# Near-field radiative heat radiation in many-body systems: non-reciprocity, topology, etc.

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Theorie der kondensierten Materie
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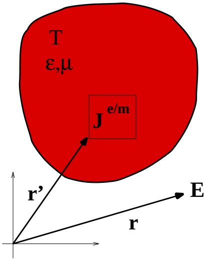
Flectro22, KITP

rerum cognoscere causas

CARL VON OSSIETZKY universität OLDENBURG

# Rytov's fluctuational electrodynamics




- Maxwell's eqs. + fluct. source currents

$$\langle \mathbf{J} \rangle = \mathbf{0}$$

- Fluctuating fields

$$E_\alpha(\omega, \mathbf{r}) = \mathrm{i}\omega\mu_0 \int_V \mathrm{d}^3 r' \, \mathbb{G}^{\mathrm{EE}}_{\alpha\beta}(\mathbf{r}, \mathbf{r}') J_\beta(\mathbf{r}', \omega)$$

- Fluctuation-dissipation theorem

$$\langle J_\alpha(\mathbf{r}, \omega) J^*_\beta(\mathbf{r}', \omega') \rangle = \Theta(\omega, T) 2\omega\epsilon_0 \left[ \mathrm{Im}(\epsilon_{\alpha\beta}) \delta(\mathbf{r} - \mathbf{r}') \right] 2\pi\delta(\omega - \omega')$$

- Mean energy of a harmonic oscillator

$$\Theta(\omega, T) := \frac{\hbar\omega}{2} + \frac{\hbar\omega}{\mathrm{e}^{\hbar\omega / k_\mathrm{B} T} - 1}$$

# Field correlation functions

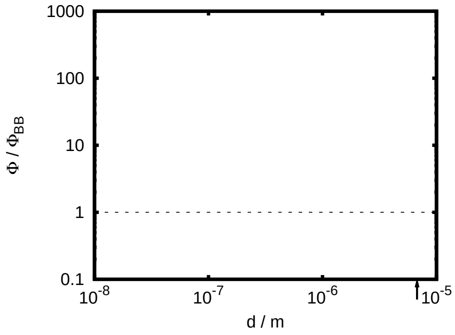
- Correlation functions (applying the FDT)

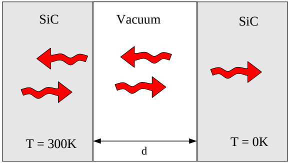
$$\langle E_\alpha(\mathbf{r},t)E_\beta(\mathbf{r}',t')\rangle = \int_{-\infty}^{\infty}\frac{\mathrm{d}\omega}{2\pi}\,\mathrm{e}^{\mathrm{i}\omega(t-t')}2\mu_0^2\omega^3\Theta(\omega,T)\int_V \mathrm{d}^3r'' \times\left(\epsilon_0\mathbb{G}^{\mathrm{EE}}(\mathbf{r},\mathbf{r}'')\underline{\underline{\epsilon}}''(\mathbf{r}'')\mathbb{G}^{\mathrm{EE}\dagger}(\mathbf{r}',\mathbf{r}'')\right)_{\alpha\beta}$$

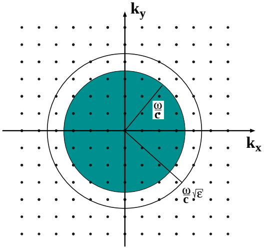
$$\langle E_\alpha(\mathbf{r},t)H_\beta(\mathbf{r}',t')\rangle = \int_{-\infty}^{\infty}\frac{\mathrm{d}\omega}{2\pi}\,\mathrm{e}^{\mathrm{i}\omega(t-t')}2\mu_0^2\omega^3\Theta(\omega,T)\int_V \mathrm{d}^3r'' \times\left(\epsilon_0\mathbb{G}^{\mathrm{EE}}(\mathbf{r},\mathbf{r}'')\underline{\underline{\epsilon}}''(\mathbf{r}'')\mathbb{G}^{\mathrm{HE}\dagger}(\mathbf{r}',\mathbf{r}'')\right)_{\alpha\beta}$$

  etc.
- Equilibrium: FDT 1. kind (G.S. Agarwal, Phys. Rev. A **11**, 230 (1975))
- Stress tensor: Casimir force (Lifshitz, JETP **2**, 73 (1956))
- Poynting vector: Rad. heat transfer (Polder, van Hove, PRB **4**, 3303 (1971))

# Consequences for radiative heat flux




$\Phi_{BB}$ = blackbody value

Polder and van Hove, PRB **4**, 3303 (1971)
Pendry, J. Phys. **11** 6621 (1999)
Volokitin and Persson, RMP **79**, 1291 (2007)

**Landauer:**
SAB, Rousseau, Greffet, PRL **105**, 234301 (2010)
Ben-Abdallah and Joulain, PRB **82**, 121419 (R) (2010)

**Limits:**
Basu, Zhang, JAP **105**, 093535 (2009)
Miller et al., PRL **115**, 204302 (2015) **,** Venkataram et al., PRL **124**, 013904 (2020)

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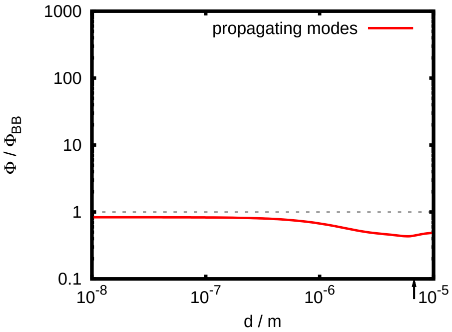


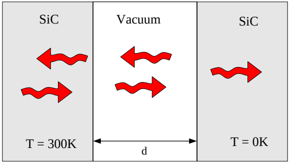


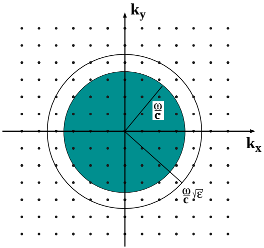


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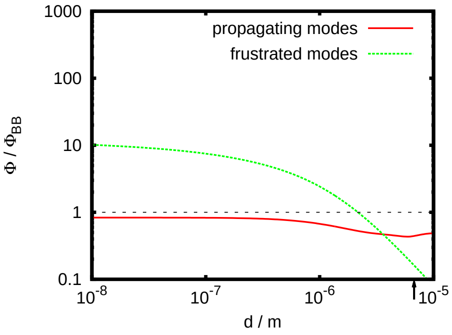


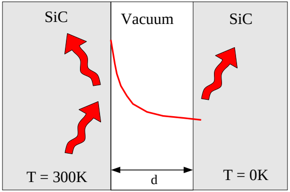


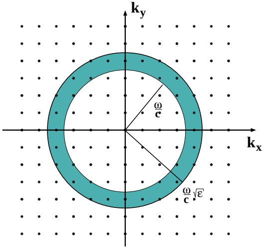


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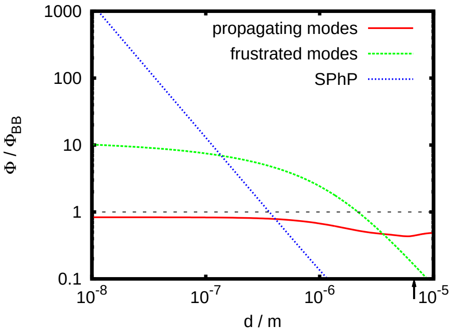


