Casimir Forces, Friction and Radiative Heat Transfer in Graphene Systems

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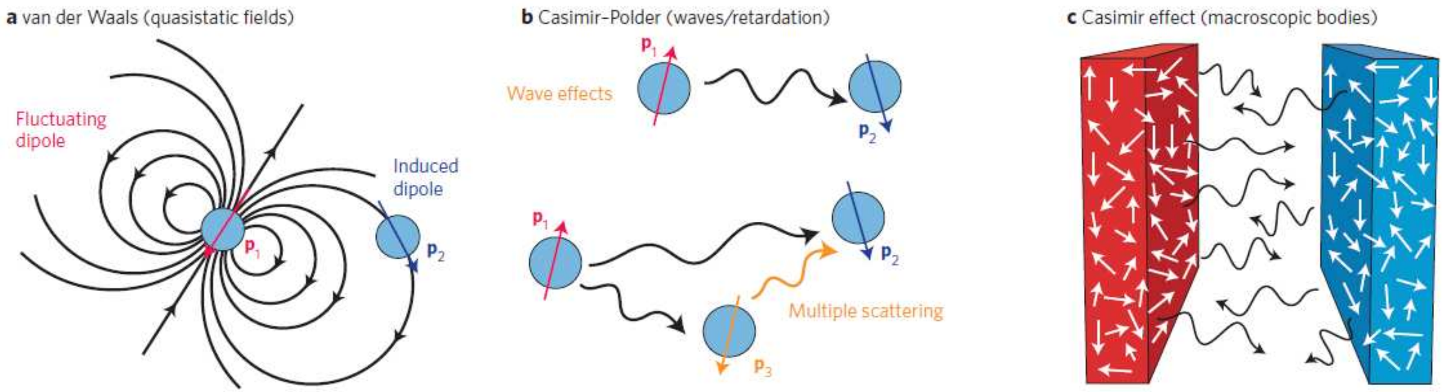
- Introduction
- Fluctuations produce forces
- Casimir forces between graphene sheets
- Casimir friction
- Using graphene to detect Casimir friction
- Radiative heat transfer in grapheme systems
- Conclusion

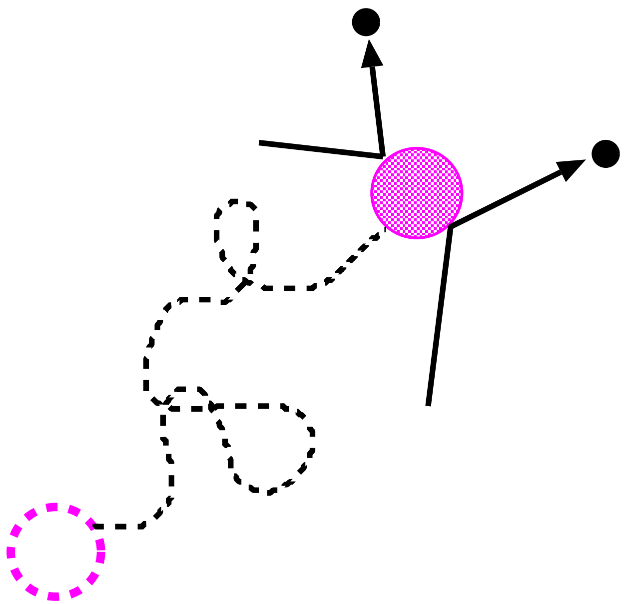
Fluctuations produce forces



H.Casimir 1948
E.Lifshitz 1954

$$\frac{F_C}{A} = \frac{\hbar c \pi}{240 d^4} = \frac{1.3 \times 10^{-27}}{d^4} \text{Nm}^2,$$

Rytov's theory



$$\nabla \times \mathbf{E} = i\frac{\omega}{c}\mathbf{B}$$

$$\nabla \times \mathbf{H} = -i\frac{\omega}{c}\mathbf{D} + \frac{4\pi}{c}\mathbf{j}^f$$

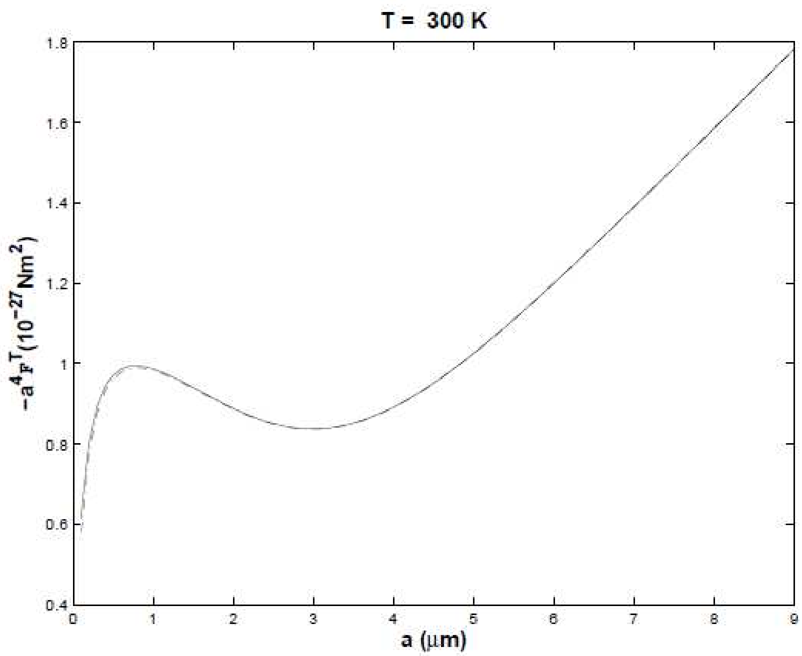
$$\left\langle j_i^f(\mathbf{r}) j_k^{f*}(\mathbf{r}') \right\rangle_\omega = \frac{\hbar}{(2\pi)^2}\left(\frac{1}{2} + n(\omega)\right)\omega^2 \mathrm{Im}\varepsilon_{ik}(\mathbf{r}, \mathbf{r}', \omega)$$

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

Application of Rytov's theory

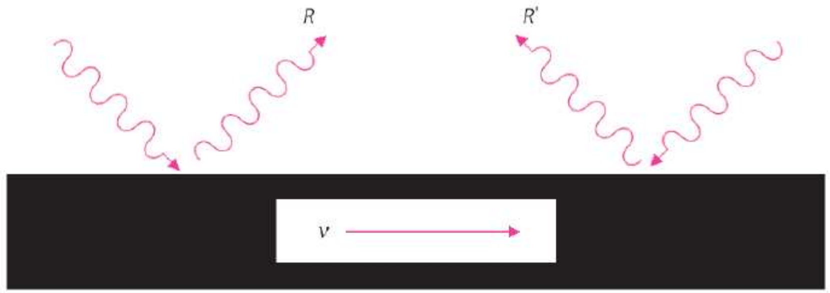
- Lifshitz E.M. Theory of the Casimir-Lifshitz interaction 1955
- Polder D. and Van Hove M. Theory of the radiative heat transfer 1971
- Volokitin A.I. and Persson B.N.J. Theory of the Casimir friction 1998, 2008 .

