Basis of nanoscale heat transfer

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PROGRESS IN PHOTOACOUSTIC AND PHOTOTHERMAL PHENOMENA: FOCUS on BIOMEDICAL, NANOSCALE, NDE ANDTHERMOPHYSICAL PHENOMENA AND TECHNOLOGIES

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

Outline

- Heat exchange at the nanoscale
- Near-field regime
- Near-field thermodynamics and energy harvesting
- Control of thermal radiation: Radiative thermal shuttling effect

How heat propagates at the nanoscale?

-Heat exchange by conduction needs of a continuum medium to proceed.

$$J_q = -\lambda \nabla T$$

Fourier

-In nanoscale systems heat radiation is an important mechanism.

$$J_q = \sigma (T_2^4 - T_1^4)$$

Stefan-Boltzmann

-This law is not valid when distances are not much larger that the photon wave-lenght, in the near-field regime.

$$J_q = \sigma '(T_2^2 - T_1^2)$$

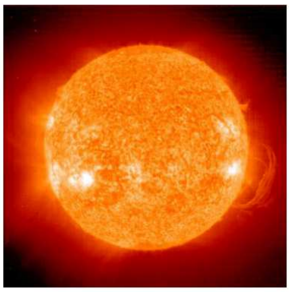
Near field

Equilibrium photon gas

$$S_0 = k_B N \ln \Omega$$

microstates

Energy conservation



$$N_\omega = \frac{1}{\exp\left(\frac{\hbar\omega}{kT}\right) - 1}$$

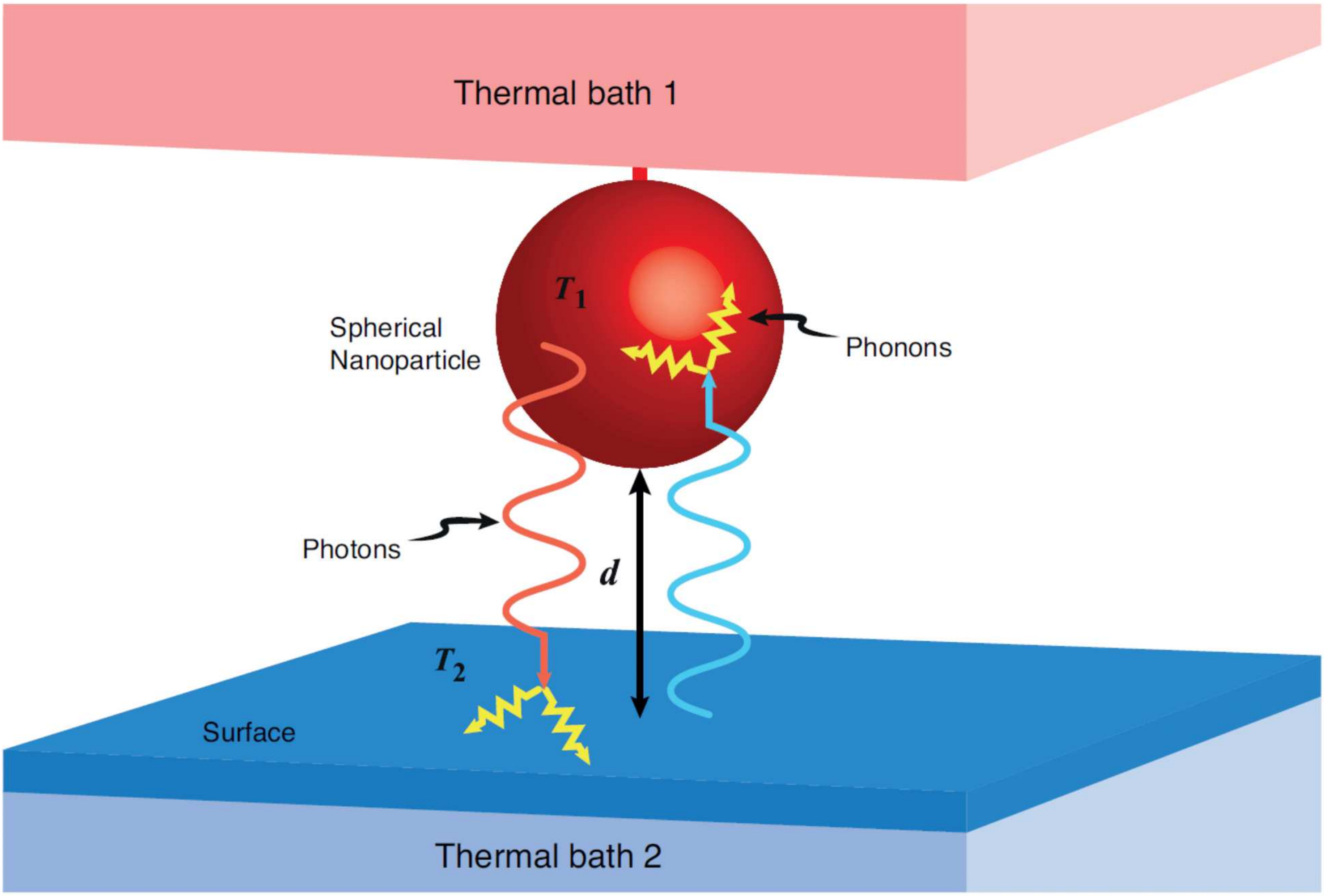
Planck distribution

TdS=dE

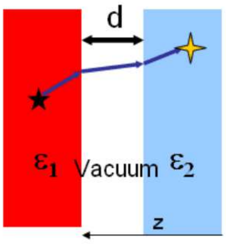
$$J_{eq} = \sigma T^4$$

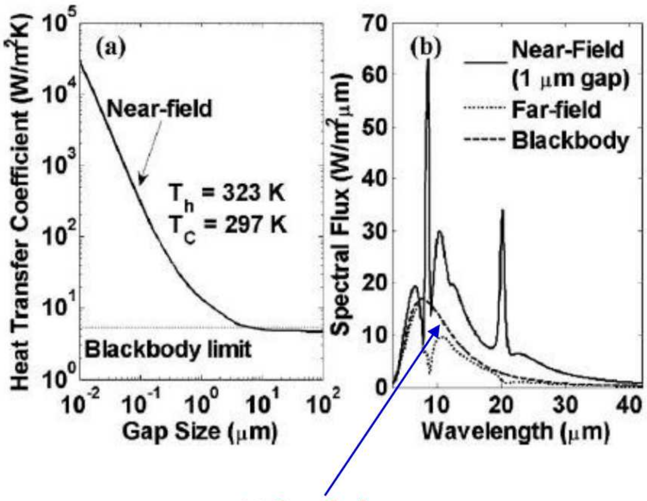
Stefan-Boltzmann

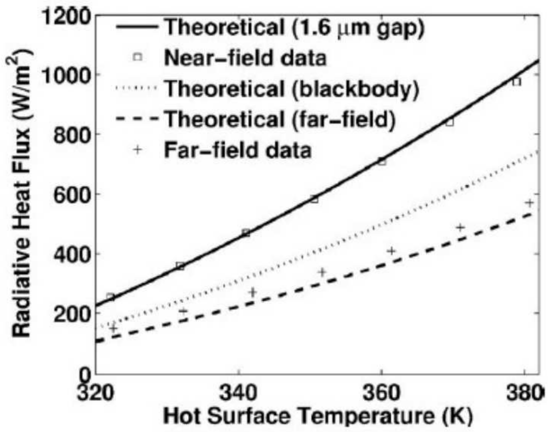
Planck's theory is not valid when length scales are comparable to the wave length of thermal radiation


Thermal bath 1
T_1
Spherical
Nanoparticle
Phonons
Photons
d
T_2
Surface
Thermal bath 2

