BEC
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Quantum simulation of quantum field theory and gravitational phenomena in circuit QED devices and ultracold atomic clouds

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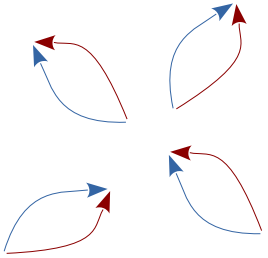
Classical vacuum

Just empty space:
a passive stage for physics

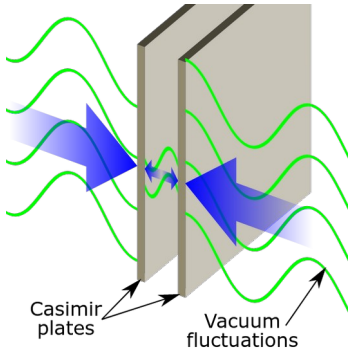
Quantum vacuum



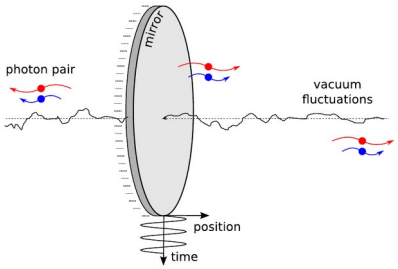
Full of virtual particle-antiparticle pairs
(survive for Heisenberg-limited time $\Delta E\, \Delta t < 1$)

Zero-point quantum fluctuations
of all fields

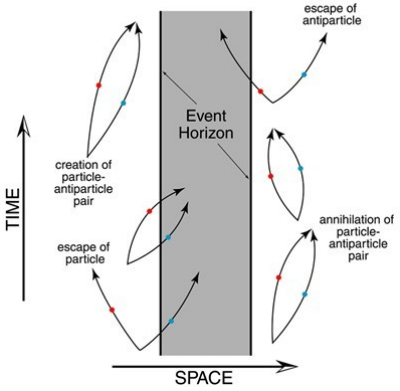
A number of predicted phenomena….



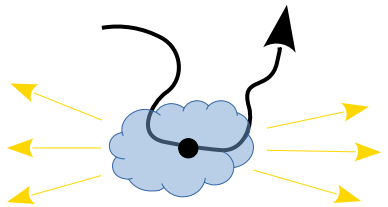
(Static) Casimir effect: attractive force in vacuo
Source: Wikipedia



(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

… typically difficult to observe !!

