Quantum dissipative effects in moving imperfect mirrors

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Plan of the talk

- Motivations
- Functional approach, dissipation, and dynamical Casimir effect
- Dissipative effects in imperfect moving mirrors

  I. Normal motion

  II. Vacuum friction
- Inertial forces on accelerated mirrors
- Conclusions

References:

- C.D. Fosco, F.C. Lombardo and F.D. Mazzitelli, Phys. Rev. D82, 125039 (2010)
- C.D. Fosco, F.C. Lombardo and F.D. Mazzitelli, ArXiv 1105.2745, submited to Phys. Rev. D

Main motivations

• analysis of the Dynamical Casimir effect taking into account the microscopic degrees of freedom of the moving mirrors

• develop techniques to study vacuum effects for imperfect deforming mirrors

Functional approach, dissipation, and dynamical Casimir effect

Main idea:

Vacuum field + microscopic degrees of freedom on the moving mirrors

$$\boxed{\text{Dissipative effects} \longleftrightarrow \left|\text{Vacuum persistence amplitude}\right| < 1}$$

$$< 0_{in} | 0_{out} > \Big|_{q(t)} = \int DA_\mu D\xi \;\; e^{iS} \equiv e^{i\Gamma_{in-out}[q(t)]}$$

em field

Internal degrees of freedom

The motion of the mirrors can produce excitations of the electromagnetic field and/or of the microscopic degrees of freedom in the mirrors

Different sources of dissipation:

- photon creation
- excitation of internal degrees of freedom due to exchange of virtual photons (vacuum friction)
- excitation of internal degrees of freedom due to inertial forces

Technical points:

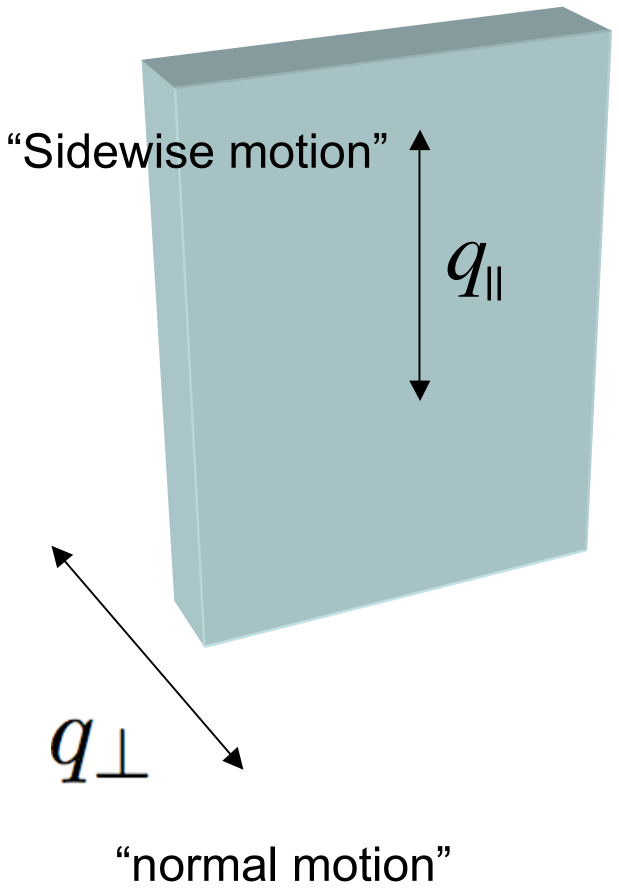
For simplicity we will work with a **scalar** vacuum field and **thin** mirrors

