Casimir Friction

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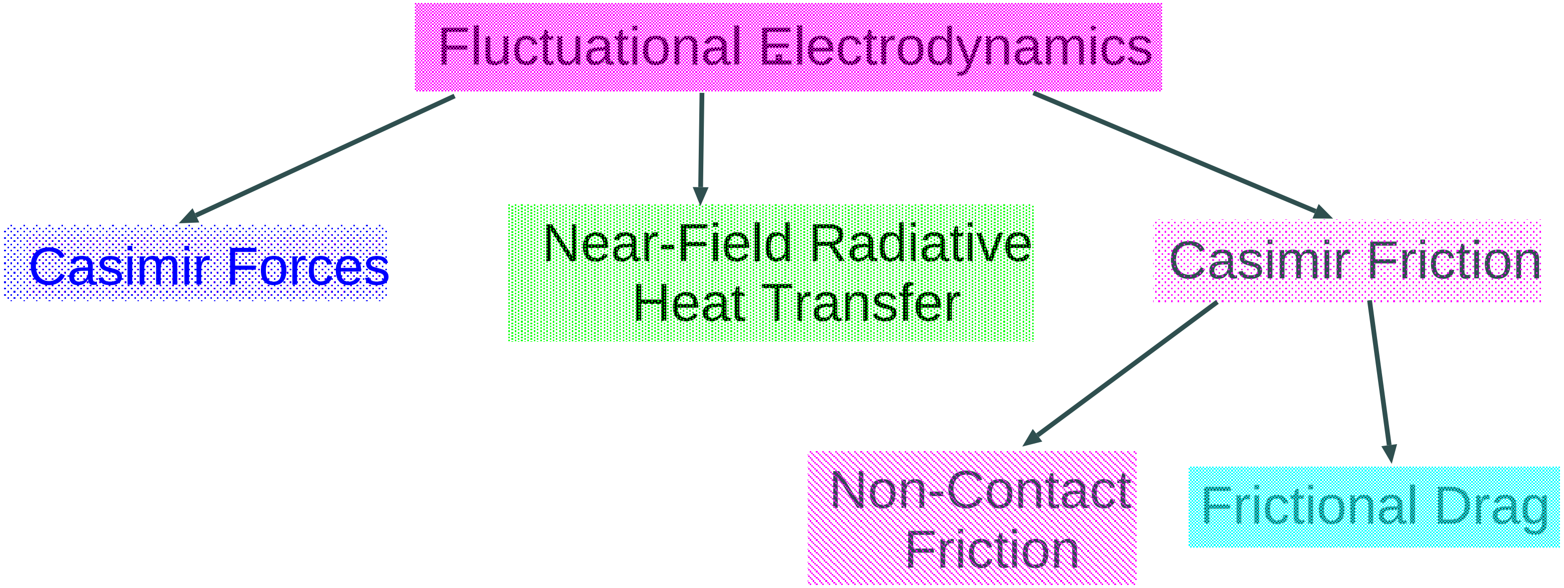
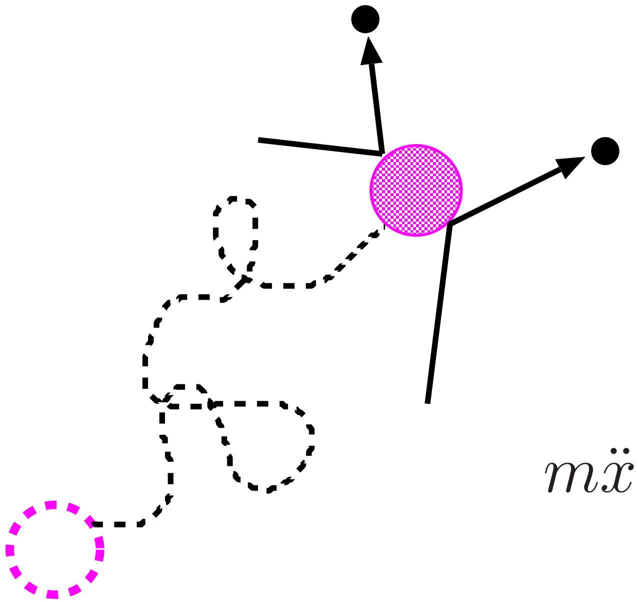
Research Center Jülich and Samara State Technical University



Fluctuation-Dissipation Theorem

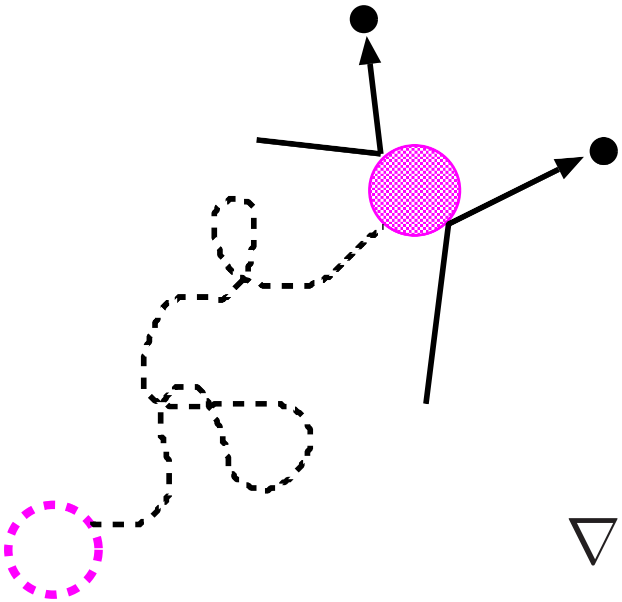


$$m\ddot{x} + m\omega_0^2 x + \Gamma\dot{x} = F(t)$$

$$\mathbf{\Gamma} = (k_B T)^{-1}\mathrm{Re}\int_0^\infty dt\left\langle \hat{\mathbf{F}}(t)\hat{\mathbf{F}}(0)\right\rangle$$

- The detection of single spins by MRFM for: (a) 3D atomic imaging (b) quantum computation
- Measurements of gravitation force at short length scale
- Measurements of Casimir forces

Rytov's Theory



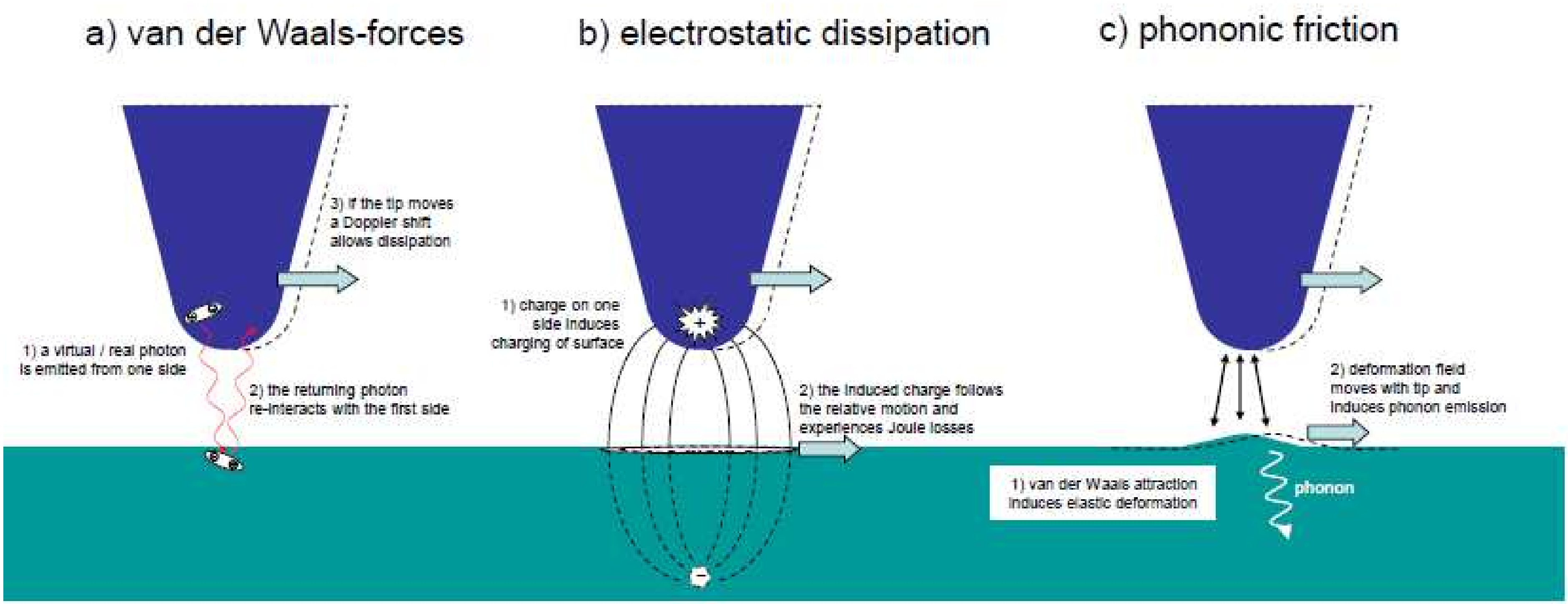
$$\nabla \times \mathbf{E} = i\frac{\omega}{c}\mathbf{B}$$

