Consecuencias observables de las fluctuaciones cuánticas del vacío

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OUTLINE

OUT LINE

Zero point energy and vacuum effects

Dynamical Casimir in superconducting circuits

Non-contact quantum friction

Experimental proposal

New Ideas

ZERO – POINT ENERGY

ZERO-POINT ENERGY

- **1912** — **Planck** → Zero-point energy

$$E_0 = \frac{1}{2}\hbar\omega$$

- **1927** — **Heisenberg** → Uncertainty principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

- **1933** — **Pauli** → Arguments against the application of the zero-point energy to the EM field

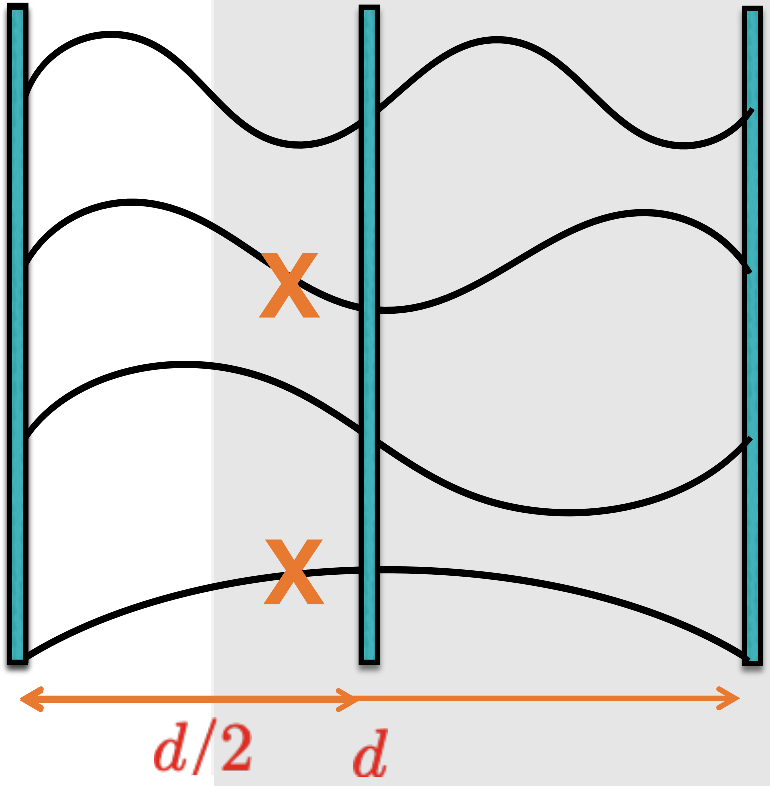
“At this point, it should be mentioned that it is more consistent not t… …e a zero-point energy of $\frac{1}{2}h\nu$ per degree of freedom, in contrast to the material oscillator. Because, on the one hand, this would lead to an infinitely large energy per unit volume due to the infinite number of degrees of freedom; on the other hand, this infinite energy

[4] W. Pauli, *Die allgemeinen Prinzipien der Wellenmechanik*, in H. Geiger, H. and K. Scheel (eds.), *Handbuch der Physik, Band 24/1* (Julius Springer, Berlin, 1933).

ZERO-POINT ENERGY

Fourier mode of the EM field with frequency ω ⟷ (Electromagnetic field) ⟷ Quantum harmonic oscillator with frequency ω

$$E_0 = \frac{1}{2}\hbar\omega$$



$$E(d/2) < E(d)$$

ATTRACTIVE FORCE!

CASIMIR EFFECT

CASIMIR
EFFECT

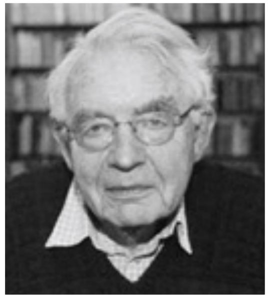
- Zero-point energy in vacuum

$$\rightarrow \quad E_0 = \sum_\lambda \frac{1}{2}\hbar\omega_\lambda = \infty$$

- Zero-point energy with boundaries

$$\rightarrow \quad E_0(d) = \sum_{\lambda'} \frac{1}{2}\hbar\omega_{\lambda'} = \infty$$

But $E_0 - E_0(d) \neq \infty$!



Hendrick Casimir (1948)

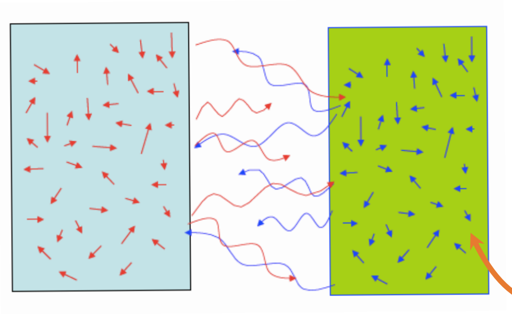
Lamoreaux experiment (1997)

$$\frac{F}{A} = -\frac{\pi^2}{240}\frac{\hbar c}{d^4}$$

- Casimir force between two perfectly conducting plates

Quantum vacuum fluctuations also produce forces:

- Between two atoms (Van der Waals force)
- Between and atom/particle and a plate (Casimir-Polder force)
- Between two imperfect mirrors



Charge and current fluctuations induced by the vacuum fluctuations

Alternative interpretation

QUANTUM VACUUM EFFECTS

How about direct observation of vacuum fluctuations?

→Amplification of vacuum fluctuations

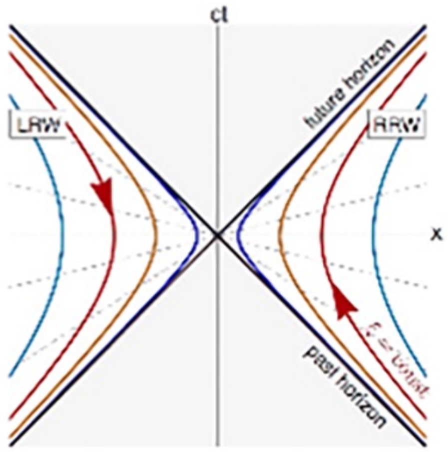
Vacuum fluctuations at the event horizon results in the breaking up of pairs of virtual particles. One is trapped in the BH and the other escapes to infinity

Hawking Radiation

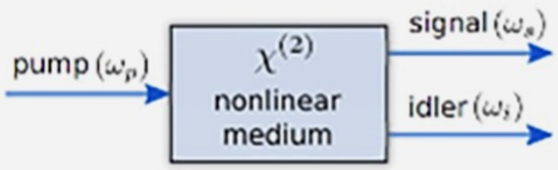
An accelerated observer in vacuum sees a field in a thermal state.

Vacuum fluctuations “promoted” to thermal fluctuations

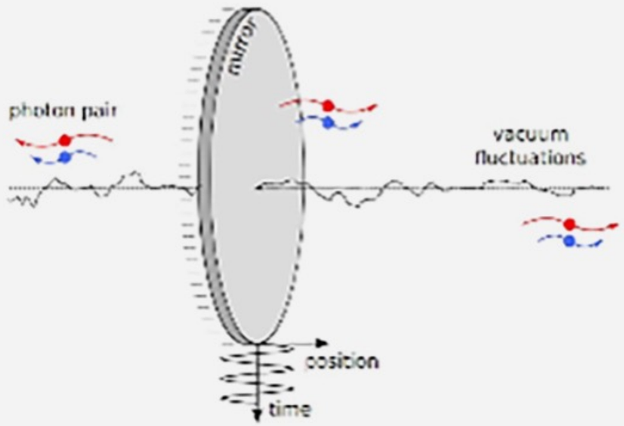
Unruh effect



Parametric amplifier



Dynamical Casimir effect



Note: HR and UE only involved an observer, which only detects the state of the field and does not affect the modes of the field as in DCE

A mirror undergoing nonuniform relativistic motion can modify the mode structure of vacuum non-adiabatically. Can result in the conversion of virtual photons (vacuum fluctuations) to real detectable photons.

DYNAMICAL CASIMIR EFFECT

Vacuum excitation due to time dependent external conditions

Accelerated neutral objects

↓

DISSIPATIVE FORCES

PHOTON CREATION

DYNAMICAL CASIMIR EFFECT

Vacuum excitation due to time dependent external conditions

Accelerated neutral objects

↓

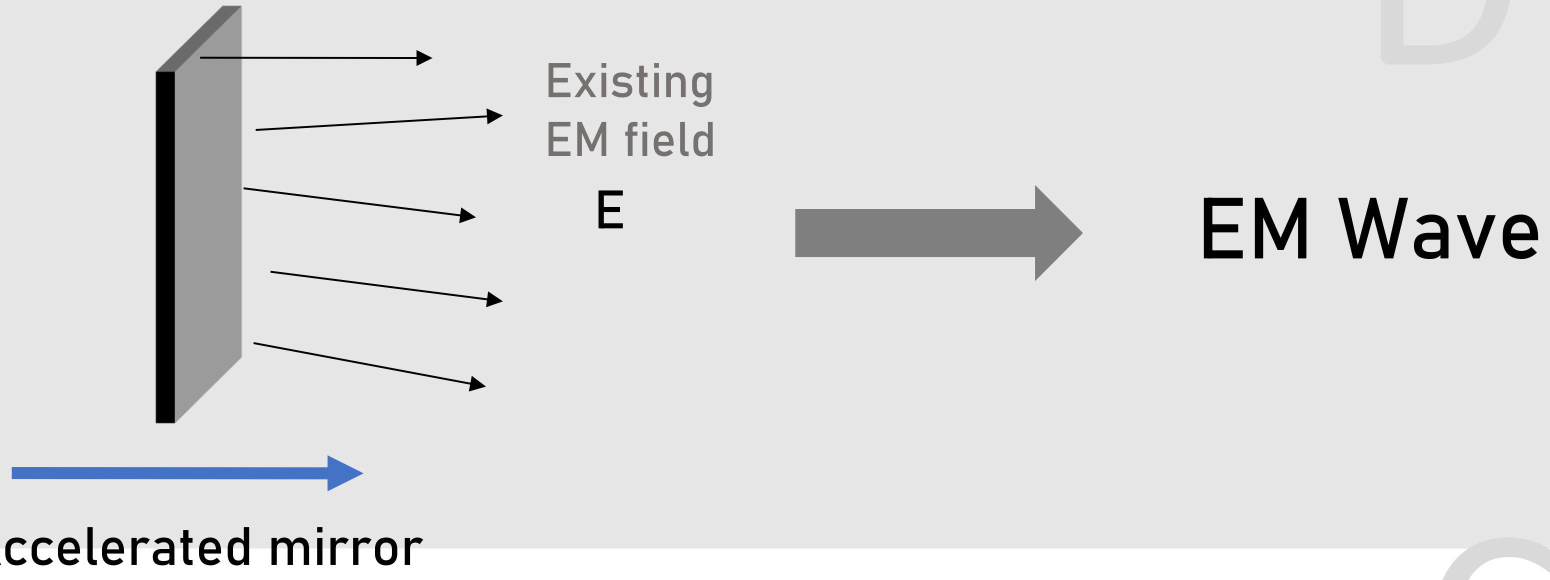
DISSIPATIVE FORCES

PHOTON CREATION

→ Variation of electromagnetic properties of the media (conductivity, permittivity, etc)

SOME INTUITION

classical

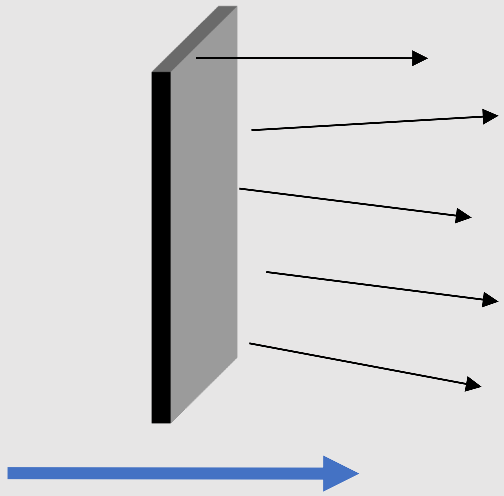


DYNAMICAL CASIMIR

SOME INTUITION

DYNAMICAL CASIMIR EFFECT

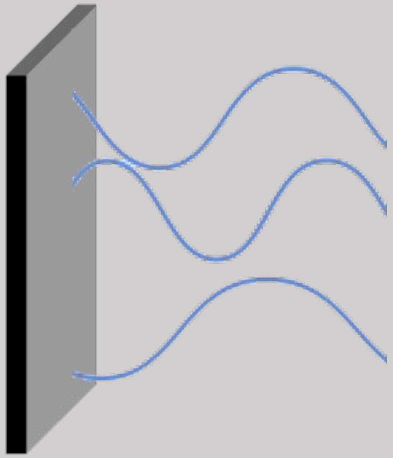
classical



Accelerated mirror

→ EM Wave

quantum



→ Photon creation

Reaction force on the mirror

OLD RESULTS FOR MOVING MIRRORS

Simplest case: massless scalar field in 1+1 D

Dirichlet boundary conditions

$$L = \frac{1}{2}\int_0^{L(t)} dx \left(\dot{\phi}^2 - \phi'^2\right)$$

$$\phi(t,0) = \phi(t, L(t)) = 0$$

Static equidistant spectrum

OLD RESULTS FOR MOVING MIRRORS

DYNAMICAL CASIMIR EFFECT

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$$\phi(t,0) = \phi(t, L(t)) = 0$$

Static equidistant spectrum

$$\phi(t,x) = \sum_n q_n(t) \sin\left(\frac{n\pi x}{L(t)}\right)$$

Instantaneous basis (useful for intermediate calculations, no intention to define N(t)!)

Set of coupled harmonic oscillators

SECULAR EFFECTS

external frequency = eigenfrequency

DYNAMICAL CASIMIR EFFECT

Equidistant spectrum

↓

All modes are coupled

↓

The number of particles created grows quadratically with t.

Total energy in the cavity grows exponentially (Dodonov & Klimov 1996)

DYNAMICAL CASIMIR EFFECT

More general boundary conditions

Massive case → non-equidistant spectrum

↓

posibility of parametric resonance for a single mode (or a few modes)

↓

exponential growth

Cavities in 3+1 dimensions

Villar & Soba, PRE 2017

Very difficult to observe…

Rate of photon production
by a single oscillating mirror
in vacuum

$$\frac{N}{T} = \frac{A}{60\pi^2}\frac{\Omega^3}{c^2}\left(\frac{v_{max}}{c}\right)^2$$

$$\frac{v_{max}}{c} = 10^{-7} \quad \Omega = 10GHz \quad A = 10cm^2$$

1 photon/day!!

Very difficult to observe…

Rate of photon production by a single oscillating mirror *in vacuum*

$$\frac{N}{T} = \frac{A}{60\pi^2}\frac{\Omega^3}{c^2}\left(\frac{v_{max}}{c}\right)^2$$

$$\frac{v_{max}}{c} = 10^{-7} \quad \Omega = 10GHz \quad A = 10cm^2$$

1 photon/day!!

For *cavities* the situation is better due to parametric resonace… but still difficult

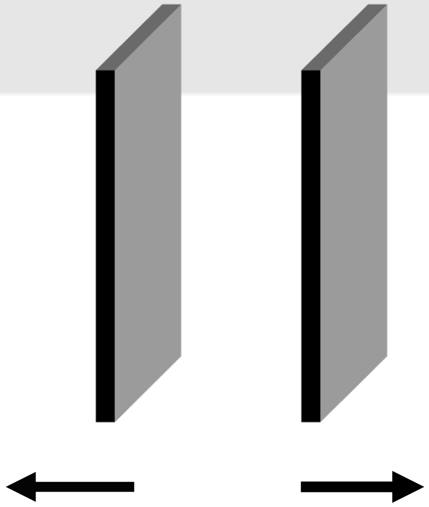
$$N = e^{\eta\epsilon\Omega t}, \eta = O(1)$$

$$N_{max} \simeq e^{\epsilon Q} \leq e^{10^{-8}Q}$$

- In order to produce 5 GHz photons, we need mechanical oscillations with 10GHz
- Actual limit: 6GHz

DYNAMICAL CASIMIR EFFECT

2 moving mirrors → "interference" effects in the particle creation rate



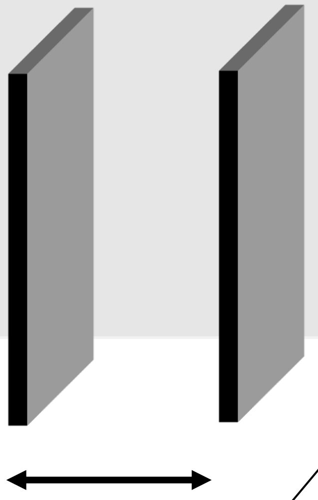
"breathing" mode

"shaker" mode

Mainly studied for Dirichlet fields in 1+1

Dalvit & Mazzitelli (1999) – Villar, Soba & F.C.L. (fully numerical approach (2017)

DYNAMICAL CASIMIR EFFECT



Secular behaviour for integer values of q

$$L(t) = \epsilon A_L \sin\left(\frac{q\pi t}{\Lambda}\right) \equiv 0 + \epsilon\delta L(t)$$

$$R(t) = \Lambda - \epsilon A_R \sin(\phi) + \epsilon A_R \sin\left(\frac{q\pi t}{\Lambda} + \phi\right) \equiv \Lambda + \epsilon\delta R(t)$$

when a or b do not vanish

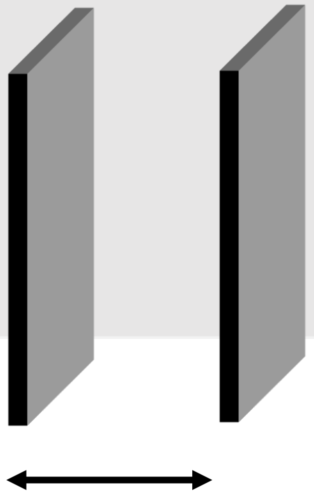
$$a \equiv \frac{\epsilon}{\Lambda}\frac{\pi}{2}\left[\frac{A_L}{\Lambda} + \frac{A_R}{\Lambda}(-1)^{q+1}\cos(\phi)\right]$$

$$b \equiv \frac{\epsilon}{\Lambda}\frac{\pi}{2}\frac{A_R}{\Lambda}(-1)^{q+1}\sin(\phi).$$

