Controlling near-field thermal energy for conversion devices and sensing

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Outline

I. Context

II. Near-field thermal radiation vs T

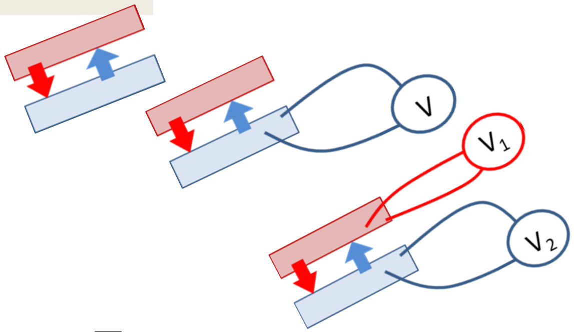
III. Near-field thermophotovoltaics

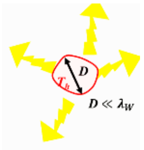
IV. Near-field thermophotonics

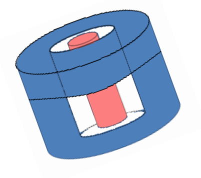
V. Sub-wavelength thermal emission vs T

VI. Concentric cylinders

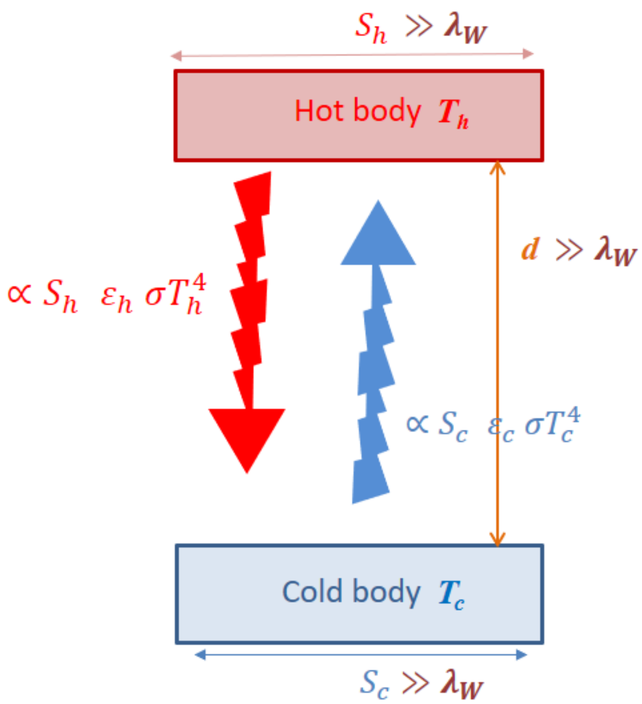
VII. Some prospects



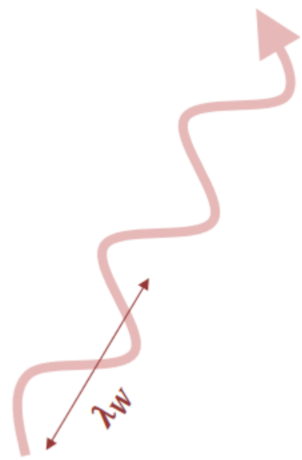


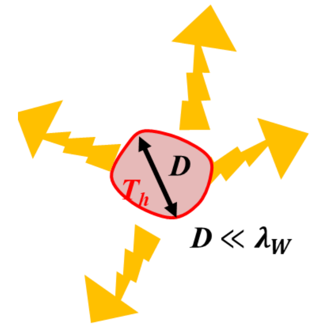


Thermal radiation involving small sizes…

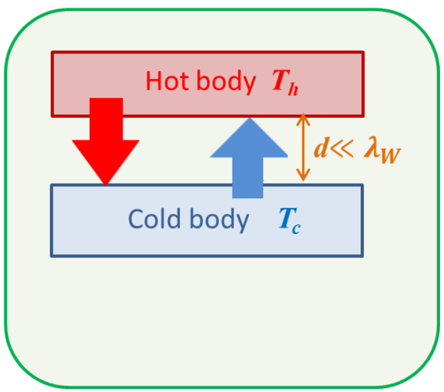


$$Q \propto S\,T^4$$





Sub-λ thermal emission

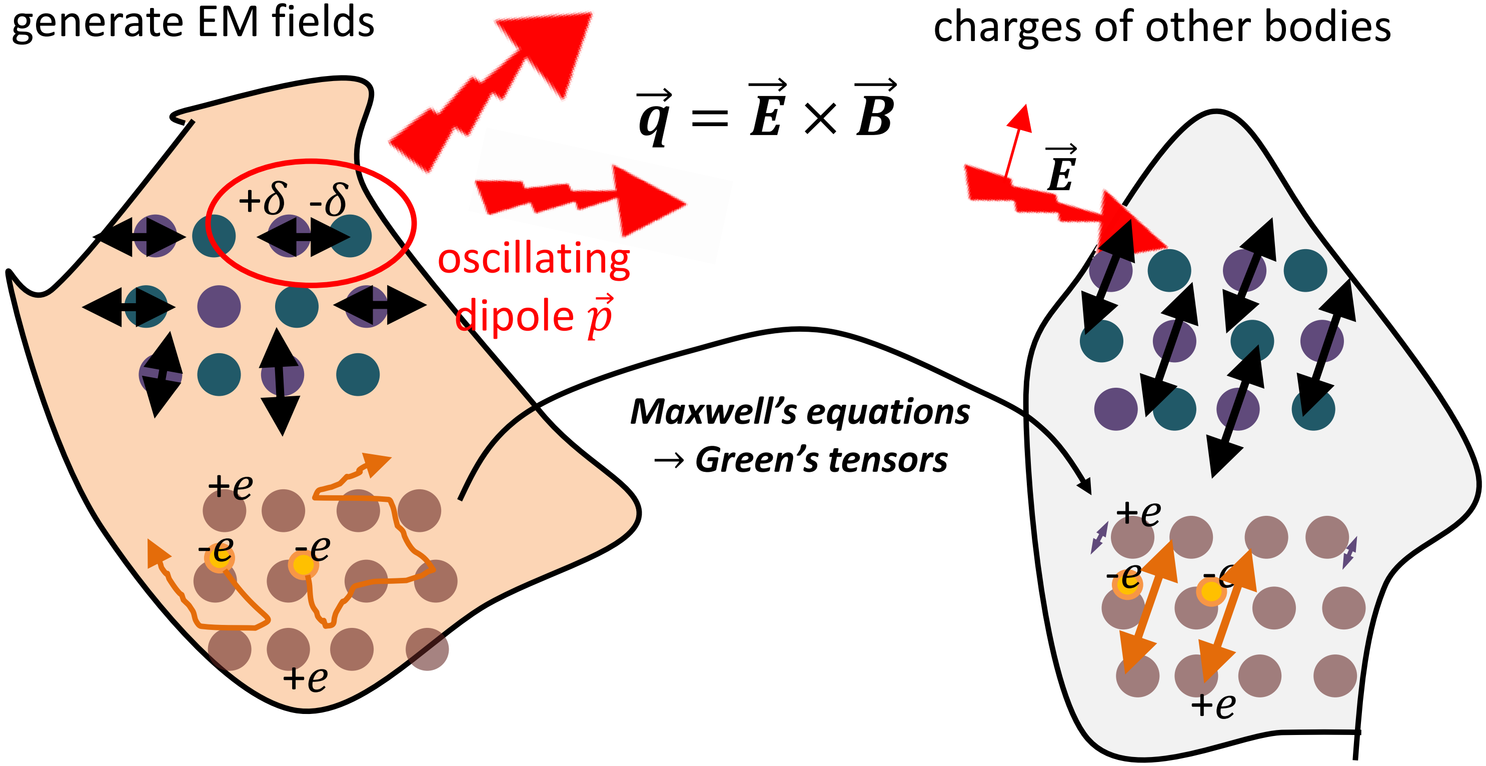


Near-field thermal radiation

Back to basics…

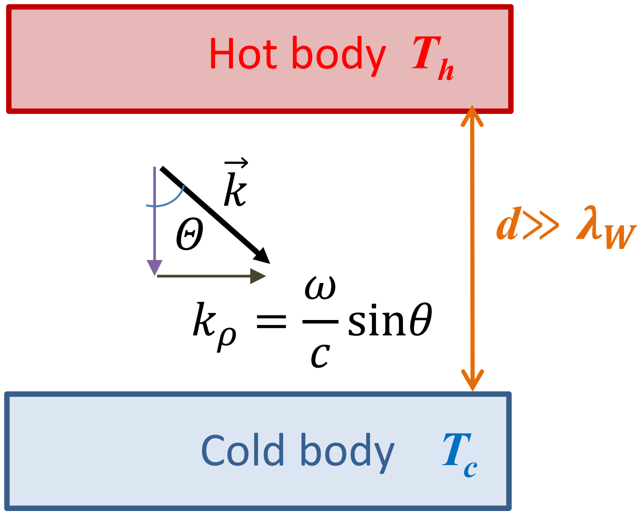
Random motion of charges generate EM fields

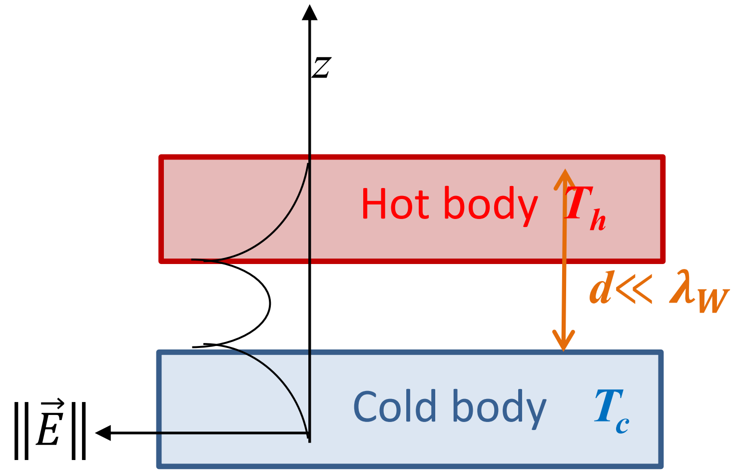
These fields act on charges of other bodies



FDT + Maxwell's equations = Fluctuational Electrodynamics

Fundamentals: thermal radiation between 2 surfaces





$$q = \sum_{pol=TE,TM} \int d\omega \frac{\omega^2}{4\pi^2 c^2} \hbar\omega \left(\frac{1}{e^{\frac{\hbar\omega}{k_B T_{hot}}} - 1} - \frac{1}{e^{\frac{\hbar\omega}{k_B T_{cold}}} - 1} \right) \left[\int_0^{\frac{\omega}{c}} dk_\rho \tau_{prop}^{pol}(\omega, k_\rho) + \int_{\frac{\omega}{c}}^{\infty} dk_\rho \tau_{evan}^{pol}(\omega, k_\rho) \right]$$

Planck's law

$e(\omega)$
(generalized)
emissivity

photon
tunneling
at nanoscale

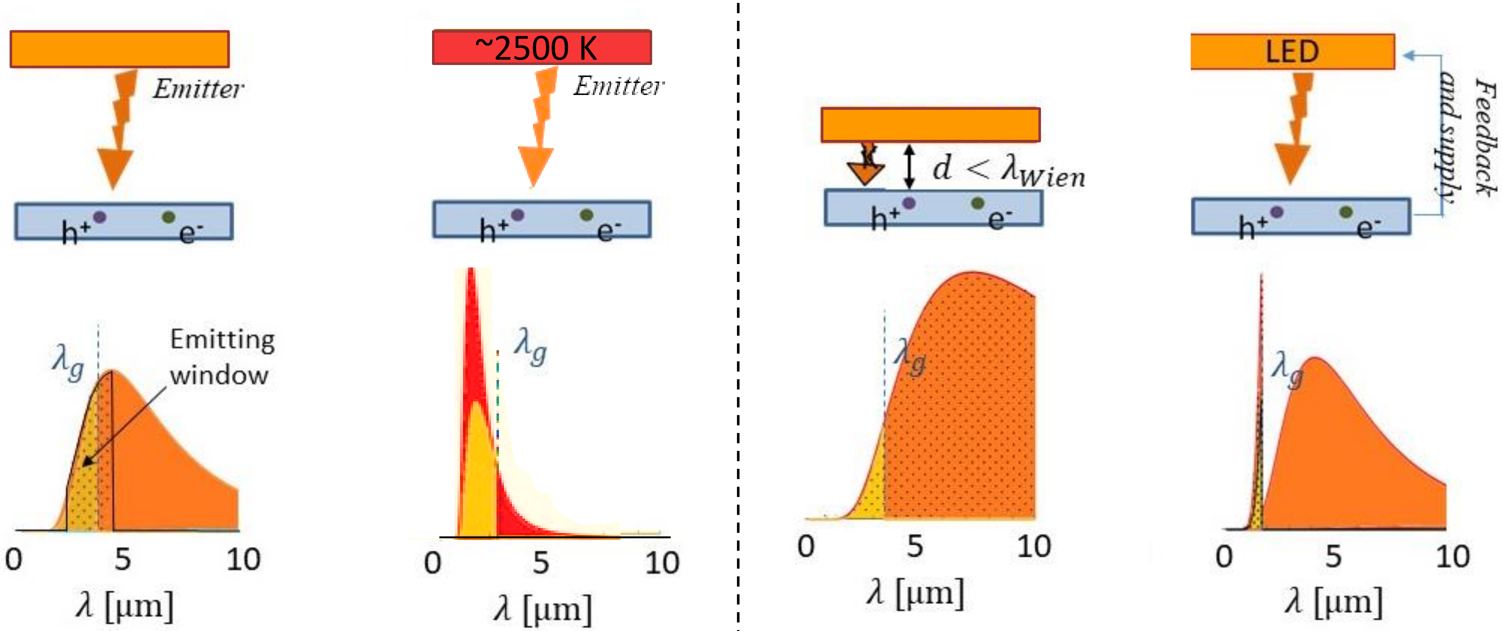
Polder & Van Hove, PRB (**1971**)

$$x = \frac{\hbar\omega}{k_B T} = \frac{cst}{\lambda T} \rightarrow d.T$$

$$\tau_{evan}^{pol}(\omega, k_\rho) \propto e^{-2|k_z|d}$$

Converting thermal energy into electrical power…

Thermo-photovoltaics	High-temperature TPV	**Near-field TPV**	**Thermophotonics**	**Hybrid devices**



TPV
+
TE
TI
etc.

Planck's law

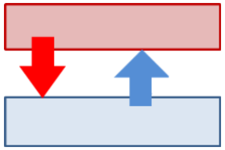
$$n(\omega, T) = \frac{1}{\left(e^{\frac{\hbar\omega}{k_B T}} - 1\right)}$$

$$q_{max} = \sigma T^4$$

$$h_{max} = \frac{q}{\Delta T} = 4\sigma T^3$$

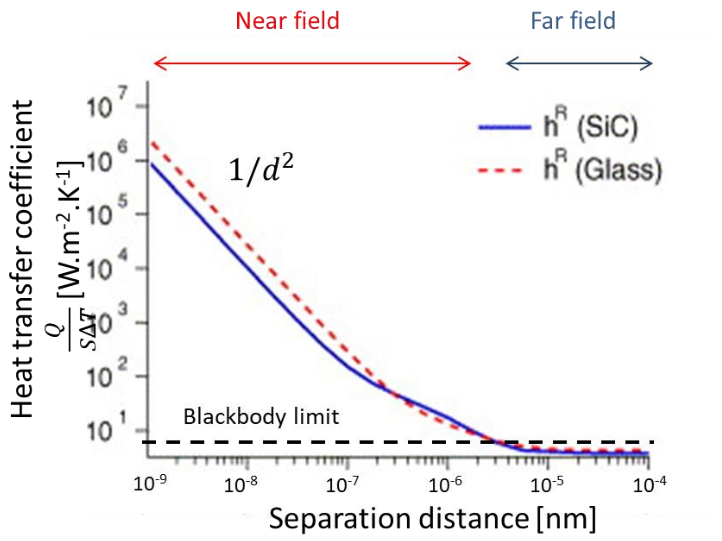
…breaking Planck/Bose-Einstein limits

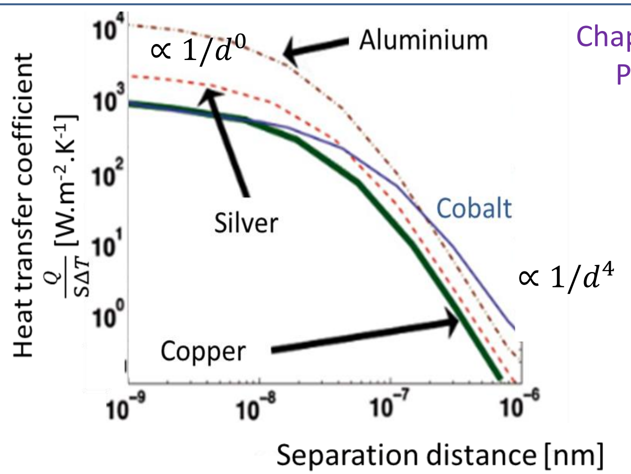

C. Lucchesi



Features of near-field transfer between surfaces

Mulet *et al.*, MTE (2002)

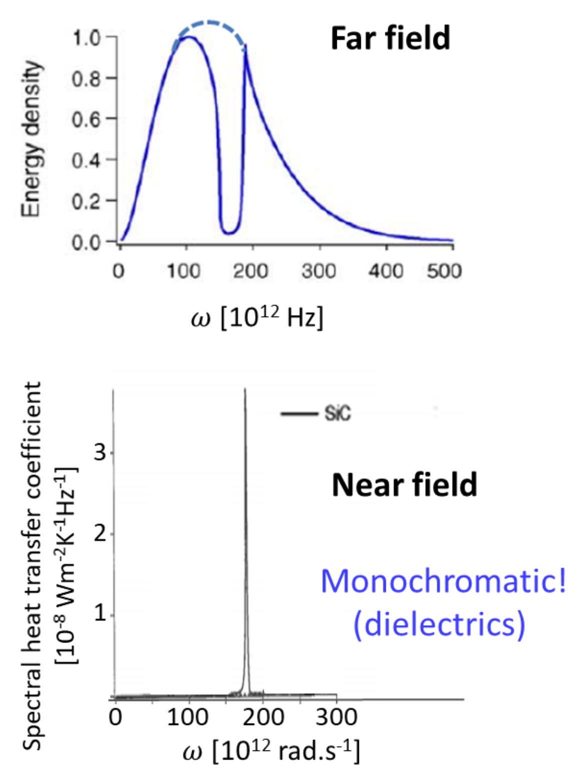




Chapuis *et al.*, PRB (2008)

Enhancement of heat flux

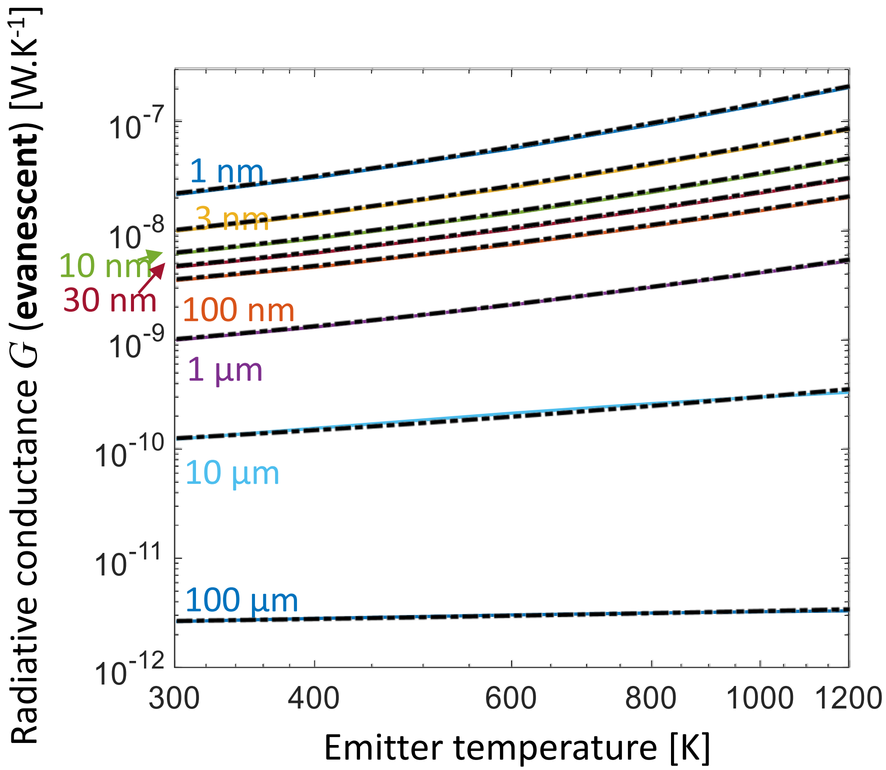
From Shchegrov *et al.*, PRL (2000)



Modification of spectrum

Effect of temperature?