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

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

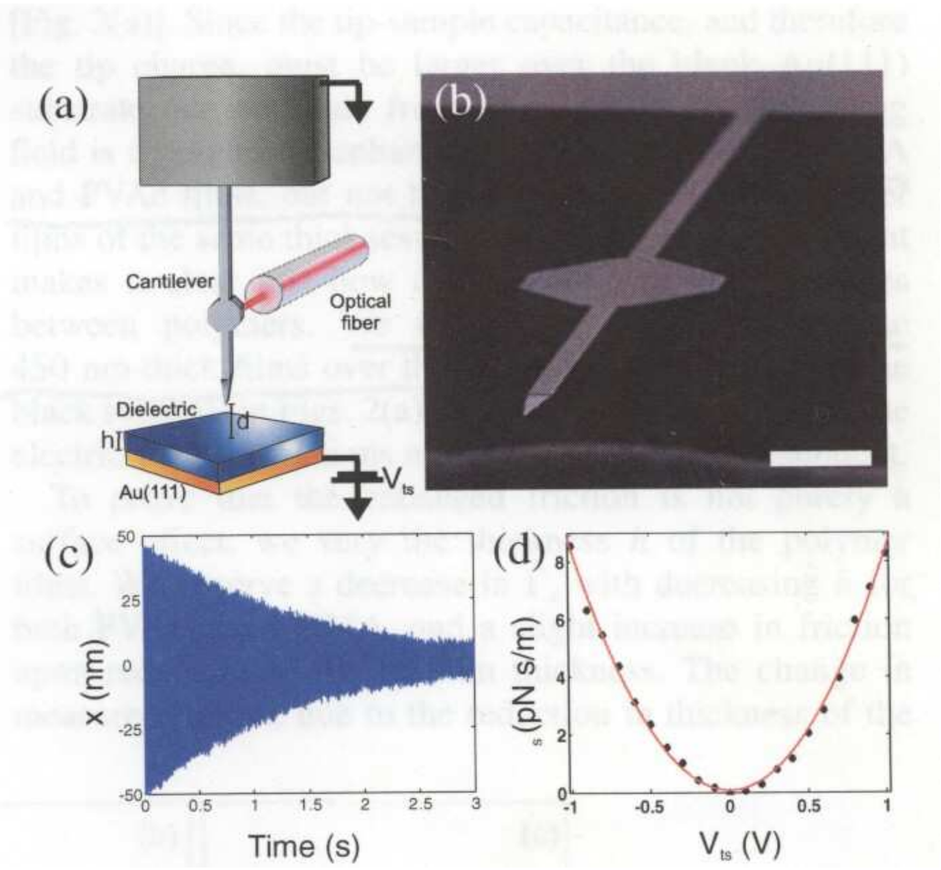
$$n(\omega) = [e^{\hbar\omega/k_B T} - 1]^{-1}$$

Origin of Non-Contact Friction



A.I. Volokitin and B.N.J. Persson, *Rev.Mod.Phys.*, **79**, 1291 (2007)

Non-contact Friction



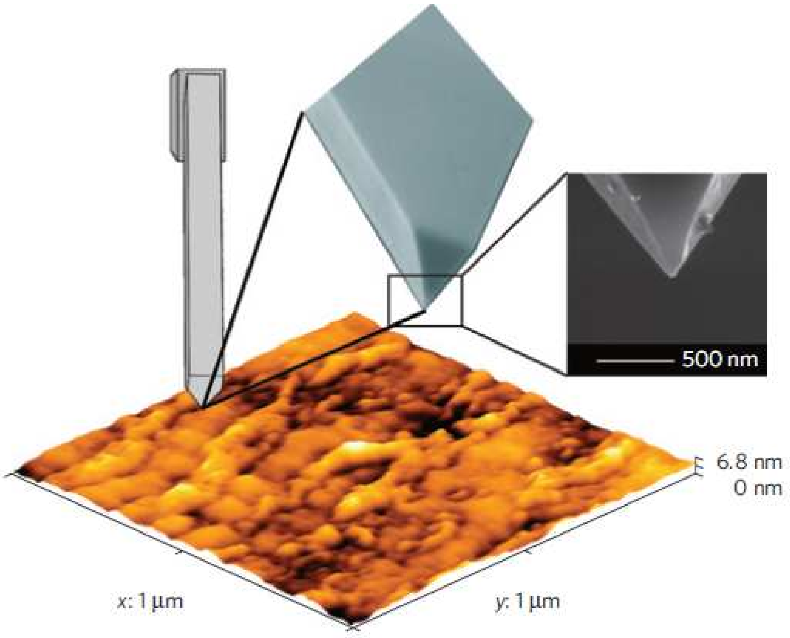
Experiment: Stipe B.C. *et.al* *PRL*, **87**, 096801 (2001)

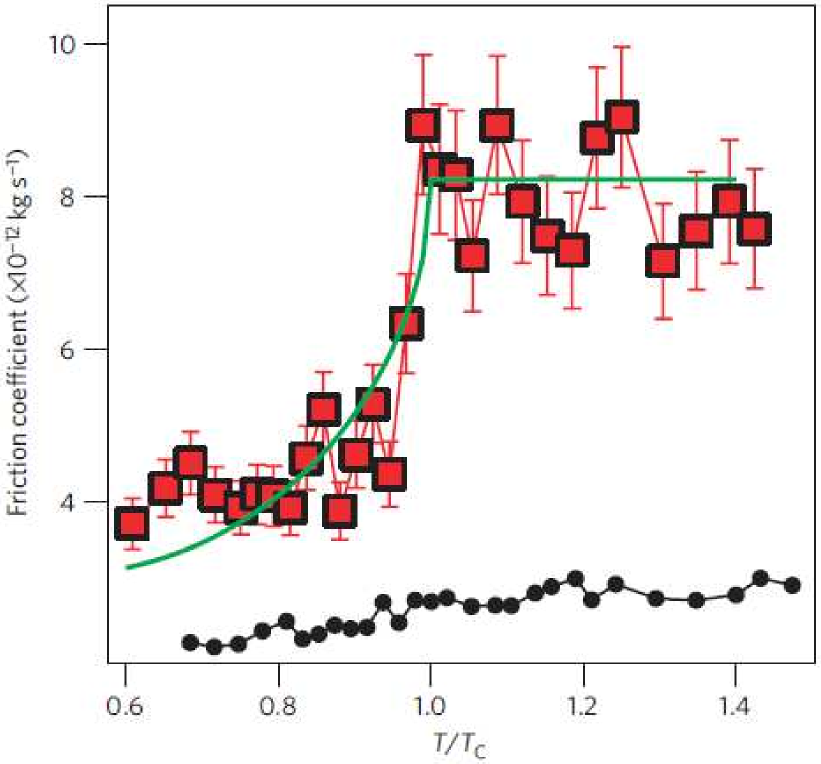
$F_{friction} = \Gamma v$, $\Gamma \sim 10^{-13} - 10^{-12}\mathrm{kg/s}$ at $d \sim 1 - 100$ nm.

