Thermal Energy Transport in a Surface Phonon-Polariton Crystal

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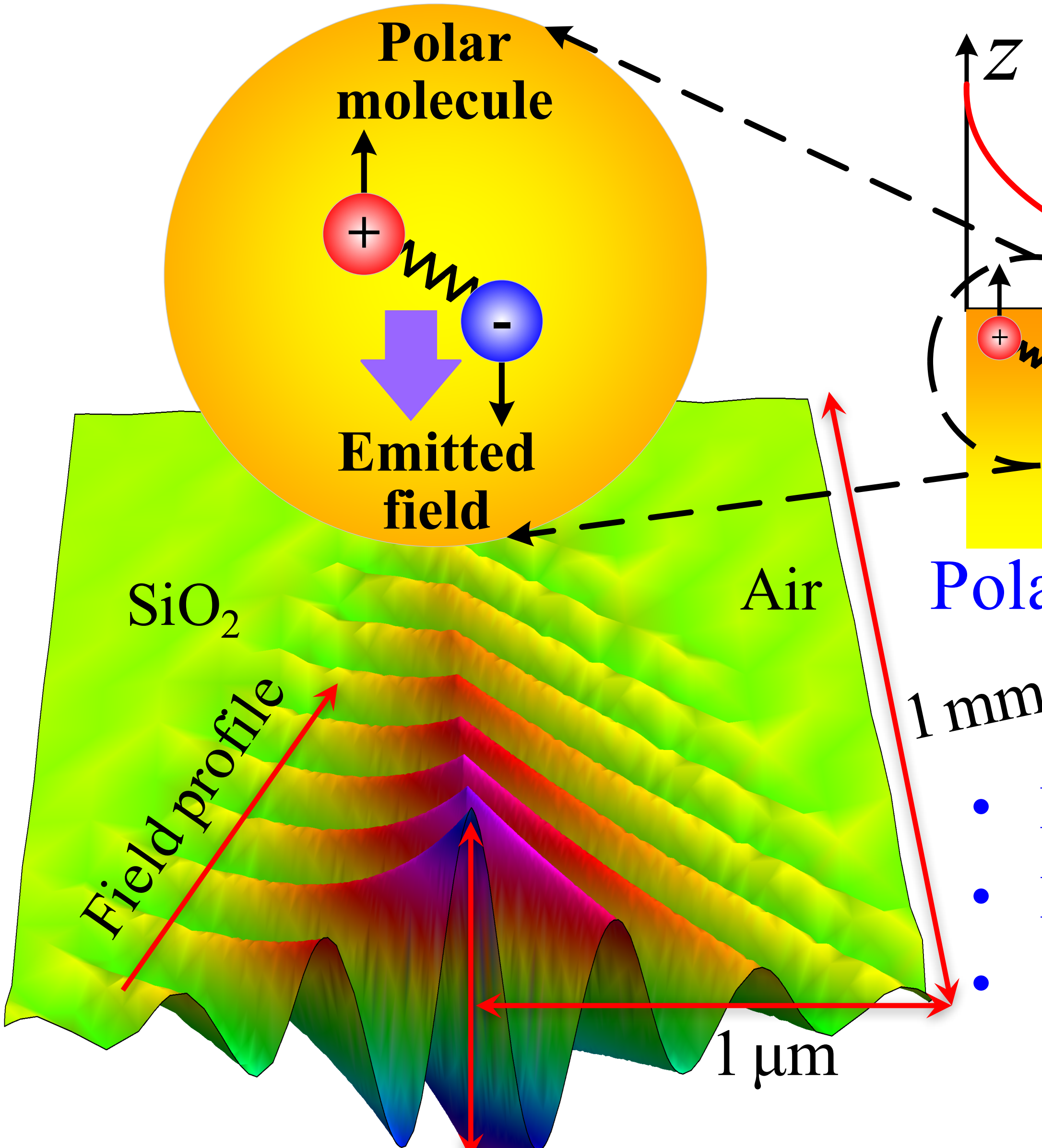
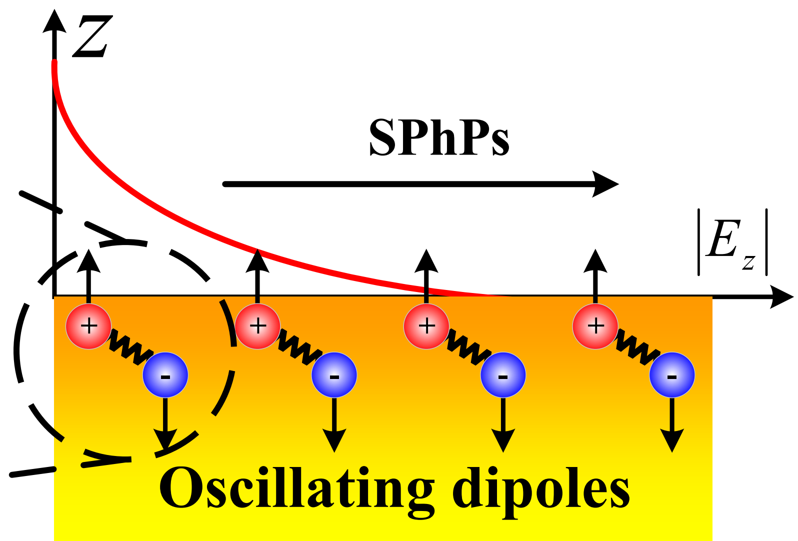
Heat Transfer and Heat Conduction on the Nanoscale

Bad Honnef, April 14, 2016

Surface Phonon-Polaritons (SPhPs)

Surface electromagnetic waves due to the phonon-photon coupling.



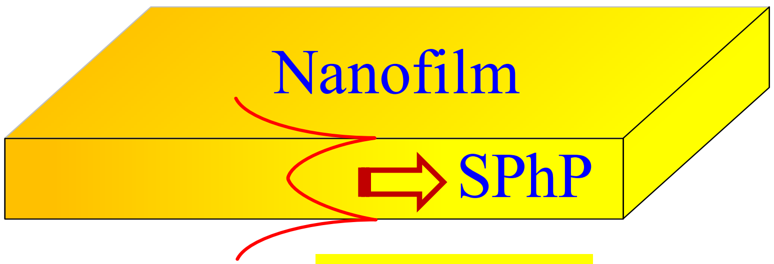


Polar material (SiO_2, SiC)

SPhPs:

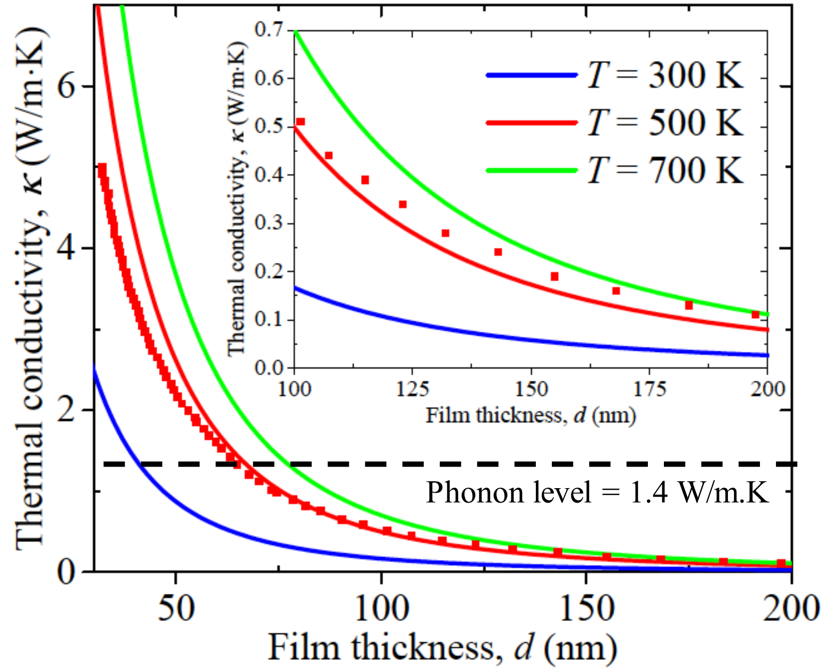
- Heat up materials.
- Energy carriers as phonons.
- Strong effects in nanomaterials.

