On the interplay between optomechanics and the dynamical Casimir effect

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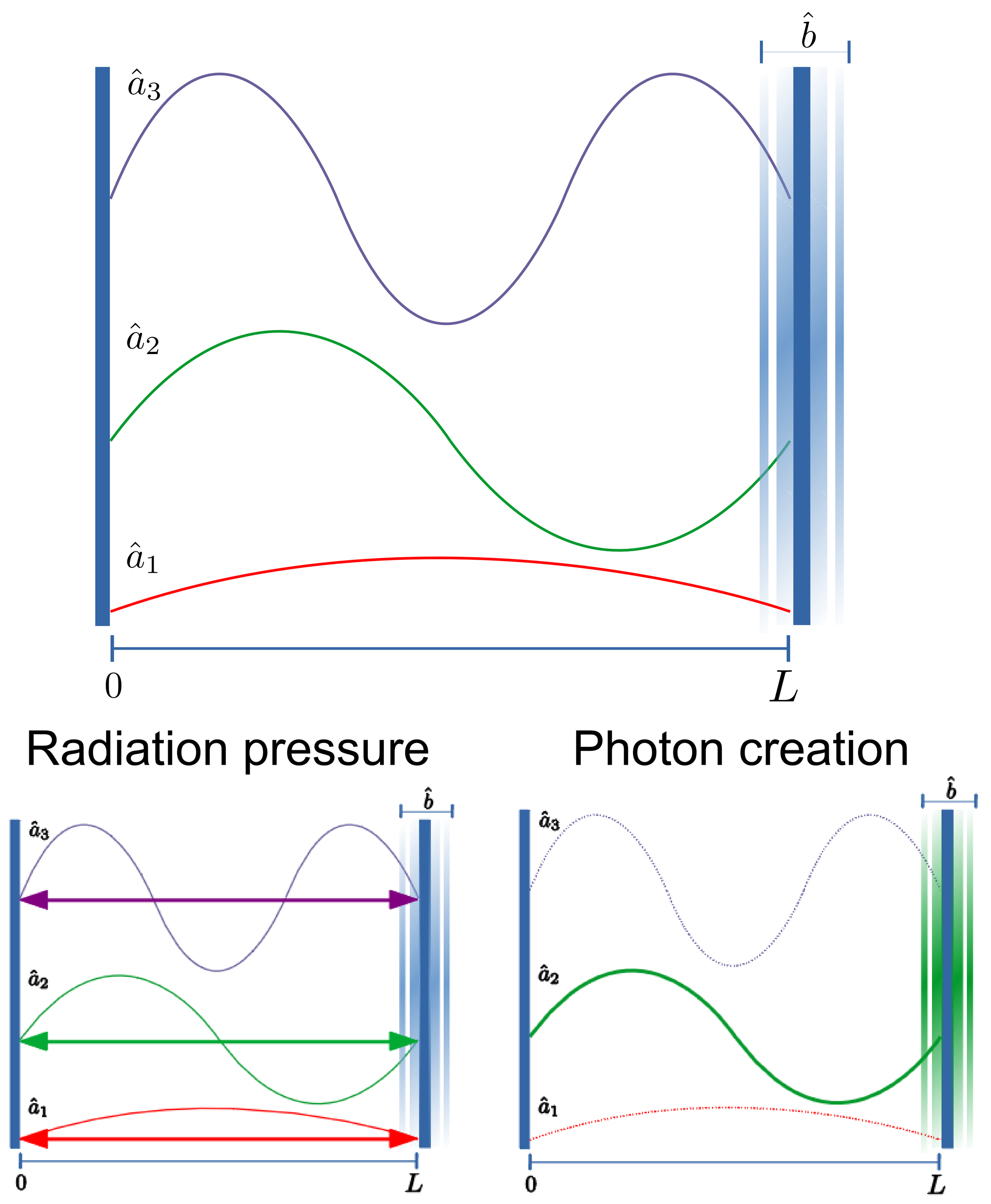
Introduction. In a cavity system with a mobile wall, the radiation pressure, stemming from the confined light, causes the motion of the mobile wall. On the other hand, when the frequency of the motion of a cavity wall is in resonance with the frequency of one of the cavity modes, photons can arise within the cavity: this phenomenon is called dynamical Casimir effect. In this work, we present an alternative protocol to introduce both the optomechanical coupling and the photon-pair creation term starting by a static scenario.



