Heat Transfer at Proximity

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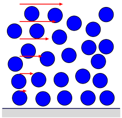
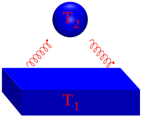
Thorsten Emig, Paris
Giuseppe Bimonte, Naples
Joseph Brader, Fribourg





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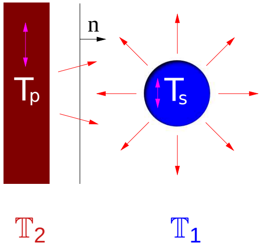
Scattering approach for Non-eq. QED (Rytov ∼1960)

Phenomenology

- Single object: Heat radiation
- Immerse other objects
- Force
  - Formula for *N* arbitrary objects (2012)
  - Generalizes equilibrium result

Rahi, Emig, Graham, Jaffe, Kardar (2009)



Heat transfer (2012)

$$H = \frac{2\hbar}{\pi}\int d\omega \frac{\omega}{e^{\frac{\hbar\omega}{k_B T_S}}-1}\,\mathrm{Tr}\left\{\left[\mathrm{Re}[\mathbb{T}_2] + \mathbb{T}_2^\dagger\mathbb{T}_2\right]\frac{1}{1-\mathbb{U}\mathbb{T}_1\mathbb{U}\mathbb{T}_2}\mathbb{U}\left[\mathrm{Re}[\mathbb{T}_1] + \mathbb{T}_1\mathbb{T}_1^\dagger\right]\mathbb{U}^\dagger\frac{1}{1-\mathbb{T}_2^\dagger\mathbb{U}^\dagger\mathbb{T}_1^\dagger\mathbb{U}^\dagger}\right\}.$$

Krüger, Bimonte, Emig, Kardar, *Phys. Rev. B* **86**, 115423 (2012)
Krüger, Emig, Kardar, *Phys. Rev. Lett.* **106**, 210404 (2011)
Messina, Antezza (2011)
Rodriguez, Reid, Johnson (2012)
Narayanaswamy, Zheng (2013)

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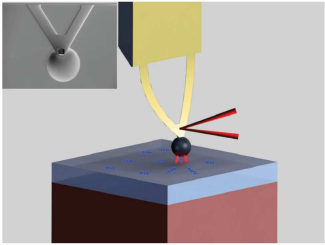
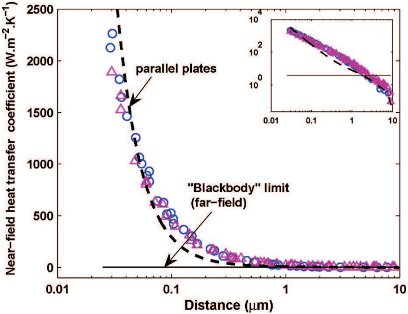
Typical setups: Curved surfaces





Sphere-plate

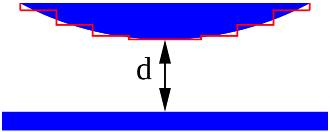
Sheng, Narayanaswamy, Chen (2009)
Rousseau *et. al.* (2009)

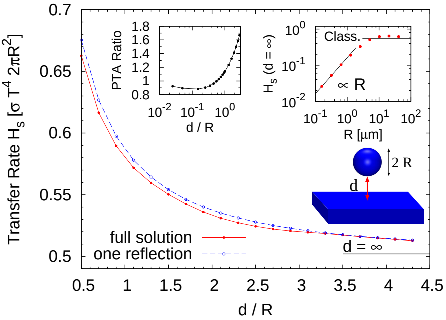
Heat transfer: Theory

Asymptotic

$$d \ll \{R, \lambda_T\} : H \to 2\pi R \int_d^{d+R} ds\, H_{\mathrm{PP}}(s) \propto \frac{1}{d}$$

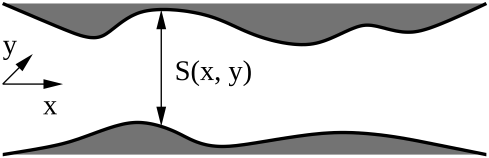
$$d \gg \{R, \lambda_T\} : \lim_{\{R \gg \lambda_T\}} H \propto R^2 \qquad \lim_{\{R \ll \lambda_T\}} H \propto R^3$$





