Studying the quantum vacuum using superconductor-based circuit QED devices

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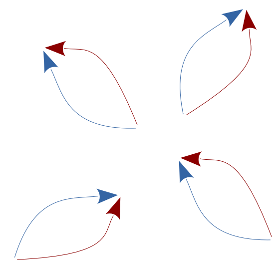
Classical vacuum

Just empty space:
a passive stage for physics

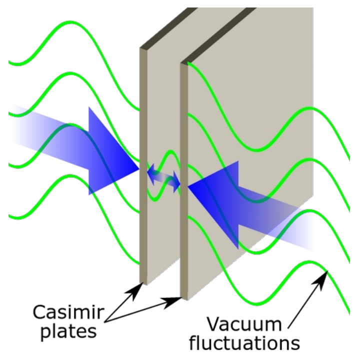
Quantum vacuum



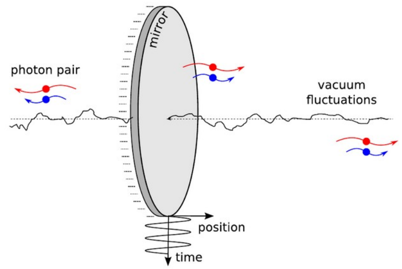
Full of virtual particle-antiparticle pairs
(survive for Heisenberg-limited time $\Delta E \, \Delta t < 1$)

Zero-point quantum fluctuations
of all fields

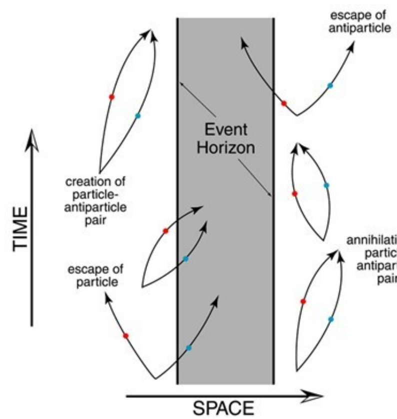
Many observable consequences



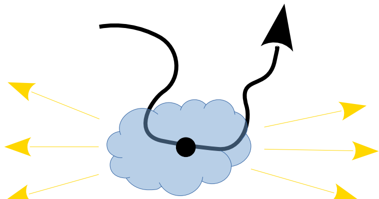
(Static) Casimir effect: attractive force in vacuo
Source: Wikipedia



(Dynamical) Casimir effect: light emission
from (non-intertially) moving mirror
Sketch from Nation et al., RMP 2012

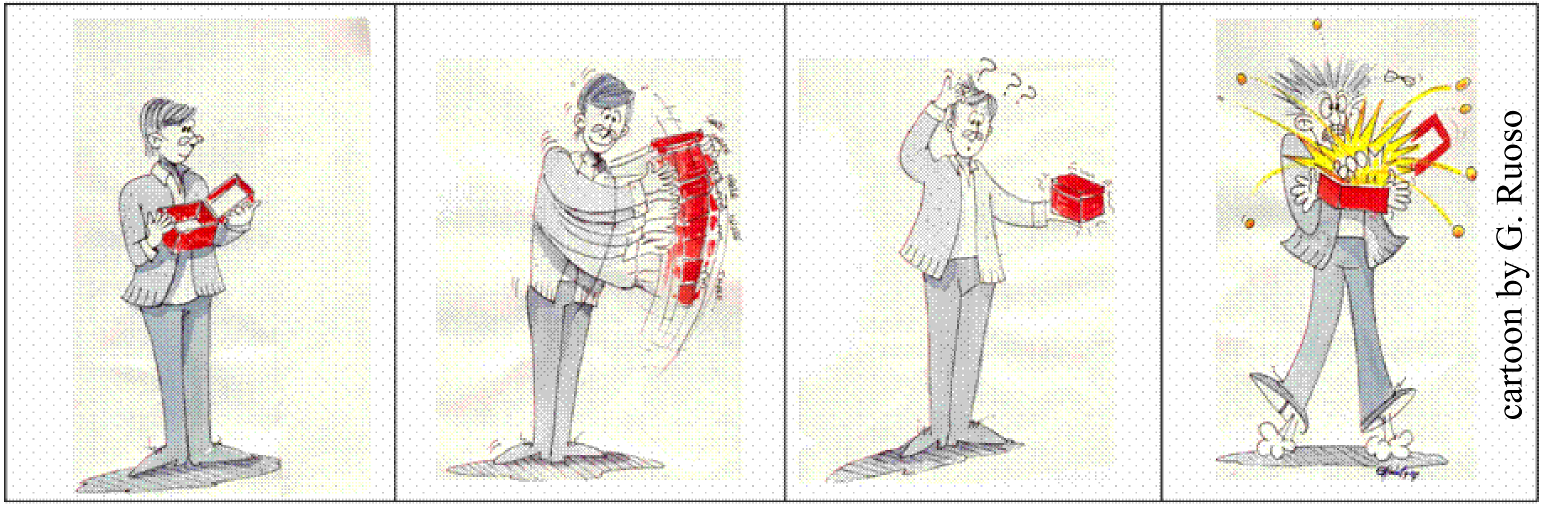


Hawking emission from black holes
Source: Physics Stack Exchange



Neutral medium in non-inertial motion
Quantum fluctuations scattered into real radiation
In return: feels quantum vacuum friction force

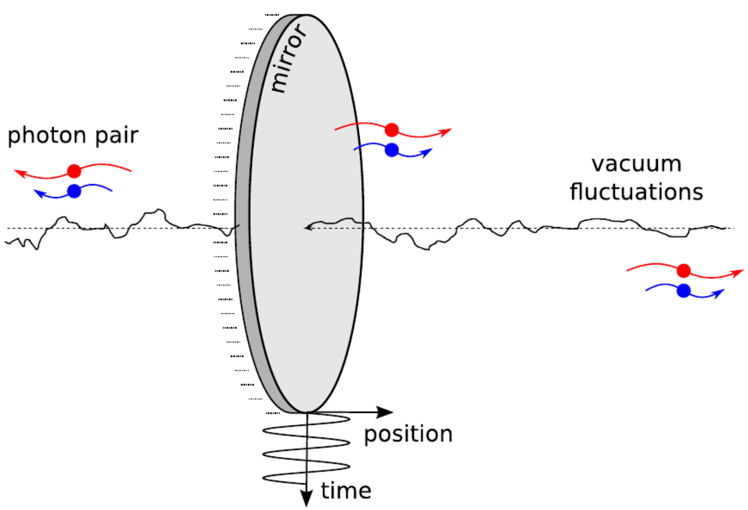
Dynamical Casimir effect



Take an optical cavity
in the e.m. vacuum state

Mechanically
shake it very fast

Beware when you open it again:
(a few) photons may burn you !!