Enhancement of the heat flux in the near-field







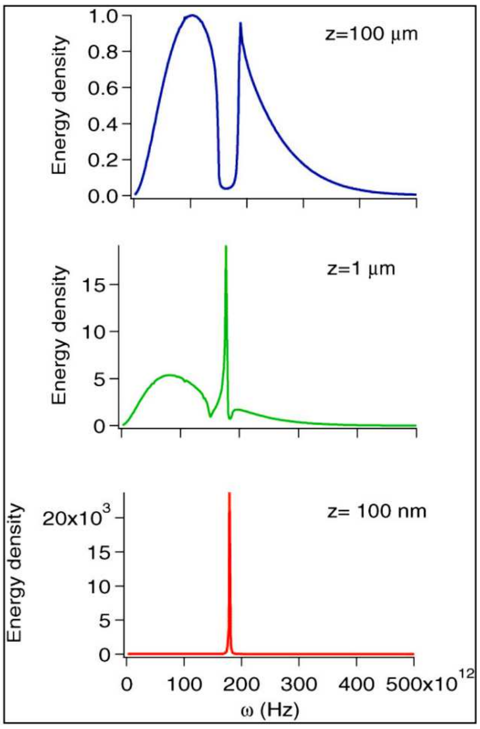
Wien's law

Hu et al., Appl. Phys. Lett. 92, 133106 (2008)

ELECTROMAGNETIC WAVES CONFINED IN A VERY NARROW GAP

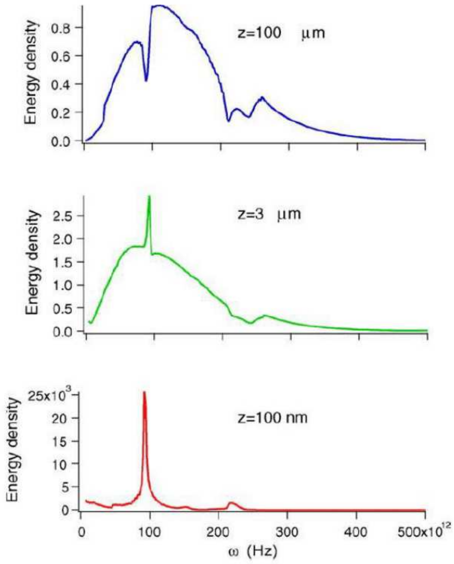
When the distance diminishes, thermal radiation becomes a highly directional beam of coherent radiation.

The narrow gap acts as a resonant cavity



Spectrum of electromagnetic energy for different detection distances above surface of silicon carbide normalized by its maximum value in far field at T= 300 K. (J.-J. Greffet and C. Henkel, 2007)

Electromagnetic energy density above a plane interface separating glass (amorphous, optical phonons poorly defined) at T = 300 K from vacuum at T = 0 K



Photon tunneling: near-field regime

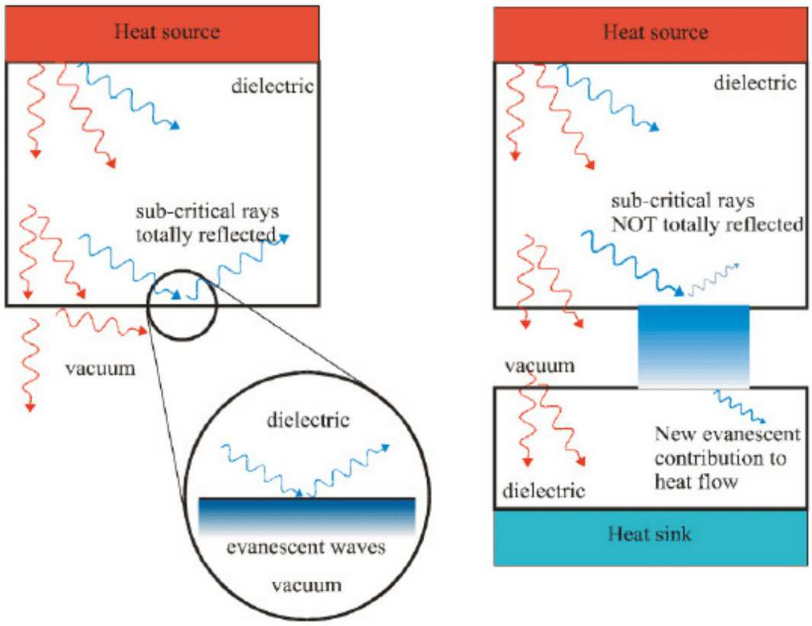
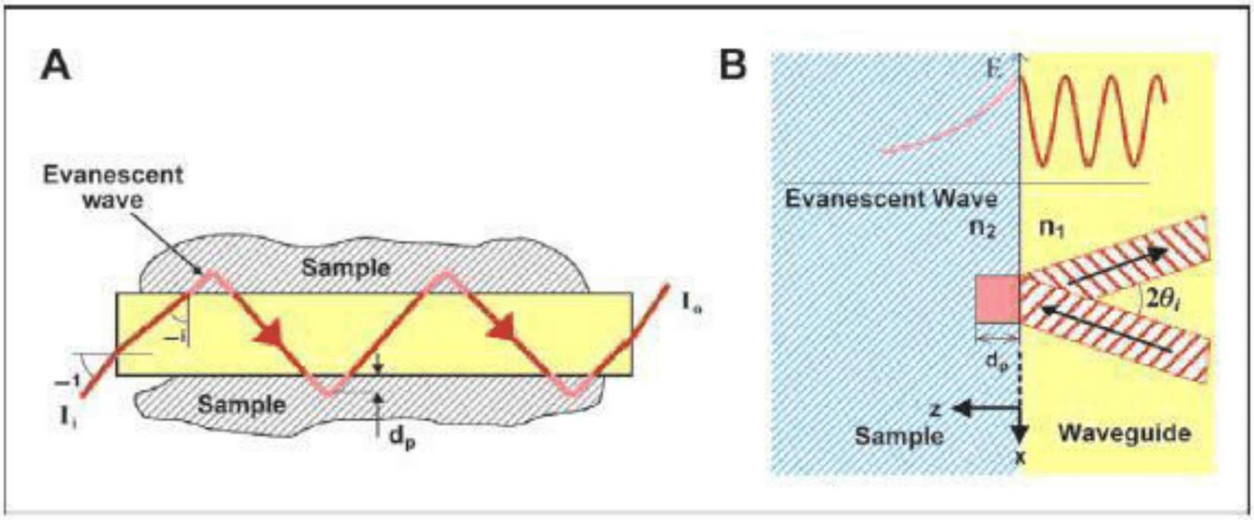


Figure: Evanescent waves play no role in heat loss from a hot dielectric surface to vacuum, left hand figure, but evanescent waves can carry heat from a hot to a cold dielectric surface, right hand figure. [J. B. Pendry, J. Phys.: Condens. Matter 11 (1999) 6621-6633]

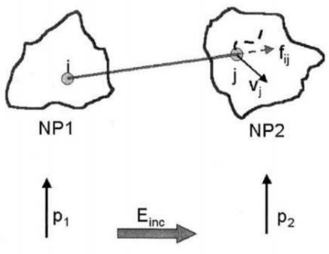
Heat flux much larger than blackbody limit! $\Phi_{\rm bb} = \sigma T^4$

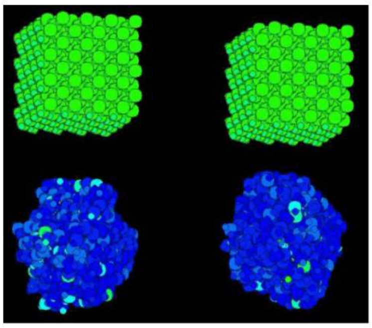
Evanescent waves

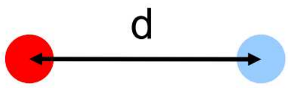


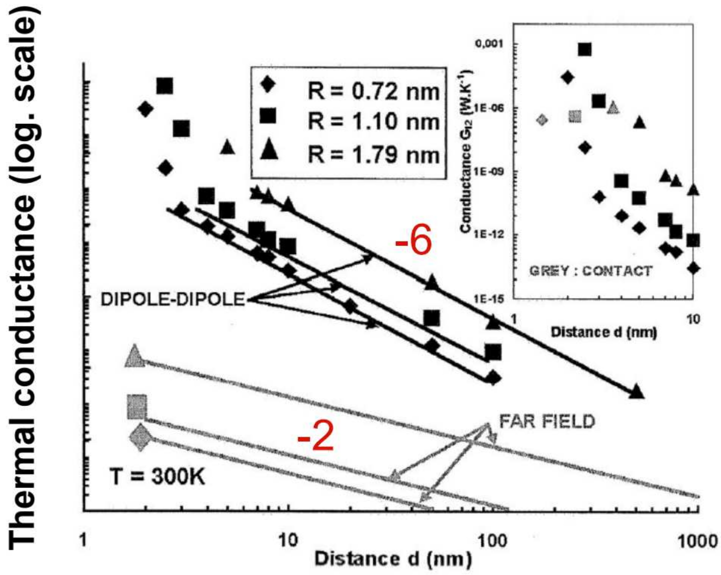
(A) *Evanescent wave in a waveguide, in contact with a sample.* (B) *Evanescent wave at the interface between two media, under total internal reflection.*

