Dynamical Casimir effect in quantum information processing and in quantum thermodynamics

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OUTLINE

Non-adiabatic regime (finite-time quantum electrodynamics): manifestations of the *dynamical Casimir effect*

Interaction between a qubit and a single mode of the field in the ultrastrong coupling regime: the rotating wave approximation cannot be applied (Rabi model)

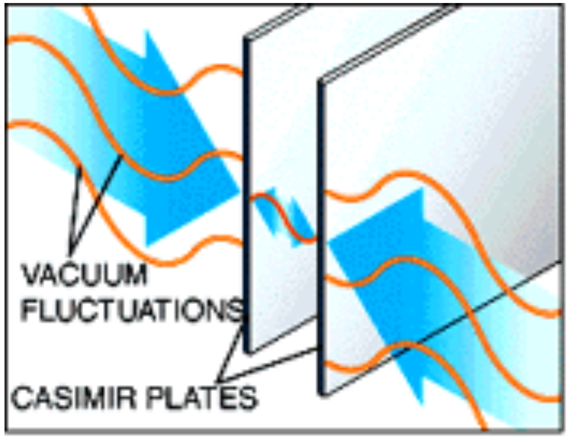
Dynamical Casimir effect as a fundamental limitation to the maximum speed of quantum protocols

Dynamical Casimir effect as fundamental limitation of cooling to absolute zero

(Static) Casimir effect

Casimir (1948): Two uncharged conducting parallel plates experience attractive forces

Effect explained in terms of quantum mechanical vacuum fluctuations of the electromagnetic field: The two plates impose boundary conditions on the field, so that the density of electromagnetic modes between the plates depend on their distance d.

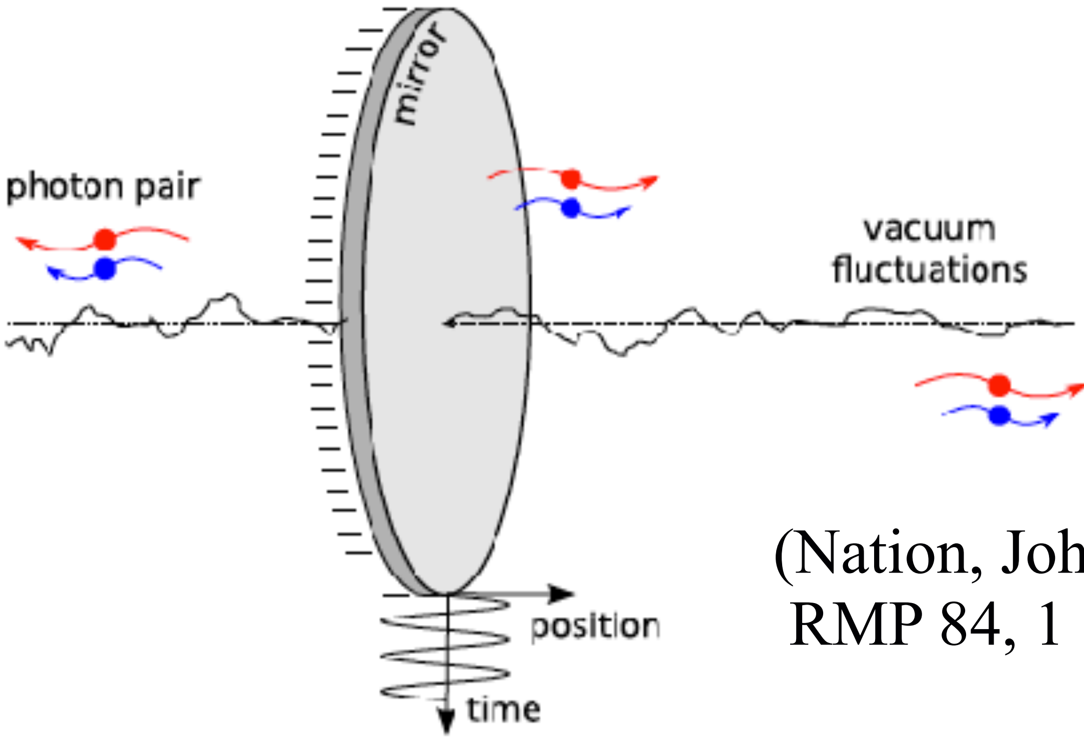


$$F \propto d^{-4}$$

Casimir effect important both for investigations in fundamental physics and for basic limitations of nanomechanical technologies