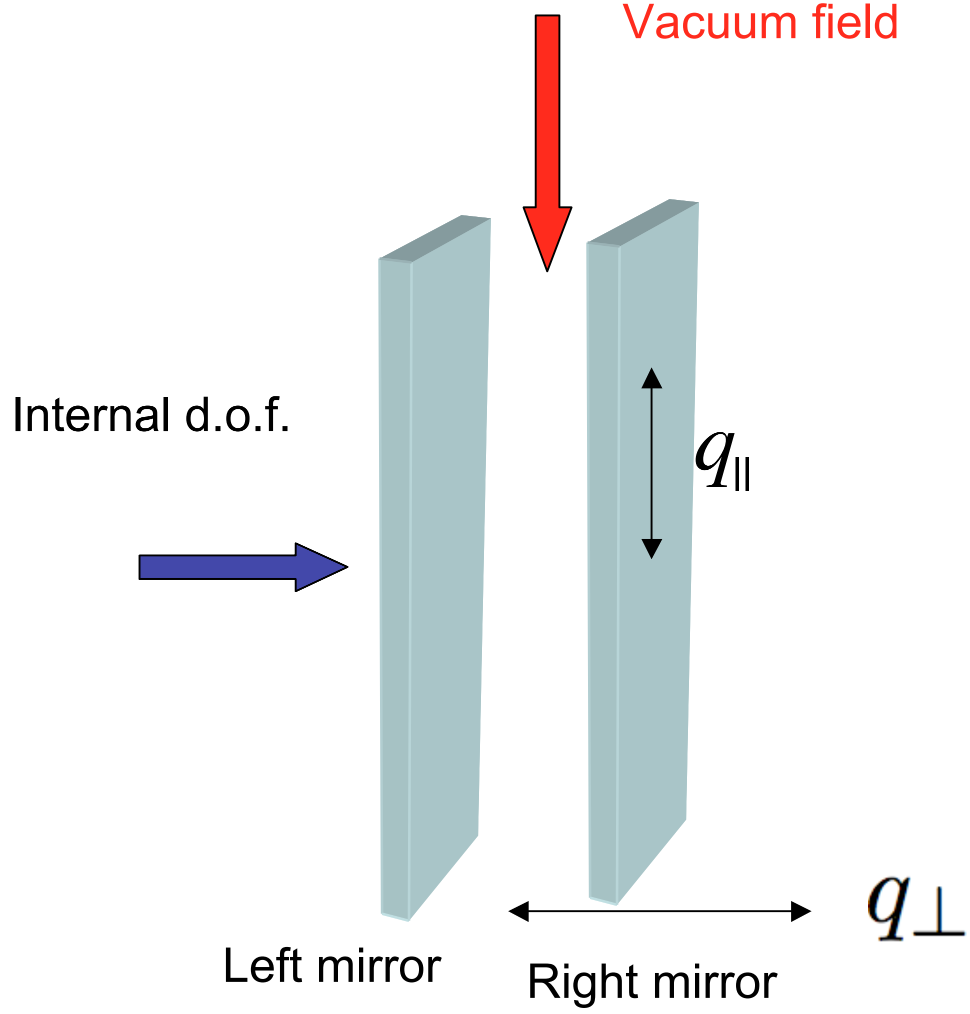
We will compute the **Euclidean** effective action and then obtain the vacuum persistence amplitude using a **Wick rotation**, and the force on the mirror using a **retarded prescription**

$$\Gamma_E[q(t)] \rightarrow \Gamma_{in-out}[q(t)]$$

$$\frac{\delta\Gamma_E}{\delta q} \rightarrow \left.\frac{\delta\Gamma}{\delta q}\right|_{retarded} = F_{dis}$$

Imperfect flat mirrors: sidewise and normal motions





The effective action is of the form:

$$e^{-\Gamma(q_\perp, q_\parallel)} = \int \mathcal{D}\varphi \mathcal{D}\psi \, e^{-S_0(\varphi) - S_m^{(0)}(\psi) - S_m^{(\mathrm{int})}(\varphi, \psi)}$$

For a scalar vacuum field $$S_0 = \frac{1}{2} \int d^4x \left[(\partial\varphi)^2 + m^2\varphi^2 \right]$$

The effective action is of the form:

$$e^{-\Gamma(q_\perp,q_\parallel)} = \int \mathcal{D}\varphi\mathcal{D}\psi\, e^{-S_0(\varphi)-S_m^{(0)}(\psi)-S_m^{(\mathrm{int})}(\varphi,\psi)}$$

For a scalar vacuum field

$$S_0 = \frac{1}{2}\int d^4x\,\left[(\partial\varphi)^2 + m^2\varphi^2\right]$$

After integration of the internal degrees of freedom (linear response theory)

$$e^{-\Gamma(q_\perp,q_\parallel)} = \int \mathcal{D}\varphi\, e^{-S_0(\varphi)-S_I(\varphi)}$$

$$S_I(\varphi) = \frac{1}{2}\int d^4x d^4x'\,\varphi(x')V(x,x')\varphi(x)$$

$$V(x,x') = \delta\big(x_3 - q_\perp(x_0)\big)\,\Lambda(x_0,x_\parallel;x_0',x_\parallel')\,\delta\big(x_3' - q_\perp(x_0')\big)$$