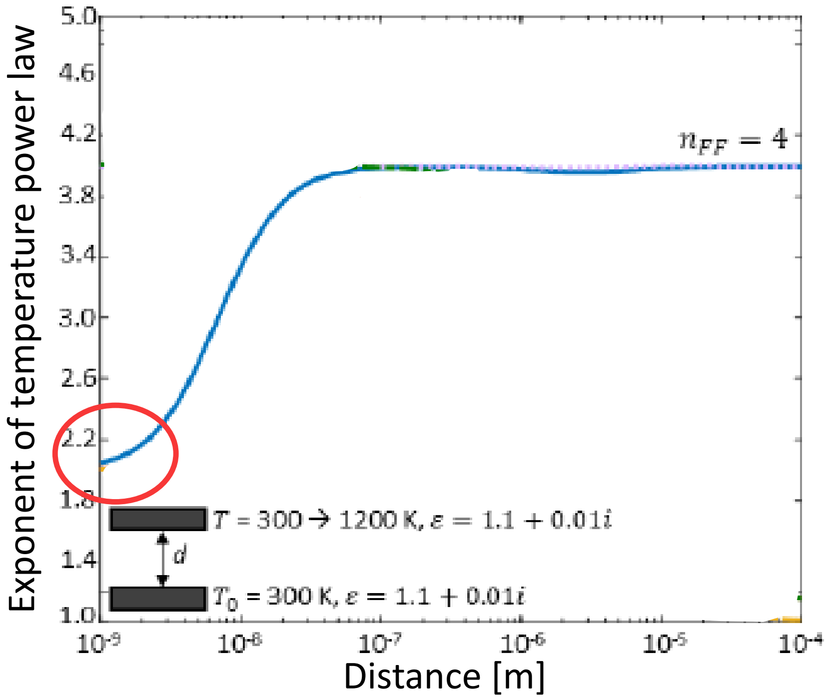
Stefan-Boltzmann's law in near field?



$$G = \frac{Q}{\Delta T} = \boldsymbol{C}\sigma \frac{T^{\boldsymbol{n}} - T_0^{\boldsymbol{n}}}{T - T_0}$$

exponent

pre-factor

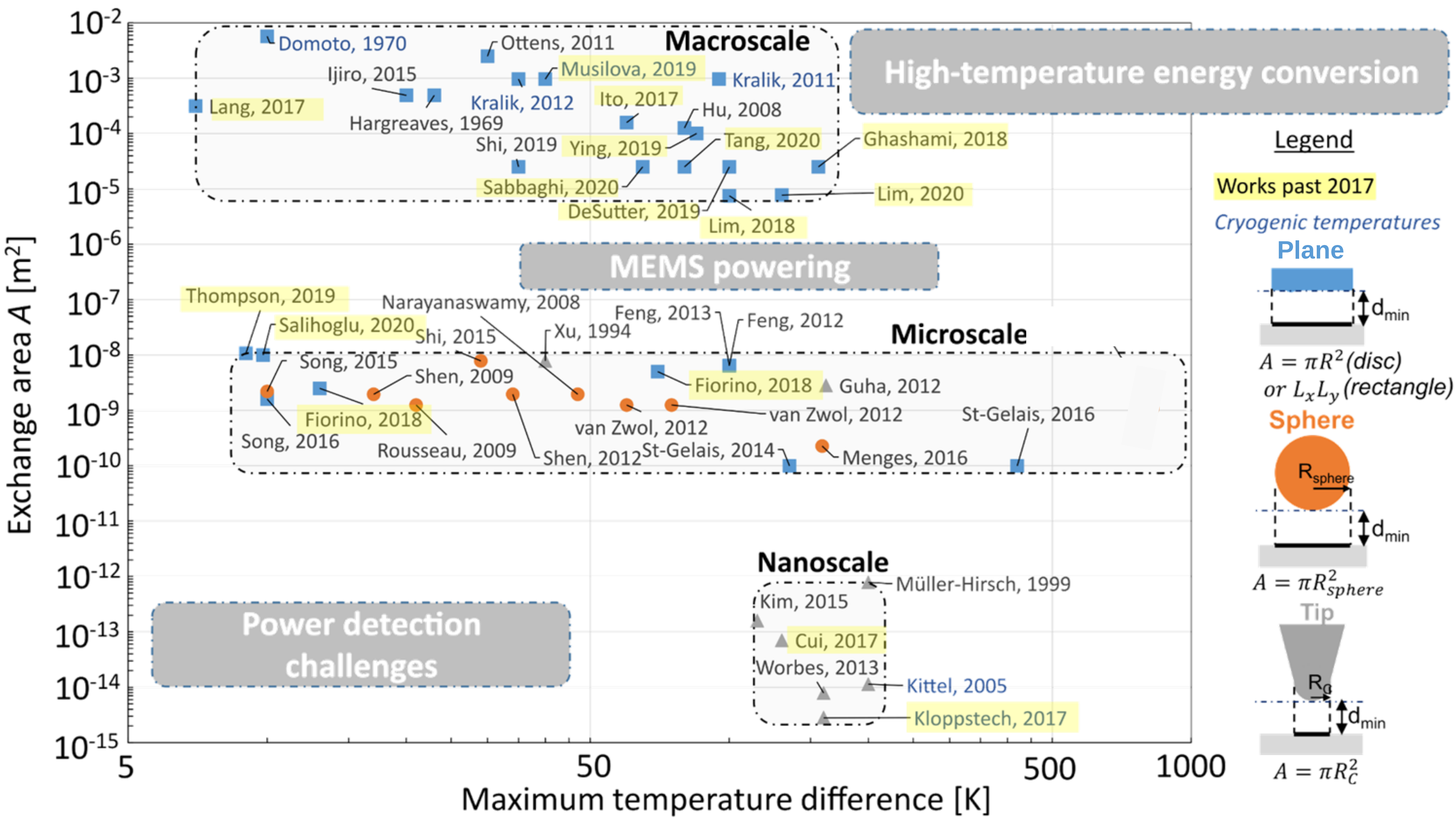


$$q = \sigma T^4 \longrightarrow q \propto T^2$$

Temperature exponent seems different

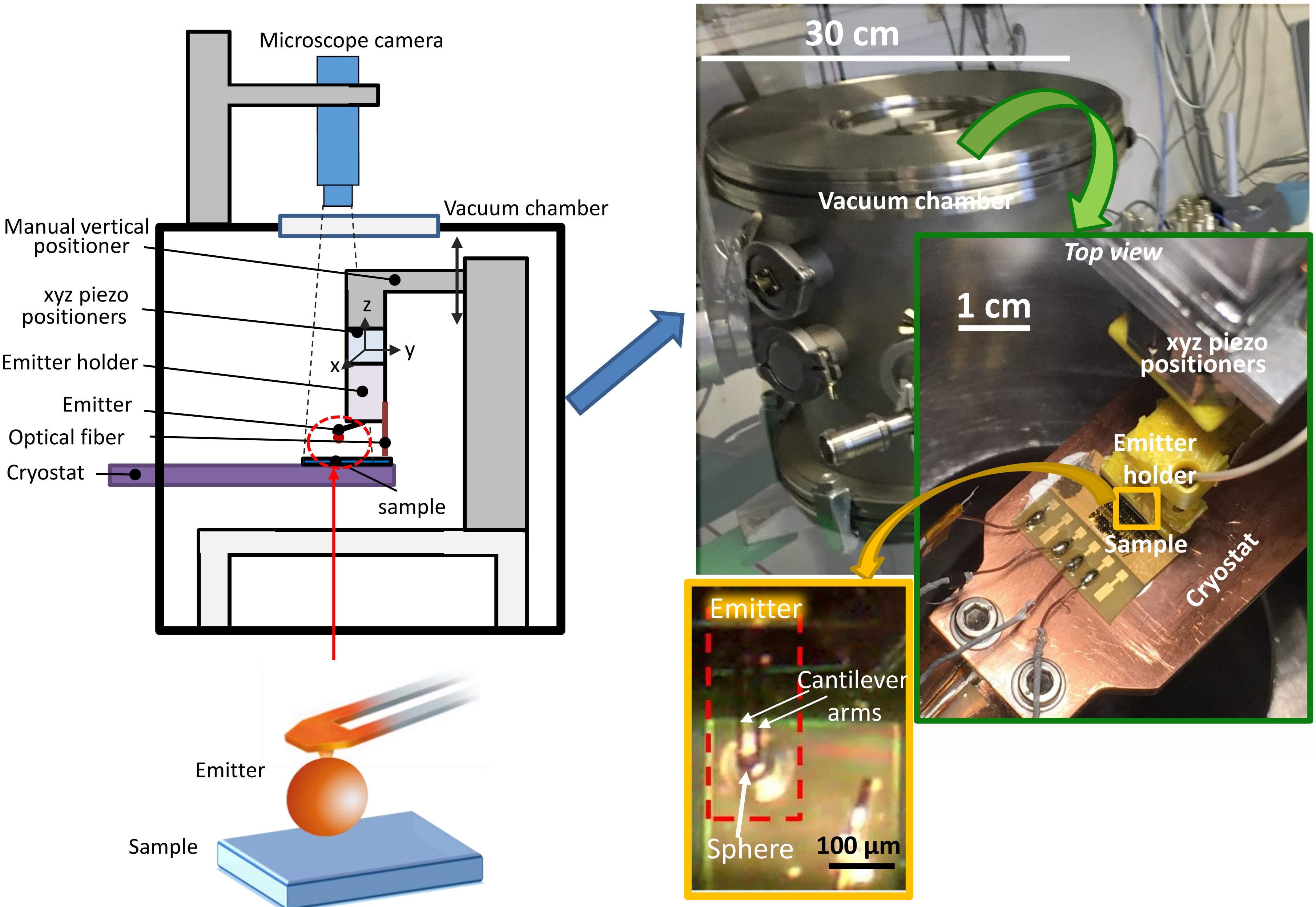
Lucchesi *et al.*, Materials Today Physics 21, 100562 (2021)

>40 experiments in the last decade

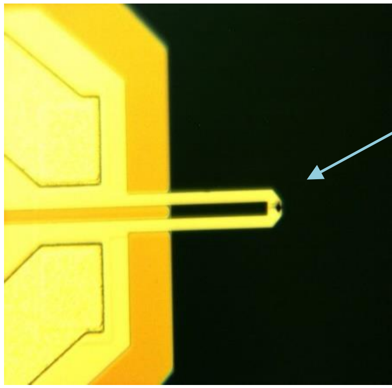


Lucchesi *et al.*, Nanoscale Horizons 6, 201 (2021)

Our microsphere near-field experiment

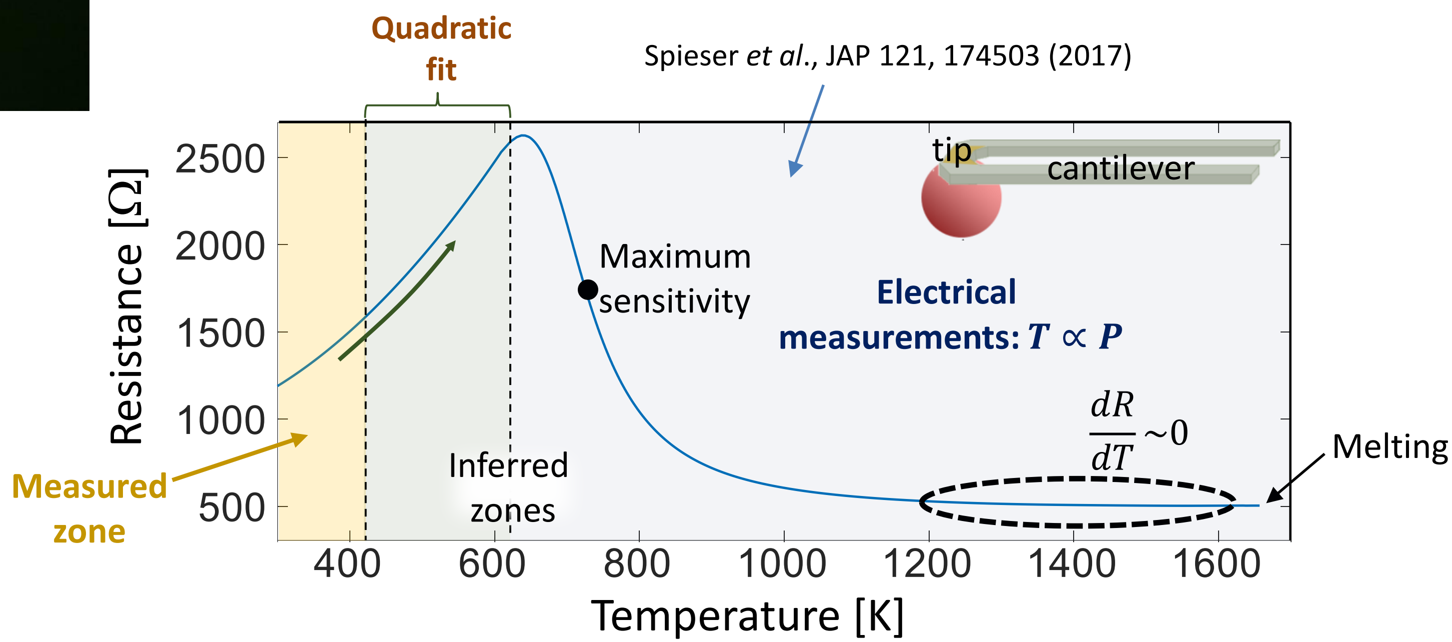


Measurement of emitter temperature: $R(T)$



self-heating RI^2

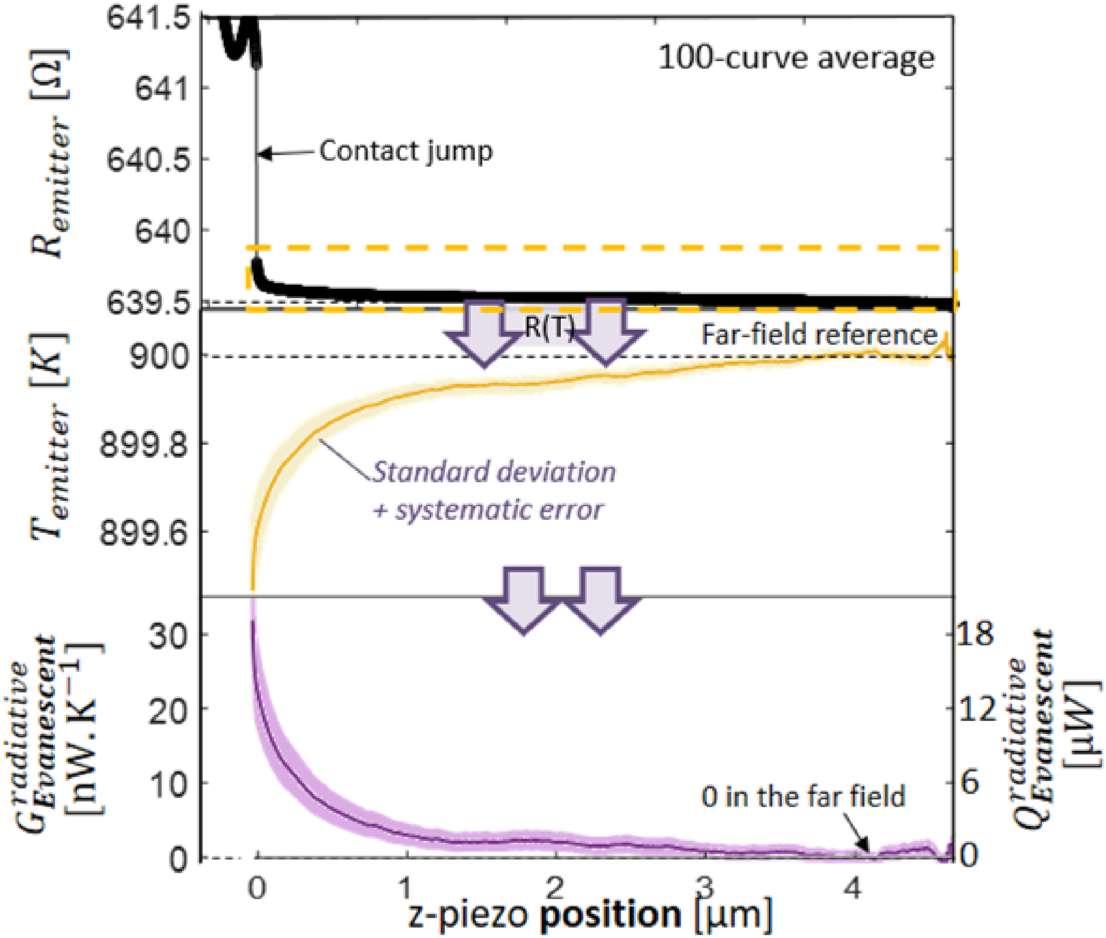
→ **Resistive thermometry**



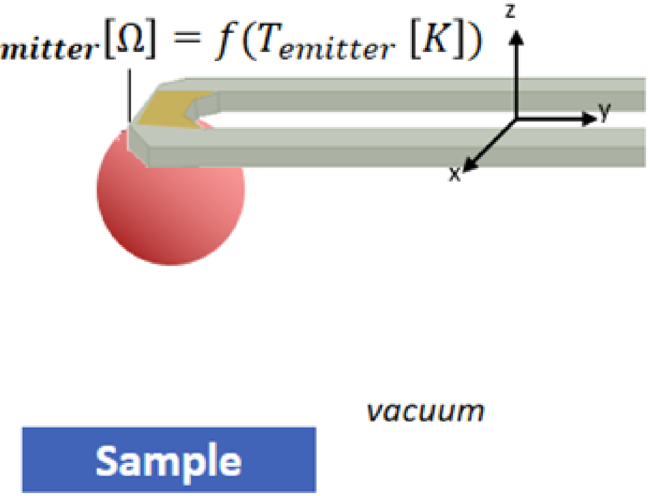
Better calibration: Piqueras et al.

