Near-field heat transfer and thermal emission control with complex plasmonic systems

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cnrs advancing the frontiers

"Nanoscale Radiative Heat Transfer, Les Houches, 2013"

INSTITUT d'OPTIQUE GRADUATE SCHOOL

Collaborations

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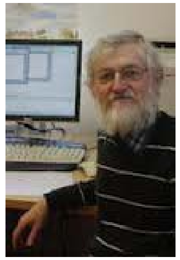

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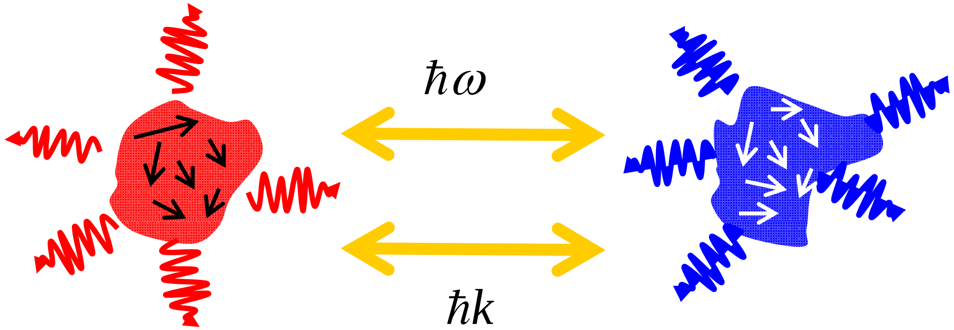


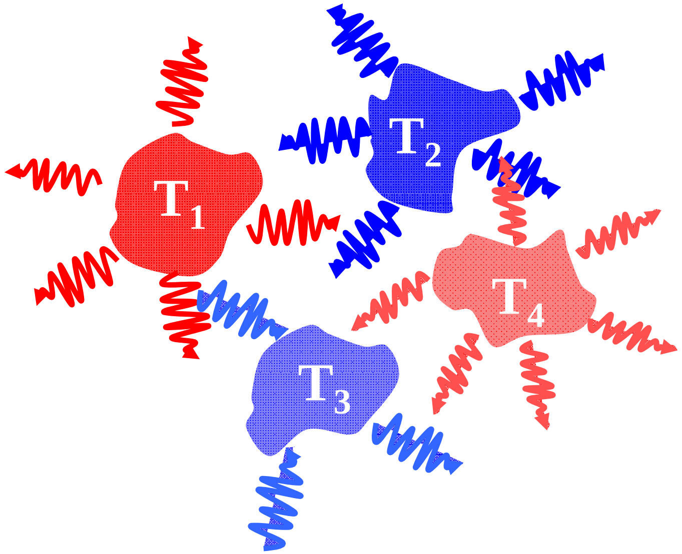
Fluctuating and uncorrelated local sources lead to :

- energy and momentum exchange

These exchanges are well described by the fluctuational electrodynamic theory (Rytov)

applied to
- Radiative heat transfer (Polder and Van Hove)
- Casimir force (Lifschitz)

Open questions



● How does the heat and momentum transport for a collection of individual objects in mutual interaction look like?

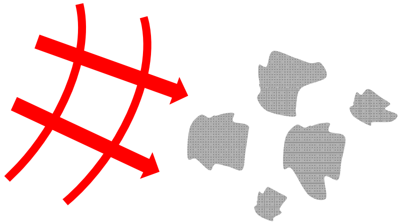
●Are there specific many body effects?

●What relation between disorder and heat transport?

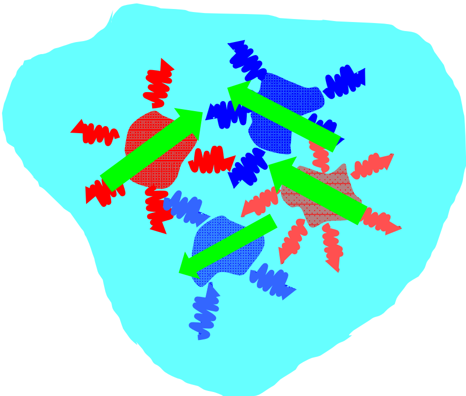
etc…

Needs a N-body heat and momentum transfer theory

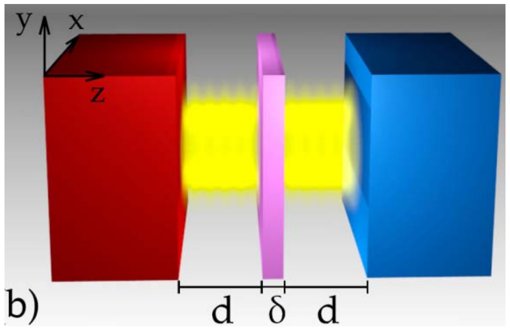
Outline



- I) Engineering the light absorption spectrum from multiple scattering interactions in dipolar systems

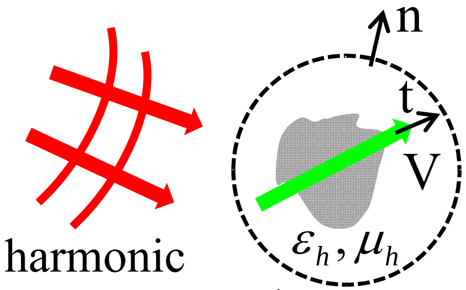


- II) Near-field heat transfer in many body systems : dipolar approximation



- III) Many body heat transfer beyond the dipolar approximation

Engineering light absorption from multiple scattering interactions : absorption by a simple particle



Rate of doing work by the em field in a volume V :

$$\wp(\omega) = \frac{1}{2}\int_V \mathrm{Re}(j^*.E)dV$$

Poynting theorem (energy conservation):

$$\frac{1}{2}\int_V j^*.EdV = -\frac{1}{2}\int_V \nabla.[E\times H^*]dV + i\frac{\omega}{2}\int_V (\mu_h|H|^2 - \varepsilon_h^*|E|^2)dV$$

In a transparent host medium $\wp(\omega) = \underbrace{-\frac{1}{2}\int_S \mathrm{Re}[E\times H^*.n]dS}_{\text{Poynting flux}}$

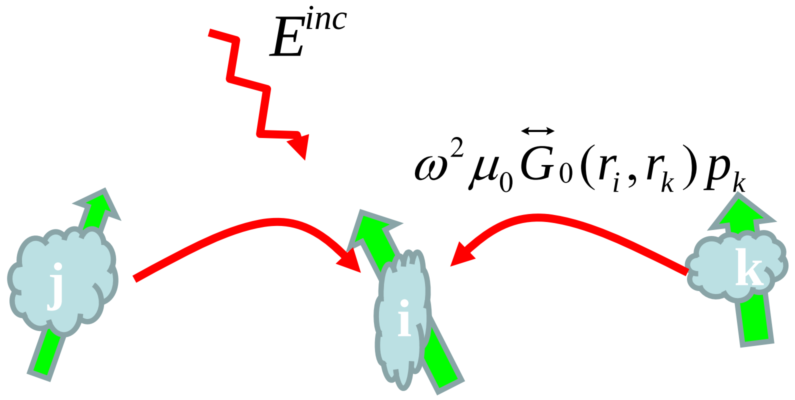
Also we have

$$E(r) = E^{ext} + i\omega\mu_0\int_V \overleftrightarrow{G}_0(r,r')j(r')dr' \quad + \quad j(r) = -i\omega p\delta(r)$$

Thus

$$\wp(\omega) = -\frac{\omega}{2}\mathrm{Im}[p^*E^{inc}(0)] - \frac{\omega^3|p|^2\mu_0}{2}t.\mathrm{Im}[\overleftrightarrow{G}_0(0,0)].t$$

Engineering light absorption from multiple scattering interactions : absorption by a set of particles

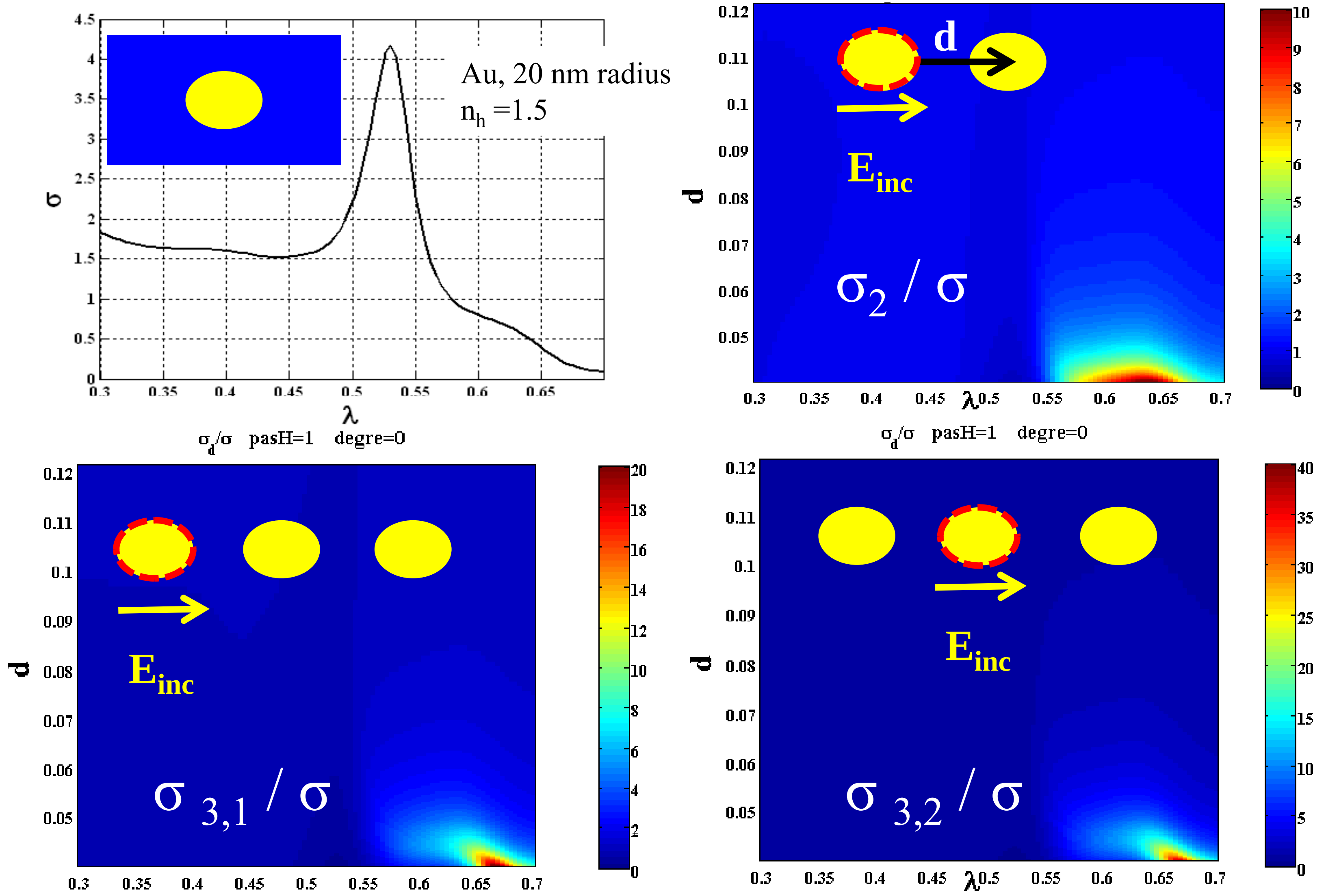


External field on the particle i: $E_i^{ext} = E_i^{inc} + \omega^2 \mu_0 \sum_{j \neq i} \overleftrightarrow{G}_0(r_i, r_j)\, p_j$