Note: we are neglecting terms independent of the vacuum field. We will come back to this point…

$$V(x,x') \;=\; \delta\big(x_3 - q_\perp(x_0)\big)\,\Lambda(x_0,x_\|;x'_0,x'_\|)\,\delta\big(x'_3 - q_\perp(x'_0)\big)$$

Example 1: a set of harmonic oscillators on a static mirror generate a delta-potential for the vacuum field

$$S_m^{(0)} = \frac{1}{2}\int dx_0 \int d^2x_\| \left[\dot{Q}(x_\|,x_0)^2 + \Omega^2 Q(x_\|,x_0)^2\right]$$

$$S_m^{\rm int} = ig\int d^4x\, Q(x_\|,x_0)\delta(x_3)\varphi(x_0,x_\|,x_3)\,,$$

$$\Lambda(x_0,x_\|;x'_0,x'_\|) \;=\; \lambda(x_0-x'_0)\,\delta^{(2)}(x_\|-x'_\|)$$

$$\lambda(x_0-x'_0) \to \left(\frac{g}{\Omega}\right)^2 \delta(x_0-x'_0) \qquad g,\Omega \to \infty$$

Example 2: relativistic massless fermions coupled to the electromagnetic field

$$S_I \approx \int d^3y \;\; d^3y' \;\; A_a(y,0)\Pi_{ab}(y,y')A_b(y',0)$$

$$\tilde{\Pi}_{ab}(k) = e^2\delta_{ab}(k)\,|\,k\,|$$ ← **2+1 dimensional momentum**

No dimensionful constants

Static Casimir force proportional to $\frac{1}{a^4}$

Fosco, Lombardo, FDM, PLB (2008)

Graphene sheet if $c \leftrightarrow v_{F,}$ Bordag et al PRB (2009)

Effective action for a single mirror:

$$e^{-\Gamma(q_\perp, q_\parallel)} = \int \mathcal{D}\varphi \, e^{-S_0(\varphi) - S_I(\varphi)}$$

$$\Gamma(q_\perp, q_\parallel) \;=\; \frac{1}{2} \log \det(-\partial^2 + V) \;=\; \frac{1}{2} \mathrm{Tr} \log(-\partial^2 + V)$$

Effective action for two mirrors:

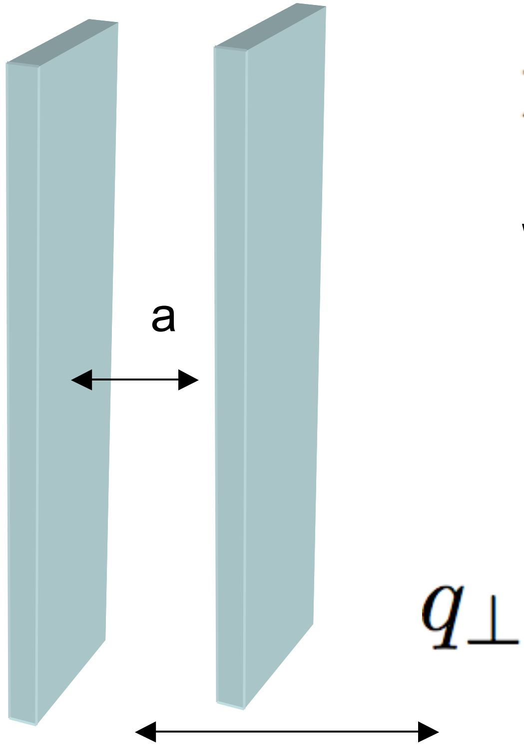
$$\Gamma(q_L, q_R) = \frac{1}{2} \log \det(-\partial^2 + V_L + V_R) = \frac{1}{2} \mathrm{Tr} \log(-\partial^2 + V_L + V_R)$$

Each one can have normal or sidewise motion

We will assume that V is spatially local in the rest frame of the mirror

$$\Lambda(x_0, x_\parallel; x'_0, x'_\parallel) \;=\; \lambda(x_0 - x'_0)\, \delta^{(2)}(x_\parallel - x'_\parallel)$$