Method: conformal transformation → Moore equation → RG improved solution

Dalvit & Mazzitelli (1999) – Villar, Soba & Lombardo (2017)

Mirrors



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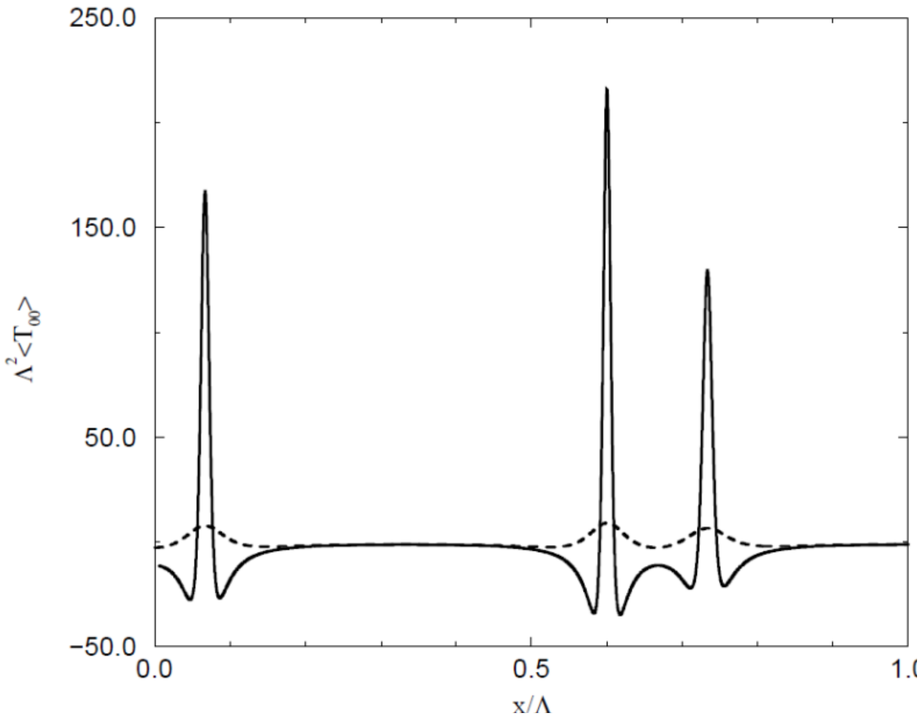
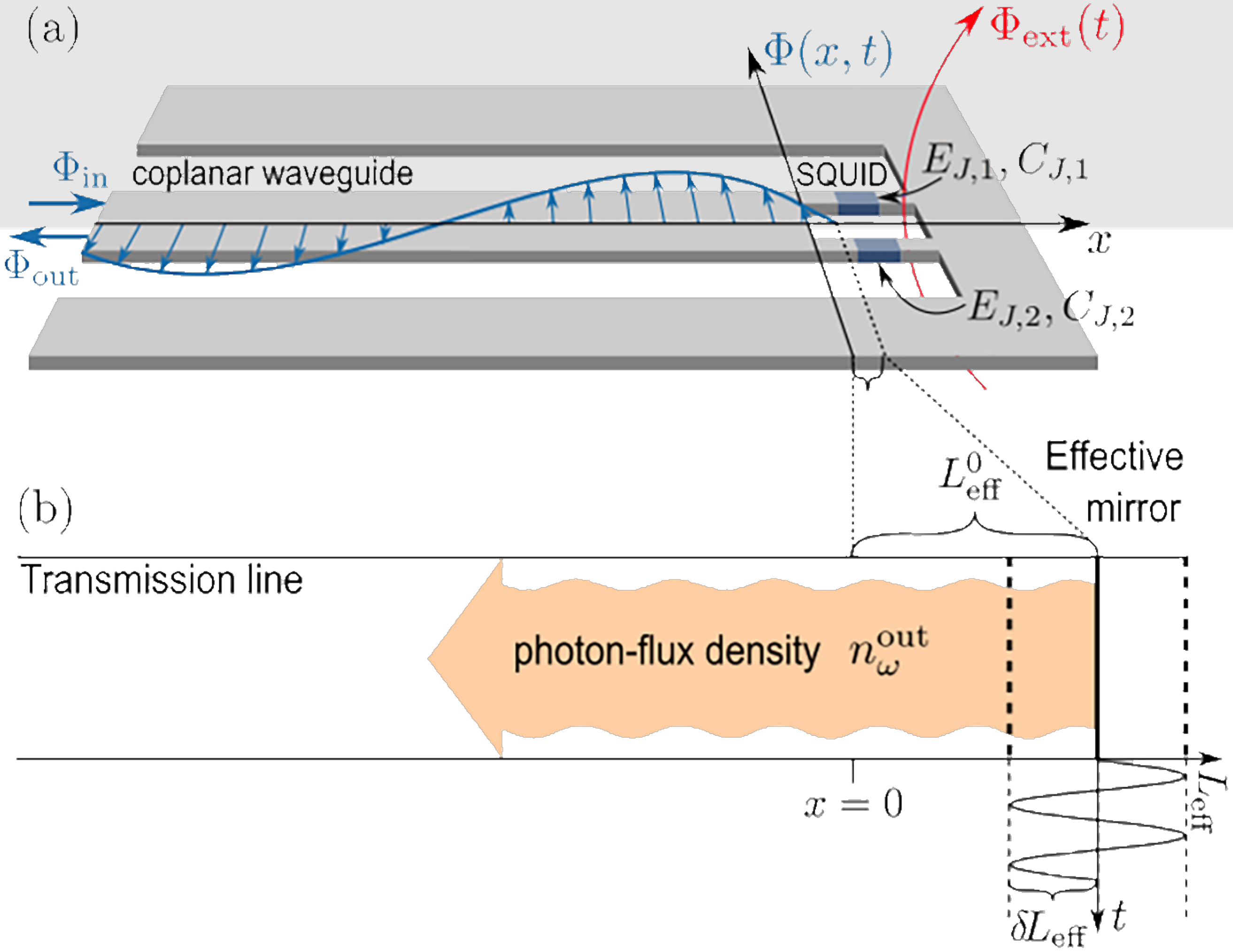


shaker mode, q=3 (compared with 1 mirror oscilation)

Dalvit & Mazzitelli 1999

EXPERIMENTAL VERIFICATION OF DCE (2011)

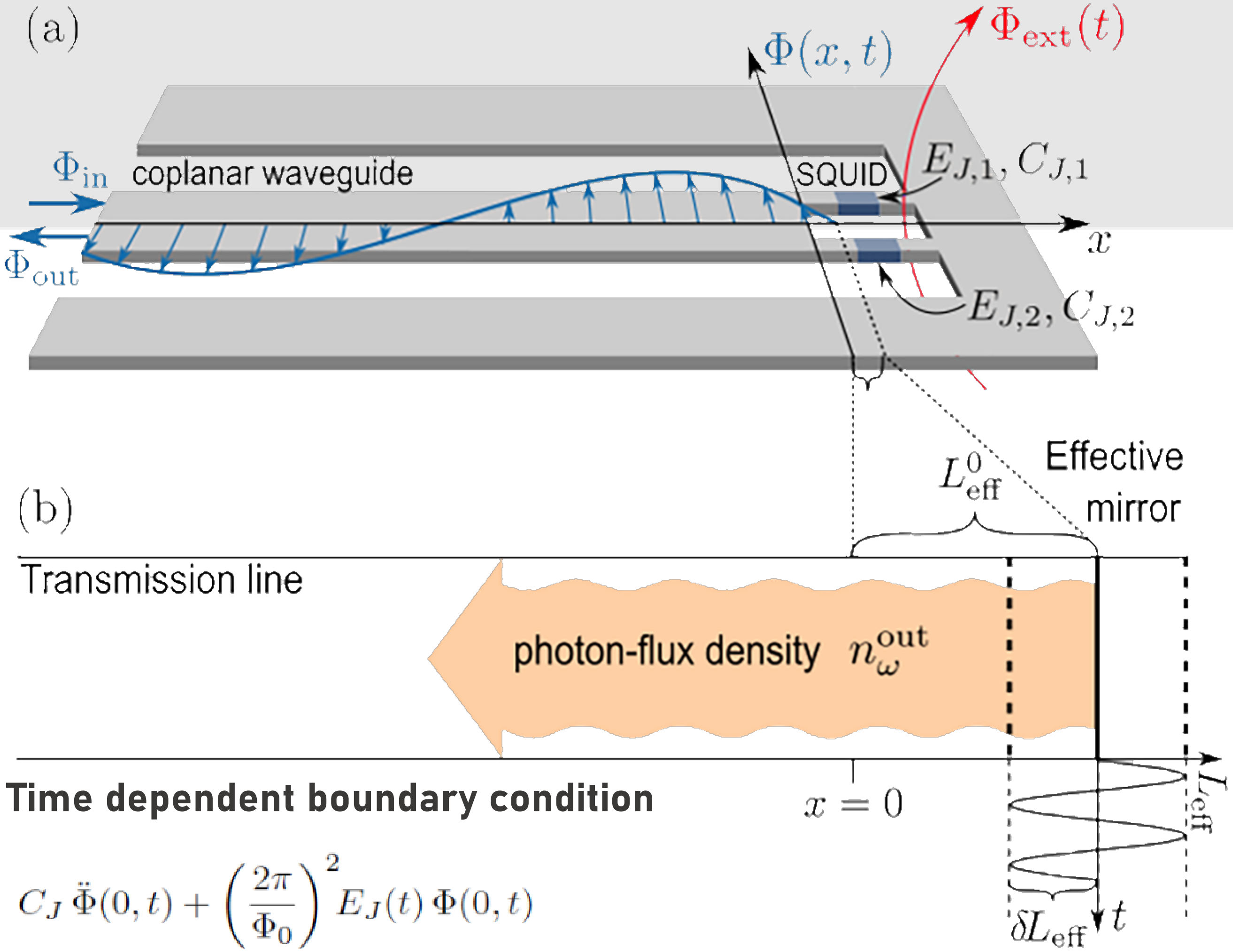
By applying a time-dependent magnetic flux through the SQUID we get a time-dependent inductance, which in turn produces a time-dependent boundary condition for the field in the waveguide



Modulated inductance of SQUID at high frequencies (> 10 GHz)

Wilson et al, 2011

Circuit QED

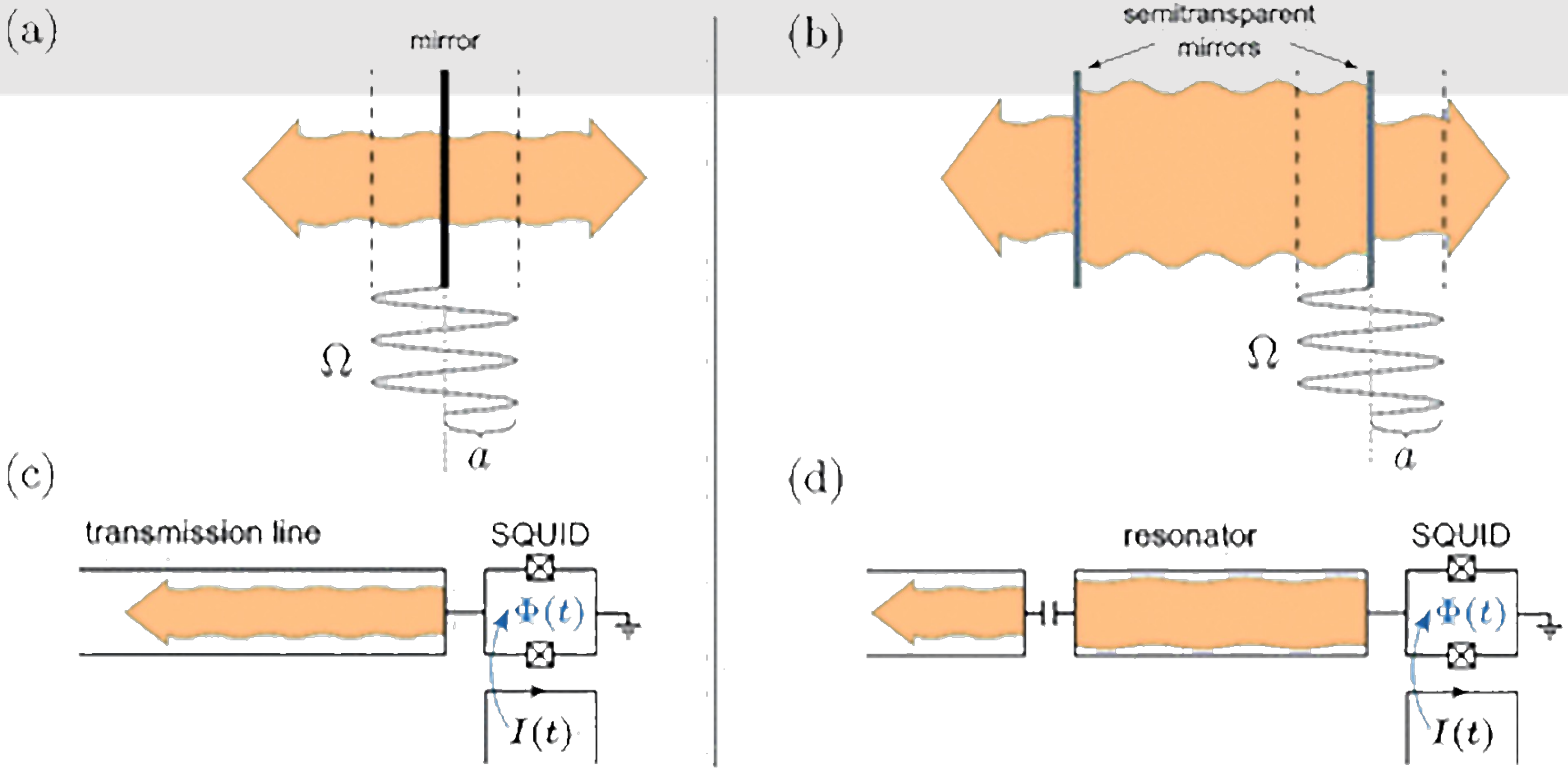


Time dependent boundary condition

$$C_J \, \ddot{\Phi}(0,t) + \left(\frac{2\pi}{\Phi_0}\right)^2 E_J(t)\,\Phi(0,t) + \frac{1}{L_0}\,\frac{\partial \Phi(x,t)}{\partial x}\bigg|_{x=0} = 0$$

Wilson et al, 2011

DIFFERENT EXPERIMENTAL REALIZATIONS OF DCE



Circuit QED

MORE RECENT EXPERIMENTAL RESULTS
(doubly tunable resonator)

- **Particle creation with simultaneous excitation of both SQUIDs**
- **Observation of interference effects.**

DYNAMICAL CASIMIR EFFECT

$$\Omega_L = \Omega_R = 2k_n$$

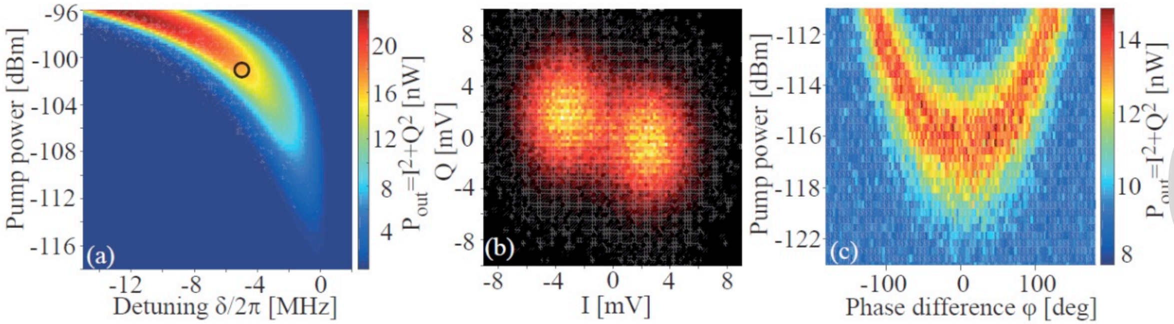


Figure 3. (a) Photon down-conversion. Measured with a single pump applied to the left flux line at the bias point $(0.3, 0.3)\,\Phi_0$. (b) Histogram taken at the point marked with a black circle in (a). We measure two π-shifted states. (c) Double-pump measurement, where the phase difference, φ between the pump signals is varied. Here the SQUID bias is $(0.2, 0.2)\,\Phi_0$ and the generated radiation for $\delta = -1\,\mathrm{MHz}$ is displayed.