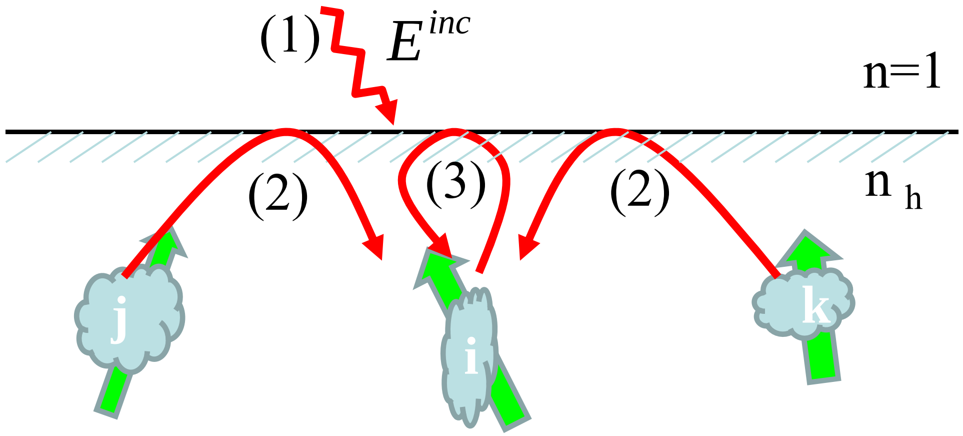
Thus

$$\wp_i(\omega) = -\frac{\omega}{2} \mathrm{Im}[p_i^{*} E_i^{inc}] - \frac{\omega^3 \mu_0}{2} |p_i|^2 t_i . \overleftrightarrow{G}_0(r_i, r_i) . t_i - \underbrace{\frac{\omega^3 \mu_0}{2} \mathrm{Im}[p_i^{*} \sum_{j \neq i} \overleftrightarrow{G}_0(r_i, r_j) . p_j]}_{\text{Multiple interactions}}$$

Engineering light absorption : dressed absorption in dipolar chains



Engineering light absorption: design of an absorber



$$\Delta G \equiv G - G_0$$

Find the optimal distribution of dipoles to get an absorption spectrum target

$$\underbrace{E_i^{ext} = E_i^{inc}}_{(1)} + \underbrace{\omega^2 \mu_0 \sum_{j \neq i} \overleftrightarrow{G}(r_i, r_j) p_j}_{(2)} + \underbrace{\Delta \overleftrightarrow{G}(r_i, r_i) p_i}_{(3)}$$

$$\wp_i(\omega) = -\frac{\omega}{2} \mathrm{Im}[p_i^* E_i^{ext}] - \frac{\omega^3 \mu_0}{2} p_i^* . \mathrm{Im}[\overleftrightarrow{G}_0(r_i, r_i)] . p_i$$

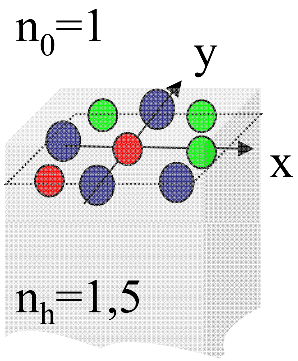
$$a = 1 - T - R \equiv \frac{\sum_i \wp_i}{A \Phi_{inc}}$$

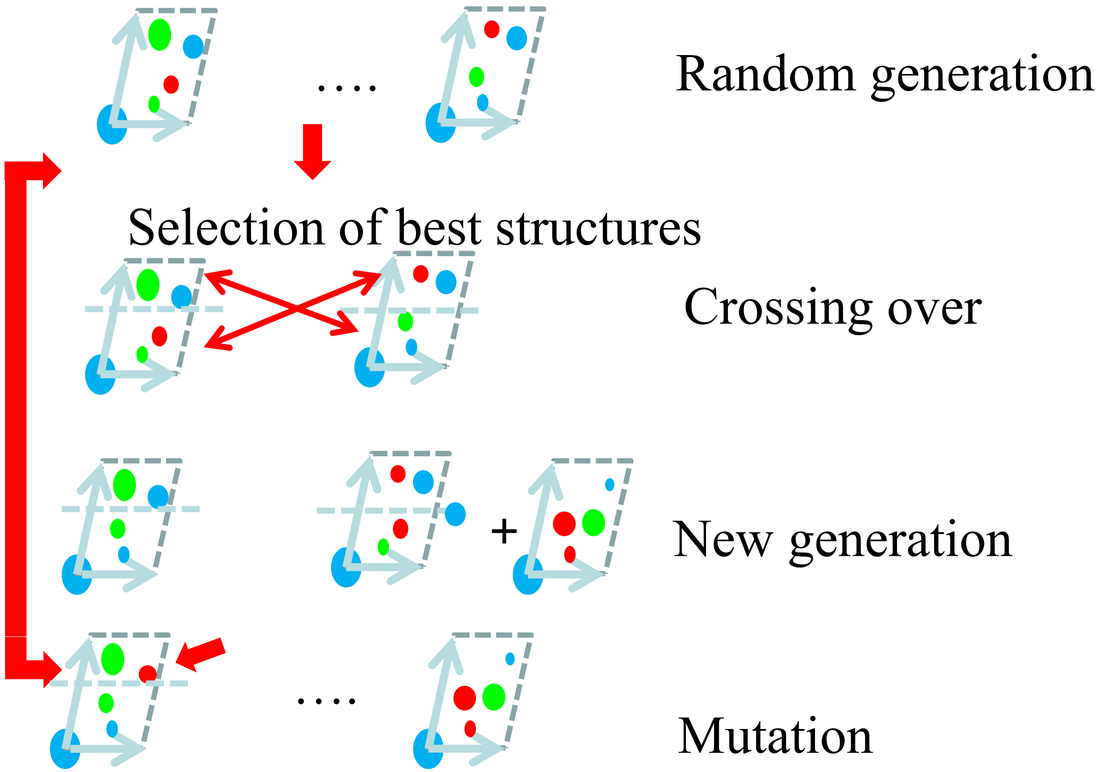
Engineering light absorption: design of an absorber

Find the position and the size of particles in the unit cell of a n-ary lattice so that:

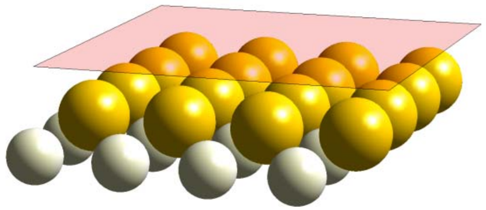
$$\int_{\lambda_{min}}^{\lambda_{max}} a(\lambda)d\lambda \to \max$$

<u>Evolutionary algorithm</u>:

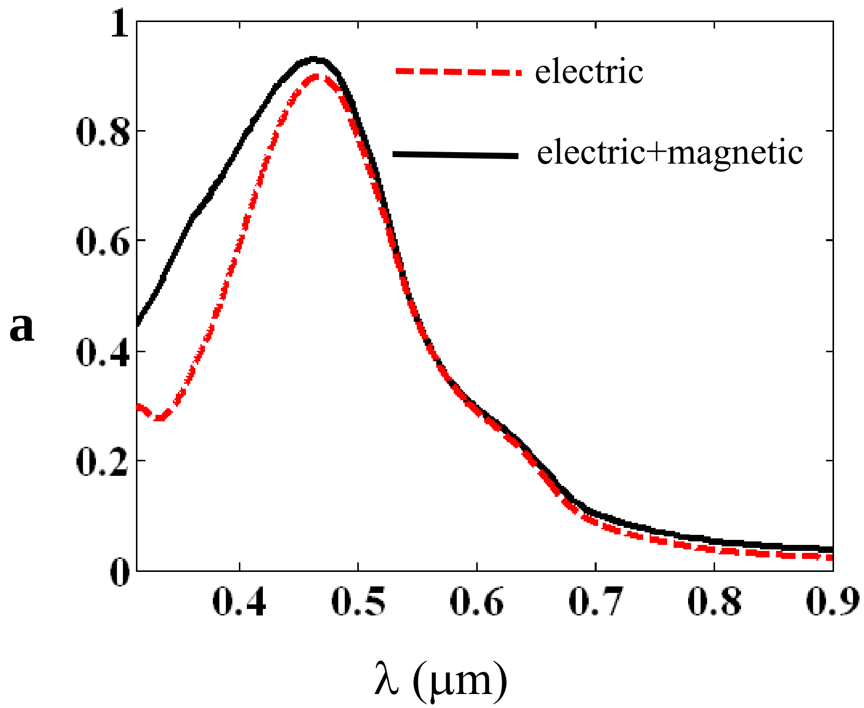




Engineering light absorption: design of an absorber



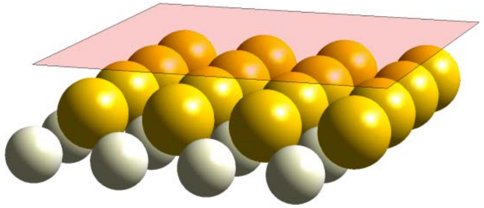
Au-Ag lattice



dipolar approximation

Langlais, Besbes, Hugonin, Ben-Abdallah, submitted

Engineering light absorption: design of an absorber



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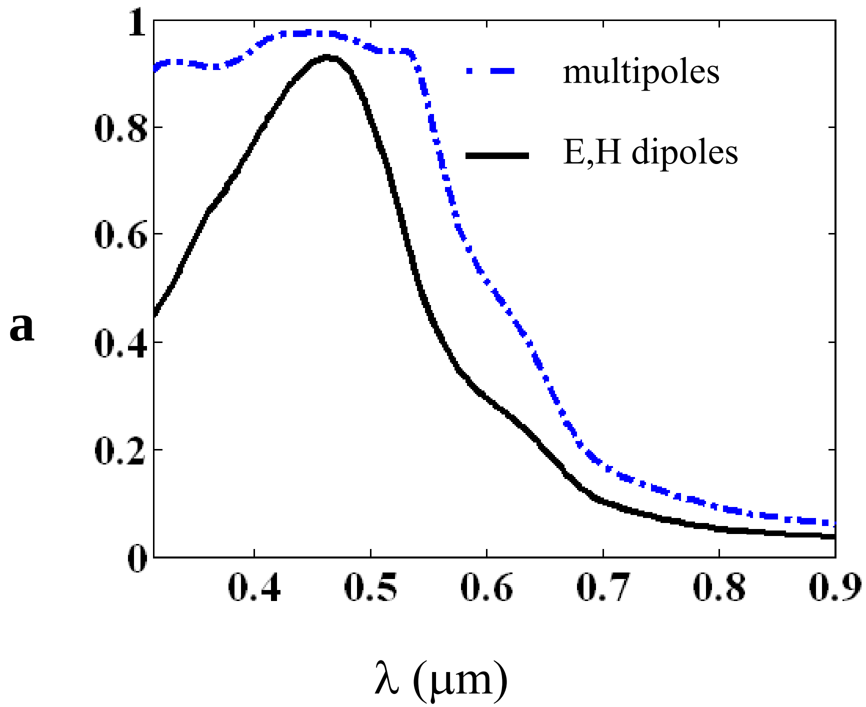
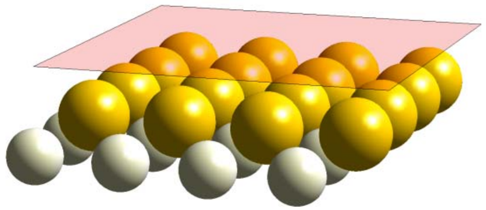