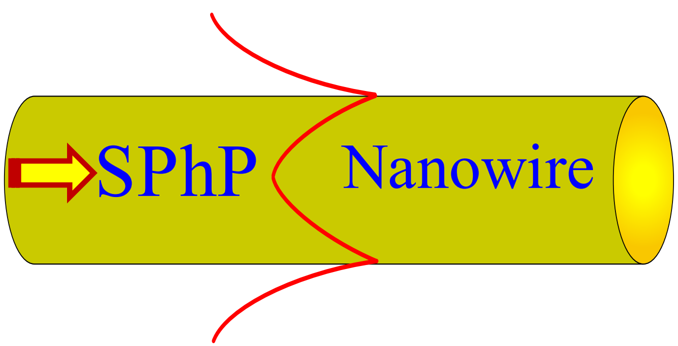
SPhP Energy Transport



$$\kappa = \frac{A}{d^3} + \frac{B}{d}$$

JAP **113,** 084311 (2013).

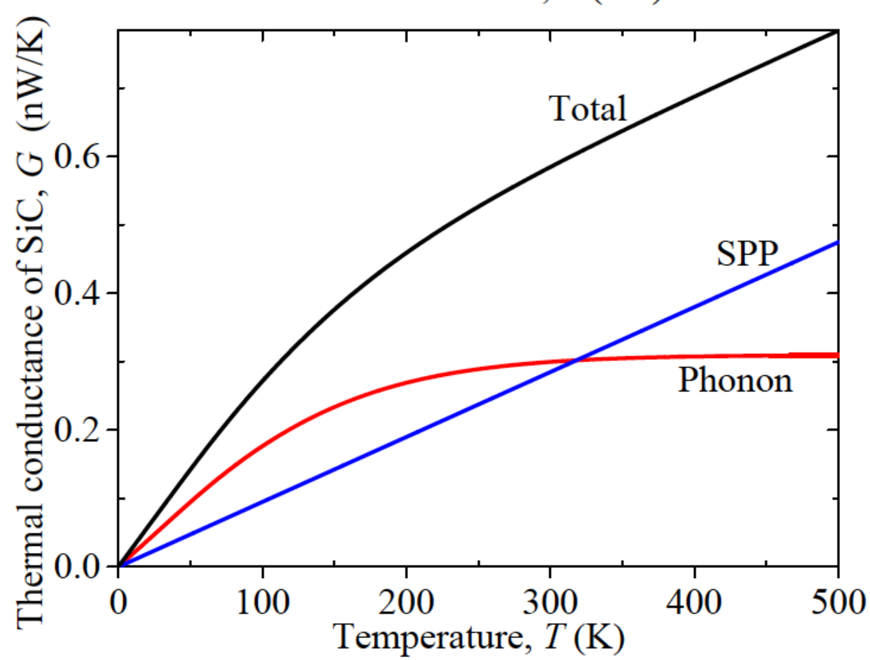




$$G_0 = \frac{\pi^2 k_B^2 T}{3h} = 0.95x10^{-12} T \ (\text{W/K})$$

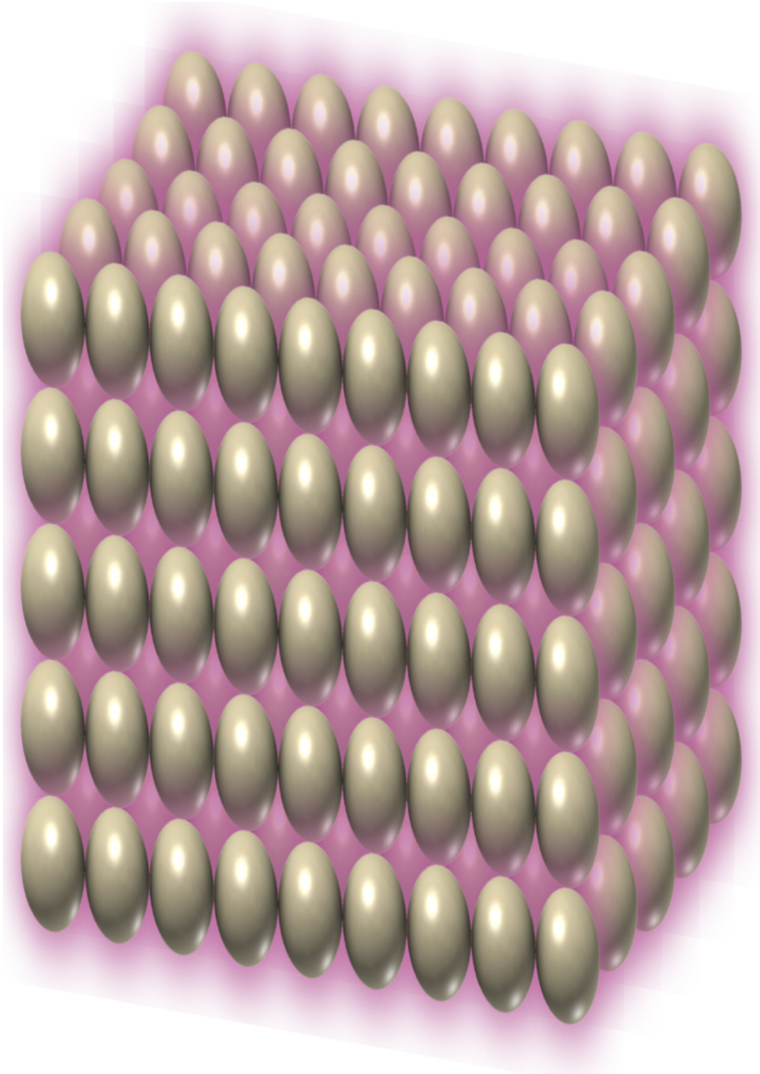
Universal value!

PRL **112**, 055901 (2014).