The dynamical Casimir effect

The dynamical Casimir effect concerns the generation of real photons from the vacuum due to time-dependent boundary conditions



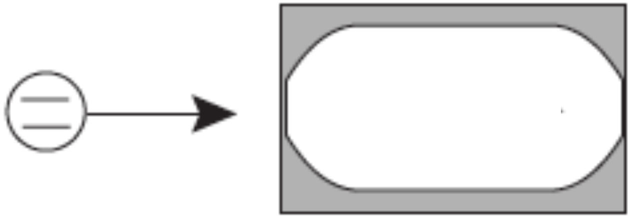
(Nation, Johansson, Blencowe, Nori, RMP 84, 1 (2012))

Related to other vacuum amplification effects, the Hawking radiation (radiation released by black holes) and Unruh effect (blackbody radiation observed by an accelerated observer)

Experimental observation in superconducting circuits (SQUIDs embedded in a cavity, with the effective length of the cavity modulated -at speeds of the few per cent of the speed of light- by time-varying the external flux)

(Wilson et al., Nature 479, 376 (2011); Lähteenmäki et al., PNAS 110, 4234 (2013))

Qubit-oscillator system



Rabi Hamiltonian with a switchable coupling:

$$H(t) = H_0 + H_I(t),$$

$$H_0 = -\frac{1}{2}\omega_a\sigma_z + \omega\left(a^\dagger a + \frac{1}{2}\right),$$

$$H_I(t) = f(t)\left[g\,\sigma_+\left(a^\dagger + a\right) + g^\star\sigma_-\left(a^\dagger + a\right)\right]$$

$$\sigma_+|g\rangle = |e\rangle,\ \sigma_+|e\rangle = 0,$$

$$\sigma_-|g\rangle = 0,\ \sigma_-|e\rangle = |g\rangle$$

$$a^\dagger|n\rangle = \sqrt{n+1}|n+1\rangle,$$

$$a|n\rangle = \sqrt{n}|n-1\rangle$$

Focus on the resonant case $(\omega = \omega_a)$

Rotating-wave approximation

RWA: neglect the term which simultaneously excites the two-level system and creates a photon or de-excites the two-level system and annihilates a photon

Jaynes-Cummings model:

$$H_I(t) = f(t)[g\sigma_+ a + g^\star \sigma_- a^\dagger]$$

For two-level atoms in a cavity the frequency of Rabi oscillations between states |g>|n> and |e>|n-1> is much smaller than the cavity frequency:

$$\Omega_n = g\sqrt{n} \ll \omega, \quad (\Omega \equiv \Omega_1 \sim 10^{-6}\omega)$$

Ultra-strong coupling regime

In circuit quantum electrodynamics the ultrastrong coupling regime can be achieved, with $\Omega > 0.1\,\omega$ (or even of the same order: Forn-Diaz et al. Nat. Phys. 13, 39 (2017); Yoshihara et al., Nat. Phys. 13, 44 (2017))

The RWA is no longer valid

This regime beyond the RWA is unavoidable in the search for fast quantum gates, to operate fault-tolerantly, with many gates within the decoherence time scale, or for fast quantum communication