Power exchanged between nanoparticles









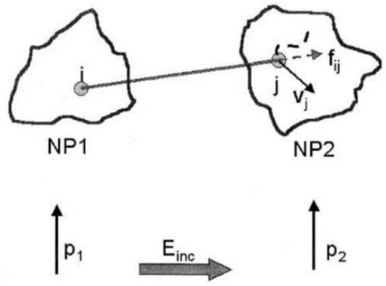
Verification with molecular dynamics (dielectric)

Domingues et al., Phys. Rev. Lett. 94, 085901 (2005)

Fluctuation-dissipation regime

Fluctuating electrodynamics

$$\mathbf{E}_{inc} = \mathbf{G} \cdot \mathbf{p}$$



$$Q_{1\longrightarrow 2}(\omega) = \frac{\omega\varepsilon_0}{2}\alpha_2'' \left|\mathbf{E}_{inc}(\mathbf{r}_2)\right|^2$$

$$\left|\mathbf{E}_{inc}(\mathbf{r}_2)\right|^2 \sim \langle p_k p_l \rangle$$

FDT

$$\langle p_k p_l \rangle = \frac{\varepsilon_0 \alpha_1''(\omega)}{\pi\omega}\Theta(\omega, T_1)\delta(\omega - \omega')\delta_{kl}$$

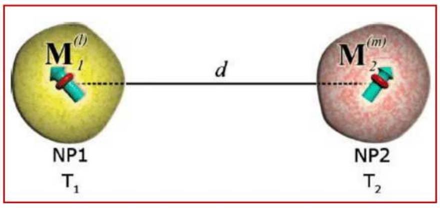
$$Q_{12}^{NF}(\omega) = \frac{3}{4\pi^3}\frac{\alpha_1''(\omega)\alpha_2''(\omega)}{d^6}\left[\Theta(\omega, T_1) - \Theta(\omega, T_2)\right]$$

Domingues et al., PRL, 94, 085901 (2005)

A. Perez, L. Lapas, J.M. Rubi, PRL, 103, 048301 (2009)

Valid when thermalization is very fast

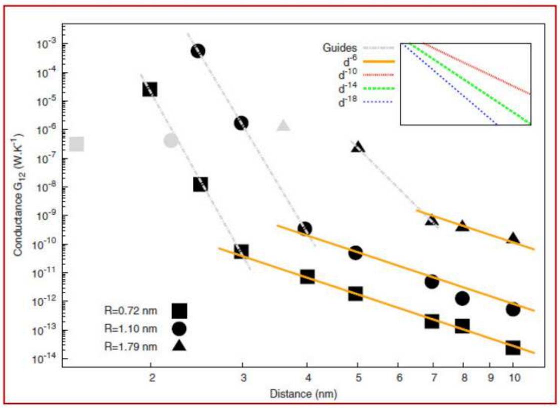
Beyond the dipolar approximation…

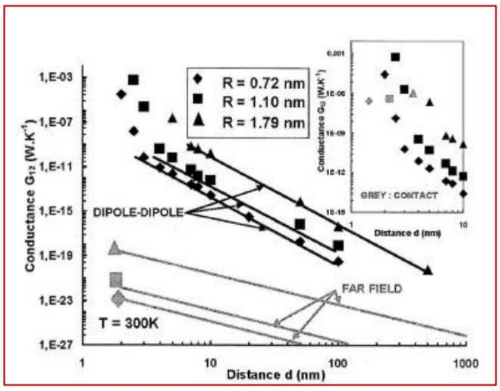


A.Pérez, J.M.Rubi., L. Lapas, Phys. Rev. B 77, 155417 (2008)

$$G_{12}^{dip}(T_0) = \frac{3}{8\pi^3}\left(\int_0^\infty \Theta'(\omega, T_0)\alpha''_{(1)}\alpha''_{(2)}d\omega\right)d^{-6}$$

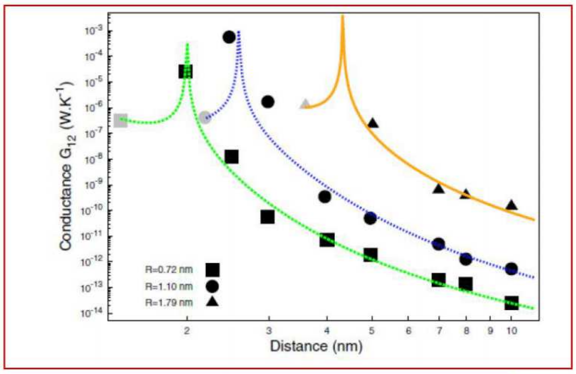
$$G_{12}^{qd}(T_0) \;=\; \frac{1}{2\pi^3}\int_0^\infty \Theta'(\omega, T_0)\left\{45\left(\alpha''_{(1)}\beta''_{(2)} + \;\alpha''_{(2)}\beta''_{(1)}\right)d^{-8} + \frac{15}{4}\,\beta''_{(1)}(\omega)\beta''_{(2)}(\omega)d^{-10}\right\}d\omega$$



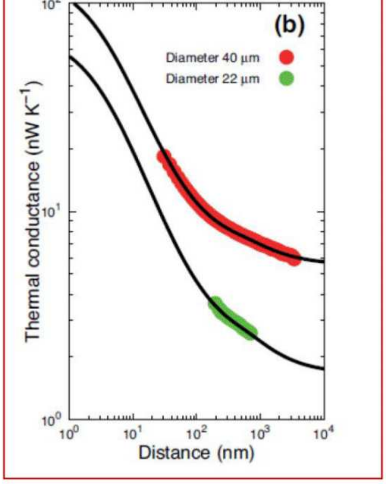


Dipolar approximation: d>8R

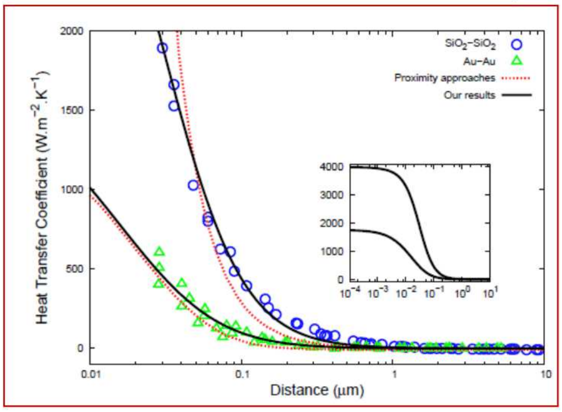
Domingues *et al.*,PRL, 94, 085901 (2005)



[10] G. Domingues, S. Volz, K. Joulain, and J.-J. Greffet, Phys. Rev. Lett. **94** (2005), 085901.



[6] E. Rousseau, A. Siria, G. Jourdan, S. Volz, F. Comin, J. Chevrier, and J.-J. Greffet, Nature Photon. **3** (2009), 514.

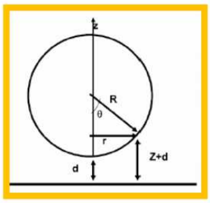


S. Shen, A. Mavrokefalos, P. Sambegoro, and G. Chen, Appl. Phys. Lett. 100, 233114 (2012).

Proximity approximation:

$$G = (1/A)\int_0^R H[\tilde{d}(r), T_0] 2\pi r dr$$

$$\tilde{d}(r) = d + b + R - \sqrt{R^2 - r^2}$$



-A. Perez-Madrid, L. Lapas, J.M. Rubi, Phys. Rev. Lett., 103, 148301 (2009); Plos One, 8, e58770 (2013)

-L.Lapas, A. Perez-Mdrid, J.M.Rubi, Phys. Rev. Lett., **116, 110601 (2016)**

Near-field thermodynamics and energy harvesting

Questions:

-How much work can we extract from the radiation?
What is the efficiency of the process?
How to compute the dissipation?

-What is the optimal structure for heat transfer?