Part 1

Ultracold atomic clouds

Hawking radiation and beyond

"Fishic" (but not fishy!) horizon

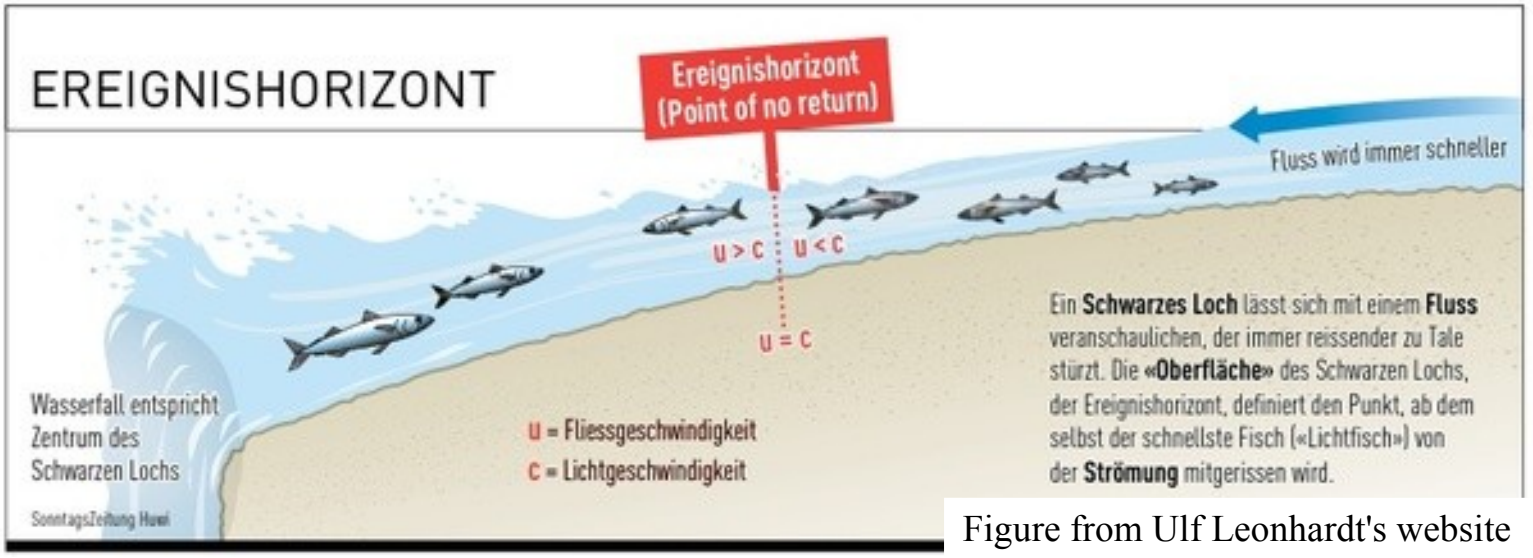


Figure from Ulf Leonhardt's website

Fish swim at $v=c_s$ in the river's frame, i.e. at $c_s \pm v_{flow}$ in the land's frame

- Horizon (where $c_s=v_{flow}$) separates sub-fishic flow (upstream) from super-fishic flow (downstream)
- Fish in super-fishic region can not swim back through fishic horizon

Behavior analogous to geometrical optics around astrophysical black hole horizon

Can we learn something on black holes from these condensed matter systems?

