Radiative Heat Transfer at the Nanoscale

Jean-Jacques Greffet

Institut d'Optique, Université Paris Sud
Institut Universitaire de France
CNRS

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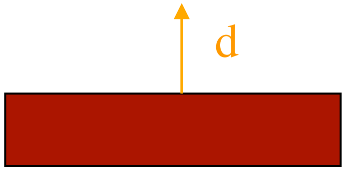
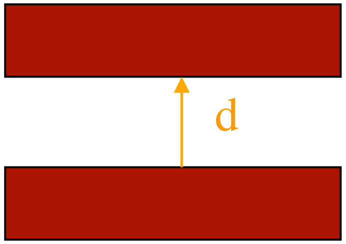
Outline of the lectures

1. Introduction



2. Heat radiation close to a surface

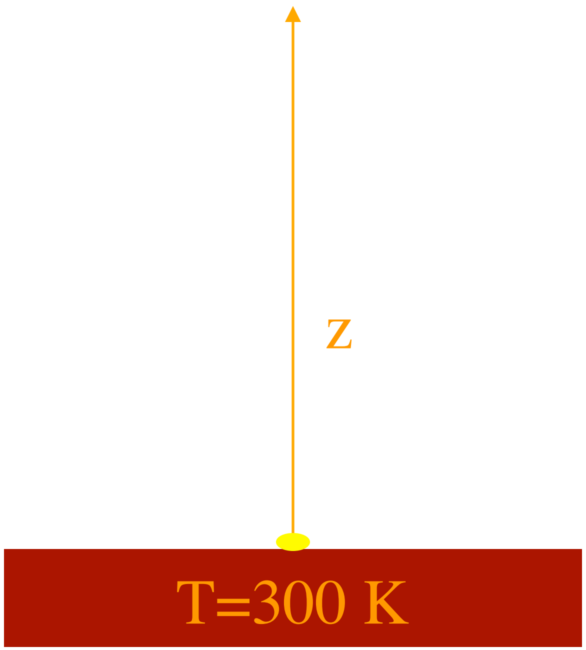


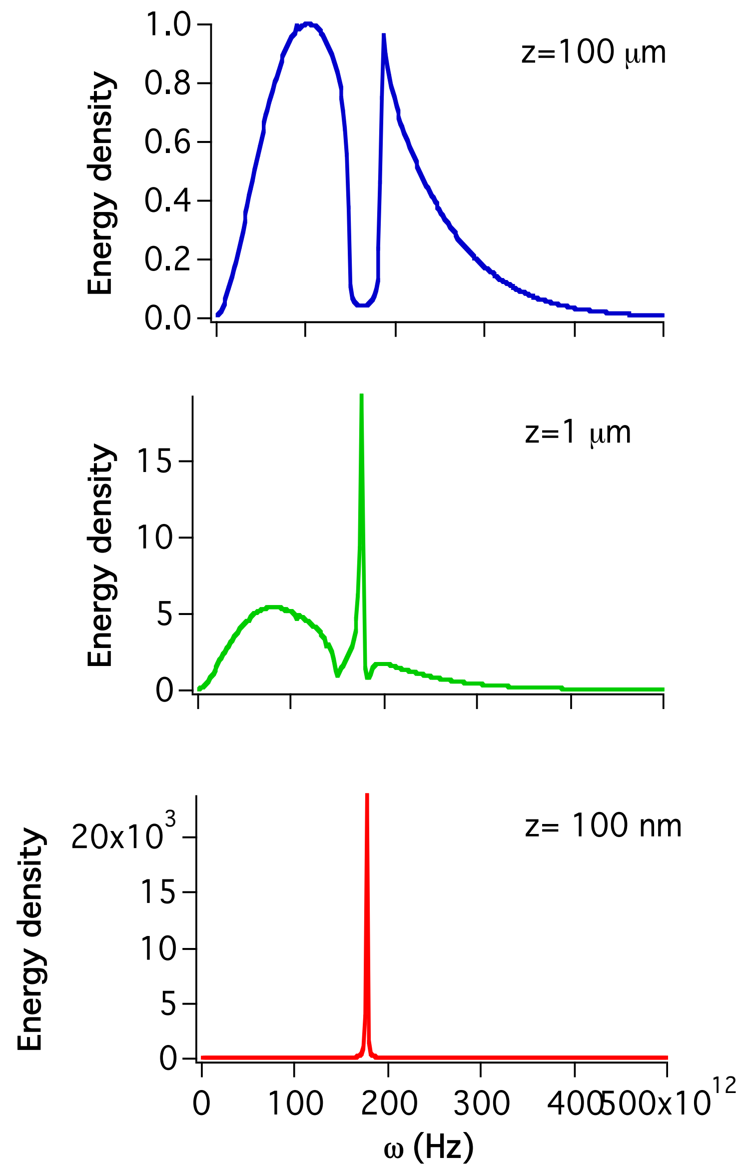
3. Heat transfer between two planes.
Mesoscopic approach, fundamental limits
and Applications

4. Tailoring spontaneous emission with surface
 waves

Heat radiation at the nanoscale : Introduction 1

Density of energy near a SiC-vacuum interface





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

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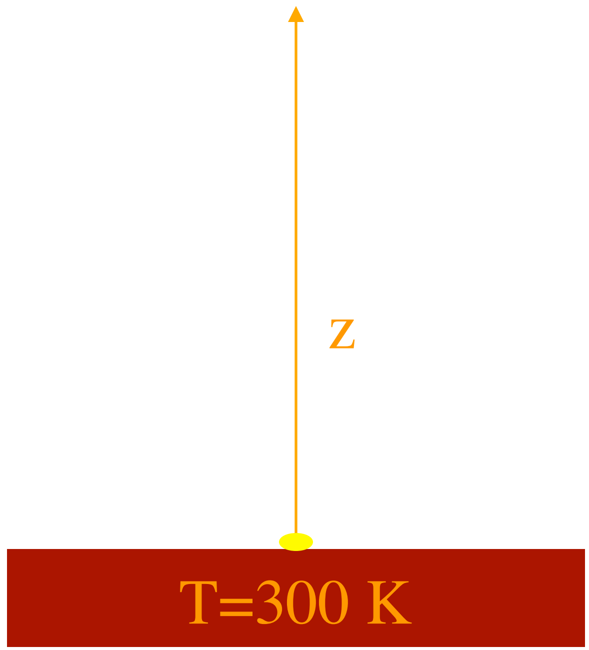
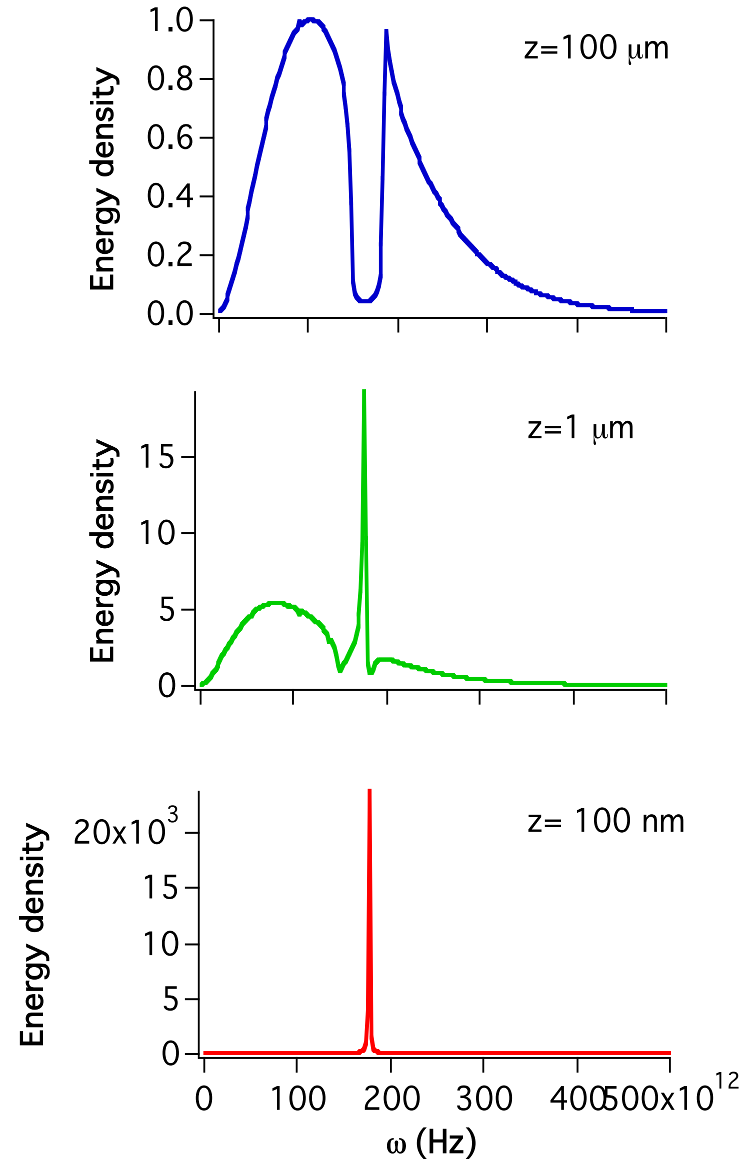


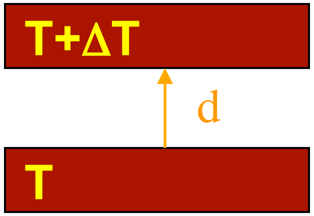


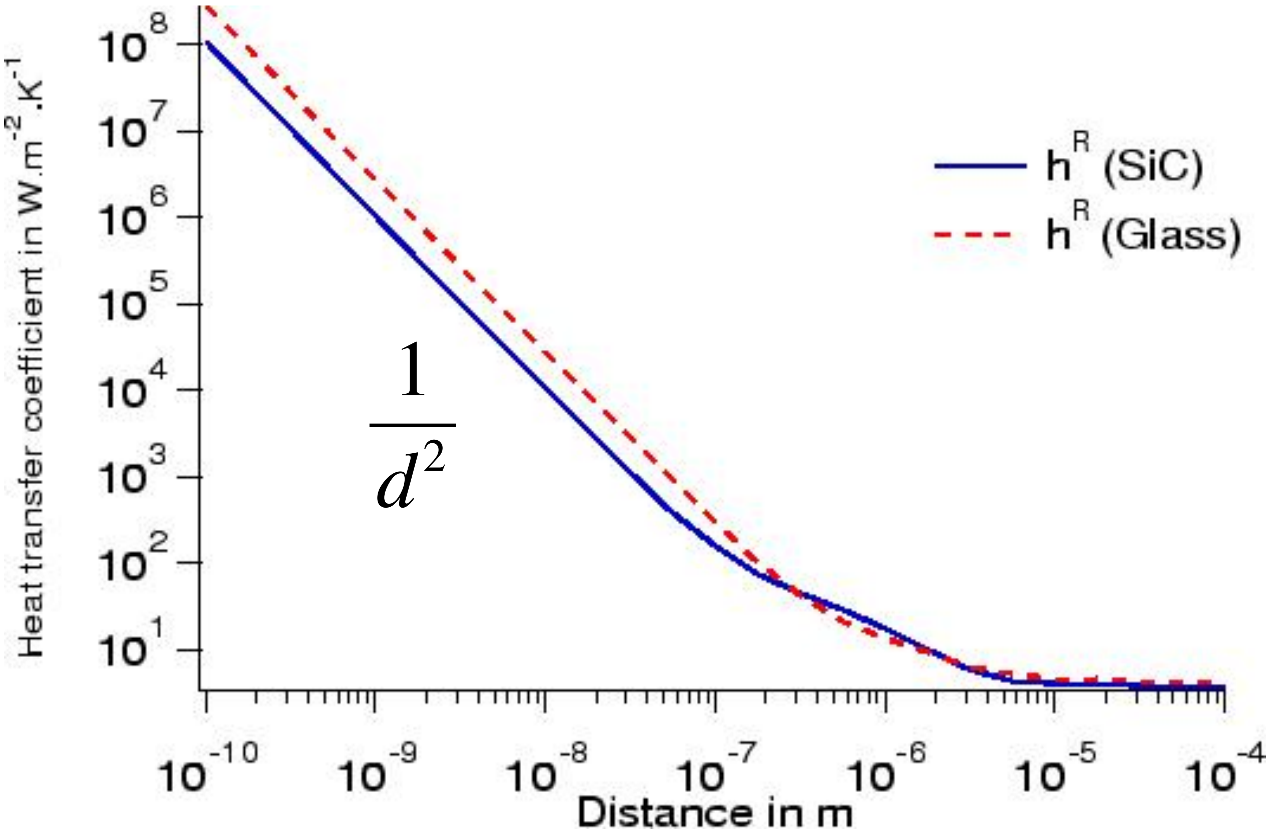
Energy density close to surfaces is orders of magnitude larger than blackbody energy density and monochromatic (temporally coherent)

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

Heat radiation at the nanoscale : Introduction 2

$$\Phi = h^R \Delta T$$

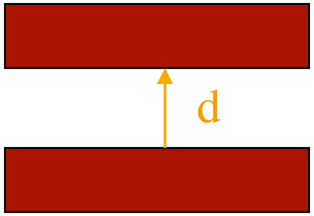




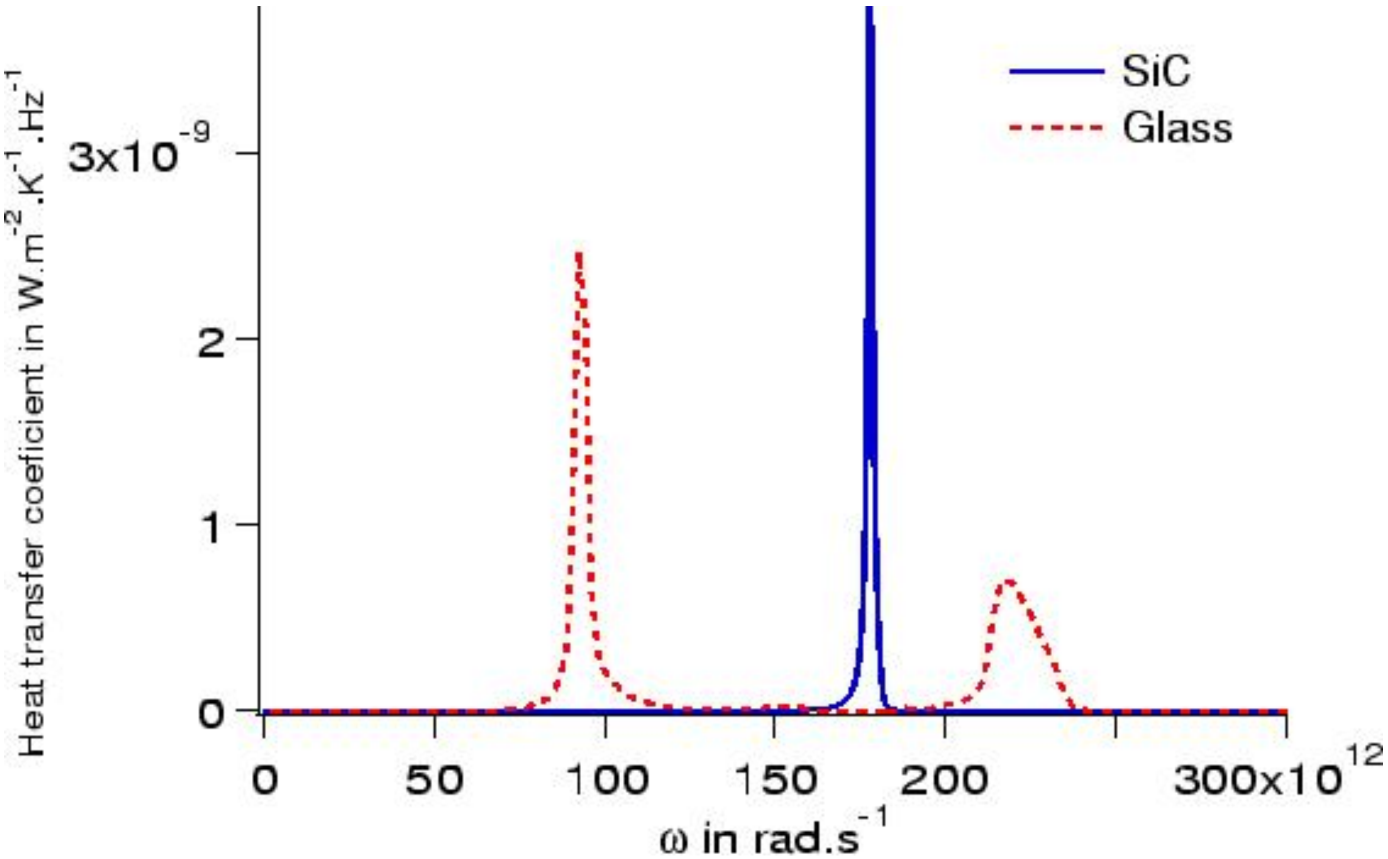
The flux is several orders of magnitude larger than Stefan-Boltzmann law.

Microscale Thermophysical Engineering 6, p 209 (2002)

Heat radiation at the nanoscale : Introduction 3



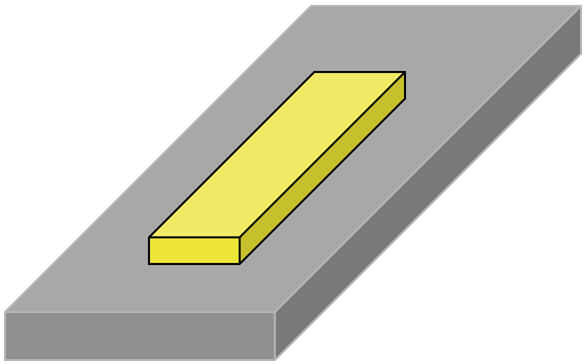
d=10 nm, T=300K

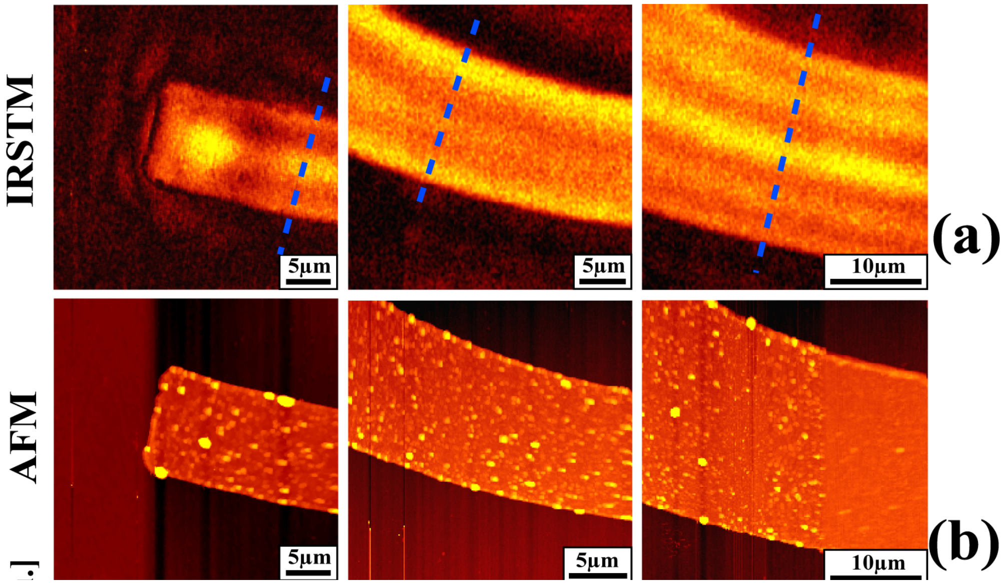


Heat transfer can be quasimonochromatic

Microscale Thermophysical Engineering 6, p 209 (2002)

Heat radiation at the nanoscale : Introduction 4

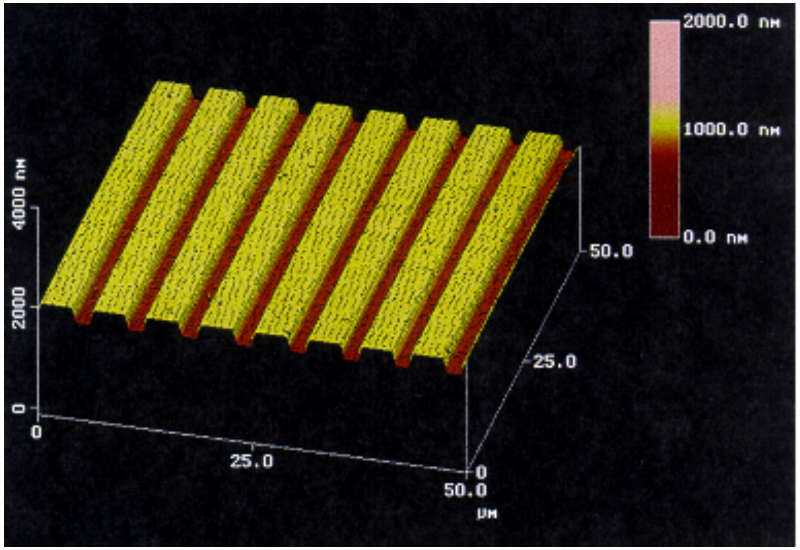


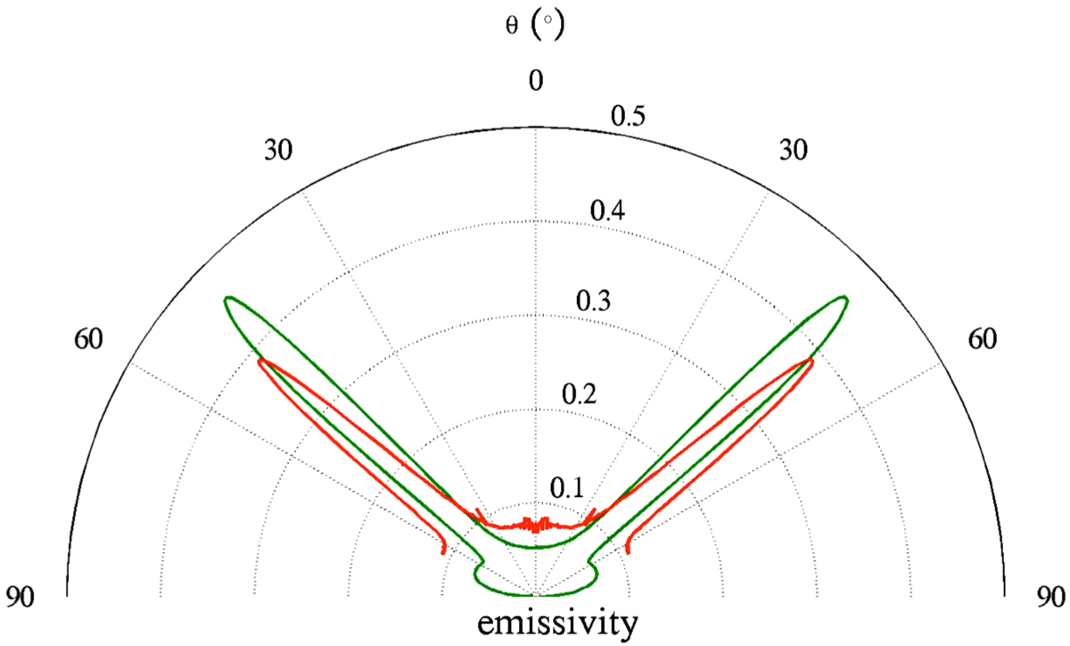


Thermally excited fields can be spatially coherent in the near field.

de Wilde et al. Nature (2006)

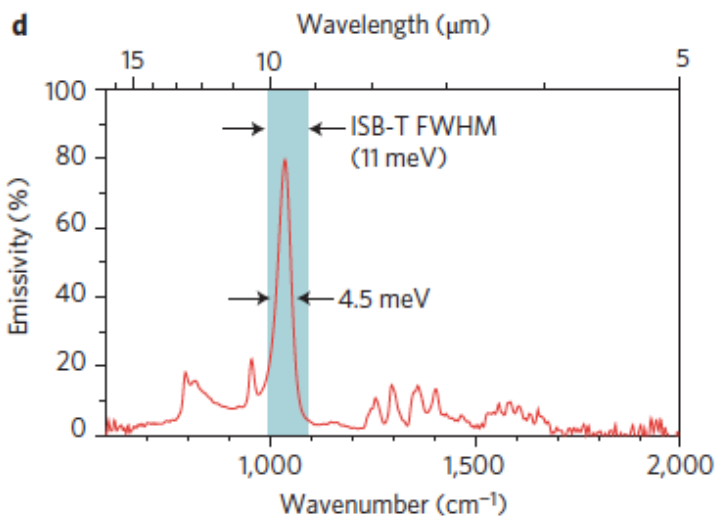
Thermal sources can be spatially coherent. Introduction 5

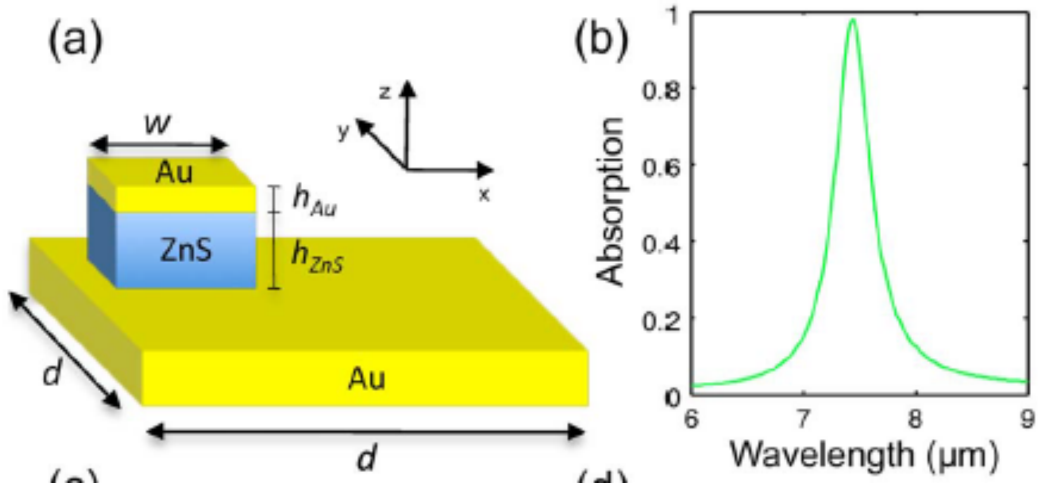




Greffet et al., Nature **416**, 61 (2002)

Thermal sources can be quasimonochromatic. Introduction 6





De Zoysa et al. , Nature Photonics (2012)

Bouchon et al. Opt. Lett. 37, p 1038 (2012)

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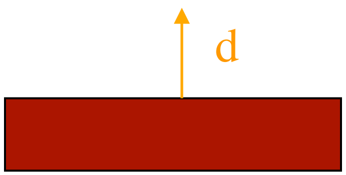

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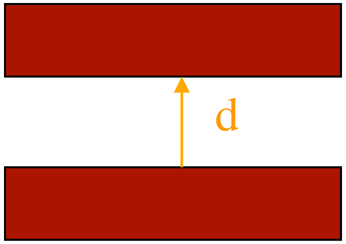

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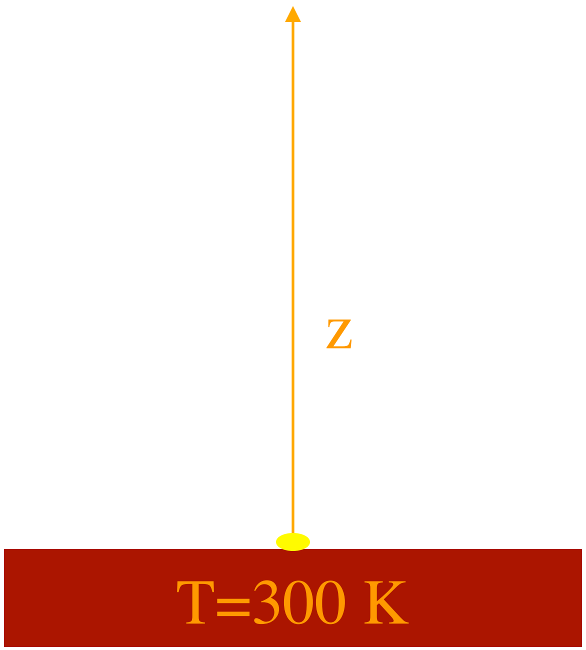
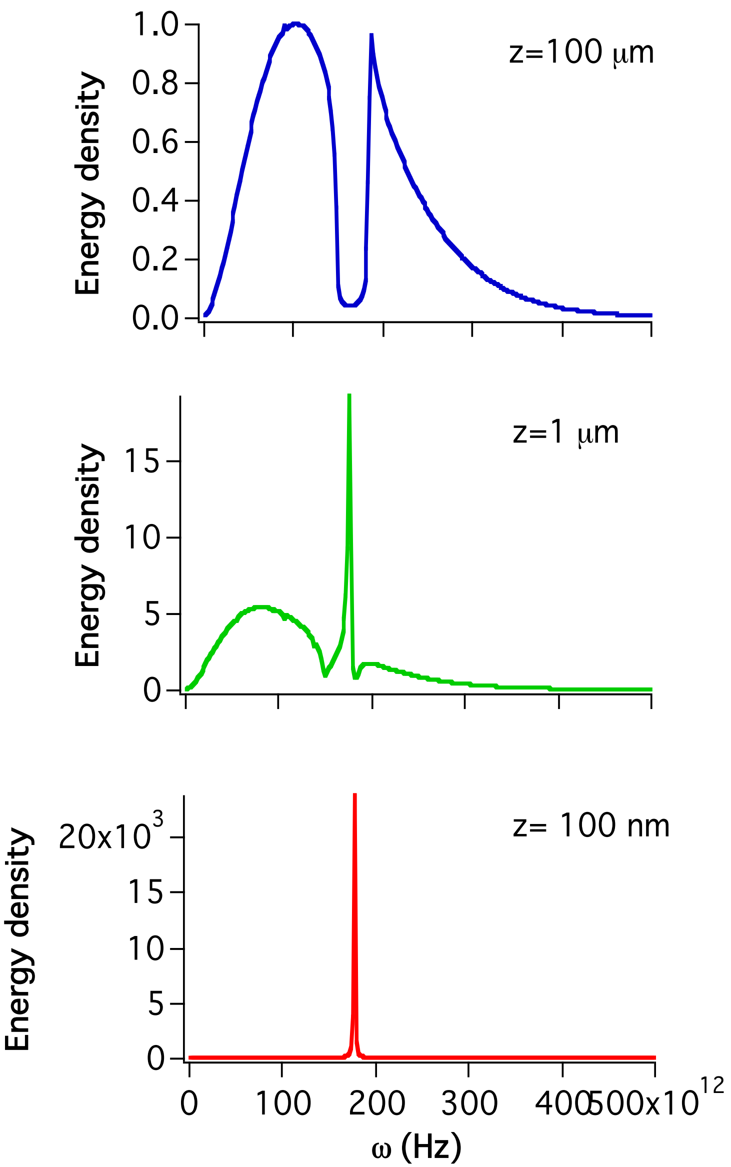
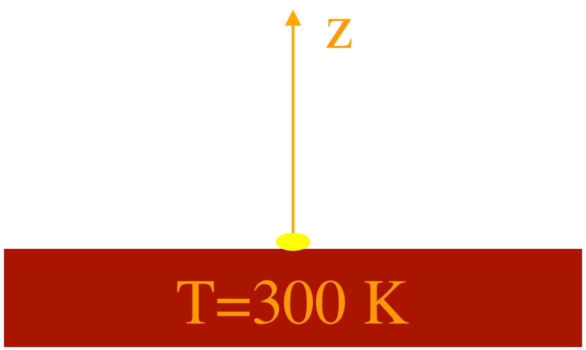
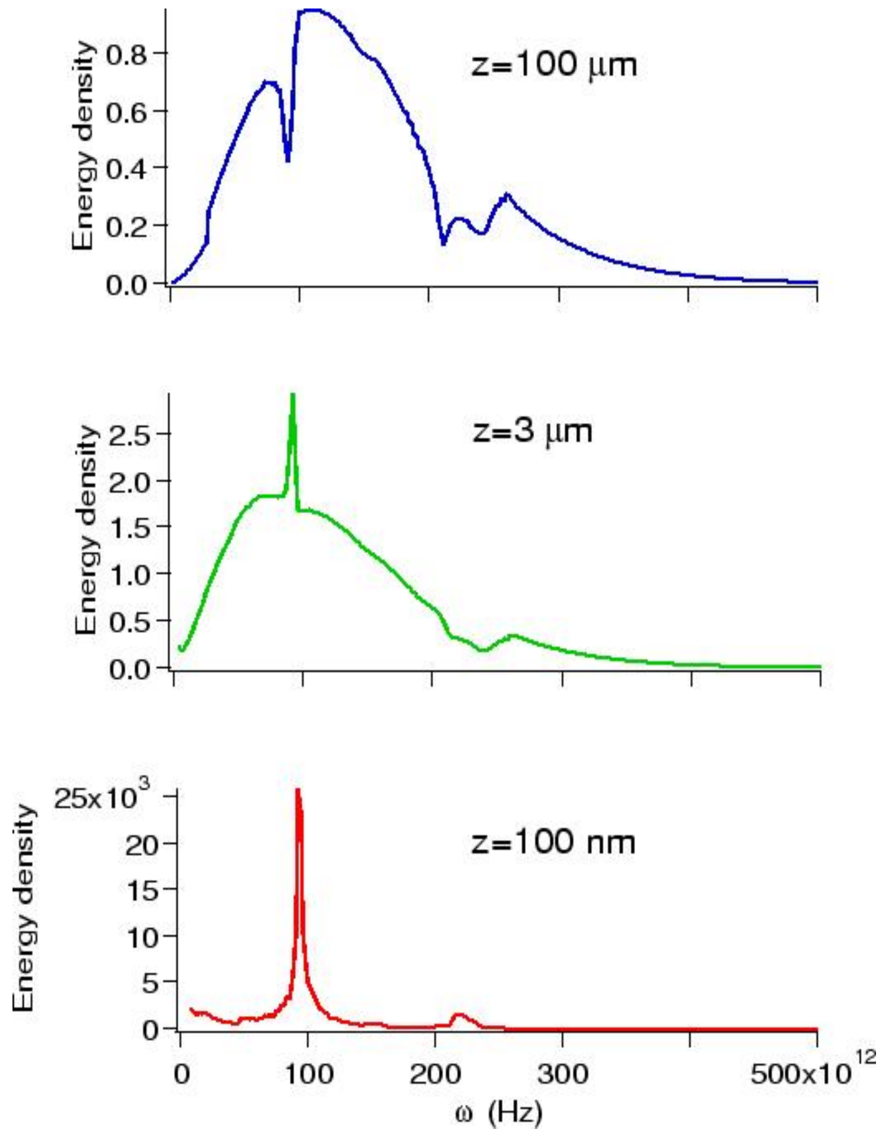