M. Krüger, T. Emig and M. Kardar, *Phys. Rev. Lett.* **106**, 210404 (2011)
Otey and Fan (2011)

Gradient expansion



Gradient expansion

$$H[S(\mathbf{x})] = \int_\Sigma d^2\mathbf{x}\, H_{pp}(S) + \int_\Sigma d^2\mathbf{x}\; \beta\; H_{pp}(S)\, \nabla S \cdot \nabla S + \cdots$$

Sphere-plate near $d = 0$ $\qquad H_{pp} \propto \frac{1}{S^2}$

$$H = \frac{2\pi R \lambda}{d}\left[1 + (2\beta - 1)\frac{d}{R}\log\frac{d}{R}\right] + \mathcal{O}(d^0)$$

Proximity Gradient expansion

Golyk, Krüger, McCauley, Kardar, *Europhys. Lett.* **101**, 34002 (2013)
Fosco, Lombardo, Mazzitelli (2011)
Bimonte, Emig, Jaffe, Kardar (2012)

Sphere near $d = 0$

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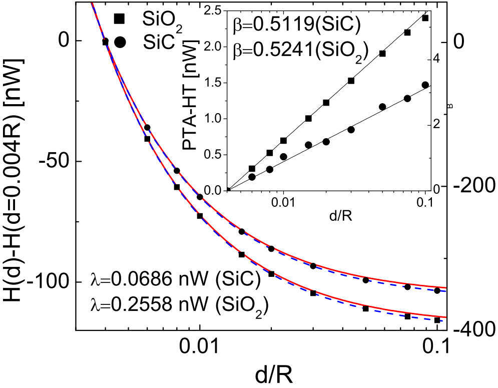
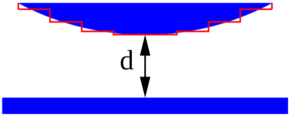
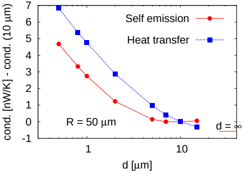
Proximity Gradient expansion







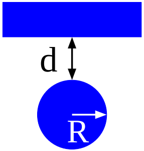
Golyk, Krüger, McCauley, Kardar, *Europhys. Lett.* **101**, 34002 (2013)

Different geometries

Sphere and plate

$$H(d) = \frac{2\pi R\lambda}{d}\left[1 - (2\beta - 1)\frac{d}{R}\log\frac{d}{d_0}\right] + \mathcal{O}(d^0),$$

- $\beta \approx \frac{1}{2}$ for SiC, SiO_2
  $\rightarrow$ logarithm almost absent



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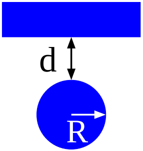
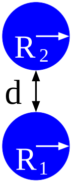


Two spheres

$$H(d) = \frac{2\pi\lambda}{d}\frac{R_1R_2}{R_1+R_2}\left[1 + \frac{d}{R_1+R_2}\log\frac{d}{d_0}\right.$$
$$\left. -(2\beta - 1)\left(\frac{d}{R_1}+\frac{d}{R_2}\right)\log\frac{d}{d_0}\right] + \dots$$



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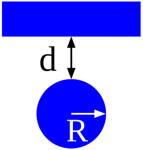
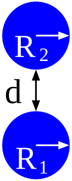


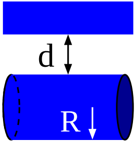
Two spheres

$$H(d) = \frac{2\pi\lambda}{d}\frac{R_1 R_2}{R_1 + R_2}\left[1 + \frac{d}{R_1 + R_2}\log\frac{d}{d_0} - (2\beta - 1)\left(\frac{d}{R_1} + \frac{d}{R_2}\right)\log\frac{d}{d_0}\right] + \dots$$



Cylinder and plate

$$\frac{H(d)}{L} = \frac{\pi\sqrt{R}\lambda}{\sqrt{2}d^{3/2}}\left[1 + \left(2\beta - \frac{3}{4}\right)\frac{d}{R}\right] + \mathcal{O}(d^0)$$



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Maximal non-contact transfer?

Proximity approximation

Parallel surfaces $H \propto \frac{1}{d^2}$.