Acoustic horizon

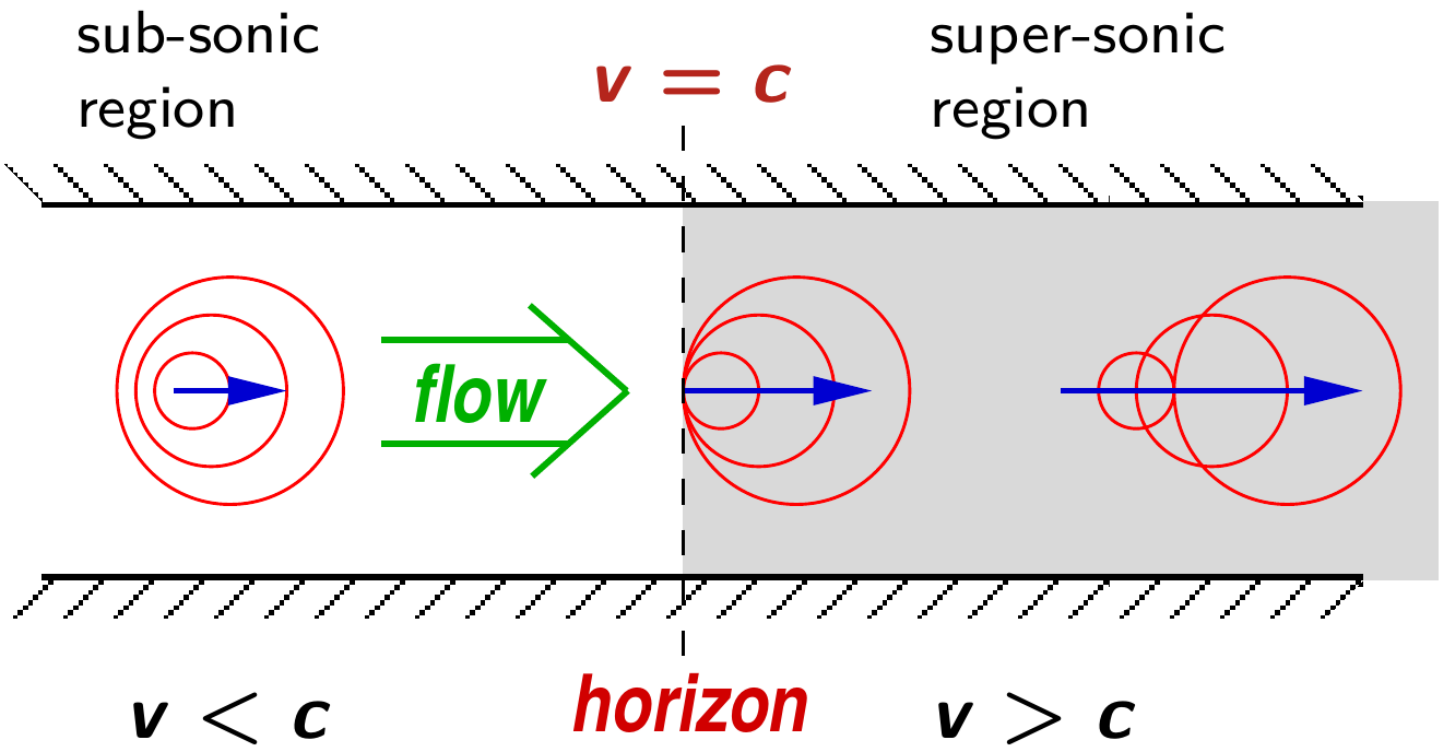


Figure from N. Pavloff's website

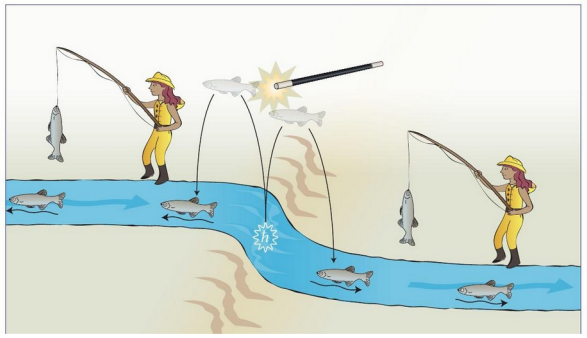
- Sound emitted in super-sonic region is dragged by the flow in the downstream direction
- Excitations in super-sonic region can not travel back through horizon
- Acoustic analog of black hole horizon in gravity

- What happens with quantized radiation field ? Hawking radiation of sound ?

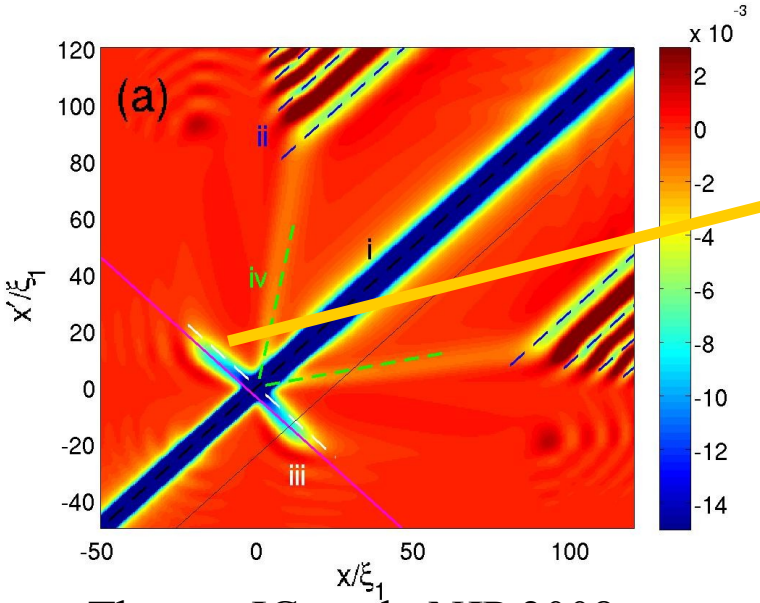
Unruh, *Experimental Black-Hole Evaporation?,* PRL 1981 (earlier than 1982 celebrated Feynman's work)
Barceló, Liberati, Visser, Liv. Rev. Relativity **14**, 3 (2011)

Analog Hawking radiation detected in the lab!