Goal of our Work

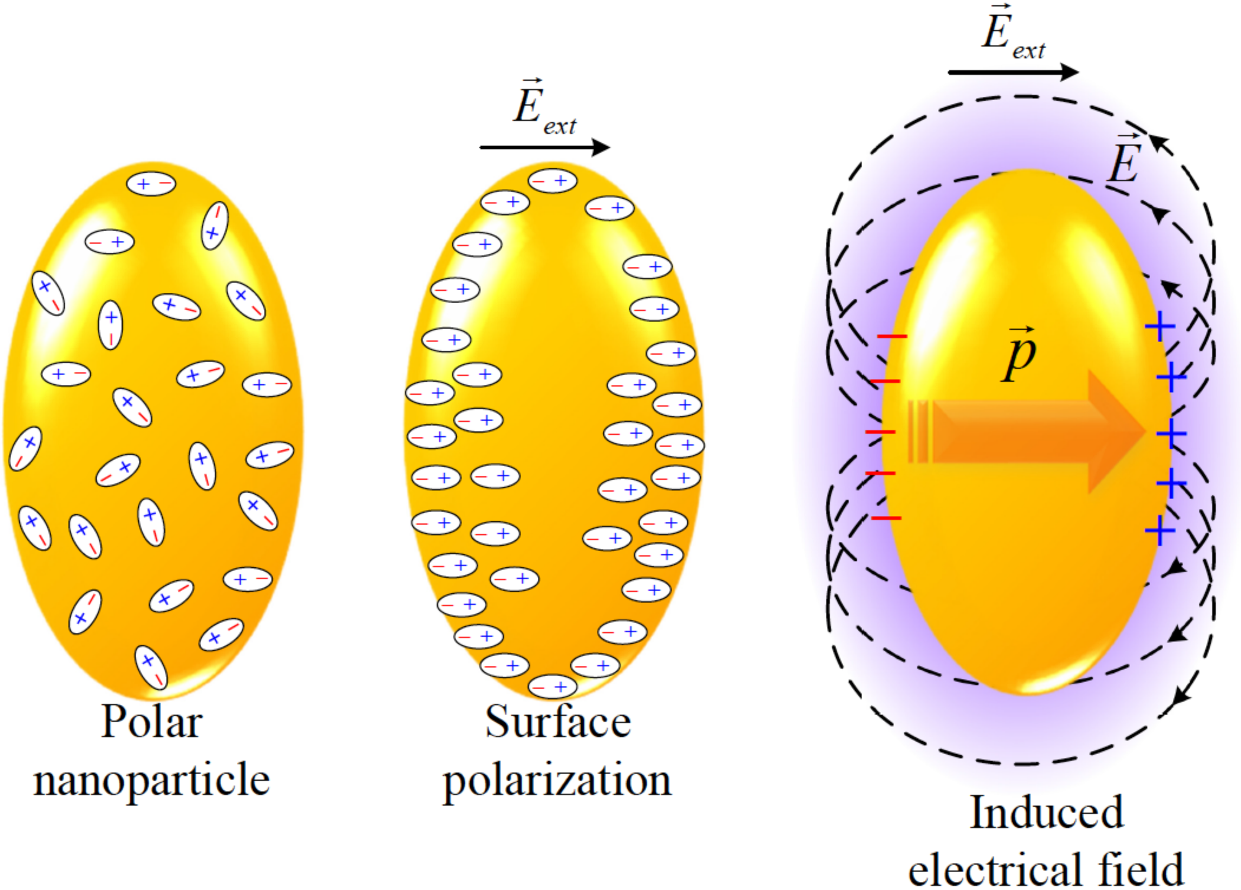
SPhP energy transport along a 3D ensemble of spheroidal nanoparticles

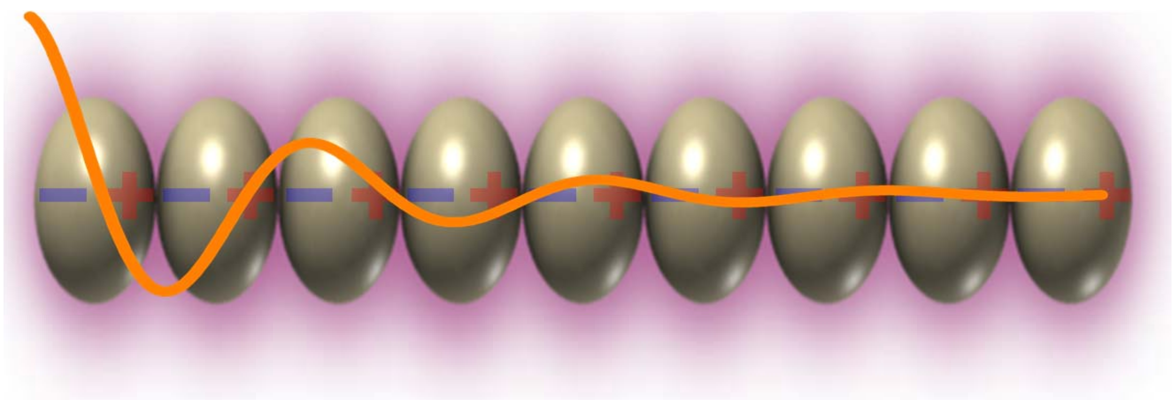


SPhP crystal

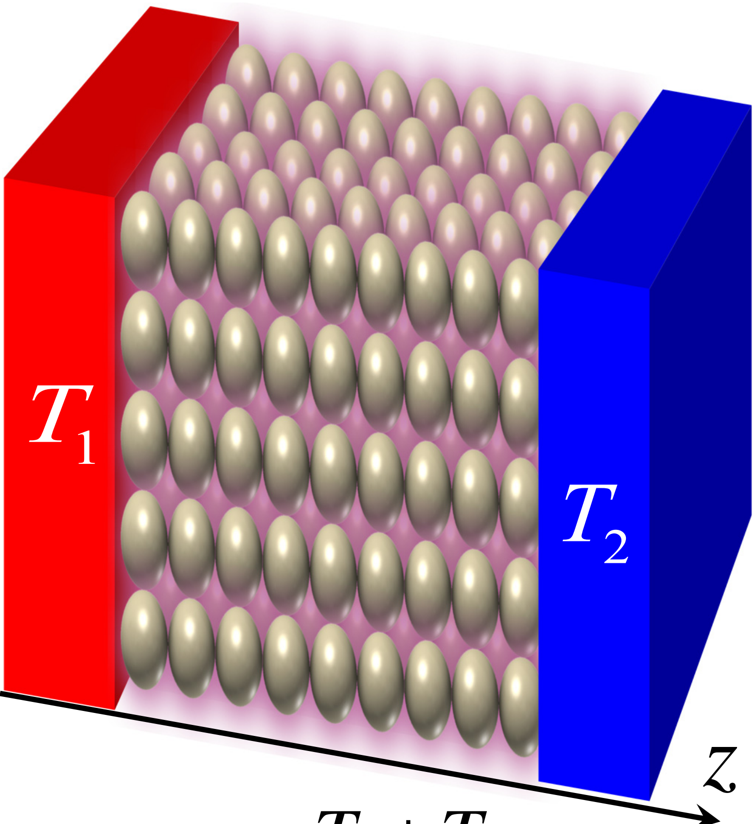
- Ultralow phonon energy transport.
- High surface area-to-volume ratio.