Temperature Effect



Quantum fluctuations dominate for $d < \lambda_T = c\hbar/k_B T$
Thermal fluctuations dominate for $d > \lambda_T = c\hbar/k_B T$
Sushkov A.O. *et al* 2011

Doppler Effect



J.Pendry 1997
A.I.Volokitin and B.N.J.Persson 2008

Casimir force between moving bodies

$$F_z = F_{zT} + F_{z0},$$

where the temperature dependent term F_{zT} and the zero-temperature contribution F_{z0} are given by

$$F_{zT} = \frac{\hbar}{\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x q e^{-2qd}\Bigg\{\int_0^\infty d\omega\left(\frac{\mathrm{Im}R_1(\omega)\mathrm{Re}R_2(\omega^+)n_1(\omega)+\mathrm{Re}R_1(\omega)\mathrm{Im}R_2(\omega^+)n_2(\omega^+)}{\mid 1-e^{-2qd}R_1(\omega)R_2(\omega^+)\mid^2}\right.$$

$$\left.+(1\leftrightarrow 2)\right) + \int_0^{q_x v} d\omega\left(\frac{\mathrm{Re}R_1(\omega^-)\mathrm{Im}R_2(\omega)n_2(\omega)}{\mid 1-e^{-2qd}R_1(\omega^-)R_2(\omega)\mid^2} + (1\leftrightarrow 2)\right)\Bigg\},$$

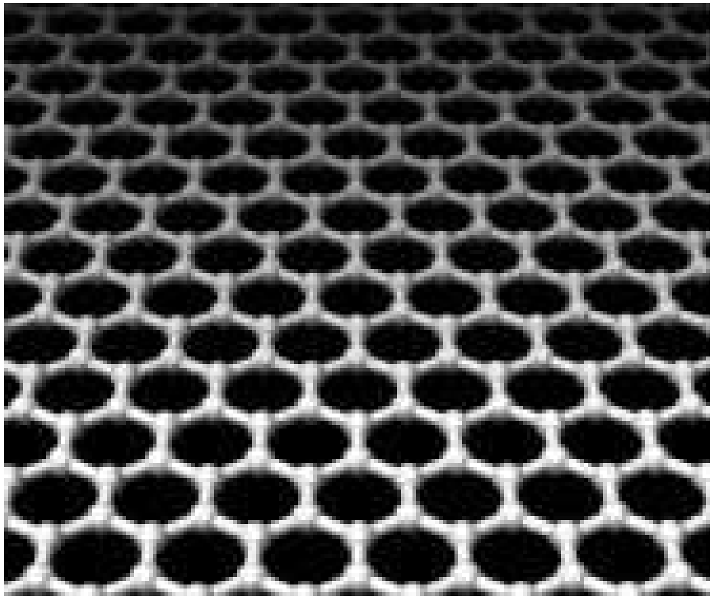
$$F_{z0} = \frac{\hbar}{2\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x \Bigg\{\mathrm{Re}\int_0^\infty d\omega s e^{-2sd}\left(\frac{R_1(i\omega)R_2(i\omega+q_x v)}{1-e^{-2sd}R_1(i\omega)R_2(i\omega+q_x v)}\right.$$

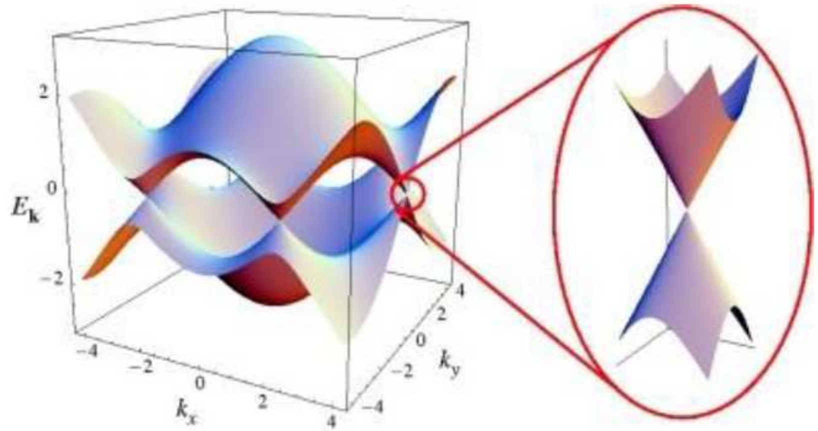
$$\left.+(1\leftrightarrow 2)\right) + \int_0^{q_x v} d\omega q e^{-2qd}\left(\frac{\mathrm{Im}R_1(\omega)\mathrm{Re}R_2(\omega^-)}{\mid 1-e^{-2qd}R_1(i\omega)R_2(\omega^-)\mid^2} + (1\leftrightarrow 2)\right)\Bigg\},$$