Svensson et al 2018

DOUBLY TUNABLE SUPERCONDUCTING CAVITY

Model

Scalar field in the cavity

$$L_{\text{cav}} = \left(\frac{\hbar}{2e}\right)^2 \frac{C_0}{2} \int_0^d dx \left(\dot{\phi}^2 - v^2 \phi'^2\right) + \left[\left(\frac{\hbar}{2e}\right)^2 \frac{2C_J^L}{2} \dot{\phi}_0^2 - E_J^L \cos f^L(t) \phi_0^2\right]$$
$$+ \left[\left(\frac{\hbar}{2e}\right)^2 \frac{2C_J^R}{2} \dot{\phi}_d^2 - E_J^R \cos f^R(t) \phi_d^2\right]$$

SQUIDs at x=0 and x=d

$\phi_0 = \phi(t, 0) \qquad \phi_d = \phi(t, d)$

Wustmann Shumeiko 2013

DYNAMICAL CASIMIR EFFECT

Model

Scalar field in the cavity

$$L_{\mathrm{cav}} = \left(\frac{\hbar}{2e}\right)^2 \frac{C_0}{2} \int_0^d dx \left(\dot{\phi}^2 - v^2 \phi'^2\right) + \left[\left(\frac{\hbar}{2e}\right)^2 \frac{2C_J^L}{2} \dot{\phi}_0^2 - E_J^L \cos f^L(t) \phi_0^2\right]$$
$$+ \left[\left(\frac{\hbar}{2e}\right)^2 \frac{2C_J^R}{2} \dot{\phi}_d^2 - E_J^R \cos f^R(t) \phi_d^2\right]$$

Phases across the SQUIDs controlled by external magnetic fluxes

SQUIDs at x=0 and x=d

$\phi_0 = \phi(t, 0) \qquad \phi_d = \phi(t, d)$

Wustmann Shumeiko 2013

Model

Scalar field in the cavity

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Phases across the SQUIDs controlled by external magnetic fluxes

SQUIDs at x=0 and x=d

$$\phi_0 = \phi(t,0) \qquad \phi_d = \phi(t,d)$$

Quantum field in 1+1 dimensions with terms localized on the borders

Wustmann Shumeiko 2013

Model

Setting $v = 1/\sqrt{L_0 C_0} \equiv 1$, $C_J^L = C_L^R = C_J$, $E_C = (2e)^2/(2C_J)$ and $E_{L,\mathrm{cav}} = (\hbar/2e)^2(1/L_0 d)$ we have

$$\ddot{\phi} - \phi'' = 0\,,$$

with the "boundary conditions"

$$\frac{\hbar^2}{E_C}\ddot{\phi}_0 + 2E_J^L \cos f^L(t)\phi_0 + E_{\mathrm{L,cav}} d\phi_0' = 0$$

$$\frac{\hbar^2}{E_C}\ddot{\phi}_d + 2E_J^R \cos f^R(t)\phi_d + E_{\mathrm{L,cav}} d\phi_d' = 0$$

DYNAMICAL CASIMIR EFFECT

Model

Setting $v = 1/\sqrt{L_0 C_0} \equiv 1$, $C_J^L = C_L^R = C_J$, $E_C = (2e)^2/(2C_J)$ and $E_{L,\mathrm{cav}} = (\hbar/2e)^2(1/L_0 d)$ we have

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$$\frac{\hbar^2}{E_C}\ddot{\phi}_d + 2E_J^R \cos f^R(t)\phi_d + E_{\mathrm{L,cav}} d\phi_d' = 0$$

Unusual boundary conditions ⟷ localized degrees of freedom

Neglecting this term → time dependent Robin boundary conditions → Approximate Dirichlet boundary conditions on a time dependent position

$$\phi(t,d) + L_{eff}(t)\phi'(t,d) \simeq \phi(t, d + L_{eff}(t)) = 0$$

PARTICLE CREATION IN A DOUBLY TUNABLE CAVITY

Particle creation

$$f^{L,R}(t) = f_0^{L,R} + \theta(t)\theta(t_F - t)\epsilon_{L,R}\sin(\Omega_{L,R}t + \phi_{L,R})$$

← Time dependent magnetic flux

$$\phi(x,t) = \frac{2e}{\hbar}\sqrt{\frac{2}{C_0 d}}\sum_n q_n(t)\cos(k_n x + \varphi_n)$$

← Expansion of the field in terms of modes of the static cavity

$$k_n d\tan(k_n d + \varphi_n) = \frac{2E_J^R\cos f_0^R}{E_{\mathrm{L,cav}}} - \frac{2C_J}{C_0 d}(k_n d)^2$$

$$k_n d\tan\varphi_n = -\frac{2E_J^L\cos f_0^L}{E_{\mathrm{L,cav}}} + \frac{2C_J}{C_0 d}(k_n d)^2$$

← Equations that define the static spectrum

Lombardo, Mazzitelli, Soba & Villar 2018

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Equations that define the static spectrum

Insert in the Lagrangian → set of coupled harmonic oscillators

Lombardo, Mazzitelli, Soba & Villar 2018

FIELD EQUATION

$$\ddot{q}_n + k_n^2 q_n = \frac{2V_0^R}{d^2 M_n}\epsilon_R \theta(t)\theta(t_F - t)\sin(f_0^R)\sin(\Omega_R t + \phi_R)\cos(k_n d + \varphi_n)\sum_m q_m(t)\cos(k_m d + \varphi_m)$$

$$+ \frac{2V_0^L}{d^2 M_n}\epsilon_L \theta(t)\theta(t_F - t)\sin(f_0^L)\sin(\Omega_L t + \phi_L)\cos\varphi_n \sum_m q_m(t)\cos\varphi_m,$$

Particle creation

with

$$M_n = 1 + \frac{\sin[2(k_n d + \varphi_n)]}{2k_n d} - \frac{\sin 2\varphi_n}{2k_n d} + 2\chi_0 \cos^2(k_n d + \varphi_n)$$

and $\chi_0 = 2C_J/(C_0 d)$, $V_0^{L,R} = 2E_J^{L,R}/E_{\mathrm{L,cav}}$, $\epsilon_{L,R} \ll 1$.

$$\ddot{q}_n + k_n^2 q_n = \frac{2V_0^R}{d^2 M_n}\epsilon_R \theta(t)\theta(t_F - t)\sin(f_0^R)\sin(\Omega_R t + \phi_R)\cos(k_n d + \varphi_n)\sum_m q_m(t)\cos(k_m d + \varphi_m)$$

$$+ \frac{2V_0^L}{d^2 M_n}\epsilon_L \theta(t)\theta(t_F - t)\sin(f_0^L)\sin(\Omega_L t + \phi_L)\cos\varphi_n \sum_m q_m(t)\cos\varphi_m,$$

Particle creation

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and $\chi_0 = 2C_J/(C_0 d)$, $V_0^{L,R} = 2E_J^{L,R}/E_{\mathrm{L,cav}}$, $\epsilon_{L,R} \ll 1$.

$$\hat{q}_n(t) = \hat{a}_n^{in}\frac{e^{-ik_n t}}{\sqrt{2k_n}} + \hat{a}_n^{in\dagger}\frac{e^{ik_n t}}{\sqrt{2k_n}} \quad t < 0$$

Heisenberg representation

$$\hat{q}_n(t) = \hat{a}_n^{out}\frac{e^{-ik_n t}}{\sqrt{2k_n}} + \hat{a}_n^{out\dagger}\frac{e^{ik_n t}}{\sqrt{2k_n}} \quad t < t_F$$

$$\hat{a}_n^{out} = \sum_m (\alpha_{nm}\hat{a}_m^{in} + \beta_{nm}^* \hat{a}_m^{in\dagger})$$

Bogoliubov transformation

Number of particles in mode n

$$N_n = \langle 0_{in}|a_n^{out\,\dagger} a_n^{out}|0_{in}\rangle = \sum_m |\beta_{nm}|^2$$

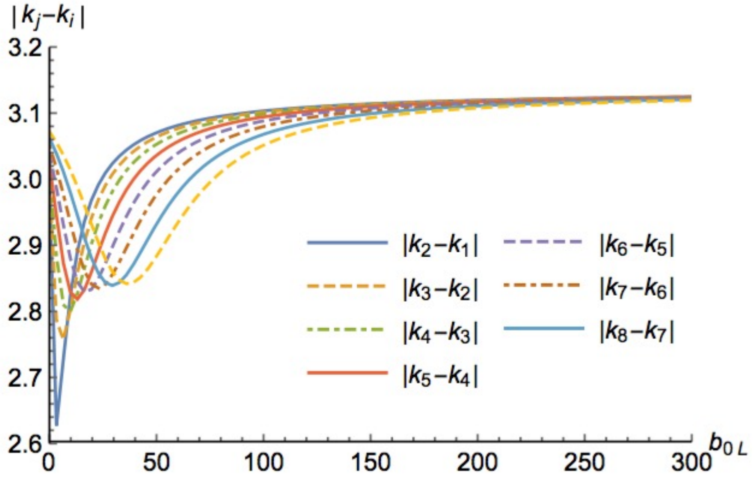
SPECTRUM

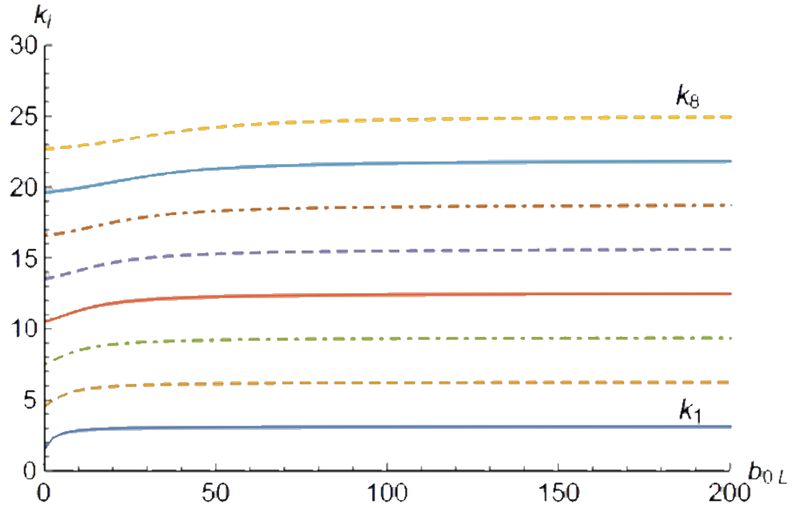
$$(k_n d)\tan(k_n d + \varphi_n) + \chi_0 (k_n d)^2 = b_0^R$$
$$-(k_n d)\tan\varphi_n + \chi_0 (k_n d)^2 = b_0^L$$

$$b_0^{L,R} = V_0^{L,R}\cos f_0^{L,R}$$

Nonequidistant spectrum unless

$$b_0^{L,R} \gg 1$$





$$b_0^R = 500 \quad \chi_0 = 0.05$$

SPECTRUM: SUMMARY

- The spectrum is determined by the static parameters of the SQUID's
- Parameters can be adjusted to have equidistant or non-equidistant spectra
- The space of parameters is richer and easier to adjust compared with the case of mirrors (would involve a manipulation of their electromagnetic properties)

ANALYTICAL RESULTS

Particle creation

$$\ddot{q}_n + \omega_n^2(t) q_n = \sum_{m \neq n} \sum_j S_{nm}^{(j)} \sin(\Omega_j t + \phi_j)\,, \quad j = L, R$$

$$\omega_n^2(t) = k_n^2 - \sum_j \alpha_n^{(j)} \sin(\Omega_j t + \phi_j)$$

$$S_{mn}^R = \frac{2V_0^R}{d^2\sqrt{M_n M_m}} \epsilon_R \sin f^R(0) \cos\left(k_n d + \varphi_n\right) \cos\left(k_m d + \varphi_m\right)$$

$$S_{mn}^L = \frac{2V_0^L}{d^2\sqrt{M_n M_m}} \epsilon_L \sin f^L(0) \cos\varphi_n \cos\varphi_m$$

$$\alpha_n^R = \frac{2V_0^R}{d^2 M_n} \epsilon_R \sin f^R(0) \cos^2(k_n d + \varphi_n)$$

$$\alpha_n^L = \frac{2V_0^L}{d^2 M_n} \epsilon_L \sin f^L(0) \cos^2(\varphi_n).$$

Particle creation

$$\ddot{q}_n + \omega_n^2(t) q_n = \sum_{m\neq n} \sum_j S_{nm}^{(j)} \sin(\Omega_j t + \phi_j), \quad j = L, R$$

external frequencies and phases

$$\omega_n^2(t) = k_n^2 - \sum_j \alpha_n^{(j)} \sin(\Omega_j t + \phi_j)$$

$$S_{mn}^R = \frac{2V_0^R}{d^2\sqrt{M_n M_m}} \epsilon_R \sin f^R(0) \cos(k_n d + \varphi_n) \cos(k_m d + \varphi_m)$$

$$S_{mn}^L = \frac{2V_0^L}{d^2\sqrt{M_n M_m}} \epsilon_L \sin f^L(0) \cos\varphi_n \cos\varphi_m$$

$$\alpha_n^R = \frac{2V_0^R}{d^2 M_n} \epsilon_R \sin f^R(0) \cos^2(k_n d + \varphi_n)$$

$$\alpha_n^L = \frac{2V_0^L}{d^2 M_n} \epsilon_L \sin f^L(0) \cos^2(\varphi_n).$$

All couplings depend nontrivially on the parameters of the SQUIDs

Method of multiple scales (MSA)

$$q_n(t,\tau) = A_n(\tau)\frac{e^{-ik_n t}}{\sqrt{2k_n}} + B_n(\tau)\frac{e^{ik_n t}}{\sqrt{2k_n}}$$ → $\tau = \epsilon t$ → Average over fast oscillations

Particle creation

$$4k_n\frac{dA_n}{dt} = -B_n\sum_j \alpha_n^{(j)}\delta(\Omega_j - 2k_n)e^{-i\phi_j} + \sum_{m\neq n}\sum_j S_{mn}^{(j)}[A_m\left(\delta(\Omega_j - k_m + k_n)e^{i\phi_j} - \delta(\Omega_j + k_m - k_n)e^{-i\phi_j}\right) - B_m\delta(\Omega_j - k_n - k_m)e^{-i\phi_j}]$$

$$4k_n\frac{dB_n}{dt} = -A_n\sum_j \alpha_n^{(j)}\delta(\Omega_j - 2k_n)e^{i\phi_j} - \sum_{m\neq n}\sum_j S_{mn}^{(j)}[B_m\left(\delta(\Omega_j + k_m - k_n)e^{i\phi_j} - \delta(\Omega_j + k_n - k_m)e^{-i\phi_j}\right) + A_m\delta(\Omega_j - k_n - k_m)e^{i\phi_j}]$$

Resonance conditions

$$\Omega_{L,R} = 2k_n \quad \Omega_{L,R} = |k_n \pm k_j|$$

A single resonant mode: $\Omega_L = \Omega_R = 2k_n$

$$4k_n \frac{dA_n}{dt} = -B_n[\alpha_n^L + \alpha_n^R e^{-i\phi_R}]$$
$$4k_n \frac{dB_n}{dt} = -A_n[\alpha_n^L + \alpha_n^R e^{-i\phi_R}]$$

Exponential growth with a rate:

$$\Gamma_n = \frac{1}{4k_n}\sqrt{(\alpha_n^R)^2 + (\alpha_n^L)^2 + 2\alpha_n^R\alpha_n^L \cos\phi_R}$$

$$N_n \simeq e^{\Gamma_n t} = e^{\eta\Omega\epsilon t} \qquad \eta = O(1)$$

A single resonant mode: $\Omega_L = \Omega_R = 2k_n$

$$4k_n \frac{dA_n}{dt} = -B_n[\alpha_n^L + \alpha_n^R e^{-i\phi_R}]$$

$$4k_n \frac{dB_n}{dt} = -A_n[\alpha_n^L + \alpha_n^R e^{-i\phi_R}]$$

Exponential growth with a rate:

$$\Gamma_n = \frac{1}{4k_n}\sqrt{(\alpha_n^R)^2 + (\alpha_n^L)^2 + 2\alpha_n^R\alpha_n^L \cos\phi_R}$$

Interference due to phase difference of external magnetic fluxes

Two resonant modes: $\Omega_L = \Omega_R = k_m + k_n$

Coupled A-B eqns

$$4k_n \frac{dA_n}{dt} = -B_m(S^L_{mn} + S^R_{mn} e^{-i\phi_R})$$

$$4k_m \frac{dB_m}{dt} = -A_n(S^L_{mn} + S^R_{mn} e^{i\phi_R})$$

Coupled A-B eqns

$$4k_m \frac{dA_m}{dt} = -B_n(S^L_{mn} + S^R_{mn} e^{-i\phi_R})$$

$$4k_n \frac{dB_n}{dt} = -A_m(S^L_{mn} + S^R_{mn} e^{i\phi_R}) \,.$$

Exponential growth with a rate $\frac{|\Gamma_{mn}|}{4\sqrt{k_m k_n}}$

$$\Gamma_{mn} = S^L_{mn} + S^R_{mn} e^{-i\phi_R}$$

Two resonant modes: $\Omega_L = \Omega_R = k_m + k_n$

Coupled
A-B eqns

$$4k_n \frac{dA_n}{dt} = -B_m(S^L_{mn} + S^R_{mn} e^{-i\phi_R})$$

$$4k_m \frac{dB_m}{dt} = -A_n(S^L_{mn} + S^R_{mn} e^{i\phi_R})$$

Coupled
A-B eqns

$$4k_m \frac{dA_m}{dt} = -B_n(S^L_{mn} + S^R_{mn} e^{-i\phi_R})$$

$$4k_n \frac{dB_n}{dt} = -A_m(S^L_{mn} + S^R_{mn} e^{i\phi_R})\,.$$

Exponential growth
with a rate $\dfrac{|\Gamma_{mn}|}{4\sqrt{k_m k_n}}$

interference

$$\Gamma_{mn} = S^L_{mn} + S^R_{mn} e^{-i\phi_R}$$

ANALYTICAL RESULTS

SUMMARY

Resonance conditions

$$\Omega_{L,R} = 2k_n \quad \Omega_{L,R} = |k_n \pm k_j|$$

Parametric resonance for a finite number of modes

- Rate of growth depends on eigenvalues and phases
- Interference → dephased external excitation
- “Contrast” can be easily tuned with the static parameters