Multipolar calculation

Langlais, Besbes, Hugonin, Ben-Abdallah, submitted

Engineering light absorption: design of an absorber



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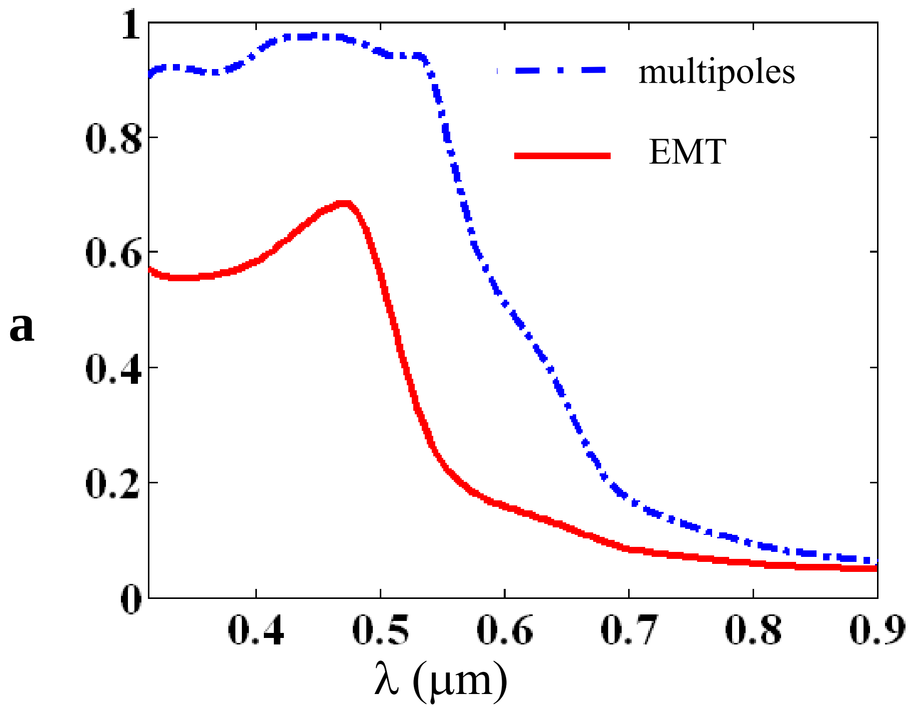
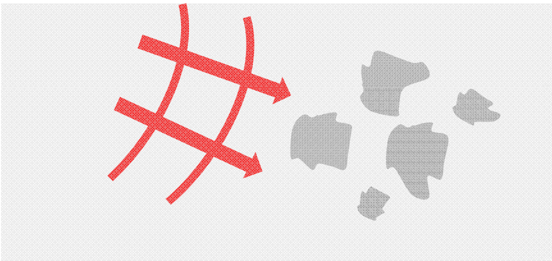


Effective medium theory

Langlais, Besbes, Hugonin, Ben-Abdallah, submitted

Outline



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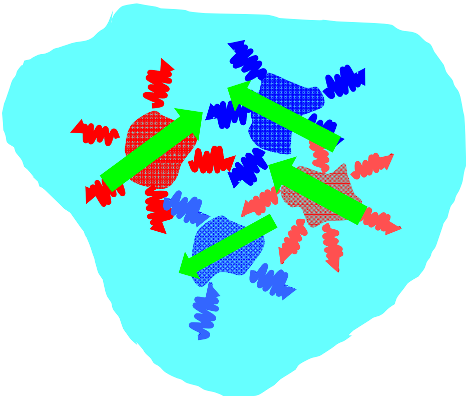
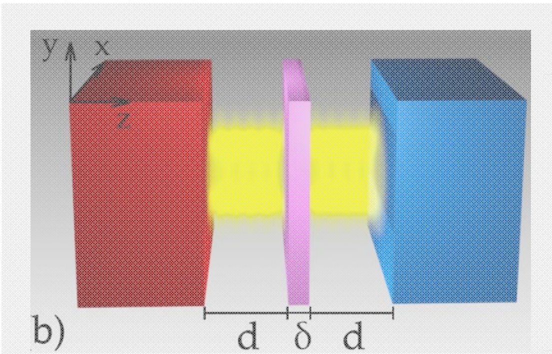
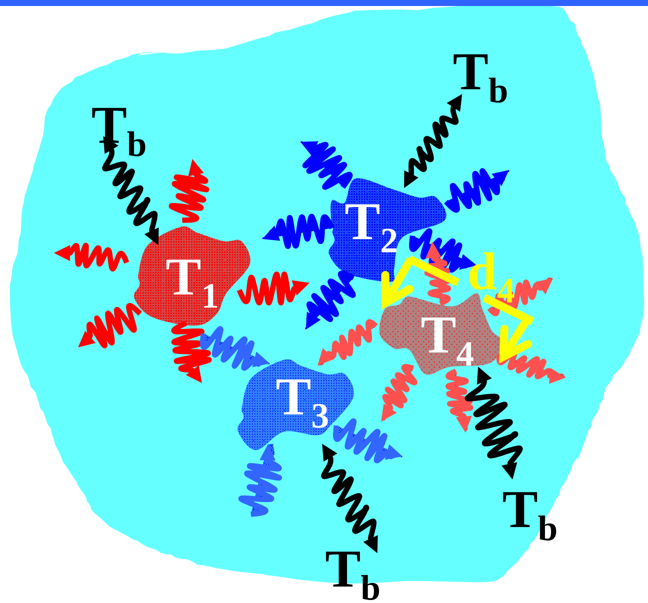


●II) Near-field heat transfer in many body systems : dipolar approximation



●III) Many body heat transfer beyond the dipolar approximation

Near-field heat transfer in many body systems: dipolar approximation



- $d_i < \min(\lambda_{T_j})$ with $\lambda_{T_j} = c\hbar/(k_B T_j)$
- Objects exchange in far field with the bath

⬇

N fluctuating dipoles in mutual interaction
inside a bosonic field

<u>Local field</u>

$$E(r) = E_b(r) + \omega^2 \mu_0 \sum_j \overleftrightarrow{G}_0(r, r_j) p_j$$

<u>Dipole moments</u>

$$p_i = p_i^{fluc} + p_i^{ind} \quad \text{with} \quad p_i^{ind} = \varepsilon_0 \alpha_i [E_{b,i} + \sum_{j \neq i} \overleftrightarrow{G}_0(r_i, r_j) p_j]$$

$$\begin{pmatrix} p_1 \\ \vdots \\ p_N \end{pmatrix} = \overline{\overline{M}} \begin{pmatrix} p_1^{fluc} \\ \vdots \\ p_N^{fluc} \end{pmatrix} + \overline{\overline{N}} \begin{pmatrix} E_1^b \\ \vdots \\ E_N^b \end{pmatrix} \qquad \begin{pmatrix} E_1 \\ \vdots \\ E_N \end{pmatrix} = \overline{\overline{O}} \begin{pmatrix} p_1^{fluc} \\ \vdots \\ p_N^{fluc} \end{pmatrix} + \overline{\overline{P}} \begin{pmatrix} E_1^b \\ \vdots \\ E_N^b \end{pmatrix}$$

where $\overline{\overline{M}}, \overline{\overline{N}}, \overline{\overline{O}}, \overline{\overline{P}}$ are function of $\overleftrightarrow{G}_0(r_i, r_j), \alpha_1, \ldots, \alpha_N$

Energy balance

Time evolution of temperatures is governed by :

$$\rho_i C_i V_i \frac{dT_i}{dt} = \wp_i(t, T_1, \ldots, T_N, T_b)$$

with $\wp_i = \int_{V_i} \langle j.E \rangle dV_i \approx \left\langle \frac{d\tilde{p}_i}{dt}, E \right\rangle$ (dipolar approximation)

Using the convention $\tilde{p}_i(t) = 2\,\mathrm{Re}\left(\int_0^\infty p_i(\omega) \frac{e^{-i\omega t}}{2\pi} d\omega \right)$

$$\wp_i = \int_0^\infty \frac{d\omega}{2\pi} \omega \int_0^\infty \frac{d\omega'}{2\pi} \mathrm{Im}[\langle p_i(\omega) E_i^\dagger(\omega') \rangle e^{-i(\omega-\omega')t}]$$

Assuming no correlation between the fluctuating dipole moments and the field of bath

$$\langle p_i(\omega) E_i^\dagger(\omega') \rangle = \sum_\alpha \sum_{jj'} \sum_{\beta\beta'} M_{ij,\alpha\beta} \langle p_{j,\beta}^{fluc}(\omega) p_{j'\beta'}^{fluc}(\omega') \rangle O'^\dagger_{j'i,\beta'\alpha} + N_{ij,\alpha\beta} \langle E_{j,\beta}^b(\omega) E_{j'\beta'}^b(\omega') \rangle P^\dagger_{j'i,\beta'\alpha}$$

Energy balance

Using the FDT:

$$\begin{cases} \left\langle p^{fluc}_{j,\beta}(\omega)\, p^{fluc\dagger}_{j'\beta'}(\omega')\right\rangle = 2\pi\hbar\varepsilon_0\delta_{jj'}\delta_{\beta\beta'}\chi_j\delta(\omega-\omega')(1+2n(\omega,T_j)) \text{ with } \chi_j = \mathrm{Im}(\alpha_j) - \frac{\omega^3}{6\pi c^3}\left|\alpha_j\right|^2 \\ \left\langle E^{b}_{j,\beta}(\omega)\, E^{b\dagger}_{j'\beta'}(\omega')\right\rangle = 2\pi\hbar\frac{\omega^2}{\varepsilon_0 c^2}\mathrm{Im}(\overleftrightarrow{G}_{0,jj',\beta\beta'})\delta(\omega-\omega')(1+2n(\omega,T_b)) \end{cases}$$

$$\left\langle p_i(\omega) E^{\dagger}_i(\omega')\right\rangle = 2\pi\delta(\omega-\omega')$$

$$\times[\hbar\varepsilon_0\sum_j \chi_j(1+2n(\omega,T_j))Tr(M_{ij}O^{\dagger}_{ji}) + \frac{\hbar\omega^2}{\varepsilon_0 c^2}(1+2n(\omega,T_b))Tr(\overline{\overline{N}}\,\mathrm{Im}(\overleftrightarrow{G}_0)\overline{\overline{P}}^{\dagger})_{ii}]$$