Sketch from Nation et al., RMP 2012

The main experimental difficulty:
need to shake really fast to detect very few photons

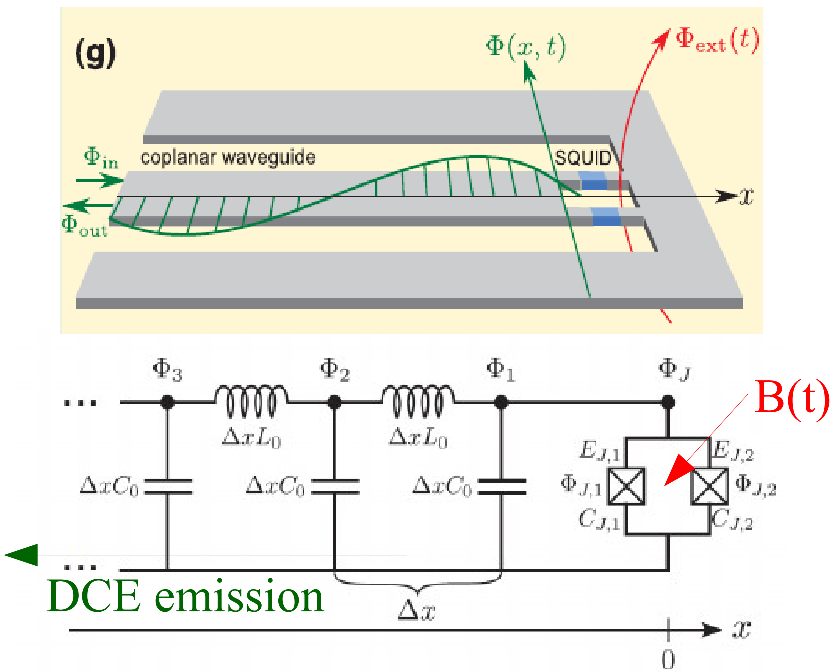
Characteristic (Unruh) temperature $k_B T_U \sim h a / 4 \pi^2 c$
very small !!!

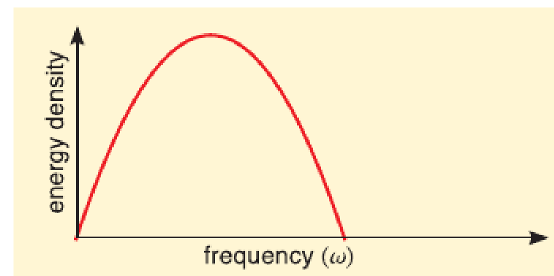
Circuit-QED observation of (analog) DCE

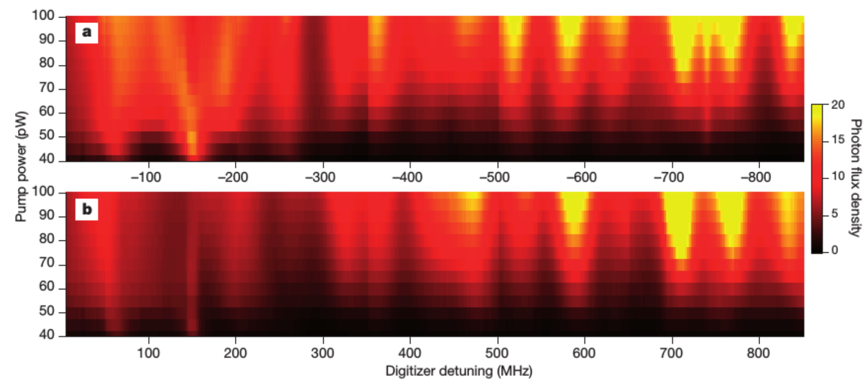
doi:10.1038/nature10561

Observation of the dynamical Casimir effect in a superconducting circuit

C. M. Wilson[1], G. Johansson[1], A. Pourkabirian[1], M. Simoen[1], J. R. Johansson[2], T. Duty[3], F. Nori[2,4] & P. Delsing[1]



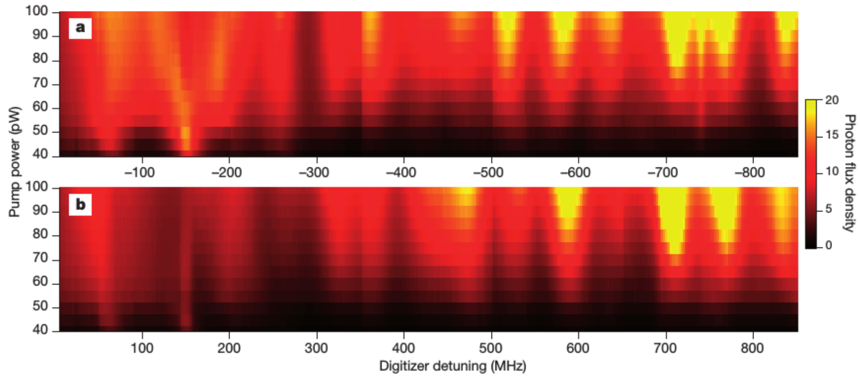




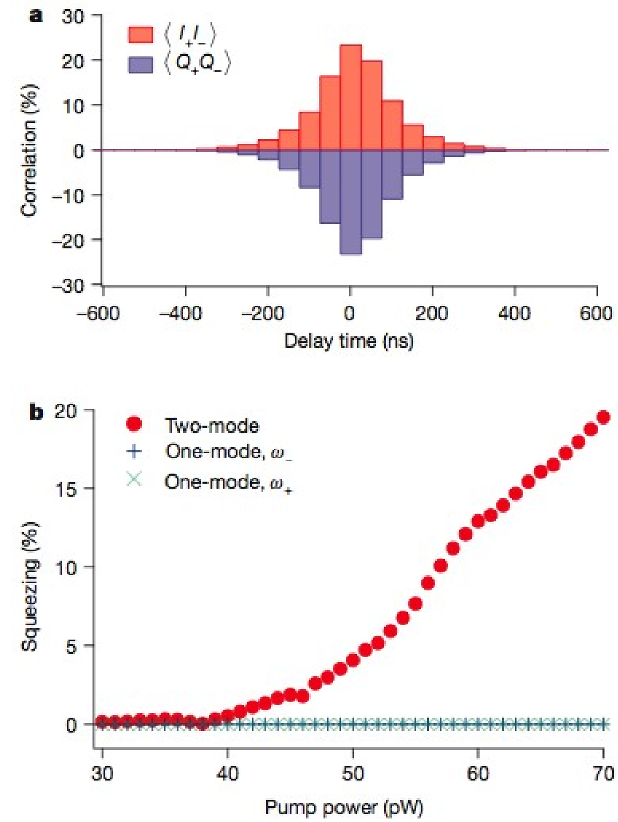
- Co-planar waveguide (CPW) for microwaves terminated on SQUID
- Effective mirror position controlled via B-field threaded through SQUID, oscillates at Ω
- Modulation of B(t) allows to shake very fast with large amplitude → observable DCE