SPhPs: Longitudinal Polarization





Modeling of the Thermal Conductance (G)



SPhP heat flux

$$\vec{q} = \frac{1}{4\pi}\int \hbar\omega\vec{V}\left[f(T_1) - f(T_2)\right]D(\omega)\,d\omega\,d\Omega$$

$$f(T) = \frac{1}{e^{\hbar\omega/k_B T} - 1} \qquad d\Omega = \sin(\theta)\,d\theta\,d\phi$$

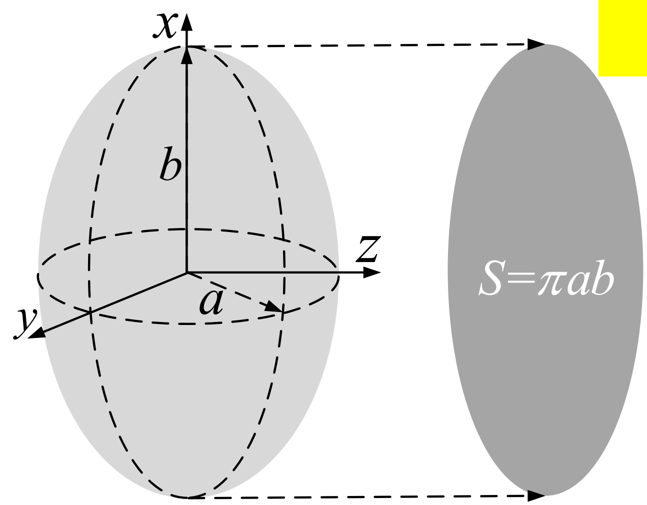
3D density of states: $D(\omega) = \dfrac{\beta_R^2(\omega)}{2\pi^2 V}$

Thermal conductance: $G = \dfrac{qS}{T_1 - T_2}$

For: $T = \dfrac{T_1 + T_2}{2} \gg T_1 - T_2$

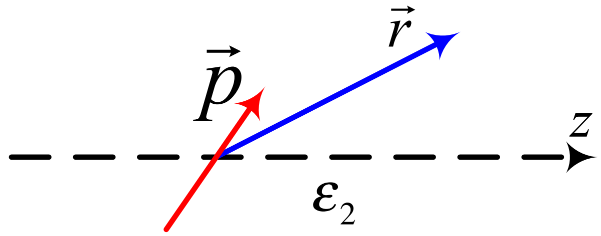
$$G = \frac{S}{8\pi^2}\int_{\omega_{\min}}^{\omega_{\max}} \hbar\omega\beta_R^2 \frac{\partial f}{\partial T}\,d\omega$$

3D effect: $S\beta_R^2/4\pi$

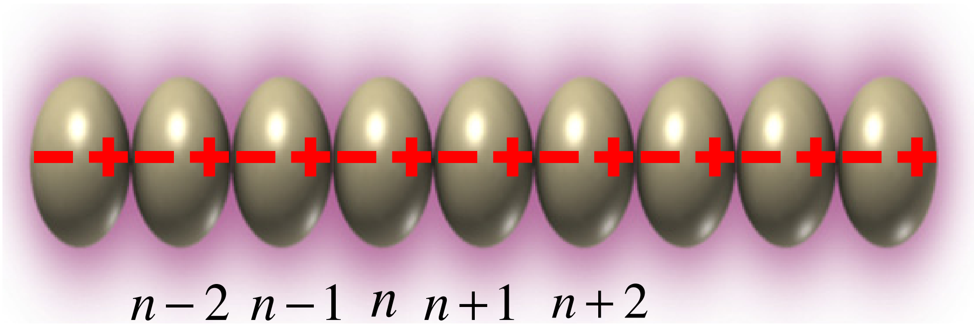


$\beta_R = \mathrm{Re}(\beta) = ?$

Dispersion Relation



$$\vec{E}(\vec{r},t)=\frac{1}{4\pi\varepsilon_2}\left(\frac{\vec{A}}{r^3}-\frac{ik\vec{A}}{r^2}+\frac{k^2\vec{B}}{r}\right)e^{i(kr-\omega t)}$$



$$\vec{E}_n=\sum_{m\neq n}\vec{E}_m(|m-n|d,t)$$

$$\vec{p}_n=\vec{p}_0e^{i(\beta nd-\omega t)} \qquad \vec{p}_n=\alpha\vec{E}_n$$

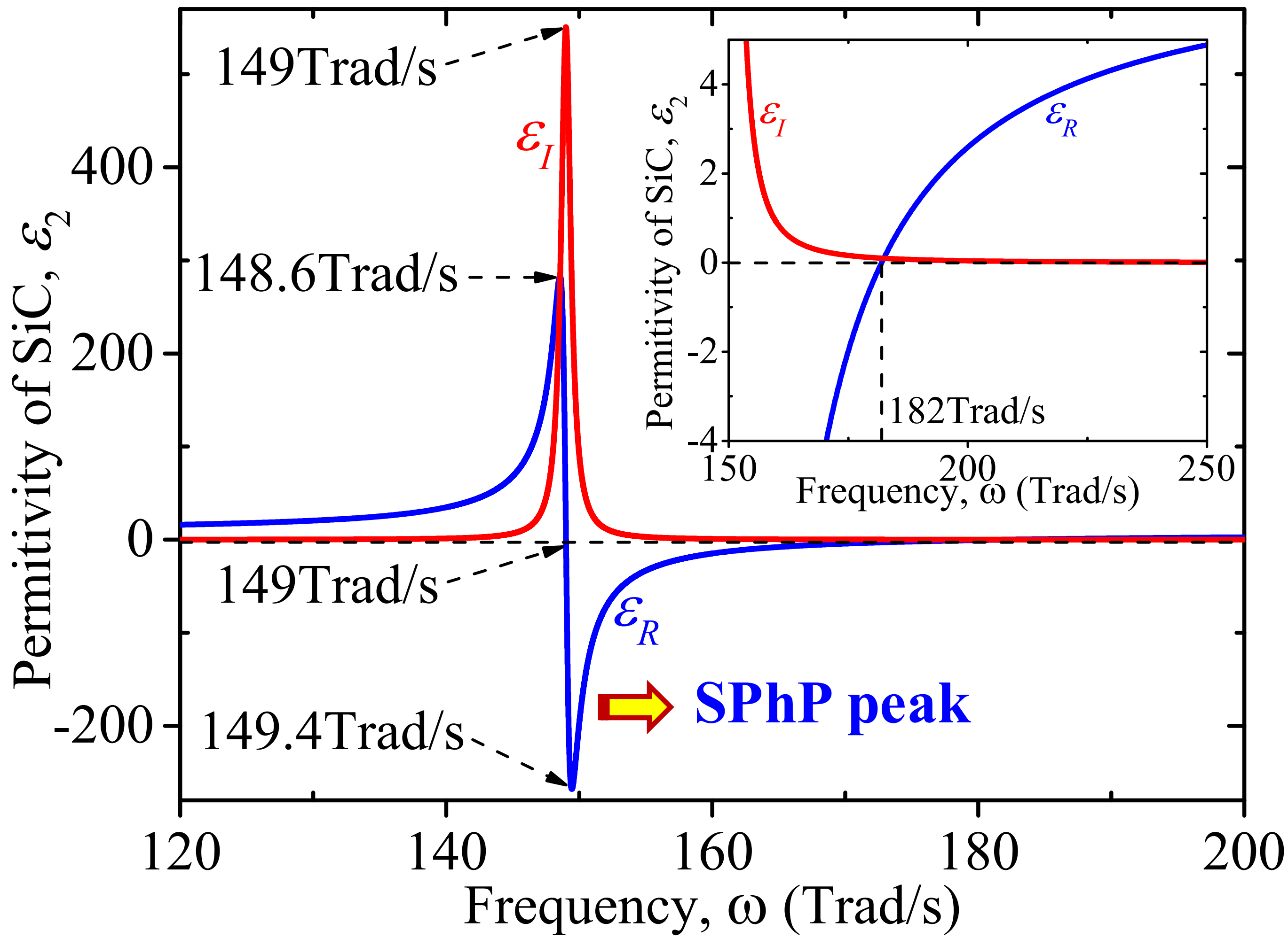
$$-i+\alpha_e^{-1}=\frac{3}{x^3}\left[f_3(\beta,k_2)-ik_2f_2(\beta,k_2)\right] \qquad k_2=\frac{\omega}{c}\sqrt{\varepsilon_2}$$