PRL, ***85*** *p 1548 (2000)*

Density of energy near a Glass-vacuum interface





The fluctuational electrodynamics approach

Rytov, Kravtsov, Tatarskii, Principles of radiophysics, Springer

The fluctuational electrodynamics approach

1) The medium is assumed to be at local thermodynamic equilibrium volume element = random electric dipole

$$\mathbf{j}(\mathbf{r},t) \text{ with } \left\langle \mathbf{j}(\mathbf{r},t) \right\rangle = 0$$

2) Radiation of random currents = thermal radiation

$$\mathbf{E}(\mathbf{r},\omega) = i\,\mu_o\,\omega \int \mathbf{G}\left(\mathbf{r},\mathbf{r}',\omega\right) \bullet \mathbf{j}\left(\mathbf{r}',\omega\right) d\mathbf{r}'$$

The fluctuational electrodynamics approach

3) Spatial correlation (cross-spectral density)

$$\left\langle E_j E^*_k \right\rangle (\mathbf{r},\mathbf{r}',\omega) = \mu_o^2 \omega^2 \int G_{jm}(\mathbf{r},\mathbf{r}_1) G^*_{kn}(\mathbf{r}',\mathbf{r}_2) \left\langle j_m(\mathbf{r}_1) j^*_n(\mathbf{r}_2) \right\rangle d\mathbf{r}_1 d\mathbf{r}_2$$

$$U(\mathbf{r},\omega) \propto \left\langle \left| \mathbf{E}(\mathbf{r},\omega) \right|^2 \right\rangle$$

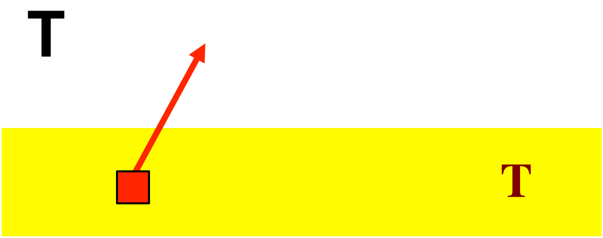
4) The current-density correlation function is given by the FD theorem

$$\left\langle j_m(\mathbf{r}_1) j^*_n(\mathbf{r}_2) \right\rangle = \frac{\omega}{\pi} \varepsilon_o \operatorname{Im}\left[\varepsilon(\omega)\right] \delta_{mn}\, \delta(\mathbf{r}_1 - \mathbf{r}_2) \frac{\hbar\omega}{\exp\left(\hbar\omega / k_B T\right) - 1}$$

Fluctuation

Absorption

Understanding far-field thermal emission



Radiation of random currents = thermal radiation

$$\mathbf{E}(\mathbf{r},\omega) = i\,\mu_o\,\omega \int \mathbf{G}(\mathbf{r},\mathbf{r}',\omega) \bullet \mathbf{j}(\mathbf{r}',\omega)\, d\mathbf{r}'$$

Emissivity= transmission factor

$$I_\omega^e(T) = \varepsilon I_\omega^{BB}(T) = T_F I_\omega^{BB}(T)$$

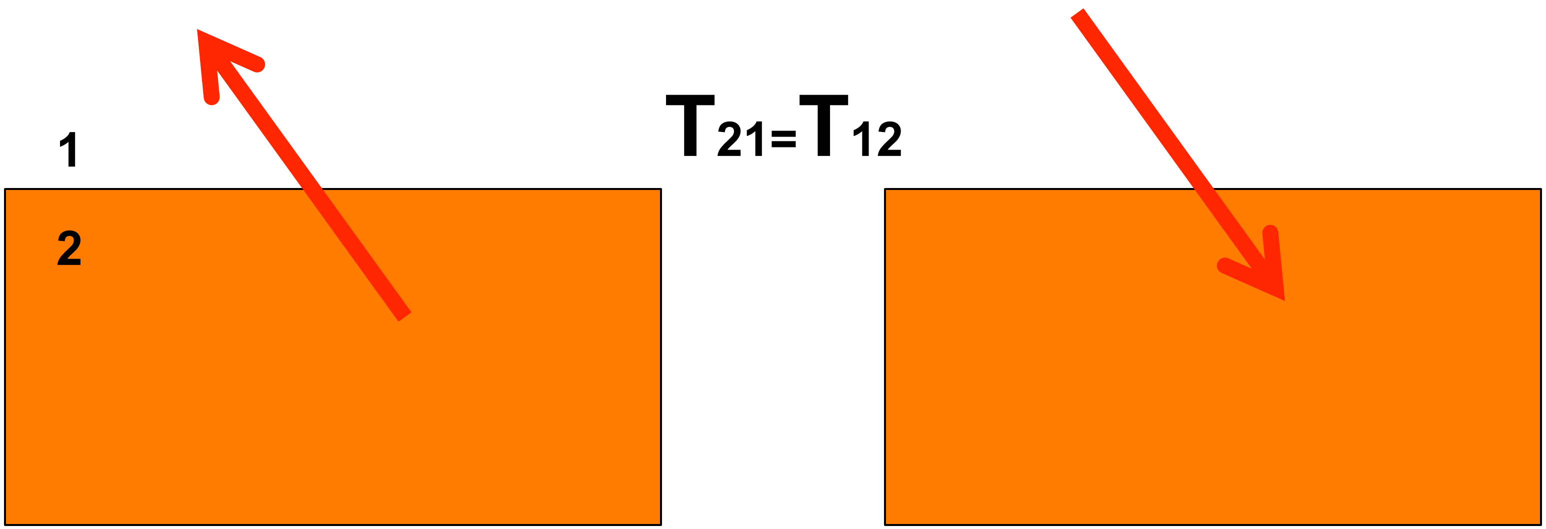
Physical origin of Kirchhoff's law

Physical meaning of emissivity and absorptivity

Kirchhoff's law:

$$\varepsilon = \alpha$$

$$T_{21} = T_{12}$$



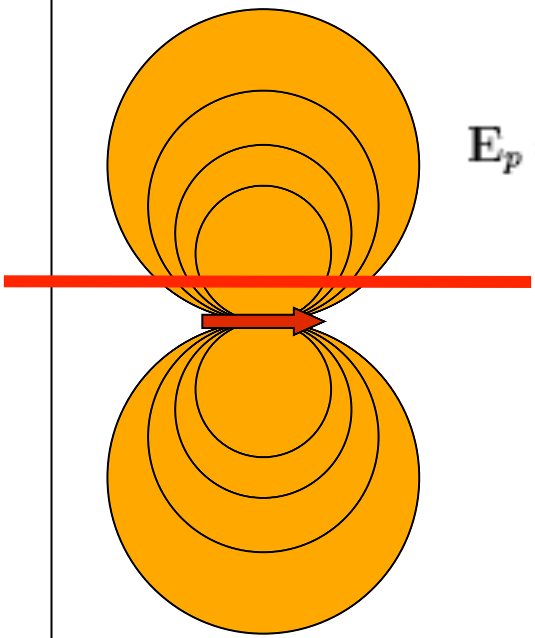
$$I_\omega^e(T) = \varepsilon I_\omega^{BB}(T) = T_F I_\omega^{BB}(T) = \alpha I_\omega^{BB}(T)$$

Basic concepts of near field

What is so special about near field ?

Understanding near-field thermal emission

Back to basics : dipole radiation



$$\mathbf{E}_p = \frac{k_0^2}{4\pi\epsilon_0}\frac{e^{ik_0 r}}{r}\left[(\mathbf{I}-\mathbf{uu}) + \left(\frac{i}{k_0 r} - \frac{1}{(k_0 r)^2}\right)(\mathbf{I}-3\mathbf{uu})\right]\mathbf{p}$$

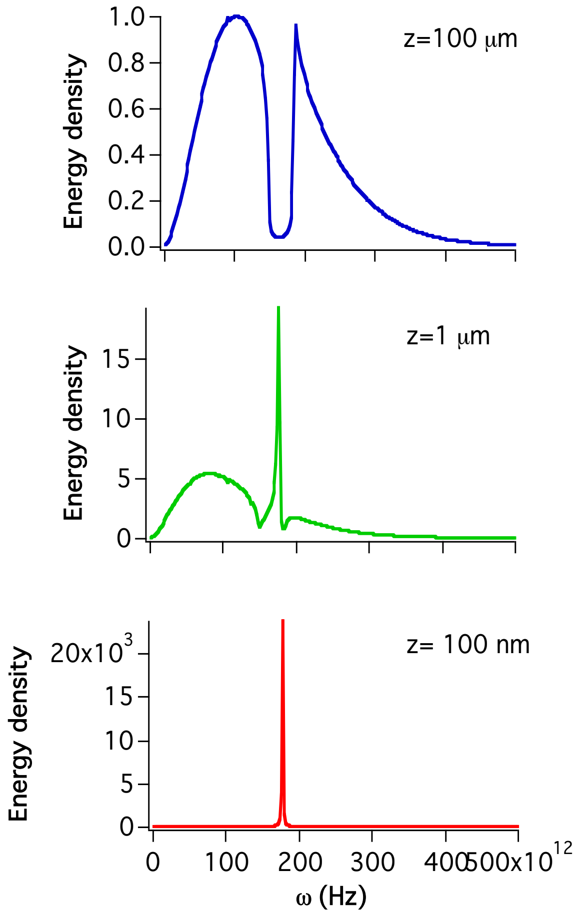
1/r terms
Radiation

$1/r^2$ and $1/r^3$ terms
Near field

Near field: $k_0 r << 1$, $k_0 = 2\pi/\lambda$

Understanding near-field thermal emission

$$\mathbf{E}_p = \frac{k_0^2}{4\pi\epsilon_0}\frac{e^{ik_0r}}{r}\left[(\mathrm{I}-\mathbf{uu}) + \left(\frac{i}{k_0r} - \frac{1}{(k_0r)^2}\right)(\mathrm{I}-3\mathbf{uu})\right]\mathbf{p}$$



$1/r^2$ and $1/r^3$ terms

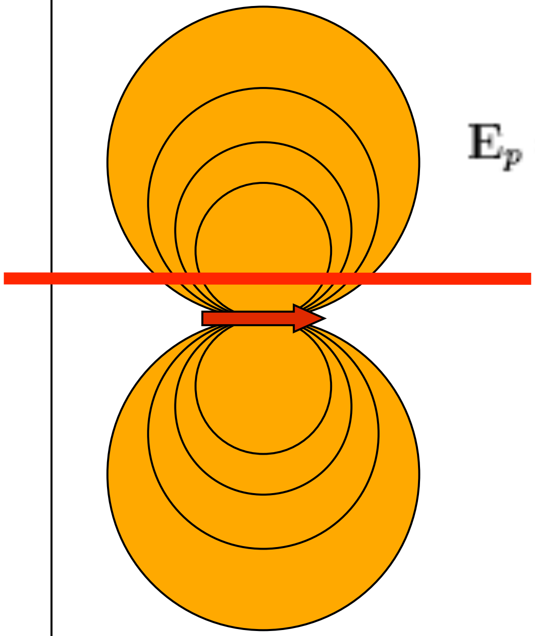
Near field

Dipole spectral resonances

Near field: $k_0r<<1$, $k_0=2\pi/\lambda$

Basic concepts of near field

Back to basics : dipole radiation



$$\mathbf{E}_p = \frac{k_0^2}{4\pi\epsilon_0}\frac{e^{ik_0 r}}{r}\left[(\mathbf{I}-\mathbf{u}\mathbf{u}) + \left(\frac{i}{k_0 r} - \frac{1}{(k_0 r)^2}\right)(\mathbf{I}-3\mathbf{u}\mathbf{u})\right]\mathbf{p}$$

1/r terms
Radiation

$1/r^2$ and $1/r^3$ terms
Near field

Near field: $k_0 r \ll 1$, $k_0 = 2\pi/\lambda$

Basic concepts of near field: ***evanescent waves***

$$\frac{\exp[ikR]}{R} = \frac{i}{2\pi} \iint \frac{dk_x dk_y}{k_z} \exp\left[i(k_x x + k_y y + k_z |z|)\right]$$

$$k_\perp < \frac{\omega}{c} \quad ; \quad k_z = \sqrt{\frac{\omega^2}{c^2} - k_\perp^2} \quad ; \quad k_\perp = (k_x, k_y)$$

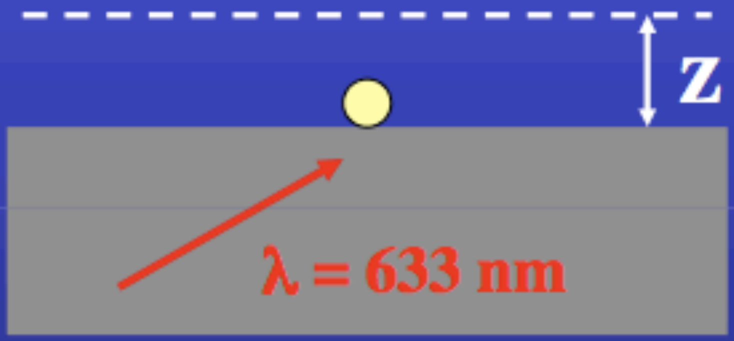
$$k_\perp > \frac{\omega}{c} \quad ; \quad k_z = i\sqrt{\left|\frac{\omega^2}{c^2} - k_\perp^2\right|}$$

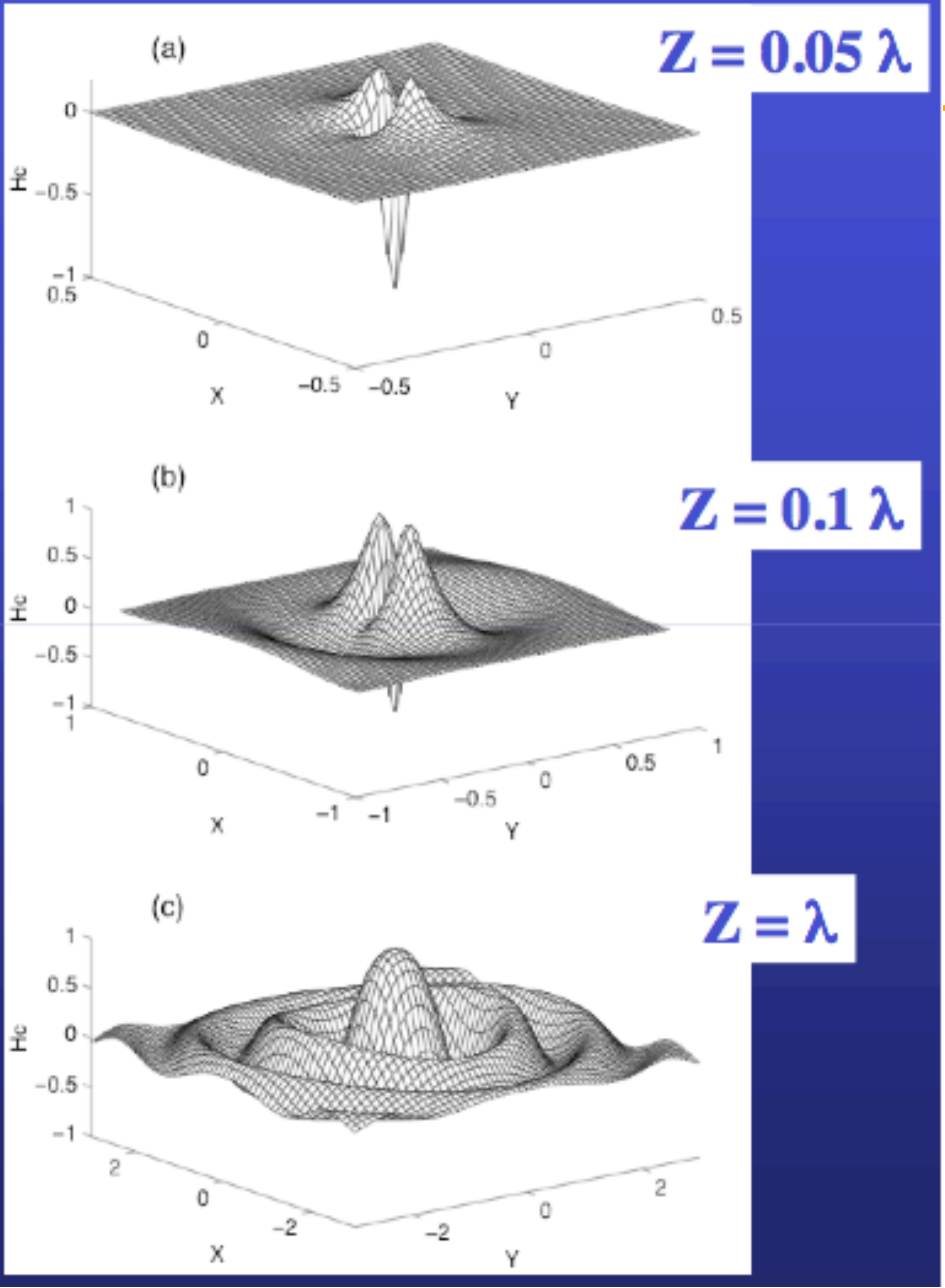
$$k_\perp >> \frac{\omega}{c} \quad ; \quad k_z \approx ik_\perp$$

$$\exp\left[ik_z |z|\right] \approx \exp\left[-k_\perp z\right]$$

Take home message: large k are confined to distances 1/k.

Evanescent waves filtering





Energy density:

in vacuum,
close to a nanoparticle,
close to a surface

Blackbody radiation in vacuum

$$g(\omega) = \frac{\omega^2}{\pi^2 c^3}$$

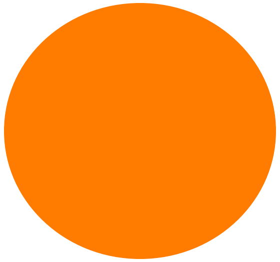
$$U = \int_0^\infty \frac{\omega^2}{\pi^2 c^3} \frac{\hbar\omega}{e^{\hbar\omega/kT} - 1} \, \mathrm{d}\omega$$

Black body radiation close to a nanoparticle

Questions to be answered :

Is the field orders of magnitude larger close to particles ?
If yes, why ?
Is the thermal field quasi monochromatic ? If yes, why ?

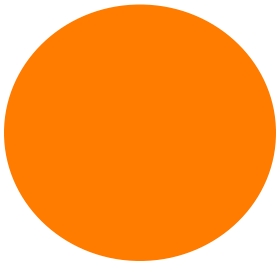
Black body radiation close to a nanoparticle



$$\mathbf{E}_p = \frac{k_0^2}{4\pi\epsilon_0}\frac{e^{ik_0 r}}{r}\left[(\mathrm{I}-\mathrm{uu}) + \left(\frac{i}{k_0 r} - \frac{1}{(k_0 r)^2}\right)(\mathrm{I}-3\mathrm{uu})\right]\mathrm{p}$$

$$\left\langle p_m(\mathbf{r}_1)p_n^*(\mathbf{r}_2)\right\rangle = \frac{2}{\pi\omega}\varepsilon_o \,\mathrm{Im}\left[\alpha(\omega)\right]\delta_{mn}\,\delta(\mathbf{r}_1-\mathbf{r}_2)\frac{\hbar\omega}{\exp\left(\hbar\omega/k_B T\right)-1}$$

Black body radiation close to a nanoparticle



$$\mathbf{E}_p = \frac{k_0^2}{4\pi\epsilon_0}\frac{e^{ik_0 r}}{r}\left[(\mathrm{I}-\mathrm{uu}) + \left(\frac{i}{k_0 r} - \frac{1}{(k_0 r)^2}\right)(\mathrm{I}-3\mathrm{uu})\right]\mathrm{p}$$

$$\left\langle p_m(\mathbf{r}_1)\, p_n^*(\mathbf{r}_2)\right\rangle = \frac{2}{\pi\omega}\varepsilon_o \,\mathrm{Im}\left[\alpha(\omega)\right]\delta_{mn}\,\delta(\mathbf{r}_1-\mathbf{r}_2)\frac{\hbar\omega}{\exp\left(\hbar\omega/k_B T\right)-1}$$

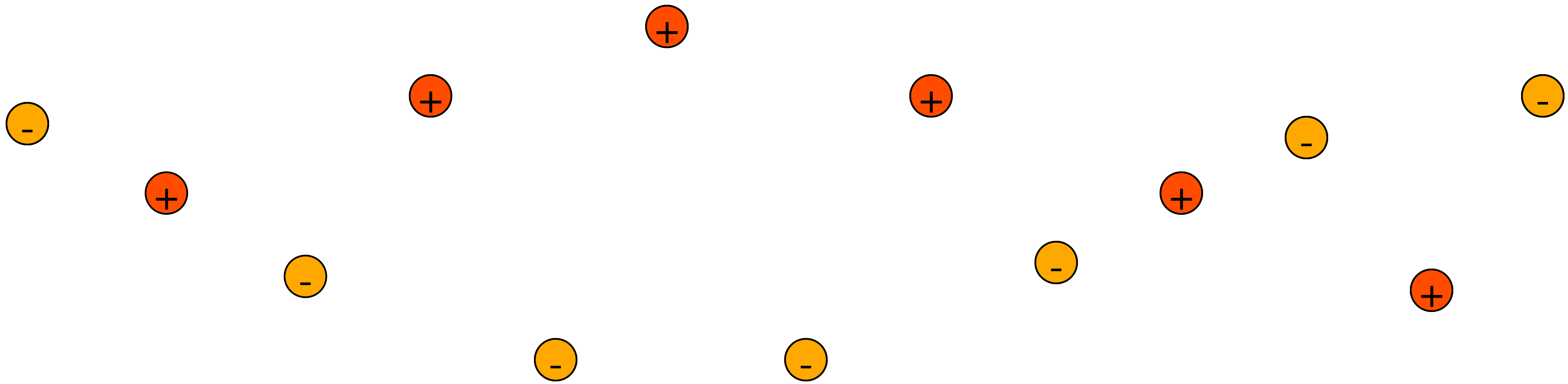
1. The particle is a random dipole.
2. The field increases close to the particle: electrostatic field !
3. The field may have a resonance, plasmon resonance.

Where are these (virtual) modes coming from ?

Polaritons

Strong coupling between material modes and photons produces

polaritons: Half a photon and half a phonon/exciton/electron.



Where are the modes coming from ?

Estimation of the number of electromagnetic modes in vacuum:

$$\frac{N}{V} = \int_0^{\omega} g(\omega')d\omega' = \frac{\omega^3}{3\pi^2 c^3} \qquad N \approx \frac{V}{\lambda^3}$$

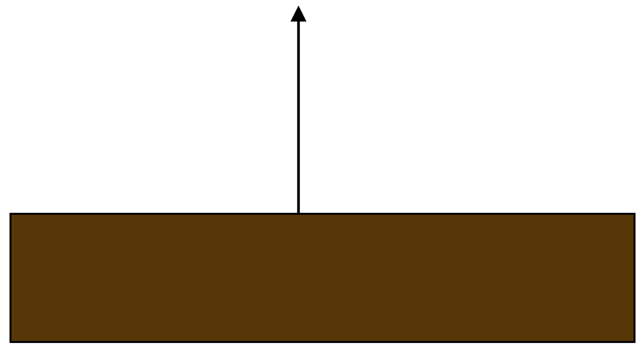
Estimation of the number of vibrational modes (phonons):

$$N \approx \frac{V}{a^3}$$

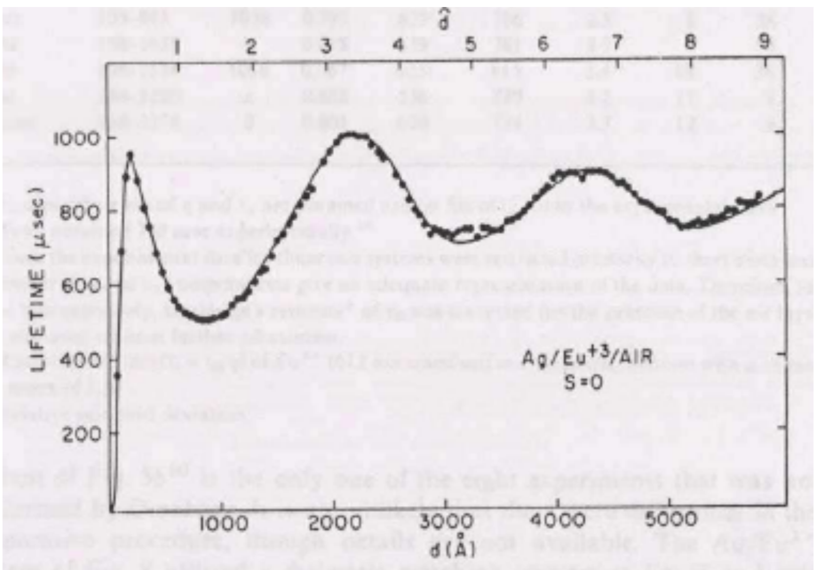
The electromagnetic field inherits the DOS of matter degrees of freedom

Can we define a (larger and local) *electromagnetic* density of states close to a particle or a surface ?

Local density of states close to an interface



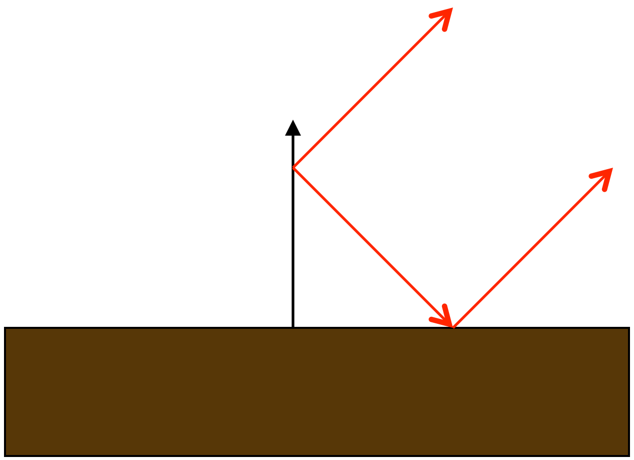
Lifetime of Europium 3+ above a silver mirror



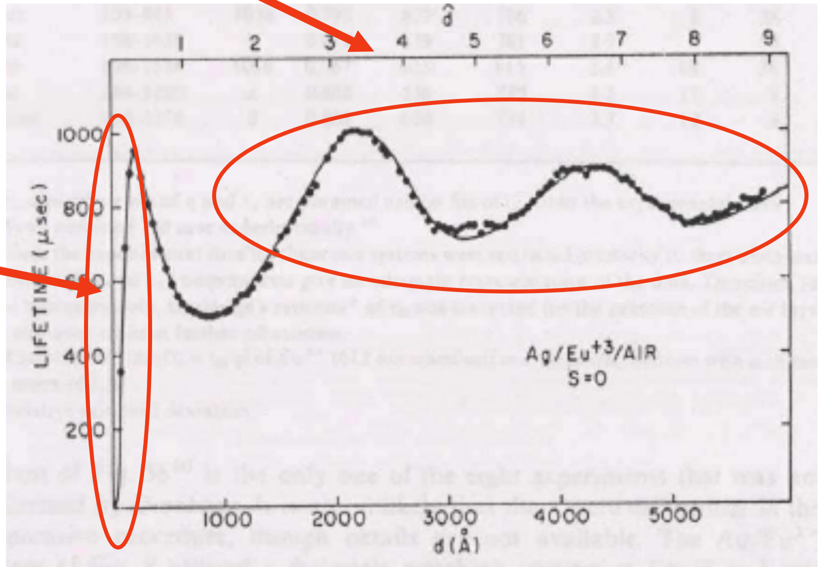
Drexhage, 1970

Electrical Engineering point of view

- Interference effects
- (microcavity type)



Near-field contribution

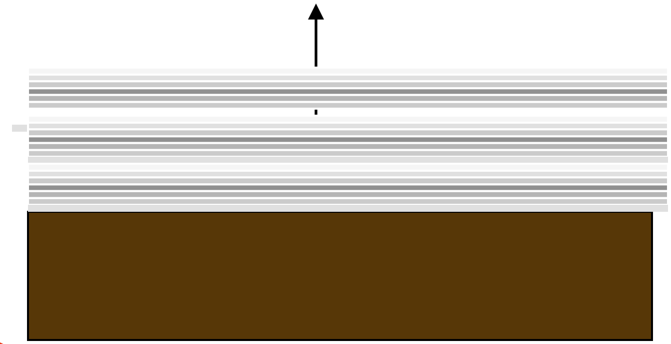


Drexhage, 1970

Quantum optics point of view:

LDOS above a surface

- Interference effects
- (microcavity type)



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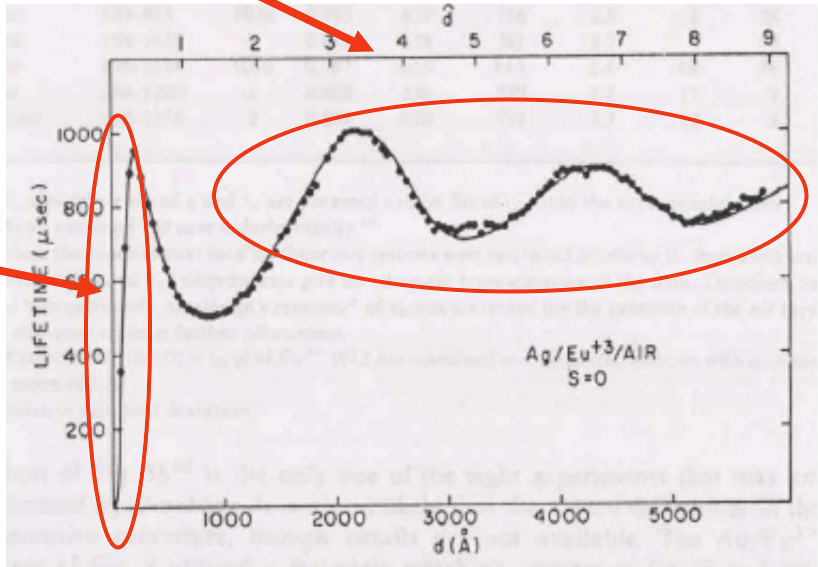
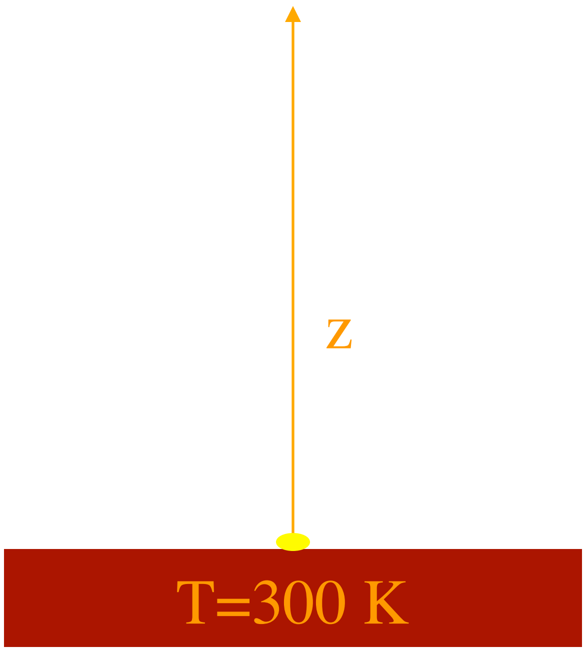
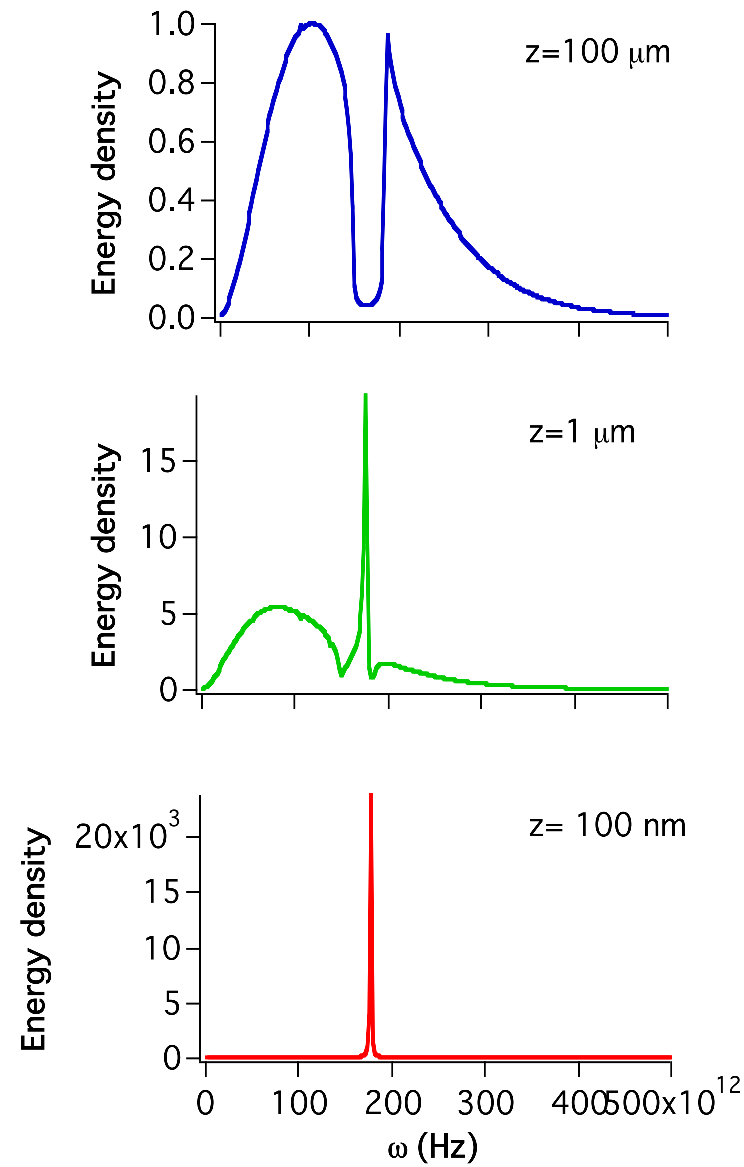


Drexhage, 1970

Energy density above a SiC surface

Density of energy near a SiC-vacuum interface





Energy density close to surfaces is orders of magnitude larger than blackbody energy density and monochromatic.