- Observed as radiation along CPW: emission centered around $\Omega/2$ (with spurious modulation)

Quantum correlations in (analog) DCE emission



Figures from: Wilson et al., Nature 479, 376 (2011)



Emission centered around $\Omega/2$ (with spurious modulations)

Field correlations detected from field quadratures
as measured by linear amplifiers

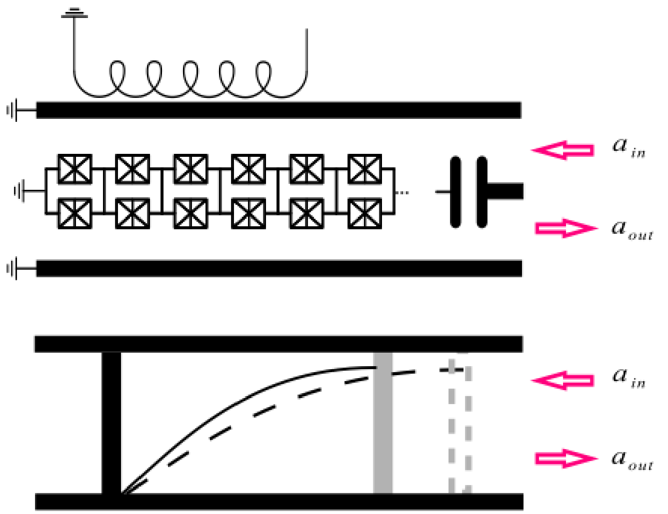
Non-classical features observed, e.g. two-mode squeezing

Analog DCE as no real mechanically moving element !!

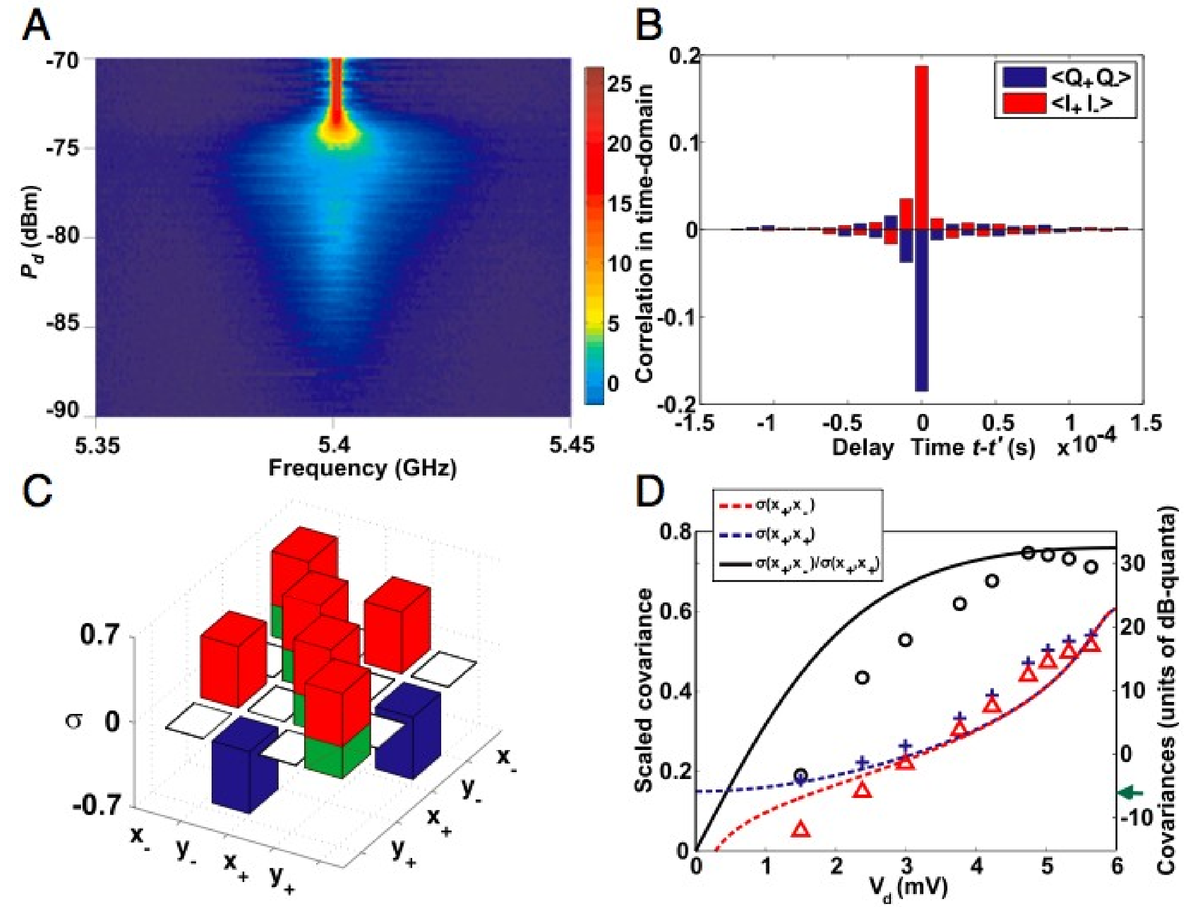
NOTE: When waveguide closed by second mirror, hard to observe DCE:

- quickly above parametric threshold (Wilson et al., PRL 2010)
- classical emission loses quantum features

A related experiment



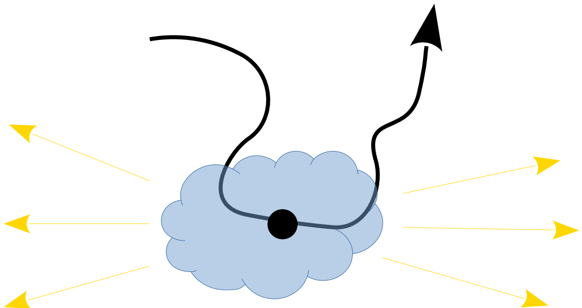
Figures from Lähteenmäki et al., PNAS 110, 4234 (2013)



- External microwave signal at Ω drives string of Josephson elements
- Modulates effective refractive index of cavity material
- Similar experimental features as in previous experiment

Again, no mechanically moving element → analog DCE effect !