$\Gamma \approx d^{-n}$ with $n = 1.3 \pm 0.3$ and $n = 0.5 \pm 0.3$, $\Gamma \sim V^2$

Theory: A.I. Volokitin and B.N.J. Persson, *PRB*, **73**, 165423 (2006)

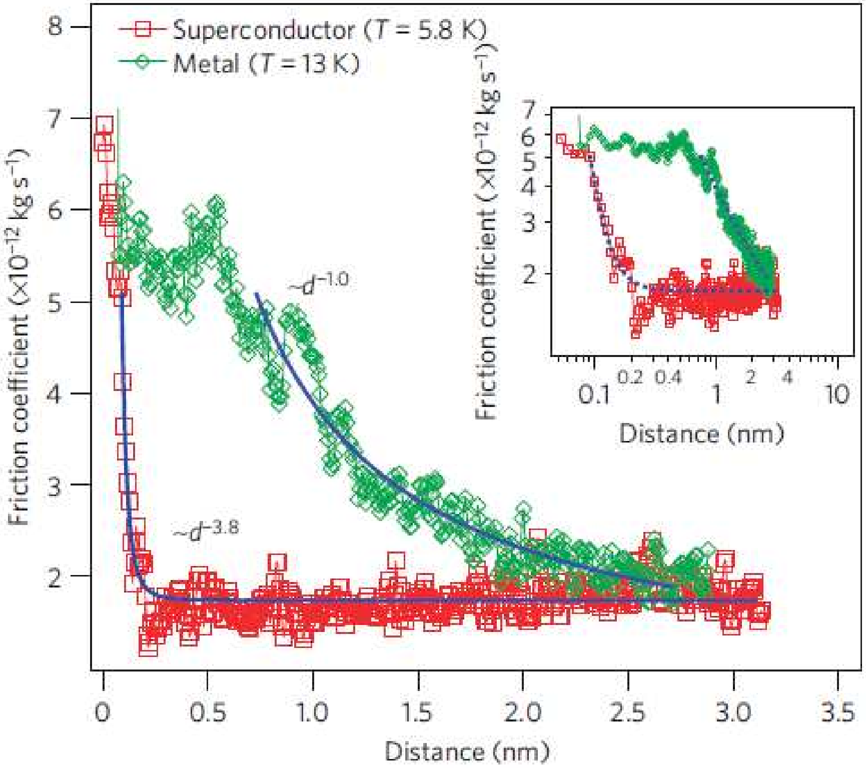
Electronic versus Phononic Friction

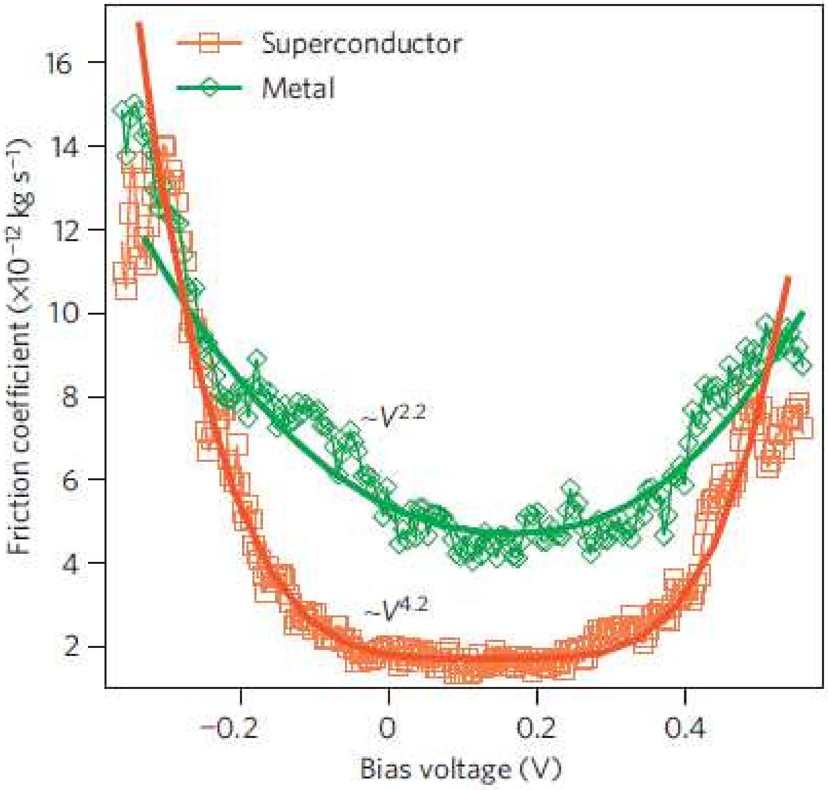




Experiment: M. Kisiel *et.al* *Nat. Materials*, **10**, 119 (2011)

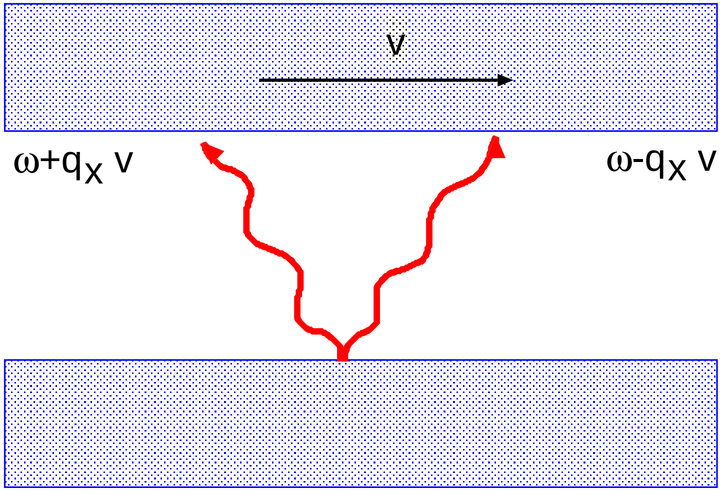
Electronic versus Phononic Friction





Theory: A.I. Volokitin and B.N.J. Persson, *PRB*, **73**, 165423 (2006)

Casimir Friction



Pendry J.B. *JPCM* **9**, 10301 (1997)
A.I. Volokitin and B.N.J. Persson, *JPCM*, **11**, 345 (1999)

Frictional Stress

$$\sigma_{xz} = \int_0^\infty \frac{d\omega}{2\pi} \sum_{i=(s,p)} \int \frac{d^2q}{(2\pi)^2} \hbar q_x \mathrm{sgn}(\omega') \left(n_2(\omega') - n_1(\omega)\right) \Gamma_i(\omega, \mathbf{q}),$$

$$\Gamma_i(\omega, \mathbf{q}) = \frac{1}{2k_z \mid 1 - e^{2ik_z d} R_{1i}(\omega) R_{2i}(\omega') \mid^2}$$

$$\times \Big[(k_z + k_z^*)(1- \mid R_{1i}(\omega) \mid^2)(1- \mid R_{2i}(\omega' \mid^2)$$

$$+4(k_z - k_z^*) \mathrm{Im} R_{1i}(\omega) \mathrm{Im} R_{2i}(\omega') e^{-2d \mathrm{Im} k_z} \Big]$$

$$\omega' = \omega - q_x v, \; n_i(\omega) = [\exp(\hbar\omega / k_B T_i) - 1]^{-1}, \; k_z = \sqrt{(\omega/c)^2 - q^2}$$

A.I. Volokitin and B.N.J. Persson, *JPCM*, **11**, 345 (1999)

Small Velocities

$$v \ll v_T = k_B T d/\hbar,\ d \ll \lambda_T = c\hbar/k_B T,$$

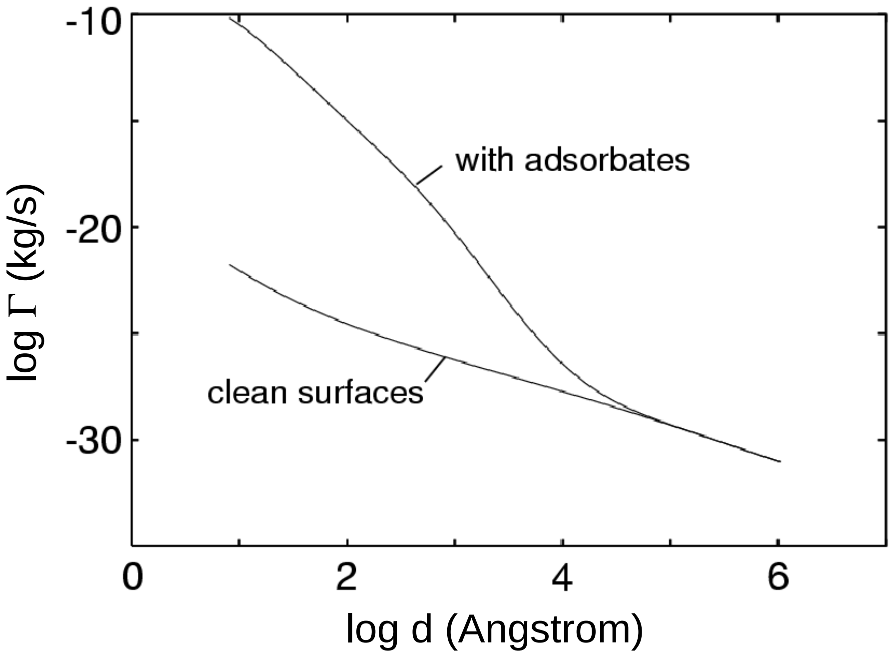
$$\sigma_{xz} = \gamma v,$$

$$\gamma = \frac{\hbar^2}{8\pi^3 k_B T}\int_0^\infty \frac{d\omega}{\sinh(\hbar\omega/k_B T)} \sum_{i=p,s} \int d^2q q_x^2 e^{-2qd}$$