Lucchesi *et al.*, Nano Lett. 21, 4524 (2021)

Approach curves and radiative heat transfer



$$R_{emitter}[\Omega] = f(T_{emitter}\ [K])$$



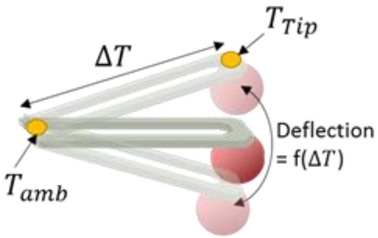
$$\frac{\Delta G_{tot}}{G_{tot}} = \frac{\Delta P}{P} - \frac{\Delta \theta}{\theta}$$

$$G_{NF} = G_{tot}\left[(T_{ref} - T)\left(\frac{1}{\theta} - \alpha\right) + 2\frac{I - I_{ref}}{I}\right]$$

Lucchesi *et al.*, Materials Today Physics 21, 100562 (2021)

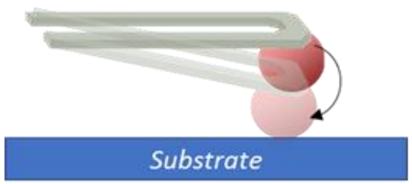
Distance uncertainties

- Temperature gradient



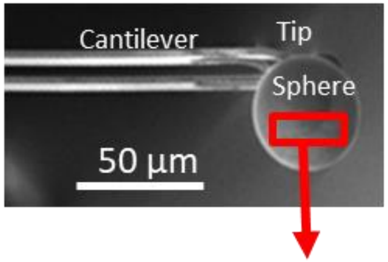
Measured by AFM
Negligible for small temperature variations

- Attraction forces



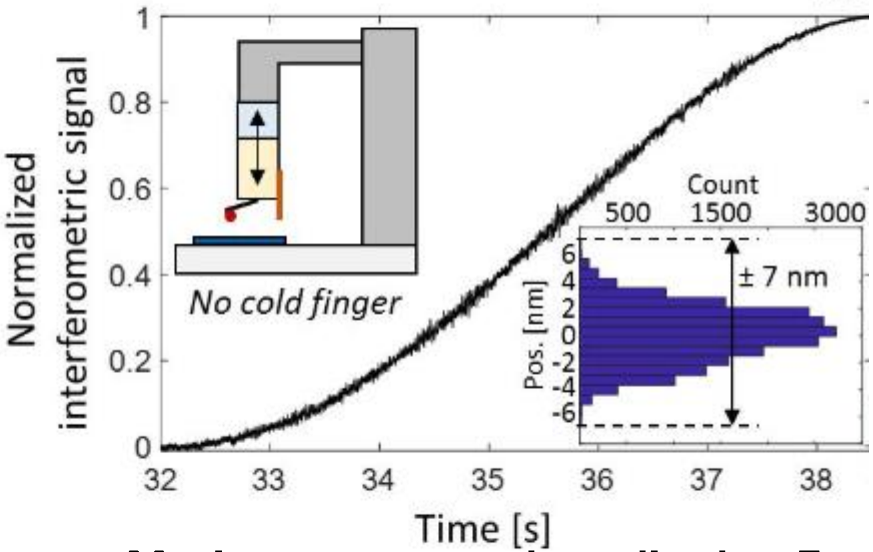
Measured by AFM
3 nm

- Roughness

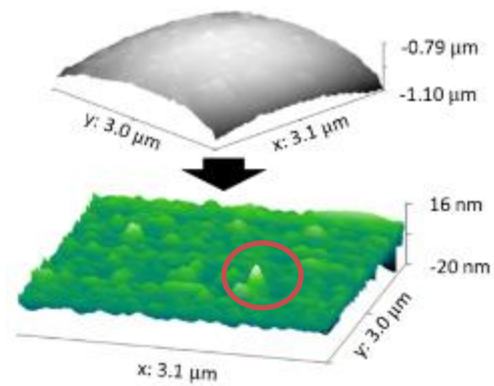


Measured by AFM
max = 30 nm

❑ Mechanical vibrations → *measured by interferometry*



Maximum measured amplitude = 7 nm
for sample at room temperature

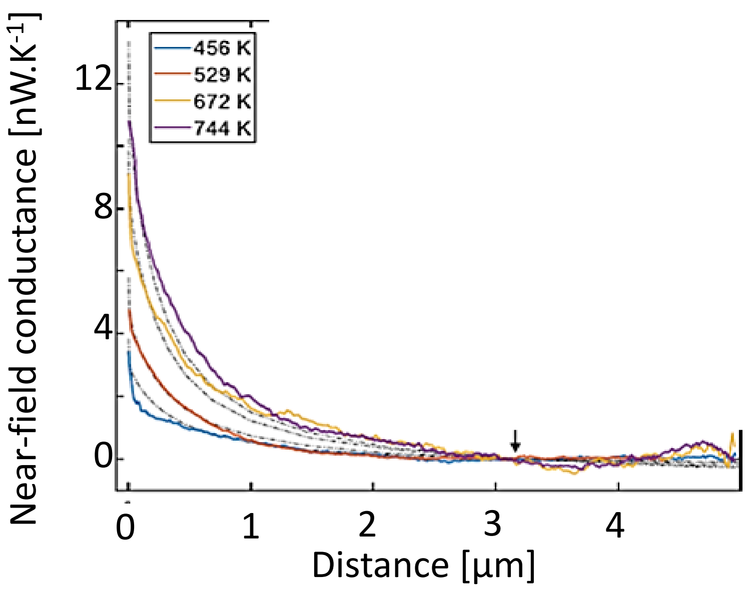


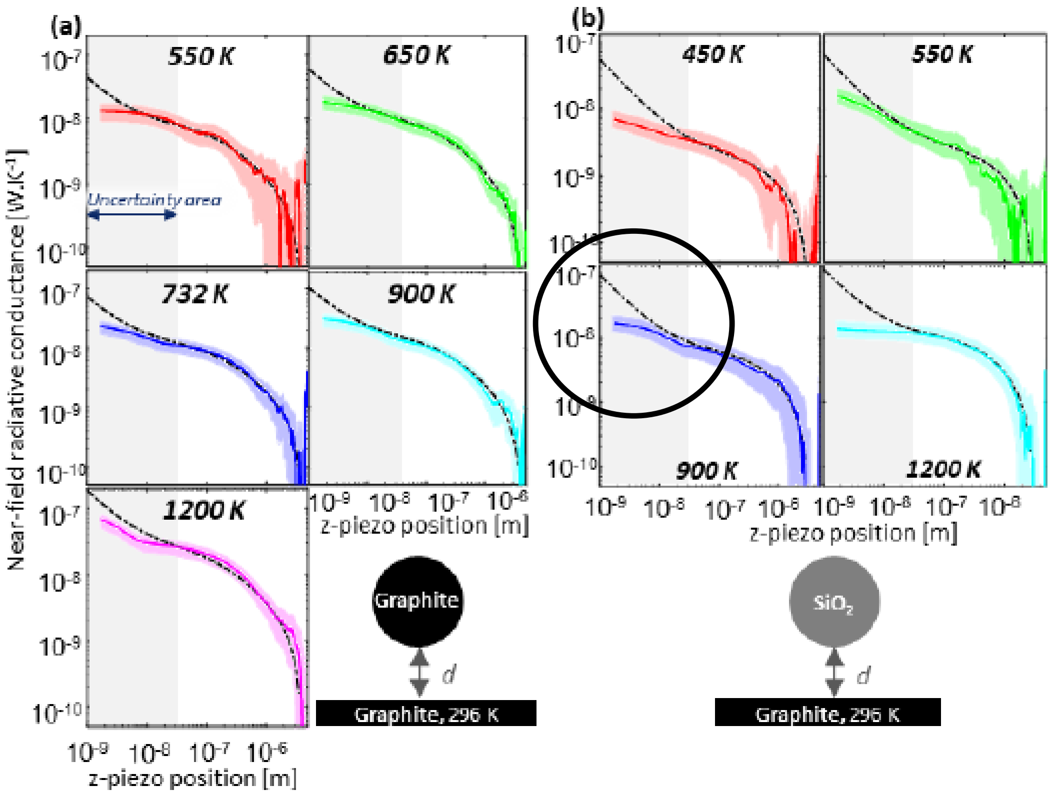
~~rms~~ sparse peaks!

$\approx$ **30 nm**

Lucchesi *et al.*, Nano Lett. 21, 4524 (2021)

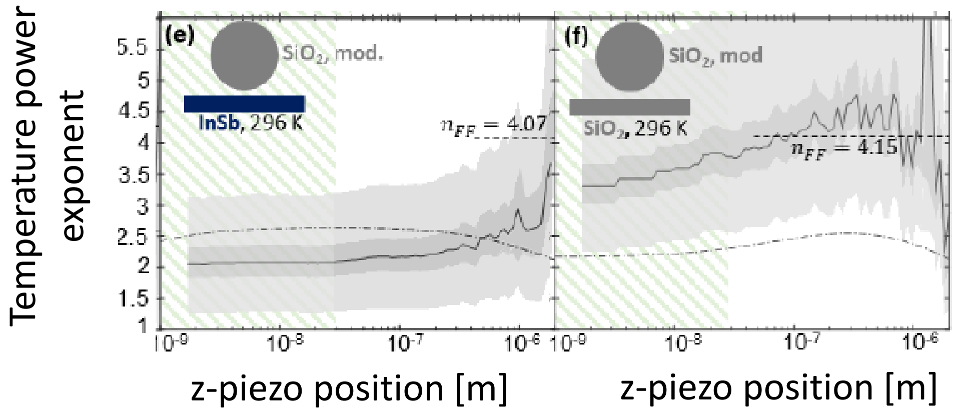
Approach curves as a function of temperature





Lucchesi *et al.*, Materials Today Physics 21, 100562 (2021)

Temperature exponent in near field



Sphere-substrate configuration	ΔT_{max} [K]	Maximum conductance at ΔT_{max} [nW.K^{-1}]	Temperature power law exponent of the near-field radiative conductance		
			Far-field (calculated)	d = 100 nm	
				Calculated	Measured
Graphite-SiO_2	477	4.9 ± 1.0	4.30	2.88	2.84 ± 0.31
Modified SiO_2-SiO_2	493	7.4 ± 1.5	4.15	2.46	4.11 ± 0.42
Modified SiO_2-InSb	904	7.6 ± 2.1	4.07	2.61	2.21 ± 0.27
Graphite-InSb	448	10.8 ± 2.1	4.18	3.01	3.67 ± 0.39
Modified SiO_2-Graphite	904	16.7 ± 3.3 (at ΔT = 604 K)	4.30	2.89	2.80 ± 0.36
Graphite-Graphite	904	68.9 ± 13.7	4.32	2.82	2.92 ± 0.31

Softening of temperature dependence in near field

Lucchesi *et al.*, Materials Today Physics 21, 100562 (2021)

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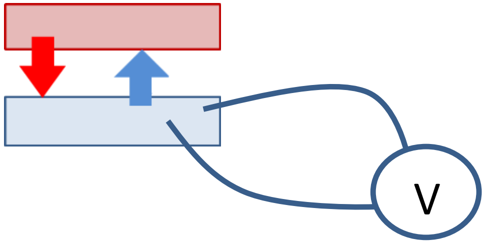
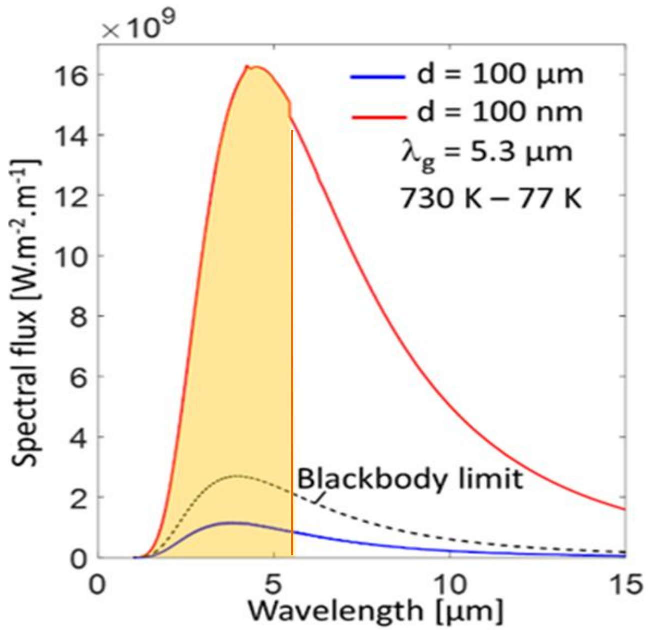
C. Lucchesi



Efficient near-field thermophotovoltaic conversion?

no experiment with efficiency above 1% in 2020…



Work	Cell	E_g [eV]	Emitter T [K]	Efficiency [%]	P [W.cm^{-2}]
Bhatt *et al.*[3], Nat. Com. 2020	Ge	0.67 *at 300 K*	880	0.003 *estimated*	1.3 10^{-6}
Inoue *et al.*[2], Nano Lett. 2019	InGaAs	0.73 *at 300 K*	1065	0.98 *estimated*	7.5 10^{-4}
Fiorino *et al.*[1], Nat. Nano 2018	InAsSb	0.35 *at 300 K*	655	0.015 *estimated*	3.4.10^{-5}
Mittapaly *et al.*[1], Nat. Com. 2021	InAsSb	0.35 *at 300 K*	1250	~8	0.5
Lucchesi et al., 2019	**InSb**	**0.23** *at 77 K*	~700		

Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

Near-field TPV cell design

Poisson

$$\frac{dE}{dz}(z) = -\frac{e}{\varepsilon}\left(n(z) - p(z) + N_a(z) - N_d(z)\right)$$

$$\frac{dJ_n}{dz}(z) = -e\left(R(z) - G(z)\right)$$

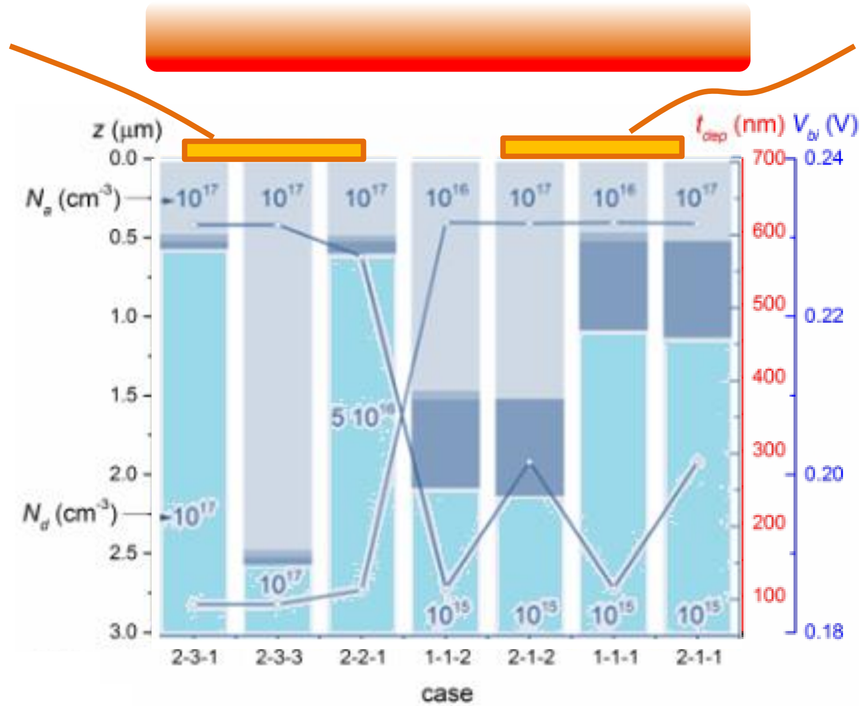
$$\frac{dJ_p}{dz}(z) = e\left(R(z) - G(z)\right)$$