$\omega^\pm = \omega \pm q_x v$

A.I.Volokitin and B.N.J.Persson 2008, 2013

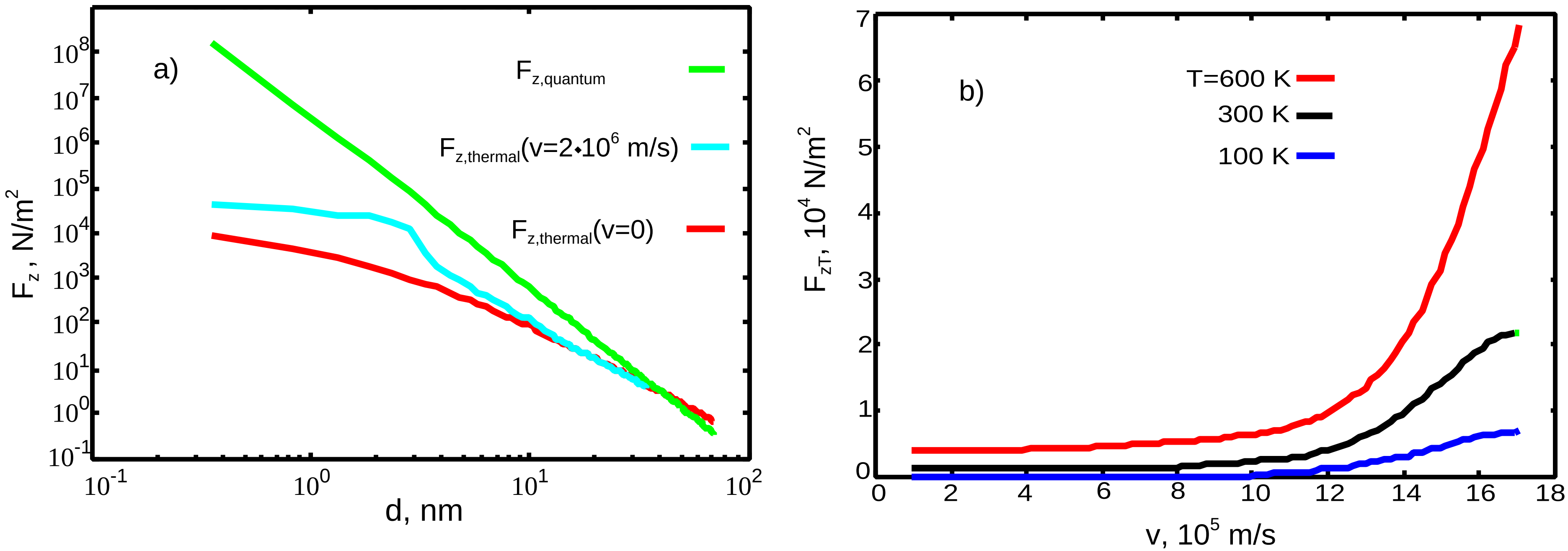
The rise of graphene





Quantum fluctuations dominate for $d < \zeta_T = v_F\hbar/k_B T$
Thermal fluctuations dominate for $d > \zeta_T = v_F\hbar/k_B T$
Drift velocity $v_D \approx 10^6$m/s

Casimir force between graphene sheets



Resonant photon tunneling enhancement

$v > 2v_F \approx 2 \cdot 10^6$m/s

A.I.Volokitin and B.N.J.Persson 2013

Casimir friction

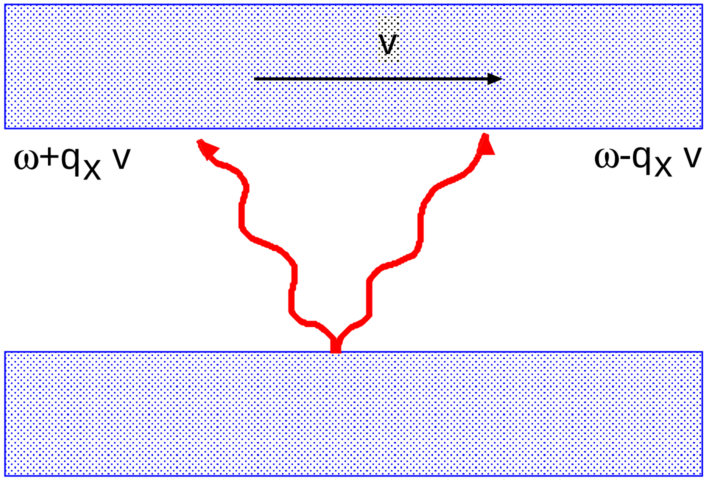
$$F_{xT} = \frac{\hbar}{\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x q_x e^{-2qd}\left\{\int_0^\infty d\omega\left(\frac{\mathrm{Im}R_1(\omega)\mathrm{Im}R_2(\omega^+)}{\mid 1-e^{-2qd}R_1(\omega)R_2(\omega^+)\mid^2}\times[n_1(\omega)-n_2(\omega^+)]+(1\leftrightarrow 2)\right)\right.$$

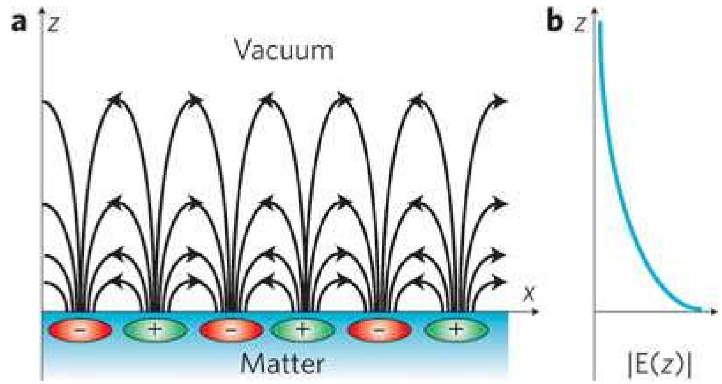
$$\left. -\int_0^{q_x v} d\omega\left(\frac{\mathrm{Im}R_d(\omega)\mathrm{Im}R_g(\omega^-)}{\mid 1-e^{-2qd}R_1(\omega)R_2(\omega^-)\mid^2}n_1(\omega)+(1\leftrightarrow 2)\right)\right\},$$

$$F_{x0} = -\frac{\hbar}{2\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x q_x e^{-2qd}\int_0^{q_x v} d\omega\left(\frac{\mathrm{Im}R_1(\omega)\mathrm{Im}R_2(\omega^-)}{\mid 1-e^{-2qd}R_1(\omega)R_2(\omega^-)\mid^2}n_1(\omega)+(1\leftrightarrow 2)\right).$$