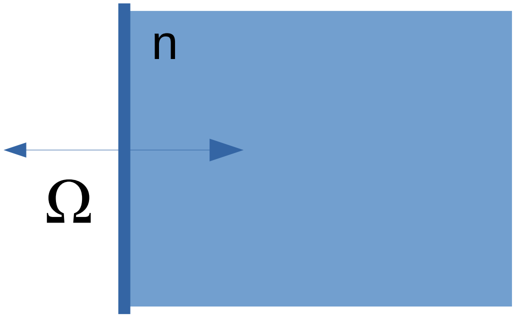
Next challenge: back-reaction effect of dynamical Casimir emission



Neutral dielectric medium in non-inertial motion
Emits radiation: quantum fluctuations scattered into real radiation
In return: feels quantum vacuum friction force

Simplest configuration:

- Half-space slab of refractive index n and mass M
- Mechanically oscillating at frequency Ω



- Prediction for the dissipated energy within 1D scalar model:

$$Q^{-1} = \frac{\tau}{2\pi E_{osc}} \frac{dE_{diss}}{dt} = \frac{1}{6}\left(\frac{n-1}{n}\right)^2 \frac{\hbar\Omega}{Mc^2}$$

Barton and Eberlein, Ann. Phys. 227, 222 (1993)

➔ value is ridiculously small

➔ experimental observation by mechanical means with bulk objects appears hopeless, but quantum optomechanics gives new hopes...

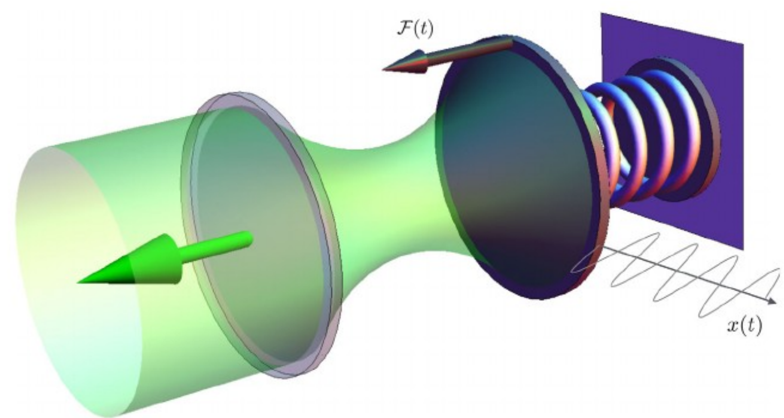
An opto-mechanical toy-model

Single-mode optical cavity *a*

Mirror mounted on mechanically moving part
with harmonic restoring force *b*

Opto-mechanical coupling via radiation pressure
on mirror or length-dependent shift of cavity resonance

$$\hat{H} = \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar\omega_b \hat{b}^\dagger \hat{b} + \hbar\omega_c \left(\hat{a} + \hat{a}^\dagger\right)^2 \left(\hat{b} + \hat{b}^\dagger\right)$$



If $\omega_b \sim 2\omega_a$, dynamical Casimir emission (with time-indep. H)
energy transferred from mechanical to optical field

Simple on paper, a bit harder in experiment:

- generally mechanical frequencies << optical frequencies
- appears feasible in μ-waves with recent GHz acoustics experiments
  (e.g. Schoelkopf's group, Science 2017)

PHYSICAL REVIEW X **8**, 011031 (2018)

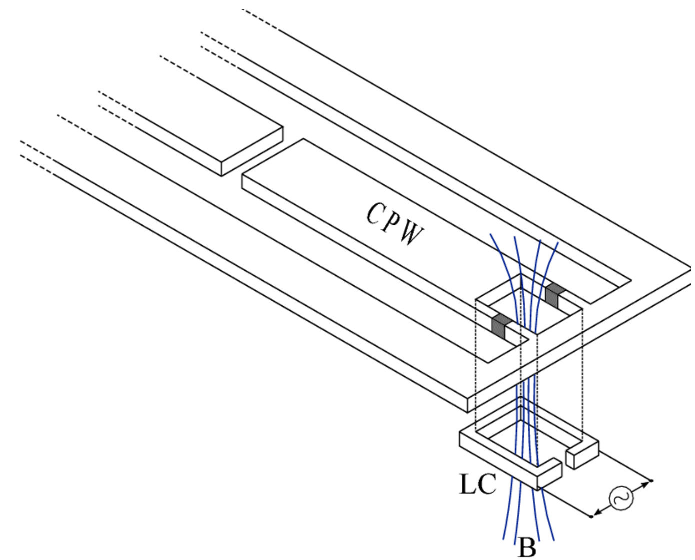
Nonperturbative Dynamical Casimir Effect in Optomechanical Systems: Vacuum Casimir-Rabi Splittings

Vincenzo Macrì,[1,2] Alessandro Ridolfo,[2] Omar Di Stefano,[2] Anton Frisk Kockum,[2] Franco Nori,[2,3] and Salvatore Savasta[1,2]

Even simpler option: circuit-QED device with mirror as independent e.m. DOF

B-field generated by LC circuit concatenated to SQUID

- LC circuit → mechanical oscillator
- DCE effect → coplanar waveguide



To enhance DCE & back-reaction effect:

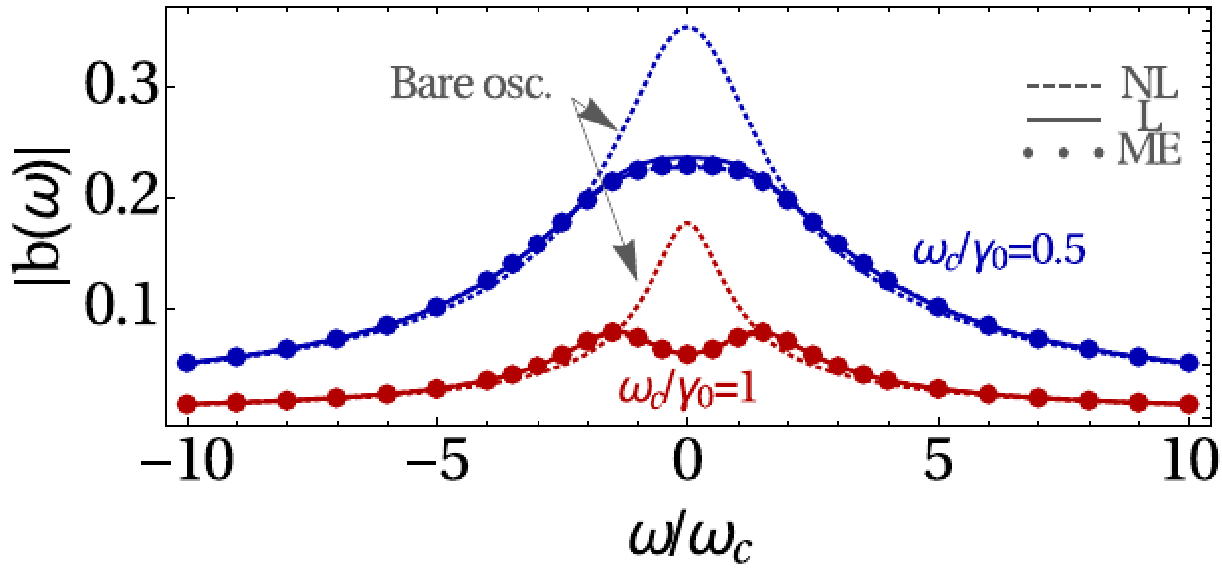
- close CPW with second mirror to create cavity
  and resonantly enhance DCE
- Back-reaction of DCE expected to be visible
  as additional dissipation on LC circuit
- To be electronically probed on the LC dynamics