Thermodynamics for the NF

Thermodynamics of thermal radiation

Energy flux radiated:

$$\dot{U}(T) = \int_0^\infty d\omega\, \hbar\omega n(\omega, T)\varphi(\omega)$$

$$n(\omega, T) = \left(e^{\hbar\omega/k_B T} - 1\right)^{-1}$$

Spectral flux of modes

Entropy flux:

$$\frac{1}{T} = \frac{d\dot{S}}{d\dot{U}}.$$

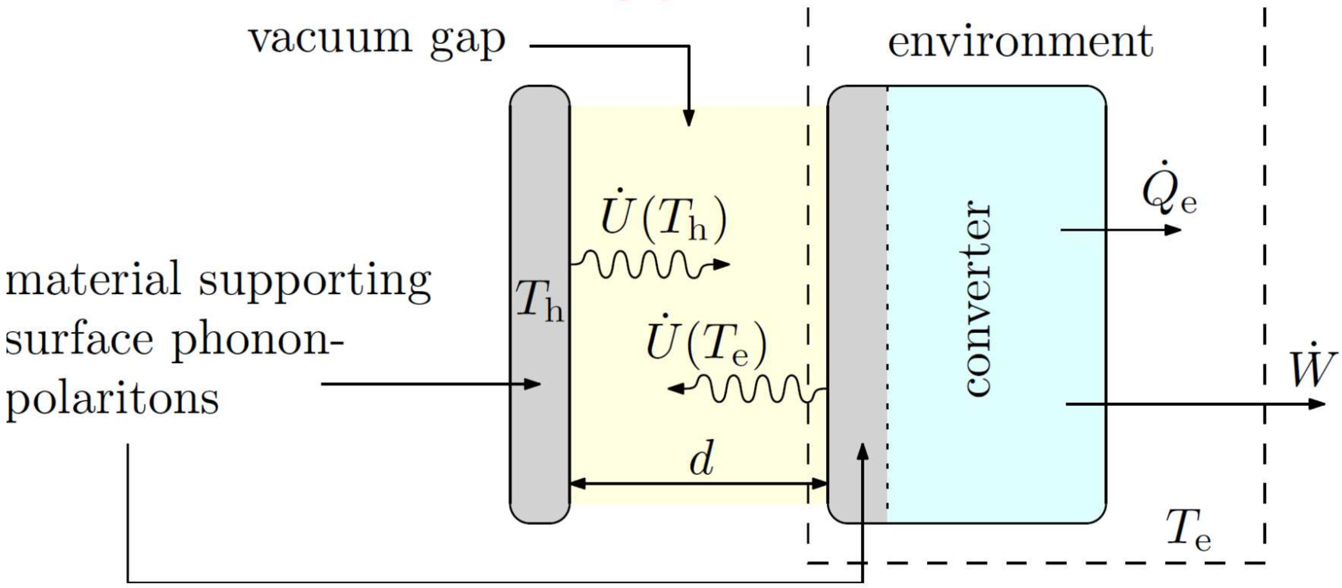
$$\dot{S}(T) = \int_0^T dT' \frac{1}{T'} \frac{d\dot{U}(T')}{dT'}$$

$$\dot{S}(T) = \int_0^\infty d\omega\, k_B m(\omega, T)\varphi(\omega)$$

$$m(\omega, T) = [1 + n(\omega, T)]\ln[1 + n(\omega, T)] - n(\omega, T)\ln n(\omega, T),$$

I. Latella, A. Pérez-Madrid , L. C. Lapas, J. M. Rubi
J. Appl. Phys. 115, 124307 (2014)

Energy conversion



1st Law:

$$\Delta\dot{U} + \dot{Q}_e + \dot{W} = 0,$$

$$\Delta\dot{U} = \dot{U}(T_e) - \dot{U}(T_h)$$

2nd Law:

$$\Delta\dot{S} + \Delta\dot{S}_e = \Delta\dot{S}_{irr} \geq 0,$$

$$\Delta\dot{S} = \dot{S}(T_e) - \dot{S}(T_h)$$

$$\Delta\dot{S}_e = \dot{Q}_e/T_e$$

Efficiency

Work:

$$\dot{W} = T_e \Delta \dot{S} - \Delta \dot{U} - T_e \Delta \dot{S}_{irr}$$

Ideal work:

$$\dot{\mathcal{W}} \equiv T_e \Delta \dot{S} - \Delta \dot{U}$$

$$\eta \equiv \frac{\dot{W}}{\dot{U}(T_h)} = \frac{\dot{\mathcal{W}} - T_e \Delta \dot{S}_{irr}}{\dot{U}(T_h)}$$

$$\bar{\eta} = \frac{\dot{\mathcal{W}}}{\dot{U}(T_h)} \geq \eta.$$

$$\Delta\dot{U} = \int_0^\infty d\omega\, \hbar\omega [n(\omega, T_2) - n(\omega, T_1)] \varphi(\omega)$$

Spectral flux of modes:

$$\varphi(\omega) = \sum_{\alpha=\mathrm{p,s}} \left\{ \int_0^{\omega/c} \frac{d\kappa\, \kappa}{4\pi^2} \frac{[1 - |R_\alpha(\kappa, \omega)|^2]^2}{|1 - e^{2i\gamma d} R_\alpha^2(\kappa, \omega)|^2} + \int_{\omega/c}^\infty \frac{d\kappa\, \kappa}{\pi^2} \frac{e^{-2|\gamma| d} \mathrm{Im}^2[R_\alpha(\kappa, \omega)]}{|1 - e^{-2|\gamma| d} R_\alpha^2(\kappa, \omega)|^2} \right\}.$$

$$\gamma = \sqrt{(\omega/c)^2 - \kappa^2}$$

Lorentz model:

$$\varepsilon(\omega) = \varepsilon_\infty \frac{\omega_{\mathrm{L}}^2 - \omega^2 - i\Gamma\omega}{\omega_{\mathrm{T}}^2 - \omega^2 - i\Gamma\omega}$$

When:

$$d \ll \lambda_T = c\hbar / k_{\mathrm{B}} T$$

$\lambda_T = 7.6\,\mu\mathrm{m}$ for $T = 300\,\mathrm{K}$

Emission is dominated by SPPs

Ex.: SiC, hBN

Black body radiation

The reflection coefficient vanishes:

$$\varphi_{\mathrm{bb}}(\omega) = \left(\frac{\omega}{2\pi c}\right)^2$$

$$\dot{U}_{\mathrm{bb}} = \sigma T^4$$

$$\dot{S}_{\mathrm{bb}} = 4\sigma T^3/3$$

$$\dot{\mathcal{W}}_{\mathrm{bb}} = \sigma\left(T_{\mathrm{h}}^4 - T_{\mathrm{e}}^4\right) - \frac{4}{3}\sigma T_{\mathrm{e}}\left(T_{\mathrm{h}}^3 - T_{\mathrm{e}}^3\right)$$

$$\overline{\eta}_{\mathrm{bb}} = 1 - \frac{4}{3}\frac{T_{\mathrm{e}}}{T_{\mathrm{h}}} + \frac{1}{3}\left(\frac{T_{\mathrm{e}}}{T_{\mathrm{h}}}\right)^4$$

Near-field

When the surfaces are close enough the spectral flux of modes is dominated by p-polarized evanescent modes

$$\dot{U}_{\rm nf}(T) = \int_0^\infty d\omega\, \hbar\omega n(\omega,T)\frac{\mathrm{Im}[\mathrm{Li}_2(R_{\rm p}^2(\omega))]}{4\pi^2 d^2 f(\omega)},$$

$$\simeq \hbar\omega_0 n_0(T)\frac{\mathrm{Re}[\mathrm{Li}_2(R_{\rm p}^2(\omega_0))]}{4\pi d^2 f'(\omega_0)},$$

$$R_{\rm p}(\omega) = \frac{\varepsilon(\omega)-1}{\varepsilon(\omega)+1}$$

$$f(\omega) = \frac{\mathrm{Im}[R_{\rm p}^2(\omega)]}{\mathrm{Im}^2[R_{\rm p}(\omega)]}$$