New research direction on strongly correlated light-matter states

Differences with standard QED

A single mode of the field rather than an infinite number of modes is considered

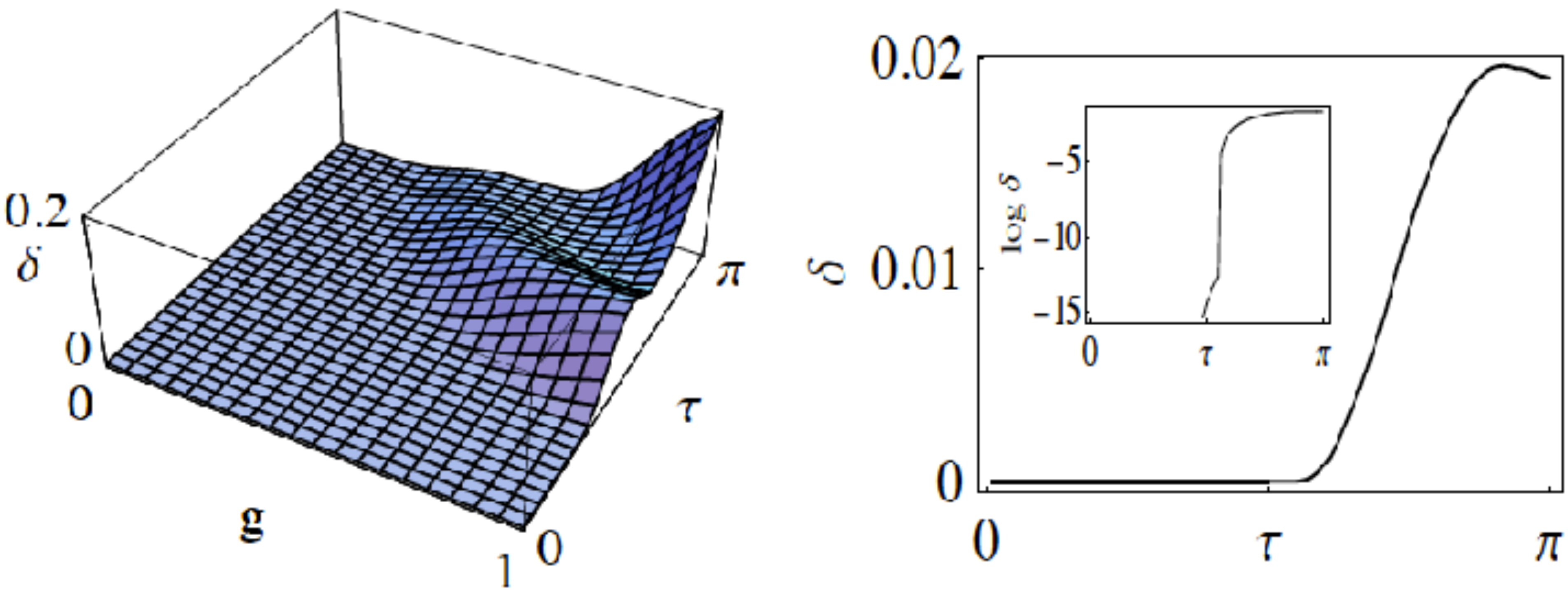
The quantization volume (of the cavity) is fixed and the limit of infinite volume is not taken at the end of the computation

Non-adiabaticity: the interaction is switched on abruptly and we focus on transient phenomena (finite-time QED)

Ultra-strong-coupling: Quantization volume much smaller than λ^3

Generation of non-classical field states

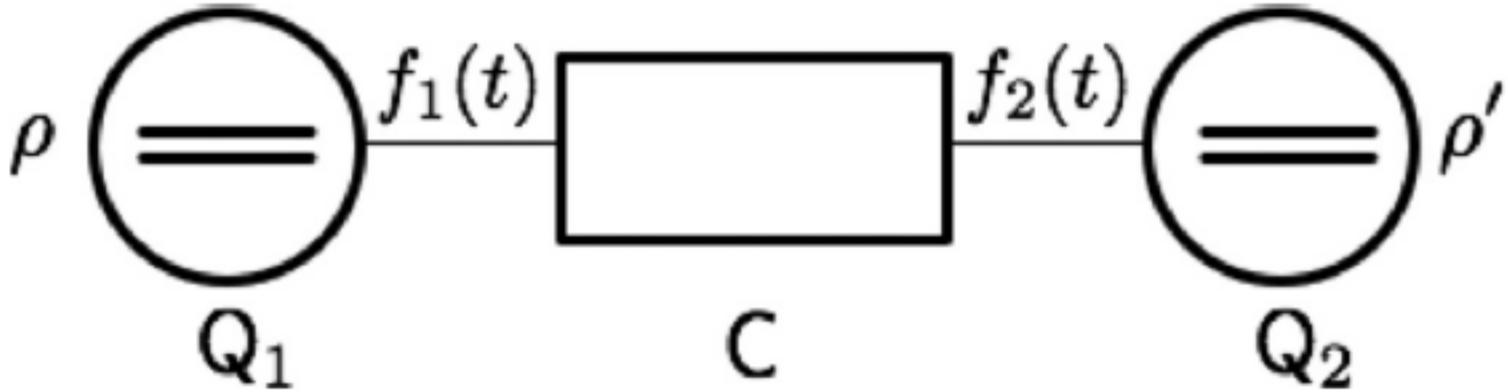
Negativity parameter $\delta = \int\int [\,|W(x,p)| - W(x,p)\,]\,dx\,dp$