By considering exchanges with other dipoles, the thermal bath and emission :

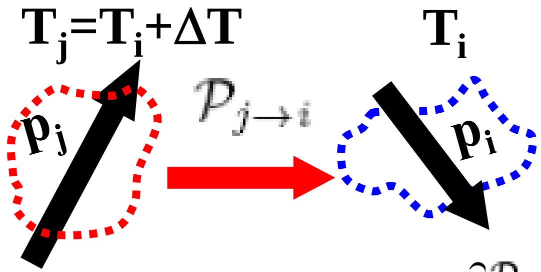
$$\wp_i = \sum_{j\neq i}\wp_{j\to i} + \wp_{b\to i} - \wp^{emi}_i$$

with

$$\wp_{j\to i} = 3\int_0^{\infty}\frac{d\omega}{2\pi}\hbar\omega n(\omega,T_j)\tau_{ij}(\omega) \qquad \tau_{ij}(\omega) = \frac{4}{3}\left(\frac{\omega}{c}\right)^4\chi_i\chi_j Tr[\overleftrightarrow{G}(r_i,r_j)\overleftrightarrow{G}^{\dagger}(r_i,r_j)]$$

Ben-Abdallah, Biehs, Joulain, PRL, **107**, 114301 (2011); Messina, Ben-Abdallah, submitted

Landauer-like formulation of heat transport



Introducing the heat conductance between two objects $G_{ij} = \dfrac{\partial \mathcal{P}_{j\to i}}{\partial T_j}$ (Linearization of exchanged power)

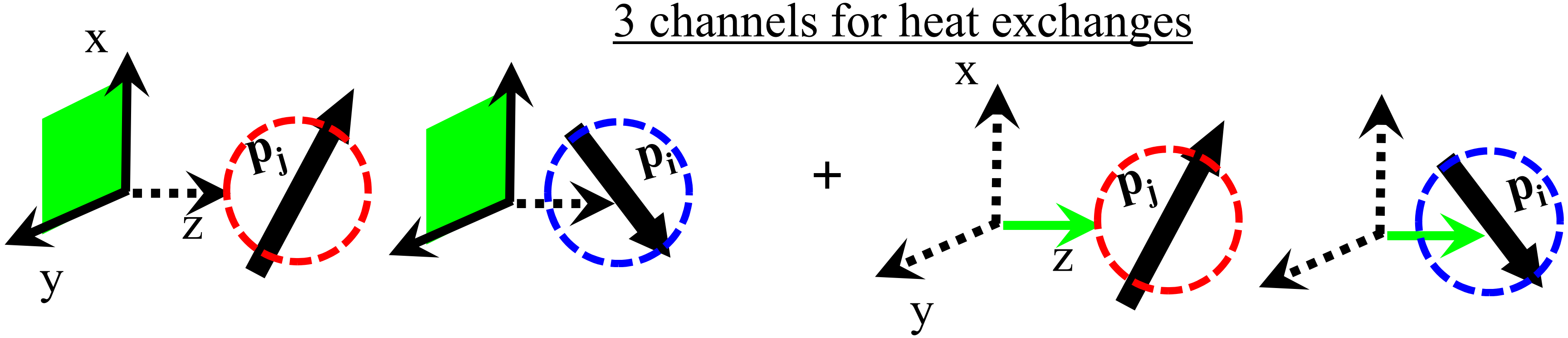
$$\wp_{j\to i} = G_{ij}\Delta T = 3\left(\frac{\pi^2 k_B^2 T_i}{3h}\right)\bar{\tau}_{ij}\Delta T$$

(Pendry, Math. Gen., 1983
Schwab, Nature 2000)

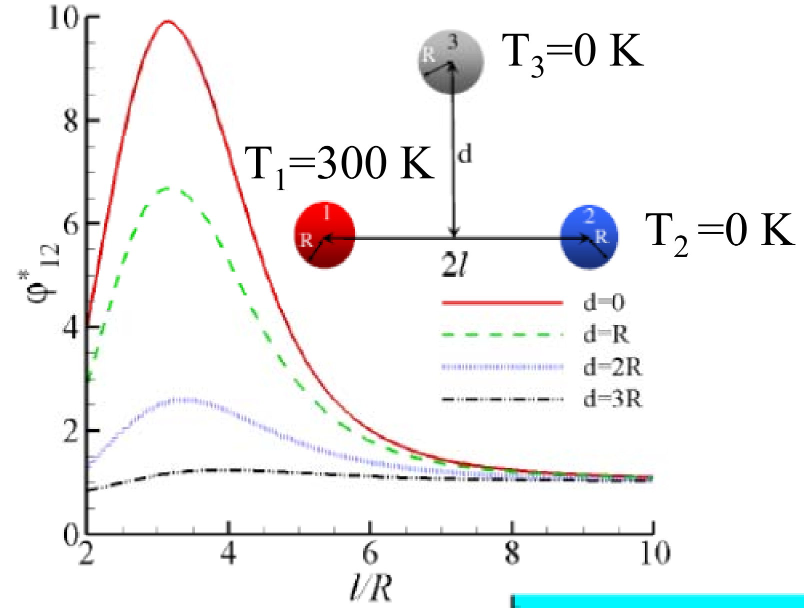
$$\bar{\mathcal{T}}_{i,j} = \frac{3}{\pi^2}\int dx \frac{x^2 e^{-x}}{(e^x - 1)^2}\mathcal{T}_{i,j}$$

Mean transmission coefficient

<u>3 channels for heat exchanges</u>

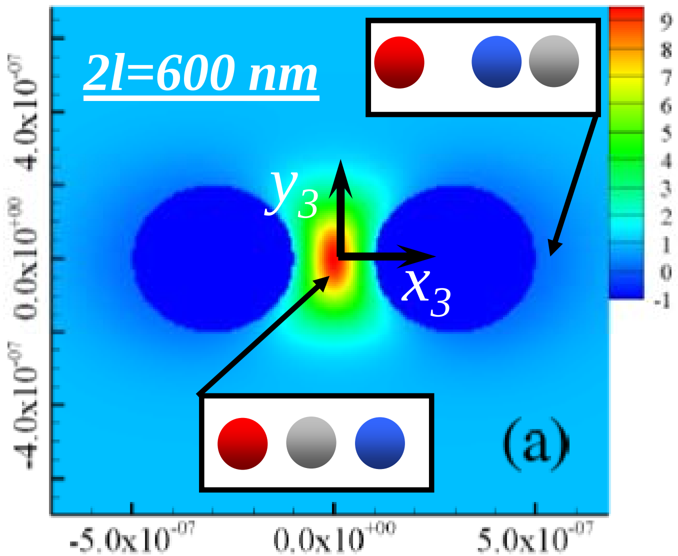


Many body effects in N body systems

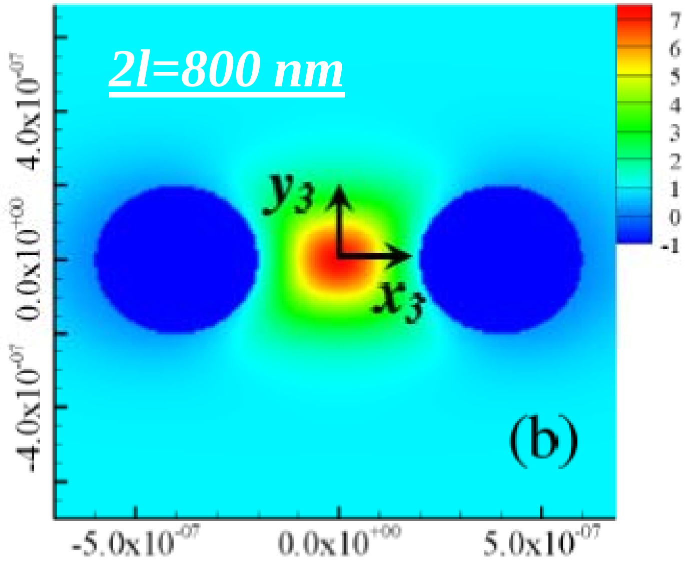


SiC particles
R=100 nm

$\varphi^*_{12}(x_3,y_3)$



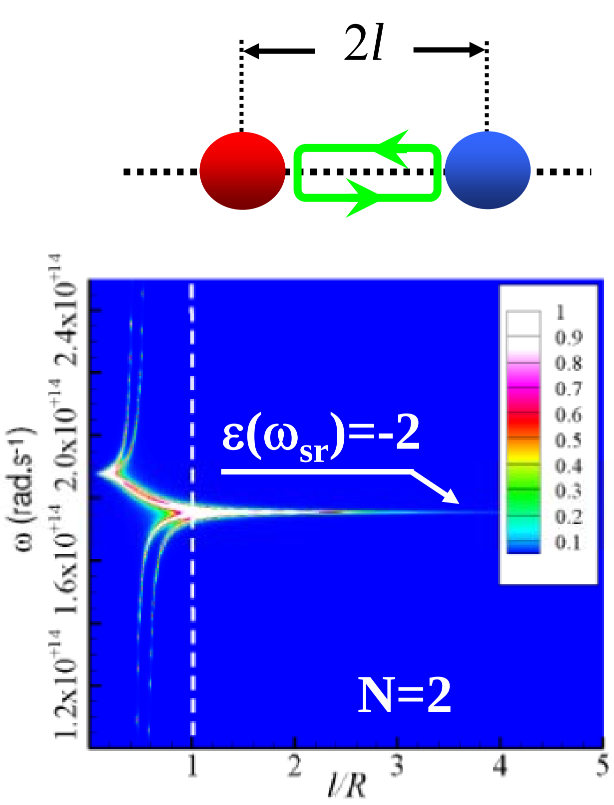
2l=600 nm



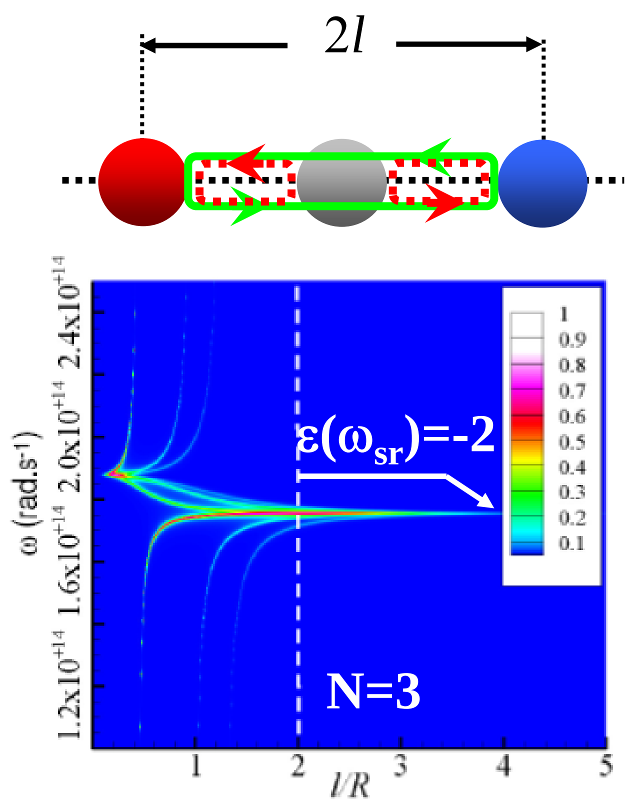
2l=800 nm

Ben-Abdallah, Biehs, Joulain, PRL, **107**, 114301 (2011)