- Estimated single-quantum coupling ~10kHz,
  not far from typical decay

S. Giulio Butera

S. G. Butera & IC, *Mechanical back-reaction effect of the dynamical Casimir emission*, Phys.Rev. A 99, 053815 (2019)

Response of LC to external monochromatic drive



DCE results in broadened resonance by $\gamma_{DCE} \sim 2\,\omega_c^2/\gamma$

Strong DCE coupling $\omega_c > \gamma$ gives nonlinear Rabi splitting of resonance

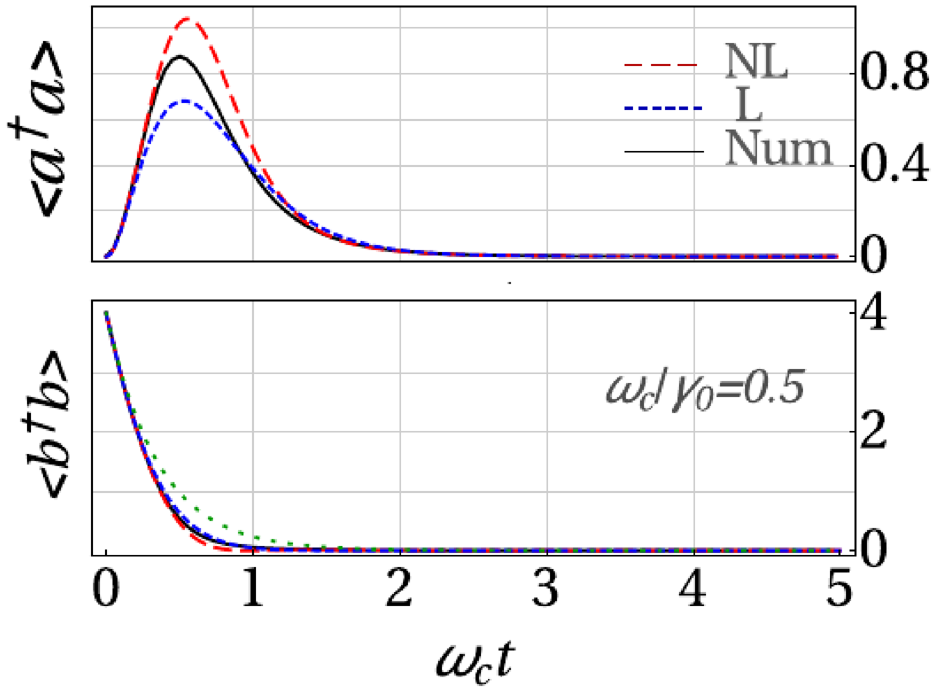
$$\hat{H} = \hbar\omega_0 \hat{a}^\dagger \hat{a} + \hbar\omega_b \hat{b}^\dagger \hat{b} + \hbar\omega_c \left(\hat{b}^\dagger \hat{a}^2 + \hat{b} \left(\hat{a}^\dagger\right)^2 \right)$$

Next steps:

- extend the calculation to open CPW where DCE is broadband and no resonant enhancement of DCE
- design optimal set-up and try the experiment
  (Q@TN collab. A. Vinante, F. Mantegazzini, F. Ahrens, N. Crescini - Trento)

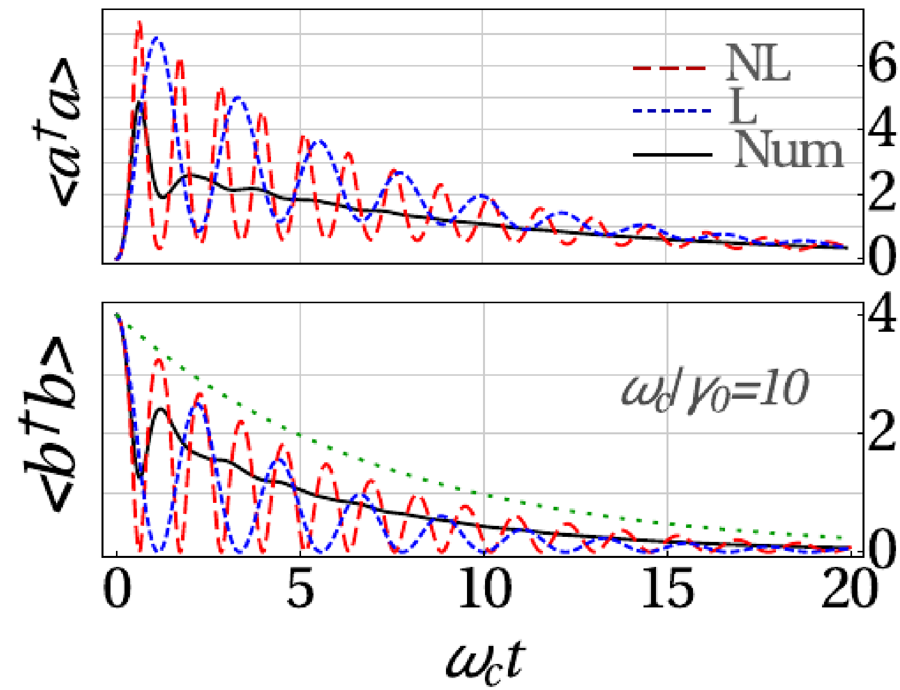
S. G. Butera & IC, *Mechanical back-reaction effect of the dynamical Casimir emission*, Phys.Rev. A 99, 053815 (2019).

Free evolution after initial kick of LC



Weak DCE coupling

reinforced decay due to DCE emission



Strong DCE coupling

periodic exchange of energy

[also in Macrì et al., PRX 2018]

S. G. Butera & IC, *Mechanical back-reaction effect of the dynamical Casimir emission*, Phys.Rev. A 99, 053815 (2019).

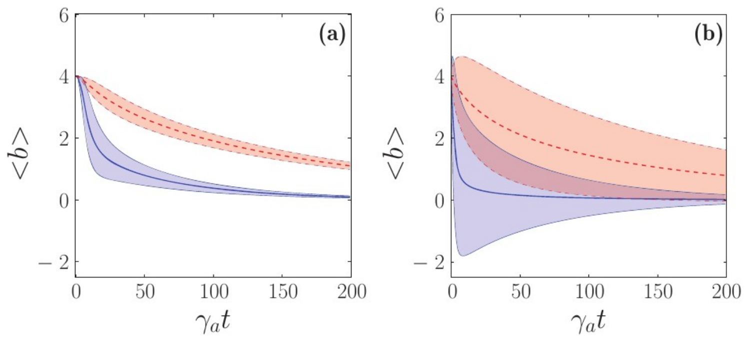
Quantum fluctuation effects

Numerical integration of Master Equation

- Temporal decay of the mechanical oscillations by DCE friction
- Quantum fluctuations (shading) much larger in non-resonant case