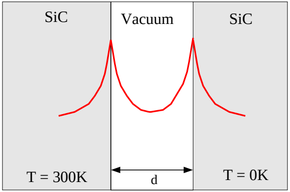


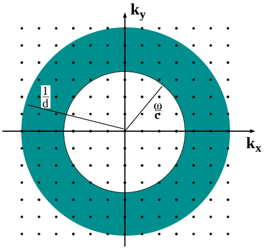


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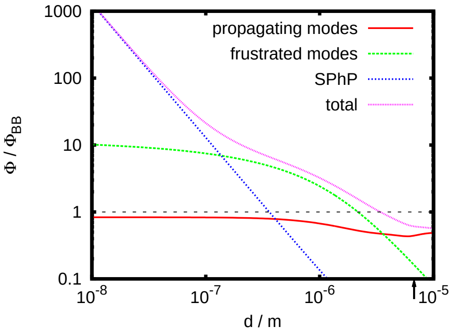


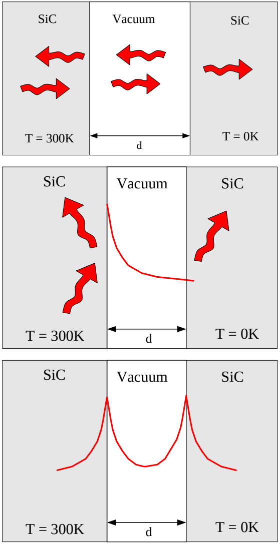


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**Limits:**
Basu, Zhang, JAP **105**, 093535 (2009)
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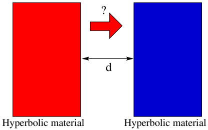
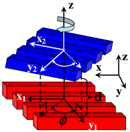
# Two-body near-field heat transfer

## Enhancement: Hyperbolic materials



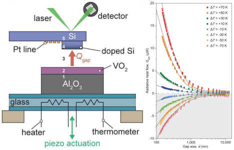

Nefedov, Simovski, PRB **84**, 195459 (2011)
SAB et al., Opt. Expr. **19**, A1088 (2011)
SAB et al., PRL **109**, 104301 (2012)
SAB et al., PRL **115**, 174301 (2015)

## Modulation: mech., elec., magn.



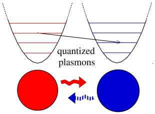

SAB et al., APL **98**, 243102 (2011)
van Zwol et al., PRB **83**, 201404(R) (2011)
Huang et al., APL **105** 244102 (2014)
Ekeroth et al., ACS Phot. **5**, 705 (2018)

## Thermotronics: Phase-change Diode



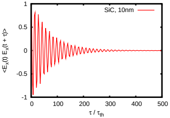

Otey et al., PRL **104**, 154301 (2010)
Ben-Abdallah, SAB, APL **103**, 191907 (2013)
Fiorino et al., ACS Nano **12**, 5774 (2018)

## Quantum models



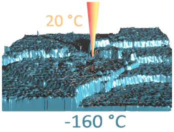

Janowicz et al., PRA **68**, 043823 (2003)
SAB, Agarwal, JOSAB **30**, 700 (2013)
Barton, J. Stat. Phys. **165**, 1153 (2016)
Wang, Peng EPL **118**, 24001 (2017)

## Fluctuations



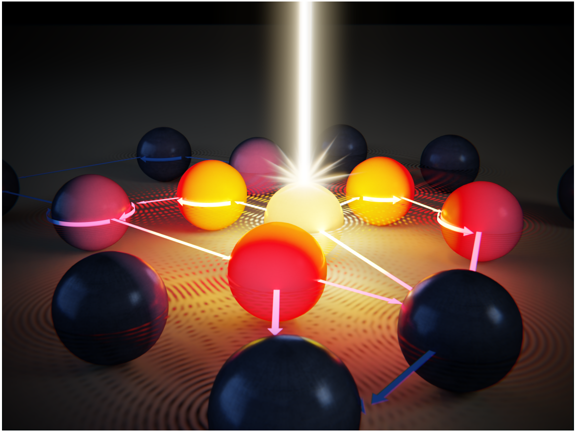

Golyk et al., PRB **88**, 155117 (2013)
SAB, Ben-Abdallah, PRB **97**, 201406(R) (2018)
Herz, SAB, EPL **127**, 44001 (2019)
Herz et al., EPL **130**, 44003 (2020)

## Experiments




Kittel et al., PRL **95**, 224301 (2005)
Kittel et al., APL **93**, 193109 (2008)
Kloppstech et al., Nat. Comm. **8**, 14475 (2017)

# Thermal near-field radiation in many-body systems



Ben-Abdallah, SAB, Joulain, PRL **107**, 107, 114301 (2011)
...
Messina, Antezza PRA **84**, 042102 (2011)
Krüger, Bimonte, Emig, Kardar, PRB **86**, 115423 (2012)
...
...
SAB, Messina, Venkataram, Rodriguez, Cuevas, Ben-Abdallah, Rev. Mod. Phys. **93**, 025009 (2021)

# Thermal near-field radiation in many-body systems

- Power exchanged between particles with polarizability $\underline{\underline{\alpha}}$

$$\langle P_i \rangle = \sum_{j \neq i}^{N} 3 \int_0^\infty \frac{d\omega}{2\pi} \Big( \big[ \Theta(\omega, T_j) - \Theta(\omega, T_i) \big] \mathcal{T}_{ji}(\omega) \Big)$$

- Mean energy of harmonic oscillator

$$\Theta(\omega, T) = \frac{\hbar\omega}{e^{\hbar\omega/k_B T} - 1} \qquad \langle P_1 \rangle = 3 \left( \frac{\pi^2 k_B^2 T}{3h} \right) \overline{\mathcal{T}}_{12} \Delta T_{12}$$

- Transmission coefficient (proportional to absorptivity $\frac{\underline{\underline{\alpha}} - \underline{\underline{\alpha}}^\dagger}{2i}$)

$$\mathcal{T}_{ij}(\omega) = \frac{4}{3} \mathrm{ImTr} \left[ \boldsymbol{T}_{ij}^{-1} \frac{\underline{\underline{\alpha}} - \underline{\underline{\alpha}}^\dagger}{2i} (\boldsymbol{T}_{ij}^{-1})^\dagger \underline{\underline{\alpha}}^{-1\dagger} \right]$$

- 'Transfer matrix'

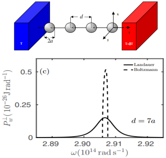
$$\boldsymbol{T}_{ij} = \delta_{ij} \mathbb{1} - (1 - \delta_{ij}) k_0^2 \underline{\underline{\alpha}} \mathbb{G}_{ij}^E$$

- Access to all observables: mean Poynting vector, energy density, etc.

SAB, Messina, Venkataram, Rodriguez, Cuevas, Ben-Abdallah, Rev. Mod. Phys. **93**, 025009 (2021)

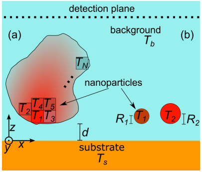
# Application of many-body theory

## Boltzmann vs. Landauer



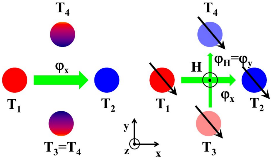

Ben-Abdallah, et al., PRL **111**, 174301 (2013)
Kathmann et al., PRB **98**, 115434 (2018)

## Coupled dipole method



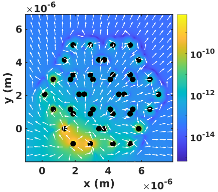

Herz, SAB, PRB **105**, 205422(2022)

## Non-Reciprocal systems



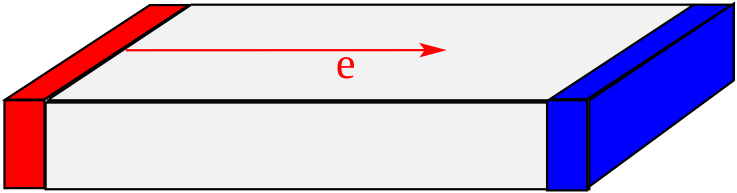

Ben-Abdallah, PRL **116**, 084301 (2016)
Ott et al., J. Phot. En. **9**, 032711 (2019)
Ott et al., PRB **101**, 241411(R) (2020)