Many body effects in N body systems



$$\mathcal{T}^{(N)}_{i,j}(\omega) = \frac{4}{3} k_0^2 Im^2\alpha \, tr[G_N G_N^+]$$



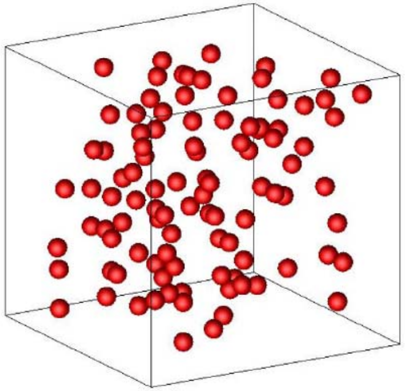
$\tau^{(2)}_{i,j}(\omega_{SR}, l = 3R) = 0.12$

$\tau^{(3)}_{i,j}(\omega_{SR}, l = 3R) = 0.3$

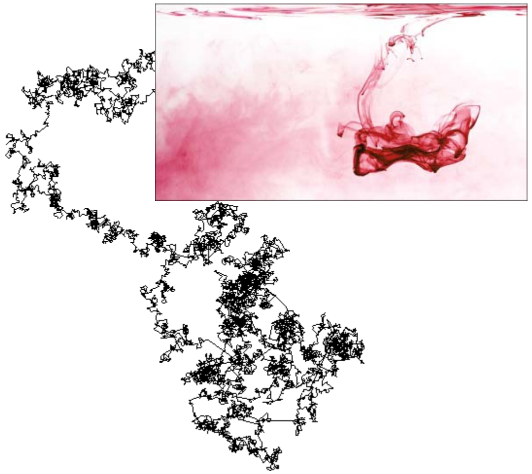
→ More efficient coupling at longer separation distances with a third particle

Heat transport regimes in plasmonic networks

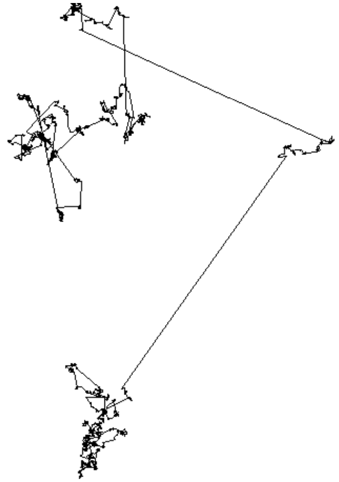
<u>How heat propagates throughout the network ?</u>



100 SiC nanoparticle



Gaussian
(diffusive)



Anomalous
(sub/superdiffusive)

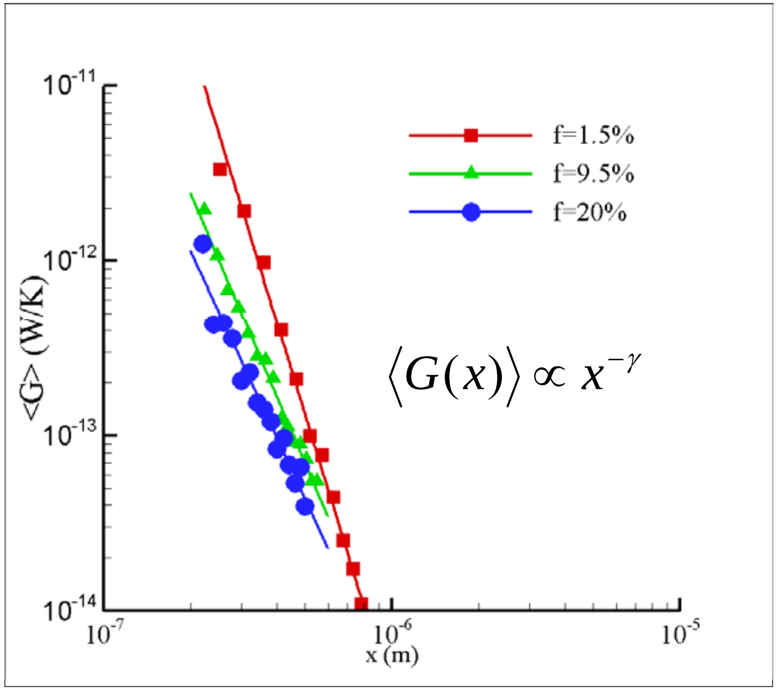
$$\rho_i C_i V_i \frac{dT_i}{dt} = \sum_j G(|r_i - r_j|)(T_j - T_i) + \overline{C}_{abs,i}\sigma(T_b^4 - T_i^4) \approx \sum_j G(|r_i - r_j|)(T_j - T_i)$$

$\overline{C}_{abs,i}$ thermal average dressed absorption

Yannopapas, Vitanov, PRL. **110**, 044302, 2013

Heat transport regimes in plasmonic networks

Remarking that $\wp_{j\to i} = G(|r_i - r_j|)(T_j - T_i)$ is formally an Ohm's law



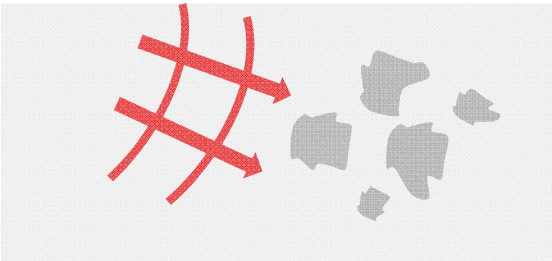
N=250 realizations generated with uniform distribution

$$\langle G\rangle = \frac{1}{N}\sum_{i=1}^{N} G^{(i)}$$

$$\rho_i C_i V_i \frac{\partial T_i}{\partial t} = -\sum_j \frac{\Gamma_{d;\alpha}}{|r_i - r_j|^{d+\alpha}}(T_i - T_j) \approx \beta_i \Delta^{\alpha/2} T\Big|_i$$ (Fractional diffusion equation)

$\alpha(f = 0.2) \approx 0{,}6$ → superdiffusion

Outline



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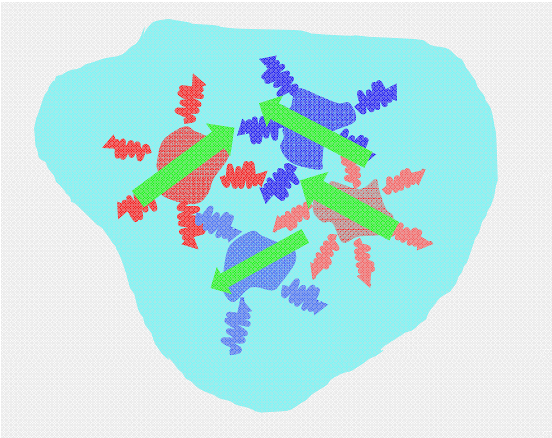

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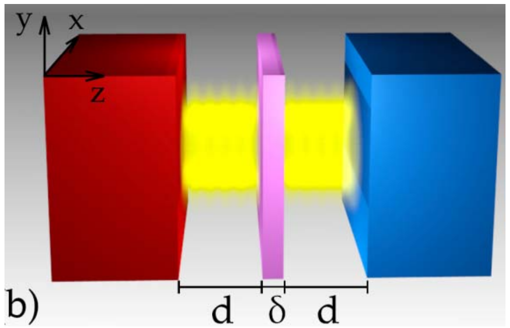
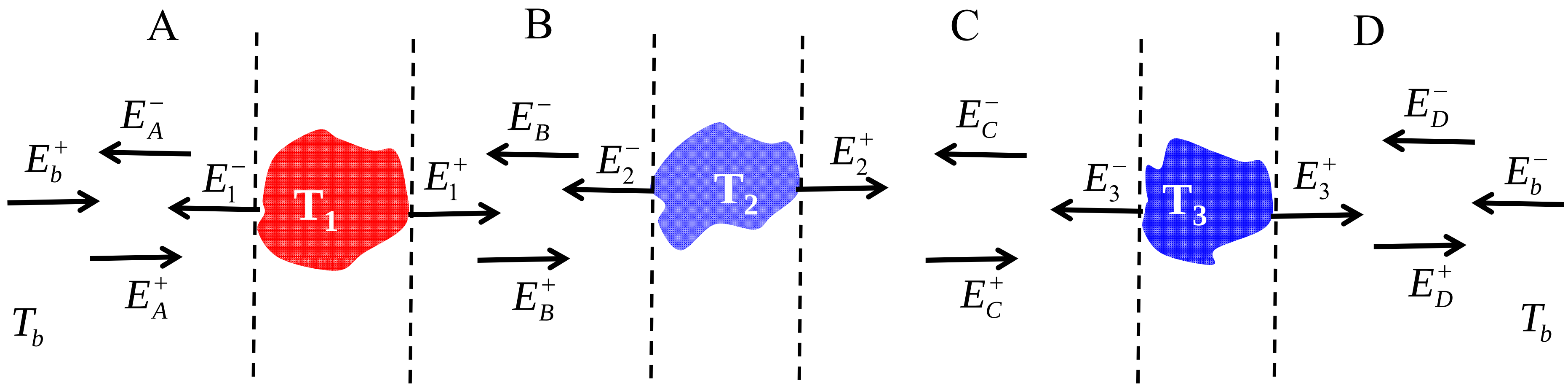


●III) Many body heat transfer beyond the dipolar approximation

Many body heat transfer: beyond the dipolar approximation



3 temperatures T_1 , T_2 ,T_3 + T_b

From the scattering matrix theory:

$$E_B^+ = E_1^+ + t_1 E_b^+ + r_1 E_B^-$$

$$E_B^- = E_2^- + t_2 E_b^- + r_2 E_B^+$$

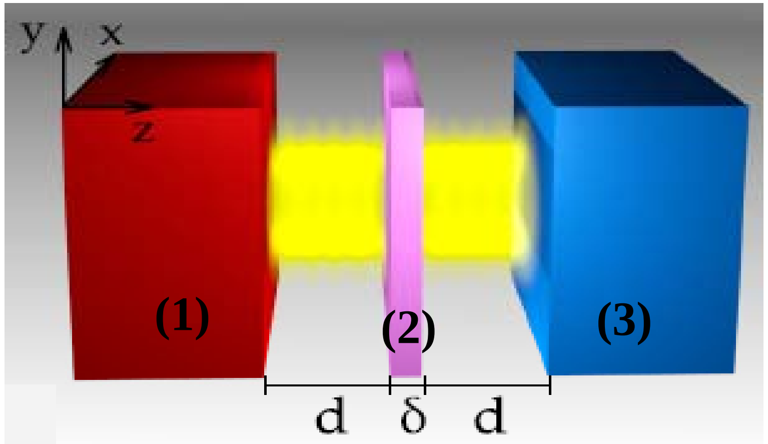
t_i, r_i partial transmission and reflection

etc…

Normal component of Poynting vector:

$$\langle S \rangle . e_z = \langle E \times H \rangle . e_z = \sum_p \int \frac{d^2 k}{(2\pi)^2} \int_0^\infty \frac{d\omega}{2\pi} F_p(k,\omega) \langle E_p(k,\omega), E_p(k,\omega) \rangle$$