$$\times \frac{\mathrm{Im}R_{1i}(\omega)\mathrm{Im}R_{2i}(\omega)}{\mid 1 - e^{-2qd}R_{1i}(\omega)R_{2i}(\omega) \mid^2},$$

$$\Gamma = \int dS\gamma(z(x,y))$$

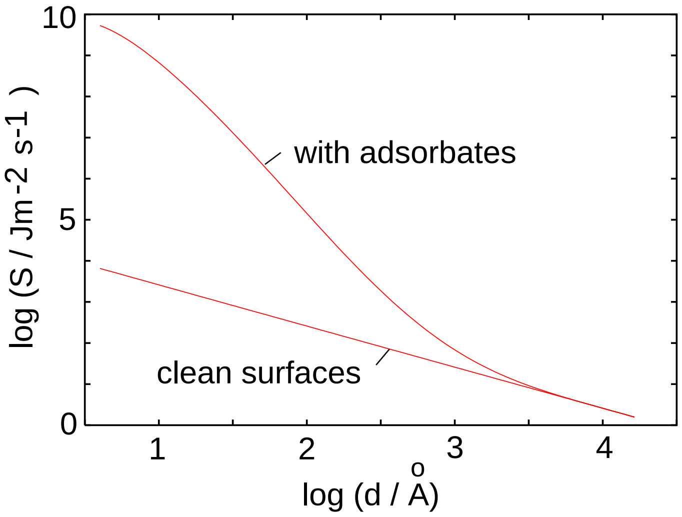
Adsorbate enhancement of Casimir friction



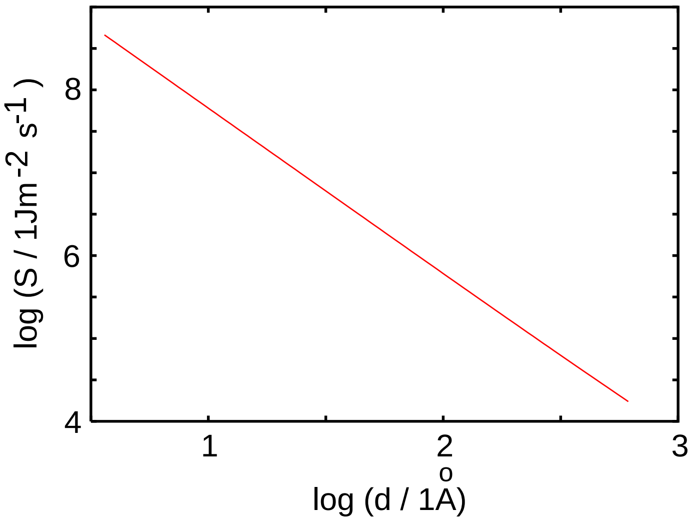
Cs/Cu(100)

A.I. Volokitin and B.N.J. Persson, *PRB*, **73**, 165423 (2006)

Radiative Heat Transfer.



K/Cu(001)

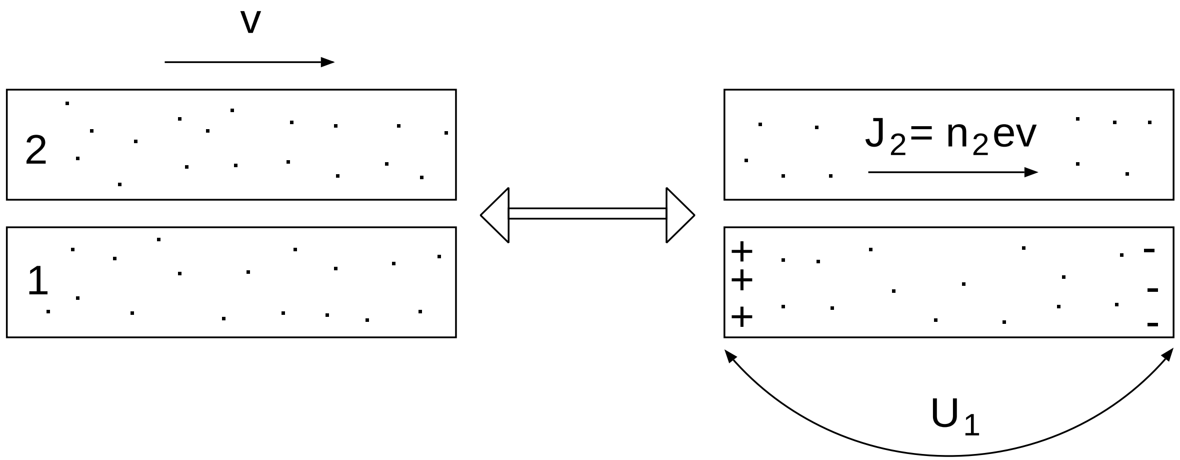


SiC

$$T_1 = 273 \text{ K}, T_2 = 0 \text{ K}$$

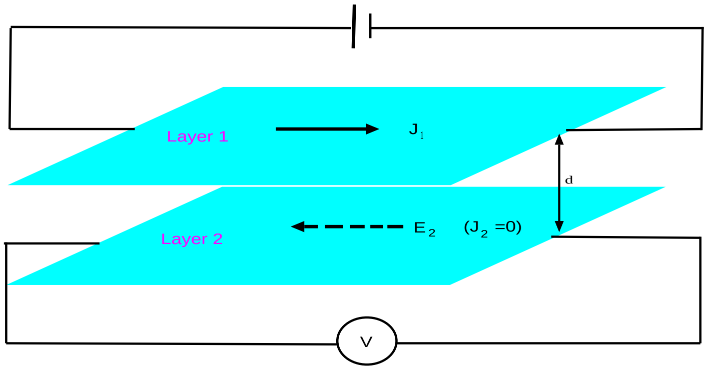
Volokitin A.I. and Persson B.N.J. *PRB*, **69**, 045417 (2004)

Two ways to study Casimir friction



Left:Upper block is sliding relative to block at the bottom
Right: The current is induced in the upper block .

Frictional Drag in 2D-systems



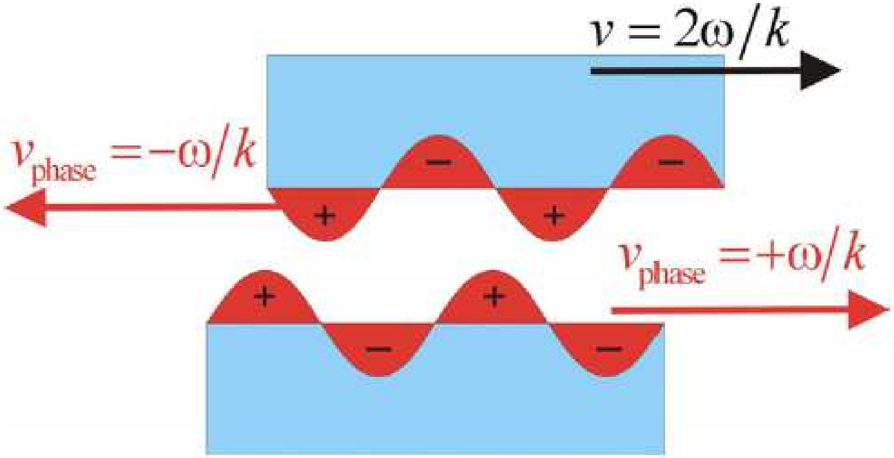
Theory - Coulomb Drag. M. B. Pogrebenskii *Sov.Phys.Second.*,**11** (1977) 372, P. J. Price *Physica B+C*,**117** (1983) 750

Experiment - Quantum wells T. J. Gramila *et.al* *PRL*,**66** (1991) 1216, U. Sivan *et.al* *PRL*,**68** (1992) 1196

Experiment - Graphene Sheets S. Kim *et.al* *PRB*,**83** (2011) 161401, R.V. Gorbachev *et.al* *Nat.Phys.*,**8** (2012) 896

