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Curved space-times in condensed matter physics:
from the dynamical Casimir effect in vibrating cavities
to Hawking radiation from acoustic black holes
The collaboration

Trento-BEC
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R. Balbinot
gravitational physics
cosmology

Univ. Pavia
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solid state physics
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semiconductor optics
circuit-QED

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solid state physics
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Experimental partners

JILA, Boulder, CO
E. Cornell
expts of acoustic HR in atomic BECs

Univ. Paris 6
A. Bramati, E. Giacobino
expts of acoustic HR in exciton-polariton BECs

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A. Bramati, E. Giacobino
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UAM Madrid
L. Viña, C Tejedor
expts of acoustic HR in exciton-polariton BECs
Intro - Quantum fields on curved space-times
what is an elementary particle?

Inertial Lorentzian frames, flat space-time:
- free propagation conserves particle number
- particles only created by some interaction (e.m, weak, strong...)

Non-inertial, accelerated frames:
- Unruh effect: accelerated observer observes a temperature $T = \frac{h a}{c k_B}$

Curved or time-dependent space-time:
- creation of particles off the quantum vacuum
- time-dependent boundary condition: dynamical Casimir effect
- amplification of quantum fluctuations during cosmological inflation, seed for large scale structure of universe
- Hawking radiation from black holes
1 - The 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!!

cartoon by G. Ruoso
Why experimentally so challenging?

- Mirrors have to be shaken at twice the cavity frequency
- Hard to do by mechanical motion, even in rf domain
- Hard to distinguish from (parametrically amplified) thermal radiation
Our point of view

Identify and characterise a **simple system** that:

- allows for **high-frequency modulation of cavity optical length**
- **coherent modulation** to avoid **heating and thermal radiation**
- **intrinsic optical nonlinearity** to isolate **quantum vacuum radiation**

Several candidates:

- **ultracold atoms** in Mott insulator state in a EIT regime
  (IC, M. Antezza, F. Bariani, S. De Liberato, C. Ciuti, PRA 2008)

- **doped quantum wells** in **semiconductor microcavities**

- **Cooper-pair boxes** in **superconducting strip-line cavities**
  (S. De Liberato, D. Gerace, IC, C. Ciuti, to appear)
Superconductor Cooper-pair box in microwave stripline cavity:

- **Ultra-strong light-matter coupling**: quantum vacuum state deformed. Contains finite number of bound photons.
- **Non-adiabatic modulation** releases these photons.
- Modulation of optical length via frequency and/or light-matter coupling modulation demonstrated at microwave frequency.
- **Two level emitter** easily saturated: vacuum radiation spectrally isolated.

S. De Liberato, D. Gerace, I. Carusotto, C. Ciuti, to appear
Steady but non-uniform flow

Horizon separates region of sub-sonic and super-sonic flow

No sonic perturbation can propagate back from super-sonic region

Low-k, hydrodynamic region: linear phonon dispersion $\omega = c_s |k| + v k$

Mathematical analogy with light propagation in curved metric

$$ds^2 = G_{\mu \nu} dx^\mu dx^\nu = \frac{n(x)}{c_s(x)} \left[-c_s(x)^2 dt^2 + (d \vec{x} - \vec{v}(x) dt)(d \vec{x} - \vec{v}(x) dt)\right]$$

Wave equation for BEC phase

$$\frac{1}{\sqrt{-G}} \partial_\mu \left[\sqrt{-G} G^{\mu \nu} \partial_\nu\right] \phi(x, t) = 0$$

Once quantized $\rightarrow$ quantum field theory in a curved space-time
Astrophysical black-holes

- emit Hawking radiation at 
  \[ T_H = \frac{\hbar c^3}{8 \pi G M k_B} \]
- solar mass BH: \( T_H = 0.4 \, \mu K \), hardly visible
  if compared to cosmological background at 2.73 K

Acoustic black holes:

- Hawking radiation of phonons at 
  \[ T_H = \frac{\hbar}{4 \pi k_B c_s} \left[ \frac{d}{dx} \left( c_s^2 - v^2 \right) \right]_H \]
- in nK range for \( \mu m \)-sized ultracold atomic BECs
  ( not so bad... )
How to detect Hawking radiation?

HR is thermal only if seen from outside
Entanglement between in- and out-going partners
Both accessible w/o irreversible consequences on experimentalist

Density fluctuations of BEC $G^{(2)}(x, x') = \frac{\langle : n(x) n(x') : \rangle}{\langle n(x) \rangle \langle n(x') \rangle}$

Prediction of gravitational analogy :

$\rightarrow$ entanglement in Hawking pairs gives long-range in/out correlations

$$G_2(x, x') = 1 - \frac{\xi_1 \xi_2}{16 \pi c_1 c_2} \frac{k^2}{n^2 \xi_1 \xi_2} \frac{c_1 c_2}{(c_1 - v)(v - c_2)} \cosh^{-2} \left[ \frac{k}{2} \left( \frac{x}{c_1 - v} + \frac{x'}{v - c_2} \right) \right]$$

$\rightarrow$ allows to isolate Hawking phonons from incoherent thermal phonons

Dynamical Casimir emission

Hawking in / out

Density plot of: \((n \xi_1) \ast [G^{(2)}(x,x') - 1]\)

Many-body antibunching

Hawking in / in

What have we learnt about black holes?

Standard derivations of Hawking radiation:
- linear dispersion $\omega(k) = c |k|$ at all length scales
- infinite blue shift at horizon, relativity and QFT valid up to arbitrary energies

These assumptions violated in analogs:
- HR is robust w/r to deviation from hydrodynamics
- but thermal HR spectrum modified by “Planck-scale” physics

Open question:
- does this provide new features in BH signal at LHC (and possibly contribute to save the world)?
Towards the REAL experiment

Eric Cornell's smart trick to reinforce HR signal in atomic BEC experiments

A preliminary snapshot of Davide's investigations on HR in exciton-polariton BECs in semiconductor microcavities
Non-equilibrium quantum gases in optical devices:
- non-equilibrium BEC vs. lasing
- exotic strong correlation phenomena
  Collab: C. Ciuti (Paris 7), M. Wouters (EPFL), A. Imamoglu (ETHZ), D. Gerace (Pavia)
  Exp: A. Bramati, E. Giacobino (Paris 6), B. Deveaud (EPFL), L. Viña (UAM)

Slow light physics and applications:
- microscopic diagnostic of strongly correlated phases in ultracold gases
  Collab: Y. Castin (LKB), C. Kollath, A. Georges (Ec. Polytechnique)

Opto-mechanical forces in photonic devices:
- atomic BECs in high-Q optical cavities
  Exp: T. Esslinger (ETHZ)
- microring solid-state resonators
  Exp: M. Ghulinyan (FBK), L. Pavesi (Trento)