## Topological systems



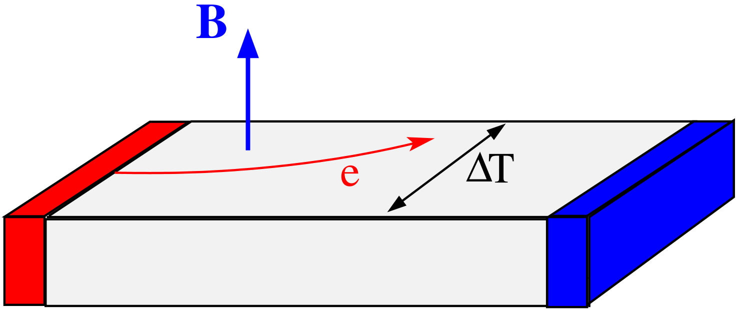

Ott, SAB, PRB **102**, 115417 (2020)
Ott, SAB, IJHMT **190**, 122796(2022)

# Righi-Leduc or thermal Hall effect



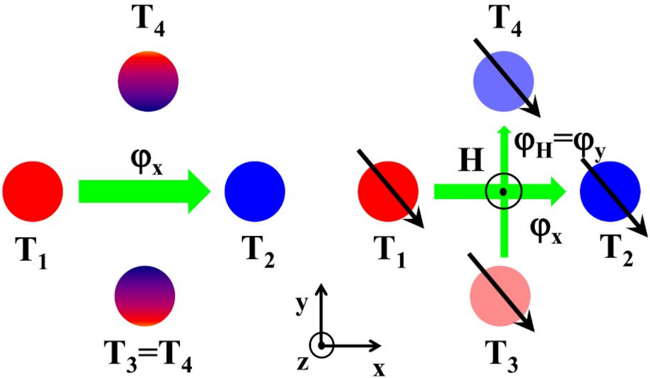

A. Righi, Mem. Acc. Lincei 4, 433 (1887); M. A. Leduc, J. Phys. 2e série 6, 378 (1887)

# Righi-Leduc or thermal Hall effect




A. Righi, Mem. Acc. Lincei 4, 433 (1887); M. A. Leduc, J. Phys. 2e série 6, 378 (1887)

# Hall effect for thermal radiation



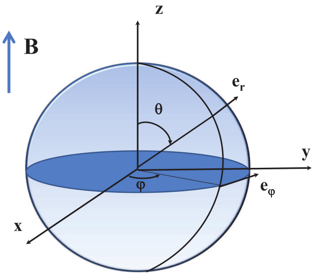

How can the photon trajectories be bent?

Ben-Abdallah, PRL **116**, 084301 (2016)

# Fluctuational fields around a nanoparticle

- Fluctuational fields

$$\vec{E}_{\text{fl}} = \omega^2 \mu_0 \mathbb{G}^E(\vec{r}, \vec{r'}, \omega) \cdot \vec{p}_{\text{fl}}(\omega, t)$$
$$\vec{H}_{\text{fl}} = \omega^2 \mu_0 \mathbb{G}^H(\vec{r}, \vec{r'}, \omega) \cdot \vec{p}_{\text{fl}}(\omega, t)$$




- Fluctuation-dissipation theorem of second kind

$$\langle \vec{p}_{\text{fl}} \otimes \vec{p}^*_{\text{fl}} \rangle = \frac{2\epsilon_0}{\omega} \Theta(\omega, T_p) \frac{1}{2i} (\underline{\underline{\alpha}} - \underline{\underline{\alpha}}^\dagger)$$

- Polarizability (spherical particle)

$$\underline{\underline{\alpha}} = 4\pi R^3 (\underline{\underline{\epsilon}} - \mathbb{1})(\underline{\underline{\epsilon}} + 2\mathbb{1})^{-1}$$

- Non-reciprocal permittivity ($\underline{\underline{\alpha}}^t \neq \underline{\underline{\alpha}}, \quad \underline{\underline{\epsilon}}^t \neq \underline{\underline{\epsilon}}$)

$$\underline{\underline{\epsilon}} = \begin{pmatrix} \epsilon_1 & -i\epsilon_2 & 0 \\ i\epsilon_2 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_3 \end{pmatrix} \quad \Rightarrow \quad \underline{\underline{\alpha}} = \begin{pmatrix} \alpha_1 & \alpha_{12} & 0 \\ -\alpha_{12} & \alpha_1 & 0 \\ 0 & 0 & \alpha_3 \end{pmatrix}$$

Ott, Ben-Abdallah, SAB, PRB **97**, 205414 (2018)

# Heat flux, momentum, angular momentum, and spin

- Mean poynting vector

$$\langle \vec{S}_\omega \rangle = 2\mathrm{Re}\langle \vec{E}_{\text{fl}} \times \vec{H}^*_{\text{fl}} \rangle$$

- Canonical linear momentum density

$$\langle \vec{P}_\omega \rangle = \frac{1}{\omega}\mathrm{Im}\Big( \frac{\epsilon_0}{2}\langle \vec{E}^*_{\text{fl}}(\nabla)\vec{E}_{\text{fl}} \rangle + \frac{\mu_0}{2}\langle \vec{H}^*_{\text{fl}}(\nabla)\vec{H}_{\text{fl}} \rangle \Big)$$

- Angular momentum density

$$\langle \vec{L}_\omega \rangle = \vec{r} \times \langle \vec{P}_\omega \rangle$$

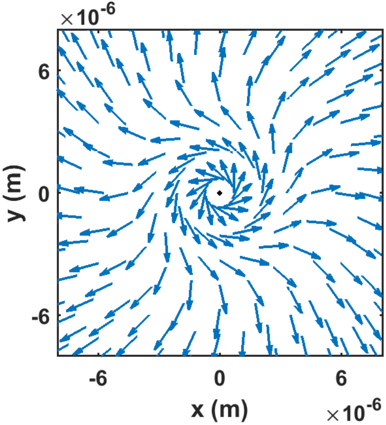
- Spin angular momentum density

$$\langle \vec{S}_{d\,\omega} \rangle = \frac{1}{\omega}\mathrm{Im}\Big( \frac{\epsilon_0}{2}\langle \vec{E}^*_{\text{fl}} \times \vec{E}_{\text{fl}} \rangle + \frac{\mu_0}{2}\langle \vec{H}^*_{\text{fl}} \times \vec{H}_{\text{fl}} \rangle \Big)$$

Bliokh and Nori, Phys. Rep. **592**, 1 (2015)

Ott, Ben-Abdallah, SAB, PRB **97**, 205414 (2018)

# Poynting vector around one InSb nanoparticle




- Polarizability

$$\underline{\underline{\alpha}} = 4\pi R^3(\underline{\underline{\epsilon}} - \mathbb{1})(\underline{\underline{\epsilon}} + 2\mathbb{1})^{-1}$$

- Applied magnetic field

$$\underline{\underline{\alpha}} = \begin{pmatrix} \alpha_1 & \alpha_{12} & 0 \\ -\alpha_{12} & \alpha_1 & 0 \\ 0 & 0 & \alpha_3 \end{pmatrix}$$

- Non-reciprocal

$$\underline{\underline{\alpha}}^t \neq \underline{\underline{\alpha}}$$

$$S_\varphi(\omega) = \frac{\Theta(\omega, T_p) k_0^3}{2\pi^2 r^2} \mathrm{Re}(\alpha_{12}) \left( \frac{1}{k_0 r} + \frac{1}{k_0^3 r^3} \right)$$

Ott, Ben-Abdallah, SAB, PRB **97**, 205414 (2018)