Normal motion



$$\Gamma_I(q_L, q_R) = \frac{\Sigma}{2}\int \frac{d^2k_\parallel}{(2\pi)^2}\,\mathrm{Tr}\left(\log\widetilde{\mathcal{K}}\right)$$

We perform an expansion in powers of $q_\perp$

$$\widetilde{\mathcal{K}} = \widetilde{\mathcal{K}}_0 + \widetilde{\mathcal{K}}_1 + \widetilde{\mathcal{K}}_2 + \ldots.$$

$$\Gamma\ (q_\perp) = \frac{1}{2}\int \frac{d^2k_\parallel}{(2\pi)^2}\,\mathrm{Tr}\left[\widetilde{\mathcal{K}}_0^{-1}(\widetilde{\mathcal{K}}_1 + \widetilde{\mathcal{K}}_2) - \frac{1}{2}(\widetilde{\mathcal{K}}_0^{-1}\widetilde{\mathcal{K}}_1)^2\right]$$

Linear term

Quadratic terms

On general grounds we expect: linear term

$$\Gamma_1(q_\perp) = \int dx_0\, q_\perp(x_0) F_C$$

Usual static Casimir force between thin mirrors

Explicitly:

$$\Gamma_1(q_\perp) = -\frac{1}{2} \int dx_0\, q_\perp(x_0) \int \frac{d\omega}{2\pi} \int \frac{d^2 k_\parallel}{(2\pi)^2} \frac{1}{\sqrt{\omega^2 + k_\parallel^2 + m^2}}$$

$$\times \quad \frac{e^{-2a\sqrt{\omega^2+k_\parallel^2+m^2}}}{\left(\frac{1}{\tilde{\lambda}(\omega)} + \frac{1}{2\sqrt{\omega^2+k_\parallel^2+m^2}}\right)^2 - \frac{e^{-2a\sqrt{\omega^2+k_\parallel^2+m^2}}}{4(\omega^2+k_\parallel^2+m^2)}}.$$

The quadratic term:

$$\Gamma_2(q_\perp) = \frac{1}{2}\int dx_0 \int dx'_0\, q_\perp(x_0) F(x_0 - x'_0) q_\perp(x'_0)$$

$$F_{dis}(x_0) = \int dx'_0\, F_{ret}(x_0 - x'_0) q(x'_0)$$

$$\Gamma_{2,\text{in}-\text{out}}(q_\perp) = \frac{1}{2}\int dx_0 \int dx'_0\, q_\perp(x_0) F_{\text{in}-\text{out}}(x_0 - x'_0) q_\perp(x'_0)$$

Fourier transform of the form factor $F = F^{(1)} + F^{(2)}$

$$\widetilde{F^{(1)}}(\omega) = -\frac{1}{4\pi}\int d\nu \int \frac{d^2k_{\|}}{(2\pi)^2}\frac{c(\nu+\omega)\sqrt{\nu^2+k_{\|}^2+m^2}}{c^2(\nu+\omega,k_{\|})-b^2(\nu+\omega,k_{\|})}$$

$$\widetilde{F^{(2)}}(\omega) = -\frac{1}{8\pi}\int \frac{d^2k_{\|}}{(2\pi)^2}\int d\nu \frac{1}{c^2(\omega+\nu,k_{\|})-b^2(\omega+\nu,k_{\|})}\frac{1}{c^2(\nu,k_{\|})-b^2(\nu,k_{\|})}$$
$$\times\Big[c(\omega+\nu,k_{\|})c(\nu,k_{\|})e^{-2a\sqrt{(\omega+\nu)^2+k_{\|}^2+m^2}} +$$
$$b(\omega+\nu,k_{\|})b(\nu,k_{\|})e^{-a\sqrt{(\omega+\nu)^2+k_{\|}^2+m^2}}e^{-a\sqrt{\nu^2+k_{\|}^2+m^2}}\Big]$$

With:

$$b(\omega,k_{\|}) = \frac{e^{-a\sqrt{\omega^2+k_{\|}^2+m^2}}}{2\sqrt{\omega^2+k_{\|}^2+m^2}}$$

$$c(\omega,k_{\|}) = \frac{1}{\widetilde{\lambda}(\omega)} + \frac{1}{2\sqrt{\omega^2+k_{\|}^2+m^2}}$$