Continuity

$$J_n = e \cdot n(z)\mu_n E(z) + e \cdot D_n \frac{dn}{dz}(z)$$

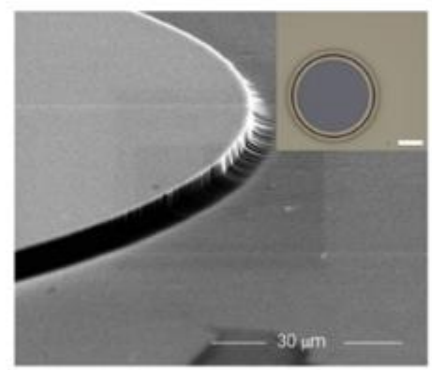
$$J_p = e \cdot p(z)\mu_p E(z) - e \cdot D_p \frac{dp}{dz}(z)$$

Drift-diffusion



- Non-linearities
- Coupled equations

→ **iterative** process



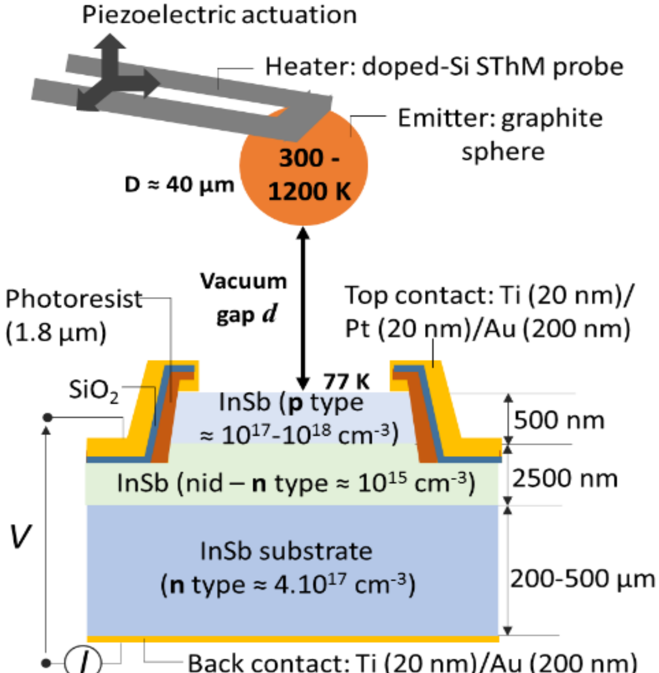
Mesa geometry

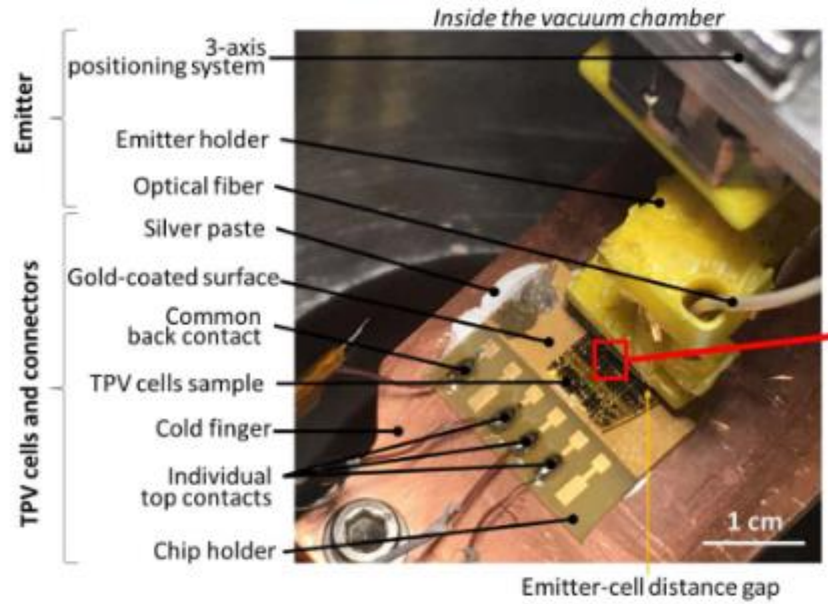
Blandre et al., Sci. Rep. 7, 15860 (2017)

see also Francoeur et al., Tervo et al., and Feng et al.

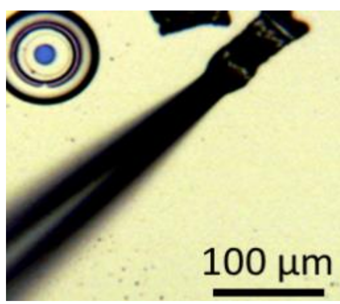
Vaillon et al., Optics Express 24, 347515 (2019)
Cakiroglu et al., Sol. Mat. 203, 110190 (2019)

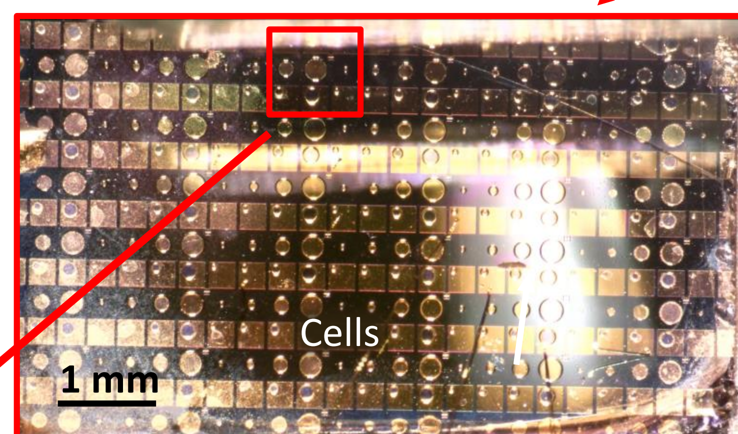
Near-field TPV cell design





*Cryostat 77 K for **InSb** cells to operate*

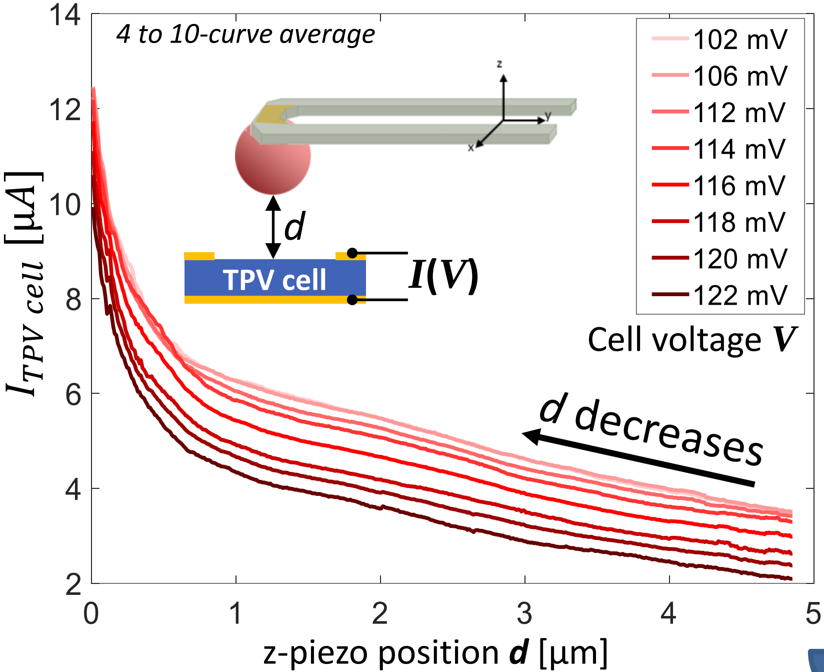


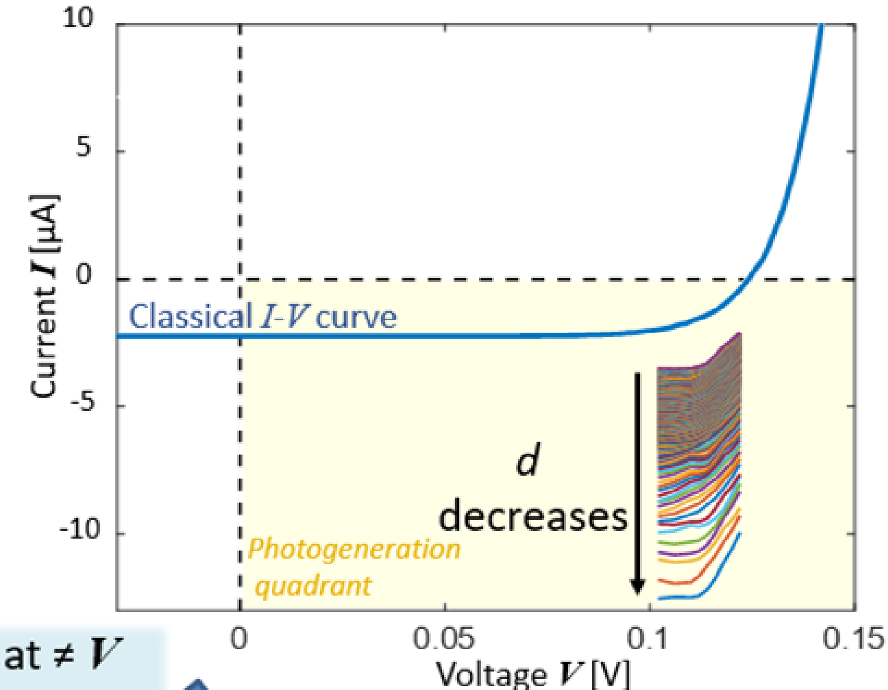


Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

Output power measurement as a function of distance

Fixed V, $I(d)$ measurements





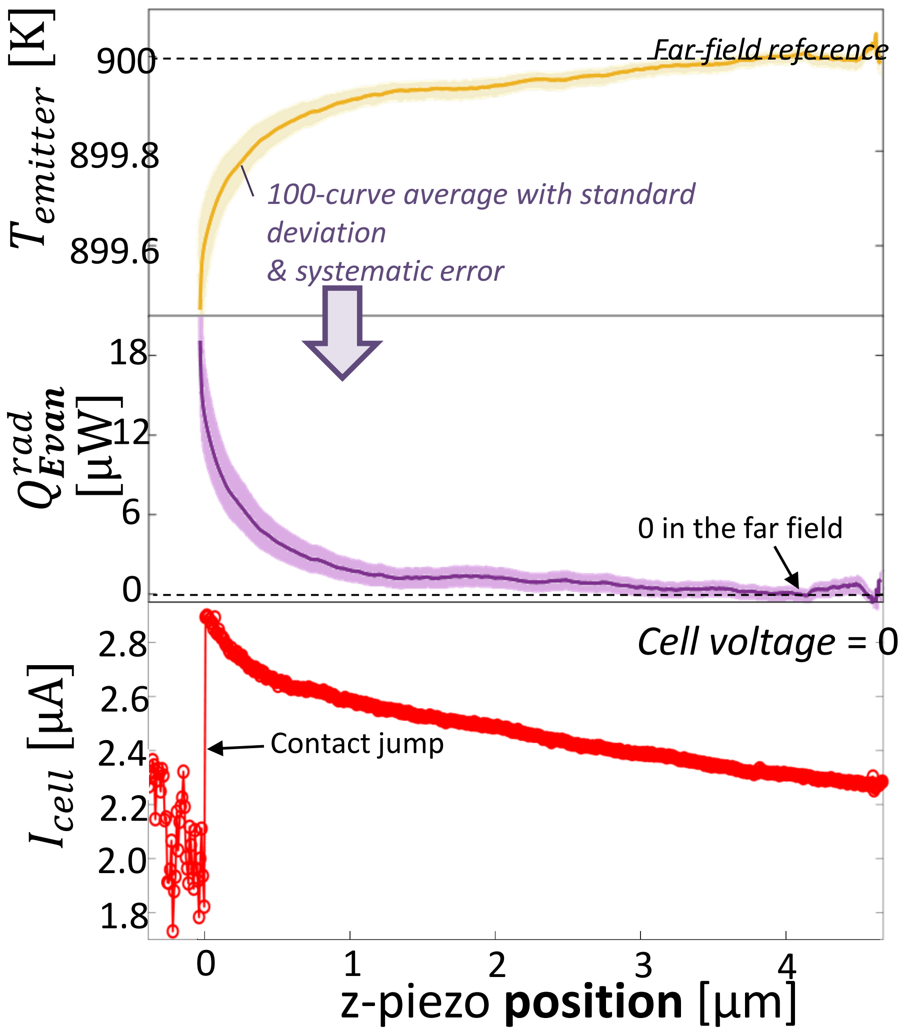
$I(d)$ at ≠ V
→ $I(V)$ at ≠ d

→ Reconstruction of $I(V)$ = f(d)

→ **Maximum power as a function of distance**

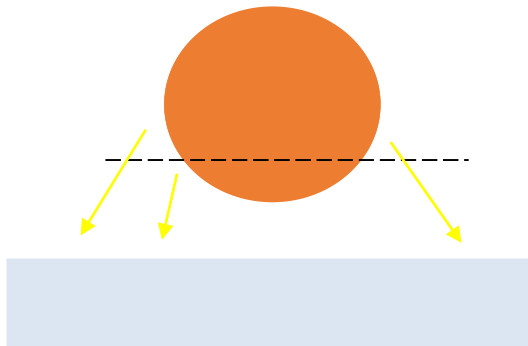
Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

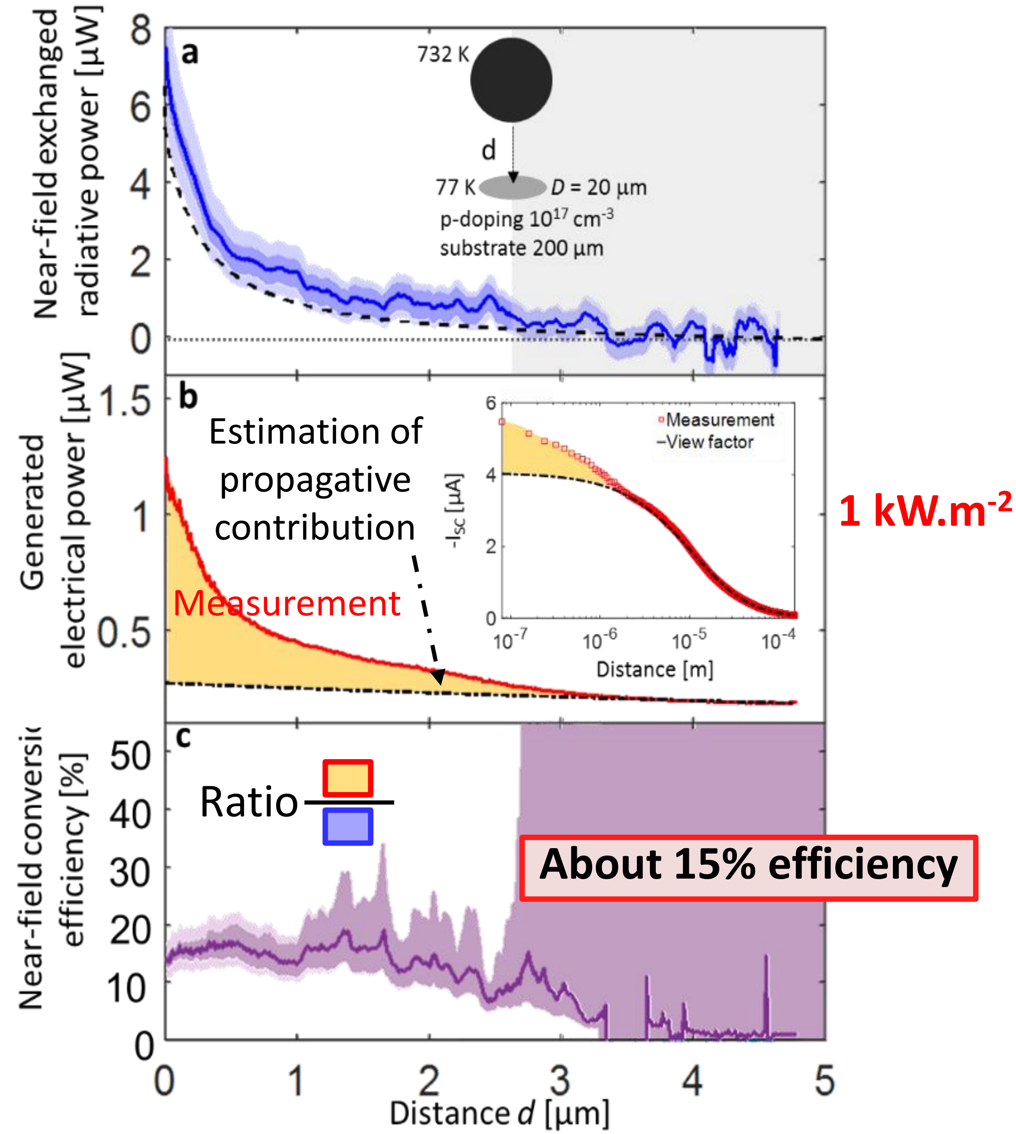
Contact determination….



Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

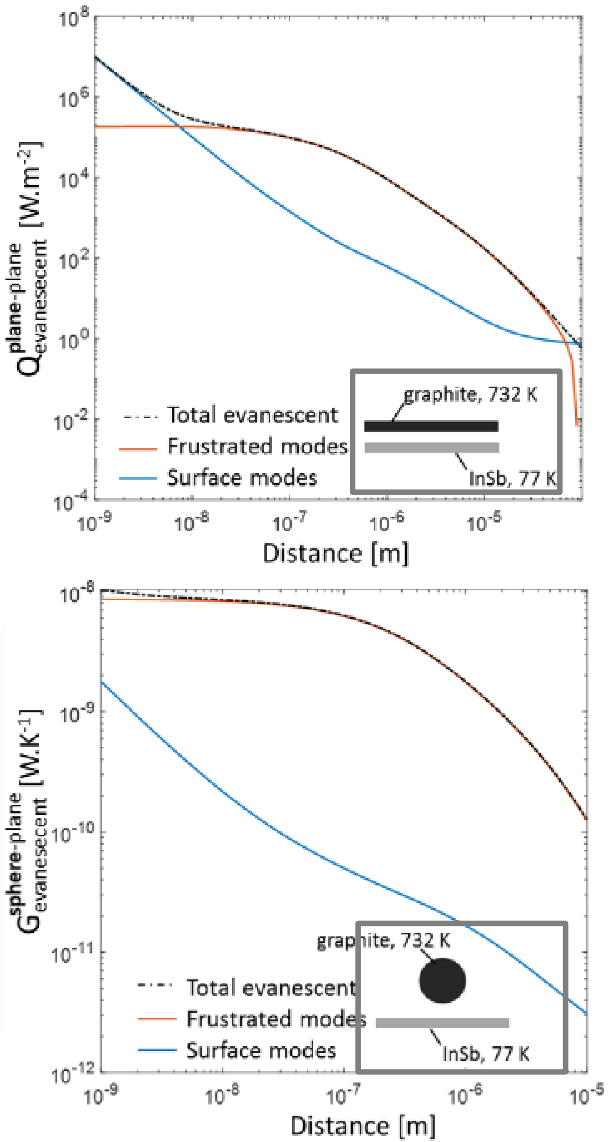
Near-field thermophotovoltaic conversion

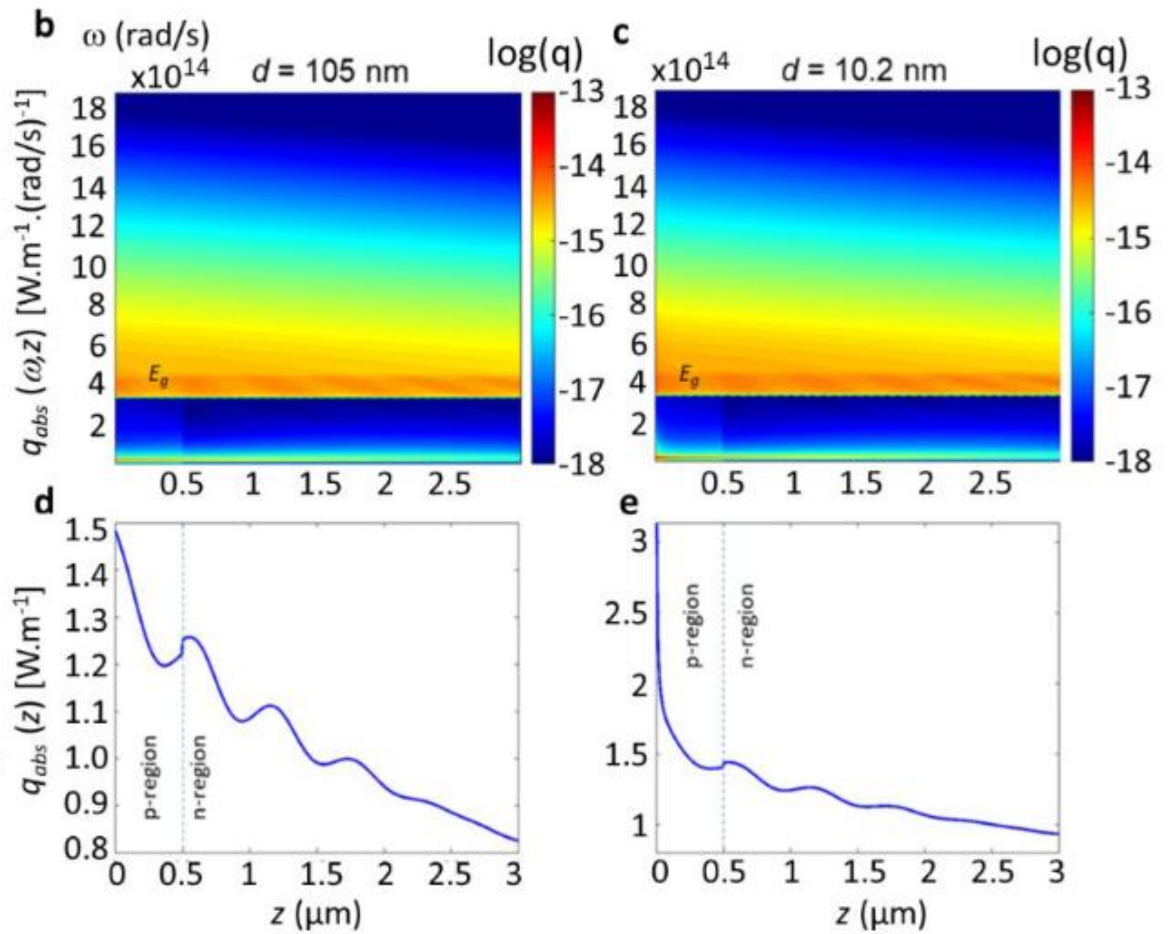




Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

Which modes contribute?

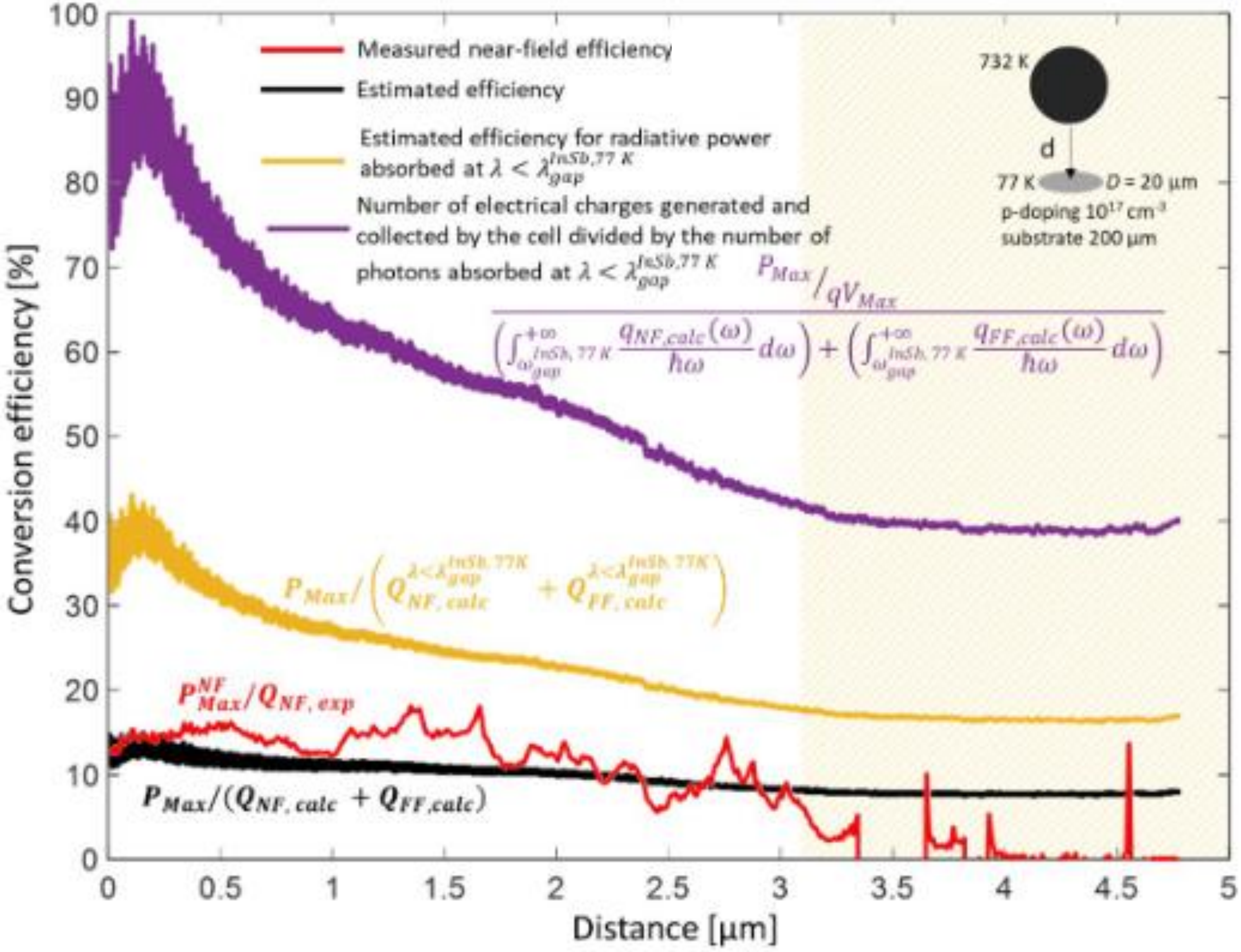




Frustrated modes!

Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

Photon conversion into electron-hole pairs



Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

Current SoA for near-field thermophotovoltaics

Work	Cell	E_g [eV]	Emitter T [K]	Efficiency [%]	P [$W.cm^{-2}$]
Bhatt *et al.*[3], Nat. Com. 2020	Ge	0.67 *at 300 K*	880	0.003 *estimated*	$1.3\ 10^{-6}$
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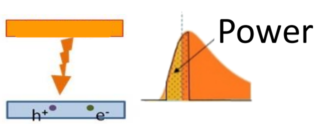
Lucchesi et al., 2019	**InSb**	**0.23** *at 77 K*	~700	**14.1 ± 2.9** ***measured*** *(near-field)*	**0.75**



- Low-bandgap semiconductors allow for both high efficiency and high power output
- **Need now to be developed at room temperature**

Lucchesi *et al.*, ArXiV (2019) - Nano Lett. 21, 4524 (2021)

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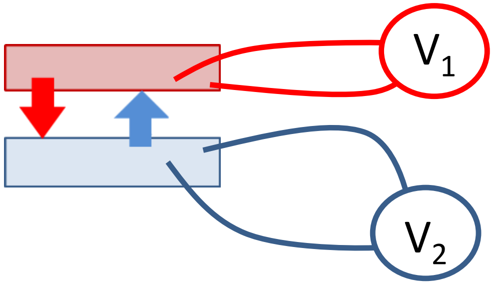
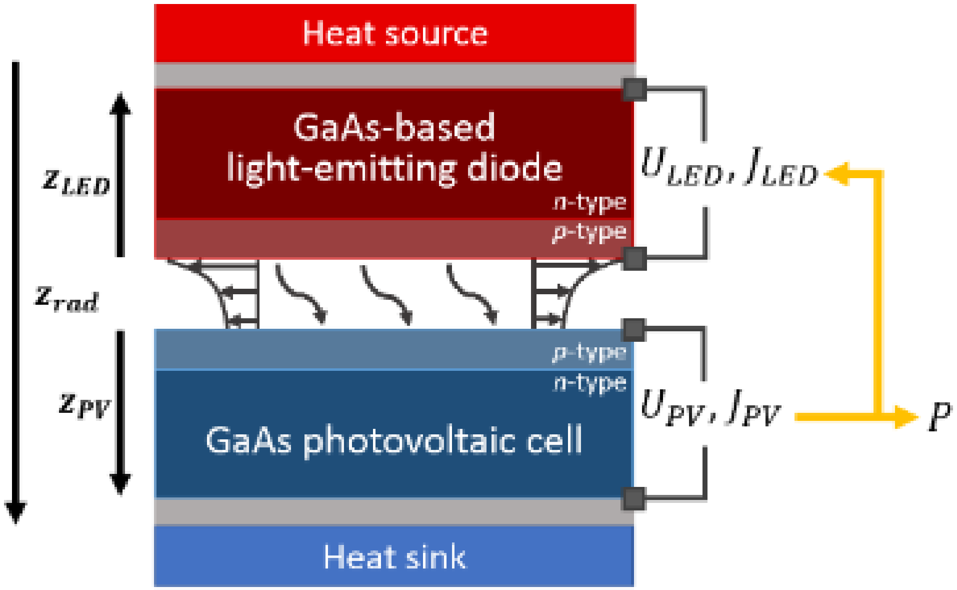


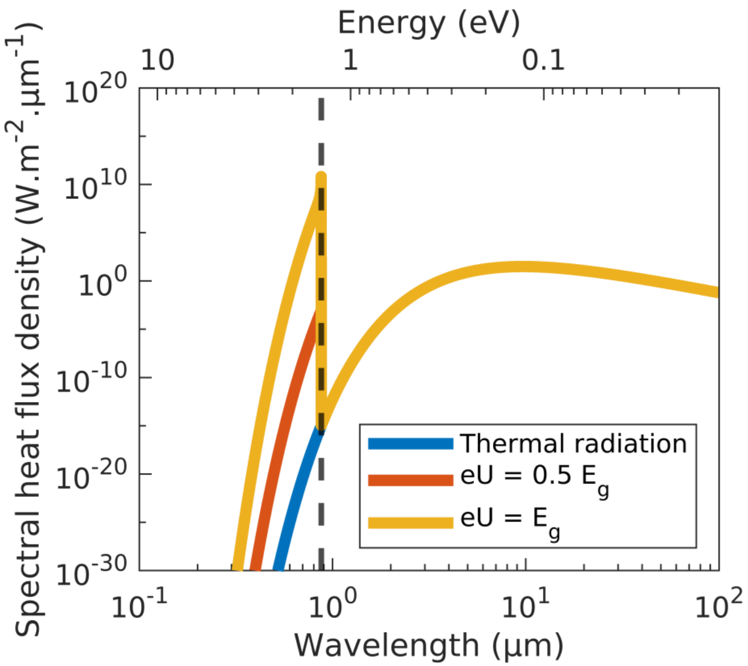
Controlling also the emitter spectrum… thermophotonics (TPX)



Harder & Green, SST(2003)
see also Oksanen et al.

Near-field: see Zhao *et al*. Nano Lett. 18, 5224 (2018)

Modified Planck's law

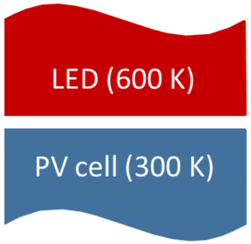


$$n^0(\omega, U, T) = \begin{cases} \left[e^{\frac{\hbar\omega}{k_B T}} - 1\right]^{-1} & , \hbar\omega < E_g \\ \left[e^{\frac{\hbar\omega - eU}{k_B T}} - 1\right]^{-1} & , \hbar\omega \geq E_g \end{cases}$$

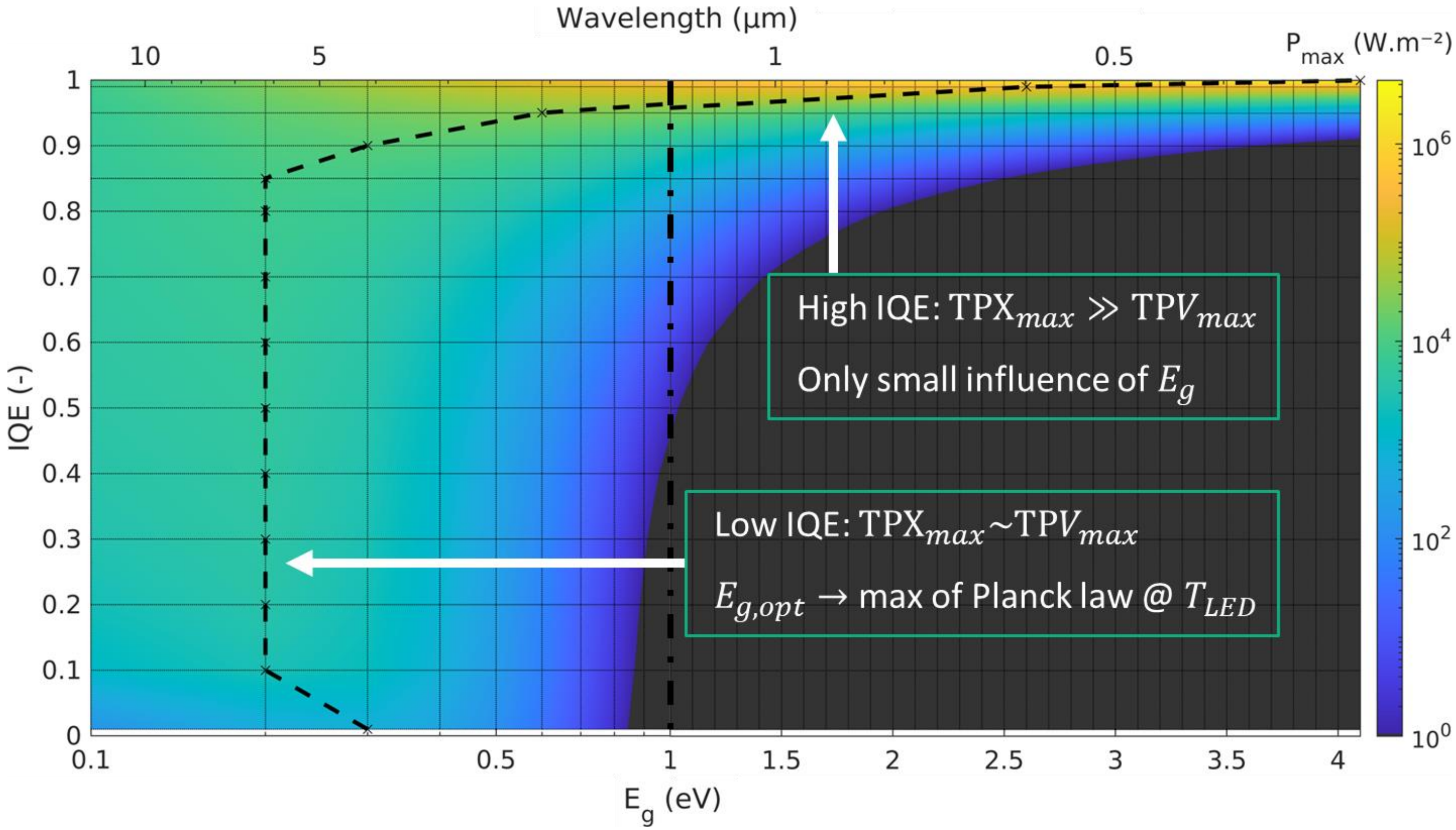
Nonidealities: Internal Quantum Efficiency

$$J = e\left(\gamma_{net} - \frac{1-\text{IQE}}{\text{IQE}}\left(\gamma_{em}^{U} - \gamma_{em}^{0}\right)\right)$$