NUMERICAL ANALYSIS

METHOD

$0 < t < t_F$ Solve using Runge-Kutta-Merson

$$\ddot{\epsilon}_n^{(m)} + \omega_n^2(t)\epsilon_n^{(m)} = \sum_{n \neq j} \left(S_{nj}^L(t) + S_{nj}^R(t)\right) \epsilon_j^{(m)}$$

$$\epsilon_n^{(m)}(t) = e^{-ik_n t}\delta_{nm} \quad \text{for} \quad t < 0$$ (initial condition)

$t_F < t < t_{\max}$

$$\epsilon_n^{(m)}(t) = \alpha_{nm} e^{-ik_n t} + \beta_{nm} e^{ik_n t}$$

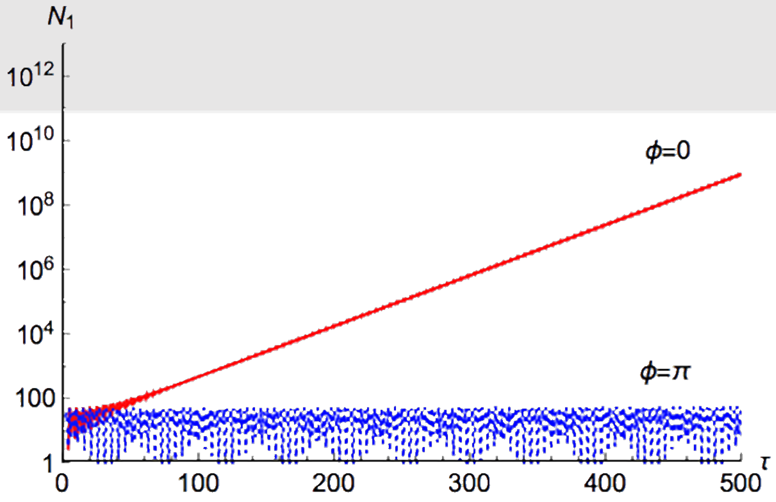
Multiply by $e^{-ik_n t}$ and average to obtain β_{nm}

→ $$N_n(t_F) = \sum_m |\beta_{nm}(t_F)|^2$$

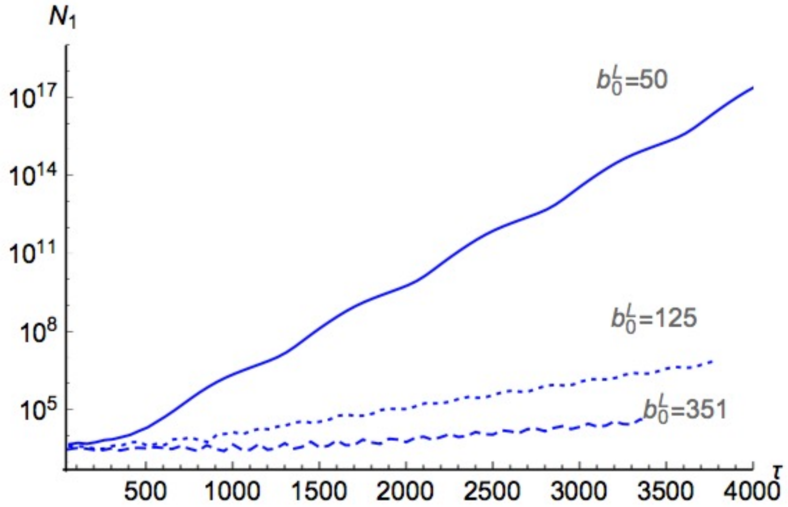
Numerics: P. Villar & A. Soba

NUMERICAL ANALYSIS

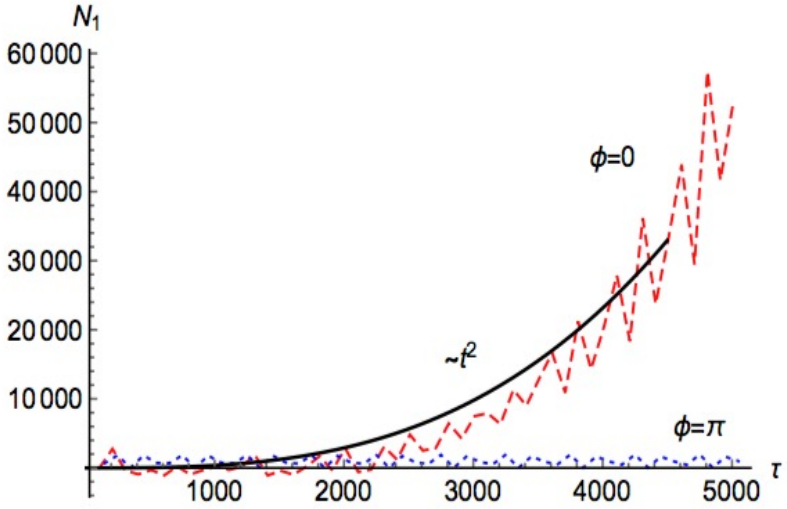
RESULTS



From exponential (non-equidistant)....



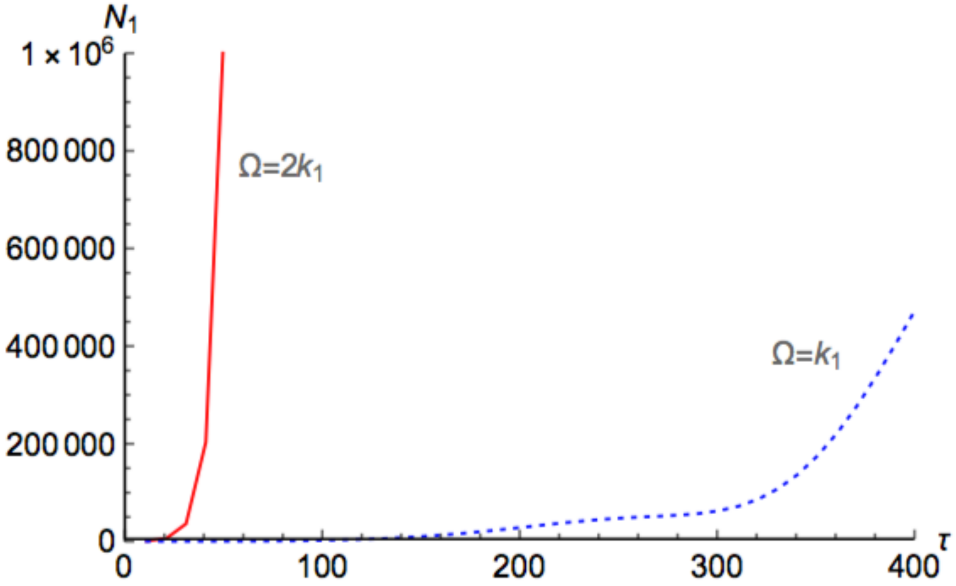
....to quadratic (equidistant)



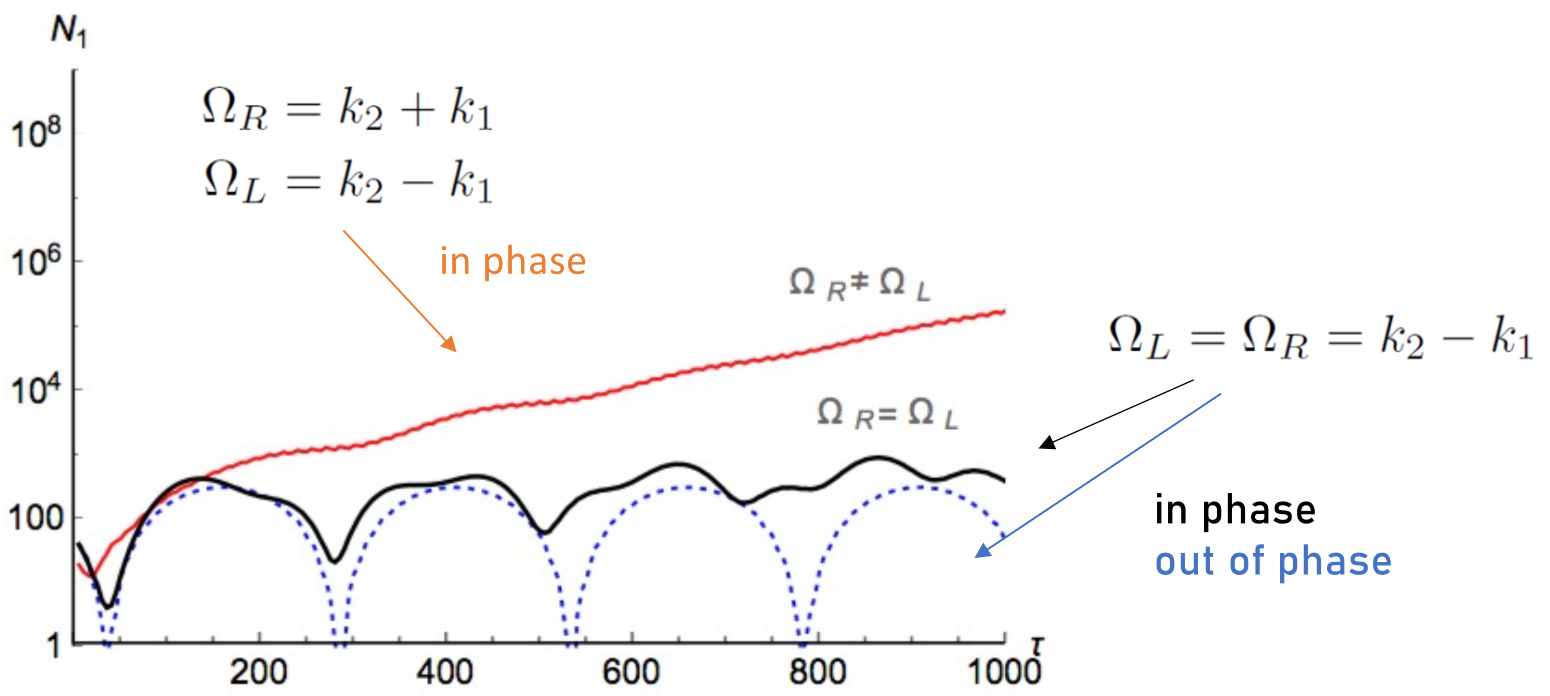
Non-leading resonance:

Usual leading order resonance in MSA $\Omega_L = \Omega_R = 2k_n$

Beyond leading order: $\Omega_L = \Omega_R = k_n$

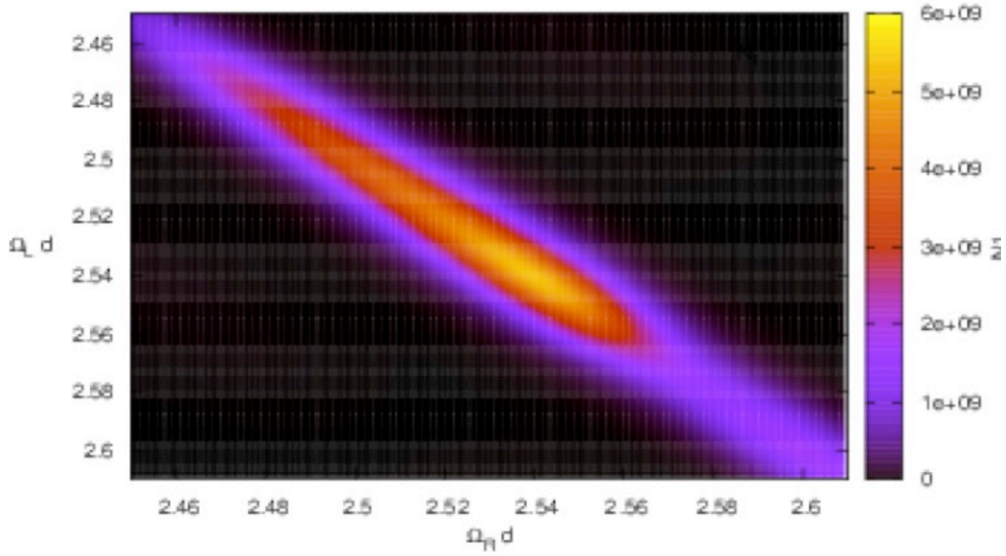


Different external frequencies:



DETUNING

MAIN RESONANCE

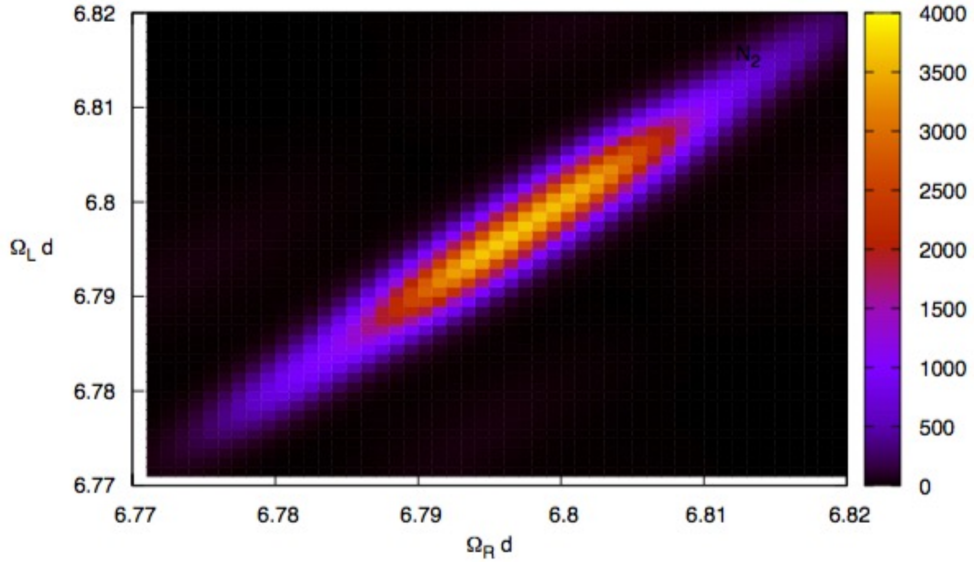


$$\Omega_L \simeq \Omega_R \simeq 2k_1$$

first mode N_1

second mode N_2

$$\Omega_L \simeq \Omega_R \simeq 2k_2$$



CONCLUSIONS: DCE

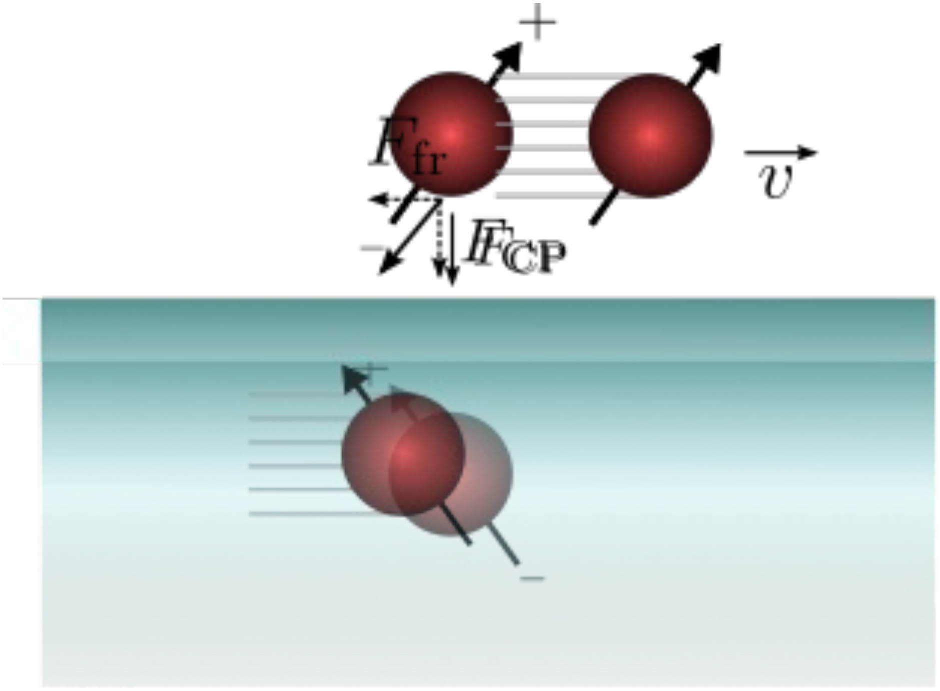
DYNAMICAL CASIMIR EFFECT

- Numerical an analytical analysis of the particle creation in a doubly tunable superconducting cavity
- The description of the system involves generalized boundary conditions or degrees of freedom concentrated on the boundaries
- Parameters can be tuned to change the characteristics of the spectrum
- Rate of particle creation strongly depends on the eigenvalues and phases of the static eigenfunctions
- Interference effects by dephasing the external magnetic fields on both SQUIDs
- Analytical results based on Multiple Scale Analysis (more recently on Magnus approximation – Fosco, F.L. & Mazzitelli 2018)
- Numerical results confirm and extend analytical analysis

F.C. L., F.D.Mazzitelli, P. I. Villar and A. Soba (2018)

QUANTUM FRICTION

INTUITIVE PICTURE



CASIMIR-POLDER

FRICTION

Sir John B. Pendry

- Short-ranged
- Small magnitude
- Avoids experimental detection so far
- A lot of effort being put into trying to find systems where the force is enhanced
- Direct or indirect ways of detecting quantum friction

- Im... fluct... ...ton of the charge ... mirr... (Doppler shift)
- Correlation between the two dipoles' oscillations
- Phase lag in the correlations
- Dipole-dipole interaction
- Tilted force
- Vertical component: CP
- Directed on the line that connects the two dipoles
- Horizontal component: **frictional force**