A.I.Volokitin and B.N.J.Persson 2008, 2011

Resonant photon tunneling





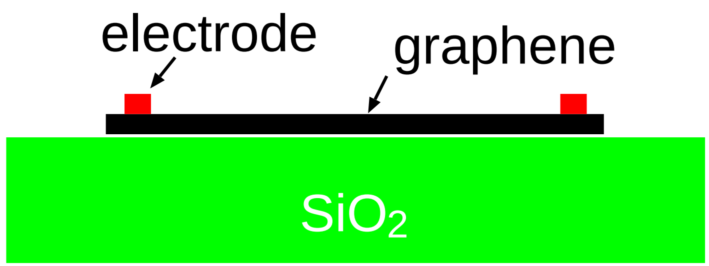
Thermal fluctuations dominate at $v < v_T = k_B T d/\hbar$

Quantum fluctuations dominate at $v > v_T = k_B T d/\hbar$

(a) $vq_x = \omega_1 + \omega_2$

(b) $vq_x = \omega_1 - \omega_2$

Quantum friction



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Quantum Friction

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We investigate the van der Waals friction between graphene and an amorphous SiO_2 substrate. We find that due to this friction the electric current is saturated at a high electric field, in agreement with experiment. The saturation current depends weakly on the temperature, which we attribute to the quantum friction between the graphene carriers and the substrate optical phonons. We calculate also the frictional drag between two graphene sheets caused by van der Waals friction, and find that this drag can induce a voltage high enough to be easily measured experimentally.

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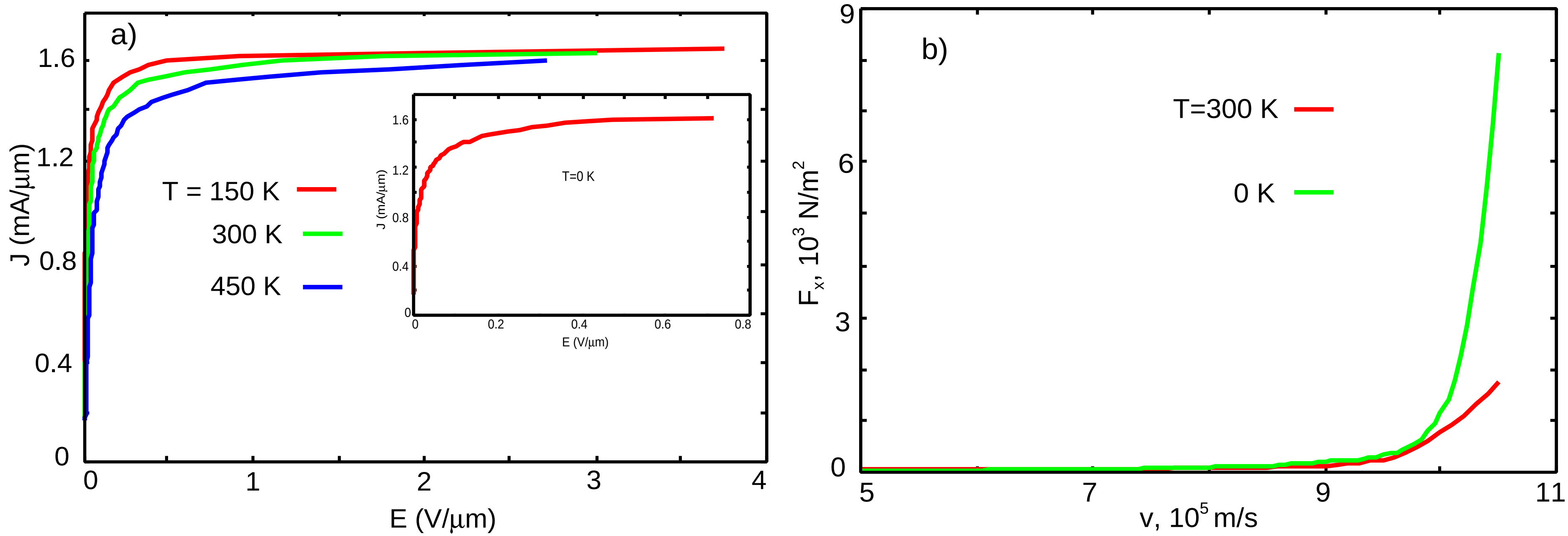
Current density-electric field dependence in graphene on SiO_2