Radiation highly monochromatic

$$\omega_0 = \left(\frac{\varepsilon_\infty\omega_{\rm L}^2+\omega_{\rm T}^2}{\varepsilon_\infty+1}\right)^{1/2}$$

$$\varphi_{\rm nf}(\omega) = g_d(\omega)\delta(\omega-\omega_0)$$

$$g_d(\omega) = \frac{\mathrm{Re}[\mathrm{Li}_2(R_{\rm p}^2(\omega))]}{4\pi d^2 f'(\omega)}$$

$$\dot{S}_{\rm nf}(T) = \int_0^\infty d\omega\, k_{\rm B} m(\omega,T)\varphi_{\rm nf}(\omega) = k_{\rm B} m_0(T) g_d(\omega_0)$$

Work:

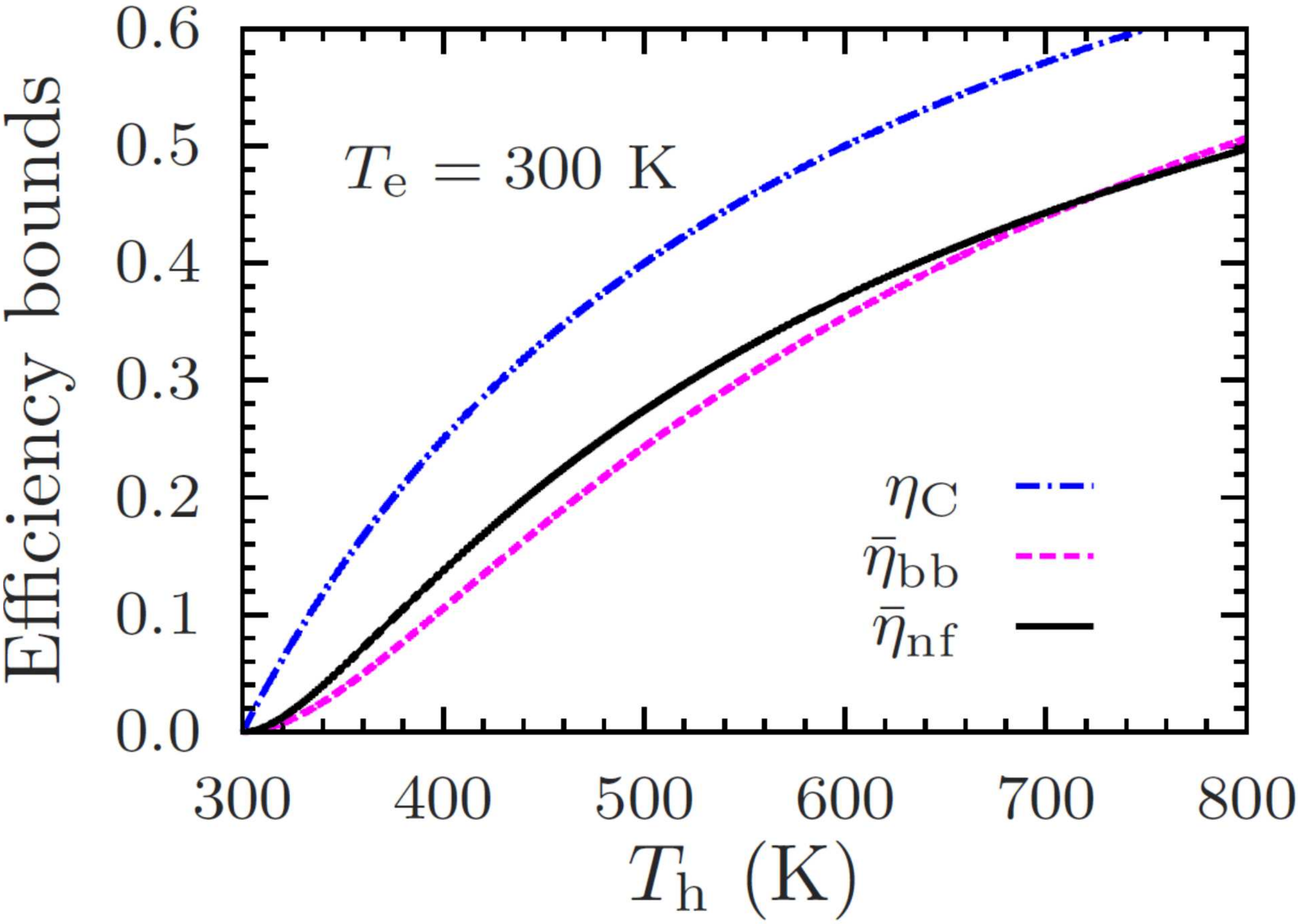
$$\dot{\mathcal{W}}_{\rm nf} = \hbar\omega_0 g_d(\omega_0)\left\{ \frac{k_{\rm B}T_{\rm e}}{\hbar\omega_0}[m_0(T_{\rm e}) - m_0(T_{\rm h})] - [n_0(T_{\rm e}) - n_0(T_{\rm h})]\right\}.$$

Efficiency:

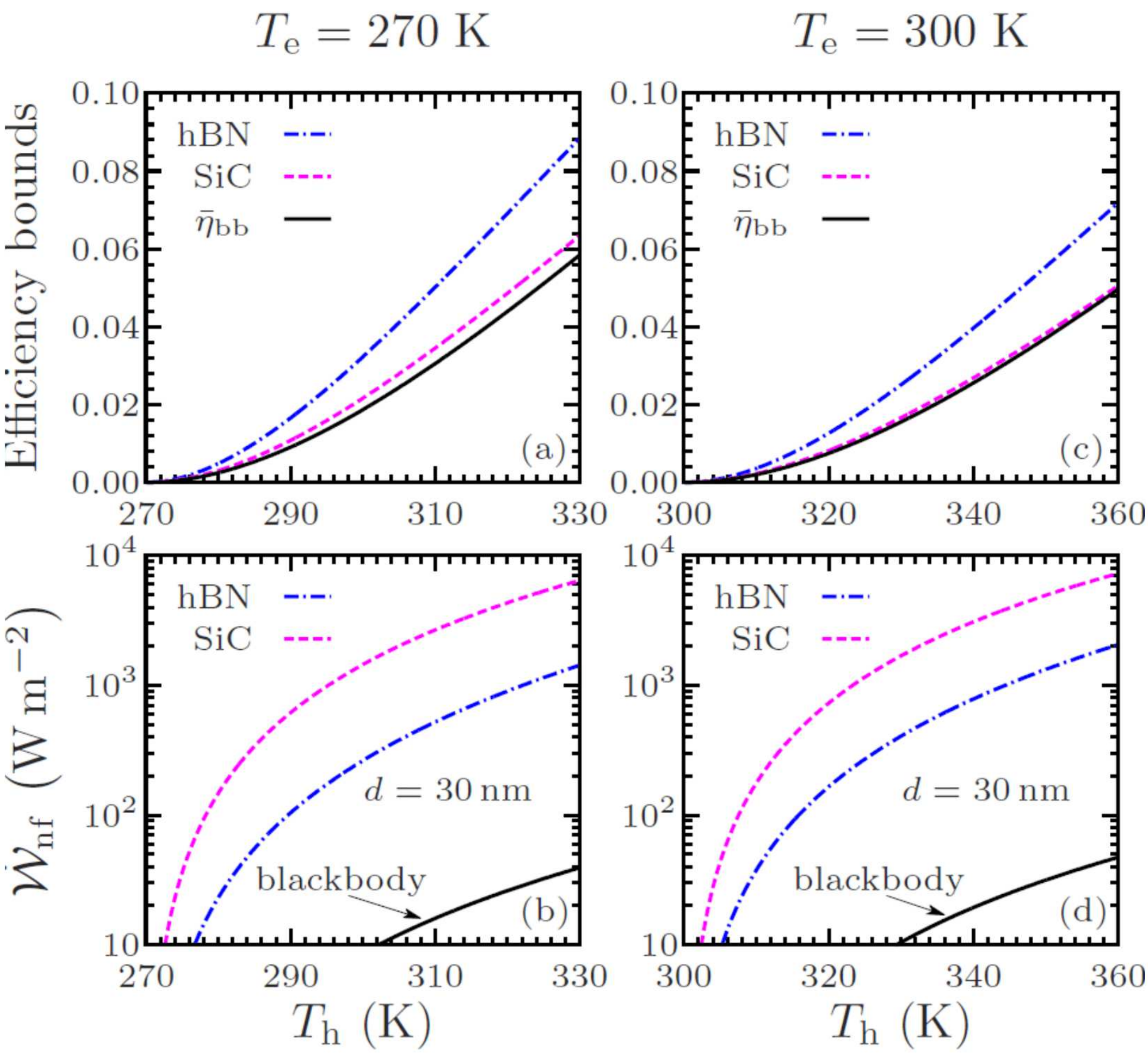
$$\bar{\eta}_{\rm nf} = 1 - \frac{n_0(T_{\rm e})}{n_0(T_{\rm h})} + \frac{k_{\rm B}T_{\rm e}}{\hbar\omega_0}\frac{m_0(T_{\rm e}) - m_0(T_{\rm h})}{n_0(T_{\rm h})}$$