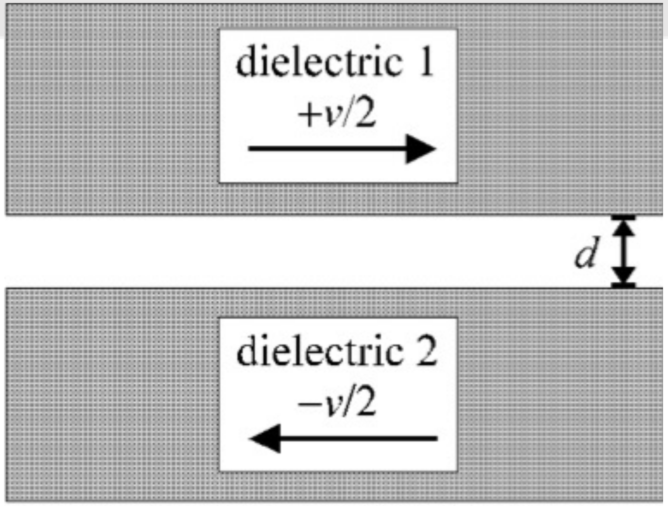
Dielectric plate (1977)

Criticized by Philbin & Leonhardt (2009)

Quantum Friction: fact or fiction? (2010)

OTHER DISIPATIVE EFFECTS

Friction between imperfect moving mirrors (Pendry 1997)



Simplest case:

$$F = \left[\Im \frac{\varepsilon - 1}{\varepsilon + 1} \right]^2 \frac{3\hbar v}{2^6 \pi^2 d^4}$$

Dissipative forces due to excitation of internal degrees of freedom
(C. Fosco, F.C. L., F.D. Mazzitelli, 2010 y 2011)

Plane mirrors which are not in contact undergo constant-speed relative parallel motion

QUANTUM FRICTION

QUANTUM FRICTION

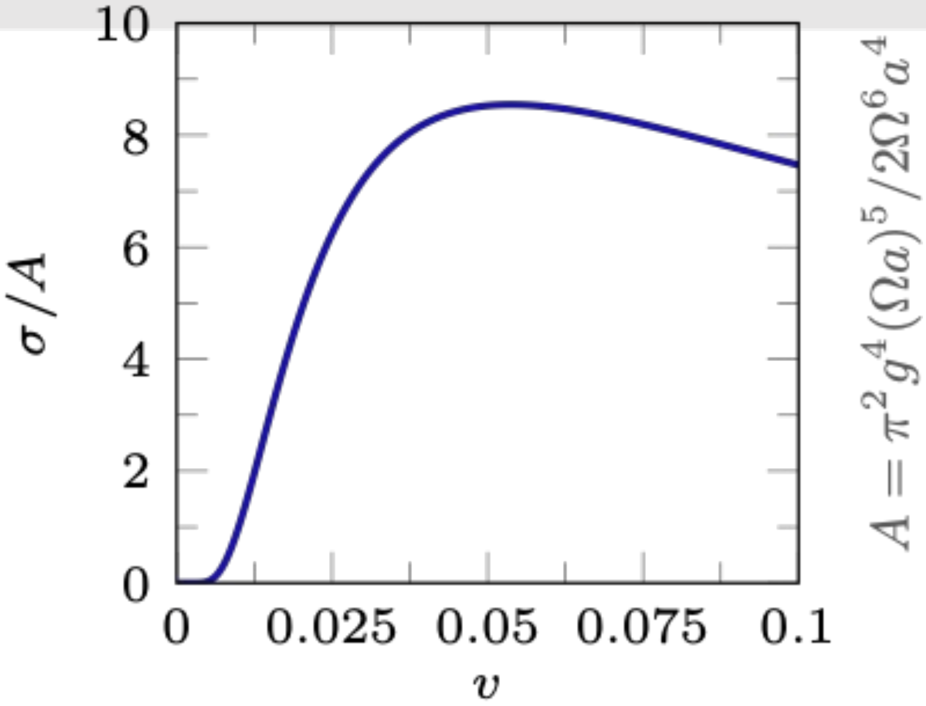
Quantum friction can be understood in terms of an exchange of virtual photons between the two bodies, which in turn excite their internal degrees of freedom

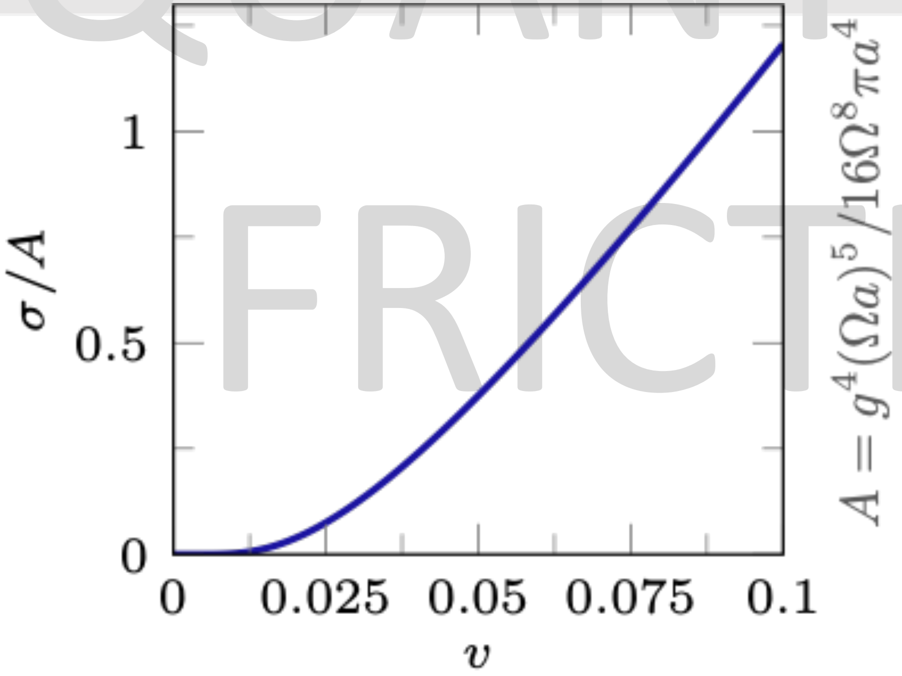
RELATED EFFECTS

- Quantum Cerenkov ($v > c_m$)
- Atom – Atom
- Atom – Plate (Casimir Polder)
- Tip of an Atomic Force Microscope - surface
- Dynamical Casimir (Real photons /accelerated objects)

QUANTUM FRICTION

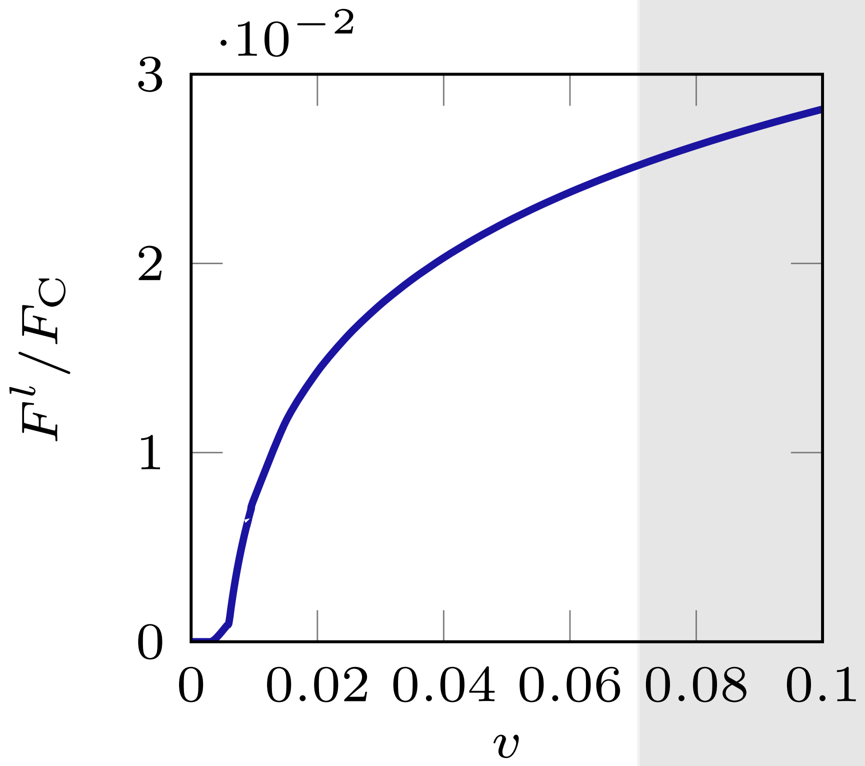
$$\sigma = -\frac{\pi^2}{2a^4}\frac{g^4}{\Omega^6}\frac{1}{v}(\Omega\, a)^5 \int dx \frac{e^{-\frac{2}{v}\sqrt{(\Omega a)^2(4-v^2)+x^2}}}{(\Omega a)^2(4-v^2)+x^2}$$

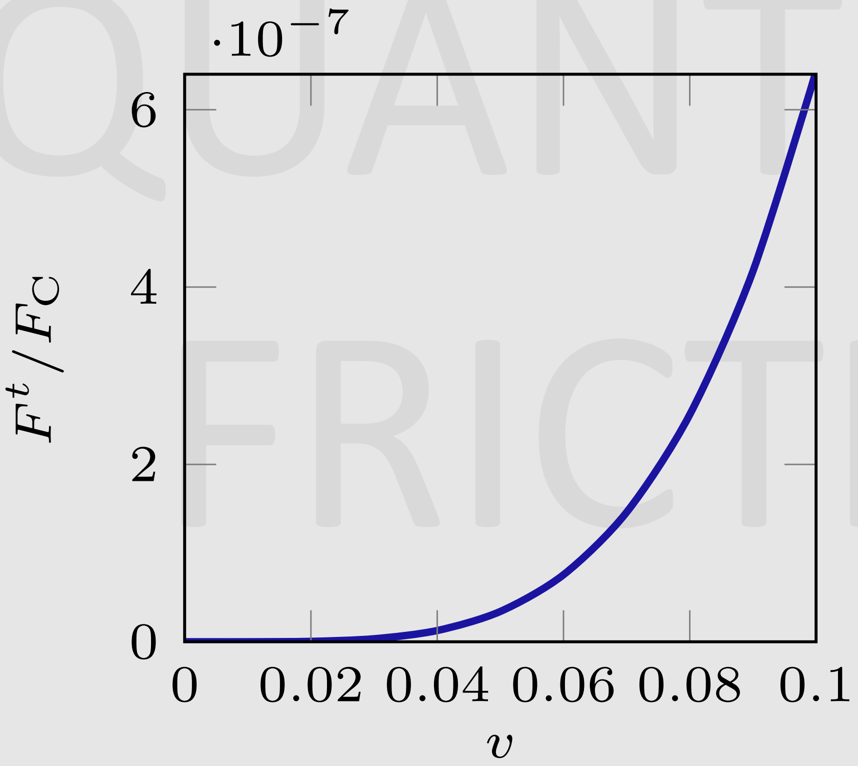




M.B. Farías, C.D. Fosco, F.C.L,
F.D Mazzitelli, & A.E. R. López,
Phys. Rev. D 91 (2015) 105020

QUANTUM FRICTION



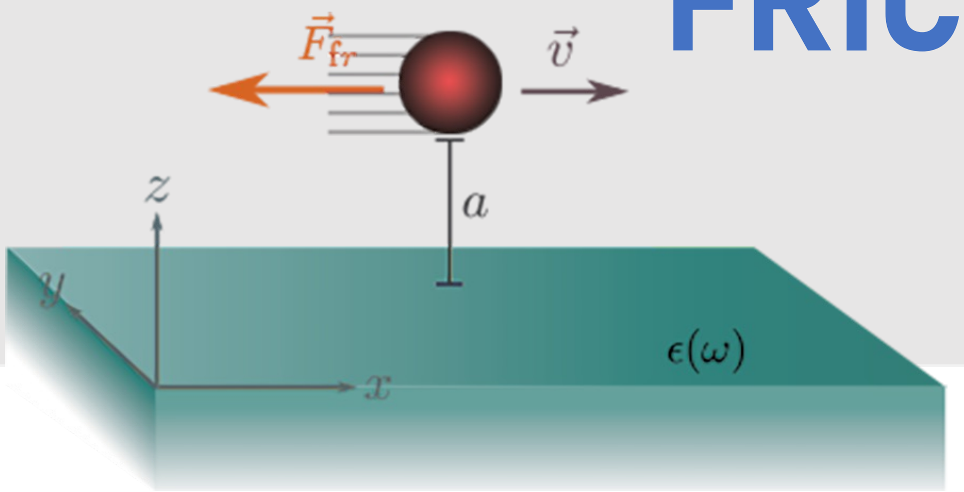


$$F_C \approx \frac{3\alpha_N^2}{128\pi}\frac{1}{a^4}\frac{1}{v_F}$$

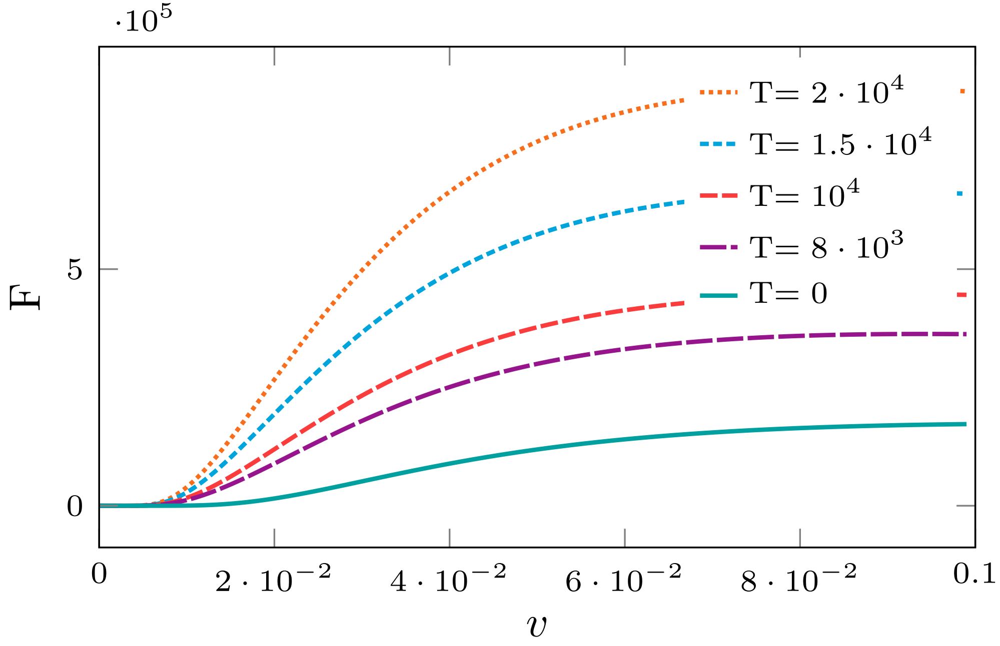
For speeds of 1% of the speed of light (very high) the force results in two orders of magnitude less than that of static Casimir (which is even less than the force between perfect conductors)

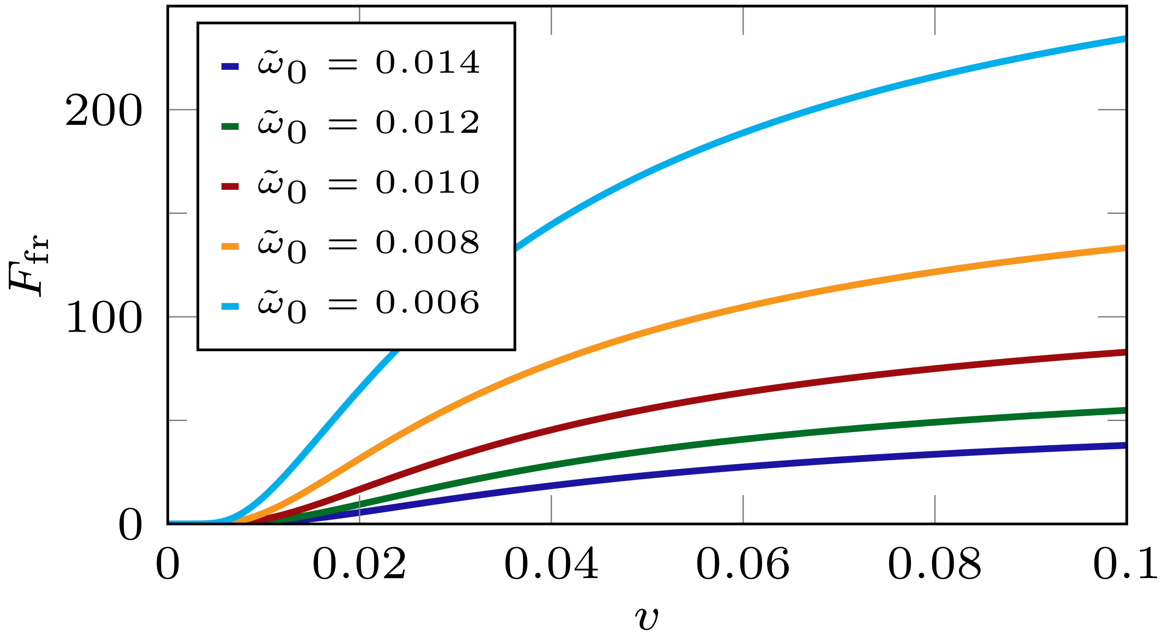
M.B. Farias, C.D. Fosco, F.C.L. & F.D. Mazzitelli.
"Quantum friction between graphene sheets."
Phys. Rev. D **95**, (2017) 065012