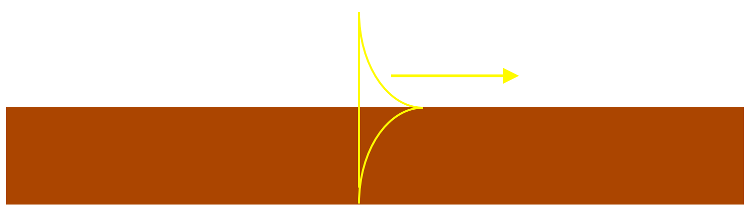
PRL, ***85*** *p 1548 (2000)*

Alternative explanation in k-space: mode analysis of the LDOS

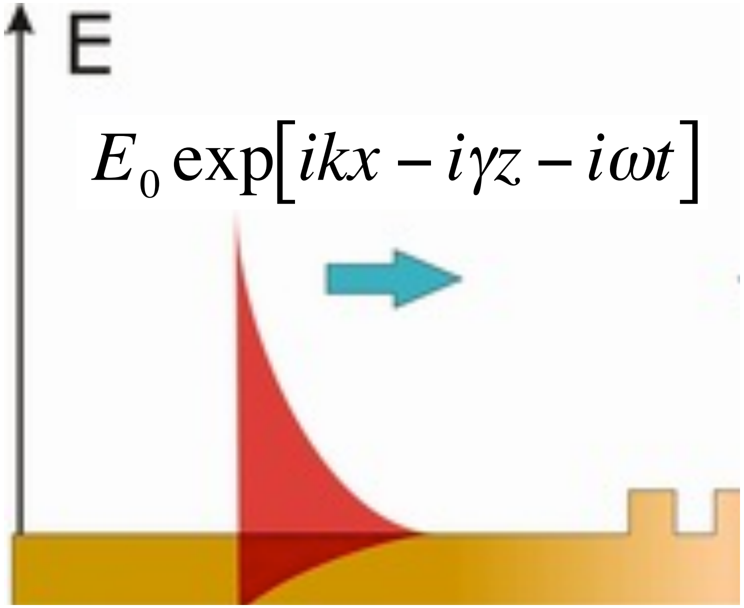
The density of energy is the product of

- the density of states,
- the energy $h\nu$
- the Bose Einstein distribution.

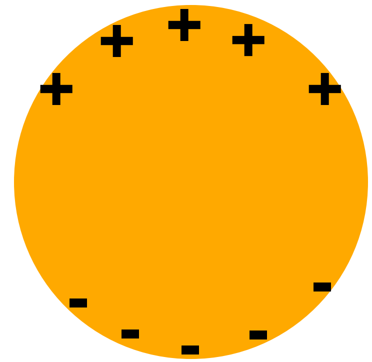
The density of states can diverge due to the presence of surface waves : Surface phonon-polaritons.



What is a surface plasmon ?



$$E_0 \exp\left[ikx - i\gamma z - i\omega t\right]$$



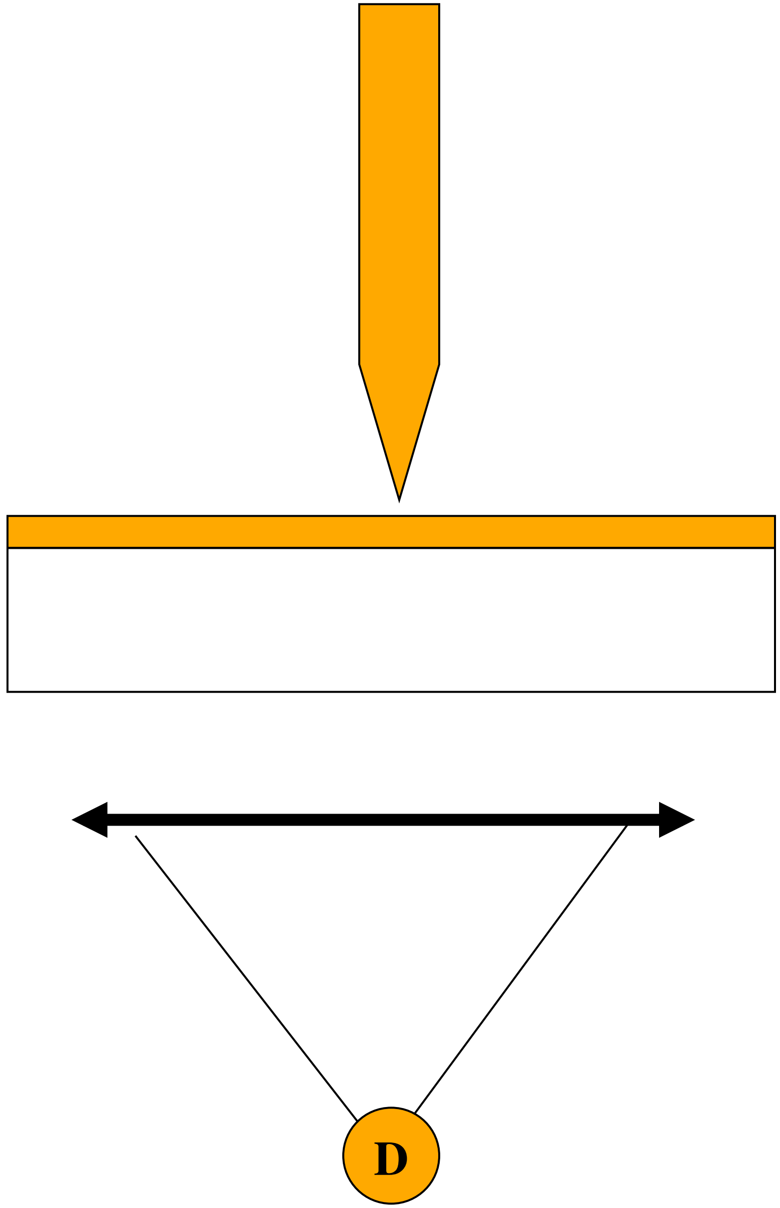
$$r_F = \frac{\varepsilon_2 k_{z1} - \varepsilon_1 k_{z2}}{\varepsilon_2 k_{z1} + \varepsilon_1 k_{z2}}$$

$$\alpha = 4\pi a^3 \frac{\varepsilon_m(\omega) - 1}{\varepsilon_m(\omega) + 2}$$

$$\varepsilon_2 k_{z1} + \varepsilon_1 k_{z2} = 0$$

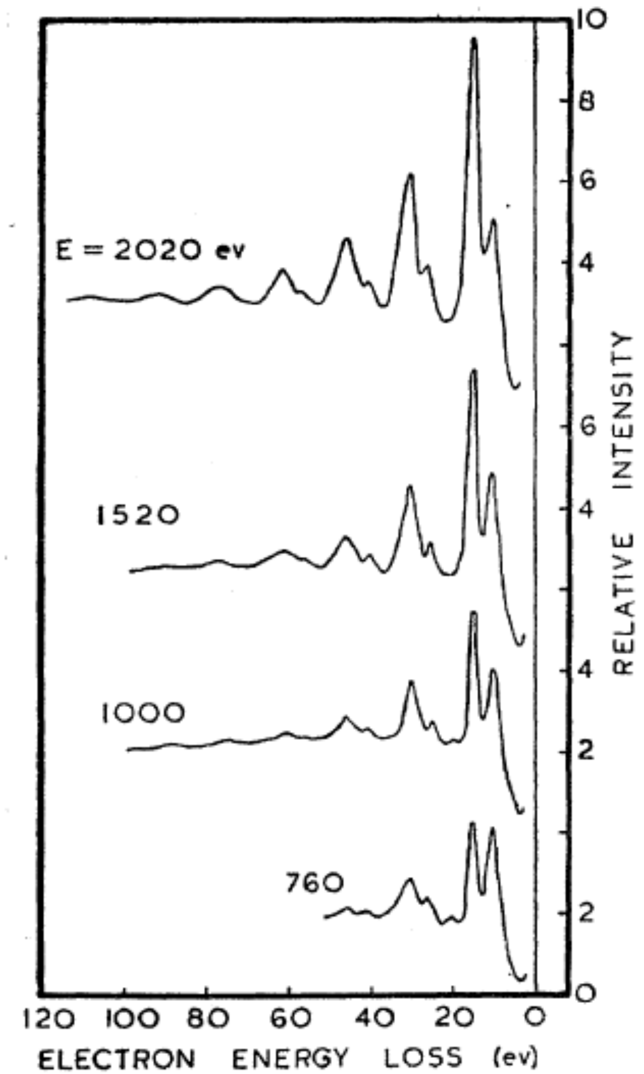
$$\varepsilon_m(\omega) + 2 = 0$$

Exciting a plasmon with a small aperture



Credit: Alexandre Bouhelier, D. Pohl

Surface plasmons

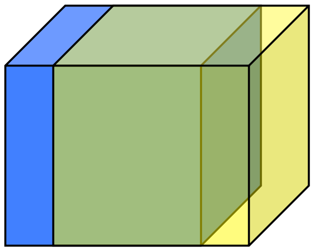


Phys Rev 115, p 869 (1959)

Qualitative introduction

Exemple : thin metallic film

collective oscillation of the electrons



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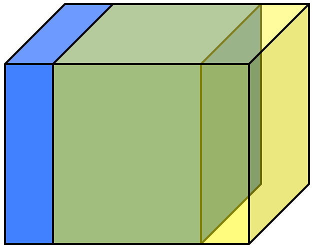
collective oscillation of the electrons



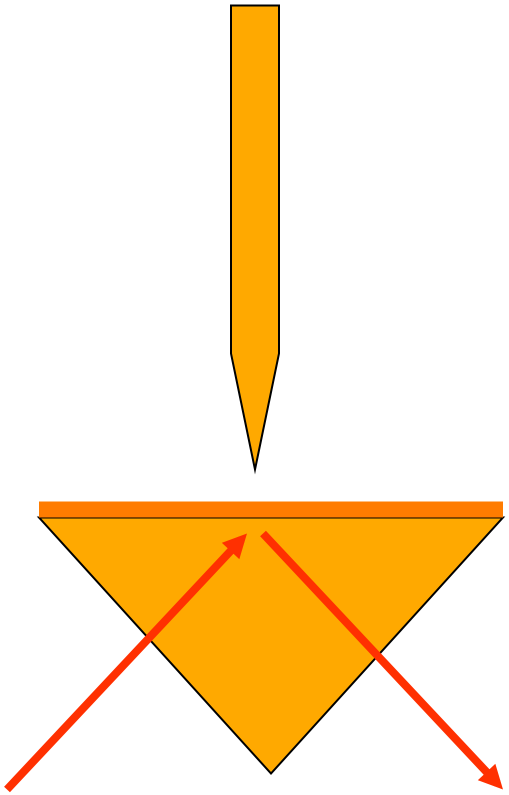
$$\omega_p^2 = \frac{ne^2}{m\varepsilon_0}$$

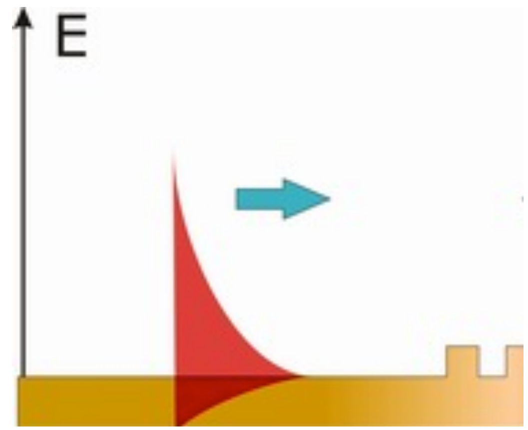
$$m\ddot{x} = -eE - \gamma m\dot{x} = -n\frac{e^2}{\varepsilon_0}x - \gamma m\dot{x}$$

Length scales (gold/vacuum)

λ_i (μm)	0.633	1	10	36
δ_x (μm)	9.8	91.6	38 880	504 243
δ_{z1} (μm)	0.165	0.51	57.3	702.67
δ_{z2} (μm)	0.014	0.012	0.011	0.013

First picture of a surface plasmon



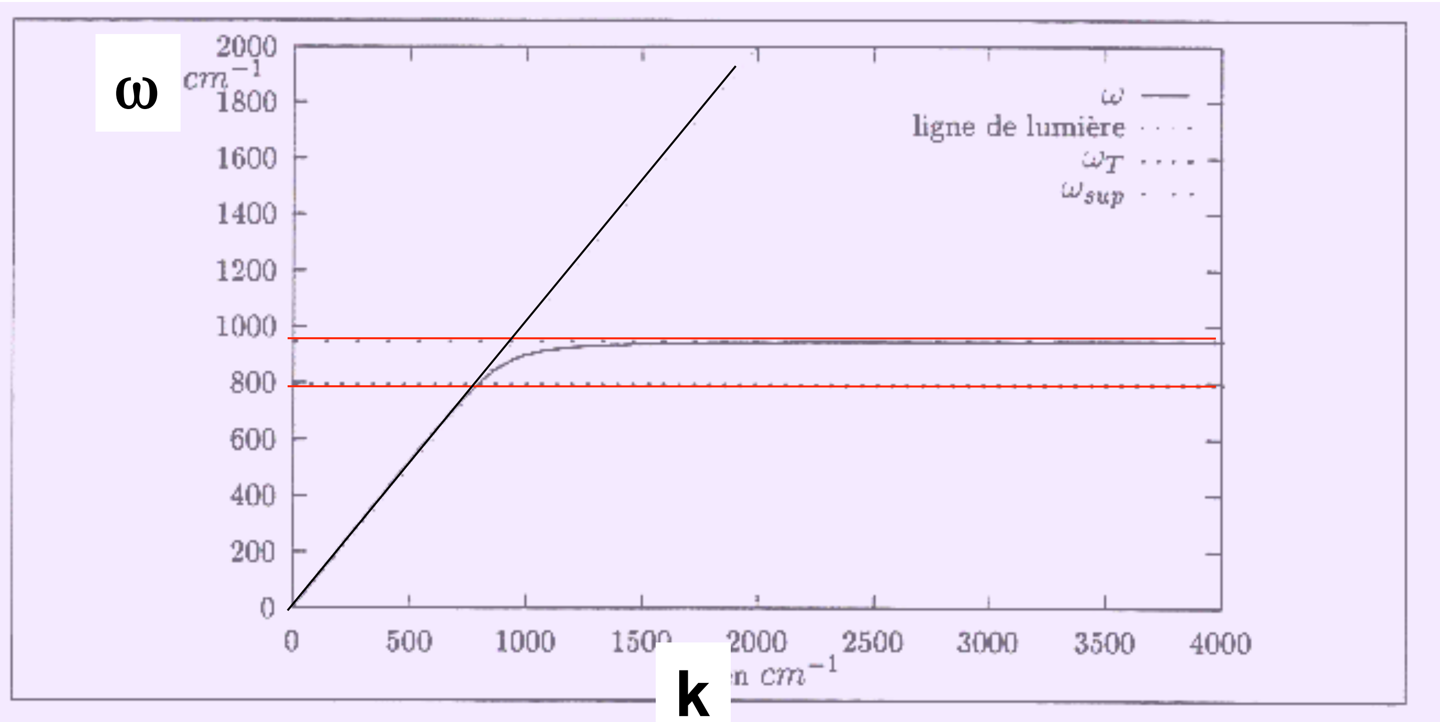


$$E_x \exp[ikx - i\gamma z - i\omega t]$$

Dawson, Phys.Rev.Lett.

Dispersion relation of a surface phonon-polariton

$$k = \frac{\omega}{c}\sqrt{\frac{\varepsilon(\omega)}{\varepsilon(\omega)+1}}$$



It is seen that the number of modes diverges for a particular frequency.

PRB, ***55*** *p 10105 (1997)*

LDOS in near field above a surface

$$U(\mathbf{r},\omega) = \rho(\mathbf{r},\omega)\frac{\hbar\omega}{\exp\left(\hbar\omega/k_{\mathrm{B}}T\right) - 1}.$$

$$U(\mathbf{r},\omega)=4\Bigg((\epsilon_0/2)\sum_{i=1,3}\mathcal{E}_{ii}(\mathbf{r},\mathbf{r},\omega) + (\mu_0/2)\sum_{i=1,3}\mathcal{H}_{ii}(\mathbf{r},\mathbf{r},\omega)\Bigg)$$

LDOS is also used to deal with spontaneous emission using Fermi golden rule

Joulain et al., Surf Sci Rep. **57**, 59 (2005), Phys.Rev.B **68**, 245405 (2003)

LDOS in the presence of losses

$$U(\mathbf{r},\omega)=4\left((\epsilon_0/2)\sum_{i=1,3}\mathcal{E}_{ii}(\mathbf{r},\mathbf{r},\omega)\right.$$

$$\left.+(\mu_0/2)\sum_{i=1,3}\mathcal{H}_{ii}(\mathbf{r},\mathbf{r},\omega)\right)$$

$$\mathcal{E}_{ij}(\mathbf{r},\mathbf{r}',t-t')=\frac{1}{2\pi}\int d\omega\,\mathcal{E}_{ij}(\mathbf{r},\mathbf{r}',\omega)e^{-i\omega(t-t')}$$

$$=\langle E_i(\mathbf{r},t)E_j^*(\mathbf{r}',t')\rangle,$$

$$\mathcal{H}_{ij}(\mathbf{r},\mathbf{r}',t-t')=\frac{1}{2\pi}\int d\omega\,\mathcal{H}_{ij}(\mathbf{r},\mathbf{r}',\omega)e^{-i\omega(t-t')}$$

$$=\langle H_i(\mathbf{r},t)H_j^*(\mathbf{r}',t')\rangle.$$

Joulain et al., PRB 68, 245405 (2003)

LDOS in the presence of losses

Problem: deriving the correlation function of the fields

Solution: FD theorem

Green tensor is (also) a linear response coefficient !

$$\mathbf{E}(\mathbf{r},\omega) = i\mu_0\omega \int \overleftrightarrow{\mathbf{G}}^E(\mathbf{r},\mathbf{r}',\omega)\cdot\mathbf{j}(\mathbf{r}')d^3\mathbf{r}'$$

Generalized response **Generalized force**

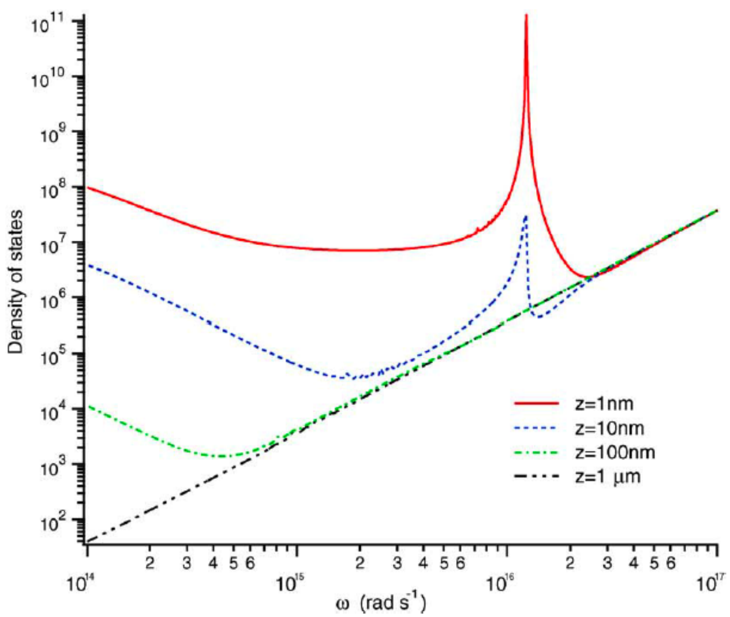
$$\mathcal{E}_{ij}(\mathbf{r},\mathbf{r}',\omega) = \frac{\hbar\omega}{[\exp(\hbar\omega/k_B T)-1]}\frac{\mu_0\omega}{2\pi}\mathrm{Im}\, G^E_{ij}(\mathbf{r},\mathbf{r}',\omega)$$

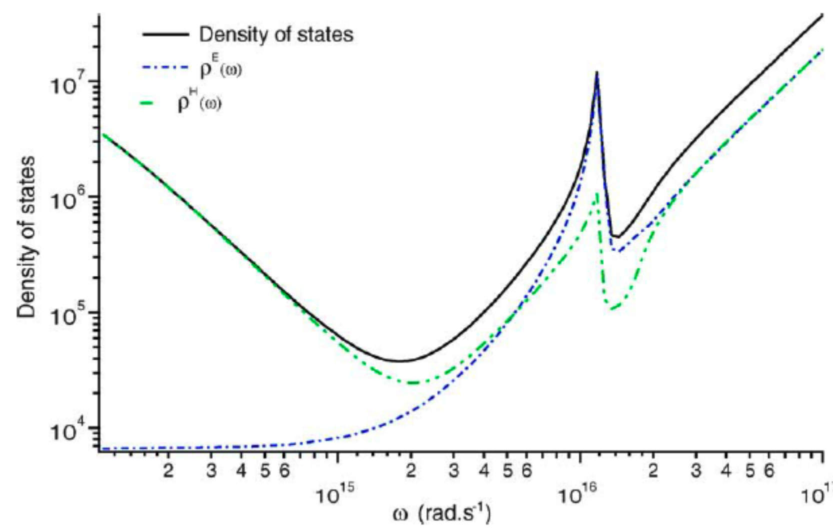
Joulain et al., PRB 68, 245405 (2003)

LDOS in the near field above a surface

$$\rho(\mathbf{r},\omega)=\frac{\omega}{\pi c^2}\mathrm{Im}\ \mathrm{Tr}\left[\overleftrightarrow{\mathbf{G}}^{EE}(\mathbf{r},\mathbf{r},\omega)+\overleftrightarrow{\mathbf{G}}^{HH}(\mathbf{r},\mathbf{r},\omega)\right]=\rho^E(\mathbf{r},\omega)+\rho^H(\mathbf{r},\omega).$$

This can be computed close to an interface !





Joulain et al., Surf Sci Rep. **57**, 59 (2005), Phys.Rev.B **68**, 245405 (2003)

LDOS *in the near field* above a surface

$$U(\mathbf{r},\omega) = \rho(\mathbf{r},\omega)\frac{\hbar\omega}{\exp\left(\hbar\omega/k_{\mathrm{B}}T\right)-1}.$$

$$\rho^E(z,\omega) = \frac{\rho_{\mathrm{v}}}{|\varepsilon_2+1|^2}\frac{\varepsilon_2''}{4k_0^3z^3},$$

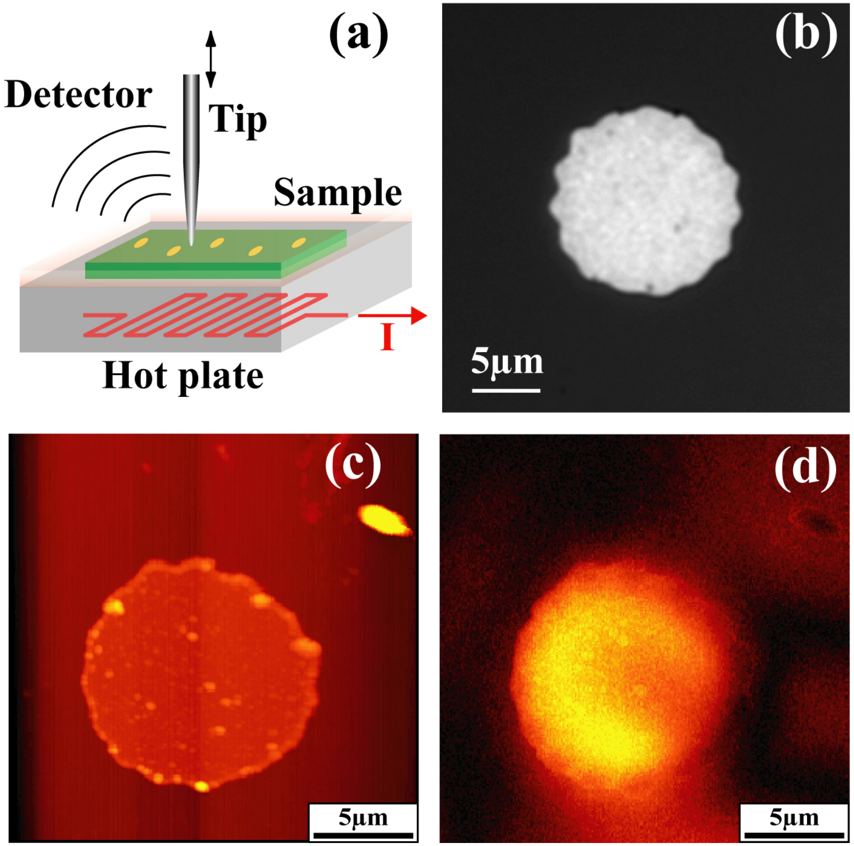
$$\rho^H(z,\omega) = \rho_{\mathrm{v}}\left[\frac{\varepsilon_2''}{8k_0z}+\frac{\varepsilon_2''}{2|\varepsilon_2+1|^2k_0z}\right].$$