Fourier transform of the form factor

$$F = F^{(1)} + F^{(2)}$$

$$\widetilde{F^{(1)}}(\omega) = -\frac{1}{4\pi}\int d\nu \int \frac{d^2k_{\|}}{(2\pi)^2} \frac{c(\nu+\omega)\sqrt{\nu^2+k_{\|}^2+m^2}}{c^2(\nu+\omega,k_{\|}) - b^2(\nu+\omega,k_{\|})}$$

$$\widetilde{F^{(2)}}(\omega) = -\frac{1}{8\pi}\int \frac{d^2k_{\|}}{(2\pi)^2}\int d\nu \frac{1}{c^2(\omega+\nu,k_{\|}) - b^2(\omega+\nu,k_{\|})} \frac{1}{c^2(\nu,k_{\|}) - b^2(\nu,k_{\|})}$$

$$\times \Big[c(\omega+\nu,k_{\|})c(\nu,k_{\|})e^{-2a\sqrt{(\omega+\nu)^2+k_{\|}^2+m^2}} +$$

$$b(\omega+\nu,k_{\|})b(\nu,k_{\|})e^{-a\sqrt{(\omega+\nu)^2+k_{\|}^2+m^2}}e^{-a\sqrt{\nu^2+k_{\|}^2+m^2}} \Big]$$

Poles at resonant frequencies for perfect mirrors

$$\Omega_{ext} = \omega_1 + \omega_2$$

1+1 dimensions, "graphene-like" coupling

$$\tilde{\lambda}(\omega) = \zeta|\omega|$$

(no additional dimensionful constants)

The vacuum field propagates at a velocity $1/\sqrt{1+\zeta}$

Electromagnetic analogy: $\zeta = \varepsilon - 1$

$$\widetilde{F^{(1)}}(\omega) = -\frac{1}{2\pi}\int d\nu\,|\nu+\omega|\,|\nu|\,\frac{\chi}{\chi^2 - e^{-2a|\nu+\omega|}}$$

$$\widetilde{F^{(2)}}(\omega) = -\frac{1}{2\pi}\int d\nu\, e^{-2a|\omega+\nu|}\,\frac{|\omega+\nu||\nu|}{\left(\chi^2 - e^{-2a|\omega+\nu|}\right)}\,\frac{\left(\chi^2 + e^{-2a|\nu|}\right)}{\left(\chi^2 - e^{-2a|\nu|}\right)}$$

$$\chi = (2+\zeta)/\zeta$$

Limit of perfect mirrors: $\zeta \to \infty \quad or \quad \chi \to 1$ **(strong coupling)**

$$\widetilde{F_\infty}(\omega) = \widetilde{F_\infty^{(1)}}(\omega) + \widetilde{F_\infty^{(2)}}(\omega)$$
$$= \frac{|\omega|^3}{12\pi} - \frac{\omega^2\pi}{6a^3}\left(1 + \frac{\omega^2 a^2}{\pi^2}\right)\sum_{n\geq 1}\frac{1}{\omega^2 + \frac{n^2\pi^2}{a^2}}$$

$$F_{\rm ret}(x_0) = \frac{\delta'''(x_0)}{12\pi} - \frac{\pi}{6a^2}\theta(t)\sum_{n\geq 0}\delta'(x_0 - 2na)$$

$$-\frac{1}{6\pi}\theta(t)\sum_{n\geq 0}\delta'''(x_0 - 2na)$$

Well known result: Jaeckel & Reynaud, Maia Neto & Mundarain

Weak coupling $\zeta \to 0 \quad or \quad \chi \to \infty$

$$\widetilde{F^{(1)}}(\omega) = -\frac{1}{2\pi\chi}\int d\nu\, |\nu+\omega|\,|\nu|\ (1 + \frac{e^{-2a|\nu+\omega|}}{\chi^2}) + \ldots$$

$$\widetilde{F^{(2)}}(\omega) = -\frac{1}{2\pi\chi^2}\int d\nu\, |\omega+\nu||\nu|e^{-2a|\omega+\nu|} + \ldots\ .$$

$$\widetilde{F}(\omega) = -\frac{1}{6\pi\chi}|\omega|^3 - \frac{1}{4\pi a^3\chi^2}[e^{-2a|\omega|}(1 + a|\omega|) + a|\omega|] + \ldots$$