FRICTION FORCE: ATOM-MIRROR



$$F_{\rm fr} = \frac{\pi^2}{2a^2}\frac{\lambda^2}{\Omega^3}\frac{g^2}{\omega_0}\tilde{\Omega}^3\tilde{\omega}_0 \frac{e^{-\frac{2}{v}\sqrt{(\tilde{\omega_0}+\tilde{\Omega})^2-v^2\tilde{\Omega}^2}}}{(\tilde{\omega_0}+\tilde{\Omega})^2-v^2\tilde{\Omega}^2}$$

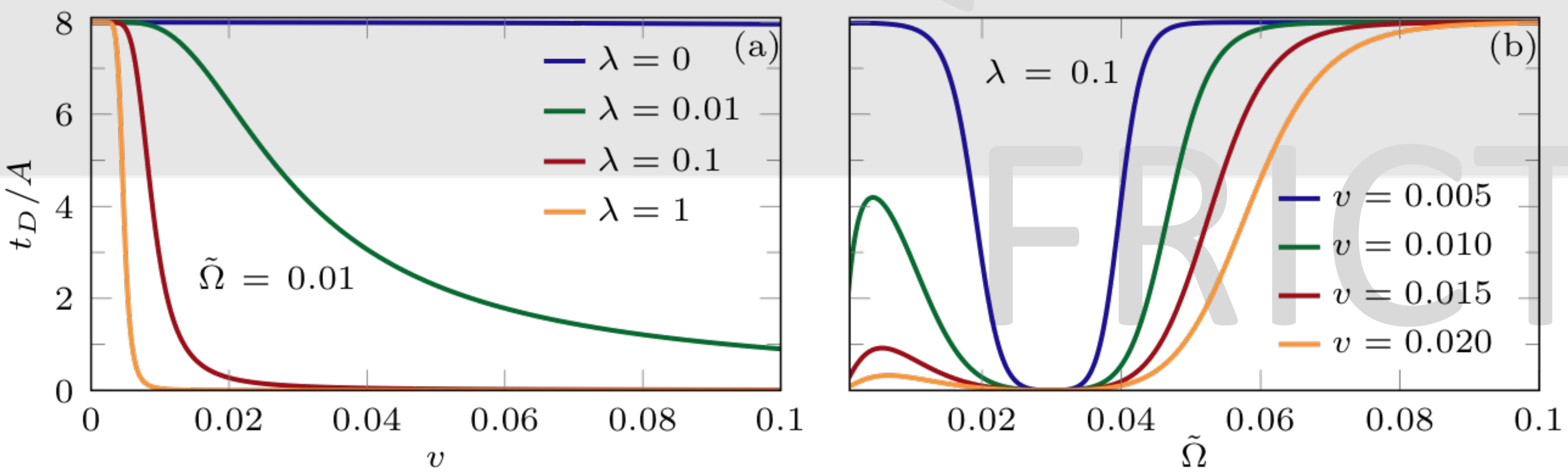




L. Viotti, M.B. Farías, F.C. L, & P.I. Villar, "Thermal corrections to quantum friction", *Phys. Rev. D* ***99*** (2019) 105095

DECOHERENCE OVER THE ATOM

Enhancement of the decoherence due to friction



M.B. Farías & F.C.L. *Phys. Rev. D* 93, 065035 (2016)

The presence of the plate reduces the decoherence time, but only for non- vanishing relative velocity. For very small velocities, decoherence time is not reduced, even for greater values of the coupling constant between the plate and the vacuum field

t_D is shown as a function of the plate's characteristic dimensionless frequency, for different values of its macroscopic velocity v. A clear minimum appears for every value of v, and it is located in $\Omega = \omega_0$. Decoherence is maximal in the resonant case, hence making the decoherence time vanish. Far from the resonance, for $\Omega >> \omega_0$, decoherence time tends to the limiting value that corresponds to the case $\lambda = 0$ (the case with no plate)

QUANTUM FRICTION INPRINTS ON THE GEOMETRIC PHASE OF A MOVING ATOM

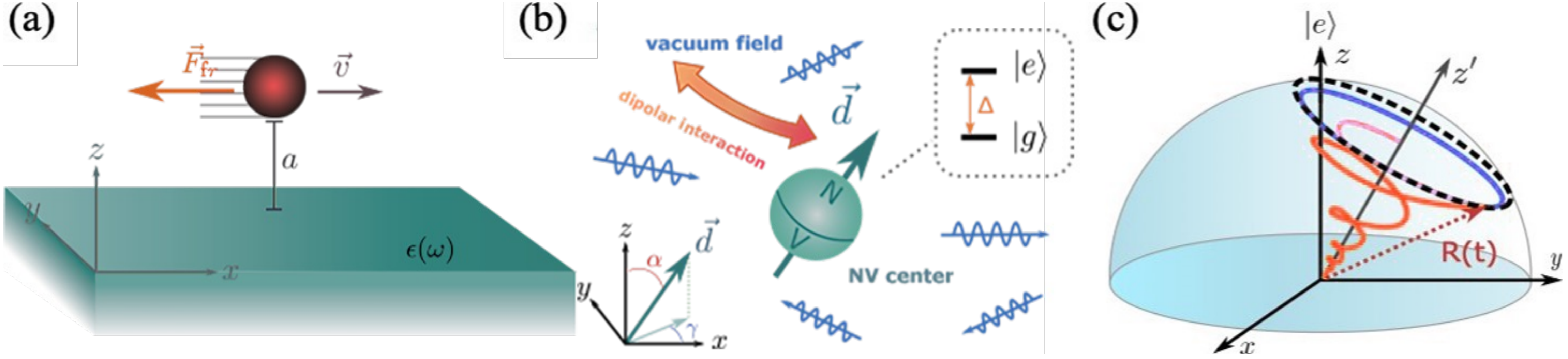
- As a consequence of quantum friction, we compute the non-unitary geometric phase for the moving particle under the presence of the vacuum field and the dielectric mirror

- We show in which cases decoherence effects could, in principle, be controlled in order to perform a measurement of the geometric phase using standard procedures as Ramsey interferometry

F.C.L & P.I. Villar, Europhys. Letts. 118, 50003 (2017)

Model: moving atom + EM field

$$H = \hbar/2 \; \Delta \; \sigma_z + H_{\mathcal{SE}} + H_{\mathcal{E}}$$



$$H_{\mathcal{SE}} = \hat{\mathbf{d}} \cdot \boldsymbol{\nabla}\Phi$$

$$d_i = \langle g|\hat{d}_i|e\rangle = \langle e|\hat{d}_i|g\rangle$$

EM potential
(dressed photons)

$$\hat{\Phi}(\mathbf{r},t) = \int d^2k \int_0^\infty d\omega \left(\phi(\mathbf{k},\omega)\hat{a}_{\mathbf{k},\omega} e^{i(\mathbf{k}\cdot\mathbf{r}-\omega t)} + h.c.\right)$$

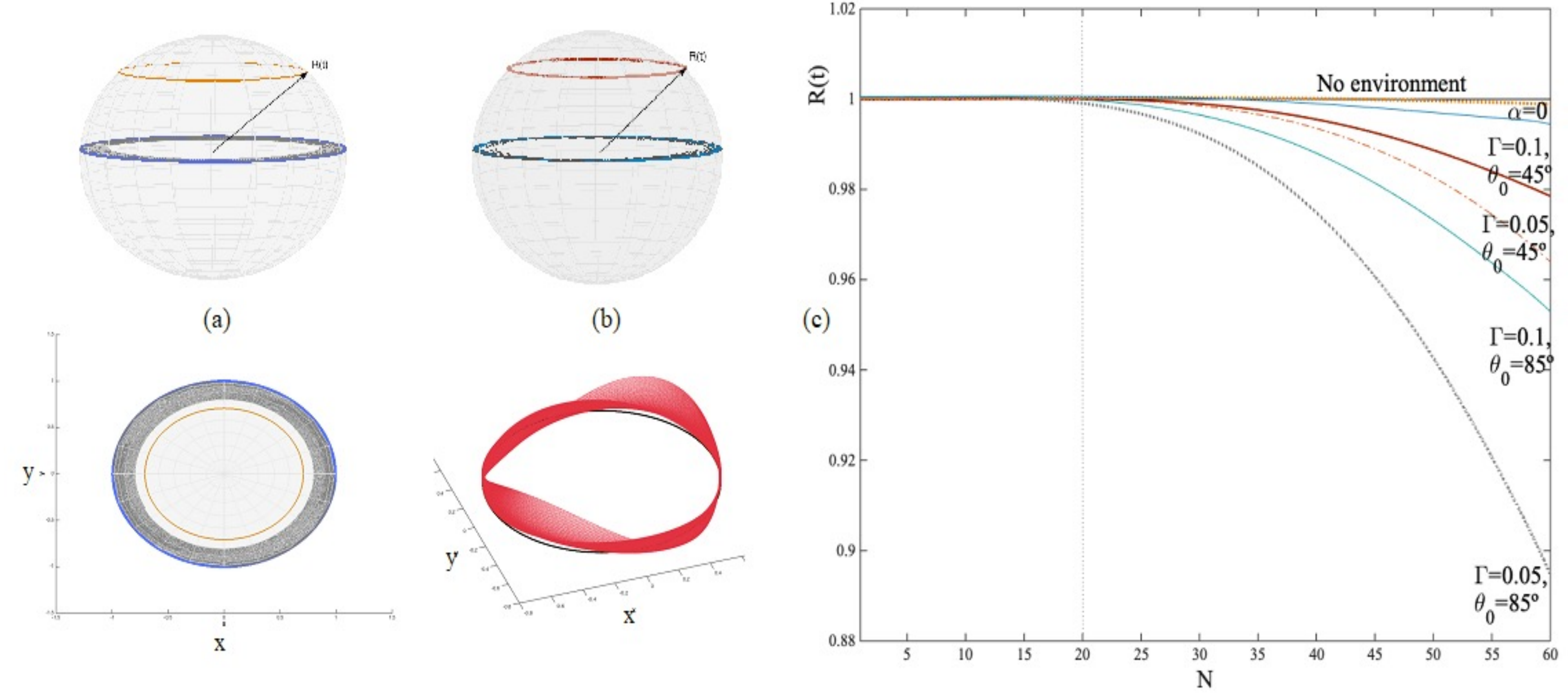
creating and destroying “photons” in a wider meaning, since they are creation and destruction operators of composite states (field plus material)

$$|\phi(\mathbf{k},\omega)|^2 = \frac{\hbar}{2\pi^2}\frac{e^{-2kz}}{k}\mathrm{Im}\frac{\epsilon(\omega)-1}{\epsilon(\omega)+1}$$

$$\epsilon(\omega) = \omega_{\mathrm{pl}}^2/(\omega_0^2 - \omega^2 - i\omega\Gamma)$$

Drude-Lorentz permittivity

$$\hbar\dot{\rho} = -i\left[H_a, \rho\right] - D(\mathbf{v}, t)\left[\sigma_x, \left[\sigma_x, \rho\right]\right] - f(\mathbf{v}, t)\left[\sigma_x, \left[\sigma_y, \rho\right]\right] + i\zeta(\mathbf{v}, t)\left[\sigma_x, \left\{\sigma_y, \rho\right\}\right]$$



GEOMETRIC PHASE

GEOMETRIC PHASE

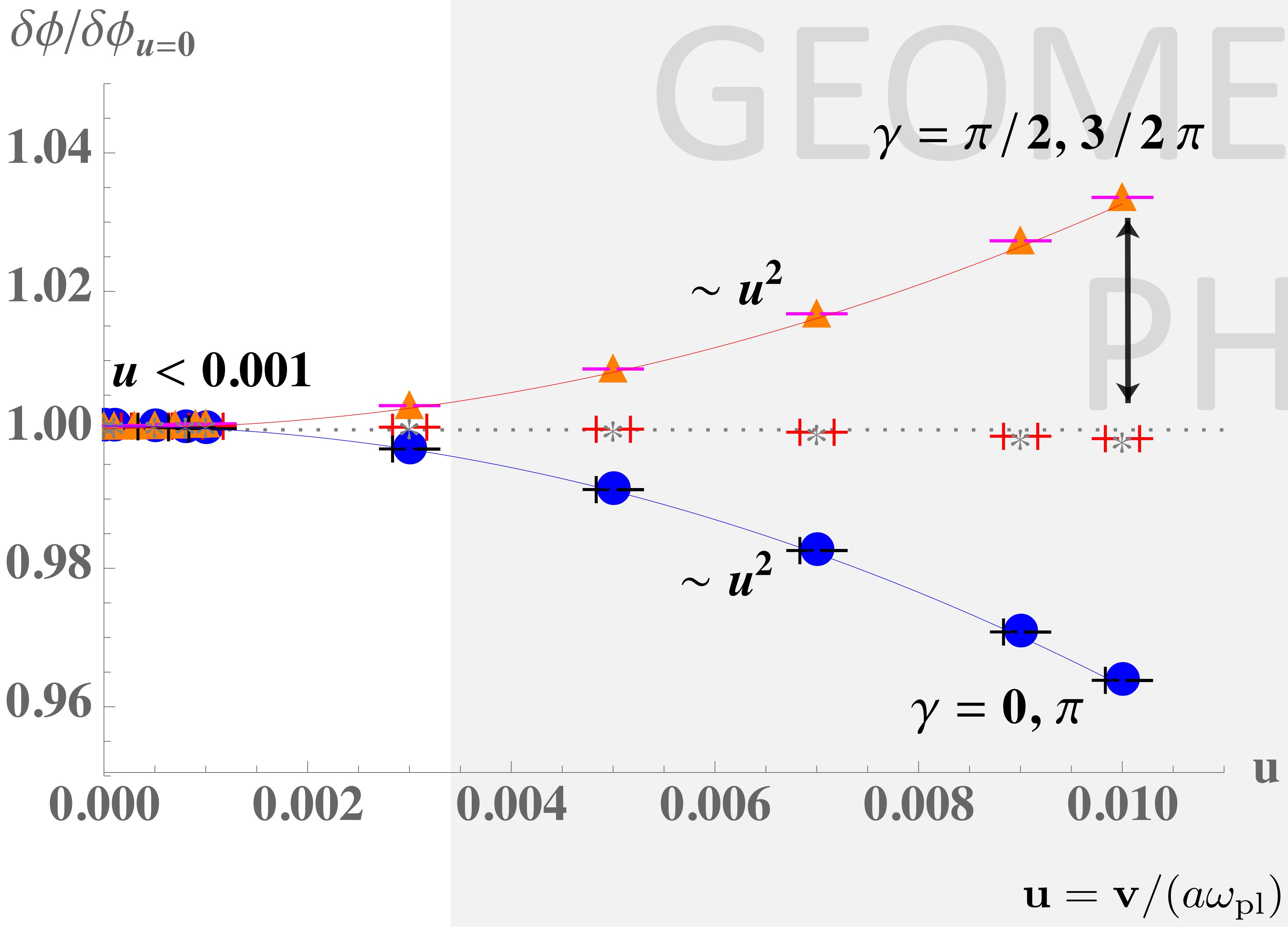
$$\phi_g = \arg\left[\sum_k \sqrt{\epsilon_k(\tau)\epsilon_k(0)}\,\langle k(0)|k(\tau)\rangle\, e^{-\int_0^\tau dt \langle k|\frac{\partial}{\partial t}|k\rangle}\right]$$

GP is gauge invariant in that it only depends upon the path in state space of the considered system.

GP for nonunitarily evolving mixed states leads to the well-known results when the evolution is unitary.

Cucchietti, Zhang, F. L., Villar, Laflamme
Phys. Rev. Lett. 105, 240406 (2010)

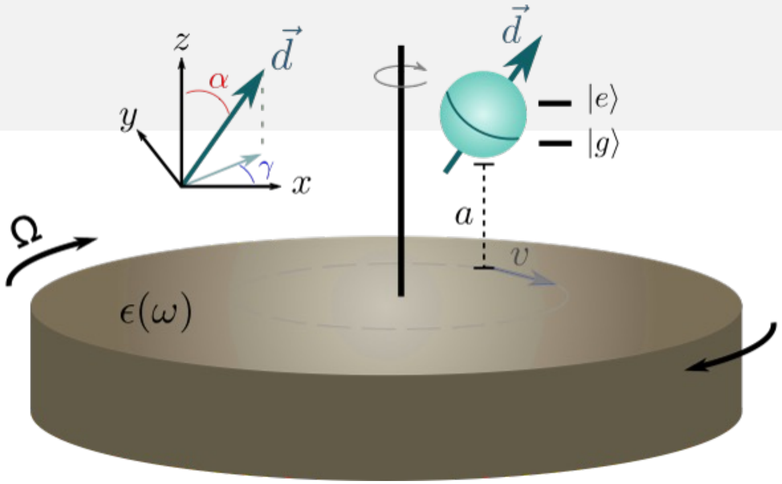
Tong, Sjoqvist, Kwek, and Oh
Phys. Rev. Lett.93, 080405 (2004)



GEOMETRIC PHASE
$\delta\phi/\delta\phi_{u=0}$
1.04
1.02
1.00
0.98
0.96
0.000
0.002
0.004
0.006
0.008
0.010
u
$\gamma = \pi/2, 3/2\,\pi$
$\sim u^2$
$u < 0.001$
$\sim u^2$
$\gamma = 0, \pi$
$\mathbf{u} = \mathbf{v}/(a\omega_{\rm pl})$

EXPERIMENTAL PROPOSAL

M.B. Farías, F.C.L, A.Soba, P.I. Villar & R.S. Decca: Nature Quant. Inf. (2020)



12cm diameter Au-coated Si disks rotated up to Ω = 2π7000 rad/s.