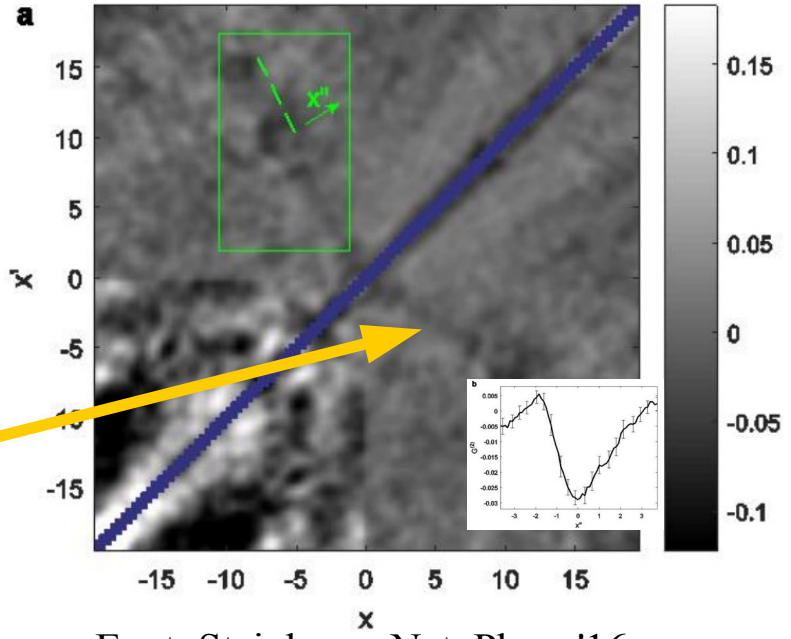
- Analog black hole configuration obtained by sending atomic BEC through a nozzle (created with an optical potential)
- Experiment exploits correlation between Hawking particles and partners to separate Hawking emission from background



Picture from IC-Balbinot, Nat. Phys. N&V, Aug. 2016



Theory: IC et al., NJP 2008



Expt: Steinhauer Nat. Phys. '16

Experimental evidence:
Balbinot-Fabbri moustache in
correlation function of density fluctuations

What physics can be learnt on 'real' black holes ?

Standard derivations of Hawking radiation assume:

- linear dispersion $\omega(k) = c\,|k|$ at all length scales
- infinite blue shift of modes at horizon, GR and QFT valid up to arbitrary energies

These assumptions violated in analogs:

- closer look: microscopic mechanism of HR very different
- key role of deviations from hydrodynamics at high energies

What do we learn from the observation of analog HR?

- thermal HR robust to "Planck-scale" physics and Lorentz-violations
- Peculiar features imprinted onto HR spectrum

- Observable @ LHC ? explain why we survived 2008 switch-on?

pseudo-La Repubblica 11/9/08

W. G. Unruh, Phys. Rev. D 51, 2827 (1995); R. Brout et al., Phys. Rev. D 52, 4559 (1995)
T. A. Jacobson and R. Parentani, *An echo of Black Holes*, Scientific American, Dec. 2005.

Open questions to be addressed with atomic BECs: short run

Crucial advantages from experiments with two-component BECs:

- speed of spin sound << speed of density sound → HR protected by superfluidity
- all field components observable → HR visible in all quadratures
- entanglement between Hawking and partner accessible
- complex geometries achievable, e.g. rotating space-times for superradiance

A. Berti PhD thesis, UniTN '24. And don't miss Gabri's talk !

False vacuum decay

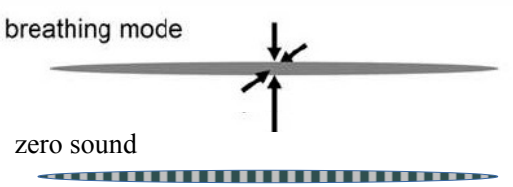
First experimental observations available – don't miss Gabri's talk

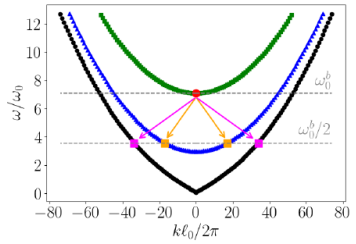
Open questions to be addressed with atomic BECs: long run

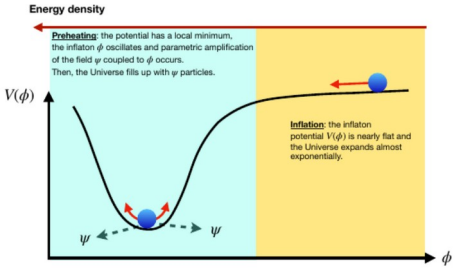
Back-reaction phenomena

- Theory available for particle generation during cosmological pre-heating
- Quantum emission provides friction to inflaton oscillations
- Unexpected crucial role of quantum fluctuations (Butera-IC, PRL 2023, also in circuit-QED systems)

- Theory to be extended to BH… very challenging!!
- May provide insight into long-term fate of a BH ??