Heat transfer in a three slab system



Monochromatic heat flux on semi-infinite medium (3) decomposes into:

$$\varphi_3(\omega, d, \delta) = \varphi_3^{(12)}(\omega, d, \delta) + \varphi_3^{(23)}(\omega, d, \delta)$$

where $$\varphi_3^{(12)} = \hbar\omega \sum_p \int \frac{d^2k}{(2\pi)^2} [n(\omega, T_1) - n(\omega, T_2)] \tau_p^{(12)}(\omega, k, d, \delta)$$

$$\varphi_3^{(23)} = \hbar\omega \sum_p \int \frac{d^2k}{(2\pi)^2} [n(\omega, T_2) - n(\omega, T_3)] \tau_p^{(23)}(\omega, k, d, \delta)$$

$$\tau_p^{(23)} = \frac{4\,\mathrm{Im}(\rho_{12,p}(\delta))\,\mathrm{Im}(\rho_{3,p})e^{-2\,\mathrm{Im}(k_z)d}}{\left|1-\rho_{12,p}(\delta)\rho_{3,p}e^{-2\,\mathrm{Im}(k_z)d}\right|^2} \qquad \tau_p^{(12)} = \frac{4\left|t_{2,p}(\delta)\right|^2 \mathrm{Im}(\rho_{1,p})\,\mathrm{Im}(\rho_{3,p})e^{-4\,\mathrm{Im}(k_z)d}}{\left|1-\rho_{12,p}(\delta)\rho_{3,p}e^{-2\,\mathrm{Im}(k_z)d}\right|^2 \left|1-\rho_{1,p}\rho_{2,p}(\delta)e^{-2\,\mathrm{Im}(k_z)d}\right|^2}$$

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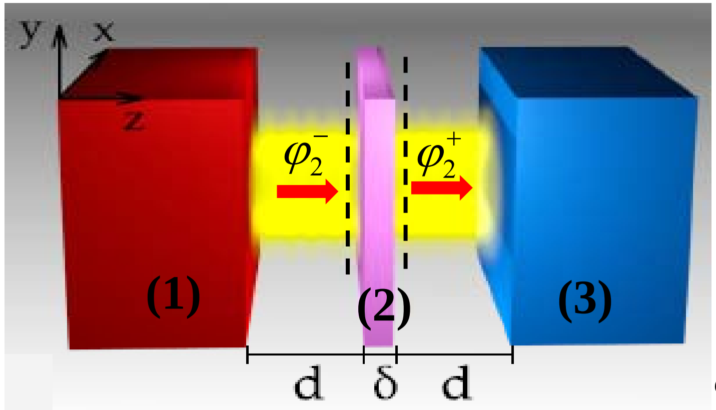
Temperature of the intermediate layer



At thermal steady state: $\varphi_1 + \varphi_2 + \varphi_3 = 0$

$$\varphi_2 = -(\varphi_1 + \varphi_3) = -\hbar\omega \sum_p \int \frac{d^2k}{(2\pi)^2} \left\{ [n_{12} + n_{32}]\tau_p^{12} + [n_{23} + n_{21}]\tau_p^{23} \right\}$$

Symmetrical geometric configuration ➡

$$= \hbar\omega [2n(T_2) - n(T_1) - n(T_3)] \sum_p \int \frac{d^2k}{(2\pi)^2} (\tau_p^{12} - \tau_p^{23})$$

For a quasi-monochromatic heat flux spectrum around $\omega = \omega^*$

$$\int \varphi_2 d\omega \approx \hbar\omega^* \Delta\omega [2n(\omega^*, T_2) - n(\omega^*, T_1) - n(\omega^*, T_3)] \sum_p \int \frac{d^2k}{(2\pi)^2} (\tau_p^{12} - \tau_p^{23}) = 0$$

$$2n(\omega^*, T_2) - n(\omega^*, T_1) - n(\omega^*, T_3) = 0$$

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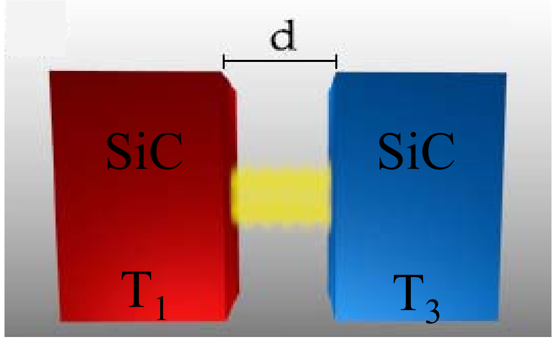
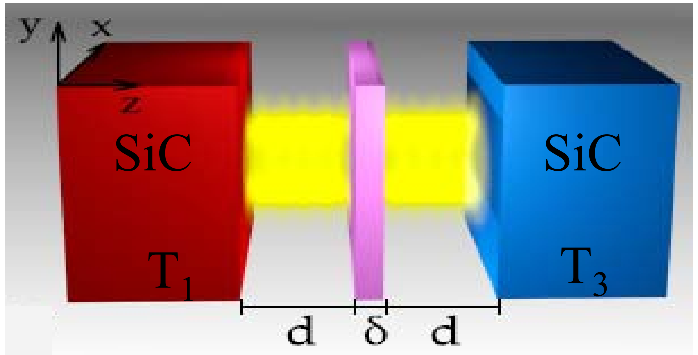
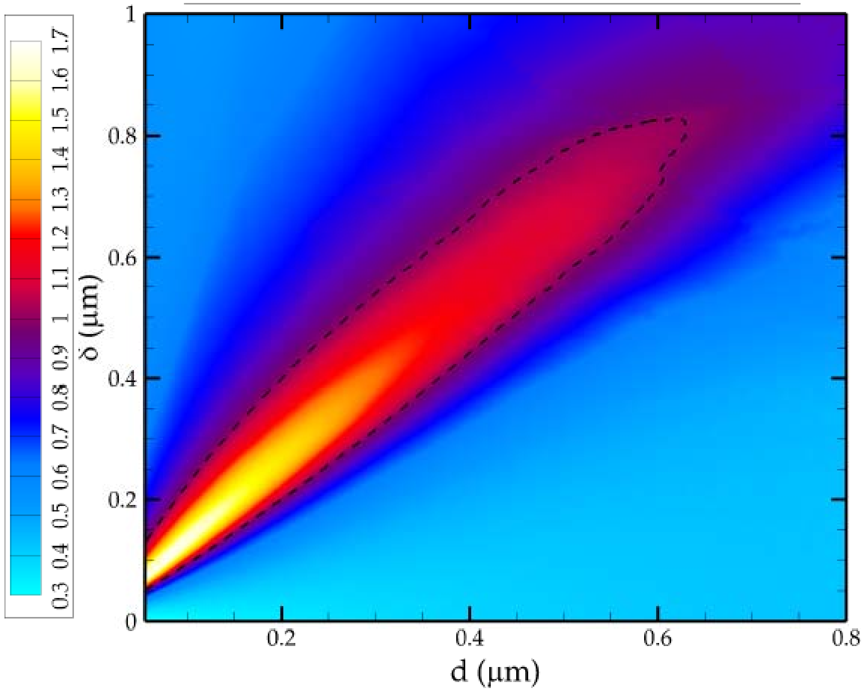
Heat flux amplification







$$\varepsilon_2 = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \quad \text{(Drude)}$$

Surface plasmon at :

$$\omega^* \approx \omega_p / \sqrt{2} \text{ with } \omega_p = \sqrt{2}\omega_{SPP\_SiC}$$

$$\omega_{SPP\_SiC} = 1.787 \times 10^{14} \, rad.s^{-1}$$

T_1 =400K; T_3 =300K

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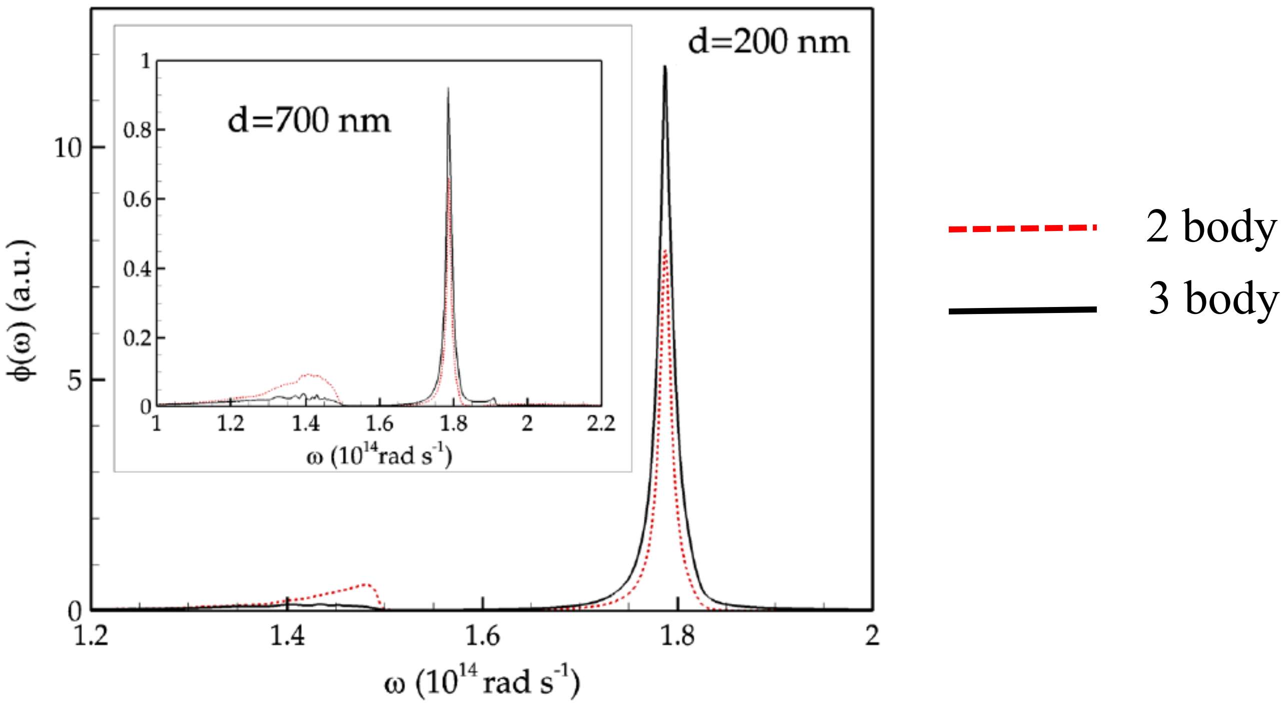
Origin of amplification mechanism

Flux spectrum for different values of d at the optimal value of δ:



→ 3 body heat flux is enhanced at ω_{SPP}

→ The presence of intermediate slab does not enhance flux at smaller frequencies (quasi-monochromatic enhancement)