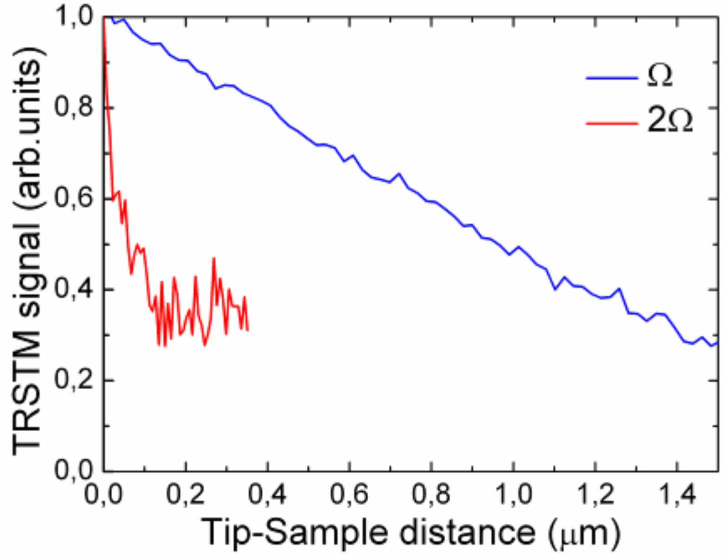
Plasmon resonance

Electrostatic enhancement

Experimental evidence of thermally excited near fields

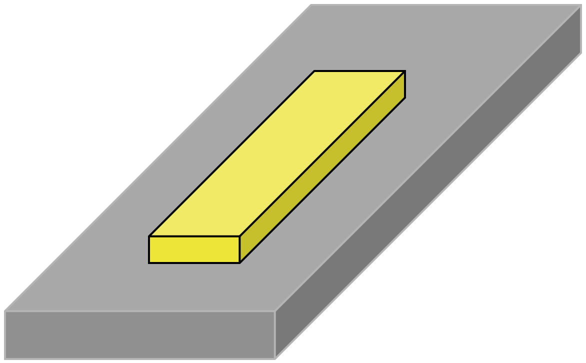
Direct experimental evidence

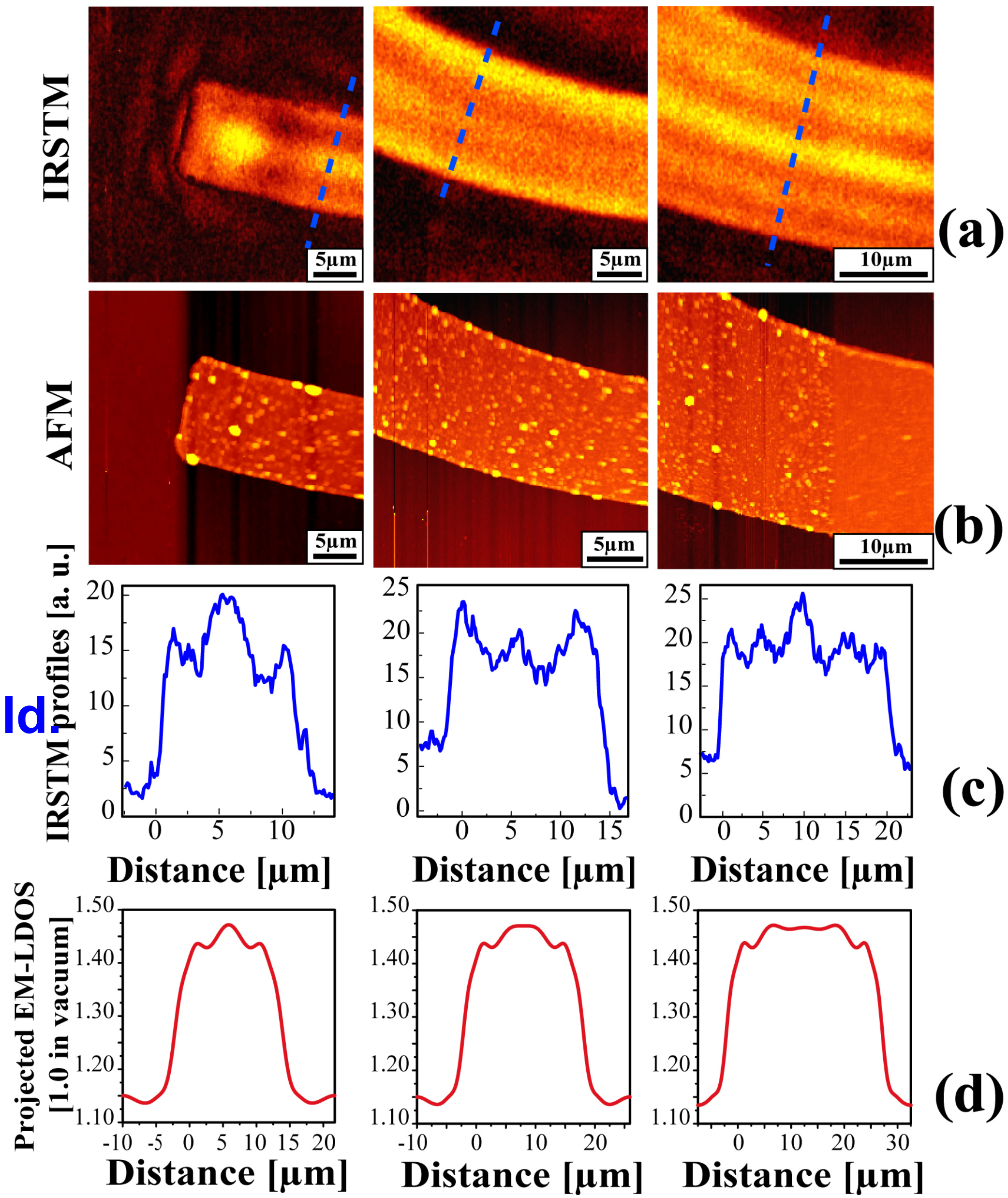




de Wilde et al. Nature ***444****, p 740 (2006)*

Imaging the LDOS of surface plasmons

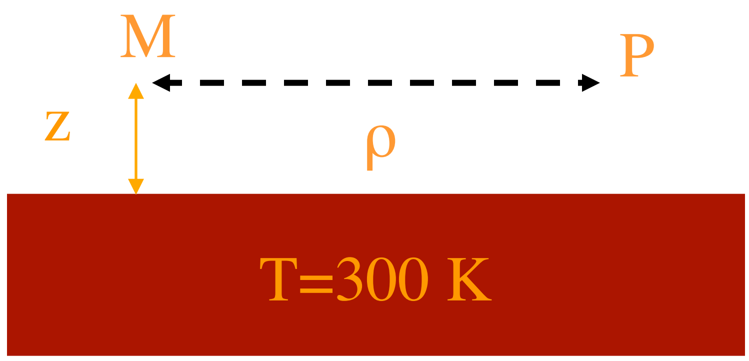


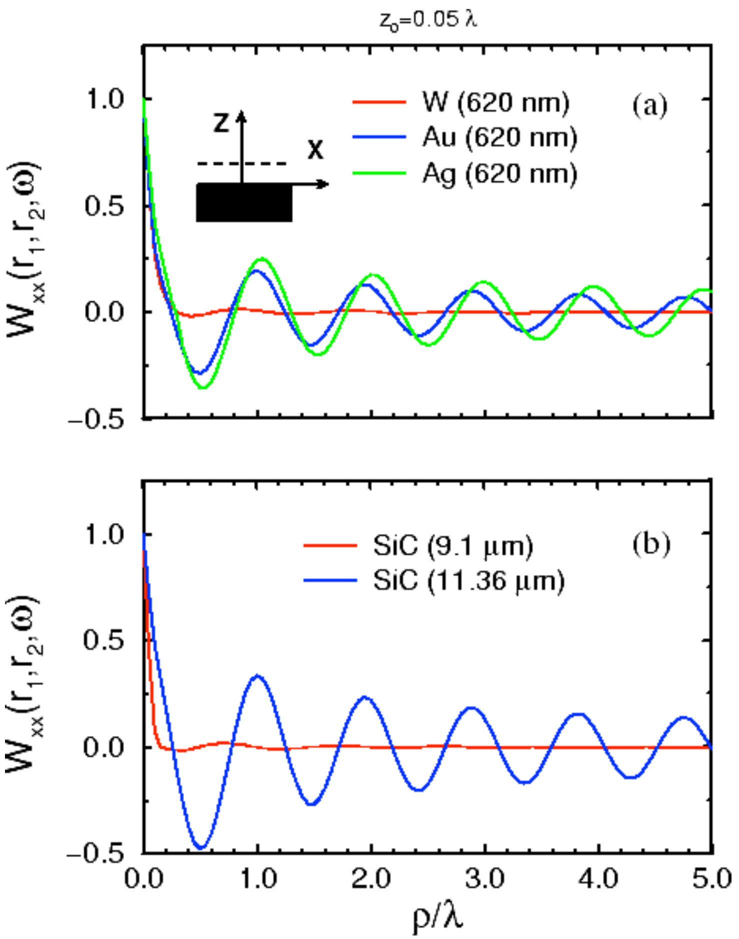


Thermally excited fields can be spatially coherent in the near field.

de Wilde et al. Nature (2006)

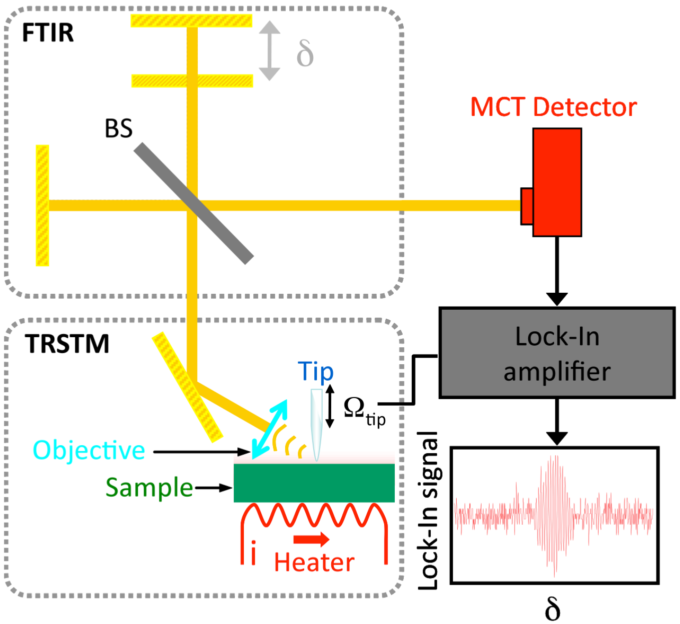
Spatial coherence of thermal radiation

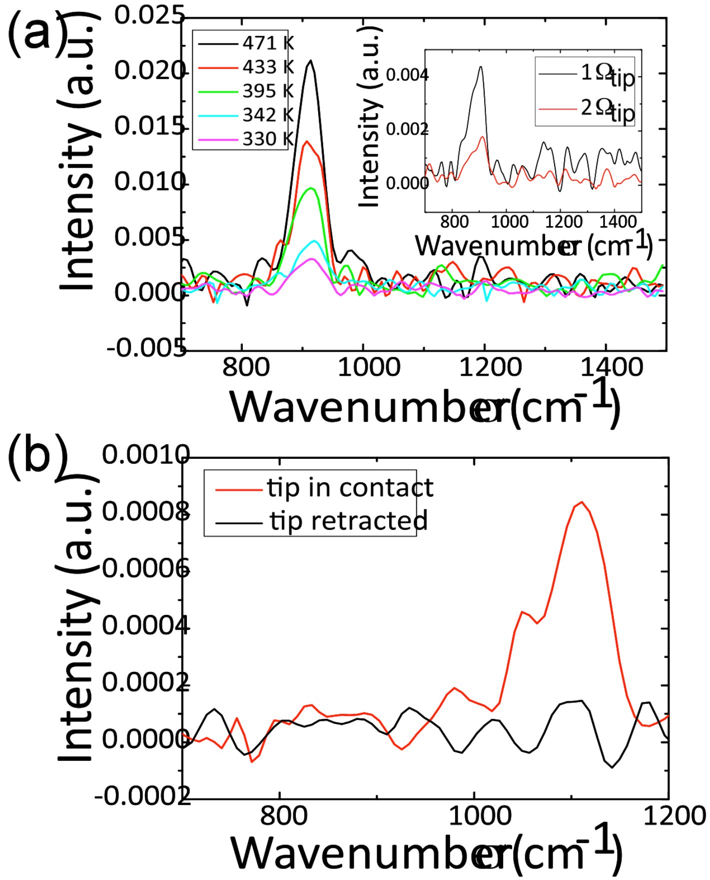




PRL **82**, 1660 (1999)

Spectrum of the thermal near field



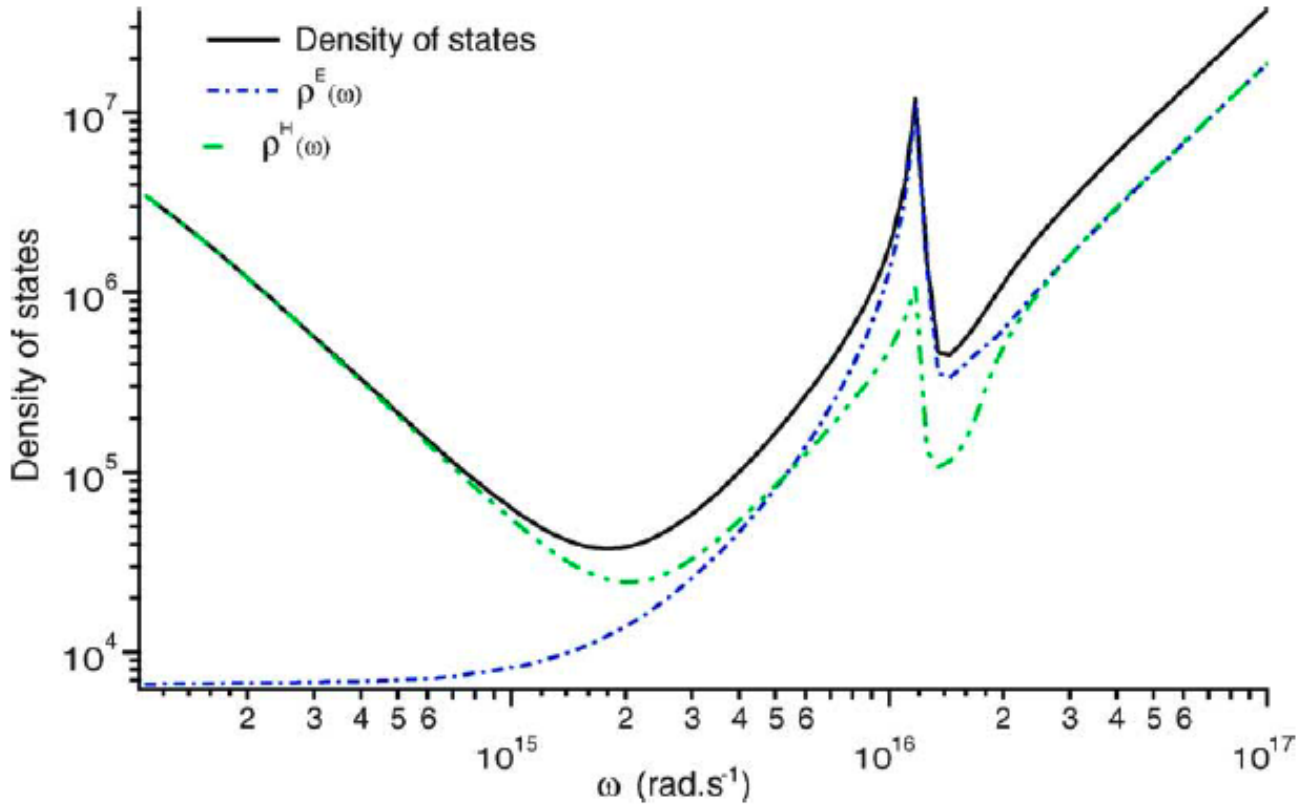


*Babuty et al. PRL **110**, 146103 (2013)*

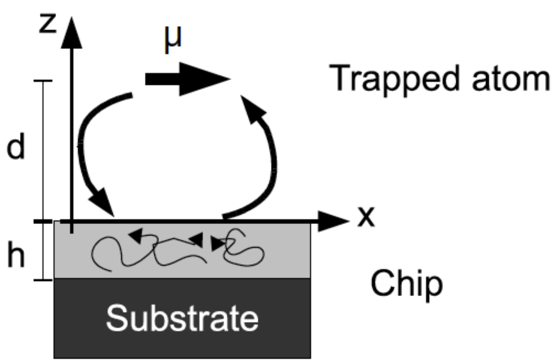
LDOS above a metallic surface

$$\rho^E(z,\omega) = \frac{\rho_v}{|\varepsilon_2 + 1|^2} \frac{\varepsilon_2''}{4k_0^3 z^3},$$

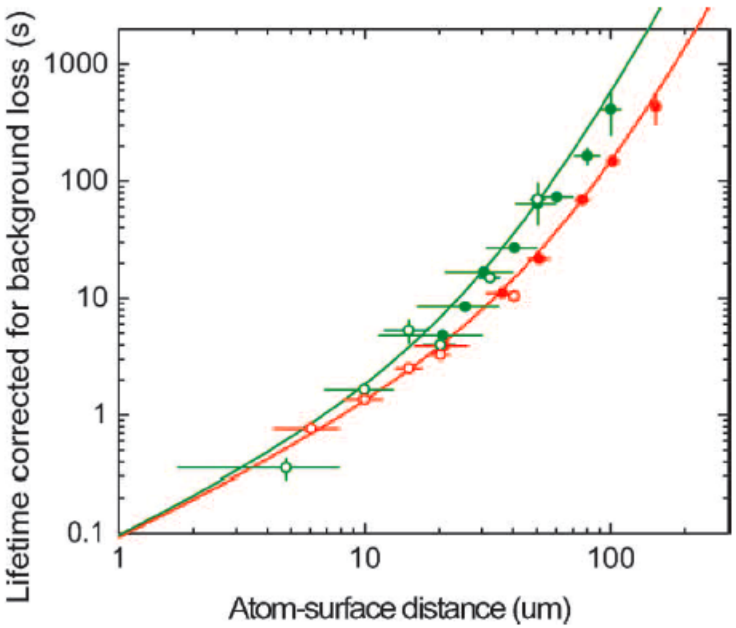
$$\rho^H(z,\omega) = \rho_v \left[\frac{\varepsilon_2''}{8k_0 z} + \frac{\varepsilon_2''}{2|\varepsilon_2 + 1|^2 k_0 z} \right].$$



Lifetime of an atom in a magnetic trap



Superconducting niobium



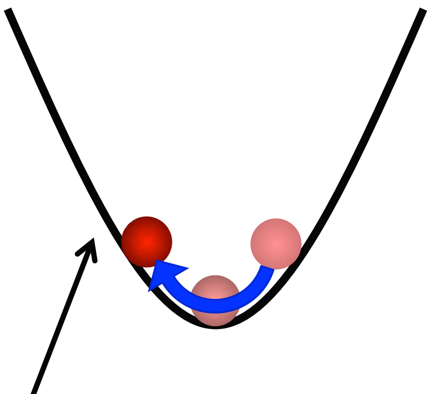
Copper 1.8 and 6.24 MHz

Lifetime in a magnetic trap versus distance to surface.

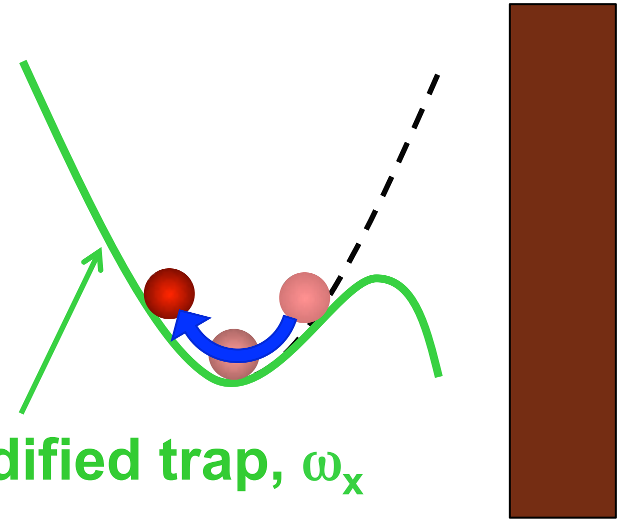
Thermal blackbody is increased by ten orders of magnitude.

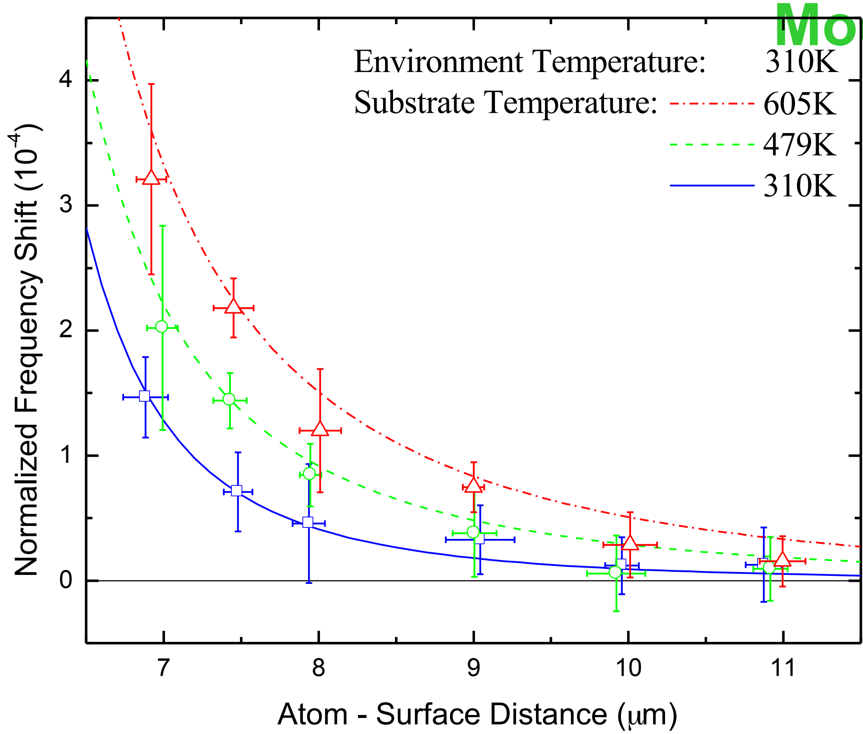
*D. Harber et al., J.Low Temp.Phys. **133**, 229 (2003);*
*C. Henkel et al. Appl.Phys.B **69**, 379 (1999)*
*C. Roux et al., EPL **87**, 13002, (2009)*

Casimir-Polder force measurement



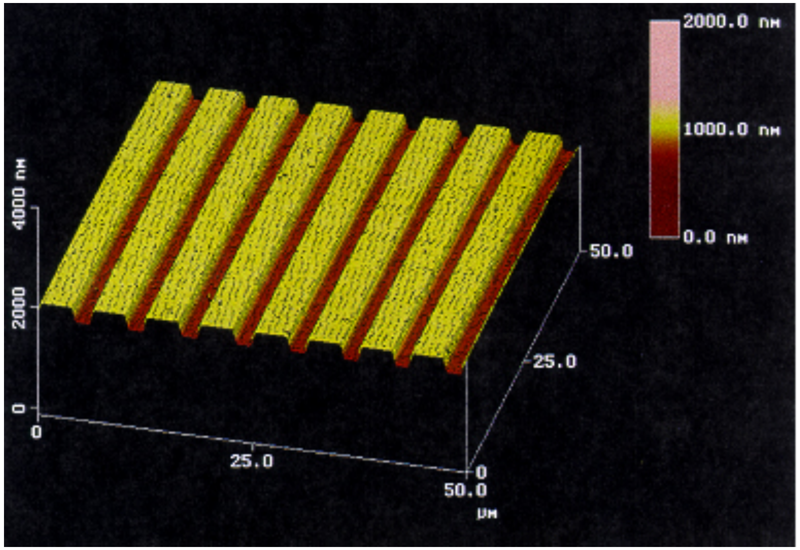
Move near the surface

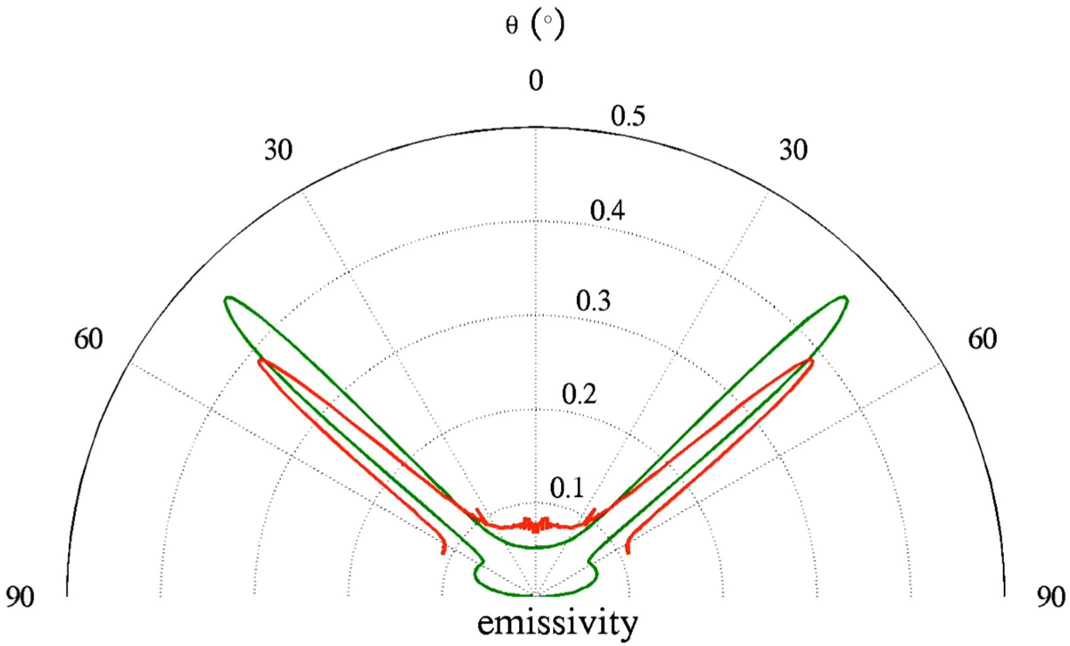




J.Obrecht et al. , Phys.Rev.Lett. 98, 063201 (2007)

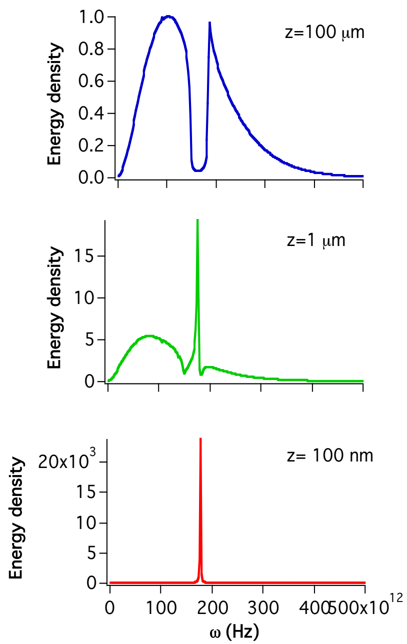
Proof of spatial coherence of thermal radiation

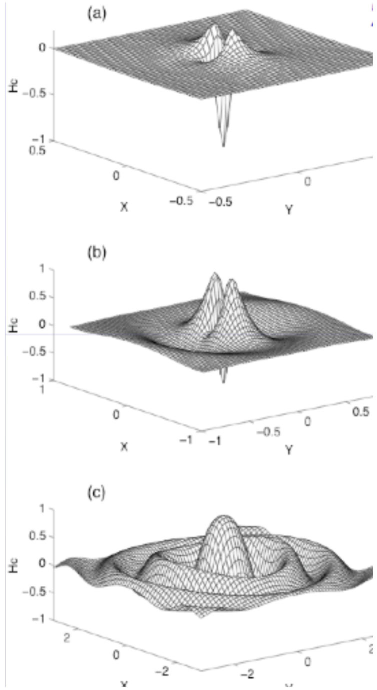


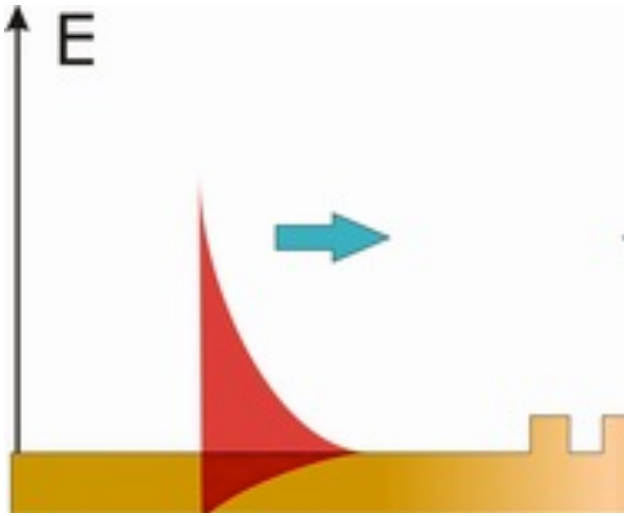


*Greffet, Nature **416**, 61 (2002)*

Take Home messages







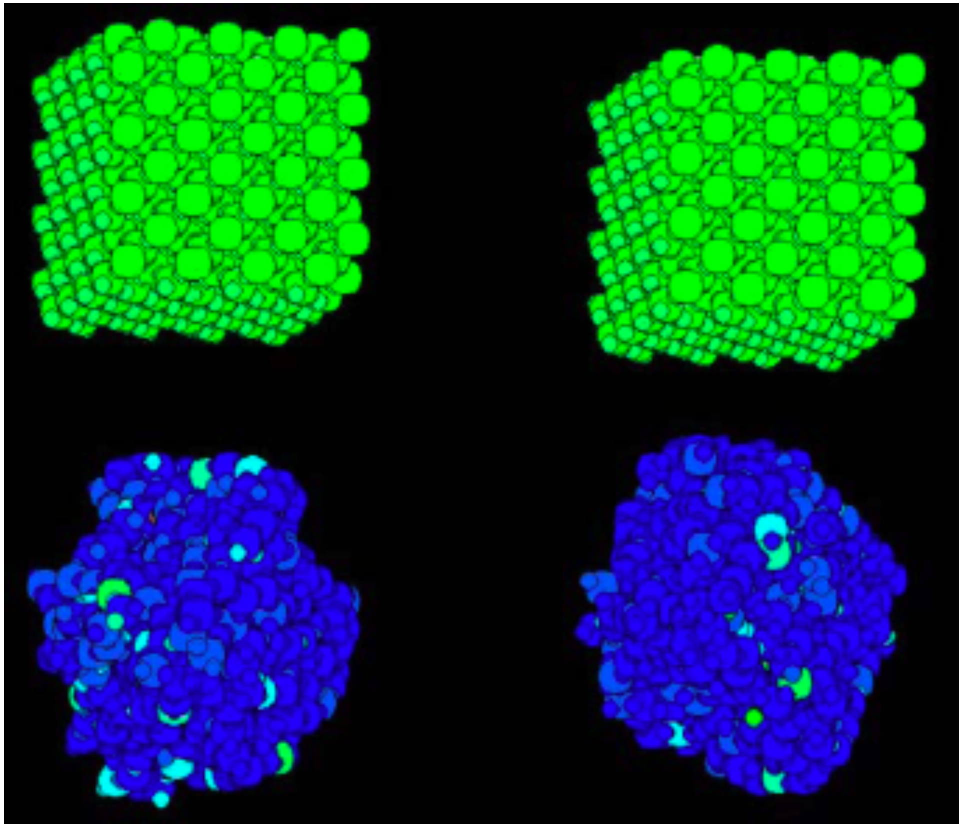
$$\rho(\mathbf{r},\omega) = \frac{\omega}{\pi c^2}\,\mathrm{Im}\ \mathrm{Tr}\left[\overset{\leftrightarrow}{\mathbf{G}}^{EE}(\mathbf{r},\mathbf{r},\omega) + \overset{\leftrightarrow}{\mathbf{G}}^{HH}(\mathbf{r},\mathbf{r},\omega)\right]$$

Second Lecture

Radiative heat transfer at the nanoscale

Heat transfer between two nanoparticles

Heat transfer between two nanoparticles



PRL ***94****, 85901, (2005)*

Heat transfer between two nanoparticles

Heat conductance

$$\frac{Q_{12}(\omega)}{T_0} = G_{12}^*(\omega)\Delta T(\omega),$$

Fluctuations power spectral density

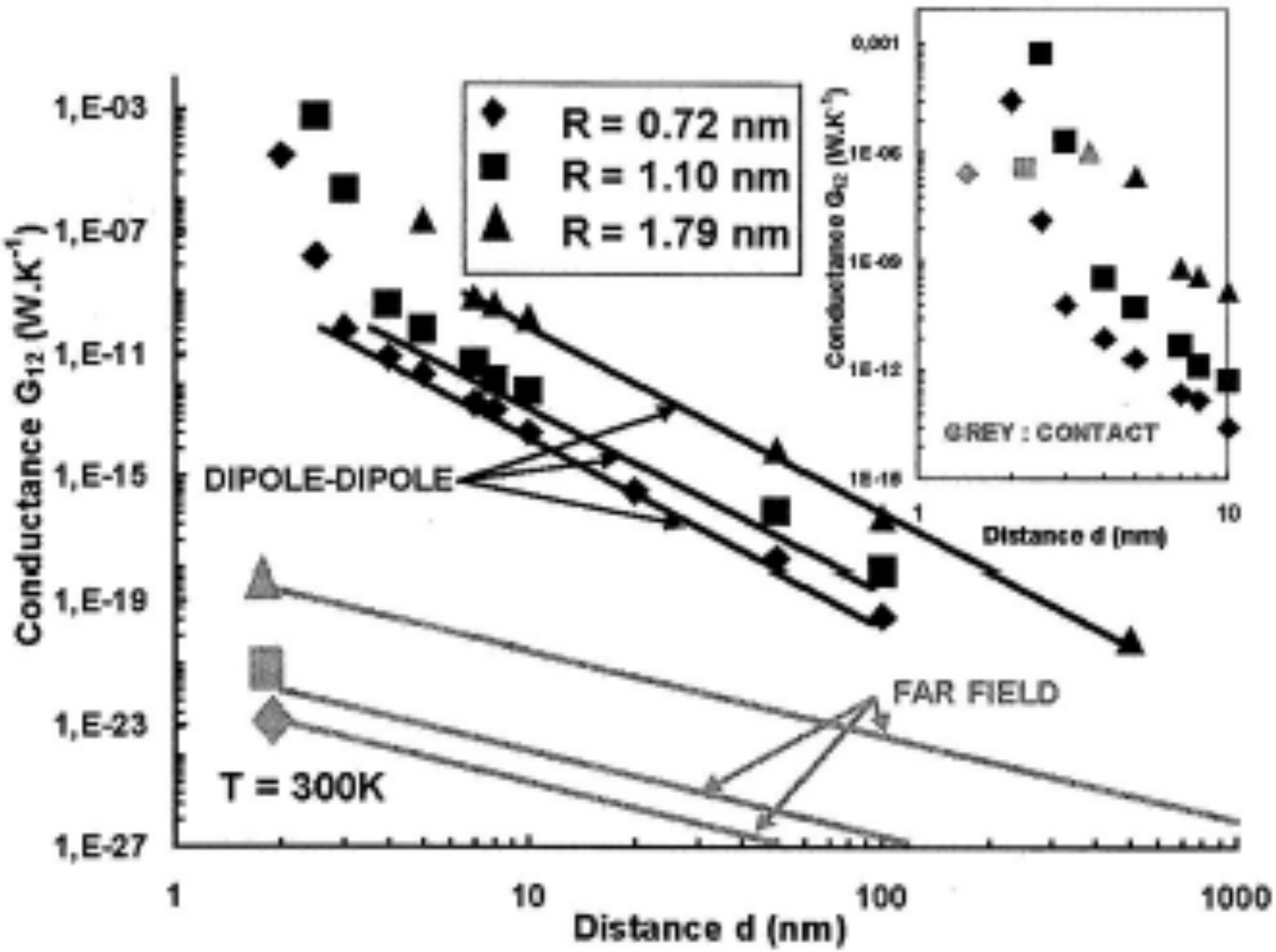
$$P_{\Delta T}(\omega) = \frac{P_{Q_{12}}(\omega)}{|G_{12}^* T_0|^2}.$$