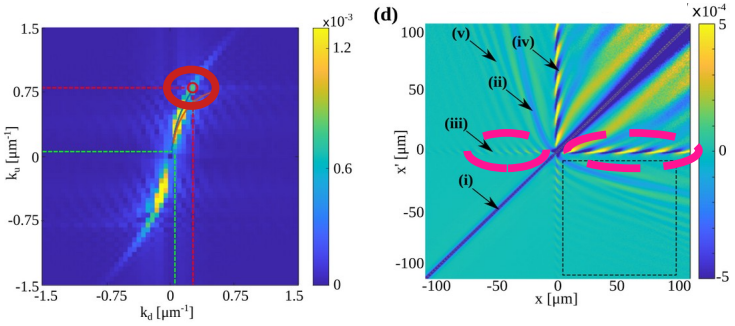






Intrinsic quantum fluctuations of BH space-time:

- Space-time structure & grey-body → spectral peaks in HR @ quasi-normal mode frequencies
- BH shape "quantum fluctuates" in reaction to HR (Jacquet, Giacomelli, ...IC … , PRL 2023)



Effects originally discovered in analog models, but likely relevant also in astrophysical context

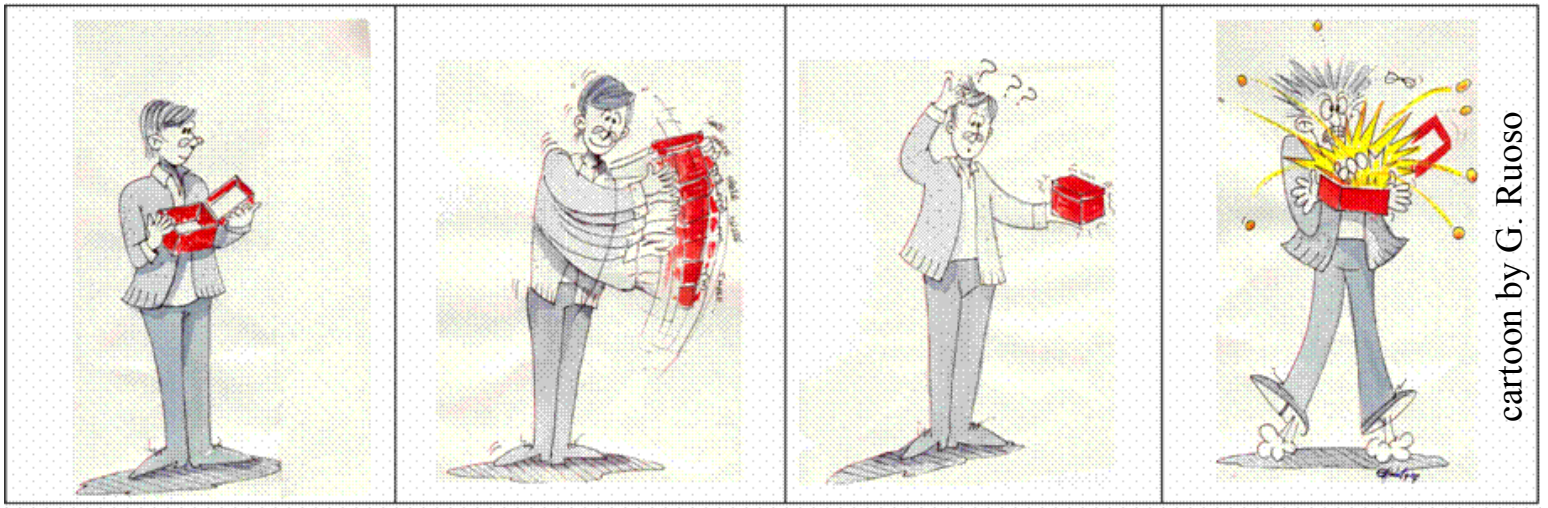
New astrophysical observations? Conceptual impact on information paradox?