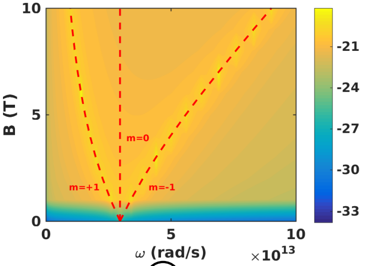
# Dipolar resonances,($l = 1$, $m = -1, 0, +1$)

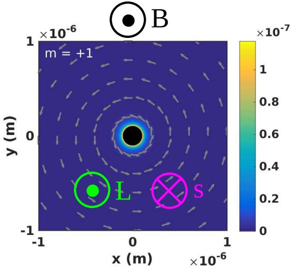
- Dipolar resonances

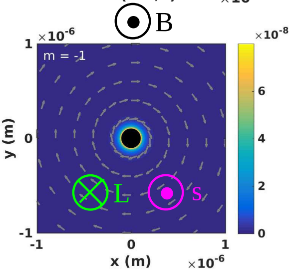
$$\omega_{m=0} = \sqrt{\frac{\epsilon_\infty \omega_p^2}{\epsilon_\infty + 2}}$$

$$\omega_{m=\pm 1} = \sqrt{\frac{\epsilon_\infty \omega_p^2}{\epsilon_\infty + 2} + \frac{\omega_c^2}{4}} \mp \frac{\omega_c}{2}$$

plot of $|\alpha_{12}|$ ($m^3$)



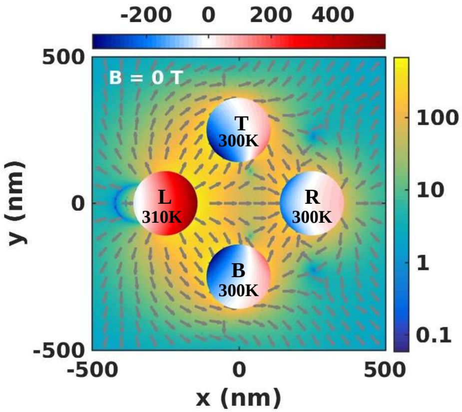




Ott, Ben-Abdallah, SAB, PRB **97**, 205414 (2018)

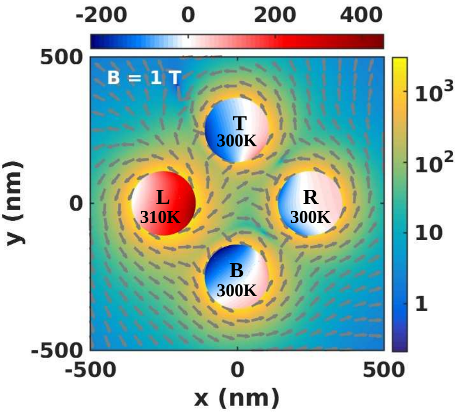
spin, angular momentum, heat flux **persist** in equilibrium
[see also M.G. Silveirinha, PRB **95**, 115103 (2017)]

# Heat flux and emitted/received power
# ($R = 100\,\mathrm{nm}$, $d = 500\,\mathrm{nm}$)



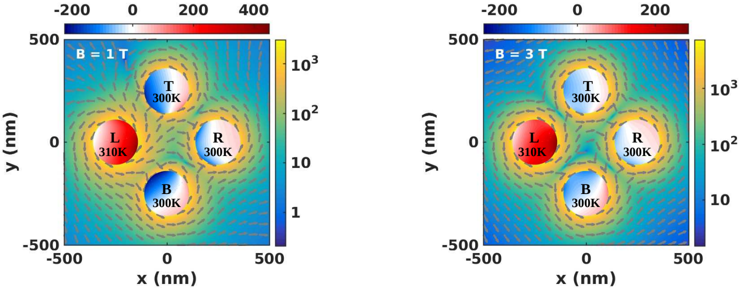

Ott, Messina, Ben-Abdallah, SAB, J. Photon. Energy **9**, 032711 (2019)

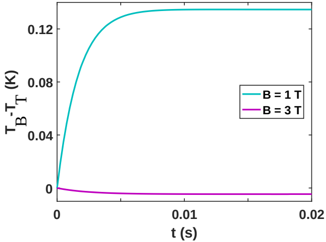
# Heat flux and emitted/received power ($R = 100\,\mathrm{nm}$, $d = 500\,\mathrm{nm}$)




Ott, Messina, Ben-Abdallah, SAB, J. Photon. Energy **9**, 032711 (2019)

# Photonic thermal Hall effect



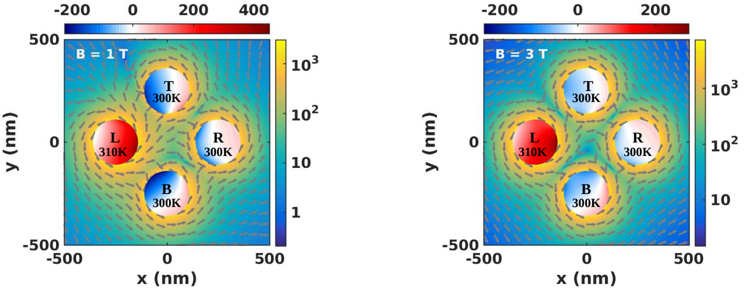

"Righi-Leduc coefficient"

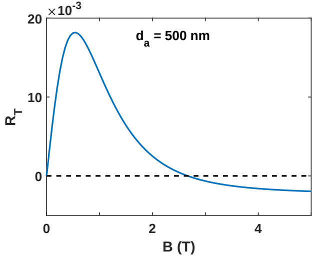
$$R_{\rm T} = \frac{T_{\rm B}^{(st)} - T_{\rm T}^{(st)}}{T_{\rm L} - T_{\rm R}} = \frac{G_{LB} - G_{BL}}{G_{LB} + G_{BL} + 2G_{BT}}$$

Ott, Messina, Ben-Abdallah, SAB, J. Photon. Energy **9**, 032711 (2019)

Anomalous Hall effect for Weyl semi metals: Ott, SAB, Ben-Abdallah, PRB **101**, 241411(R) (2020)

# Photonic thermal Hall effect



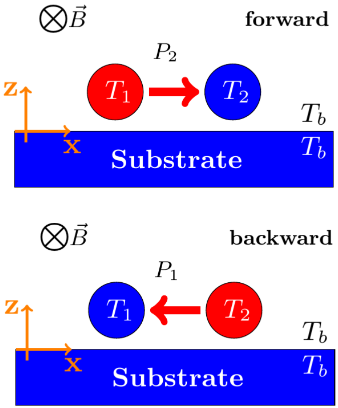

"Righi-Leduc coefficient"

$$R_{\mathrm{T}} = \frac{T_{\mathrm{B}}^{(st)} - T_{\mathrm{T}}^{(st)}}{T_{\mathrm{L}} - T_{\mathrm{R}}} = \frac{G_{LB} - G_{BL}}{G_{LB} + G_{BL} + 2G_{BT}}$$

Ott, Messina, Ben-Abdallah, SAB, J. Photon. Energy **9**, 032711 (2019)

Anomalous Hall effect for Weyl semi metals: Ott, SAB, Ben-Abdallah, PRB **101**, 241411(R) (2020)

# Heat flux diode with non-reciprocal surface waves



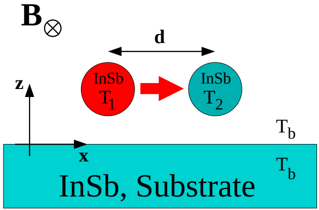

Ott, Messina, Ben-Abdallah, SAB, APL **114**, 163105 (2019)