Fluctuation-Dissipation theorem

$$P_{\Delta T}(\omega) = \frac{\mathrm{Re}(G_{12}^*)}{|G_{12}^*(\omega)|^2}\Theta(\omega, T_0),$$

$$Q_{12} = \sum_{\substack{i\in \mathrm{NP1}\\ j\in \mathrm{NP2}}} \mathbf{f}_{ij}\cdot \mathbf{v}_j - \sum_{\substack{i\in \mathrm{NP1}\\ j\in \mathrm{NP2}}} \mathbf{f}_{ji}\cdot \mathbf{v}_i.$$

*PRL **94**, 85901, (2005)*

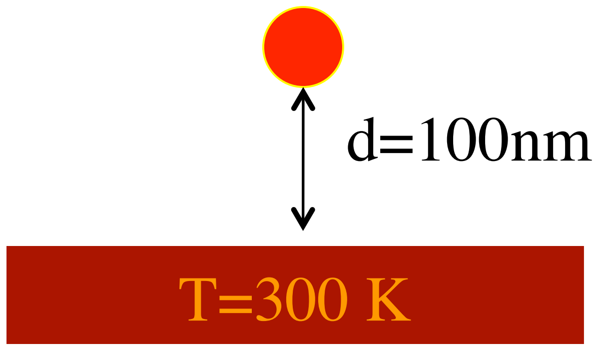


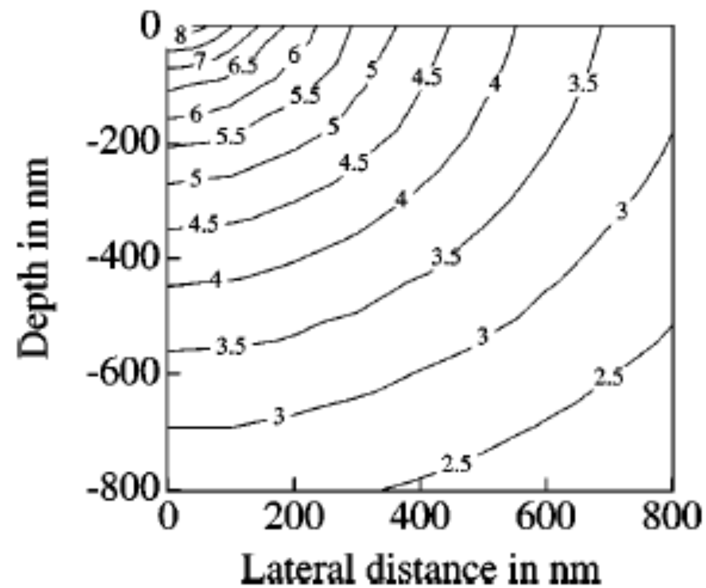
PRL ***94****, 85901, 2005*

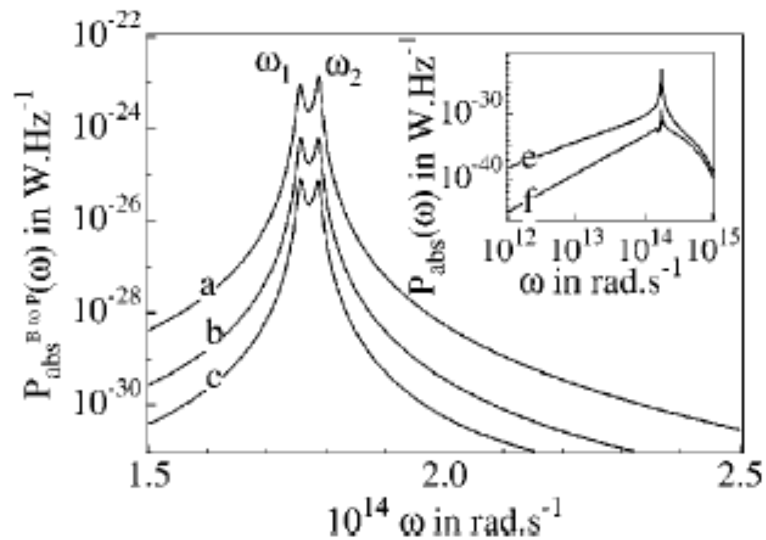
Heat transfer between a particle and a dielectric (SiC) surface

$$\varepsilon_B(\omega) = \varepsilon_P(\omega) = \varepsilon(\omega) = \varepsilon_\infty \left(1 + \frac{\omega_L^2 - \omega_T^2}{\omega_T^2 - \omega^2 - i\Gamma\omega} \right)$$

Energy transfer betwen a particle and a plane



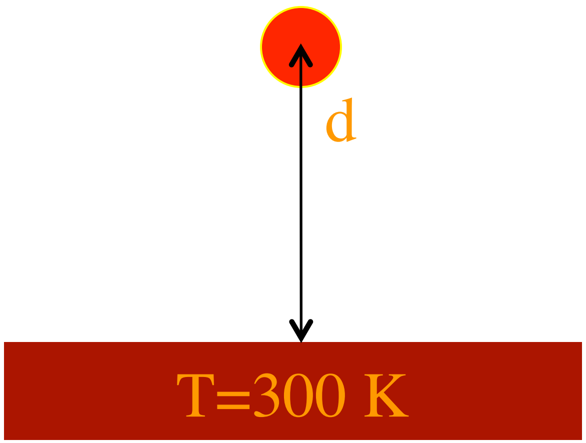




Take home message:
For source at distance d,
the power is dissipated within
a distance 2 d.

Mulet et al. Appl.Phys.Lett. 78, p 2931 (2001)

Energy transfer between a particle and a plane



Key feature 1

$$P_{\mathrm{abs}}^{B\to P}(d,\omega)\sim \frac{1}{4\pi^2 d^3}$$

$$\times \underbrace{4\pi a^3 \frac{3\varepsilon''(\omega)}{|\varepsilon(\omega)+2|^2}}_{\text{particle}} \underbrace{\frac{\varepsilon''(\omega)}{|\varepsilon(\omega)+1|^2}}_{\text{bulk}} \Theta(\omega,T_B).$$

Key feature 2

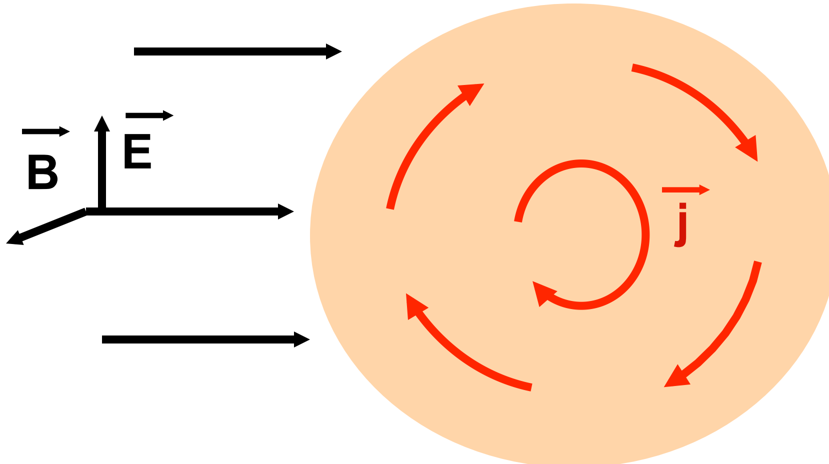
Microscopic resonance if ε(ω)+2=0

Take home message: The flux is dramatically enhanced by the surface waves resonances

Mulet et al. Appl.Phys.Lett. 78, p 2931 (2001)

Heat transfer between a particle and a metallic surface

Radiative heat transfer between a particle and a surface



The magnetic field induces eddy currents that produce Joule losses.

Losses are given by the product of two terms :

$$P_E = 2\omega \,\mathrm{Im}(\alpha_E)\frac{<\varepsilon_0 |\vec{E}|^2>}{2} + \boxed{2\omega \,\mathrm{Im}(\alpha_M)\frac{<|\vec{B}|^2>}{2\mu_0}}$$

Chapuis, Phys.Rev.B 125402, 2008

Radiative heat transfer between a particle and a surface

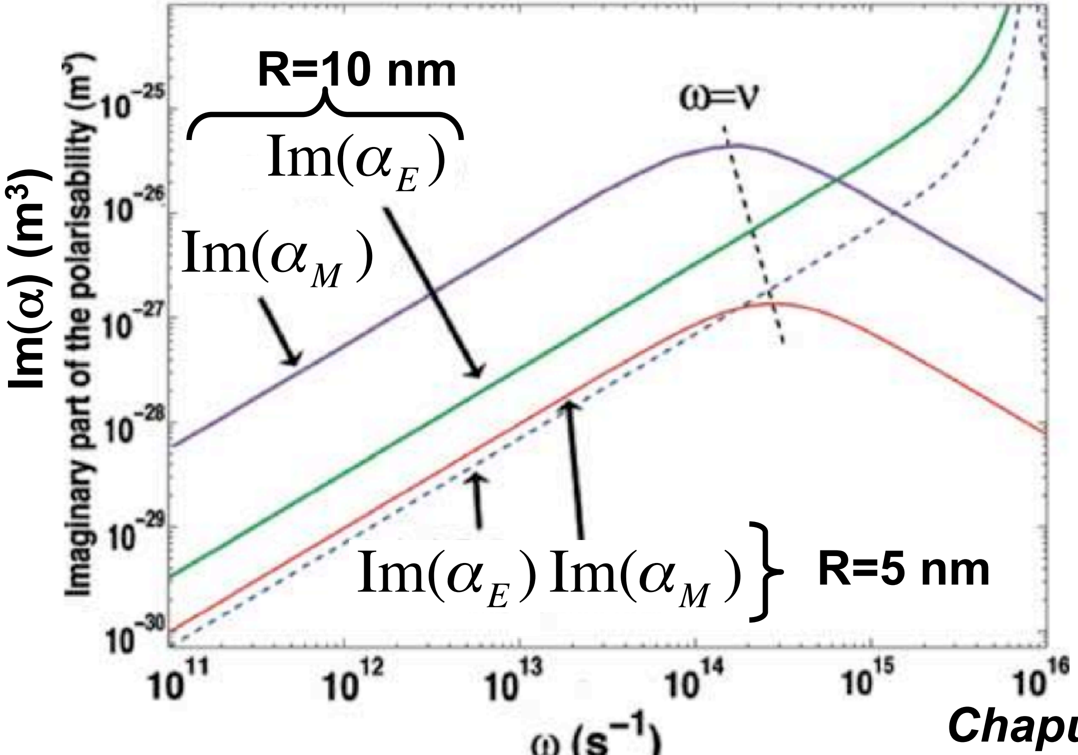
Magnetic losses versus electric losses

- Electric dipole $\longrightarrow$
- Magnetic polarisability

$|\alpha_M| << |\alpha_E|$ **for R → 0**

$$\alpha_E = 4\pi R^3 \frac{\varepsilon - 1}{\varepsilon + 2}$$

$$\alpha_M = \frac{2\pi}{15} R^3 \frac{R^2}{\lambda^2} (\varepsilon - 1)$$



$|\varepsilon| >> 1$

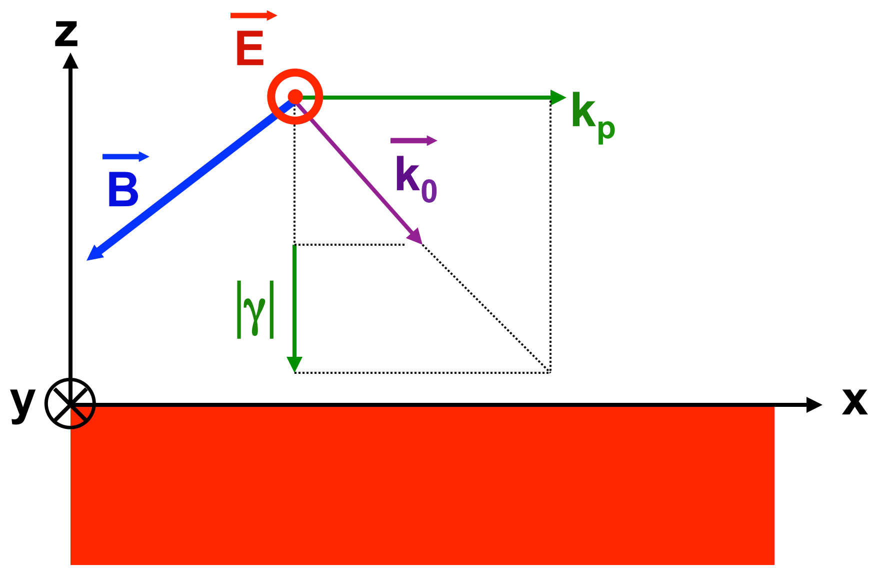
for a metal at low frequencies

Chapuis, Phys.Rev.B 125402, 2008

Radiative heat transfer between a particle and a surface

Electric and magnetic energy density above an interface :

an unusual property



s polarisation:magnetostatics

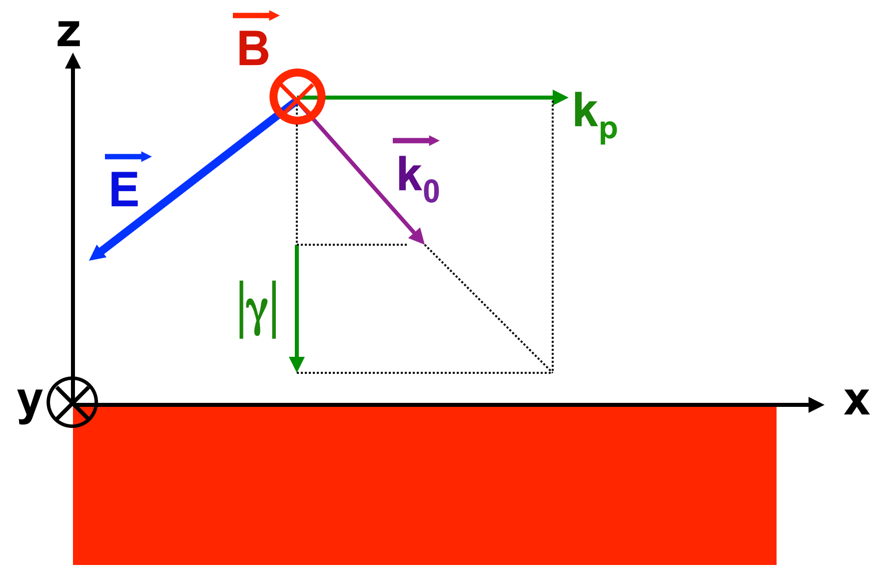
propagating

$$B = \frac{E}{c}$$

evanescent

$$B = \frac{E}{c}\sqrt{2\left(\frac{k_p}{k_0}\right)^2 - 1}$$

Magnetostatics



p polarisation: electrostatics

propagating

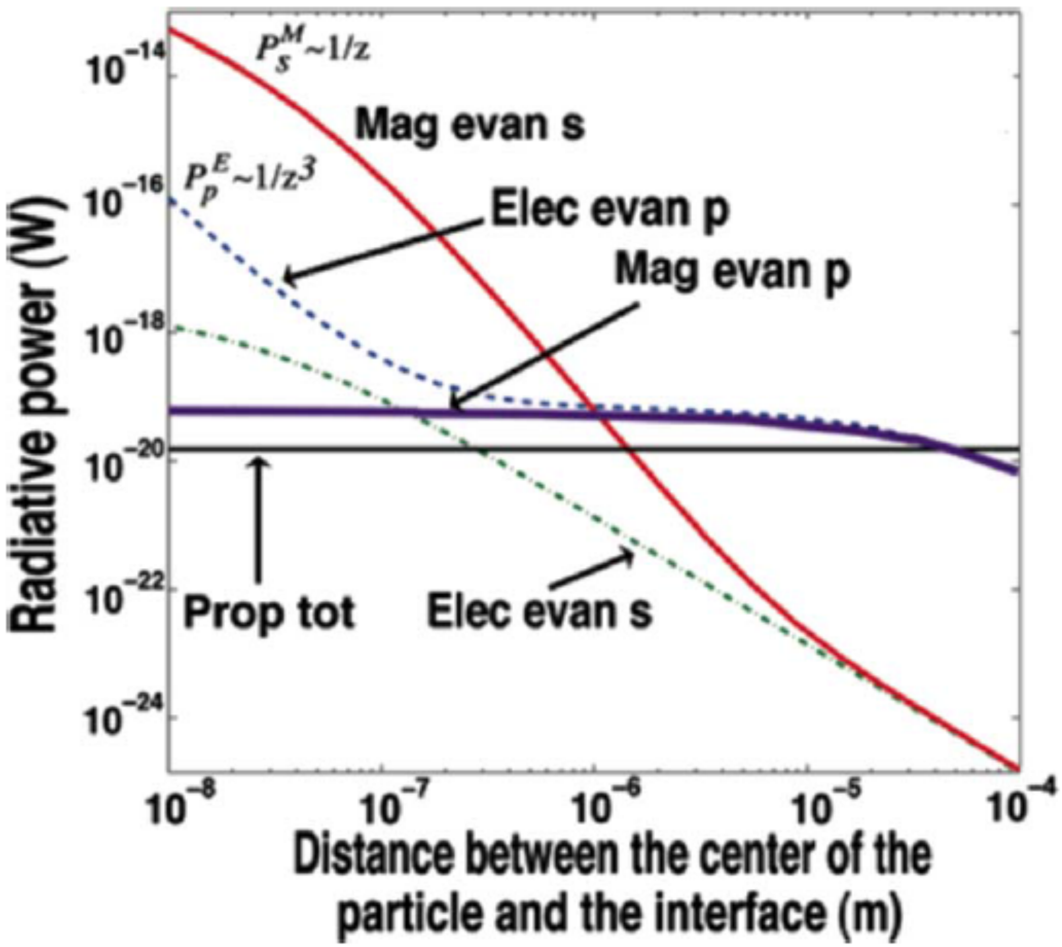
$$E = cB$$

evanescent

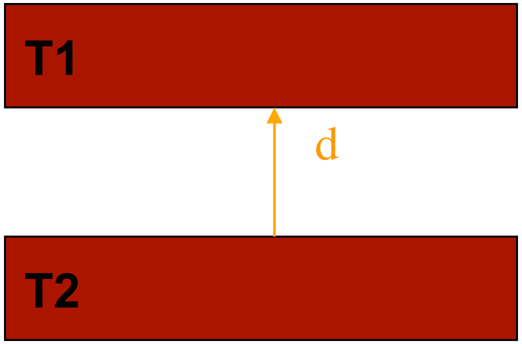
$$E = cB\sqrt{2\left(\frac{k_p}{k_0}\right)^2 - 1}$$

Chapuis, Phys.Rev.B 125402, 2008

Radiative heat transfer between a particle and a surface



Radiative heat transfer between two surfaces

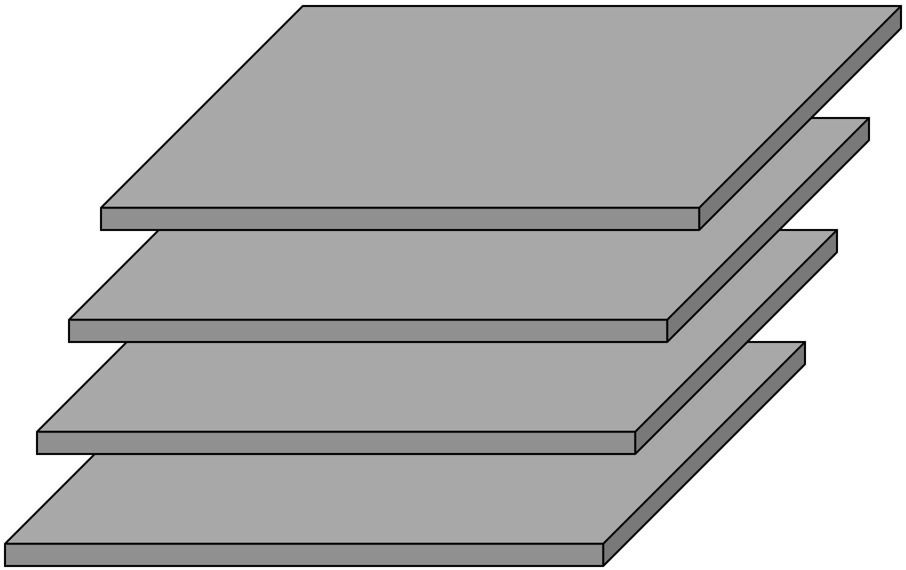


$$\Phi \; < \; \sigma\left(T_1^4 - T_2^4\right)$$

Theme : influence of surface waves on the mesoscopic energy transfer

Anomalous heat transfer

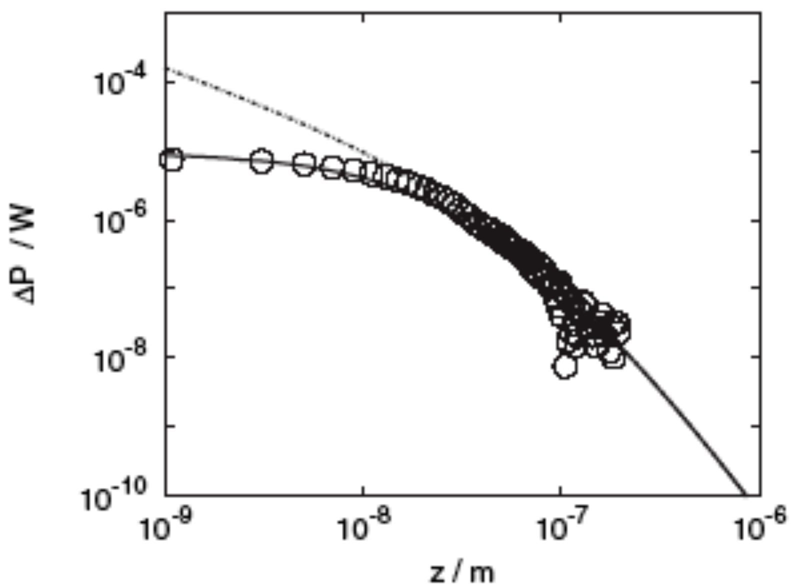
Radiation shield



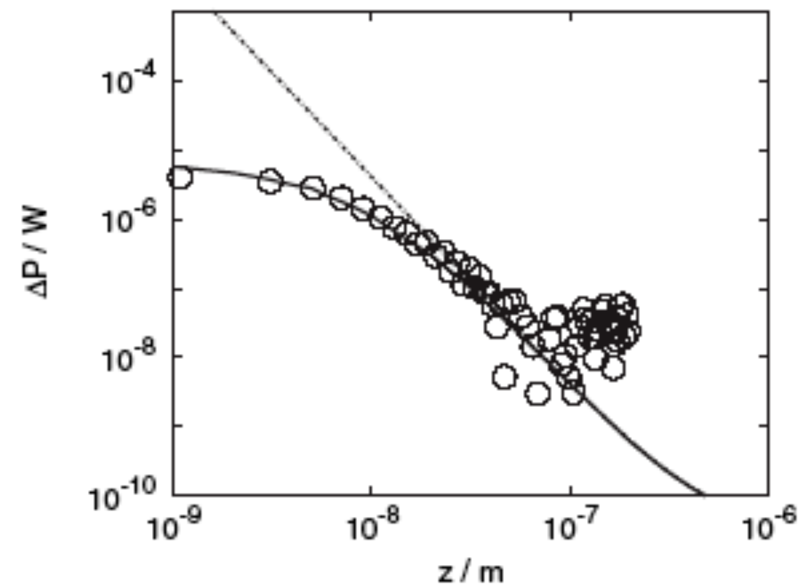
Hargreaves, *1969 Anomalous heat transfer*

Radiative heat transfer at nanoscale : Experimental data

1) **Measurements at low temperature, Hargreaves (69),**
2) **Measurements between metals in the infra red, Xu: inconclusive,**
3) **Measurements in the nm regime with metal (Oldenburg, 2005).**



Au

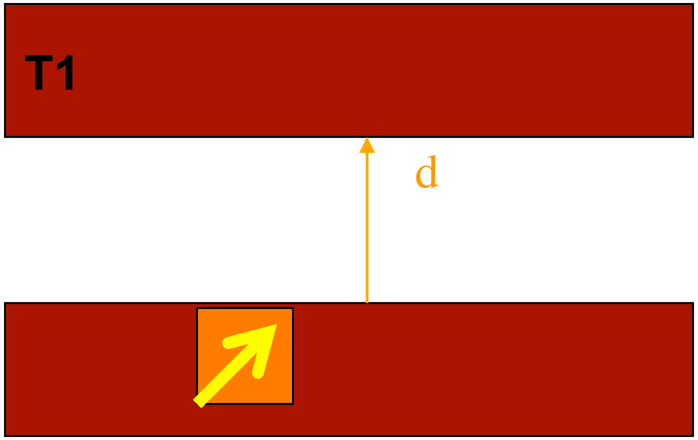


GaN

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

Radiative heat transfer at the nanoscale

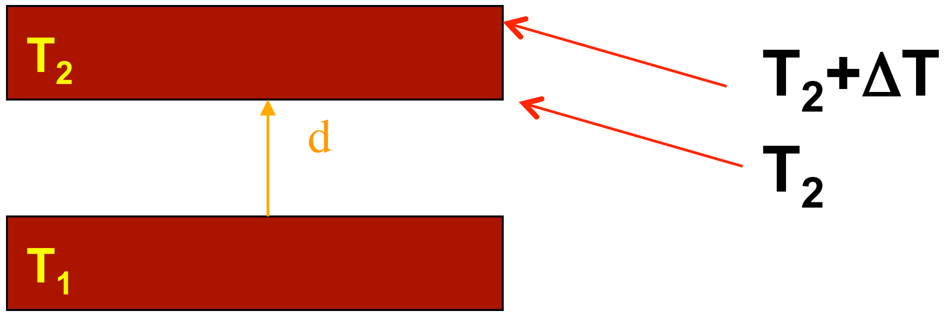
Radiometric approach



$$q(\omega) = \int_0^{2\pi} \cos\theta \, \mathrm{d}\Omega \int_0^{\infty} \mathrm{d}\omega \, \frac{\varepsilon'_{1\omega}\varepsilon'_{2\omega}}{1-\rho'_{1\omega}\rho'_{2\omega}} [I^0_\omega(T_1) - I^0_\omega(T_2)],$$

Dealing with non-equilibrium situation

$$\left\langle j_m(\mathbf{r}_1) j_n^*(\mathbf{r}_2) \right\rangle = \frac{\omega}{\pi} \varepsilon_o \operatorname{Im}\left[\varepsilon(\omega)\right] \delta_{mn}\, \delta(\mathbf{r}_1 - \mathbf{r}_2) \frac{\hbar\omega}{\exp\left(\hbar\omega / k_B T\right) - 1}$$



What about the temperature gradient ?
Can we assume the temperature to be uniform ?

$$h\left(T_2 - T_1\right) = -k \frac{\partial T}{\partial z}$$

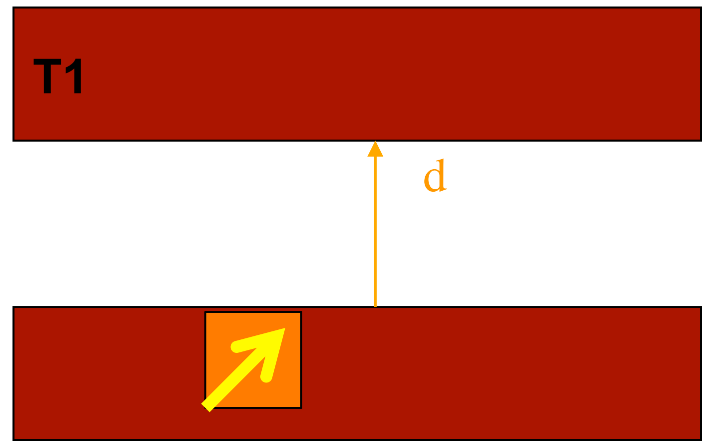
$$\Delta T \approx \frac{\partial T}{\partial z} d \approx \frac{h(T_2 - T_1)}{k} d$$

$$\frac{\Delta T}{(T_2 - T_1)} \approx \frac{1000}{1} 10^{-7} \approx 10^{-4}$$

Radiative heat transfer at the nanoscale

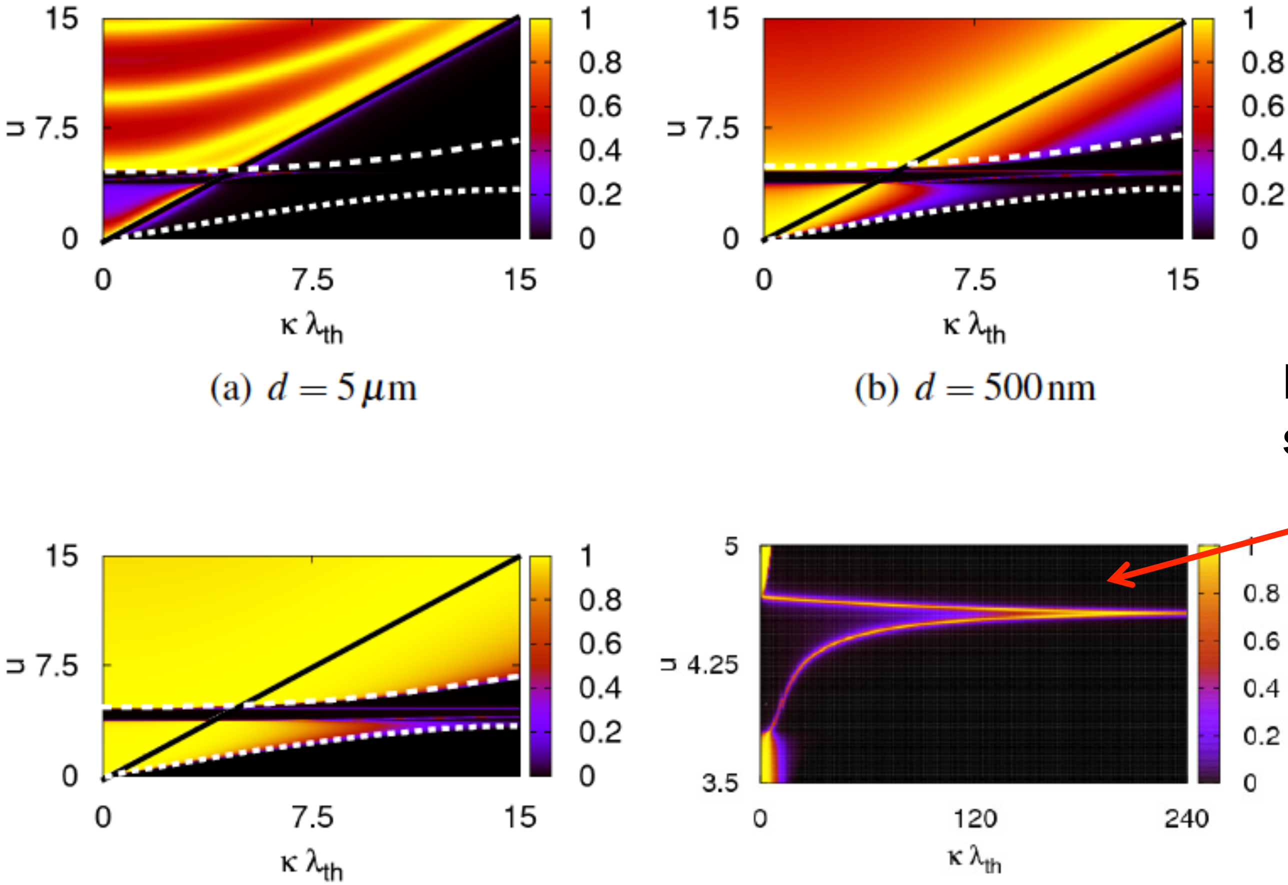
Theory : *Polder, van Hove, PRB 1971*
(Tien, Caren, Rytov, Pendry)

$$\phi = \int_{\omega=0}^{+\infty} d\omega [I_\omega^0(T_1) - I_\omega^0(T_2)]$$
$$\times \sum_{\alpha=s,p} \left[\int_0^{\omega/c} \frac{KdK}{\omega^2/c^2} \frac{(1-|r_{31}^\alpha|^2)(1-|r_{32}^\alpha|^2)}{|1-r_{31}^s r_{32}^\alpha e^{2i\gamma_3 d}|^2} \right.$$
$$\left. + \int_{\omega/c}^{\infty} \frac{KdK}{\omega^2/c^2} \frac{4\,\mathrm{Im}(r_{31}^\alpha)\mathrm{Im}(r_{32}^\alpha) e^{-2\gamma_3'' d}}{|1-r_{31}^\alpha r_{32}^\alpha e^{-2\gamma_3'' d}|^2} \right],$$