Theory - Casimir Friction. A.I. Volokitin and B.N.J. Persson, *J.Phys.:Condens.Matter*, **13**, 859 (2001); *ibid*, *EPL* **103** 24002 (2013)

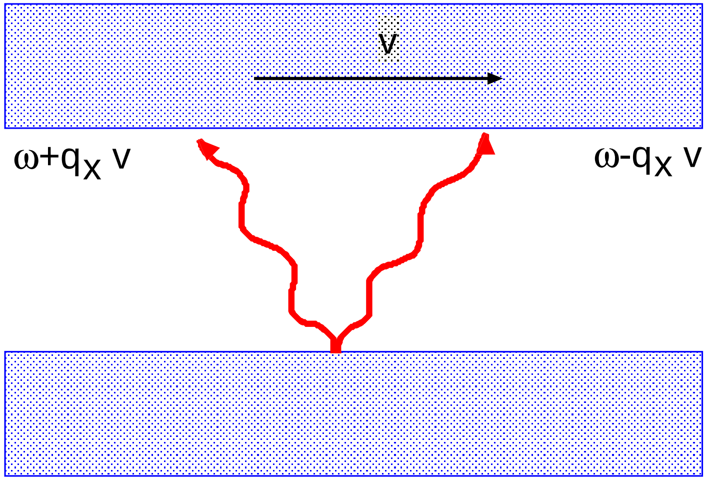
Quantum Friction

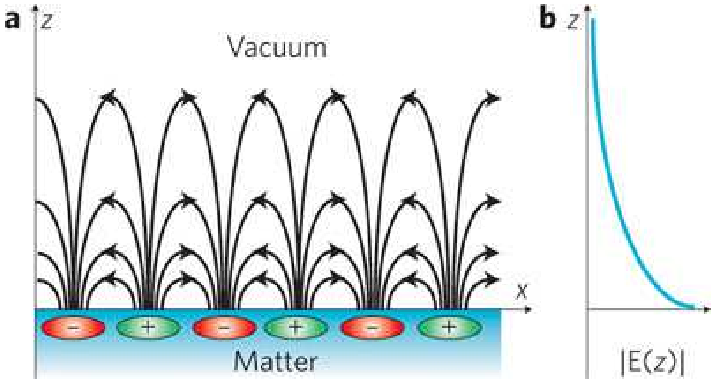


$q_x v = \omega_1 + \omega_2$

Pendry J.B. *JPCM* **9**, 10301 (1997)
Volokitin A.I. and Persson B.N.J. *JPCM*, **11**, 345 (1999)
Volokitin A.I. and Persson B.N.J. *PRB*, **78**, 155437 (2008)

Anomalous Doppler Effect





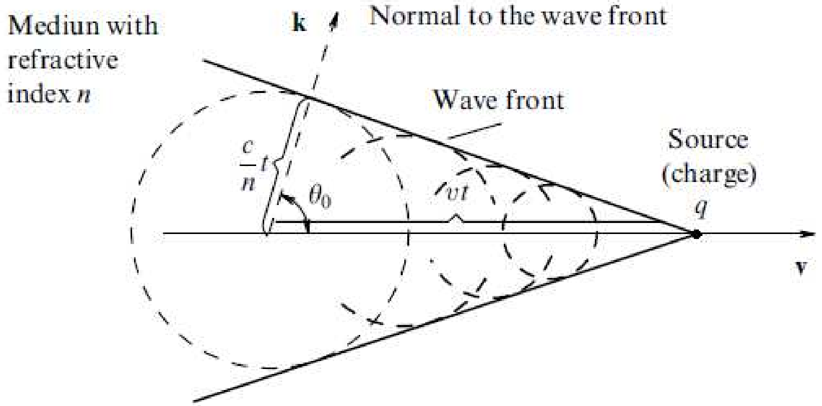
Normal Doppler effect $\omega' = \omega - q_x v > 0$

Anomalous Doppler effect $\omega' = \omega - q_x v$<0

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

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

Classical Vavilov-Cherenkov Radiation

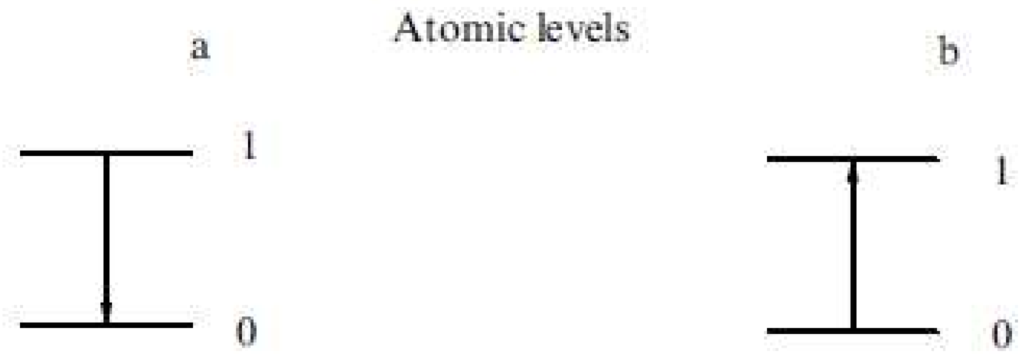


Cherenkov P.A. *Dokl. Akad. Nauk SSSR*, **2**, 451 (1934)

Resonant condition: $q_x v = cq/n > v_0 = cq_x/n$

Threshold velocity: $v > c/n$

Quantum Vavilov-Cherenkov Radiation

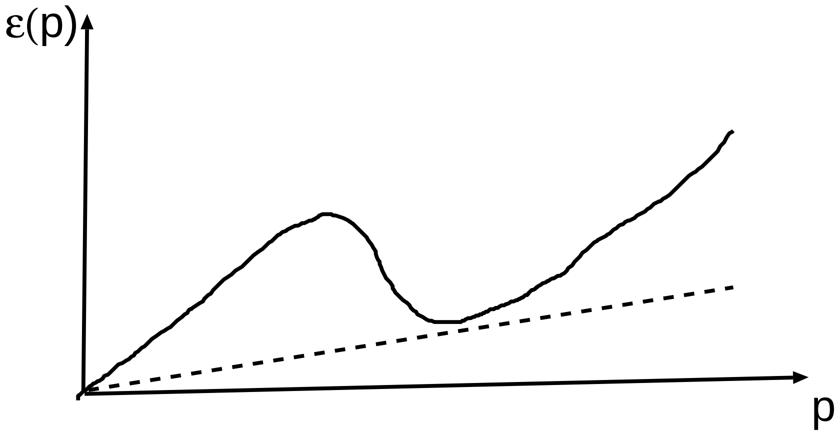


Frank M.I. *J.Phys.USSR*, **7**, 49 (1943)

Doppler effect (a): $\omega_{ph} = \omega_0 - g_x v > 0$

Doppler effect (b): $\omega_0 - g_x v < 0; \omega_{ph} = q_x v - \omega_0$

The Landau criterion for the critical velocity of a superfluid



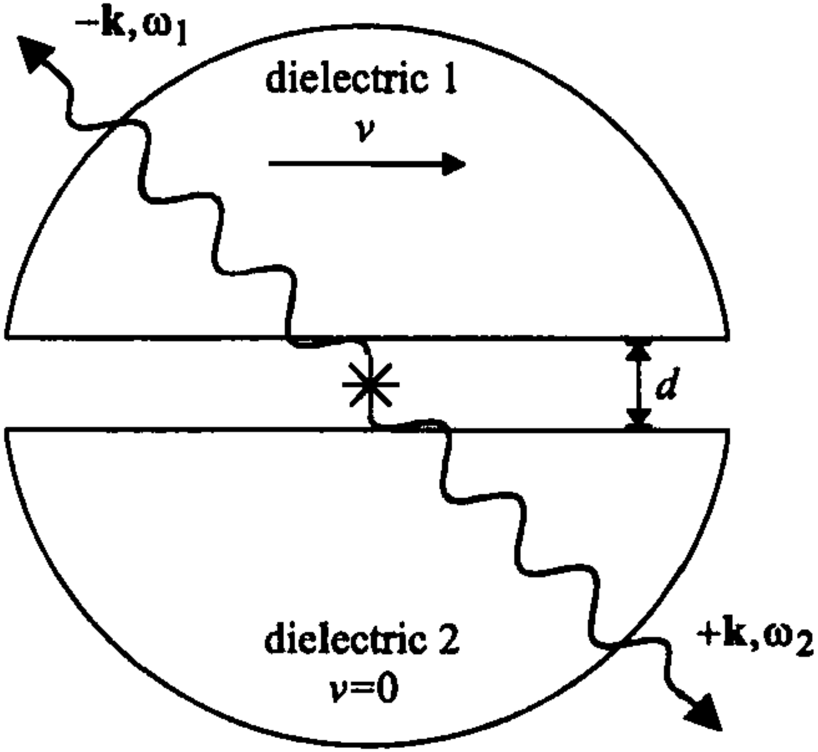
$$E = \frac{Mv^2}{2} + \varepsilon(p) - pv$$