Our feasible experimental setup would be based on the use of a single NV center in diamond as an effective two-level system at the tip of a modified AFM tip.

The distance can be controlled from a few nanometers to tenths of nanometers with sub-nanometer resolution. The NV system presents itself as an excellent tool for studying geometric phases

State-of-the-art phase-detection experiments in NV centers in diamond permit the detection of ~ 50 mrad phase change over 10^6 repetitions

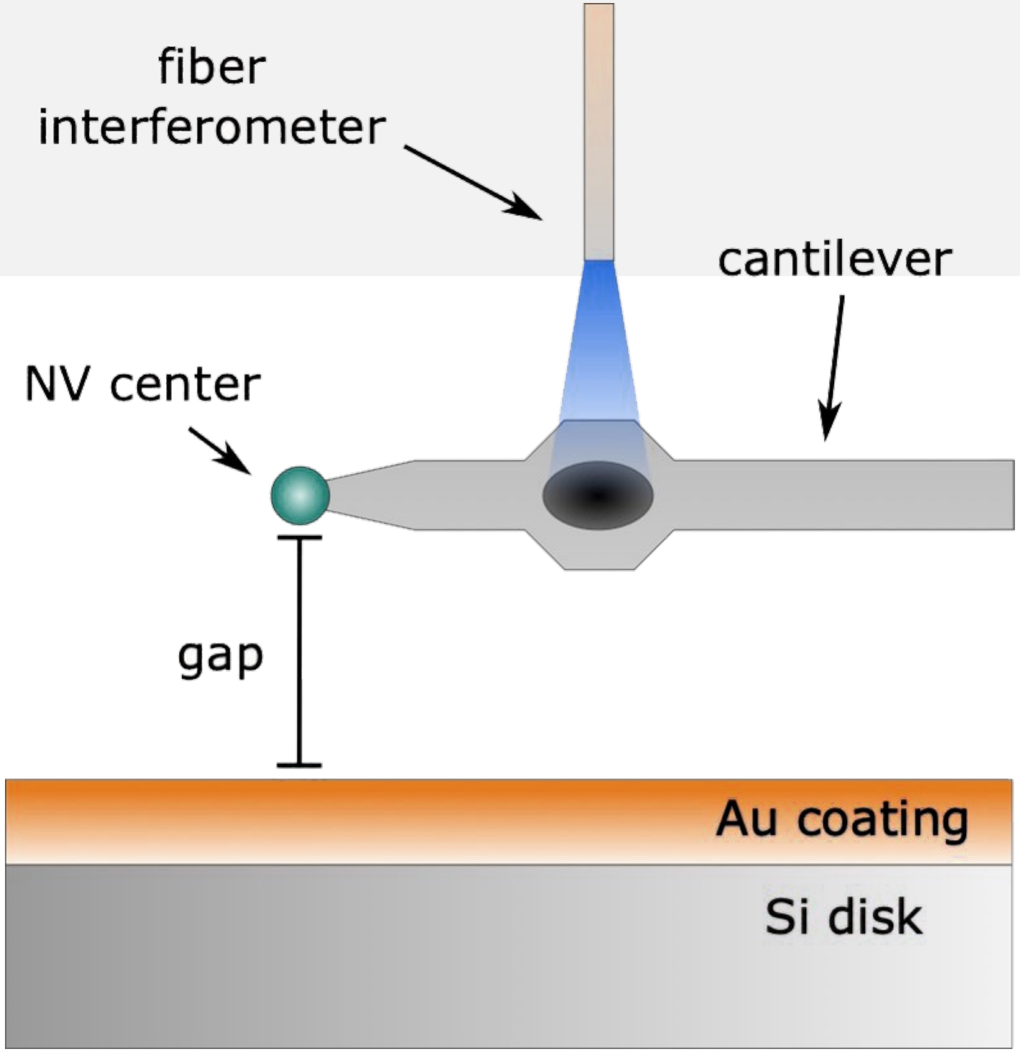
non-inertial effects can be completely neglected in order to model a particle moving at a constant speed on the material sheet. Since it is critical to keep the separation uniform, to prevent spurious decoherence, it is important to asses the plausibility of the proposed experimental setup.

- **The NV center consists of a vacancy, or missing carbon atom, in the diamond lattice lying next to a nitrogen atom, which has substituted for one of the carbon atoms**

- **The NV center offers a system in which a single spin can be initialized, coherently controlled, and measured. It is also possible to mechanically move the NV center**

EXPERIMENTAL PROPOSAL

In the proposed experimental setup, the sample is constituted by a Si disk laminated in metal (we propose to use Au or n-doped Si coating).



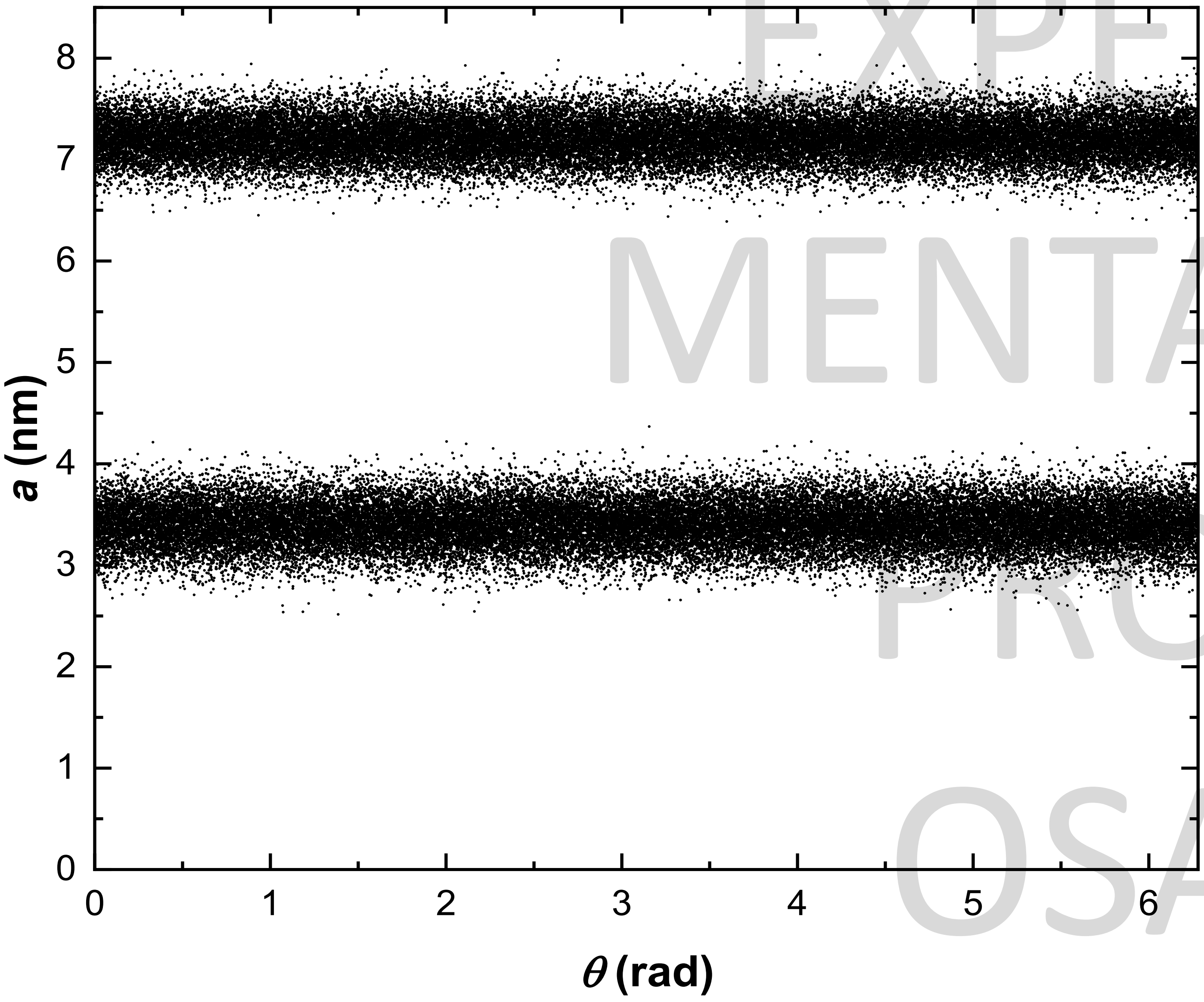
Parameters of the Drude-Lorentz model for Au are ω_{pl} = 1.37 10^16rad/s; $\Gamma/\omega_{pl} \sim 0.05$, and ω_{pl} = 3.5 10^14 rad/s; $\Gamma/\omega_{pl} \sim 1$ for n-Si). The coated Si disk is mounted on a turntable.

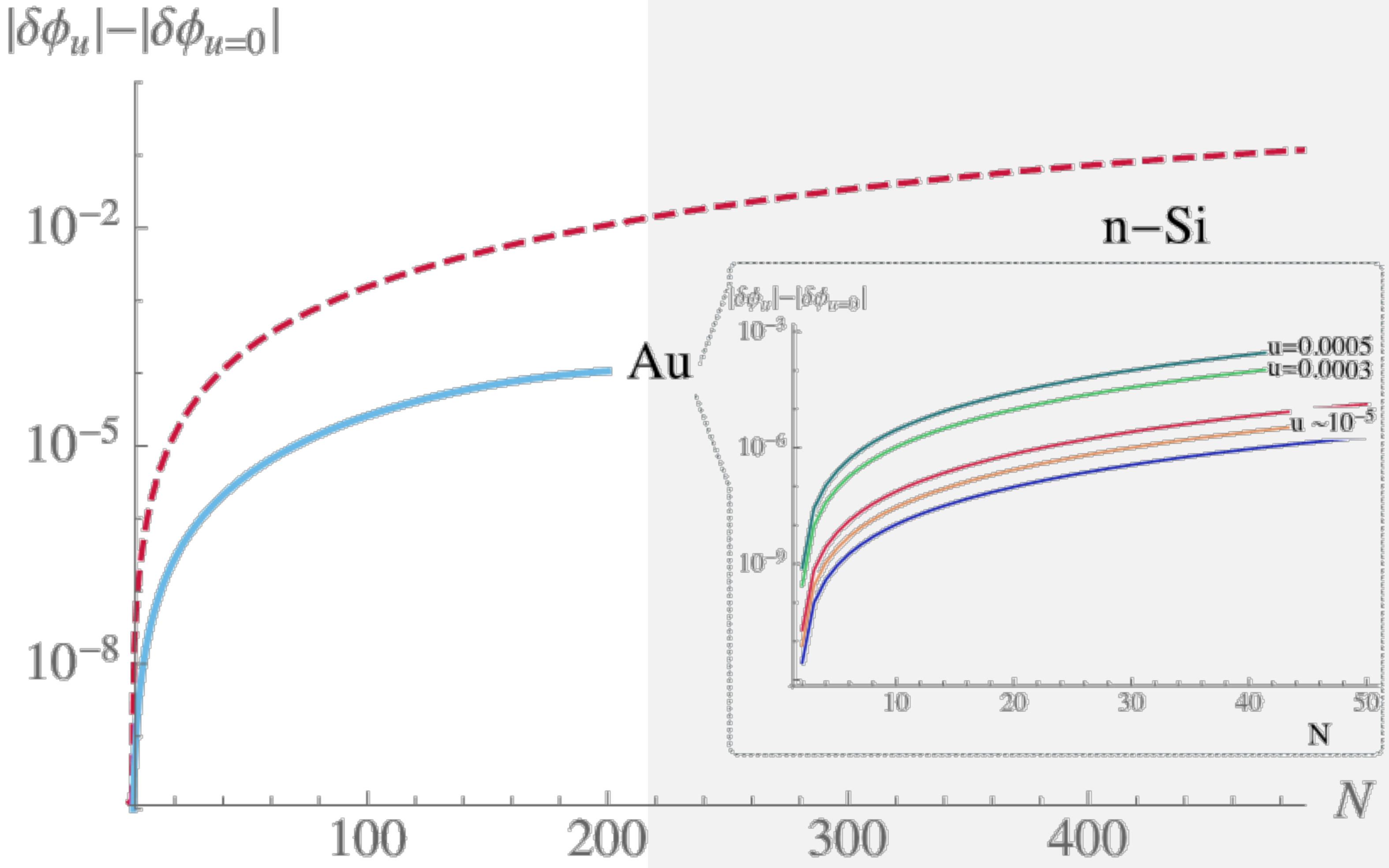
Measurement of the separation between the AFM tip

The nominal separation “a” between the tip and the sample are 7.2 and 3.4 nm.

The AFM tip moves vertically appox. 27.3 nm to keep the separation constant.

The overall change in thickness of the rotating plate could be as large as 50 nm at a given radius, the feedback control maintains the specified separation “a” to better than δa = 1 nm. The experiment is doable at a = 3 nm, with δa (possible fluctuations in distance) induced decoherence effects being negligible compared to the quantum friction ones.





Numerical simulation in experimental conditions with n-Si (u = 0.0025) and Au (u = 6.4 10^−5) coating disk.

The inset shows |δϕu| − |δϕu=0| for a range of velocities u derived by the assumption of values of “a” ranged between 3 and 10 nm; all of them for the case of Au coating.

In experimental conditions, we can achieve different velocities u depending the metal coating of the Si disk. When it is coated with n-doped Si, the dimensionless velocity u is bigger, u = 0.0025 making it measurable with the actual technology.

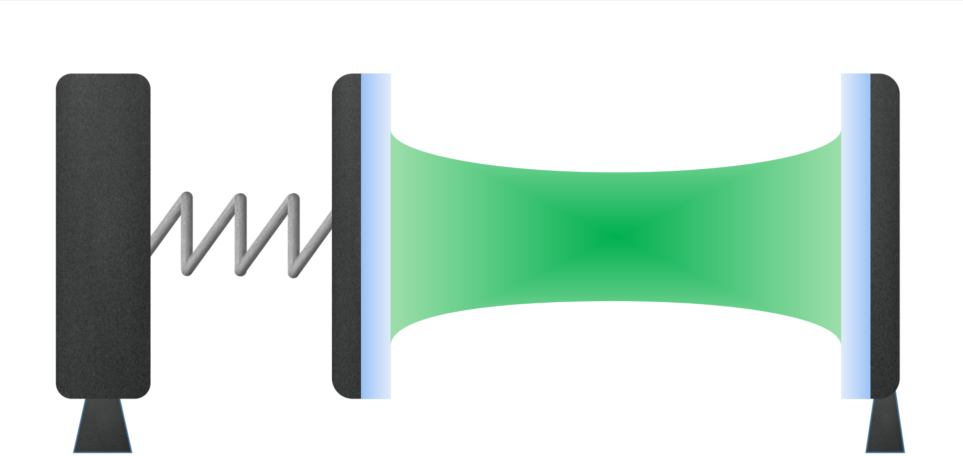
CONCLUSIONS: FRICTION

- We have found a proper scenario to indirectly detect quantum friction by measuring the geometric phase aquired by a particle
- The system preserves purity for several cycles, which allows us to ensure that the GP could be measured
- After many cycles the correction to the accummulated GP due to the velocity of the particle becomes relevant
- We have proposed an experimental setup which determines the feasibility of the experiment and would be the first one in tracking traces of quantum friction through the study of decoherence effects on a two-level system
- In experimental conditions, we can achieve different velocities depending the metal coating of the Si disk. When it is coated with n-doped Si, the dimensionless velocity u is big enough, making GP measurable with the actual technology
- The emerging micro- and nanomechanical systems promising new applications in sensors and information technology may suffer or benefit from non-contact quantum friction

M.B. Farías, F.C. L., P. Villar, A. Soba & R. Decca; Nature Quant. Inf. (2020)

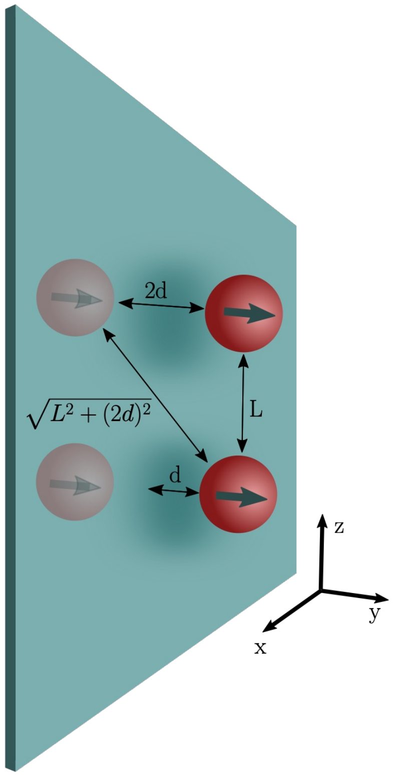
New stuff

DYNAMICAL CASIMIR EFFECT



Optomechanical cavity: phonons to photons

N. Del Grosso, F.C. L., P. Villar - Phys. Rev D (2019)



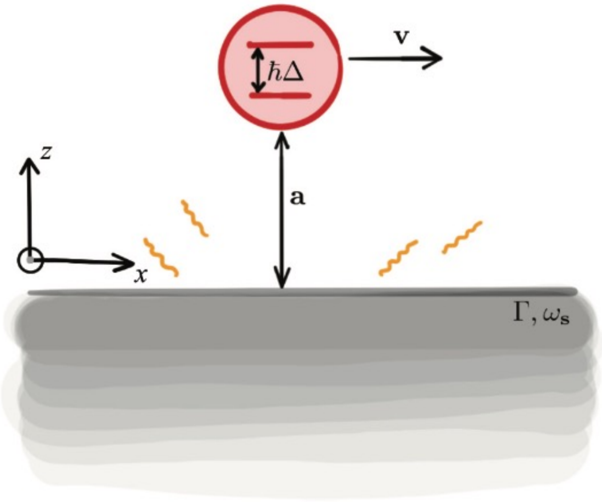
Entanglement, Decoherence & Geometric phase: GP sensor