Part 2

Circuit QED devices

Dynamical Casimir effect and beyond

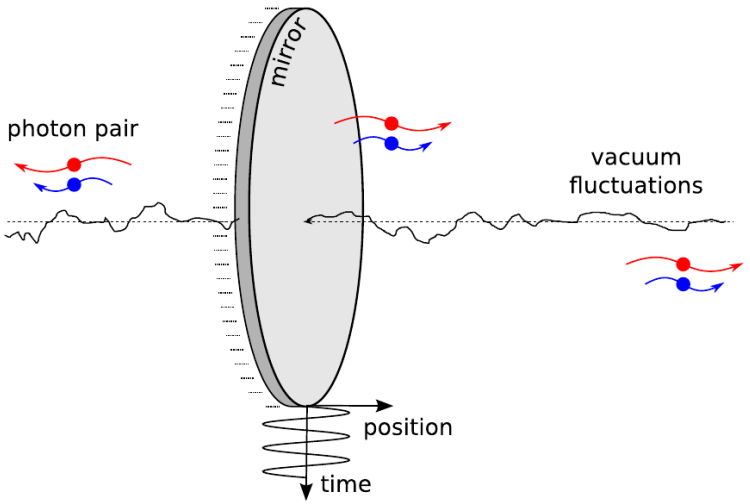
Dynamical Casimir effect



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

Main experimental difficulty: need to shake really fast

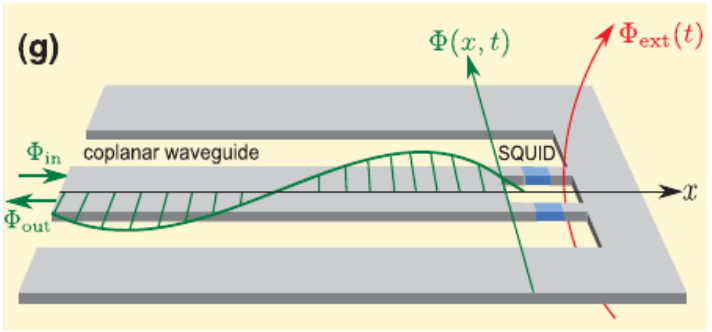
- Characteristic (Unruh) temperature $k_B T_U \sim h a / 4 \pi^2 c$ very small !!!
- Friction from back-reaction even weaker

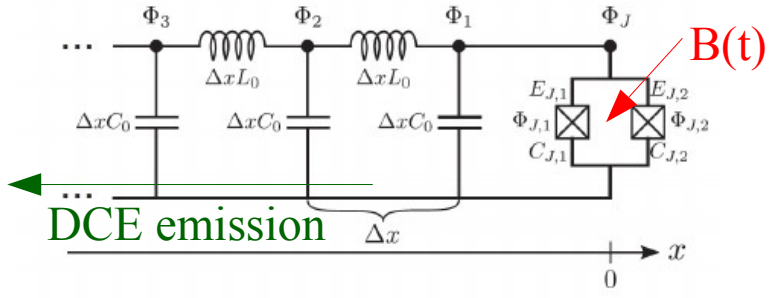
Circuit-QED observation of (analog) DCE

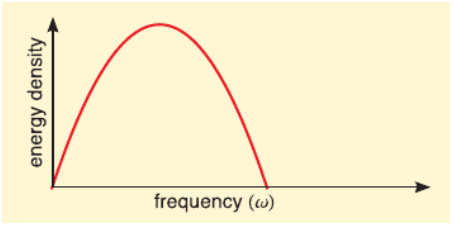
doi:10.1038/nature10561

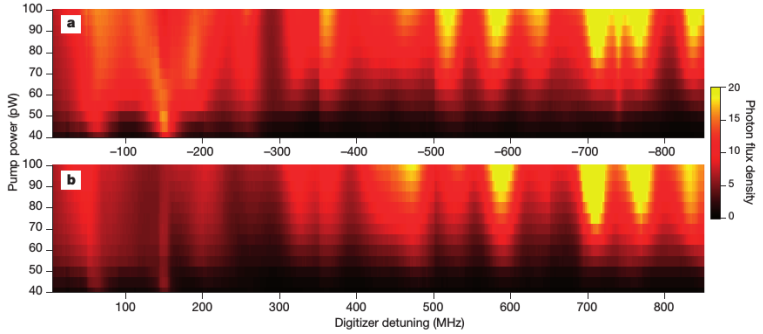
Observation of the dynamical Casimir effect in a superconducting circuit

