Nonclassical microwave radiation from the dynamical Casimir effect

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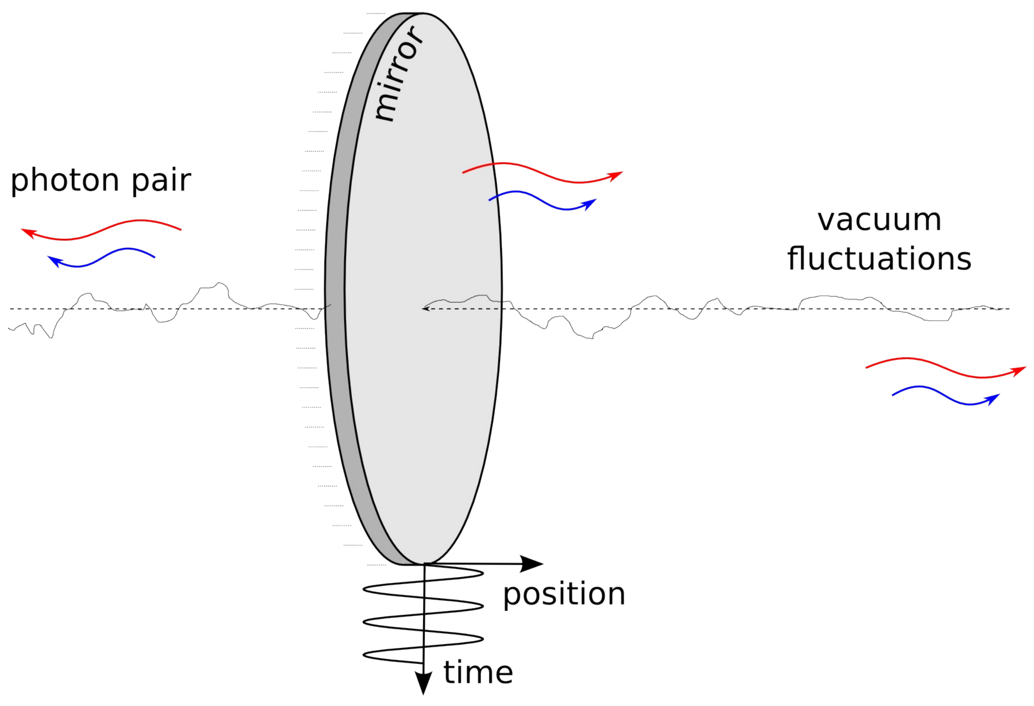
Summary

We investigate quantum correlations in microwave radiation produced by the dynamical Casimir effect in a superconducting waveguide [1-3] terminated and modulated by a superconducting quantum interference device [4]. We apply nonclassicality tests and evaluate the entanglement for the predicted field states. For realistic circuit parameters, including thermal background noise, the results indicate that the produced radiation can be strictly nonclassical and can have a measurable amount of intermode entanglement. If measured experimentally, these nonclassicalilty indicators could give further evidence of the quantum nature of the dynamical Casimir radiation in these circuits.



What is the dynamical Casimir effect?

The dynamical Casimir effect (DCE) is the creation of photons from the vacuum state of a quantum field due to time-dependent boundary conditions. Example: a mirror moving in vacuum emits photons.

But for significant photon production to occur, the boundary condition must be changed *nonadiabatically with respect to the speed of light*.

Photon production rate (N/t) for a single oscillating mirror with frequency Ω is very small unless the maximum speed of the mirror v is comparable to speed of light c:

