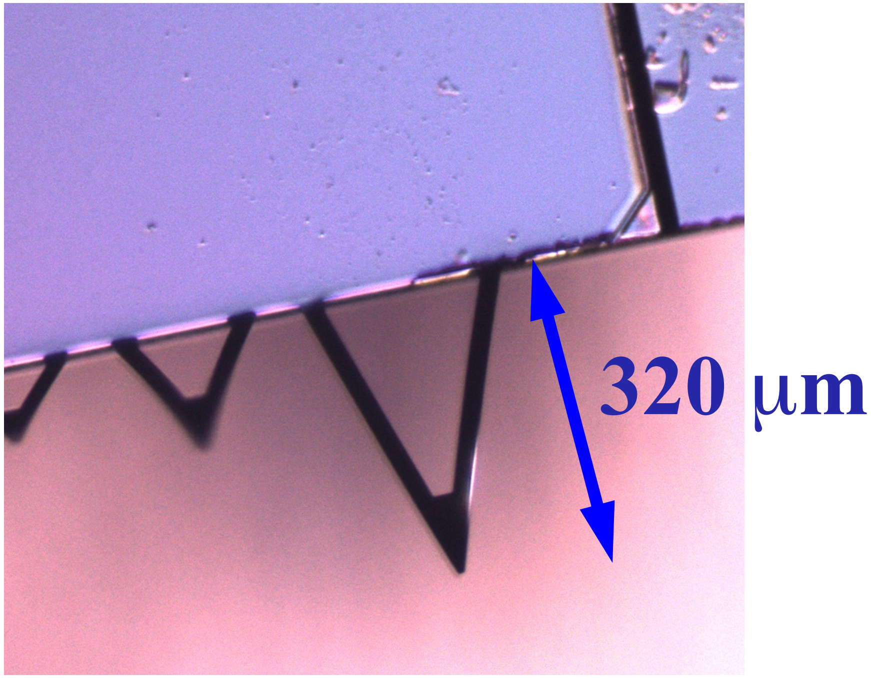




Emmanuel.rousseau@univ-montp2.fr

A very sensitive fluxmeter: a bimorph based on an AFM cantilever





Material	Elastic modulus, E [10^{11} N m^{-2}]	Thermal expansion coefficient, α [10^{-6} K^{-1}]
Silicon nitride	1.80	0.8
Silicon	1.00	2.6
Gold	0.73	14.2
Aluminum	0.80	23.6

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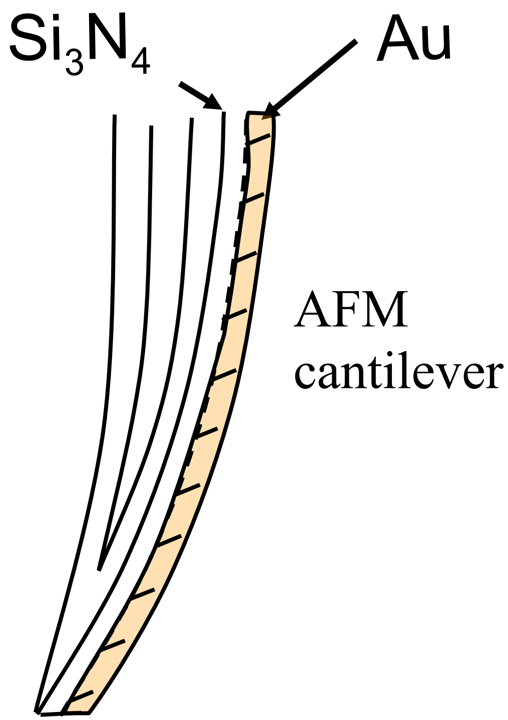
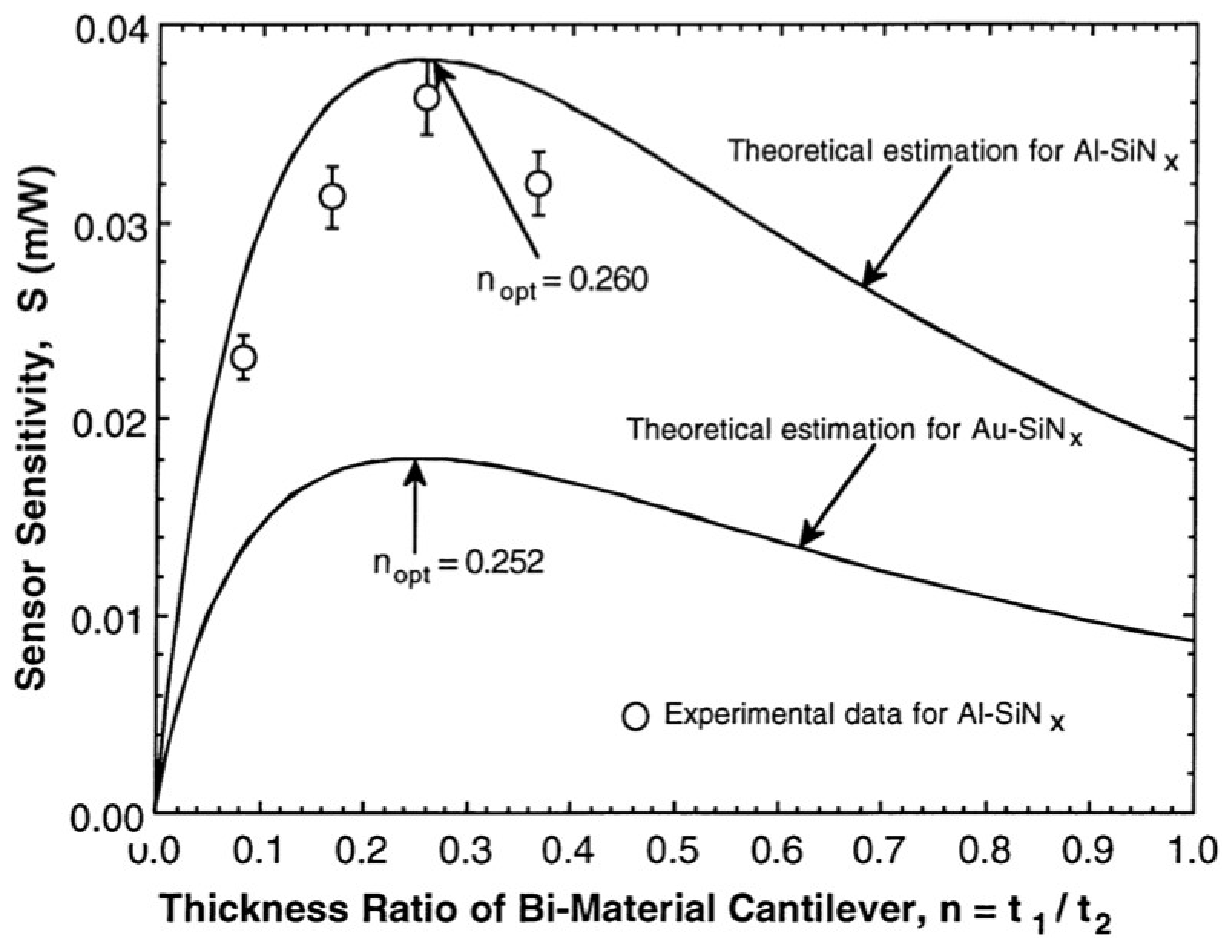


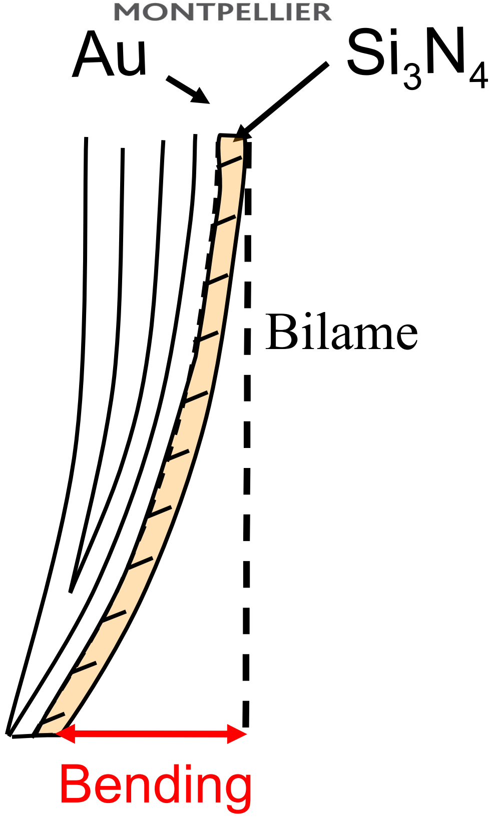


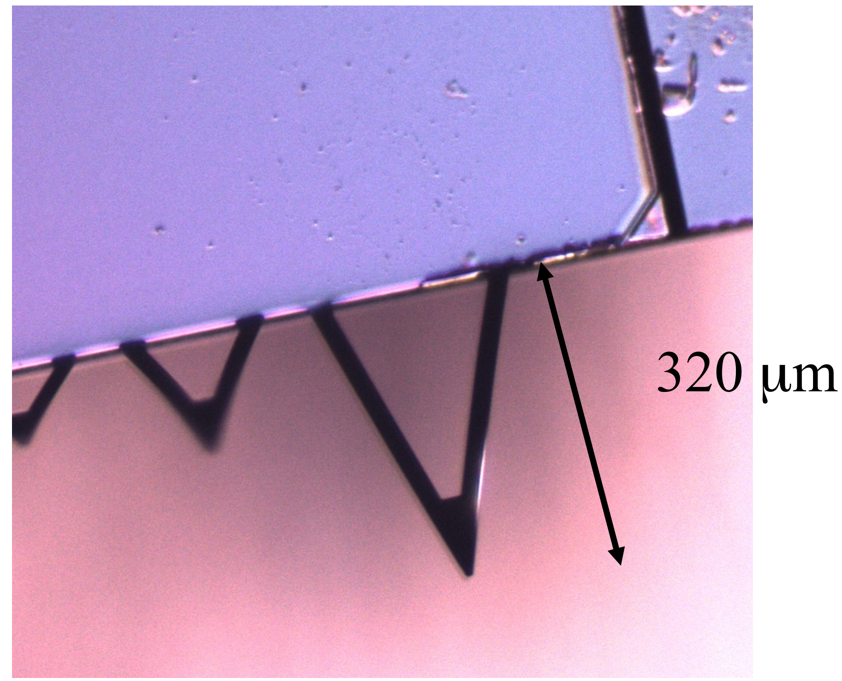
From Lai et al. Sensors and Actuators A 58 113 *(1997)*