Weak coupling $\zeta \to 0 \quad or \quad \chi \to \infty$

$$\widetilde{F^{(1)}}(\omega) = -\frac{1}{2\pi\chi}\int d\nu\,|\nu+\omega|\,|\nu|\,(1+\frac{e^{-2a|\nu+\omega|}}{\chi^2})+\ldots$$
$$\widetilde{F^{(2)}}(\omega) = -\frac{1}{2\pi\chi^2}\int d\nu\,|\omega+\nu||\nu|e^{-2a|\omega+\nu|}+\ldots.$$

$$\widetilde{F}(\omega) = -\frac{1}{6\pi\chi}|\omega|^3 - \frac{1}{4\pi a^3\chi^2}[e^{-2a|\omega|}(1+a|\omega|)+a|\omega|]+\ldots$$

Leading term independent of a and similar to perfect conductor

Weak coupling $\zeta \to 0 \quad or \quad \chi \to \infty$

$$\widetilde{F^{(1)}}(\omega) = -\frac{1}{2\pi\chi}\int d\nu\,|\nu+\omega|\,|\nu|\,(1+\frac{e^{-2a|\nu+\omega|}}{\chi^2}) + \dots$$

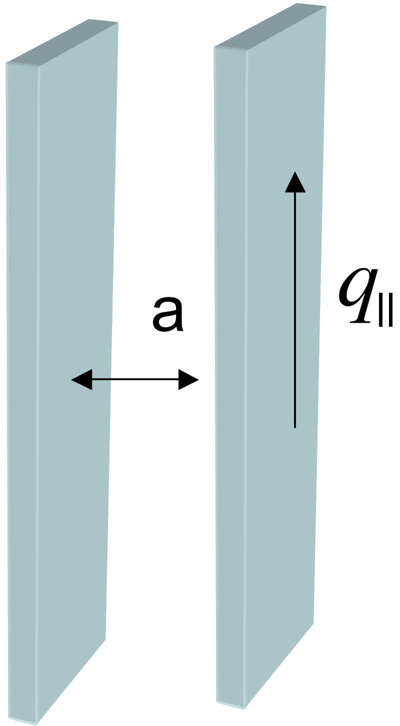
$$\widetilde{F^{(2)}}(\omega) = -\frac{1}{2\pi\chi^2}\int d\nu\,|\omega+\nu||\nu|e^{-2a|\omega+\nu|} + \dots .$$

$$\widetilde{F}(\omega) = -\frac{1}{6\pi\chi}|\omega|^3 - \frac{1}{4\pi a^3\chi^2}[e^{-2a|\omega|}(1+a|\omega|)+a|\omega|] + \dots$$

$1/\chi^2$-retarded contributions are proportional to $\delta'(x_0), \delta(x_0-2a)$, and $\delta'(x_0-2a)$

(the time of flight between the two mirrors does not depend on χ)

Sidewise motion



Single accelerated mirror (Barton 1996)

We consider two parallel mirrors:

$$V_L(x,x') = \delta(x_3)\,\lambda(x_0 - x_0')\delta^{(2)}(x_{||} - x_{||}')\,\delta(x_3')$$

$$V_R(x,x') = \delta(x_3 - a)\,\lambda(x_0 - x_0')\,\delta[x_1 - x_1' - q_{||}(x_0) + q_{||}(x_0')]\,\delta(x_2 - x_2')\,\delta(x_3' - a)$$

For constant velocity

$$\Gamma \approx \frac{T\Sigma}{64\pi^3}\int d^3p\,\frac{e^{-2a\sqrt{p_0^2+p_1^2+p_2^2}}}{p_0^2+p_1^2+p_2^2}\widetilde{\lambda}(p_0)\widetilde{\lambda}(p_0+p_1v)$$

No imaginary part when the effective interaction is local

The usual static Casimir force depend on the velocity

For constant velocity

$$\Gamma \approx \frac{T\Sigma}{64\pi^3} \int d^3p \frac{e^{-2a\sqrt{p_0^2+p_1^2+p_2^2}}}{p_0^2+p_1^2+p_2^2} \boxed{\widetilde{\lambda}(p_0)\widetilde{\lambda}(p_0+p_1 v)}$$

The structure is similar to Pendry's result:

$$F_x = \frac{\hbar}{\pi} \int \frac{d^2\mathbf{k}}{(2\pi)^2} k_x e^{-2|\mathbf{k}|d} \int_0^{k_x v} d\omega \boxed{\mathrm{Im}\left[\frac{\epsilon(\omega)-1}{\epsilon(\omega)+1}\right] \mathrm{Im}\left[\frac{\epsilon(k_x v-\omega)-1}{\epsilon(k_x v-\omega)+1}\right]}$$