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Transmission probability in a SiC-Drude-SiC system

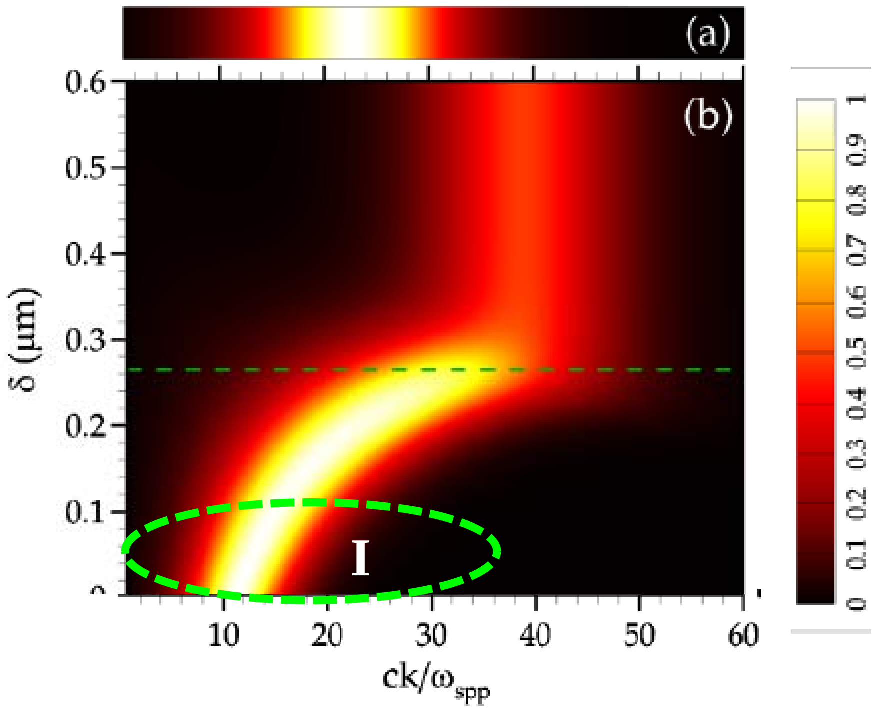
Quasimonochromaticity of transfer ➡ $n_{12}(\omega_{SPP}) = n_{23}(\omega_{SPP}) = \dfrac{n_{13}(\omega_{SPP})}{2}$

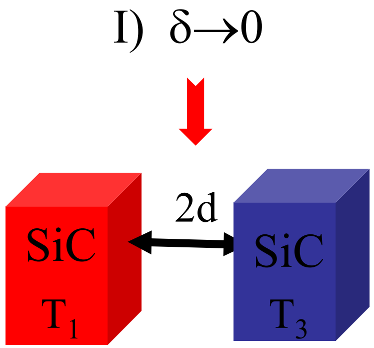
Thus

$$\begin{cases} \varphi_3(\omega_{SPP}) = n_{12}\hbar\omega \sum_p \int \dfrac{d^2k}{(2\pi)^2} [\tau_{3,p}^{(12)} + \tau_{3,p}^{(23)}] \\ \varphi_2(\omega_{SPP}) = n_{13}\hbar\omega \sum_p \int \dfrac{d^2k}{(2\pi)^2} \tau_{2,p} = 2n_{12}\hbar\omega \sum_p \int \dfrac{d^2k}{(2\pi)^2} \tau_{2,p} \end{cases}$$

➡ To compare the coupling efficiency between modes in 2 and 3 body configurations we must compare τ_2 with $\tau_3 = (\tau_3^{(12)} + \tau_3^{(23)})/2$

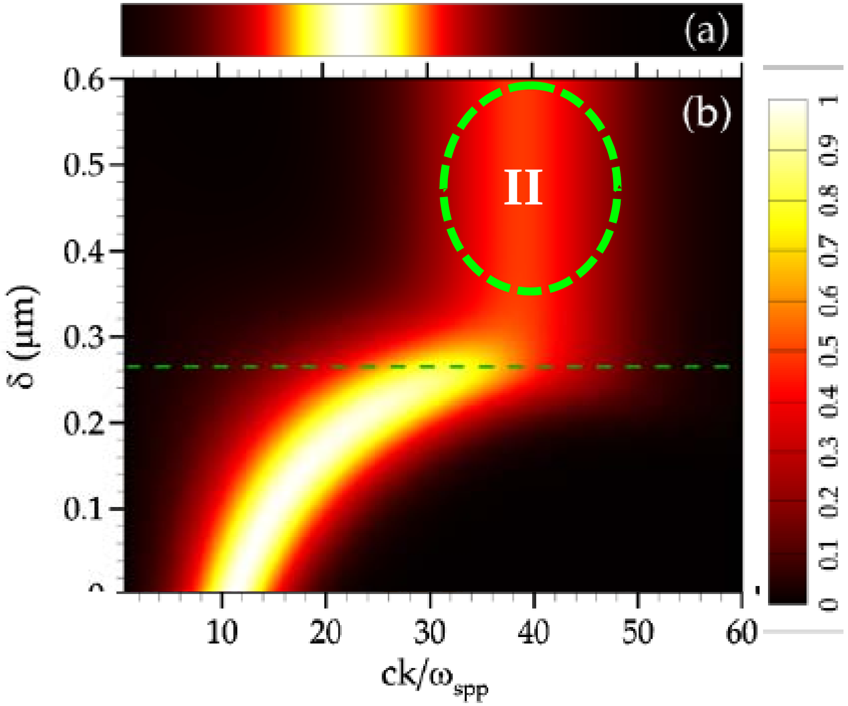
Transmission probability : asymptotic regimes



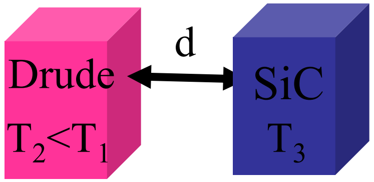


Compared to 2 body, the shift of the cut off wavector k_c comes from the difference of distance from d to 2d

Transmission probability : asymptotic regimes



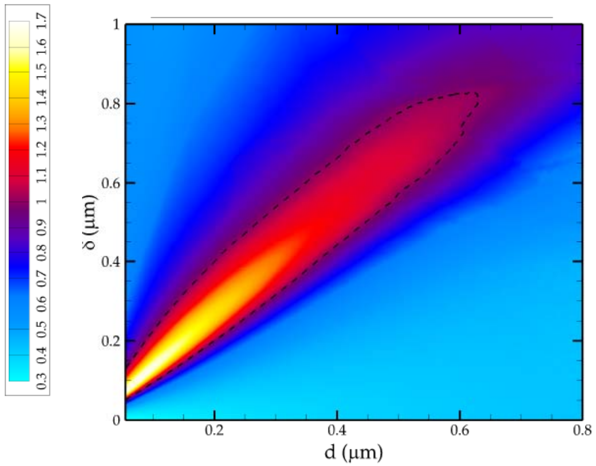
II) δ>>d



(τ_3 does not depend on δ)

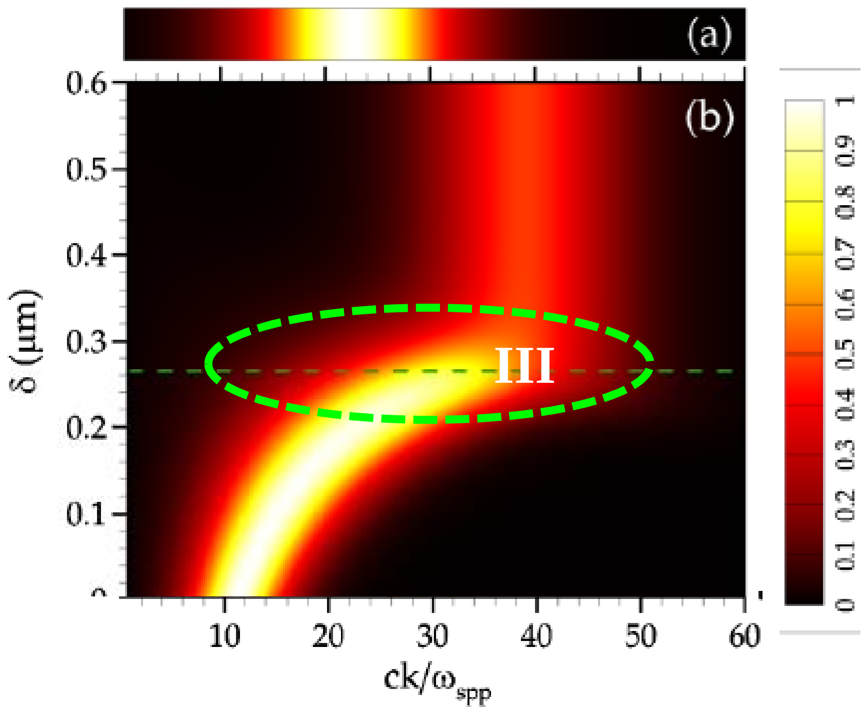
$$k_c \propto \frac{1}{\sqrt{\mathrm{Im}\,\varepsilon_{Drude}\ \mathrm{Im}\,\varepsilon_{SiC}}} \text{ and } \mathrm{Im}\,\varepsilon_{Drude} < \mathrm{Im}\,\varepsilon_{SiC}$$

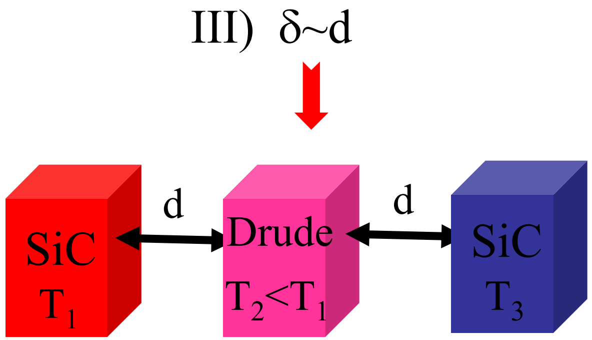
Compared to 2 body SiC-SiC, the cut off wavevector k_c is shifted toward larger values



$\varphi_3 < \varphi_2$ because $T_2<T_1$

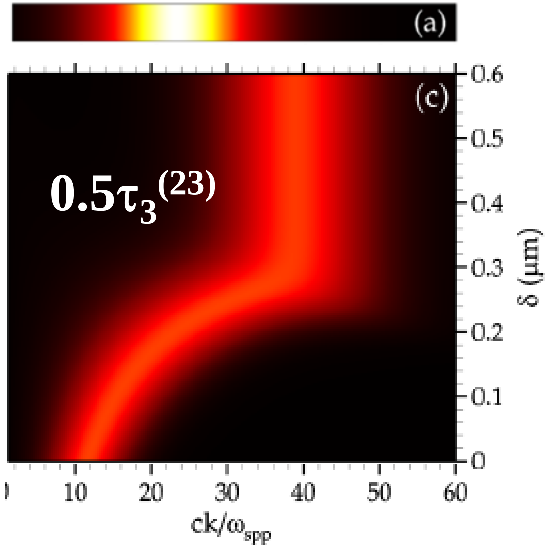
Transmission probability : three body regime