Optimisation is difficult because of SiN_x

Commercially available SiN_x / Au

A very sensitive fluxmeter





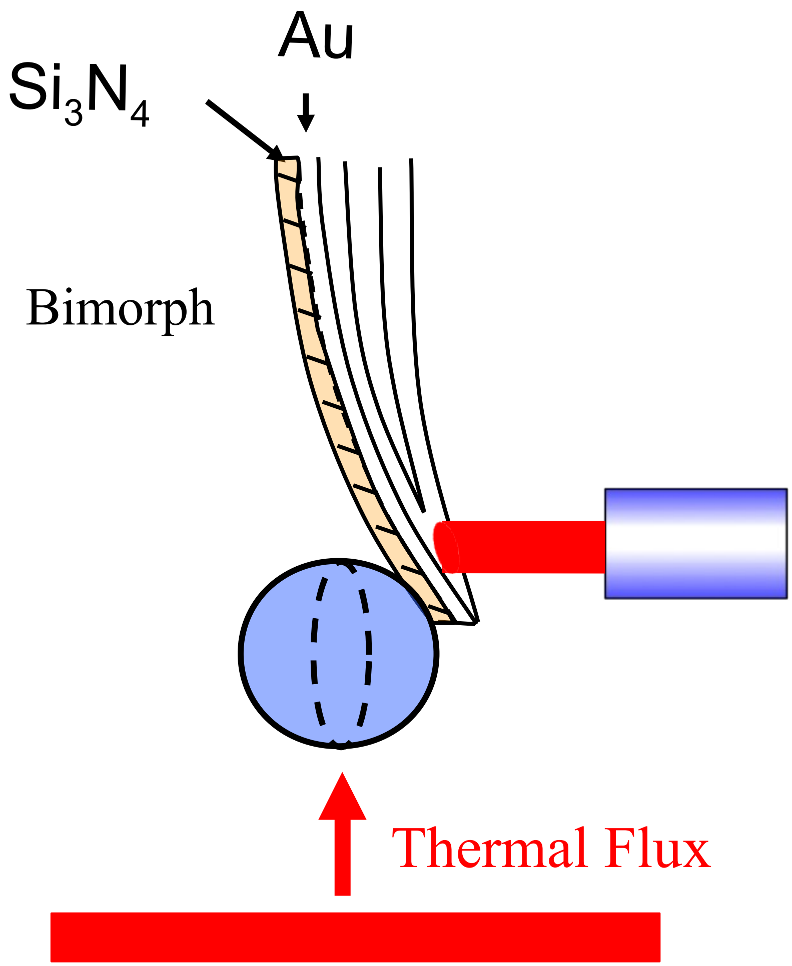
Cantilever bending is proportional to the thermal flux through the bimorph

Flux measurement => bending measurement

Sensitivity: 0.1 nm ● T~10 µK ● ~10 pW

Emmanuel.rousseau@univ-montp2.fr

Sketch of the experiment



Experimental difficulties taken into account:

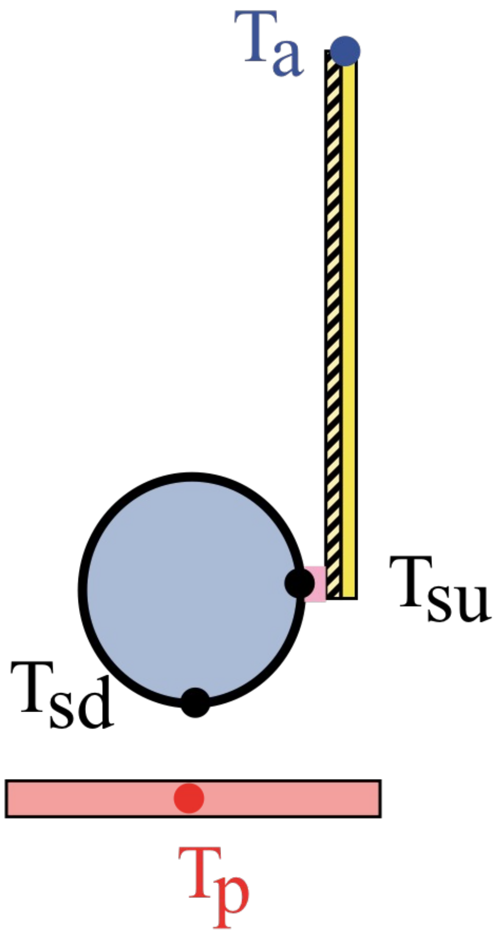
1- Glue a sphere at the end of the cantilever. **Work in vacuum!**

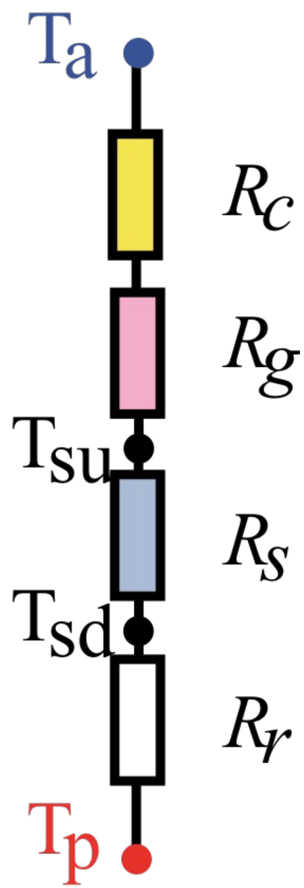
2- bring a hot plate closer and closer

3- measure the bending of the bimorph

Emmanuel.rousseau@univ-montp2.fr

Thermal circuit





R_r=160 10^6 K/W @ 10 µm
R_r=53 10^6 K/W @ 50 nm

R_g= 0.6 10^6 K/W
R_s=40 10^3 K/W
$R_{c=}$ 0.4 10^6 K/W

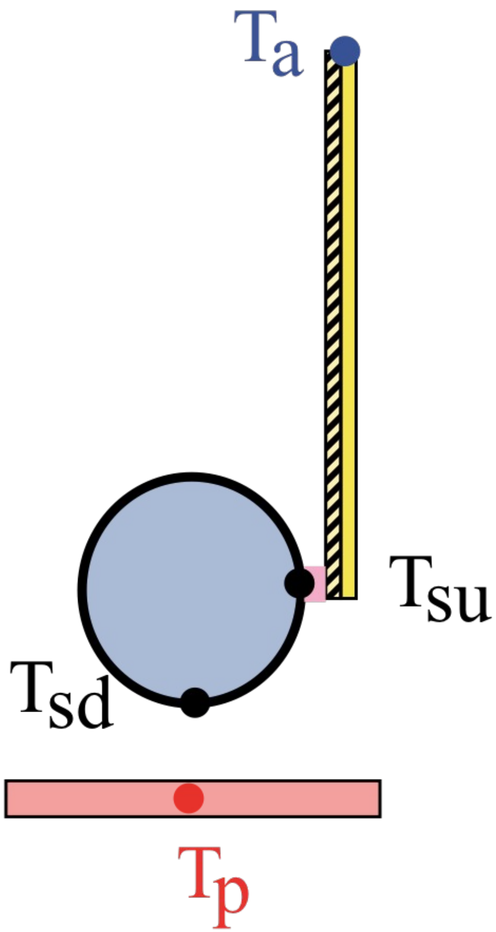
$$\frac{T_{sd} - T_p}{T_a - T_p} \geq 0.98$$

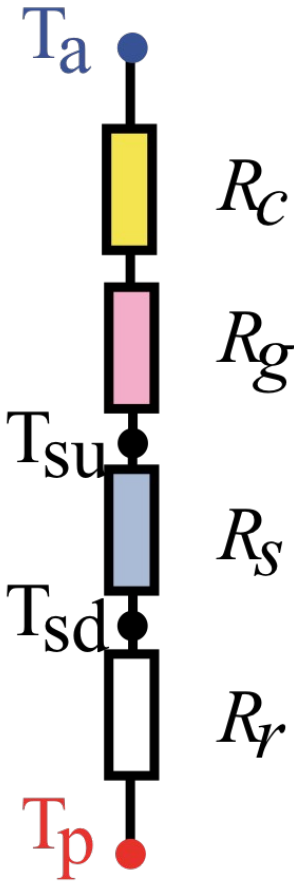
$$T_{sd} - T_p = \frac{R_r}{R_r + R_s + R_g + R_c}(T_a - T_p)$$