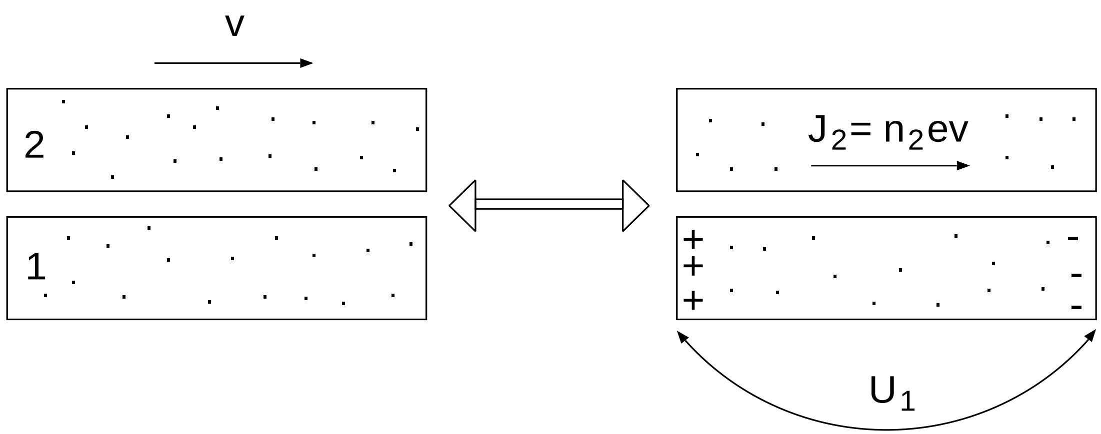


$$F_x(T_d, T_g, v)v = S_z(T_d, T_g, v) + \alpha_{phon}(T_g - T_d)$$

$$v_{sat} \sim \omega_{ph}/k_F \sim 10^6 m/s$$

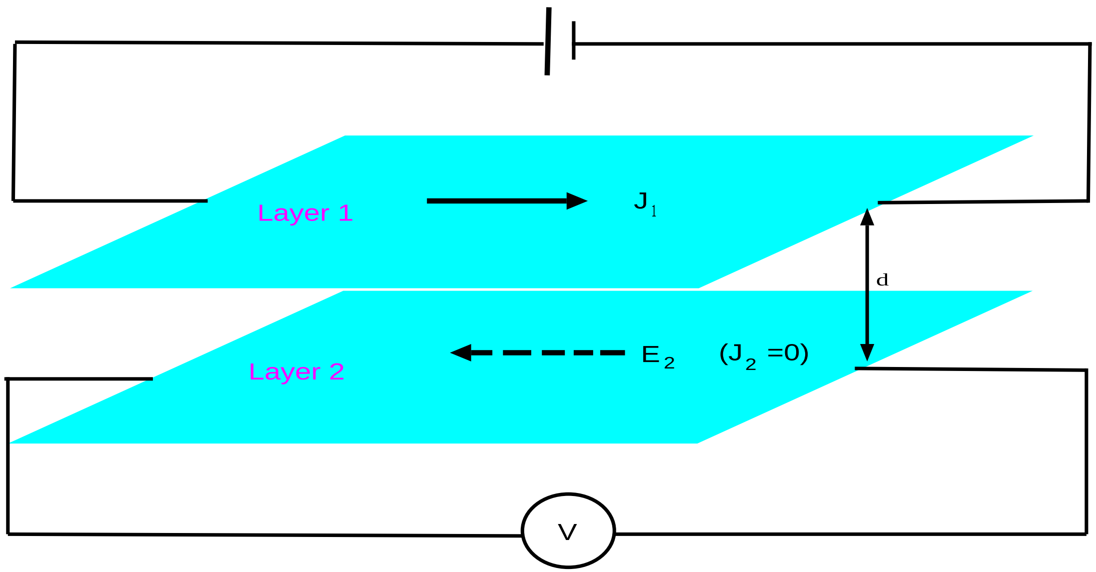
$$J_{sat} = e n_s v_{sat} \sim 1\, mA/\mu m$$

Two ways to study Casimir friction



Left:a metallic block is sliding relative to the metallic substrate with velocity v.
Right: A drift motion of t he free carries of charge (electrons or ions) is induced in the upper medium.

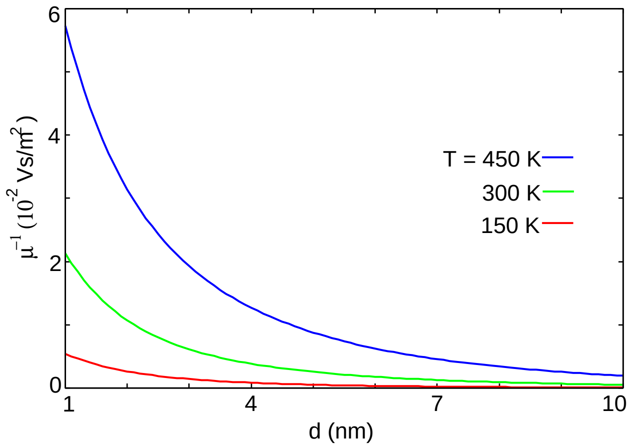
Frictional Drag in 2D-systems



Theory. M. B. Pogrebenskii 1977, P. J. Price 1983
Experiment - Quantum wells T. J. Gramila *et.al* 1991, U. Sivan *et.al* 1992
Experiment - Graphene Sheets S. Kim *et.al* 2012, R.V. Gorbachev *et.al* 2012

Frictional Drag between Graphene Sheets

Low Velocities



At l $v \ll v_F$ induced electric field $E = \rho_D J = \mu^{-1} v$.

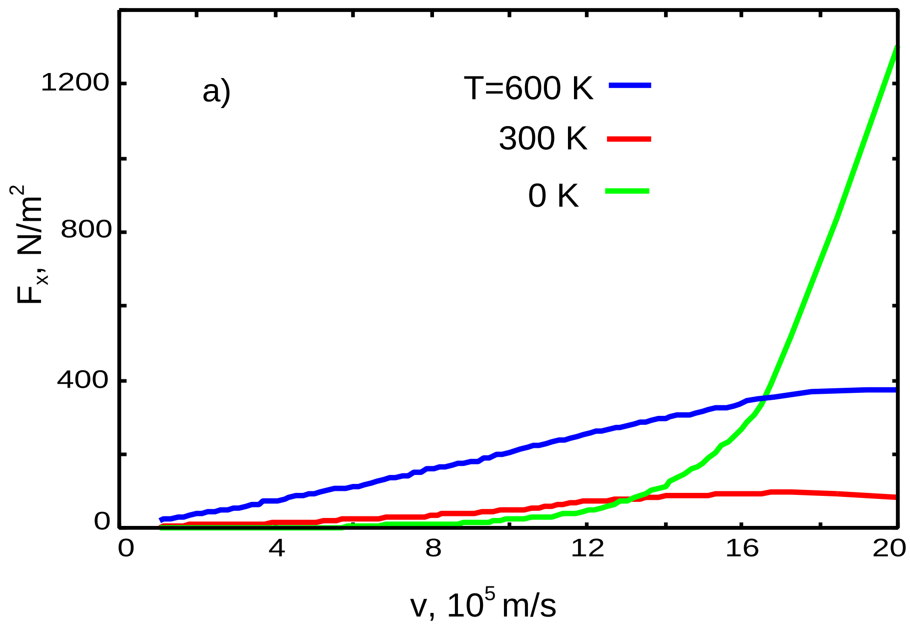
$$\rho_D = \frac{\Gamma}{(ne)^2} = \frac{h}{e^2}\frac{\pi\zeta(3)}{32}\left(\frac{k_B T}{\epsilon_F}\right)^2 \frac{1}{(k_F d)^2}\frac{1}{(k_{TF} d)^2},$$

$$F_{x0} = \frac{\hbar v}{d^4}\frac{15\zeta(5)}{128\pi^2}\left(\frac{v}{v_F}\right)^2 \frac{1}{(k_{TF} d)^2}.$$