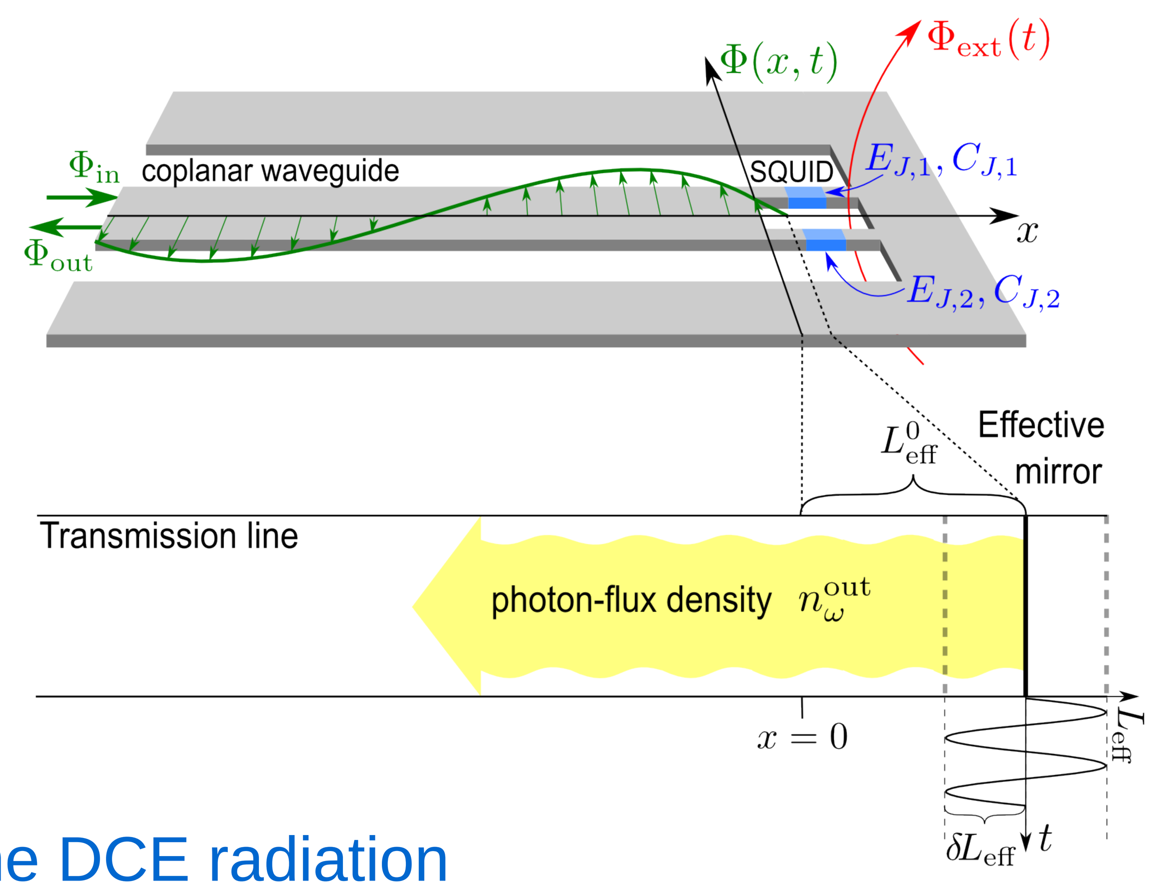
$$\frac{N}{\tau} = \frac{\Omega}{6\pi}\left(\frac{v}{c}\right)^2$$

[Lambrecht *et al.*, PRL 1996]

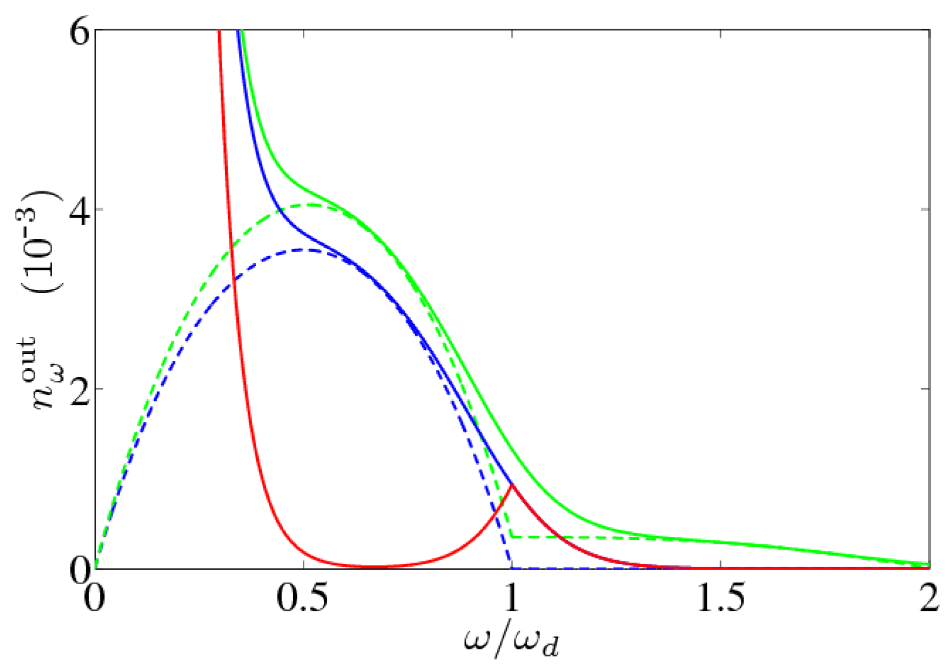
Superconducting circuit for DCE

Our proposal [1-2] for realizing the DCE: a superconducting **microwave** circuit consisting of a coplanar waveguide that is terminated by a SQUID. The boundary condition that the SQUID impose on the waveguide can be tuned via the applied magnetic field through the loop.