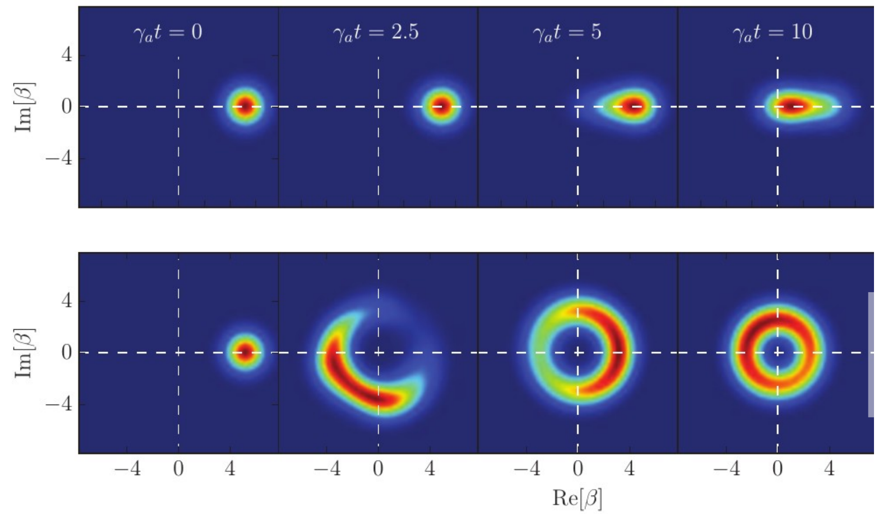
Resonant DCE

Slightly non-resonant DCE



Phase space interpretation:

- Resonant → fluctuations in DCE damping force
- Non-resonant → fluctuations in DCE frequency shift



Resonant

Slightly non-resonant

Fluctuations are experimentally accessible in circuit-QED by measuring quantum state of LC circuit

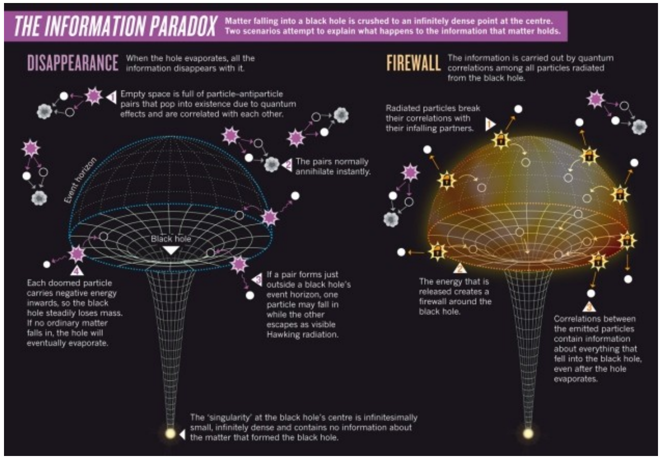
Physically: unexpected role of quantum fluctuations of the quantum friction force

S. G. Butera & IC, *Quantum fluctuations of the friction force induced by the dynamical Casimir emission,* EPL 128, 24002 (2020).

Back-reaction in more complex geometries

The BIG question: what is the long-term fate of a BH ?

- HR carries away energy, so BH horizon must (slowly) shrink to conserve energy/mass
- What is left once BH has evaporated?
- Is there any remnant of what has fallen into the BH ?

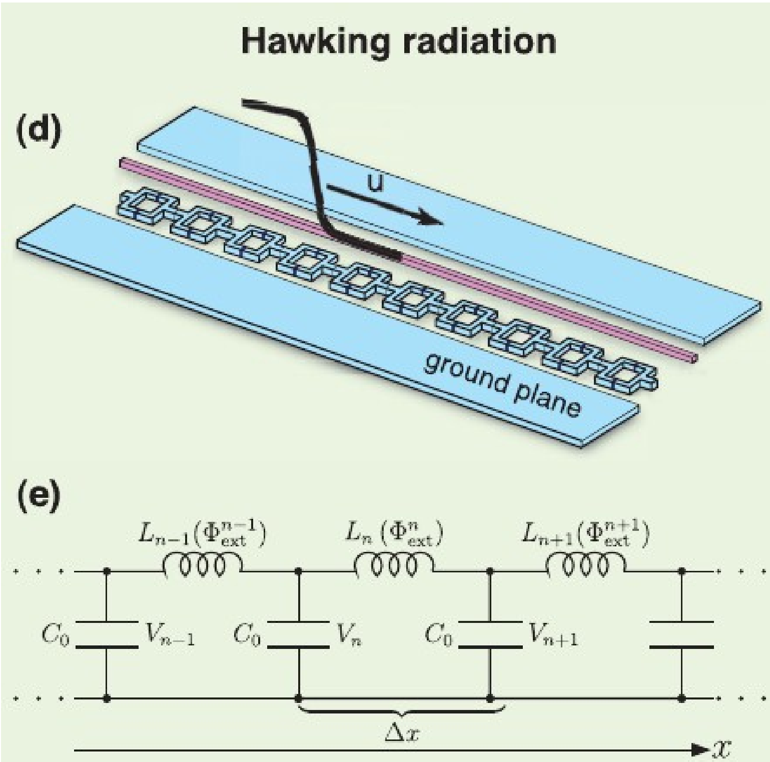


Our approach:

- Analog models “quantum simulate” QFT on curved space-time…
- ...but Einstein eqs. (coupling of matter/energy to metric) not implemented

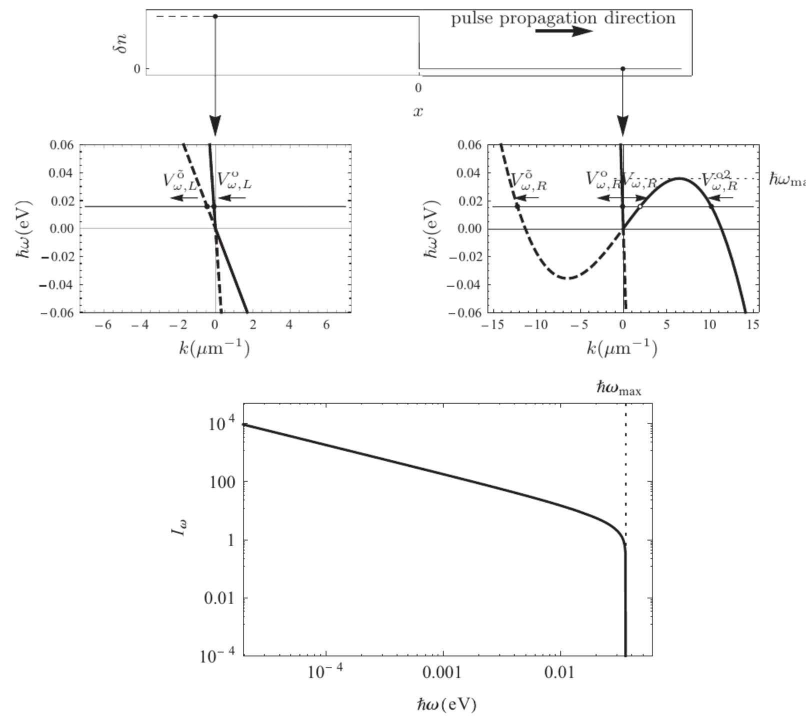
- Still, any hint from higher order couplings of quantum fluctuations to macroscopic DOFs?
- What can a quantum optician’s point of view teach on this physics?
- Let’s start from simplest configurations !