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

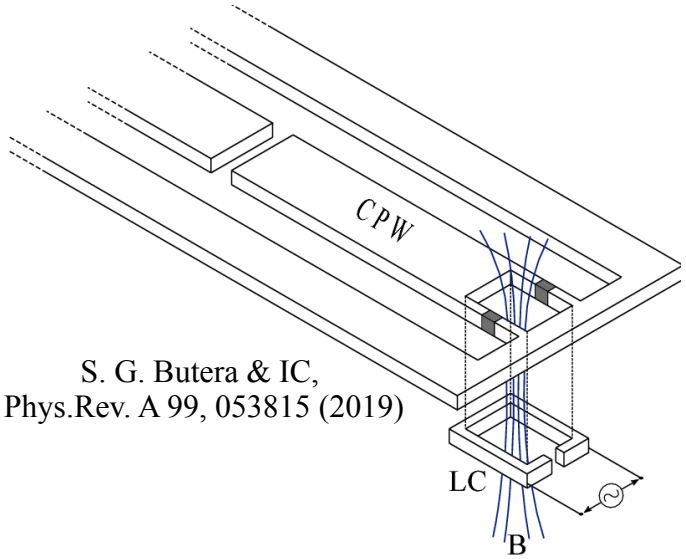
- Observed as radiation along CPW: emission centered around Ω/2 (with spurious modulation)
- Non-classical features observed, e.g. two-mode squeezing

Short run: towards back-reaction phenomena

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



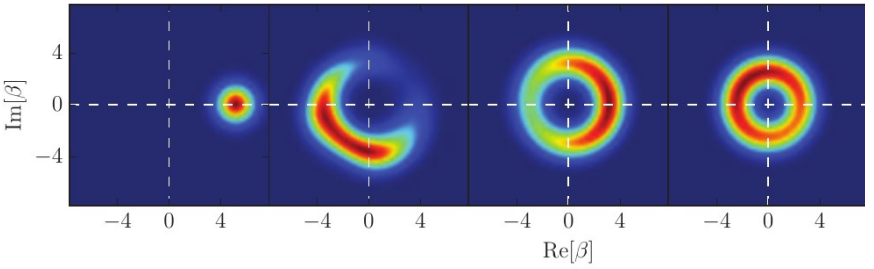
S. G. Butera & IC,
Phys.Rev. A 99, 053815 (2019)

To enhance DCE & back-reaction effect:

- back-reaction of DCE expected to be visible as additional dissipation on LC circuit
- to be electronically probed on the LC dynamics

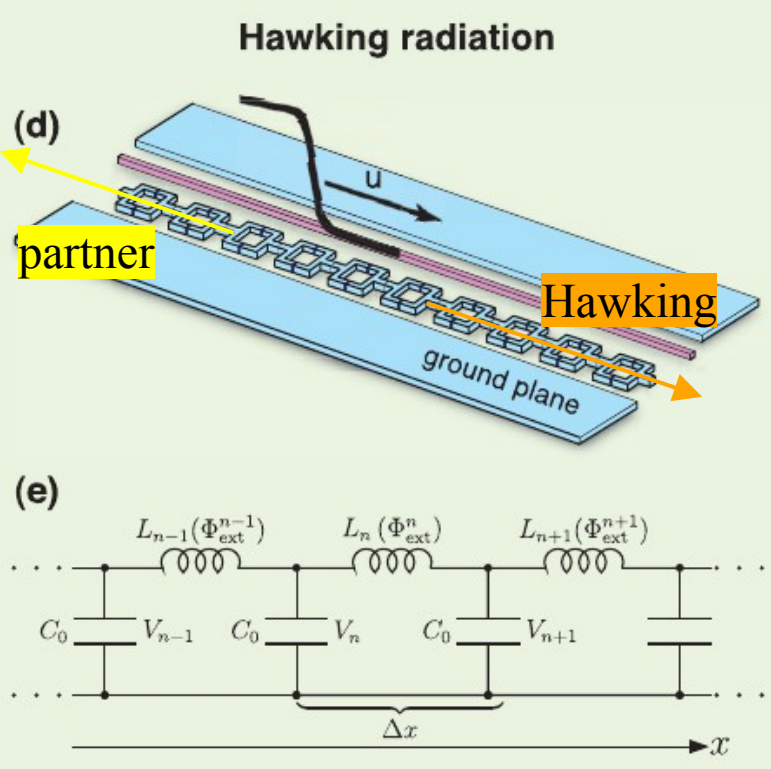
Strong role of quantum fluctuations:

- Dephasing of oscillation amplitude on top of amplitude decay
- Simplest example of back-reaction effect

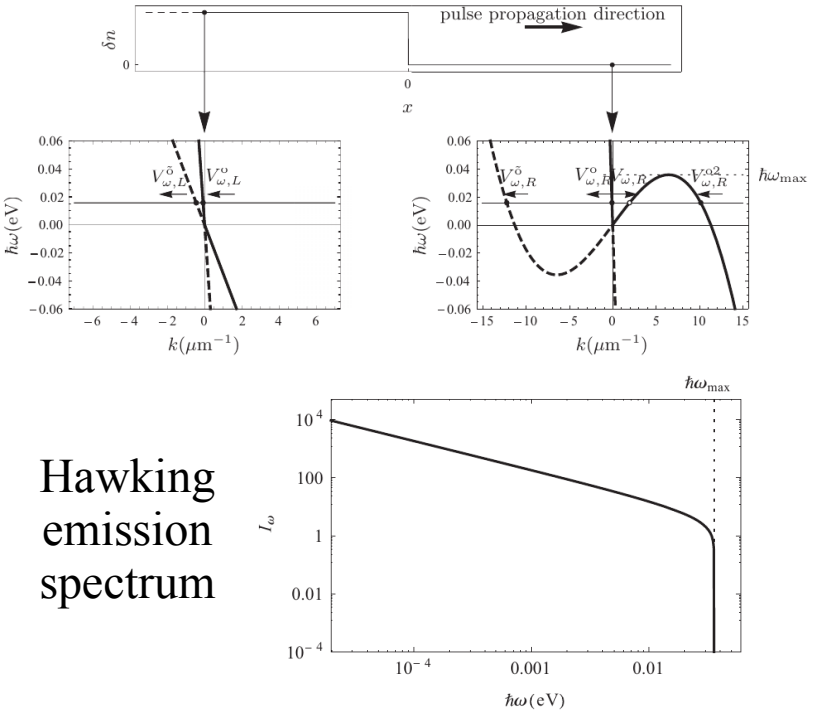


S. G. Butera & IC, EPL 128, 24002 (2020).

Longer run: analog horizons and Hawking emission



Sketch from Nation et al., RMP 2012
Proposed by Schützhold-Unruh, PRL 2005



Hawking emission spectrum

General theoretical framework
Finazzi, IC, PRA 2013

- Moving e.m. front changes speed of light via nonlinear effects
- Radiation modes see effective moving horizon → Hawking emission
- Quantum correlations encoded in entangled photon pairs

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

Conclusions

Ultracold atomic gases & superconducting circuit-QED devices
very powerful platform to study
observable consequences of the zero-point fluctuations of quantum vacuum
in controllable environments

Recent milestone observations:

- analog Hawking emission in atomic BECs
- analog Dynamical Casimir emission in circuit-QED

New frontier: back-reaction effects

- dynamical Casimir emission → quantum friction onto mirror
- Spontaneous particle emission in cosmological pre-heating stage
  → quantum fluctuation effects onto inflaton mode
- Hawking emission → black hole evaporation.
  - Unknown role of quantum fluctuations onto BH horizon?
  - Impact on information paradox?

Experimental realization in condensed matter analog models
→ physical insight on what happens in astrophysical and cosmological context

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

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Carlos Barceló, Stefano Liberati, Matt Visser

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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

PhD & PostDoc positions soon available
iacopo.carusotto@unitn.it

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 85, JANUARY–MARCH 2013

Quantum fluids of light

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I. Carusotto, C. Ciuti, Rev. Mod. Phys. **85**, 299 (2013)