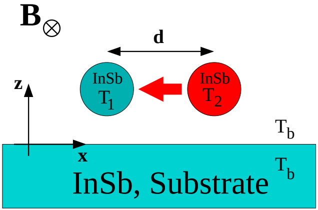
Ott, SAB, PRB **101**, 155428 (2020)

## Enhancement by surface:

Sääskilathi et al., PRB **89**, 134301 (2014)
Asheichyk et al., PRB **96**, 155402 (2017)
Dong et al., PRB **97**, 075422 (2018)
Messina et al., PRB **97**, 165437 (2018)

# Rectification and non-reciprocity




$$P_2 = 3\int_0^\infty \frac{d\omega}{2\pi}\left[\Theta(T_1) - \Theta(T_2)\right]\mathcal{T}_{12}$$

$$\mathcal{T}_{12} = \frac{4}{3}k_0^4 \mathrm{Tr}\left[\underline{\chi}\mathbb{G}_{12}\underline{\chi}\mathbb{G}_{12}^\dagger\right]$$

$$P_1 = 3\int_0^\infty \frac{d\omega}{2\pi}\left[\Theta(T_2) - \Theta(T_1)\right]\mathcal{T}_{21}$$

$$\mathcal{T}_{21} = \frac{4}{3}k_0^4 \mathrm{Tr}\left[\underline{\chi}\mathbb{G}_{21}\underline{\chi}\mathbb{G}_{21}^\dagger\right]$$

- No rectification if

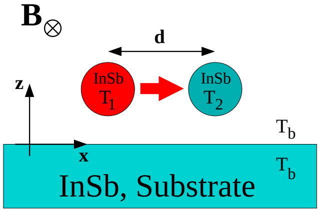
$$\mathbb{G}_{12} = \mathbb{G}_{21} \quad \text{or} \quad \mathbb{G}_{12} = \mathbb{G}_{21}^t$$

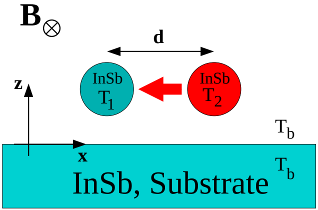
- Non-reciprocal substrate

$$r_{pp}(k_x) \neq r_{pp}(-k_x) \Rightarrow \mathbb{G}_{12} \neq \mathbb{G}_{21}^t$$

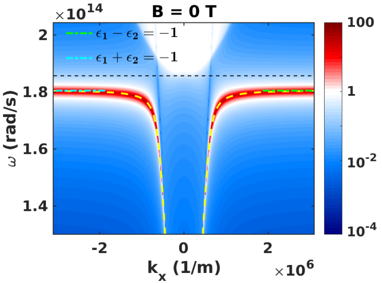
Ott, Messina, Ben-Abdallah, SAB, APL **114**, 163105 (2019); Ott, SAB, PRB **101**, 155428 (2020)

# Rectification and non-reciprocity



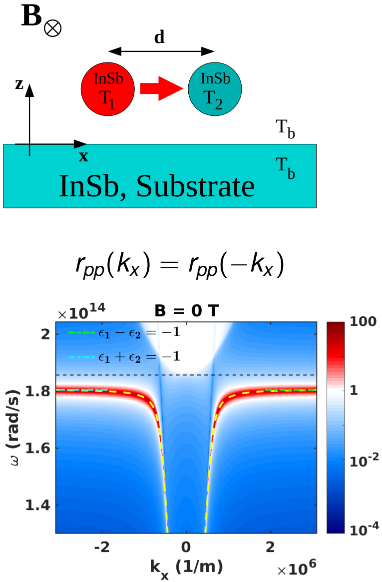



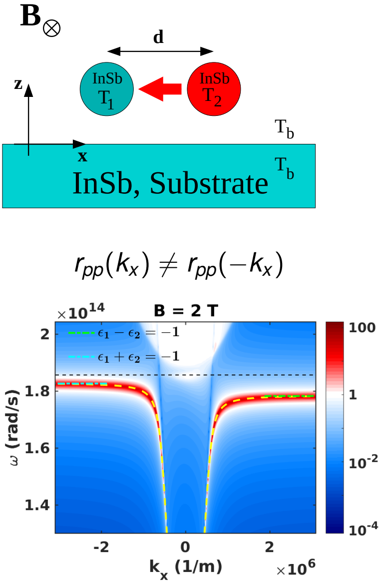

$$r_{pp}(k_x) = r_{pp}(-k_x)$$




Ott, Messina, Ben-Abdallah, SAB, APL **114**, 163105 (2019); Ott, SAB, PRB **101**, 155428 (2020)

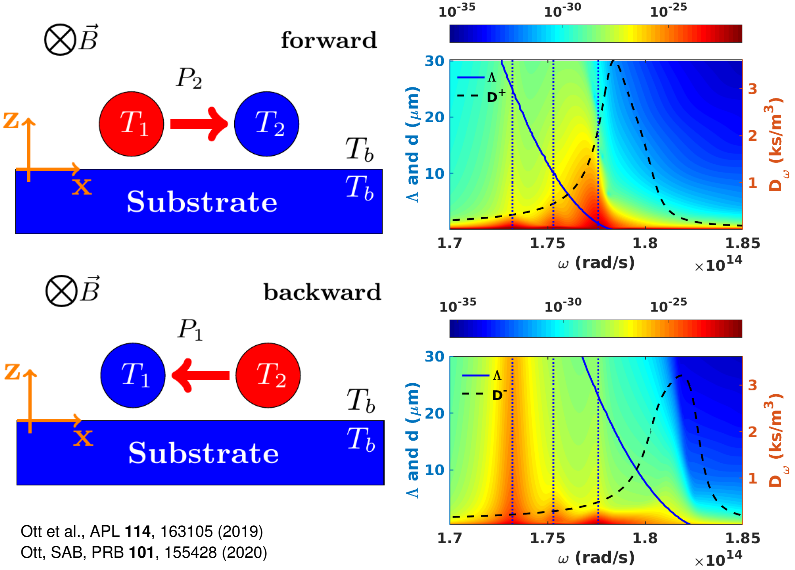
# Rectification and non-reciprocity



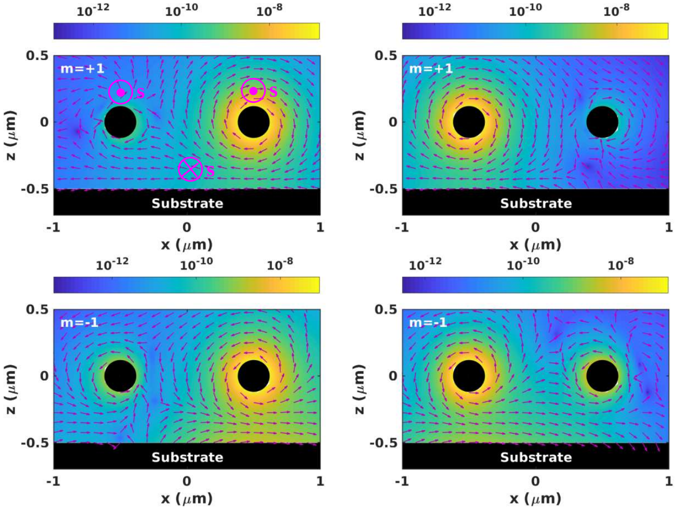

Ott, Messina, Ben-Abdallah, SAB, APL **114**, 163105 (2019); Ott, SAB, PRB **101**, 155428 (2020)

# Heat flux diode (doped InSb, $R = 100\,\mathrm{nm}$, $z = 5R$, 2T)




Ott et al., APL **114**, 163105 (2019)
Ott, SAB, PRB **101**, 155428 (2020)

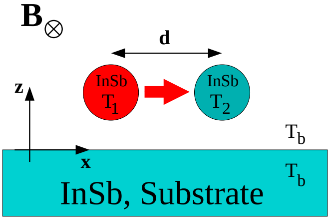
# Coupling of dipolar and surfaces modes