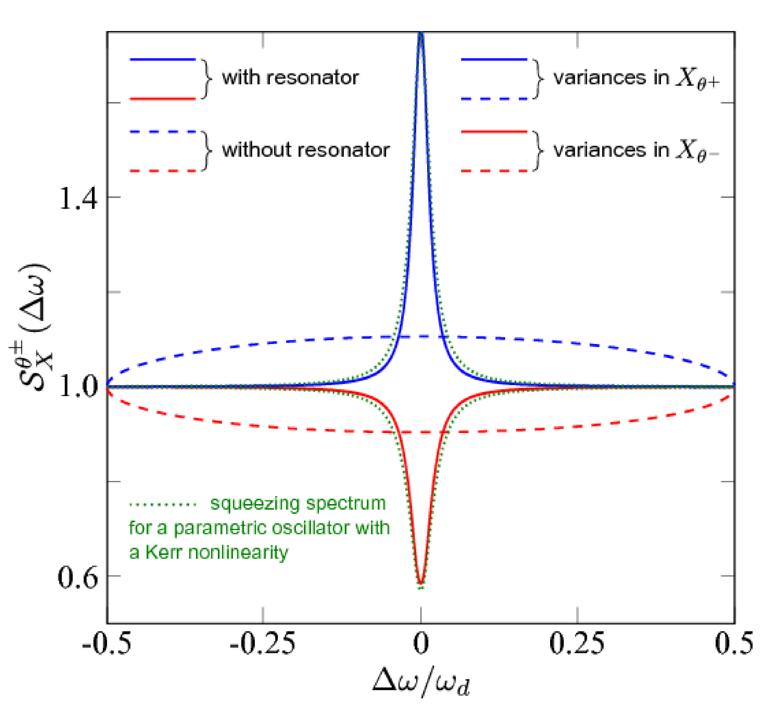
Advantage: Due to the high sensitivity of the SQUID, we can achieve a relatively large ratio between the modulation speed v to the speed of light in the waveguide c, *and therefore reach the nonadiabatic regime and a large photon-production rate [3].*



Photon production rate



Spectrum of quadrature squeezing



Properties of the DCE radiation

We analyze the problem using scattering theory, to obtain an expression for the output field operator b in terms of the input field operator a. The result is an output field that is correlated at frequencies symmetrically around half the modulation frequency:

$$b_\pm = -a_\pm - i\frac{\delta L_{\rm eff}}{v}\sqrt{\omega_+\omega_-}\,a^\dagger_\mp$$

We then assume that the input field is, for example, in the vacuum or thermal state and calculate various properties of the output field, such as the photon production rate and spectra of squeezing.

Testing for nonclassicality of the DCE radiation

The DCE radiation is clearly correlated at different frequencies (two-mode squeezing) [3].
But are these classical or quantum mechanical correlations (entanglement)? And does nonclassicality remain at experimentally relevant temperatures and conditions?

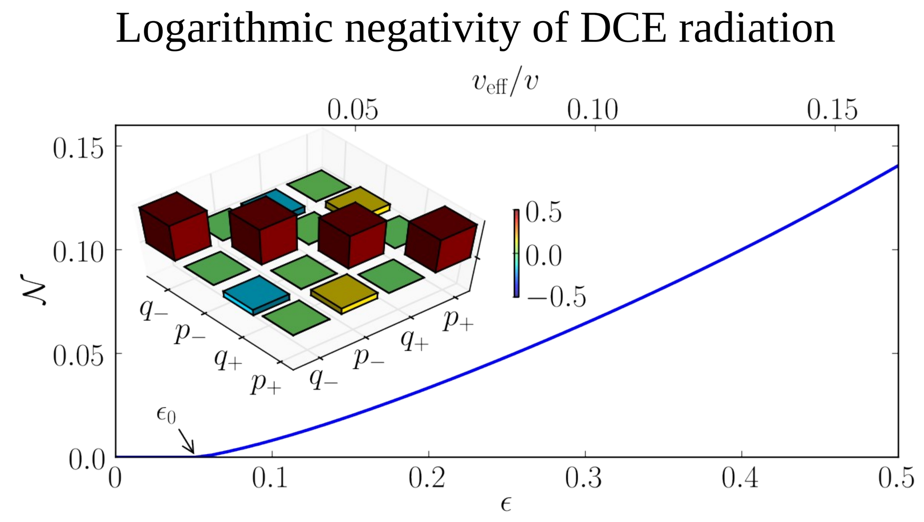
To answer this question, we evaluate nonclassicality tests for the DCE radiation in our proposed circuit [4].
We use the logarithmic negativity $\mathcal{N}$ and the following nonclassicality test [Miranowicz PRA 2010]:

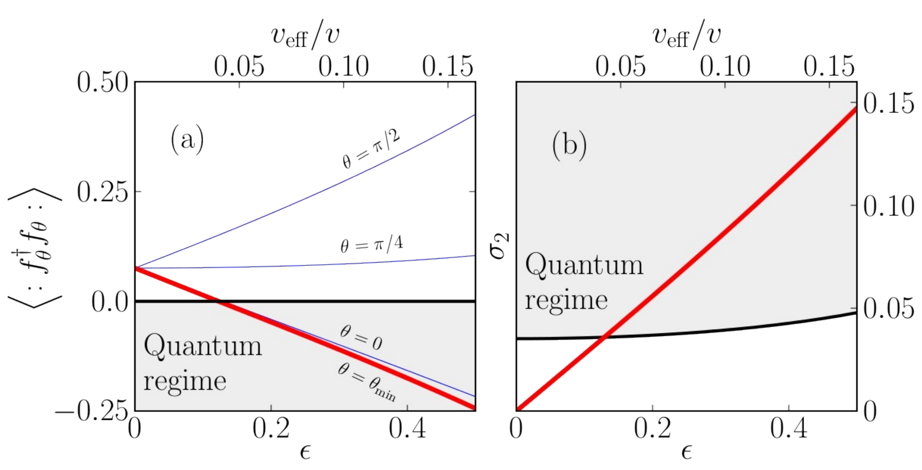
$$\langle : \hat{f}^\dagger \hat{f} : \rangle < 0 \rightarrow \text{nonclassical}$$

$$\hat{f}_\theta = e^{i\theta}\hat{b}_- + e^{-i\theta}\hat{b}^\dagger_- + i(e^{i\theta}\hat{b}_+ - e^{-i\theta}\hat{b}^\dagger_+)$$

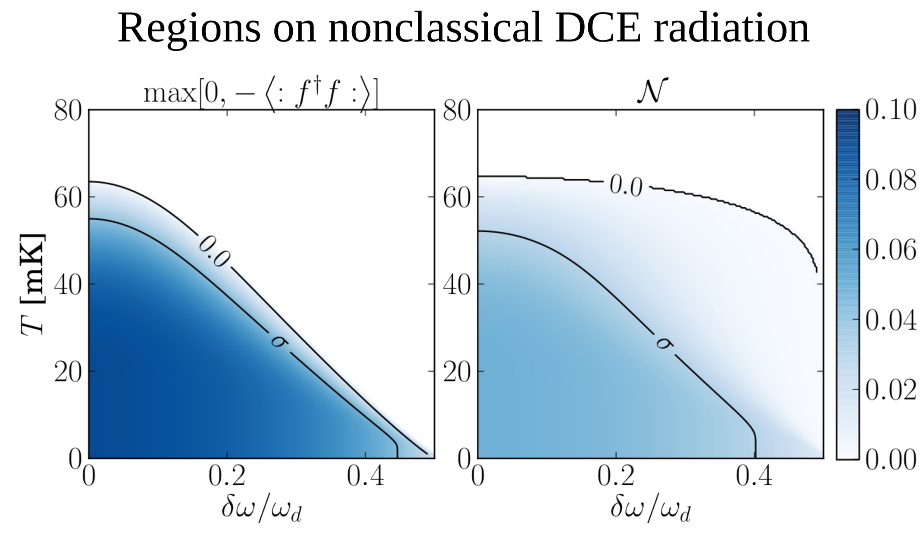
$$\left\langle : f^\dagger_\theta f_\theta : \right\rangle = 2(n^{\rm th}_+ + n^{\rm th}_-) - 4\cos 2\theta \frac{\delta L_{\rm eff}}{v}\sqrt{\omega_+\omega_-}(1 + n^{\rm th}_+ + n^{\rm th}_-)$$

Logarithmic negativity of DCE radiation





Regions on nonclassical DCE radiation



Conclusions

We have theoretically investigated the photon statistics of the DCE radiation and we conclude that not only is the DCE a quantum mechanical photon-production process, but the resulting radiation also contains correlations that goes beyond what is allowed classically. We predict that the nonclassicality tests should be violated under currently available experimental conditions.

References

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1. *Dynamical Casimir effect in a superconducting coplanar waveguide*, JRJ et al., Phys. Rev. Lett. 103, 147003 (2009)
2. *Dynamical Casimir effect in superconducting microwave circuits*, JRJ et al., Phys. Rev. A 82, 052509 (2010)
3. *Observation of the Dynamical Casimir Effect in a Superconducting Circuit*, C.M. Wilson et al., Nature 479, 376 (2011)
4. *Nonclassical microwave radiation from the dynamical Casimir effect*, JRJ et al., arXiv:1207.1988 (2012)