Dispersion relation: $\beta=\beta_R+i\beta_I=?$

$$\alpha_e=\frac{2}{9k_2^3a^2b}\left[\frac{\varepsilon_1-\varepsilon_2}{\varepsilon_2+L(\varepsilon_1-\varepsilon_2)}\right] \qquad \beta_I=\mathrm{Im}(\alpha_e^{-1})\frac{\partial\beta_R}{\partial\mathrm{Re}(\alpha_e^{-1})}$$

Polarizability

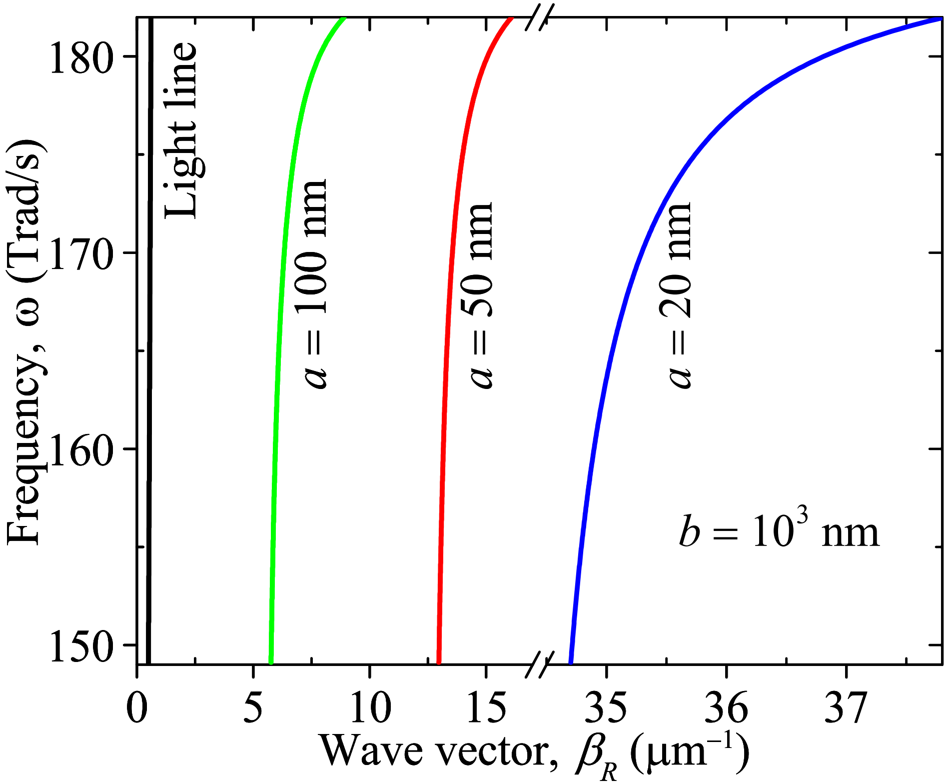
Permittivity of SiC

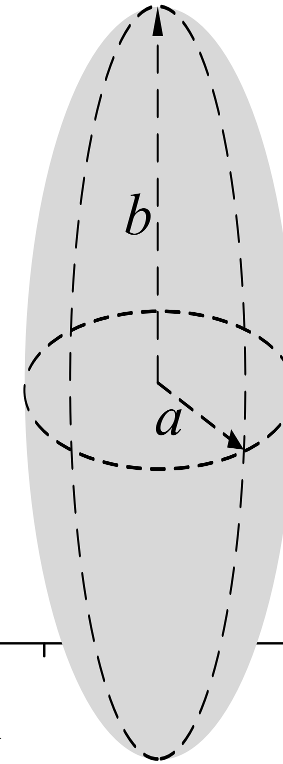


$$\varepsilon_2 < 0$$

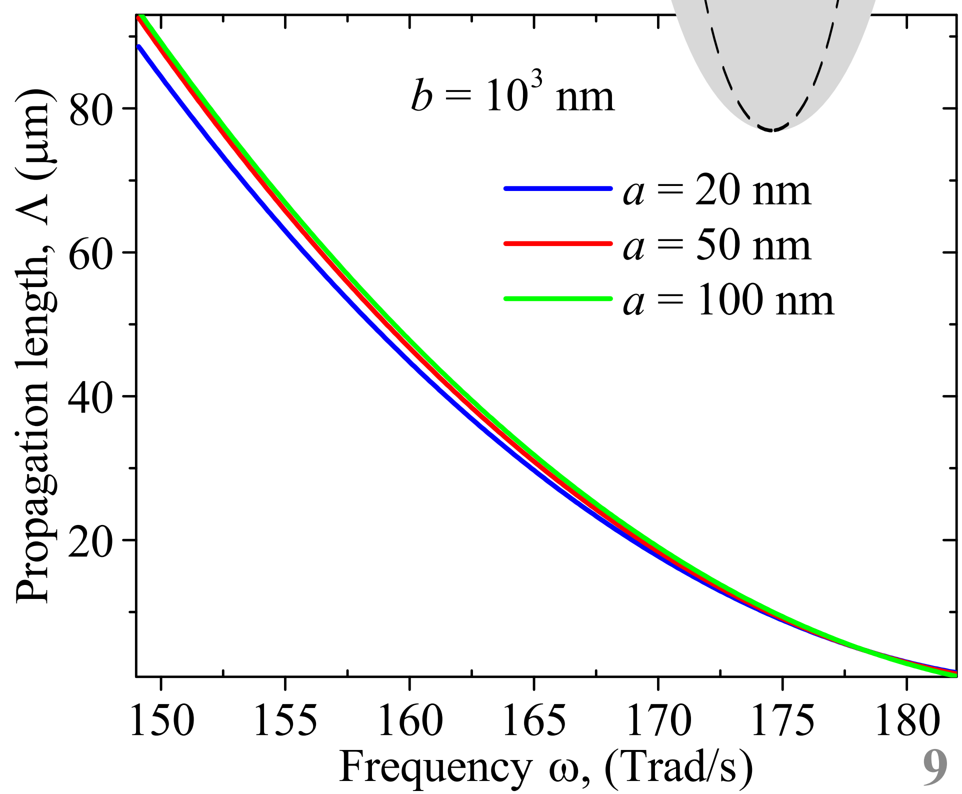
$$149\,\text{Trad/s} < \omega < 182\,\text{Trad/s}$$