First step: Hawking emission



Sketch from Nation et al., RMP 2012

Proposed by Schützhold-Unruh, PRL 2005



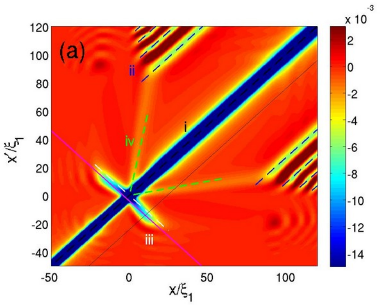
Theoretical calculation of Hawking spectrum
Finazzi, IC, PRA 2013

Towards back-reaction and BH info paradox: Hawking emission from moving self-bound soliton
(Katayama, Fujii, Blencowe, PRD 2020, PRR 2022, etc.)

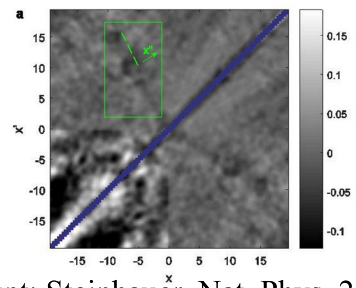
Other platforms… strong synergies possible!

Ultracold atomic clouds & Bose-Einstein condensates

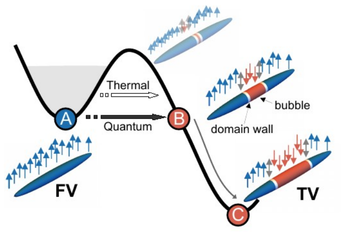
Analog Hawking emission detected via Balbinot-Fabbri moustache

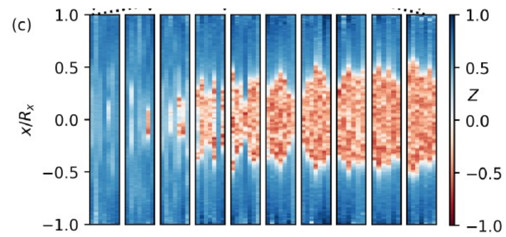


Theory: IC et al, NJP 2008



Expt: Steinhauer, Nat. Phys. 2016



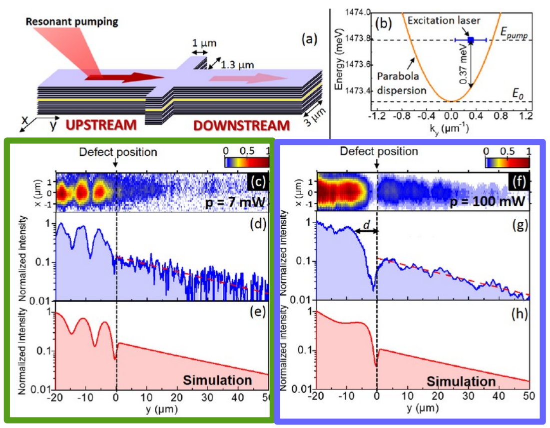


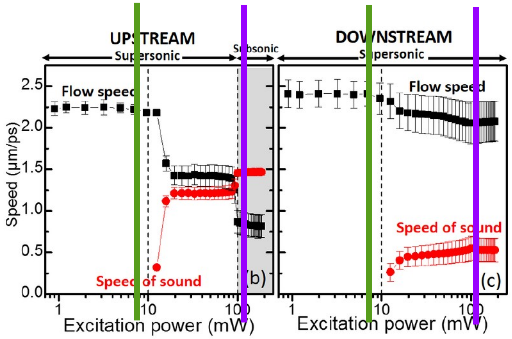
False vacuum decay via bubble formation in ferromagnetic BEC

Zenesini et al., arXiv 2305.05225 (Pitaevskii BEC Center + collaborators)

Quantum fluids of light

Expt.:
Nguyen et al. PRL 2015
Jacquet et al., arXiv 2023





Analog black hole created.
Hunt for HR is open!

Many more challenges: cosmological particle generation & inflation; superradiance from rotating BHs, BH quasi-normal modes,...

Conclusions

Superconducting circuit-QED devices very powerful platform to study observable consequences of the zero-point fluctuations of quantum vacuum

Dynamical Casimir emission (DCE) from moving mirror experimentally established

- Emission detected + quantum correlations

Back-reaction of dynamical Casimir emission on mirror → Quantum friction

Circuit-QED allow for all-electromagnetic configuration

- extra e.m. oscillator coupled to SQUID plays role of mirror
- quantum state of "analog mirror" can be read out with circuit-QED techniques

Future developments: complex geometries, e.g. analog black holes

- Analog Hawking emission from horizon

- Holy grail: evaporation of black hole under effect of back-reaction
- Insight on information paradox??

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Q@TN

QST

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NextGenerationEU

Living Reviews in Relativity
December 2011, 14:3 | Cite as

Analogue Gravity

Authors | Authors and affiliations

Carlos Barceló, Stefano Liberati, Matt Visser

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First Online: 11 May 2011

Superradiant phenomena
Lessons from and for Bose–Einstein condensates

Luca Giacomelli

Ph.D. thesis submitted to Dipartimento di Fisica
Università degli studi di Trento

Under the supervision of
Dr. Iacopo Carusotto
Prof. Massimiliano Rinaldi

news & views

QUANTUM HYDRODYNAMICS

Acoustic Hawking radiation

A milestone for quantum hydrodynamics may have been reached, with experiments on a black hole-like event horizon for sound waves providing strong evidence for a sonic analogue of Hawking radiation.