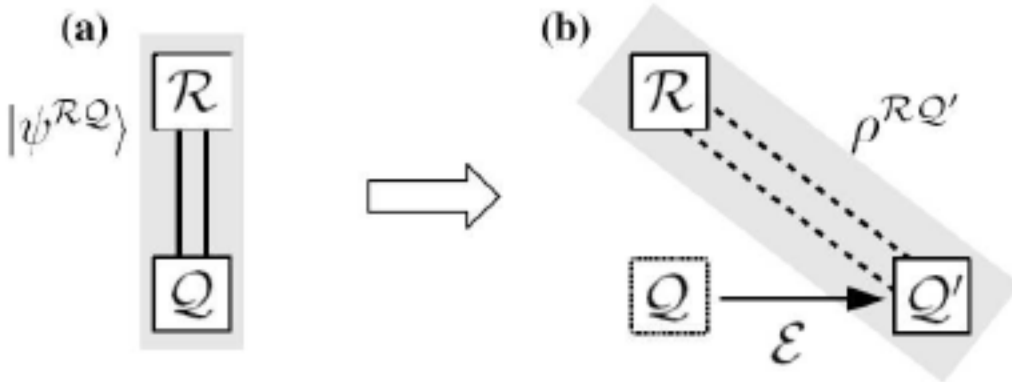
(G.B., S. Siccardi, G. Strini, EPJD 68, 139 (2014))