$$\varepsilon(p) - pv < 0$$

$$v > v_c = min\left(\frac{\varepsilon(p)}{p}\right)$$

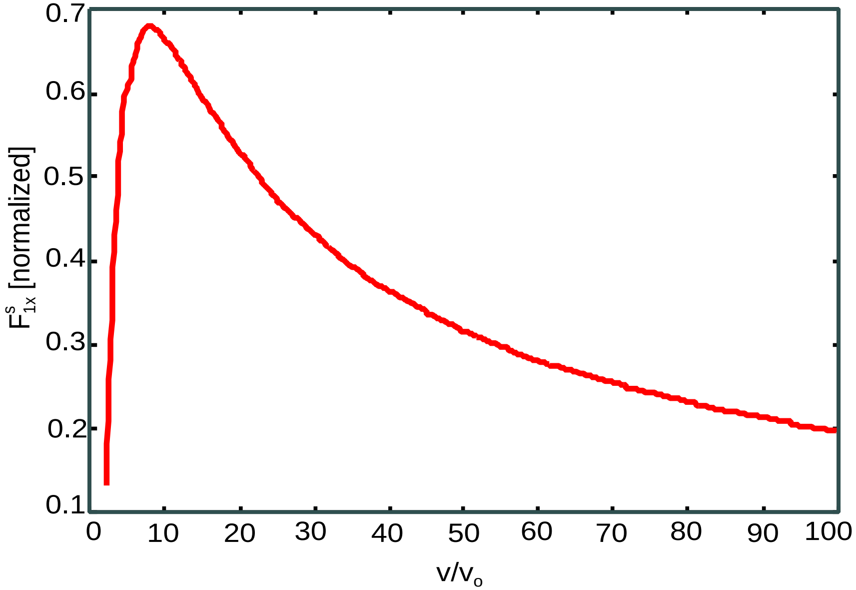
Landau L.D., *Zh. Eksp. Teor. Fiz.* 11, 592 (1941)

Radiation at shearing two transparent plates



Pendry J.B. *JMO* **45**, 2389 (1998).
Magreby F.M., Golestian R., and Kardar M., *PRA* **88**, 042509 (2013).
Volokitin A.I. and Persson B.N.J. *PRB* **93**, 035407 (2016).

Non-Relativistic Theory



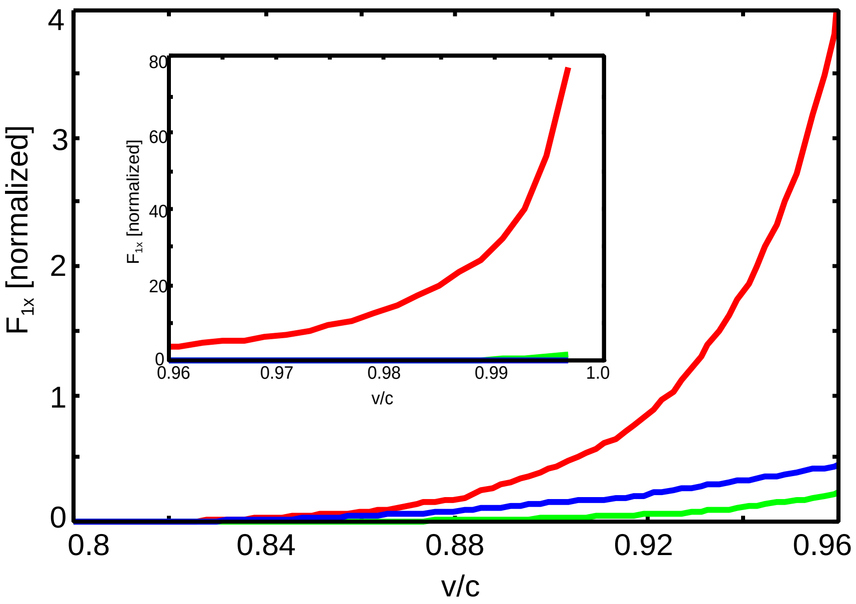
Resonant condition: $\omega_{ph} = q_x v - cq/n = cq/n, v > v_0 = 2c/n$

$$F^s_{1x} = \frac{\hbar v_0}{\pi^3 d^4} F^s_{1x}\text{[normalized]}$$

$$R_s = \frac{\sqrt{(\omega/c)^2 - q^2} - \sqrt{(n\omega/c)^2 - q^2}}{\sqrt{(\omega/c)^2 - q^2} + \sqrt{(n\omega/c)^2 - q^2}}$$

Magreby F.M., Golestian R., and Kardar M., *PRA* **88**, 042509 (2013).
Volokitin A.I. and Persson B.N.J. *PRB* **93**, 035407 (2016).

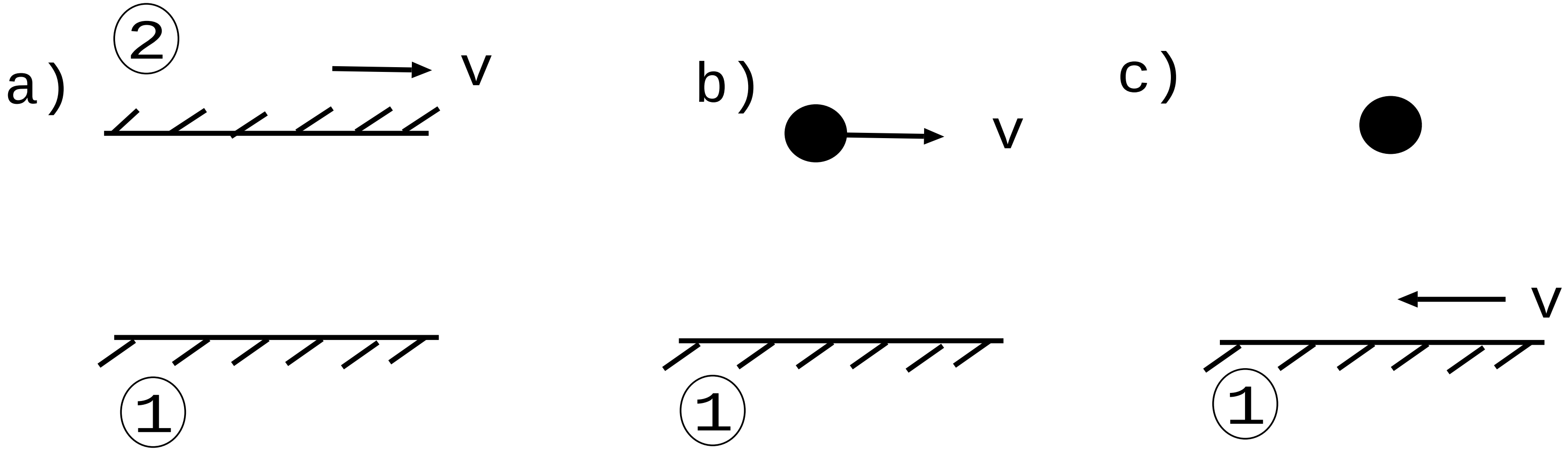
Relativistic Theory



$$\omega_{ph} = q_x v - cq'/\gamma n = cq/n, v > v_0 = 2cn/(n^2 + 1)$$

Volokitin A.I. and Persson B.N.J. *PRB* **78**, 155437 (2008)
Volokitin A.I. and Persson B.N.J. *PRB* **93**, 035407 (2016).