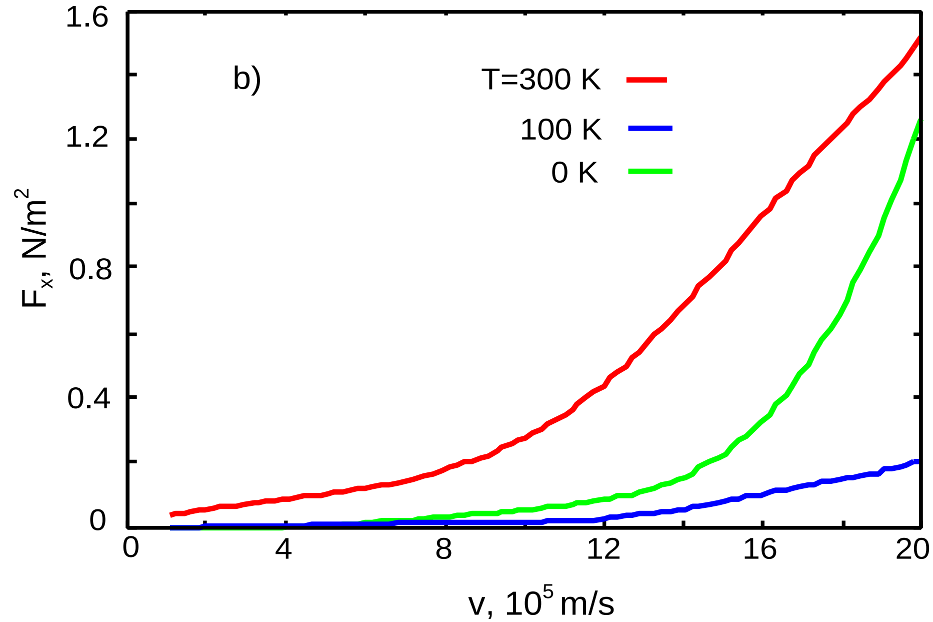
$F_{x0}/F_{xT} \approx (15/8\pi^2)(v/v_T)^2$, where $v_T = \omega_T d \approx 10^5$m/s.

Frictional Drag between Graphene Sheets

High Velocities

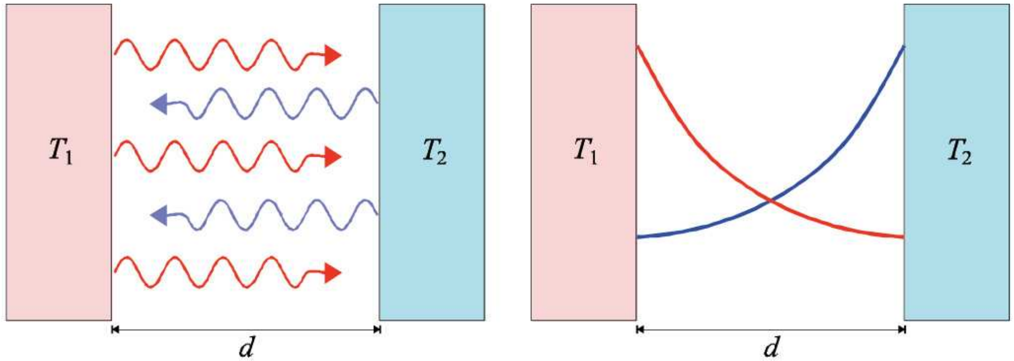


d=1 nm



d=10 nm

Radiative Heat Transfer.



$d \gg \lambda_T = c\hbar/k_B T$

$$S = \frac{\pi^2 k_B^4}{60\hbar^3 c^2}\left(T_1^4 - T_2^4\right),$$

Theory. D.Polder and M. Van Hove 1971

Experiment. Rousseau E. *et al* 2009; Shen S. *et al* 2009

Radiative heat transfer between moving bodies

$$S_z = \frac{\hbar}{\pi^3}\int_0^\infty dq_y \int_0^\infty dq_x e^{-2qd}\Bigg\{\int_0^\infty d\omega\Bigg(-\frac{\omega \mathrm{Im}R_1(\omega)\mathrm{Im}R_2(\omega^+)}{\mid 1-e^{-2qd}R_1(\omega)R_2(\omega^+)\mid^2}\times$$

$$[n_1(\omega)-n_2(\omega^+)] + \frac{\omega^+ \mathrm{Im}R_d(\omega^+)\mathrm{Im}R_g(\omega)}{\mid 1-e^{-2qd}R_1(\omega^+)R_2(\omega)\mid^2}[n_2(\omega)-n_1(\omega^+)]\Bigg)+$$

$$\int_0^{q_x v} d\omega \frac{\omega \mathrm{Im}R_1(\omega)\mathrm{Im}R_2(\omega^-)}{\mid 1-e^{-2qd}R_1(\omega)R_2(\omega^-)\mid^2}[n_2(\omega^-)-n_1(\omega)]\Bigg\},$$

$$F_x(T_d,T_g)v = S_z(T_d,T_g) + \alpha_{ph}(T_g - T_d)$$

A.I.Volokitin and B.N.J.Persson 2008, 2011

Friction generates Heat Transfer

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **83**, 241407(R) (2011)

Near-field radiative heat transfer between closely spaced graphene and amorphous SiO_2

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We study the near-field radiative energy transfer between graphene and an amorphous SiO_2 substrate. In comparison with the existing theories of near-field radiative heat transfer our theory takes into account that the free carriers in graphene are moving relative to the substrate with a drift velocity v. In this case the heat flux is determined by both thermal and quantum fluctuations. We find that quantum fluctuations give an important contribution to the radiative energy transfer for low temperatures and high electric field (large drift velocities). For nonsuspended graphene the near-field radiative energy transfer gives a significant contribution to the heat transfer in addition to the contribution from phononic coupling. For suspended graphene (large separation) the corresponding radiative energy transfer coefficient at a nanoscale gap is ∼3 orders of magnitude larger than radiative heat transfer coefficient of the blackbody radiation limit.