Transmission factor

Heat transfer between two SiC half spaces



(a) $d = 5\,\mu\mathrm{m}$
(b) $d = 500\,\mathrm{nm}$
(c) $d = 100\,nm$
(d) $d = 100\,nm$

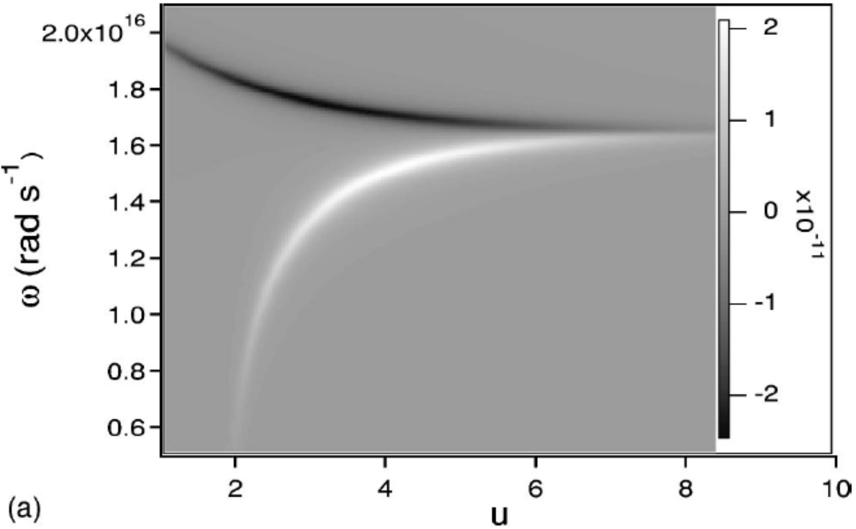
Enhancement due to surface waves

Mulet et al., Microscale Thermophysical Engineering ***6****, 209, (2002)*
Mulet et al. Appl.Phys.Lett. ***78****, 2931 (2001)*

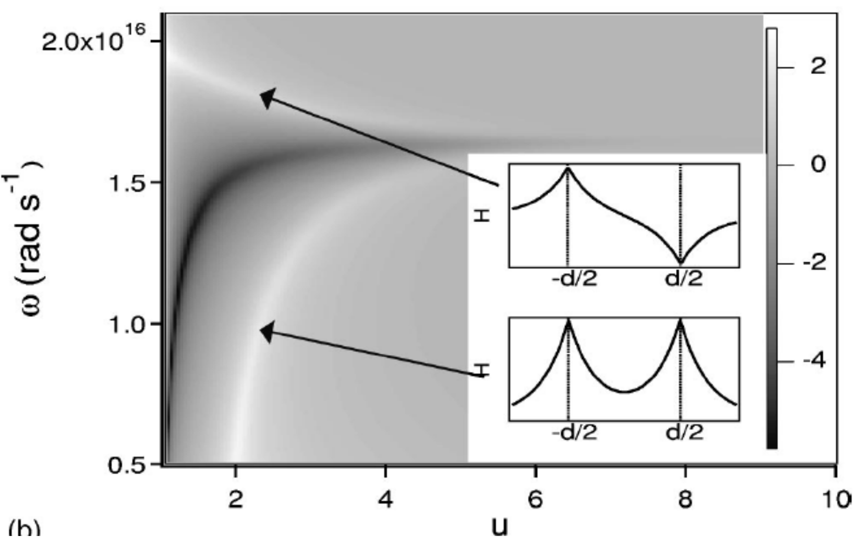
Analogy with Casimir force

$$F=\int_0^\infty \frac{d\omega}{2\pi}\int_0^\infty \frac{du}{2\pi}F(u,\omega),$$

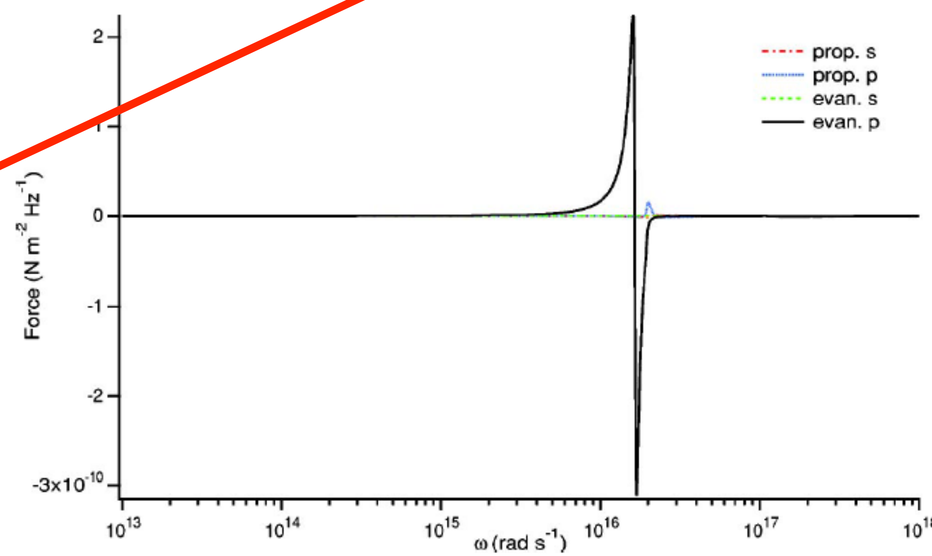
$$F(u,\omega)=\frac{2\hbar\omega^3 u}{c^3}\mathrm{Im}\left(v\sum_{\mu=s,p}\frac{r_\mu^2(u,\omega)e^{-2\omega v d}}{1-r_\mu^2(u,\omega)e^{-2\omega v d/c}}\right)$$



(a)

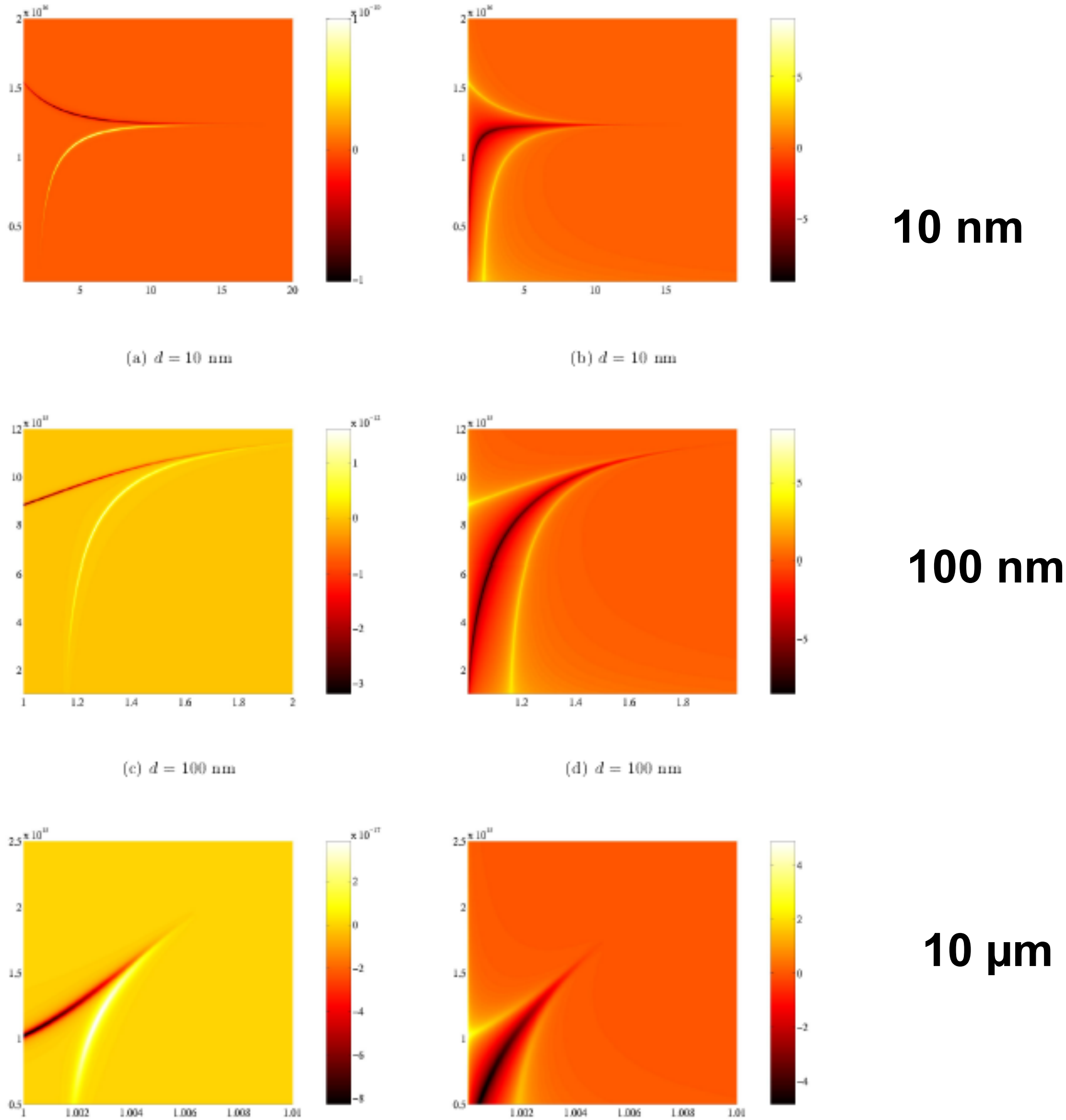


(b)



Henkel et al., Phys.Rev.A 69, 023808 (2004)

Casimir force for aluminum



(a) $d = 10$ nm (b) $d = 10$ nm

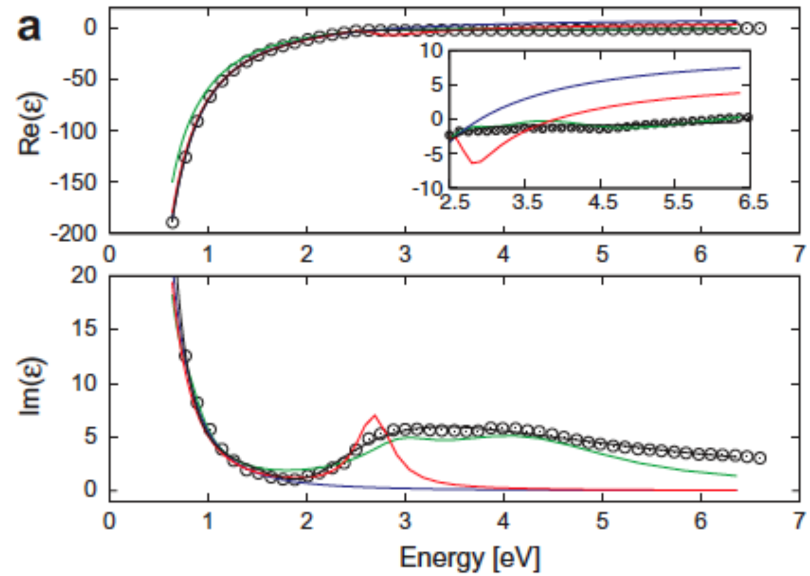
(c) $d = 100$ nm (d) $d = 100$ nm

(e) $d = 10\,\mu$m (f) $d = 10\,\mu$m

Henkel et al., Phys.Rev.A 69, 023808 (2004)

Drude model is not accurate

Gold

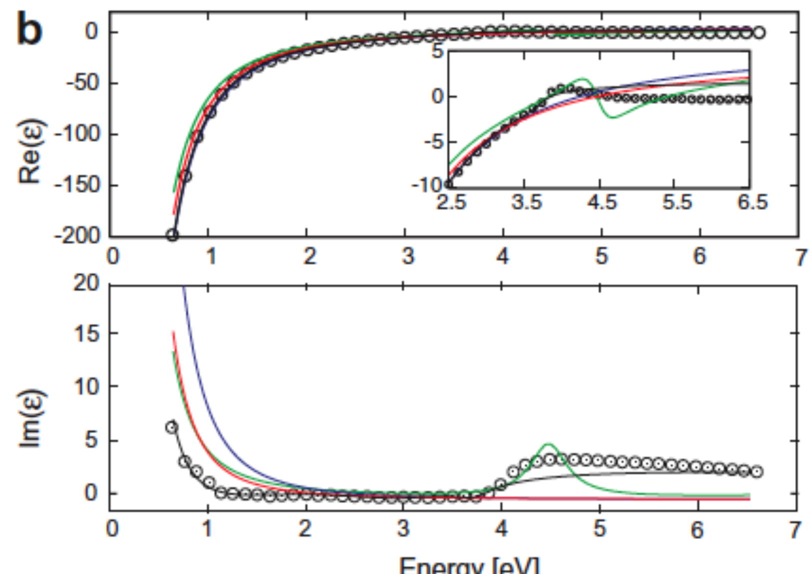


Nordlander's model

$$\epsilon(\omega) = \epsilon_\infty + \frac{\sigma/\epsilon_0}{j\omega} + \sum_{p=1}^{P} \frac{C_p}{\omega^2 + A_p j\omega + B_p}.$$

4 Lorentzian terms are used

Silver



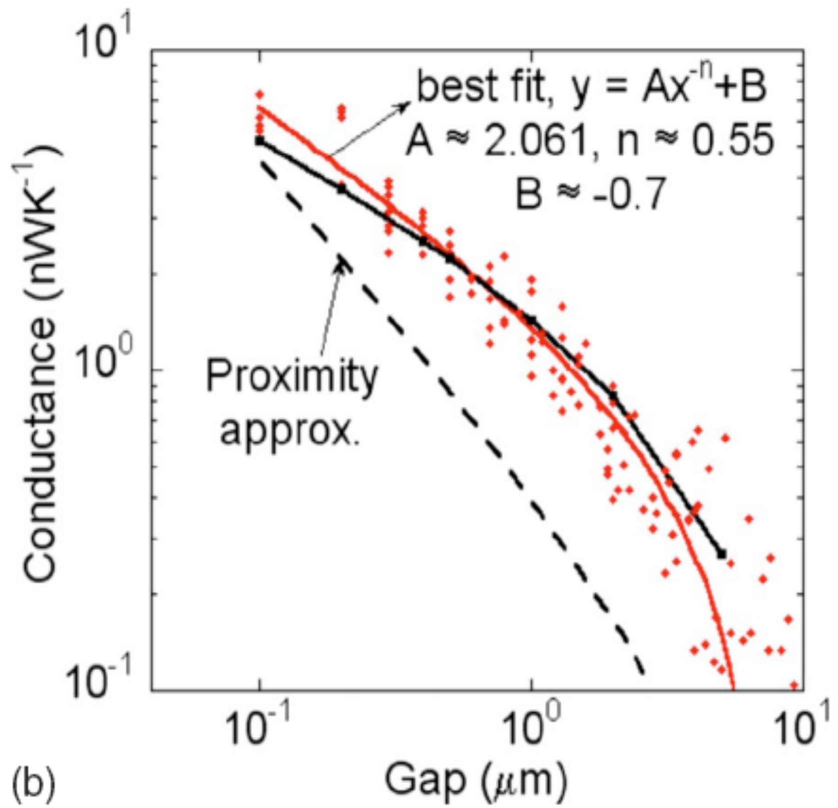
Circle: Johnson and Christy
Blue : Drude model

Hao and Nordlander, Chem.Phys.Lett. 446, 115 (2007)

Recent experimental results

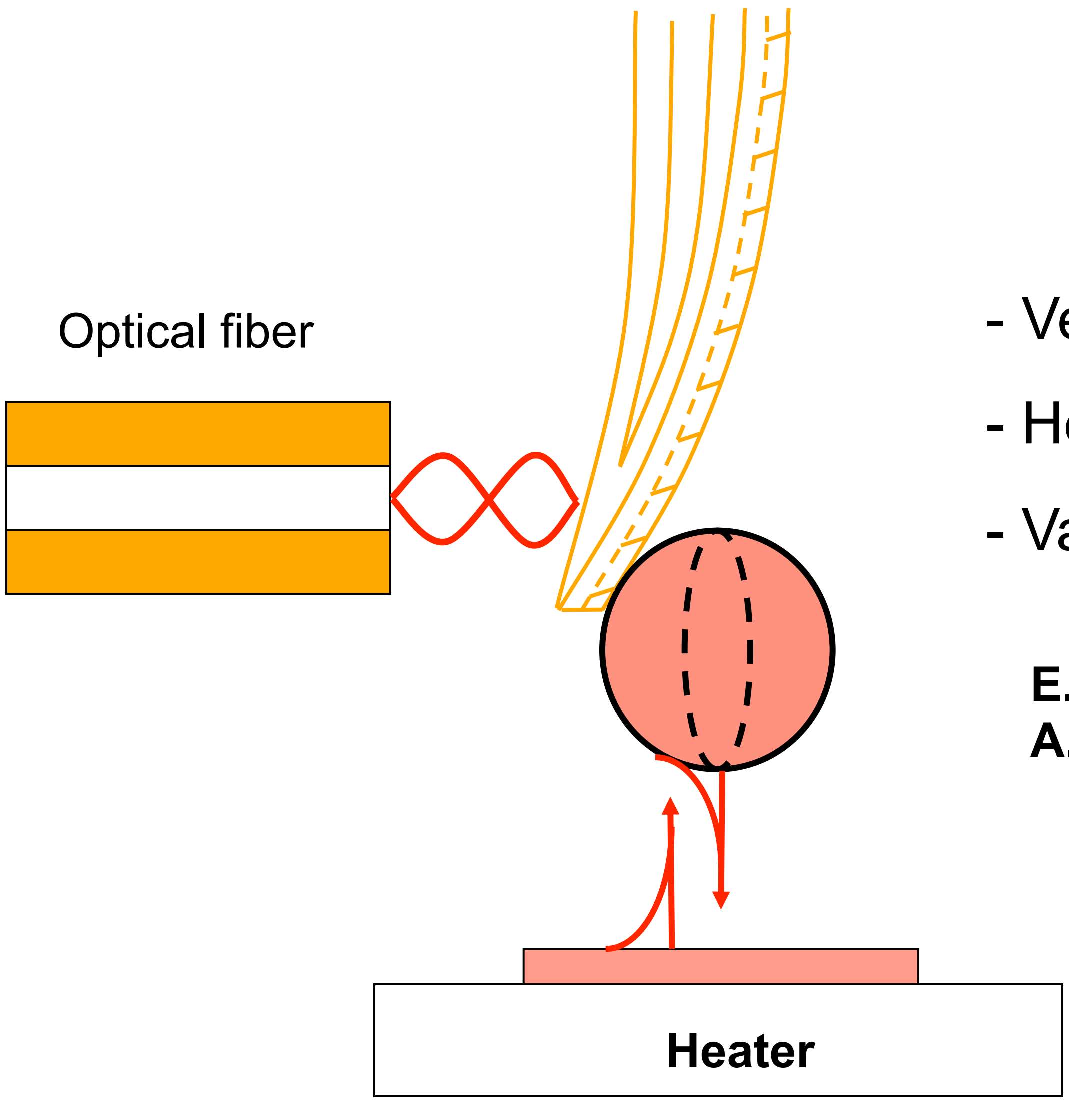
Radiative heat transfer at nanoscale

Measurements with silica



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

Detection scheme

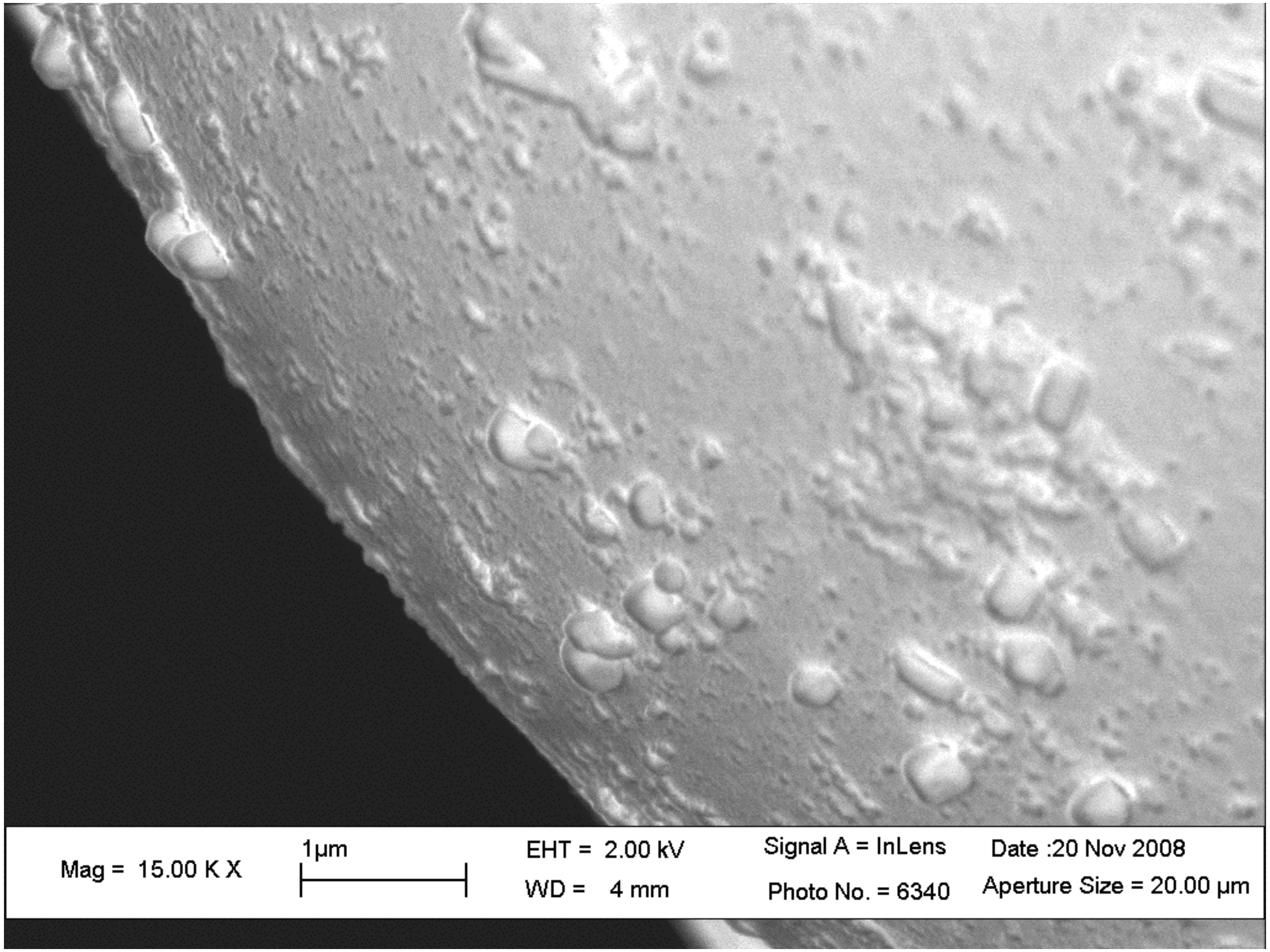


- Vertical configuration
- Heating of the sample
- Vacuum $P \sim 10^{-6}$ mbar

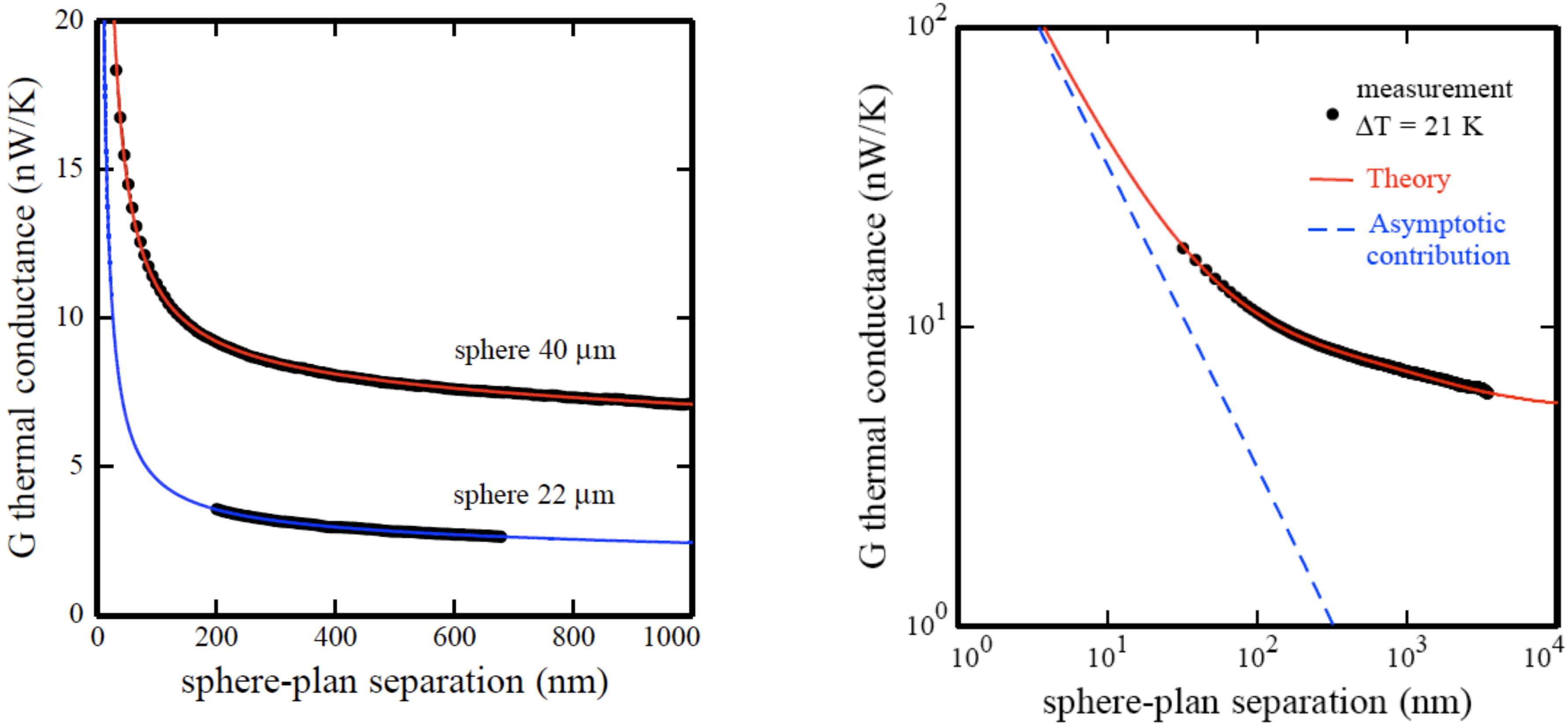
E. Rousseau
A. Siria, J. Chevrier

Nature Photonics ***3****, p 154 (2009)*

Defects size



Comparison theory/data

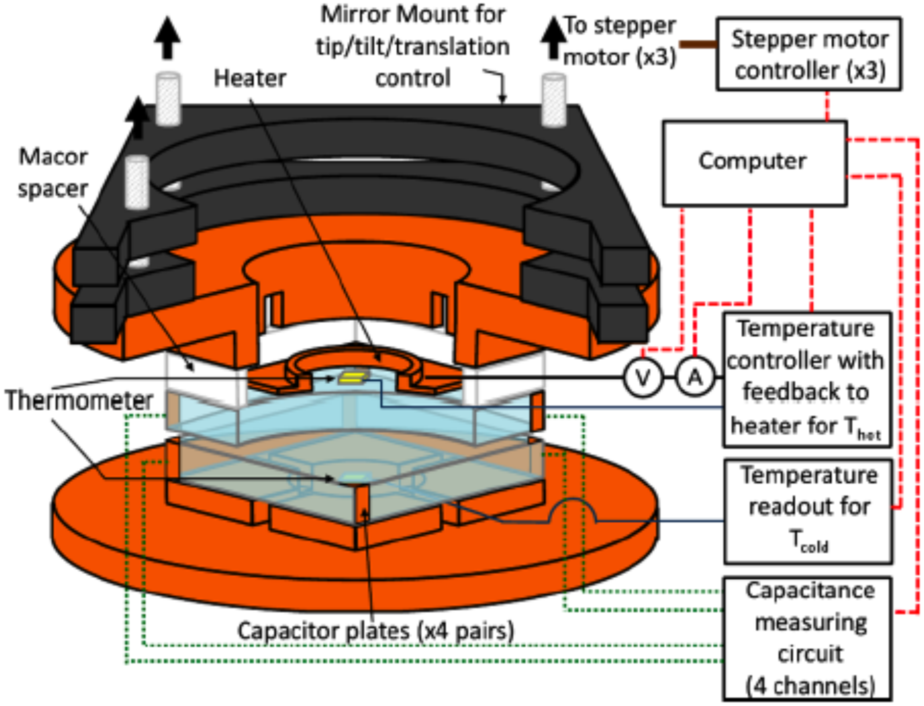


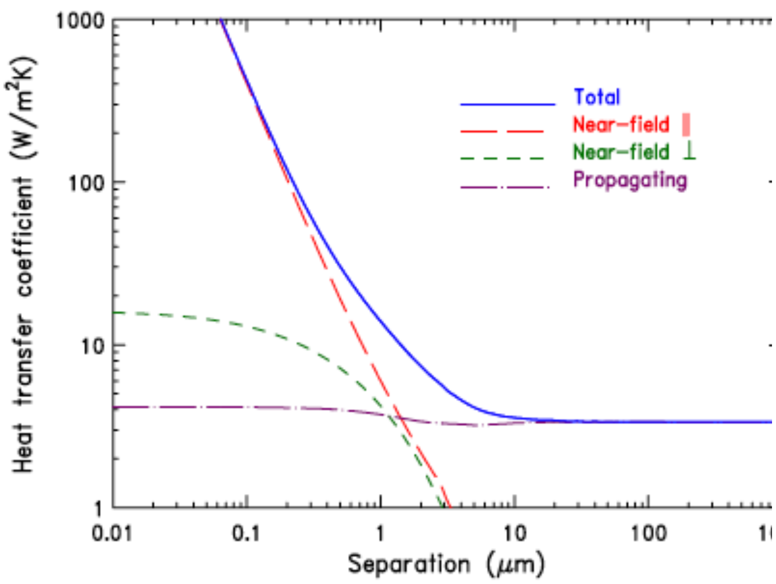
Nature Photonics ***3****, p 154 (2009)*

PRL 107, 014301 (2011) PHYSICAL REVIEW LETTERS week ending 1 JULY 2011

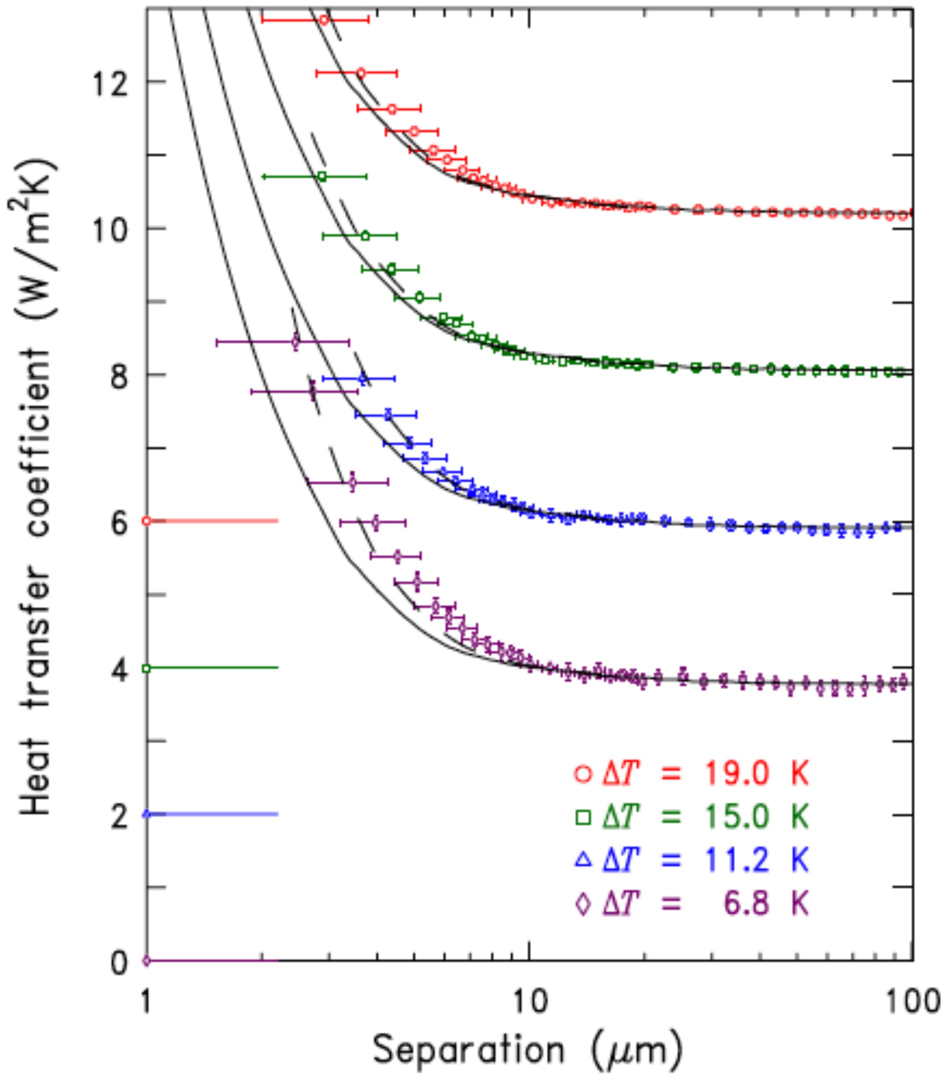
Near-Field Radiative Heat Transfer between Macroscopic Planar Surfaces