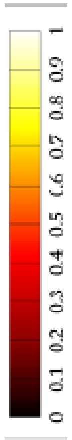


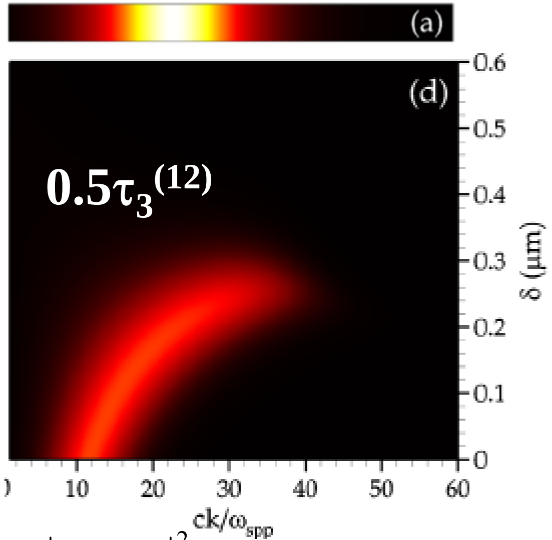


3 body interactions take place

Transmission probability : three body regime

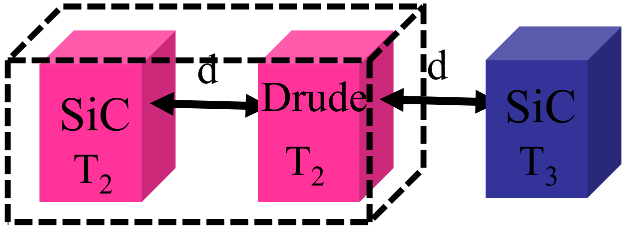


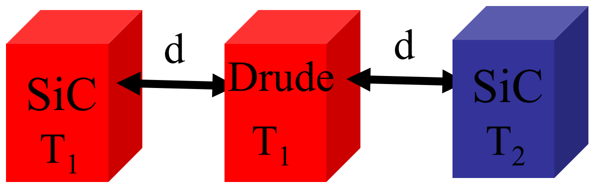




$$\tau_p^{(23)} = \frac{4\,\mathrm{Im}(\rho_{12,p}(\delta))\,\mathrm{Im}(\rho_{3,p})e^{-2\,\mathrm{Im}(k_z)d}}{\left|1-\rho_{12,p}(\delta)\rho_{3,p}e^{-2\,\mathrm{Im}(k_z)d}\right|^2}$$

$$\tau_p^{(12)} = \frac{4\left|t_{2,p}(\delta)\right|^2\,\mathrm{Im}(\rho_{1,p})\,\mathrm{Im}(\rho_{3,p})e^{-4\,\mathrm{Im}(k_z)d}}{\left|1-\rho_{12,p}(\delta)\rho_{3,p}e^{-2\,\mathrm{Im}(k_z)d}\right|^2\left|1-\rho_{1,p}\rho_{2,p}(\delta)e^{-2\,\mathrm{Im}(k_z)d}\right|^2}$$





2 body exchange between
the couple (1,2) at temperature T_2 and (3)

purely 3 body effect

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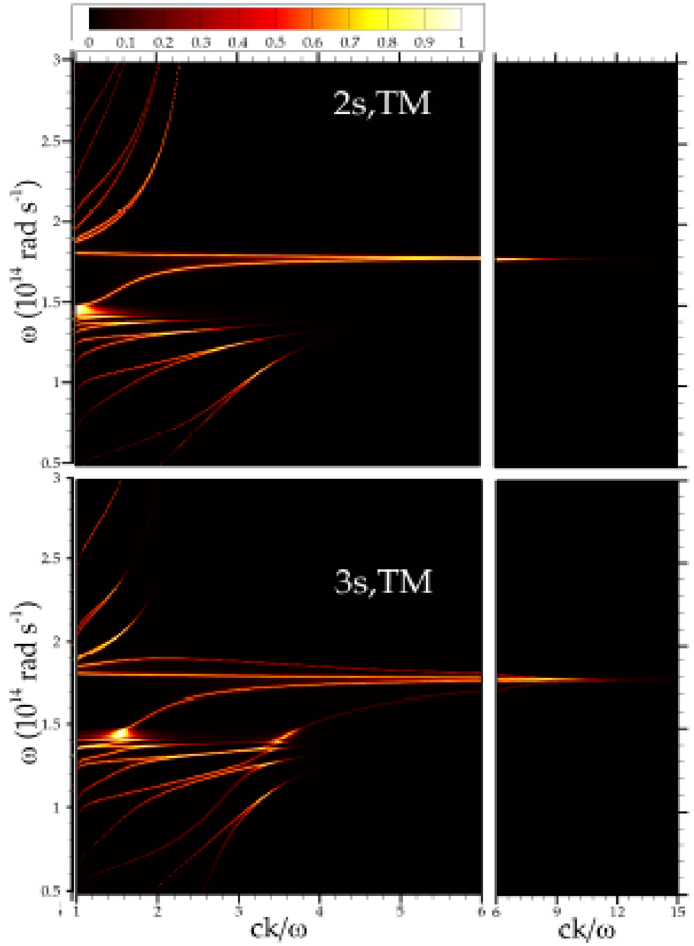
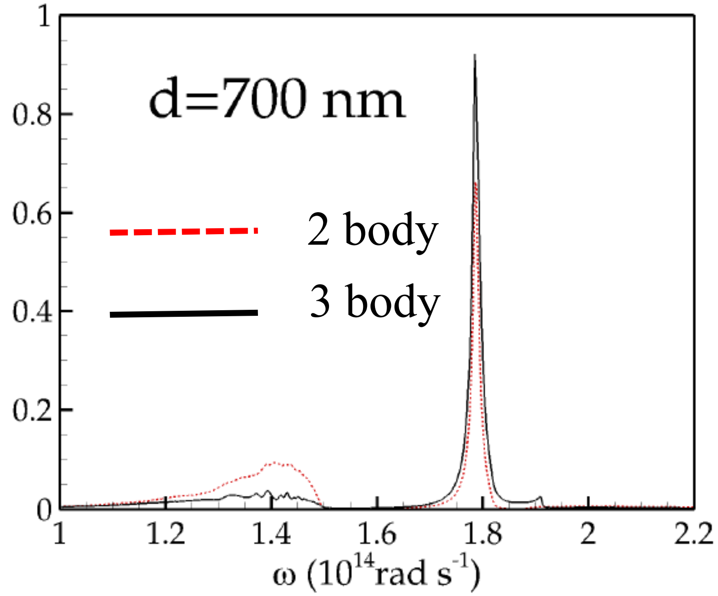
Transmission probability : three body regime





The 3 body amplification of photon tunneling result from a shifting of the cutoff wavector toward higher values thanks to the presence passive relay

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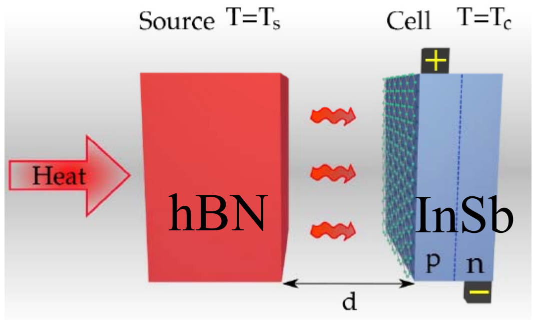
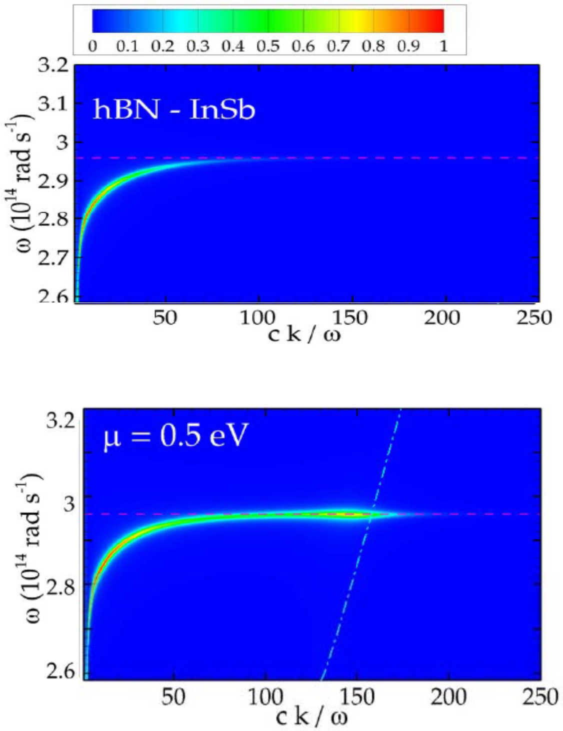
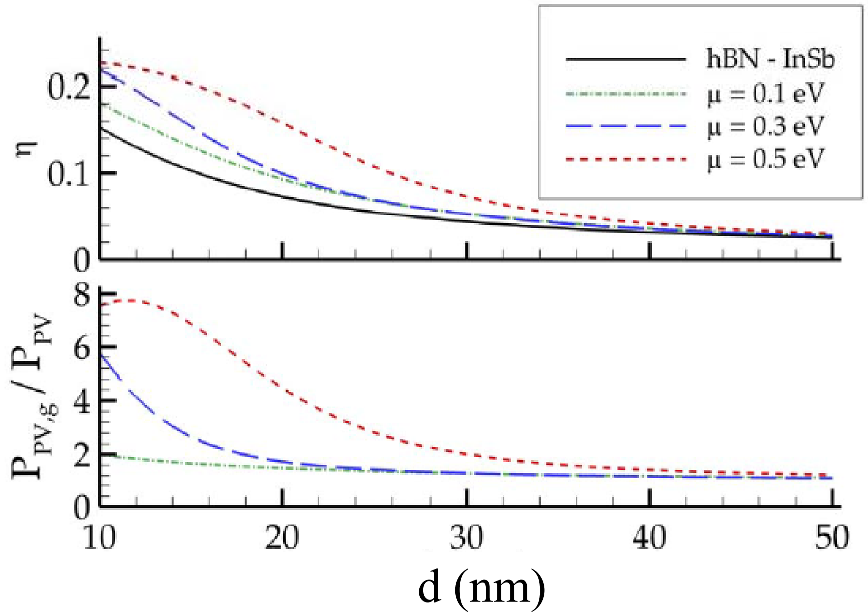
Application: graphene-beased PV cell for near-field energy conversion



Transmission





Messina, Ben-Abdallah, Sci. Rep., 3, 1383 (2013)

Concluding remarks

- Dipolar (multipolar) interactions in N-body systems can be used to enhance and to tailor the absorption spectrum

- Revisited the fluctuationnal electrodynamics in multiple dipolar systems

- Highlighted N-body near-field properties
  - enhancing or inhibating heat exchanges
  - export the near-field effects at longer separation distances
  - existence of anomalous heat transport regimes

- Applications : NTPV, thermal management at nanoscale

- Still open questions:
  - -role of localized modes in the heat transport in disordered plasmonic systems
  - -transport in N-body systems at mesocopic scale
  - -dynamic of cooling/heating
  - …