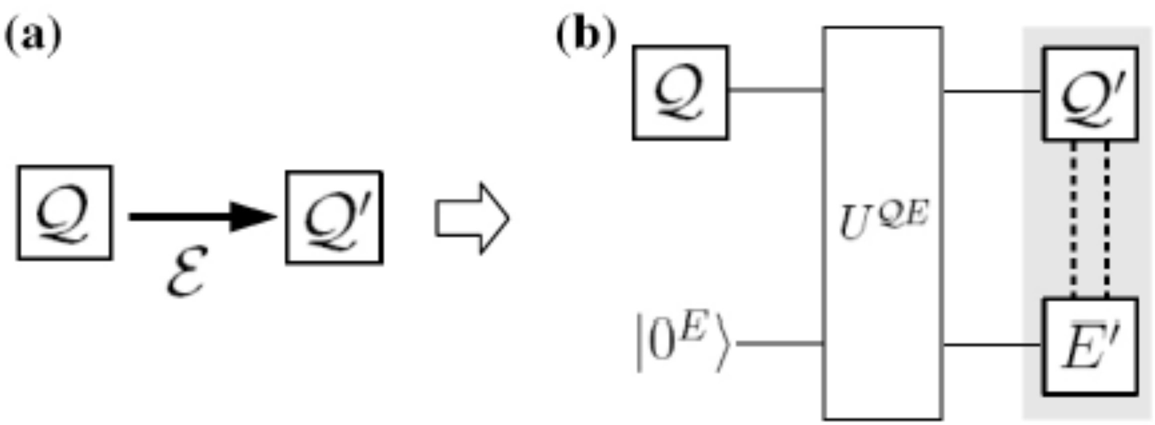
DCE in quantum information processing

Example: quantum communication protocol in the ultra strong coupling regime



Coherent information





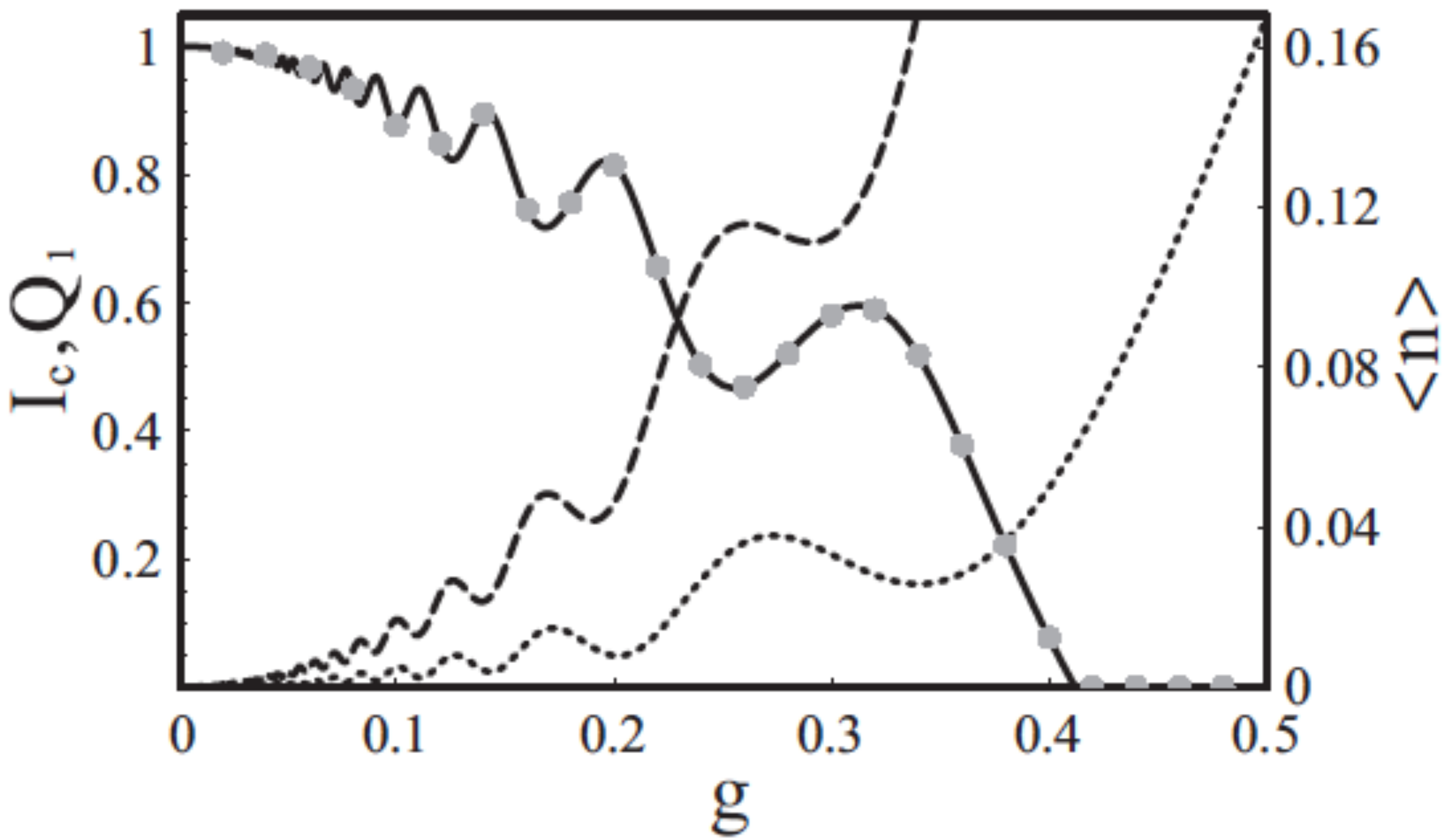
$$S_e = S_e(\rho, \mathcal{E}) = S(\rho^{E'})$$