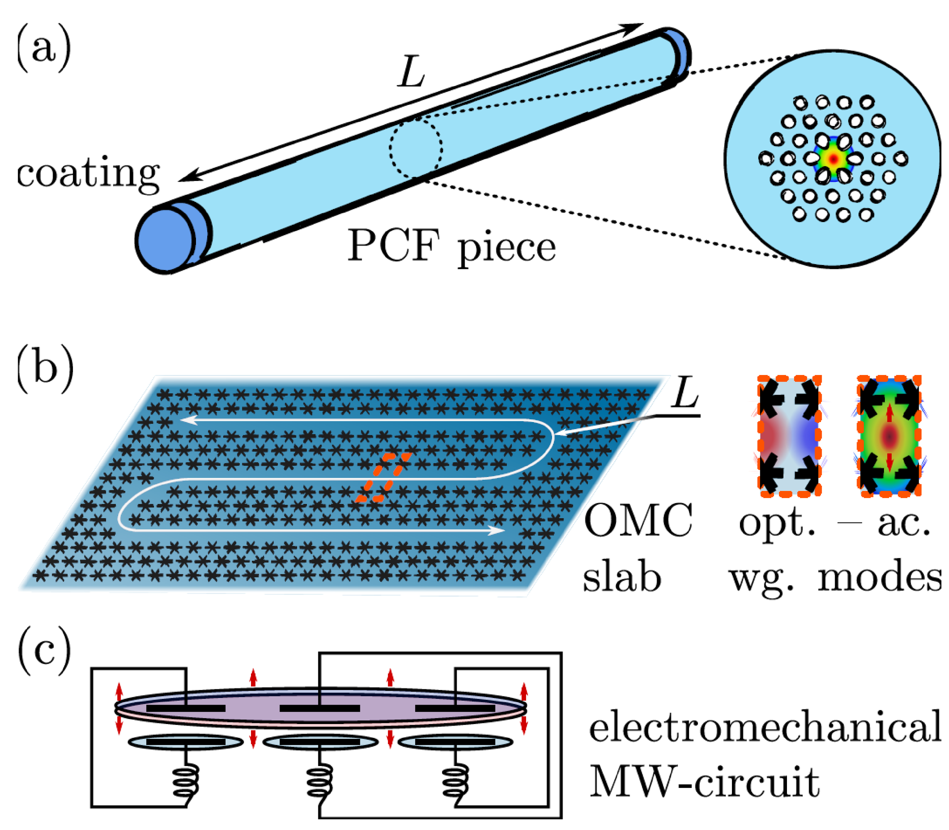
Quantization protocol

1) Solve the equation of motion with static BCs;
2) Extend the length of the cavity by a small amount δL;
3) Expand the Hamiltonian density with respect to the length increment;
4) Integrate the Hamiltonian density;
5) Promote both the field and the oscillation amplitude to quantum operators.

Mathematical tools

Hamiltonian zero	$\hat{H}_0 := \sum_n \hbar\omega_n\, \hat{a}_n^\dagger \hat{a}_n + \hbar\omega \hat{b}^\dagger \hat{b}$
Field-wall interaction	$\hat{H}_{\rm I} := -4\epsilon \sum_{nm} (-1)^{n+m} \hbar\sqrt{\omega_n\omega_m}\, \hat{X}_n \hat{X}_m \hat{X}_b.$
External drives	$\hat{H}_{\rm dr}(t) := \hat{H}_{\rm dk}(t) + \hat{H}_{\rm dk'}(t) + \hat{H}_{\rm db}(t)$
with	$\hat{H}_{\rm dj}(t) = 2\lambda_{xj}(t)\hat{X}_j + 2\lambda_{pj}(t)\hat{P}_j$
Mechanical external drive	$\lambda_b(t) = -\frac{g\Omega}{2} e^{-\Omega t} e^{-i\omega t}$
Initial state	$\hat{\rho}(0) = \prod_n \lvert 0_n\rangle\langle 0_n\rvert \otimes \hat{\rho}_{\rm m}^{(\rm DST)}$