$\gamma_{net} \rightarrow \gamma_{abs} - \gamma_{em}$



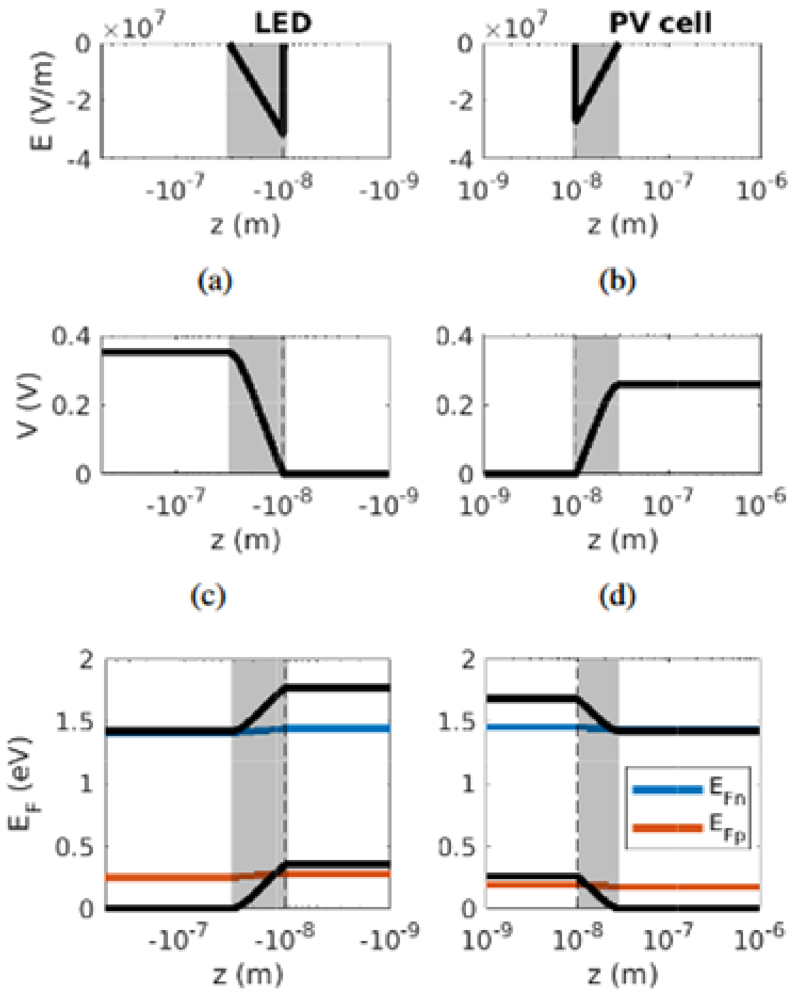
$d = 10$ nm
$\varepsilon = 10 + i$

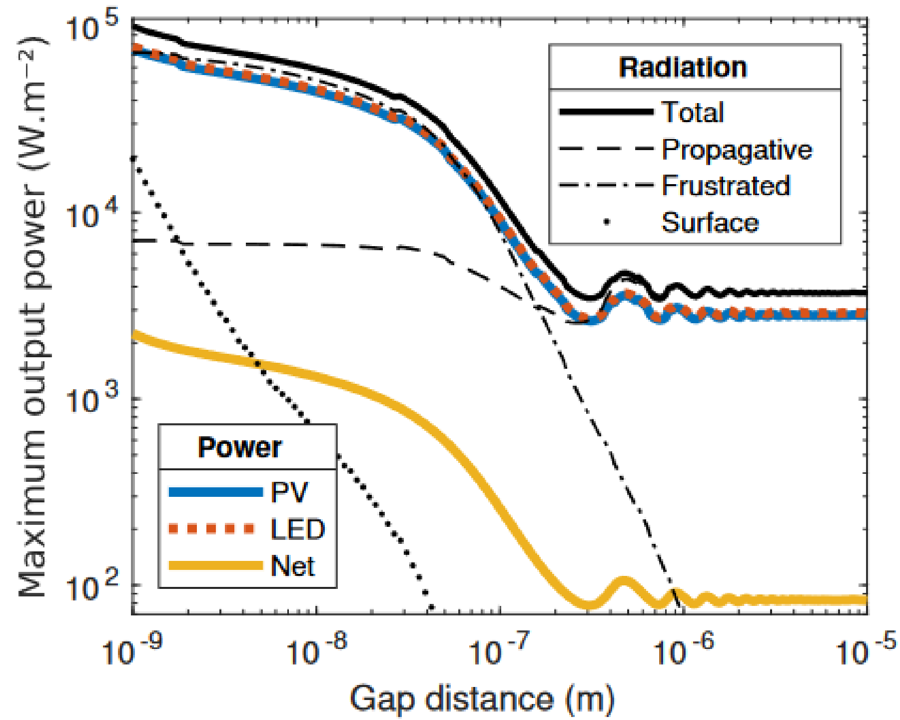


→ Thermal frequencies not required if IQE is high

Drift-diffusion equation in both LED and PV devices

High doping: simplifications





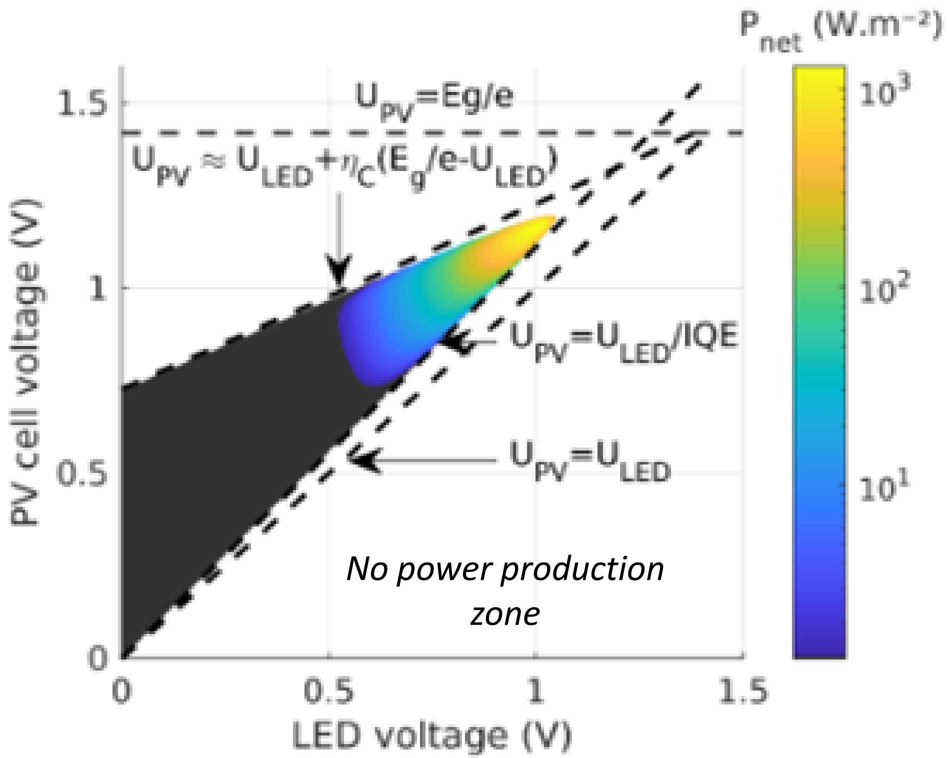
Huge flux emitted and converted, only a fraction is harvested

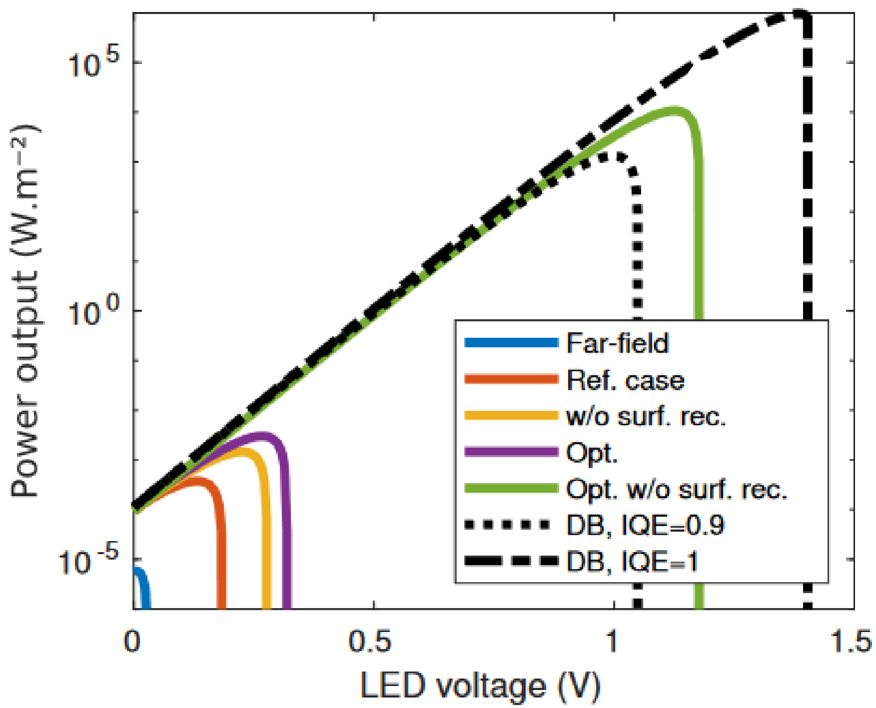
Legendre & Chapuis, Sol.Mat. 238, 111594 (2022)

Performances of PN GaAs-based NF-TPX devices

$E_g = 1.4\ \text{eV}$

High doping

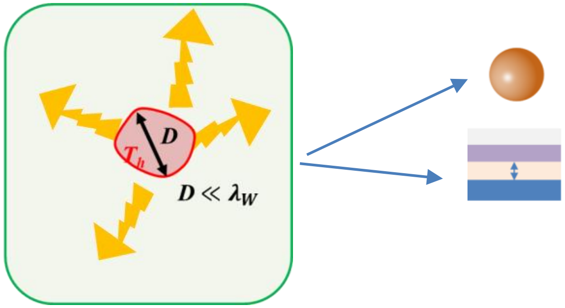




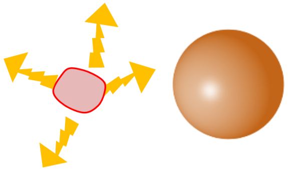
- **Managing electrical losses and recombinations is critical**
- **Increasing the depleted zone in pin junctions**

Legendre & Chapuis, Sol.Mat. 238, 111594 (2022)


K.L. Nguyen



Thermal emission of a sphere



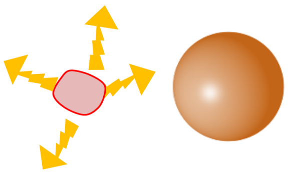
$$Q = \int_0^\infty d\omega \frac{\hbar\omega}{e^{\frac{\hbar\omega}{k_B T}} - 1} \underbrace{\frac{2}{\pi} \sum_{P=E,M} \sum_{l=1}^{\infty} (2l+1) \left[\mathrm{Re}(\mathcal{T}_l^P) - |\mathcal{T}_l^P|^2 \right]}_{\mathfrak{I}(\omega)}$$

~*Mie*

$$e_{\mathrm{eff,tot}} = \frac{Q_S}{\sigma T^4 4\pi R^2}$$

Kattawar & Eisner, Appl. Optics 9 (**1970**)
Krüger et al., PRB 86 (2012)

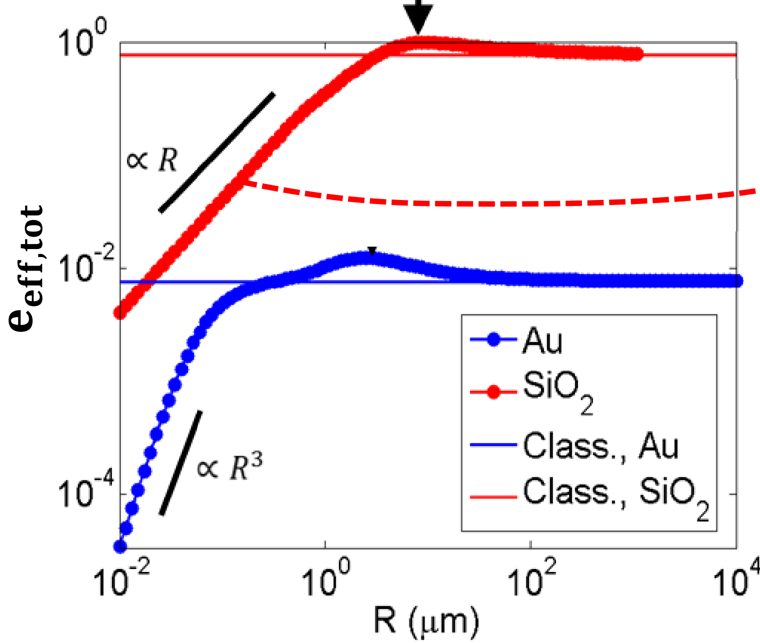
Thermal emission of a sphere



$$Q = \int_0^\infty d\omega \frac{\hbar\omega}{e^{\frac{\hbar\omega}{k_B T}}-1} \underbrace{\frac{2}{\pi}\sum_{P=E,M}\sum_{l=1}^{\infty}(2l+1)\left[\mathrm{Re}(\mathcal{T}_l^P) - |\mathcal{T}_l^P|^2\right]}_{\mathfrak{I}(\omega)}$$

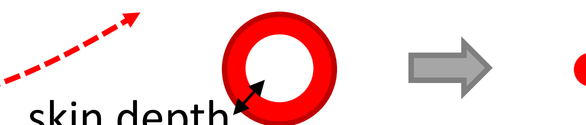
$$e_{\mathrm{eff,tot}} = \frac{Q_S}{\sigma T^4 4\pi R^2}$$

$e_{\mathrm{eff,tot}} > 1$

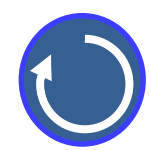


Size dependence different than for large objects

$Q_s \propto R^2 \rightarrow R^3$: volume emission



$Q_s \propto R^5$
magnetic dipole

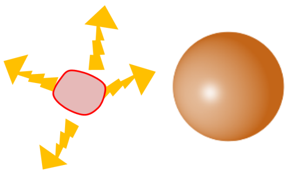


strong electromagnetic effects

Nguyen *et al.*, APL 112, 111906 (2018)

see also Kattawar, Krüger

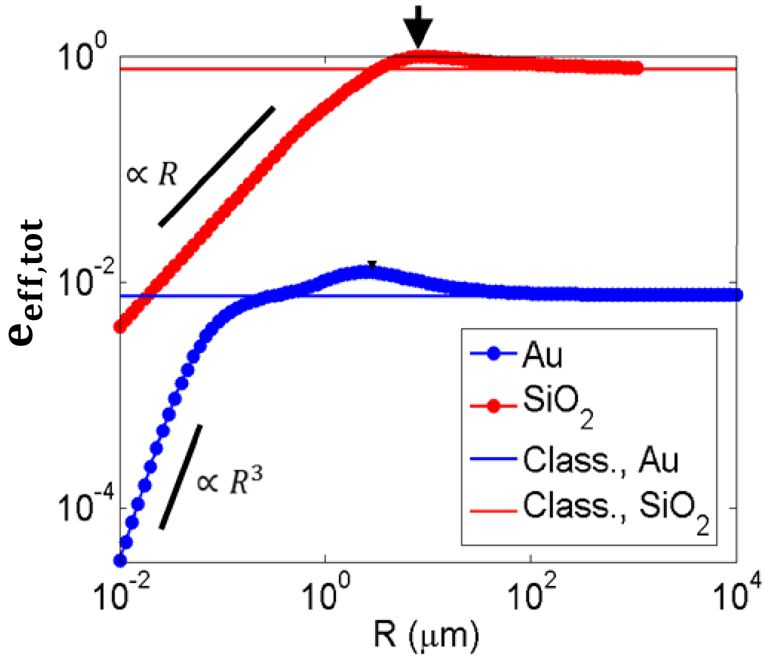
Thermal emission of a sphere



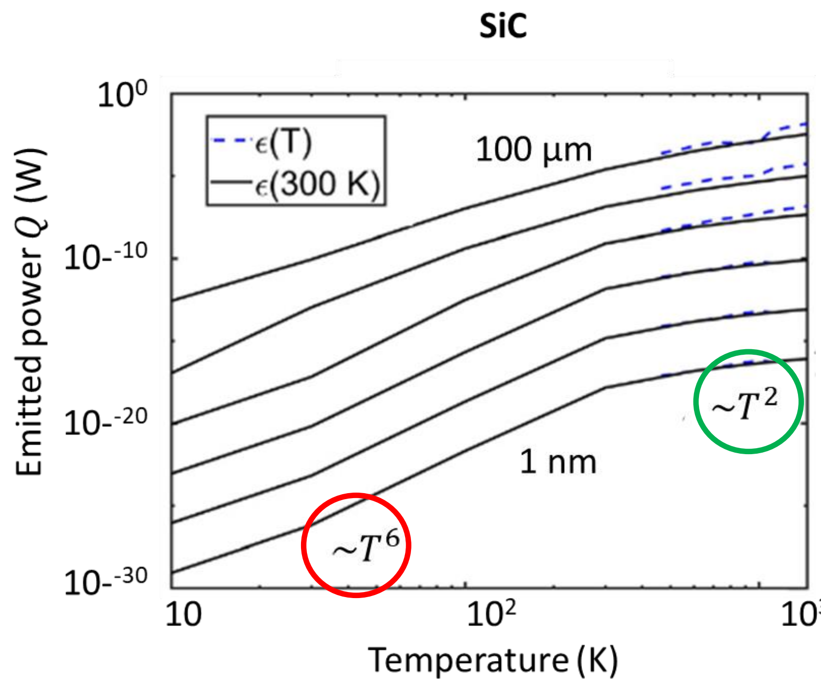
$$Q = \int_0^\infty d\omega \frac{\hbar\omega}{e^{\frac{\hbar\omega}{k_B T}}-1} \underbrace{\frac{2}{\pi} \sum_{P=E,M} \sum_{l=1}^{\infty} (2l+1) \left[\mathrm{Re}(\mathcal{T}_l^P) - |\mathcal{T}_l^P|^2 \right]}_{\Im(\omega)}$$

$$e_{\text{eff,tot}} = \frac{Q_S}{\sigma T^4 4\pi R^2}$$

$e_{\text{eff,tot}} > 1$



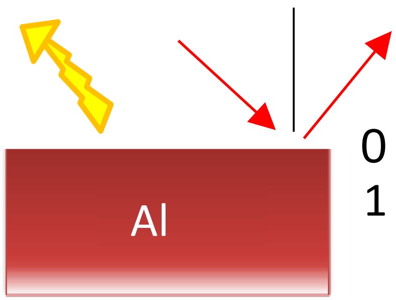
Size dependence different than for large objects