entropy exchange

$$I_c(\rho, \mathcal{E}) = S[\mathcal{E}(\rho)] - S_e(\rho, \mathcal{E})$$

coherent information

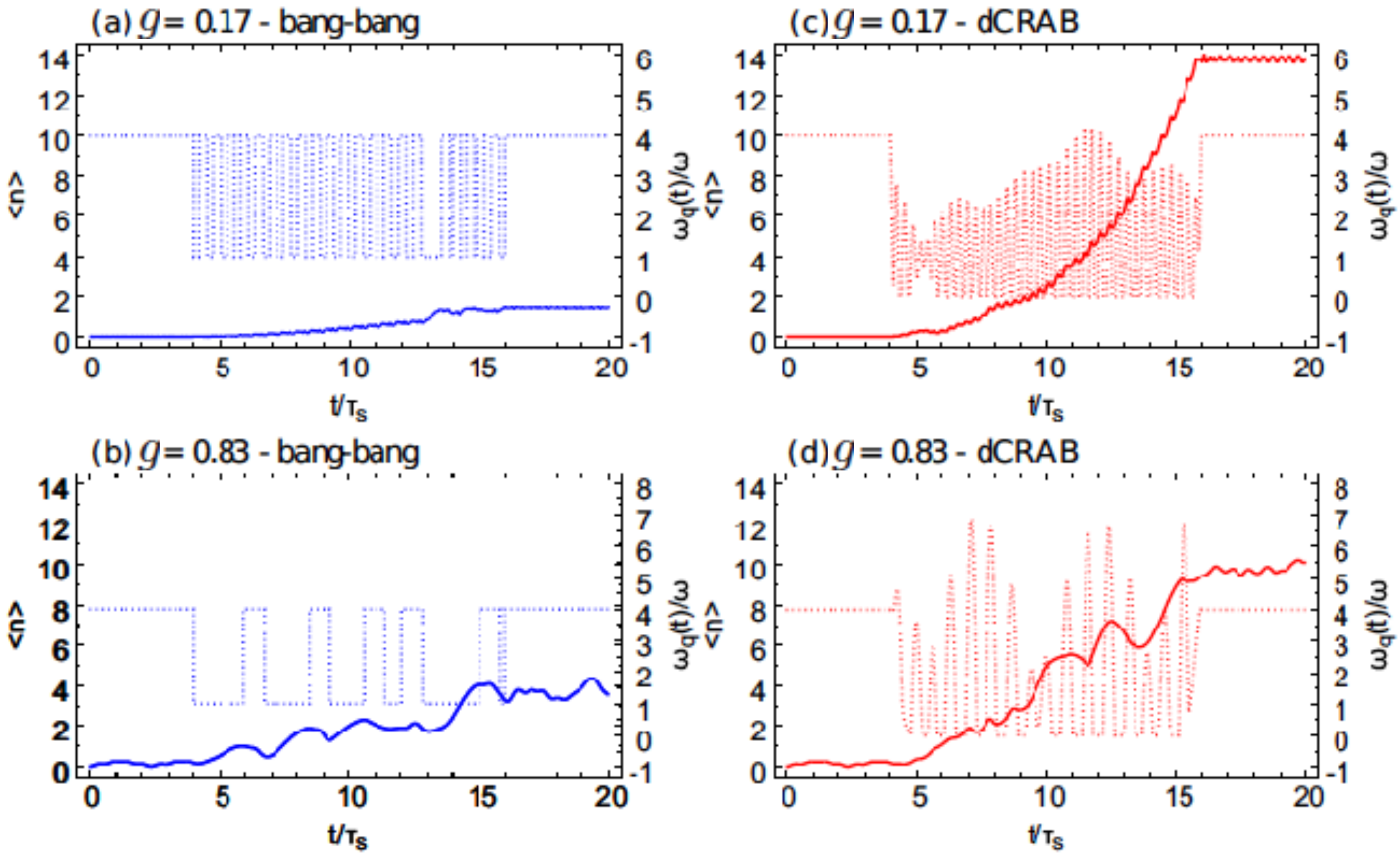
Connection between DCE and quantum protocol performance



Strategies to (partially) counteract the DCE needed (adabatic switching of the interaction, optimization of interaction times, …)

(G.B., A. D'Arrigo, S. Siccardi, G. Strini, PRA 90, 052313 (2014))

Amplification of the DCE via optimal control



(F. Hoeb, F. Angaroni, J. Zoller, T. Calarco, G. Strini, S. Montangero, G.B., PRA 96, 033851 (2017))

DCE and (finite-time) quantum thermodynamics

Nernst's unattainability principle (dynamical formulation of the third law of thermodynamics): it is impossible to cool a system to T=0 in finite time

Minimal model: a quit coupled to an oscillator (the working medium), shuttling heat to a hot reservoir (quantum Otto cycle)

- Matter-field interaction treated at the fundamental level of QED
- No master equations and/or RWA approximations

(Quantum) Otto cycle

(1) *Isochore* A $\to$ B: the working medium is in contact with the cold bath at temperature T_c; the work parameter, i.e., the oscillator frequency is maintained constant, $\omega(t) = \omega_c$.