Carnot efficiency:

$$\lim_{\omega_0\to\infty}\bar{\eta}_{\rm nf} = 1 - T_{\rm e}/T_{\rm h}$$

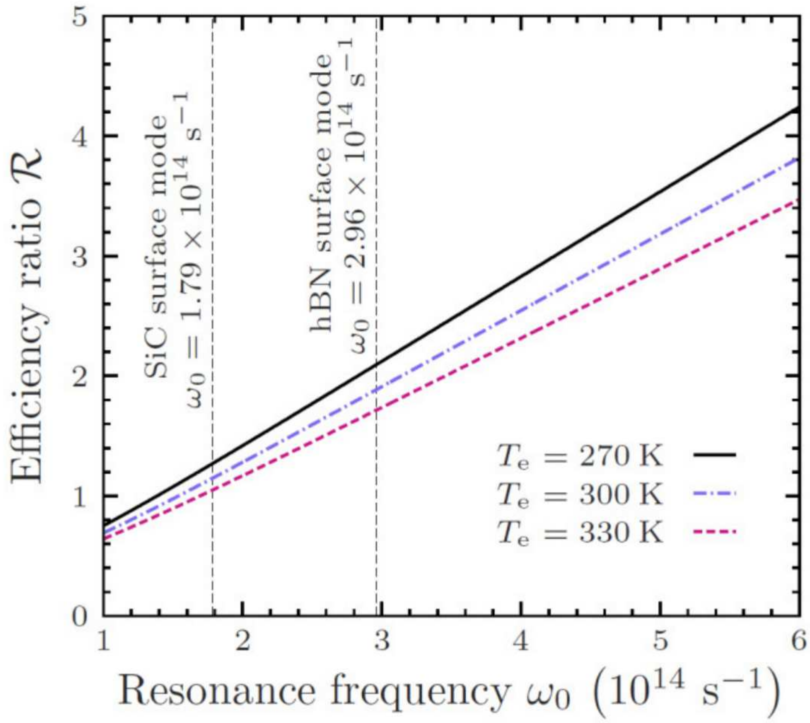


0.6
0.5
0.4
0.3
0.2
0.1
0.0
Efficiency bounds
$T_e = 300$ K
η_C
$\bar{\eta}_{bb}$
$\bar{\eta}_{nf}$
300
400
500
600
700
800
T_h (K)



$T_e = 270$ K
$T_e = 300$ K
Efficiency bounds
hBN
SiC
$\bar{\eta}_{bb}$
(a)
(c)
$\dot{\mathcal{W}}_{nf}$ (W m^{-2})
$d = 30$ nm
blackbody
(b)
(d)
T_h (K)

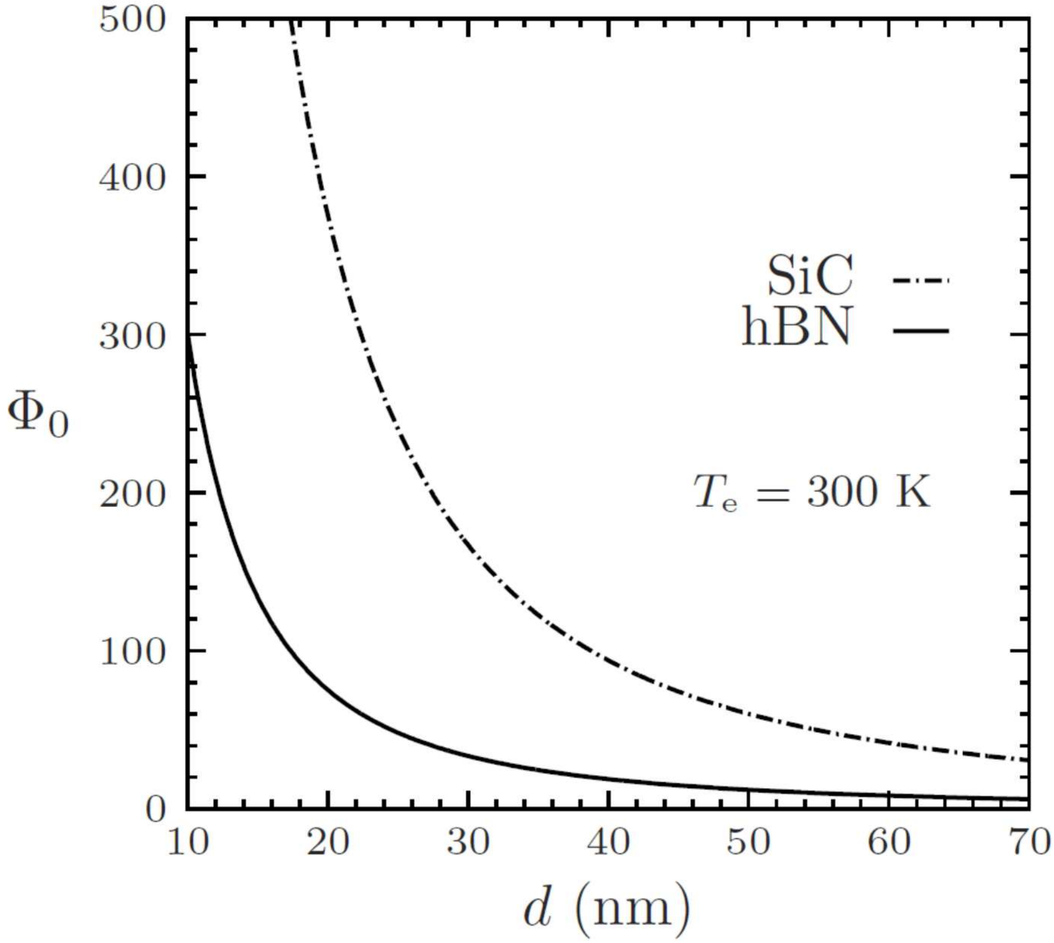
$$\bar{\eta}_{\rm bb} = 1 - \frac{4}{3}\frac{T_{\rm e}}{T_{\rm h}} + \frac{1}{3}\left(\frac{T_{\rm e}}{T_{\rm h}}\right)^4$$



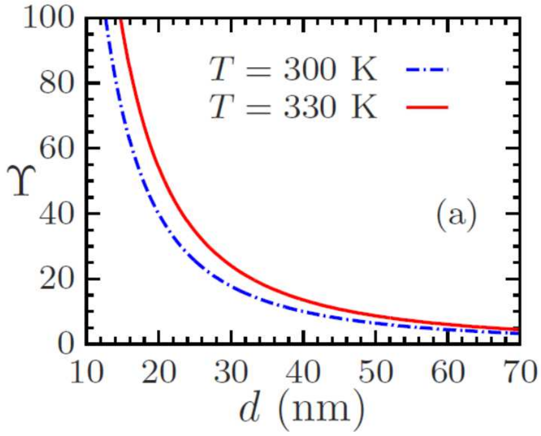
$$\mathcal{R} \equiv \lim_{T_{\rm h}\to T_{\rm e}} \frac{\bar{\eta}_{\rm nf}}{\bar{\eta}_{\rm bb}} = \frac{\hbar\omega_0}{4k_{\rm B}T_{\rm e}}\left[1 - \exp\left(-\frac{\hbar\omega_0}{k_{\rm B}T_{\rm e}}\right)\right]^{-1}$$