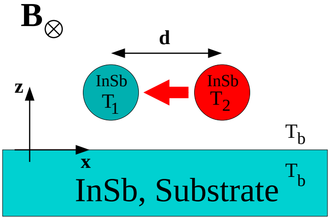



Ott et al., APL **114**, 163105 (2019)
Ott, SAB, PRB **101**, 155428 (2020)

spin-momentum locking:
Bliokh et al., Science **348**, 1448 (2015);
Van Mechelen,Jacob, Optica **3**, 118 (2016)

# Rectification coefficient (R = 100nm, z = 500nm)



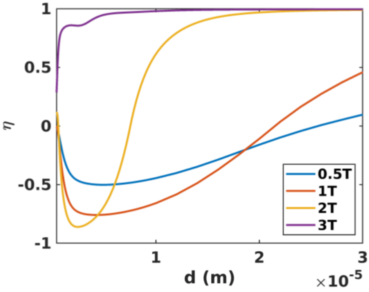




- Rectification coeff.

$$\eta = \frac{P_1 - P_2}{\max(P_1, P_2)}$$

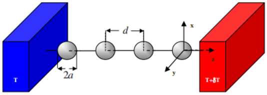
n-doping
($n = 1.4 \times 10^{19}\,\mathrm{cm}^{-3}$)

Ott et al., APL **114**, 163105 (2019)
Ott, SAB, PRB **101**, 155428 (2020)



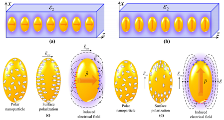
# Boltzmann equation approach for plasmonics

## Chain of nanoparticles



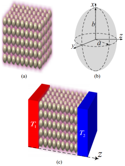

Ben-Abdallah, PRB **77**, 075417 (2008)

## Spheroidal nanoparticles



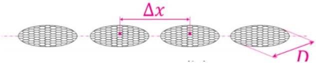

Ordonez-Miranda et al., PRB **92**, 115409 (2015)

## Plasmonic crystal



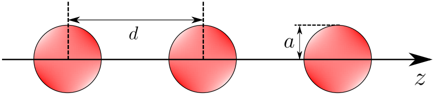

Ordonez-Miranda et al., PRB **93**, 035428 (2016)

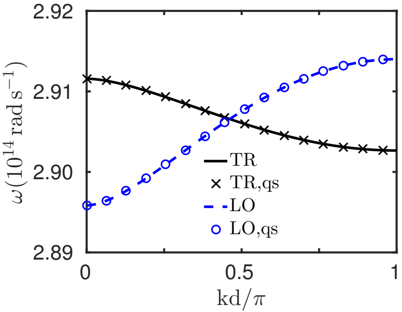
## Graphene disks




Ramirez, McGaughey, PRB **96**, 165428 (2017)

# hBN nanoparticle chain (a = 25nm, d = 100nm)




Kathmann, Messina, Ben-Abdallah, SAB, PRB **98**, 115434 (2018)

- Heat current density

$$j = \frac{1}{LA}\sum_k (f_k - f_k^0) v_{g,k} \hbar\omega_k$$

- Boltzmann equation

$$\frac{\partial f_k}{\partial t} + v_{g,k}\frac{\partial f_k}{\partial z} = -\frac{f_k - f_k^0}{\tau_k}$$

- Transferred power ($\frac{\mathrm{d}T}{\mathrm{d}z} \approx \frac{\Delta T}{L}$)

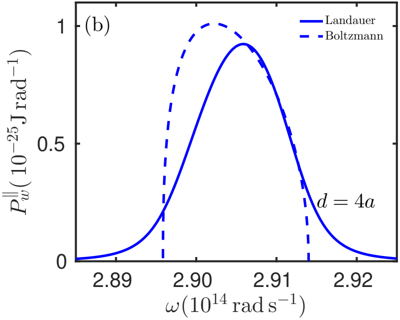
$$P_d = Aj = \int \frac{\mathrm{d}\omega}{2\pi}\Theta_{1N}\frac{2}{L}\left(2\Lambda_\omega^\perp + \Lambda_\omega^\parallel\right)$$

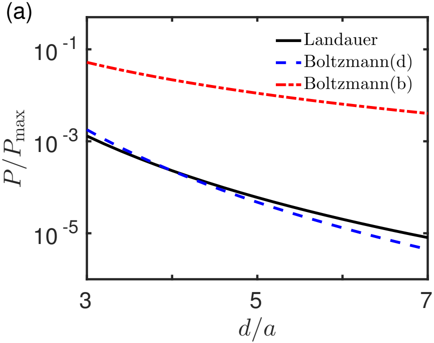
- Propagation length [$\exp(-\mathrm{i}\omega t)$]

$$\Lambda_\omega = \left|\frac{\mathrm{d}\omega'}{\mathrm{d}k}\frac{1}{2\omega''}\right|$$

# Boltzmann vs. Landauer (hBN, a = 25nm)

- Spectral transferred power
- Full transferred power

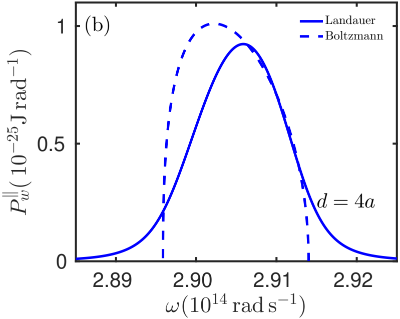


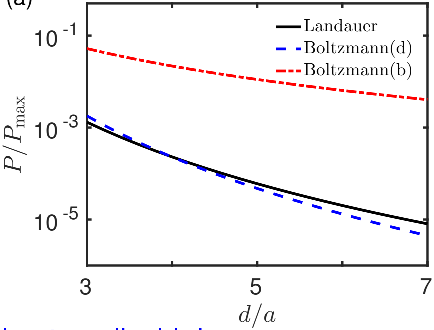

Kathmann, Messina, Ben-Abdallah, SAB, PRB **98**, 115434 (2018)

# Boltzmann vs. Landauer (hBN, a = 25nm)

- Spectral transferred power
- Full transferred power




(a)

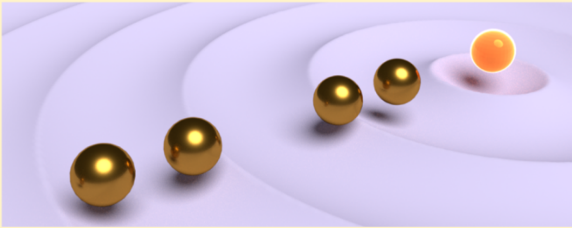



Boltzmann approach is in general not applicable!

see also Tervo et al, JQSRT 246, 106947 (2020)

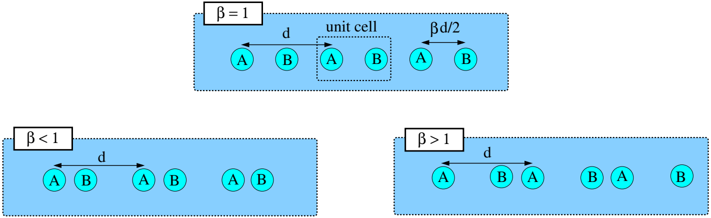
Kathmann, Messina, Ben-Abdallah, SAB, PRB **98**, 115434 (2018)

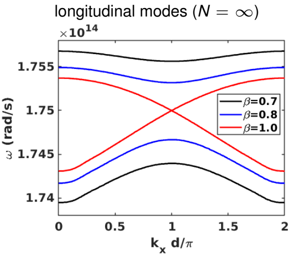
# Su-Schrieffer-Heeger model in plasmonics

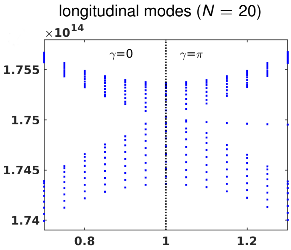


Ling et al, Opt. Expr. **23**, 2021 (2015)
Downing, Weick, PRB **95**, 125426 (2017)
Pocock et al., ACS Photonics **5**, 2271 (2018)
. . .