Propagation Parameters





$b >> a$

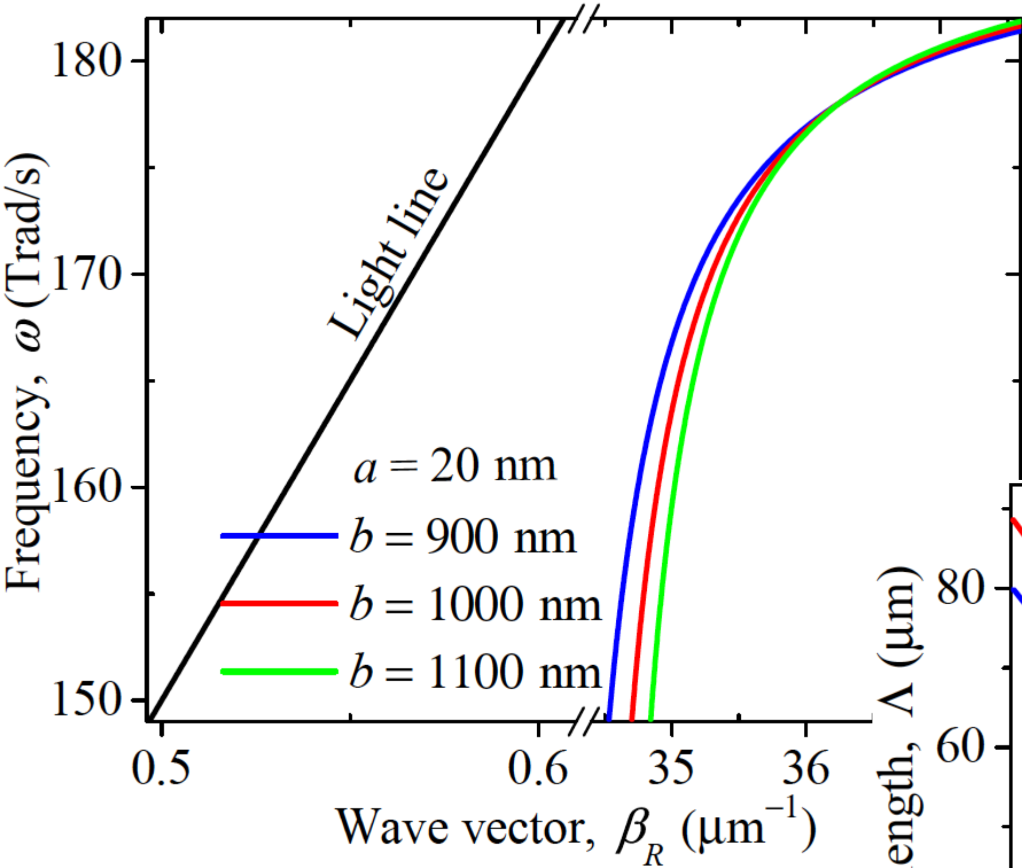


Confinement ⇧⇩ a

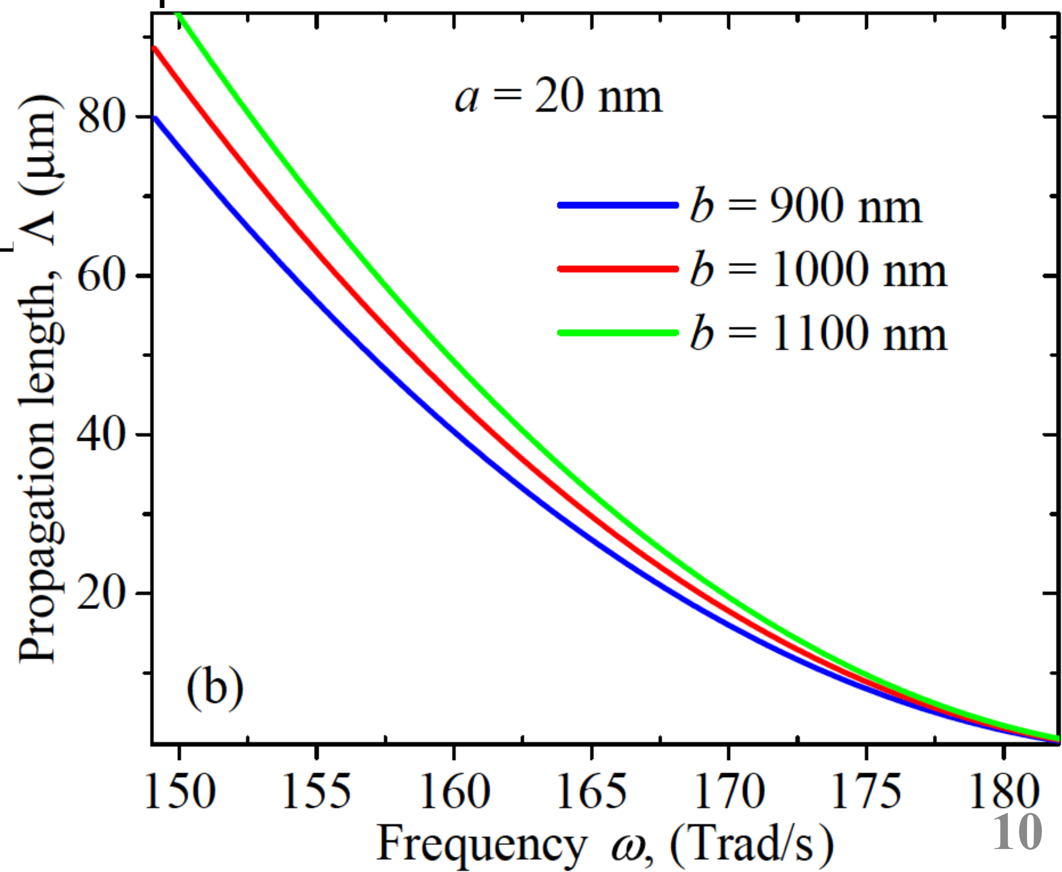
Propagation length ≠ $\Lambda(a)$

$\Lambda > 100$ nanoparticles

Propagation Parameters 2

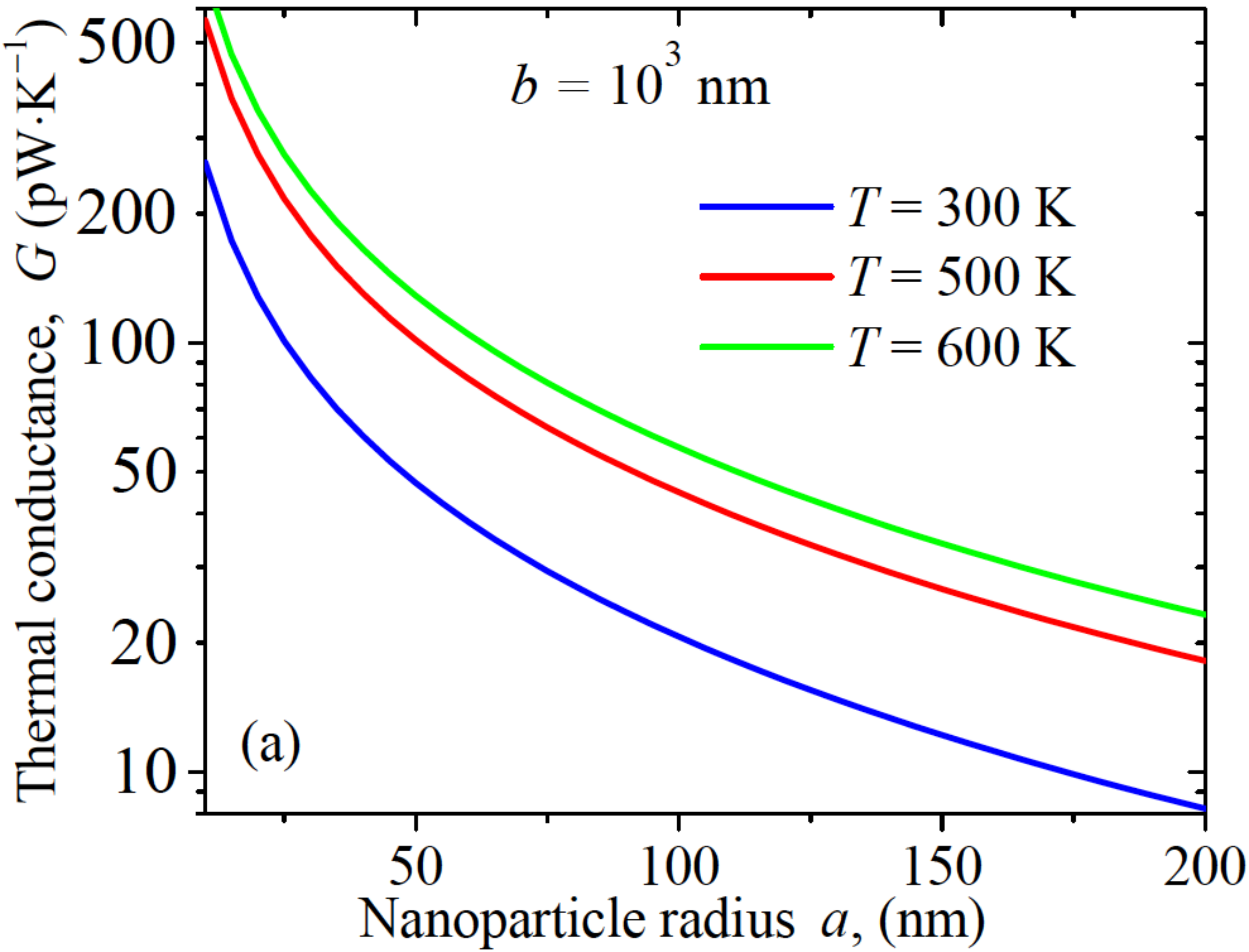


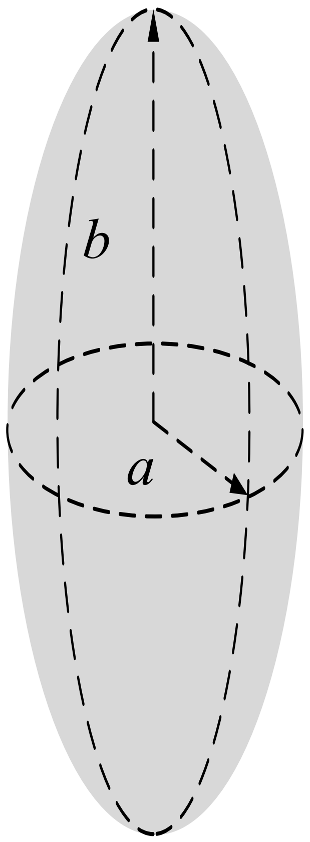
A size change of 200 nm does not affect significantly neither the dispersion relation nor the propagation length.



For $b >> a$. the SPhP energy is not significantly modified by the nanoparticle size dispersion.

Thermal Conductance (*G*)