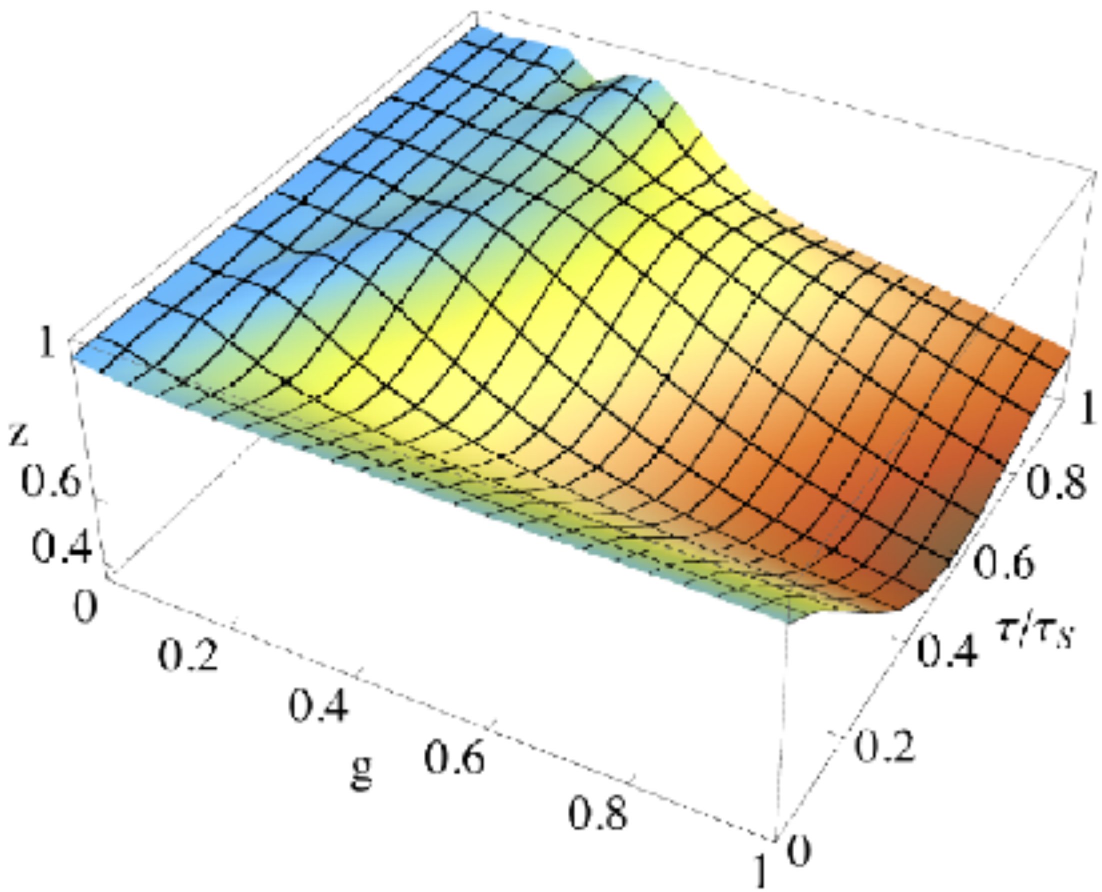
(2) *Adiabatic compression* B $\to$ C: the frequency $\omega(t)$ of the working medium changes in time from ω_c to ω_h.

(3) *Isochore* C $\to$ D: the working medium is in contact with the hot bath at temperature T_h; the oscillator frequency is constant, $\omega(t) = \omega_h$.

(4) *Adiabatic expansion* D $\to$ A: the frequency $\omega(t)$ changes from ω_h to ω_c.

Single stroke A⇒B

Most favourable instance:
$$\rho_q(0) = |g\rangle\langle g|,$$
$$\rho_o(0) = |0\rangle\langle 0|$$



Cyclic thermal machine

Most favourable instance: at the end of each cycle

$$\rho_o(0) = |0\rangle\langle 0|$$

Quantum map (collision model):