$$\Delta T_{can} \sim 5\ mK$$

Emmanuel.rousseau@univ-montp2.fr

Thermal drift- Time constant





$$\Delta T_{can} \sim 5\ mK$$

Room temperature T_a should be highly stable
during measurement

Measurements are done fast:
100ms between two data points

Diffusion time in sphere ~ 0.5 ms
Diffusion time in cantilever ~ 2 ms

Less than 2 min for one acquisition curve

The measurement chamber

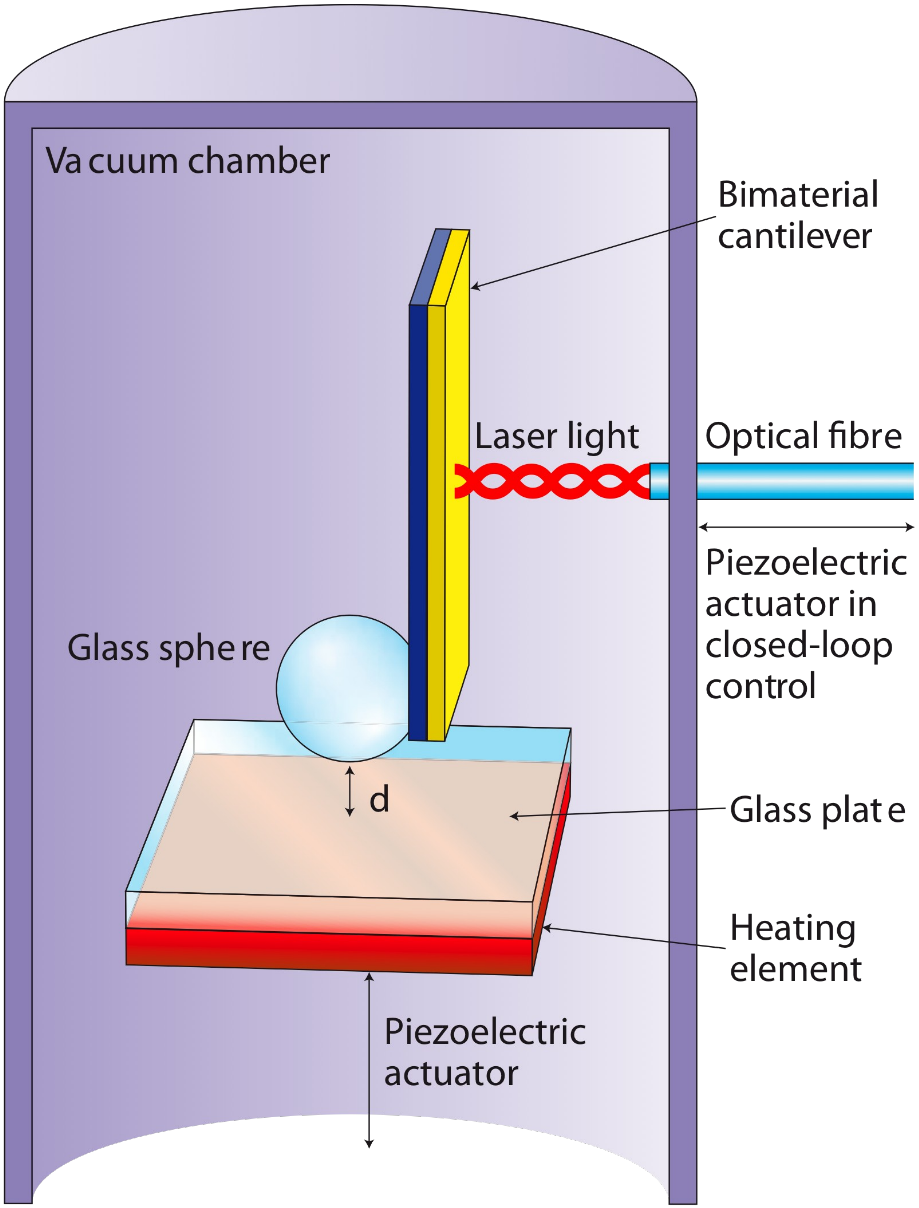
Vacuum condition P~10^{-6} mbar

Vertical geometry to prevent bending from electrostatic forces

Plate heated by a Peltier element

Plate is risen to the sphere with nanometric precision (step 7 nm)

Sphere-plate distance change from 5 µm to contact



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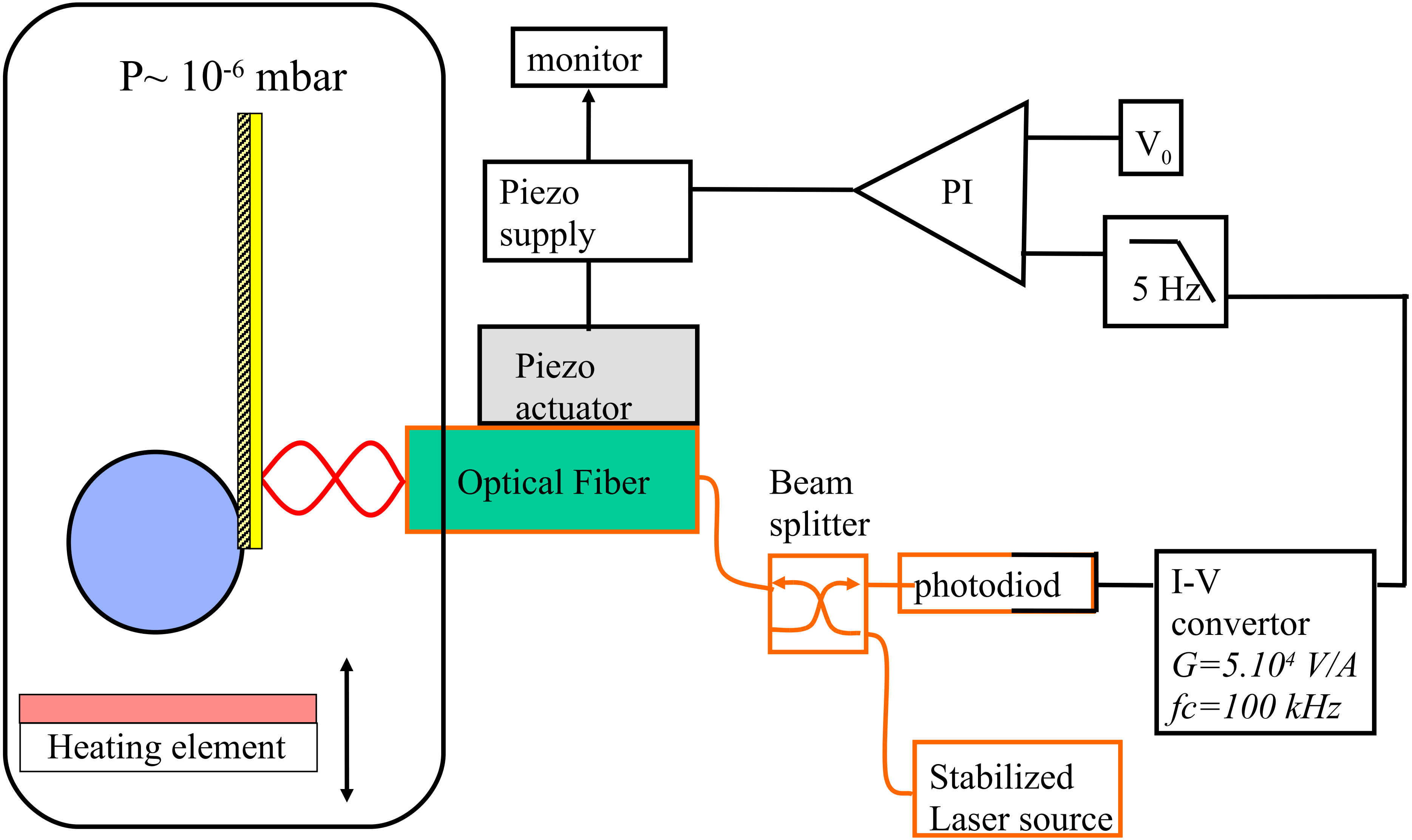
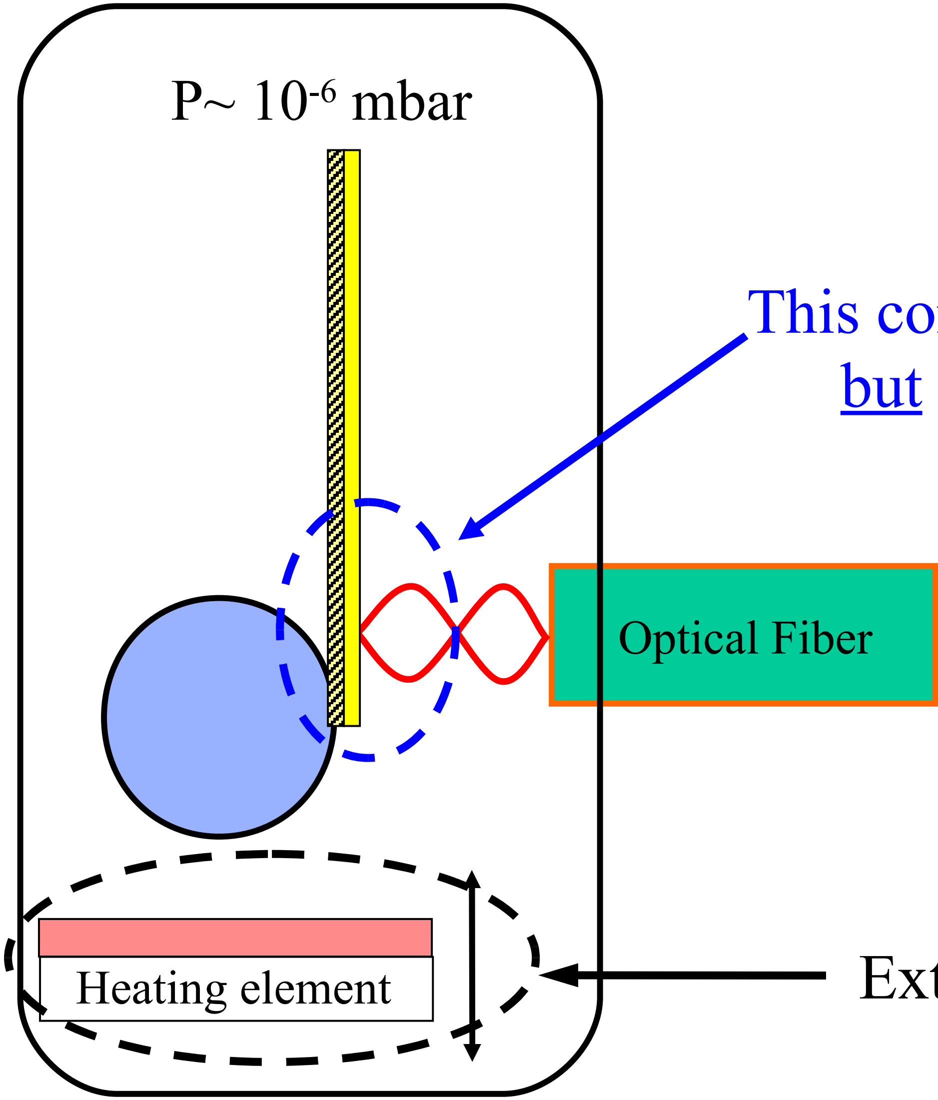

P~ 10-6 mbar
monitor
Piezo supply
PI
V0
5 Hz
Piezo actuator
Optical Fiber
Beam splitter
photodiod
I-V convertor
G=5.10⁴ V/A
fc=100 kHz
Stabilized Laser source
Heating element