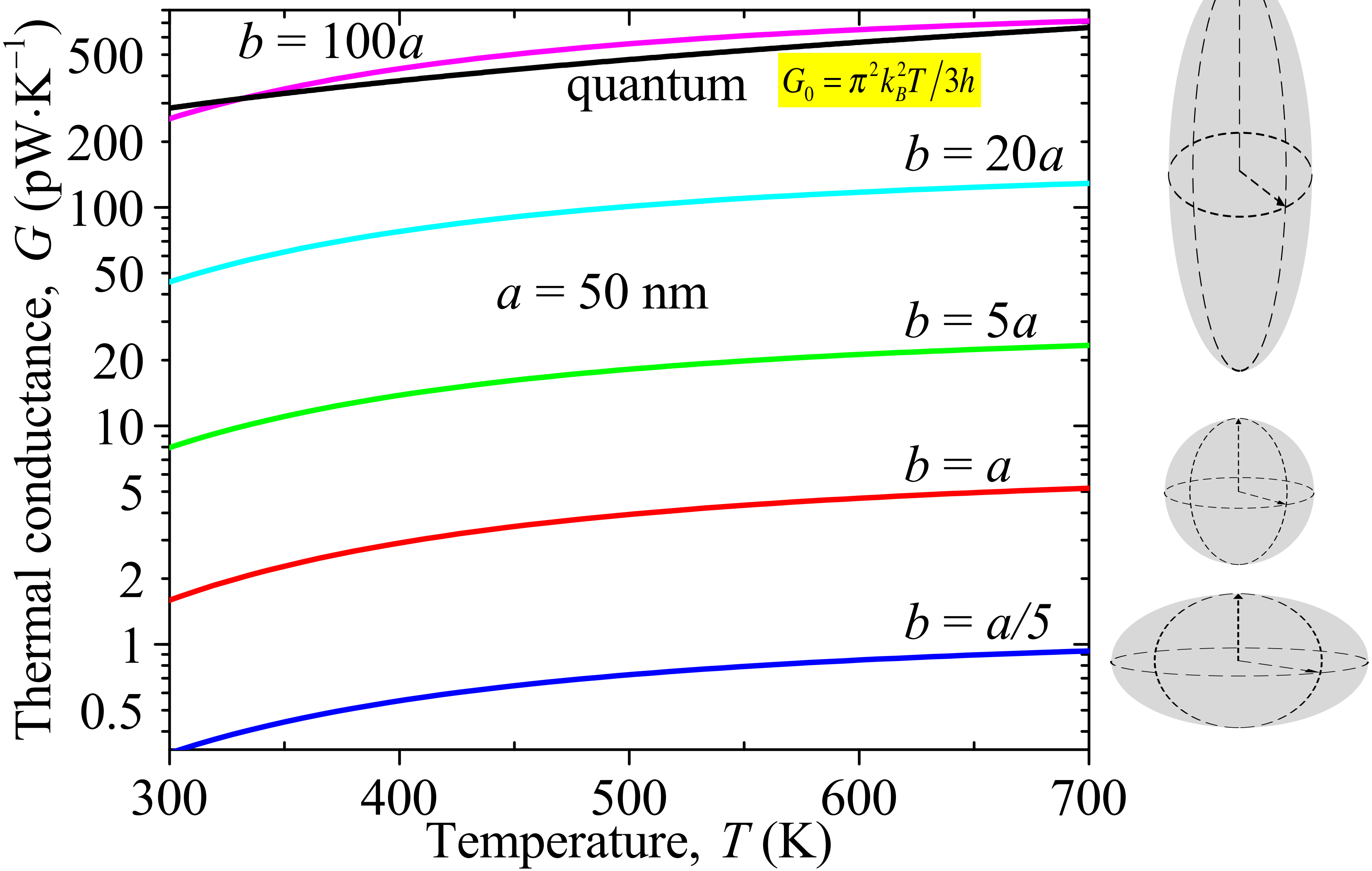




$b >> a$

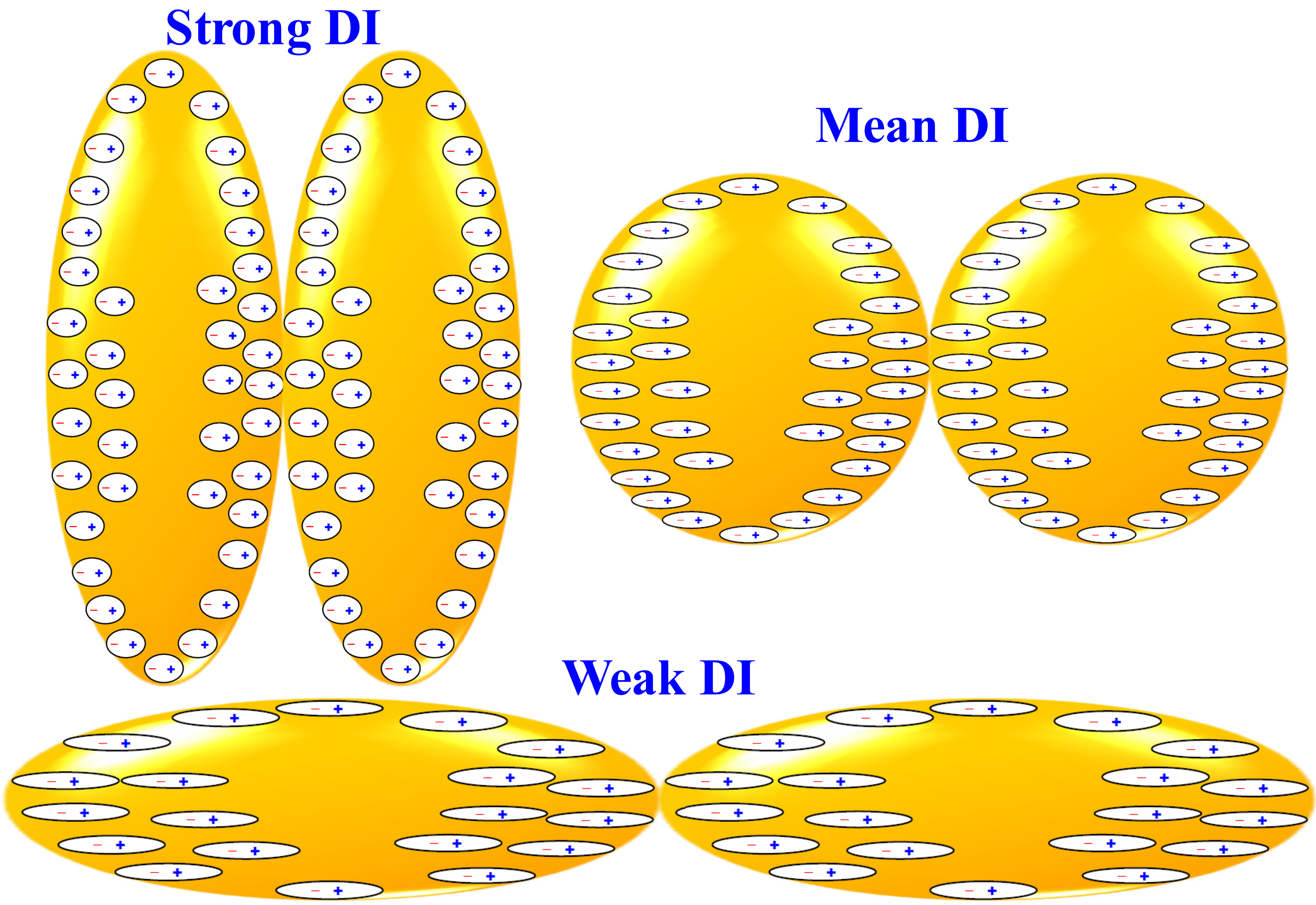
G ⇧ ⇩ a

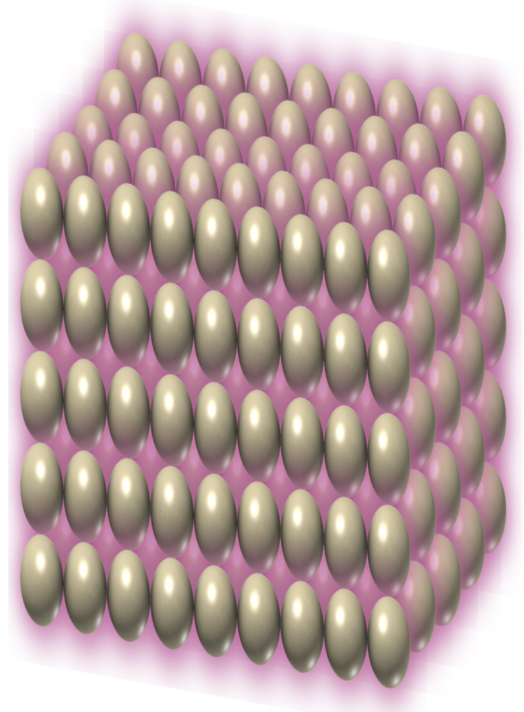
Thermal Conductance 2



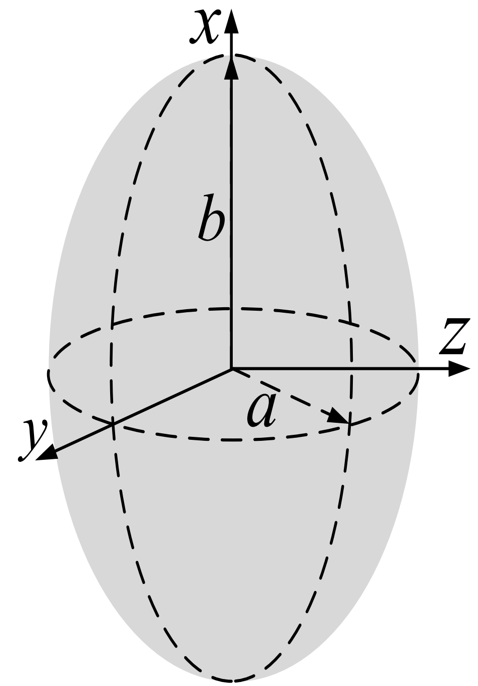
G ⇧⇧ b/a

Dipole Interaction (DI)





Conclusions



SPhP thermal conductance

G ⇑⇑ b/a

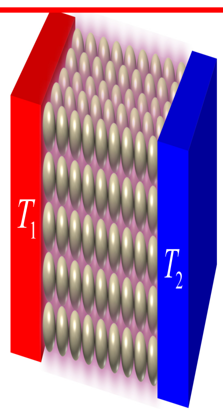
Cylindrical nanoparticles much better than spherical ones.

$$a = 50 \text{ nm}, \quad b = 1\ \mu\text{m}$$

$$G \sim \frac{\pi^2 k_B^2 T}{3h}$$

Quantum of thermal conductance

J. Ordonez-Miranda et al, PRB 93, 035428 (2016); PRL 112, 055901 (2014)



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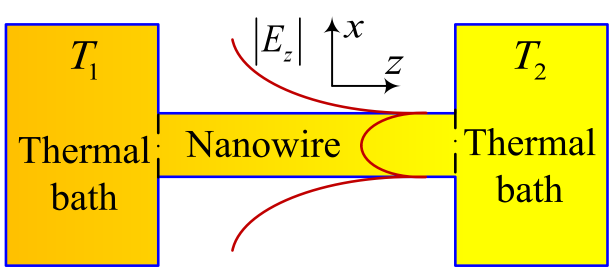

Merci!

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Papers and preprints

www.researchgate.net/profile/Jose_Ordonez-Miranda