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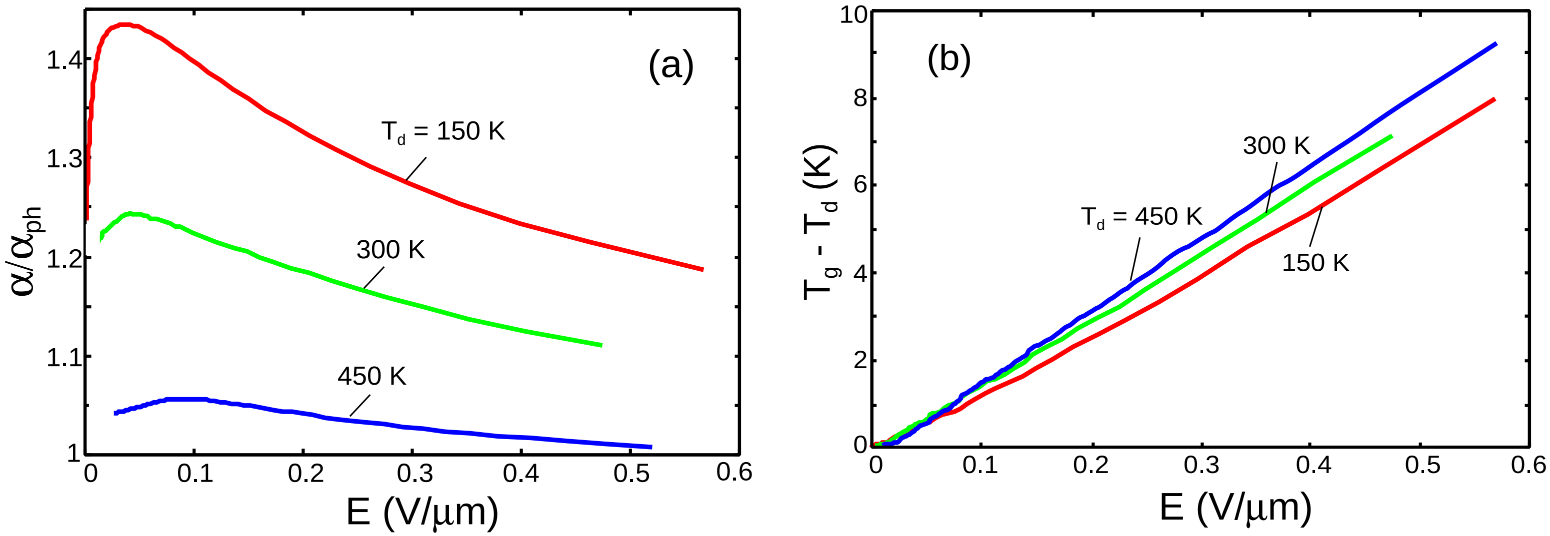
$$F_x(T_d, T_g, v)v = S_z(T_d, T_g, v) + \alpha_{phon}(T_g - T_d)$$

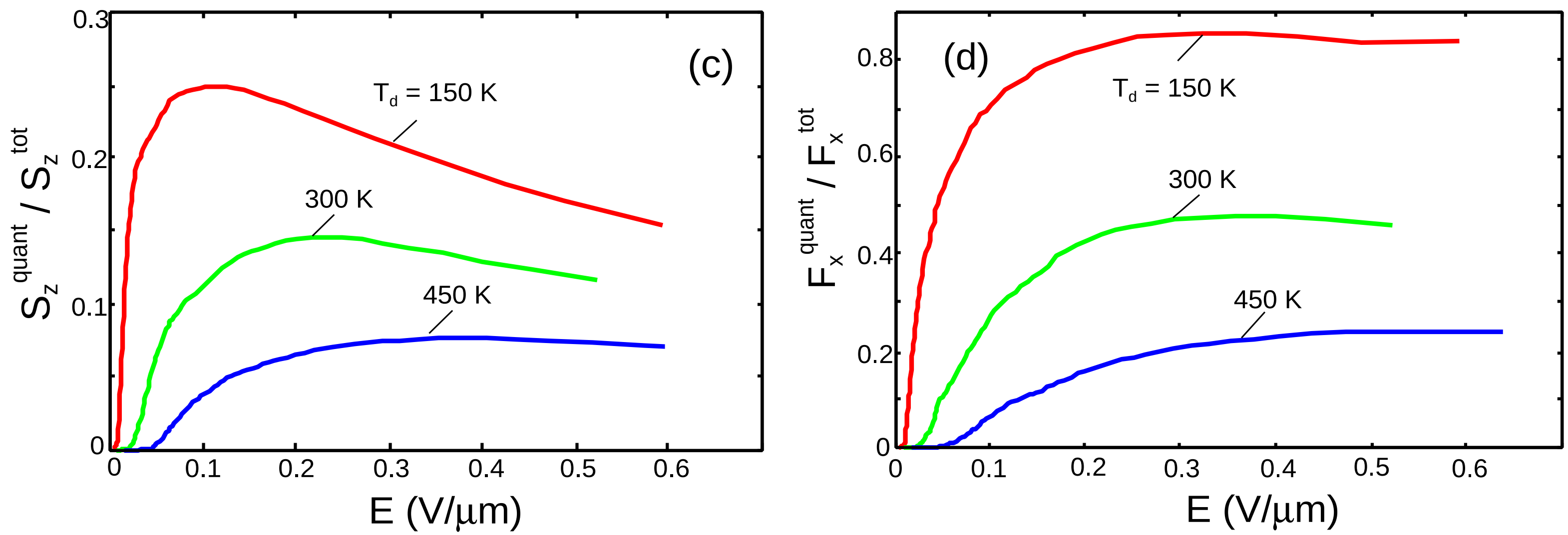
Phononic and Radiative Heat Transfer



$$n = 10^{16}\, m^{-2},\; d = 0.35\, nm,\; \alpha_{ph} = 1.0 \times 10^{8}\, W\, m^{-2}\, K^{-1}$$