Temperature dependence different than predicted by Stefan-Boltzmann's law

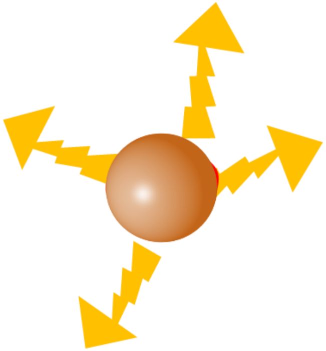
Nguyen *et al.*, APL 112, 111906 (2018)

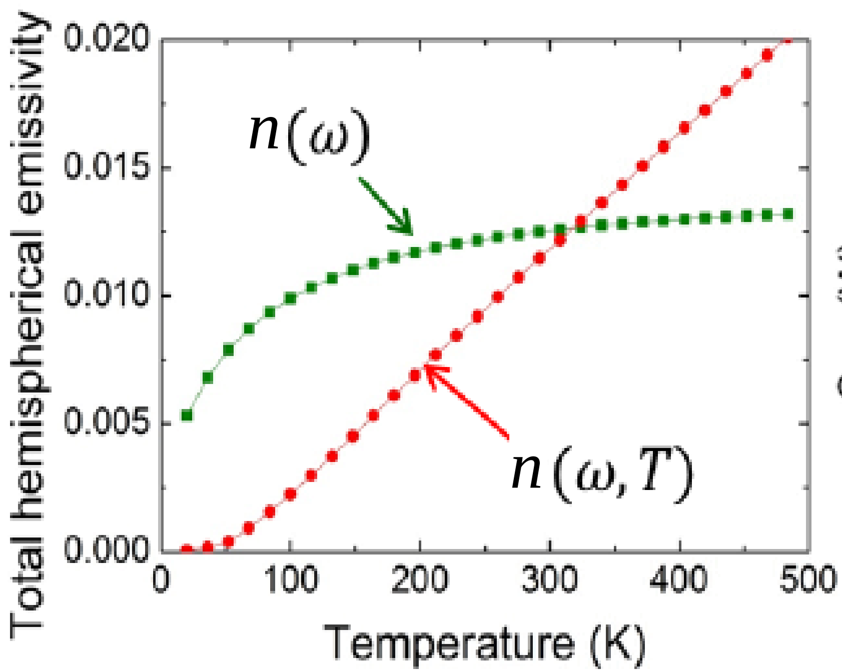
Temperature dependence of permittivity
Case of metals

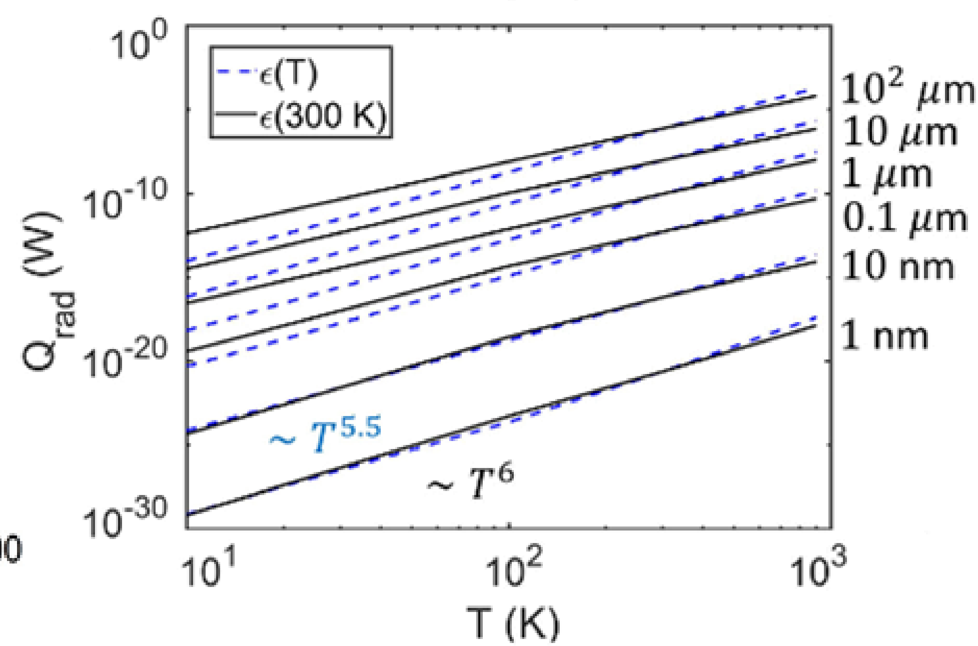


$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + i\Gamma)}$$

$$\omega_p^2 = \frac{Ne^2}{m^* \epsilon_0} \qquad \Gamma = \frac{Ne^2 \rho}{m^*}$$



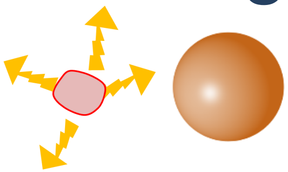




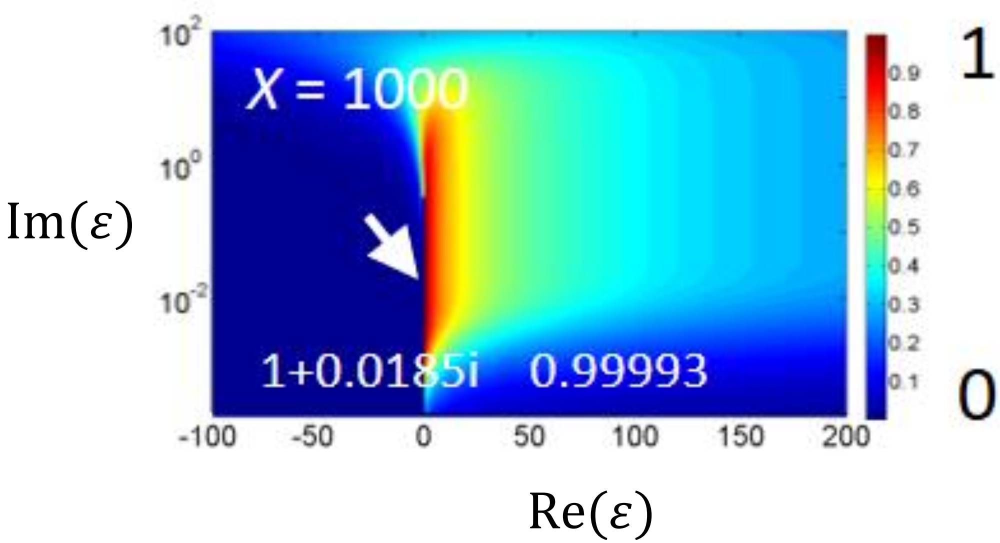
Blandre *et al.*, Opt. Exp. 24, A374 (2016)

Nguyen *et al.*, APL 112, 111906 (2018)

Optimizing thermal emission with Mie resonances



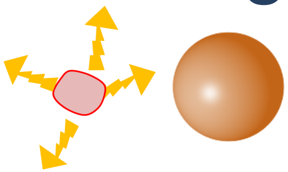
Emissivity of a large sphere



Blackbody = non-reflective medium that absorbs all radiation

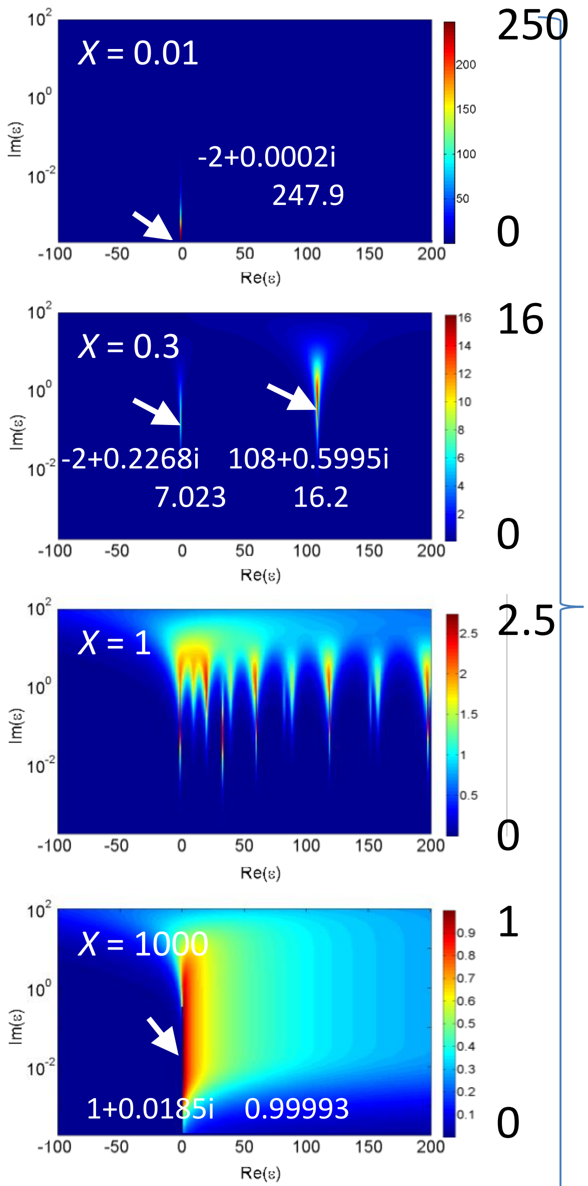
Nguyen *et al.*, APL 112, 111906 (2018)

Optimizing thermal emission with Mie resonances



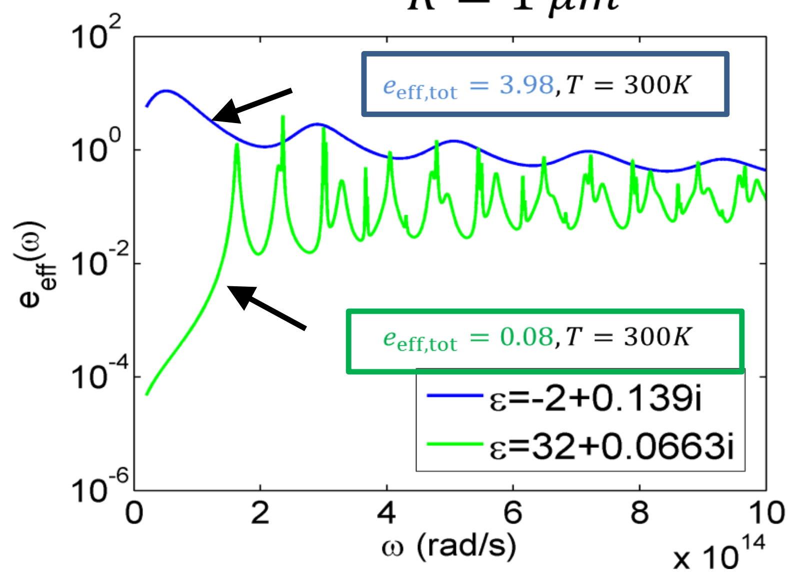
$\mathrm{Re}(\varepsilon) \approx -2$

$\mathrm{Re}(\varepsilon) \approx 1$



ϵ supposed constant

$R = 1\ \mu m$

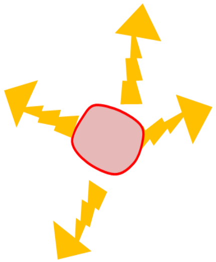


Dipole resonance more efficient because 'broadband'

Nguyen *et al.*, APL 112, 111906 (2018)

see also ACS Photonics 2, 263 (2015)

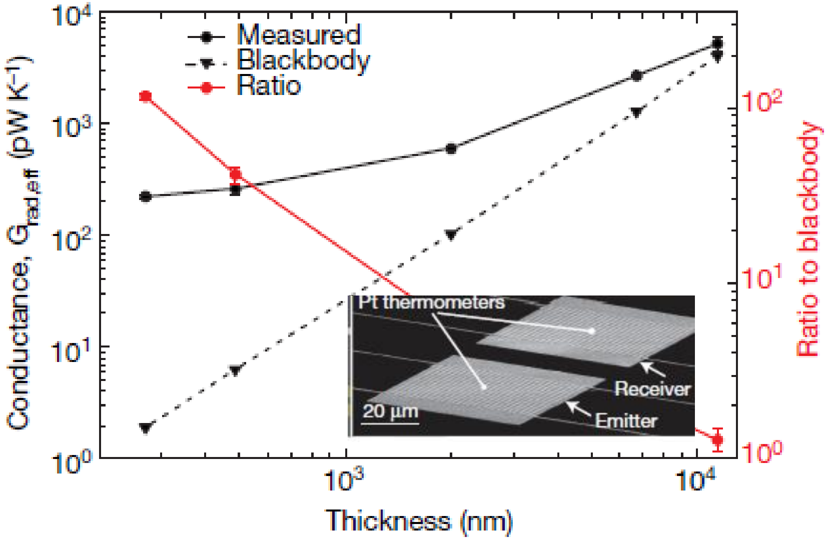
Recap for sub-λ finite objects



- Effective emissivity can be larger than 1
- $S\,T^4$ incorrect over large ranges of size/temperature
- Dipole resonance more broadband-compatible than Mie geometric ones
- Is it possible to tune the temperature-dependance and increase it for large surfaces with sub-λ elements?

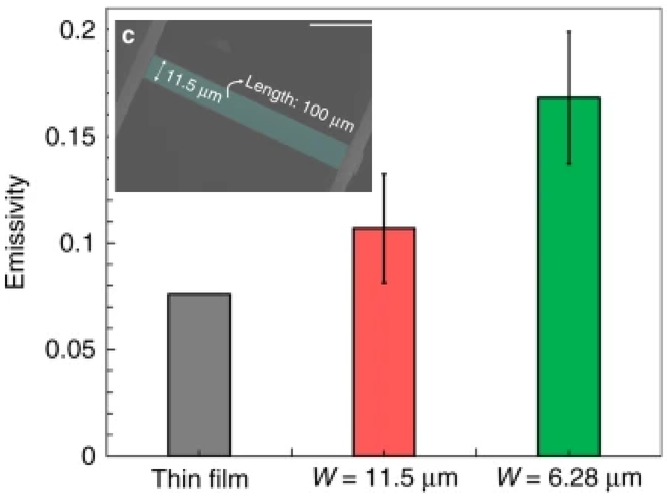
Recent measurements involve also the shape of the objects

Heat transfer between suspended calorimeters



Thompson *et al.*, Nature 561 (2018)

Thermal emission from ribbons



Shin *et al.*, Nat. Com 10 (2019)

I. Context

II. Near-field thermal radiation vs T

III. Near-field thermophotovoltaics

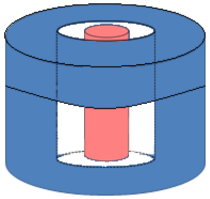
IV. Near-field thermophotonics

V. Sub-wavelength thermal emission vs T

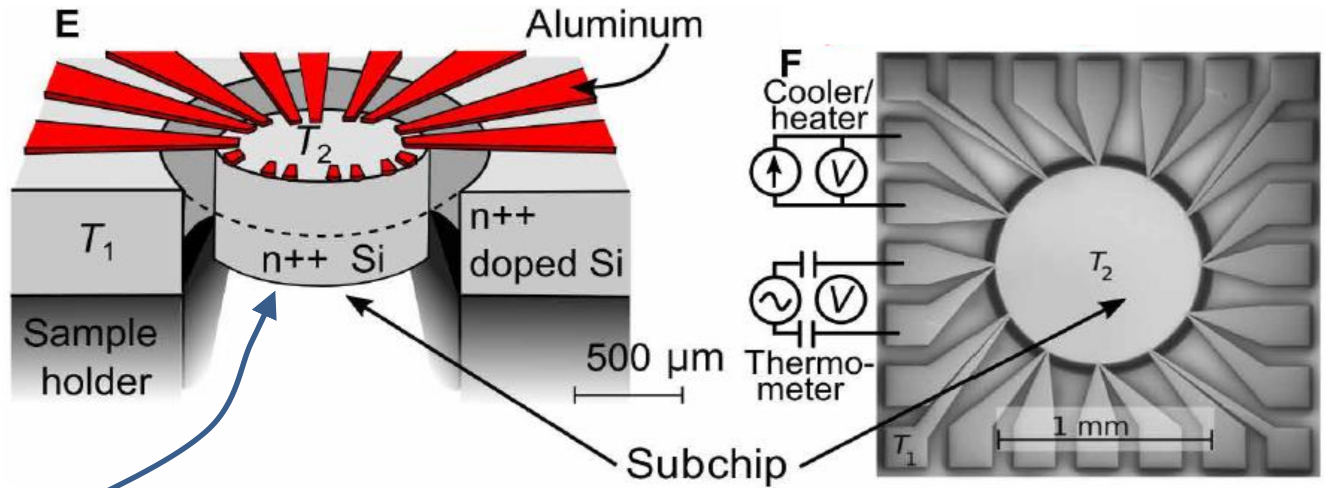
VI. Concentric cylinders

VII. Some prospects

A. Alwakil

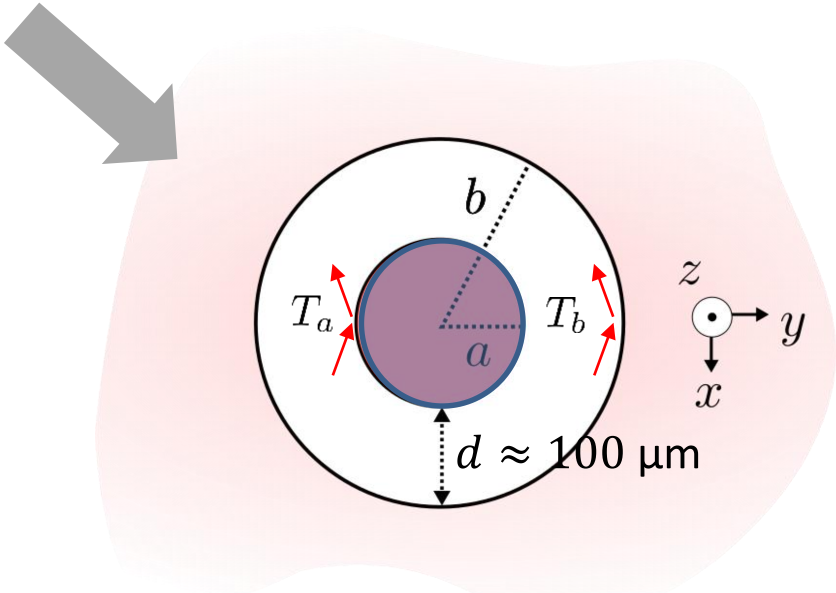


Refrigeration device: concentric cylinders



Cold zone

Mykkänen et al., Sci. Adv. 6, eaax9191 (2020)