Applications



Theoretical results

Position of the wall

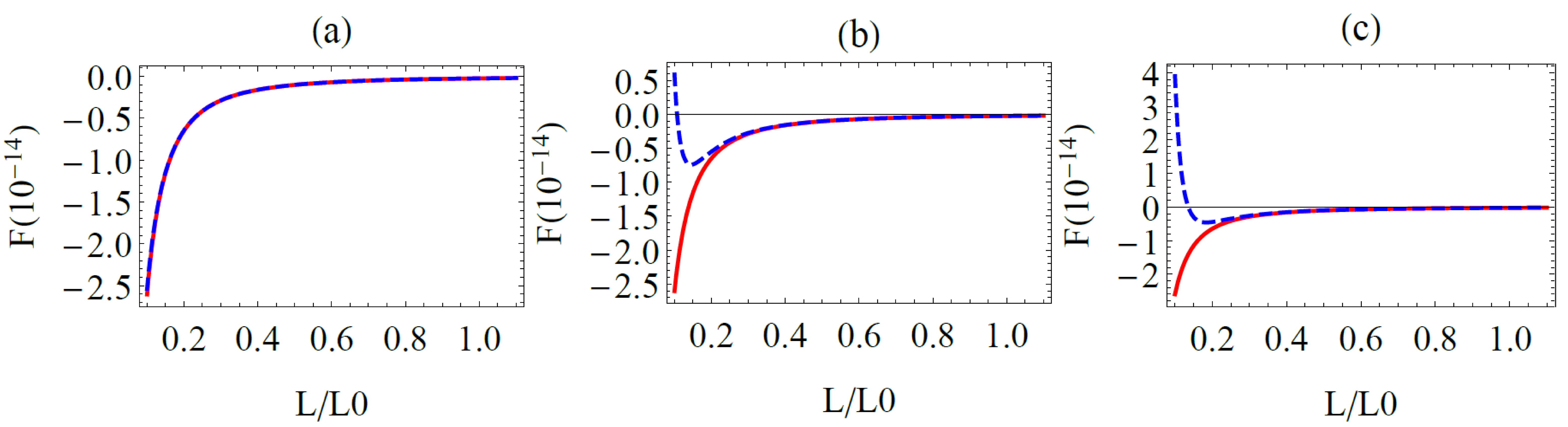
$$\frac{x(t)}{L} \simeq 1 + \epsilon\, e^{-\frac{\epsilon^2\omega_k^2 t^2}{4}} \left[2|\beta|\cos\theta\cos(2\omega_k t) + (g + 2|\beta|\sin\theta)\sin(2\omega_k t)\right]$$

Number of photons

$$\langle N_k^{(2)}\rangle_\tau \simeq \frac{\omega_k^2\tau^2}{3}\left(\sinh^2 r + N_T + 2N_T\sinh^2 r\right) + \frac{\omega_k^2\tau^2}{12}\left(4|\beta|^2 + g^2 + 4|\beta|\sin\theta\right)$$

Force between the two cavity walls

$$\langle F\rangle_\tau \simeq -\frac{\hbar\pi c}{24L^2} + \left(|\beta|^2 + \sinh^2 r + N_T\cosh(2r) + g^2/4 + g|\beta|\sin\theta\right)\frac{\epsilon^2\hbar\omega_k^3\tau^2}{6L}$$



Conclusion. The protocol here presented allows to introduce nonlinear interactions, such as the typical optomechanical coupling and the exchange of excitations in cavity systems. We investigated the time evolution of the system, focusing on the dynamics of the moving wall, the number of photons and the force between the two walls. Such procedure can be extended to massive scalar fields straightforwardly. The extension to fermionic fields is currently investigated. More info: https://arxiv.org/abs/2204.10724