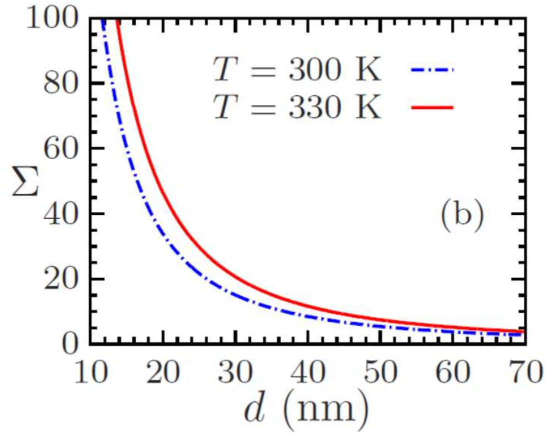
$\bar{\eta}_{\rm nf} > \bar{\eta}_{\rm bb}$ $\qquad$ $\omega_0 > 3.921\,\frac{k_{\rm B}T_{\rm e}}{\hbar}$

$\Phi_0 = \dot{\mathcal{W}}_{\rm nf}/\dot{\mathcal{W}}_{\rm bb}$



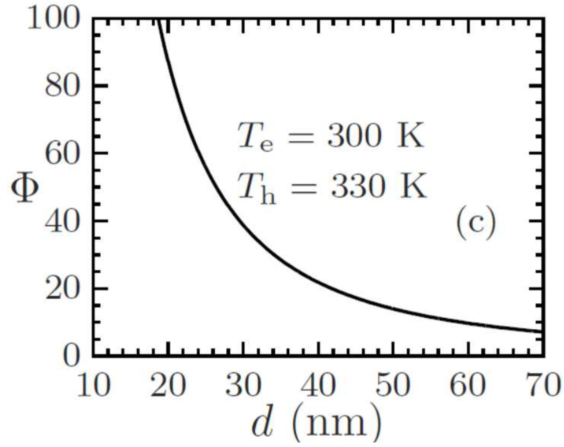
Comparison with blackbody





$$\Upsilon(d,T) \equiv \dot{U}_{\mathsf{nf}}(d,T)/\dot{U}_{\mathsf{bb}}(T)$$

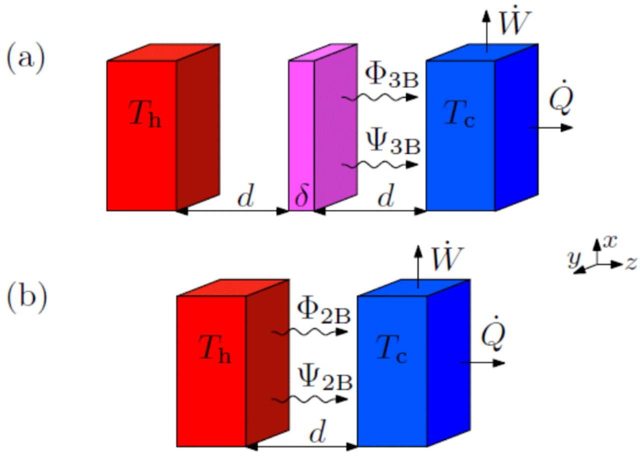
$$\Sigma(d,T) \equiv \dot{S}_{\mathsf{nf}}(d,T)/\dot{S}_{\mathsf{bb}}(T)$$



$$\Phi(d,T_h,T_e) \equiv \dot{\mathcal{W}}_{\mathsf{nf}}(d,T_h,T_e)/\dot{\mathcal{W}}_{\mathsf{bb}}(T_h,T_e)$$

What is the optimal structure for heat transmission?

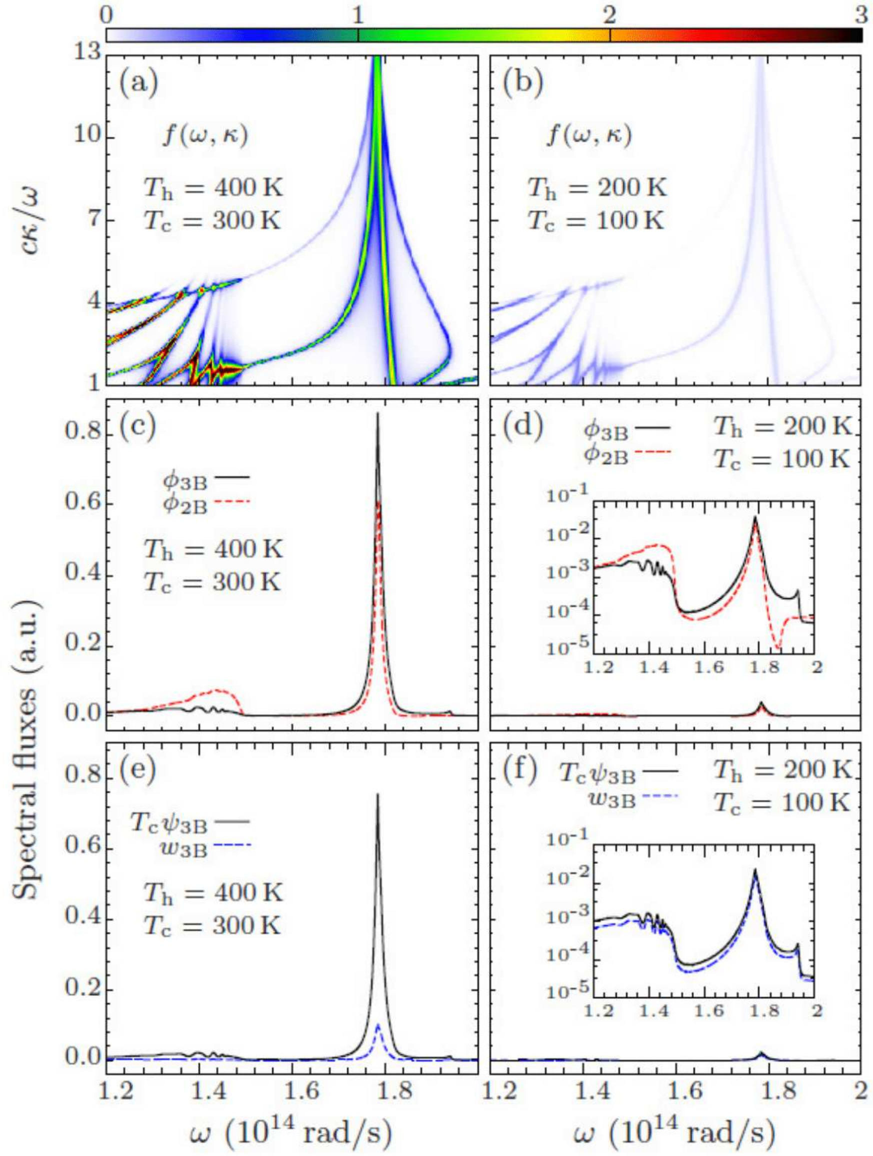
- two 5 μm-thick SiC samples: SPP at $\omega_{\rm spp} \simeq 1.79 \times 10^{14}$ rad/s
- metal-like medium: surface mode (a plasmon) at $\omega_{\rm spp}$



Near-field:

$d \ll \lambda_T = \hbar c/(k_B T)$, $\lambda_T = 7.6\,\mu$m for $T = 300$ K

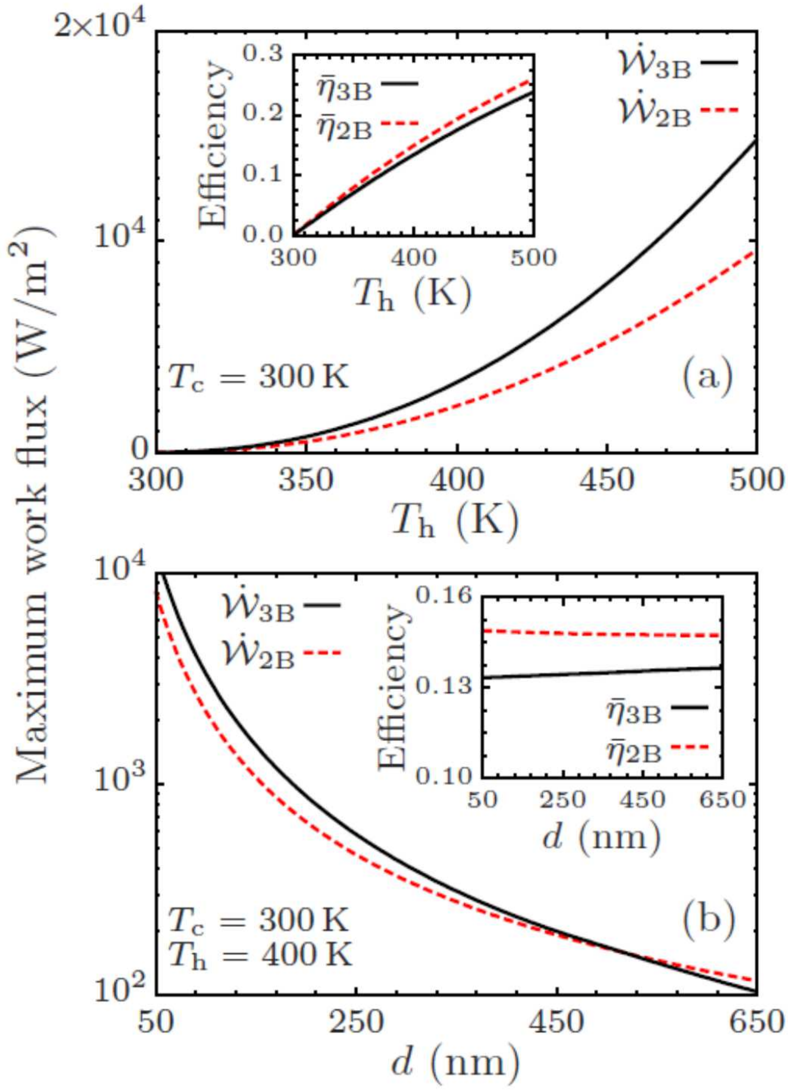
I. Latella, A. Pérez-Madrid, J. M. Rubi, S. Biehs, P. Ben-Abdallah, Phys. Rev. App. 4, 011001 (2015)



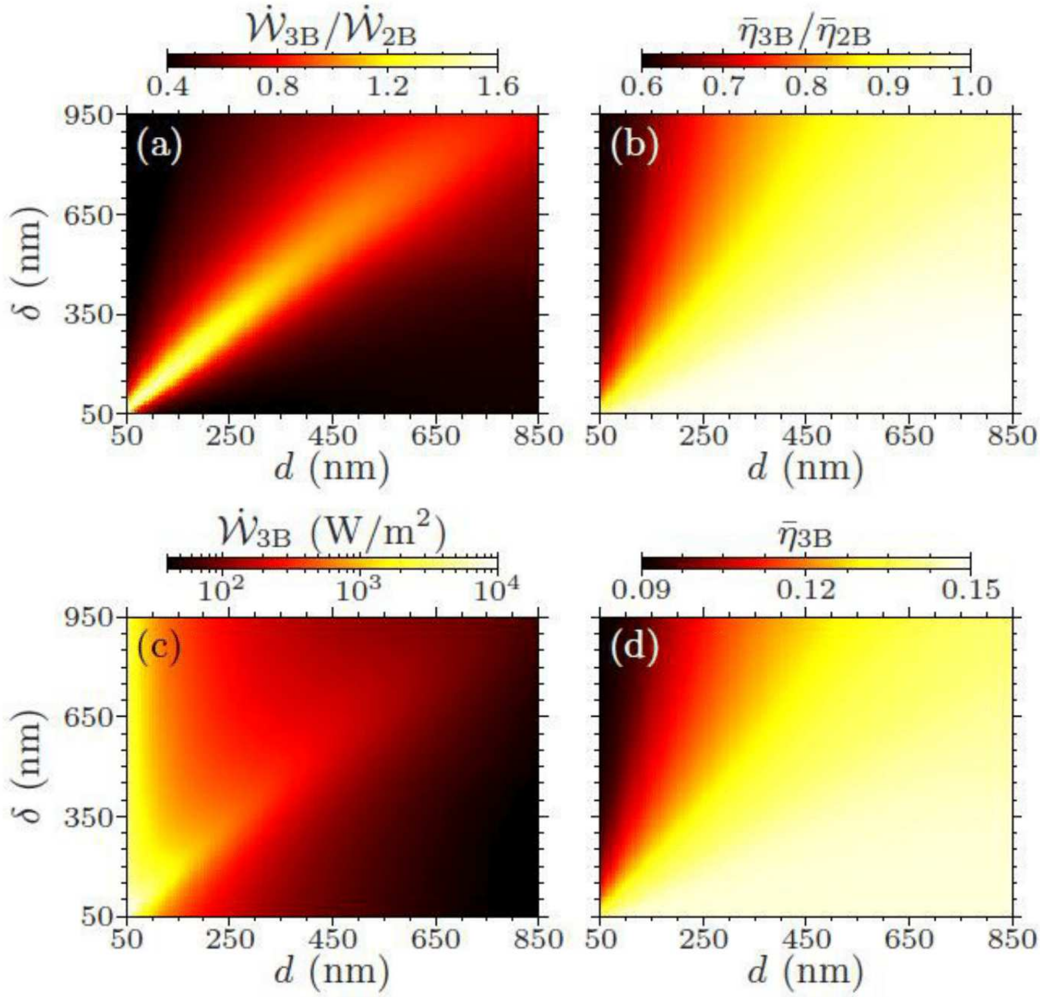
$d = 500$ nm and $\delta = 667$ nm

$$f(\omega, \kappa) = 10^{22} \times \left(n_{hi} \mathcal{T}_p^{(hi)} + n_{ic} \mathcal{T}_p^{(ic)} \right)$$

$$w_{3B} = \phi_{3B} - T_c \psi_{3B}$$

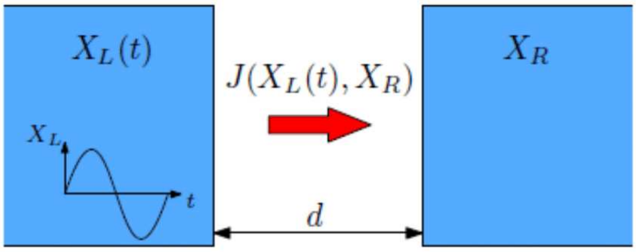


Maximum work flux (W/m^2)
$\dot{\mathcal{W}}_{3B}$
$\dot{\mathcal{W}}_{2B}$
Efficiency
$\bar{\eta}_{3B}$
$\bar{\eta}_{2B}$
T_h (K)
$T_c = 300$ K
(a)
d (nm)
$T_c = 300$ K
$T_h = 400$ K
(b)



(a)
(b)
(c)
(d)
$\dot{\mathcal{W}}_{3B}/\dot{\mathcal{W}}_{2B}$
0.4 0.8 1.2 1.6
$\bar{\eta}_{3B}/\bar{\eta}_{2B}$
0.6 0.7 0.8 0.9 1.0
$\dot{\mathcal{W}}_{3B}$ (W/m^2)
10^2 10^3 10^4
$\bar{\eta}_{3B}$
0.09 0.12 0.15
δ (nm)
950 650 350 50
d (nm)
50 250 450 650 850

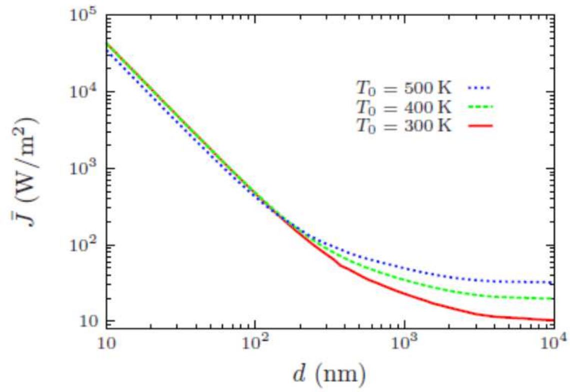
Control of thermal radiation:
Radiative thermal shuttling effect



$$X_L(t) = x_L + \delta X \sin(\Omega t)$$
$$X_R = x_R,$$

$$X : T, \mu$$

Enhancing the heat exchange



Novel strategy for an active management
Of radiative exchanges

I. Latella, R. Messina, J. M. Rubi, P. Ben-Abdallah
Phys. Rev. Lett. 121, 023903 (2018)

Conclusions

- Enhancement of the heat conductance in the near-field regime.
- Near-field thermodynamics, **NFT**
- We show that the maximum work that can be obtained from the thermal radiation emitted between two planar sources in the **near-field** regime is much larger than that corresponding to the **blackbody limit**.
- We also show that thermal radiation energy conversion can be **more efficient** in the near-field regime.
- New possibilities for the design of **energy converters** that can be used to harvest energy from sources of moderate temperature at the nanoscale