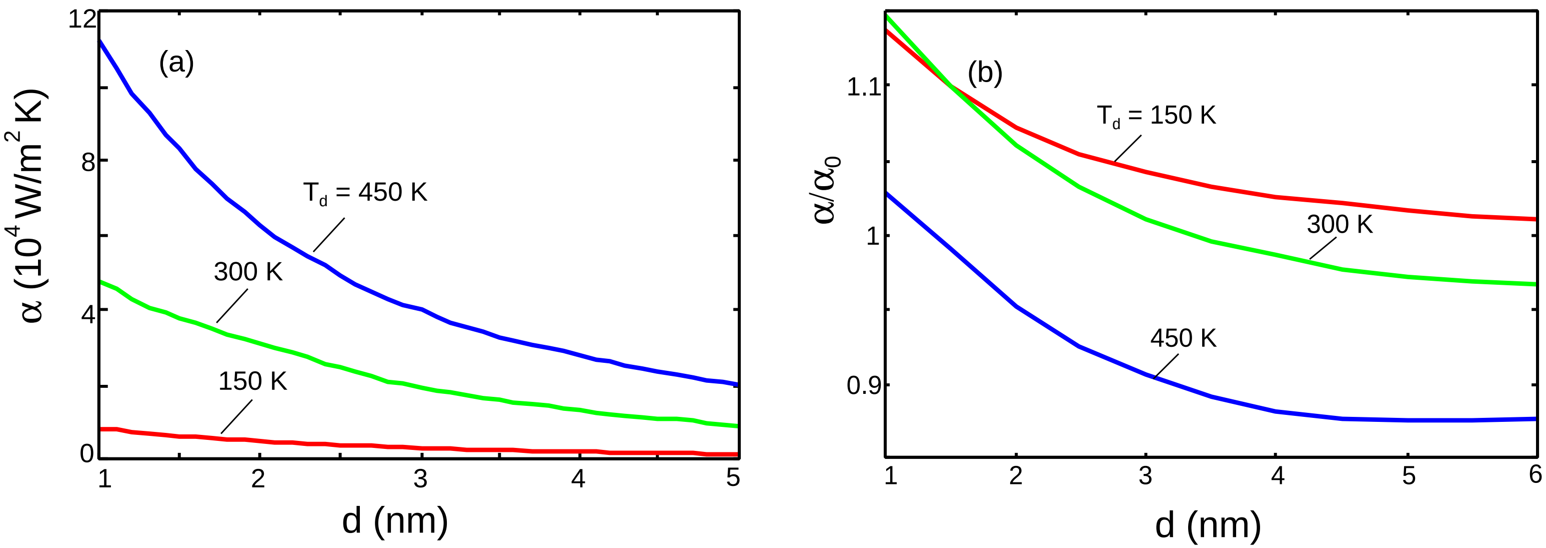
$$\alpha = \frac{S_z(T_d, T_g) + \alpha_{ph}\Delta T}{\Delta T} \approx \frac{(\alpha_{ph} + S'_{z0})F_{t0}v - S_{z0}F'_{t0}v}{F_{t0}v - S_{z0}}$$

Quantum and Thermal Energy Transfer



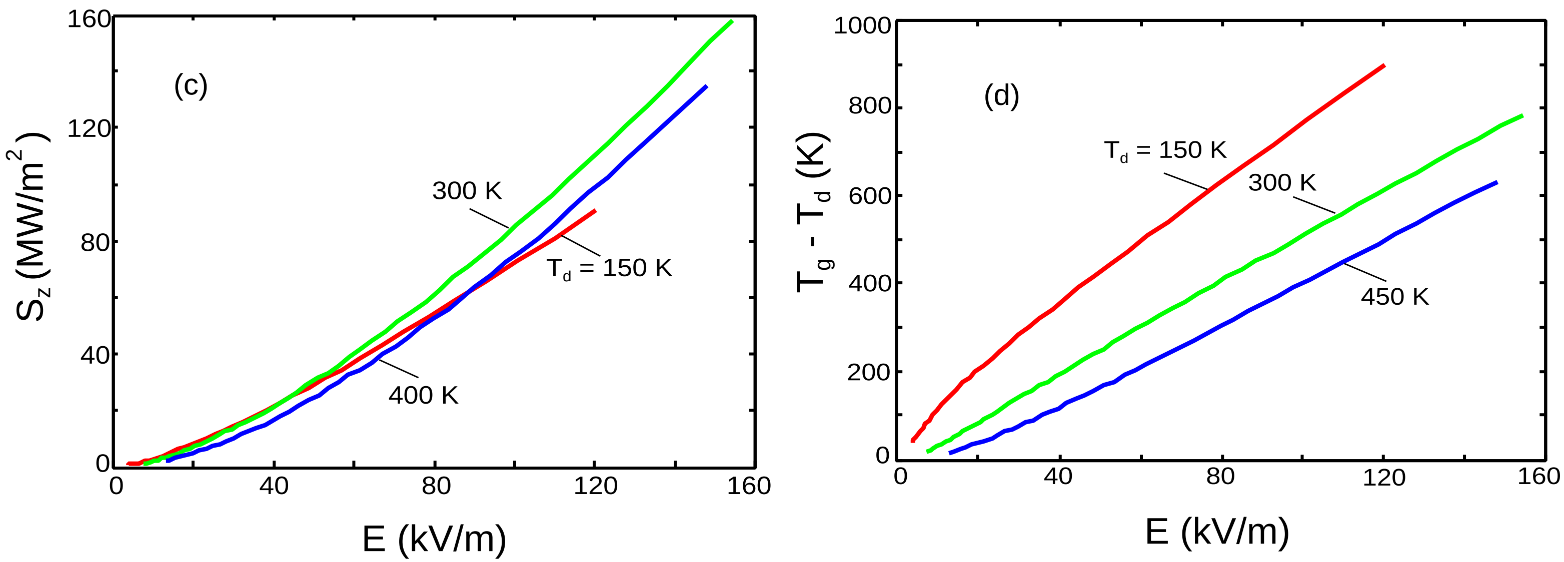
$$n = 10^{16}\, m^{-2},\, d = 0.35\, nm$$

Radiative Energy Transfer



$$\frac{\alpha}{\alpha_0} = \frac{F_{fr}(T,v)v}{F_{fr}(T,V)v - S_z(T,v)}$$

Dependence of Heat Flux on Electric Field



$$d = 1\,nm$$

Conclusion

- Electric current in graphene sheet can produce measurable change of Casimir force between graphene sheets
- The thermal Casimir force as well as the Casimir friction are strongly enhanced in the case of resonant photon tunneling
- Casimir friction and its limiting case - quantum friction can be studied in frictional drag experiment between grapheme sheets and by measuring electric current-electric field dependence for graphene field-effect transistor
- Quantum fluctuations can generates radiative energy transfer comparable with radiative heat transfer due to thermal fluctuations

Thank you for your attention!