Iacopo Carusotto and Roberto Balbinot

Nat. Phys., Aug.15h, 2016

REVIEWS OF MODERN PHYSICS, VOLUME 84, JANUARY–MARCH 2012

***Colloquium*: Stimulating uncertainty: Amplifying the quantum vacuum with superconducting circuits**

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PhD & PostDoc positions
soon available
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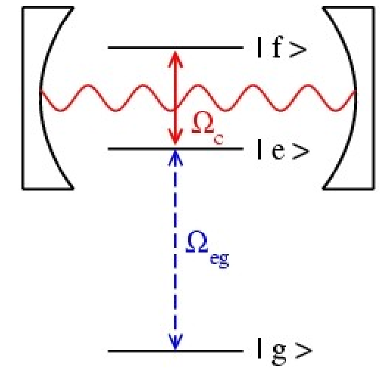
All-optical back-reaction effect

PHYSICAL REVIEW A **85**, 023805 (2012)

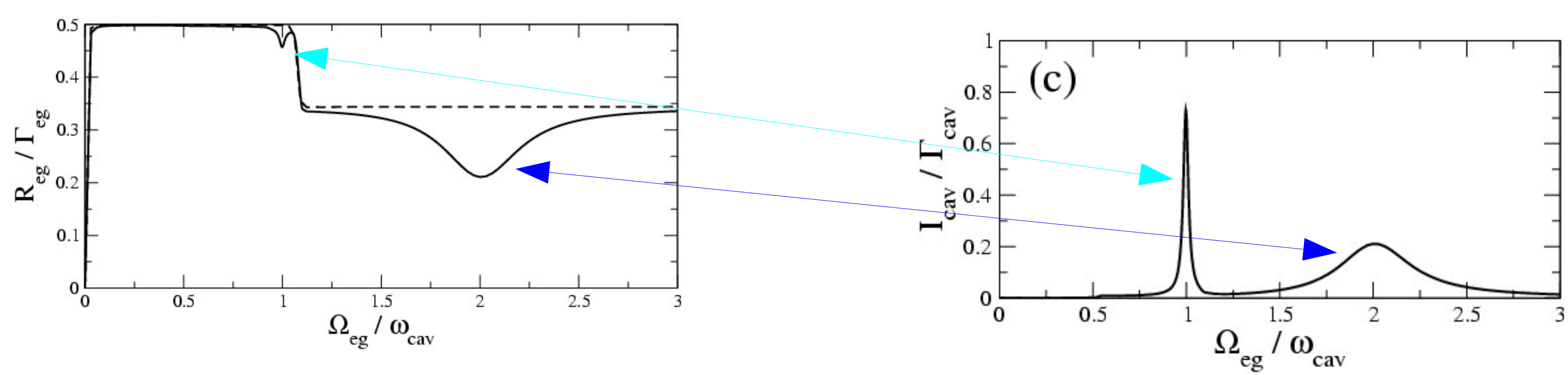
Back-reaction effects of quantum vacuum in cavity quantum electrodynamics

I. Carusotto,[1,*] S. De Liberato,[2] D. Gerace,[3] and C. Ciuti[2]



Coherently-driven 3-level emitter embedded in optical cavity

- Drive laser on g ↔ e transition → Rabi oscillations at Ω_R, cavity periodically modulated
- Generates DCE emission, strongest when Ω_R resonant with cavity
- Absorption of drive laser: $R_{eg} = 2\Omega_{eg}\,\mathrm{Im}\{\mathrm{Tr}[\hat{c}^{\dagger}_{eg}\,\rho_{ss}]\}.$
- Peaks in DCE give dip in absorption: stronger “friction” reduces absorption rate

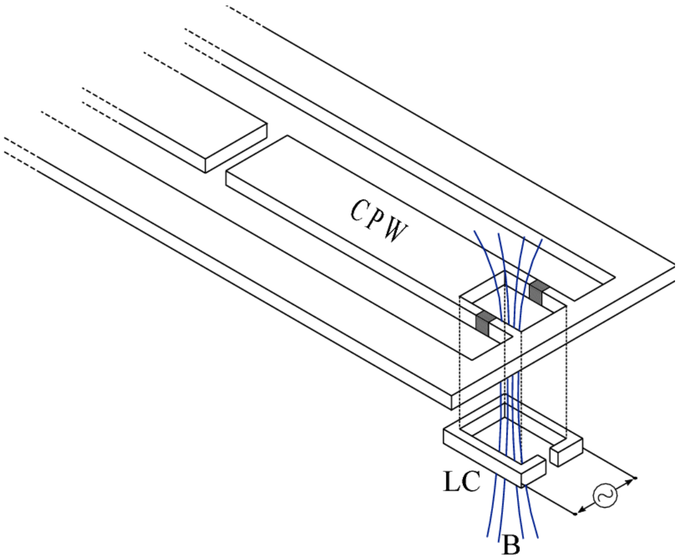


- Feasible with optical or μ-wave (circuit-QED) techniques

Circuit-QED: mirror as an independent DoF

B-field generated by LC circuit concatenated to SQUID

- LC circuit → mechanical oscillator
- DCE effect → coplanar waveguide



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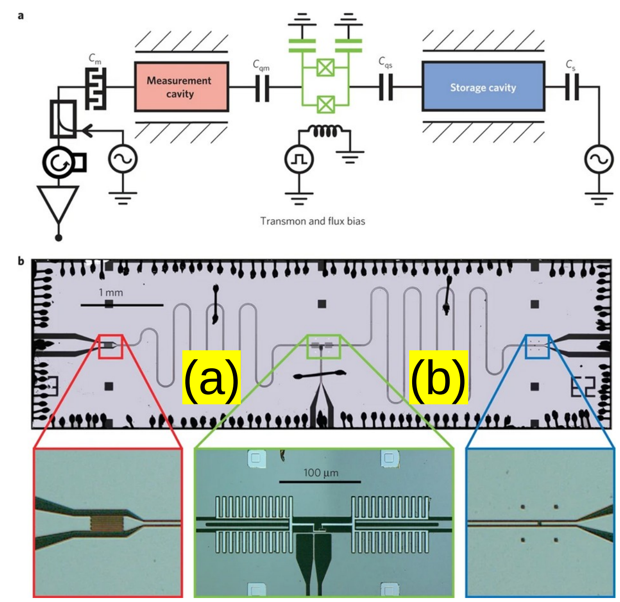
- Back-reaction of DCE expected to be visible as additional dissipation on LC circuit
- To be electronically probed on the LC dynamics
- Estimated single-quantum coupling ~10kHz, not far from typical decay

Another useful configuration (to exploit 2nd-hand samples):

- Two (a,b) cavities, connected by cross-Kerr Josephson element
- Send μw's into (b) to modulate effective length of (a)
- Watch DCE emission into (a), backreaction in (b)



Sketch from Johnson et al, Nat. Phys. 2

S. G. Butera & IC, *Mechanical back-reaction effect of the dynamical Casimir emission*, Phys.Rev. A 99, 053815 (2019)
Further steps in collaboration with *DartWars* INFN project – P. Falferi, A. Vinante, C. Gatti