# Nanoparticle chains (R = 100nm, d = 1$\mu$m)

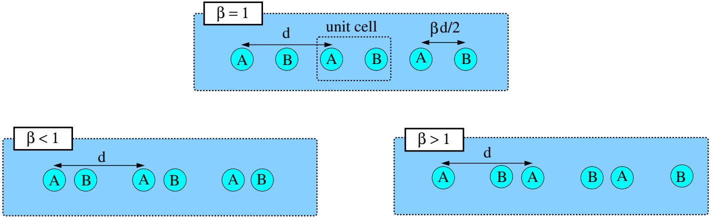


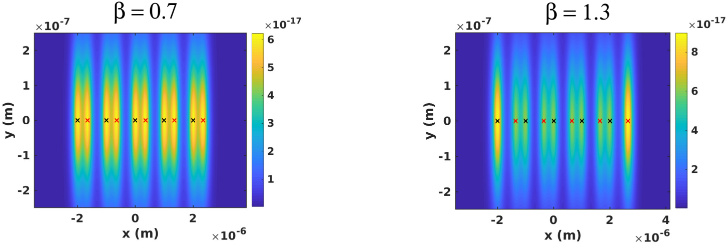

Ott, SAB, PRB **102**, 115417 (2020)

# Nanoparticle chains (R = 100nm, d = 1$\mu$m)



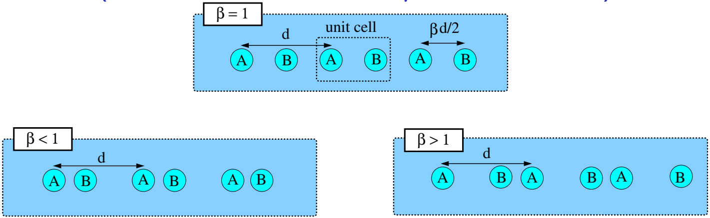

spectral energy density ($z$ = 300 nm, Js/m$^3$, $N$ = 10)

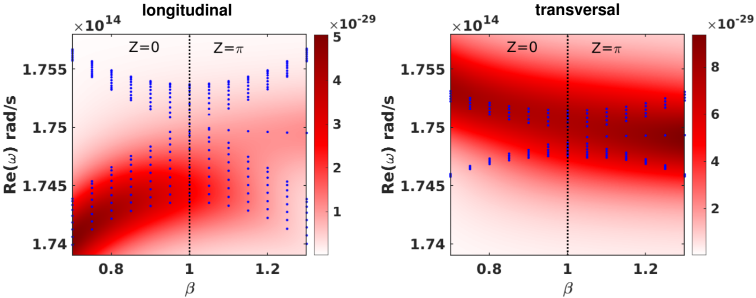
spectral energy density ($z$ = 300 nm, Js/m$^3$, $N$ = 10)




Ott, Kittel, An, SAB, PRB **104**, 165407(2021)

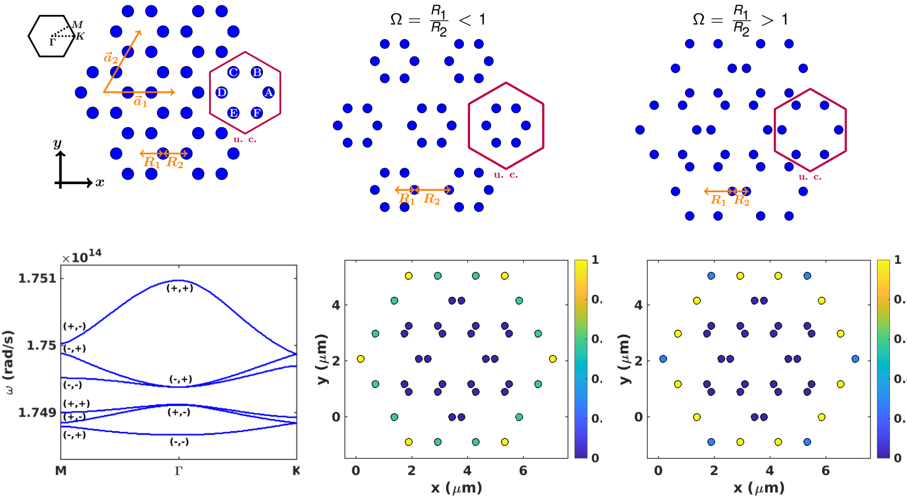
# Spectral heat flux in SSH chains ($R = 100$nm, $d = 1\mu$m, $N = 20$)



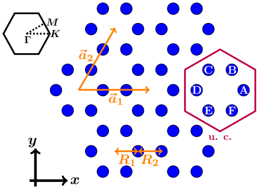

Ott, SAB, PRB **102**, 115417 (2020)

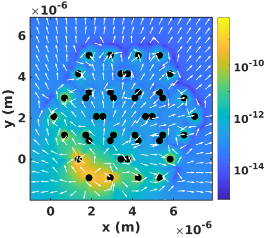
# Edge and corner modes (R = 100nm, d = 1$\mu$m)

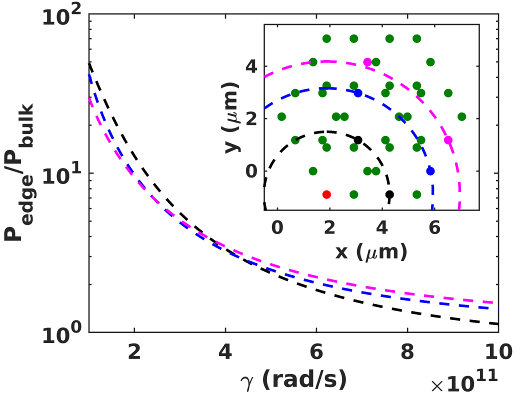



Ott, SAB, Int. J. Heat & Mass Transf. **190**, 122796(2022)

# Edge mode heat transfer (R = 100nm, d = 1$\mu$m)



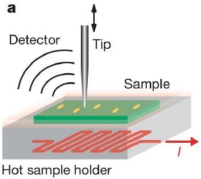




Ott, SAB, Int. J. Heat & Mass Transf. **190**, 122796(2022)

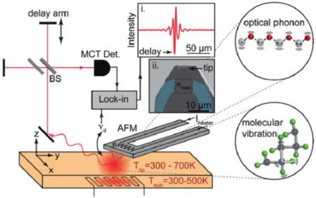
# Near-field thermal imaging

**Thermal radiation tunneling microscope**



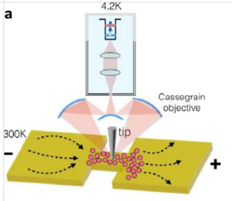

De Wilde et al., Nature **444**, 740 (2006)

**Thermal infrared near-field spectroscopy**



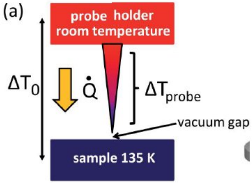

Jones, Raschke, Nano Lett. **12**, 1475 (2012)

**Scanning noise microscope**



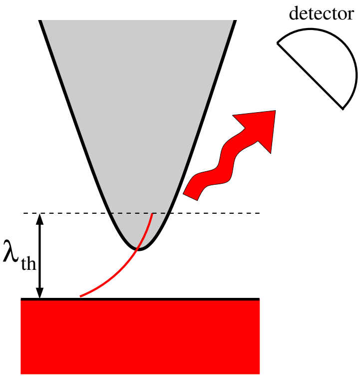

Weng,..,SAB,.., Science **360**, 775 (2018)