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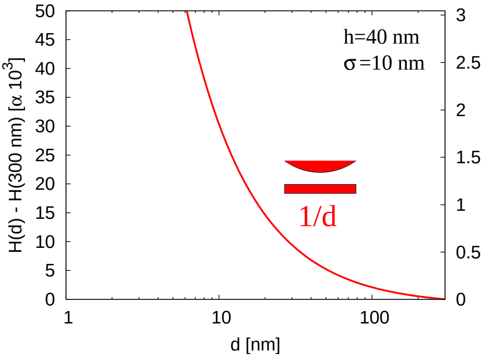
$H \propto \frac{1}{d}$ $\mathcal{C} = 1$



Krüger, Golyk, Bimonte, Kardar, arXiv:1303.2499

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McCauley, Reid, Krüger, Johnson, *Phys. Rev. B* **85**, 165104 (2012)

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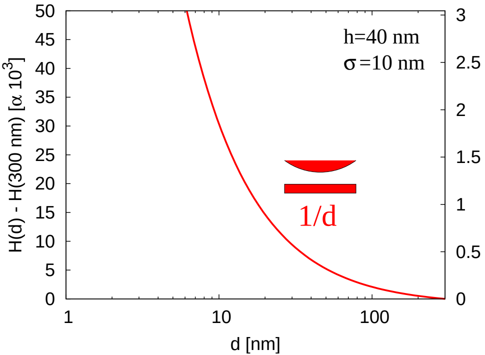
$H \propto \log d$ $\mathcal{C} = 2$



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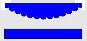

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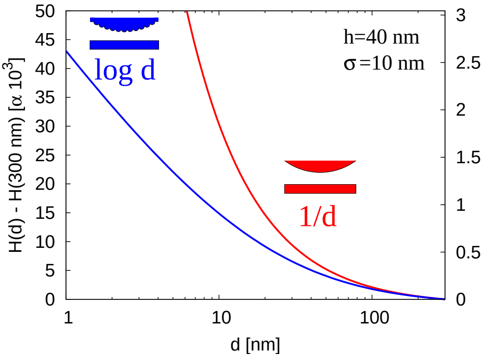

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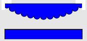 $H \propto \log d$ $\mathcal{C} = 2$

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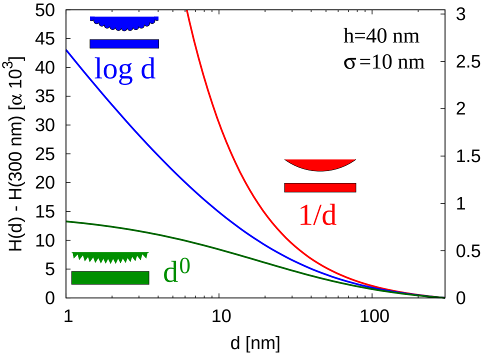
 $H \propto d^0$ $\mathcal{C} = 3$



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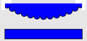

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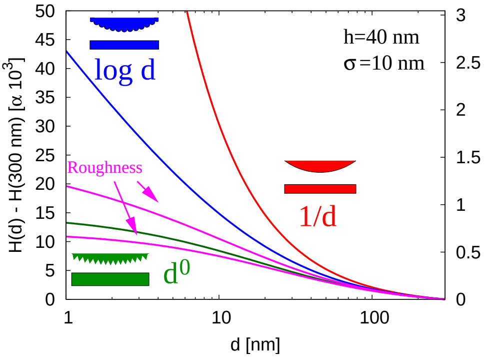
Roughness: $\mathcal{C} = 2 \ldots 3$



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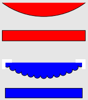
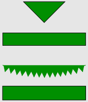


$H \propto \frac{1}{d}$ $\mathcal{C} = 1$

$H \propto \log d$ $\mathcal{C} = 2$



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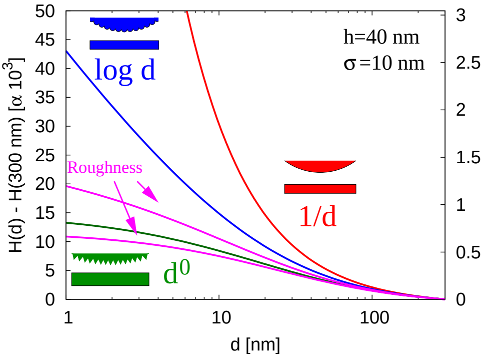
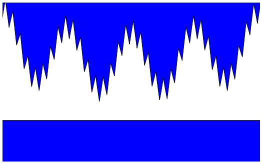


Geometry with $\mathcal{C} = 4$:



Force: $F \propto \frac{1}{d^3} \to d^0$

Krüger, Golyk, Bimonte, Kardar, arXiv:1303.2499

Summary

- Gradient expansion quantifies corrections to proximity transfer approximation
- Near field adjusted plot suitable to apply PTA
- Effects of roughness/modulation can be estimated in simple scheme