R. S. Ottens,[1] V. Quetschke,[2] Stacy Wise,[1,*] A. A. Alemi,[1,†] R. Lundock,[1,‡] G. Mueller,[1]
D. H. Reitze,[1] D. B. Tanner,[1] and B. F. Whiting[1]





Heat transfer coefficient (W/m²K)
1000
100
10
1
0.01
0.1
1
10
100
Separation (μm)
Total
Near−field ∥
Near−field ⊥
Propagating

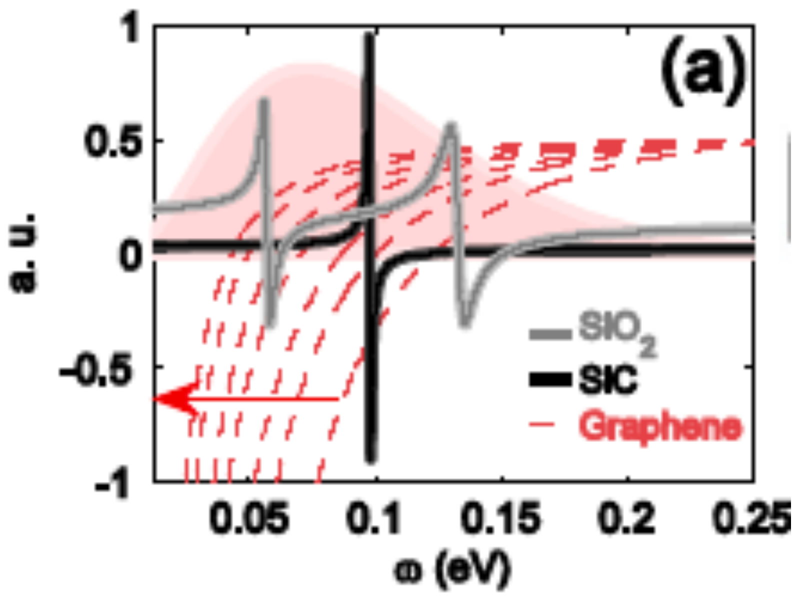


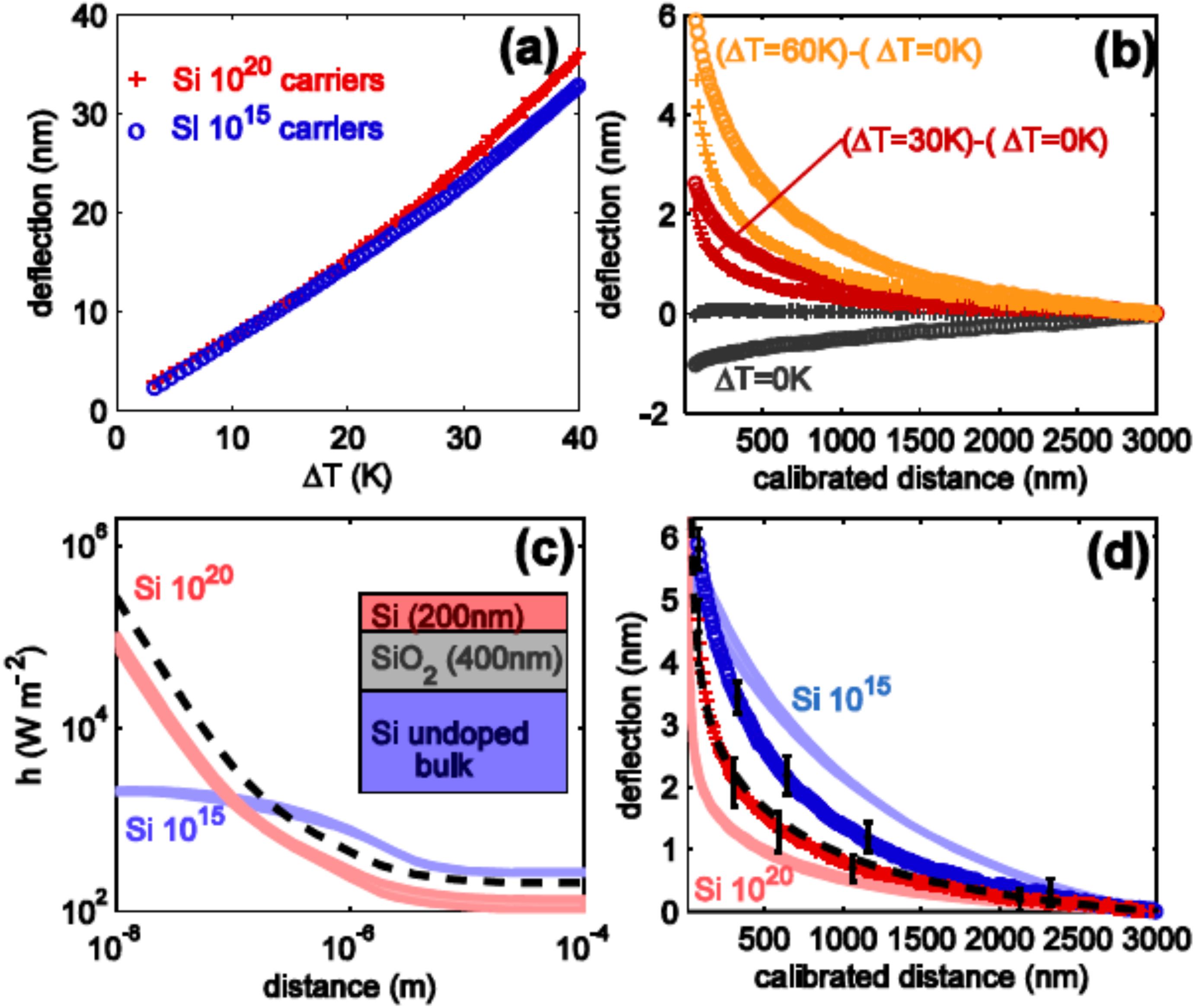
Heat transfer coefficient (W/m²K)
12
10
8
6
4
2
0
1
10
100
Separation (μm)
○ ΔT = 19.0 K
□ ΔT = 15.0 K
△ ΔT = 11.2 K
◊ ΔT = 6.8 K

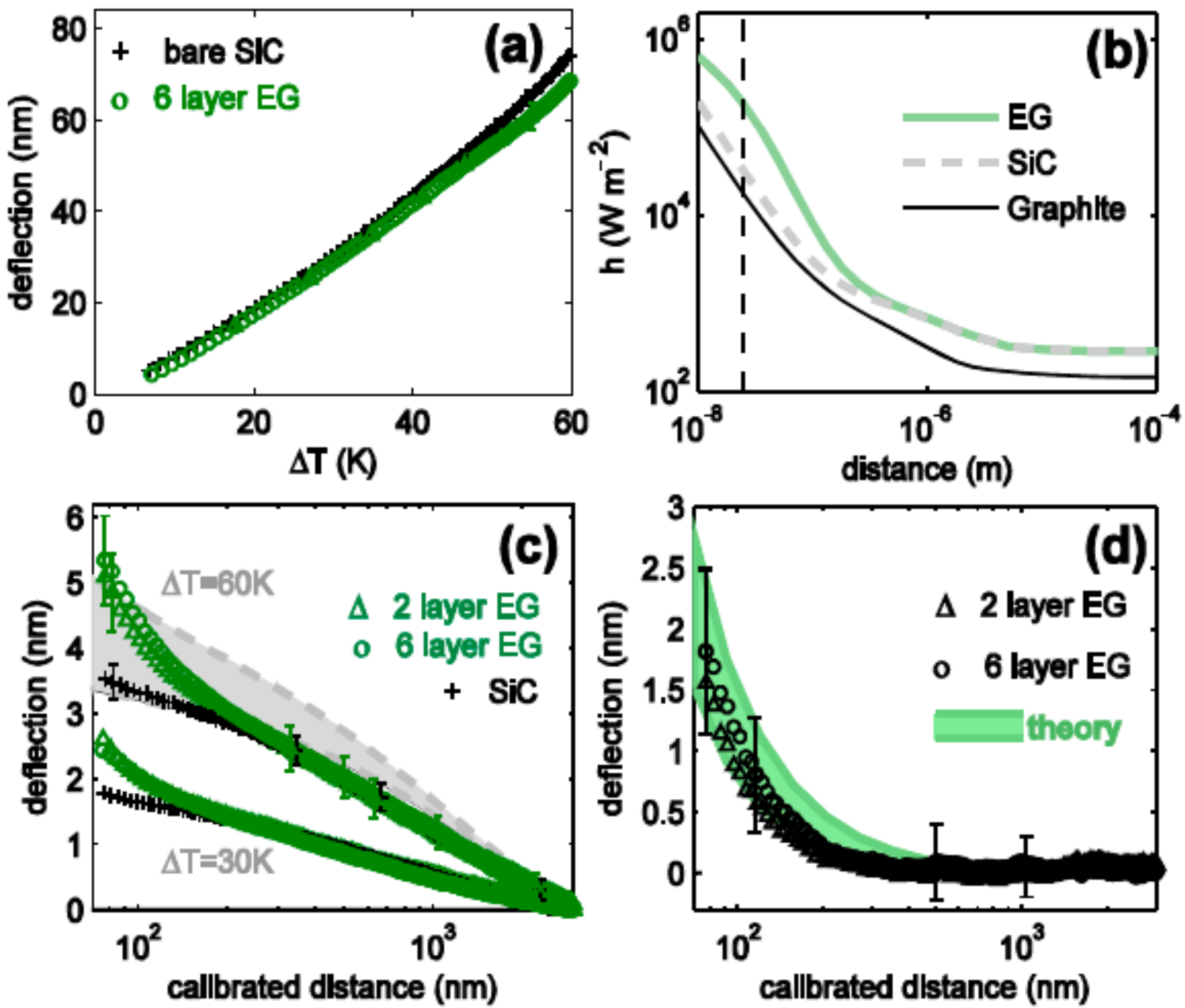
Observation of enhanced nanoscale radiative heat flow due to surface plasmons in graphene and doped silicon

P.J. van Zwol[1], S. Thiele[1], C. Berger[1,2], W. A. de Heer[2], J. Chevrier[1]

1 Institut Néel, CNRS and Universite Joseph Fourier Grenoble, BP 166 38042 Grenoble Cedex 9, France
2 School of Physics, Georgia Institute of Technology, Atlanta, GA 30332, USA.




(a)
Si 10^20 carriers
Si 10^15 carriers
deflection (nm)
ΔT (K)
(b)
(ΔT=60K)-(ΔT=0K)
(ΔT=30K)-(ΔT=0K)
ΔT=0K
deflection (nm)
calibrated distance (nm)
(c)
Si 10^20
Si 10^15
Si (200nm)
SiO2 (400nm)
Si undoped bulk
h (W m^-2)
distance (m)
(d)
Si 10^15
Si 10^20
deflection (nm)
calibrated distance (nm)

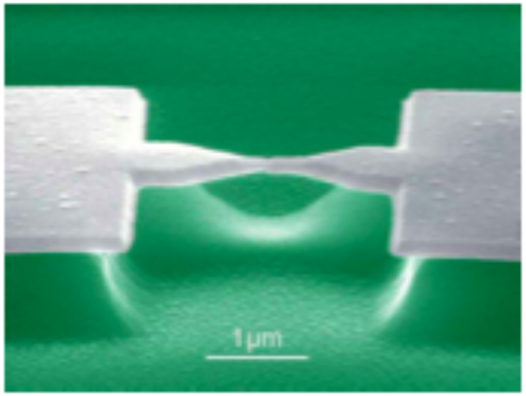

(a)
bare SiC
6 layer EG
deflection (nm)
ΔT (K)
(b)
EG
SiC
Graphite
h (W m^{-2})
distance (m)
(c)
ΔT=60K
ΔT=30K
2 layer EG
6 layer EG
SiC
deflection (nm)
calibrated distance (nm)
(d)
2 layer EG
6 layer EG
theory
deflection (nm)
calibrated distance (nm)

Introduction to the concept of quantum conductance
Mesoscopic analysis of heat transfer at the nanoscale

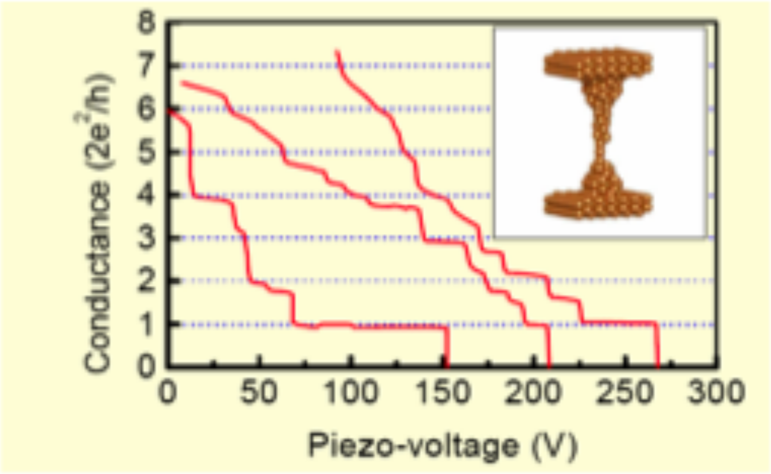
$$
\begin{aligned}
\phi = \int_{\omega=0}^{+\infty} d\omega [I_\omega^0(T_1) - I_\omega^0(T_2)] \\
\times \sum_{\alpha=s,p} \left[\int_0^{\omega/c} \frac{KdK}{\omega^2/c^2} \frac{(1-|r_{31}^\alpha|^2)(1-|r_{32}^\alpha|^2)}{|1-r_{31}^s r_{32}^\alpha e^{2i\gamma_3 d}|^2} \right. \\
\left. + \int_{\omega/c}^{\infty} \frac{KdK}{\omega^2/c^2} \frac{4\,\mathrm{Im}(r_{31}^\alpha)\mathrm{Im}(r_{32}^\alpha) e^{-2\gamma_3'' d}}{|1-r_{31}^\alpha r_{32}^\alpha e^{-2\gamma_3'' d}|^2} \right],
\end{aligned}
$$

Mesoscopic charge transport : a tutorial

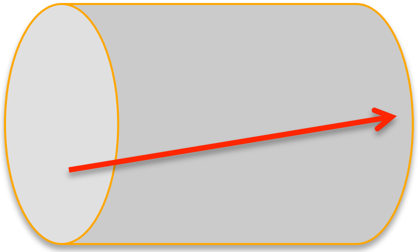
1 Experimental observation



contact ponctuel atomique



2 Landauer formalism



$$I = \Gamma V$$

$$\Gamma = \sum_n \left[\frac{2e^2}{h}\right] T_n$$

Fundamental limits to radiative heat transfer at the nanoscale

Sum over modes

$$\Phi \Delta t L^2 = \int_0^\infty \frac{\mathrm{d}\omega}{(2\pi/\Delta t)} [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \sum_{j=\{\mathrm{s,p}\}} \int \frac{\mathrm{d}^2\kappa}{(2\pi/L)^2} \mathscr{T}_j(\omega, \kappa; d).$$

$$\int_0^\infty \frac{\mathrm{d}\omega}{2\pi} [\Theta(\omega, T_1) - \Theta(\omega, T_2)] \approx g_0 [T_1 - T_2],$$

$$g_0 = \int_0^\infty \frac{\mathrm{d}\omega}{2\pi} \frac{\partial \Theta}{\partial T} = \frac{\pi^2 k_B^2 T}{3h},$$

A mesoscopic formulation of radiative heat transfer at nanoscale

$$\phi = \int_{\omega=0}^{+\infty} d\omega [I_\omega^0(T_1) - I_\omega^0(T_2)]$$
$$\times \sum_{\alpha=s,p}\left[\int_0^{\omega/c}\frac{KdK}{\omega^2/c^2}\frac{(1-|r_{31}^\alpha|^2)(1-|r_{32}^\alpha|^2)}{|1-r_{31}^s r_{32}^\alpha e^{2i\gamma_3 d}|^2}\right.$$
$$\left.+ \int_{\omega/c}^{\infty}\frac{KdK}{\omega^2/c^2}\frac{4\,\mathrm{Im}(r_{31}^\alpha)\mathrm{Im}(r_{32}^\alpha)e^{-2\gamma_3'' d}}{|1-r_{31}^\alpha r_{32}^\alpha e^{-2\gamma_3'' d}|^2}\right],$$

$$I = \sum_n T_n \left[\frac{2e^2}{h}\right] V$$

$$\Phi = \iint \frac{d^2\mathbf{k}}{4\pi^2}\, \overline{T(\mathbf{k})} \left[\frac{\pi^2}{3}\frac{k_B^2 T}{h}\right] \Delta T$$

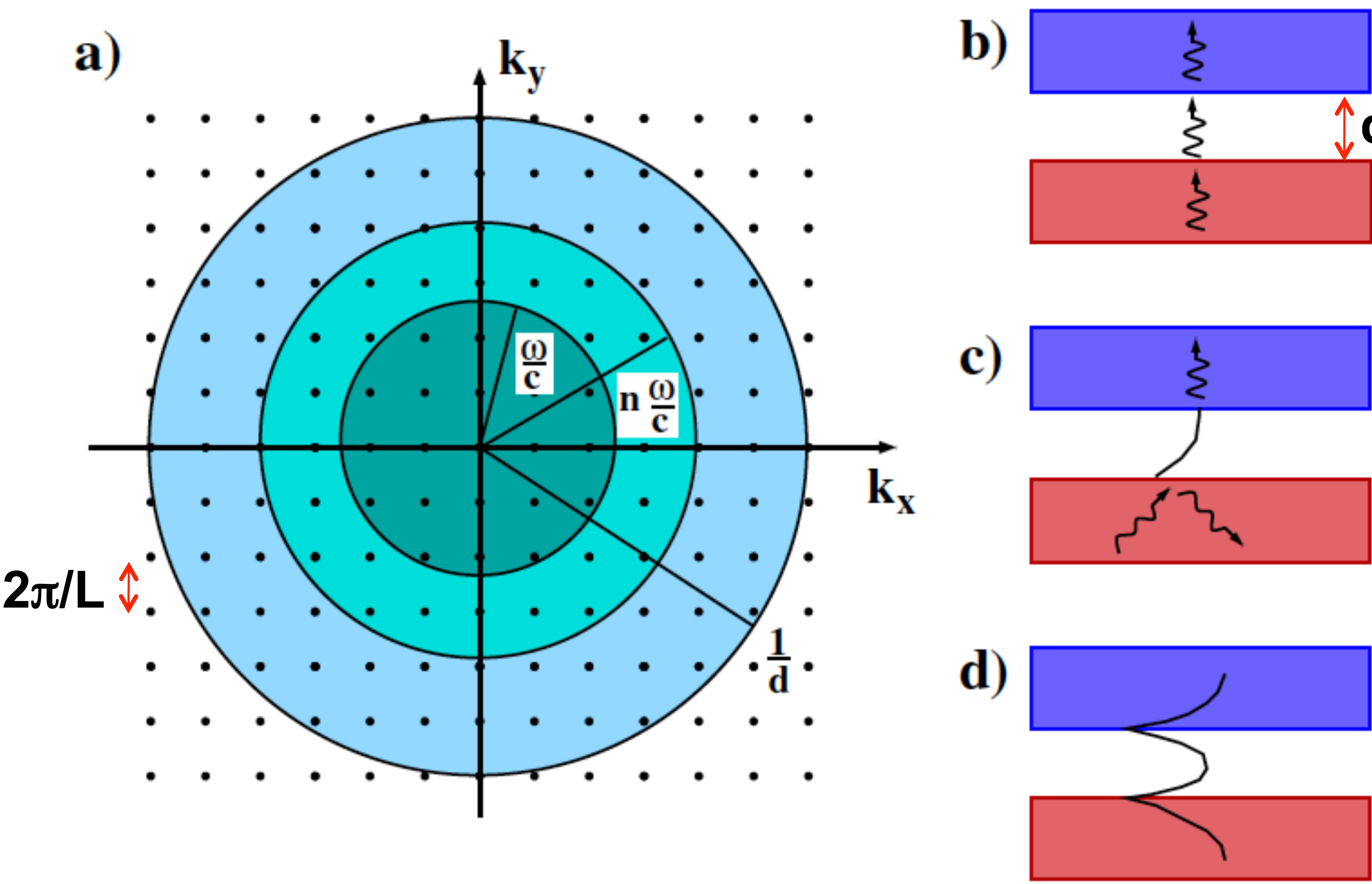
Transmission factor

Thermal quantum conductance

$$T_j^{12}(\omega,\kappa,d) = \begin{cases} \dfrac{(1-|r_j^1|^2)(1-|r_j^2|^2)}{|D_j|^2} & ,\kappa \le k_0 \\ \dfrac{4\mathrm{Im}(r_j^1)\mathrm{Im}(r_j^2)\mathrm{e}^{-2\gamma d}}{|D_j|^2} & ,\kappa > k_0 \end{cases}$$

$$\Phi = g_0 \left(\sum_{j=\mathrm{s,p}} \int \frac{\mathrm{d}^2\kappa}{(2\pi)^2} \overline{\mathscr{T}}_j \right) [T_1 - T_2]$$

$$\overline{\mathscr{T}}_j = \frac{\int_0^\infty \mathrm{d}u\, f(u)\, \mathscr{T}_j(u, \kappa; d)}{\int_0^\infty \mathrm{d}u\, f(u)}$$



Biehs et al., Phys.Rev.Lett. ***105****, 234301 (2010)*

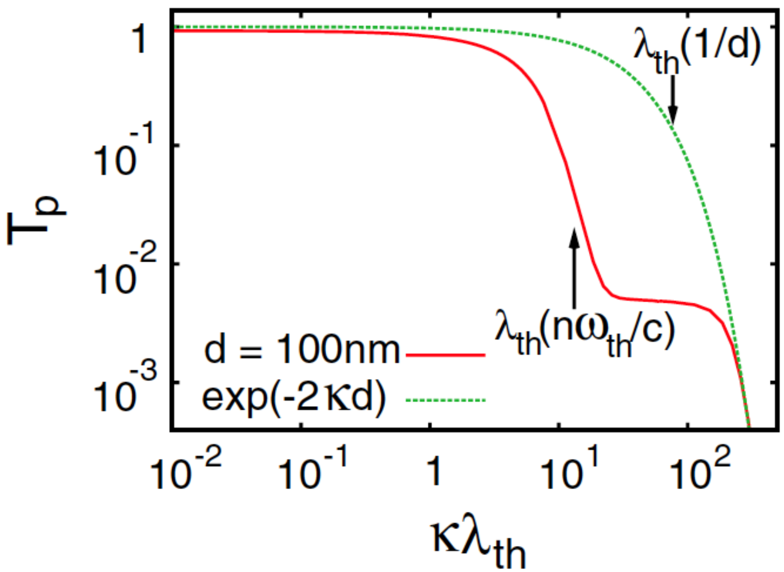
Fundamental limit: a new perspective on Stefan's constant

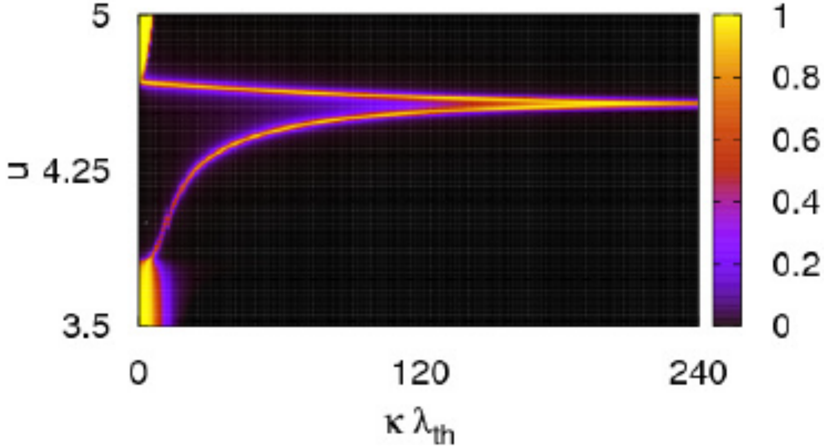
$$\Phi_{\mathrm{BB}} = \int_0^\infty [\Theta(\omega,T_1) - \Theta(\omega,T_2)] \left(\frac{\omega^2}{c^3\pi^2}\right) \frac{c}{4} = \sigma_{\mathrm{BB}}(T_1^4 - T_2^4)$$

$$\Phi_{\mathrm{BB}} = g_0 \frac{2\pi}{5\lambda_T^2}(T_1 - T_2). \quad \lambda_T = \hbar c/(k_{\mathrm{B}}T)$$

$$\Phi_{\max} = g_0 \frac{k_c^2}{2\pi}(T_1 - T_2) = g_0 \frac{2}{\pi d^2}(T_1 - T_2)$$

Are we there yet ?

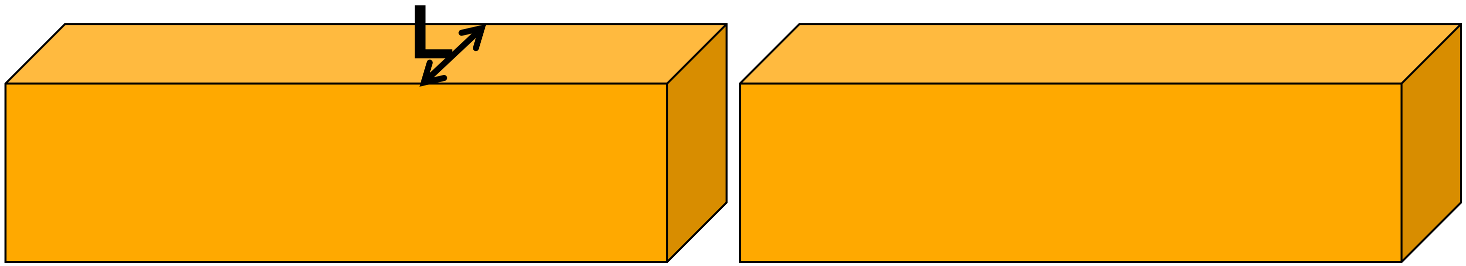




(d) $d = 100\,nm$

Biehs et al., Phys.Rev.Lett. ***105****, 234301 (2010)*

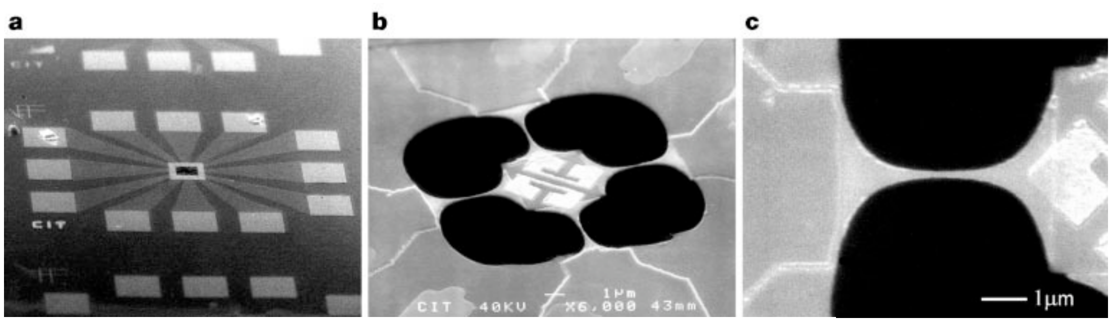
Quantized radiative thermal conductance

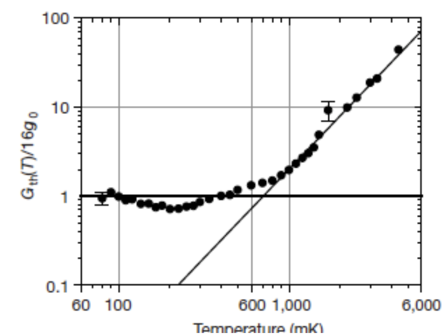


If L is on the order of the thermal wavelength,

$$\iint \frac{d^2\mathbf{k}}{4\pi^2} \quad \rightarrow \quad \sum_n$$

Biehs et al., Phys.Rev.Lett. ***105****, 234301 (2010)*





Measurement of the quantum of thermal conductance

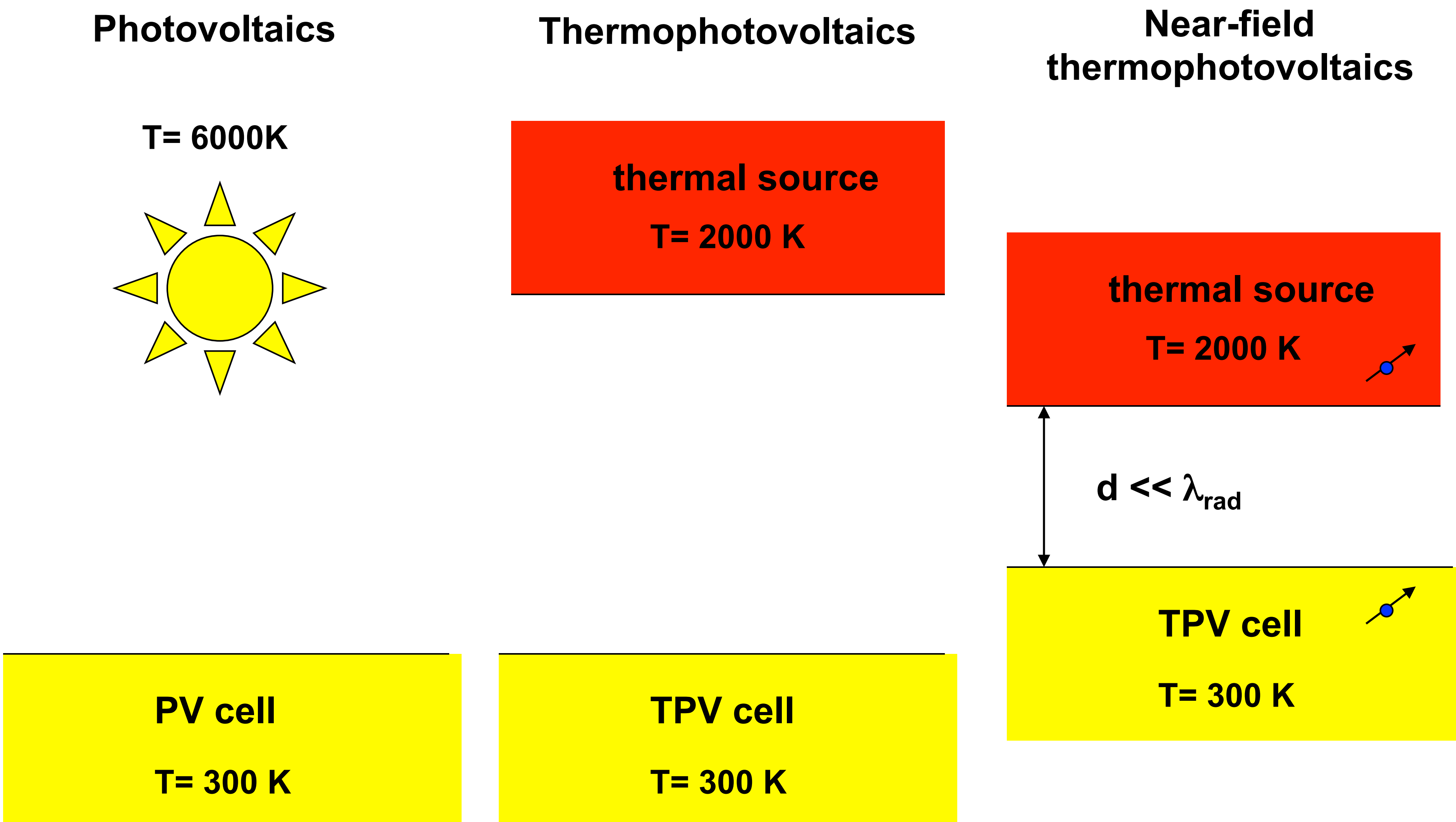
K. Schwab*, E. A. Henriksen*, J. M. Worlock*† & M. L. Roukes*