**Near-field scanning thermal microscope**



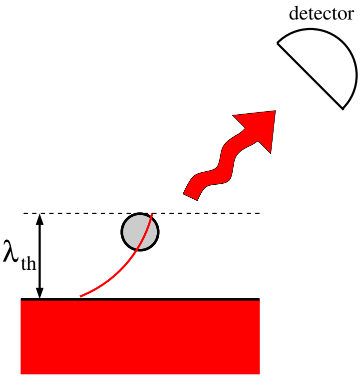

Kittel,..,SAB,.., PRL **95**, 224301 (2005)

# Theoretical model



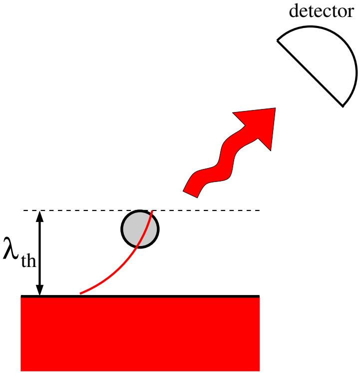

Joulain et al., JQSRT **136**, 1 (2014)
Herz et al., PRAppl **10**, 044051 (2018)
Herz, SAB, JQSRT **266**, 107572 (2021)

# Theoretical model



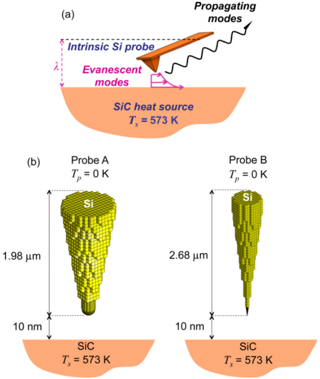

Joulain et al., JQSRT **136**, 1 (2014)
Herz et al., PRAppl **10**, 044051 (2018)
Herz, SAB, JQSRT **266**, 107572 (2021)

# Theoretical model



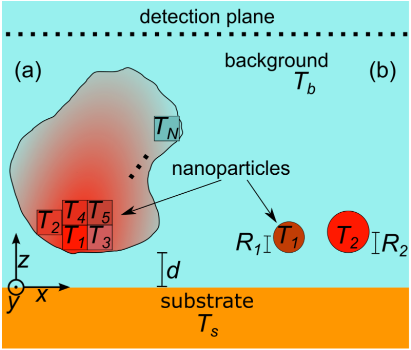

Joulain et al., JQSRT **136**, 1 (2014)
Herz et al., PRAppl **10**, 044051 (2018)
Herz, SAB, JQSRT **266**, 107572 (2021)

**Discrete Dipole Approximation**




Edalatpour et al., JQSRT **133**, 364 (2014)
Edalatpour, Francoeur, PRB **94**, 045406 (2016)
Ekeroth et al., PRB **95**, 235428 (2017)

# Coupled dipole method for far-field thermal radiation

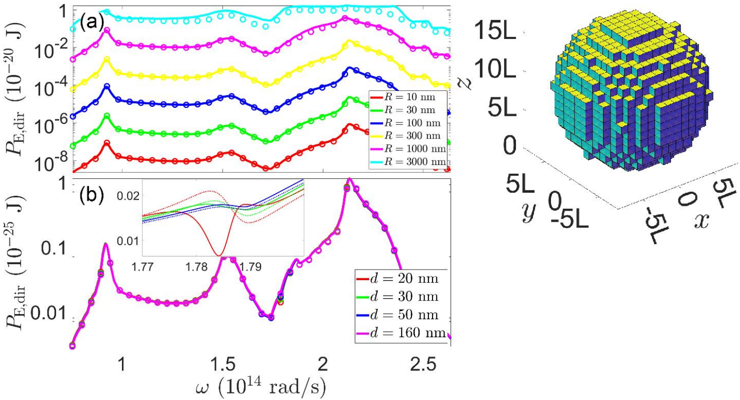



Herz, SAB, PRB **105**, 205422(2022)

- Fields of $N$ coupled dipoles + environment
- Electric and magnetic moments
- Local temperatures
  - $T_i$ for each particle
  - $T_s$ for substrate
  - $T_b$ for background
- Power in detection plane

$$P = \int \mathrm{d}x \int \mathrm{d}y \, \langle S_z \rangle$$
$$= P^{\mathrm{sub}} + P^{\mathrm{dir}} + P^{\mathrm{abs}} + P^{\mathrm{sc}}$$

# Direct thermal radiation, $SiO_2$ sphere ($N = 2553$) (vacuum and SiC substrate)



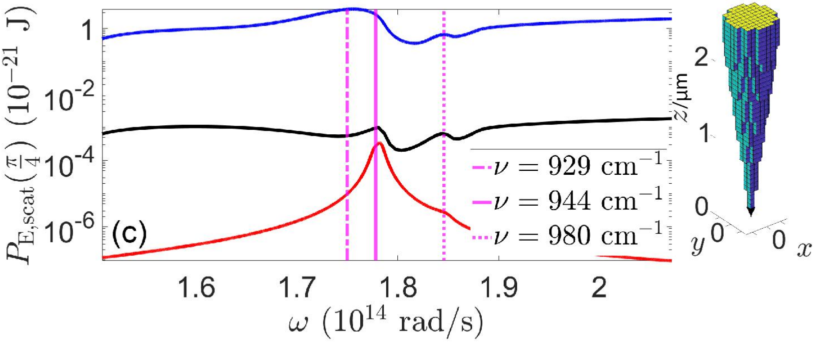

- Vacuum: agreement with

  Kattawar, Eisner, Appl. Opt. **9**, 2685 (1970)/ Ekeroth et al., PRB **95**, 235428 (2017)

- SiC-substrate: coupling with surface waves

Herz, SAB, PRB **105**, 205422(2022)

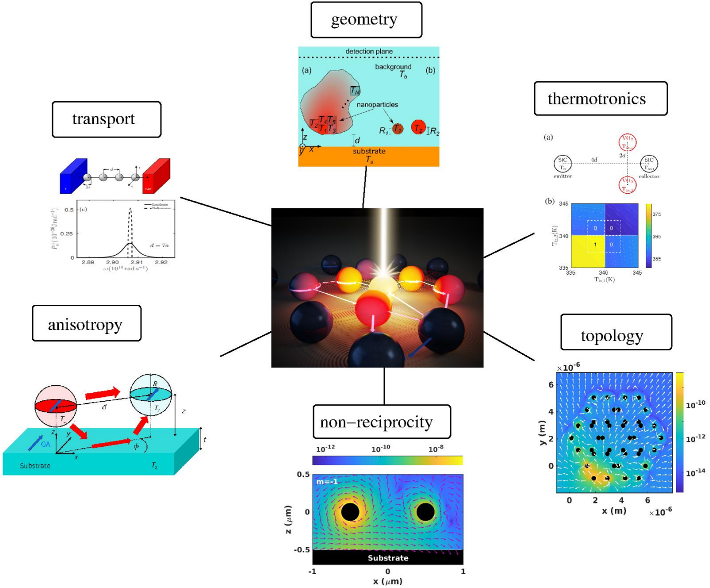
# Scattering by Si tip above SiC substrate ($N = 5388$)




- DDA-results agree with Edalatpour, Francoeur, PRB **94**, 045406 (2016)
- dipole model reproduces most prominent features

Herz, SAB, PRB **105**, 205422(2022)

# Summary


geometry
detection plane
background
nanoparticles
substrate
thermotronics
emitter
collector
transport
anisotropy
Substrate
topology
x (m)
y (m)
non–reciprocity
m=-1
Substrate
x (μm)
z (μm)

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