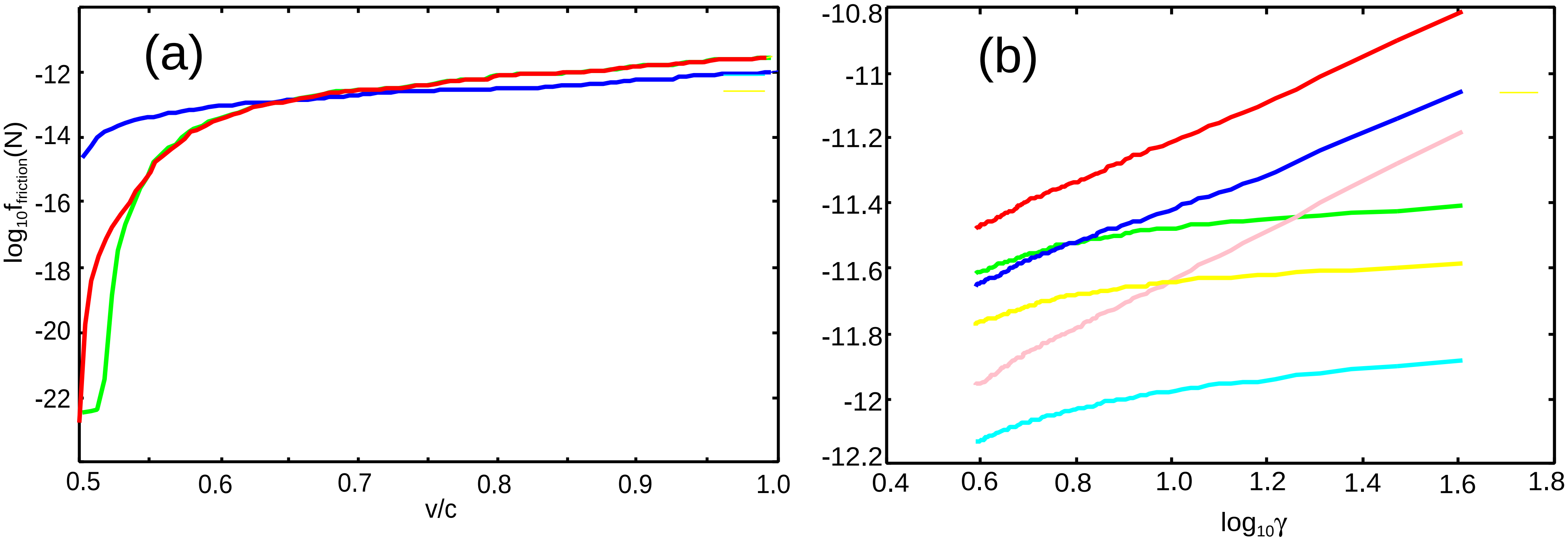
Radiation From Moving Neutral Particle



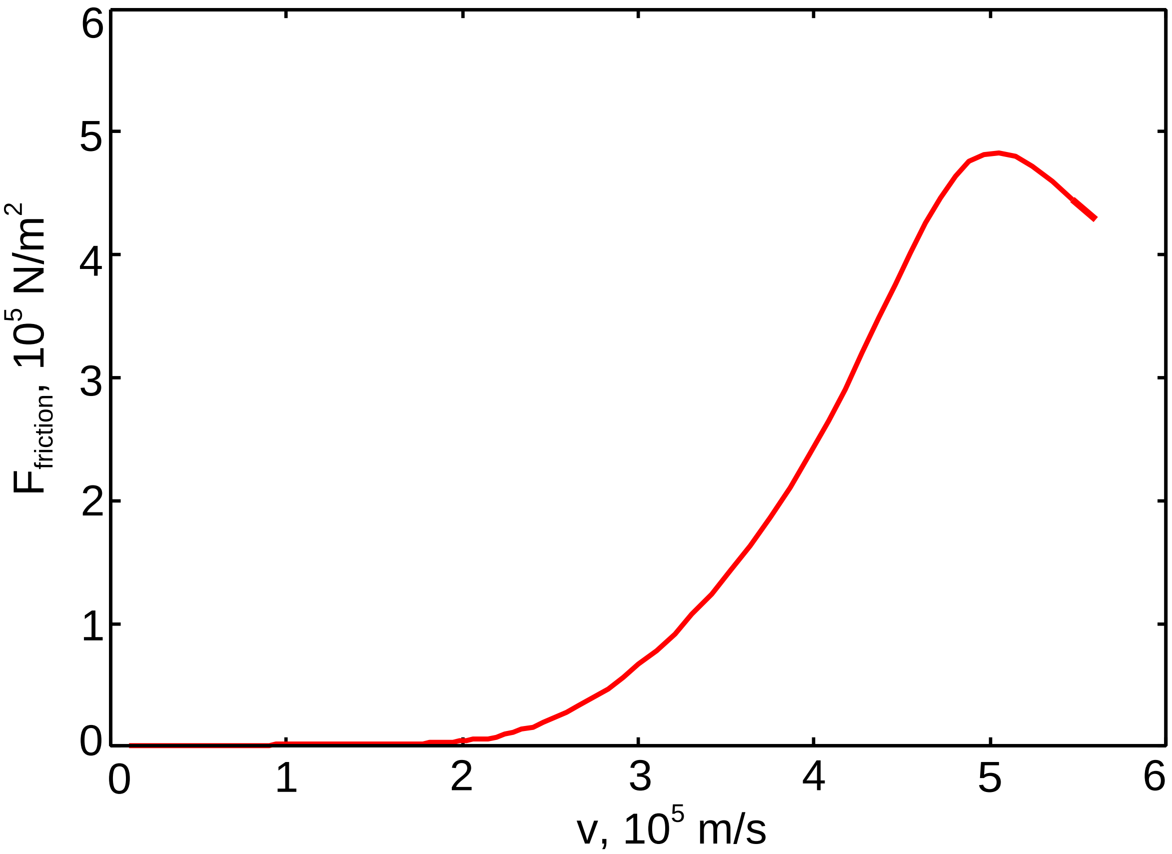
$$\omega_{ph} = q_x v - \omega_0/\gamma = cq/n, v > v_0 = c/n$$

Pieplow G. and Henkel C., *JPCM* **27**, 035407 (2015).
Volokitin A.I. and Persson B.N.J. arxiv.org/abs/1512.04366 (2016).

Quantum Friction for Particle



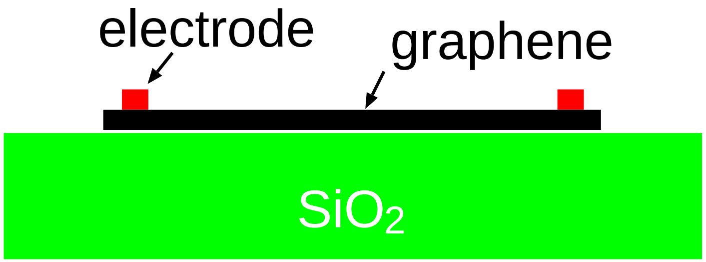
Polar Dielectric SiO_2



Resonant condition: $\omega_{ph} = q_x v - \omega_0 = \omega_0$

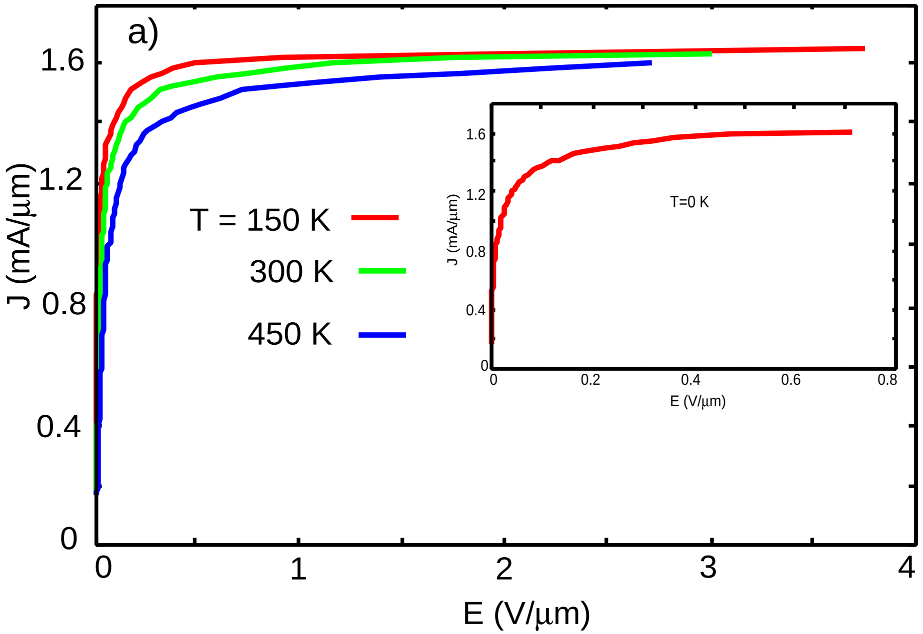
Threshold velocity: $v > 2\omega_0 / q_{xmax} \sim 2\omega_0 d \sim 2 \cdot 10^5$ m/s