NATURE | VOL 404 | 27 APRIL 2000

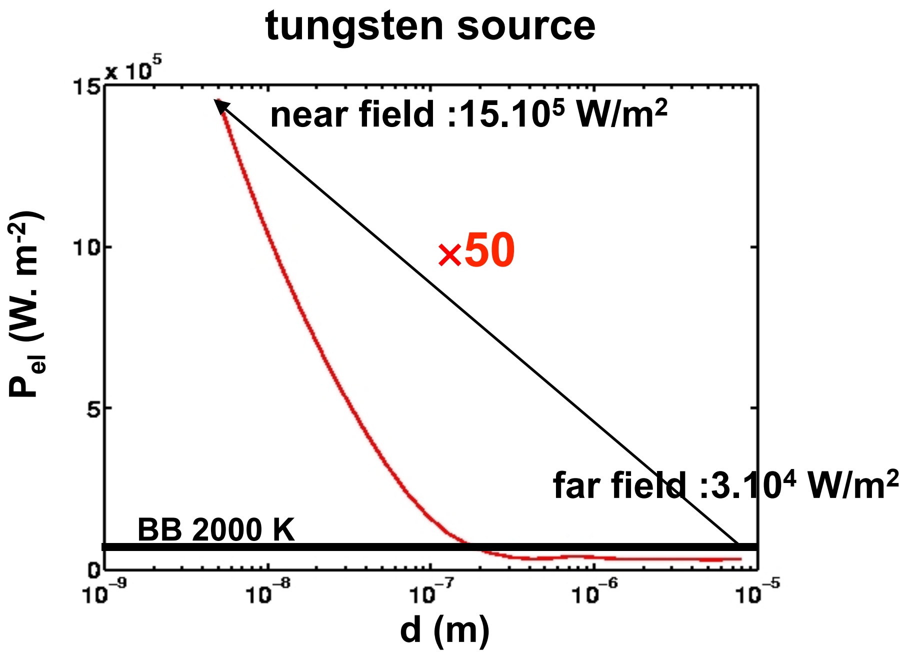
Applications

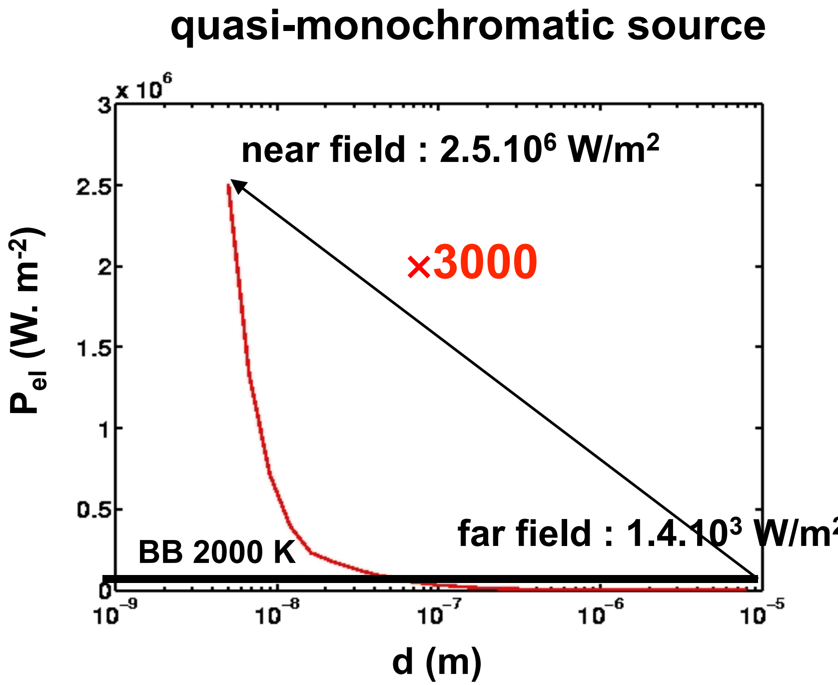
Thermophotovoltaics

Application : thermophotovoltaics



Near-field output electric power



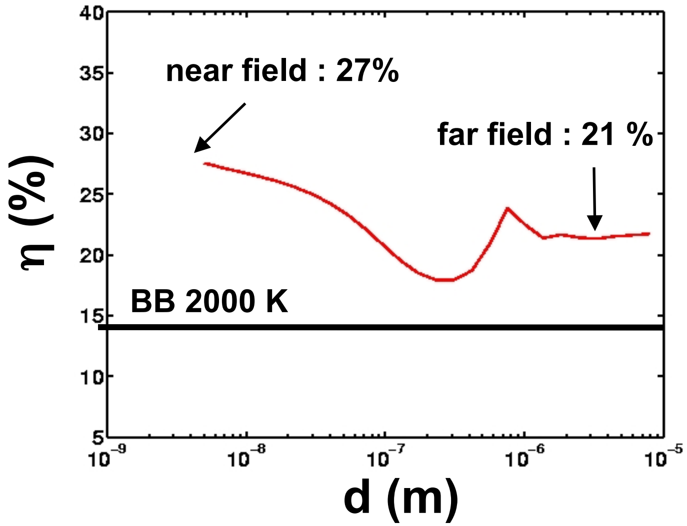


output electric power enhanced by at least one order of magnitude

Laroche et al. J. Appl.Phys. ***100****, 063704 (2006)*

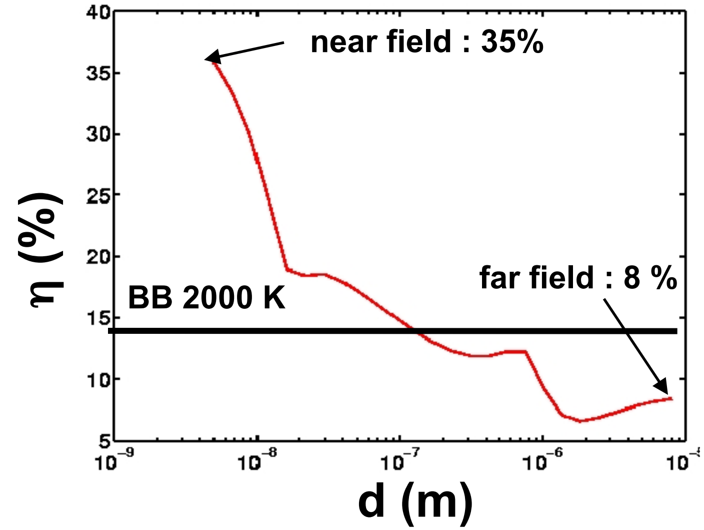
Near-field TPV converter efficiency

tungsten source



$$\eta = \frac{P_{el}}{P_{rad}}$$

quasi-monochromatic source



significant increase of the efficiency

Laroche et al. J. Appl.Phys. ***100****, 063704 (2006)*

Modulators

Modulator with phase change material

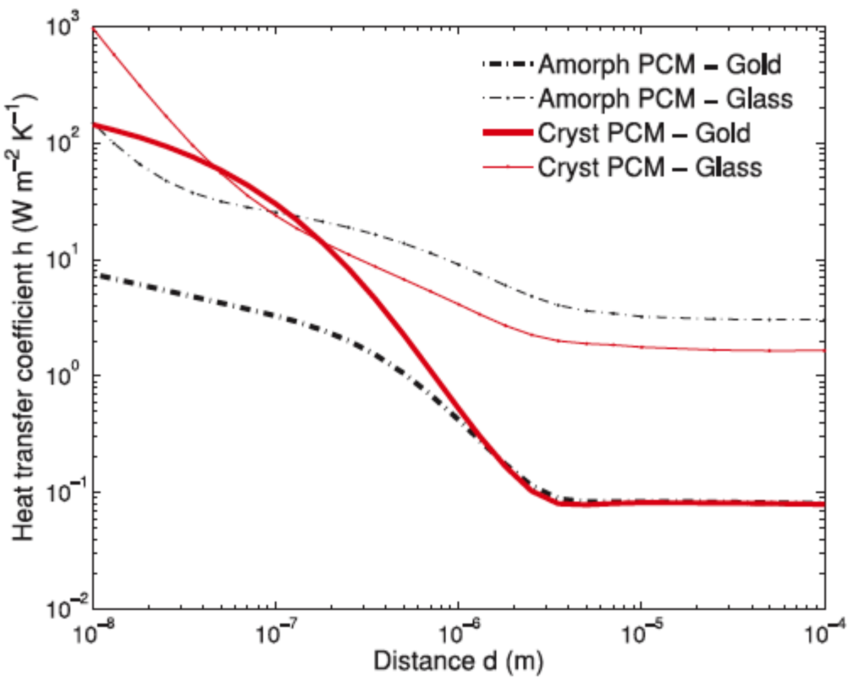


FIG. 3. (Color online) Radiative heat transfer for PCM glass and PCM gold.

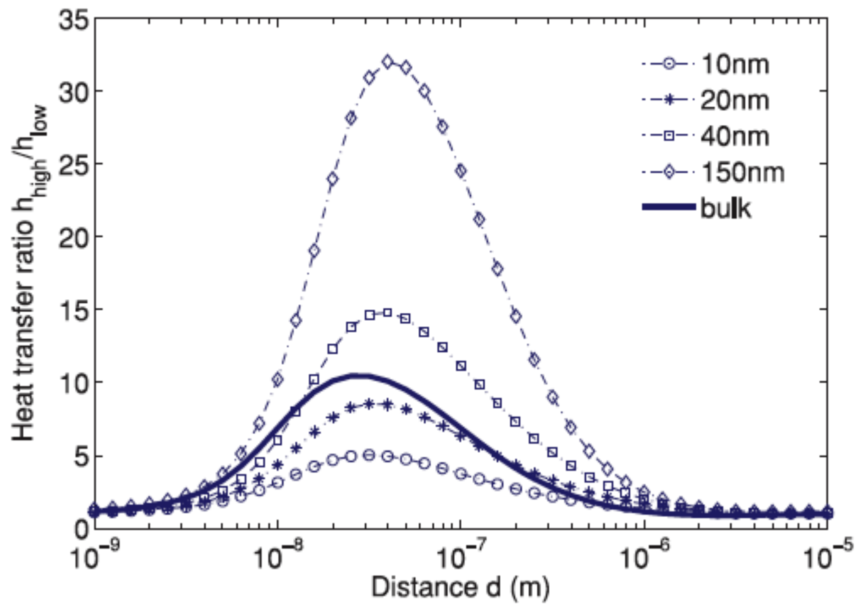
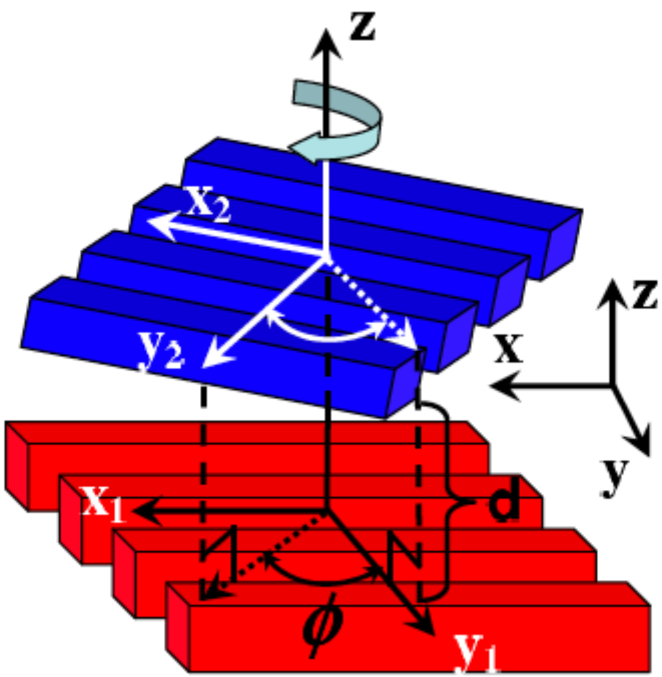
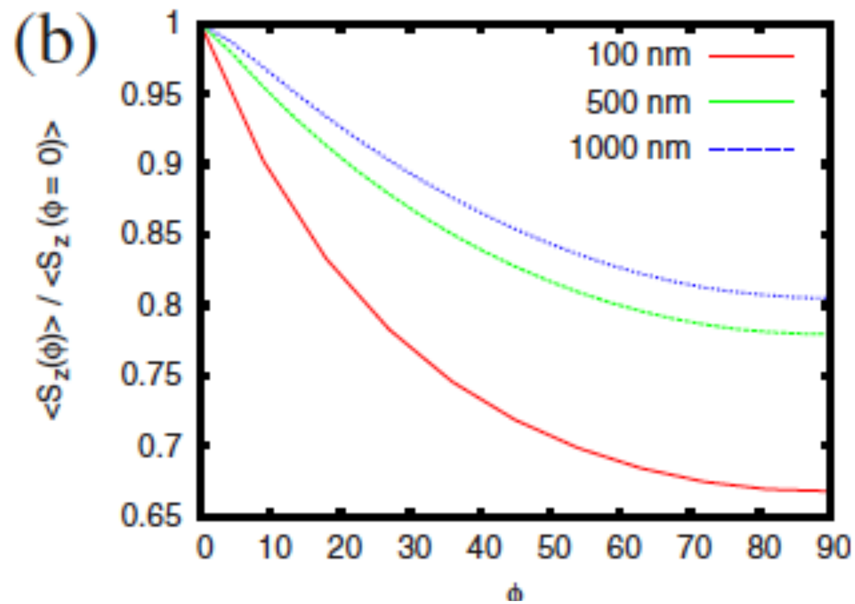


FIG. 4. (Color online) Modulation of heat transfer in vacuum between a gold surface and a switchable PCM (AIST) layer on a glass substrate protected by a 5 nm glass top layer. Data are shown for different thicknesses of the PCM material.

Van Zwol et al. , Phys.Rev.B ***83****, 201404 (R) (2011)*

Modulator with anisotropic metamaterials





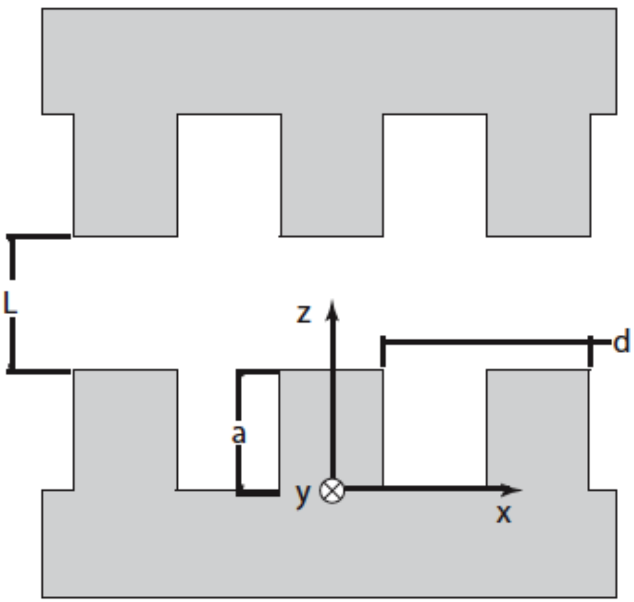
APPLIED PHYSICS LETTERS **98**, 243102 (2011)

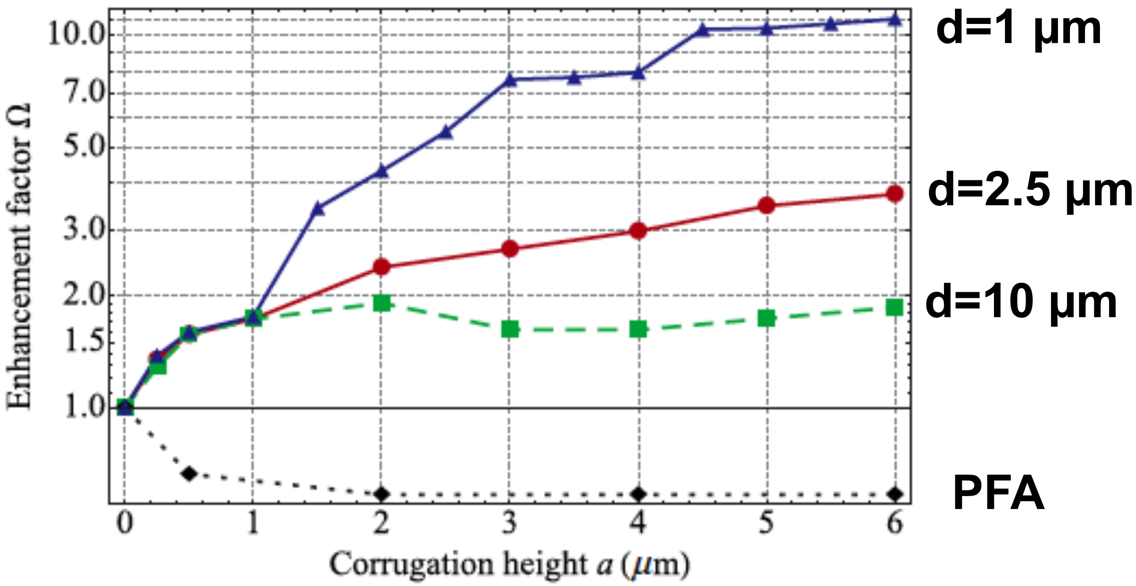
Modulation of near-field heat transfer between two gratings

S.-A. Biehs,[a)] F. S. S. Rosa, and P. Ben-Abdallah
Laboratoire Charles Fabry, Institut d'Optique, CNRS, Université Paris-Sud, Campus Polytechnique, RD128, 91127 Palaiseau Cedex, France

Textured surfaces

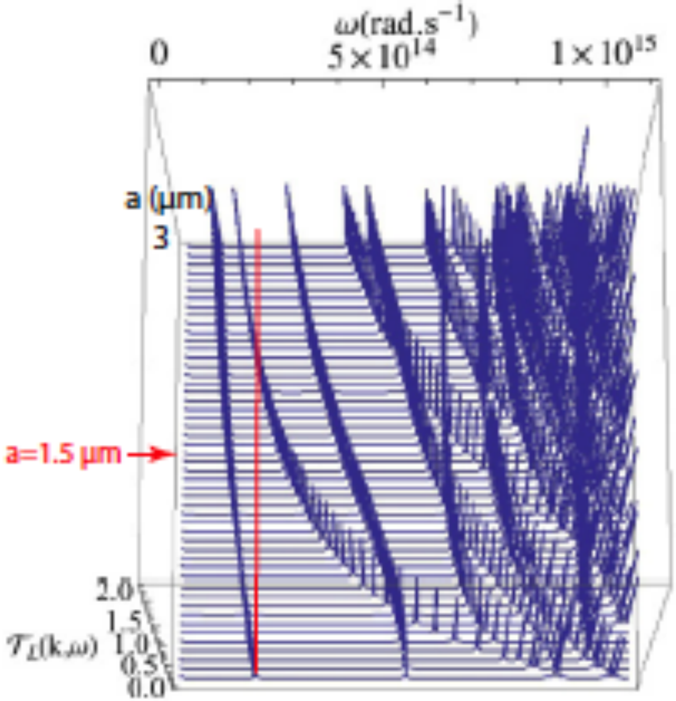
Heat transfer between gold gratings

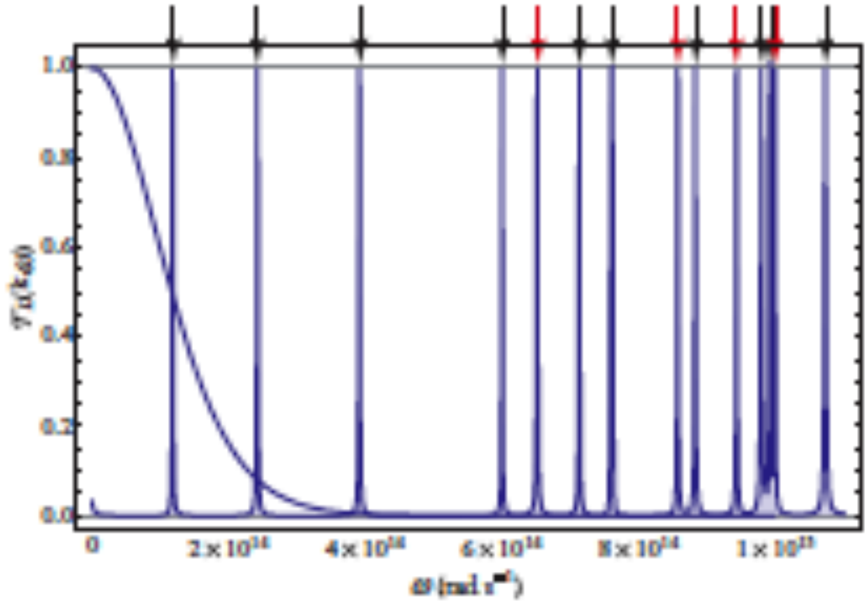




R. Guerout et al., Phys.Rev.B ***85****, 180301 (2012)*

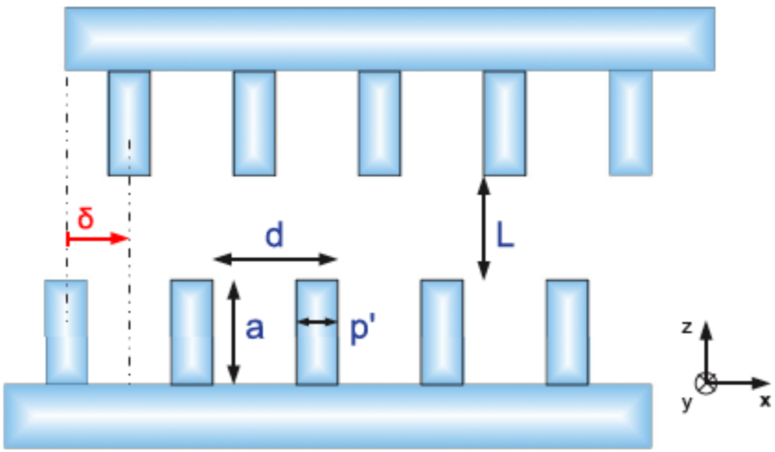
Textured surfaces

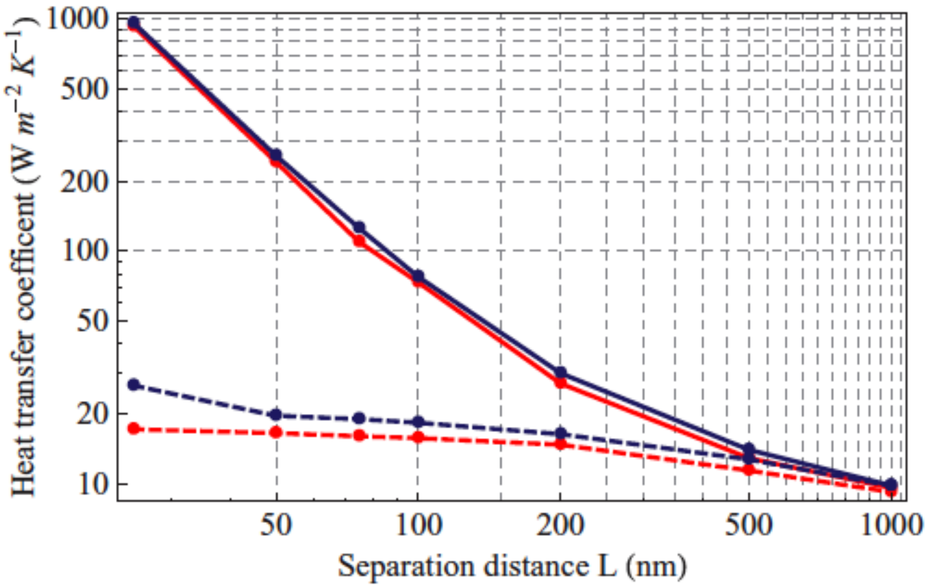




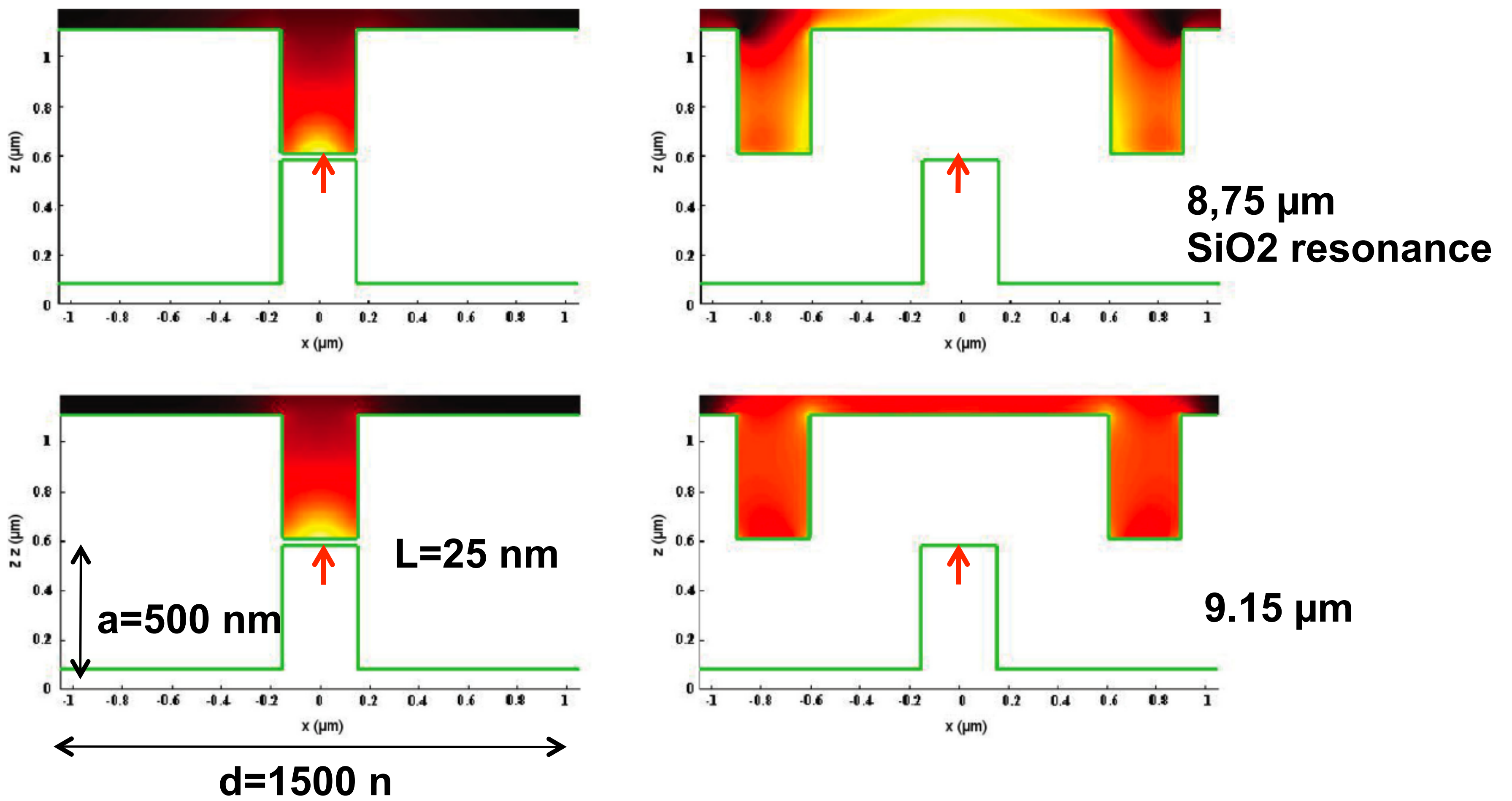
*R. Guerout et al., Phys.Rev.B **85**, 180301 (2012)*

Heat transfer between SiC gratings



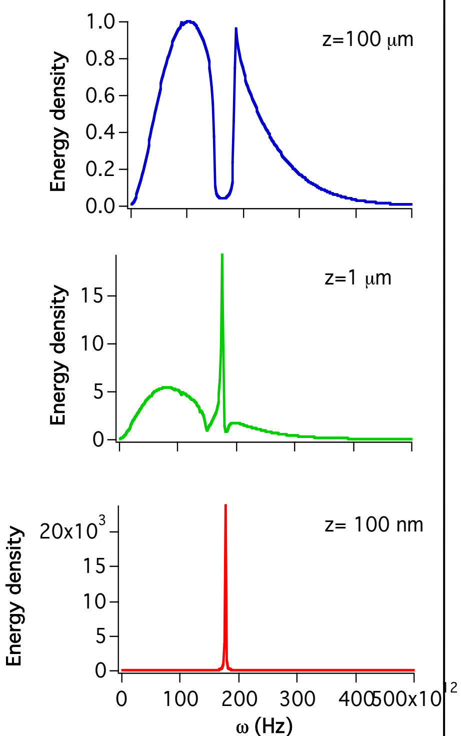


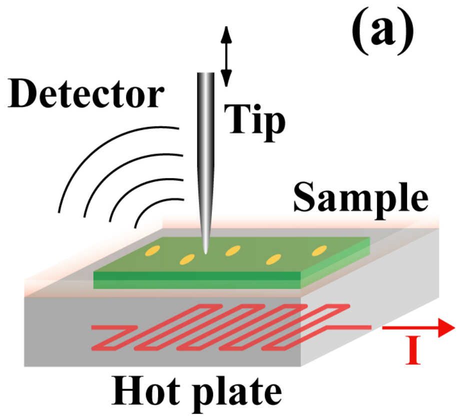
Heat transfer between two SiO2 gratings: Physical mechanism

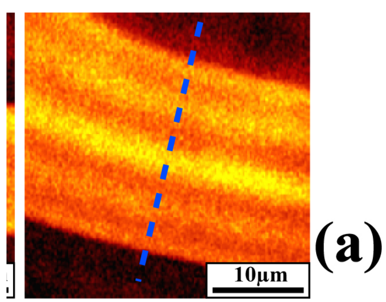


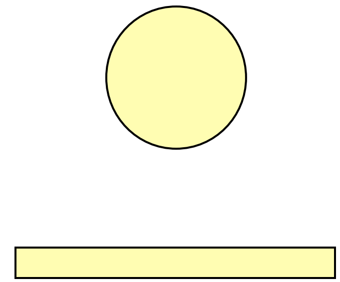
*J. Lussange et al., Phys.Rev.B **86**, 085432 (2012)*

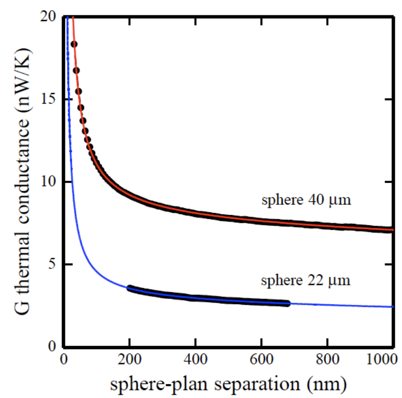
Summary

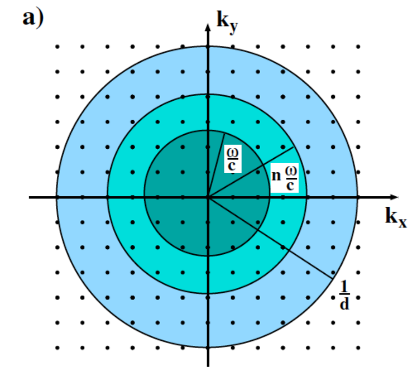












$$\Gamma_0 = \frac{\pi^2}{3}\frac{k_B^2 T}{h}$$