Some precautions

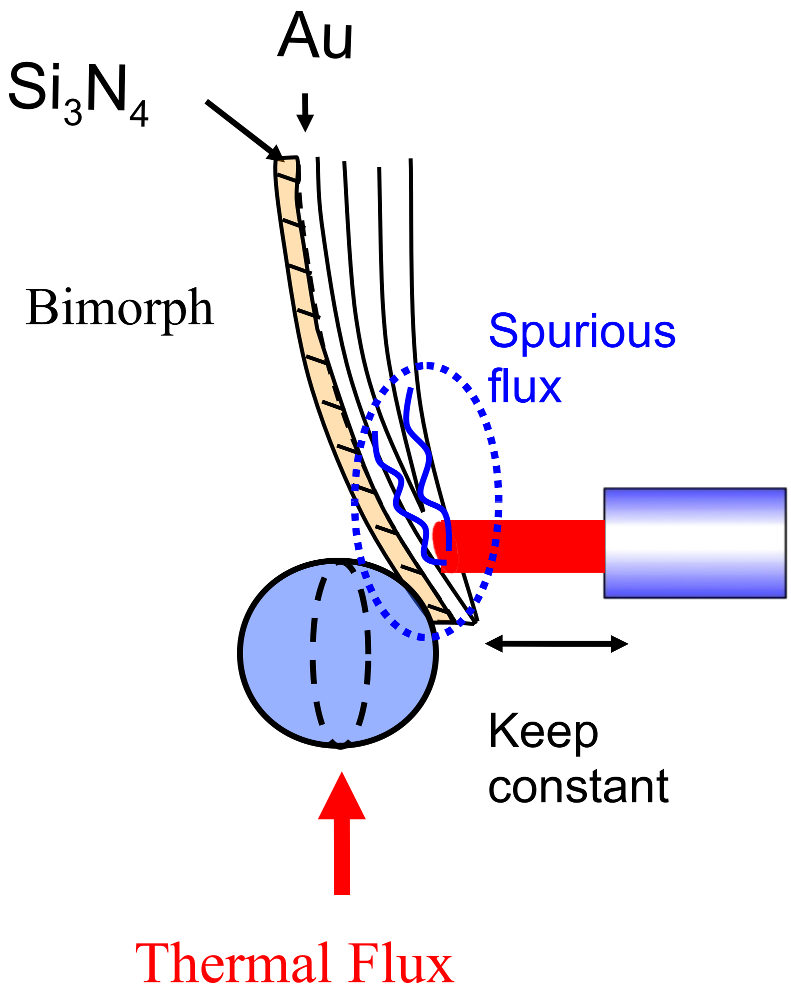


This contribution is a constant but relative measurement

Laser power is low in order to reduce photon noise

External heating

Some precautions



Experimental difficulties taken into account:

1- thermal drift: 1 nm/min

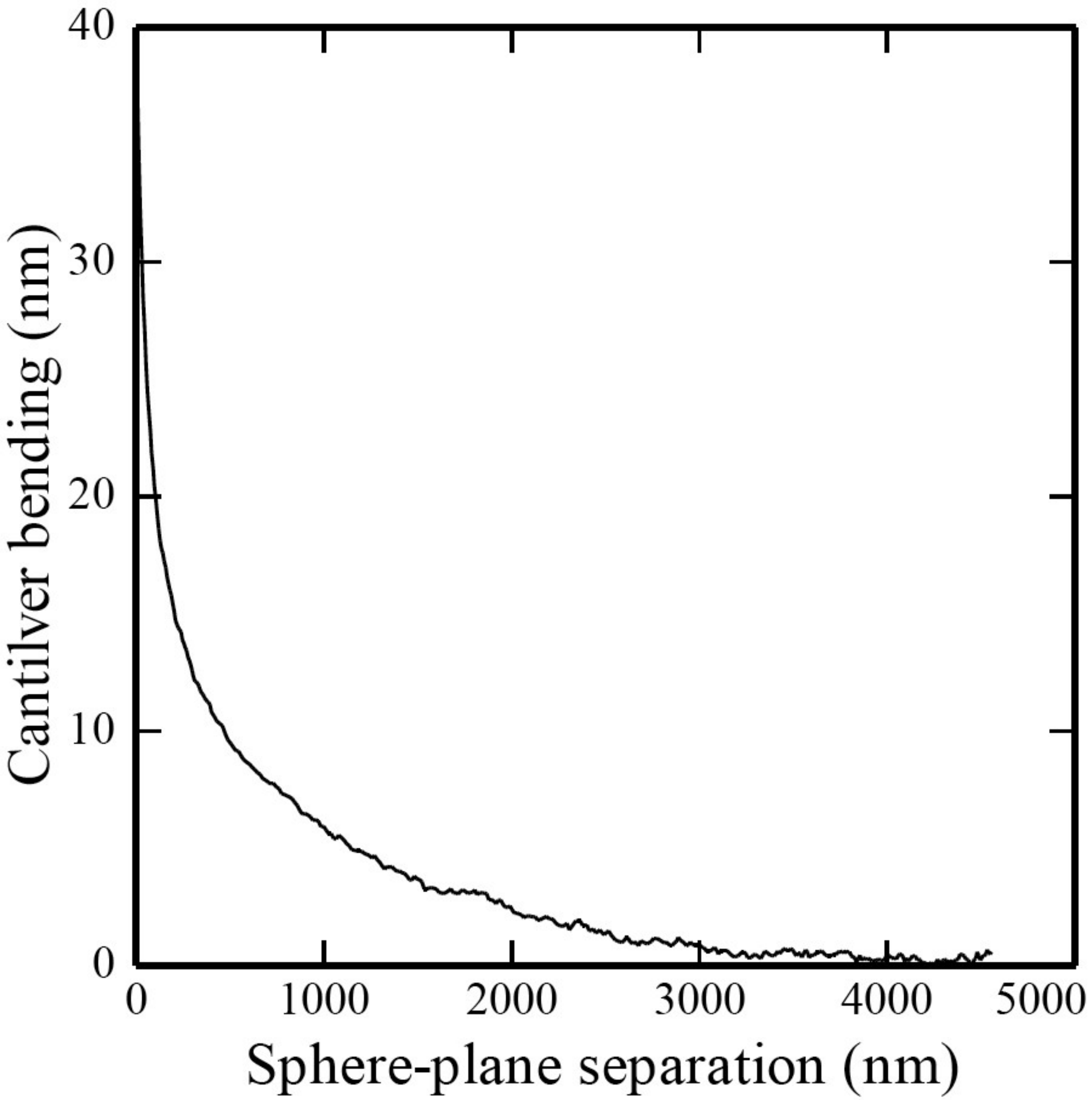
2- spurious flux to due to laser. Low laser power to reduce heating and photon noise

⇒ closed-loop keeps the distance bimorph-fibre (i.e. spurious flux) constant: we move the fibre

⇒ relative measurement

Emmanuel.rousseau@univ-montp2.fr

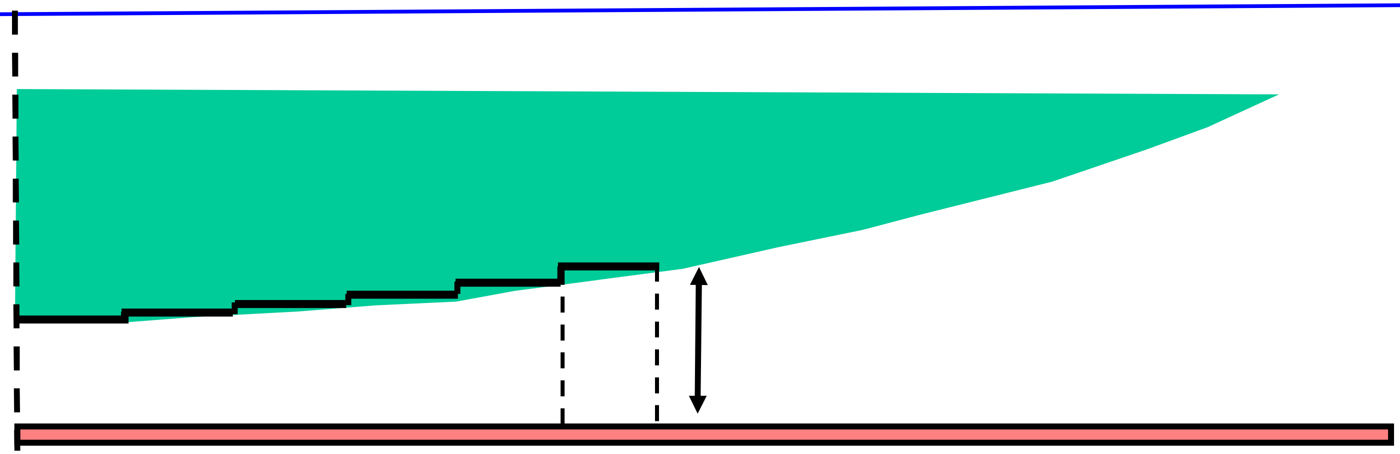
measurements

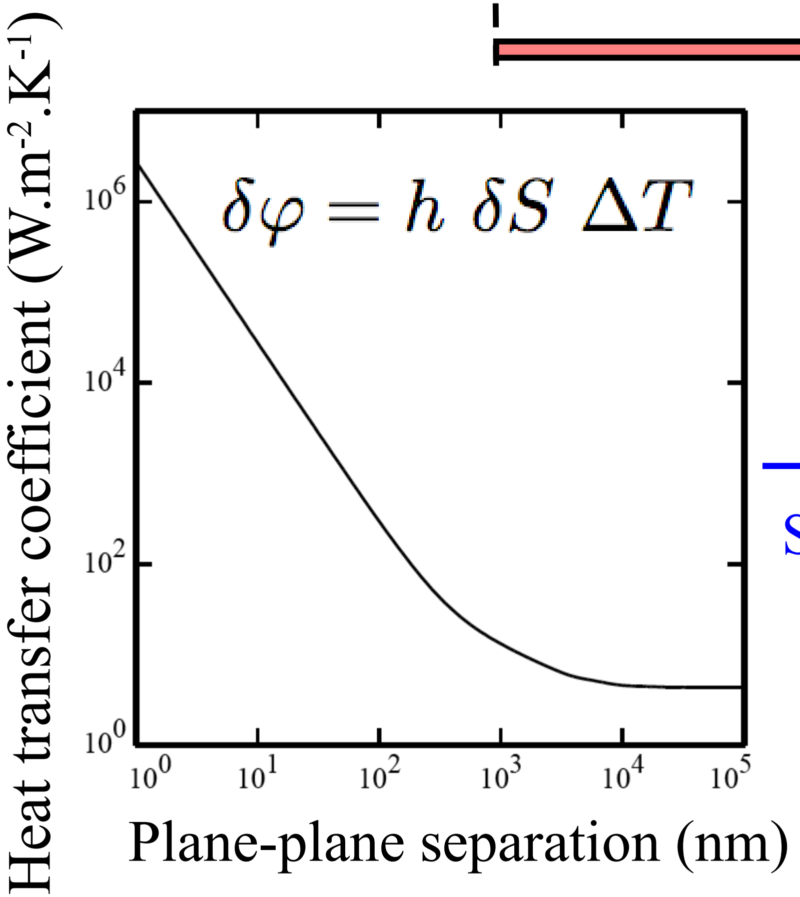


Bending vs sphere-plane distance.