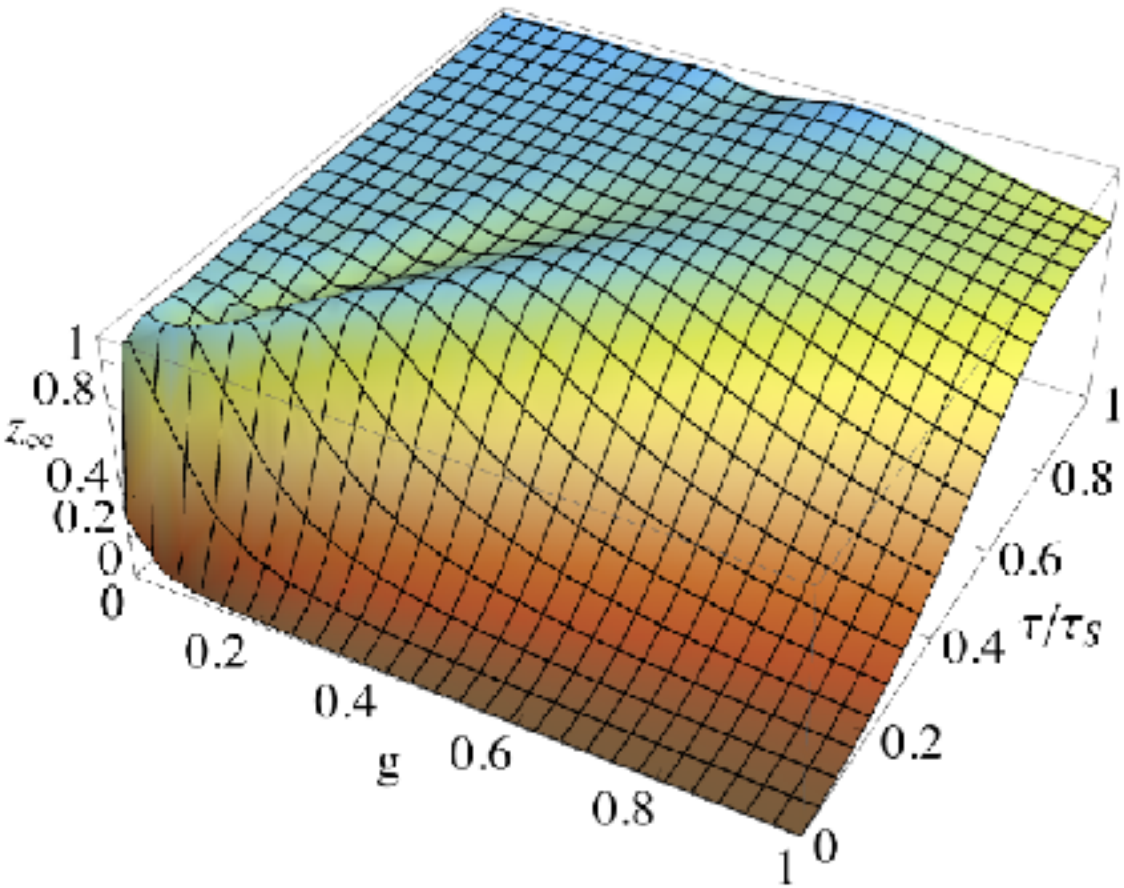
$$\rho_{q,n} = \mathrm{Tr}_o\left[U(\rho_{q,n-1} \otimes |0\rangle\langle 0)|U^\dagger\right]$$

$$\left[\frac{\mathbf{r}_n}{1}\right] = \mathcal{M}\left[\frac{\mathbf{r}_{n-1}}{1}\right] = \left[\begin{array}{c|c} \mathbf{M} & \mathbf{a} \\ \hline \mathbf{0}^T & 1 \end{array}\right]\left[\frac{\mathbf{r}_{n-1}}{1}\right],$$

$$\mathbf{M} = \begin{pmatrix} m_{xx} & m_{xy} & 0 \\ m_{yx} & m_{yy} & 0 \\ 0 & 0 & m_{zz} \end{pmatrix}, \quad \mathbf{a} = \begin{pmatrix} 0 \\ 0 \\ a_z \end{pmatrix}$$

Purely quantum limitation to cooling

The qubit thermalizes at non-zero temperature: for finite-time cycles, the T=0 limit is not achieved, also in the limit of infinite number of cycles



(G.B., G. Strini, PRA 91, 020502(R) (2015))

Summary

Interesting new physics in the ultrastrong (light-matter) coupling regime

Dynamical Casimir effect in finite-time quantum electrodynamics

DCE fundamental limitation for (ultrafast) quantum information processes

How to counteract DCE? Adiabatic switching of the interaction, optimal control,…

Relevance of the DCE in finite-time quantum thermodynamics