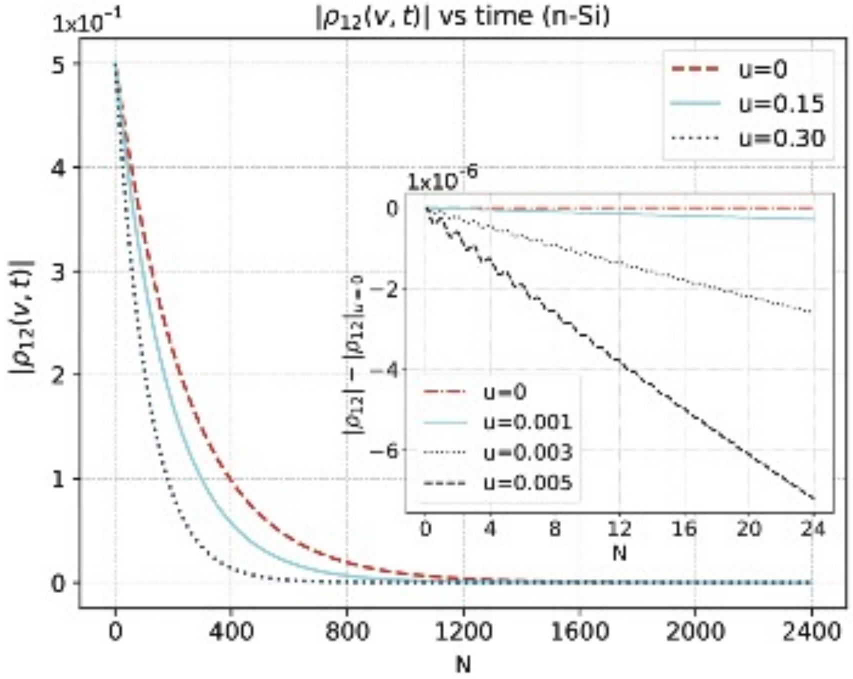
L. Viotti, F.C. L., P. Villar – Phys. Rev. A (2019)

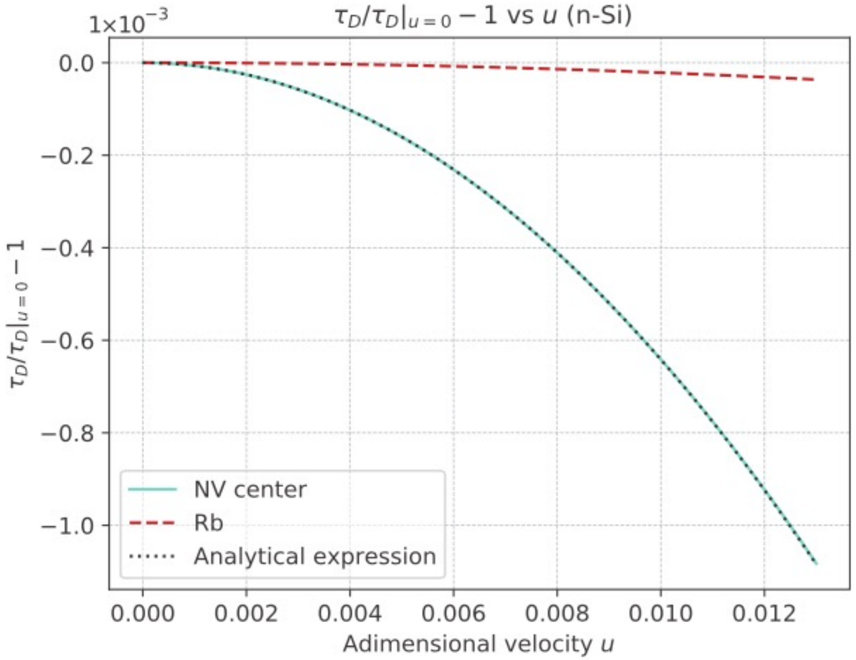
PHYSICAL REVIEW A **103**, 032809 (2021)

Enhanced decoherence for a neutral particle sliding on a metallic surface in vacuum

Ludmila Viotti, Fernando C. Lombardo, and Paula I. Villar

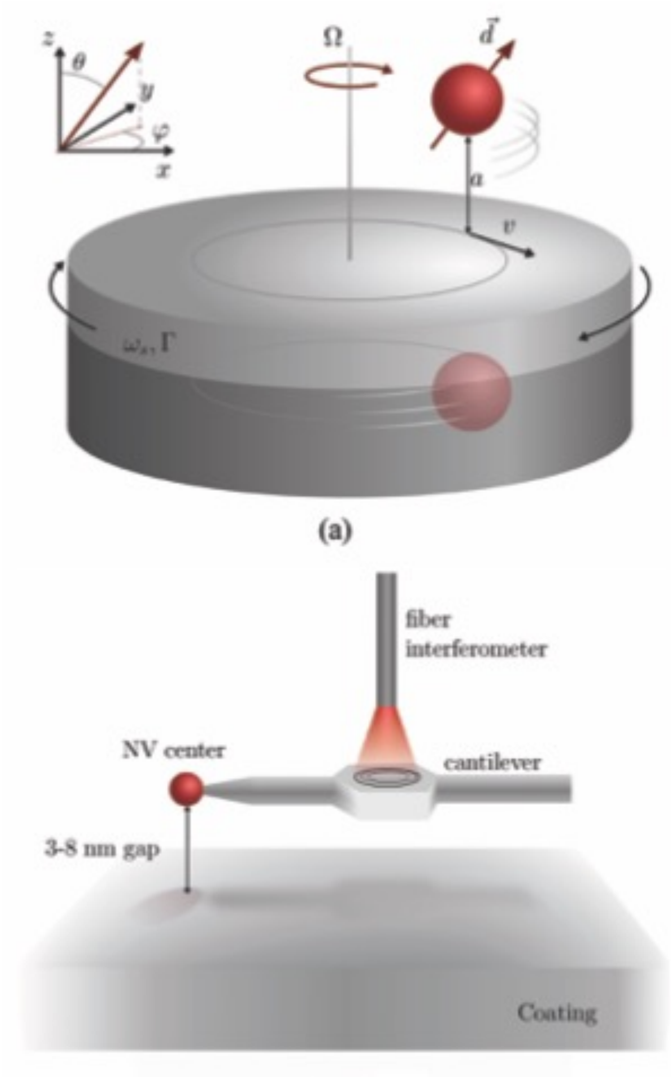






Detectable Signature of Quantum Friction on a Sliding Particle in Vacuum

Fernando C. Lombardo,[1,2] Ricardo S. Decca,[3] Ludmila Viotti,[1] and Paula I. Villar[1,2]



Advanced Quantum Technologies, 2021

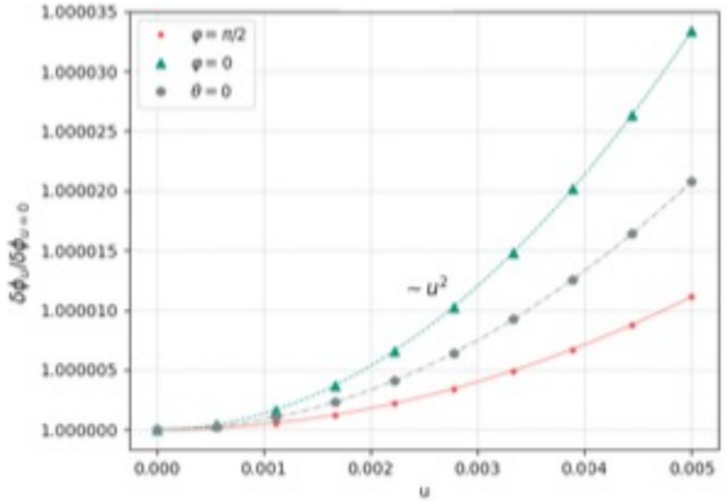


FIG. 6. Correction to the geometric phase $\delta\phi_u$ (normalized with respect to the static correction $\delta\phi_{u=0}$) as a function of the dimensionless velocity u, considering different polarization directions of the particle. Red line (circle) corresponds to $\theta = \pi/2$ and $\varphi = \pi/2$ values which yields a polarization along the y axis, parallel to the surface and perpendicular to the motion. Gray line with (hexagon) corresponds to the $\theta = 0$ case, yielding a polarization perpendicular to the dielectric surface, along the z axis. Green line with (triangle) corresponds to the case in which the atom is polarized in the direction of motion $\theta = \pi/2$ and $\varphi = 0$. As it has been reported, for very small velocities the presence of the quantum field dressed by the dielectric is dominant. However, for bigger velocities, the theory predicts that $\delta\phi_{u\neq 0}$ becomes relevant making it possible to detect differences as the geometric phase accumulates. Parameters used: $N = 100$, $\tilde{\Gamma} = 1$, $r_0/\omega_s = 10^{-2}$, $\tilde{\Delta} = 0.2$.

PHYSICAL REVIEW A **105**, 022202 (2022)

Quantum Otto cycle in a superconducting cavity in the nonadiabatic regime

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Quantum Thermodynamics in superconducting cavities and circuit QED

PHYSICAL REVIEW A **105**, 052217 (2022)

Shortcut to adiabaticity in a cavity with a moving mirror

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Shortcuts to adiabaticity constitute a powerful alternative that speed up time evolution while mimicking adiabatic dynamics. In this paper we describe how to implement shortcuts to adiabaticity for the case of a massless scalar field inside a cavity with a moving wall, in $1 + 1$ dimensions. The approach is based on the known solution to the problem that exploits the conformal symmetry, and the shortcuts take place whenever there is no dynamical Casimir effect. We obtain a fundamental limit for the efficiency of an Otto cycle with the quantum field as a working system, that depends on the maximum velocity that the mirror can attain. We describe possible experimental realizations of the shortcuts using superconducting circuits.

We analyze the efficiency of the quantum Otto cycle applied to a superconducting cavity. We consider its description in terms of a full quantum scalar field in a one-dimensional cavity with a time-dependent boundary condition that can be externally controlled to perform and extract work unitarily from the system. We study the performance of this machine when acting as a heat engine as well as a refrigerator. It is shown that, in a nonadiabatic regime, the efficiency of the quantum cycle is affected by the dynamical Casimir effect that induces a sort of quantum friction that diminishes the efficiency. We also find regions of parameters where the effect is so strong that the machine can no longer function as an engine since the work that would be produced is completely consumed by the quantum friction. However, this effect can be avoided for some particular temporal evolutions of the boundary conditions that do not change the occupation number of the modes in the cavity, leading to a highly improved efficiency.

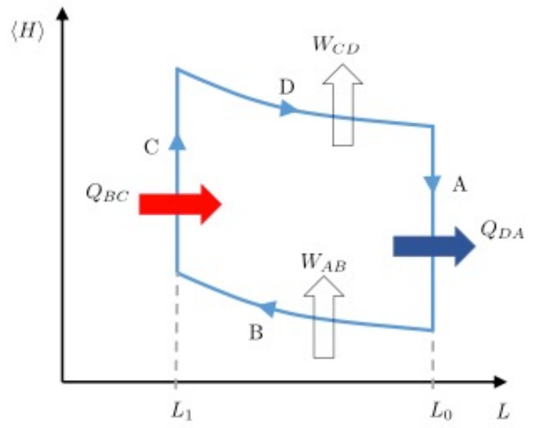

FIG. 1. The four strokes of the Otto cycle in terms of the length of cavity L and the mean energy of the quantum field inside it.

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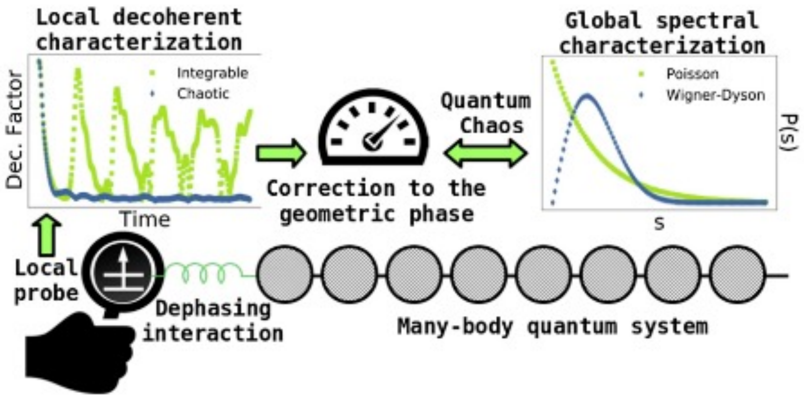
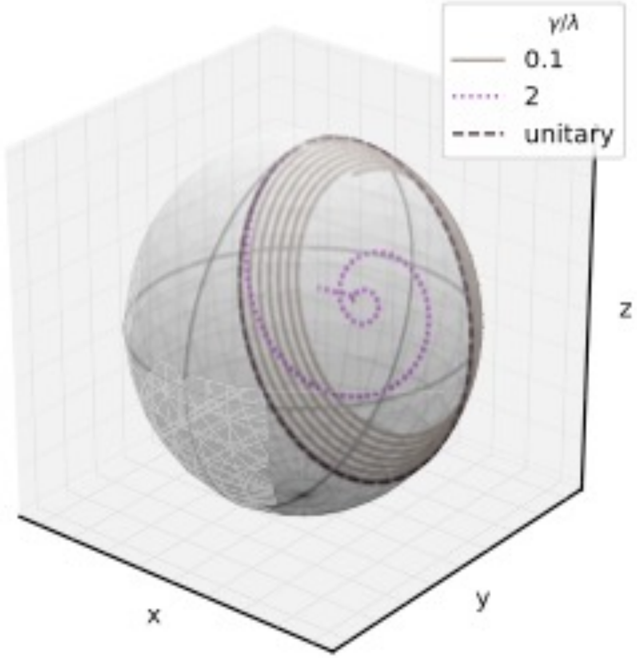
Quantum Science and Technology

PAPER

Sensing quantum chaos through the non-unitary geometric phase

Nicolás Mirkin*, Diego A. Wisniacki, Paula I Villar and Fernando C Lombardo





PHYSICAL REVIEW A **105**, 022218 (2022)

Belén Rodriguez, GP in circuit QED (Tesis Lic)

Geometric phase in a dissipative Jaynes-Cummings model: Theoretical explanation for resonance robustness

Ludmila Viotti

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Fernando C. Lombardo and Paula I. Villar

PHYSICAL REVIEW D **105,** 045019 (2022)

Motion induced excitation and radiation from an atom facing a mirror

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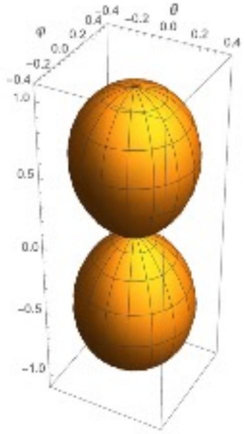
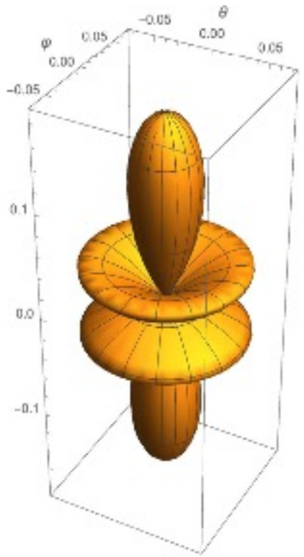
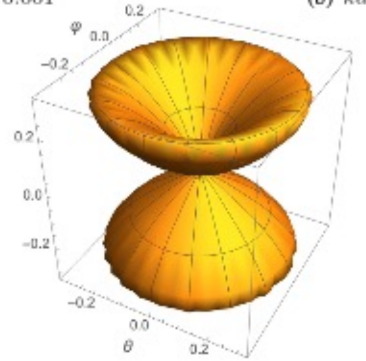
We study quantum dissipative effects due to the non-relativistic, bounded, accelerated motion of a single neutral atom in the presence of a planar perfect mirror, i.e. a perfect conductor at all frequencies. We consider a simplified model whereby a moving 'scalar atom' is coupled to a quantum real scalar field, subjected to either Dirichlet or Neumann boundary conditions on the plane. We use an expansion in powers of the departure of the atom with respect to a static average position, to compute the vacuum persistence amplitude, and the resulting vacuum decay probability. We evaluate transition amplitudes corresponding to the excitation of the atom plus the emission of a particle, and show explicitly that the vacuum decay probabilities match the results obtained by integrating the transition amplitudes over the directions of the emitted particle. We also compute the spontaneous emission rate of an oscillating atom that is initially in an excited state.



(a) $ka = 0.001$



(b) $ka = 2.5$



(c) $ka = 5$

In a previous work we computed the probability of excitation and photon emission for a single neutral atom undergoing non-relativistic, accelerated motion, in the presence of a perfectly-conducting plane. We considered a simplified model where the atom was coupled to a quantum scalar field. In this paper we extend those results to the more realistic case of the atom coupled to the quantum electromagnetic field. We pay particular attention to the spontaneous emission rate produced when the accelerated atom is initially in an excited state, and to its comparison with the case in which the atom is at rest in front of a moving mirror.

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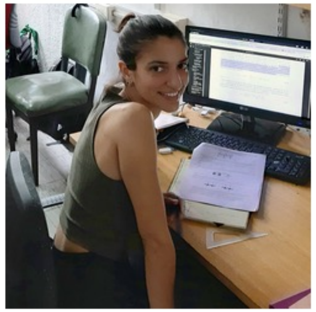

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