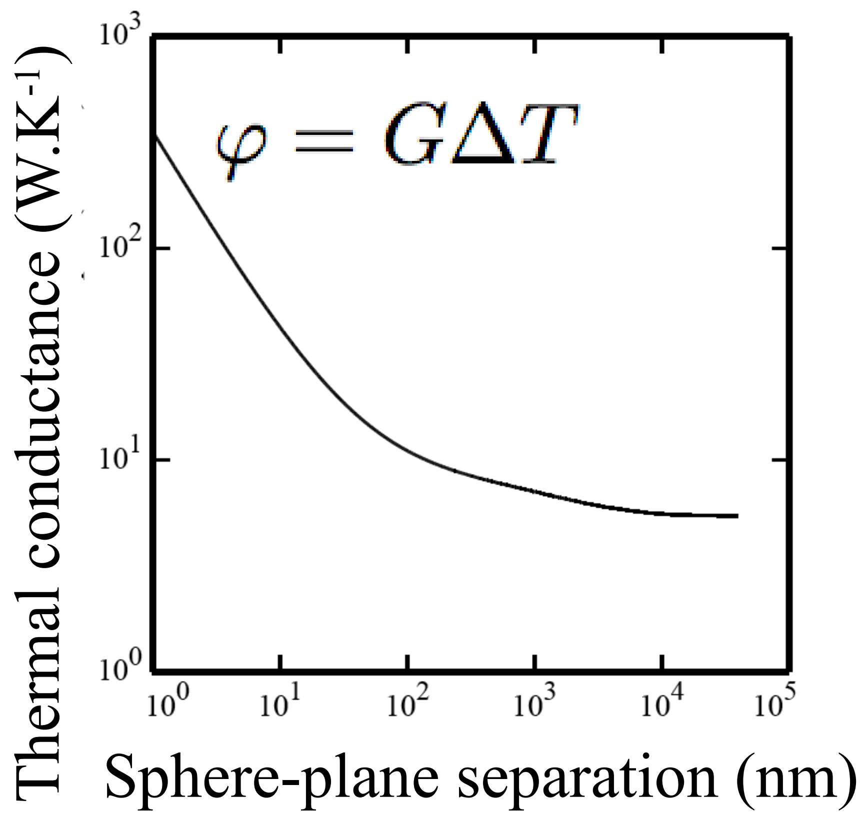
Comparison with theory.

Derjaguin approximation



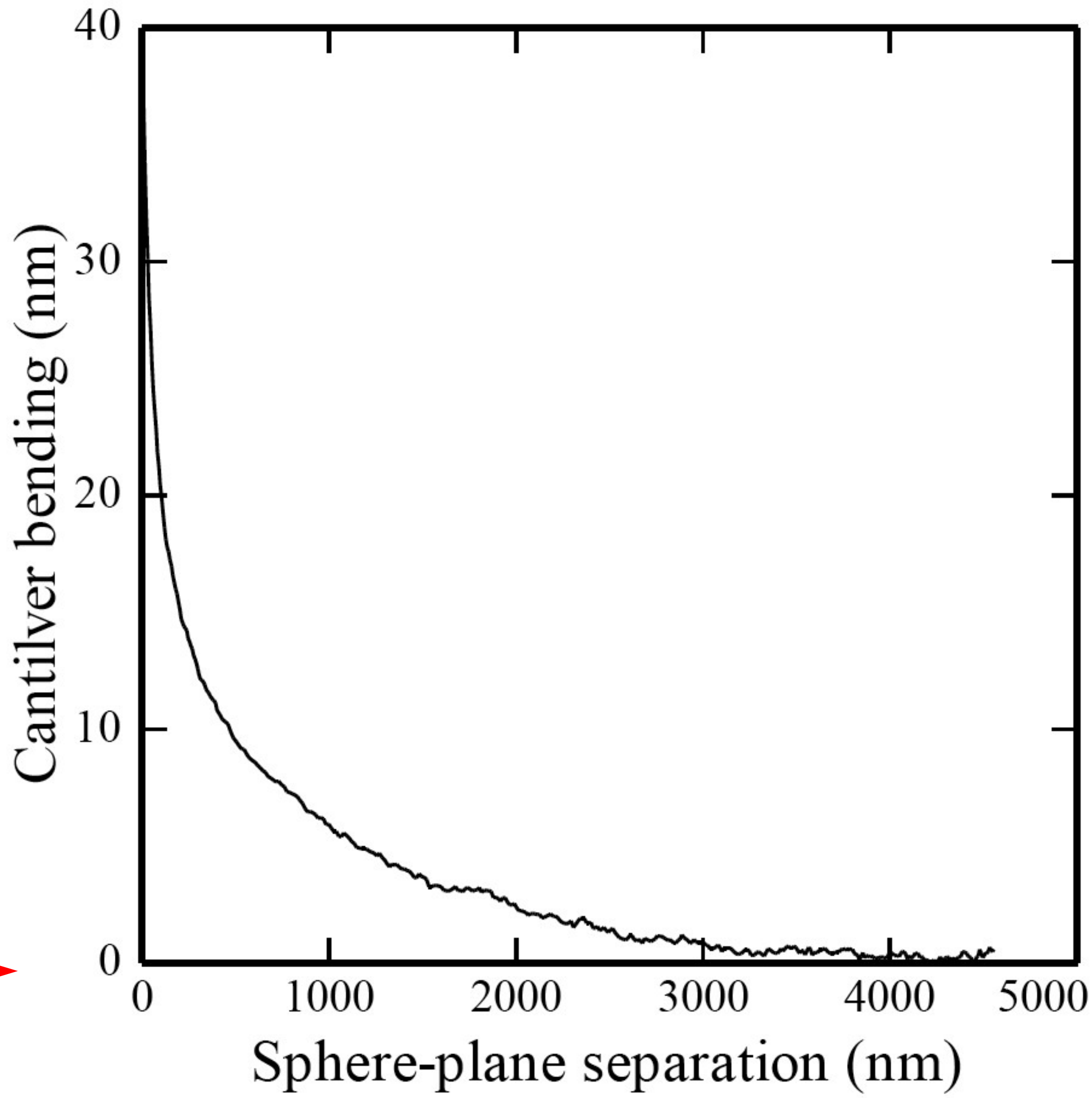


Summation



Emmanuel.rousseau@univ-montp2.fr

1- Y-axis: Far-field contribution.



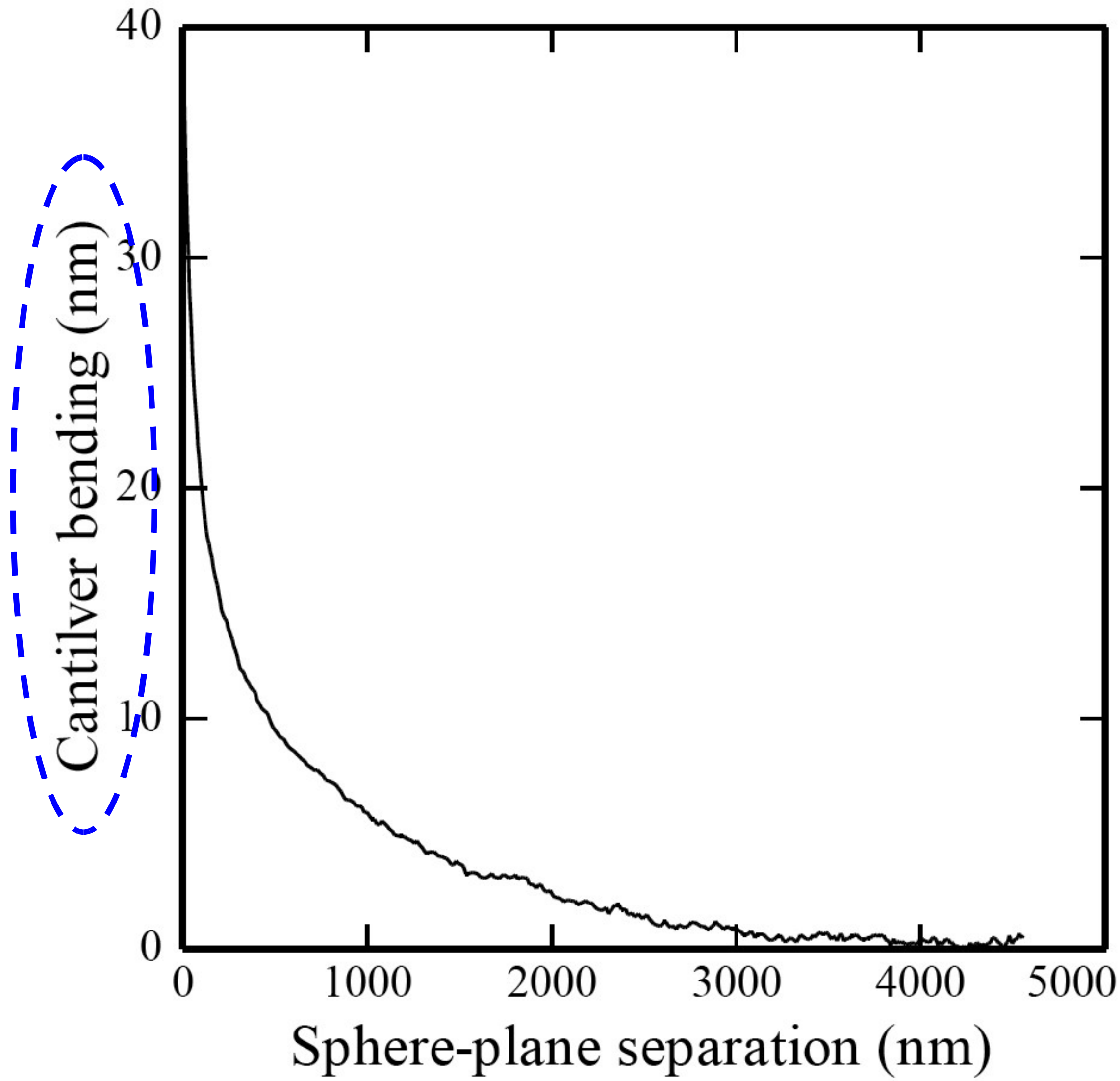
Zero flux?
No!
Relative measurement!