For constant velocity

$$\Gamma \approx \frac{T\Sigma}{64\pi^3} \int d^3p \frac{e^{-2a\sqrt{p_0^2+p_1^2+p_2^2}}}{p_0^2+p_1^2+p_2^2} \boxed{\widetilde{\lambda}(p_0)\widetilde{\lambda}(p_0+p_1 v)}$$

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For the particular case: $\tilde{\lambda}(\omega) = \zeta|\omega|$

$$\mathrm{Im}\Gamma_{\mathrm{in-out}} \approx \frac{T\Sigma\zeta^2}{576\pi^3}\frac{|v|^3}{a^3} + O(v^4)$$

And we expect: $F_{dis} = \frac{\Sigma\zeta^2}{a^4} f(\mathrm{v})$

(problems with the analytic continuation)

Inertial effects on deforming mirrors: A simple example

$$S = S_f + S_m + S_I$$

Vacuum field

$$S_f(\varphi) = \frac{1}{2}\int d^{d+1}x\, \partial_\mu\varphi(x)\partial_\mu\varphi(x)$$

Internal d.o. f.

$$S_m(\xi;\mathcal{M}) = \frac{1}{2}\int d^d\sigma\sqrt{g(\sigma)}\big[g^{\alpha\beta}(\sigma)\partial_\alpha\xi(\sigma)\partial_\beta\xi(\sigma) + \mu^2\xi^2(\sigma)\big] ,$$

$\mathcal{M}$ is the spacetime volume swept by a deforming mirror

$g_{\alpha\beta}$ Induced metric

Interaction term

$$S_I(\varphi,\xi;\mathcal{M}) = -i\,\zeta\int d^d\sigma\,\sqrt{g(\sigma)}\,\xi(\sigma)\,\varphi[y(\sigma)]$$

Integrating the internal degrees of freedom

$$e^{-\Gamma_m(\varphi;\mathcal{M})} \equiv \int \mathcal{D}\xi \; e^{-S_m(\xi;\mathcal{M})-S_I(\varphi,\xi;\mathcal{M})}$$

$$\Gamma_m(\varphi;\mathcal{M}) = \Gamma_i(\mathcal{M}) + \Gamma_b(\varphi;\mathcal{M})$$

$$\Gamma_i(\mathcal{M}) \equiv \Gamma_m(\varphi;\mathcal{M})|_{\varphi=0},$$

Inertial effects. Do not depend on the coupling to the vacuum field

$$\Gamma_b(\varphi;\mathcal{M}) = \Gamma_m(\varphi;\mathcal{M}) - \Gamma_m(\varphi;\mathcal{M})|_{\varphi=0}$$

Provides a boundary condition for the vacuum field as described before

The acceleration of the mirror excites the internal degrees of freedom

$$\Gamma_i(\mathcal{M}) = \frac{1}{2}\,\mathrm{Tr}\ln\mathcal{K}$$

$$\mathcal{K} = -\partial_\alpha\left[g^{1/2}g^{\alpha\beta}\partial_\beta\right] + g^{1/2}\mu^2 = g^{1/2}\left(-\Delta_{\mathcal{M}} + \mu^2\right)$$

Known result from Quantum Field Theory in Curved Spacetimes: for massless internal d.o.f:

$$\Gamma_i(\mathcal{M}) \simeq -\frac{1}{64\times 2^{3/2}}\int d^3\sigma\sqrt{g(\sigma)}\Big[a_1 R_{\alpha\beta}(-\Delta)^{-\frac{1}{2}}R_{\alpha\beta} + a_2 R(-\Delta)^{-\frac{1}{2}}R\Big] + \Gamma_{local} \quad + \ldots..$$

The acceleration of the mirror excites the internal degrees of freedom

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$$\mathcal{K} = -\partial_\alpha \left[g^{1/2} g^{\alpha\beta} \partial_\beta \right] + g^{1/2}\mu^2 = g^{1/2} \left(-\Delta_{\mathcal{M}} + \mu^2 \right)$$