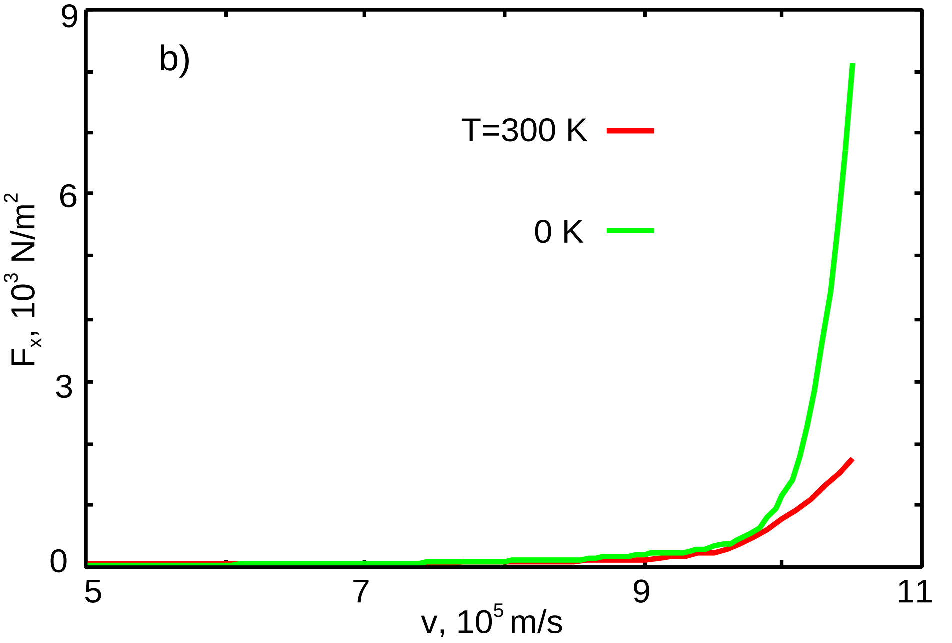
Graphene on SiO$_2$



Threshold velocity: $v > v_F + \omega_0/q_{xmax} \approx v_F \sim 10^6$m/s
Resonant condition: $\omega_{ph} = q_x v - v_F q = \omega_0$
Experiment:Freitag M.,Steiner M., Martin Y., Perebeinos V., Chen Z., Tsang J.C., and Avouris P., *Nano Lett.* **9**, 1883 (2009).
Theory:Volokitin A.I. and Persson B.N.J. *PRL* **106** 094502 (2011)

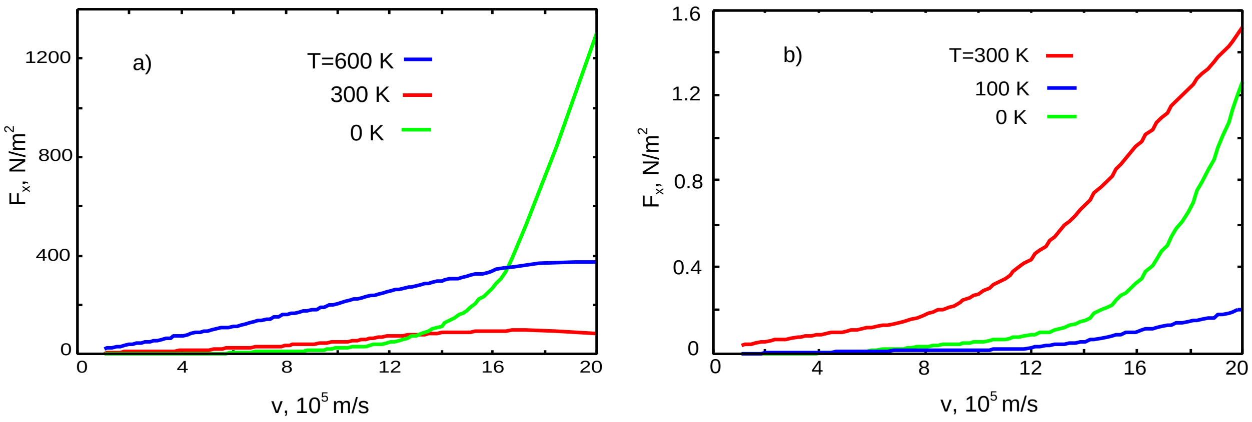
Current density-electric field dependence in graphene on SiO_2





$$v_{sat} \sim v_F \sim 10^6 m/s$$
$$J_{sat} = e n_s v_{sat} \sim 1\, mA/\mu m$$

Frictional Drag between Graphene Sheets



d=1 nm d=10 nm

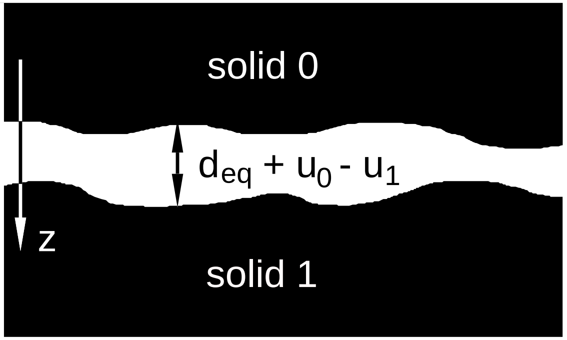
At l $v \ll v_F$ induced electric field $E = \rho_D J = \mu^{-1} v$.

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

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

Volokitin A.I. and Persson B.N.J. *EPL* **103** 24002 (2013)

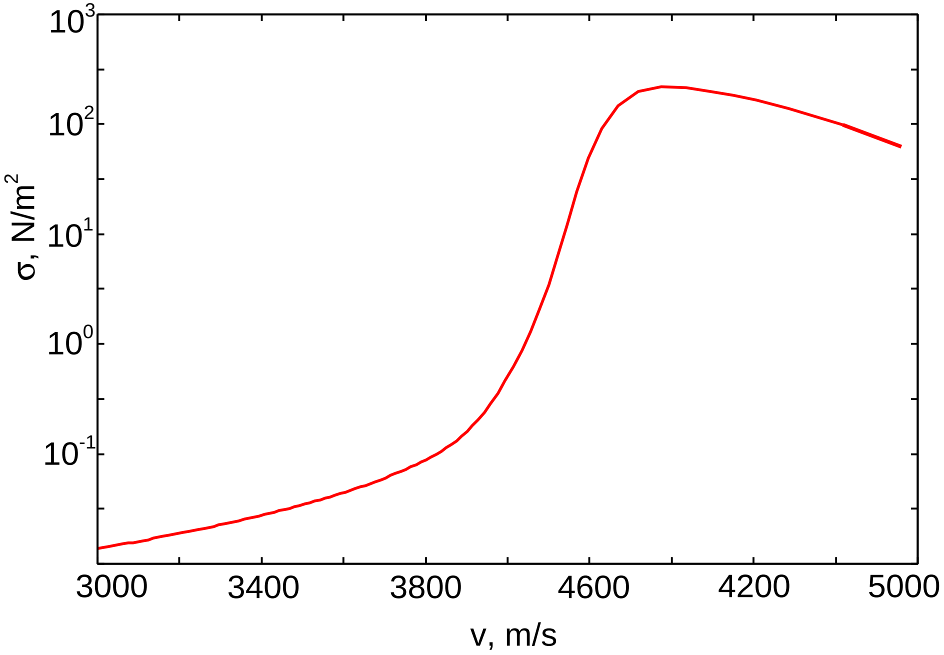
Acoustic Phonon Emission



$$\sigma(\mathbf{x}, t) = K[u_0(\mathbf{x} - \mathbf{v}t, t) - u_1(\mathbf{x}, t)],$$

Persson B.N.J., Volokitin A.I. and Ueba H., *JPCM* **23** 045009 (2011)

Acoustic Phonon Emission



Summary

- Casimir friction can be studied using modern experimental setups for observation of frictional drag in graphene systems..
- The challenging problem is to study frictional drag for graphene for strong electric field (large drift velocity) when Casimir friction is dominated by quantum fluctuations (quantum friction).
- The challenging problem for experimentalists is to develop setup for mechanical detection of Casimir friction using AFM.
- Quantum friction is strongly enhanced above the threshold velocity.
- The threshold velocity is determined by a type of excitations which are responsible for quantum friction.