Add far-field contribution

2- Y-axis: calibration

$\phi = H\delta(d)$

nW ⟷ nm



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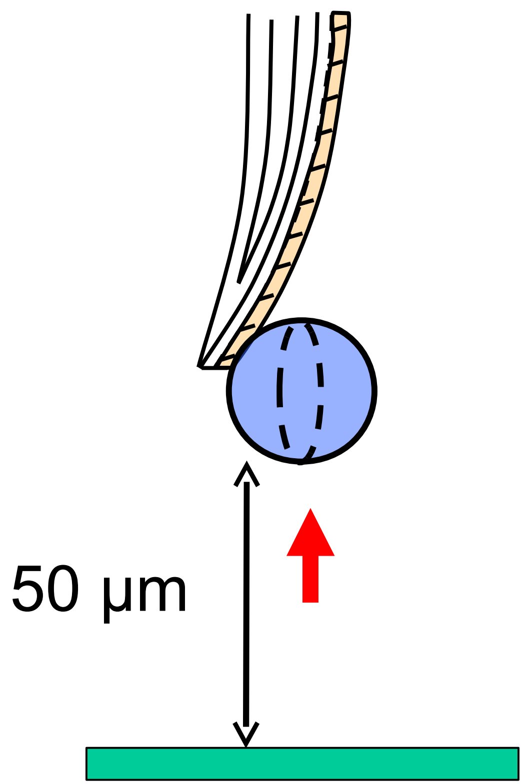
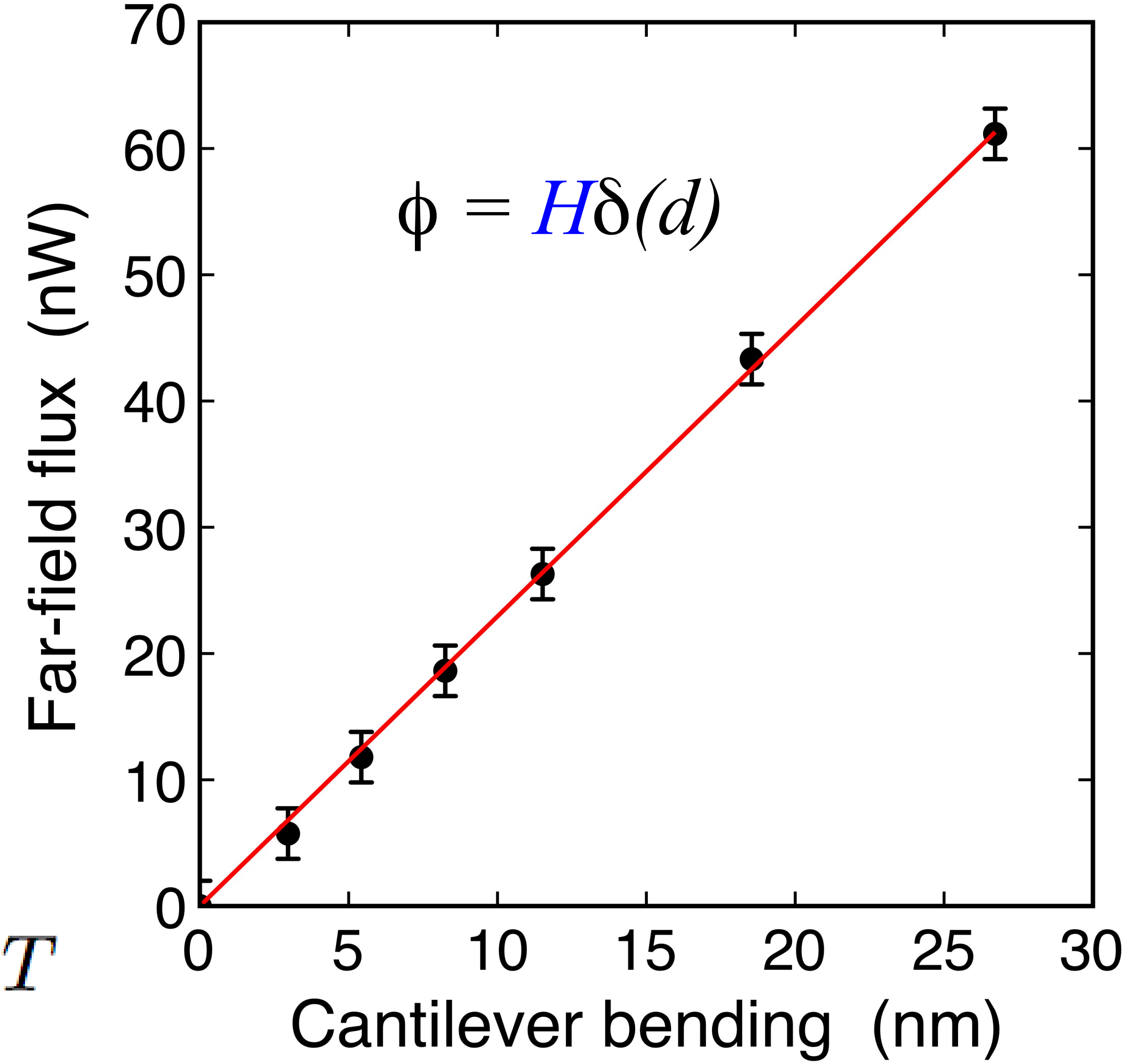
2- Y-axis: can be calibrated in far-field