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$$\Gamma_i(\mathcal{M}) \simeq -\frac{1}{64 \times 2^{3/2}} \int d^3\sigma \sqrt{g(\sigma)} \Big[a_1 R_{\alpha\beta} (-\Delta)^{-\frac{1}{2}} R_{\alpha\beta} + a_2 R (-\Delta)^{-\frac{1}{2}} R \Big] + \Gamma_{local} \, , \quad (35)$$

Nonlocal effective action

curvature associated to the mirror

More explicitly:

$$\mathrm{Im}\,[\Gamma_i] \simeq \frac{1}{2^{3/2}64}\int_0^\infty dm \int \frac{d^2k}{(2\pi)^2} \times \frac{|\widetilde{B}(k_0=\omega_{\mathbf{k}},\mathbf{k})|^2 + |\widetilde{B}(k_0=-\omega_{\mathbf{k}},\mathbf{k})|^2}{\omega_{\mathbf{k}}}$$

$$|\widetilde{B}(k)|^2 = \widetilde{R}_{\alpha\beta}(k)\widetilde{R}_{\rho\sigma}(-k)[\eta^{\alpha\rho}\eta^{\beta\sigma} - \frac{1}{8}\eta^{\alpha\beta}\eta^{\rho\sigma}]$$

For standing waves on the mirror

$$y(\sigma^0,\sigma^1,\sigma^2) = y_0\cos(\Omega\sigma^0)\cos\left(\sigma^1/L\right)$$

$$\boxed{\frac{\mathrm{Im}\,[\Gamma_i]}{T\Sigma} \sim \frac{\hbar y_0^4\Omega^3}{v_F^2 L^4}}$$

Comparison with the usual DCE (perfect mirrors)

$$\frac{\mathrm{Im}\left[\Gamma_i\right]}{T\Sigma} \sim \frac{\hbar y_0^4 \Omega^3}{v_F^2 L^4}$$

$$\frac{\mathrm{Im}\left[\Gamma^{\mathrm{DCE}}\right]}{T\Sigma} \sim \frac{\hbar y_0^2 \Omega^5 (1 - \frac{c^2}{L^2\Omega^2})^{5/2}}{c^4}.$$

(Golestanian & Kardar, Saharian)

$$\frac{\mathrm{Im}\left[\Gamma_i\right]}{\mathrm{Im}\left[\Gamma^{\mathrm{DCE}}\right]} \sim \left(\frac{y_0}{L}\right)^2 \left(\frac{c}{v_F}\right)^2 \left(\frac{c}{\Omega L}\right)^2 \left(1 - \frac{c^2}{L^2\Omega^2}\right)^{-5/2}$$

Comparison with the usual DCE (perfect mirrors)

$$\frac{\mathrm{Im}\,[\Gamma_i]}{T\Sigma} \sim \frac{\hbar y_0^4 \Omega^3}{v_F^2 L^4}$$

threshold

$$\frac{\mathrm{Im}\,[\Gamma^{\mathrm{DCE}}]}{T\Sigma} \sim \frac{\hbar y_0^2 \Omega^5 \boxed{(1 - \frac{c^2}{L^2\Omega^2})^{5/2}}}{c^4}.$$

(Golestanian & Kardar, Saharian)

$$\frac{\mathrm{Im}\,[\Gamma_i]}{\mathrm{Im}\,[\Gamma^{\mathrm{DCE}}]} \sim \left(\frac{y_0}{L}\right)^2 \left(\frac{c}{v_F}\right)^2 \left(\frac{c}{\Omega L}\right)^2 \left(1 - \frac{c^2}{L^2\Omega^2}\right)^{-5/2}$$

Conclusions

- We have studied dissipative effects on imperfect moving mirrors using the functional approach. The analysis of the vacuum persistence amplitude allowed us to consider on the same footing different kinds of dissipative effects
- For “normal motion” we obtained general expressions for the effective action in terms of the (analogous of the) polarization tensor that decribes the interaction between the vacuum field and the internal degrees of freedom of the mirror
- Explicit examples in 1+1 dimensions
- For “sidewise motion” we found that in general there is “vacuum friction” between thin mirrors even for constant velocity. The interaction must be non local
- We described a new dissipative effect related to the excitation of the internal degrees of freedom of the mirrors due to the acceleration.
- For simplicity we worked with a scalar vacuum field. We are studying the generalization to the electromagnetic field and to realistic internal degrees of freedom, using the Schwinger-Keldysh formalism