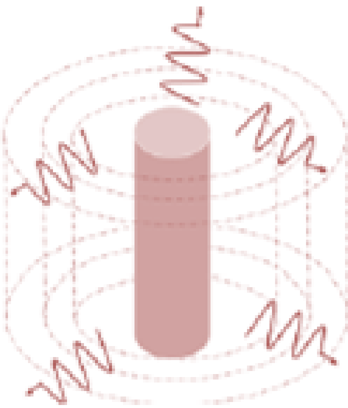


$T < 1$ K

$\lambda_{th} > 3$ **mm**

Thermal radiation is a parasitic heating channel

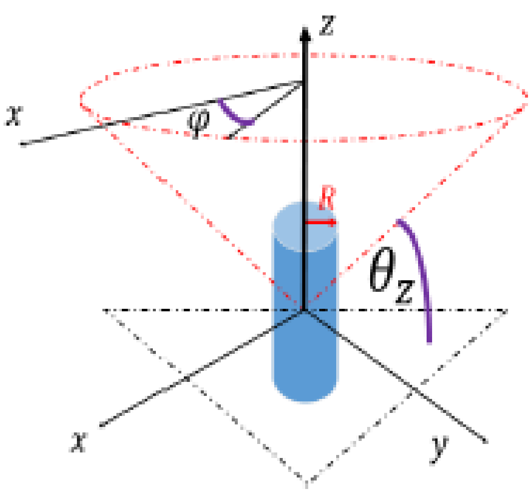
Electromagnetic modes for cylindrical objects



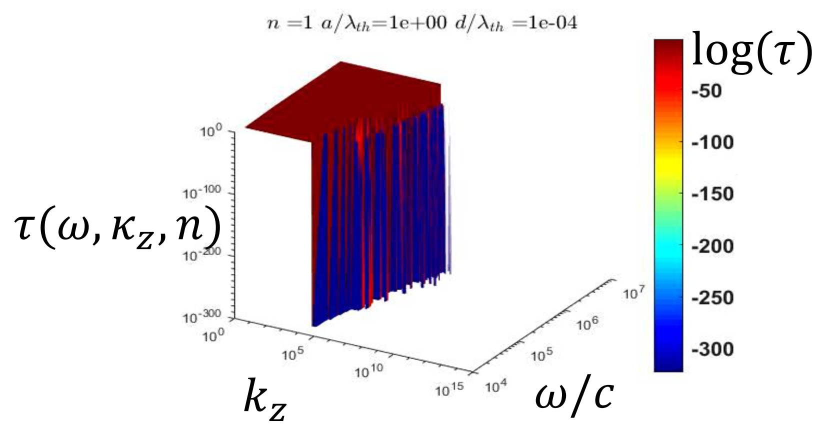
- Cylindrical waves $\cos(n\varphi), \sin(n\varphi)$
- Waves act as plane waves along z-axis $e^{ik_z z}$
- Polarizations are coupled

Golyk et al. PRE 85 (2012)

- E/N-polarization $E_{\parallel z}$
- H/M-polarization $H_{\parallel z}$



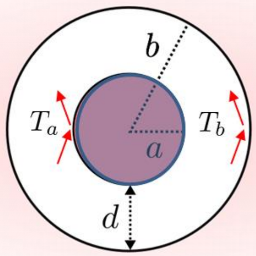
$$\begin{Bmatrix} E \\ H \end{Bmatrix} = f \left\{ \begin{Bmatrix} J_n(\kappa_\rho \rho) \\ H_n^{(1)}(\kappa_\rho \rho) \end{Bmatrix} \left\{ e^{i\kappa_z z} \right\} \begin{Bmatrix} \cos(n\varphi) \\ \sin(n\varphi) \end{Bmatrix} \right\}$$



Radiative heat transfer from inner to outer cylinder

Trace formula for unbounded medium

vs Krüger al., PRB B 86, 115423 (2012)



Unbounded Green's tensor

$$\mathcal{T}(\omega) = -\frac{2}{\pi}\,\mathrm{Tr}\,\mathrm{Im}\left\{(1+\mathbb{G}_0\mathbb{T}_b)\frac{1}{1-\mathbb{G}_0\mathbb{T}_a\mathbb{G}_0\mathbb{T}_b}\mathbb{G}_0 \cdot [Im\{\mathbb{T}_a\} - \mathbb{T}_a\,\mathrm{Im}\{\mathbb{G}_0\}\mathbb{T}_a^*]\frac{1}{1-\mathbb{G}_0^*\mathbb{T}_a^*\mathbb{G}_0^*\mathbb{T}_b^*}\right\}$$

Heaviside

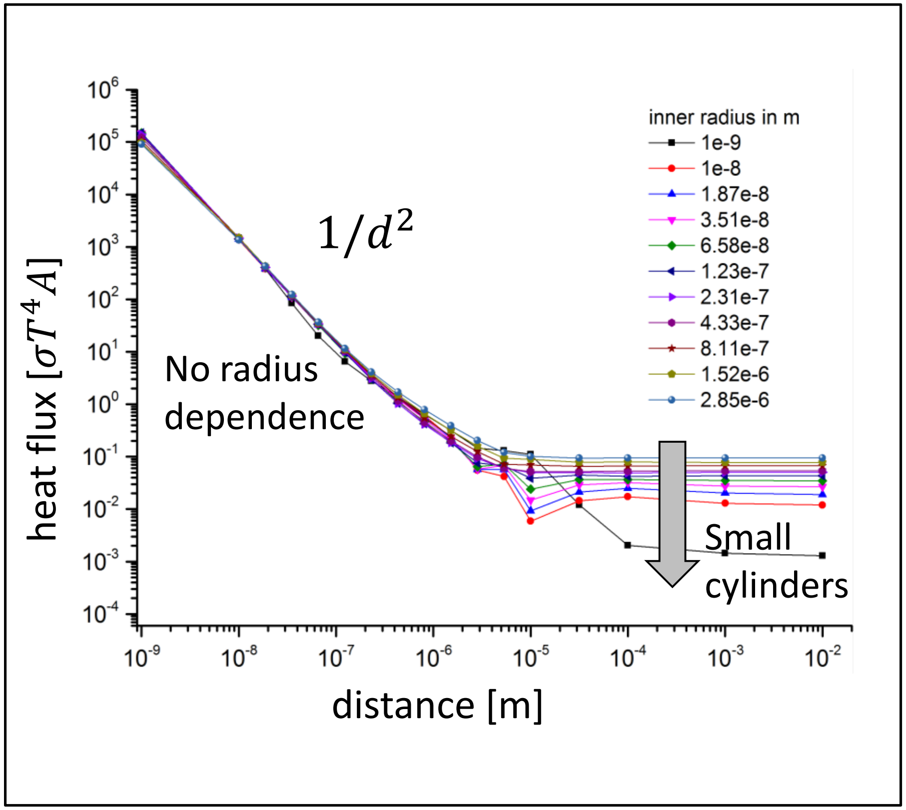
$$= -\frac{2}{\pi}H(k_0-k_z)\mathrm{Re}\{W_{PP}(1+W_{PP}+L_{PP}+D_{PP})^* + W_{P'P}(L_{P'P}+W_{P'P}+D_{P'P})^*\} - \frac{1}{\pi}\mathrm{Re}\{W_{PP}C_{PP}^* + L_{PP}(1+D_{PP})^* + W_{P'P}C_{P'P}^* + L_{P'P}D_{P'P}^*\}$$

Polarizations

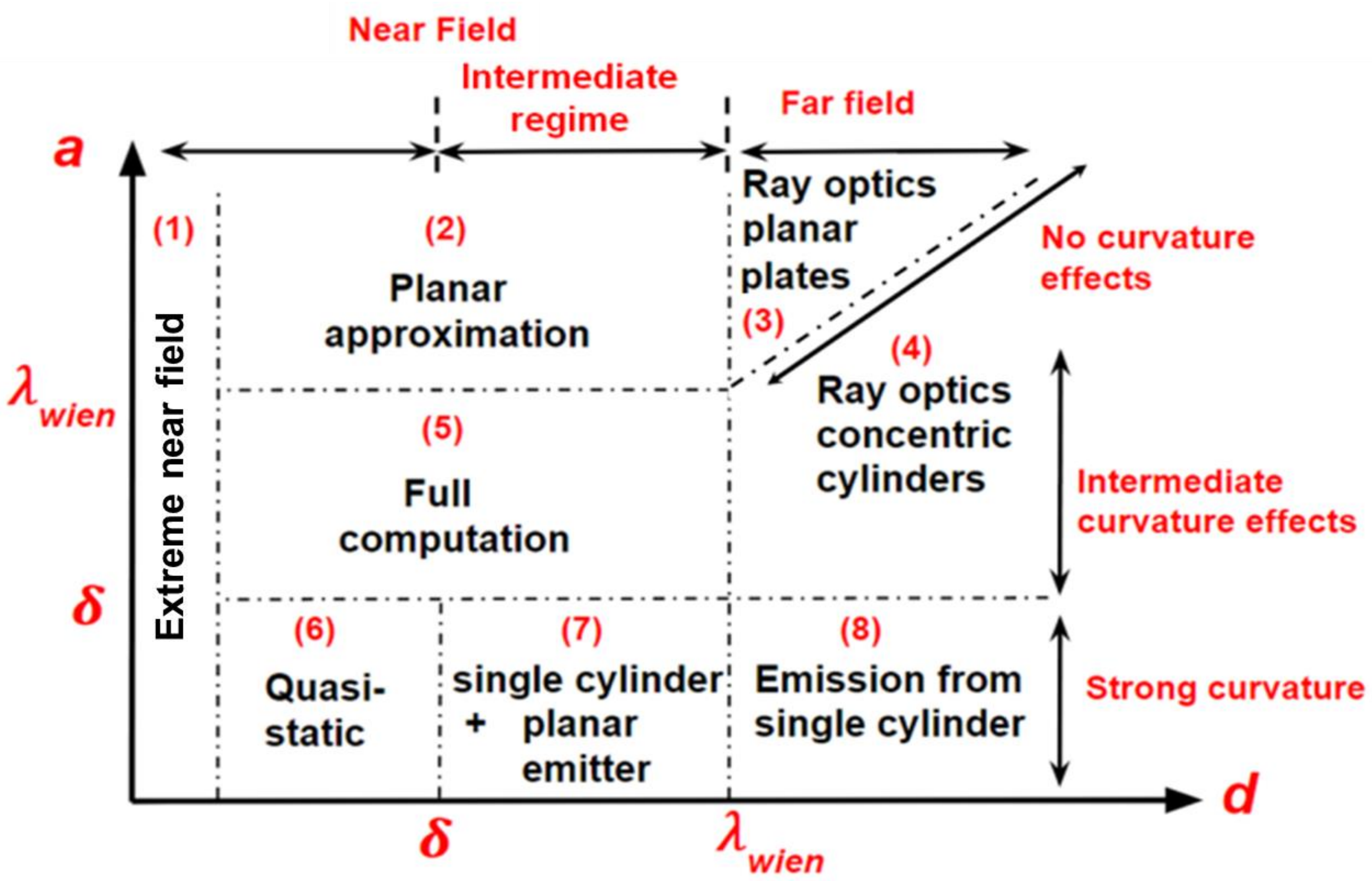
C, D, L, W :

Coefficients expressed in terms of ratios of cylindrical Bessel functions (poles & singularities…)

$$T_{MM}^a = -\frac{J_n(\kappa_{\rho,0}a)}{H_n(\kappa_{\rho,0}a)}\frac{\Delta_1^a\Delta_4^a - K_a^2}{\Delta_1^a\Delta_2^a - K_a^2} \qquad \Delta_1^a = \frac{1}{\kappa_{\rho,A}a}\frac{J_n'(\kappa_{\rho,A}a)}{J_n(\kappa_{\rho,A}a)} - \frac{1}{\epsilon_A\kappa_{\rho,0}a}\frac{H_n'^{(1)}(\kappa_{\rho,0}a)}{H_n^{(1)}(\kappa_{\rho,0}a)}$$



Regime map vs (a, d) and (λ, δ)



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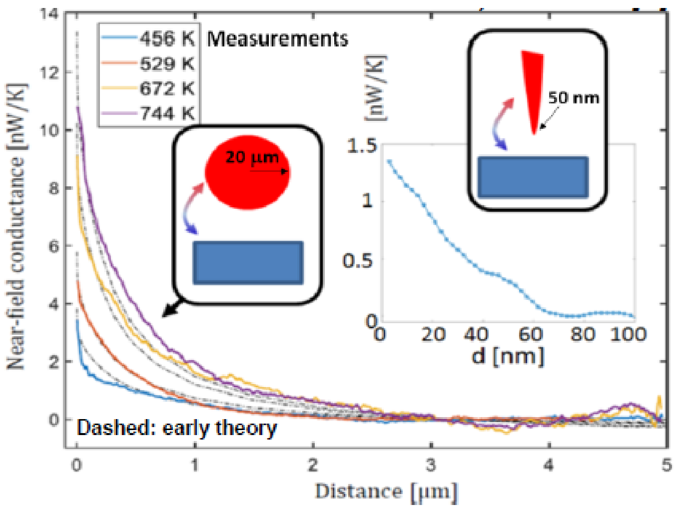
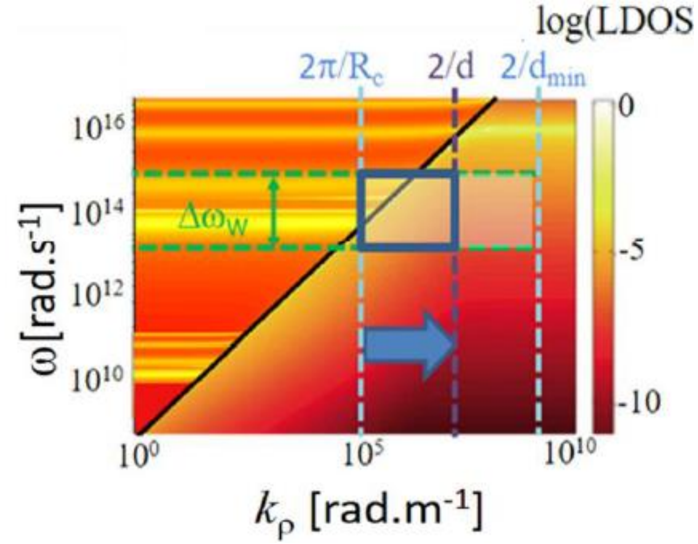
Spectroscopy without spectroscope?

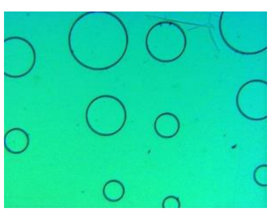
Near-field radiative 'spectroscopy'

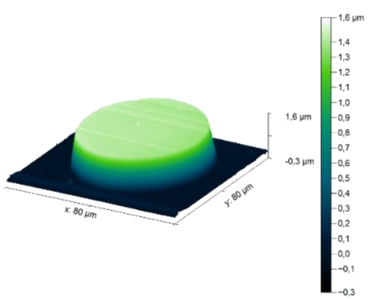
(θ, ω)

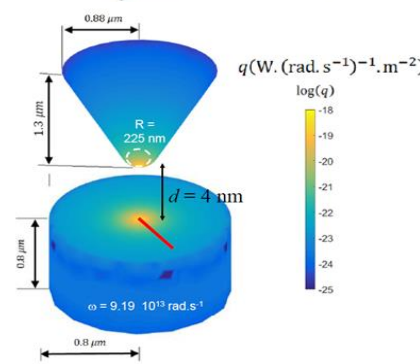
(d, T)





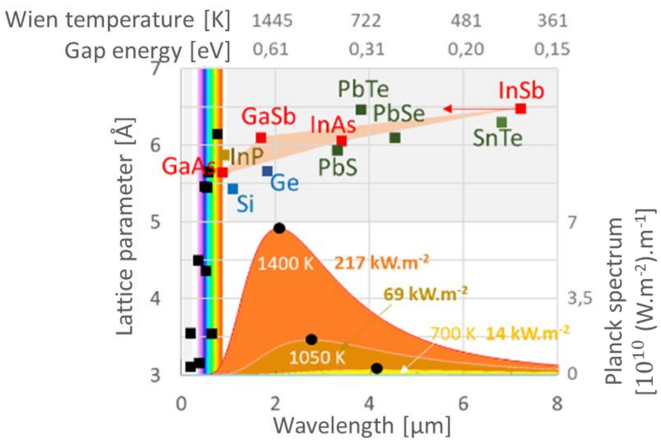






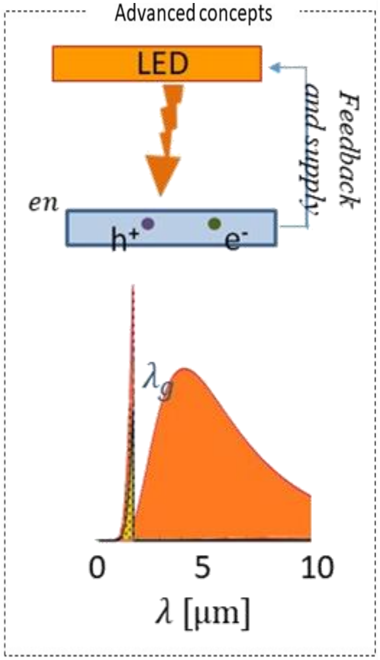
Energy-conversion devices

Near-field thermophotovoltaics



- Room temperature cells
- Higher operating temperature
- Smaller distances

Near-field thermophotonics



- Refrigeration
- Implementation…
- Moving to IR?

Other near-field thermo-electric phenomena

Thermionics and coupling with near-field thermal radiation

Acknowledgements

SEVENTH FRAMEWORK PROGRAMME

Quanti Heat

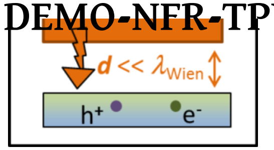
EF NED

TPX-Power

OPTAGON

Financé par ANR

DEMO-NFR-TPV



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Thermal Radiation to Electrical Energy conversion (TREE)

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'Special Topic' issue in APL

'Thermal radiation at nanoscale and applications'

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Deadline for submission: July 2022

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Alejandro Rodriguez, Princeton, USA