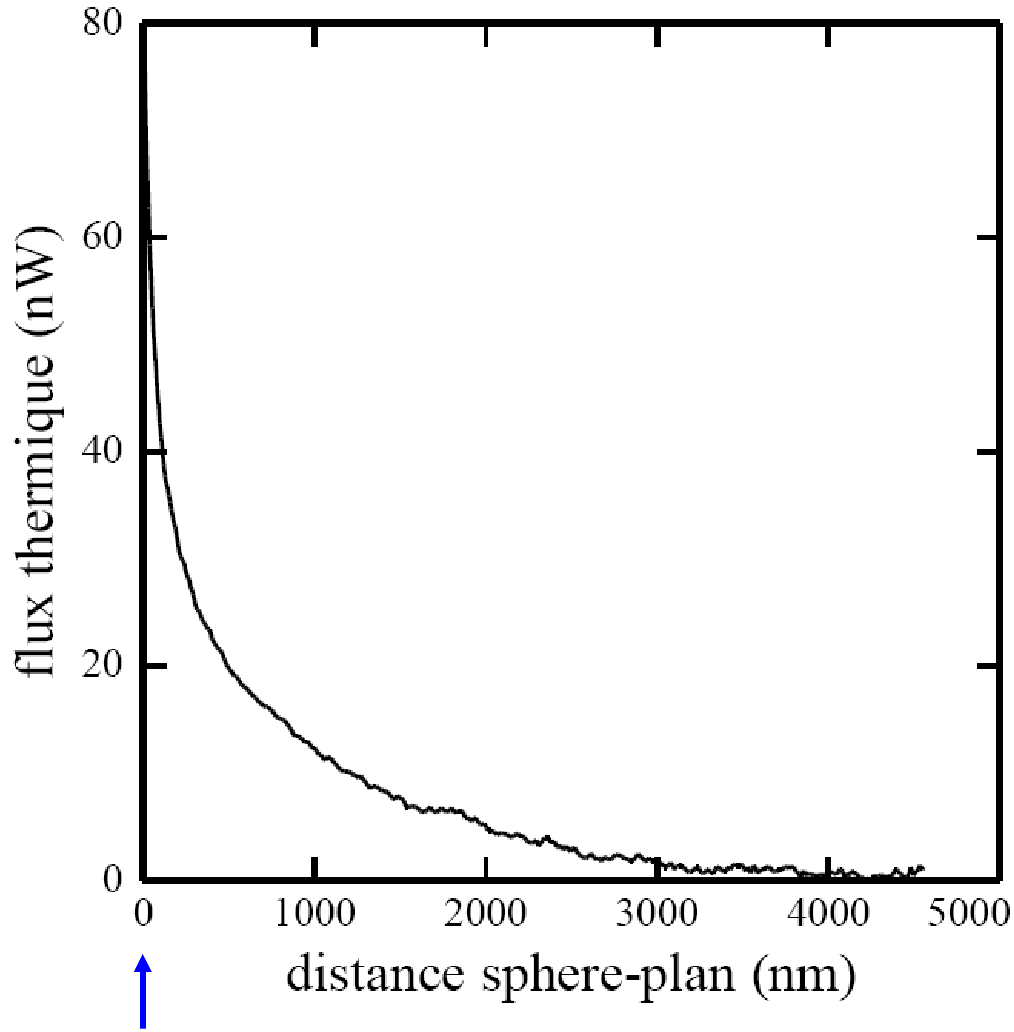


$$\varphi = 2\pi R^2 4\varepsilon\sigma T^3 \Delta T$$

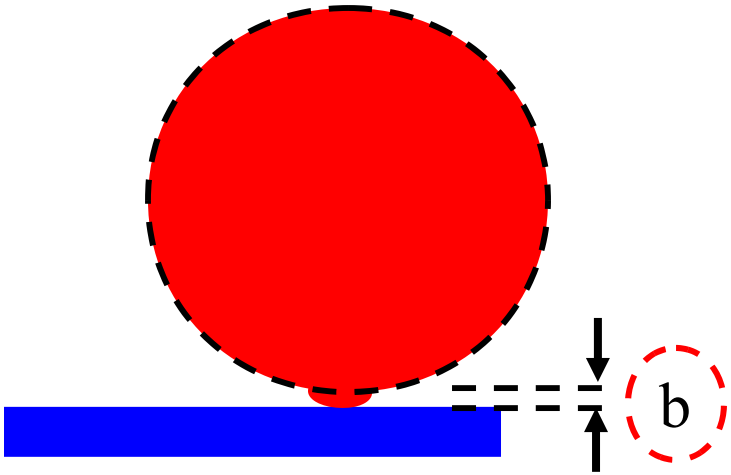
Emissivity from litterature

H=2.30 +/- 0.05 nW/nm

3- X-axis: distance mean-surface-plate



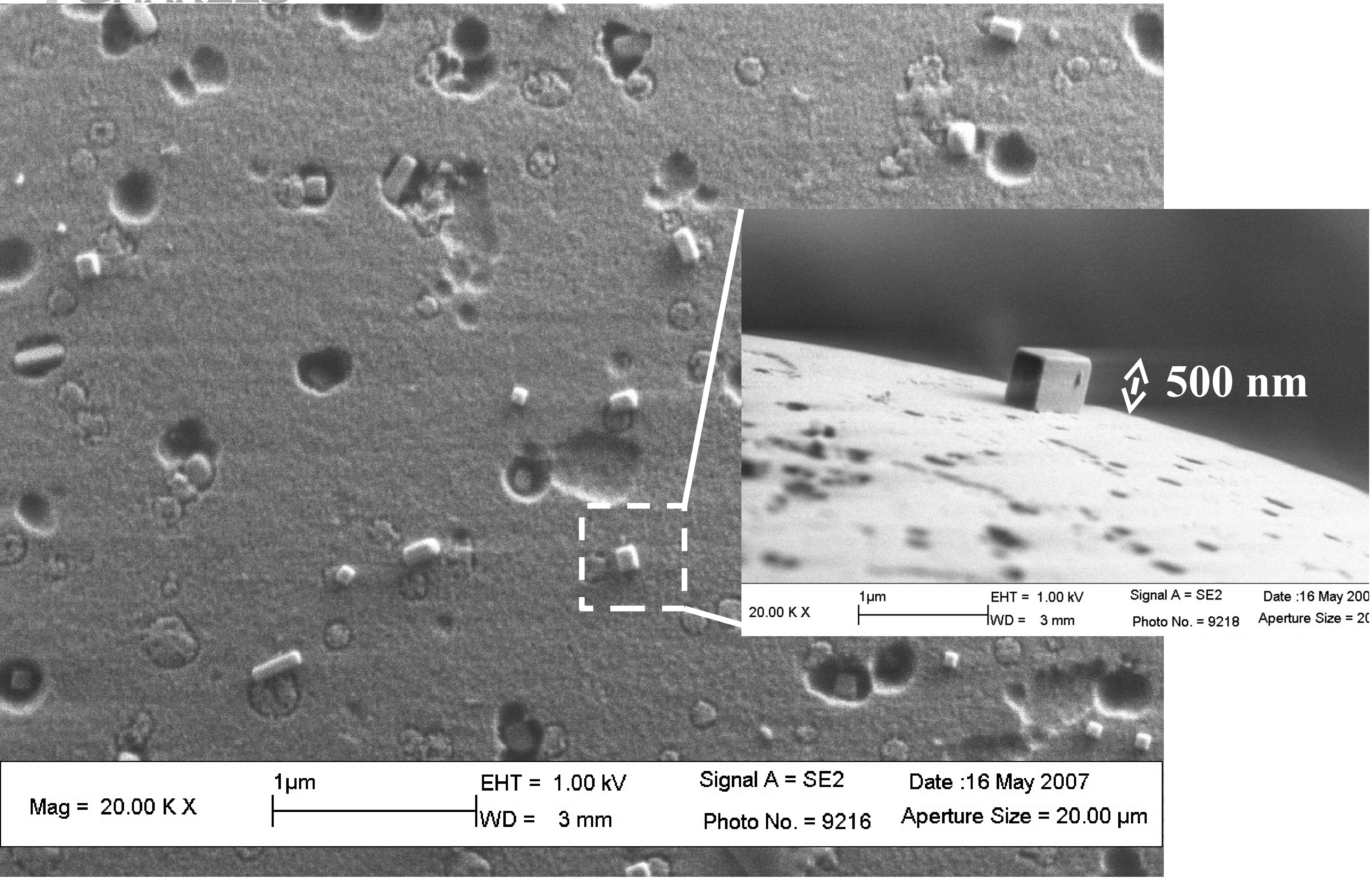
Contact? No!



No way to be measured.

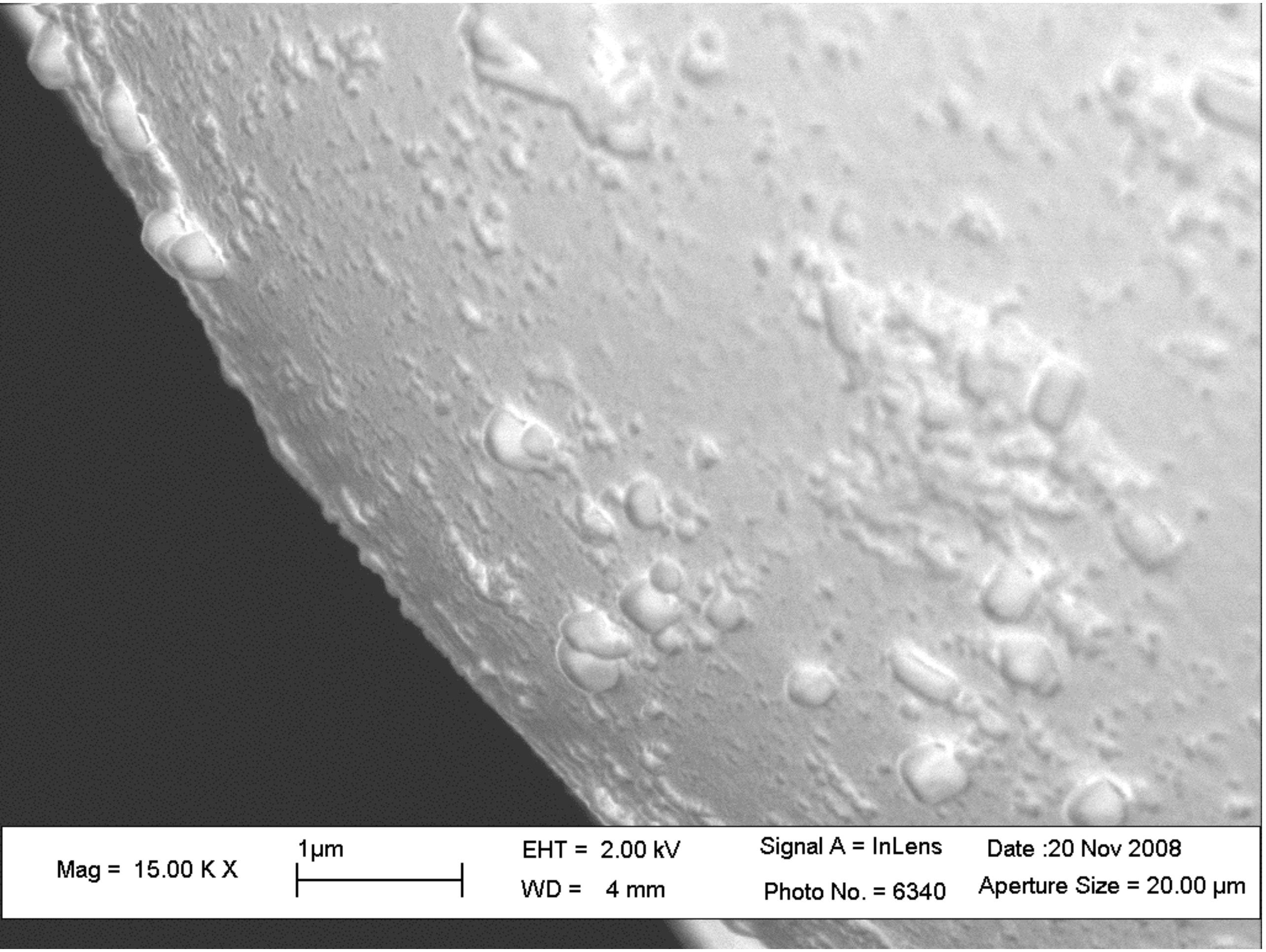
Emmanuel.rousseau@univ-montp2.fr

Sphere surface



Emmanuel.rousseau@univ-montp2.fr

Another sphere surface



Asperity size

Up to 150 nm

Emmanuel.rousseau@univ-montp2.fr

Fitting the data

Measured with Thermocouple

$$G_{exp} = G_{ff} + H\delta(d+b)/\Delta T \qquad G_{ff} = 2\pi R^2 4\sigma\varepsilon T^3$$

Compared with

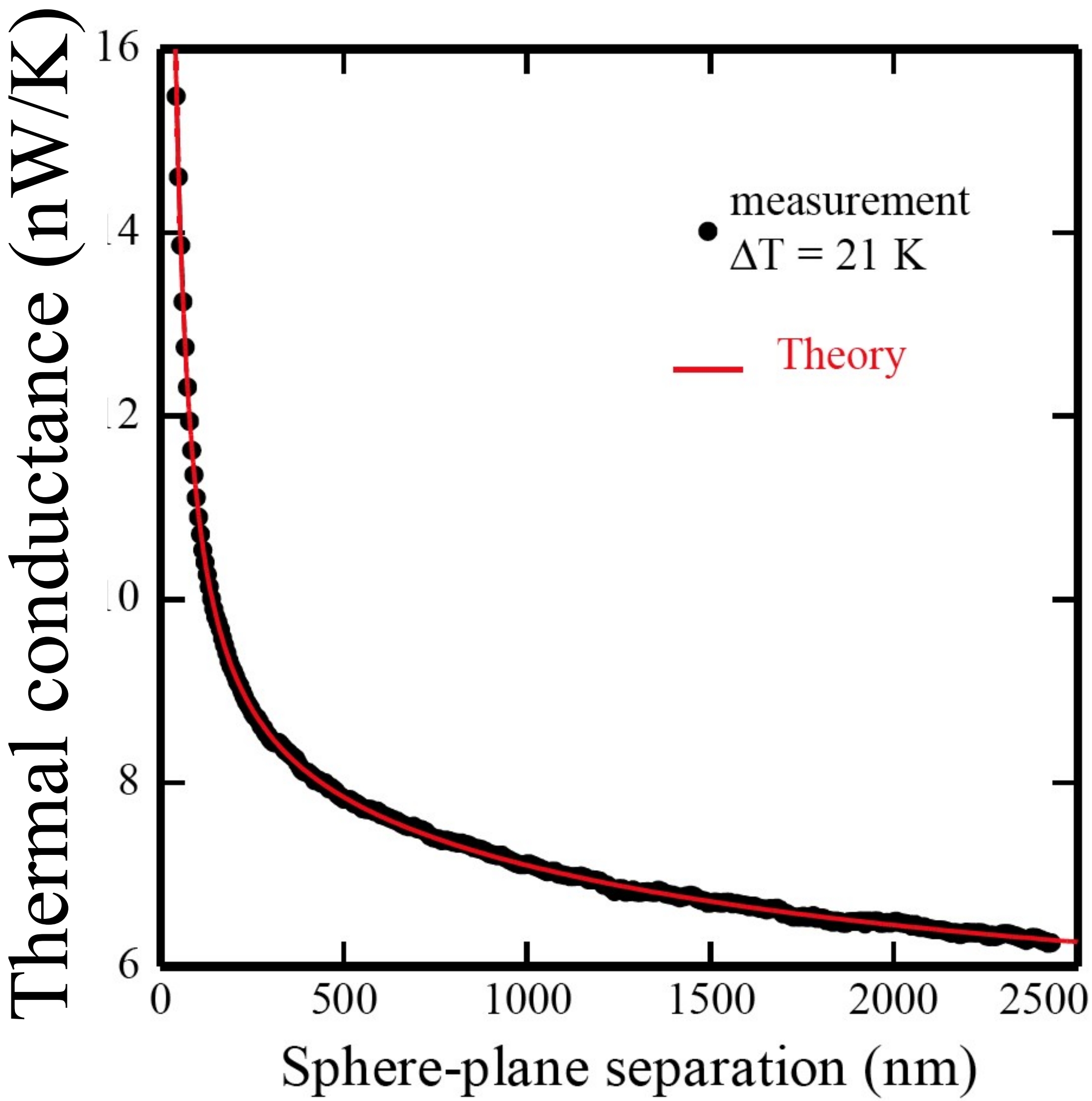
Asperity size

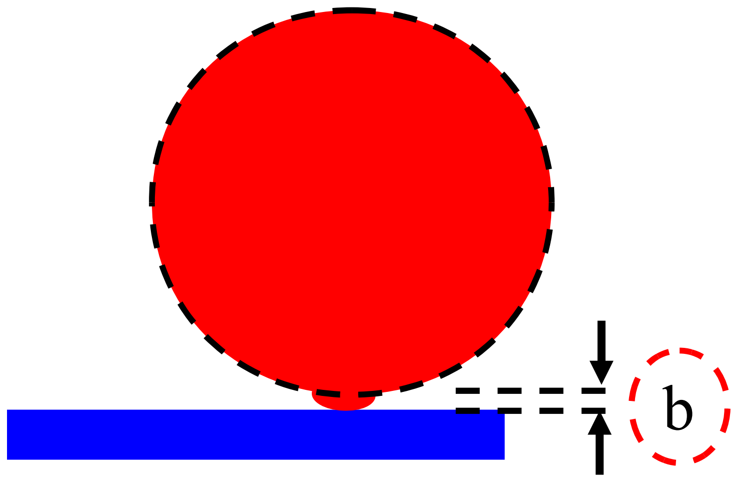
Conversion factor

Fitting parameters

From the Derjaguin approximation

Comparison experiments-theory





b = 31.8 ± 0.2 nm

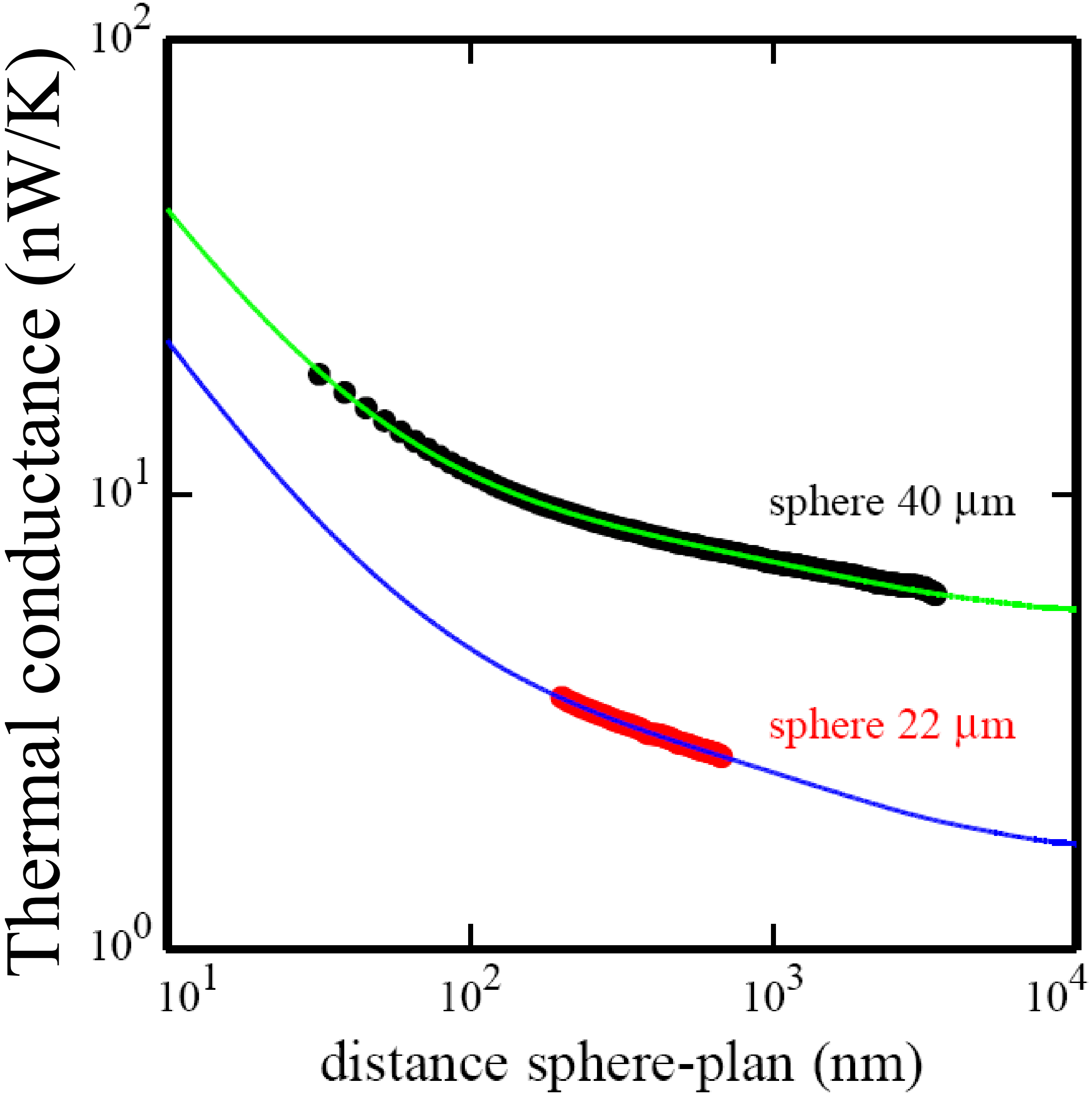
H=2.162 ± 0.005 nW/nm

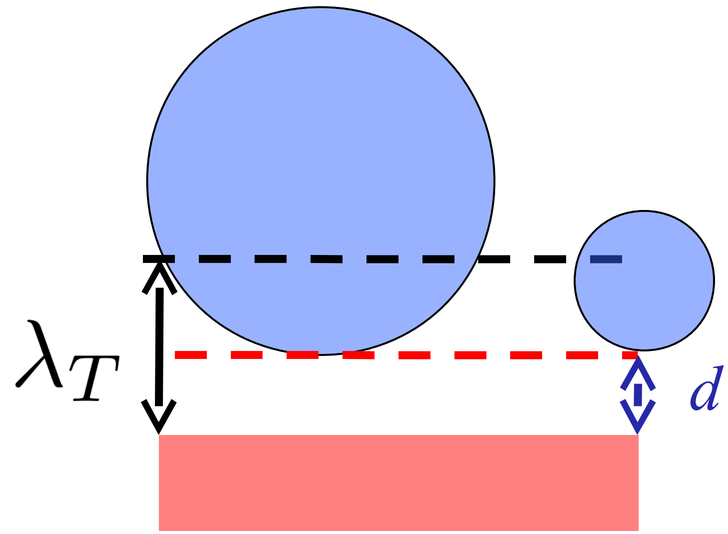
From calibration

H=2.30 +/- 0.05 nW/nm

From Rousseau et al. Nature Photonics **3** 514 (2009)

Sphere with smaller radius



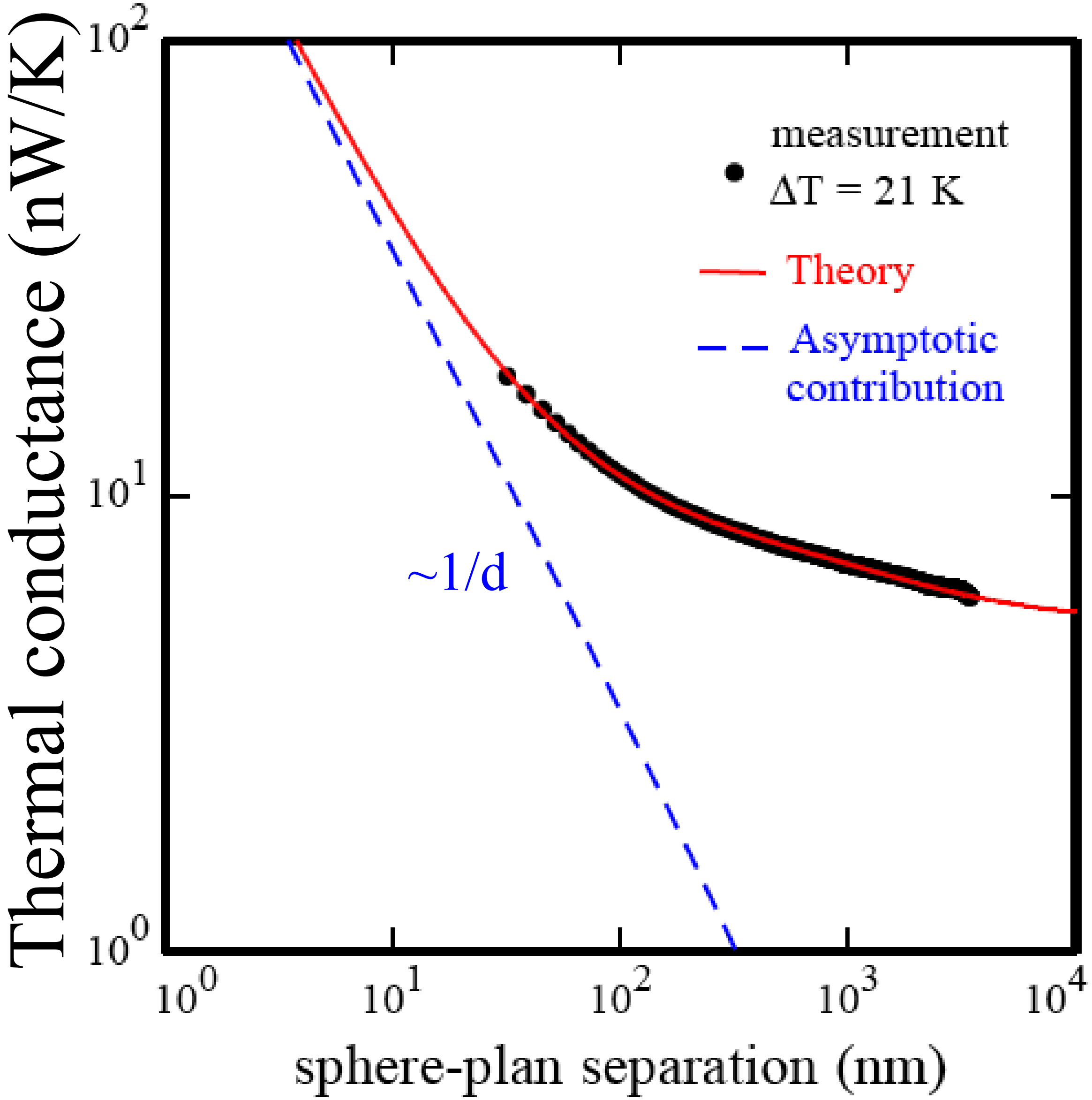


Unfortunately

b ~ 150 nm

From Rousseau et al.
Nature Photonics **3** 514 (2009)

Surface mode contribution ?



Increased by a factor 3

several order plane/plane

SPP distance dependance

$1/d^2$ @ 200 nm

For a sphere, the asymptotic regime is reached below 10 nm

See Joël Chevrier talk